Opening-up the parameter space for Axion-Like-Particle Dark Matter

Dark Matter from rotating axions

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DESY/U.Hamburg

"COSMIC WISPers" COST Colloquium,
02-04-2025

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

This talk

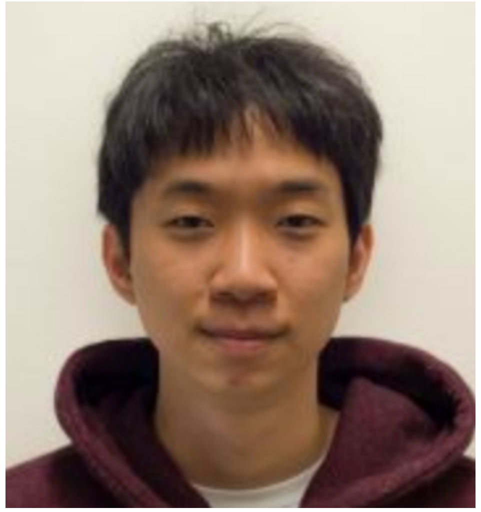
Based on collaborations with:

Cem Eroncel

Yann Gouttenoire

Ryosuke Sato

Philip Sørensen



Peera Simakachorn

Connected to the theme of rotating axions & kinetic misalignment

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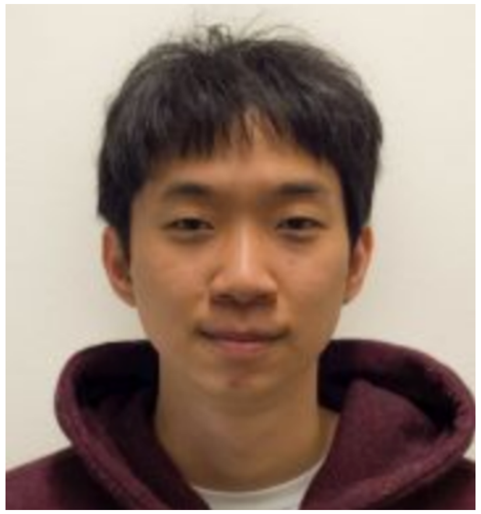

Peera Simakachorn

Rotating axions : Beyond the standard misalignment mechanism

[Eroncel, Soerensen, Sato, Servant, 2206.14259]   Kinetic fragmentation

[Eroncel, Soerensen, Sato, Servant, 2408.08355]   Detailed parameter scan for UV completions

[Eroncel, Gouttenoire, Sato, Servant, Simakachorn, 2503.04880]   Curvature-induced axion DM production

Gravitational signatures (axion mini-clusters)

[Eroncel, Servant 2207.10111]

Impact on primordial gravitational-wave backgrounds

[Gouttenoire, Servant, Simakachorn, 1912.02569, 2108.10328 , 2111.01150]

Universal bound on kination

[Eroncel, Gouttenoire, Sato, Servant, Simakachorn, 2501.17226]

More on axion fragmentation

[Fonseca, Morgante, Sato, Servant, 1911.08472]

[Fonseca, Morgante, Sato, Servant, 1911.08473]

[Chatrchyan, Eroncel, Koschnitzke, Servant, 2305.03756]

Axions & Axion-Like-Particles

Axions could arise either as a higher dimensional gauge field, or as a Pseudo Nambu Goldstone boson (PNGB) from spontaneous breaking of global symmetry which is not exact but broken weakly.

In this talk I assume the second possibility as a simple benchmark. (for a discussion of rotating stringy axions see Krippendorf, Muia, Quevedo 1806.04690)

Important for cosmology: Axion is accompanied by its partner, the radial mode of a complex scalar field.

Axion-Like-Particles (ALPs).

Consider complex scalar field

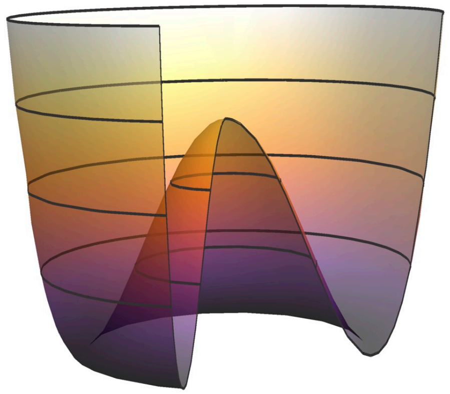
$$\Phi = \phi e^{i\theta}$$

charged under anomalous U(1) global symmmetry (Peccei-Quinn symmetry)

Spontaneously broken at scale f_a

$$V(\varphi) = \lambda \left(|\varphi|^2 - \frac{f_a^2}{2} \right)^2$$

$$\langle \boldsymbol{\varphi} \rangle = f_a / \sqrt{2}$$



Axion as Goldstone boson

$$\theta \rightarrow \theta + \text{const.}$$

$$\boxed{\theta = a / f_a}$$

ALPs.

Non-perturbative effects at energy $\Lambda_b \ll f_a$ break the shift symmetry and generate a potential/mass for the axion

$$V = m_a^2(T) f_a^2 \left[1 - \cos(\theta)\right]$$

$$m_a = \Lambda_b^2 / f_a$$

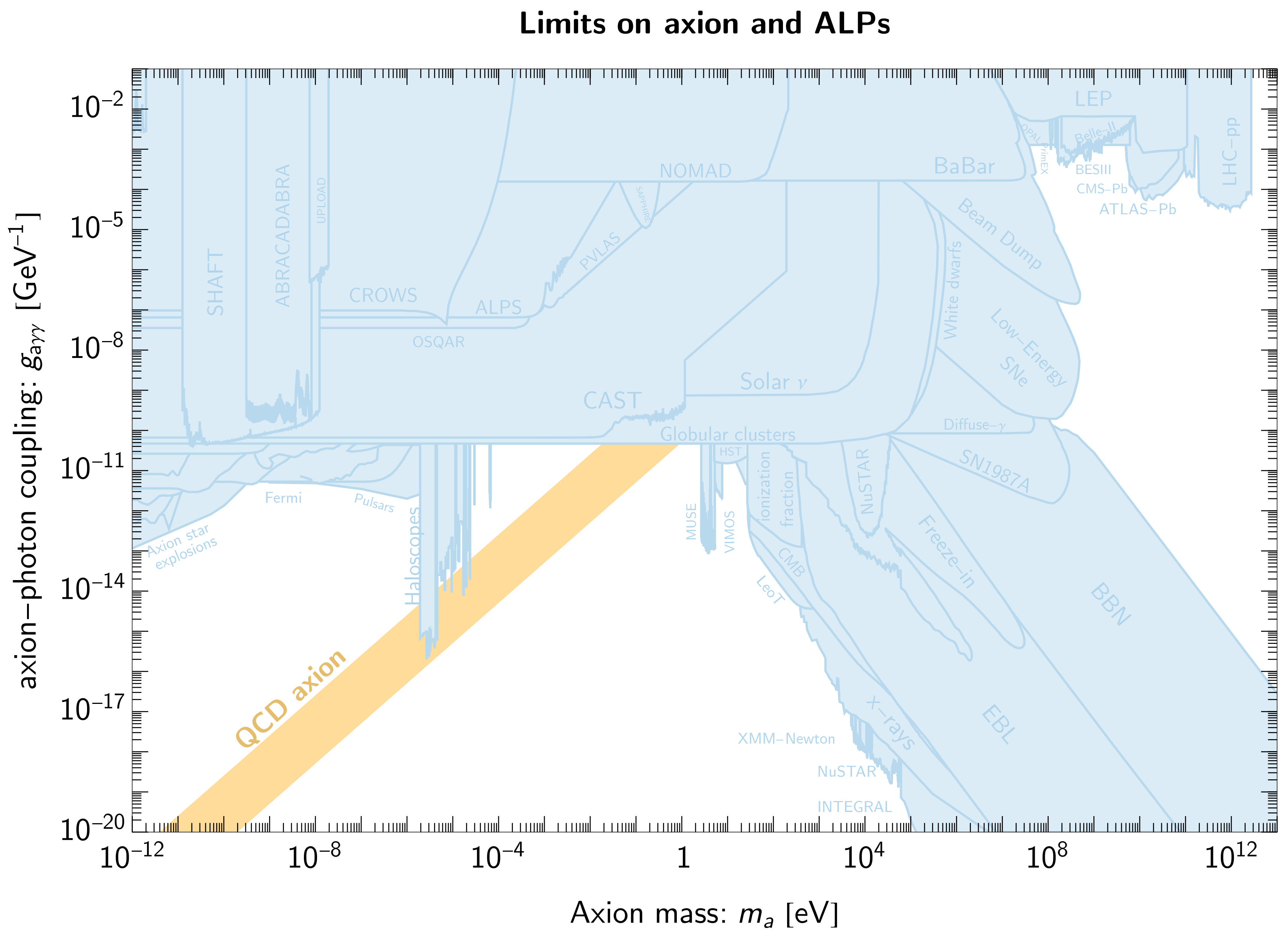
QCD axion

$$m_a^2 f_a^2 \approx (76\ \mathrm{MeV})^4$$

Generic ALP

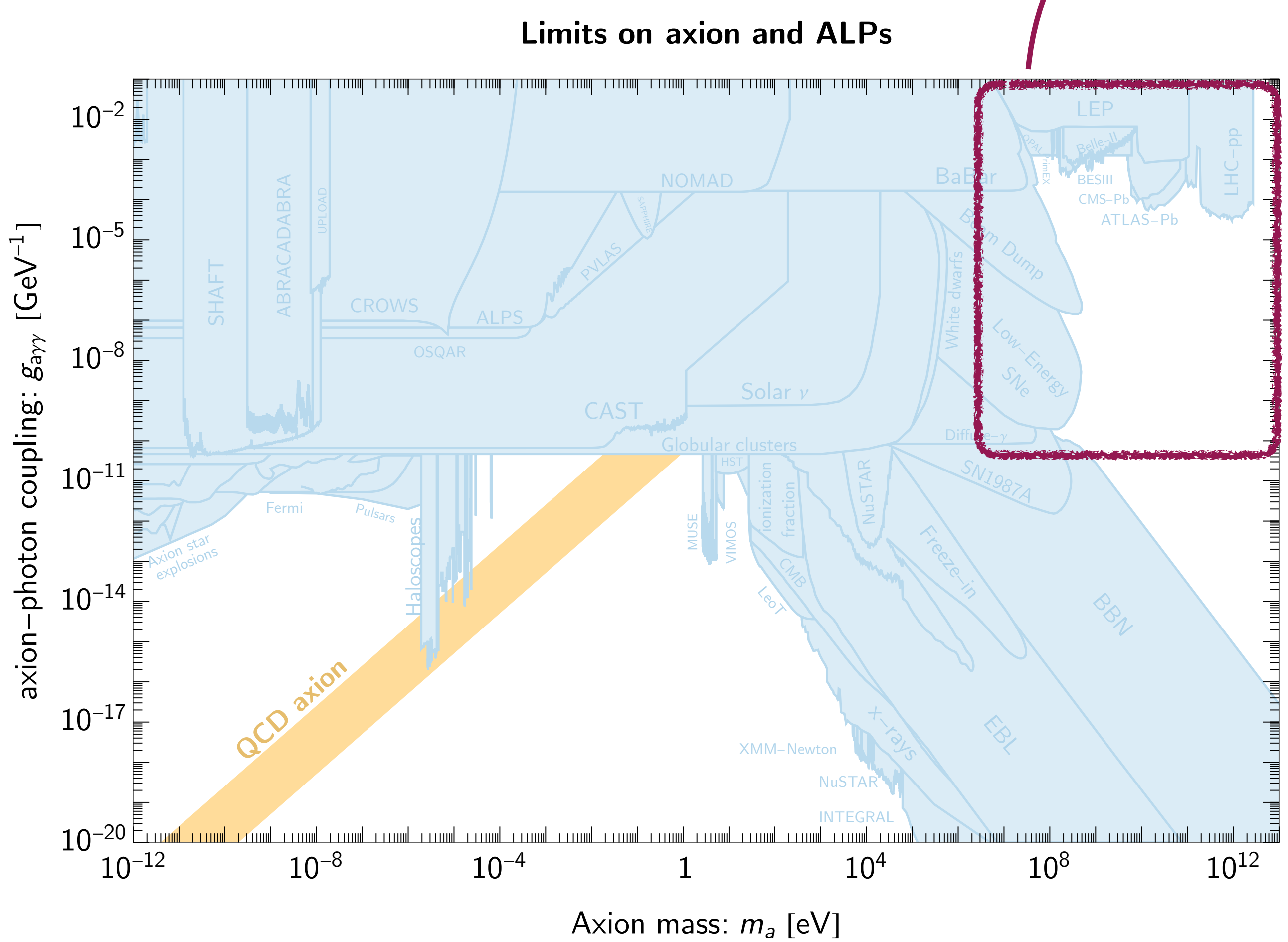
m_a and f_a : free parameters

An international race.



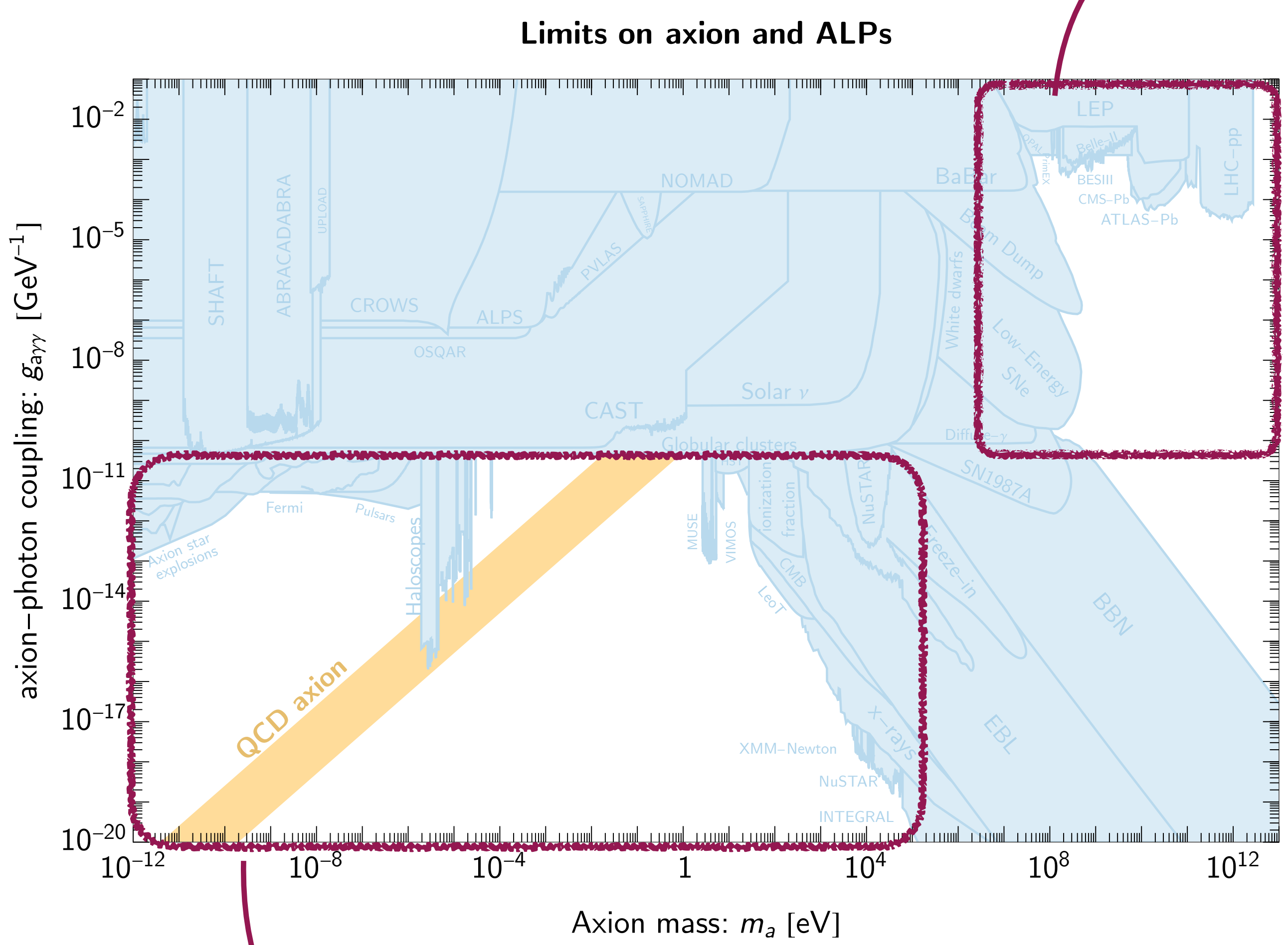
Which of these axions can make Dark Matter ?

An international race.



Searches for cosmologically unstable axion-like-particles at colliders

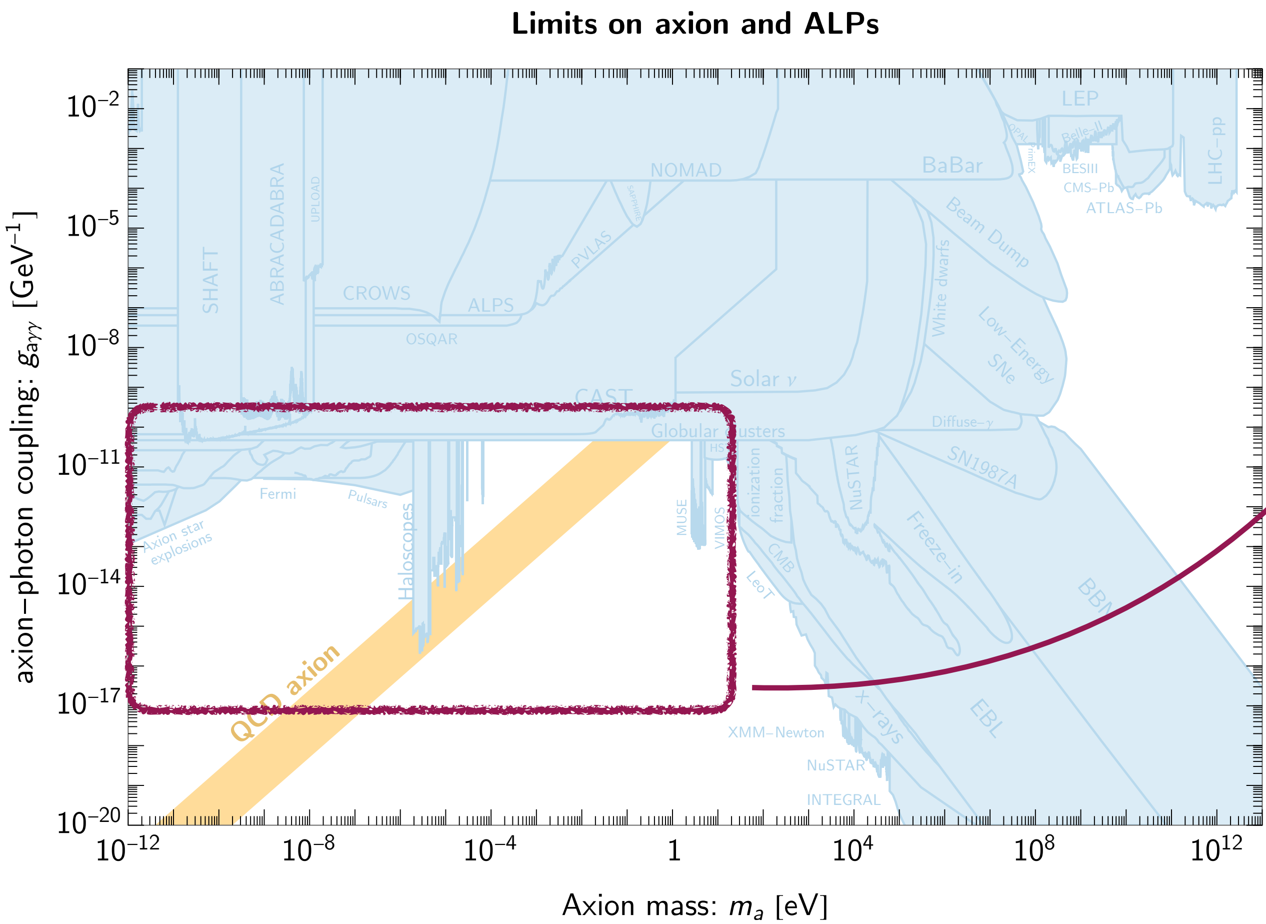
An international race.

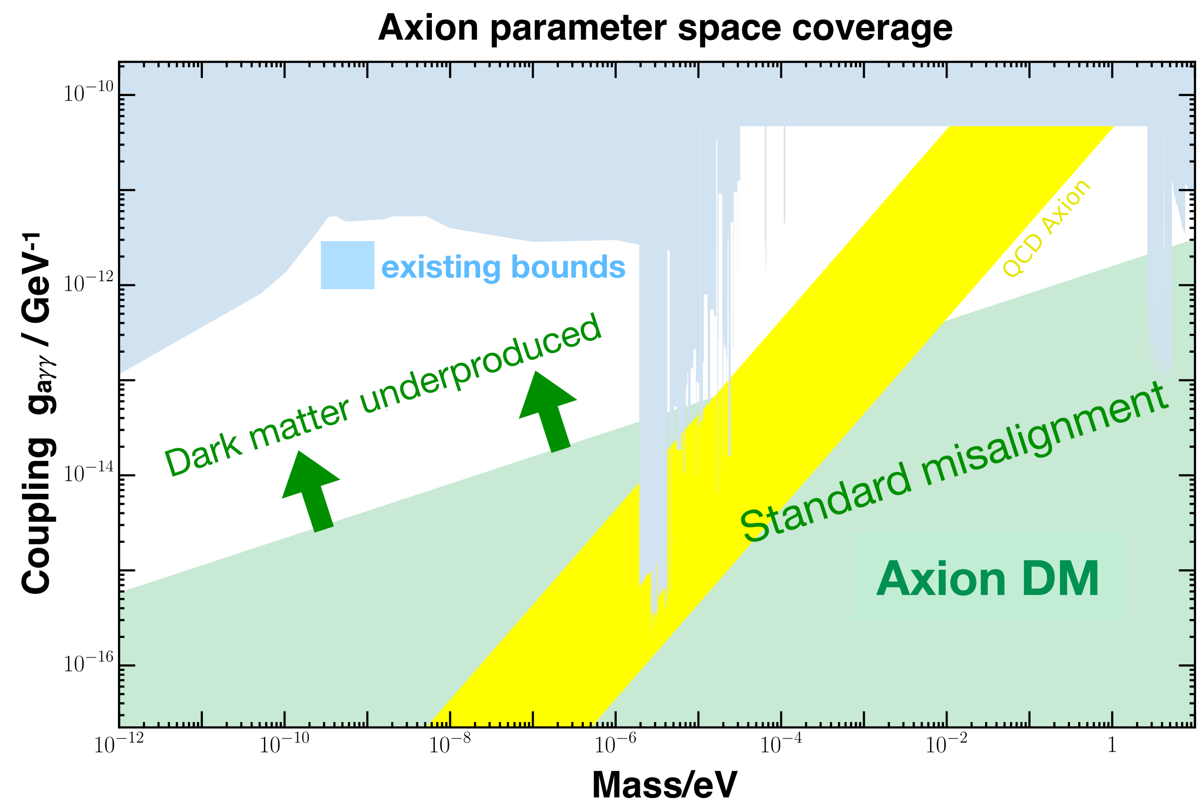


Searches for cosmologically unstable axion-like-particles at colliders

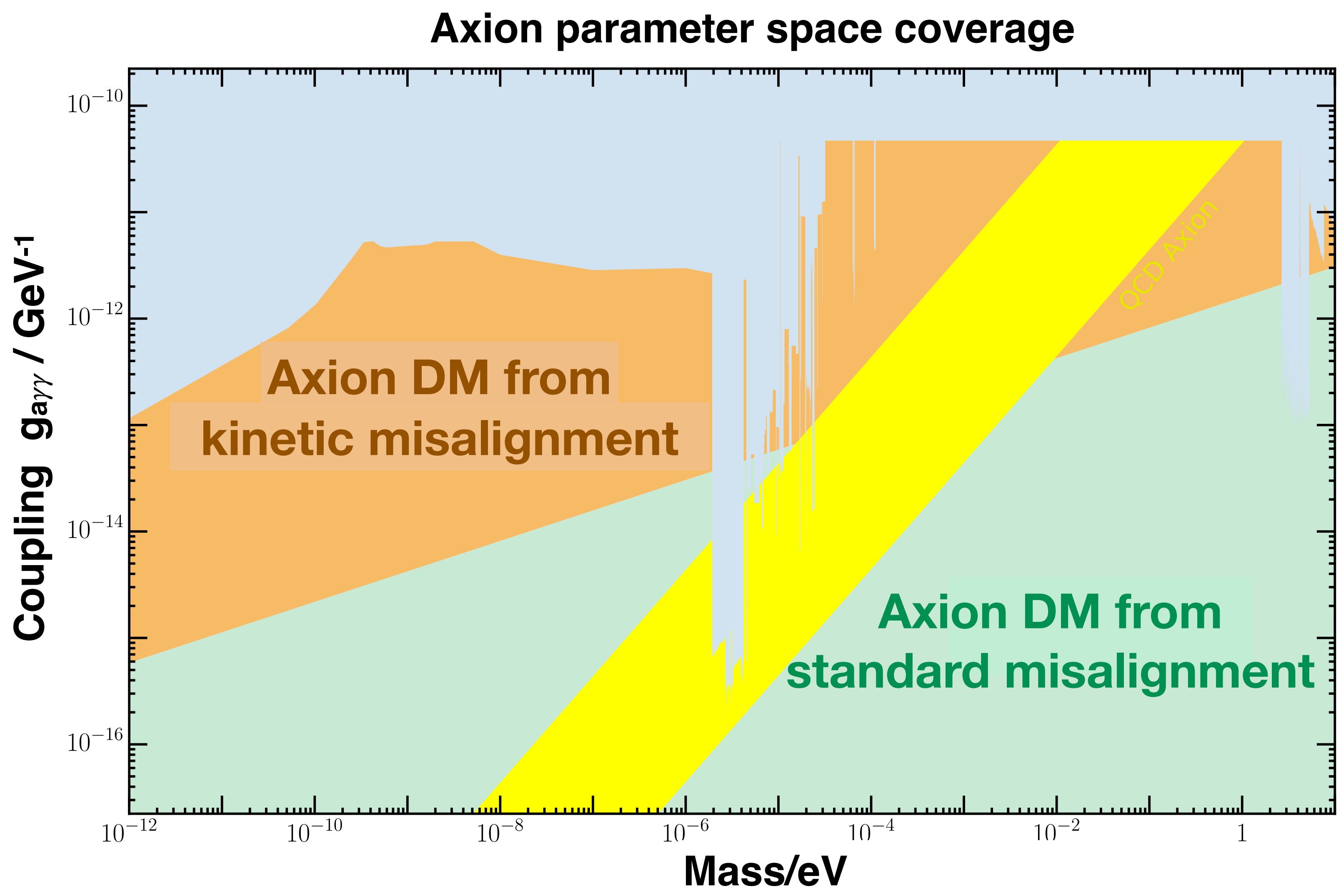
cosmologically stable axions: dark matter?

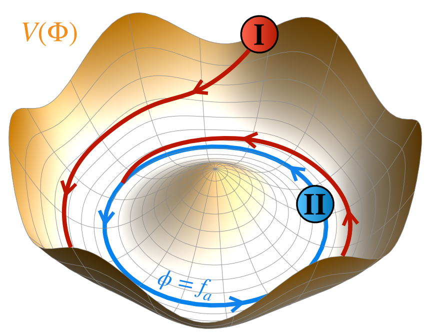
Conventional misalignment makes too little dark matter.





Opening up the parameter space with kinetic misalignment.

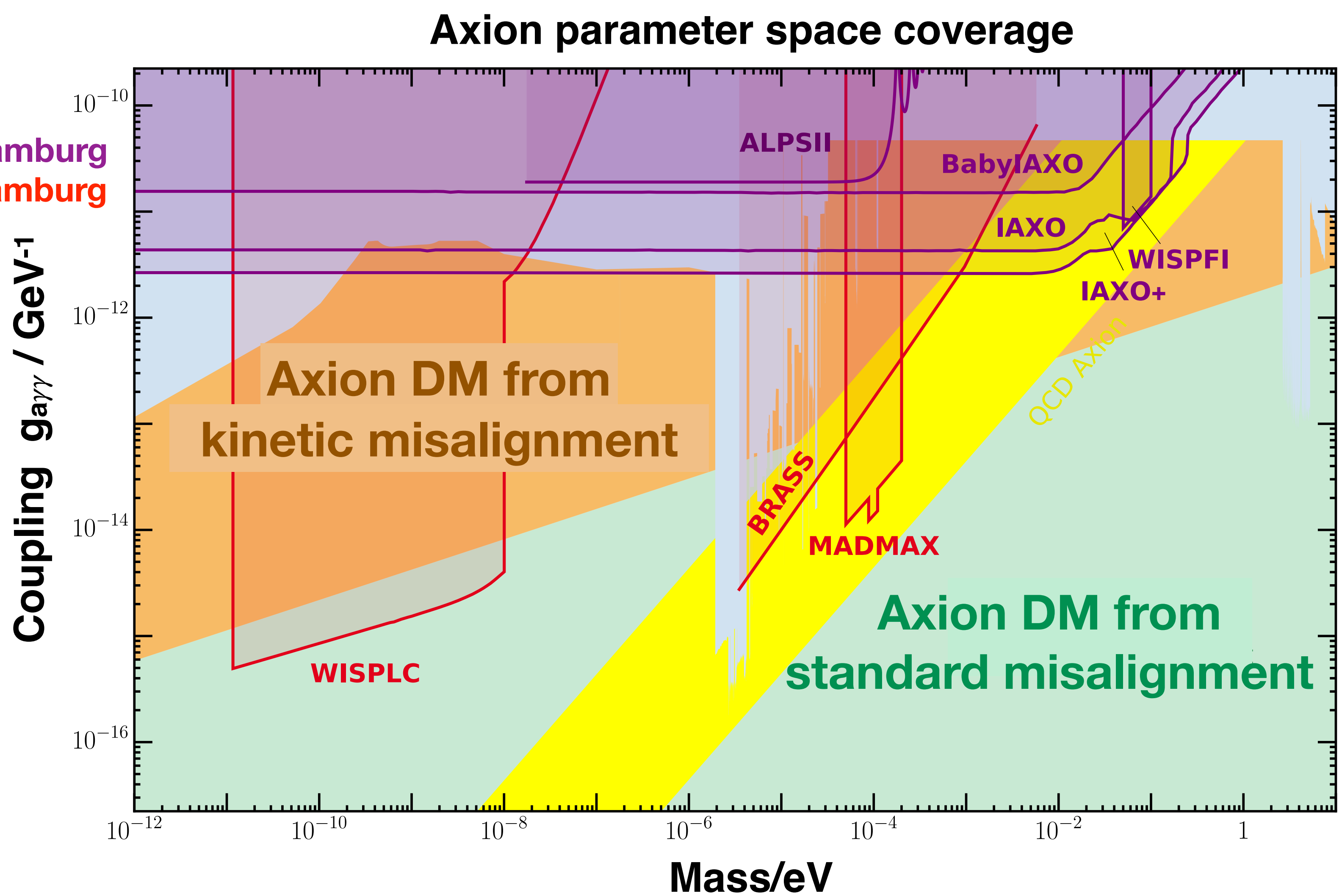


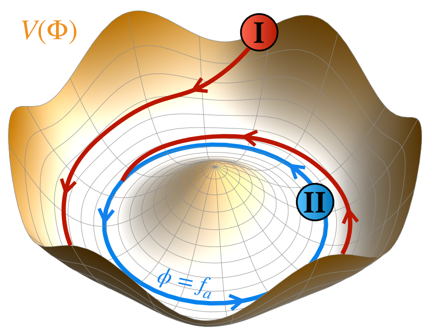


[2206.14259, 2408.08355]

Opening up the parameter space with kinetic misalignment.

—any axion searches in Hamburg
—axion DM searches in Hamburg





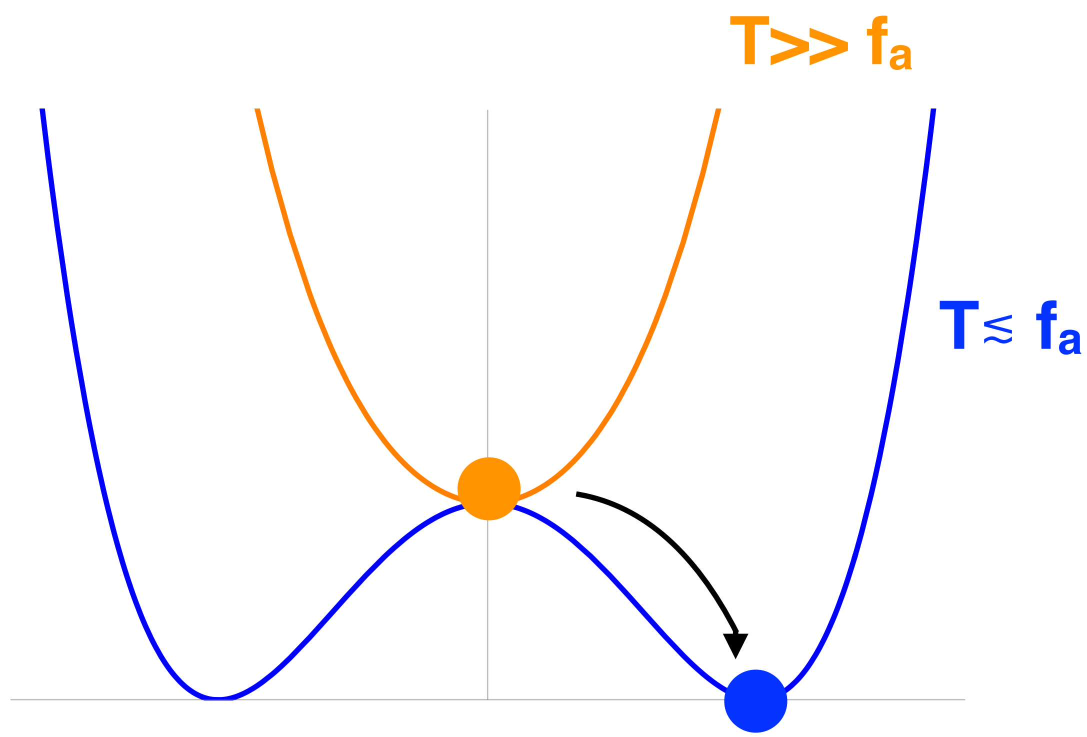
[2206.14259, 2408.08355]

Peccei-Quinn field cosmology.

"Common" story:

Starts at $\langle \phi \rangle = 0$

Studies axion cosmology ignoring the radial mode

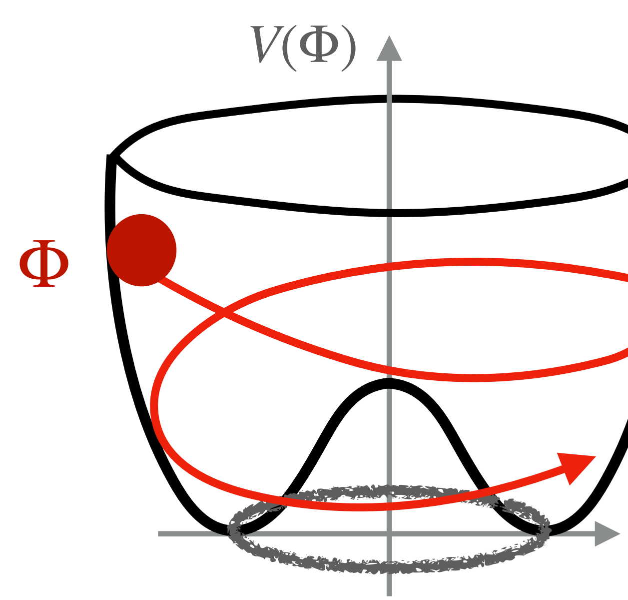


Alternative:

Starts at $\langle \phi \rangle \gg f_a$

(field can be driven naturally to these large field values during inflation due to a negative Hubble-induced mass term)

Radial mode /axion interplay



How did the axion acquire a kick?

If PQ symmetry is broken explicitly at high energies
—> mexican hat potential is tilted

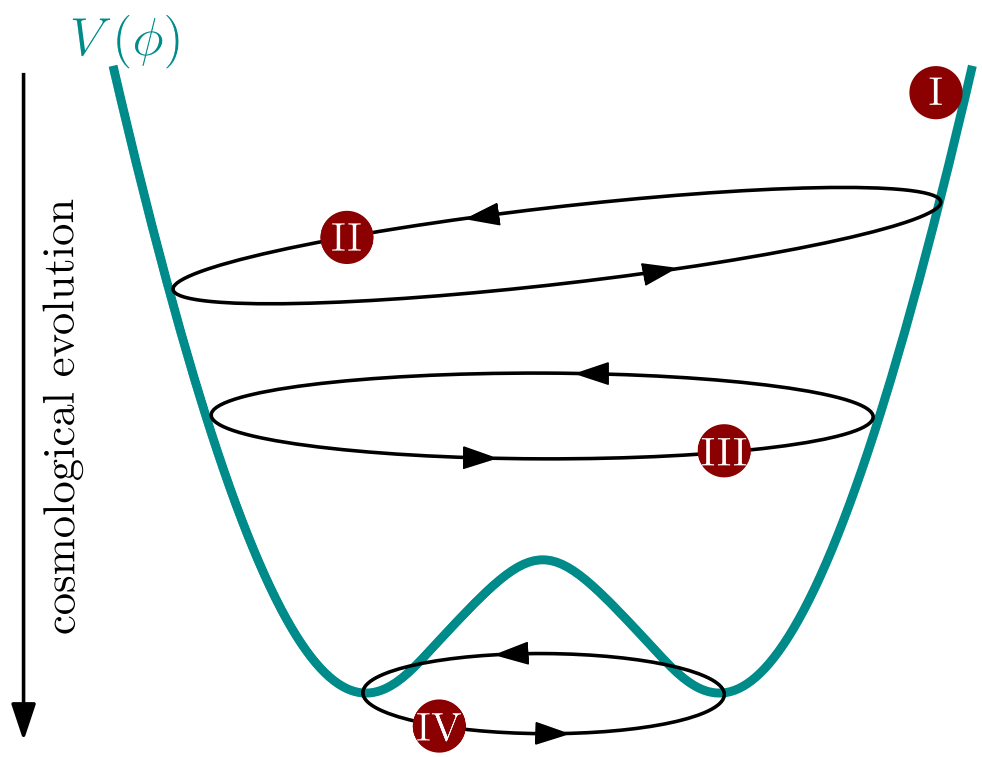


Figure by P. Simakachorn

If radial mode of PQ field starts at large VEV, the angular mode gets a large kick in the early universe

With initial conditions: $\frac{1}{2}\dot{\Theta}_i^2 \gg 2m^2(T_i)$

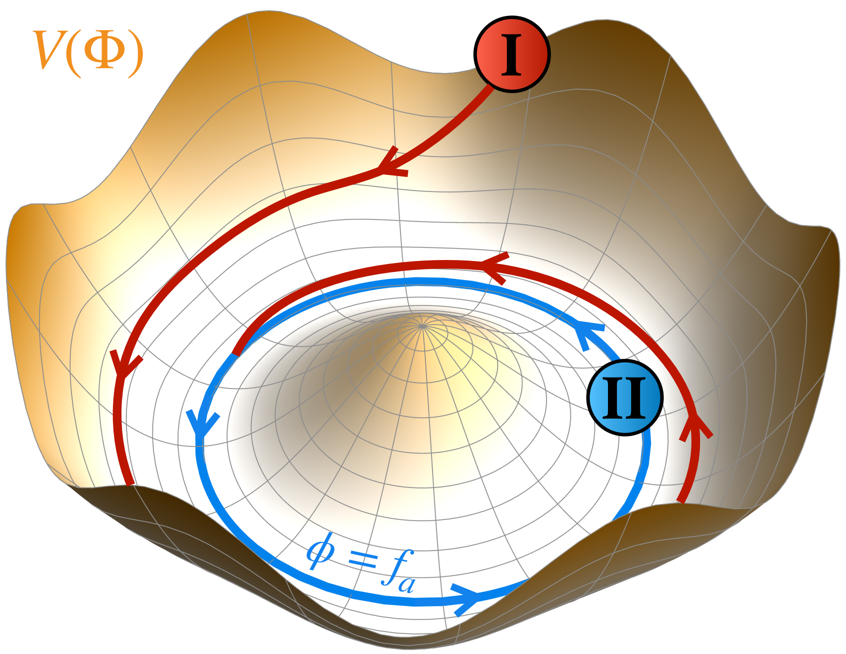
Delayed axion oscillations !

-> kinetic misalignment mechanism

[Co, Harigaya, Hall'19] 1910.14152

2004.00629

Initial conditions.



Similar to Affleck-Dine '85 scenario

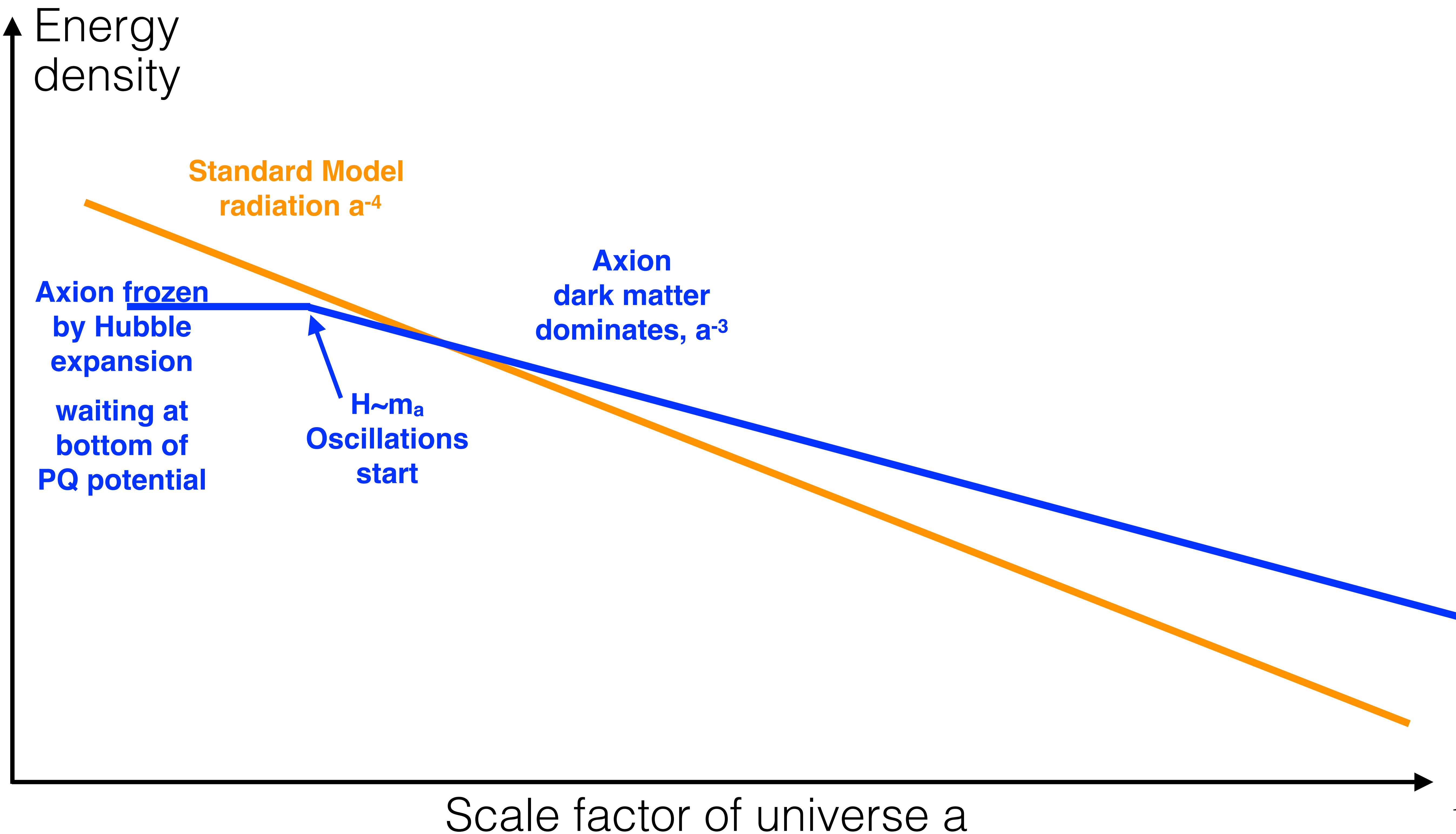
At early times, ϕ is driven away from ϕ =0,
towards $\langle\phi\rangle$ >> f_a
by negative Hubble-induced mass term H >> m_ϕ

$$V_H(\Phi, H) \supset -cH^2|\Phi|^2$$

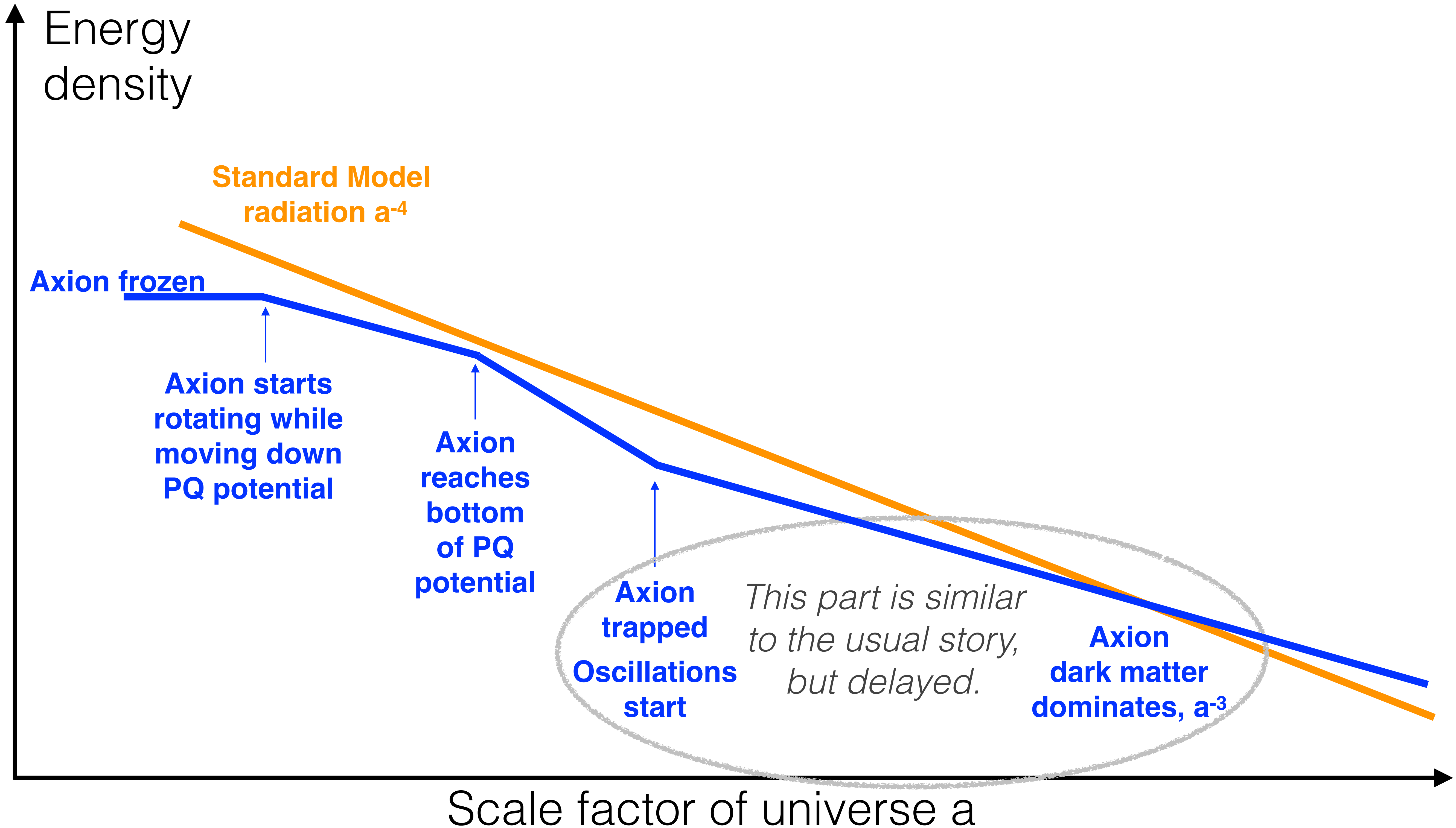
Dine, Randall, Thomas '95

+ explicit U(1) breaking term transfers radial mode motion into kick for the axion

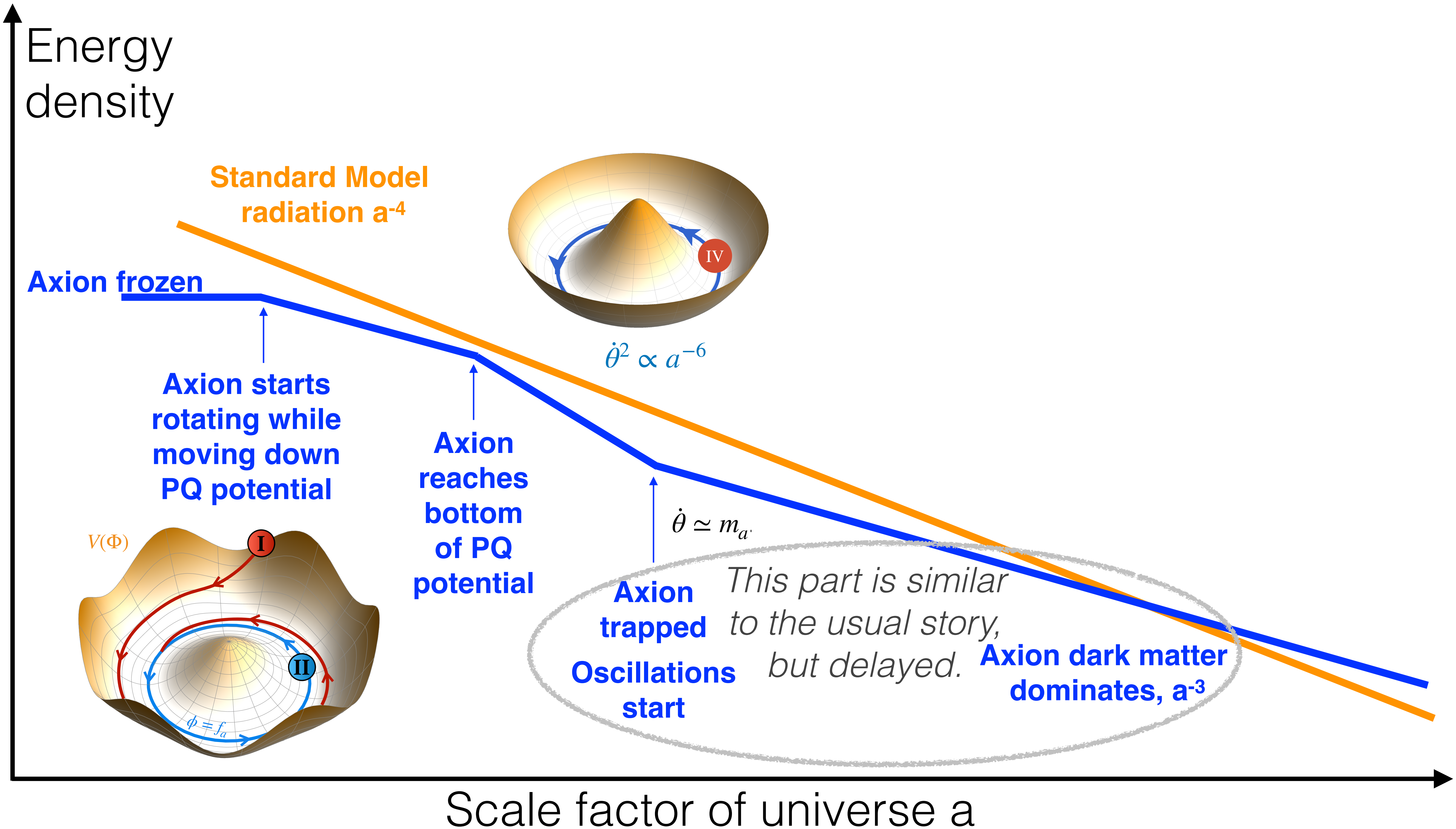
Usual story.


Energy density
Standard Model radiation a^{-4}
Axion dark matter dominates, a^{-3}
Axion frozen by Hubble expansion
waiting at bottom of PQ potential
$H \sim m_a$
Oscillations start
Scale factor of universe a

New story.


Energy density
Standard Model radiation a^{-4}
Axion frozen
Axion starts rotating while moving down PQ potential
Axion reaches bottom of PQ potential
Axion trapped
Oscillations start
This part is similar to the usual story, but delayed.
Axion dark matter dominates, a^{-3}
Scale factor of universe a

New story.

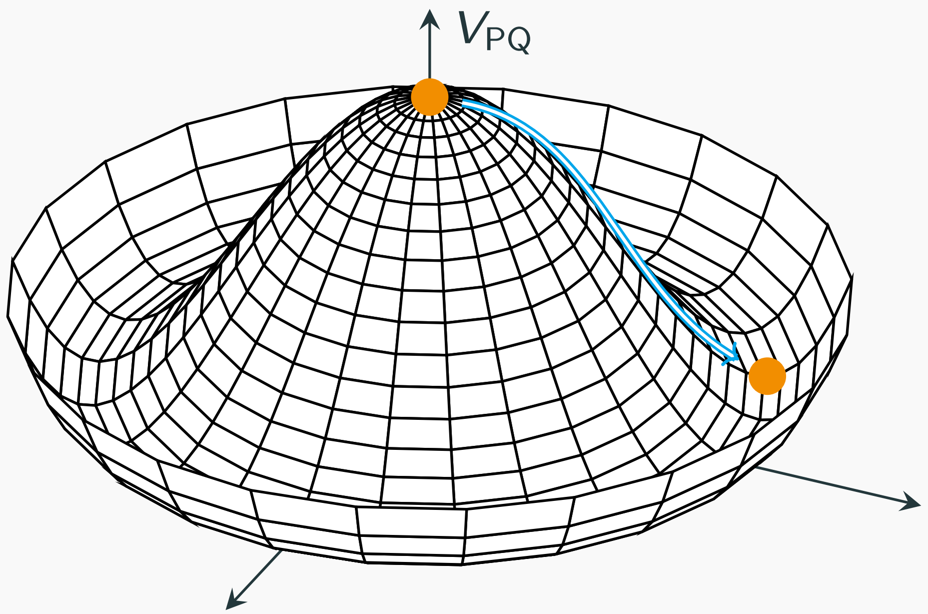


Energy density
Standard Model radiation a-4
Axion frozen
Axion starts rotating while moving down PQ potential
Axion reaches bottom of PQ potential
$\dot{\theta}^2 \propto a^{-6}$
IV
$V(\Phi)$
I
II
$\phi = f_a$
$\dot{\theta} \simeq m_a$
Axion trapped
Oscillations start
This part is similar to the usual story, but delayed.
Axion dark matter dominates, a-3
Scale factor of universe a

This was the main pitch.
Let me now go in more details.

Pre- and post-inflationary scenarios.

Potential of full complex PQ scalar field



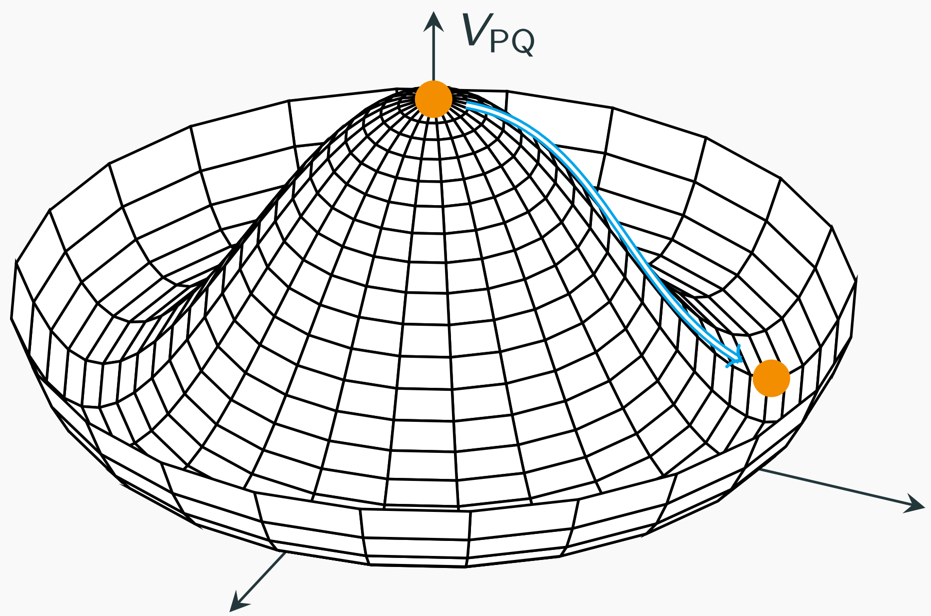
Post-inflationary scenario

- Different initial angle in each Hubble patch.
- Inhomogeneous including topological defects.

Pre-inflationary scenario

- Random initial angle in the observable universe.
- Initially homogeneous w/o topological defects.

Pre- and post-inflationary scenarios.



Post-inflationary scenario

- Different initial angle in each Hubble patch.
- Inhomogeneous including topological defects.

GLOBAL (axionic) COSMIC STRINGS

primordial GW bgd

Pre-inflationary scenario

- Random initial angle in the observable universe.
- Initially homogeneous w/o topological defects.

This talk

although with a different initial position for the field

Axions from the misalignment mechanism.

Axion late cosmology

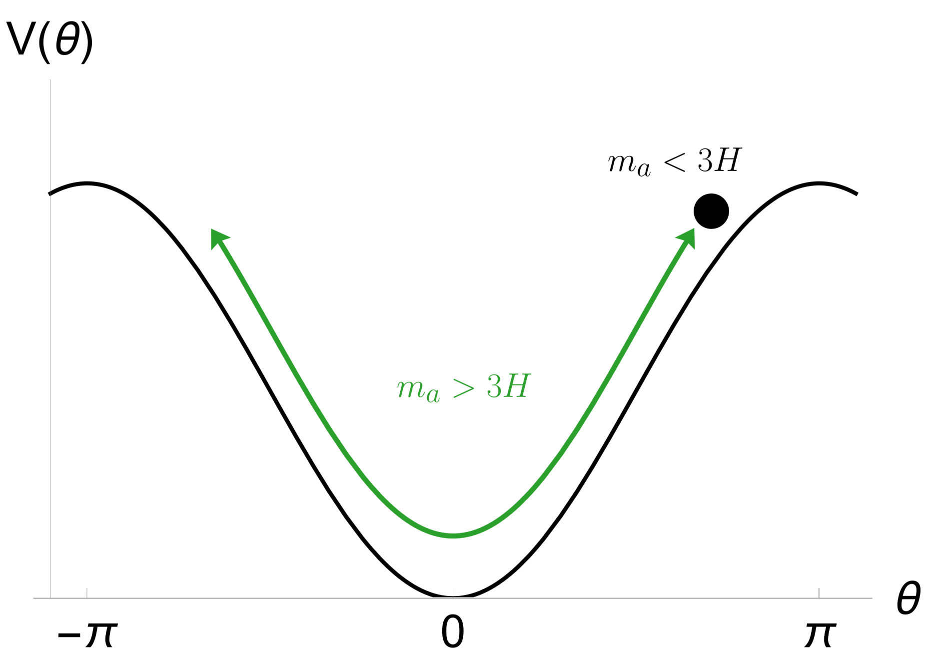
a

Neglecting fluctuations, the homogeneous zero-mode satisfies

$$\ddot{\Theta} + 3H\dot{\Theta} + m_{\rm a}^2(T)\sin(\Theta) = 0,$$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

With initial conditions: $\Theta(t_i) = \Theta_i, \quad \dot{\Theta}(t_i) = 0.$ ***standard assumption***



> $m_a \ll 3H \iff \rho_a \propto a^0$ (Frozen)

> $m_a \gg 3H \iff \rho_a \propto a^{-3}$ (Oscillating)

—> standard misalignment mechanism

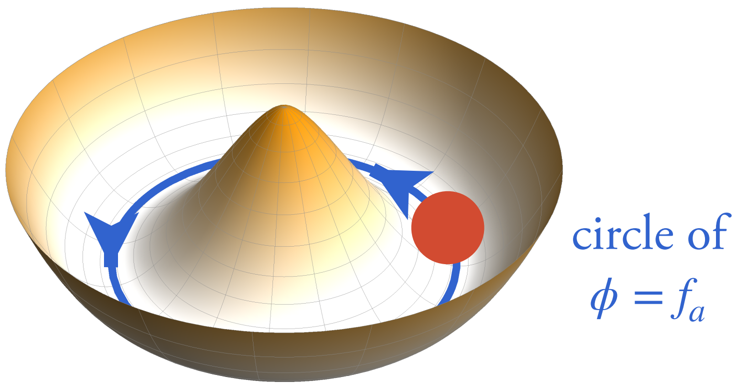
For $\Theta_i \sim 1 \qquad \rho_{\rm DM} \sim \rho_{osc}\left(\frac{a_{osc}}{a_0}\right)^3 \sim m_a^2 f_a^2 \left(\frac{T_0}{T_{osc}}\right)^3$

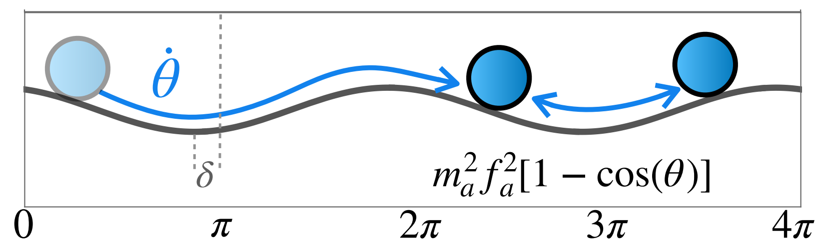
$$T_{osc} \sim \sqrt{m_a M_{Pl}}$$

$\rho_{\rm DM}$ grows with f_a —> Axion Dark Matter overabundance for too large f_a

Kinetic misalignment.

Add kinetic energy to delay onset of oscillations





> Delay oscillations
$\Rightarrow$ less redshift
$\Rightarrow$ more DM
$\Rightarrow$ lower f_a

-> ALP can be DM for low f_a

Co, Hall, Harigaya et al '19'20
Chang, Cui'19
Eröncel et al, '22

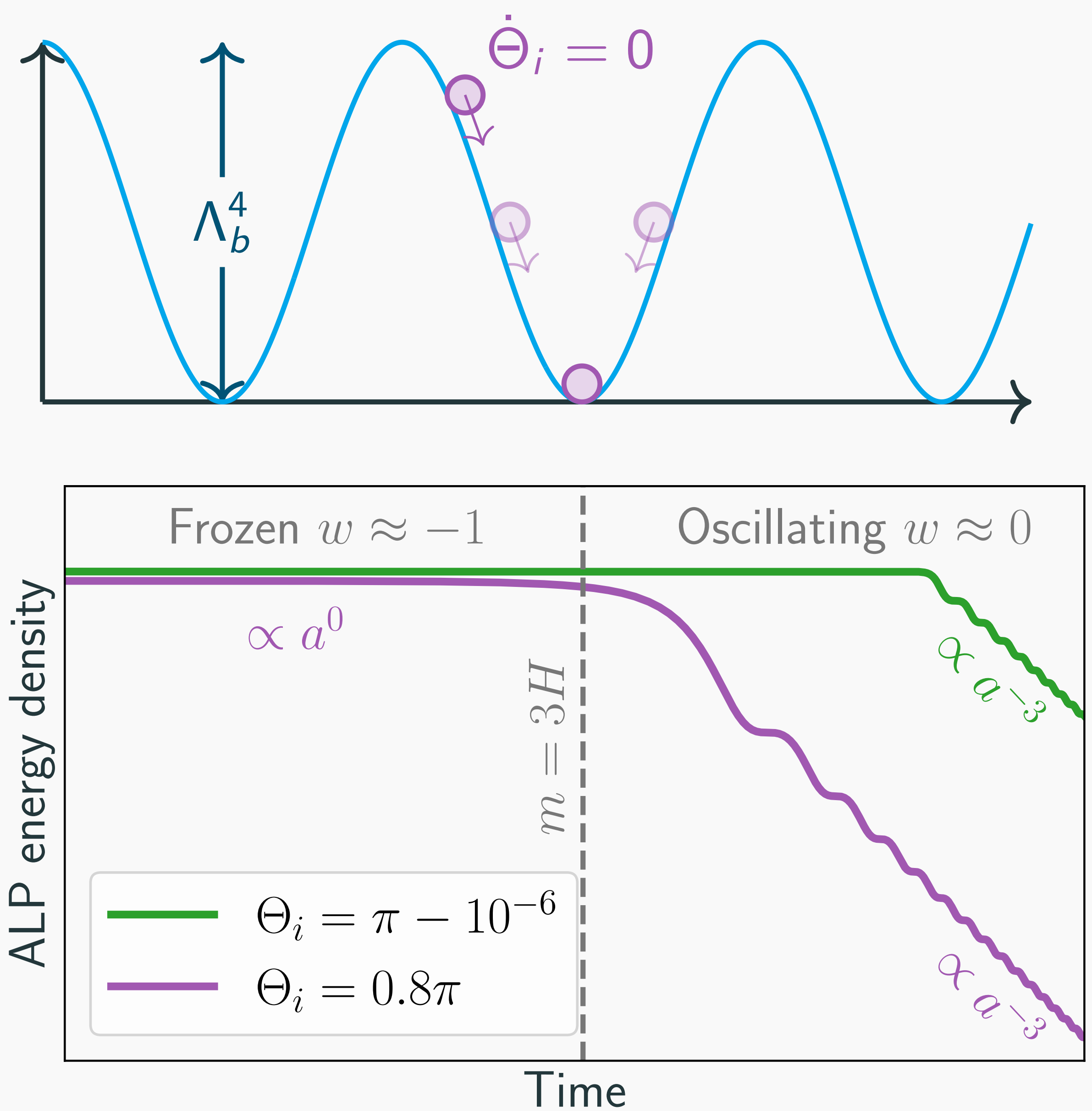
Standard versus kinetic Misalignment.

Two ways to delay the onset of oscillations

Initial field value tuned to top of potential:

Standard (Large) misalignment

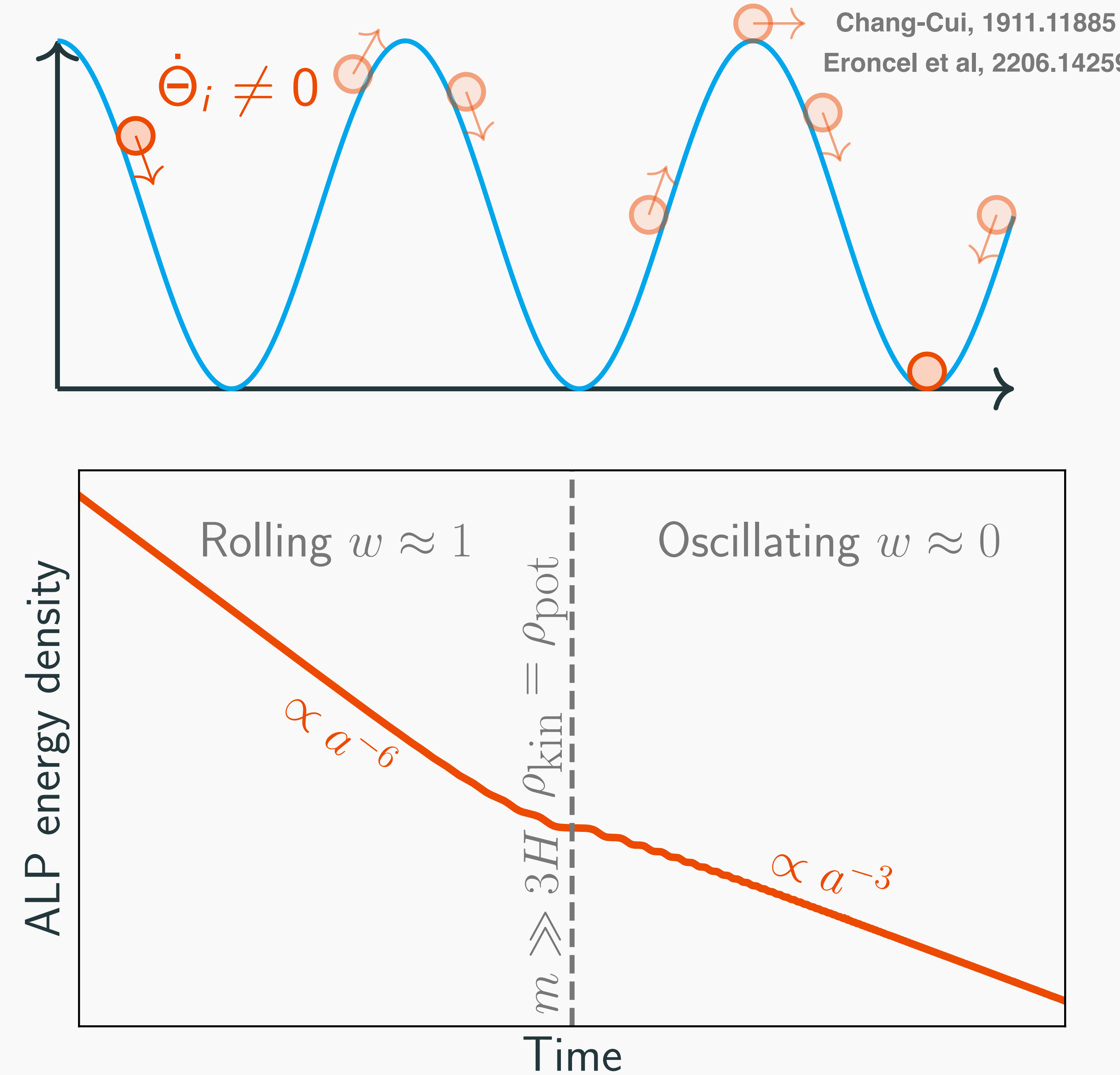
Zhang,Chiueh 1705.01439; Arvanitaki et al. 1909.11665



Large initial velocity

Kinetic misalignment

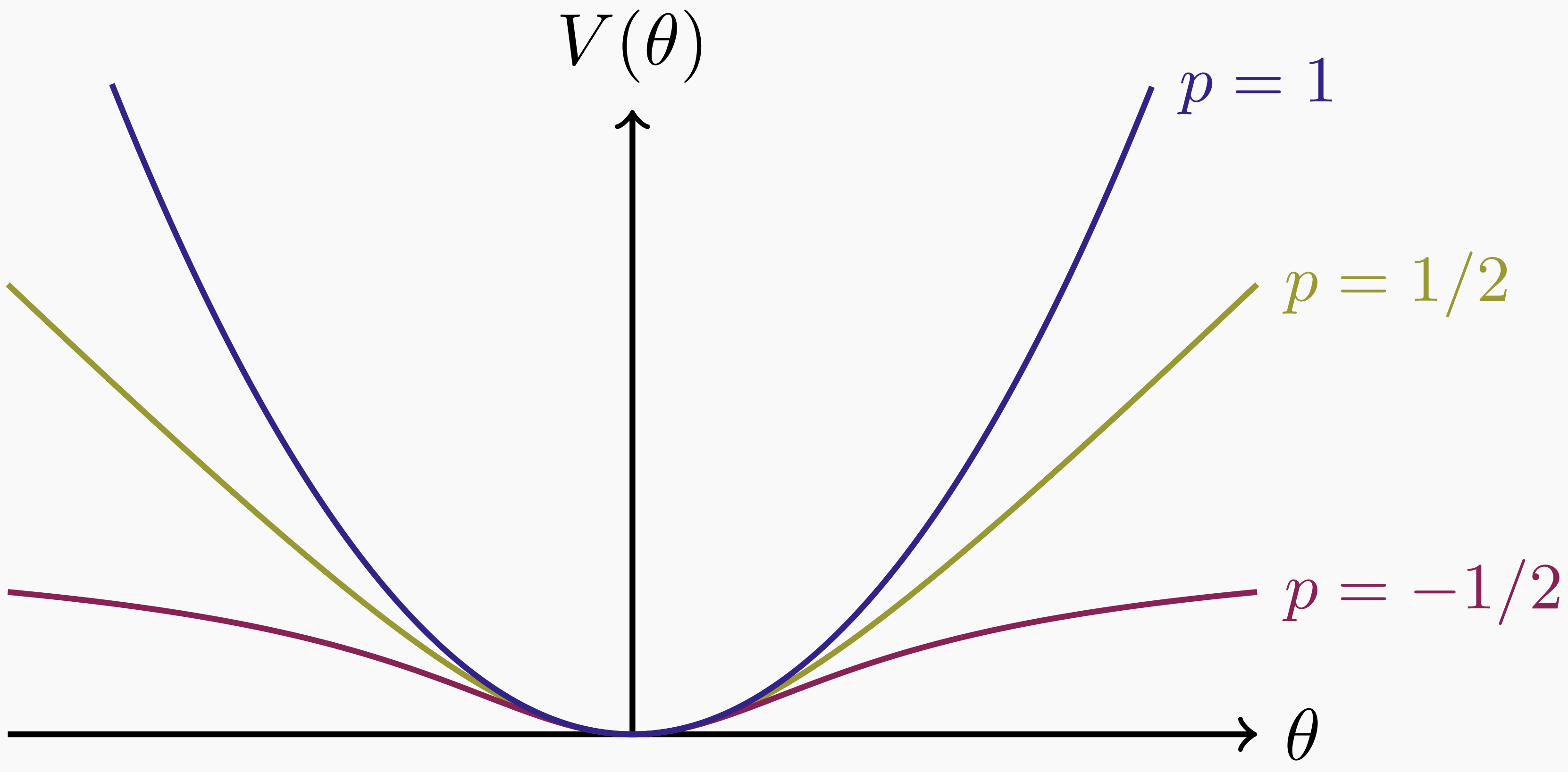
Co et al. 1910.14152
Chang-Cui, 1911.11885
Eroncel et al, 2206.14259



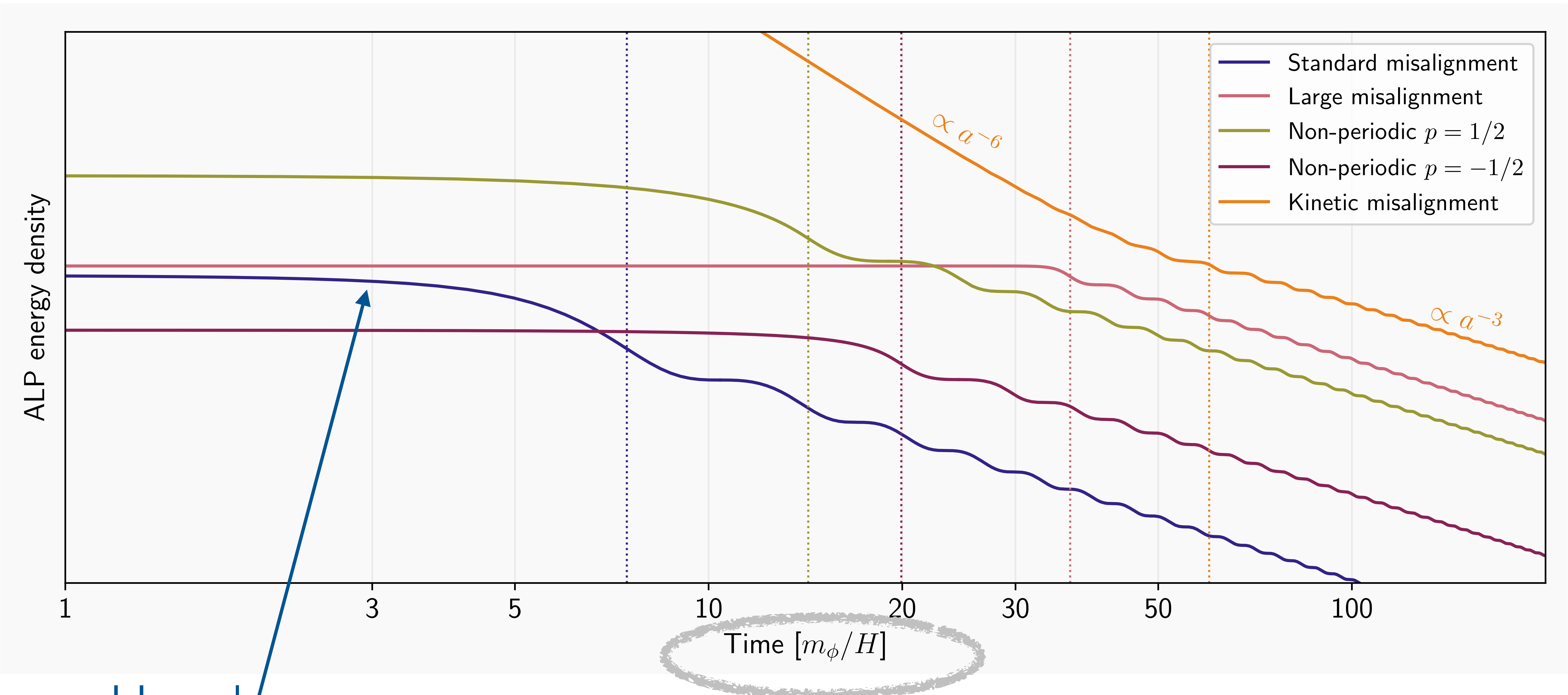
A third way to delay the onset of oscillations: a non-periodic potential.

1906.06352, 2305.03756

$$V(\theta) = \frac{m_\phi^2 f_\phi^2}{2p}\left[\left(1+\theta^2\right)^p - 1\right], \quad p < 1.$$



Common property of all these cases: onset of oscillations is delayed which boosts the dark matter abundance, and extends the ALP dark matter parameter space to lower decay constants.



Usual story

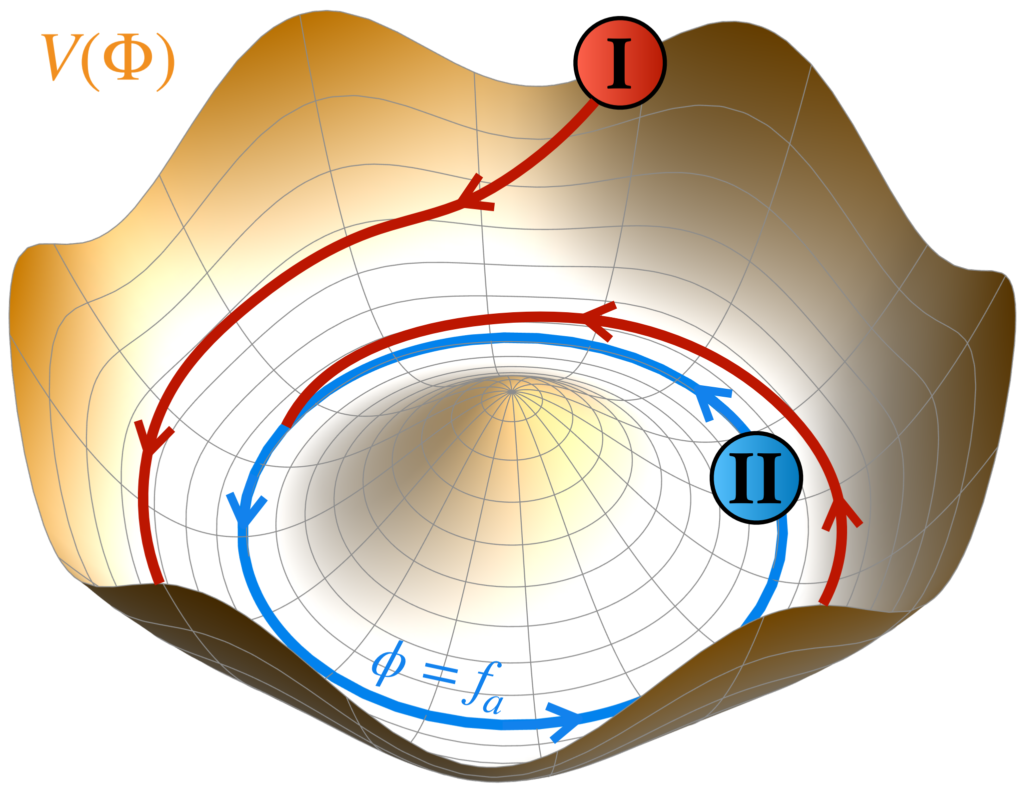
Model implementations of a rotating axion .

Complex scalar field

“Affleck-Dine Baryogenesis” (Affleck, Dine, 1985)

“Axiogenesis” (Co, Hall, Harigaya, et. al., ’19)

“Kination cosmology” (Gouttenoire et al, ’21)



$\Phi \sim \phi e^{i\theta}$ with $U(1)$-symmetry

Radial mode ϕ oscillates in potential with mass $\sqrt{V''(\Phi)}$.

Angular mode θ “axion” spins, with large kinetic energy.

Requirements

1. $U(1)$-symmetric (quadratic) potential with spontaneous symmetry-breaking minimum

2. Large initial scalar VEV

3. Explicit $U(1)$-breaking term (wiggle for angular velocity)

4. Damping of radial motion

Ingredients 1 & 2 : scalar potential

$$V(\Phi) = m_r^2|\Phi|^2\left[\log\left(\frac{|\Phi|^2}{f_a^2}\right) - 1\right] + \left[A\frac{\Phi^n}{M_{Pl}^{n-3}}. + h.c\right] + \frac{|\Phi|^{2n-2}}{M_{Pl}^{2n-6}}$$

I. $U(1)$-conserving potential (quadratic) with a minimum f_a

(motivated by supersymmetric setups)

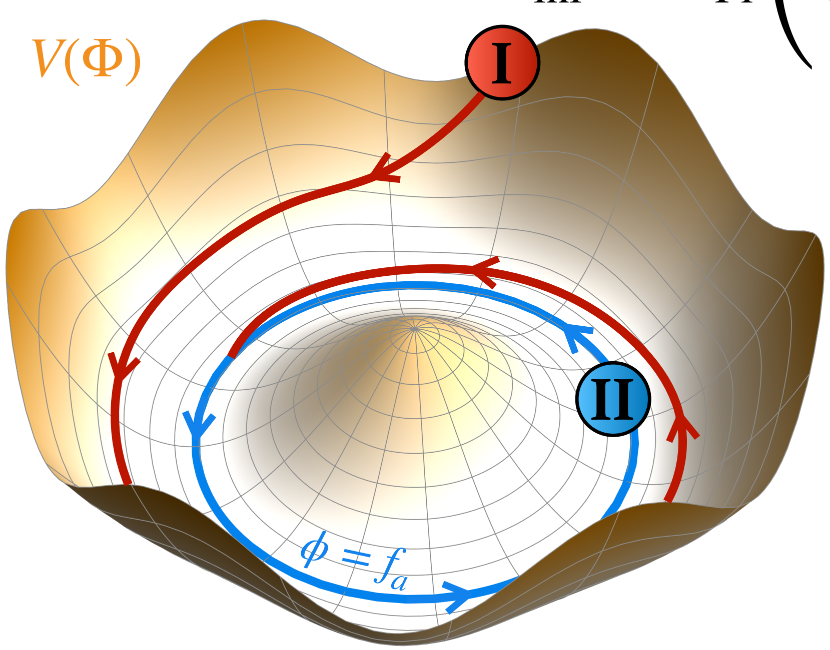
$\propto \cos(l\theta)$

II. explicit breaking term (e.g. $U(1)$ is not exact at high scales.)

stabilization

i.e., at large $|\Phi|$

$$\phi_{\rm ini} \simeq M_{\rm Pl}\left(\sqrt{\frac{c}{\lambda^2}}\cdot\frac{m_r}{M_{\rm Pl}}\right)^{1/(n-2)}$$



Ingredient 3 : large initial VEV $\phi_{\rm ini}$

By adding a negative Hubble mass

$$V_H(\Phi, H) \supset -cH^2|\Phi|^2$$

ϕ is driven away from $\phi = 0$ at early times $(H \gg m_r)$

(e.g. Dine, Randall, Thomas, 1995, Fujita & Harigaya 1607.07058)

Fate of radial mode.

Radial mode oscillations can overclose universe.

Can be damped.

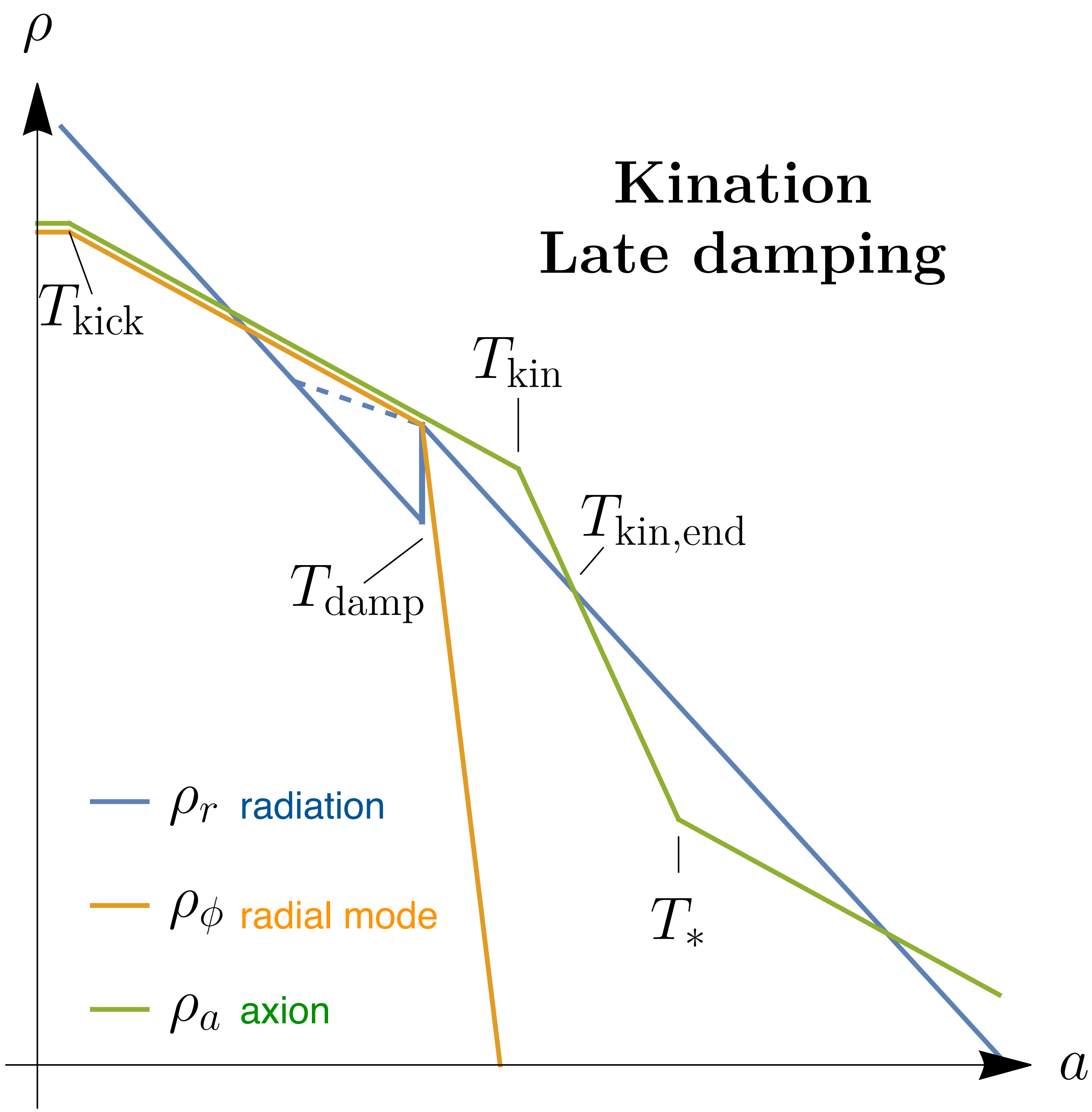
WHEN: **before radial mode dominates → no entropy production**

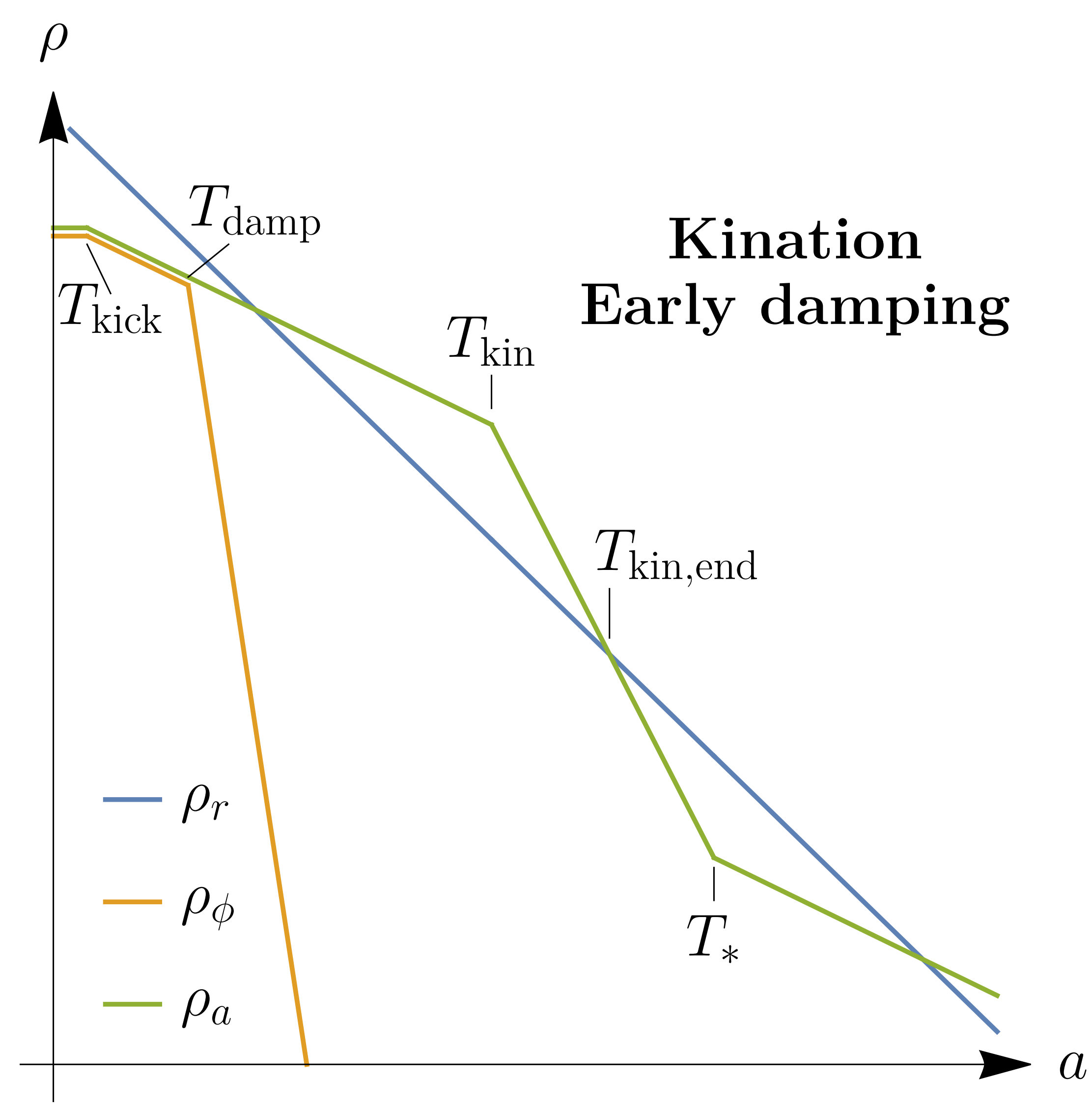
after radial mode dominates → entropy production

HOW: **Coupling with fermion χ : $\phi\chi\chi$**

Coupling with Higgs : $\phi^2 H^2$

Ingredient 4: Damping



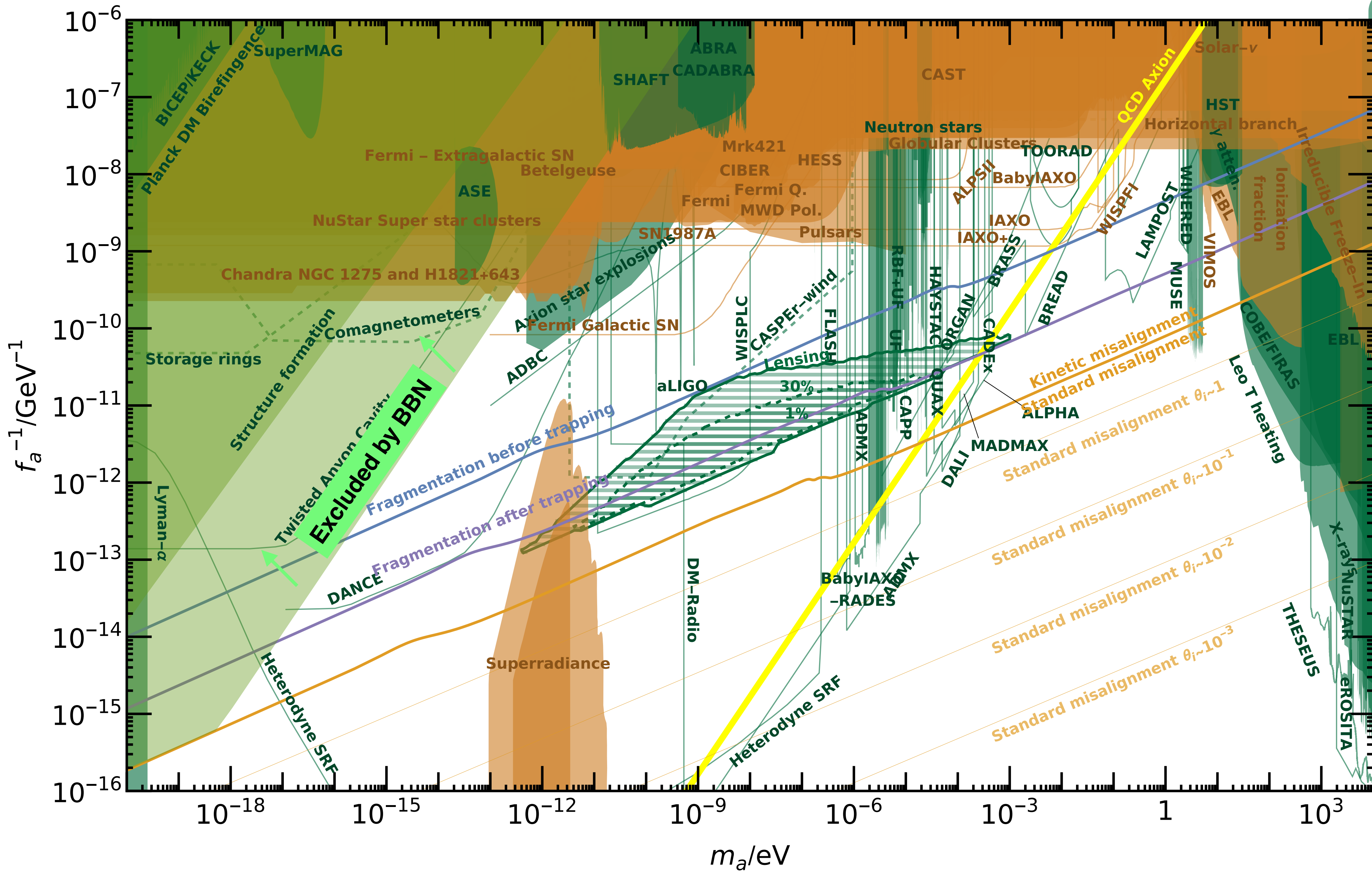


[2408.08355]

The hunt for axions.

Any ALP

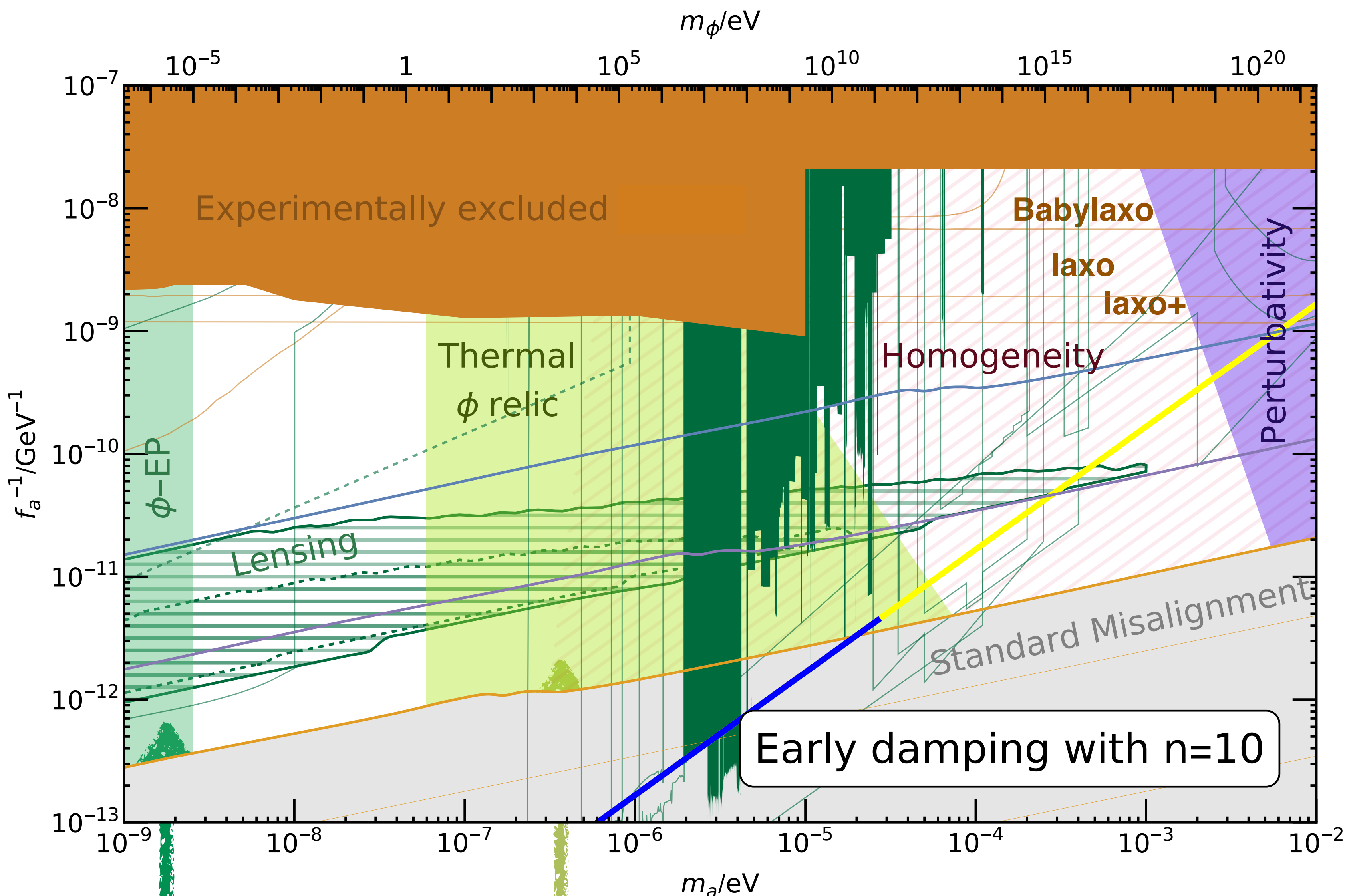
Only DM



(KSVZ-like coupling)

2206.14259 $g_{\theta\gamma} = (\alpha_{\mathbf{em}}/2\pi)(1.92/f)$

Explicit UV completions realising the axion kinetic misalignment: unspecified early radial-mode damping.



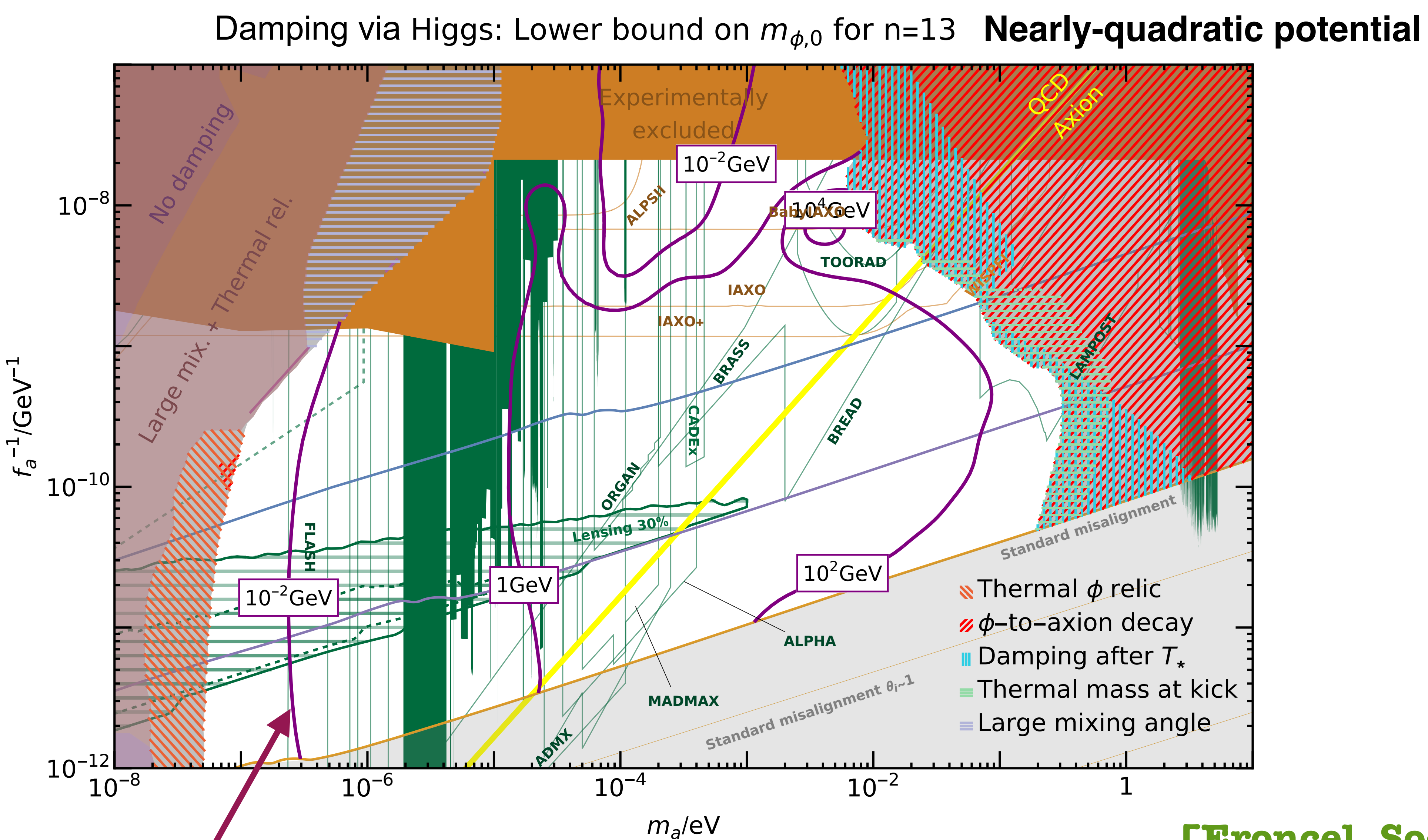
5th force/equivalence principle violation by radial mode

dangerous thermal production of radial mode

[Eroncel, Soerensen, Sato, Servant, 2408.08355]

Explicit UV completions realising the axion kinetic misalignment.

Thermal damping via Higgs portal.

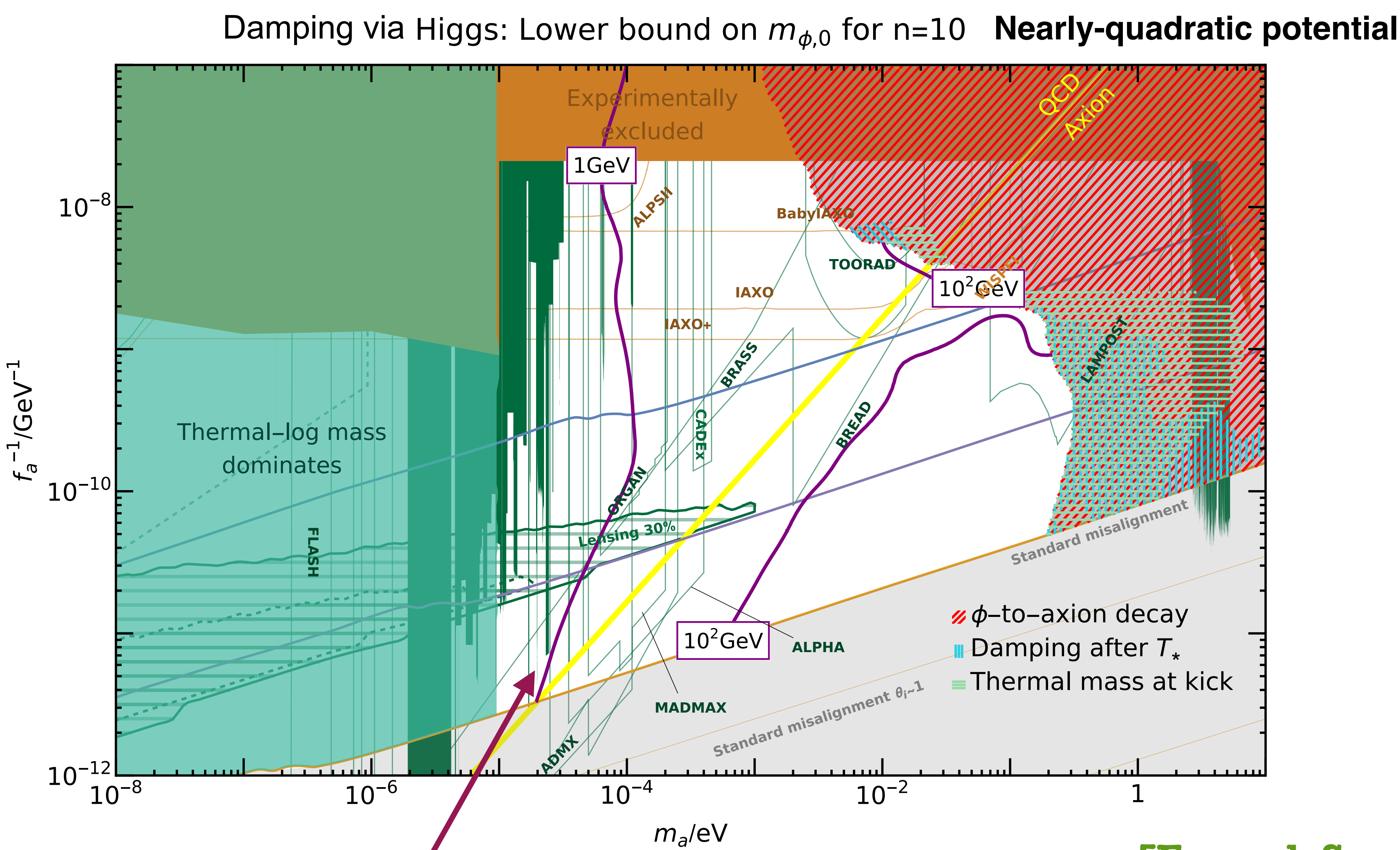


[Eroncel, Soerensen, Sato, Servant, 2408.08355]

Radial-mode mass contours

Explicit UV completions realising the axion kinetic misalignment.

Thermal damping via Higgs portal.



Radial-mode mass contours

[Eroncel, Soerensen, Sato, Servant, 2408.08355]

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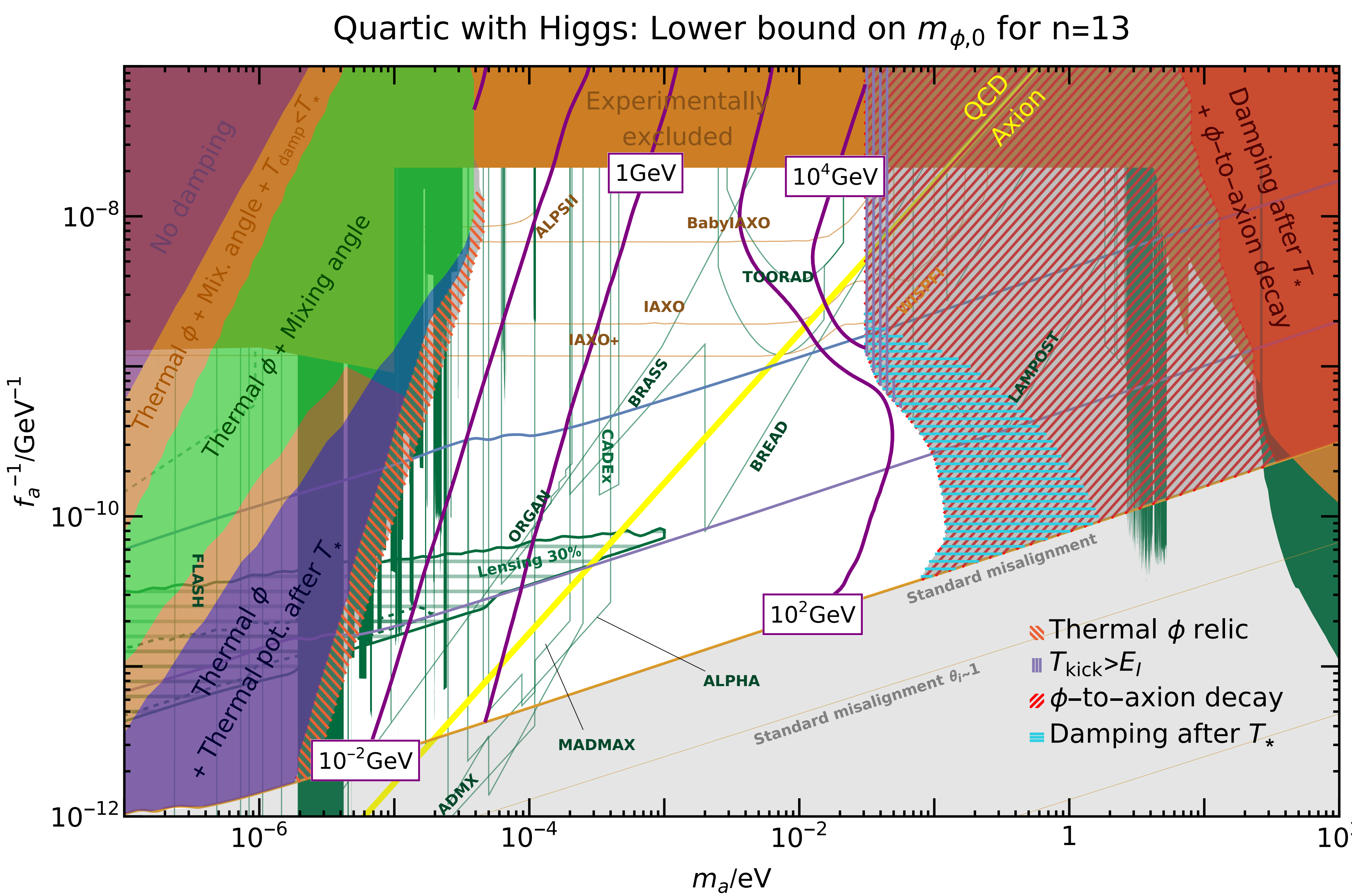
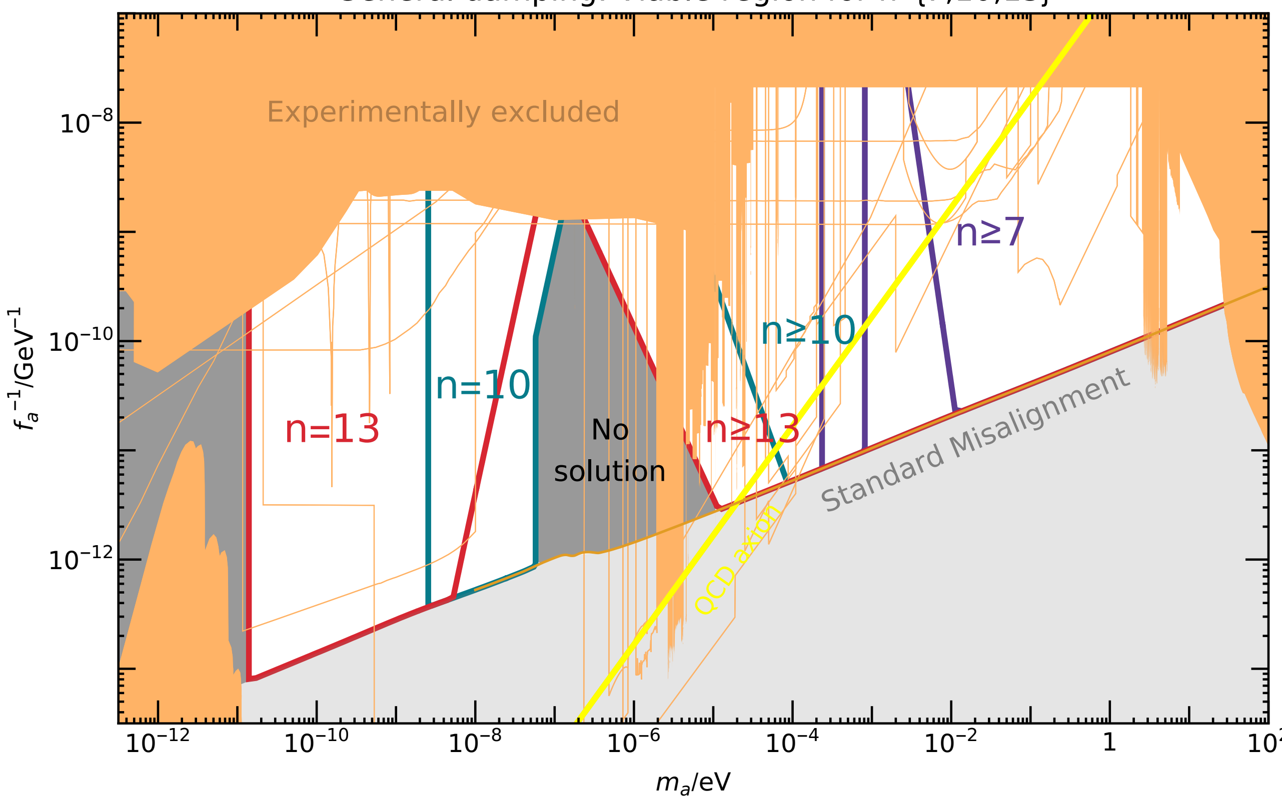


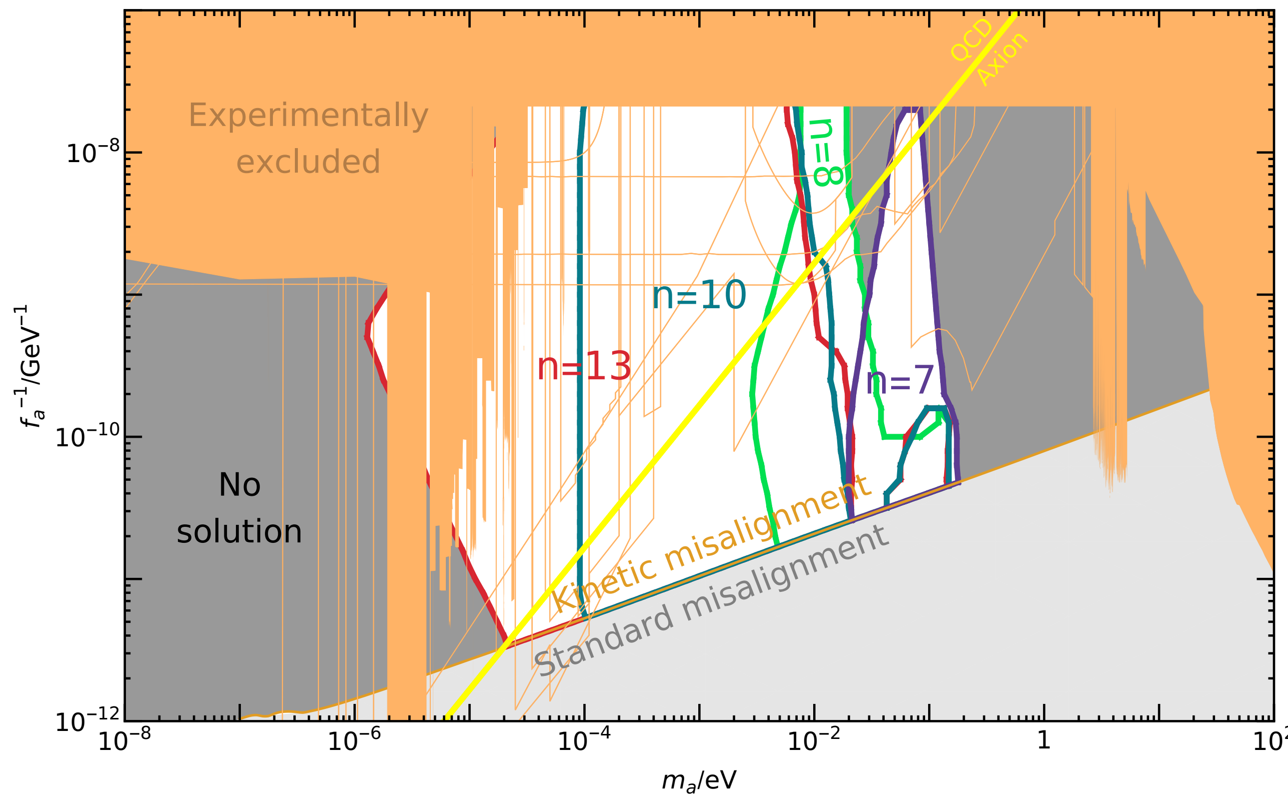
[Eroncel, Soerensen, Sato, Servant, 2408.08355]

Explicit UV completions realising the axion kinetic misalignment, some overview.

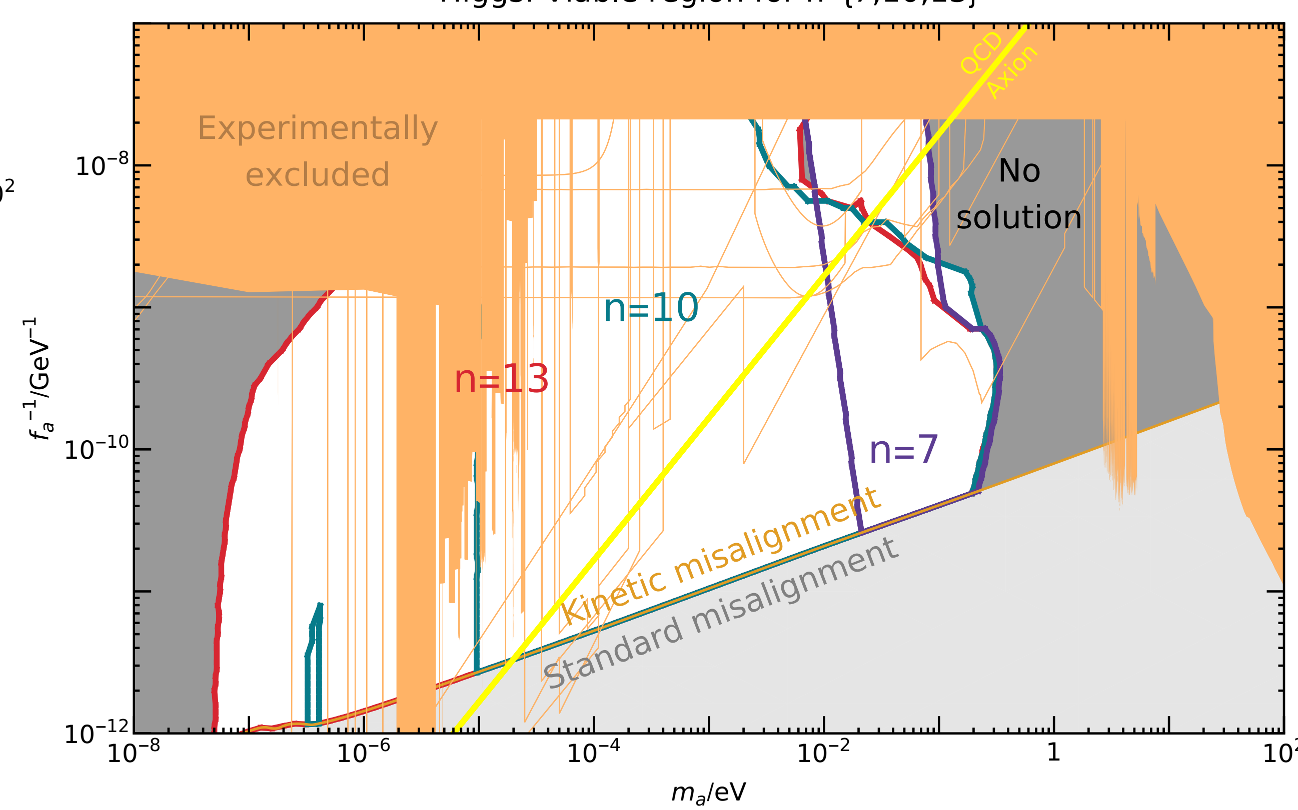
General damping: Viable region for n={7,10,13}



Yukawa: Viable region for n={7,8,10,13}

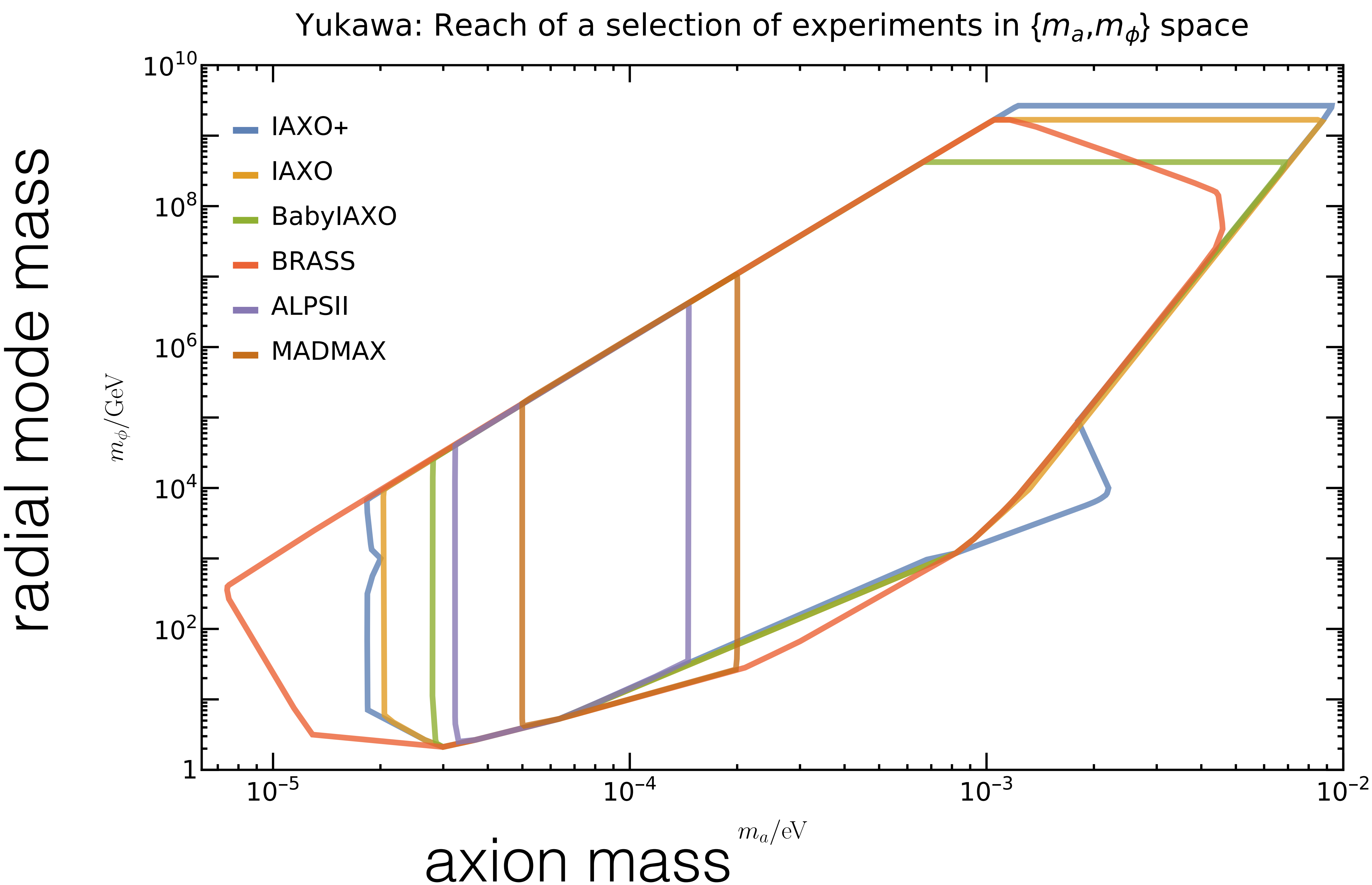


Higgs: Viable region for n={7,10,13}



[Eroncel et al, 2408.08355]

Correlations between axion mass and radial-mode mass.



[Eroncel et al, 2408.08355]

Axion kinetic misalignment:

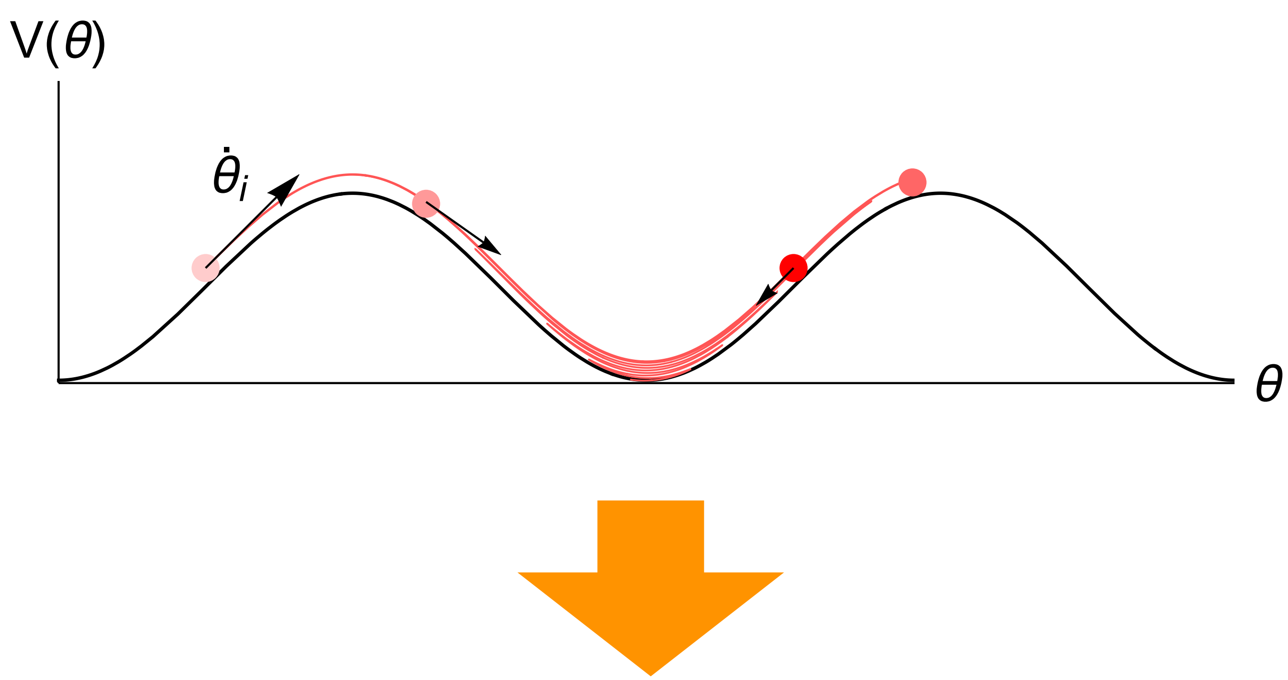
↓

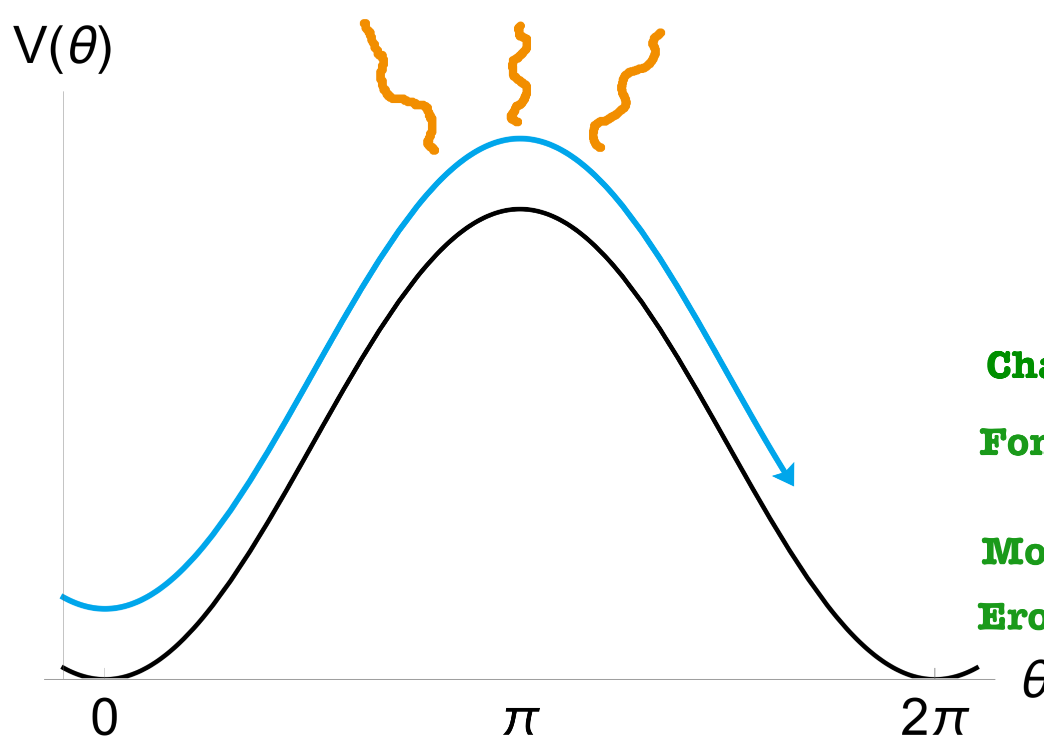
Axion fragmentation.

↓

Compact axion halos.

Axion fragmentation





Chatrchyan et al, 1903.03116, 2004.07844

Fonseca, Morgante, Sato, Servant, 1911.08472, 1911.08473

Morgante et al, 2109.13823

Eroncel et al' 2206.14259, 23065.103756

Axion Fragmentation.

Not considered in usual axion phenomenology with oscillations around one minimum: Fragmentation suppressed unless the field starts very close to the top of the potential (“large misalignment mechanism”) or for specific potentials with more than one cosine -> parametric resonance.

Greene, Kofman, Starobinsky, hep-ph/9808477
Chatrchyan et al, 1903.03116, 2004.07844
Arvanitaki et al, 1909.11665

However, becomes very relevant when field crosses many wiggles, with interesting implications, e.g. for the relaxion mechanism, but also as a new axion Dark Matter production mechanism.

Chatrchyan et al, 1903.03116, 2004.07844
Fonseca,Morgante,Sato, Servant’19
Morgante et al, 2109.13823

Generalization Eroncel et al, 2206.14259, 23065.103756
(fragmentation before and after trapping + detailed application to DM)

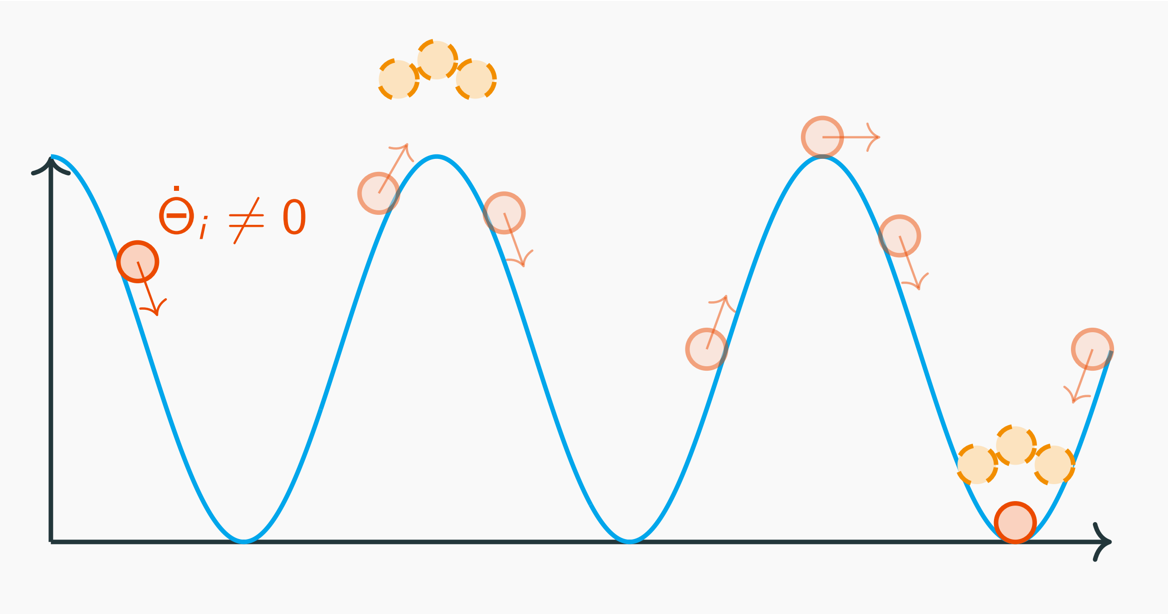
ALP fluctuations.

- Even in pre-inflationary scenario, ALP field has some fluctuations on top of the homogeneous background, which can be described by the mode functions in the Fourier space.

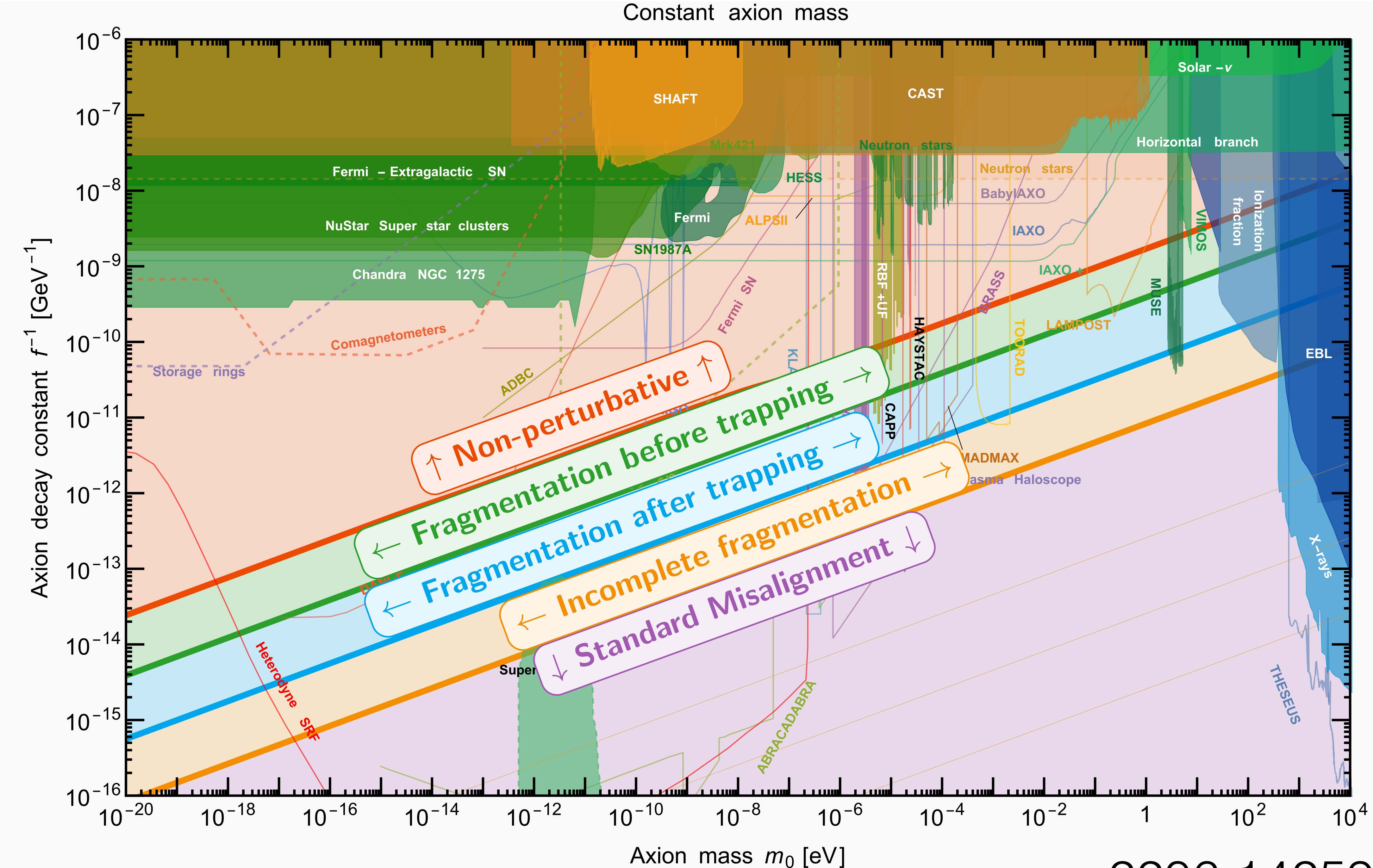
$$\theta(t,x) = \Theta(t) + \int \frac{d^3k}{(2\pi)^3}\theta_k e^{i\vec{k}\cdot\vec{x}} + \text{h.c.}$$

- Even though the fluctuations are small initially, they can be enhanced exponentially later via parametric resonance yielding to fragmentation.

- In the case of efficient fragmentation, all the energy of the homogeneous mode can be transferred to the fluctuations. [Fonseca et al. 1911.08472; Morgante et al. 2109.13823]

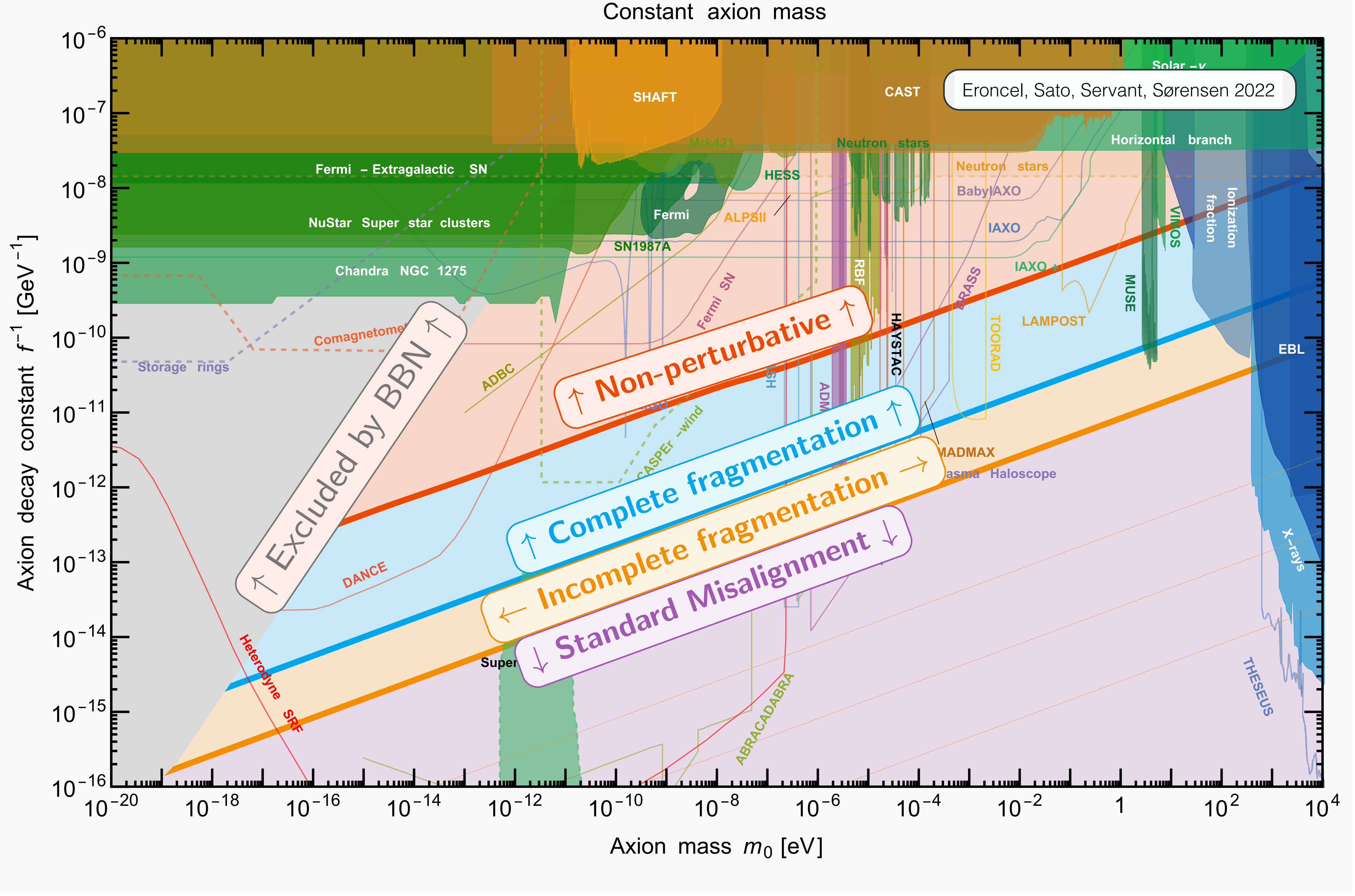


Fragmentation regions in ALP parameter space.



2206.14259

Fragmentation regions in ALP parameter space.



ALP fluctuations.

$$\phi(t,\mathbf{x}) = \bar{\phi}(t) + \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \phi_k e^{i\vec{k}\cdot\vec{x}} + \text{h.c.}$$

EoM for the unavoidable adiabatic perturbations :

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \underbrace{\left[\frac{k^2}{a^2} + V''(\phi)\Big|_{\bar{\phi}}\right]}_{\text{eff. frequency}} \phi_k = \underbrace{2\,\Phi_k\, V'(\phi)\Big|_{\bar{\phi}} - 4\dot{\Phi}_k \dot{\bar{\phi}}}_{\text{source term}}$$

unstable when the effective frequency

- becomes negative $\Rightarrow$ tachyonic instability
- is oscillating $\Rightarrow$ parametric resonance

Growth rate of the perturbations depends exponentially on $\left.\frac{m_\phi}{H}\right|_{\rm osc}$

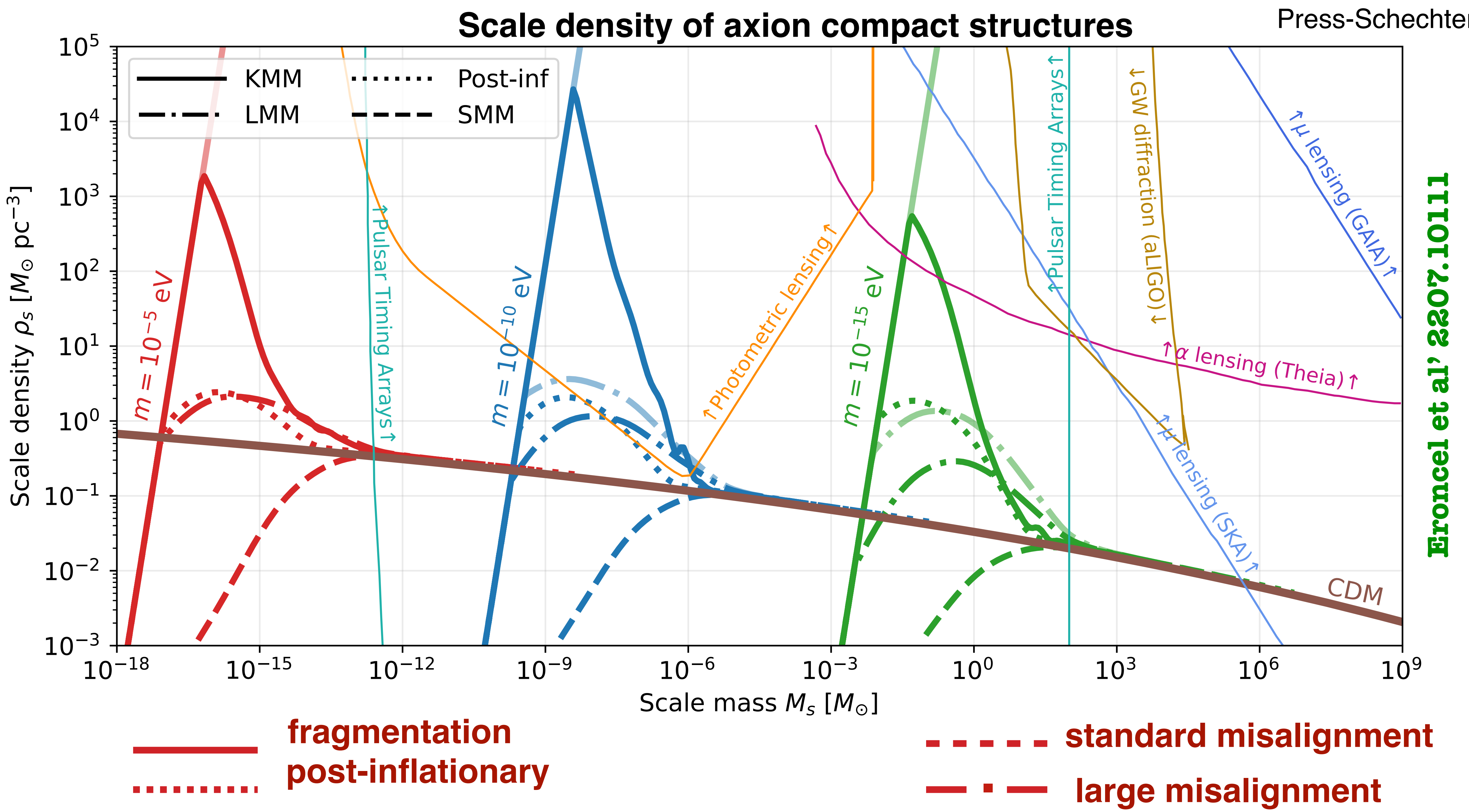
Dense and compact ALP mini-clusters (clumps of ALP DM) can also be formed in the pre-inflationary scenario!

Observational tests: compact axion halos.

kinetic misalignment—>axion fragmentation-> structure formation enhancement

Small m → Large mini-cluster

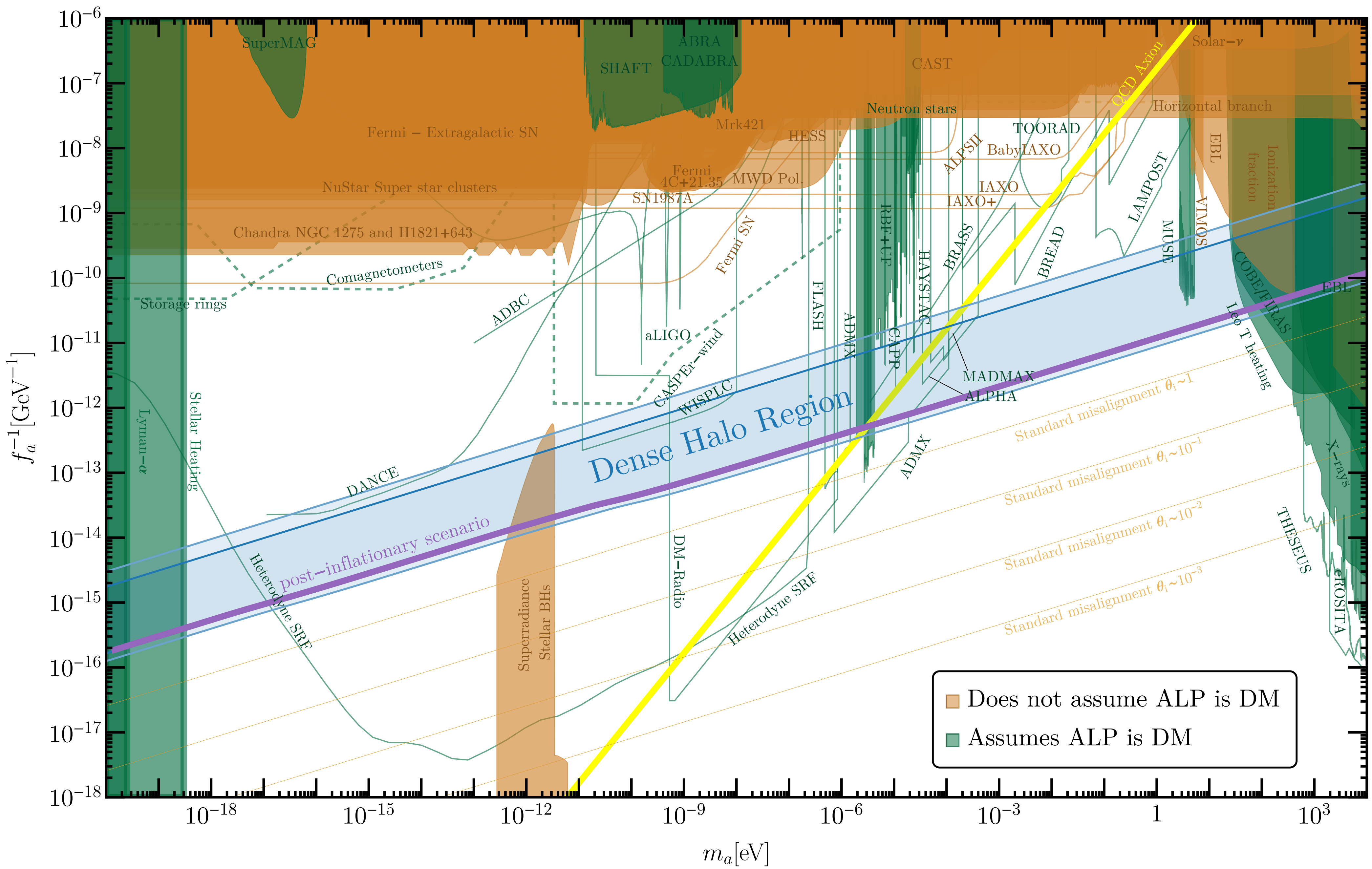
Perturbative analysis + Press-Schechter formalism



Studied in the context of large misalignment scenario in [Arvanitaki et al'19]

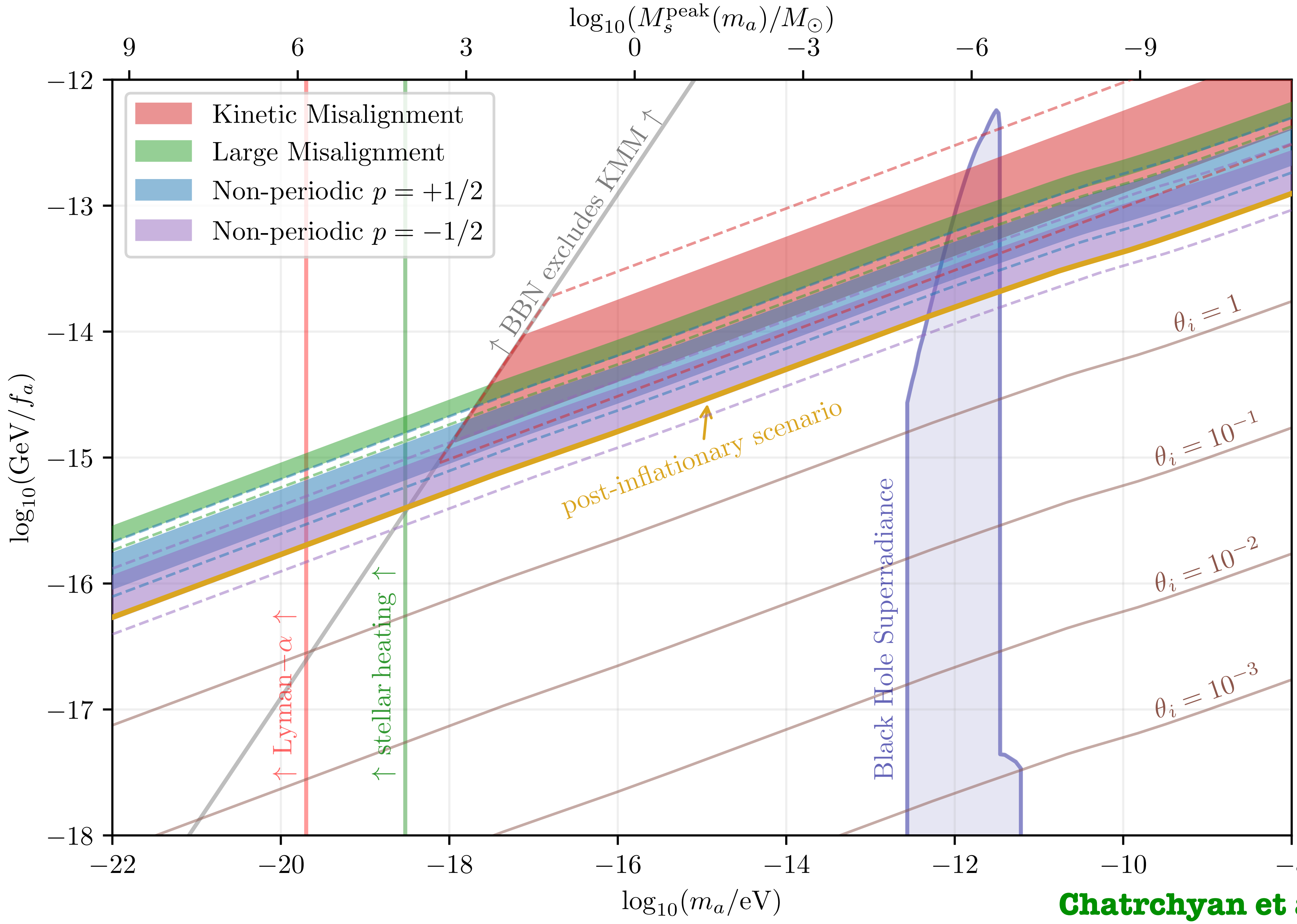
Different in the context of axion kinetic fragmentation [Eroncel et al , 2207.10111]

Parameter space where parametric resonance can create compact halos.



Chatrchyan et al, 2305.03756

Parameter space where parametric resonance can create compact halos (with $\rho_s \gtrsim 10\, M_\odot\, \mathrm{pc}^{-3}$).



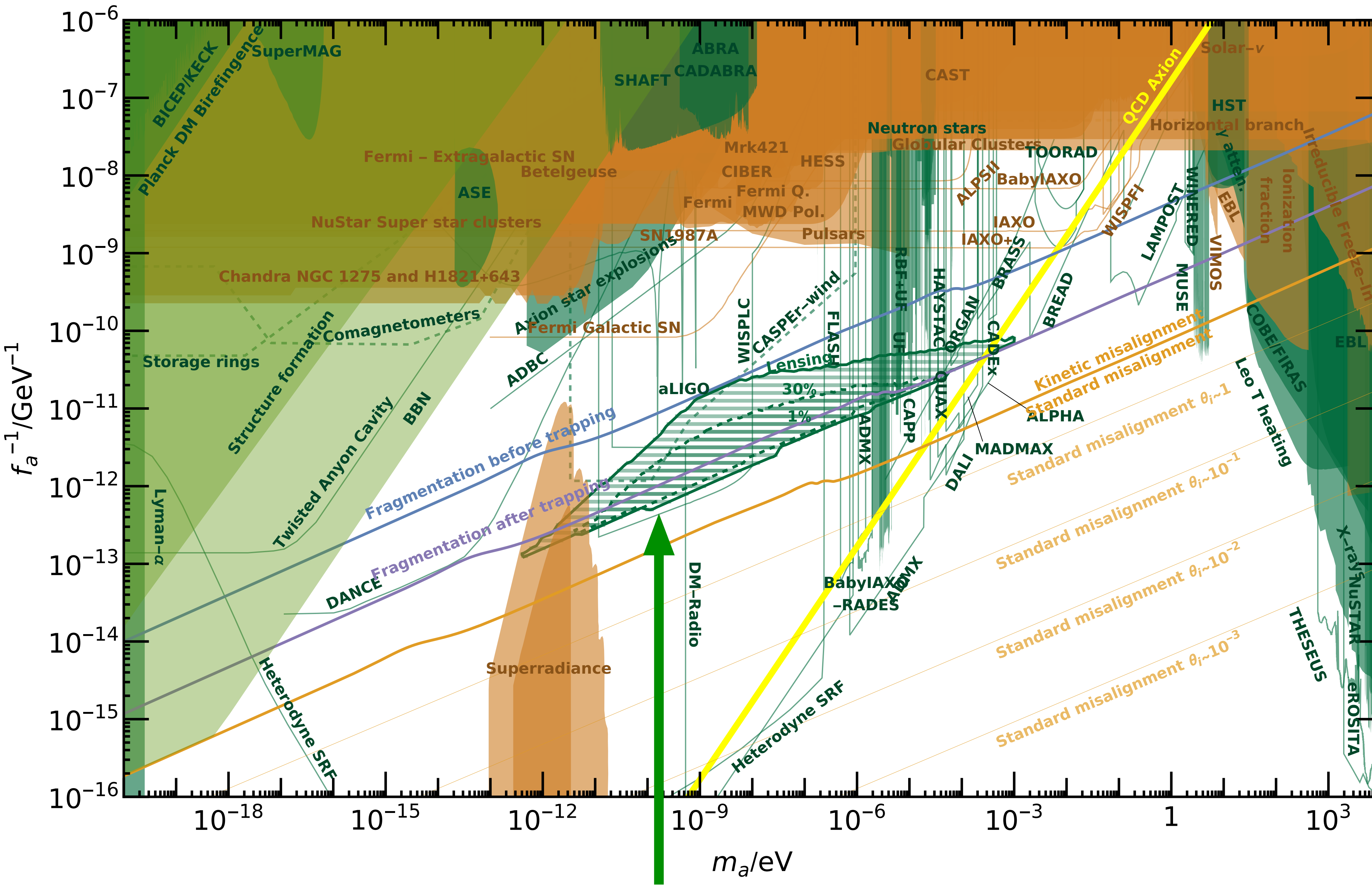
Chatrchyan et al 2305.03756

The dense halo regions from ≠ production mechanisms mostly overlap.
Difficult to infer the production mechanism from observations.
However, observations of dense structure gives information about f_a even when ALP does not couple to the SM!

Observability of compact halos from kinetic misalignment.

Any ALP

Only DM



Region that can be probed by photometric lensing

(KSVZ-like coupling)

$$g_{\theta\gamma} = (\alpha_{\mathbf{em}}/2\pi)(1.92/f)$$

2206.14259

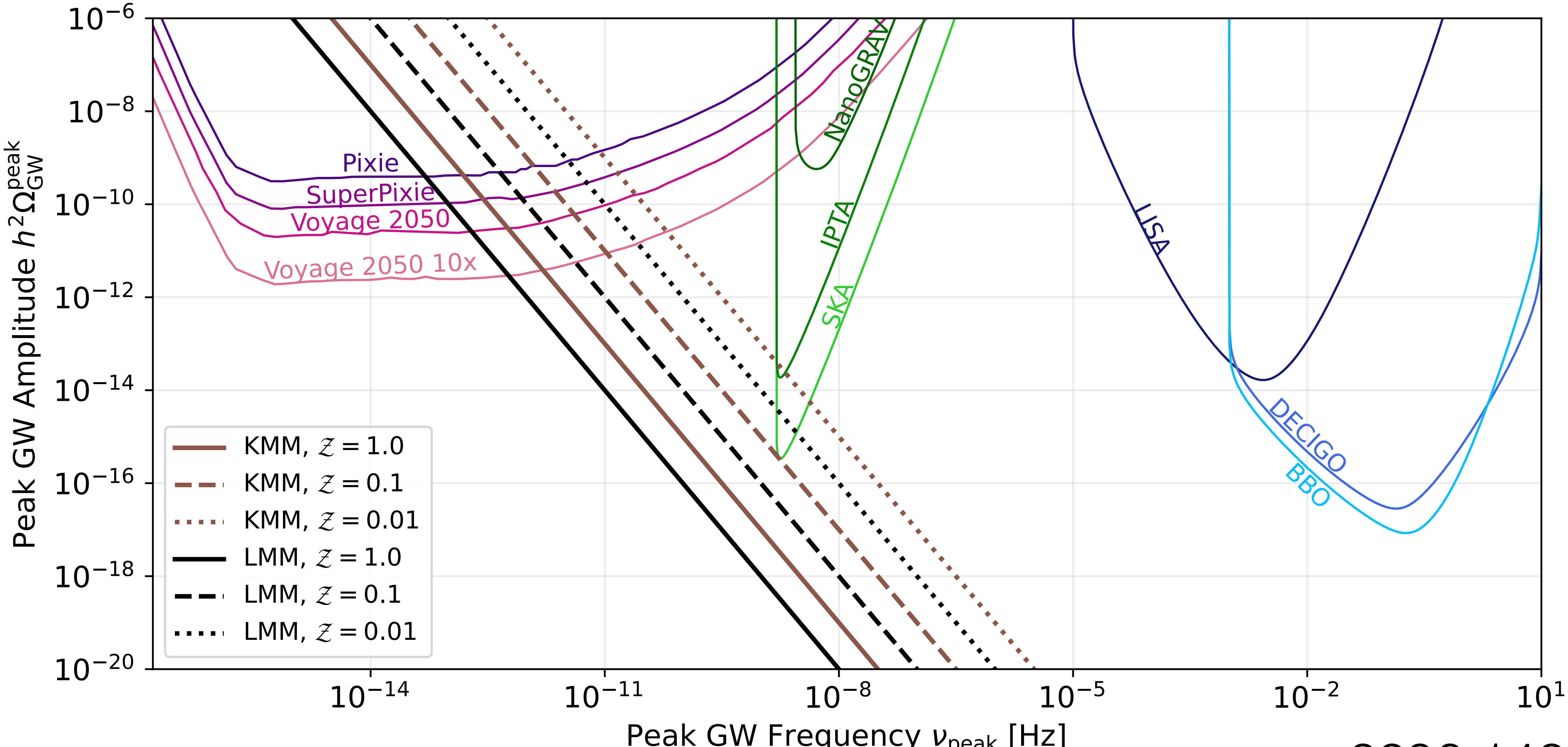
GWs from axion fragmentation.

The transfer of energy in the early universe from the homogeneous axion field into axion quantum fluctuations, inevitably produces a stochastic background of gravitational waves of primordial origin with a peak frequency controlled by the axion mass.

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\Delta h_{ij}}{a^2} = \frac{16\pi}{M_{\rm pl}^2}\Pi_{ij}^{\rm TT},$$

$$\Pi_{ij}^{\rm TT}(t,\vec{x}) = \frac{1}{a^2}\left[\partial_i\phi(t,\vec{x})\partial_j\phi(t,\vec{x}) - \frac{1}{3}\delta_{ij}(\partial_k\phi(t,\vec{x})\partial_k\phi(t,\vec{x}))\right]$$

Gravitational waves from ALP DM fragmentation.



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$\mathcal{Z}$ = needed dilution factor of ALP energy density

Summary so far on axion fluctuations.

Axion fluctuations:

- **sourced by primordial inflationary curvature perturbations**
- **exponentially amplified by parametric resonance induced by kinetic misalignment, when the ALP field is rolling over the potential barriers and when it is oscillating around the minimum, around the time when the axion is trapped, leading to axion fragmentation**
- **Observational signatures: axion mini-clusters and low-frequency gravitational waves**
- **This *late* fragmentation does not affect much the dark matter relic abundance: It is only a transfer of energy from the zero-mode condensate to higher-modes, that occurs when the axion is already non-relativistic.**
- **This *late* effect has thus a weak dependance on the power of primordial fluctuations $\mathscr{P}_{\mathscr{R}}(k)$. Because of the exponential growth, the amplitude of the initial fluctuations does not matter much.**

We have discussed axion fluctuations generated around the (late) time of axion trapping when axion oscillations start.

However, axion fluctuations may come to dominate much earlier.

Eroncel et al, 2206.14259
Eroncel et al, 2408.08355
Eroncel et al, 2501.17226

Axion fluctuations

A novel source for axion Dark Matter production: Curvature-induced.

Eroncel et al, 2503.04880

+

Bodas, Co, Ghalsasi, Harigaya, Wang, 2503.04888

Different from the axion fluctuations produced during fragmentation at late (trapping) time.

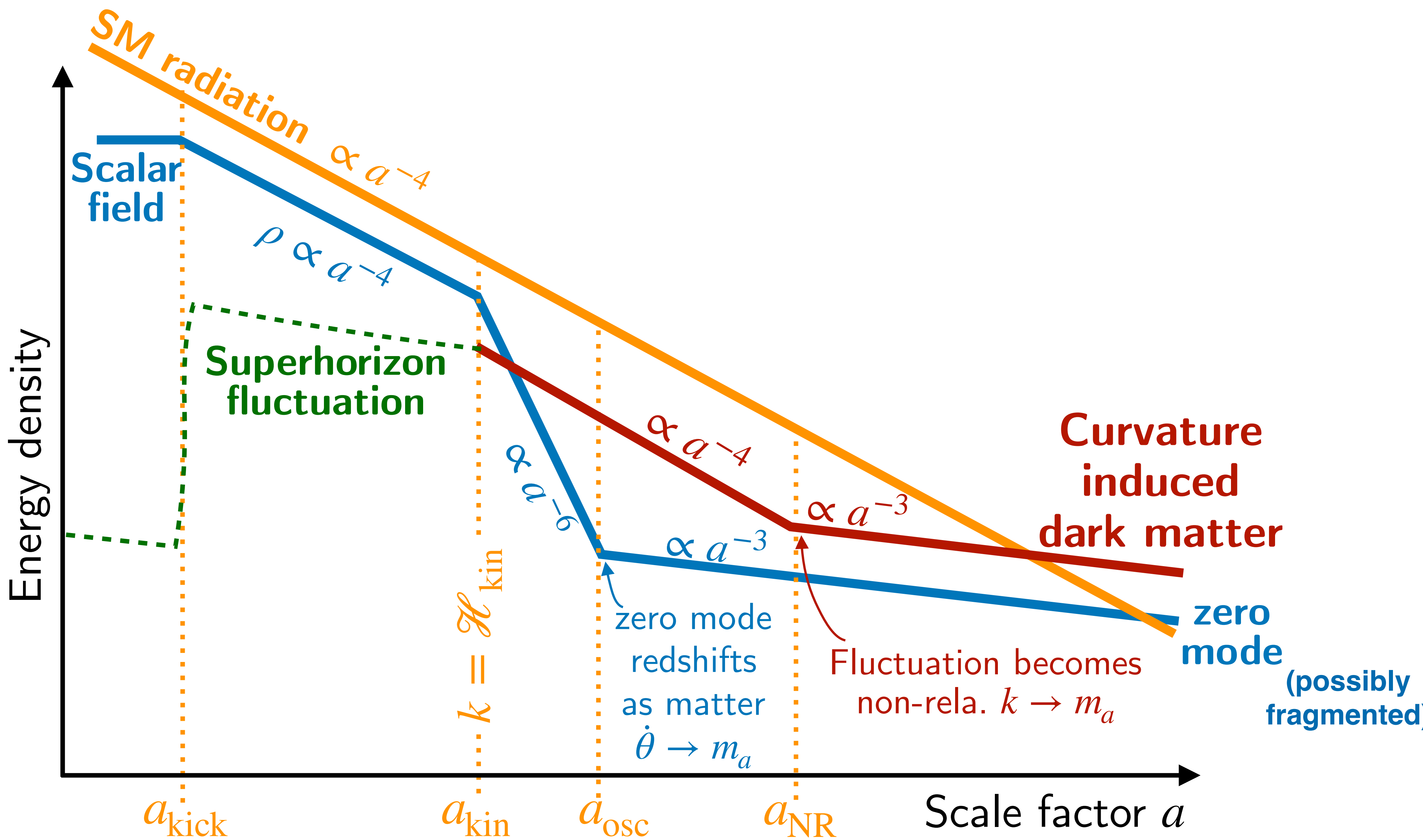
Axion fluctuations induced by curvature perturbations also occur at very early times when axion is still massless and highly relativistic.

They are sourced by non-vanishing velocity of the axion field.

They have a crucial dependance on the primordial (inflationary) power spectrum.

They may end up dominating eventually, after the axion has become non-relativistic, over the zero-mode condensate, and independently from its late fragmentation.

Do not neglect axion fluctuations!



2503.04880

Effect of curvature fluctuations on scalar field

Warning: Change of notation in the following, ϕ denotes the axion and is decomposed as

$$\phi(\eta, \mathbf{x}) = \underbrace{\overline{\phi}(\eta)}_{\text{background}} + \underbrace{\delta\phi(\eta, \mathbf{x})}_{\text{fluctuations}} = \overline{\phi}(\eta) + \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3} \underbrace{\delta\phi_{\mathbf{k}}(\eta)}_{\text{fluctuation Fourier modes}} e^{-i\mathbf{k}\cdot\mathbf{x}}$$

Equations of motion

Homogeneous mode:

$$\overline{\phi}'' + 2\mathcal{H}\overline{\phi}' + a^2\frac{\partial V}{\partial \phi} = 0,$$

V: potential

Source term due to curvature perturbations

Fluctuations:

$$\delta\phi''_{\mathbf{k}} + 2\mathcal{H}\delta\phi'_{\mathbf{k}} + \left(k^2 + a^2\frac{\partial^2 V}{\partial \phi^2}\right)\delta\phi_{\mathbf{k}} = -2\Phi_{\mathbf{k}}\frac{\partial V}{\partial \phi} + 4\Phi'_{\mathbf{k}}\overline{\phi}'$$

Conformal Hubble =a H

Φ_k = Fourier modes of the curvature perturbations

$'$: derivative with respect to conformal time

where $$ds^2 = a^2\Big[-(1+2\Phi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\Big]$$

space-time metric in conformal Newtonian gauge

Φ is the scalar metric fluctuation

Neglecting the mass

$$\delta\phi_{\mathbf{k}}'' + 2\mathcal{H}\,\delta\phi_{\mathbf{k}}' + k^2\delta\phi_{\mathbf{k}} = 4\Phi_{\mathbf{k}}'\overline{\phi}'$$

The scalar speed $\overline{\phi}'$ combined with the curvature perturbation Φ_k' sources the scalar fluctuation with momentum k

This is the main difference with standard misalignment which has $\overline{\phi}'$ = 0

—> the adiabatic fluctuations remain zero until oscillations start.

In contrast, in kinetic misalignment, the ALP field receives a kick at a much earlier time, so the right side of the equation is active much earlier. While the mass term is still negligible, fluctuations then quickly behave as free fluctuations, i.e. as radiation (see 2501.17226).

Solution for the curvature perturbations in radiation era (they are constant in matter domination)

$$\Phi_{\mathbf{k}}(k\eta) = \frac{9}{\sqrt{3}} \frac{\Phi_{\mathbf{k}}(0)}{k\eta} j_1\left(\frac{k\eta}{\sqrt{3}}\right)$$

$\Phi_k(0)$:stochastic variable that depends on the amplitude of the scalar primordial fluctuations A_s

$$\left\langle |\Phi_k(0)|^2 \right\rangle = \left(\frac{2}{3}\right)^2 \left\langle |\mathcal{R}_k(0)|^2 \right\rangle = \left(\frac{2}{3}\right)^2 \left(\frac{2\pi^2}{k^3}\right) A_s \left(\frac{k}{k_\star}\right)^{n_s - 1}$$

$\mathscr{R}_k$ **: comoving curvature perturbation**

n_s : spectral tilt

k_* = 0.05 Mpc^{-1} : the pivot scale

we take n_s = 1 for simplicity, and set A_s = 2.1 ×10^{-9}

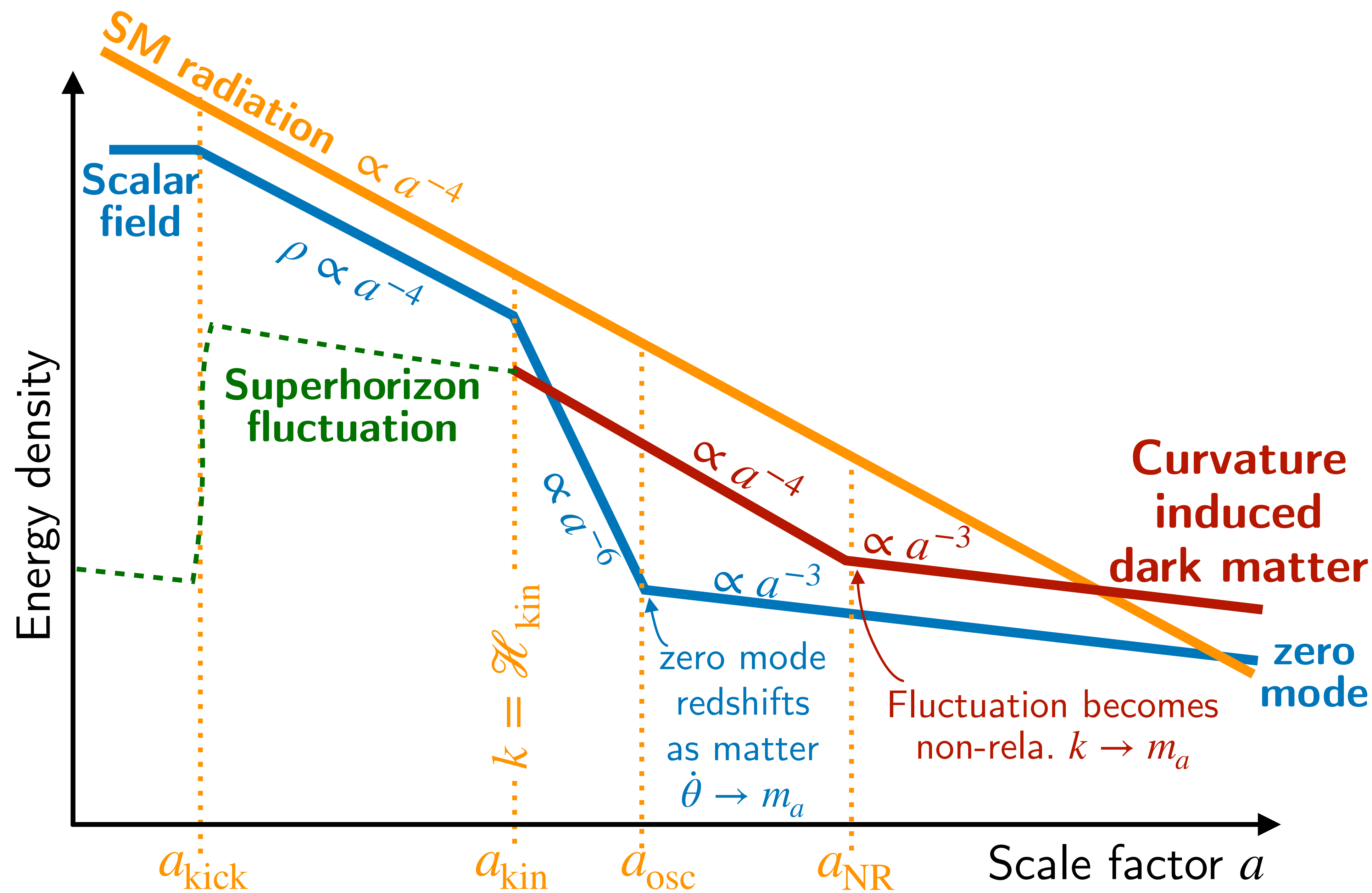
Solution for the energy density today stored in the axion fluctuations

$$\phi_k(t) \propto \Phi_k(0) \propto \mathscr{R}_k(0)$$

$$\Omega^0_{\rm fluct} \propto \mathscr{P}_{\mathscr{R}}(k_{\rm kin})$$

$$\frac{\Omega^0_{\rm fluct}}{\Omega^0_{\rm zero}} \simeq 0.9\,\alpha^2 \Omega_\phi^{1/2}(\eta_{\rm kin}) \left(\frac{10^{10}\,{\rm GeV}}{f_a}\right) \left(\frac{\mathcal{P}_{\mathcal{R}}(k_{\rm kin})}{2.1\cdot 10^{-9}}\right)$$

Axion fluctuations not to be neglected!



Note

The source term in $$\delta\phi_{\mathbf{k}}'' + 2\mathcal{H}\,\delta\phi_{\mathbf{k}}' + k^2\delta\phi_{\mathbf{k}} = 4\Phi_{\mathbf{k}}'\overline{\phi}'$$

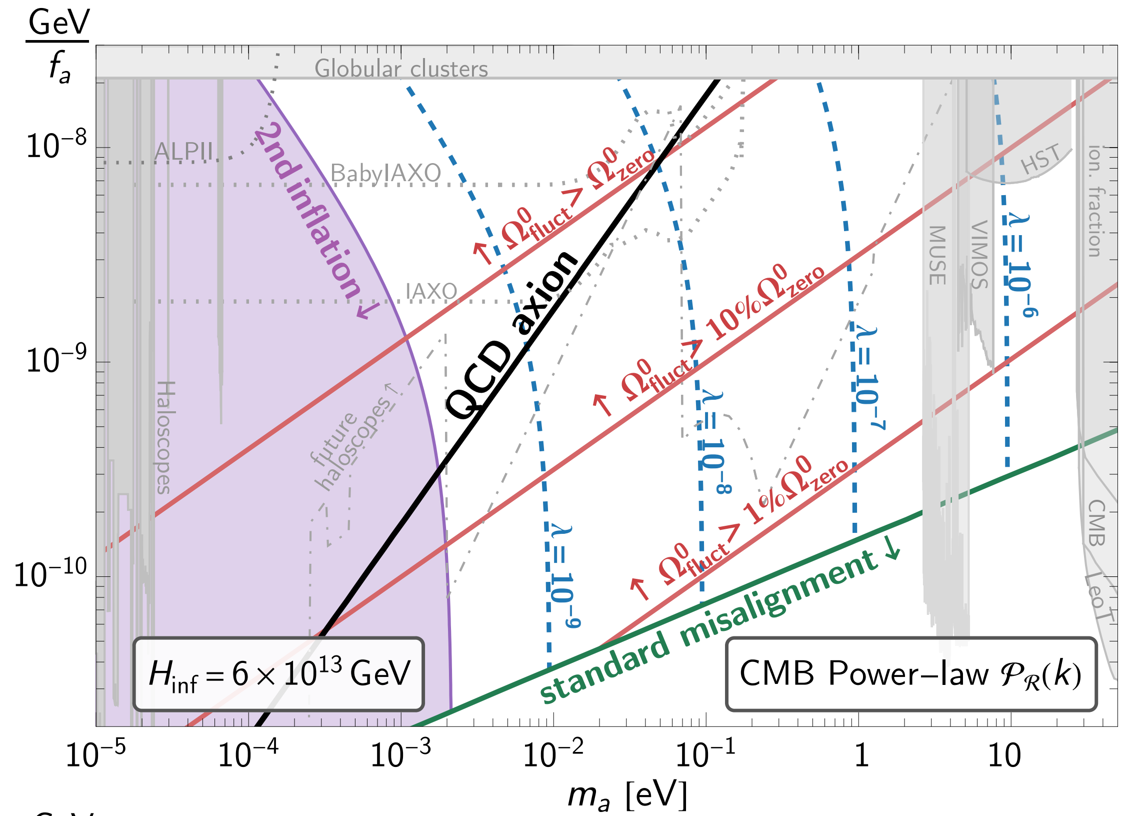
is suppressed quickly after generating the fluctuations (see Appendix C of 2501.17226 and Eq. C11).

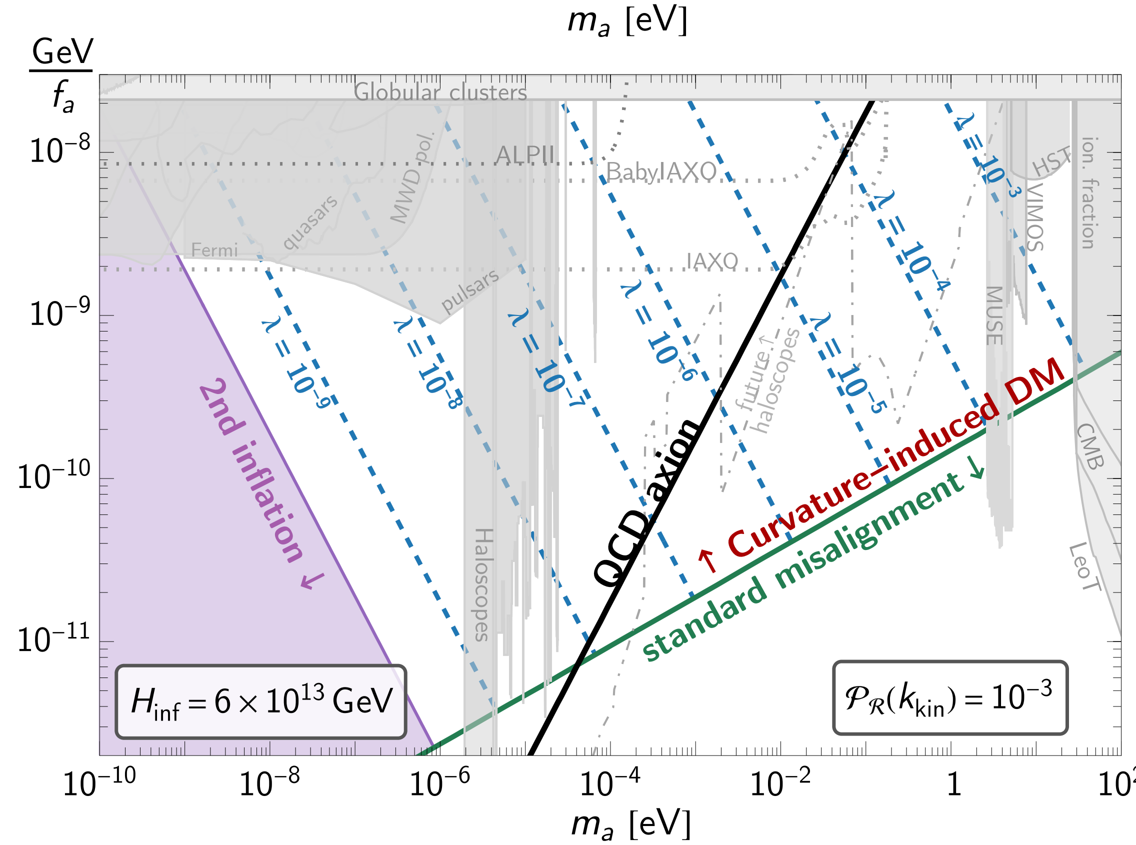
Thus, fluctuations $\delta\phi_{\mathbf{k}}$ behave as *free fluctuations* (i.e like radiation) even when the energy density of fluctuations dominates the zero-mode energy density, and there is *no backreaction issue in the regime where the potential approximately vanishes*.

Our calculation using the perturbative expansion is valid because we calculate the amount of fluctuations only at the time of horizon entry when the fluctuation is initially very small compared to zero modes. After some time, the fluctuation and zero modes evolve independently, and the fluctuation can dominate the energy density.

A novel contribution to axion DM.

$$\frac{\Omega^0_{\rm fluct}}{\Omega^0_{\rm zero}} \simeq 0.9\,\alpha^2 \Omega_\phi^{1/2}(\eta_{\rm kin}) \left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)\left(\frac{\mathcal{P}_\mathcal{R}(k_{\rm kin})}{2.1\cdot 10^{-9}}\right)$$

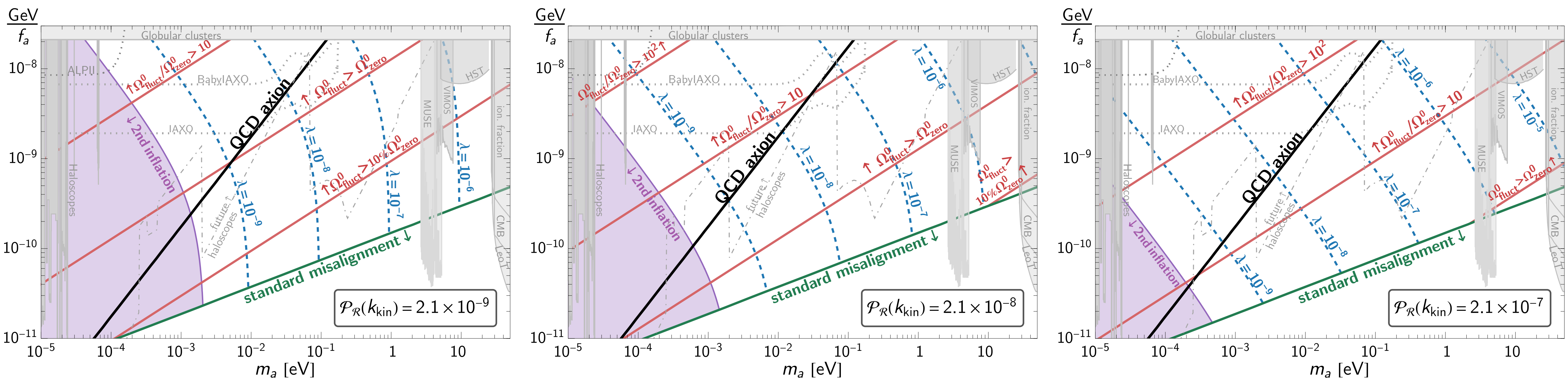




[2503.04880]

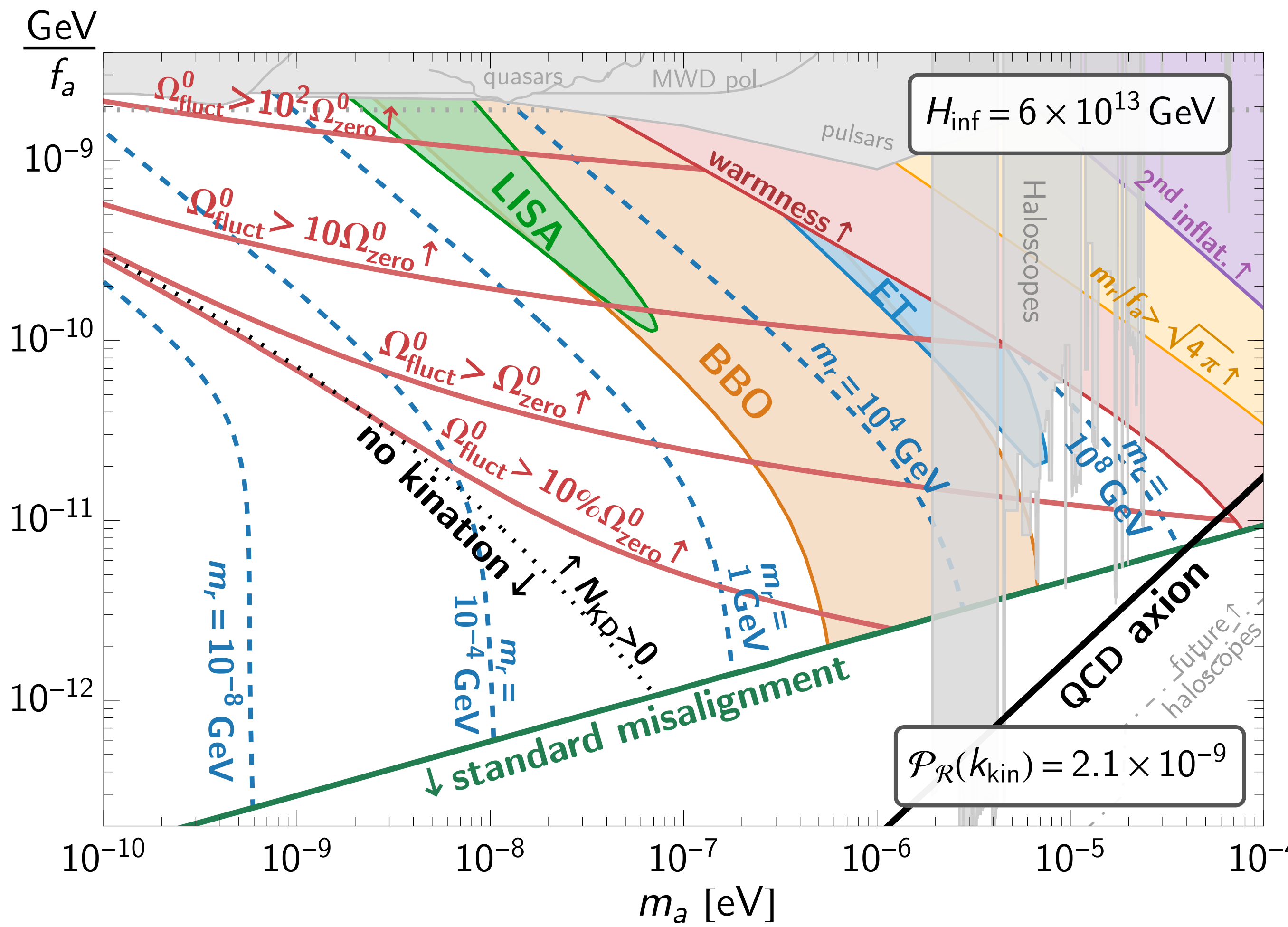
A novel contribution to axion DM.

$$\frac{\Omega^0_{\rm fluct}}{\Omega^0_{\rm zero}} \simeq 0.9\,\alpha^2\Omega_\phi^{1/2}(\eta_{\rm kin})\left(\frac{10^{10}\,{\rm GeV}}{f_a}\right)\left(\frac{\mathcal{P}_\mathcal{R}(k_{\rm kin})}{2.1\cdot 10^{-9}}\right)$$



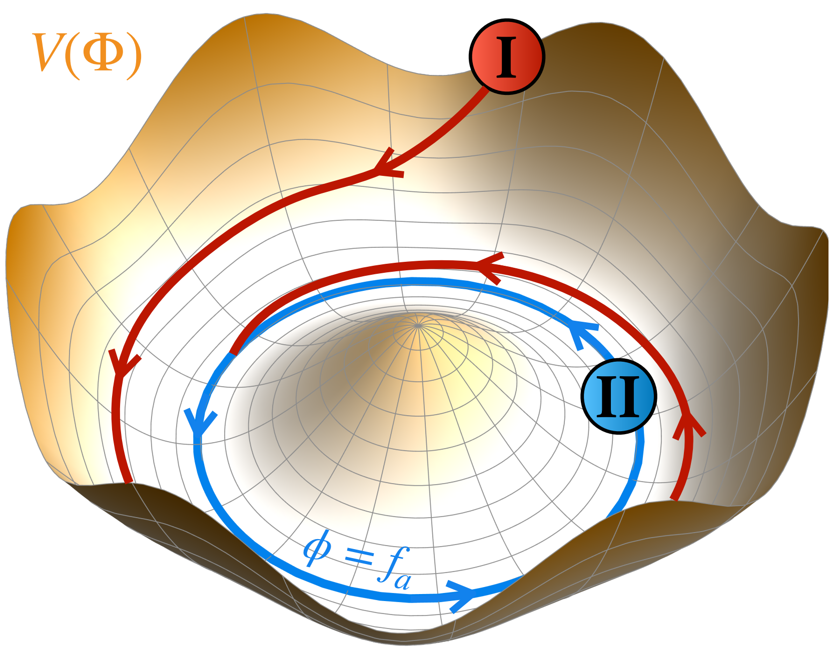
[2503.04880]

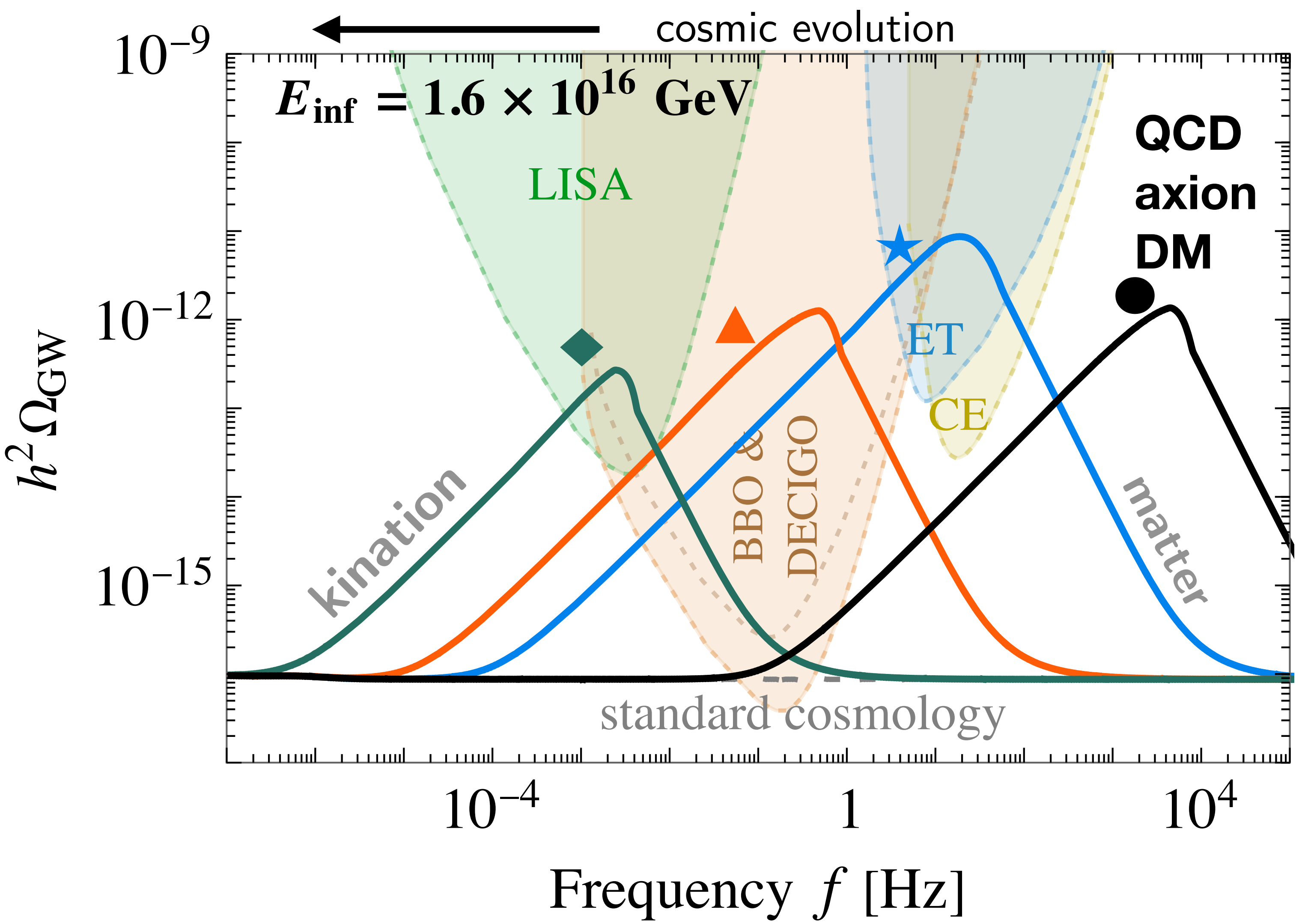
Detectability of the kination peak of inflationary gravitational waves.



[2503.04880]

Amplification of inflationary GW from axion-induced kination era.





$f_a \sim 10^{10}$GeV
$N_{KD} = 5$

[Gouttenoire et al 2108.10328 & 2111.01150]

Open questions.

Precise predictions will need to be checked with numerical simulations because of back-reaction effects that enter when the axion mass term becomes relevant (which is only much later, long after the energy density of fluctuations dominates over the zero-mode).

A new analysis will be required to study the formation of compact structures in this new scenario.

A re-analysis along the lines of [2408.08355] will be required to determine the details of the modified parameter space in UV-completion models since the DM abundance is of different origin.

Summary.

-Standard Misalignment Mechanism cannot account for dark matter in the ALP parameter space where the experiments are most sensitive.

-Kinetic Misalignment Mechanism moves the ALP Dark Matter window into testable territory.

-All axion experiments are in principle sensitive to axion dark matter (even helioscopes and light-shining-through-the-wall experiments)

- QCD axion Dark Matter inside MADMAX and Iaxo sensitivities

-Axion not alone, e.g, its radial mode partner is a key player.
May be light and could also be searched for.

-There is much more to the original kinetic misalignment mechanism:
—> axion fragmentation
—> curvature-induced axion fluctuations may dominate over the zero-mode condensate with a different dependence of the DM relic abundance on UV parameters

Summary continued .

-ALP mini-clusters can be formed even in the pre-inflationary scenario from kinetic fragmentation.

- Band in the (m_a, f_a)-plane where dense structures can be formed does not depend drastically on the production mechanism.
- Existence of this band allows us to obtain information about the decay constant, even if ALP does not couple to the Standard Model.

- Gravitational waves: not discussed much in this talk, however:
  Kination era leads to a unique amplification of the primordial GW background from inflation & from cosmic strings (2111.01150)
  + another independent GW source (and weaker) comes from axion fluctuations (2206.14259).