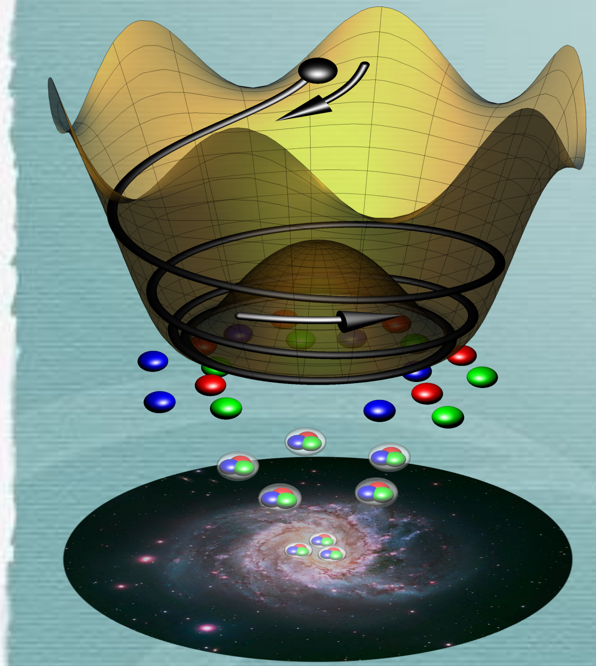
03/30/2023, UCLA Dark Matter 2023

Cosmology of Axion rotation

Keisuke Harigaya (U Chicago)



1910.02080 : Co and KH
1910.14152 : Co, Hall and KH
2301.09647 : Badziak and KH

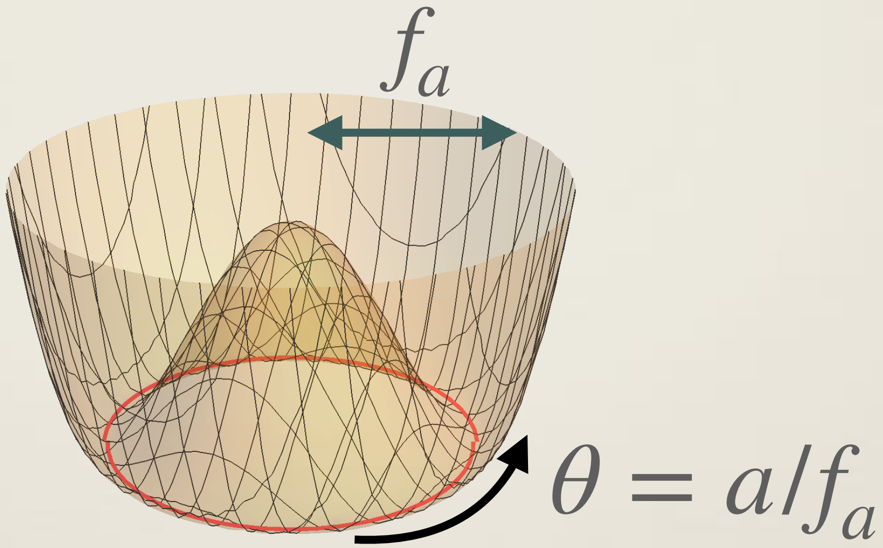
QCD axion

- solves the strong CP problem

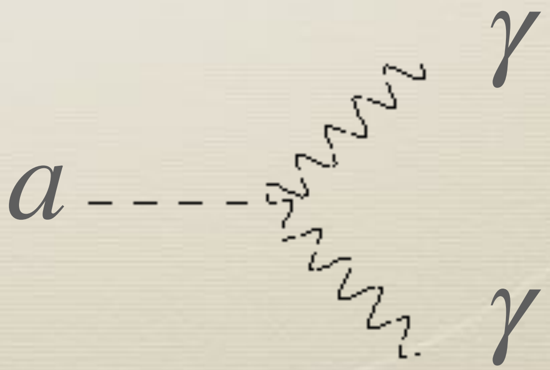
Peccei and Quinn (1977)
Weinberg (1978), Wilczek (1978)

- is a good dark matter candidate

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



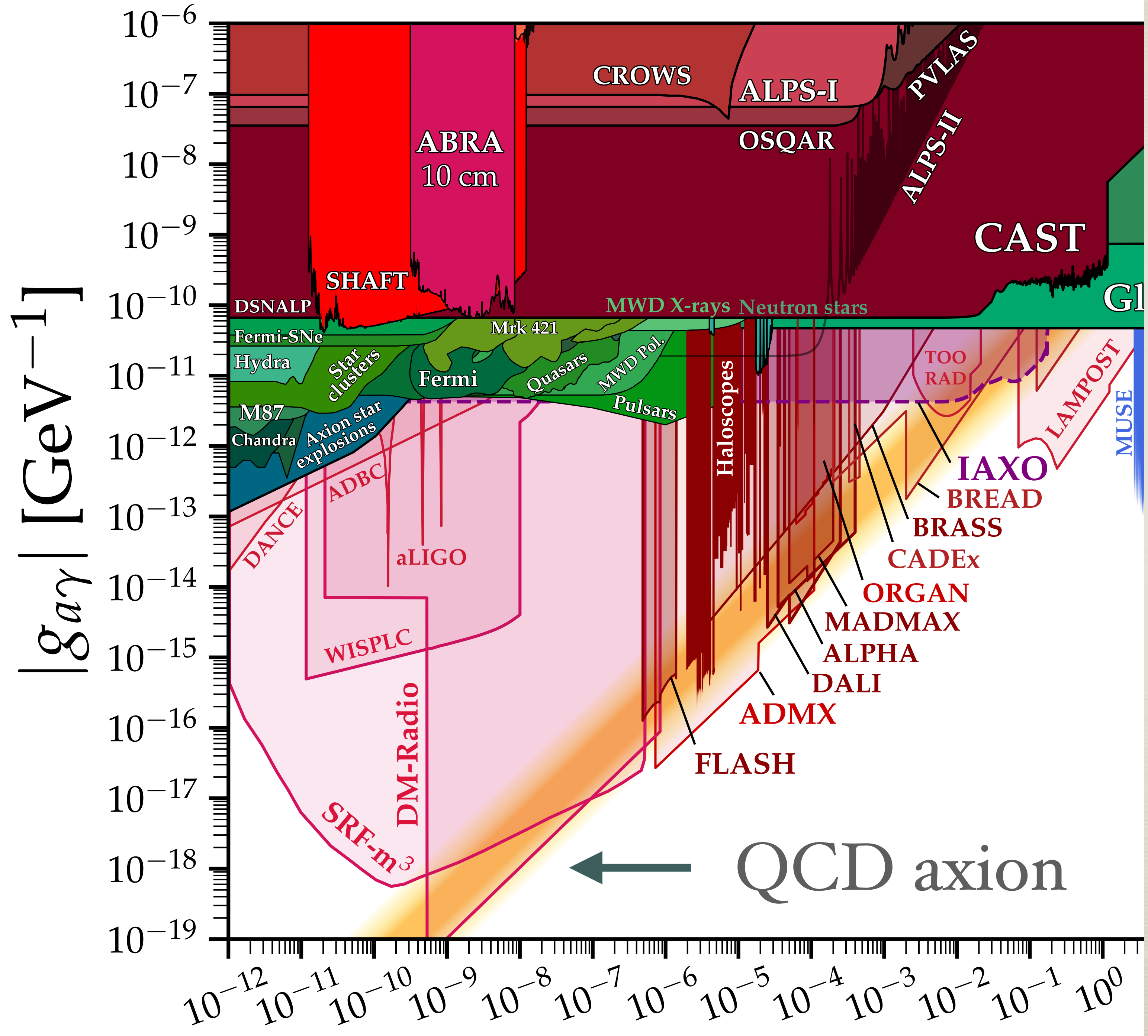
$$m_a = 6\ \text{meV}\,\frac{10^9\ \text{GeV}}{f_a}$$



$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

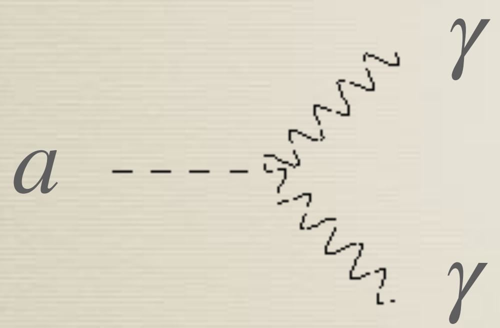
Axion search

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

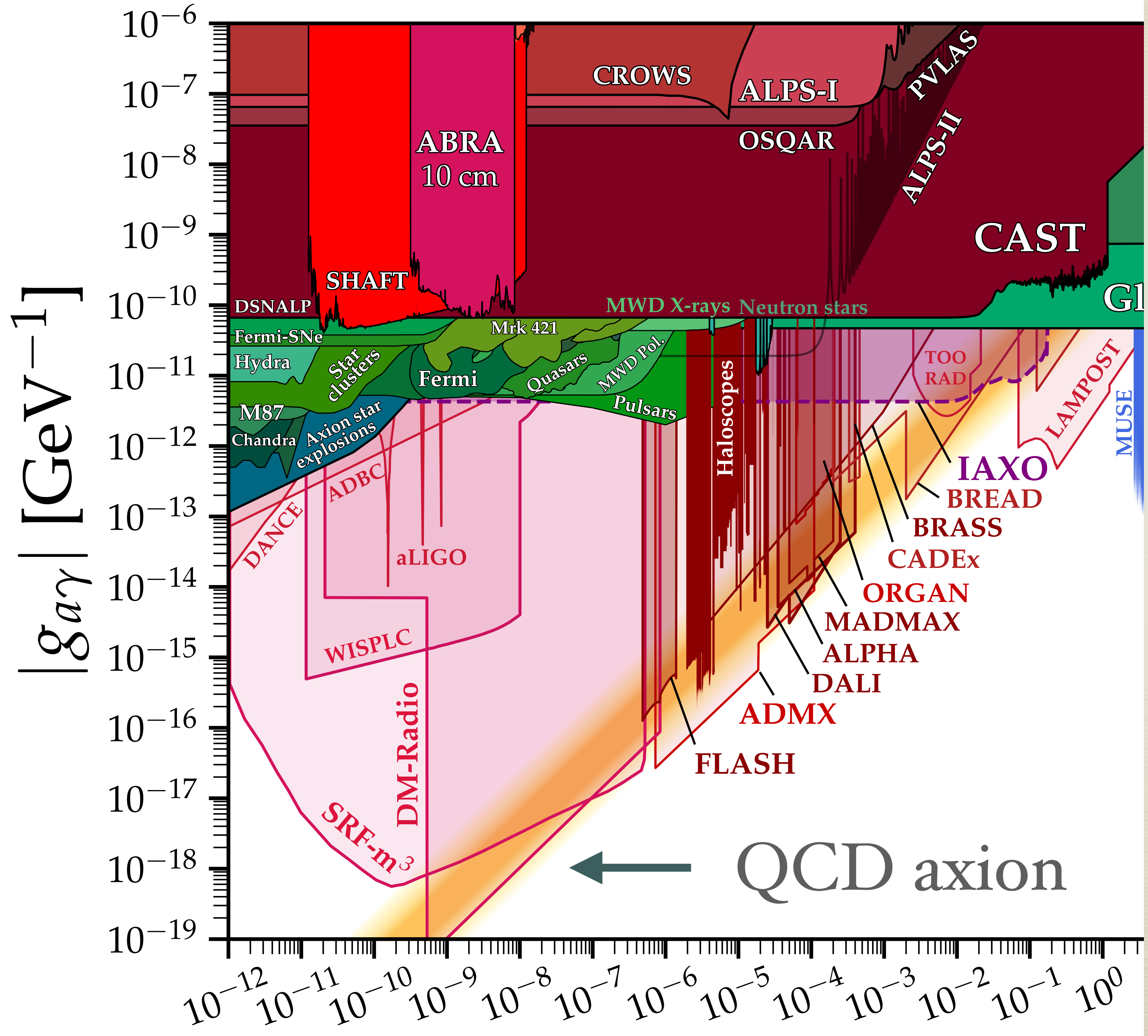


cajohare.github.io/AxionLimits/

Dark Matter?



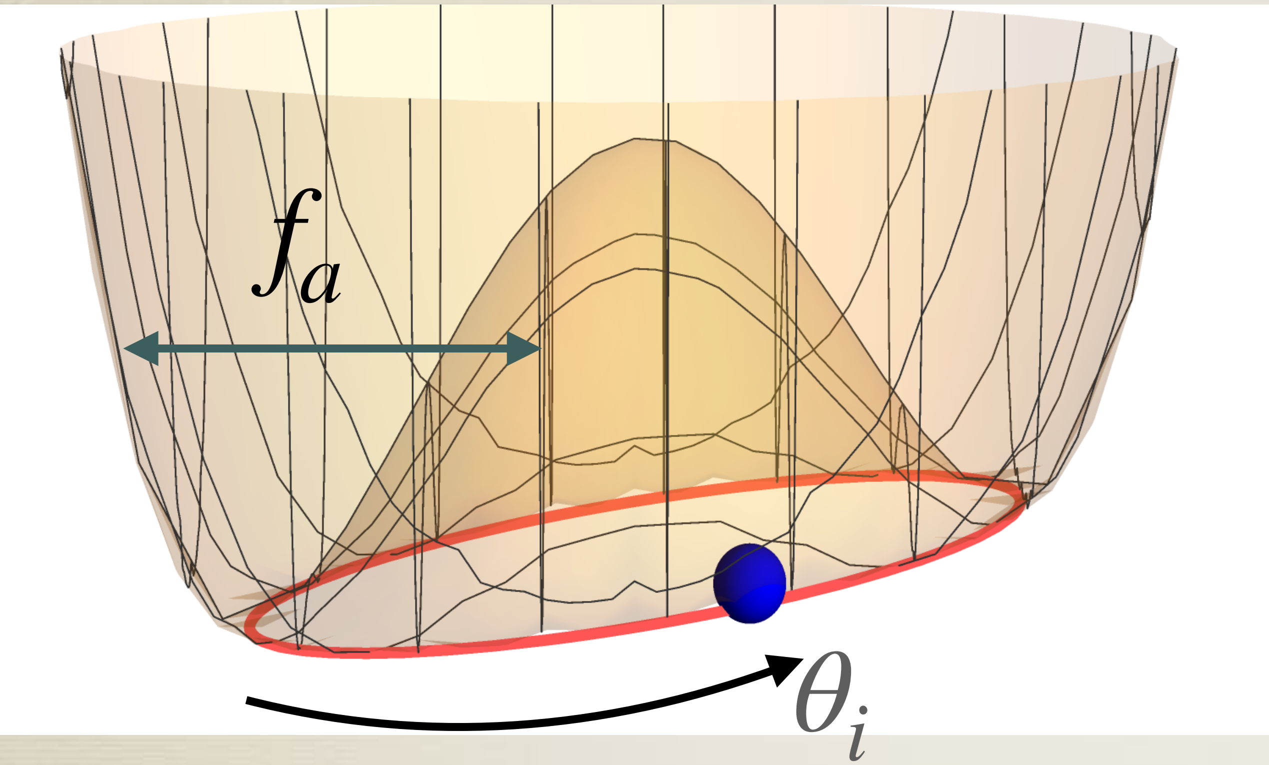
$$\propto \frac{1}{f_a}$$



cajohare.github.io/AxionLimits/

Misalignment mechanism

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

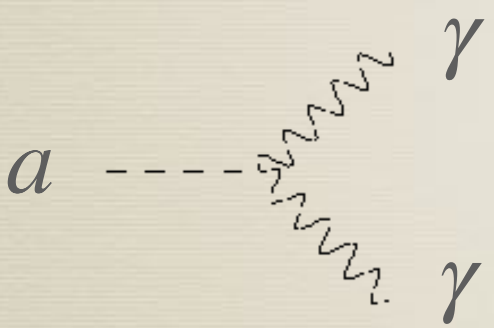


For the QCD axion,

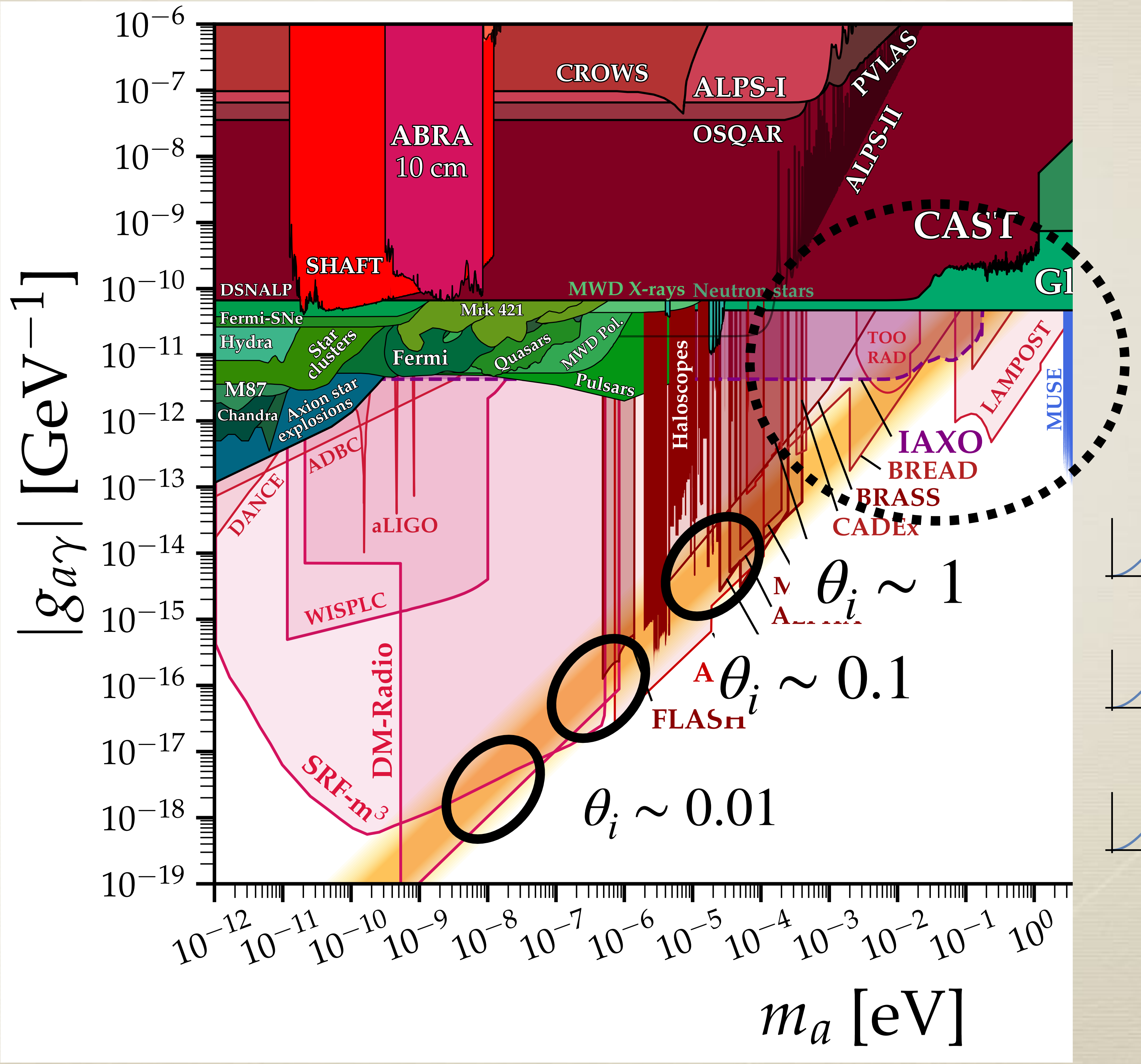
$$\frac{\rho_a}{\rho_{\rm DM}} = \theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{1.19}$$

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

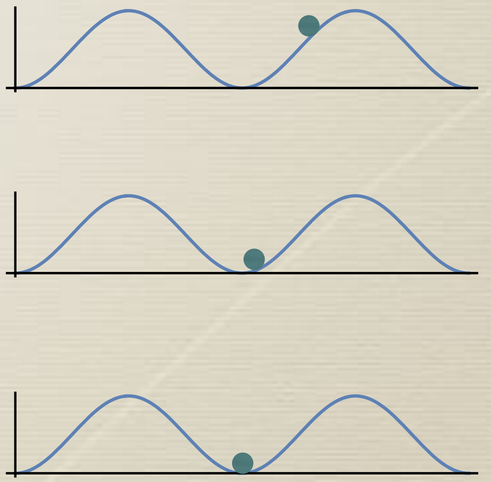
Dark matter



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

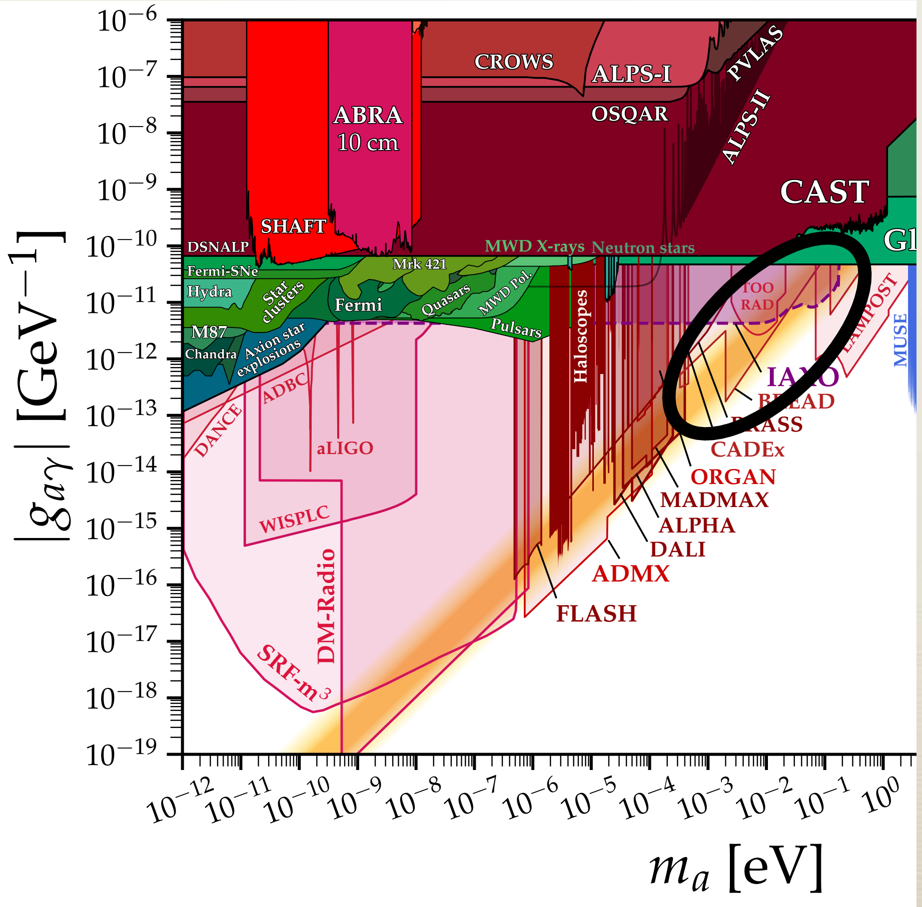


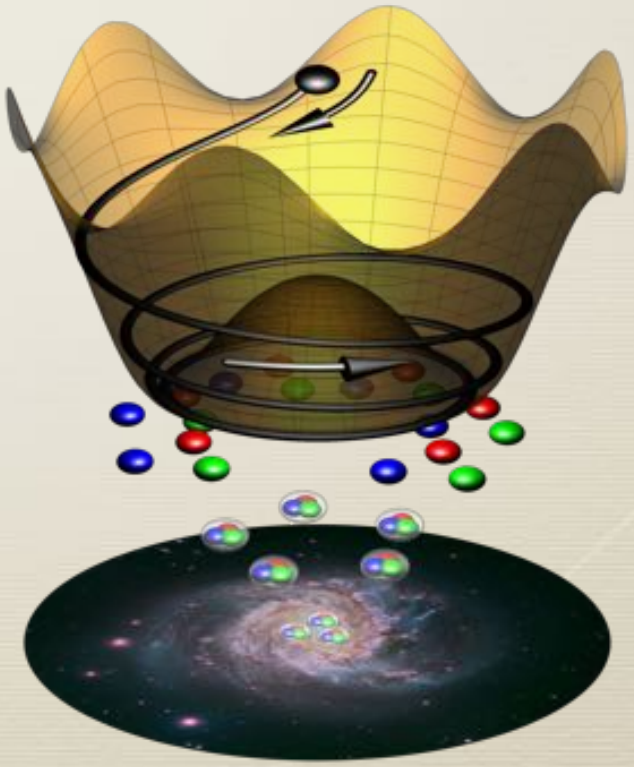
under-produced



I will present new cosmological dynamics of the axion, rotations, which

- enhance axion dark matter abundance and predict larger couplings
- create baryon asymmetry
- have implications for new physics other than the axion





Outline

- Axion rotation and dark matter
- Axion rotation and baryon asymmetry
- Discussion

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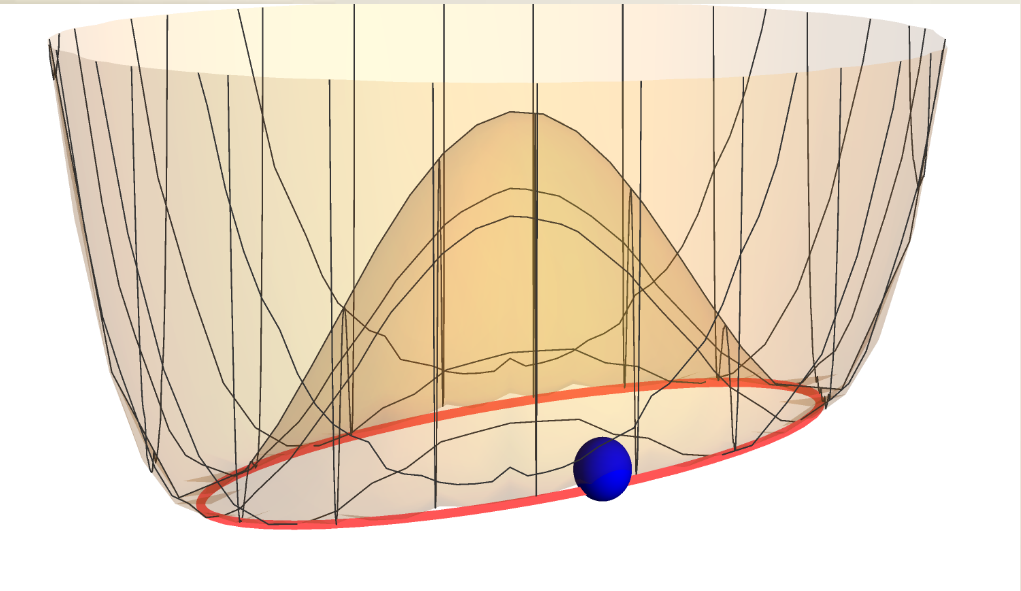
- Discussion

Kinetic misalignment

Rotation?

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

Conventional picture

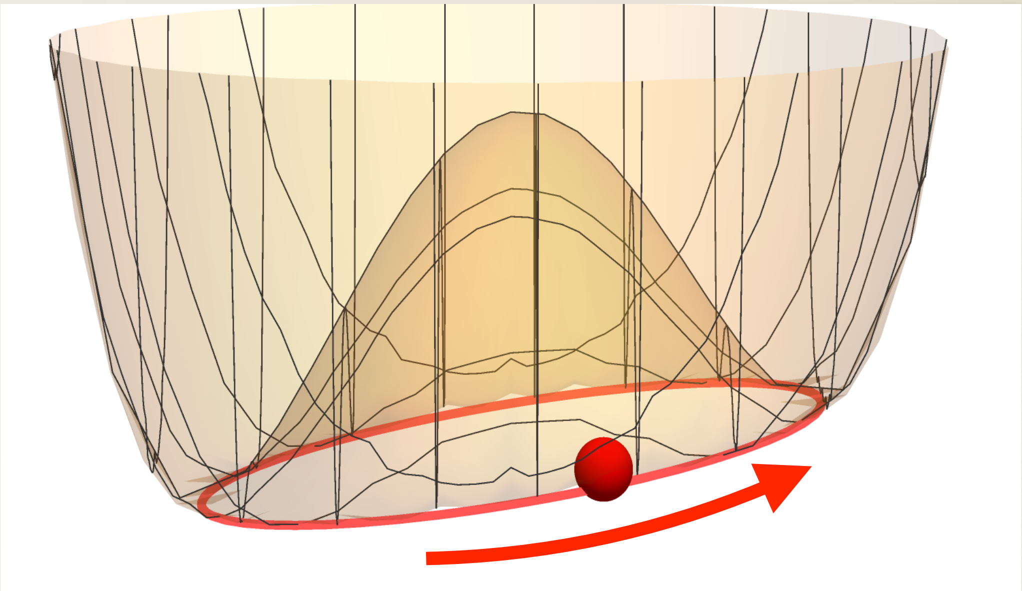


$$\dot{\theta}_i = 0$$

$$V$$

The kinetic energy goes to axions, enhancing the axion abundance

Non-zero initial angular velocity?

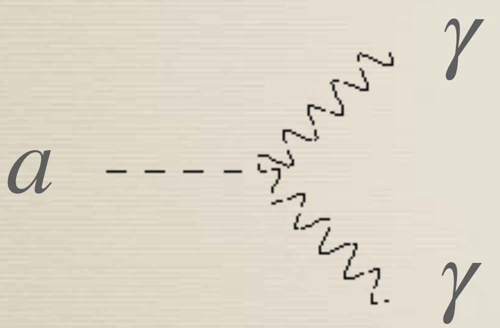


$$\dot{\theta}_i \neq 0$$

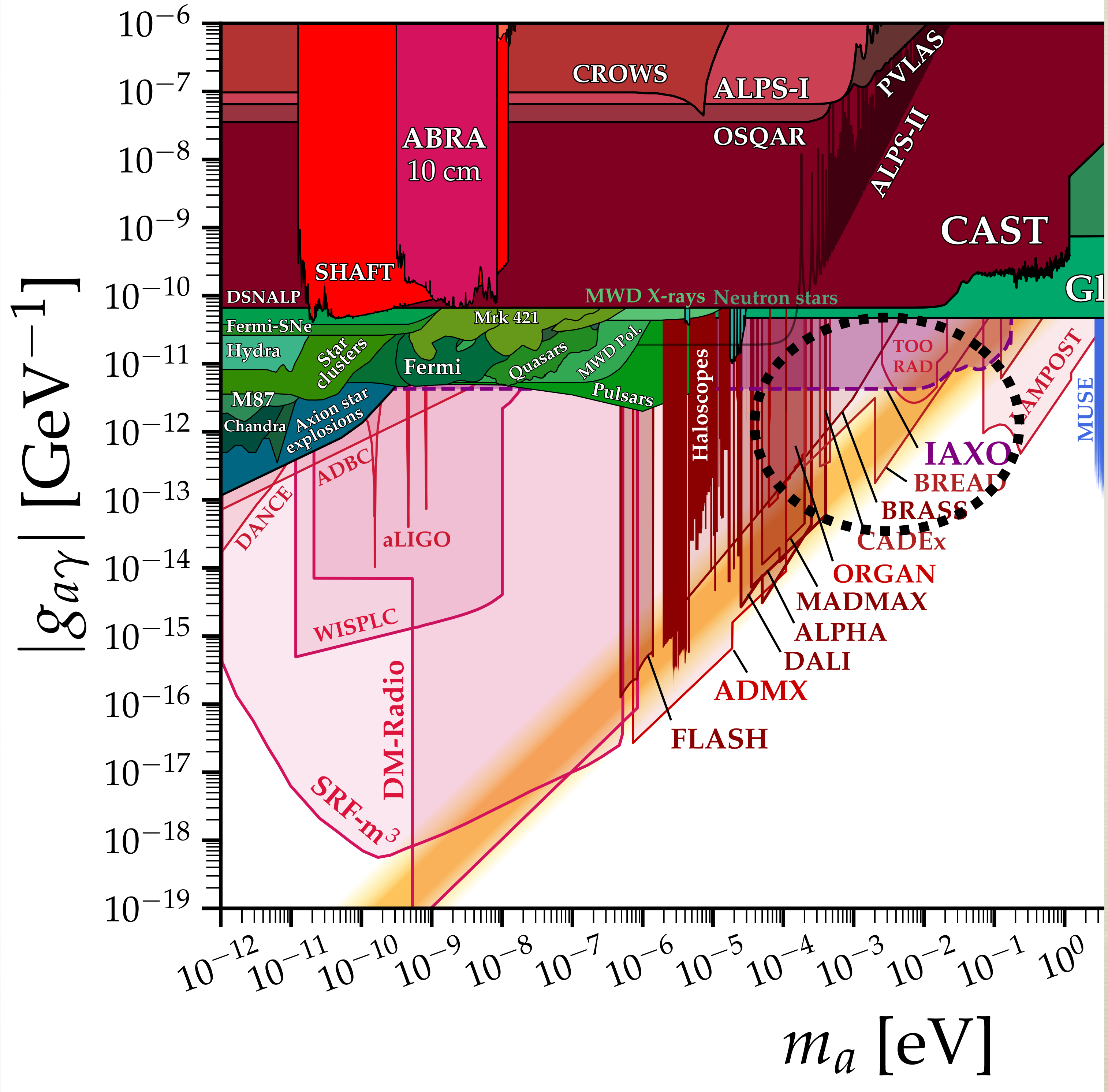
$$V + K$$

Kinetic Misalignment

Without rotation

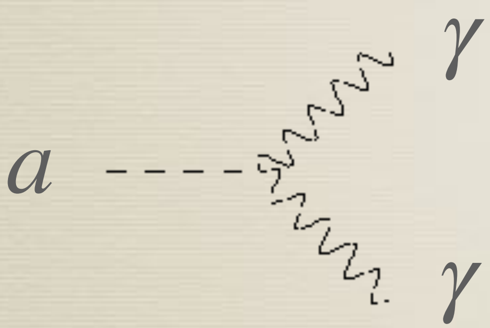


$$\propto \frac{1}{f_a}$$

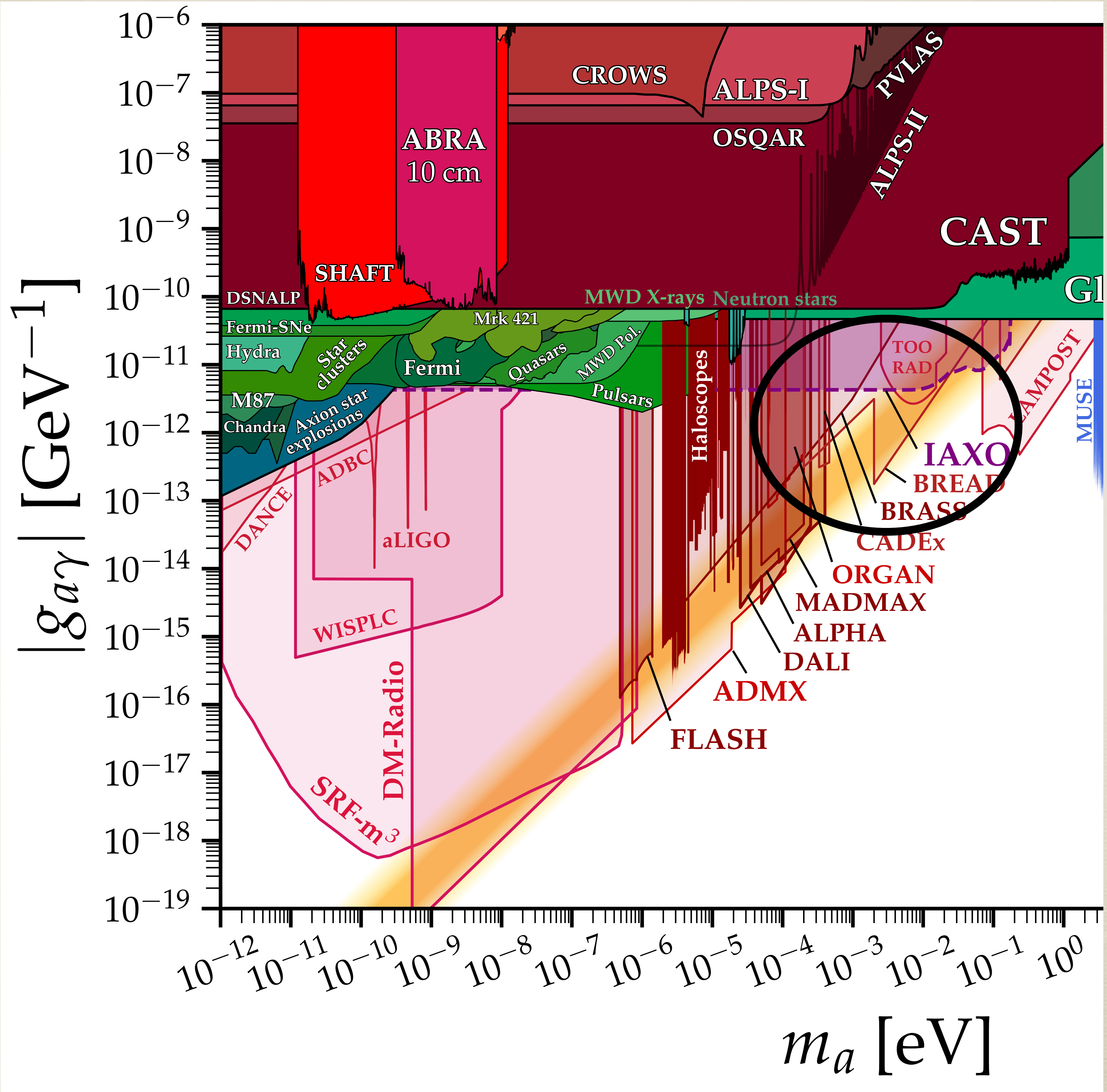


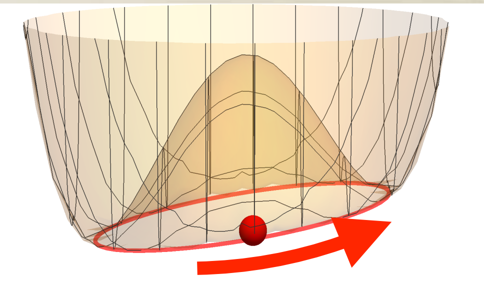
under-produced

Kinetic misalignment



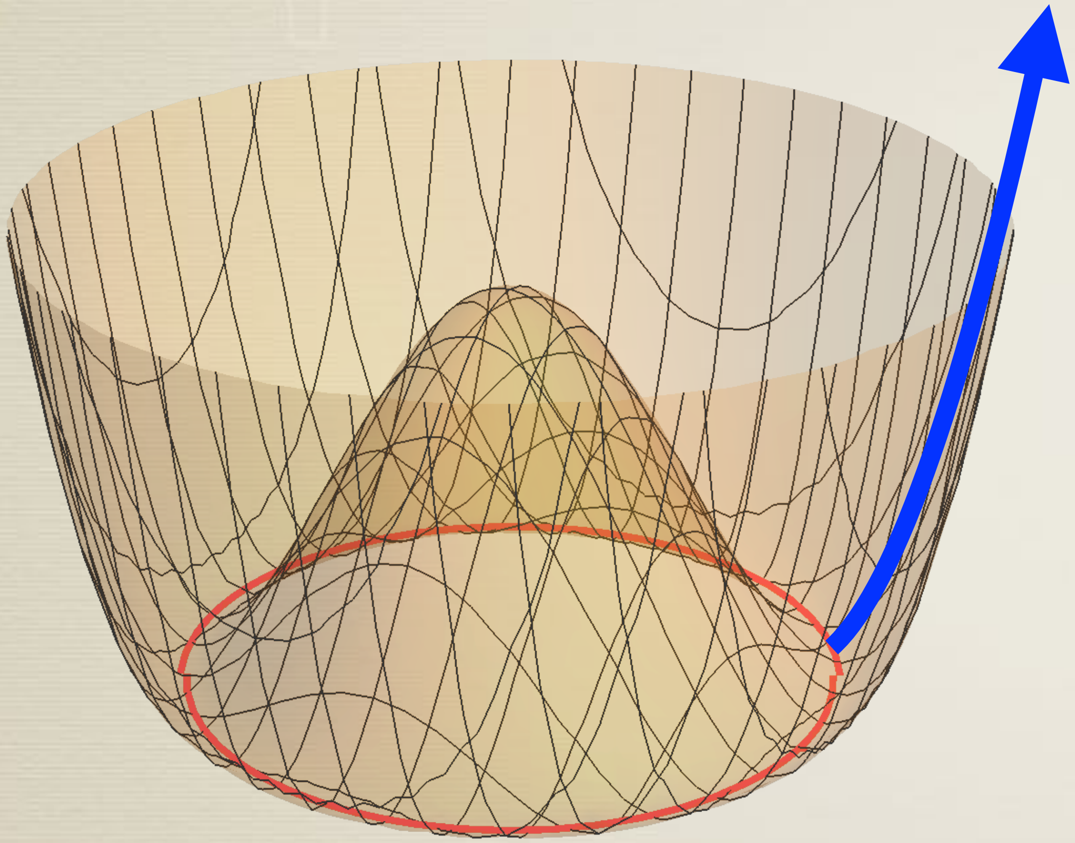
$$\propto \frac{1}{f_a}$$





How to initiate the rotation

Co and KH (2019)



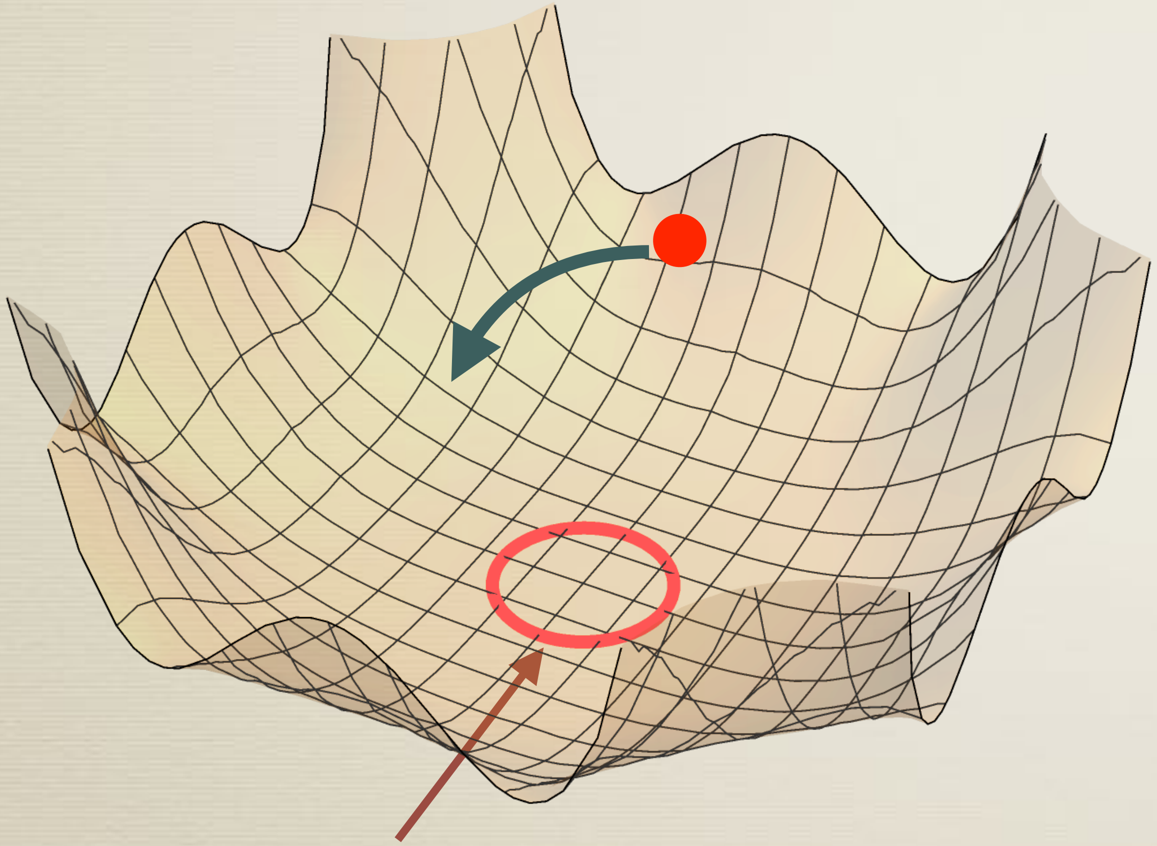
Consider the dynamics of the radial direction

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

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

How to initiate the rotation

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



minimum $|P| \sim f_a$

Assume a large initial radial field value

↓

Higher order terms

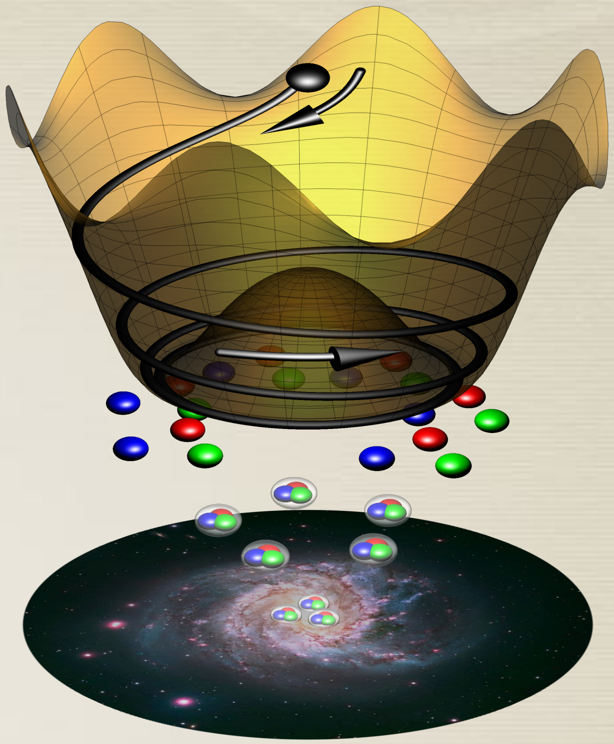
$V \sim P^n \sim S^n \cos(n\theta)$

may be effective

↓

Angular motion is induced by the potential gradient

Outline



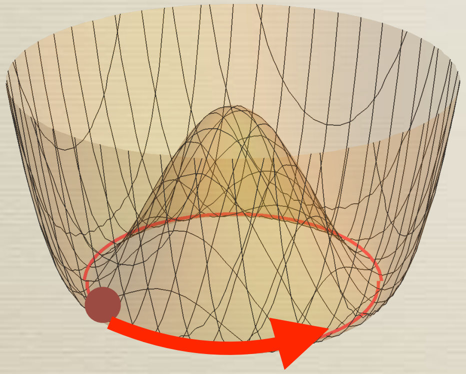
- Axion rotation and dark matter
- Axion rotation and baryon asymmetry
- Discussion

Axiogenesis

Minimal axiogenesis

Co and KH (2019)

The angular momentum of axion rotation (PQ charge) is transferred into baryon asymmetry via QCD and weak interactions

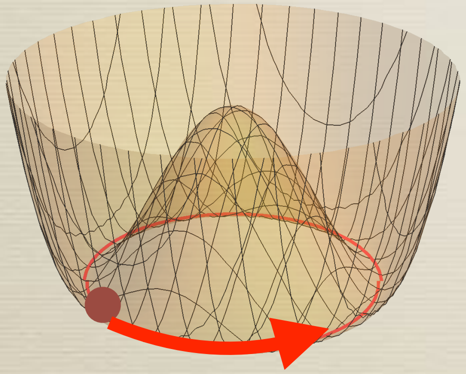


$$\boxed{\text{PQ}} \xrightarrow{\text{QCD}} \boxed{\text{Chiral charge}} \xrightarrow{\text{weak}} \boxed{\text{Baryon}}$$

Minimal axiogenesis

Co and KH (2019)

Baryon asymmetry is fixed upon the electroweak phase transition

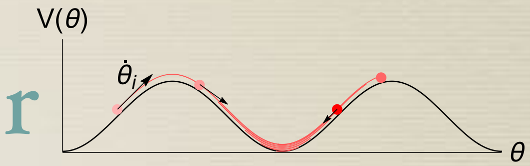


$$\boxed{\text{PQ}} \xrightarrow{\text{QCD}} \boxed{\text{Chiral charge}} \xrightarrow{\cancel{\text{weak}}} \boxed{\text{Baryon}}$$

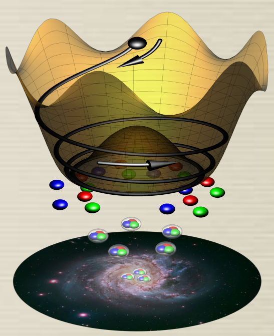
Minimal axiogenesis

Co and KH (2019)

1. Angular velocity $\dot{\theta} f_a^2$
2. Decay constant f_a
3. Electroweak phase transition temperature $T_{\rm EW}$



1. Dark Matter
2. Baryon asymmetry



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

$$\boxed{T_{\rm EW} = 1\ \text{TeV} \left(\frac{f_a}{10^8\ \text{GeV}} \right)^{1/2} \left(\frac{0.1}{c_B} \right)^{1/2}}$$

c_B : model-dependent $O(0.1)$ constant

Minimal axiogenesis

$$T_{\mathrm{EW}} = 1\ \mathrm{TeV} \left(\frac{f_a}{10^8\ \mathrm{GeV}} \right)^{1/2} \left(\frac{0.1}{c_B} \right)^{1/2}$$

- DFSZ and KSVZ axion

Astrophysical lower bound
$f_a >$ few × 10^8 GeV

→

Higher T_{EW} than the SM
by new physics
that couples to Higgs

Electroweak
scale physics

↔

QCD axion

Minimal axiogenesis

$$T_{\rm EW} = 100\ \mathrm{GeV} \left(\frac{f_a}{10^6\ \mathrm{GeV}} \right)^{1/2} \left(\frac{0.1}{c_B} \right)^{1/2}$$

- Astrophobic axion

Luzio, Mescia, Nardi, Panci and Ziegler (2017)

Suppressed axion-nucleon, electron, and photon coupling

(This can be naturally realized by appropriate PQ charges of SM fermions)

Badziak and KH (2023)

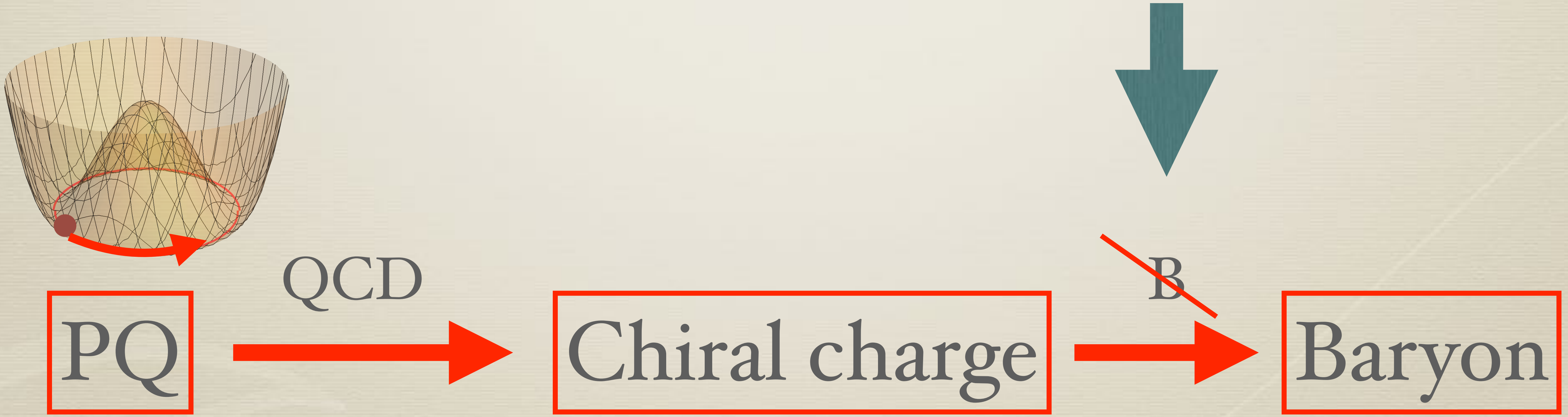
$m_a = O(1)$ eV is predicted

Axiogenesis and BSM

Co and KH (2019)

Baryon number violation from BSM

Majorana neutrino mass, RPV, ...
any BSM that you like and contains $\cancel{B}$



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

BSM and QCD axion

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

1. Dark Matter
2. Baryon asymmetry

One relation among BSM parameters and f_a

Other BSM ↔ QCD axion

Examples

- Majorana neutrino mass

Co, Fernandez, Ghalsasi, Hall and KH (2020)
Domcke, Ema, Mukaida, and Yamada (2020)
Kawamura and Raby (2021)
Bernes, Co, KH and Pierce (2022)

- Baryon number violation in supersymmetric model (RPV)

Co, KH, Johnson and Pierce (2021)

- Sphaleron processes in new gauge interaction

KH and Wang (2021)

Summary

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

Axion dark matter with a large coupling

$f_a \ll 10^{11}$ GeV

- **Axiogenesis** : Axion rotation produces baryon asymmetry

Baryon number violation by weak anomaly:
Modified electroweak phase transition or
astrophobic axion with $m_a \sim$ eV

That by BSM :
A relation between BSM parameters and f_a

Astrophysical implications

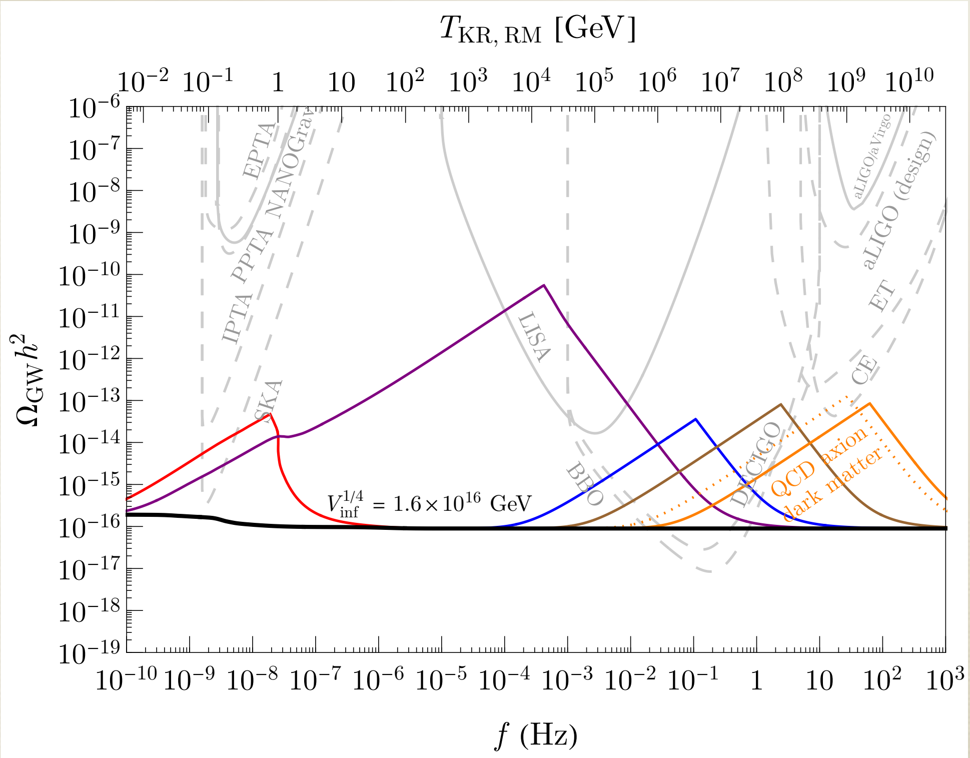
- Axion dark matter has large density fluctuations

Eroncel and Servant (2022)

Mini-clusters can be formed

Possible spectrum is not yet completely understood

- Kinetic energy of the rotation can dominate the universe

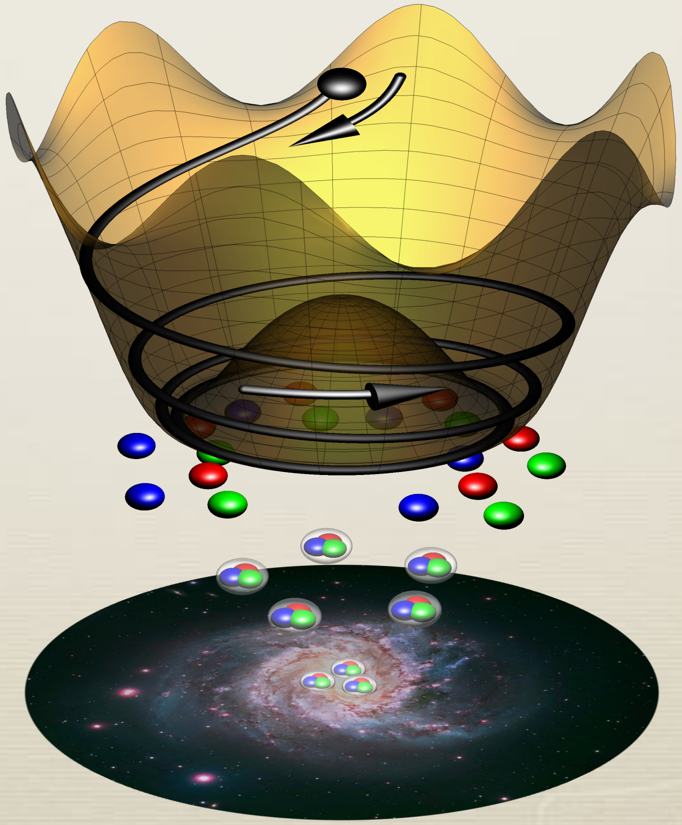


KH et.al. (2019, 2021), Gouttenoire, Servant and Simakachorn (2021)

Imprints on primordial gravitational waves

Axion rotation

More particle-physics, cosmological, and astrophysical implications?



Back up

Kinetic misalignment

Axion fragmentation

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

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

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

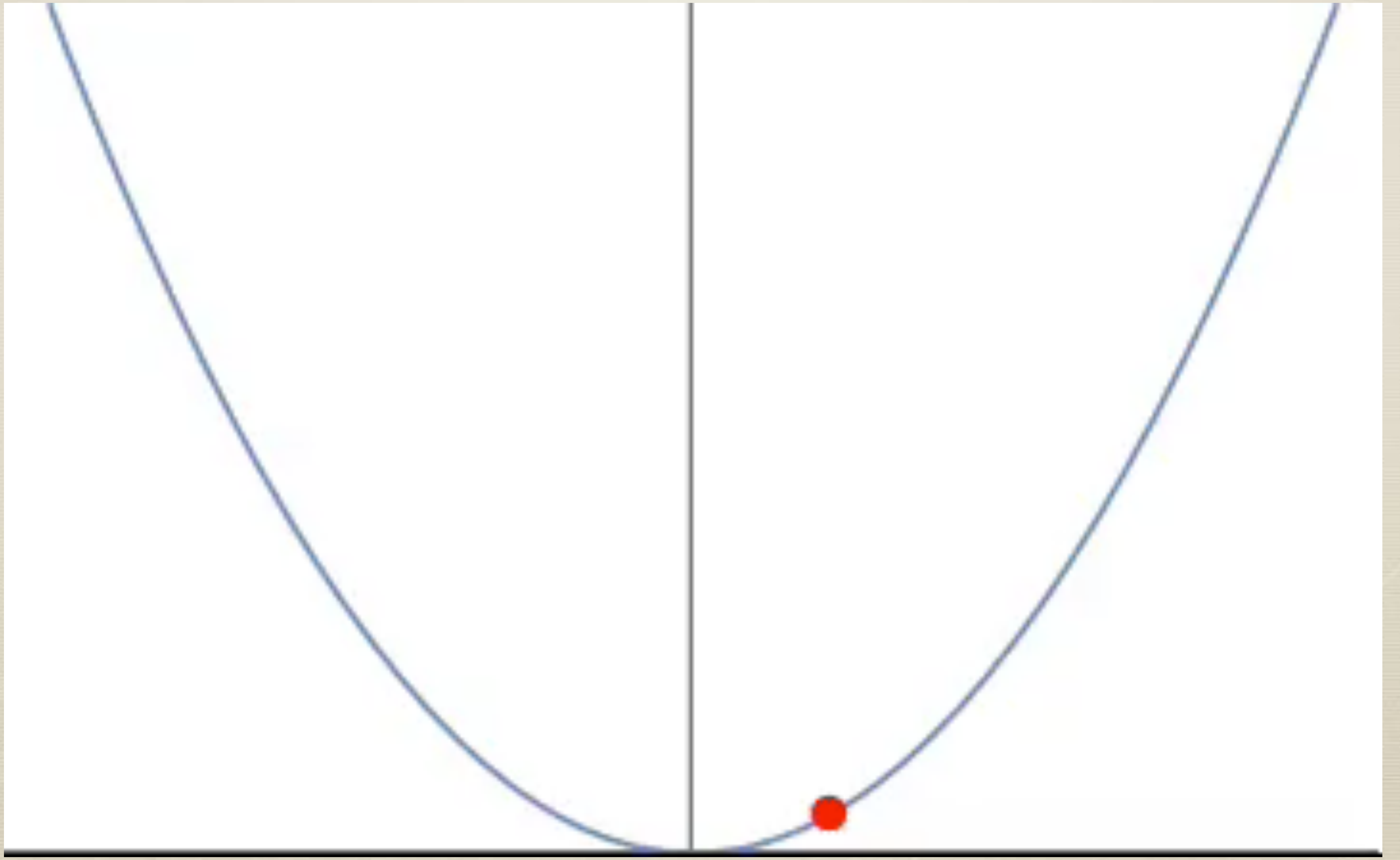
EOM of the fluctuation at the linear level:

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

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)

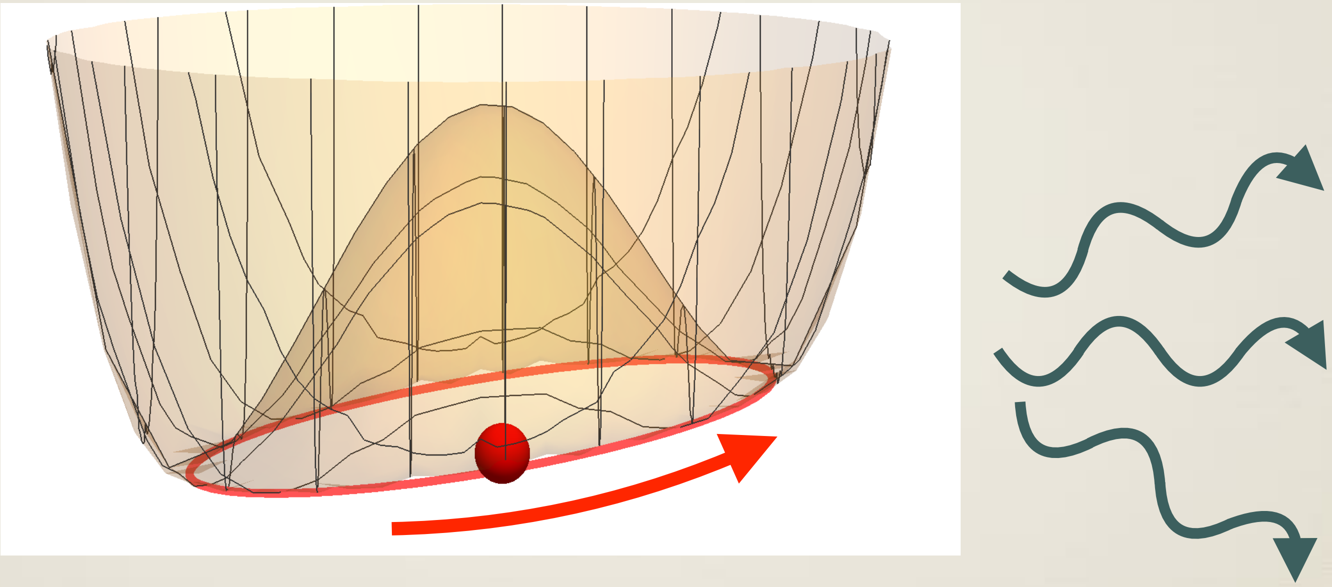
$$\ddot{a}_k + \left(k^2 + m_a^2 \cos\dot{\theta}t\right) a_k = 0$$

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

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

Axion abundance

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



axions with

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

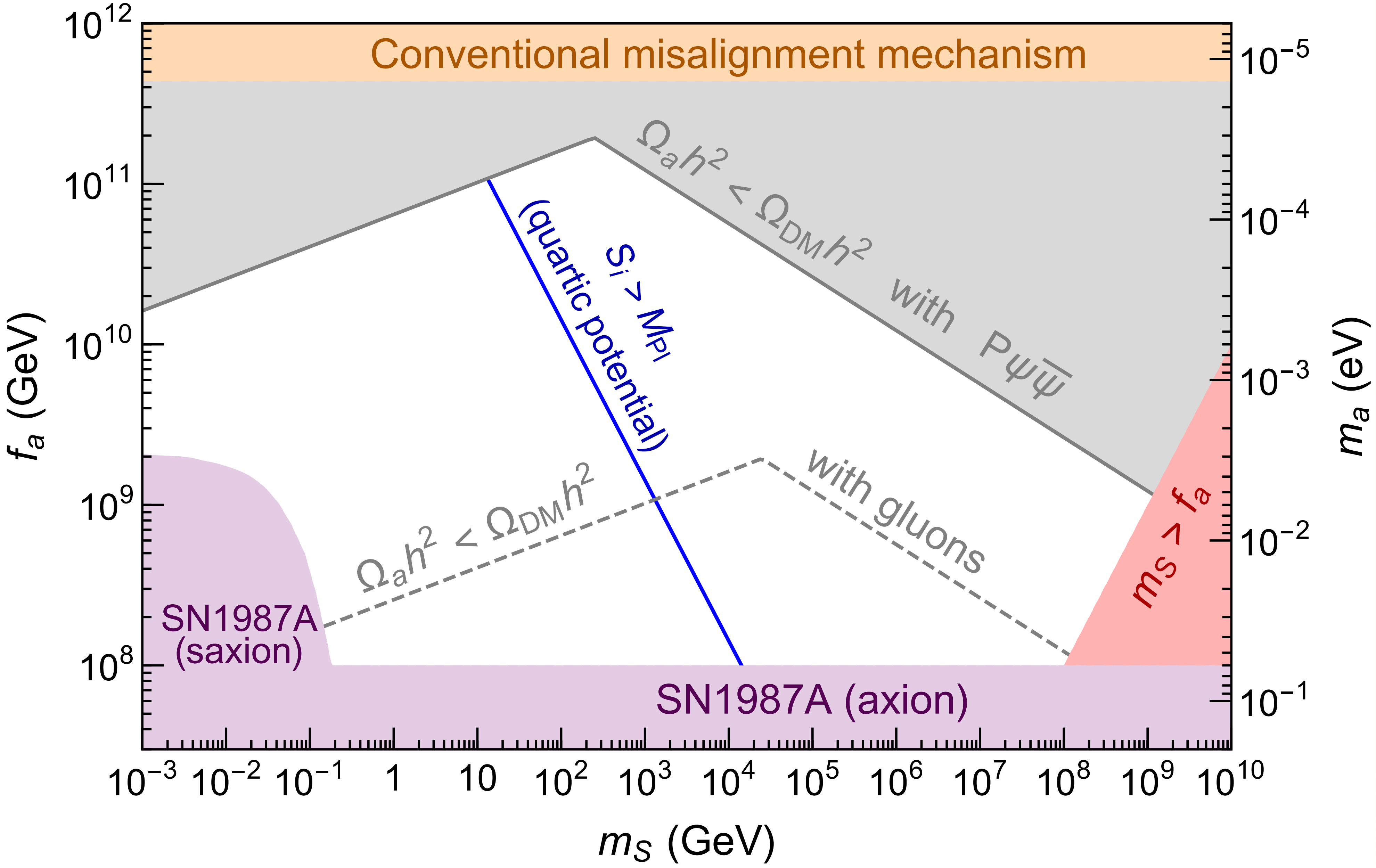
$$n_{a,{\rm PR}} = \frac{\rho_{\rm rot}}{k_{\rm PR}} \simeq \frac{\dot{\theta}^2 f_a^2/2}{\dot{\theta}/2} = \dot{\theta} f_a^2 = n_{\rm PQ}$$

Co, KH and Pierce (2021)

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

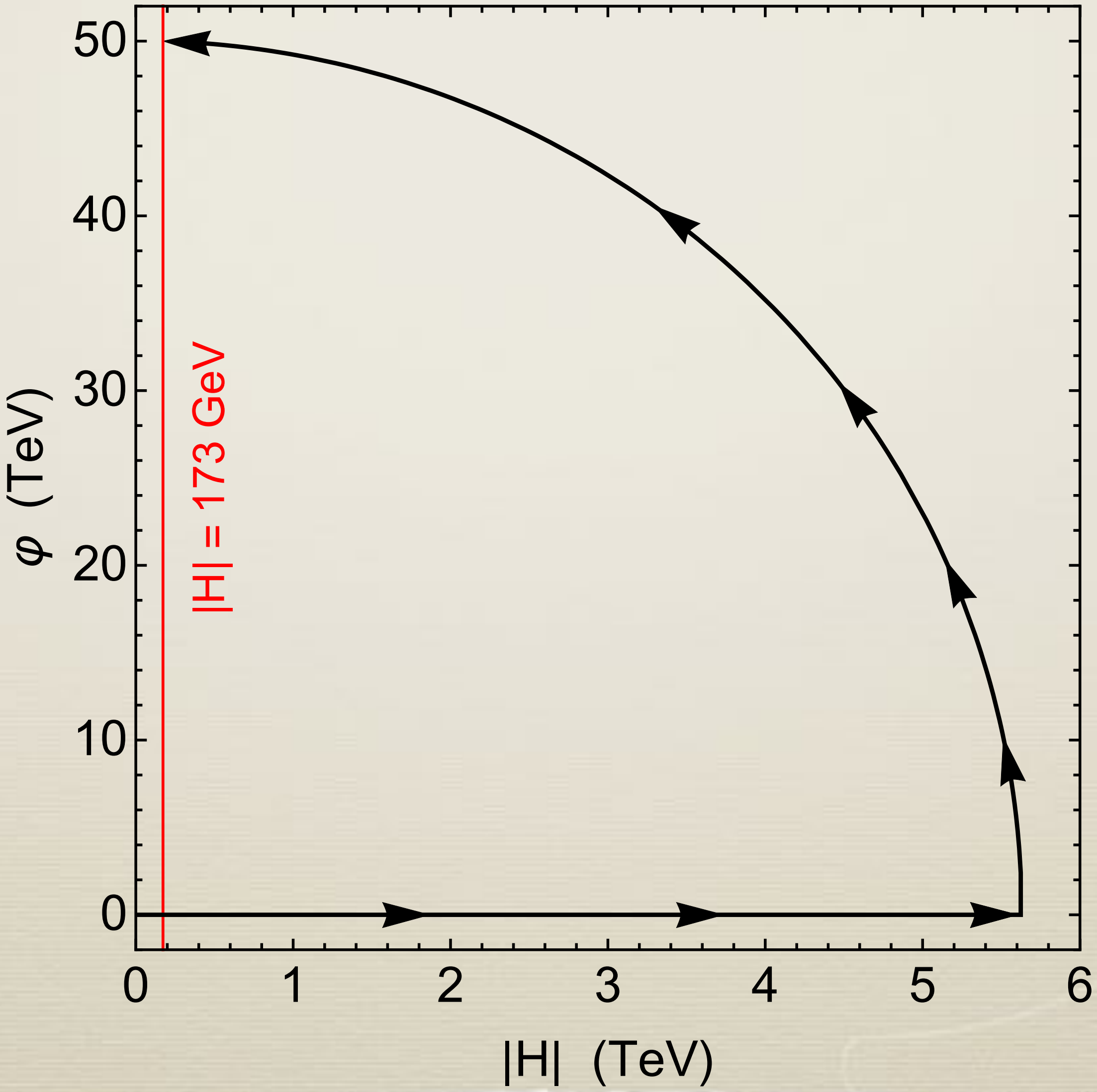
Thermalization

Co, Hall and KH (2019)



Earlier EW phase transition

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



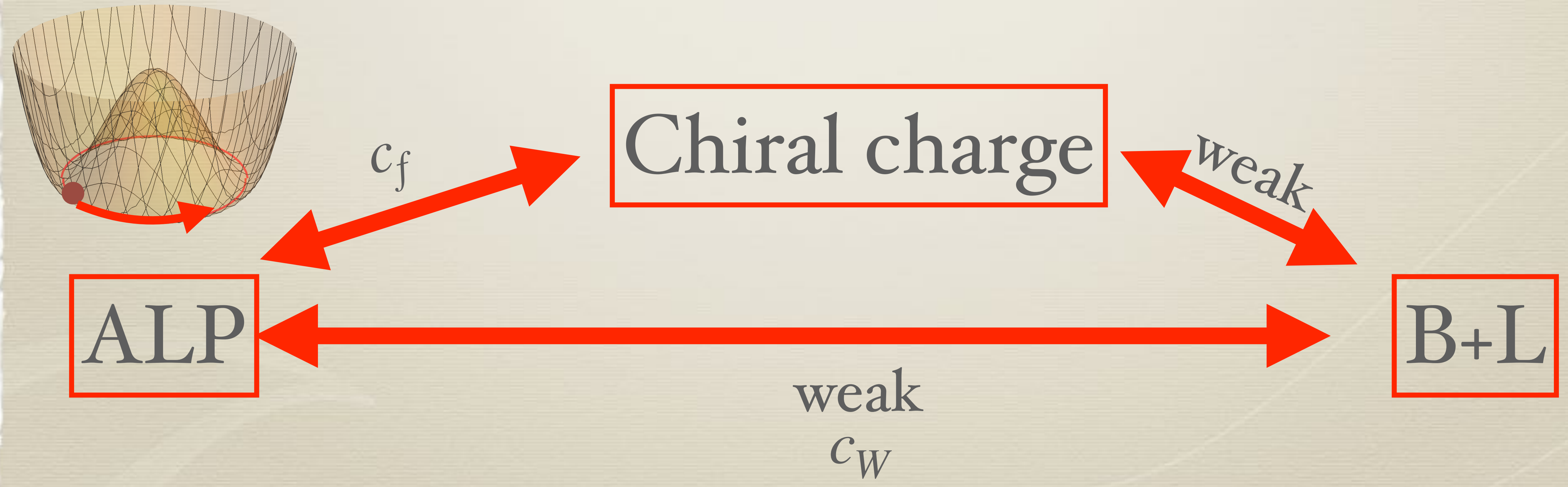
ALP cogenesis

ALP genesis

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

A similar mechanism works for generic ALPs

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

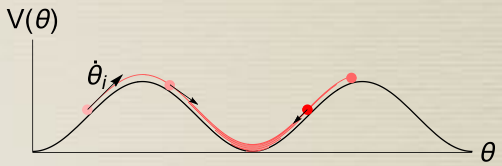


ALP cogenesis

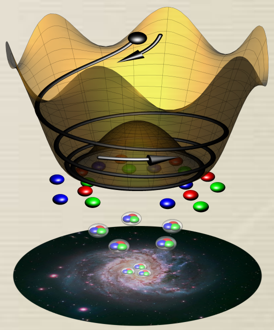
Co, Hall and KH (2020)

Assuming the standard EW phase transition,

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



1. Dark Matter
2. Baryon asymmetry

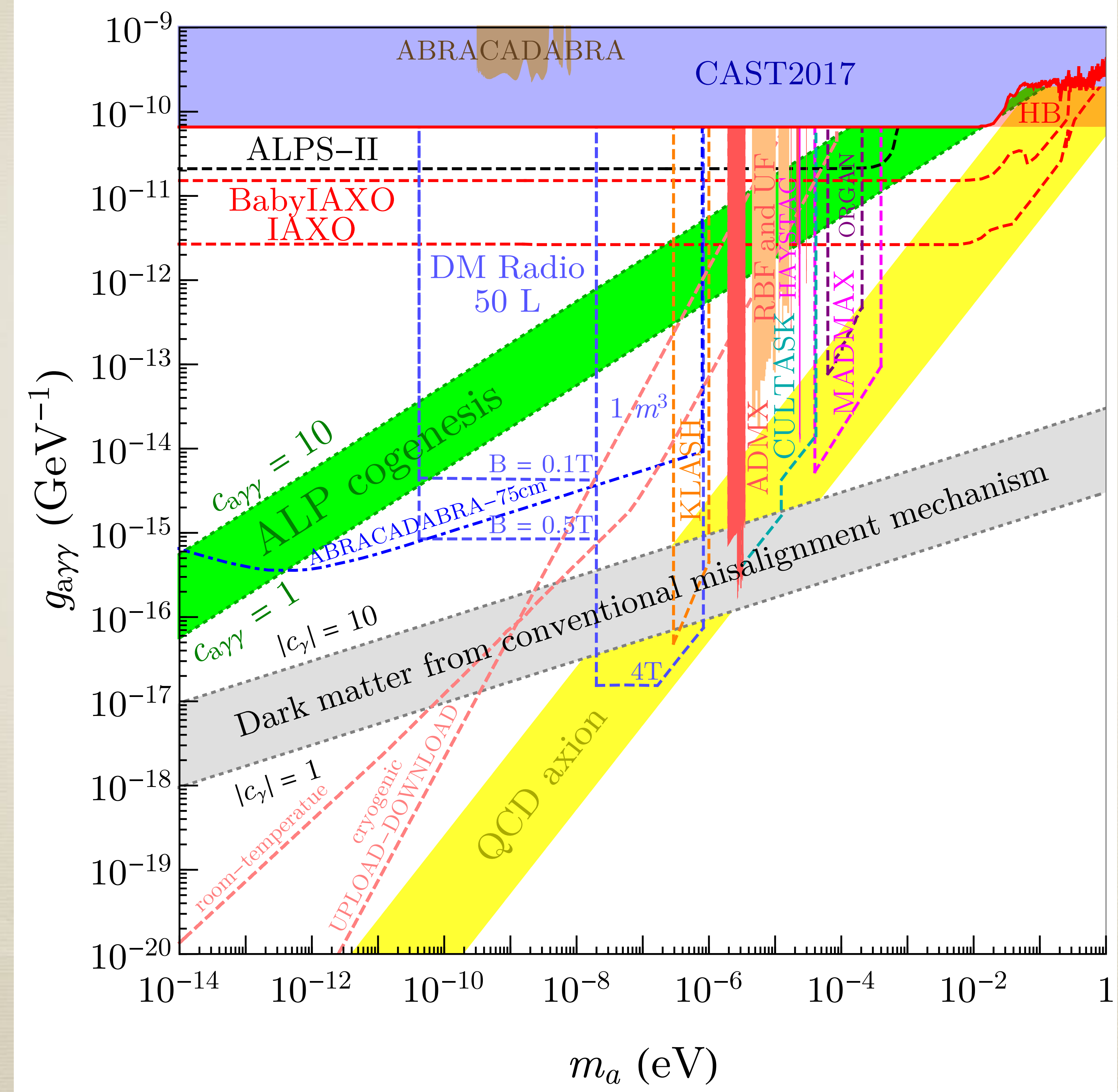


3 free parameters − 2 densities to fit
= 1 free parameter

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

Prediction on the ALP coupling

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



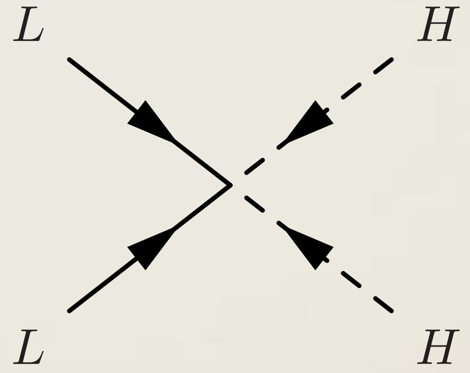
Lepto-axiogenesis

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

Majorana neutrino mass

Majorana neutrino masses break the lepton symmetry

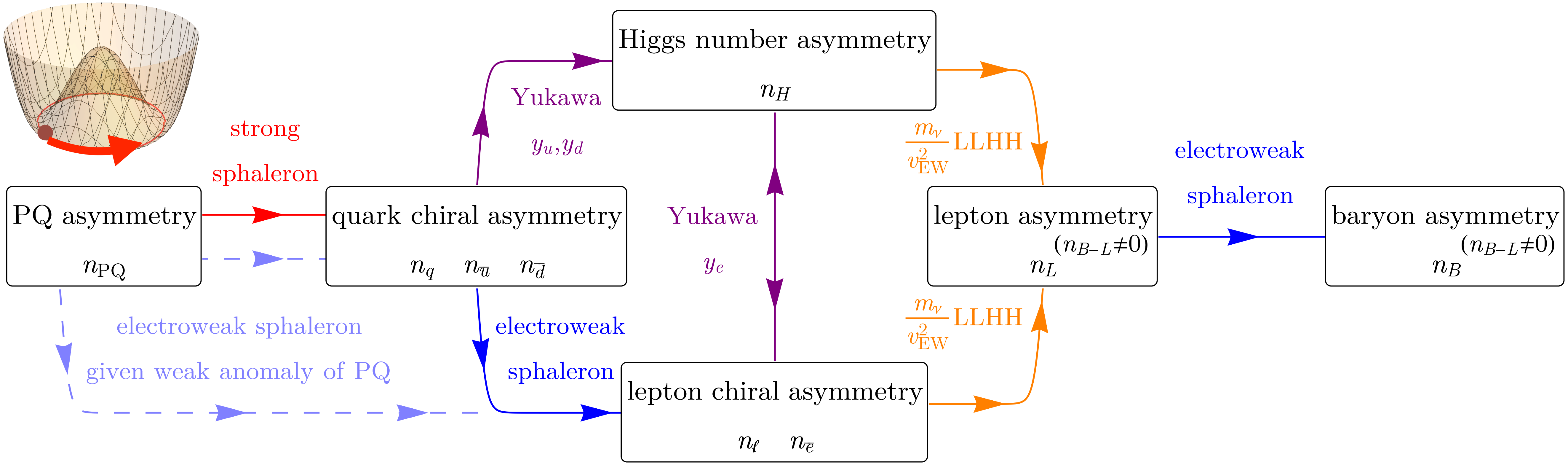
$$\frac{1}{M}LLHH$$



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

Charge flow

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



PQ asymmetry

n_{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

electroweak sphaleron given weak anomaly of PQ

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

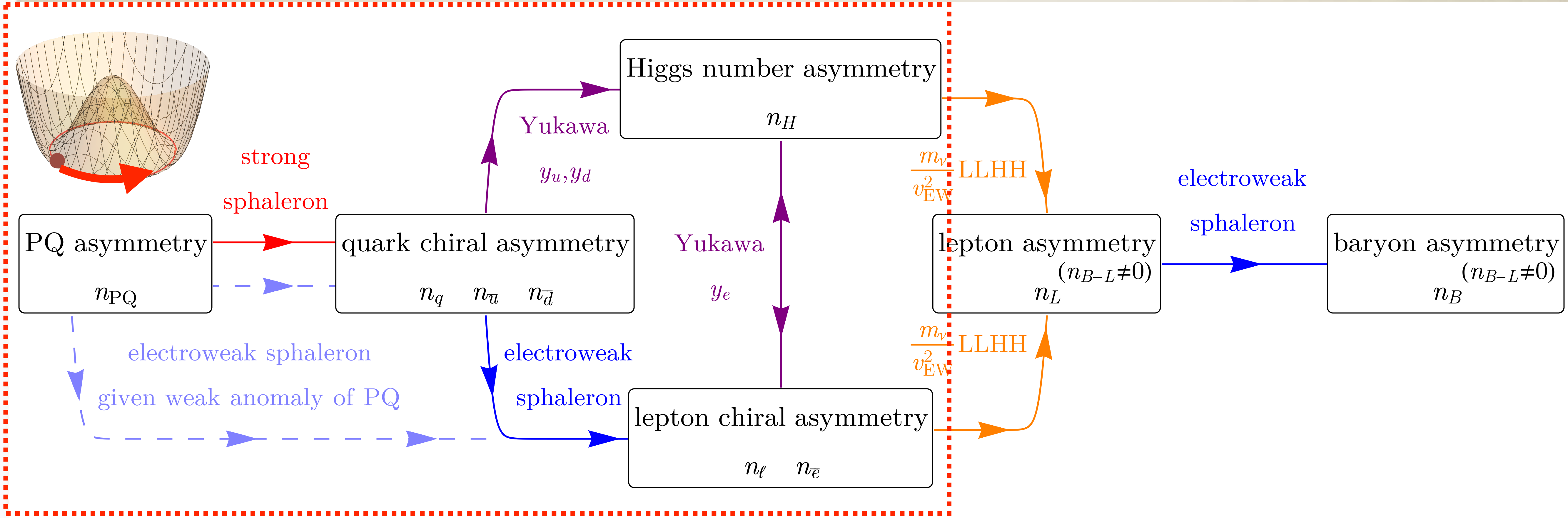
baryon asymmetry

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

n_B

Charge flow

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



Higgs number asymmetry

n_H

PQ asymmetry

n_{PQ}

strong

sphaleron

quark chiral asymmetry

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

Yukawa

y_u, y_d

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

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

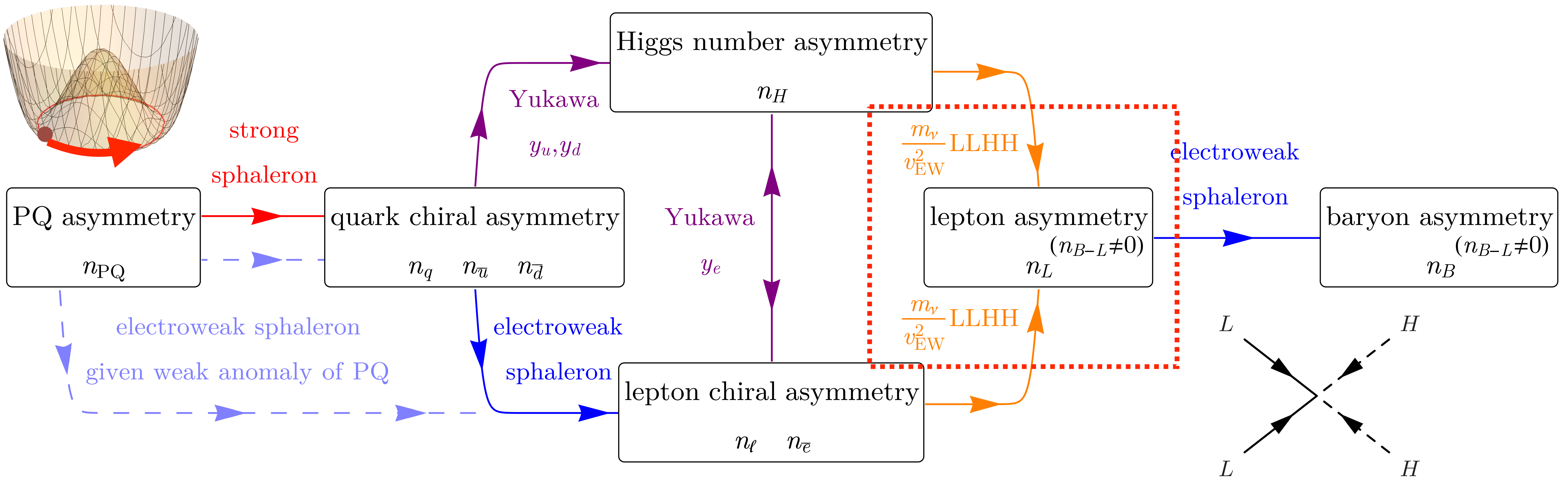
n_B

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_{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

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

electroweak sphaleron given weak anomaly of PQ

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

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

electroweak sphaleron

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

L H L H

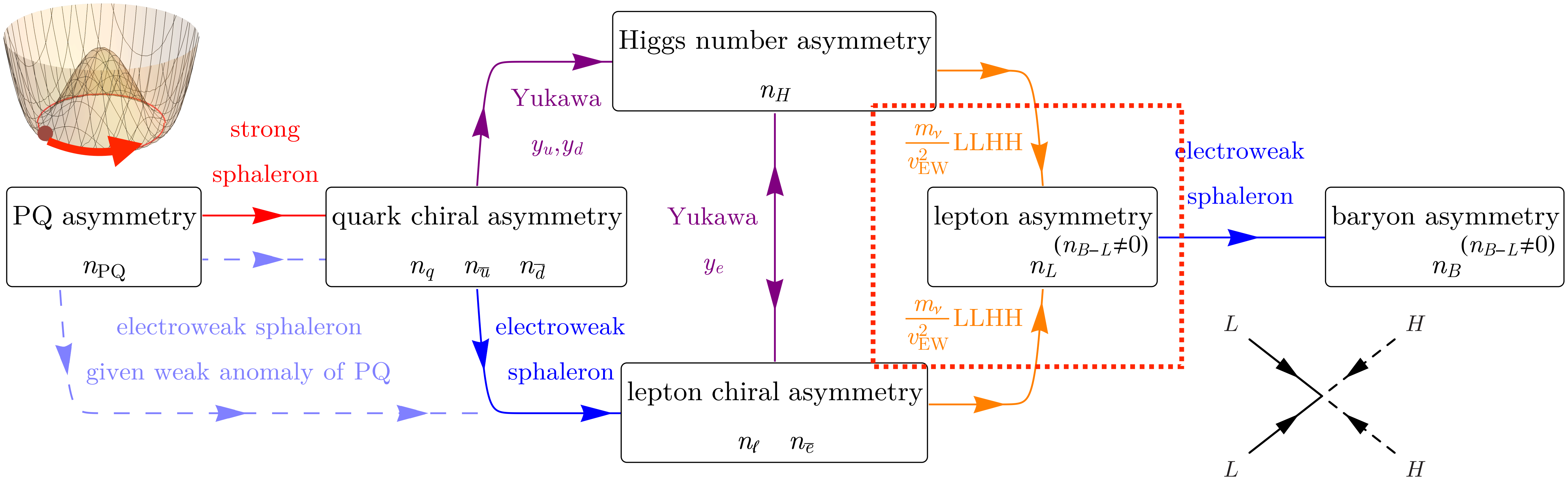
At high temperatures

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

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

Charge flow

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



PQ asymmetry n_{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

electroweak sphaleron given weak anomaly of PQ

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

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

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

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

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

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

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

Charge flow

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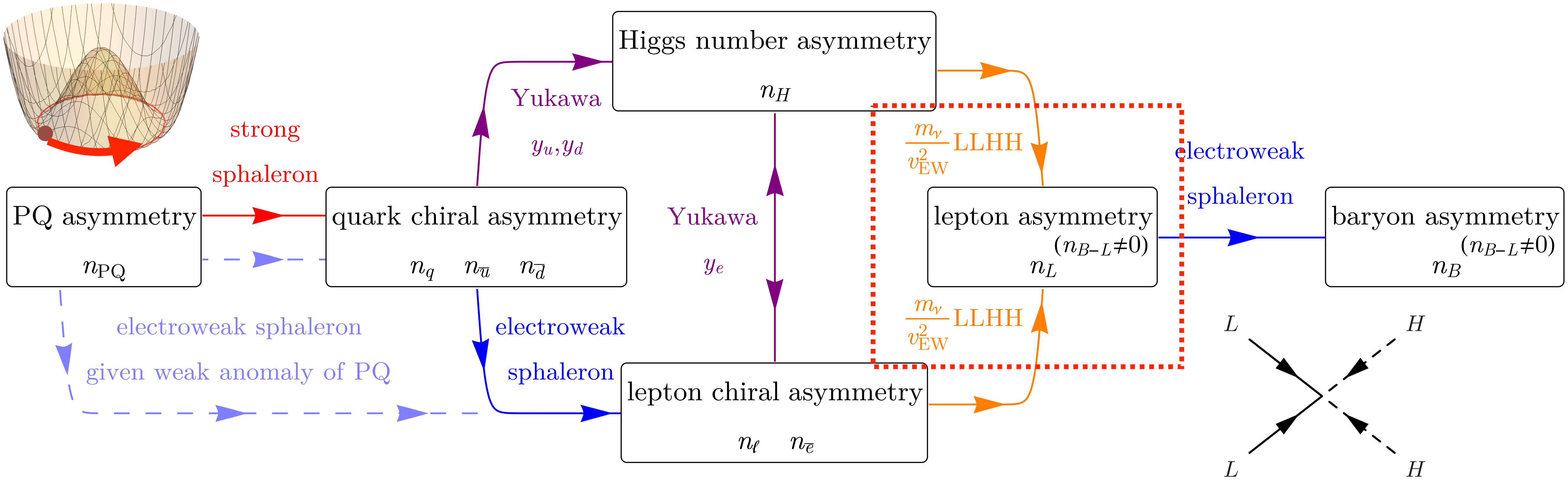

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electroweak sphaleron

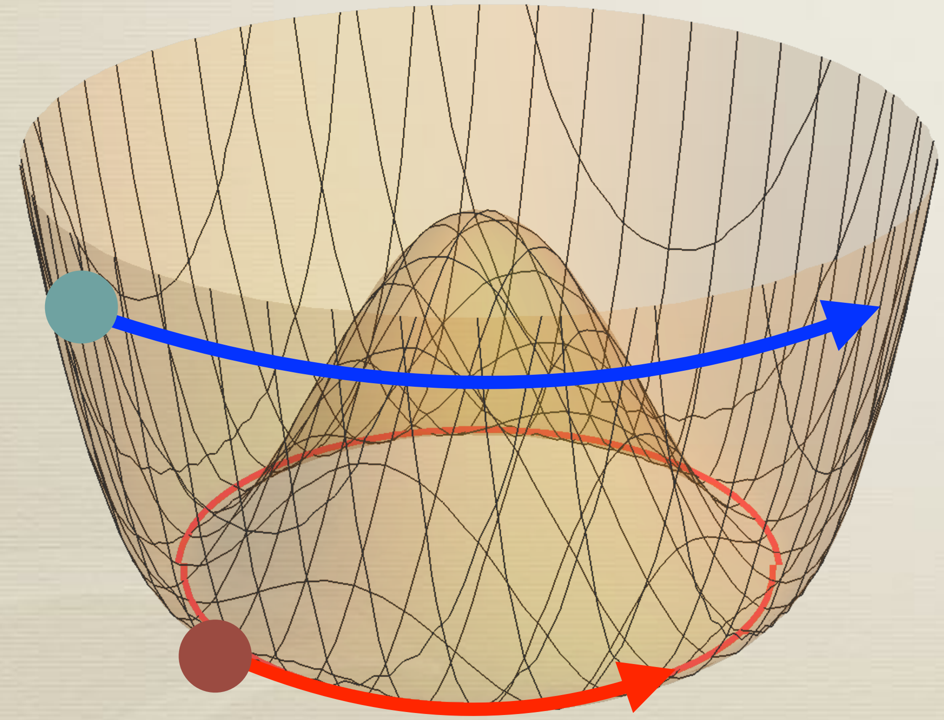
baryon asymmetry ($n_{B-L}\neq 0$) n_B

L H L H

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

Angular velocity?

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



Early time

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

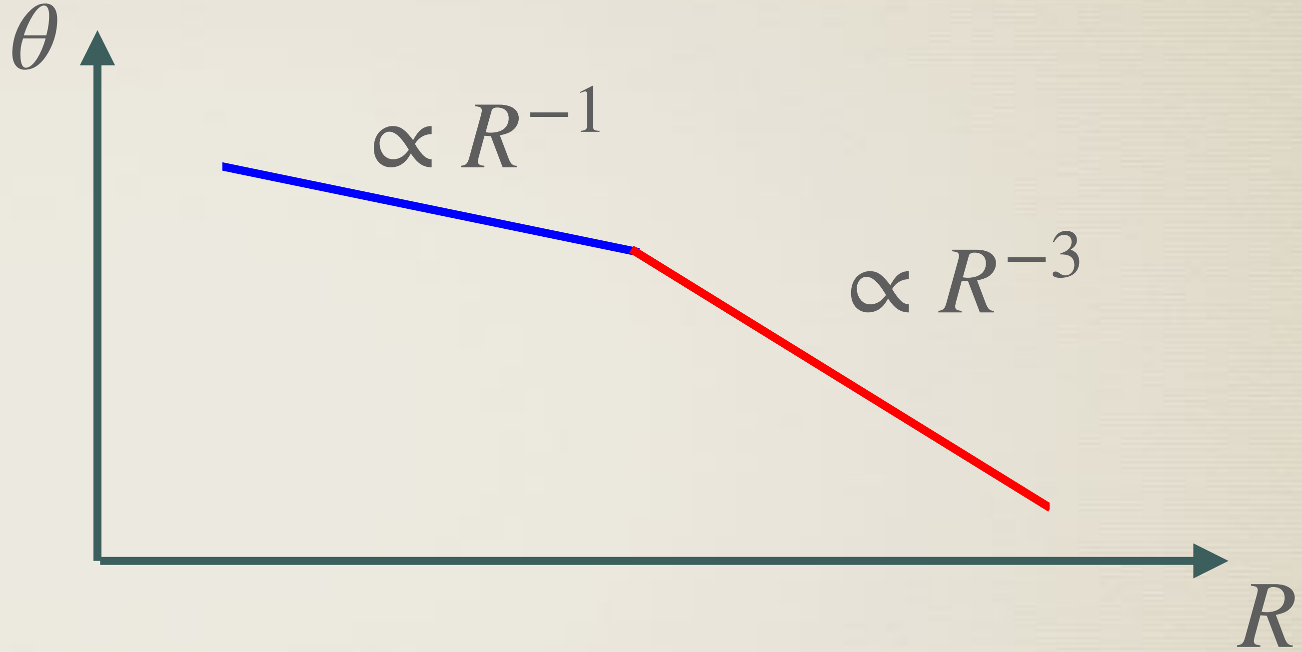
Around the electroweak phase transition

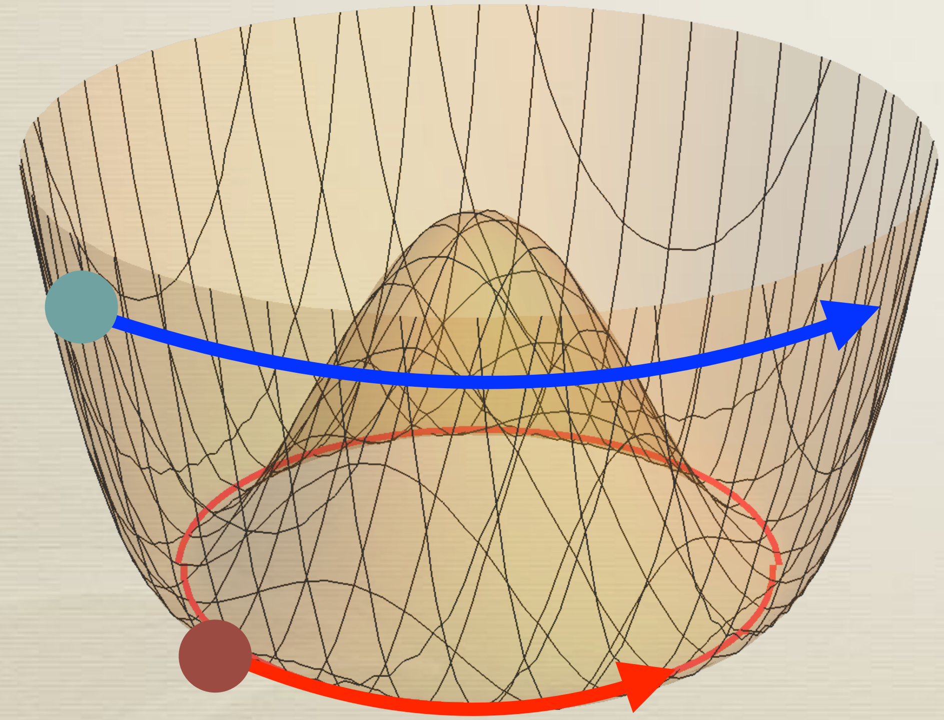
$$\dot{\theta} \propto R^{-3}$$

Angular velocity?

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

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





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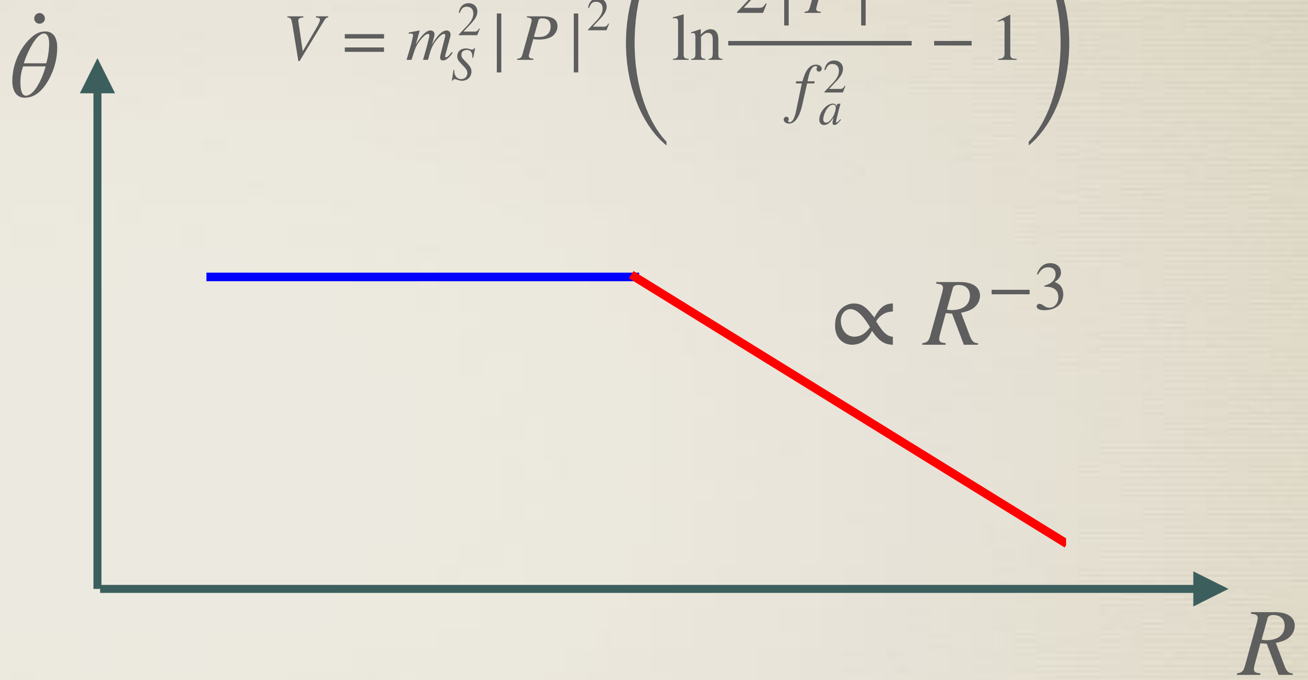
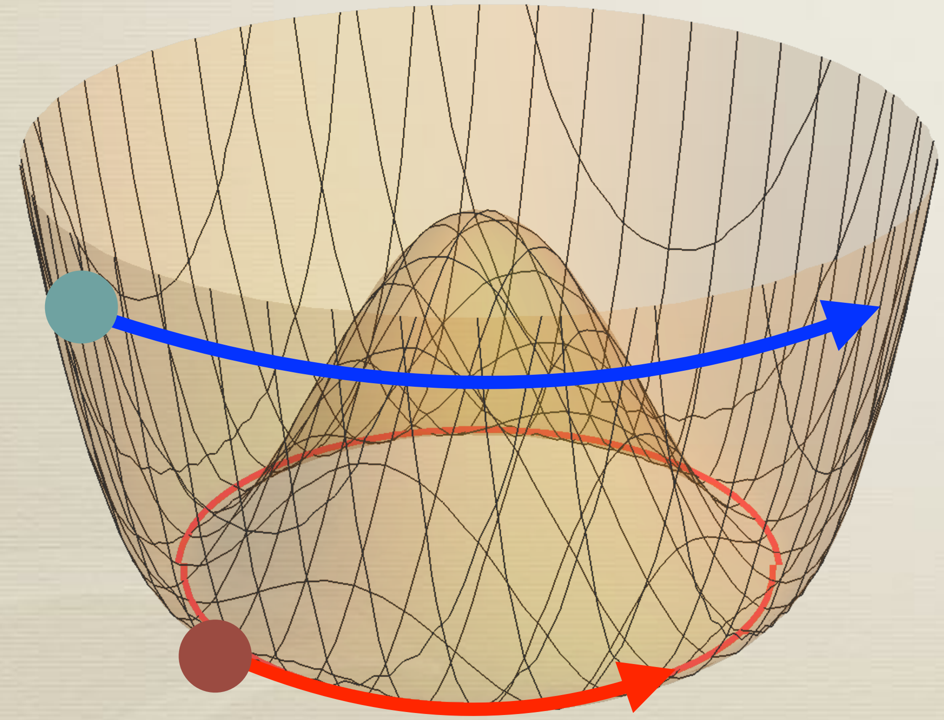
$$\frac{\Delta n_B}{s} \simeq 10^{-11}\frac{\dot\theta}{10\ \mathrm{TeV}}\frac{\sum m_\nu^2}{0.03\mathrm{eV}^2}$$

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





Early time

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Around the electroweak phase transition

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

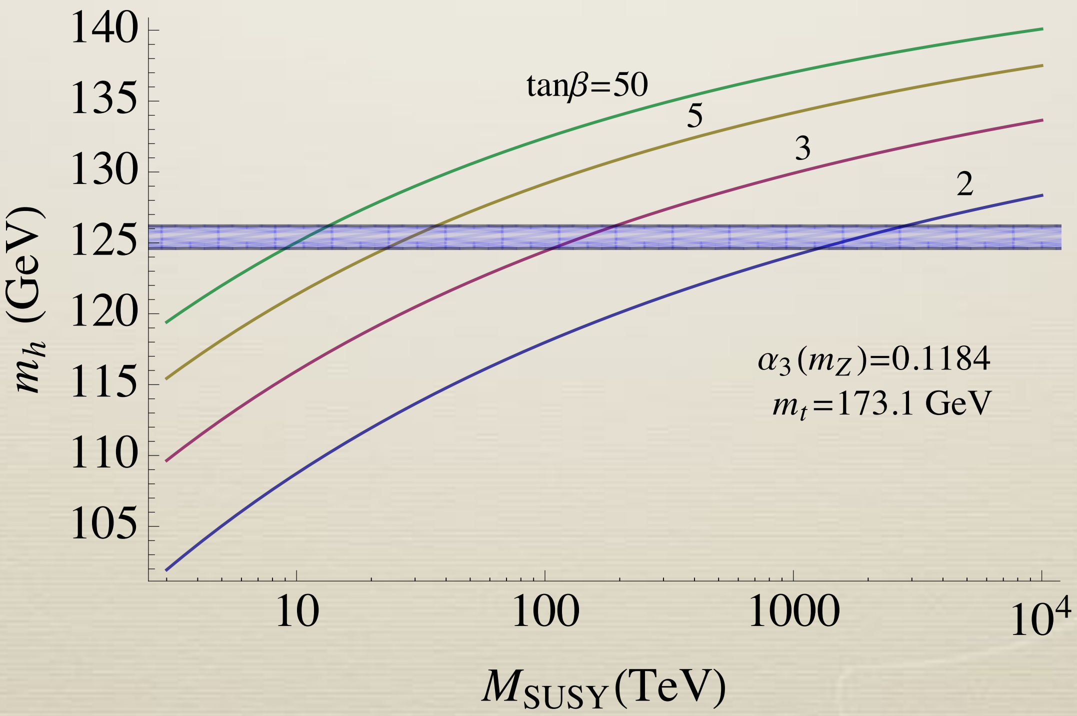
Supersymmetry

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

In supersymmetric models,

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

Consistent with the Higgs mass



Supersymmetry

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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

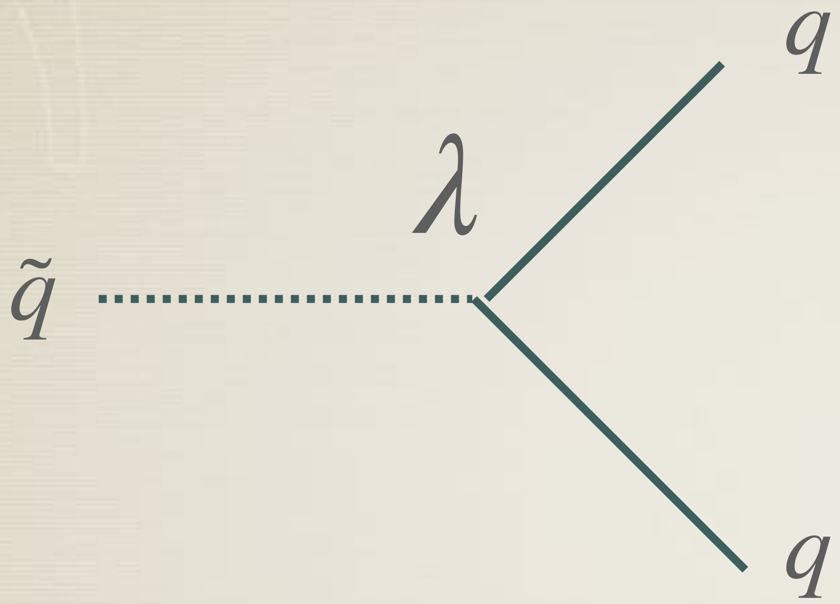
- Electroweak hierarchy $m_{\rm SUSY} \sim 100\ {\rm GeV}$
- Gauge coupling unification $m_{\rm SUSY} \lesssim 10^6\ {\rm GeV}$
- Lightest supersymmetric particle as DM $m_{\rm SUSY} \lesssim 10^3\ {\rm GeV}$
  (invalid with RPV)
- Baryogenesis from axion rotation and neutrino mass

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

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

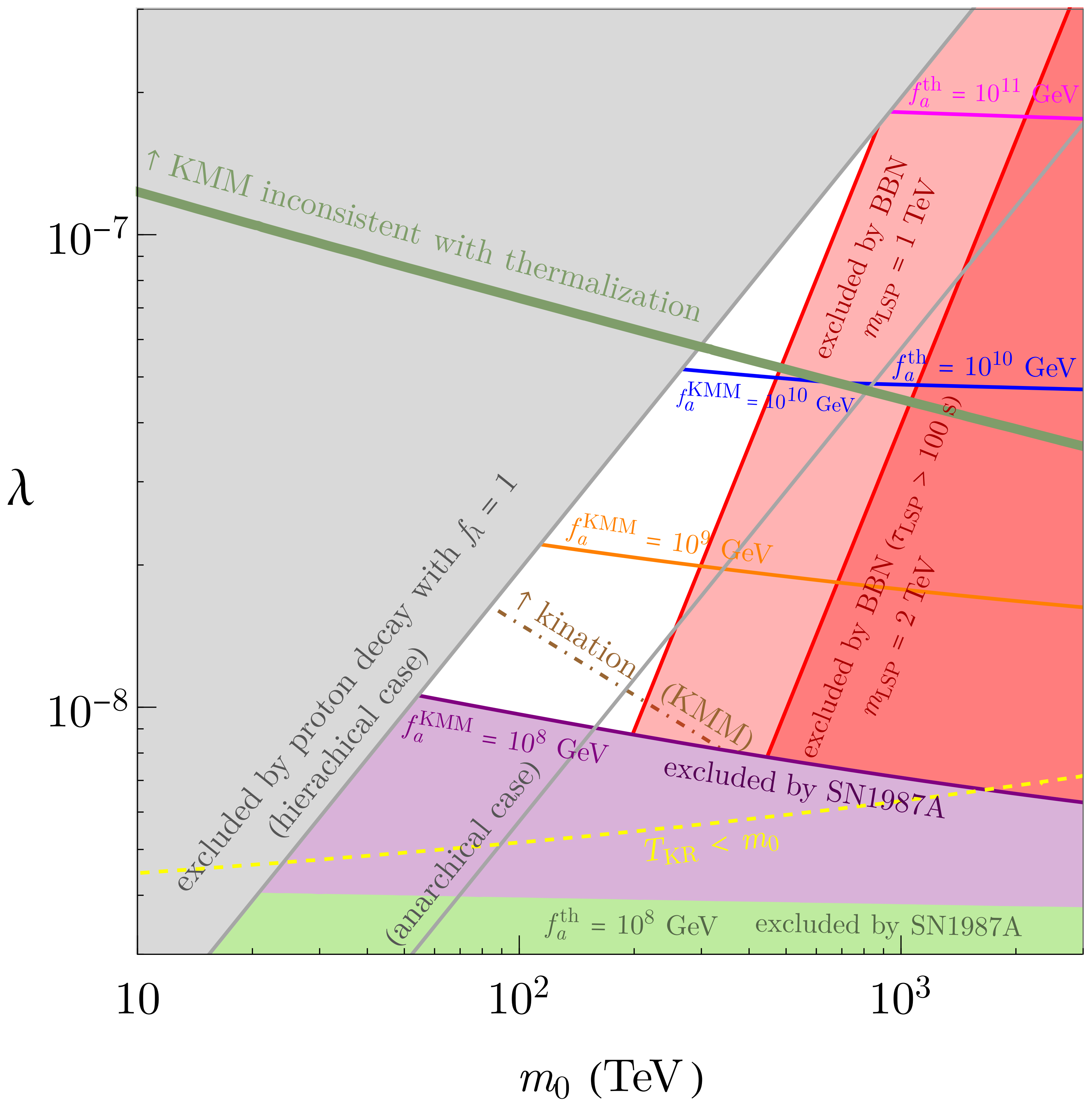
$$W = \frac{1}{2}\lambda_{ijk} 10_i \bar{5}_k \bar{5}_k = \lambda_{ijk}(Q_i \bar{d}_j L_k + \frac{1}{2}\bar{u}_i \bar{d}_j \bar{d}_k + \frac{1}{2}\bar{e}_i L_j L_k)$$

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 : $\lambda_{i12} \sim \lambda_{i13} \sim \lambda_{i23}$

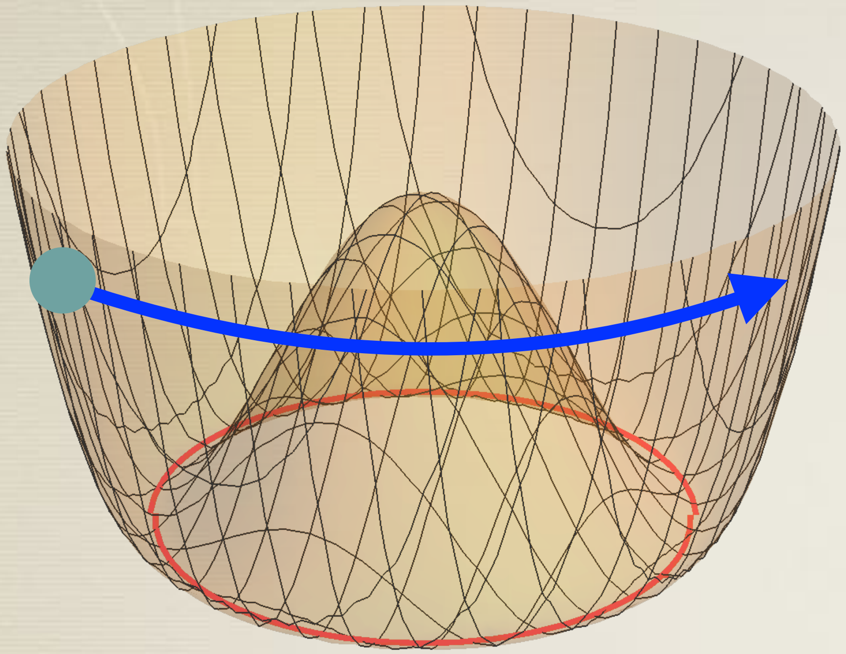
Hierarchical 5-plets : $\lambda_{i12}, \lambda_{i13} \ll \lambda_{i23}$


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

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,

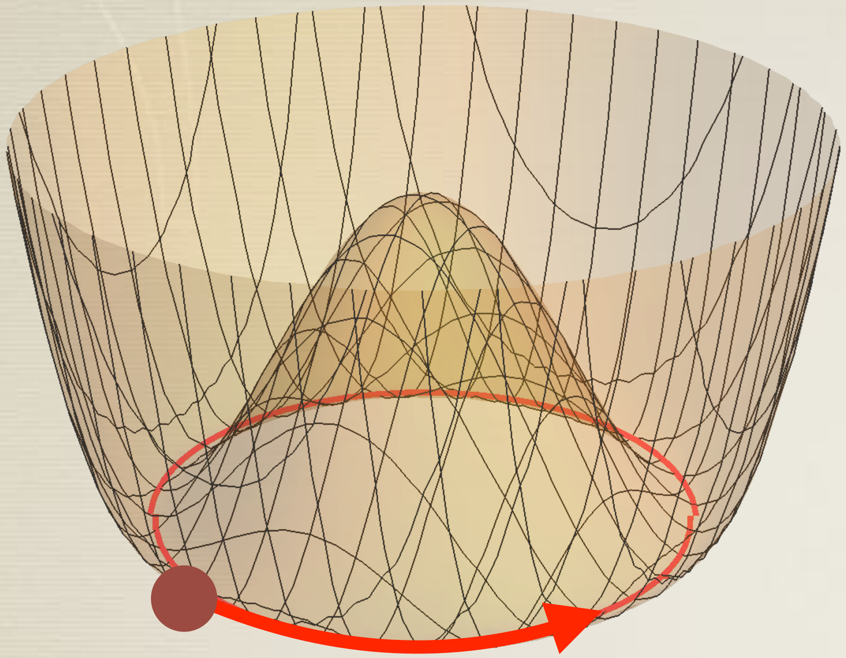
$$\dot{\theta} = \mathrm{const}, \quad S^2 \propto R^{-3}$$

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

matter

Equation of state of rotations

Co and KH (2019)



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

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

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

$$\Downarrow$$

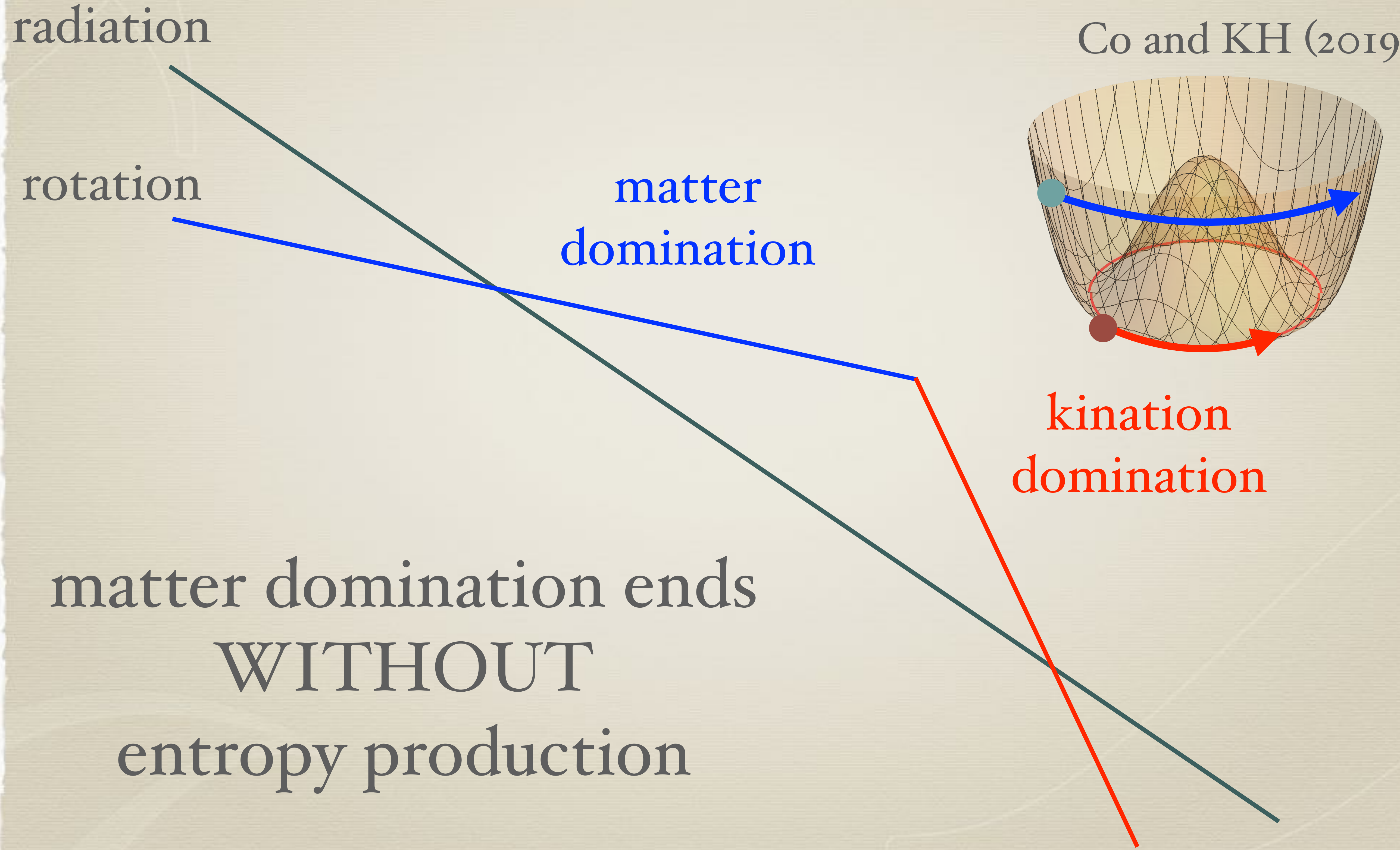
$$\rho = \dot{\theta}^2 S^2 \propto R^{-6}$$

kination

Axion energy is dominantly from the kinetic term

Axion kination

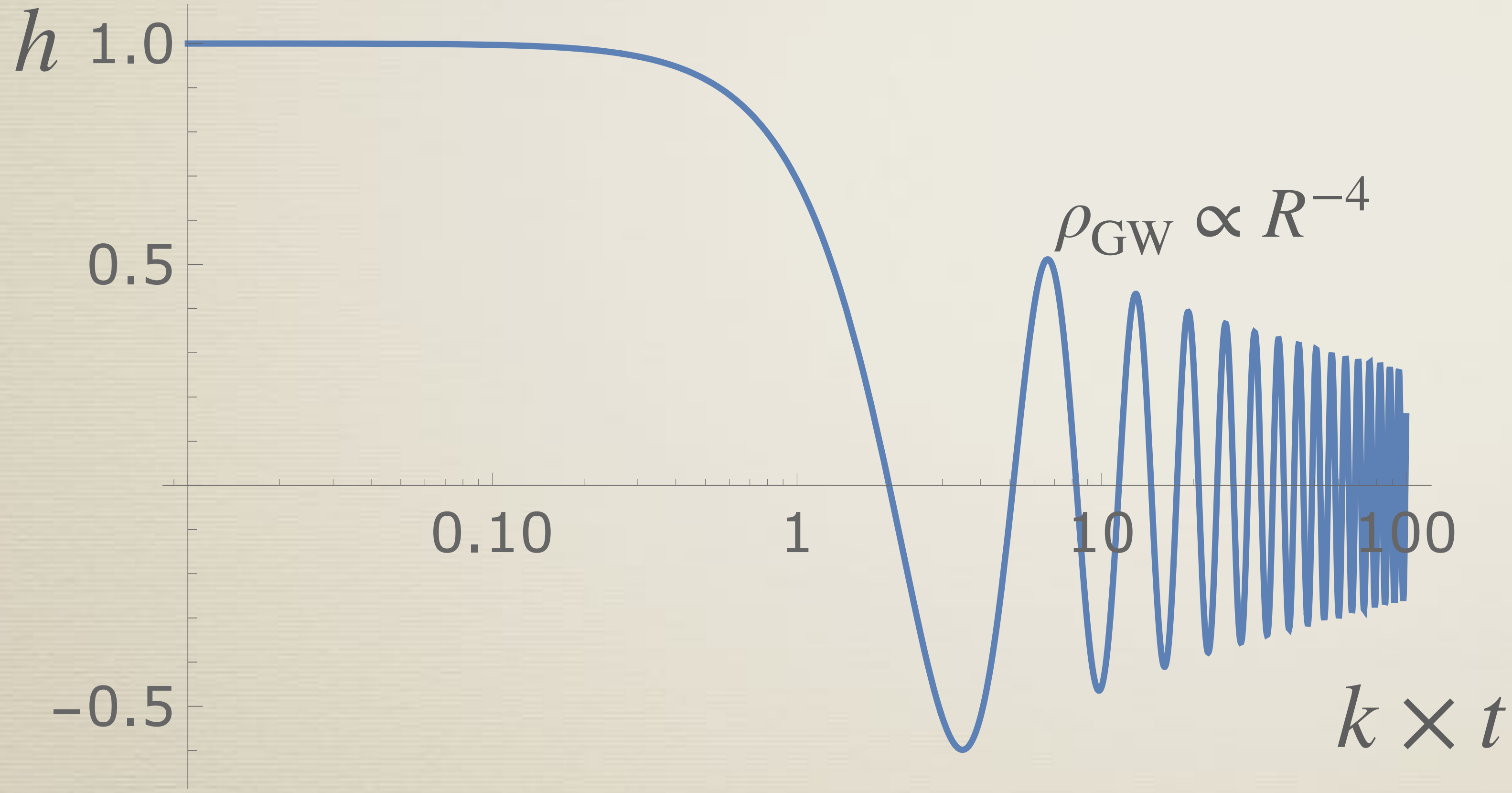
Co and KH (2019)



matter domination ends
WITHOUT
entropy production

Effect on primordial gravitational waves

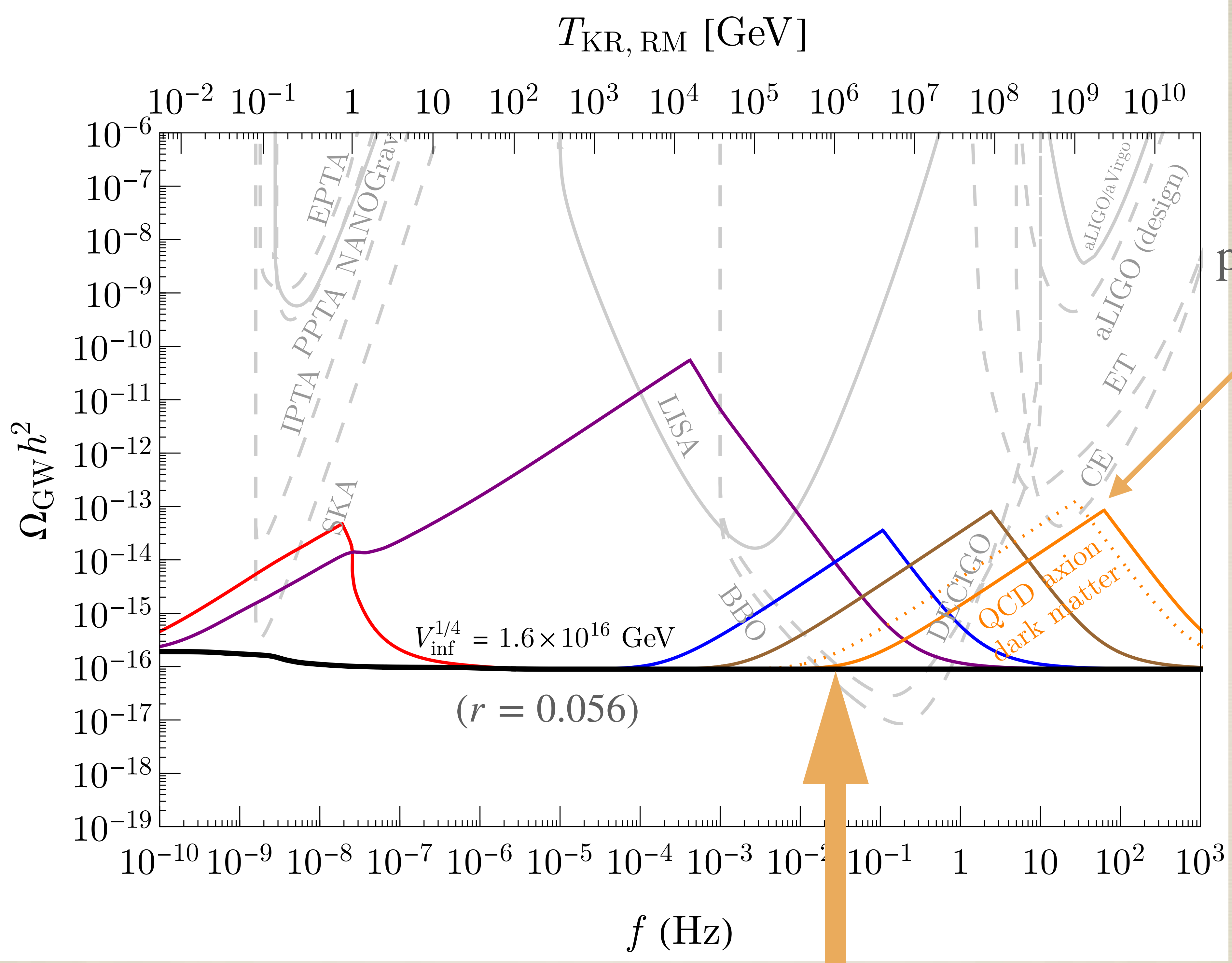
ex. inflationary gravitational waves



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

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

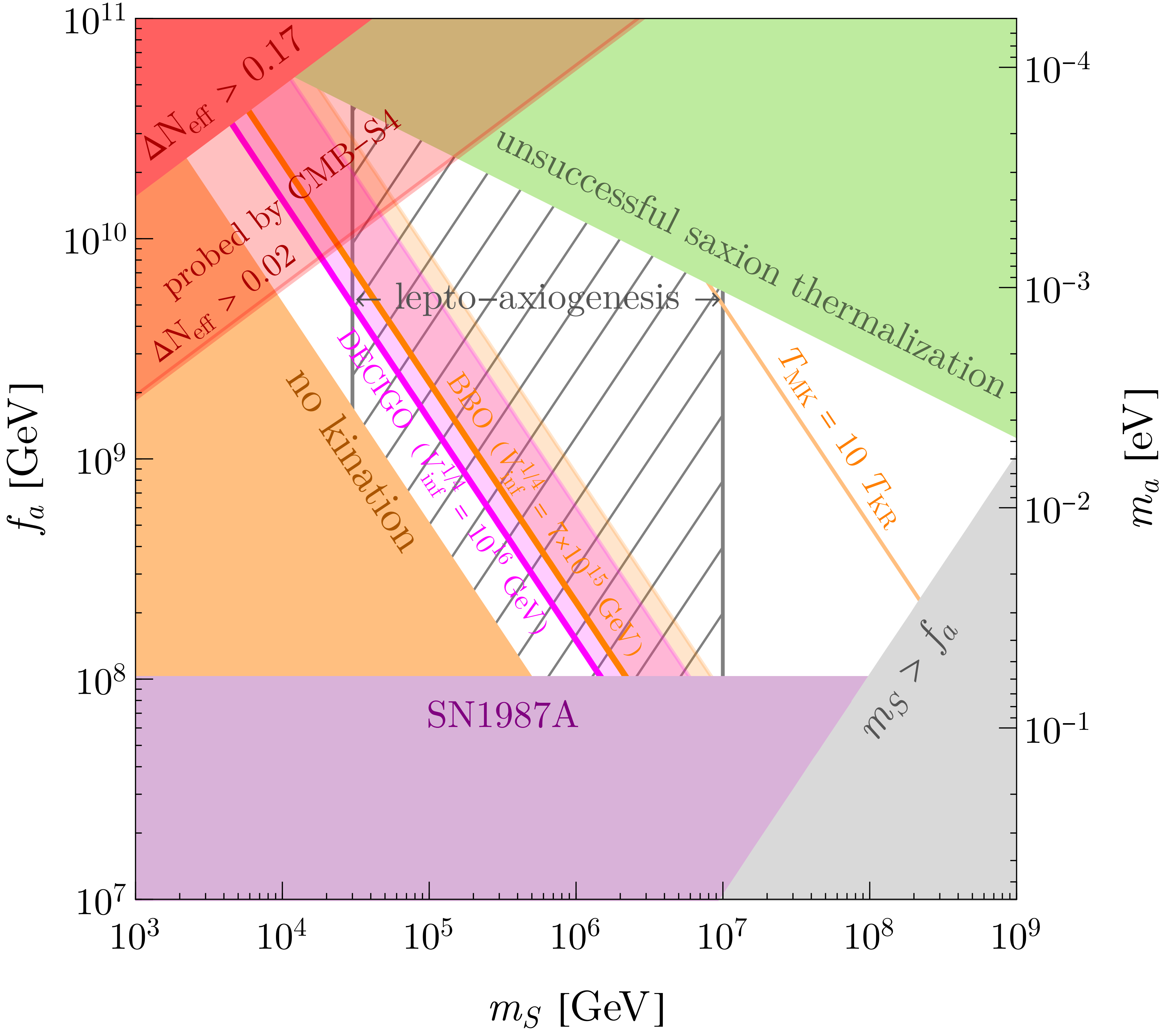
enhanced if the mode enters the horizon ($k \sim H$)
when the rotation dominates



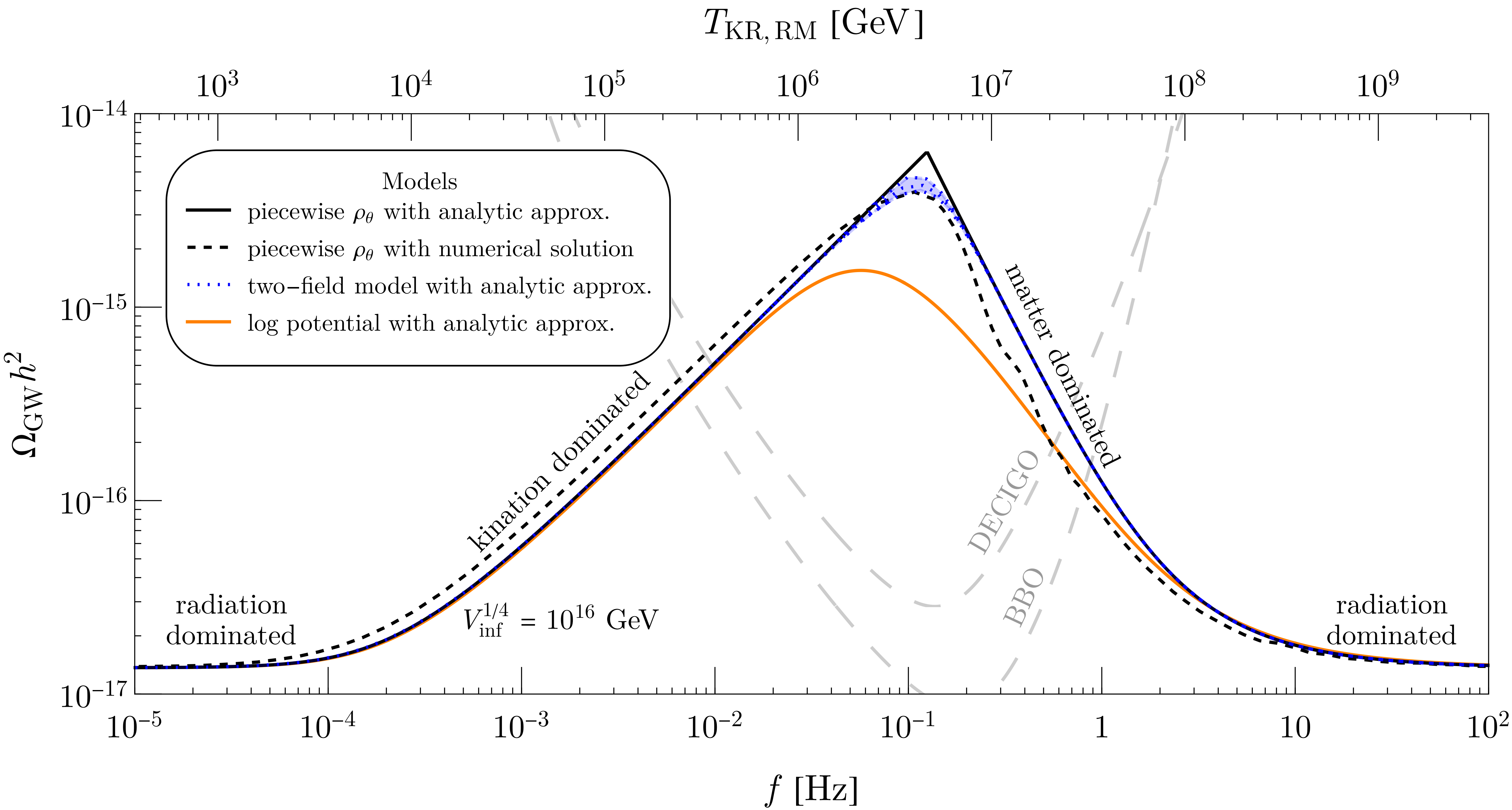
peak position depends on $m_S f_a$

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)



QCD axion dark matter: $T_{\rm KR} \simeq 2{\times}10^6$ GeV


$T_{\mathrm{KR,\,RM}}$ [GeV]
10^3
10^4
10^5
10^6
10^7
10^8
10^9
$\Omega_{\mathrm{GW}}h^2$
10^{-14}
10^{-15}
10^{-16}
10^{-17}
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
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
f [Hz]