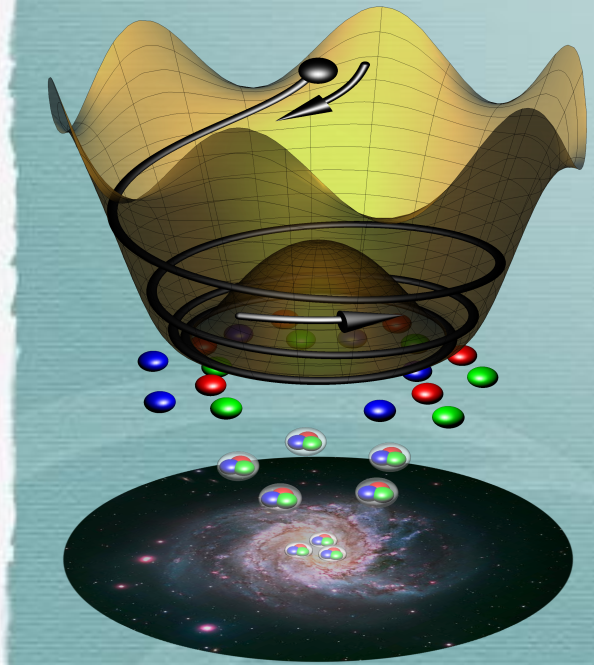
02/1/2021, Dark Matter as a Portal to New Physics

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

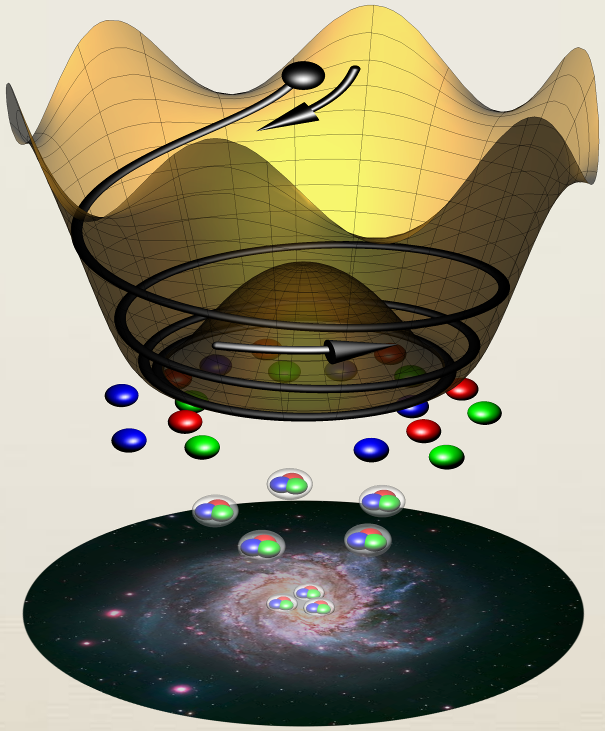
- What is dark matter?
- How did cosmic inflation occur?
- How was the baryon asymmetry of the universe created?
- Why does QCD preserve CP symmetry?
- What sets the Higgs potential parameters?
- ....

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

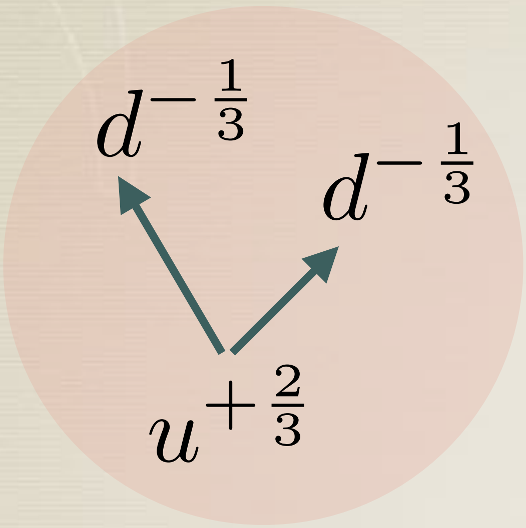
New cosmological dynamics of the QCD axion
and an axion-like particle (ALP)

- 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

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

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

$$d_n/e < 2.9 \times 10^{-26} \text{ cm}$$ 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)

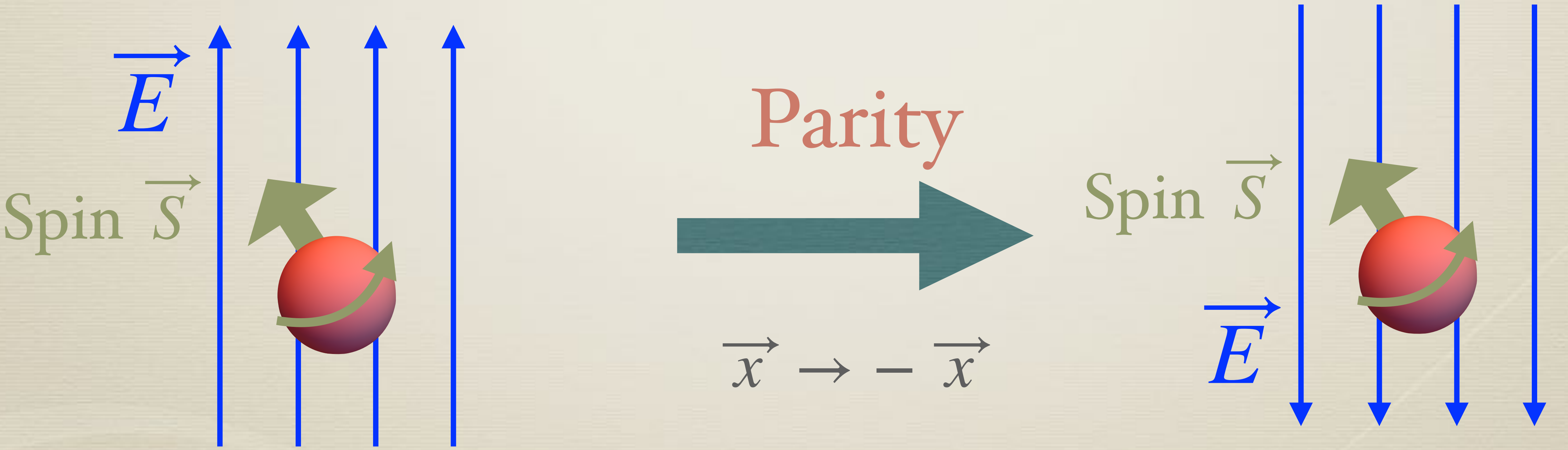
Known Solutions

- 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)



$\vec{x} \rightarrow -\vec{x}$

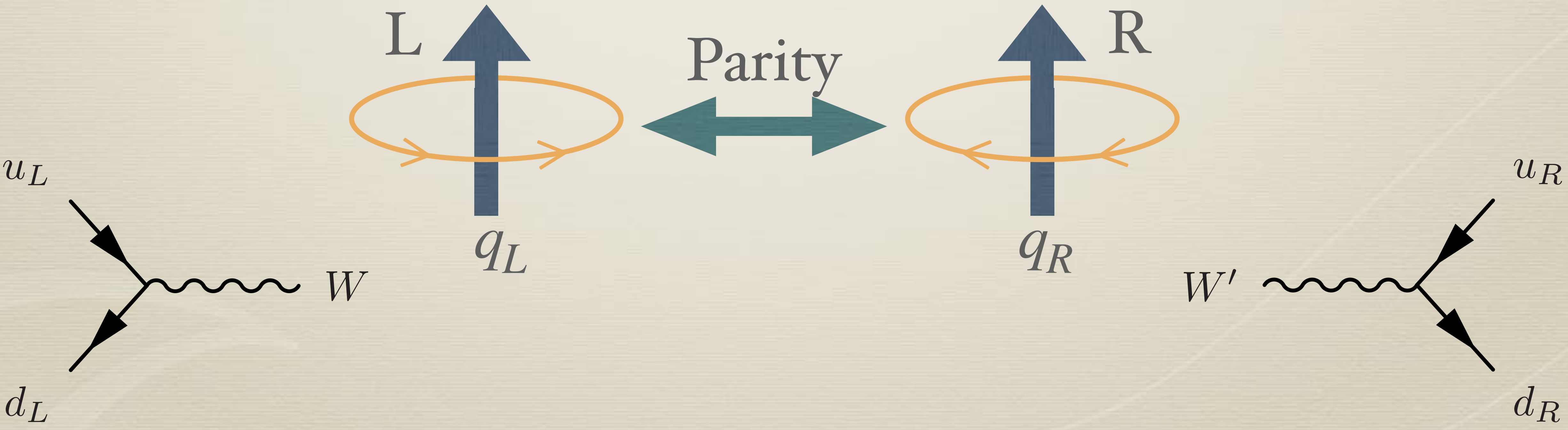
$\vec{S} =$ “$\vec{x} \times \vec{v}$”

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

Known Solutions

- Spontaneously broken parity
- Spontaneously broken CP
- QCD axion

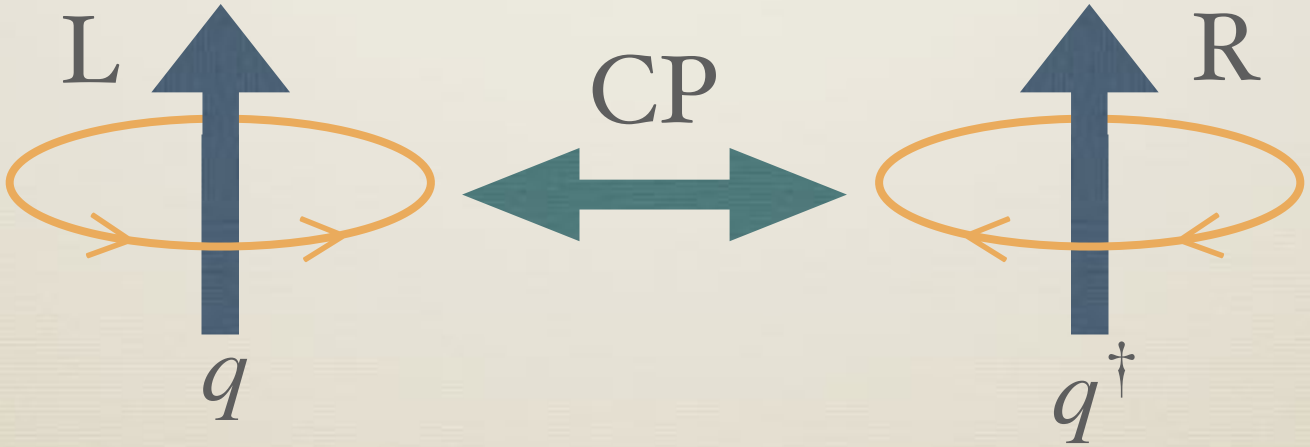
Mohapatra and Senjanovic (1978)
Beg and Tsao (1978)
Babu and Mohapatra (1989)
Barr, Chang and Senjanovic (1991)
Hall and KH (2018,2019)
Dunsky, Hall and KH (2019)



Known Solutions

Nelson (1984), Barr (1984)

- Spontaneously broken parity
- Spontaneously broken CP
- QCD axion

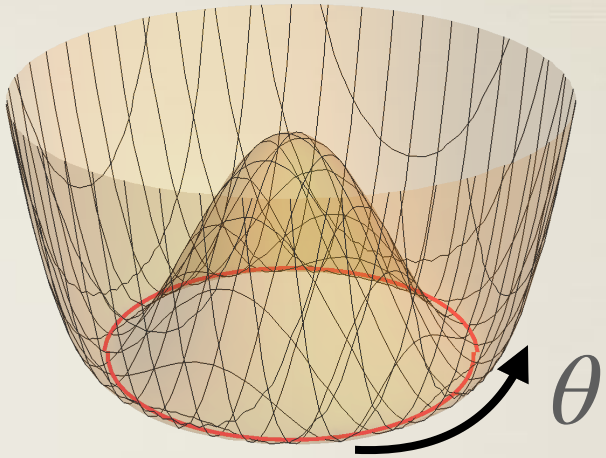


Breaks CP spontaneously to introduce CP phases in quark masses, but without introducing the strong CP phase

Known Solutions

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

- Spontaneously broken parity
- Spontaneously broken CP
- QCD axion



$\theta = a/f_a$

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

Spontaneous breaking

pseudo-Nambu Goldstone boson, the QCD axion

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

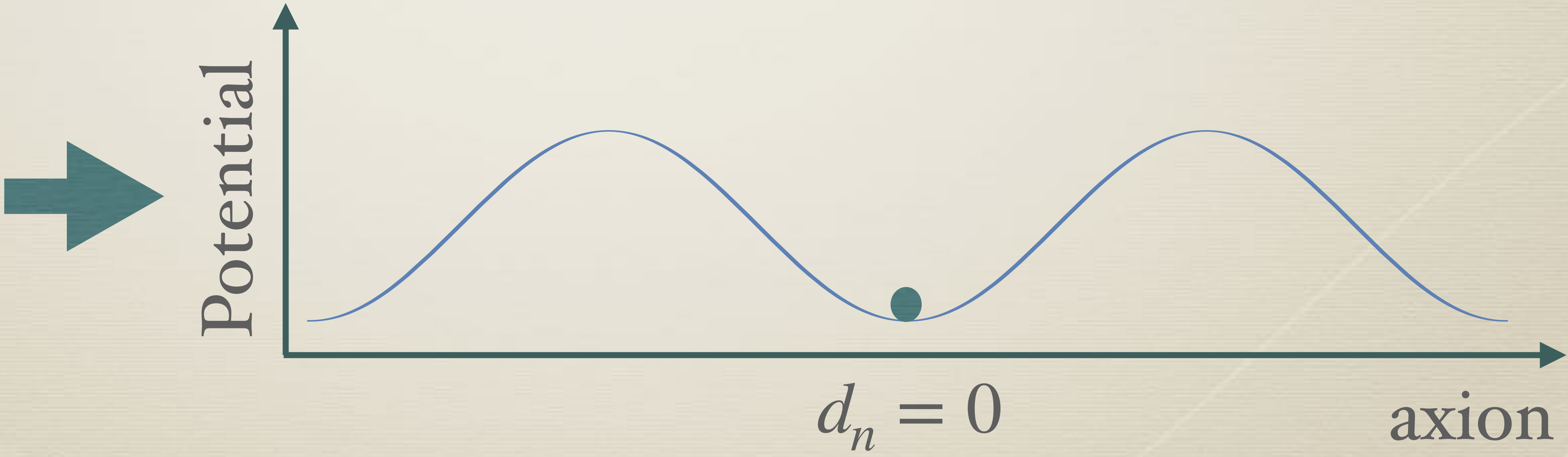
f_a : the decay constant

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 . $\eta \to \pi^+\pi^-$

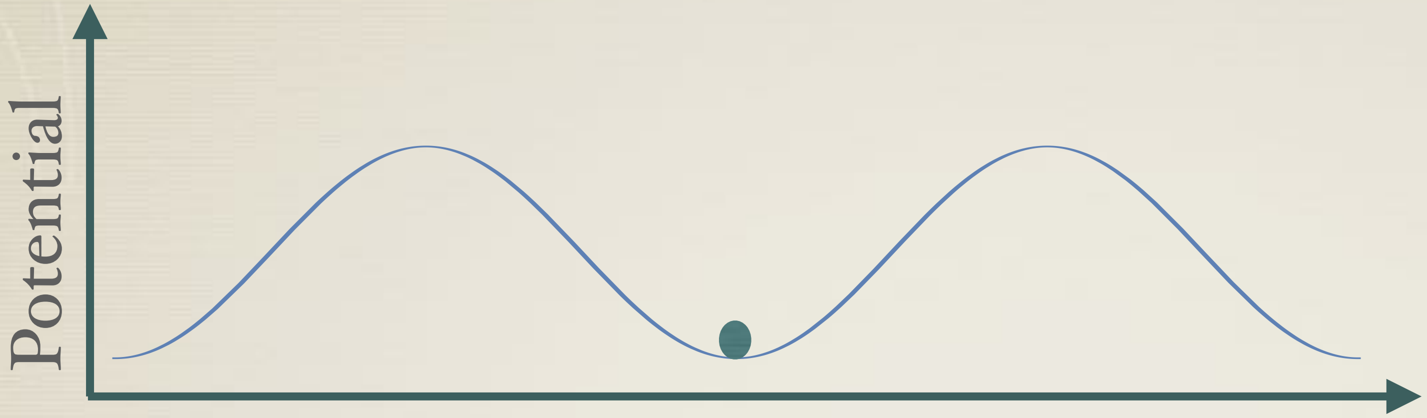
Known Solutions

- Spontaneously broken parity
- Spontaneously broken CP
- QCD axion
- ....

Why QCD axion ?

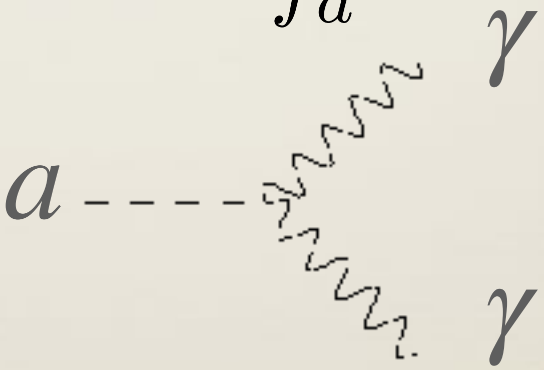
QCD axion dark matter

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

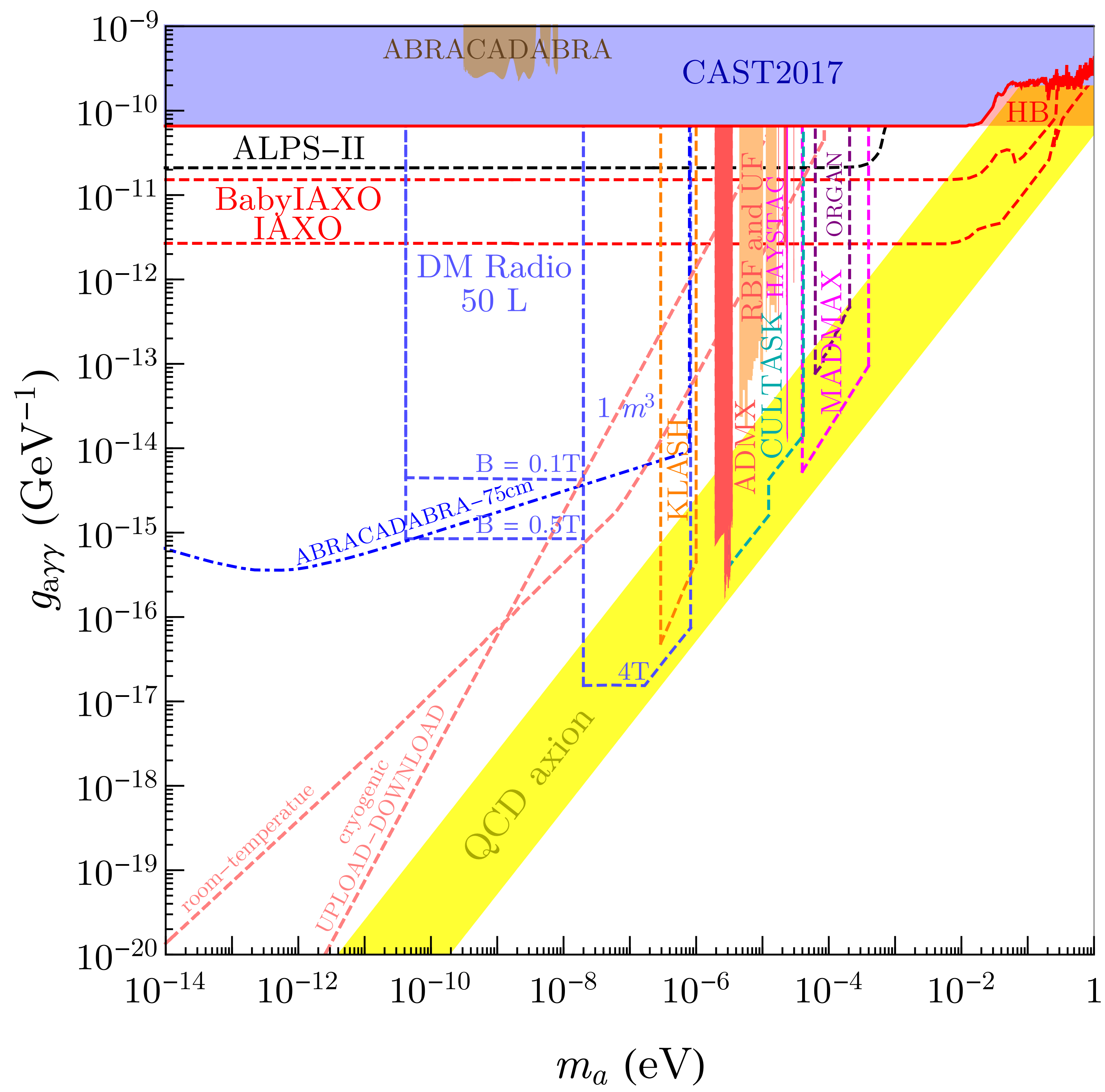


$\propto \frac{1}{f_a}$

➡ 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

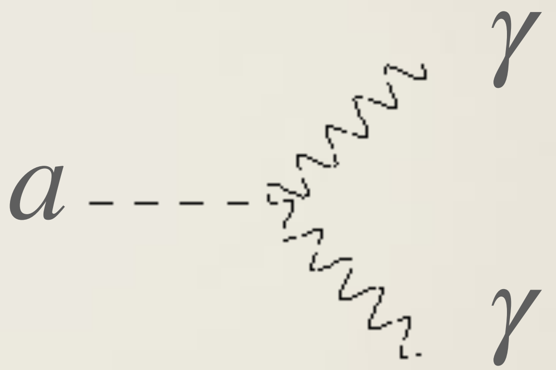


ALP dark matter

A pseudo-Nambu Goldstone boson from some global symmetry

naturally light

and weakly coupled



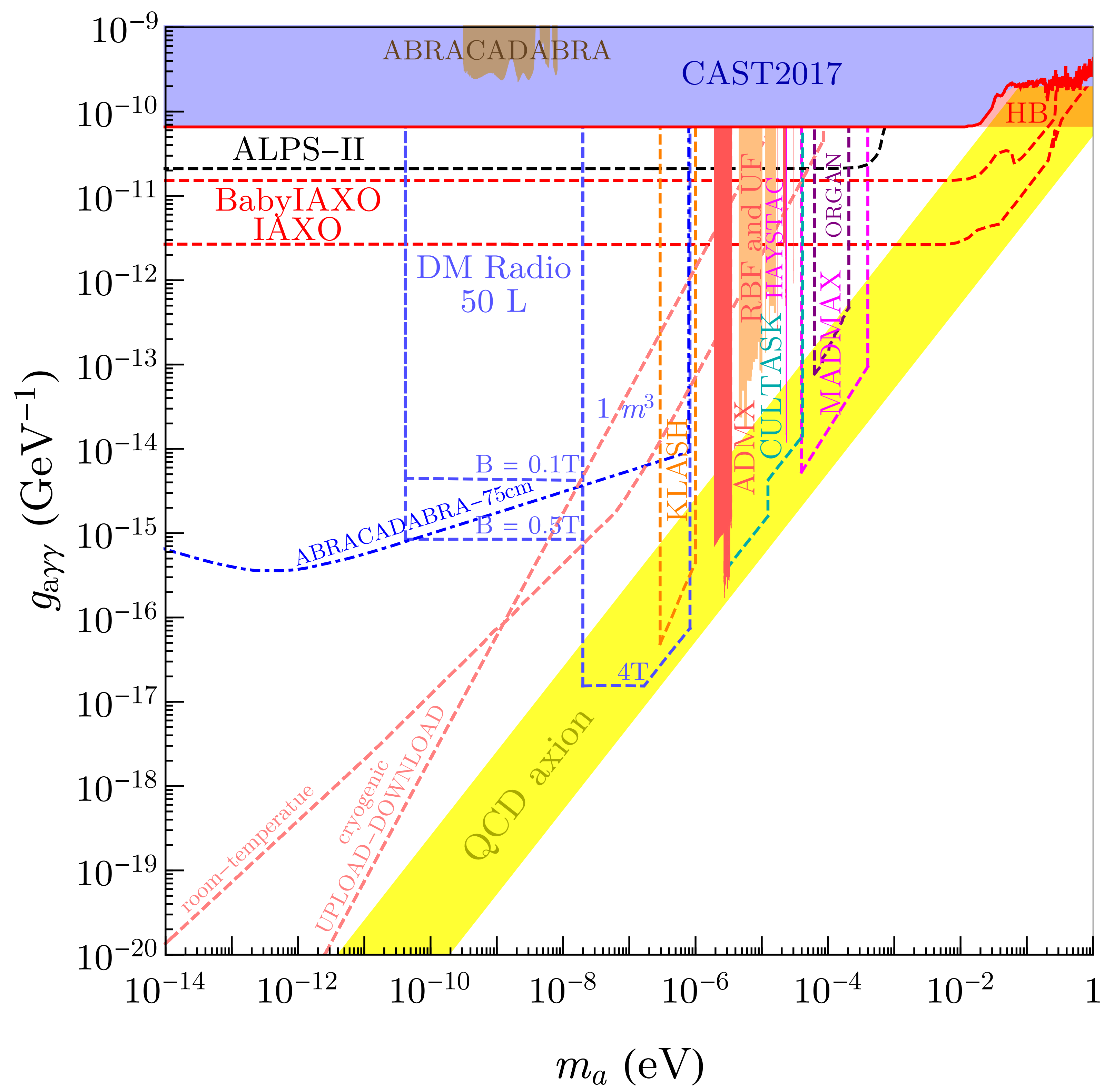
$$\propto \frac{1}{f_a}$$

naturally long-lived

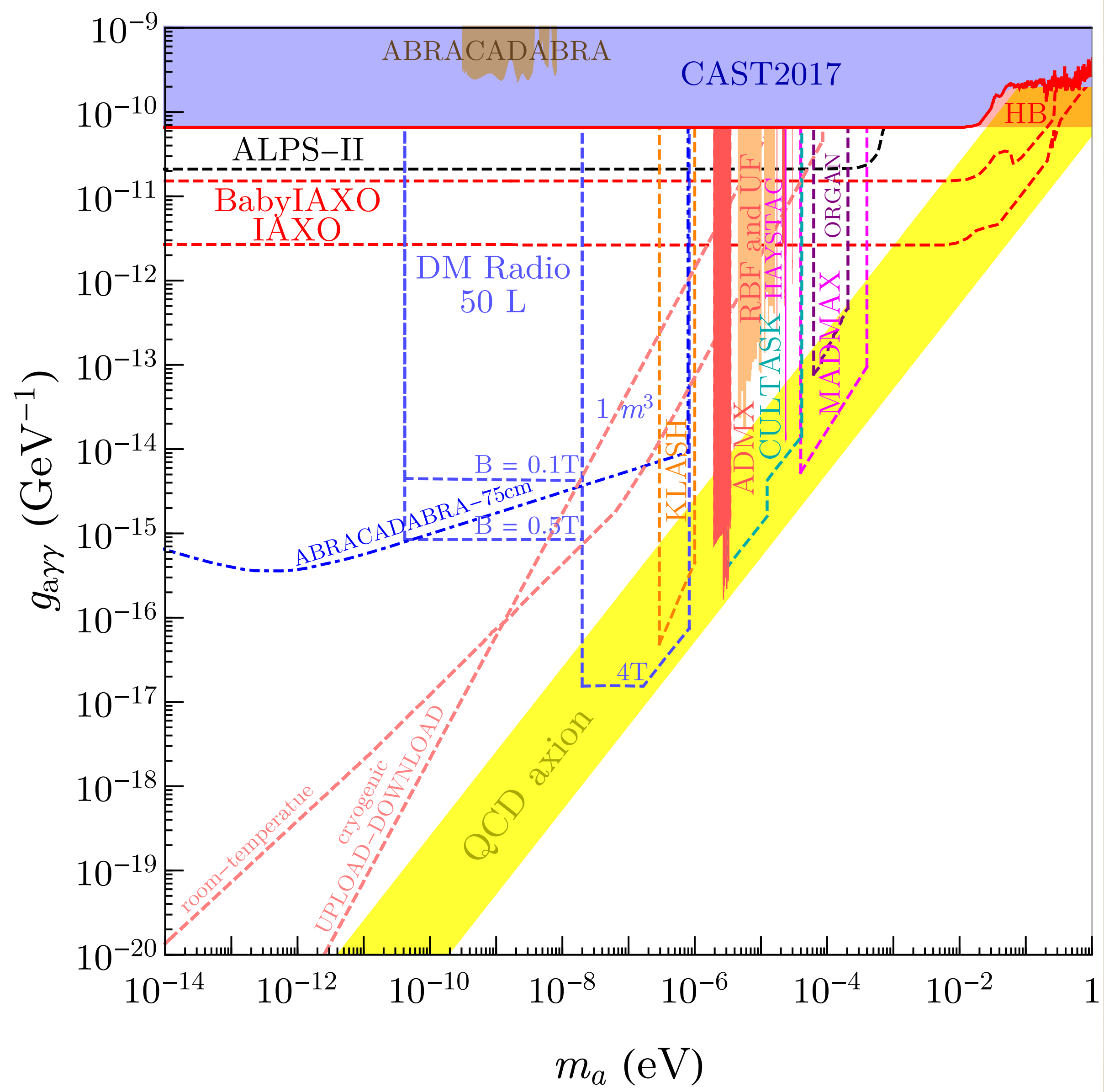
$$\tau_a \sim 10^{10} \times t_{\rm univ} \left(\frac{f_a}{10^9 \ {\rm GeV}} \right)^2 \left(\frac{\rm eV}{m_a} \right)^3$$

Dark Matter candidate

Axion search



Dark matter?

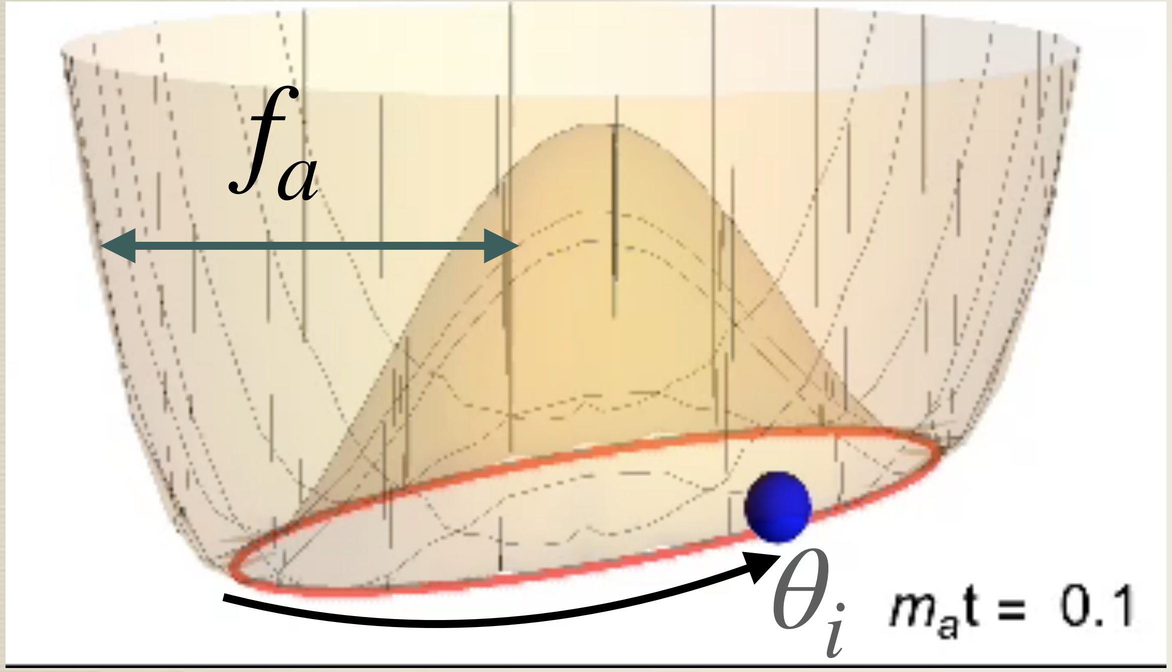


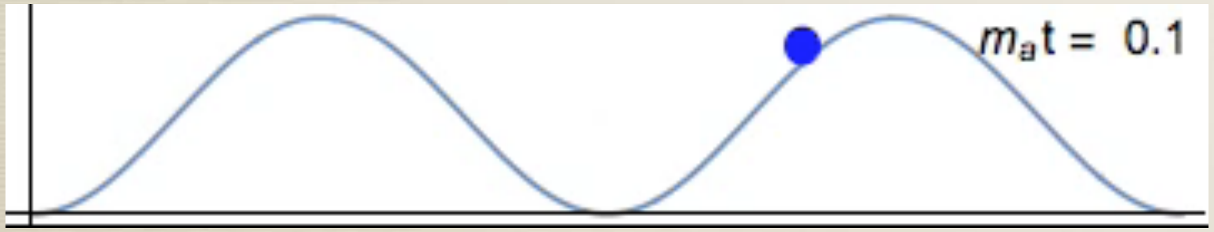
$\rho_{\rm DM} \simeq 1.3 \times 10^{-5}$ GeV/cm^3 (Planck 2018)

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,

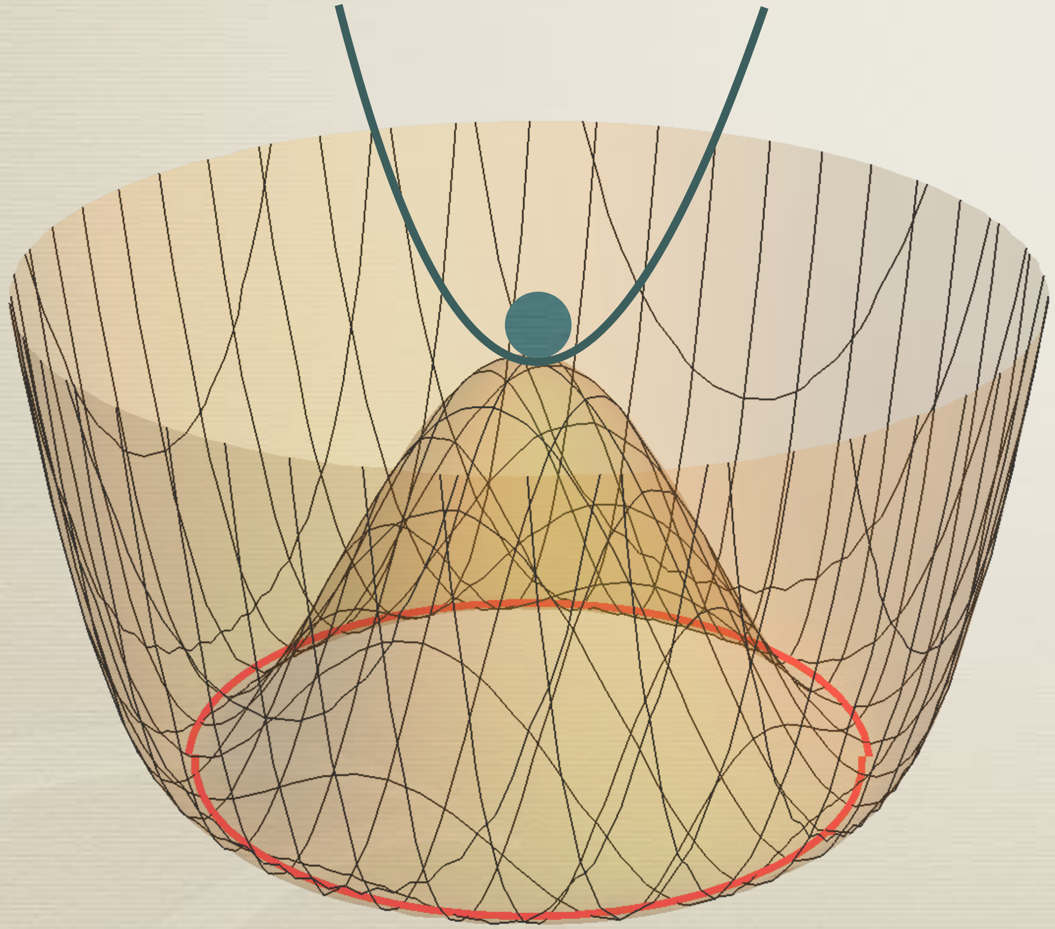
$$\frac{\rho_a}{\rho_{\rm DM}} = \theta_i^2 \left(\frac{f_a}{10^{12}\ {\rm GeV}} \right)^{1.19}$$

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

animation is available at http://www.sns.ias.edu/-keisukeharigaya/mm.html

Cosmic strings

trapping by thermal potential,
coupling with inflaton, etc.

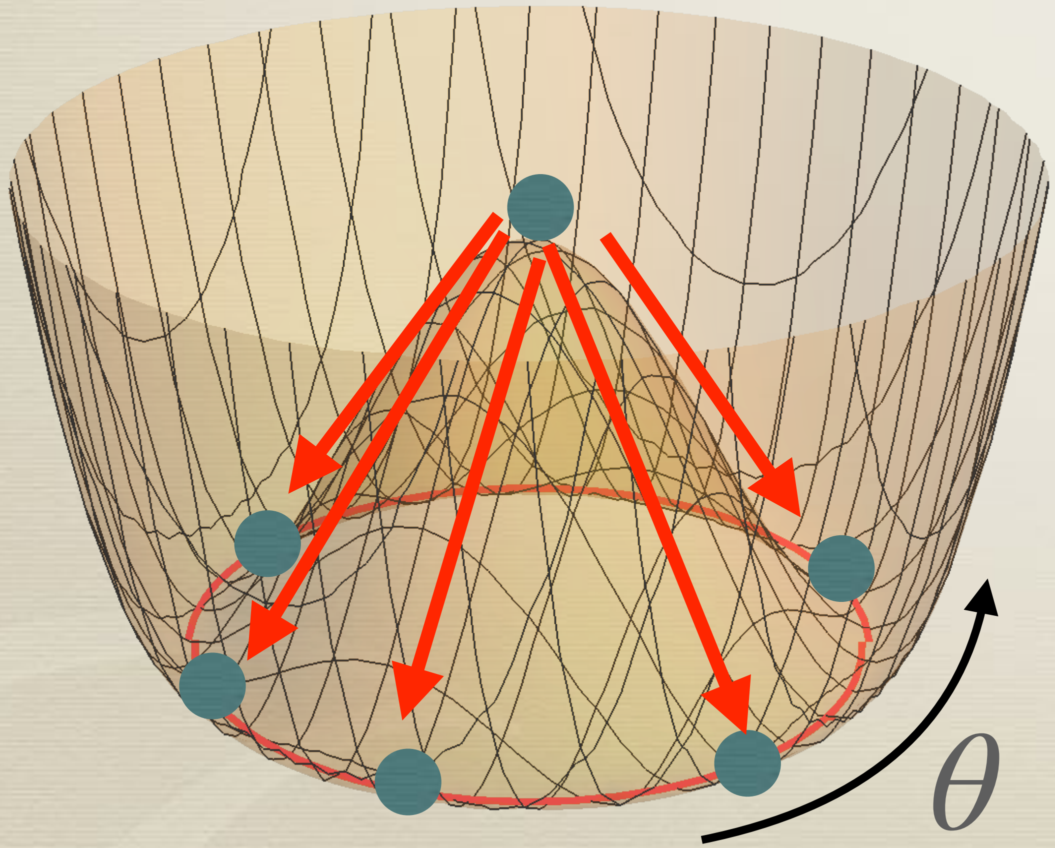


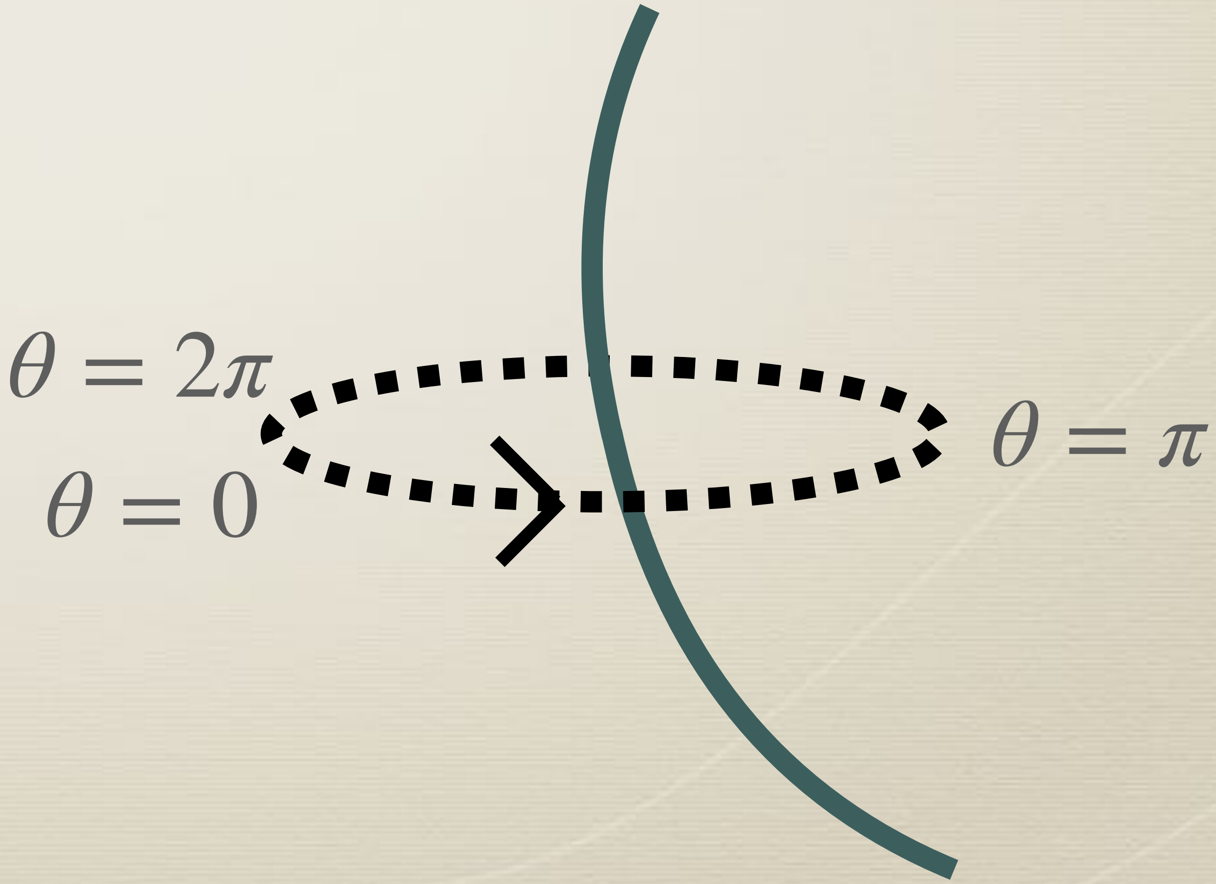
$$V = (-m^2 + c_T T^2 + c_H H_{\rm inf}^2)\,|P|^2 + \cdots$$

Cosmic strings

Phase transition

Inhomogeneous configurations
including cosmic strings





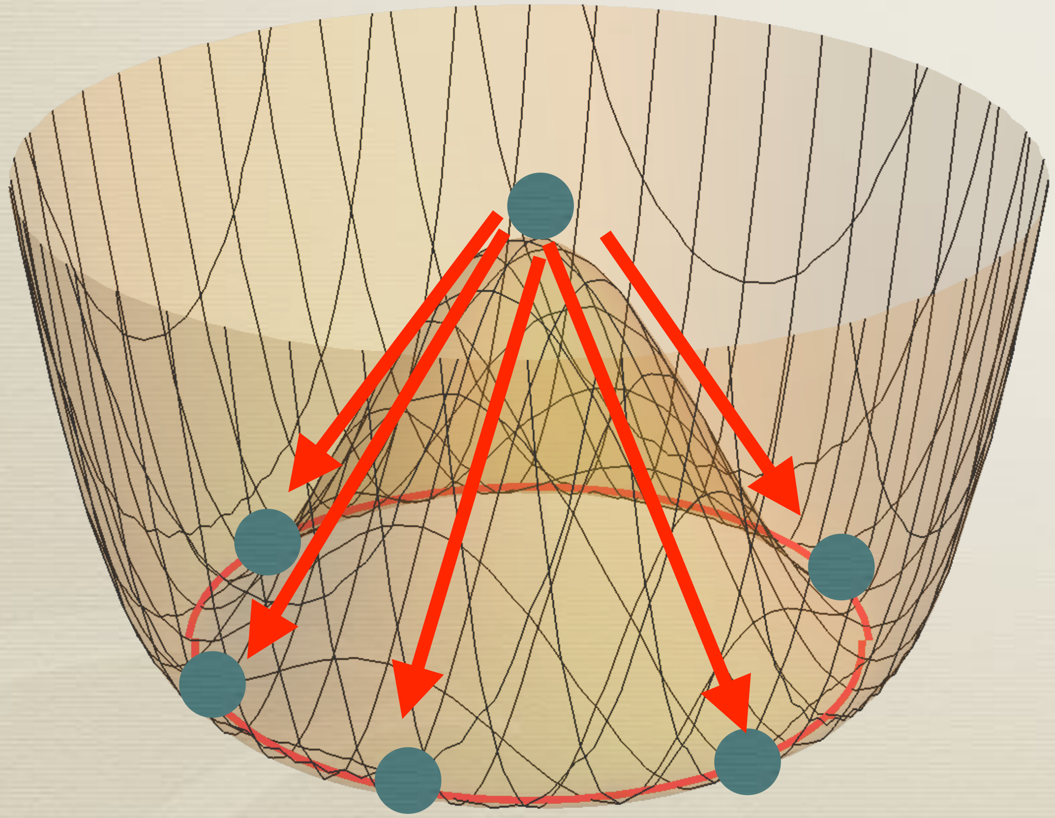
Cosmic strings

Phase transition → Inhomogeneous configurations including cosmic strings

↓

Axions are radiated

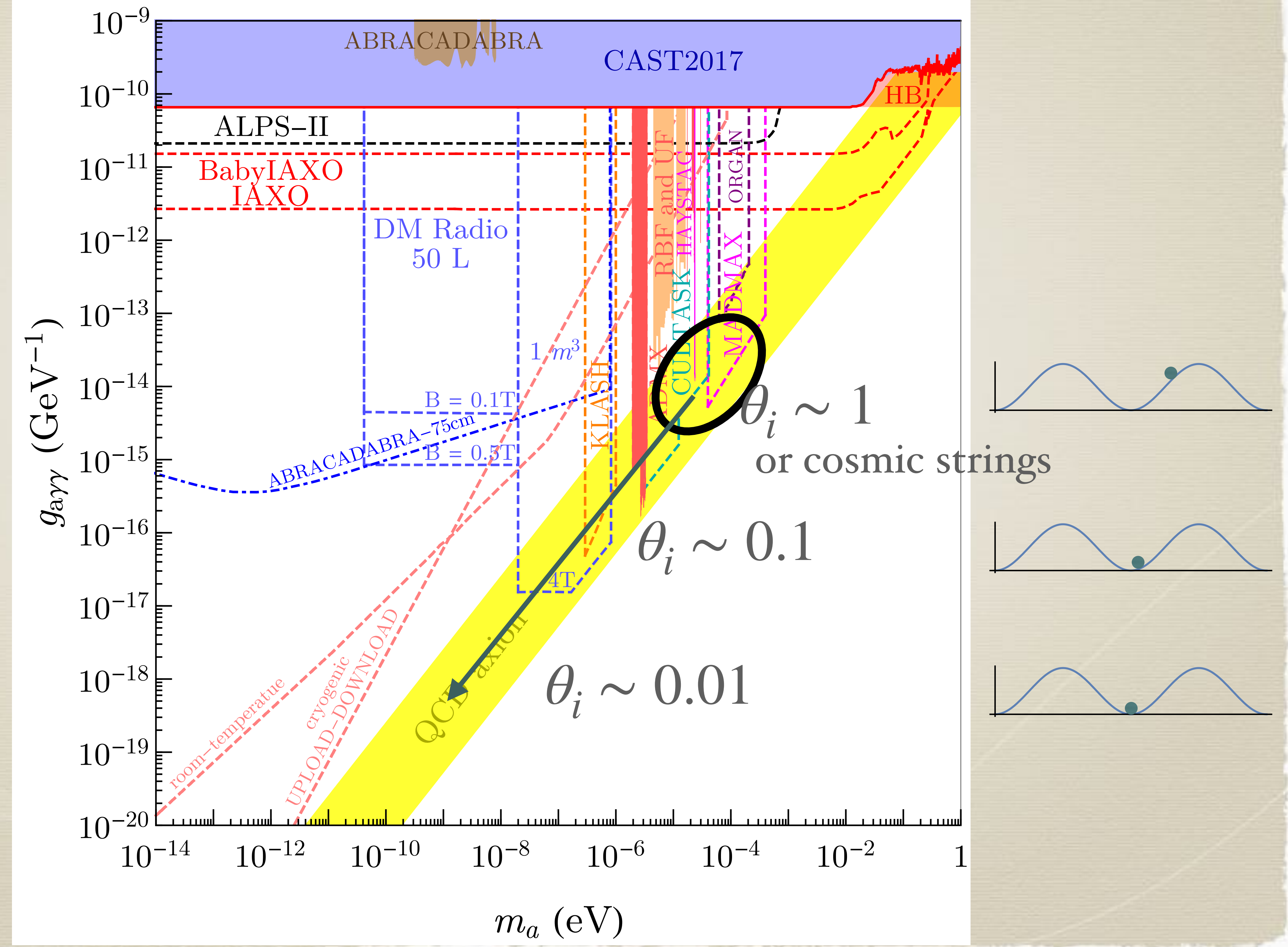
Davis (1986)



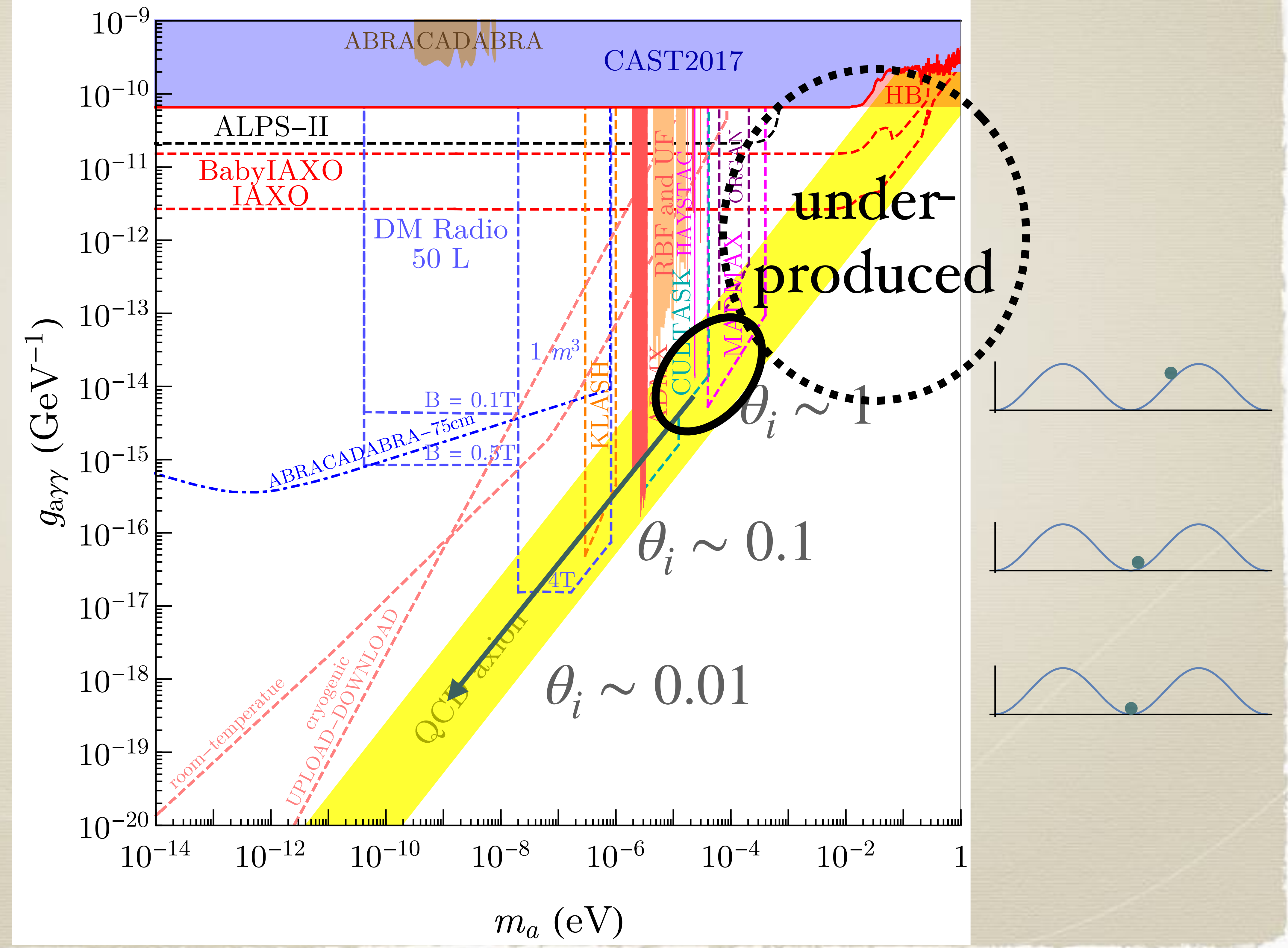
$$\frac{\rho_a}{\rho_{\mathrm{DM}}} = 0.4 - 10 \left(\frac{f_a}{10^{11}\ \mathrm{GeV}}\right)^{1.19}$$

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

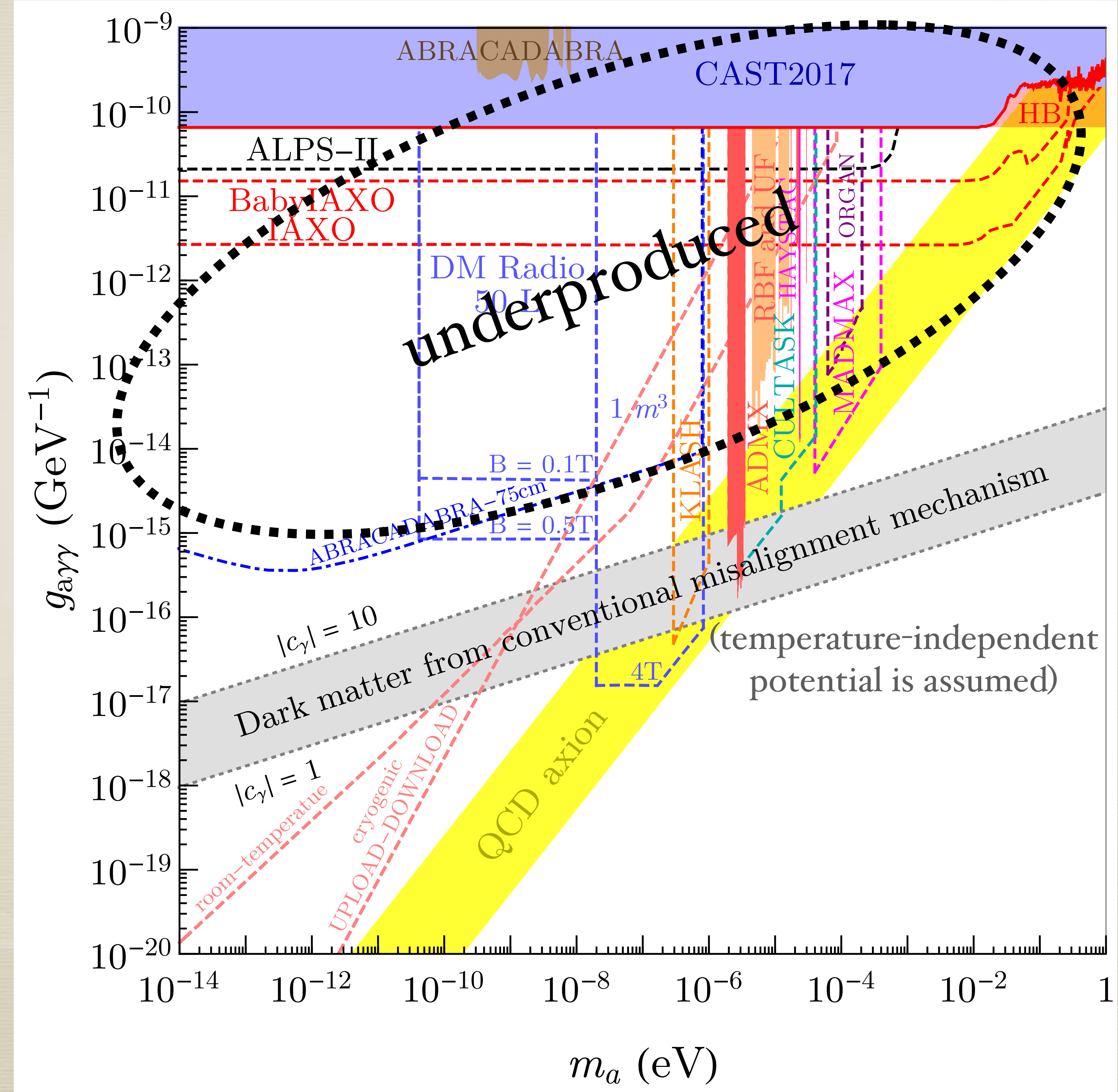
QCD axion

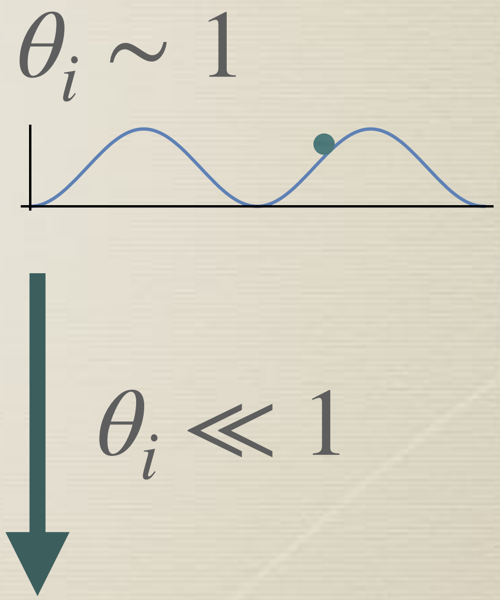

10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
m_a (eV)
ABRACADABRA
CAST2017
HB
ALPS–II
BabyIAXO
IAXO
DM Radio
50 L
1 m^3
B = 0.1T
B = 0.5T
4T
ABRACADABRA–75cm
KLASH
ADMX
RBF and UF
CULTASK
HAYSTAC
MADMAX
ORGAN
room–temperatue
cryogenic
UPLOAD–DOWNLOAD
QCD axion
$\theta_i \sim 1$
or cosmic strings
$\theta_i \sim 0.1$
$\theta_i \sim 0.01$

QCD axion


ABRACADABRA
CAST2017
HB
ALPS–II
BabyIAXO
IAXO
DM Radio
50 L
1 m^3
B = 0.1T
B = 0.5T
4T
ABRACADABRA–75cm
KLASH
ADMX
RBF and UF
CULTASK
HAYSTAC
MADMAX
ORGAN
room–temperatue
cryogenic
UPLOAD–DOWNLOAD
QCD axion
under-
produced
$\theta_i \sim 1$
$\theta_i \sim 0.1$
$\theta_i \sim 0.01$
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1

Axion Like Particle



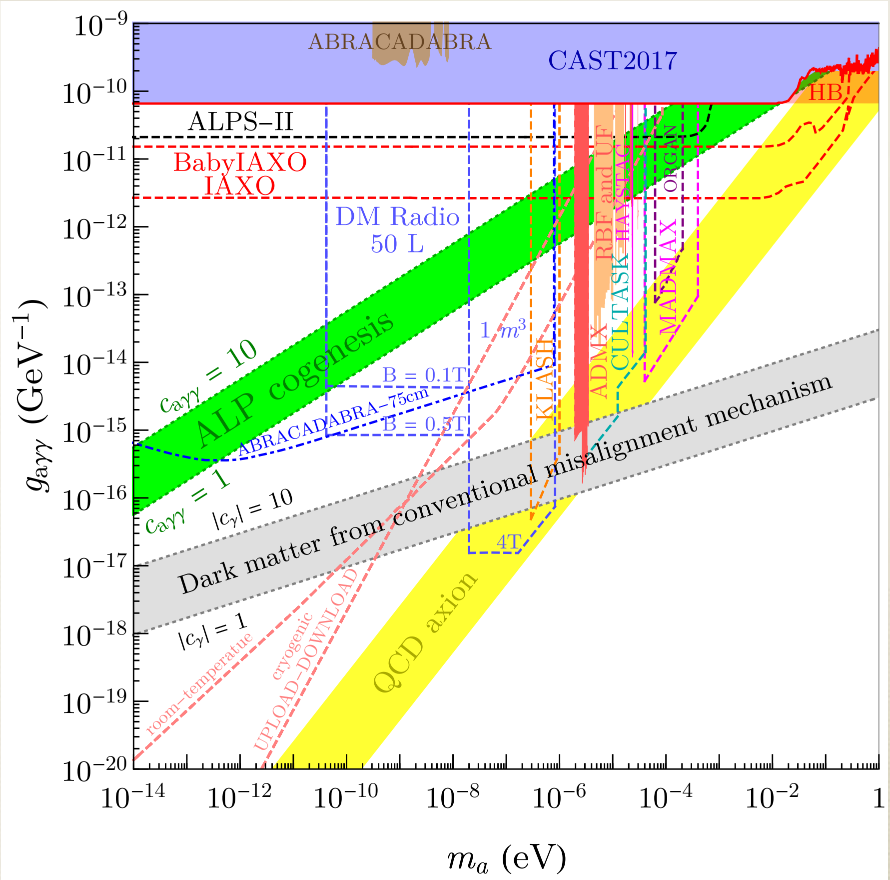


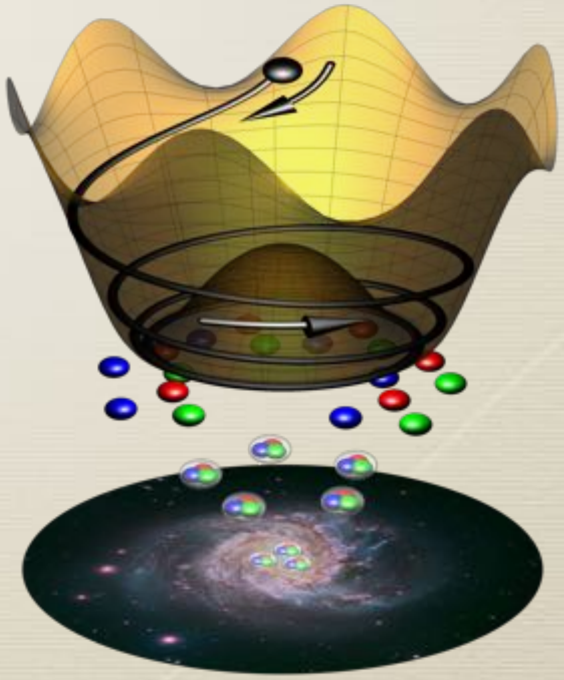
$\theta_i \sim 1$

$\theta_i \ll 1$

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





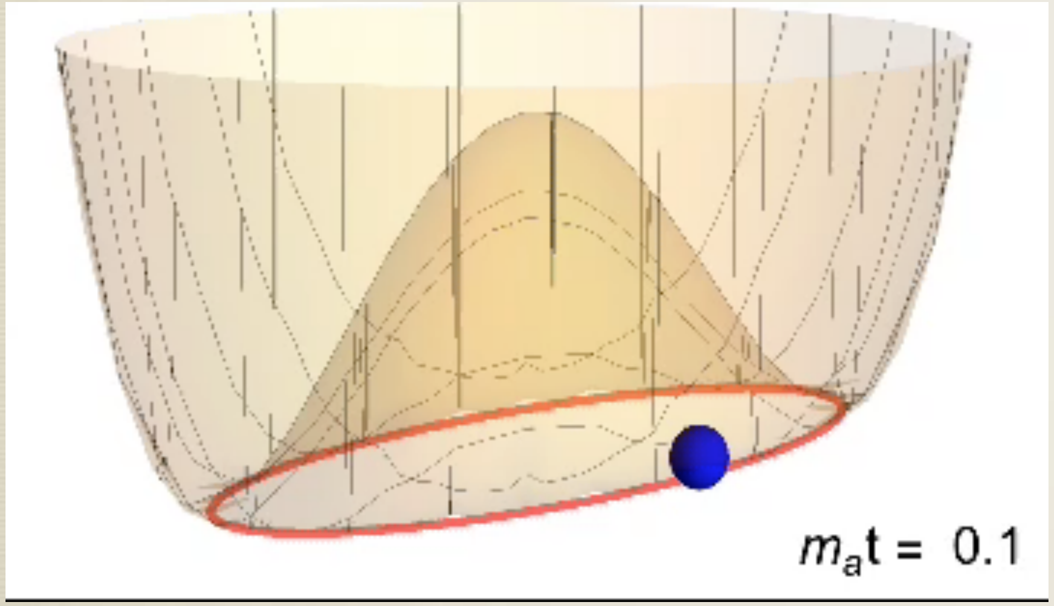
Outline

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

Rotation?

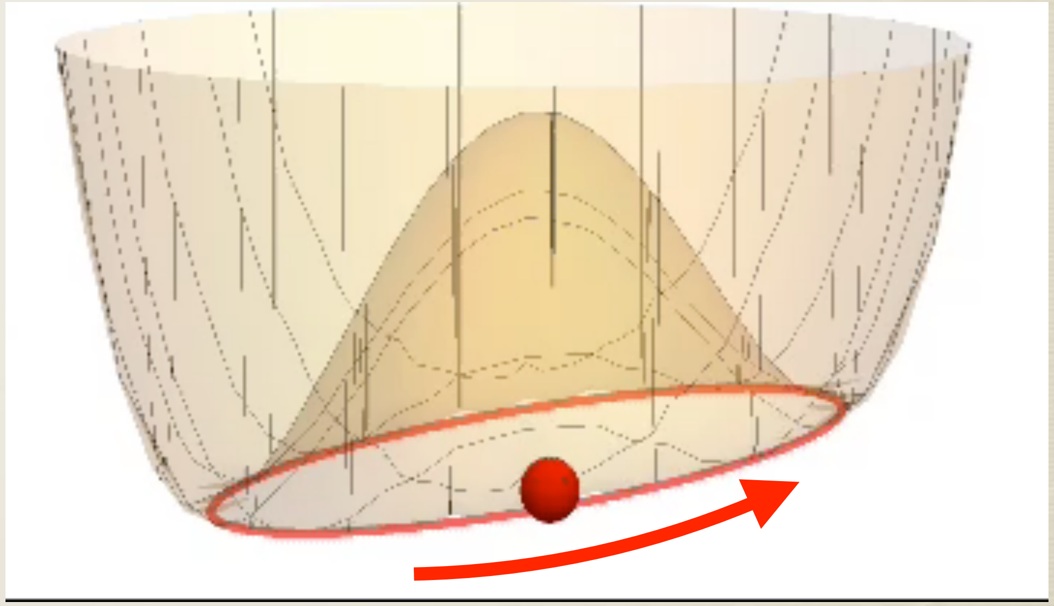
Co and KH, PRL (2020)
Co, Hall and KH, PRL (2020)

Conventional picture



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

Non-zero initial angular velocity?

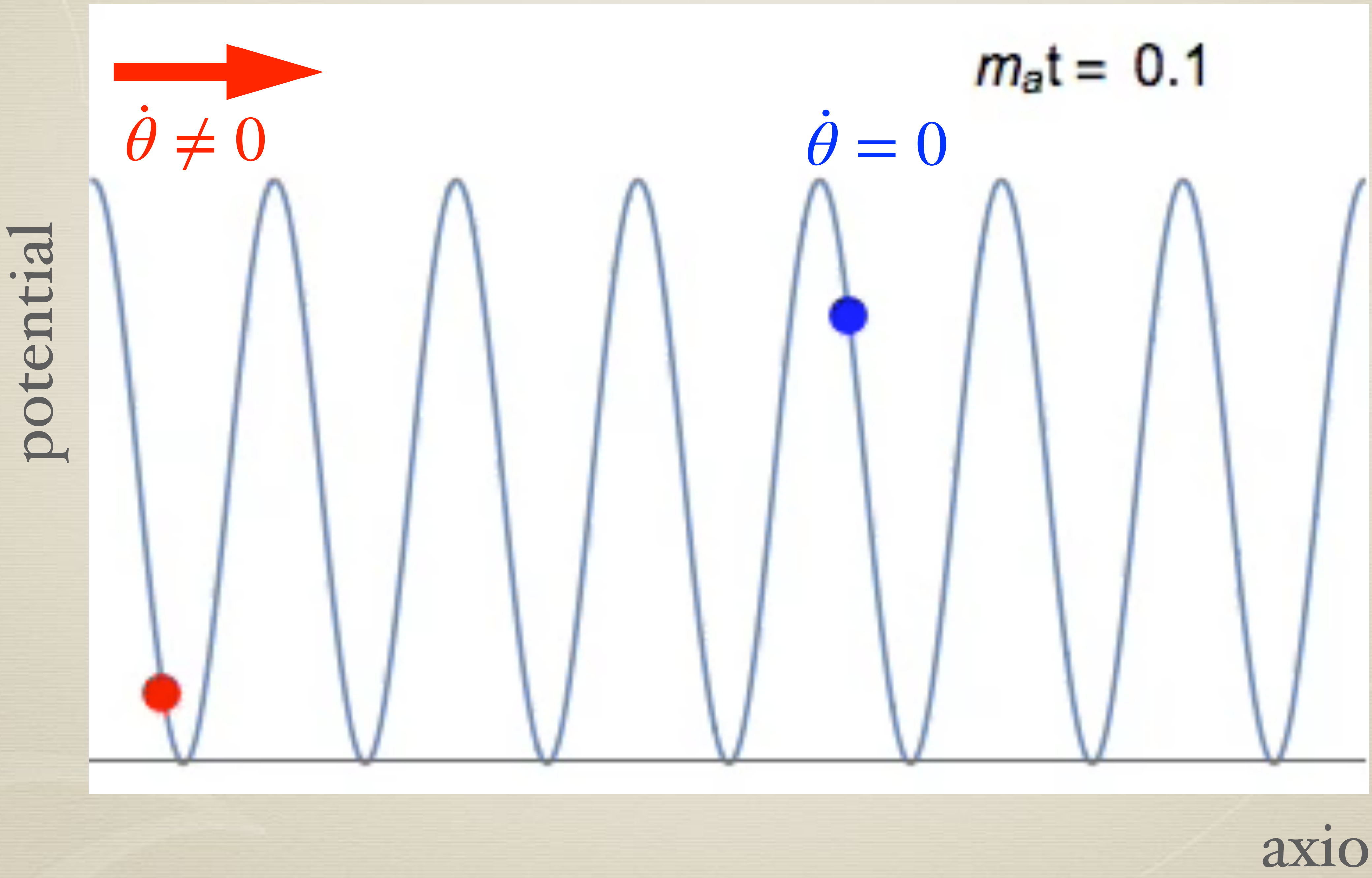


$$\dot{\theta}_i \neq 0$$

(I will later explain how to initiate rotations)

animation is available at http://www.sns.ias.edu/-keisukeharigaya/rotation.html equation of motion: $\ddot{a} + 3H\dot{a} + V'(a) = 0$

friction by cosmic expansion



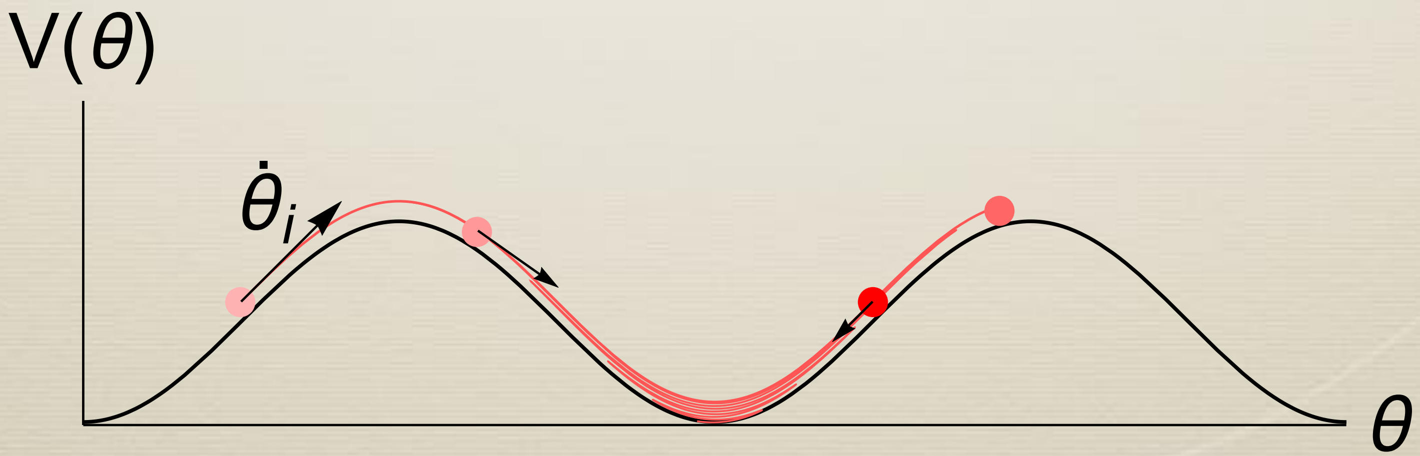
animation is available at http://www.sns.ias.edu/-keisukeharigaya/kmm.html

Impact on dark matter abundance

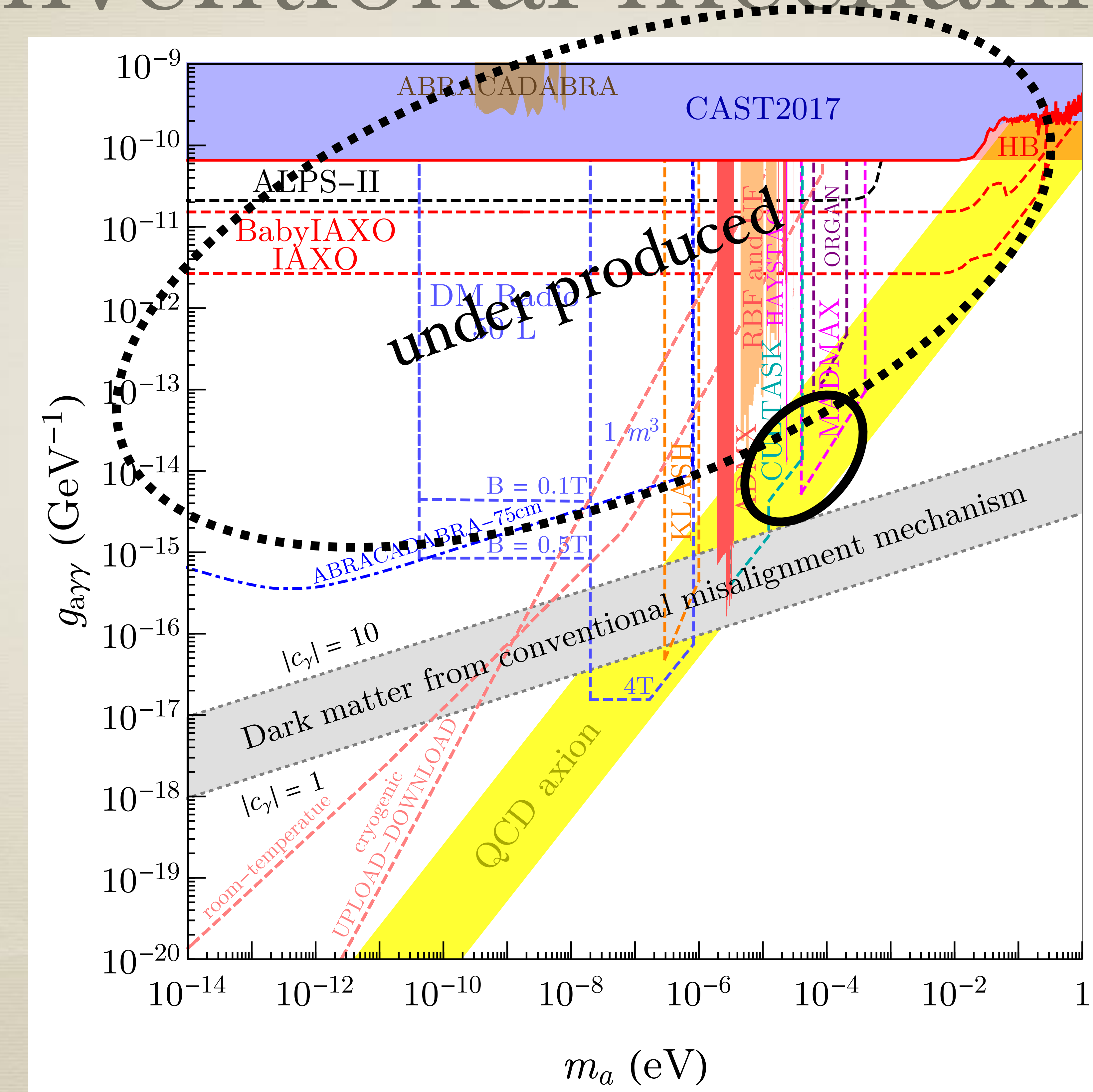
Co, Hall and KH (2019)

The beginning of the oscillation is delayed, enhancing the axion energy density

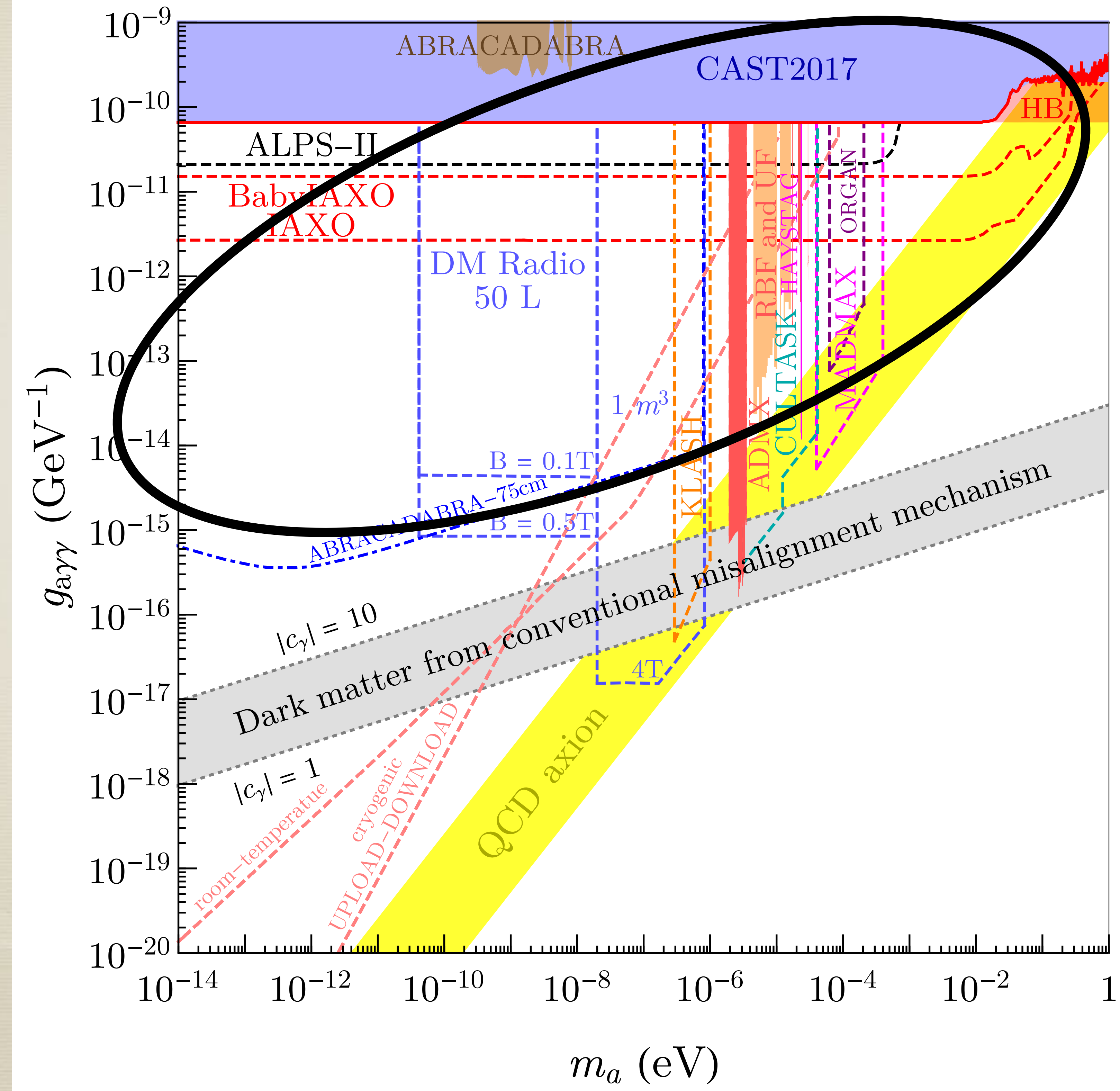
Kinetic Misalignment Mechanism (KMM)

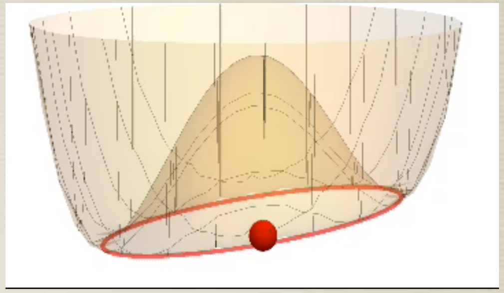


Conventional mechanisms



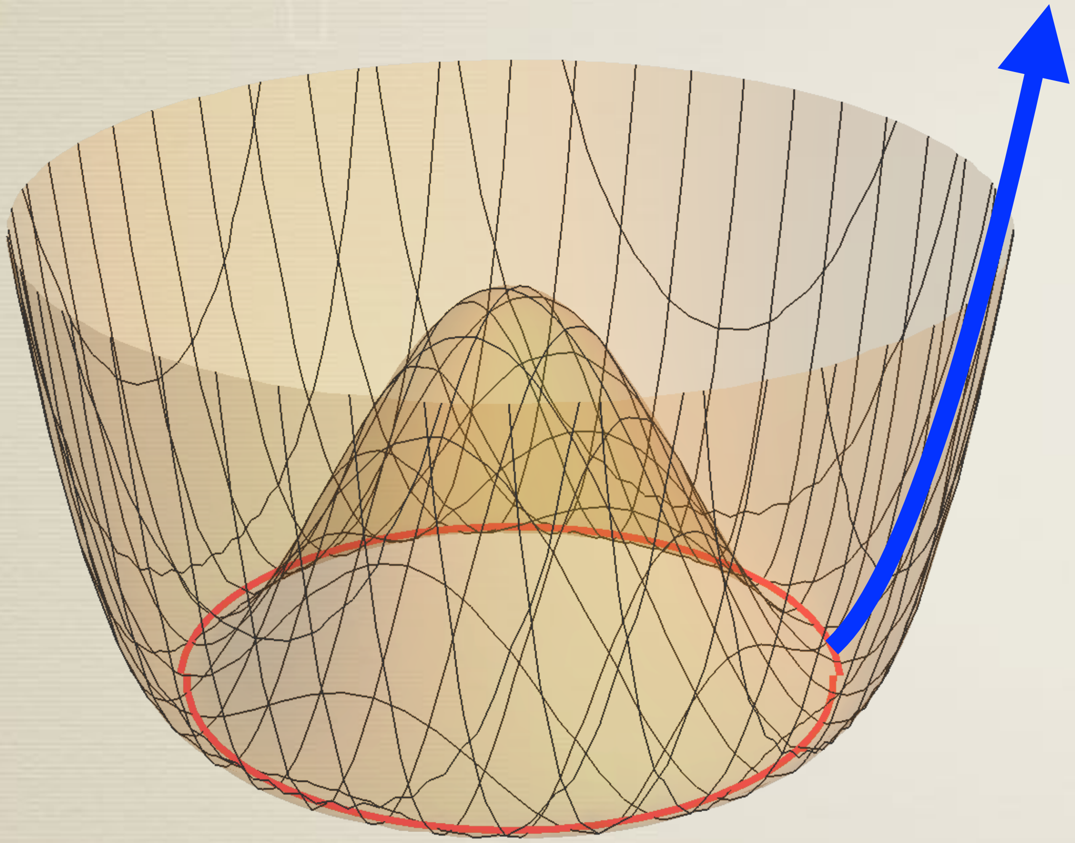
Kinetic misalignment





How to initiate the rotation

Co and KH, PRL (2020)



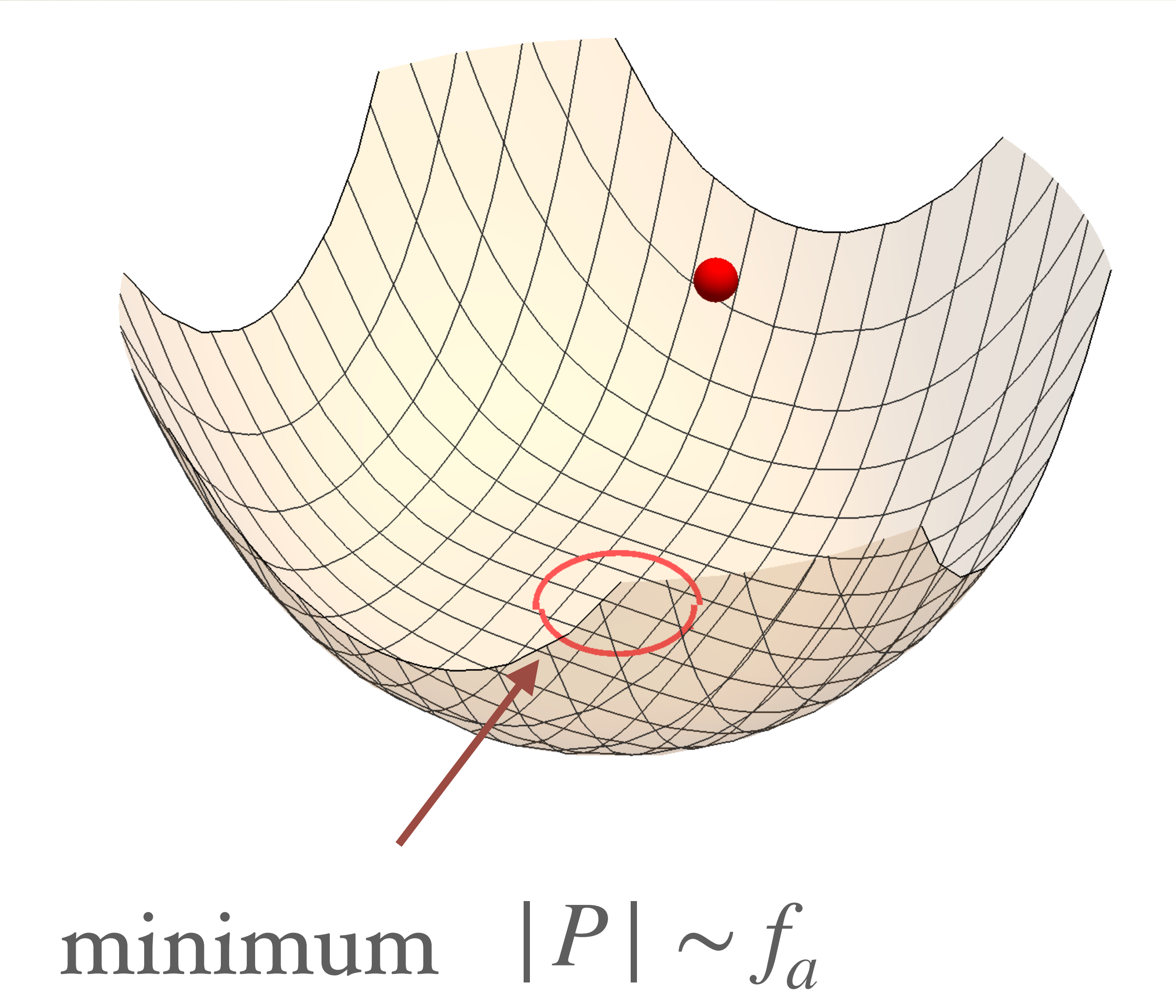
Consider the dynamics of the radial direction

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

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

How to initiate the rotation

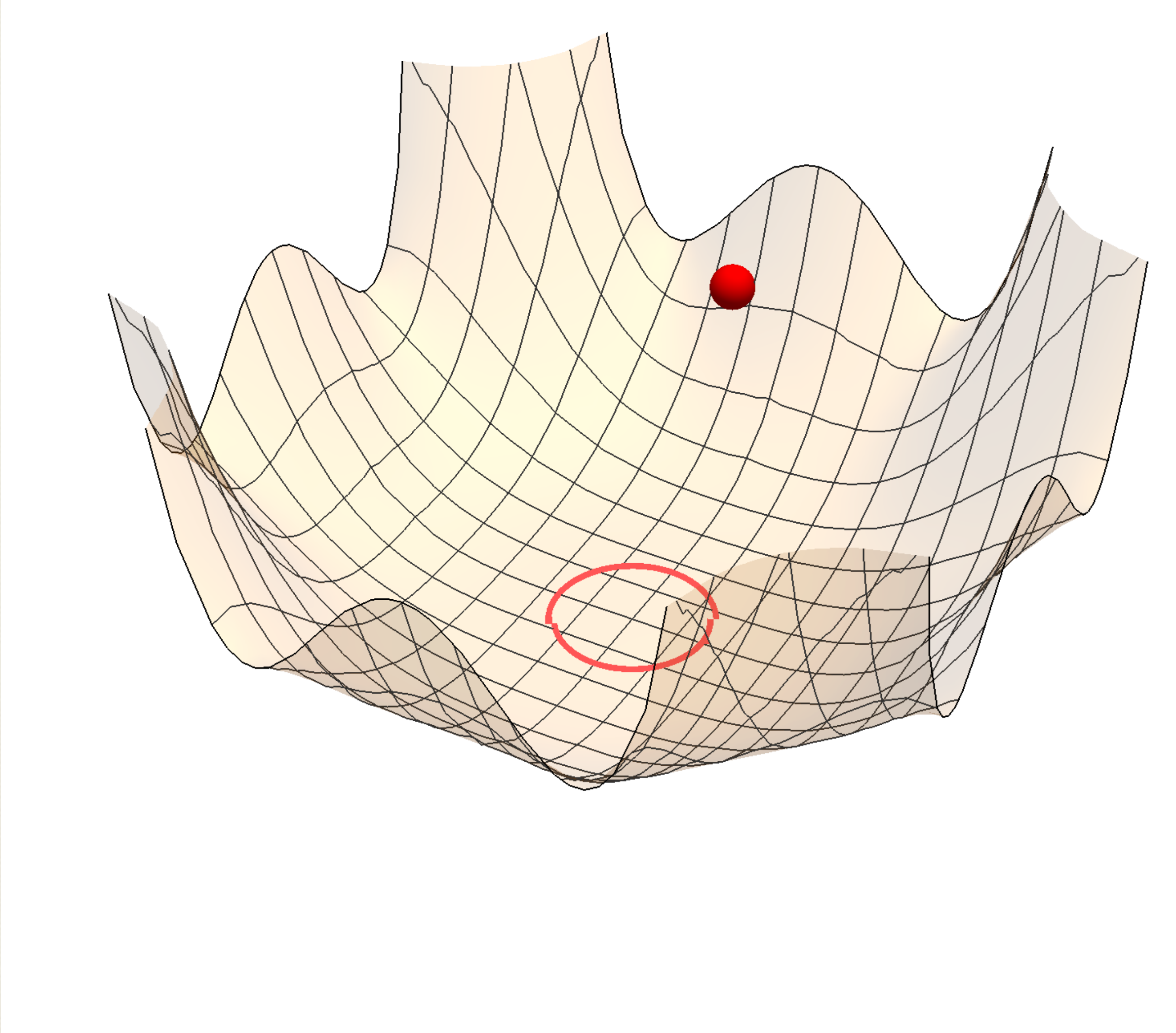
$P = S \times \exp(i\theta)$



Assume a large initial radial field value

How to initiate the rotation

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



Assume a large initial
radial field value

↓

Higher order terms

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

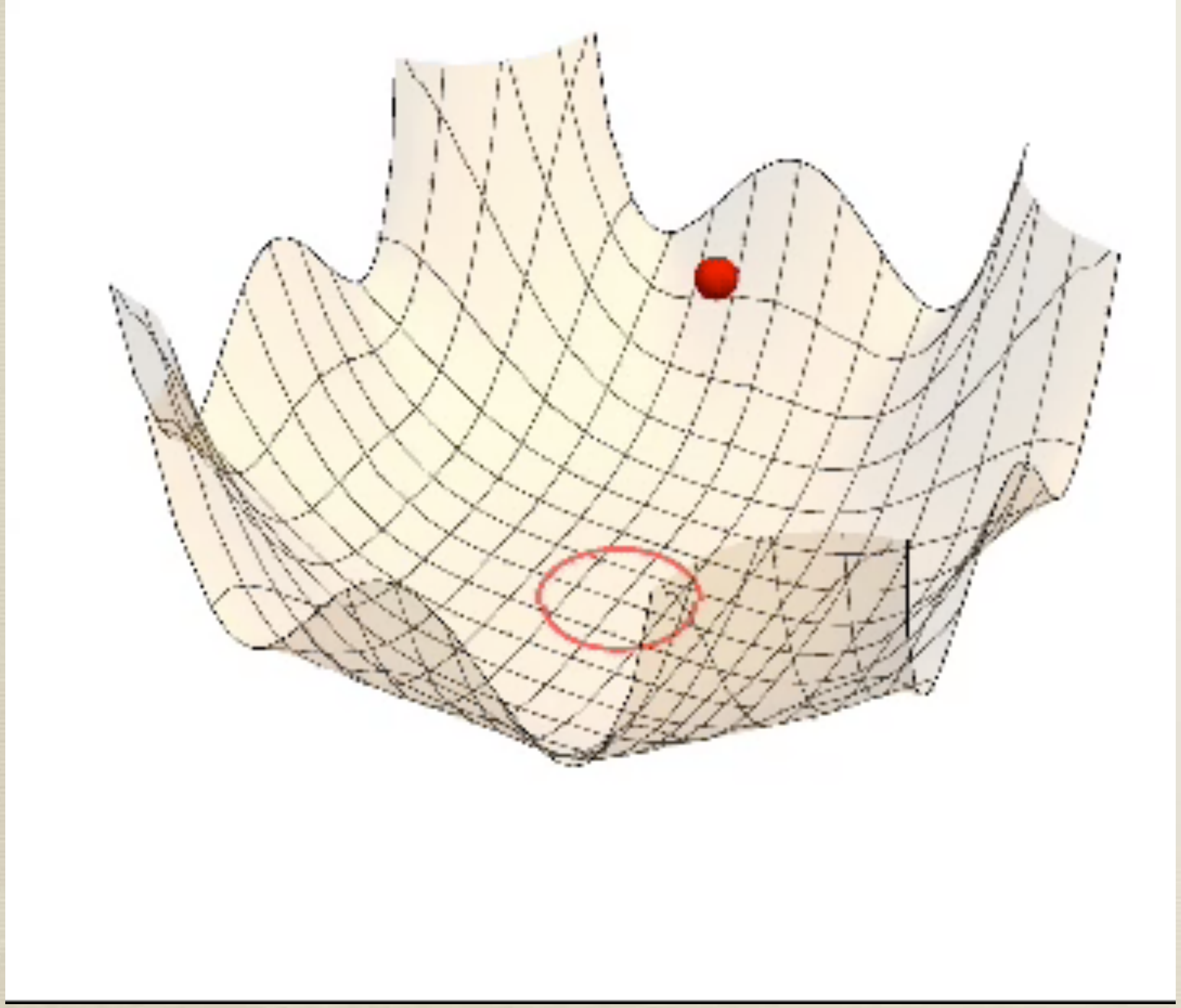
may be effective

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

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

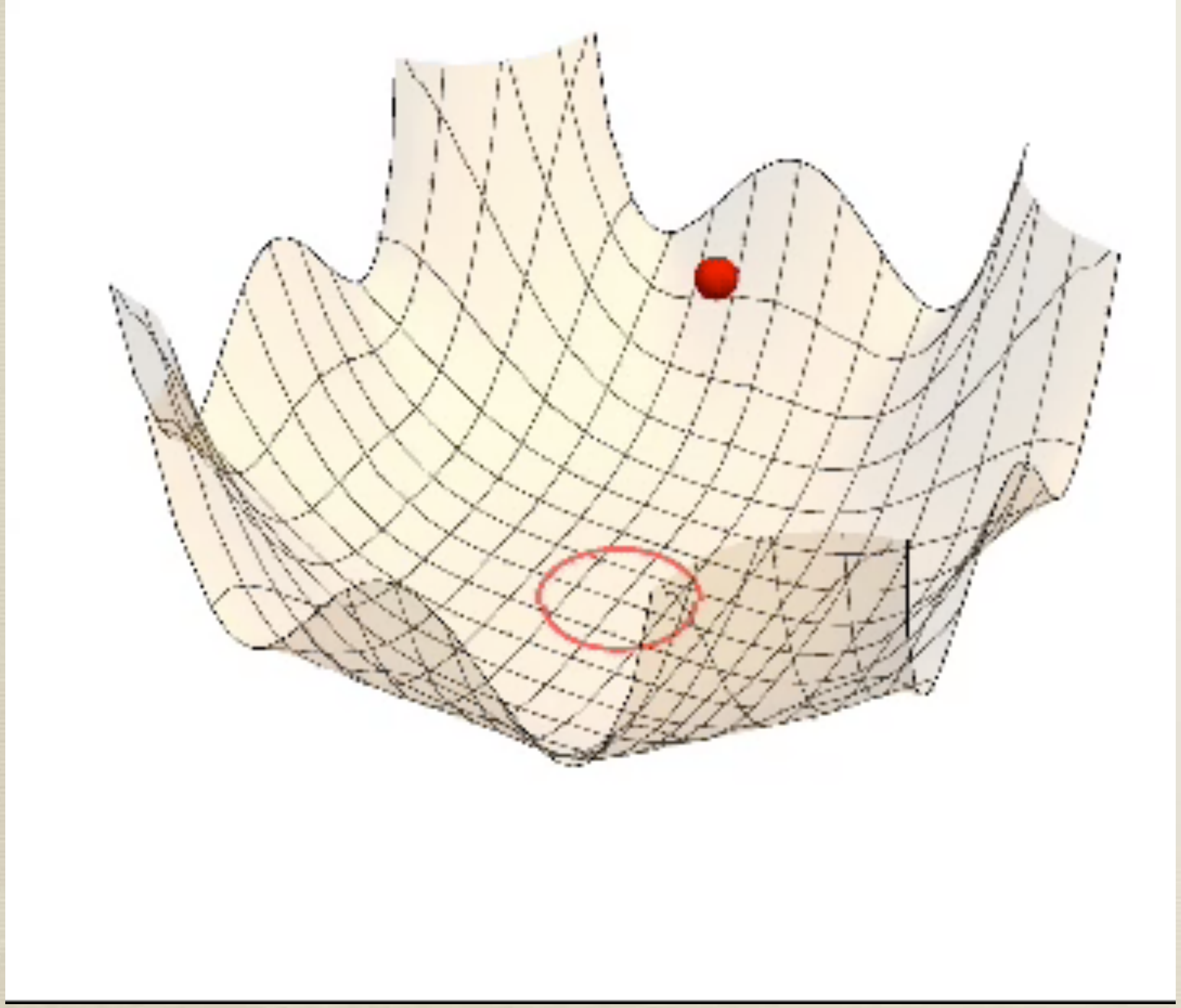
may be effective

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

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



r 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

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

Dark matter abundance

Co, Hall and KH (2019)

It is convenient to define the “yield” before the axion oscillation phase begins

$$Y_{\rm PQ} \equiv \frac{n_{\rm PQ}}{s}$$

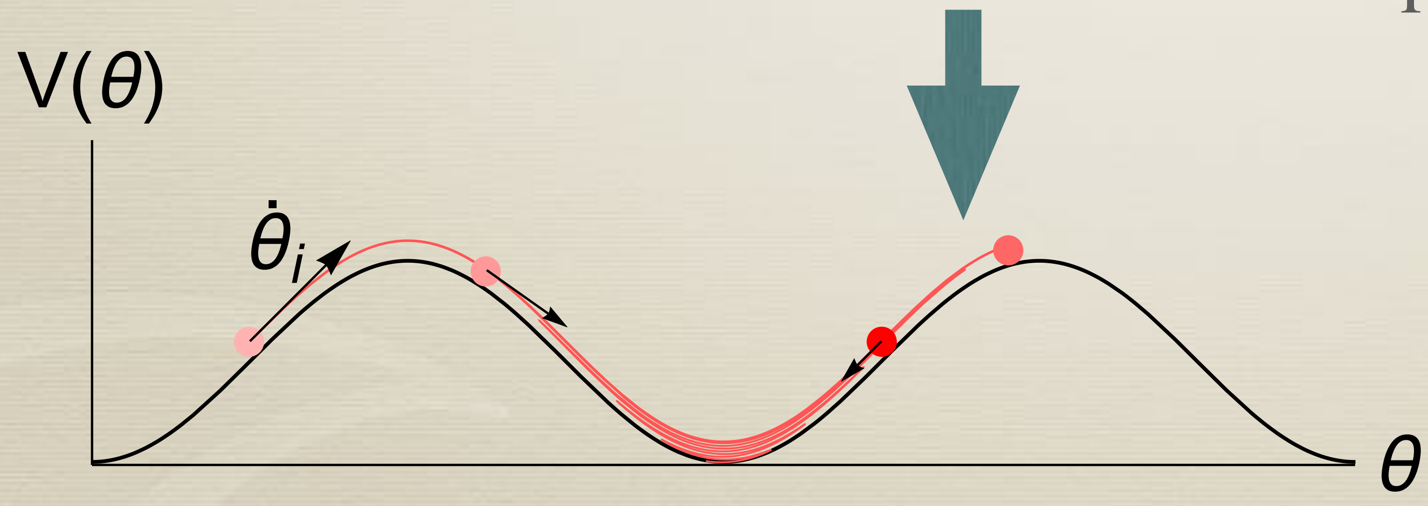
$n_{\rm PQ} = \dot{\theta}\, f_a^2$: PQ charge

$s = \frac{2\pi^2}{45} g T^3$: entropy density

$\propto R^{-3}$

$\dot{\theta} \simeq m_a$

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



Dark matter abundance

Co, Hall and KH (2019)

It is convenient to define the "yield" before the axion oscillation phase begins

$$Y_{\rm PQ} \equiv \frac{n_{\rm PQ}}{s}$$

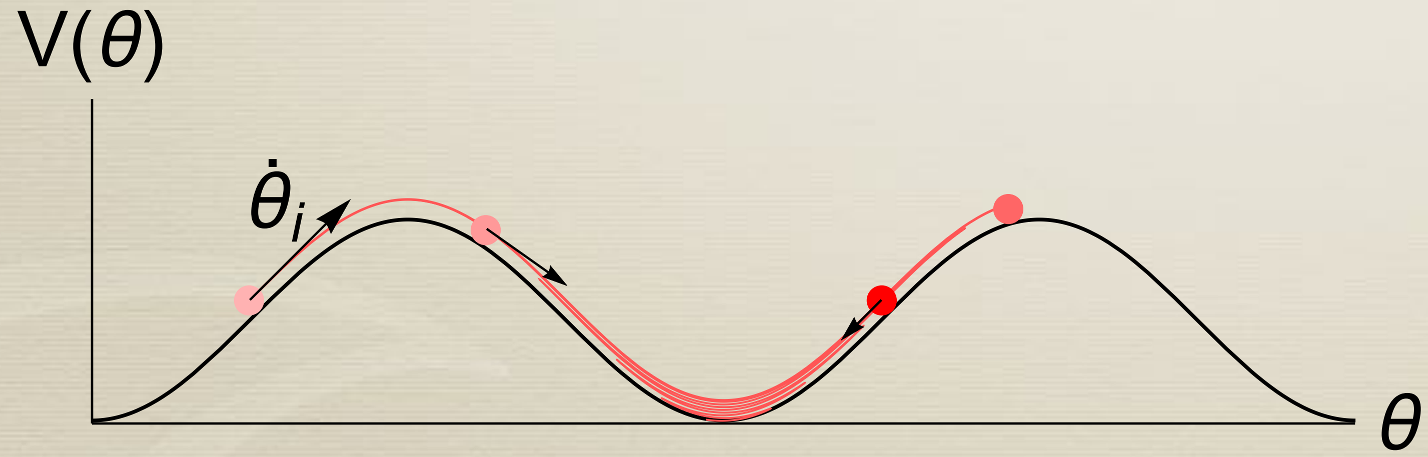
$n_{\rm PQ} = \dot{\theta}\, f_a^2$: PQ charge

$s = \frac{2\pi^2}{45} g T^3$: entropy density

$\propto R^{-3}$

$$Y_a \equiv \frac{n_{a,\rm osc}}{s} \simeq Y_{\rm PQ}$$

after the oscillations begin

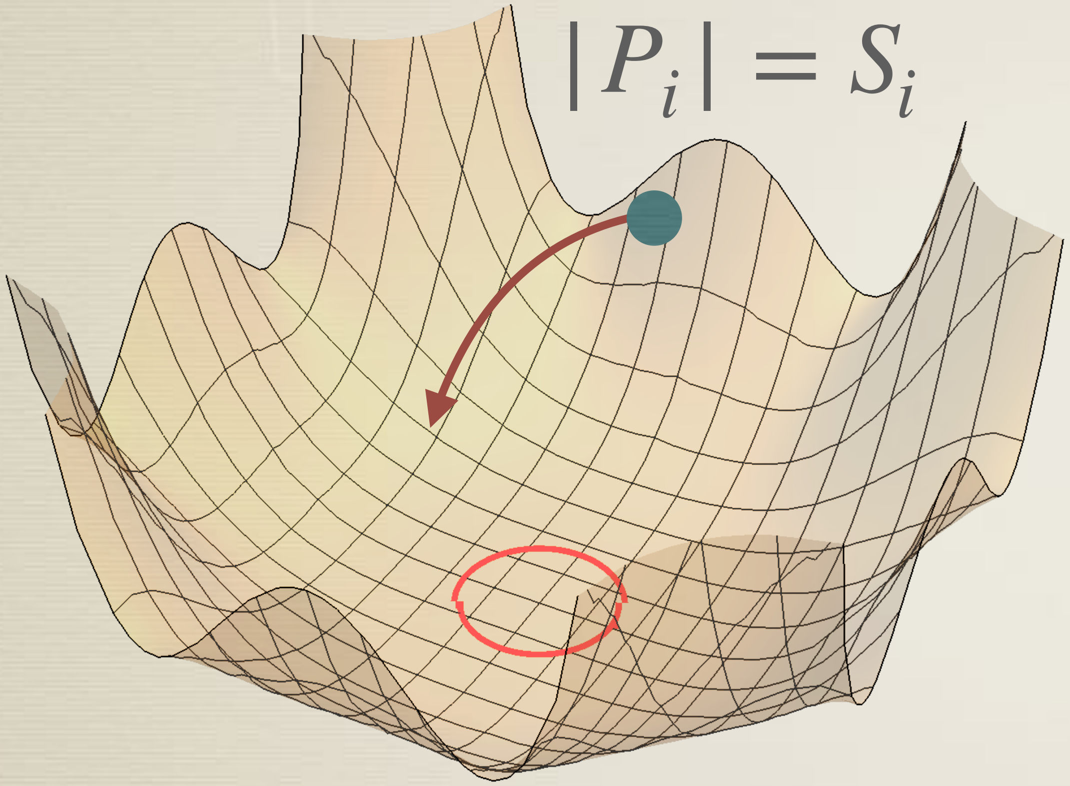


$$\boxed{\frac{\rho_a}{\rho_{\rm DM}} \simeq \frac{m_a}{6\ {\rm meV}} \frac{Y_{\rm PQ}}{40}}$$

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

for the QCD axion

Estimation of PQ charge



Initial number density of the radial direction

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

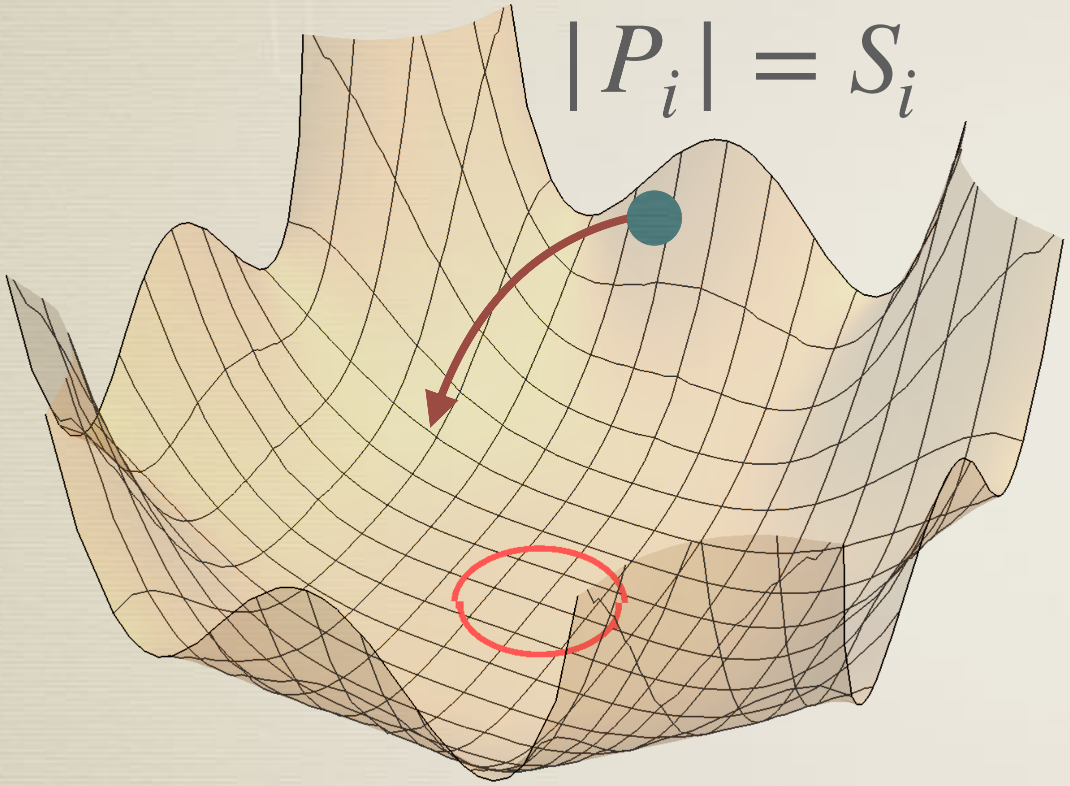
mass around S_i

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

$\epsilon = 0$: 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

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

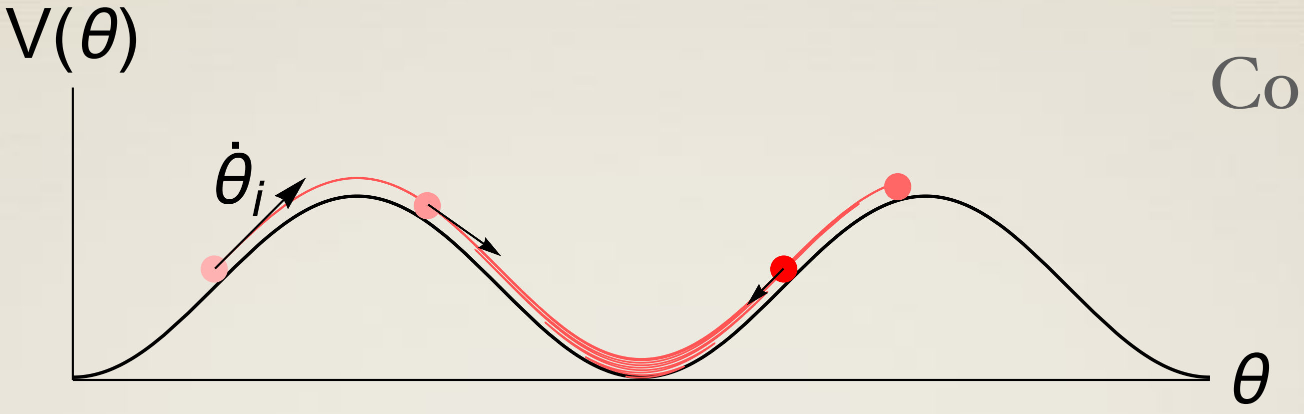
$$n_{PQ} = \epsilon n_S = \epsilon m_{S,i}\, S_i^2$$

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

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

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

Estimation of PQ charge



Co, Hall and KH (2019)

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

↓

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

for the QCD axion

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

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

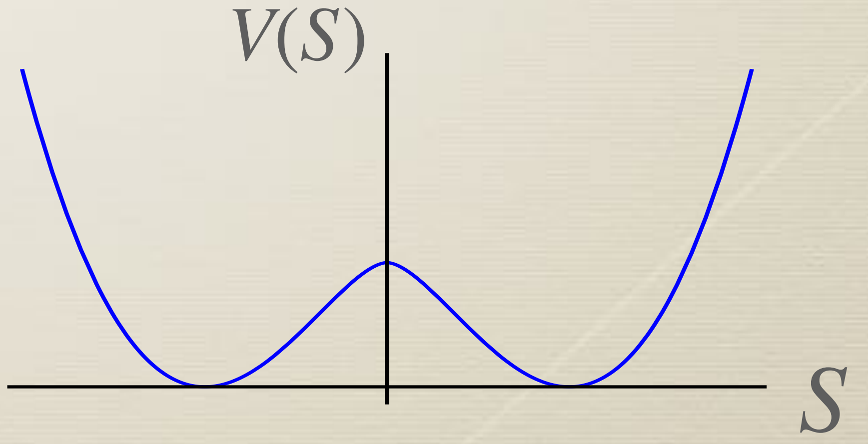
A flat potential with $m_{S,i} = \sqrt{V''(S_i)} \ll S_i$ is required

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

Ex. Potential of P solely from supersymmetry breaking

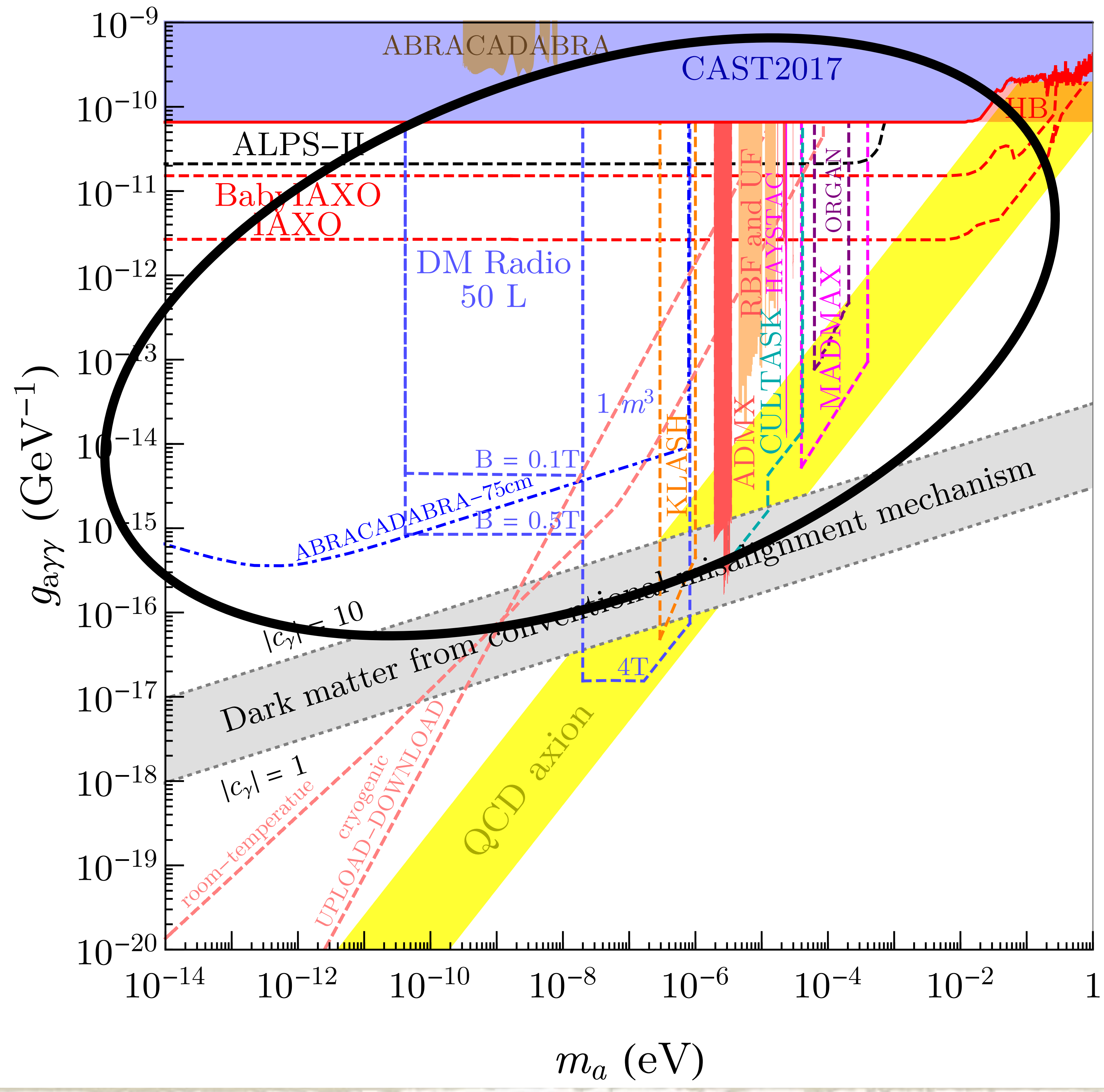
$$V = m_S^2 |P|^2 \left(\ln \frac{2|P|^2}{f_a^2} - 1 \right)$$

Quantum correction
to the soft mass



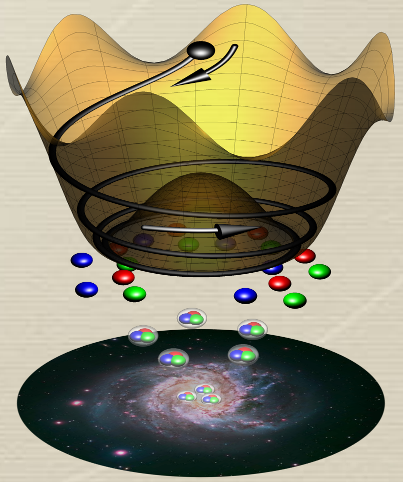
$$\sqrt{V''(S_i)} \sim m_S \ll S_i$$

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

Co and KH (2019)

For now let us assume the QCD axion

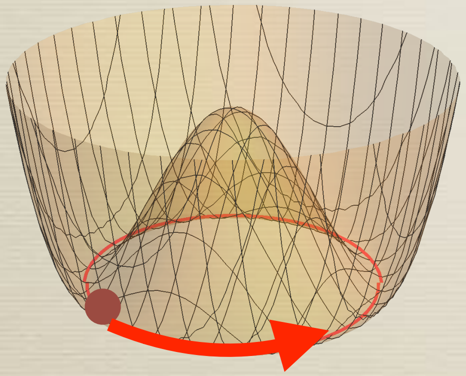
The PQ symmetry is quantum mechanically broken
by the QCD interaction (anomaly)

$$\partial_\mu J^\mu_{\rm PQ} \sim G\tilde{G}$$

+

So is the quark chiral symmetry

$$\partial_\mu J^\mu_A \sim G\tilde{G}$$



PQ → Chiral charge

QCD

B+L

Axiogenesis

Co and KH (2019)

For now let us assume the QCD axion

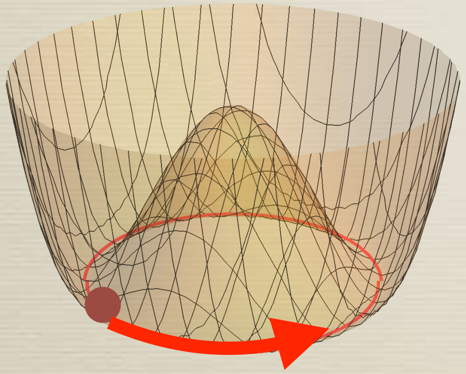
The chiral symmetry is quantum mechanically broken by the weak interaction

$\partial_\mu J^\mu_A \sim W\tilde{W}$

+

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

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



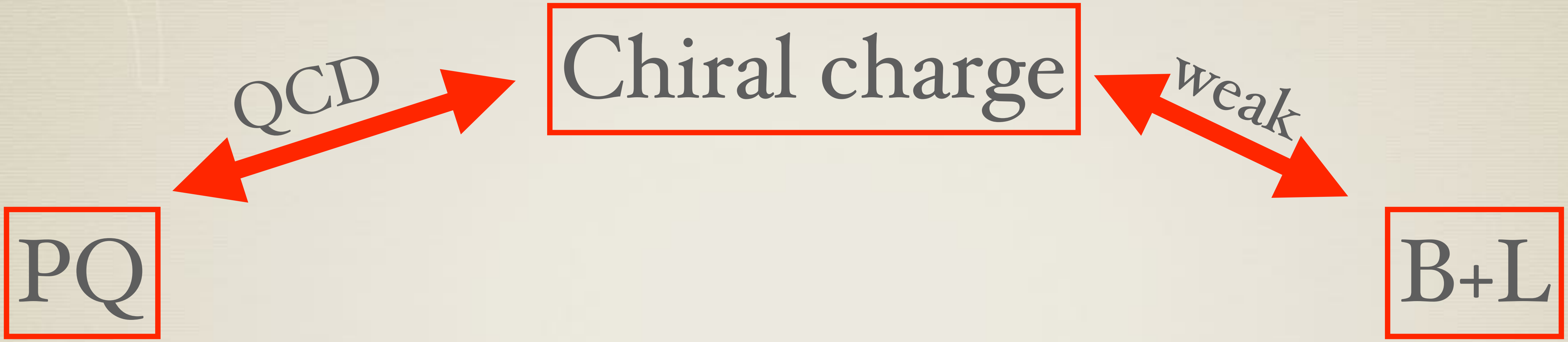
PQ

Chiral charge → B+L

weak

Axiogenesis

Co and KH (2019)



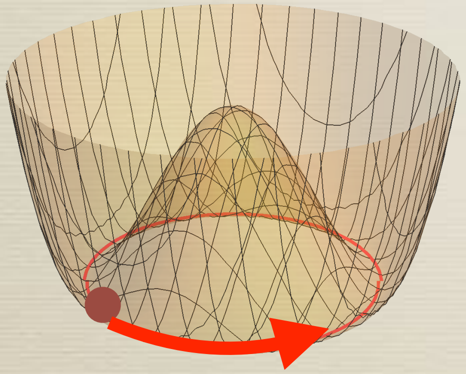
Chiral charge

QCD

weak

PQ

B+L



cf. leptogenesis

weak

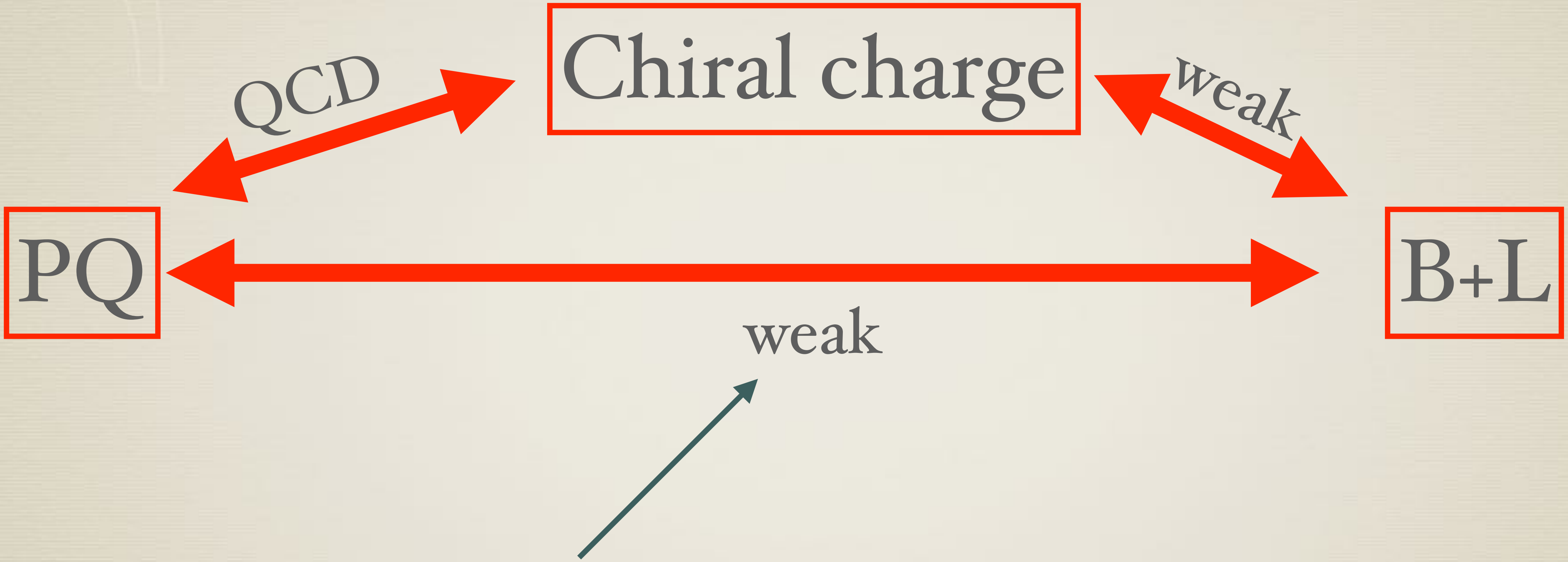
L

B

Fukugita and Yanagida (1986)

Axiogenesis

Co and KH (2019)



QCD

Chiral charge

weak

PQ

B+L

weak

If the PQ symmetry also has weak anomaly

(Naively the case for unified theory)

Axiogenesis

Co and KH (2019)

Chiral charge

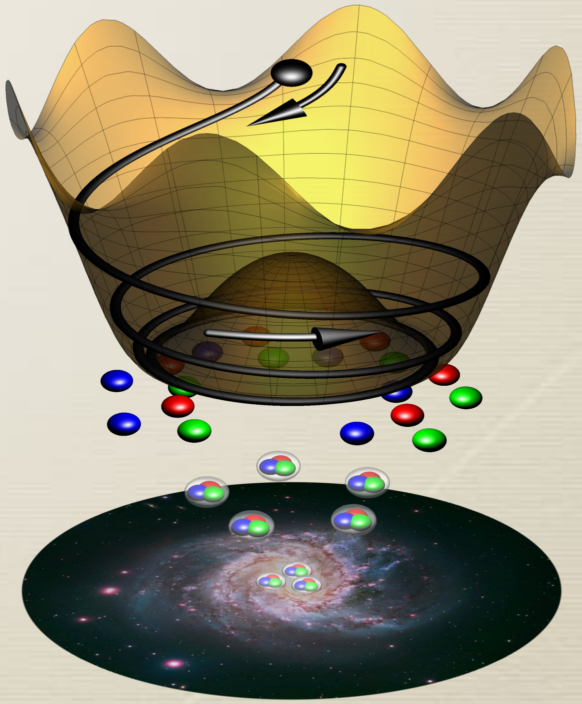
QCD

weak

PQ

B+L

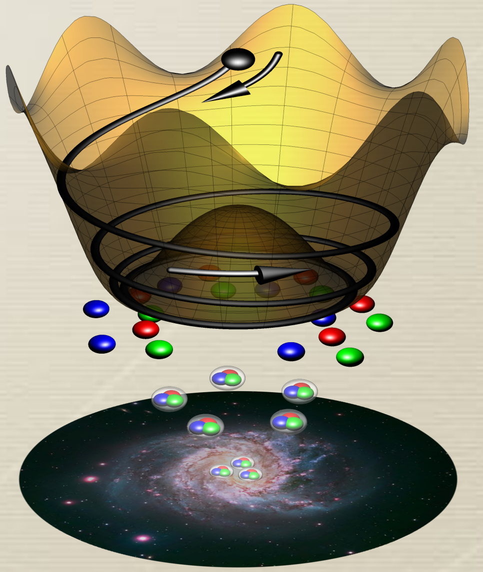
weak



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 $n_{\rm PQ}$ 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

$$\Delta F = \sim + \frac{\Delta n^2}{T^2}$$

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 $n_{\rm PQ}$ is transferred into the charge asymmetry of particles in the thermal bath

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

$$\Rightarrow \quad \Delta n \sim \boxed{\dot{\theta}\, T^2} \ll n_{\rm PQ} = \dot{\theta}\, f_a^2$$

$$\text{if} \;\; T \ll f_a$$

Co and KH (2019)

Axiogenesis

Co and KH (2019)

Chiral charge

QCD

weak

PQ

B+L

weak

The asymmetries reach
thermal equilibrium values

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

Axiogenesis

Co and KH (2019)

Chiral charge

QCD

weak

PQ

B+L

weak

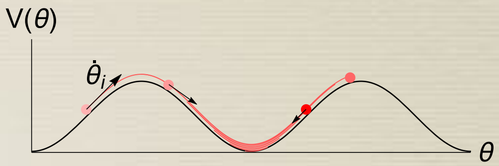
weak interaction becomes ineffective
after electroweak phase transition

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

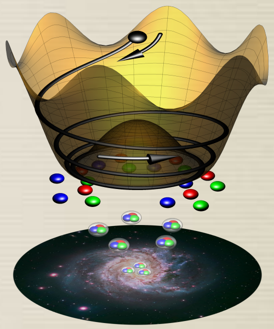
Axiogenesis

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

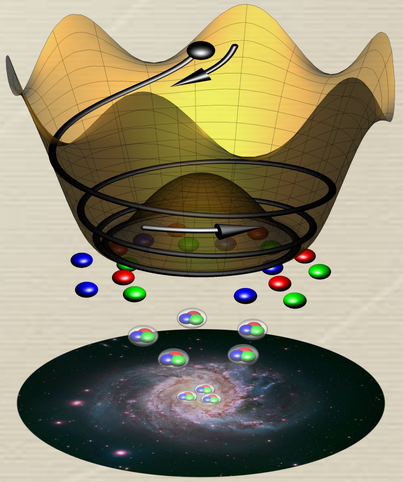
$$\boxed{T_{\rm EW} = 1\ \mathrm{TeV}\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^{1/2}}$$

Astrophysical lower bound $f_a > 10^8$ 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

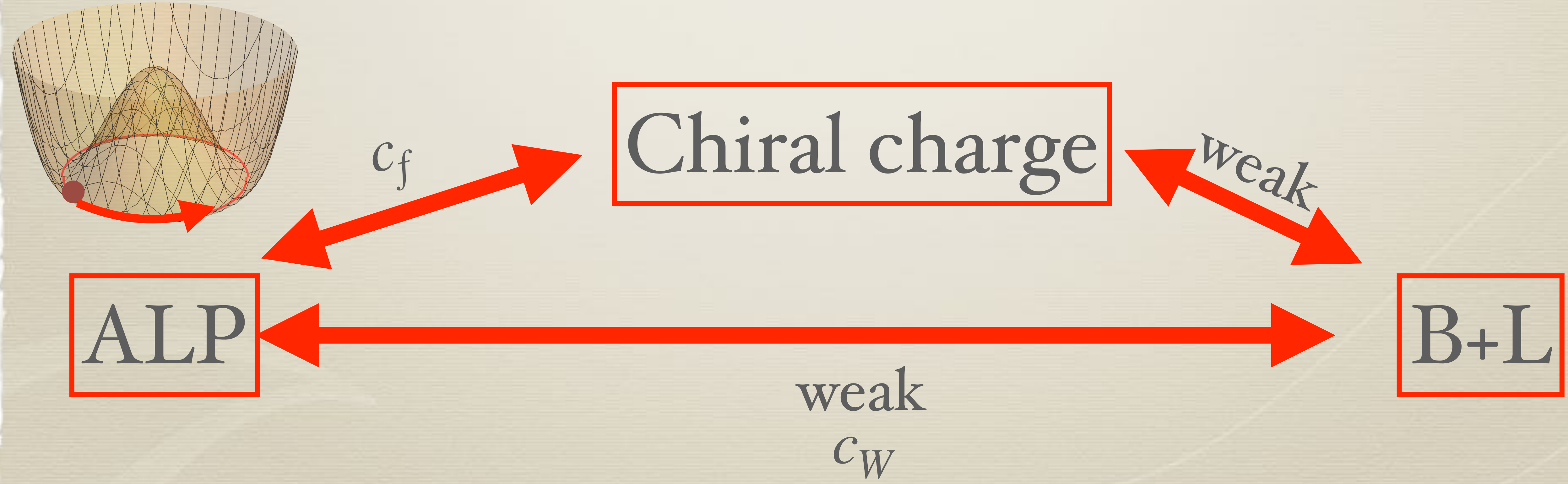


ALP genesis

Co, Hall and KH (2020)

A similar mechanism works for generic ALPs

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



Chiral charge

c_f

weak

ALP

B+L

weak

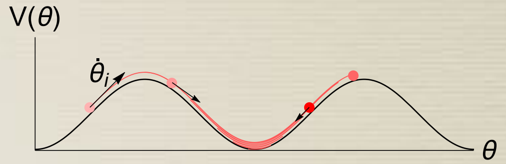
c_W

ALP cogenesis

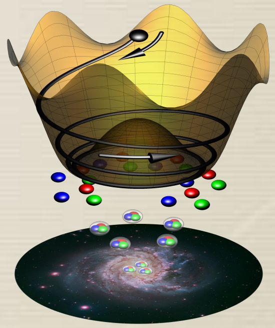
Co, Hall and KH (2020)

Assuming the standard EW phase transition,

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



1. Dark Matter
2. Baryon asymmetry

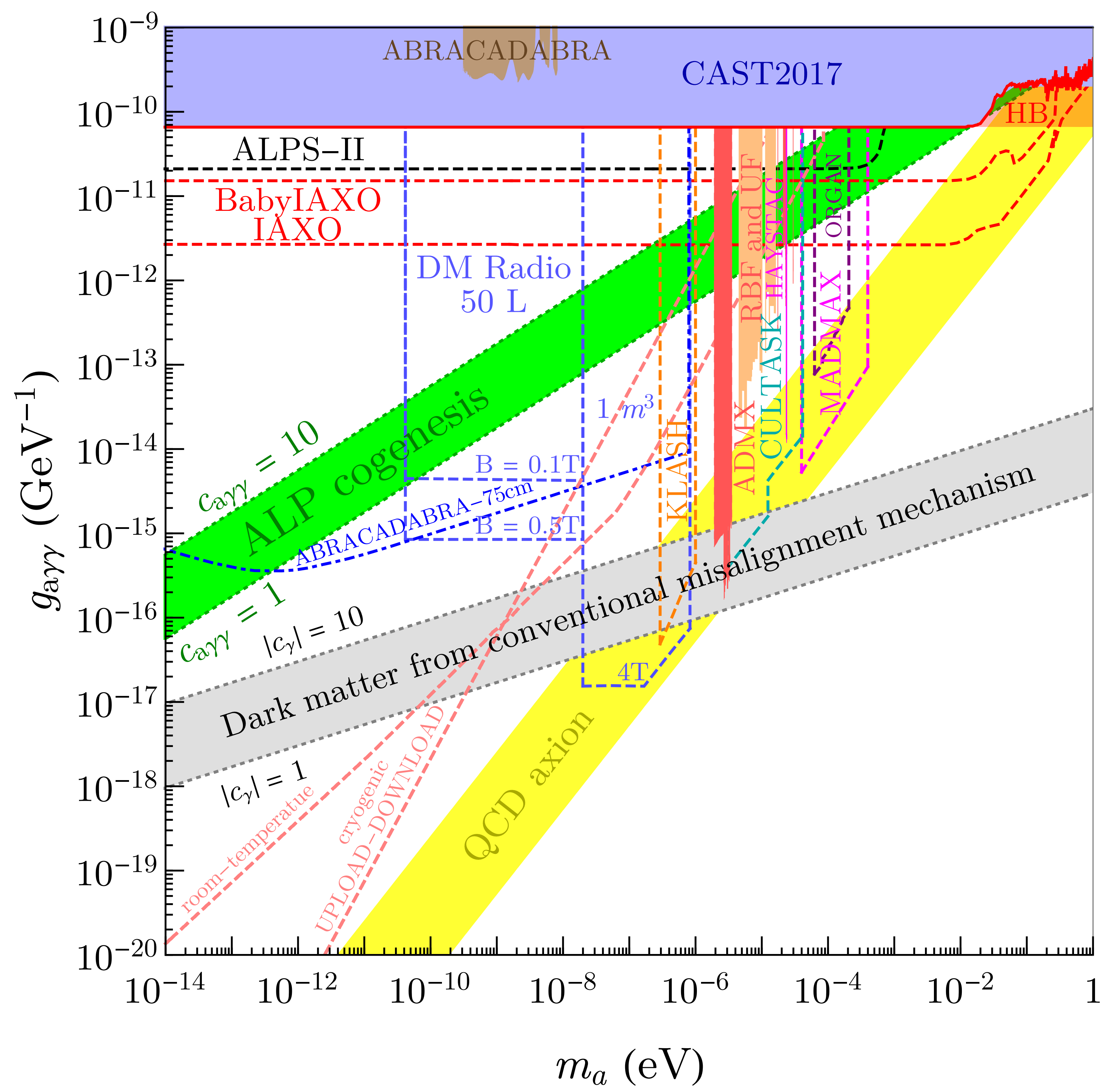


3 free parameters – 2 densities to fit
= 1 free parameter

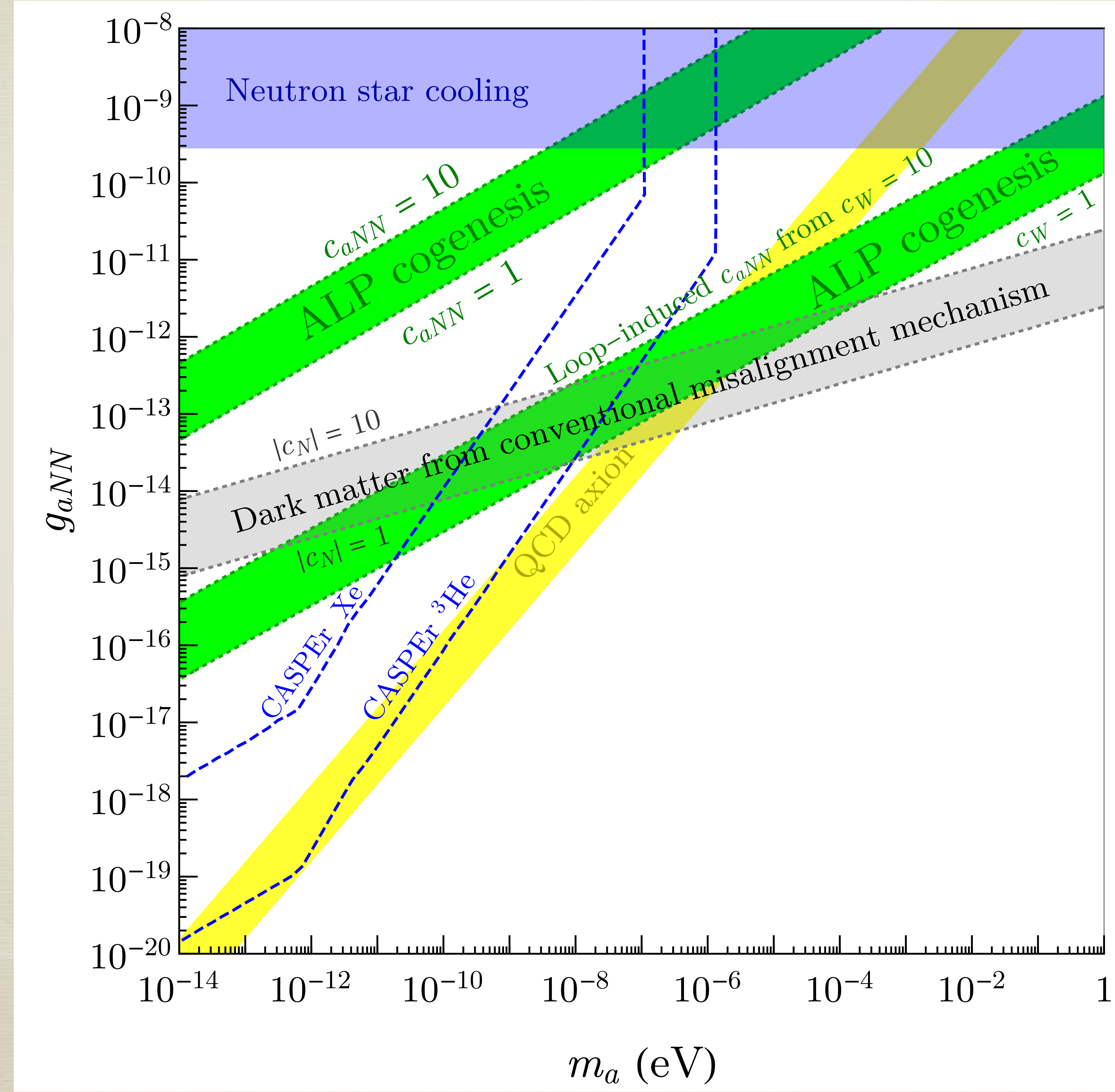
$$\boxed{f_a = 2 \times 10^9 \ \mathrm{GeV} \left(\frac{1 \mu\mathrm{eV}}{m_a} \right)^{1/2}}$$

Prediction on the ALP coupling

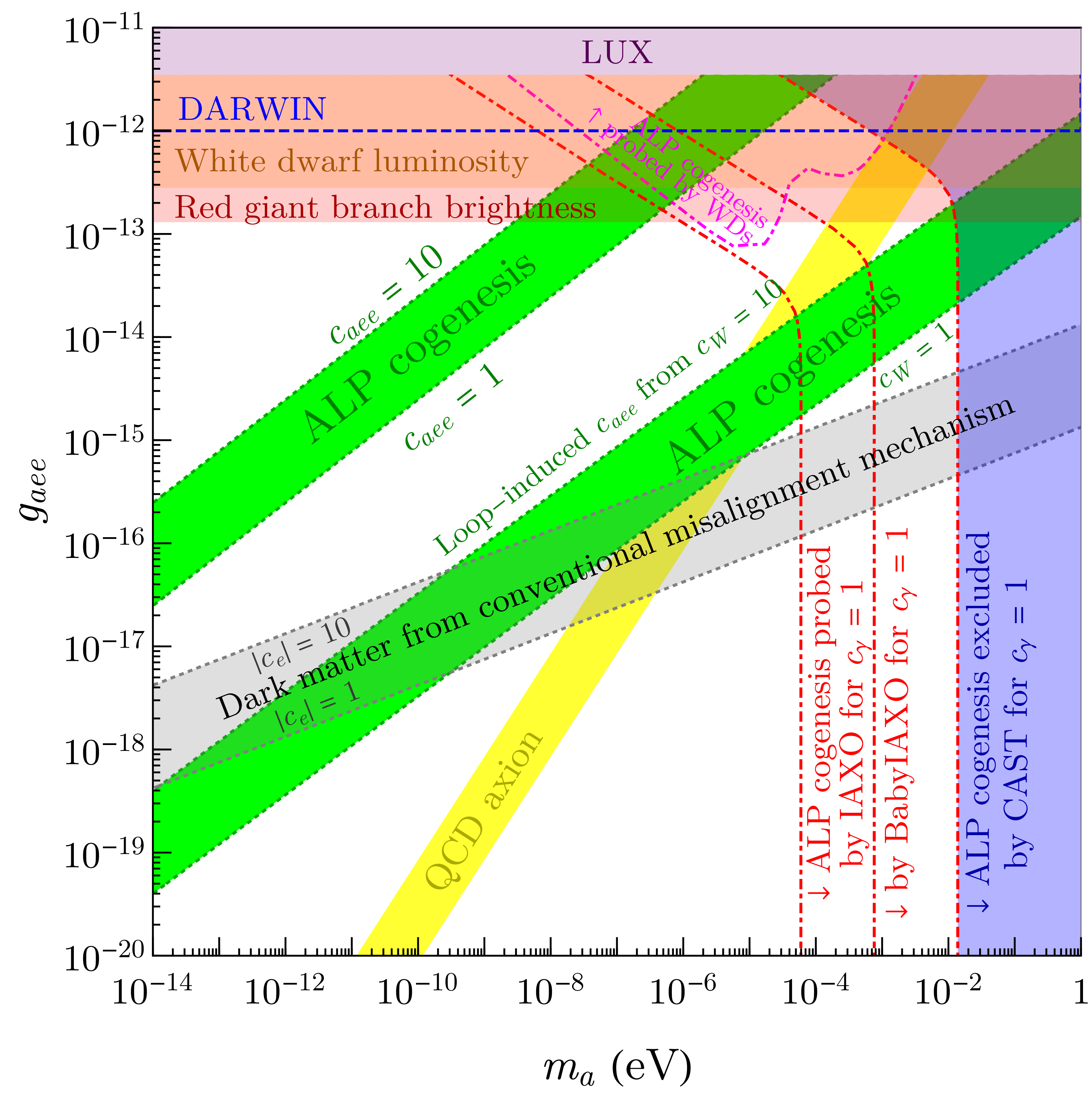
$$\sim \frac{\alpha}{4\pi}\frac{1}{f_a}$$



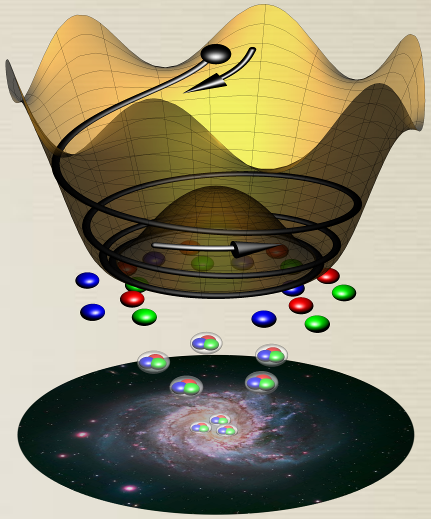
Prediction on the ALP coupling



Prediction on the ALP coupling

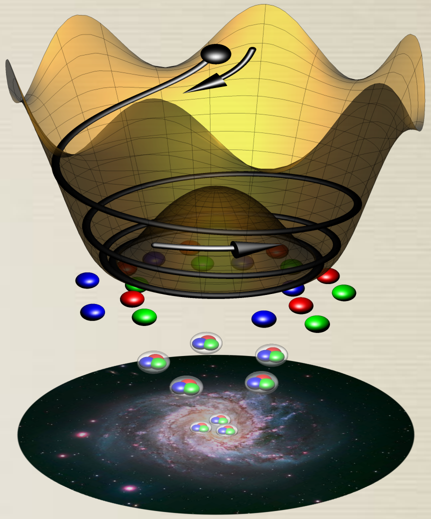


An ALP solves
two mysteries of the universe



- 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?
- ….

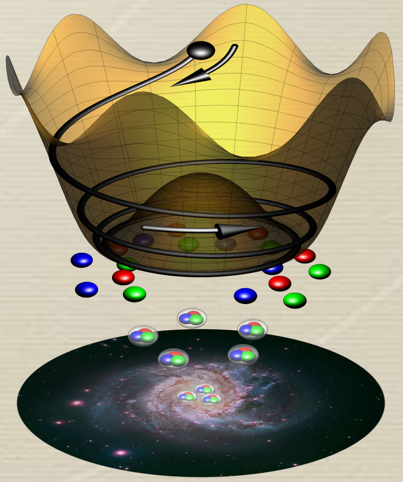
An ALP solves
N>2 mysteries of the universe ?



- 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

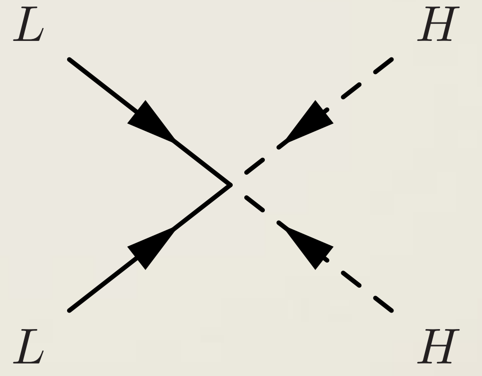


Lepto-axiogenesis

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

Majorana neutrino masses break the lepton symmetry

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



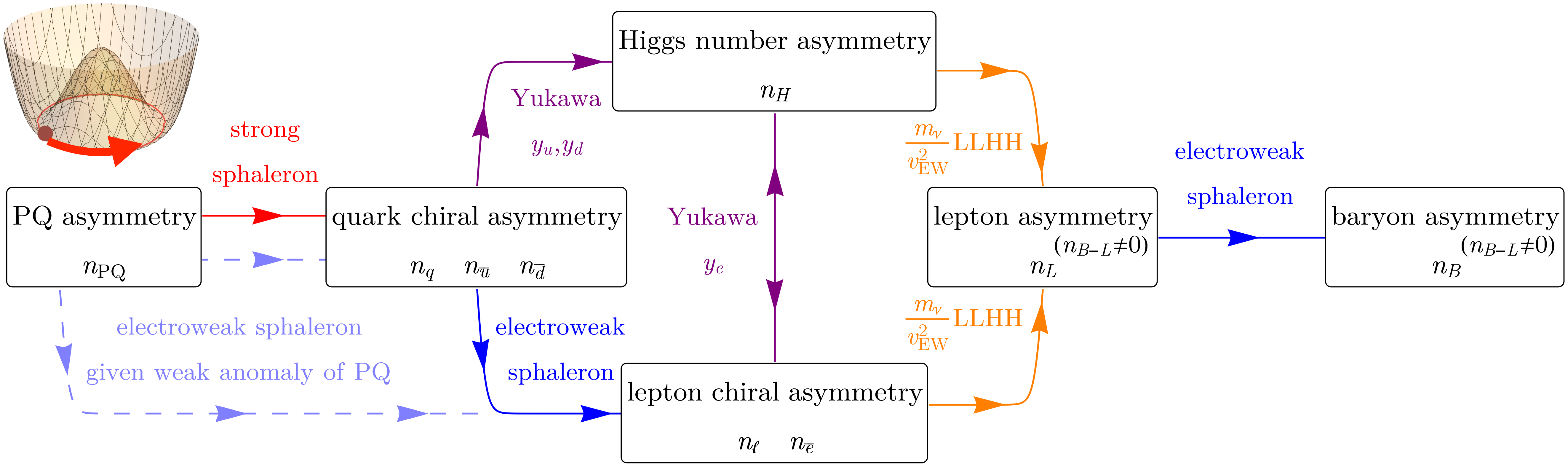
$$m_\nu = \frac{< H >^2}{M}$$

Can they assist baryogenesis from the QCD axion?

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

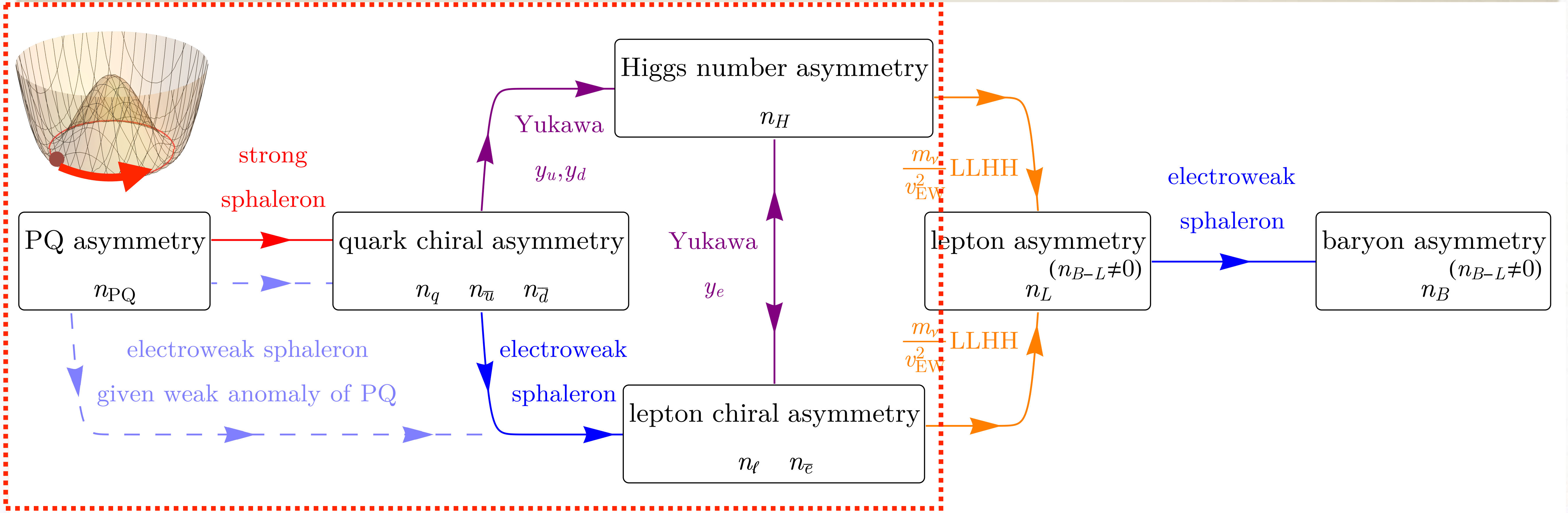
Charge flow

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



Charge flow

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



PQ asymmetry

$n_{\rm PQ}$

strong

sphaleron

quark chiral asymmetry

n_q $n_{\overline{u}}$ $n_{\overline{d}}$

Yukawa

y_u, y_d

Higgs number asymmetry

n_H

Yukawa

y_e

electroweak sphaleron

given weak anomaly of PQ

electroweak

sphaleron

lepton chiral asymmetry

n_ℓ $n_{\overline{e}}$

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

lepton asymmetry

$(n_{B-L} \neq 0)$

n_L

electroweak

sphaleron

baryon asymmetry

$(n_{B-L} \neq 0)$

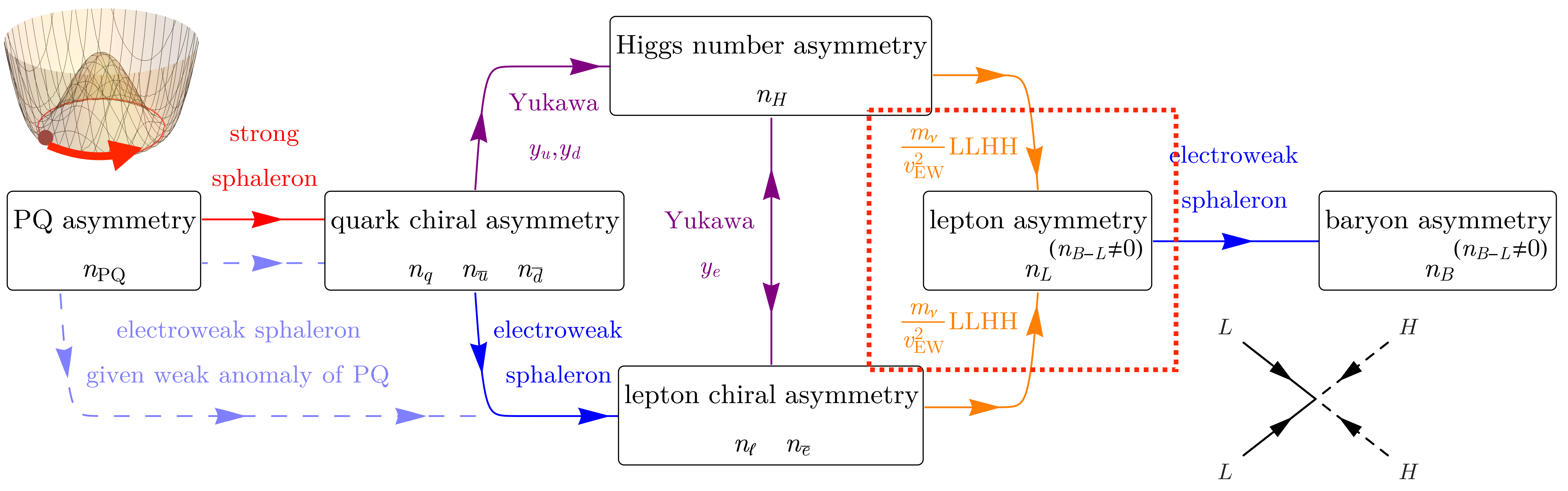
n_B

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)



PQ asymmetry $n_{\rm PQ}$

strong sphaleron

electroweak sphaleron given weak anomaly of PQ

quark chiral asymmetry $n_q \quad n_{\overline{u}} \quad n_{\overline{d}}$

Yukawa y_u, y_d

electroweak sphaleron

Higgs number asymmetry n_H

Yukawa y_e

lepton chiral asymmetry $n_\ell \quad n_{\overline{e}}$

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

lepton asymmetry $(n_{B-L}{\neq}0)$ n_L

electroweak sphaleron

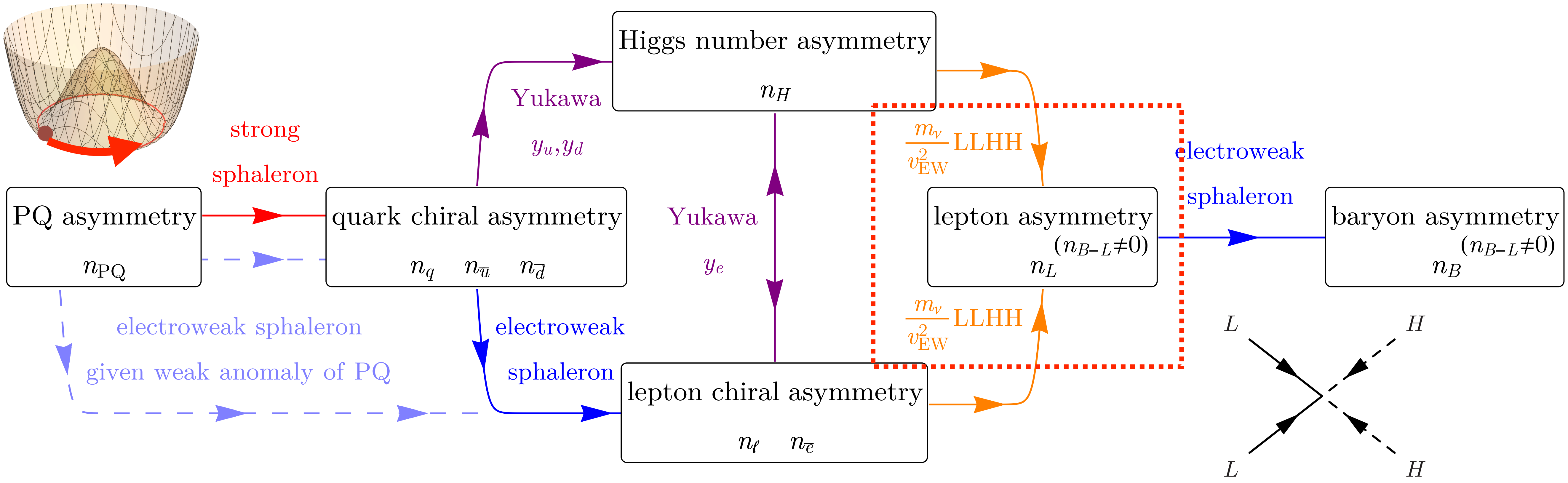
baryon asymmetry $(n_{B-L}{\neq}0)$ n_B

At high temperatures $$\frac{n_{B-L}}{s}\Big|_{\rm eq} \simeq \frac{\dot{\theta}T^2}{s}$$

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

Charge flow

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



strong sphaleron

PQ asymmetry n_{PQ}

quark chiral asymmetry n_q $n_{\overline{u}}$ $n_{\overline{d}}$

Yukawa y_u, y_d

Higgs number asymmetry n_H

Yukawa y_e

electroweak sphaleron given weak anomaly of PQ

electroweak sphaleron

lepton chiral asymmetry n_ℓ $n_{\overline{e}}$

$\frac{m_\nu}{v_{\mathrm{EW}}^2}$ LLHH

$\frac{m_\nu}{v_{\mathrm{EW}}^2}$ LLHH

lepton asymmetry $(n_{B-L}\neq 0)$ n_L

electroweak sphaleron

baryon asymmetry $(n_{B-L}\neq 0)$ n_B

not efficient at
low temperatures

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

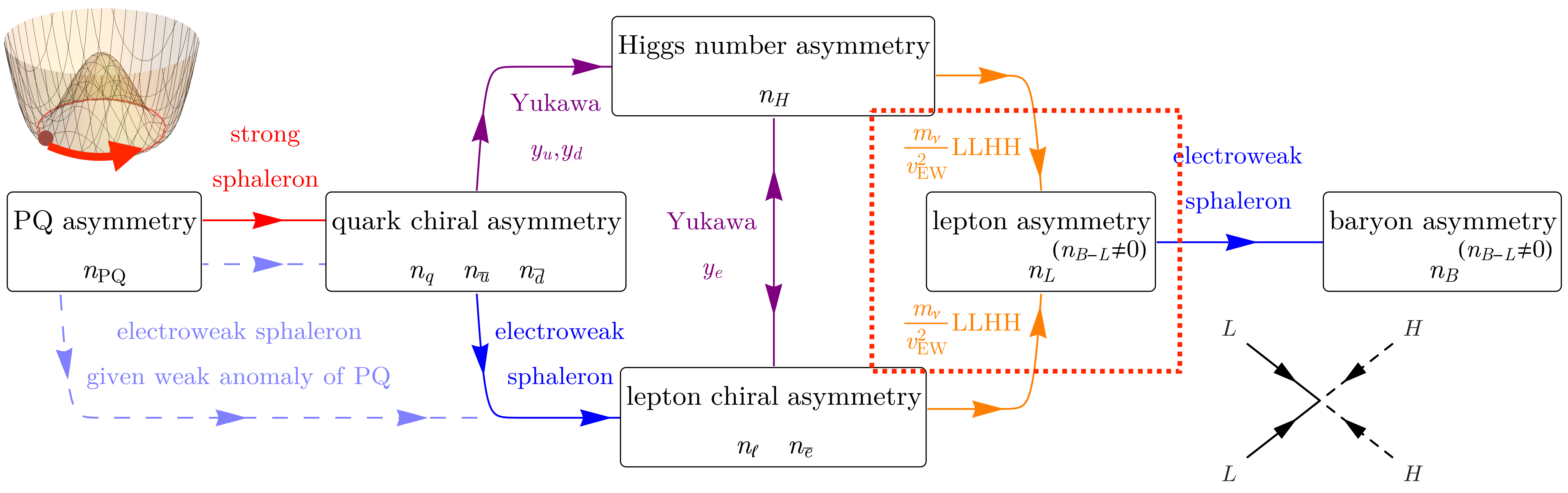
$$\propto \dot{\theta} \times T^0$$

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

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

Charge flow

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



PQ asymmetry n_{PQ}

strong sphaleron

quark chiral asymmetry $n_q \quad n_{\overline{u}} \quad n_{\overline{d}}$

Yukawa y_u, y_d

Higgs number asymmetry n_H

Yukawa y_e

electroweak sphaleron

electroweak sphaleron given weak anomaly of PQ

lepton chiral asymmetry $n_\ell \quad n_{\overline{e}}$

$\frac{m_\nu}{v_{\text{EW}}^2}$ LLHH

lepton asymmetry $(n_{B-L}\neq 0)$ n_L

$\frac{m_\nu}{v_{\text{EW}}^2}$ LLHH

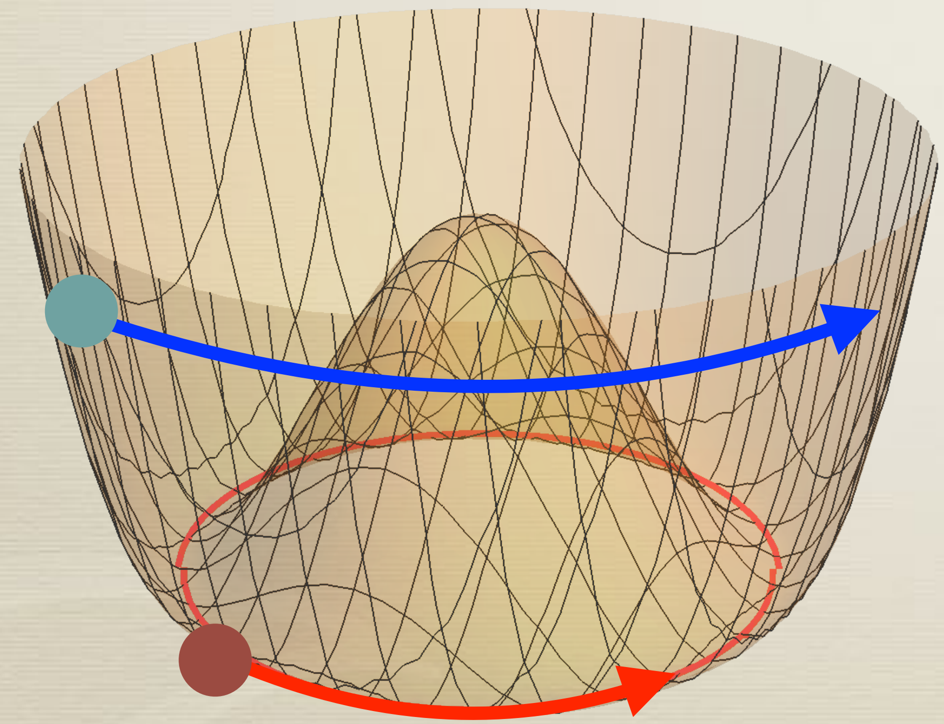
electroweak sphaleron

baryon asymmetry $(n_{B-L}\neq 0)$ n_B

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

Angular velocity?

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



Early time

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

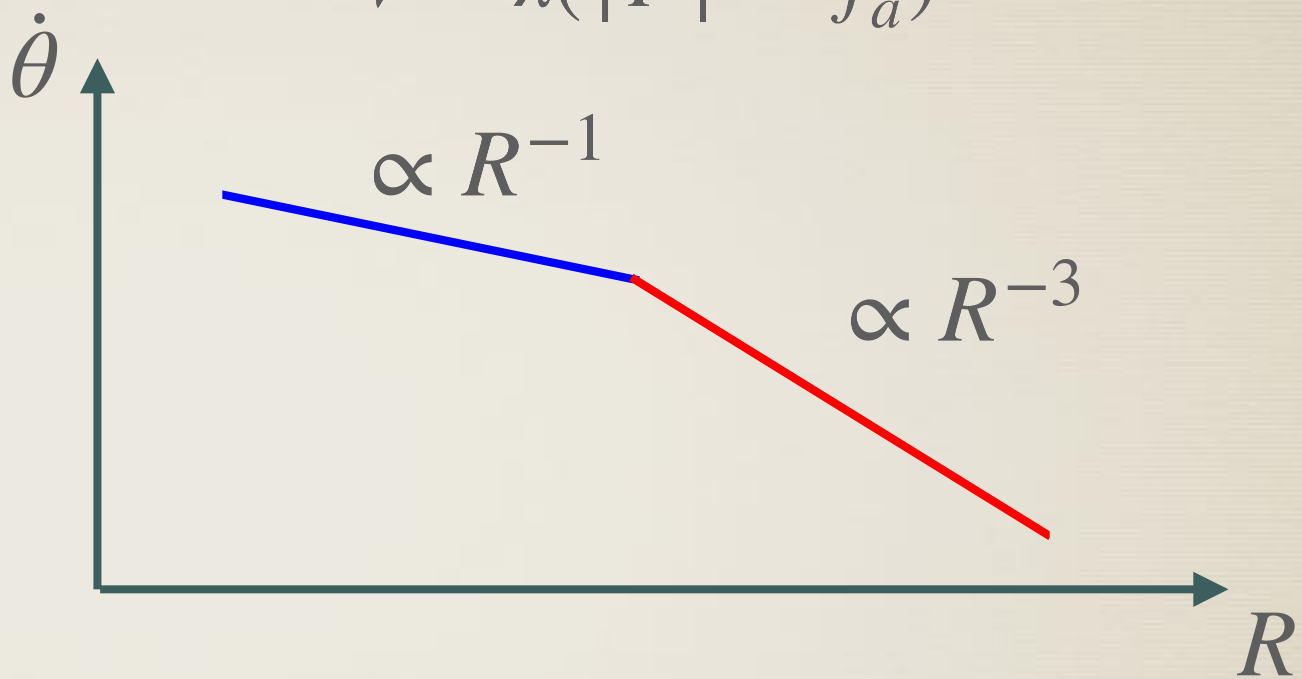
Around the electroweak phase transition

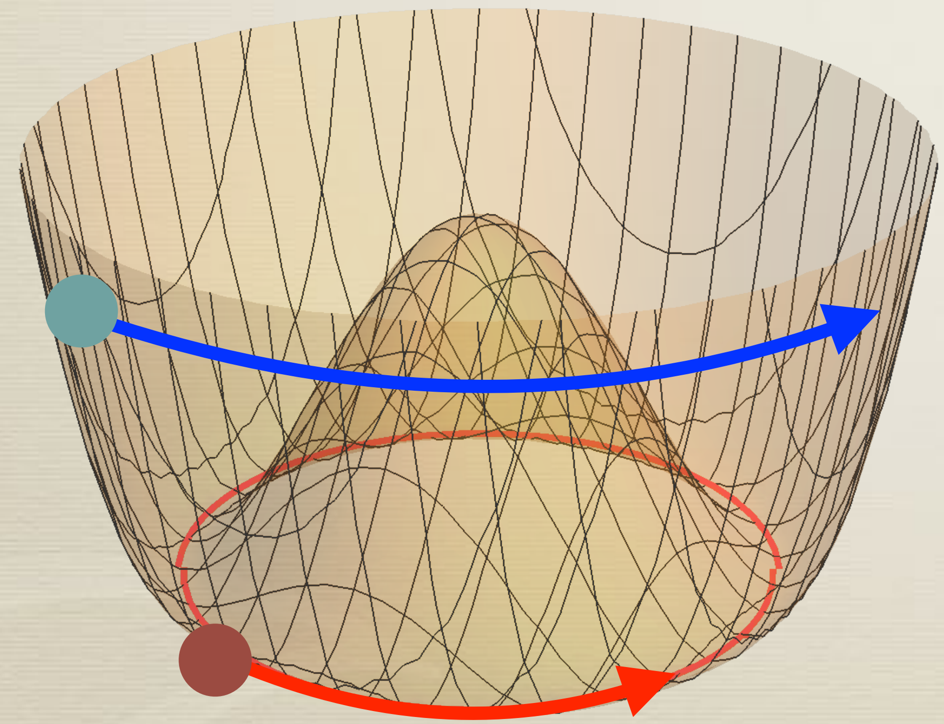
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

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

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





Early time

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

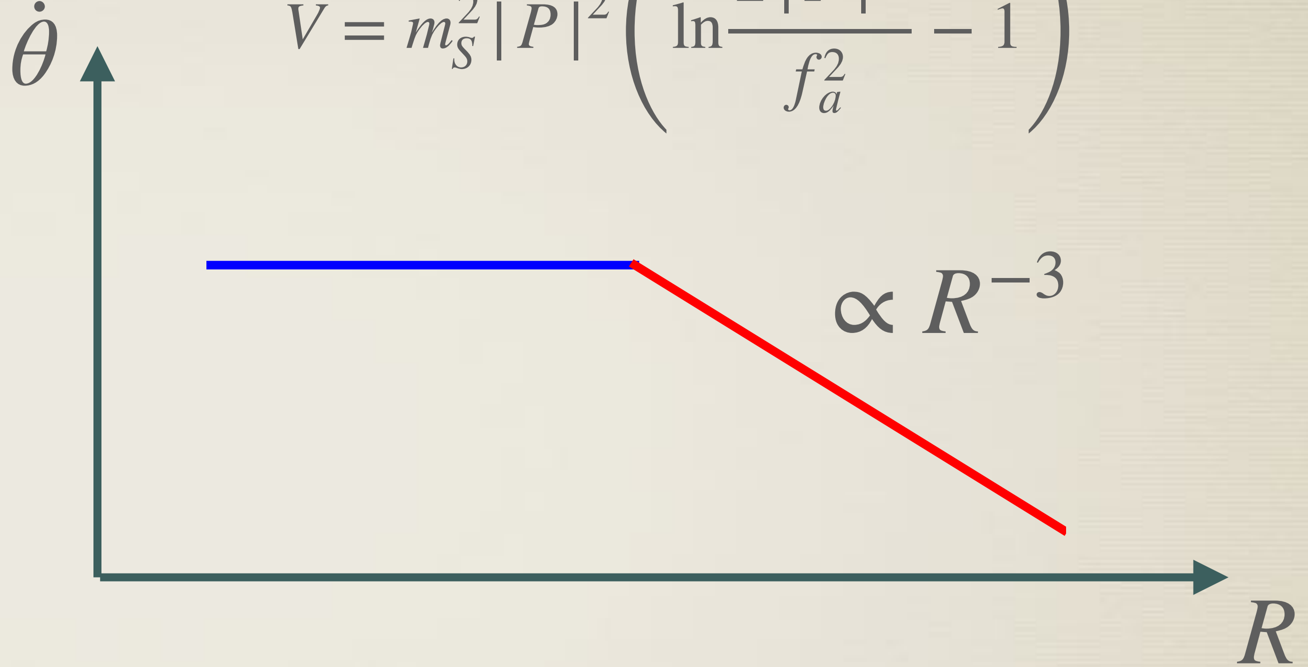
Around the electroweak phase transition

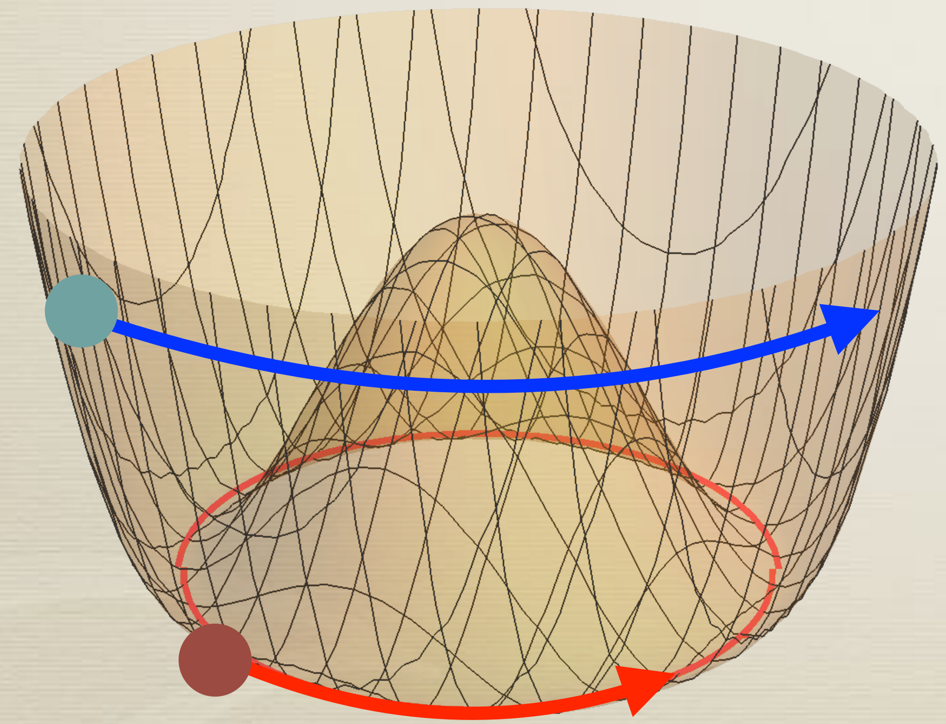
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

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

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





Early time

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

Around the electroweak phase transition

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

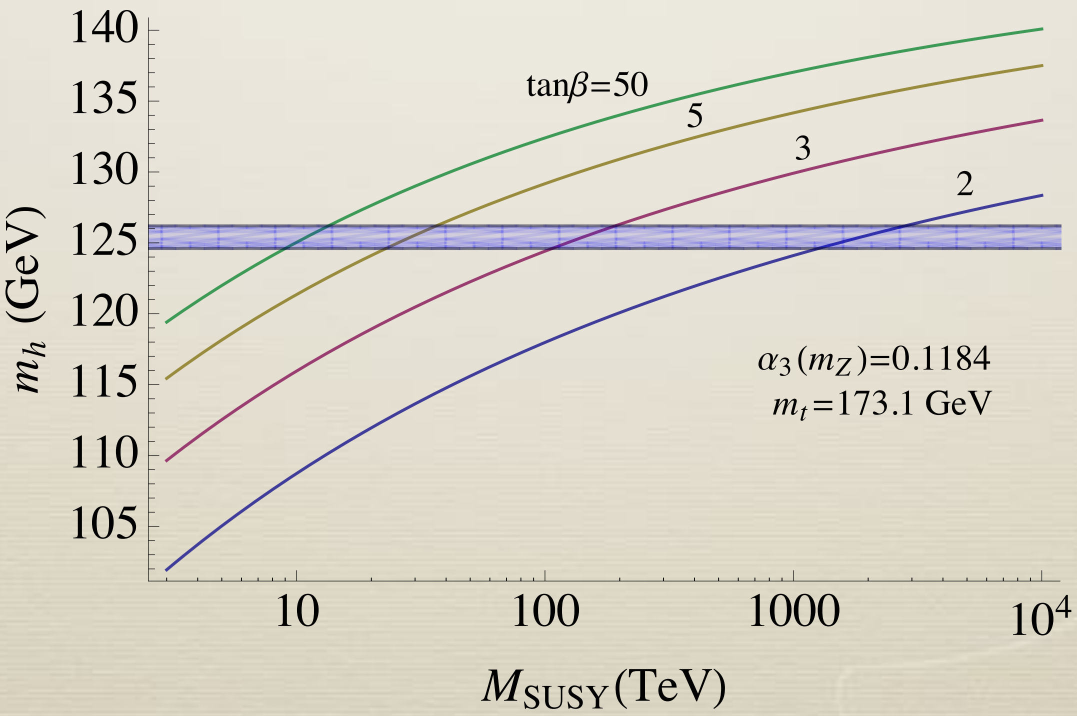
Supersymmetry

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

In supersymmetric models,

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

Consistent with the Higgs mass



Supersymmetry

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

In supersymmetric models,

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

Consistent with the without-singlets scenarios

Giudice, Luty, Murayam, Rattazzi (1998)

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

- gaugino masses are given by anomaly mediation, ~ 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

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

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