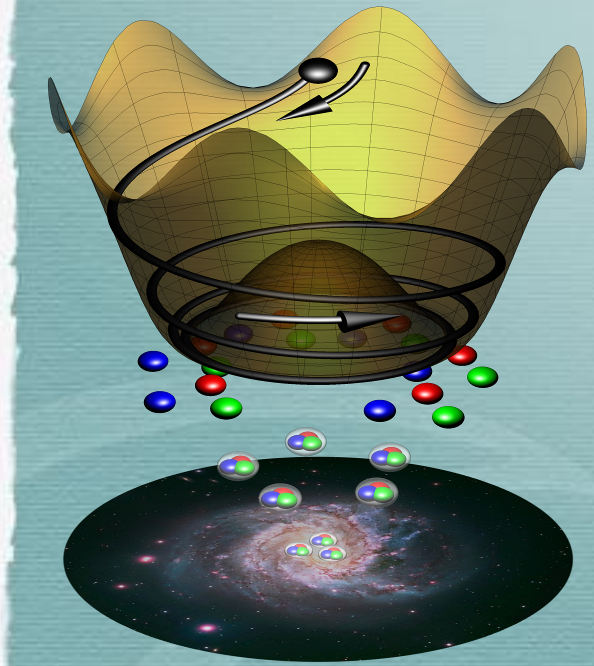
02/06/2022, Planck conference

Cosmology of Axion rotation

Keisuke Harigaya (CERN)



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

Outline

- Introduction to axion dark matter
- Dark matter from axion rotation
- Baryon asymmetry from axion rotation
- Discussion

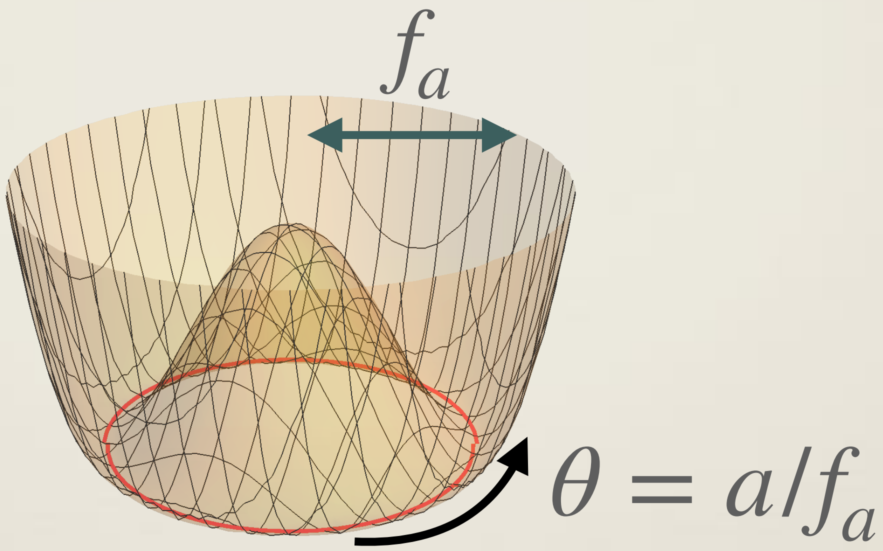
QCD axion

- solves the strong CP problem

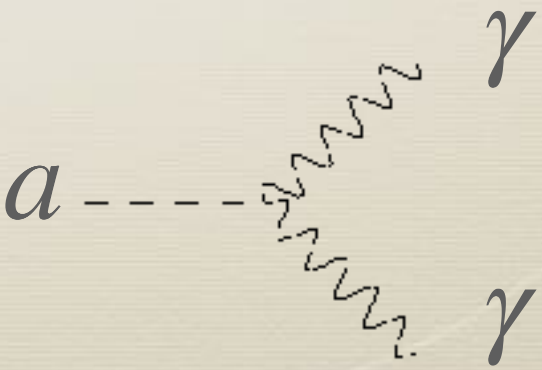
Peccei and Quinn (1977)
Weinberg (1978), Wilczek (1978)

- is a good dark matter candidate

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

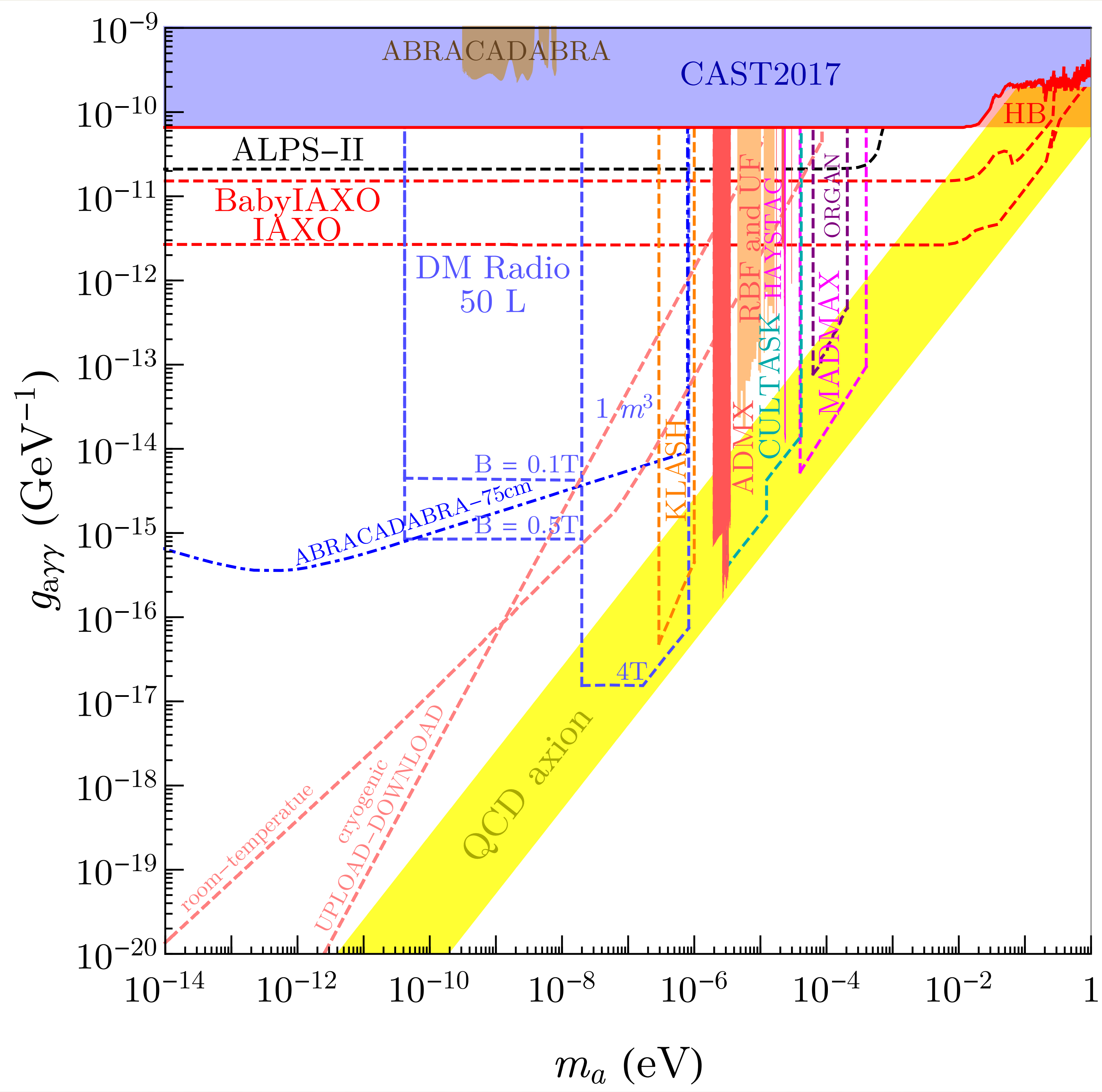


$$m_a = 6 \text{ meV} \, \frac{10^9 \text{ GeV}}{f_a}$$

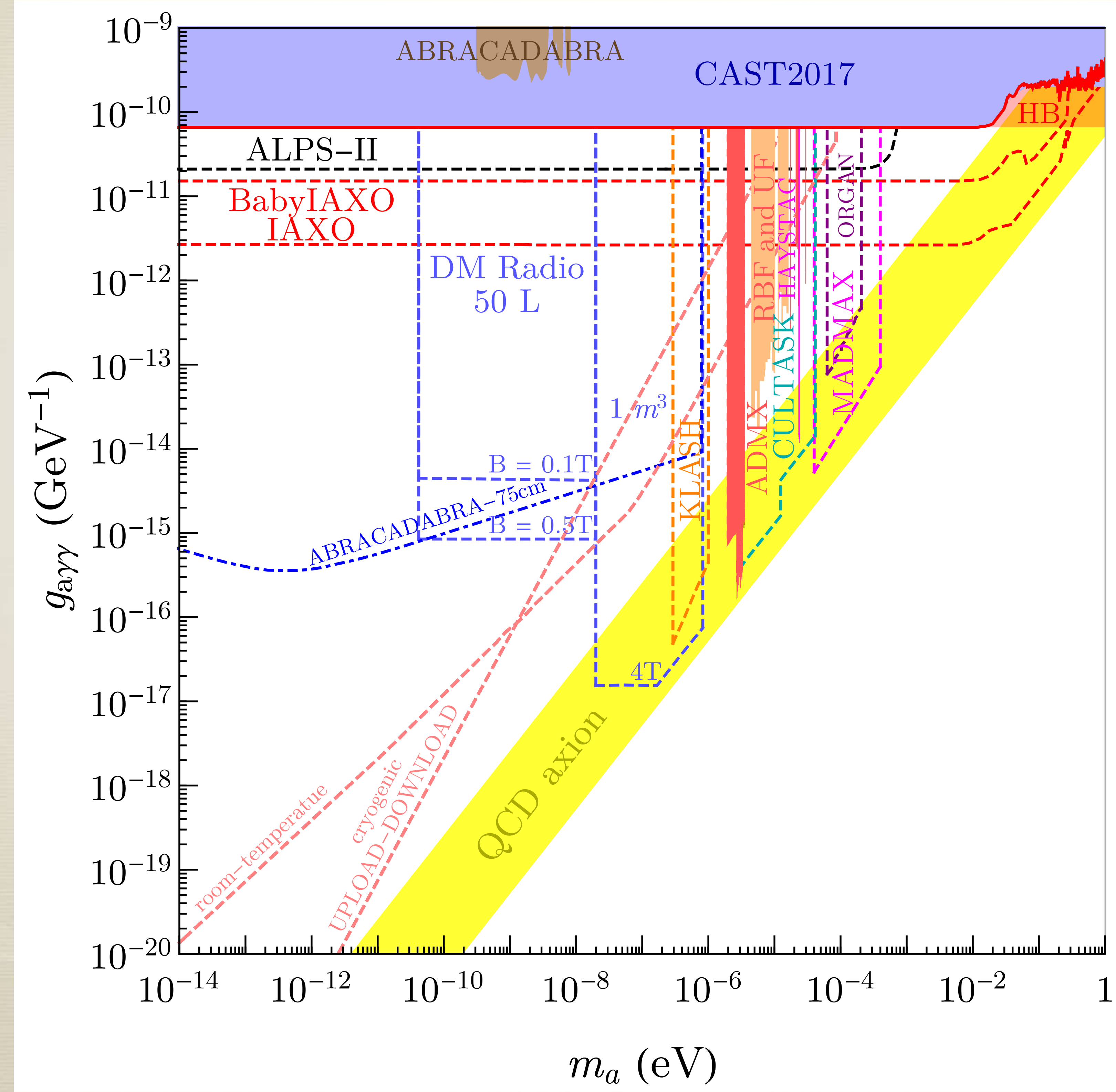


$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

Axion search

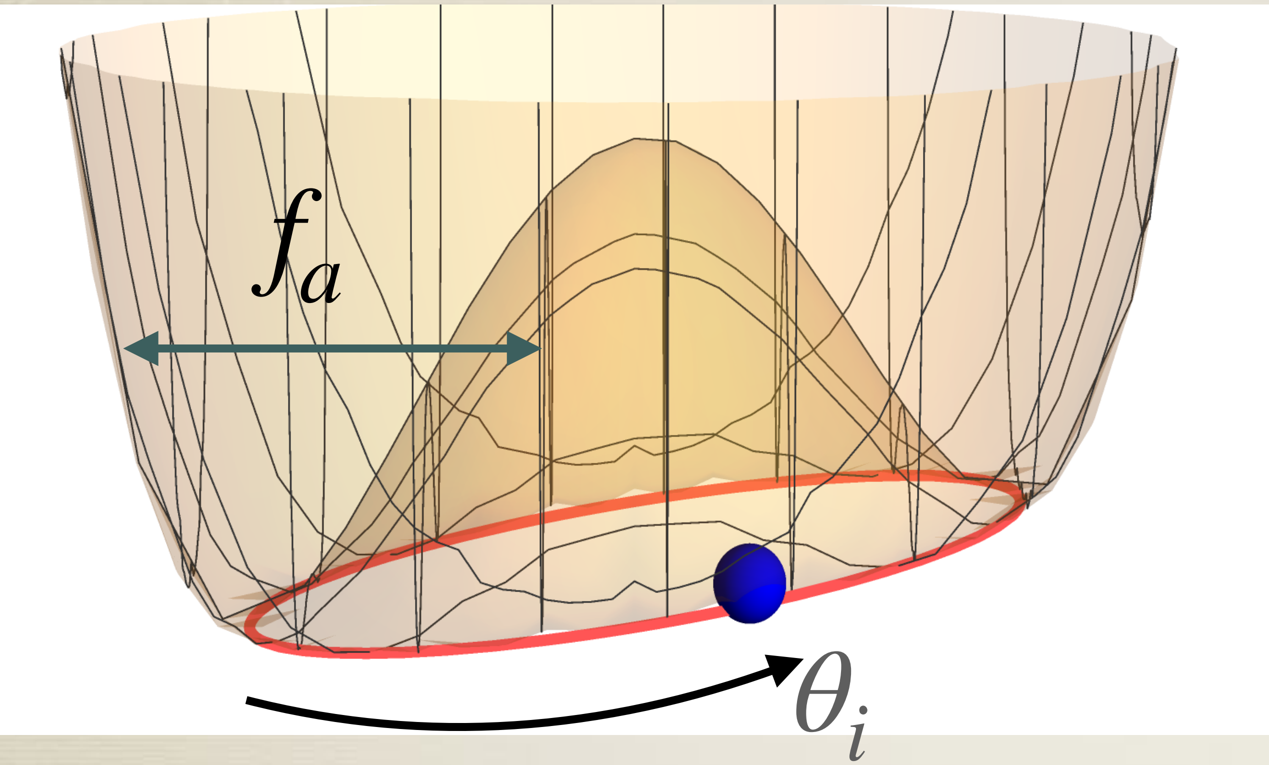


Dark matter?


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

Misalignment mechanism

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

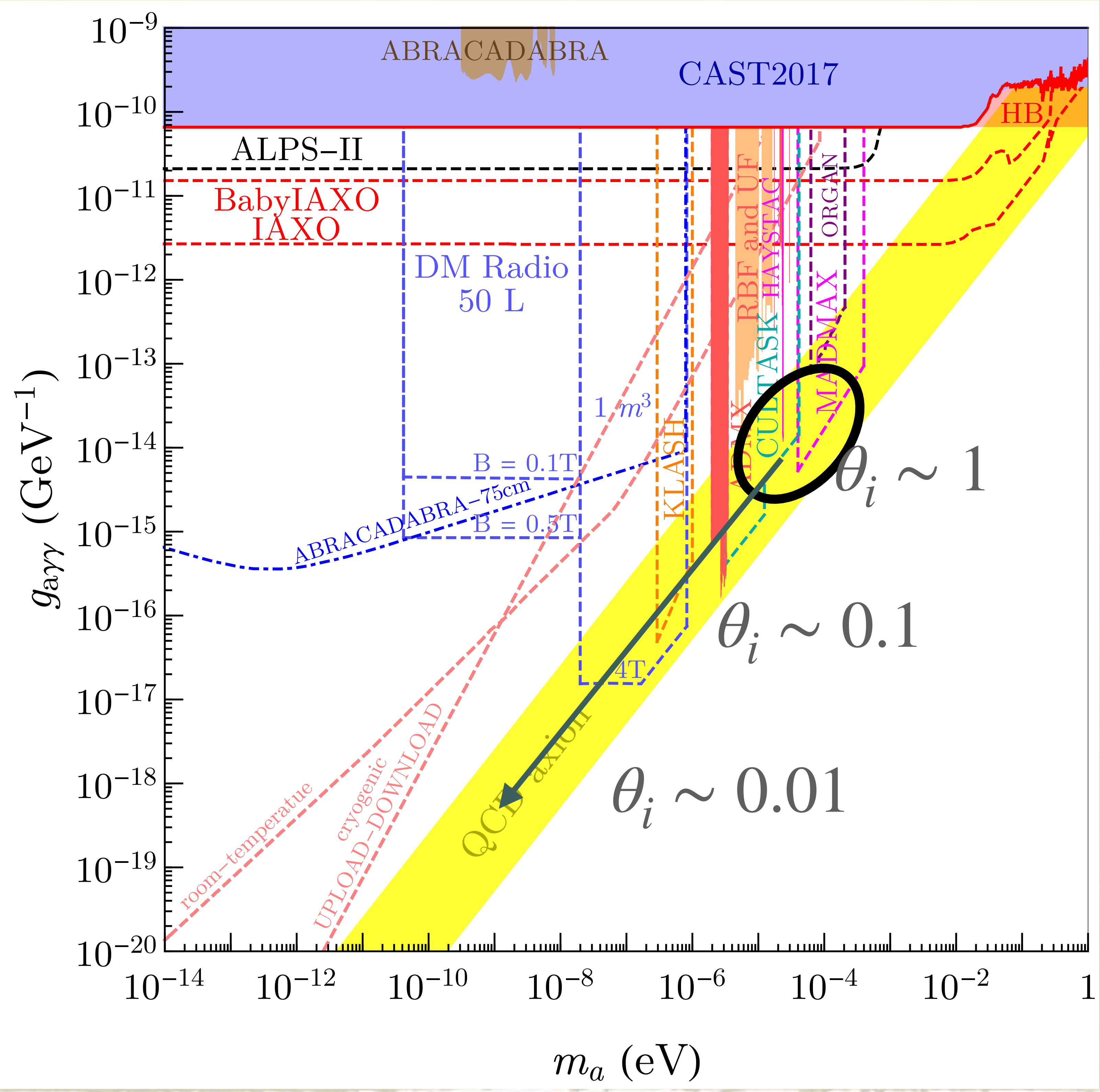


For the QCD axion,

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

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

Dark matter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QCD axion
room–temperatue
cryogenic
UPLOAD–DOWNLOAD
$\theta_i \sim 1$
$\theta_i \sim 0.1$
$\theta_i \sim 0.01$
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)
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10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
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10^{-18}
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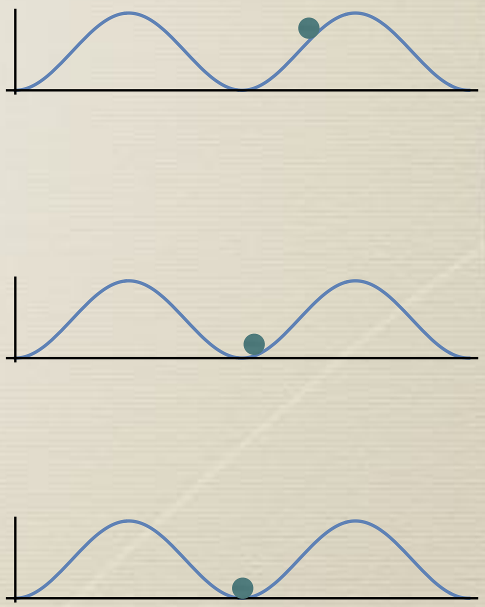
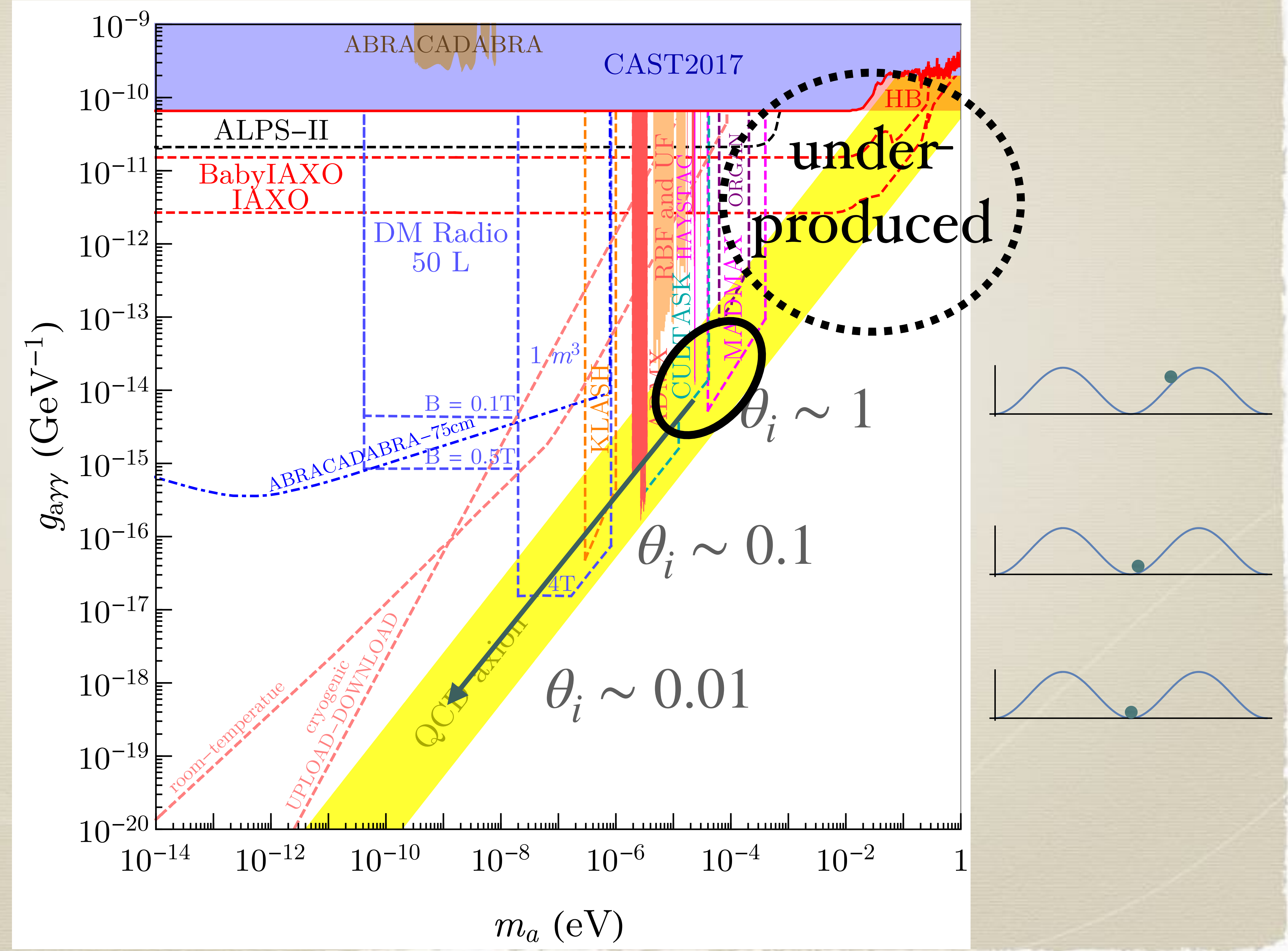
10^{-4}
10^{-2}
1



Dark matter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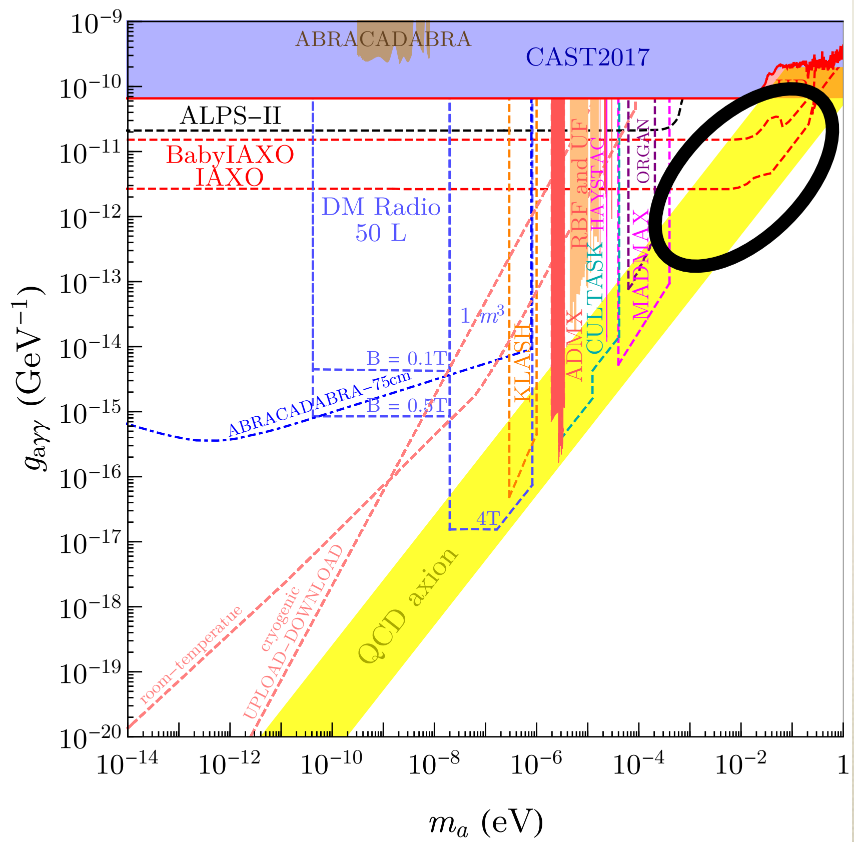
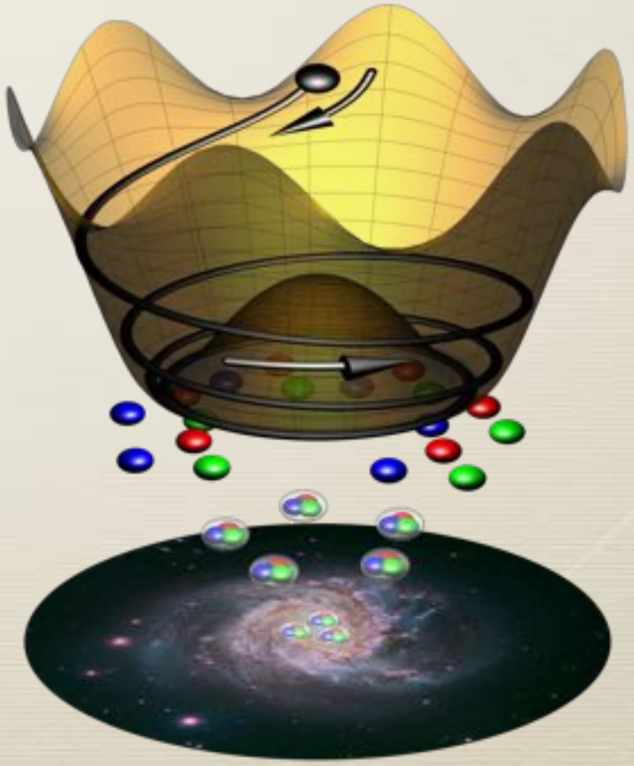
10^{-2}
1

I will present new cosmological dynamics of the axion

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





Outline

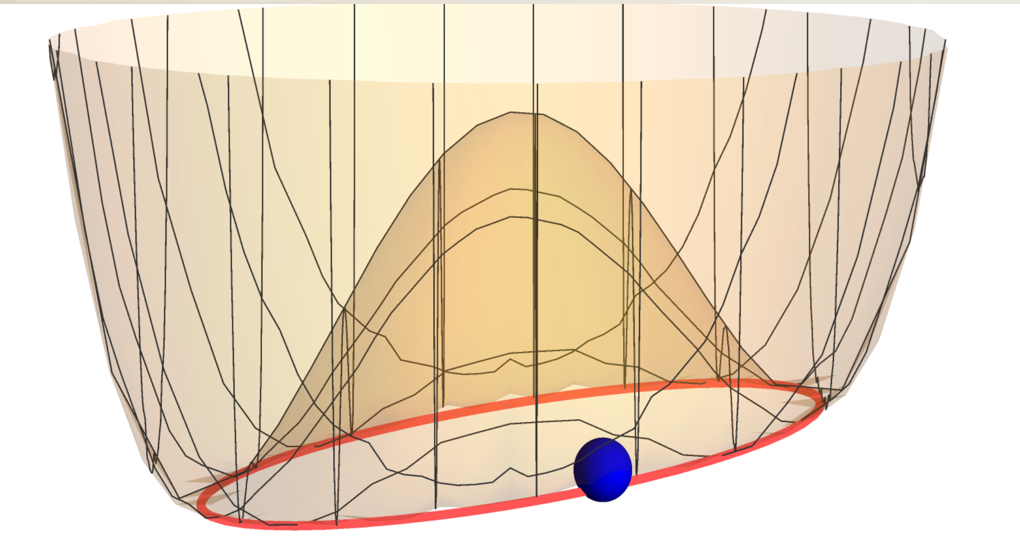
- Introduction to axion dark matter
- Dark matter from axion rotation
- Baryon asymmetry from axion rotation
- Discussion

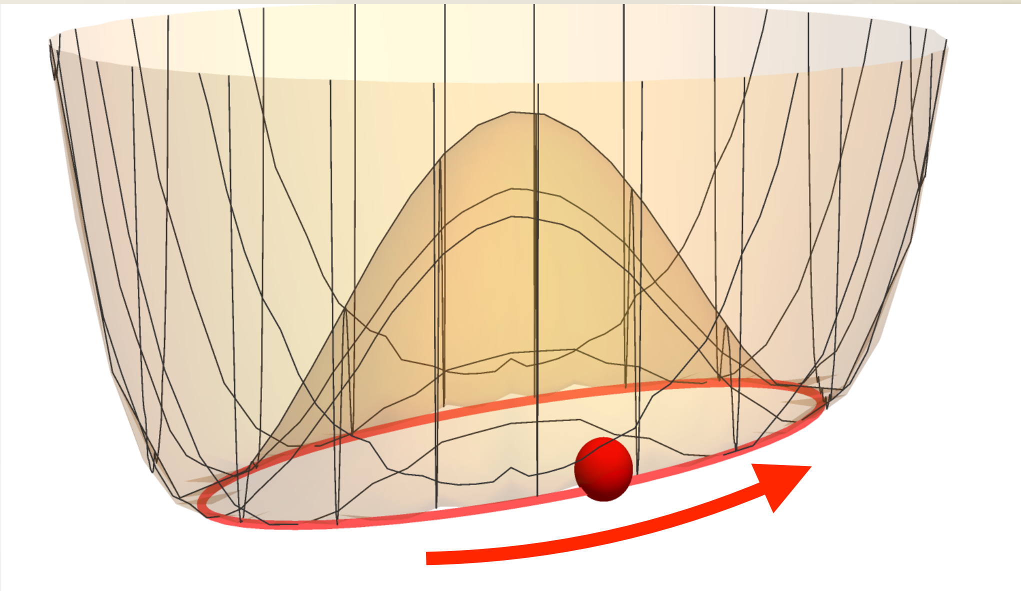
Rotation?

Co and KH(2019)
Co, Hall and KH(2019)
Geraldine Servant (Wed.)

Conventional picture

Non-zero initial angular velocity?





$\dot{\theta}_i = 0$

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

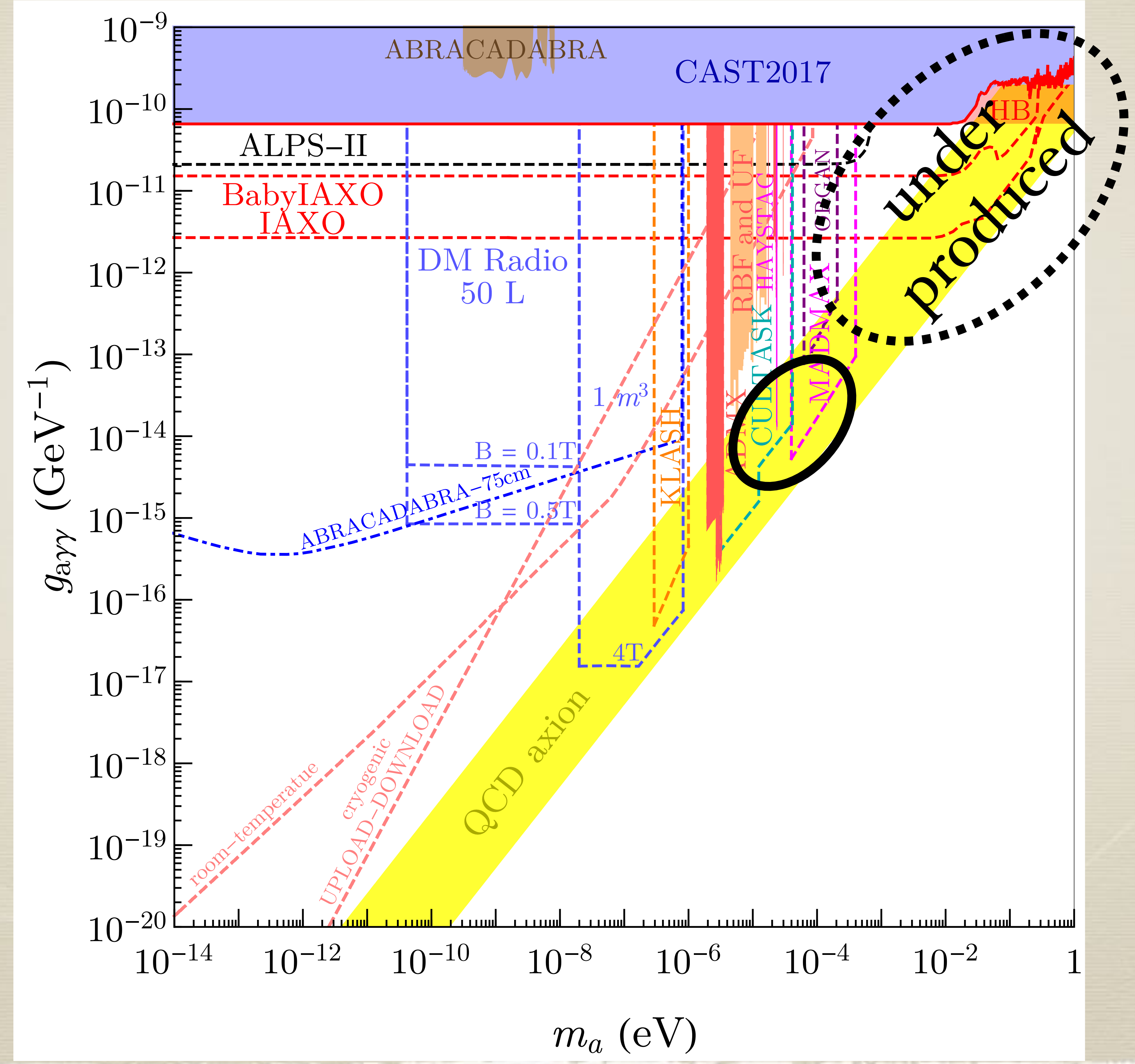
V

$V + K$

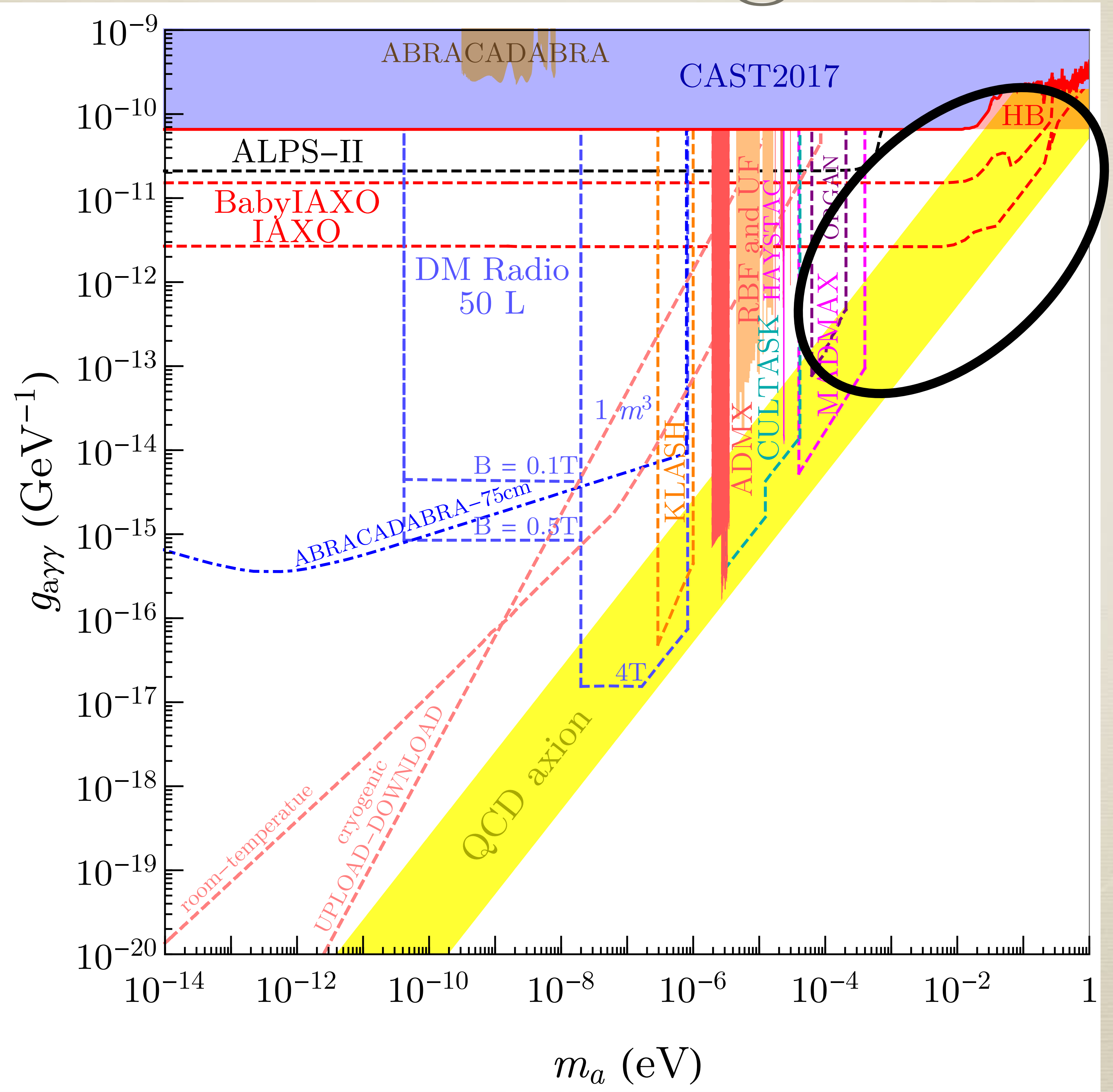
The kinetic energy goes to axions,
enhancing the axion abundance

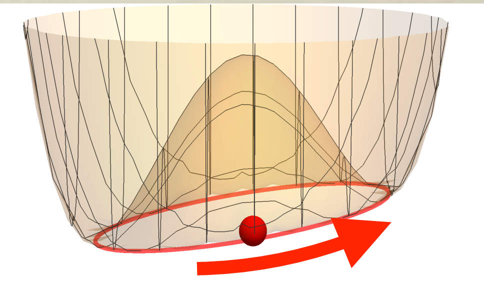
Kinetic Misalignment

Conventional mechanisms



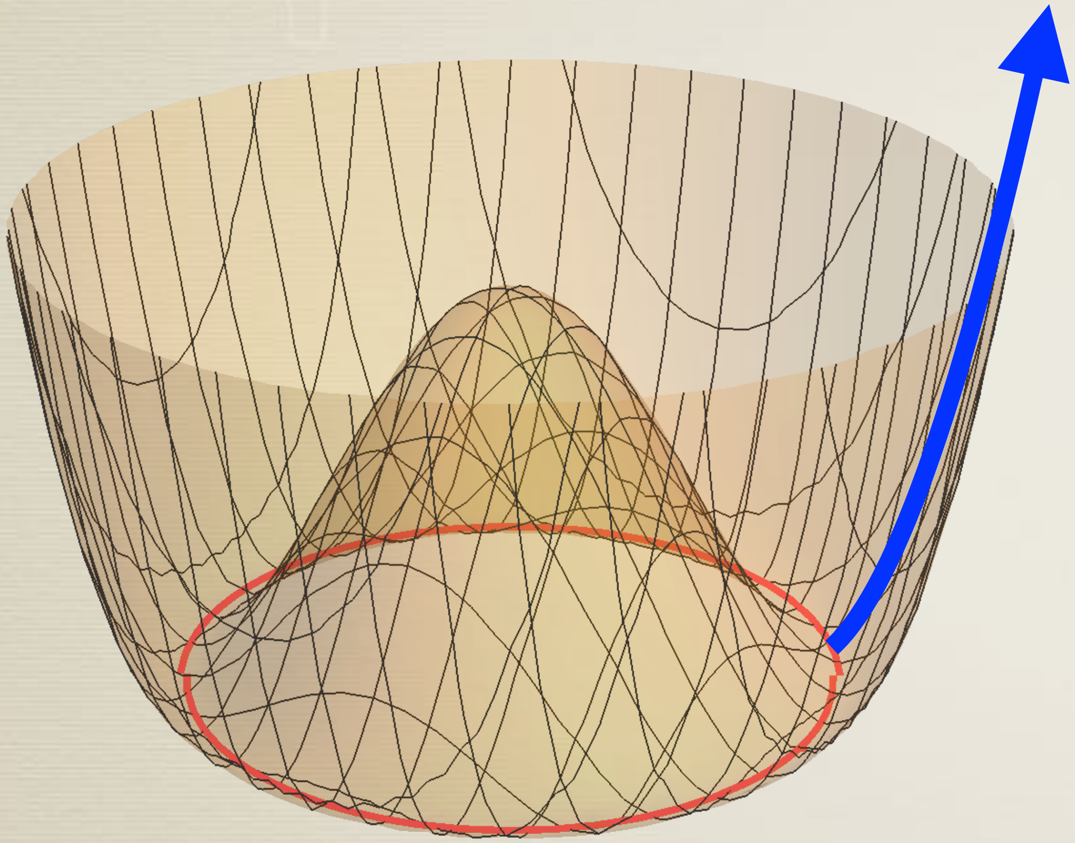
Kinetic misalignment





How to initiate the rotation

Co and KH (2019)
Geraldine Servant (Wed.)



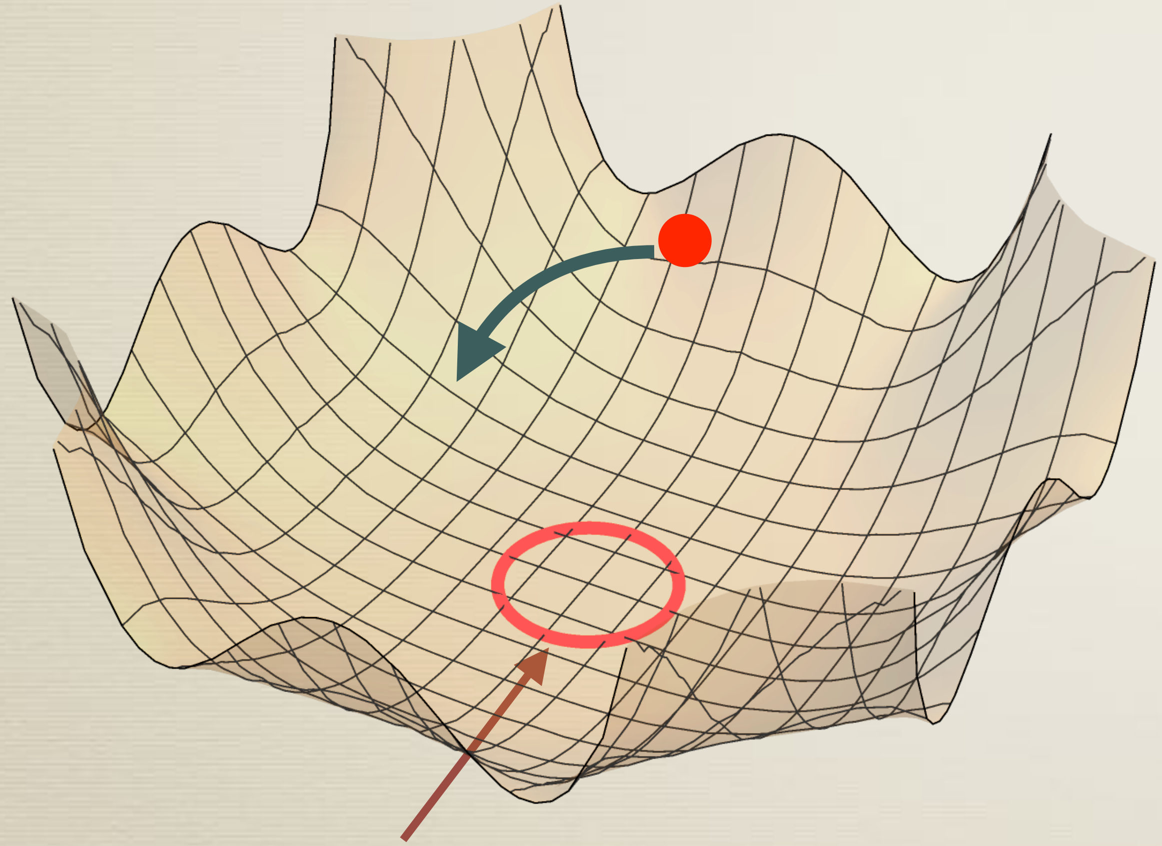
Consider the dynamics of the radial direction

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

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

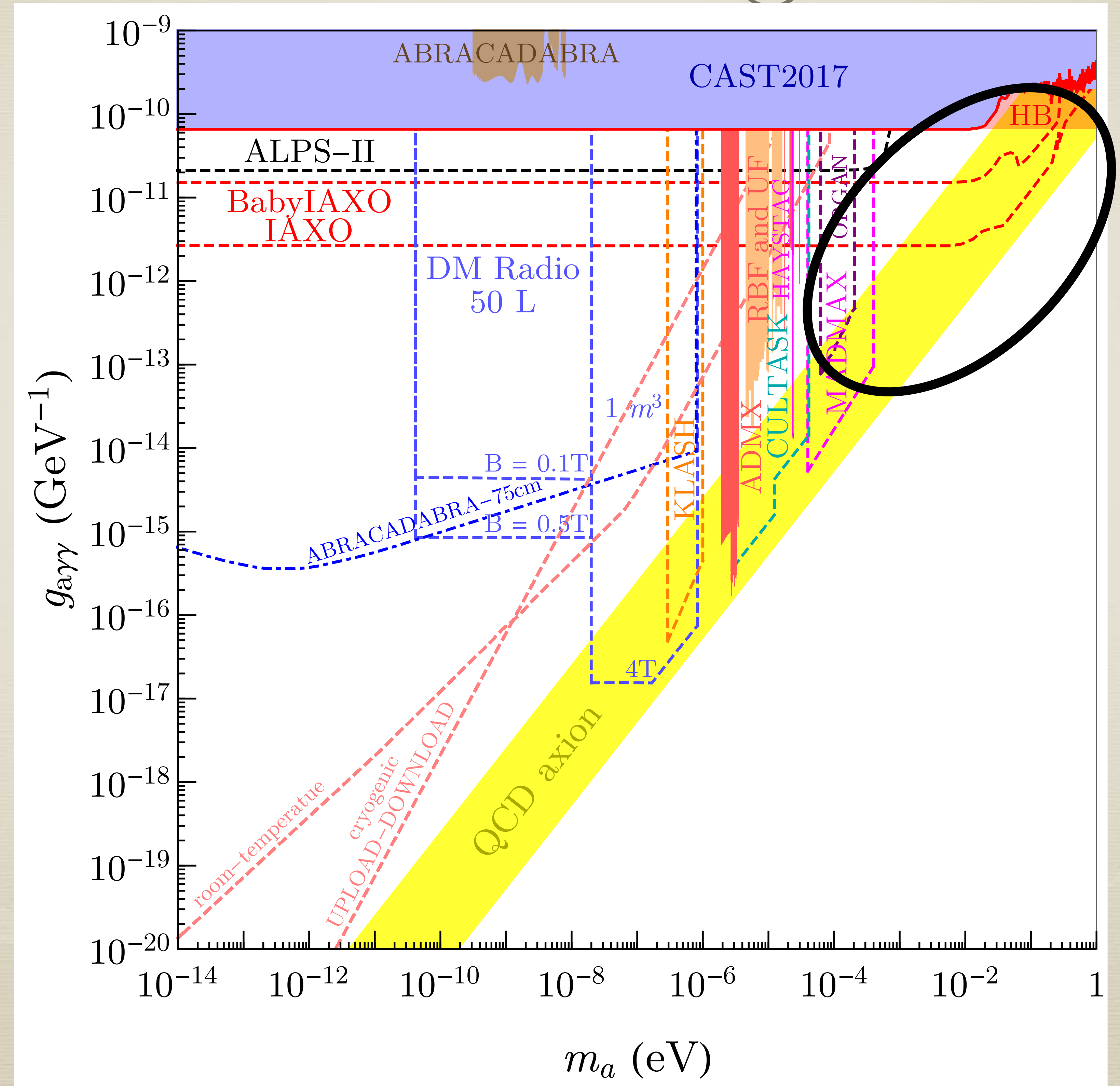
Higher order terms

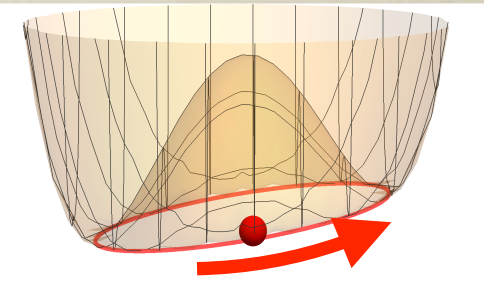
$$V \sim P^n \sim S^n \cos(n\theta)$$

may be effective

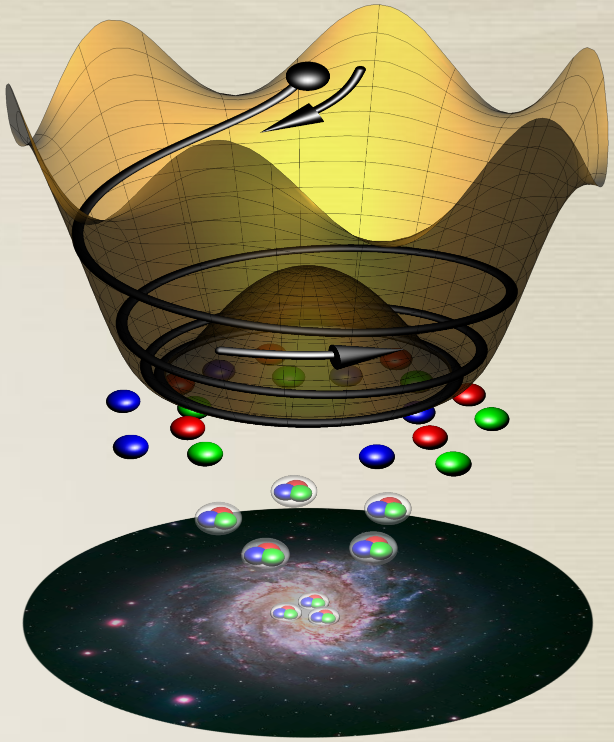
Angular motion is induced by the potential gradient

Kinetic misalignment





Outline



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Axiogenesis

Minimal axiogenesis

Co and KH (2019)

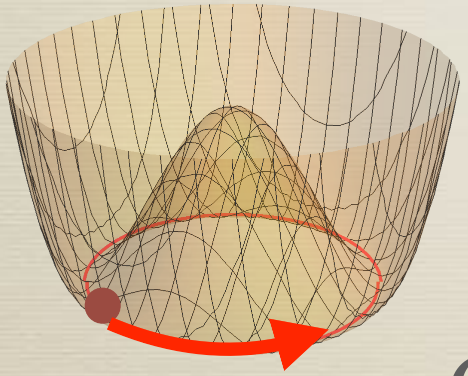
The PQ symmetry is quantum mechanically broken by the QCD interaction (anomaly)

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

+

So is the quark chiral symmetry

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



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

Minimal axiogenesis

Co and KH (2019)

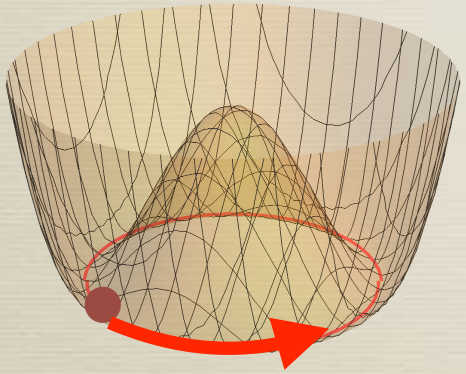
The chiral symmetry is quantum mechanically broken by the weak interaction

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

+

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

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



↓

weak

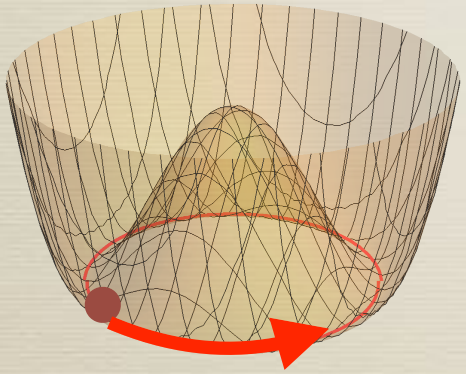
PQ

Chiral charge → B+L

Minimal axiogenesis

Co and KH (2019)

B is frozen upon
the electroweak phase transition



PQ

~~weak~~

Chiral charge → B+L

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 $T_{\rm EW} \sim 100$ GeV

Minimal axiogenesis

Co and KH (2019)

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

1. Dark Matter
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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

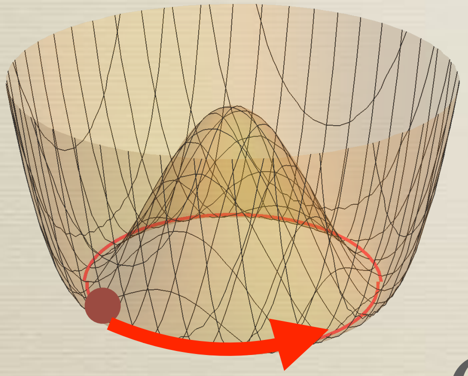
Axiogenesis and BSM

Co and KH (2019)

Baryon number violation from BSM

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

$$\Downarrow$$



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

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)

- Baryon number violation in supersymmetric model (RPV)

Co, KH, Johnson and Pierce (2021)

- Sphaleron processes in new gauge interaction

KH and Wang (2021)

Summary

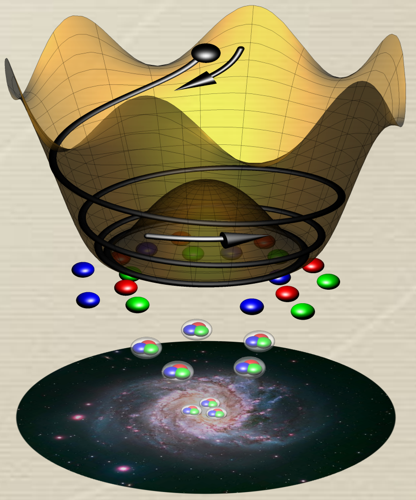
- Kinetic Misalignment : Rotation of the axion field produces axion dark matter

Axion dark matter with a decay constant

$$f_a \ll 10^{11}\ \text{GeV}$$

- Axiogenesis : Axion rotation produces baryon asymmetry

A relation between BSM parameters and f_a

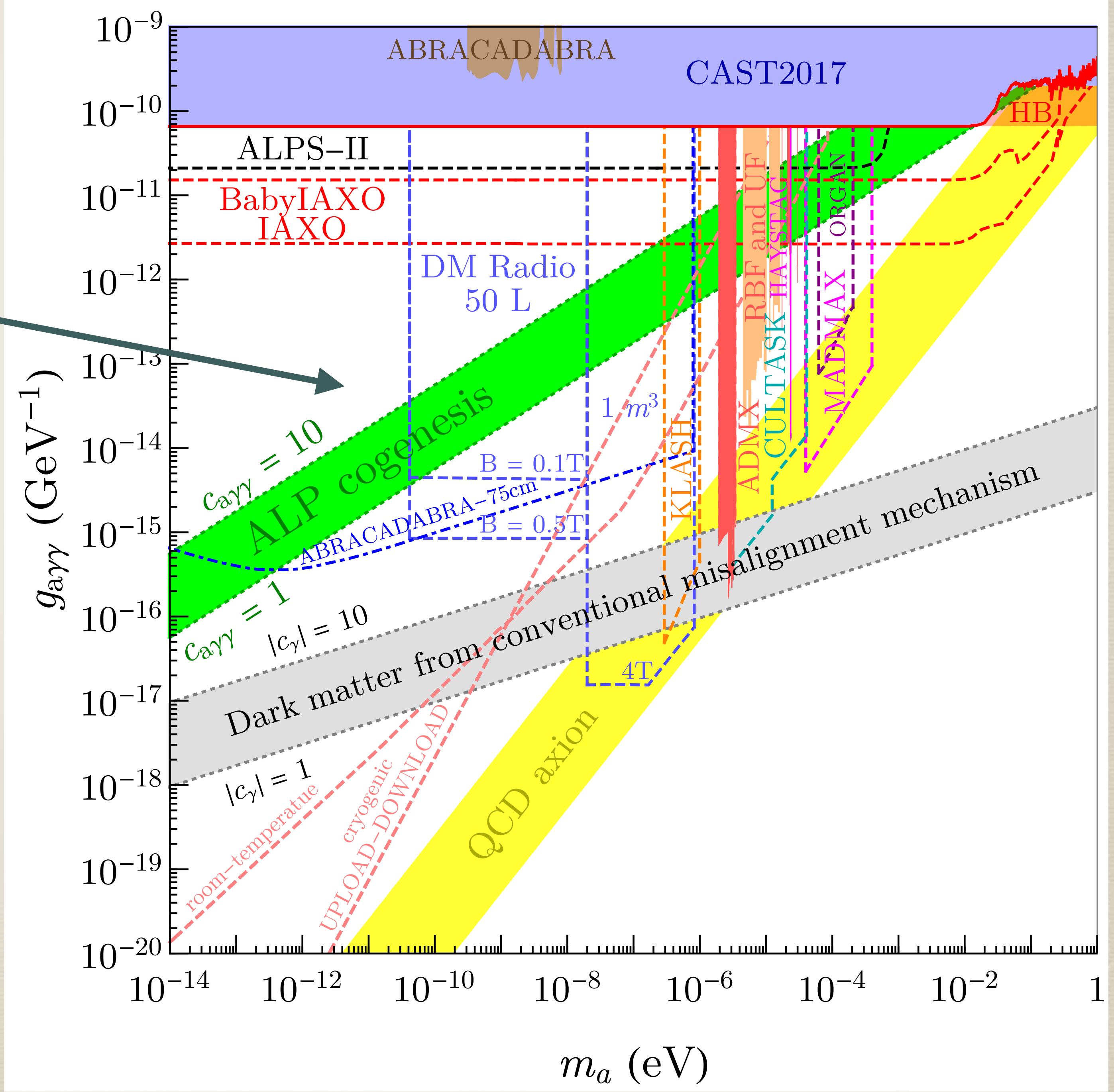


Beyond the standard QCD axion

- Axion-Like Particle

Co, Hall and KH (2020)

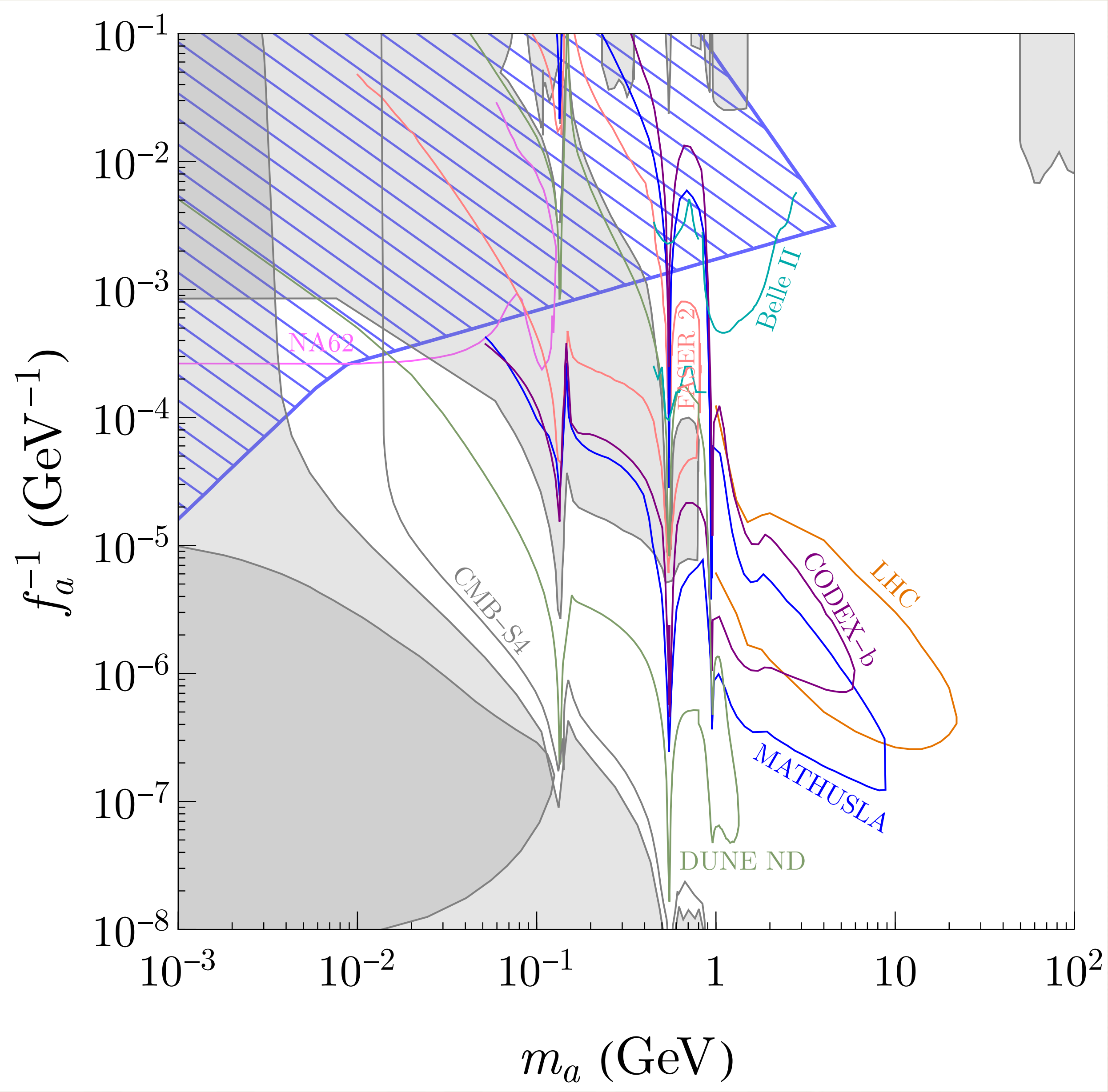
Assuming the standard electro weak phase transition,



- Heavy QCD axion

Beyond the standard QCD axion

- Axion-Like Particle



- Heavy QCD axion

Tony Gherghetta (Tue.)
David Dunsky (Thu.)

Co, Gherghetta and KH (2022)

Axion decays, so the DM-abundance constraint is absent

More cosmological roles

- Kination by axion rotation

Imprints on primordial gravitational waves

Co and KH (2019),
Co, Dunsky, Fernandez, Ghalsasi, Hall, KH and Shelton (2021)
Gouttenoire, Servant and Simakachorn (2021)
Geraldine Servant (Wed.)
Yann Gouttenoire (Wed.)

- Cosmic perturbations

Local non-gaussianity $f_{\rm NL} \lesssim -2.5$

Co, KH and Pierce (2022)

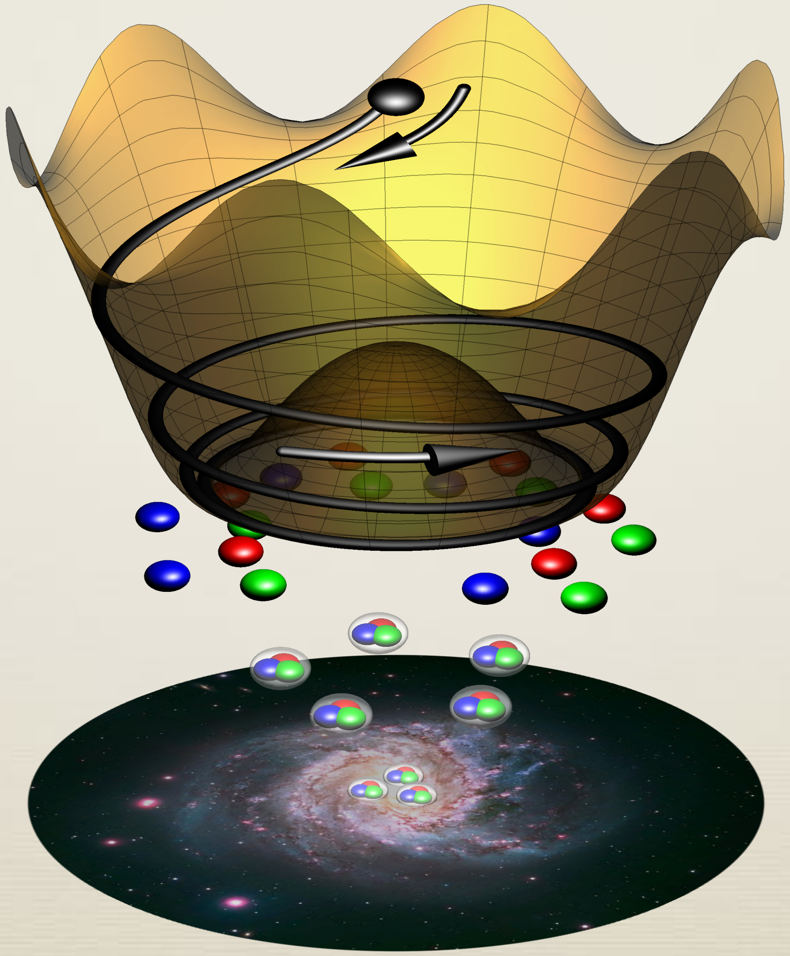
- Gravitational waves via couplings with dark photons

Produce gravitational waves

Co, KH and Pierce (2021)
Madge, Ratzinger, Schmitt and Schwaller (2021)

Axion rotation

Maybe more cosmological roles?



Back up

Kinetic misalignment

Axion fragmentation

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

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

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

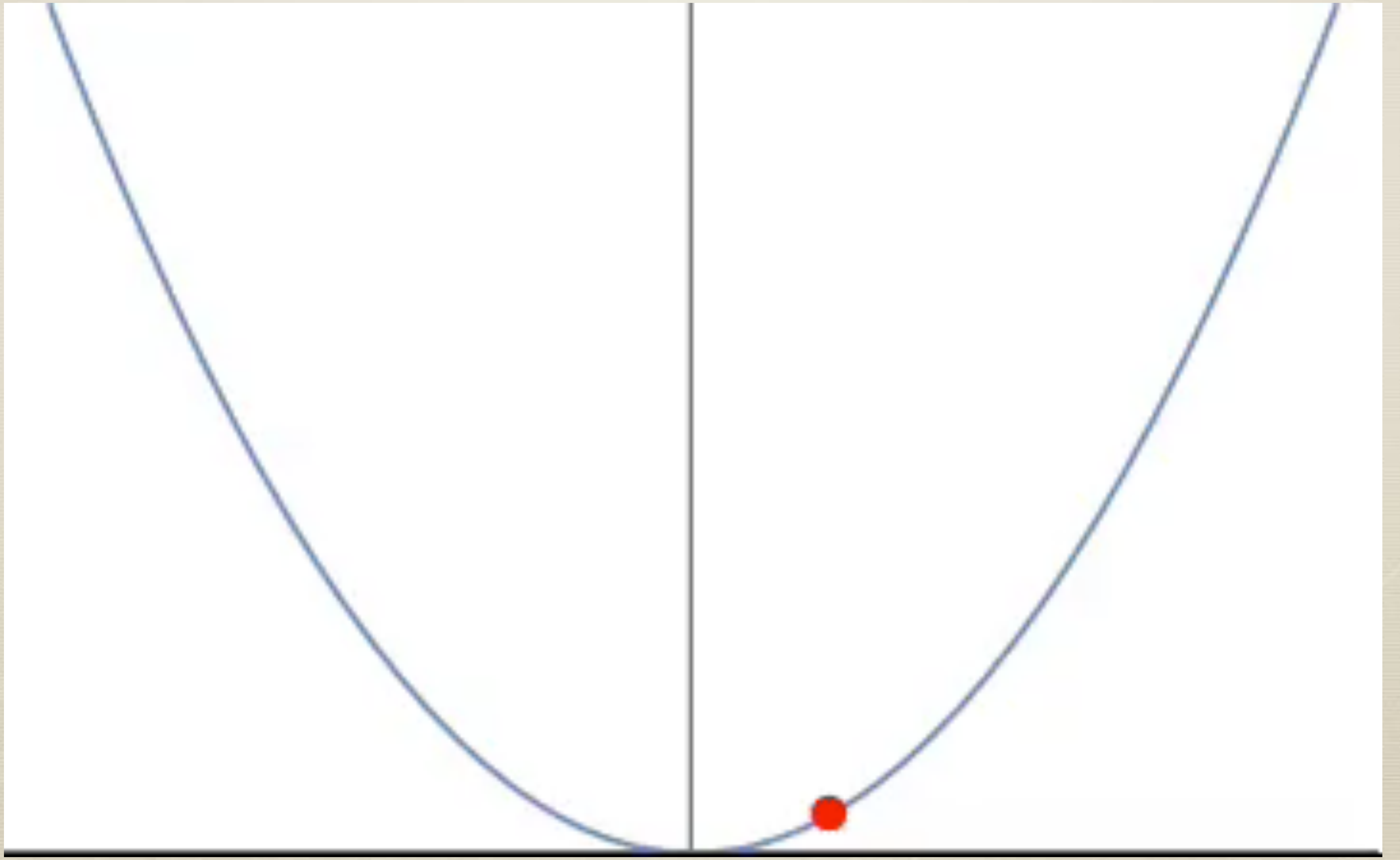
EOM of the fluctuation at the linear level:

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

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)

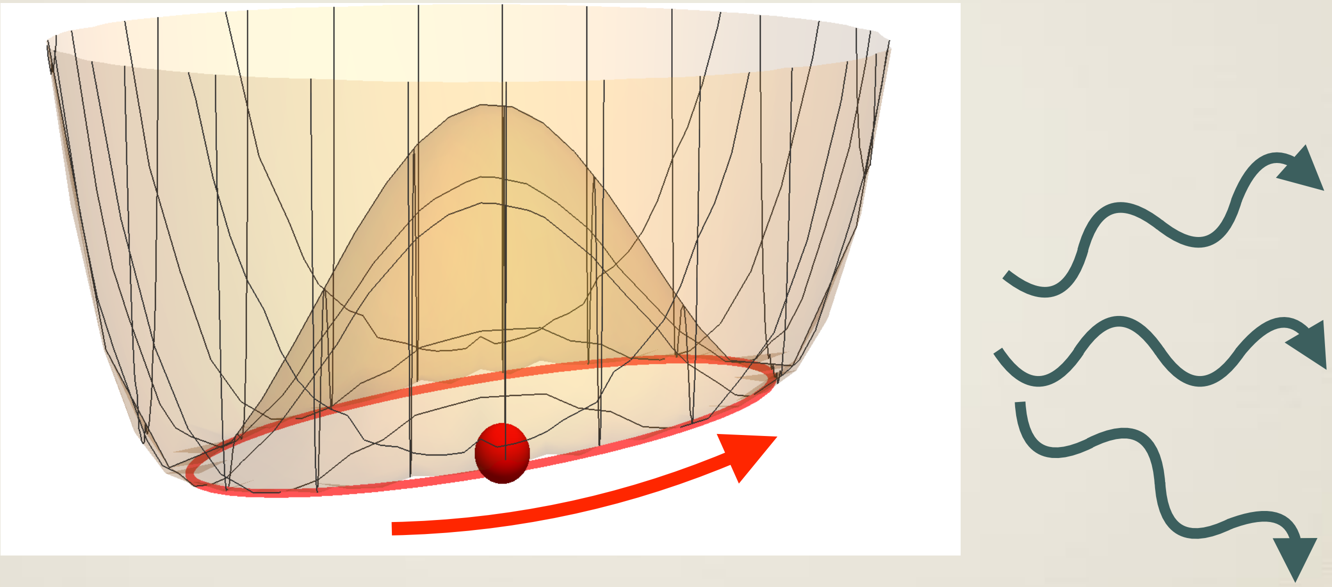
$$\ddot{a}_k + \left(k^2 + m_a^2 \cos\dot{\theta}t\right) a_k = 0$$

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

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

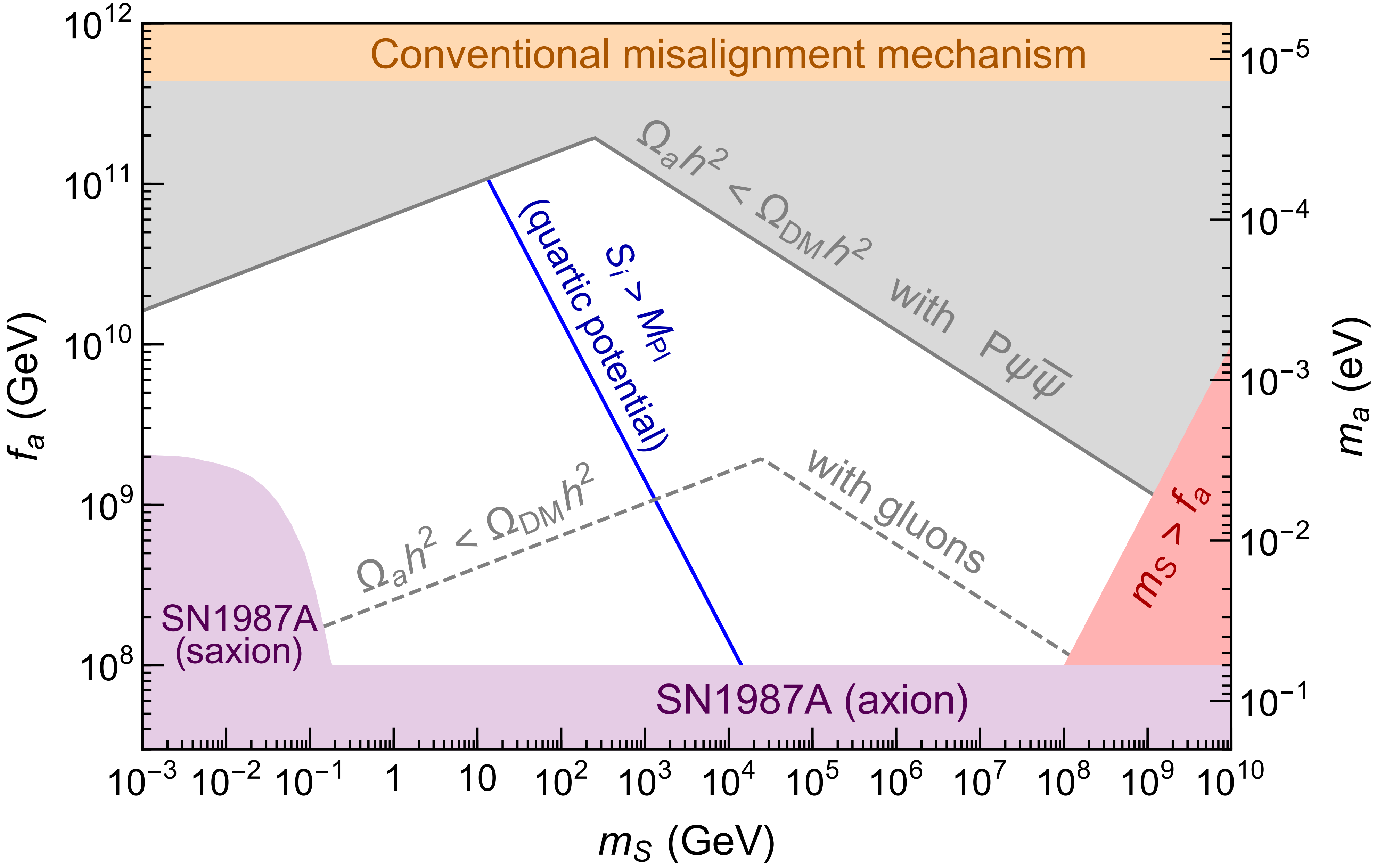
$$n_{a,\mathrm{PR}} = \frac{\rho_{\mathrm{rot}}}{k_{\mathrm{PR}}} \simeq \frac{\dot{\theta}^2 f_a^2/2}{\dot{\theta}/2} = \dot{\theta} f_a^2 = n_{\mathrm{PQ}}$$

Co, KH and Pierce (2021)

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

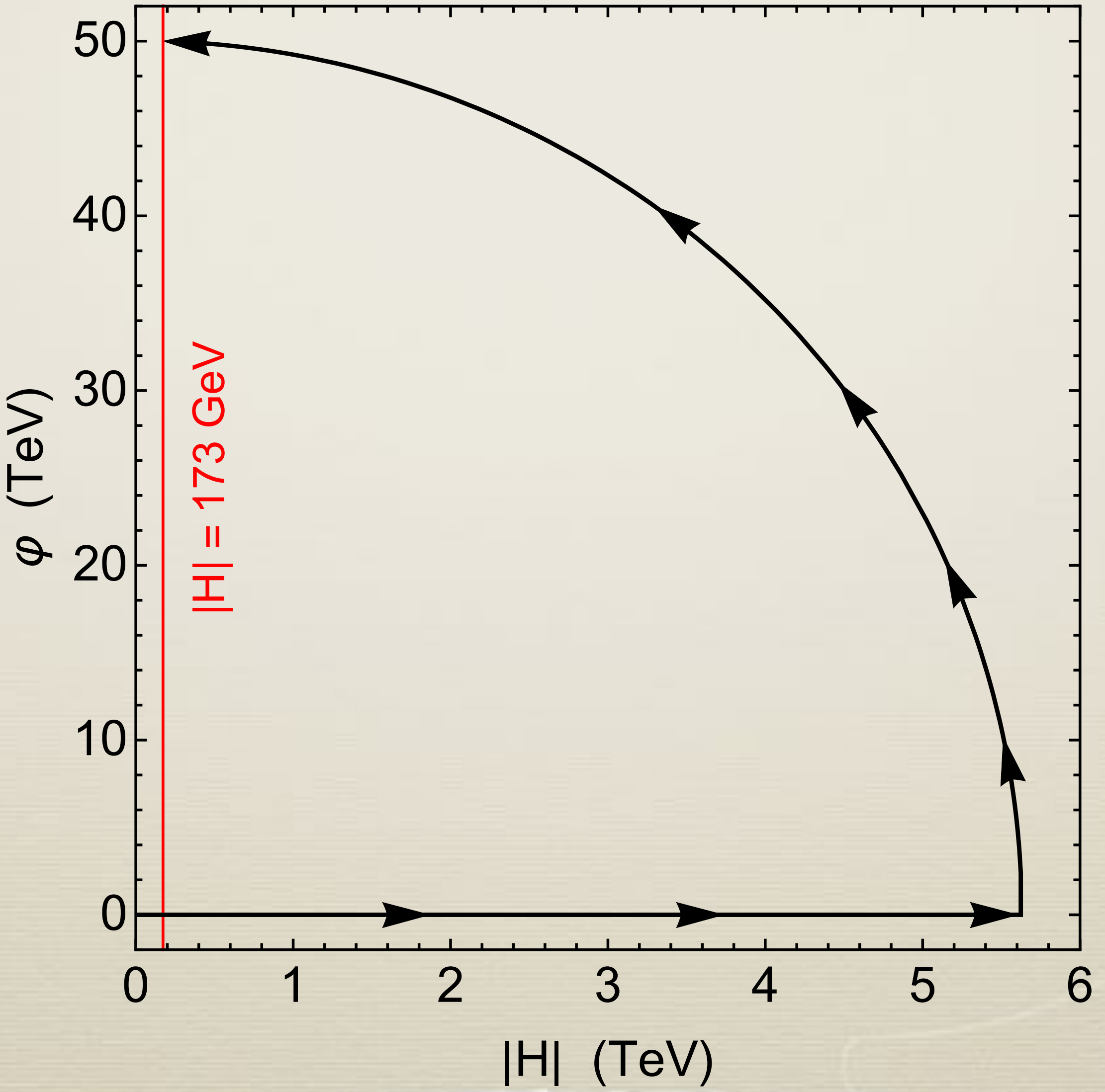
Thermalization

Co, Hall and KH (2019)



Earlier EW phase transition

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



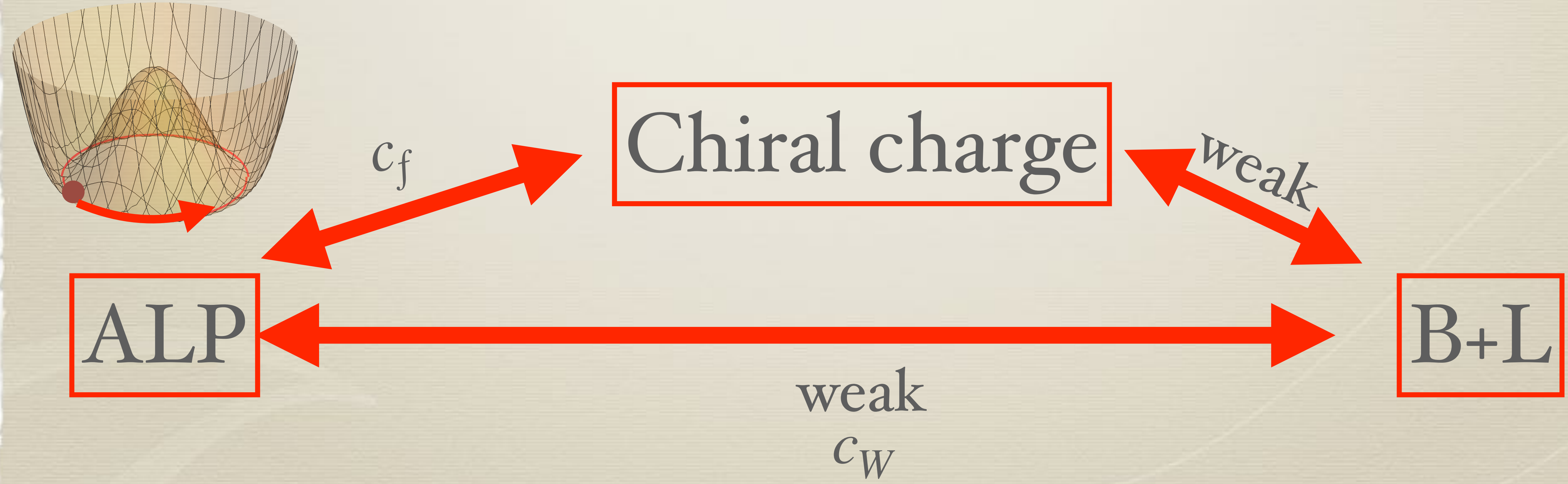
ALP cogenesis

ALP genesis

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

A similar mechanism works for generic ALPs

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



Chiral charge

c_f

weak

ALP

B+L

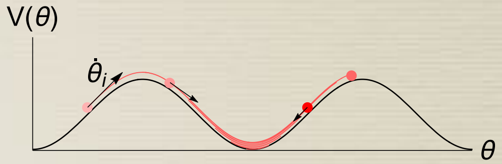
weak
c_W

ALP cogenesis

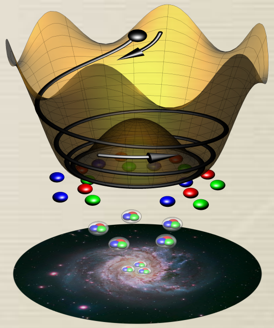
Co, Hall and KH (2020)

Assuming the standard EW phase transition,

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



1. Dark Matter
2. Baryon asymmetry

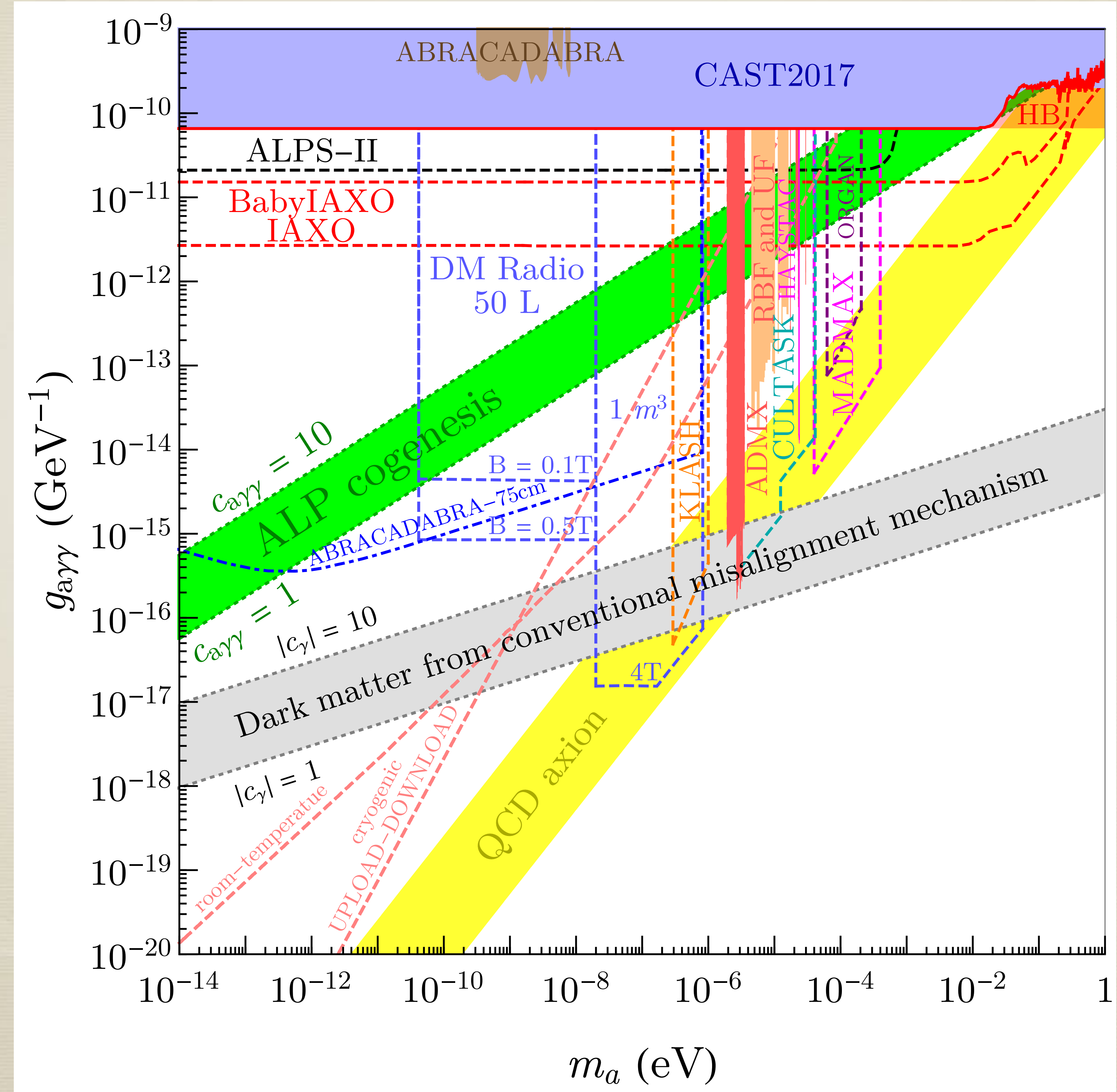


3 free parameters − 2 densities to fit
= 1 free parameter

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

Prediction on the ALP coupling

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



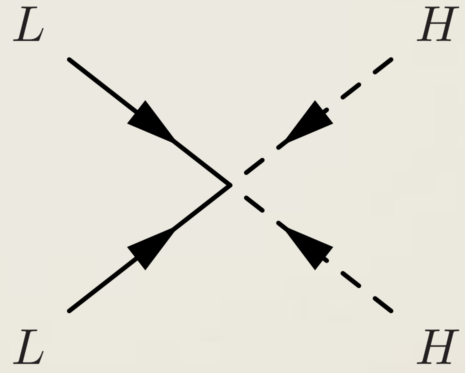
Lepto-axiogenesis

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

Majorana neutrino mass

Majorana neutrino masses break the lepton symmetry

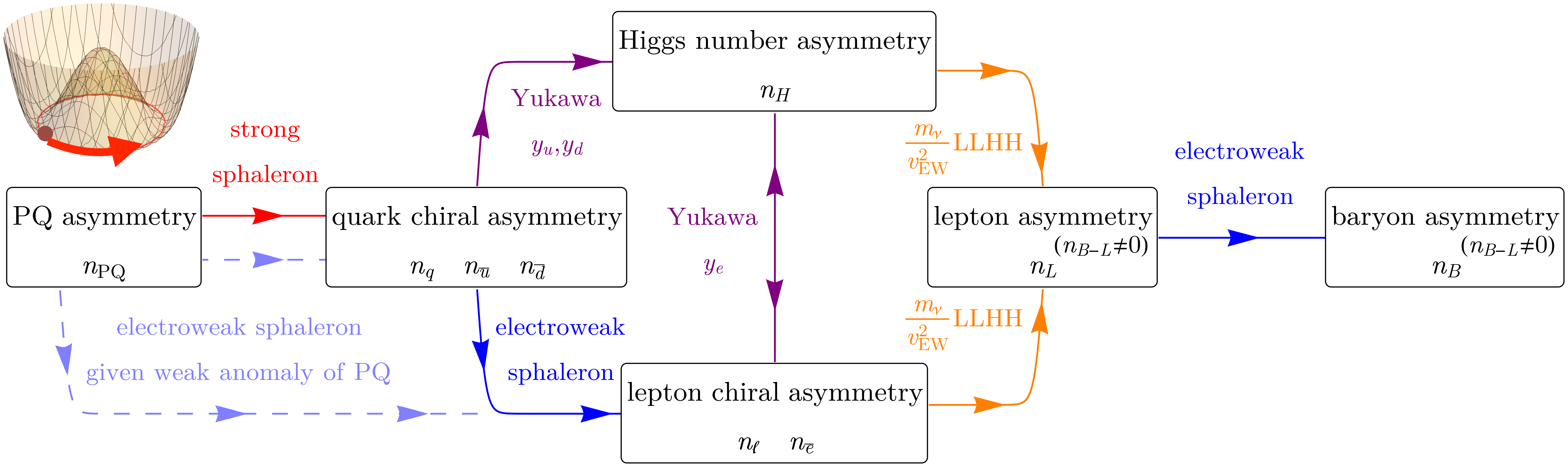
$$\frac{1}{M} LLHH$$



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

Charge flow

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



PQ asymmetry $n_{\rm PQ}$

strong sphaleron

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

Yukawa y_u, y_d

Higgs number asymmetry n_H

Yukawa y_e

electroweak sphaleron

electroweak sphaleron given weak anomaly of PQ

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

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

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

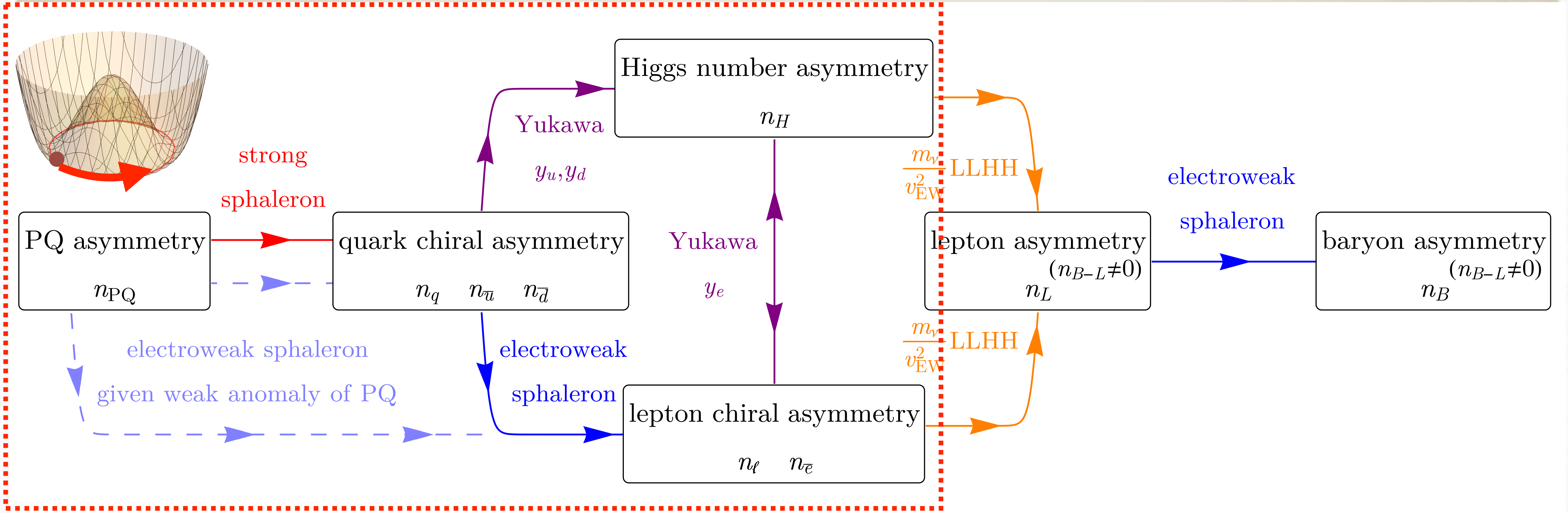
lepton asymmetry $(n_{B-L}\neq 0)$ n_L

electroweak sphaleron

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

Charge flow

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



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n_{PQ}

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

electroweak
sphaleron

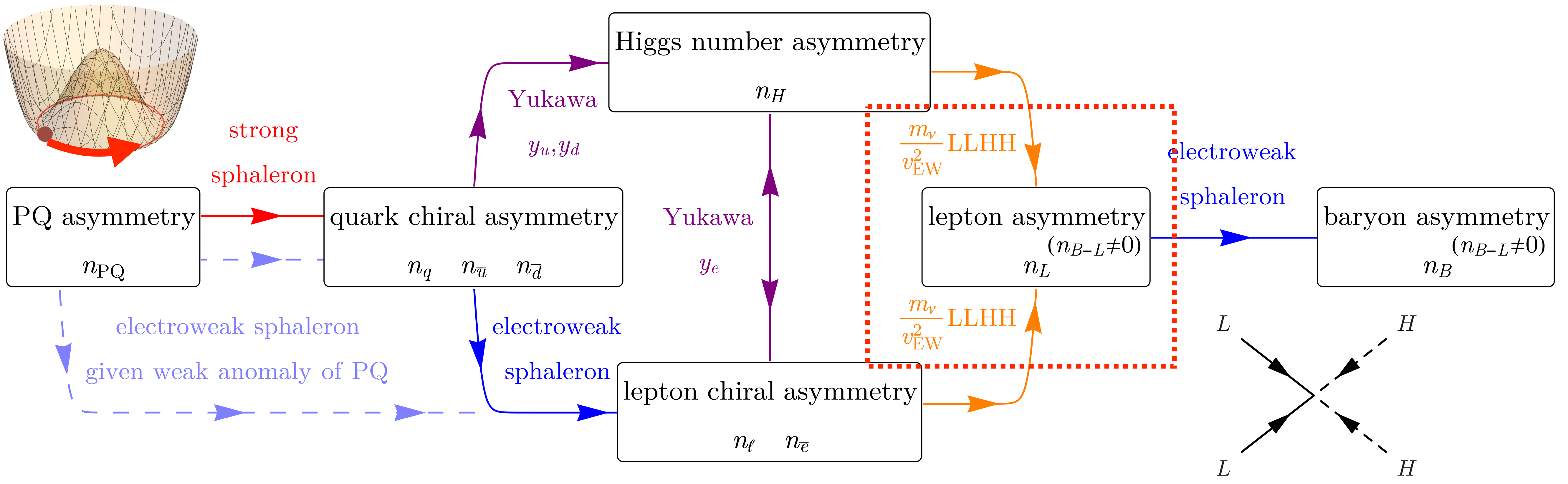
baryon asymmetry
$(n_{B-L} \neq 0)$
n_B

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)



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

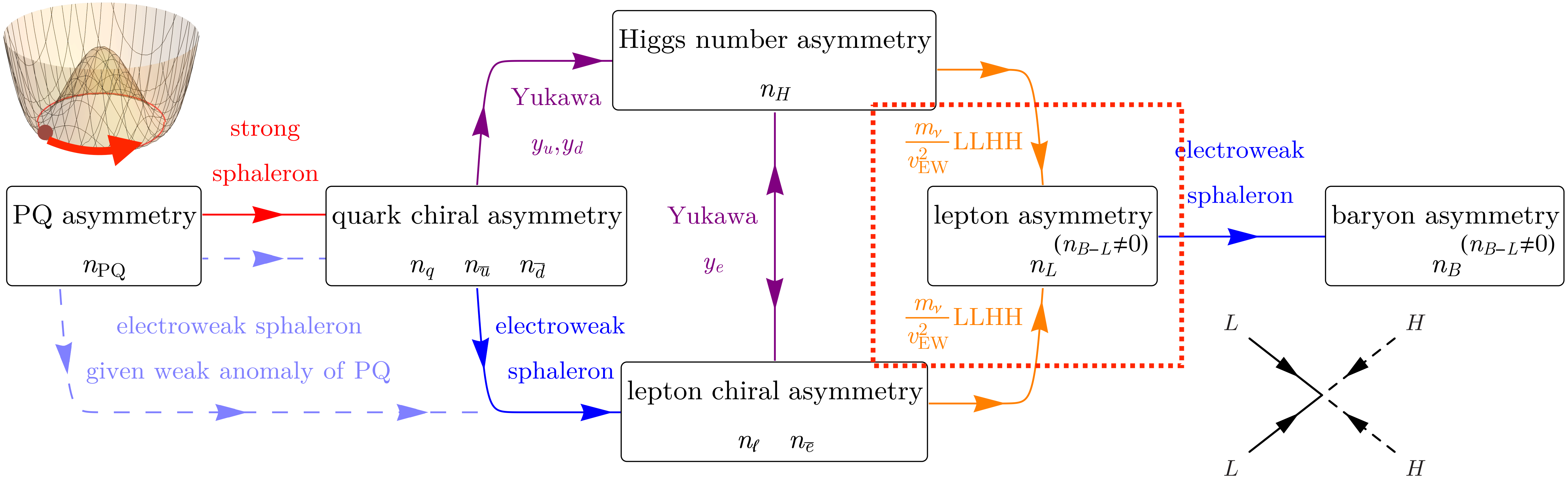
At high temperatures

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

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

Charge flow

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



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

not efficient at low temperatures

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

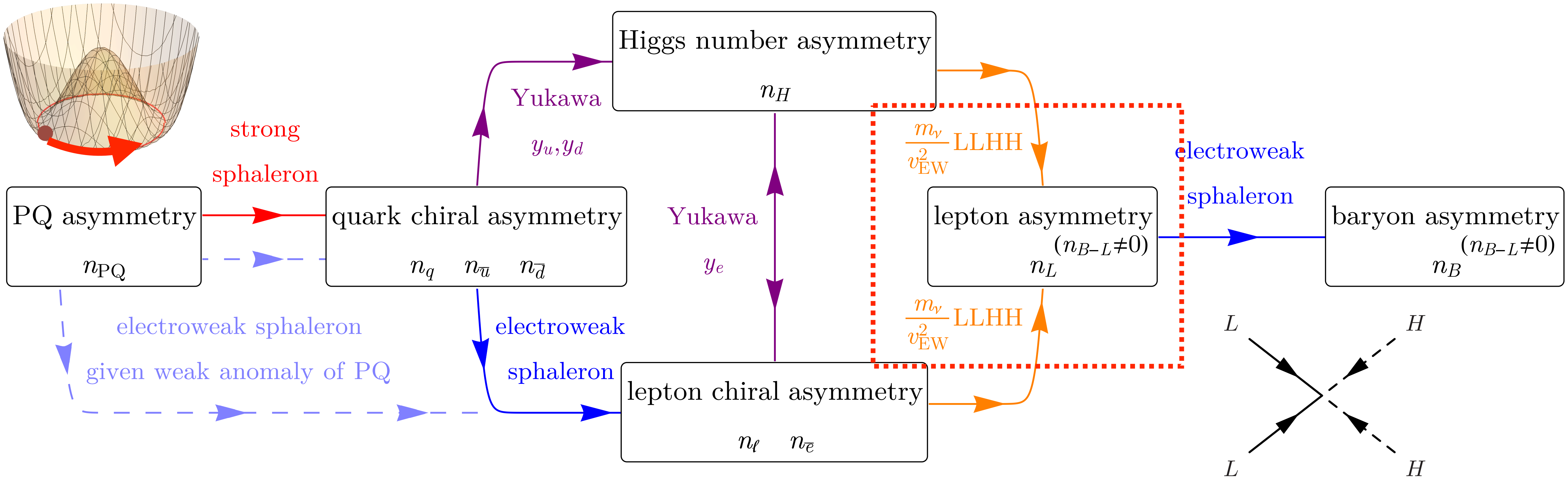
$$\propto \dot{\theta} \times T^0$$

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

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

Charge flow

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



PQ asymmetry

$n_{\rm PQ}$

strong

sphaleron

quark chiral asymmetry

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

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y_u, y_d

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lepton asymmetry

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

n_L

electroweak

sphaleron

baryon asymmetry

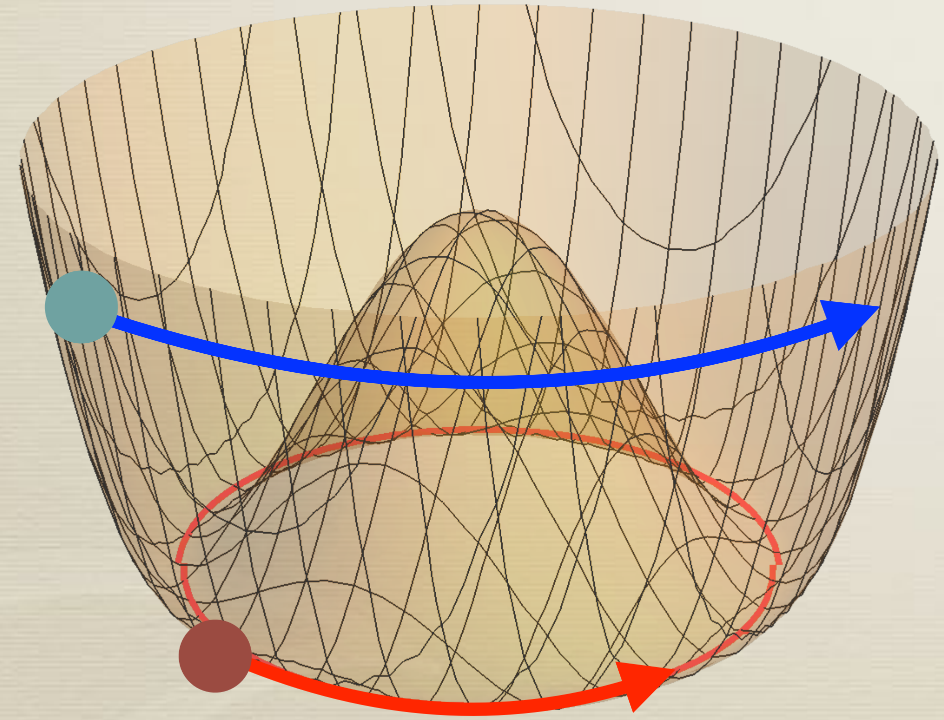
$(n_{B-L} \neq 0)$

n_B

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

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

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

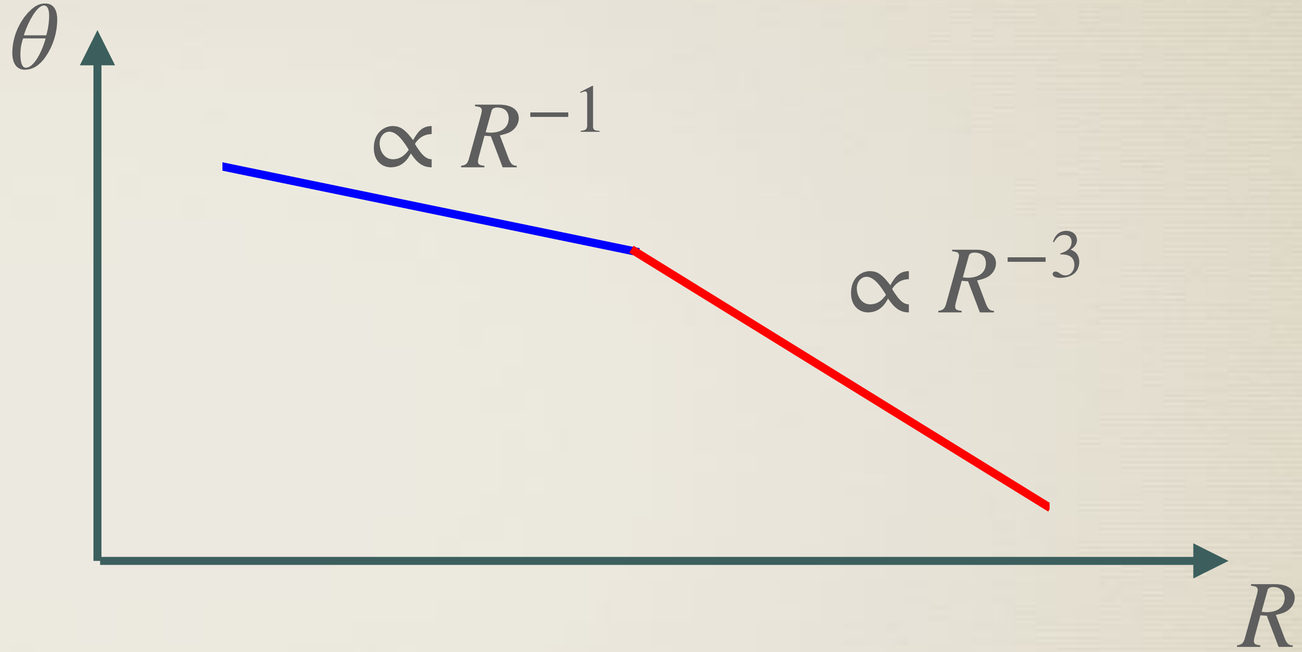
Around the electroweak phase transition

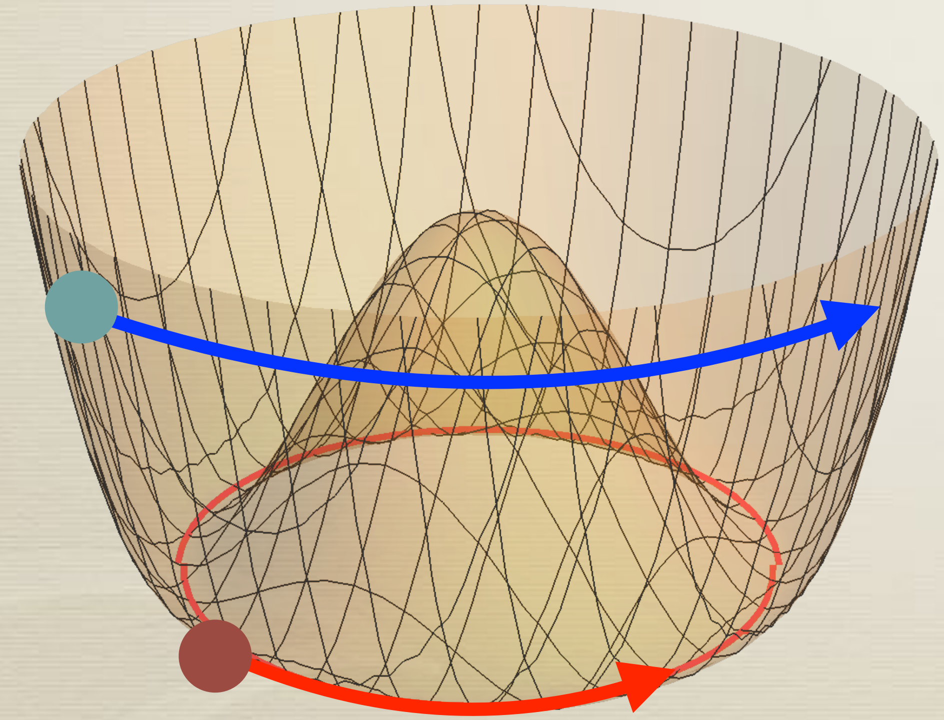
$$\dot{\theta} \propto R^{-3}$$

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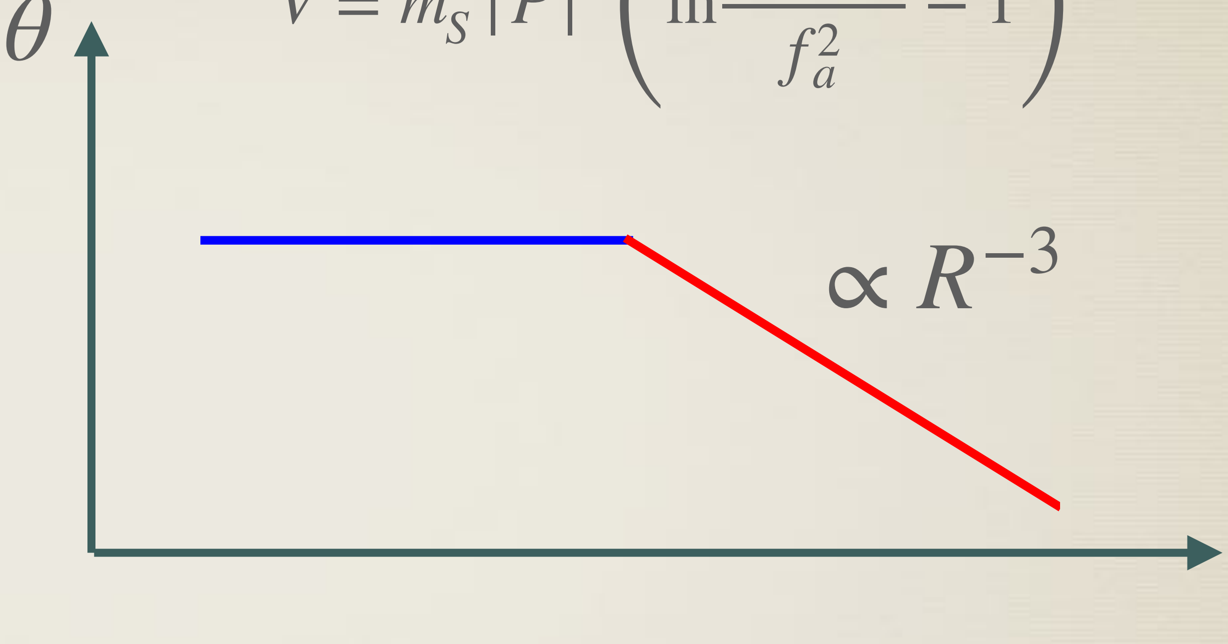
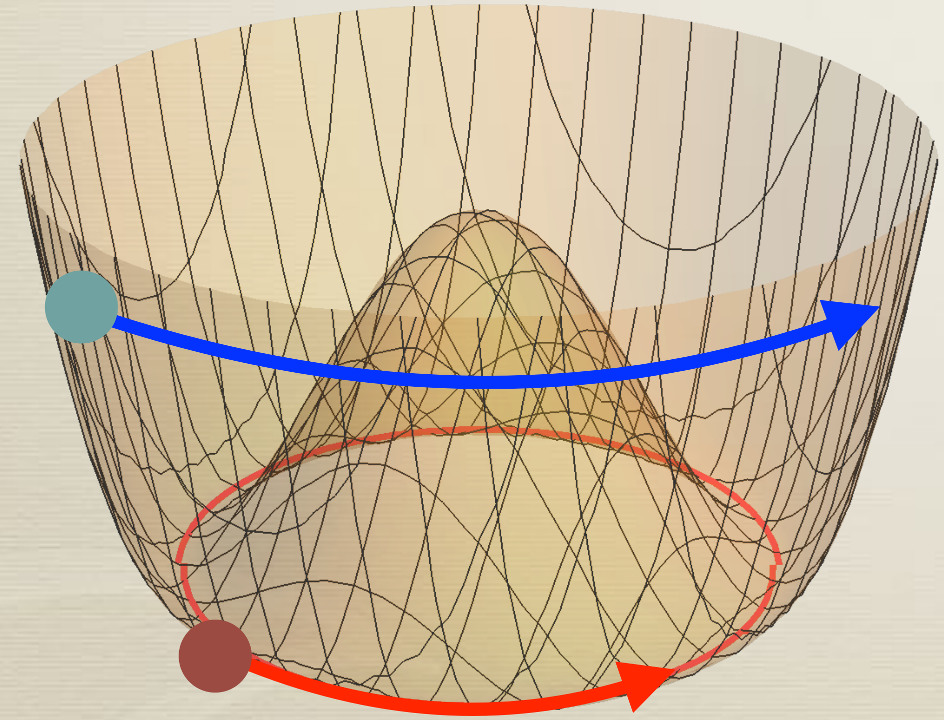
$$V = m_S^2 |P|^2 \left(\ln \frac{2|P|^2}{f_a^2} - 1 \right)$$





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Around the electroweak phase transition

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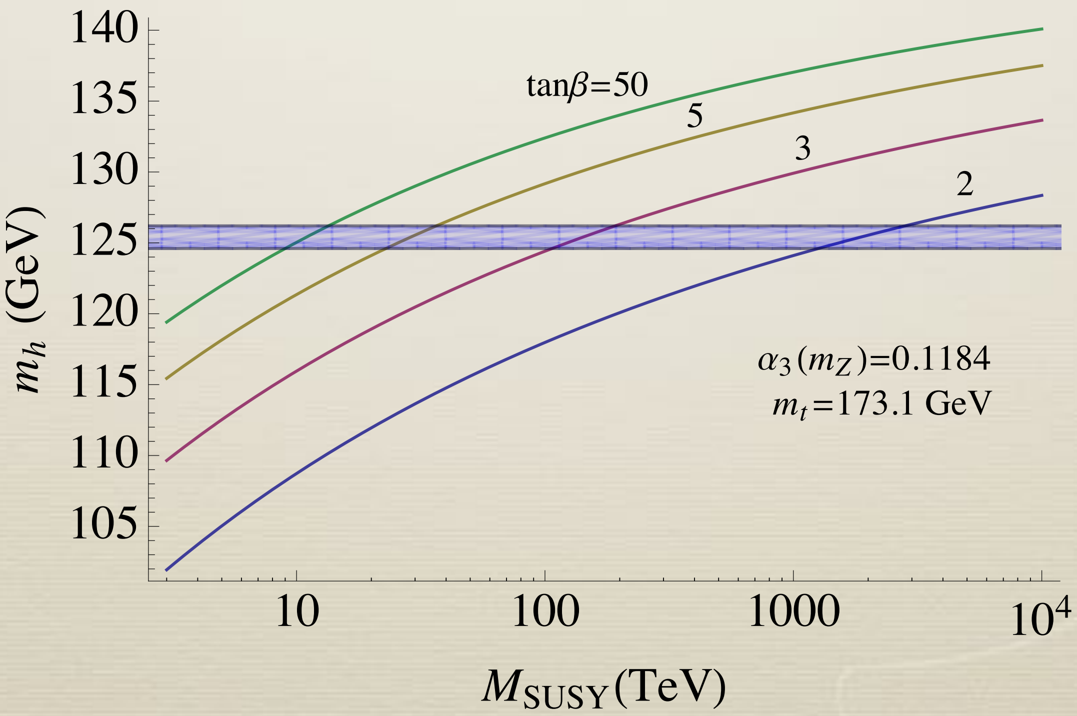
Supersymmetry

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

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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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 $m_{\rm SUSY} \sim 100~\text{GeV}$
- Gauge coupling unification $m_{\rm SUSY} \lesssim 10^6~\text{GeV}$
- Lightest supersymmetric particle as DM $m_{\rm SUSY} \lesssim 10^3~\text{GeV}$

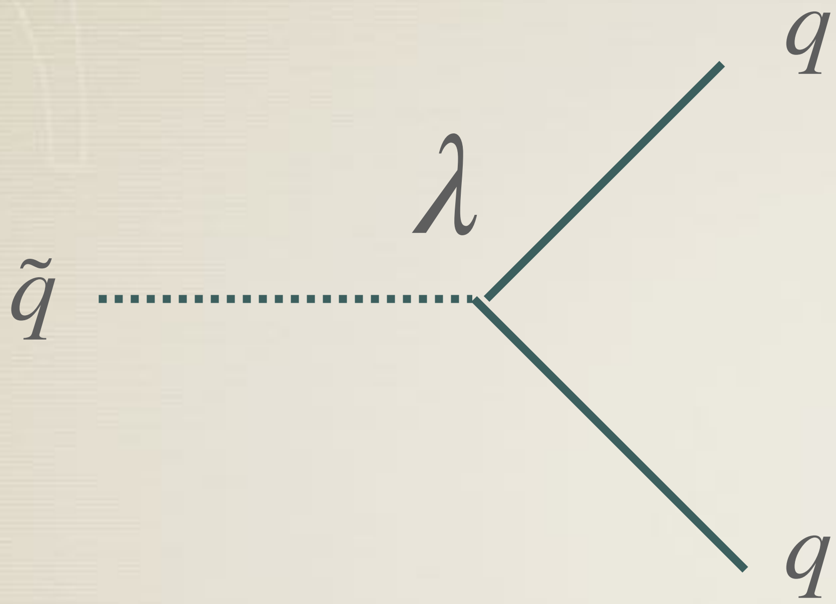
  (invalid with RPV)
- Baryogenesis from axion rotation and neutrino mass

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

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

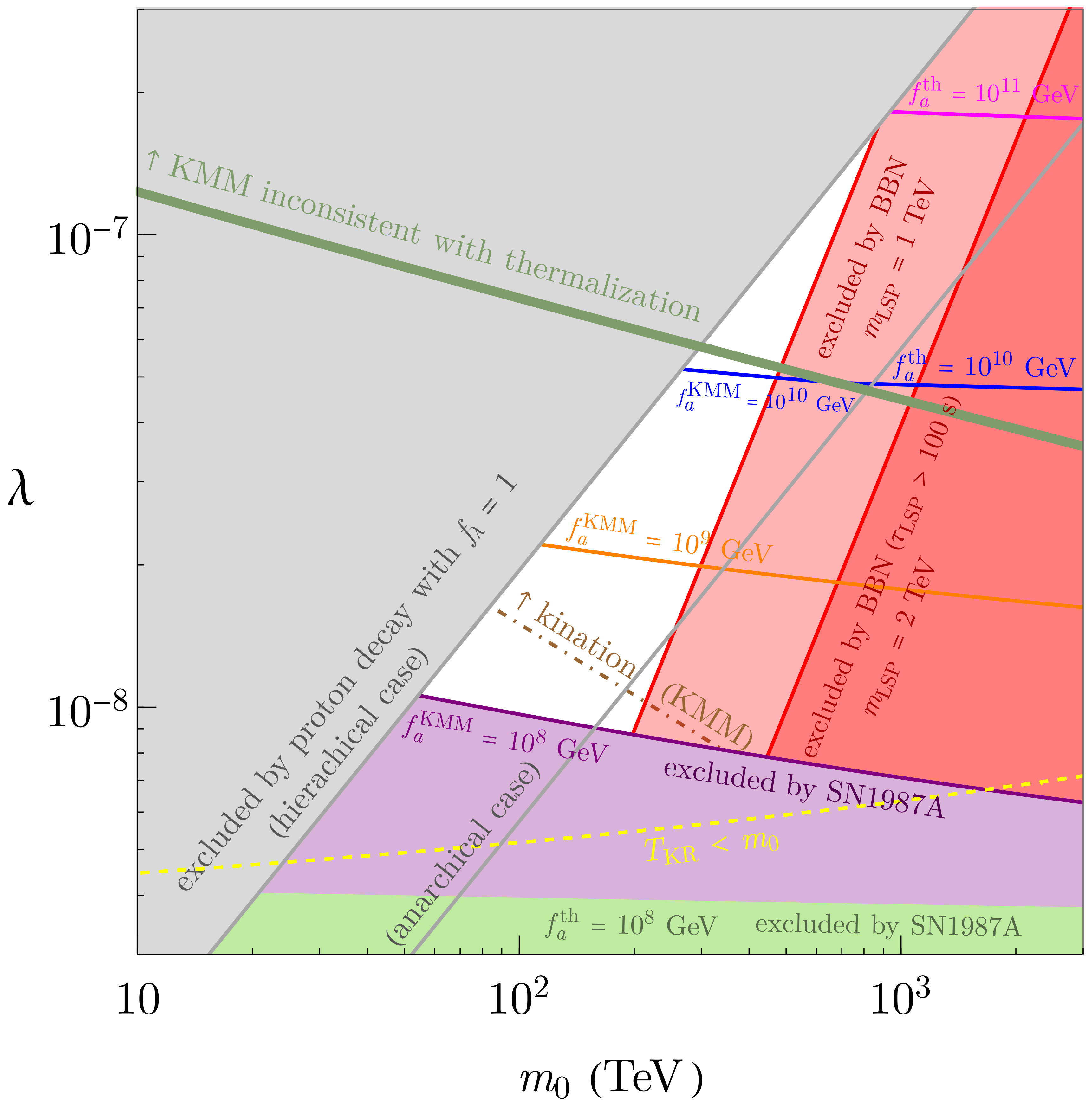
$$W = \frac{1}{2}\lambda_{ijk}10_i\bar{5}_k\bar{5}_k = \lambda_{ijk}(Q_i\bar{d}_jL_k + \frac{1}{2}\bar{u}_i\bar{d}_j\bar{d}_k + \frac{1}{2}\bar{e}_iL_jL_k)$$

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

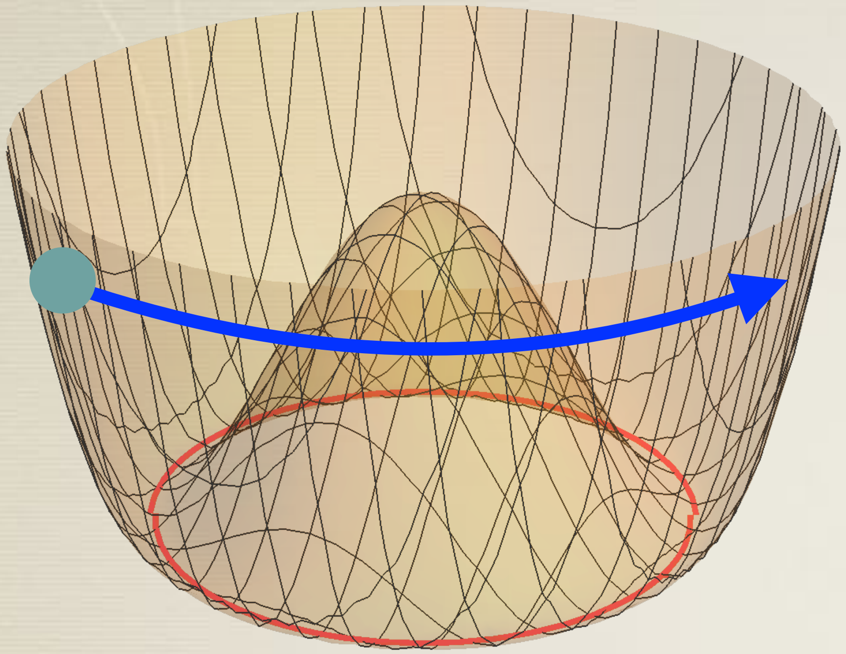
Hierarchical 5-plets : $\lambda_{i12}, \lambda_{i13} \ll \lambda_{i23}$


↑ 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
$f_a^{\rm KMM}$ = 10^9 GeV
↑ kination
(KMM)
excluded by proton decay with f_λ = 1
(hierachical case)
(anarchical case)
$f_a^{\rm KMM}$ = 10^8 GeV
excluded by SN1987A
$T_{\rm KR} < m_0$
$f_a^{\rm th}$ = 10^8 GeV
excluded by SN1987A
10^{-7}
10^{-8}
λ
10
10^2
10^3
m_0 (TeV)

Axion Kination

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,

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

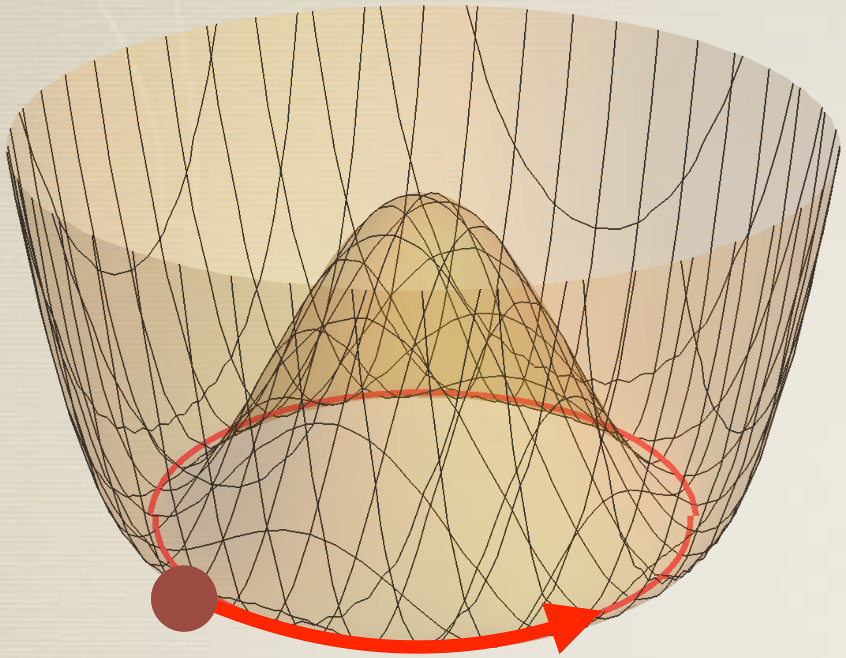
$$\Downarrow$$

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

matter

Equation of state of rotations

Co and KH (2019)



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

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

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

$$\Downarrow$$

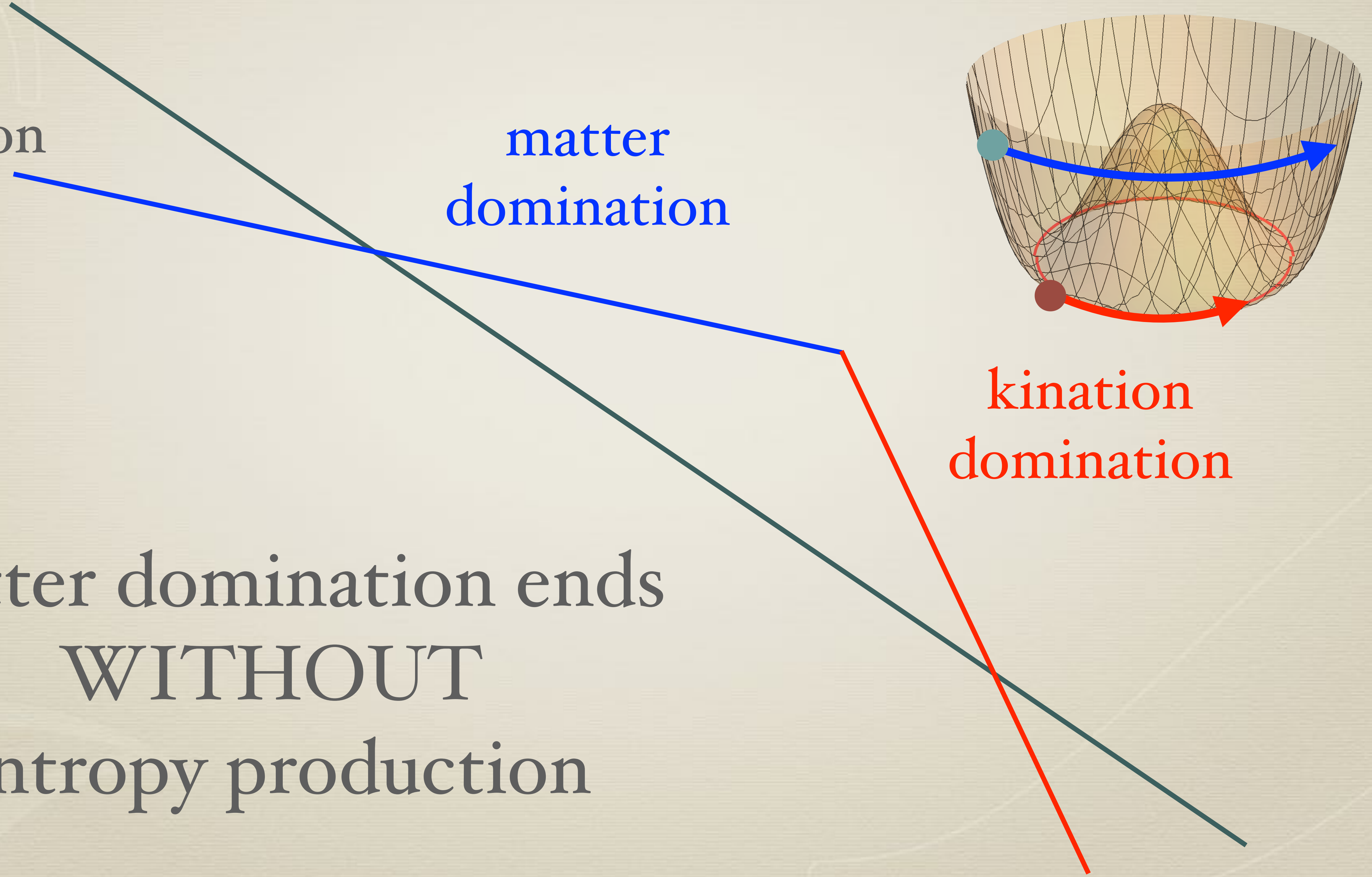
$$\rho = \dot{\theta}^2 S^2 \propto R^{-6}$$

kination

Axion energy is dominantly from the kinetic term

Axion kination

Co and KH (2019)



radiation

rotation

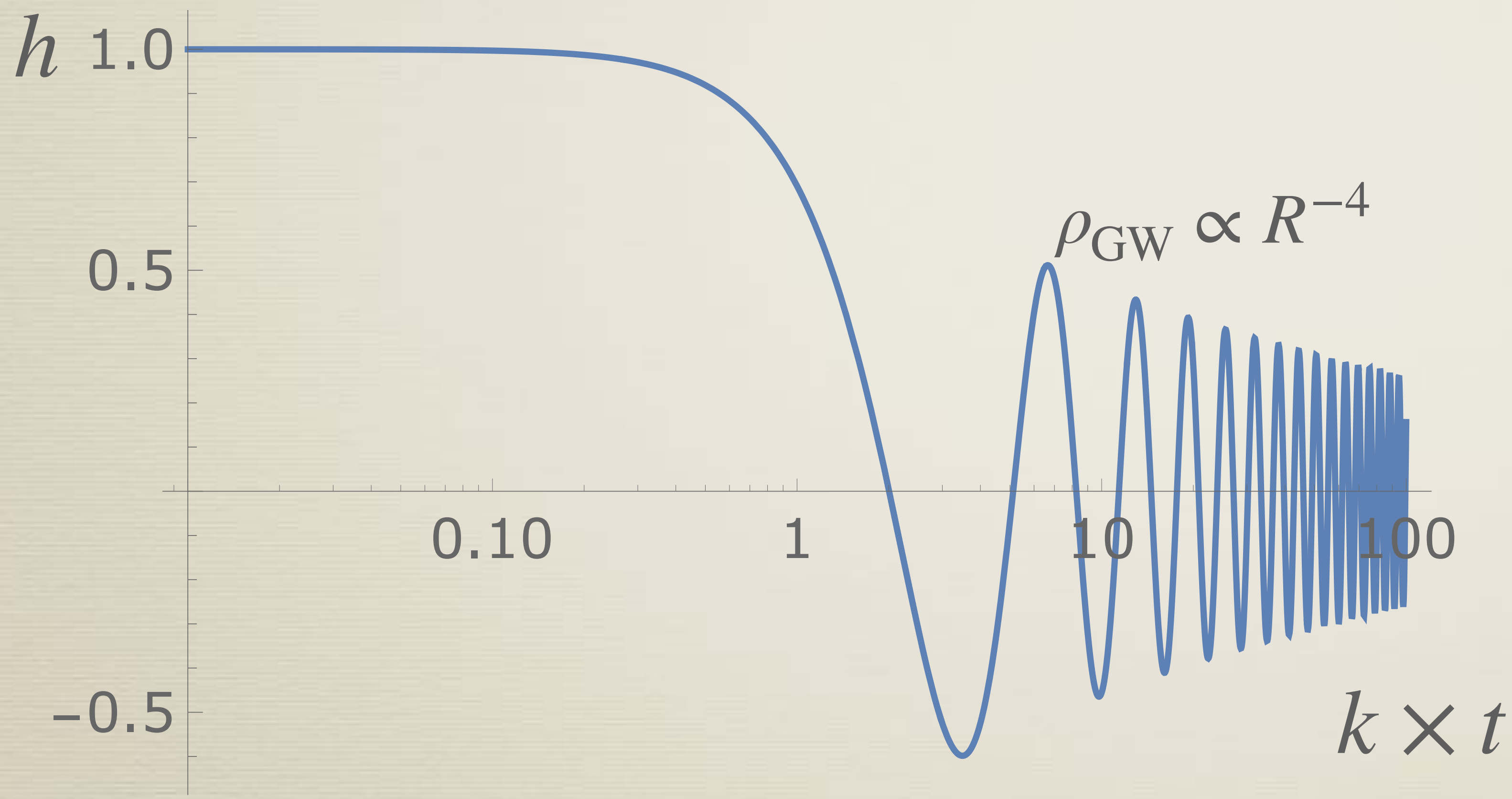
matter domination

kination domination

matter domination ends
WITHOUT
entropy production

Effect on primordial gravitational waves

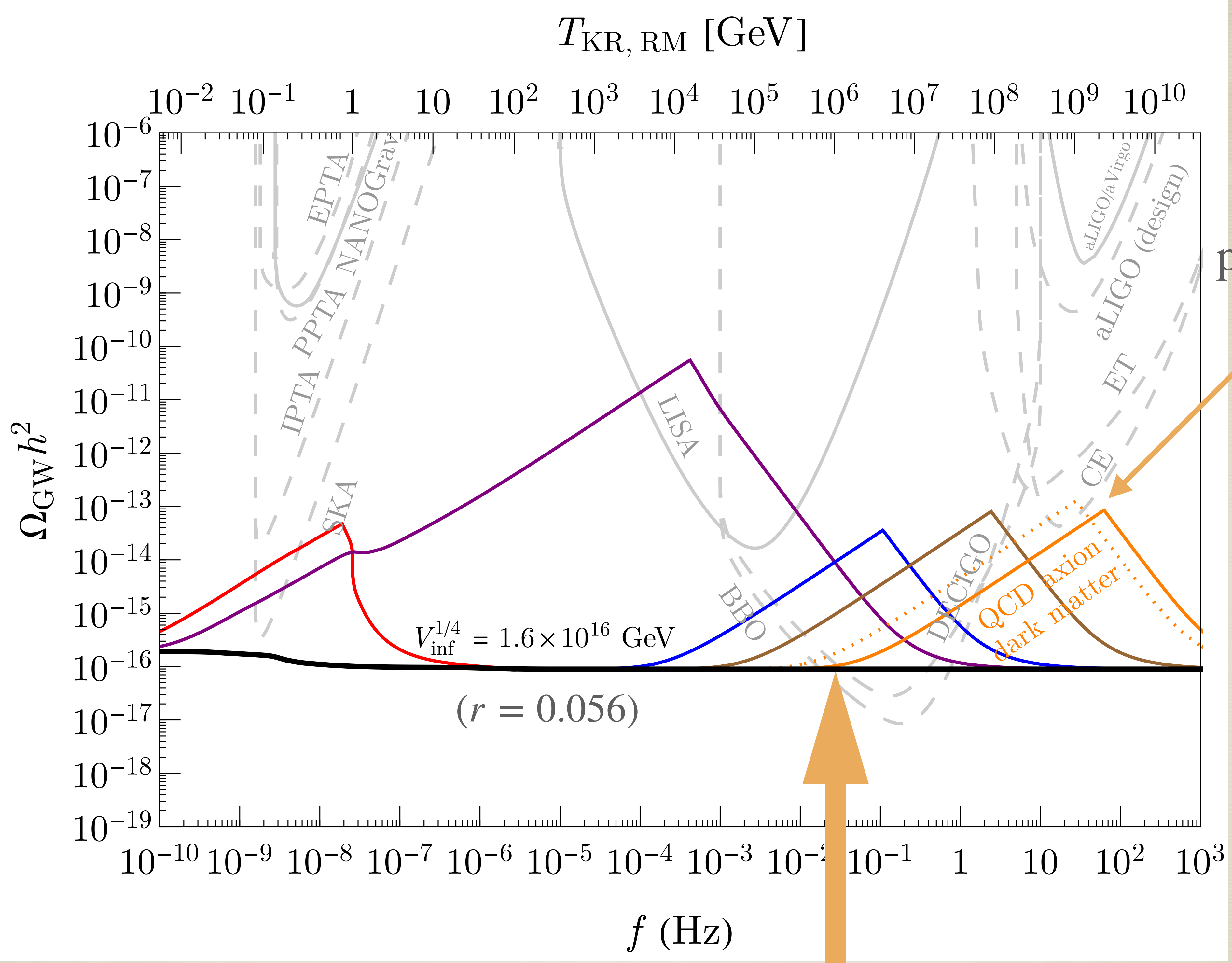
ex. inflationary gravitational waves



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

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

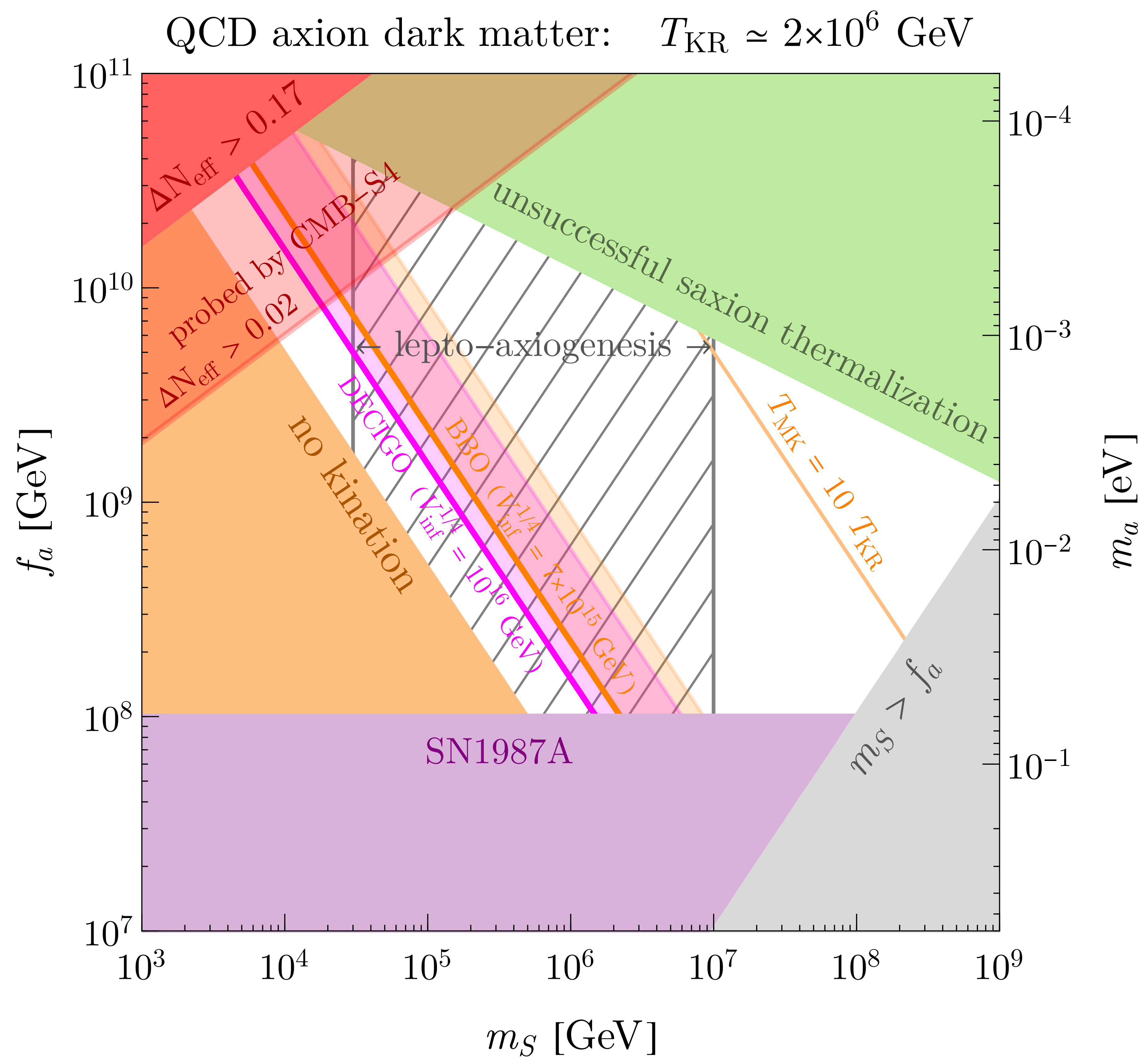
enhanced if the mode enters the horizon ($k \sim H$) when the rotation dominates

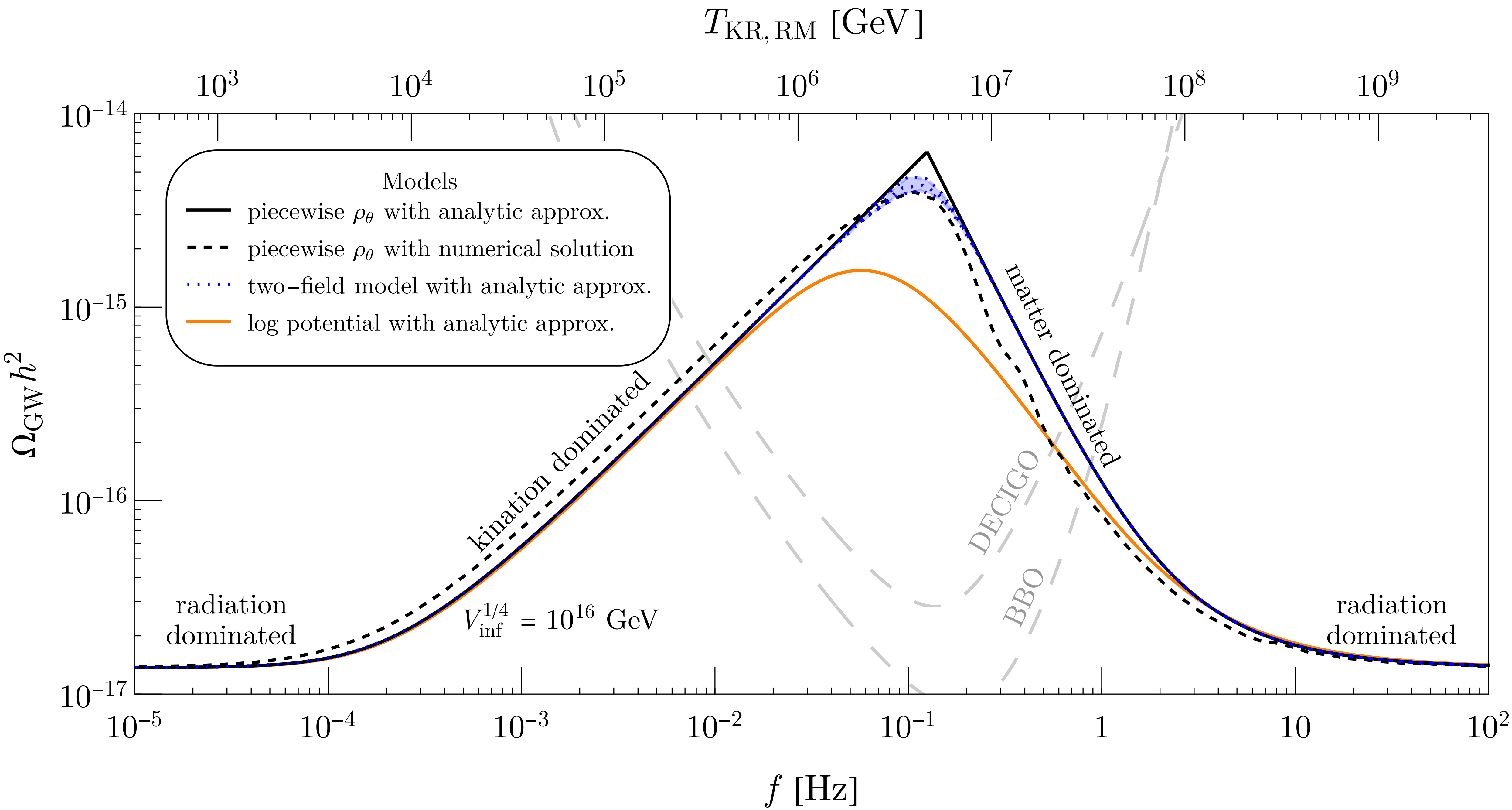


peak position depends on $m_S f_a$

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)


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
$T_{\rm MK} = 10\ T_{\rm KR}$
$m_S > f_a$
SN1987A
f_a [GeV]
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
m_a [eV]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
m_S [GeV]
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}


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