AXIONS IN THE EARLY UNIVERSE

Fabrizio Rompineve

CERN

based on

2211.03799 w/ A. Notari, G. Villadoro

2204.04228, 2107.07542 (PRL) w/ R.Z. Ferreira, A. Notari, O. Pujolàs

7th IBS-ICTP-MultiDark Workshop
29/11/2022

Background from Forbes/GETTY

AXIONS

(Pseudo)Goldstone bosons of **global U(1)** (*"Peccei-Quinn"*) **symmetries**, explicitly broken by **non-perturbative** effects.

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_a}j^\mu_{a\psi}$$

AXIONS

(Pseudo)Goldstone bosons of **global U(1)** (*"Peccei-Quinn"*) **symmetries**, explicitly broken by **non-perturbative** effects.

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_a}j^\mu_{a\psi}$$

Dimensionful coupling:
axion decay constant

AXIONS

(Pseudo)Goldstone bosons of **global U(1)** (*"Peccei-Quinn"*) **symmetries**, explicitly broken by **non-perturbative** effects.

Symmetry-breaking coupling to gauge fields (QCD)

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_a}j^\mu_{a\psi}$$

Dimensionful coupling: axion decay constant

Other non-perturbative sources of breaking possible (e.g. gravity, stringy instantons)

AXIONS

(Pseudo)Goldstone bosons of **global U(1)** (*"Peccei-Quinn"*) **symmetries**, explicitly broken by **non-perturbative** effects.

Symmetry-breaking coupling to gauge fields (QCD)

Interactions w/ matter (fermions) **respect symmetry**

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_a}j^\mu_{a\psi}$$

Dimensionful coupling: axion decay constant

$$j^\mu_{a\psi} = c_\psi \overline{\psi}\gamma^\mu\gamma_5\psi$$

Other non-perturbative sources of breaking possible (e.g. gravity, stringy instantons)

AXIONS

(Pseudo)Goldstone bosons of **global U(1)** (*"Peccei-Quinn"*) **symmetries**, explicitly broken by **non-perturbative** effects.

Symmetry-breaking coupling to gauge fields (QCD)

Interactions w/ matter (fermions) **respect symmetry**

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_a}j^\mu_{a\psi}$$

Dimensionful coupling: axion decay constant

$$j^\mu_{a\psi} = c_\psi \overline{\psi}\gamma^\mu\gamma_5\psi$$

Other non-perturbative sources of breaking possible (e.g. gravity, stringy instantons)

Theoretically well-motivated: e.g. strong-CP problem, compactifications of extra-dimensional theories

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

SCALE OF NON-PERTURBATIVE PHYSICS.

CAN BE BOTH **IR** (**CONFINING GAUGE SECTOR**, E.G. QCD AXION)
AND/OR UV (E.G. **STRINGY INSTANTONS, GRAVITY, ...**)

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

SCALE OF NON-PERTURBATIVE PHYSICS.

CAN BE BOTH **IR** (**CONFINING GAUGE SECTOR**, E.G. QCD AXION)
AND/OR UV (E.G. **STRINGY INSTANTONS, GRAVITY, ...**)

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

SCALE OF NON-PERTURBATIVE PHYSICS.

CAN BE BOTH **IR** (**CONFINING GAUGE SECTOR**, E.G. QCD AXION)
AND/OR UV (E.G. **STRINGY INSTANTONS, GRAVITY, ...**)

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

SCALE OF NON-PERTURBATIVE PHYSICS.

CAN BE BOTH **IR (CONFINING GAUGE SECTOR**, E.G. QCD AXION)
AND/OR UV (E.G. **STRINGY INSTANTONS, GRAVITY, ...**)

TYPICALLY LARGE TO AVOID CONSTRAINTS IF COUPLING TO SM IS PRESENT
($\gtrsim 10^8$ GeV **FOR QCD AXION)**

SUPPRESSES INTERACTIONS W/ MATTER AND AXION MASS

CONTAINS INFORMATION ON
UV ORIGIN OF PQ SYMMETRY

AXION, THE UV AND THE IR

Non-perturbative physics generates axion potential

$$V(a) = V(a + 2\pi f_a)$$

Which preserves discrete shift symmetry

Possible suppression due to e.g. mass of lightest quark

$\sim \sqrt{m_u/\Lambda}$

$$m_a = \kappa \frac{\Lambda^2}{f_a}$$

SCALE OF NON-PERTURBATIVE PHYSICS.

CAN BE BOTH **IR (CONFINING GAUGE SECTOR**, E.G. QCD AXION)
AND/OR UV (E.G. **STRINGY INSTANTONS, GRAVITY, ...**)

TYPICALLY LARGE TO AVOID CONSTRAINTS IF COUPLING TO SM IS PRESENT
($\gtrsim 10^8$ GeV **FOR QCD AXION)**

SUPPRESSES INTERACTIONS W/ MATTER AND AXION MASS

CONTAINS INFORMATION ON
UV ORIGIN OF PQ SYMMETRY

AXION DIVISIONS

AXION DIVISIONS

AXION DIVISIONS

ORIGIN

m_a

COSMOLOGY

AXION DIVISIONS

HEAVY

ORIGIN

Heavy dark gauge sectors/
UV instantons/small decay constants

e.g. see talk by L.Vecchi

m_a 100 GeV 100 MeV

Collider searches
(If coupled to SM)

COSMOLOGY

Decay once

$$\Gamma_a \sim \frac{m_a^3}{f_a^2} \gtrsim H$$

$$H \equiv \dot{R}/R$$

(typically before BBN)

AXION DIVISIONS

HEAVY

LIGHT

ORIGIN

Heavy dark gauge sectors/
UV instantons/small decay constants

e.g. see talk by L.Vecchi

Light gauge sectors
(including QCD)

m_a 100 GeV 100 MeV eV

Collider searches
(If coupled to SM)

Can be produced in stars
(If coupled to SM)

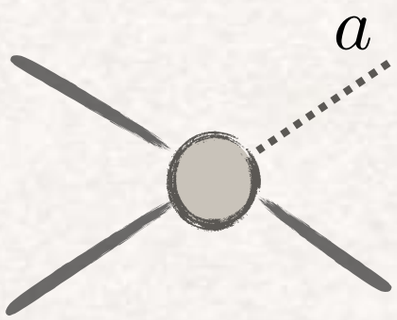
COSMOLOGY

Decay once

$$\Gamma_a \sim \frac{m_a^3}{f_a^2} \gtrsim H$$

$$H \equiv \dot{R}/R$$

(typically before BBN)



If produced in early Universe,
*behave as **hot/warm***
dark matter or dark radiation

AXION DIVISIONS

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

e.g. see talk by L.Vecchi

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

m_a 100 GeV 100 MeV eV 10^{-21} eV

Fuzzy DM

string axiverse

Collider searches ***(If coupled to SM)***

Can be produced in stars ***(If coupled to SM)***

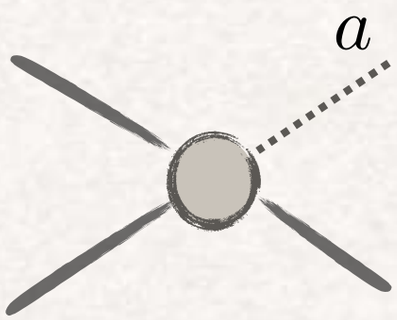
COSMOLOGY

Decay once

$$\Gamma_a \sim \frac{m_a^3}{f_a^2} \gtrsim H$$

$$H \equiv \dot{R}/R$$

(typically before BBN)



If produced in early Universe, behave as ***hot/warm dark matter or dark radiation***

AXION DIVISIONS

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

e.g. see talk by L.Vecchi

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

m_a 100 GeV 100 MeV eV 10^{-21} eV

Fuzzy DM

string axiverse

Collider searches
(If coupled to SM)

Can be produced in stars
(If coupled to SM)

Axion oscillations behave as dark matter (+ abundance from topological defects)

COSMOLOGY

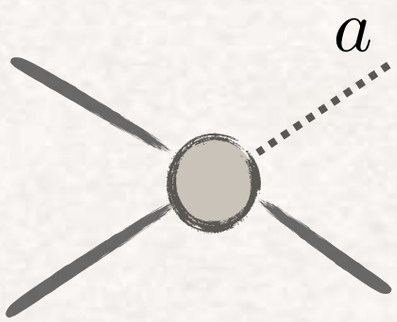
Decay once

$$\Gamma_a \sim \frac{m_a^3}{f_a^2} \gtrsim H$$

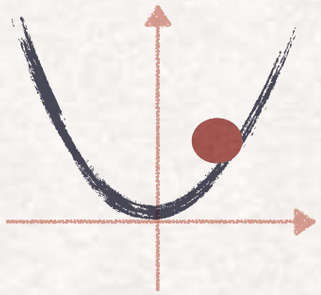
$$H \equiv \dot{R}/R$$

(typically before BBN)

$$M_p \equiv (8\pi G_N)^{-1/2} \sim 10^{18}\ \mathrm{GeV}$$



*If produced in early Universe, behave as **hot/warm dark matter or dark radiation***



$$m_a \gtrsim H$$

AXION DIVISIONS

HEAVY

LIGHT

ULTRALIGHT

Science news

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

e.g. see talk by L.Vecchi

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

m_a 100 GeV 100 MeV eV 10^{-21} eV

Fuzzy DM

string axiverse

See talk by I. Obata!

Behave as Dark Energy

Collider searches
(If coupled to SM)

Can be produced in stars
(If coupled to SM)

Axion oscillations behave as dark matter (+ abundance from topological defects)

COSMOLOGY

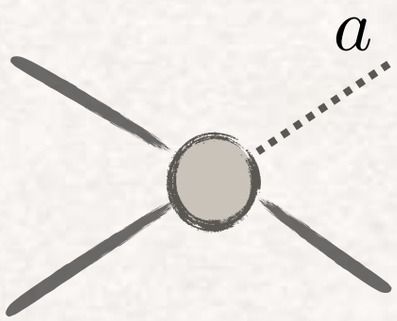
Decay once

$$\Gamma_a \sim \frac{m_a^3}{f_a^2} \gtrsim H$$

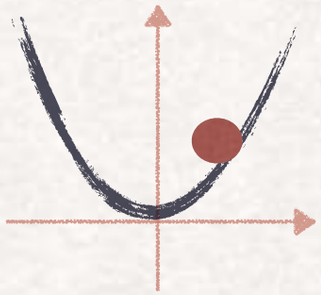
$$H \equiv \dot{R}/R$$

(typically before BBN)

$$M_p \equiv (8\pi G_N)^{-1/2} \sim 10^{18}\ \mathrm{GeV}$$



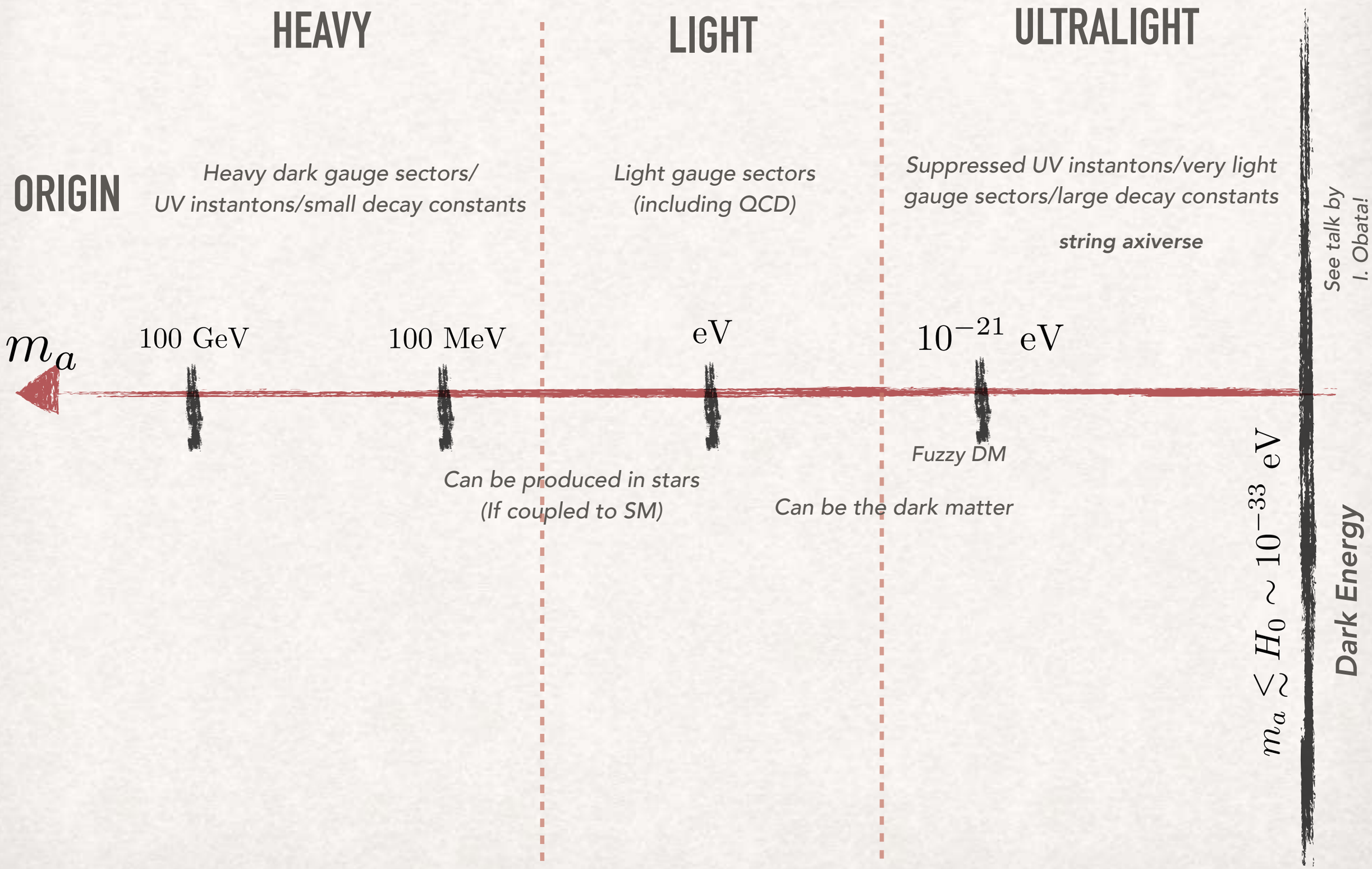
*If produced in early Universe, behave as **hot/warm** **dark matter or dark radiation***



$$m_a \gtrsim H$$

$$m_a \lesssim H_0 \sim 10^{-33}\ \mathrm{eV}$$

DISCOVERING AXIONS WITH COSMOLOGY



DISCOVERING AXIONS WITH COSMOLOGY

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

string axiverse

See talk by I. Obata!

Collider searches (If coupled to SM)

m_a

$100\ \mathrm{GeV}$ $100\ \mathrm{MeV}$ eV $10^{-21}\ \mathrm{eV}$

Fuzzy DM

Can be produced in stars (If coupled to SM)

Can be the dark matter

$m_a \lesssim H_0 \sim 10^{-33}\ \mathrm{eV}$

Dark Energy

GRAVITATIONAL WAVES

from: physicsworld.com

Can also probe light axions, ***see talk by E. Hardy***

From Peccei-Quinn Phase Transition + Topological Defects

DISCOVERING AXIONS WITH COSMOLOGY

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

string axiverse

Collider searches (If coupled to SM)

m_a

100 GeV

100 MeV

eV

10^{-21} eV

Fuzzy DM

See talk by I. Obata!

Can be produced in stars (If coupled to SM)

Can be the dark matter

$m_a \lesssim H_0 \sim 10^{-33}$ eV

Dark Energy

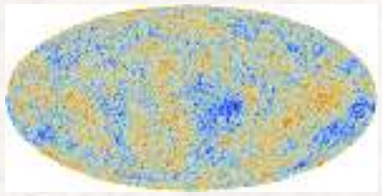
GRAVITATIONAL WAVES

from: physicsworld.com

Can also probe light axions, ***see talk by E. Hardy***

From Peccei-Quinn Phase Transition + Topological Defects

CMB



Planck, ESA

Effect on anisotropies

(and LSS, see talk by L. Xu!)

DISCOVERING AXIONS WITH COSMOLOGY

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

string axiverse

See talk by I. Obata!

Collider searches (If coupled to SM)

m_a

$100\ \mathrm{GeV}$ $100\ \mathrm{MeV}$ eV $10^{-21}\ \mathrm{eV}$

Fuzzy DM

Can be produced in stars (If coupled to SM)

Can be the dark matter

$m_a \lesssim H_0 \sim 10^{-33}\ \mathrm{eV}$

Dark Energy

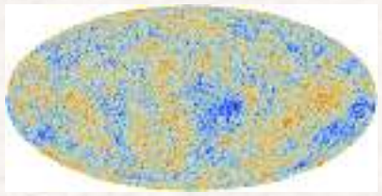
GRAVITATIONAL WAVES

from: physicsworld.com

*Can also probe light axions, **see talk by E. Hardy***

From Peccei-Quinn Phase Transition + Topological Defects

CMB



Planck, ESA

Effect on anisotropies

(and LSS, see talk by L. Xu!)

SMALL AND LARGE SCALE STRUCTURE (LSS)

from: universetoday.com

Deviations from Cold DM

DISCOVERING AXIONS WITH COSMOLOGY

Other features/ signatures possible, See talks by I. Obata, D.Cyncynates, A. Papageorgiou, A. Tesi, D. Marsh!

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

string axiverse

m_a

Collider searches (If coupled to SM)

100 GeV — 100 MeV — eV — 10^{-21} eV — $m_a \lesssim H_0 \sim 10^{-33}$ eV

Fuzzy DM

Can be produced in stars (If coupled to SM)

Can be the dark matter

Dark Energy

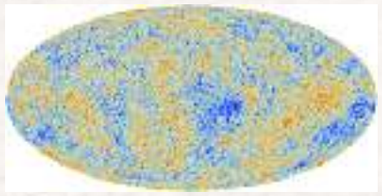
GRAVITATIONAL WAVES

19, w/ von Harling, Pomarol, Pujolàs
21, 22 w/ Ferreira, Notari, Pujolàs

from: physicsworld.com

From Peccei-Quinn Phase Transition + Topological Defects

CMB



Planck, ESA

14 w/ Hebecker, Mangat, Witkowski
20 w/ Ferreira, Notari
22 w/ Notari, Villadoro

SMALL AND LARGE SCALE STRUCTURE (LSS)

from: universetoday.com

19, 20 w/ Olle, Pujolàs
21 w/ Allali, Hertzberg

DISCOVERING AXIONS WITH COSMOLOGY

Other features/ signatures possible, See talks by I. Obata, D.Cyncynates, A. Papageorgiou, A. Tesi, D. Marsh!

HEAVY

LIGHT

ULTRALIGHT

ORIGIN

Heavy dark gauge sectors/ UV instantons/small decay constants

Light gauge sectors (including QCD)

Suppressed UV instantons/very light gauge sectors/large decay constants

string axiverse

Collider searches (If coupled to SM)

m_a

100 GeV — 100 MeV — eV — 10^{-21} eV

Fuzzy DM

Can be produced in stars (If coupled to SM)

Can be the dark matter

$m_a \lesssim H_0 \sim 10^{-33}$ eV

Dark Energy

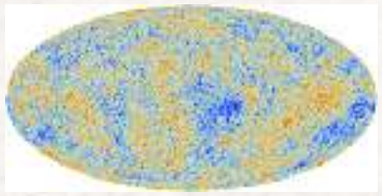
GRAVITATIONAL WAVES

19, w/ von Harling, Pomarol, Pujolàs
21, 22 w/ Ferreira, Notari, Pujolàs

from: physicsworld.com

From Peccei-Quinn Phase Transition + Topological Defects

CMB



Planck, ESA

14 w/ Hebecker, Mangat, Witkowski
20 w/ Ferreira, Notari
22 w/ Notari, Villadoro

SMALL AND LARGE SCALE STRUCTURE (LSS)

from: universetoday.com

19, 20 w/ Olle, Pujolàs
21 w/ Allali, Hertzberg

THE QCD AXION AS A LIGHT “HOT” RELIC

2211.03799 w/ A.Notari, G. Villadoro
+
2012.06566 w/ R.Ferreira, A. Notari

THE QCD AXION AS A LIGHT "HOT" RELIC

$$G_{\mu\nu} \to \text{QCD field strength}$$

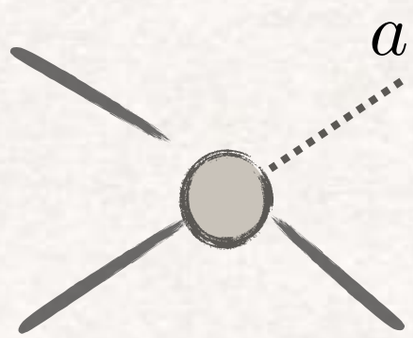
$$m_a \simeq 0.57 \text{ eV} \left(\frac{10^7 \text{ GeV}}{f_a} \right)$$

2211.03799 w/ A.Notari, G. Villadoro
+
2012.06566 w/ R.Ferreira, A. Notari

THE QCD AXION AS A LIGHT "HOT" RELIC

$$G_{\mu\nu} \to \text{QCD field strength}$$

$$m_a \simeq 0.57 \text{ eV} \left(\frac{10^7 \text{ GeV}}{f_a} \right)$$



Different contribution to total axion abundance,
Separate from cold dark matter axions produced via misalignment+topological defects

2211.03799 w/ A.Notari, G. Villadoro
+
2012.06566 w/ R.Ferreira, A. Notari

LIGHT RELICS/DARK RADIATION

See also talk by L. Xu!

*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

Akita, Yamaguchi 20/…

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

LIGHT RELICS/DARK RADIATION

See also talk by L. Xu!

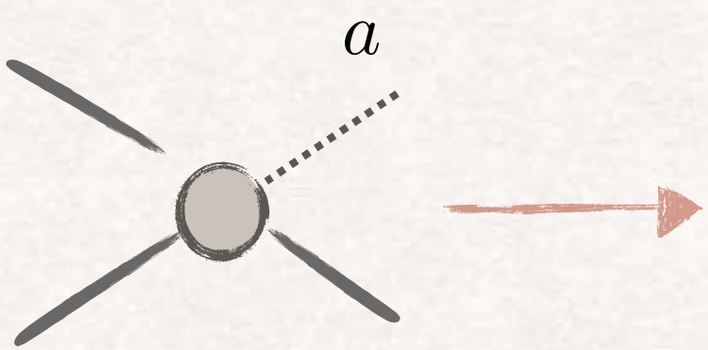
*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

Akita, Yamaguchi 20/…

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$



$$\Gamma_a \gg H$$

LIGHT RELICS/DARK RADIATION

See also talk by L. Xu!

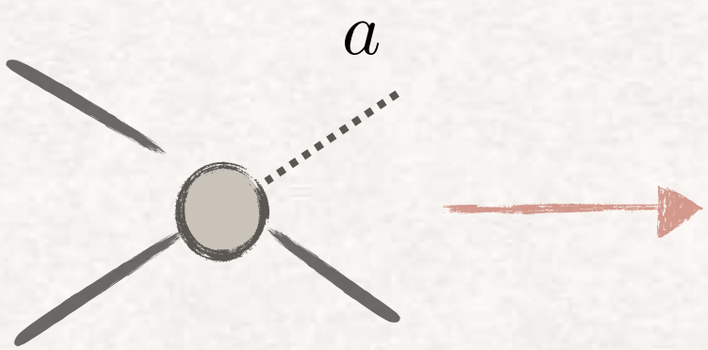
*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

Akita, Yamaguchi 20/…

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$



$$\Gamma_a \gg H$$

Decoupling (instantaneous approx) when

$$\Gamma_a(T_d) \lesssim H(T_d)$$

LIGHT RELICS/DARK RADIATION

See also talk by L. Xu!

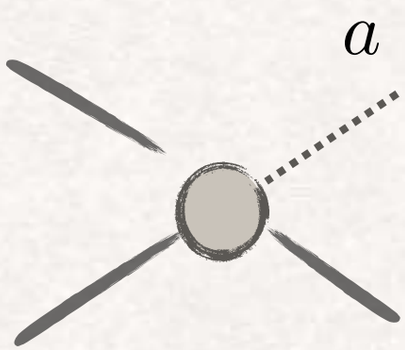
*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

Akita, Yamaguchi 20/…

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$



$$\Gamma_a \gg H$$

Decoupling (instantaneous approx) when

$$\Gamma_a(T_d) \lesssim H(T_d)$$

If

$$m_a \ll {\rm eV}$$

$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

LIGHT RELICS/DARK RADIATION

See also talk by L. Xu!

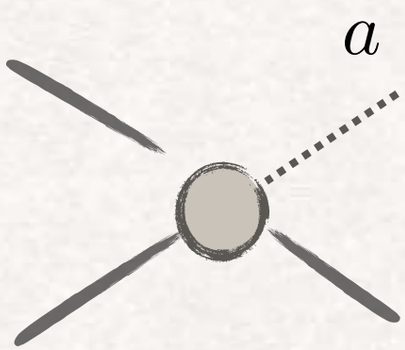
*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

Akita, Yamaguchi 20/…

$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$



$$\Gamma_a \gg H$$

Decoupling (instantaneous approx) when

$$\Gamma_a(T_d) \lesssim H(T_d)$$

If

$$m_a \ll {\rm eV}$$

$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

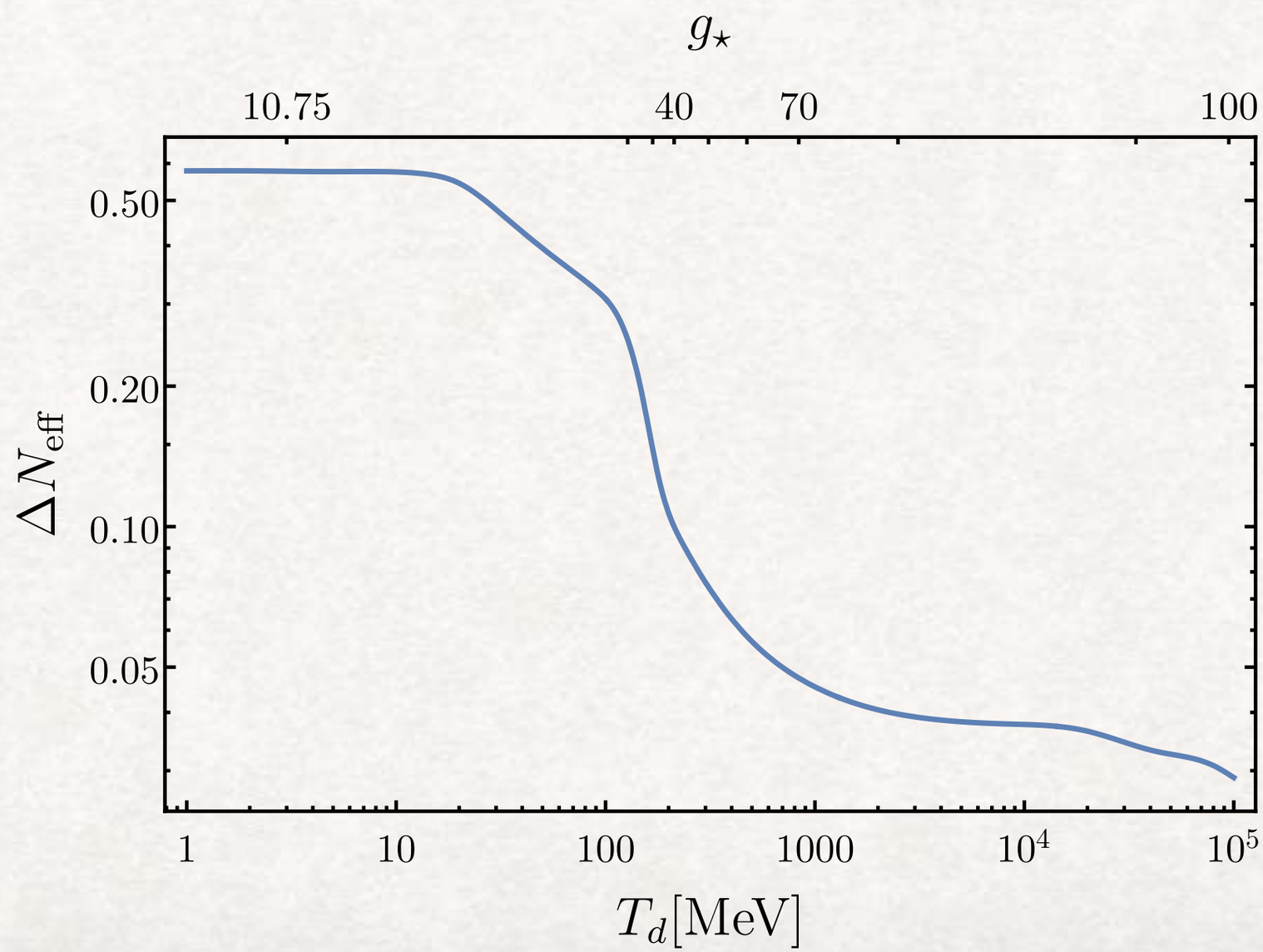
THE LARGER THE RATE, THE LOWER THE DECOUPLING TEMPERATURE, THE LARGER $\Delta N_{\rm eff}$

LIGHT RELICS/DARK RADIATION

*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff} \qquad \Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

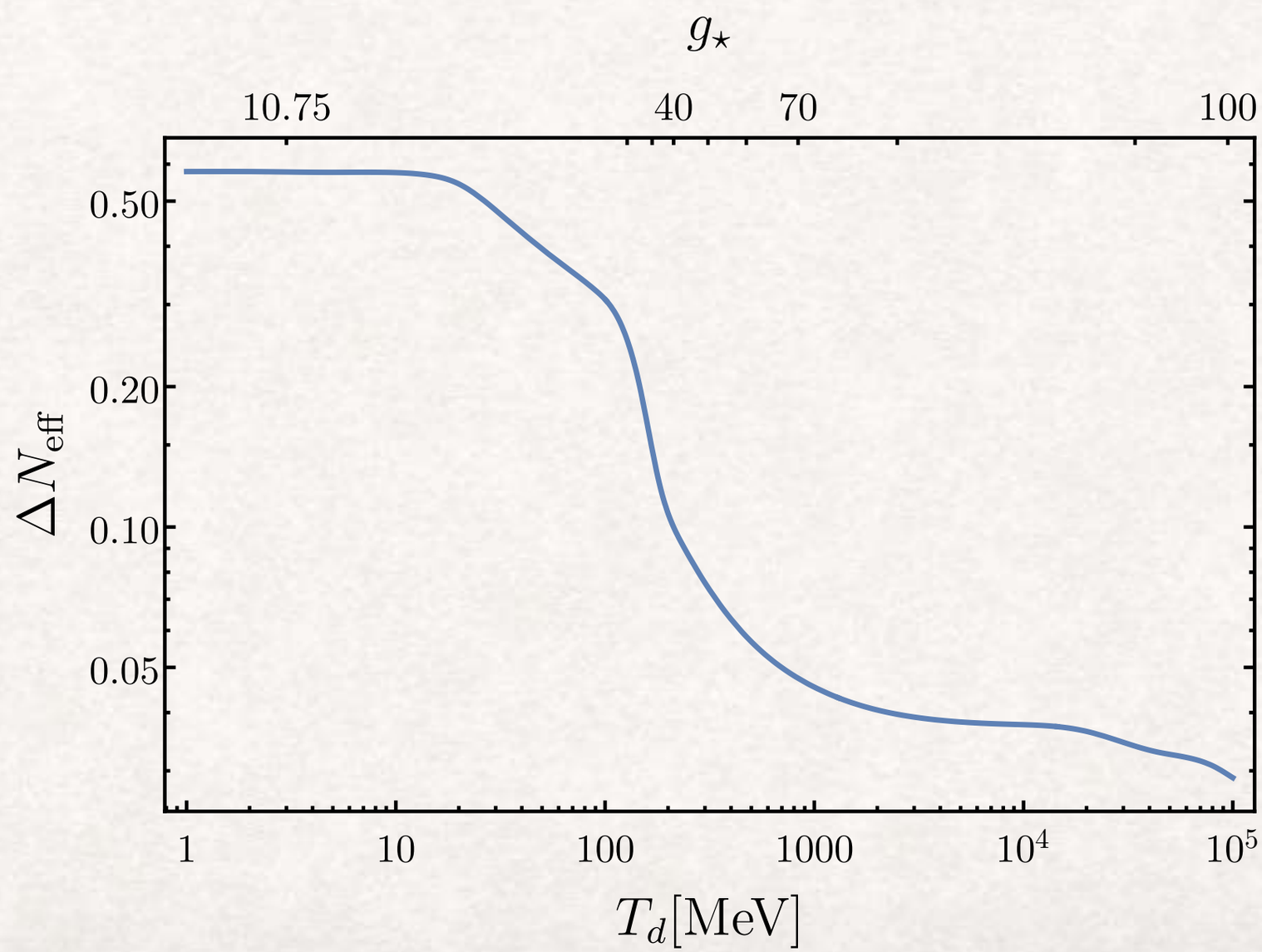
$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff} \qquad \Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

Light relics affect CMB anisotropies via:

1. Background

$$H^2 = \frac{\sum_{i=\rm all} \rho_i}{M_p^2}$$

2. Perturbations



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

*Any relativistic component at CMB (**recombination**), in addition to SM neutrinos*

Can also consider at BBN

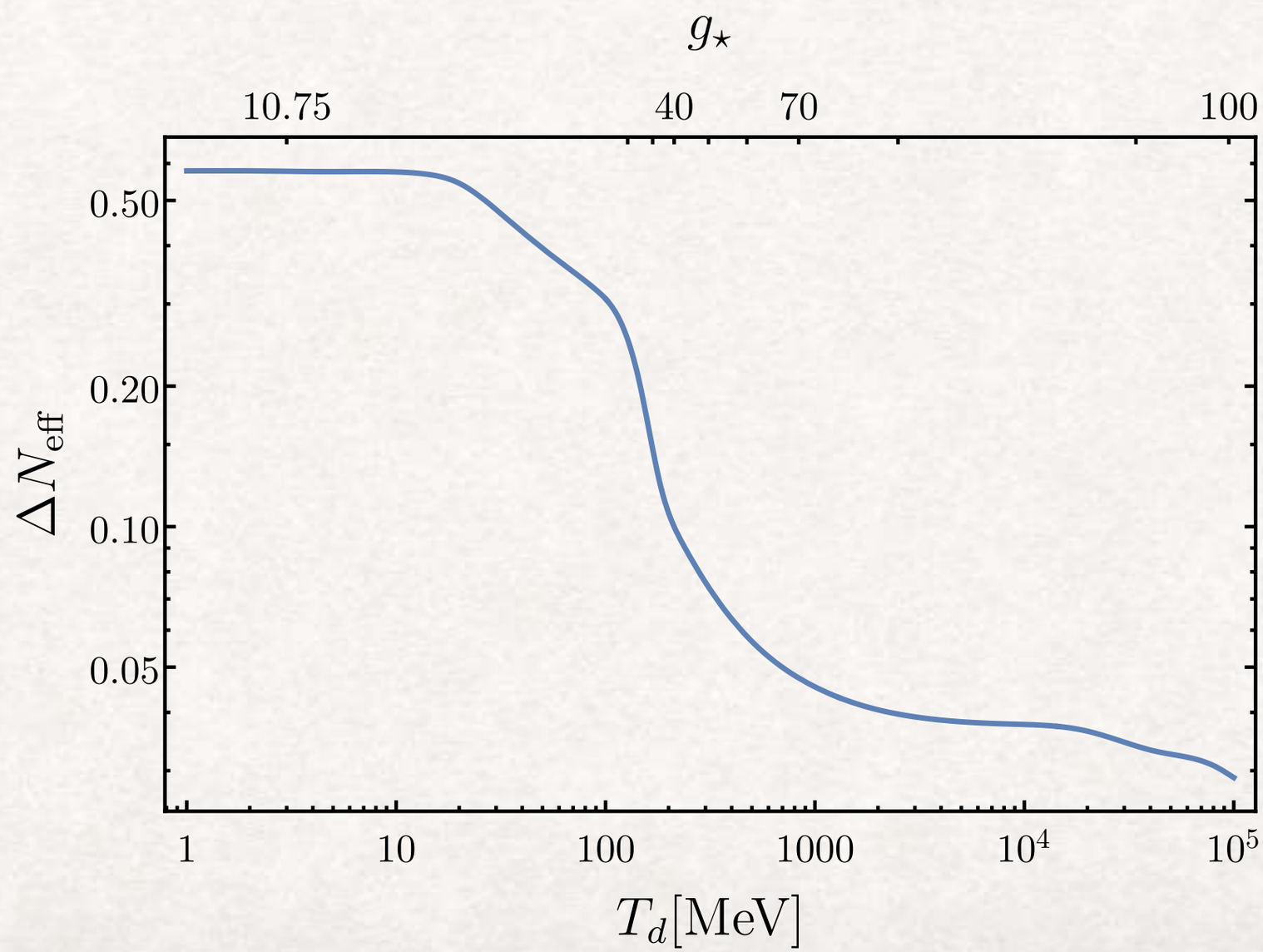
$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff} \qquad \Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

Light relics affect CMB anisotropies via:

1. Background

$$H^2 = \frac{\sum_{i=\rm all} \rho_i}{M_p^2}$$

2. Perturbations



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

Any relativistic component at recombination, in addition to SM neutrinos

Can also consider at BBN

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

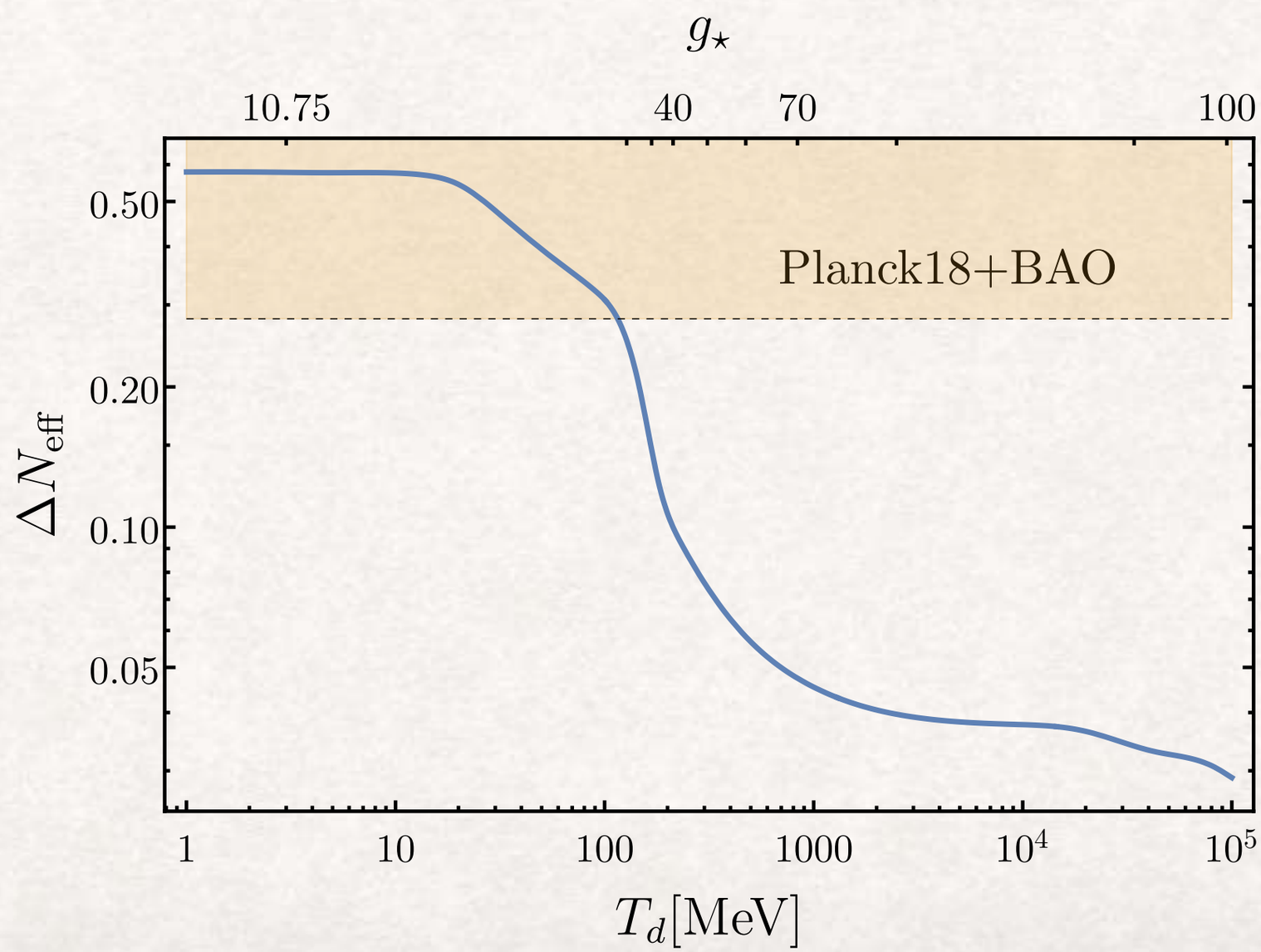
$$\Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

Light relics affect CMB anisotropies via:

1. Background

$$H^2 = \frac{\sum_{i=\rm all} \rho_i}{M_p^2}$$

2. Perturbations



g_* from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

Any relativistic component at recombination, in addition to SM neutrinos

Can also consider at BBN

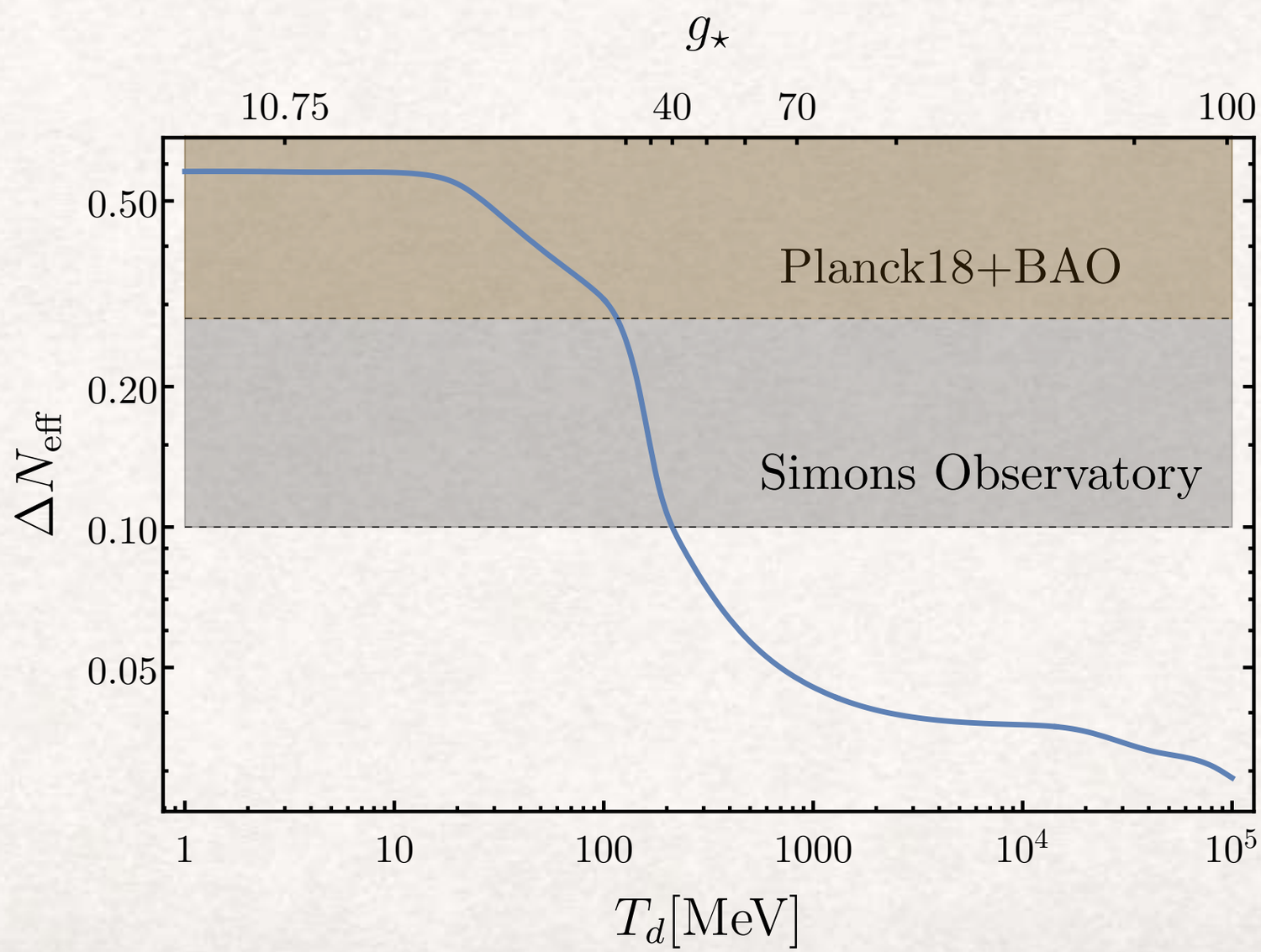
$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff} \qquad \Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

Light relics affect CMB anisotropies via:

1. Background

$$H^2 = \frac{\sum_{i=\rm all} \rho_i}{M_p^2}$$

2. Perturbations



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

Any relativistic component at recombination, in addition to SM neutrinos

Can also consider at BBN

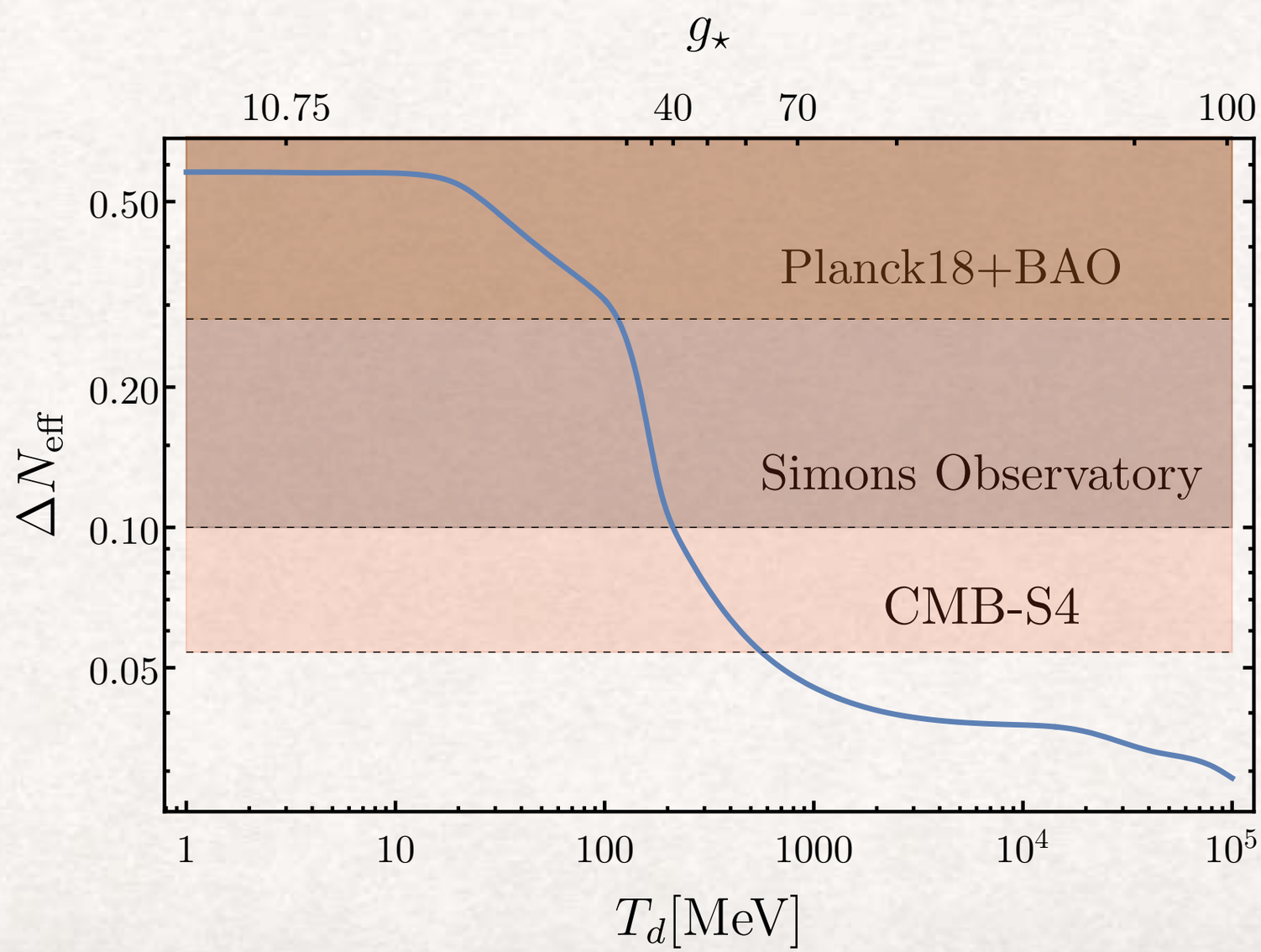
$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff} \qquad \Delta N_{\rm eff} \equiv \frac{\rho_{\rm DR}}{\rho_\nu}|_{\rm rec} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm DR}}{\rho_\gamma}|_{\rm rec}$$

Light relics affect CMB anisotropies via:

1. Background

$$H^2 = \frac{\sum_{i=\rm all} \rho_i}{M_p^2}$$

2. Perturbations



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

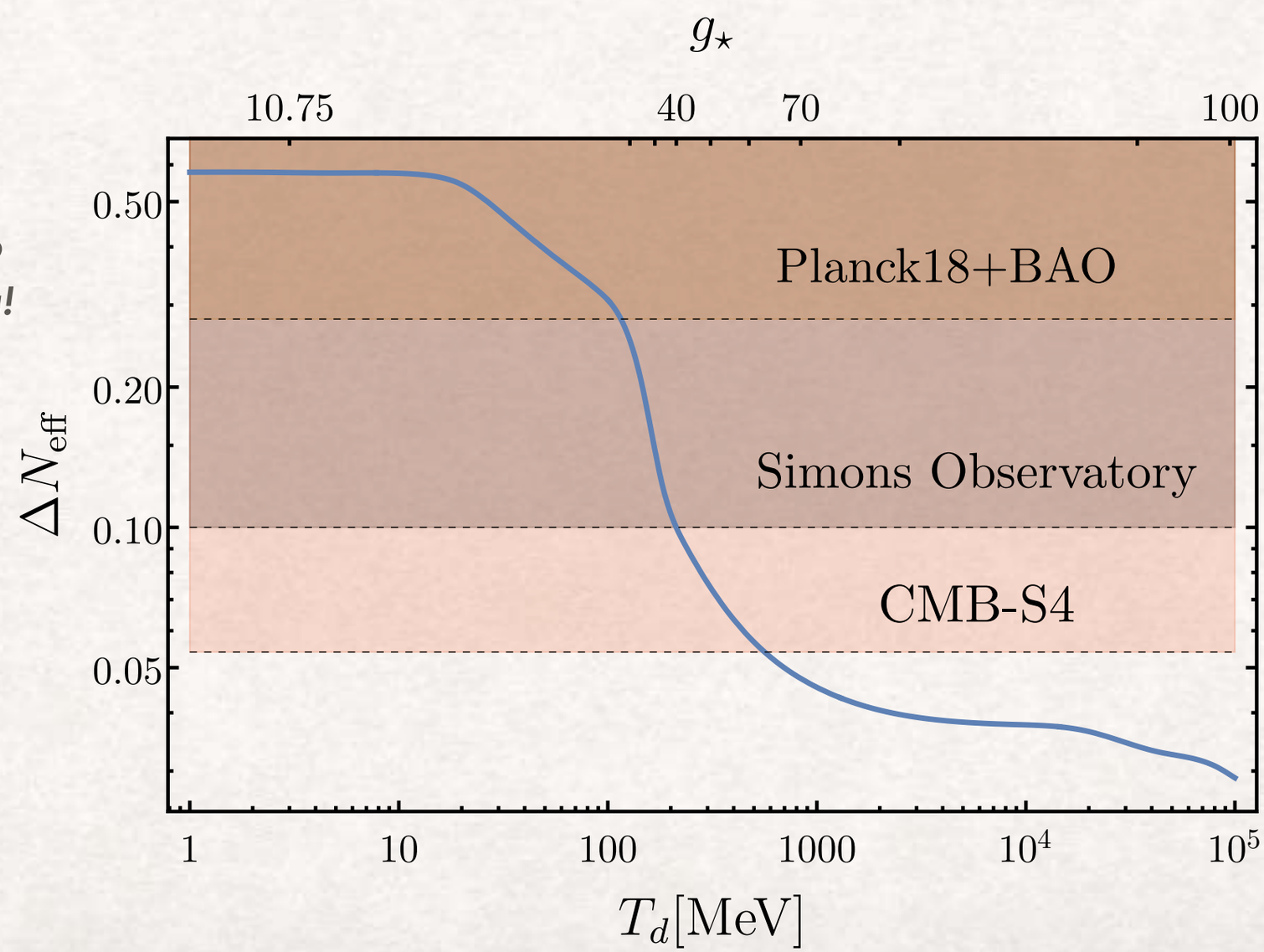
$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$



g_* from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

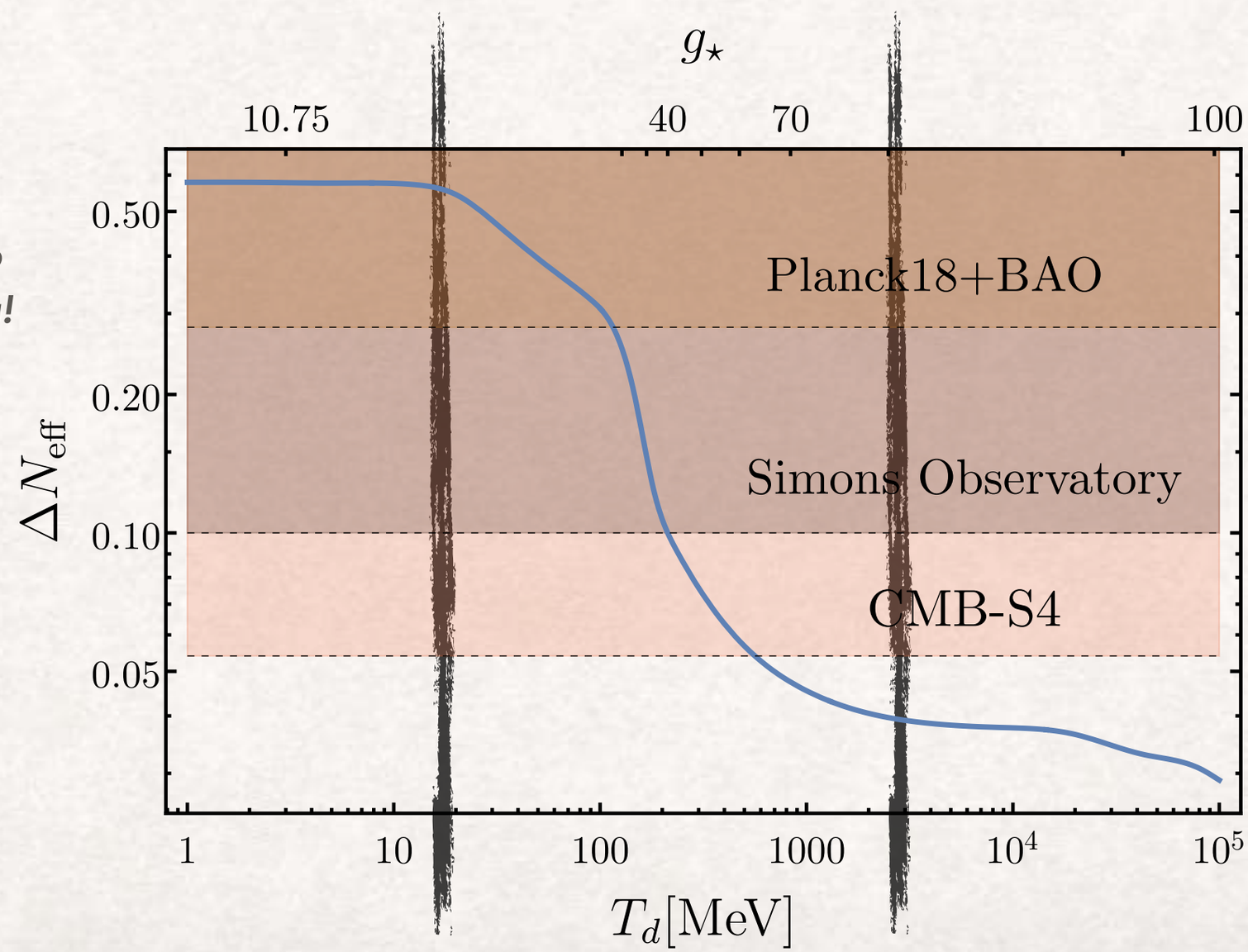
$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$

2. *Number of degrees of freedom varies rapidly, each mode sees different value.*



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

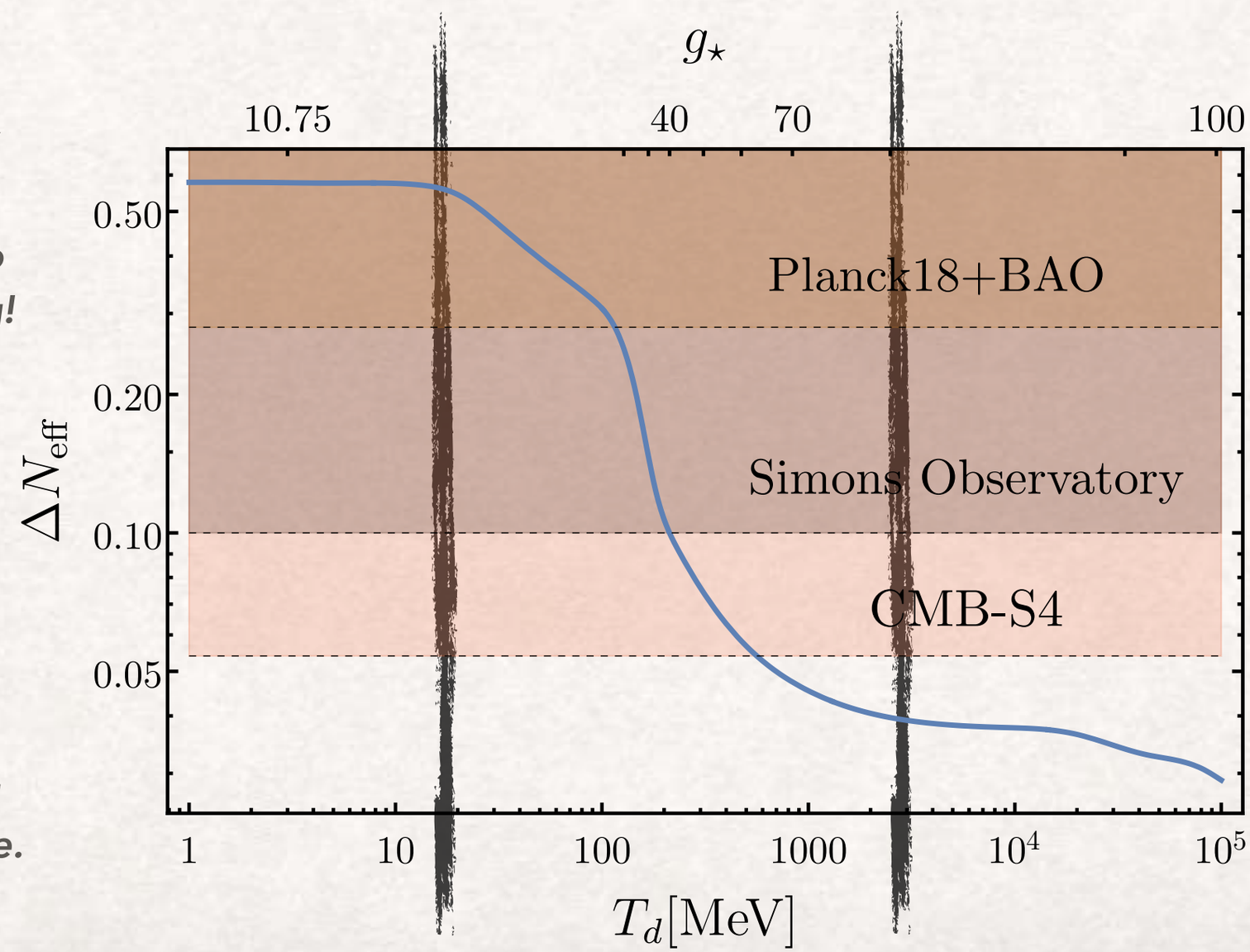
CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$

2. *Number of degrees of freedom varies rapidly, each mode sees different value.*

3. *Production may have never reached thermal equilibrium (i.e. sub thermal production)*



g_* from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

Not valid in these cases!

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

$$\cancel{\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}}$$

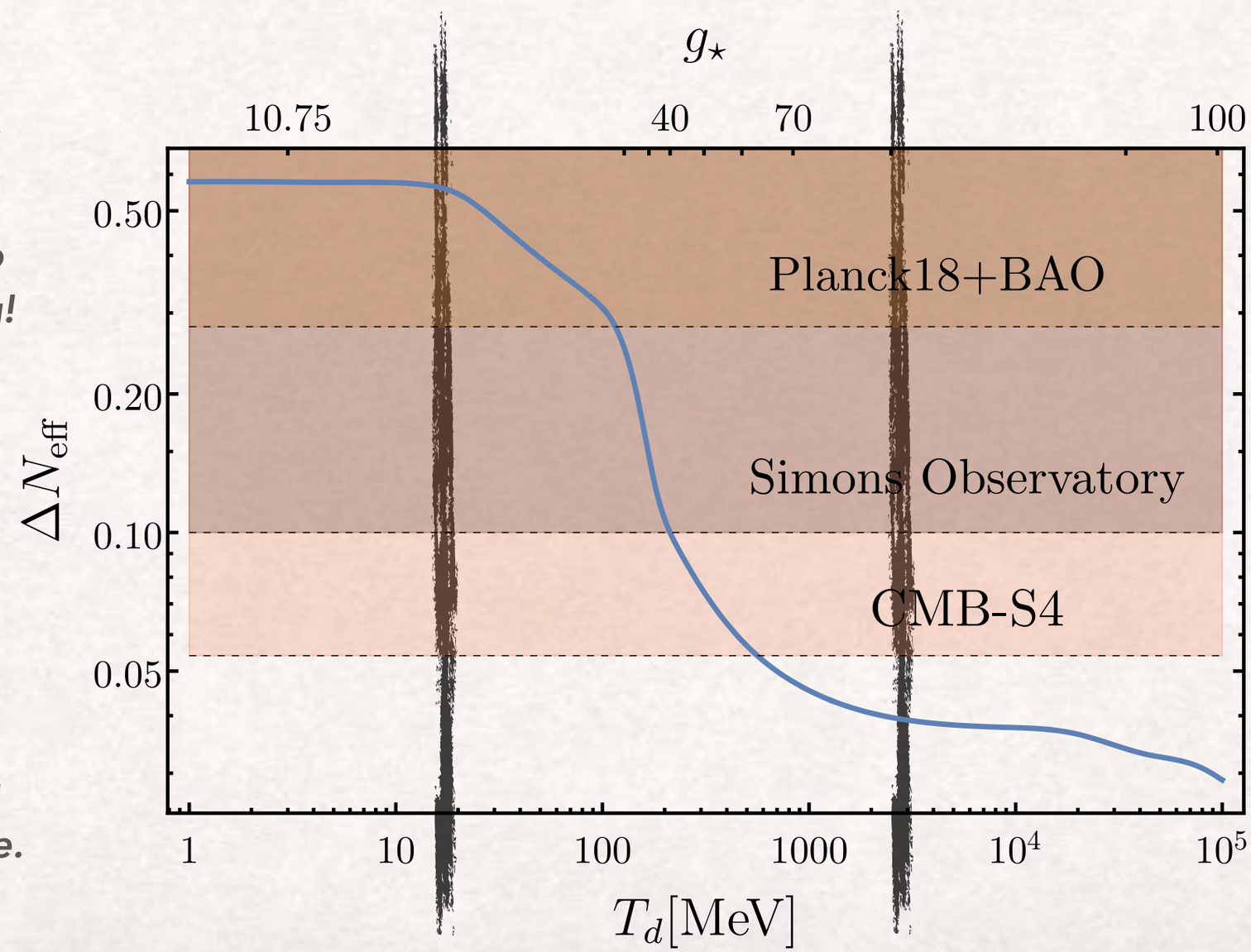
CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$

2. *Number of degrees of freedom varies rapidly, each mode sees different value.*

3. *Production may have never reached thermal equilibrium (i.e. sub thermal production)*



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

Not valid in these cases!

For QCD axion, need to solve Boltzmann equation

Ferreira, Notari 18/+D'Eramo et al 18/ Ferreira, Notari, FR 20/...

Actually.. momentum-dependent Boltzmann

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

$$\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}$$

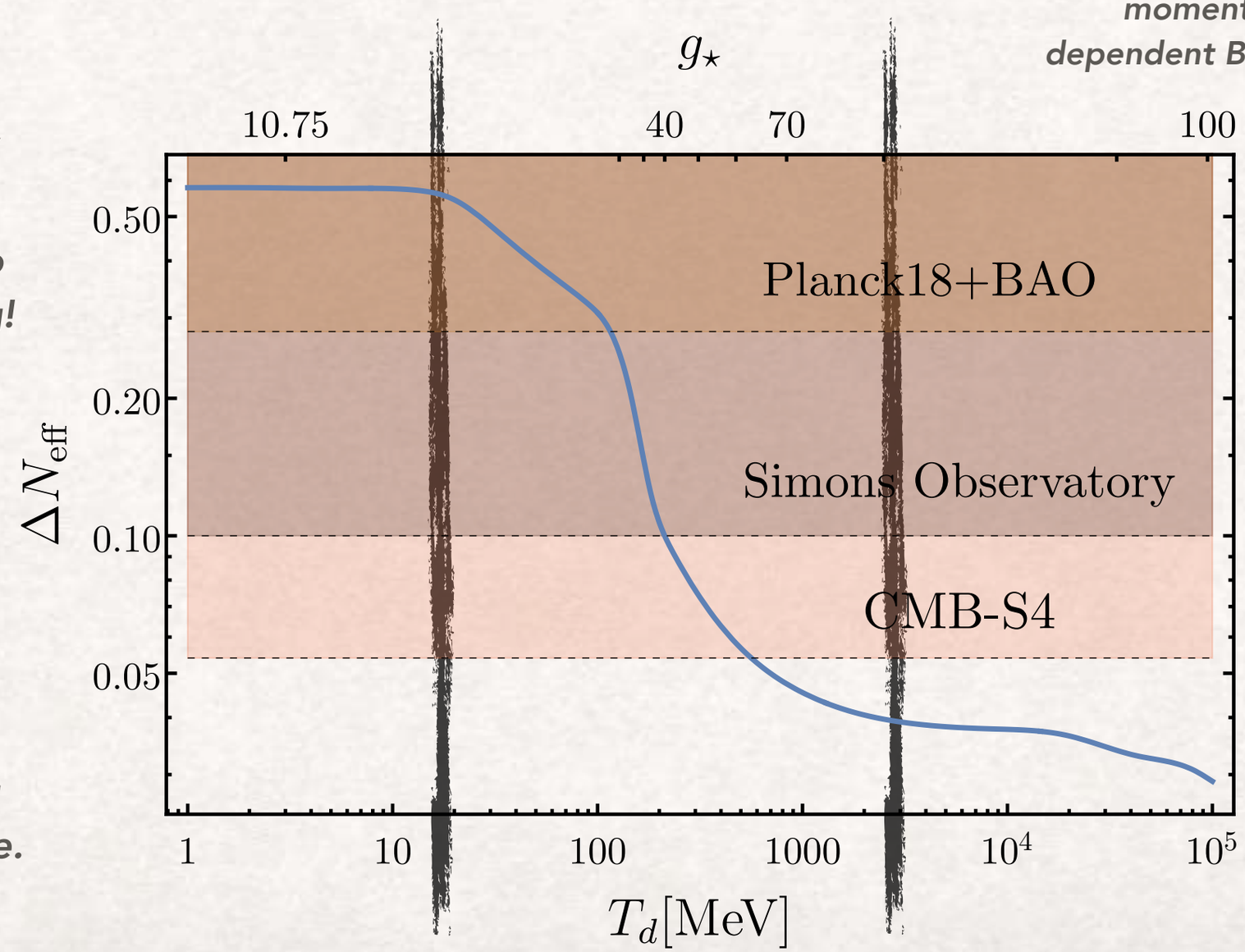
CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$

2. *Number of degrees of freedom varies rapidly, each mode sees different value.*

3. *Production may have never reached thermal equilibrium (i.e. sub thermal production)*



$g_\star$ from Borsanyi et al, Nature 539 (2016)

LIGHT RELICS/DARK RADIATION

In fact, 1. and 2. lead to + 0.044 for neutrinos, which decouple below T~3 MeV

$$N_{\rm eff} = 3.044 + \Delta N_{\rm eff}$$

$$\cancel{\Delta N_{\rm eff} \simeq 0.3 \left[\frac{g_\star(100\ {\rm MeV})}{g_\star(T_d)}\right]^{\frac{4}{3}}}$$

Not valid in these cases!

For QCD axion, need to solve Boltzmann equation

Ferreira, Notari 18/+D'Eramo et al 18/ Ferreira, Notari, FR 20/...

Actually.. momentum-dependent Boltzmann

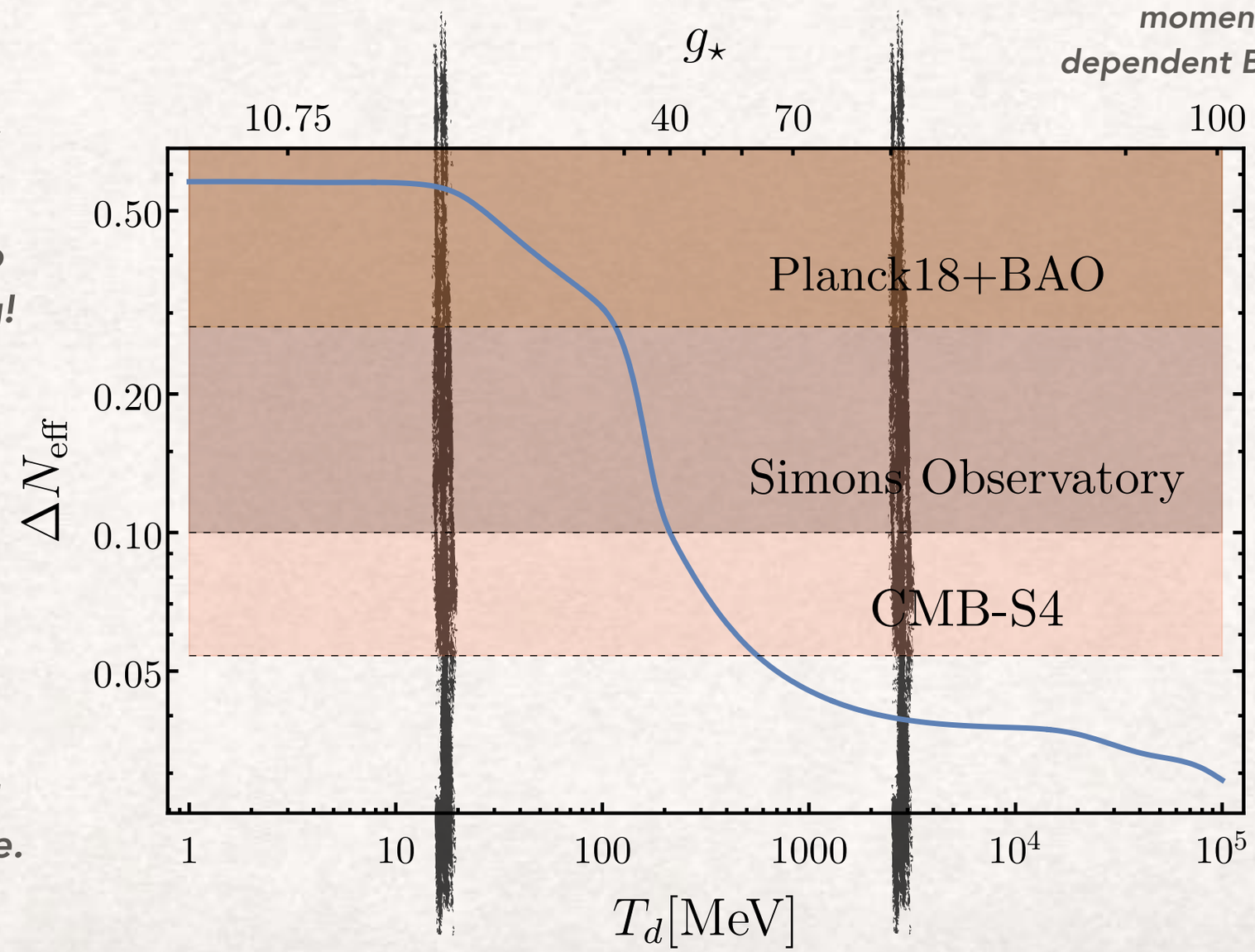
CAVEAT ON COMPUTATION

1. *Production Cross sections/ rates are generally momentum-dependent! No "instantaneous" decoupling!*

$$\sigma \equiv \sigma(s)$$

2. *Number of degrees of freedom varies rapidly, each mode sees different value.*

3. *Production may have never reached thermal equilibrium (i.e. sub thermal production)*



$g_\star$ from Borsanyi et al, Nature 539 (2016)

WHAT ABOUT THE QCD AXION?

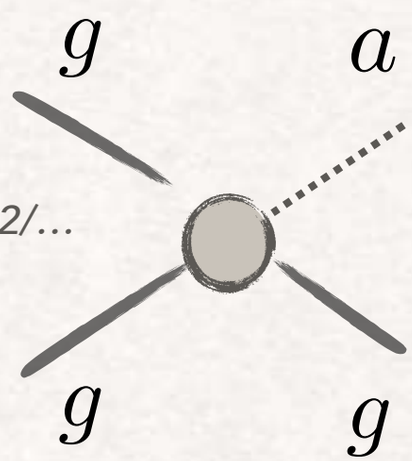
Hot axion quanta can be produced in scattering of SM states

Turner 88/
Berezhiani et al 92/

Production w/ quarks/leptons model-dependent

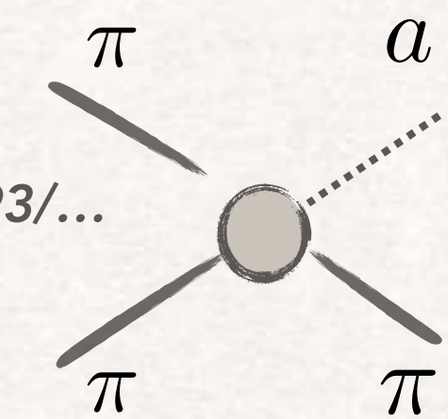
Model-independent production channels

Masso, Rota 02/…



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

Chang, Choi 93/…



$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

WHAT ABOUT THE QCD AXION?

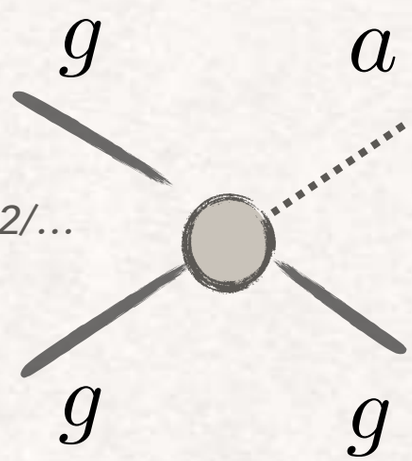
Hot axion quanta can be produced in scattering of SM states

Turner 88/
Berezhiani et al 92/

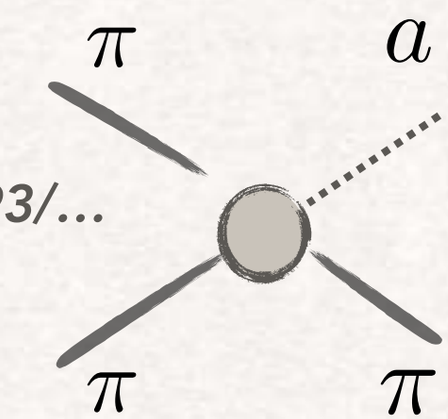
Production w/ quarks/leptons model-dependent

Model-independent production channels

Masso, Rota 02/…



Chang, Choi 93/…



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

T

$T \sim \mathrm{GeV}$

$T_{\mathrm{QCD}} \simeq 150\ \mathrm{MeV}$

Smaller decay constants $\Rightarrow$ Larger ΔN_{eff}

WHAT ABOUT THE QCD AXION?

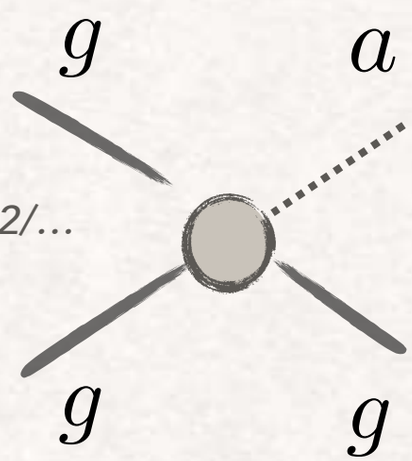
Hot axion quanta can be produced in scattering of SM states

Turner 88/
Berezhiani et al 92/

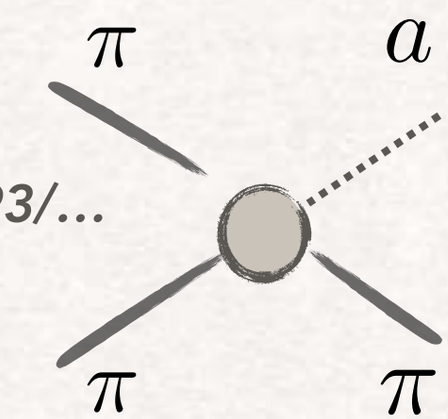
Production w/ quarks/leptons model-dependent

Model-independent production channels

Masso, Rota 02/…



Chang, Choi 93/…



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

T

$T \sim \mathrm{GeV}$

$T_{\mathrm{QCD}} \simeq 150\ \mathrm{MeV}$

Smaller decay constants $\Rightarrow$ Larger ΔN_{eff} $\Rightarrow$ Data set lower bound on f_a

WHAT ABOUT THE QCD AXION?

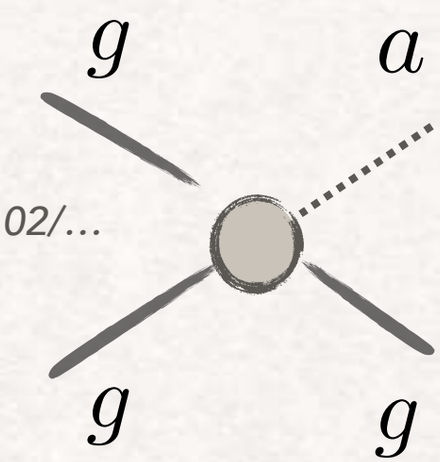
Hot axion quanta can be produced in scattering of SM states

Turner 88/
Berezhiani et al 92/

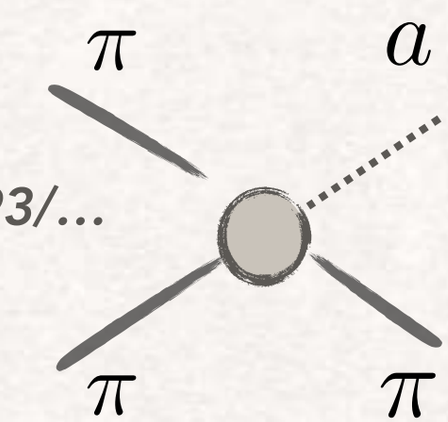
Production w/ quarks/leptons model-dependent

Model-independent production channels

Masso, Rota 02/…



Chang, Choi 93/…



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

T

$T \sim \mathrm{GeV}$

$T_{\mathrm{QCD}} \simeq 150\ \mathrm{MeV}$

Smaller decay constants $\Rightarrow$ Larger ΔN_{eff} $\Rightarrow$ Data set lower bound on f_a $\Rightarrow$ Upper bound on m_a

a.k.a. Hot Dark Matter Bound

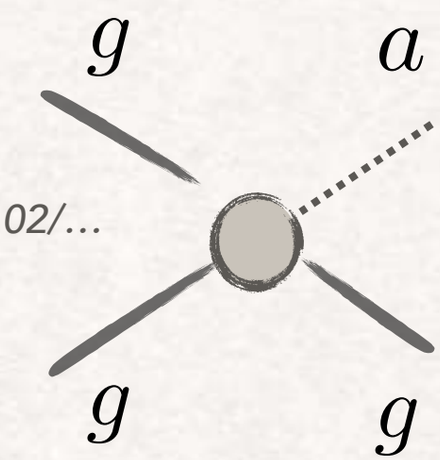
WHAT ABOUT THE QCD AXION?

Hot axion quanta can be produced in scattering of SM states

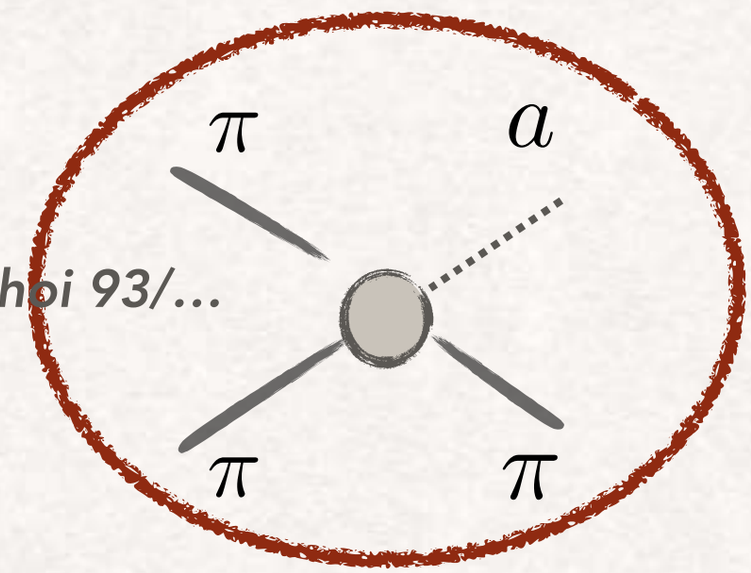
Turner 88/
Berezhiani et al 92/

For Planck18+BAO sensitivity

Masso, Rota 02/…



Chang, Choi 93/…



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

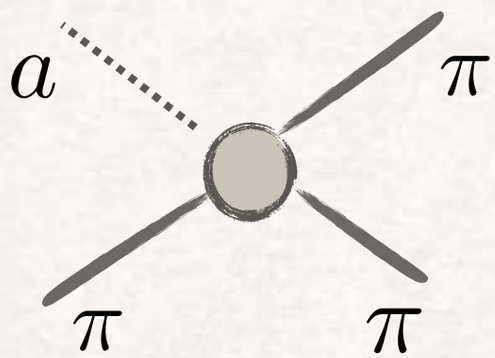
$T \sim \mathrm{GeV}$ $\qquad$ $T_{\mathrm{QCD}} \simeq 150\ \mathrm{MeV}$

Smaller decay constants $\Rightarrow$ Larger ΔN_{eff} $\Rightarrow$ Data set lower bound on f_a $\Rightarrow$ Upper bound on m_a

a.k.a. Hot Dark Matter Bound

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*

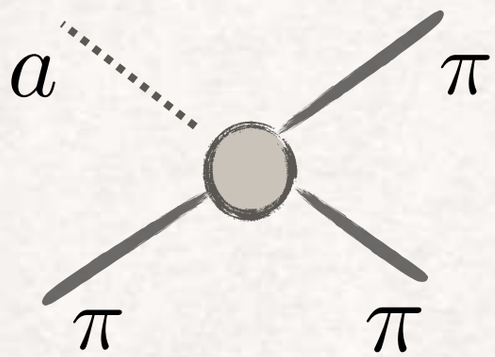


$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



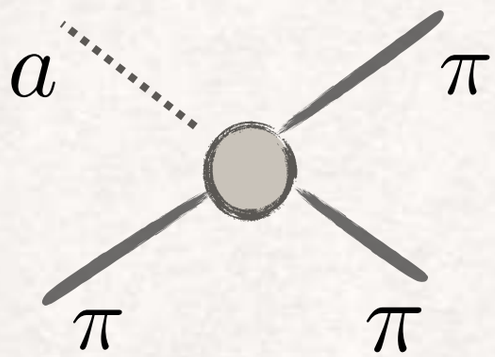
$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

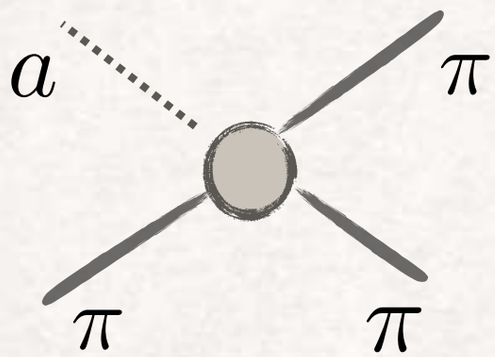
Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$

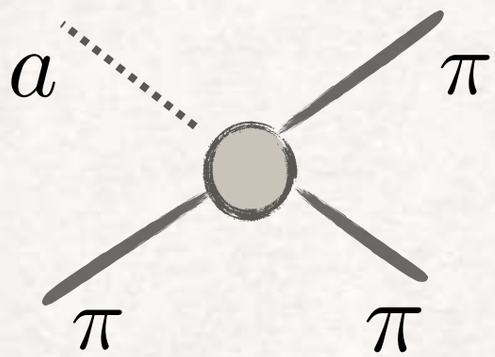
Used to set Hot Dark Matter Bound since the 90s, extending to T~200 MeV

Chang, Choi 93/Hannestad et al 05, 07/ Melchiorri et al 07/Di Valentino et al 16

See also D'Eramo, Hajkarim, Yun x2 21/ + Melchiorri et al 22

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a\left(2\partial^\mu\pi^0\pi^+\pi^- - \pi^0\partial^\mu\pi^+\pi^- - \pi^0\pi^+\partial^\mu\pi^-\right)$$

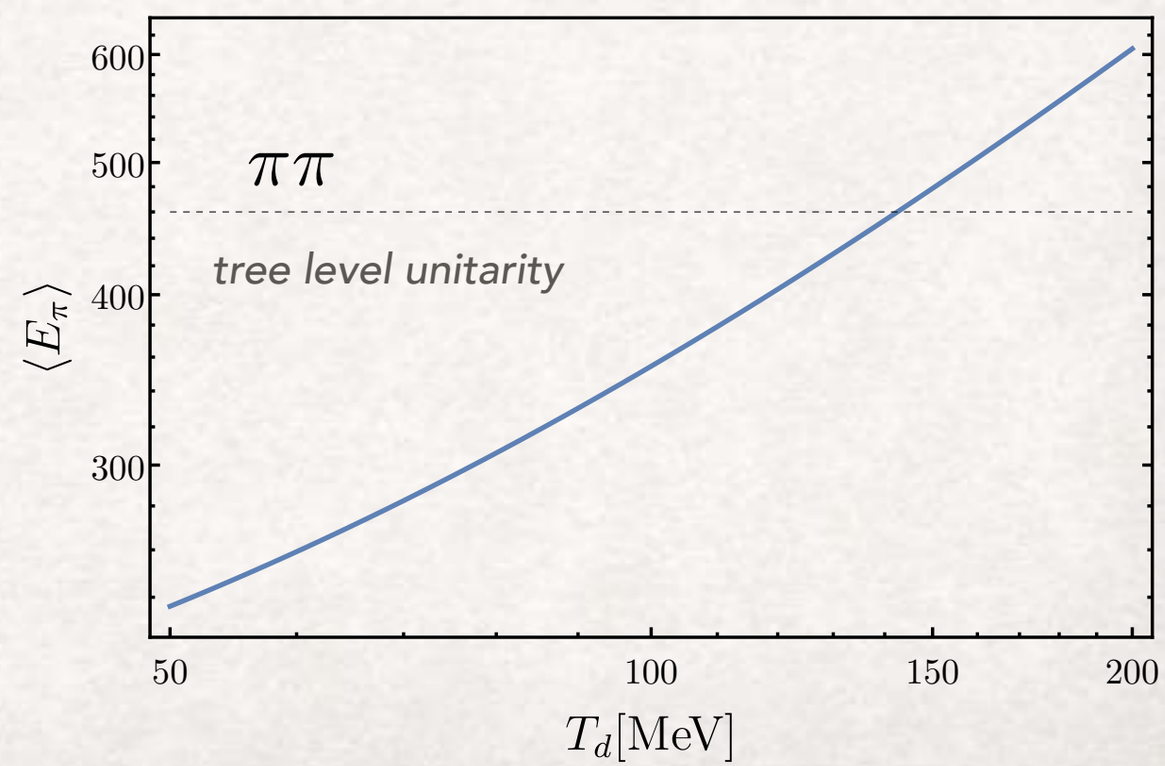
Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

However:

$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$



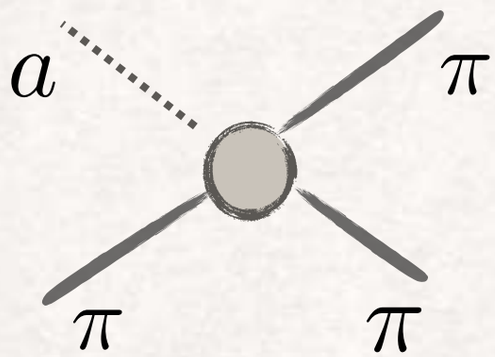
Used to set Hot Dark Matter Bound since the 90s, extending to T~200 MeV

Chang, Choi 93/Hannestad et al 05, 07/ Melchiorri et al 07/Di Valentino et al 16

See also D'Eramo, Hajkarim, Yun x2 21/ + Melchiorri et al 22

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a\left(2\partial^\mu\pi^0\pi^+\pi^- - \pi^0\partial^\mu\pi^+\pi^- - \pi^0\pi^+\partial^\mu\pi^-\right)$$

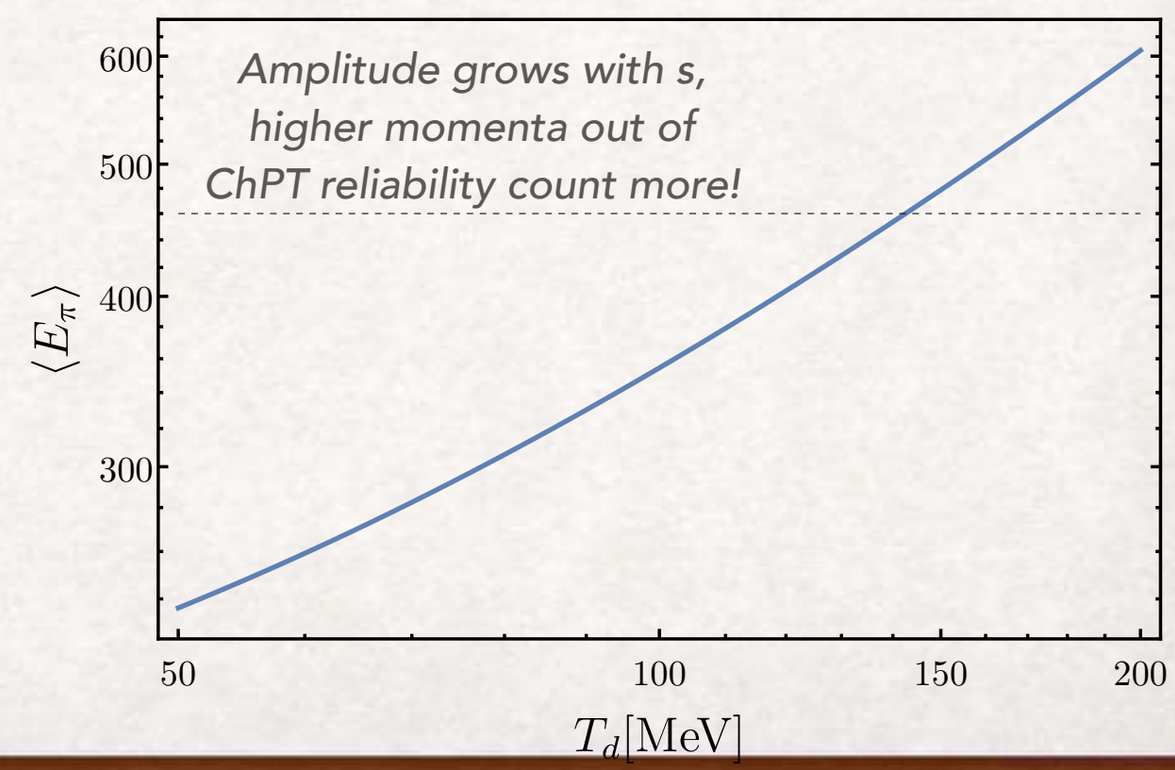
Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$

However:



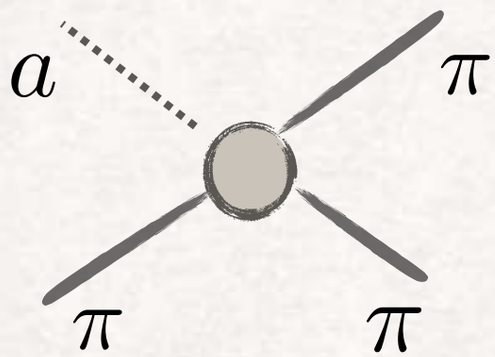
Used to set Hot Dark Matter Bound since the 90s, extending to T~200 MeV

Chang, Choi 93/Hannestad et al 05, 07/ Melchiorri et al 07/Di Valentino et al 16

See also D'Eramo, Hajkarim, Yun x2 21/ + Melchiorri et al 22

AXION-PION RATE

*At sufficiently low T, can use **chiral perturbation theory** to compute rate*



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$

Used to set Hot Dark Matter Bound since the 90s, extending to T~200 MeV

Chang, Choi 93/Hannestad et al 05, 07/ Melchiorri et al 07/Di Valentino et al 16/…

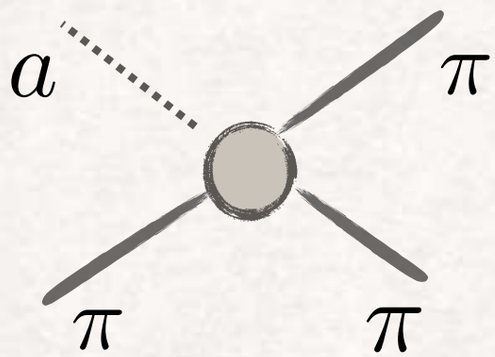
See also D'Eramo, Hajkarim, Yun x2 21/ + Melchiorri et al 22

Indeed thermal rates receive important NLO corrections below T~100 MeV

Di Luzio, Martinelli, Piazza 21 + 22

AXION-PION RATE

At sufficiently low T, can use chiral perturbation theory to compute rate



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

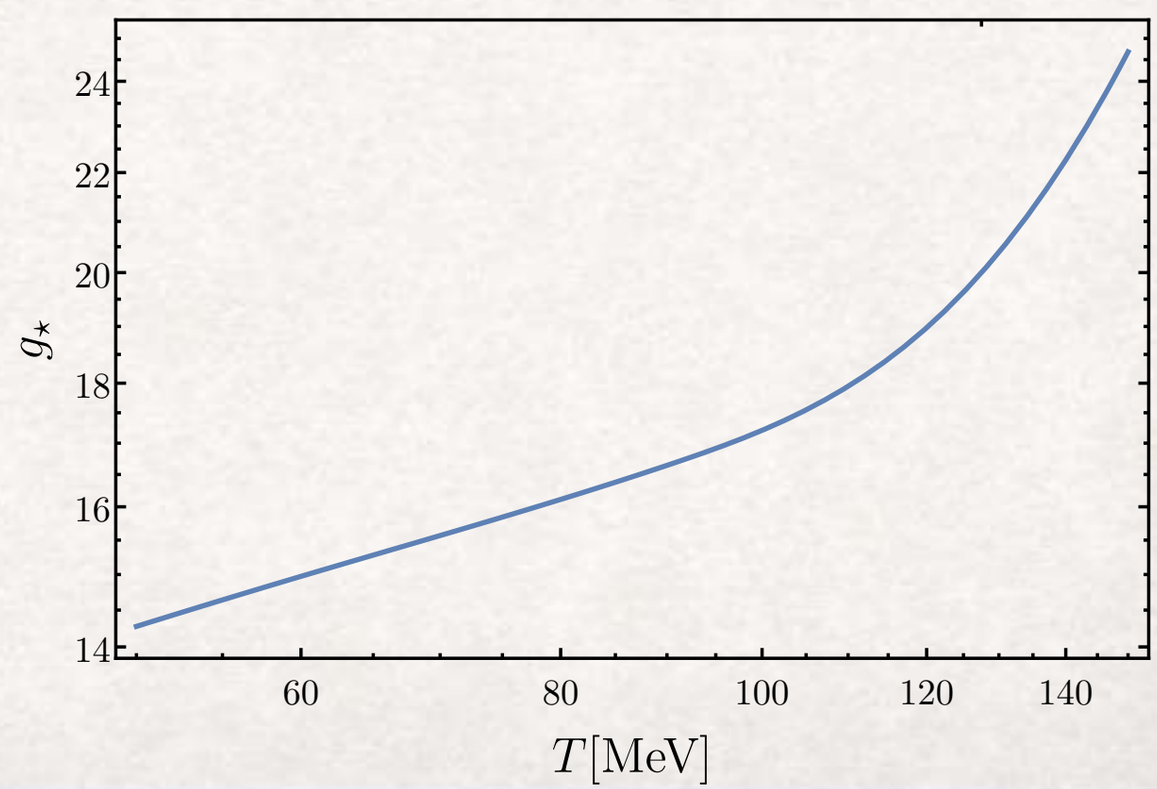
Model independent

$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

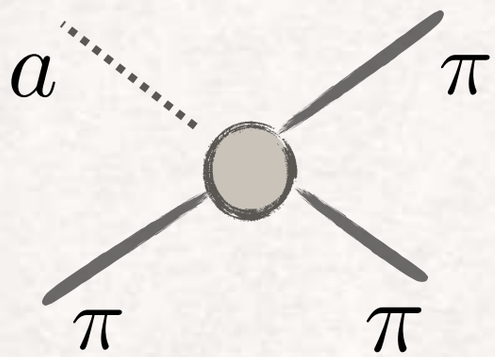
$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$

Furthermore, number of relativistic degrees of freedom still rapidly varying, with momentum-dependent amplitude!



AXION-PION RATE

At sufficiently low T, can use chiral perturbation theory to compute rate



$$\mathcal{L}_{a\pi} = \frac{1}{3}\frac{\epsilon - c_3}{f_a f_\pi}\partial_\mu a \left(2\partial^\mu \pi^0 \pi^+ \pi^- - \pi^0 \partial^\mu \pi^+ \pi^- - \pi^0 \pi^+ \partial^\mu \pi^-\right)$$

Model independent

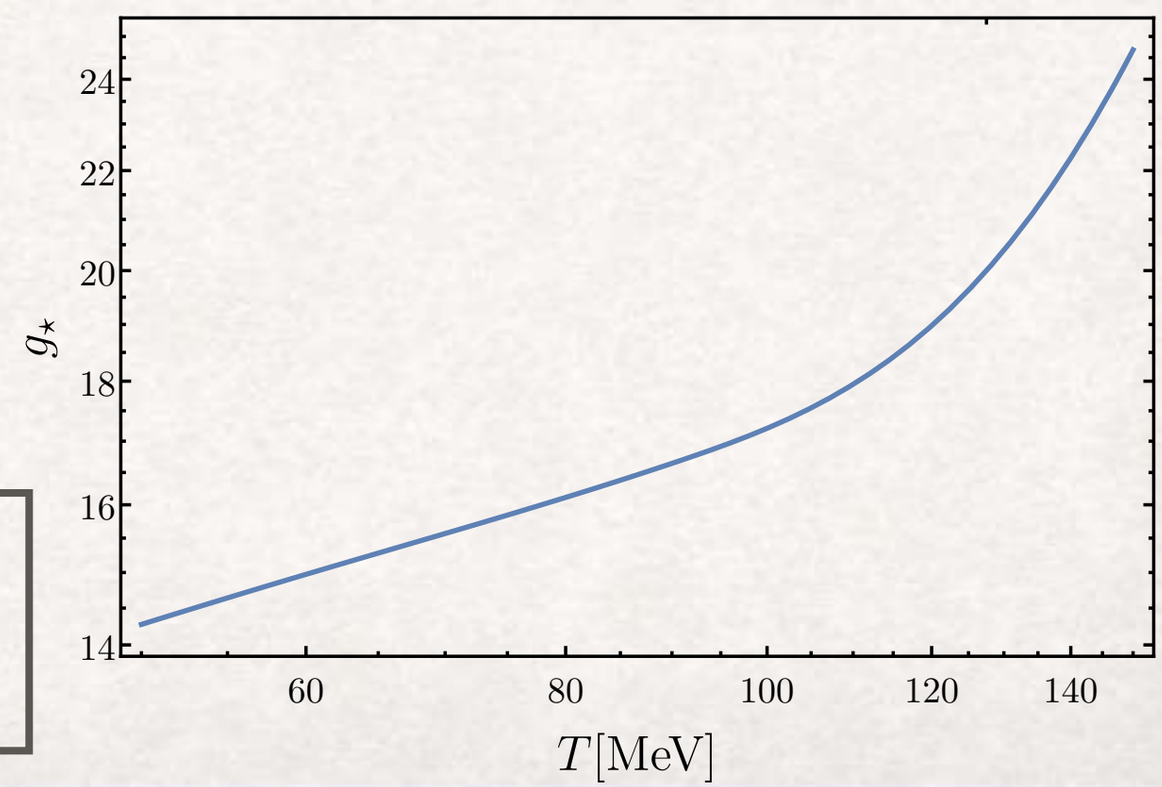
$$\epsilon \equiv \frac{m_u - m_d}{m_u + m_d}, \quad c_3 \equiv c_u - c_d$$

Model dependent UV couplings (e.g. DFSZ)

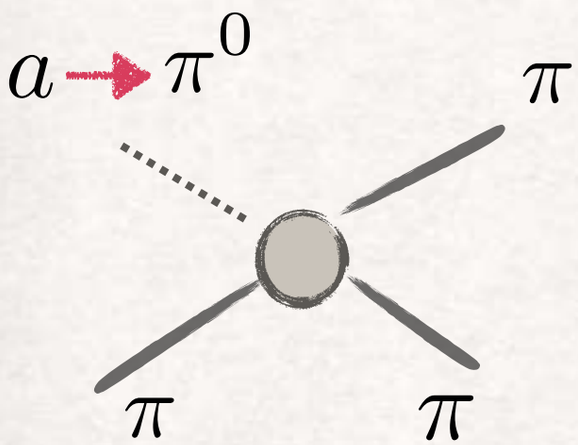
$$\Rightarrow \mathcal{M}_{\rm LO} = (\epsilon - c_3)^2 \frac{s^2 + t^2 + u^2 - 3m_\pi^4}{4 f_a^2 f_\pi^2}$$

Furthermore, number of relativistic degrees of freedom still rapidly varying, with momentum-dependent amplitude!

PREVIOUS COMPUTATIONS USING CHPT, INSTANTANEOUS DECOUPLING APPROX OR MOMENTUM-INDEPENDENT BOLTZMANN EQUATION NOT ENTIRELY CORRECT!



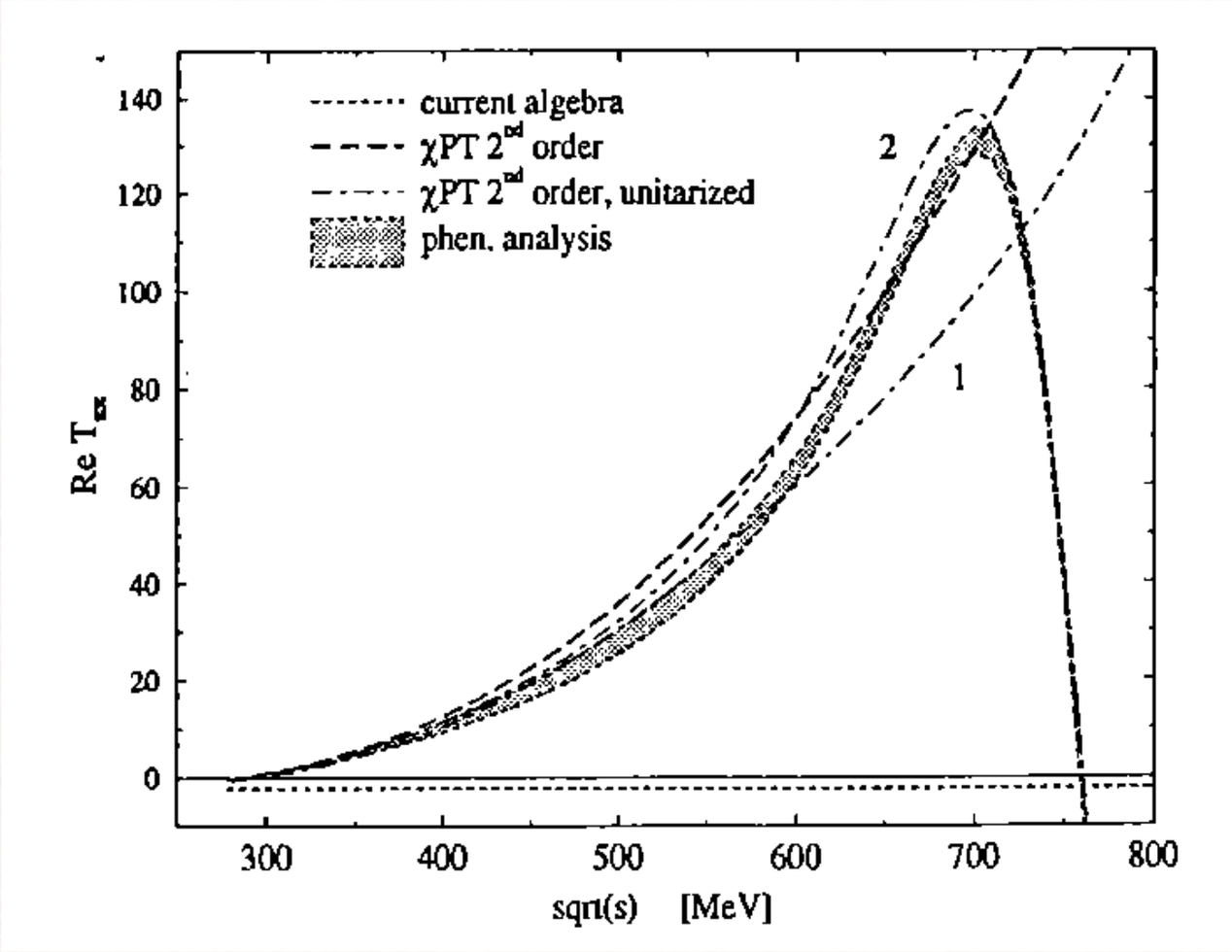
LESSON FROM PIONS



Forward scattering amplitude

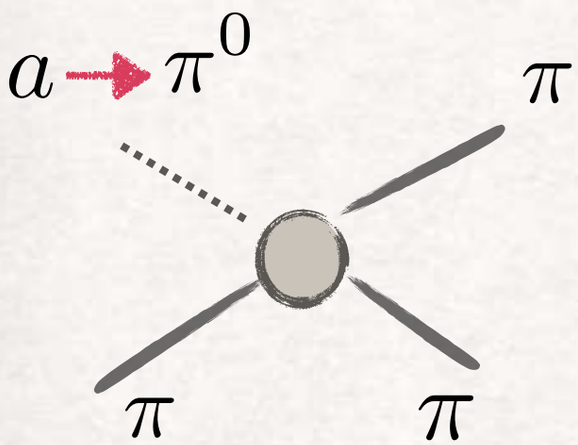
The breakdown of ChPT is well known in pion-pion scattering

Gouty, Leutwyler 89/ Schenck 93/…



Schenck 93

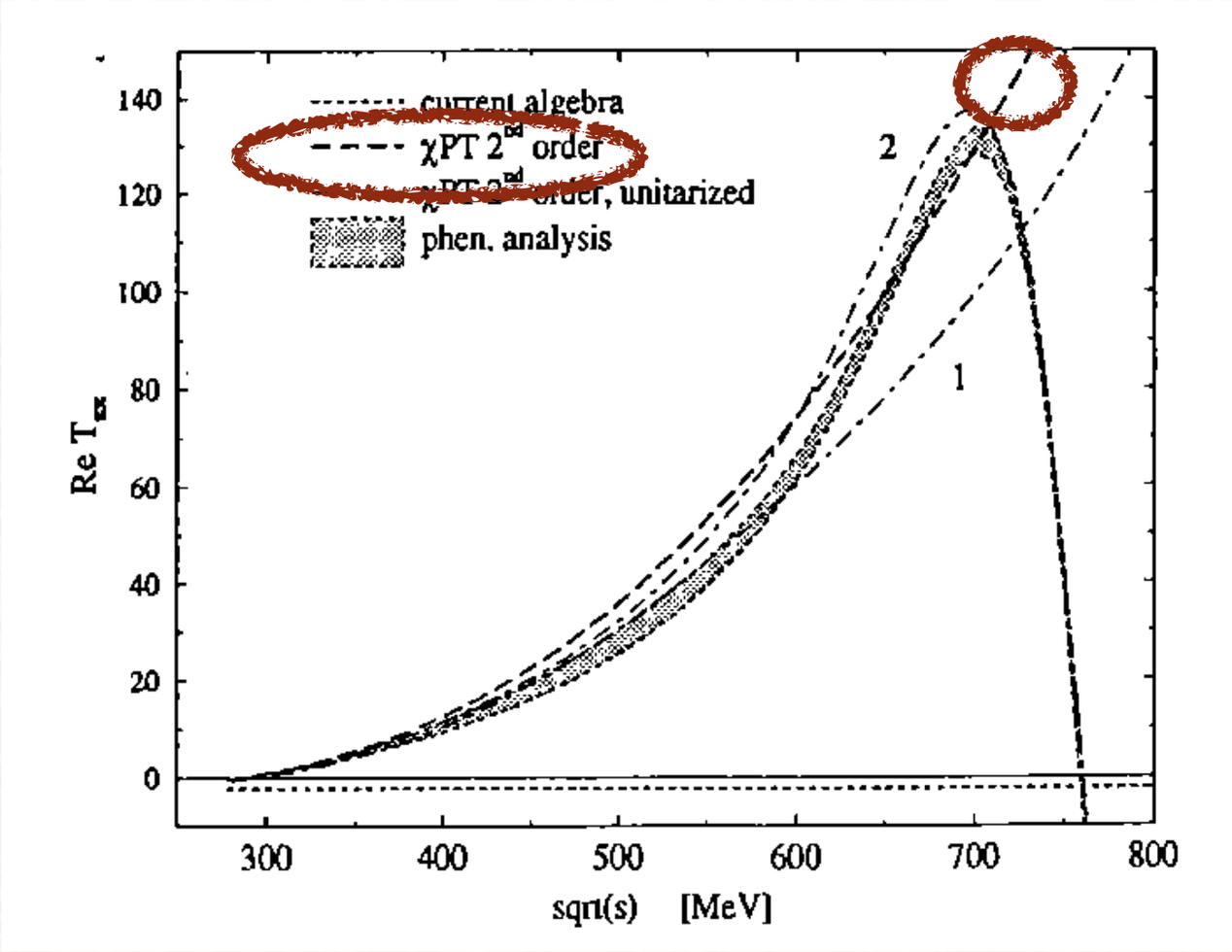
LESSON FROM PIONS



Forward scattering amplitude

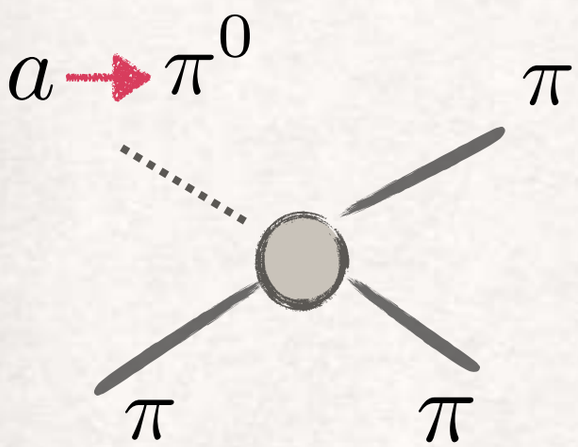
The breakdown of ChPT is well known in pion-pion scattering

Gouty, Leutwyler 89/ Schenck 93/…



Schenck 93

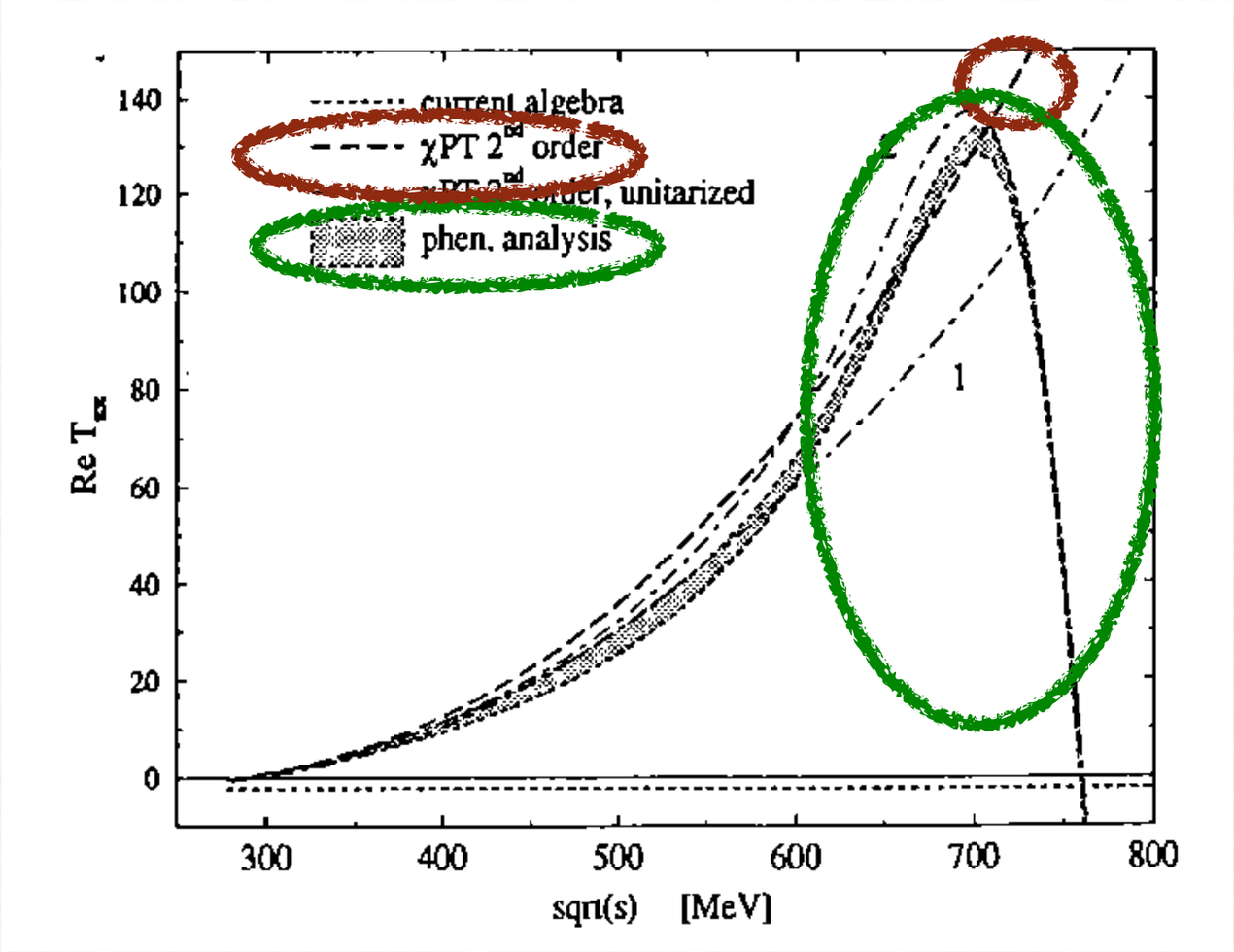
LESSON FROM PIONS



The breakdown of ChPT is well known in pion-pion scattering

Gouty, Leutwyler 89/ Schenck 93/…

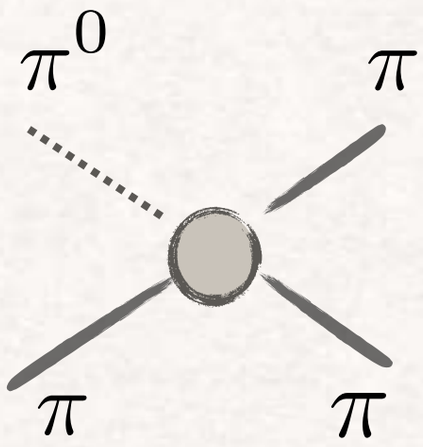
Forward scattering amplitude



Schenck 93

In this case, we have experimental data, which obviously do not exhibit unitarity violation!

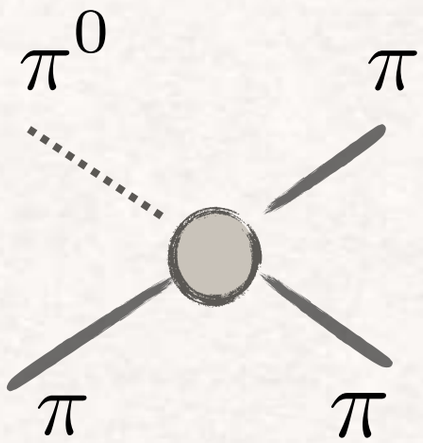
LESSON FROM PIONS



Decomposition into isospin I=0,1,2

$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

LESSON FROM PIONS



Decomposition into isospin I=0,1,2

$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

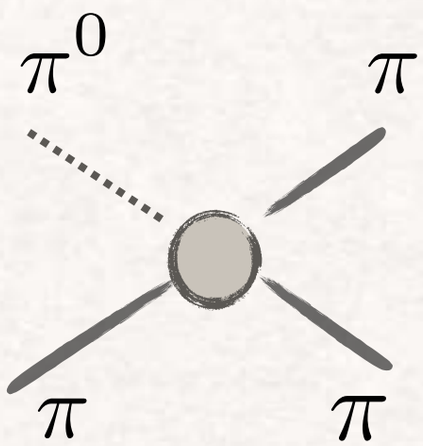
Expansion into partial waves

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

In the elastic region (<1 GeV), unitarity implies

$$t_l^I = \sqrt{\frac{s}{s - 4\, m_\pi^2}} \frac{e^{2i\delta_l^I(s)} - 1}{2i}$$

LESSON FROM PIONS



Decomposition into isospin I=0,1,2

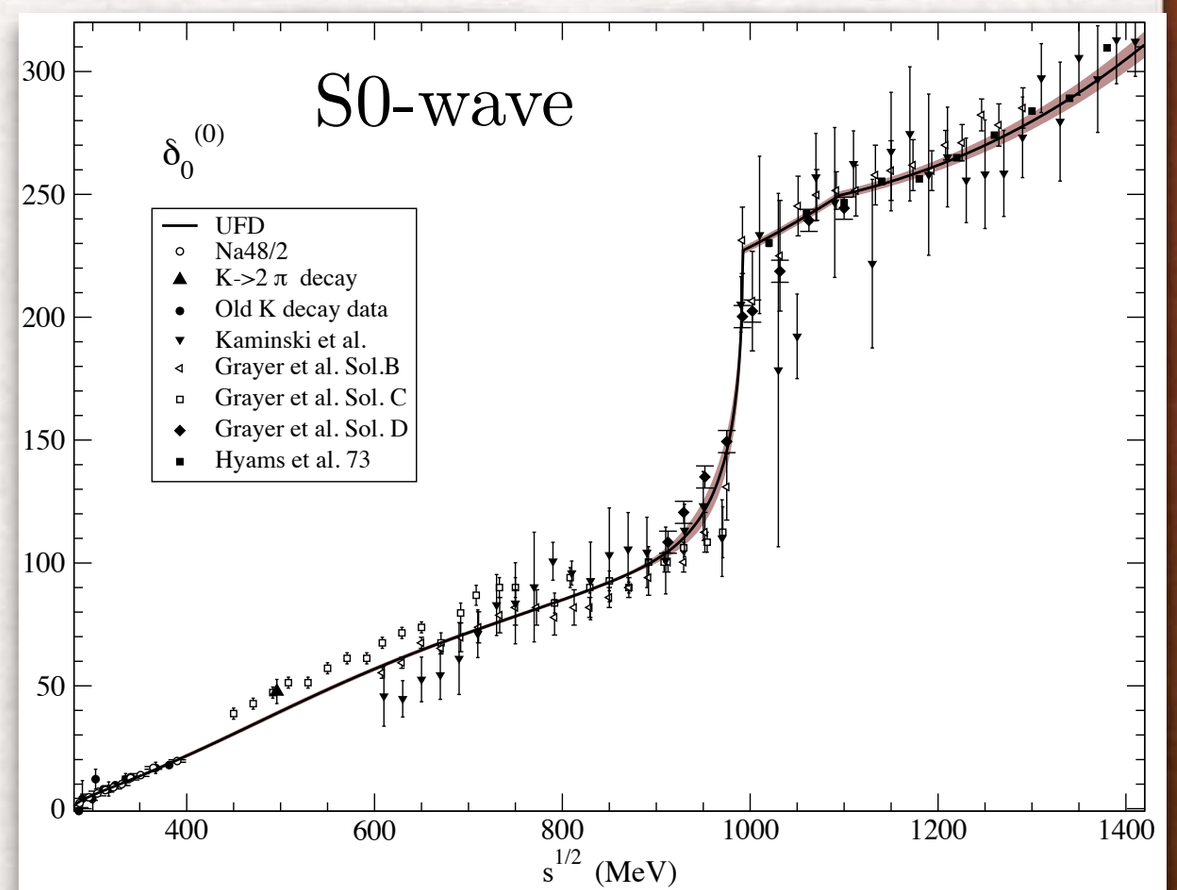
$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

Expansion into partial waves

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

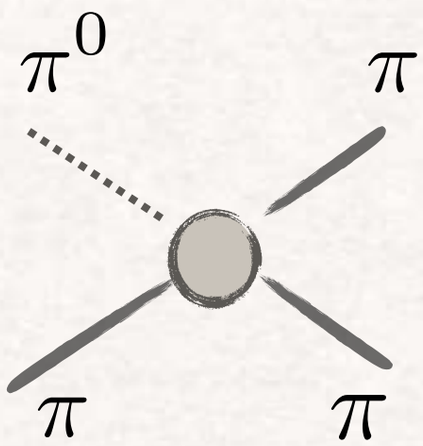
In the elastic region (<1 GeV), unitarity implies

$$t_l^I = \sqrt{\frac{s}{s-4\,m_\pi^2}}\,\frac{e^{2i\delta_l^I(s)}-1}{2i}$$



Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11

LESSON FROM PIONS



Decomposition into isospin I=0,1,2

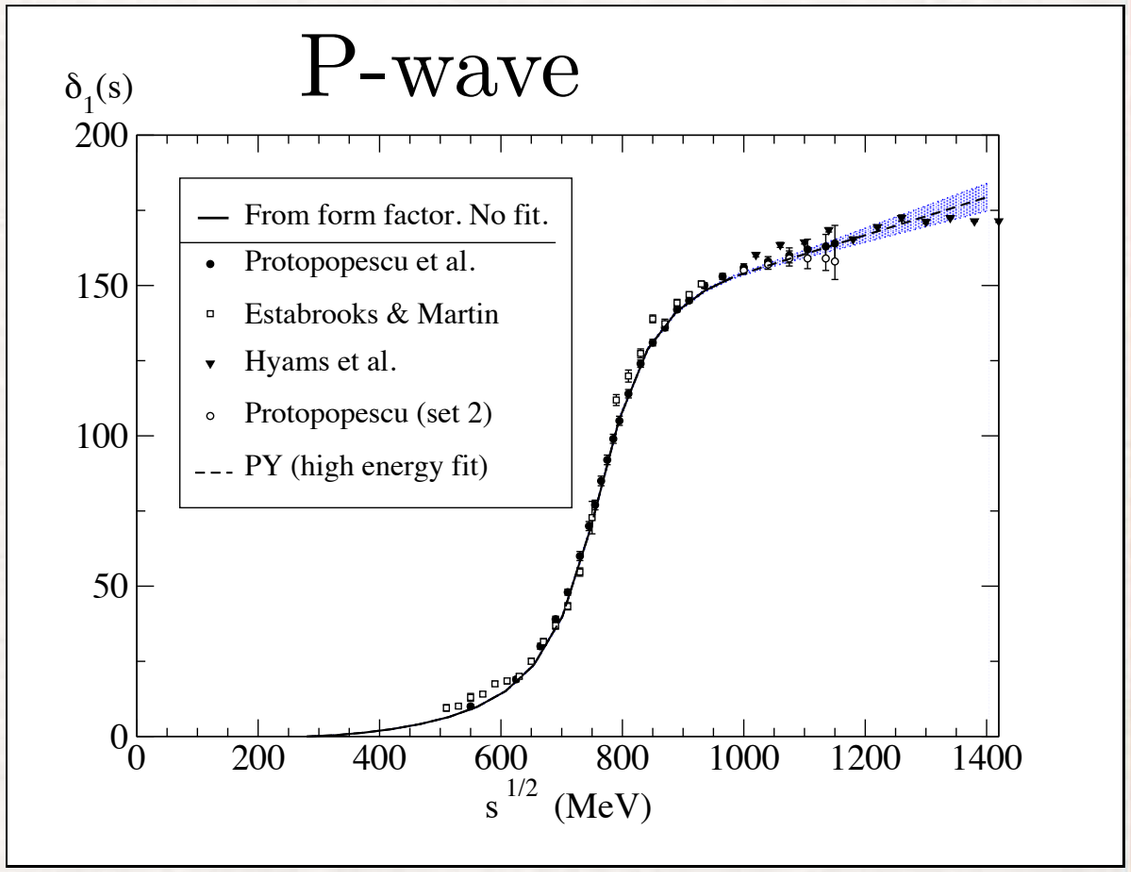
$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

Expansion into partial waves

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

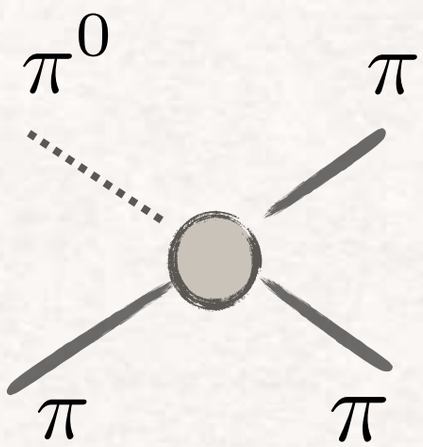
In the elastic region (<1 GeV, unitarity implies

$$t_l^I = \sqrt{\frac{s}{s-4\,m_\pi^2}}\,\frac{e^{2i\delta_l^I(s)}-1}{2i}$$



Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11

LESSON FROM PIONS



Decomposition into isospin I=0,1,2

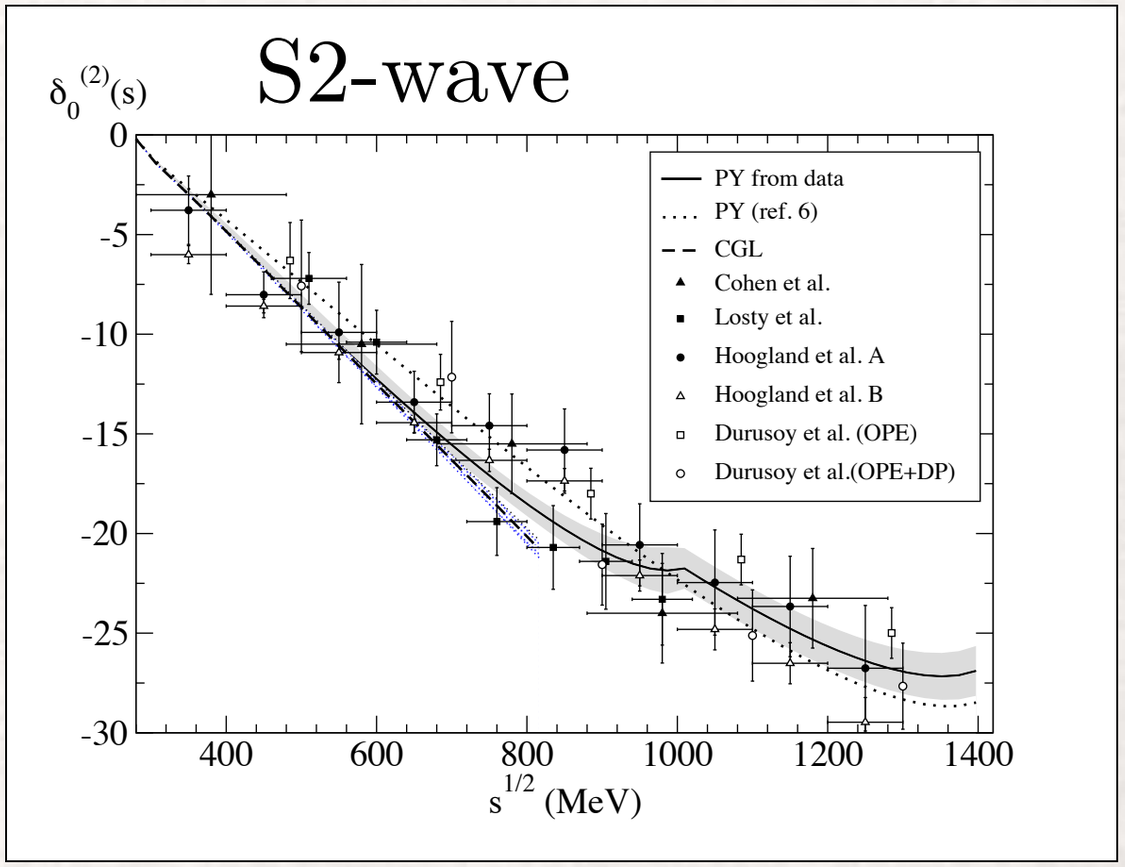
$$T^0(s,t) = 3\mathcal{M}(s,t,u) + \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t),$$
$$T^1(s,t) = \mathcal{M}(t,u,s) - \mathcal{M}(u,s,t),$$
$$T^2(s,t) = \mathcal{M}(t,u,s) + \mathcal{M}(u,s,t)$$

Expansion into partial waves

$$T^I(s,t) = 32\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) t_l^I(s)$$

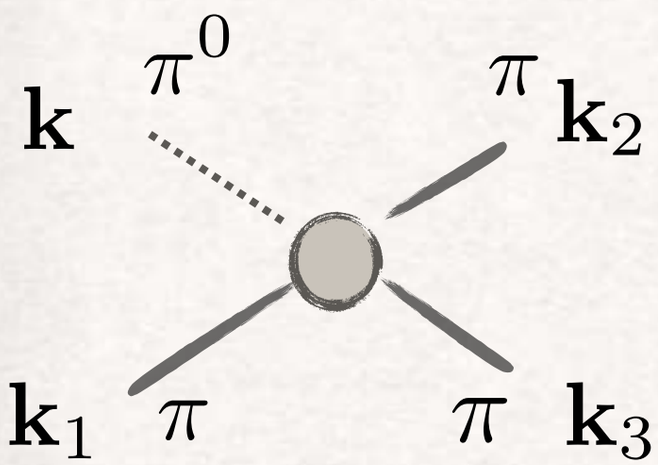
In the elastic region (<1 GeV), unitarity implies

$$t_l^I = \sqrt{\frac{s}{s-4\,m_\pi^2}}\,\frac{e^{2i\delta_l^I(s)}-1}{2i}$$



Pelaez, Yndurain 04/+Garcia Martin, Kalinski, Ruiz de Elvira 11

LESSON FROM PIONS

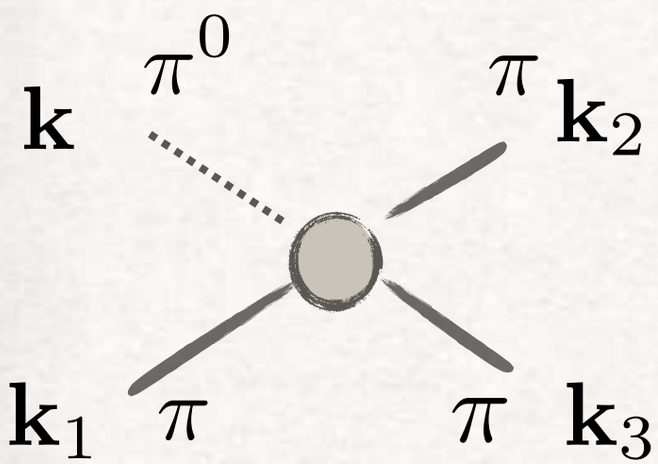


In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

Phenomenological amplitude

LESSON FROM PIONS



In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

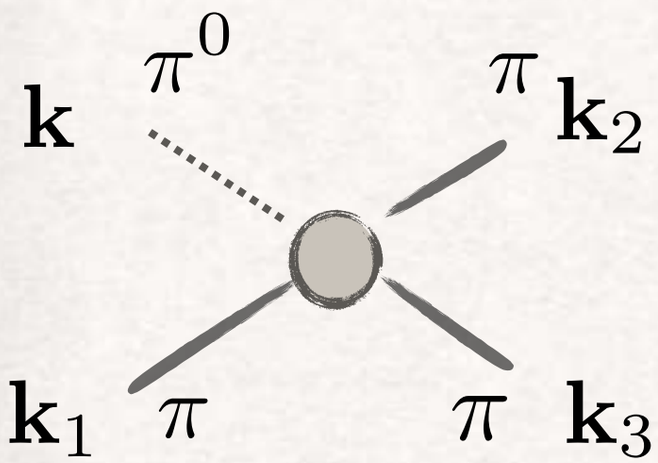
$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

Phenomenological amplitude

Destruction rate

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\mathrm{eq}}(1+f_2^{\mathrm{eq}})(1+f_3^{\mathrm{eq}})(2\pi)^4\delta^{(4)}(k^\mu+k_1^\mu-k_2^\mu-k_3^\mu)|\mathcal{M}|^2$$

LESSON FROM PIONS



In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

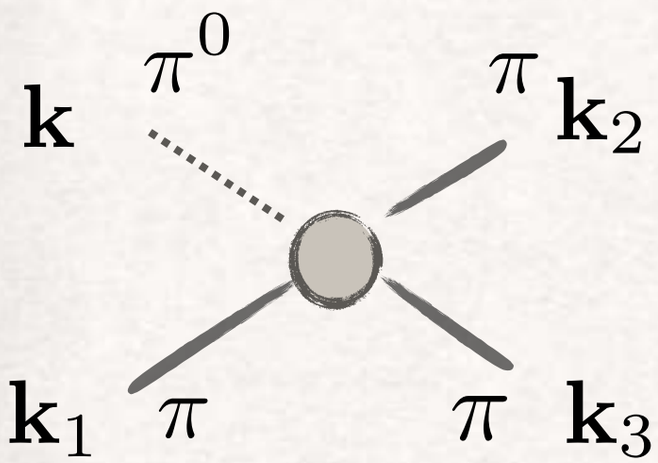
Phenomenological amplitude

Destruction rate

Bose-Einstein distribution

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\mathrm{eq}}(1+f_2^{\mathrm{eq}})(1+f_3^{\mathrm{eq}})(2\pi)^4\delta^{(4)}(k^\mu+k_1^\mu-k_2^\mu-k_3^\mu)|\mathcal{M}|^2$$

LESSON FROM PIONS



In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

Phenomenological amplitude

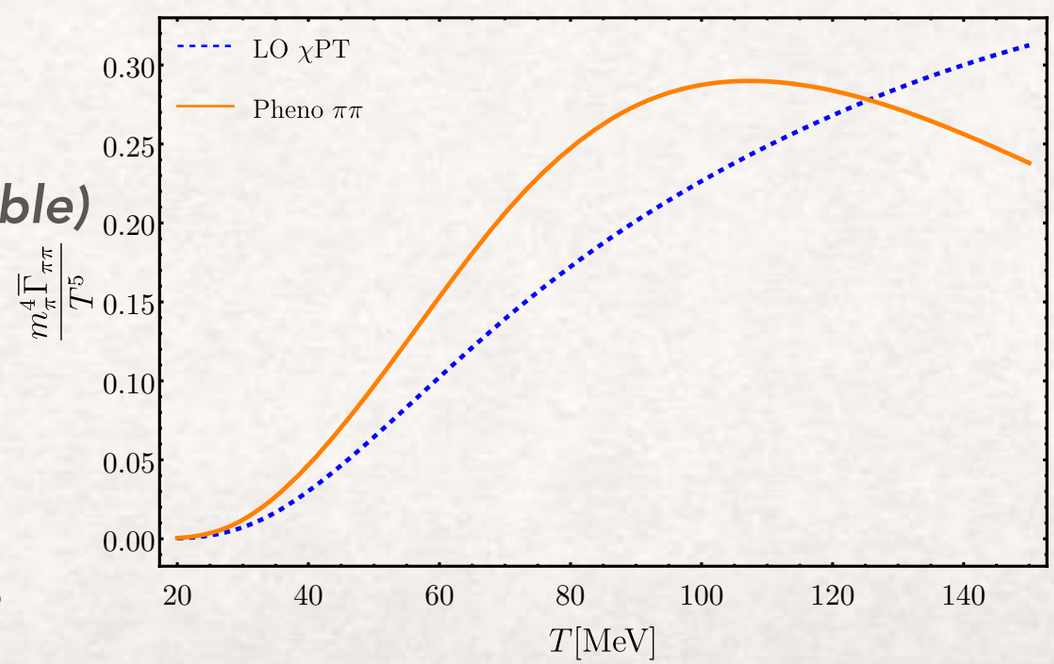
Destruction rate

Bose-Einstein distribution

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\rm eq}(1+f_2^{\rm eq})(1+f_3^{\rm eq})(2\pi)^4\delta^{(4)}(k^\mu+k_1^\mu-k_2^\mu-k_3^\mu)|\mathcal{M}|^2$$

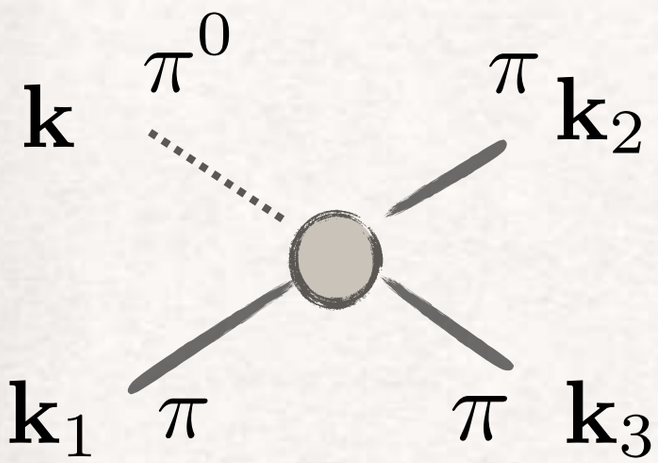
Thermally averaged rate (to be compared with Hubble)

$$\overline{\Gamma} \equiv \frac{1}{n^{\rm eq}}\int\frac{d^3\mathbf{k}}{(2\pi)^3}e^{-\frac{E}{T}}\Gamma^{>}$$



See also Schenck 93

LESSON FROM PIONS



In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

Phenomenological amplitude

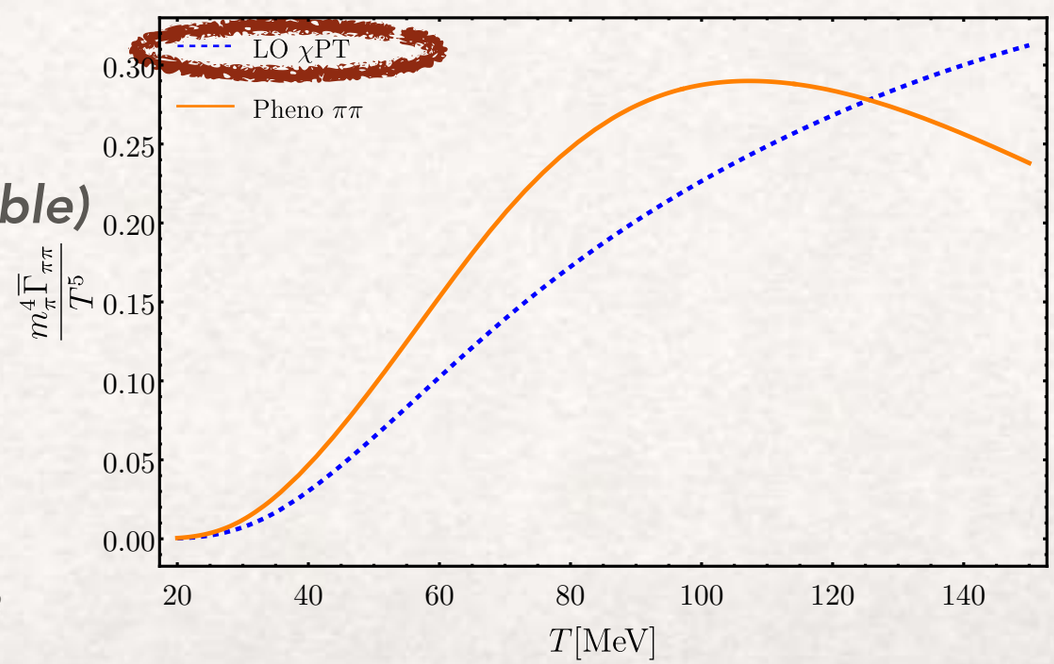
Destruction rate

Bose-Einstein distribution

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\rm eq}(1+f_2^{\rm eq})(1+f_3^{\rm eq})(2\pi)^4\delta^{(4)}(k^\mu+k_1^\mu-k_2^\mu-k_3^\mu)|\mathcal{M}|^2$$

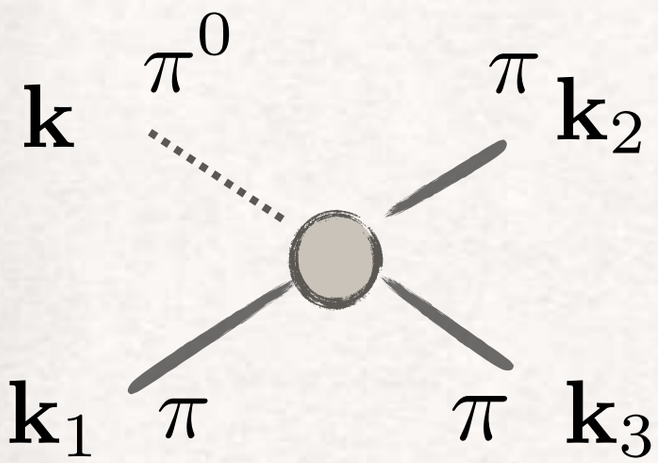
Thermally averaged rate (to be compared with Hubble)

$$\overline{\Gamma} \equiv \frac{1}{n^{\rm eq}}\int\frac{d^3\mathbf{k}}{(2\pi)^3}e^{-\frac{E}{T}}\Gamma^{>}$$



See also Schenck 93

LESSON FROM PIONS



In practice, one can use fits to phase shift data to obtain the "true" scattering amplitude.

$$\Rightarrow \quad \mathcal{M}_{\pi\pi\to\pi\pi}$$

Phenomenological amplitude

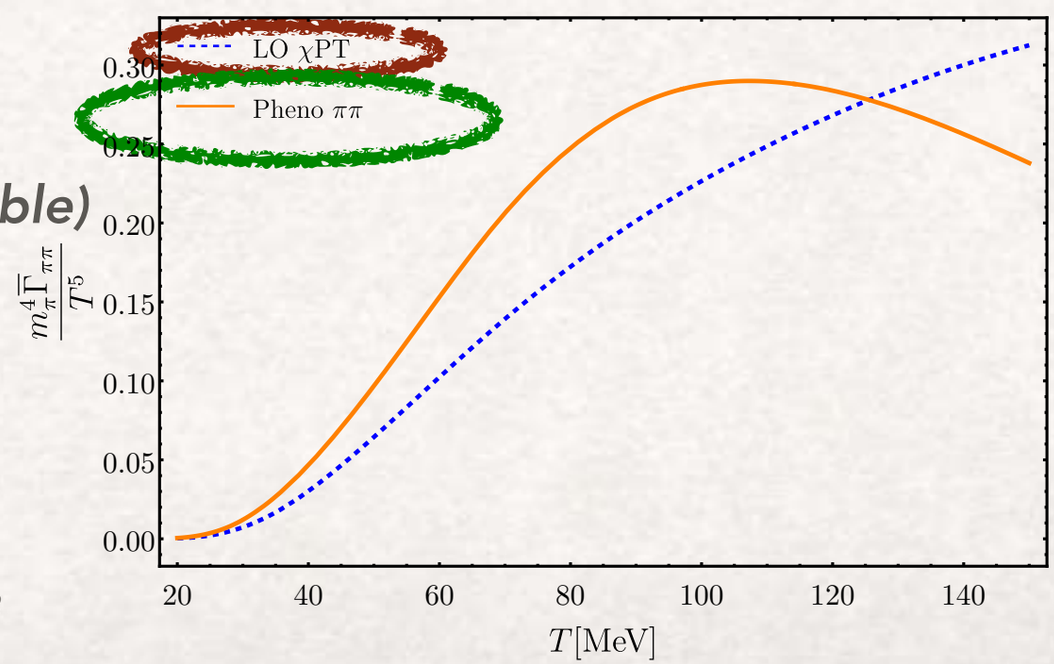
Destruction rate

Bose-Einstein distribution

$$\Gamma^{>} = \frac{1}{2E}\int\left(\prod_{i=1}^{3}\frac{d^3\mathbf{k}_i}{(2\pi)^3 2E_i}\right) f_1^{\rm eq}(1+f_2^{\rm eq})(1+f_3^{\rm eq})(2\pi)^4\delta^{(4)}(k^\mu+k_1^\mu-k_2^\mu-k_3^\mu)|\mathcal{M}|^2$$

Thermally averaged rate (to be compared with Hubble)

$$\overline{\Gamma} \equiv \frac{1}{n^{\rm eq}}\int\frac{d^3\mathbf{k}}{(2\pi)^3}e^{-\frac{E}{T}}\Gamma^{>}$$

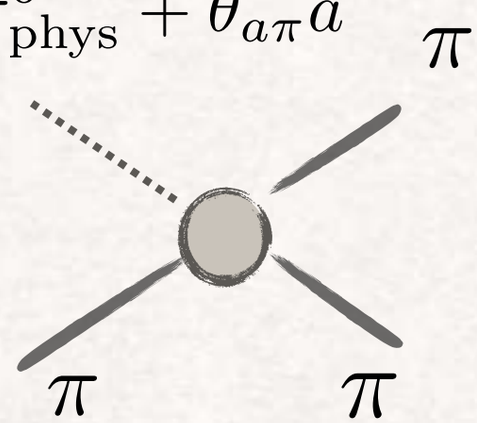


See also Schenck 93

OUR STRATEGY FOR THE AXION-PION RATE

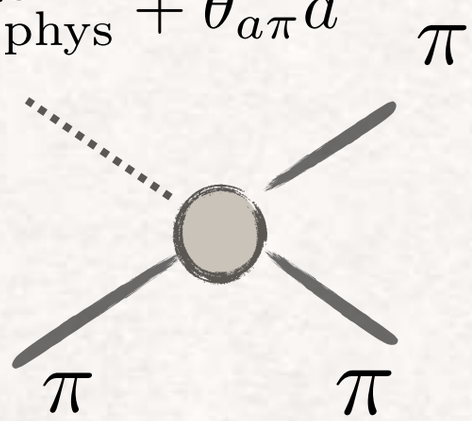
"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



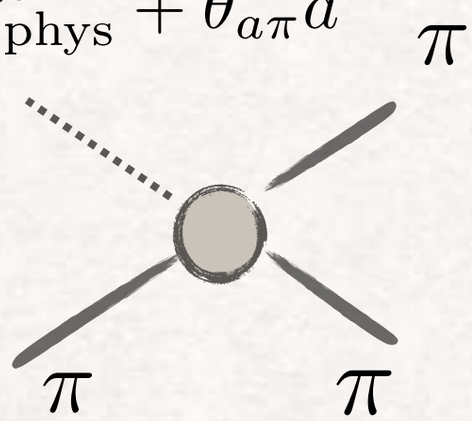
"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

Practically, only need to rescale amplitudes by axion-pion mixing

$$\mathcal{M}_{a\pi^i \to \pi^j \pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \cdot \mathcal{M}_{\pi^0 \pi^i \to \pi^j \pi^k}$$

OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

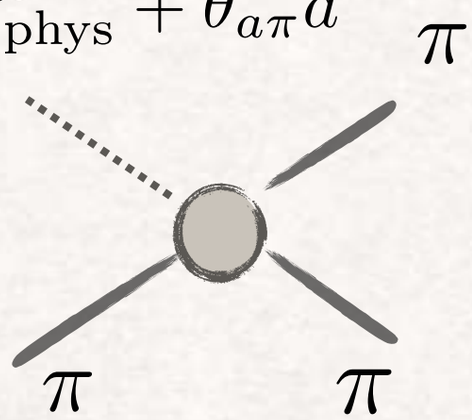
Practically, only need to rescale amplitudes by axion-pion mixing

$$\theta_{a\pi}$$

$$\mathcal{M}_{a\pi^i \to \pi^j \pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \mathcal{M}_{\pi^0 \pi^i \to \pi^j \pi^k}$$

OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

Practically, only need to rescale amplitudes by axion-pion mixing

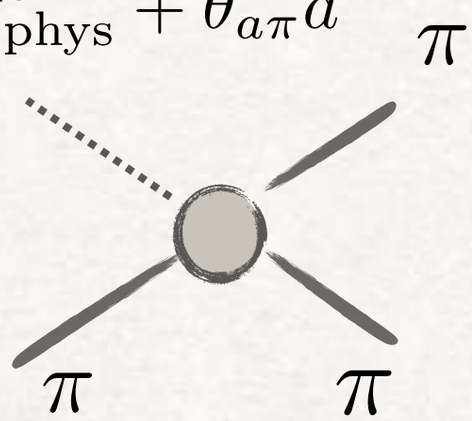
$$\theta_{a\pi}$$

$$\mathcal{M}_{a\pi^i\to\pi^j\pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \mathcal{M}_{\pi^0\pi^i\to\pi^j\pi^k} + \mathcal{O}(m_\pi^2/s)$$

$$\lesssim 10\%$$

OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

Practically, only need to rescale amplitudes by axion-pion mixing

$$\theta_{a\pi}$$

$$\mathcal{M}_{a\pi^i\to\pi^j\pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \mathcal{M}_{\pi^0\pi^i\to\pi^j\pi^k} + \mathcal{O}(m_\pi^2/s)$$

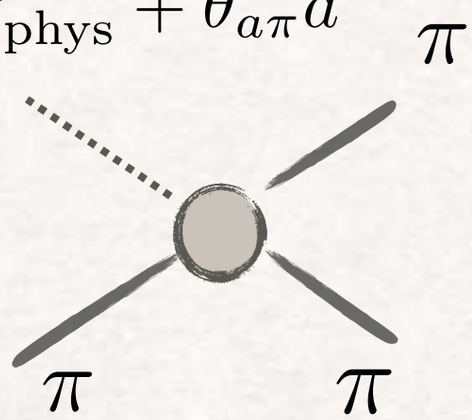
$$\lesssim 10\%$$

Focus on KSVZ models with c_3=0

See Ferreira, Notari, FR 20 for DFSZ

OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

Focus on KSVZ models with c_3=0

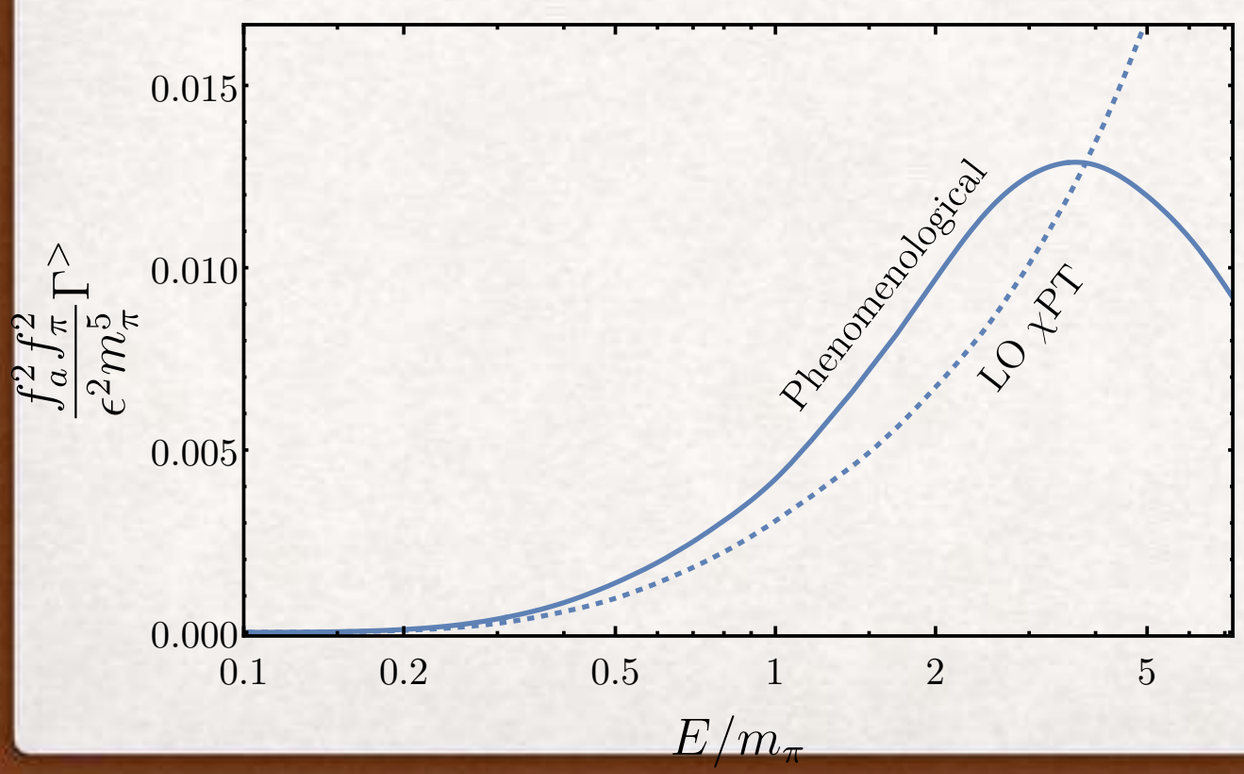
See Ferreira, Notari, FR 20 for DFSZ

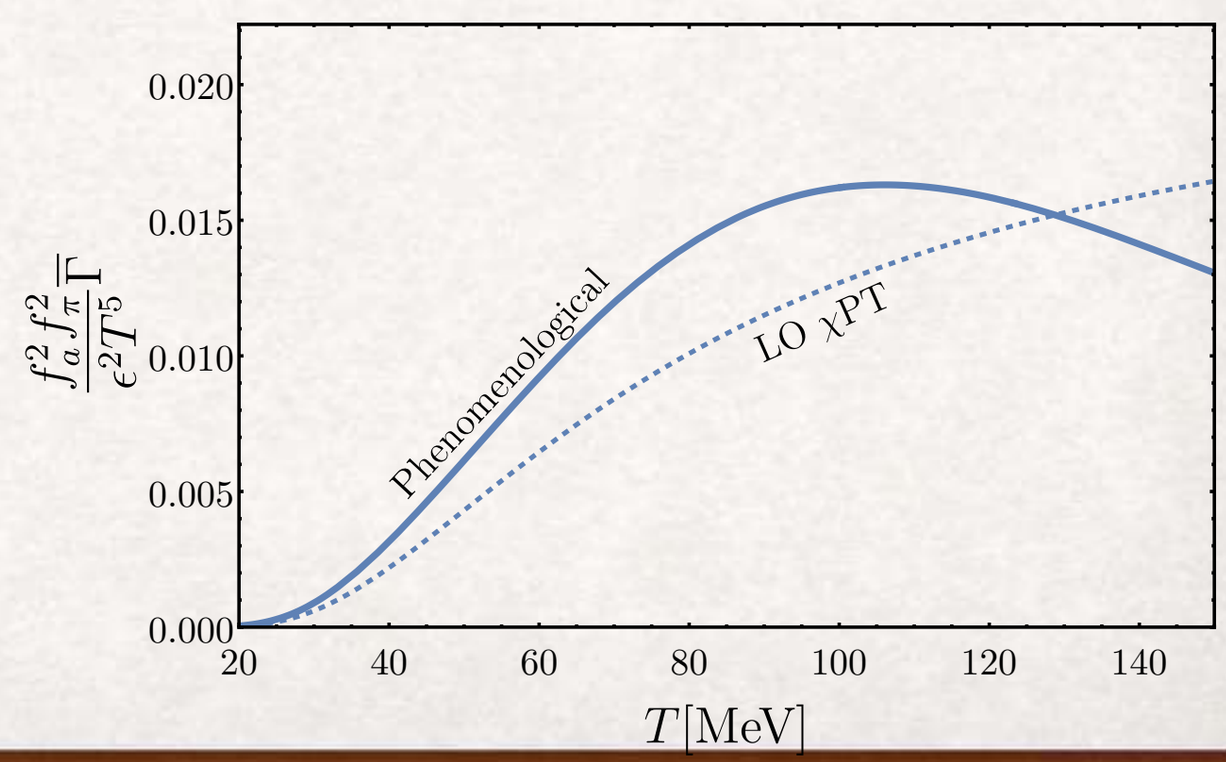
Practically, only need to rescale amplitudes by axion-pion mixing

$$\theta_{a\pi}$$

$$\mathcal{M}_{a\pi^i\to\pi^j\pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \mathcal{M}_{\pi^0\pi^i\to\pi^j\pi^k} + \mathcal{O}(m_\pi^2/s)$$

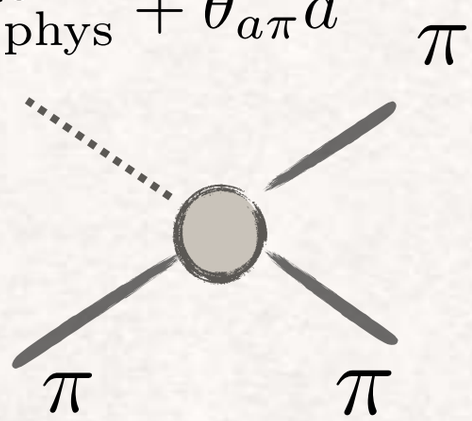
$$\lesssim 10\%$$





OUR STRATEGY FOR THE AXION-PION RATE

$$\pi^0 \simeq \pi^0_{\rm phys} + \theta_{a\pi} a$$



"Phenomenological" scattering amplitudes can be obtained from pion-pion data by replacing a pion with the axion!

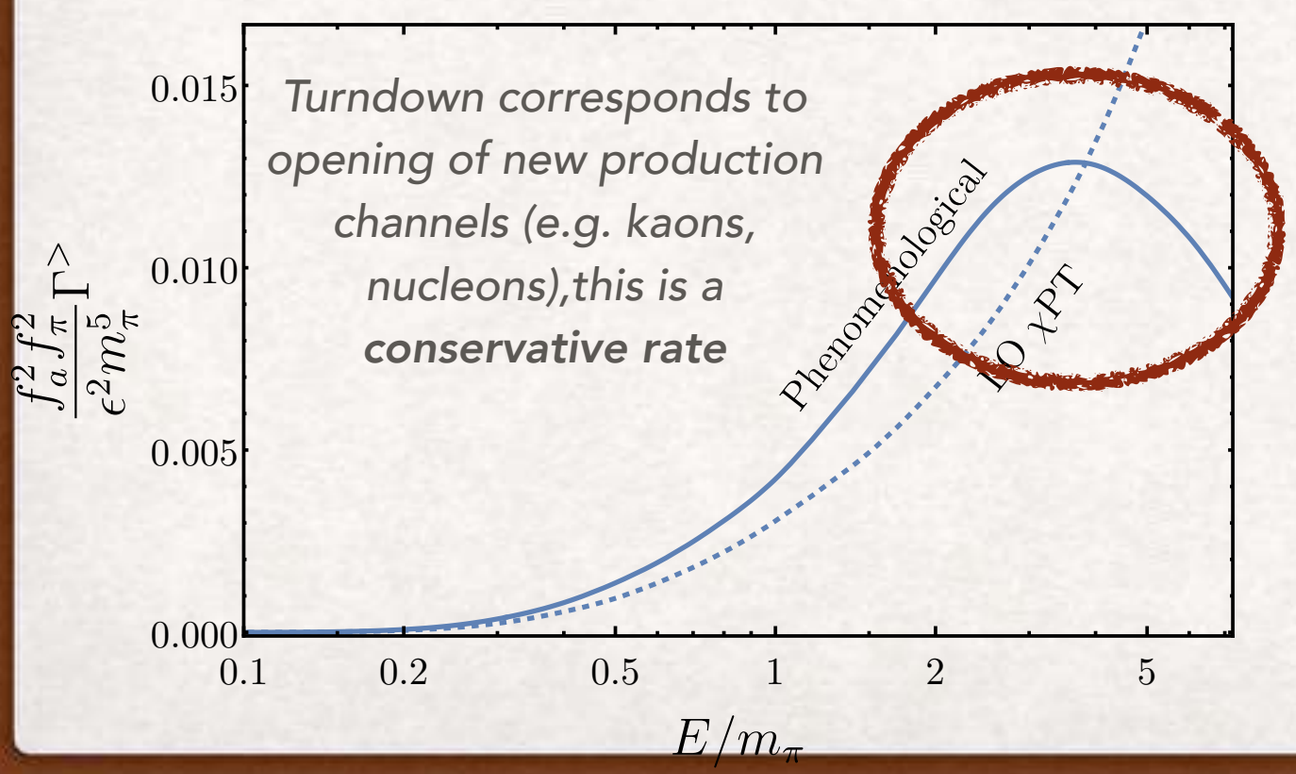
Focus on KSVZ models with c_3=0

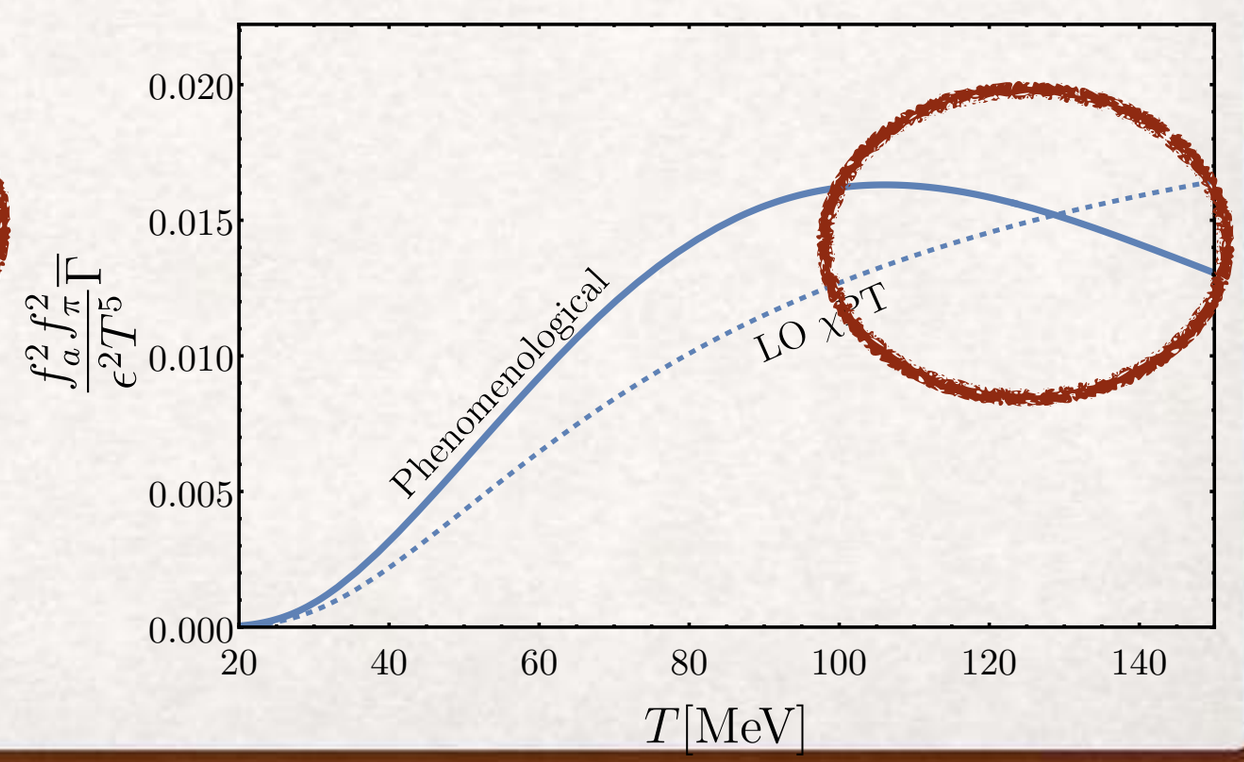
See Ferreira, Notari, FR 20 for DFSZ

Practically, only need to rescale amplitudes by axion-pion mixing

$$\theta_{a\pi} \qquad \lesssim 10\%$$

$$\mathcal{M}_{a\pi^i\to\pi^j\pi^k} \simeq \frac{(\epsilon - c_3) f_\pi}{2 f_a} \mathcal{M}_{\pi^0\pi^i\to\pi^j\pi^k} + \mathcal{O}(m_\pi^2/s)$$





OUR STRATEGY FOR MOMENTUM DEPENDENCE

Need to solve for momentum-dependent production

Boltzmann equation in comoving momenta $\mathbf{p} = R(t)\mathbf{k}$

$$\frac{df_{\mathbf{p}}}{dt} = (1 + f_{\mathbf{p}})\,\Gamma^{<} - f_{\mathbf{p}}\,\Gamma^{>}\,, \quad \Gamma^{<} = e^{-\frac{E}{T}}\,\Gamma^{>}$$

Which can be solved for a discrete set of modes

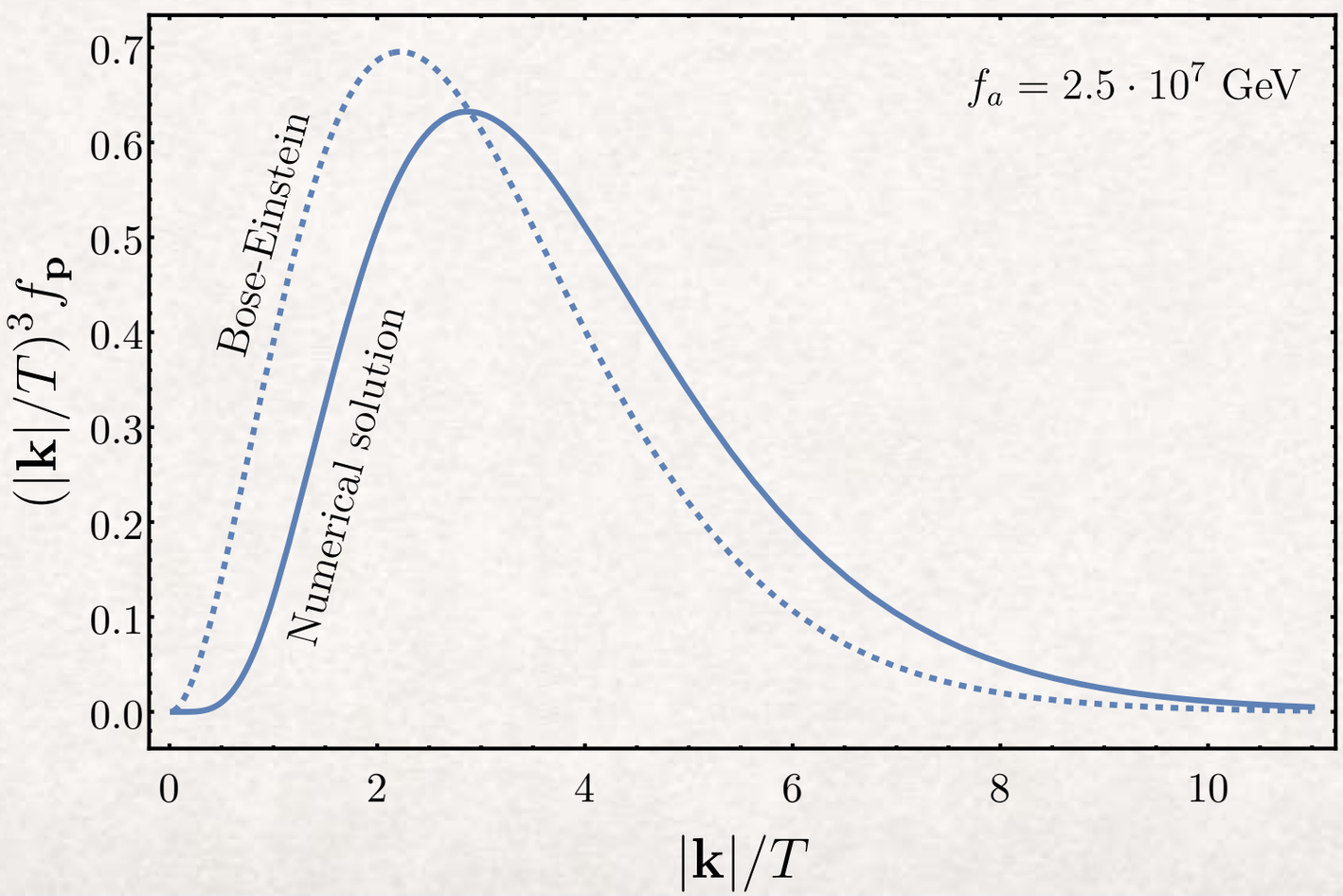
OUR STRATEGY FOR MOMENTUM DEPENDENCE

Need to solve for momentum-dependent production

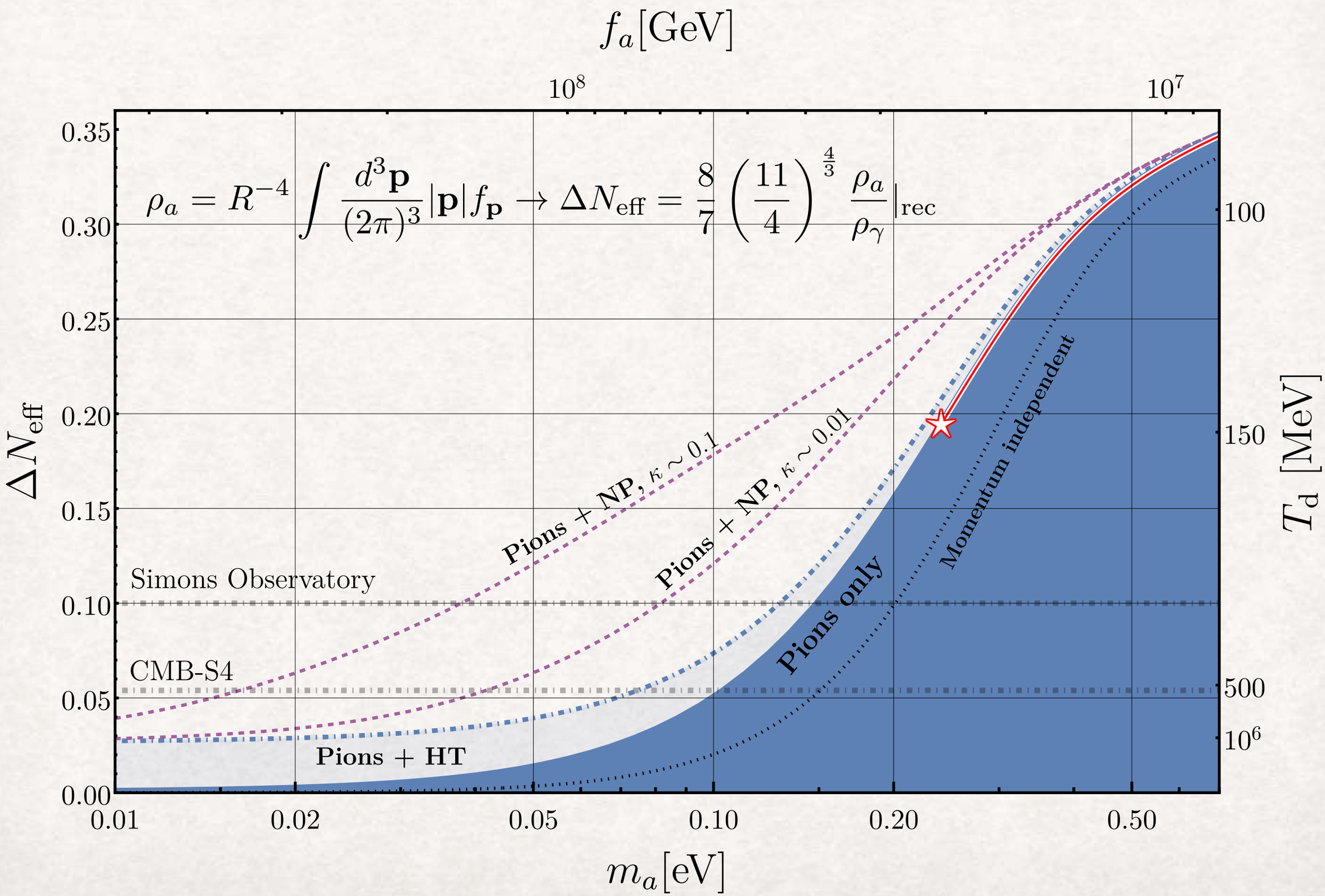
Boltzmann equation in comoving momenta $\mathbf{p} = R(t)\mathbf{k}$

$$\frac{df_{\mathbf{p}}}{dt} = (1 + f_{\mathbf{p}})\,\Gamma^{<} - f_{\mathbf{p}}\,\Gamma^{>}\,, \quad \Gamma^{<} = e^{-\frac{E}{T}}\,\Gamma^{>}$$

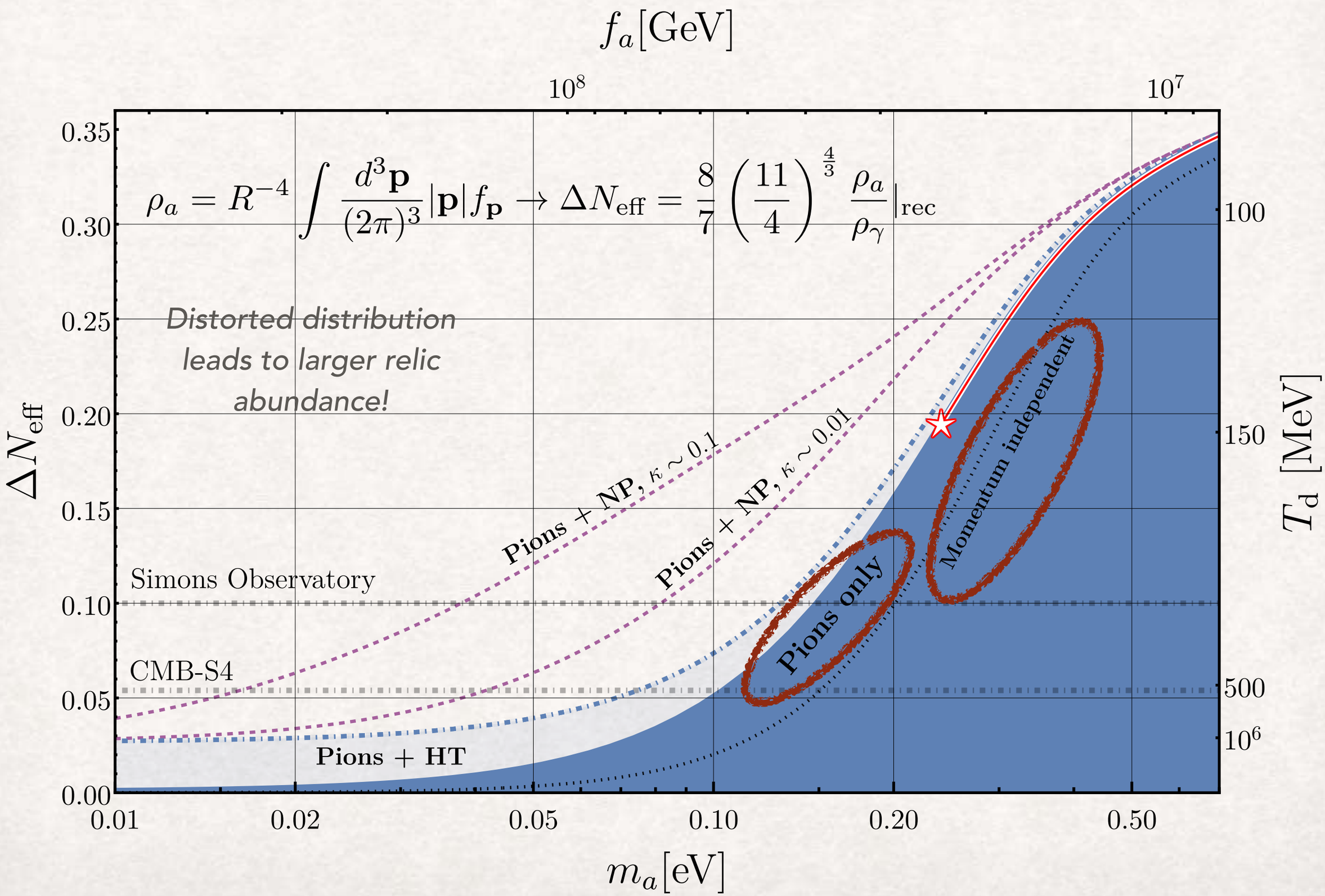
Which can be solved for a discrete set of modes



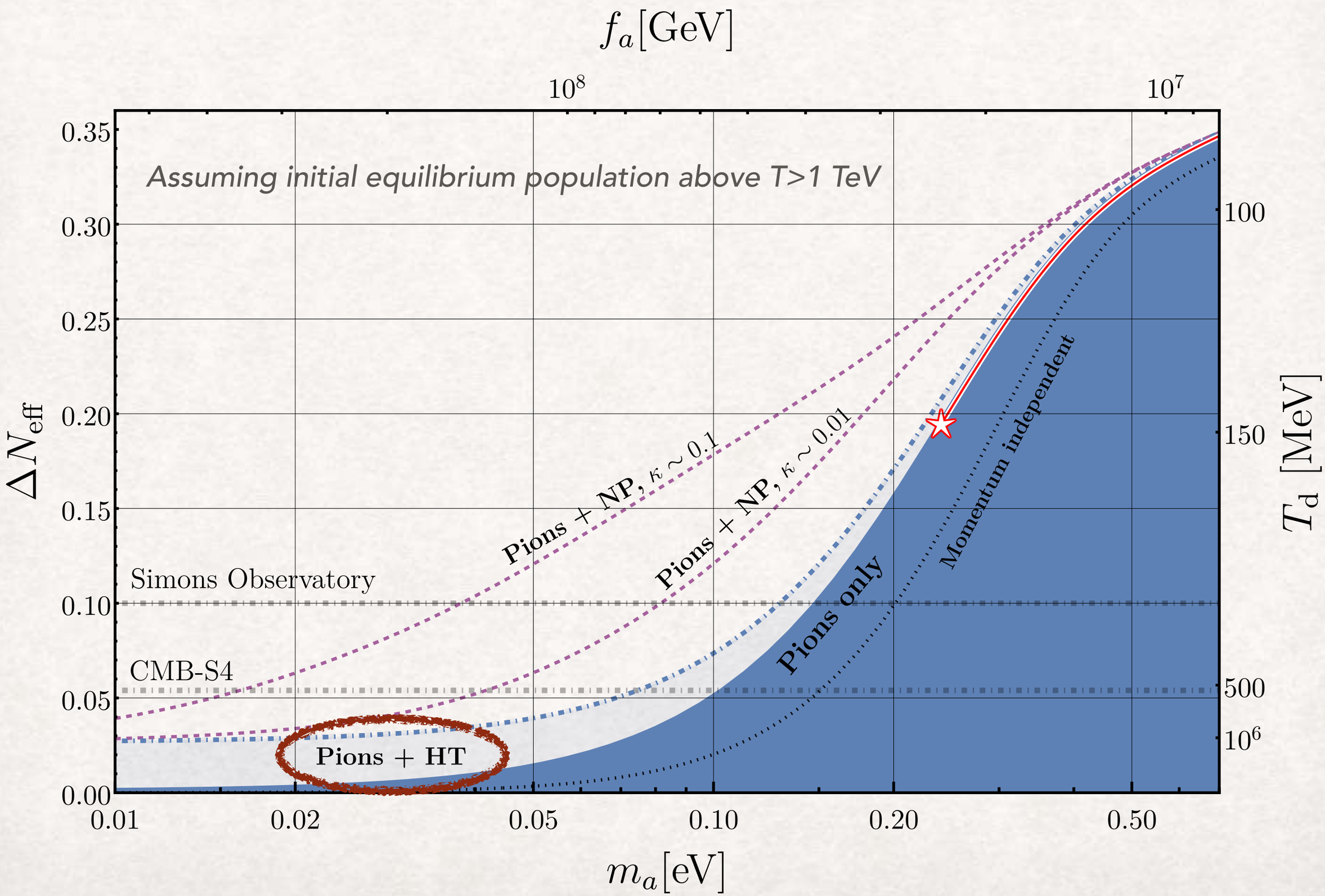
RELIC ABUNDANCE



RELIC ABUNDANCE



RELIC ABUNDANCE



COSMOLOGICAL BOUND

*We implemented the hot QCD axion species in the Boltzmann solver **CLASS**, similar to an additional massive neutrino, **including its actual non-thermal spectral distribution, which depends only on E/T and m_a***

Lesgourgues 11/et al …

Monte Carlo Markov Chain (MCMC) search performed to set a reliable upper bound on the QCD axion mass

MontePython
Audren et al 12/Brinckmann et al 18

COSMOLOGICAL BOUND

*We implemented the hot QCD axion species in the Boltzmann solver **CLASS**, similar to an additional massive neutrino, **including its actual non-thermal spectral distribution, which depends only on E/T and m_a***

Lesgourgues 11/et al …

Monte Carlo Markov Chain (MCMC) search performed to set a reliable upper bound on the QCD axion mass

MontePython
Audren et al 12/Brinckmann et al 18

Cosmological Model

$$\Lambda\mathrm{CDM} + m_a + \sum_{\nu} m_{\nu}$$

COSMOLOGICAL BOUND

*We implemented the hot QCD axion species in the Boltzmann solver **CLASS**, similar to an additional massive neutrino, **including its actual non-thermal spectral distribution, which depends only on E/T and m_a***

Lesgourgues 11/et al …

Monte Carlo Markov Chain (MCMC) search performed to set a reliable upper bound on the QCD axion mass

MontePython
Audren et al 12/Brinckmann et al 18

Cosmological Model

$$\Lambda\mathrm{CDM} + m_a + \sum_\nu m_\nu$$

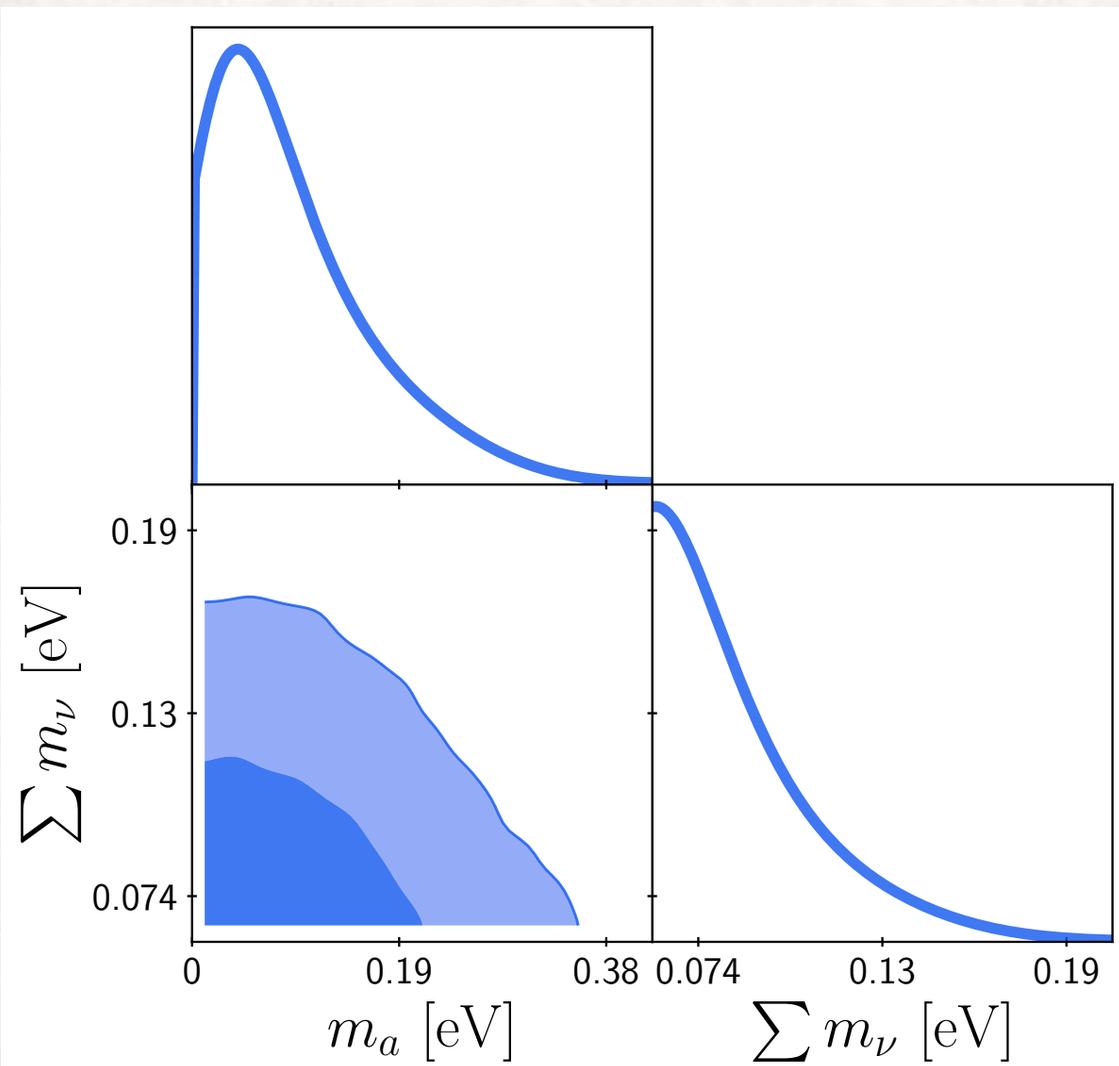
COSMOLOGICAL BOUND

*We implemented the hot QCD axion species in the Boltzmann solver **CLASS**, similar to an additional massive neutrino, **including its actual non-thermal spectral distribution, which depends only on E/T and m_a***

Lesgourgues 11/et al …

Monte Carlo Markov Chain (MCMC) search performed to set a reliable upper bound on the QCD axion mass

MontePython
Audren et al 12/Brinckmann et al 18



Cosmological Model

$$\Lambda\mathrm{CDM} + m_a + \sum_\nu m_\nu$$

Planck 2018 TT+TE+EE high+low-l+lensing
+
Baryon Acoustic Oscillations (BAO)
+
Pantheon Supernovae

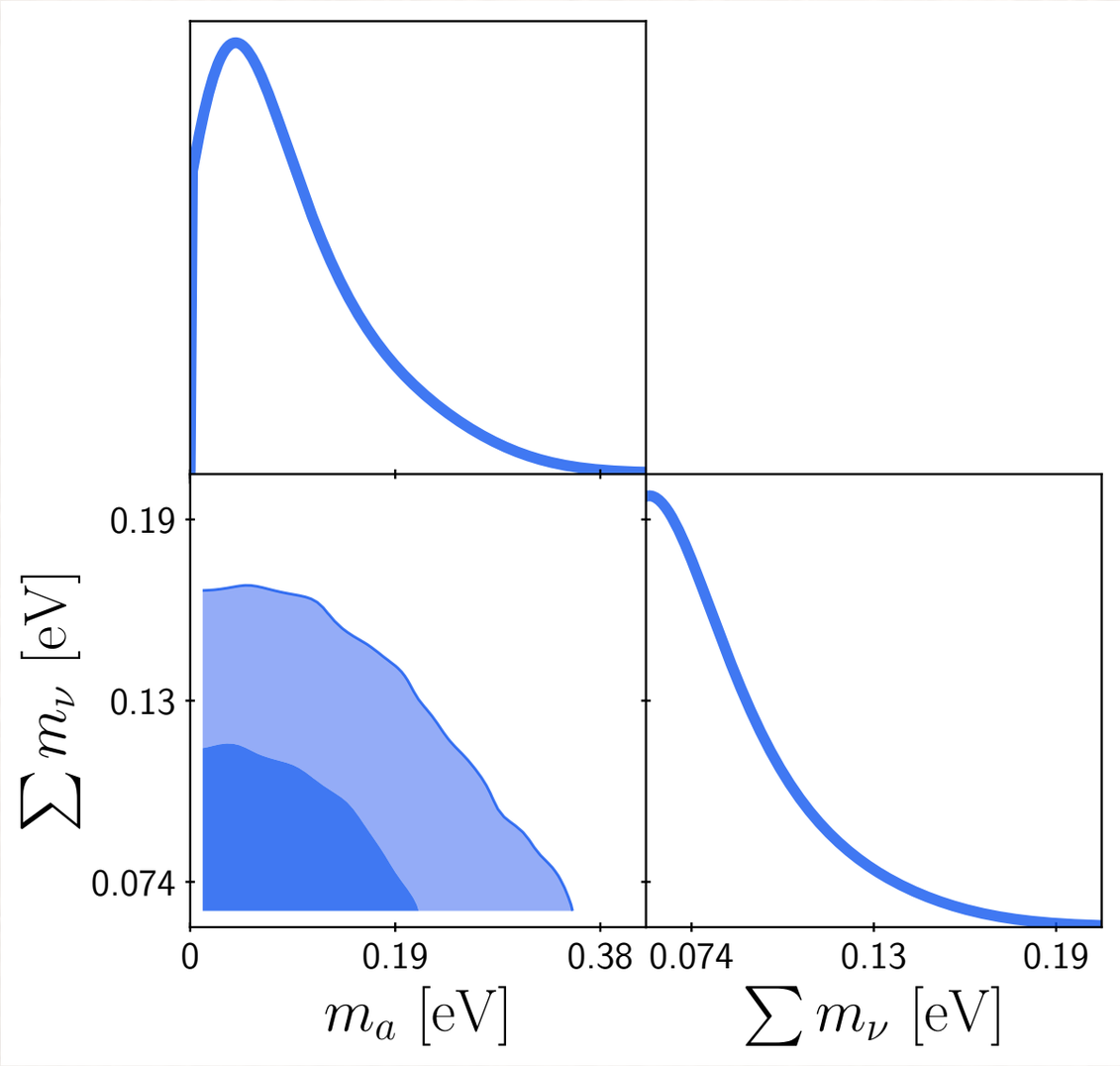
COSMOLOGICAL BOUND

*We implemented the hot QCD axion species in the Boltzmann solver **CLASS**, similar to an additional massive neutrino, **including its actual non-thermal spectral distribution, which depends only on E/T and m_a***

Lesgourgues 11/et al …

Monte Carlo Markov Chain (MCMC) search performed to set a reliable upper bound on the QCD axion mass

MontePython
Audren et al 12/Brinckmann et al 18

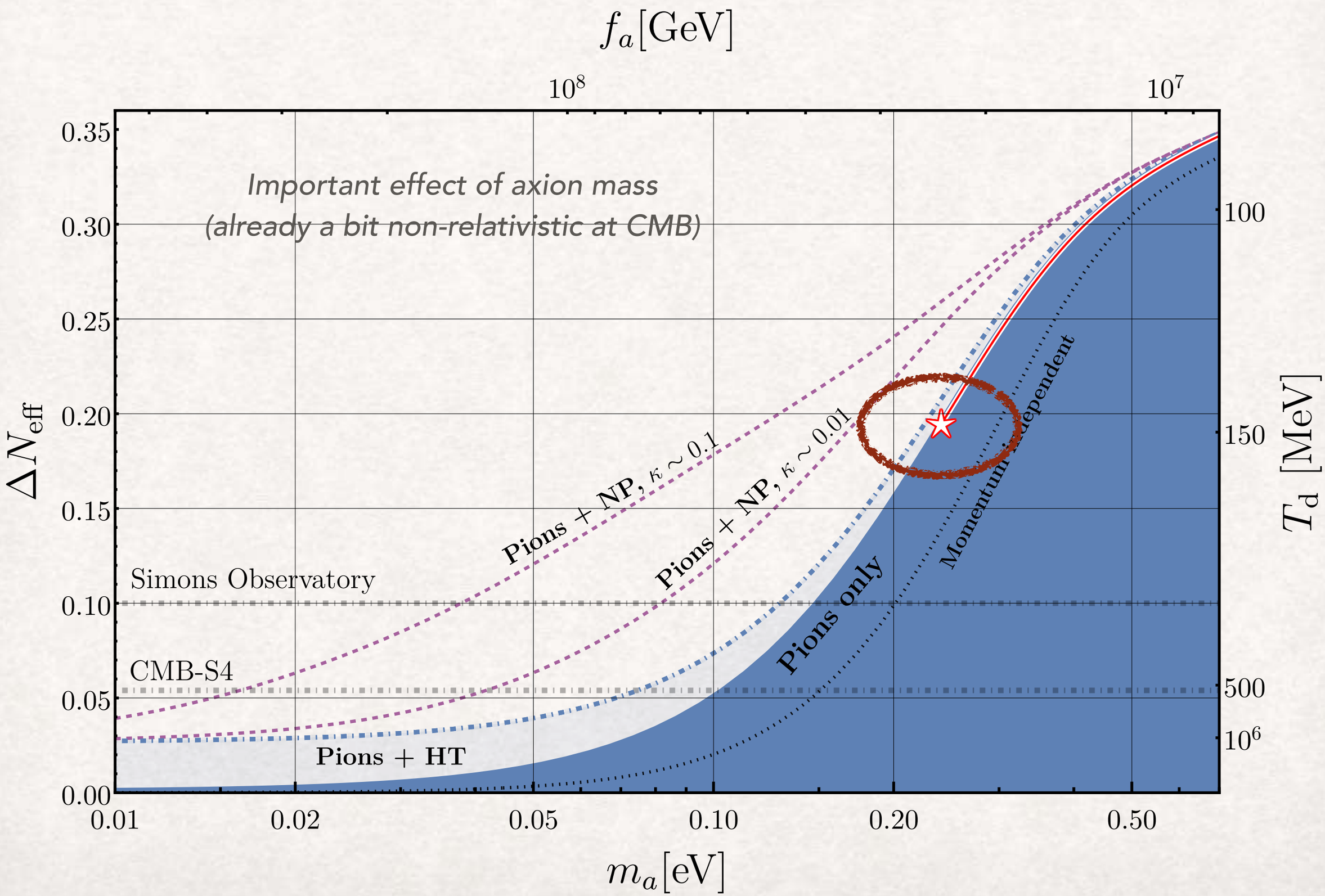


Planck 2018 TT+TE+EE high+low-l+lensing
+
Baryon Acoustic Oscillations (BAO)
+
Pantheon Supernovae

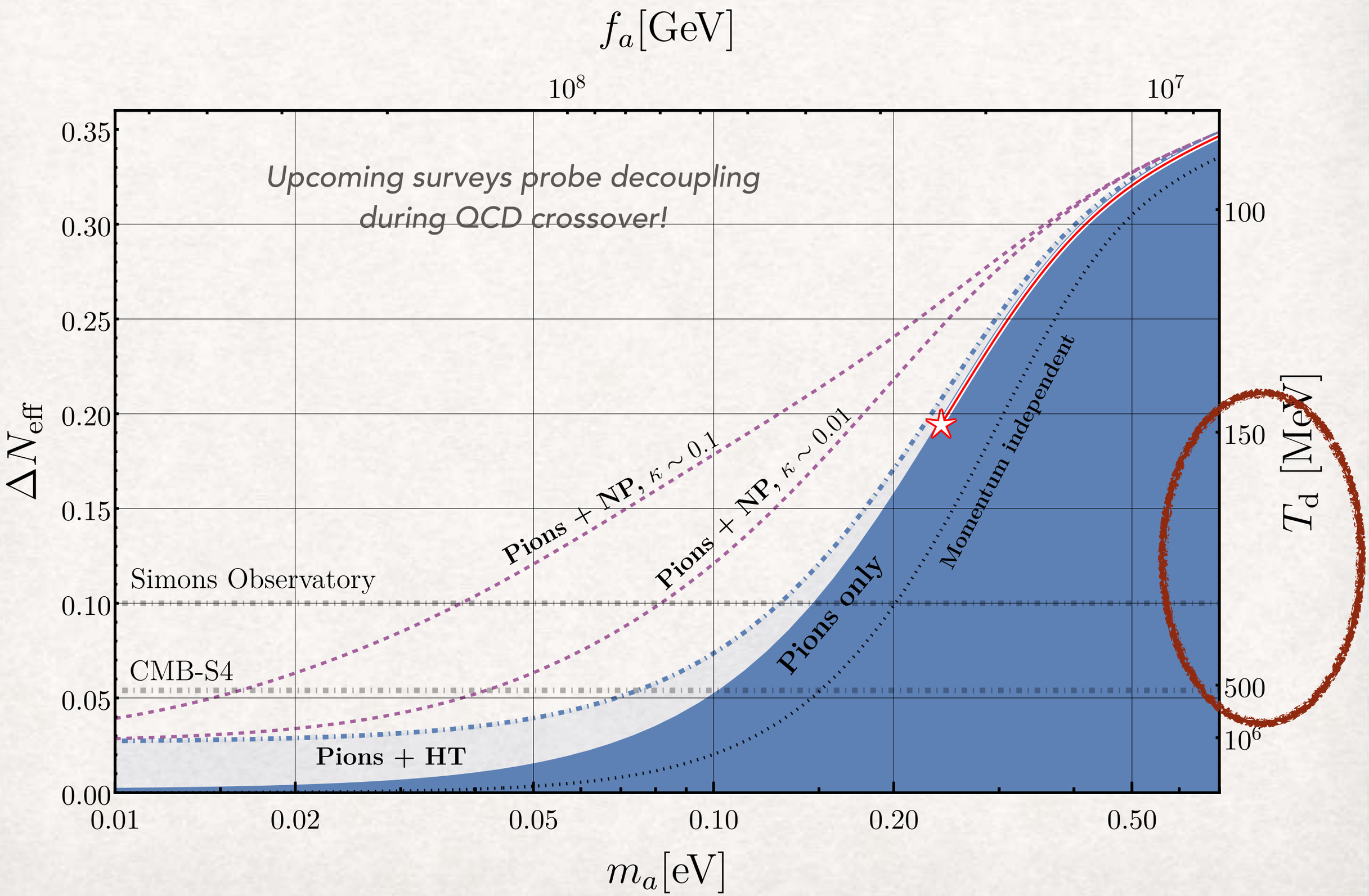
$$m_a \leq 0.24 \text{ eV}, 95\% \text{ C.L.}$$

$$\sum_\nu m_\nu \leq 0.14 \text{ eV}, 95\% \text{ C.L.}$$

THE PRESENT


f_a[GeV]
10^8
10^7
Important effect of axion mass
(already a bit non-relativistic at CMB)
Pions + NP, $\kappa \sim 0.1$
Pions + NP, $\kappa \sim 0.01$
Pions only
Momentum independent
Pions + HT
Simons Observatory
CMB-S4
$\Delta N_{\rm eff}$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.01
0.02
0.05
0.10
0.20
0.50
m_a[eV]
100
150
500
10^6
$T_{\rm d}$ [MeV]

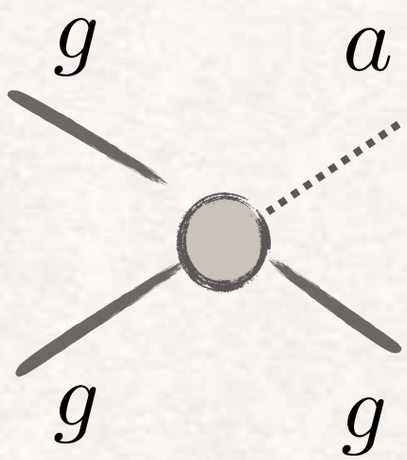
THE (NEAR) FUTURE



WHAT ABOUT THE QCD CROSSOVER?

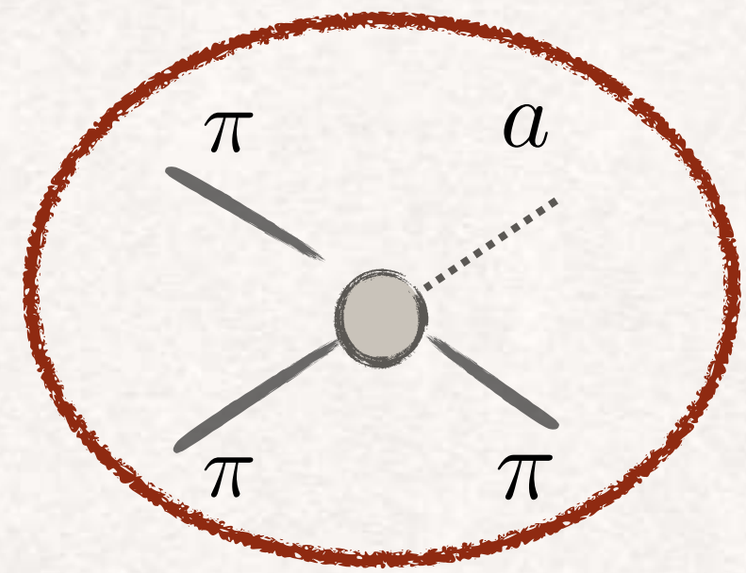
Hot axion quanta can be produced in scattering of SM states

For Planck18+BAO sensitivity



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

For Planck18+BAO sensitivity



$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

Smaller decay constants $\Rightarrow$ Larger ΔN_{eff} $\Rightarrow$ Can set lower bound on f_a $\Rightarrow$ Upper bound on m_a

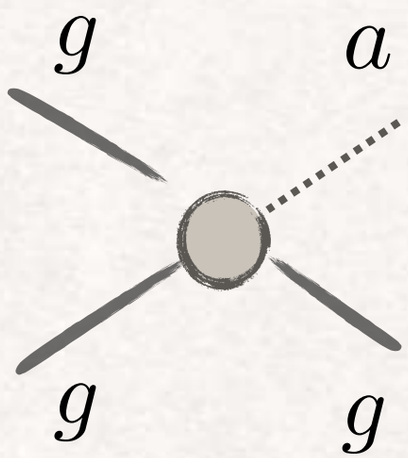
a.k.a. Hot Dark Matter Bound

WHAT ABOUT THE QCD CROSSOVER?

Hot axion quanta can be produced in scattering of SM states

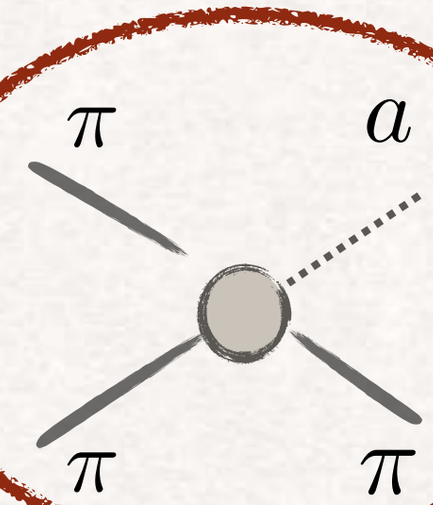
For Planck18+BAO sensitivity

For Planck18+BAO sensitivity



?!

Non-perturbative calculation needed!



$$\Gamma_{gg\to ag} \propto \frac{T^3}{f_a^2}$$

$$\Gamma_{\pi\pi\to a\pi} \propto \frac{T^5}{f_\pi^2 f_a^2}$$

T

$T \sim \mathrm{GeV}$

$T_{\mathrm{QCD}} \simeq 150\ \mathrm{MeV}$

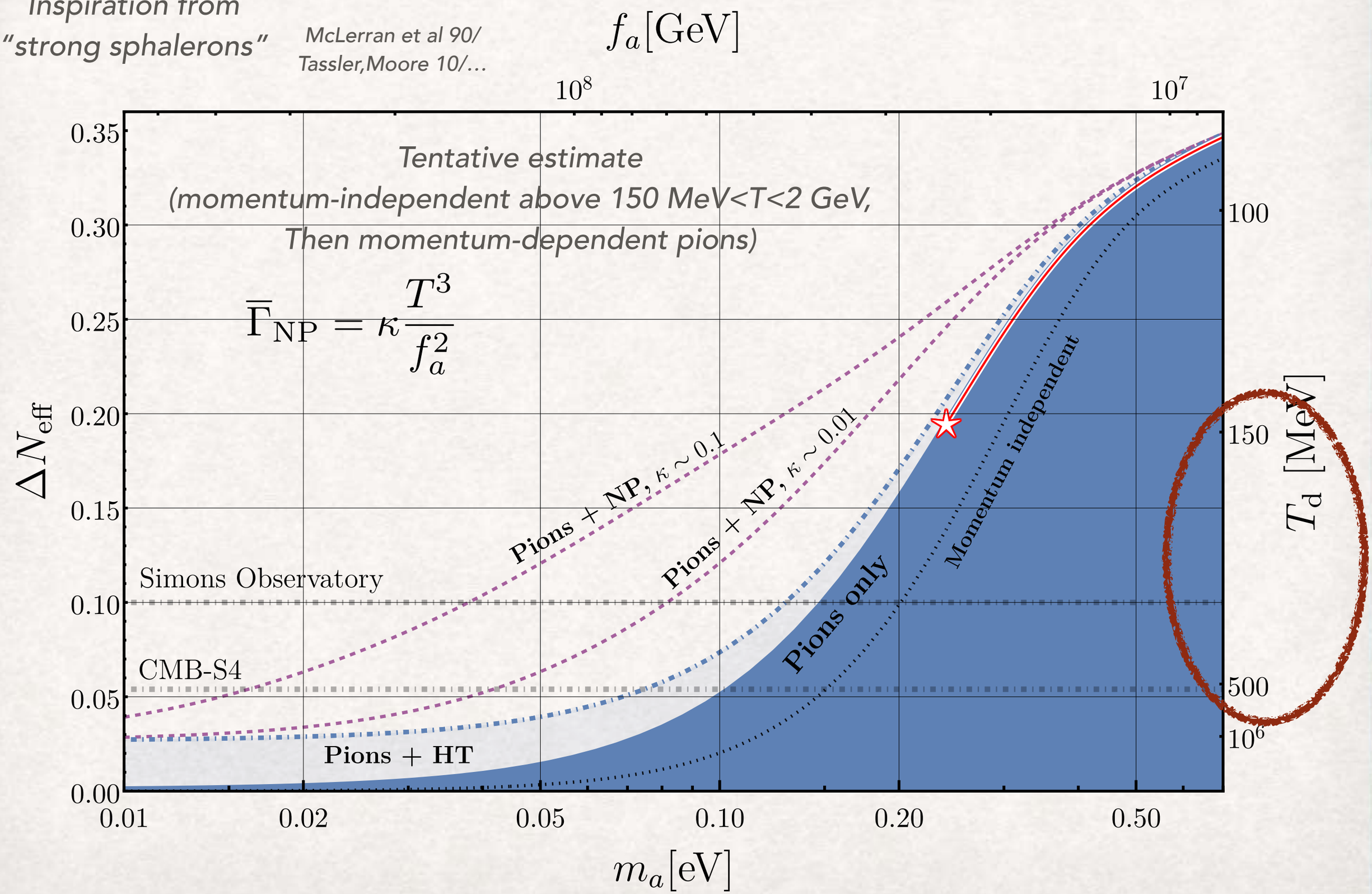
Smaller decay constants $\Rightarrow$ Larger ΔN_{eff} $\Rightarrow$ Can set lower bound on f_a $\Rightarrow$ Upper bound on m_a

a.k.a. Hot Dark Matter Bound

THE NEED FOR NON-PERTURBATIVE RATES

Inspiration from "strong sphalerons"

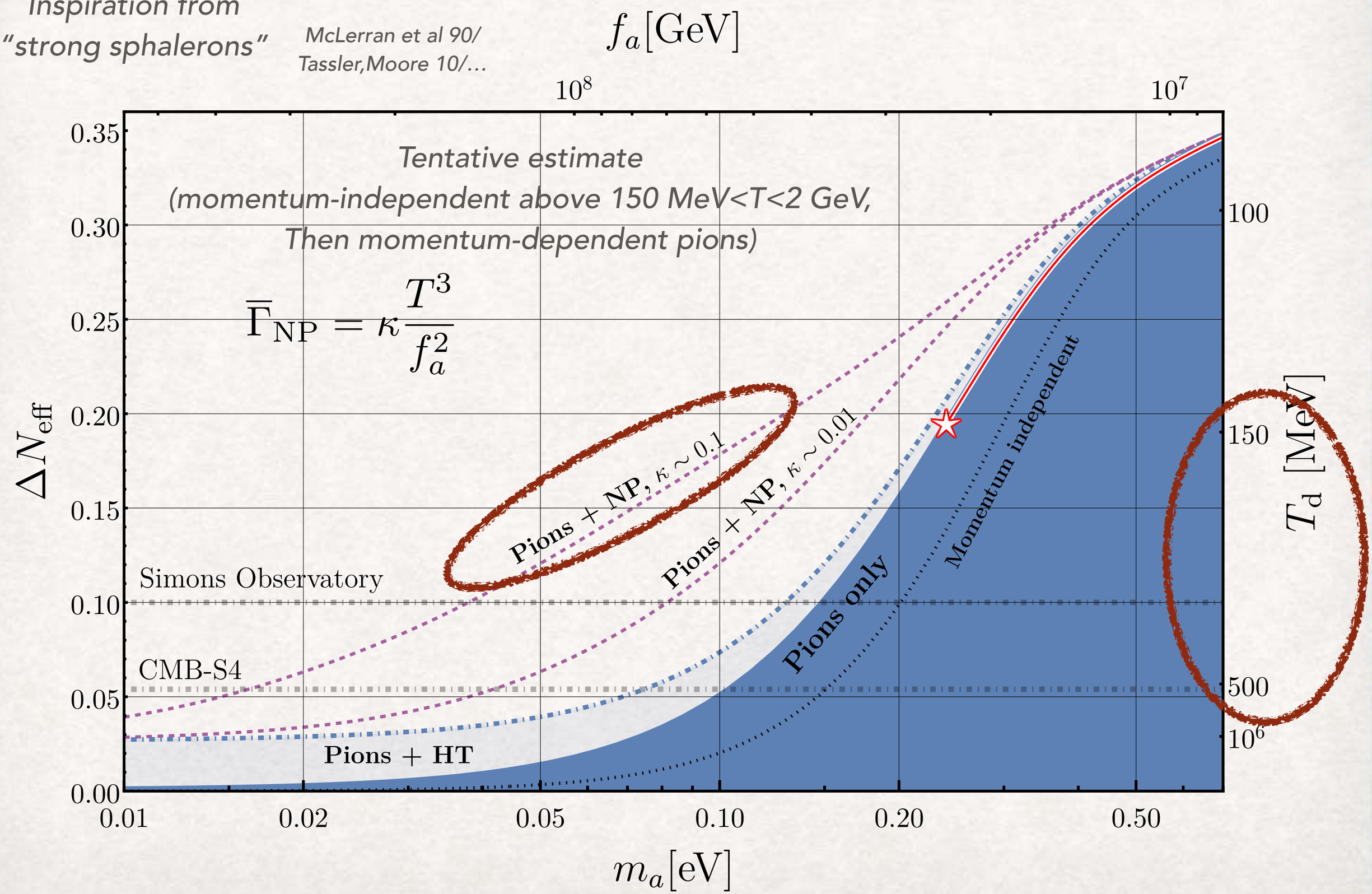
McLerran et al 90/ Tassler,Moore 10/…



THE NEED FOR NON-PERTURBATIVE RATES

Inspiration from "strong sphalerons"

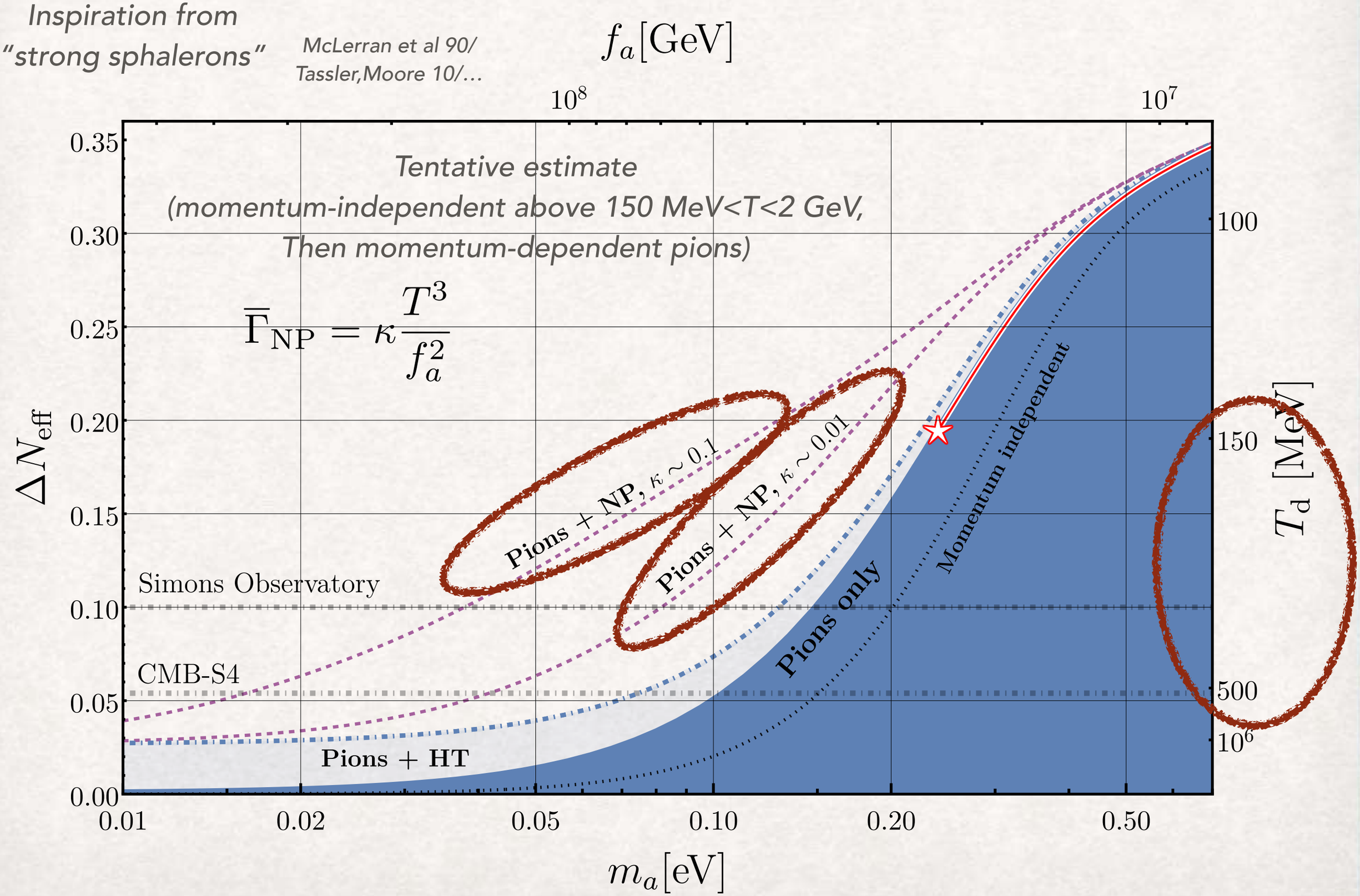
McLerran et al 90/ Tassler,Moore 10/…



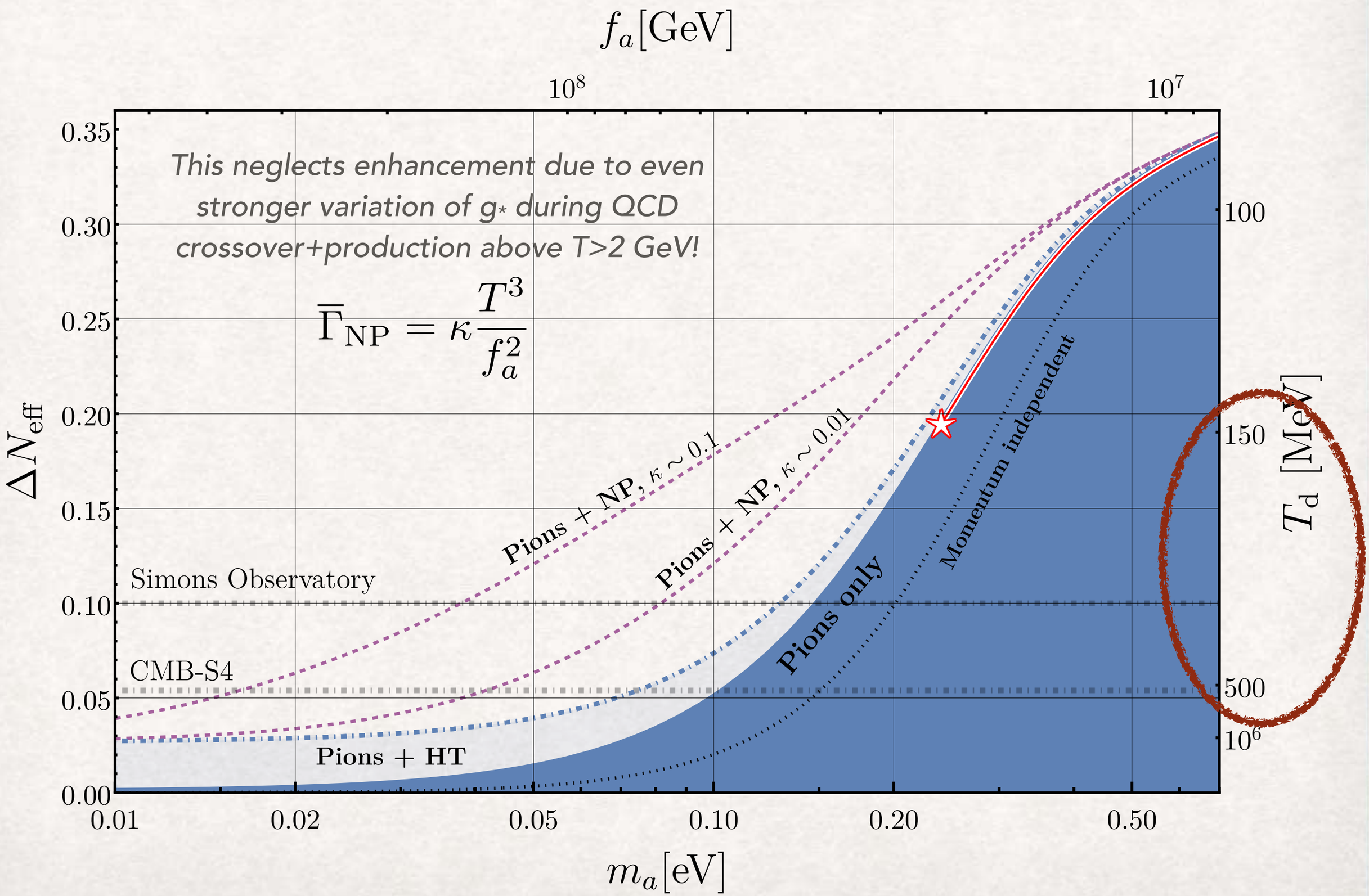
THE NEED FOR NON-PERTURBATIVE RATES

Inspiration from "strong sphalerons"

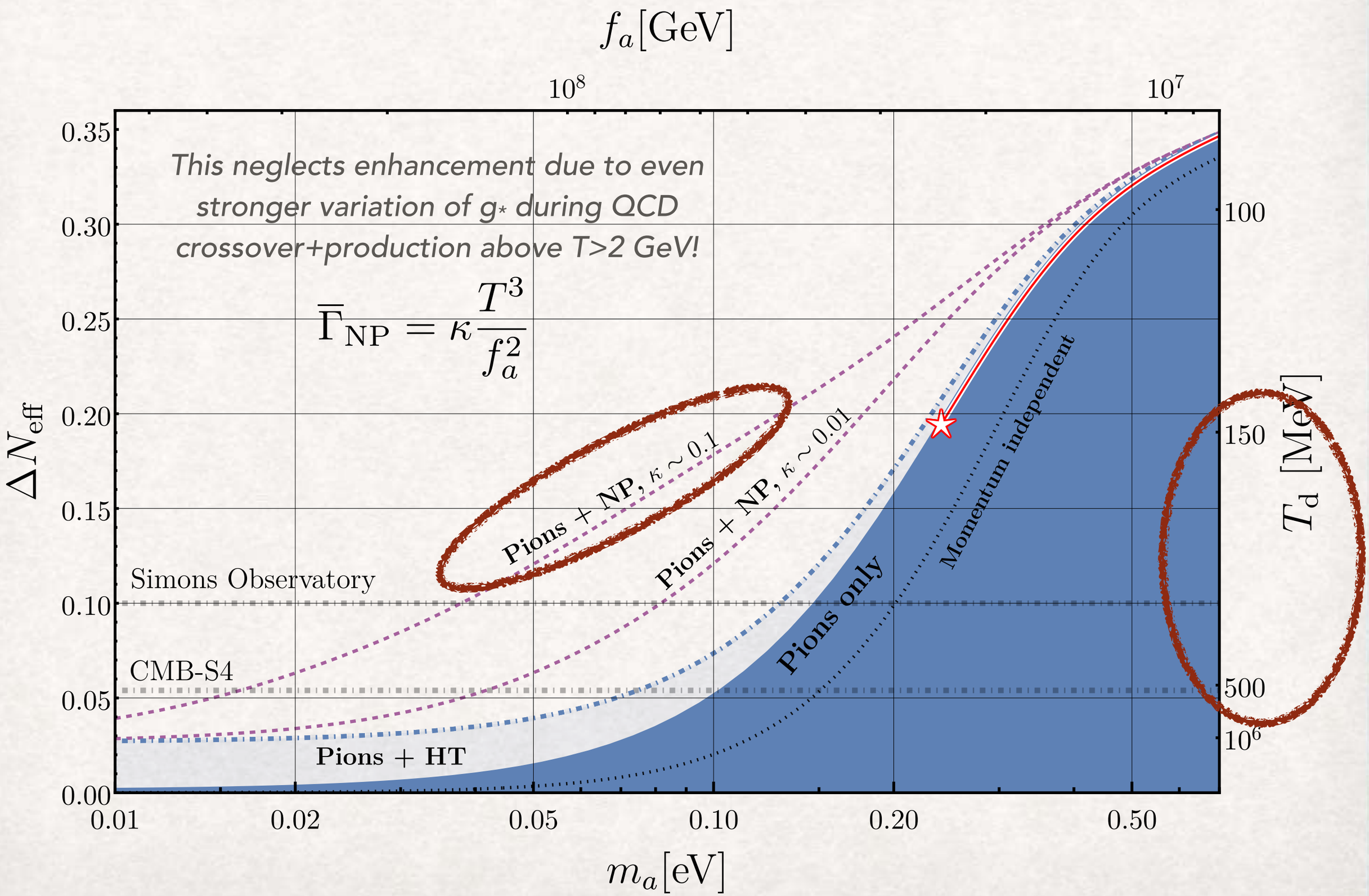
McLerran et al 90/ Tassler,Moore 10/…



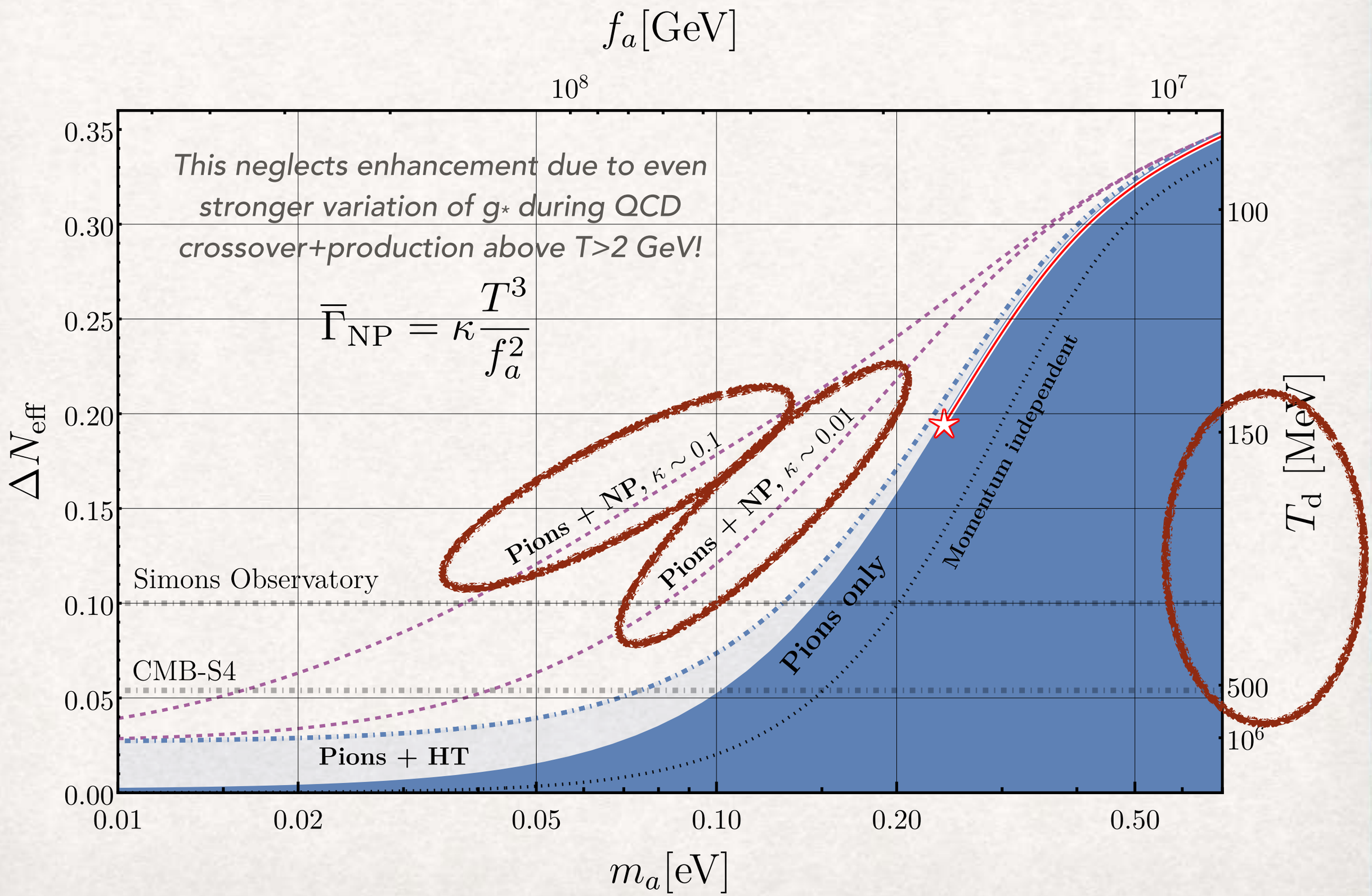
THE NEED FOR NON-PERTURBATIVE RATES



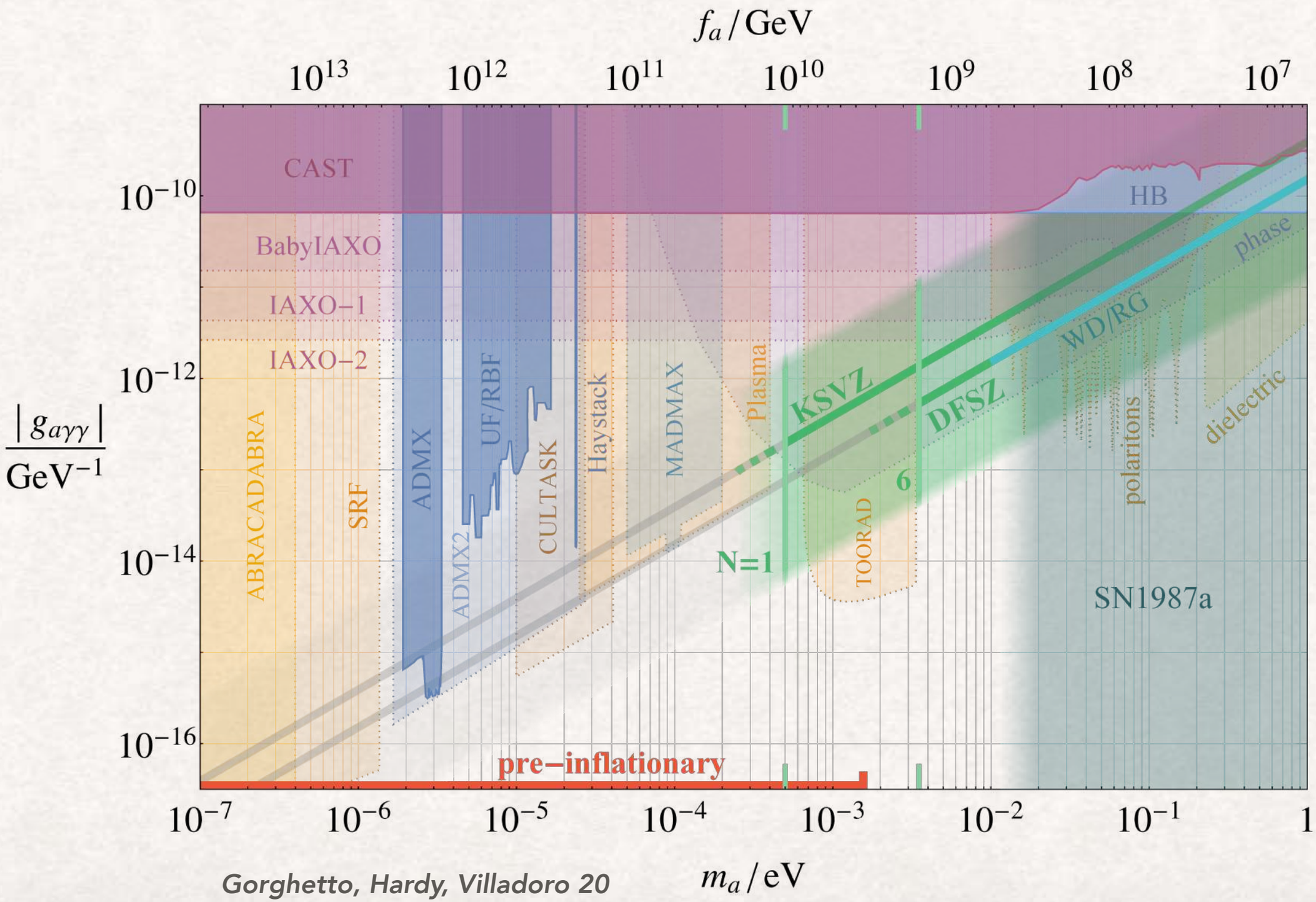
THE NEED FOR NON-PERTURBATIVE RATES



THE NEED FOR NON-PERTURBATIVE RATES

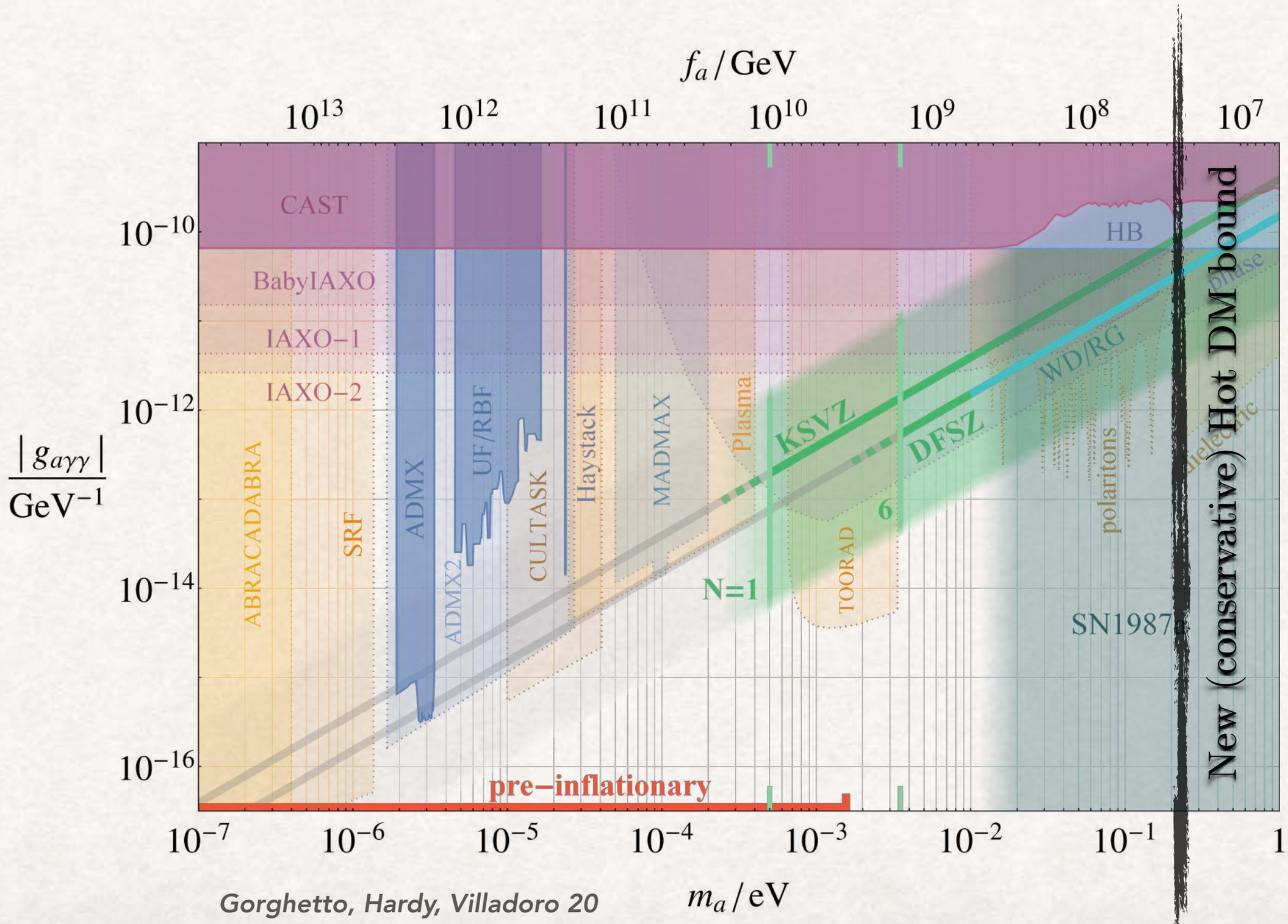


DISCOVERING THE QCD AXION WITH COSMOLOGY?



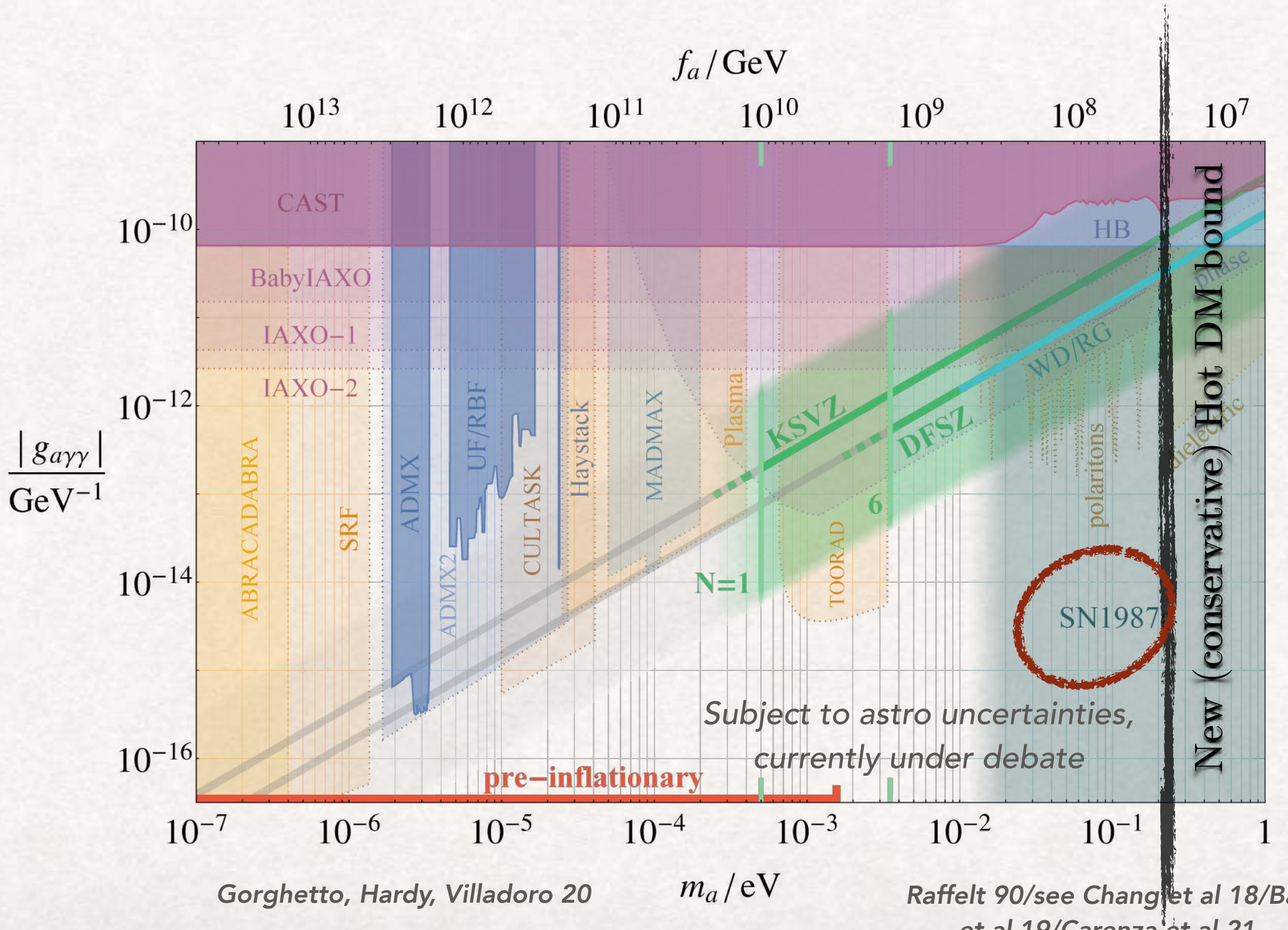
Gorghetto, Hardy, Villadoro 20

DISCOVERING THE QCD AXION WITH COSMOLOGY?



Gorghetto, Hardy, Villadoro 20

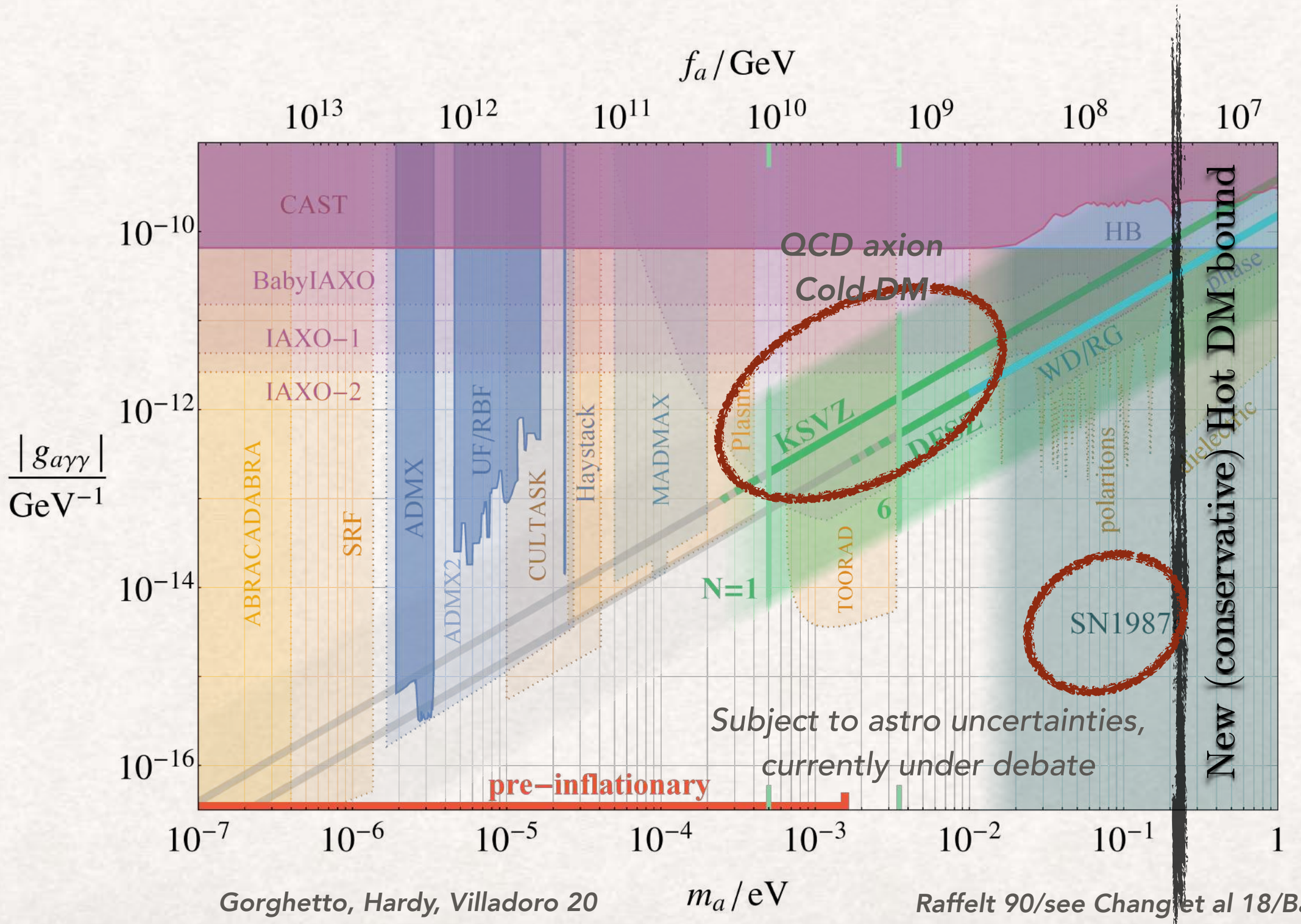
DISCOVERING THE QCD AXION WITH COSMOLOGY?



Gorghetto, Hardy, Villadoro 20

Raffelt 90/see Chang et al 18/Bar et al 19/Carenza et al 21

DISCOVERING THE QCD AXION WITH COSMOLOGY?

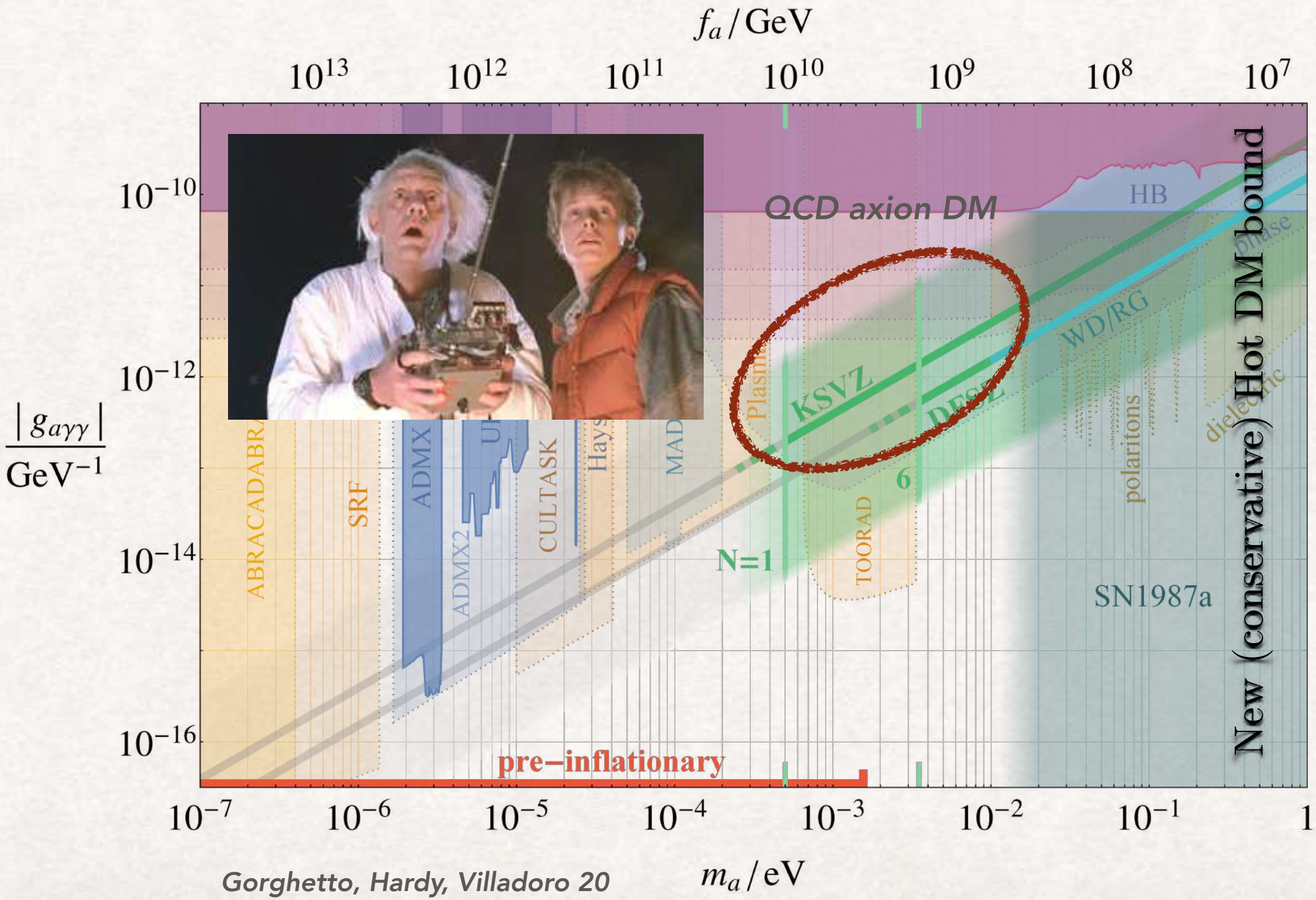


Gorghetto, Hardy, Villadoro 20

Raffelt 90/see Chang et al 18/Bar et al 19/Carenza et al 21

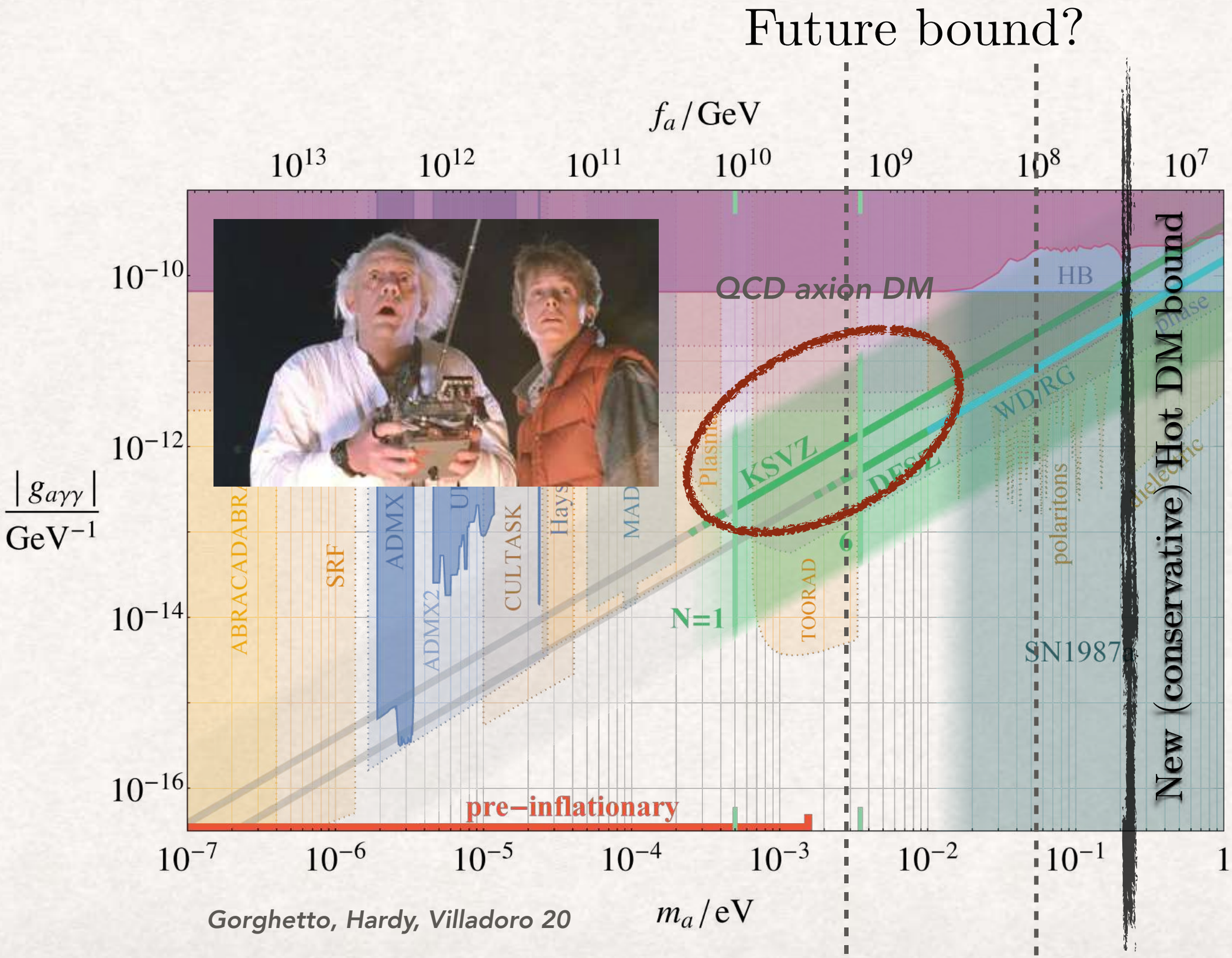
DISCOVERING THE QCD AXION WITH COSMOLOGY?

Future bound?



Gorghetto, Hardy, Villadoro 20

DISCOVERING THE QCD AXION WITH COSMOLOGY?



Gorghetto, Hardy, Villadoro 20

CONCLUSIONS 1ST PART

CONCLUSIONS 1ST PART

THE QCD AXION CAN BE PRODUCED IN THE EARLY UNIVERSE VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS)

CONCLUSIONS 1ST PART

THE QCD AXION CAN BE PRODUCED IN THE EARLY UNIVERSE VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS)

WE HAVE NOW OBTAINED A RELIABLE PRODUCTION RATE FROM PIONS BELOW THE QCD CROSSOVER.

CONCLUSIONS 1ST PART

THE QCD AXION CAN BE PRODUCED IN THE EARLY UNIVERSE VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS)

WE HAVE NOW OBTAINED A RELIABLE PRODUCTION RATE FROM PIONS BELOW THE QCD CROSSOVER.

INCLUSION OF MOMENTUM-DEPENDENCE LEADS TO OVERLOOKED ENHANCEMENT OF RELIC ABUNDANCE!

CONCLUSIONS 1ST PART

THE QCD AXION CAN BE PRODUCED IN THE EARLY UNIVERSE VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS)

WE HAVE NOW OBTAINED A RELIABLE PRODUCTION RATE FROM PIONS BELOW THE QCD CROSSOVER.

INCLUSION OF MOMENTUM-DEPENDENCE LEADS TO OVERLOOKED ENHANCEMENT OF RELIC ABUNDANCE!

NEW CONSERVATIVE "HOT DM BOUND" ON QCD AXION SET WITH PLANCK18+BAO+PANTHEON

CONCLUSIONS 1ST PART

THE QCD AXION CAN BE PRODUCED IN THE EARLY UNIVERSE VIA SCATTERINGS WITH SM STATES (PIONS, GLUONS, FERMIONS)

WE HAVE NOW OBTAINED A RELIABLE PRODUCTION RATE FROM PIONS BELOW THE QCD CROSSOVER.

INCLUSION OF MOMENTUM-DEPENDENCE LEADS TO OVERLOOKED ENHANCEMENT OF RELIC ABUNDANCE!

NEW CONSERVATIVE "HOT DM BOUND" ON QCD AXION SET WITH PLANCK18+BAO+PANTHEON

UPCOMING CMB SURVEYS REQUIRE NEW (NON-PERTURBATIVE) THEORY CALCULATION TO IMPROVE THE BOUND,
POSSIBLY REACHING EVEN IN THE COLD AXION DM WINDOW!

HEAVY AXIONS AND GRAVITATIONAL WAVES

2204.04228
+ 2107.07542, PRL 128 (2022) 14

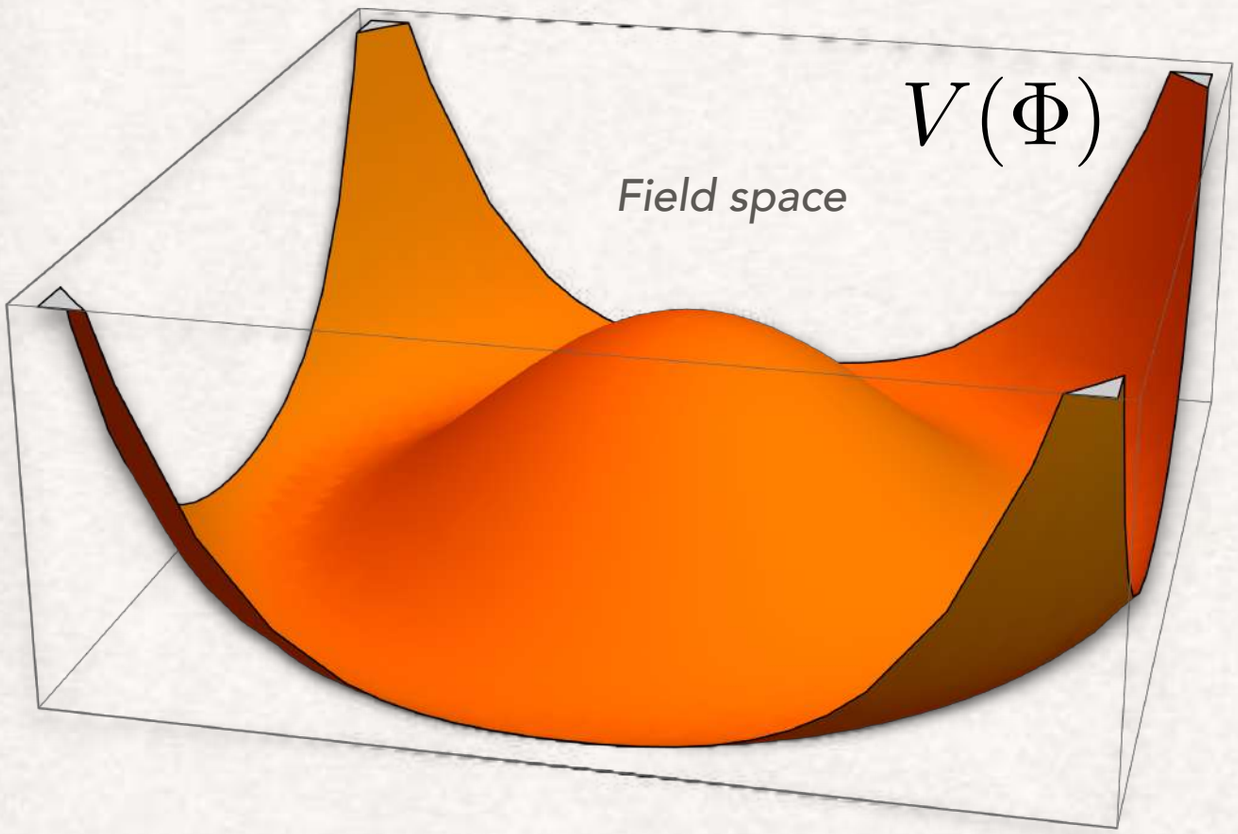
w/ R.Z.Ferreira, A.Notari and O.Pujolàs

AXIONIC DEFECTS

As a definite example, consider field theory implementation,
with PQ breaking occurring at $T \lesssim v$, **below the scale of inflation/reheating**

AXIONIC DEFECTS

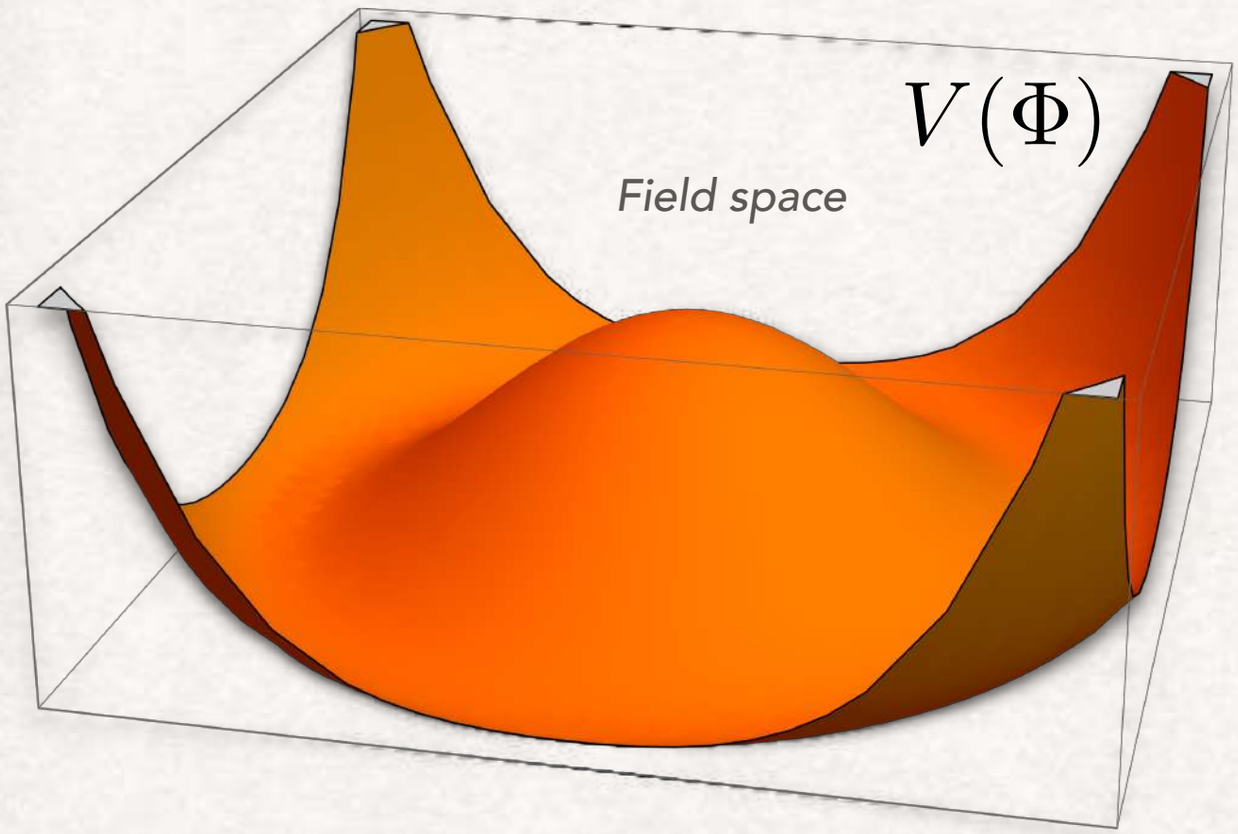
As a definite example, consider field theory implementation,
with PQ breaking occurring at $T \lesssim v$, **below the scale of inflation/reheating**



$$\Phi \sim v \; e^{ia(x,t)/v}$$

AXIONIC DEFECTS

As a definite example, consider field theory implementation,
with PQ breaking occurring at $T \lesssim v$, **below the scale of inflation/reheating**



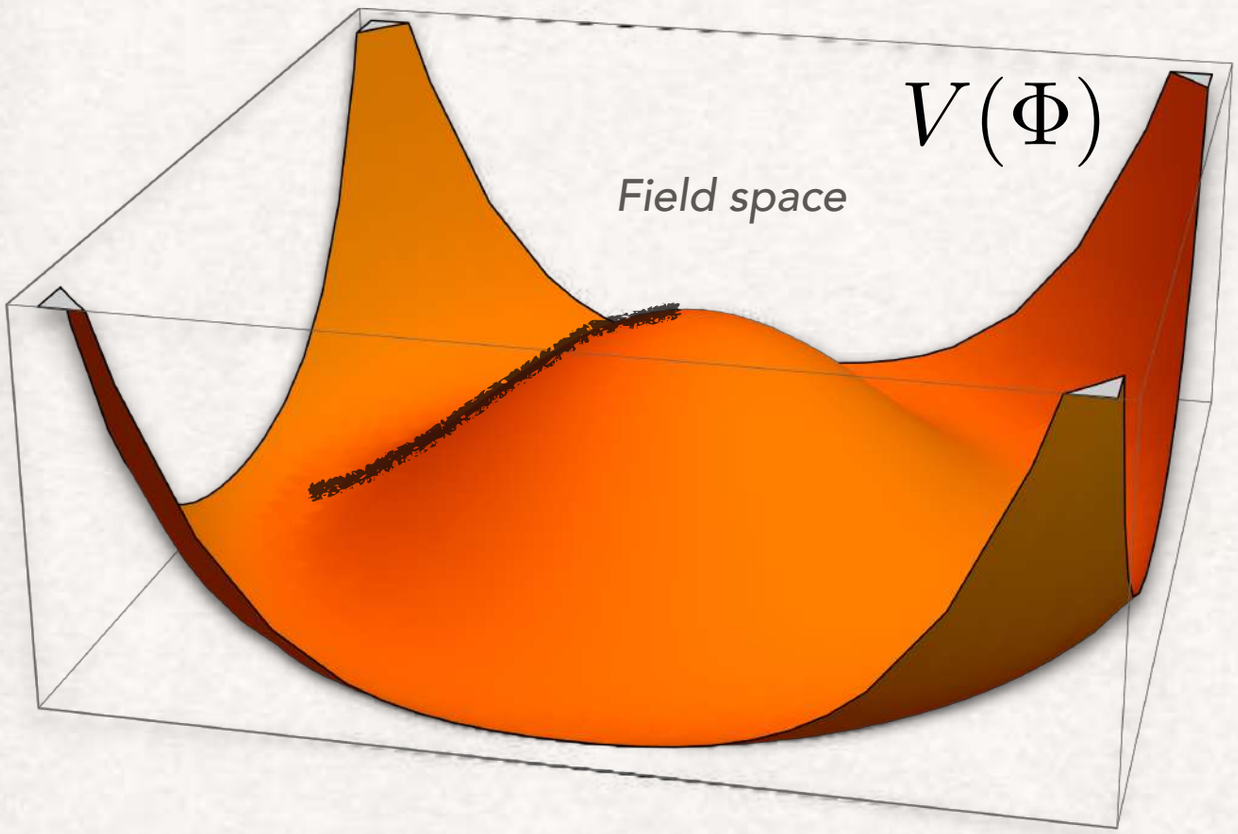
$$\Phi \sim v \; e^{ia(x,t)/v}$$

$$\Delta a = 2\pi v$$

Loop in physical space

AXIONIC DEFECTS

As a definite example, consider field theory implementation,
with PQ breaking occurring at $T \lesssim v$, **below the scale of inflation/reheating**



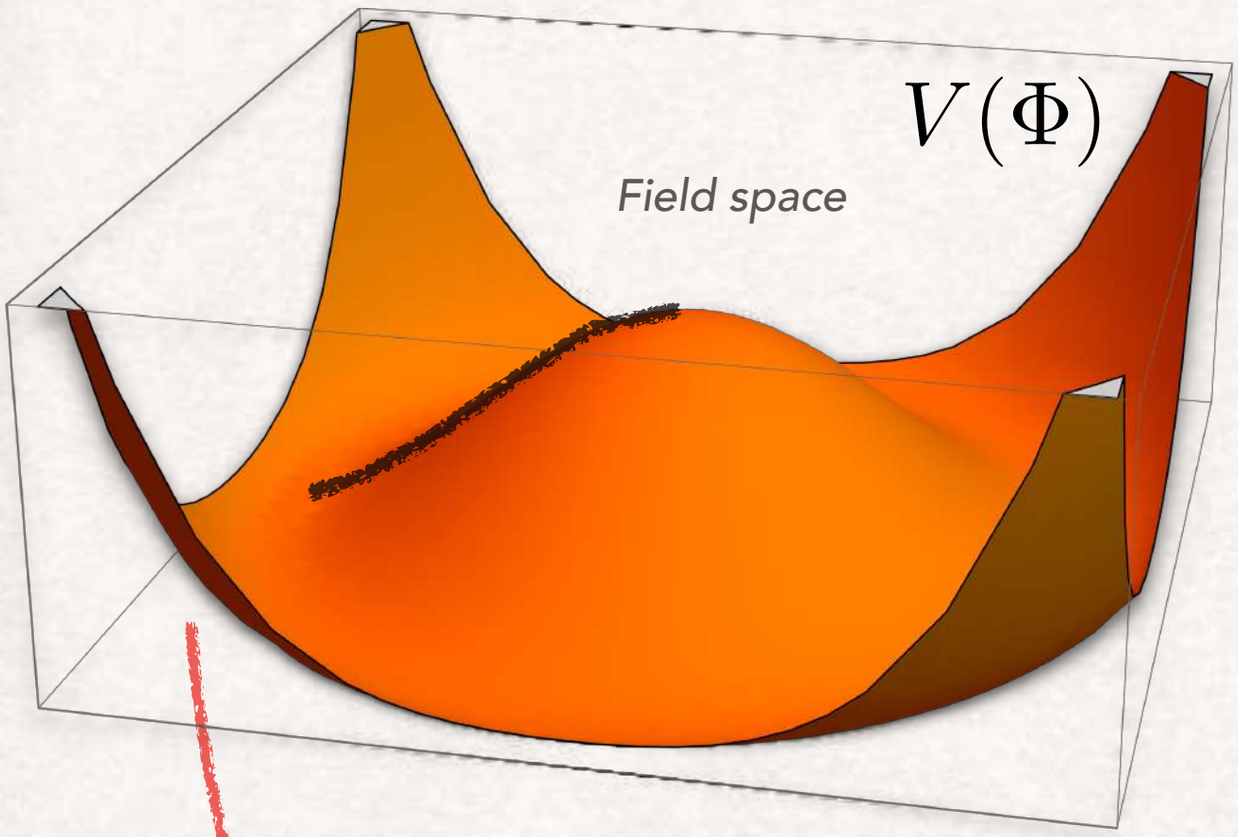
$$\Phi \sim v \; e^{ia(x,t)/v}$$

$$\Delta a = 2\pi v$$

Loop in physical space

AXIONIC DEFECTS

As a definite example, consider field theory implementation,
with PQ breaking occurring at $T \lesssim v$, **below the scale of inflation/reheating**

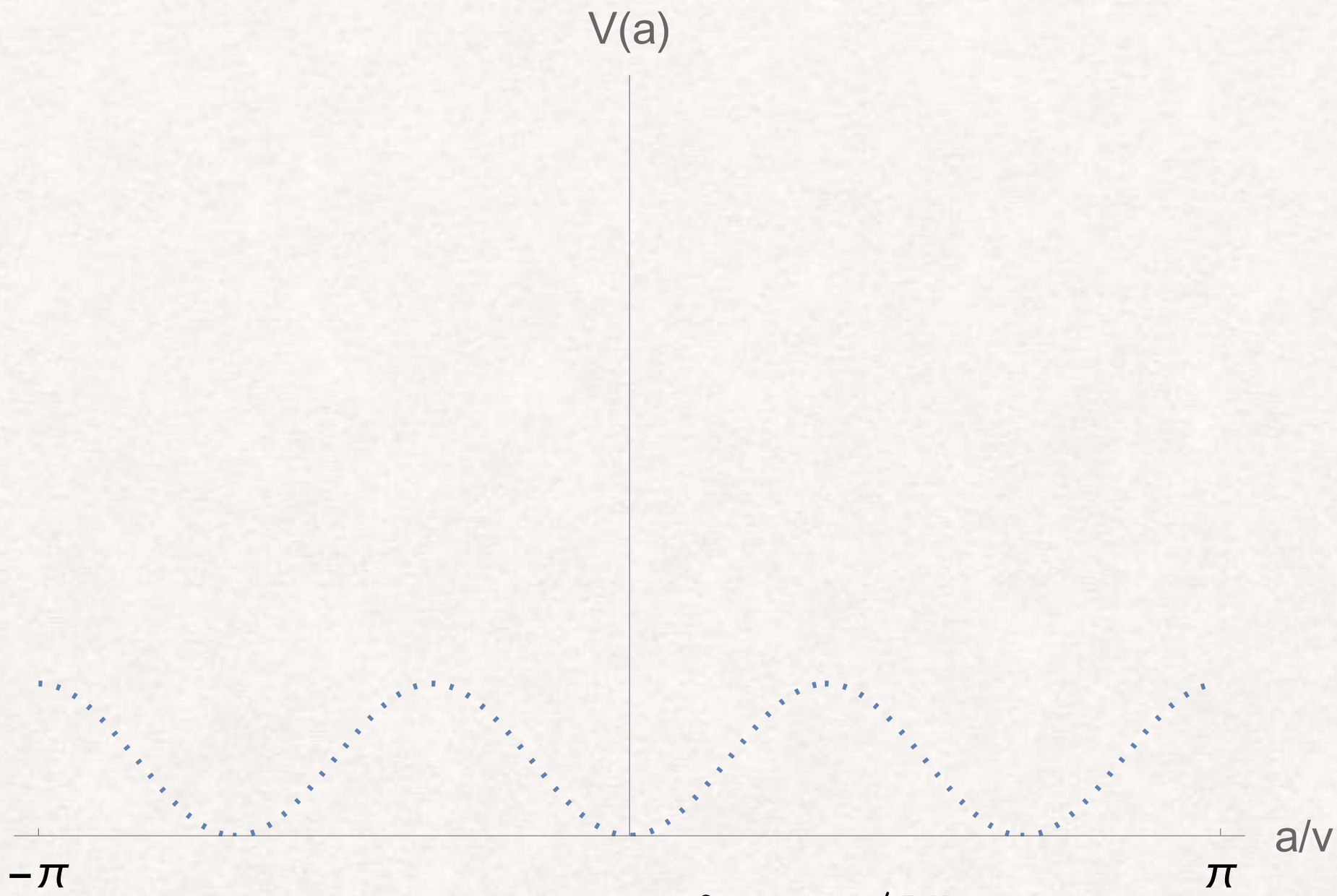


$$\Phi \sim v\ e^{ia(x,t)/v}$$

$$\Delta a = 2\pi v$$

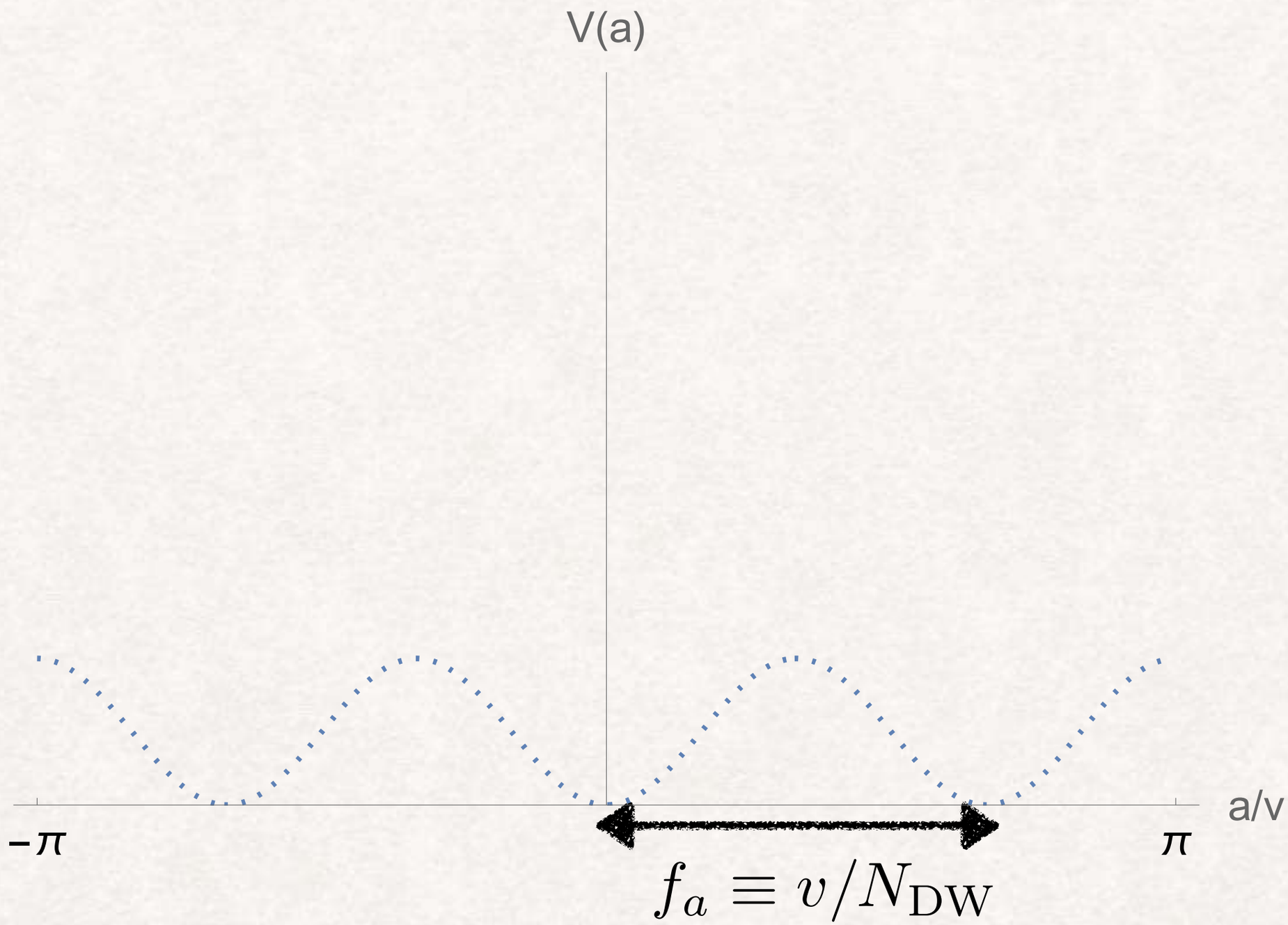
Corresponds to existence of
cosmic string defect

DOMAIN WALLS

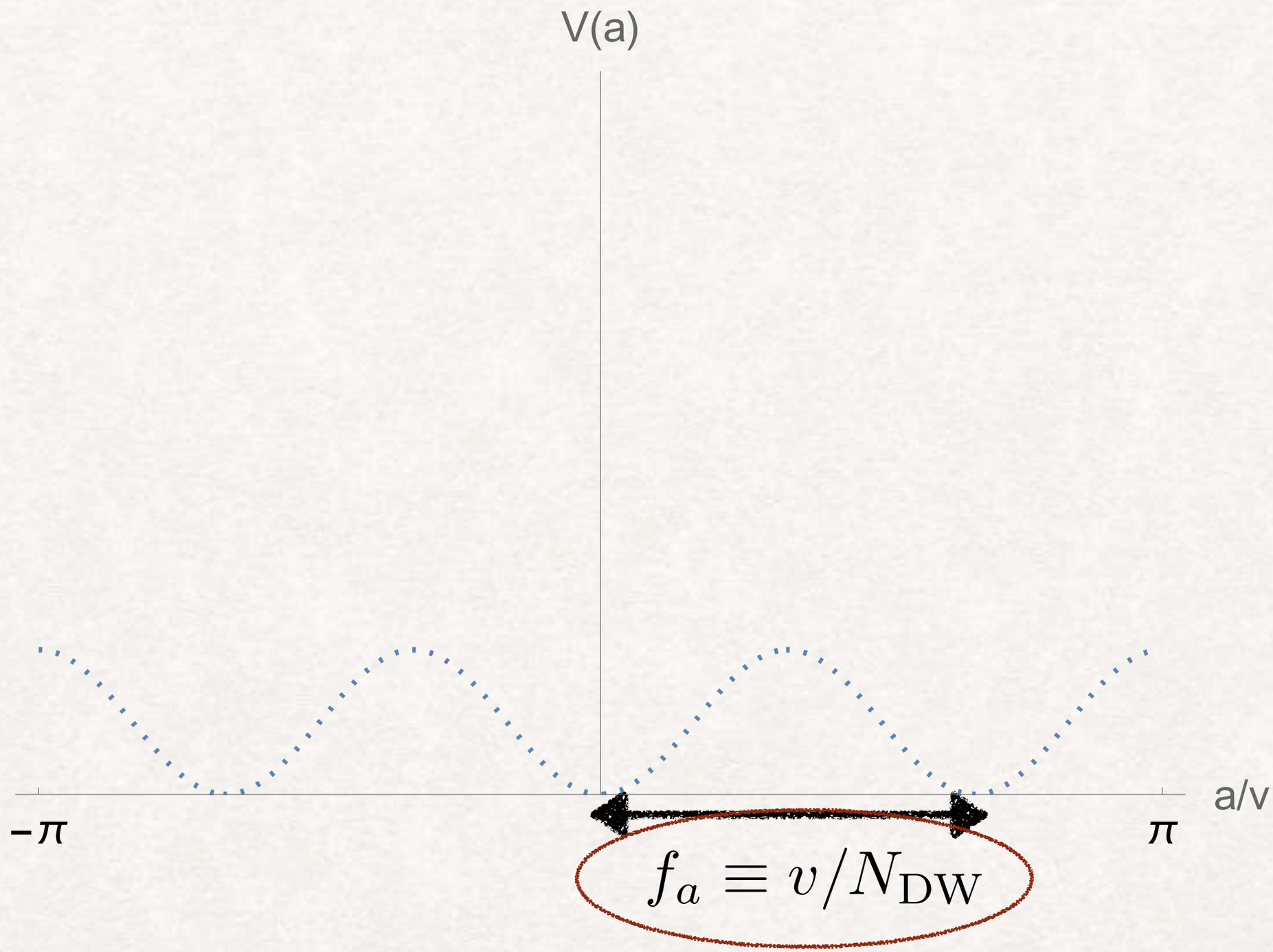


$$f_a \equiv v/N_{\rm DW}$$

DOMAIN WALLS



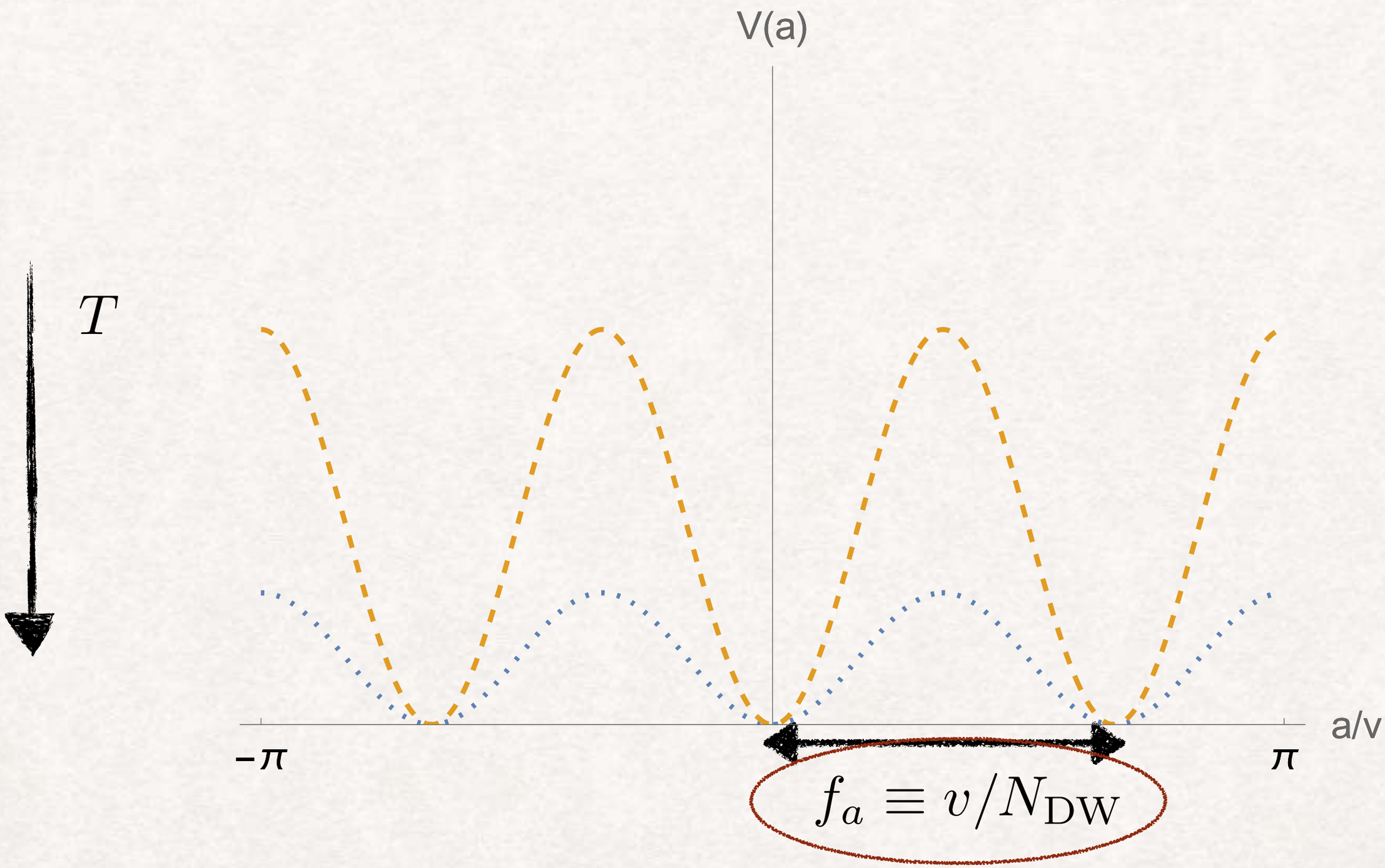
DOMAIN WALLS



Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

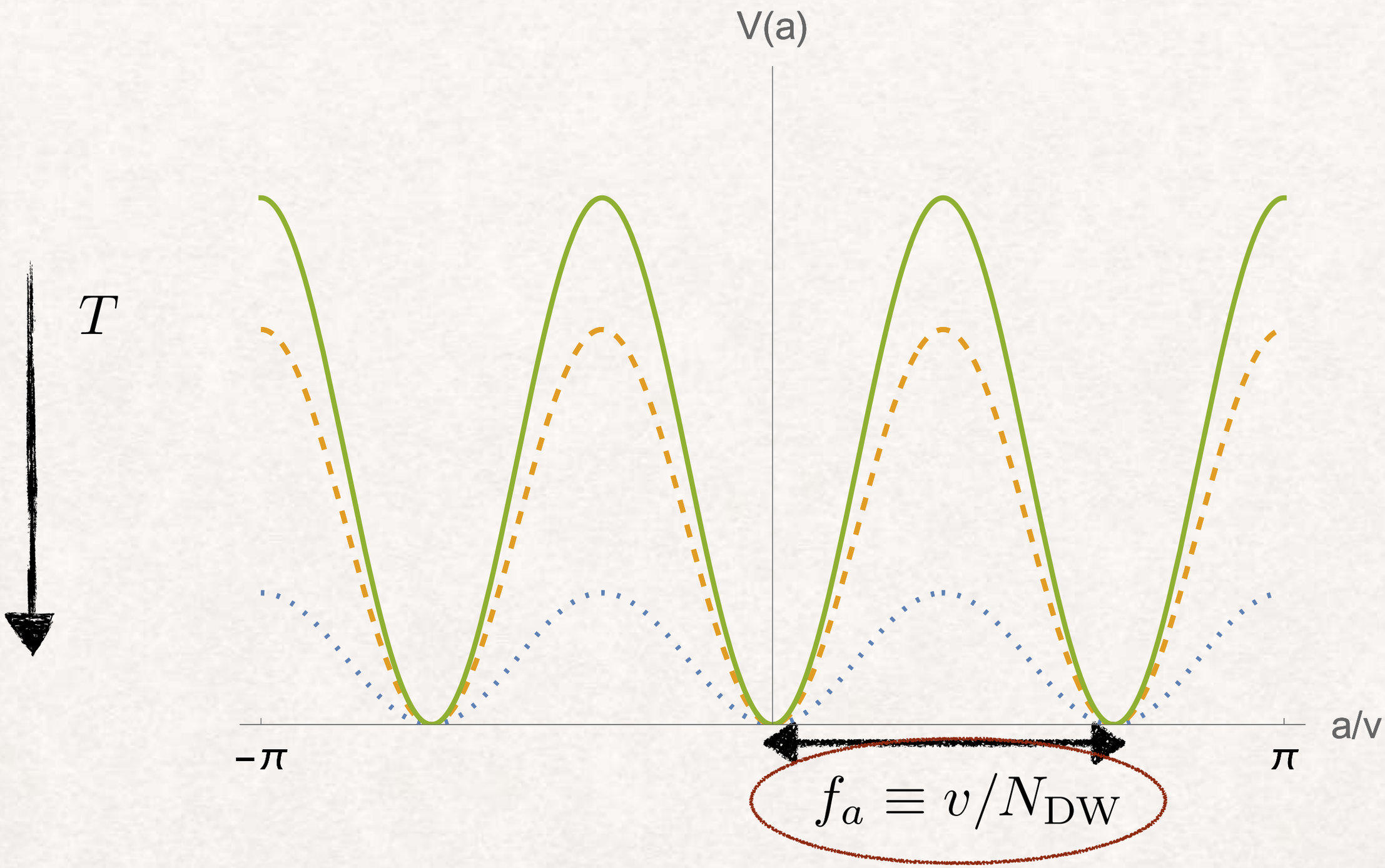
DOMAIN WALLS



Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

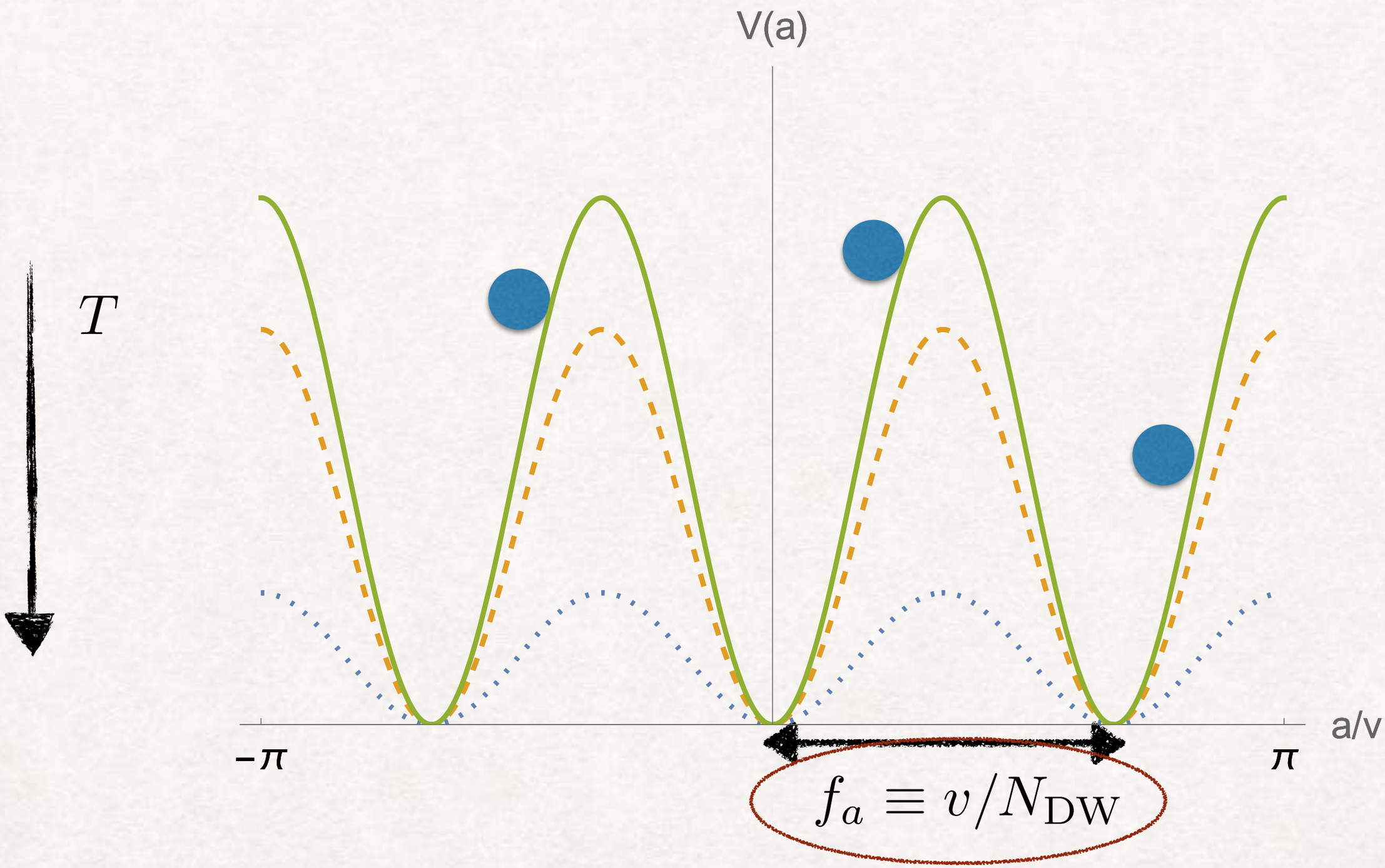
DOMAIN WALLS



Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

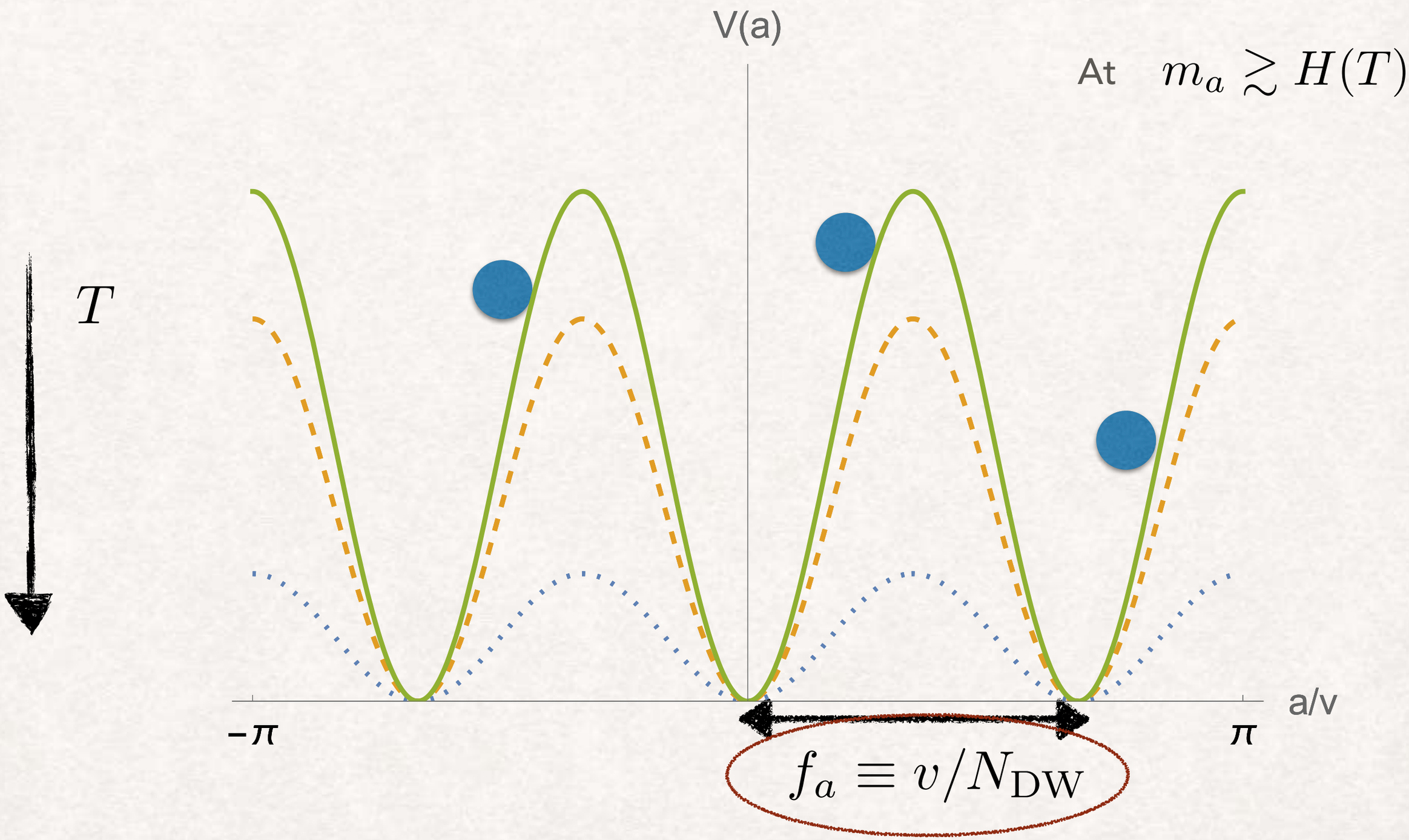
DOMAIN WALLS



Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

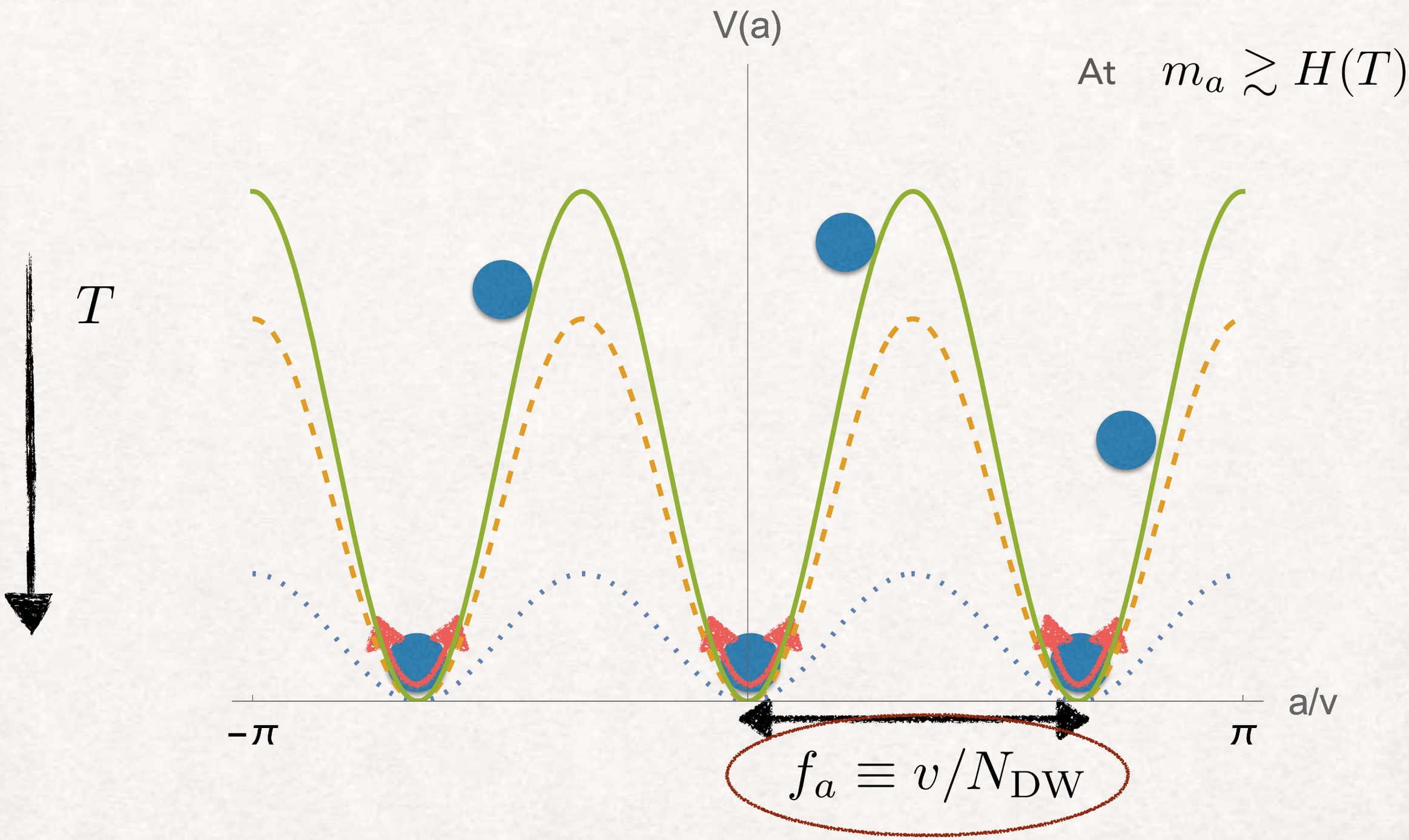
DOMAIN WALLS



Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

DOMAIN WALLS

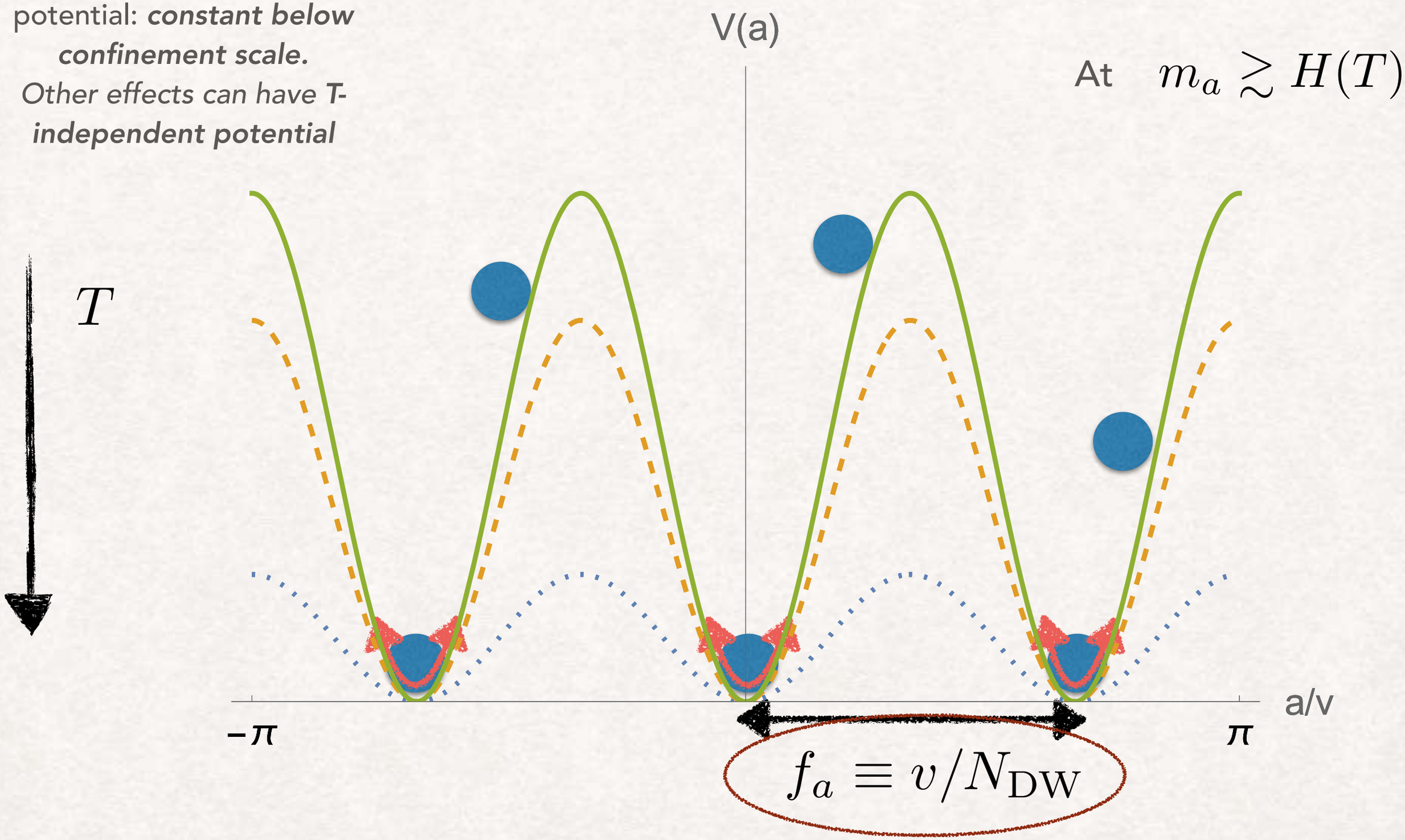


Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

DOMAIN WALLS

Gauge-theory induced potential: ***constant below confinement scale.***
*Other effects can have **T-independent potential***



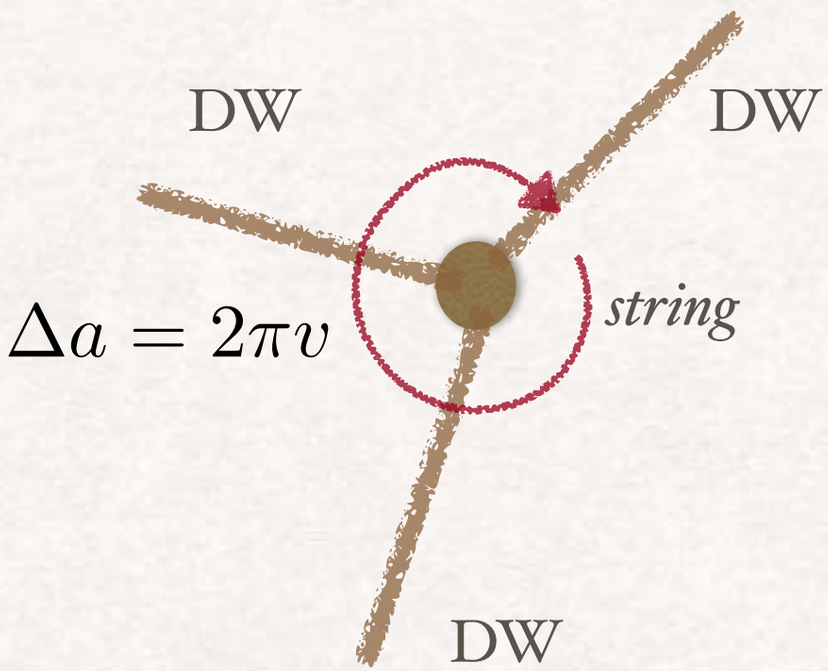
Number of minima in a full period **depends on microphysics** (e.g. # of fermions charged under PQ), **generically >1**

=1 in simple KSVZ

DOMAIN WALL NETWORK

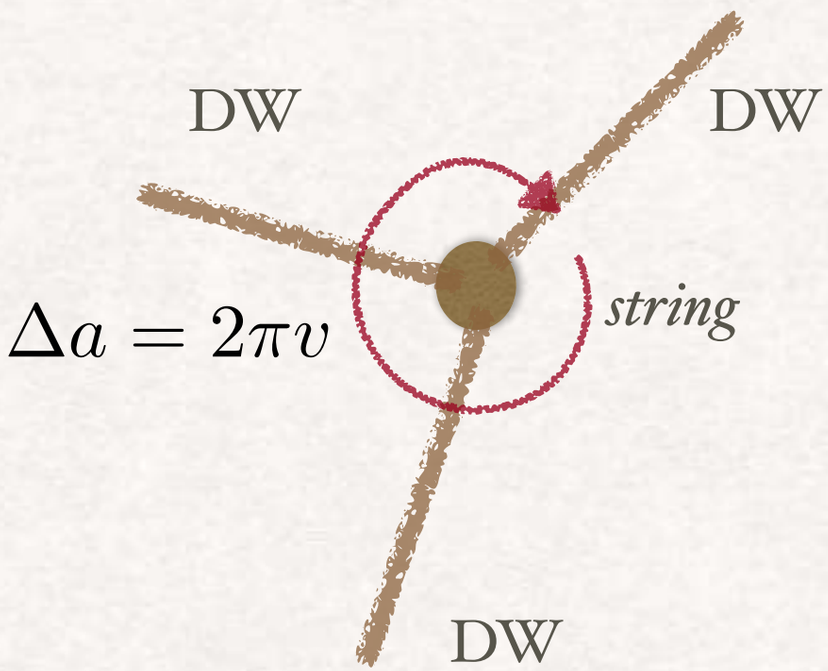
DOMAIN WALL NETWORK

Network of domain walls attached to strings forms and quickly reaches ***scaling regime***



DOMAIN WALL NETWORK

Network of domain walls attached to strings forms and quickly reaches ***scaling regime***



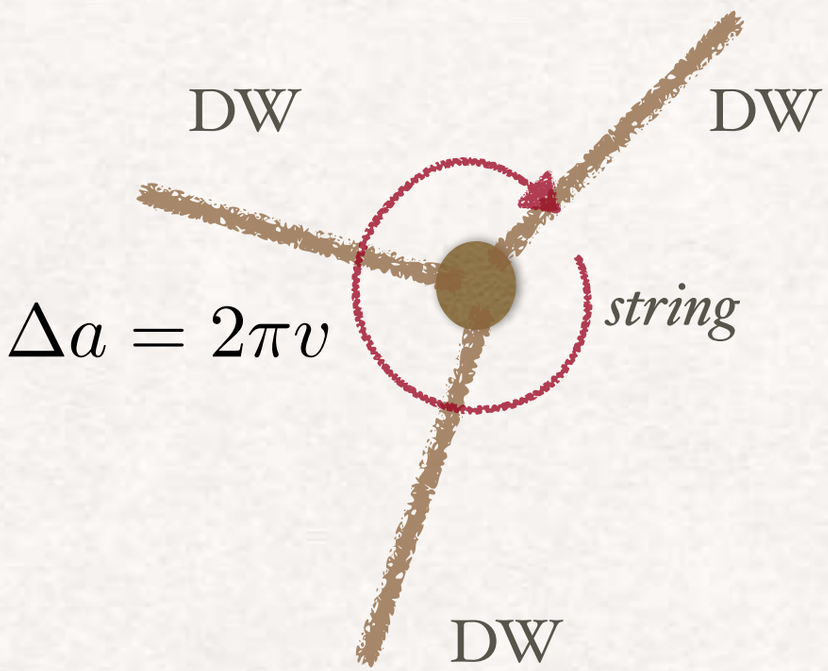
$$\rho_{\rm DW} \simeq \sigma H \sim a^{-2}$$

DW tension (mass/surface)

$$\sigma \simeq 8 m_a F_a^2$$

DOMAIN WALL NETWORK

Network of domain walls attached to strings forms and quickly reaches ***scaling regime***



$$\Delta a = 2\pi v$$

$$\rho_{\rm DW} \simeq \sigma H \sim a^{-2}$$

DW tension (mass/surface)

$$\sigma \simeq 8 m_a F_a^2$$

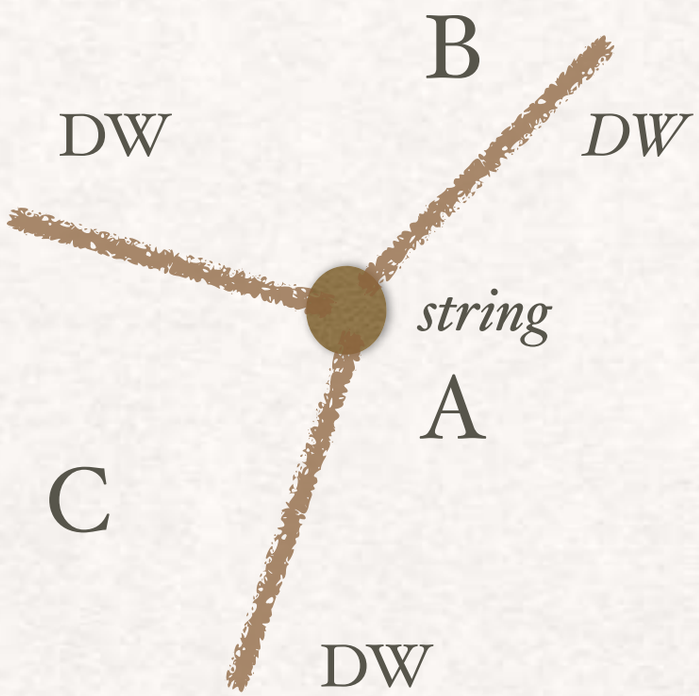
$$\Rightarrow \quad \frac{\rho_{\rm DW}}{3H^2 M_p^2} \to 1$$

DW problem

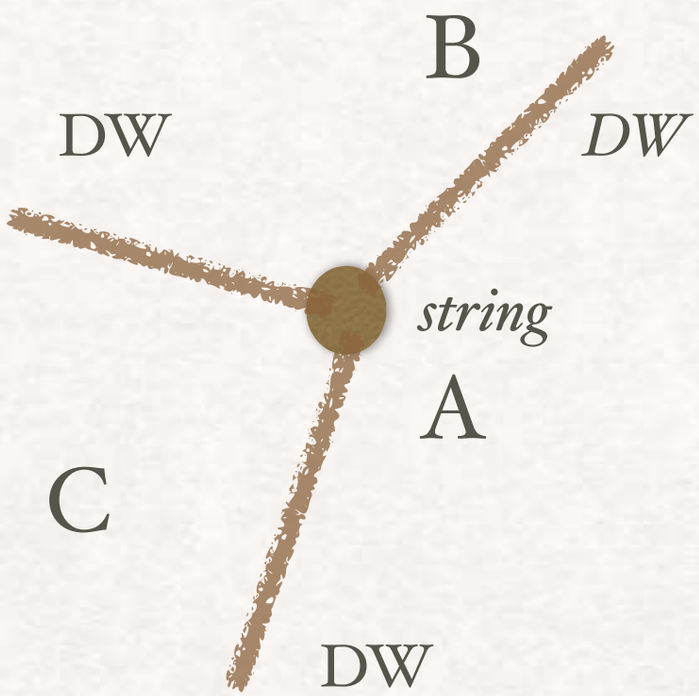
see e.g. Shellard, Vilenkin
also simulations by
Hiramatsu et al 12
Kawasaki et al 14

Zeldovich et al 74
Kibble 76

ANNIHILATING NETWORK



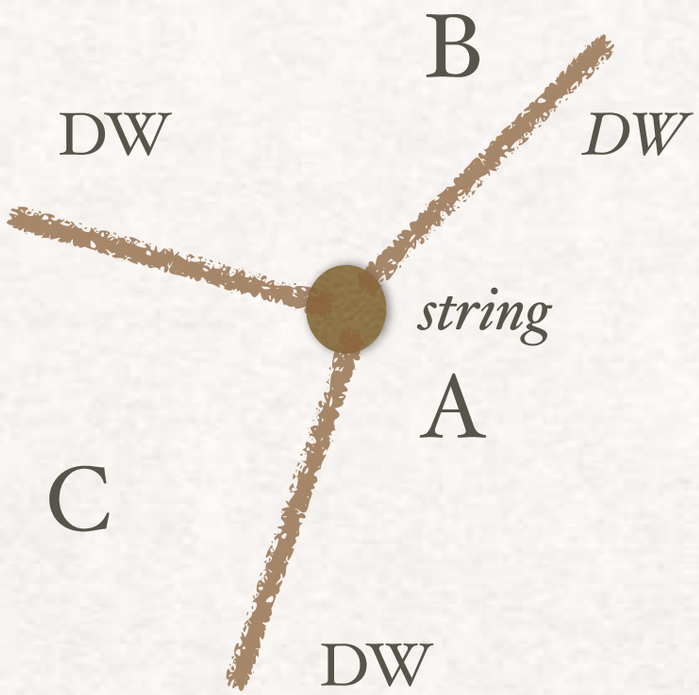
ANNIHILATING NETWORK



DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

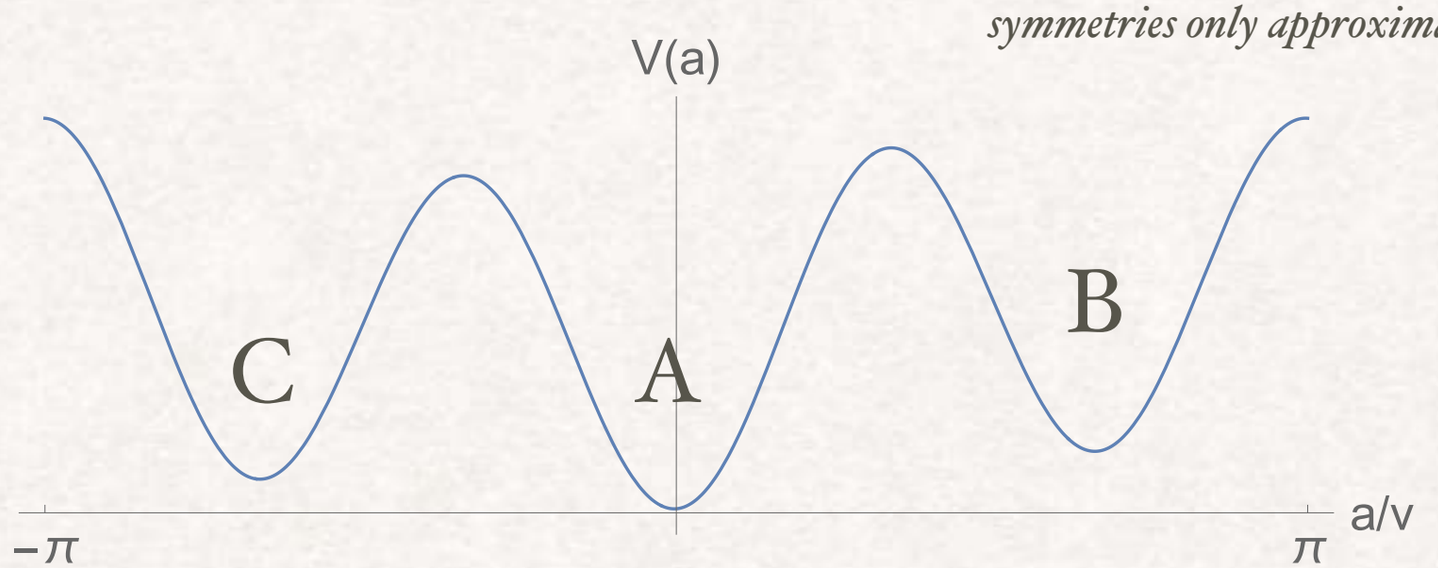
***Expectation**: Global symmetries only approximate!*

ANNIHILATING NETWORK



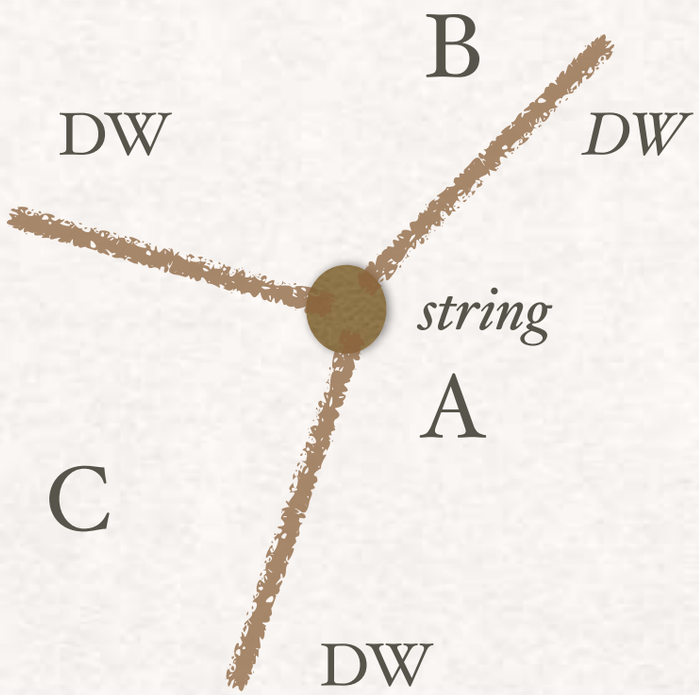
DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

***Expectation**: Global symmetries only approximate!*



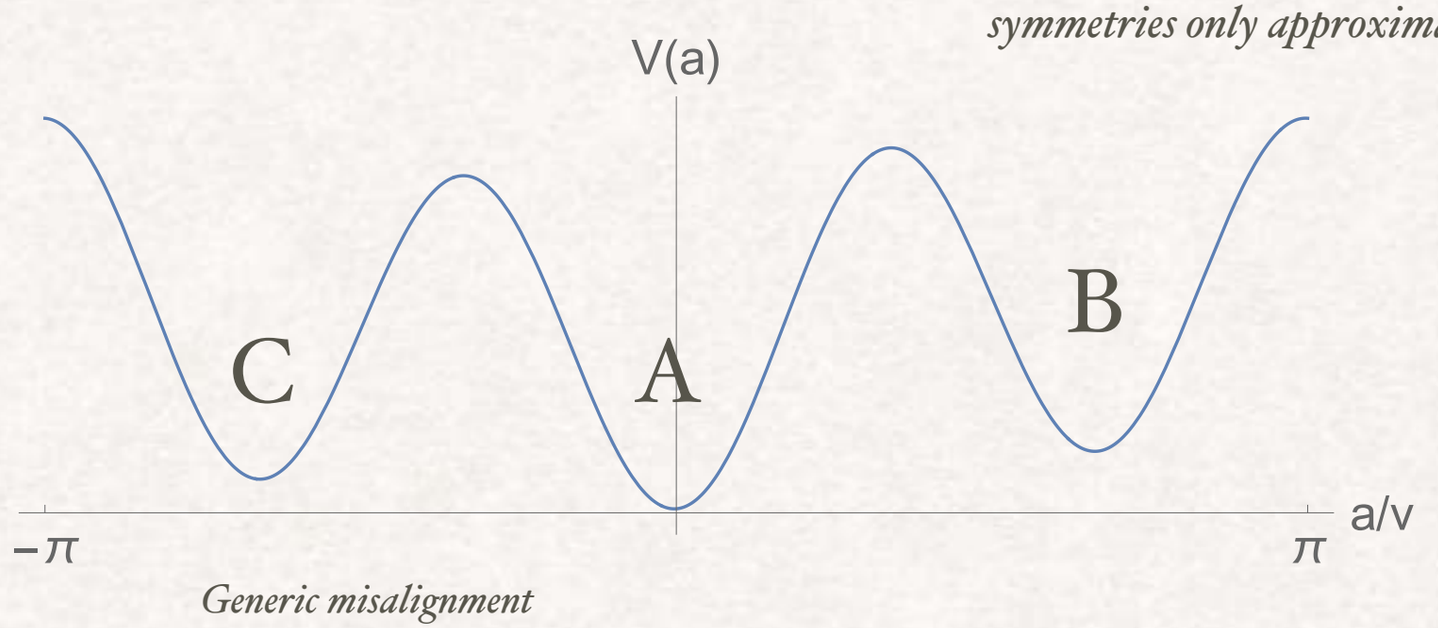
$$V = V(a) - \mu_b^4 \cos\left(\frac{a}{N_{\rm DW} F_a} - \delta\right)$$

ANNIHILATING NETWORK



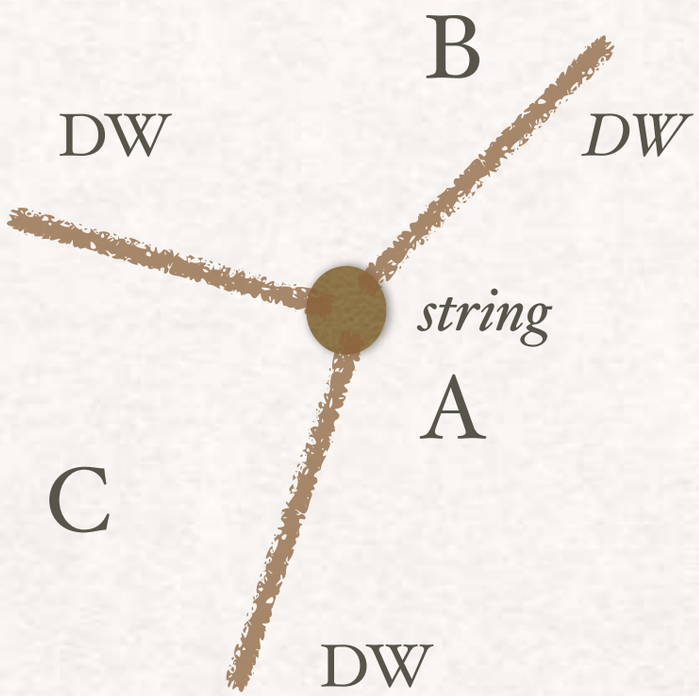
DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

***Expectation**: Global symmetries only approximate!*



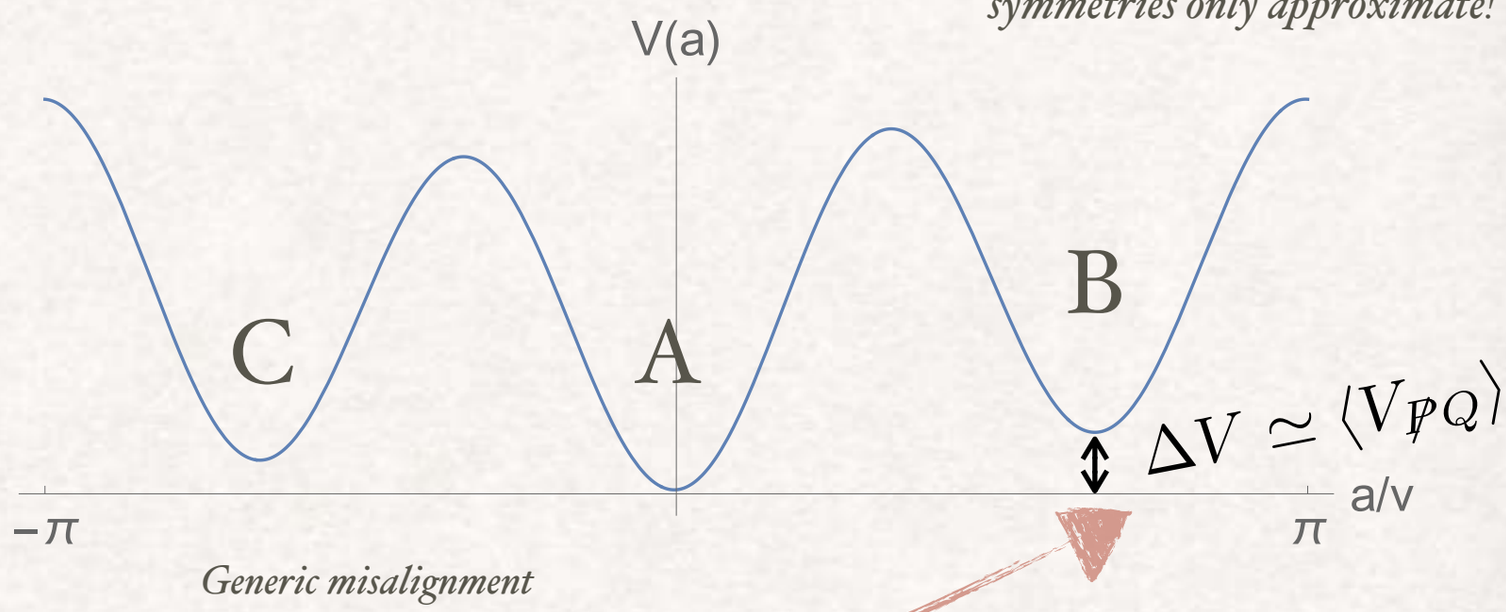
$$V = V(a) - \mu_b^4 \cos\left(\frac{a}{N_{\rm DW} F_a} - \delta\right)$$

ANNIHILATING NETWORK



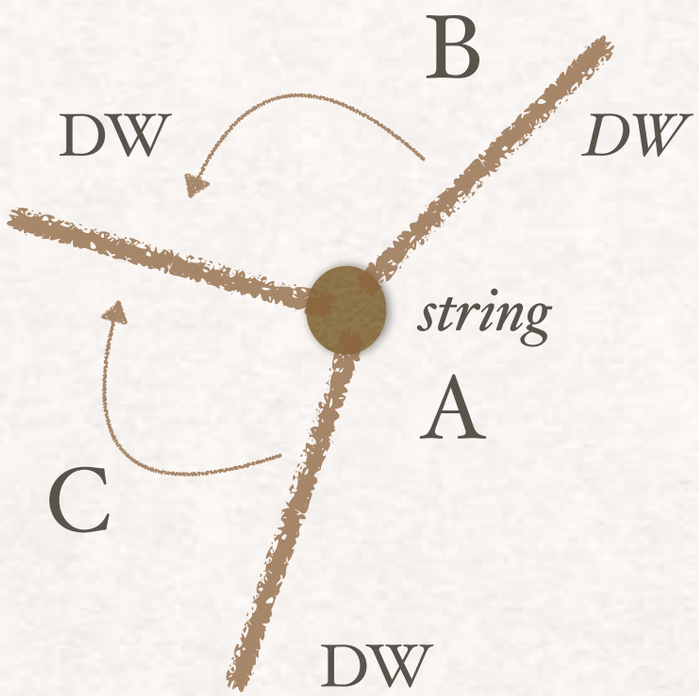
DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

***Expectation**: Global symmetries only approximate!*



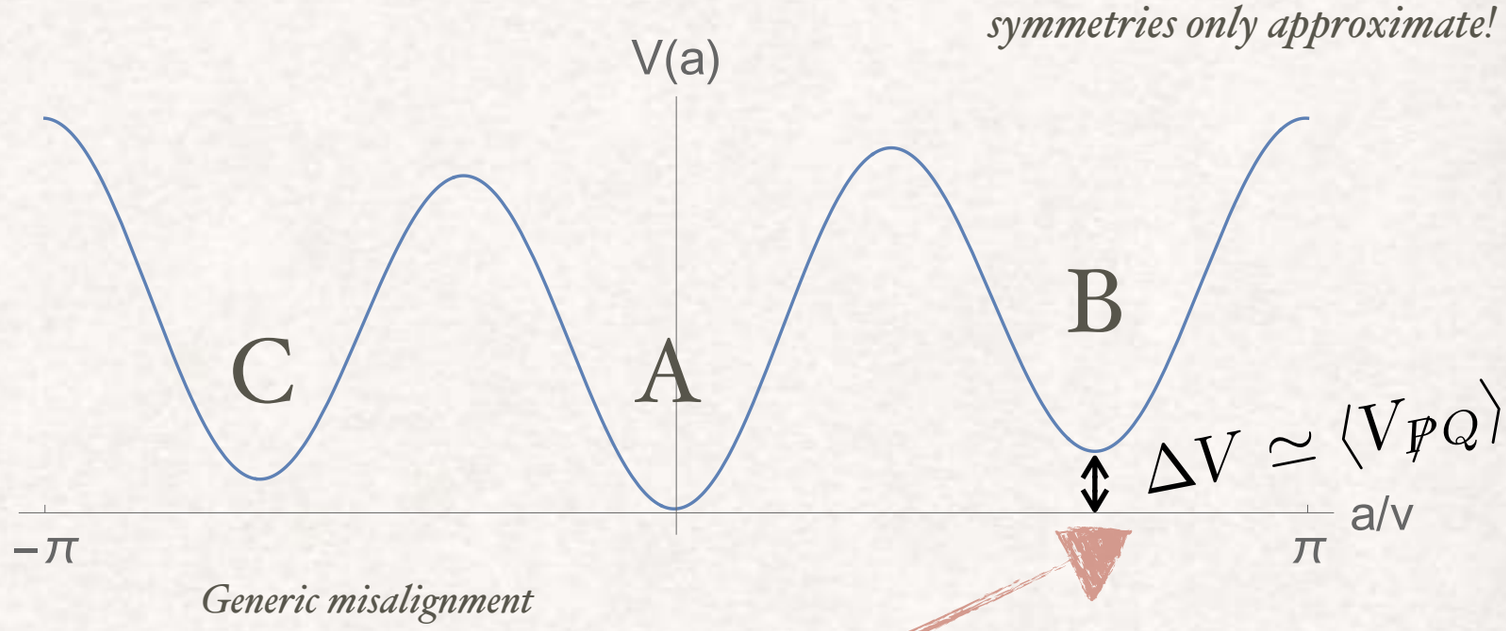
$$V = V(a) - \mu_b^4 \cos\left(\frac{a}{N_{\rm DW} F_a} - \delta\right)$$

ANNIHILATING NETWORK



DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

***Expectation**: Global symmetries only approximate!*



$$V = V(a) - \mu_b^4 \cos\left(\frac{a}{N_{\rm DW} F_a} - \delta\right)$$

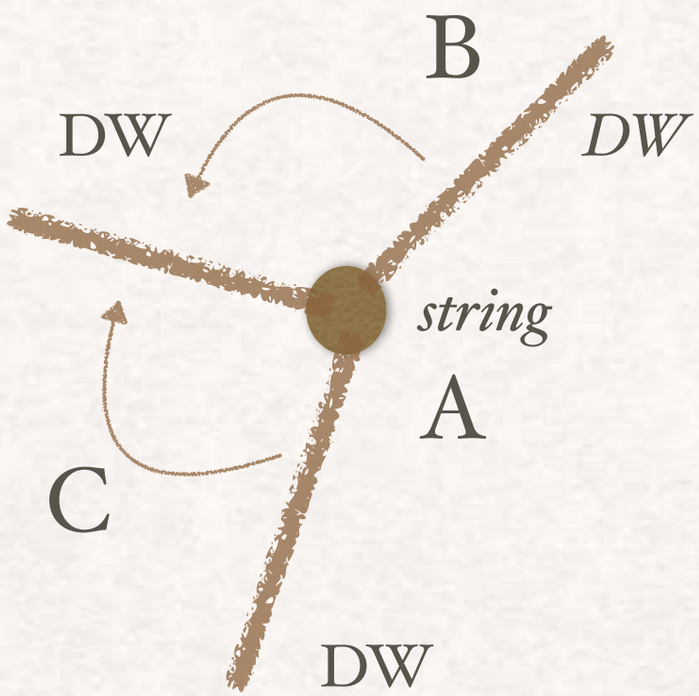
Network annihilates once

$$H_{\rm ann} \simeq \Delta V/\sigma$$

Energy difference acts as pressure force which moves DWs and makes them collide

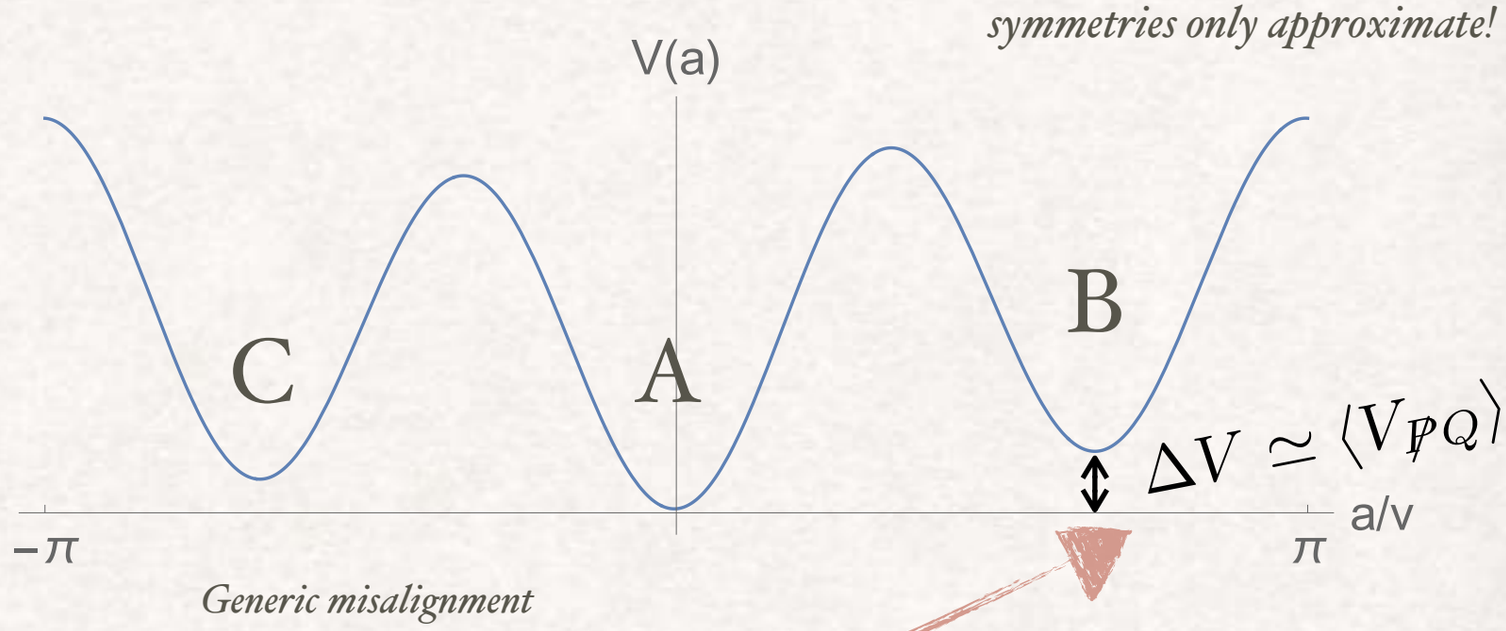
Sikivie 82

ANNIHILATING NETWORK



DW problem can however be avoided if PQ symmetry is also broken by other effects (e.g. UV)

***Expectation**: Global symmetries only approximate!*



$$V = V(a) - \mu_b^4 \cos\left(\frac{a}{N_{\rm DW} F_a} - \delta\right)$$

Network annihilates once

$$H_{\rm ann} \simeq \Delta V/\sigma$$

Energy difference acts as pressure force which moves DWs and makes them collide

Sikivie 82

THE SMALLER THE ADDITIONAL BREAKING, THE LONGER THE LIFETIME OF THE NETWORK

GW IMPRINTS OF HEAVY AXIONIC DEFECTS

Annihilation of string-wall network has significantly time-varying quadrupole moment, sources a (stochastic) gravitational wave background

Vilenkin 81/.../Hiramatsu et al 13/...

GW IMPRINTS OF HEAVY AXIONIC DEFECTS

Annihilation of string-wall network has significantly time-varying quadrupole moment, sources a (stochastic) gravitational wave background

Vilenkin 81/.../Hiramatsu et al 13/...

In scaling-regime, there is only one relevant (Hubble) scale

$$\omega_{\rm ann} \sim H_{\rm ann} \Rightarrow \omega_{\rm peak,\ today} \sim 10^{-9}\ {\rm Hz} \left(\frac{T_{\rm ann}}{10\ {\rm MeV}} \right)$$

GW IMPRINTS OF HEAVY AXIONIC DEFECTS

Annihilation of string-wall network has significantly time-varying quadrupole moment, sources a (stochastic) gravitational wave background

Vilenkin 81/.../Hiramatsu et al 13/...

In scaling-regime, there is only one relevant (Hubble) scale

$$\omega_{\rm ann} \sim H_{\rm ann} \Rightarrow \omega_{\rm peak,\ today} \sim 10^{-9}\ {\rm Hz} \left(\frac{T_{\rm ann}}{10\ {\rm MeV}} \right)$$

efficiency factor + ...

$$\Omega_{\rm GW} h^2 \simeq 0.01\ \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann} \Omega_{\rm rad} h^2 \simeq 5 \cdot 10^{-7} \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann}$$

GW IMPRINTS OF HEAVY AXIONIC DEFECTS

Annihilation of string-wall network has significantly time-varying quadrupole moment, sources a (stochastic) gravitational wave background

Vilenkin 81/.../Hiramatsu et al 13/...

In scaling-regime, there is only one relevant (Hubble) scale

$$\omega_{\rm ann} \sim H_{\rm ann} \Rightarrow \omega_{\rm peak,\ today} \sim 10^{-9}\ {\rm Hz} \left(\frac{T_{\rm ann}}{10\ {\rm MeV}} \right)$$

efficiency factor + ...

$$\Omega_{\rm GW} h^2 \simeq 0.01\ \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann} \Omega_{\rm rad} h^2 \simeq 5 \cdot 10^{-7} \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann}$$

THE SMALLER THE EXTRA PQ BREAKING EFFECTS, THE LONGER THE LIFETIME OF THE NETWORK, THE LARGER THE GW SIGNAL!

GW IMPRINTS OF HEAVY AXIONIC DEFECTS

Annihilation of string-wall network has significantly time-varying quadrupole moment, sources a (stochastic) gravitational wave background

Vilenkin 81/.../Hiramatsu et al 13/...

In scaling-regime, there is only one relevant (Hubble) scale

$$\omega_{\rm ann} \sim H_{\rm ann} \Rightarrow \omega_{\rm peak,\ today} \sim 10^{-9}\ {\rm Hz} \left(\frac{T_{\rm ann}}{10\ {\rm MeV}} \right)$$

efficiency factor + ...

$$\Omega_{\rm GW} h^2 \simeq 0.01\ \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann} \Omega_{\rm rad} h^2 \simeq 5 \cdot 10^{-7} \epsilon \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{\rm ann}$$

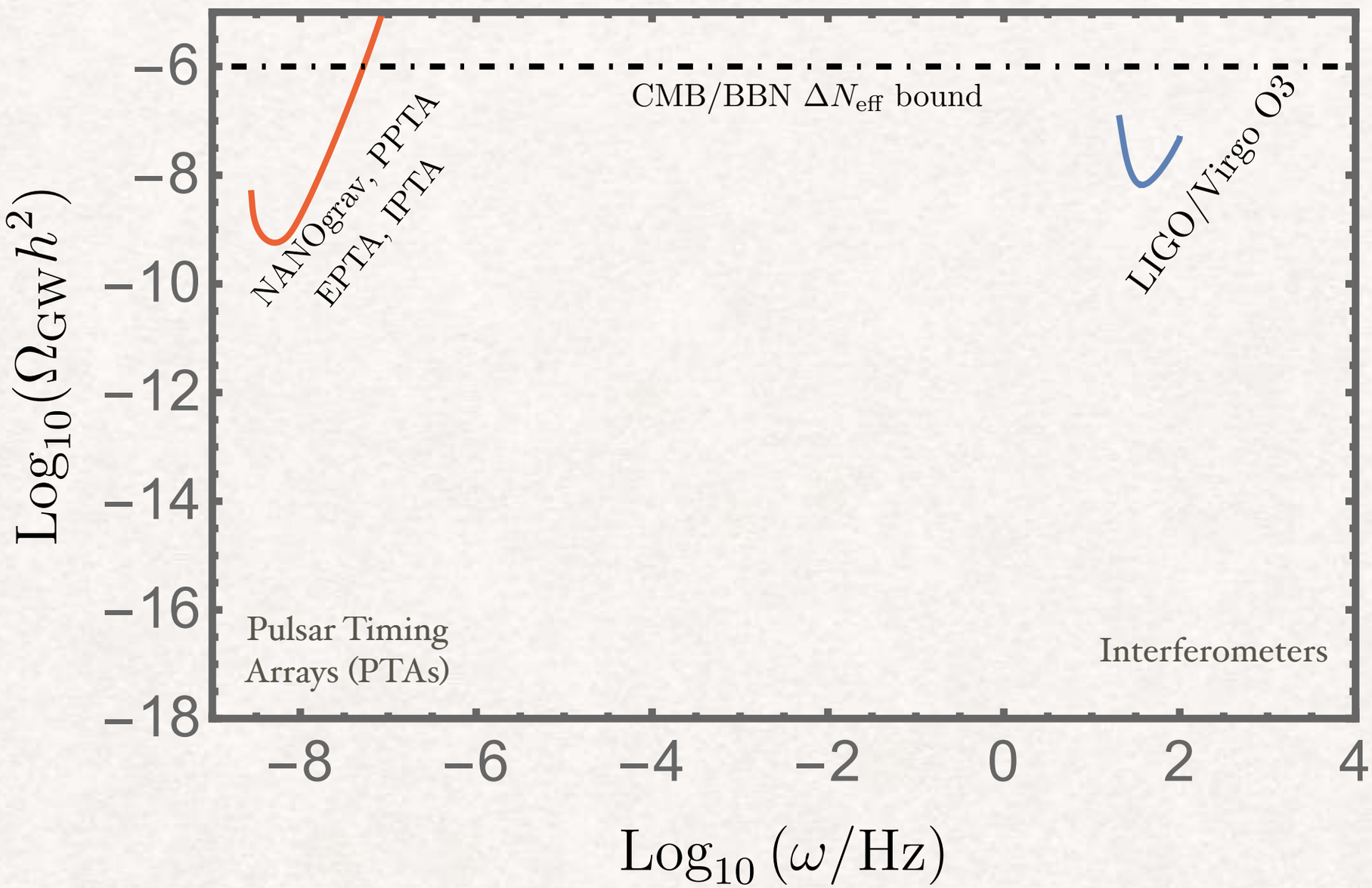
THE SMALLER THE EXTRA PQ BREAKING EFFECTS, THE LONGER THE LIFETIME OF THE NETWORK, THE LARGER THE GW SIGNAL!

→

DOMAIN WALLS AND THEIR GRAVITATIONAL WAVES ARE LABORATORIES FOR "QUALITY" OF GLOBAL SYMMETRIES!

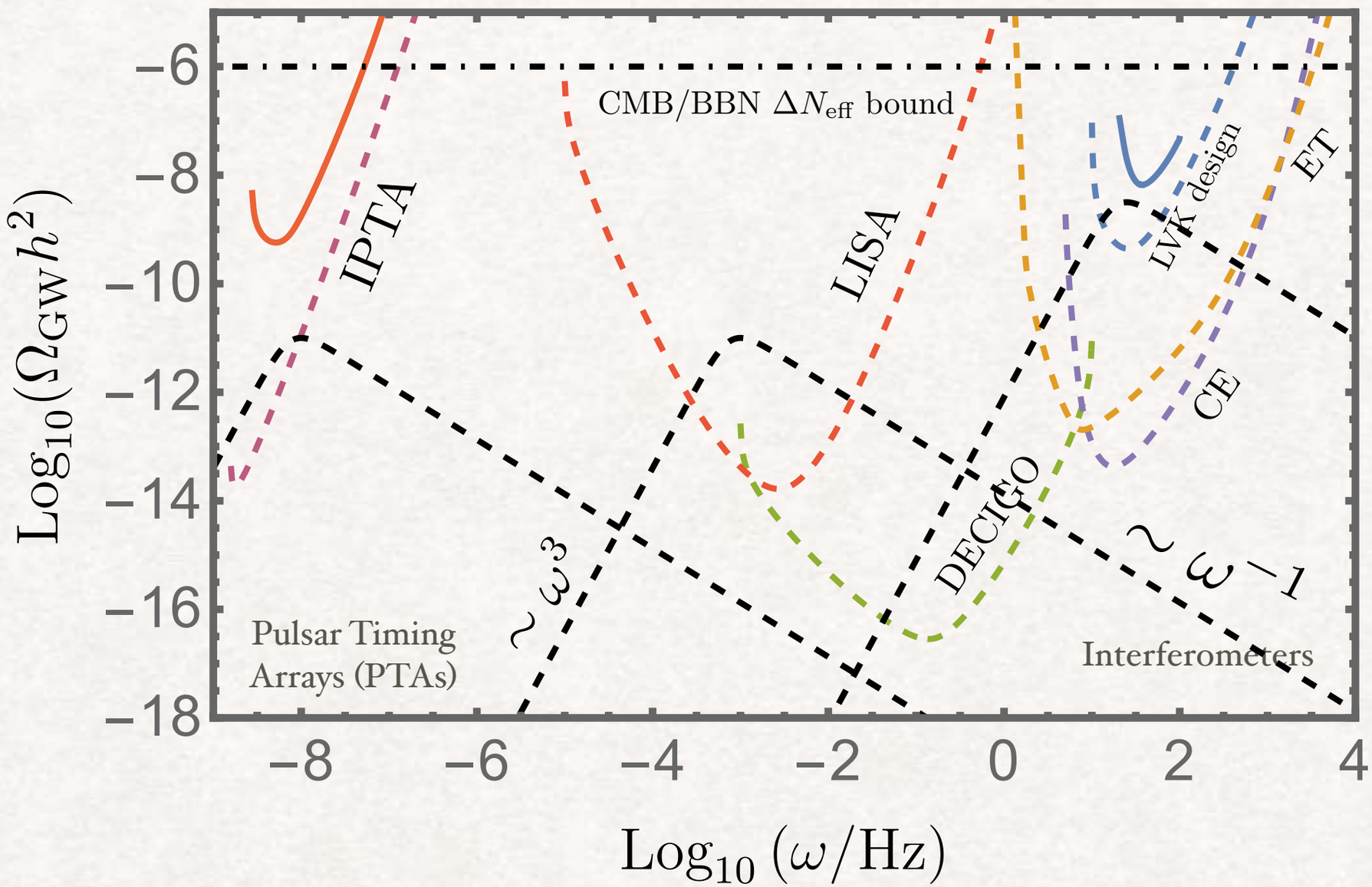
GW OBSERVATORIES

Today



GW OBSERVATORIES

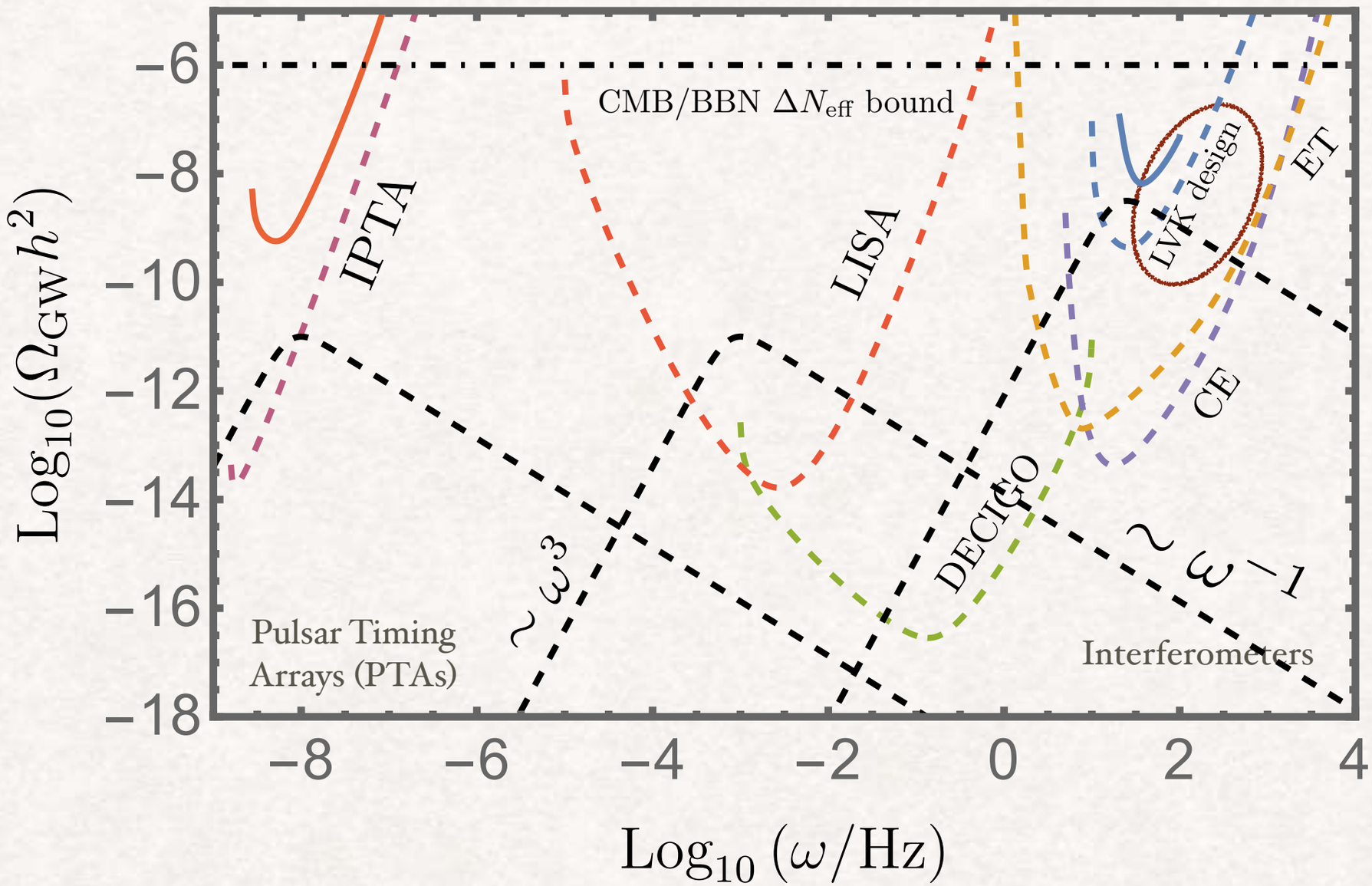
Example spectra from DW annihilation



CURRENT (FUTURE) GW OBSERVATORIES **CAN PROBE AXION SCENARIOS** WHERE DWS MAKE UP $\gtrsim 5\%(0.1\%)$ OF THE BACKGROUND ENERGY DENSITY!

GW OBSERVATORIES

Example spectra from DW annihilation



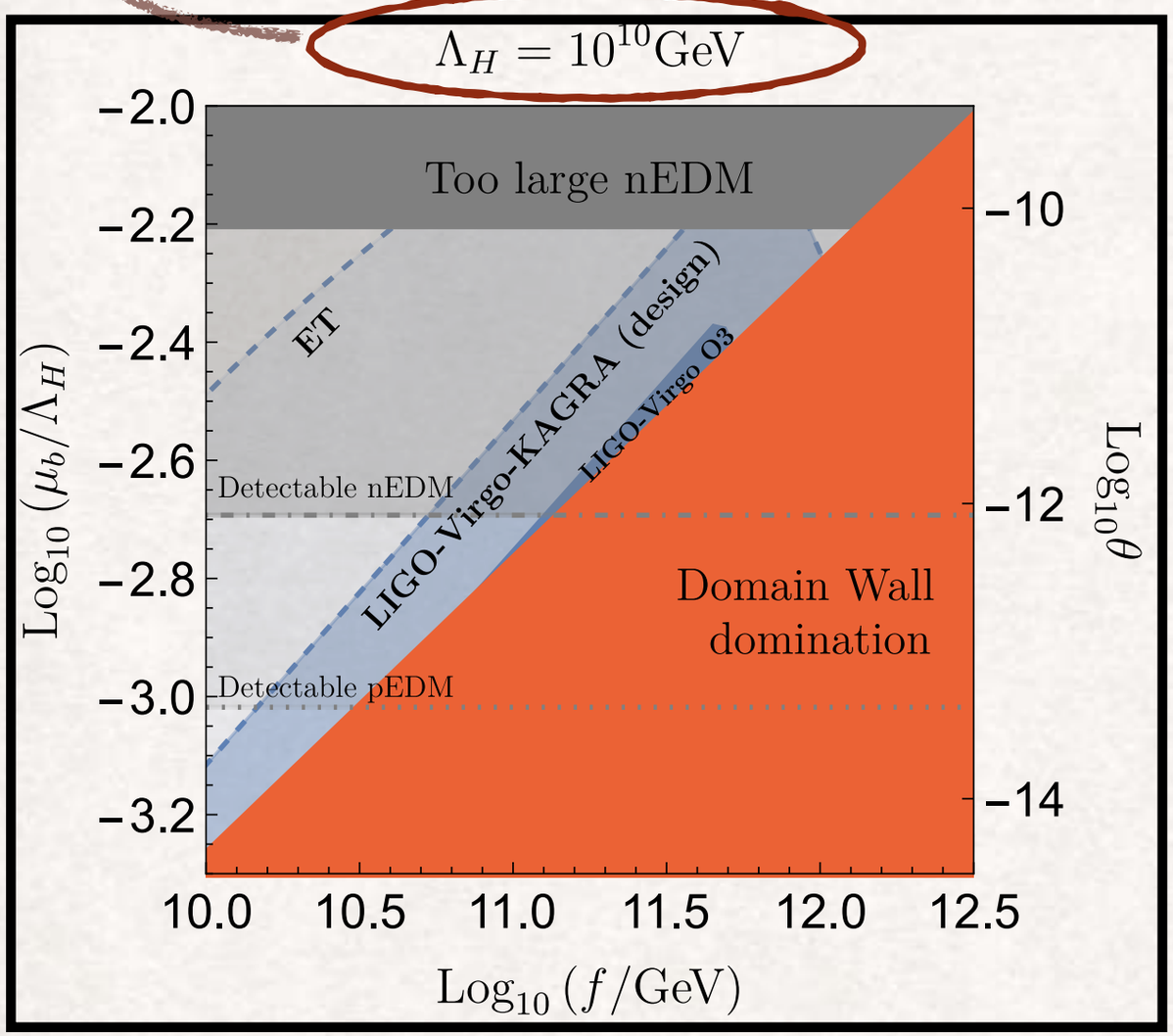
CURRENT (FUTURE) GW OBSERVATORIES **CAN PROBE AXION SCENARIOS** WHERE DWS MAKE UP $\gtrsim 5\%(0.1\%)$ OF THE BACKGROUND ENERGY DENSITY!

HEAVY QCD AXION AT GW OBSERVATORIES

2107.07542

Scale of heavy QCD axion potential
(replaces QCD scale)

$$f \equiv F_a$$

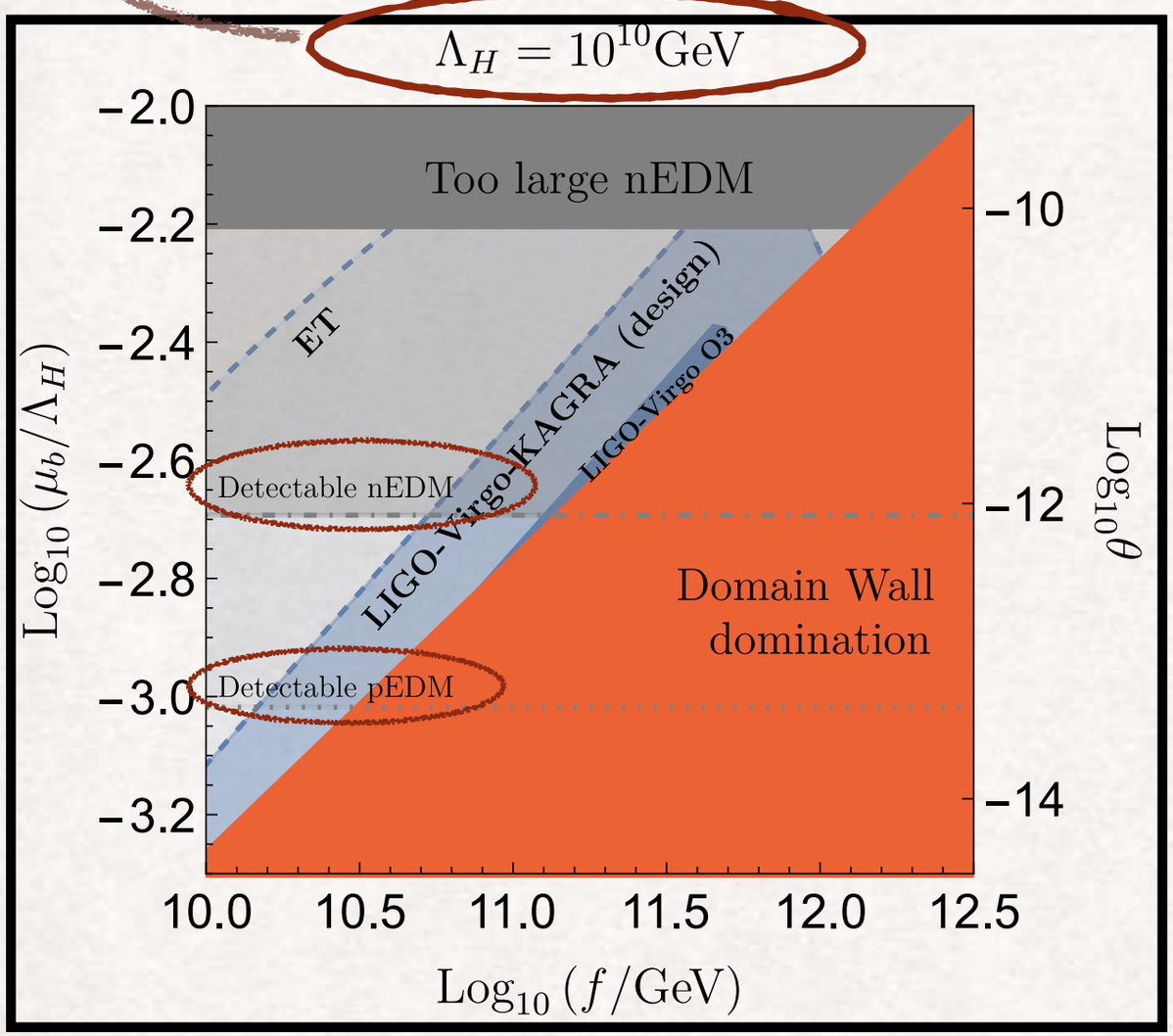


HEAVY QCD AXION AT GW OBSERVATORIES

2107.07542

Scale of heavy QCD axion potential
(replaces QCD scale)

$$f \equiv F_a$$



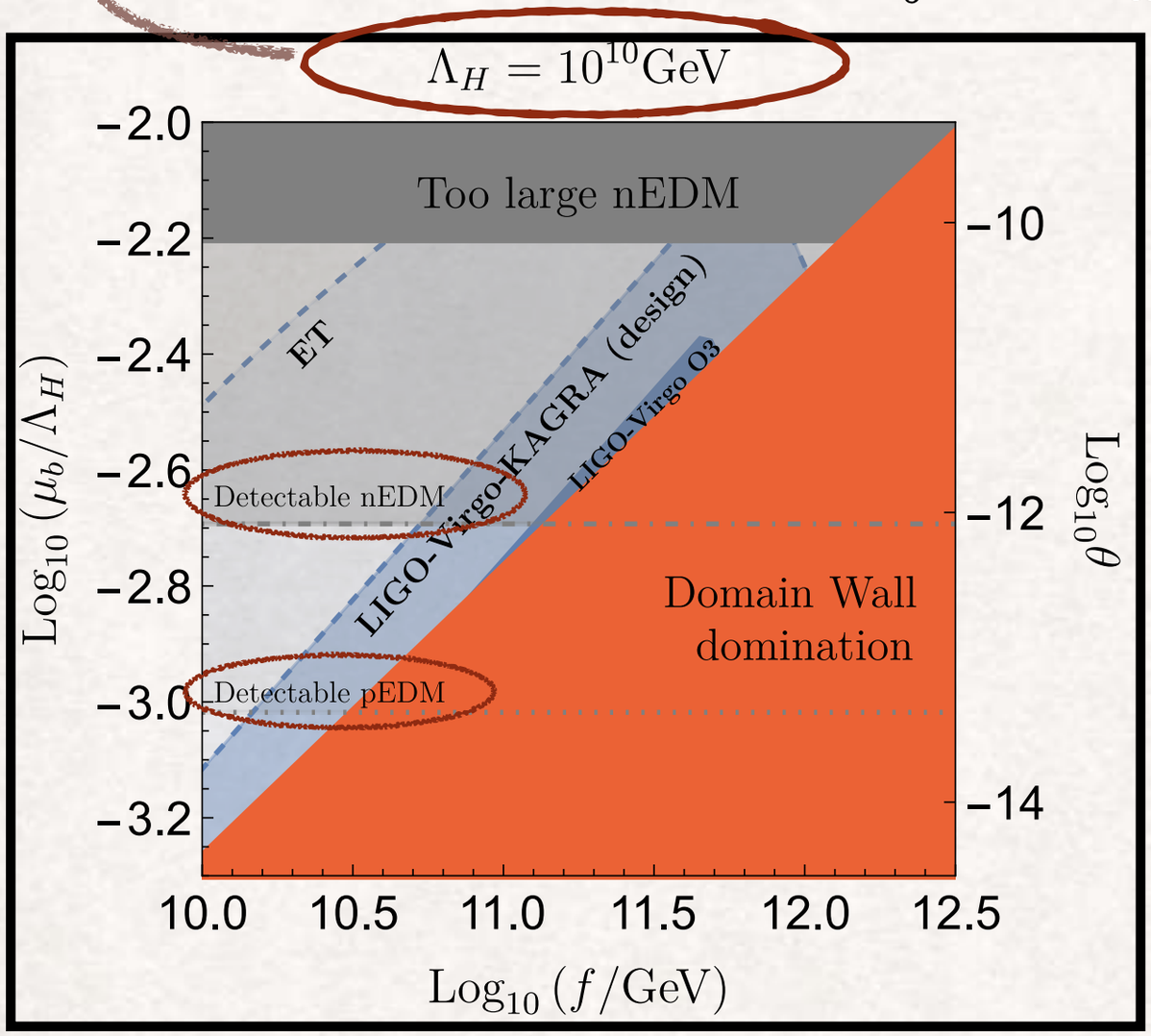
GW SIGNATURE IS CORRELATED WITH DETECTABLE NEUTRON (PROTON) ELECTRIC DIPOLE MOMENTS!

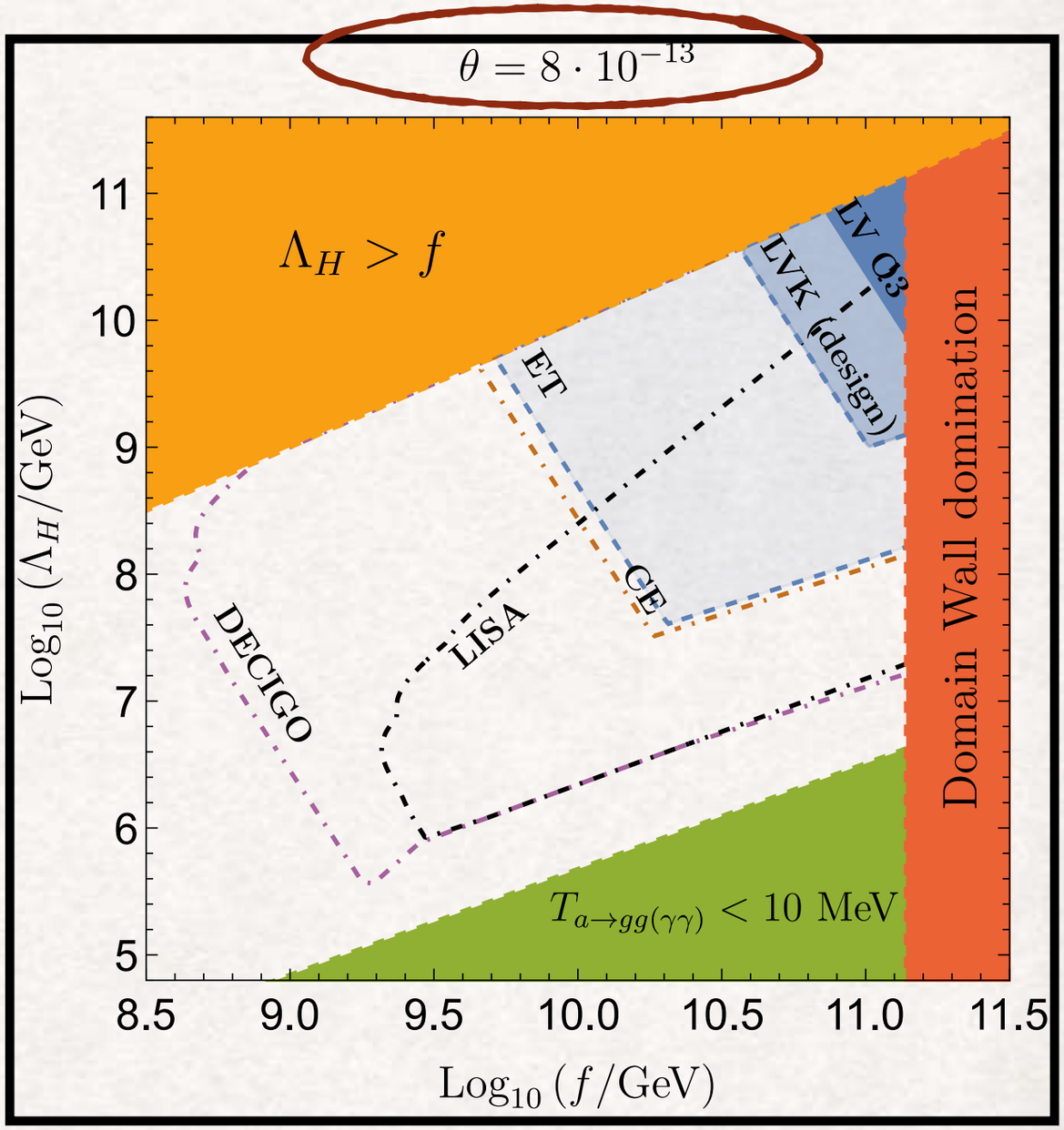
HEAVY QCD AXION AT GW OBSERVATORIES

2107.07542

Scale of heavy QCD axion potential
(replaces QCD scale)

$$f \equiv F_a$$





GW SIGNATURE IS CORRELATED WITH DETECTABLE NEUTRON (PROTON) ELECTRIC DIPOLE MOMENTS!

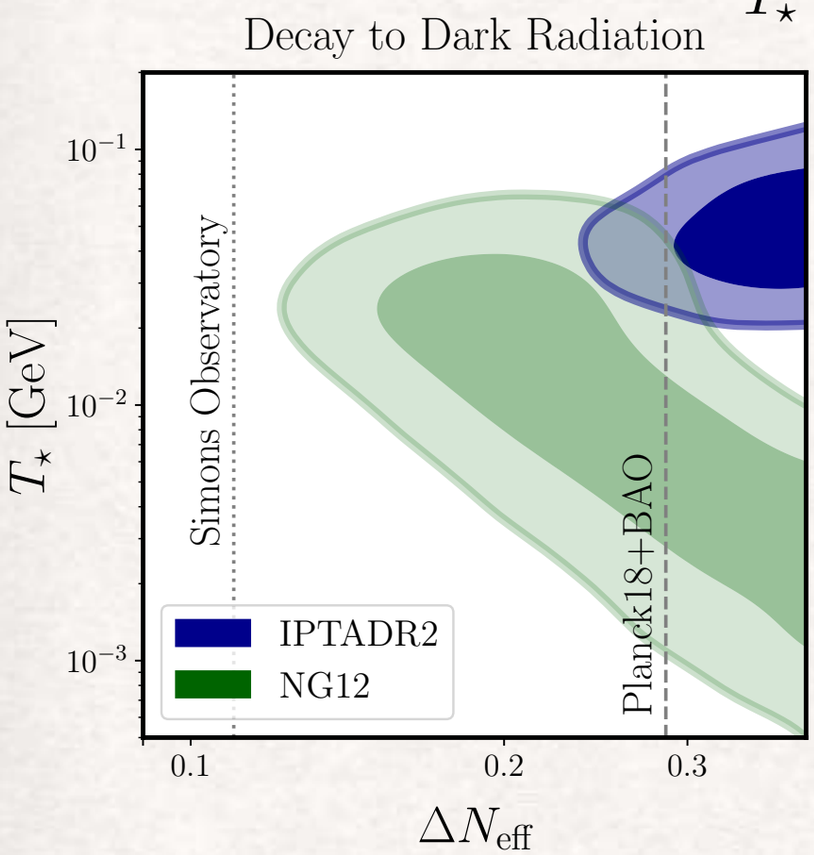
SEARCH FOR DOMAIN WALLS IN PTA DATASETS

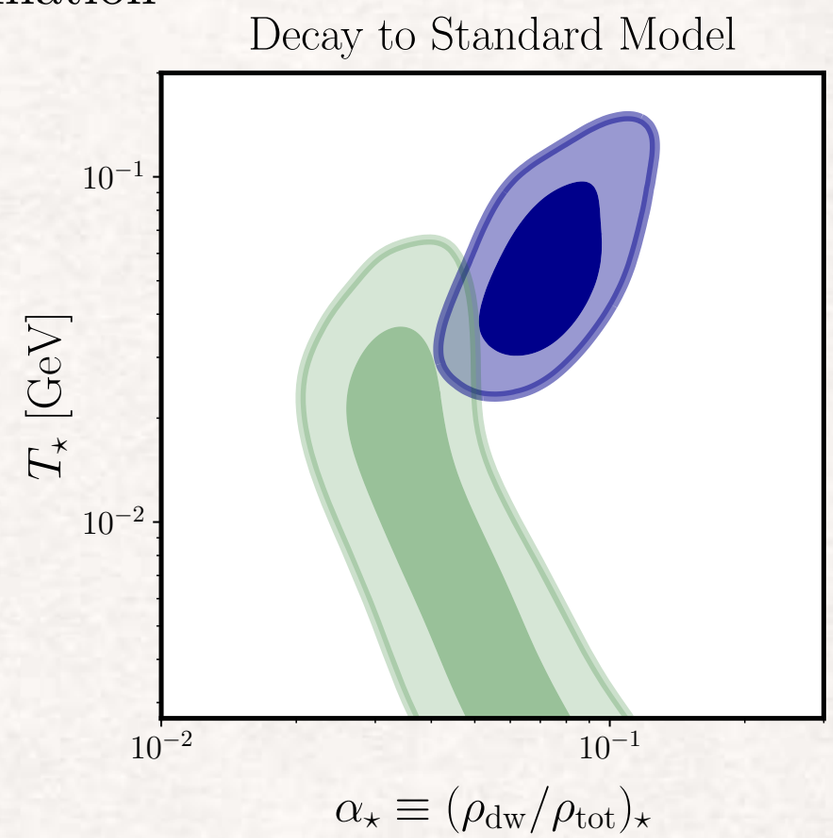
2204.04228

SEARCH FOR DOMAIN WALLS IN PTA DATASETS

2204.04228

$T_\star \equiv$ temperature of network annihilation

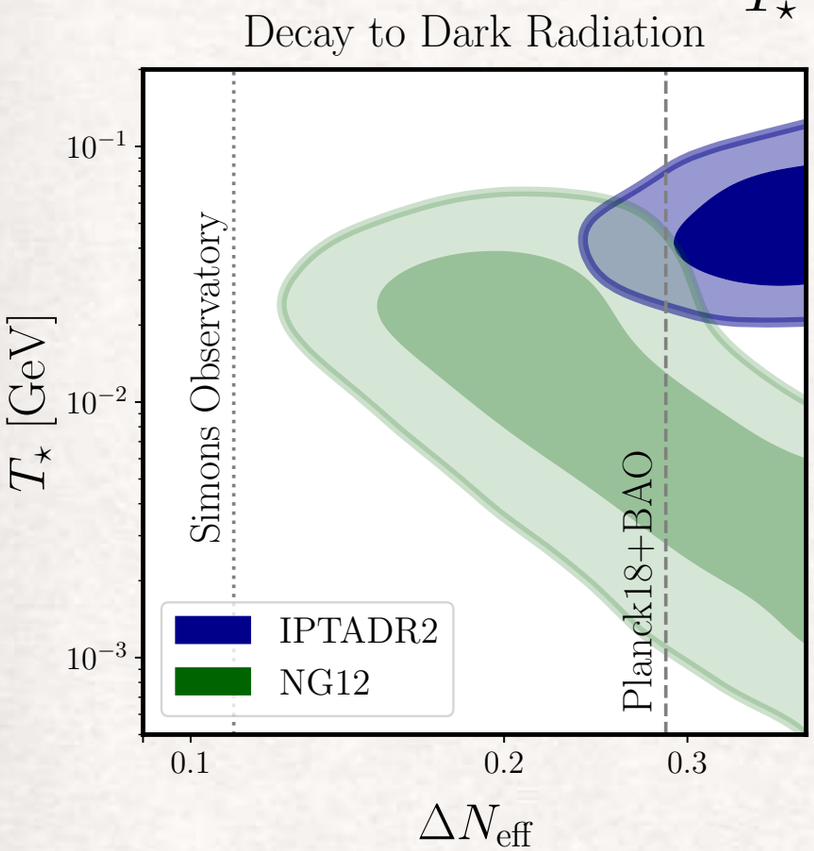


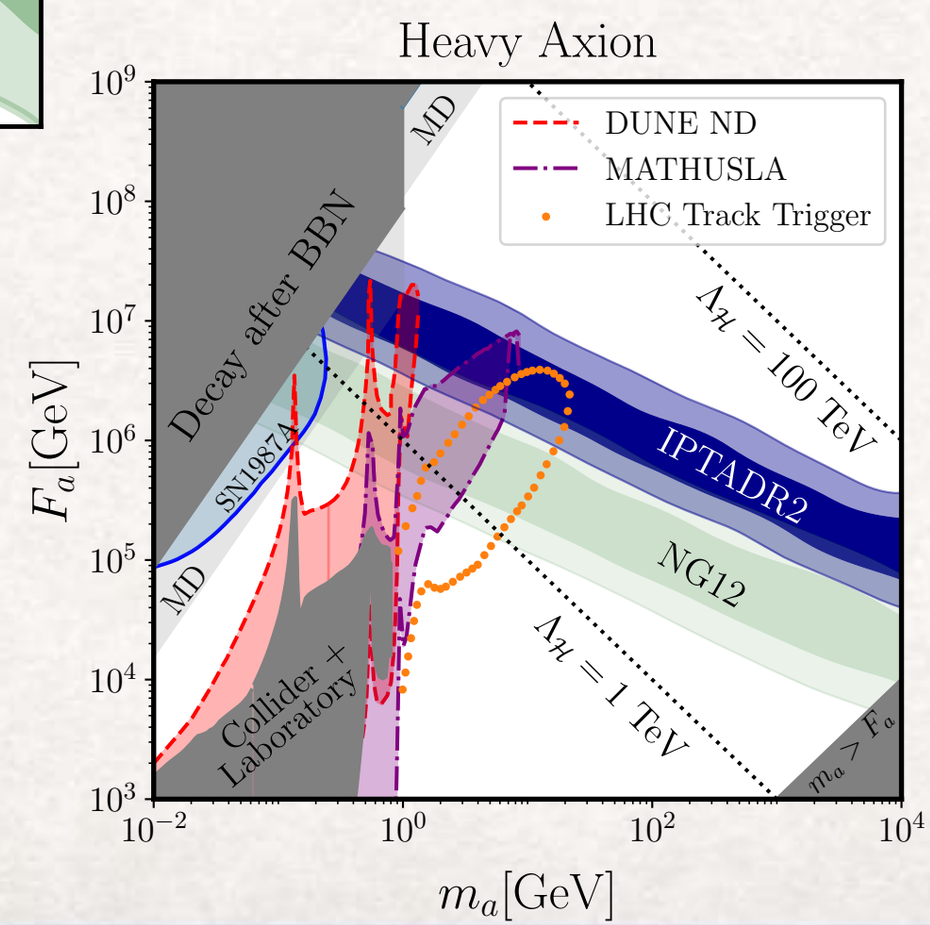


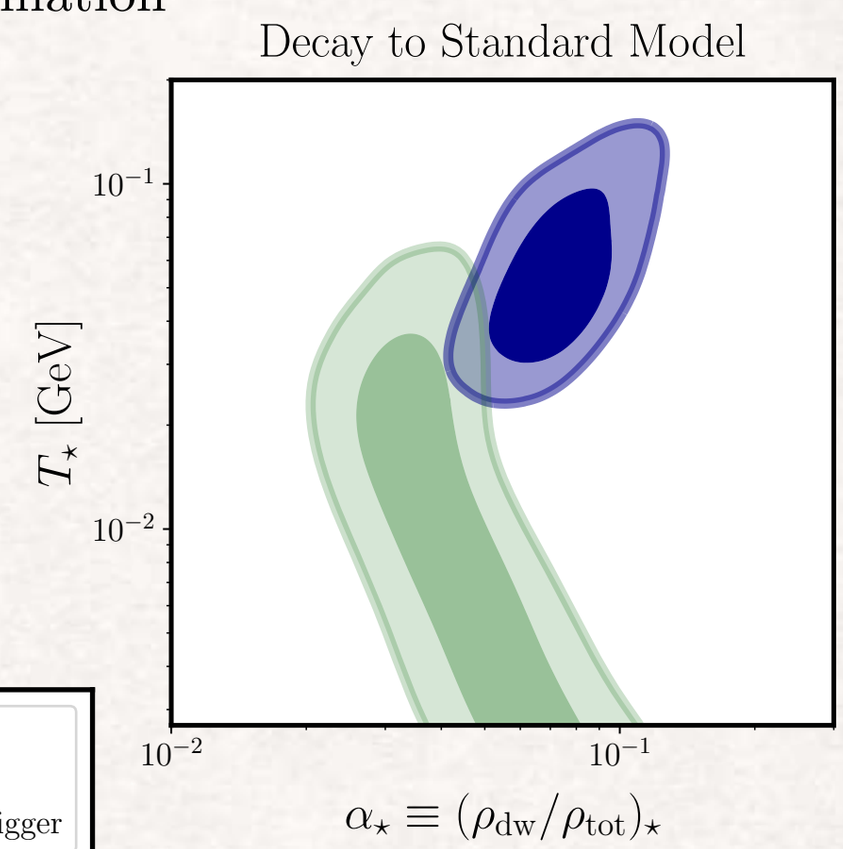
SEARCH FOR DOMAIN WALLS IN PTA DATASETS

2204.04228

$T_\star \equiv$ temperature of network annihilation



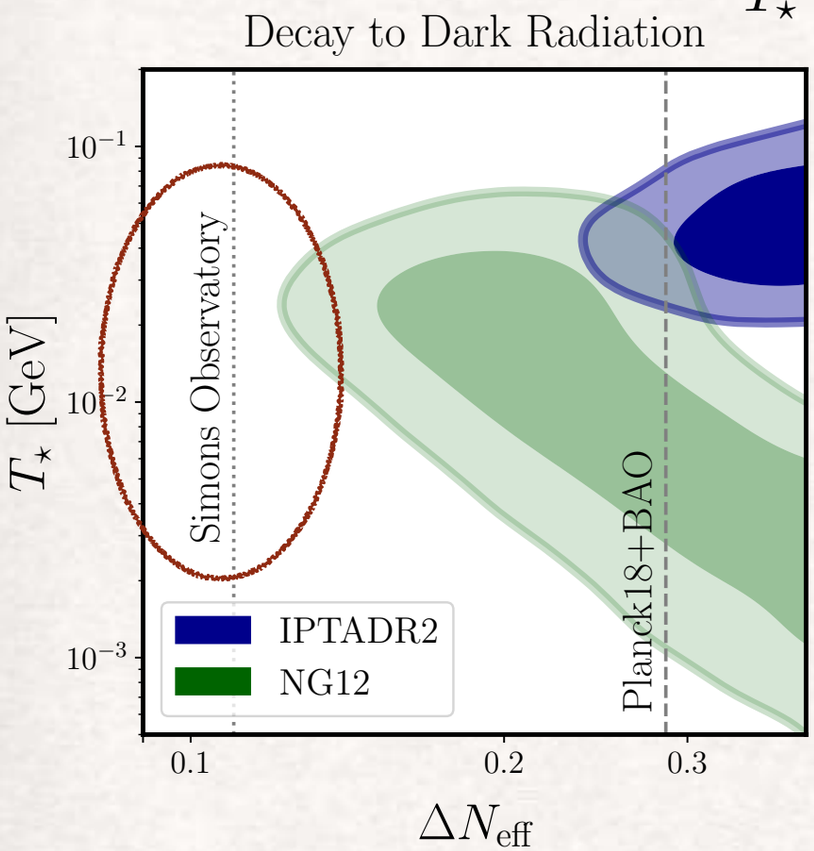


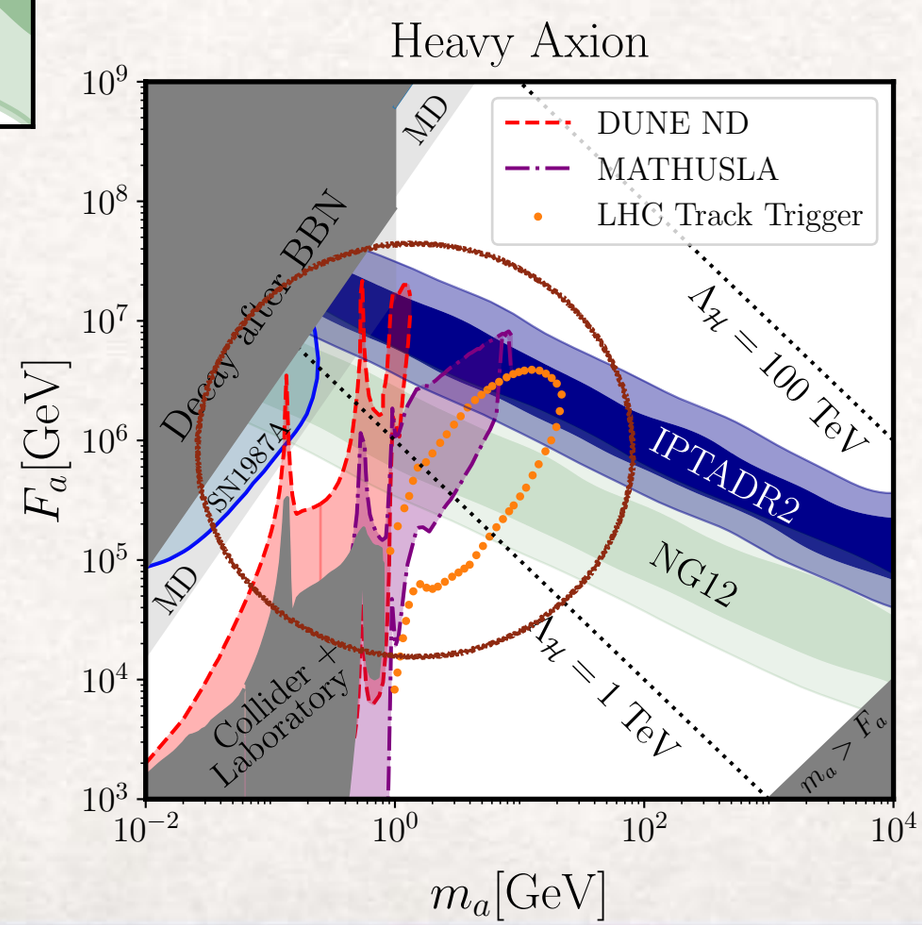


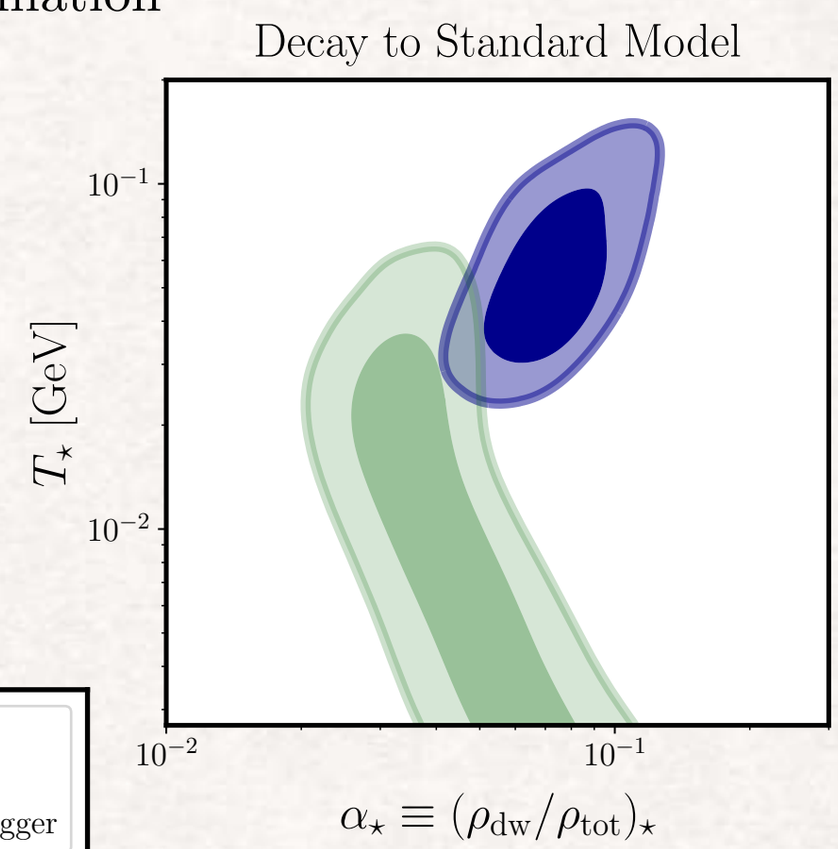
SEARCH FOR DOMAIN WALLS IN PTA DATASETS

2204.04228

$T_\star \equiv$ temperature of network annihilation







General results for any heavy axion coupled to QCD, not necessarily solving strong CP

CORRELATED SIGNATURES AT CMB OR COLLIDERS/LABORATORY EXPERIMENTS!

See also Hook et al/Kelly et al 19

CONCLUSIONS 2ND PART

CONCLUSIONS 2ND PART

MODELS WITH SPONTANEOUS BREAKING OF DISCRETE SYMMETRIES (E.G. HEAVY AXIONS, ...) CAN LEAD TO LONG LIVED DOMAIN WALL NETWORKS IN THE EARLY UNIVERSE

CONCLUSIONS 2ND PART

MODELS WITH SPONTANEOUS BREAKING OF DISCRETE SYMMETRIES (E.G. HEAVY AXIONS, ...) CAN LEAD TO LONG LIVED DOMAIN WALL NETWORKS IN THE EARLY UNIVERSE

THEIR ANNIHILATION CAN OCCUR SAFELY DUE TO SYMMETRY-BREAKING TERMS, WHOSE SIZE CAN BE INVESTIGATED BY LOOKING FOR GRAVITATIONAL WAVES AT CURRENT AND FUTURE OBSERVATORIES

CONCLUSIONS 2ND PART

MODELS WITH SPONTANEOUS BREAKING OF DISCRETE SYMMETRIES (E.G. HEAVY AXIONS, ...) CAN LEAD TO LONG LIVED DOMAIN WALL NETWORKS IN THE EARLY UNIVERSE

THEIR ANNIHILATION CAN OCCUR SAFELY DUE TO SYMMETRY-BREAKING TERMS, WHOSE SIZE CAN BE INVESTIGATED BY LOOKING FOR GRAVITATIONAL WAVES AT CURRENT AND FUTURE OBSERVATORIES

(VERY) HEAVY AXION MODELS CAN BE PROBED BY LIGO/VIRGO/KAGRA AND FUTURE INTERFEROMETERS

CONCLUSIONS 2ND PART

MODELS WITH SPONTANEOUS BREAKING OF DISCRETE SYMMETRIES (E.G. HEAVY AXIONS, ...) CAN LEAD TO LONG LIVED DOMAIN WALL NETWORKS IN THE EARLY UNIVERSE

THEIR ANNIHILATION CAN OCCUR SAFELY DUE TO SYMMETRY-BREAKING TERMS, WHOSE SIZE CAN BE INVESTIGATED BY LOOKING FOR GRAVITATIONAL WAVES AT CURRENT AND FUTURE OBSERVATORIES

(VERY) HEAVY AXION MODELS CAN BE PROBED BY LIGO/VIRGO/KAGRA AND FUTURE INTERFEROMETERS

CURRENT PULSAR TIMING ARRAY DATASETS CAN BE INTERPRETED IN TERMS OF HEAVY AXION WITH MASS 100 MEV-1 TEV

CONCLUSIONS 2ND PART

MODELS WITH SPONTANEOUS BREAKING OF DISCRETE SYMMETRIES (E.G. HEAVY AXIONS, ...) CAN LEAD TO LONG LIVED DOMAIN WALL NETWORKS IN THE EARLY UNIVERSE

THEIR ANNIHILATION CAN OCCUR SAFELY DUE TO SYMMETRY-BREAKING TERMS, WHOSE SIZE CAN BE INVESTIGATED BY LOOKING FOR GRAVITATIONAL WAVES AT CURRENT AND FUTURE OBSERVATORIES

(VERY) HEAVY AXION MODELS CAN BE PROBED BY LIGO/VIRGO/KAGRA AND FUTURE INTERFEROMETERS

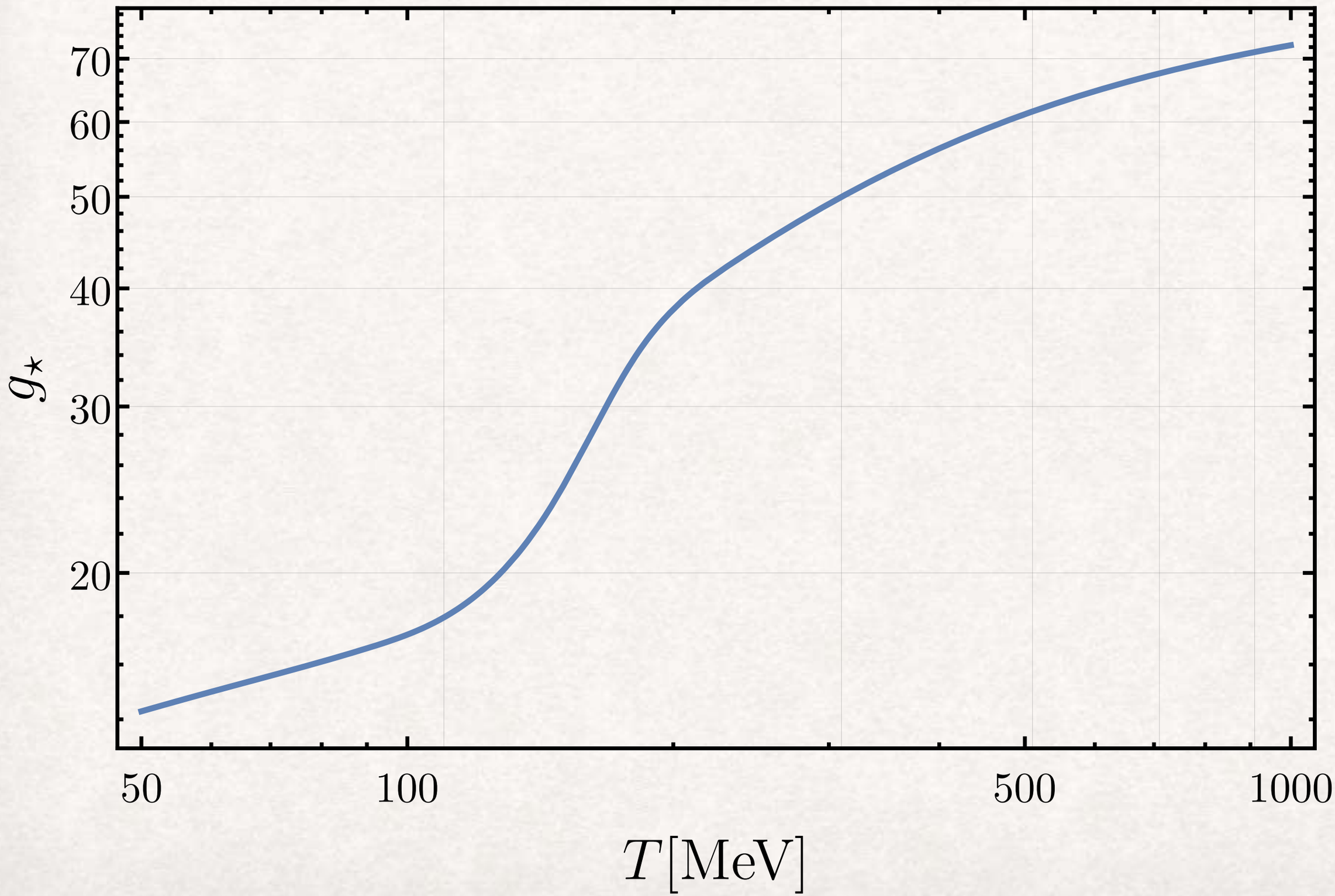
CURRENT PULSAR TIMING ARRAY DATASETS CAN BE INTERPRETED IN TERMS OF HEAVY AXION WITH MASS 100 MEV-1 TEV

CORRELATED SIGNATURES AT COLLIDERS/EDMS

THANK YOU!

BACK-UP SLIDES

Number of relativistic degrees of freedom



SCATTERING RATE

$$\Gamma^{>} = e^{\frac{E}{T}}\Gamma^{<} = \Gamma^{>}_{\rm top}/(2Ef_a^2)$$

$$\Gamma^{>}_{\rm top} \equiv \int d^4x\, e^{ik^\mu x_\mu}\, \left\langle \frac{\alpha_s}{8\pi} G\tilde{G}(x^\mu)\, \frac{\alpha_s}{8\pi} G\tilde{G}(0) \right\rangle$$

During QCD crossover, quantity to be evaluated on the lattice

At weak coupling, the rate above is dominated by 2->2 scatterings (e.g. axion-pion->pion-pion)

"STRONG" SPHALERONS

In pure SU(N)

Non-perturbative field configurations of size

$$\lambda_s \sim (N_c \alpha_s T)^{-1}$$

$$\Gamma^{>}_{\rm top}(k^\mu = 0) \to \Gamma_{\rm sphal} \simeq (N_c \alpha_s)^5 T^4$$

Moore, Tassler 10

One then expects

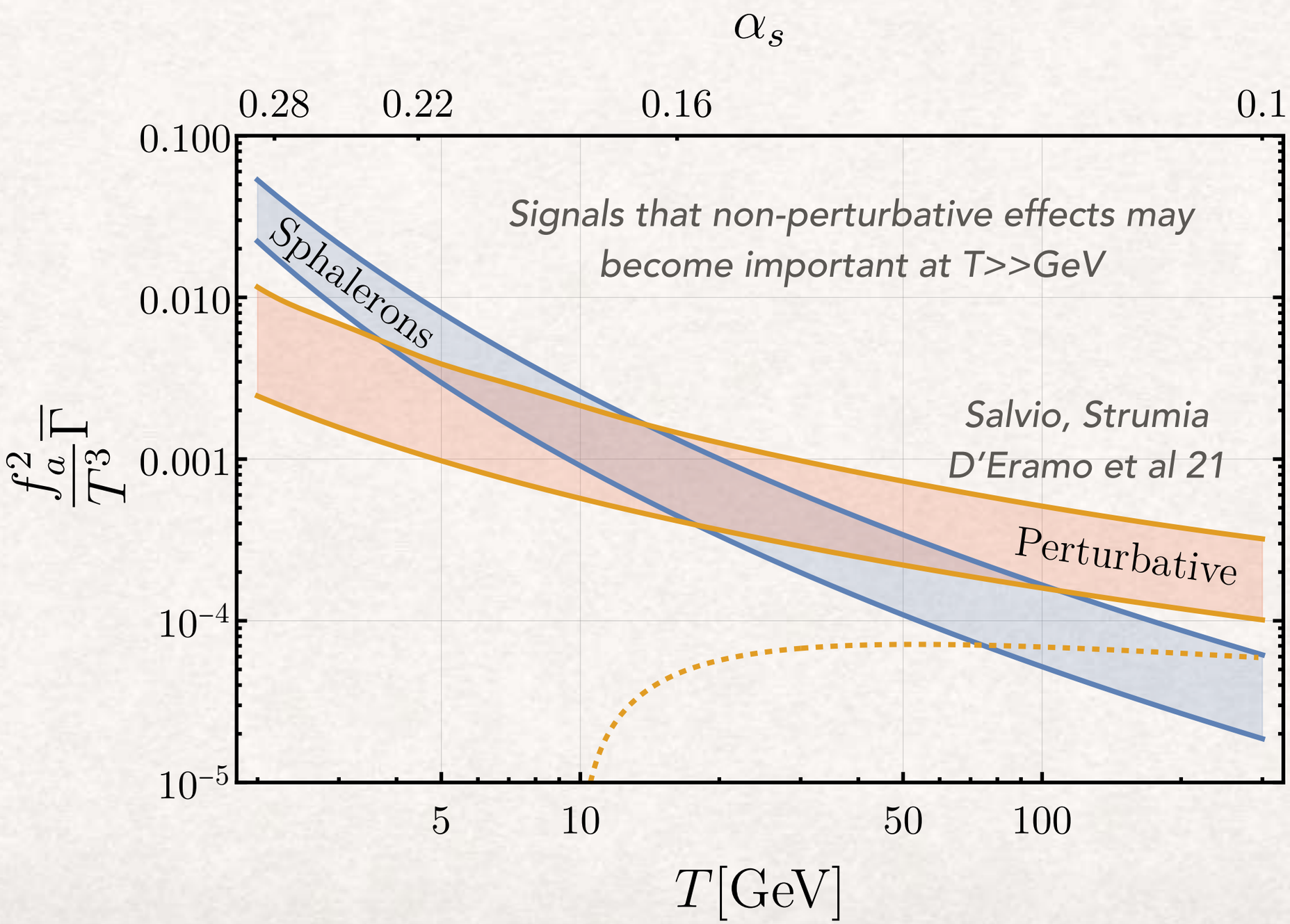
$$\overline{\Gamma}_{\rm sphal} = \frac{1}{n^{\rm eq}} \int^{|\mathbf{k}|<|\mathbf{k}_s|} \frac{d^3\mathbf{k}}{(2\pi)^3 2E} \frac{\Gamma_{\rm sphal}}{f_a^2} e^{-E/T} = \frac{(N_c\alpha_s)^5 T^3}{4\zeta_3 f_a^2} \left(1 - \left(1 + \frac{|\mathbf{k}_s|}{T}\right) e^{-|\mathbf{k}_s|/T}\right)$$

Which can be compared with perturbative a+g rates derived in the literature (which are not expected to be reliable down to T~2 GeV)

"STRONG" SPHALERONS

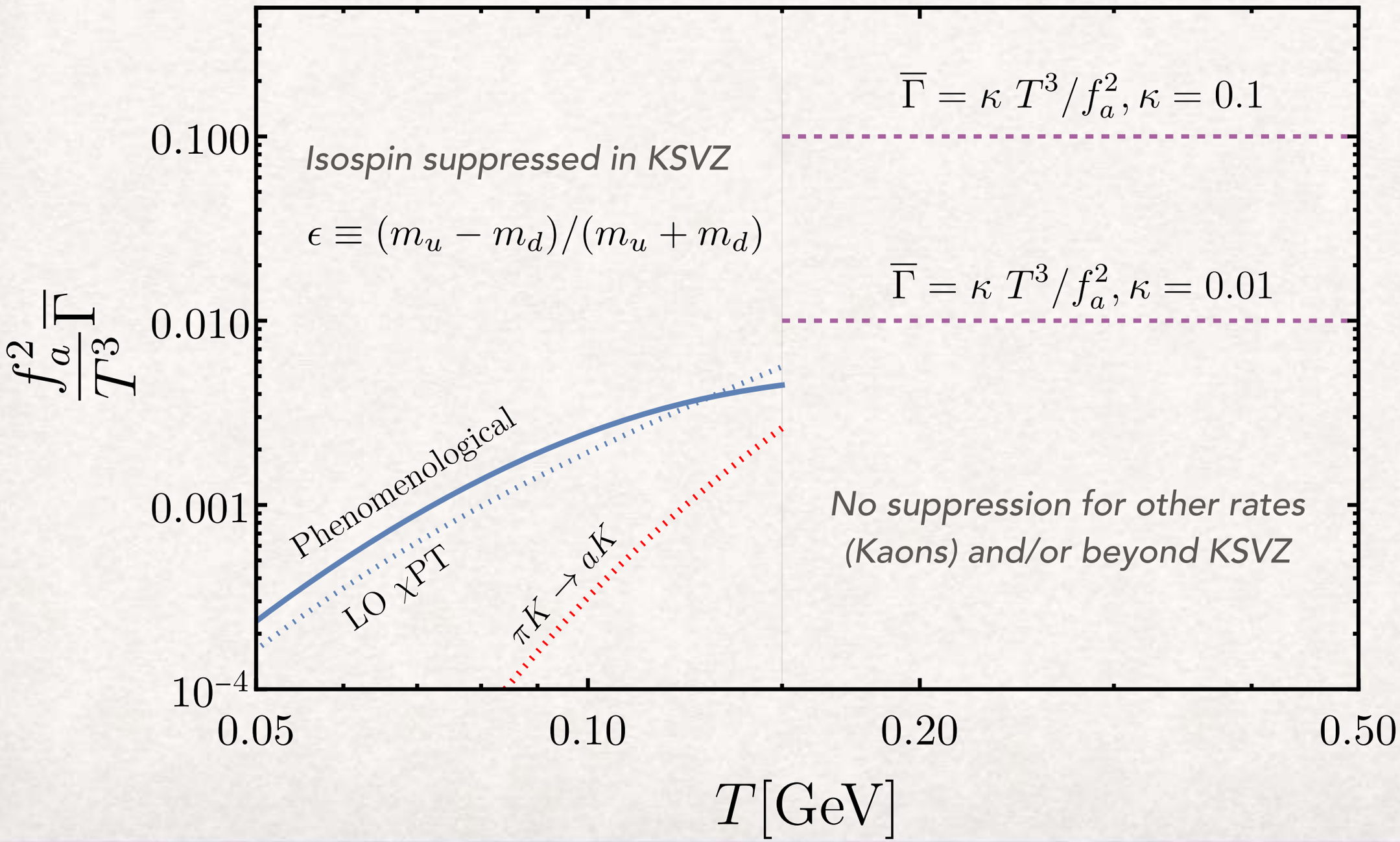
In pure SU(N)

Which can be compared with perturbative a+g rates derived in the literature (which are not expected to be reliable down to T~2 GeV)



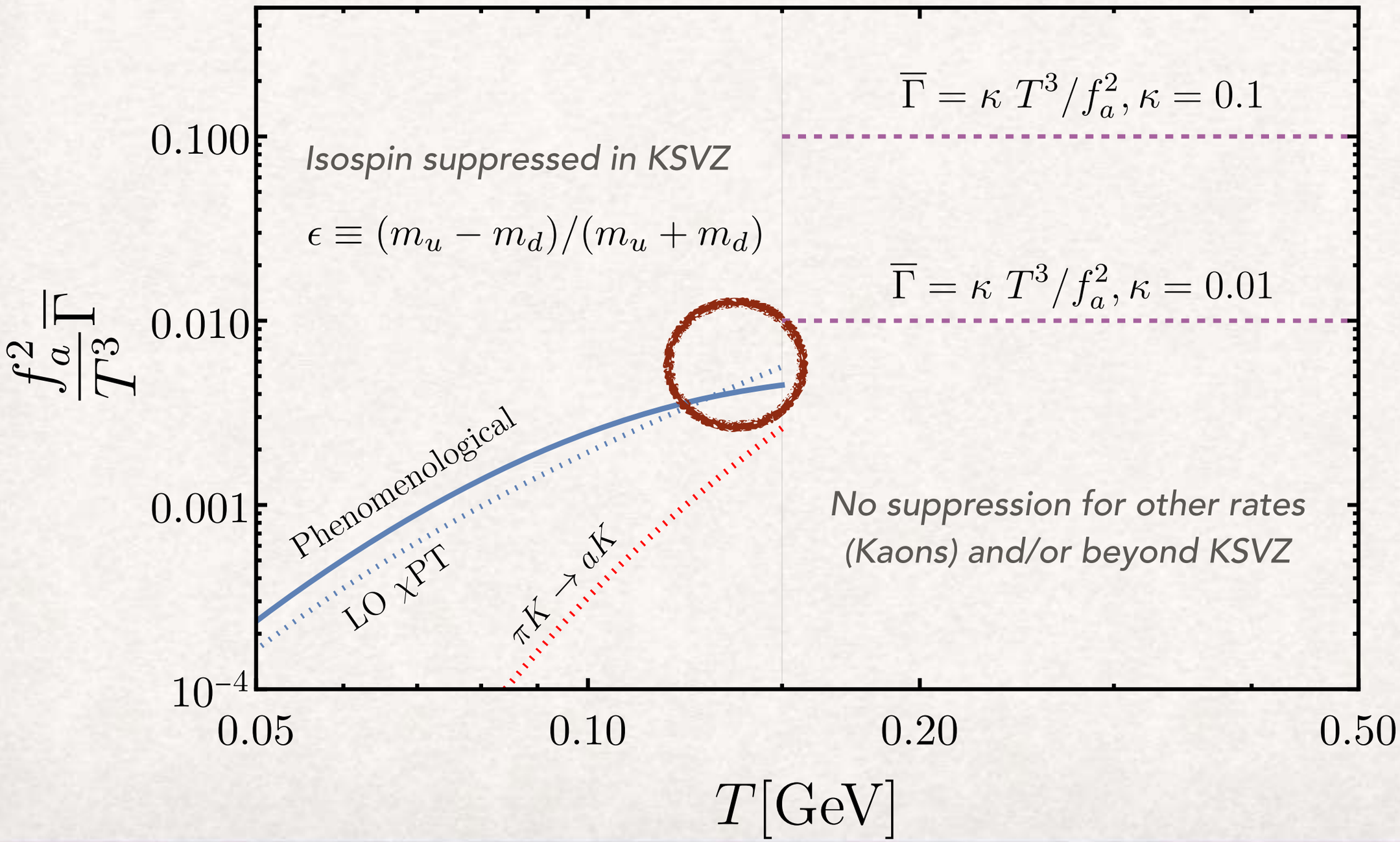
RATE ESTIMATES

Which can be compared with perturbative a+g rates derived in the literature (which are not expected to be reliable down to T~2 GeV)



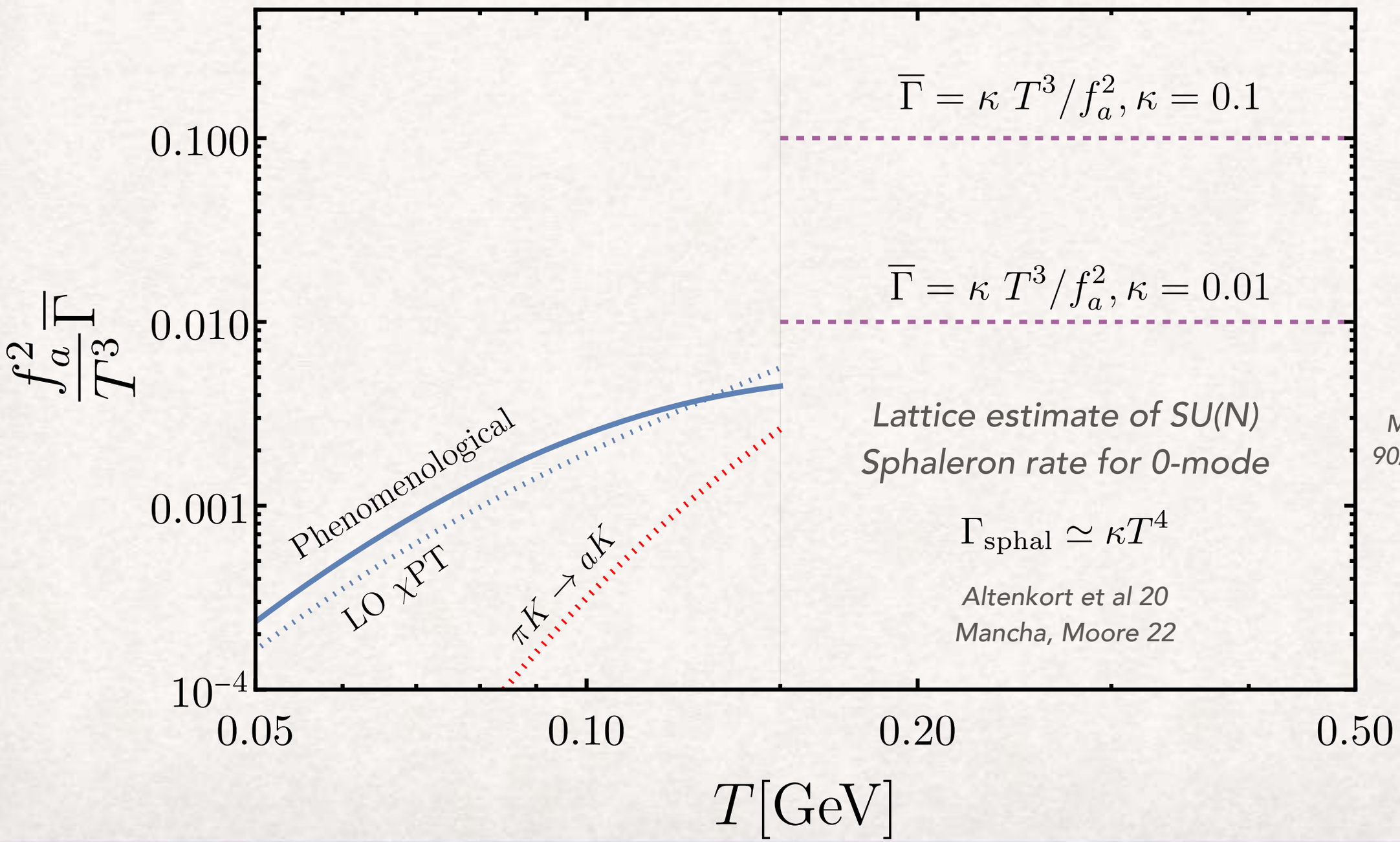
RATE ESTIMATES

Which can be compared with perturbative a+g rates derived in the literature (which are not expected to be reliable down to T~2 GeV)



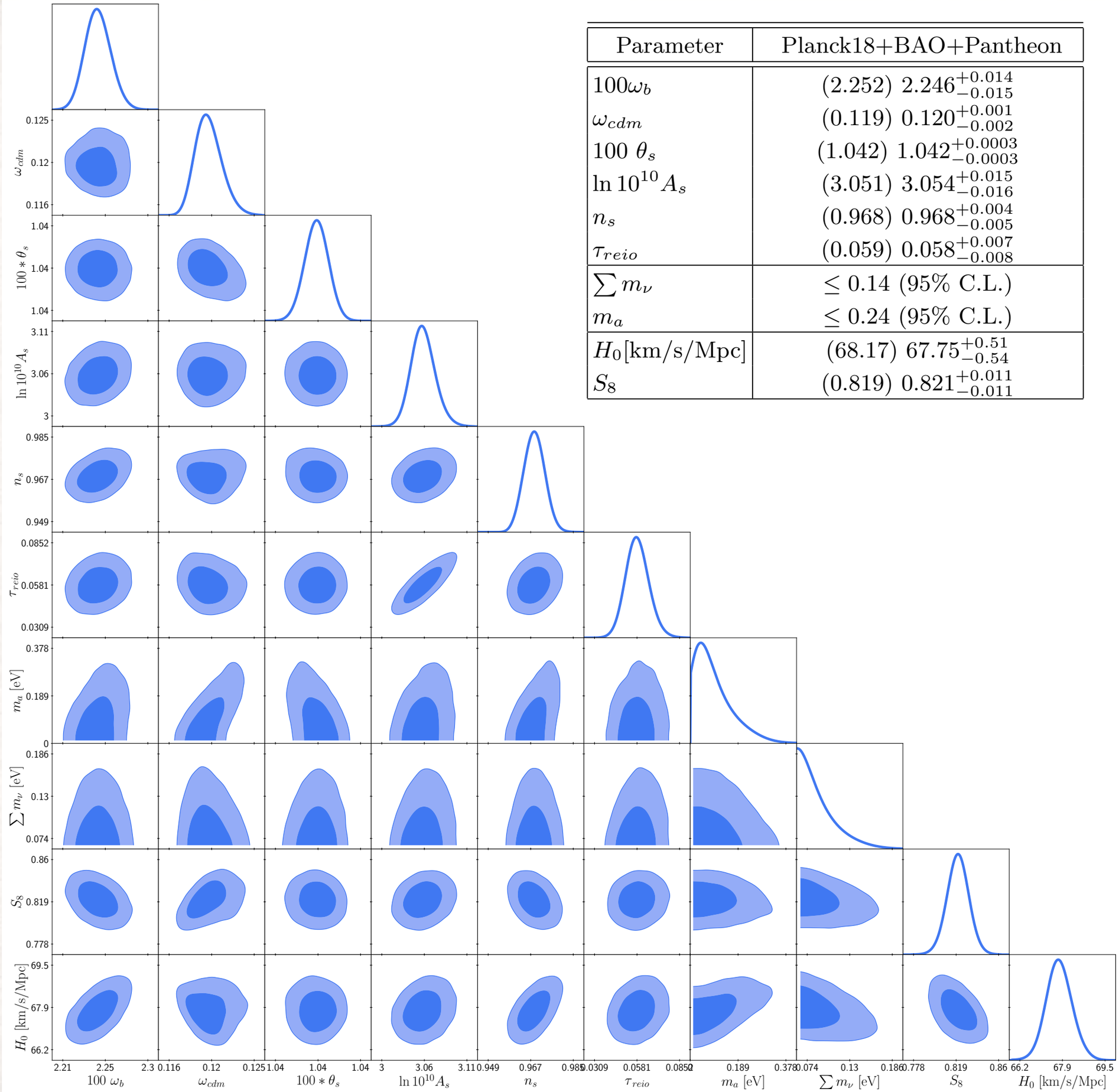
RATE ESTIMATES

Which can be compared with perturbative a+g rates derived in the literature (which are not expected to be reliable down to T~2 GeV)



McLerran et al 90/Tassler,Moore 10/…

POSTERIORS

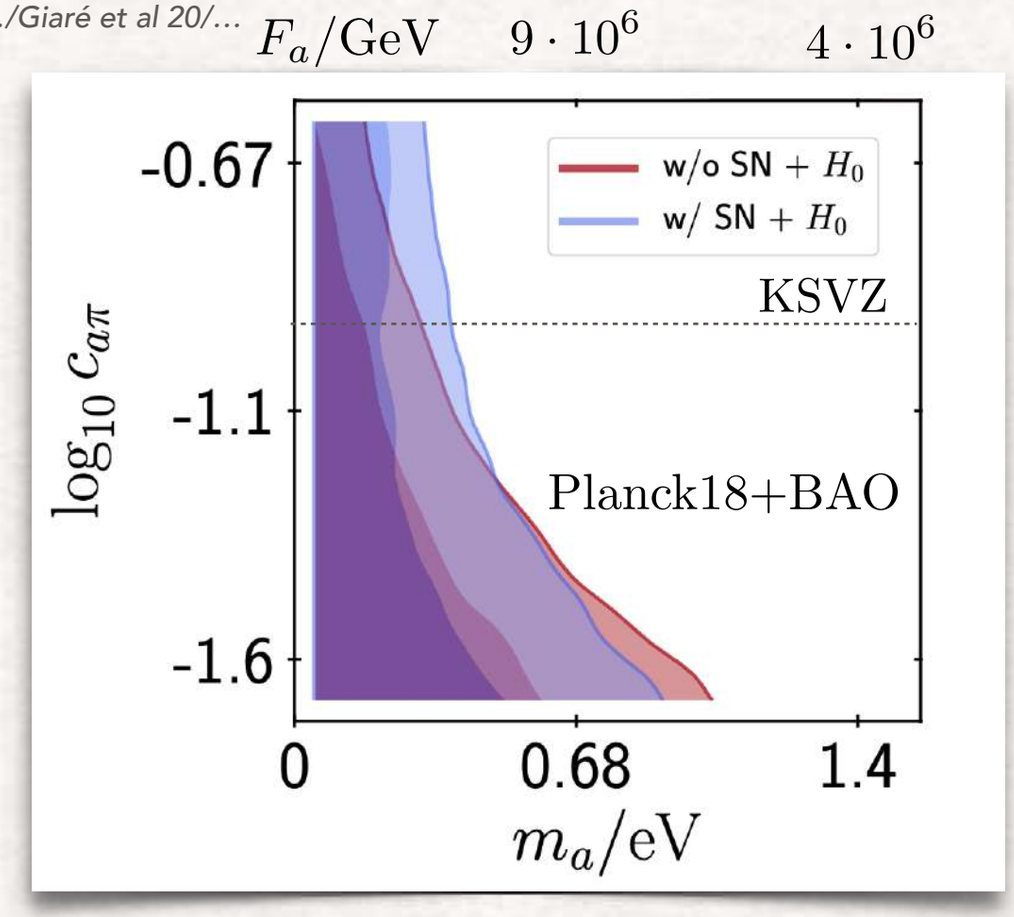


Parameter	Planck18+BAO+Pantheon
$100\omega_b$	$(2.252)\ 2.246^{+0.014}_{-0.015}$
ω_{cdm}	$(0.119)\ 0.120^{+0.001}_{-0.002}$
$100\ \theta_s$	$(1.042)\ 1.042^{+0.0003}_{-0.0003}$
$\ln 10^{10} A_s$	$(3.051)\ 3.054^{+0.015}_{-0.016}$
n_s	$(0.968)\ 0.968^{+0.004}_{-0.005}$
τ_{reio}	$(0.059)\ 0.058^{+0.007}_{-0.008}$
$\sum m_\nu$	≤ 0.14 (95% C.L.)
m_a	≤ 0.24 (95% C.L.)
H_0[km/s/Mpc]	$(68.17)\ 67.75^{+0.51}_{-0.54}$
S_8	$(0.819)\ 0.821^{+0.011}_{-0.011}$

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



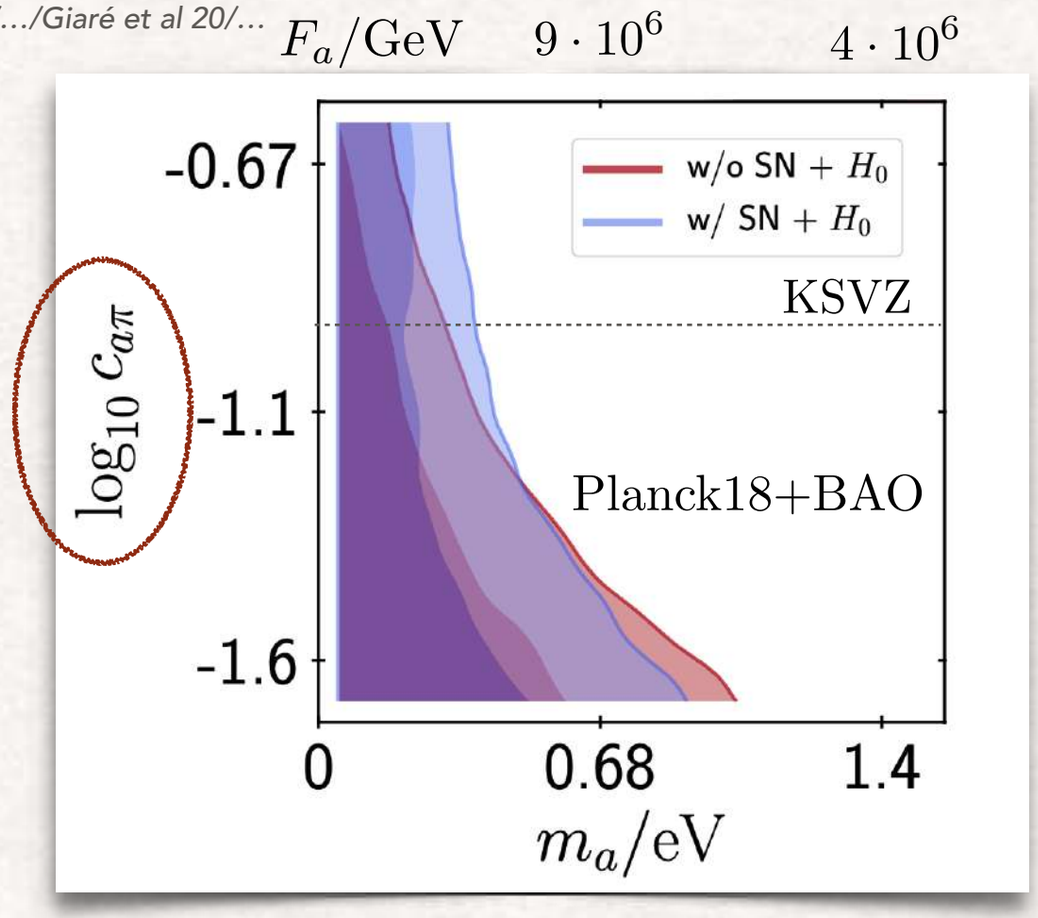
OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



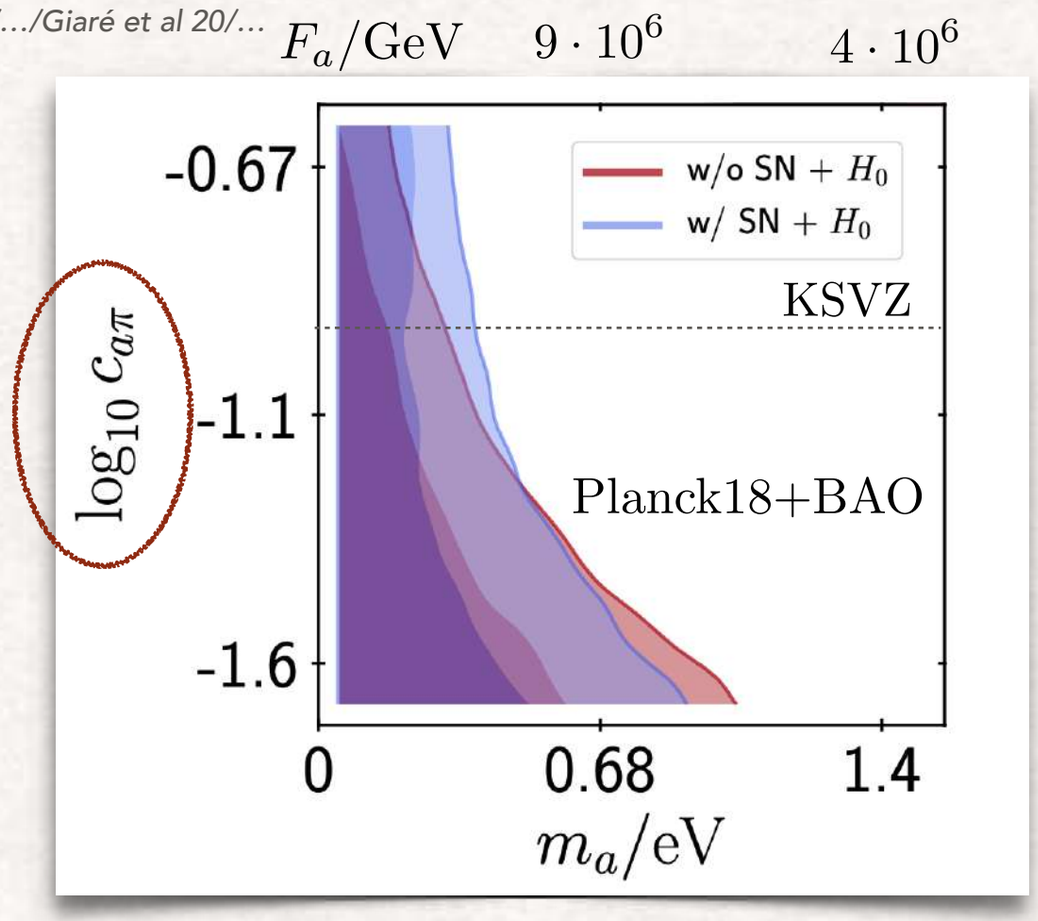
OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



COUPLING TO PIONS CAN BE ENHANCED/ SUPPRESSED IN DFSZ MODELS! PRODUCTION VIA LEPTONS (MUONS, TAUS) CAN ALSO BE RELEVANT

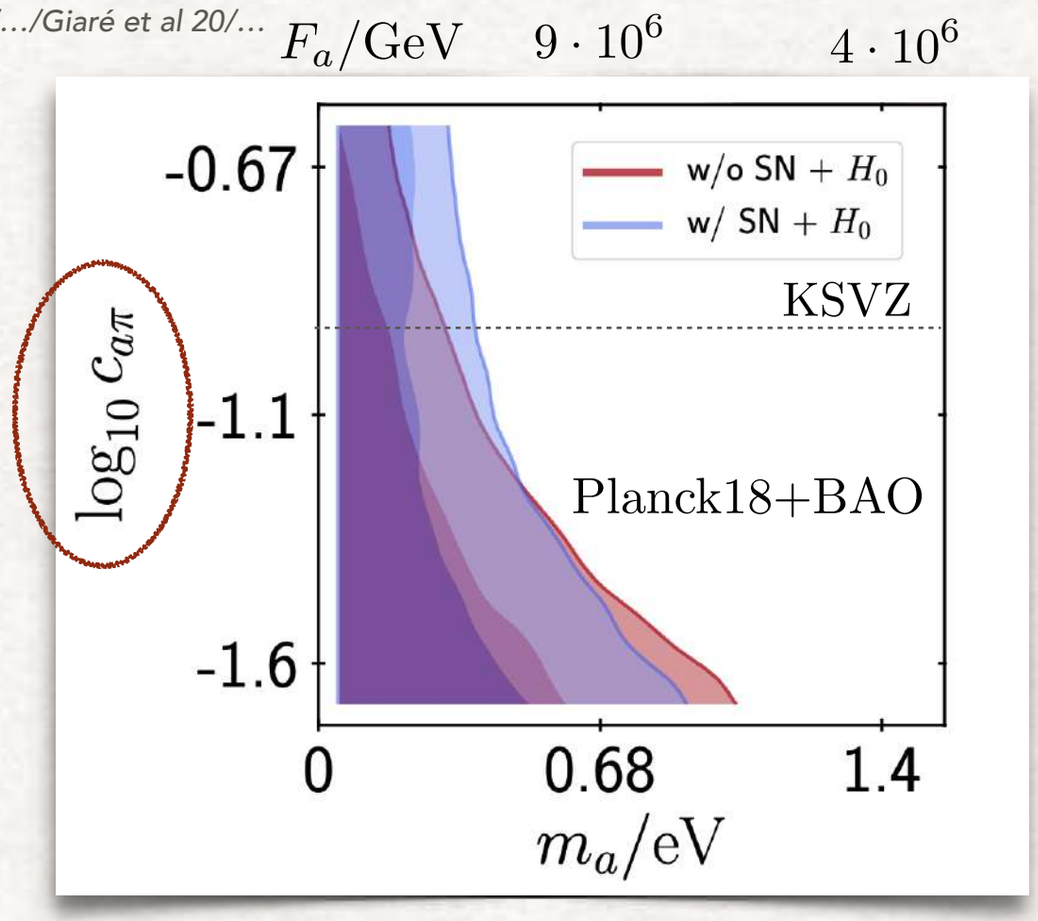
OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



COUPLING TO PIONS CAN BE ENHANCED/ SUPPRESSED IN DFSZ MODELS! PRODUCTION VIA LEPTONS (MUONS, TAUS) CAN ALSO BE RELEVANT

IMPORTANT TO COMPUTE FULL AXION PRODUCTION BY SOLVING BOLTZMANN EQUATION!

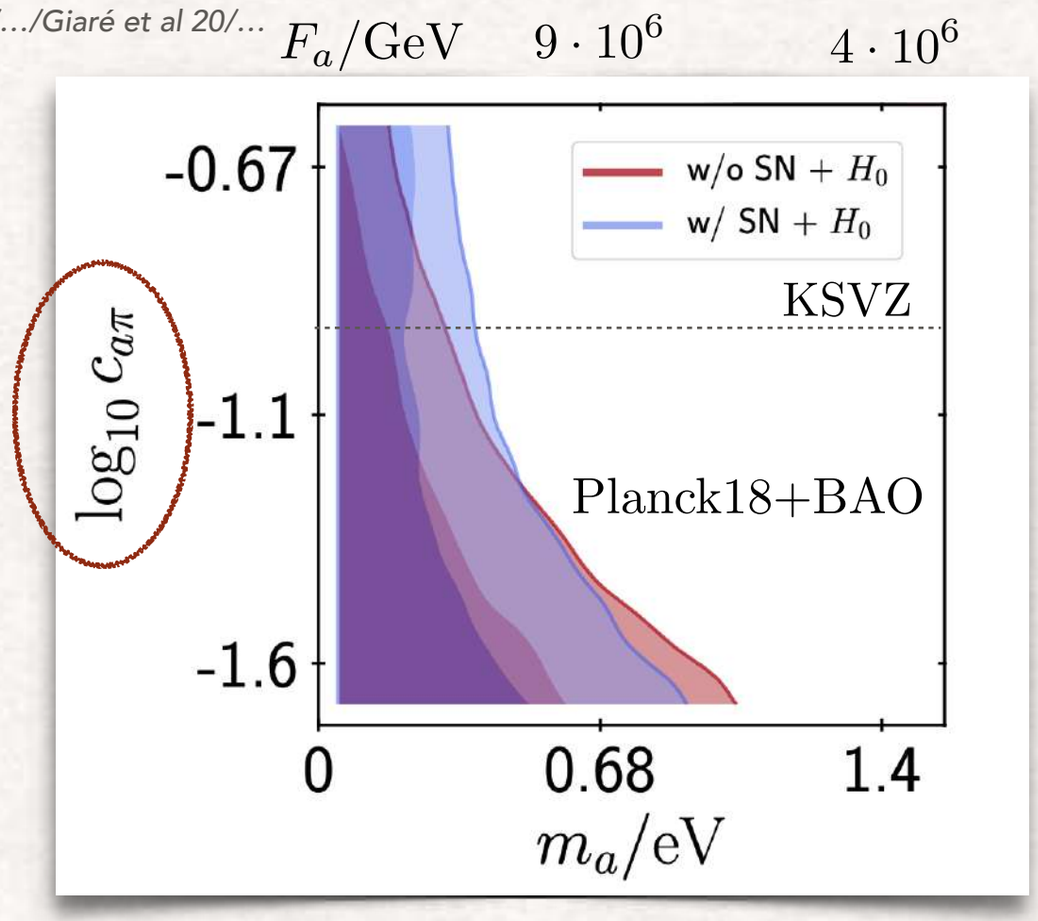
OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



COUPLING TO PIONS CAN BE ENHANCED/ SUPPRESSED IN DFSZ MODELS! PRODUCTION VIA LEPTONS (MUONS, TAUS) CAN ALSO BE RELEVANT

IMPORTANT TO COMPUTE FULL AXION PRODUCTION BY SOLVING BOLTZMANN EQUATION!

STRONGEST BOUND (MAXIMAL DFSZ COUPLING)

$$m_a \leq 0.2 \text{ eV } (F_a \geq 3 \cdot 10^7 \text{ GeV}), 95\% \text{ C.L.}$$

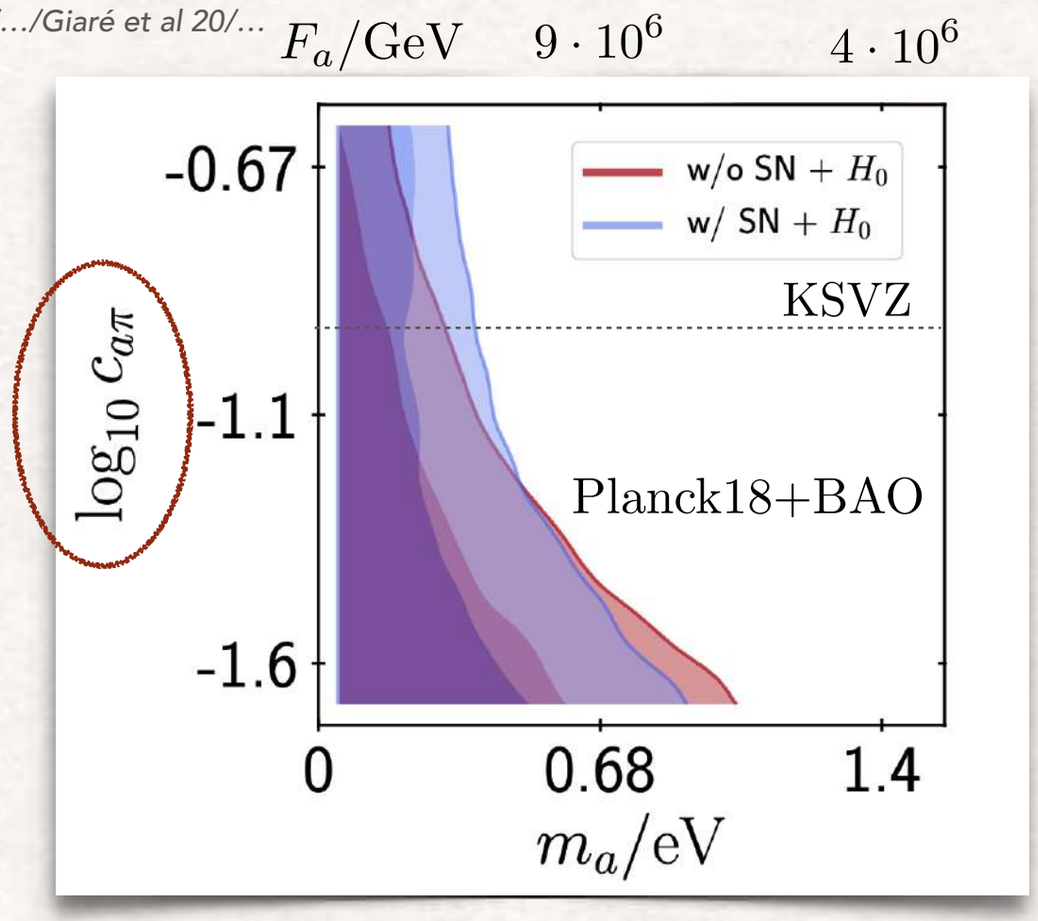
OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

DFSZ AXION

For axions coupled to the SM, production via hadronic scattering (e.g. $\pi\pi \to a\pi$) is most important. Opportunity to **robustly set lower bound on F_a , independently of astrophysical constraints (SN1987A,** possibly less robust**).**

*"**Hot axion bound**", derived for **KSVZ model** Chang,Choi 93/Hannestad et al 05/…/Giaré et al 20/…*



COUPLING TO PIONS CAN BE ENHANCED/ SUPPRESSED IN DFSZ MODELS! PRODUCTION VIA LEPTONS (MUONS, TAUS) CAN ALSO BE RELEVANT

IMPORTANT TO COMPUTE FULL AXION PRODUCTION BY SOLVING BOLTZMANN EQUATION!

STRONGEST BOUND (MAXIMAL DFSZ COUPLING)

$$m_a \leq 0.2 \text{ eV } (F_a \geq 3 \cdot 10^7 \text{ GeV}), 95\% \text{ C.L.}$$

OUTLOOK: IF PRODUCTION FROM PIONS CAN BE RELIABLY COMPUTED, CMB-S4 CAN SET A PRECISE BOUND IN THE RANGE $F_a \gtrsim 10^8$ GeV

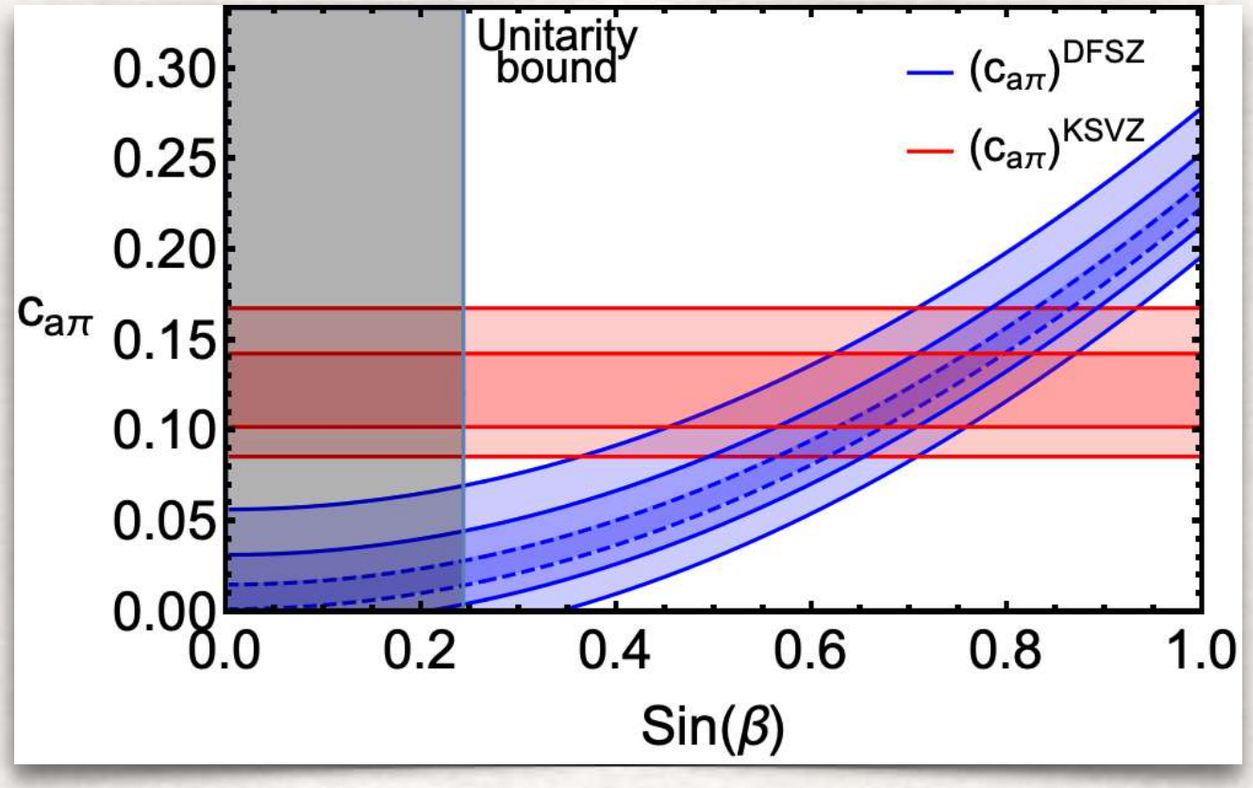
(see also D'Eramo, Hajkarim, Yun 21, D'Eramo et al 22)

CAVEAT: CHPT RATE FOR AXION PRODUCTION NOT FULLY RELIABLE AT RELEVANT TEMPERATURES (~150 MEV), DUE TO QCD PT

Di Luzio, Martinelli, Piazza 21

AXION THERMAL RATES

$$\mathcal{L}_{a\pi} = \frac{c_{a\pi}}{f_\pi}\frac{\partial_\mu a}{f}\left[2\partial^\mu\pi^0\pi^+\pi^- - \pi_0\left(\partial^\mu\pi^+\pi^- - \pi^+\partial^\mu\pi^-\right)\right], \tag{7}$$



$$\Gamma_{\pi\pi\to a\pi} = A\left(\frac{c_{a\pi}}{f_\pi f}\right)^2 T^5 h(x_\pi), \qquad \Gamma_{a\ell\to\ell\gamma} = B\, c_\ell^2\left(\frac{m_\ell}{f}\right)^2 T\, g(x_\ell),$$

GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

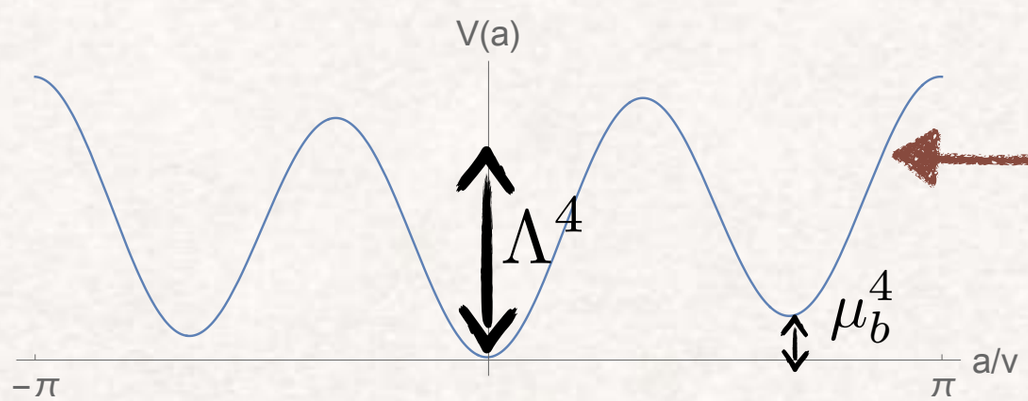
$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\Big|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

Parametrises quality of PQ symmetry

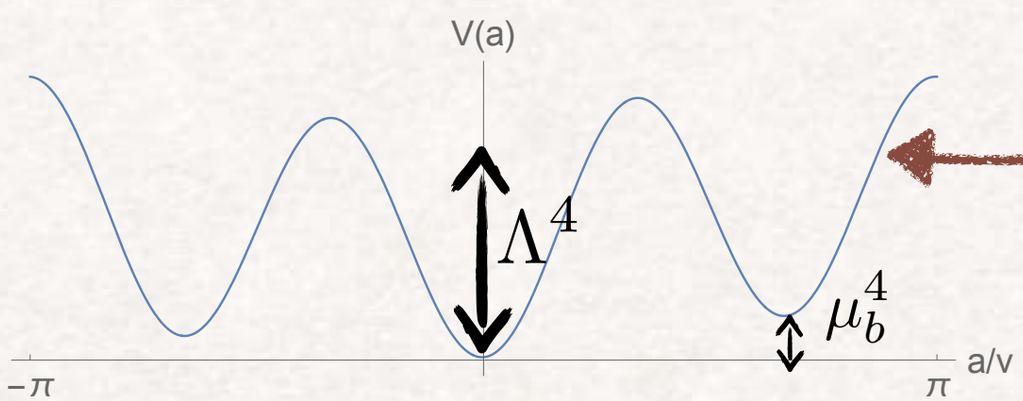


GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\Big|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

Parametrises quality of PQ symmetry



Interesting example: QCD Axion. Any breaking of PQ beyond QCD needs to be extremely suppressed, otherwise strong CP problem is not solved (*"axion quality problem"*).

Dine, Seiberg 86/.../ Kamiomkowski, March-Russell 92/.../ Svrcek, Witten 06/

$$V_{\not{P}Q} \sim c_5 |\Phi|^4 \frac{\Phi}{M} + {\rm h.c.}$$

$$V_{\not{P}Q} \sim M^4 e^{-S_{\rm inst}}$$

$$\theta_{\rm QCD} \lesssim 10^{-10} \Rightarrow c_5 \lesssim 10^{-46}$$

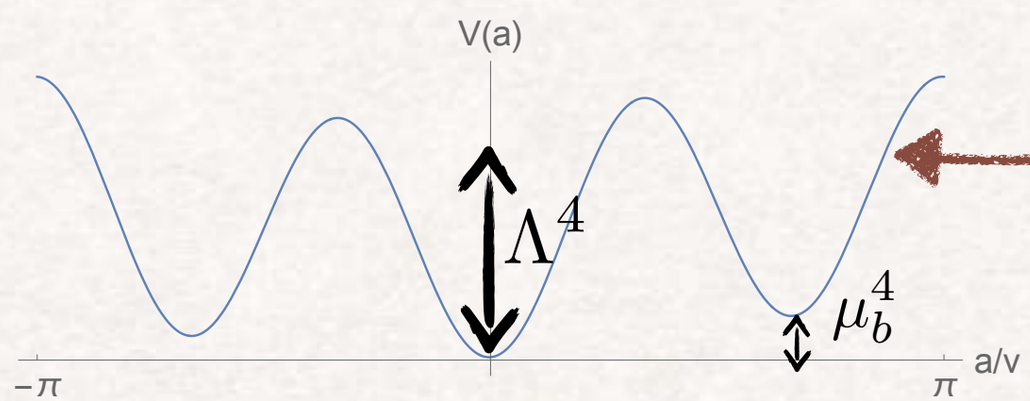
$$S_{\rm inst} \gtrsim 200$$

GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\Big|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

Parametrises quality of PQ symmetry



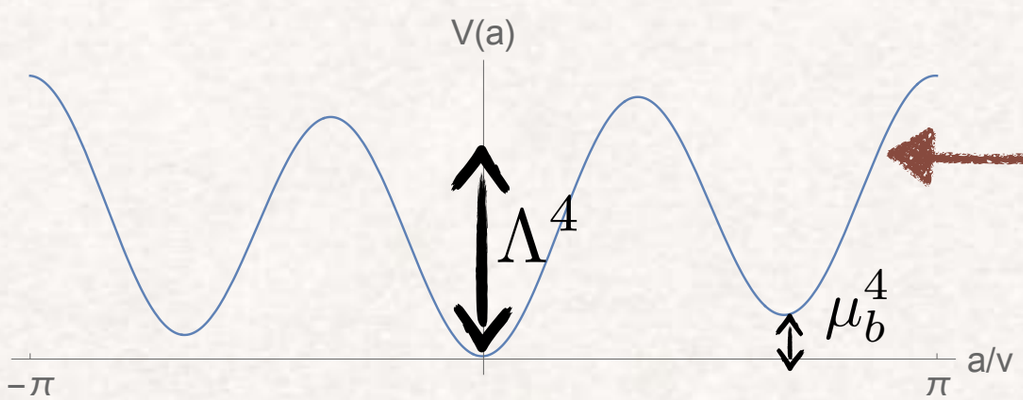
HEAVY QCD AXION SCENARIO: RAISE QCD AXION MASS TO MAKE PQ MECHANISM ROBUST AGAINST DANGEROUS UV OPERATORS

GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\Big|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

Parametrises quality of PQ symmetry



HEAVY QCD AXION SCENARIO: RAISE QCD AXION MASS TO MAKE PQ MECHANISM ROBUST AGAINST DANGEROUS UV OPERATORS

$$V(a) = (m_H^2 + m_{\rm QCD}^2)F_a^2\left[1-\cos\left(\frac{a}{F_a}\right)\right] - \mu_b^4\cos\left(\frac{a}{N_{\rm DW}F_a} - \delta\right) + \ldots$$

Extra sector aligned with QCD

Mirror Dark Sector ($\mathbb{Z}_2$)

Rubakov 97.../ Hook et al 19/...

Small Instantons

Holdom 85/.../ Agrawal et al 18/ .. Gherghetta et al 20/....

Heavy confining gauge sector Unified with QCD

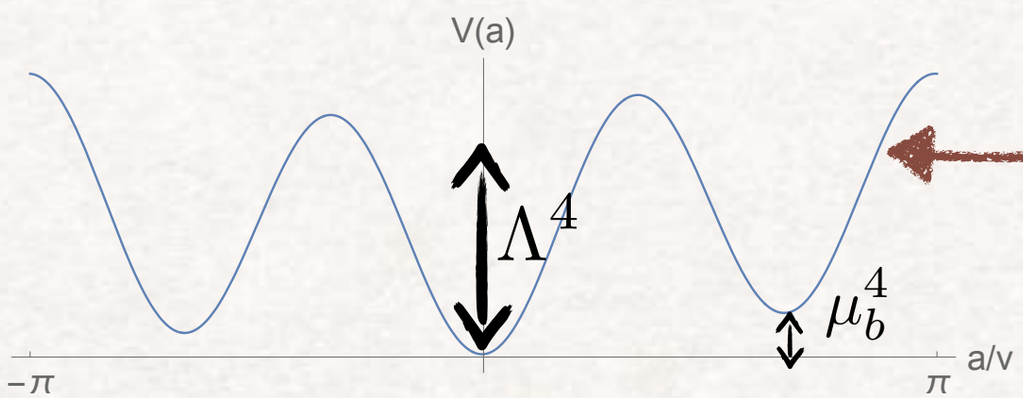
Gherghetta et al 16/....

GW IMPRINTS OF HEAVY AXIONS

Signature is generic to any **post-inflationary** axion scenario with $N_{\rm DW} > 1$

$$\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\Big|_{\rm ann} \simeq 0.1\ \kappa^2 \left(\frac{F_a}{10^{11}\ {\rm GeV}}\right)^2 \left(\frac{0.003}{\mu_b/\Lambda}\right)^4$$

Parametrises quality of PQ symmetry



Dangerous
In standard scenario now responsible for DW annihilation and GWs

HEAVY QCD AXION SCENARIO: RAISE QCD AXION MASS TO MAKE PQ MECHANISM ROBUST AGAINST DANGEROUS UV OPERATORS

$$V(a) = (m_H^2 + m_{\rm QCD}^2)F_a^2\left[1-\cos\left(\frac{a}{F_a}\right)\right] - \mu_b^4\cos\left(\frac{a}{N_{\rm DW}F_a} - \delta\right) + \ldots$$

Extra sector aligned with QCD

Mirror Dark Sector ($\mathbb{Z}_2$)

Rubakov 97.../ Hook et al 19/...

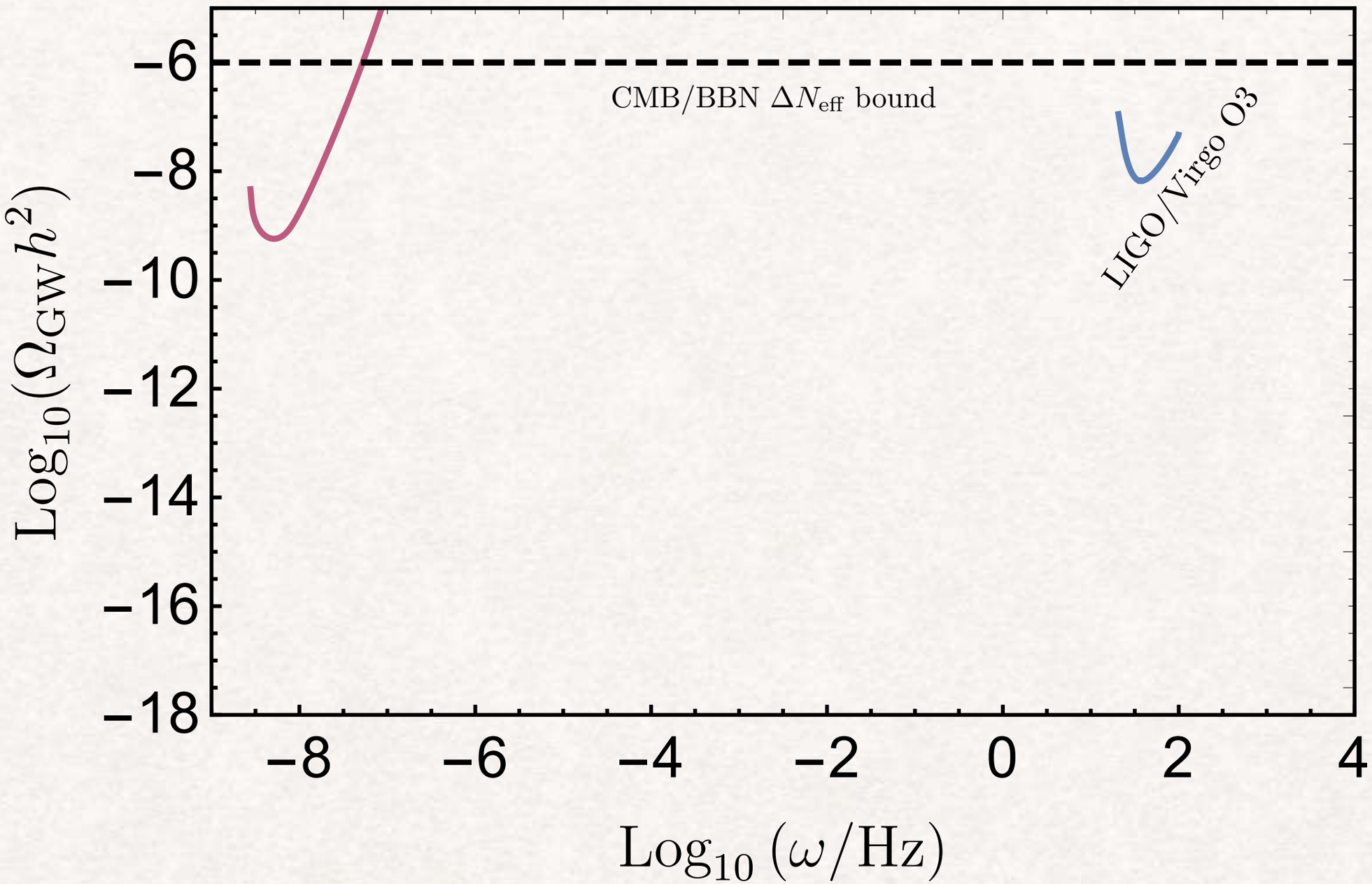
Small Instantons

Holdom 85/.../ Agrawal et al 18/ .. Gherghetta et al 20/....

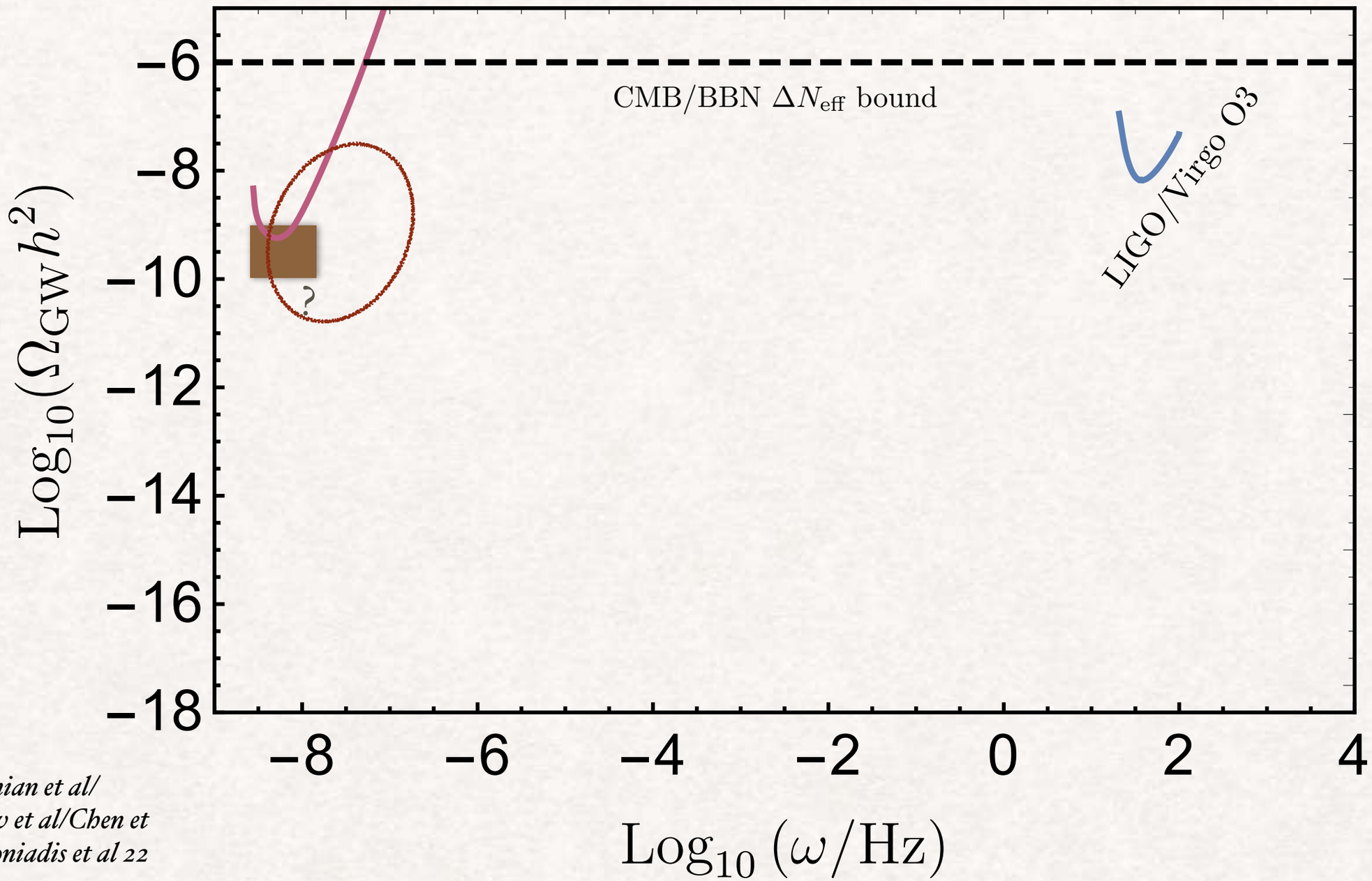
Heavy confining gauge sector Unified with QCD

Gherghetta et al 16/....

PULSAR TIMING ARRAYS



PULSAR TIMING ARRAYS

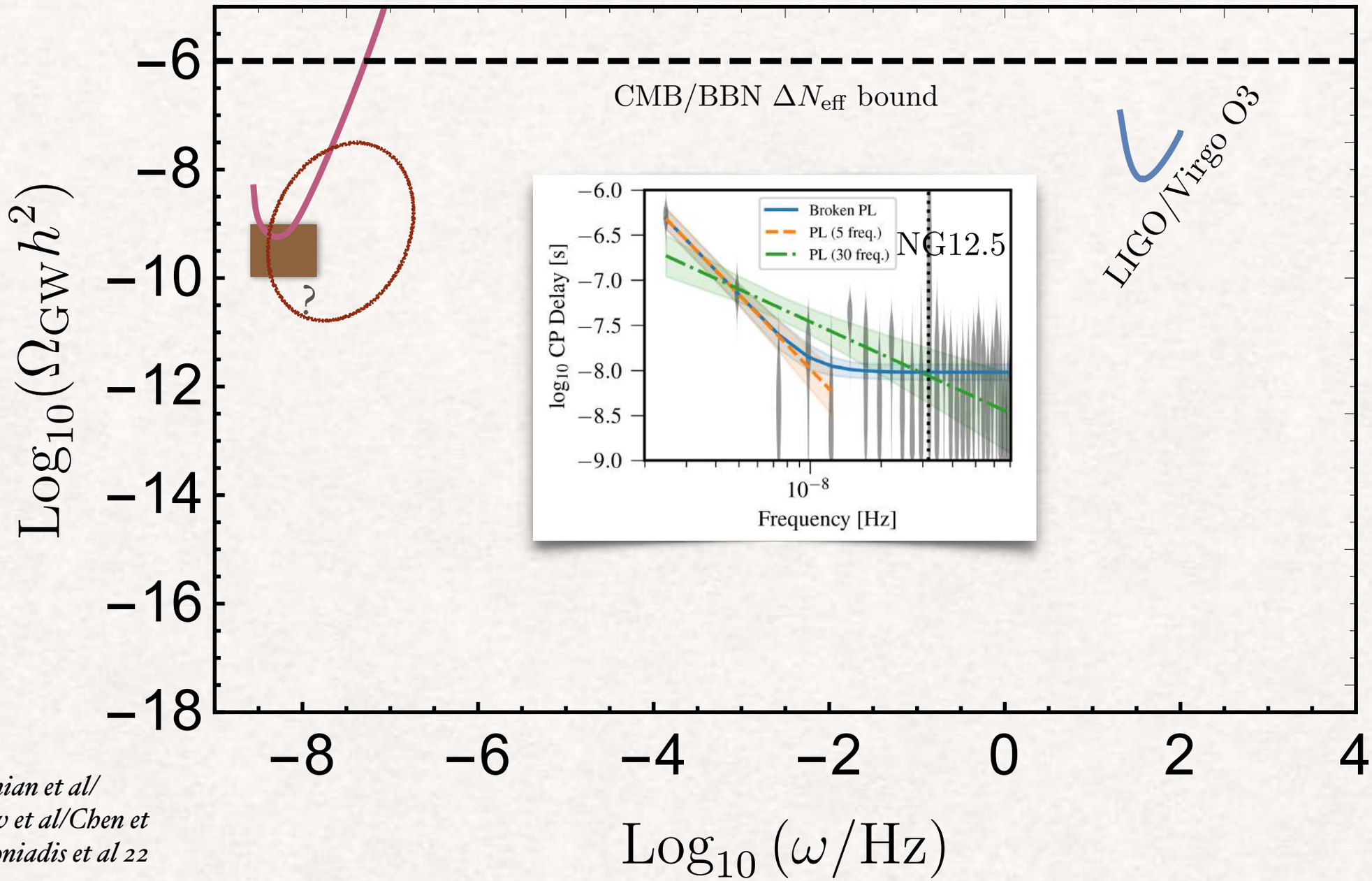


Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

Strong evidence for common spectrum process in their measurement of pulsar time delays.

(**Caveat**: Not yet evidence for stochastic GWs, since no significant evidence for quadrupolar Hellings-Downs correlations, expected near NANOgrav 18 yrs baseline, if signal due to GWs)

PULSAR TIMING ARRAYS

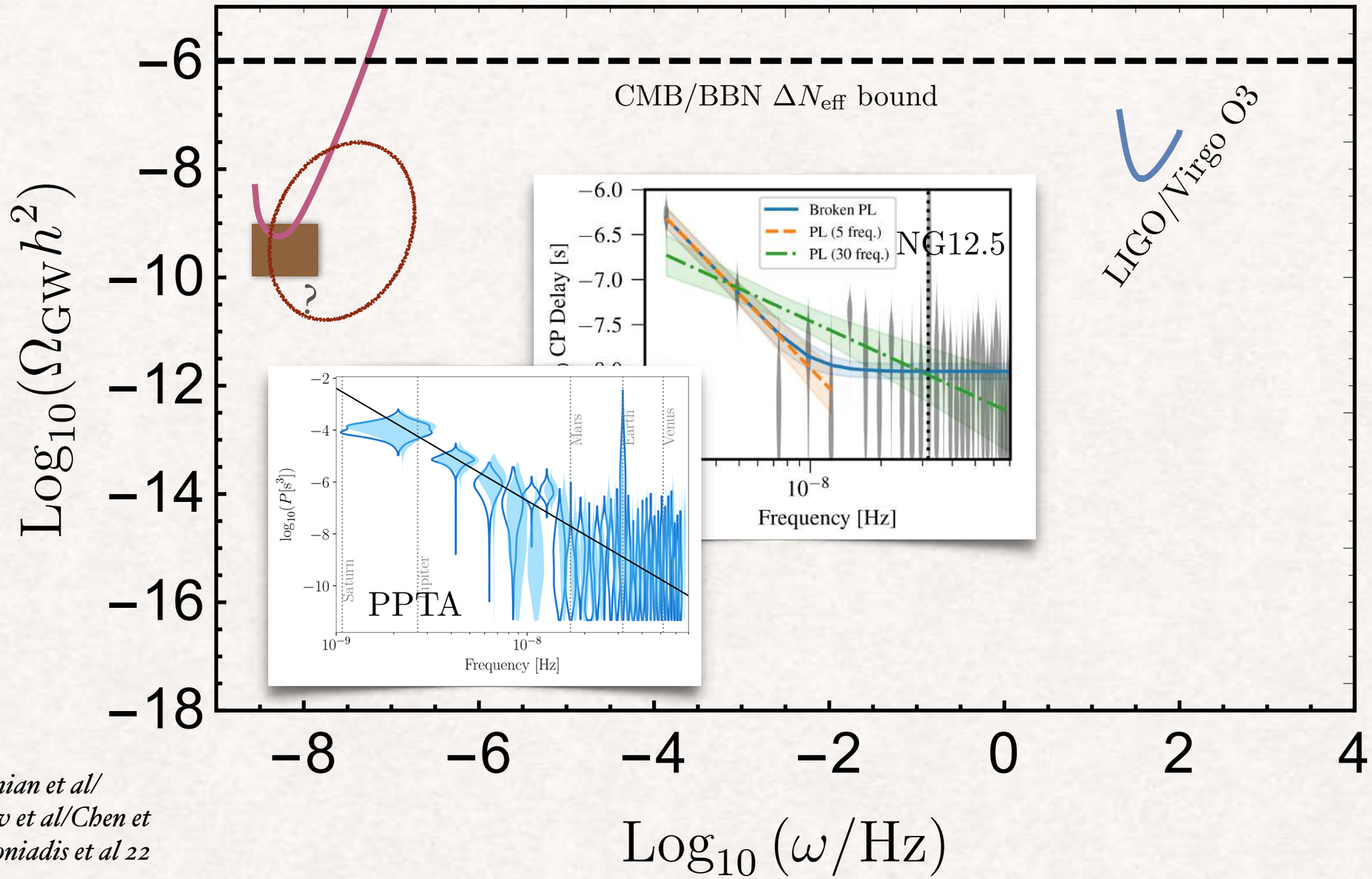


Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

Strong evidence for common spectrum process in their measurement of pulsar time delays.

(**Caveat**: Not yet evidence for stochastic GWs, since no significant evidence for quadrupolar Hellings-Downs correlations, expected near NANOgrav 18 yrs baseline, if signal due to GWs)

PULSAR TIMING ARRAYS

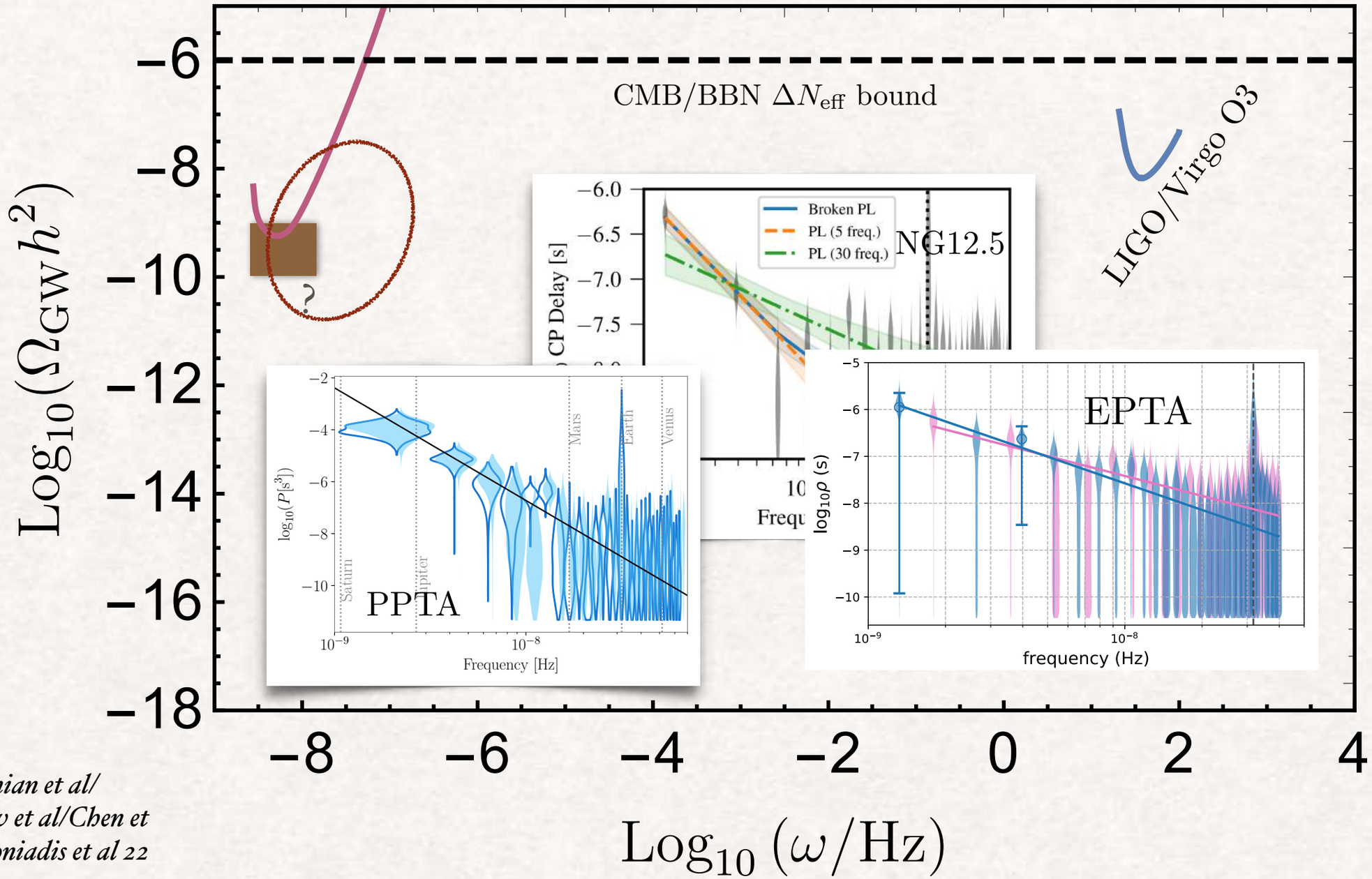


Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

Strong evidence for common spectrum process in their measurement of pulsar time delays.

(**Caveat**: Not yet evidence for stochastic GWs, since no significant evidence for quadrupolar Hellings-Downs correlations, expected near NANOgrav 18 yrs baseline, if signal due to GWs)

PULSAR TIMING ARRAYS

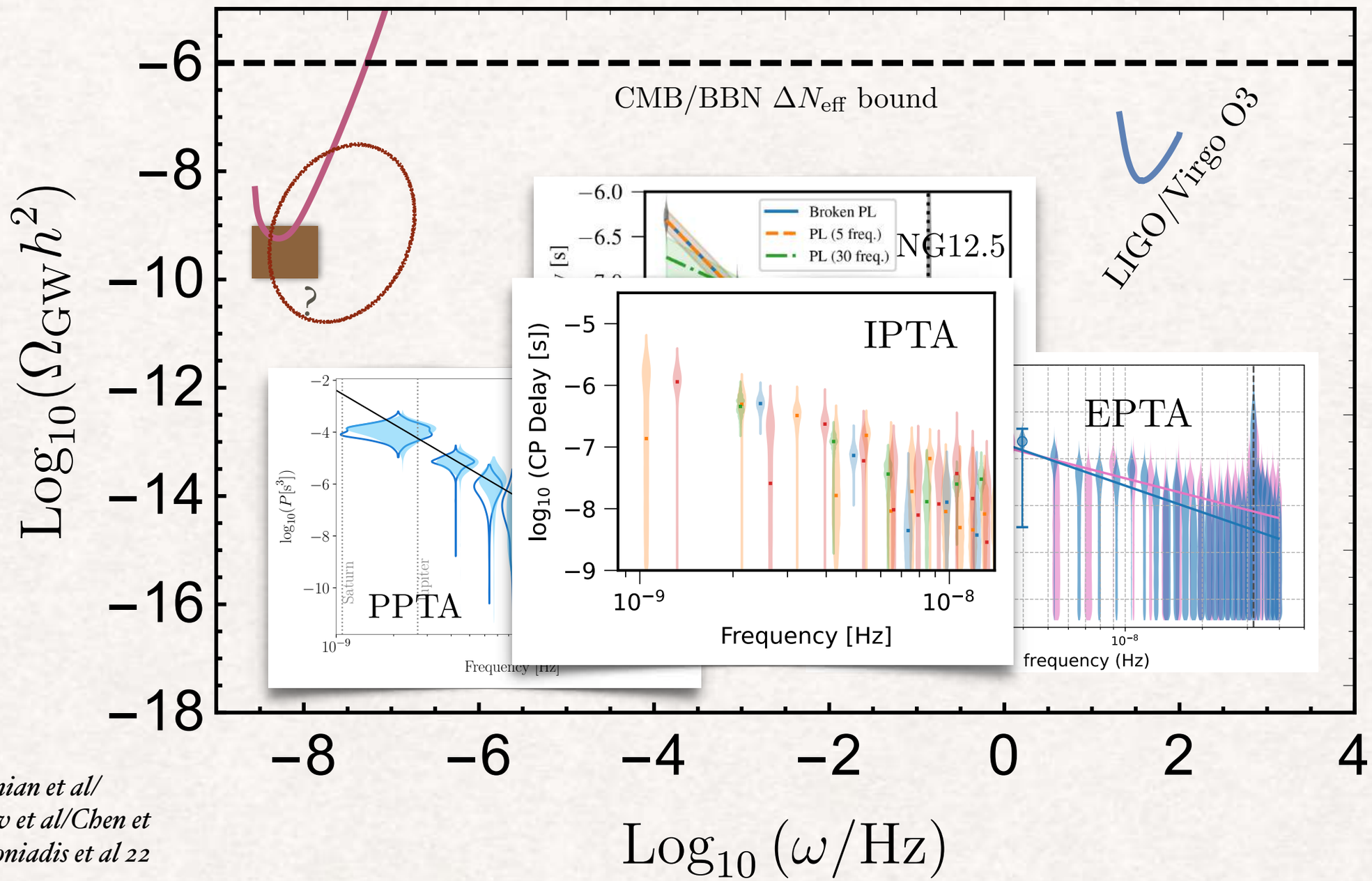


Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

Strong evidence for common spectrum process in their measurement of pulsar time delays.

(**Caveat**: Not yet evidence for stochastic GWs, since no significant evidence for quadrupolar Hellings-Downs correlations, expected near NANOgrav 18 yrs baseline, if signal due to GWs)

PULSAR TIMING ARRAYS

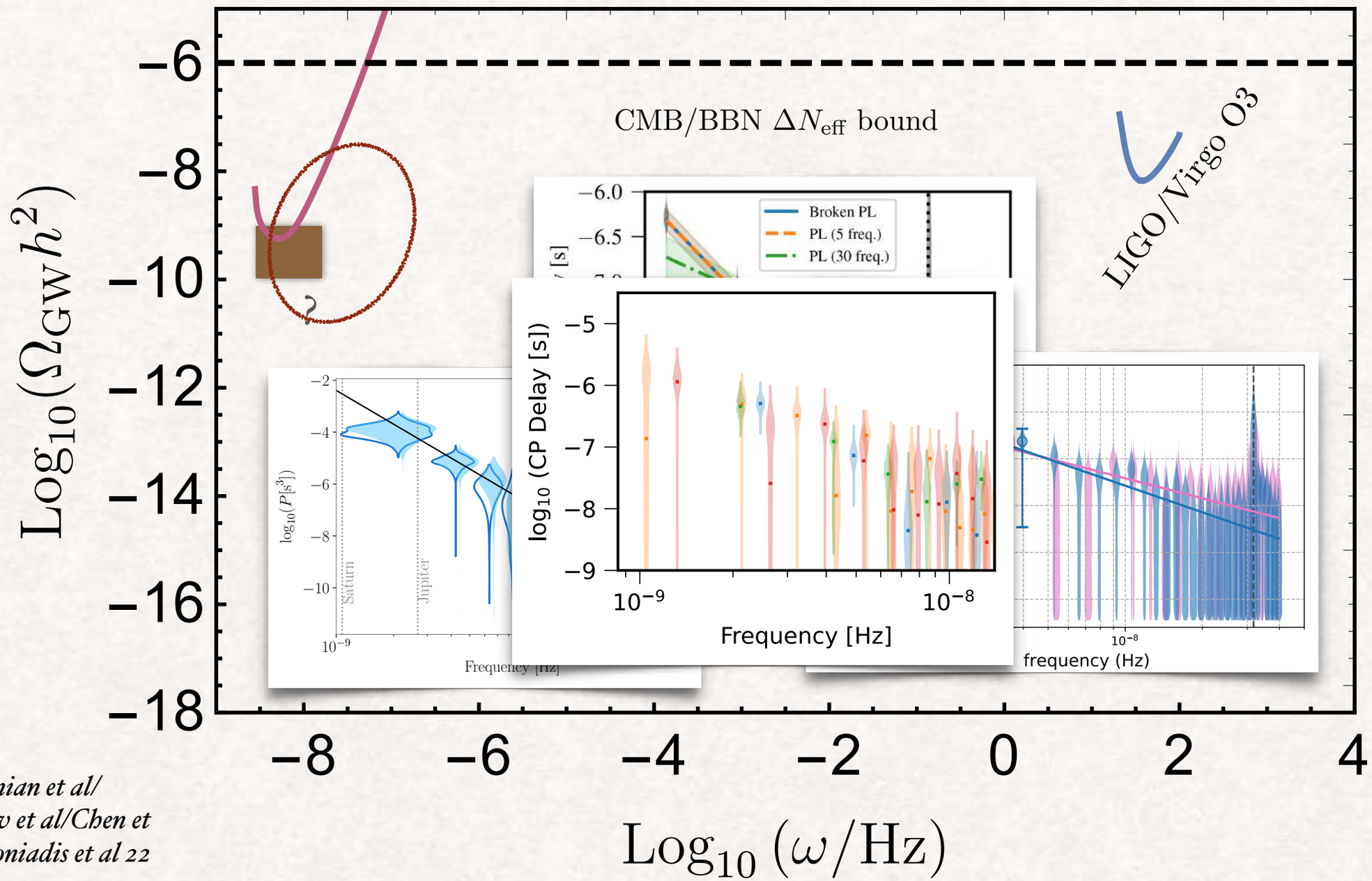


Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

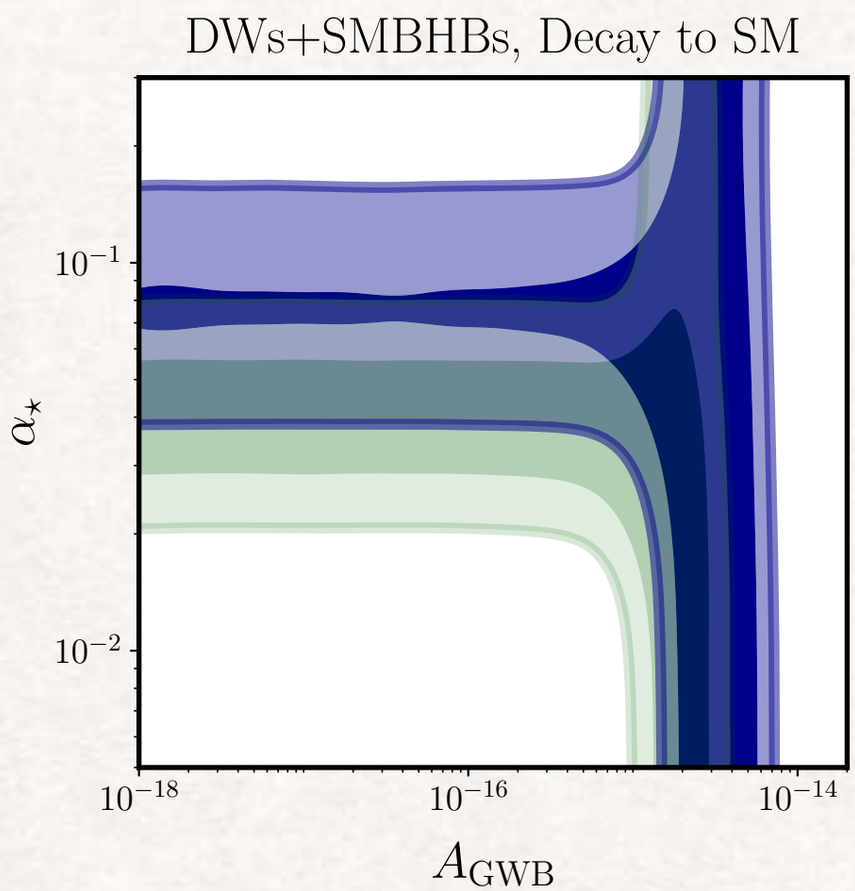
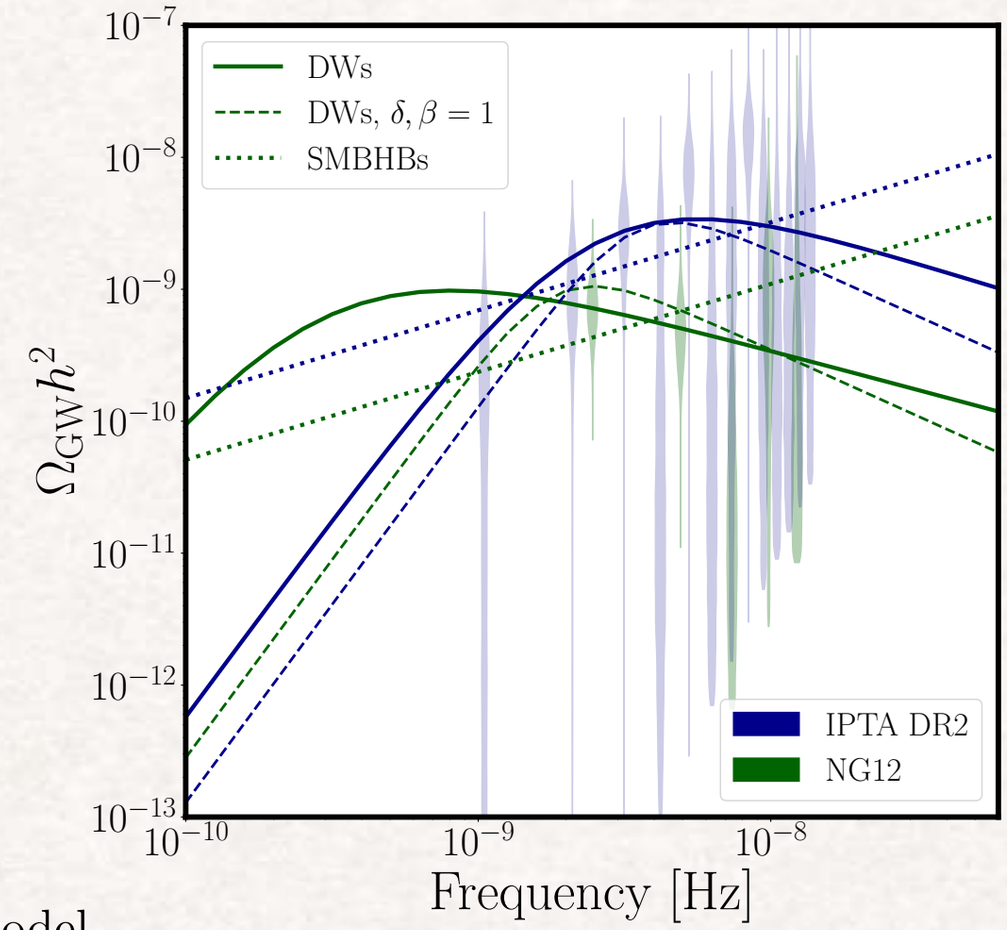
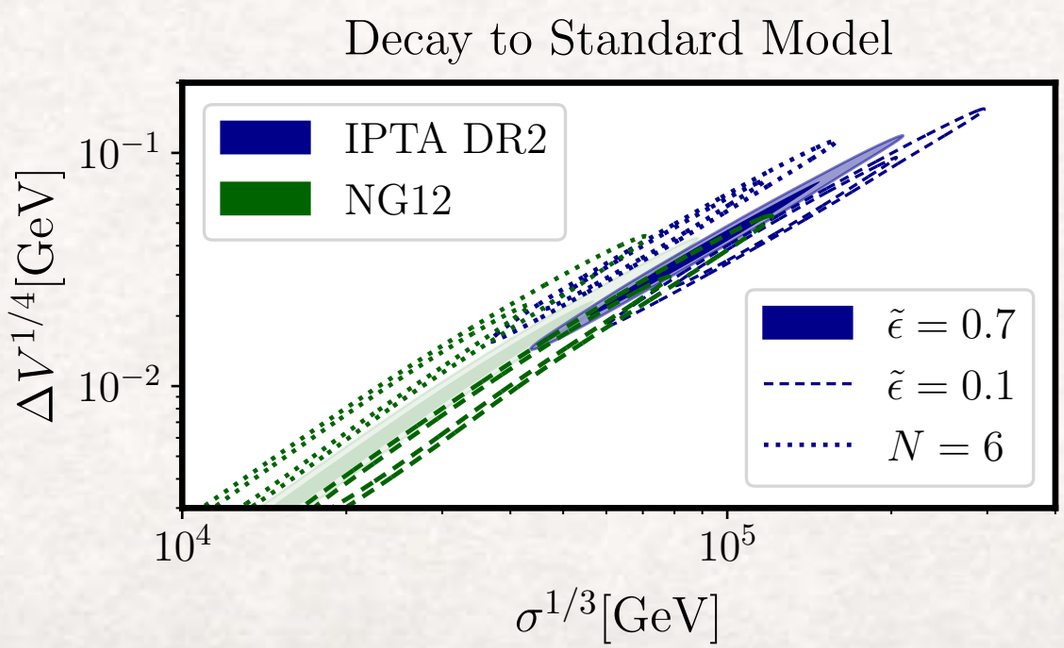
Strong evidence for common spectrum process in their measurement of pulsar time delays.

(**Caveat**: Not yet evidence for stochastic GWs, since no significant evidence for quadrupolar Hellings-Downs correlations, expected near NANOgrav 18 yrs baseline, if signal due to GWs)

PULSAR TIMING ARRAYS



Arzoumanian et al/ Goncharov et al/Chen et al 21/Antoniadis et al 22

If GWs, signal is commonly interpreted as due to Supermassive Black Hole Binaries. However, **new physics interpretation also possible and far-reaching.**

MORE PTA RESULTS