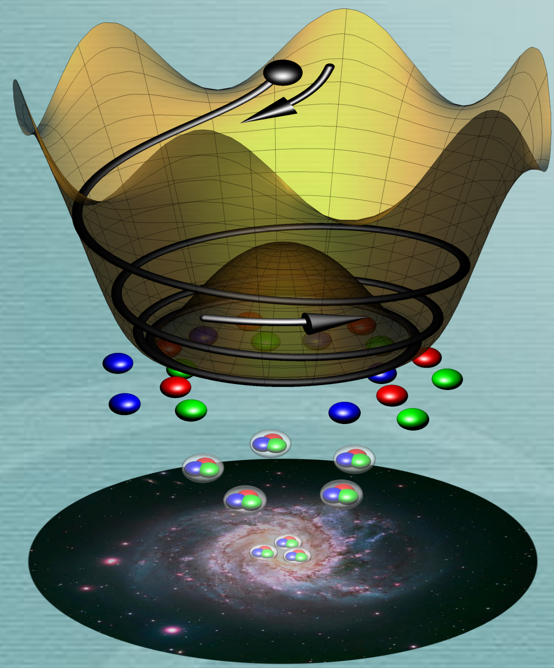
2/7/2022, CAU BSM workshop

Axion rotation

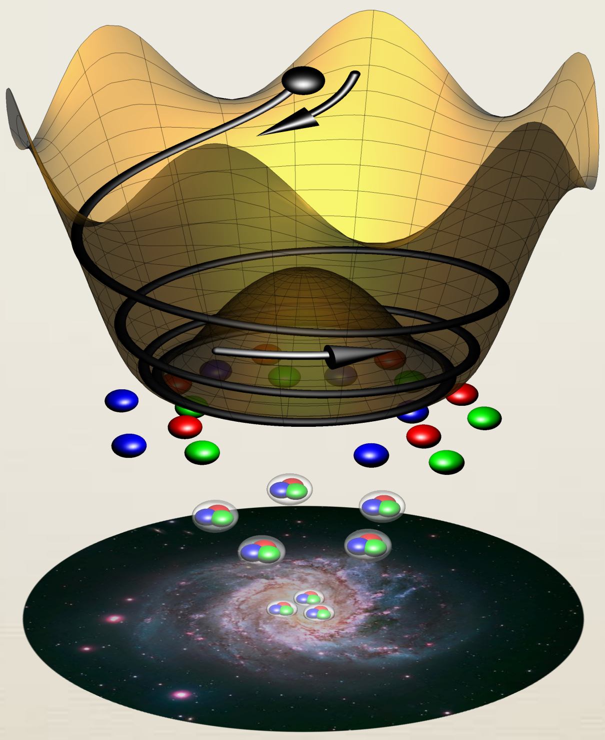
Keisuke Harigaya (CERN)



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)

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
* predicts parameters of new physics beyond axion

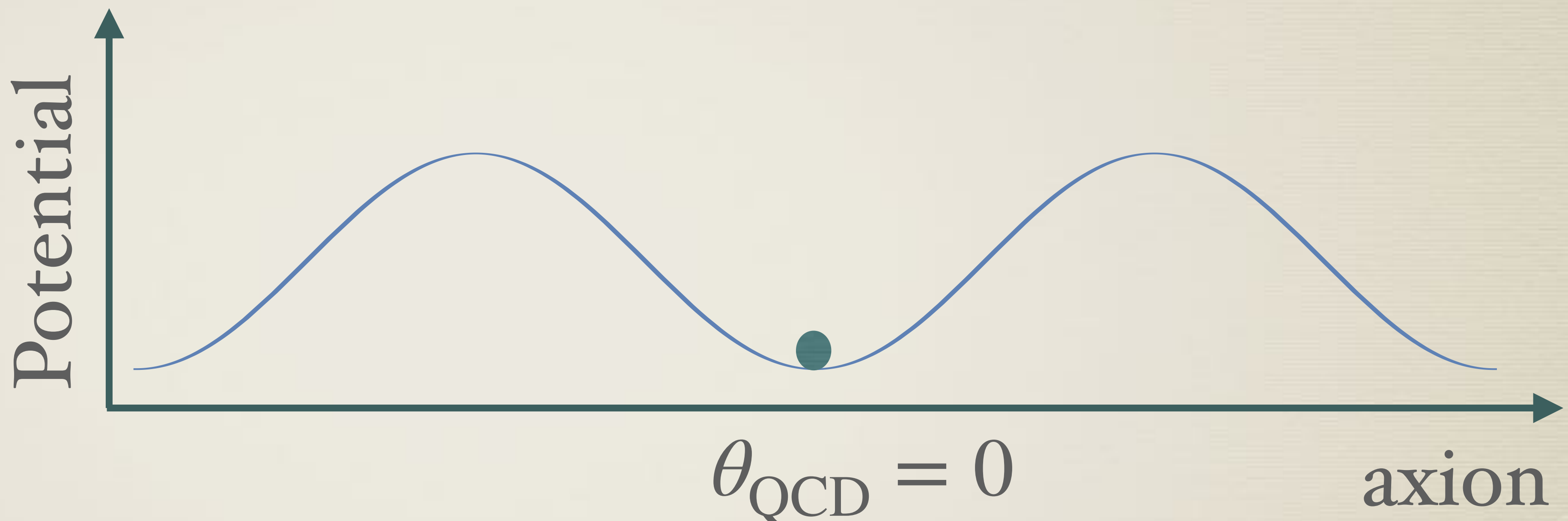
Outline

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

QCD axion

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

* solves the strong CP problem

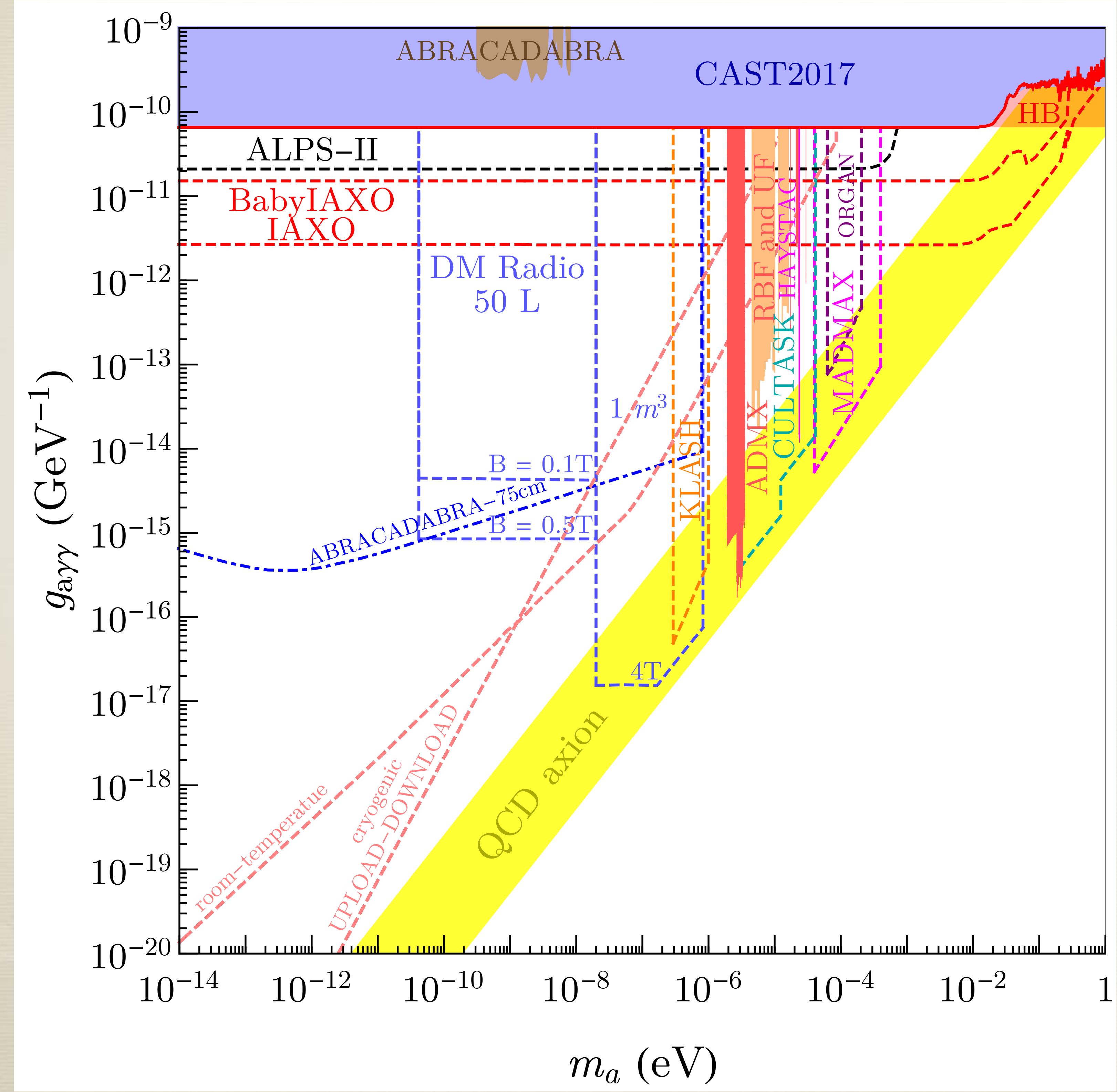


* a dark matter candidate

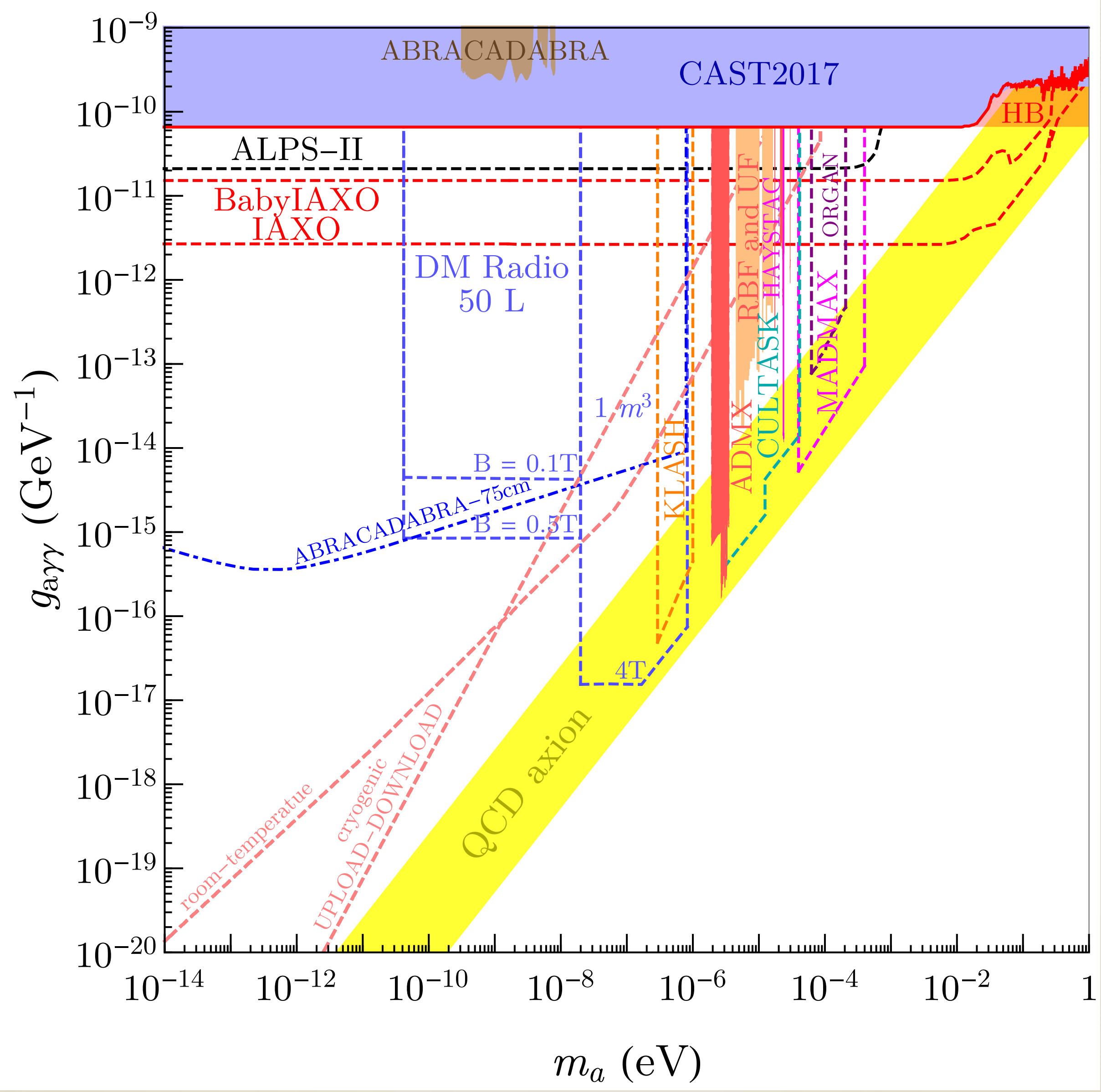
Preskill, Wise and Wilczek (1983), Abbott and Sikivie (1983), Dine and Fischler (1983)

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

Axion search



Dark matter?

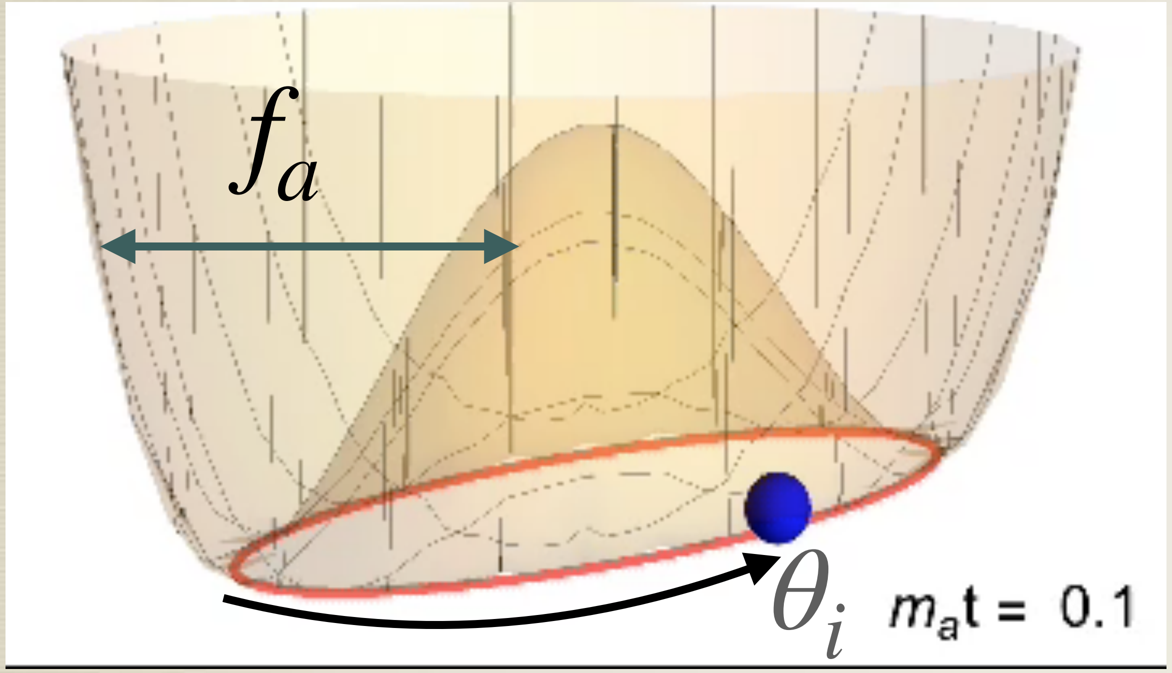


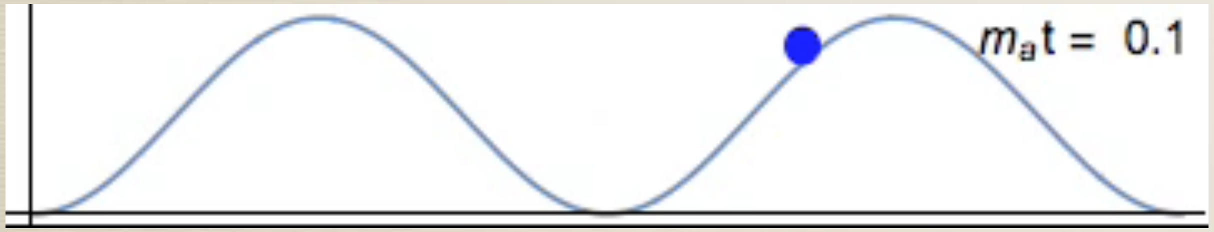
$$\rho_{\rm DM} \simeq 1.3 \times 10^{-5}\ {\rm GeV/cm^3} \quad \text{(Planck 2018)}$$

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)



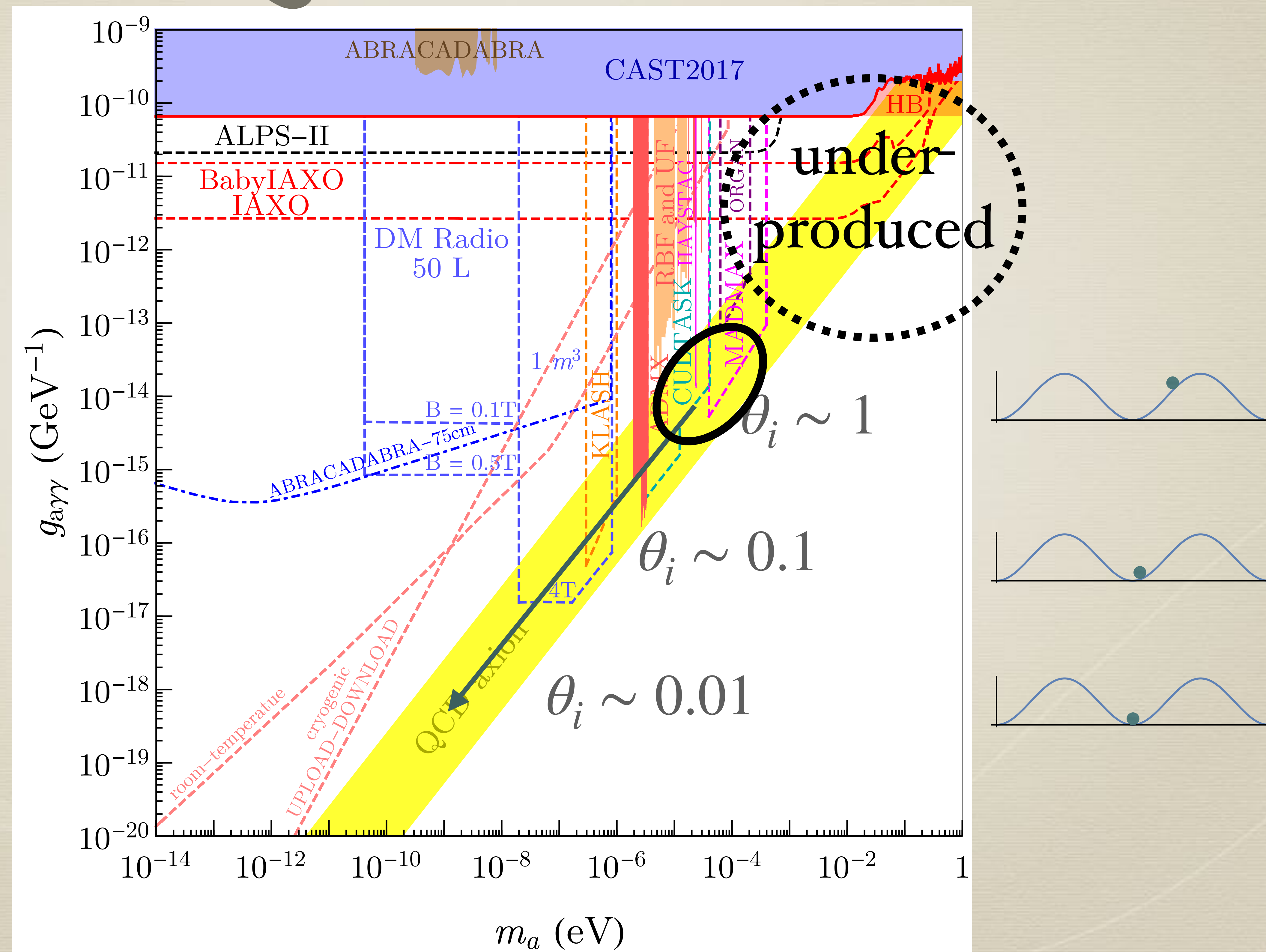


For the QCD axion,

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

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

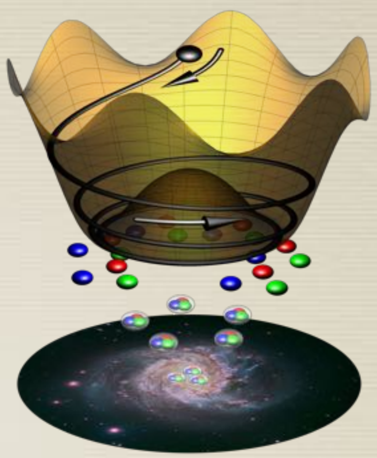
QCD axion



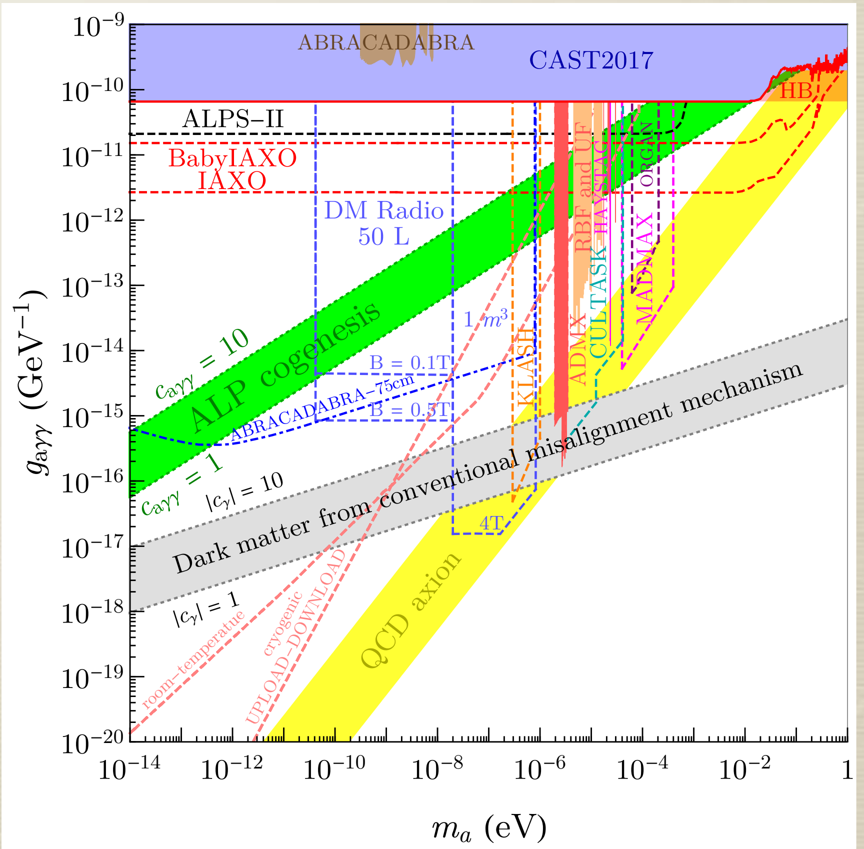
ABRACADABRA
CAST2017
HB
ALPS–II
BabyIAXO
IAXO
DM Radio
50 L
1 m^3
B = 0.1T
B = 0.5T
4T
ABRACADABRA–75cm
KLASH
ADMX
RBF and UF
HAYSTAC
CULTASK
MADMAX
ORGAN
room–temperatue
cryogenic
UPLOAD–DOWNLOAD
QCD axion
under-
produced
$\theta_i \sim 1$
$\theta_i \sim 0.1$
$\theta_i \sim 0.01$
$g_{a\gamma\gamma}$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

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 and new physics beyond the axion



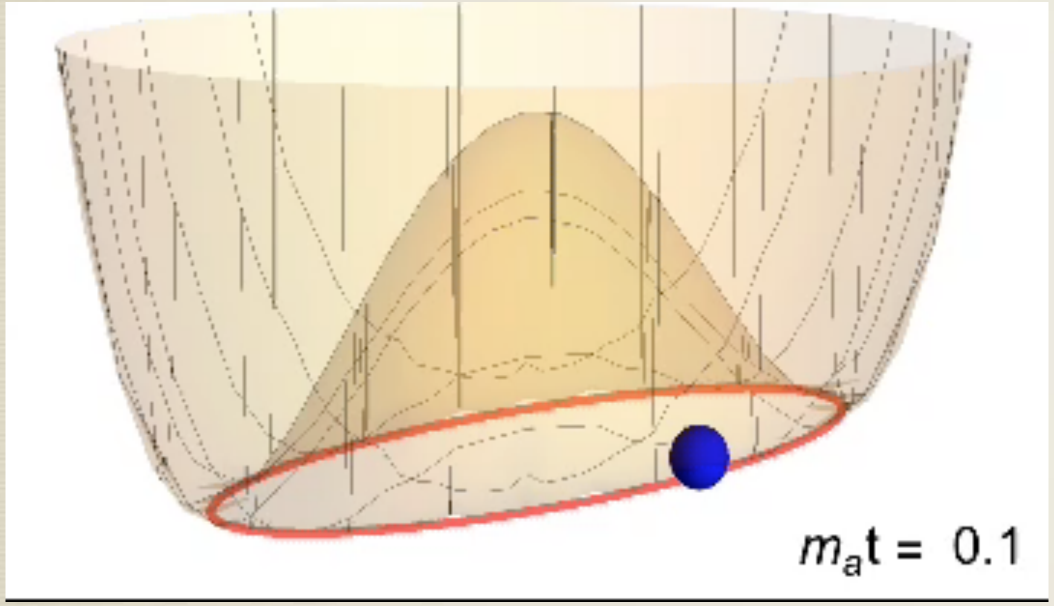
Outline

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

Rotation?

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

Conventional picture

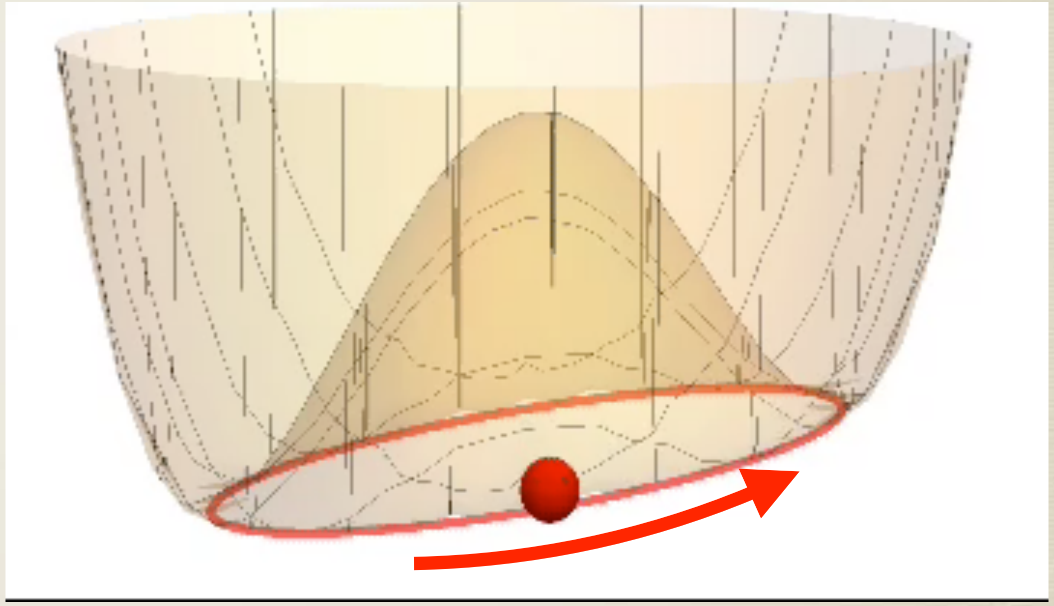


$$\dot{\theta}_i = 0$$

V

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

Non-zero initial angular velocity?



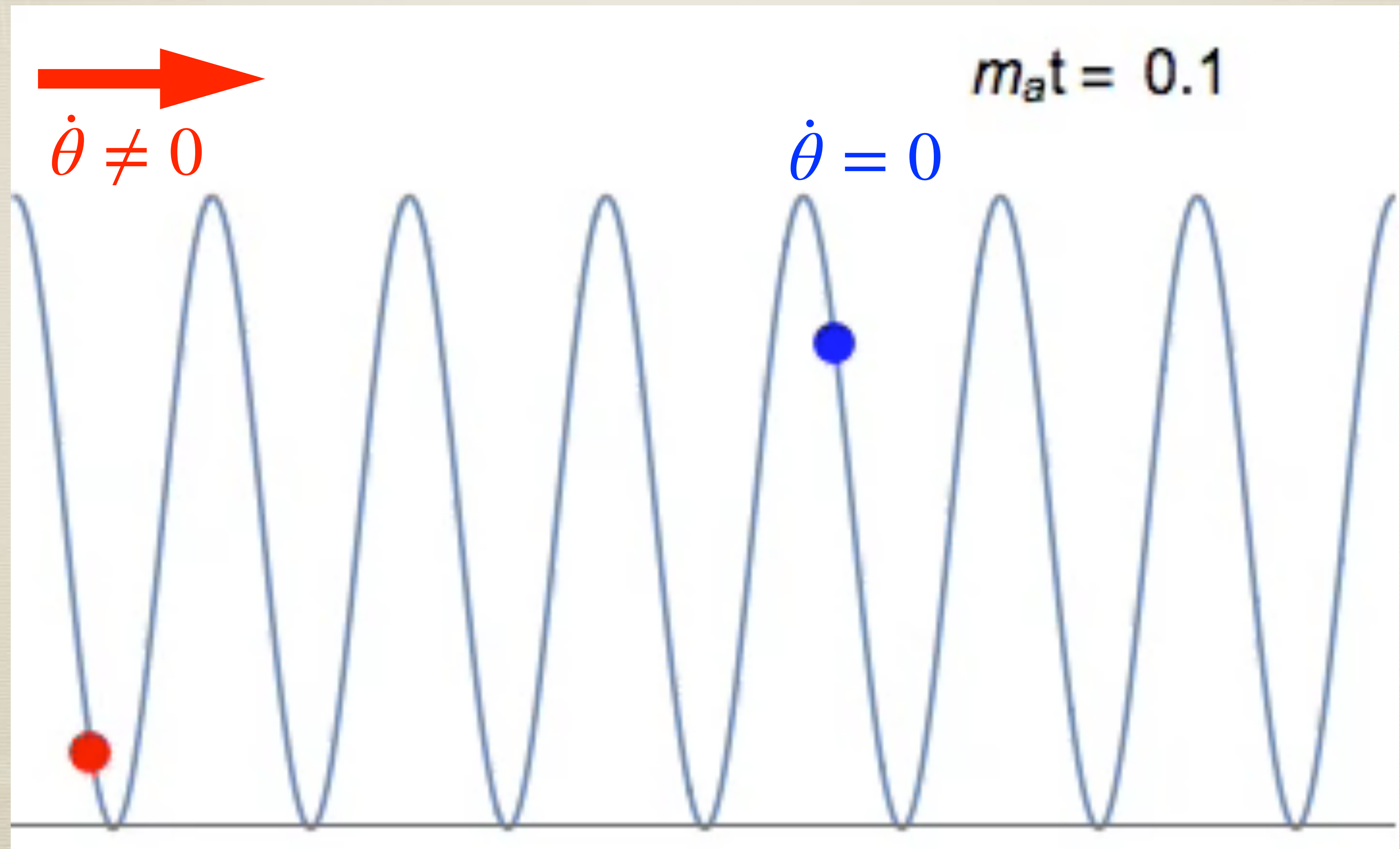
$$\dot{\theta}_i \neq 0$$

$V + K$

Kinetic Misalignment

Delayed oscillation

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

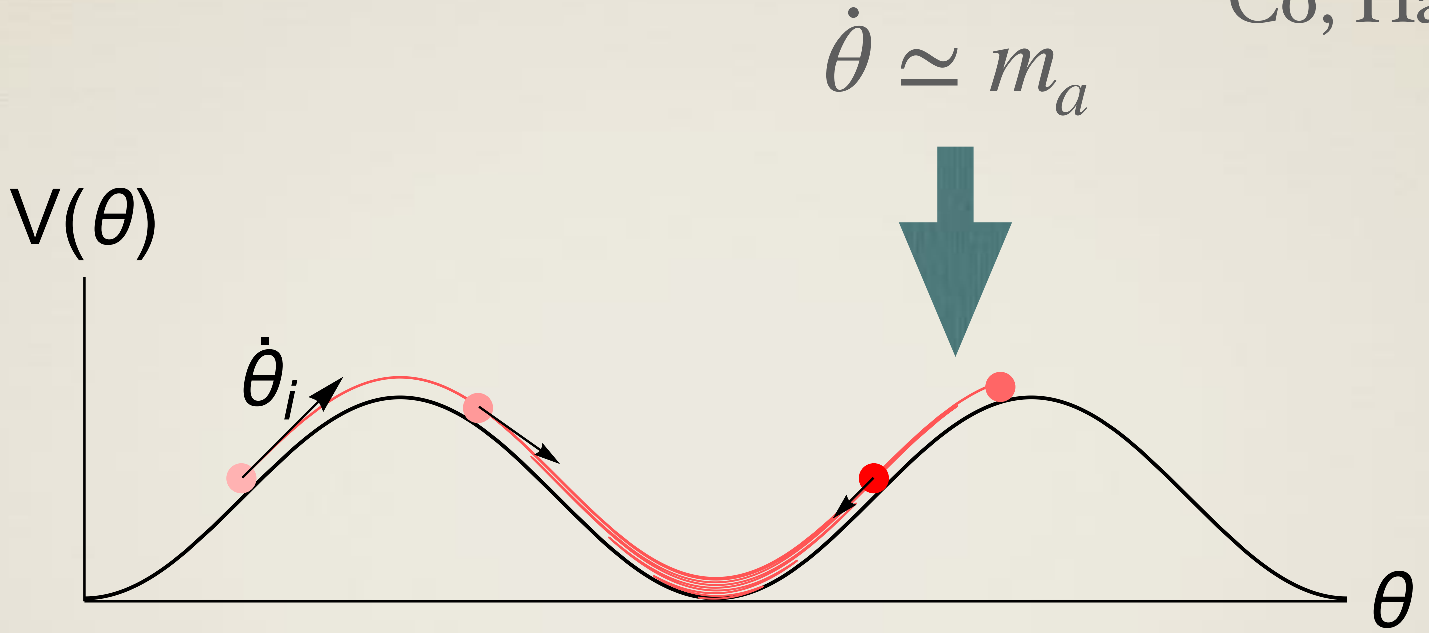


potential

axion

Delayed oscillation

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



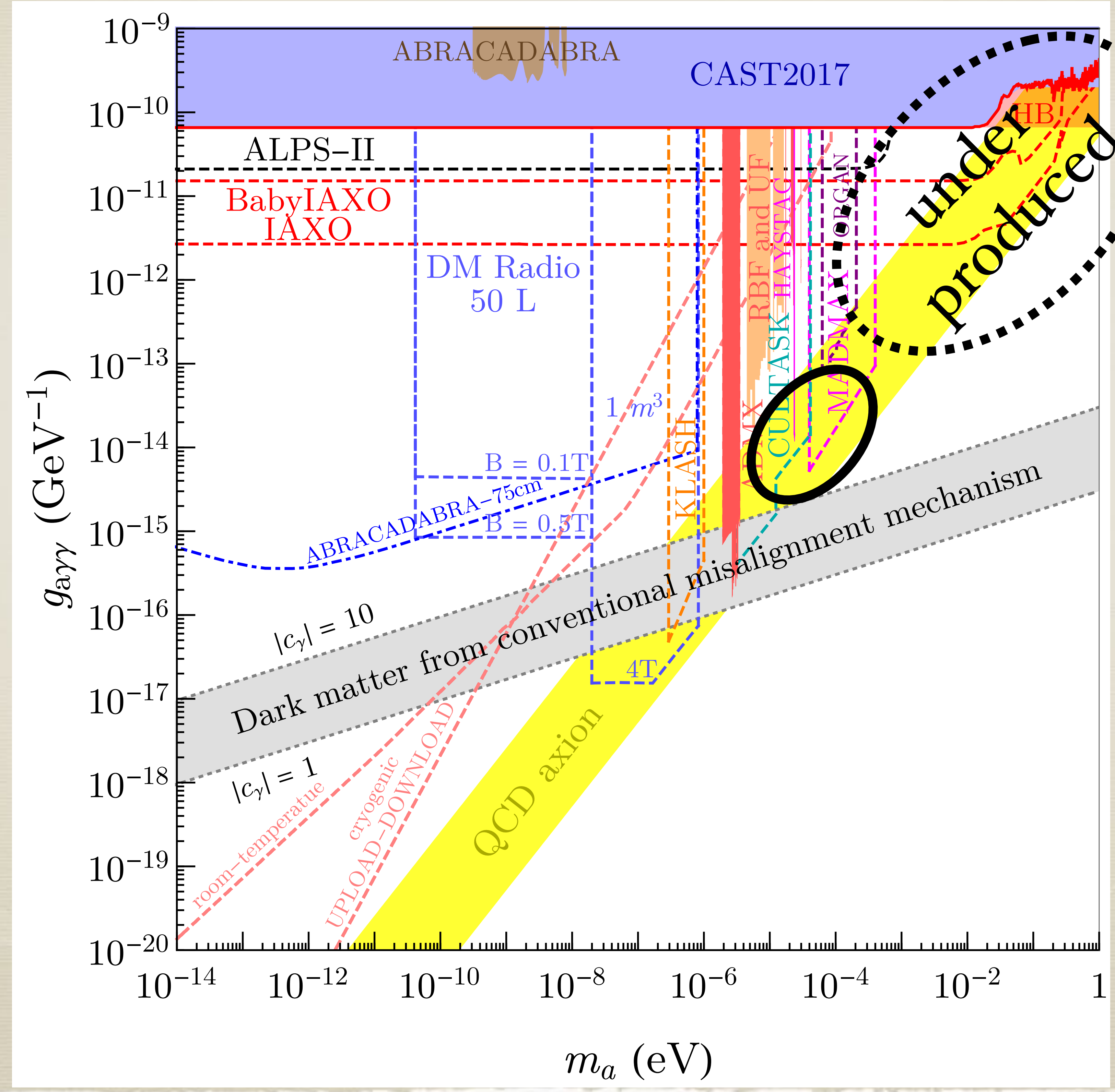
$$n_{a,\text{osc}} \simeq m_a f_a^2 \simeq \dot{\theta} f_a^2 = n_{\text{PQ}}$$

(axion number density) = (PQ charge)

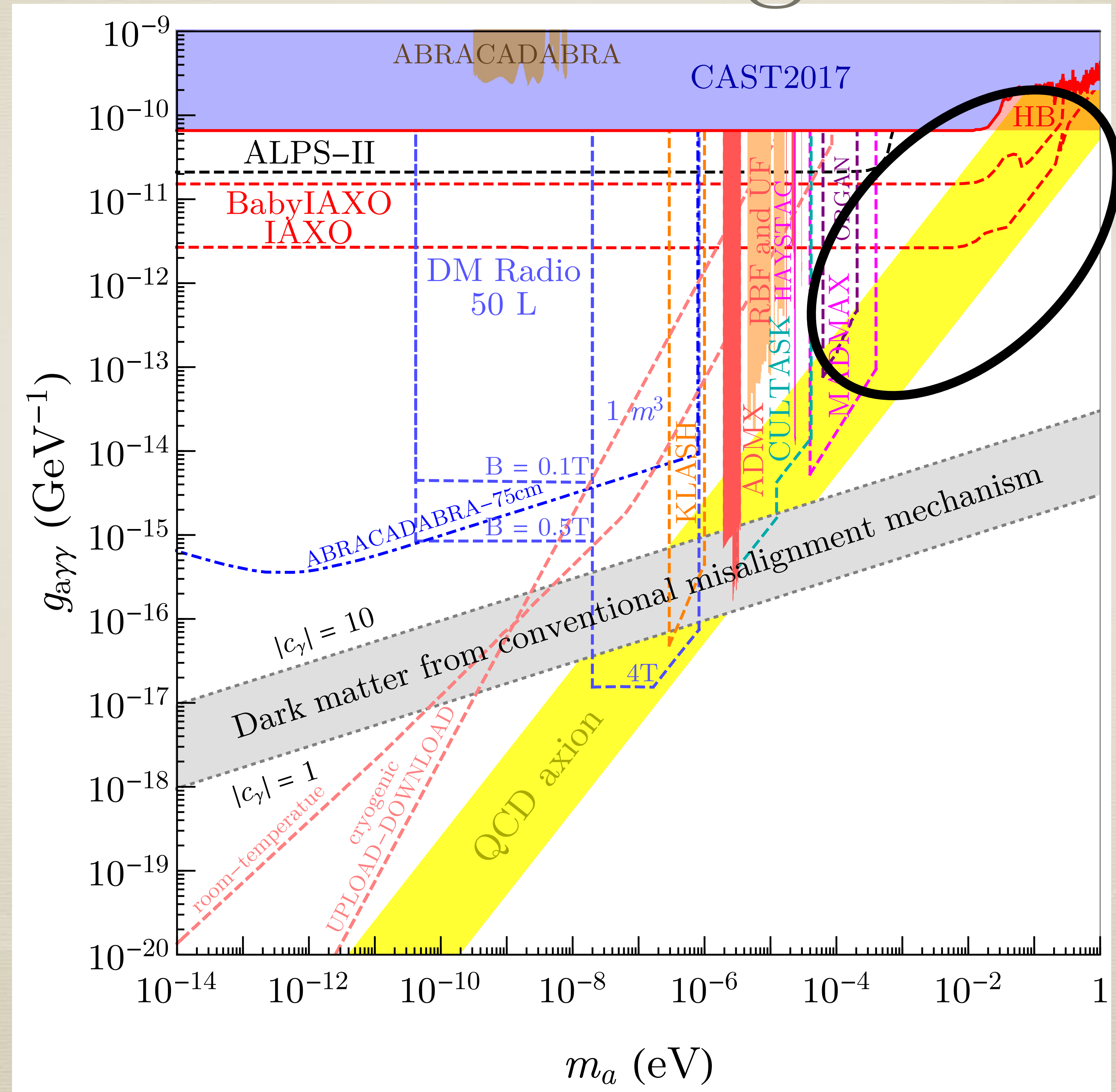
Actually, parametric resonance produces axion fluctuations, but the axion abundance remains the same

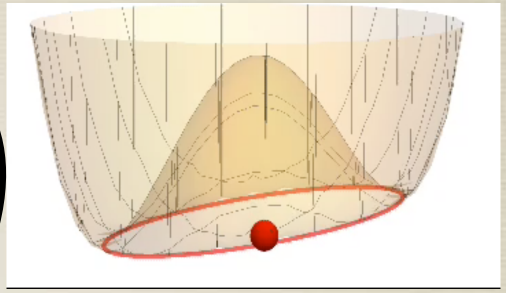
Fonseca, Morgante, Sato and Servant (2019), Co, KH and Pierce (2021)

Conventional mechanisms



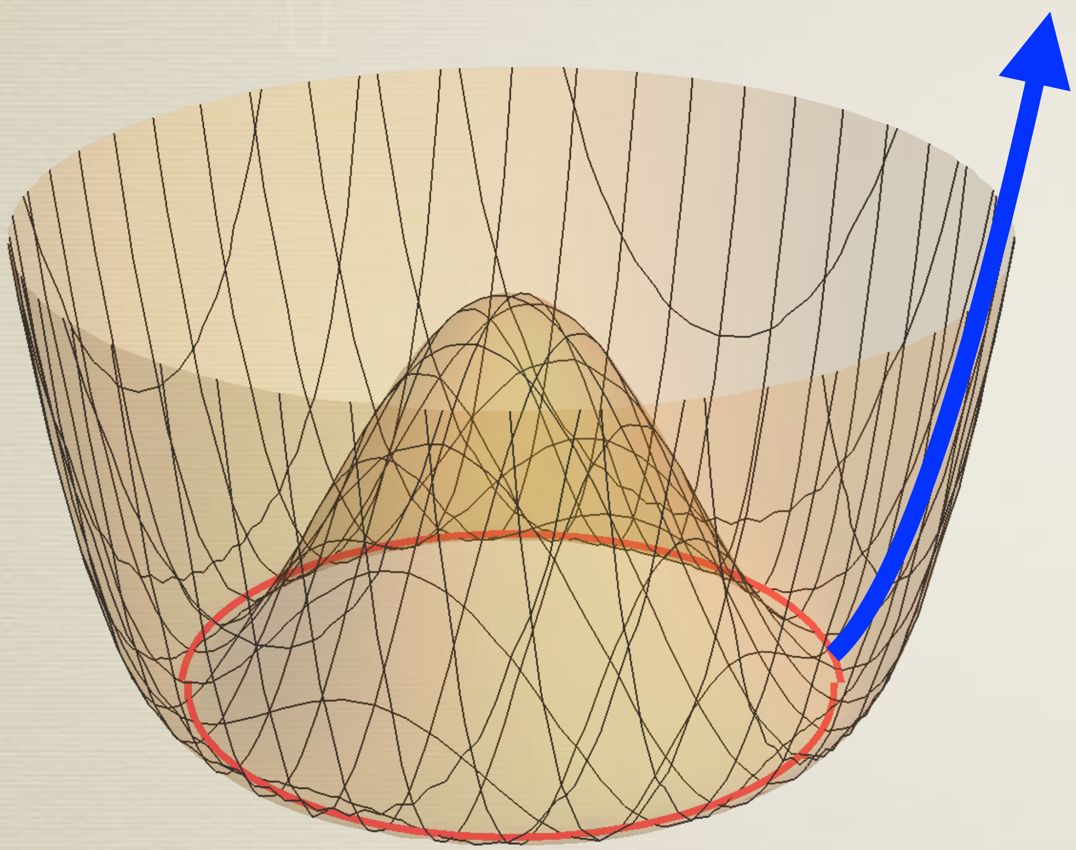
Kinetic misalignment





How to initiate the rotation

Co and KH (2019)



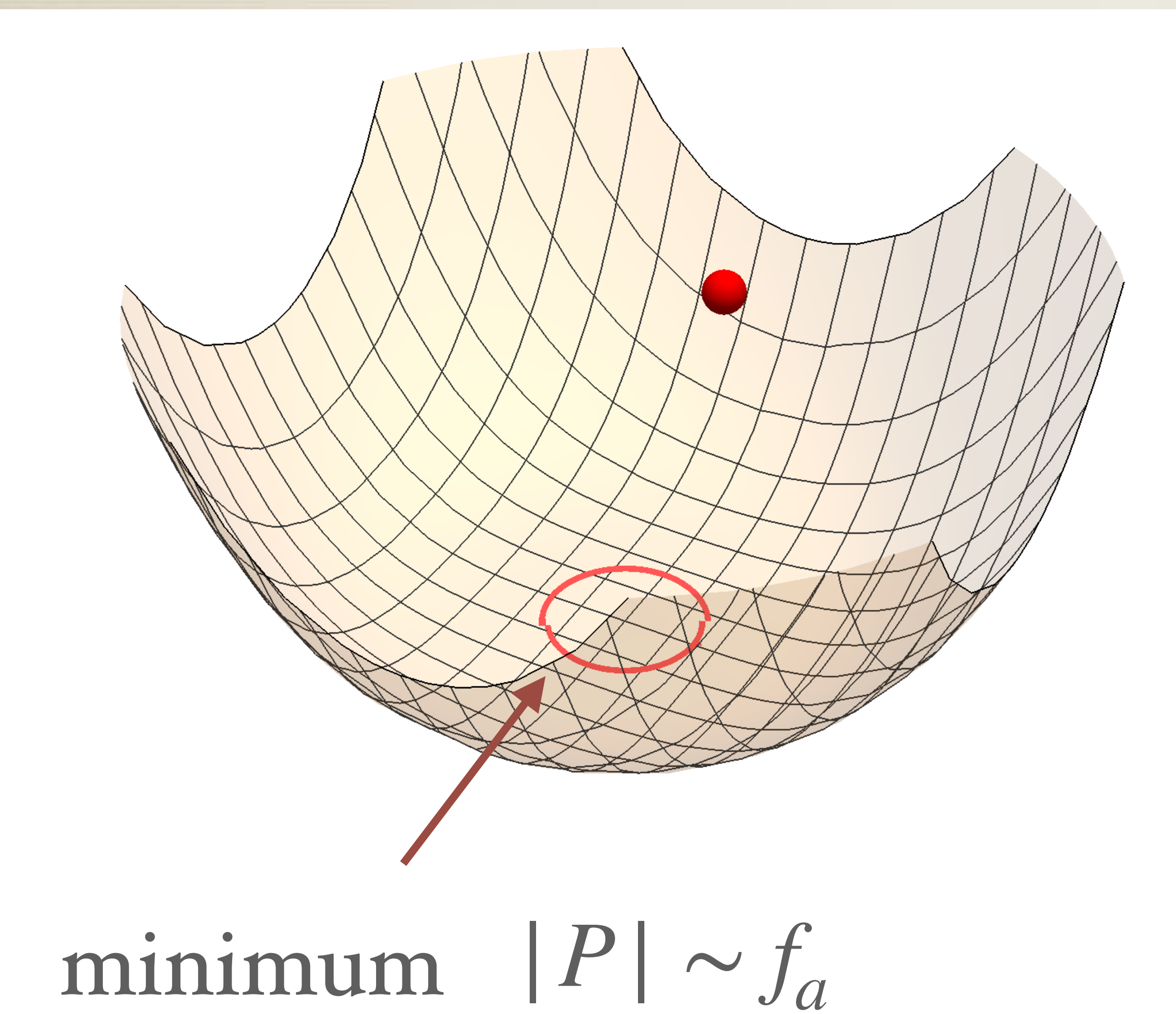
Consider the dynamics of the radial direction

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

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

How to initiate the rotation

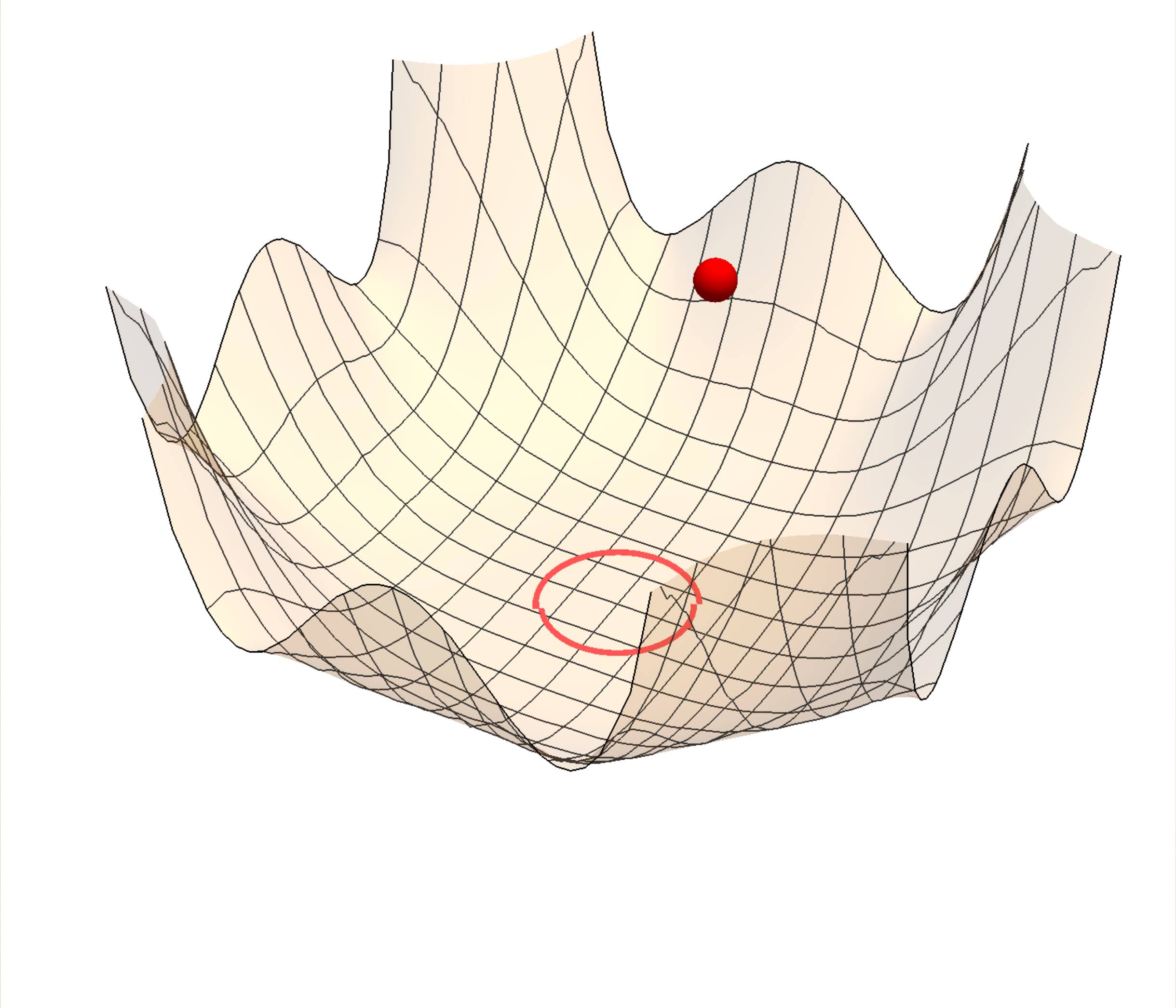
$P = S \times \exp(i\theta)$



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

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

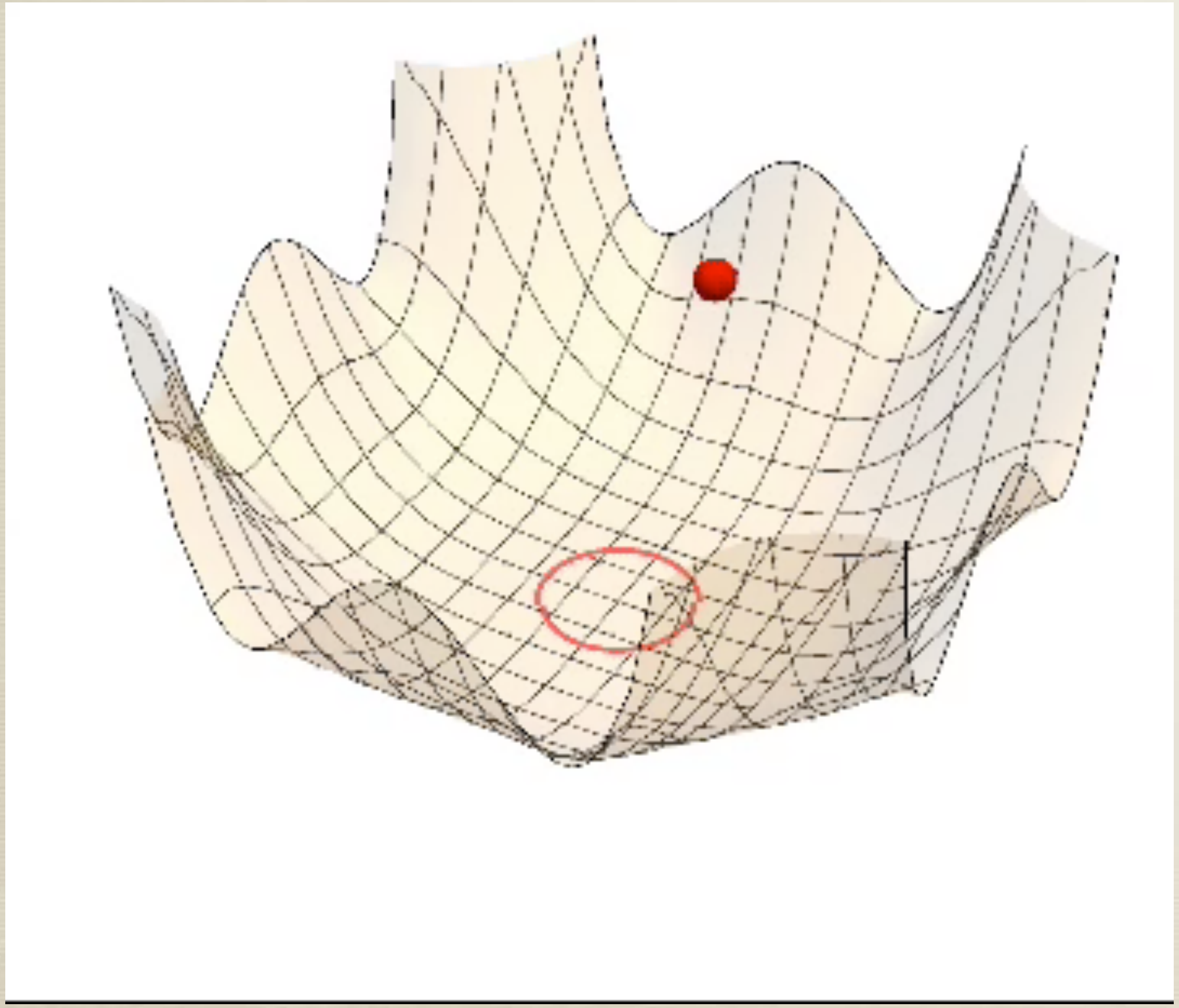
may be effective

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), Quilez+ (2018), ...

How to initiate the rotation

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



Assume a large initial radial field value

↓

Higher order terms

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

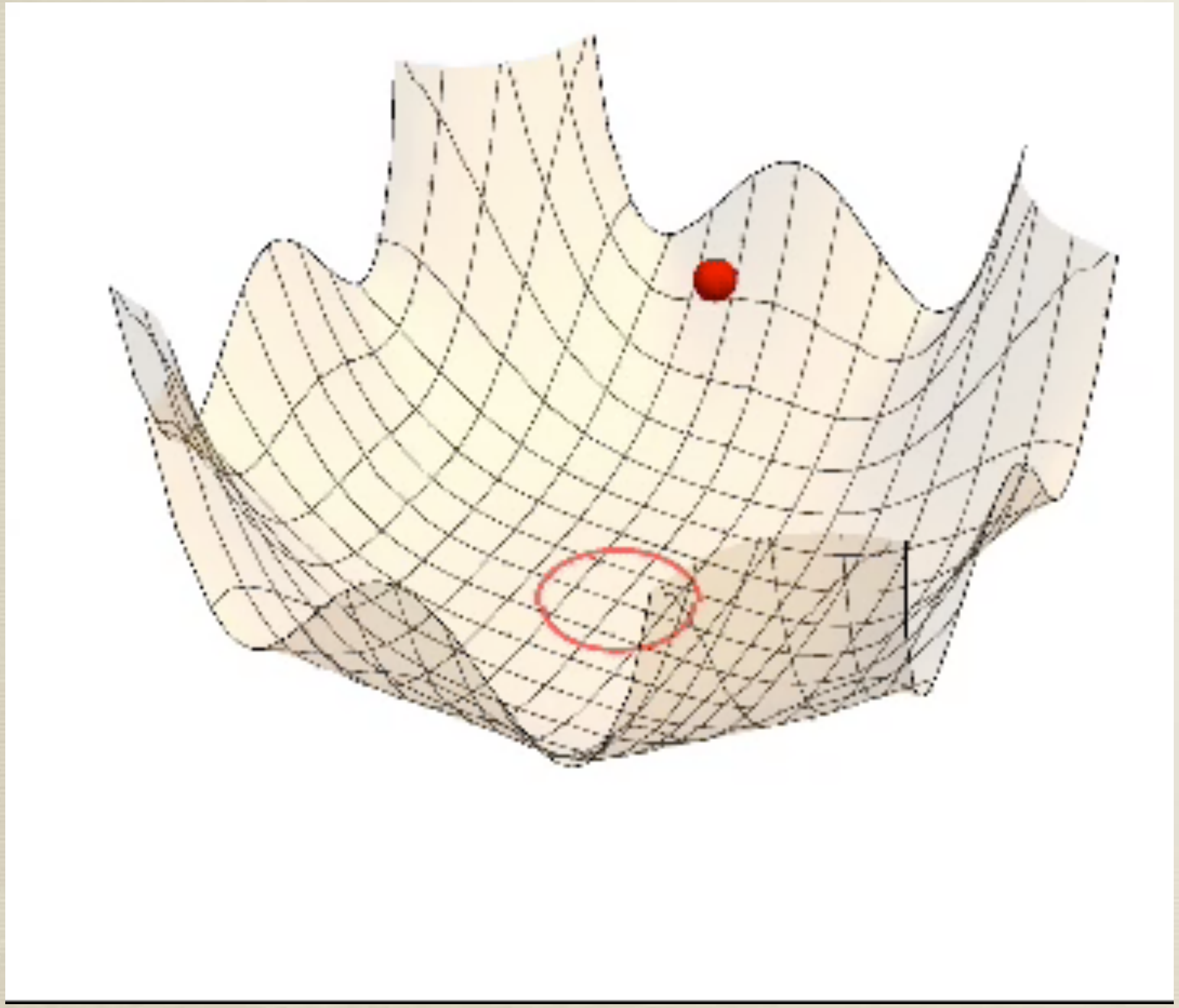
may be effective

↓

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

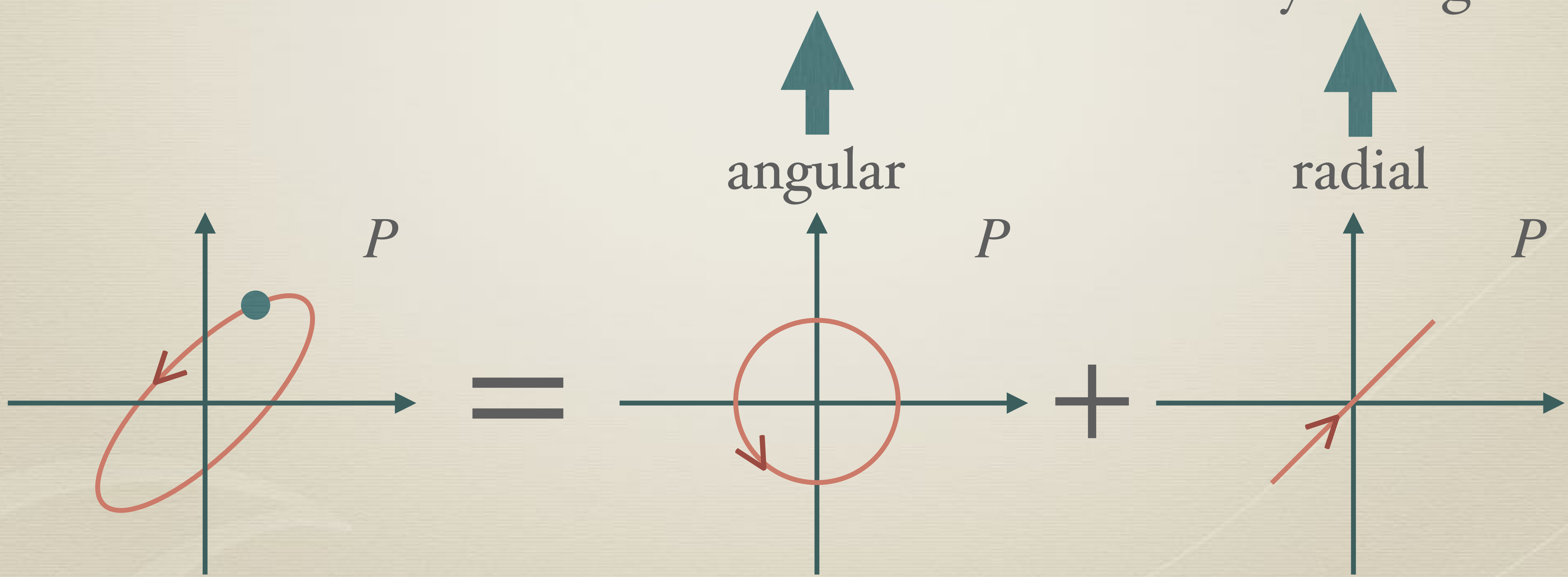
$V \simeq P^n$
is no longer effective

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

Thermalization

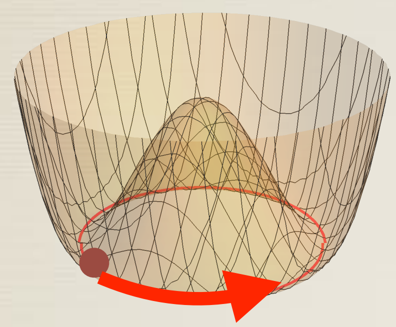
Kinetic Misalignment Mechanism

Produce entropy, should be dissipated early enough

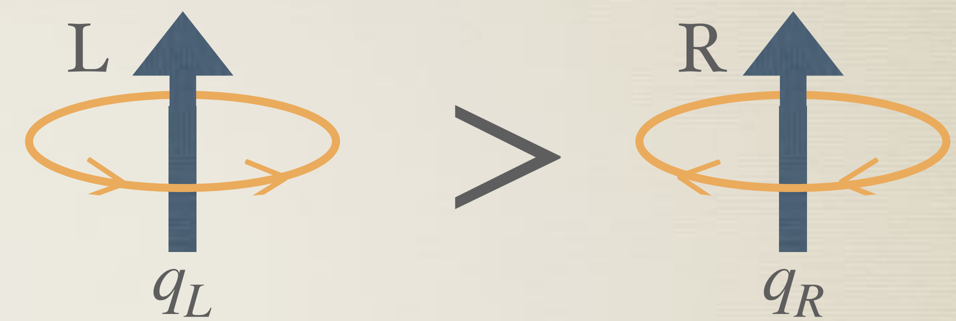


Stability of the angular mode

Rotation



particile-antiperticle
asymmetry in the bath



$$\mu_{\rm rot} \sim \frac{\dot\theta^2 f_a^2}{\dot\theta f_a^2} = \dot\theta \quad \longleftrightarrow \quad \mu_{\rm bath} \sim \dot\theta$$

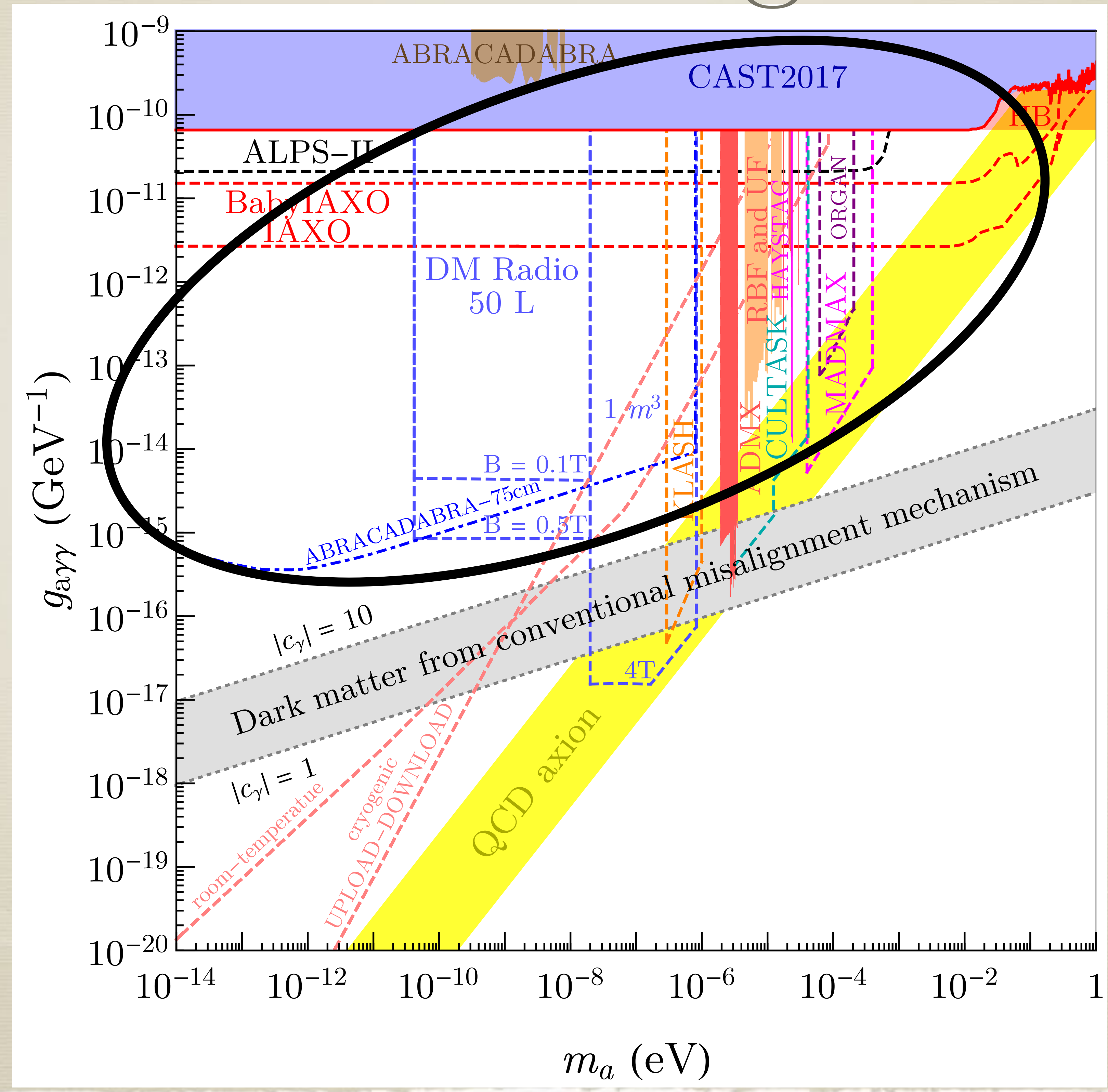
$$n_{\rm rot} = \dot\theta f_a^2 \quad \gg \quad n_{\rm bath} \sim \boxed{0.1\dot\theta T^2}$$

as long as $T \ll f_a$

This result will be used later in this talk

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

Kinetic misalignment



Outline

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Axiogenesis

Co and KH (2019)

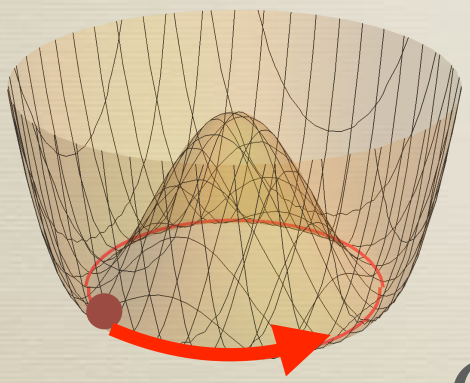
The PQ symmetry is quantum mechanically broken
by the QCD interaction (anomaly)

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

+

So is the quark chiral symmetry

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



PQ → (QCD) → Chiral charge

Baryon

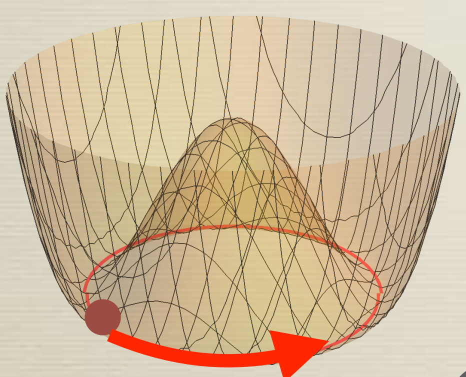
Axiogenesis

Co and KH (2019)

Baryon number violation from

SM : Weak sphaleron process
BSM : Majorana neutrino mass, RPV,
any BSM that you like and contains $\not{B}$

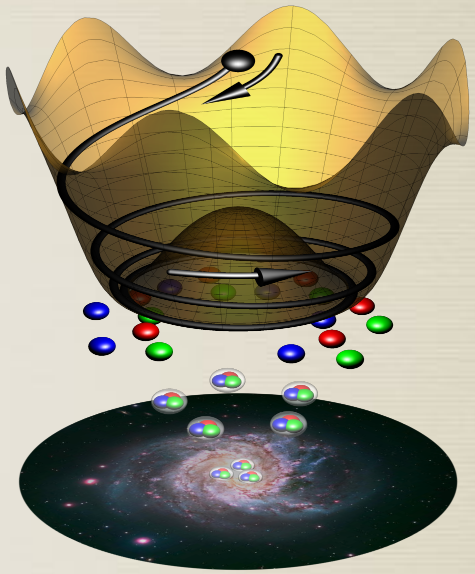
↓



PQ → (QCD) → Chiral charge → ($\not{B}$) → Baryon

Questions in particle physics

* Why does QCD preserve CP symmetry?
* What is dark matter?
* How was the baryon asymmetry of the universe created?
* ....



B violation

* Electroweak sphaleron : Minimal axiogenesis

  will be explained in detail

* Baryon number violation from BSM

  will be introduced briefly

Minimal axiogenesis

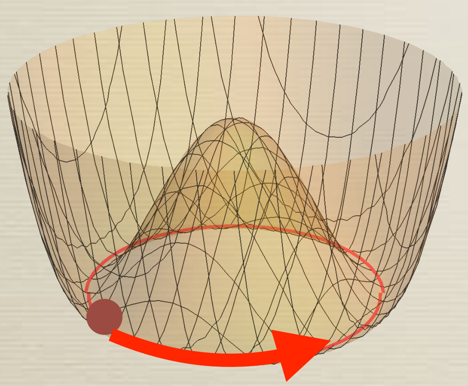
Co and KH (2019)

Chiral charge

QCD ↔ weak

PQ

B+L

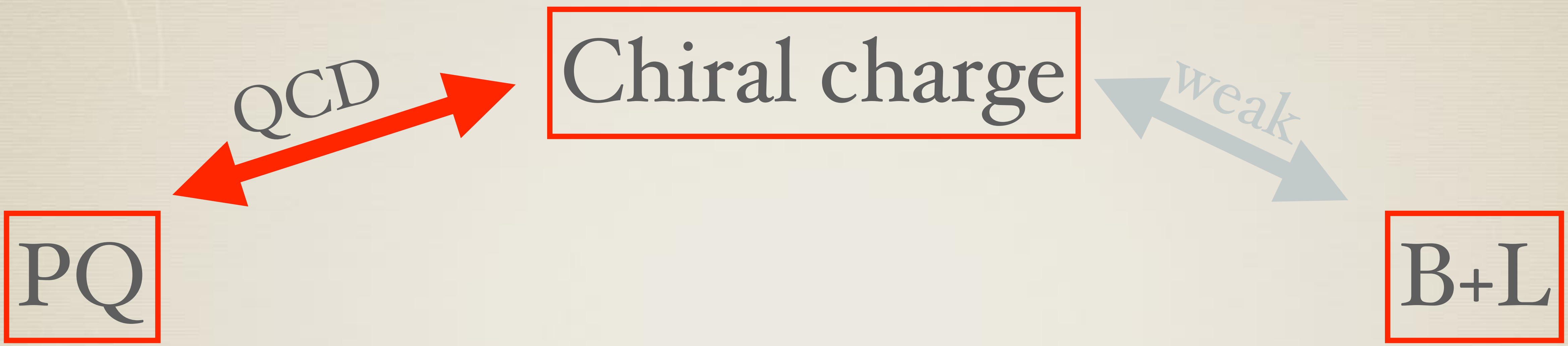


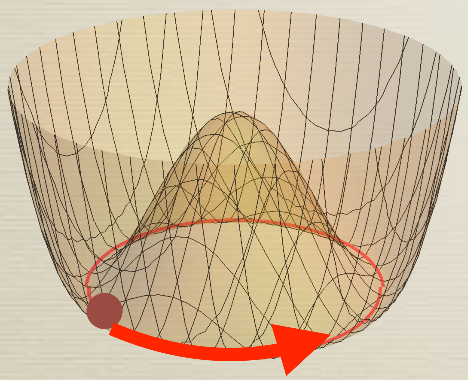
Transfer processes are effective before the electroweak phase transition.
B at thermal eq.

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

Minimal axiogenesis

Co and KH (2019)





weak interaction becomes ineffective
after electroweak phase transition

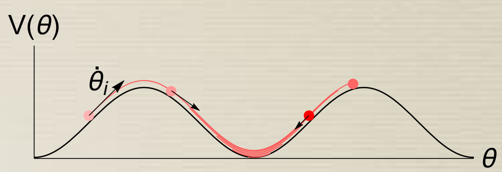
$$n_B|_{\mathrm{EW}} \simeq 0.1\dot{\theta}|_{\mathrm{EW}} T_{\mathrm{EW}}^2$$

Minimal axiogenesis

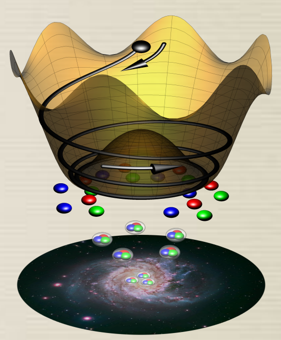
Co and KH (2019)

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

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

Astrophysical lower bound $f_a > 10^8$ GeV

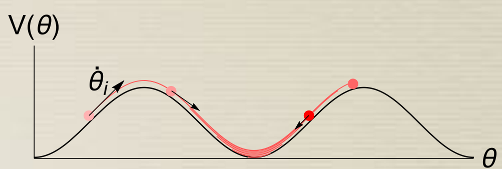
Does not work for the standard electroweak phase transition

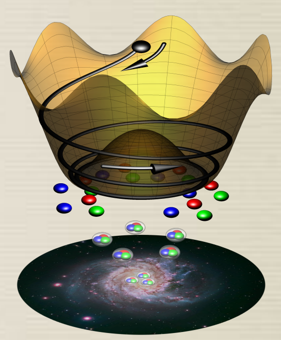
Minimal axiogenesis

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

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

Astrophysical lower bound $f_a > 10^8$ GeV

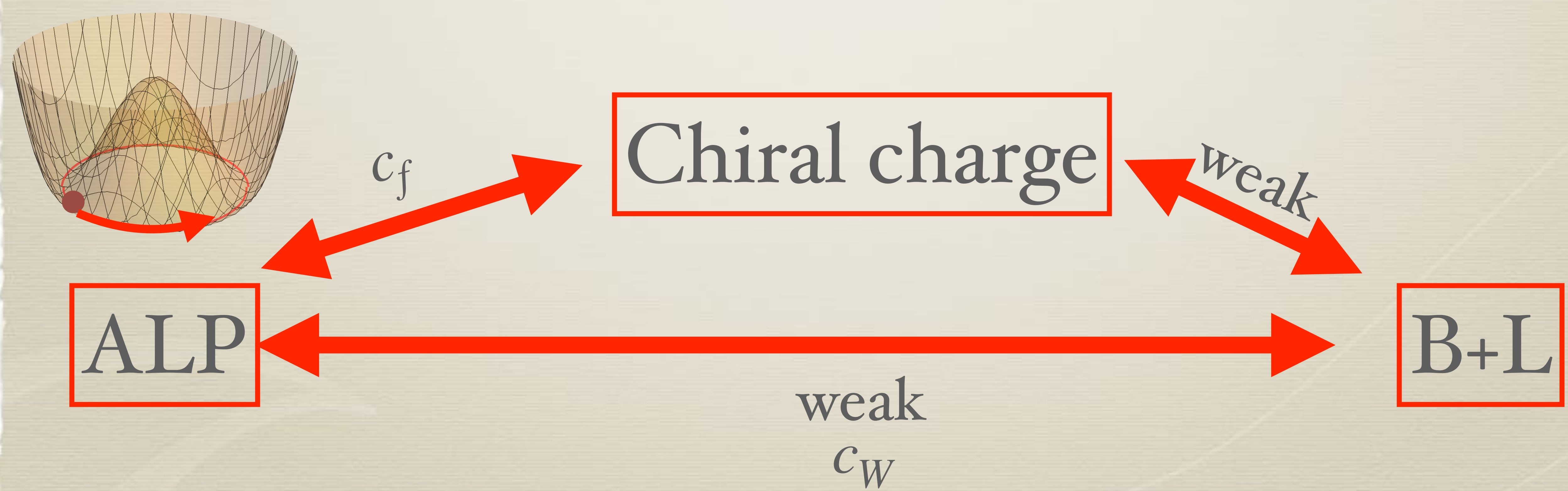
Electroweak ⟷ QCD axion

ALP genesis

Co, Hall and KH (2020)
Domcke, Ema, Mukaida, and Yamada (2020)

A similar mechanism works for generic ALPs

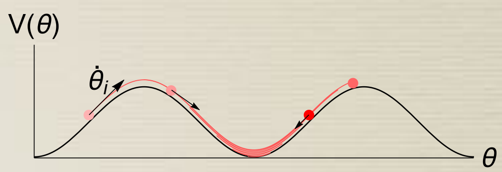
$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \sum_{f,i,j} c_{f_{ij}} \, f_i^\dagger \bar{\sigma}^\mu f_j + \frac{a}{64\pi^2 f_a} \left(c_W g^2 \, W^{\mu\nu} \tilde{W}_{\mu\nu} \right)$$



ALP cogenesis

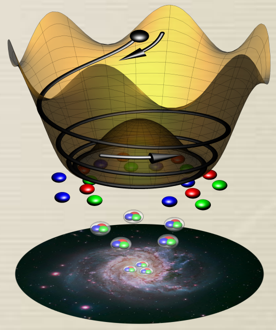
Co, Hall and KH (2020)

Assuming the standard EW phase transition,



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

1. Dark Matter
2. Baryon asymmetry

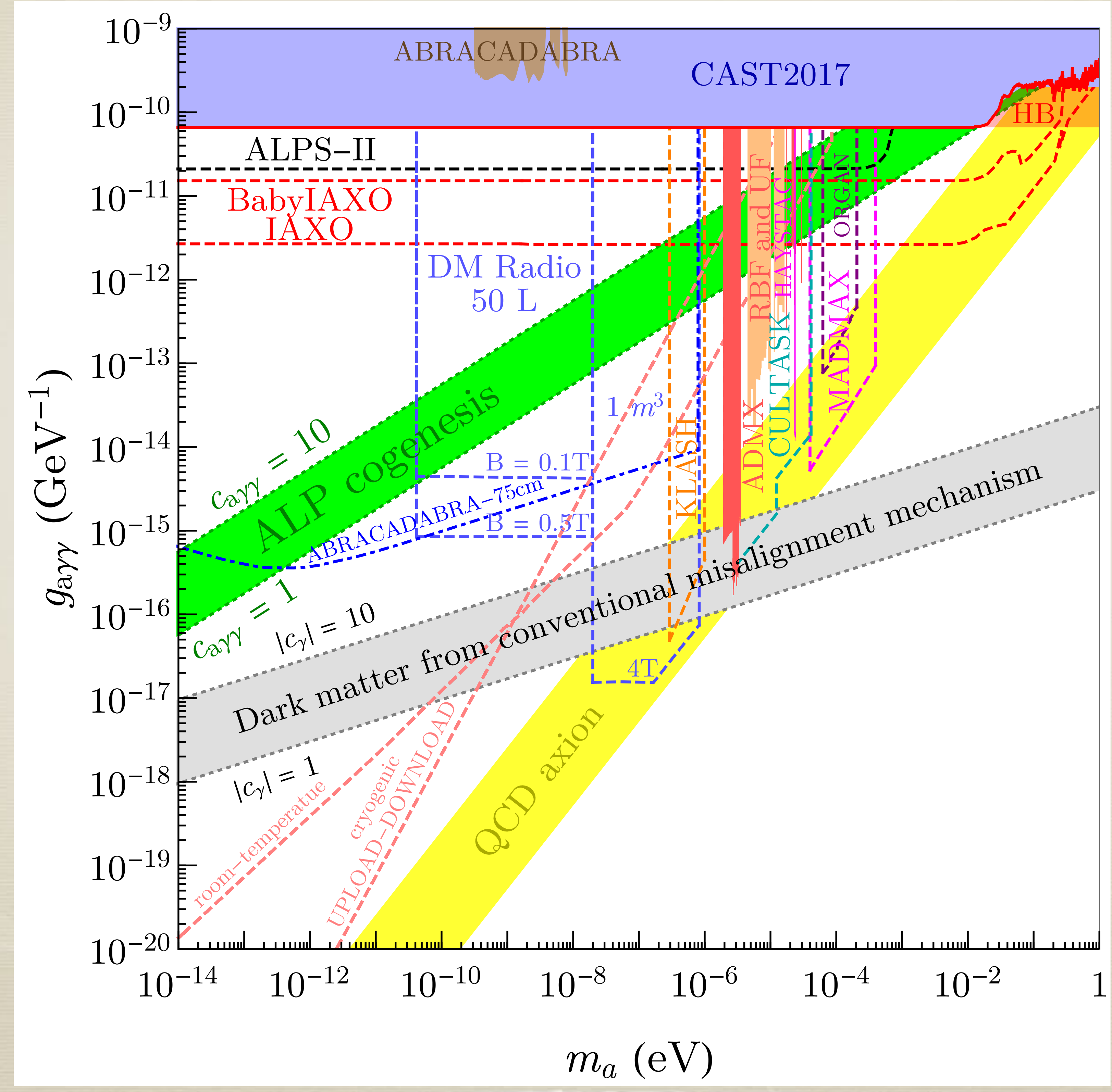


3 free parameters – 2 densities to fit
= 1 free parameter

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

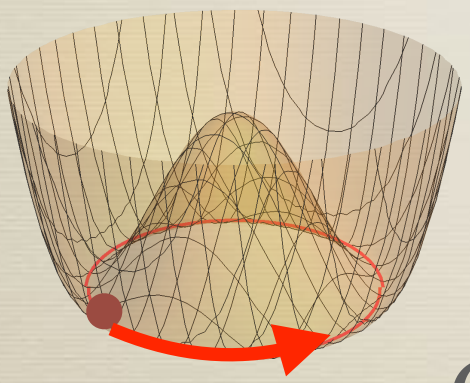
Prediction on the ALP coupling

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



B violation from BSM

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

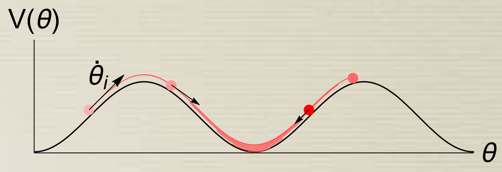


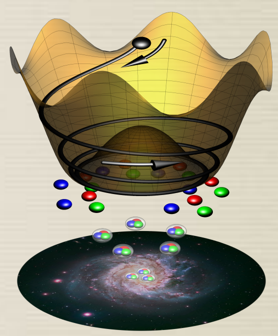
PQ —QCD→ Chiral charge —$\not{B}$→ Baryon

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)
Domcke, Ema, Mukaida, and Yamada (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

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

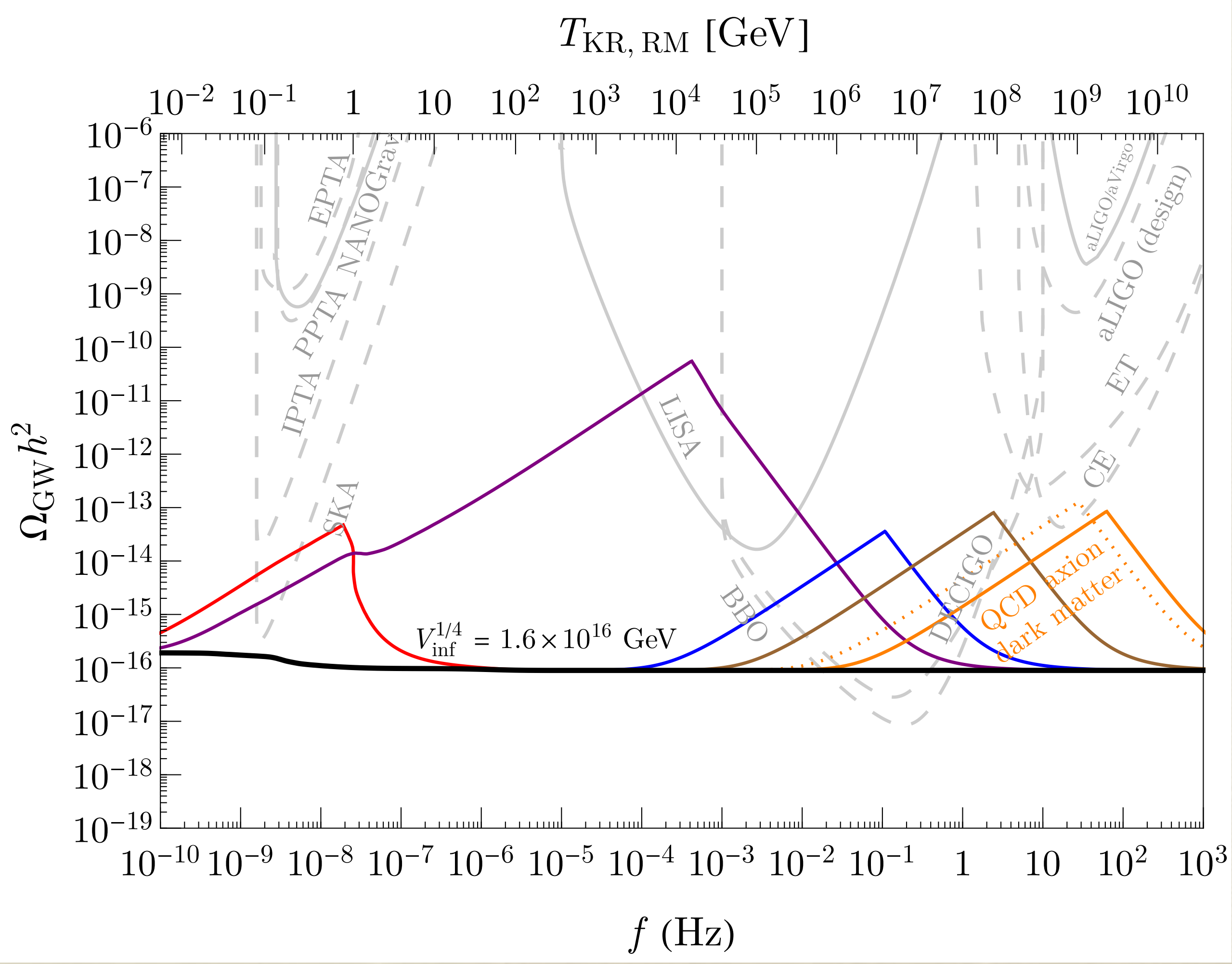
A relation between BSM parameters and f_a

Discussion

* Kination domination

Co and KH (2019),
KH et al.(2021)
Gouttenoire, Servant and Simakachorn (2021)

Axion rotation can dominate the universe and introduce kination dominated era. Change the primordial gravitational wave spectrum, e.g., from inflation



Discussion

- Cosmic perturbations

Co, KH and Pierce (2022)

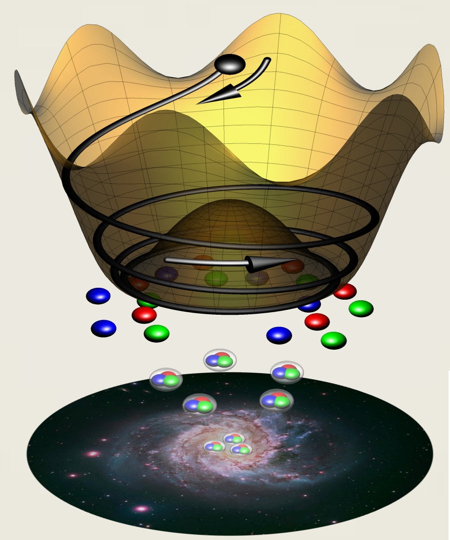
Axion rotation can explain the curvature perturbation of the universe, as in the curvaton scenario

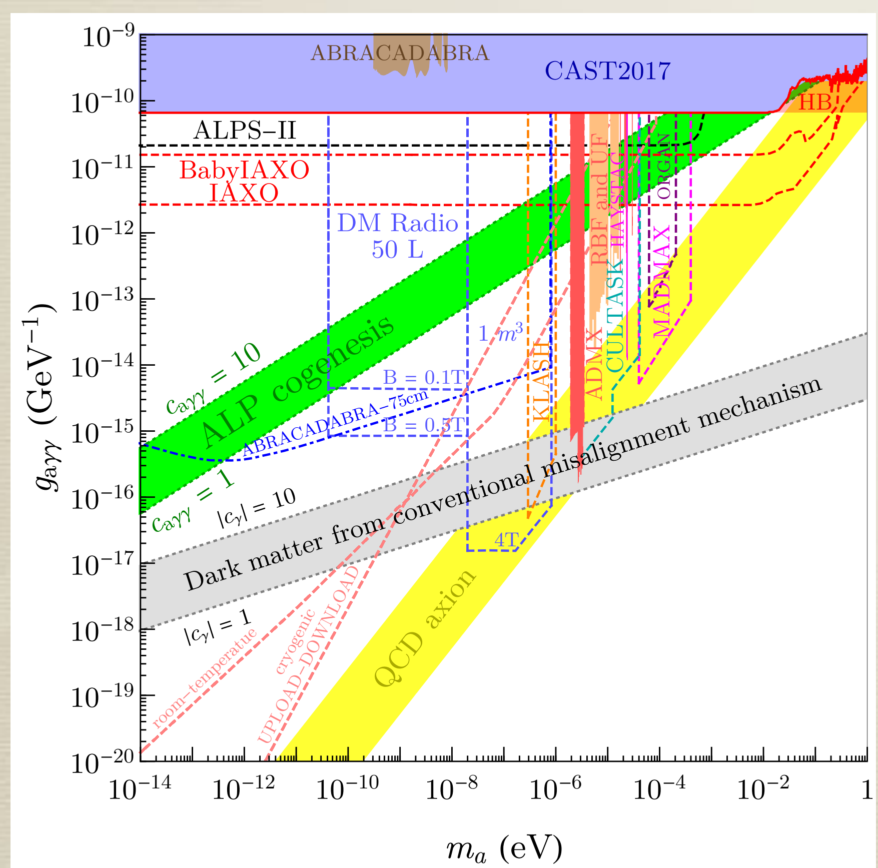
Local non-gaussianity

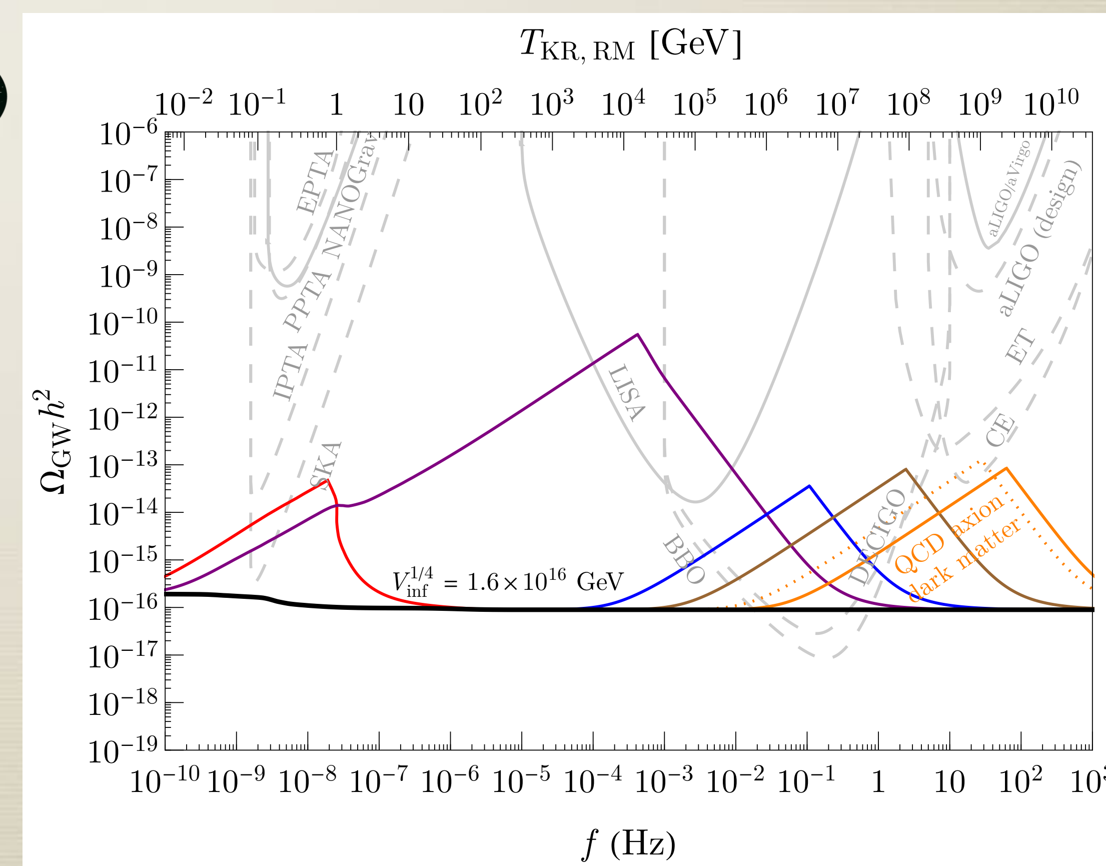
$$f_{\rm NL} \lesssim -2.5$$

Axion rotation

Maybe more cosmological roles?



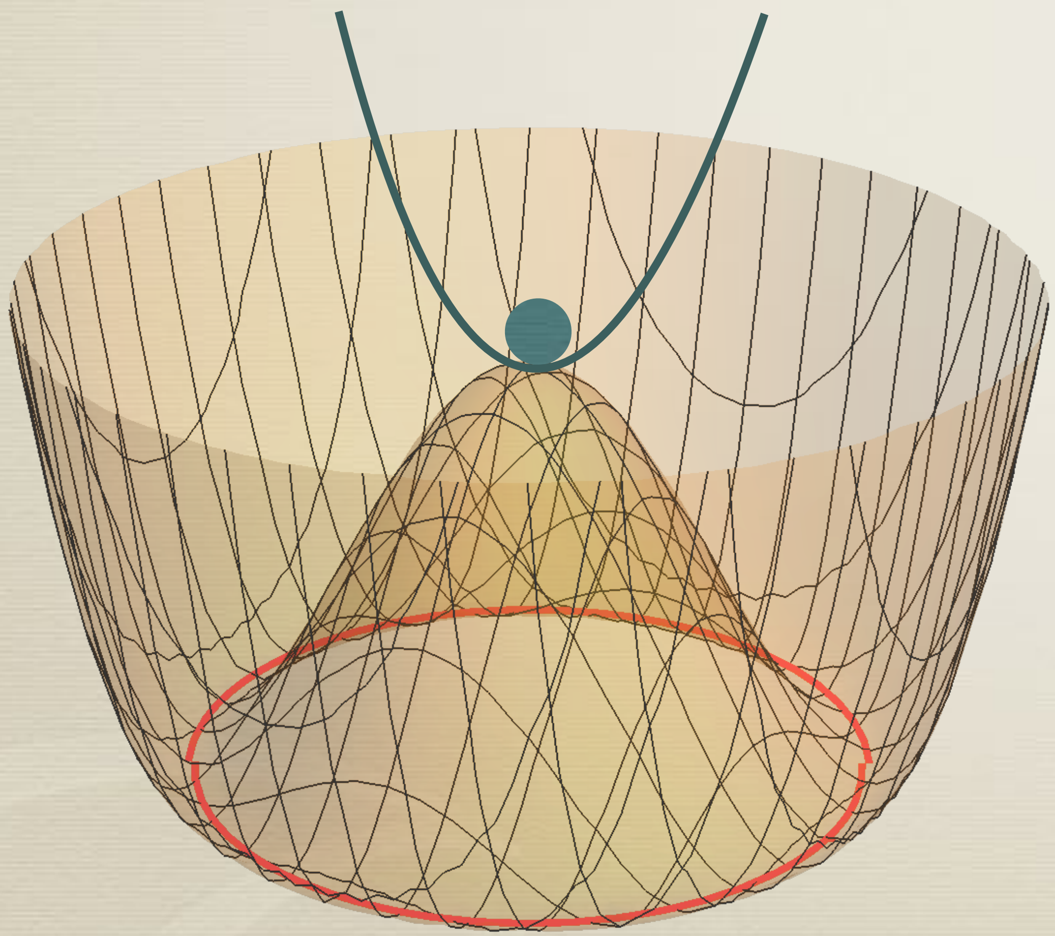




Back up

Cosmic strings

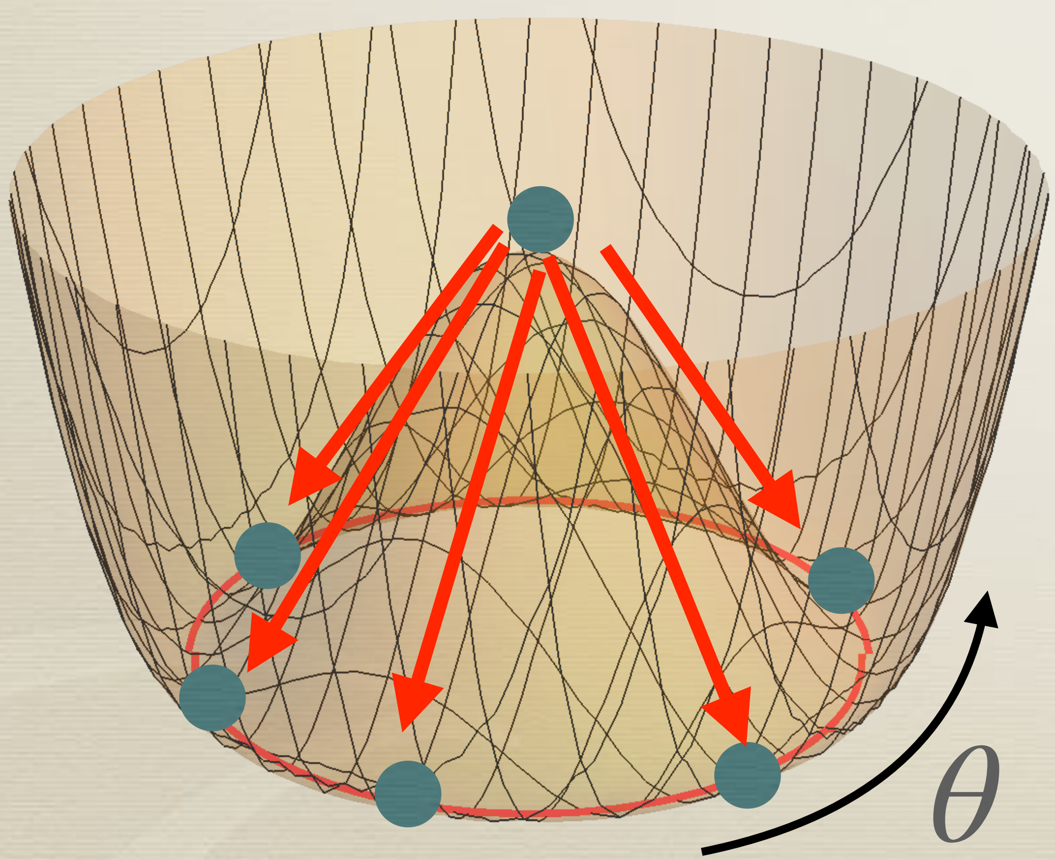
trapping by thermal potential,
coupling with inflaton, etc.

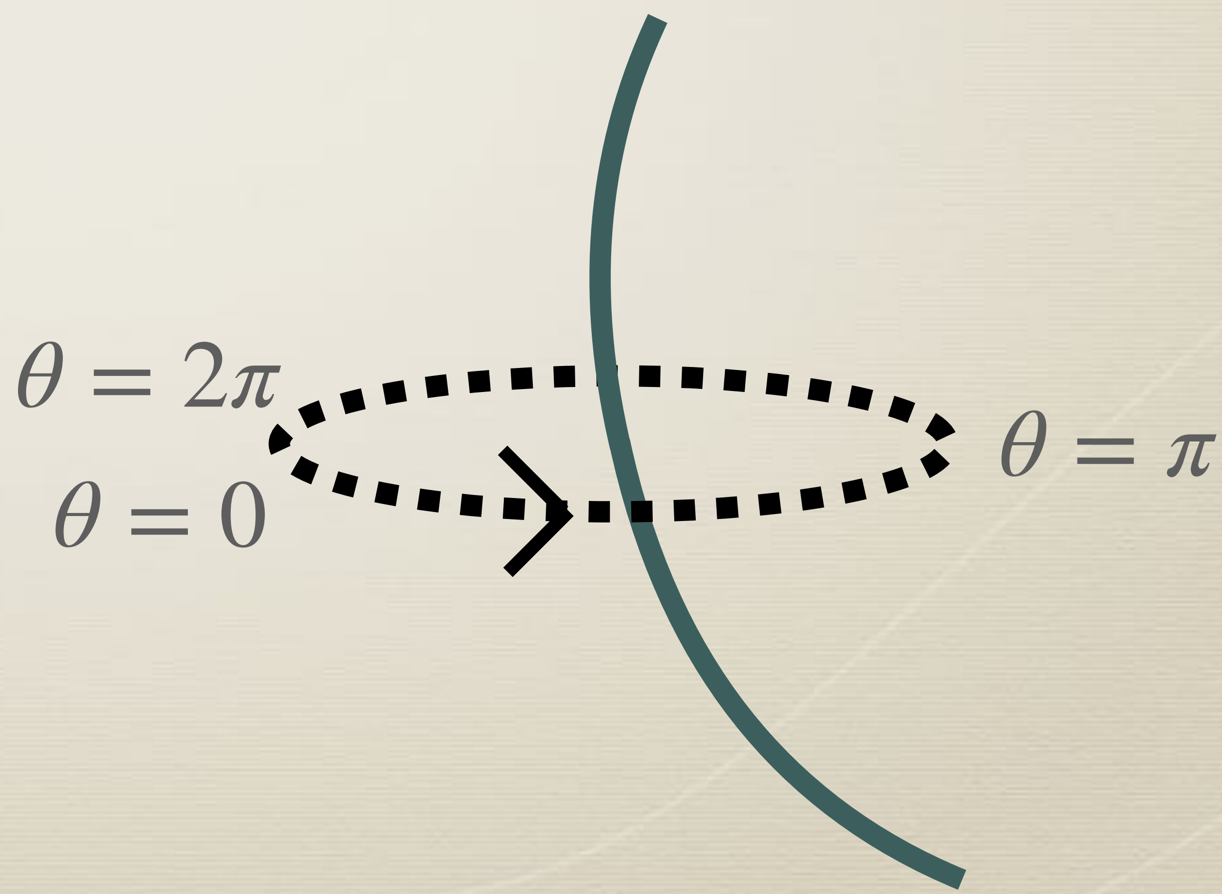


$$V = (-m^2 + c_T T^2 + c_H H_{\rm inf}^2)\,|\,P\,|^2 + \cdots$$

Cosmic strings

Phase transition → Inhomogeneous configurations including cosmic strings





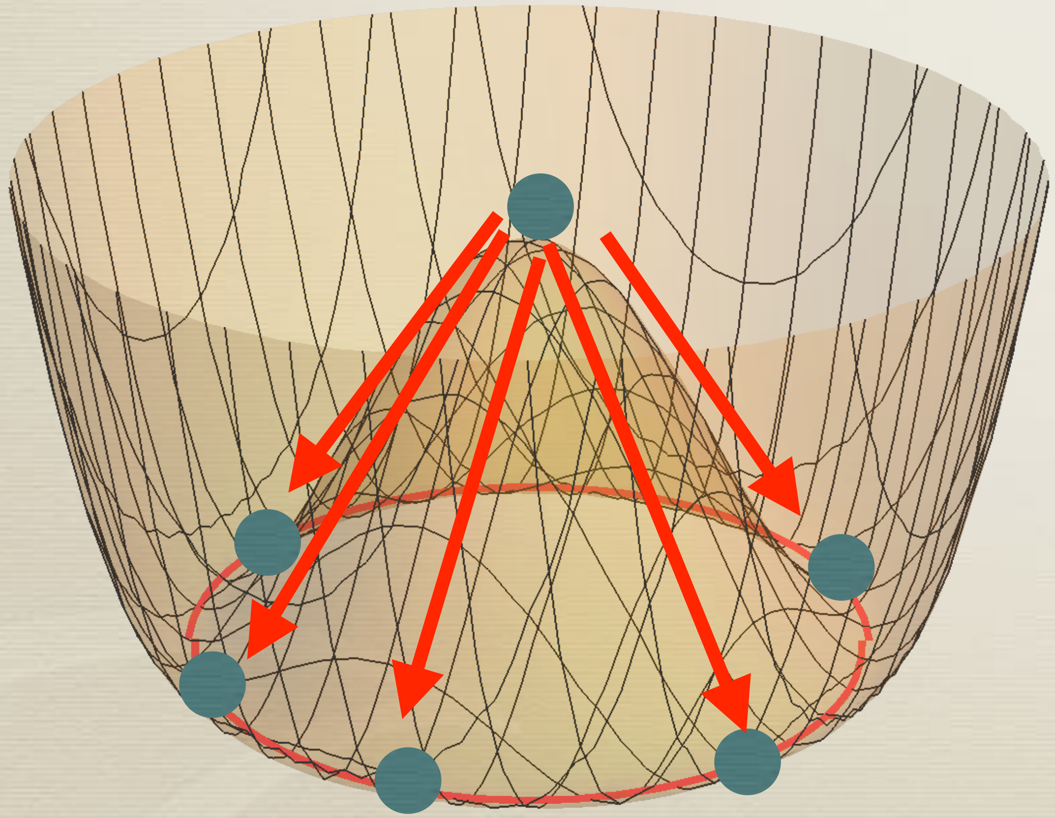
Cosmic strings

Phase transition → Inhomogeneous configurations including cosmic strings

↓

Axions are radiated

Davis (1986)

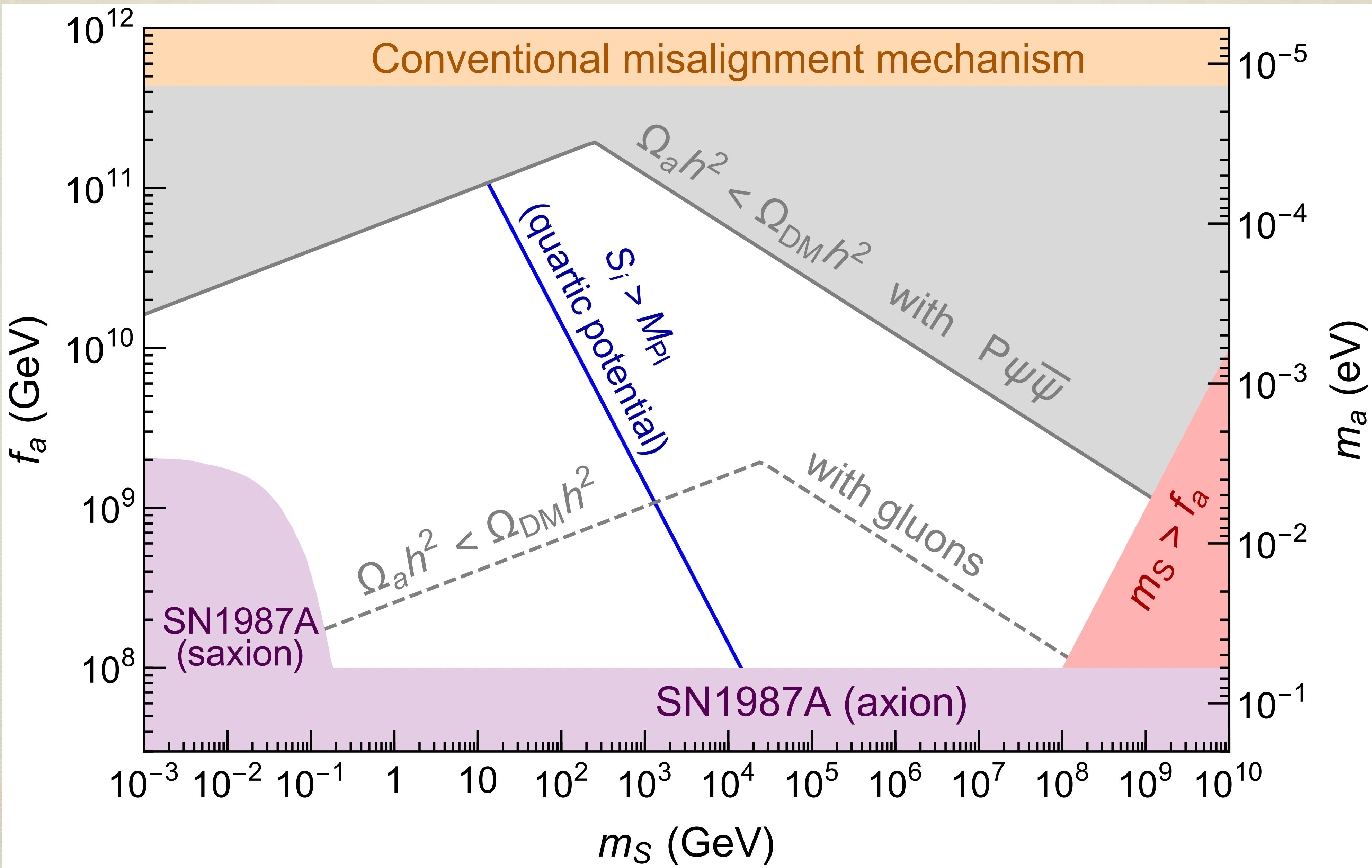


$$\frac{\rho_a}{\rho_{\rm DM}} = 0.4 - 10 \left(\frac{f_a}{10^{11}\ \mathrm{GeV}} \right)^{1.19}$$

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

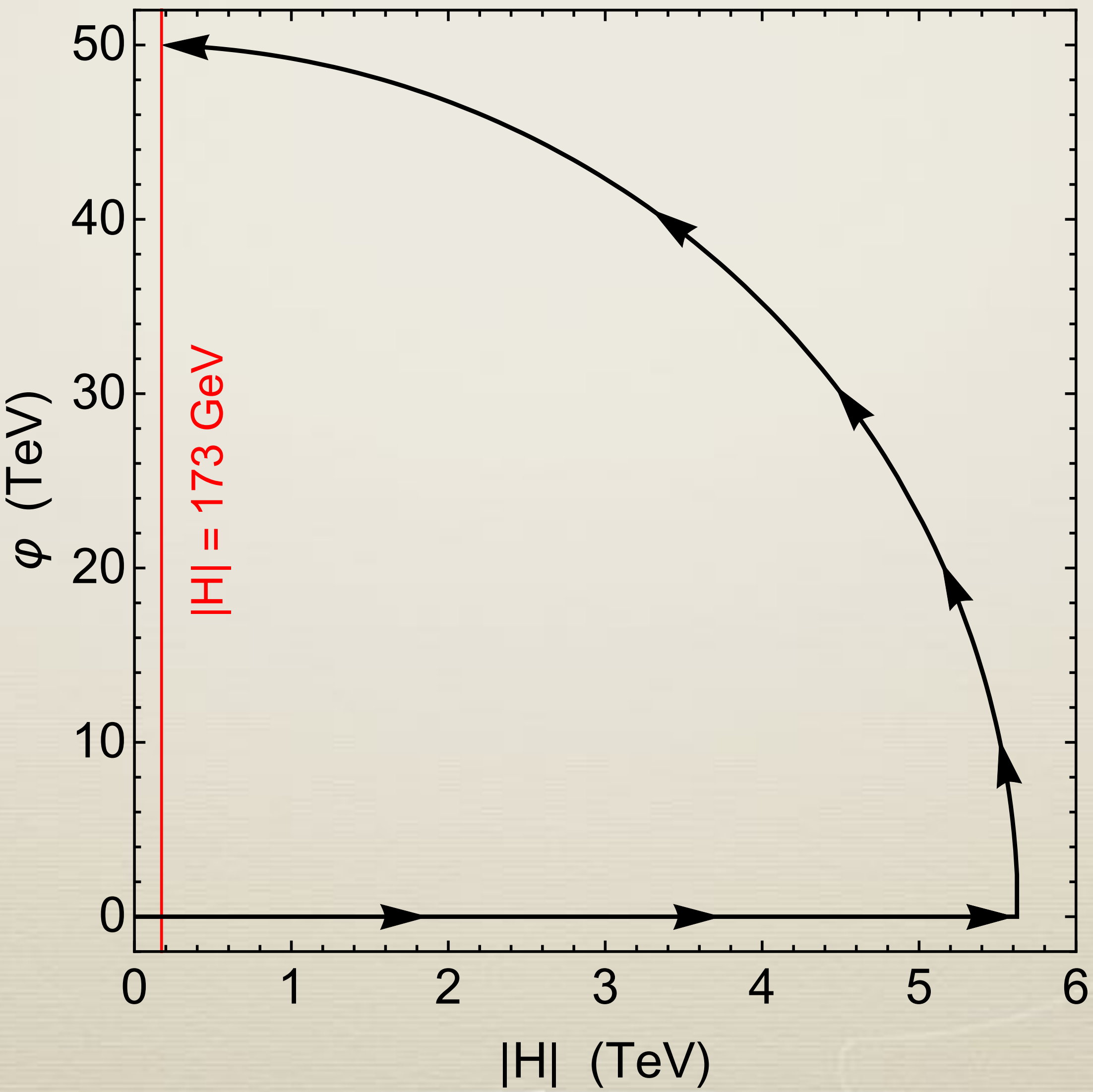
Thermalization

Co, Hall and KH (2019)



Earlier EW phase transition

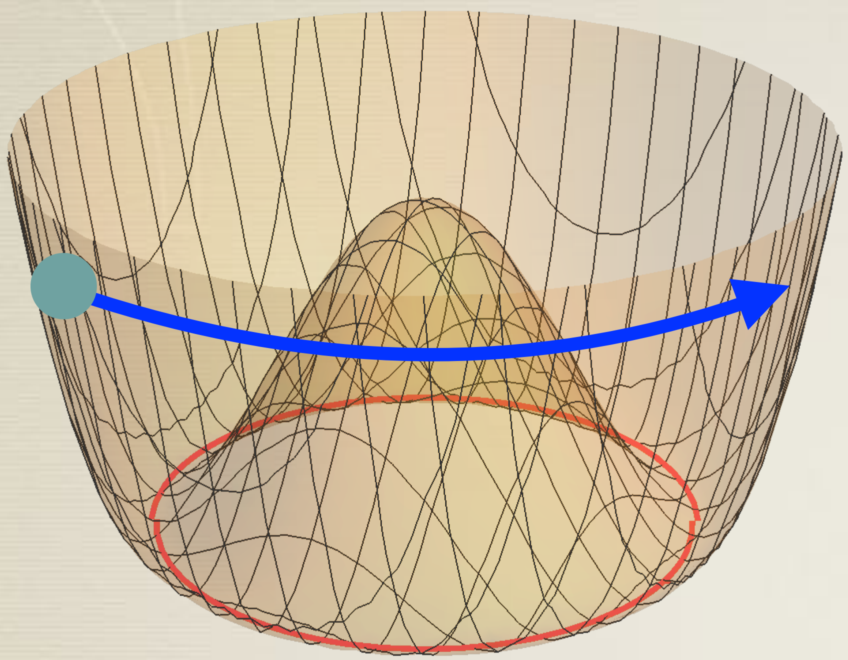
$$V(H,\varphi) = \lambda_H^2\left(|H^2| - v^2\right)^2 + \kappa^2\left(\varphi^2 - v_\varphi^2\right)^2 + \lambda^2\left(\varphi^2 - v_\varphi^2\right)\left(|H|^2 - v^2\right)$$
$$+ c_H T^2 |H|^2 + c_\varphi T^2 \varphi^2 \,.$$



Axion kination

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,

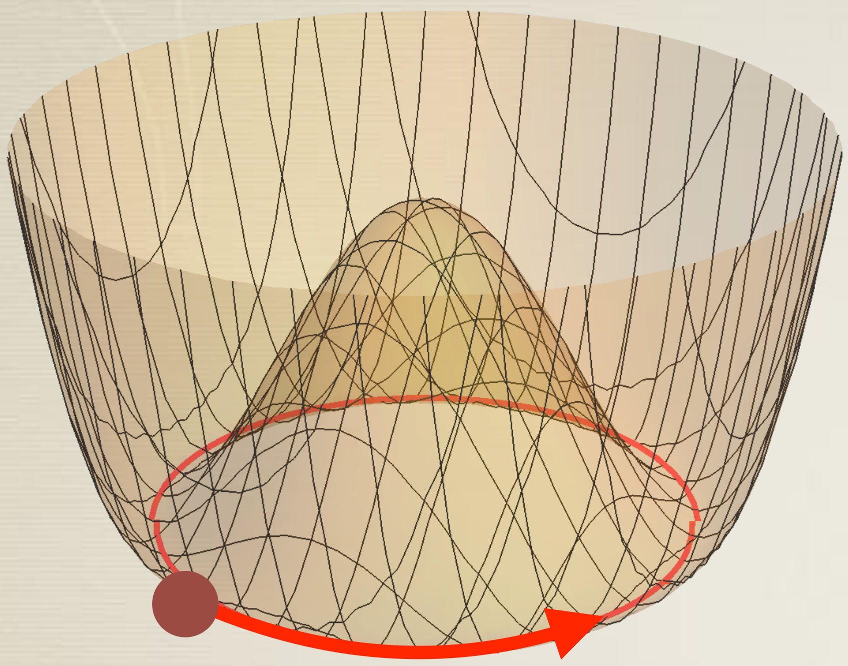
$$\dot{\theta} = \text{const}, \quad S^2 \propto R^{-3}$$

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

matter

Equation of state of rotations

Co and KH (2019)



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

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

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

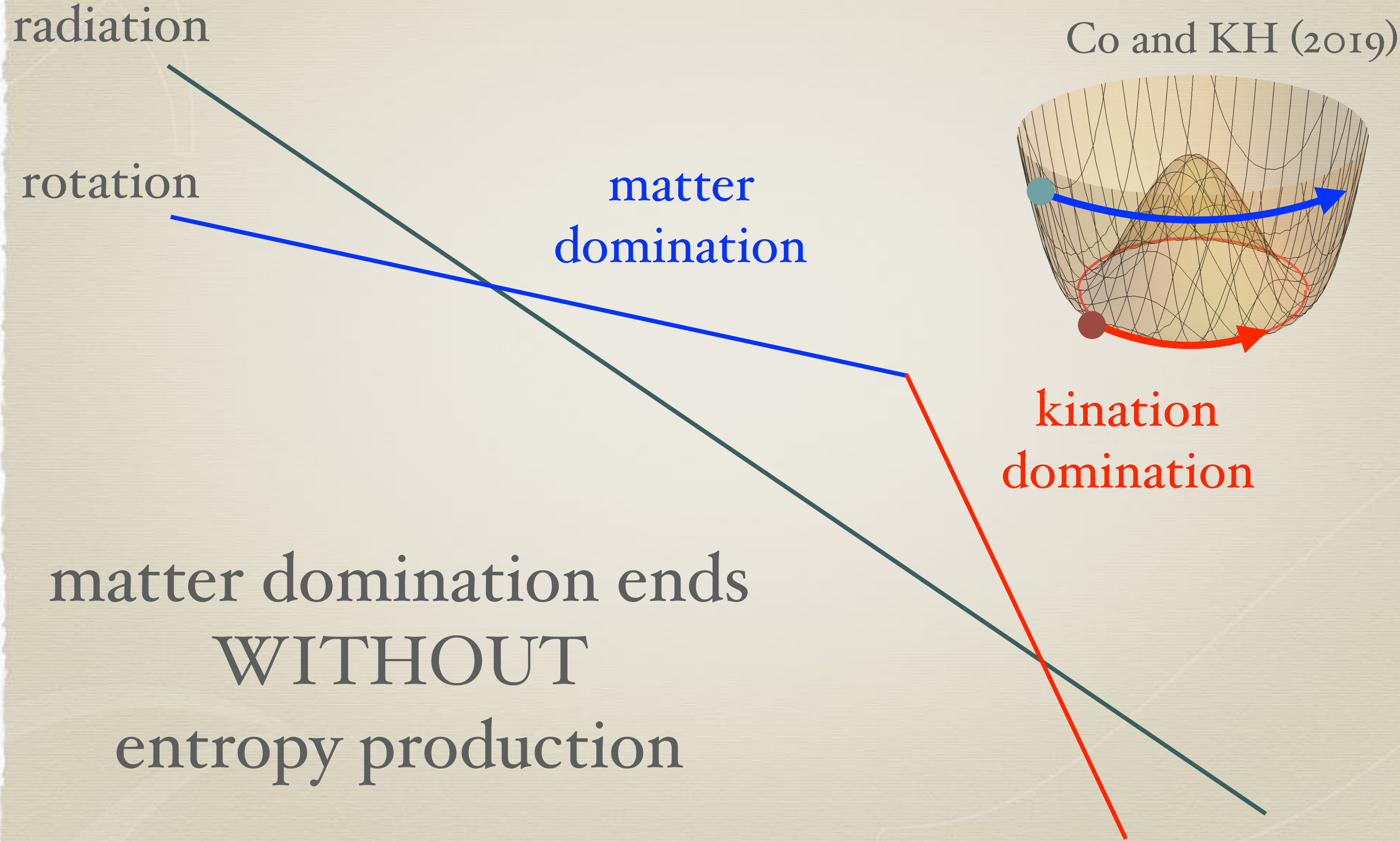
$$\rho = \dot{\theta}^2 S^2 \propto R^{-6}$$

kination

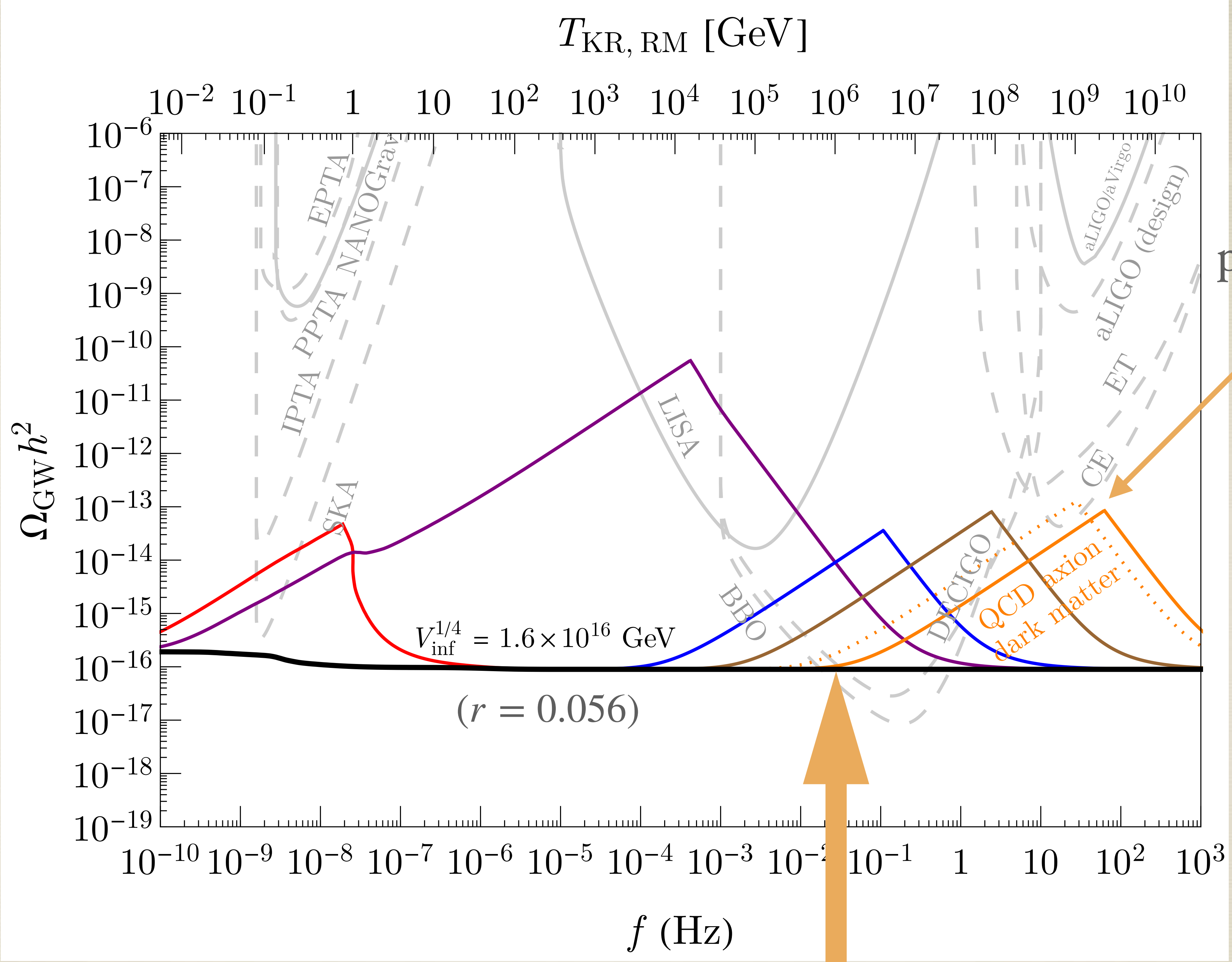
Axion energy is dominantly from the kinetic term

Axion kination

Co and KH (2019)



matter domination ends
WITHOUT
entropy production



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)

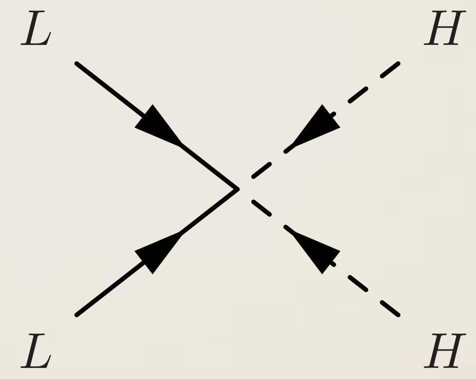
Lepto-axiogenesis

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

Majorana neutrino mass

Majorana neutrino masses break the lepton symmetry

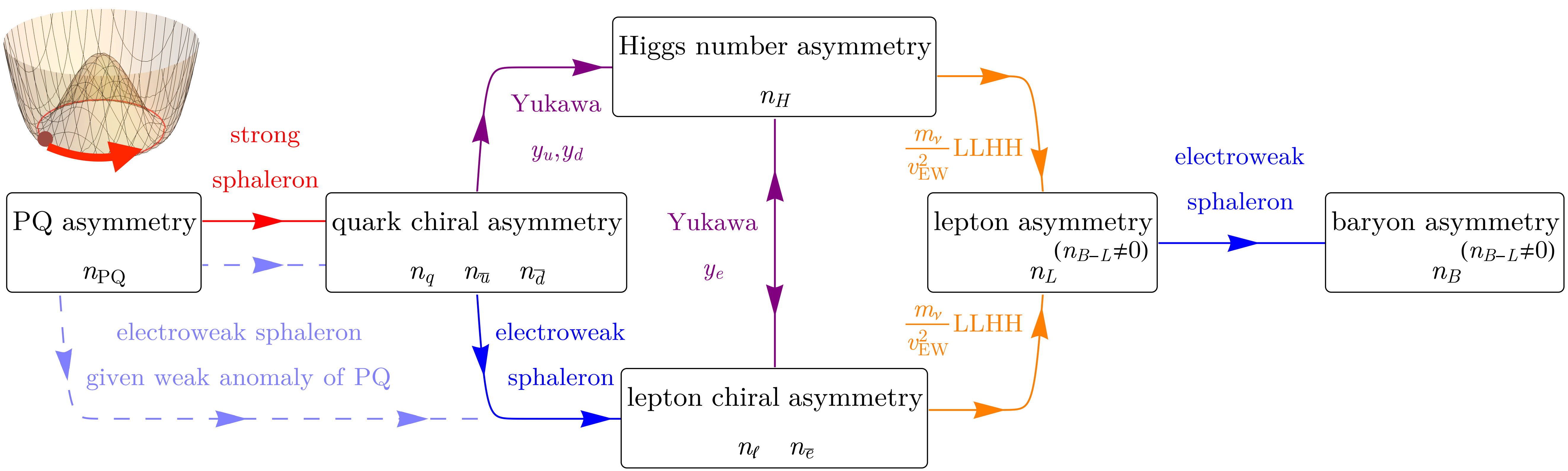
$$\frac{1}{M}LLHH$$



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

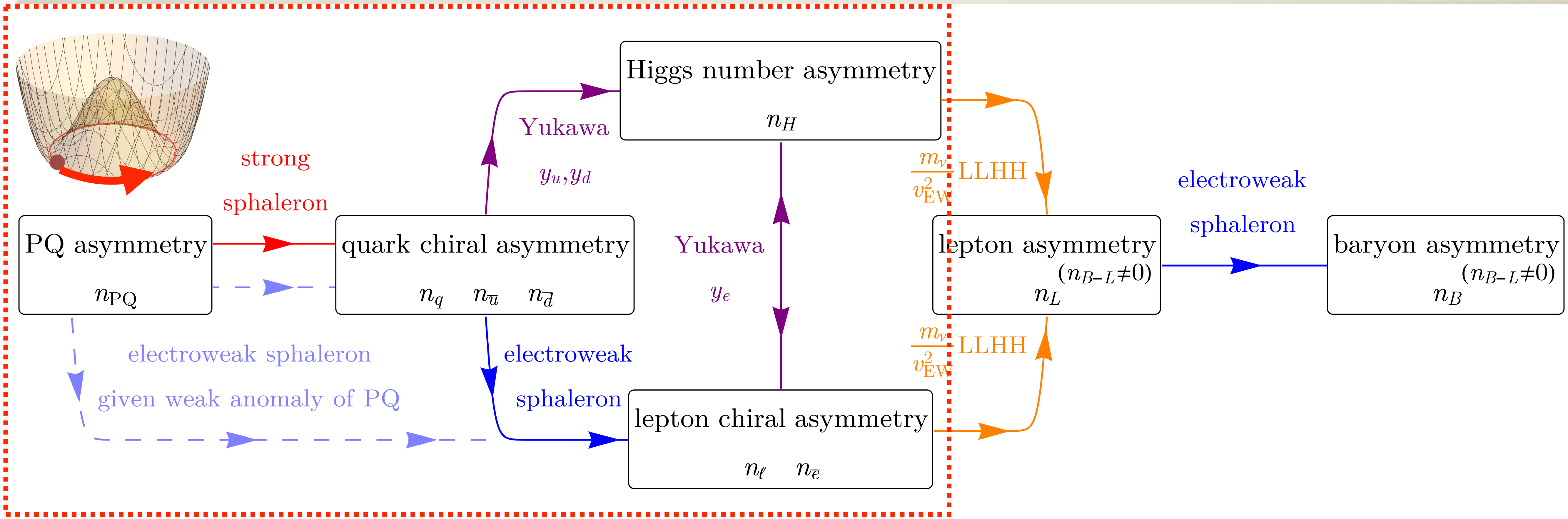
Charge flow

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



Charge flow

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

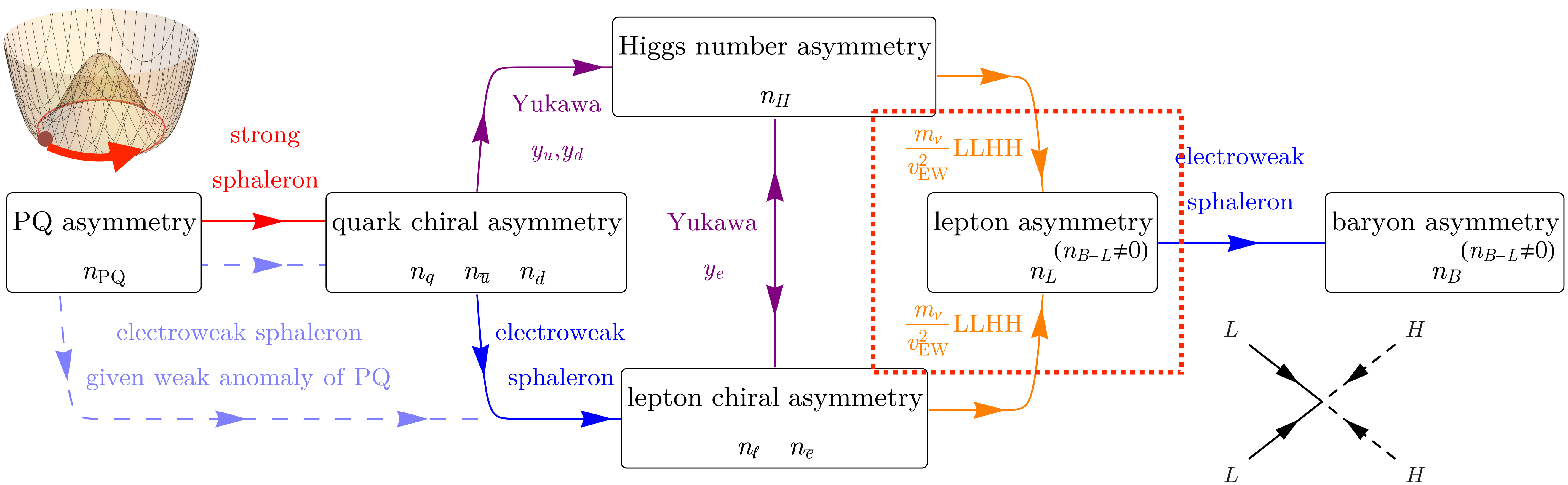


efficient and
reaches equilibrium

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

Charge flow

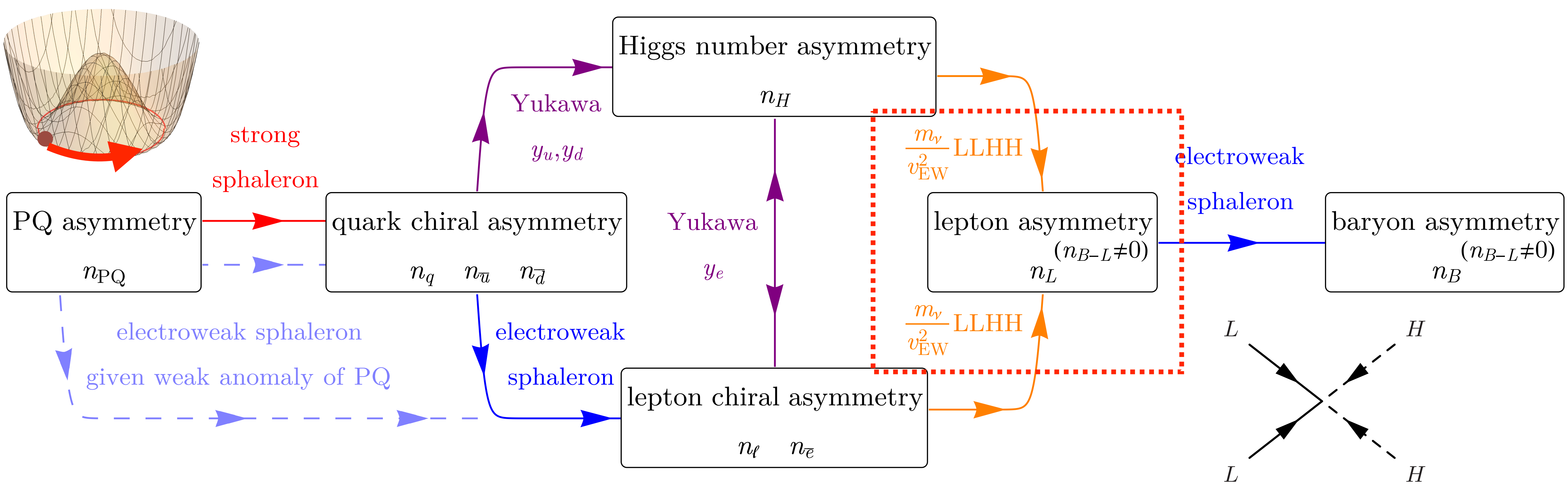
Co, Fernandez, Ghalsasi, Hall and KH (2020)



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

Charge flow

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



not efficient at low temperatures

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

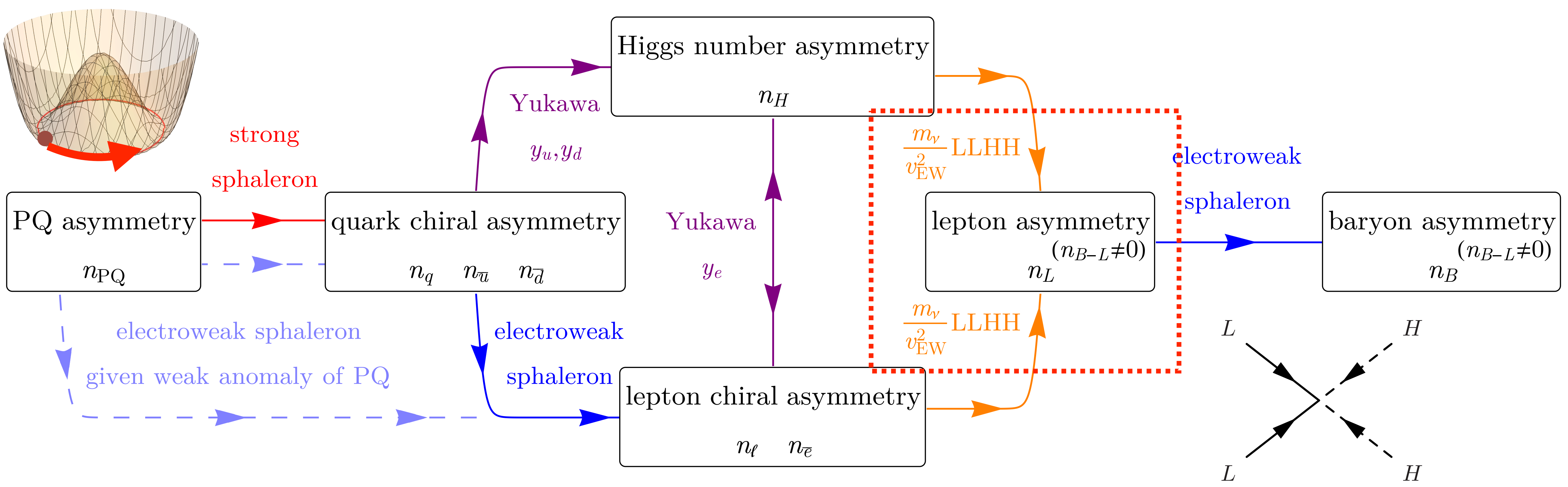
$$\propto \dot{\theta} \times T^0$$

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

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

Charge flow

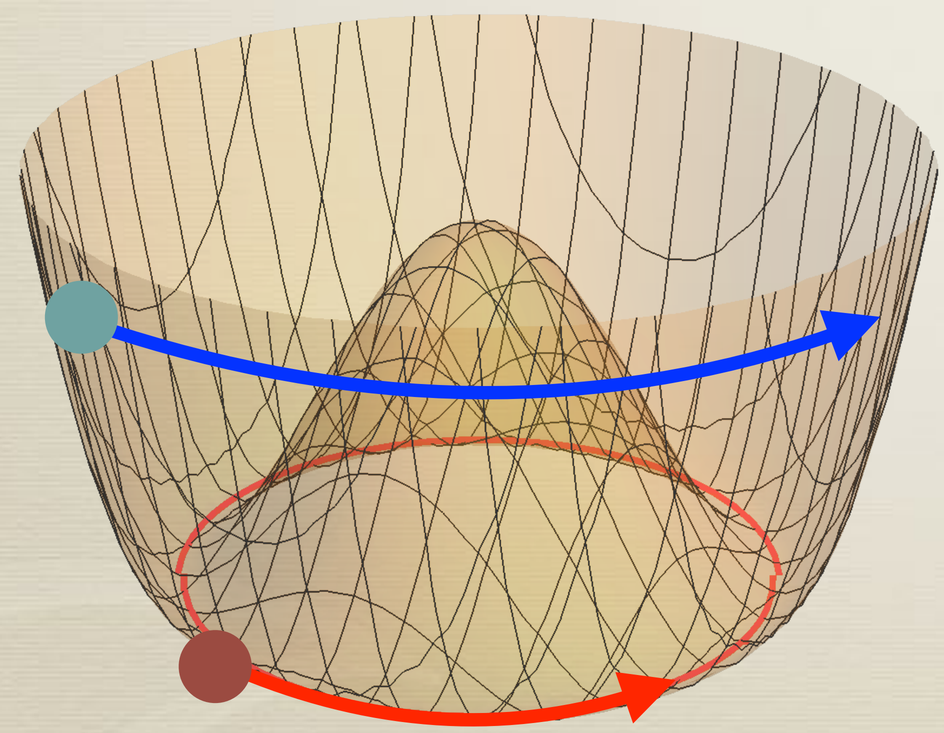
Co, Fernandez, Ghalsasi, Hall and KH (2020)



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

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

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

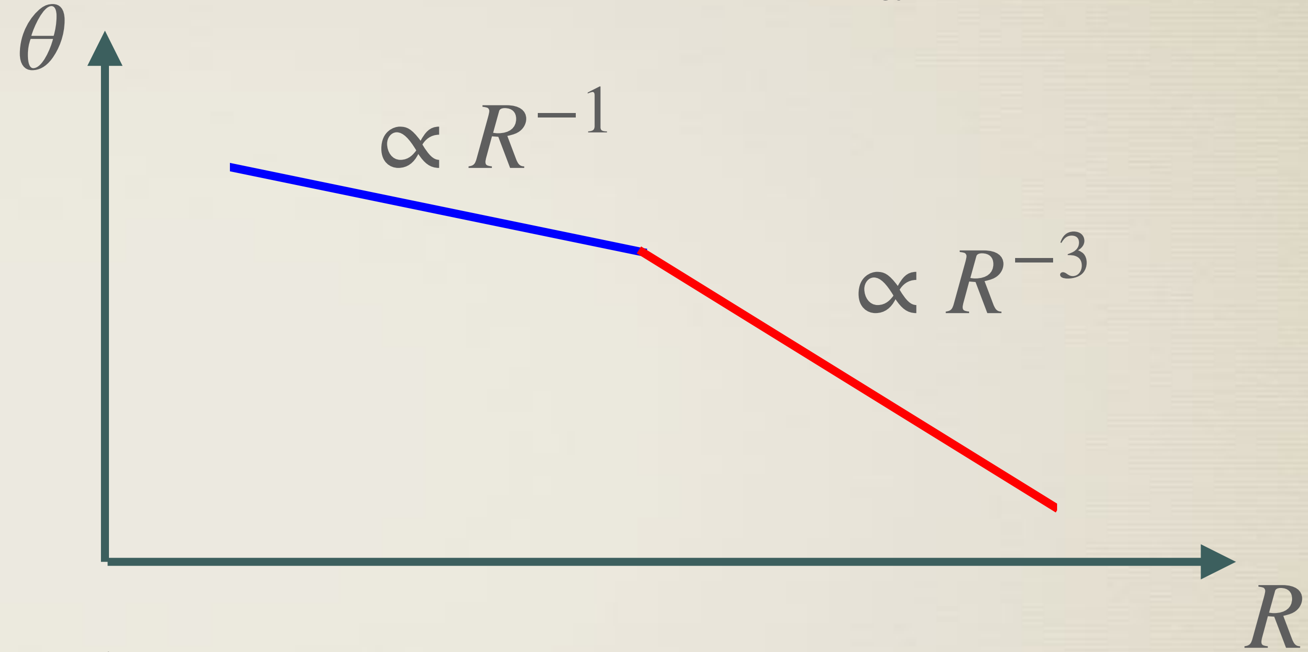
Around the electroweak phase transition

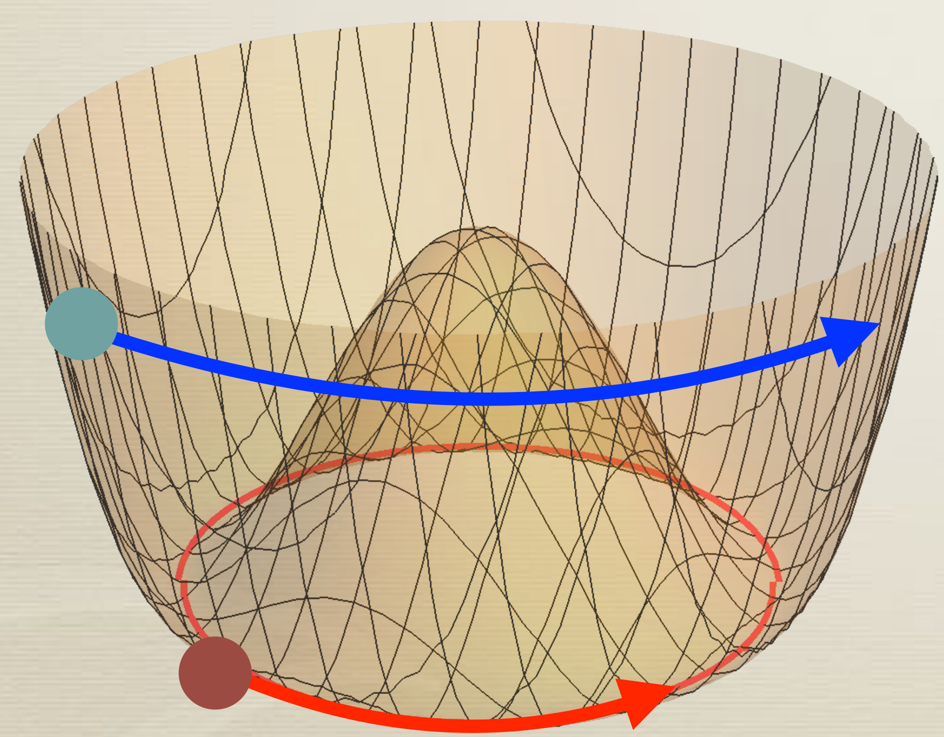
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

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

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





Early time

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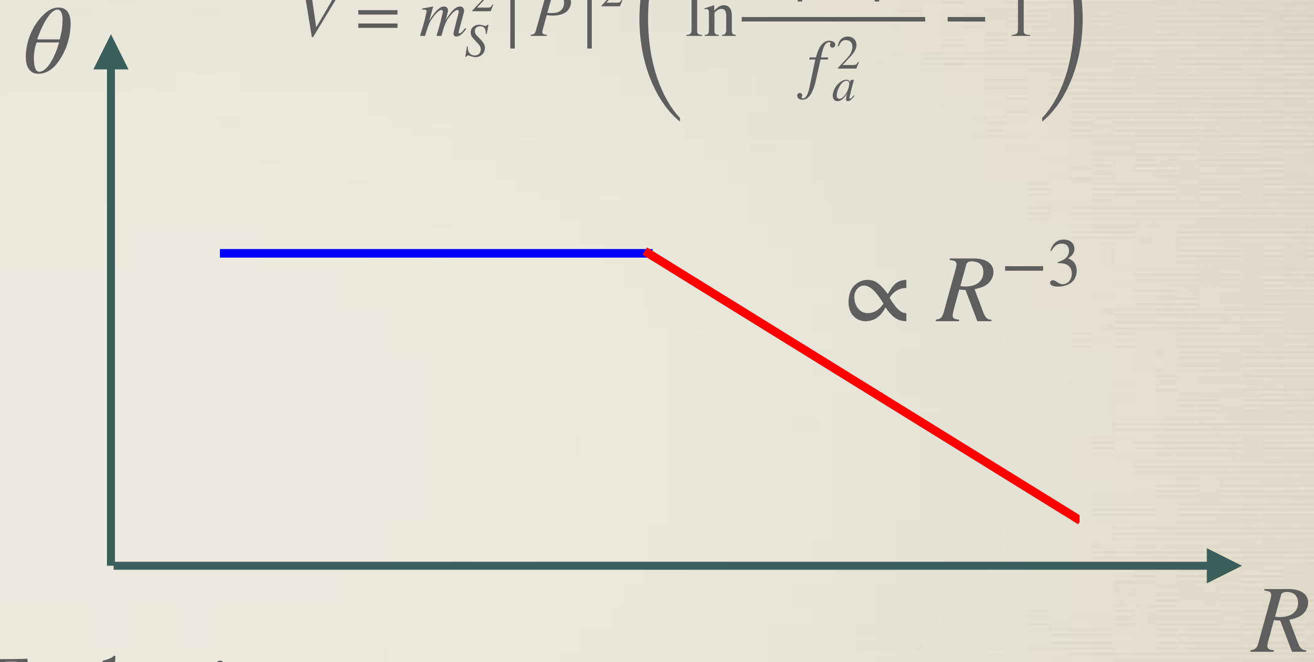
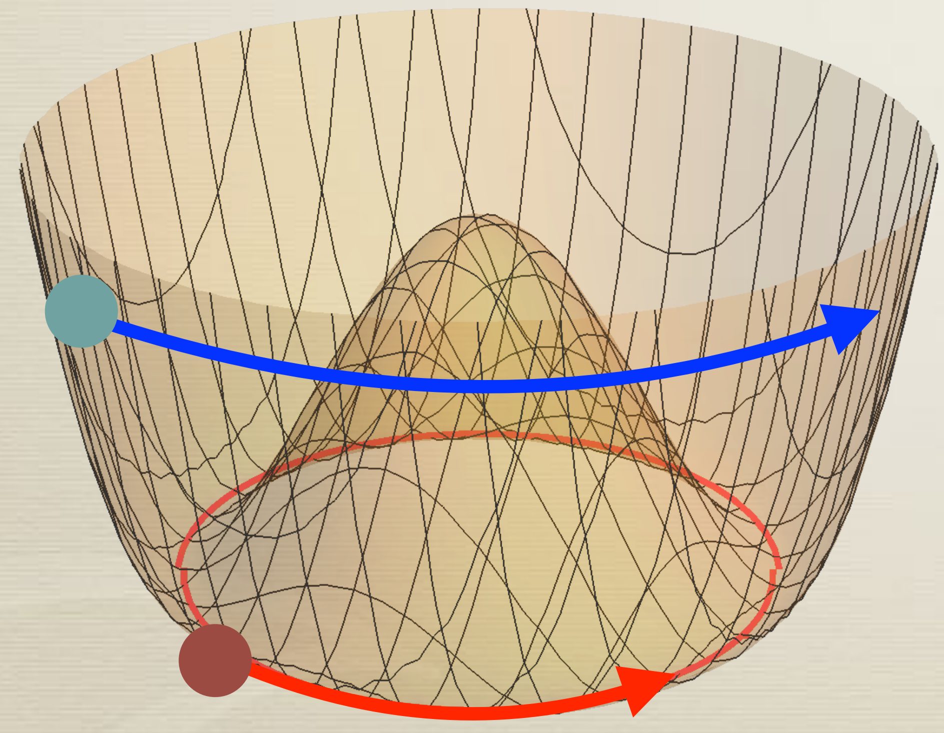
Angular velocity?

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

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





Early time

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

Around the electroweak phase transition

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

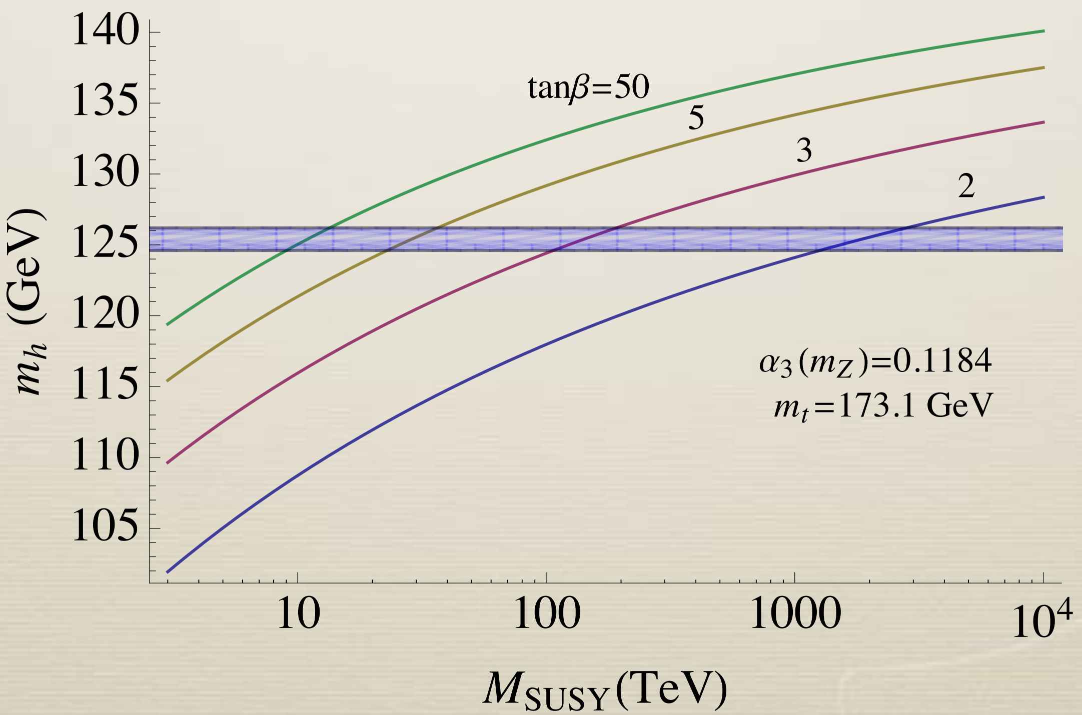
Supersymmetry

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

In supersymmetric models,

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

Consistent with the Higgs mass



Supersymmetry

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

In supersymmetric models,

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

Consistent with the 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 $m_{\text{SUSY}} \sim 100$ GeV
* Gauge coupling unification $m_{\text{SUSY}} \lesssim 10^6$ GeV
* Lightest supersymmetric particle as DM $m_{\text{SUSY}} \lesssim 10^3$ GeV

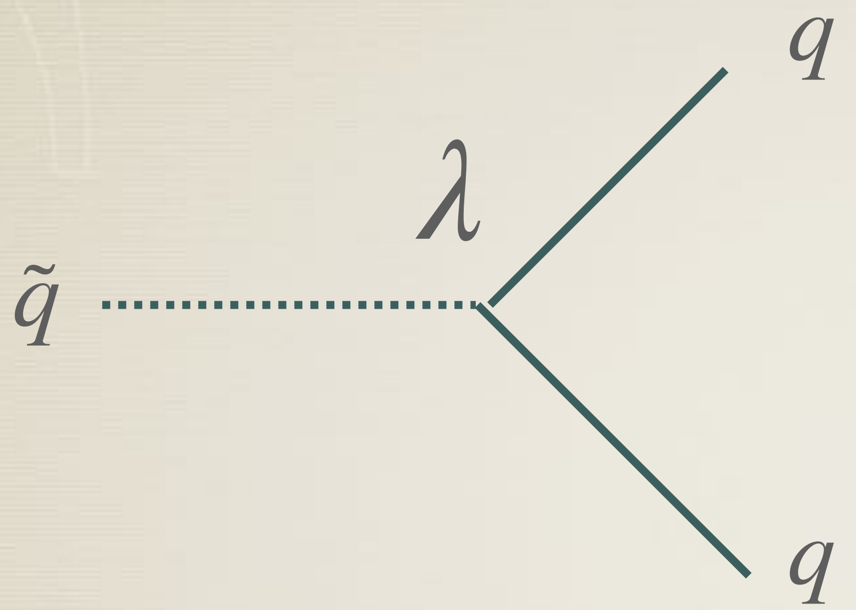
  (invalid with RPV)
* Baryogenesis from axion rotation and neutrino mass

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

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

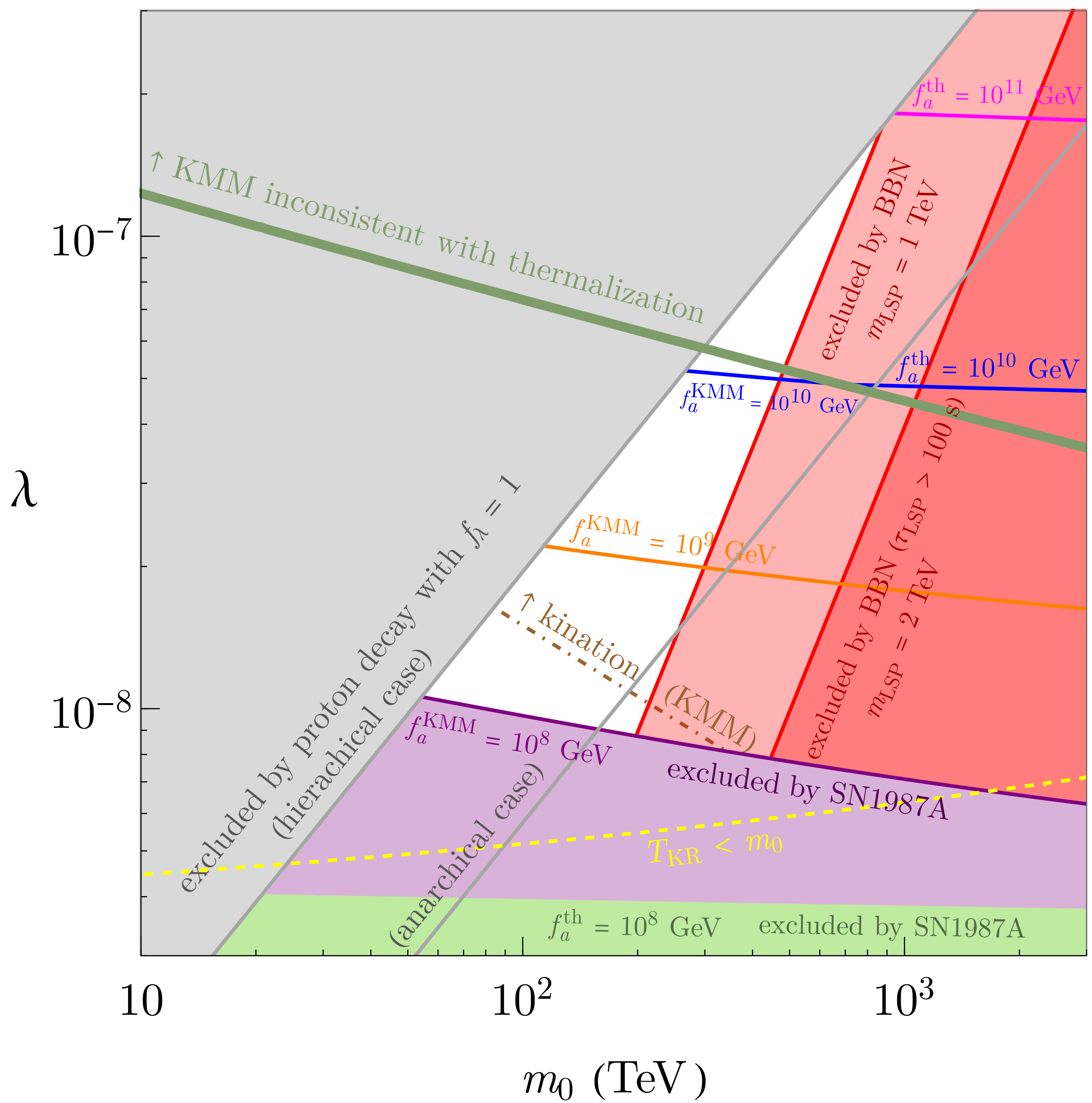
$$W = \frac{1}{2}\lambda_{ijk} 10_i \bar{5}_k \bar{5}_k = \lambda_{ijk}(Q_i \bar{d}_j L_k + \frac{1}{2}\bar{u}_i \bar{d}_j \bar{d}_k + \frac{1}{2}\bar{e}_i L_j L_k)$$

To minimized the proton decay rate,

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

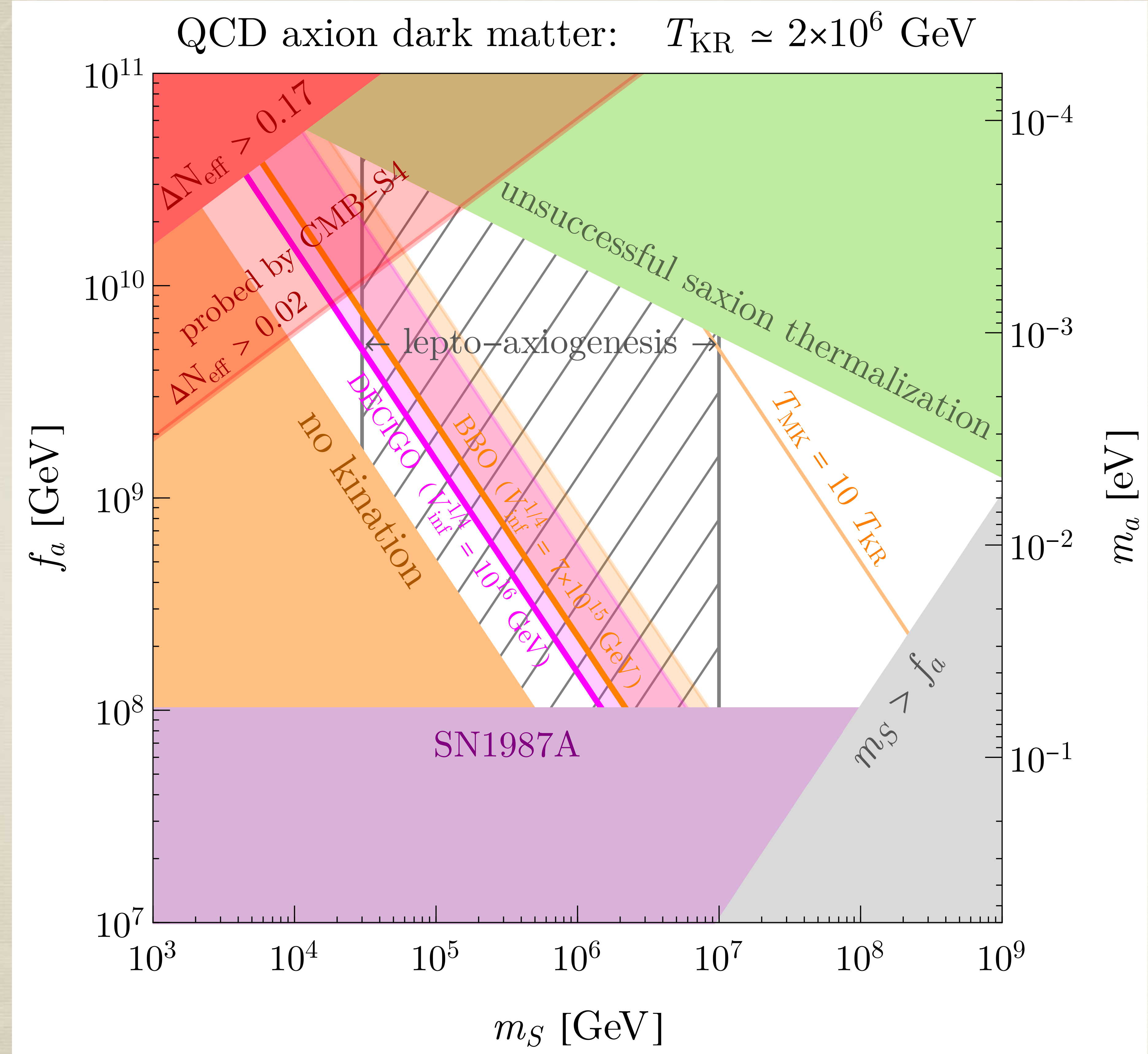
Anarchical 5-plets : $\lambda_{i12} \sim \lambda_{i13} \sim \lambda_{i23}$

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

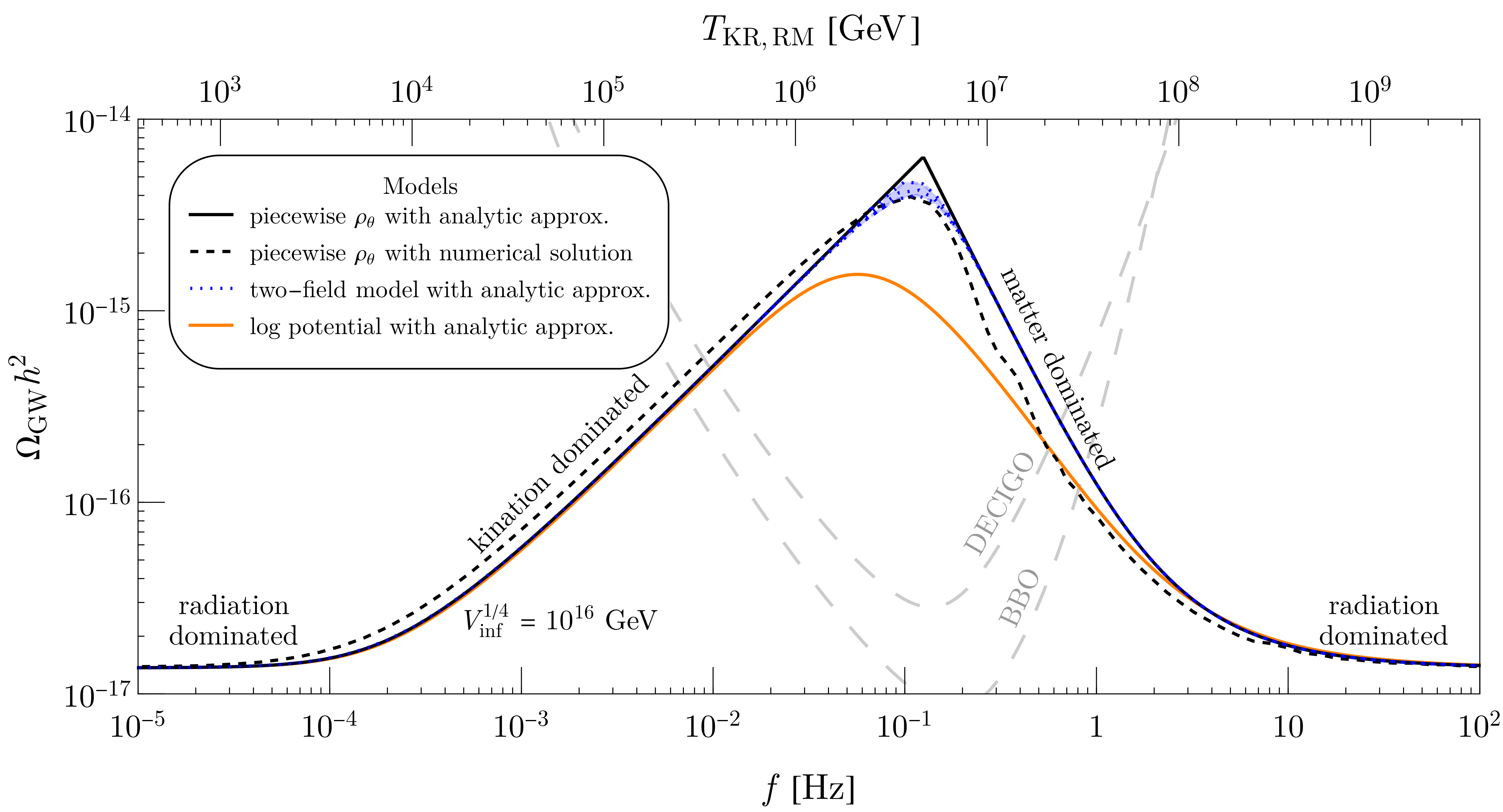


↑ KMM inconsistent with thermalization
$f_a^{\rm th}$ = 10^{11} GeV
excluded by BBN
$m_{\rm LSP}$ = 1 TeV
$f_a^{\rm th}$ = 10^{10} GeV
$f_a^{\rm KMM}$ = 10^{10} GeV
excluded by BBN ($\tau_{\rm LSP}$ > 100 s)
$m_{\rm LSP}$ = 2 TeV
excluded by proton decay with f_λ = 1
(hierachical case)
$f_a^{\rm KMM}$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

Axion Kination



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



$T_{\rm KR,\,RM}$ [GeV]
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{-14}
10^{-15}
10^{-16}
10^{-17}
$\Omega_{\rm GW}h^2$
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
DECIGO
BBO
radiation dominated
$V_{\rm inf}^{1/4}$ = 10^{16} GeV
radiation dominated
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
f [Hz]