Neutron Portal and the Dark Matter-Baryon Coincidence

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Based on: S. Girmohanta, Y. Nakai, Y. Shigekami, Z. Zhang (2604.21168)

June 07, 2026

CAU-IBS BSM 2026

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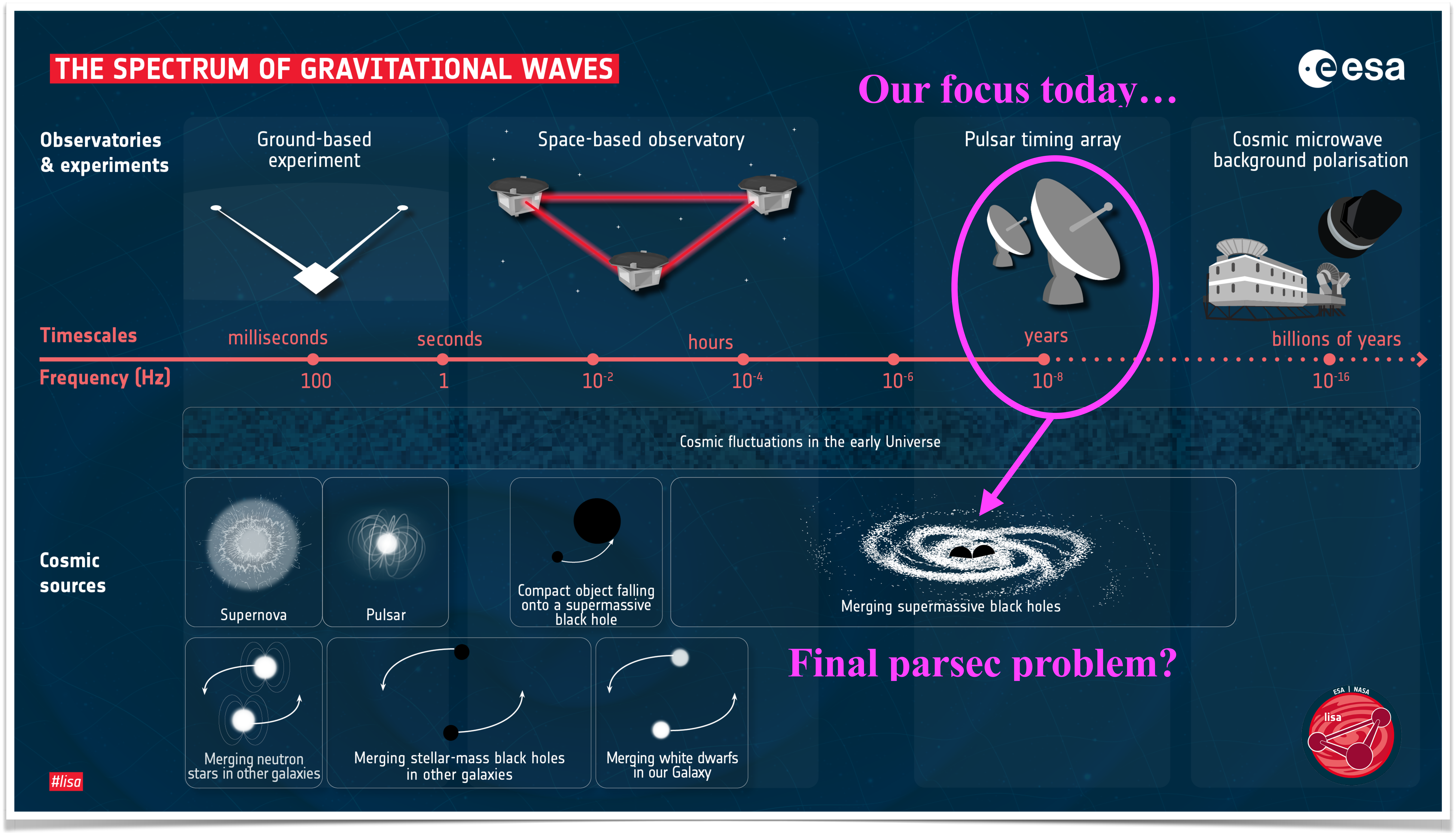
Nano-Hz stochastic gravitational waves and the PTA

The spectrum of gravitational waves

Gravitational waves: Small ripples over background spacetime.



Pulsar Timing Array as GW detector

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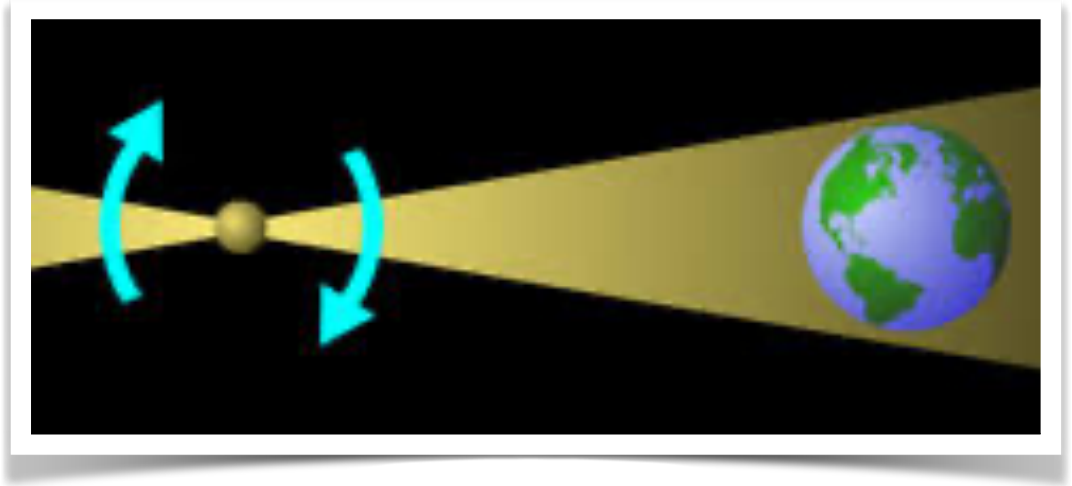
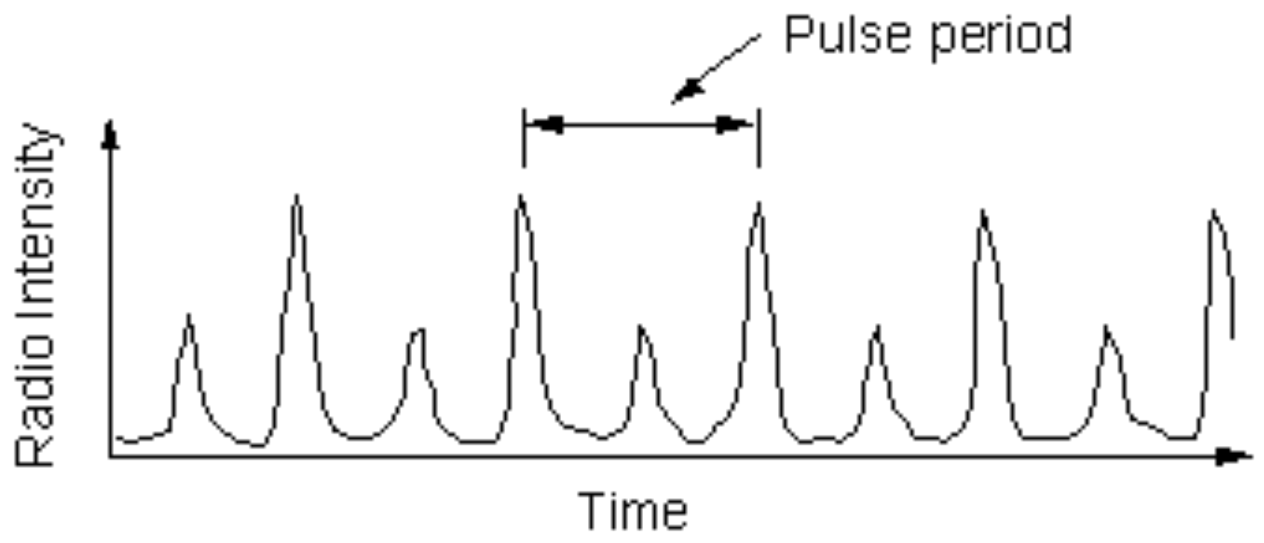
Pulsars are precise clocks.





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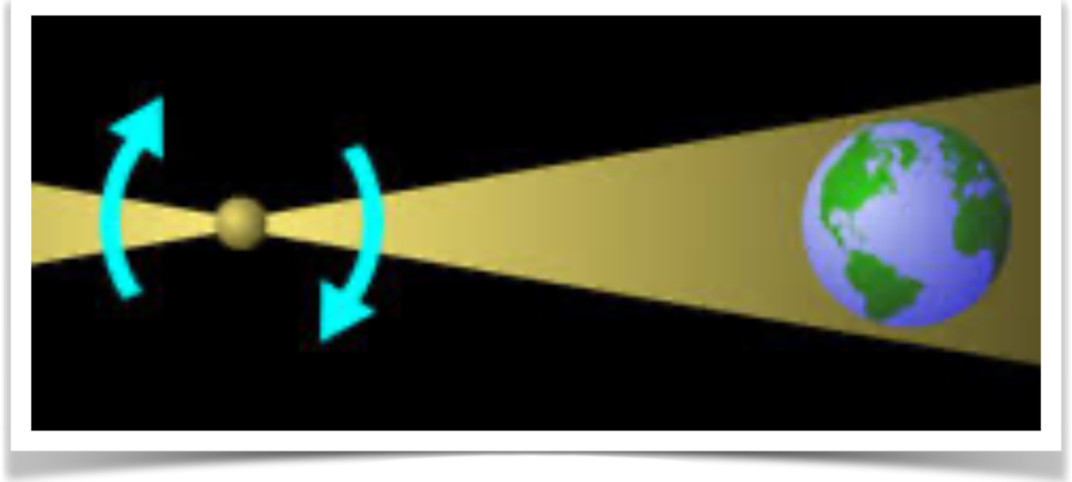

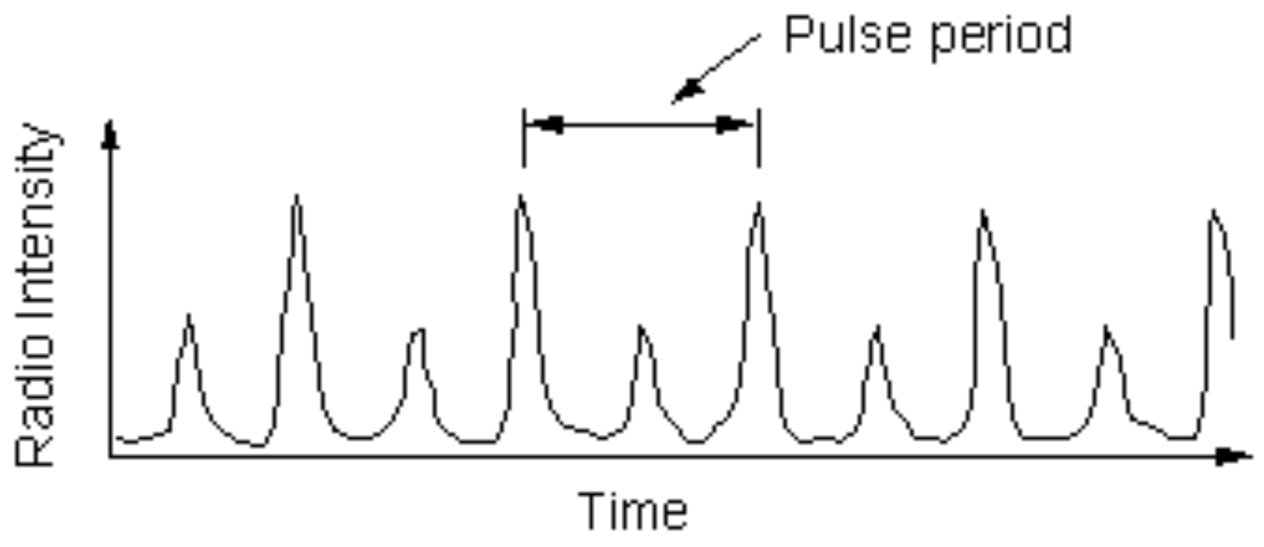

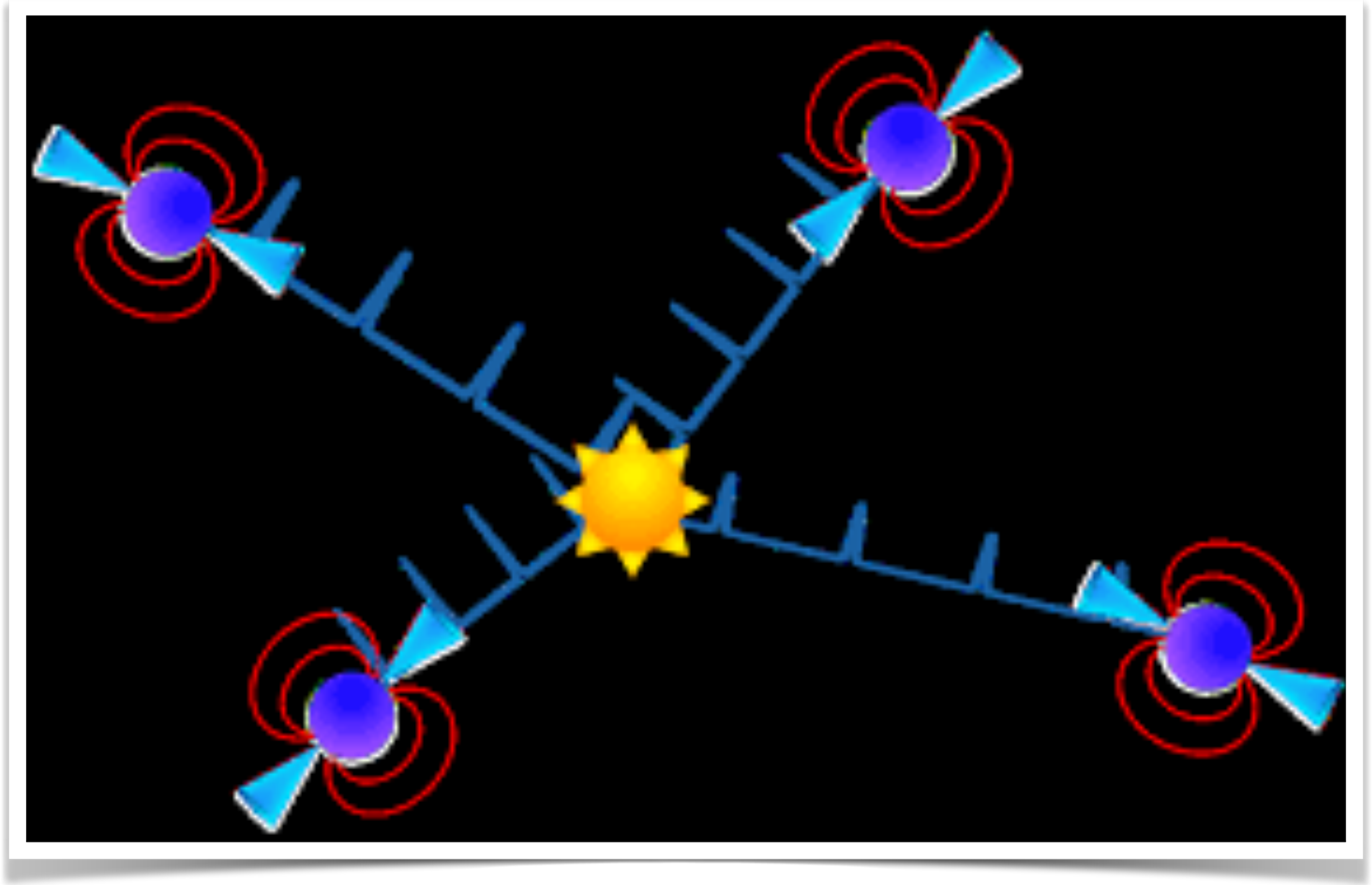

Earth-pulsar system as gravitational wave antenna.

Estabrook, Wahlquist ’75;
Sazhin ’77; Detweiler ’79
Hellings, Downs ’82

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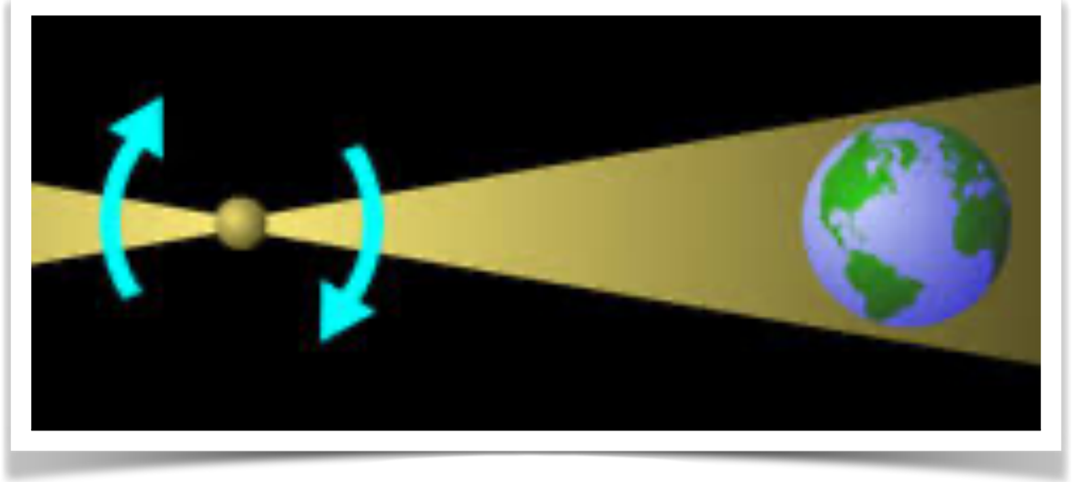

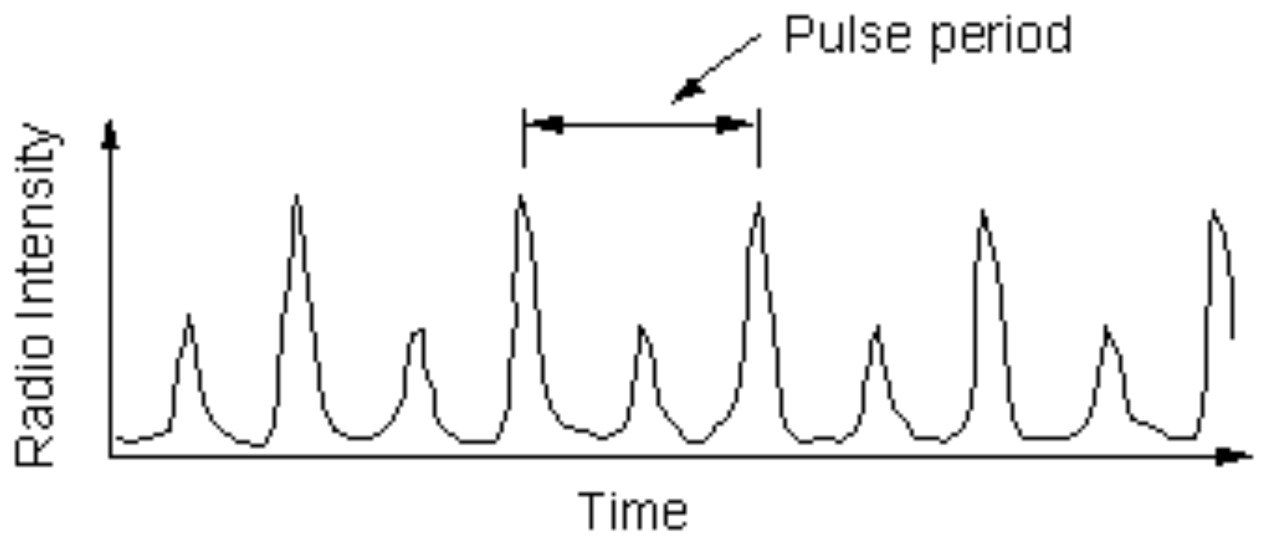

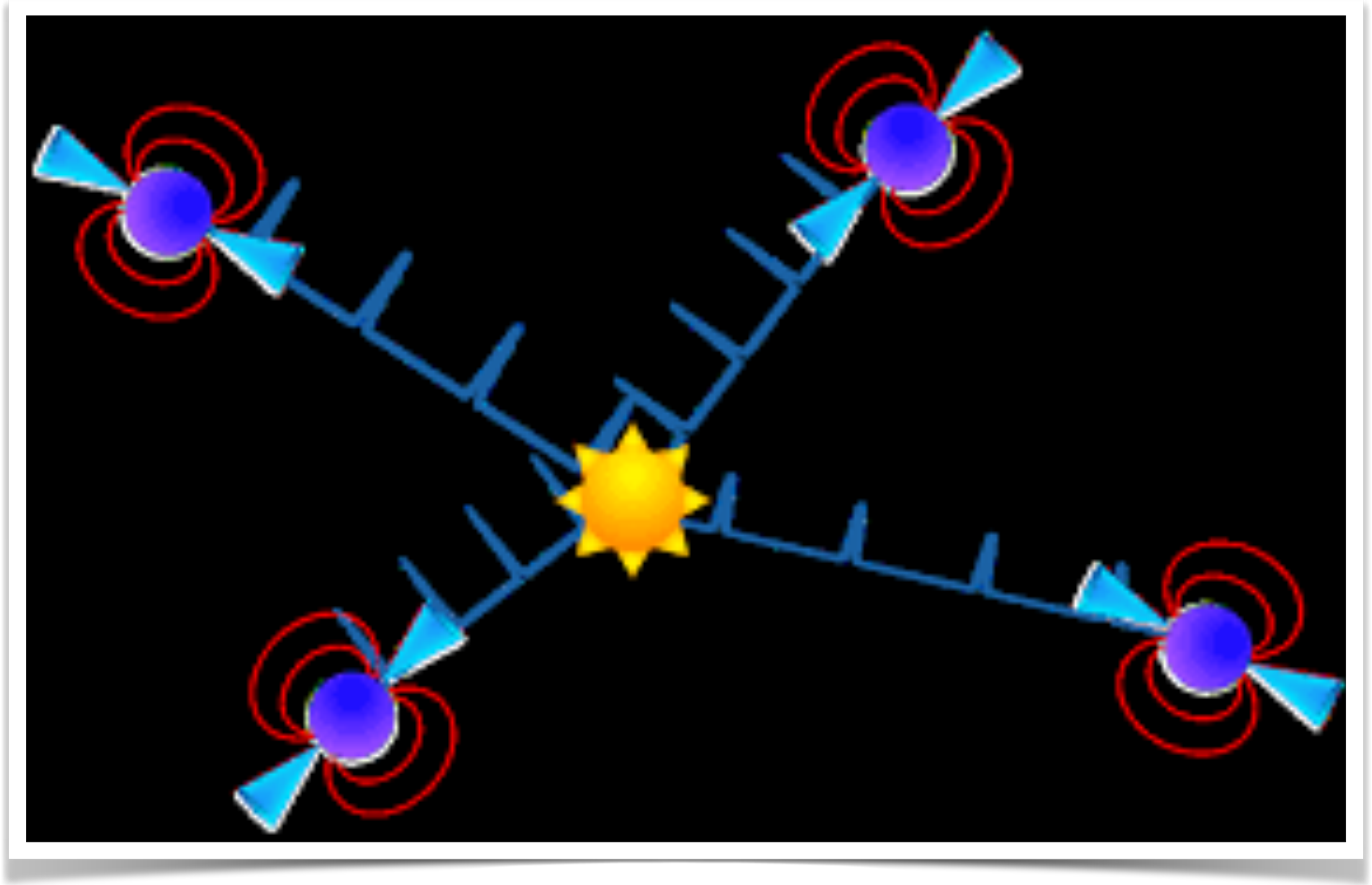

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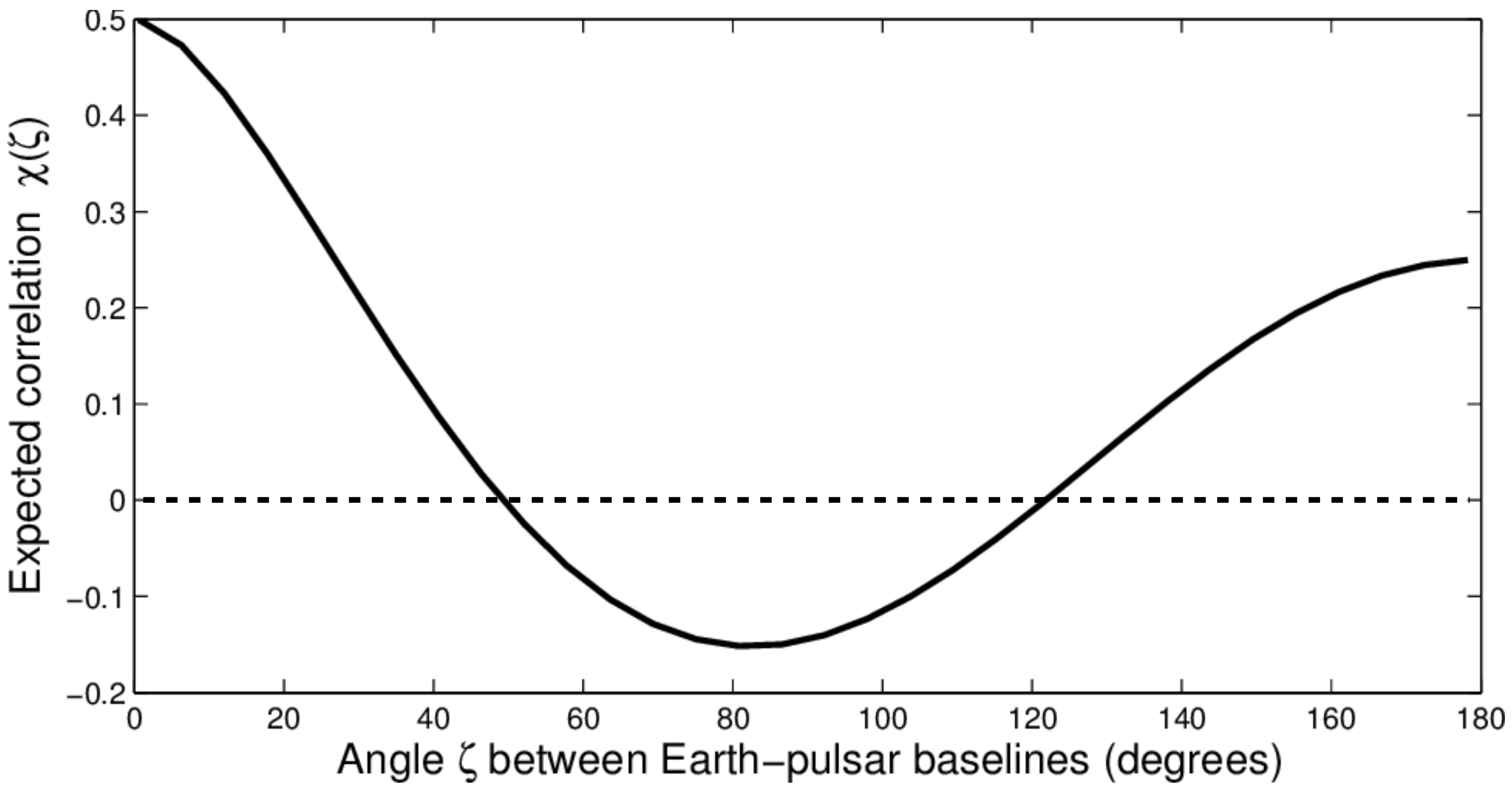

GW: distinctive quadrupolar inter-pulsar correlation.

PTA discovery of nano-Hz gravitational waves

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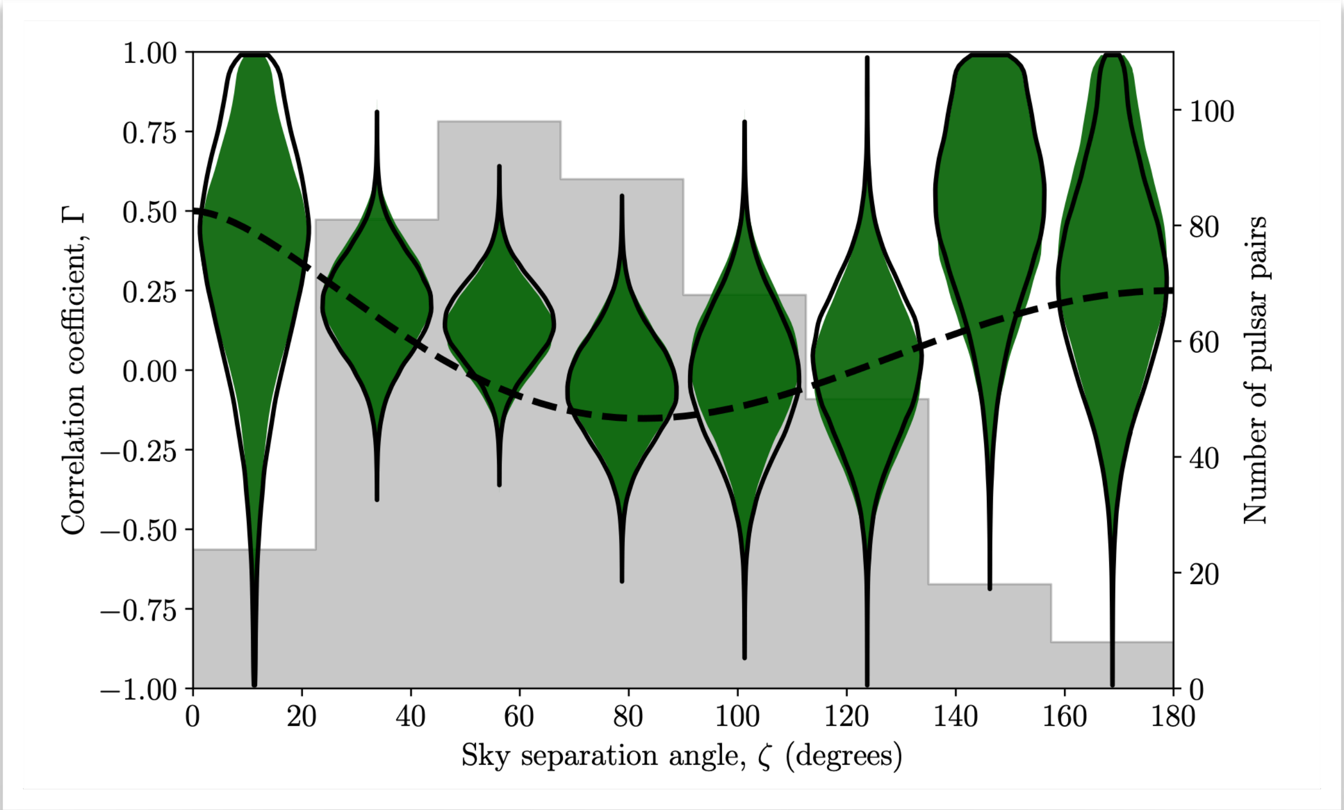
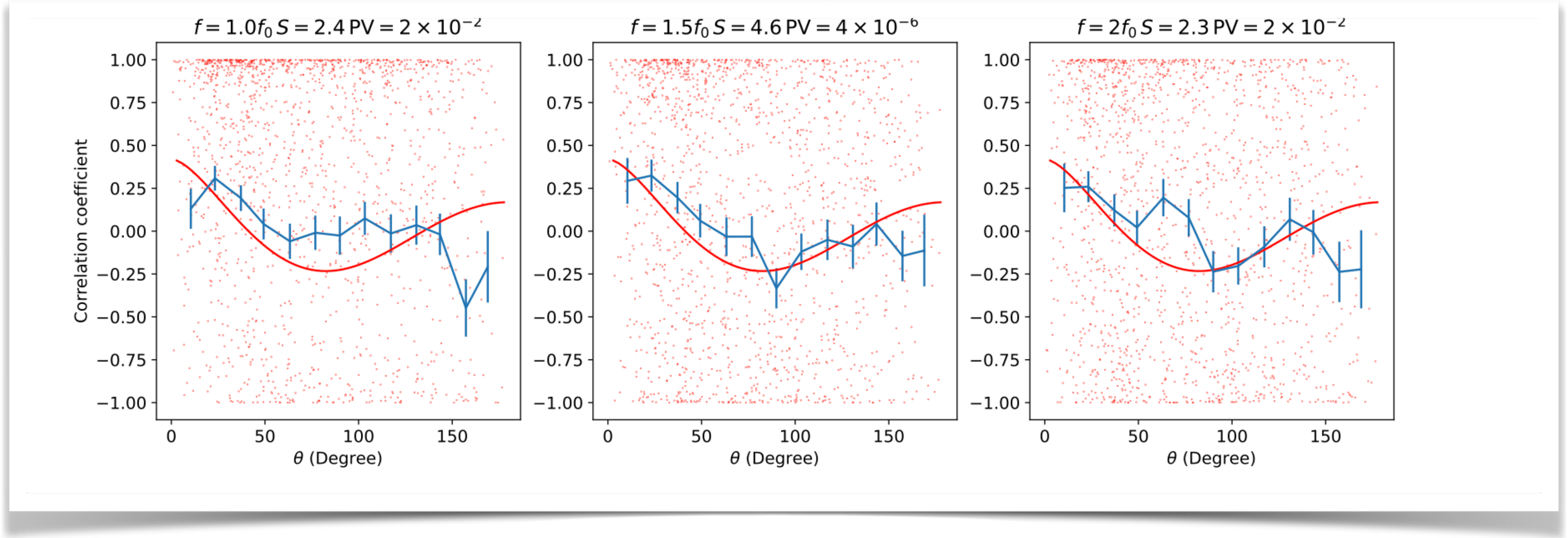
PTA collaborations have reported evidence for nano-Hz stochastic gravitational waves.

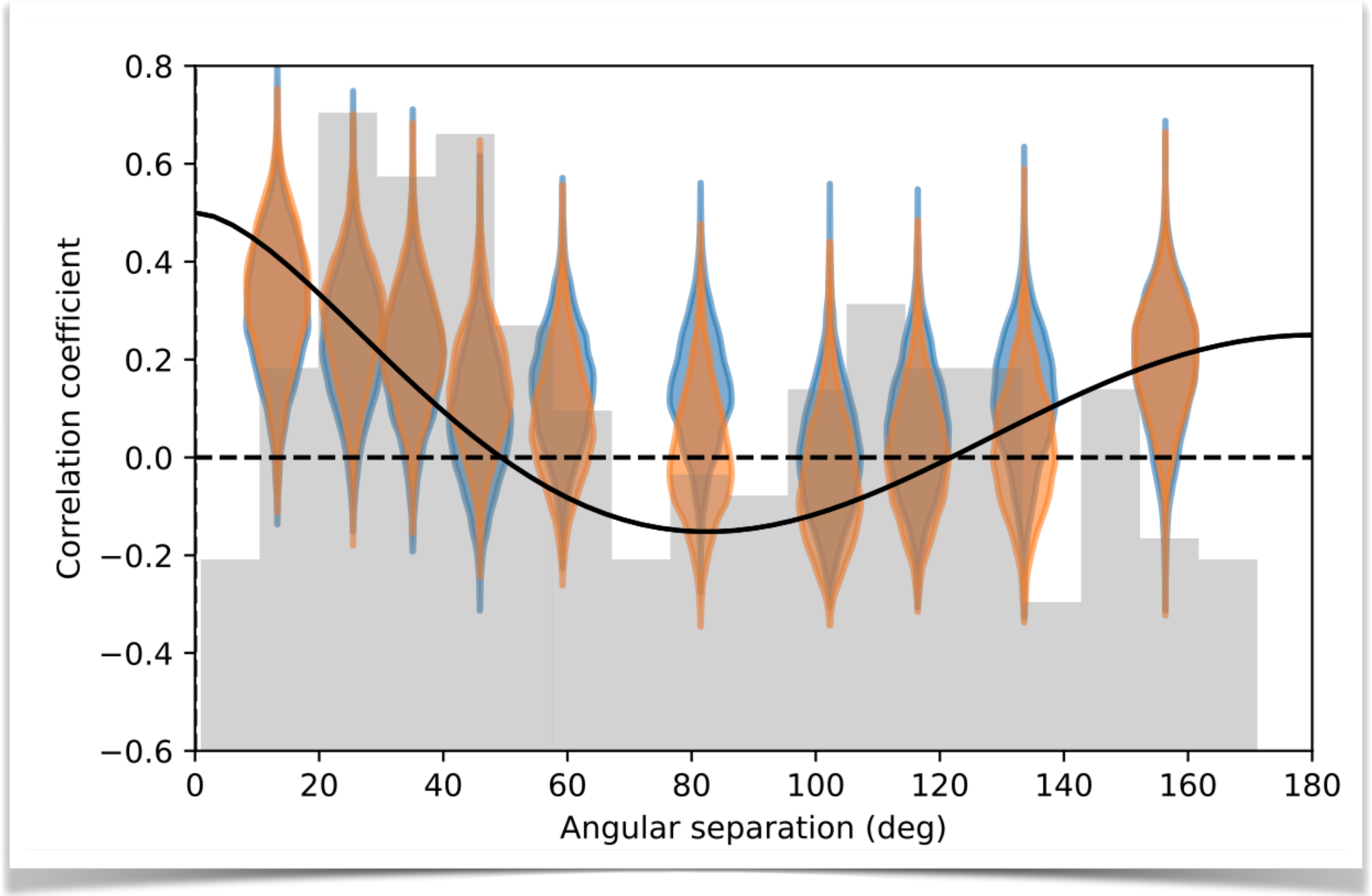
PPTA



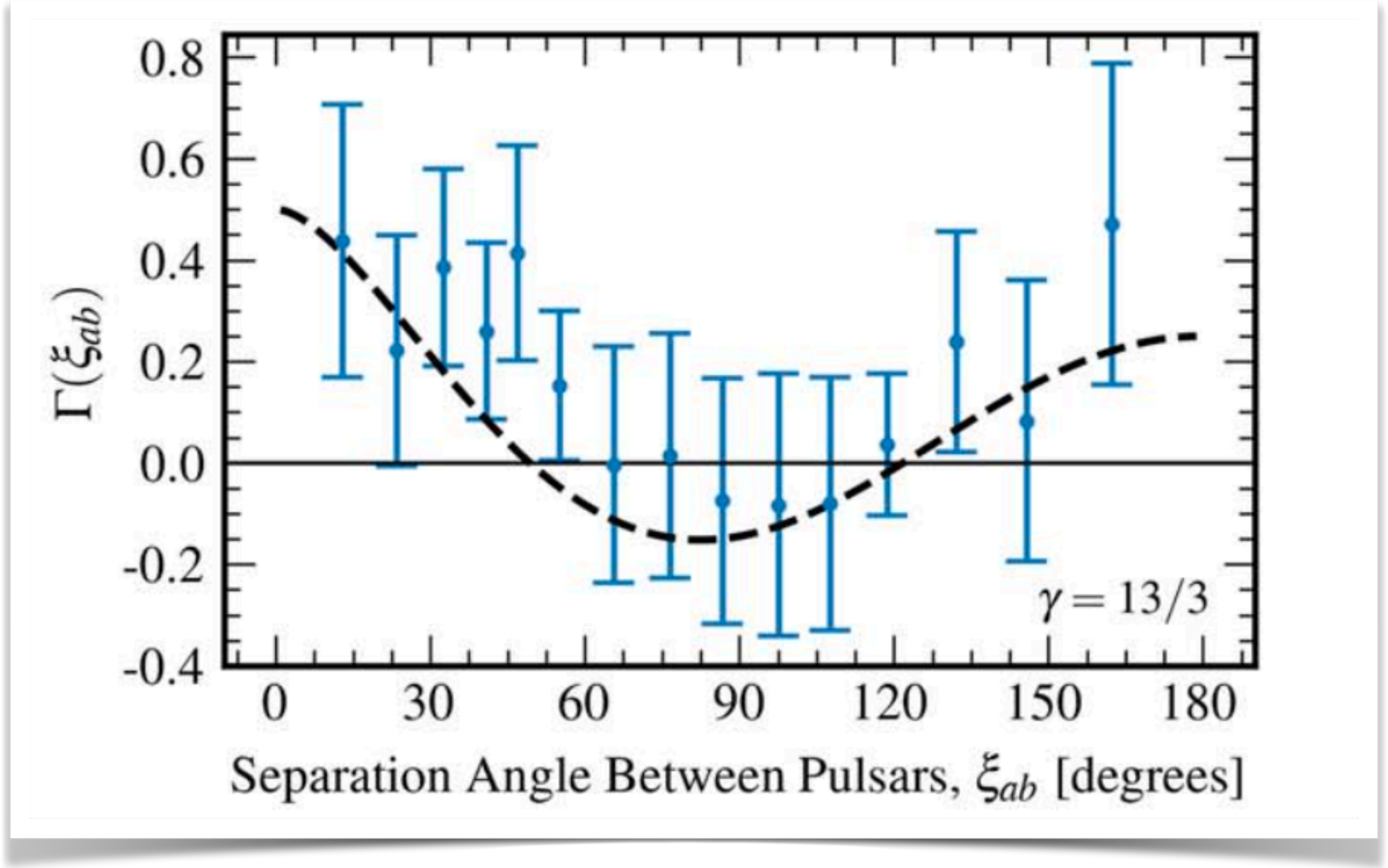
CPTA



EPTA+InPTA



NANOGrav



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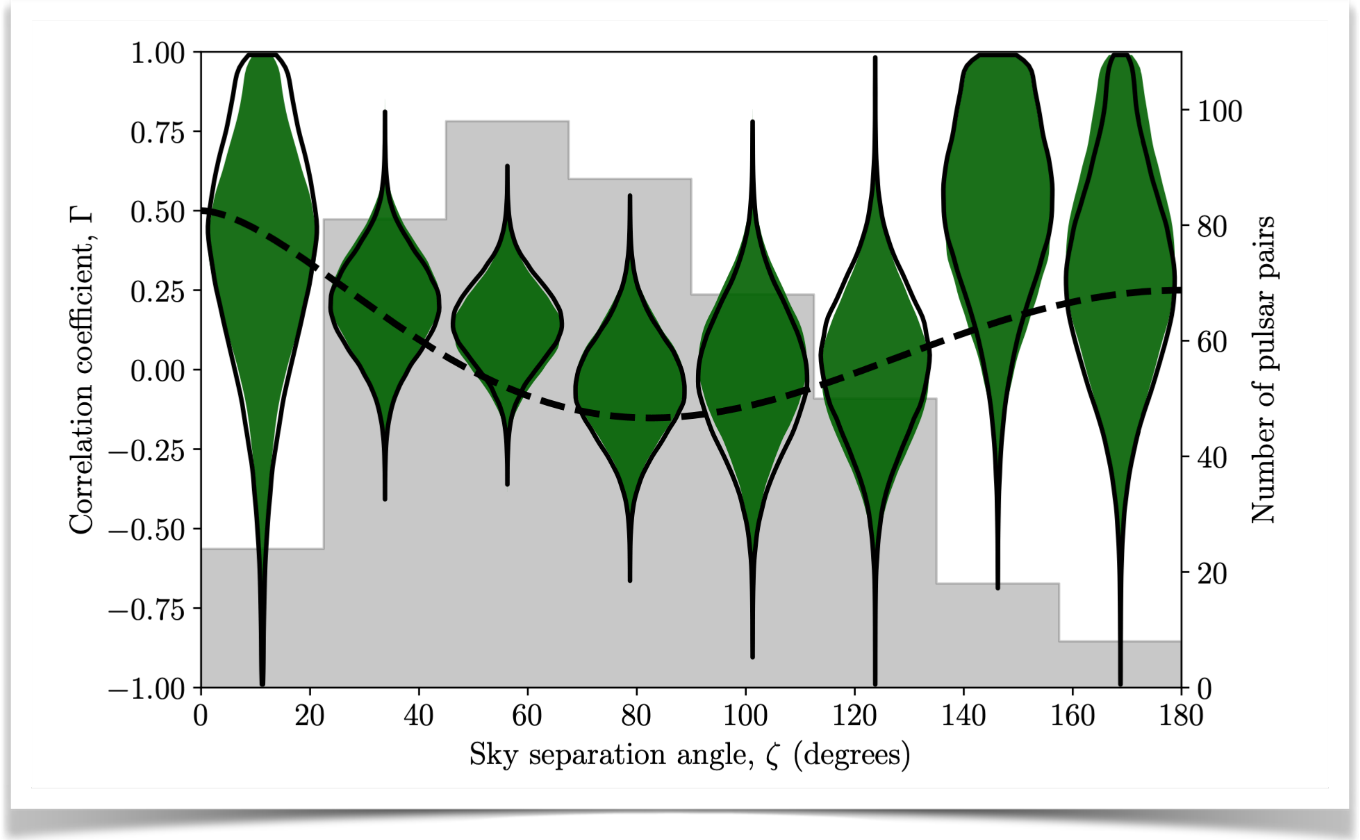

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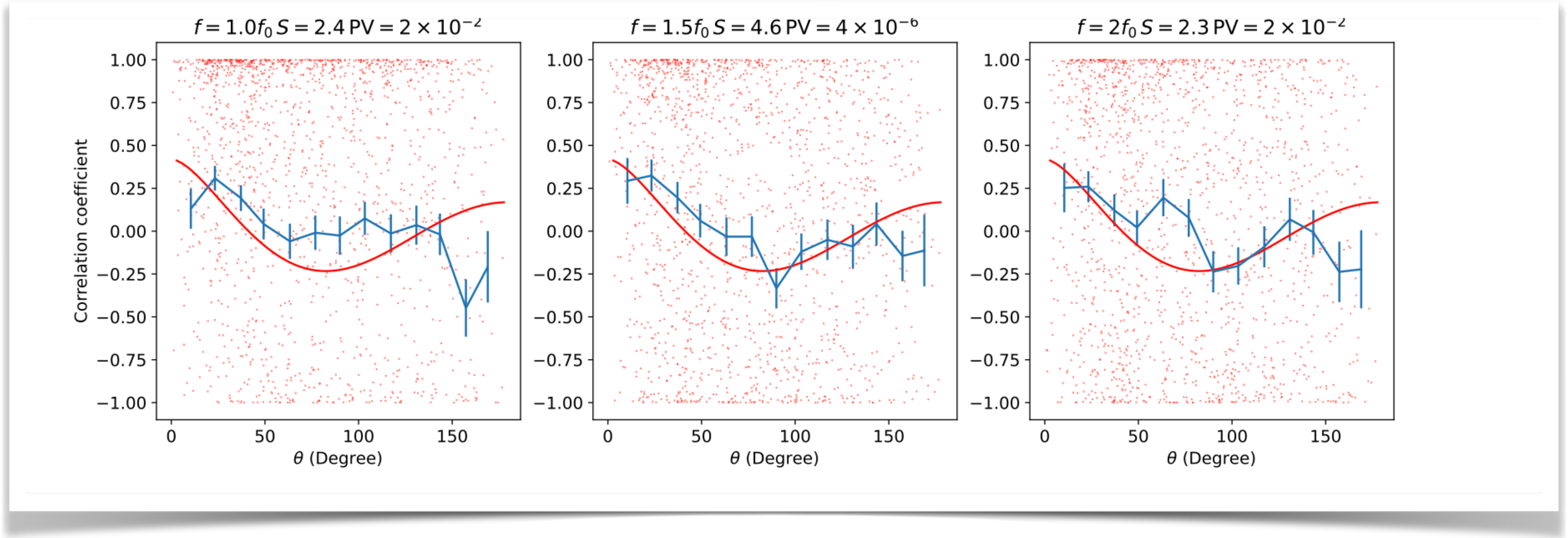

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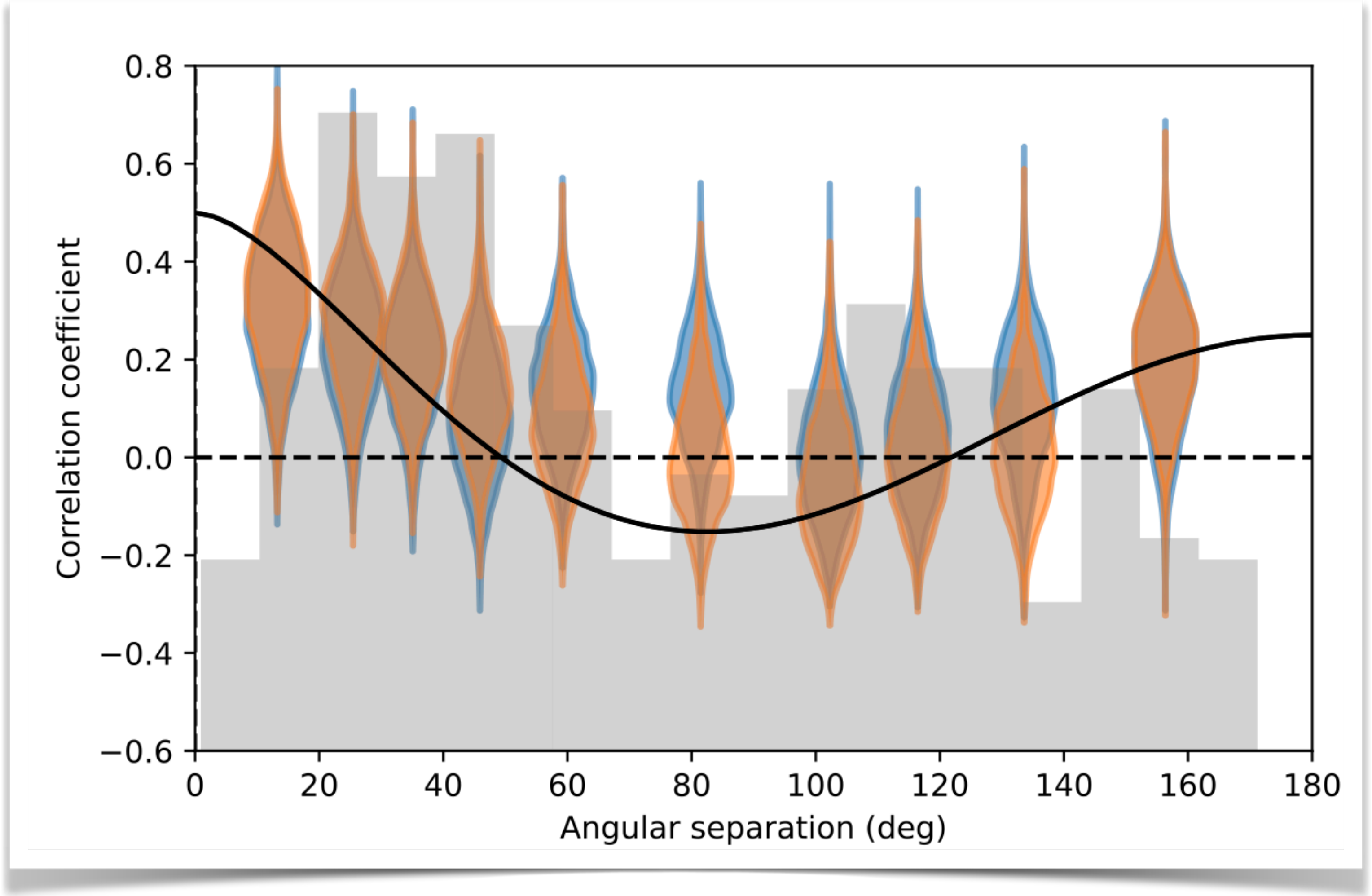

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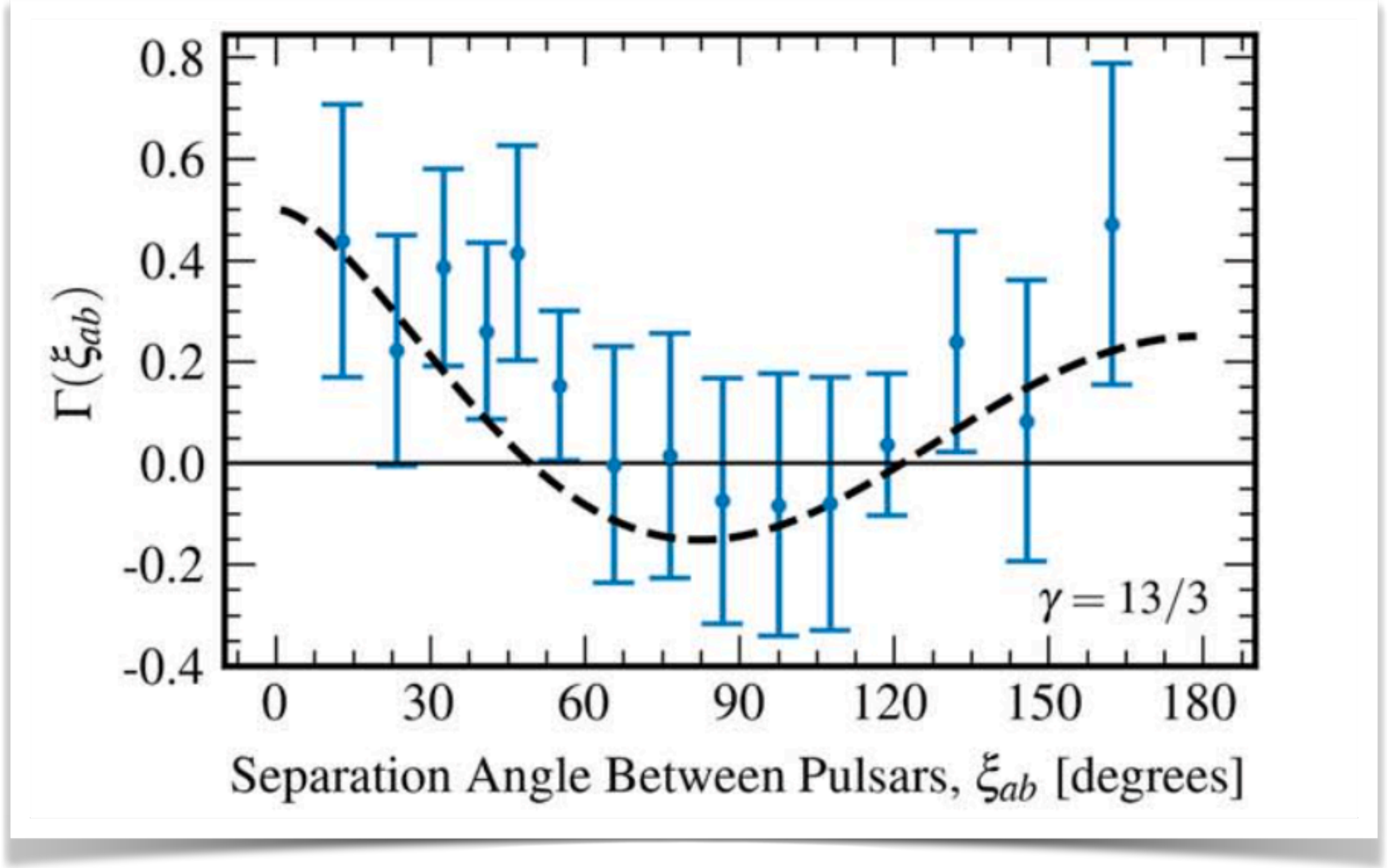
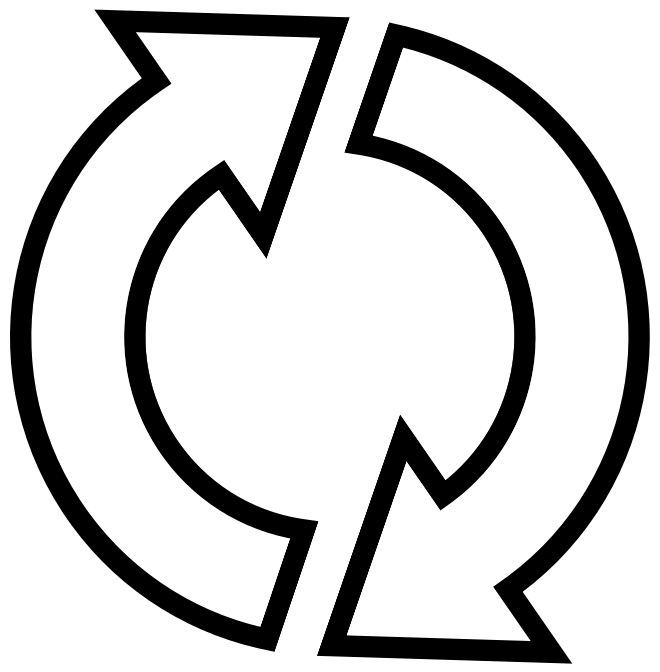


- ✻ Supermassive black hole binaries
- ✻ Defects: Cosmic strings, domain walls…
- ✻ **Cosmological phase transitions**

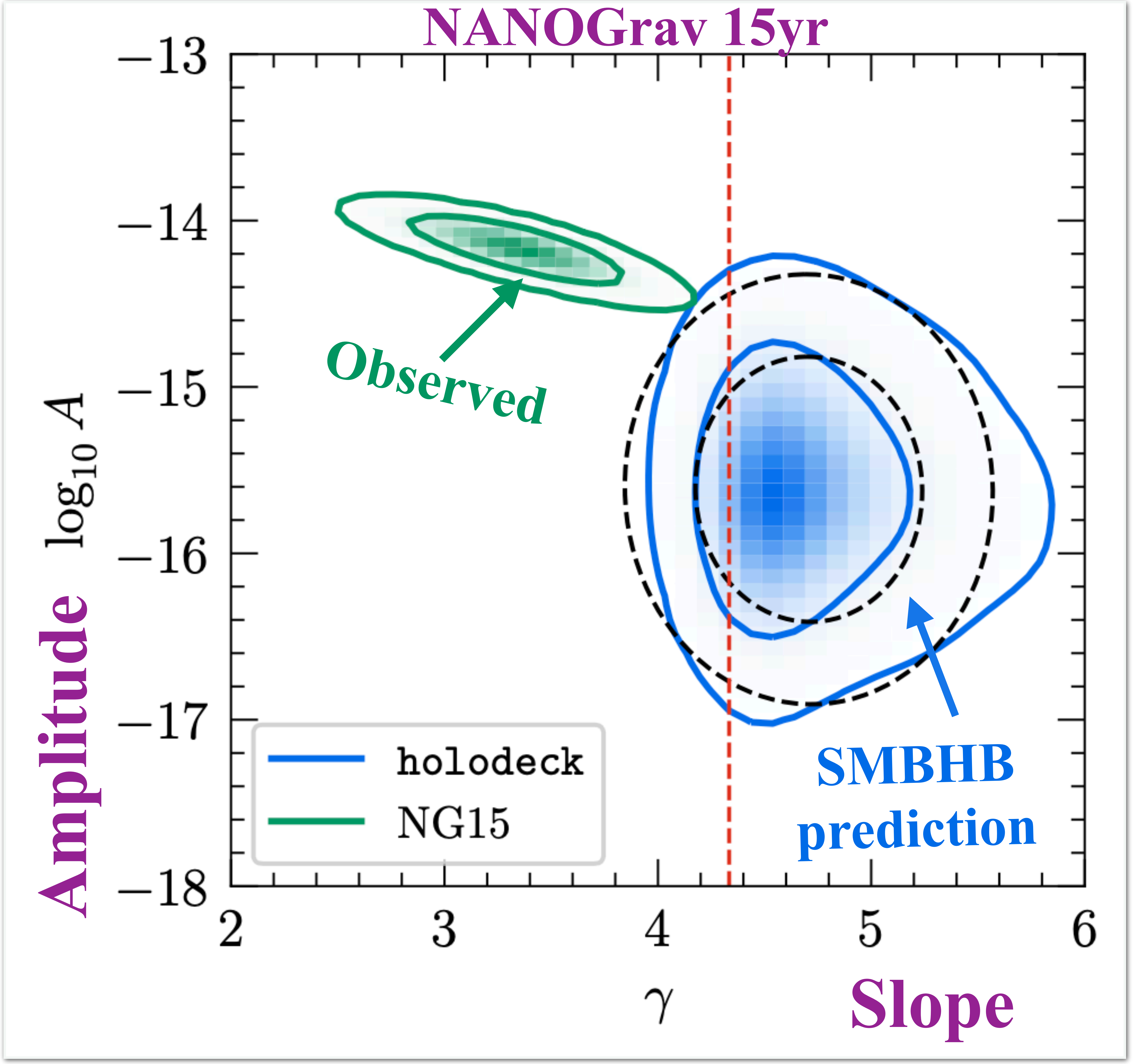
Phase transition interpretation of the PTA

PTA signal from phase transition: Motivation

- **Hint from experiment:** phase transition can better fit the observed spectral shape of GW. **Ellis et. al. (2023)**



- **Theory challenge:** find concrete field theoretic models, predict spectral shape, **is it consistent?**



Cosmological first-order phase transition

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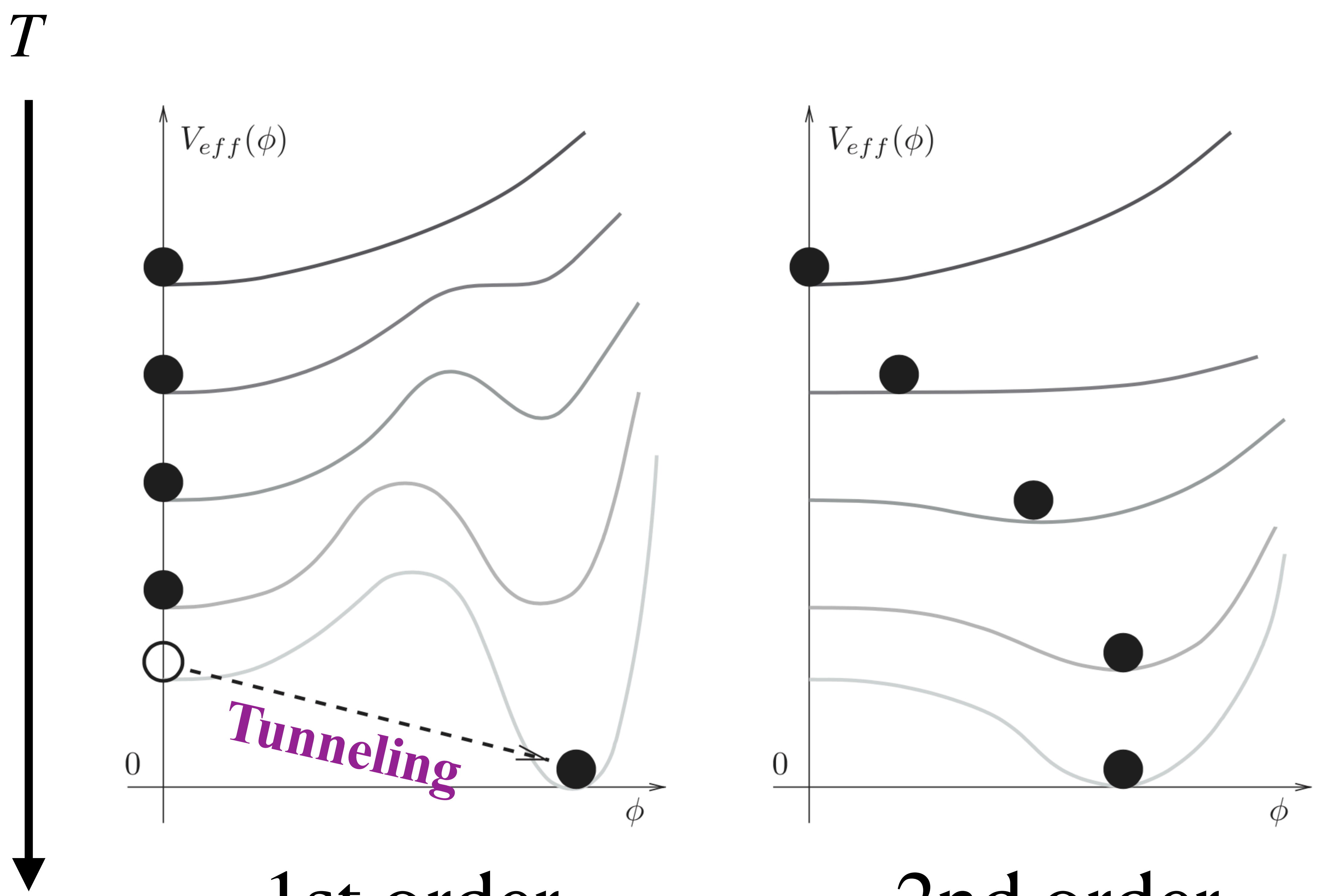
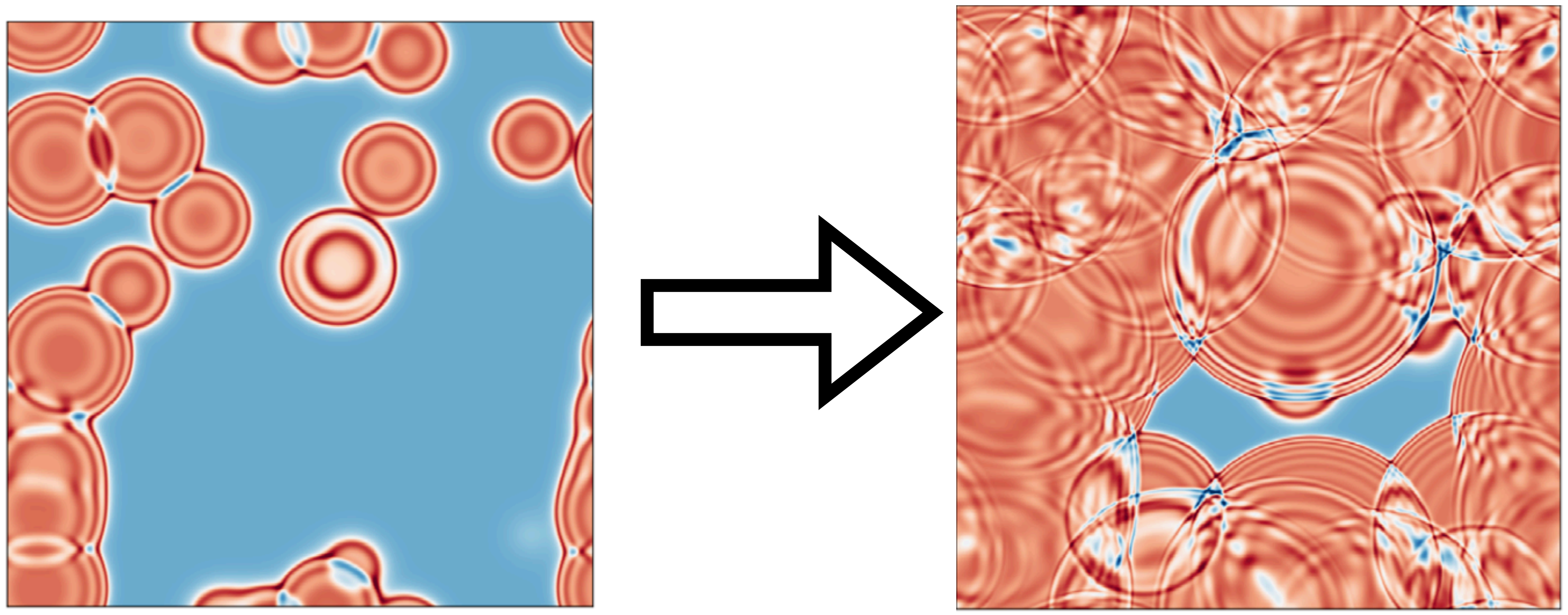


1st order

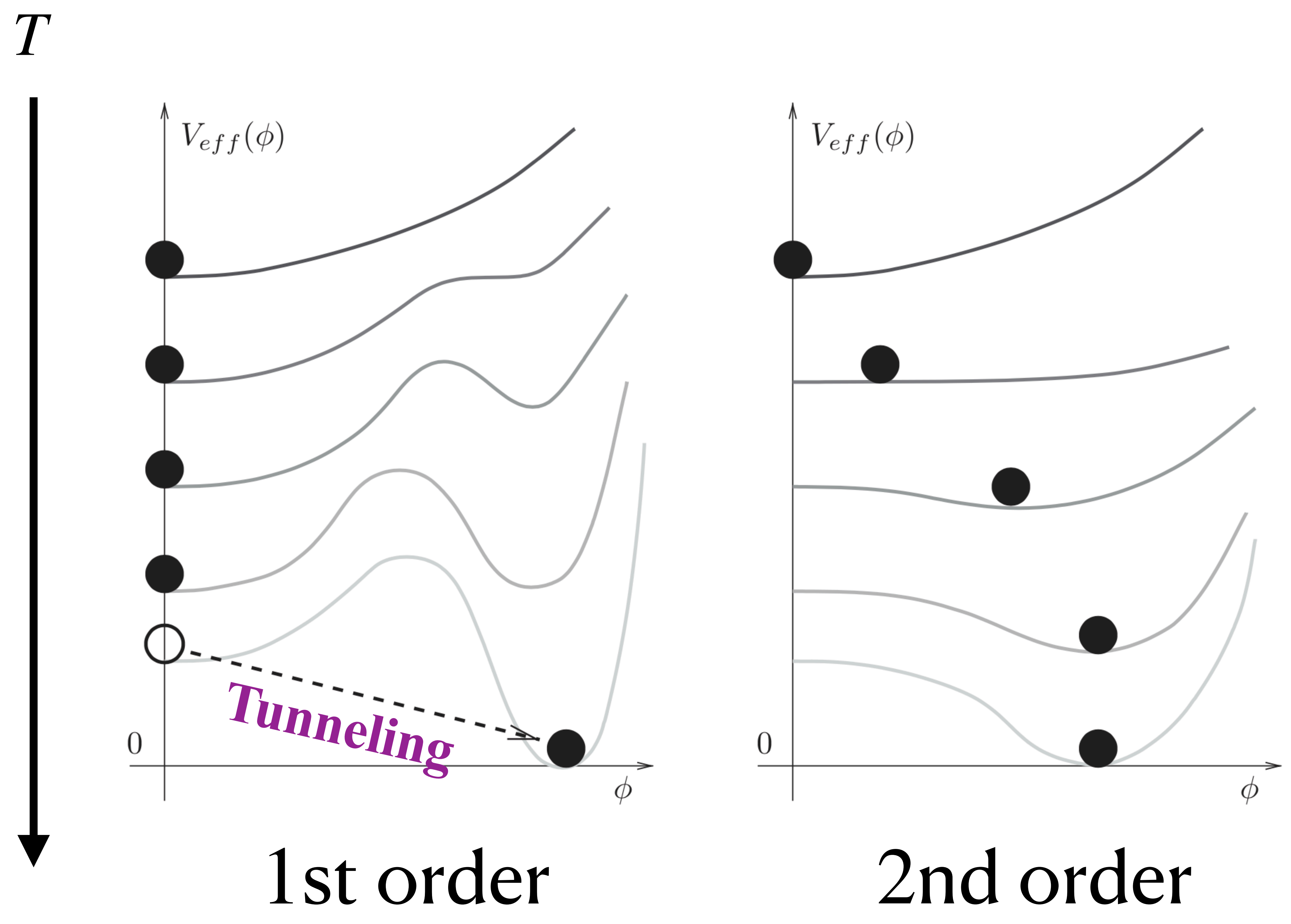
2nd order

Generation of gravitational waves



Bubble collisions

Cosmological first-order phase transition



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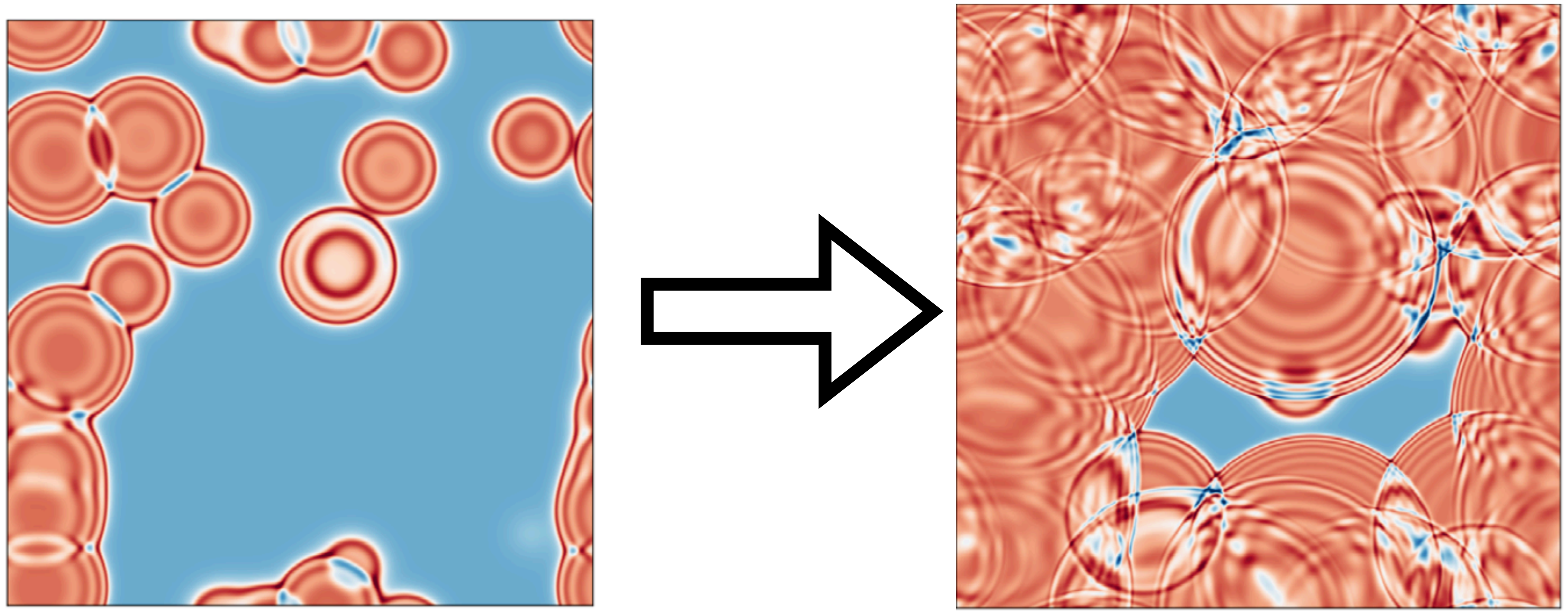

Bubble collisions

- Observed nano-Hz peak frequency implies phase transition at $\sim \mathcal{O}(\text{GeV})$ temperature.

$$f_0 \simeq 10^{-8}\ \text{Hz} \left(\frac{T_c}{1\ \text{GeV}}\right)$$

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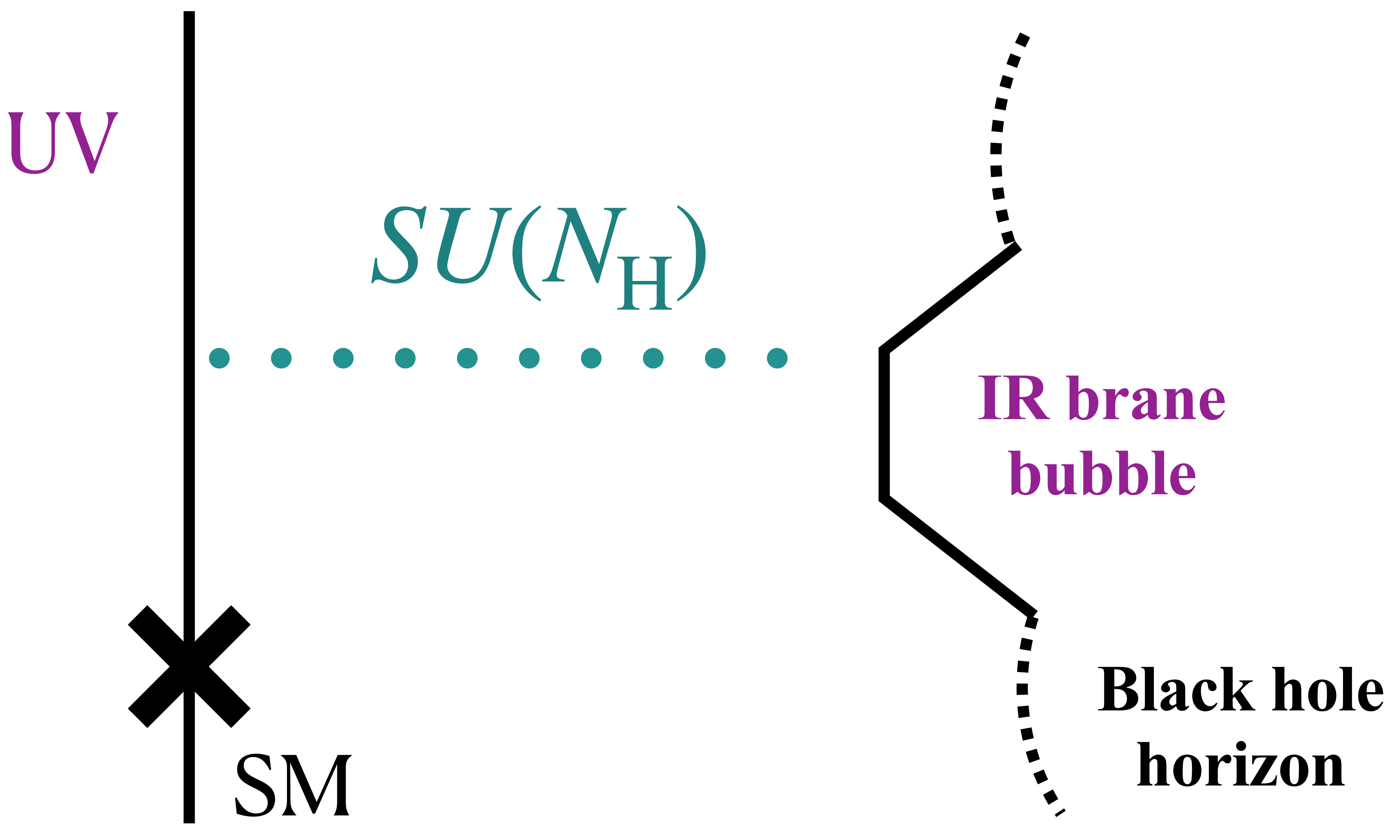
The model:
Dark sector phase transition

Nearly conformal phase transition in a dark sector

4D conformal dark sector with large N
+
dark pure $SU(N_H)$ Yang-Mills

Deconfining phase transition: strong dynamics

Holographic 5D ⟺



Weakly coupled dual Rattazzi + '02

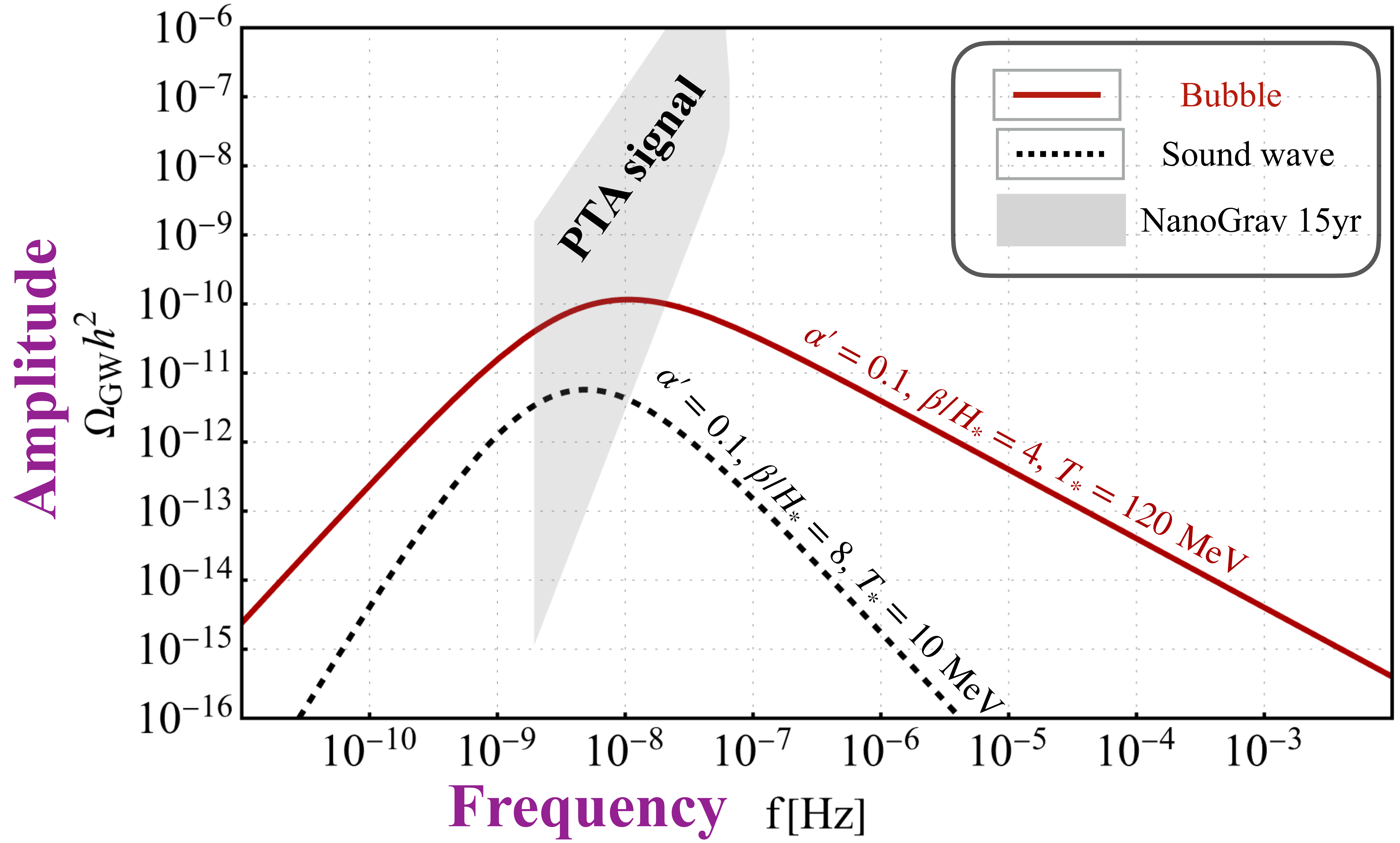
Phase transition dynamics is obtained by the dilaton effective potential

Gravitational waves from dilaton effective potential

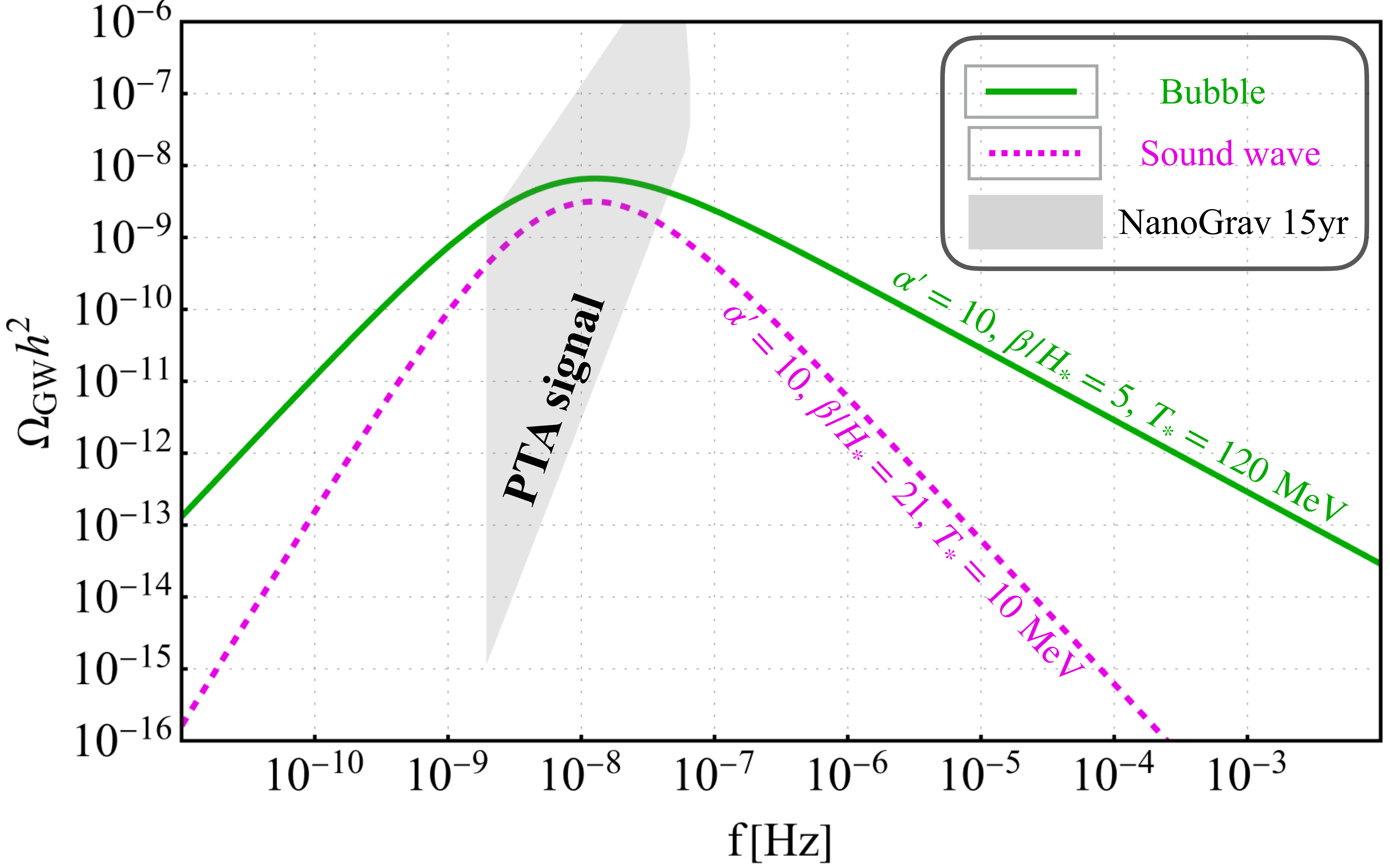
$$\frac{1}{g_H^2(Q,\varphi)} = -\frac{b_{CFT}}{8\pi^2}\ln\left(\frac{k}{\varphi}\right) - \frac{b_H}{8\pi^2}\ln\left(\frac{k}{Q}\right)$$

$$V_{\rm eff}(\varphi) = \begin{cases} V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_H}{\eta}\Lambda^4_{\rm dQCD}\left(\frac{\varphi}{\varphi_{\rm min}}\right)^{4n}, & \text{for } \varphi \geq \varphi_c \\ V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_H}{\eta}\gamma_c^4\varphi_c^4 \ , & \text{for } \varphi < \varphi_c \end{cases}$$

$\Delta N_{\rm eff}$ constraints secluded dark sector



Decaying dark sector : Portal operator needed

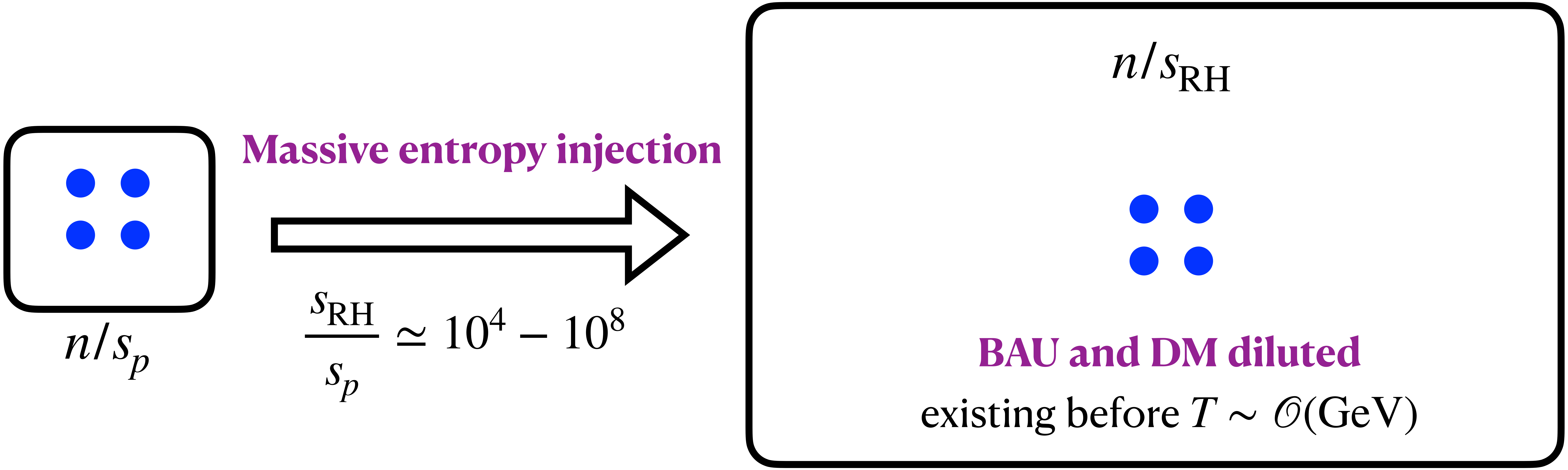


Entropy dilution problem: connection to dark matter and baryon asymmetry

The dilution problem

See eg. Schwaller + (2023)

Large supercooling is required to explain the PTA signal

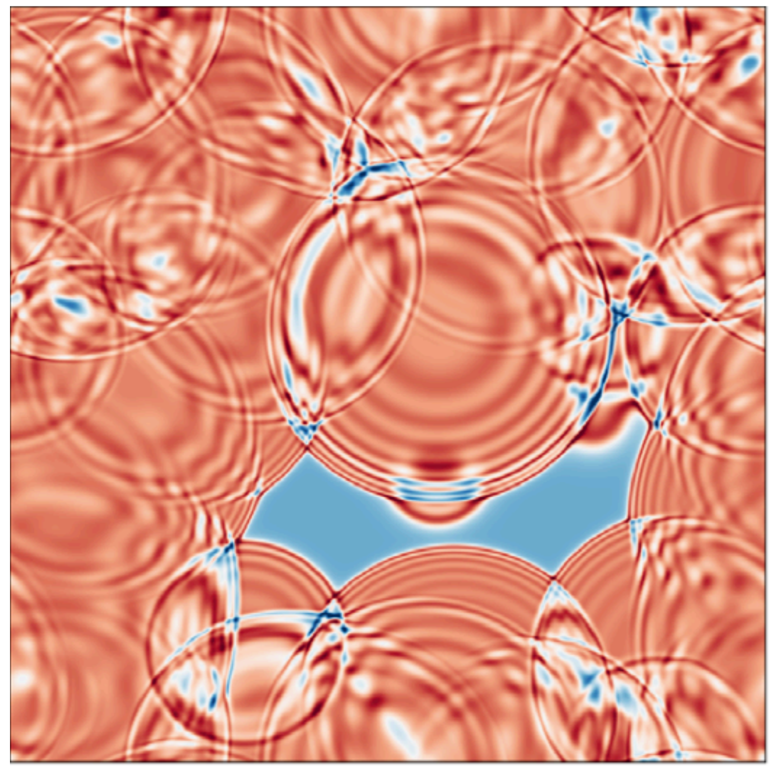


Either need a very large asymmetry before PT, **or need to create them after PT**.

Turning the problem into solution

Supercooled phase transition naturally provides **out of equilibrium condition.**

Shaposnikov et. al. (1999) ; Konstandin, Servant (2011)



Phase transition

Asymmetry creation →

Dark sector

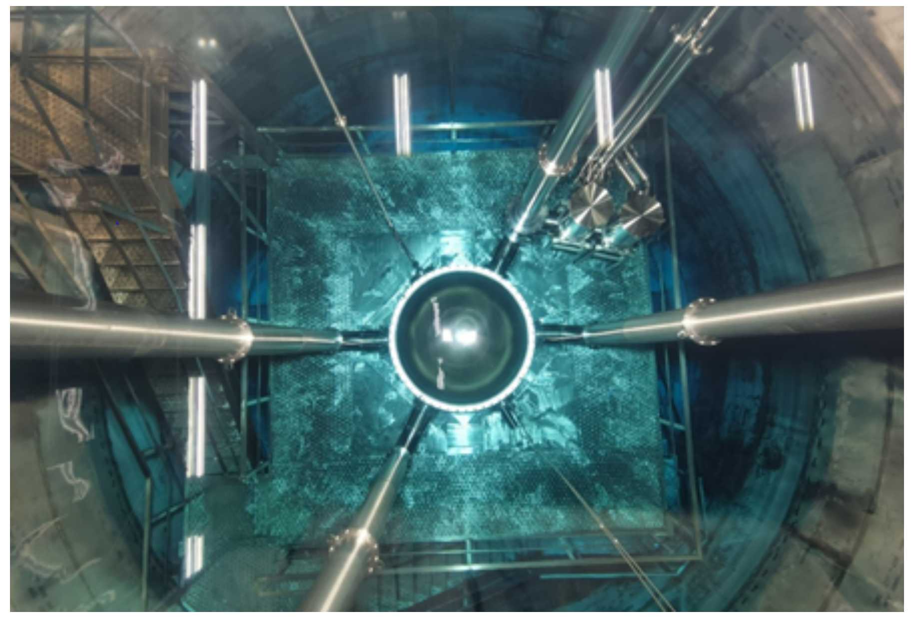
Asymmetric dark matter

Sphaleron ✕

Portal

BAU

Visible sector



Experimental signatures

1. Cold Darkogenesis

2. Post-sphaleron Darkogenesis

Why the GeV scale?

$\Lambda_{\text{dQCD}} \sim$ GeV and the three coincidences

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1. Dark QCD generates the mass gap in the CFT sector, and $\Lambda_{\rm dQCD} \simeq \mathcal{O}(\text{GeV})$ explains **PTA**.

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2. $\Lambda_{\rm dQCD} \simeq \mathcal{O}(\rm GeV)$ can explain the **DM-baryon coincidence** problem for dark baryon DM.

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm b}} = \frac{m_{\rm DM}(n_{\rm DM} - n_{\overline{\rm DM}})}{m_p(n_{\rm b} - n_{\bar{\rm b}})} \simeq \frac{m_{\rm DM}}{m_p} \simeq \frac{\Lambda_{\rm dQCD}}{\Lambda_{\rm QCD}} \simeq 5.4$$

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3. $\Lambda_{\rm dQCD} \simeq \mathcal{O}(\rm GeV)$ can yield desired **self-interaction for DM** via π_D mediation.

$$\frac{\sigma_{\rm DM-DM}}{m_{\rm DM}} \sim 1\ {\rm cm}^2/{\rm g} \left(\frac{\Lambda_{\rm dQCD}}{m_{\rm DM}}\right)\left(\frac{\Lambda_{\rm dQCD}}{a_{\rm D}^{-1}}\right)^2\left(\frac{0.2\ {\rm GeV}}{\Lambda_{\rm dQCD}}\right)^3 ;$$

$a_{\rm D}$ **: scattering length .**

Tulin Yu (2017) ; Kribs (2016)

Main idea: neutron portal and the GeV scale

Neutron portal with $2\ \text{TeV} \lesssim \Lambda_n \lesssim 100\ \text{TeV}$ is key to share asymmetry between χ and SM.

$$\mathcal{O}_{n\chi} = \frac{1}{\Lambda_n^2}\left(\overline{\chi^c} d_R^c\right)\left(\overline{u_R} d_R^c\right)$$

TeV scale particles are needed for the UV completion

Connection to μ-problem in SUSY

Dark QCD has IR fixed point

Dynamical generation of $\Lambda_{\text{dQCD}} \simeq \text{GeV}$

Integrated out at $\mu \sim \text{TeV}$

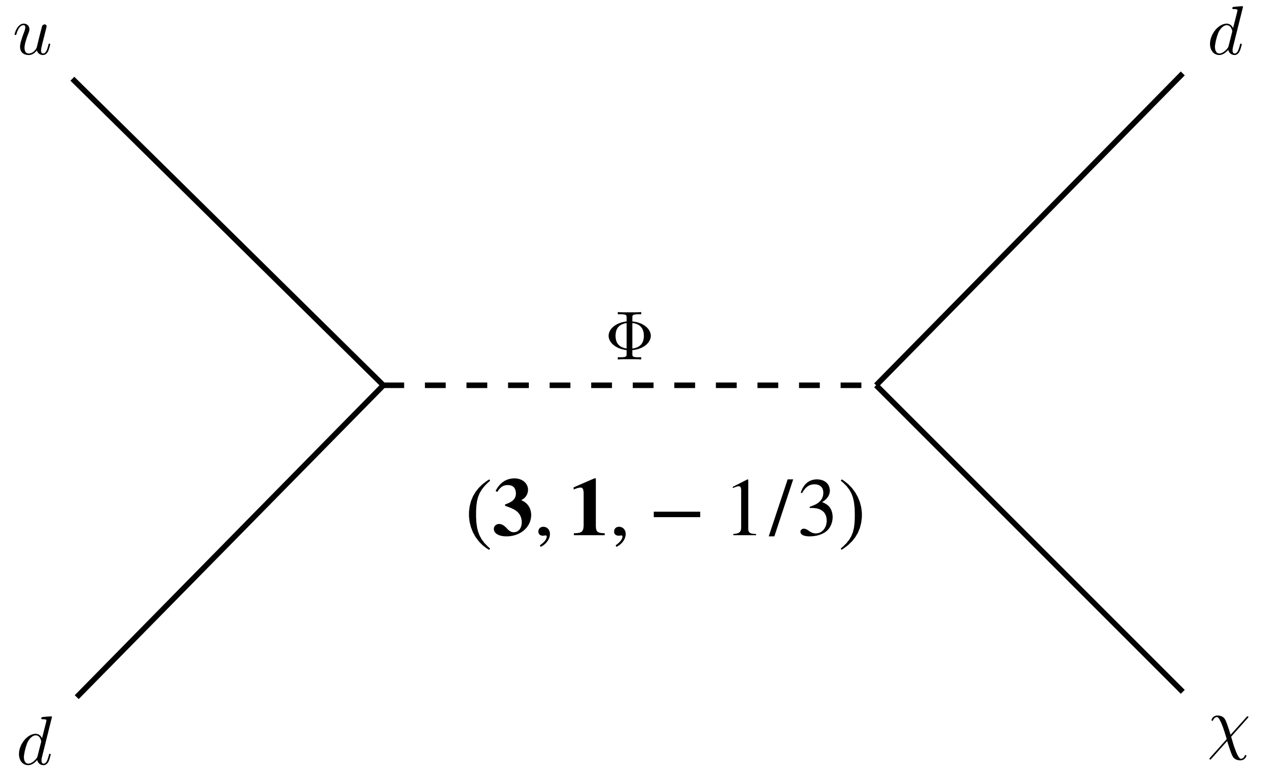
dQCD flows away from fixed point

UV completion paths

Tree level :

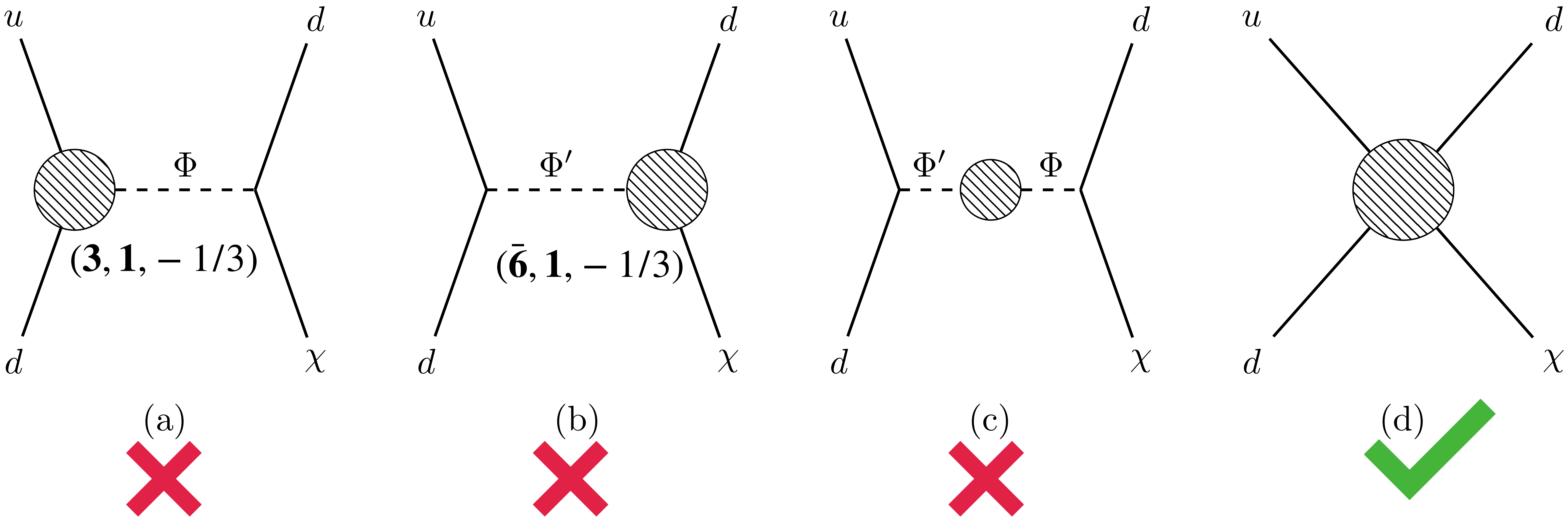
Φ **can not** have a dark QCD charge

Connection to the GeV scale is not straightforward

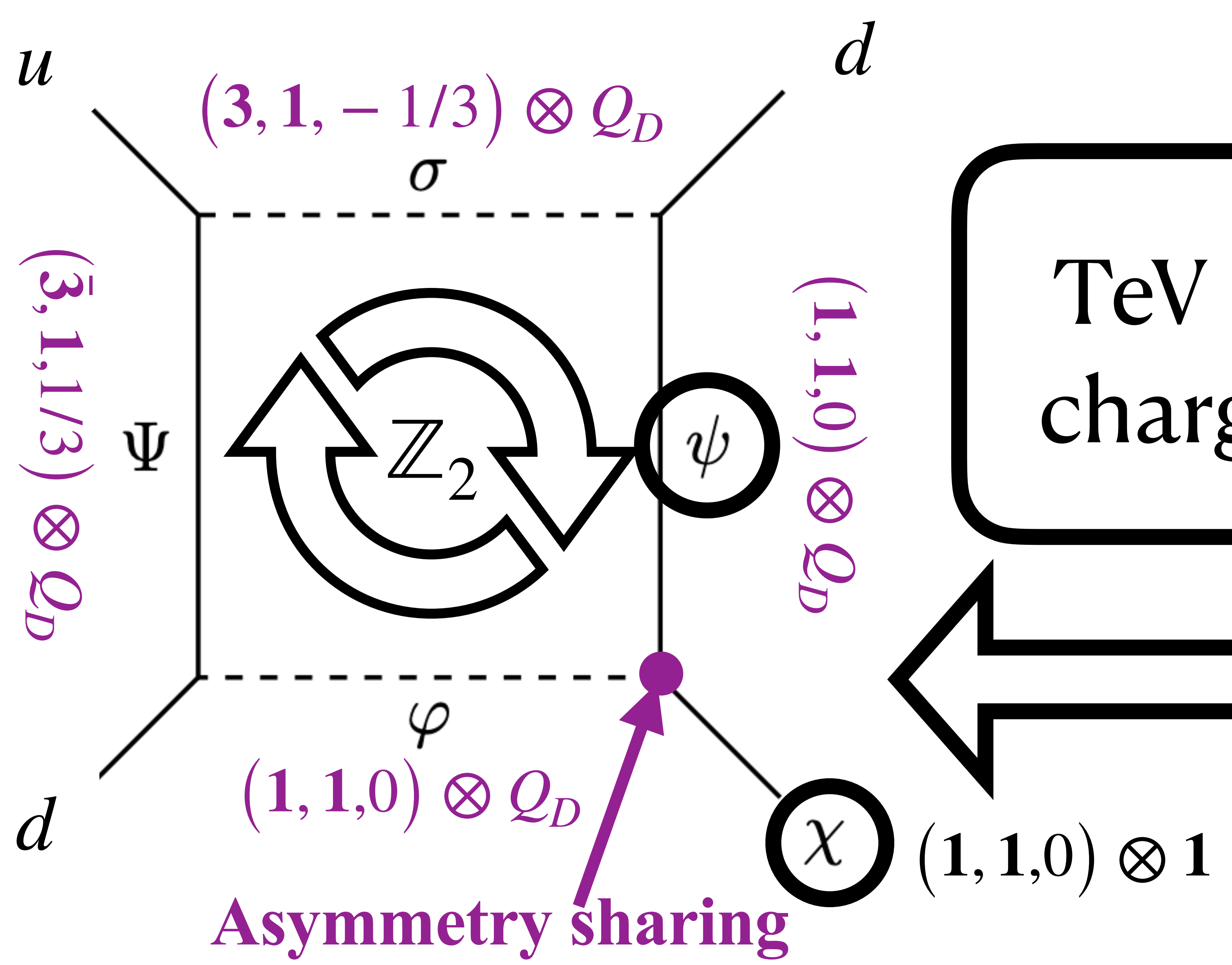


Loop level :

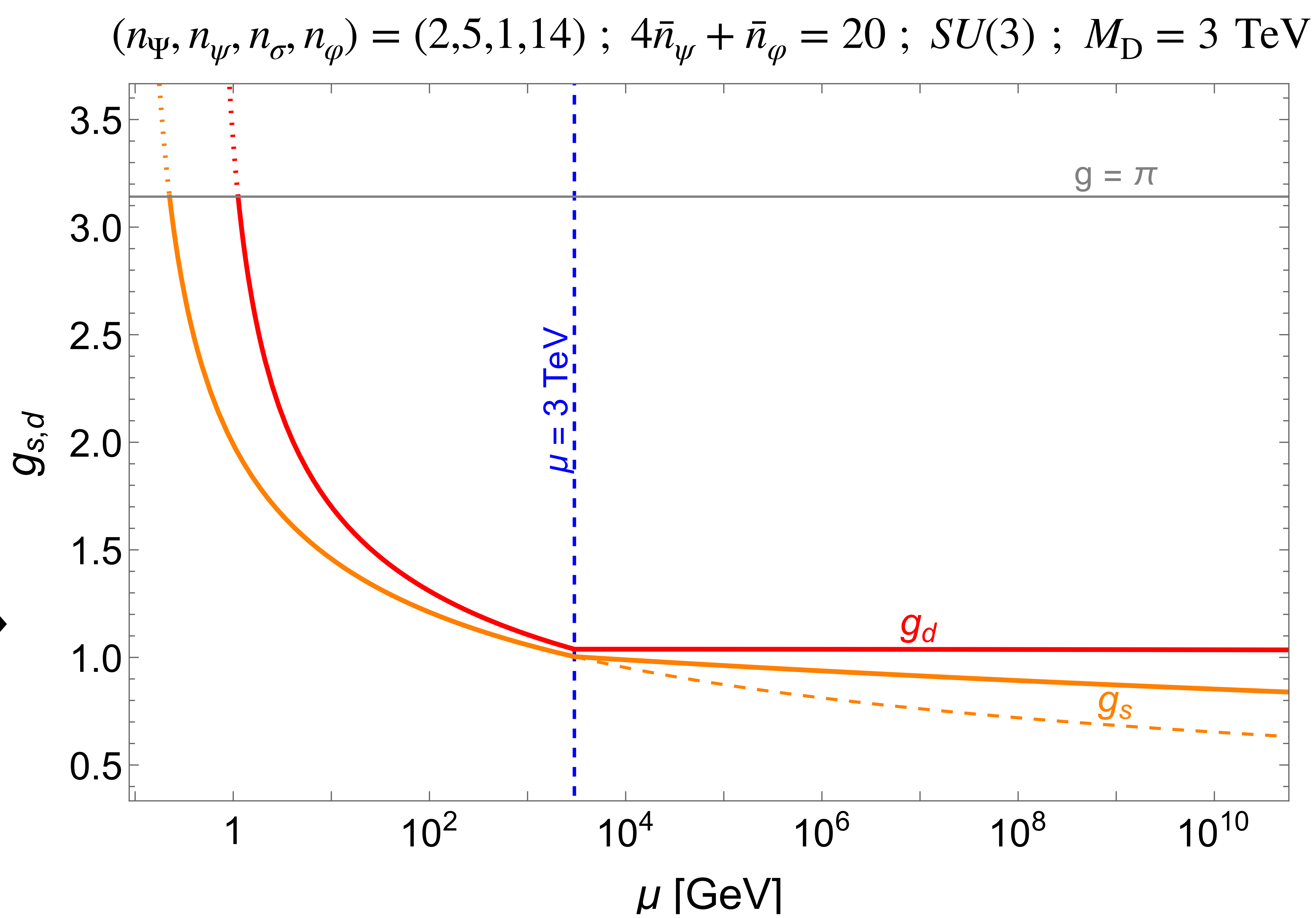
While not allowing tree-level



UV completion of neutron portal and Fixed point



TeV scale dQCD charged particles



From loop diagram calculation

Benchmark case: $\Lambda_{\rm dQCD} \simeq 1$ GeV, $\Lambda_n \simeq 3-8$ TeV .

Fixed point behavior

Bai, Schwaller (2014), Ritter, Volkas (2024)…

Portal operators from UV

Symmetric component of DM energy density ends up in dark pions. π_D must decay before BBN.

$$\langle \sigma v \rangle_{p_D \bar{p}_D \to \pi_D \pi_D} \simeq \frac{4\pi}{m_{\rm DM}^2} \gg 10^{-25}\ \mathrm{cm}^3/\mathrm{s}$$

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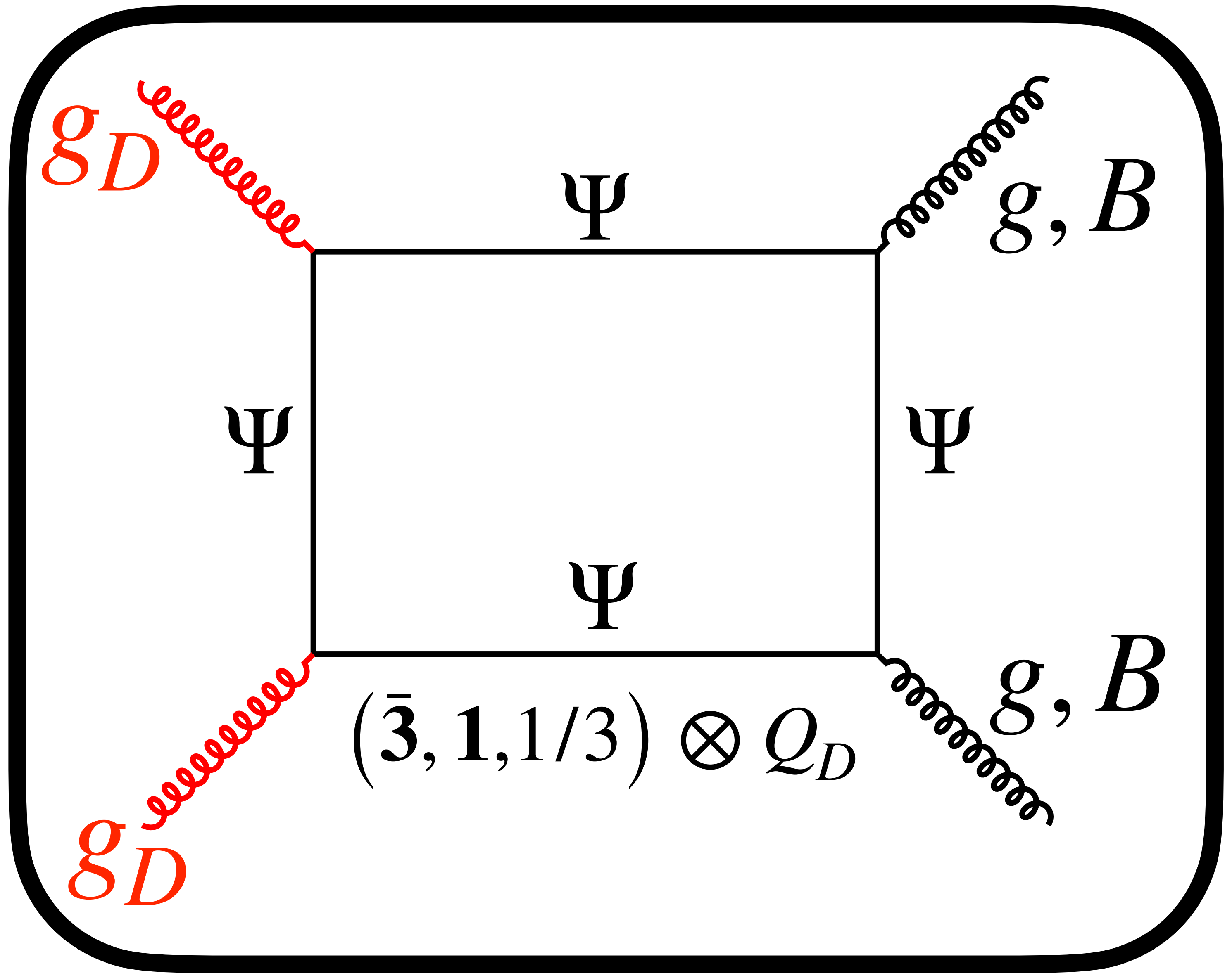

Ψ generates effective ALP portal for dark pions Juknevich (2010)

$$\mathscr{L}_{\rm ALP} \supset \frac{\alpha_s}{8\pi}\frac{\pi_D}{f_{\rm A}} G\tilde{G} + \frac{\alpha_Y}{36\pi}\frac{\pi_D}{f_A} B\tilde{B} \quad ; \quad f_{\rm A} \simeq \frac{45}{32\pi^2}\Lambda_{\rm dQCD}\left(\frac{m_\Psi}{\Lambda_{\rm dQCD}}\right)^4 \simeq 10^{11}\ {\rm GeV}$$

GeV scale meson lifetime $\simeq \mathcal{O}(1{\rm s})$, likely ruled out by BBN.

Jung+ (2026)

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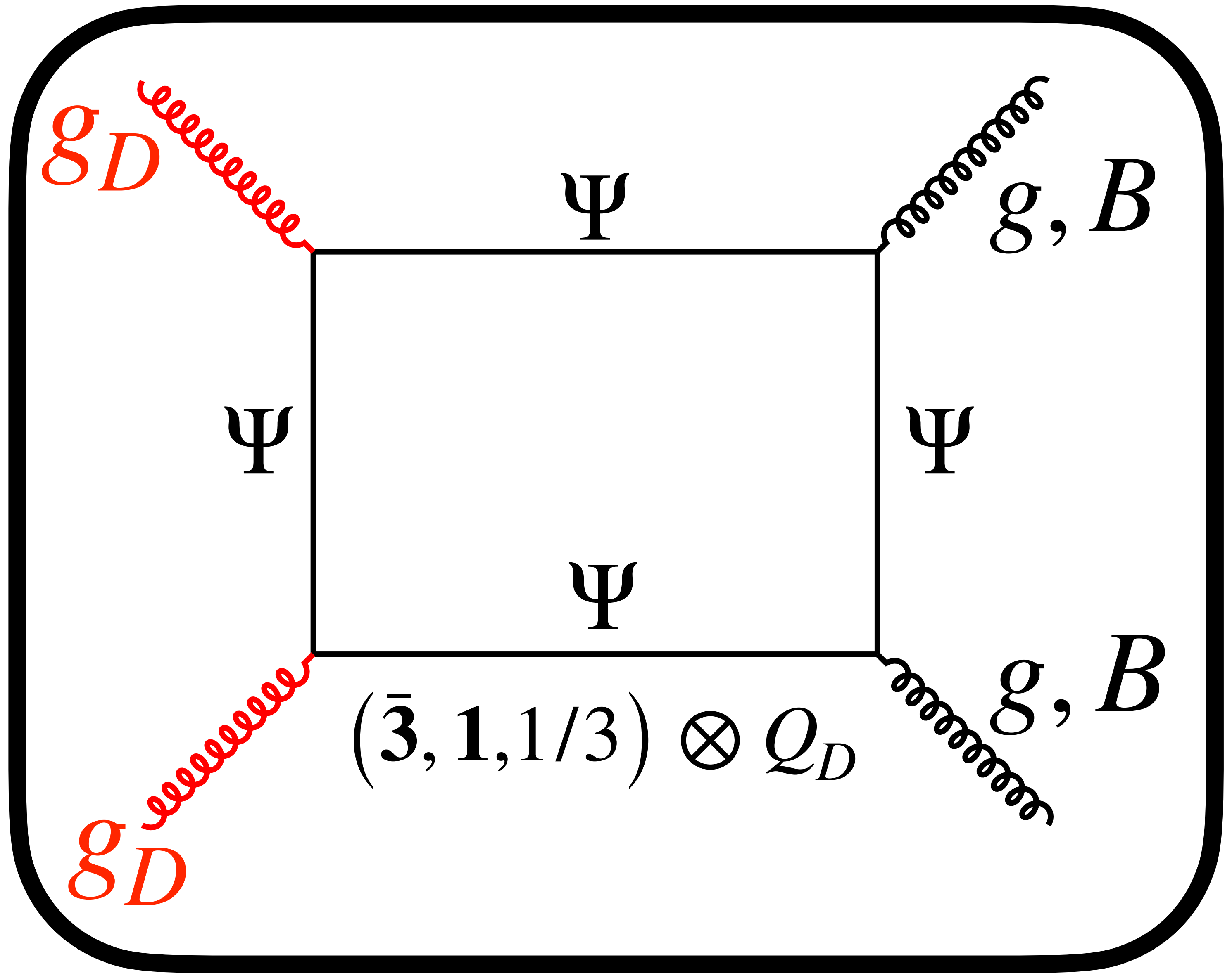

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Jung+ (2026)

Higgs portal is likely needed: $-\mathscr{L}_S \supset \bar{\psi} i\gamma^5 \psi S + \mu_S S|H|^2 \implies \theta_{h\pi_D} \simeq \frac{v\mu_S}{m_S^2}\frac{\Lambda_{\rm dQCD}^2}{4\pi}\frac{1}{m_h^2 - m_S^2}\ .$

Phenomenology of neutron portal

Decay channels

$$m_\chi < m_n + m_\pi : \quad \chi \to n\gamma, \chi \to pe^-\bar{\nu}$$

$$m_\chi > m_n + m_\pi : \quad \chi \to n\pi^0, \chi \to p\pi^-$$

These meson induced $\Gamma^{\text{strong}}_{n\leftrightarrow p}$ never dominates $\Gamma^{\text{weak}}_{n\leftrightarrow p}$

χ abundance is set by asymmetry $\simeq$ baryon abundance

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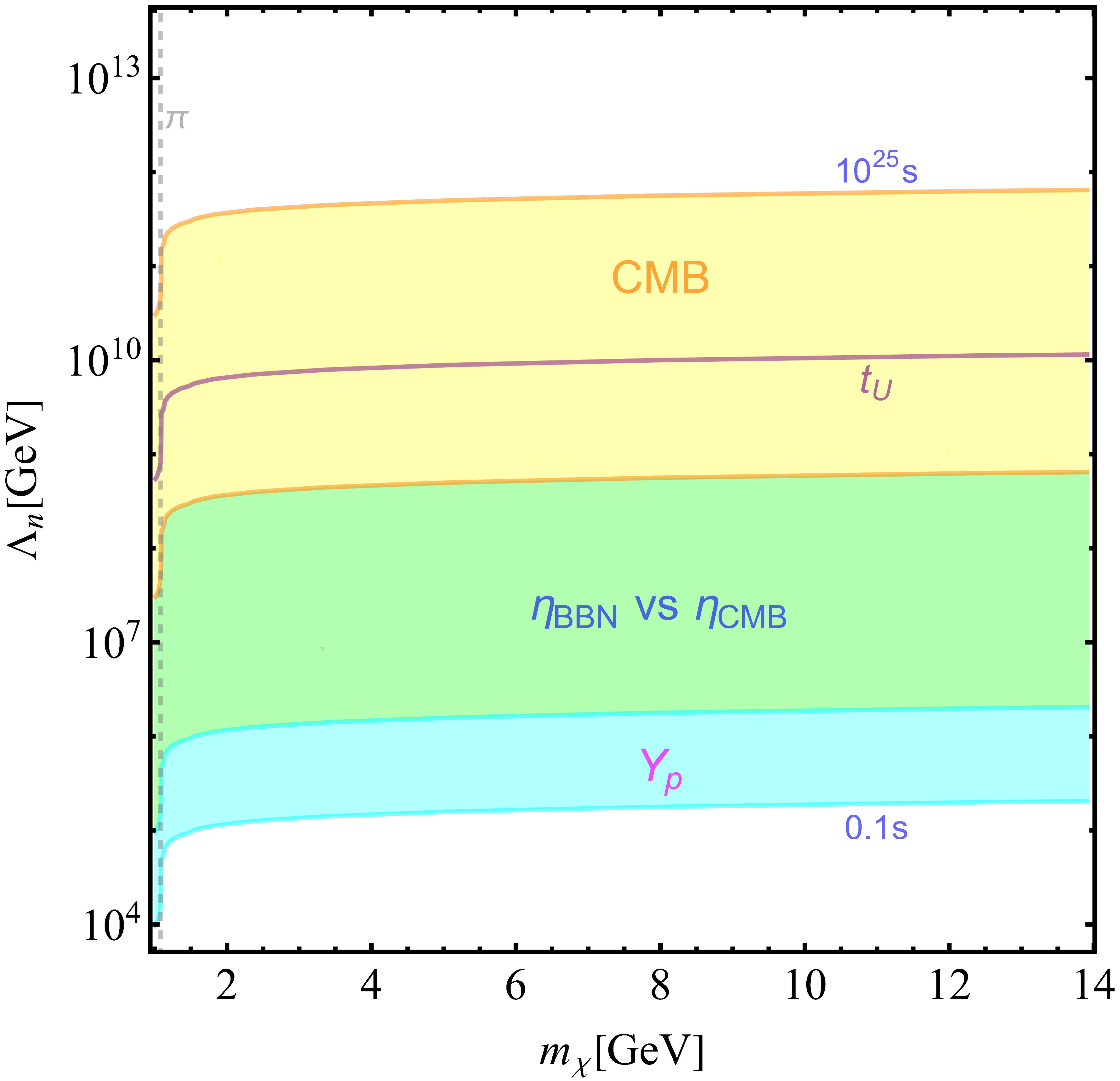
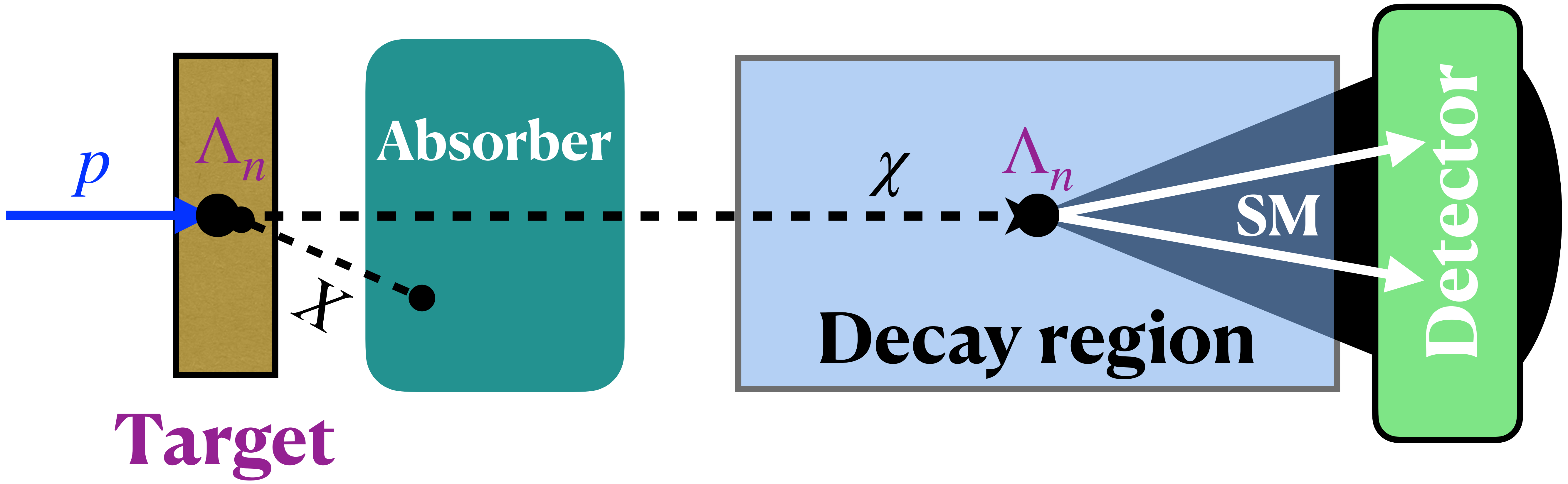
Decay time (s)	Constraint
$1 - 200$	$\delta Y_p \lesssim 0.01$
$10^3 - 10^{13}$	$\delta\eta/\eta \lesssim 0.039$
$10^{13} - 10^{25}$	CMB ionization



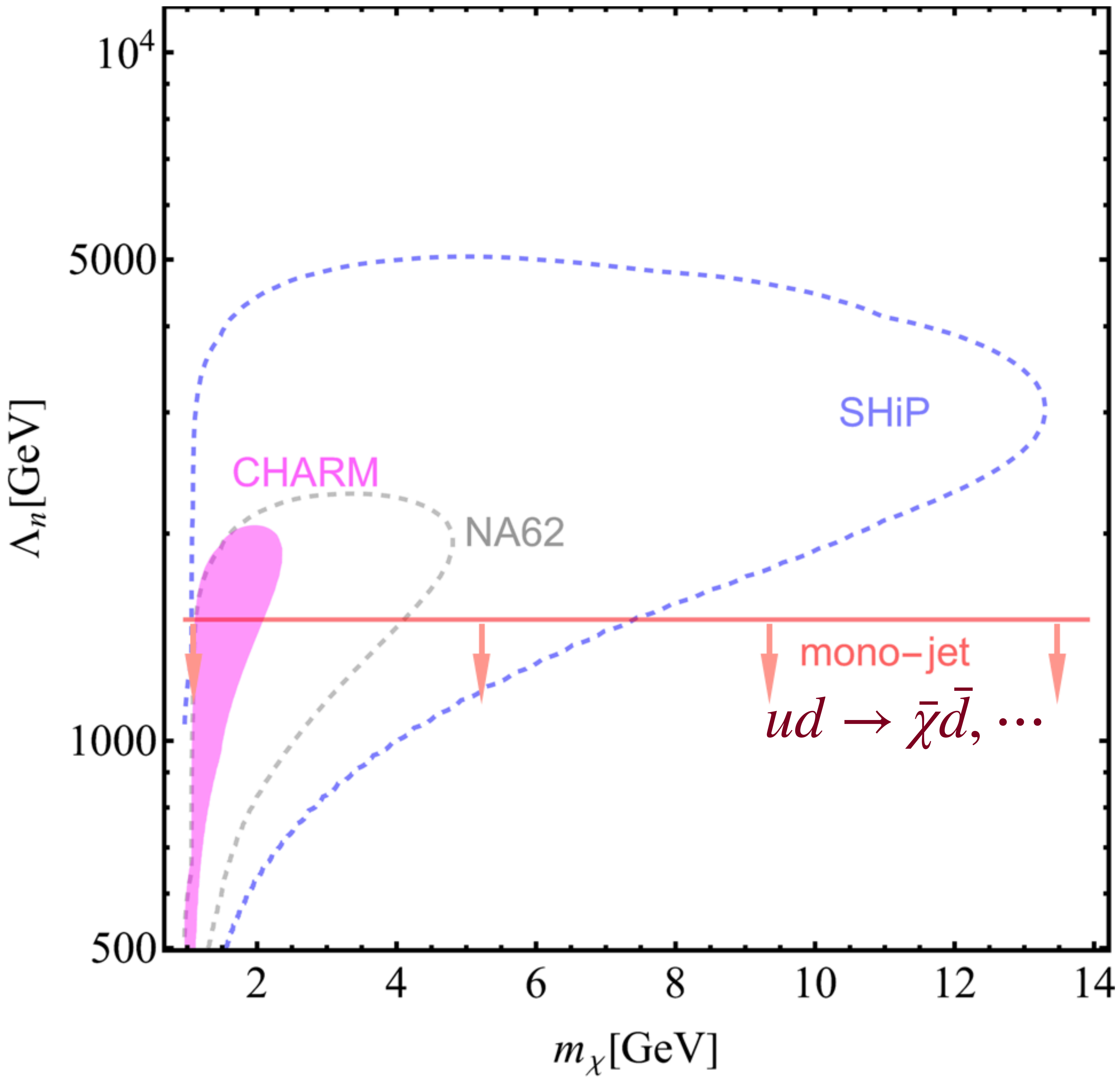
Experimental signatures of the neutron portal



Obtained from MadGraph

$$N_\chi = \frac{N_{\rm p.o.t}}{\sigma_{pN}} \int \frac{d\sigma_{pN\to\chi+X}}{dE_\chi d\theta}\, p(\ell_\chi)\, \varepsilon_{\rm rec}\, dE_\chi d\theta \geq 3$$

Decay probability



Conclusions

- ✓ **Dark first-order phase transition** is a promising interpretation of the observed PTA signal.
- ✓ The strong supercooling needed dilutes away pre-existing baryon asymmetry and DM, posing a challenge to this scenario.
- ✓ We provide **new mechanisms** where the baryon asymmetry and DM are produced utilizing the phase transition.
- ✓ **GeV scale emerges** from the UV completion of the neutron portal.

Thank you for your time. Questions?

Backup

Cold darkogenesis: The model

Fujikura, Girmohanta, Nakai, Zhang PLB 858 139045 (2024)

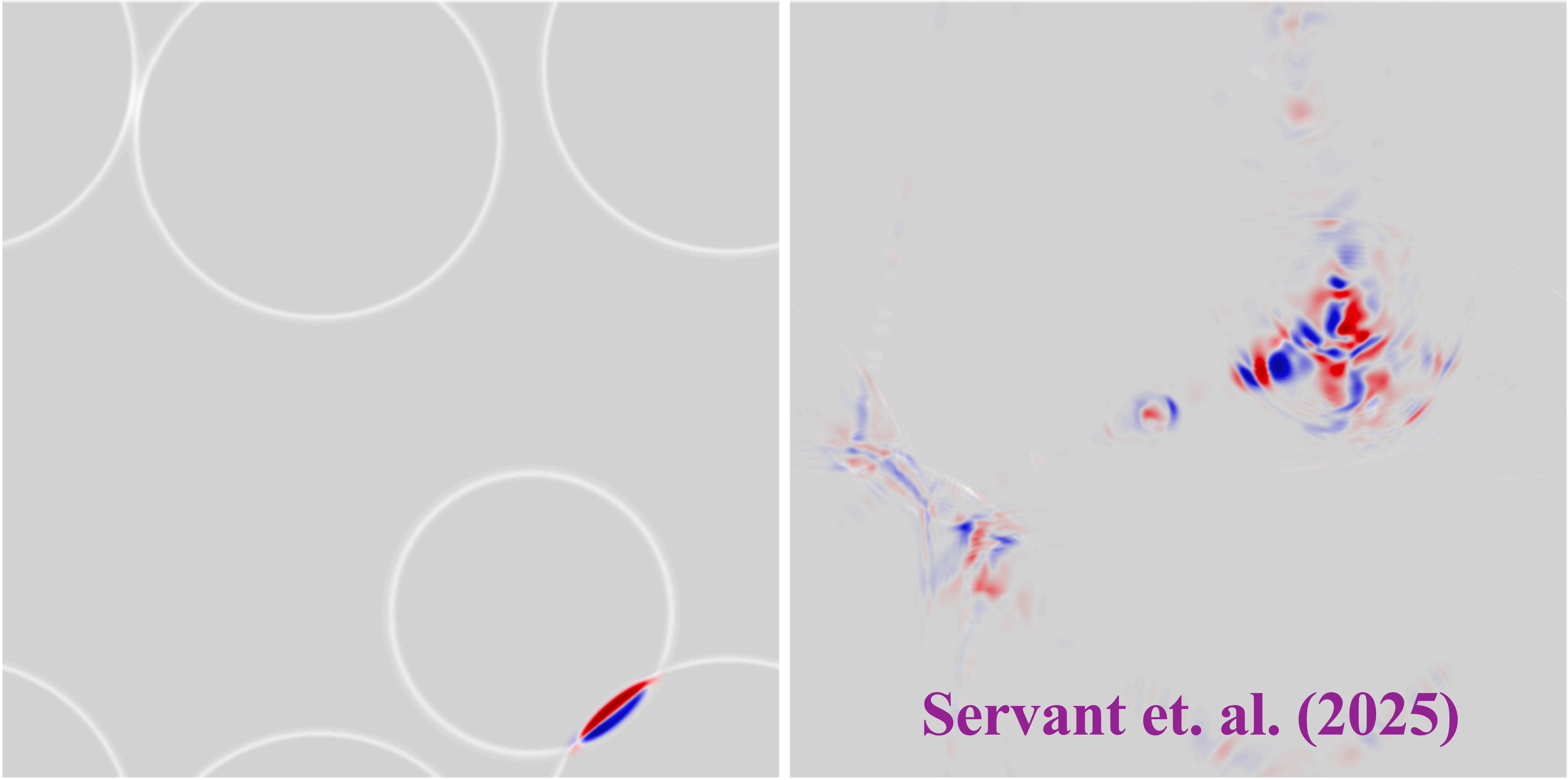
Dark number asymmetry ⇨ Baryon asymmetry & **Asymmetric DM.**

Dark QCD dilaton potential → $SU(N_H)$; Cold darkogenesis → $SU(2)_D$; Global dark baryon number → $U(1)_D$

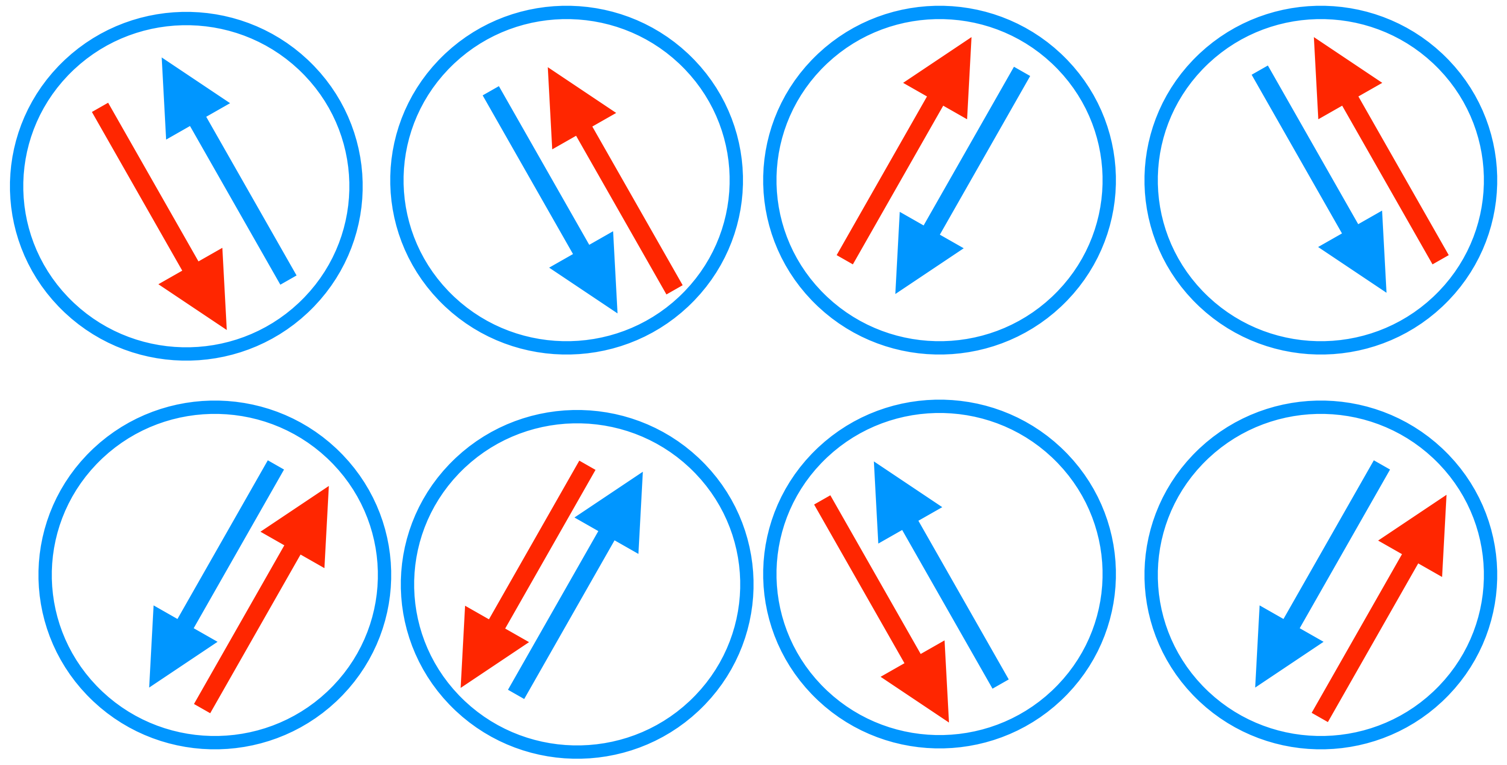
	Fields	$SU(N_H)$	$SU(2)_D$	$U(1)_D$	
Spin 0	H_D	**1**	**2**	0	⇨ Spontaneous breaking of $SU(2)_D$
Spin 1/2, Dark lepton	$L_{\chi,i} \equiv \begin{pmatrix} \chi_{1,i} \\ \chi_{2,i} \end{pmatrix}$	**1**	**2**	1	⇨ $U(1)_D$ anomalous under $SU(2)_D$
Spin 1/2, Dark lepton	$\bar{\chi}_{1,i},\ \bar{\chi}_{2,i}$	**1**	**1**	-1	⇨ Neutron portal $\left(1/\Lambda_n^2\right) \bar{\chi} udd$ for asymmetry sharing
Spin 1/2, Dark quarks	ψ_j	$\mathbf{N_H}$	**1**	$1/N_H$	
Spin 1/2, Dark quarks	$\bar{\psi}_j$	$\overline{\mathbf{N}}_\mathbf{H}$	**1**	$-1/N_H$	⇨ Baryon dark matter

$i = 1,\cdots,N_{D_L}\ ;\ j = 1,\cdots,N_{D_B}$

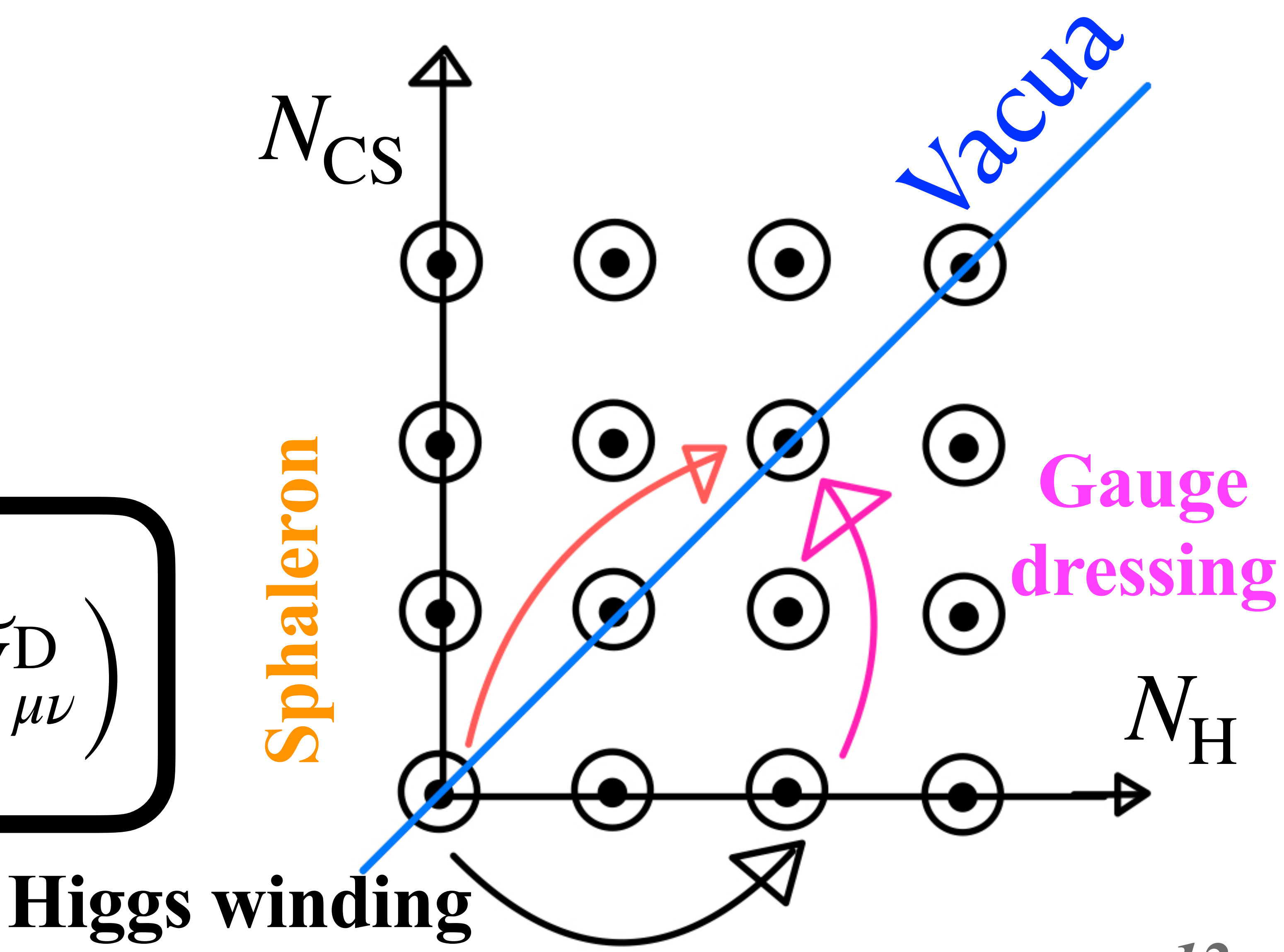
Generating the asymmetry in the dark sector



1. Higgs winding number (N_H) production



2. Gauge configuration evolves to cancel Higgs gradient energy



3. χ number violation via anomaly.

$$\partial_\mu j^\mu_{D_L} = N_{D_L} \frac{g_D^2}{32\pi^2} \mathrm{Tr}\left(W_D^{\mu\nu} \widetilde{W}^D_{\mu\nu} \right)$$

With **C & CP violation**, $\delta N \equiv N_{\rm CS} - N_{\rm H} > 0$ and $\delta N < 0$ **winding configurations evolve differently**, generating a net dark lepton number $\mathscr{D}_{\rm L,in}$.

$$\mathcal{O}_{\rm CPV} = \delta_{\rm CP} \frac{H_{\rm D}^\dagger H_{\rm D}}{\Lambda_{\rm CP}^2} \frac{g_{\rm D}^2}{32\pi^2} \mathrm{Tr}\left(W_{\rm D}^{\mu\nu} \widetilde{W}_{\mu\nu}^{\rm D} \right)$$

The produced $H_{\rm D}$ reaches **local equilibrium with the temperature**:

$T_{\rm D}^4 \sim$ released energy $\sim \lambda v_{\rm D}^4$

Sphaleron-like transition rate : $\Gamma_{\rm sph} \sim \left(\frac{g_{\rm D}^2}{4\pi} T_{\rm D} \right)^4$

$\mathcal{O}_{\rm CPV}$ acts as an effective chemical potential for χ, L_χ

$$\mu_{\rm eff} = \frac{\delta_{\rm CP}}{\Lambda_{\rm CP}^2} \frac{d}{dt} \langle H_{\rm D}^\dagger H_{\rm D} \rangle \implies \frac{dn_{\rm L}}{dt} = \Gamma_{\rm sph} \frac{\mu_{\rm eff}}{T_{\rm D}} - \Gamma_B n_{\rm L}$$

[Garcia-Bellido, Grigoriev, Kusenko,Shaposhnikov (1999)]

Sharing the asymmetry with the visible sector

The asymmetry is shared with the dark baryon and SM via effective interactions:

Baryonic DM composed of f ($\mathbb{Z}_2$ odd)

$$\mathcal{O}_{\rm D} \sim \frac{1}{\Lambda_{\rm D}^2} p_{\rm D} p_{\rm D} \chi\chi$$

$$\mathcal{O}_n \sim \frac{1}{\Lambda_n^2} \chi u_{\rm R} d_{\rm R} d_{\rm R}$$

Mono-jet searches ($ud \to \bar{\chi}\bar{d}, dd \to \bar{\chi}\bar{u}$) in colliders. Current constraint $\Lambda_n \gtrsim 2$ TeV. For equilibrium at GeV $\Lambda_n \lesssim 15$ TeV.

The DM is **self-interacting** via the mediation of dark pions $\pi_{\rm D}$ with cross-section:

$$\frac{\sigma_{p_{\rm D}p_{\rm D}}}{m_{p_{\rm D}}} \sim 1\ {\rm cm}^2/{\rm g} \left(\frac{\Lambda_{\rm dQCD}}{m_{p_{\rm D}}}\right)\left(\frac{\Lambda_{\rm dQCD}}{a_{\rm D}^{-1}}\right)^2\left(\frac{150\ {\rm MeV}}{\Lambda_{\rm dQCD}}\right)^3 ;$$

$a_{\rm D}$: scattering length .

Tulin Yu (2017) ; Kribs (2016)

Experimental predictions

Portal operator: π_D decays before BBN. $\Lambda_n \lesssim 15$ TeV for equilibrium at GeV temperature.

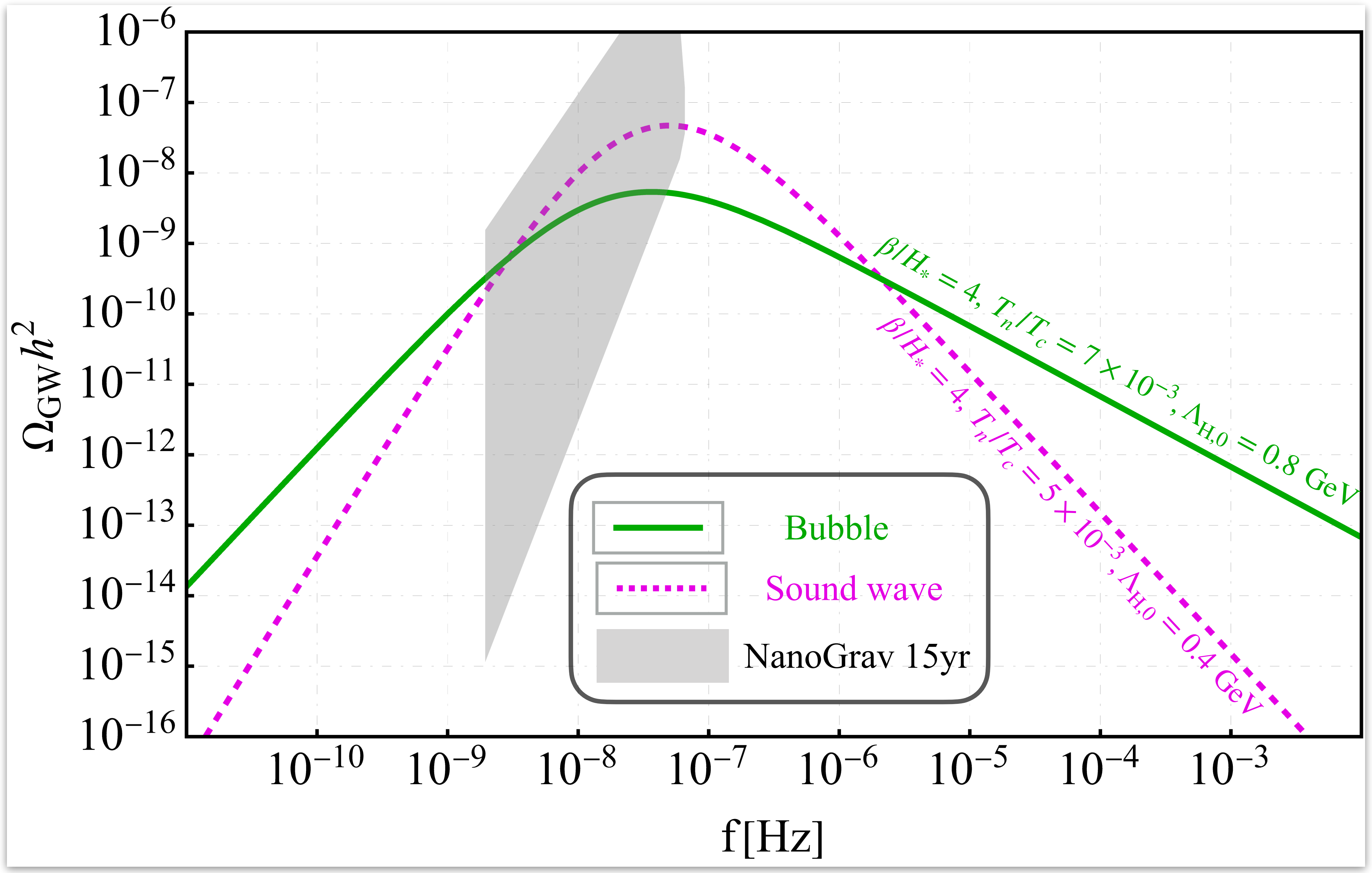
$$\mathscr{L}_H \supset -\lambda_h |H|^2 |H_D|^2$$

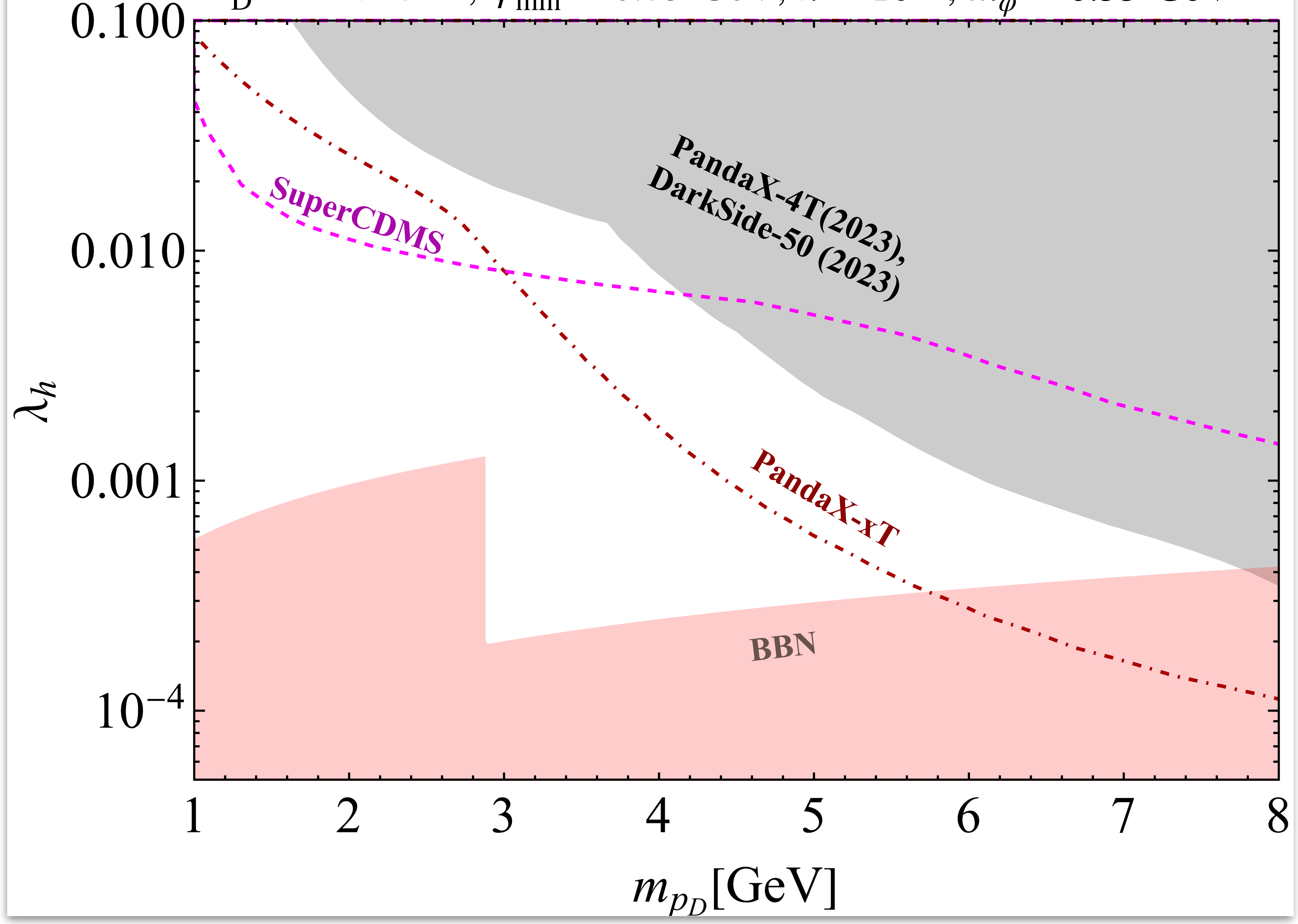
$\lambda_h \lesssim 0.1$ **from Higgs invisible decay.**

Lower bound from BBN, upper bound from DM direct detection.

PTA signal explanation together with DM and baryon asymmetry

$\lambda_\varphi = 1,\ \eta = 8,\ N = 10,\ N_H = 5,\ N_{D_B} = 10,\ n = 0.15,\ \Lambda_{dQCD} = 0.8$GeV

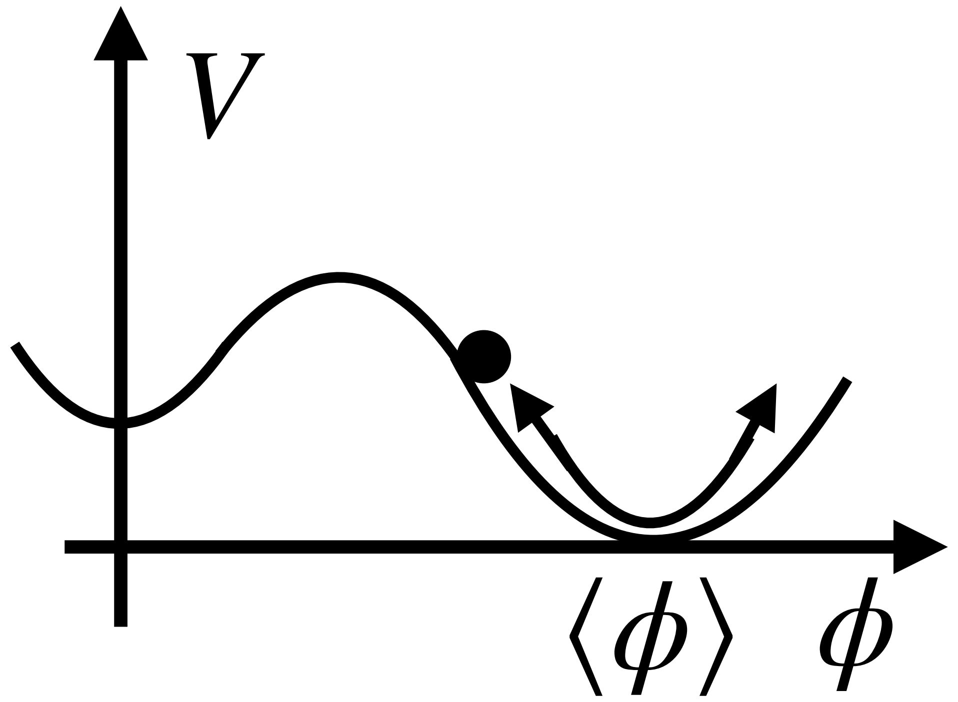




Post-sphaleron darkogenesis : The Model

Girmohanta, Nakai, Zhang PRD 112 075028 (2025)

Majorana ψ produced via **parametric excitation** during the phase transition.



oscillation of field ϕ

$\mathcal{O}(1)\mathrm{GeV}$

$$\phi(t) = \langle\phi\rangle + \varphi(t)$$
$$f(\varphi)\bar{\psi}^c\psi$$

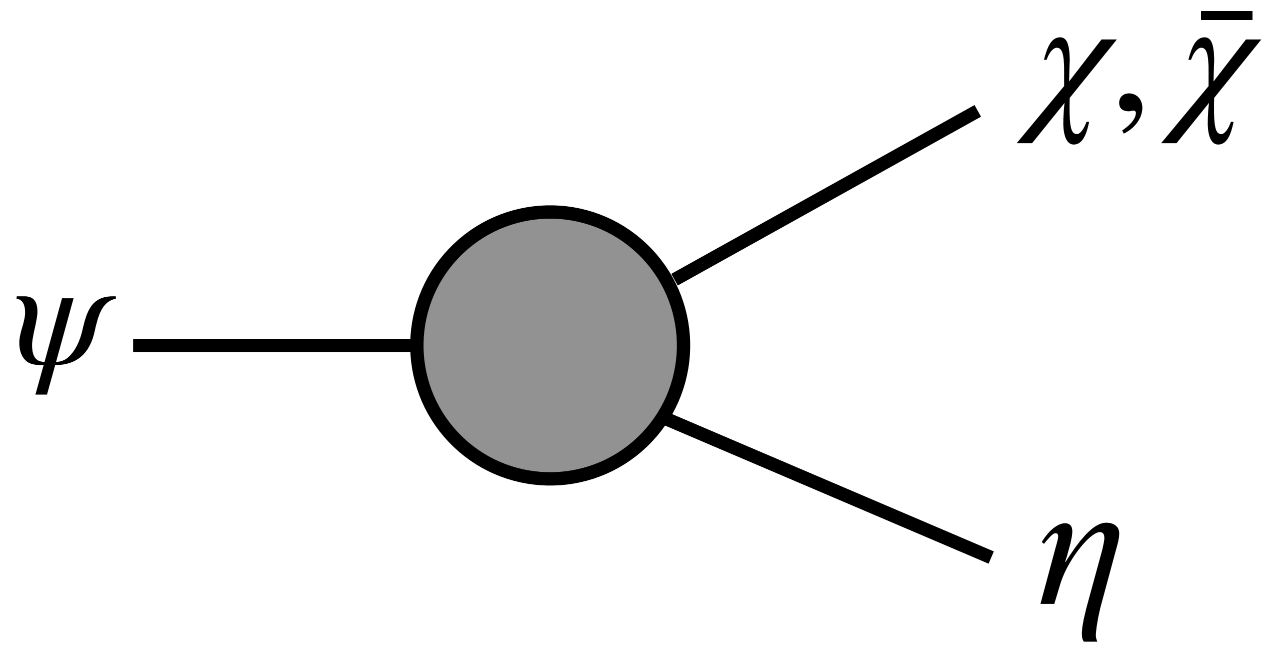
⇒

Parametric excitation

$$\left(i\gamma^\mu\partial_\mu - m_\psi^{\mathrm{eff}}(t)\right)\psi = 0$$

GeV mother particle ψ
is non-thermally produced.

$\bar{\psi}y\eta\chi$ ⇒

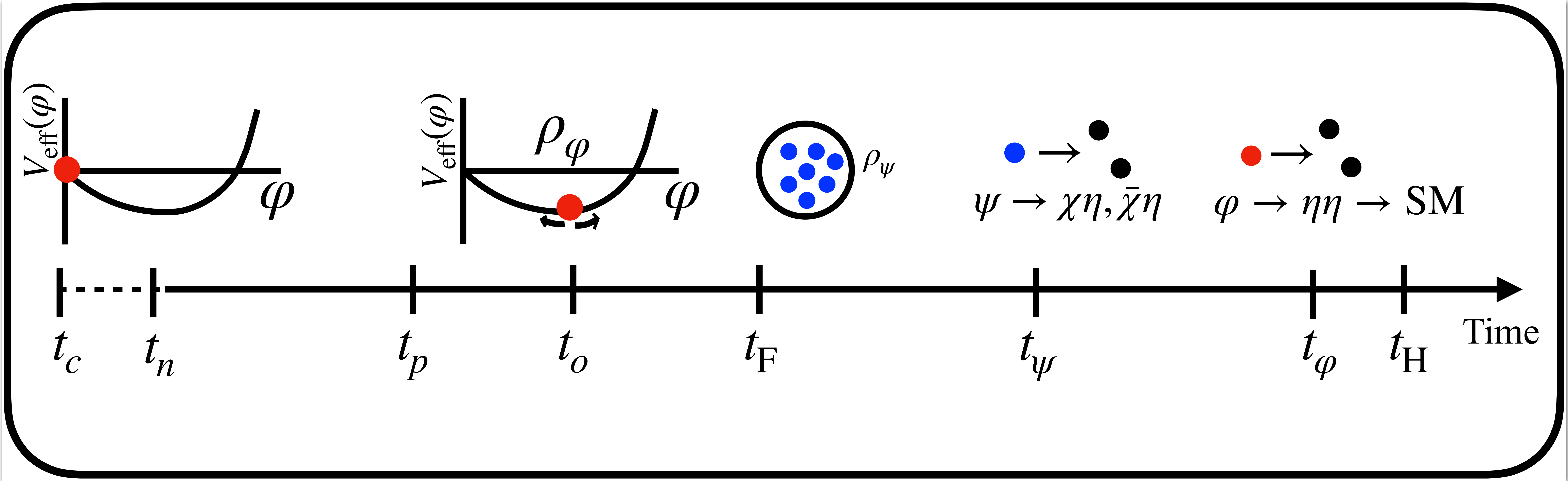


⇒ Asymmetric χ particle

Model

$$V_{\rm DS} = \bar{\chi}\mu\chi\eta + m_\chi\bar{\chi}\chi + \frac{1}{2}m_\psi\bar{\psi}^c_{\rm R}\psi_{\rm R} + \frac{1}{2}m_\eta^2\eta^2 + \bar{\psi}_{\rm R}y\eta\chi_{\rm L} + {\rm h.c.}$$

Fields	$U(1)_{\rm D}$
ψ_i	-1
χ_j	-1
η	0



Neutron portal shares the asymmetry with the visible sector.

η acts as Higgs-portal scalar.

Number density of the mother particle

The amplitude of oscillating φ is decreasing due to back-reaction.

$$m_\psi^{\rm eff}(t) = m_\psi \left[\frac{\{1+\xi(t)\cos(m_\varphi t)\}^{2b} - r}{1-r}\right]$$

m_ψ: $\mathcal{O}(1)$GeV

Particle production takes place when $m_\psi^{\rm eff} \simeq 0$, requiring

$$(1-\xi_0)^{2b} \le r \le (1+\xi_0)^{2b} \; ; \; \text{for } 0 < b < 1/2 \, ,$$

$$(1-\xi_0)^{2b} \ge r \ge (1+\xi_0)^{2b} \; ; \; \text{for } b < 0 \, ,$$

When $\xi(t)$ drops down to ξ_c, n_ψ is frozen

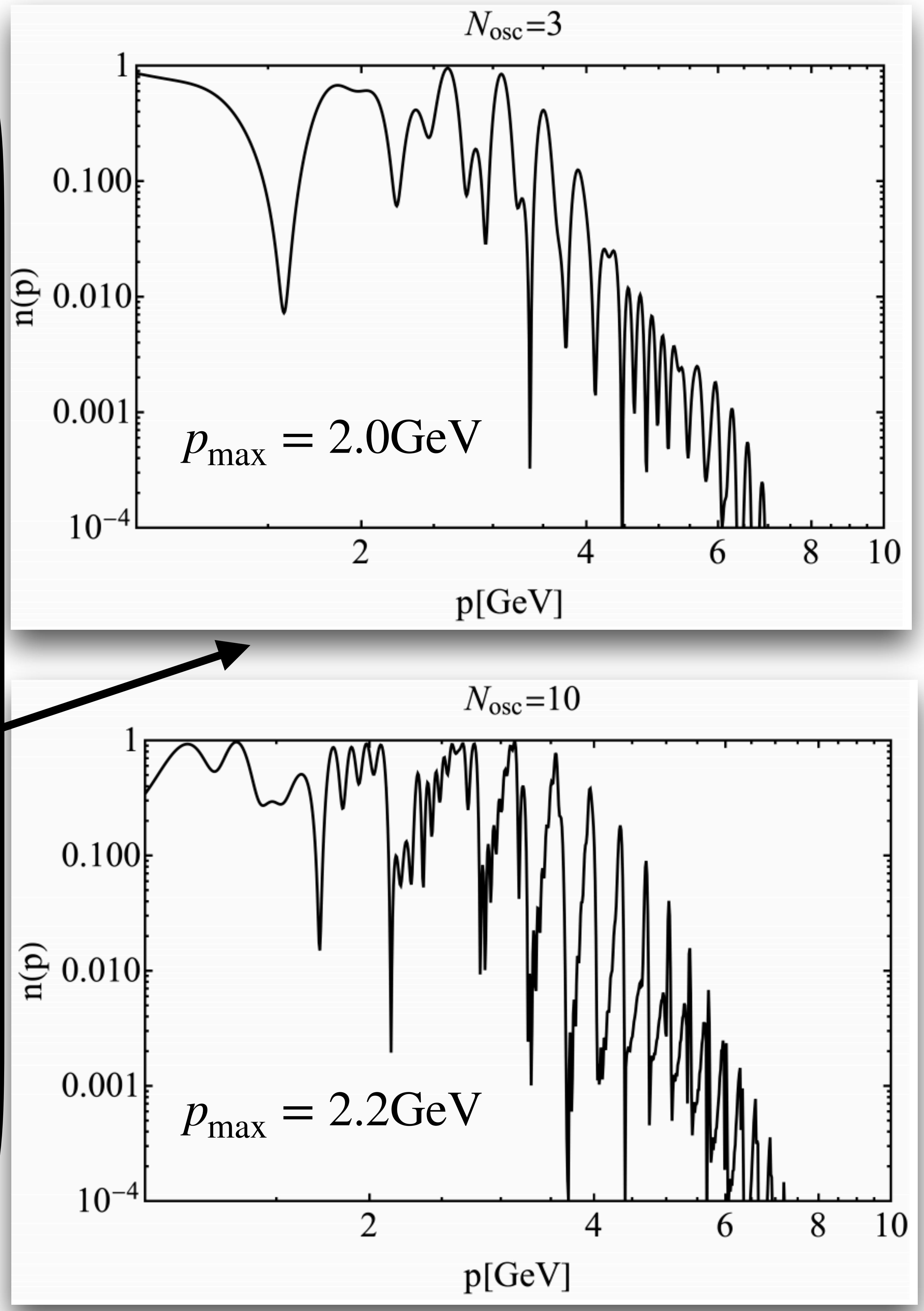
$$n_\psi^{\rm FO} \simeq \mathcal{M}(r,b)\left(\frac{m_\psi m_\varphi^2}{6\pi^2}\right) \, ,$$

$$\mathcal{M}(r,b) \equiv \left[\frac{2br}{1-r}\left(r^{-\frac{1}{2b}} - 1\right)\right]$$

non-adiabatic

$$n_\psi^{\rm FO} = \frac{p_{\rm max}^3}{3\pi^2}$$

Analytical estimation



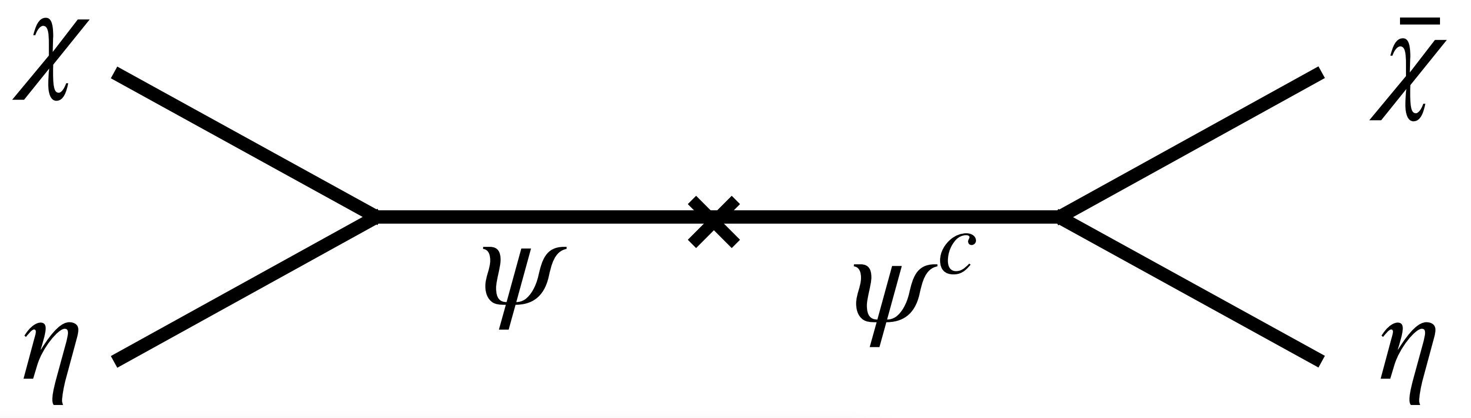
Washout and $n - \bar{n}$

Inverse-decay $\chi\eta \to \psi_1$:

$$\frac{n_\eta^{\rm eq}\langle\sigma v\rangle_{\chi\eta\to\psi_1}}{H(T_{\rm RH})} \simeq \frac{\Gamma_{\psi_1\to\chi\eta}}{H(T_{\rm RH})}\left[e^{-m_{\psi_1}/T_{\rm RH}}\left(\frac{m_{\psi_1}}{T_{\rm RH}}\right)^{3/2}\right]$$

$e^{-m_{\psi_1}/T_{\rm RH}} \ll 1$

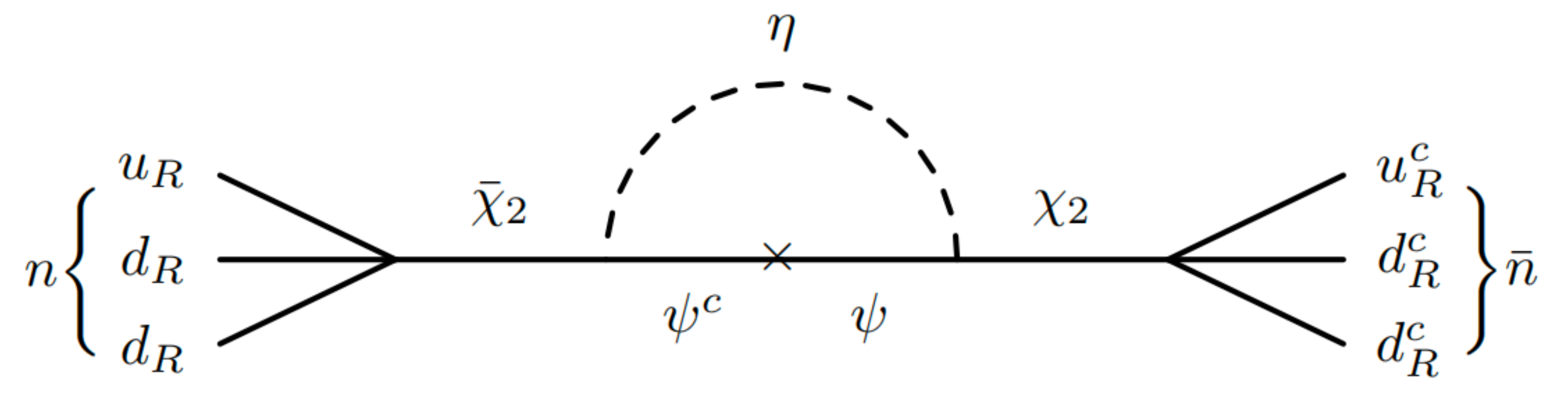
washout



$$\left(\frac{\zeta(3)}{\pi^2}T_{\rm RH}^3\right)\left(\frac{|y|^4}{8\pi m_\psi^2}\right) \lesssim 0.3\sqrt{g_*}\frac{T_{\rm RH}^2}{M_{\rm pl}} \rightarrow |y| \lesssim 2\times 10^{-4}$$

Neutron Portal

$$\mathcal{O}_n = \frac{1}{\Lambda_n^2}\chi_2 u_{R,i} d_{R,j} d_{R,k}$$

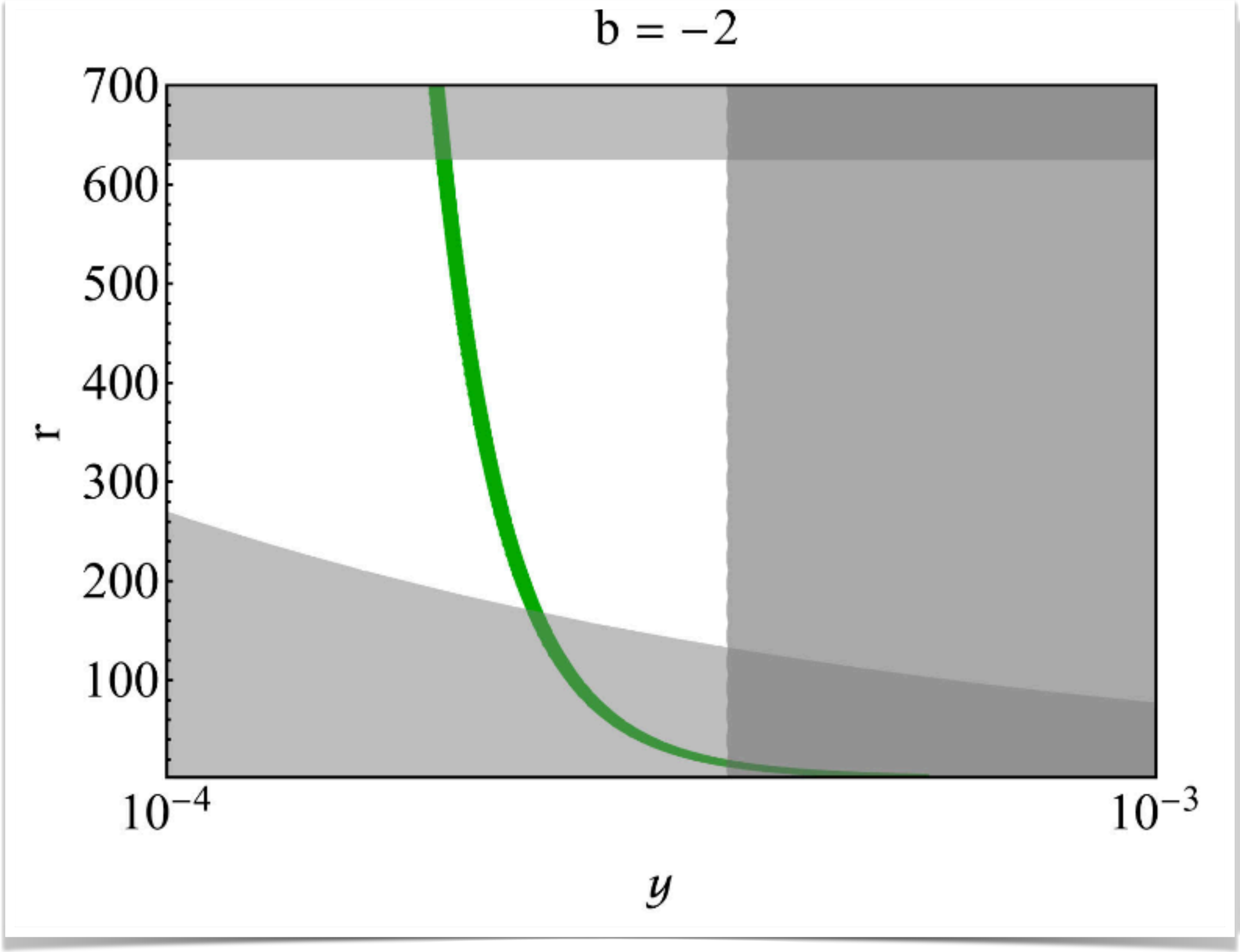


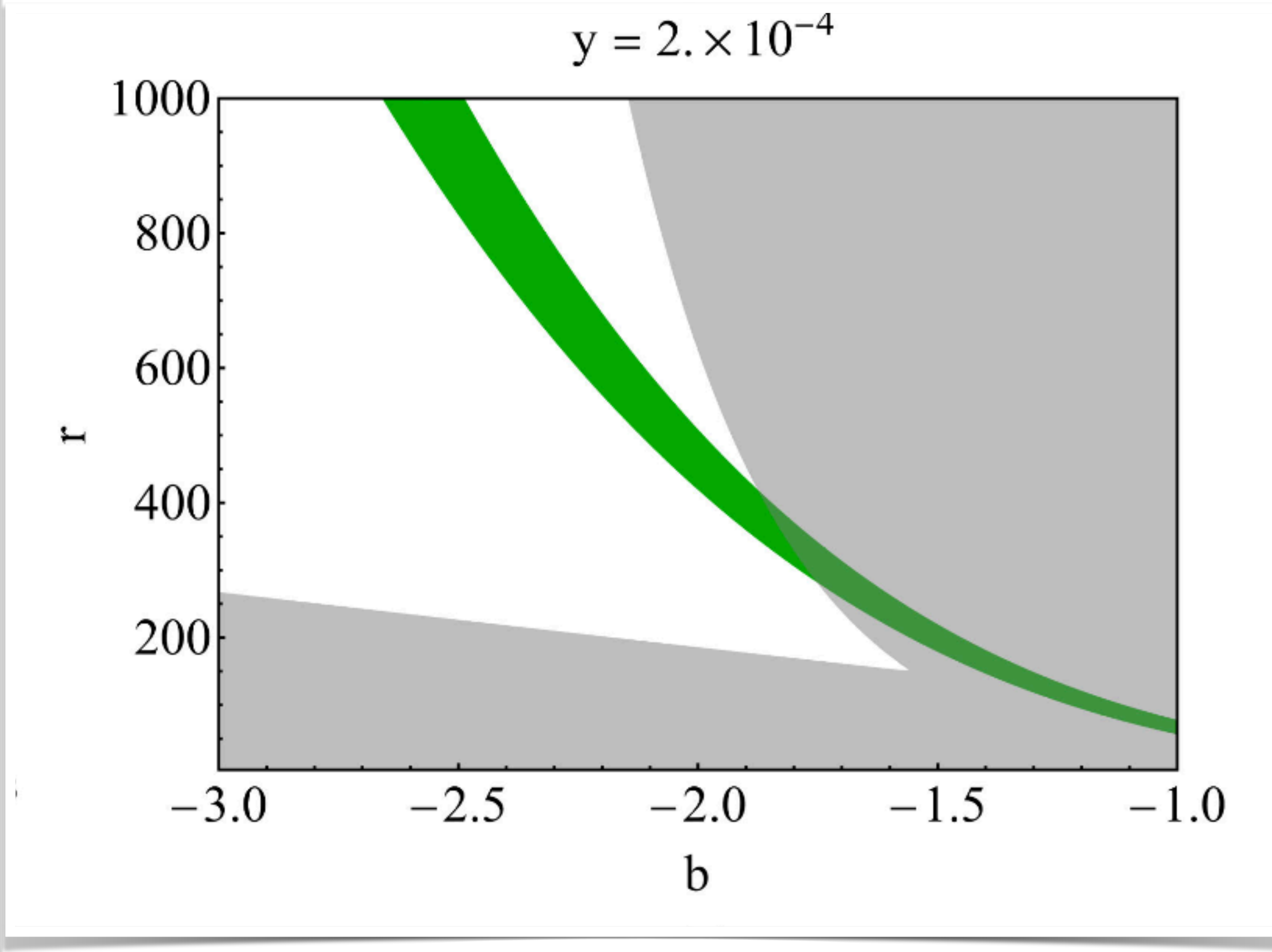
$n - \bar{n}$ oscillations

mono-jet searches → $\Lambda_n \gtrsim 2$ TeV

decay before BBN → $\Lambda_n \lesssim 200$ TeV → $\tau_{n\bar{n}} > 4.7\times 10^8 s$

Succesful BAU





Phenomenology

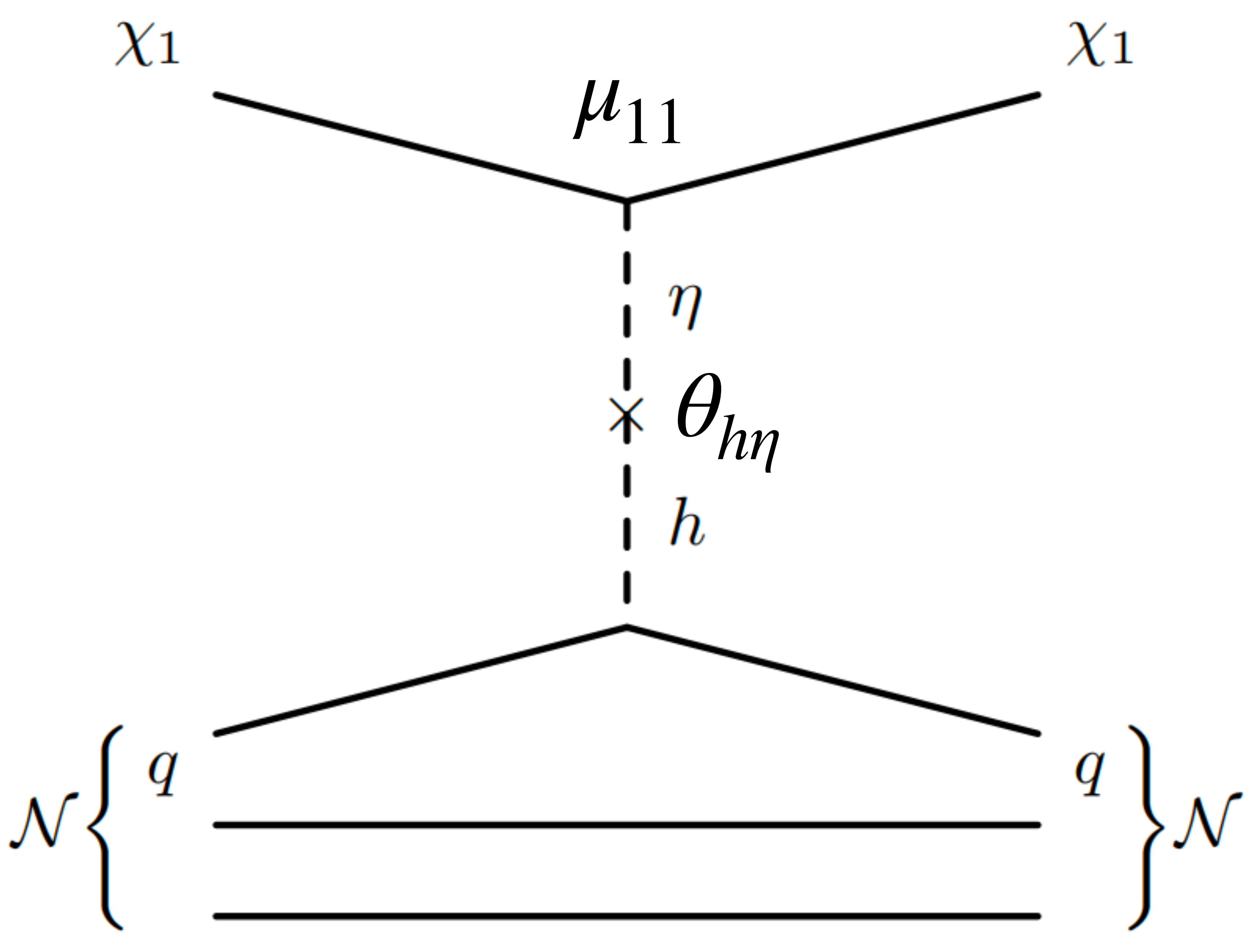
mixing angle

Higgs portal

$$-g_\eta\, \eta \left(\mathbf{H}^\dagger \mathbf{H} - \frac{v^2}{2}\right) - \frac{m_\eta^2}{2}\eta^2 \left(\frac{2\varphi}{\langle\phi\rangle} + \frac{\varphi^2}{\langle\phi\rangle^2}\right)$$

$$\tan(2\theta_{h\eta}) = \frac{2 g_\eta v}{m_h^2 - m_\eta^2}$$

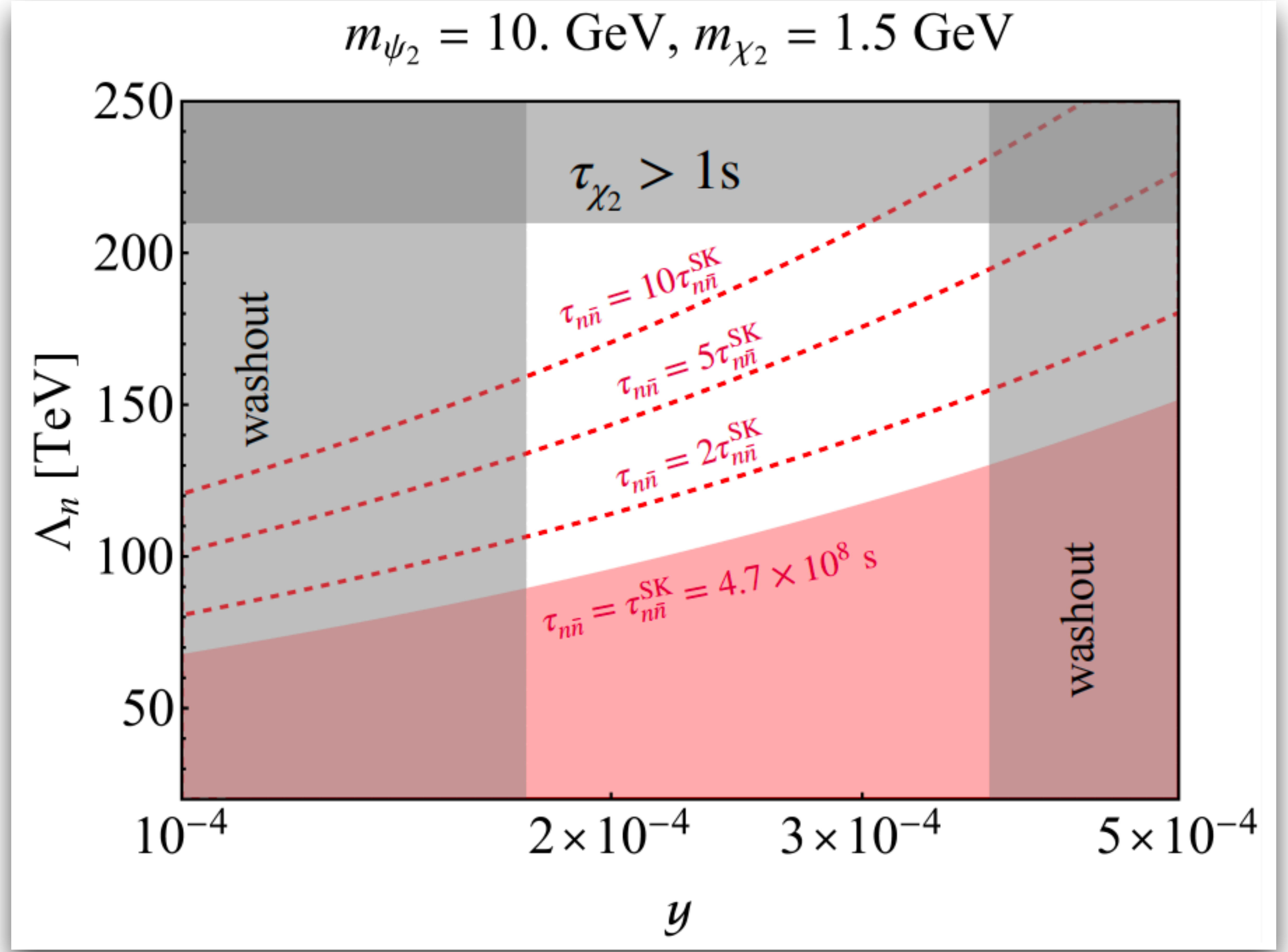
DM direct detection

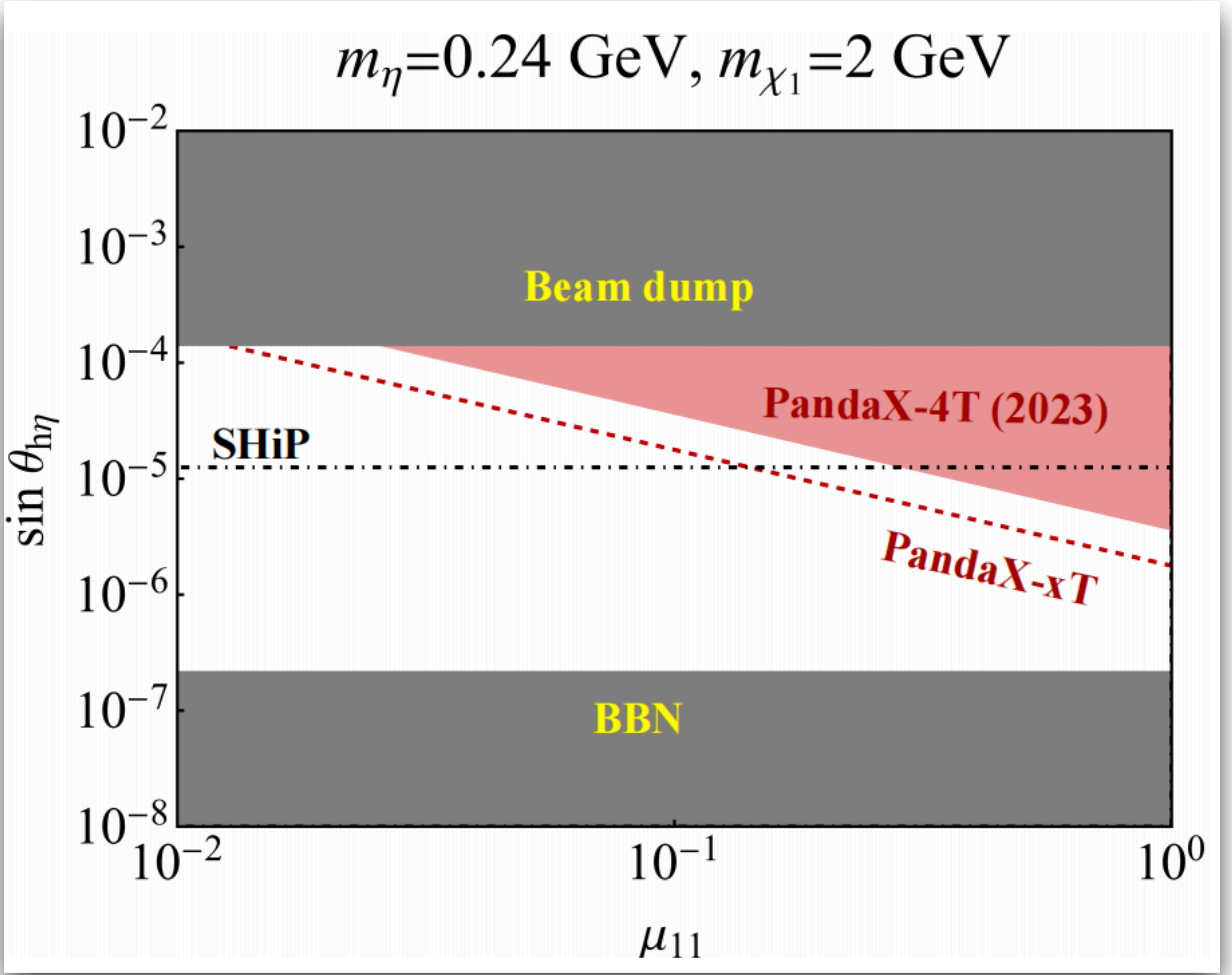


decay before BBN → $|\theta_{h\eta}| \gtrsim 10^{-7}$

$B \to K^{(*)}\eta(\to \mu^+\mu^-)$ → $|\theta_{h\eta}| \lesssim 10^{-4}$

Viable parameter space





What about the “final parsec problem”?

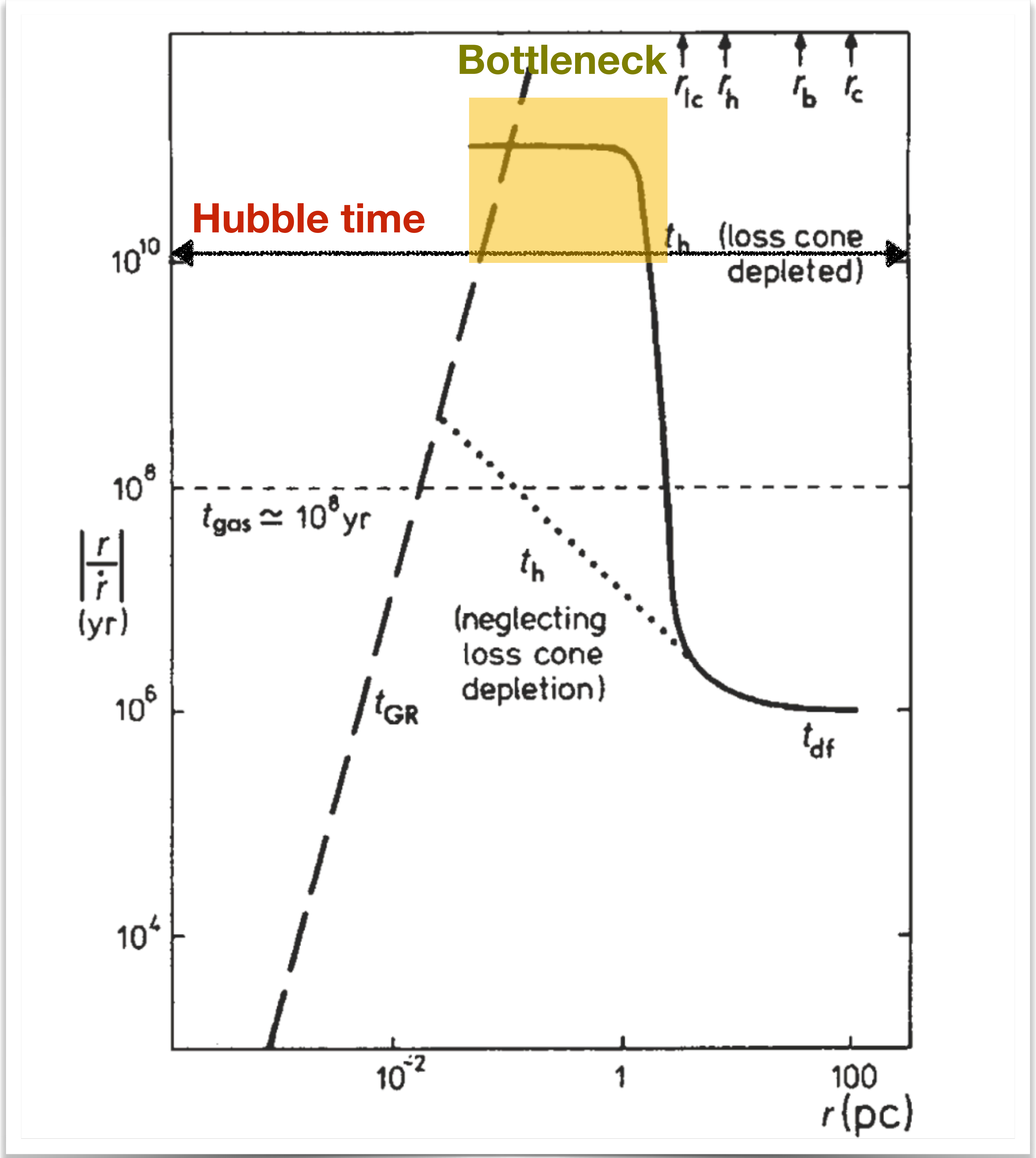
SMBHB come closer together due to dynamical friction.

This stalls at ~ 1 pc as the loss cone is depleted.

Gravitational wave does not take over until separation $\lesssim$ 0.01 pc.

Possible resolution includes triaxiality, multiple black holes, accretion…but no consensus.

There is still no convincing evidence of sub-parsec binary black hole.



Begelman, Blandford, Rees 1980

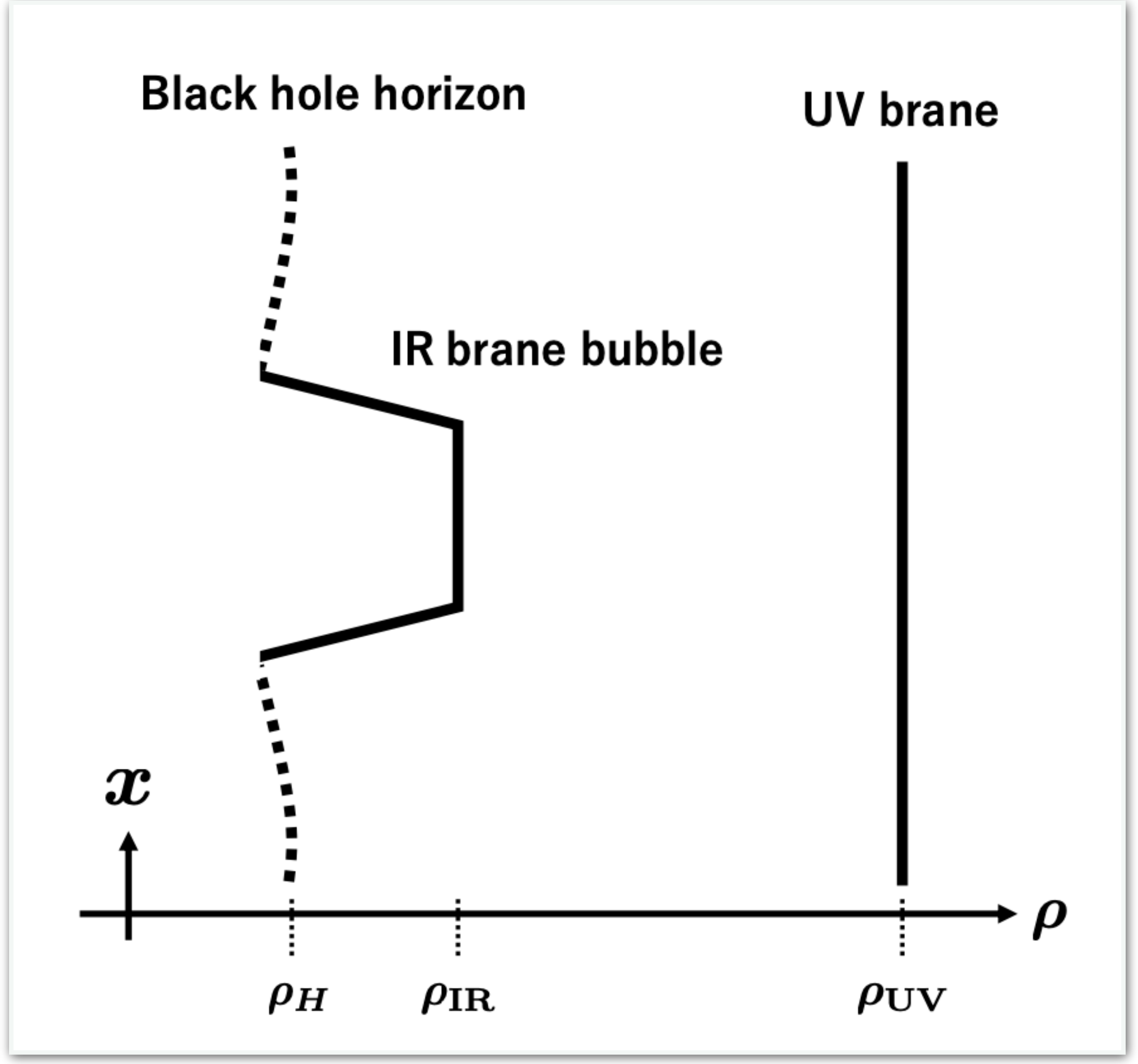
RS model at Finite Temperature and Hawking-Page Phase Transition

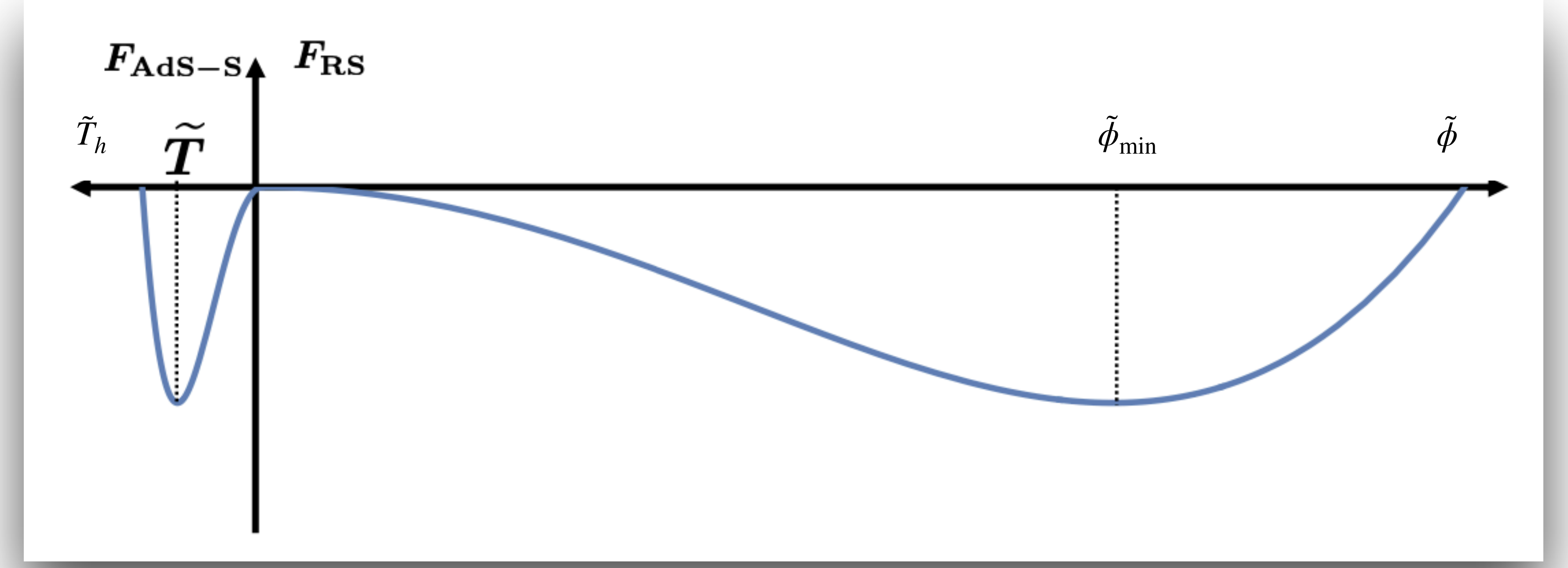
Hawking, Page '83 ; Witten '98 ; Arkani-Hamed+ 2000 ; Creminelli+ 2002 ; Nardini+ 2007; Harling+ 2017 ; Nakai+ 2020

Question: What is the finite temperature description of Randall-Sundrum model?

The high temperature phase of RS model is AdS-S space where the IR brane is replaced by the black-hole horizon.

This high temperature phase is dual to a hot thermal CFT.





$$\Delta F_{\rm AdS-S} = \frac{3}{8}\pi^2 N^2 T_h^4 - \frac{1}{2}\pi^2 N^2 T_h^3 T$$

$$\Delta F_{\rm RS} = V_{\rm eff}(\phi_{\rm min}) - V_{\rm eff}(0)$$

Below and above T_c two distinct phases are thermodynamically favored.

A phase transition takes place as T is lowered below T_c.

$$T_c = \left(\frac{8\,|\,\Delta F_{\rm RS}\,|}{\pi^2 N^2}\right)^{1/4}$$

The Model: Dark first-order deconfining phase transition

Rattazzi+ 2002 ; Servant+ 2017

$T^{(D)} \gg T_c^{(\mathrm{D})}$

4D conformal dark sector with large N
+
dark pure $SU(N_H)$ Yang-Mills

$SU(N_H)$ confines $\Longrightarrow$ drives spontaneous breaking of conformal invariance $\Longrightarrow$ generates dilaton (φ) effective potential

$T_c^{(\mathrm{D})}$

Confinement-deconfinement phase transition and generation of gravitational waves

Dual 5D description

IR brane replaced by an event horizon + $SU(N_H)$ in the bulk

Dark $SU(N_H)$ confinement generates radion potential

Below $T_c^{(\mathrm{D})}$: IR brane configuration has lower free-energy

IR brane bubbles appear and a strong first-order phase transition proceeds.

Secluded dark sector

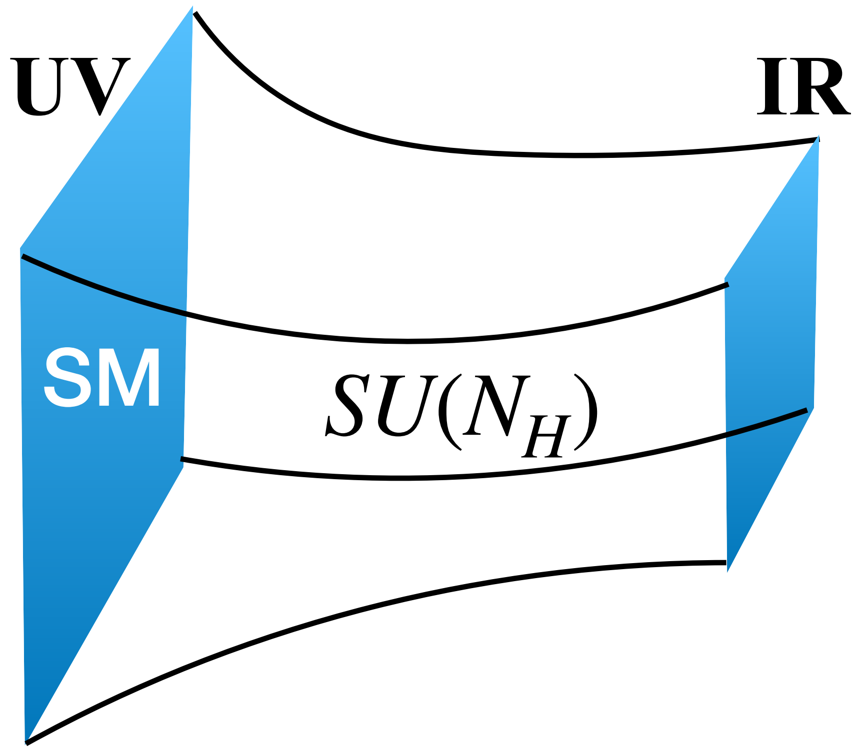
For eg: dark radiation final state.

Contributes to ΔN_{eff} and may alleviate the Hubble tension.

Decaying dark sector

$\mathscr{L}_{\mathrm{portal}} \sim O_{\mathrm{vis}} O_{\mathrm{dark}}$

Is not subject to ΔN_{eff} constraint.



$SU(N_H)$
confinement generates $V_{\mathrm{eff}}(\varphi)$

Gravitational waves: dilaton effective potential

$$\frac{1}{g_H^2(Q,\varphi)} = -\frac{b_{CFT}}{8\pi^2}\ln\left(\frac{k}{\varphi}\right) - \frac{b_H}{8\pi^2}\ln\left(\frac{k}{Q}\right)$$

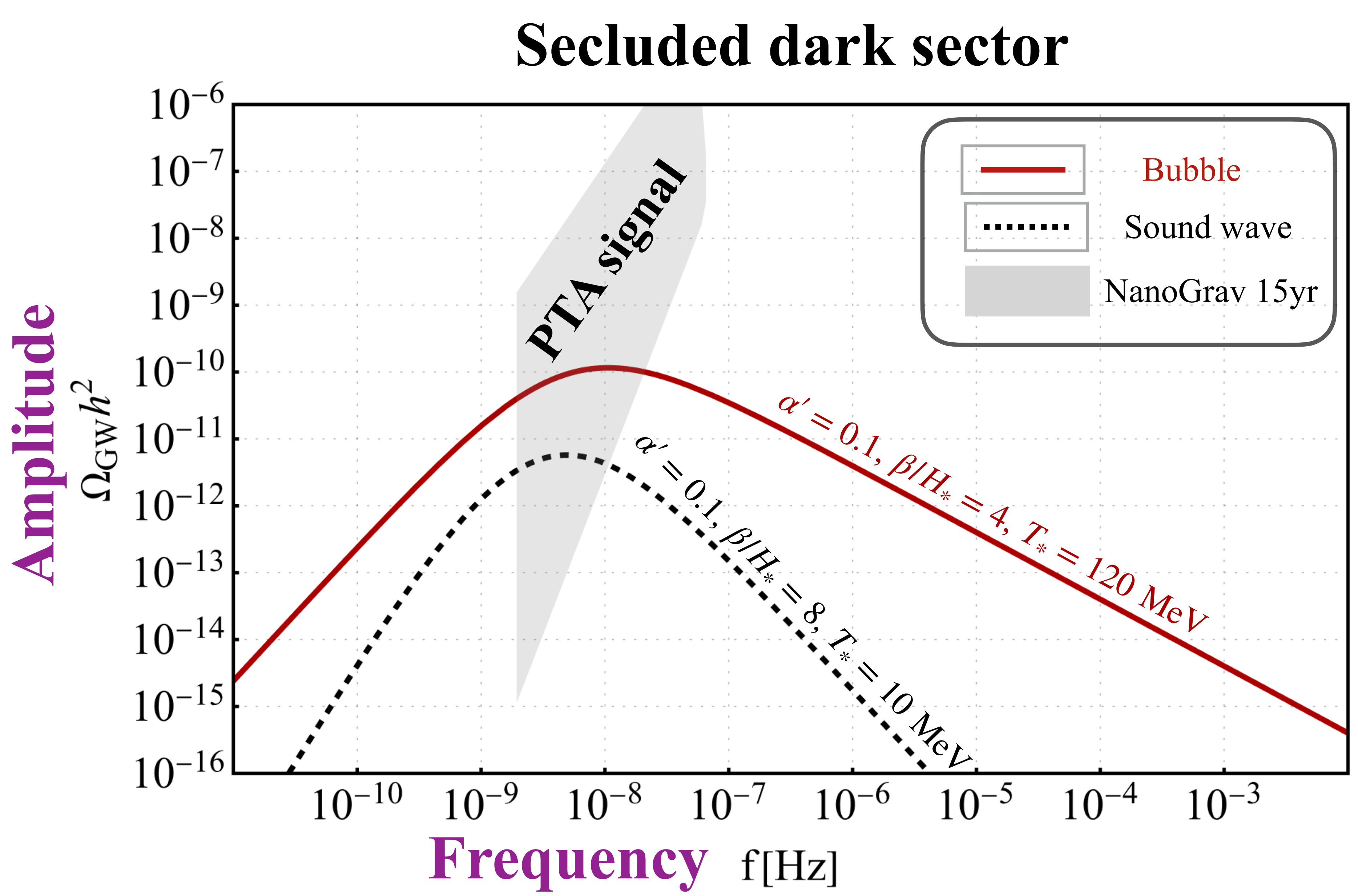
Running of $SU(N_H)$ coupling g_H from UV scale k to $Q \lesssim \varphi$. $b_{CFT} = -\xi N$, $b_H = 11N_H/3 + b_f$.

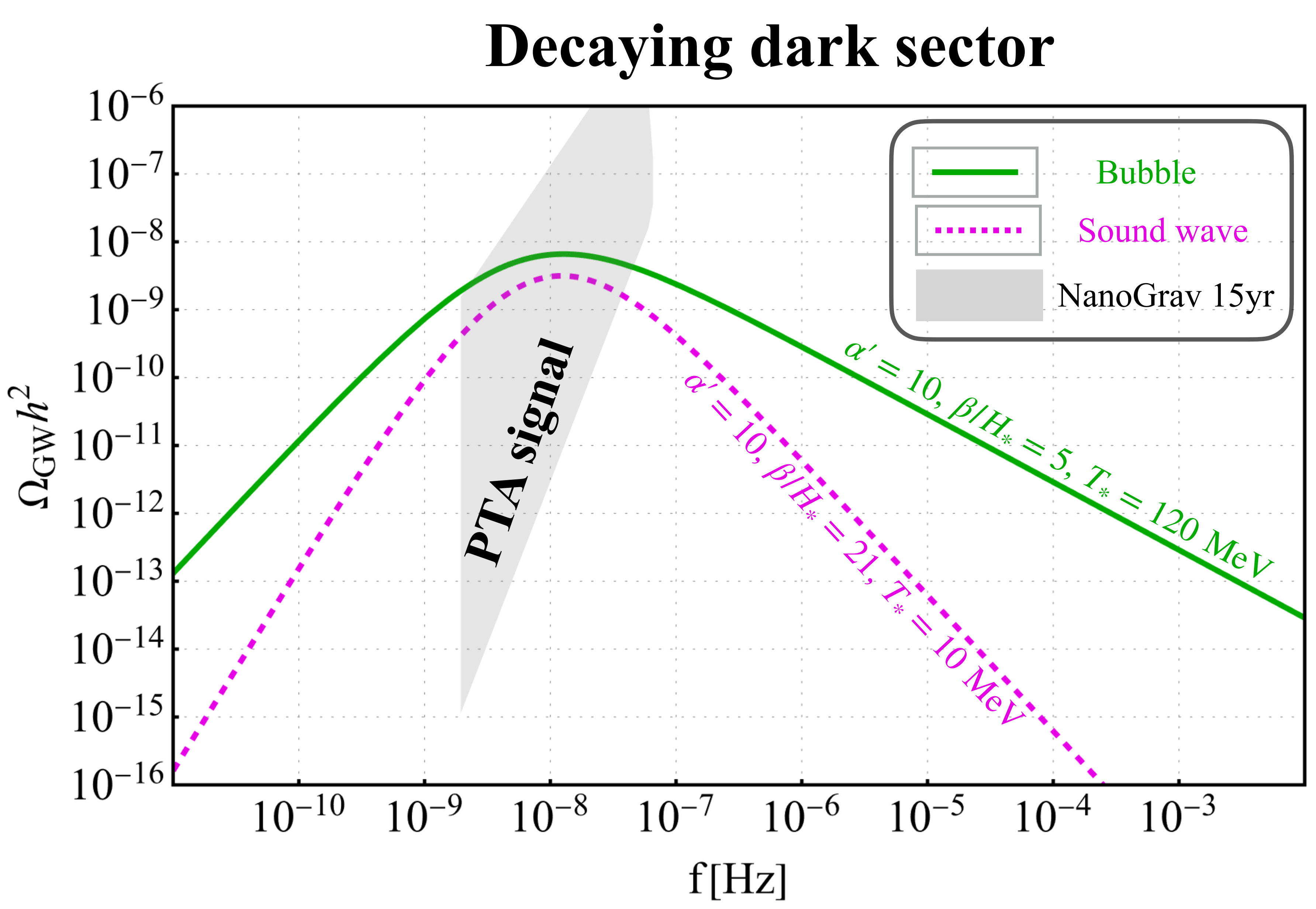
$SU(N_H)$ **confinement scale depends on** φ**. Condensate provides dilaton potential** $V_{eff}(\varphi)$**.**

$$\Lambda_H(\varphi) = k\left(\frac{\varphi}{k}\right)^{-b_{CFT}/b_H} = \Lambda_{dQCD}\left(\frac{\varphi}{\varphi_{min}}\right)^n$$

$$V_{eff}(\varphi) = \begin{cases} V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_H}{\eta}\Lambda_{dQCD}^4\left(\frac{\varphi}{\varphi_{min}}\right)^{4n}, & \text{for } \varphi \geq \varphi_c \\ V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_H}{\eta}\gamma_c^4\varphi_c^4 \quad , & \text{for } \varphi < \varphi_c \end{cases}$$

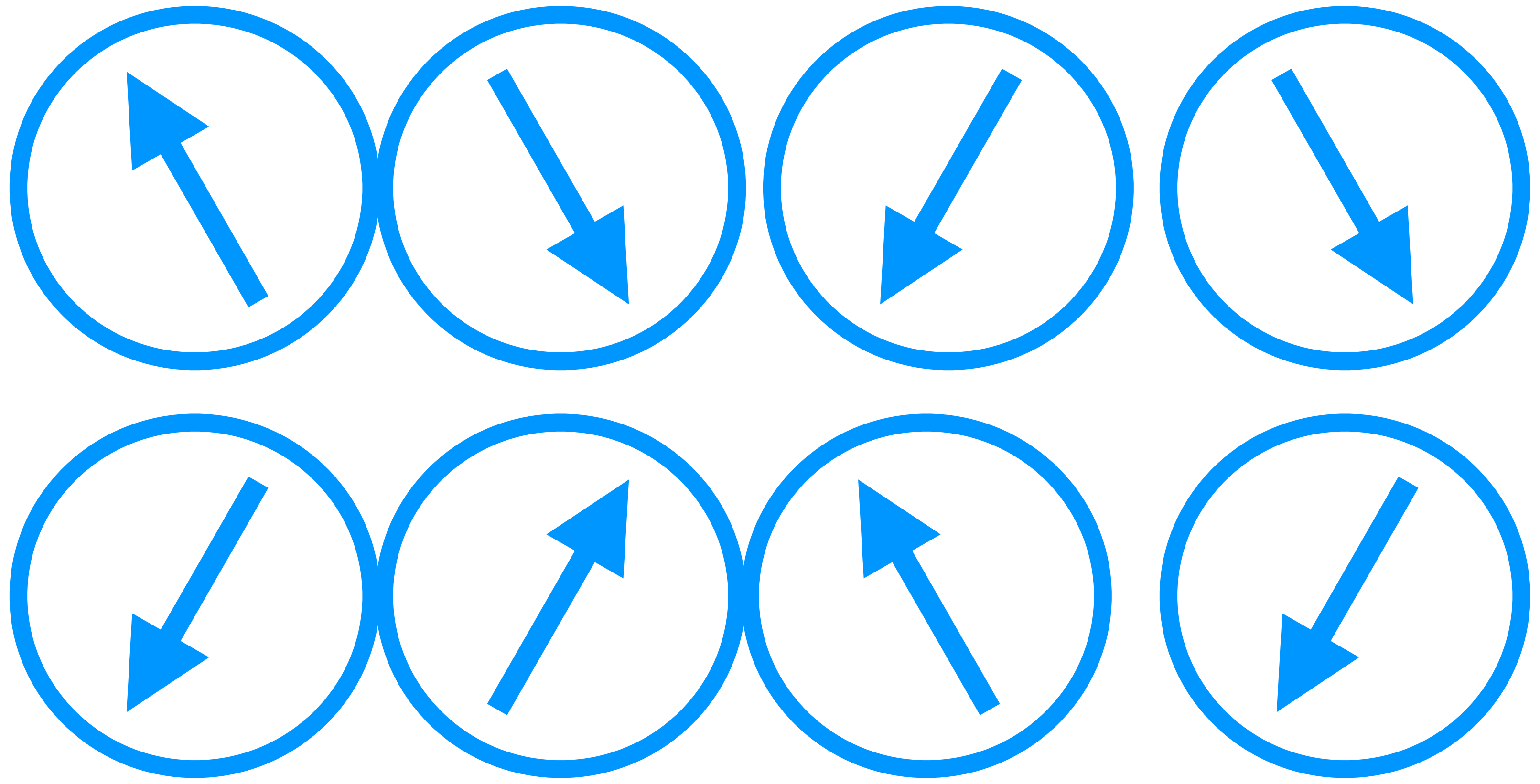
Phase transition effective parameters α, β are determined from $V_{eff}(\varphi)$, and the bounce action S_B .





Higgs Winding number production

- $SU(2)_{\rm D}$ orientation of $H_{\rm D}$ is inhomogeneous in space, abundantly producing configurations with non-zero **Higgs winding number ($N_{\rm H}$) [Textures]**.



$$\Phi = (\epsilon H_{\rm D}^*, H_{\rm D}) = \frac{\sigma}{\sqrt{2}} U(\mathbf{x})$$

$$\frac{\sigma^2}{2} = {\rm Tr}\left[\Phi^\dagger \Phi\right] \;\; ; \;\; U(\mathbf{x}) \in SU(2)_{\rm D}$$

Higgs winding number ↔

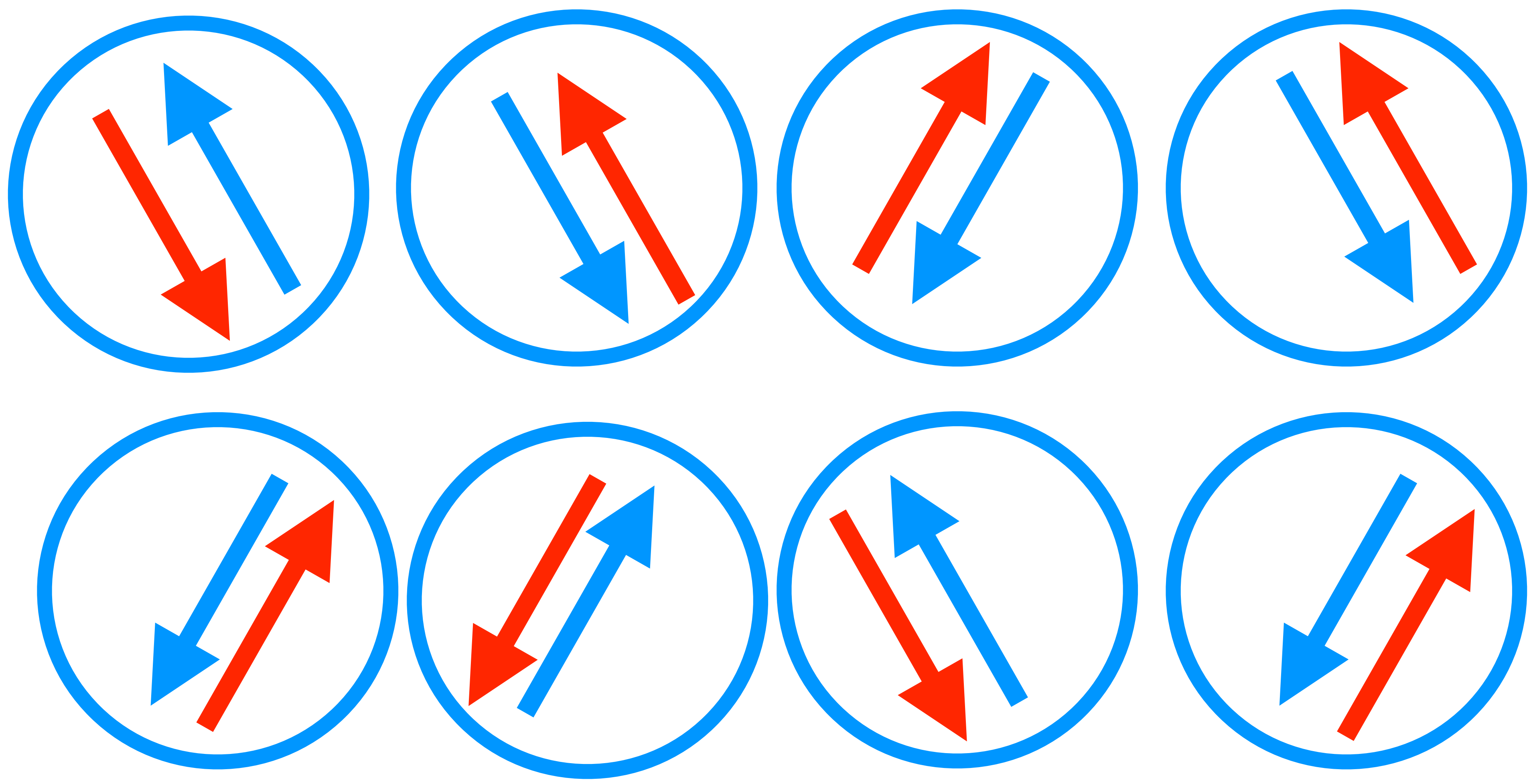
$$N_{\rm H} = \frac{1}{24\pi^2} \int d^3x \; \epsilon^{ijk} \; {\rm Tr}\left[\partial_i U U^{-1} \partial_j U U^{-1} \partial_k U U^{-1}\right]$$

CS number of the $SU(2)_{\rm D}$ gauge fields W ↔

$$N_{\rm CS} = -\frac{1}{16\pi^2} \int d^3x \; \epsilon^{ijk} \; {\rm Tr}\left[W_i \left(W_{jk} + \frac{2i}{3} W_j W_k\right)\right]$$

CS number change and production of fermions

- For H_{D} textures of size $L \gtrsim m_W^{-1}$, the gauge configurations evolve such that it cancels the Higgs gradient energy.



$$E_{\text{gradient}} \sim \left|(\partial_i - igW_i)\Phi\right| \to 0 \; .$$

$$W_i \to \frac{1}{ig}\partial_i U U^{-1}$$

- This causes a change in CS number.

$$\Delta N_{\mathrm{CS}} = \frac{g_{\mathrm{D}}^2}{32\pi^2}\int dt d^3x \ \mathrm{Tr}\left(W^{\mu\nu}\widetilde{W}_{\mu\nu}\right) \neq 0$$

- This induces **dark lepton number violation via anomaly.**

$$\partial_\mu j^\mu_{\mathrm{D_L}} = N_{\mathrm{D_L}}\frac{g_{\mathrm{D}}^2}{32\pi^2}\mathrm{Tr}\left(W^{\mu\nu}\widetilde{W}_{\mu\nu}\right)$$

Asymmetry Sharing

✦ Generated dark asymmetry $\mathscr{D}_{\rm L,in}$ is stored in L_χ , χ :

$$\mathscr{D}_{\rm L,in} \simeq 10^{-10}\left(\frac{N_{D_{\rm L}}}{2}\right)\left(\frac{\delta_{\rm CP}}{10^{-4}}\frac{\varphi^2_{\rm min}}{\Lambda^2_{\rm CP}}\right)\left(\frac{\alpha_{\rm D}}{1.5\times10^{-2}}\right)^4\left(\frac{\lambda}{10^{-4}}\right)^{-3/2}\left(\frac{5v_{\rm D}}{\varphi_{\rm min}}\right)^{1/2}\left(\frac{\varphi_{\rm min}}{3T_{\rm RH}}\right)^3$$

✦ The asymmetry is shared with the dark baryon and SM via effective interactions:

Baryonic DM composed of f ($\mathbb{Z}_2$ odd)

$$\mathcal{O}_{\rm D} \sim \frac{1}{\Lambda^2_{\rm D}} p_{\rm D} p_{\rm D}\chi\chi \quad ; \quad \mathcal{O}_n \sim \frac{1}{\Lambda^2_n}\chi u_{\rm R} d_{\rm R} d_{\rm R}$$

Mono-jet searches ($ud \to \bar{\chi}\bar{d}, dd \to \bar{\chi}\bar{u}$) in colliders. Current constraint $\Lambda_n \gtrsim 2$ TeV. For equilibrium at GeV $\Lambda_n \lesssim 15$ TeV.

✦ Asymmetries in the visible sector $\mathscr{B}_f$ and dark baryon sector $\mathscr{D}_{\rm B}$ can be related:

$$\mathscr{B}_f = \left[\frac{2+4N_{D_{\rm L}}}{4N_{D_{\rm L}}+N_{D_{\rm B}}+2}\right]\mathscr{D}_{\rm L,in} \quad ; \quad \mathscr{D}_{\rm B} = \left[\frac{N_{D_{\rm B}}}{4N_{D_{\rm L}}+N_{D_{\rm B}}+2}\right]\mathscr{D}_{\rm L,in} \quad ; \quad m_{p_{\rm D}} \simeq 5\left|\frac{\mathscr{B}_f}{\mathscr{D}_{\rm B}}\right| \text{GeV}$$

✦ The DM is **self-interacting** via the mediation of dark pions $\pi_{\rm D}$ with cross-section:

$$\frac{\sigma_{p_{\rm D}p_{\rm D}}}{m_{p_{\rm D}}} \sim 1\ {\rm cm^2/g}\left(\frac{\Lambda_{\rm H,0}}{m_{p_{\rm D}}}\right)\left(\frac{\Lambda_{\rm H,0}}{a_{\rm D}^{-1}}\right)^2\left(\frac{150\ {\rm MeV}}{\Lambda_{\rm H,0}}\right)^3 \quad ;$$

$a_{\rm D}$ **: scattering length .**

Tulin Yu (2017) ; Kribs (2016)

Simulation of CS number production during bubble collisions

Servant et. al. (2025)

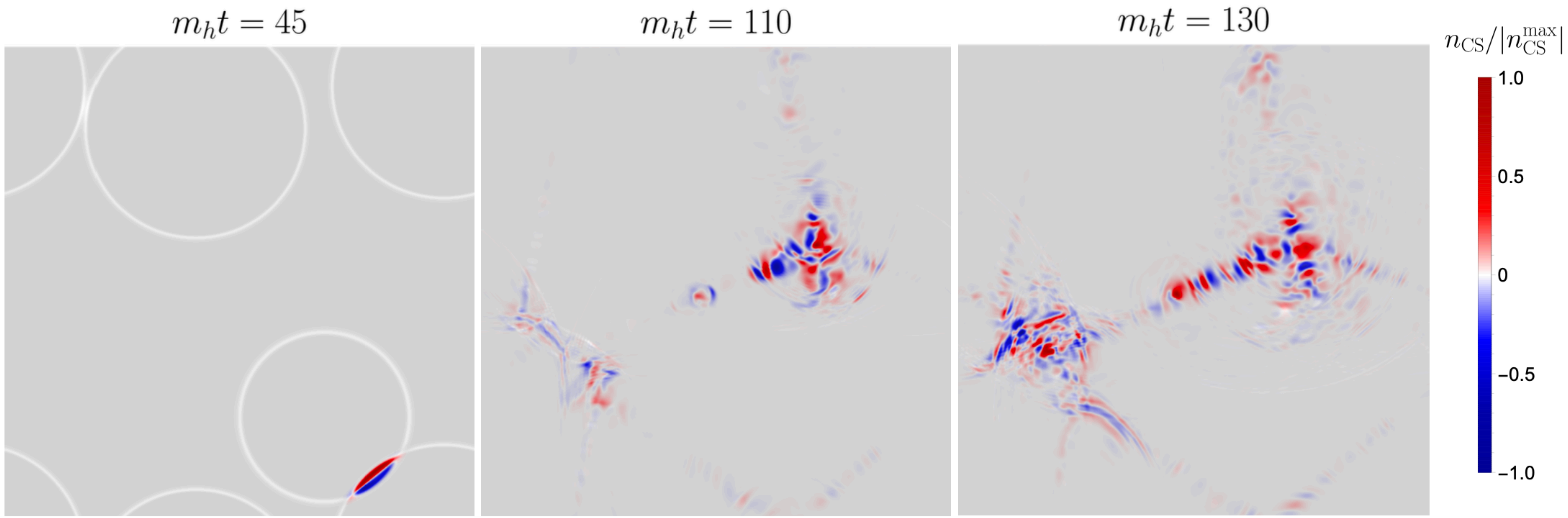
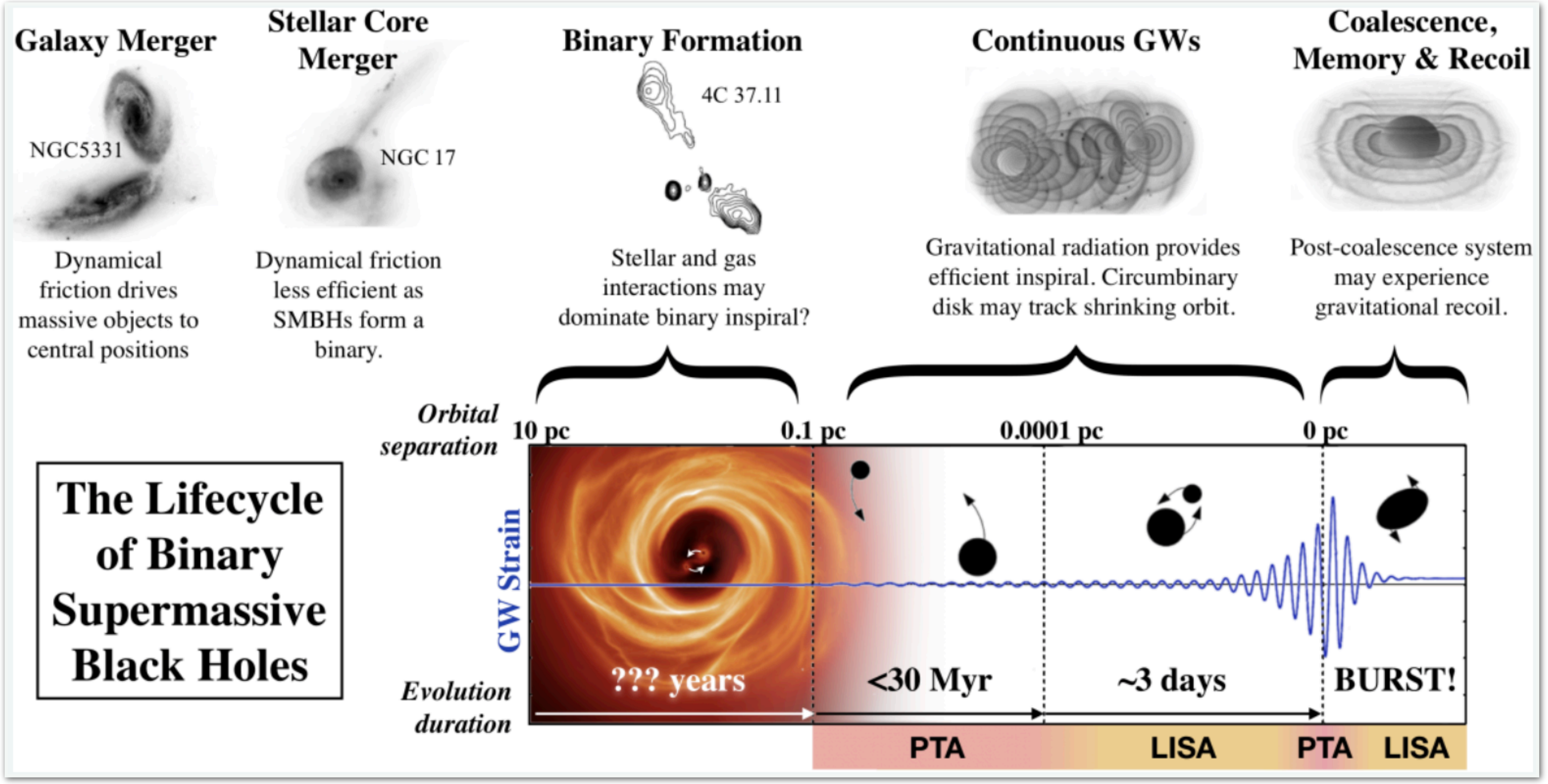


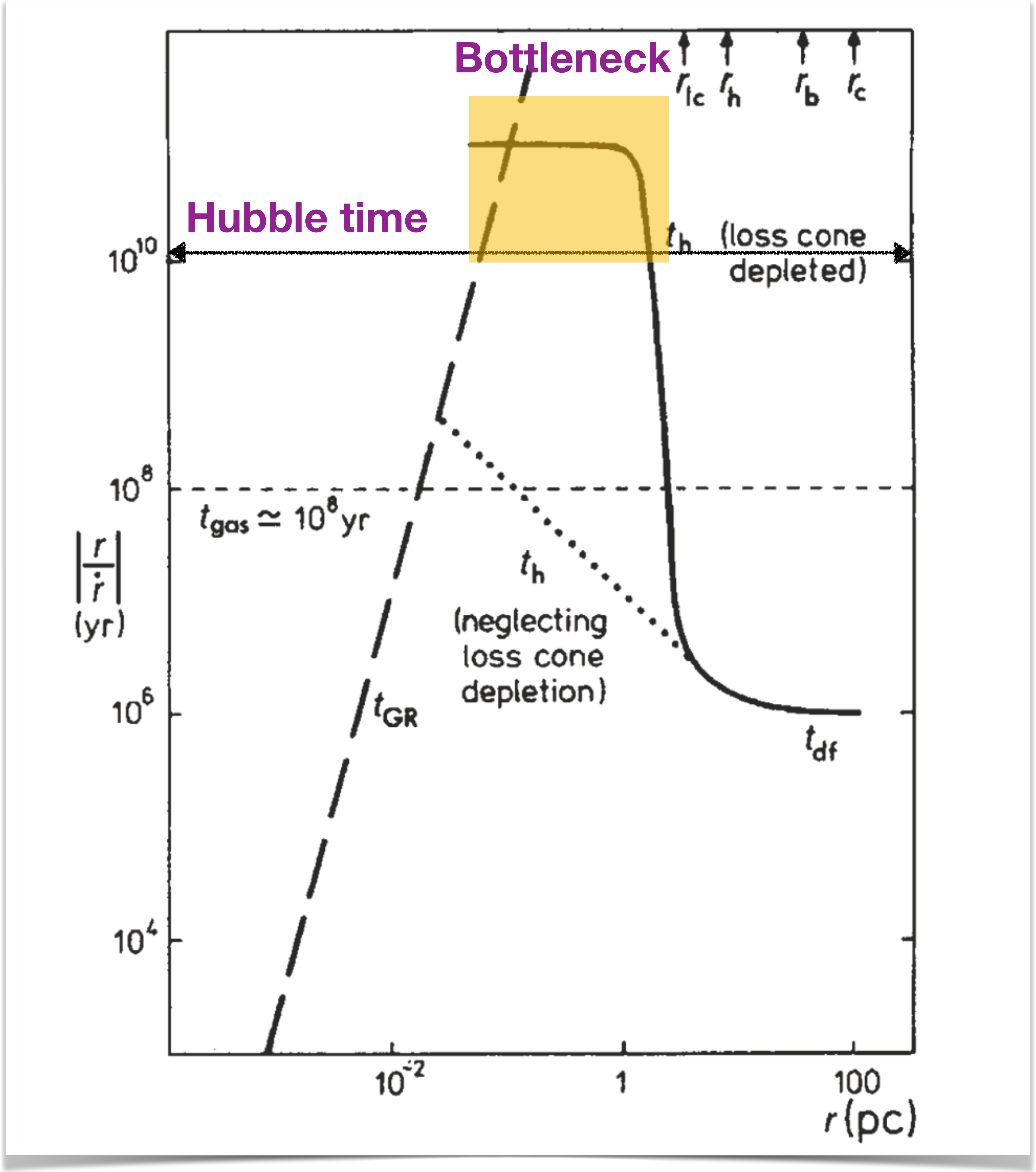
Figure 1. Snapshots of a two-dimensional slice of the Chern–Simons number density $n_{\rm CS}$ (red/blue) produced in our (3+1)D simulations from the collision of Higgs bubble walls (white), defined by $N_{\rm CS}(t) = \int d^3x\, n_{\rm CS}(t,x)$, where $n_{\rm CS} = (g^2/16\pi^2)\epsilon^{ijk}\,{\rm Tr}\left[W_i W_{jk} + \frac{2}{3} i g W_i W_j W_k\right]$, for the potential degeneracy parameter $\epsilon = 0.32$, normalized to its maximum value over the slice $n_{\rm CS}^{\rm max}(t)$. See here for an animation.

A note about the final parsec problem



Orbital separation of ~ 0.01 pc is needed to emit gravitational waves efficiently.

Solutions: triaxiality, multiple BHs, ...



Begelman, Blandford, Rees 1980

Results from Multi-Model Analysis (MMA)

Ellis et. al. 2308.08546

Scenario	Best-fit parameters	ΔBIC	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.07$	6.0	FAPS, LISA, mid-f, ~~LVK, ET~~
GW + environment-driven SMBH binaries	$p_{\rm BH} = 0.84$ $\alpha = 2.0$ $f_{\rm ref} = 34$ nHz	Baseline (BIC = 53.9)	FAPS, LISA, mid-f, ~~LVK, ET~~
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.2 (4.6)	~~FAPS~~, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.34$ GeV $\beta/H = 6.0$	-4.9 (2.9)	~~FAPS, LISA, mid-f, LVK, ET~~
Domain walls (DWs)	$T_{\rm ann} = 0.85$ GeV $\alpha_* = 0.11$	-5.7 (2.2)	~~FAPS~~, LISA?, ~~mid-f, LVK, ET~~
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.7}$/Mpc $A = 0.06$ $\Delta = 0.21$	-2.1 (5.8)	~~FAPS, LISA, mid-f, LVK, ET~~
First-order GWs (FOGWs)	$\log_{10} r = -14$ $n_{\rm t} = 2.6$ $T_{\rm rh} = -0.67$ GeV	-2.0 (6.0)	~~FAPS, LISA, mid-f, LVK, ET~~
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\rm P}$	-4.2 (3.7)	~~FAPS, LISA, mid-f, LVK, ET~~

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [308], AEDGE [310], LVK ≡ LIGO/Virgo/KAGRA [161–163], ET ≡ Einstein Telescope [312] (or Cosmic Explorer [313]), ~~signature~~ ≡ not detectable