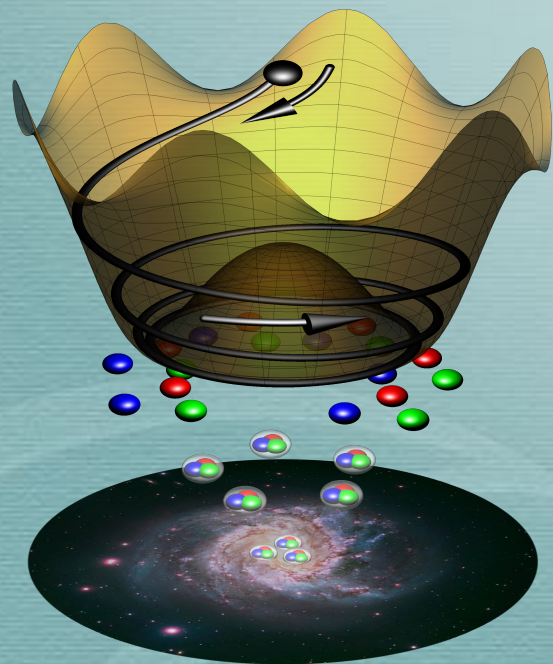


03/10/2021, IBS-CTPU

Axion Kinetic Misalignment and Baryogenesis

Keisuke Harigaya (IAS)



[1910.02080](#) : Co and KH

[1910.14152](#) : Co, Hall and KH

[2006.04809](#) : Co, Hall and KH

[2006.05687](#) : Co, Fernandez, Ghalsasi, Hall and KH

Questions in particle physics

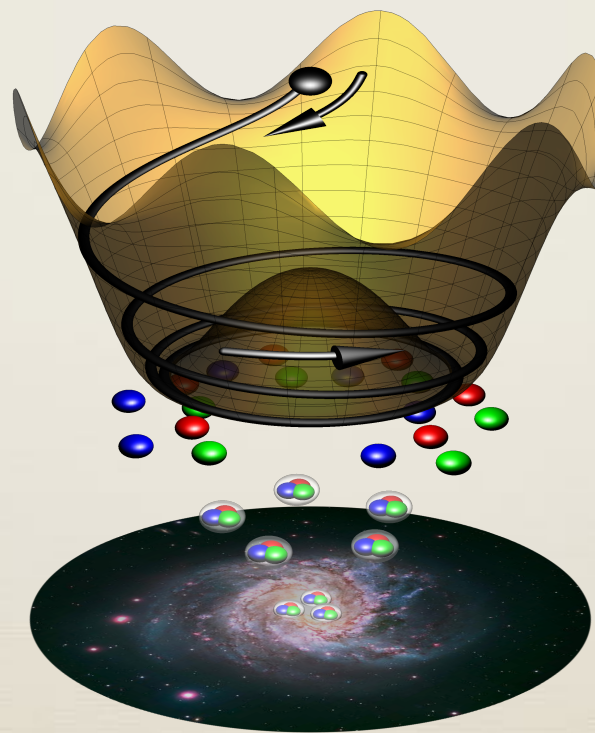
- * What is dark matter?
- * How did cosmic inflation occur?
- * How was the baryon asymmetry of the universe created?
- * Why does QCD preserve CP symmetry?
- * What sets the Higgs potential parameters?
- *

Questions in particle physics

- * What is dark matter?
- * How did cosmic inflation occur?
- * How was the baryon asymmetry of the universe created?
- * Why does QCD preserve CP symmetry?
- * What sets the Higgs potential parameters?
- *

Summary

New cosmological dynamics of the QCD axion
and an axion-like particle (ALP)



Summary

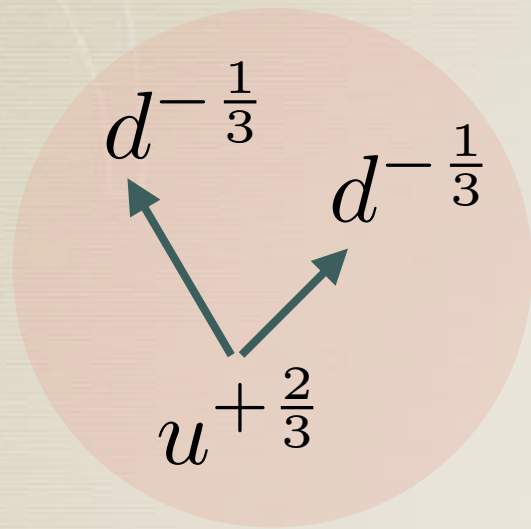
New cosmological dynamics of the QCD axion
and an axion-like particle (ALP)

- * explains **dark matter** for axion coupling constants much larger the prediction of conventional mechanisms
- * creates the **baryon asymmetry** of the universe
- * have implications for electroweak physics and axion searches

Outline

- * Introduction: QCD axion, ALP, and dark matter
- * Rotation of axion and kinetic misalignment
- * Baryon asymmetry from axion rotation
- * Summary

The strong CP problem



Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm} ?$$

$$d_n/e < 2.9 \times 10^{-26} \text{ cm} \quad \text{Baker et.al (2006)}$$

Suggests CP symmetry forbidding $H = d_n \vec{E} \cdot \vec{S}$

But CP violation from quark masses is essential for CKM phase

Strong CP problem

't Hooft (1976)

Known Solutions

- * Spontaneously broken parity
- * Spontaneously broken CP
- * QCD axion

Known Solutions

* **Spontaneously broken parity**

* Spontaneously broken CP

* QCD axion

Mohapatra and Senjanovic (1978)

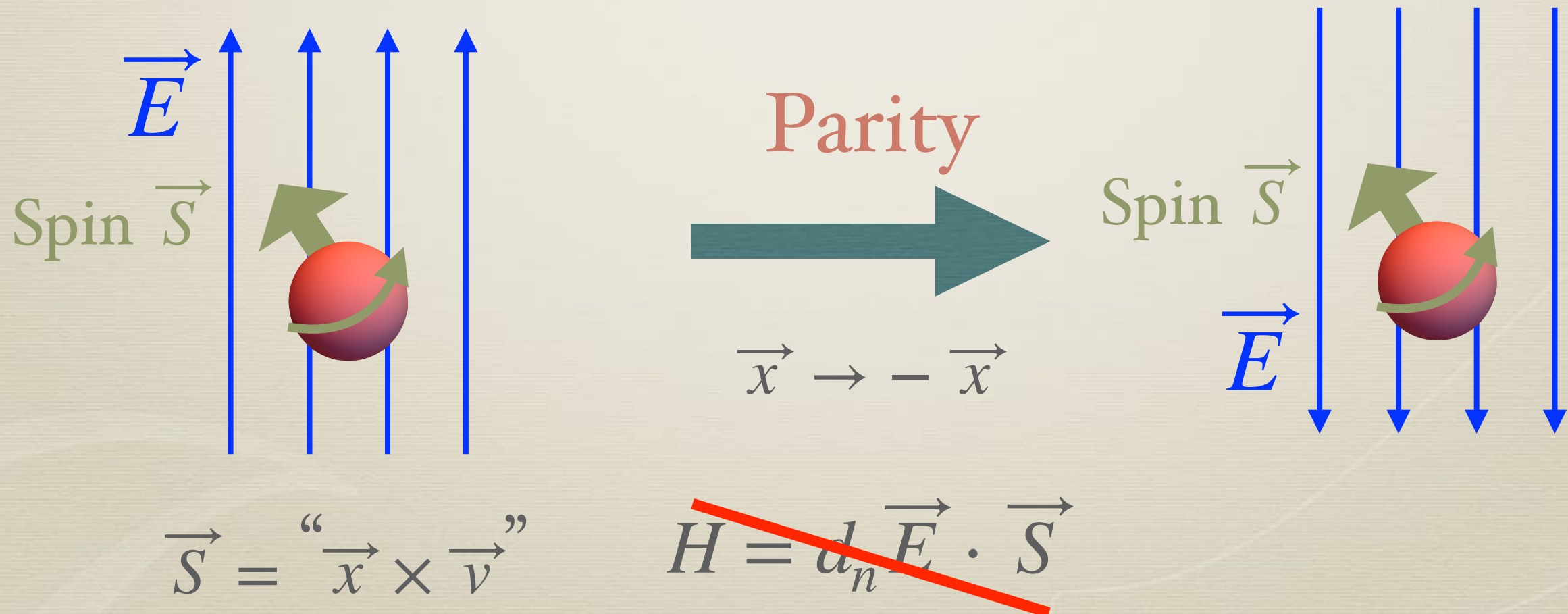
Beg and Tsao (1978)

Babu and Mohapatra (1989)

Barr, Chang and Senjanovic (1991)

Hall and KH (2018, 2019)

Dunsky, Hall and KH (2019)



Known Solutions

- * **Spontaneously broken parity**

- * Spontaneously broken CP

- * QCD axion

Mohapatra and Senjanovic (1978)

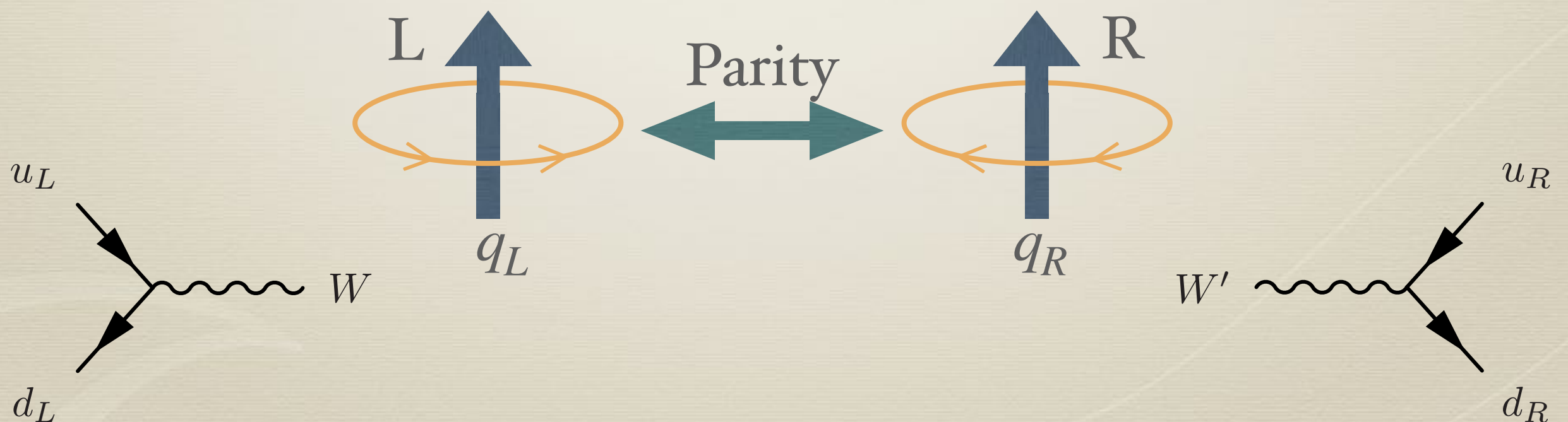
Beg and Tsao (1978)

Babu and Mohapatra (1989)

Barr, Chang and Senjanovic (1991)

Hall and KH (2018,2019)

Dunsky, Hall and KH (2019)



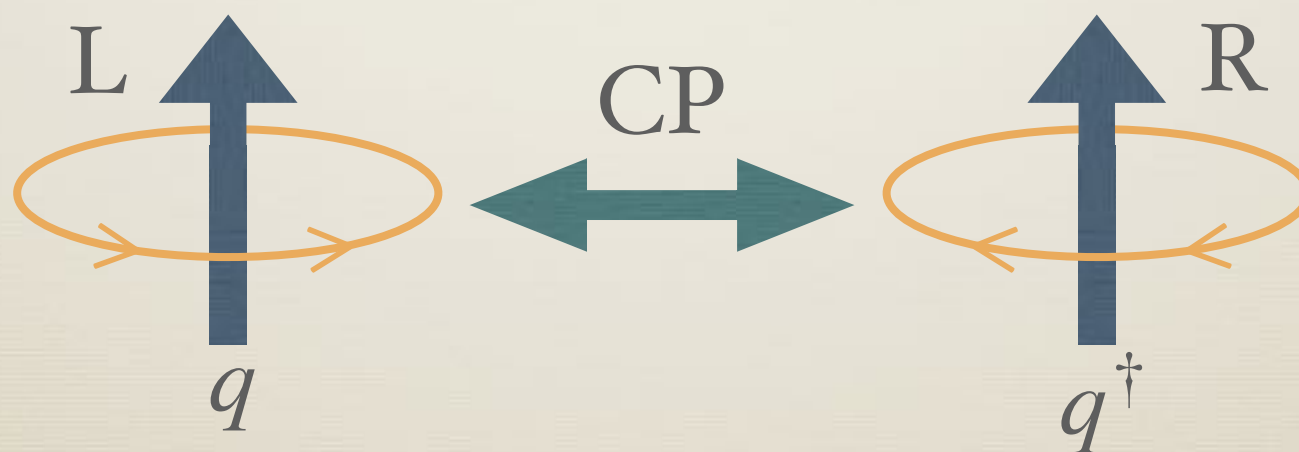
Known Solutions

- * Spontaneously broken parity

Nelson (1984), Barr (1984)

- * Spontaneously broken CP

- * QCD axion

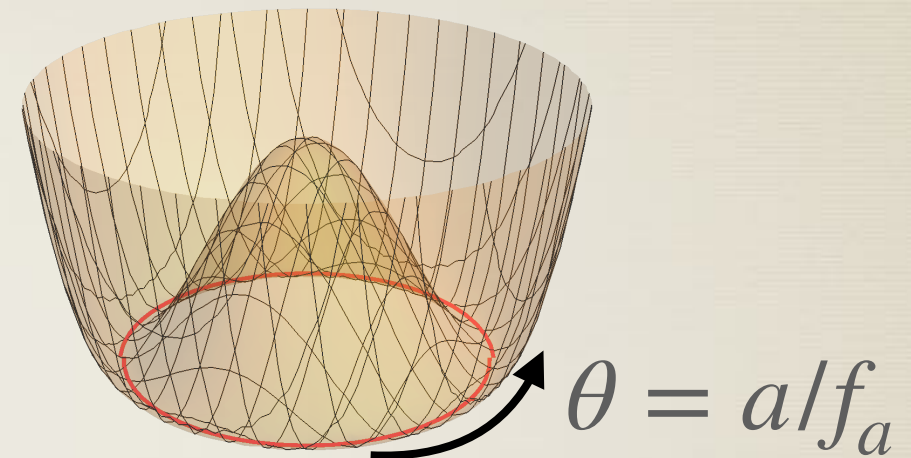


Breaks CP spontaneously to introduce CP phases in quark masses,
but without introducing the strong CP phase

Known Solutions

Peccei and Quinn (1977)
Weinberg (1978), Wilczek (1978)

- * Spontaneously broken parity
- * Spontaneously broken CP
- * **QCD axion**



U(1) global symmetry with QCD anomaly : PQ symmetry



Spontaneous breaking

pseudo-Nambu Goldstone boson, the QCD axion

$$\mathcal{L} = \frac{1}{32\pi^2} \frac{a}{f_a} G\tilde{G}$$

f_a : the decay constant

Known Solutions

Peccei and Quinn (1977)

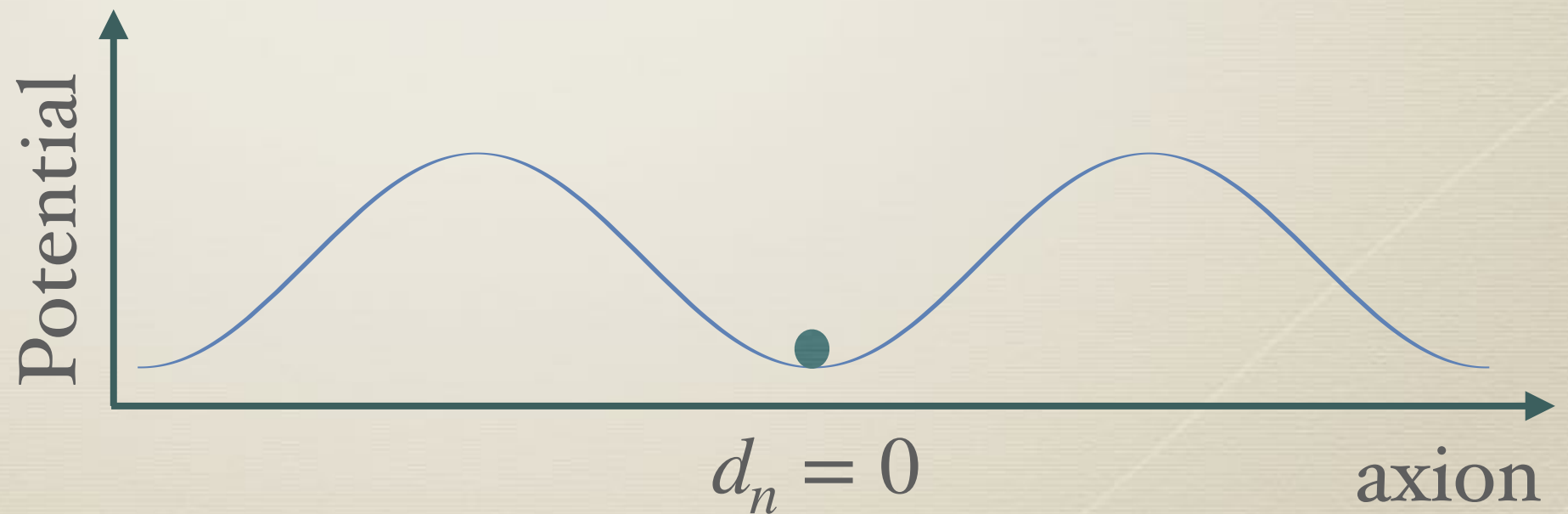
Weinberg (1978), Wilczek (1978)

- * Spontaneously broken parity

- * Spontaneously broken CP

- * **QCD axion**

$$\frac{1}{32\pi^2} \frac{a}{f_a} G\tilde{G}$$



so are other CP violations in QCD

ex . $\eta \rightarrow \pi^+ \pi^-$

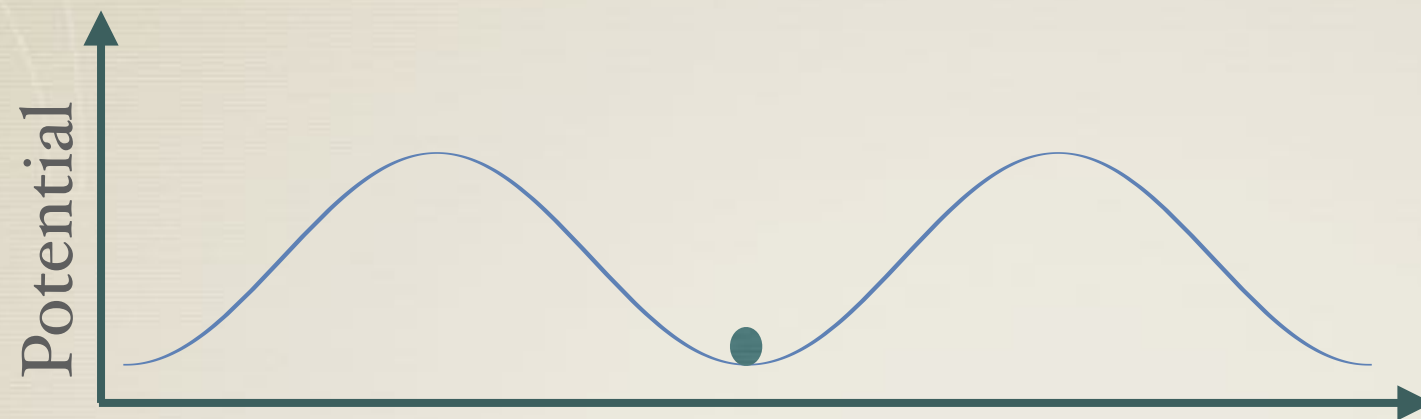
Known Solutions

- * Spontaneously broken parity
- * Spontaneously broken CP
- * QCD axion
- *

Why QCD axion ?

QCD axion dark matter

Preskill, Wise and Wilczek (1983),
Abbott and Sikivie (1983),
Dine and Fischler (1983)



Axion is light $m_a = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$ Weinberg (1978)

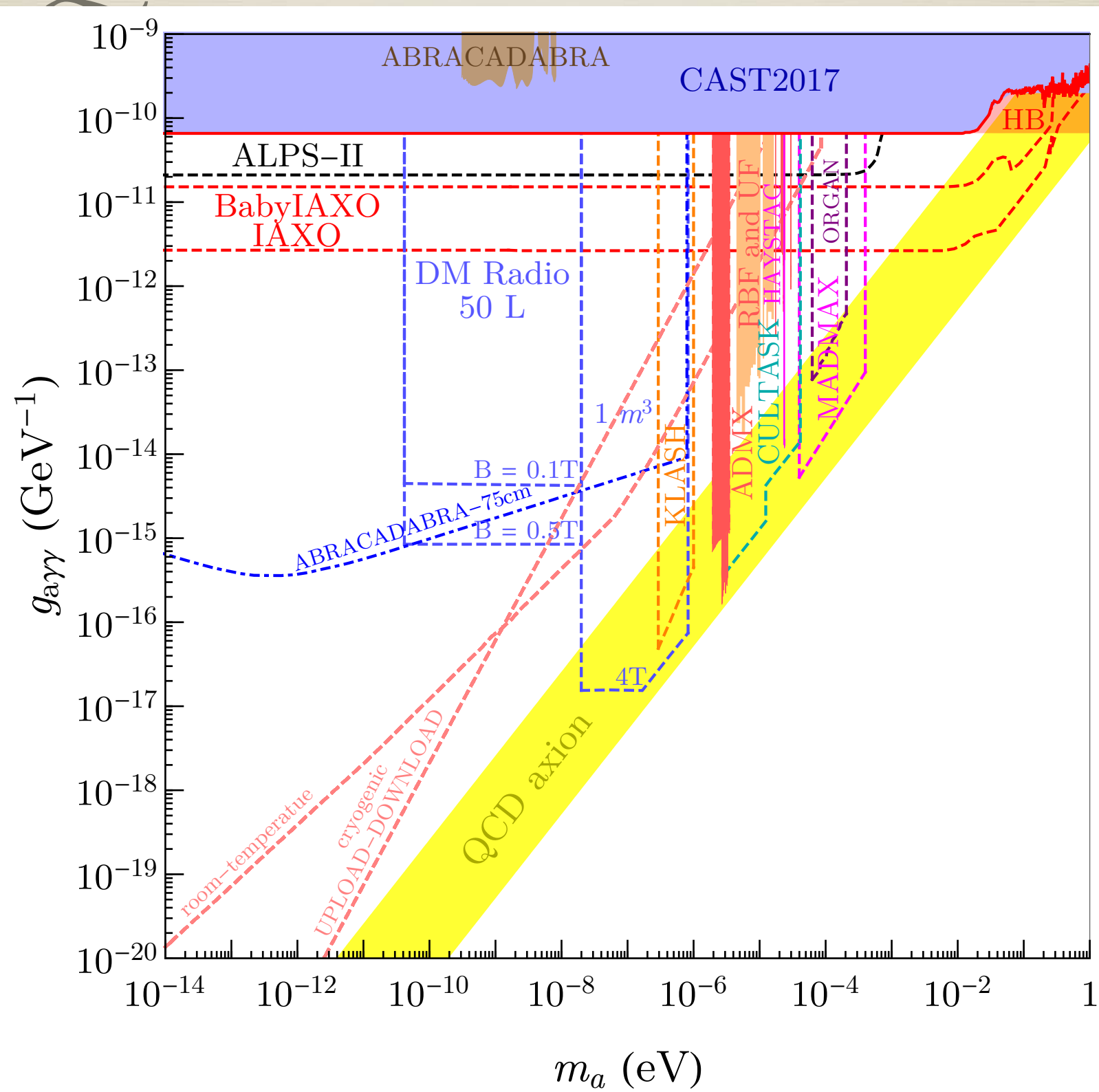
and weakly coupled

$$a \text{ --- } \gamma \gamma \propto \frac{1}{f_a}$$

➔ long-lived $\tau_a \sim 10^{17} \times t_{\text{univ}} \left(\frac{f_a}{10^9 \text{ GeV}} \right)^5$

Dark Matter candidate

QCD axion search



ALP dark matter

A pseudo-Nambu Goldstone boson from some global symmetry

naturally light

and weakly coupled



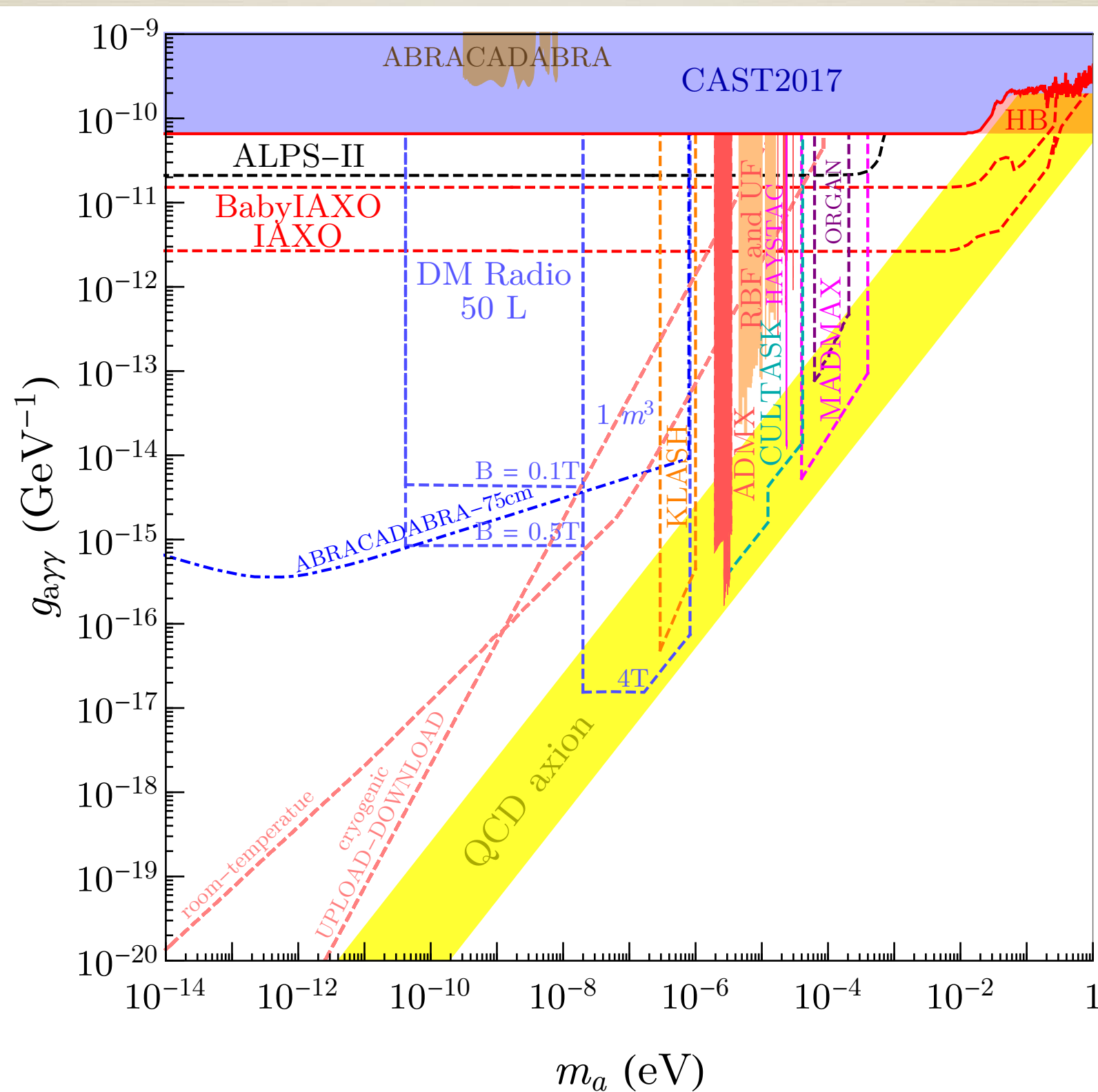
naturally long-lived

$$a \text{ --- } \begin{array}{c} \gamma \\ \gamma \end{array} \propto \frac{1}{f_a}$$

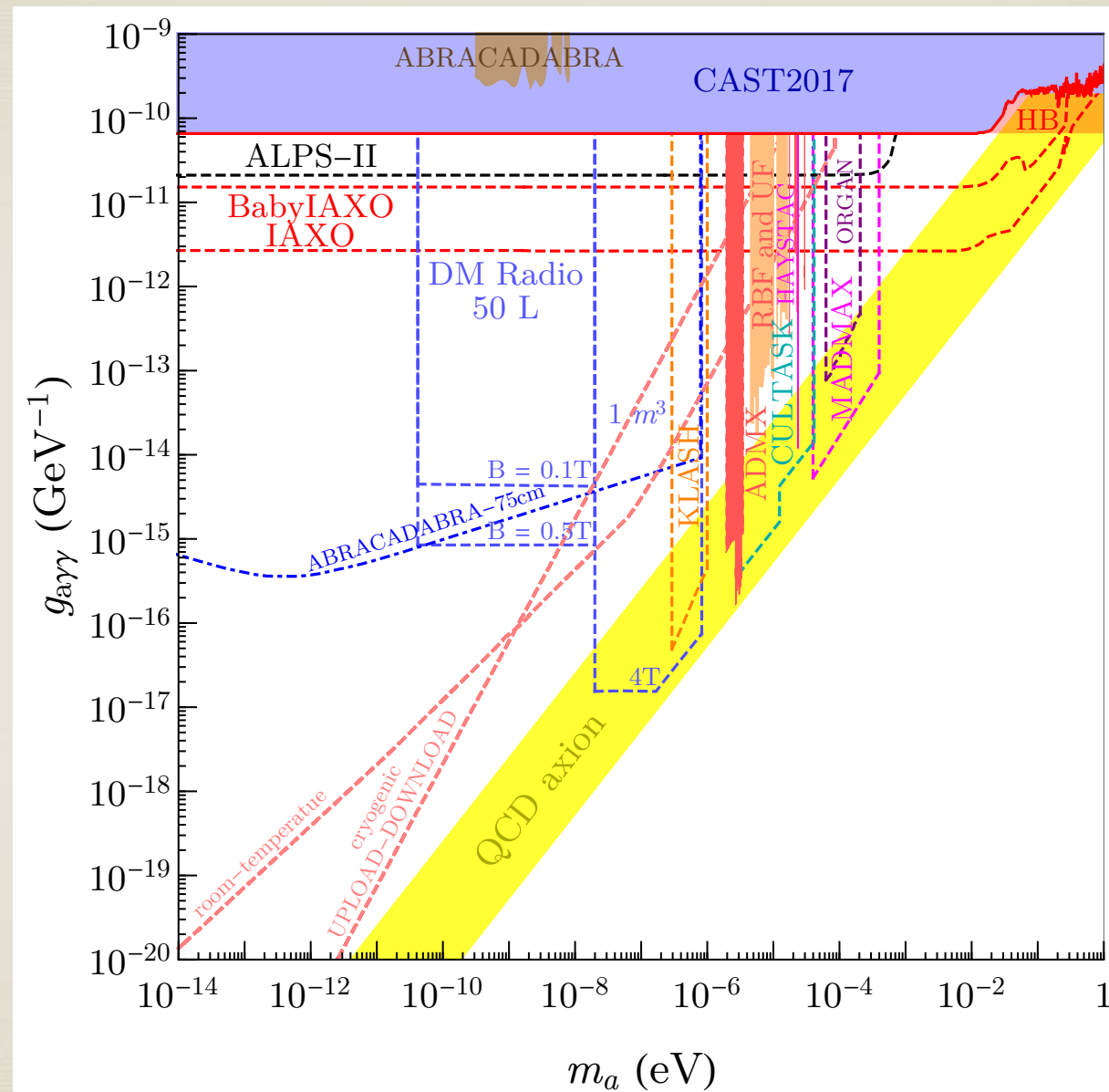
$$\tau_a \sim 10^{10} \times t_{\text{univ}} \left(\frac{f_a}{10^9 \text{ GeV}} \right)^2 \left(\frac{\text{eV}}{m_a} \right)^3$$

Dark Matter candidate

Axion search



Dark matter?

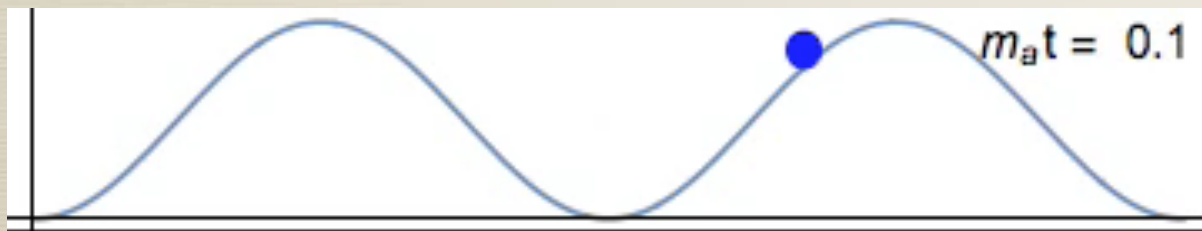
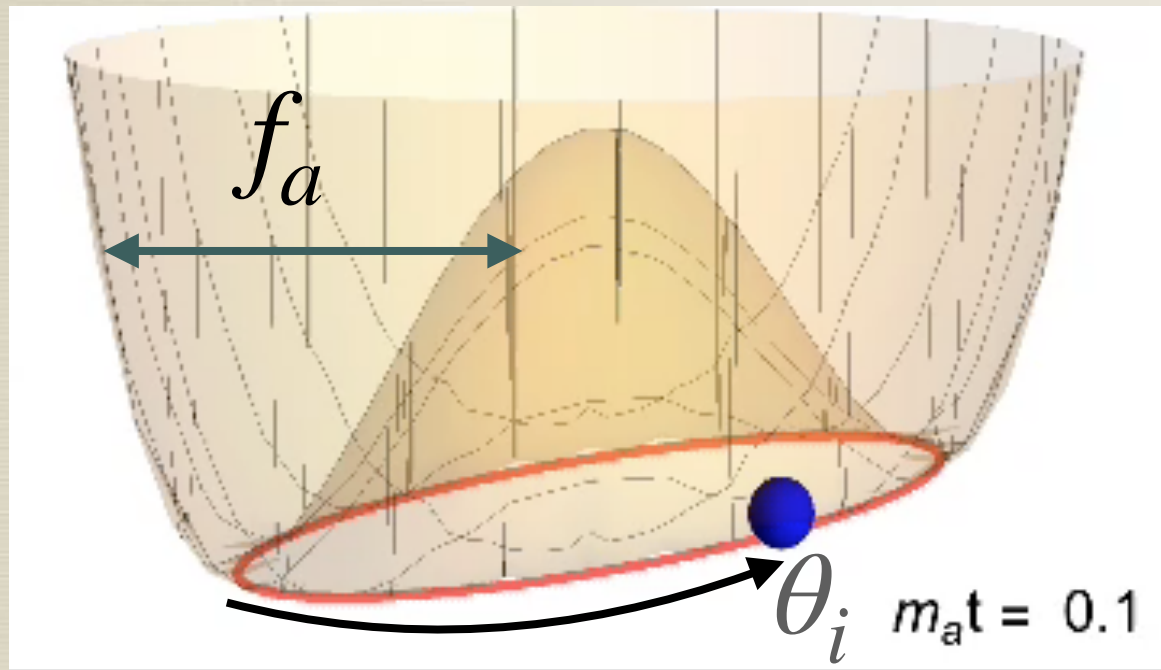


$$\rho_{\text{DM}} \simeq 1.3 \times 10^{-5} \text{ GeV/cm}^3 \quad (\text{Planck 2018})$$

Can axions of this amount be produced in the early universe?

Misalignment mechanism

Preskill, Wise and Wilczek (1983),
Abbott and Sikivie (1983),
Dine and Fischler (1983)



For the QCD axion,

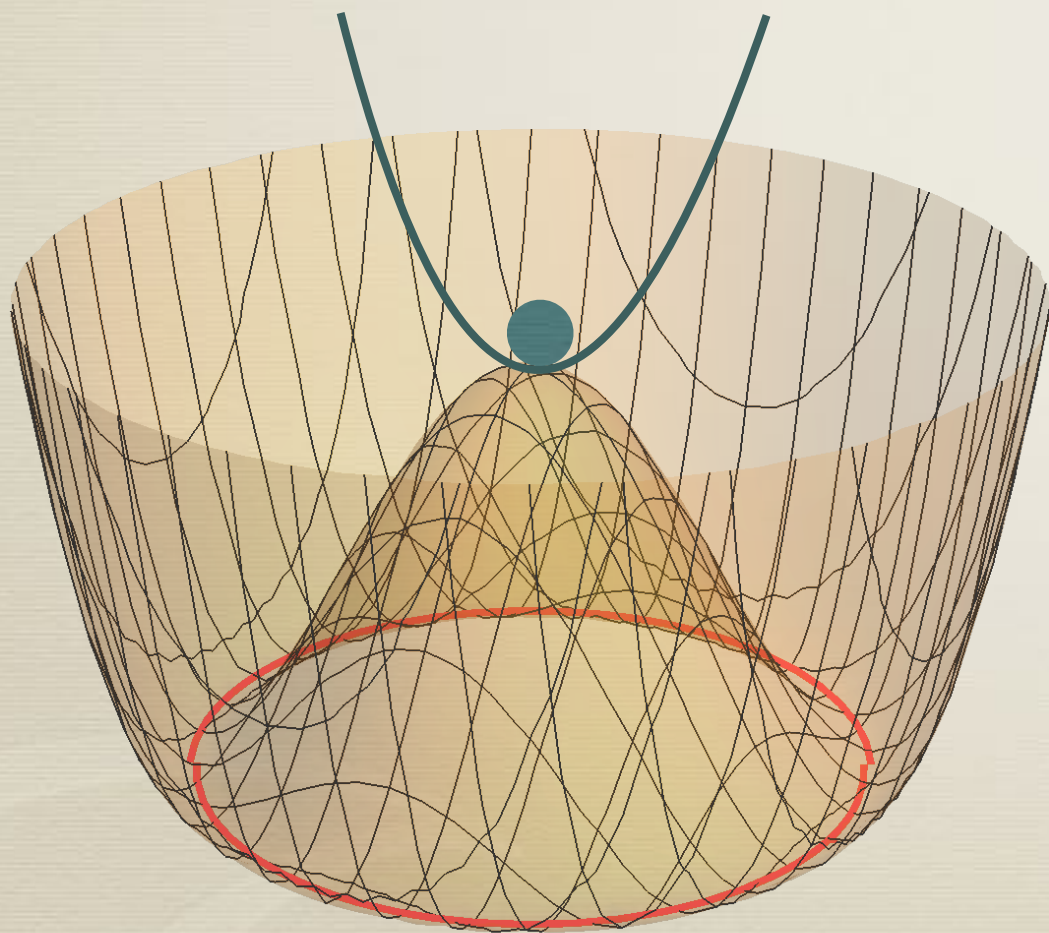
$$\frac{\rho_a}{\rho_{\text{DM}}} = \theta_i^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.19}$$

$$m_a = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

animation is available at <http://www.sns.ias.edu/~keisukeharigaya/mm.html>

Cosmic strings

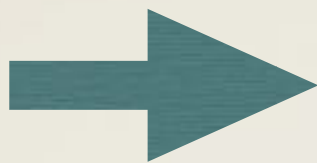
trapping by thermal potential,
coupling with inflaton, etc.



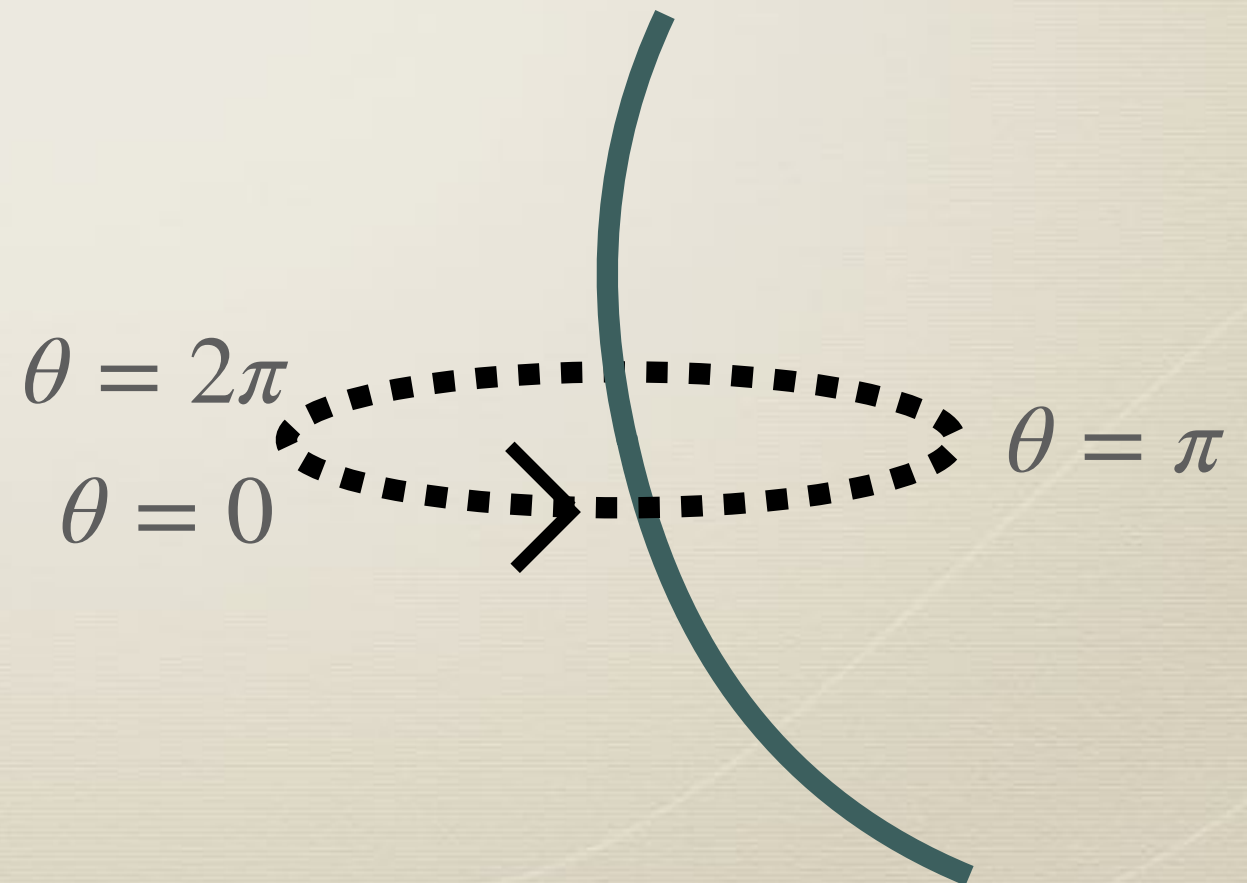
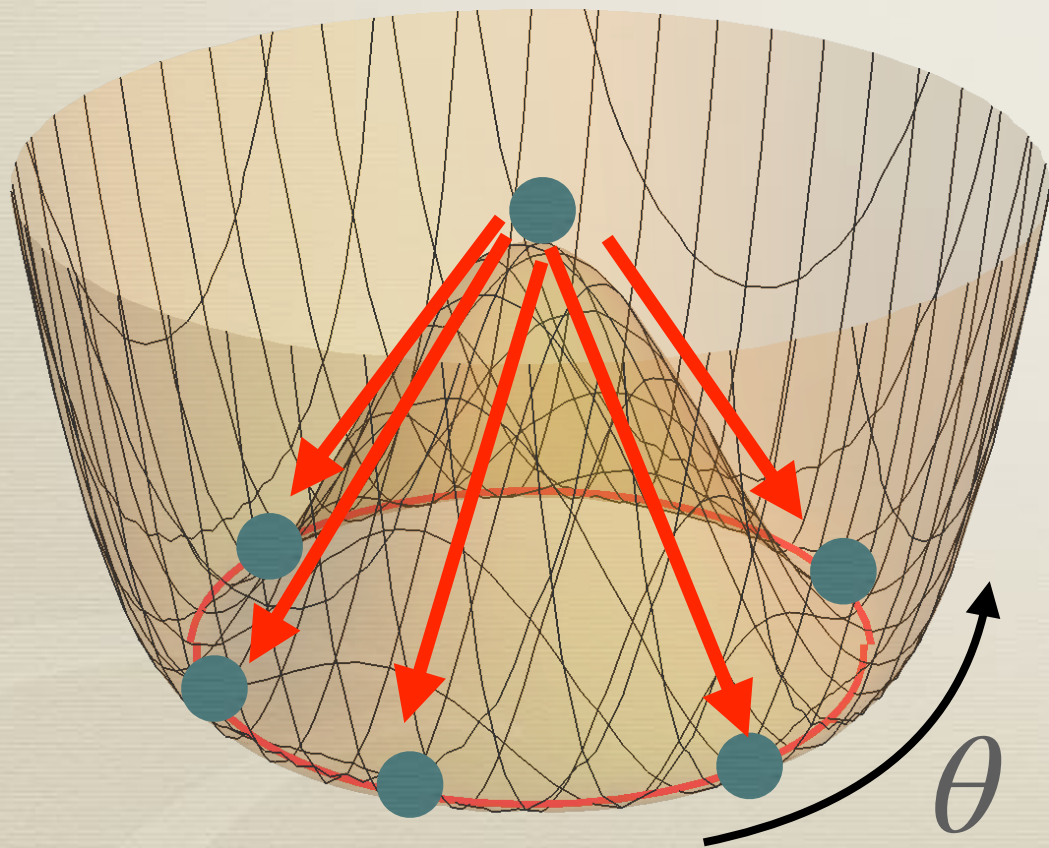
$$V = (-m^2 + c_T T^2 + c_H H_{\text{inf}}^2) |P|^2 + \dots$$

Cosmic strings

Phase transition

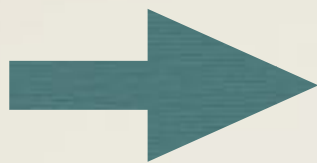


Inhomogeneous configurations
including cosmic strings



Cosmic strings

Phase transition



Inhomogeneous configurations
including cosmic strings

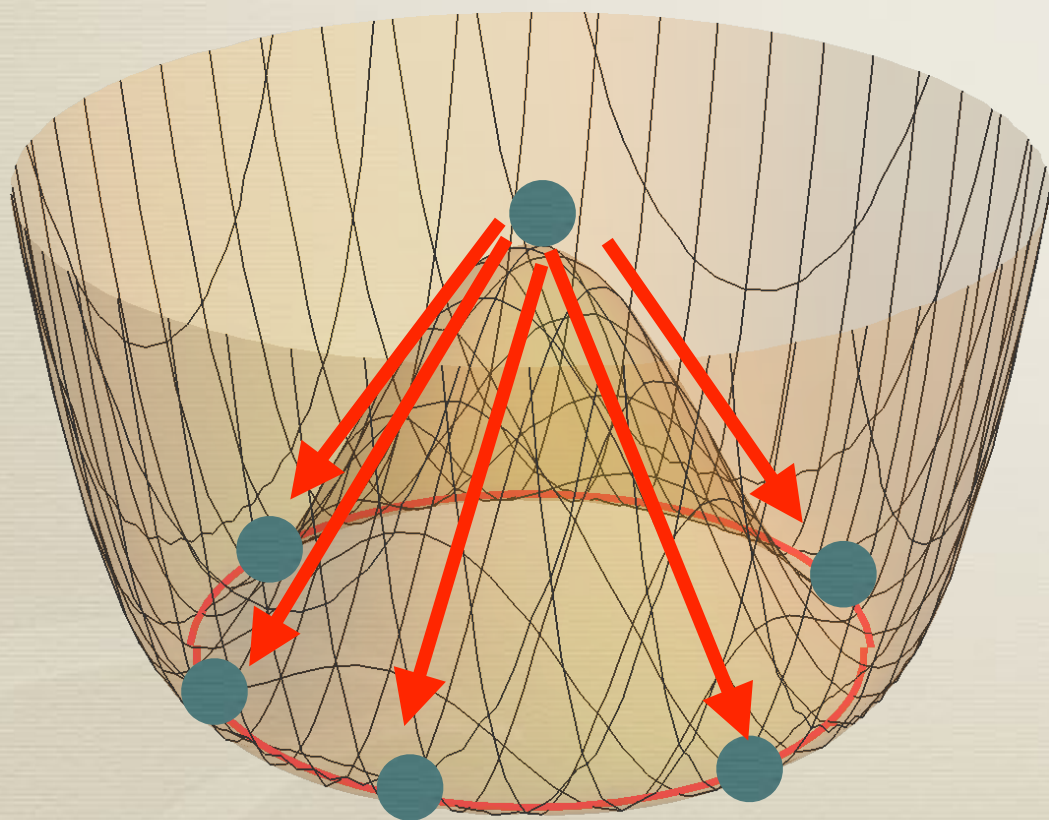


Axions are radiated

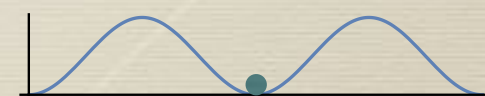
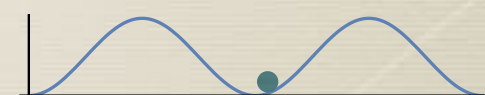
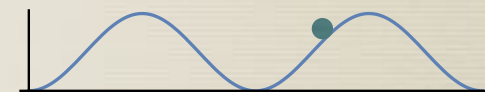
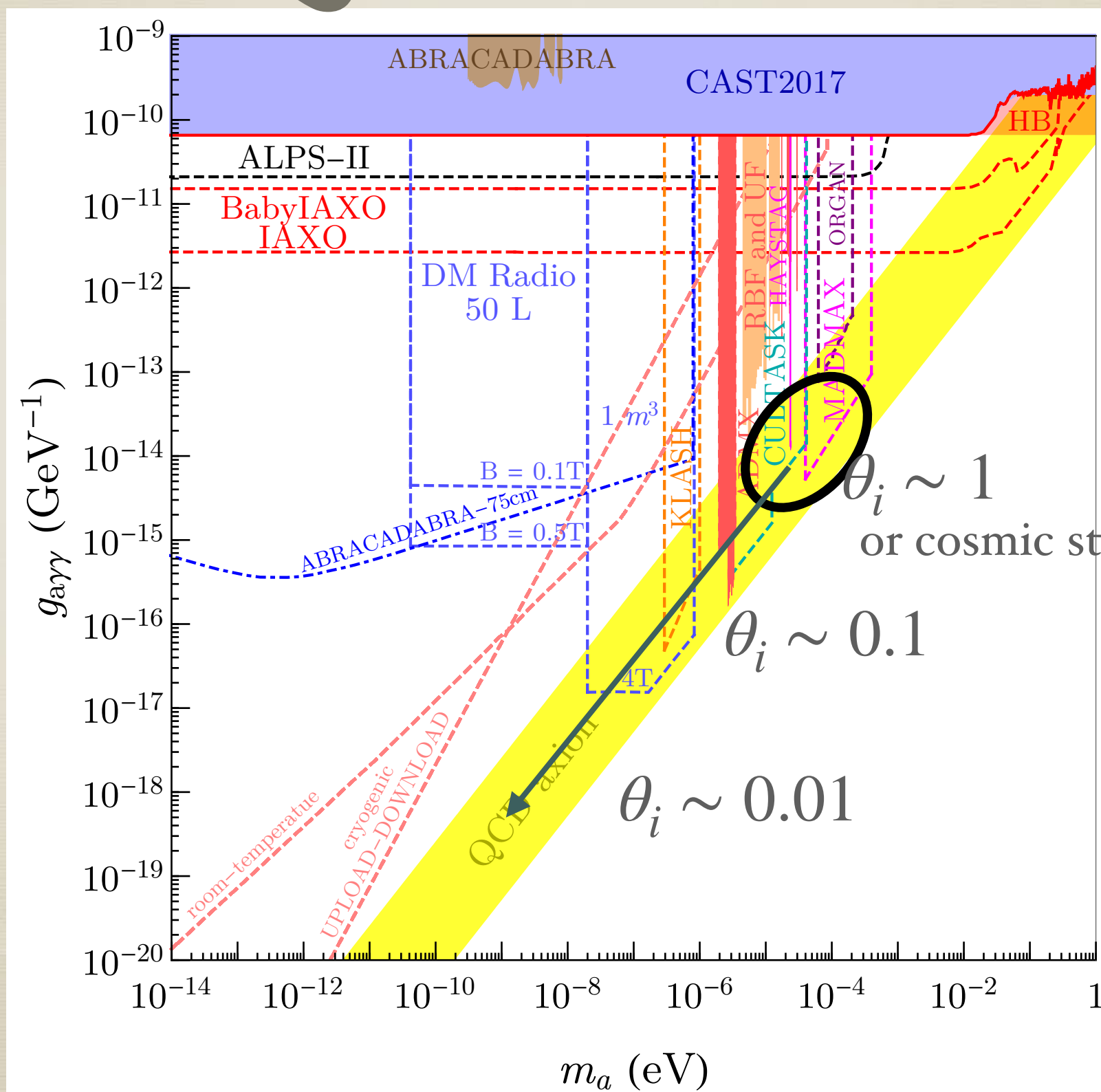
Davis (1986)

$$\frac{\rho_a}{\rho_{\text{DM}}} = 0.4 - 10 \left(\frac{f_a}{10^{11} \text{ GeV}} \right)^{1.19}$$

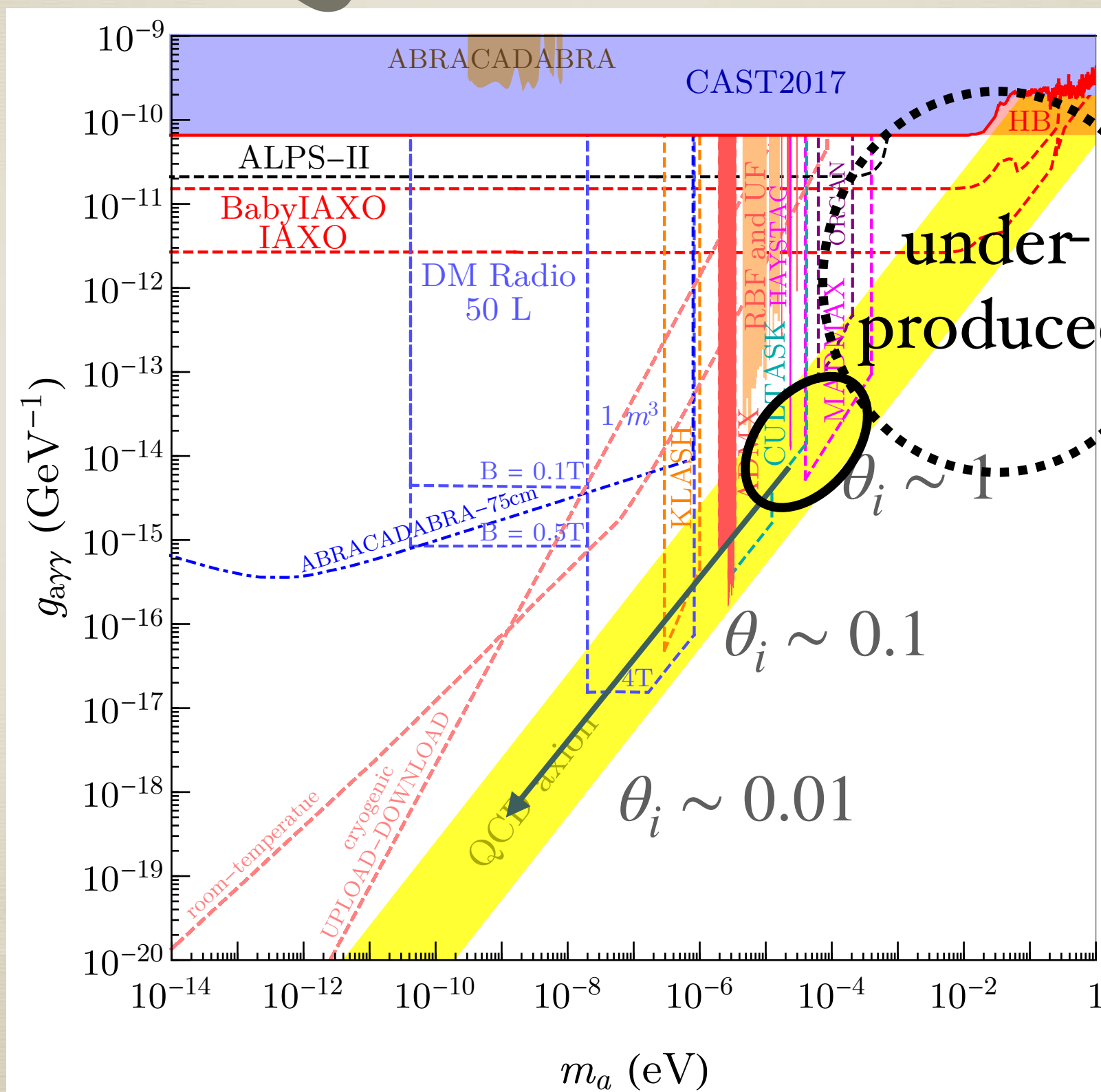
e.g. Kawasaki, Saikawa and Sekiguchi (2015),
Klaer and Moore (2017),
Gorghetto, Hardy and Villadoro (2020)



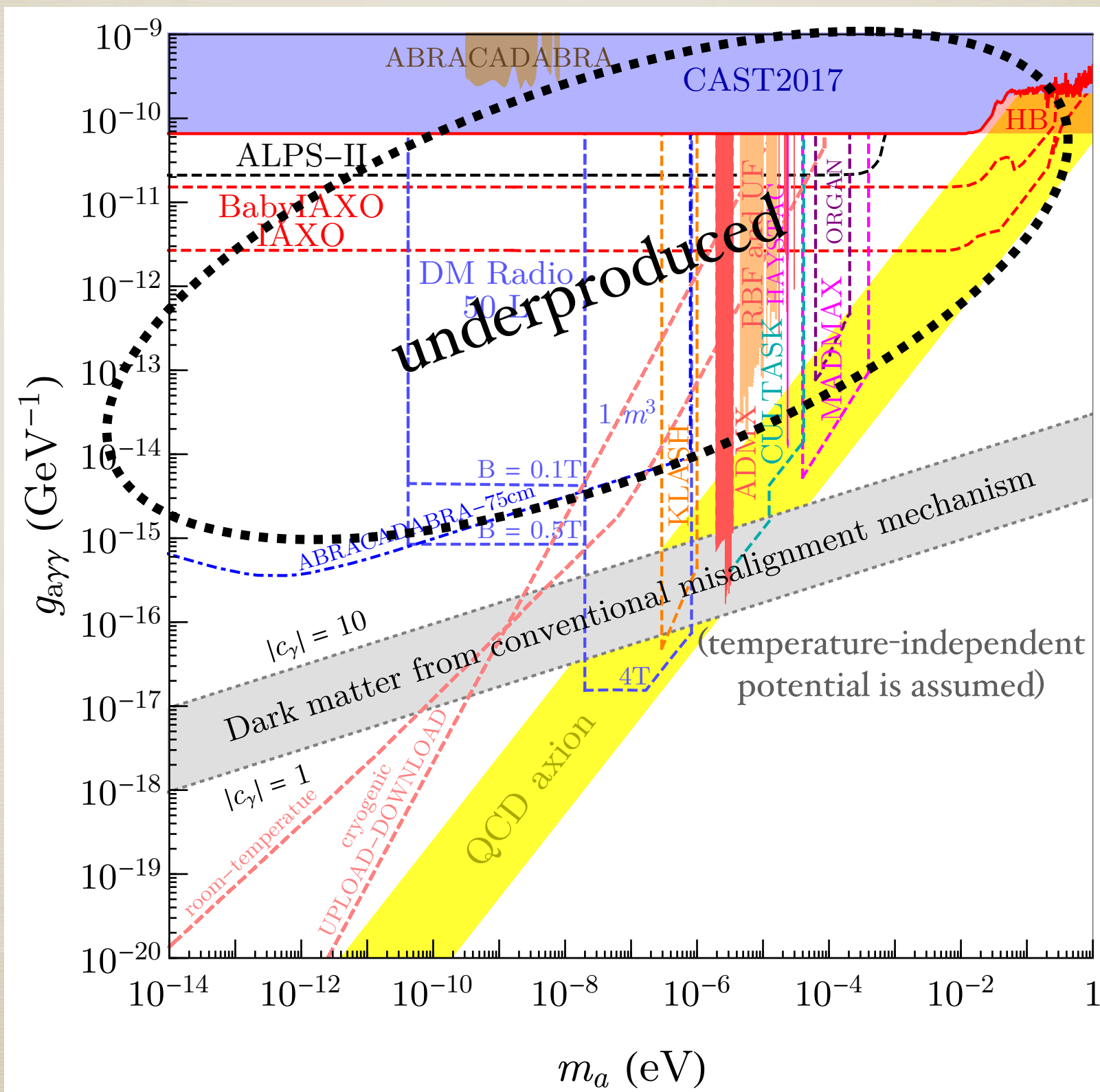
QCD axion



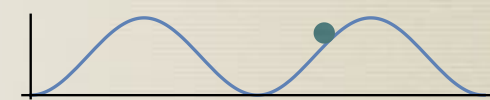
QCD axion



Axion Like Particle



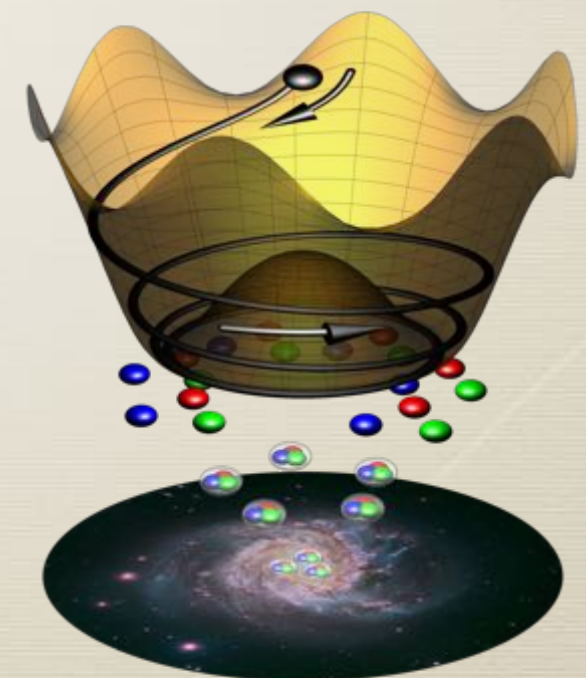
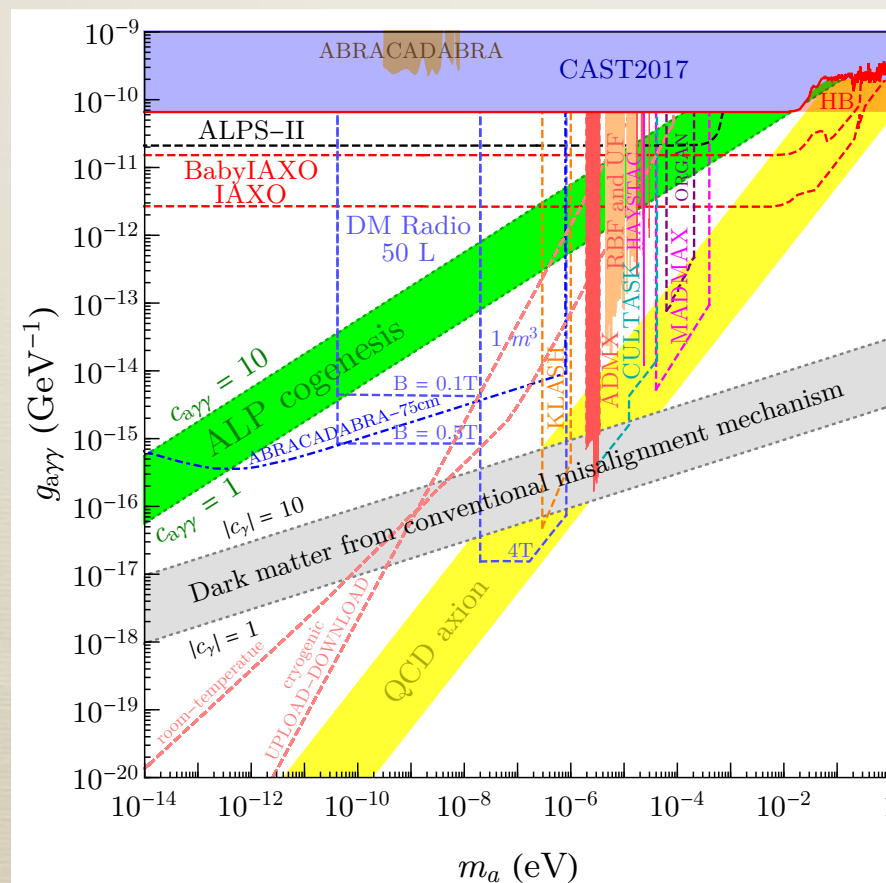
$$\theta_i \sim 1$$



$$\theta_i \ll 1$$

I will present new cosmological dynamics of an axion

- * enhance axion dark matter abundance and predict **larger couplings**
- * create **baryon asymmetry**
- * have implications for electroweak physics and axion searches



Outline

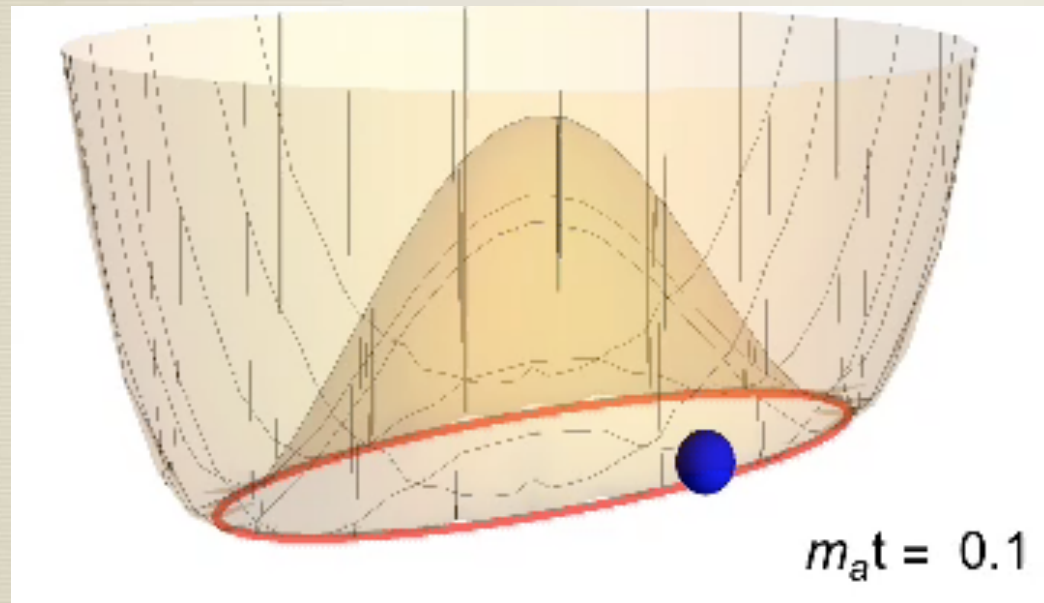
- * Introduction: QCD axion, ALP, and dark matter
- * Rotation of axion and kinetic misalignment
- * Baryon asymmetry from axion rotation
- * Summary



Rotation?

Co and KH(2019)
Co, Hall and KH(2020)

Conventional picture

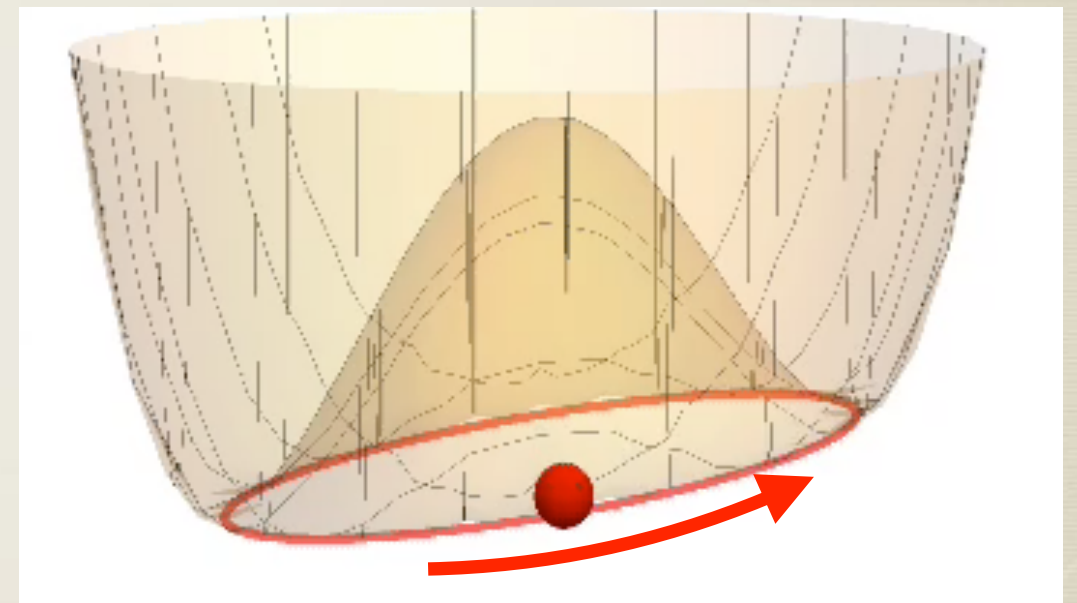


$$\dot{\theta}_i = 0$$

V

If the kinetic energy goes to axions,
axion abundance will be enhanced

Non-zero initial angular velocity?



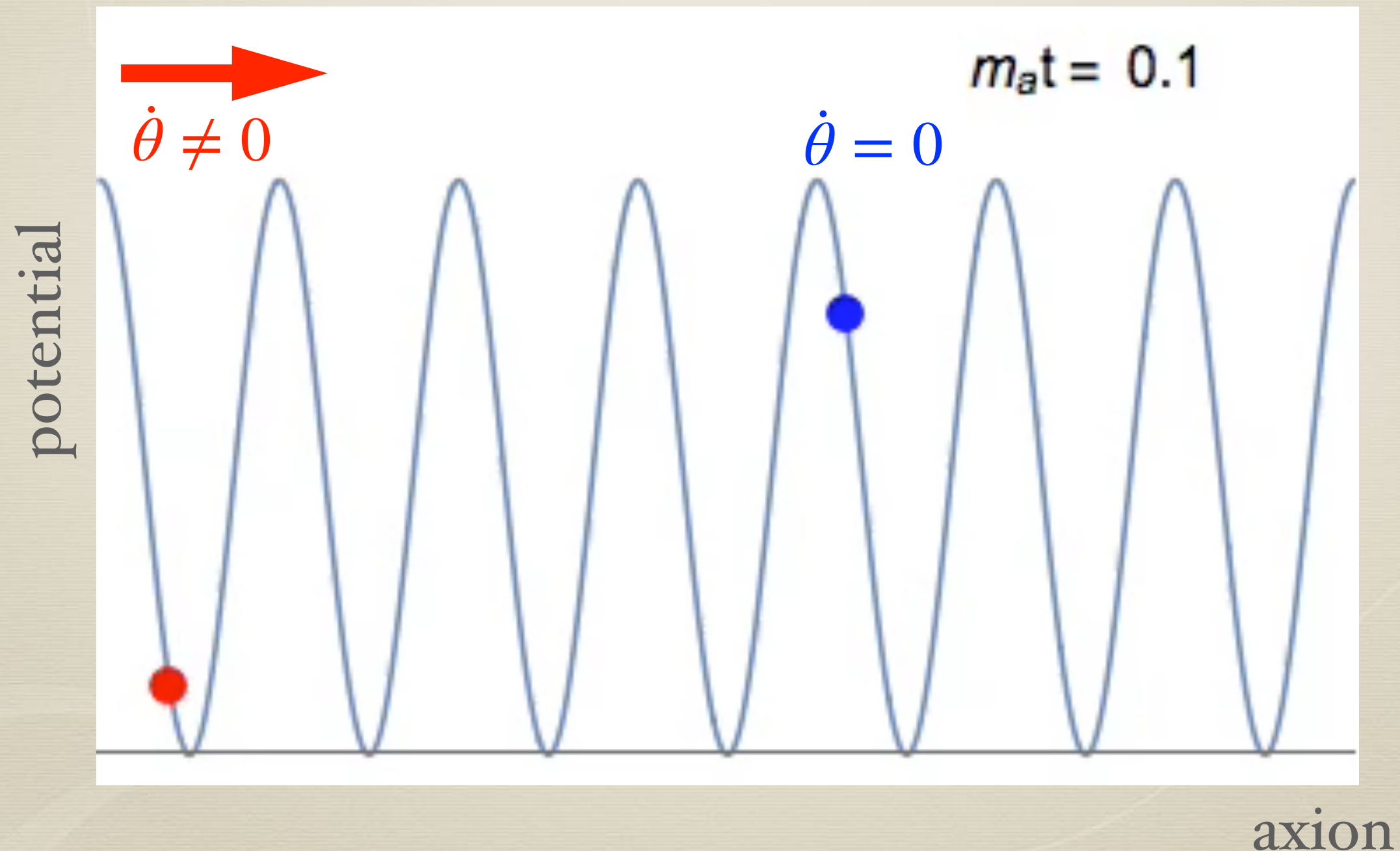
$$\dot{\theta}_i \neq 0$$

$V + K$

Kinetic Misalignment

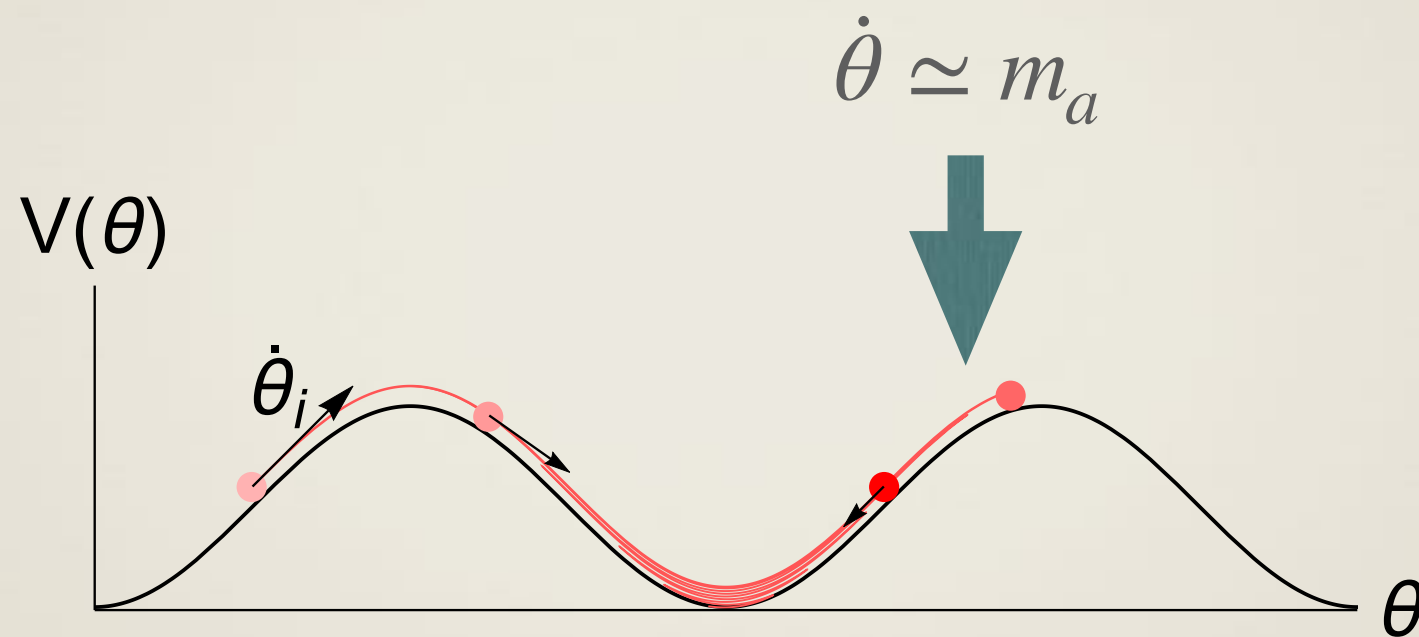
Naive picture

Co and KH(2019)
Co, Hall and KH(2020)



Naive picture

Co and KH(2019)
Co, Hall and KH(2020)



$$n_{\text{rot}} = \dot{\theta} f_a^2 \simeq m_a f_a^2 \simeq n_{a,\text{osc}}$$

Axion fragmentation

Fonseca, Morgante, Sato, Servant (2019)

$$V(a) = m_a^2 f_a^2 \left(1 - \cos \frac{a}{f_a}\right)$$

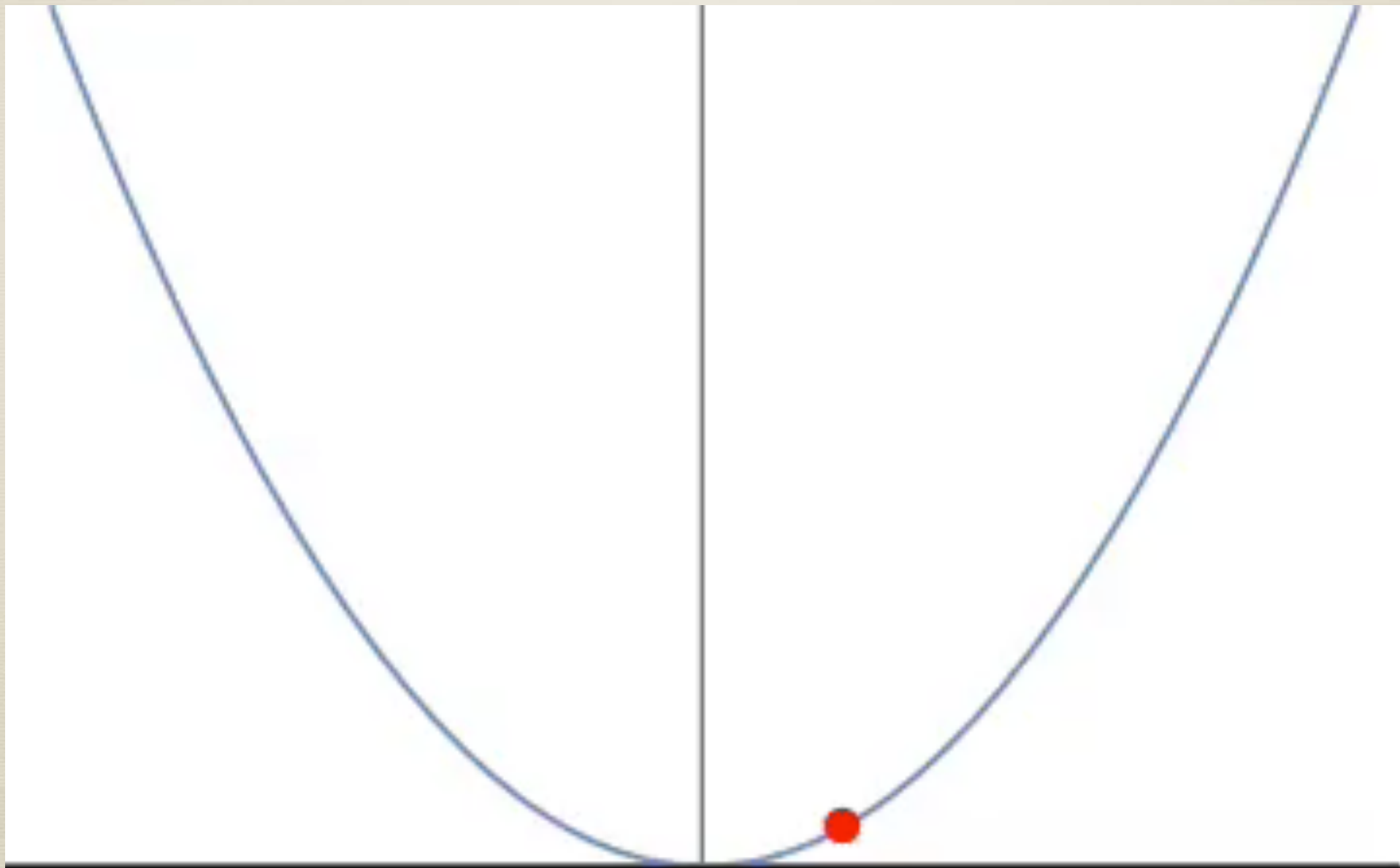
$$a \rightarrow \dot{\theta}t + a(t, x)$$

EOM of the fluctuation at the linear level:

$$\ddot{a}_k + \left(k^2 + m_a^2 \cos \dot{\theta}t\right) a_k = 0$$

oscillating frequency

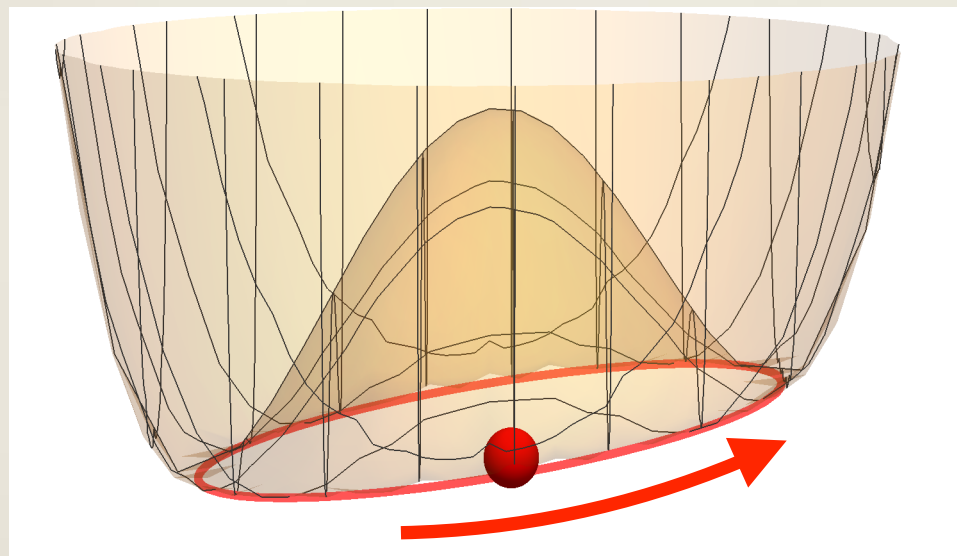
Parametric resonance



Axion fragmentation

Fonseca, Morgante, Sato, Servant (2019)

$$\ddot{a}_k + \left(k^2 + m_a^2 \cos \dot{\theta} t \right) a_k = 0$$



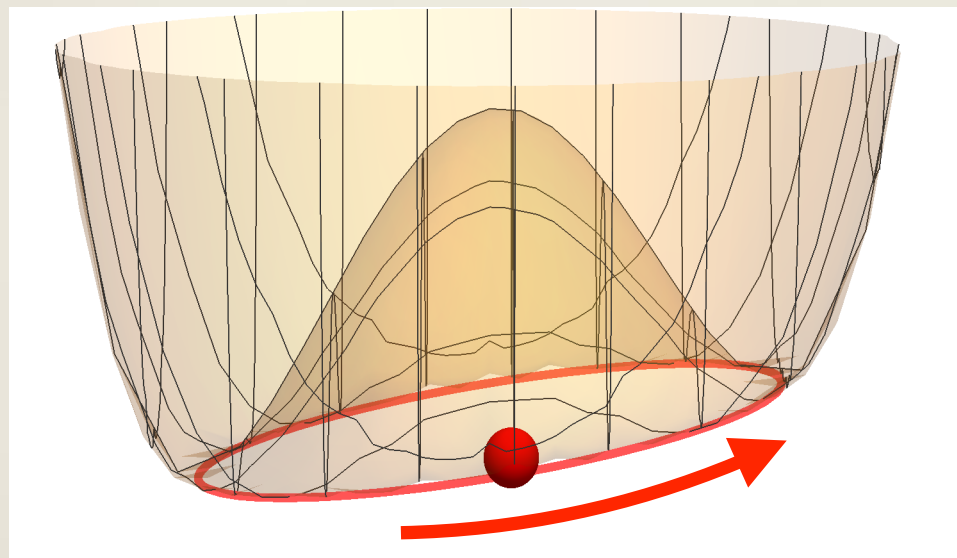
$$k_{\text{PR}} \sim \dot{\theta}$$



axions with
 k_{PR}

Correct picture

$$\ddot{a}_k + \left(k^2 + m_a^2 \cos^2 \dot{\theta} t \right) a_k = 0$$



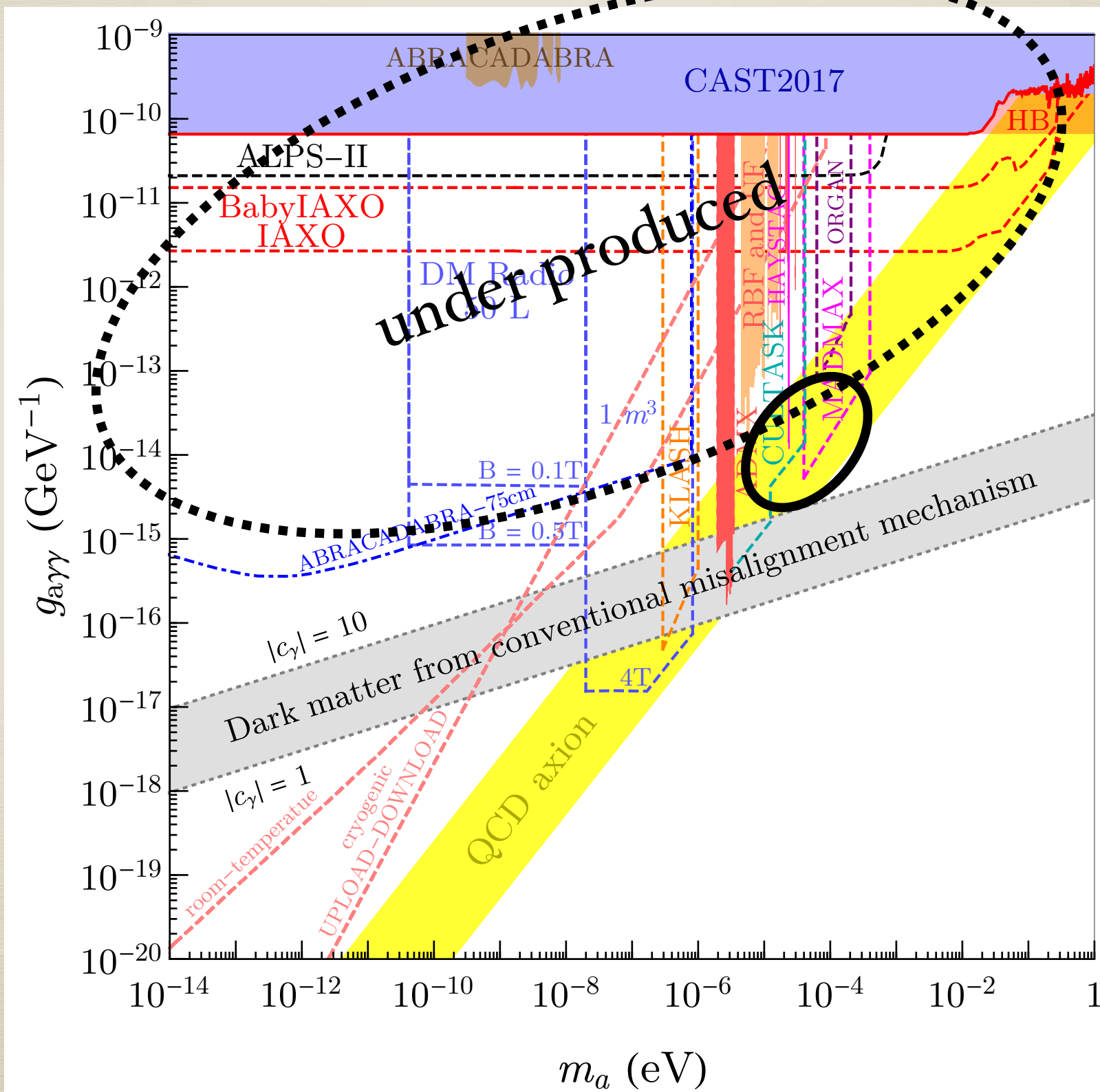
axions with
 k_{PR}

$$k_{\text{PR}} \sim \dot{\theta}$$

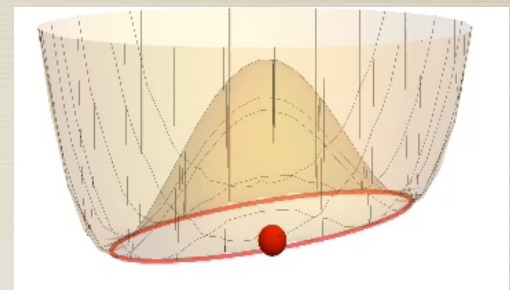
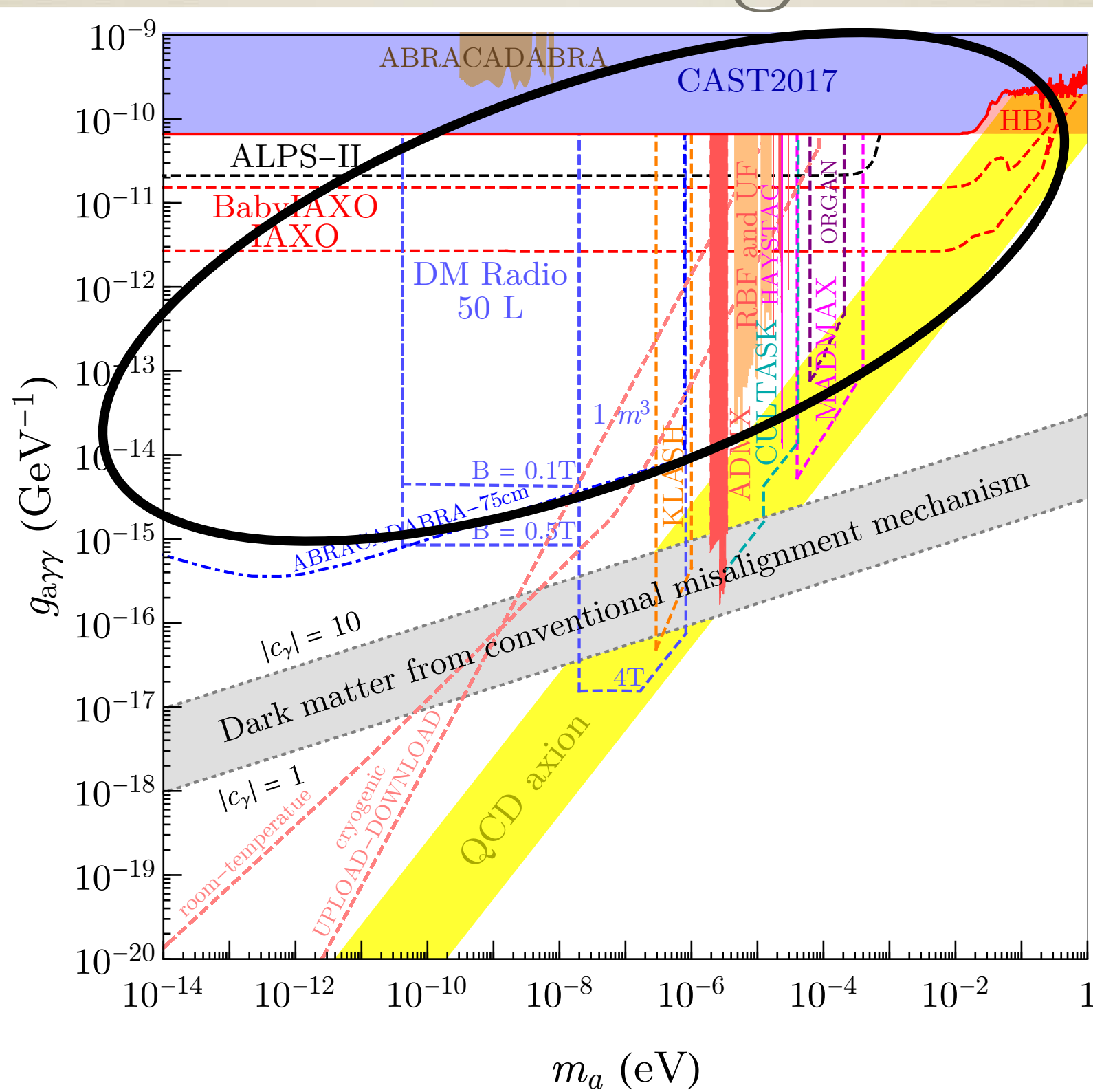
$$n_{a,\text{PR}} = \frac{\rho_{\text{rot}}}{k_{\text{PR}}} \sim \frac{\dot{\theta}^2 f_a^2}{\dot{\theta}} = \dot{\theta} f_a^2 = n_{\text{rot}}$$

Similar to that in the naive picture

Conventional mechanisms

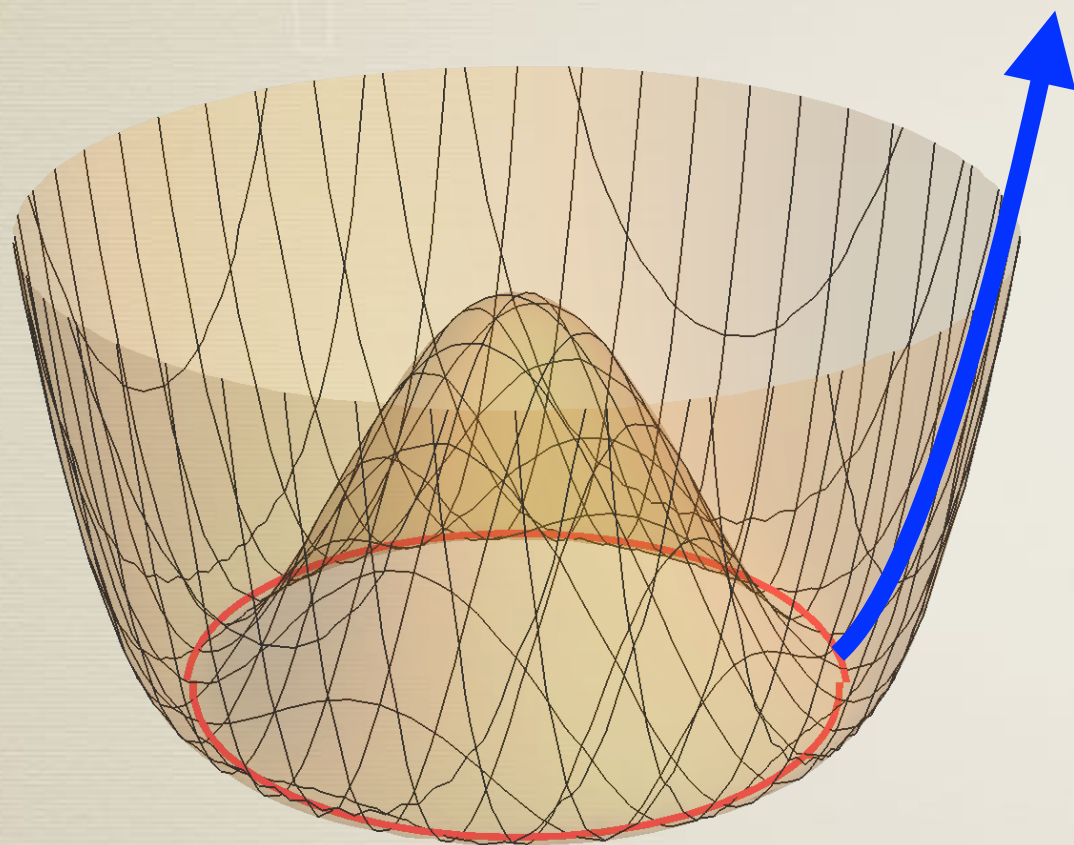


Kinetic misalignment



How to initiate the rotation

Co and KH, PRL (2020)



Consider the dynamics of
the **radial** direction

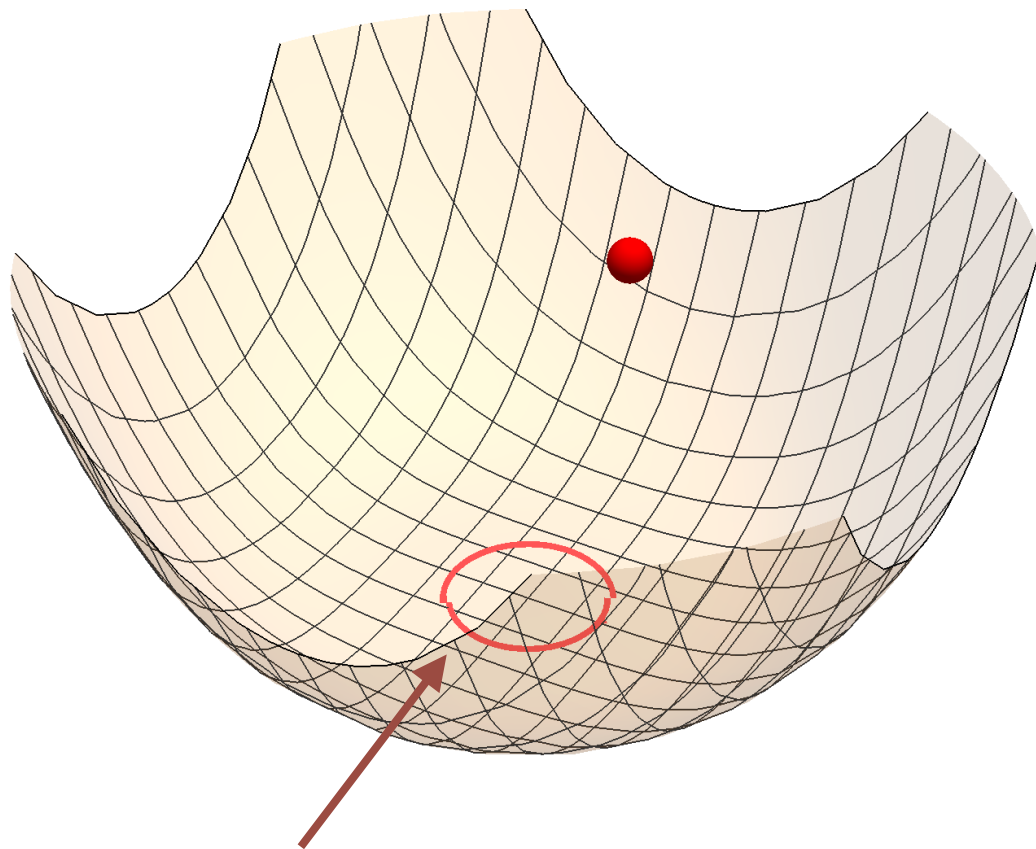
$$P = S \exp(i \theta)$$

Similar to Affleck and Dine (1985)
with rotating super-partners of quarks and leptons

How to initiate the rotation

$$P = S \times \exp(i\theta)$$

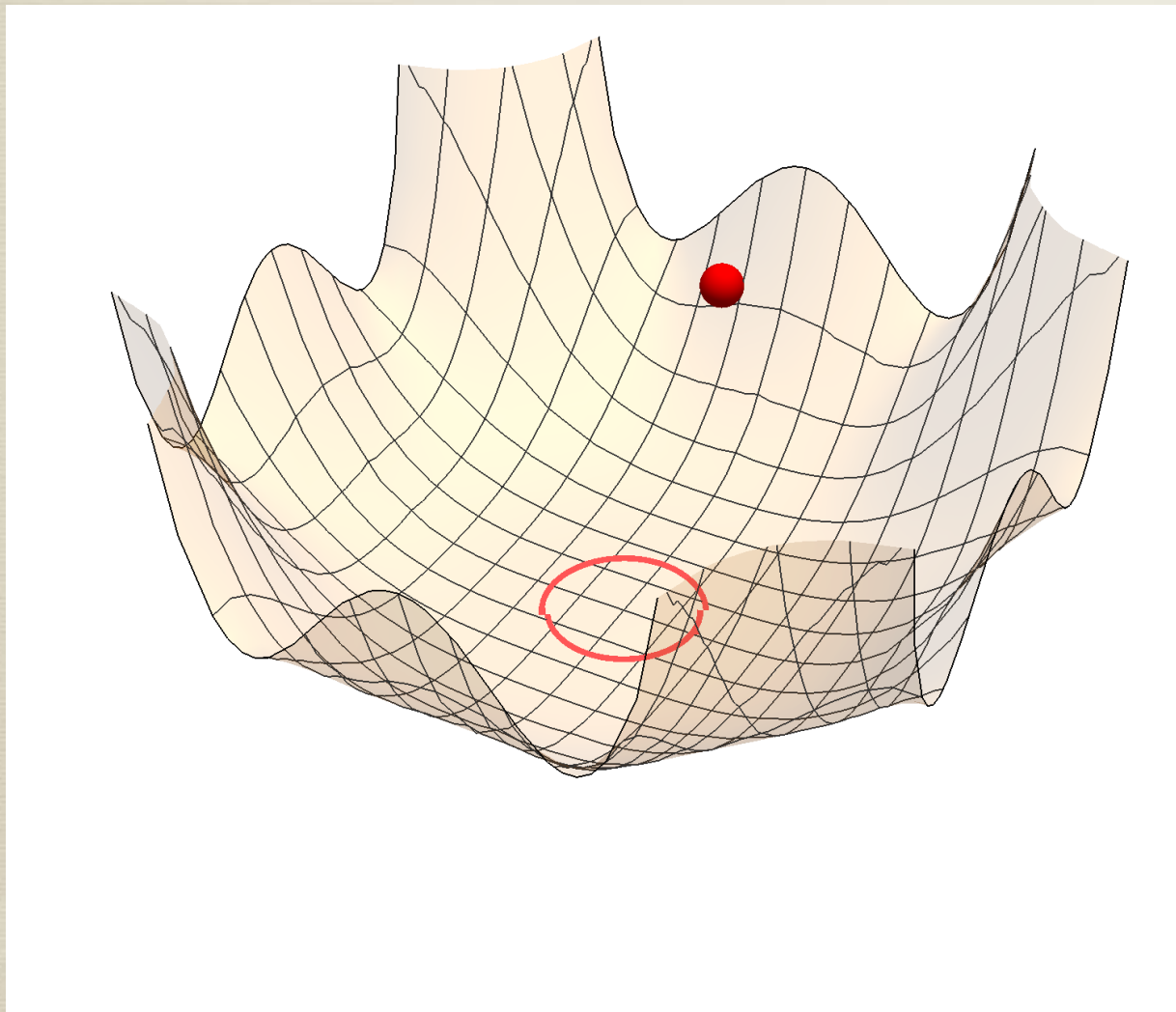
Assume a large initial
radial field value



minimum $|P| \sim f_a$

How to initiate the rotation

$$P = S \times \exp(i\theta)$$



Assume a large initial
radial field value



Higher order terms

$$V \sim P^n \sim S^n \cos(n\theta)$$

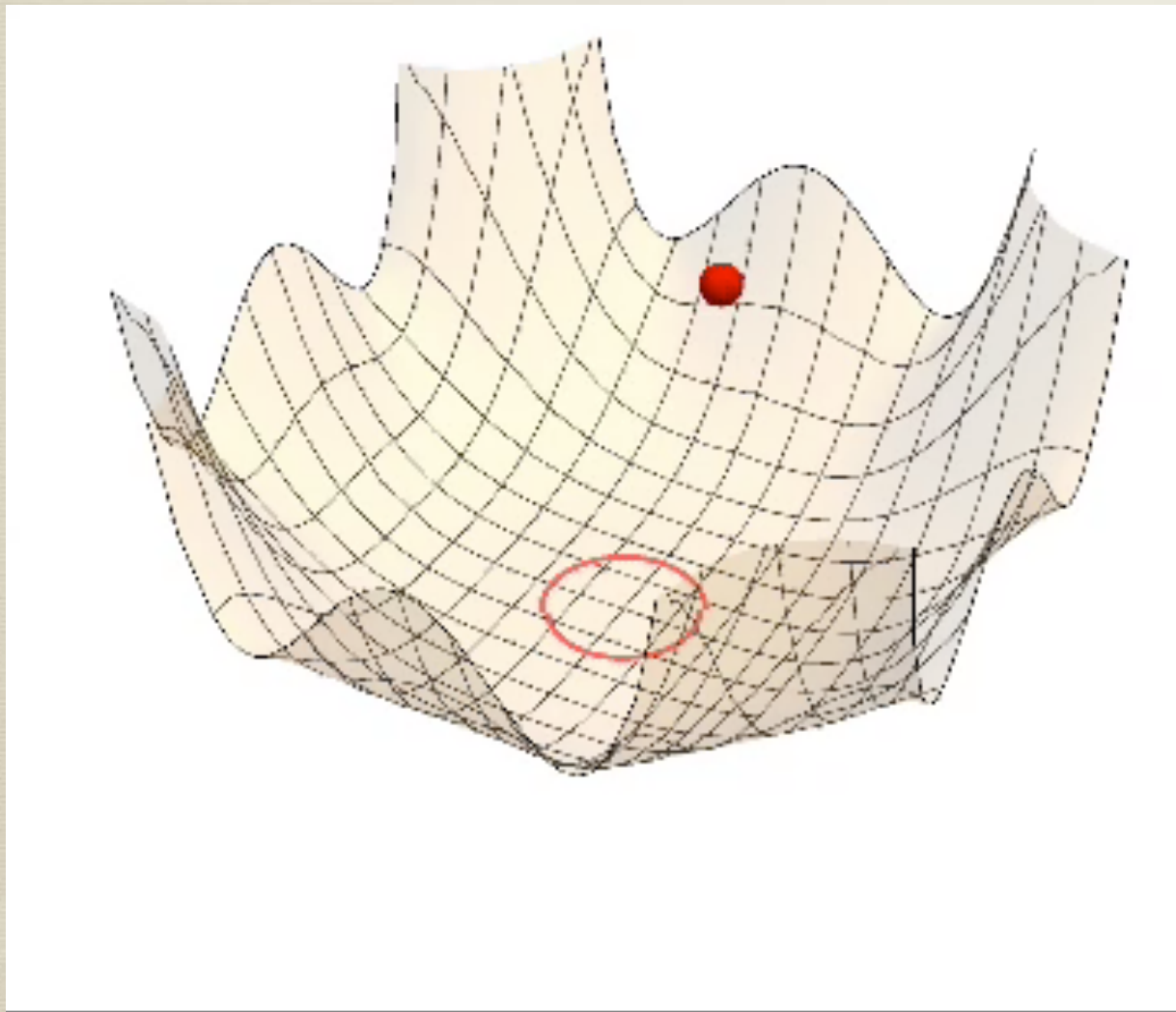
may be effective

Such terms are expected to be present
if the PQ symmetry is an accidental one

e.g., Kolb+ (1992), Barr and Seckel (1992),
Kamionkovski and March-Russel (1992), Dine (1992), **KH**+ (2013, 2015)

How to initiate the rotation

$$P = S \times \exp(i\theta)$$



Assume a large initial
radial field value



Higher order terms

$$V \sim P^n \sim S^n \cos(n\theta)$$

may be effective

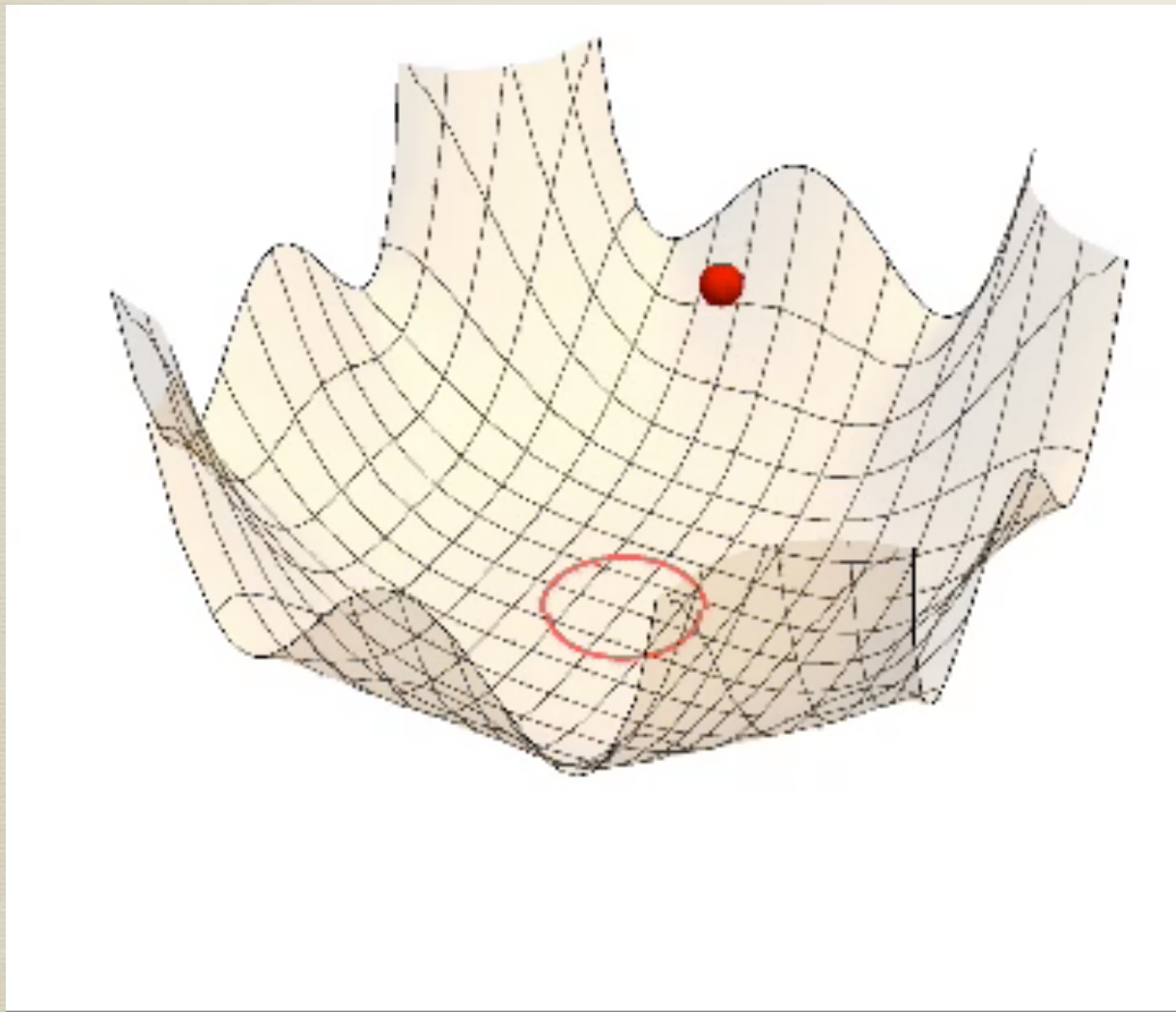


Angular motion is induced
by the potential gradient

animation is available at http://www.sns.ias.edu/~keisukeharigaya/rot_ini.html

How to initiate the rotation

$$P = S \times \exp(i\theta)$$



S decreases by
expansion of the universe



$V \simeq P^n$
is no longer effective



P continues to rotate,
conserving the angular momentum
= Noether charge of PQ symmetry

$$n_{\text{PQ}} = iP\dot{P}^* - iP^*\dot{P} \propto R^{-3}$$

Dark matter abundance

Co, Hall and KH (2019)

It is convenient to define the “yield”

$$Y_{\text{rot}} \equiv \frac{n_{\text{rot}}}{s} \quad \begin{array}{l} n_{\text{rot}} = \dot{\theta} f_a^2 : \text{ global charge} \\ s = \frac{2\pi^2}{45} g T^3 : \text{ entropy density} \end{array} \quad \propto R^{-3}$$

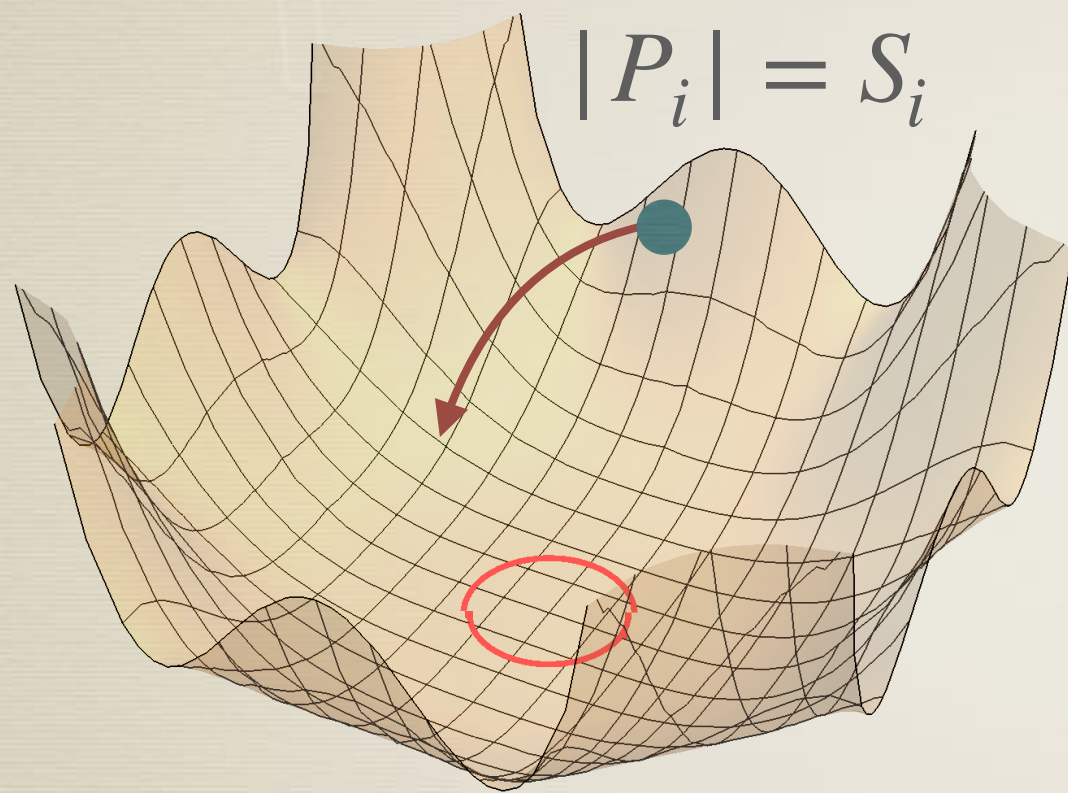
$$Y_a \equiv \frac{n_a}{s} \simeq Y_{\text{rot}} \quad \text{after the fragmentation}$$

$$\frac{\rho_a}{\rho_{\text{DM}}} \simeq \frac{m_a}{6 \text{ meV}} \frac{Y_{\text{rot}}}{40}$$

$$m_a = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

for the QCD axion

Estimation of PQ charge



Initial number density of
the radial direction

$$n_S = m_{S,i} S_i^2$$

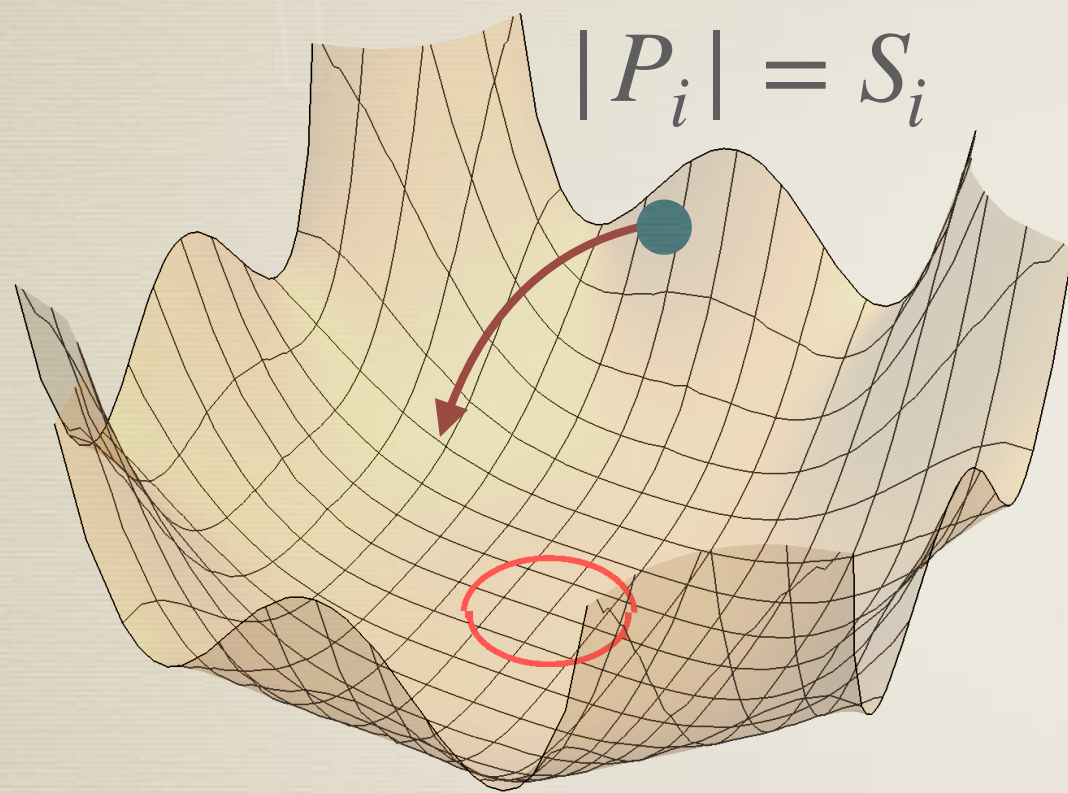
← mass around S_i

$$n_{\text{PQ}} = \epsilon n_S = \epsilon m_{S,i} S_i^2$$

$\epsilon = 0$: No potential gradient to the angular direction

$\epsilon \sim 1$: Comparable potential gradients in
angular and radial directions

Estimation of PQ charge



Initial number density of
the radial direction

$$n_S = m_{S,i} S_i^2$$

$$n_{\text{PQ}} = \epsilon n_S = \epsilon m_{S,i} S_i^2$$

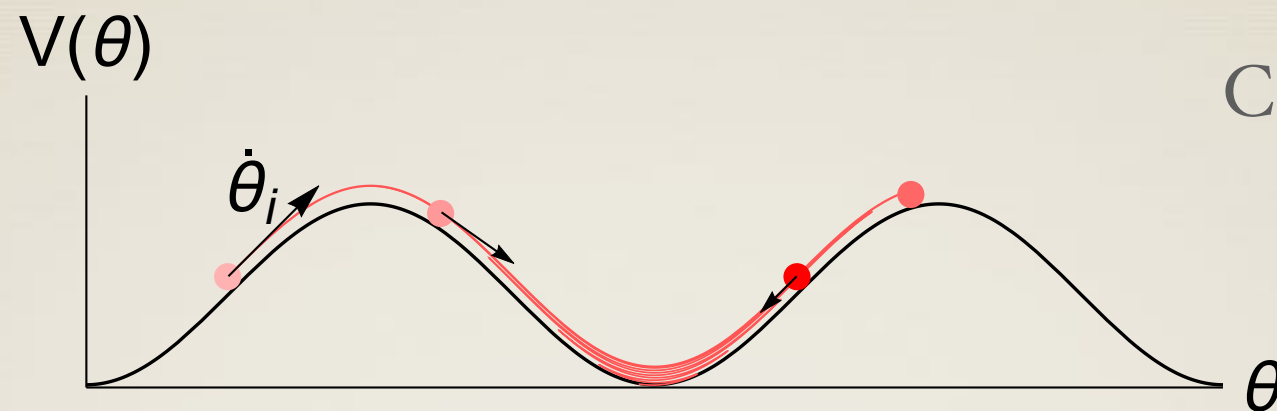
Consider the case where the rotation
begins when $H \sim m_{S,i}$



$$T \sim (m_{S,i} M_{\text{pl}})^{1/2}$$

$$Y_{\text{PQ}} = \frac{n_{\text{PQ}}}{s} \simeq 50 \times \epsilon \left(\frac{S_i}{10^{16} \text{ GeV}} \right)^2 \left(\frac{10^5 \text{ GeV}}{m_{S,i}} \right)^{1/2}$$

Estimation of PQ charge



Co, Hall and KH (2019)

$$Y_{\text{PQ}} = \frac{n_{\text{PQ}}}{s} \simeq 50 \times \epsilon \left(\frac{S_i}{10^{16} \text{ GeV}} \right)^2 \left(\frac{10^5 \text{ GeV}}{m_{S,i}} \right)^{1/2}$$



$$m_a = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

for the QCD axion

$$\frac{\rho_a}{\rho_{\text{DM}}} \simeq \frac{m_a}{6 \text{ meV}} \epsilon \left(\frac{S_i}{10^{16} \text{ GeV}} \right)^2 \left(\frac{10^5 \text{ GeV}}{m_{S,i}} \right)^{1/2}$$

A flat potential with $m_{S,i} = \sqrt{V''(S_i)} \ll S_i$ is required

Flat potential

A flat potential with $m_{S,i} = \sqrt{V''(S_i)} \ll S_i$ is required

Natural in supersymmetric theories, where the potential of S tends to vanish in supersymmetric limit

Flat potential

A flat potential with $m_{S,i} = \sqrt{V''(S_i)} \ll S_i$ is required

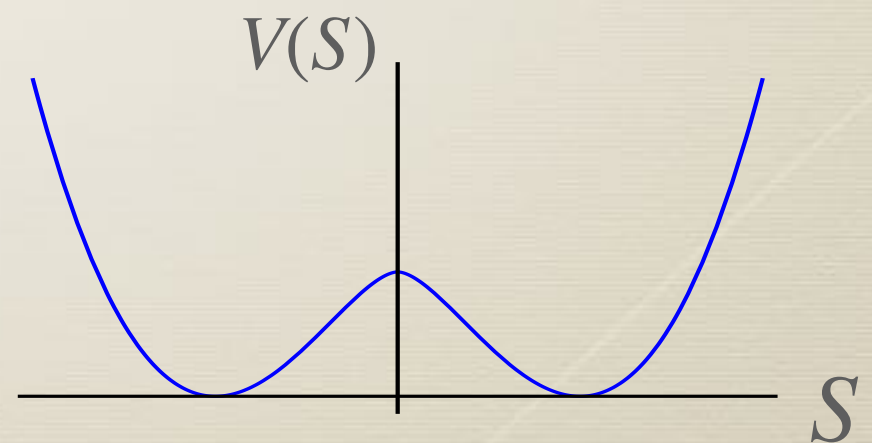
Natural in supersymmetric theories, where the potential of S tends to vanish in supersymmetric limit

Ex. Potential of P solely from supersymmetry breaking

$$V = m_S^2 |P|^2 \left(\ln \frac{2|P|^2}{f_a^2} - 1 \right)$$

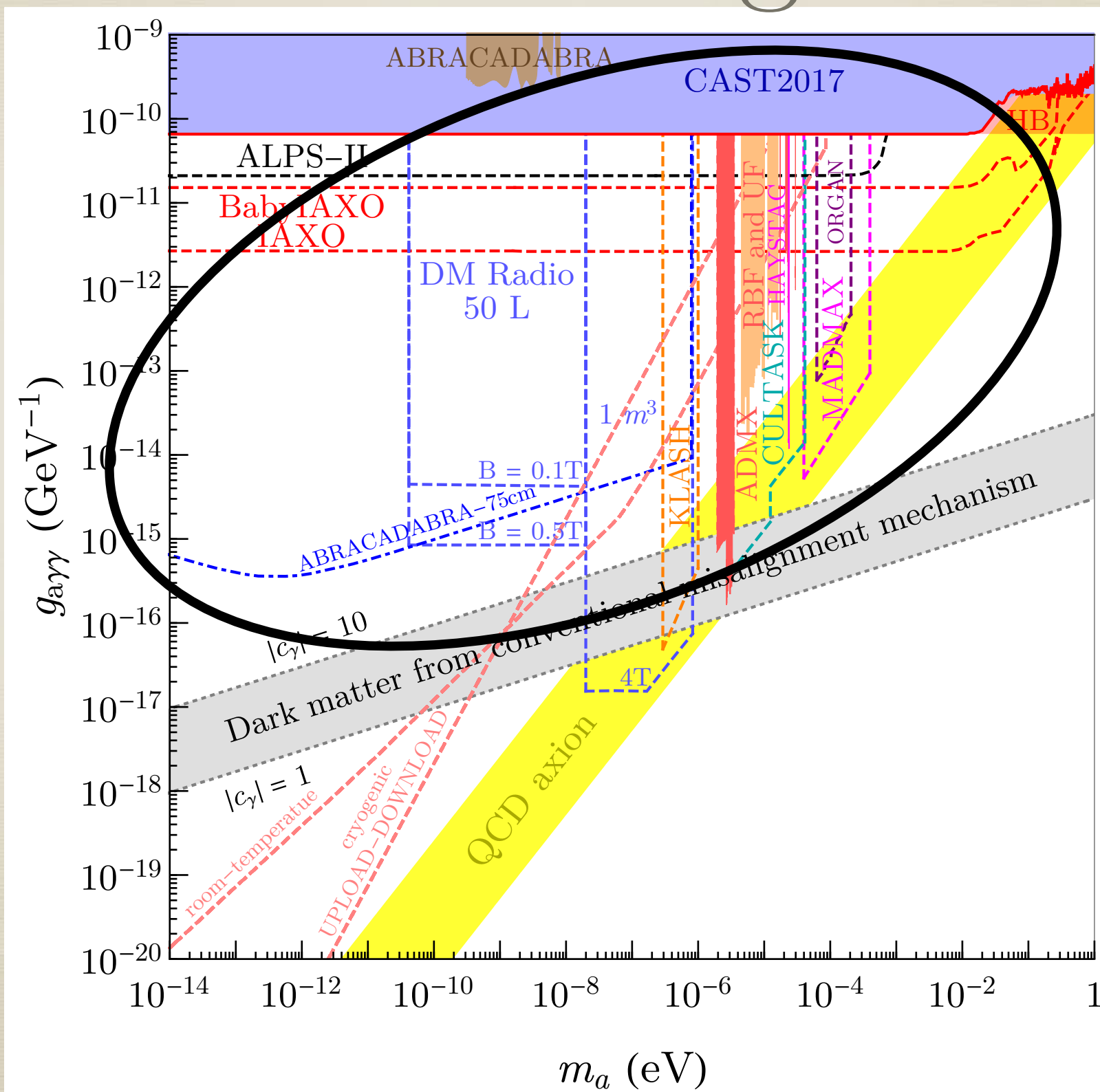


Quantum correction
to the soft mass



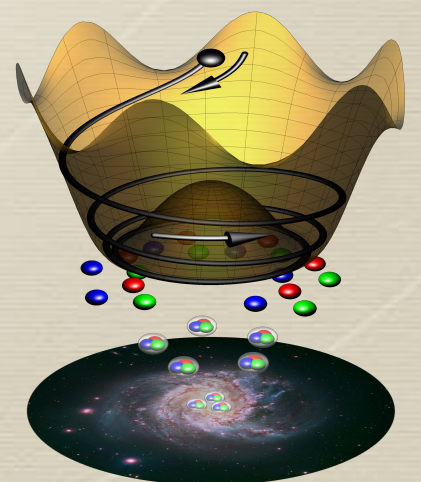
$$\sqrt{V''(S_i)} \sim m_S \ll S_i$$

Kinetic misalignment



Outline

- * Introduction: QCD axion, ALP, and dark matter
- * Rotation of axion and kinetic misalignment
- * Baryon asymmetry from axion rotation
 - axiogenesis
 - ALP genesis
 - lepto-axiogenesis
- * Summary



Axiogenesis

For now let us assume the QCD axion

Co and KH (2019)

The PQ symmetry is quantum mechanically broken
by the QCD interaction (**anomaly**)

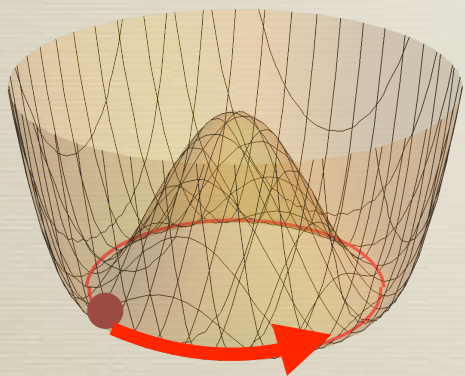
+

$$\partial_\mu J_{\text{PQ}}^\mu \sim G\tilde{G}$$

So is the quark chiral symmetry



$$\partial_\mu J_A^\mu \sim G\tilde{G}$$



PQ



QCD

Chiral charge

B+L

Axiogenesis

For now let us assume the QCD axion

Co and KH (2019)

The chiral symmetry is quantum mechanically broken
by the weak interaction

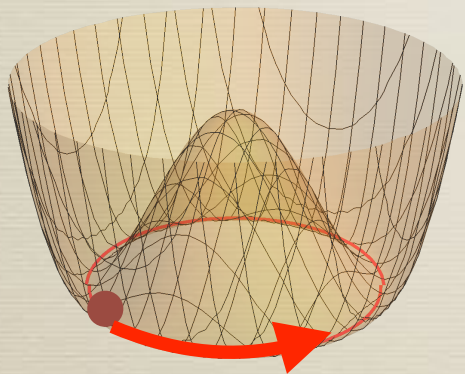
+

$$\partial_\mu J_A^\mu \sim W\tilde{W}$$

So is the baryon (B) + lepton (L) symmetry



$$\partial_\mu J_{B+L}^\mu \sim W\tilde{W}$$



PQ

Chiral charge

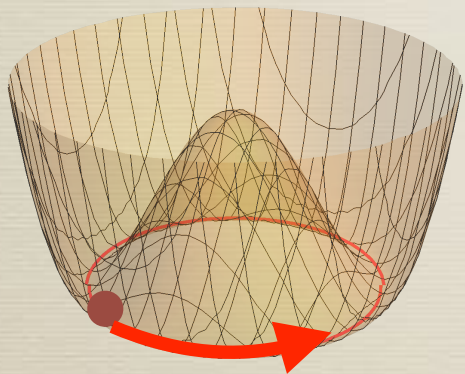
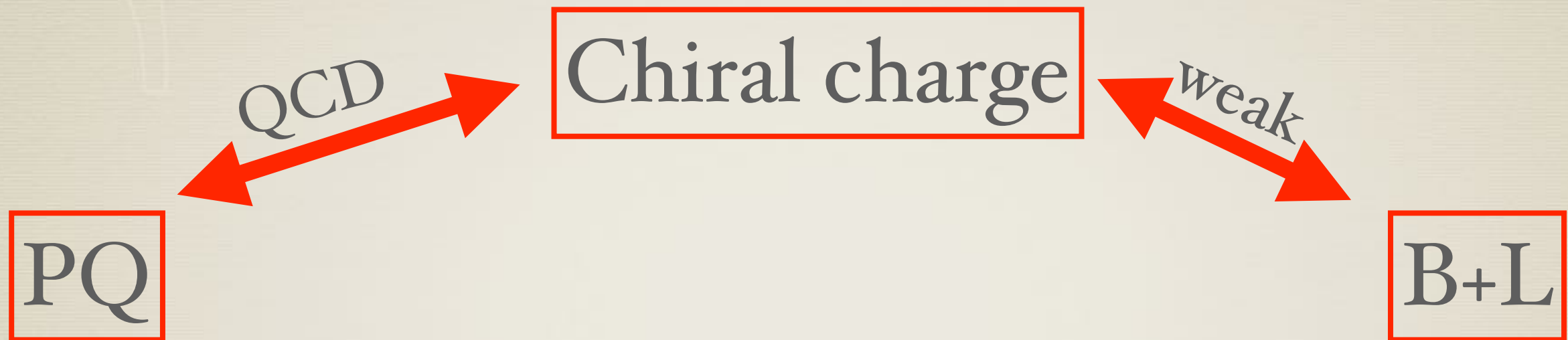


B+L

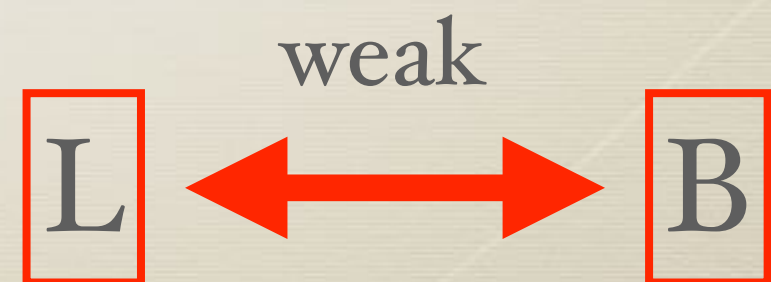
weak

Axiogenesis

Co and KH (2019)



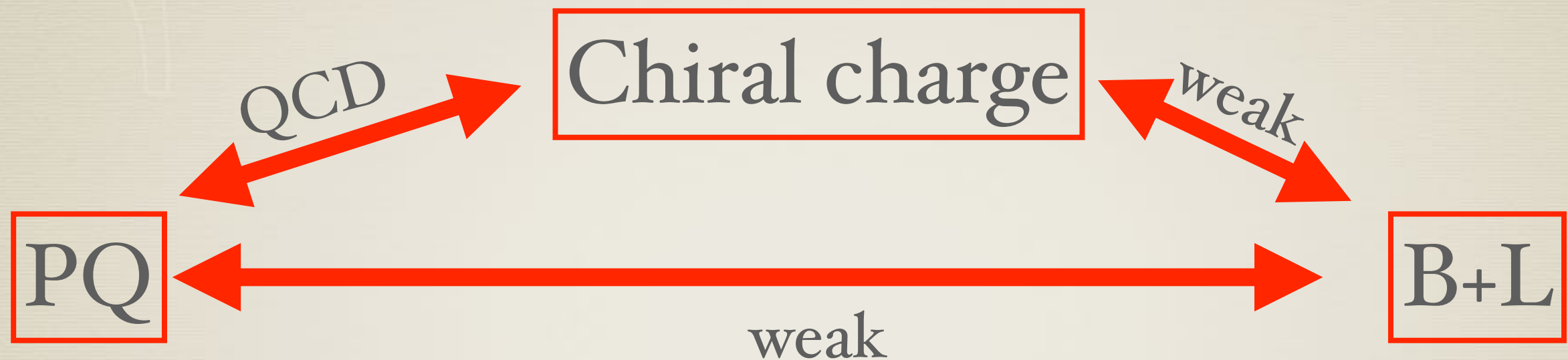
cf. leptogenesis



Fukugita and Yanagida (1986)

Axiogenesis

Co and KH (2019)

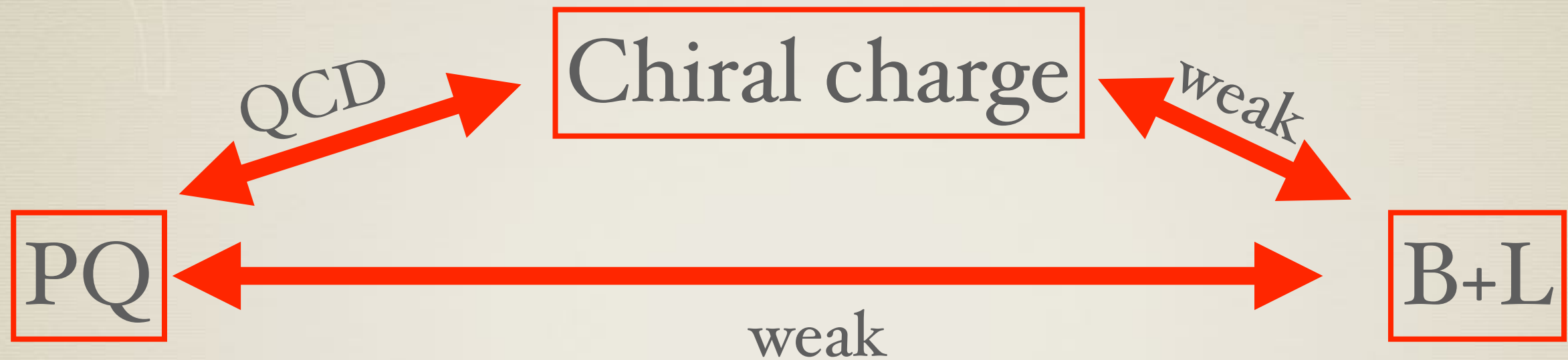


If the PQ symmetry also has weak anomaly

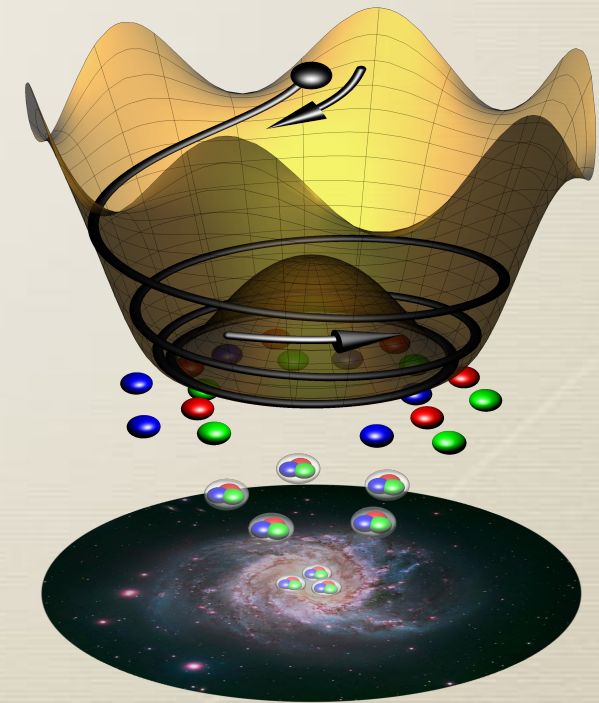
(Naively the case for unified theory)

Axiogenesis

Co and KH (2019)

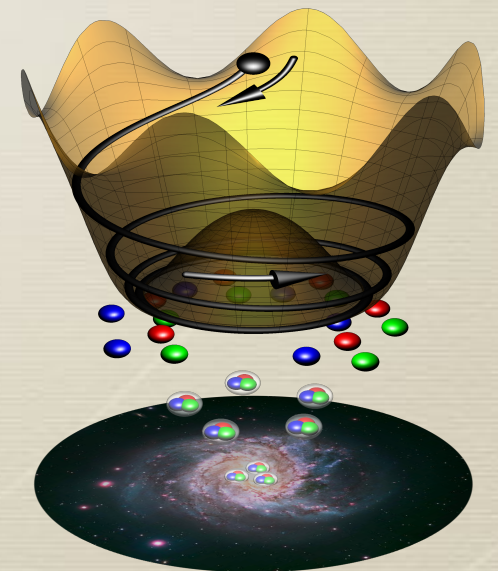


Axiogenesis



The QCD axion solves three mysteries of the universe

- * What is dark matter?
- * How did cosmic inflation occur?
- * How was the baryon asymmetry of the universe created?
- * Why does QCD preserve CP symmetry?
- * What sets the Higgs potential parameters?
- *



Amount of baryon asymmetry

Suppose that Δn out of n_{PQ} is transferred into the charge asymmetry of particles in the thermal bath

The change of free-energy density $\Delta F = \Delta(\rho - Ts)$ is minimized

* Particles in the thermal bath

$$\Delta F = \sim + \frac{\Delta n^2}{T^2} \quad \text{from the standard thermodynamics}$$

* P rotation

$$\Delta F = \sim - (\text{energy per charge}) \times \Delta n = - \dot{\theta} \Delta n$$


$$(\dot{\theta}^2 f_a^2) / (\dot{\theta} f_a^2)$$

Amount of baryon asymmetry

Suppose that Δn out of n_{PQ} is transferred into the charge asymmetry of particles in the thermal bath

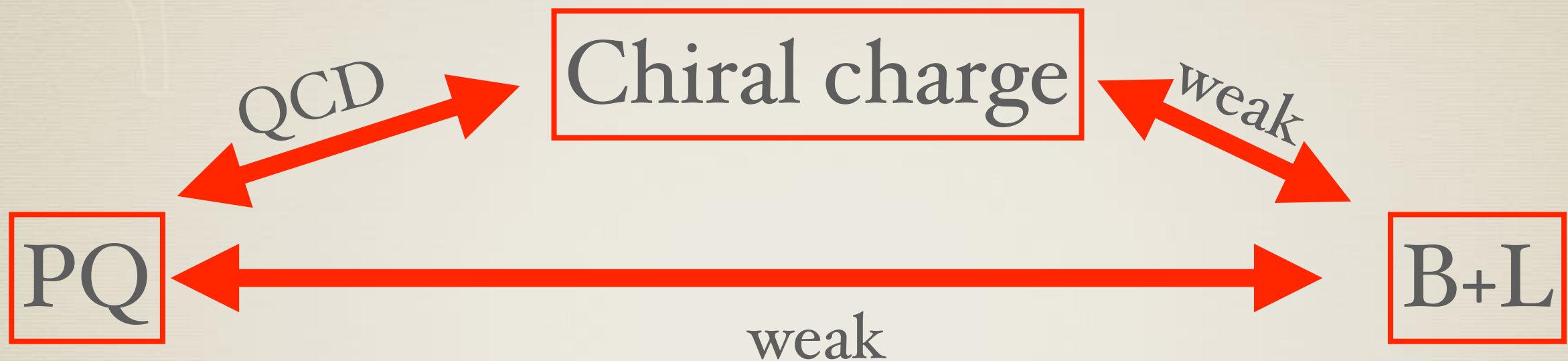
$$\Delta F = \Delta(\rho - Ts) \sim + \frac{\Delta n^2}{T^2} - \dot{\theta} \Delta n$$

→ $\Delta n \sim \dot{\theta} T^2 \ll n_{\text{PQ}} = \dot{\theta} f_a^2$
if $T \ll f_a$

Co and KH (2019)

Axiogenesis

Co and KH (2019)

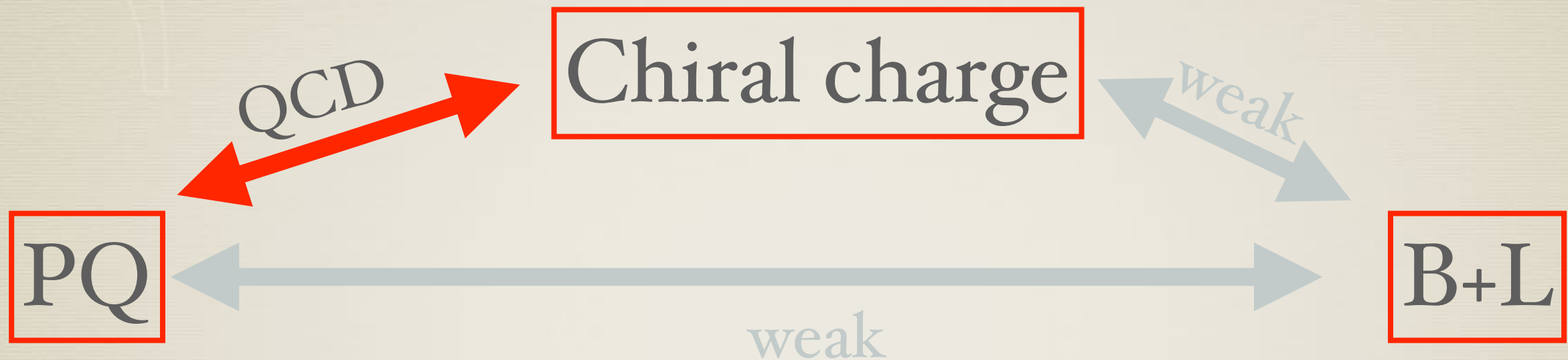


The asymmetries reach
thermal equilibrium values

$$n_B \simeq 0.1 \dot{\theta} T^2$$

Axiogenesis

Co and KH (2019)



weak interaction becomes ineffective
after electroweak phase transition

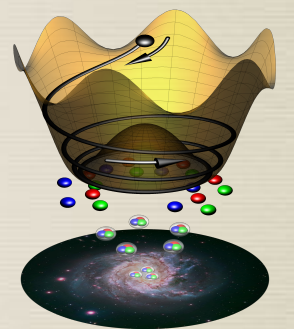
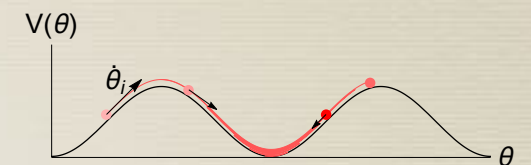
$$n_B|_{EW} \simeq 0.1 \dot{\theta}|_{EW} T_{EW}^2$$

Axiogenesis

Co and KH (2019)

1. Angular velocity
2. Decay constant
3. Electroweak phase transition temperature

1. Dark Matter
2. Baryon asymmetry



3 free parameters – 2 densities to fit
= 1 free parameter

$$T_{\text{EW}} = 1 \text{ TeV} \left(\frac{f_a}{10^8 \text{ GeV}} \right)^{1/2}$$

Astrophysical lower bound $f_a > 10^8 \text{ GeV}$

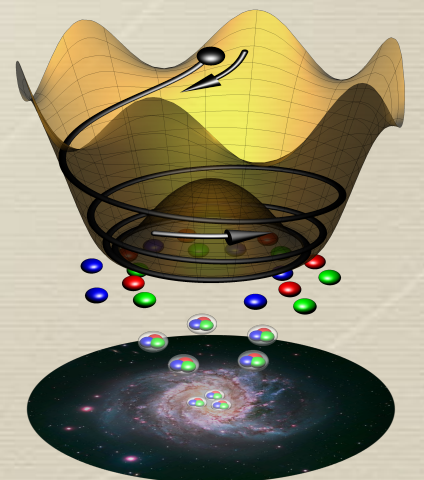
Electroweak



QCD axion

Outline

- * Introduction: QCD axion, ALP, and dark matter
- * Rotation of axion and kinetic misalignment
- * Baryon asymmetry from axion rotation
 - axiogenesis
 - ALP genesis ←
 - lepto-axiogenesis
- * Summary

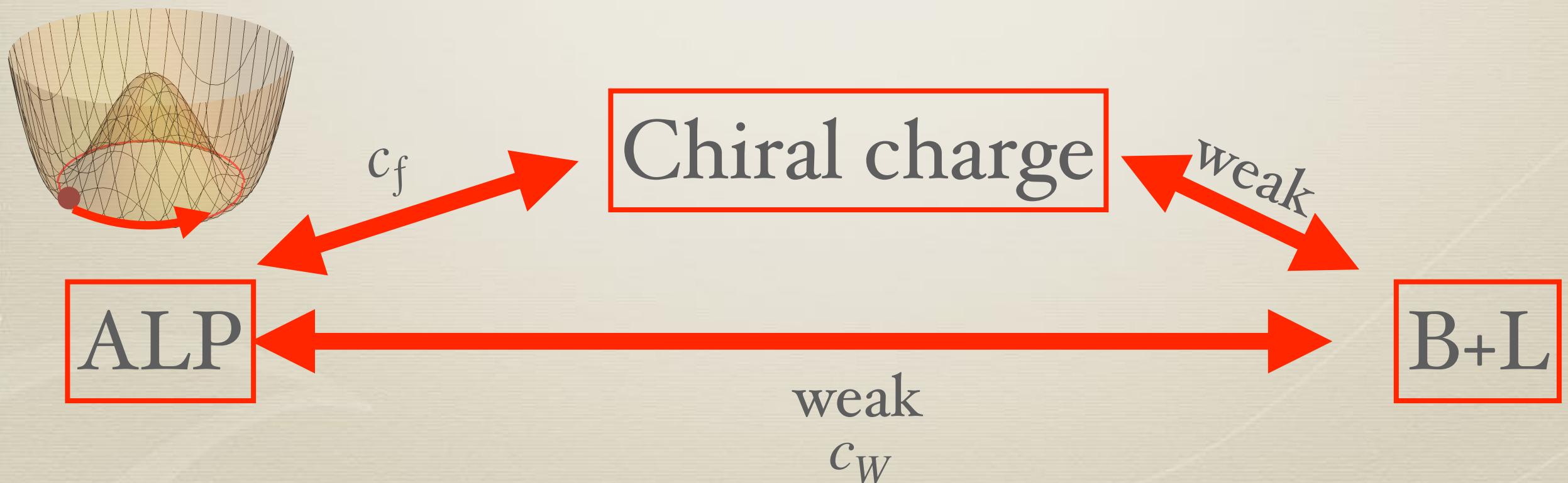


ALP genesis

Co, Hall and KH (2020)

A similar mechanism works for generic ALPs

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \sum_{f,i,j} c_{fij} f_i^\dagger \bar{\sigma}^\mu f_j + \frac{a}{64\pi^2 f_a} (c_W g^2 W^{\mu\nu} \tilde{W}_{\mu\nu})$$



ALPogenesis

Co, Hall and KH (2020)

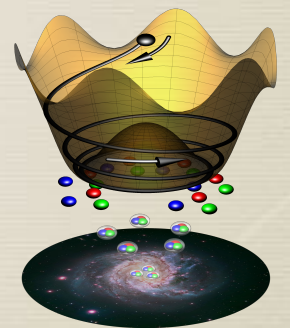
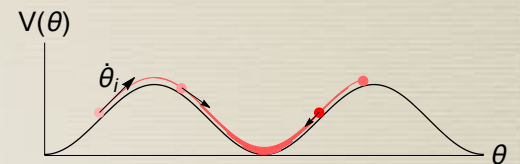
Assuming the standard EW phase transition,

1. Angular velocity
2. Decay constant
3. ALP mass

1. Dark Matter
2. Baryon asymmetry

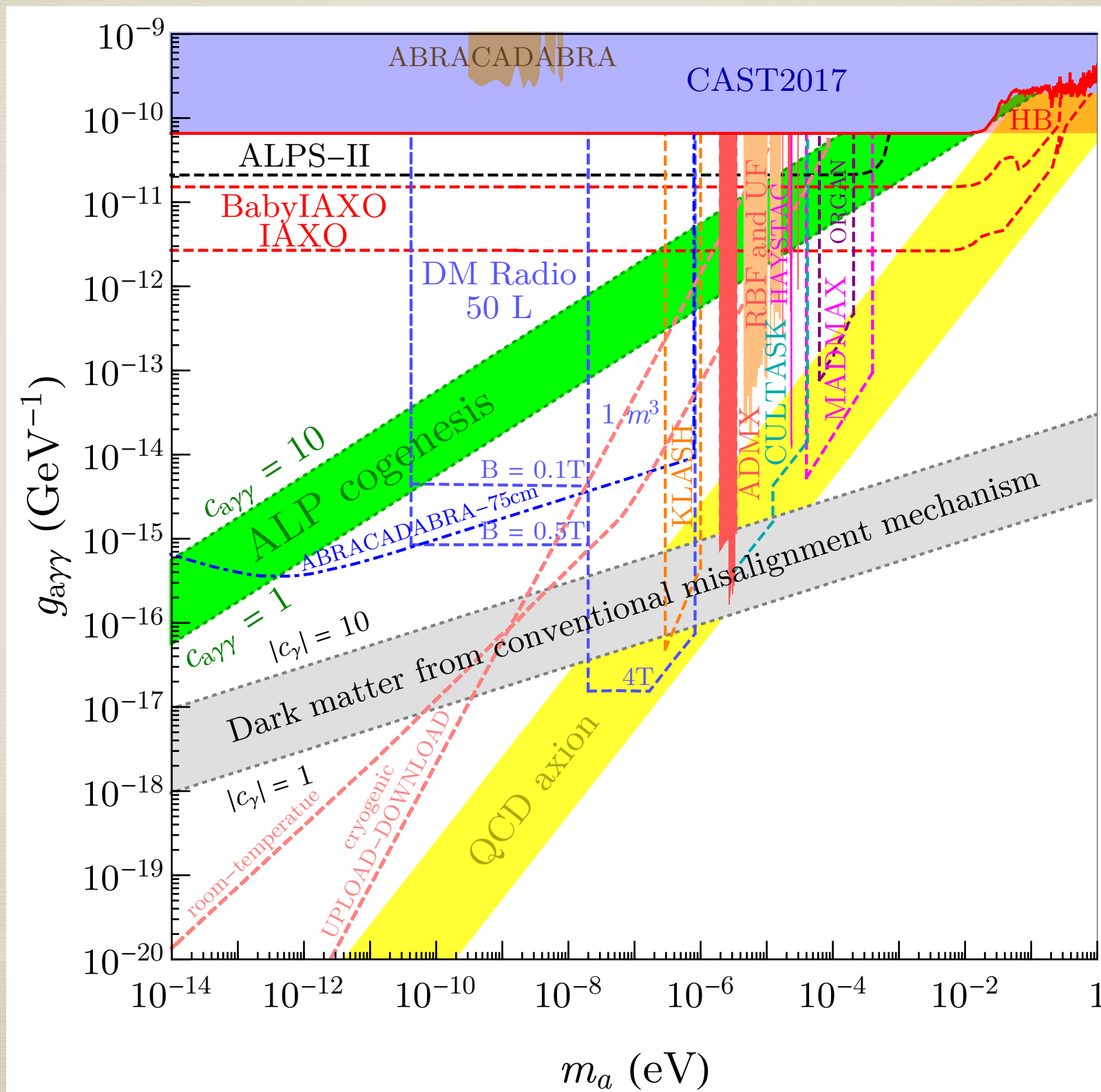
3 free parameters – 2 densities to fit
= 1 free parameter

$$f_a = 2 \times 10^9 \text{ GeV} \left(\frac{1 \mu\text{eV}}{m_a} \right)^{1/2}$$

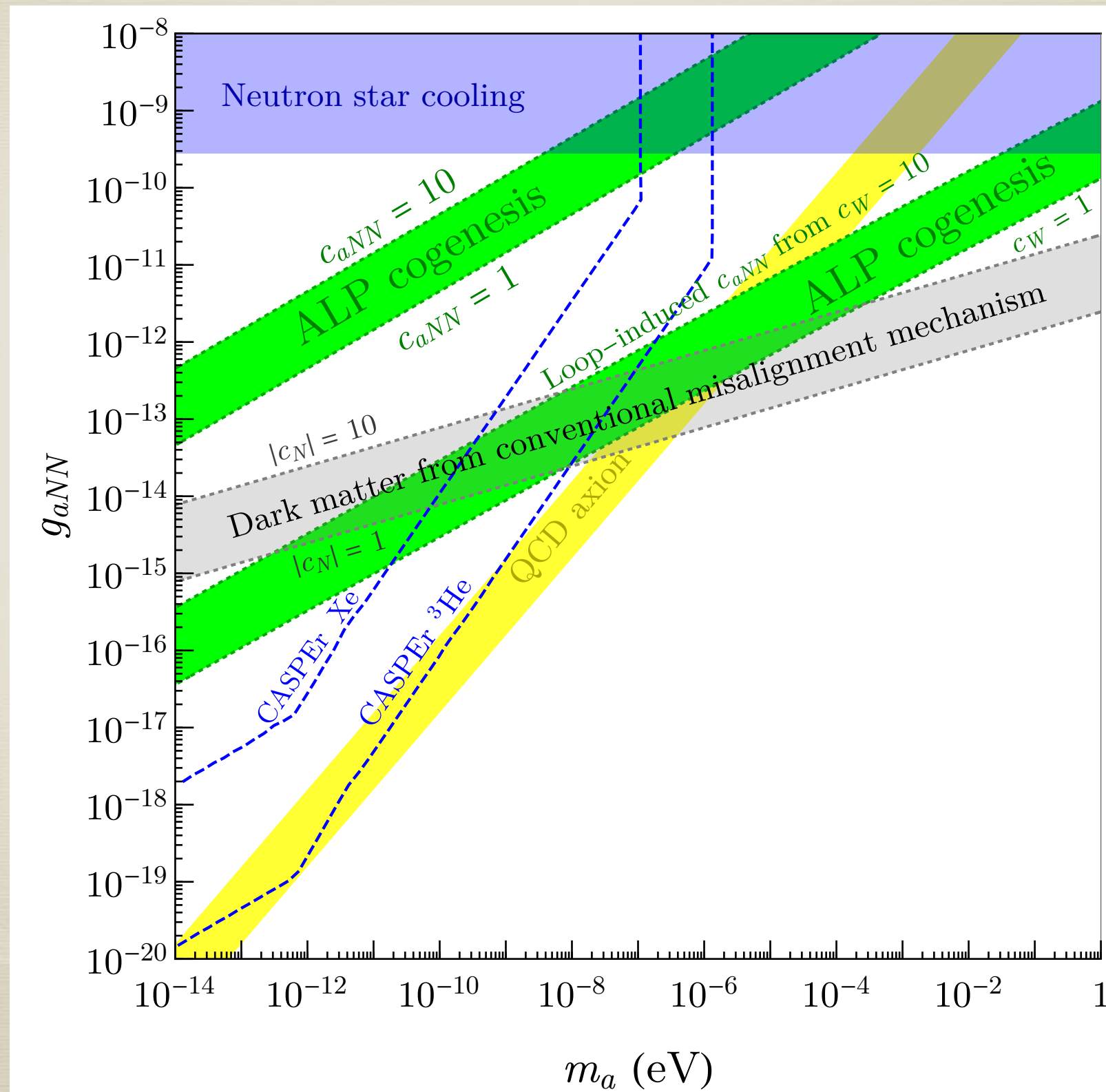


Prediction on the ALP coupling

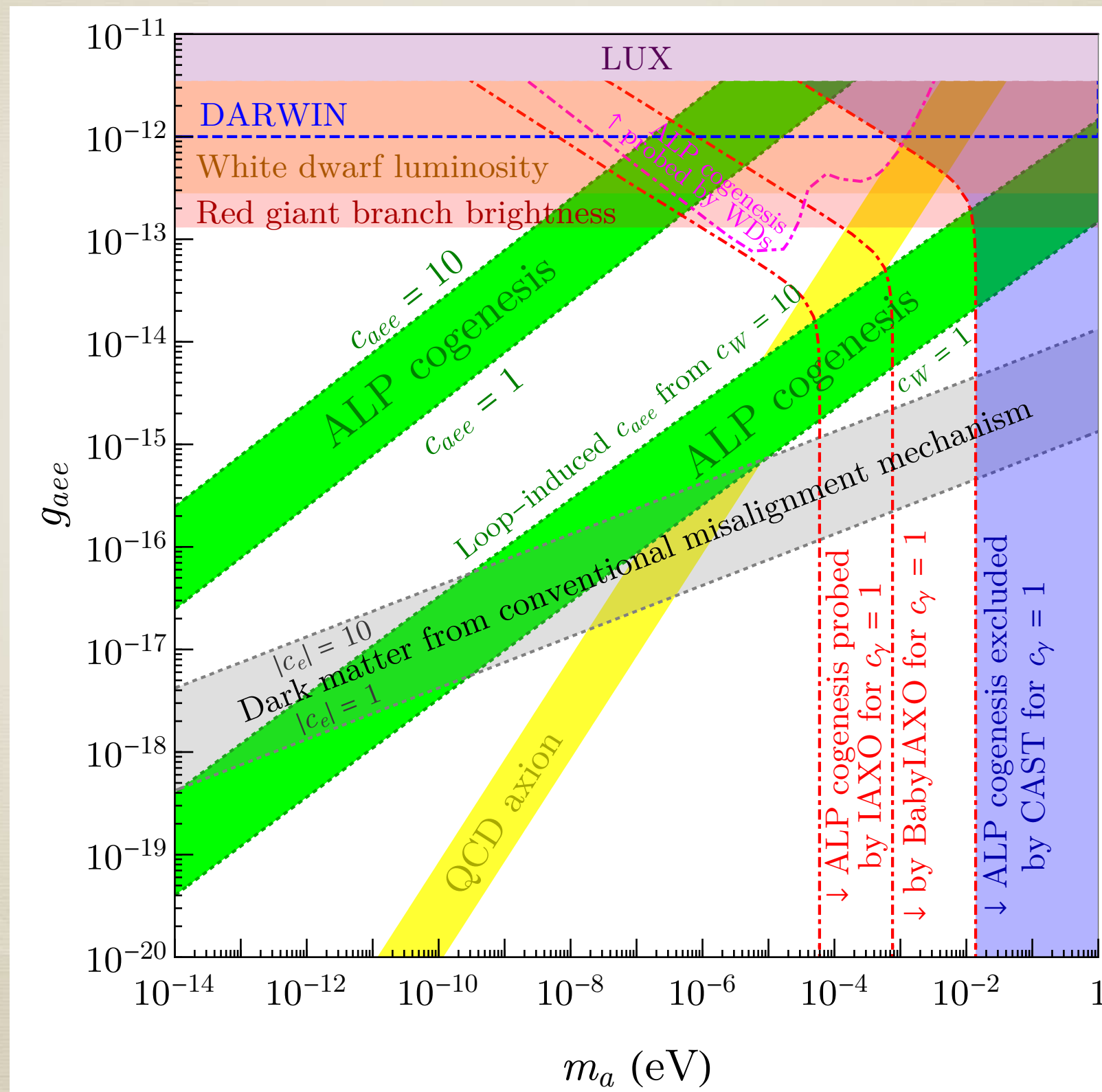
$$\sim \frac{\alpha}{4\pi} \frac{1}{f_a}$$



Prediction on the ALP coupling

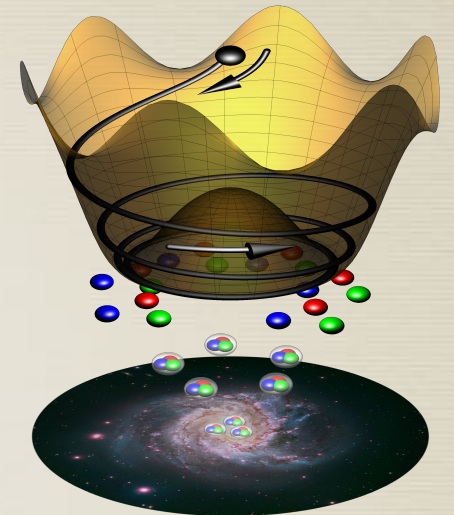


Prediction on the ALP coupling



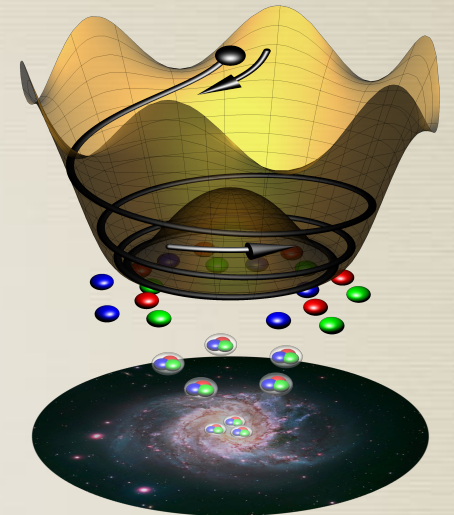
An ALP solves two mysteries of the universe

- * What is dark matter?
- * How did cosmic inflation occur?
- * How was the baryon asymmetry of the universe created?
- * Why does QCD preserve CP symmetry?
- * What sets the Higgs potential parameters?
- *



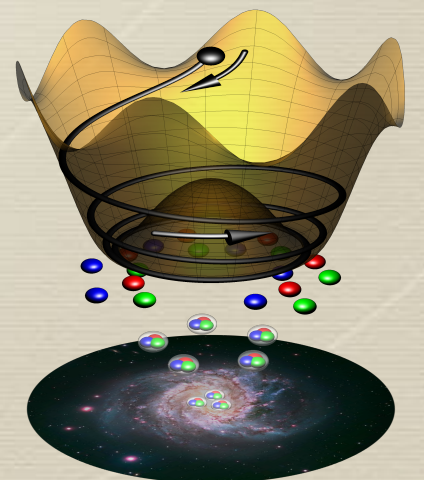
An ALP solves $N > 2$ mysteries of the universe ?

- * What is dark matter?
- * How did cosmic inflation occur?
- * How was the baryon asymmetry of the universe created?
- * Why does QCD preserve CP symmetry?
- * What sets the Higgs potential parameters?
- * ?



Outline

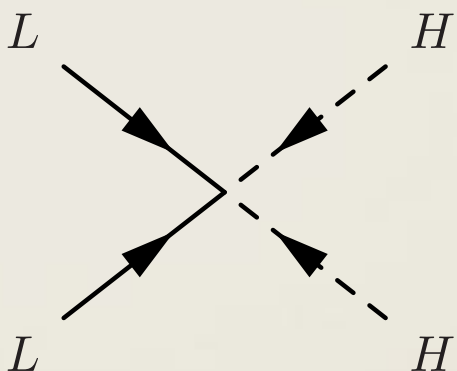
- * Introduction: QCD axion, ALP, and dark matter
- * Rotation of axion and kinetic misalignment
- * Baryon asymmetry from axion rotation
 - axiogenesis
 - ALP genesis
 - lepto-axiogenesis ←
- * Summary



Lepto-axiogenesis

So far we used B+L violation by the weak anomaly

Majorana neutrino masses break the lepton symmetry

$$\frac{1}{M} LLHH$$

$$m_\nu = \frac{\langle H \rangle^2}{M}$$

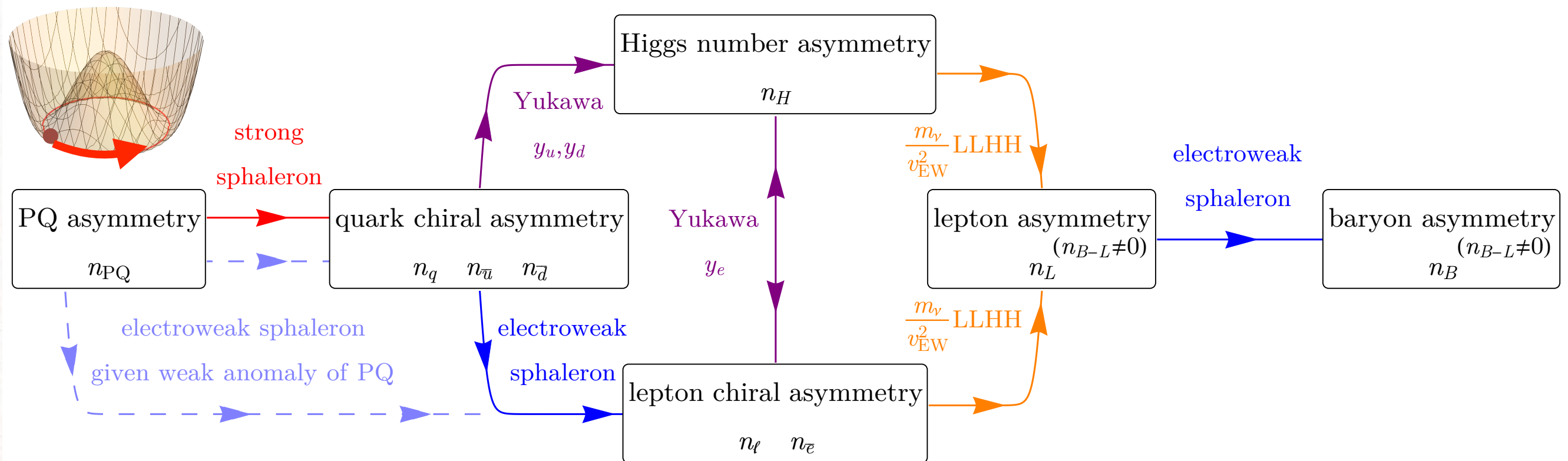
Can they assist baryogenesis from the QCD axion?

Yes

Co, Fernandez, Ghalsasi, Hall and KH (2020)

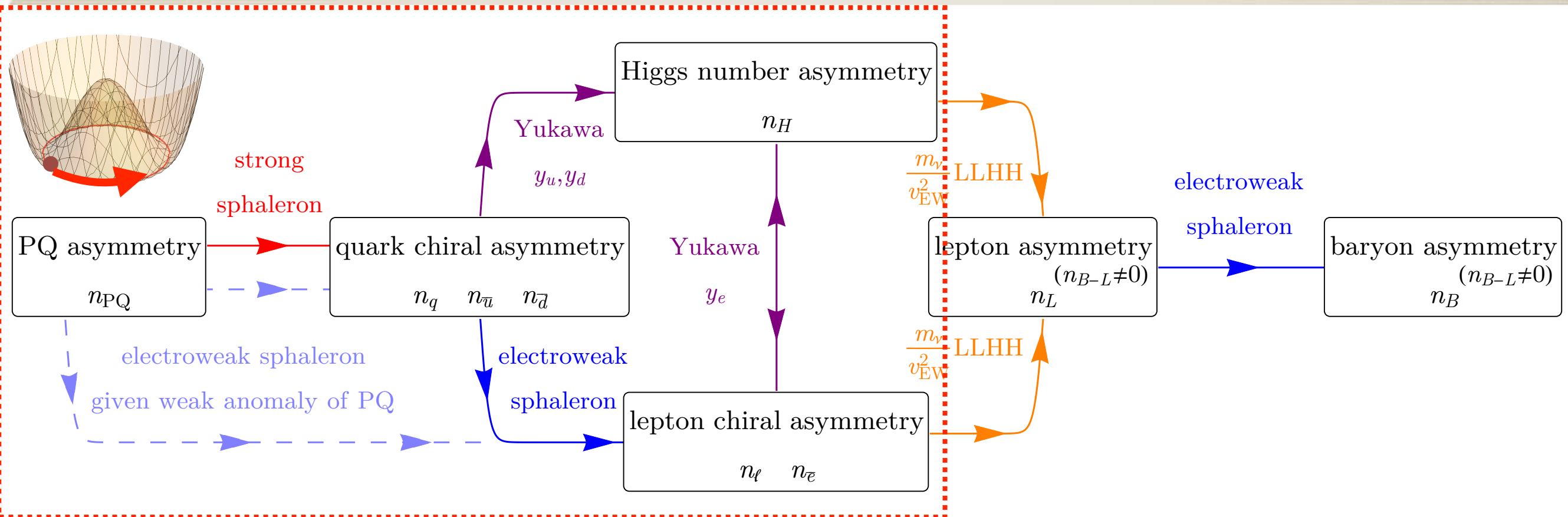
Charge flow

Co, Fernandez, Ghalsasi, Hall and KH (2020)



Charge flow

Co, Fernandez, Ghalsasi, Hall and KH (2020)

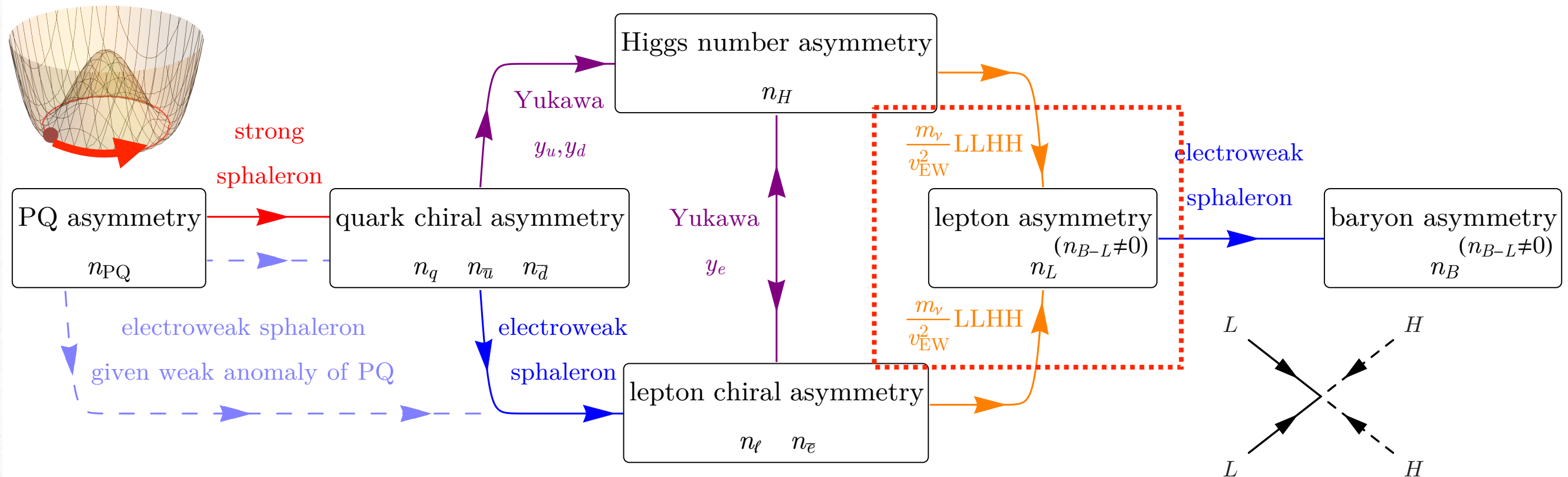


efficient and
reaches equilibrium

$$\frac{n_{H,\ell}}{s} \simeq \frac{\dot{\theta} T^2}{s}$$

Charge flow

Co, Fernandez, Ghalsasi, Hall and KH (2020)



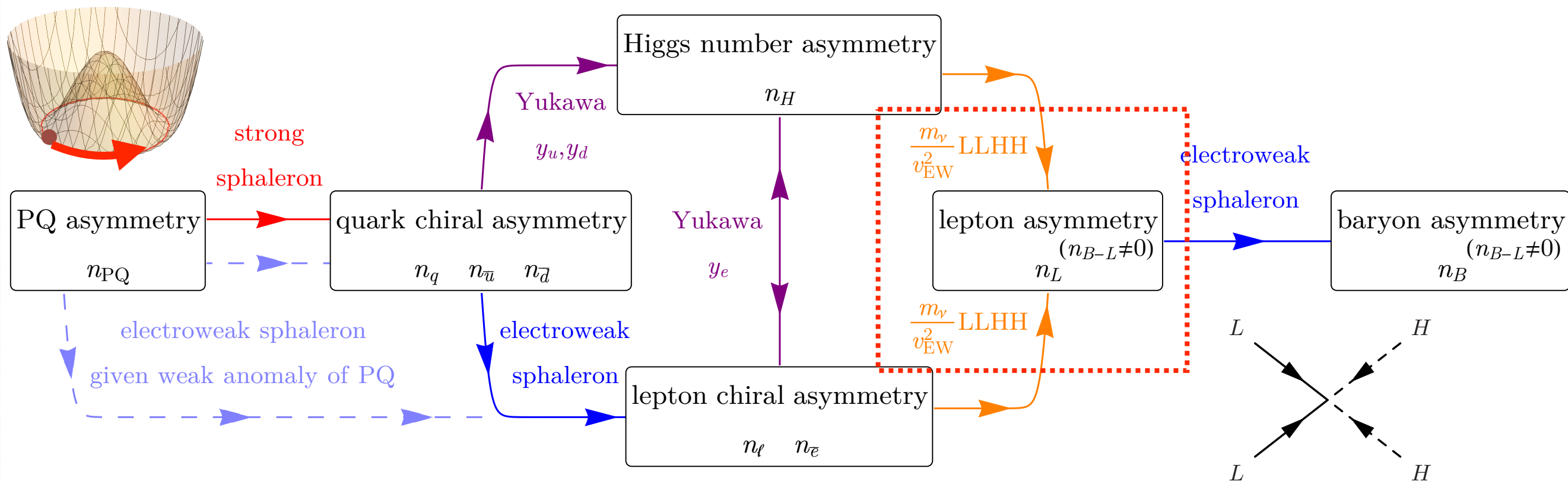
At high temperatures

$$\left. \frac{n_{B-L}}{s} \right|_{\text{eq}} \simeq \frac{\dot{\theta} T^2}{s}$$

$$\Gamma_L \sim \frac{m_\nu^2}{v_{\text{EW}}^4} T^3$$

Charge flow

Co, Fernandez, Ghalsasi, Hall and KH (2020)



not efficient at
low temperatures

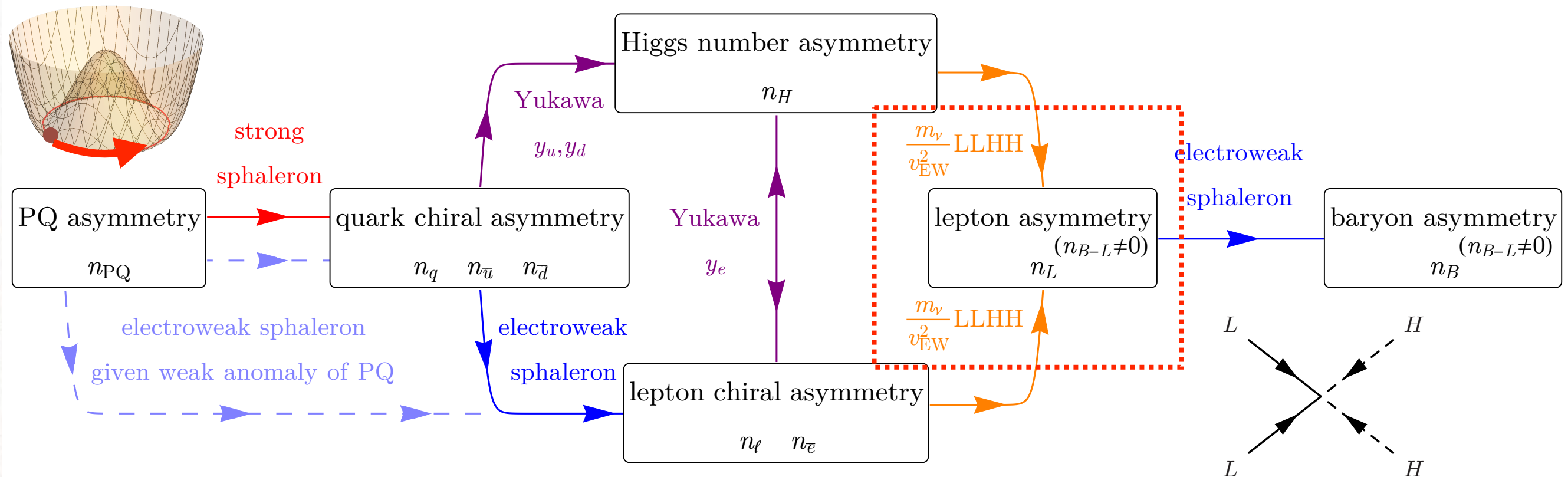
$$\frac{\Delta n_{B-L}}{s} \simeq \frac{\dot{\theta} T^2}{s} \times \frac{\Gamma_L}{H} \propto \dot{\theta} \times T^0$$

$$\Gamma_L \sim \frac{m_\nu^2}{v_{EW}^4} T^3$$

$$H \propto T^2, s \propto T^3$$

Charge flow

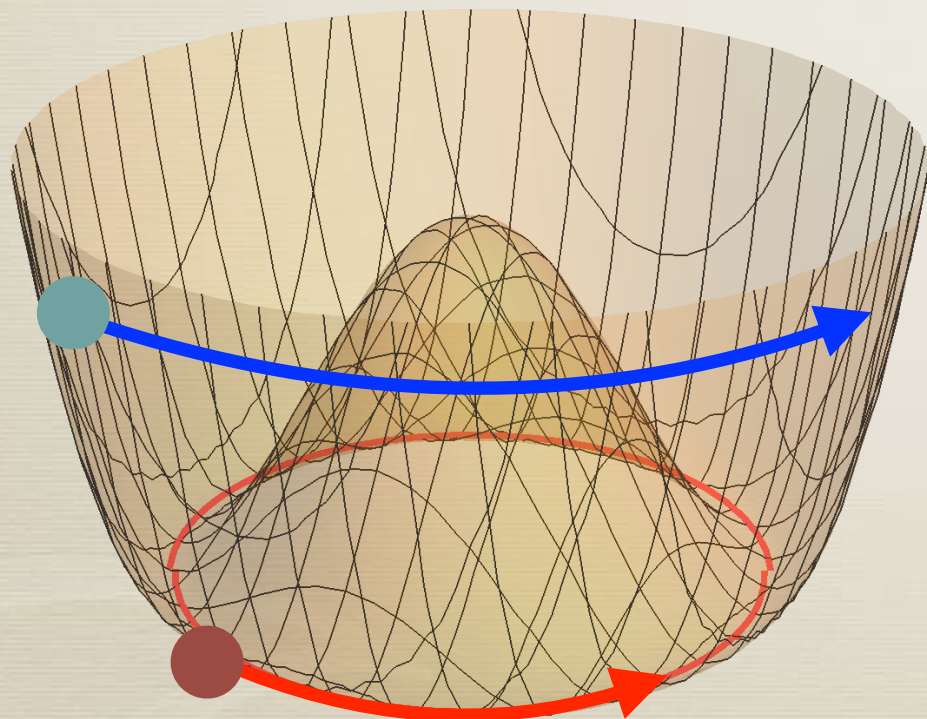
Co, Fernandez, Ghalsasi, Hall and KH (2020)



$$\frac{\Delta n_{B-L}}{s} \simeq \frac{\dot{\theta} T^2}{s} \times \frac{\Gamma_L}{H} \simeq 10^{-10} \frac{\dot{\theta}}{10 \text{ TeV}} \frac{\sum m_\nu^2}{0.03 \text{ eV}^2}$$

Angular velocity?

$$\frac{n_B}{s} \simeq 10^{-10} \frac{\dot{\theta}}{10 \text{ TeV}} \frac{\Sigma m_\nu^2}{0.03 \text{ eV}^2}$$



Early time

$$\dot{\theta} = \sqrt{V'(S)/S} \simeq m_S(S)$$

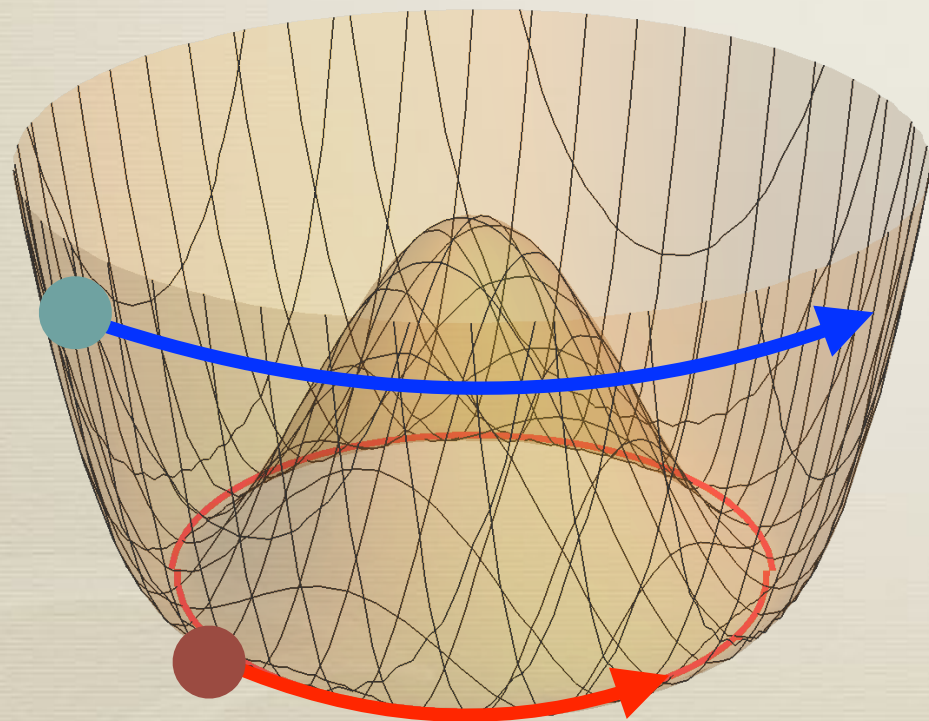
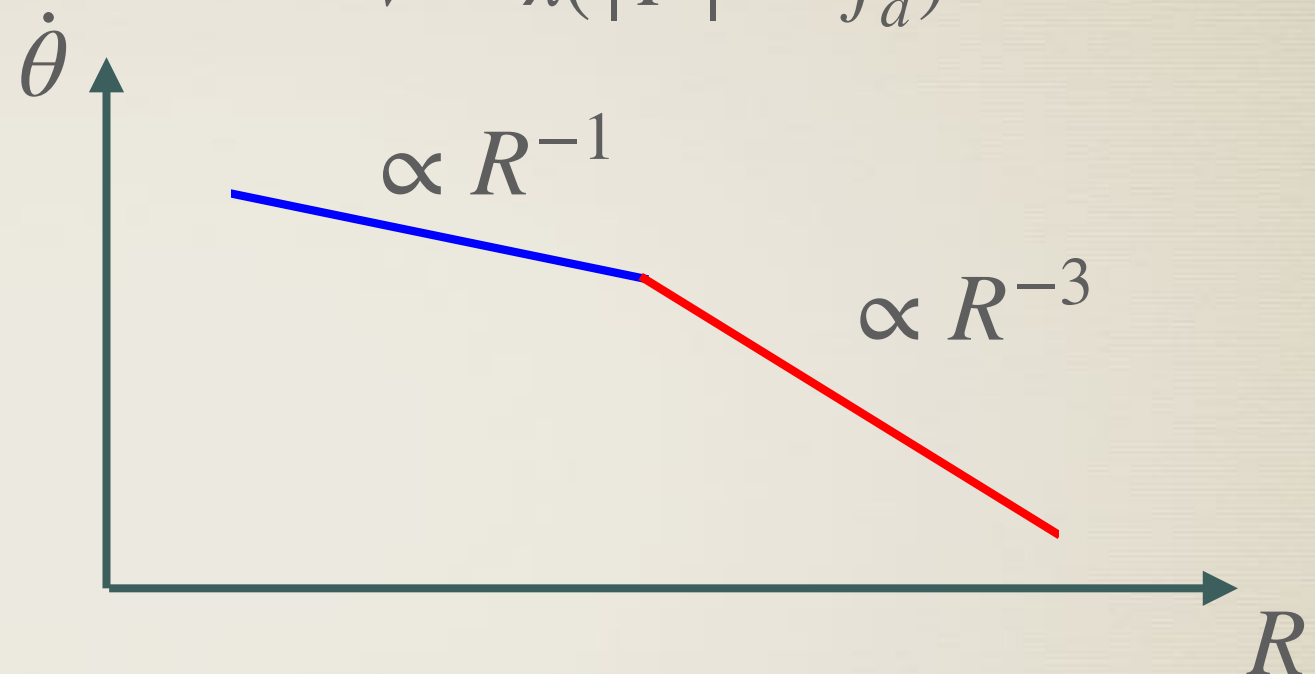
Around the electroweak phase transition

$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

$$\frac{n_B}{s} \simeq 10^{-10} \left(\frac{\dot{\theta}}{10 \text{ TeV}} \frac{\sum m_\nu^2}{0.03 \text{ eV}^2} \right)$$

$$V = \lambda(|P|^2 - f_a^2)^2$$



Early time

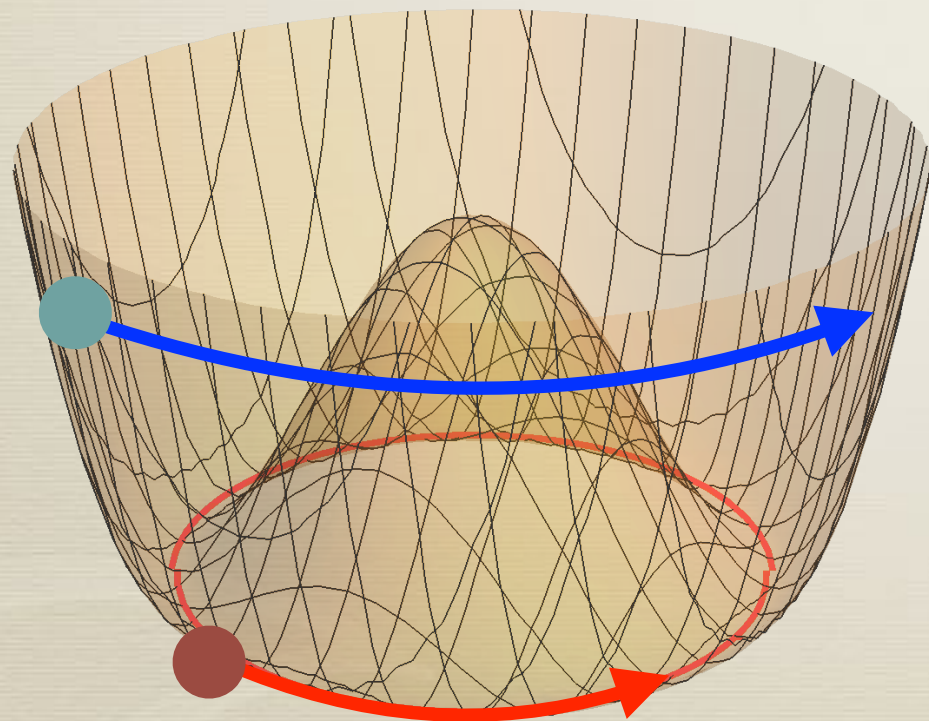
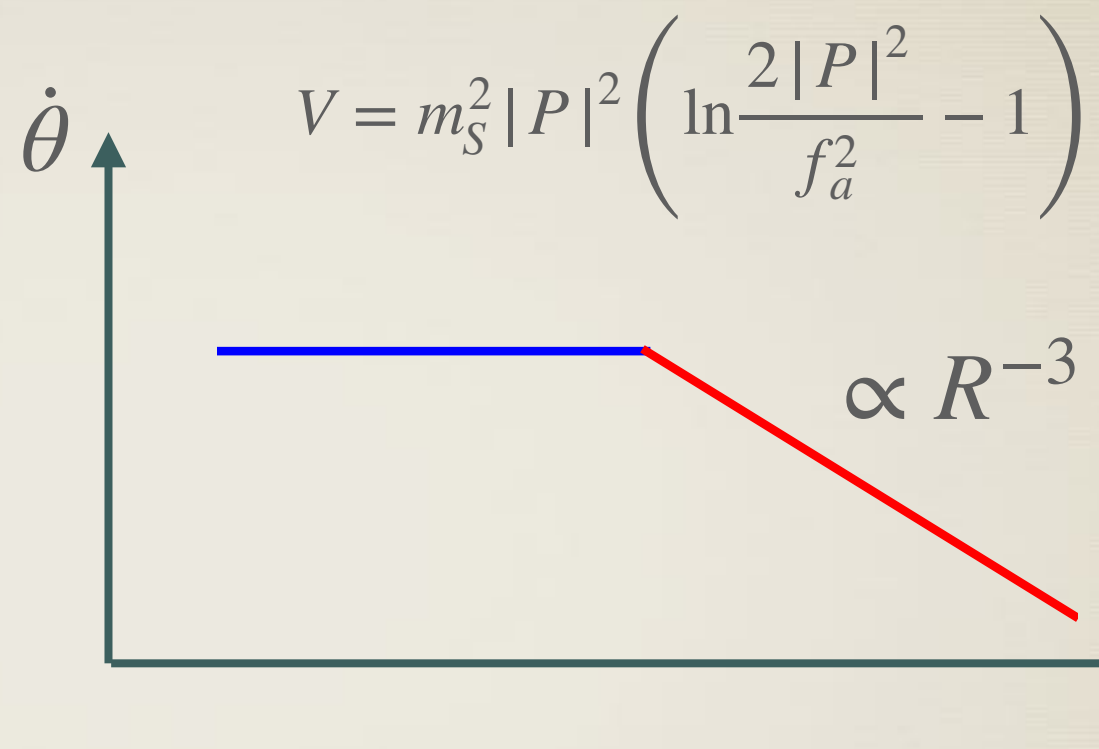
$$\dot{\theta} = \sqrt{V'(S)/S} \simeq m_S(S)$$

Around the electroweak phase transition

$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

$$\frac{n_B}{s} \simeq 10^{-10} \left(\frac{\dot{\theta}}{10 \text{ TeV}} \frac{\sum m_\nu^2}{0.03 \text{ eV}^2} \right)$$



Early time

$$\dot{\theta} = \sqrt{V'(S)/S} \simeq m_S(S)$$

Around the electroweak phase transition

$$\dot{\theta} \propto R^{-3}$$

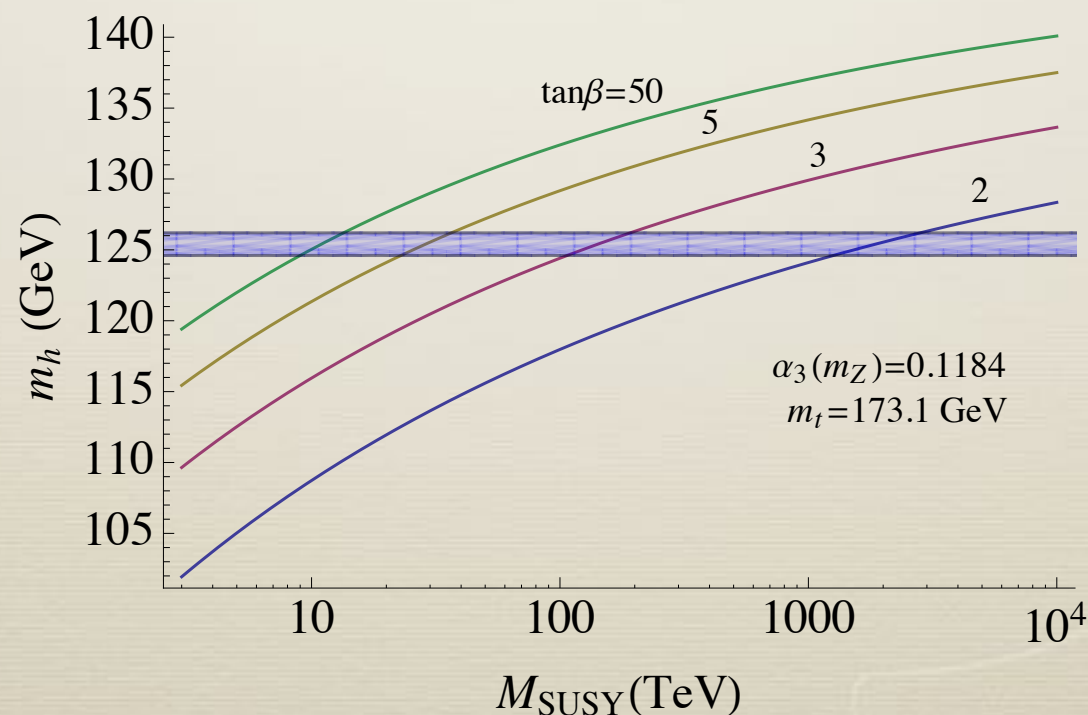
Supersymmetry

$$\frac{n_B}{s} \simeq 10^{-10} \frac{\dot{\theta}}{10 \text{ TeV}} \frac{\sum m_\nu^2}{0.03 \text{ eV}^2}$$

In supersymmetric models,

$$m_{\text{SUSY,scalar}} \sim m_S \sim \dot{\theta} \sim 10 - 100 \text{ TeV}$$

Consistent with the Higgs mass



Supersymmetry

$$\frac{n_B}{s} \simeq 10^{-10} \frac{\dot{\theta}}{10 \text{ TeV}} \frac{\sum m_\nu^2}{0.03 \text{ eV}^2}$$

In supersymmetric models,

$$m_{\text{SUSY,scalar}} \sim m_S \sim \dot{\theta} \sim 10 - 100 \text{ TeV}$$

Consistent with the without-singlets scenarios

Giudice, Luty, Murayam, Rattazzi (1998)

“Mini-split SUSY,” “Spreads SUSY,” “Pure-gravity mediation,” ...

- gaugino masses are given by anomaly mediation, $\sim \text{TeV}$
- no moduli problem from singlet SUSY breaking fields
- no gravitino problem

New perspective on SUSY scale

- * Electroweak hierarchy $m_{\text{SUSY}} \sim 100 \text{ GeV}$
- * Gauge coupling unification $m_{\text{SUSY}} \lesssim 10^6 \text{ GeV}$
- * Lightest supersymmetric particle as DM $m_{\text{SUSY}} \lesssim 10^3 \text{ GeV}$
(invalid with RPV)
- * Baryogenesis from axion rotation and neutrino mass

$$m_{\text{SUSY}} \simeq 10 - 100 \text{ TeV}$$

Summary

- * **Kinetic Misalignment** : Rotation of the axion field enhances the axion abundance
- * **Axiogenesis** : The rotation produces baryon asymmetry
- * **ALP-cogenesis** : An ALP explains DM and baryon asymmetry
- * **Lepto-axiogenesis** : Neutrino masses aides axiogenesis

