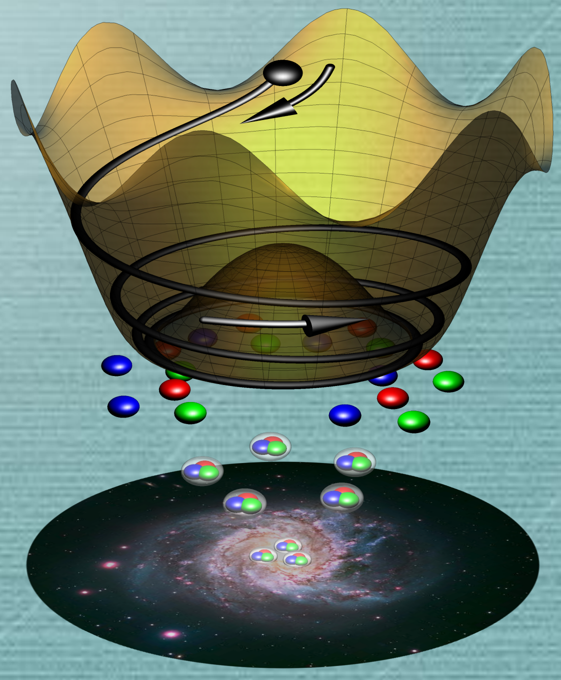
03/07/2025, Axions in Stockholm

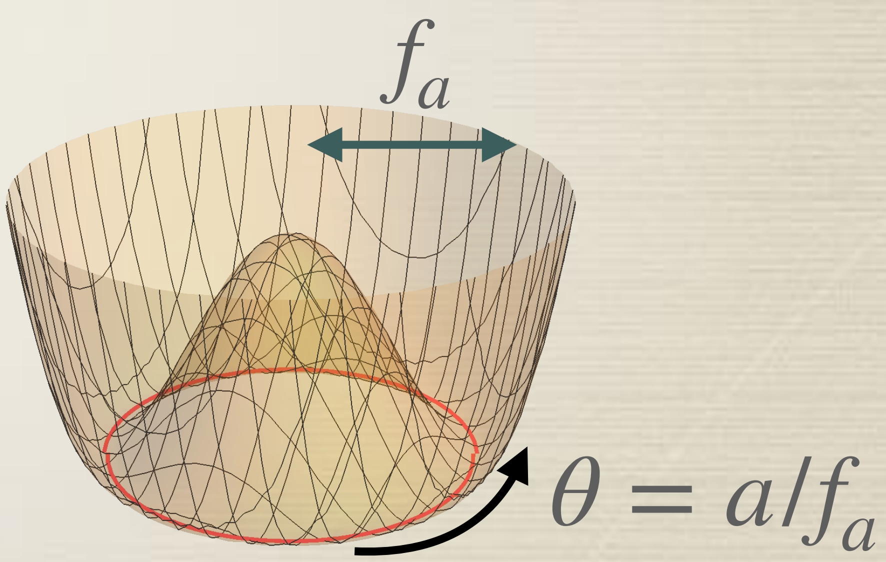
Kinetic/Acoustic Misalignment and baryon asymmetry

Keisuke Harigaya (UChicago)



Spontaneously broken continuous symmetry

* PQ symmetry: strong CP problem
* Lepton symmetry : neutrino mass models
* Flavor symmetry: flavor hierarchy
* ...

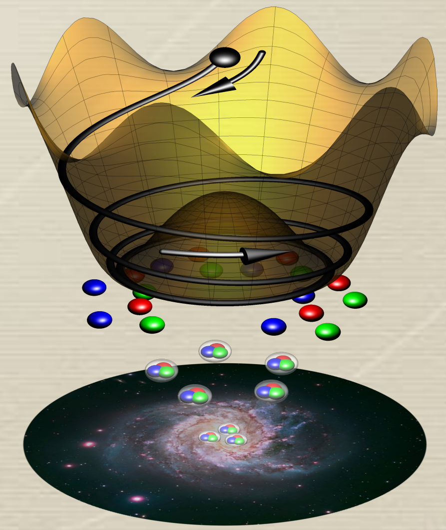


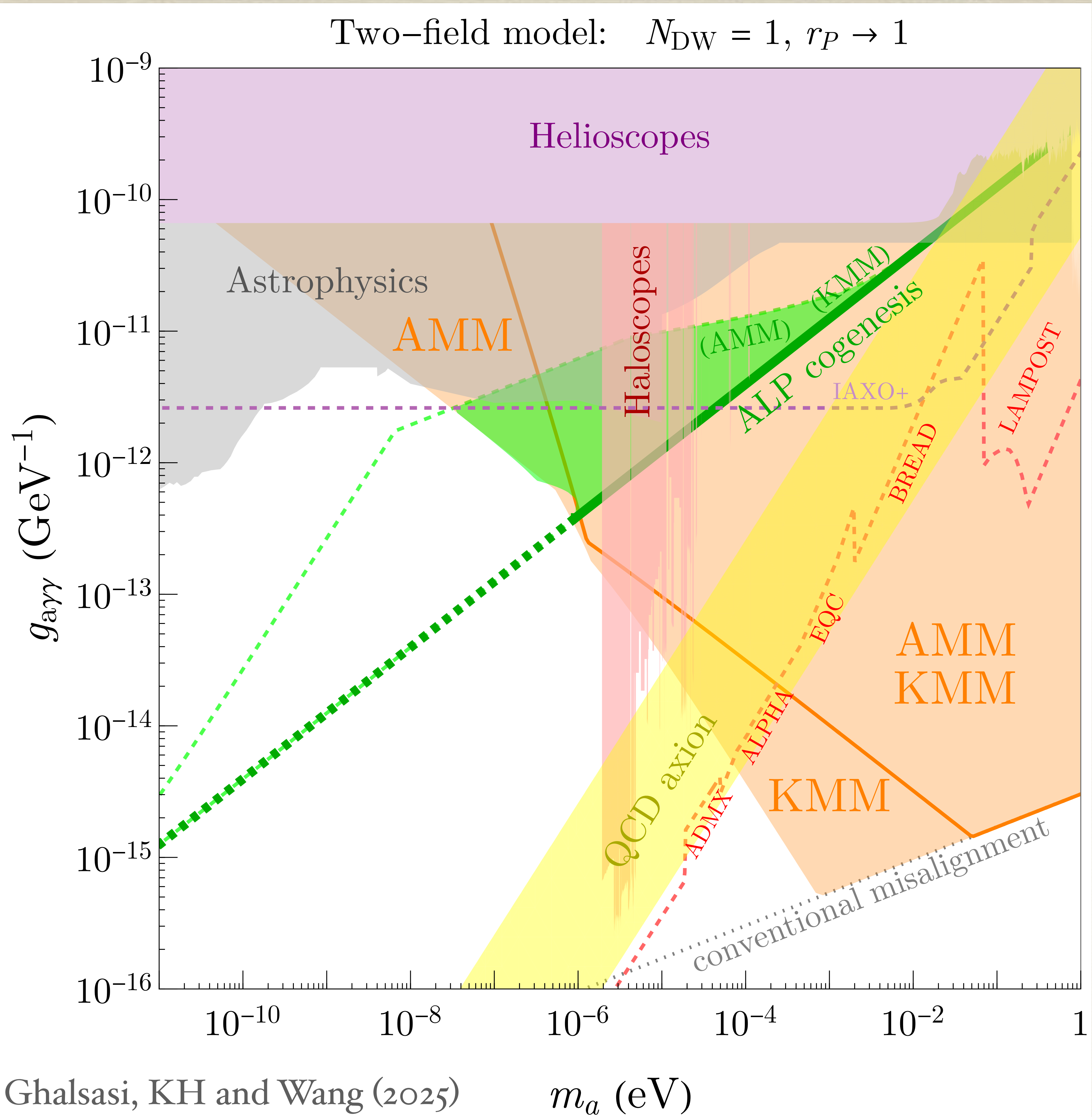
(Pseudo) Nambu-Goldstone bosons are predicted

Axions

Summary

* Rotation of axion in the field space can create matter-antimatter asymmetry
* Rotation produces axion dark matter through phonon mode excitation from cosmic perturbations or through parametric resonance
* Axions couplings are predicted to be larger than the prediction of the misalignment mechanism
* Gravitational waves may be affected or created





Bodas, Co, Ghalsasi, KH and Wang (2025)

Outline

* Axion rotation and baryon asymmetry
* Axion rotation and dark matter
* Gravitational waves
* Summary

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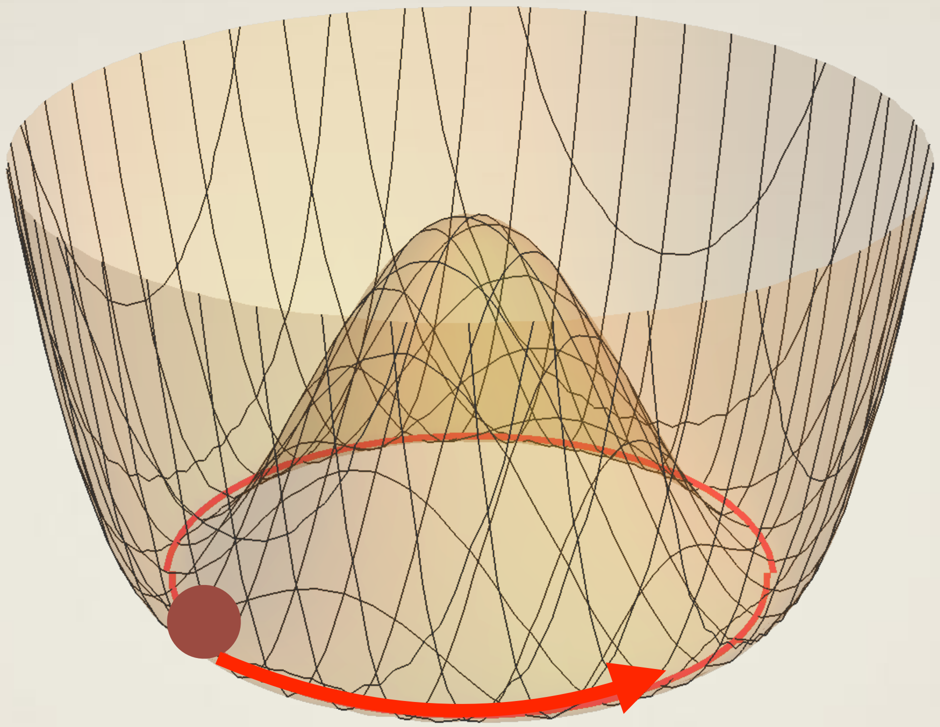
Axion rotation

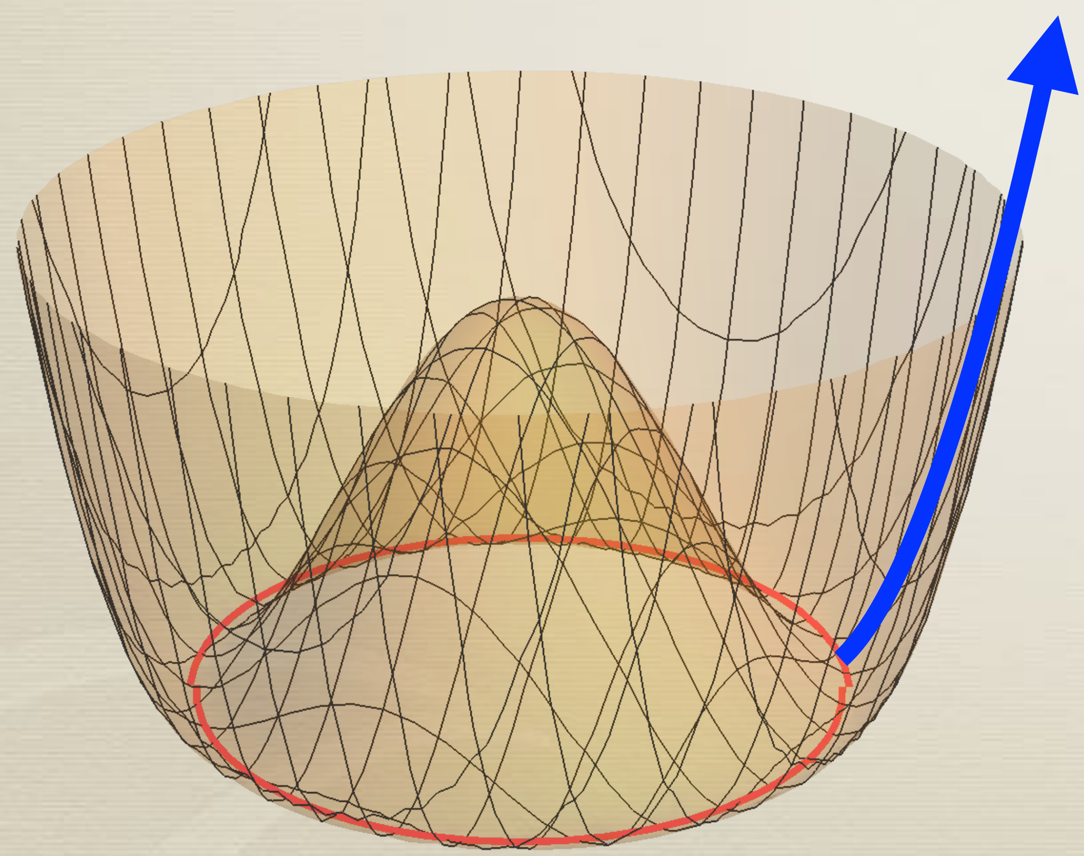


Non-zero angular momentum / U(1) charge

$$n_\theta = \dot{\theta} r^2$$

Initiation of rotation

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

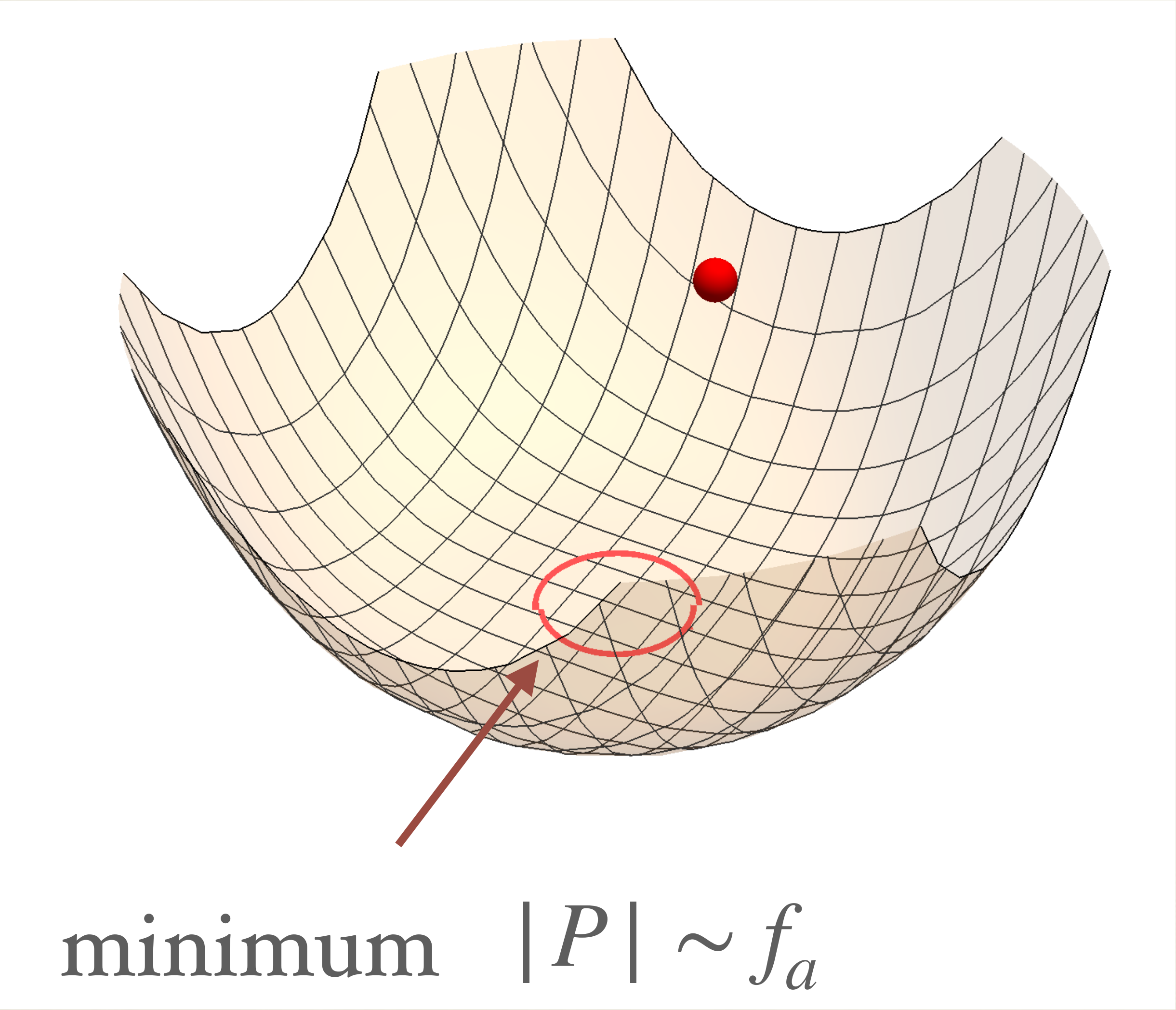


Consider the dynamics of
the radial direction

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

Initiation of rotation

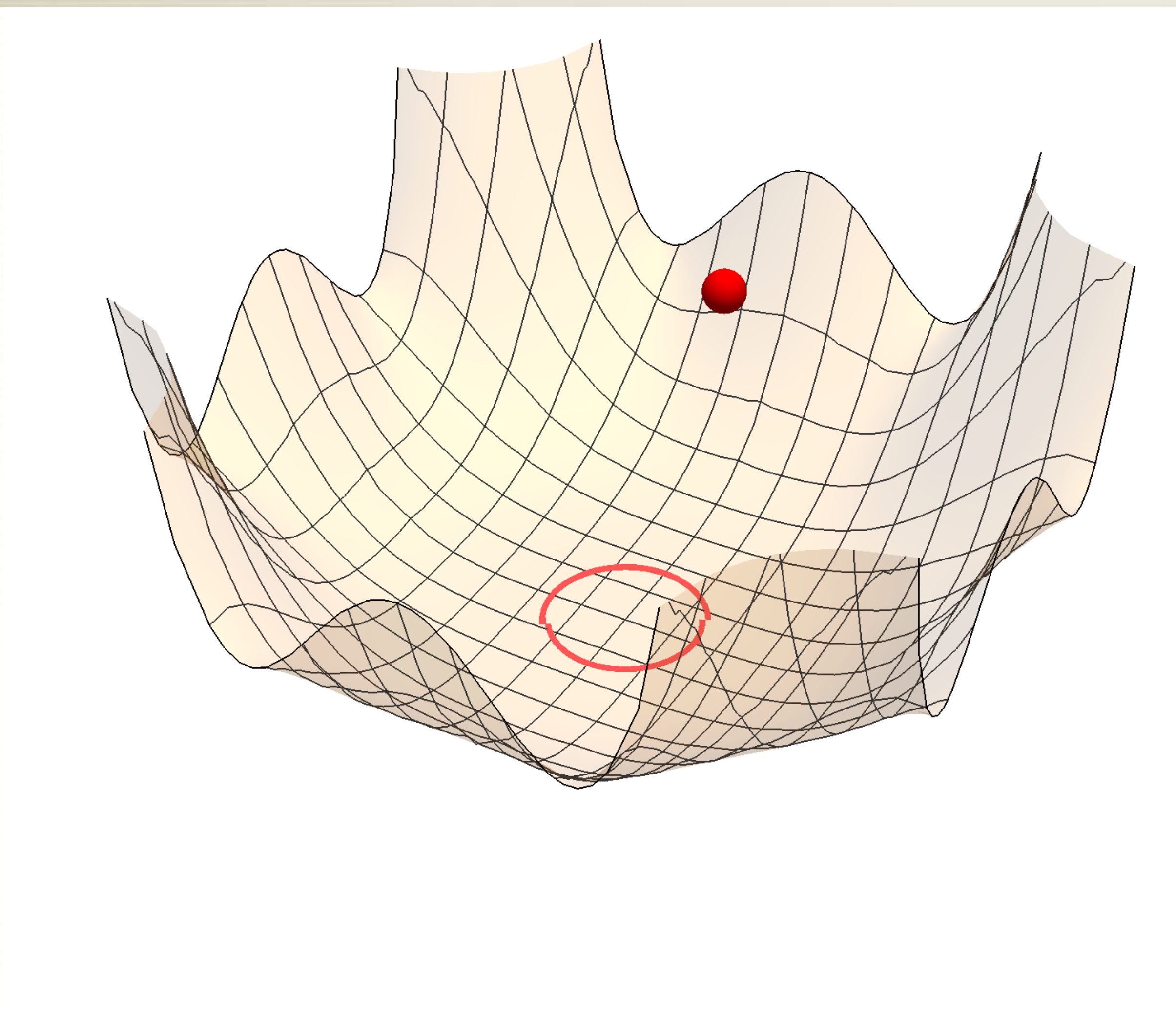
$P = r \times \exp(i\theta)$



Assume a large initial radial field value

Initiation of rotation

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



Assume a large initial radial field value

↓

Higher order terms

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

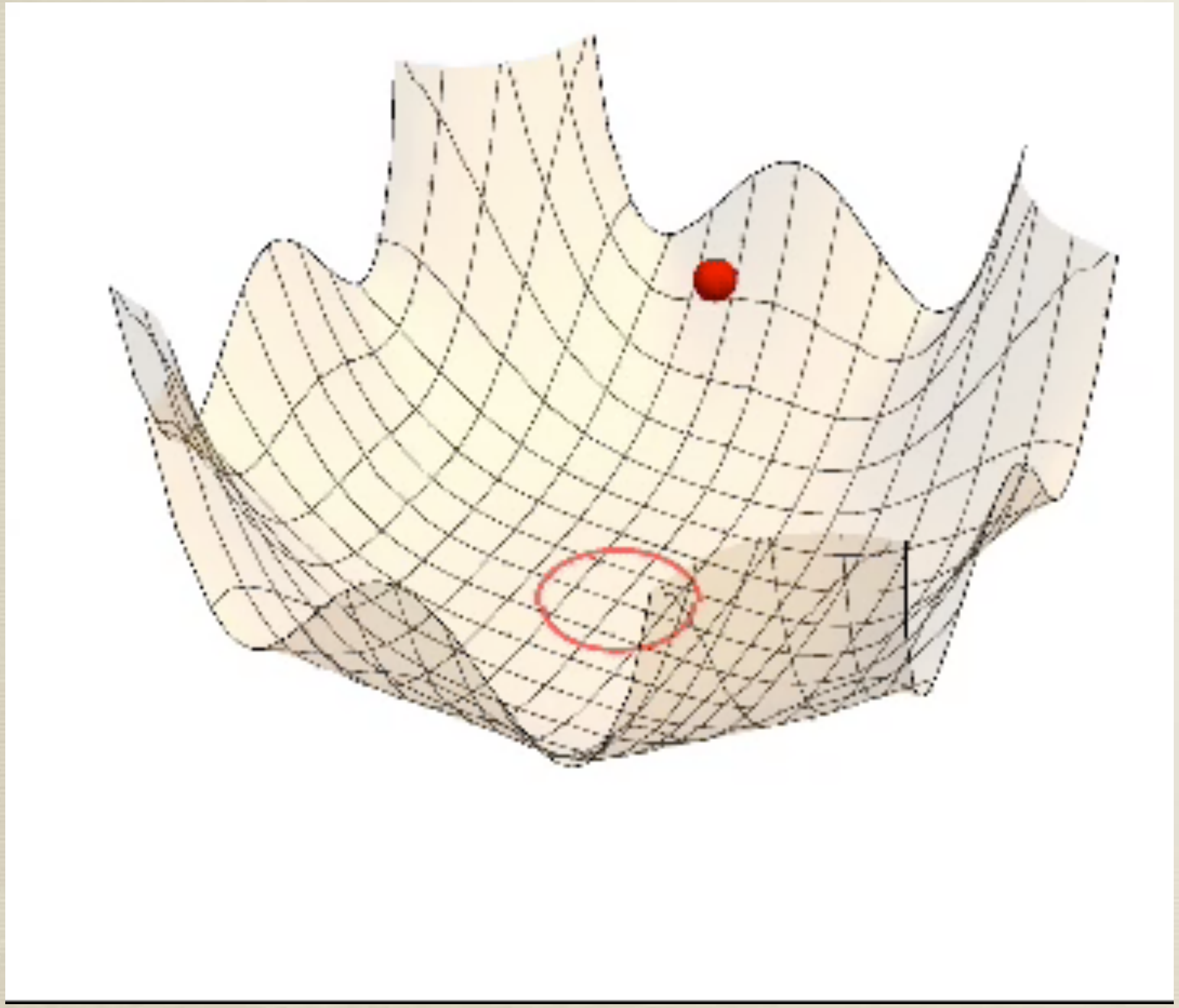
may be effective

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), ...

Initiation of rotation

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



Assume a large initial radial field value

Higher order terms

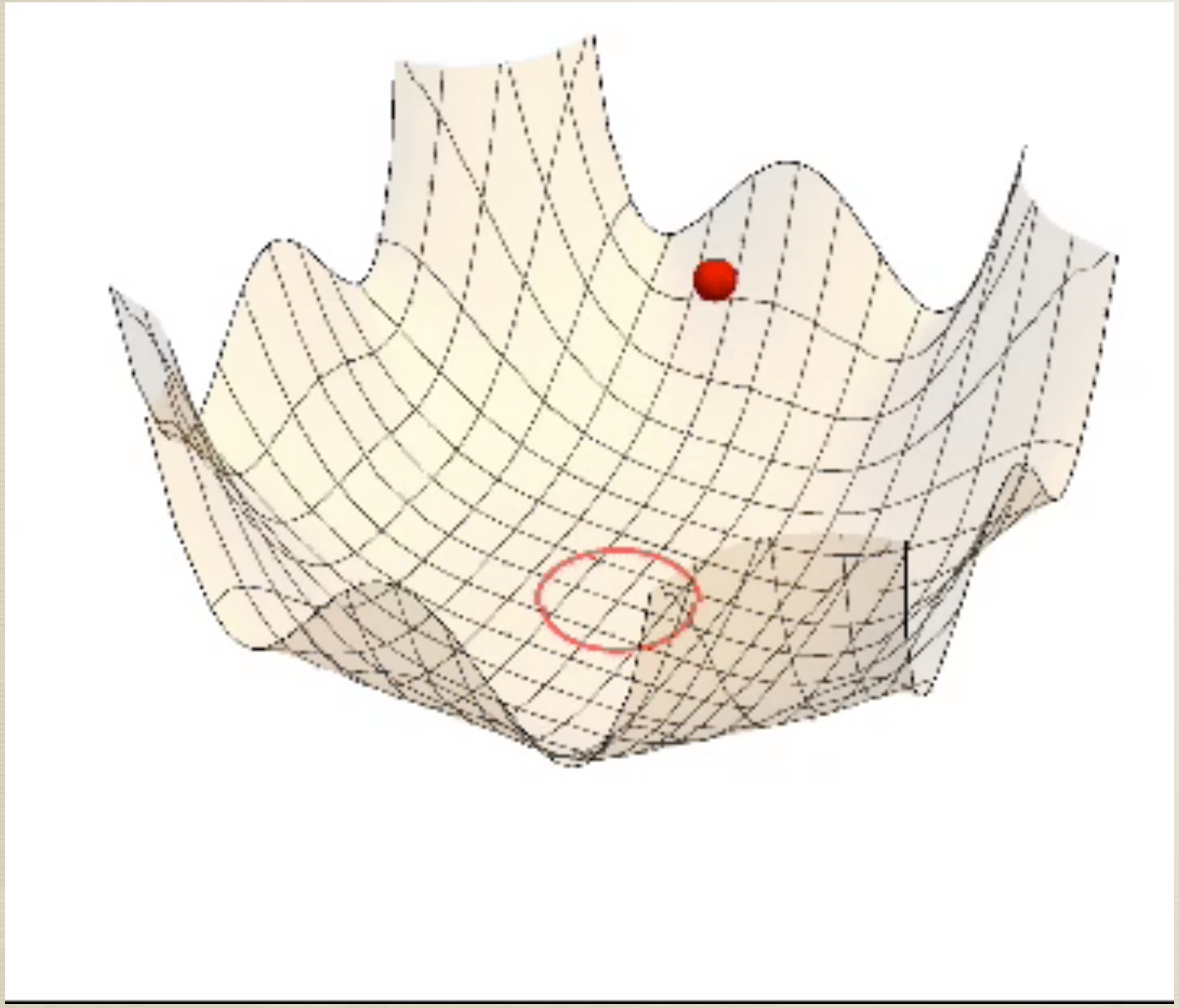
$$V \sim P^n \sim r^n \cos(n\theta)$$

may be effective

Angular motion is induced by the potential gradient

Initiation of rotation

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



r decreases by expansion of the universe

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

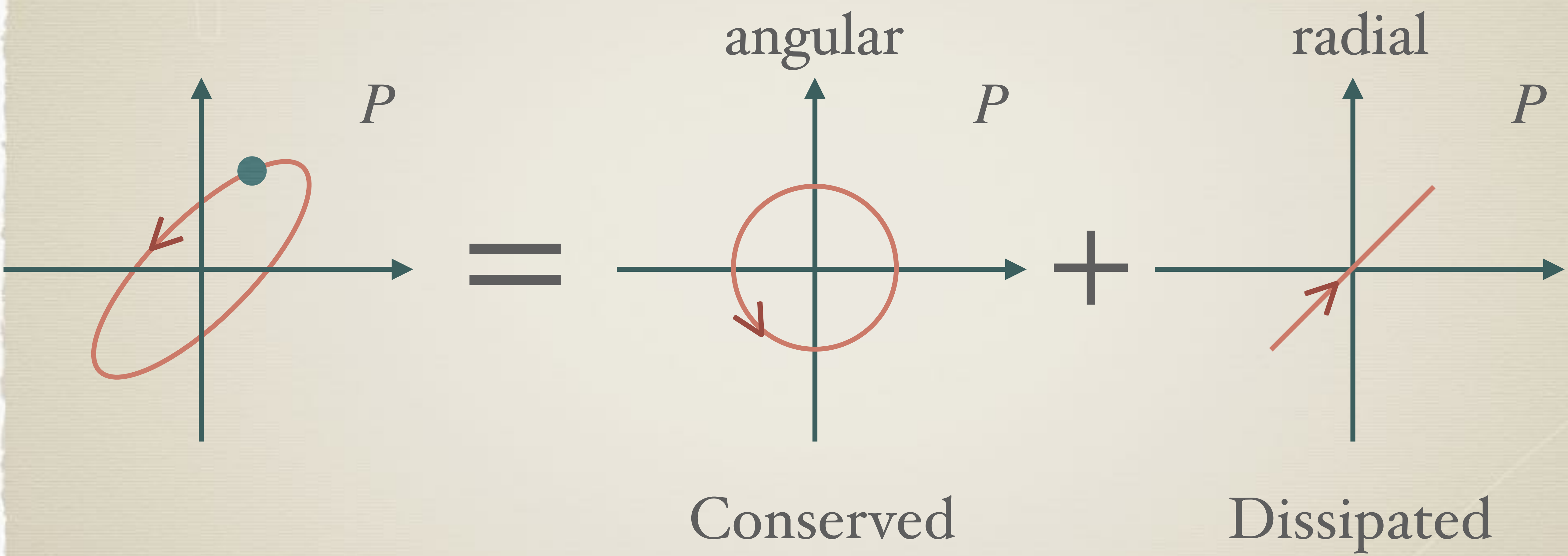
P continues to rotate, conserving the angular momentum

$$n_\theta = \dot{\theta} r^2 \propto R^{-3}$$

Thermalization

Co and KH (2019)

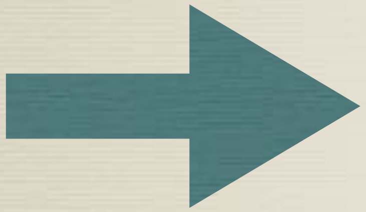
Assume P couples to the thermal bath



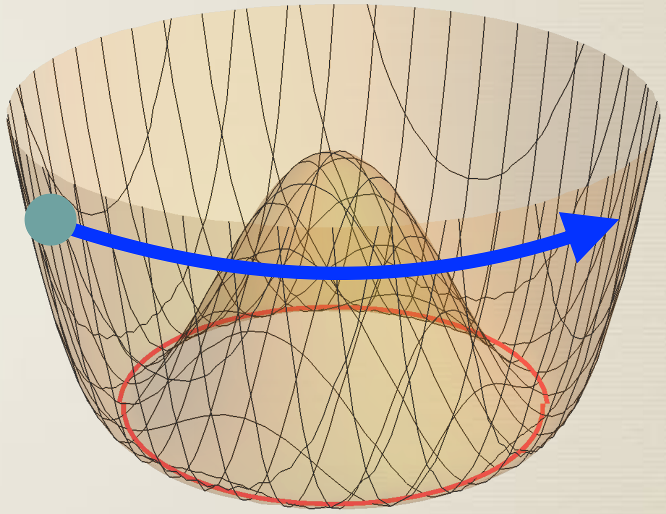
The motion becomes circular

Rotation as a BEC

Rotation = U(1) charge in the zero-mode



Bose-Einstein Condensate

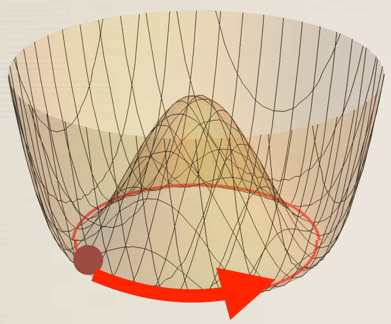


Can it evaporate into excitations
at high temperature in the early universe?

Stability of the rotation

Co and KH (2019)

Rotation



particile-antiparticle asymmetry in the bath

chemical eq.

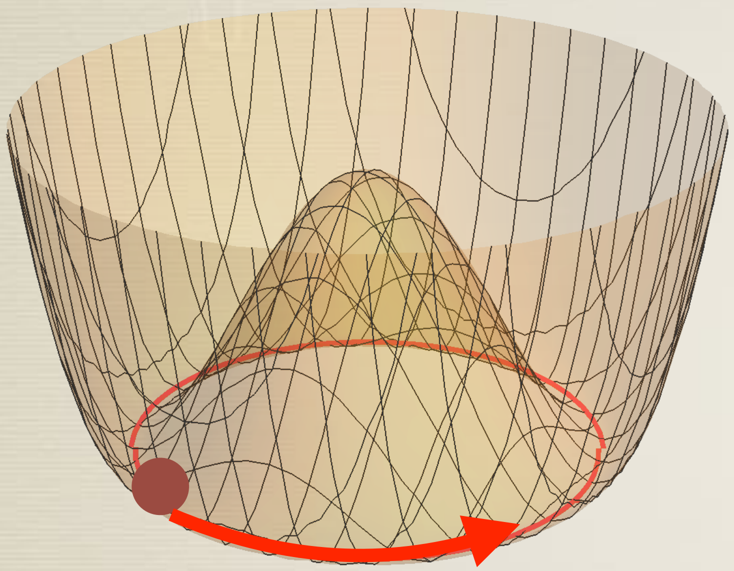
$$\mu_{\rm rot} \sim \frac{\dot\theta^2 r^2}{\dot\theta r^2} = \dot\theta \quad \Longleftrightarrow \quad \mu_{\rm bath} \sim \dot\theta$$

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

as long as $r \gg T$

Axiogenesis

Co and KH (2019)



QCD, electroweak,
yukawa, BSM interactions

U(1) → Baryon

c.f. Leptogeneis

Lepton → Baryon

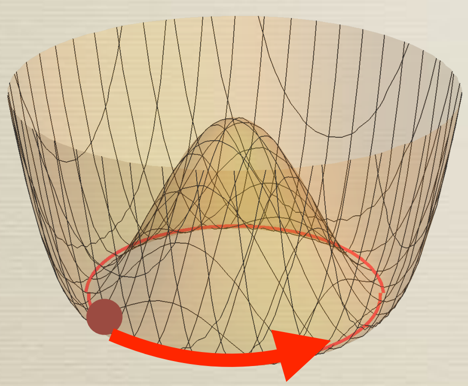
Minimal axiogenesis

Co and KH (2019)

Chiral charge

U(1) ⟷ (Axion-SM) ⟷ Chiral charge ⟷ (weak) ⟷ Baryon

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



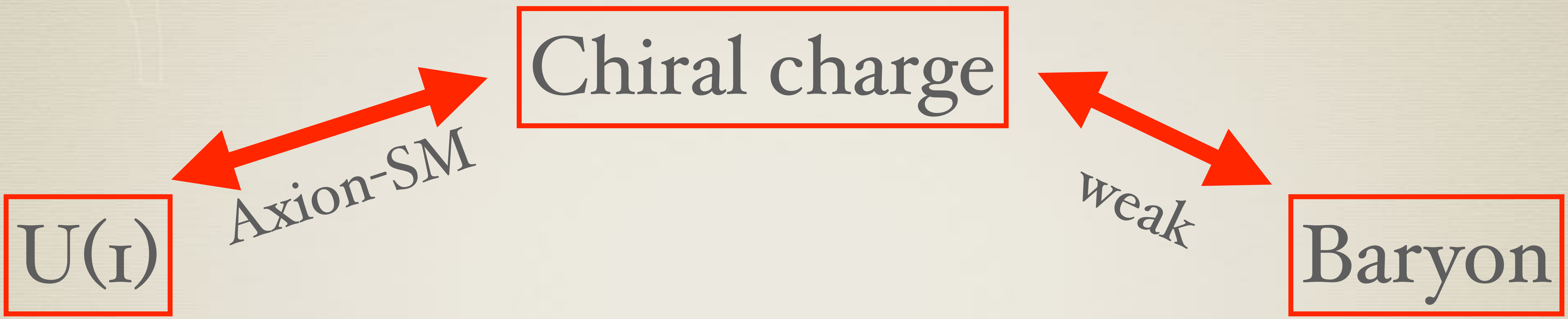
$$\mu_{\rm rot} \sim \frac{\dot{\theta}^2 r^2}{\dot{\theta} r^2} = \dot{\theta}$$

$$\mu_B \sim \dot{\theta}$$

$$n_B \sim \dot{\theta} T^2$$

Minimal axiogenesis

Co and KH (2019)



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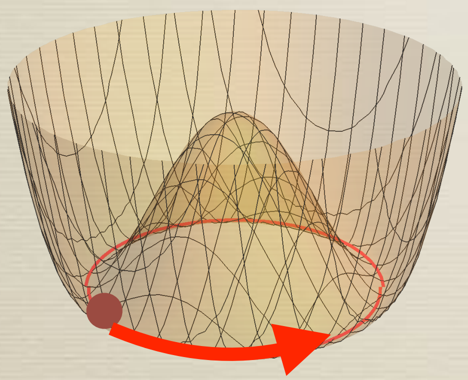


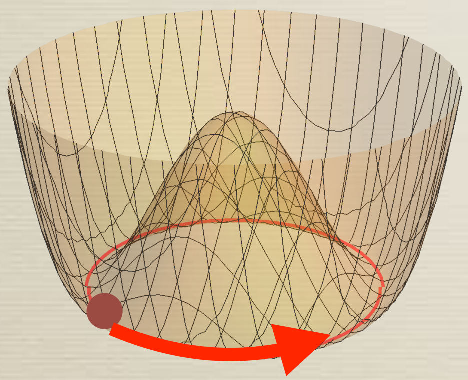
$$\frac{n_B}{s} \simeq \left.\frac{\dot{\theta} T^2}{s}\right|_{\mathrm{EW}} = n_\theta \times \frac{T_{\mathrm{EW}}^2}{f_a^2}$$

Axiogenesis and BSM

Chiral charge

U(1) ⟷ Chiral charge: Axion-SM

Chiral charge ⟷ Baryon: Majorana neutrino mass, R-parity violation, ...



Axion ⟷ other BSM

2006.05687, 2107.09679, 2108.04293, 2109.08605, 2110.05487, 2208.07878, 2307.14121, 2311.09005, 2402.10263, 2404.10283, 2405.07003

Outline

* Axion rotation and baryon asymmetry
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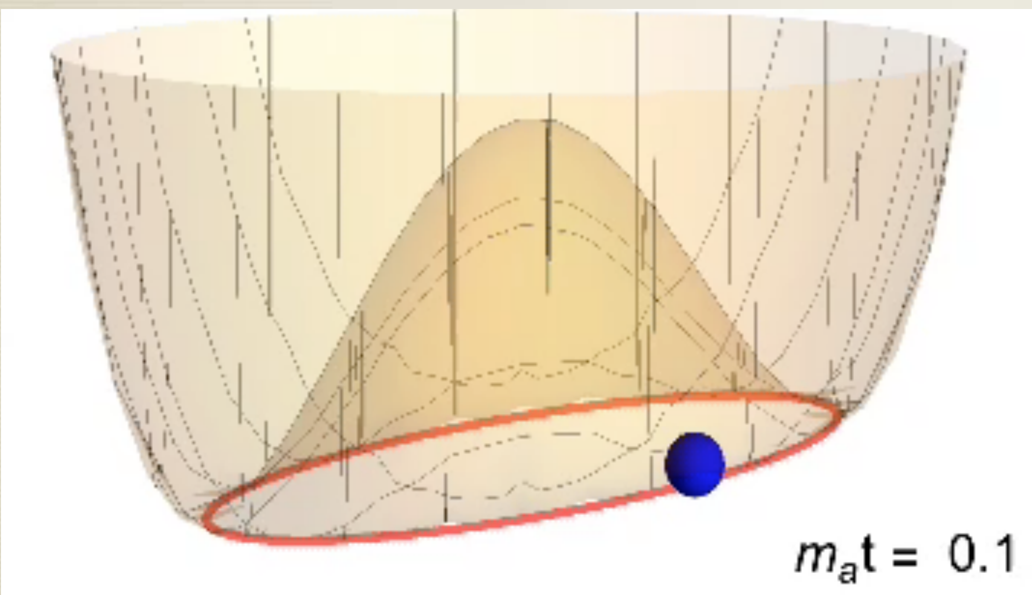
Enhanced dark matter density

Co, Hall and KH(2019)

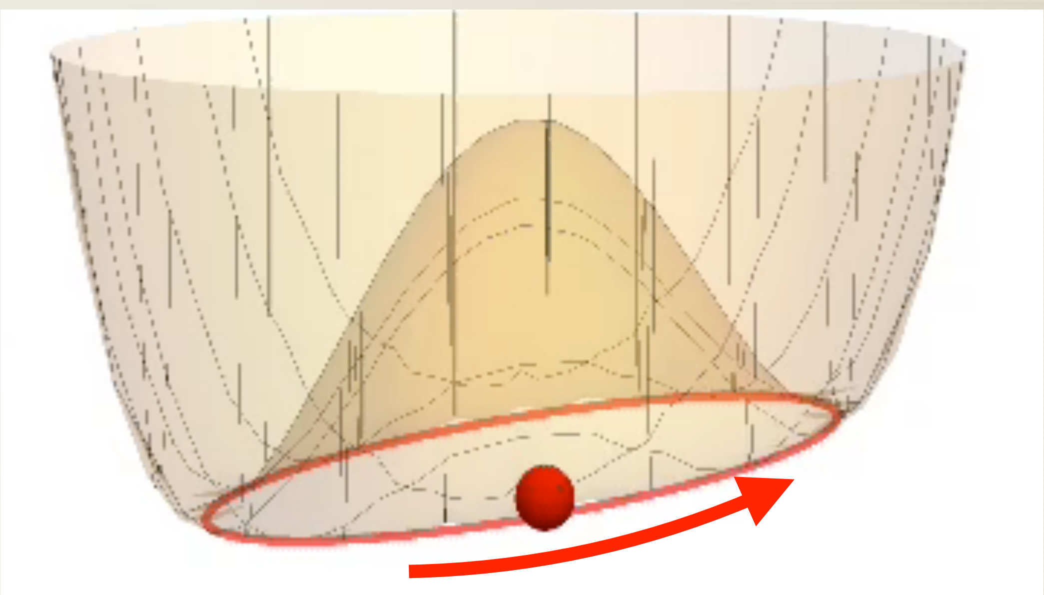
Misalignment mechanism



$\dot{\theta}_i = 0$

V

Non-zero kinetic energy



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

$V + K$

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

Enhanced dark matter density

Two sources of axion dark matter:

* Kinetic misalignment mechanism

Co, Hall and KH(2019), Co, Hall, Olive, Verner (2020)
Eroncel, Sato, Servant and Sorensen (2022)

Axion fluctuations are produced when the axion mass becomes non-negligible

$\cancel{U(1)}$

* Acoustic misalignment mechanism

Bodas, Co, Ghalsasi, KH and Wang (2025)
Eroncel, Gouttenoire, Sato, Servant and Simakachorn (2025)

Axion fluctuations are produced from cosmic perturbations of the U(1) charge

$U(1)$

Enhanced dark matter density

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Axion fluctuations are produced from cosmic perturbations of the U(1) charge

$U(1)$

Axion fragmentation

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

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

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

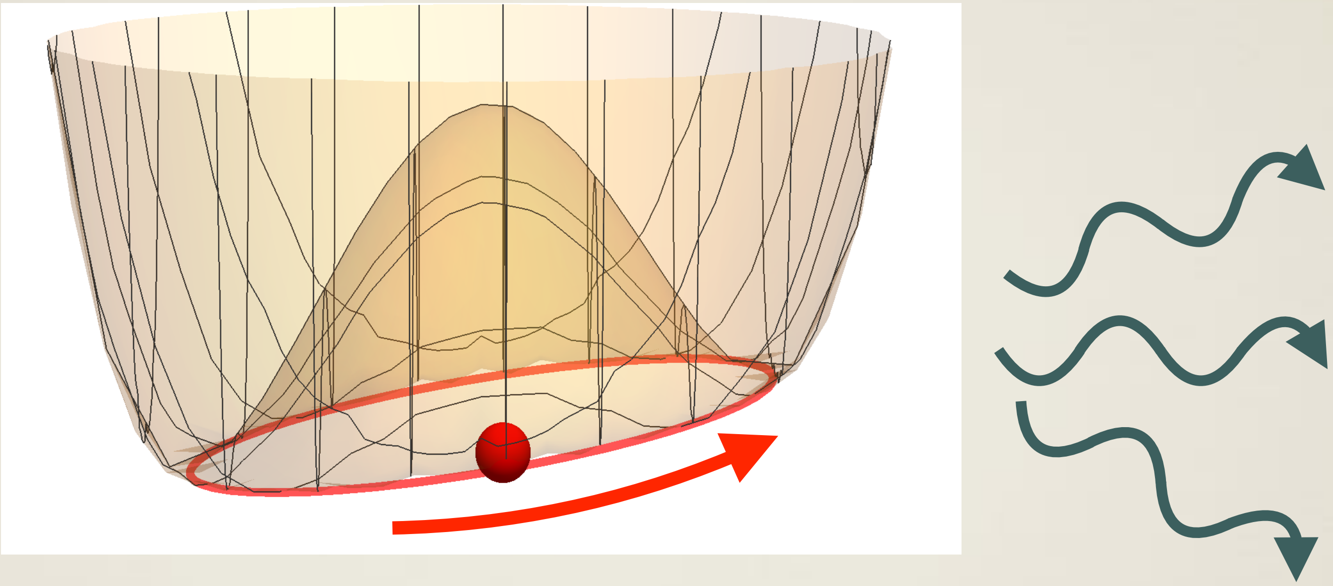
EOM of the fluctuation at the linear level:

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

oscillating frequency

Resonant production

Resonance at a natural frequency $k_{\rm PR} \sim \dot{\theta}$



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

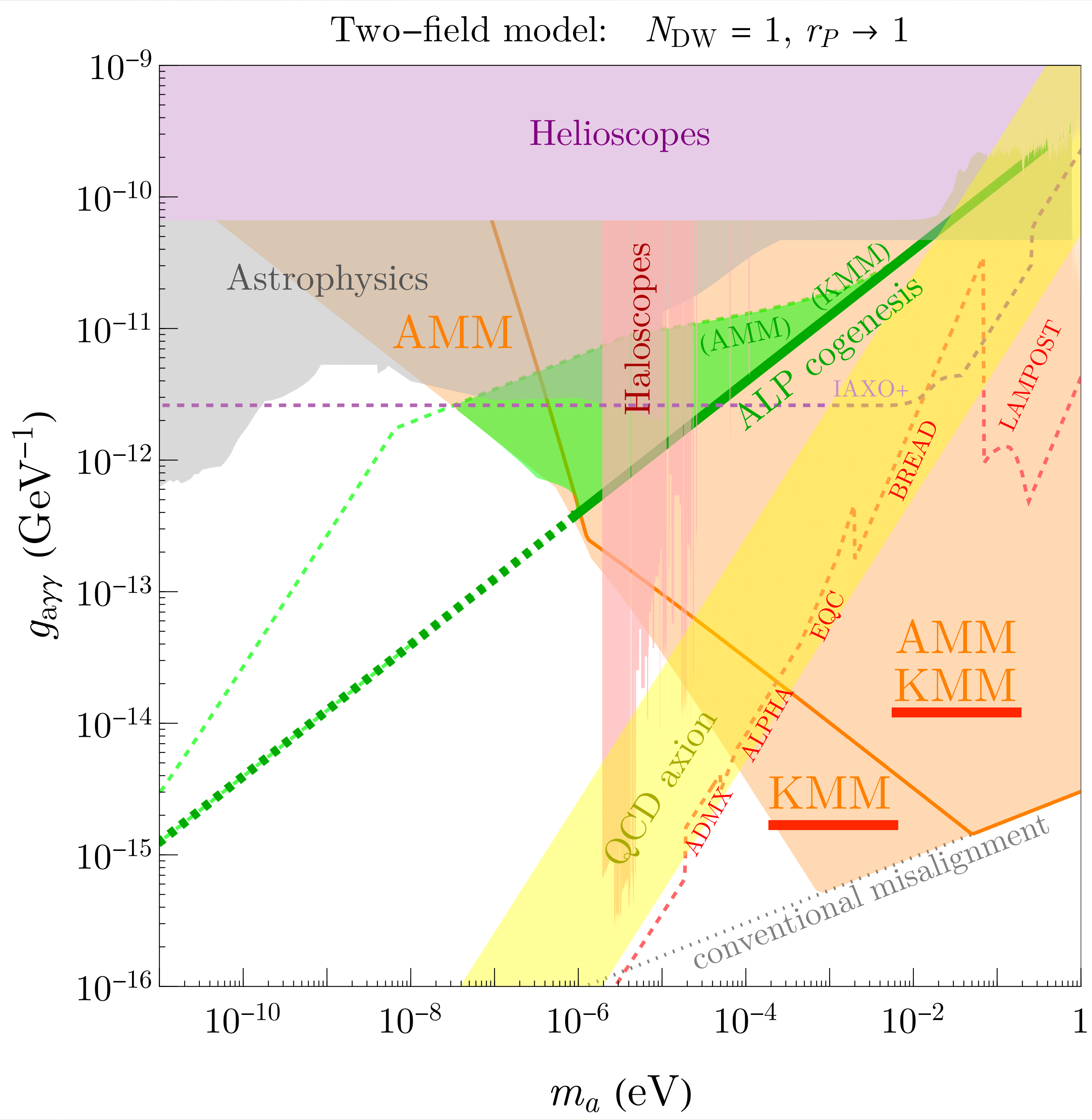
Co, KH and Pierce (2021)
Eroncel, Sato, Servant and Sorensen (2022)

Axion number density ≃ U(1) charge density

It's important to determine the relation precisely
(2507.01822 just appeared today)

Dark matter

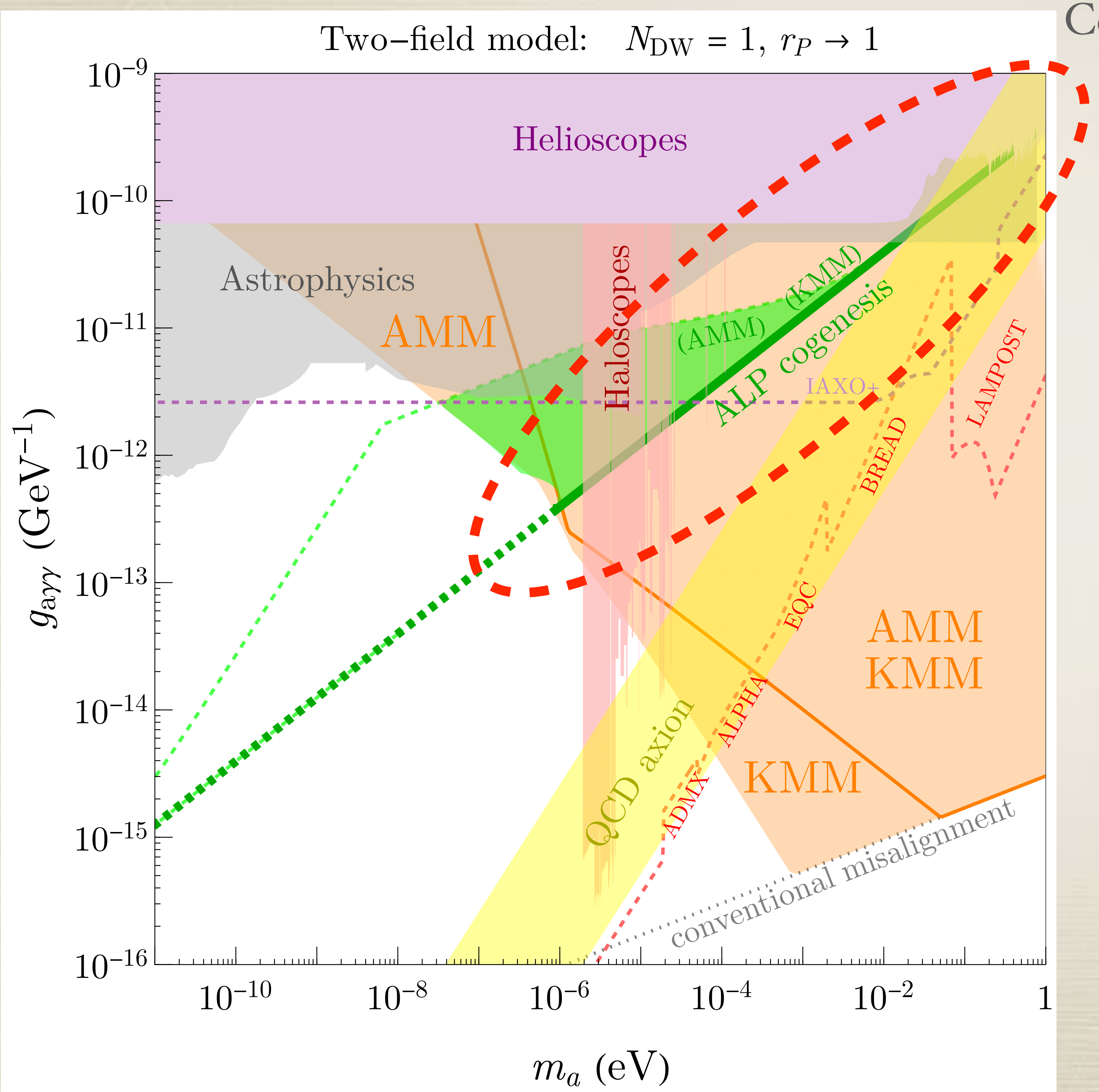
Bodas, Co, Ghalsasi, KH and Wang (2025)



In the orange-shaded region with “KMM”, the observed dark matter density can be explained by kinetic misalignment

Cogenesis of DM and baryon

Bodas, Co, Ghalsasi, KH and Wang (2025)
Co, Hall and KHH (2020)



On the green line, kinetic misalignment and axiogenesis by an electroweak process can explain both dark matter and baryon asymmetry

$$n_{a,\mathrm{PR}} \sim n_\theta$$

Exact relation?

Enhanced dark matter density

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the axion mass becomes non-negligible

$\cancel{U(1)}$

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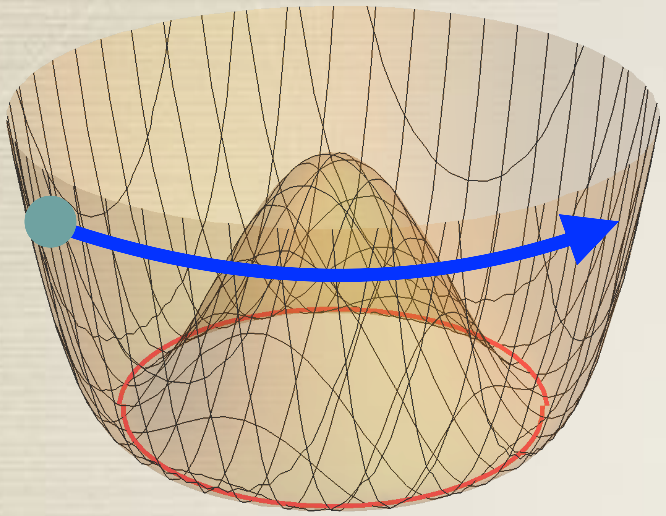
Eroncel, Gouttenoire, Sato, Servant and Simakachorn (2025)

Axion fluctuations are produced from
cosmic perturbations of the U(1) charge

$U(1)$

Phonon mode

$\dot{\theta} = \omega$



$U(1) \times$ time translation

$$\begin{cases} \theta \to \theta + \alpha \\ t \to t + \delta \end{cases}$$

$U(1)'$

$$\begin{cases} \theta \to \theta - \omega\delta \\ t \to t + \delta \end{cases}$$

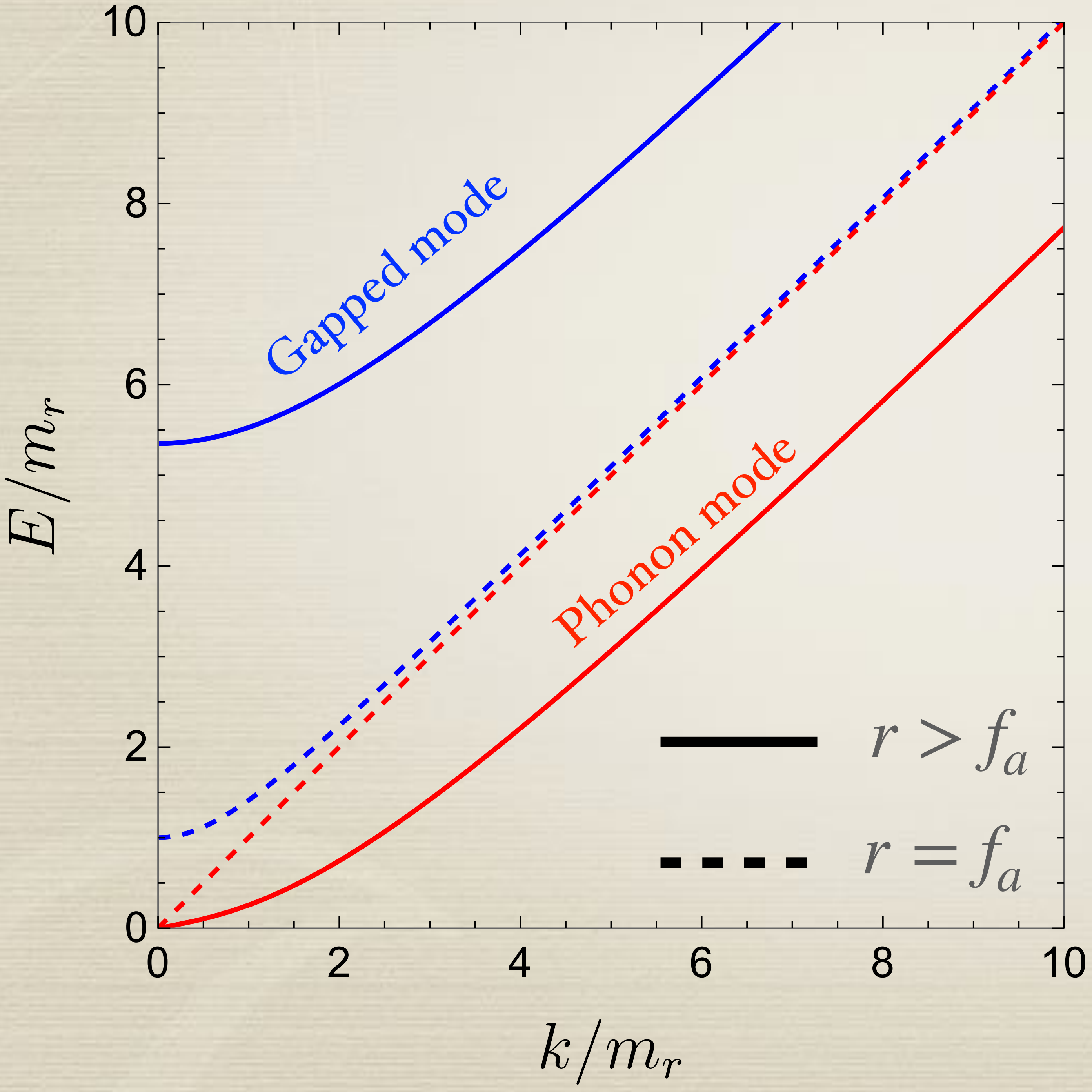
One Nambu-Goldstone mode is predicted

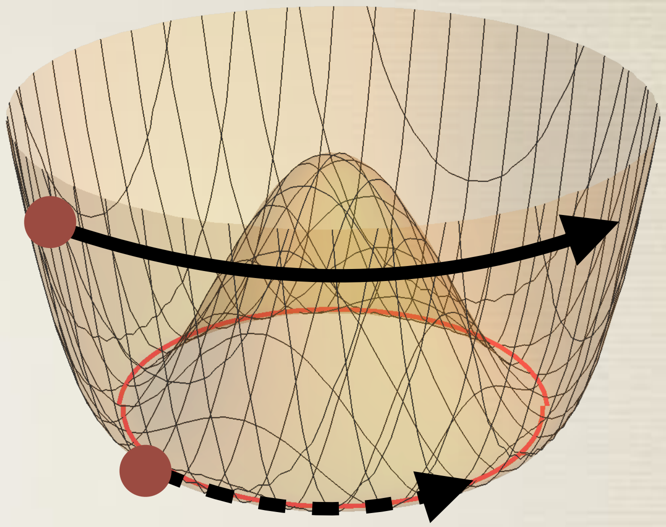
Phonon

Phonon mode

Bodas, Co, Ghalsasi, KH and Wang (2025)

Dispersion relation





Sound velocity

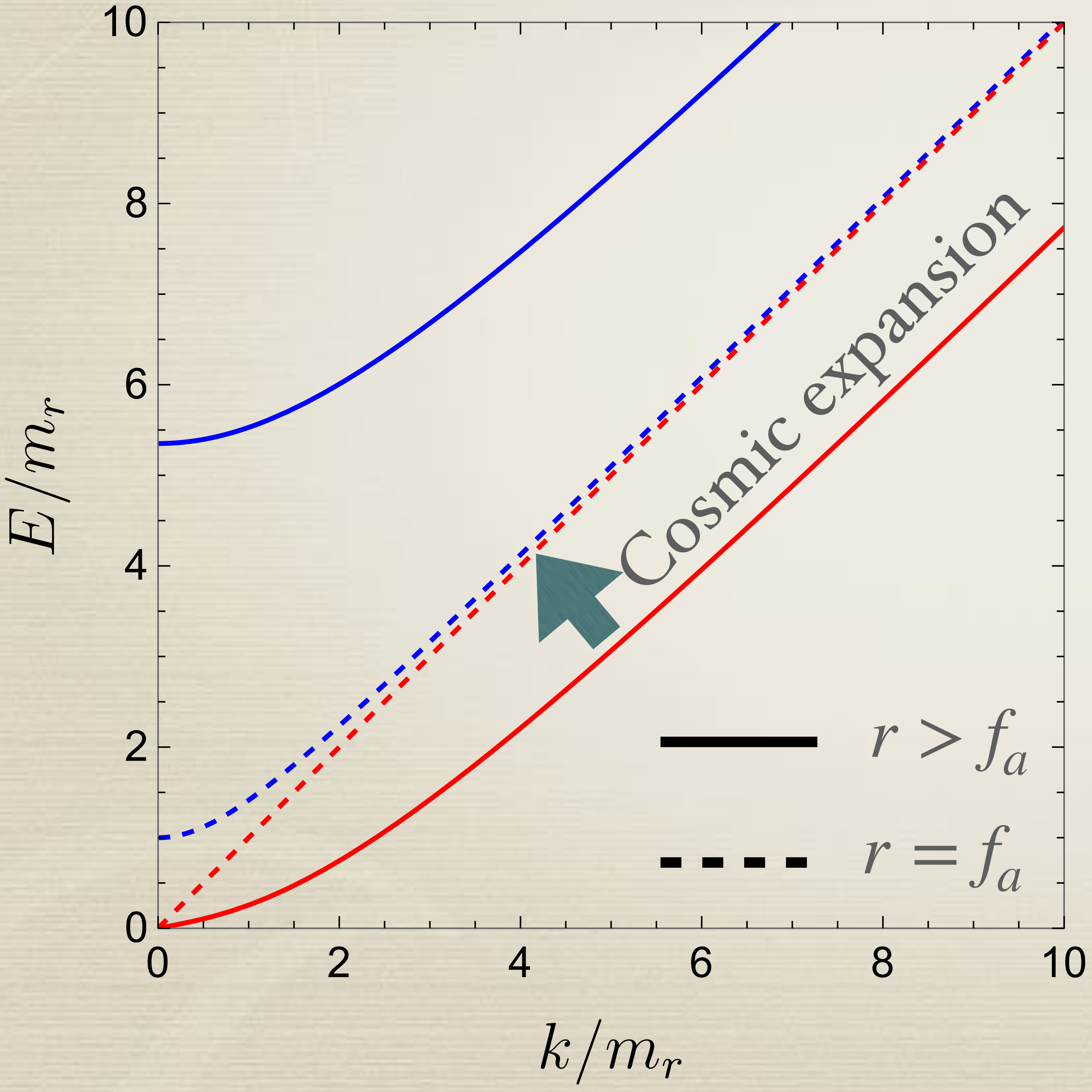
$$c_s^2 = \frac{V_{rr} - V_r/r}{V_{rr} + 3V_r/r}$$

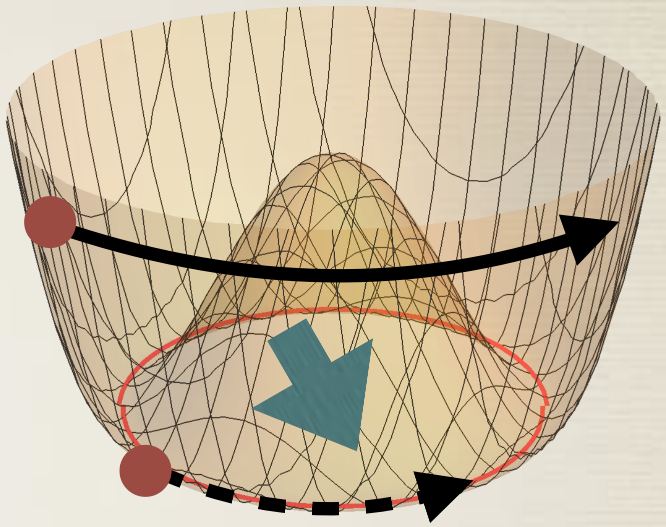
At the minimum, where $V_r = 0$,
$c_s = 1$: axion

Phonon mode

Dispersion relation

Bodas, Co, Ghalsasi, KH and Wang (2025)





Sound velocity

$$c_s^2 = \frac{V_{rr} - V_r/r}{V_{rr} + 3V_r/r}$$

At the minimum, where $V_r = 0$,
$c_s = 1$: axion

Phonon production

Bodas, Co, Ghalsasi, KH and Wang (2025)

Inflaton perturbation
(curvature perturbation)

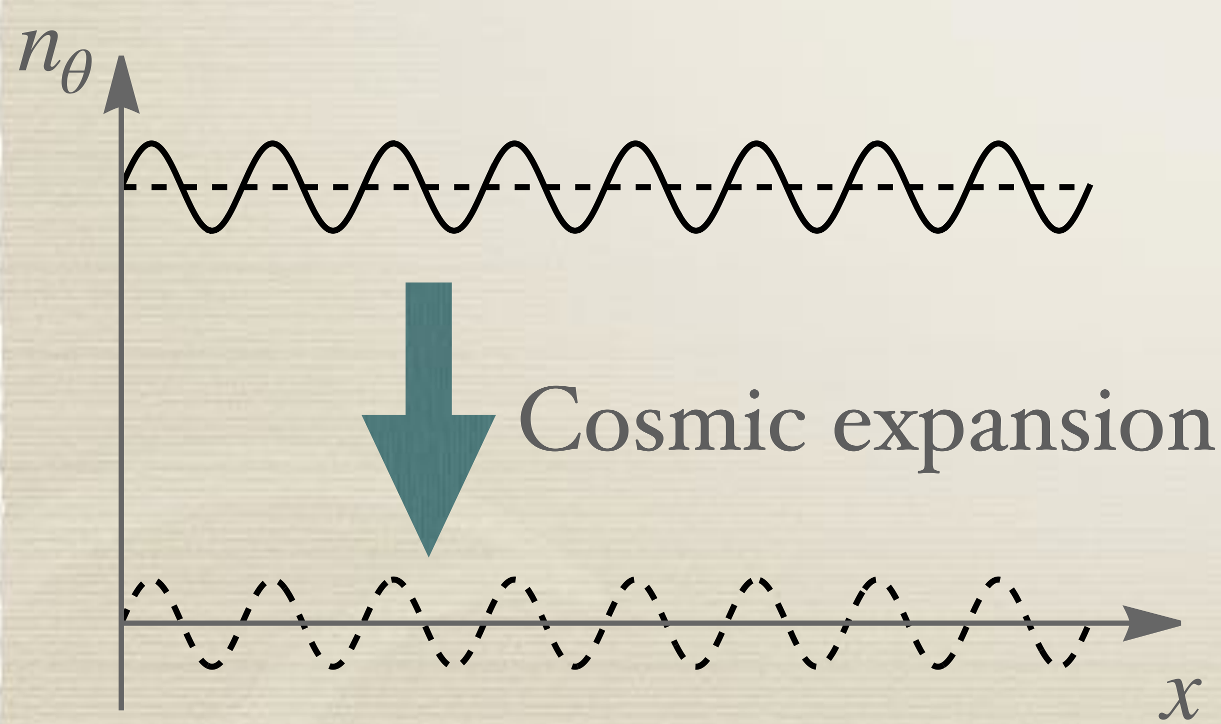
Axion perturbation
(isocurvature perturbation)

→ Perturbation of U(1) charge density
= phonon (i.e., sound wave)

↓

Axions

Acoustic misalignment

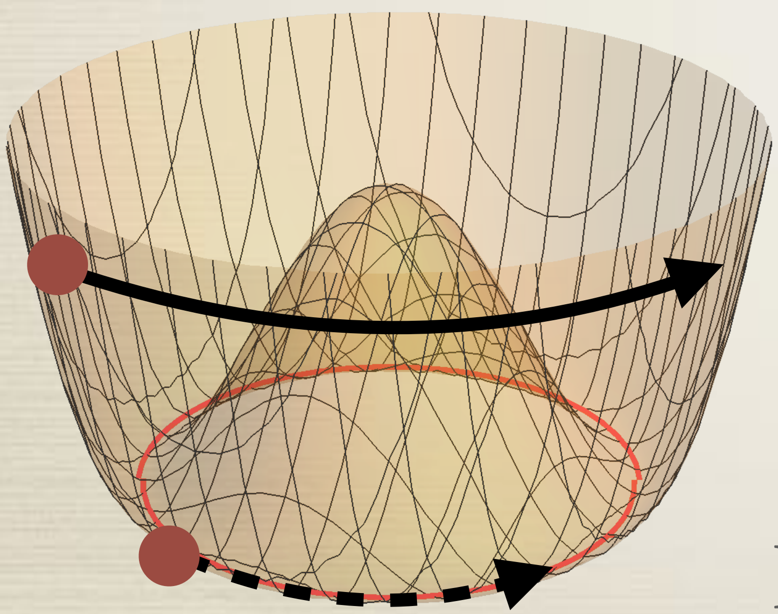


Evolution of perturbations

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

The axion abundance is sensitive to the equation of state of rotation and the sound velocity of the phonon mode

Ex. $V(r) \propto (r^2 - f_a^2)^2$



Radiation-like: $w = c_s^2 = 1/3$
No growth of fluctuations

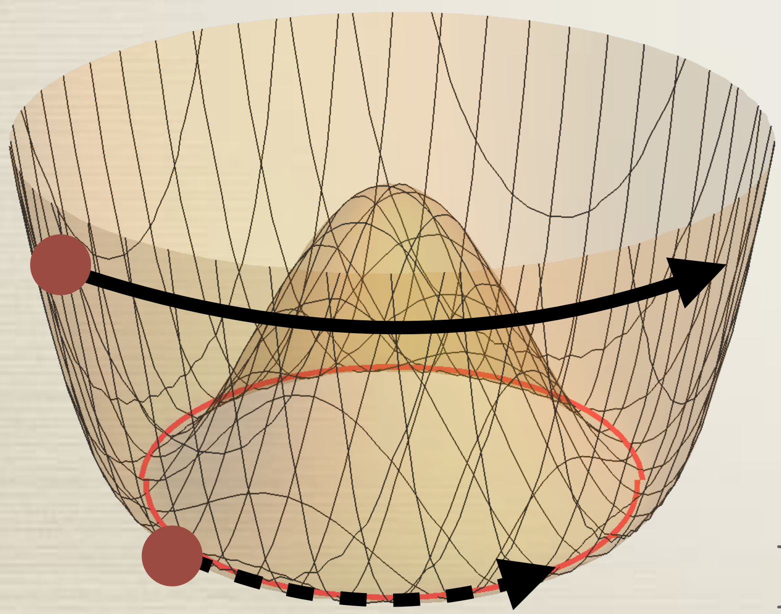
Kination

Evolution of perturbations

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

The axion abundance is sensitive to the equation of state of rotation and the sound velocity of the phonon mode

Ex. Supersymmetric model with $V(r) \propto m_r^2 r^2$ for $r \gg f_a$



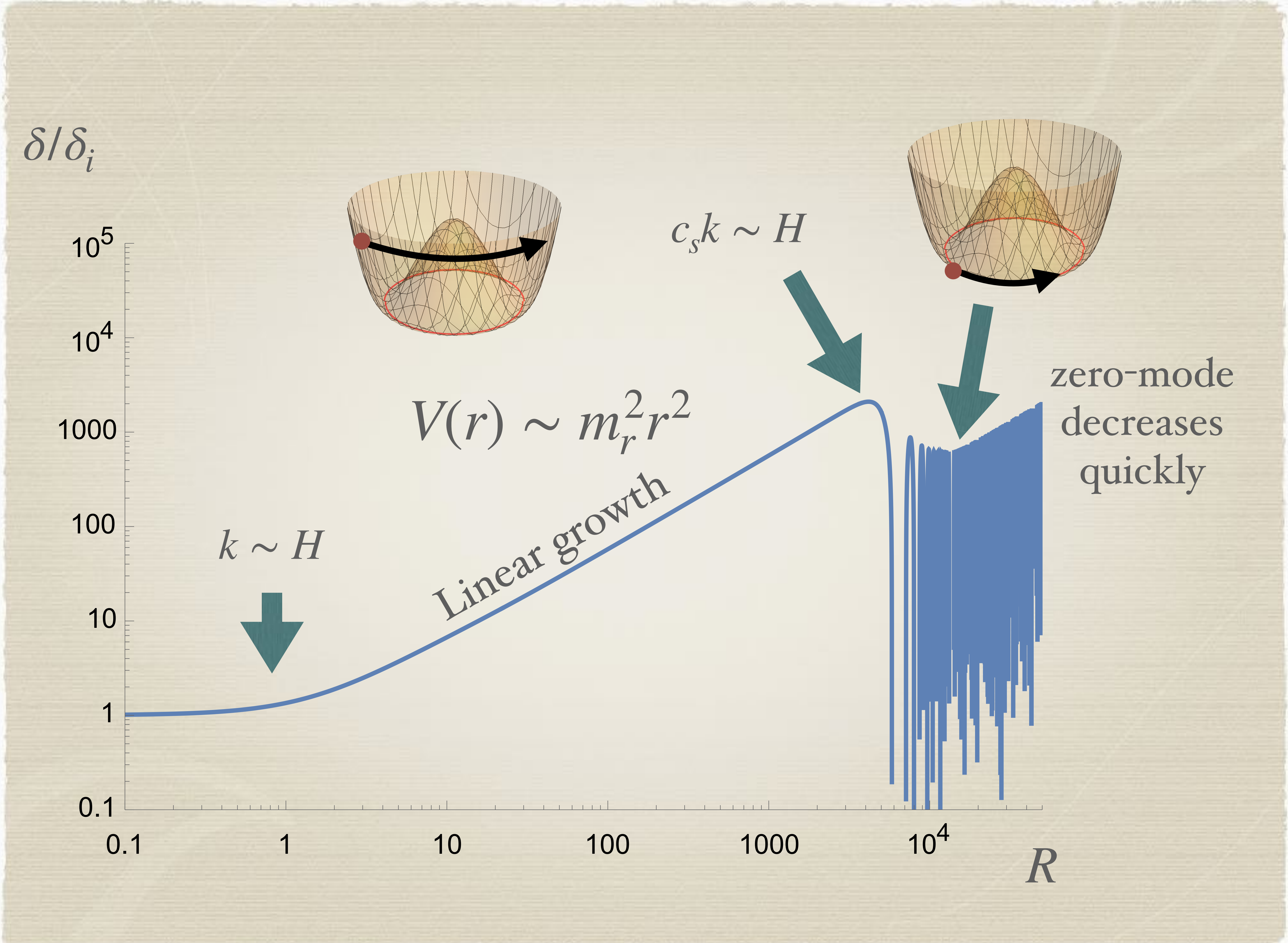
Matter-like:

$w \simeq c_S^2 \ll 1$

Growth of fluctuations if the rotation dominates the universe

Kination

Evolution should be carefully computed using cosmological perturbation theory

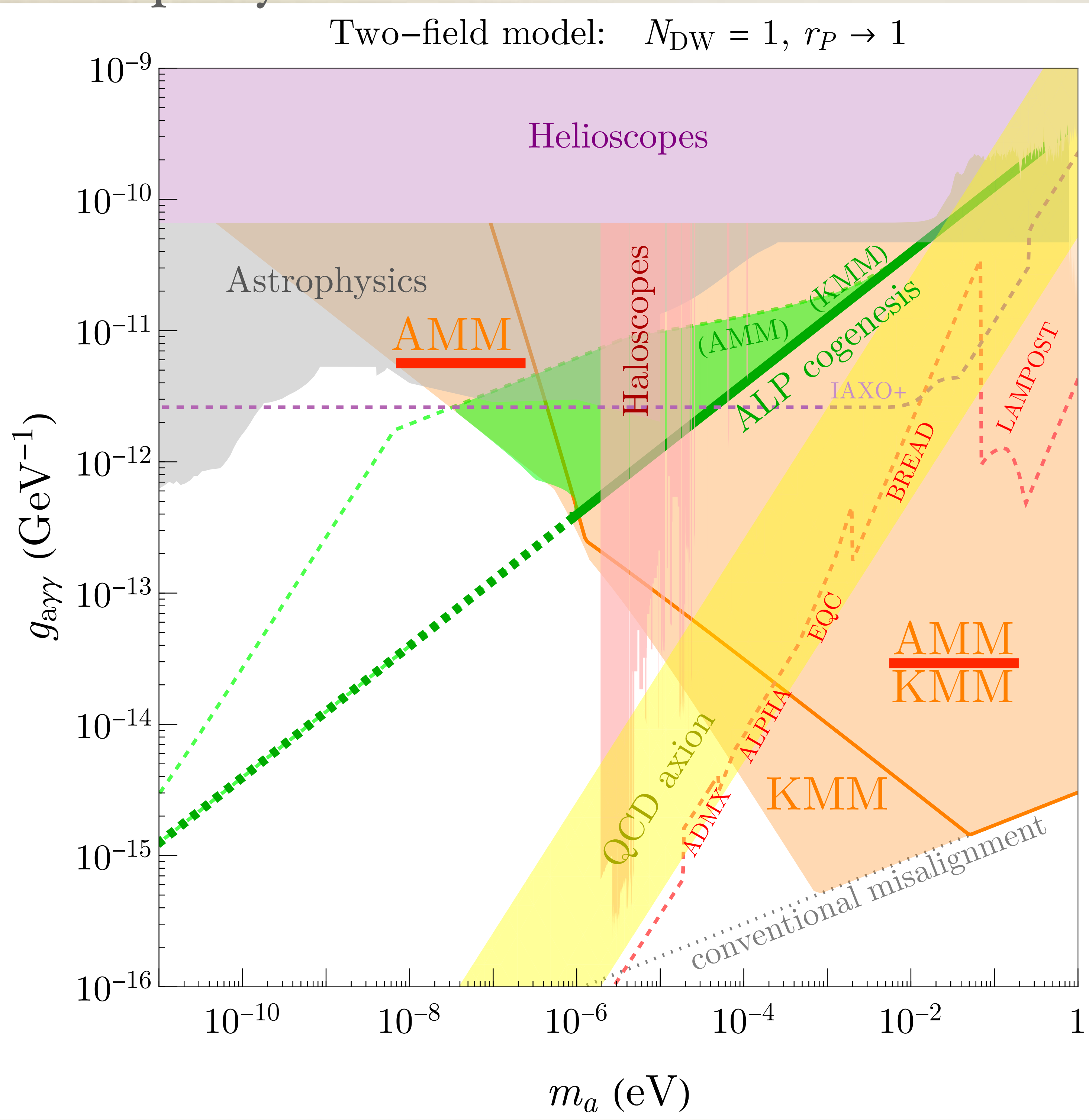


δ/δ_i
10^5
10^4
1000
100
10
1
0.1
0.1
1
10
100
1000
10^4
R
$k \sim H$
Linear growth
$V(r) \sim m_r^2 r^2$
$c_s k \sim H$
zero-mode
decreases
quickly

Dark matter

A supersymmetric model

Bodas, Co, Ghalsasi, KH and Wang (2025)



In the orange-shaded region with "AMM", the observed dark matter density can be explained by acoustic misalignment

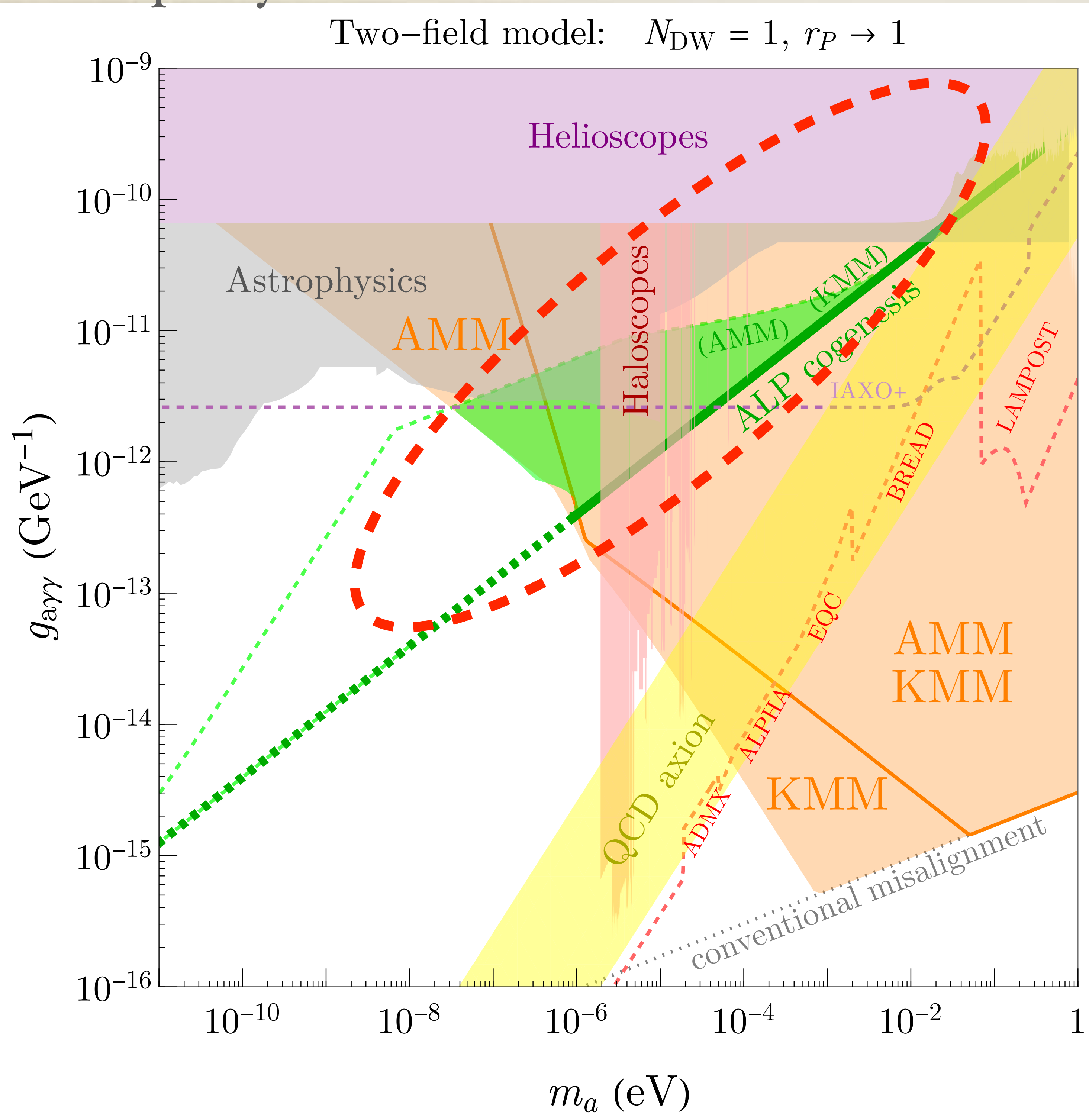
Outside the region, thermalization is not efficient or baryon asymmetry is overproduced by chiral plasma instability

Inflaton perturbation is assumed to be the only source of perturbations

Cogenesis of DM and baryon

A supersymmetric model

Bodas, Co, Ghalsasi, KH and Wang (2025)



In the green-shaded region, acoustic misalignment and axiogenesis by an electroweak process can explain both dark matter and baryon asymmetry

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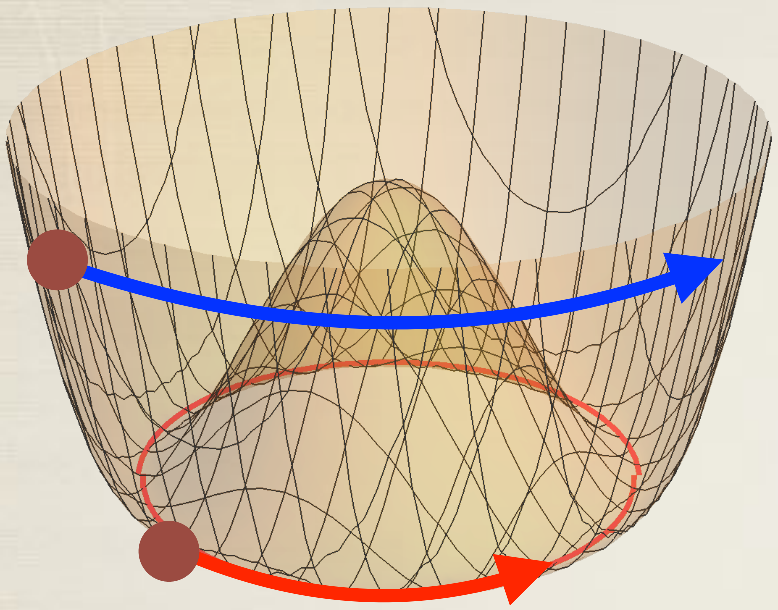
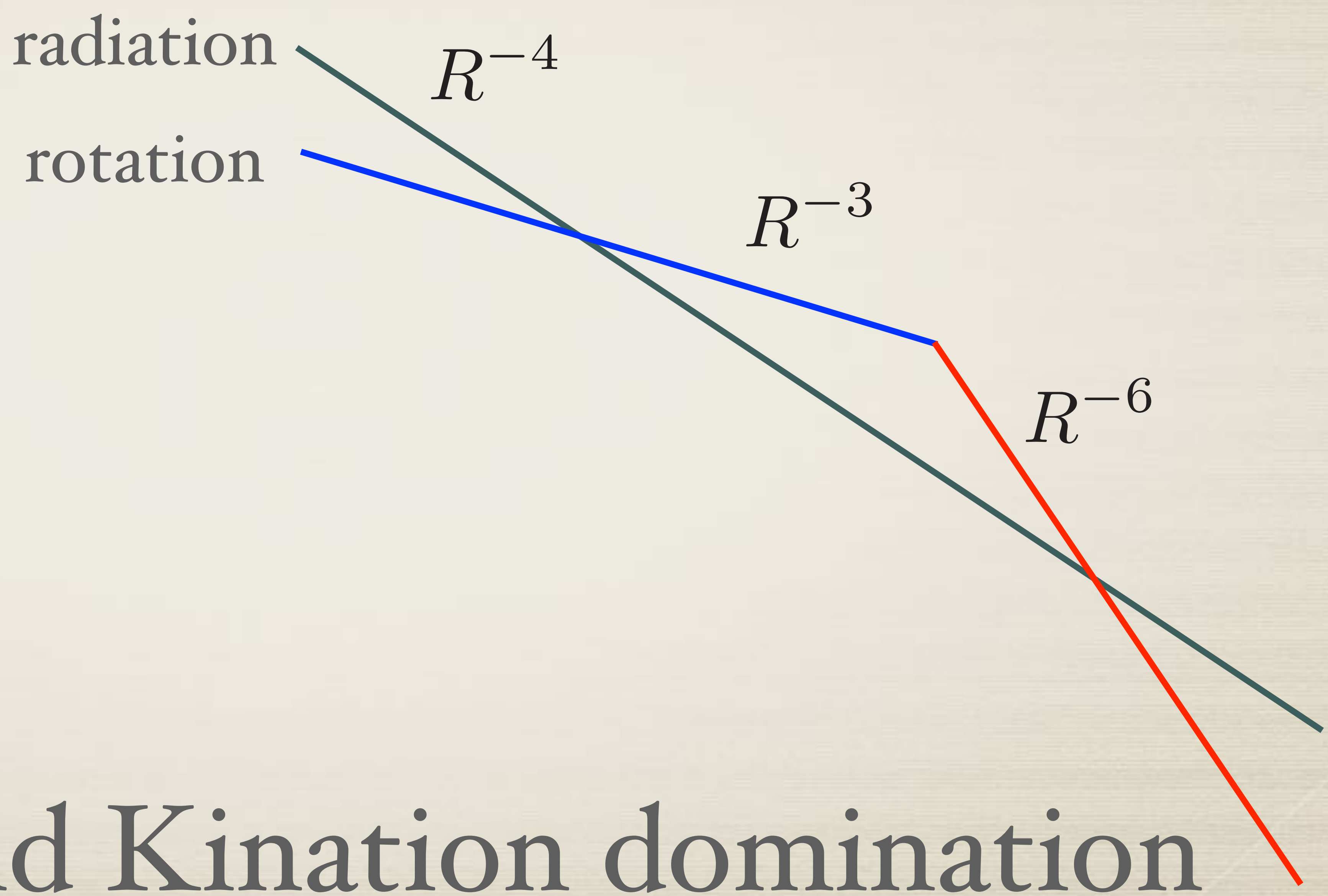
Equation of state

In a class of models (e.g. supersymmetric theories),





Matter and Kination domination

Primordial gravitational waves

Fluctuation of energy density
Quantum fluctuation
during inflation

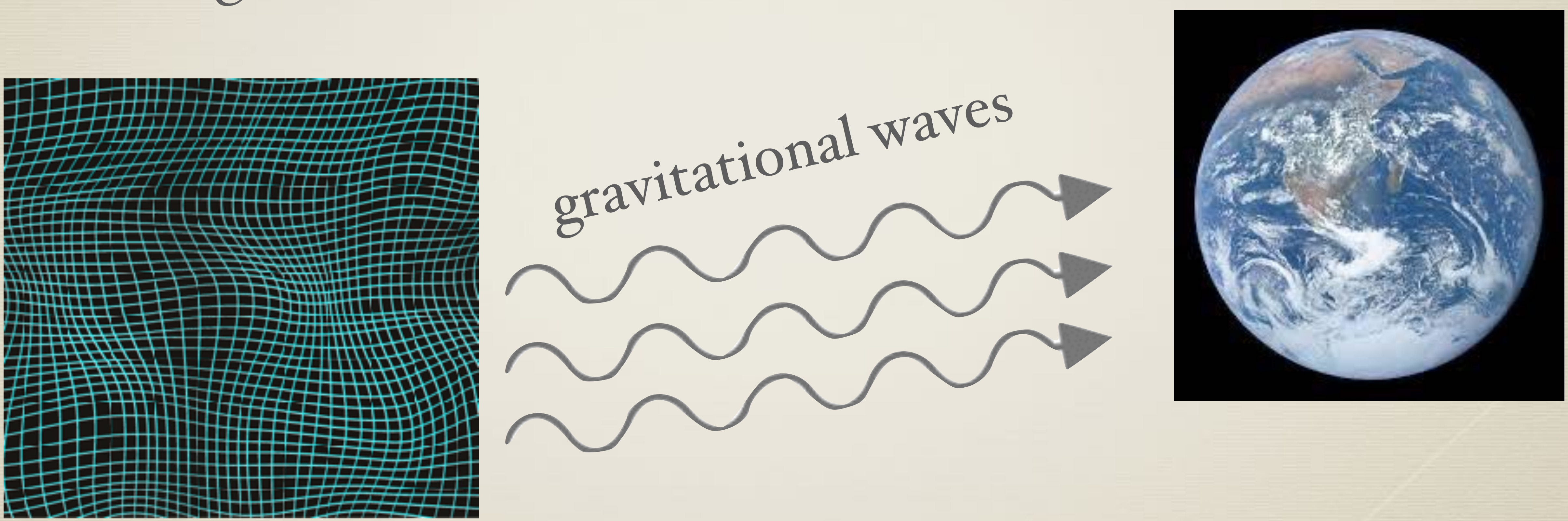
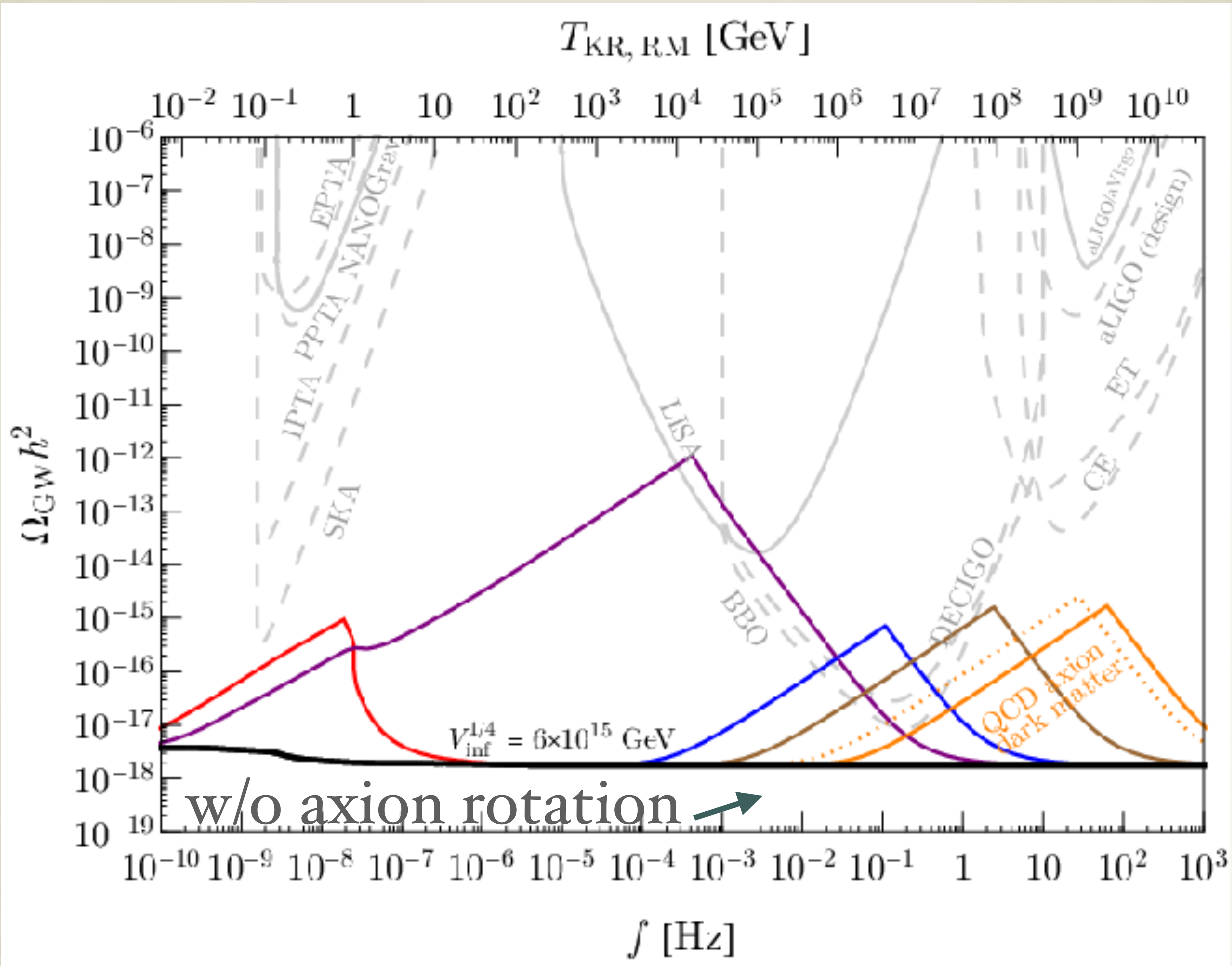


figure from ipmu.jp

Evolution/production of them depends on how the universe expanded, which is sensitive to axion kination

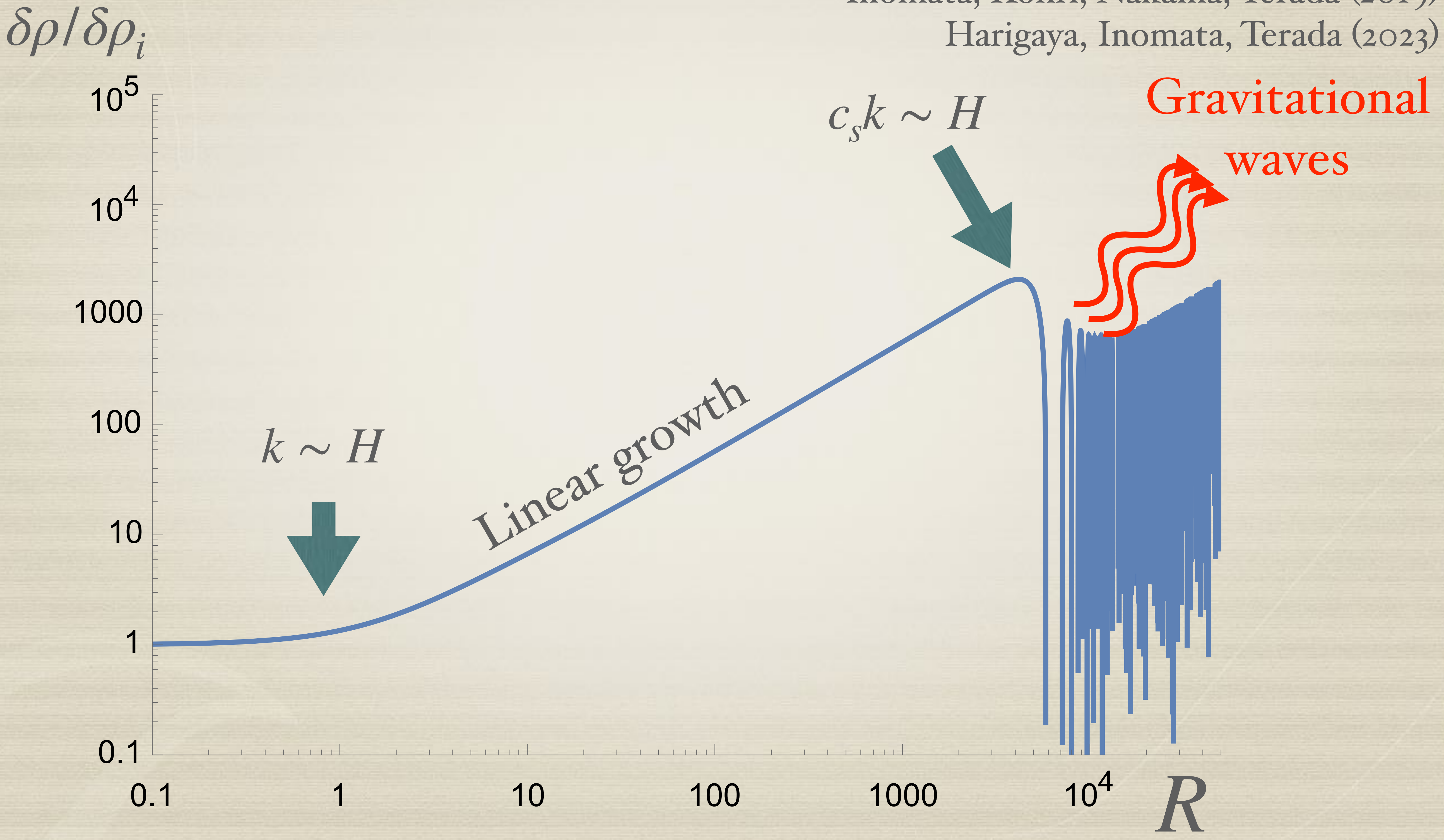
Ex. Inflation



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

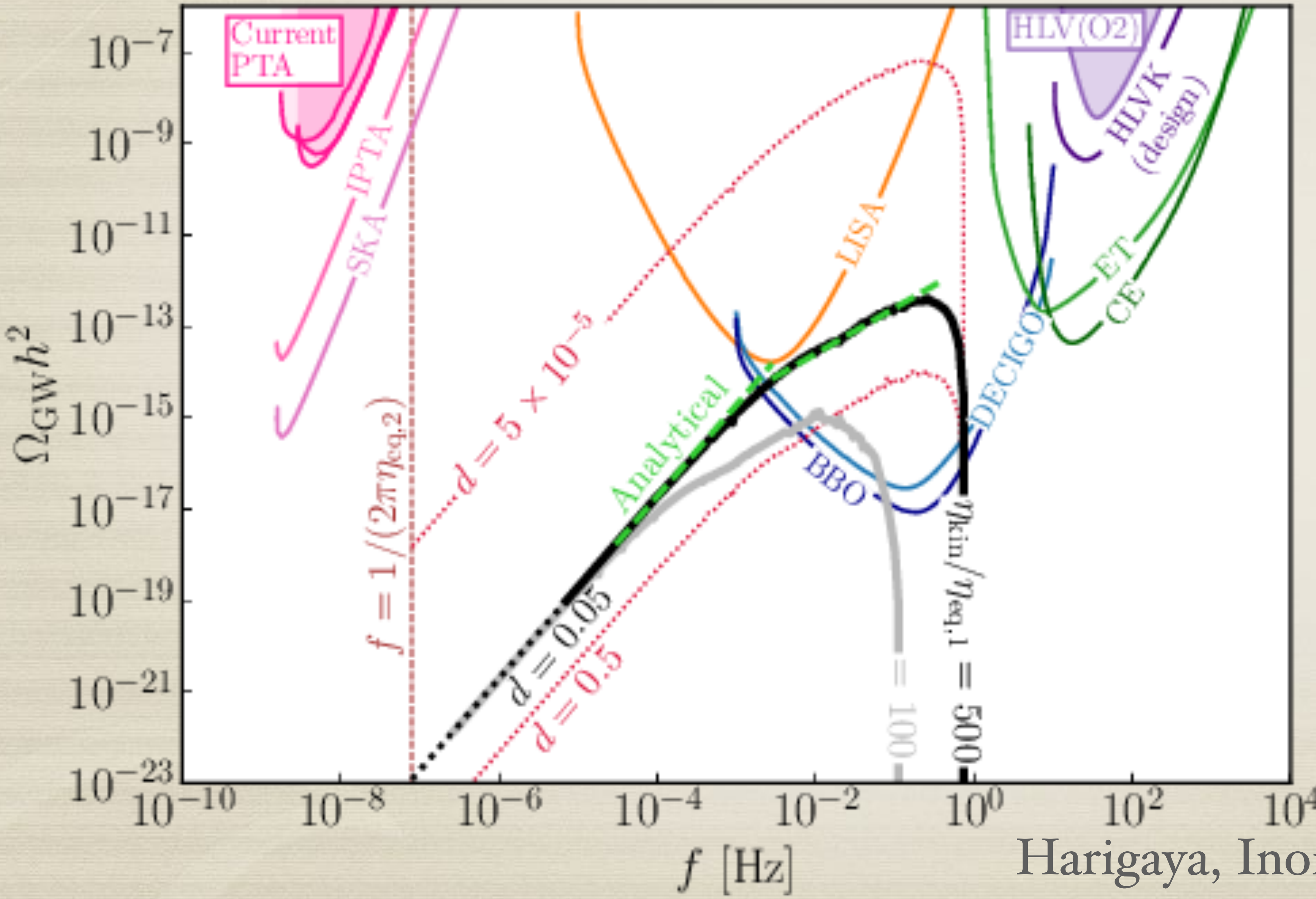
Production from rotation

Inomata, Kohri, Nakama, Terada (2019)
Harigaya, Inomata, Terada (2023)



Spectrum

A sample point for an ALP



Inflaton perturbation is assumed to be the only source of perturbations

Harigaya, Inomata, and Terada (2023)

d parameterize the rapidness of matter-kination transition

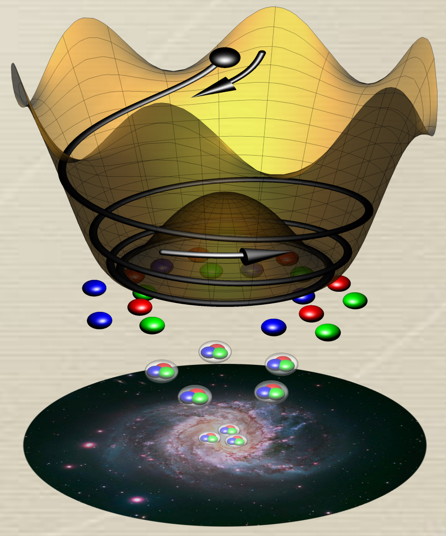
Summary

* Rotation of axion in the field space can create matter-antimatter asymmetry

* Rotation produces axion dark matter through phonon mode excitation from cosmic perturbations or through parametric resonance

* Axions couplings are predicted to be larger than the prediction of the misalignment mechanism

* Gravitational waves may be affected or created



Backup

Supersymmetric models

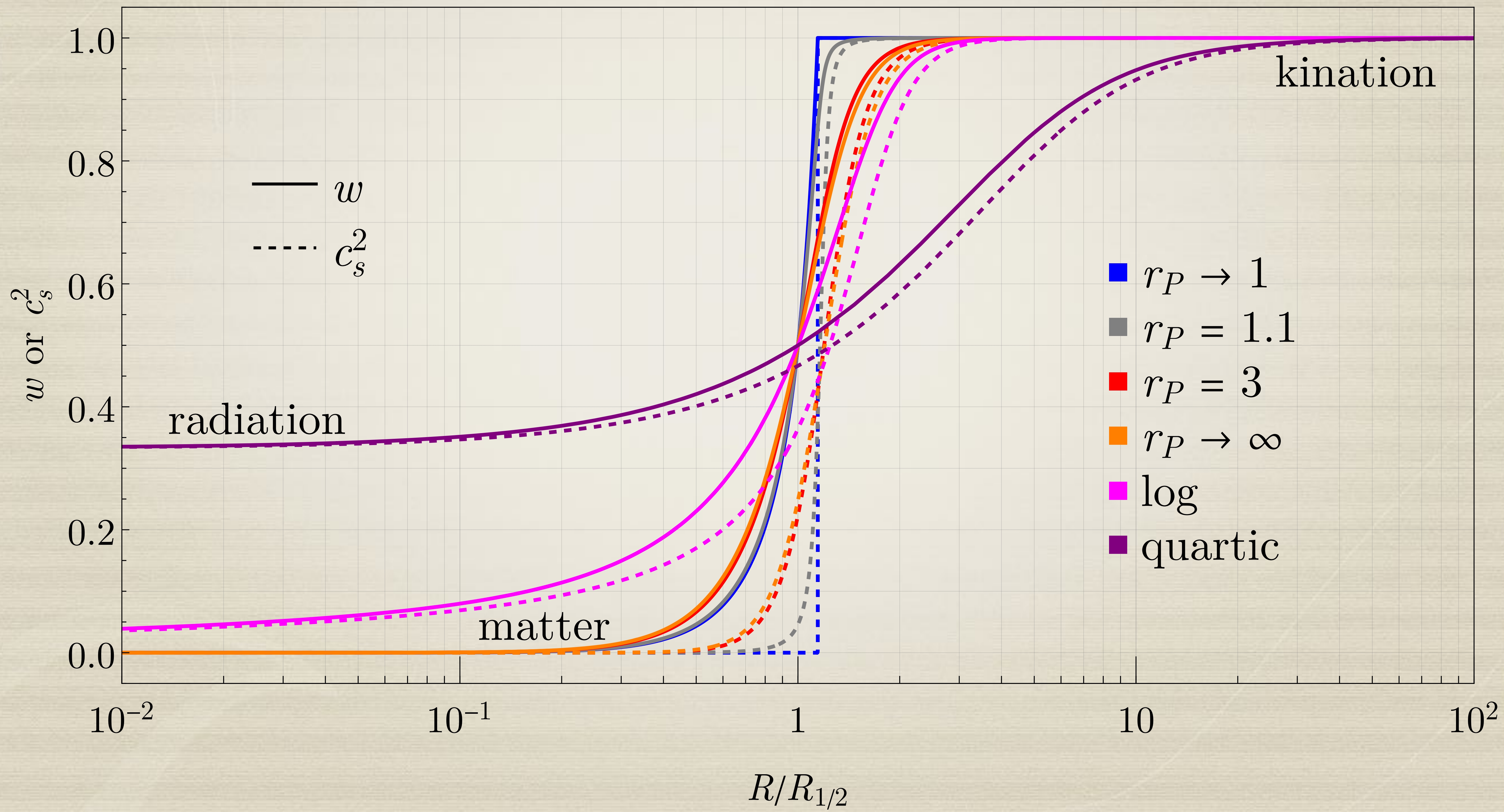
Log-potential model

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

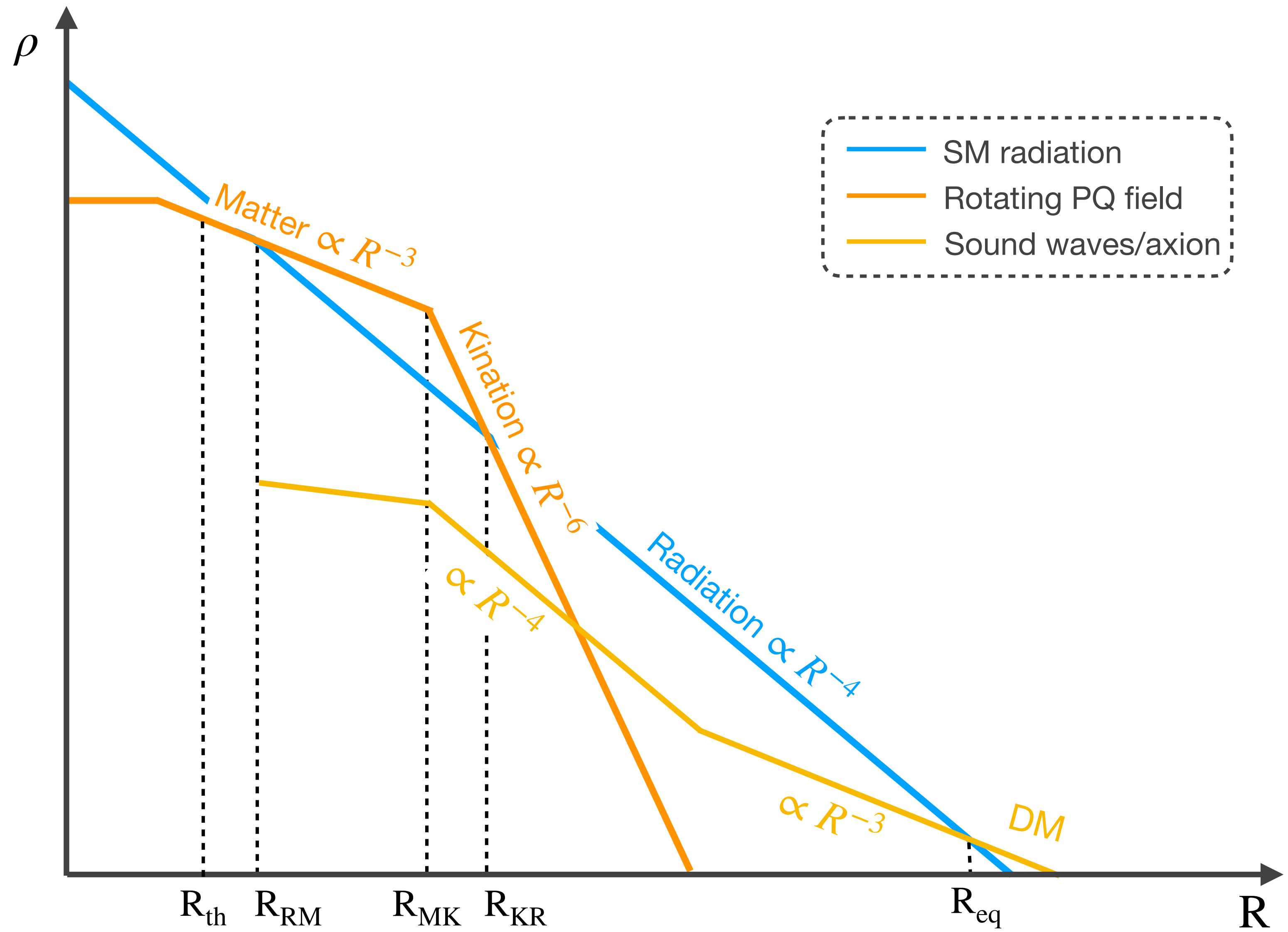
Two-field model

$$W = \lambda X (P\bar{P} - v_{\rm PQ}^2), \quad V_{\rm soft}(P) = m_P^2 |P|^2 + m_{\bar{P}}^2 |\bar{P}|^2 .$$

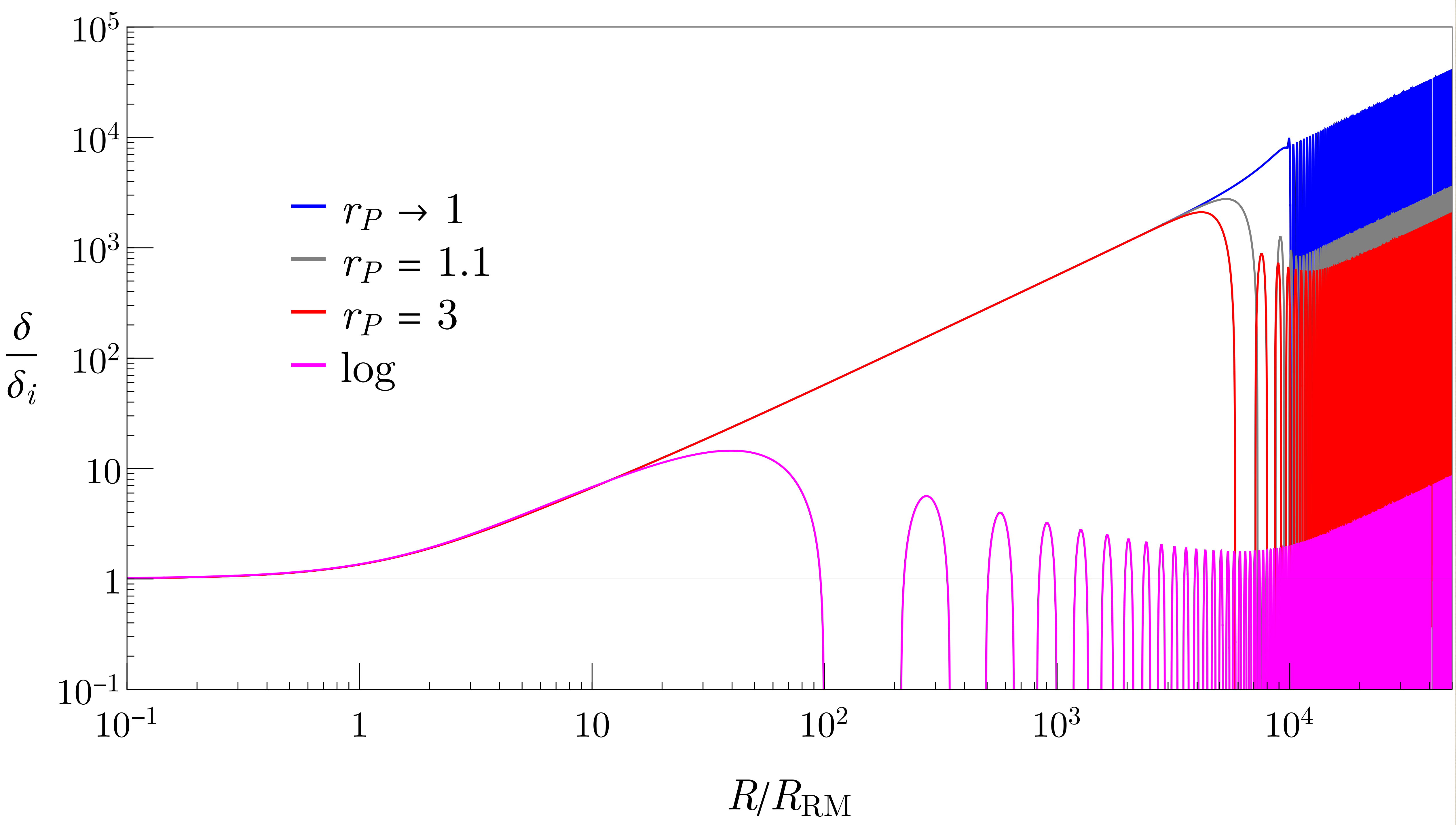
$$r_P \equiv m_{\bar{P}}/m_P$$



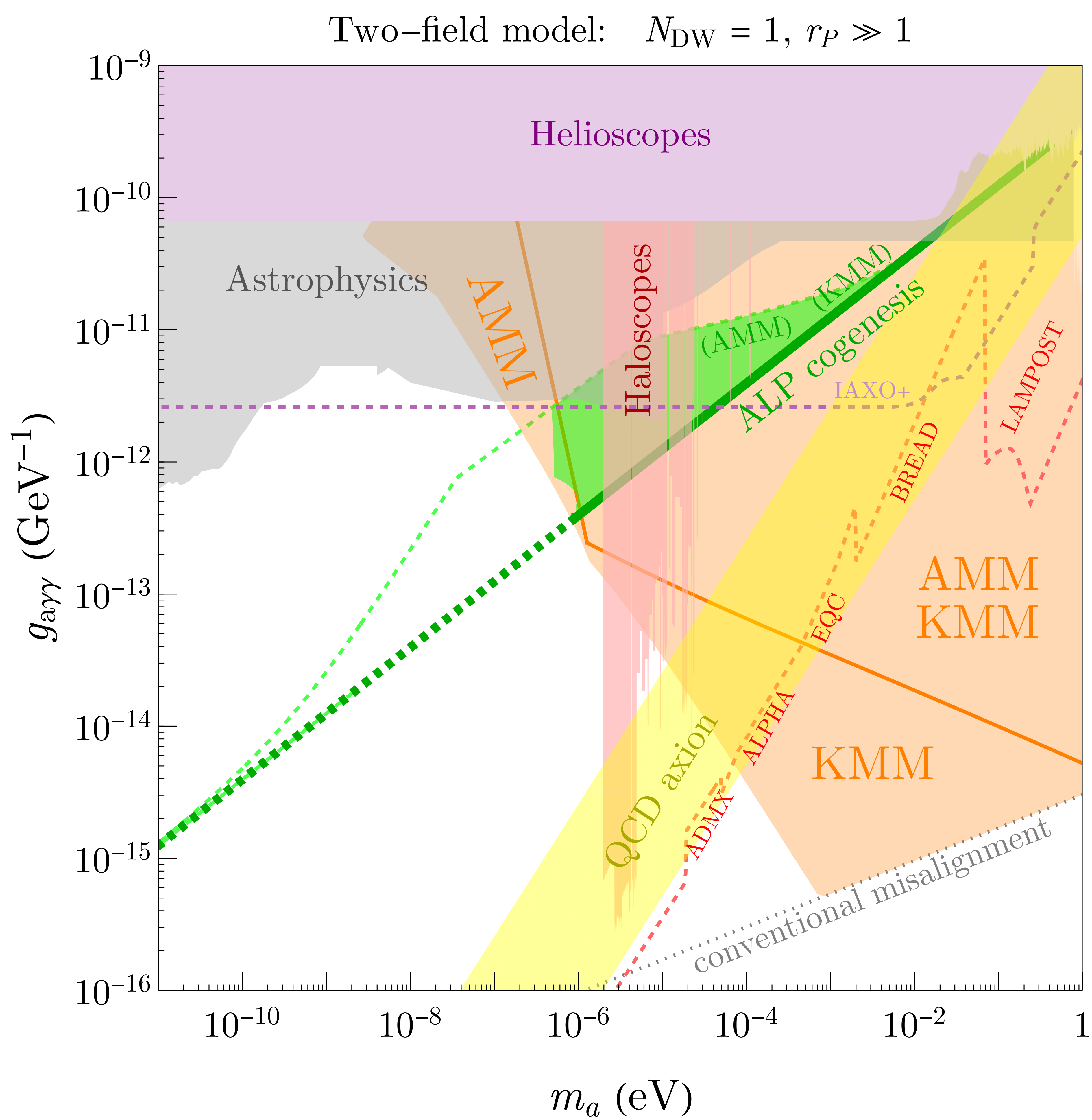
1.0
0.8
0.6
0.4
0.2
0.0
w or c_s^2
10^{-2}
10^{-1}
1
10
10^2
$R/R_{1/2}$
w
c_s^2
kination
radiation
matter
$r_P \to 1$
$r_P = 1.1$
$r_P = 3$
$r_P \to \infty$
log
quartic

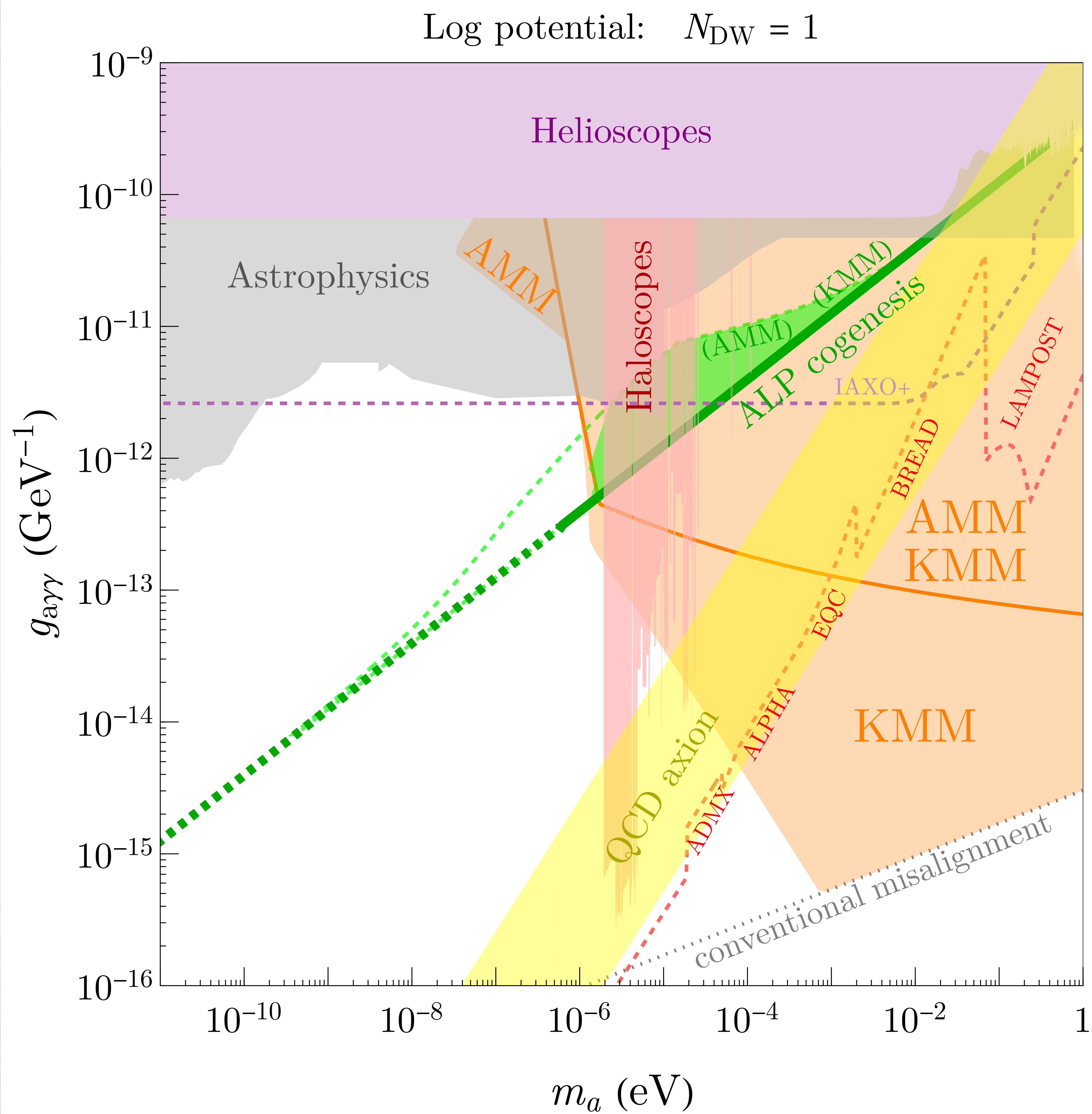


ρ
SM radiation
Rotating PQ field
Sound waves/axion
Matter ∝ R^−3
Kination ∝ R^−6
Radiation ∝ R^−4
∝ R^−4
∝ R^−3
DM
R_th
R_RM
R_MK
R_KR
R_eq
R



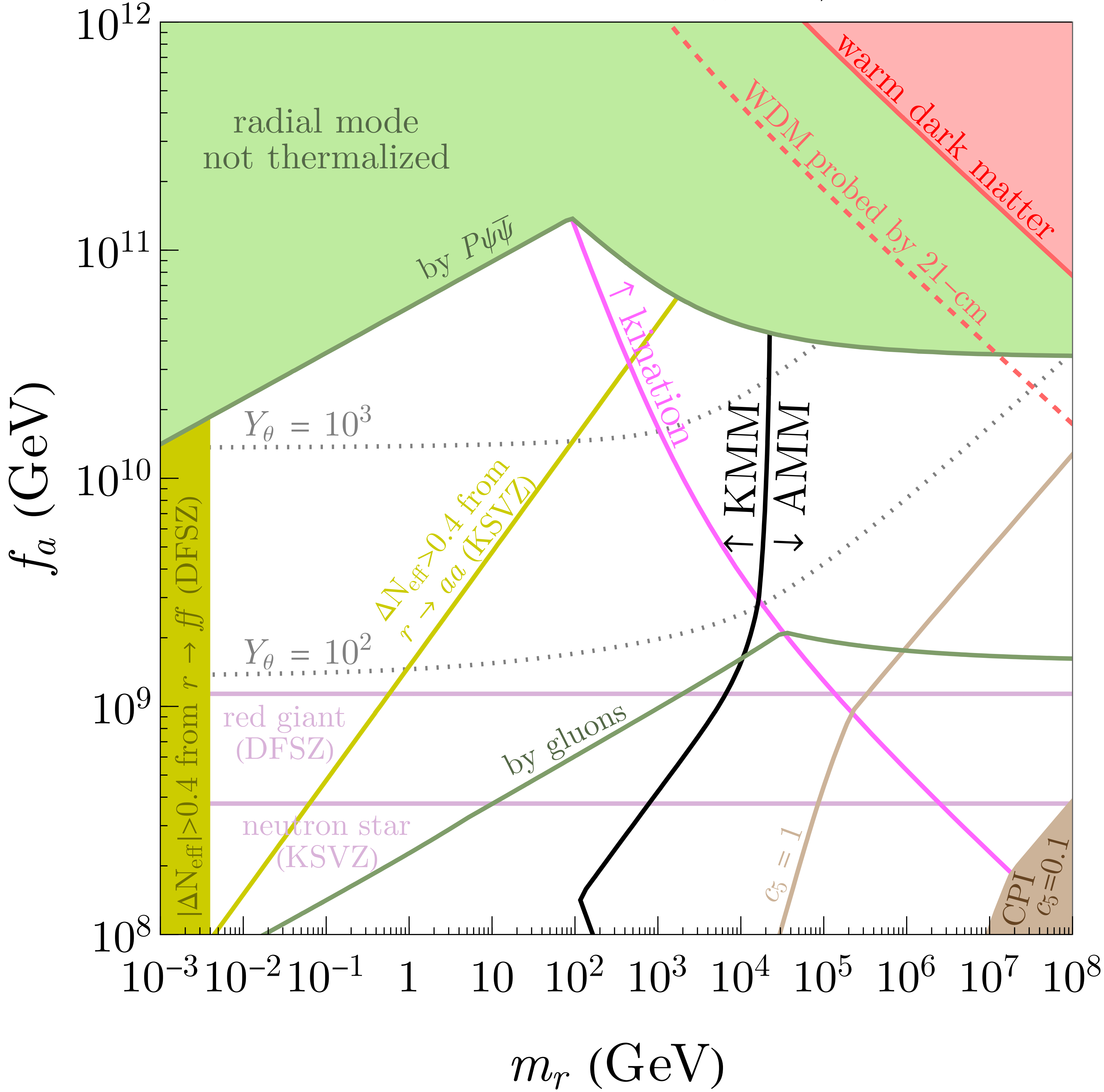
10^5
10^4
10^3
10^2
10
1
10^{-1}
$\frac{\delta}{\delta_i}$
$r_P \to 1$
$r_P = 1.1$
$r_P = 3$
log
10^{-1}
1
10
10^2
10^3
10^4
$R/R_{\rm RM}$

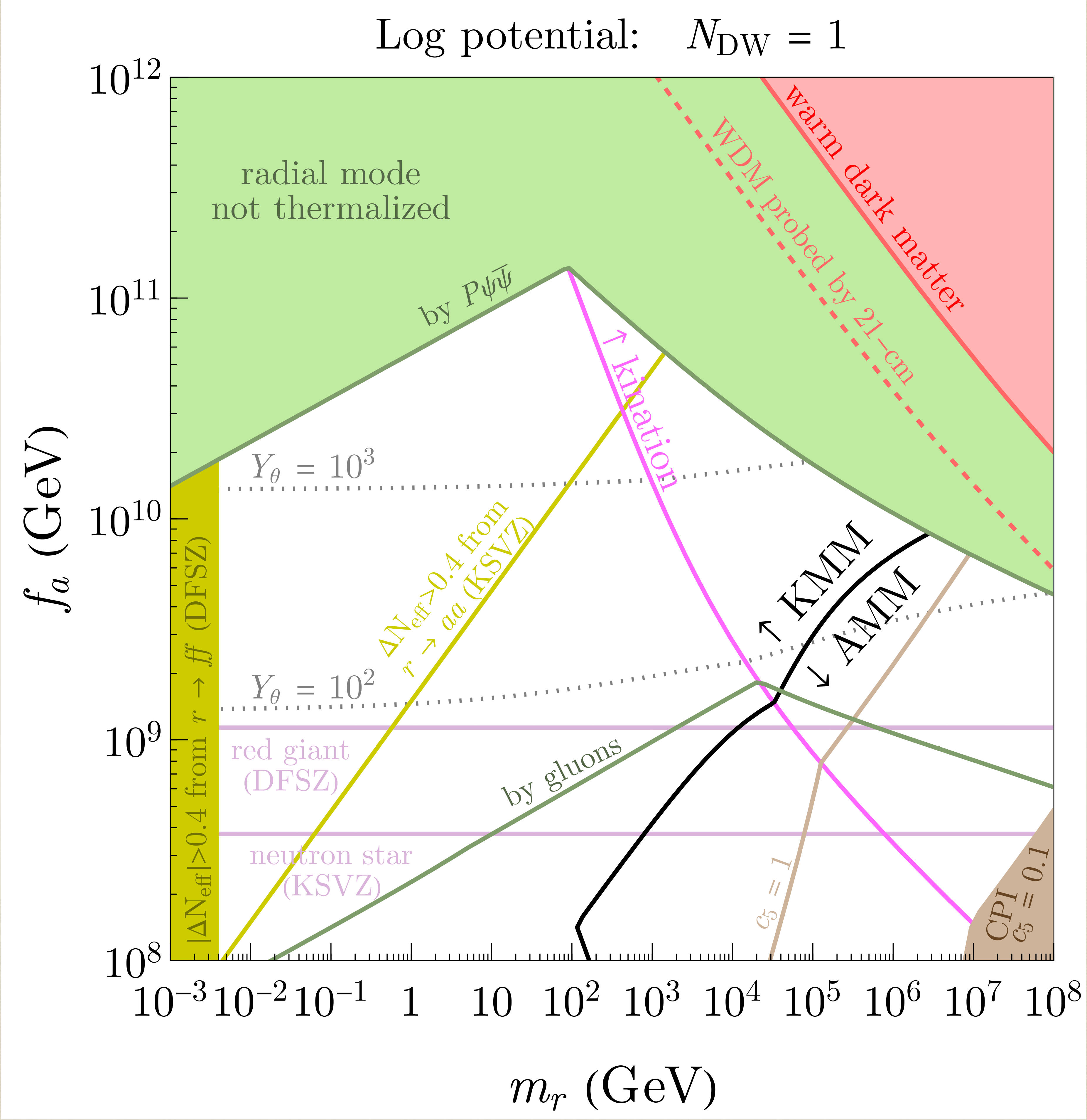

Two–field model: $N_{\rm DW} = 1,\ r_P \gg 1$
Helioscopes
Astrophysics
AMM
Haloscopes
(KMM)
(AMM)
ALP cogenesis
IAXO+
LAMPOST
BREAD
EQC
AMM
KMM
ALPHA
KMM
QCD axion
ADMX
conventional misalignment
$g_{a\gamma\gamma}$ (GeV^{-1})
m_a (eV)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1



Log potential: $N_{DW} = 1$
Helioscopes
Astrophysics
AMM
Haloscopes
(KMM)
(AMM)
ALP cogenesis
IAXO+
LAMPOST
BREAD
AMM
KMM
EQC
ALPHA
KMM
QCD axion
ADMX
conventional misalignment
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
m_a (eV)

Two–field model: $N_{\rm DW} = 1,\ r_P \to 1$

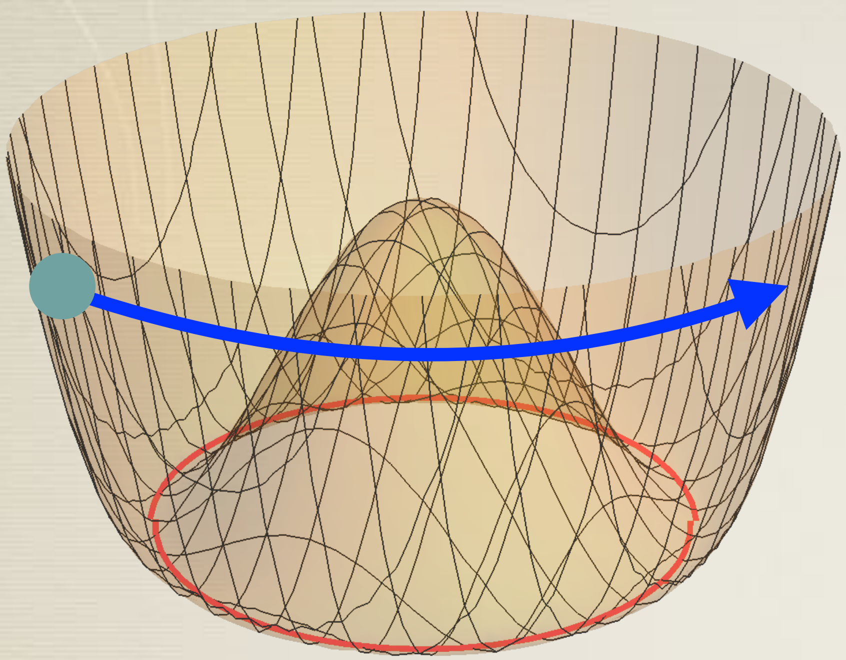




Log potential: $N_{\rm DW}$ = 1
radial mode
not thermalized
by $P\psi\bar{\psi}$
warm dark matter
WDM probed by 21-cm
↑ kination
$\Delta N_{\rm eff}$>0.4 from
$r \to aa$ (KSVZ)
Y_θ = 10^3
Y_θ = 10^2
↑ KMM
↓ AMM
$|\Delta N_{\rm eff}|$>0.4 from $r \to f\bar{f}$ (DFSZ)
red giant
(DFSZ)
by gluons
neutron star
(KSVZ)
c_5 = 1
CPI
c_5 = 0.1
f_a (GeV)
m_r (GeV)
10^{12}
10^{11}
10^{10}
10^9
10^8
10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8

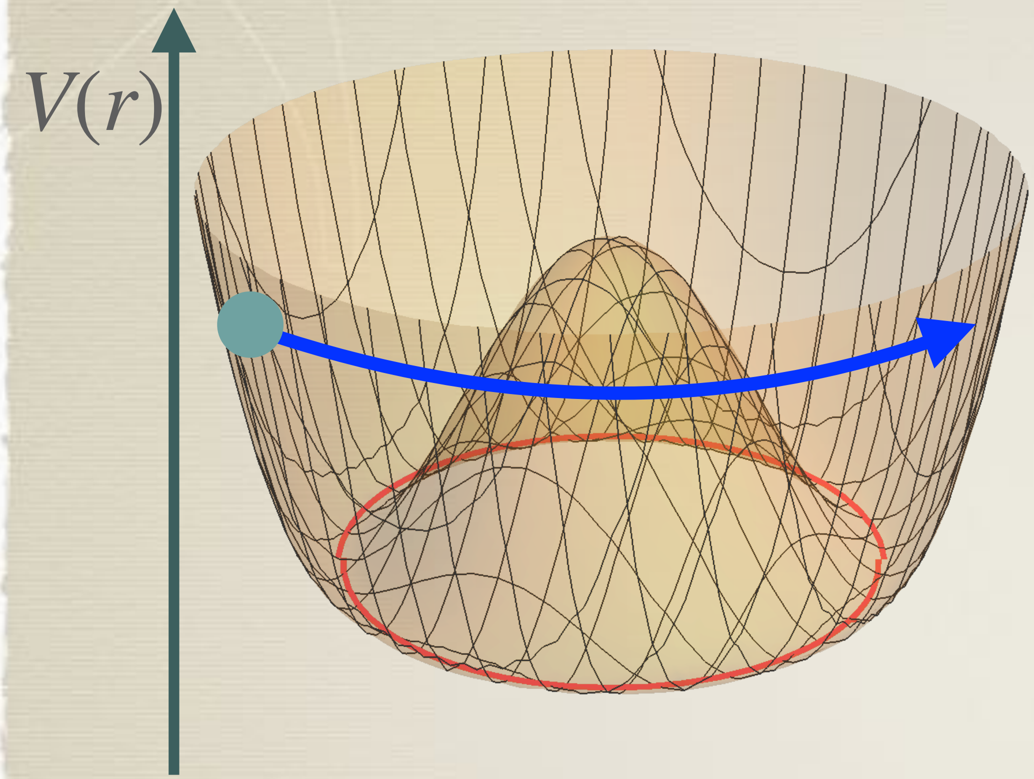
Evolution of energy density

Co and KH (2019)



Classical mechanics

Evolution of energy density



Co and KH (2019)

$$\frac{dV}{dr} = \dot{\theta}^2 r$$

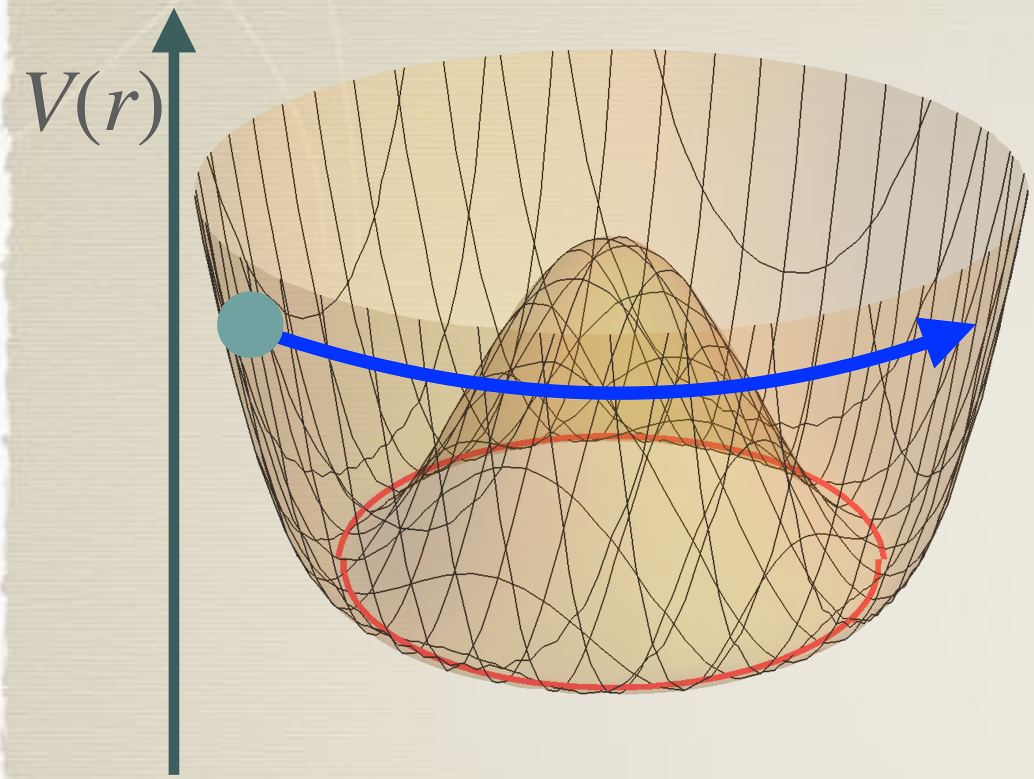
Centripetal force   Centrifugal force

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

Angular momentum conservation
(up to dilution by cosmic expansion)

Evolution of energy density

Co and KH (2019)



$$V(r) \sim \frac{1}{2} m_P^2 r^2$$

(supersymmetric theory)

$$\frac{dV}{dr} = \dot{\theta}^2 r$$

$$m_P^2 r = \dot{\theta}^2 r \rightarrow \dot{\theta} = m_P$$

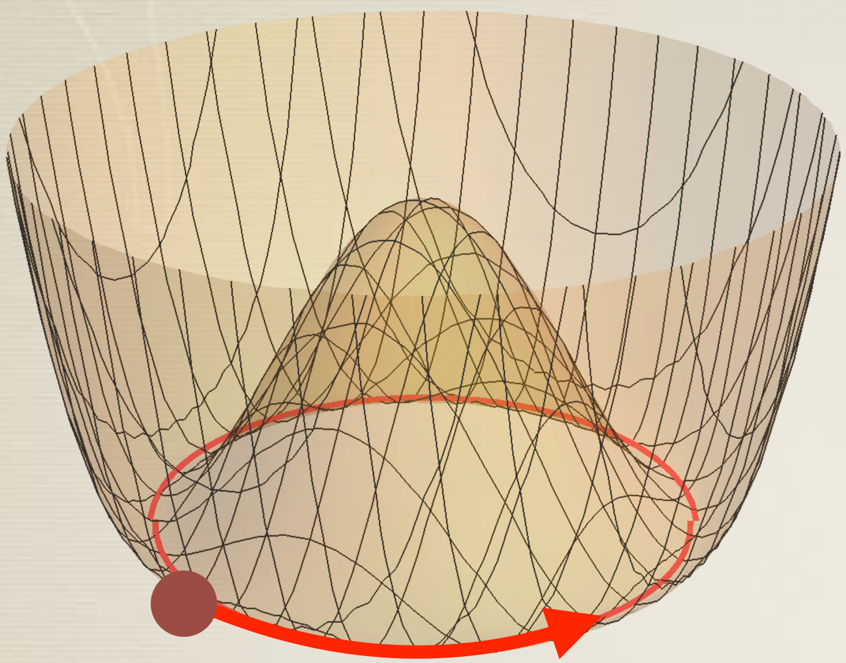
$$\dot{\theta} r^2 \propto R^{-3}$$

$$\rightarrow r^2 \propto R^{-3}$$

$$\rho \sim m_P^2 r^2 + \dot{\theta}^2 r^2 \propto R^{-3}$$ **matter**

Evolution of energy density

Co and KH (2019)



r is nearly fixed

$$\frac{dV}{dr} = \dot{\theta}^2 r$$

$\rightarrow \dot{\theta}$ decreases

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

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

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