Axion-Like-Particle dark matter from kinetic fragmentation.

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DESY/U.Hamburg

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DESY.

CLUSTER OF EXCELLENCE
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This talk .

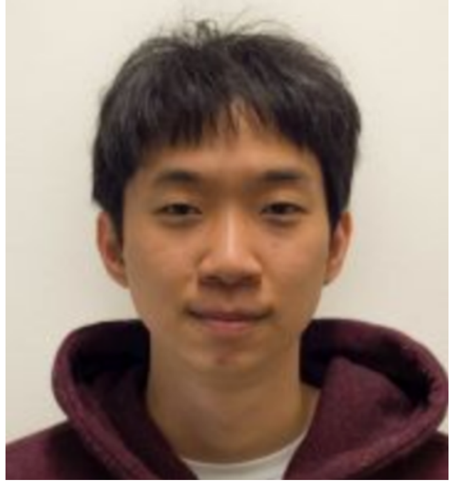
Based on collaboration with



Cem Eroncel, Philip Sørensen, Ryosuke Sato

to appear

as well as




Peera Simakachorn **Yann Gouttenoire**

ArXiv: 2108.10328
+ 2111.01150

Key message:
ALP DM window largely opened up with a spinning axion.

Axion-Like-Particles (ALPs).

Consider complex scalar field

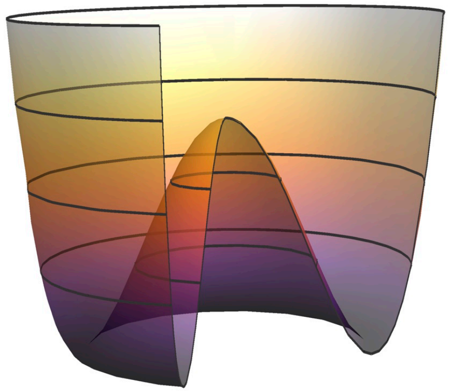
$$\Phi = \phi e^{i\theta}$$

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

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

θ=a/f_a

ALPs.

Non-perturbative effects at energy Λ_b << 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

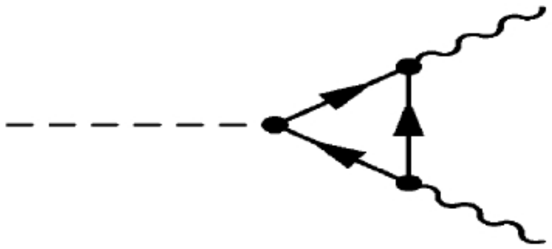
$$m_a^2 f_a^2 \approx (76\ \mathrm{MeV})^4$$

Generic ALP

m_a and f_a : free parameters

The hunt for axions.

Mainly through Axion-photon coupling

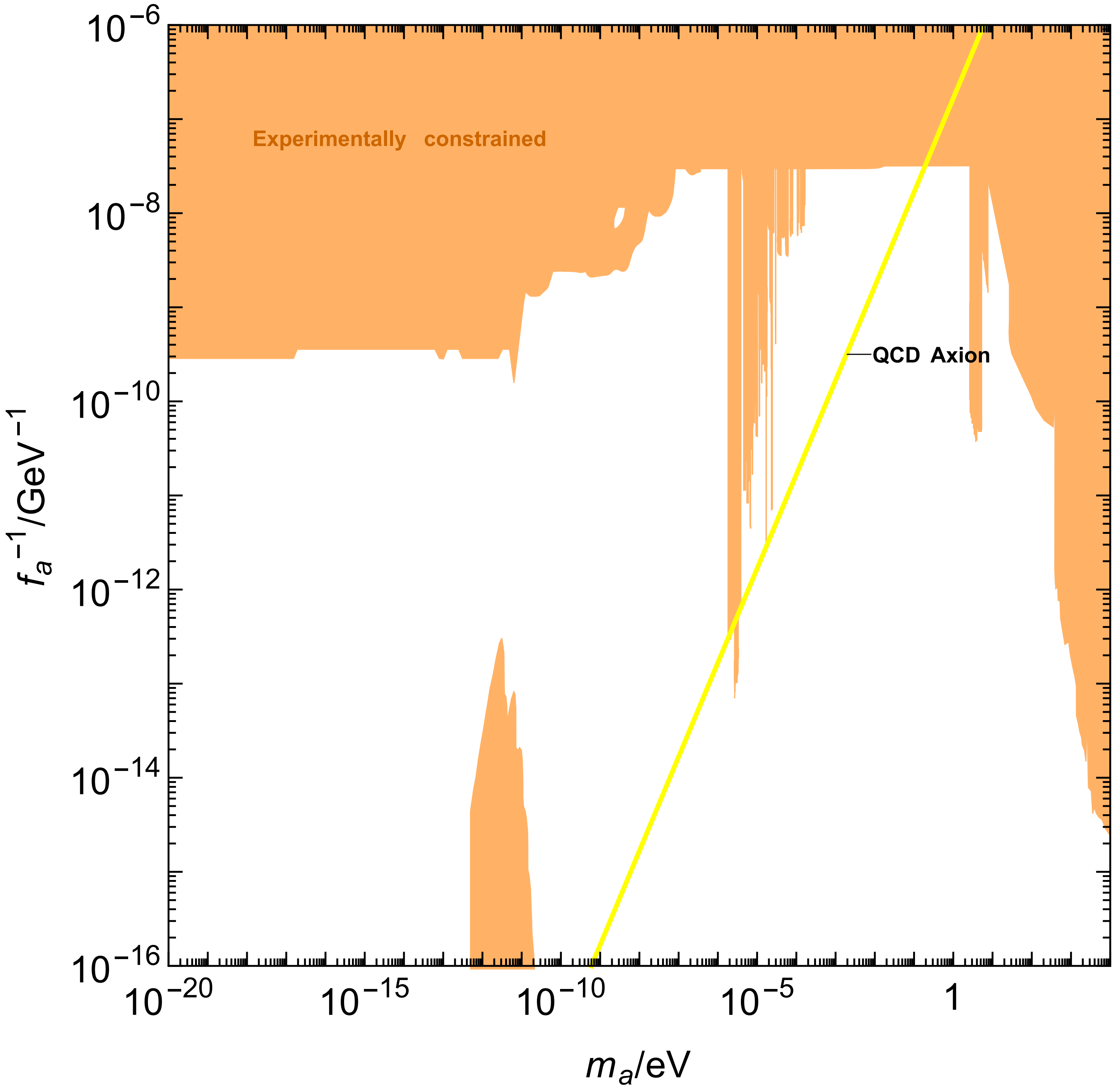


$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

If long-lived: Dark Matter candidate

The Axion-Like-Particle (ALP) parameter space.

If axions are given an interaction to photons then a long list of constraints from ALP searches apply



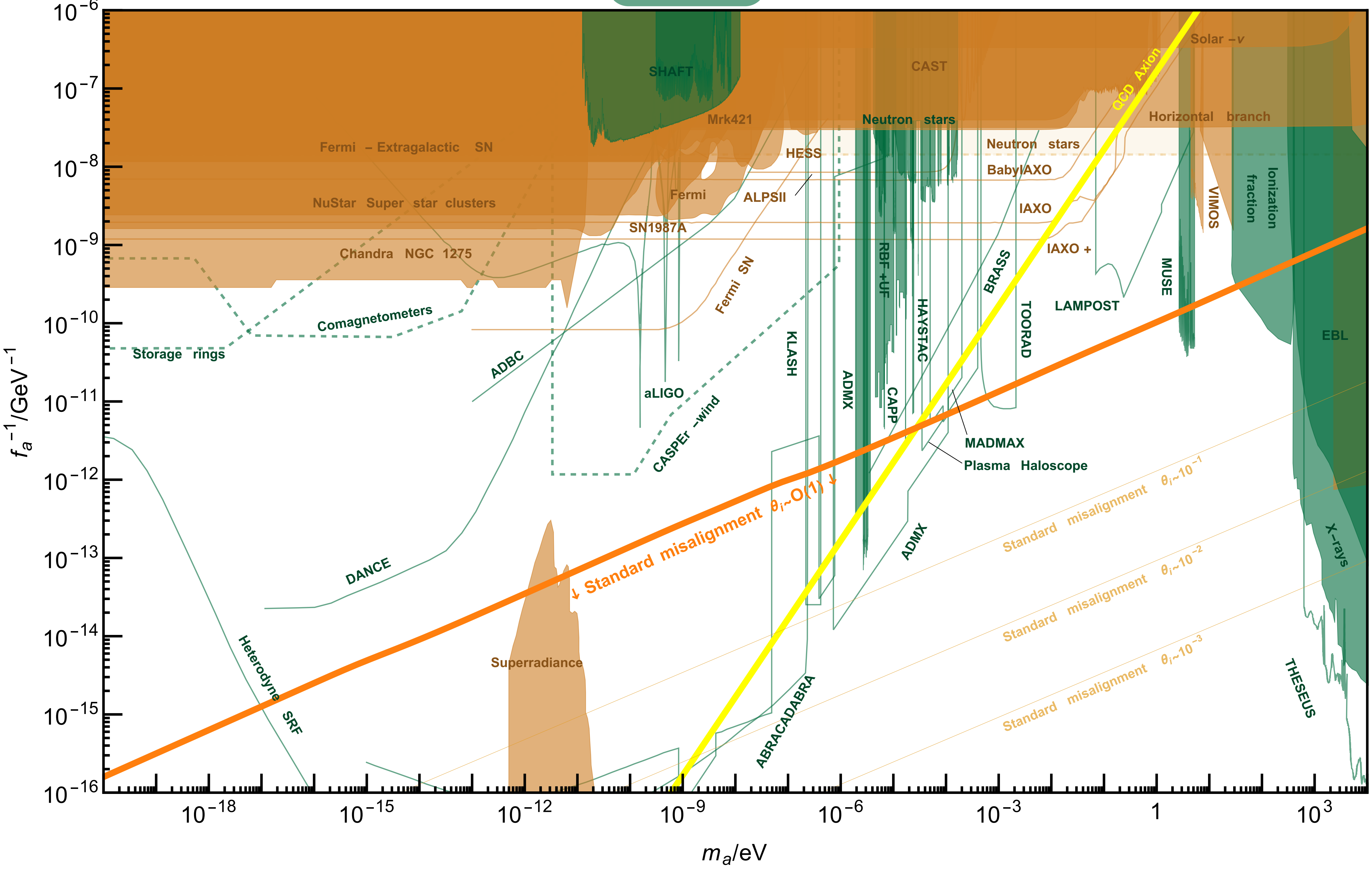
$$\frac{f_\gamma}{f_a} \approx 0.5 \times 10^3$$

assuming KSVZ-like coupling

The hunt for axions.

Any ALP

Only DM



Which of these axions can make Dark Matter ?

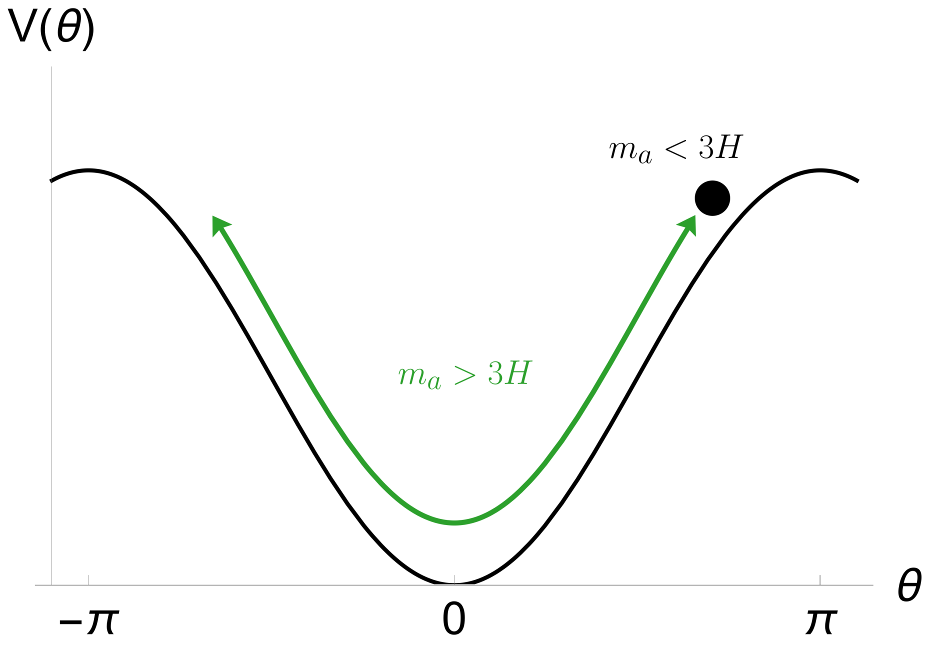
Axions from the misalignment mechanism.

Start with ALP lagrangian $\mathcal{L} = \frac{1}{2} g^{\mu\nu}\partial_\mu a \partial_\nu a - V(\phi) = \frac{1}{2} g^{\mu\nu}\partial_\mu a \partial_\nu a - m_a^2(T) f^2 \left[1 - \cos\left(\frac{a}{f}\right)\right].$

Define homogeneous zero-mode $\bar{a}(t) \equiv f\Theta(t)$

Neglecting fluctuations, it satisfies $\ddot{\Theta} + 3H\dot{\Theta} + m_a^2(T)\sin(\Theta) = 0,$

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



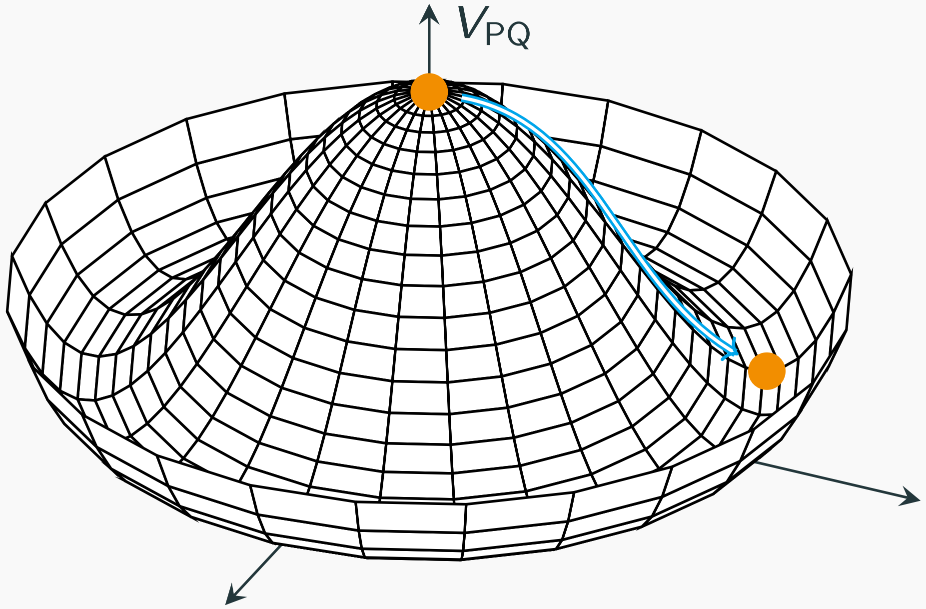
- > $m_a \ll 3H \iff \rho_a \propto a^0$ (Frozen)
- > $m_a \gg 3H \iff \rho_a \propto a^{-3}$ (Oscillating)

-> standard misalignment mechanism

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

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

Pre- and post-inflationary scenarios.



Post-inflationary scenario

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

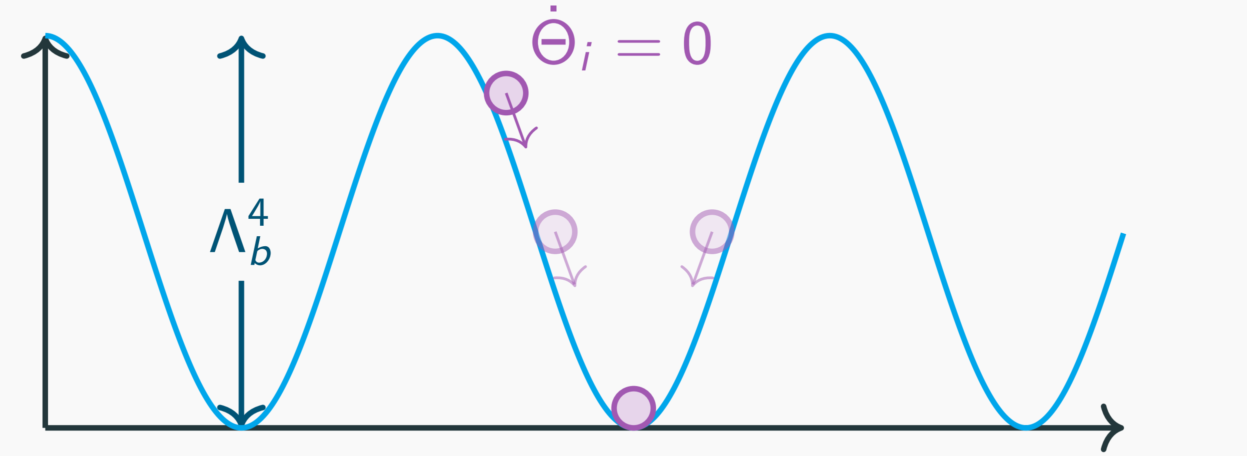
Pre-inflationary scenario **(This work)**

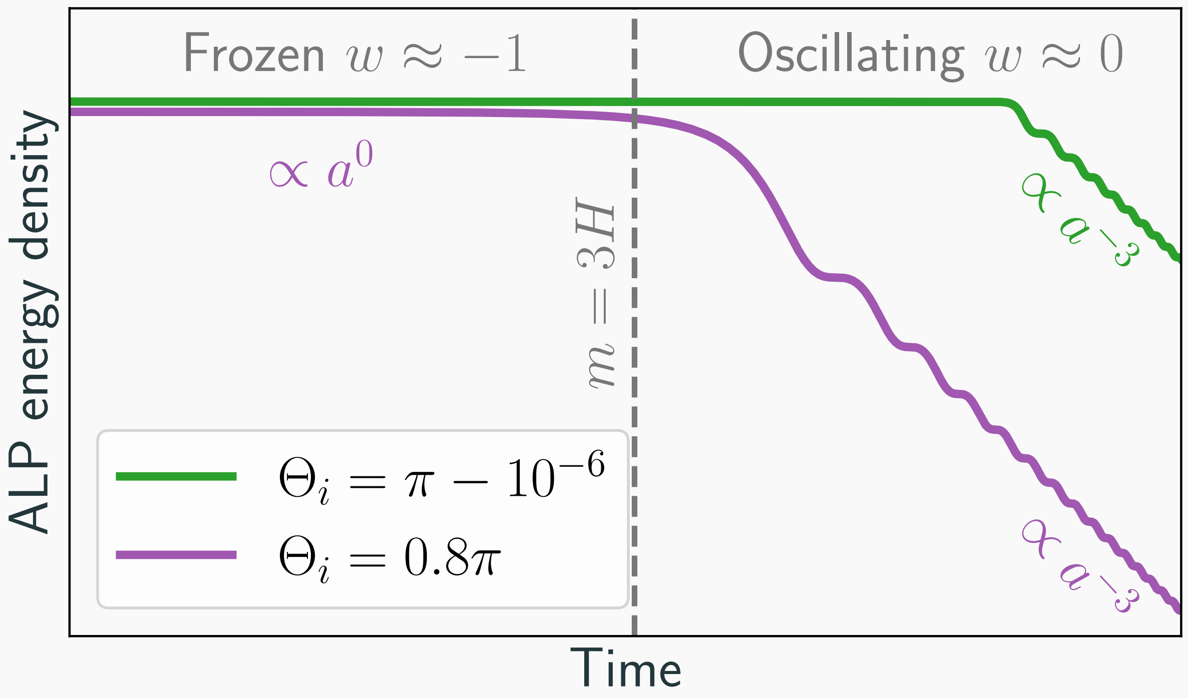
- Random initial angle in the observable universe.
- Initially homogeneous w/o topological defects.

Standard versus kinetic Misalignment.

Standard (Large) misalignment

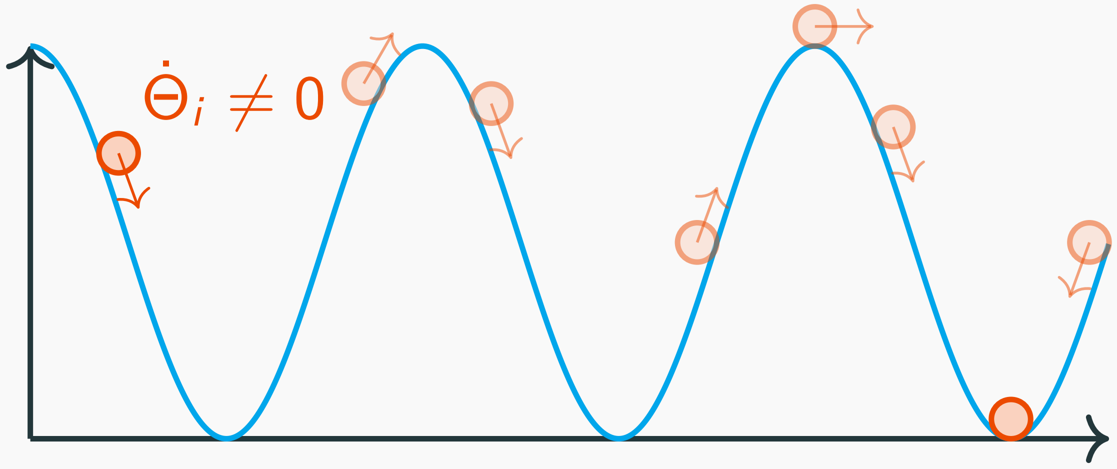
Zhang,Chiueh 1705.01439; Arvanitaki et al. 1909.11665

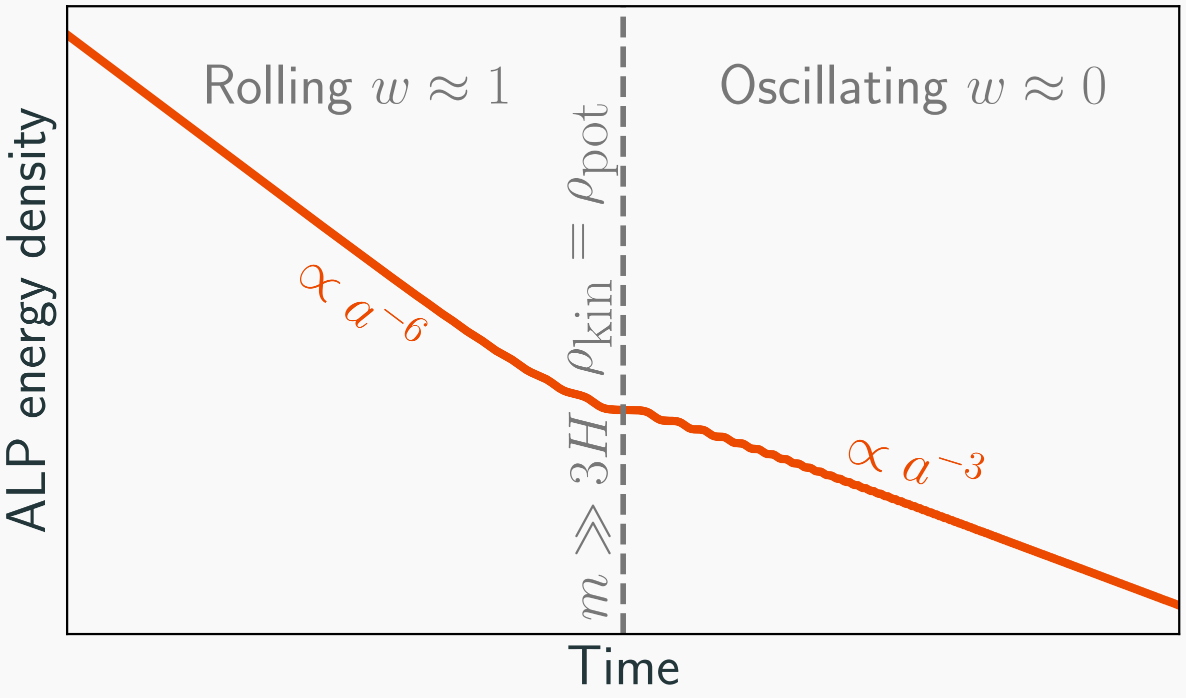




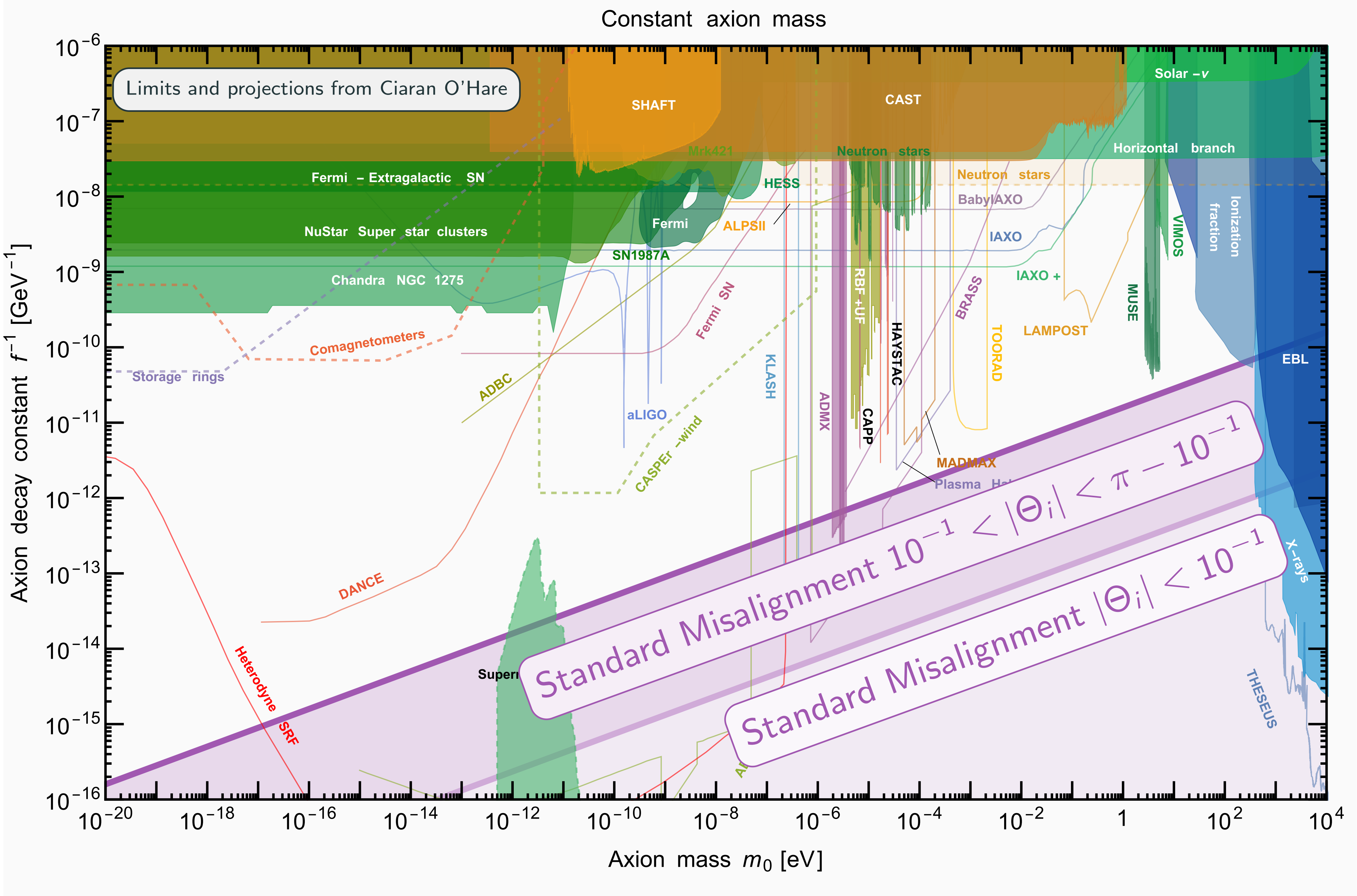
Kinetic misalignment

Co et al. 1910.14152





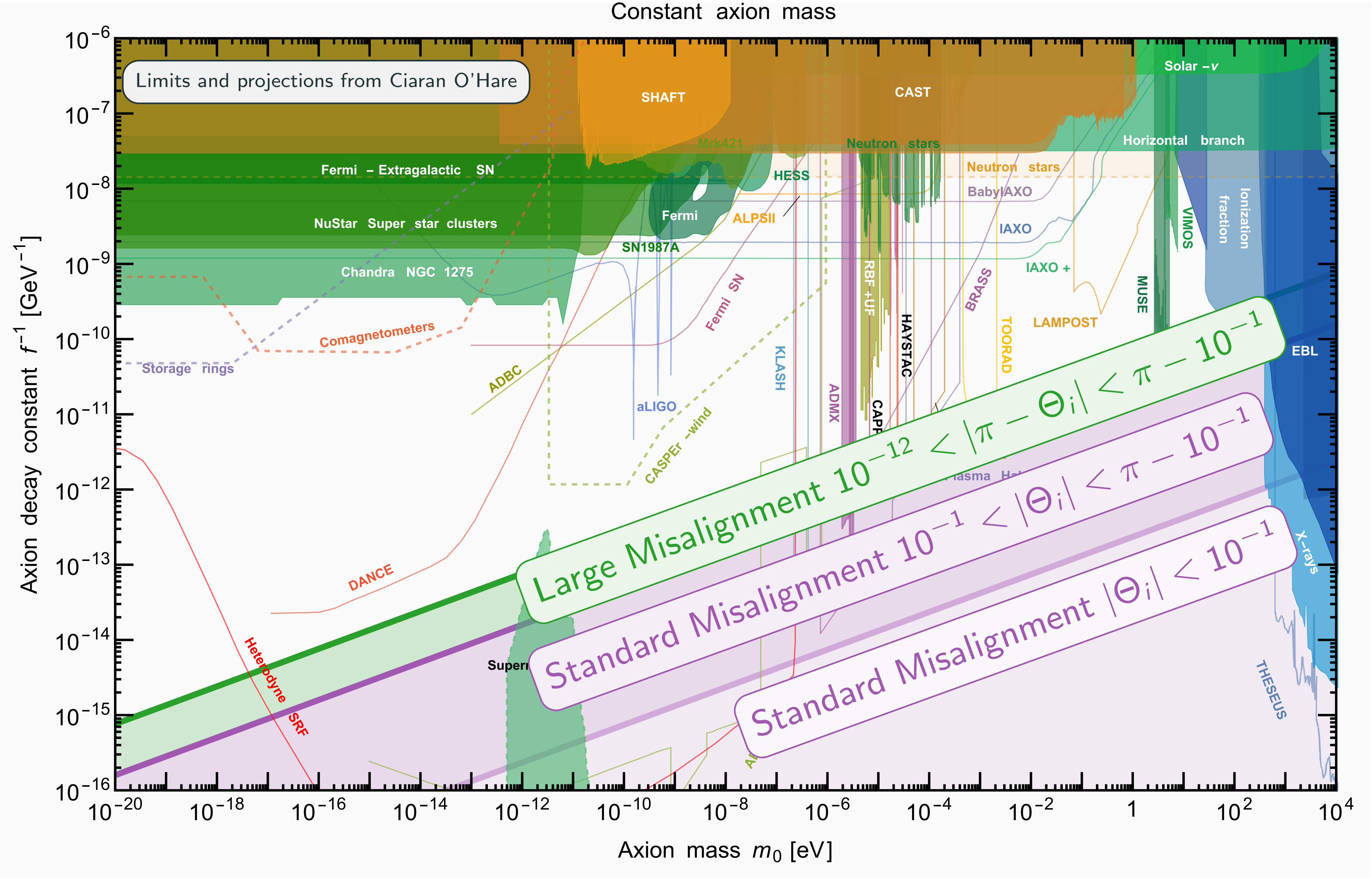
ALP DM parameter space.



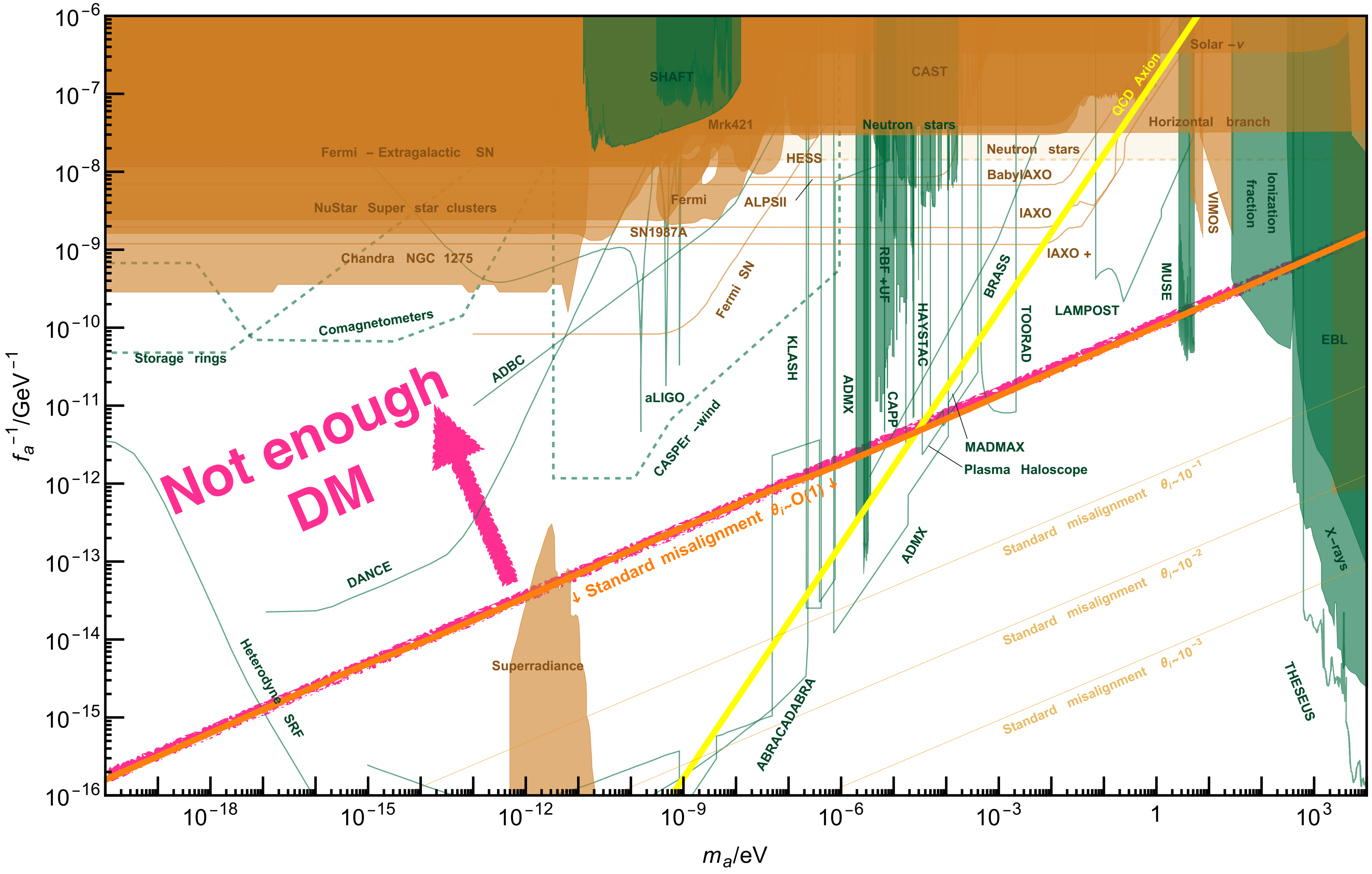
(KSVZ-like coupling)

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

ALP DM parameter space.



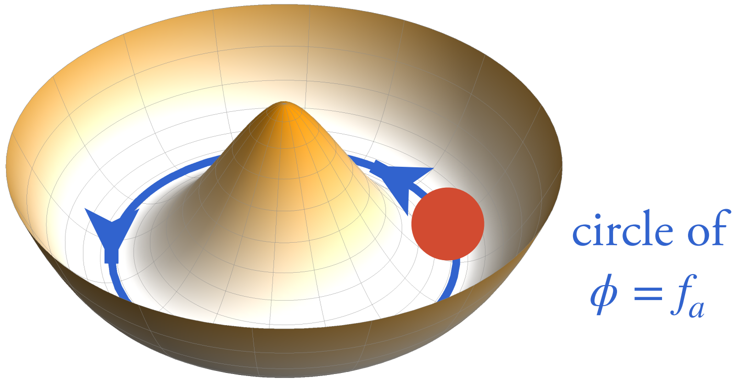
Conventional misalignement makes too little DM for low f_a .

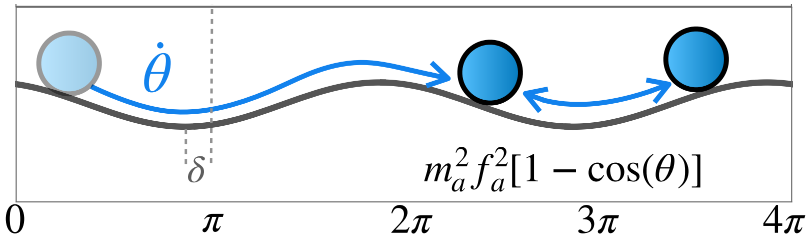


A way out: switch on initial velocity for the axion

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

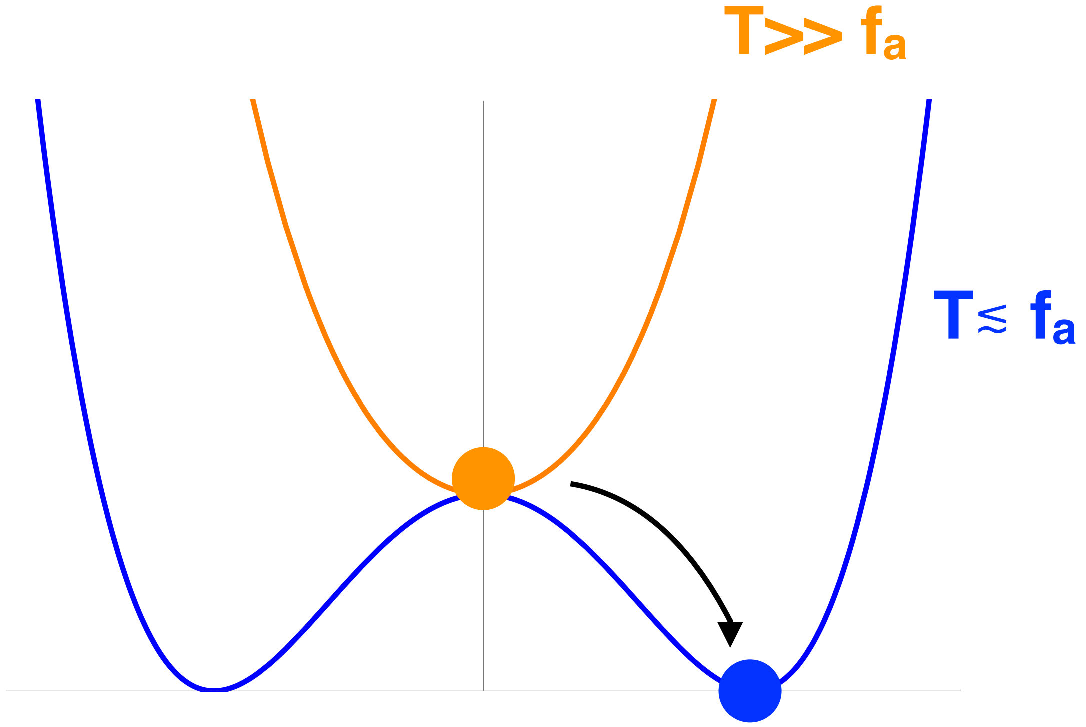
Co, Harigaya et al '19
Chang, Cui'19

Axion cosmology.

“Usual” story:

Starts at <ϕ>=0

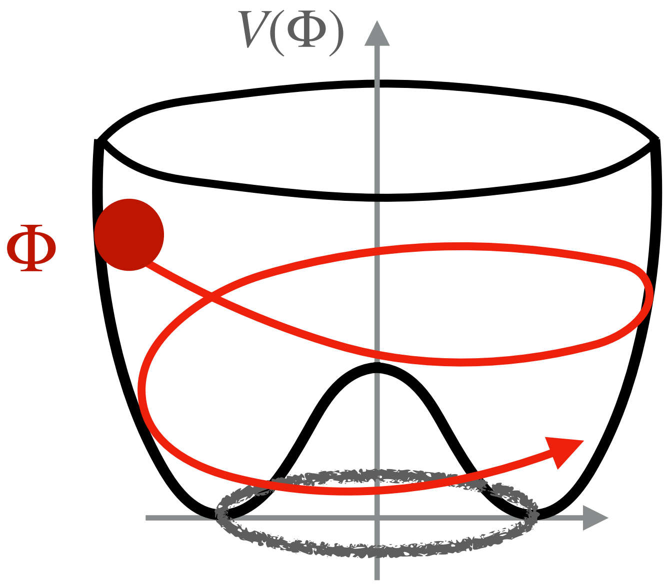
Studies axion cosmology ignoring the radial mode



Alternative:

Starts at <ϕ> >> f$_a$

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

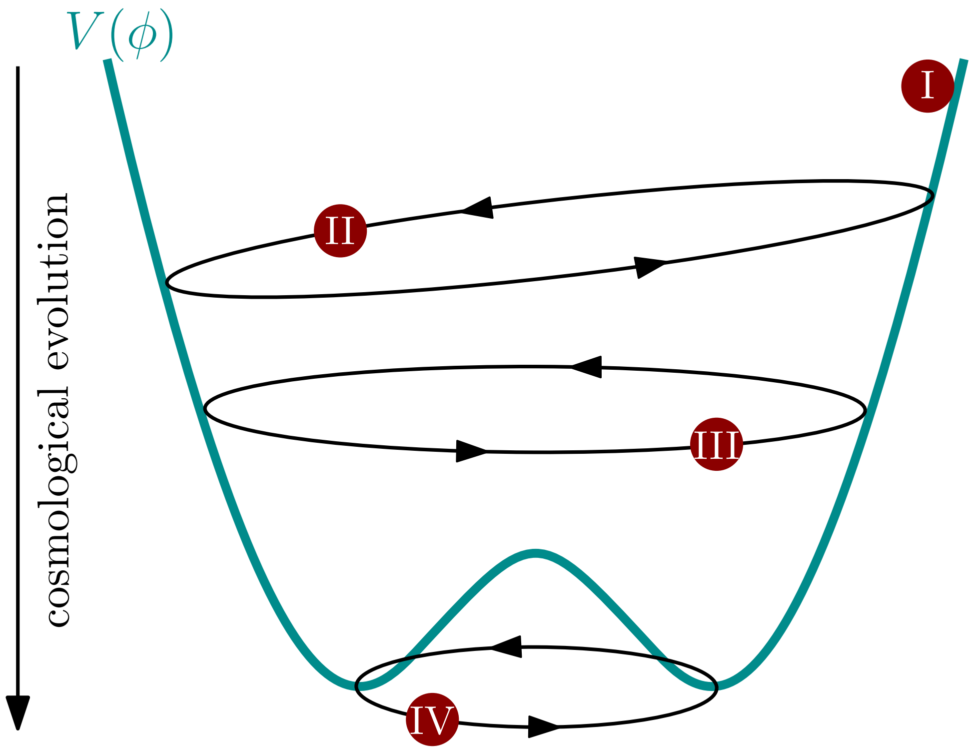


Figure by P. Simakachorn

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 !

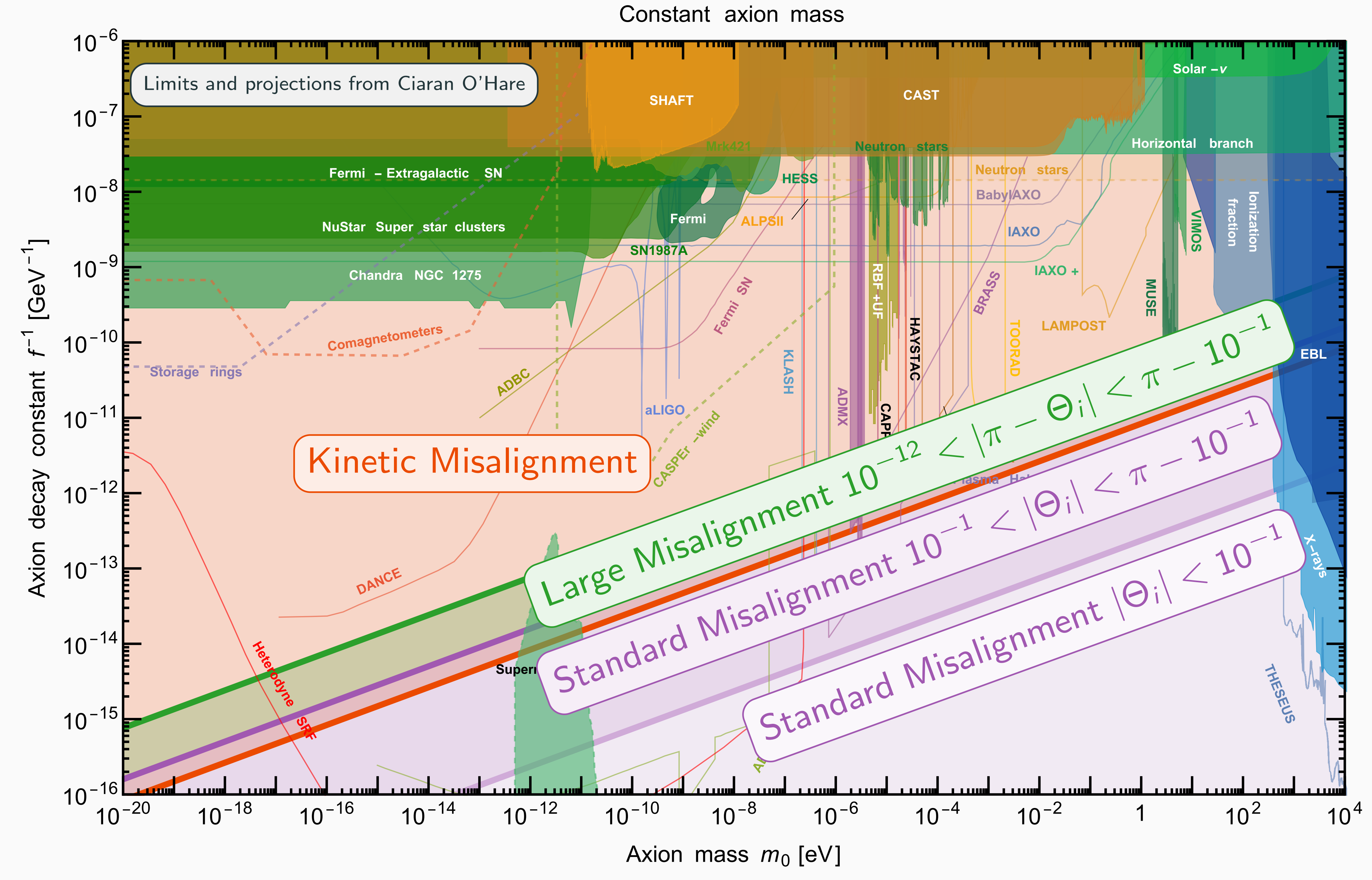
-> kinetic misalignment mechanism

[Co, Harigaya, Hall'19

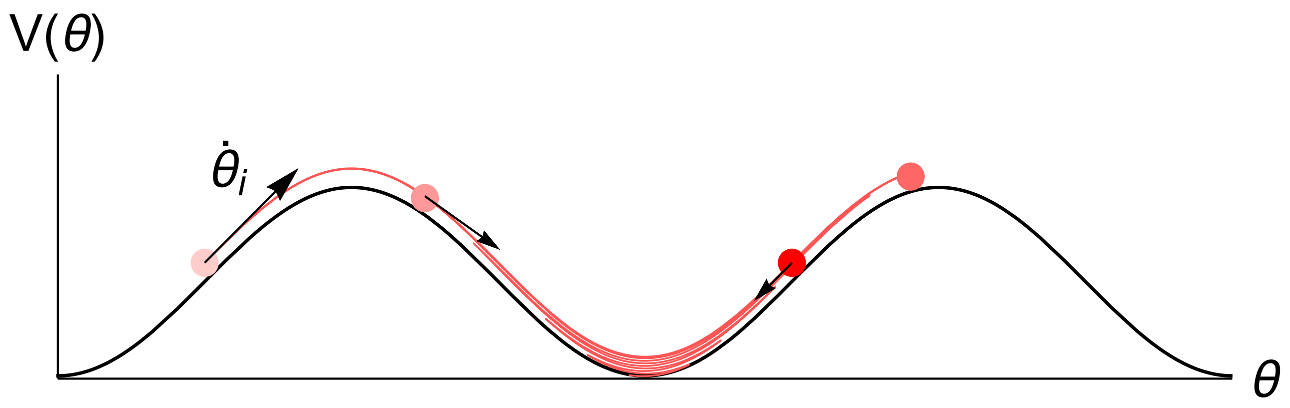
1910.14152

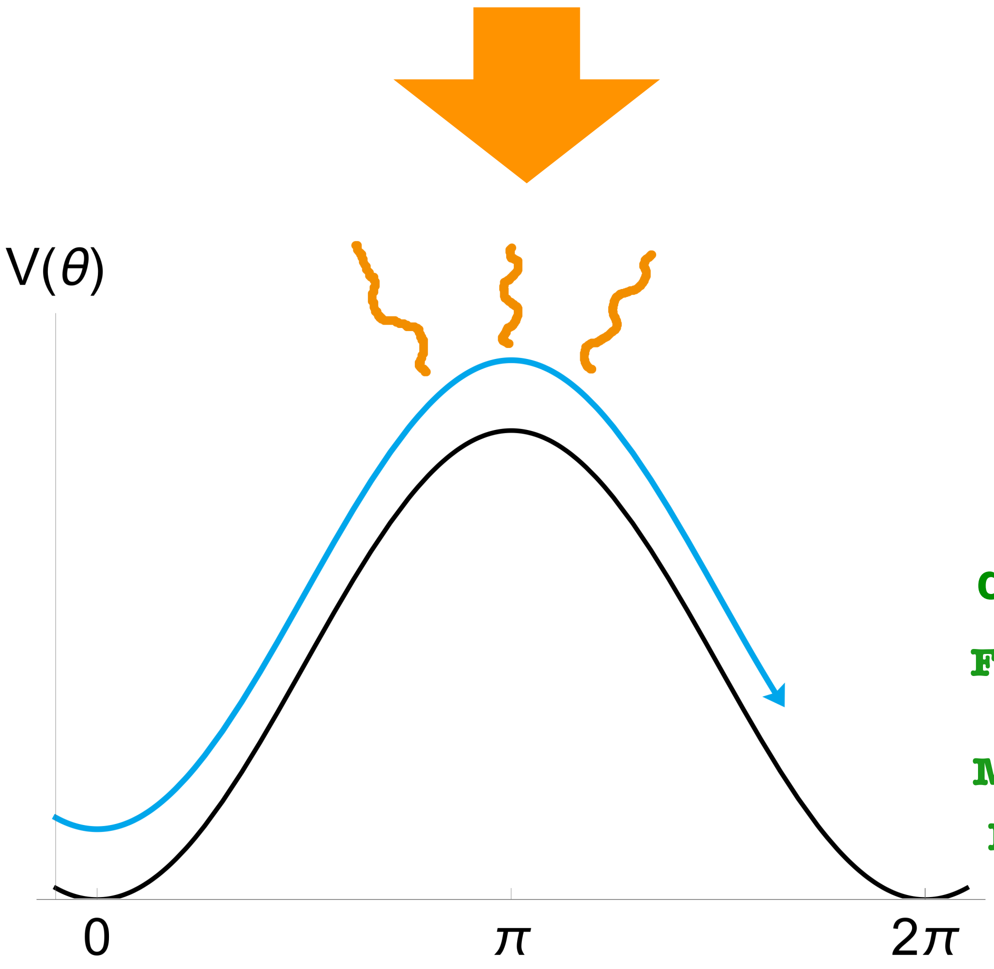
2004.00629

ALP DM parameter space.



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'22, to appear

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

This work (Eroncel et al’22, to appear):

Generalization
(fragmentation before and after trapping + detailed application to DM)

ALP fluctuations.

- **Even in the 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.**

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

- **These fluctuations are seeded by adiabatic and/or isocurvature perturbations:**

Adiabatic perturbations **(This work)**

- Due to the energy density perturbations of the dominating component, **unavoidable**.
- Initial conditions in the super-horizon limit:

$$\frac{\delta_i}{1+w_i} = \frac{\delta_j}{1+w_j}$$

Isocurvature perturbations

- If ALPs exist during inflation and are light $m \ll H_{\rm inf}$, they pick up quantum fluctuations:

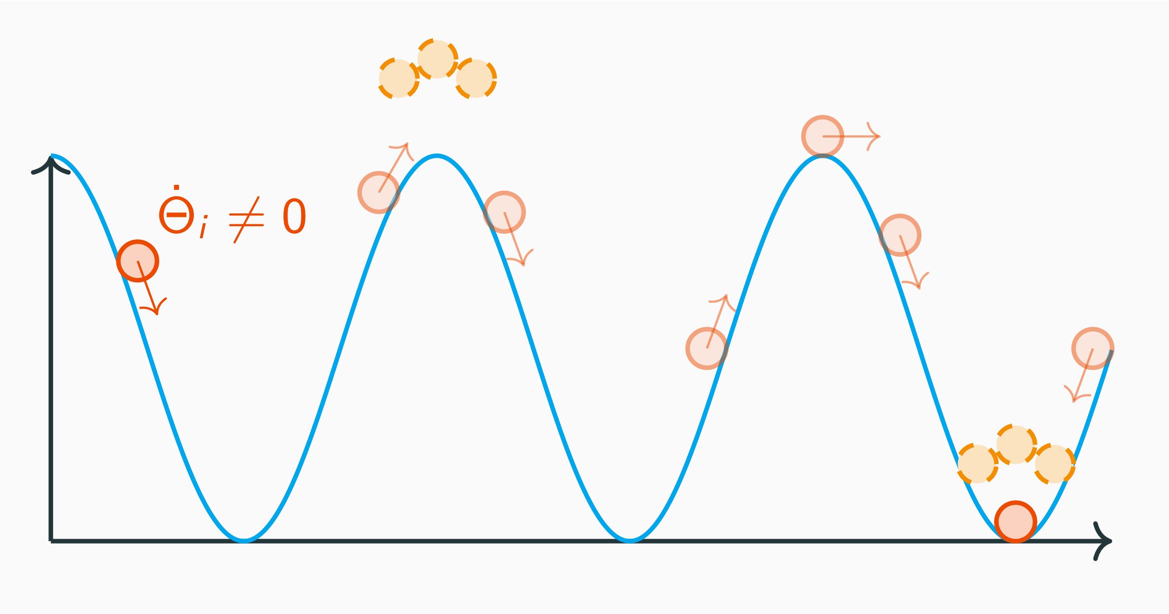
$$\delta\theta \sim \frac{H_{\rm inf}}{2\pi f_{\rm inf}}$$

- Can be avoided/suppressed if ALP has a large mass during inflation, or $f_{\rm inf} \gg f_{\rm today}$.

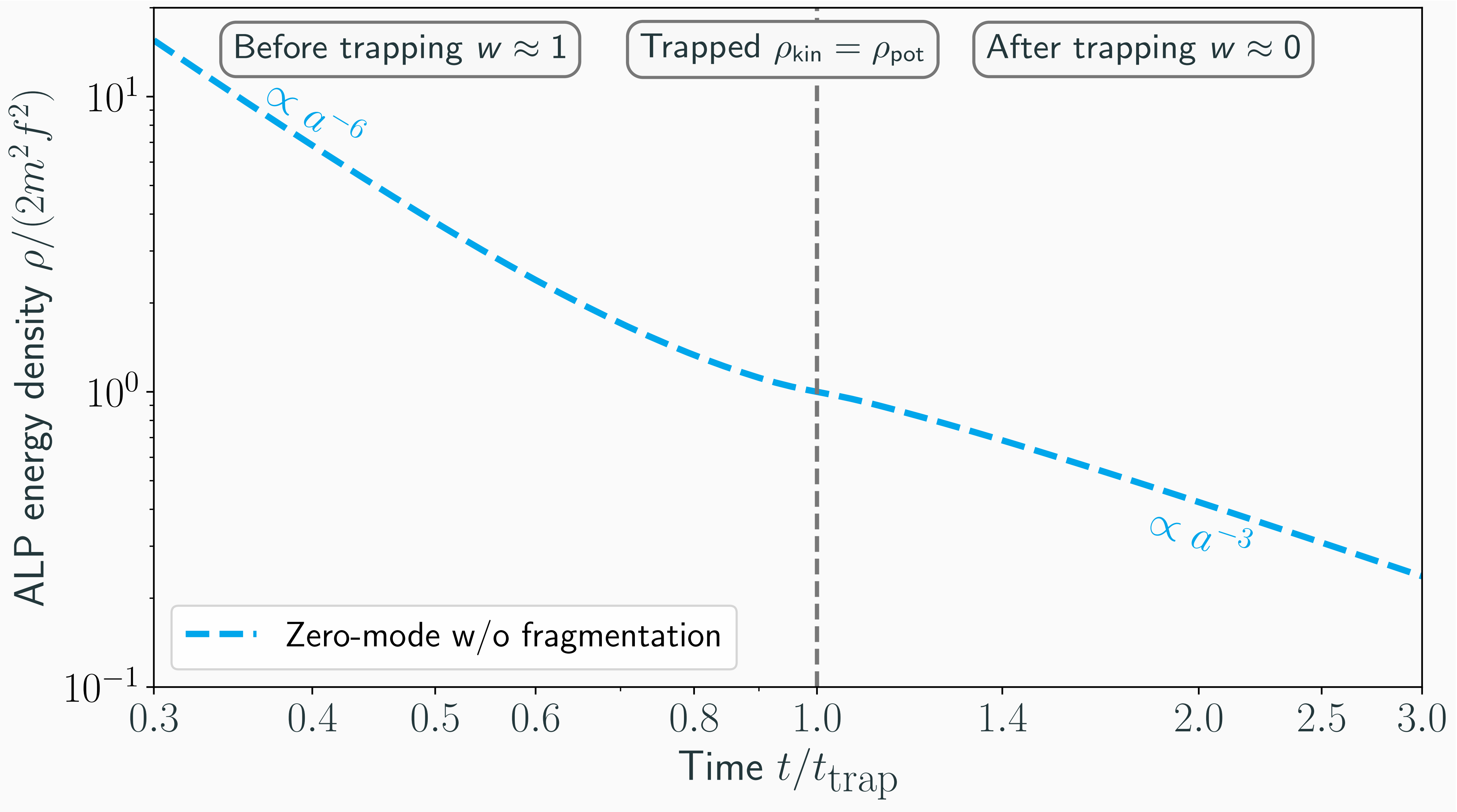
ALP fluctuations.

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

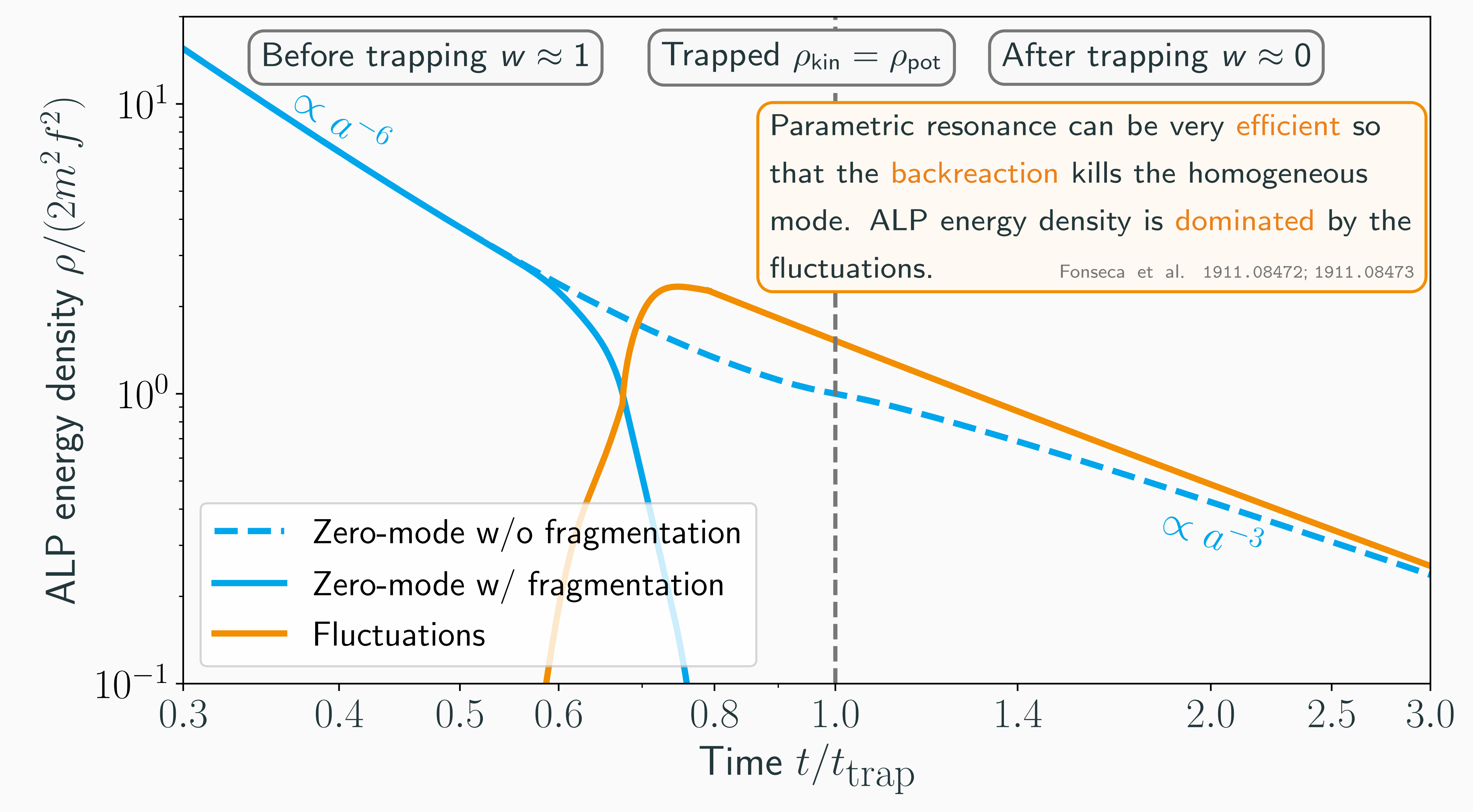
- In the case of efficient fragmentation, all the energy of the homogeneous mode can be transferred to the fluctuations. [Fonseca et al. 1911.08472; Morgante et al. 2109.13823]



Axion fragmentation in kinetic misalignment.



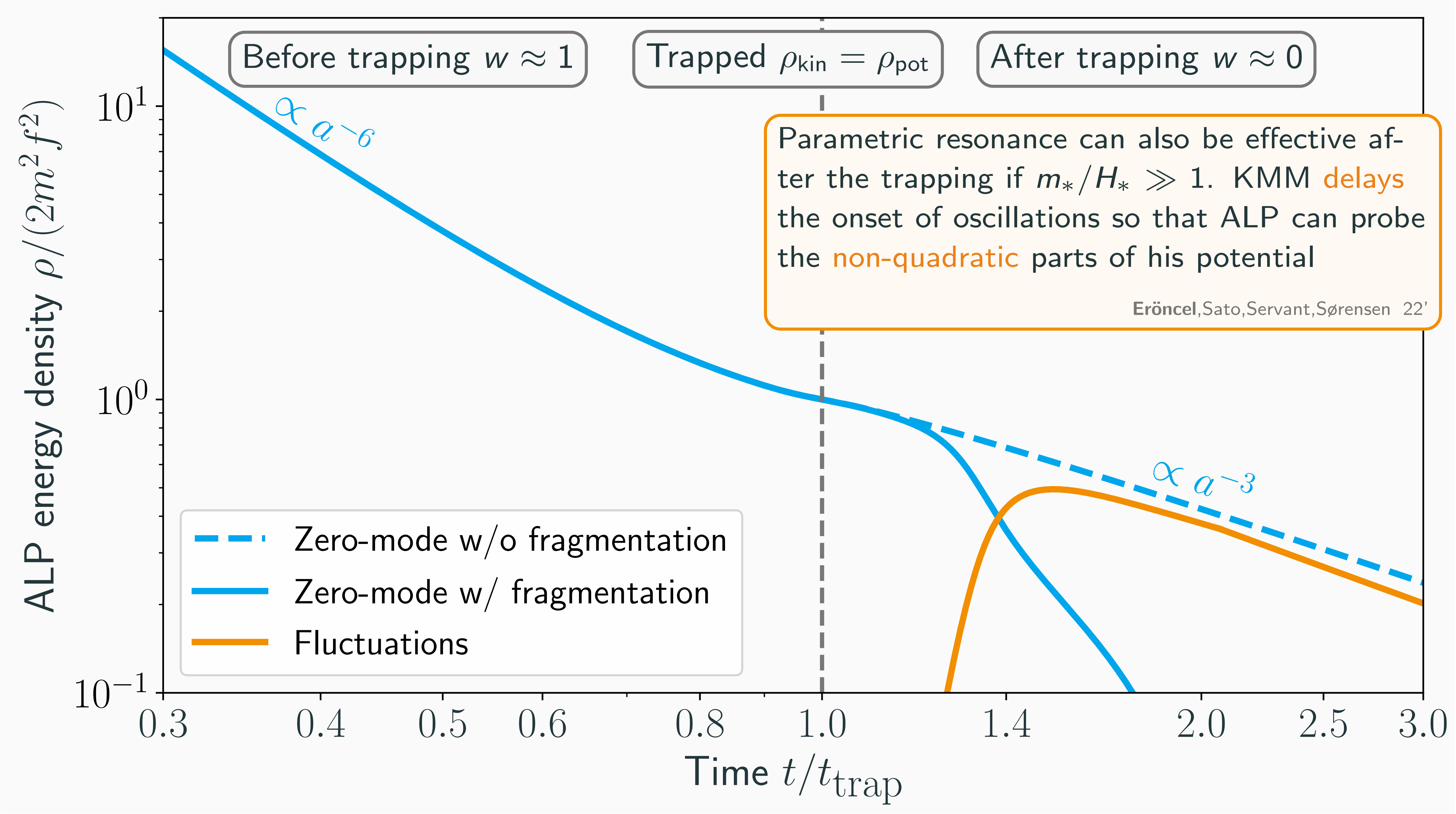
Axion fragmentation in kinetic misalignment.



Parametric resonance can be very efficient so that the backreaction kills the homogeneous mode. ALP energy density is dominated by the fluctuations.

Fonseca et al. 1911.08472; 1911.08473

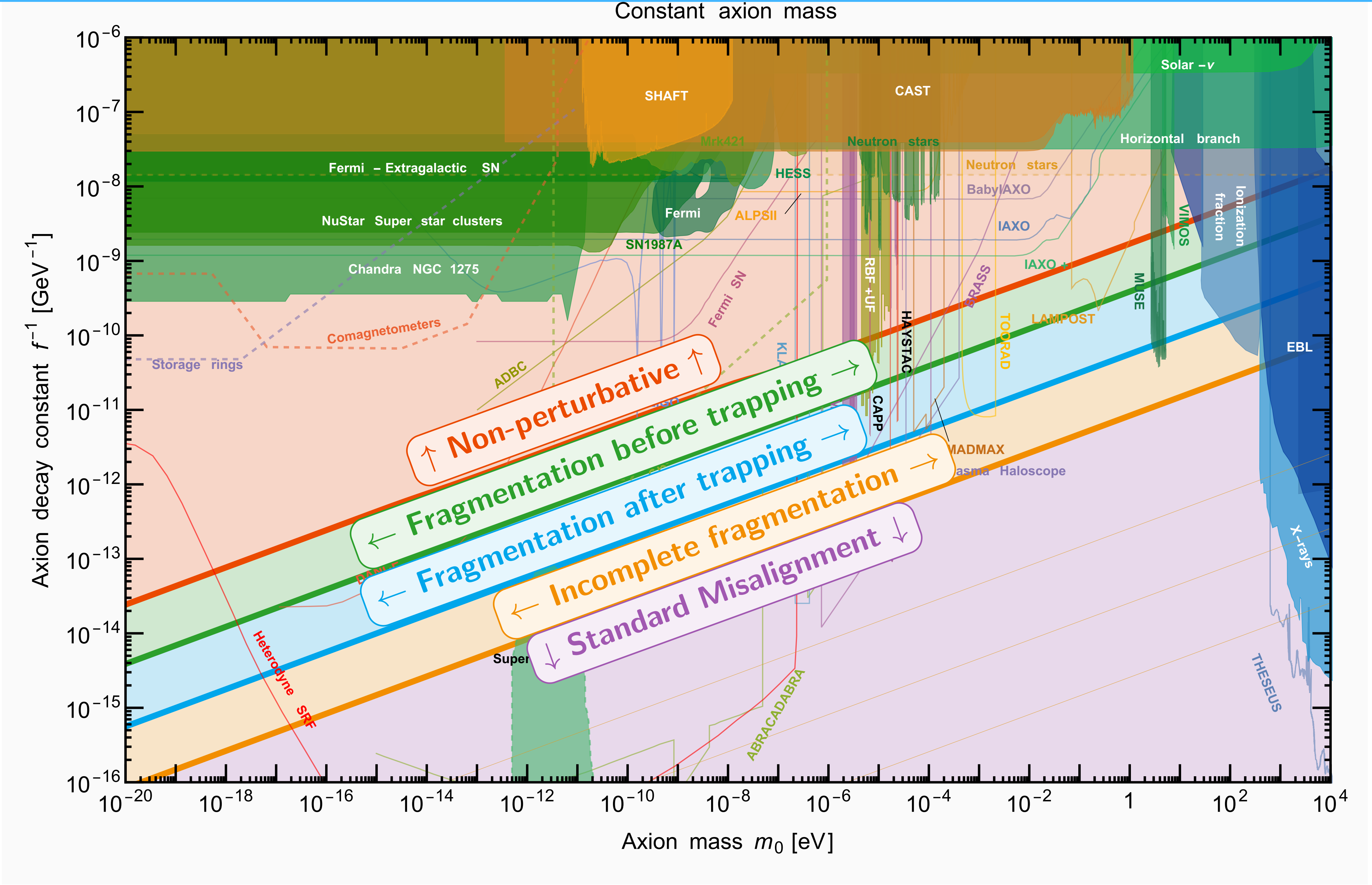
Axion fragmentation in kinetic misalignment.



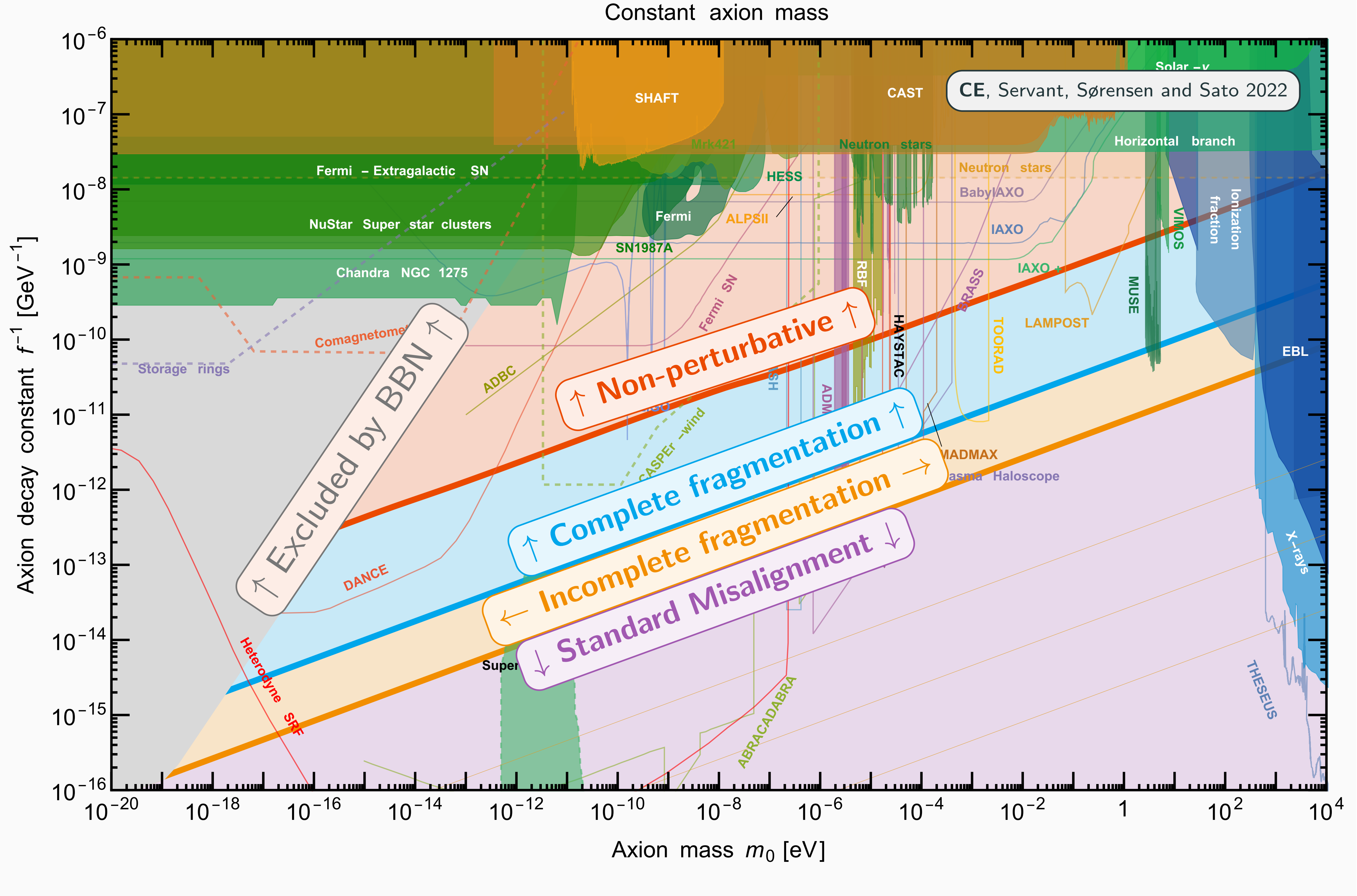
Parametric resonance can also be effective after the trapping if $m_*/H_* \gg 1$. KMM delays the onset of oscillations so that ALP can probe the non-quadratic parts of his potential

Eröncel,Sato,Servant,Sørensen 22'

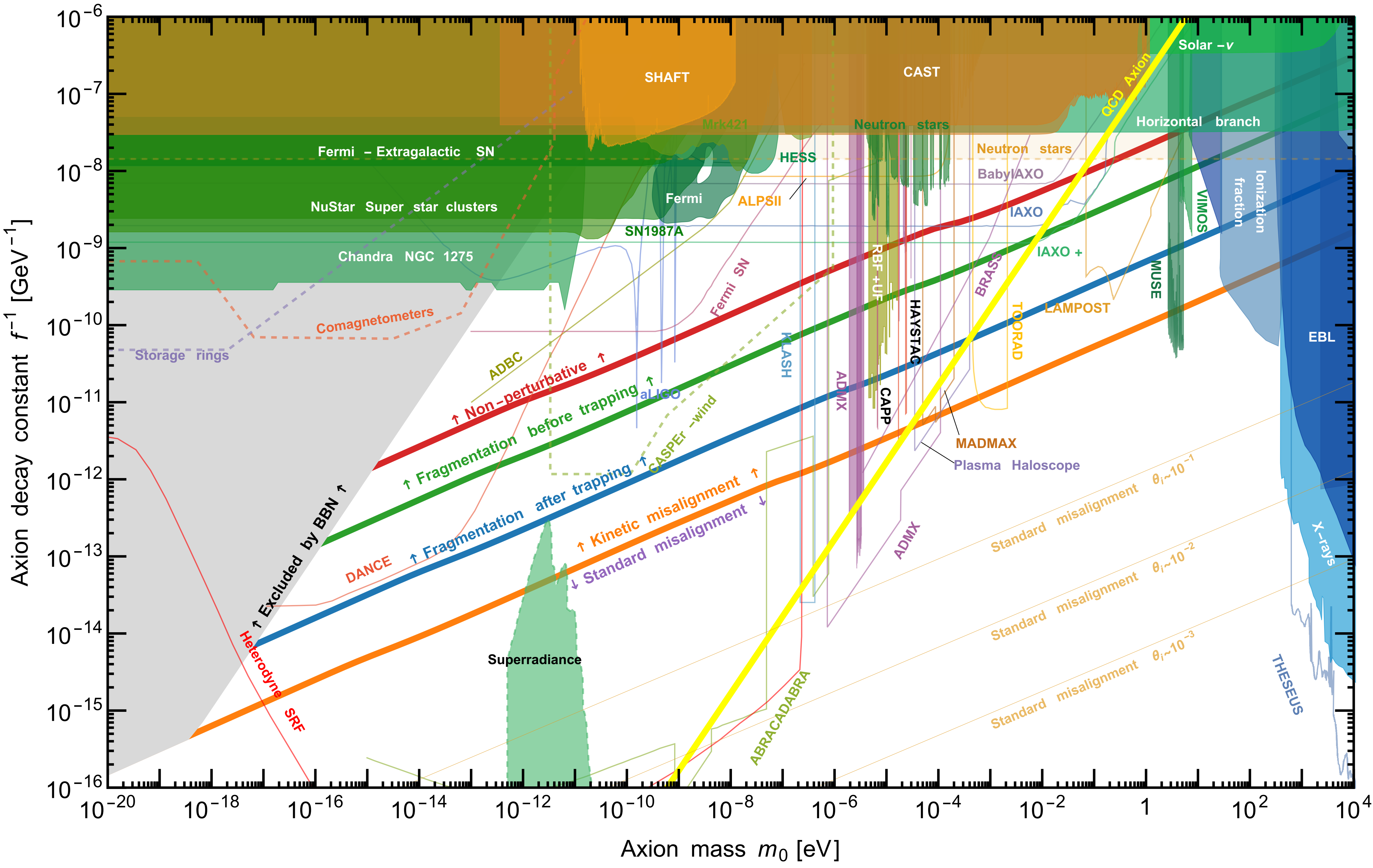
Fragmentation regions in ALP parameter space.



Fragmentation regions in ALP parameter space.

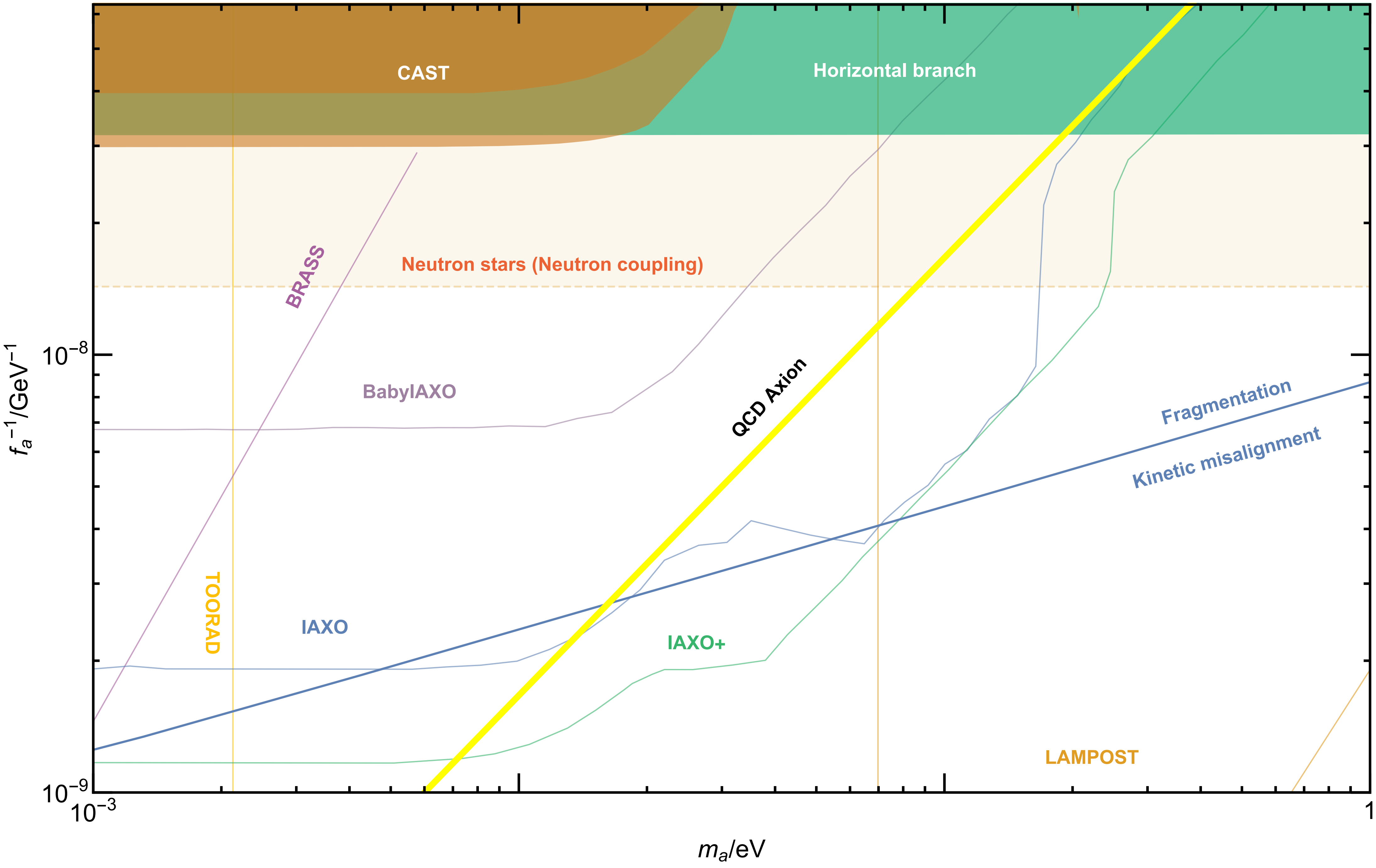


Temperature-dependent axion mass with $\gamma=8$



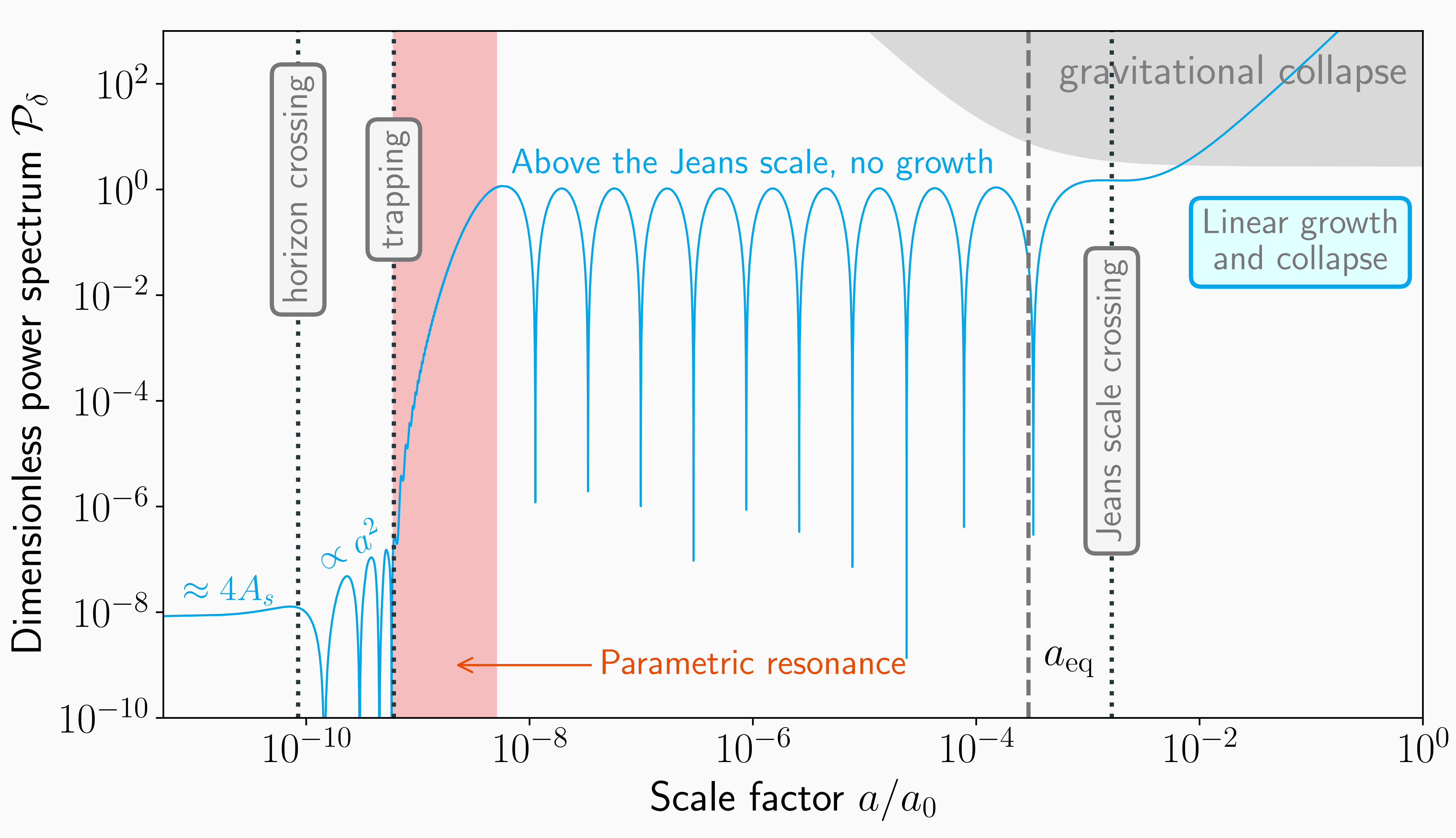
[Eroncel, Sato, Servant, Soerensen, to sppear.]

Experimental reach.

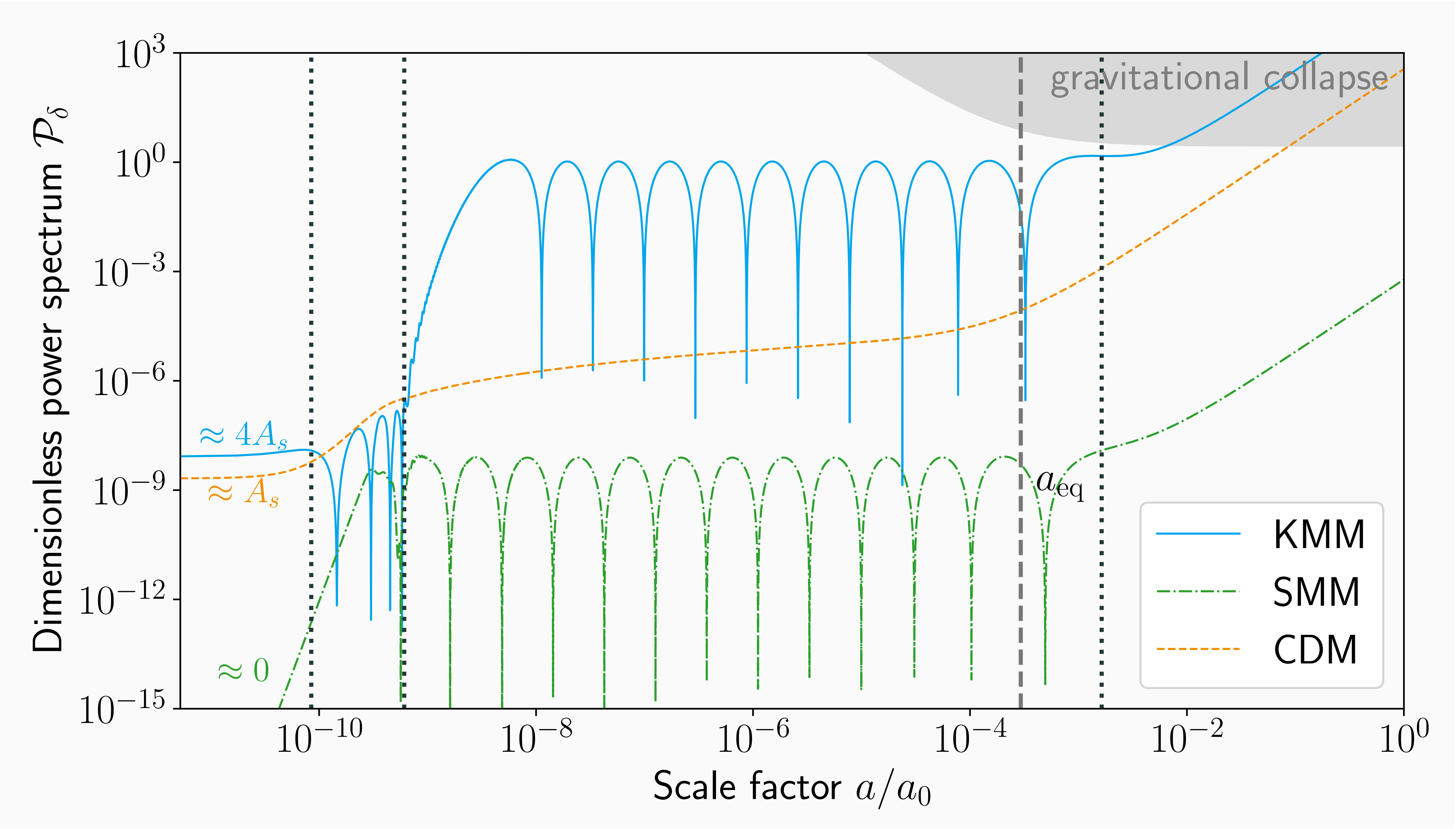


Observational prospects ?

Lifetime of a fluctuation .



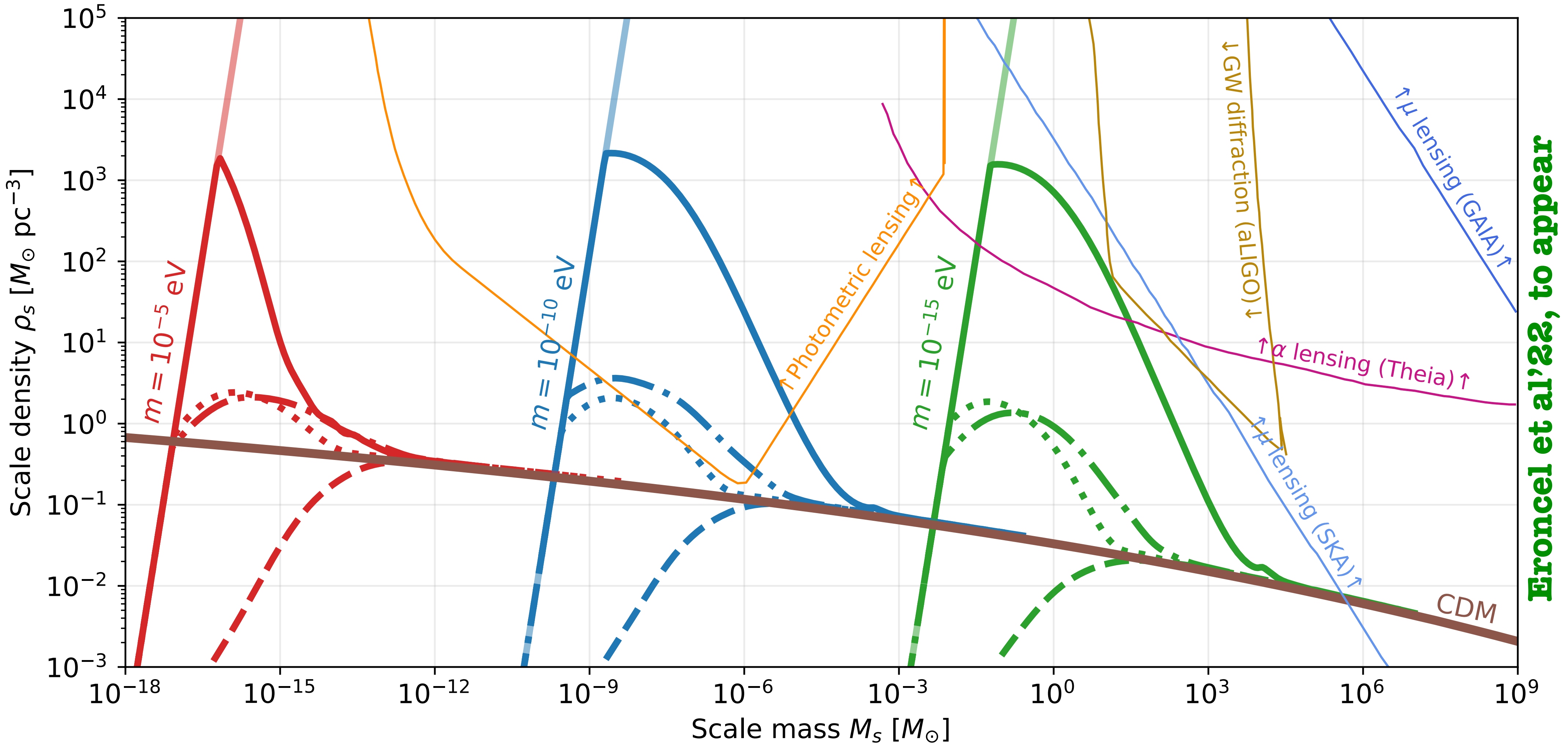
Lifetime of a fluctuation .



Observational tests: compact axion halos.

axion fragmentation-> structure formation enhancement

Scale density of axion compact structures



fragmentation

post-inflationary

standard misalignment

large misalignment

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

Different in the context of axion kinetic fragmentation: Eroncel et al'22, to appear

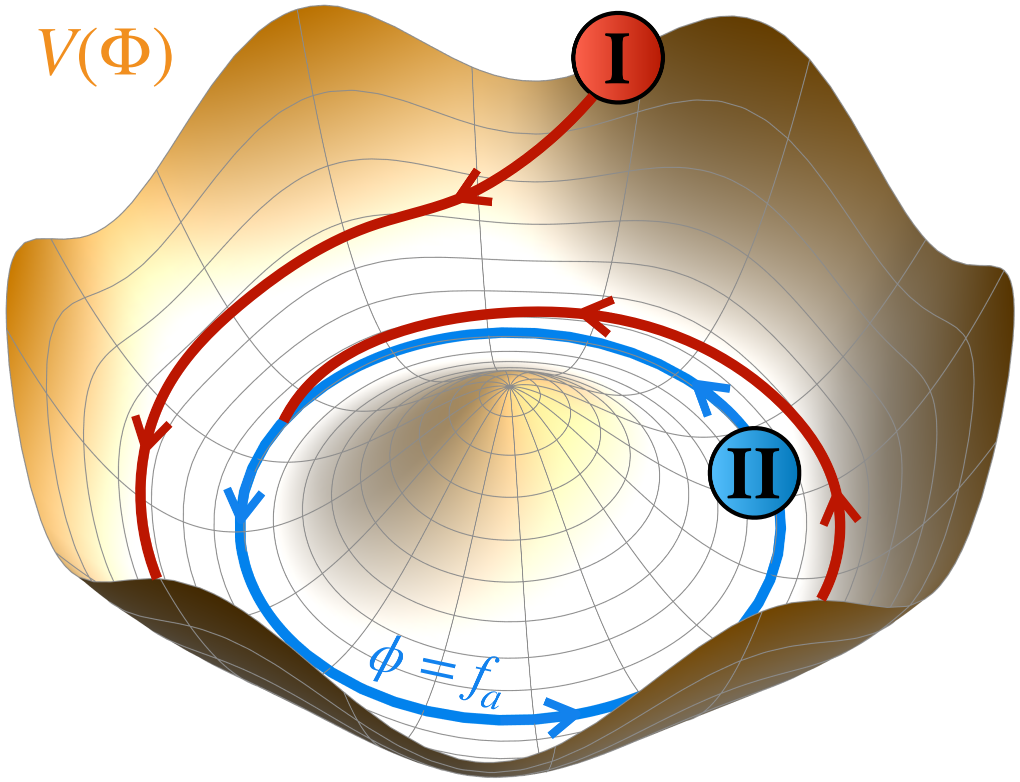
Concrete UV realizations .

Spinning axion .

Complex scalar field

"Affleck-Dine Baryogenesis" (Affleck, Dine, 1985)

"Axiogenesis" (Co, Hall, Harigaya, et. al., '19)



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

$$V(\Phi) = m_r^2|\Phi|^2\left[\log\left(\frac{|\Phi|^2}{f_a^2}\right)-1\right] + \Lambda_b^4\left[\left(\frac{\Phi}{M_{\rm Pl}}\right)^l + \left(\frac{\Phi^\dagger}{M_{\rm Pl}}\right)^l\right] + \frac{\lambda^2}{M_{\rm Pl}^{2l-6}}|\Phi|^{2l-2}$$

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

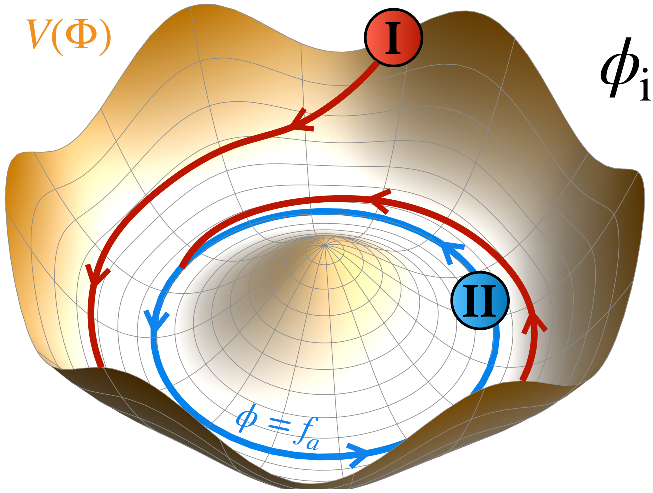
(motivated by supersymmetric setups)

$\propto \cos(l\theta)$
explicit breaking term
(e.g. $U(1)$ is not exact
at high scales.)

stabilization

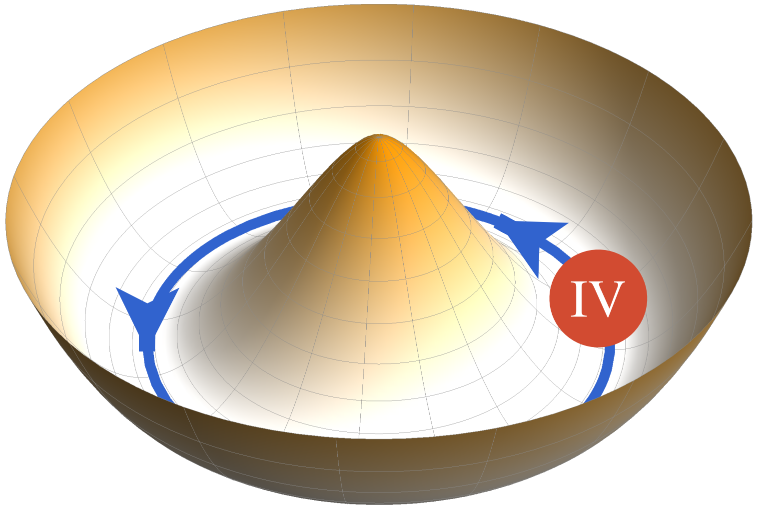
Ingredient 3 : large initial VEV $\phi_{\rm ini}$

Driven away from $\phi = 0$ at early times $(H \gg m_r)$
by a negative Hubble mass $V_H(\Phi, H) \supset -cH^2|\Phi|^2$ (e.g. Dine, Randall, Thomas, 1995)



$$\phi_{\rm ini} \simeq M_{\rm Pl}(m_r/M_{\rm Pl})^{1/(l-2)}$$

Kination from a spinning axion.



circle @ $\phi = f_a$

The conserved $U(1)$-charge is

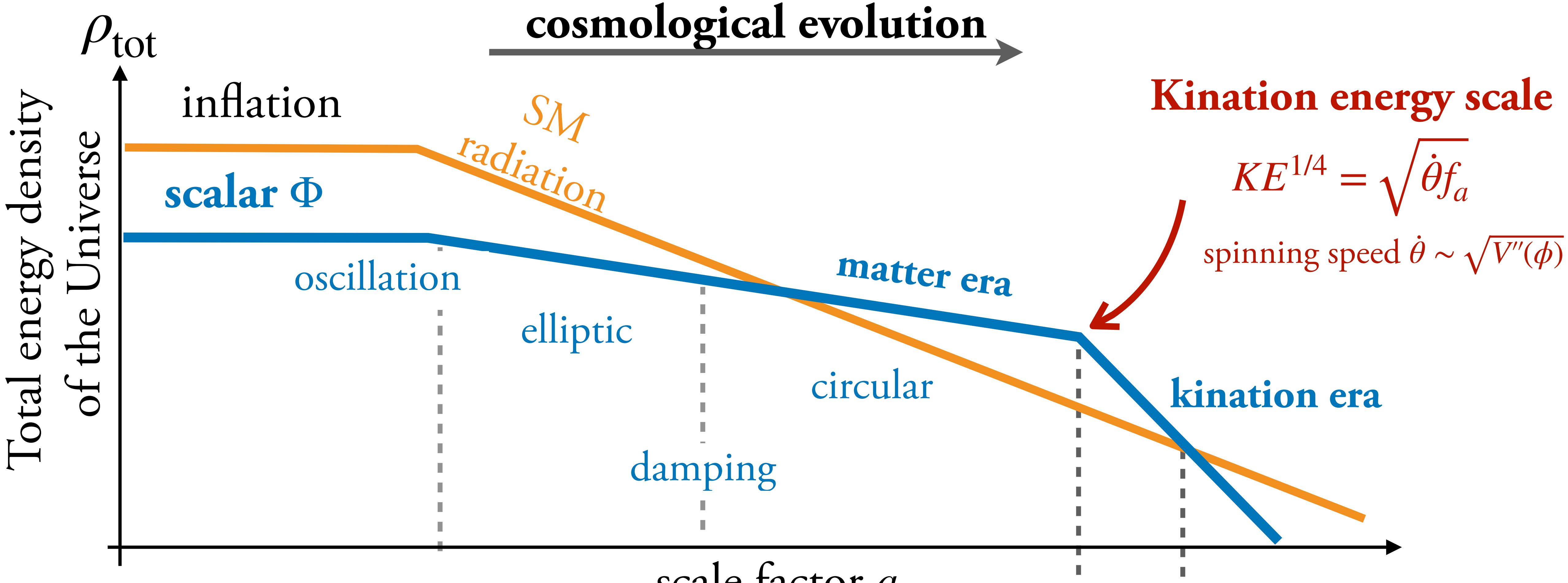
$$\frac{d}{dt}(a^3\phi^2\dot\theta) = 0 \;\Rightarrow\; \dot\theta \propto a^{-3}$$

in rotation

Kinetic energy dominates

$$\rho_\Phi = KE \propto \dot\theta^2 \propto a^{-6}$$

and behaves as kination.



Kination energy scale

$$KE^{1/4} = \sqrt{\dot\theta f_a}$$

spinning speed $\dot\theta \sim \sqrt{V''(\phi)}$

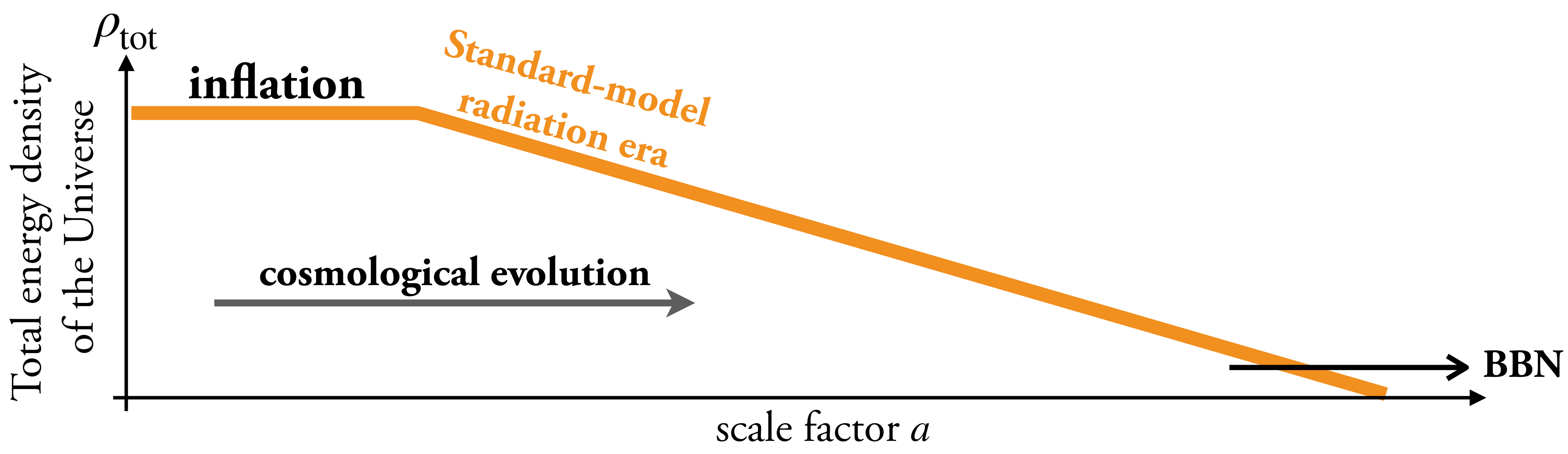
Duration: e-foldings N_{KD}

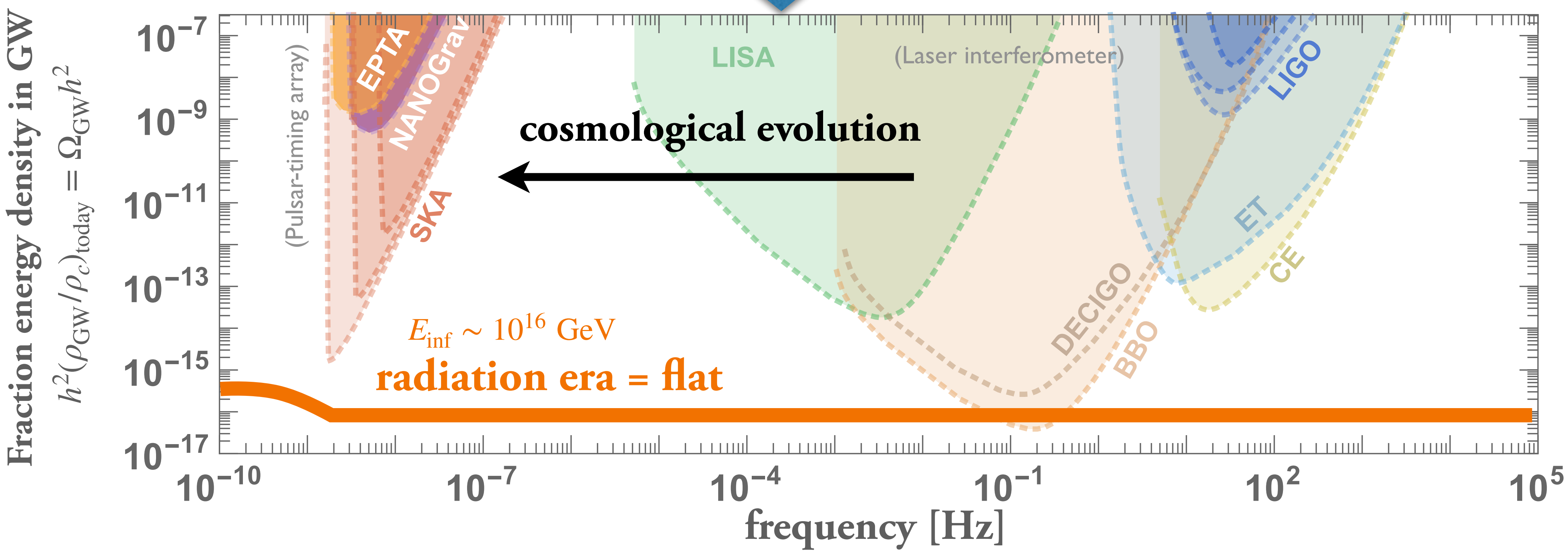
(depended on the matter domination)

Impact of kination on Inflationary Gravitational Waves.

Enhancement of the primordial inflationary gravitational-wave spectrum by a kination era.

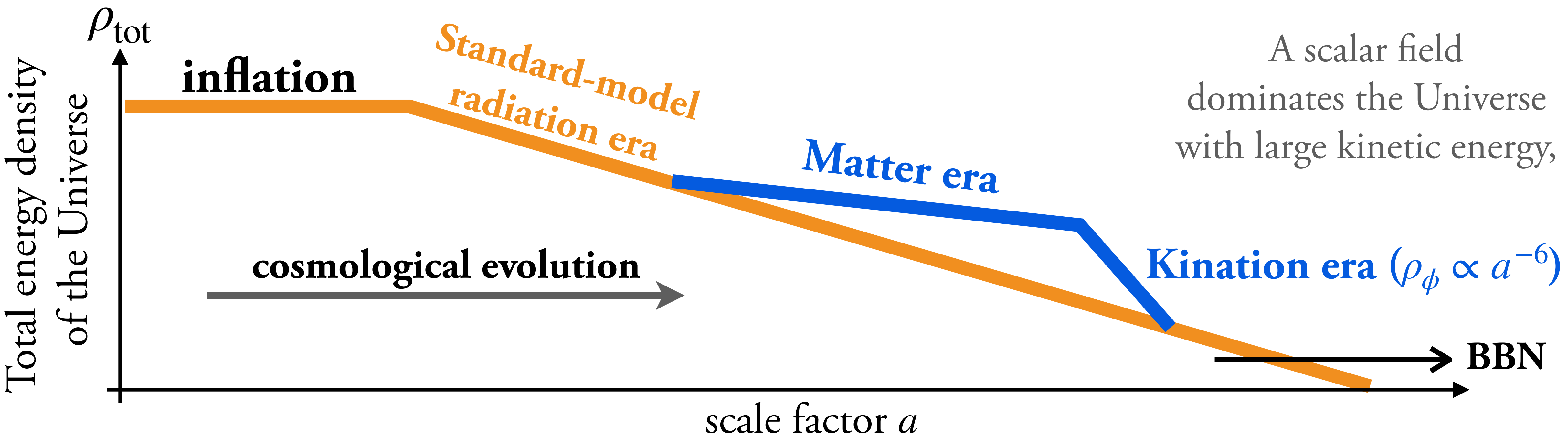
Irreducible GW bgd from quantum fluctuations during inflation .

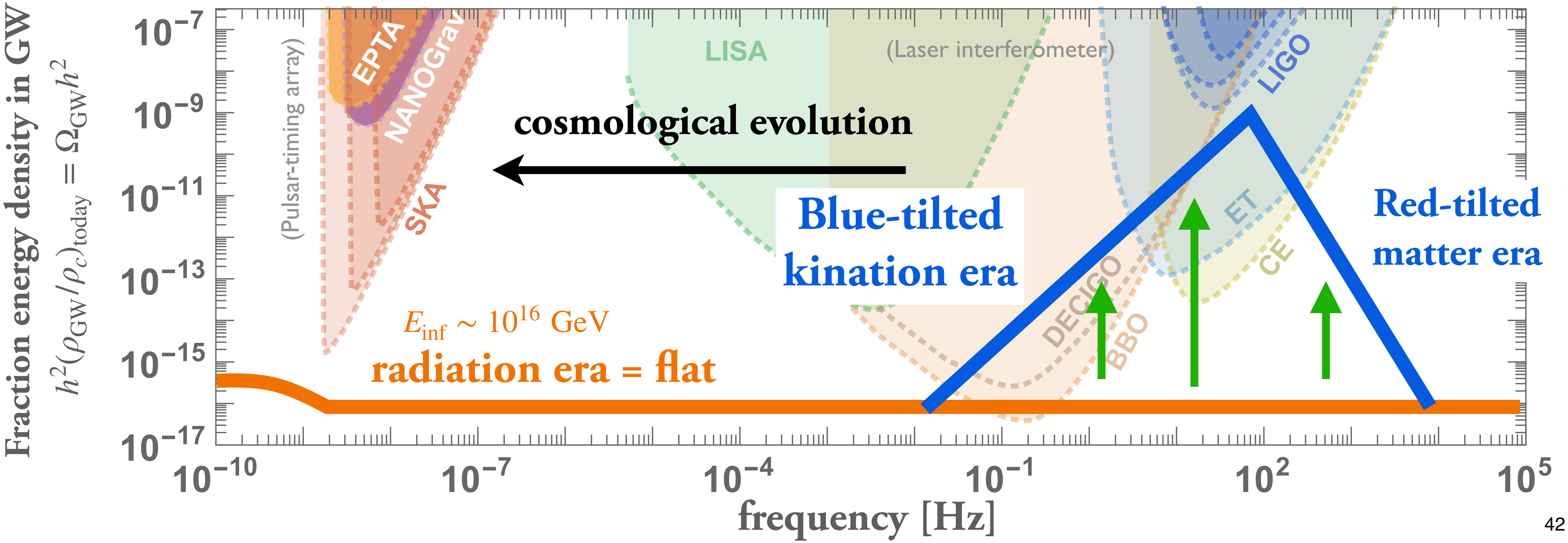




Spectral distorsions of the primordial inflationary GW: a hint on the cosmological history.

A scalar field dominates the Universe with large kinetic energy,



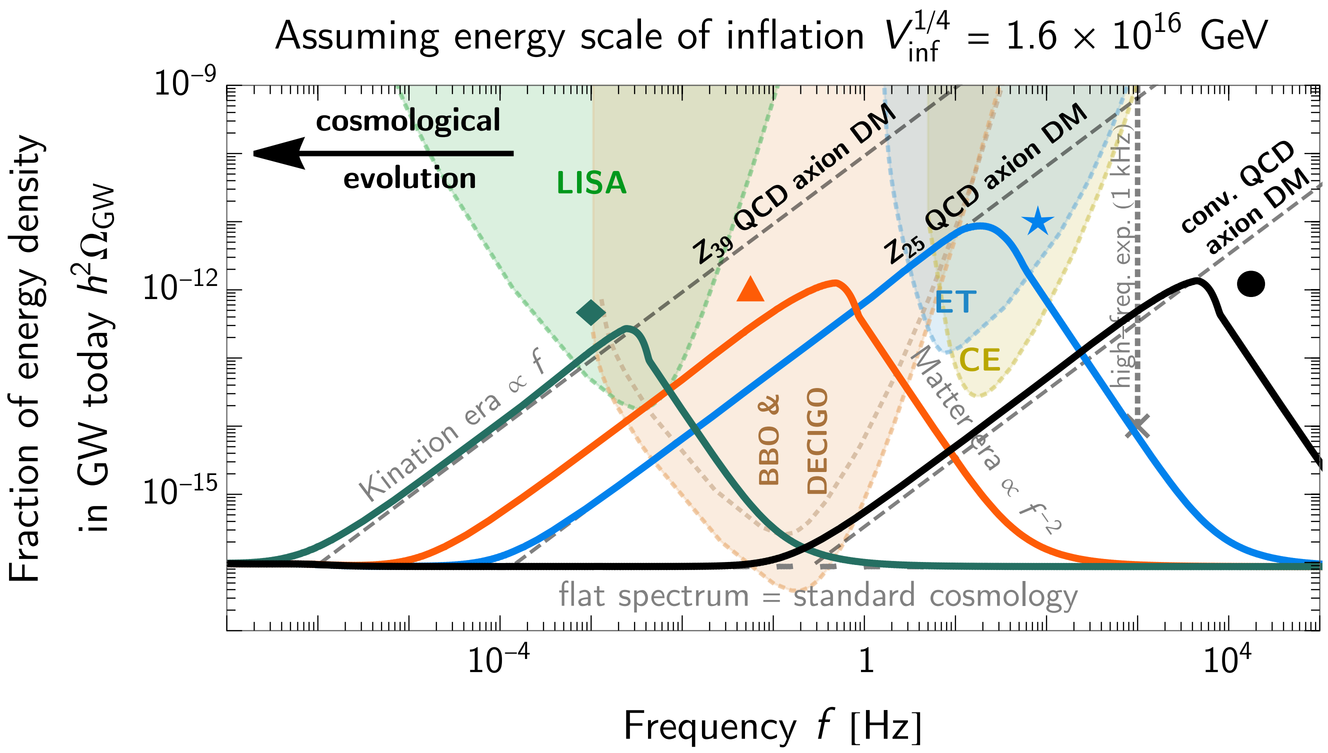


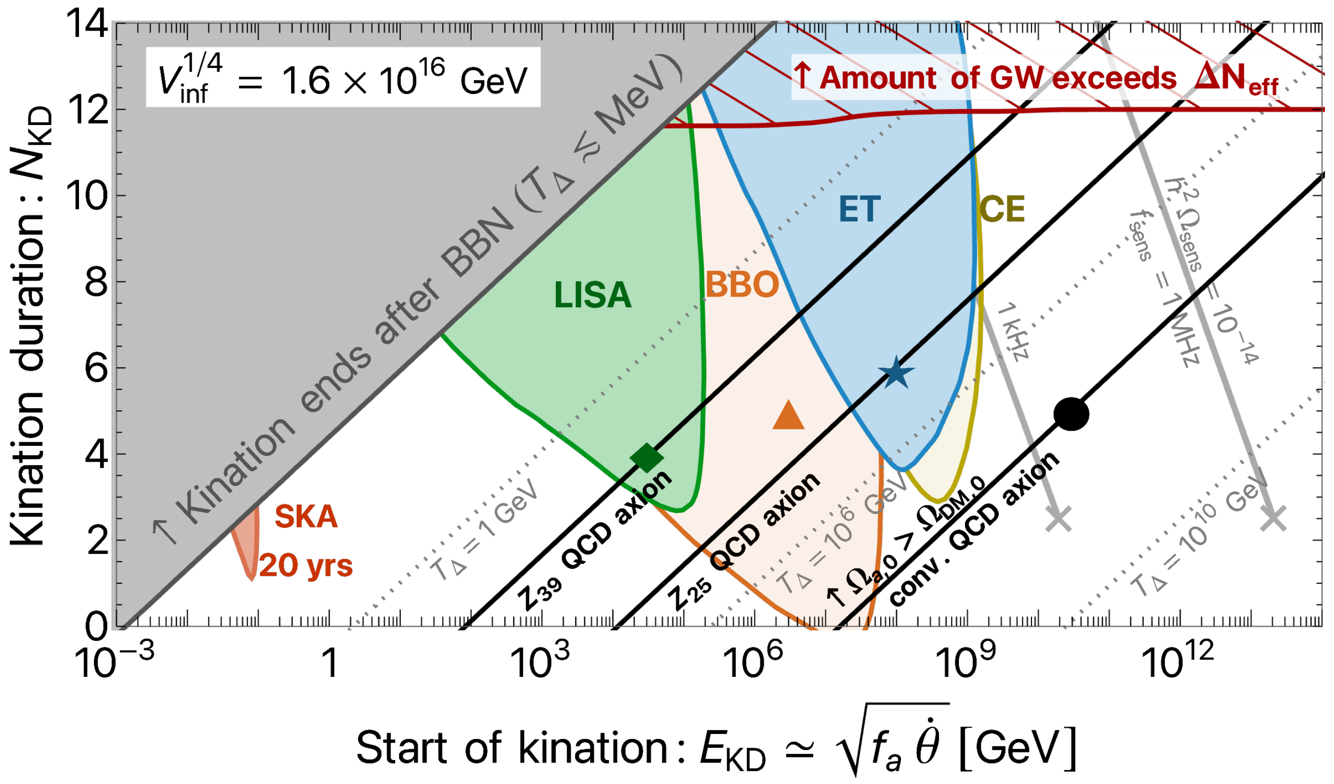
Kination-enhanced GW signal from primordial inflation.

Model-independent predictions.

Peak frequency: $f_{\rm peak} \approx 10\ {\rm Hz} \left(\frac{E_{\rm KD}}{10^8\ {\rm GeV}}\right) \left[\frac{\exp(N_{\rm KD}/2)}{10}\right]$

Peak amplitude: $\Omega_{\rm peak} h^2 \approx 10^{-12} \left(\frac{E_{\rm inf}}{1.6\times 10^{16}\ {\rm GeV}}\right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4}\right]$





cosmological evolution

←

[Gouttenoire,GS, Simakachorn 2108.10328+2111.01150]

Gravitational Waves and Axion Dark Matter.

QCD Axion Dark Matter.

via kinetic misalignment & axion fragmentation

[Co, Harigaya, Hall, '19]
[Chang, Cui, '19]

[Fonseca, Morgante, Sato, Servant, '19]
[Eröncel, Sato, Servant, Sørensen, soon!]

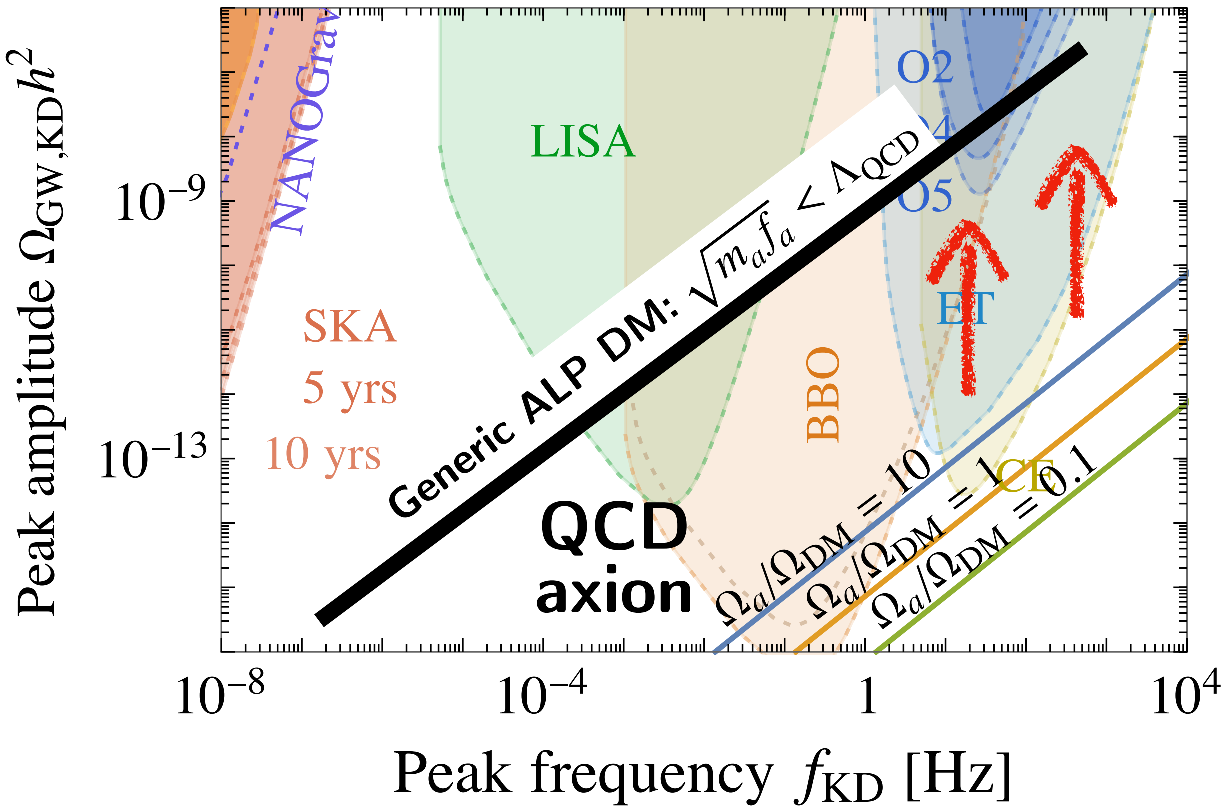
$$\left.\frac{n_a}{s}\right|_0 \simeq \frac{f_a^2\dot{\theta}}{s_{\rm KD}} \simeq \frac{f_a}{E_{\rm KD}} e^{3N_{\rm KD}/2}$$

[Gouttenoire, Servant, **PS**, 2111.01150]

GW peak & axion DM abundance

$$f_{\rm peak} \approx 21\ {\rm Hz} \left(\frac{\rm GeV}{\sqrt{m_a f_a}}\right)^{2/3} \left(\frac{E_{\rm KD}}{10^9\ {\rm GeV}}\right)^{4/3} \left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)^{1/3}$$

$$\Omega_{\rm peak} h^2 \approx 10^{-18} \left(\frac{f_{\rm KD}}{\rm Hz}\right) \left(\frac{E_{\rm inf}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{\rm GeV}{\sqrt{m_a f_a}}\right) \left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)$$



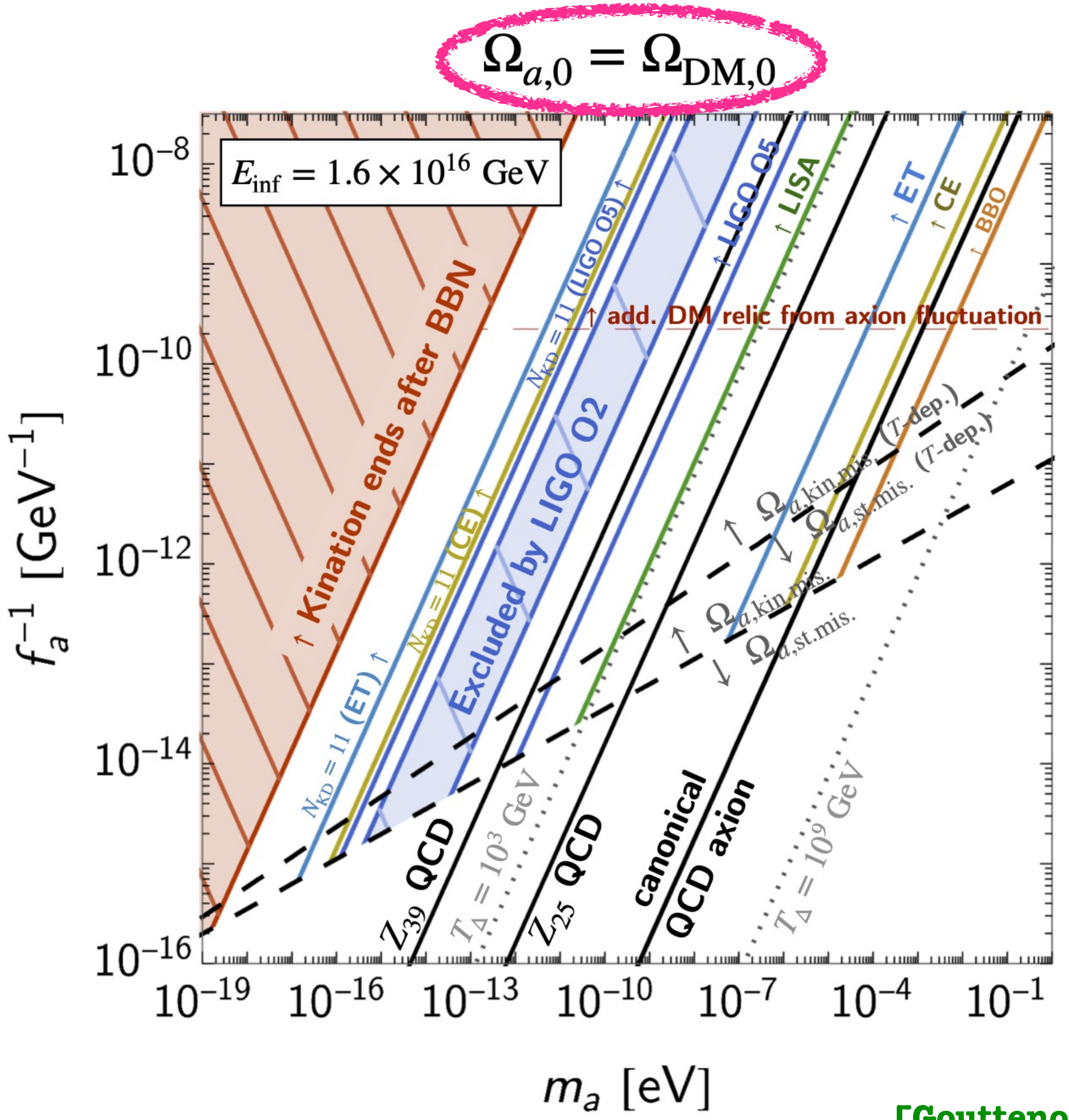
The conventional QCD axion DM cannot be observed at planned experiments,
except BBO and require ultra-high frequency GW experiments.

Observable signals for generic ALP DM and
QCD axion DM with lighter mass, e.g., the $\mathbb{Z}_N$-axion.

[Hook, '18] & [Di Luzio, Gavela, Quilez, Ringwald, '21]

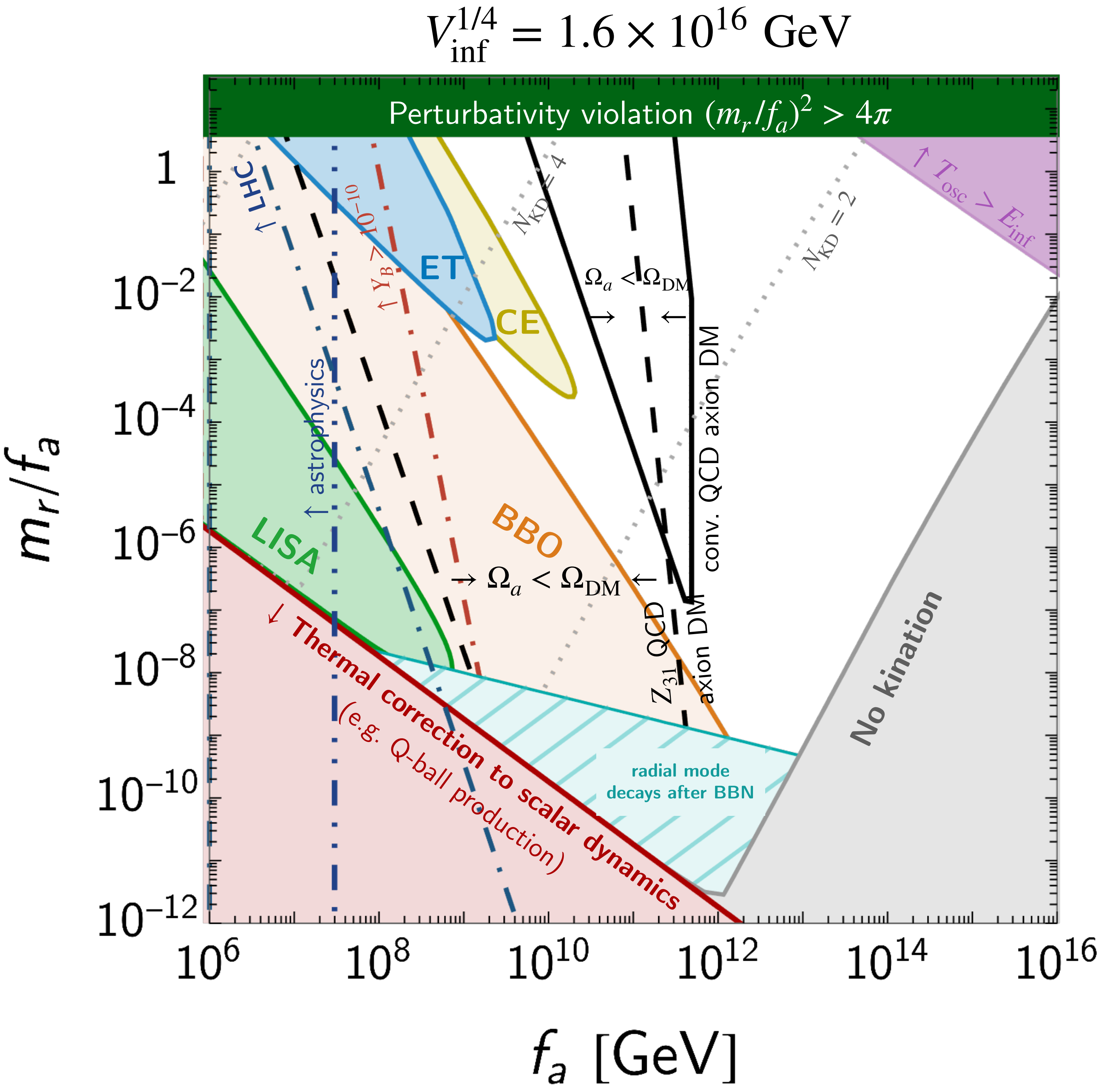
Gravitational Waves and Axion Dark Matter.

If the axion is Dark Matter:



[Gouttenoire,GS, Simakachorn 2111.01150]

Detectability of rotating axion models.

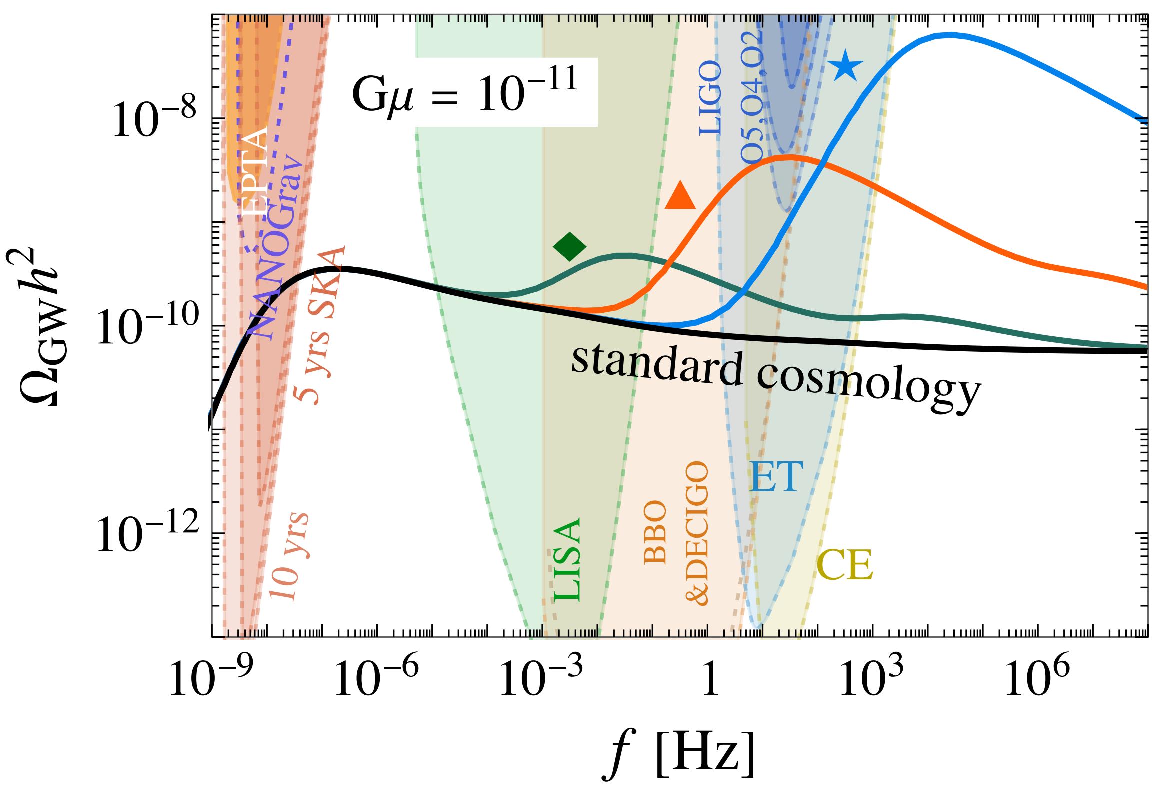


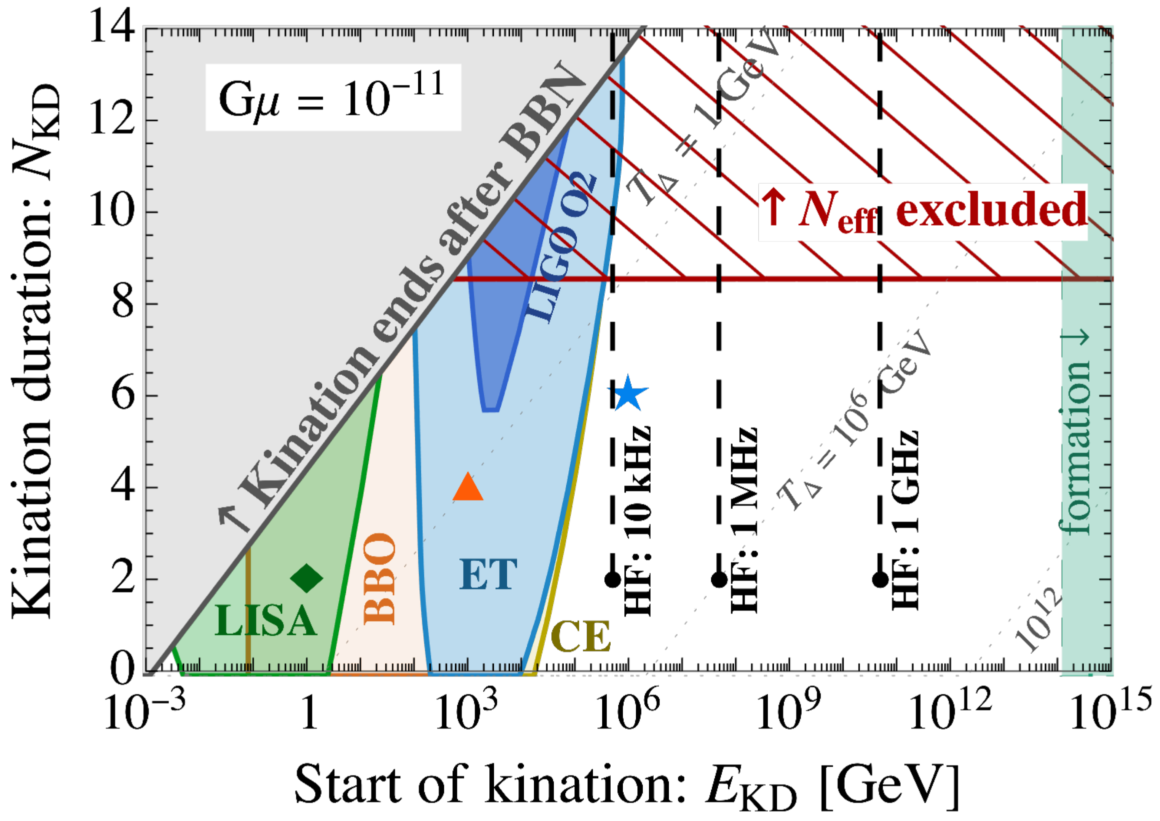
(radial mode mass)

2111.01150

Impact of kination on Gravitational Waves from Cosmic Strings.

Kination-enhanced GW from local cosmic strings.



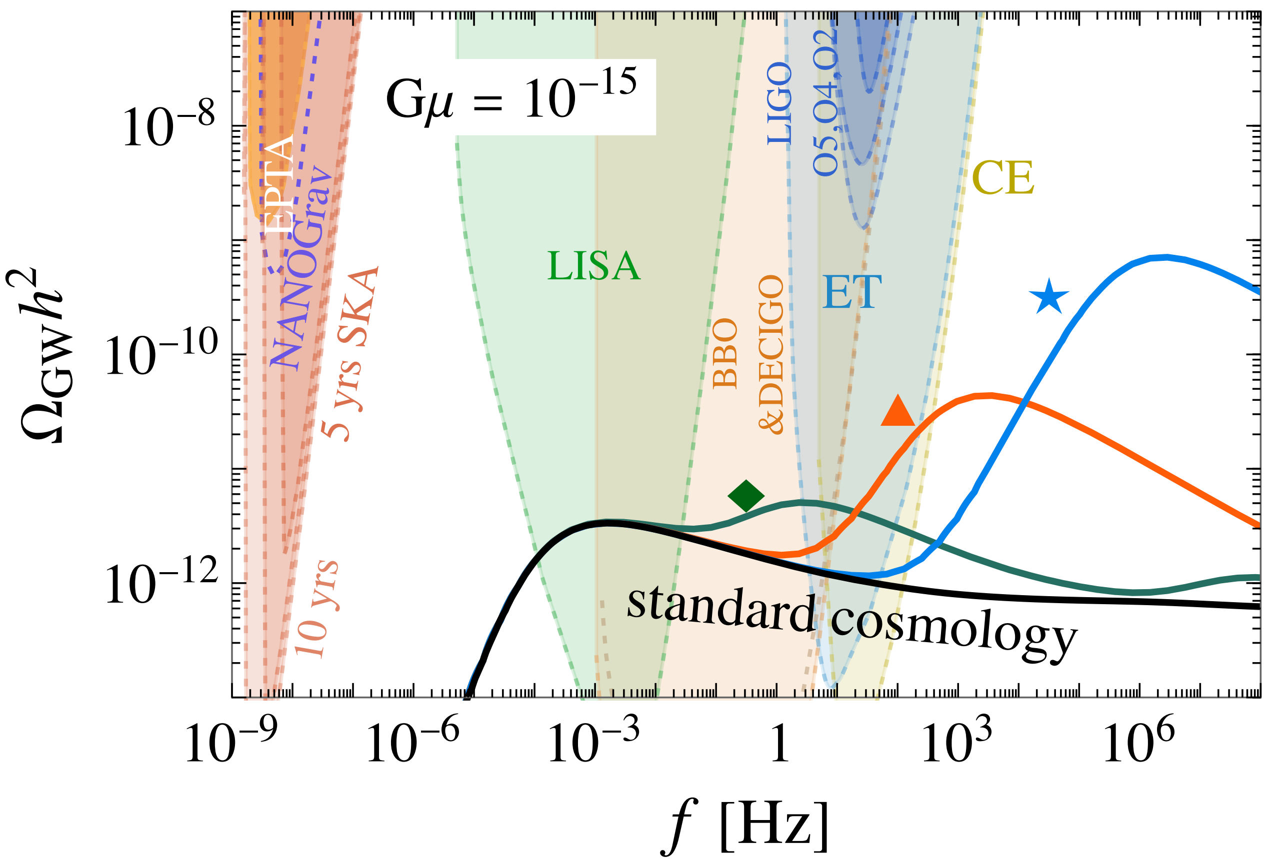


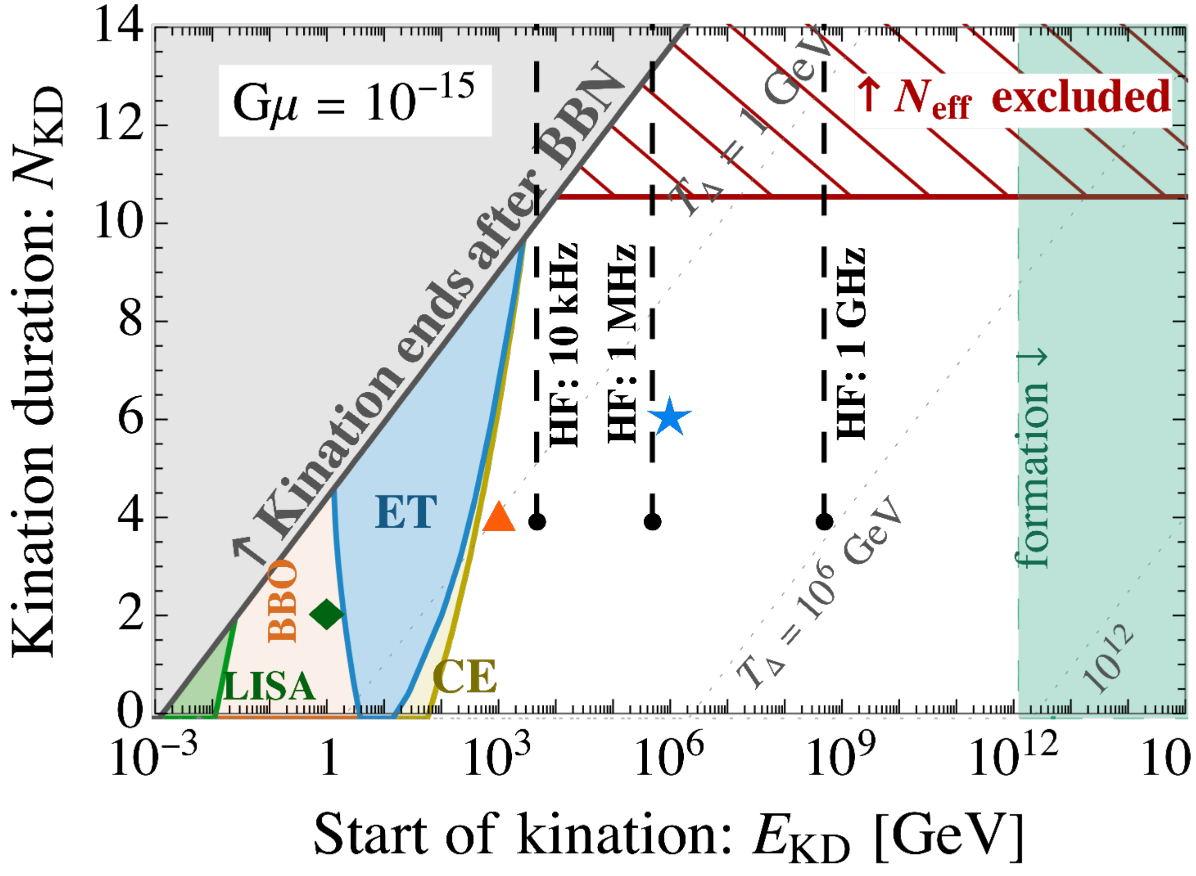
[Gouttenoire,GS, Simakachorn 2111.01150]

Peak frequency:

$$f_{\rm KD} \simeq \begin{cases} (1.3\times10^{3}\ \text{Hz})\left(\frac{0.1\times50\times10^{-11}}{\alpha\Gamma G\mu}\right)^{1/2}\left(\frac{E_{\rm KD}}{10^{5}\ \text{GeV}}\right) & \text{for } N_{\rm KD} < \frac{1}{3}\log\left(\frac{\alpha}{2\Gamma G\mu}\right), \\ (6.1\times10^{2}\ \text{Hz})\left(\frac{0.1}{\alpha}\right)^{2/3}\left(\frac{50\times10^{-11}}{\Gamma G\mu}\right)^{1/3}\left(\frac{E_{\rm KD}}{10^{5}\ \text{GeV}}\right)\left[\frac{\exp(N_{\rm KD}/2)}{10}\right] & \text{for } N_{\rm KD} > \frac{1}{3}\log\left(\frac{\alpha}{2\Gamma G\mu}\right), \end{cases}$$

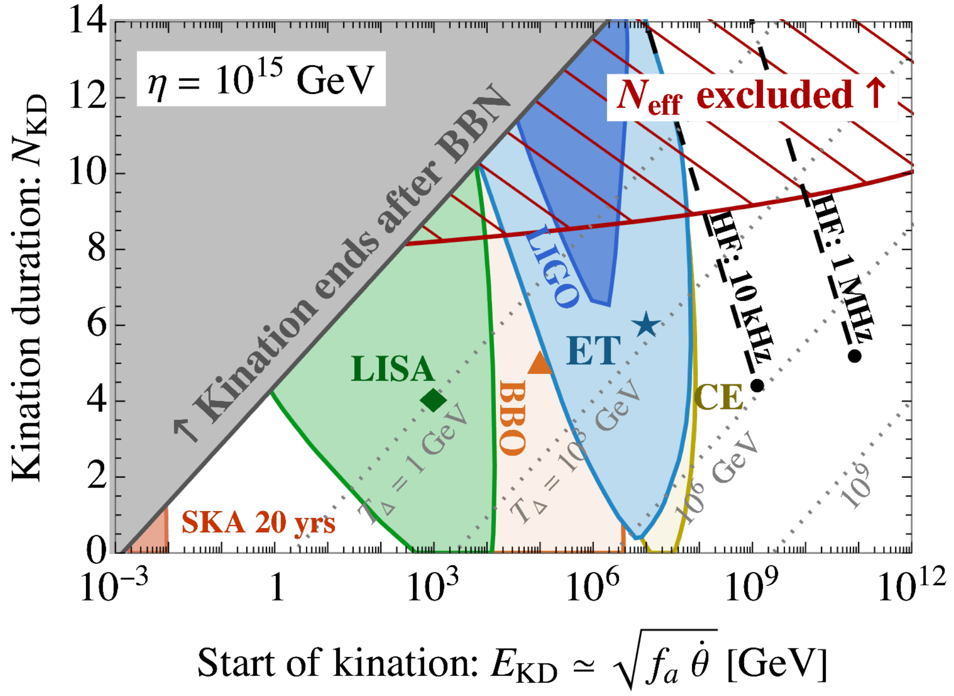
Kination-enhanced GW from local cosmic strings.

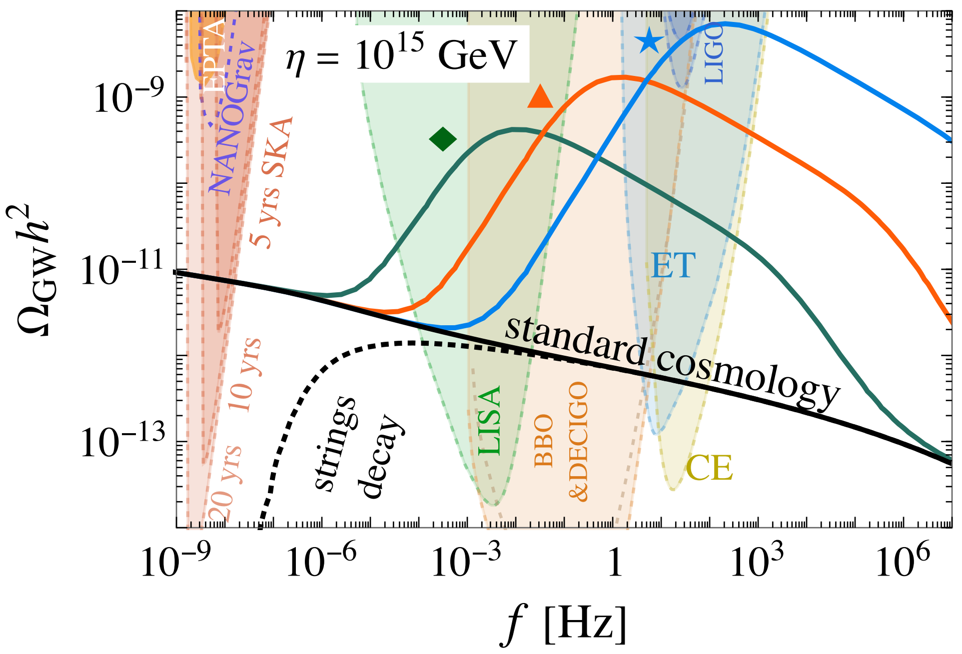


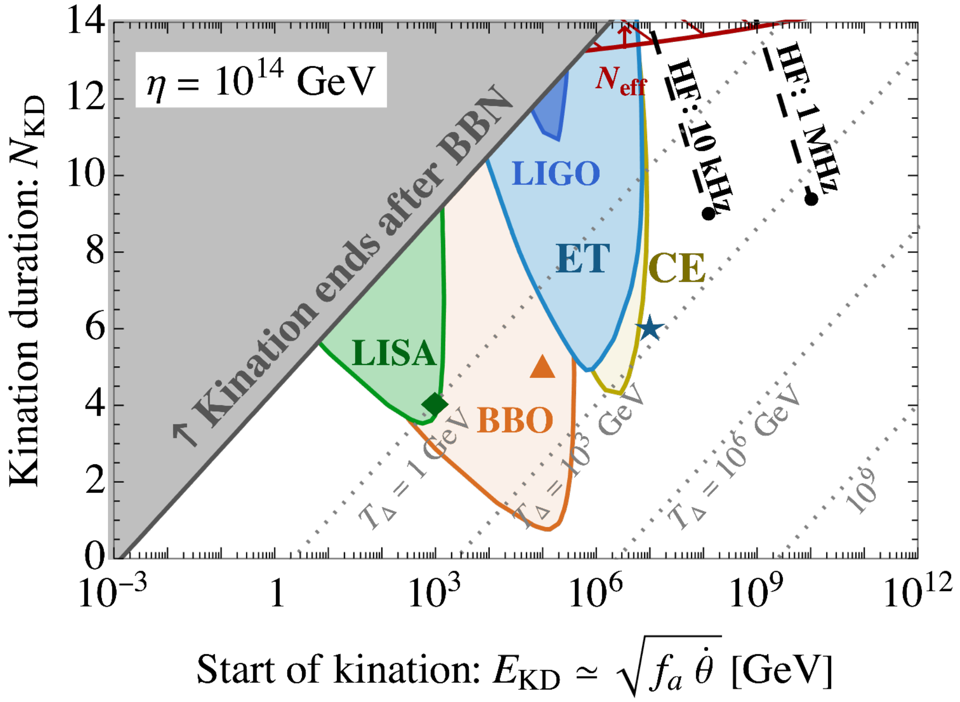


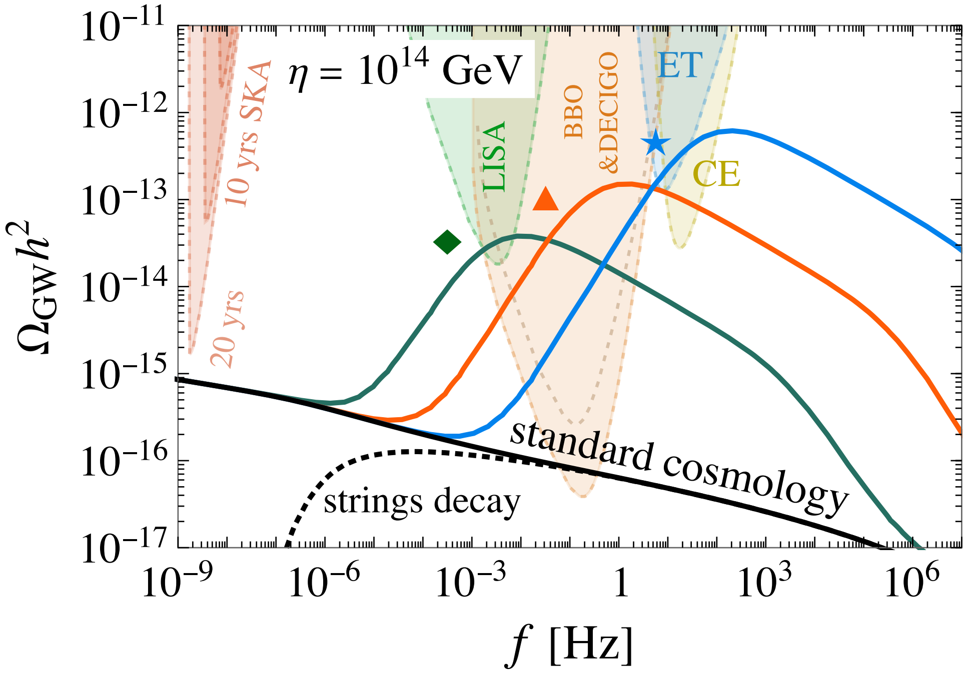
[Gouttenoire,GS, Simakachorn 2111.01150]

GW from global strings.







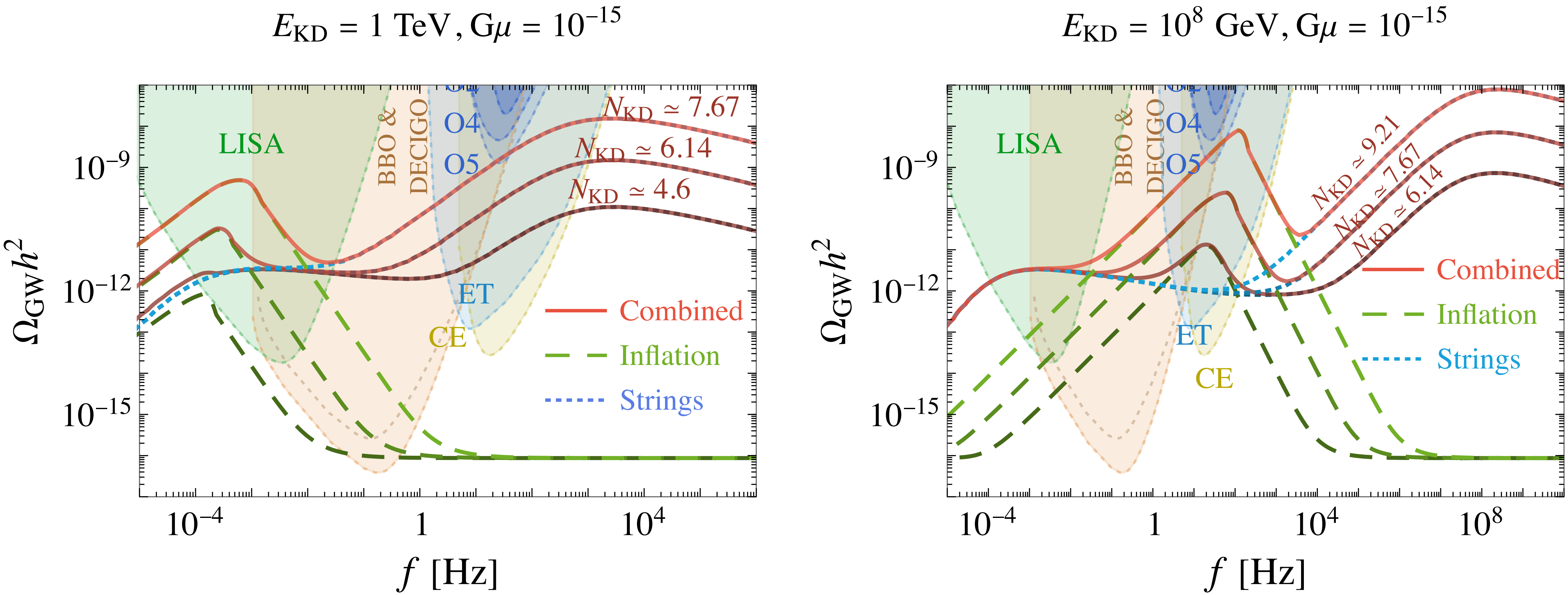


[Gouttenoire,GS, Simakachorn 2111.01150]

Peak frequency:

$$f_{\rm KD} \simeq (0.916\ \text{Hz})\left(\frac{0.1}{\alpha}\right)\left(\frac{E_{\rm KD}}{10^5\ \text{GeV}}\right)\left[\frac{\exp(N_{\rm KD}/2)}{10}\right],$$

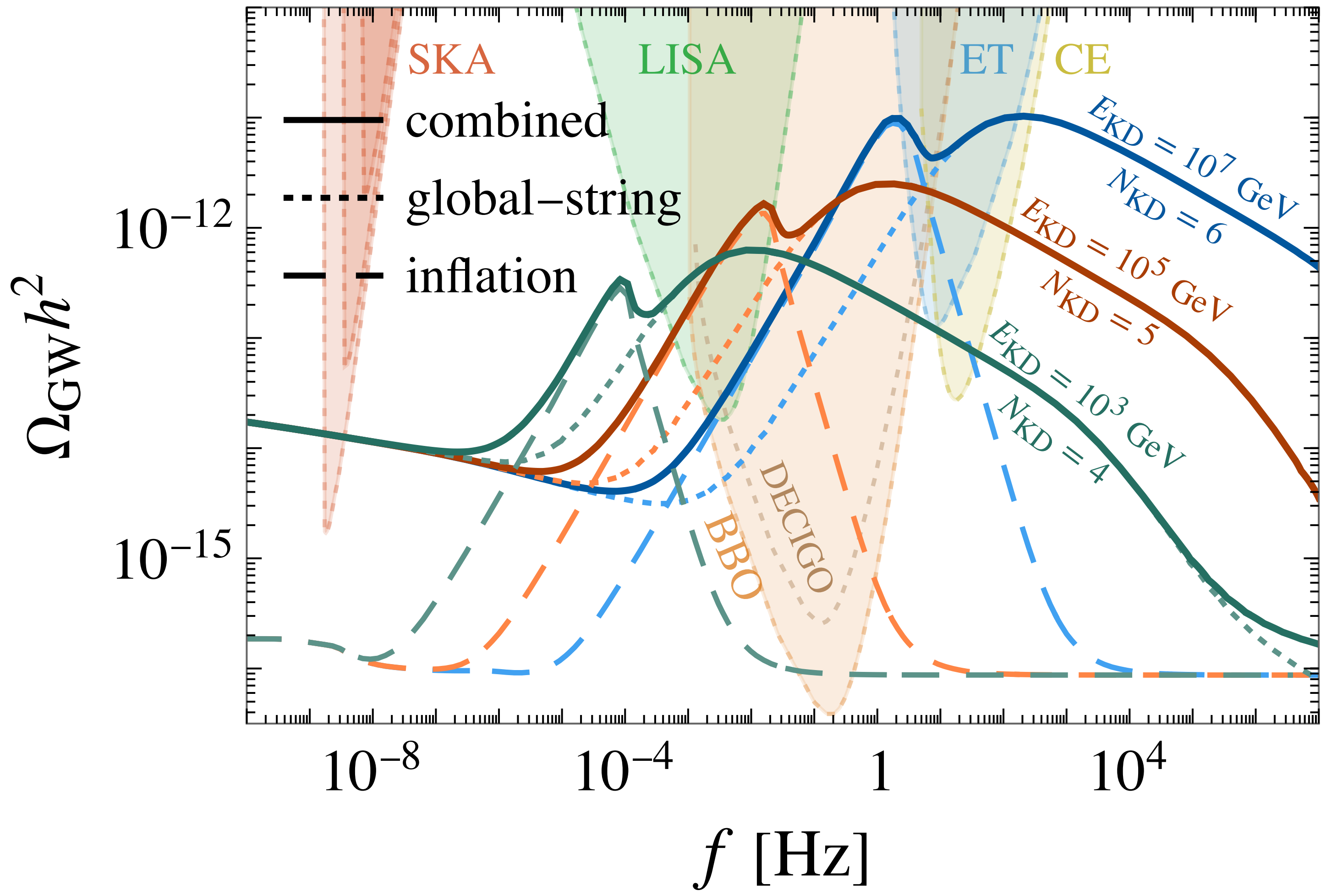
GW from primordial inflation + local cosmic strings.



[Gouttenoire,GS, Simakachorn 2111.01150]

GW from primordial inflation + global cosmic strings.

Two-peak signature



Fixed peak separation $f_{\rm inf}/f_{\rm glob} = \mathcal{O}(10^{-2})$

[Gouttenoire,GS, Simakachorn 2111.01150]

Conclusion.

Kinetic Misalignment mechanism revisited

Kinetic fragmentation : A well-motivated production mechanism for ALP DM

Moves the ALP Dark Matter window into testable territory.

QCD axion DM inside Iaxo sensitivity

Observational tests: Gravitational waves from a spinning axion

Another promising probe: Much denser compact axion dark matter halos

Axion cosmology: Rich spectrum of possibilities, role of radial mode!

GW signal.

- **Kination: period when energy density of the universe is dominated by a scalar field with large kinetic energy.**

- **Kination era amplifies primordial long-lasting sources of GW**

  e.g. inflationary GW spectrum gets blue-tilted

- **A spinning axion, as motivated by the interplayed dynamics between radial and angular mode of complex scalar field can generate a short and low-scale kination during the pre-BBN epoch.**

- **Peaked GW signature:**

LISA for $E_{\rm KD} \sim 10^{2-5}$ GeV kination | ET & CE for $E_{\rm KD} \sim 10^{6-9}$ GeV kination.

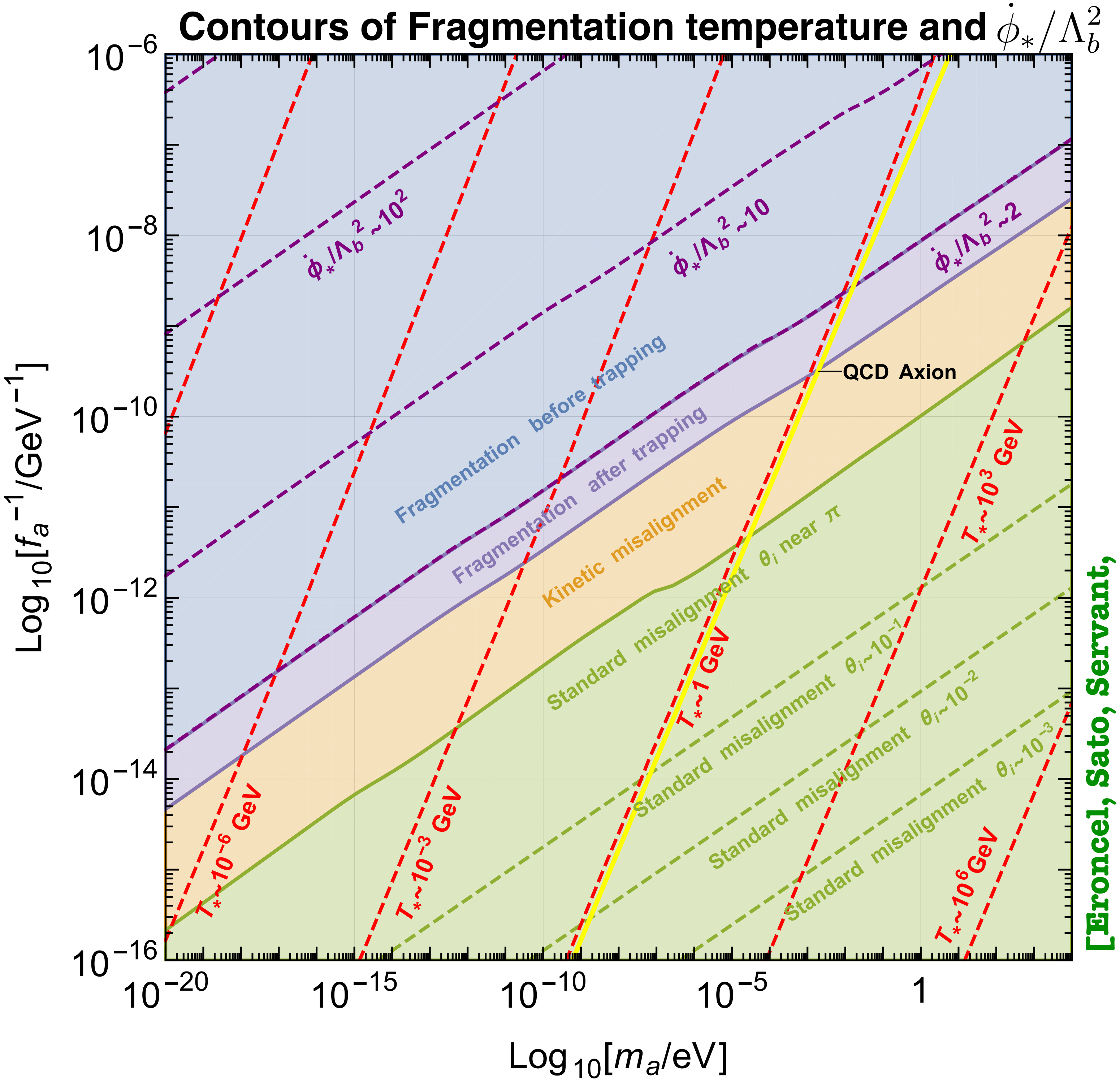
- **GW amplitude $\propto$ kination duration**

- **Peak frequency $\propto$ kination duration & kination energy scale**

- **Applies to any ALP, in particular to QCD axion**

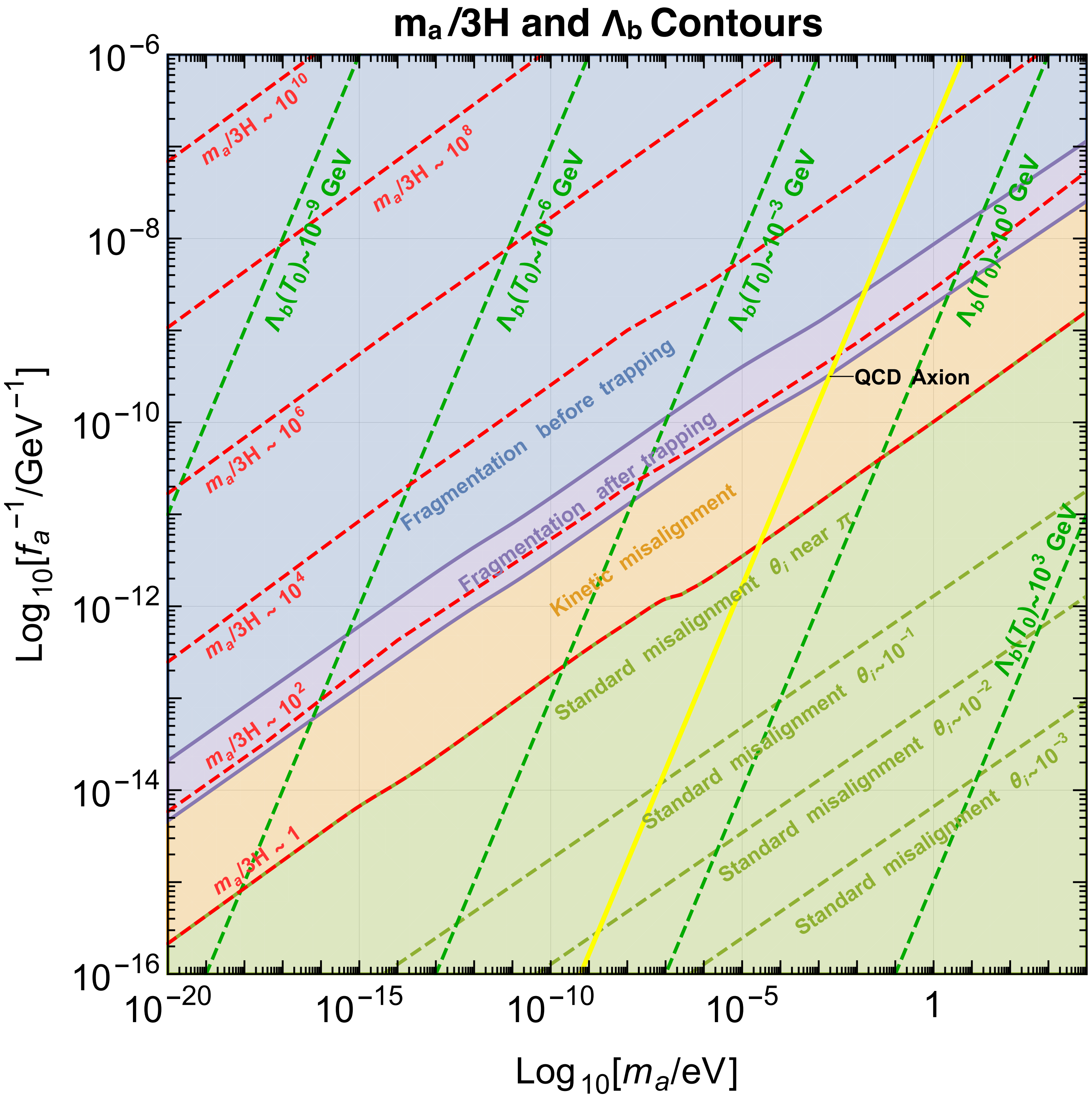
Annexes.

The axion production mechanism landscape.



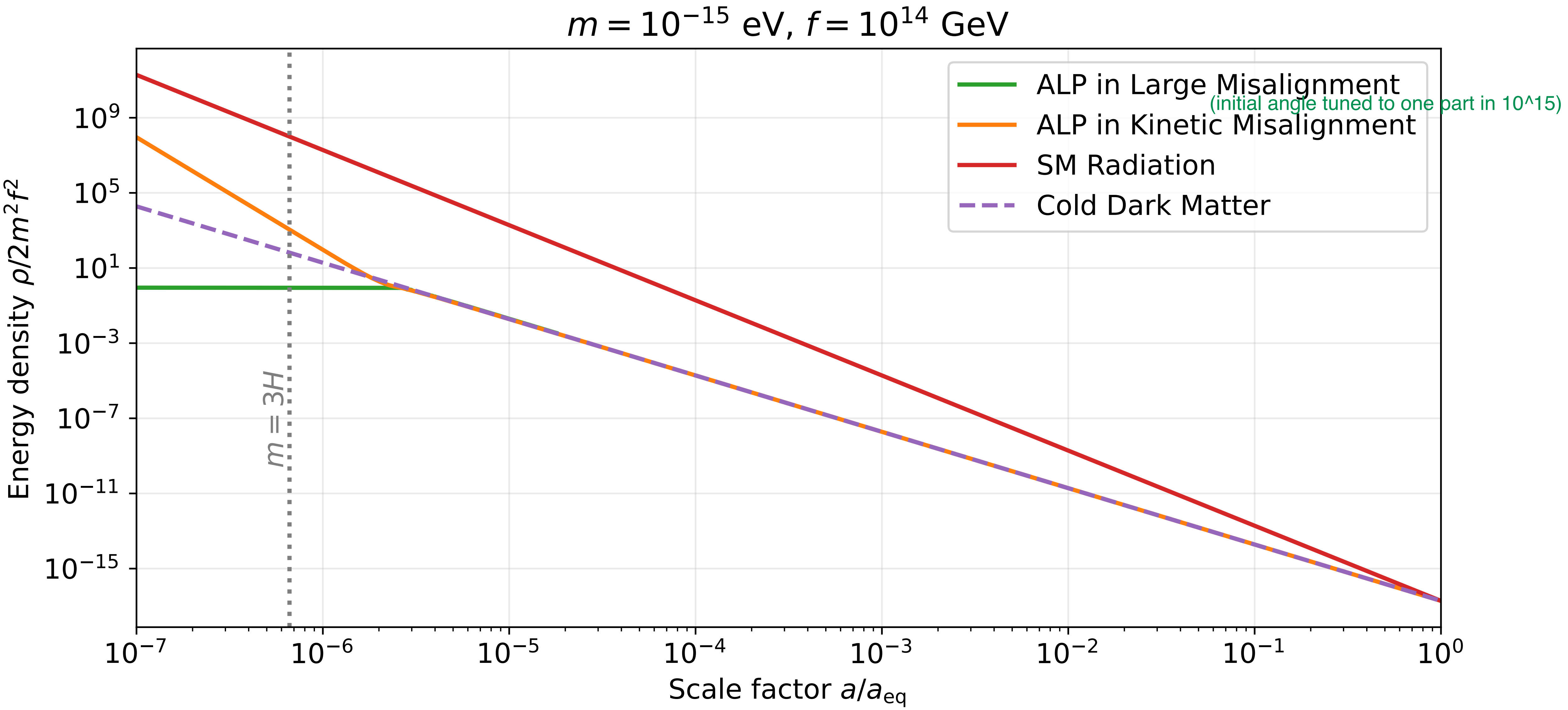
[Eroncel, Sato, Servant, Soerensen, in prep.]

The axion production mechanism landscape.



[Eroncel, Sato, Servant, Soerensen, in prep.]

Evolution of ALP energy density.



(initial angle tuned to one part in 10^15)

Equations of motion.

The evolution of the homogeneous field configuration is controlled by the Klein-Gordon equation in an expanding universe

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\partial}{\partial \Phi^\dagger}\left(V + V_{\cancel{U(1)}}\right) \;=\; 0,$$

it describes a Keplerian motion in a rotationally-invariant potential *V* ,

in the presence of small wiggles and Hubble friction.

Origin of the kick.

Angular equation of motion:

$$\dot{n}_\theta + 3Hn_\theta = \boxed{-\frac{\partial V_{\cancel{U(1)}}}{\partial \theta},} \qquad \text{with} \quad n_\theta \equiv \phi^2 \dot{\theta}.$$

comoving Noether charge of the restored *U* (1) symmetry.

In absence of *U* (1)-breaking:

$$\frac{d}{dt}\left(a^3 n_\theta\right) = 0,$$

charge conservation equation

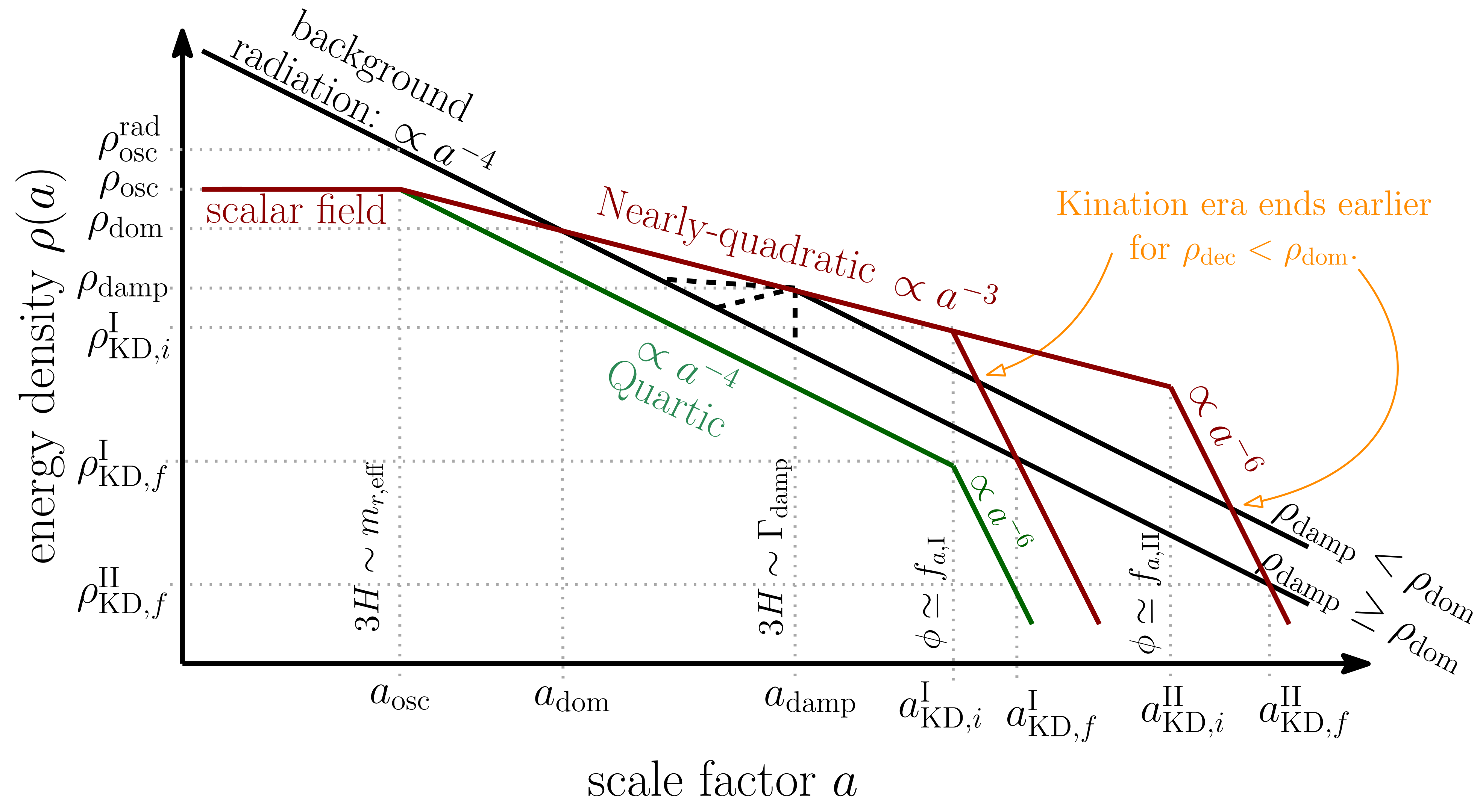
Kination era.

$$a^3 \phi^2 \dot{\theta} = \text{constant},$$

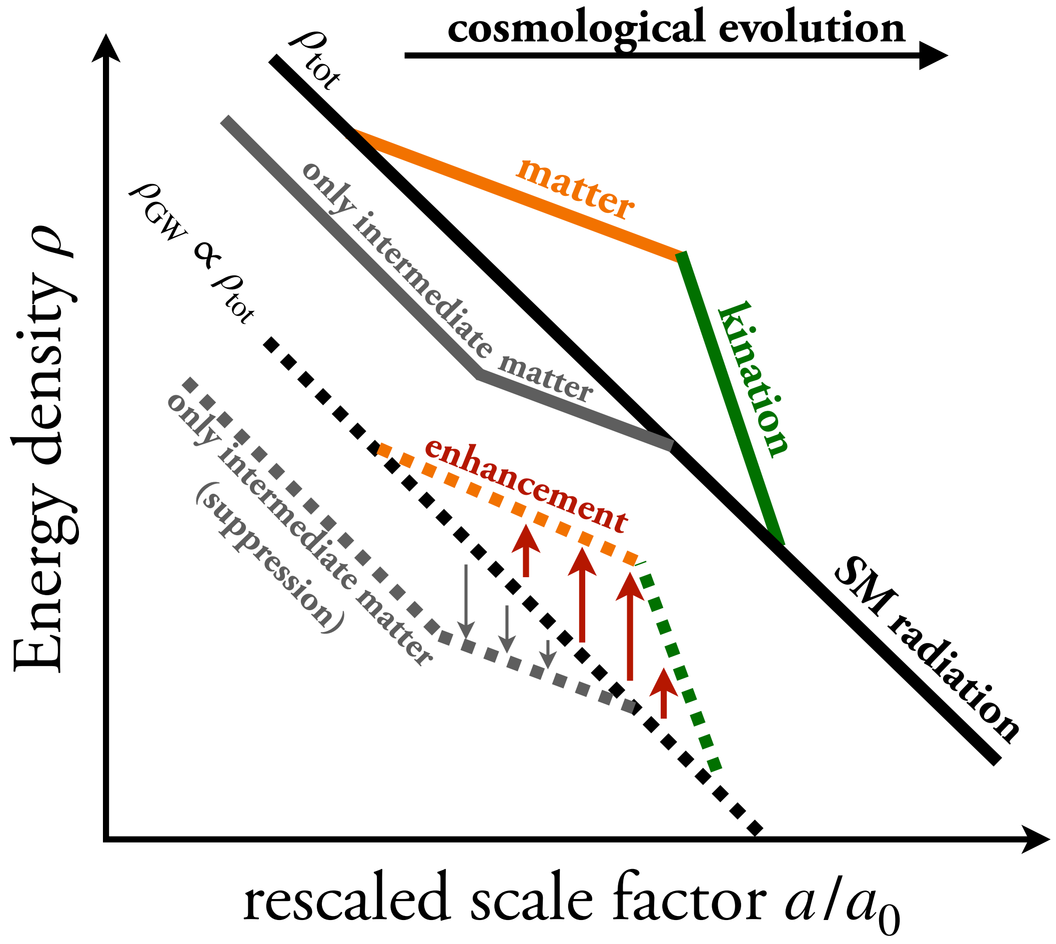
once $\phi \rightarrow f_a, \quad \dot{\theta} \propto a^{-3} \qquad \text{and} \qquad \rho_\Phi = \frac{\phi^2 \dot{\theta}^2}{2} \propto a^{-6}.$

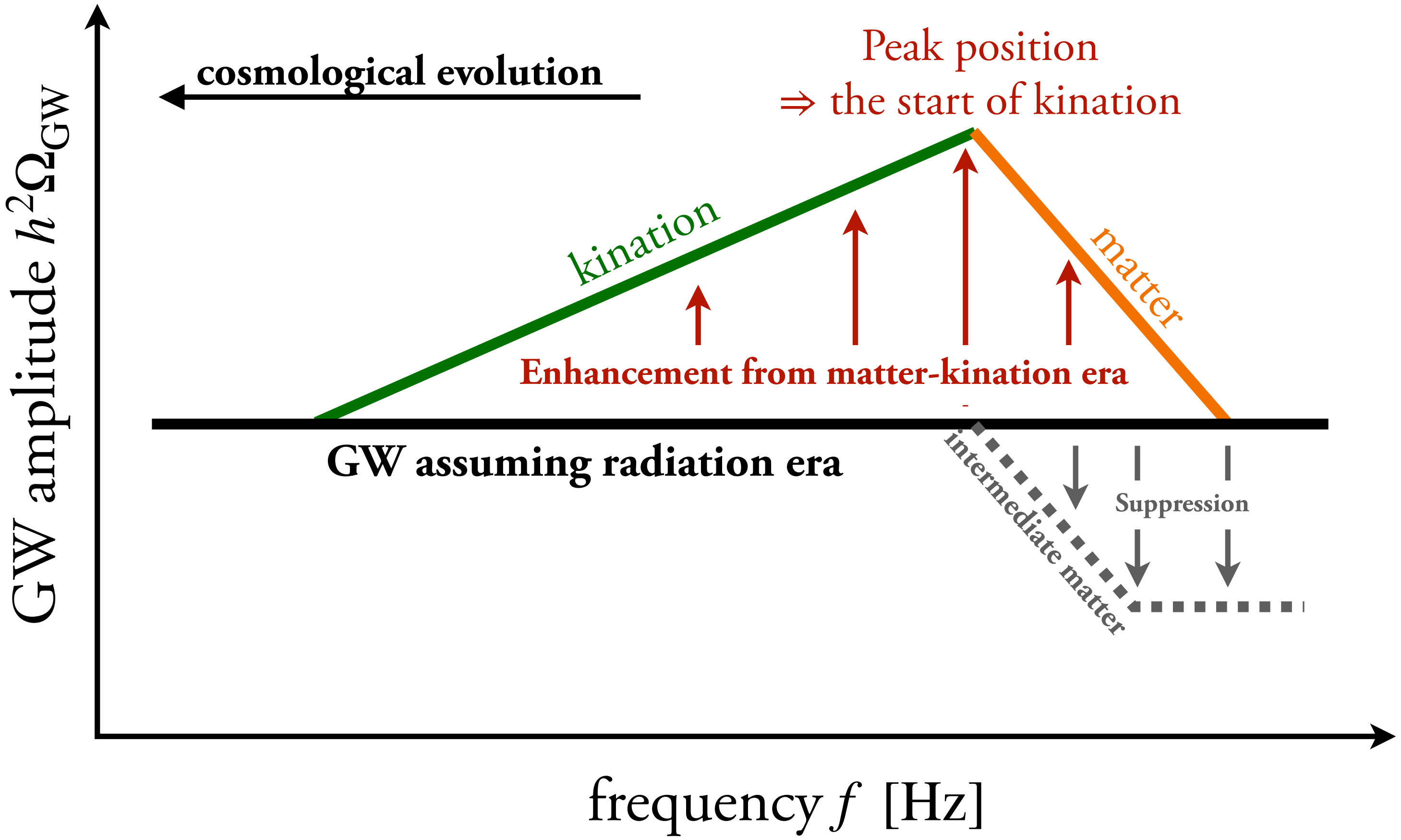
in absence of radial mode kinetic energy -> kination equation of state

Rotating axion models.

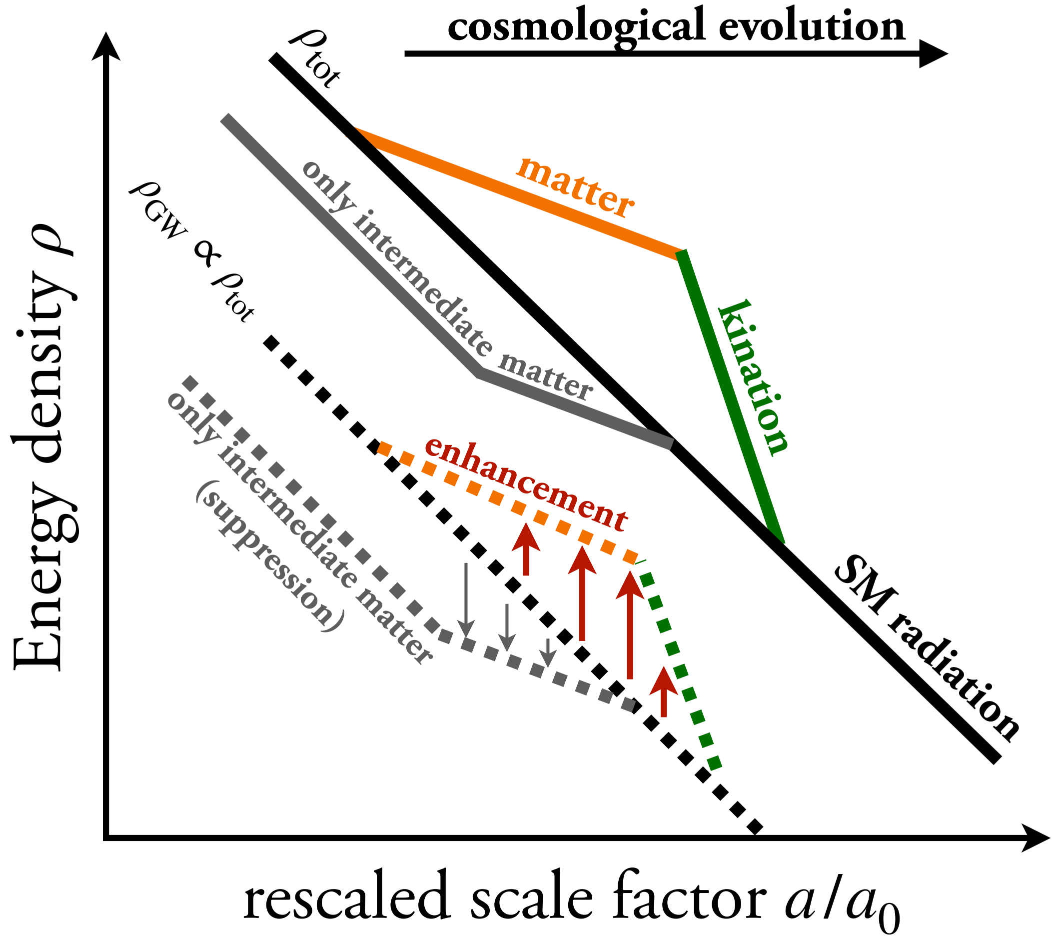


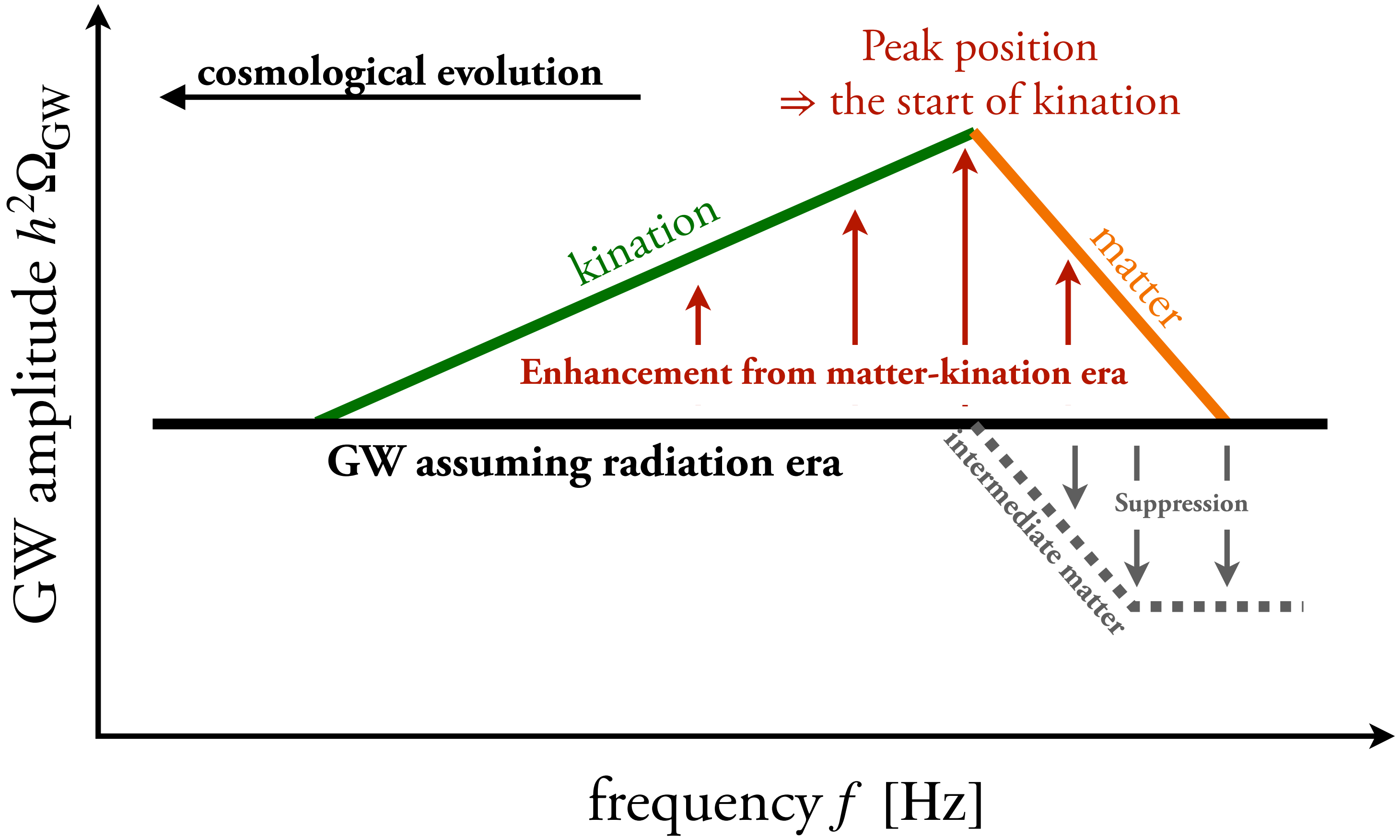
A peaked GW signature.





A peaked GW signature.



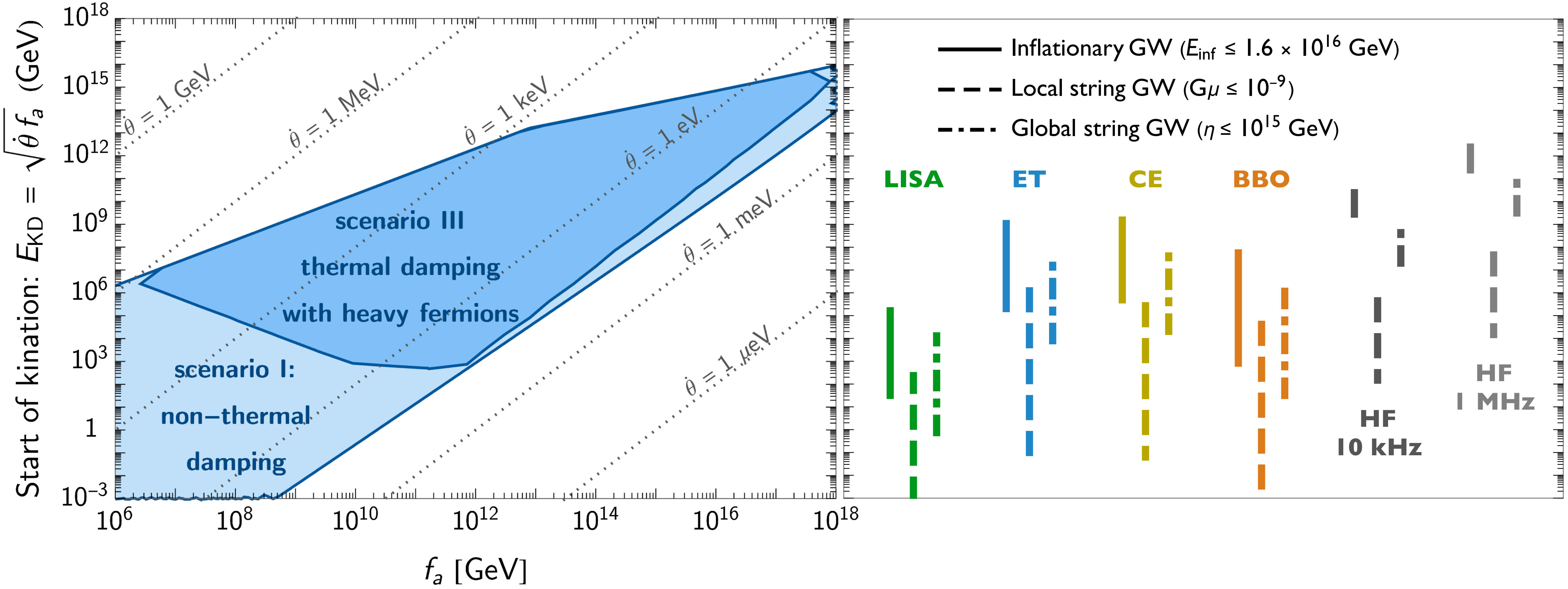


Inflationary GW:

Frequency of today GW: $f^{\rm GW}_{\rm today} \simeq H_k a_k/a_0 \propto a_k^{-2}$ (kination), a_k^{-1} (radiation), $a_k^{-1/2}$ (matter)

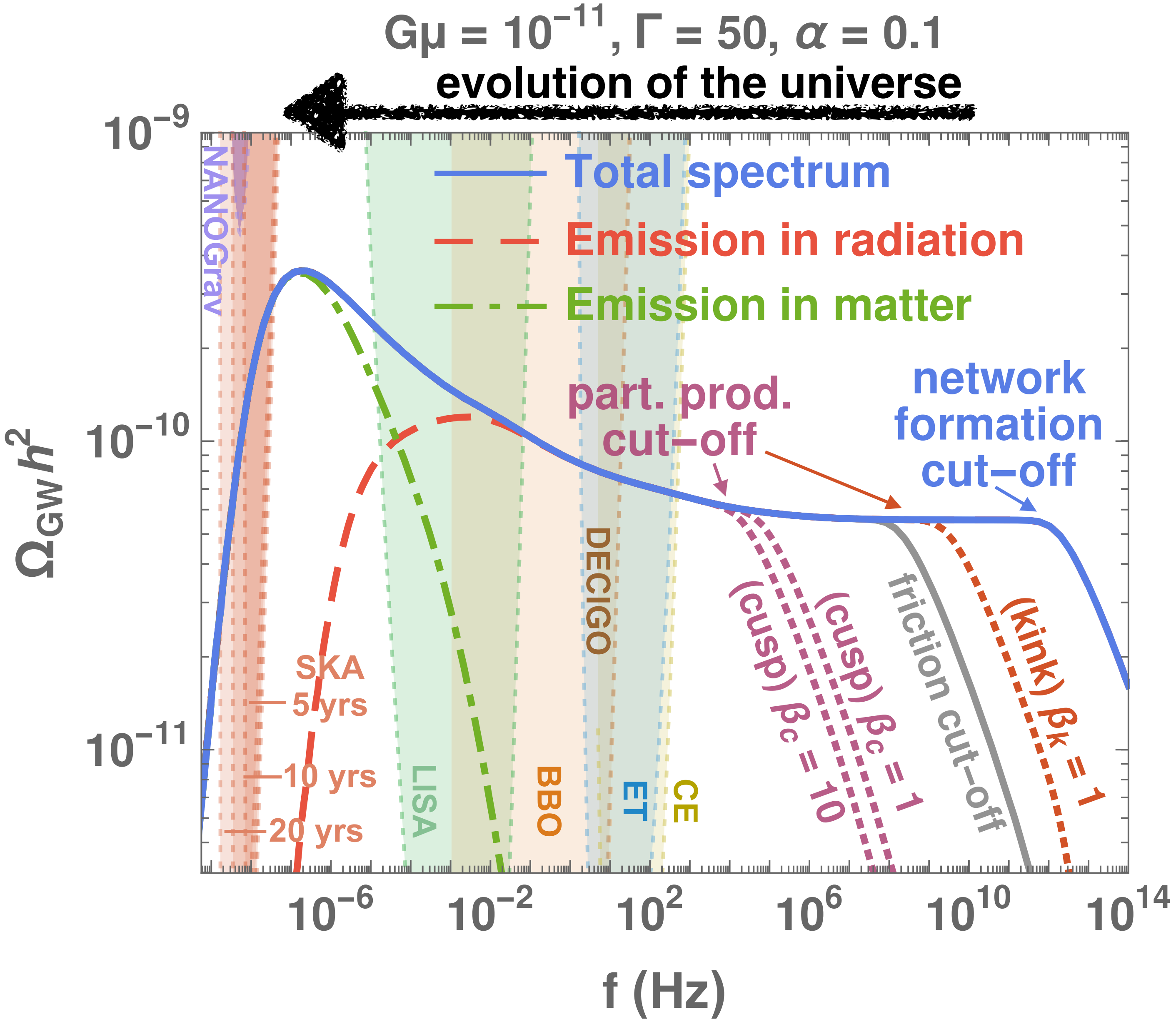
spectral tilt: $\Omega_{\rm GW} \simeq \left(\frac{H_k^2 a_k^4}{H_0^2}\right)\left(\frac{E_{\rm inf}}{M_{\rm Pl}}\right)^4 \propto f_{\rm today}$ (kination), $f^0_{\rm today}$ (radiation), $f^{-2}_{\rm today}$ (matter)

Summary of prospects.



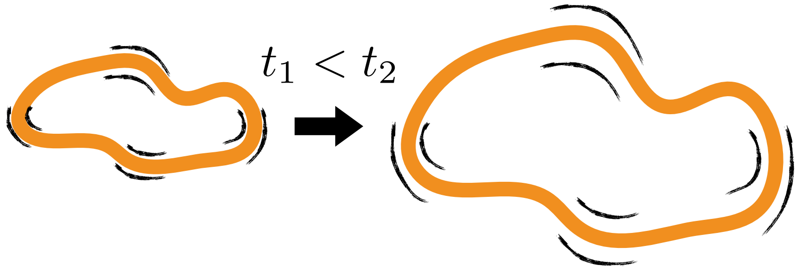
Gravitational Waves from Cosmic strings.

(long-lasting sources).



[1912.02569]

Higher f ⇔ Earlier emission



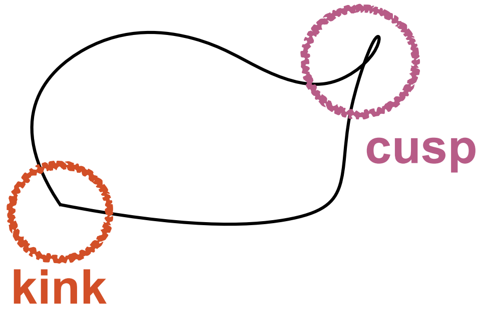
smaller loop ⇔ higher oscillation f

@ earlier t_i

more GW from more loops
but more red-shift

⇨ Flat during radiation

singular structures on loop
(beyond NG approx.)



lead to particle emission

Damping scenarios

Scenario I (non-thermal): e.g. parametric resonance extracts energy from zero-mode
Damping happens fast after oscillation. (Completely damped? Further study)

✓?

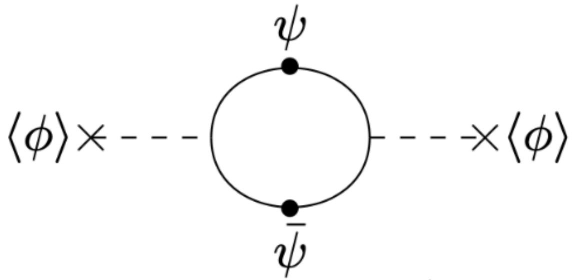
Thermal damping: $\mathscr{L} \supset y_\psi \phi \psi_L^\dagger \psi_R + h.c. + g\,\bar{\psi}\gamma^\mu\psi\, A_\mu$

e.g. [Abbott, Farhi, Wise 1982]
[Mukaida, Nakayama, 2012]

Relativistic fermion @ oscillation ($y_\psi \phi \lesssim T$)

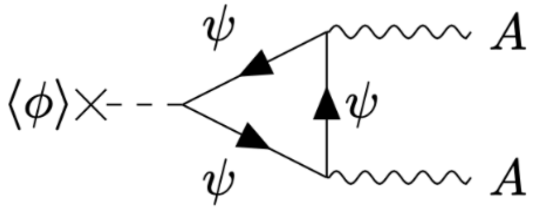
$\Gamma \sim y_\psi^2 \alpha T$

$V_{\rm th}(\phi) \sim y_\psi^2 \phi^2 T^2$



(if $m_r > m_\psi$, damping by the direct decay $\Gamma \sim y_\psi^2 m_r$ instead.)

Non-relativistic fermion @ oscillation ($y_\psi \phi \gtrsim T$)



$\Gamma \sim \alpha^2 T^3/\phi^2$

$V_{\rm th}(\phi) \sim \alpha^2 T^4 \ln\left(\frac{y_\psi^2 \phi^2}{T^2}\right)$

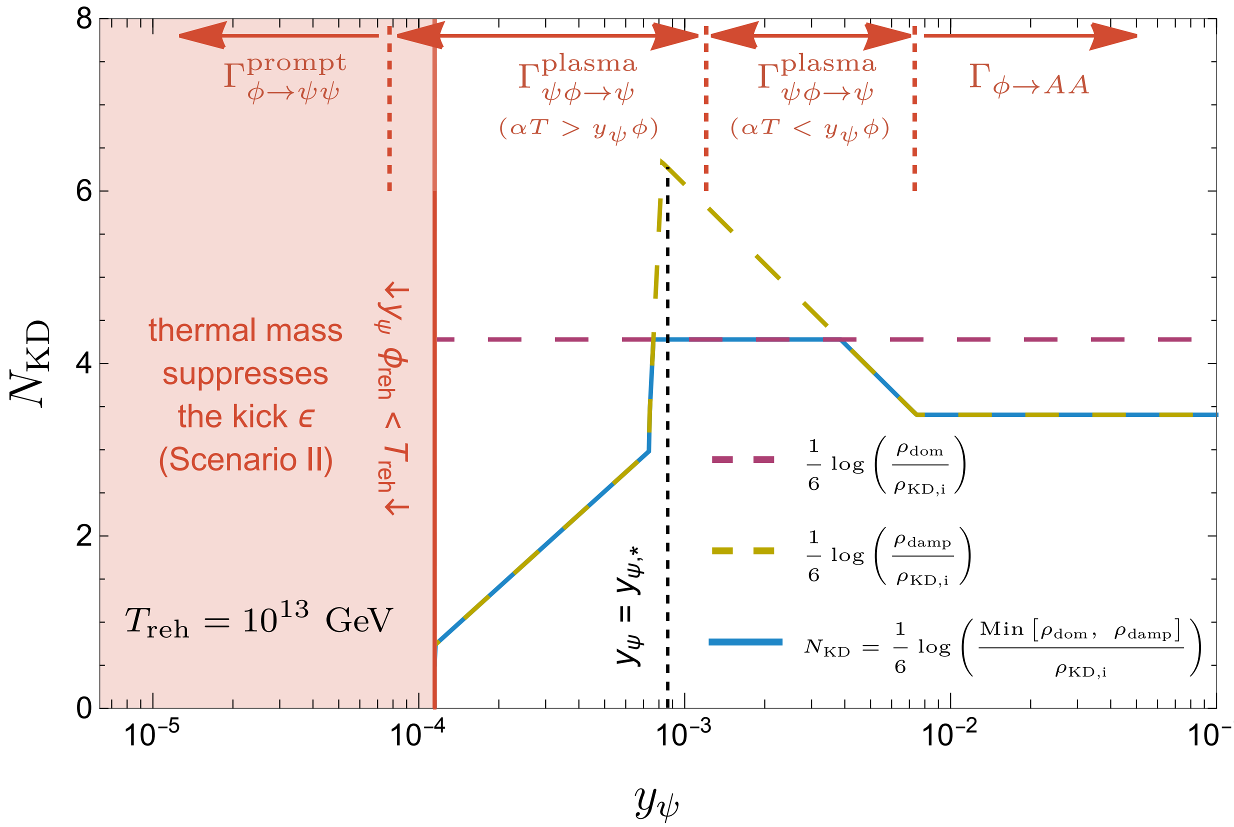
Scenario II: relativistic fermion @ oscillation ⇒ *too large thermal mass*
Axion rotation is suppressed and kination era is absent.

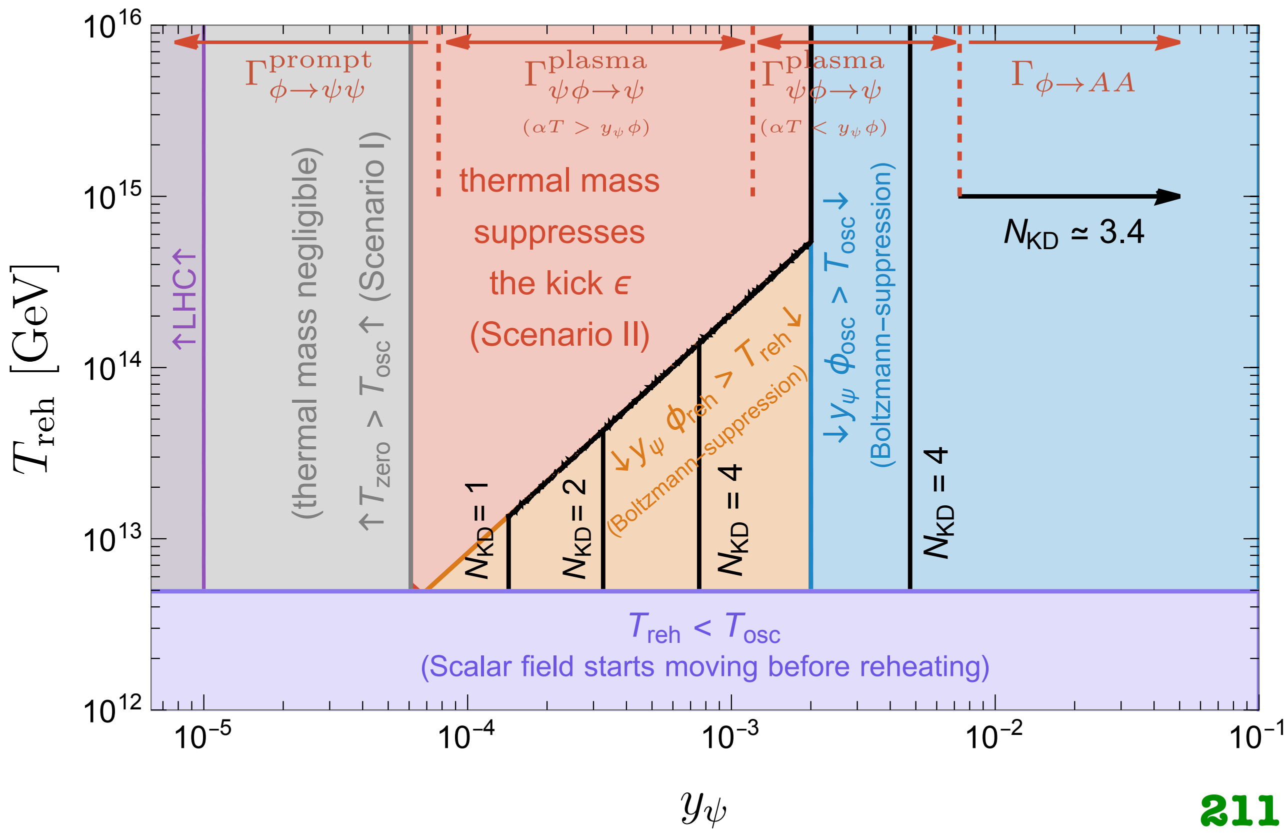
⊗

Scenario III: non-relativistic fermions @ oscillation
Thermal correction can be *smaller* than the zero-T potential.
Realized by having large y_ψ or lowering $T_{\rm reh}$

✓

Thermal damping of radial mode.


$m_r = f_a = 10^8$ GeV, $\alpha = 0.1$, $(\lambda, \text{l}) = (1, 9)$


$m_r = f_a = 10^8$ GeV, $\alpha = 0.1$, $(\lambda, \text{l}) = (1, 9)$

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