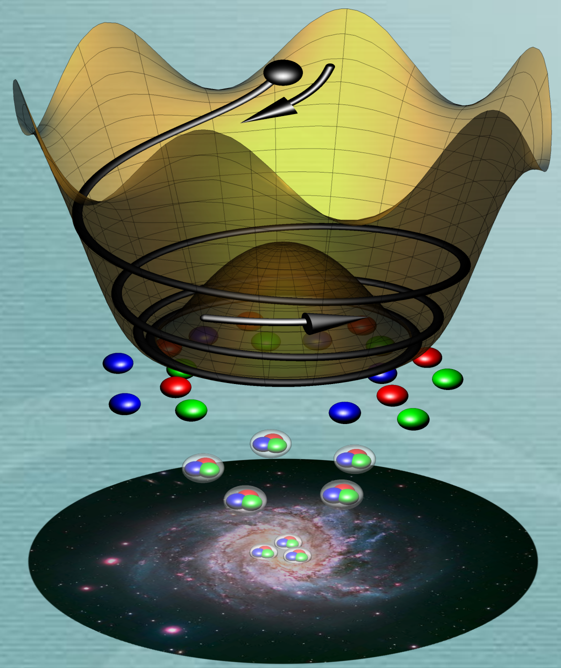
22/11/2021, DESY

Cosmology of Axion rotation

Keisuke Harigaya (CERN)



1910.02080 : Co and KH
1910.14152 : Co, Hall and KH
2108.09299 : Co, Dunsky, Fernandez, Ghalsasi, Hall, KH and Shelton
2006.05687 : Co, Fernandez, Ghalsasi, Hall and KH
2107.09679 : KH and Wang
2110.05487 : Co, KH, Johnson and Pierce

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?
* ....

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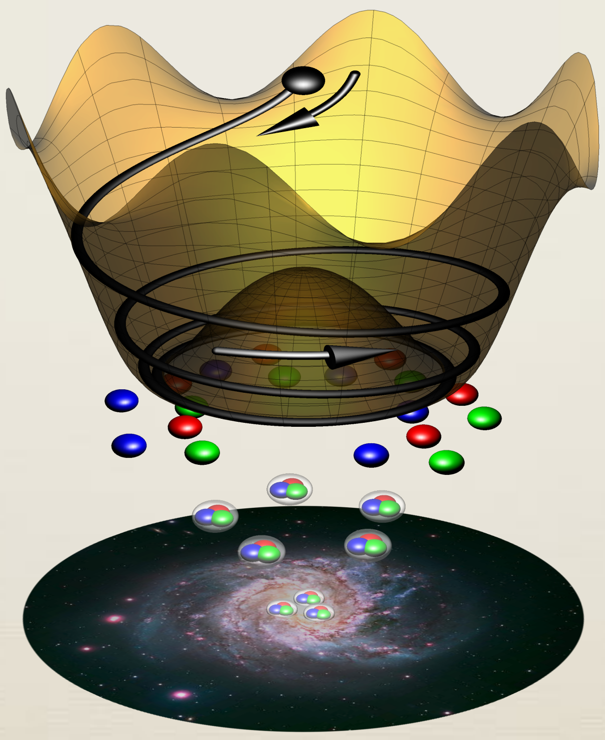
Summary

New cosmological dynamics of the axion



Summary

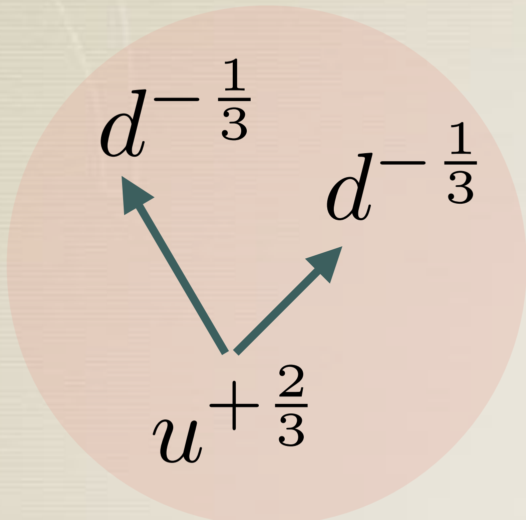
New cosmological dynamics of the axion

* explains dark matter for axion coupling constants much larger the prediction of conventional mechanisms
* creates the baryon asymmetry of the universe
* has implications for new physics other than the axion and gravitational wave searches

Outline

* Introduction: axion and dark matter
* Dark matter from axion rotation
* Baryon asymmetry from axion rotation
* Kination 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

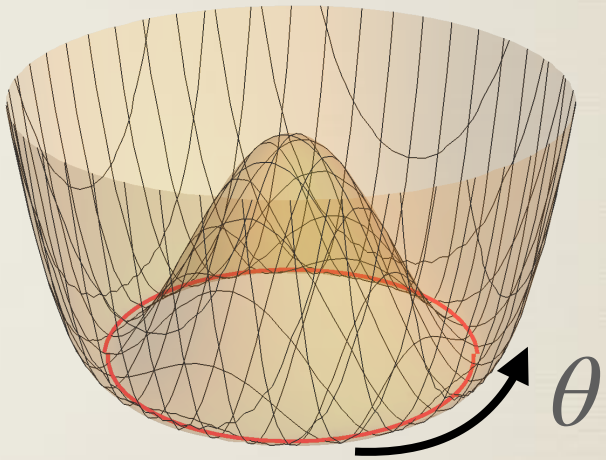
't Hooft (1976)

QCD axion

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

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

Spontaneous breaking



pseudo-Nambu Goldstone boson, the QCD axion

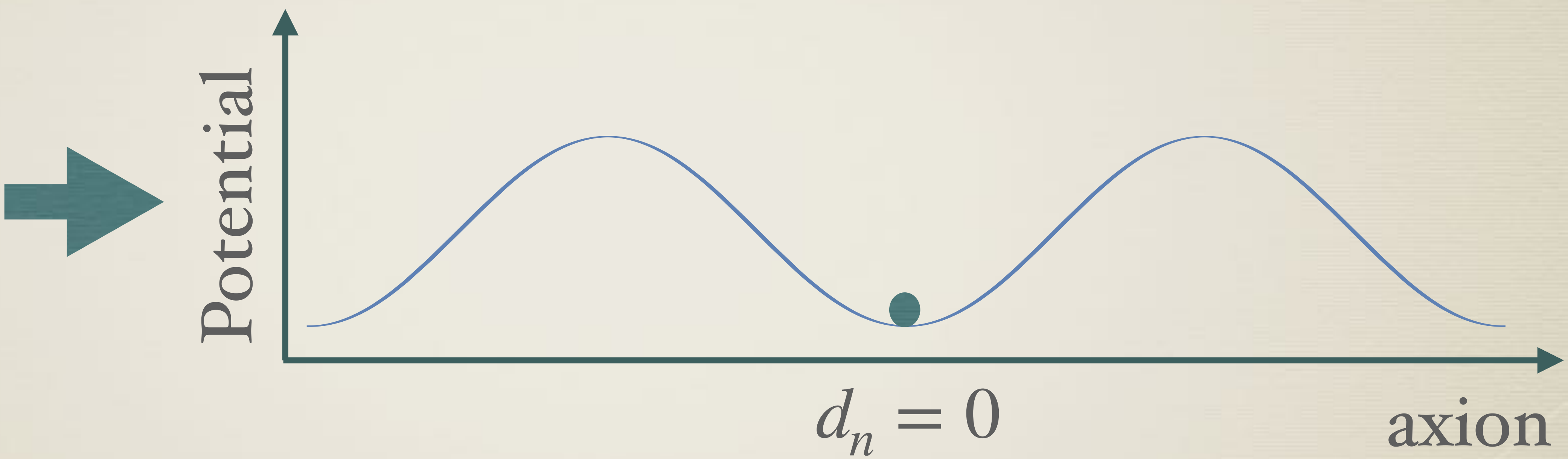
$$\mathscr{L} = \frac{1}{32\pi^2}\frac{a}{f_a}G\tilde{G}$$

f_a : the decay constant

QCD axion

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

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

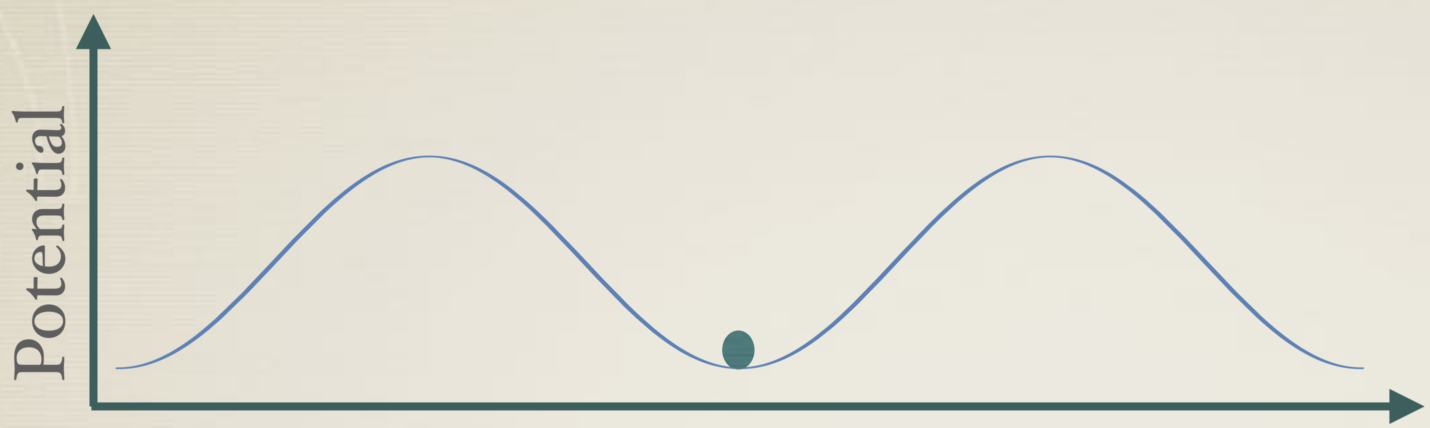


so are other CP violations in QCD

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

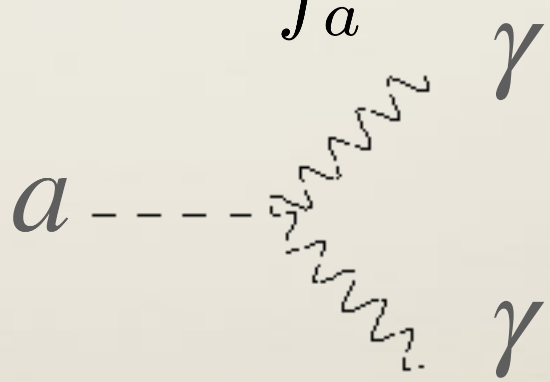
QCD axion dark matter

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

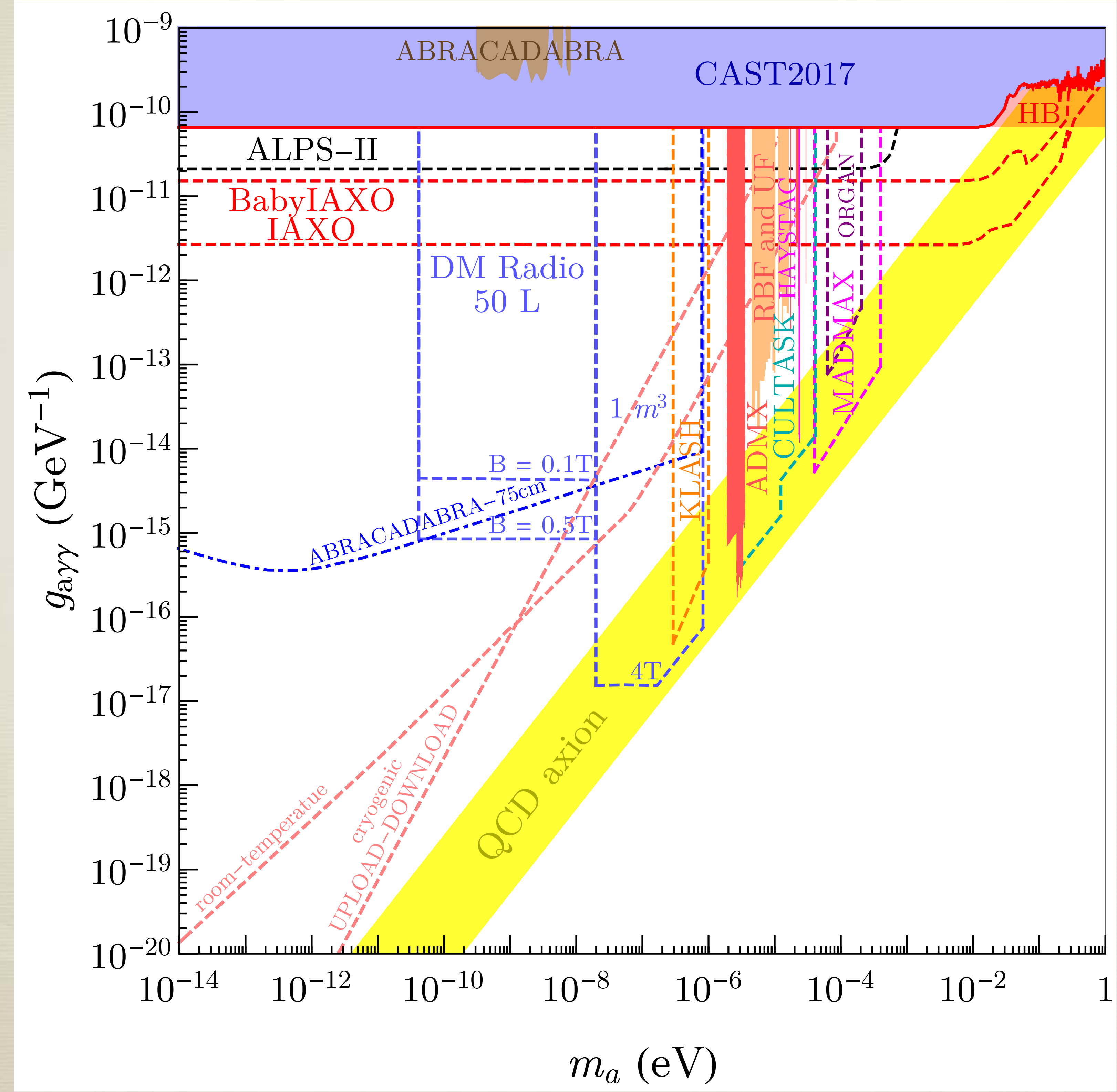


$\propto \frac{1}{f_a}$

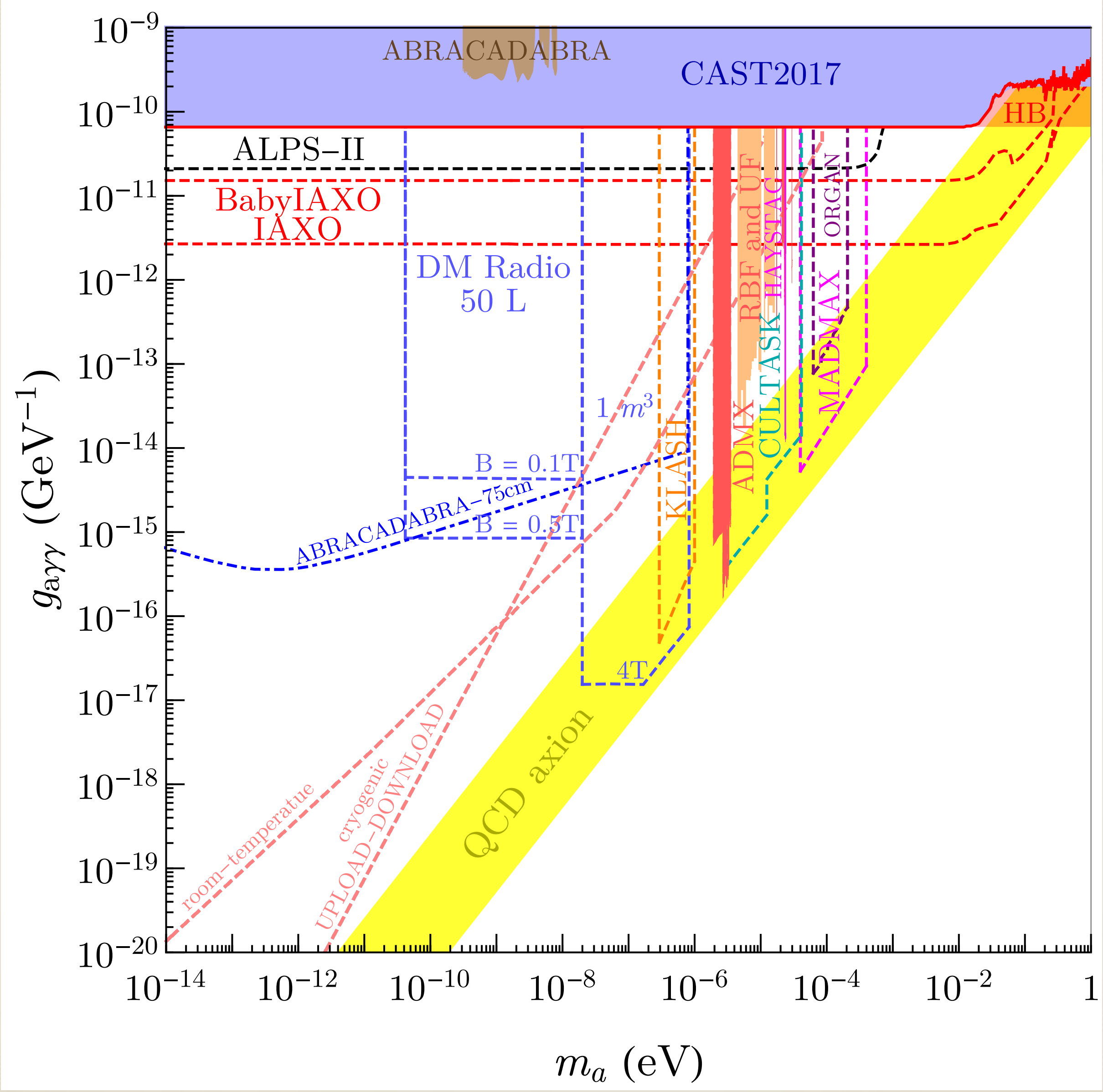
long-lived $\tau_a \sim 10^{17} \times t_{\text{univ}} \left(\frac{f_a}{10^9 \text{ GeV}} \right)^5$

Dark Matter candidate

Axion search



Dark matter?

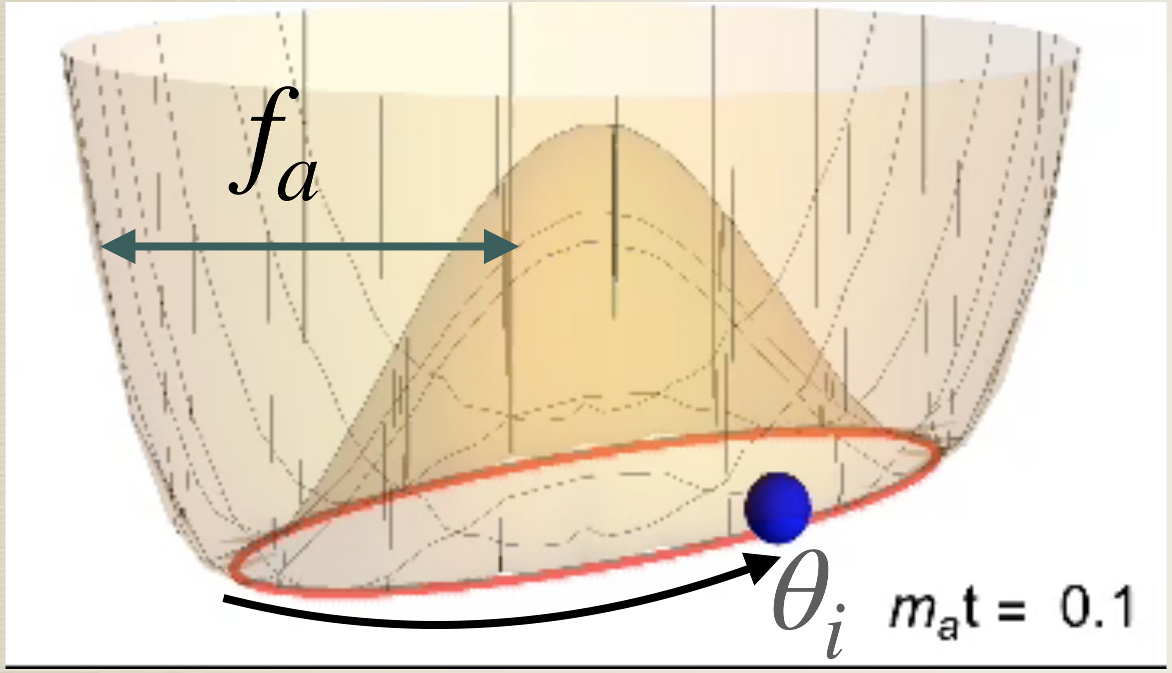


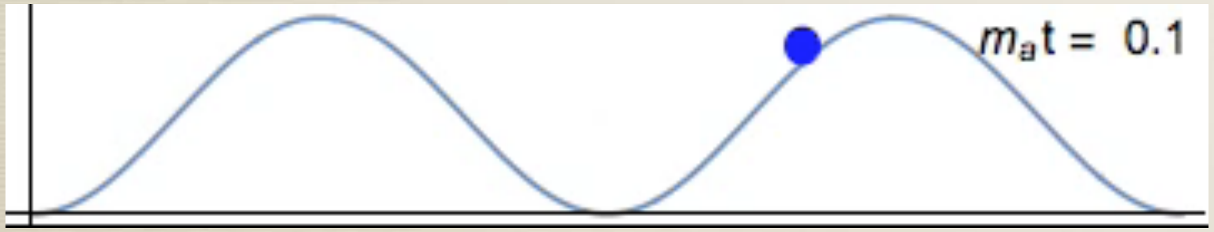
$\rho_{\rm DM} \simeq 1.3 \times 10^{-5}$ GeV/cm^3 (Planck 2018)

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)



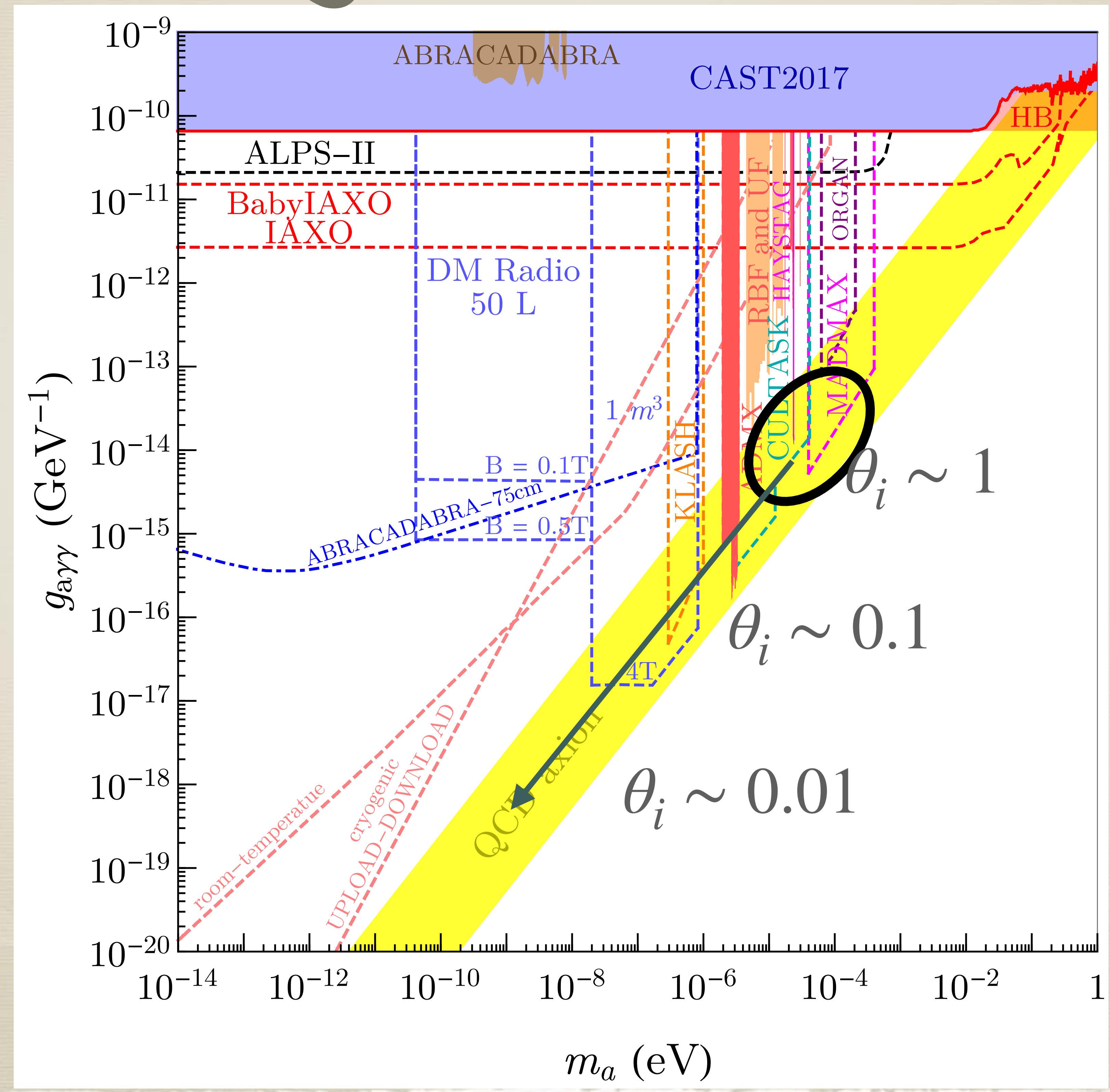


For the QCD axion,

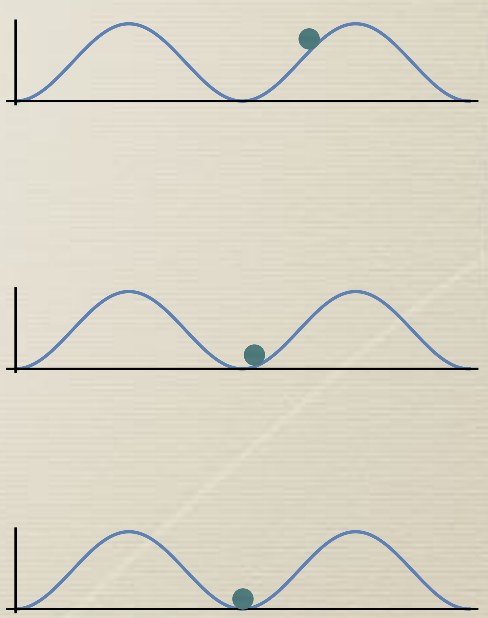
$$\frac{\rho_a}{\rho_{\rm DM}} = \theta_i^2 \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{1.19}$$

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

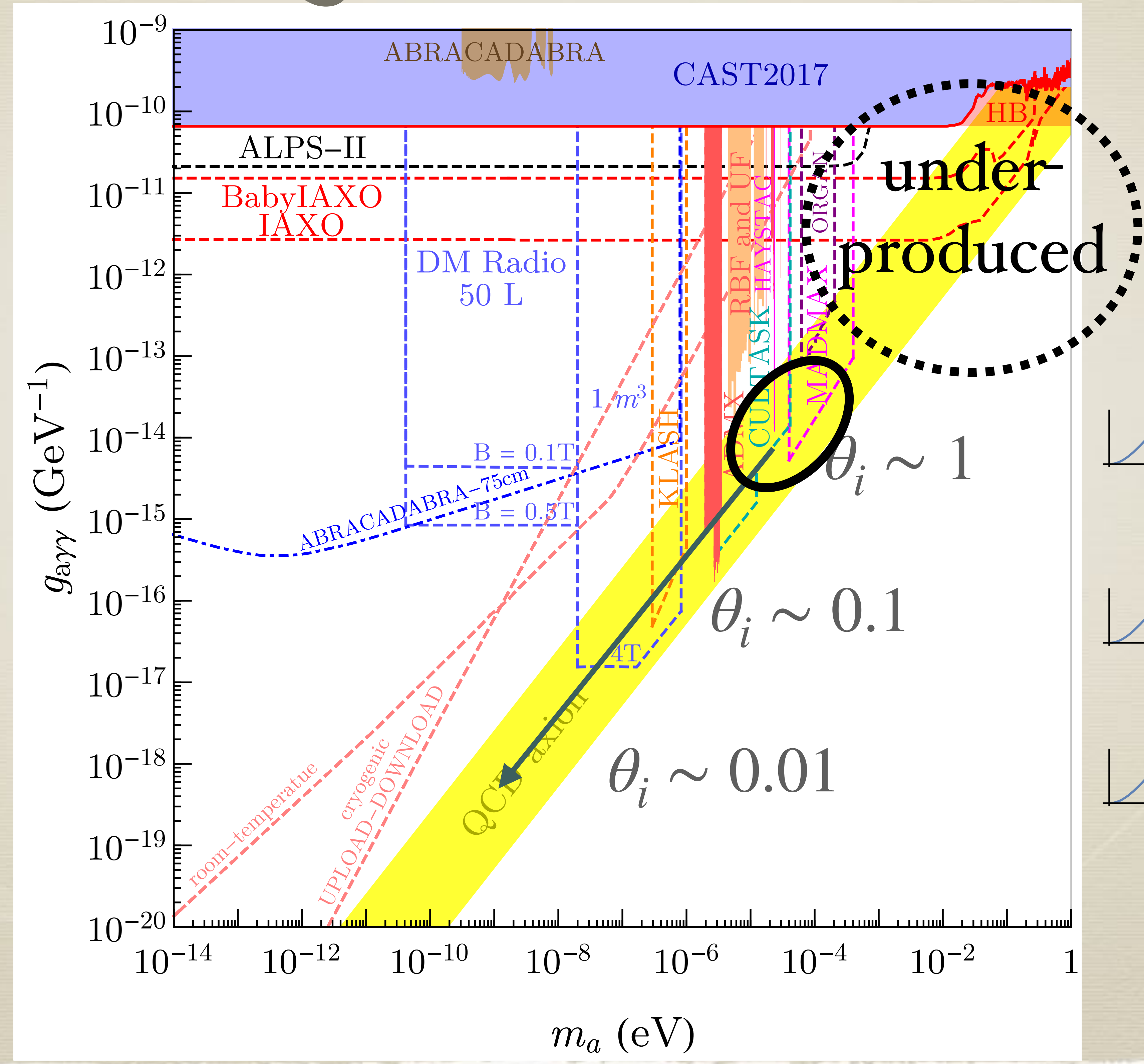
QCD axion



ABRACADABRA
CAST2017
HB
ALPS–II
BabyIAXO
IAXO
DM Radio
50 L
RBF and UF
HAYSTAC
ORGAN
CULTASK
MADMAX
KLASH
ADMX
1 m^3
B = 0.1T
B = 0.5T
4T
ABRACADABRA–75cm
room–temperatue
cryogenic
UPLOAD–DOWNLOAD
QCD axion
$\theta_i \sim 1$
$\theta_i \sim 0.1$
$\theta_i \sim 0.01$
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)



QCD axion



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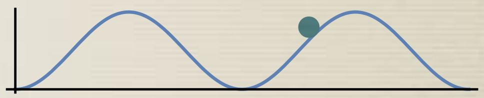
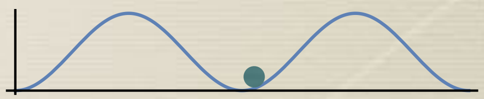
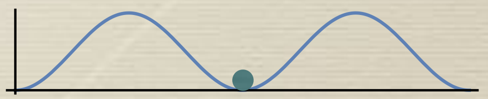
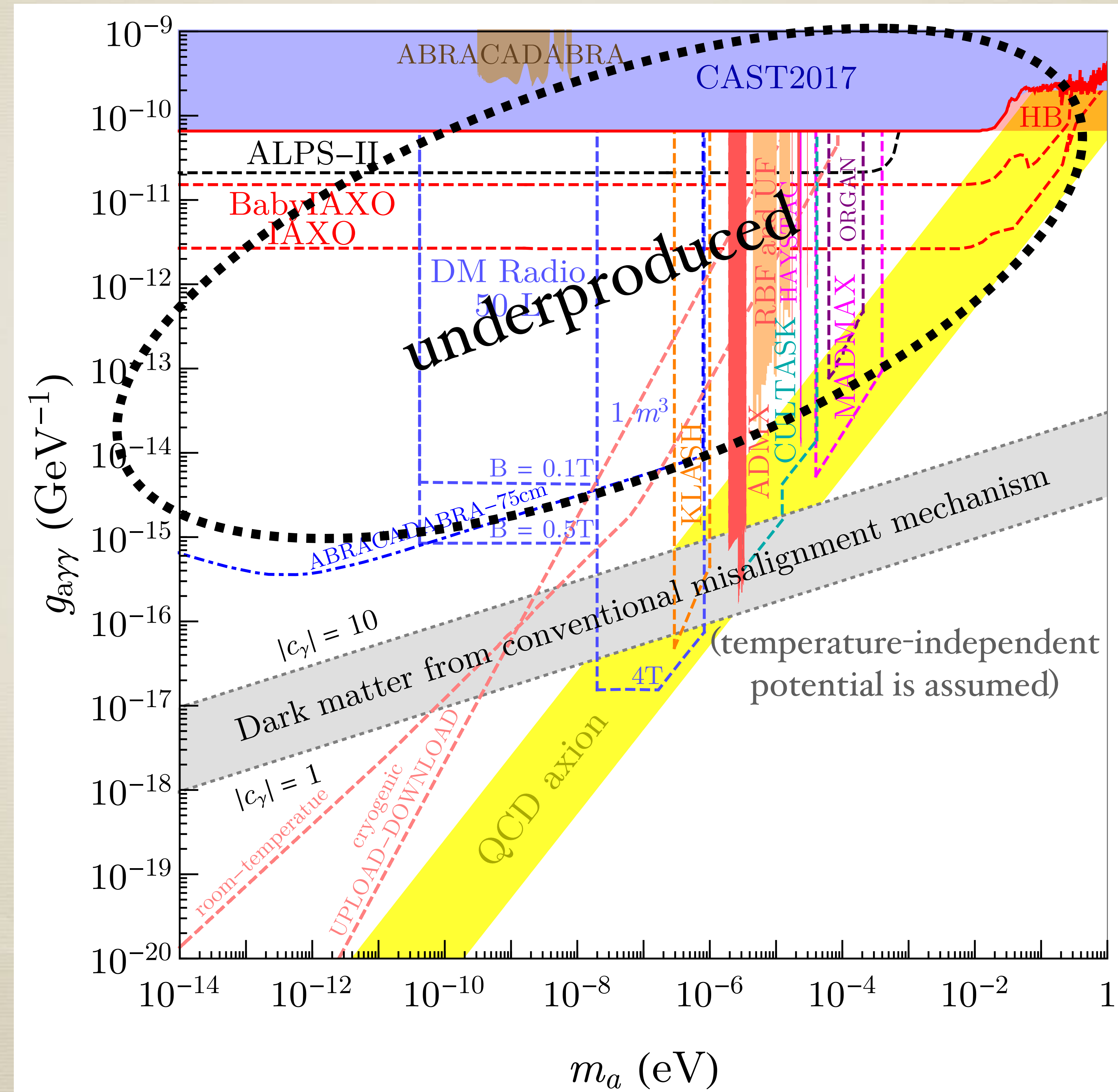


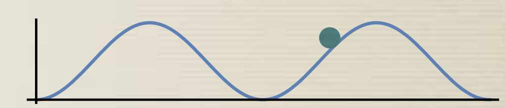




Axion Like Particle



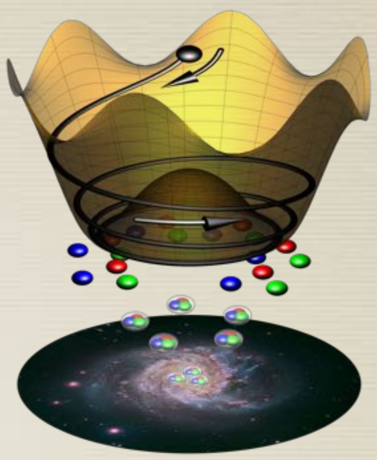
$\theta_i \sim 1$



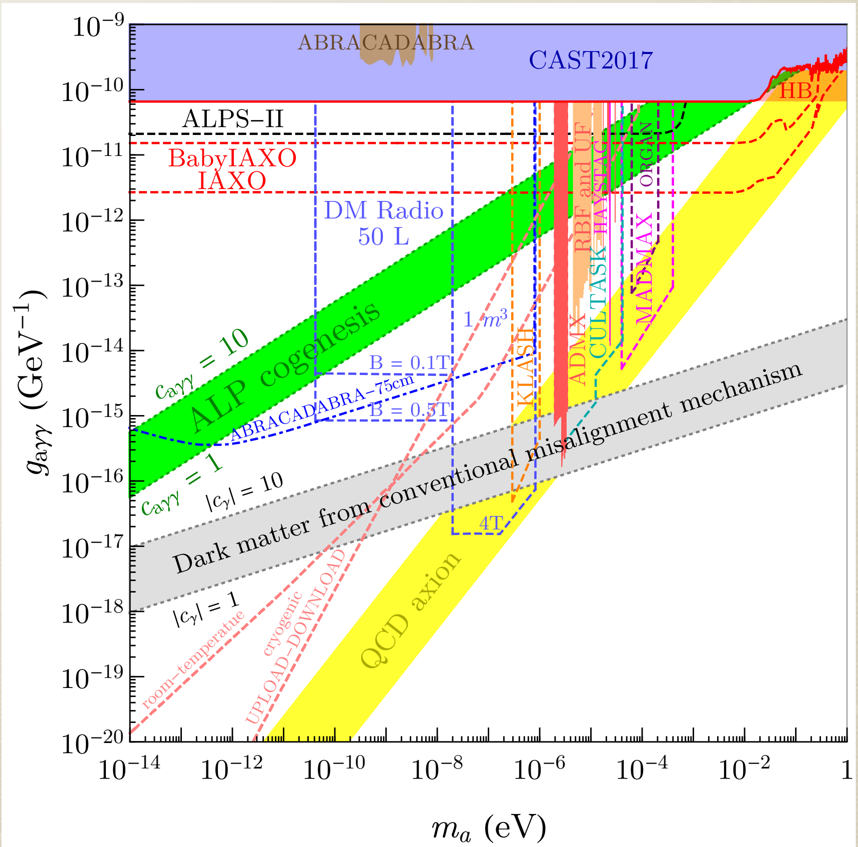
$\theta_i \ll 1$

I will present new cosmological dynamics of the axion

* enhance axion dark matter abundance and predict larger couplings



* create baryon asymmetry
* have implications for axion searches, new physics other than the axion, and gravitational wave searches



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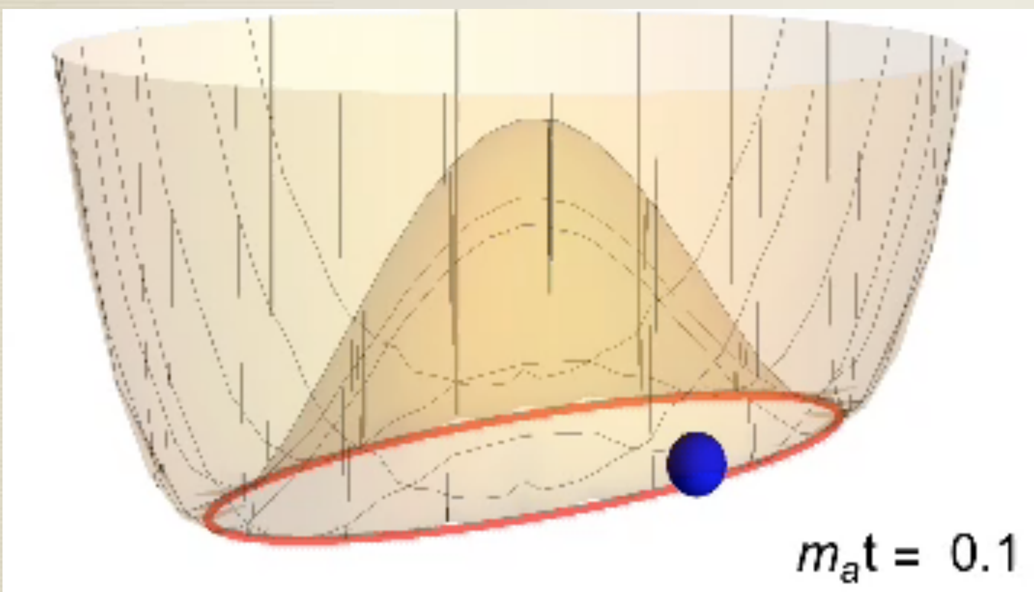
Rotation?

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

Conventional picture

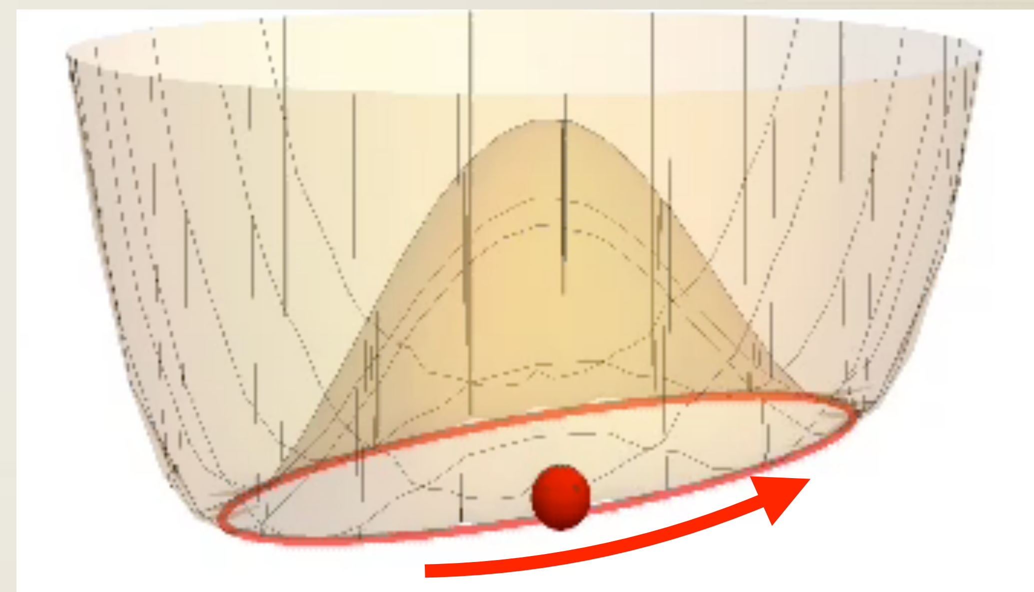


$$\dot{\theta}_i = 0$$

$$V$$

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

Non-zero initial angular velocity?



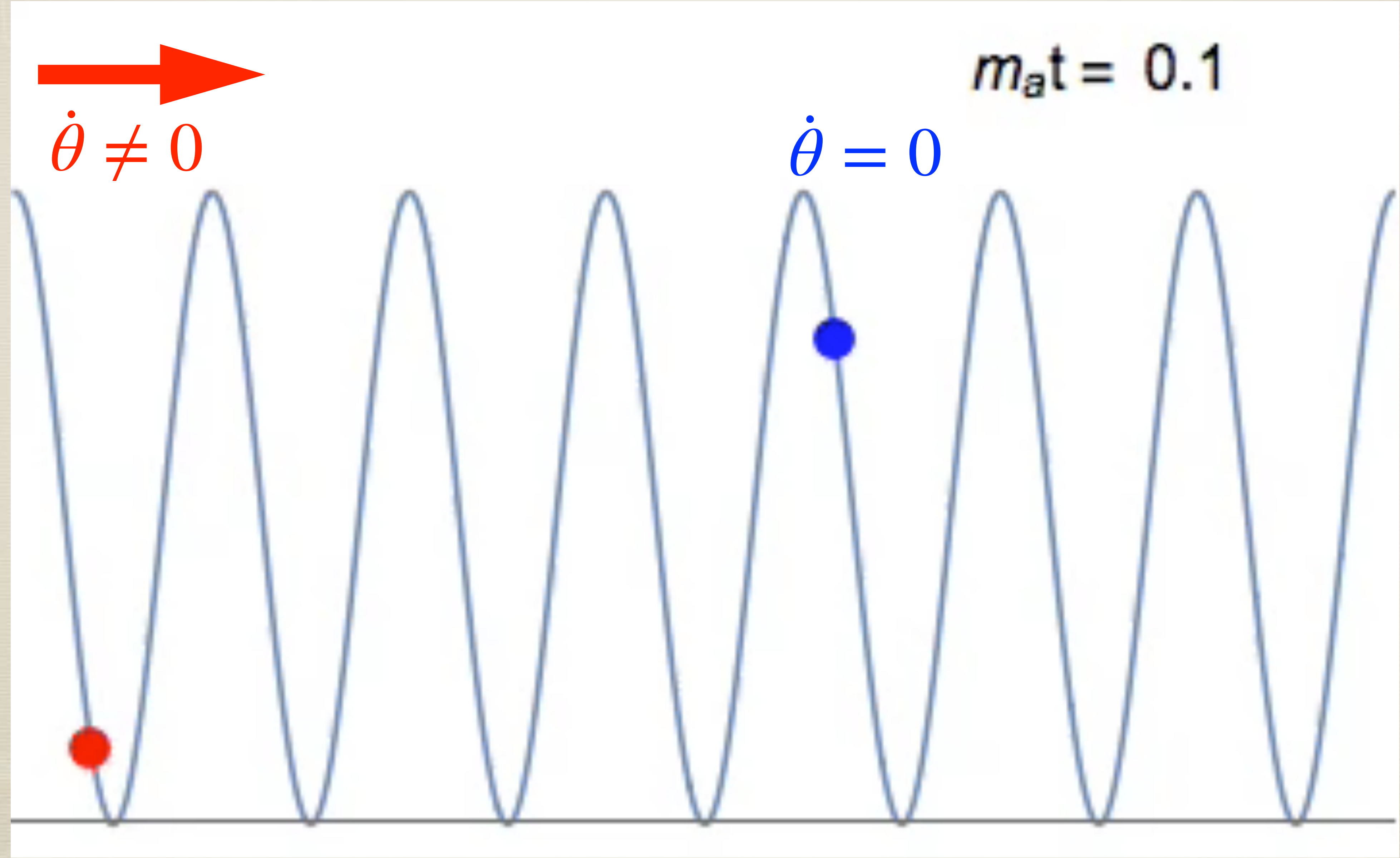
$$\dot{\theta}_i \neq 0$$

$$V + K$$

Kinetic Misalignment

Coherent motion

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



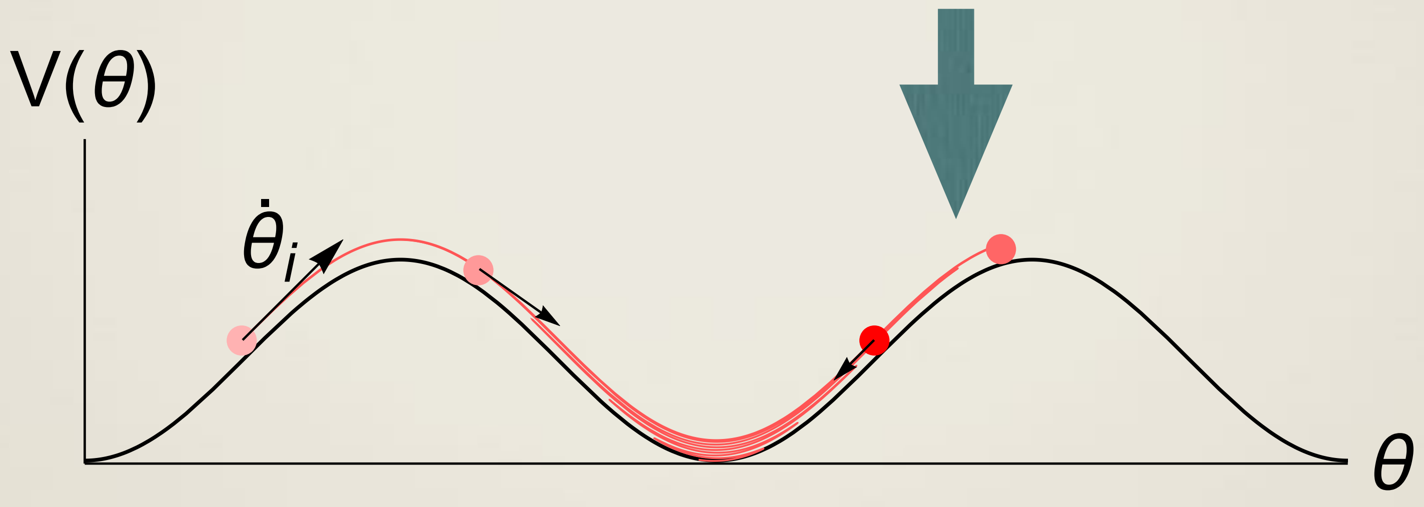
potential

axion

Coherent motion

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

$\dot{\theta} \simeq m_a$



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

(axion number density) = (PQ charge)

Axion fragmentation

Fonseca, Morgante, Sato, Servant (2019)
Morgante, Ratzinger, Sato, Stefanek (2021)

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

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

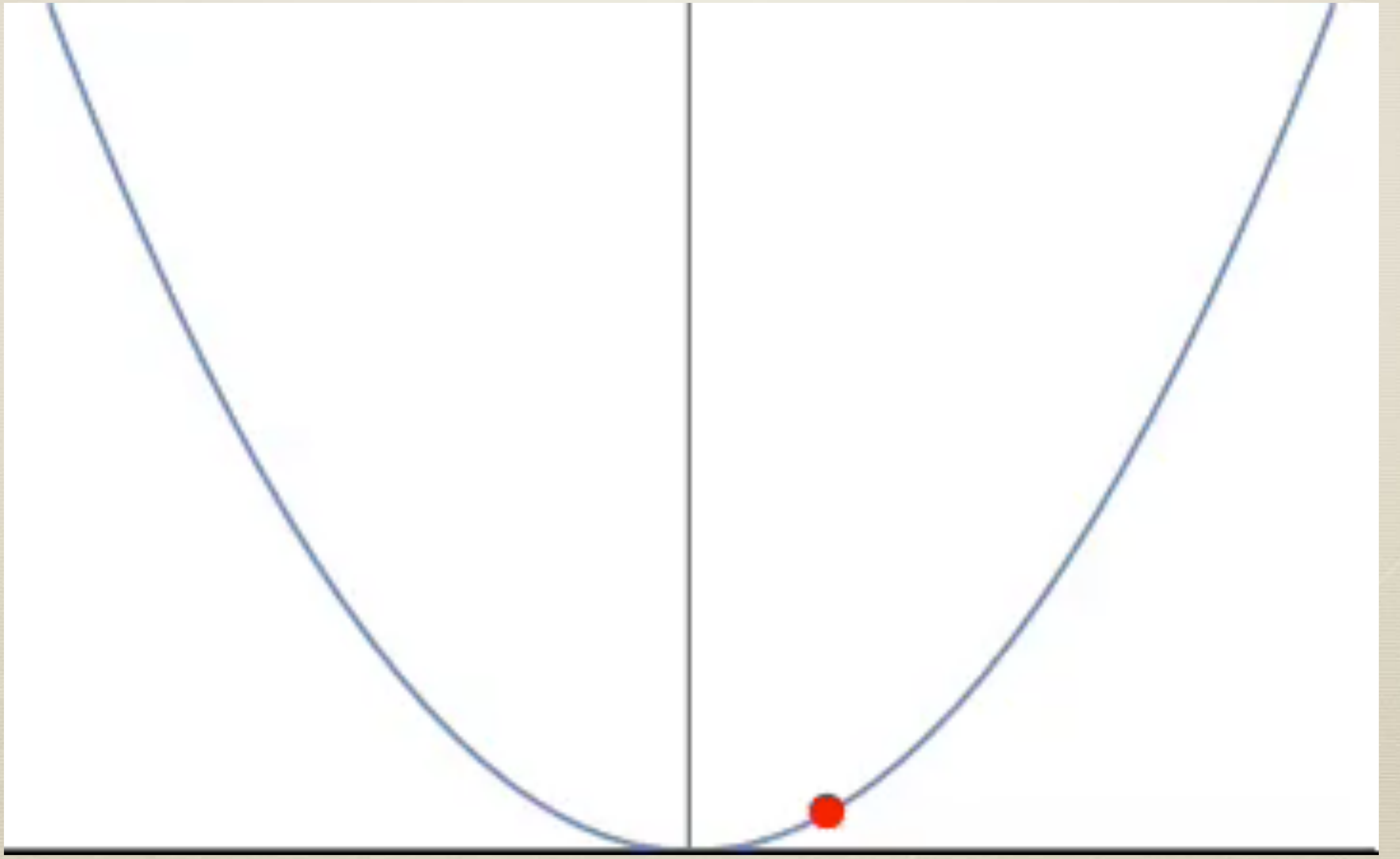
EOM of the fluctuation at the linear level:

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

oscillating frequency

Parametric resonance

Dolgov and Kirilova (1990), Traschen and Brandenberger (1990),
Kofman, Linde and Starrobinsky (1994, 1997),
Shatov, Traschen and Brandenberger (1994)



Axion fragmentation

Fonseca, Morgante, Sato, Servant (2019)
Morgante, Ratzinger, Sato, Stefanek (2021)

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

Resonance at $\quad k_{\rm PR} = \dot{\theta}/2$

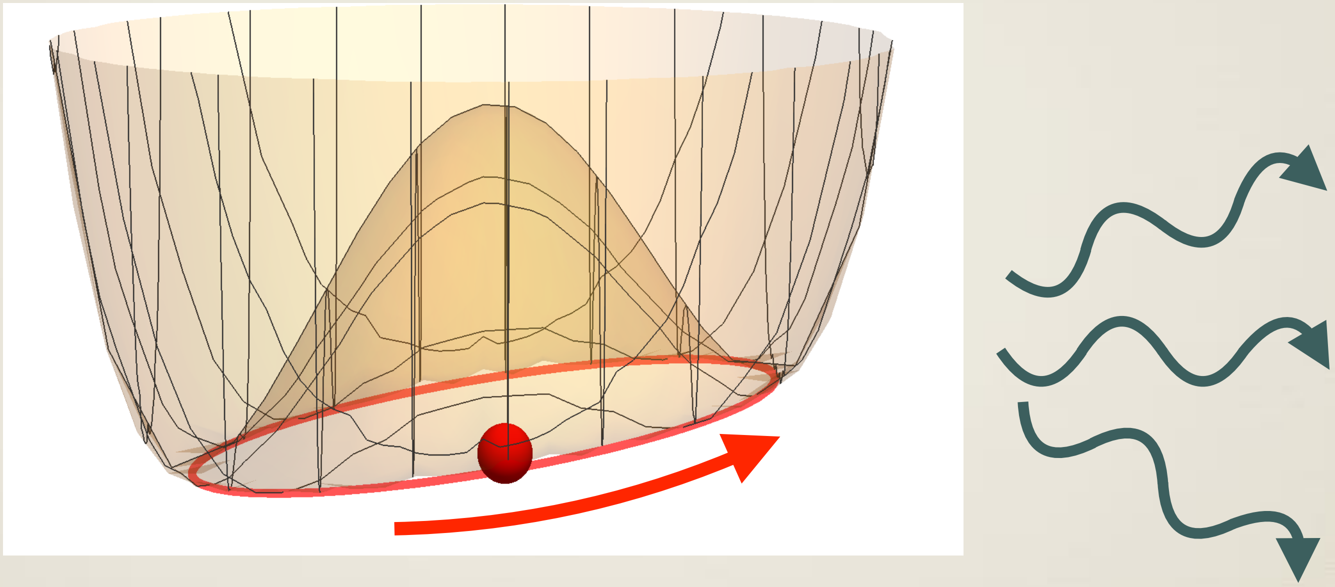
(Effective) rate $\quad \Gamma_{\rm PR} \sim \dfrac{m_a^4}{\dot{\theta}^3}$

Parametrically, $\Gamma_{\rm PR} \sim m_a > H$

when the oscillation would begin ($\dot{\theta} \sim m_a$)

Axion abundance

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



axions with
$k_{\rm PR} = \dot{\theta}/2$

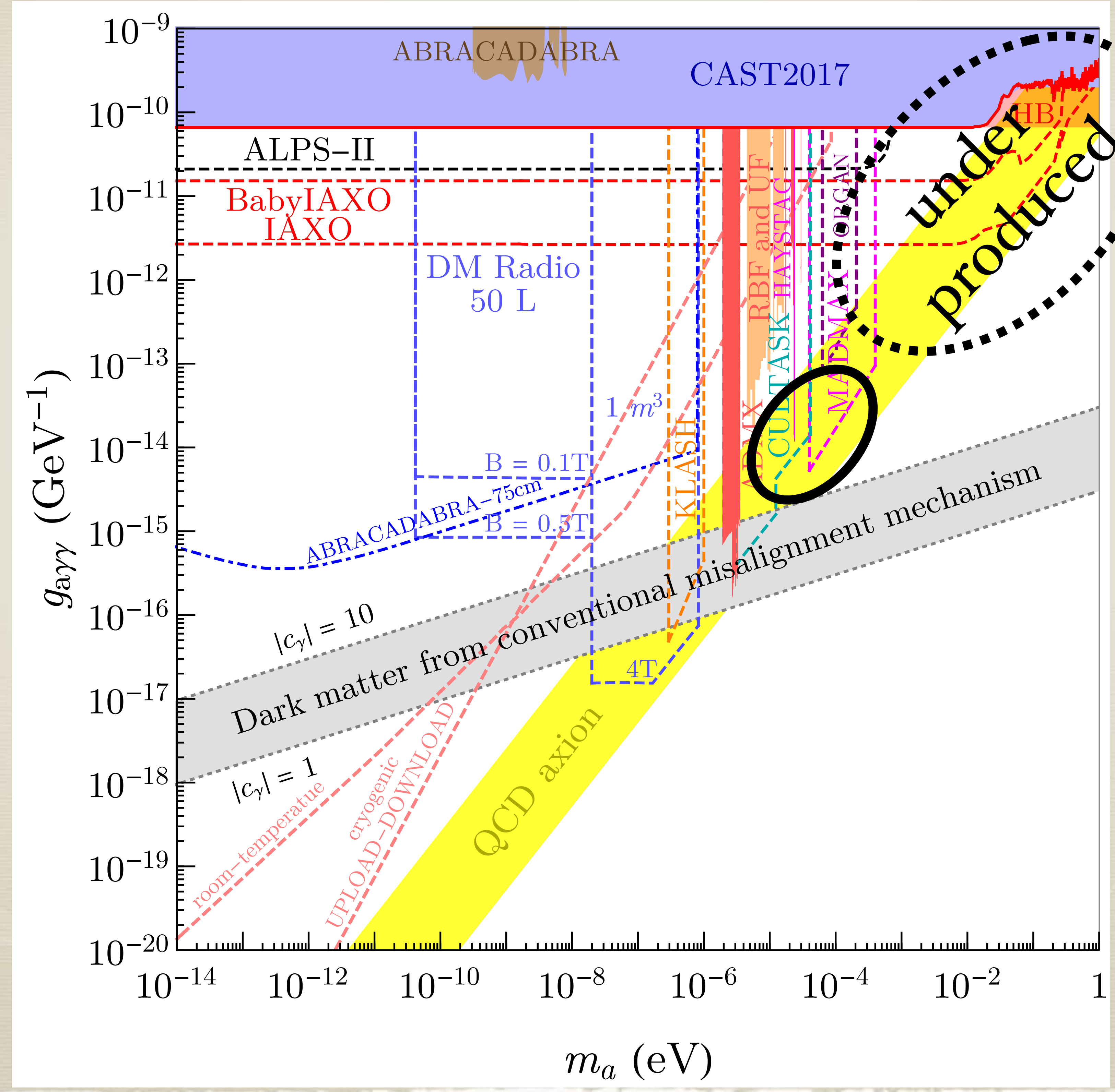
$$n_{a,\rm PR} = \frac{\rho_{\rm rot}}{k_{\rm PR}} \simeq \frac{\dot{\theta}^2 f_a^2/2}{\dot{\theta}/2} = \dot{\theta} f_a^2 = n_{\rm PQ}$$

Co, KH and Pierce (2021)

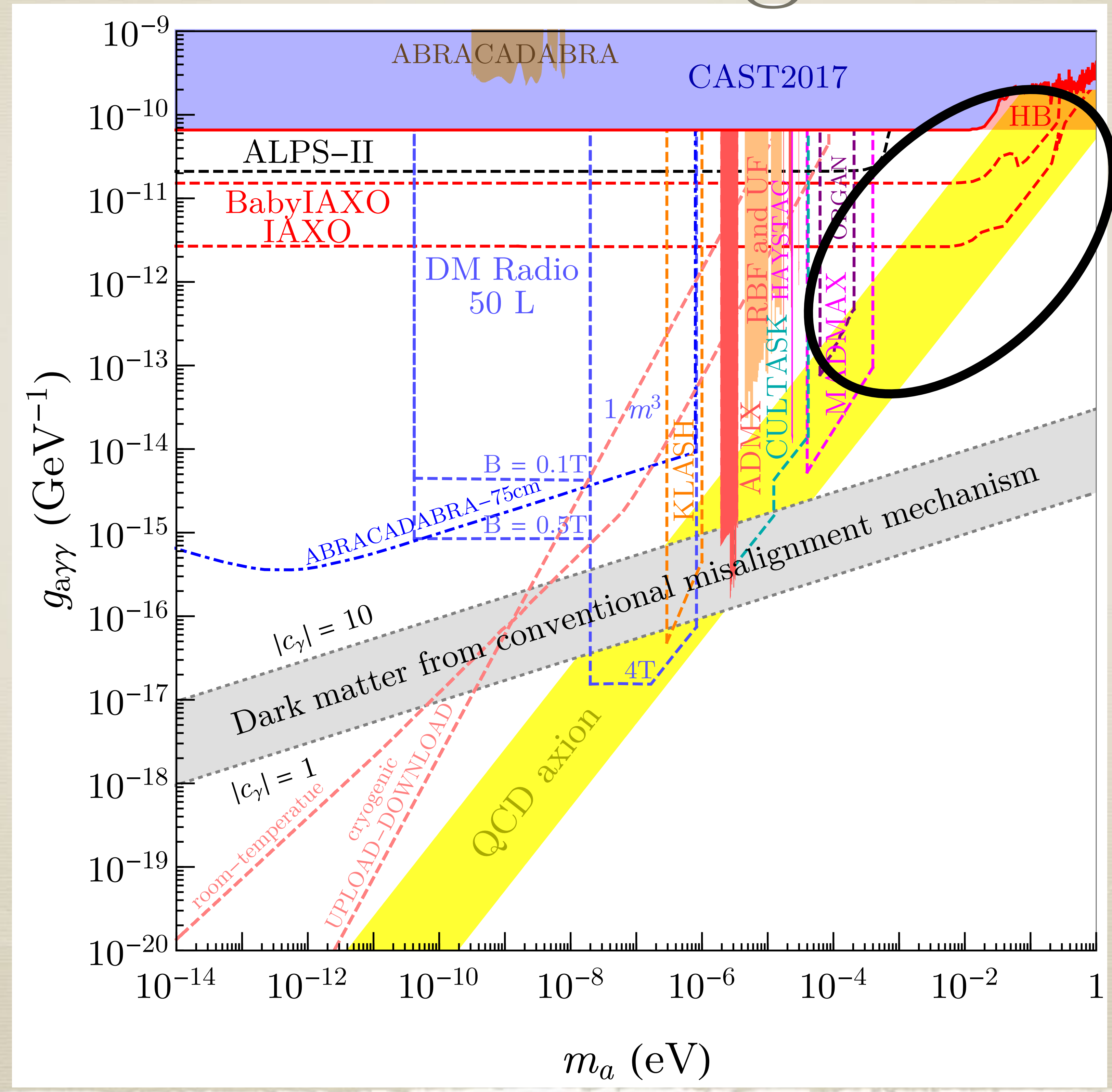
(Scattering can change the abundance by O(1) factor)

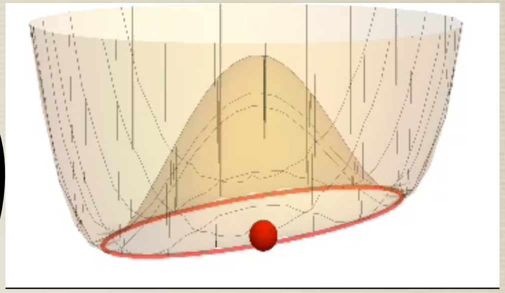
(axion number density) $\simeq$ (PQ charge)

Conventional mechanisms



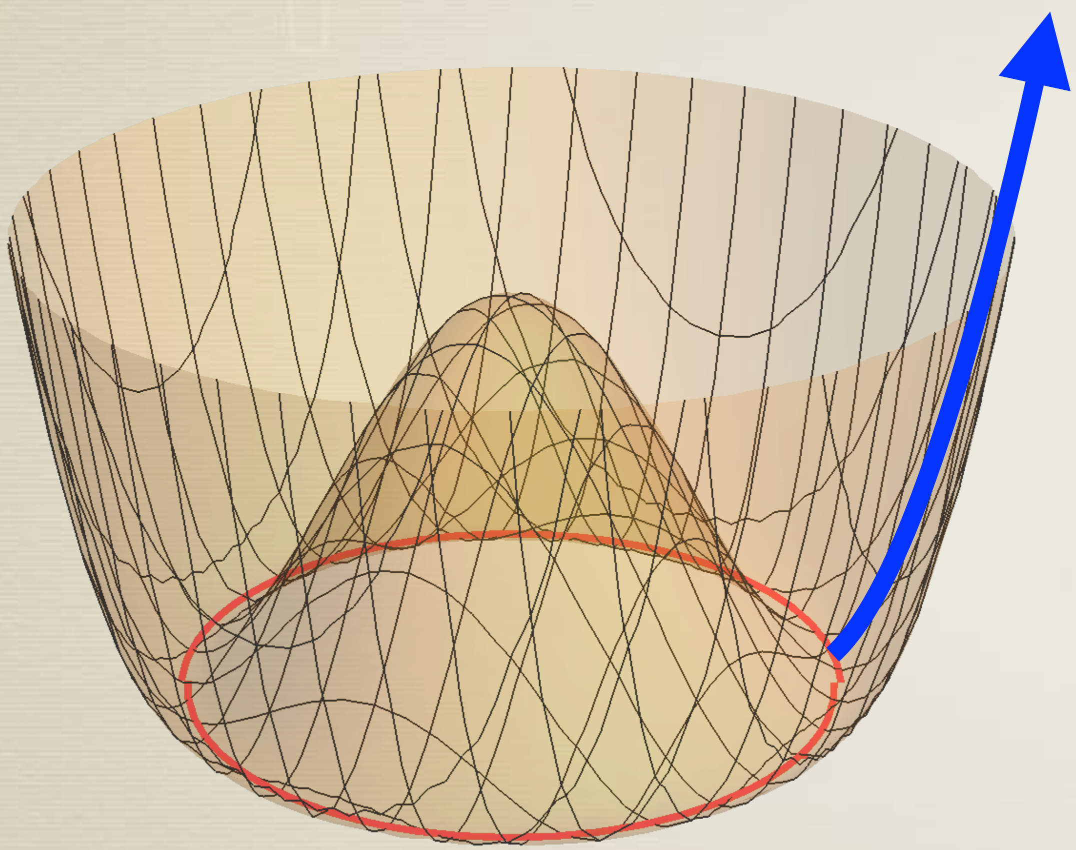
Kinetic misalignment





How to initiate the rotation

Co and KH (2019)



Consider the dynamics of
the radial direction

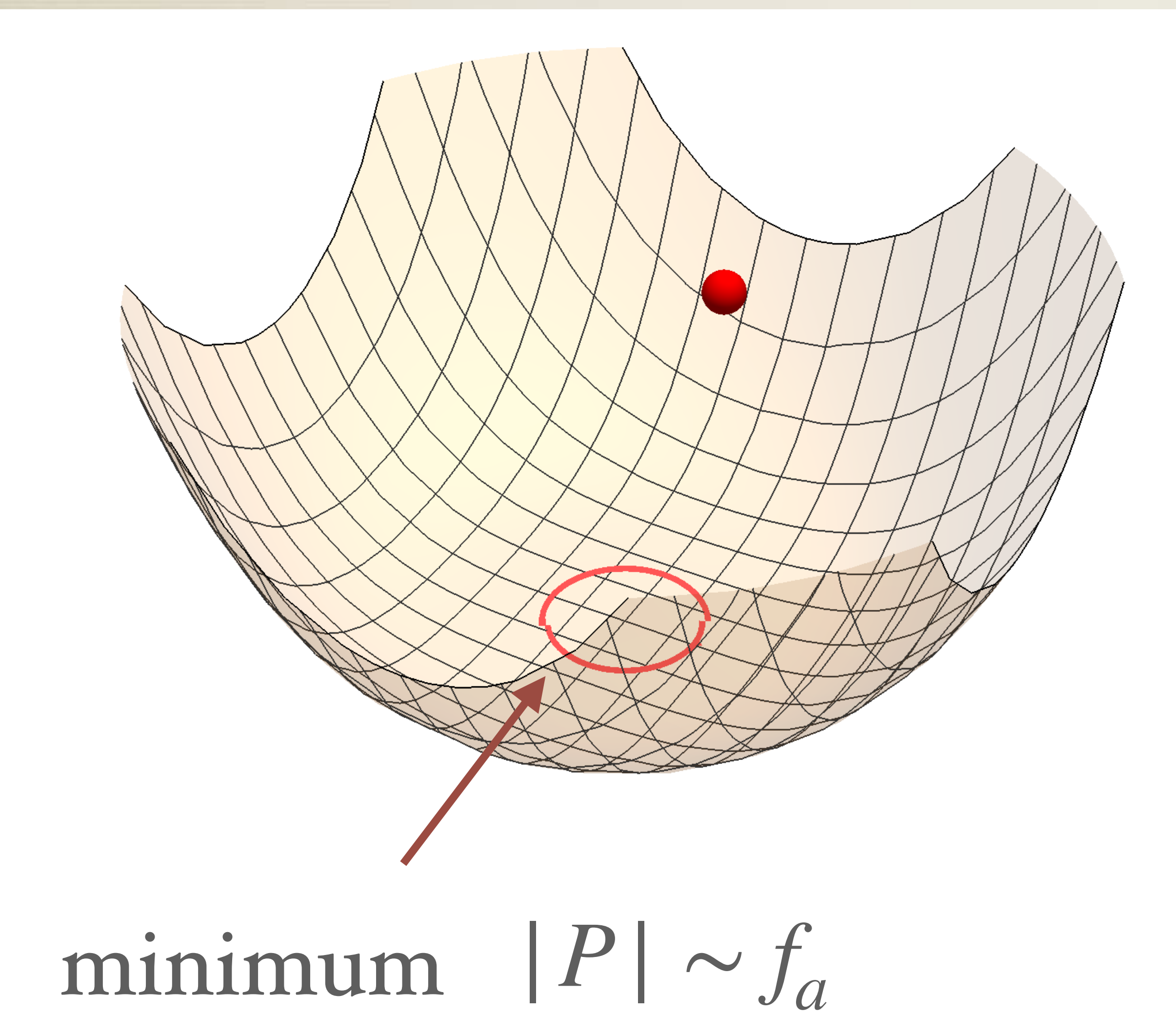
$$P = S\exp(i\,\theta\,)$$

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

Another type of realization : Di Luzio, Gavela, Quilez and Ringwald(2021)

How to initiate the rotation

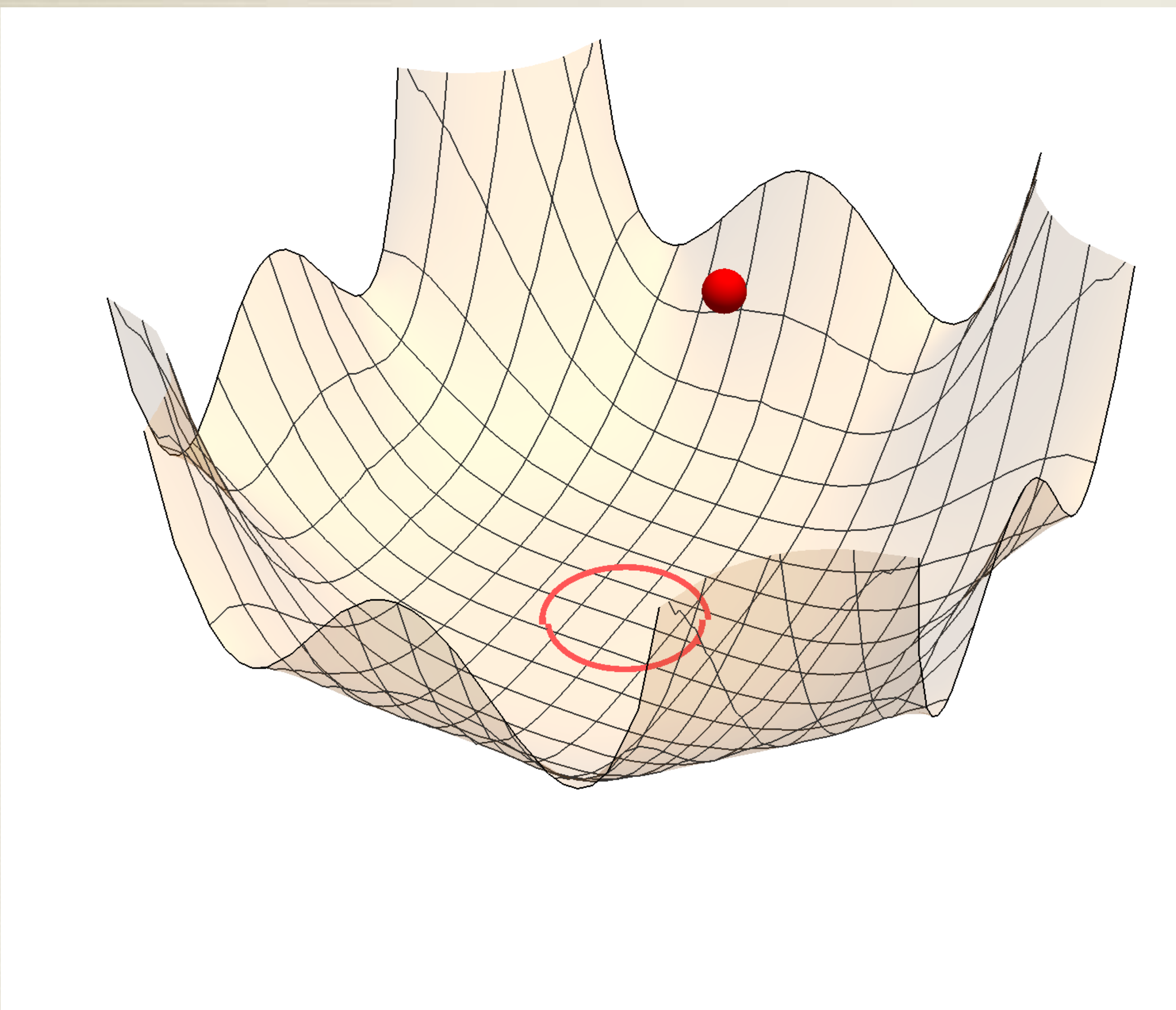
$$P = S \times \exp(i\theta)$$



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

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

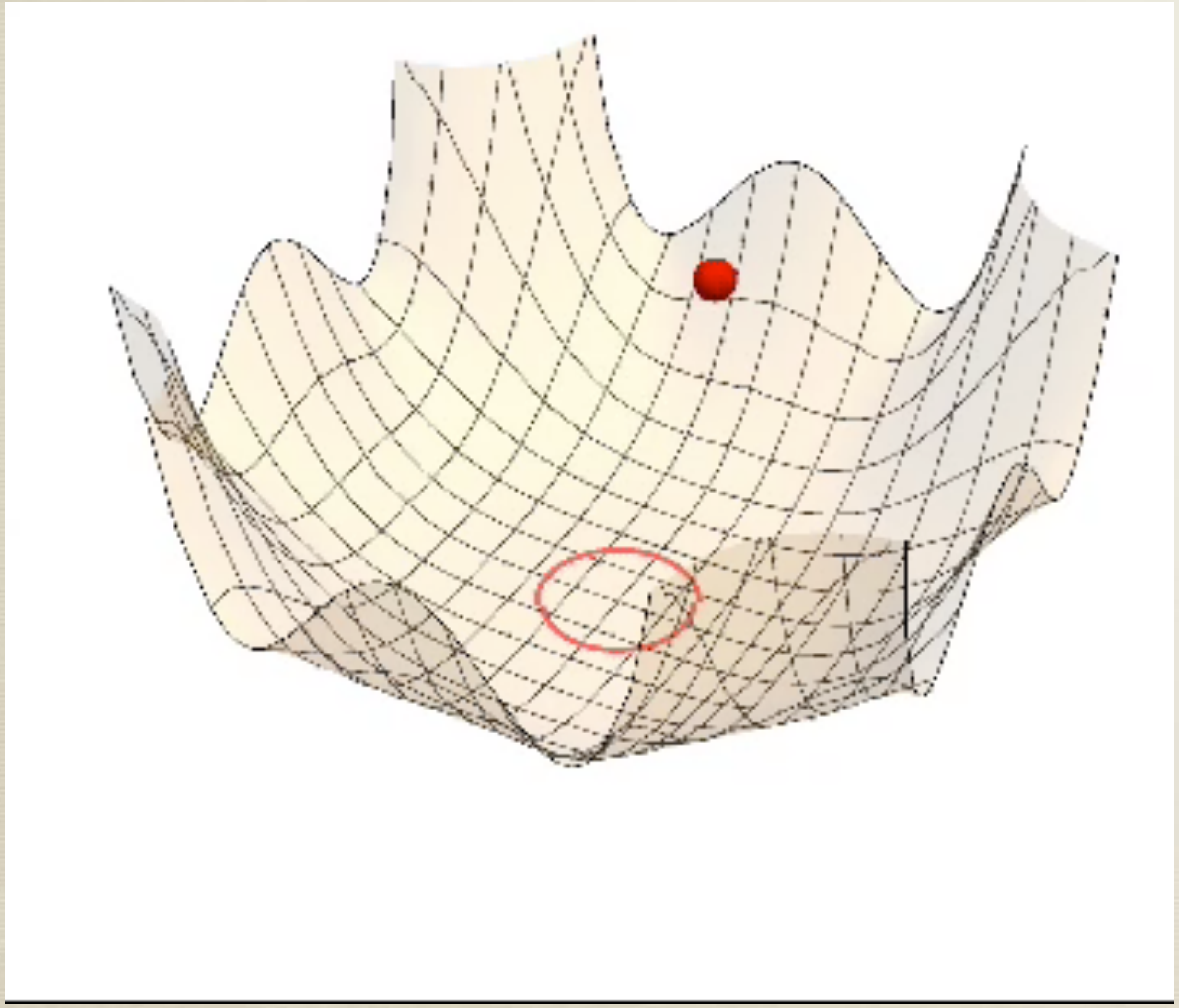
may be effective

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 (19
Dine (1992), KH+ (2013, 2015), Quilez+ (2018), ...

How to initiate the rotation

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



Assume a large initial radial field value

Higher order terms

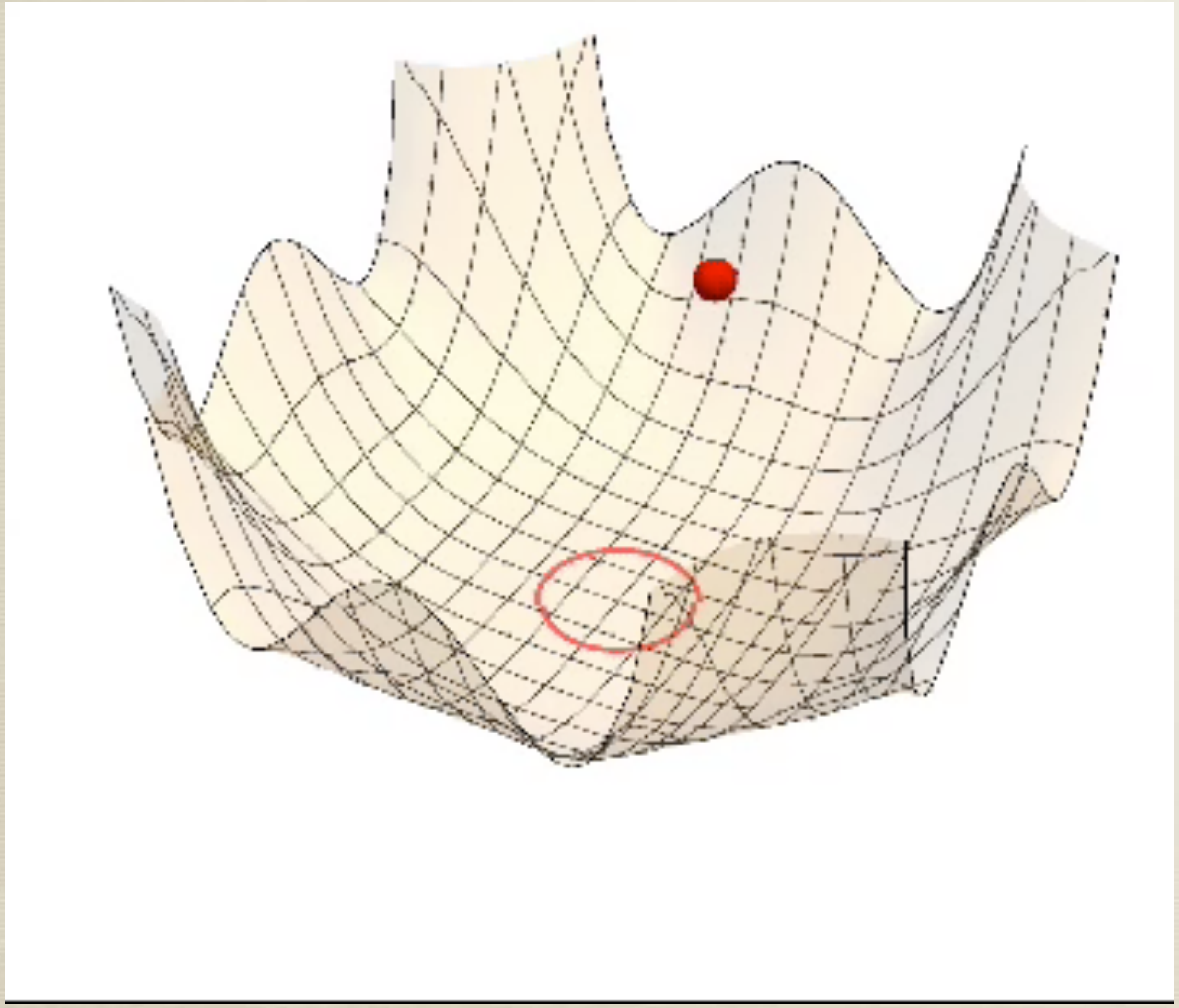
$$V \sim P^n \sim S^n \cos(n\theta)$$

may be effective

Angular motion is induced by the potential gradient

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

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

Dark matter abundance

Co, Hall and KH (2019)

It is convenient to define the "yield"

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

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

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

$\propto R^{-3}$

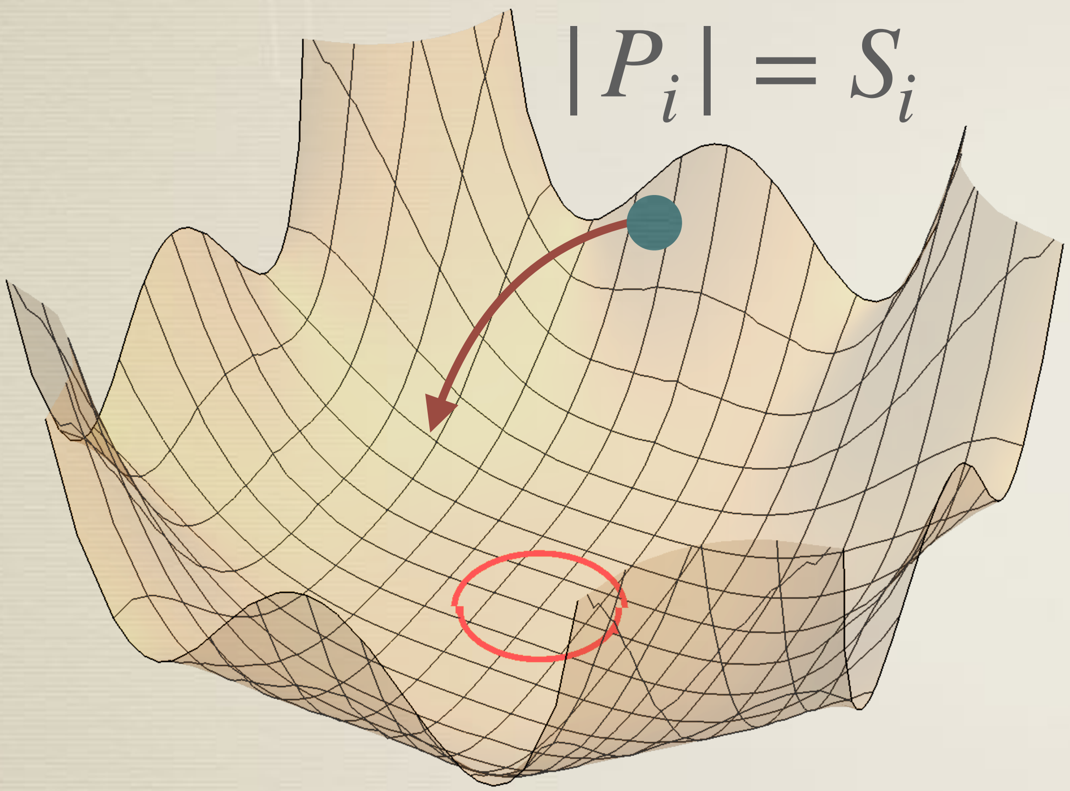
$$Y_a \equiv \frac{n_a}{s} \simeq Y_{\rm PQ}$$

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

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

for the QCD axion

Estimation of PQ charge



Initial number density of
the radial direction

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

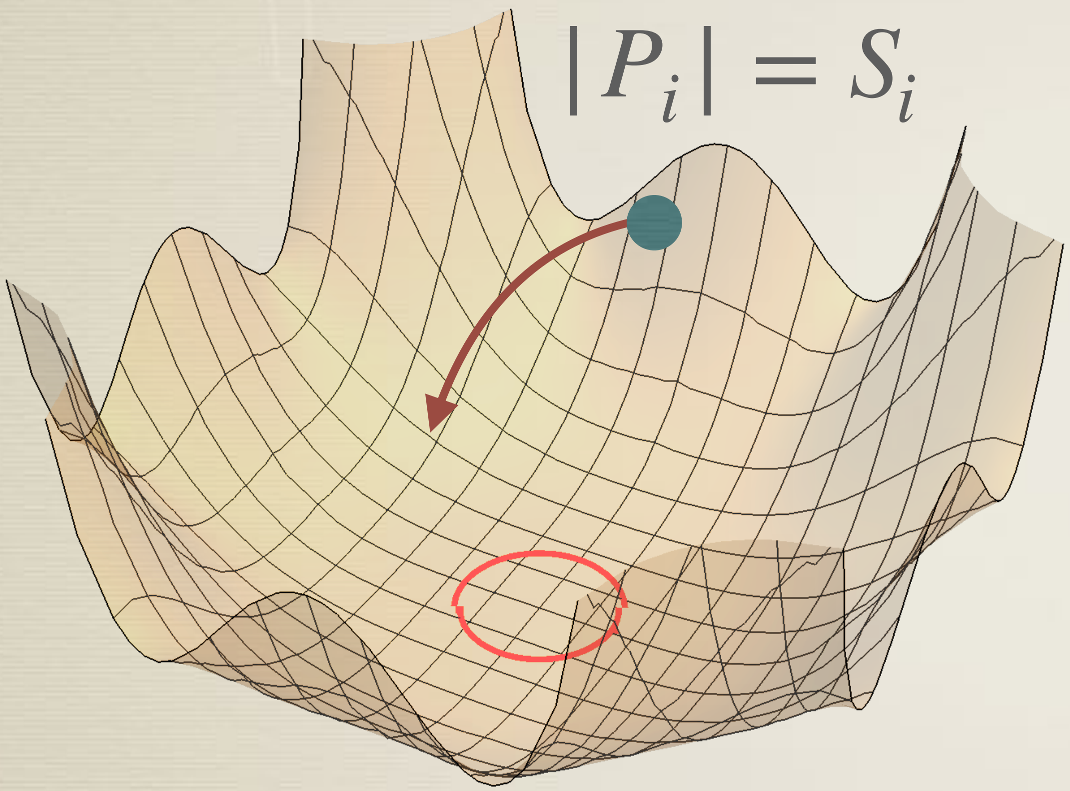
mass around S_i

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

$\epsilon = 0$: 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

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

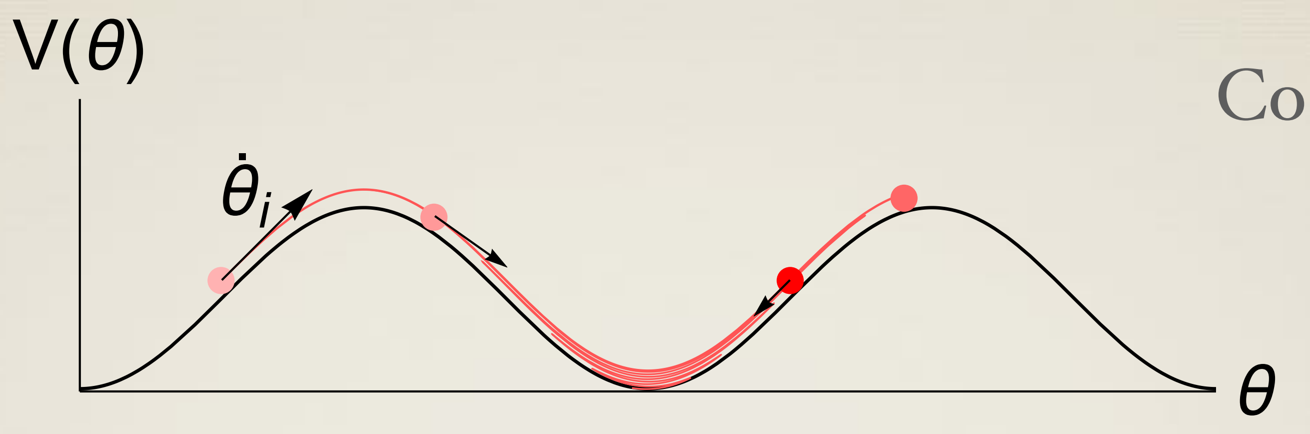
$$n_{\mathrm{PQ}} = \epsilon n_S = \epsilon m_{S,i}\, S_i^2$$

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

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

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

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

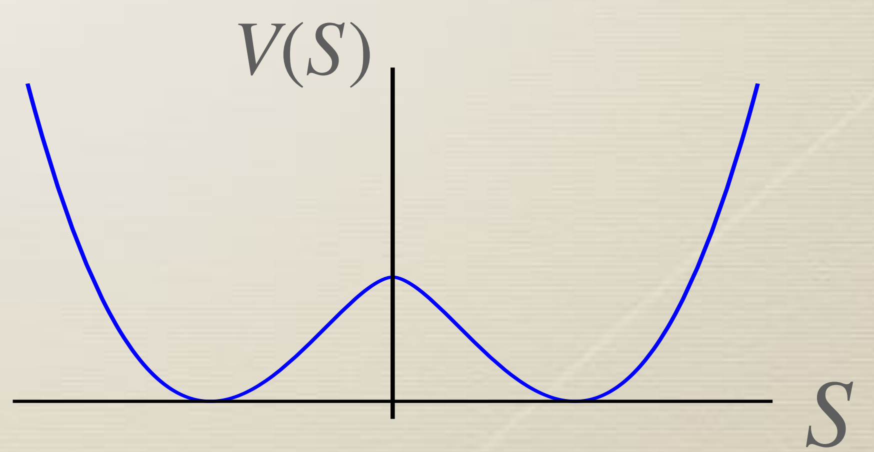
A flat potential with $m_{S,i} = \sqrt{V''(S_i)} \ll S_i$ is required

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



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

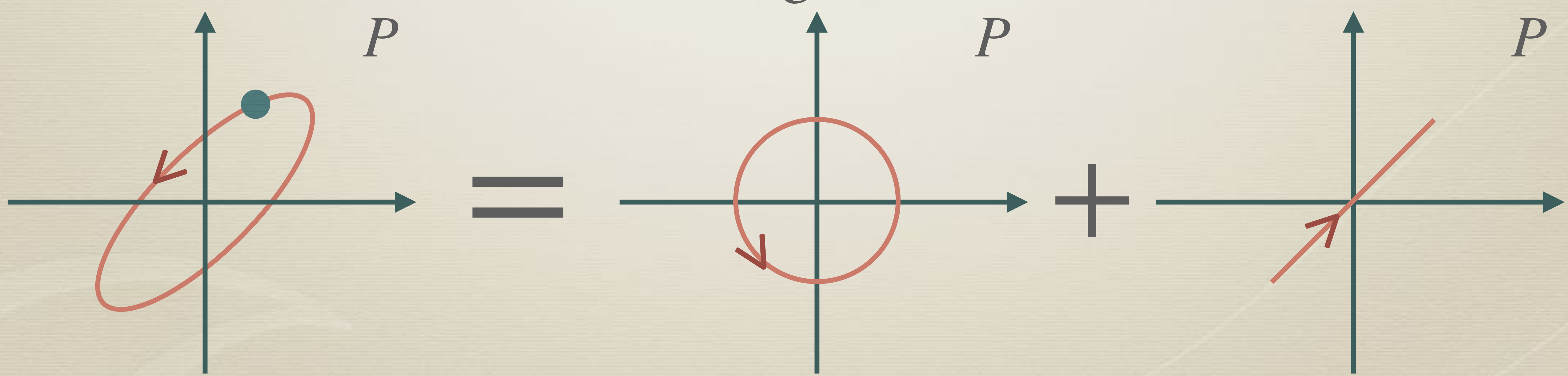
Thermalization

Kinetic Misalignment Mechanism

Produce entropy, should be dissipated early enough

angular

radial



Stability of the angular mode

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

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

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

Stability of the angular mode

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

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

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

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

Most of the charge in the rotation

Laine and Shaposhnikov (1998)
Co and KH (2019)

Stability of the angular mode

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

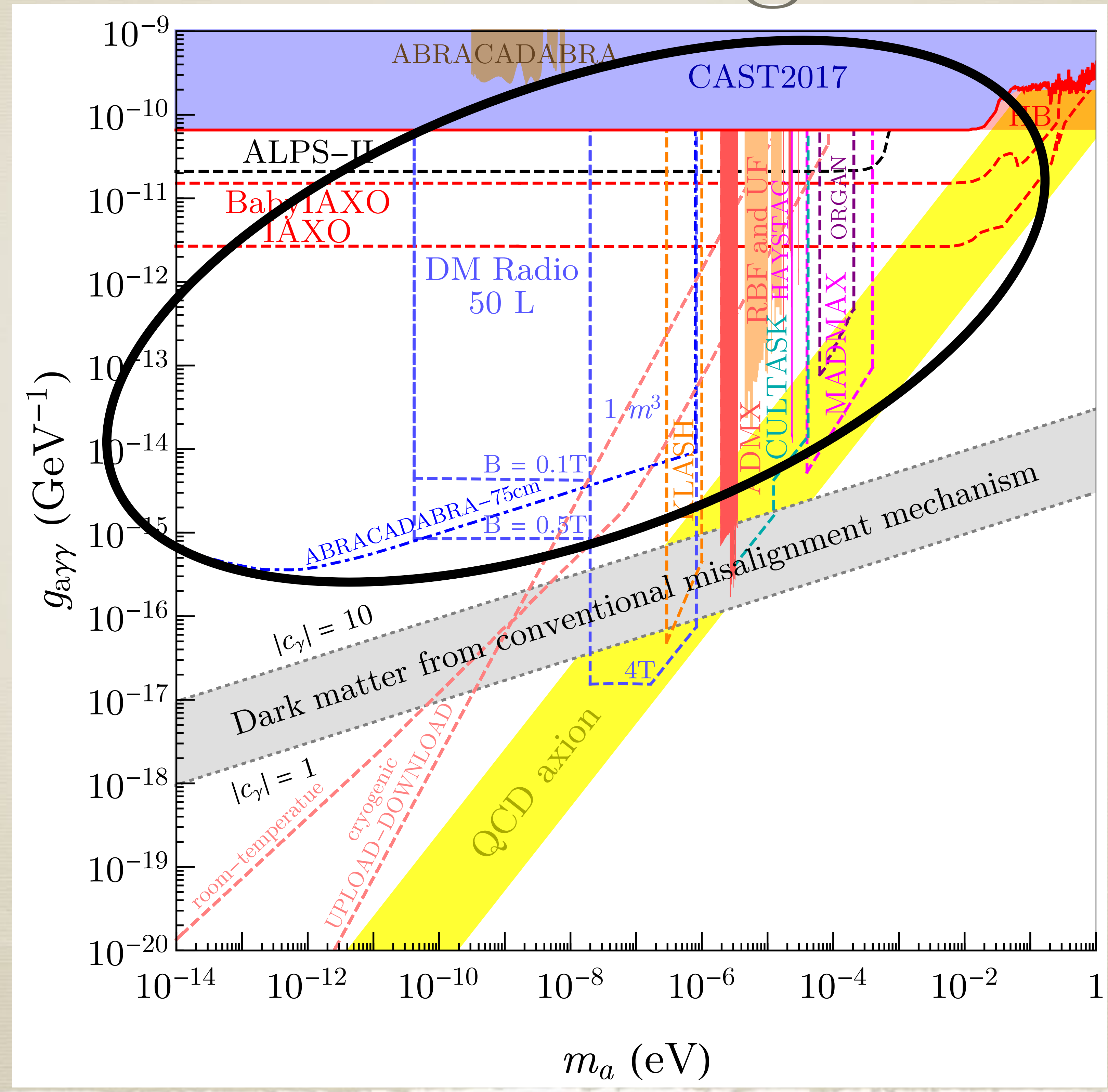
$$\Delta F = \Delta(\rho - Ts) \sim \quad + \frac{\Delta n^2}{T^2} \quad - \dot{\theta} \Delta n$$

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

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

This result will be used later in this talk

Kinetic misalignment



Outline

* Introduction: QCD axion and dark matter
* Dark matter from axion rotation
* Baryon asymmetry from axion rotation
* Kination from axion rotation
* Summary

Axiogenesis

Co and KH (2019)

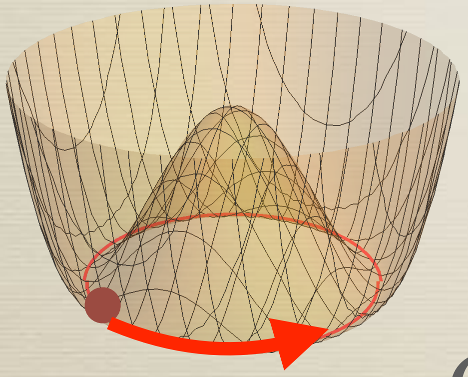
The PQ symmetry is quantum mechanically broken
by the QCD interaction (anomaly)

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

+

So is the quark chiral symmetry

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



$\boxed{\text{PQ}} \xrightarrow{\text{QCD}} \boxed{\text{Chiral charge}}$ $\quad \boxed{\text{Baryon}}$

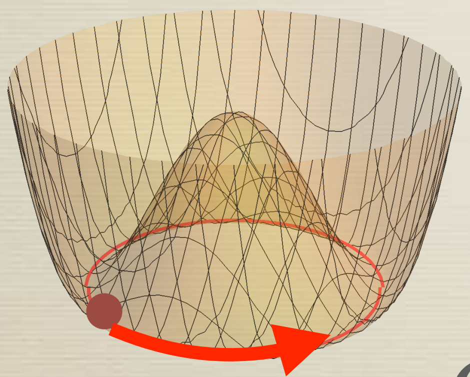
Axiogenesis

Co and KH (2019)

Baryon number violation from

SM : Weak sphaleron process
BSM : Majorana neutrino mass, RPV,
any BSM that you like and contains $\cancel{B}$

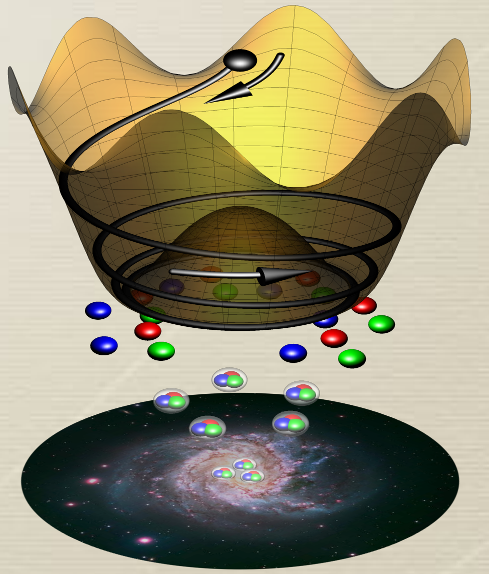
$$\Downarrow$$



$$\boxed{\text{PQ}} \xrightarrow{\text{QCD}} \boxed{\text{Chiral charge}} \xrightarrow{\cancel{B}} \boxed{\text{Baryon}}$$

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?
* ....



B violation

* Electroweak sphaleron : Minimal axiogenesis

  will be explained in detail

* Baryon number violation from BSM

  will be introduced briefly

Minimal axiogenesis

Co and KH (2019)

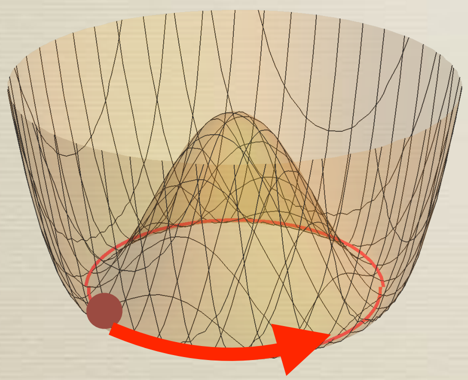
Chiral charge

QCD

weak

PQ

B+L



Transfer processes are effective before
the electroweak phase transition.
B at thermal eq.

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

Minimal axiogenesis

Co and KH (2019)

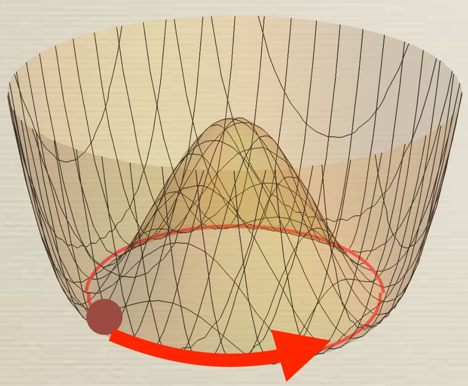
Chiral charge

QCD

weak

PQ

B+L



weak interaction becomes ineffective
after electroweak phase transition

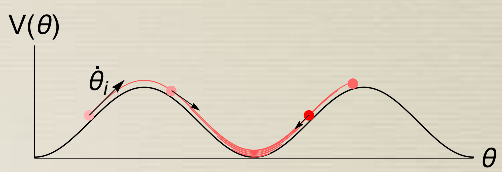
$$n_B|_{\rm EW} \simeq 0.1\dot{\theta}|_{\rm EW}T_{\rm EW}^2$$

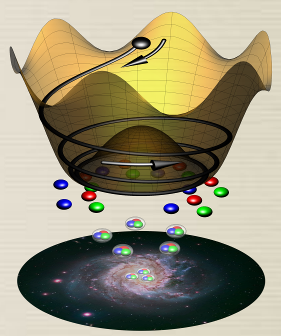
Minimal axiogenesis

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

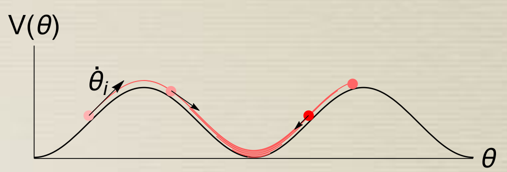
Does not work for the standard electroweak phase transition

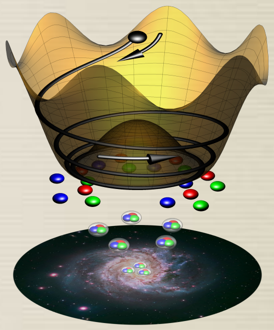
Minimal axiogenesis

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

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

Astrophysical lower bound $f_a > 10^8$ GeV

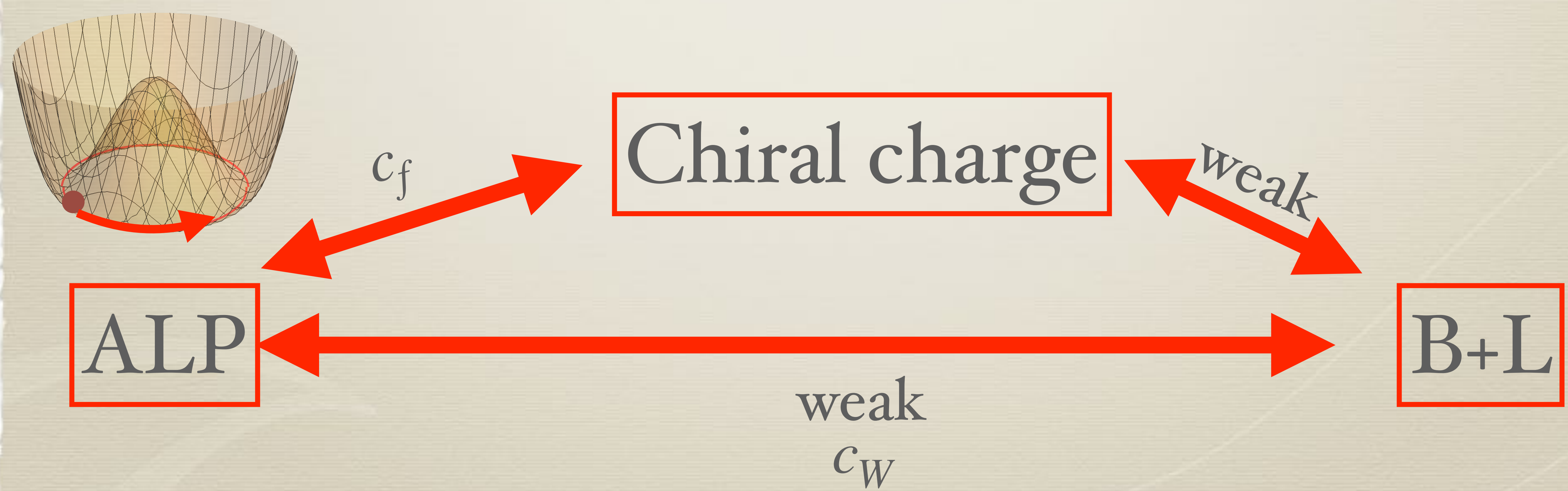
Electroweak ⟷ QCD axion

ALP genesis

Co, Hall and KH (2020)

A similar mechanism works for generic ALPs

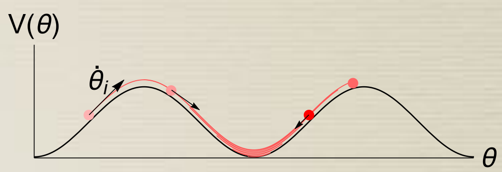
$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \sum_{f,i,j} c_{f_{ij}}\, f_i^\dagger \bar{\sigma}^\mu f_j + \frac{a}{64\pi^2 f_a} \left(c_W g^2\, W^{\mu\nu} \tilde{W}_{\mu\nu} \right)$$



ALP cogenesis

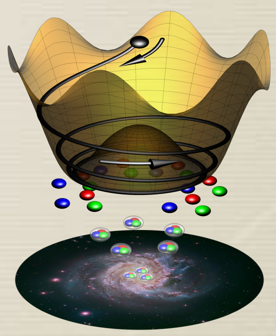
Co, Hall and KH (2020)

Assuming the standard EW phase transition,



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

1. Dark Matter
2. Baryon asymmetry

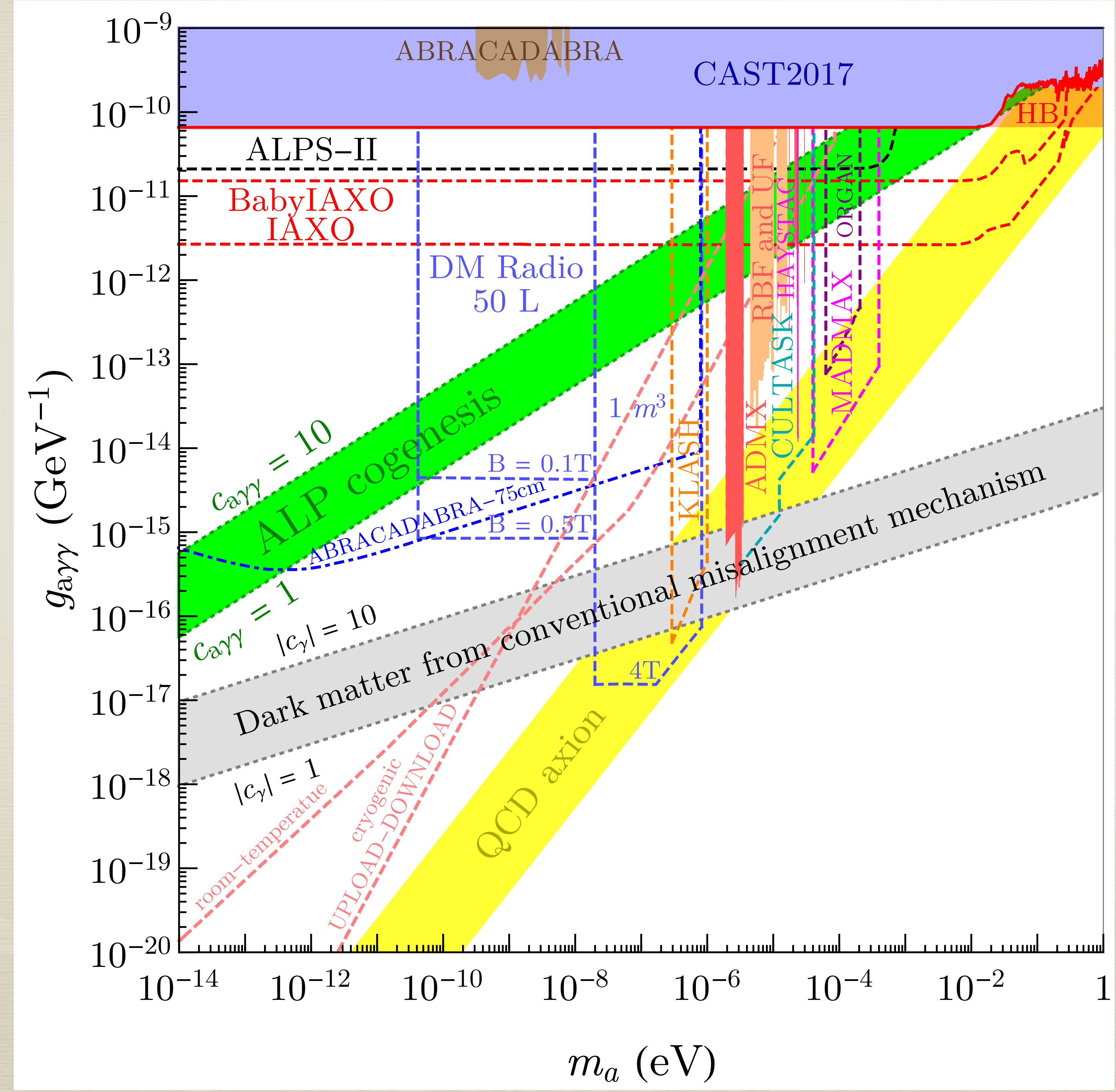


3 free parameters – 2 densities to fit
= 1 free parameter

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

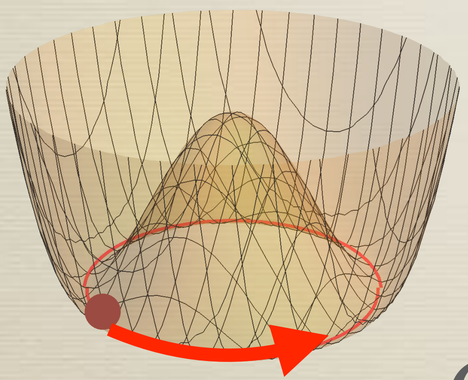
Prediction on the ALP coupling

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



B violation from BSM

* Majorana neutrino mass
* R-parity violation in supersymmetric theory
* What you like

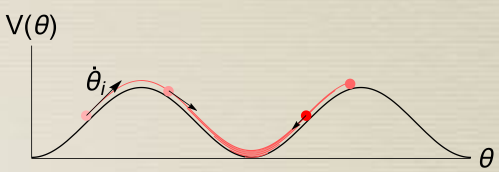


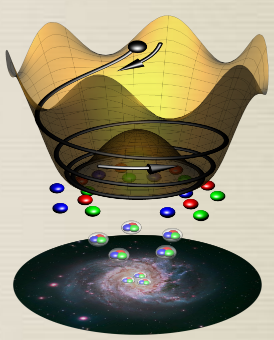
$$\boxed{\text{PQ}} \xrightarrow{\text{QCD}} \boxed{\text{Chiral charge}} \xrightarrow{\cancel{\text{B}}} \boxed{\text{Baryon}}$$

B violation from BSM

1. Angular velocity
2. Decay constant
3. BSM parameters

1. Dark Matter
2. Baryon asymmetry





One relation among BSM parameters and f_a

BSM ⟷ QCD axion

B violation from BSM

* Majorana neutrino mass

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

  Mass of the radial direction (= scalar scale in SUSY)

* Baryon number violation in supersymmetric model (RPV)

  Co, KH, Johnson and Pierce (2021)

  Magnitude of RPV and scalar masses.
  For dimensionless RPV, assuming SU(5) relation, proton decay

* Sphaleron processes in new gauge interaction

  KH and Wang (2021)

  Mass of new gauge bosons

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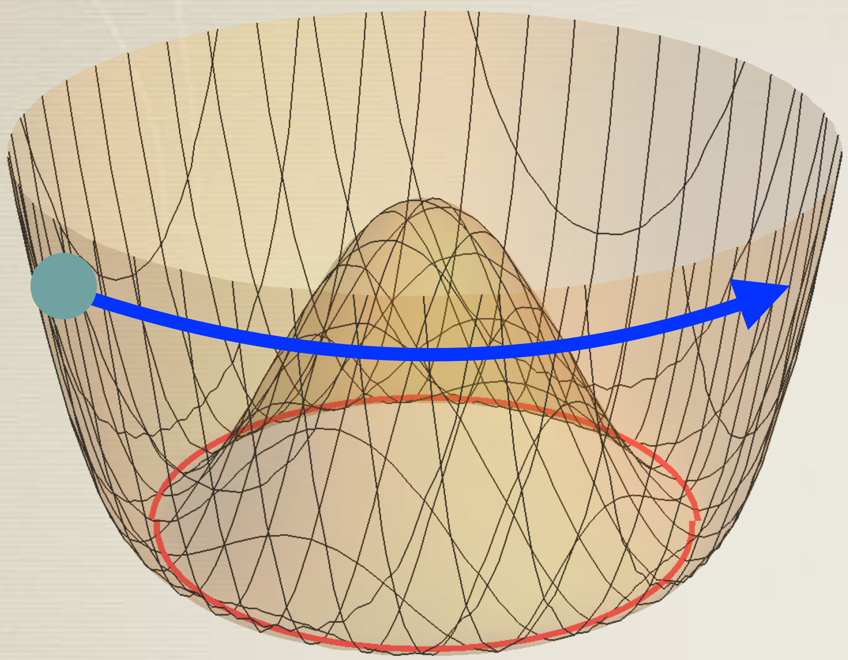
Equation of state of rotations

Co and KH (2019)



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

$$\dot{\theta} S^2 \propto R^{-3}$$

SUSY

If the potential of S is nearly quadratic,

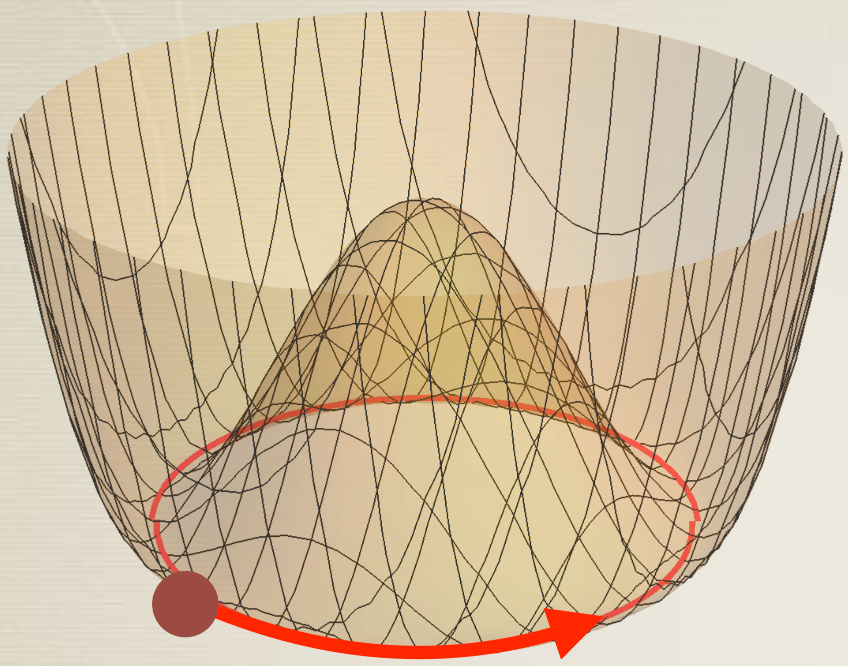
$$\dot{\theta} = \text{const}, \quad S^2 \propto R^{-3}$$

$$\rho = \dot{\theta}^2 S^2 \propto R^{-3}$$

matter

Equation of state of rotations

Co and KH (2019)



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

$$\dot{\theta} S^2 \simeq \dot{\theta} f_a^2 \propto R^{-3}$$

$$\dot{\theta} \propto R^{-3}, \quad S^2 = f_a^2$$

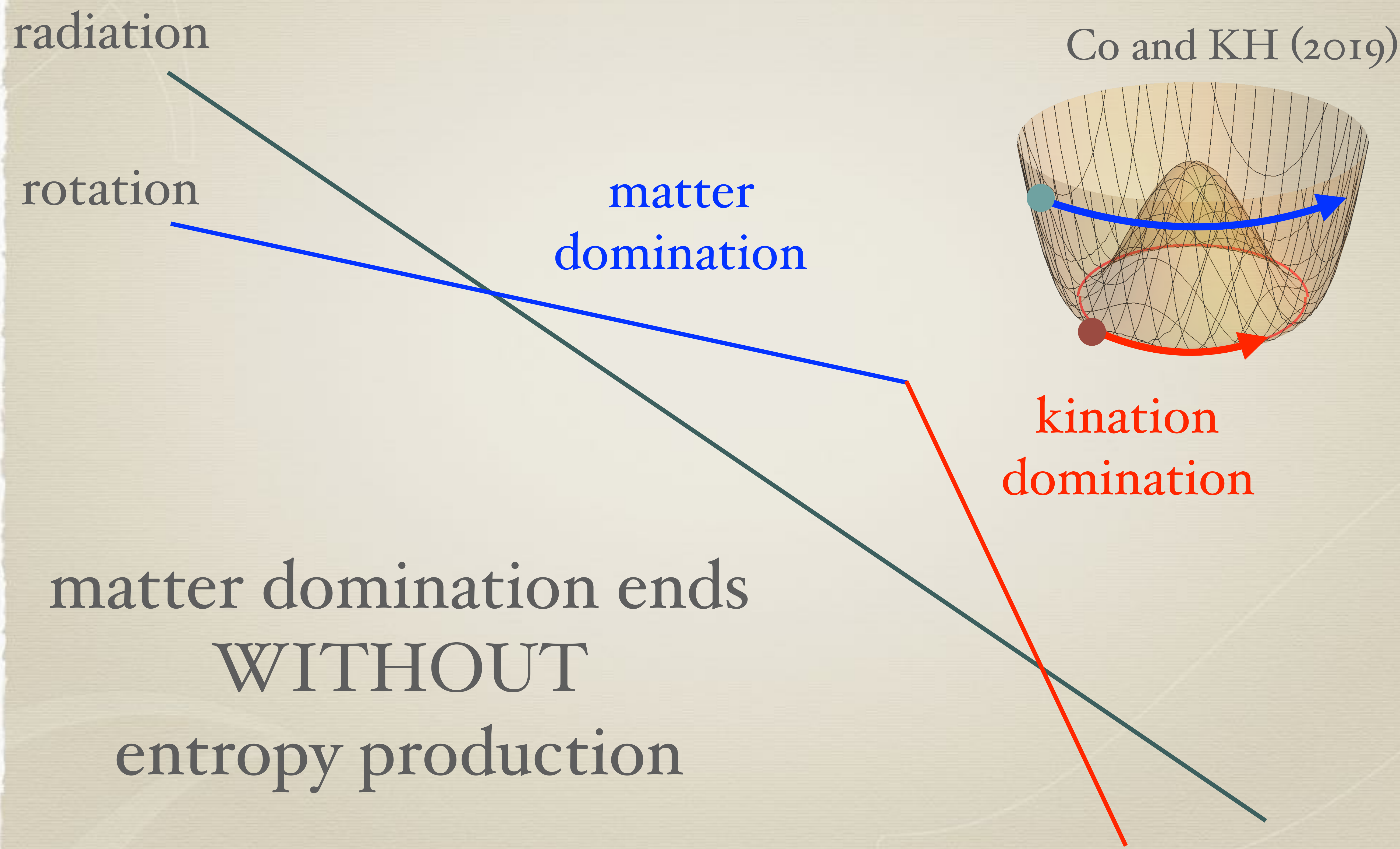
$$\rho = \dot{\theta}^2 S^2 \propto R^{-6}$$

kination

Axion energy is dominantly from the kinetic term

Axion kination

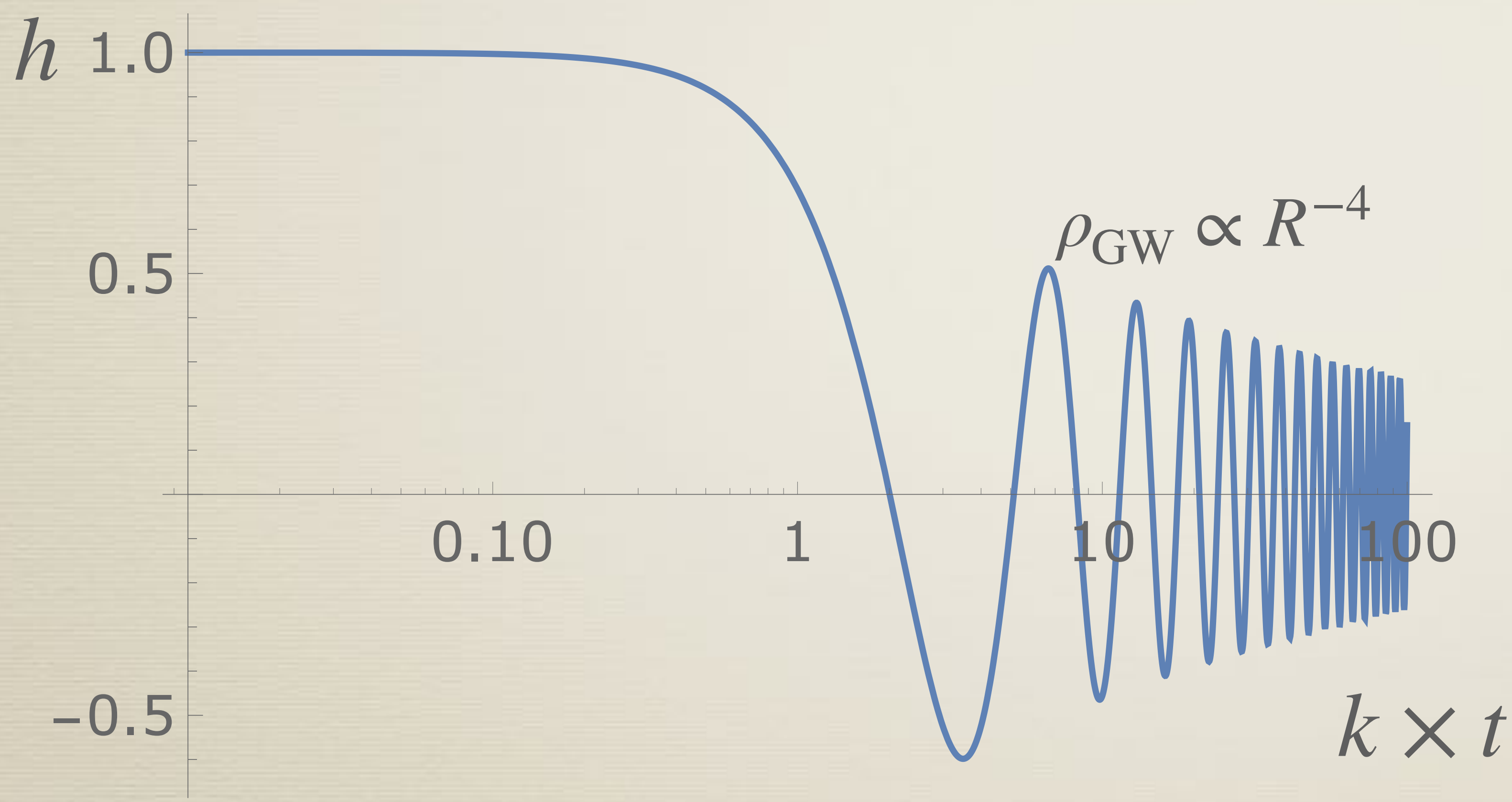
Co and KH (2019)



matter domination ends
WITHOUT
entropy production

Effect on primordial gravitational waves

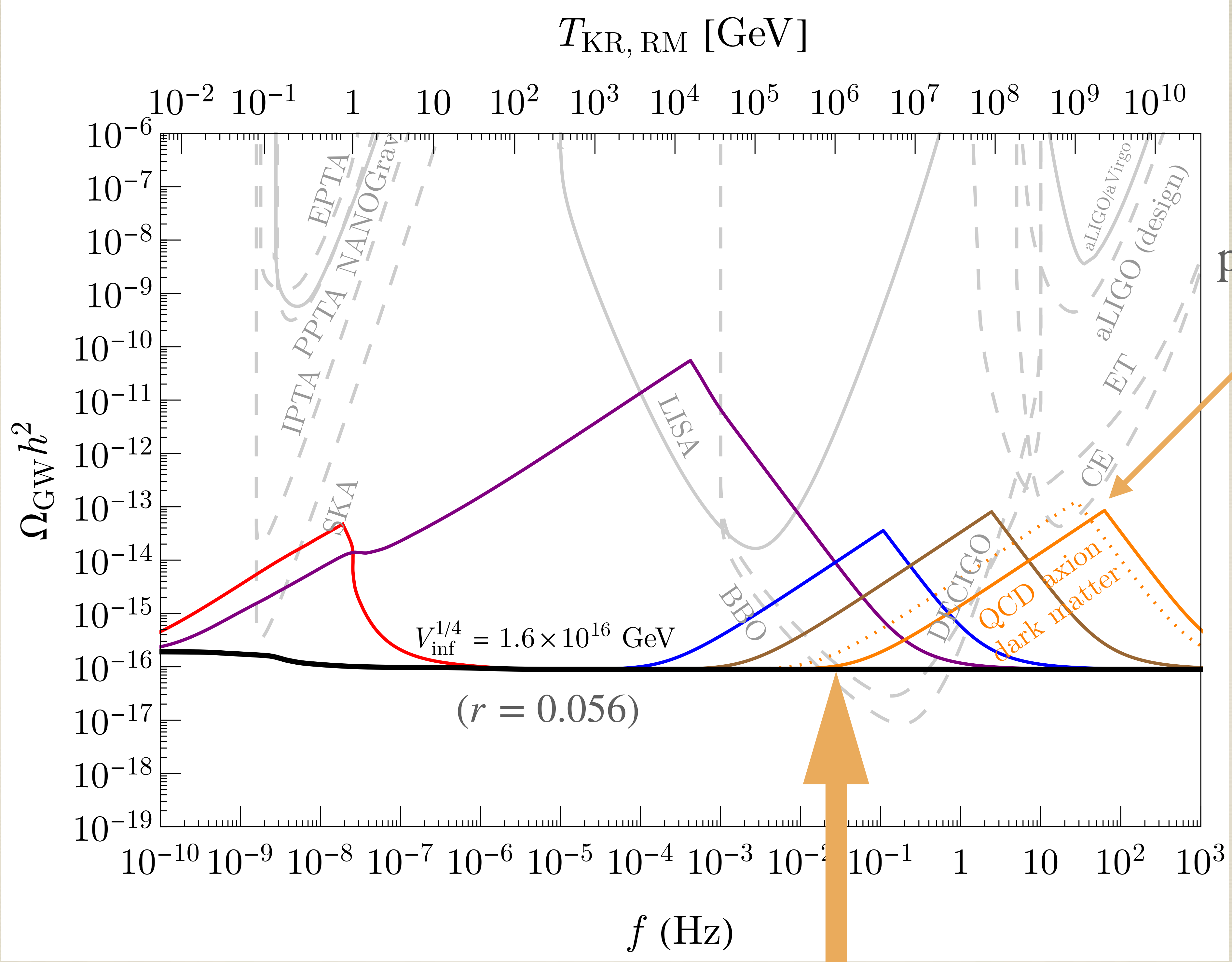
ex. inflationary gravitational waves



$$\frac{\rho_{\rm GW}(k)}{\rho_\gamma} \sim \left(\frac{k^2 h^2 M_{\rm pl}^2}{\rho_\gamma} \right)_{k=H}$$

$$\propto \left(\frac{\rho_{\rm tot}}{\rho_\gamma} \right)_{k=H}$$

enhanced if the mode enters the horizon ($k \sim H$)
when the rotation dominates



peak position depends on $m_S f_a$

Co, Dunsky, Fernandez, Ghalsasi, Hall, KH and Shelton (2021)
Gouttenoire, Servant and Simakachorn (2021)

For the QCD axion, modification can occur at $f \gtrsim 0.01$ Hz
(If kination lasts longer, dark matter is overproduced)

Summary

* Kinetic Misalignment : Rotation of the axion field produces axion dark matter

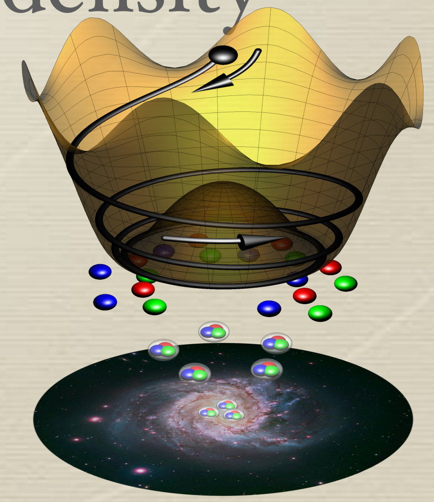
  Axion dark matter with a decay constant
  $$f_a \ll 10^{11}\ \mathrm{GeV}$$

* Axiogenesis : Axion rotation produces baryon asymmetry

  A relation between BSM parameters and f_a

* Axion kination : Axion rotation dominates the energy density of the universe

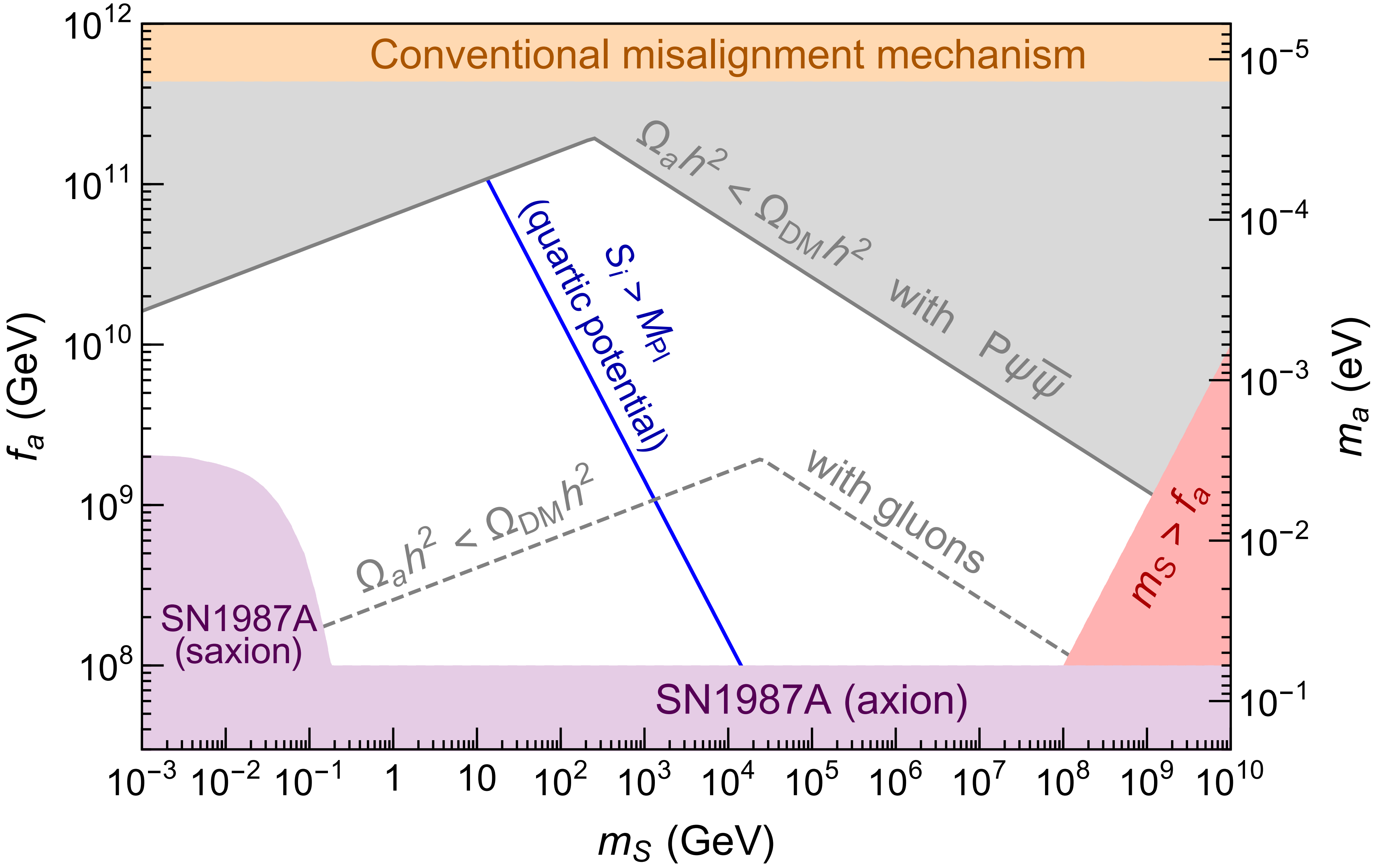
  Imprint on gravitational wave spectrum



Back up

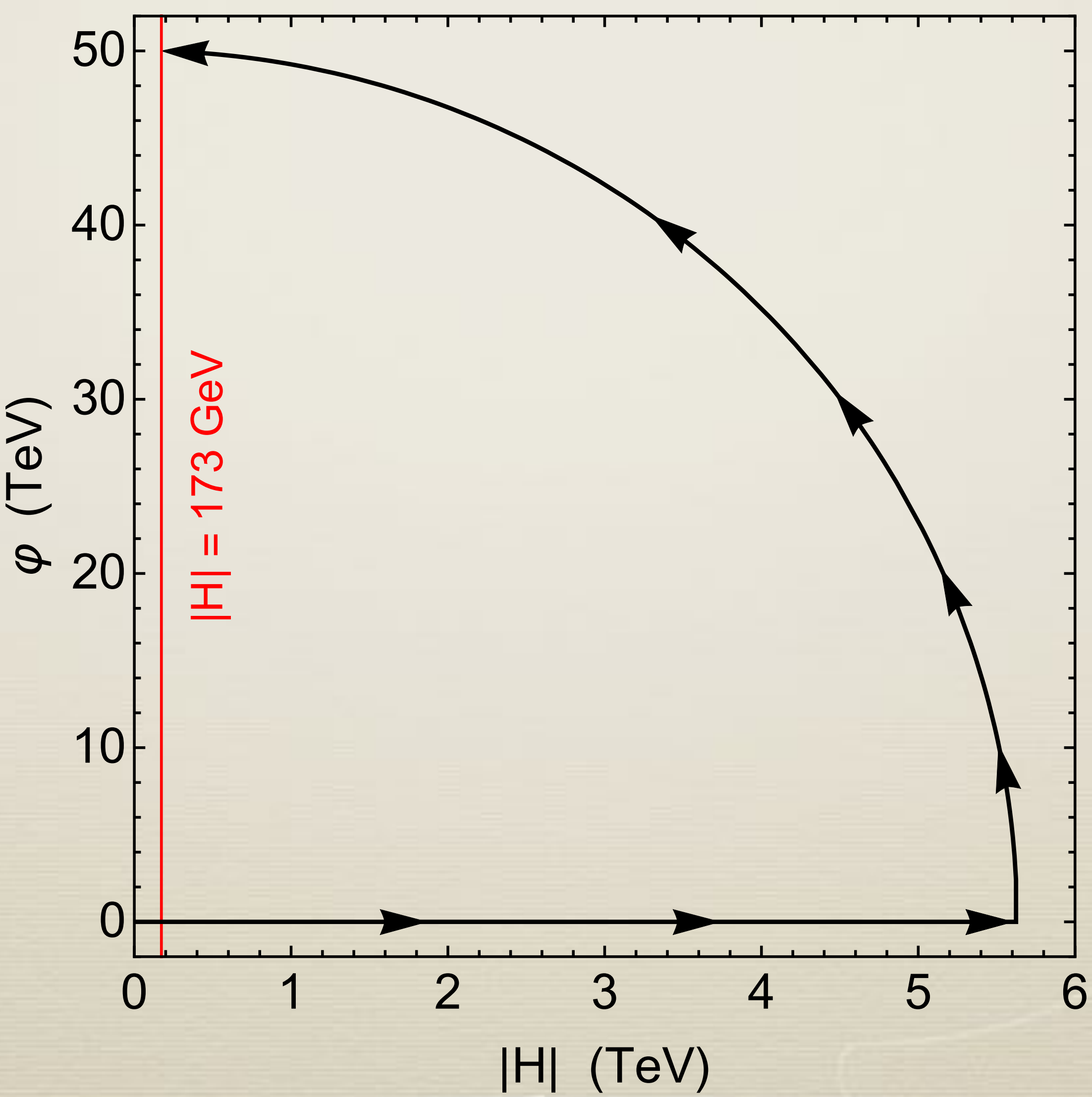
Thermalization

Co, Hall and KH (2019)



Earlier EW phase transition

$$V(H,\varphi) = \lambda_H^2 \left(|H^2| - v^2 \right)^2 + \kappa^2 \left(\varphi^2 - v_\varphi^2 \right)^2 + \lambda^2 \left(\varphi^2 - v_\varphi^2 \right) \left(|H|^2 - v^2 \right)$$
$$+ c_H T^2 |H|^2 + c_\varphi T^2 \varphi^2 \, .$$



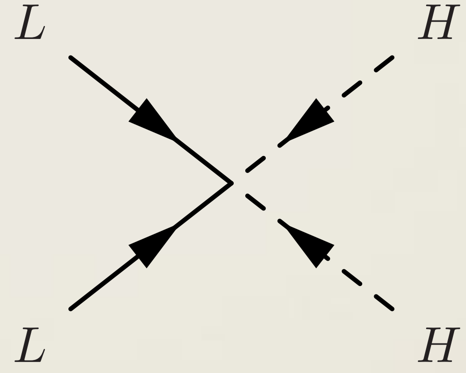
Lepto-axiogenesis

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

Majorana neutrino mass

Majorana neutrino masses break the lepton symmetry

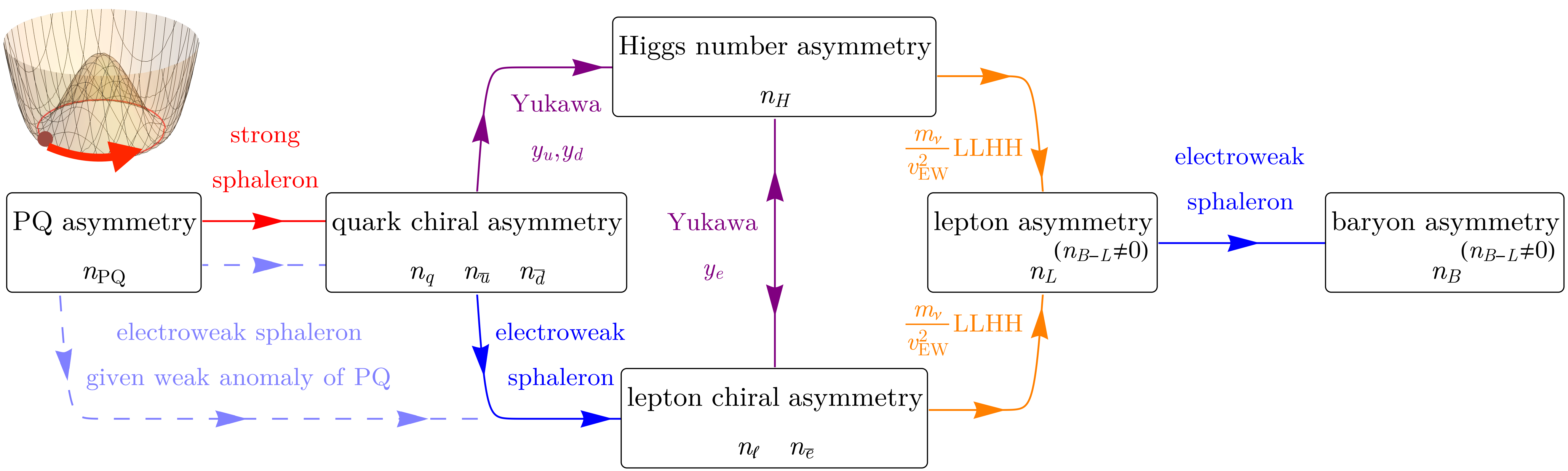
$$\frac{1}{M}LLHH$$



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

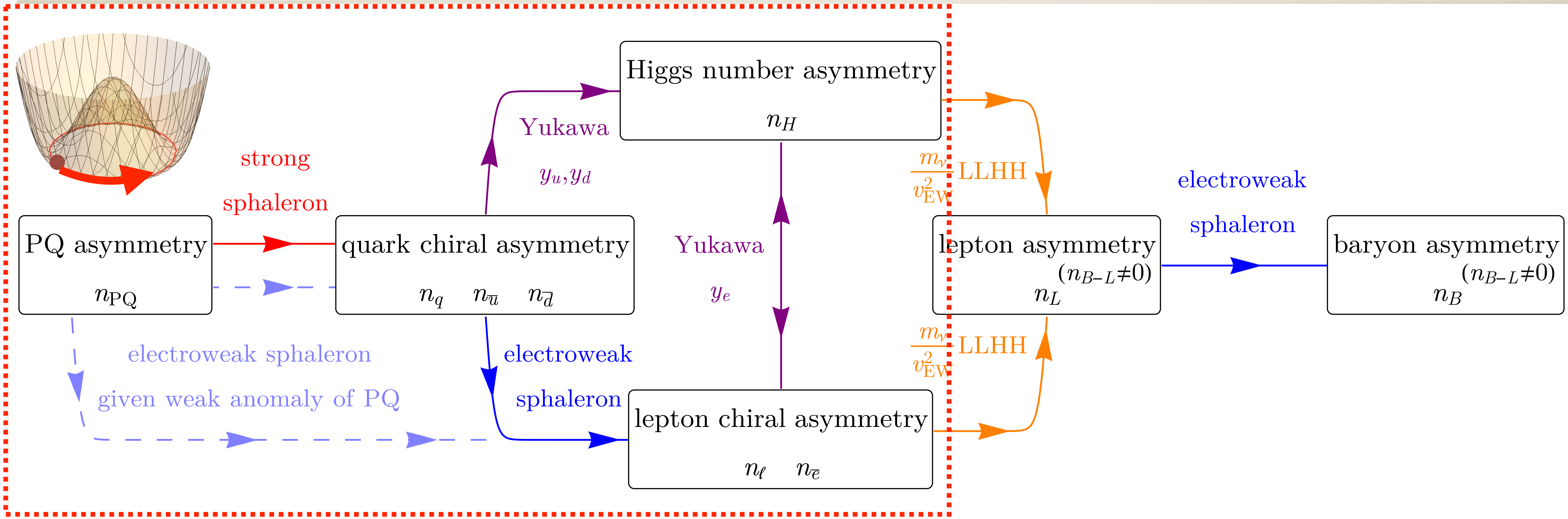
Charge flow

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



Charge flow

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

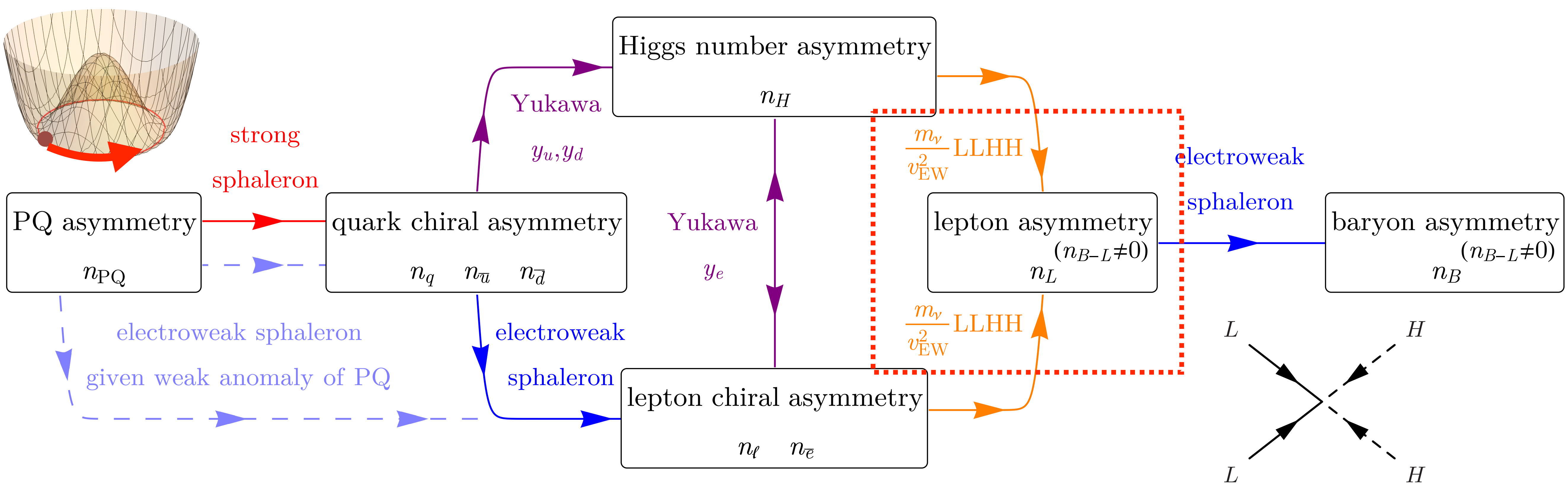


efficient and
reaches equilibrium

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

Charge flow

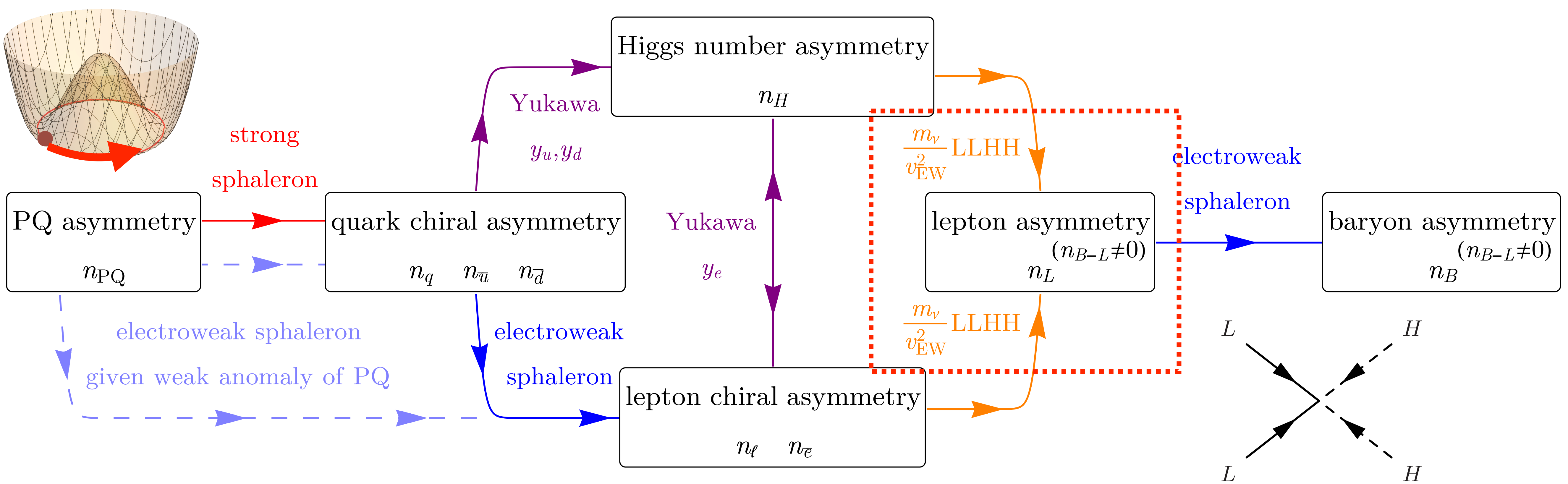
Co, Fernandez, Ghalsasi, Hall and KH (2020)



At high temperatures $\quad \frac{n_{B-L}}{s}\Big|_{\rm eq} \simeq \frac{\dot{\theta} T^2}{s}$ $\qquad \Gamma_L \sim \frac{m_\nu^2}{v_{\rm EW}^4} T^3$

Charge flow

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



not efficient at
low temperatures

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

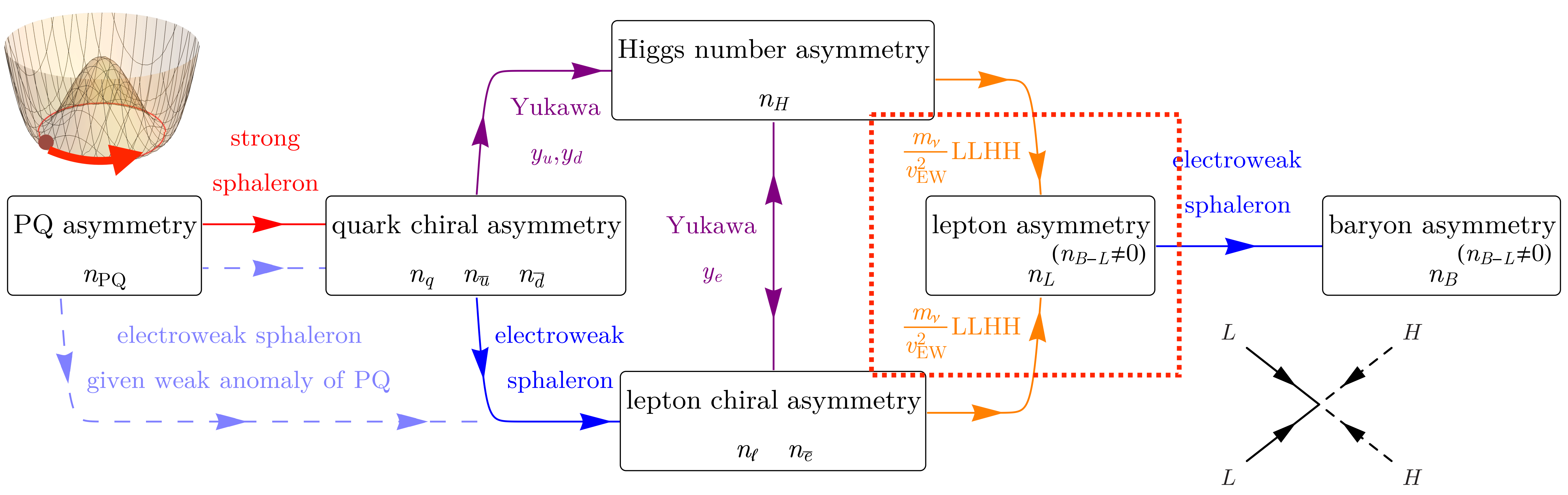
$$\propto \dot{\theta} \times T^0$$

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

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

Charge flow

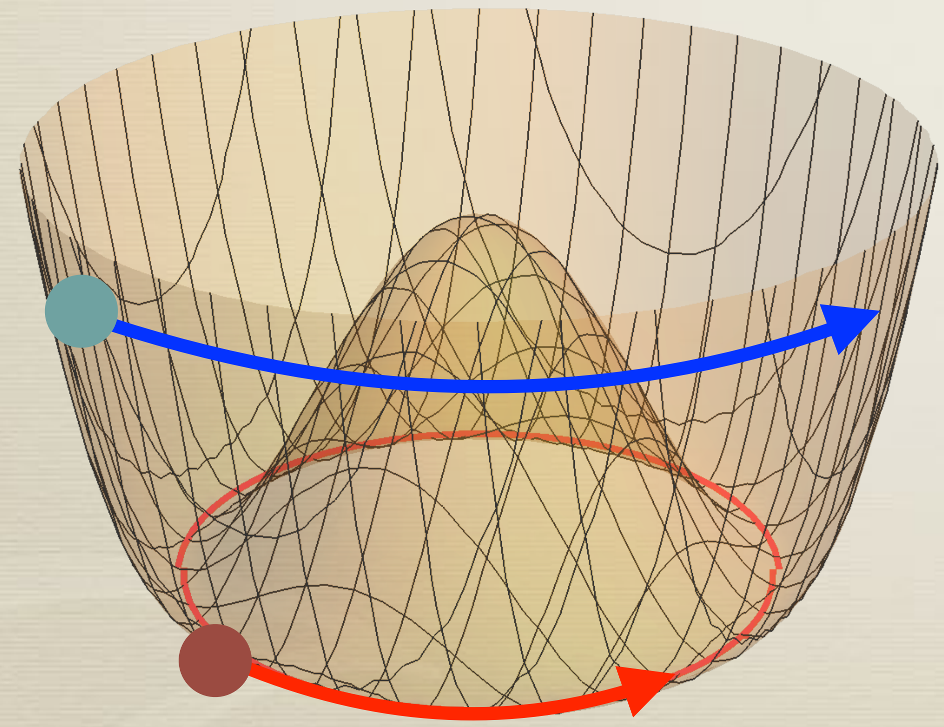
Co, Fernandez, Ghalsasi, Hall and KH (2020)



$$\frac{\Delta n_{B-L}}{s} \simeq \frac{\dot{\theta} T^2}{s} \times \frac{\Gamma_L}{H} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \mathrm{TeV}} \frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$

Angular velocity?

$$\frac{\Delta n_B}{s} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \mathrm{TeV}} \frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$



Early time

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

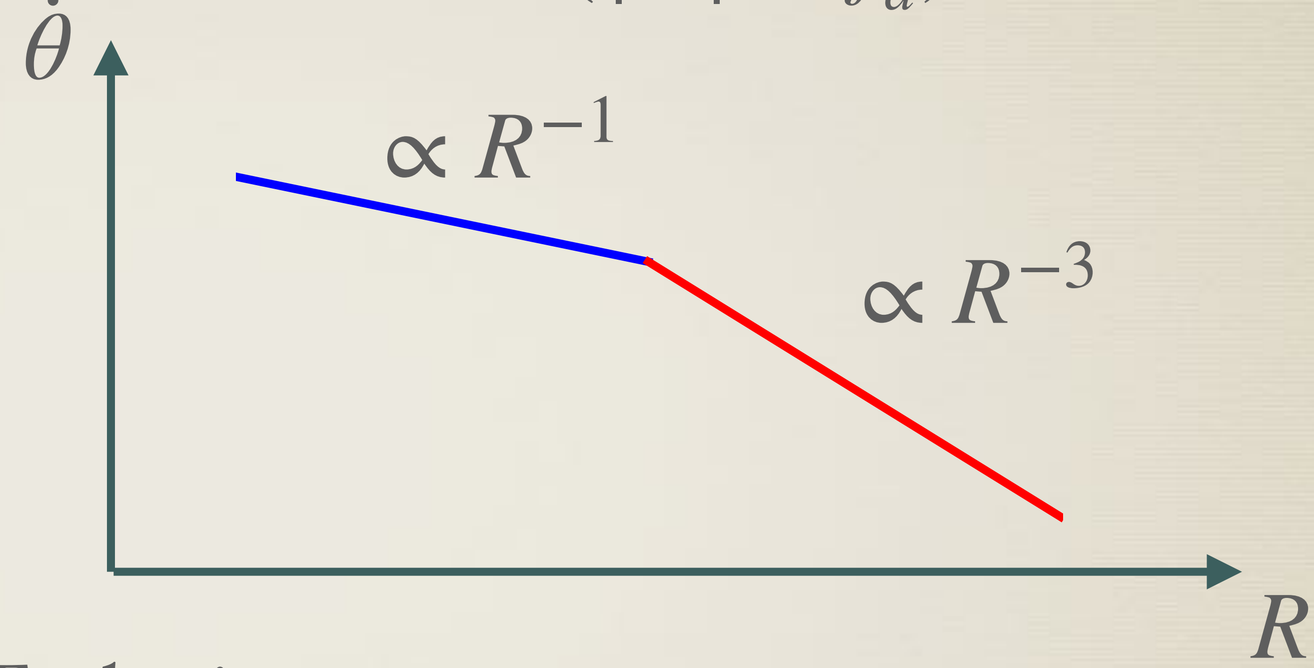
Around the electroweak phase transition

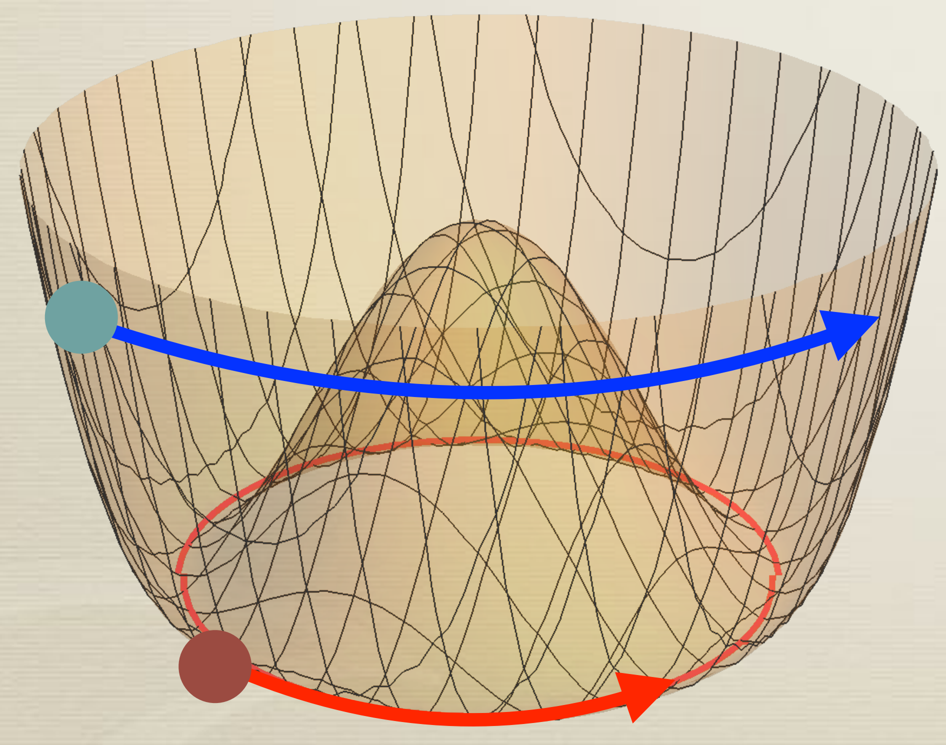
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

$$\frac{\Delta n_B}{s} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \mathrm{TeV}} \frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$

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





Early time

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

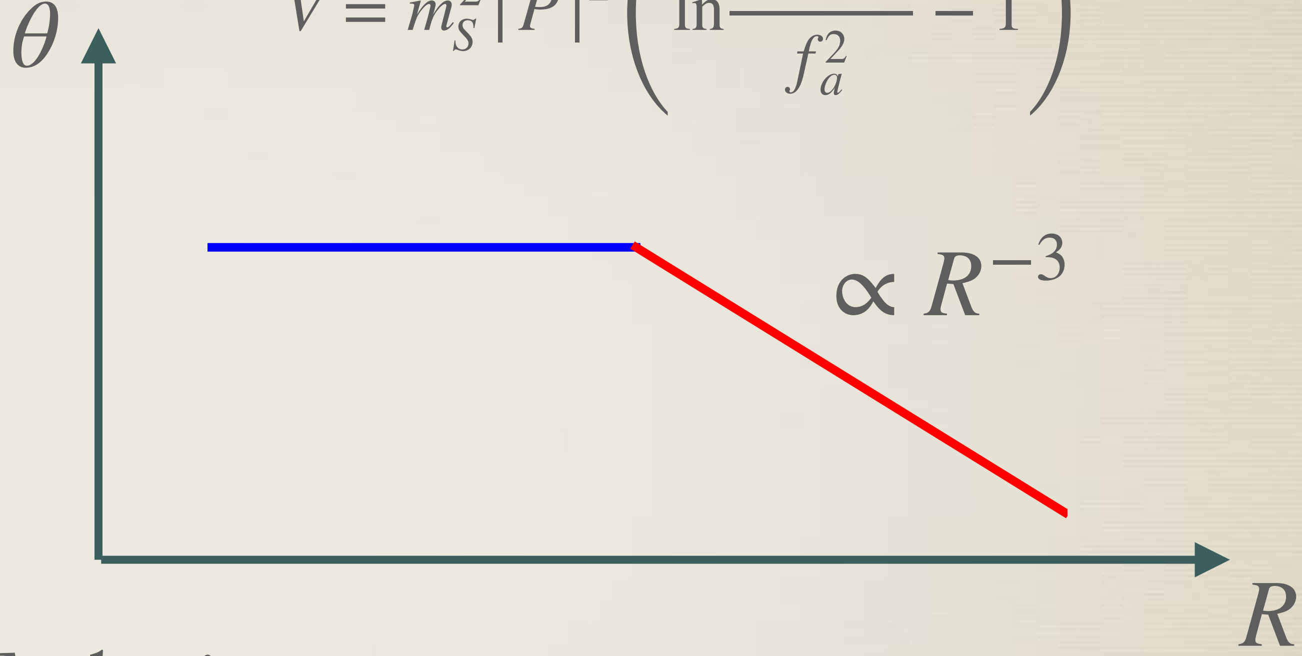
Around the electroweak phase transition

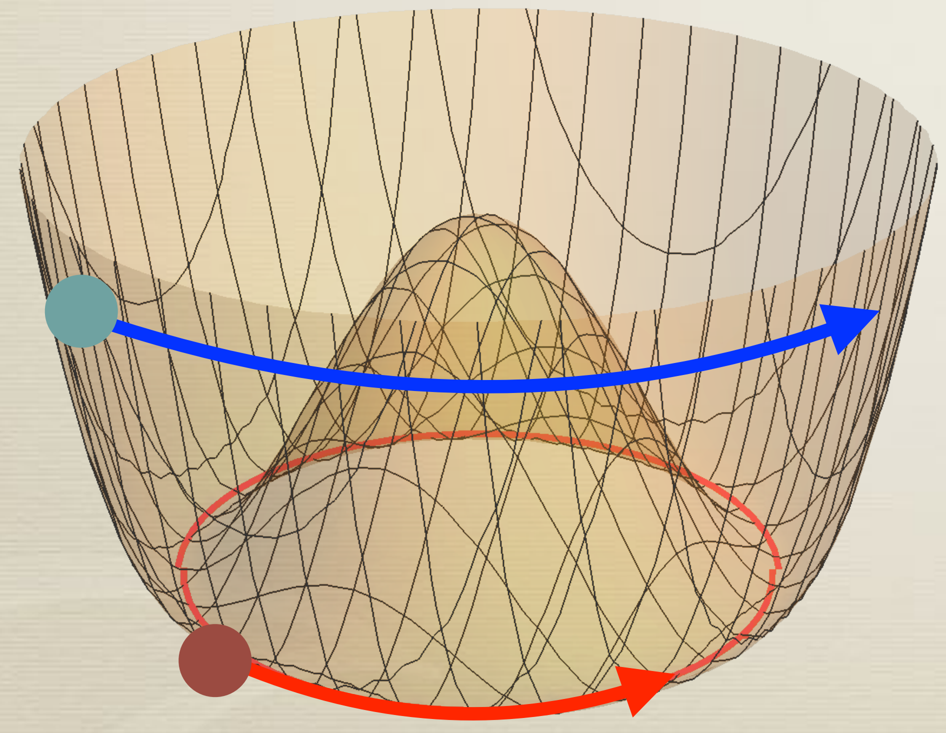
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

$$\frac{\Delta n_B}{s} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \mathrm{TeV}} \frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$

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





Early time

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

Around the electroweak phase transition

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

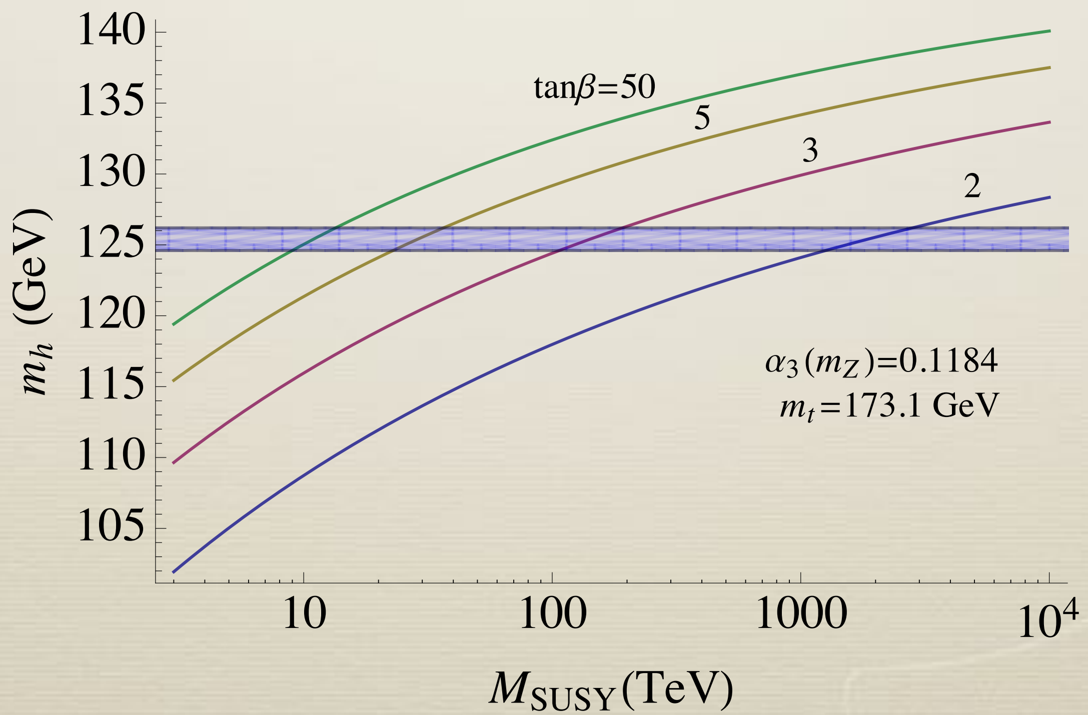
Supersymmetry

$$\frac{\Delta n_B}{s} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \mathrm{TeV}} \frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$

In supersymmetric models,

$$m_{\mathrm{SUSY,scalar}} \sim m_S \sim \dot{\theta} \sim 10 - 1000\ \mathrm{TeV}$$

Consistent with the Higgs mass



Supersymmetry

$$\frac{\Delta n_B}{s} \simeq 10^{-11} \frac{\dot{\theta}}{10\ \text{TeV}} \frac{\sum m_\nu^2}{0.03\text{eV}^2}$$

In supersymmetric models,

$$m_{\text{SUSY,scalar}} \sim m_S \sim \dot{\theta} \sim 10 - 1000\ \text{TeV}$$

Consistent with the without-singlets scenarios

Giudice, Luty, Murayama, Rattazzi (1998)

"Mini-split SUSY," "Spreads SUSY," "Pure-gravity mediation,"...

- gaugino masses are given by anomaly mediation, ~ TeV
- no moduli problem from singlet SUSY breaking fields
- no gravitino problem

New perspective on SUSY scale

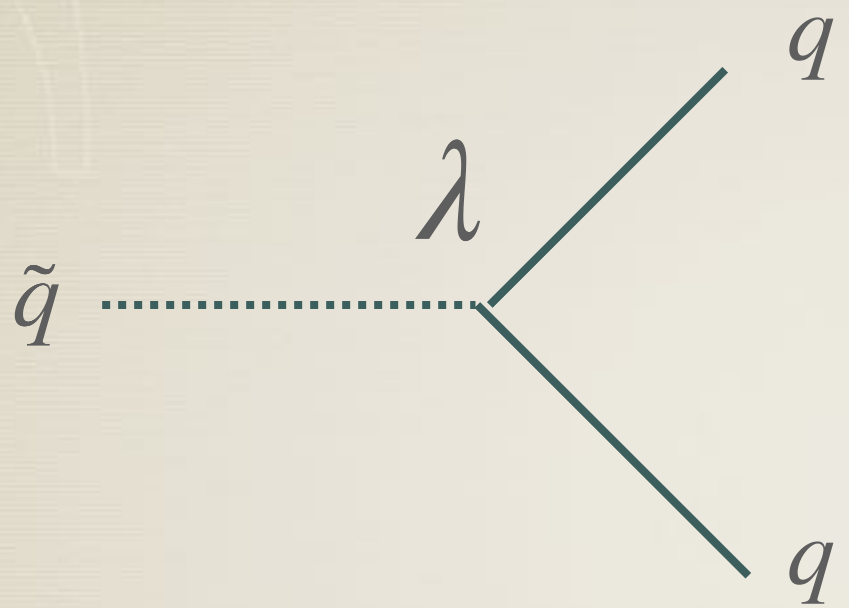
- Electroweak hierarchy $m_{\rm SUSY} \sim 100$ GeV
- Gauge coupling unification $m_{\rm SUSY} \lesssim 10^6$ GeV
- Lightest supersymmetric particle as DM $m_{\rm SUSY} \lesssim 10^3$ GeV
  (invalid with RPV)
- Baryogenesis from axion rotation and neutrino mass

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

RPV axiogenesis

Co, KH, Johnson and Pierce (2021)

R-parity violation



$\lambda, \mu', m_{\text{scalar}}, f_a$ are constrained by DM and baryon densities

possible signals: proton decay, decay of the lightest supersymmetric particle

Ex. SU(5) texture

Consider the case with dimensionless RPV with SU(5) relation

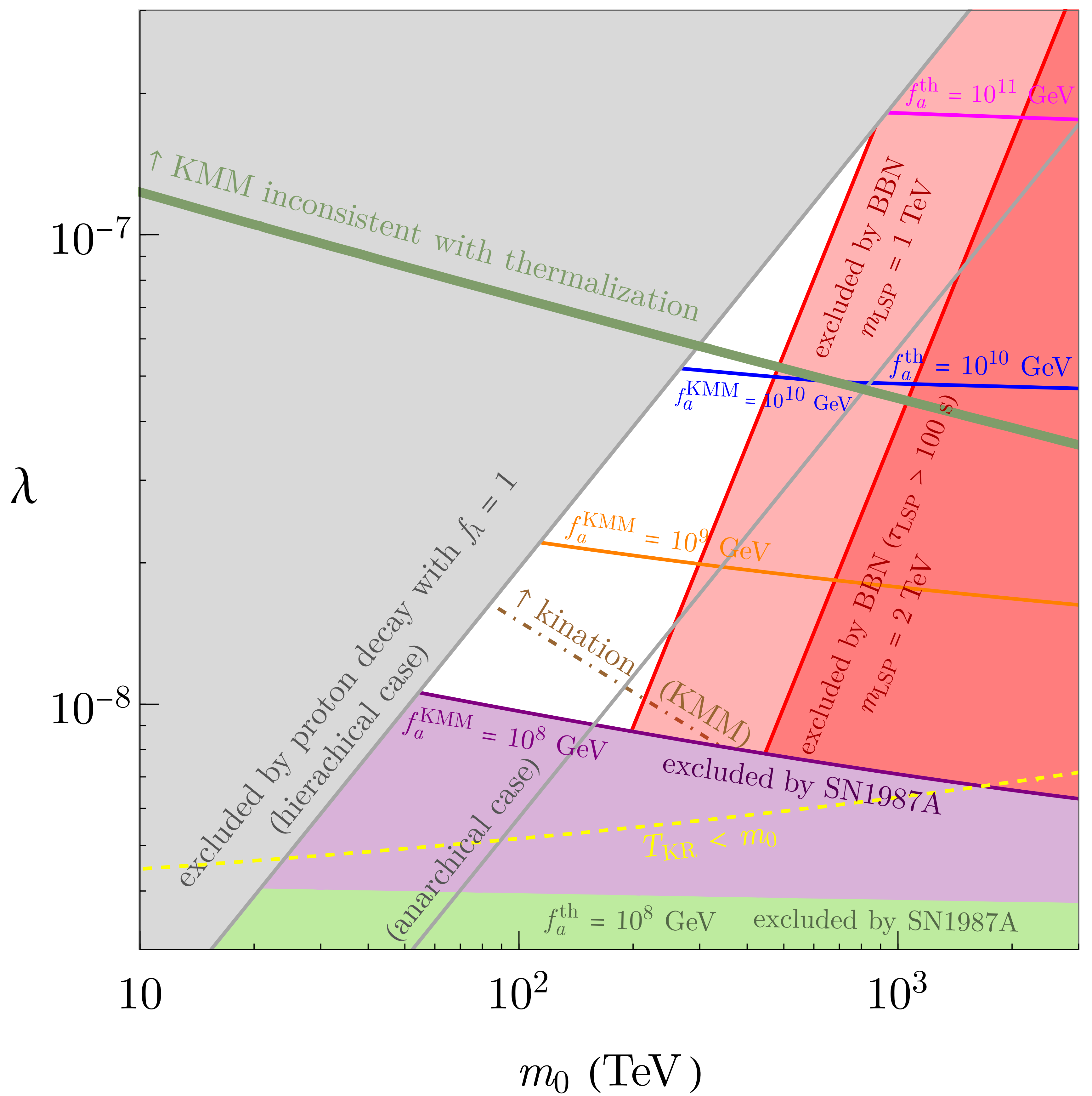
$$W = \frac{1}{2}\lambda_{ijk} 10_i \bar{5}_k \bar{5}_k = \lambda_{ijk}(Q_i \bar{d}_j L_k + \frac{1}{2}\bar{u}_i \bar{d}_j \bar{d}_k + \frac{1}{2}\bar{e}_i L_j L_k)$$

To minimized the proton decay rate,

$$\lambda_{1jk} \sim \theta_{13}^{\mathrm{CKM}} \lambda_{3jk},\ \lambda_{2jk} \sim \theta_{23}^{\mathrm{CKM}} \lambda_{3jk}$$

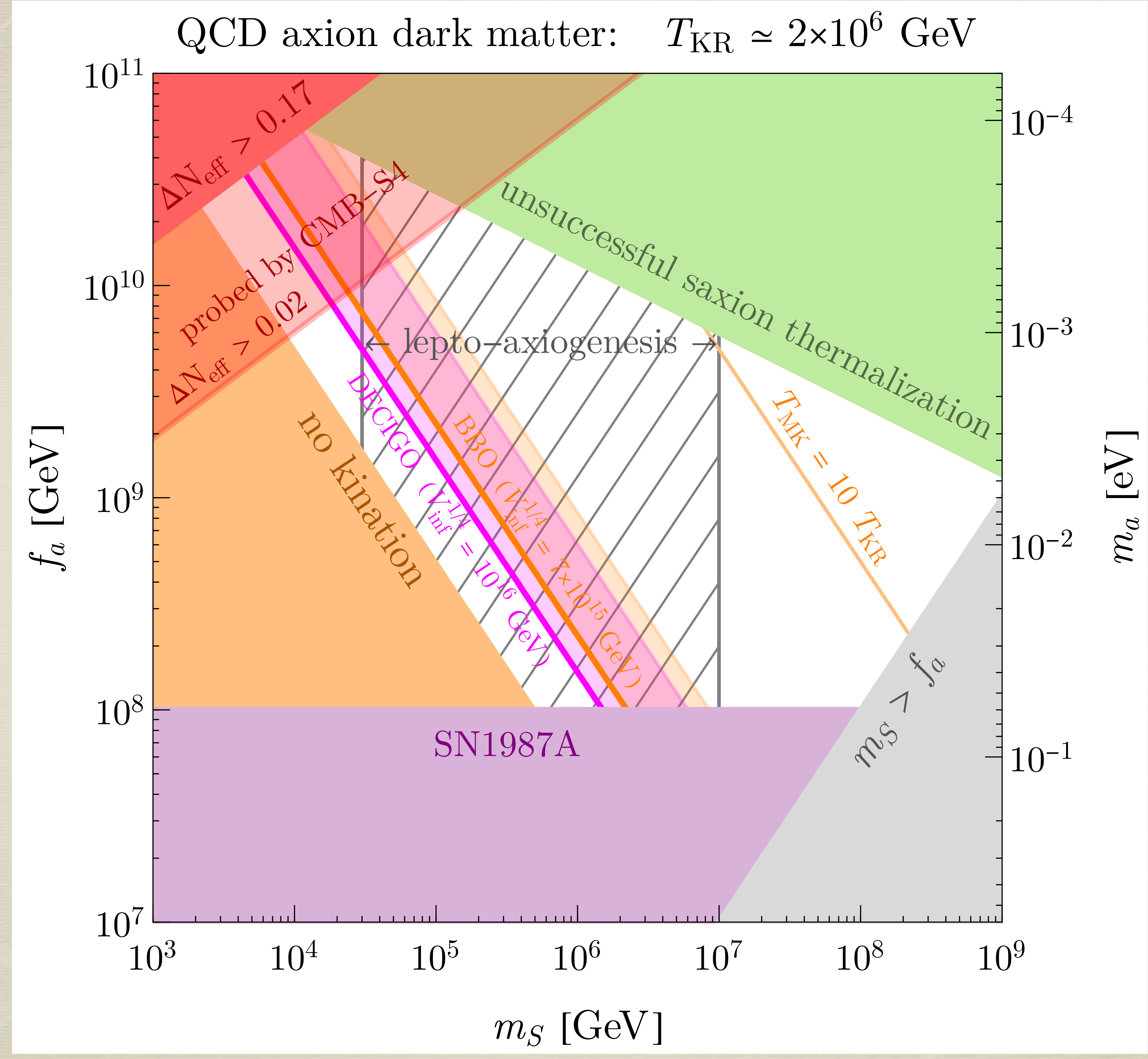
Anarchical 5-plets : $\lambda_{i12} \sim \lambda_{i13} \sim \lambda_{i23}$

Hierarchical 5-plets : $\lambda_{i12}, \lambda_{i13} \ll \lambda_{i23}$

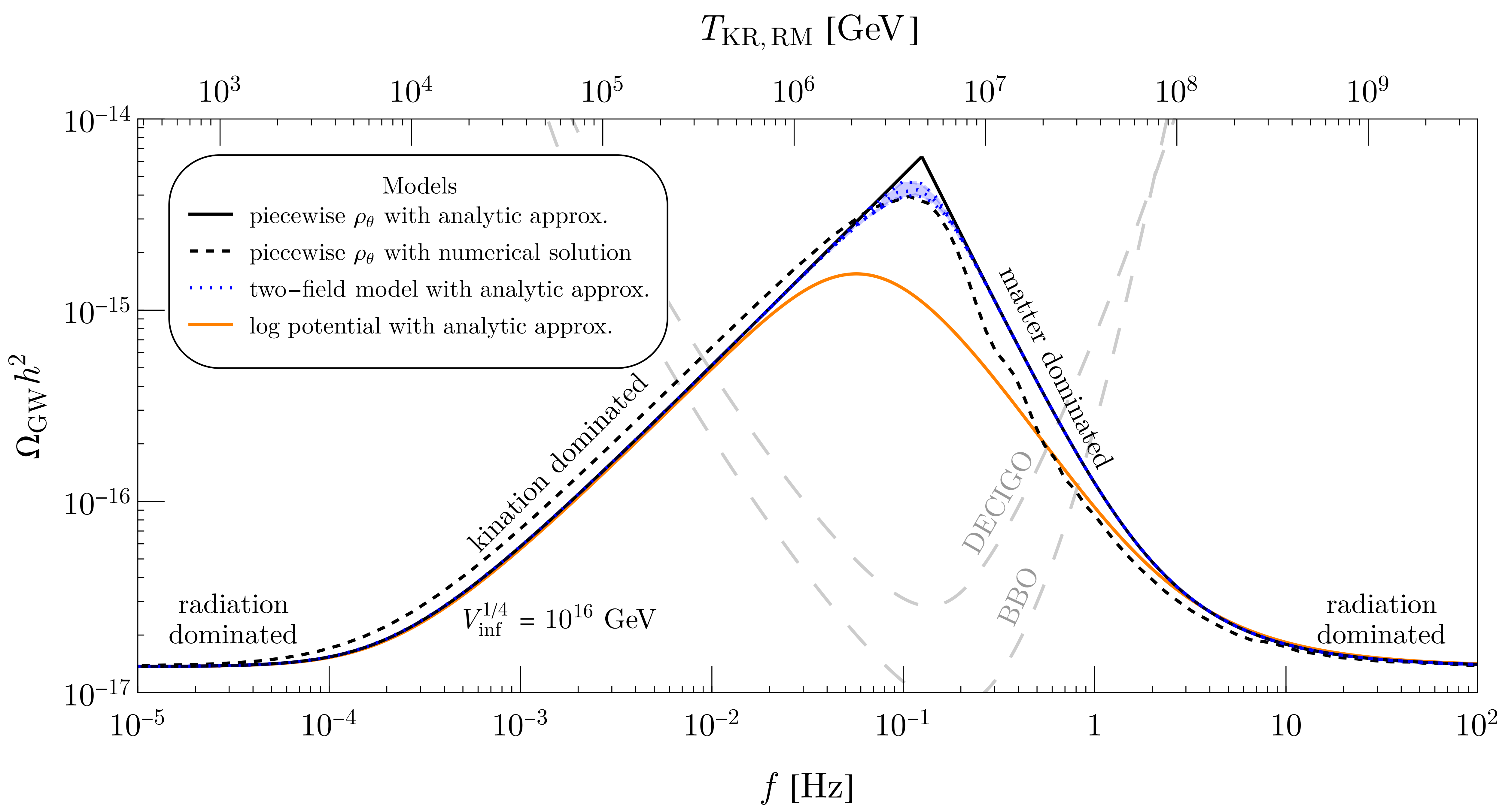


$f_a^{\rm th}$ = 10^{11} GeV
↑ KMM inconsistent with thermalization
10^{-7}
excluded by BBN
$m_{\rm LSP}$ = 1 TeV
$f_a^{\rm th}$ = 10^{10} GeV
$f_a^{\rm KMM}$ = 10^{10} GeV
λ
excluded by proton decay with f_λ = 1
(hierachical case)
$f_a^{\rm KMM}$ = 10^9 GeV
↑ kination
(KMM)
excluded by BBN ($\tau_{\rm LSP}$ > 100 s)
$m_{\rm LSP}$ = 2 TeV
10^{-8}
$f_a^{\rm KMM}$ = 10^8 GeV
excluded by SN1987A
(anarchical case)
$T_{\rm KR} < m_0$
$f_a^{\rm th}$ = 10^8 GeV
excluded by SN1987A
10
10^2
10^3
m_0 (TeV)

Axion Kination



QCD axion dark matter: $T_{\rm KR} \simeq 2\times10^6$ GeV
$\Delta N_{\rm eff} > 0.17$
probed by CMB-S4
$\Delta N_{\rm eff} > 0.02$
unsuccessful saxion thermalization
← lepto-axiogenesis →
DECIGO ($V_{\rm inf}^{1/4} = 10^{16}$ GeV)
BBO ($V_{\rm inf}^{1/4} = 7\times10^{15}$ GeV)
no kination
$T_{\rm MK} = 10\ T_{\rm KR}$
SN1987A
$m_S > f_a$
f_a [GeV]
m_a [eV]
m_S [GeV]



$T_{\mathrm{KR,\,RM}}$ [GeV]
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Models
piecewise ρ_θ with analytic approx.
piecewise ρ_θ with numerical solution
two−field model with analytic approx.
log potential with analytic approx.
kination dominated
matter dominated
radiation dominated
radiation dominated
$V_{\mathrm{inf}}^{1/4} = 10^{16}$ GeV
DECIGO
BBO
$\Omega_{\mathrm{GW}} h^2$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
f [Hz]