Axion fragmentation & axion dark matter

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N. Fonseca, E. Morgante, RS, G. Servant, 1911.08472, JHEP 04 (2020) 010
E. Morgante, W. Ratzinger, RS, B.A. Stefanek, 2109.13823, JHEP 12 (2021) 037
C. Eröncel, RS, G. Servant, P. Sørensen, 2206.14259, JCAP 10 (2022) 053
C. Eröncel, RS, G. Servant, P. Sørensen, 240x.xxxxx

2024. 3. 5 @ UGAP2024

ALP : Axion-like particle

Axion field : ϕ

- PQ symmetry (NG boson) + $\phi G_{\mu\nu}\tilde{G}^{\mu\nu}$-type coupling w/ gauge fields

$$\phi \rightarrow \phi + \delta\phi$$

$$\frac{1}{f}\phi G_{\mu\nu}\widetilde{G^{\mu\nu}}$$

Photon,
Gluon,
Hidden gauge boson,
…

- PQ symmetry breaking by strong dynamics

$$V(\phi) \sim -\Lambda_b^4 \cos\frac{\phi}{f}$$

Axion-like particle → good candidate of DM

- Light and (almost) stable spin-0 particle is predicted from $\Lambda_b \ll f$.

ALP mass $\quad m_\phi = \sqrt{V''} \sim \dfrac{\Lambda_b^2}{f}$

ALP lifetime $\quad \tau_\phi \propto \dfrac{f^2}{m_\phi^3} \sim \dfrac{f^5}{\Lambda_b^6}$

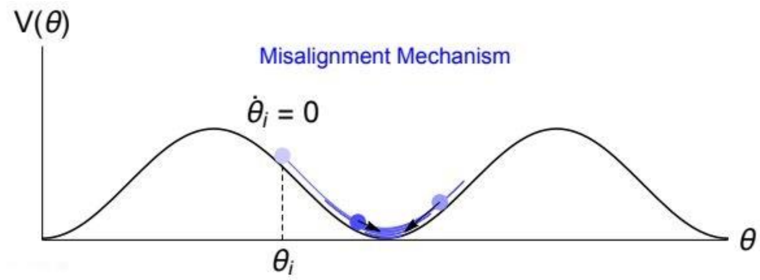
Axion-like particle DM scenario

Misalignment mechanism

[Preskill, Wise, Wilczek (1983)]
[Abbott, Sikivie (1983)]
[Dine, Fischler (1983)]

Initial condition $\phi = \phi_0 \neq 0$, $\dot{\phi} = 0$

EOM $$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda_b^4(T)}{f}\sin\frac{\phi}{f} = 0$$



[taken from Co, Hall, Harigaya (2019)]

The axion starts to oscillate when $3H(T) \sim m(T)$

$$\Rightarrow \quad \rho_{DM} \sim m_\phi \times \left(\frac{a(T_{osc})}{a_0}\right)^3 \times \frac{\Lambda_b(T_{osc})^4\theta_i^2}{m_\phi(T_{osc})}$$

w/ $m_\phi(T_{osc}) \sim 3H(T_{osc})$

mass — Dilution factor — Number density at $T = T_{osc}$

Axion-like particle DM scenario

Misalignment mechanism

[Preskill, Wise, Wilczek (1983)]
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Initial condition $\phi = \phi_0 \neq 0$, $\dot{\phi} = 0$

What happens if $\dot{\phi} > \Lambda_b^2$?

EOM $$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda_b^4(T)}{f}\sin\frac{\phi}{f} = 0$$

[taken from Co, Hall, Harigaya (2019)]

The axion starts to oscillate when $3H(T) \sim m(T)$

$$\rho_{DM} \sim m_a \times \left(\frac{a(T_{osc})}{a_0}\right)^3 \times \frac{\Lambda_b(T_{osc})^4 \theta_i^2}{m_a(T_{osc})}$$ w/ $m_a(T_{osc}) \sim 3H(T_{osc})$

mass — Dilution factor — Number density at $T = T_{osc}$

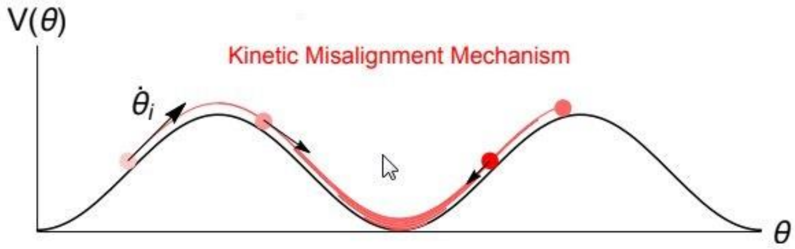
Axion-like particle DM scenario

Kinetic Misalignment mechanism

[Co, Hall, Harigaya (2019)]
[Chang, Cui (2019)]

Initial condition $\dot{\phi} > \Lambda_b^2$

EOM $$\ddot{\phi} + 3H\dot{\phi} + \frac{\Lambda_b^4(T)}{f}\sin\frac{\phi}{f} = 0$$



[taken from Co, Hall, Harigaya (2019)]

The axion starts to oscillate when $\dot{\phi}^2(T) \sim \Lambda_b^4(T)$

$$\Rightarrow \quad \rho_{DM} \sim m_\phi \times \left(\frac{a(T_{osc})}{a_0}\right)^3 \times \frac{\Lambda_b(T_{osc})^4}{m_\phi(T_{osc})}$$

w/ $\dot{\phi}^2(T_{osc}) \sim \Lambda_b^4(T_{osc})$

mass — Dilution factor — Number density at $T = T_{osc}$

Delay of onset of oscillation → larger ρ_{DM}

Why interesting?

- KMM predicts larger ρ_{DM} than conventional MM
- For given axion mass, conventional MM predicts smaller ρ_{DM} for smaller f_a

⇩

KMM tends to predicts smaller f_a (~ larger $g_{a\gamma\gamma}$)
motivates axion detection experiments !!

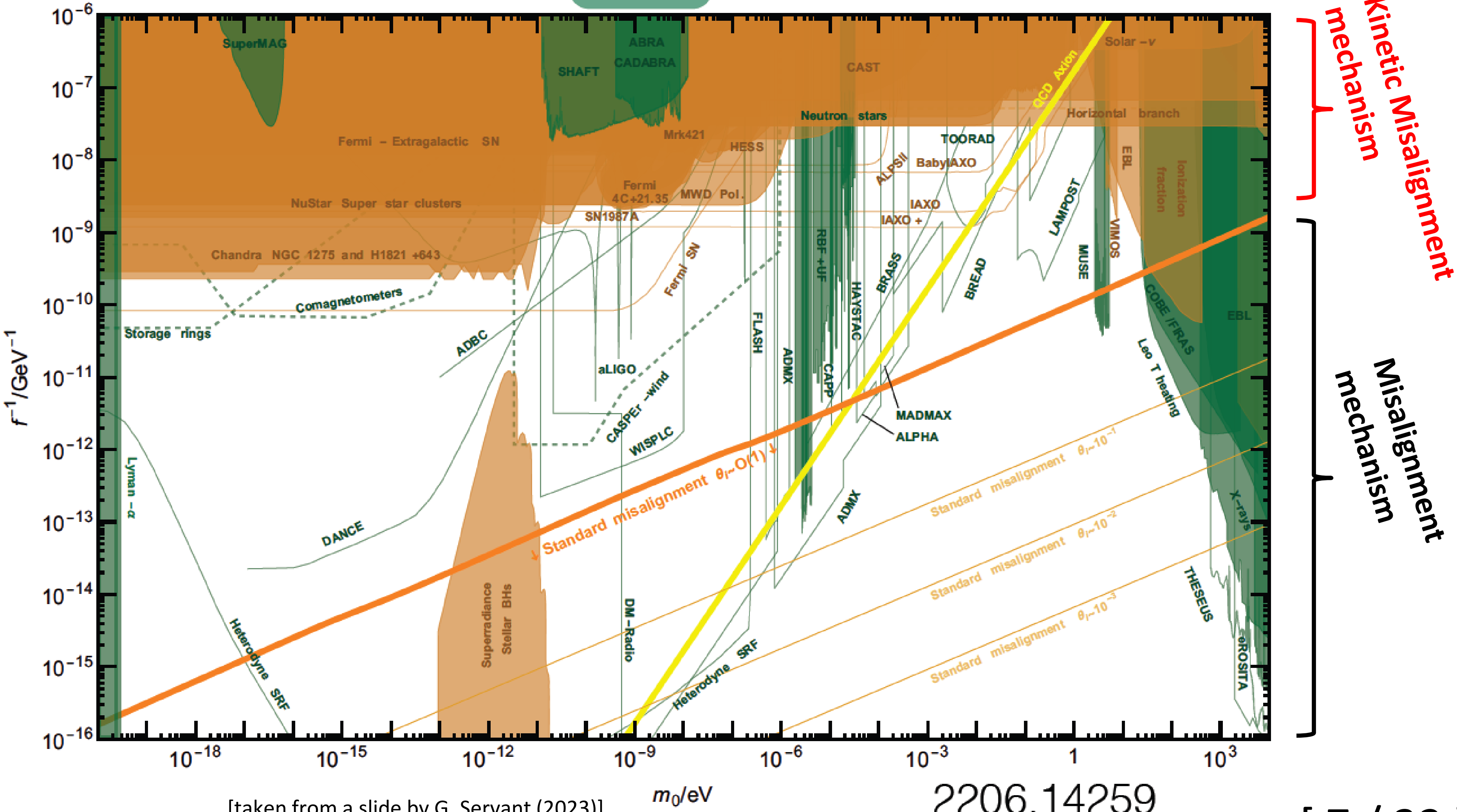
($L = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$)

Why interesting?

Any ALP

Only DM

(assuming KSVZ-like relation : $g_{a\gamma\gamma} \sim 2 \times 10^{-3}/f$)



[taken from a slide by G. Servant (2023)]

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Axion fluctuation?

What people usually do

Solving EOM for spatially homogeneous field : $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

However…

Even we start from (almost) homogeneous field configuration,
fluctuations can grow later.

Velocity as PQ charge

Velocity $\dot{\phi}$ is PQ charge : $\rho_{\mathrm{PQ}} = f \dfrac{\partial L}{\partial \dot{\phi}} = f \dot{\phi}$

$\phi \to \phi + f\,\delta$

PQ sym. transf.

Explicit breaking of PQ sym. : $V(\phi) \sim -\Lambda_b^4 \cos \dfrac{\phi}{f}$

PQ charge will be lost
= axion kinetic energy will be lost
= energy dissipation

Axion fragmentation [Fonseca, Morgante, RS, Servant (2019)]

For related earlier works, see
[Green, Kofman, Starobinsky (1998)]
[Flauger, McAllister, Pajer, Westphal, Xu (2009)]
[Jaeckel, Mehta, Witkowski (2016)]
[Arvanitaki, Dimopoulos, Galanis, Lehner, Thompson, Van Tilburg (2019)]

1. Introduction

2. How axion fragmentation works

(What happen if initial $\dot{\phi} \neq 0$?)

3. ALP DM fragmentation scenario

(Who gives initial $\dot{\phi} \neq 0$?)

EOM of axion

Let us investigate the simplest case.

- $H = 0$ (no cosmic expansion)
- $V(\phi) = \Lambda_b^4 \cos(\phi/f)$

We have only three parameters :

$\dot{\phi}_0$: initial velocity
f : decay constant
Λ_b^4 : height of barrier

EOM of axion :

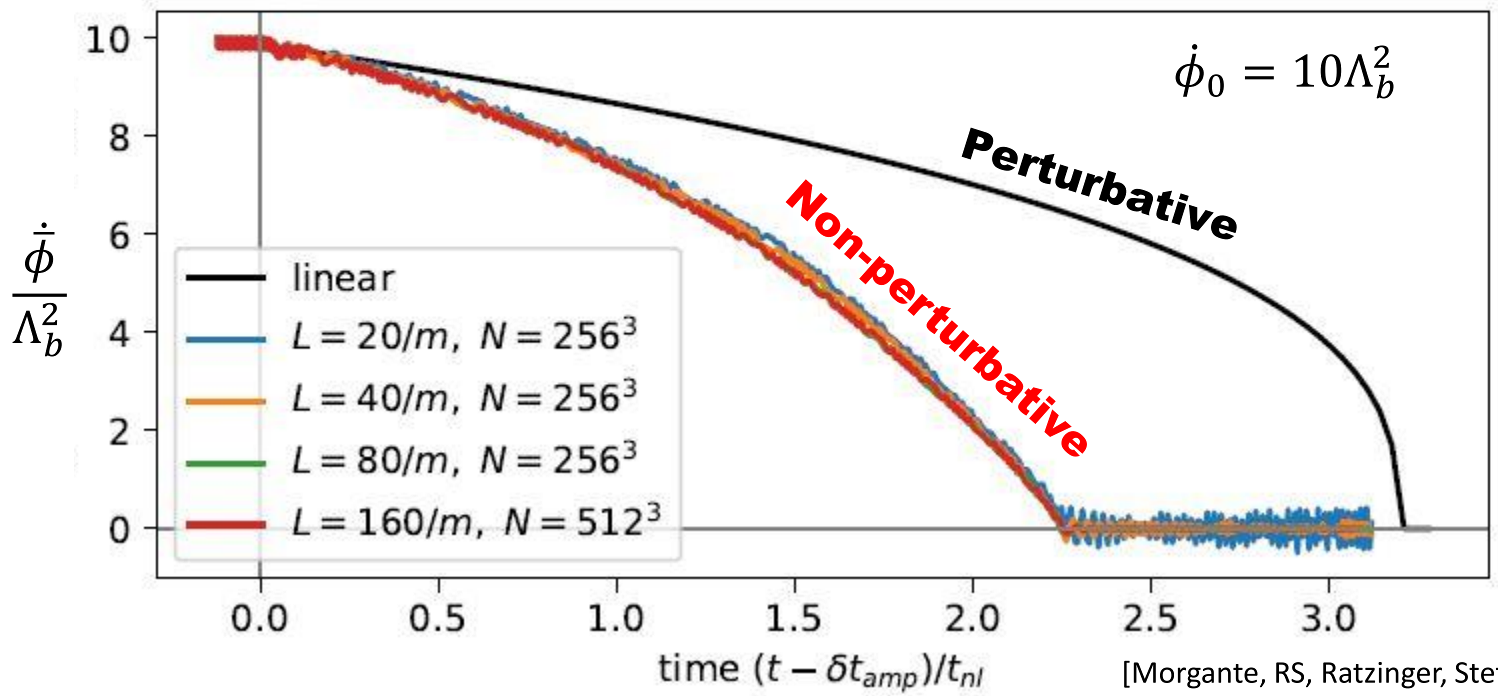
$$\frac{d^2\phi}{dt^2} - \nabla^2\phi - \frac{\Lambda_b^4}{f}\sin\frac{\phi}{f} = 0$$

⇨ Classical lattice simulation

$$\begin{aligned}\frac{d^2\phi_{i,j,k}}{dt^2} =& \frac{1}{a^2}\left(\phi_{i+1,j,k} - 2\phi_{i,j,k} + \phi_{i-1,j,k}\right)\\ &+ \frac{1}{a^2}\left(\phi_{i,j+1,k} - 2\phi_{i,j,k} + \phi_{i,j-1,k}\right)\\ &+ \frac{1}{a^2}\left(\phi_{i,j,k+1} - 2\phi_{i,j,k} + \phi_{i,j,k-1}\right)\\ &+ \frac{\Lambda_b^4}{f}\sin\frac{\phi_{i,j,k}}{f}.\end{aligned}$$

An example of numerical result

Confirmed energy dissipation in non-perturbative calculation!



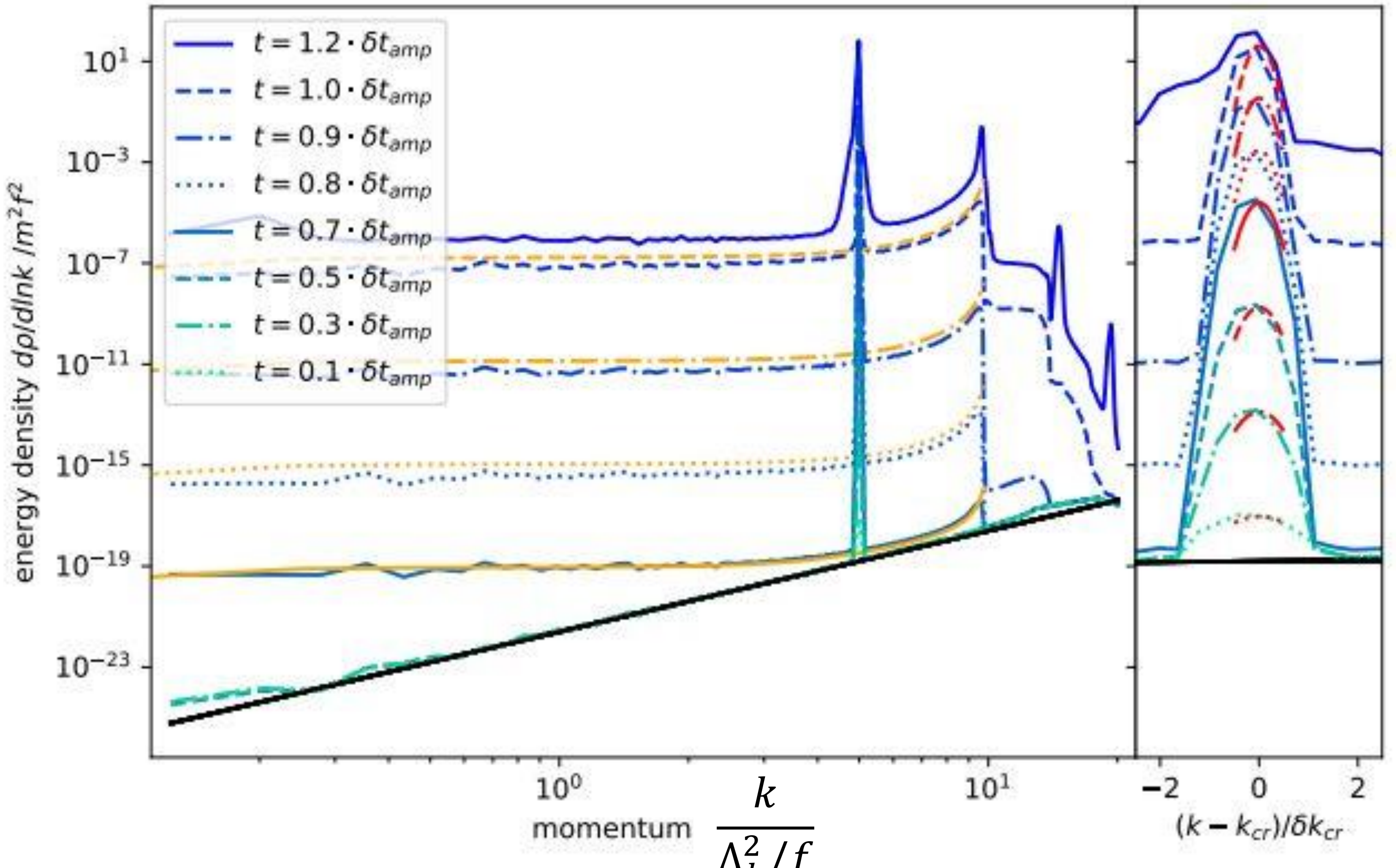
[Morgante, RS, Ratzinger, Stefanek (2021)]

Time scale of fragmentation : $\Delta t \sim \frac{f\dot{\phi}_0^3}{\Lambda_b^8}$ $\left(t_{nl} = \frac{f\dot{\phi}_0^3}{\Lambda_b^8}\right)$

Field excursion during fragmentation : $\Delta\phi \sim \frac{f\dot{\phi}_0^4}{\Lambda_b^8}$

Growth of spectrum (early stage)

$\dot{\phi}_0 = 10\Lambda_b^2$



[Morgante, RS, Ratzinger, Stefanek (2021)]

$$\delta t_{amp} \equiv \frac{f\dot{\phi}}{\Lambda_b^4}\log\frac{16f^4}{\dot{\phi}^2}$$

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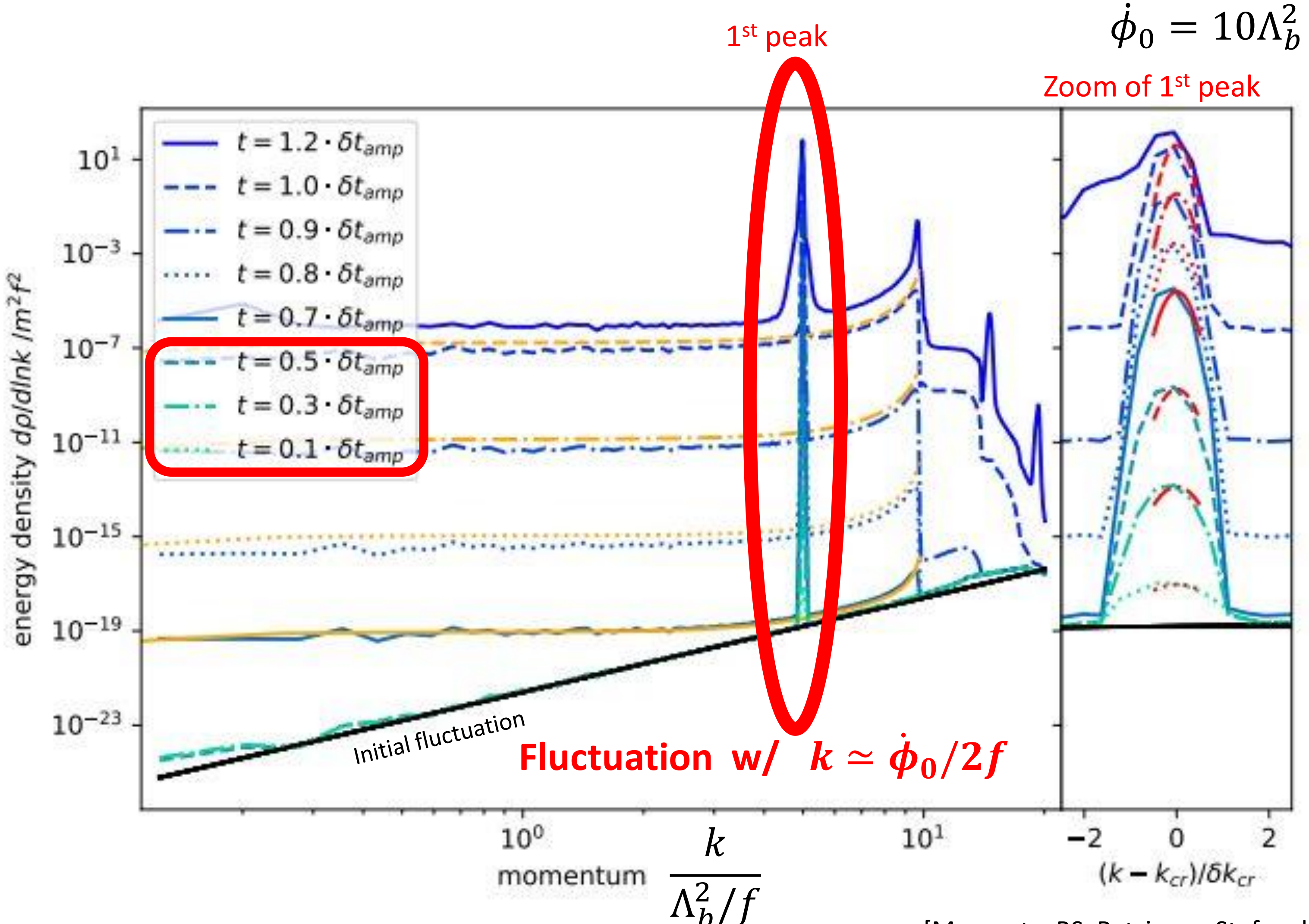

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Growth of spectrum w/ Mathieu eq

EOM of axion :

$$\frac{d^2\phi}{dt^2} - \nabla^2\phi - \frac{\Lambda_b^4}{f}\sin\frac{\phi}{f} = 0$$

$$\phi(x,t) \simeq \bar{\phi}(t) + \delta\phi(x,t)$$

$O(\delta\phi^0)$ $$\frac{d^2\bar{\phi}}{dt^2} - \frac{\Lambda_b^4}{f}\sin\frac{\bar{\phi}}{f} = 0$$

$O(\delta\phi^1)$ $$\frac{d^2\delta\phi}{dt^2} - \nabla^2\delta\phi - \frac{\Lambda_b^4}{f^2}\cos\frac{\bar{\phi}}{f}\delta\phi = 0$$

Growth of spectrum w/ Mathieu eq

EOM of axion :

$$\frac{d^2\phi}{dt^2} - \nabla^2\phi - \frac{\Lambda_b^4}{f}\sin\frac{\phi}{f} = 0$$

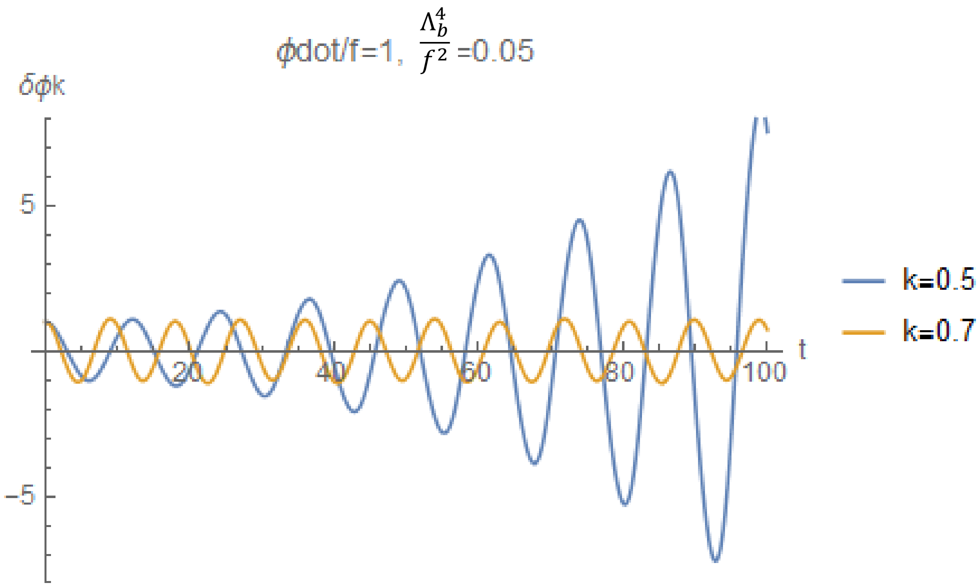
$$\Downarrow \quad \phi(x,t) \simeq \bar{\phi}(t) + \delta\phi(x,t)$$

$O(\delta\phi^0)$ $$\frac{d^2\bar{\phi}}{dt^2} - \frac{\Lambda_b^4}{f}\sin\frac{\bar{\phi}}{f} = 0 \quad \xRightarrow{\dot{\bar{\phi}} \gg \Lambda_b^2} \quad \bar{\phi}(t) \simeq \dot{\bar{\phi}}_0 t$$

$O(\delta\phi^1)$ $$\frac{d^2\delta\phi_k}{dt^2} + \left(k^2 - \frac{\Lambda_b^4}{f^2}\cos\frac{\dot{\bar{\phi}}t}{f}\right)\delta\phi_k = 0$$

Mathieu equation

Growth of spectrum w/ Mathieu eq

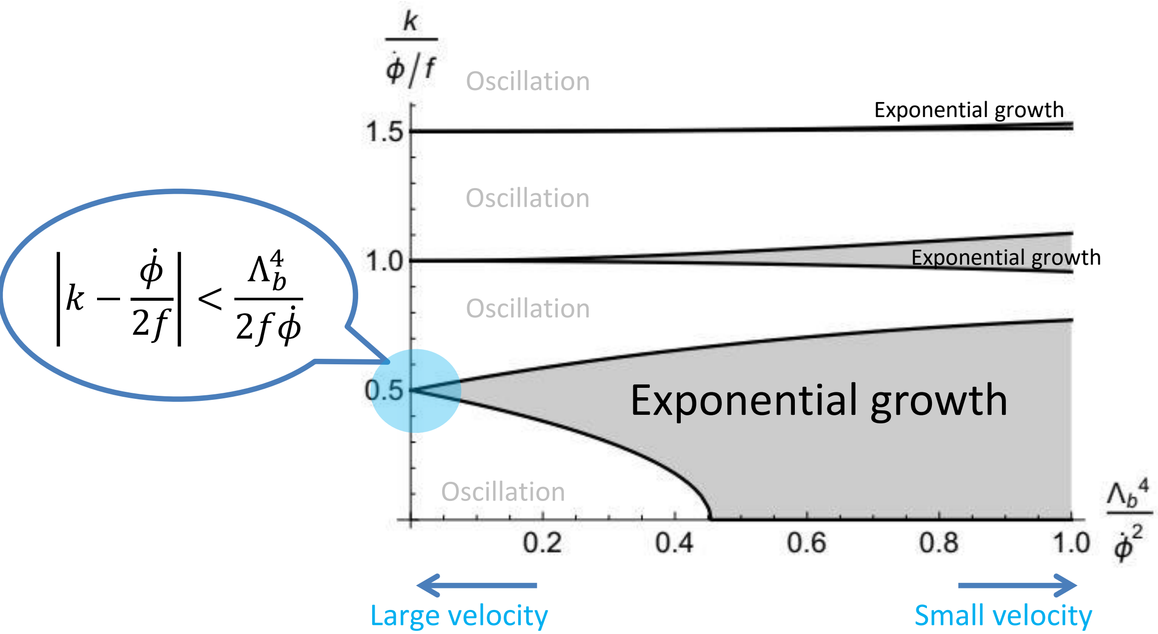


There exist resonant solutions for this.
It's like a swing!

$$\frac{d^2\delta\phi_k}{dt^2}+\left(k^2-\frac{\Lambda_b^4}{f^2}\cos\frac{\dot{\bar{\phi}}t}{f}\right)\delta\phi_k = 0 \qquad (\bar{\phi}\approx\dot{\bar{\phi}}t)$$

Mathieu equation

Growth of spectrum w/ Mathieu eq



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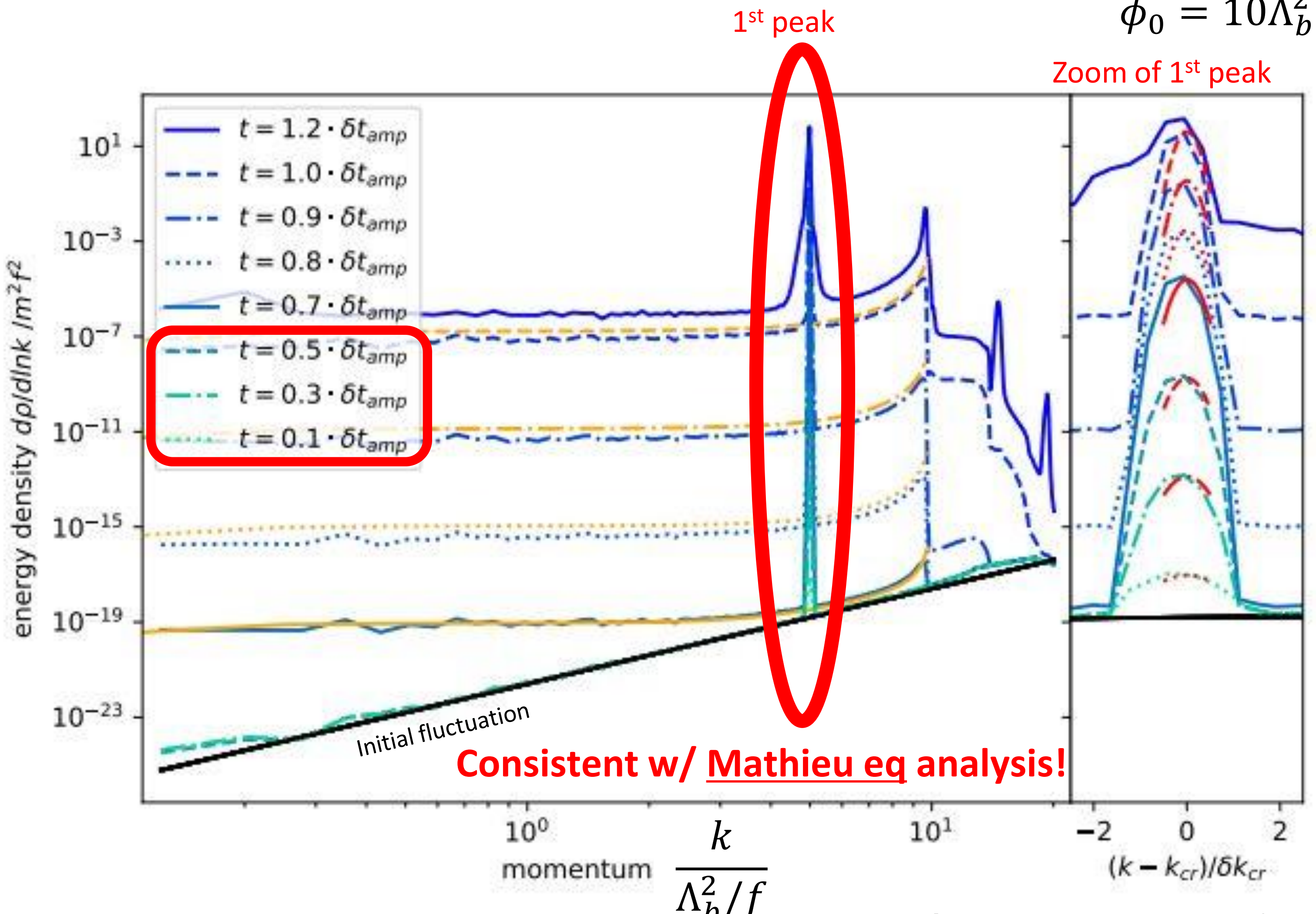
Mathieu equation

Growth of spectrum (early stage)

$\dot{\phi}_0 = 10\Lambda_b^2$



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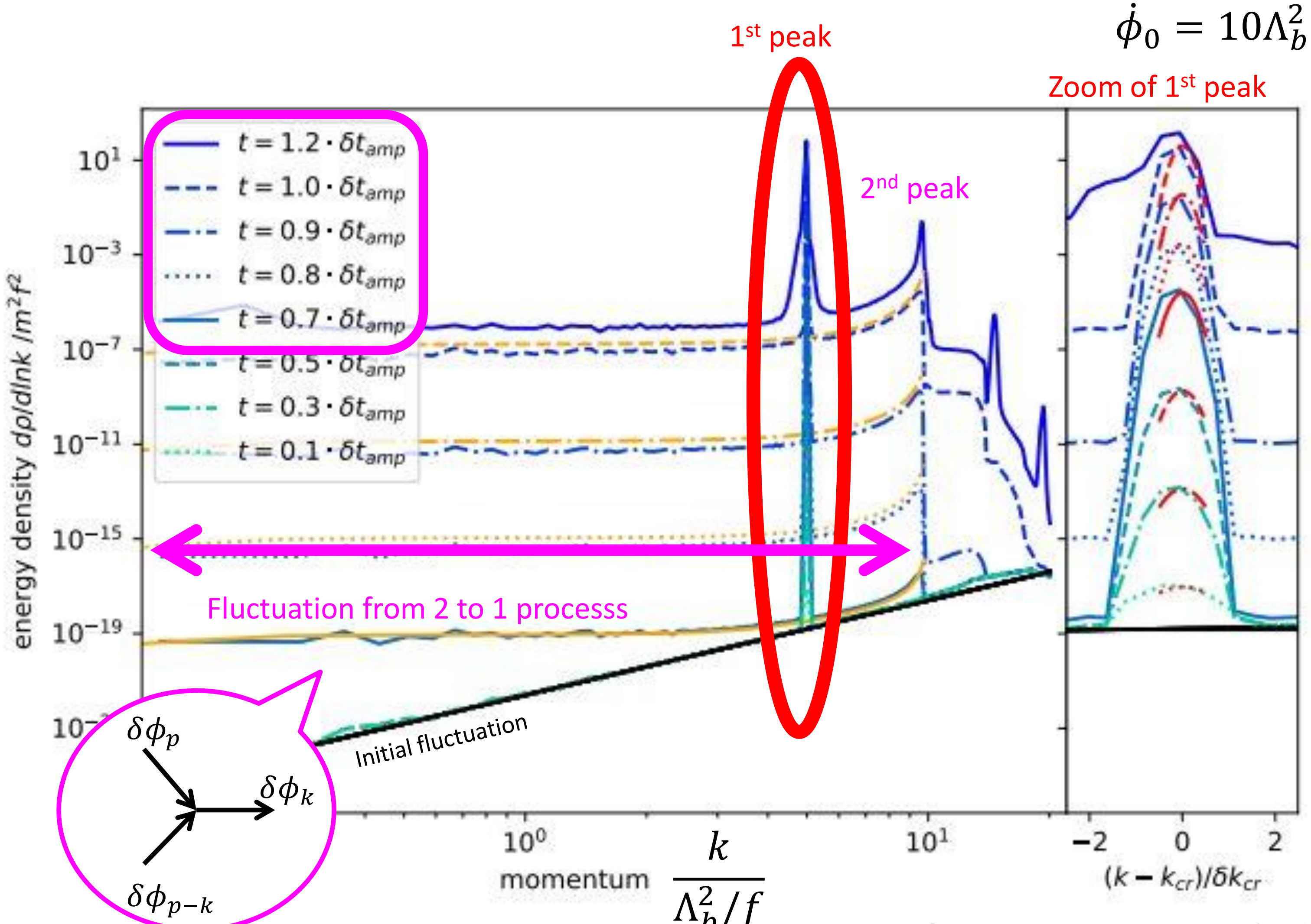

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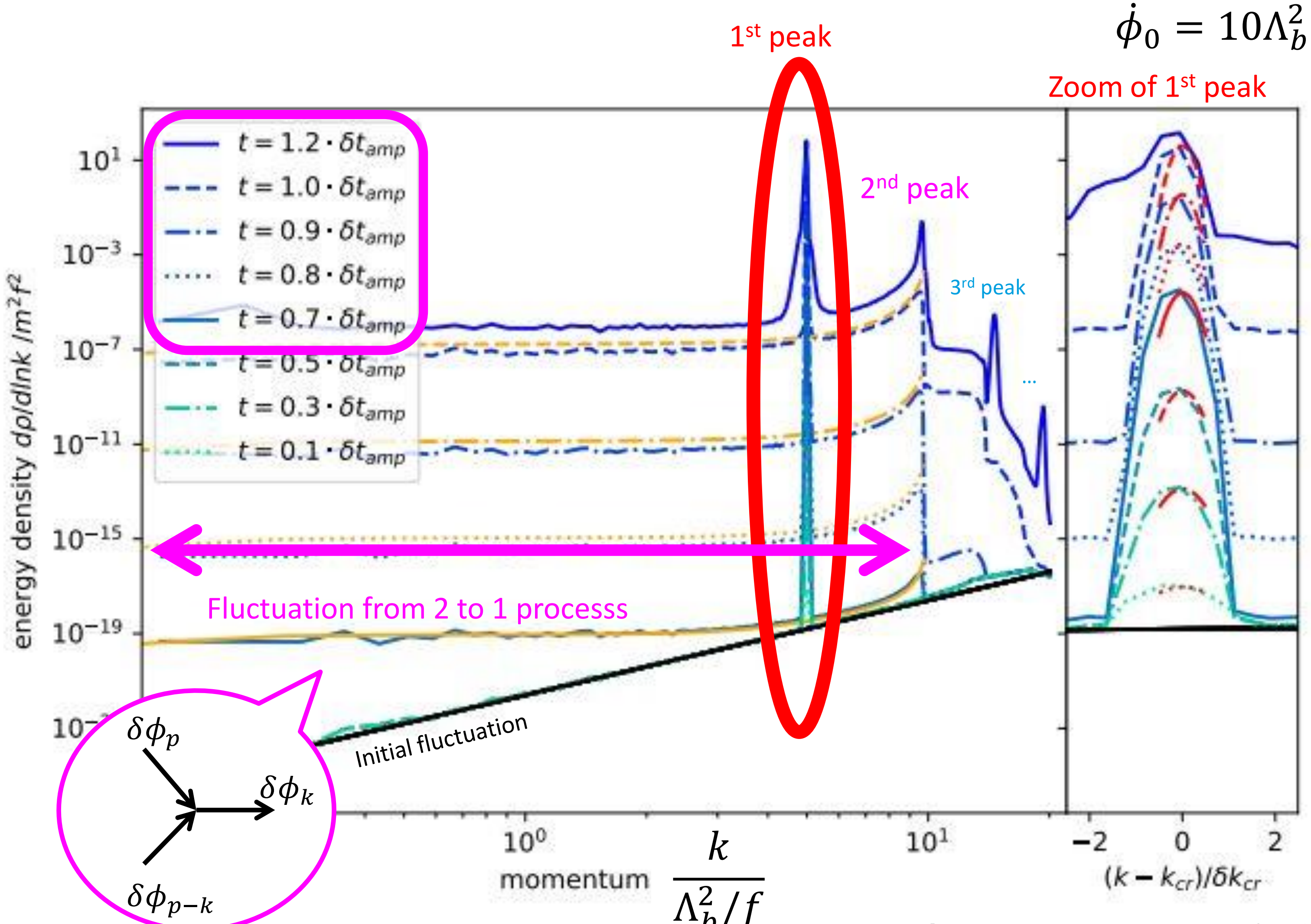

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Growth of spectrum

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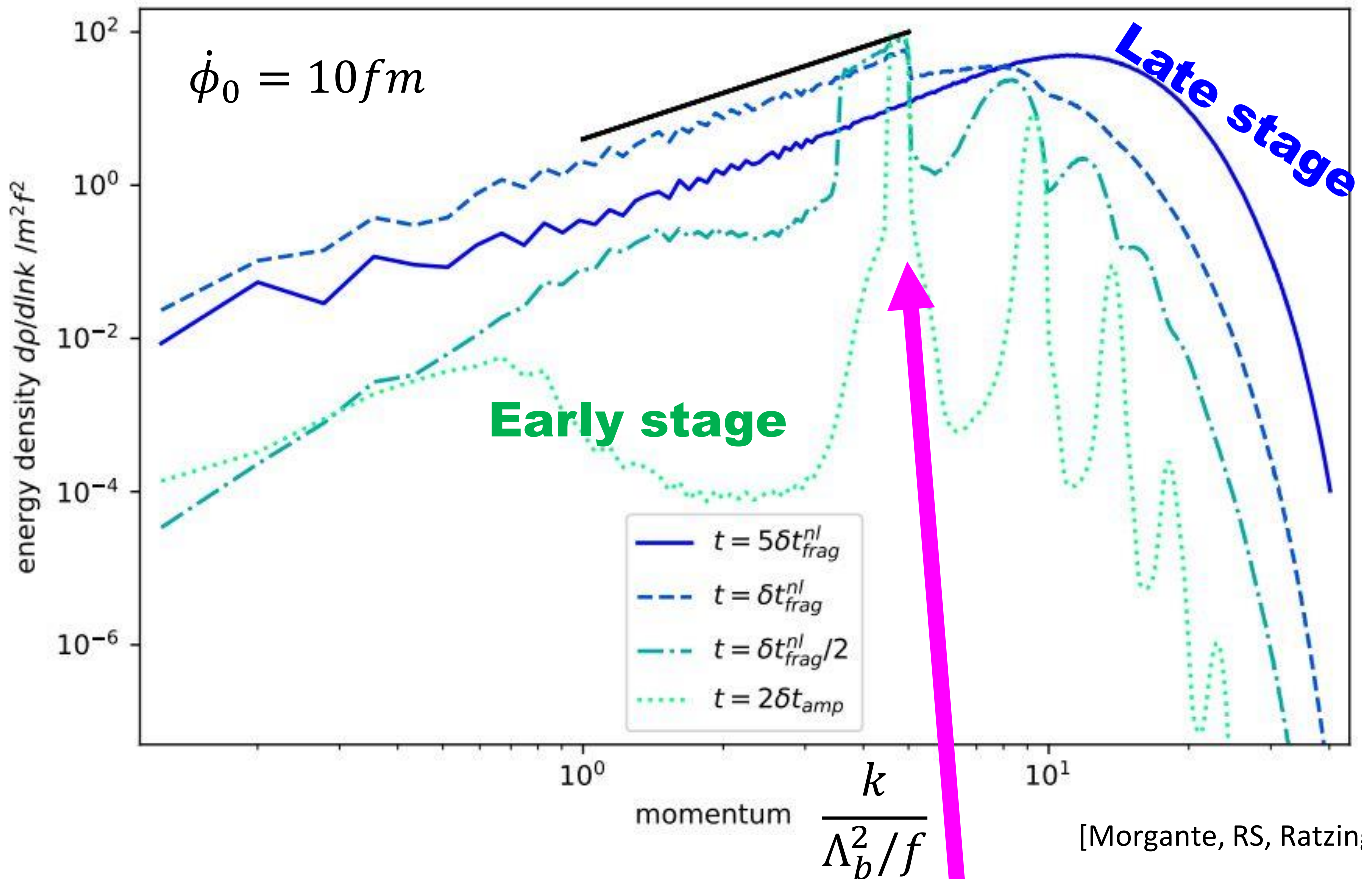

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[Morgante, RS, Ratzinger, Stefanek (2021)]

Resonance from Mathieu Eq. $k = \frac{\dot{\phi}_0}{2f}$

- Parametric resonance in early stage
- Broad spectrum from non-linear effect

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(What happen if initial $\dot{\phi} \neq 0$?)

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(Who gives initial $\dot{\phi} \neq 0$?)

Axion fragmentation & ALP dark matter

How do we get initial $\dot{\phi} \neq 0$??

Affleck-Dine mechanism

[Affleck, Dine (1985)]
[Dine, Randall, Thomas (1996)]

$$P = \frac{1}{\sqrt{2}} s \exp\left(\frac{i\phi}{f}\right)$$

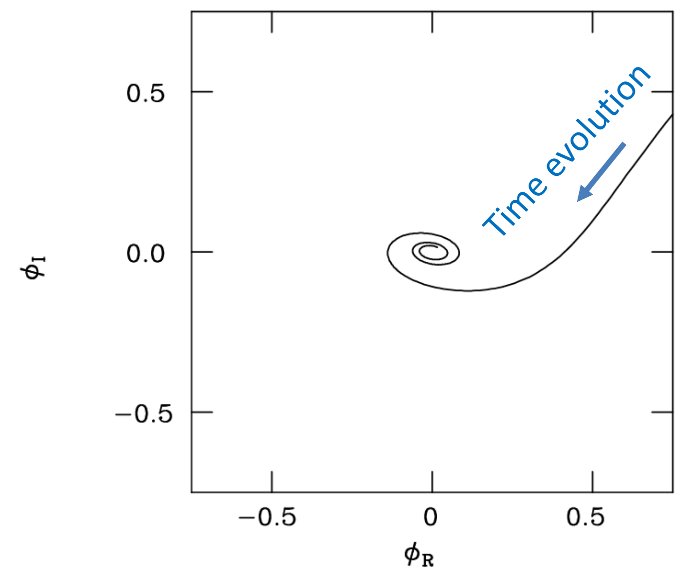
P : PQ charged scalar
s : saxion
ϕ : axion

$$V(P) = V_{PQ}(|P|) + V_{\not{PQ}}(P)$$

PQ invariant term

PQ violating term

e.g., $V_{\not{PQ}} \sim \frac{P^n}{\Lambda^{n-4}} + h.c.$



Taken from [Dine, Randall, Thomas (1996)]

In addition, we also need

- large initial |P|
- Elimination of saxion oscillation (to avoid overclosure)

A model

[Co, Fernandez, Ghalsasi, Hall, Harigaya (2020)]

$$V = m^2|P|^2\left(-\frac{1}{2}+\frac{1}{2}\log\frac{2|P|^2}{f^2}\right)$$

$$-c_H H^2|P|^2 + \left(A\frac{P^n}{M^{n-3}}+h.c.\right) + \frac{|P|^{2n-2}}{M^{2n-6}}$$

A model

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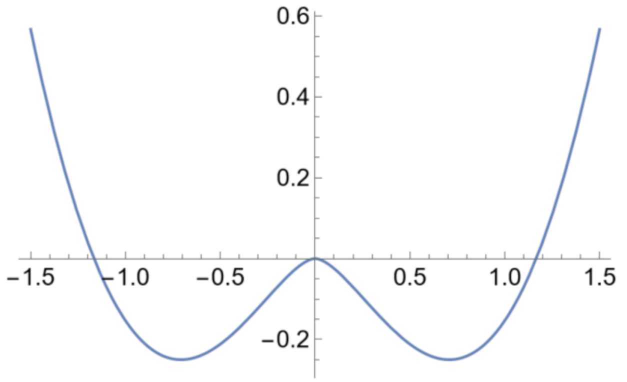


PQ breaking [Moxhay, Yamamoto (1985)]

$$V = m^2|P|^2\left(-\frac{1}{2}+\frac{1}{2}\log\frac{2|P|^2}{f^2}\right)$$

$$-c_H H^2|P|^2 + \left(A\frac{P^n}{M^{n-3}} + h.c.\right) + \frac{|P|^{2n-2}}{M^{2n-6}}$$

How to get kick ($\dot{\phi} \neq 0$)

→ Affleck-Dine mechanism

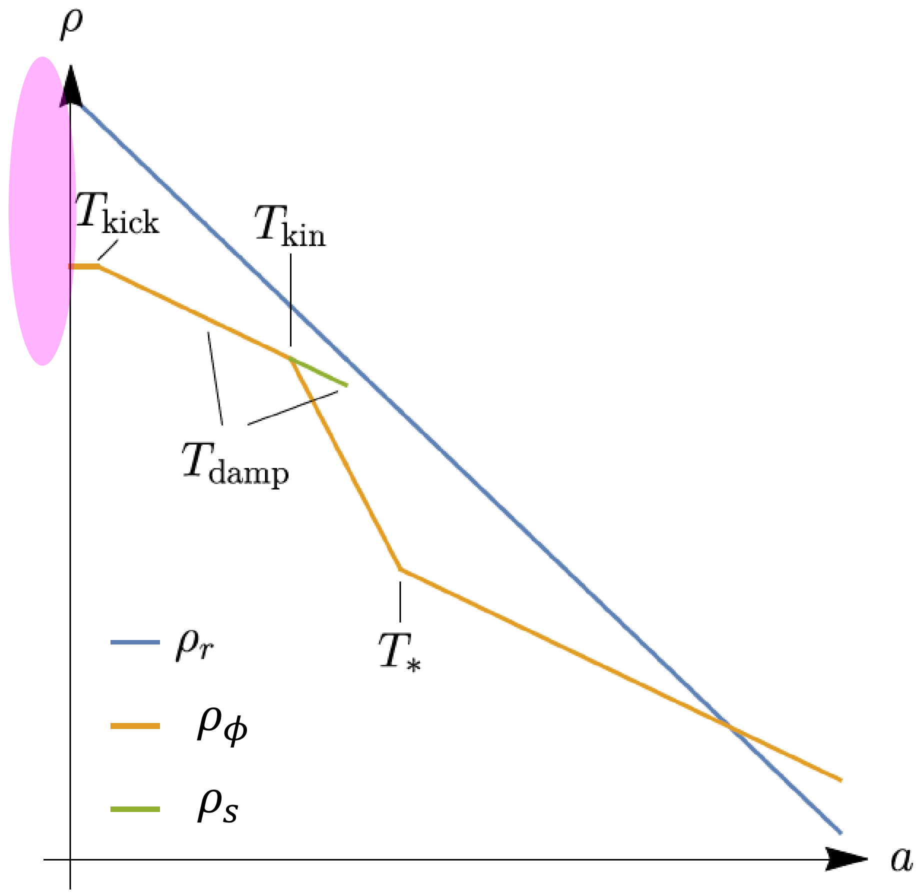
[Affleck, Dine (1985)]

A thermal history

Tachyonic mass drives Large VEV

$$\phi_{early} \sim (HM^{n-3})^{\frac{1}{n-2}}$$

$$V \simeq -c_H H^2 |P|^2 + \left(A \frac{P^n}{M^{n-3}} + h.c. \right) + \frac{|P|^{2n-2}}{M^{2n-6}}$$



[Eröncel, RS, Sørensen, Servant, in preparation]

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ϕ starts to roll

$$m \sim H, \qquad T_{kick} \sim \sqrt{mM_{pl}}$$

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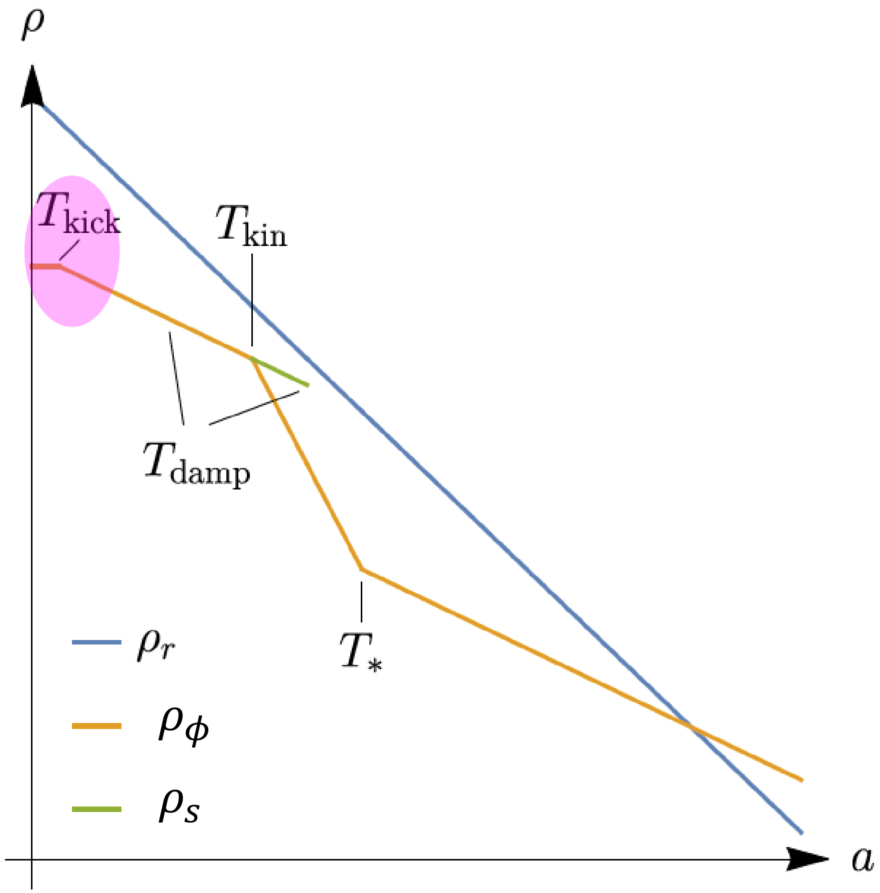

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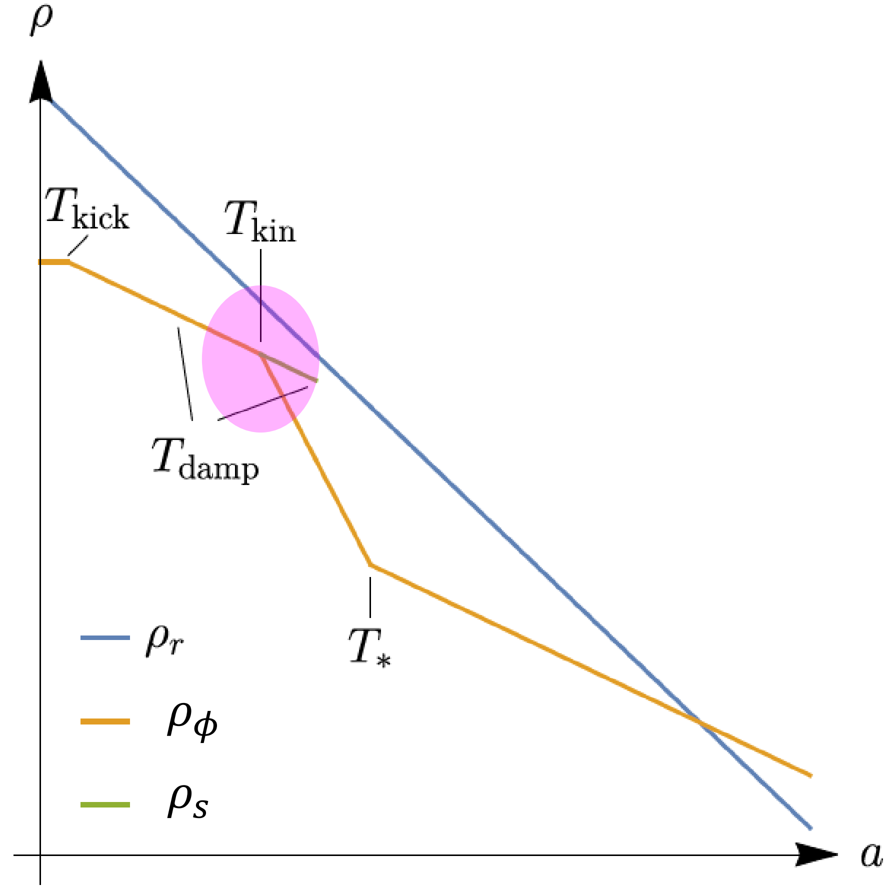
Energy in s dissipates (via, e.g., $L \sim s\bar{\chi}\chi$)

Nonzero $\dot{\phi} \propto a^{-3}$ survives

$$V \simeq m^2|P|^2\left(-\frac{1}{2}+\frac{1}{2}\log\frac{2|P|^2}{f^2}\right)$$



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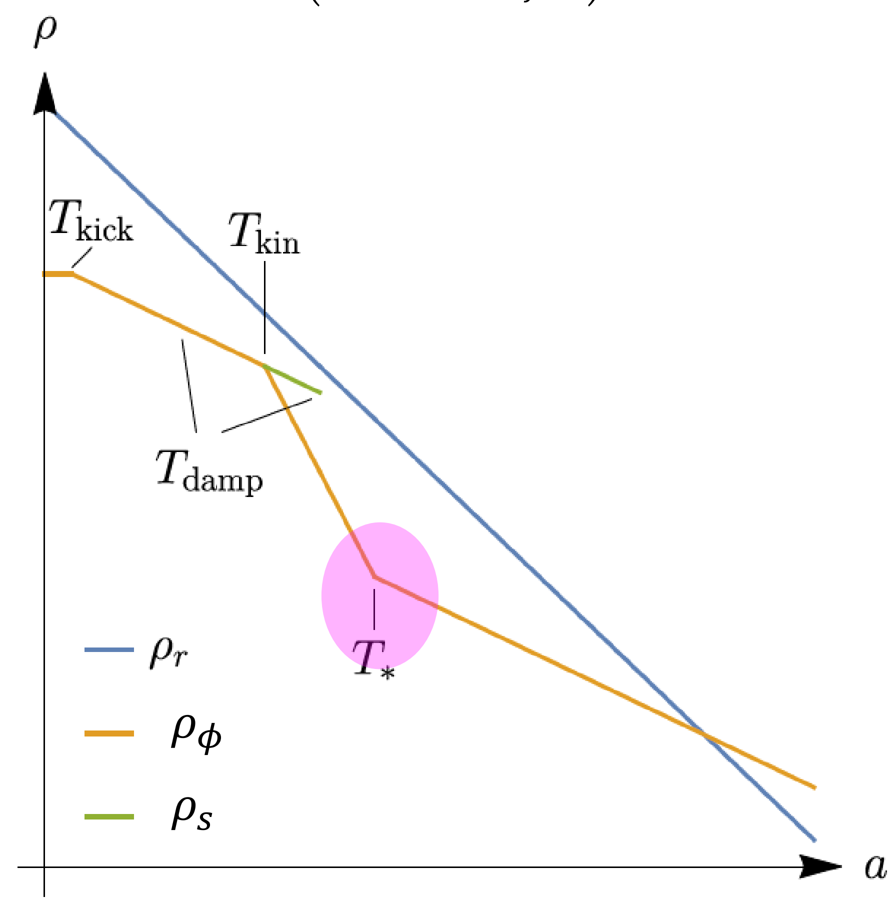
Trapping by potential, fragmentation, etc

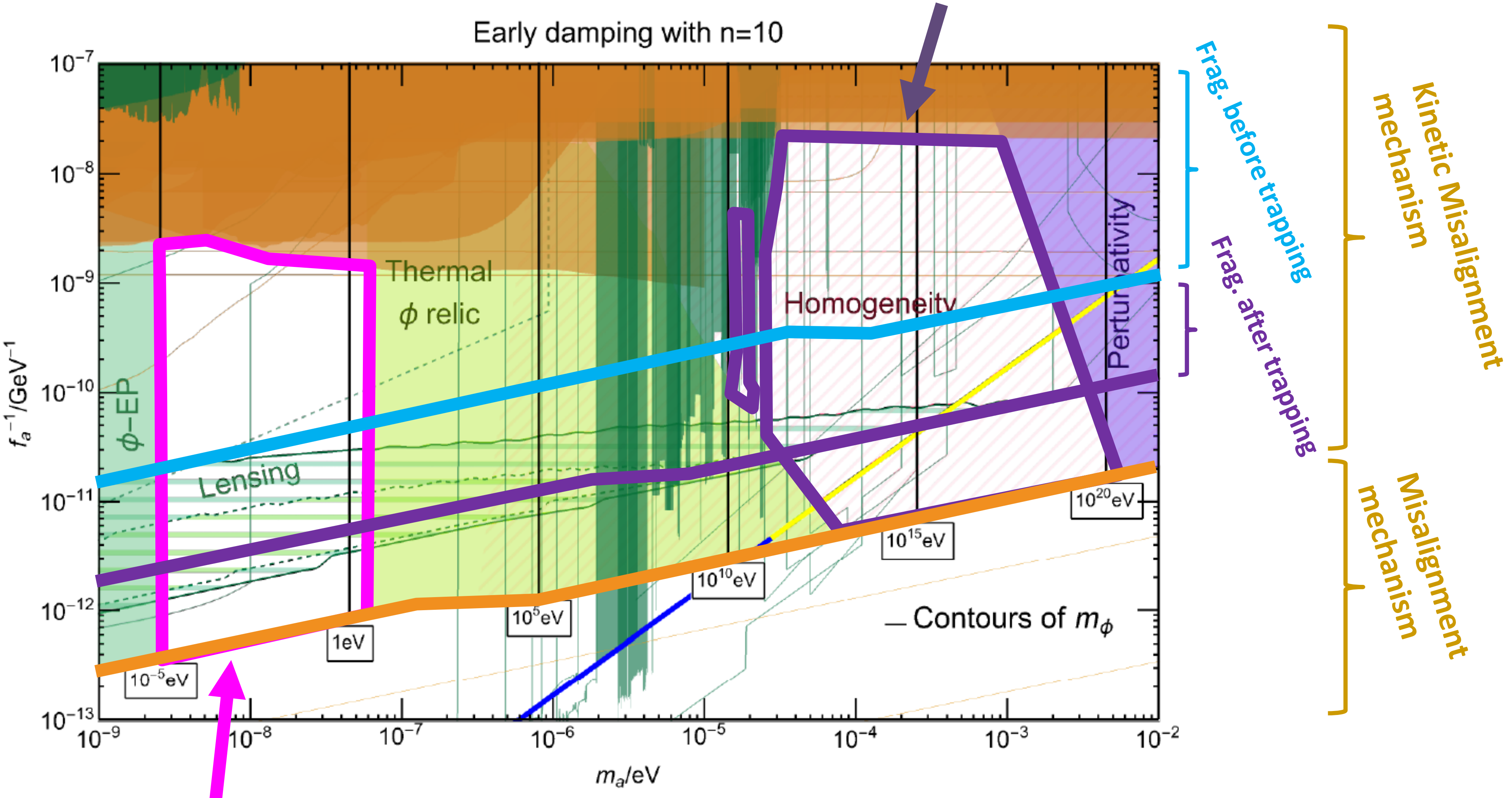
$$V \simeq m^2|P|^2\left(-\frac{1}{2}+\frac{1}{2}\log\frac{2|P|^2}{f^2}\right)$$



[Eröncel, RS, Sørensen, Servant, in preparation]

A parameter space

Initial adiabatic fluctuation could dominate (depending on inflation scenario)



Kinetic misalignment (+ fragmentation)

Summary

- ALP DM w/ kinetic misalignment is an interesting experimental target
- Zeromode kinetic energy dissipates into fluctuations
- Generic phenomena w/ periodic potential and large velocity
- Fragmentation can happen in ALP DM scenario
- Other theoretical applications
    - Relaxion scenario (1911.08473, Fonseca-Morgante-Sato-Servant)
      Relaxion fragmentation can be a source of friction to stop relaxion.
    - Any other interesting idea?

Backup

Necessity of non-linear analysis

Naïve dimensional analysis

Initial kinetic energy : $\dot{\phi}_0^2/2$

Typical wavenumber : $\dot{\phi}_0/f$

Energy conservation : $(\delta\phi)^2 \times \left(\dot{\phi}_0/f\right)^2 \sim \dot{\phi}_0{}^2$

⇨ Typical field variation : $\delta\phi \sim f$ **NOT SMALL !!**

Classical lattice simulation

$$\ddot{\phi} = \nabla^2\phi + \frac{\Lambda_b^4}{f}\sin\frac{\phi}{f}$$

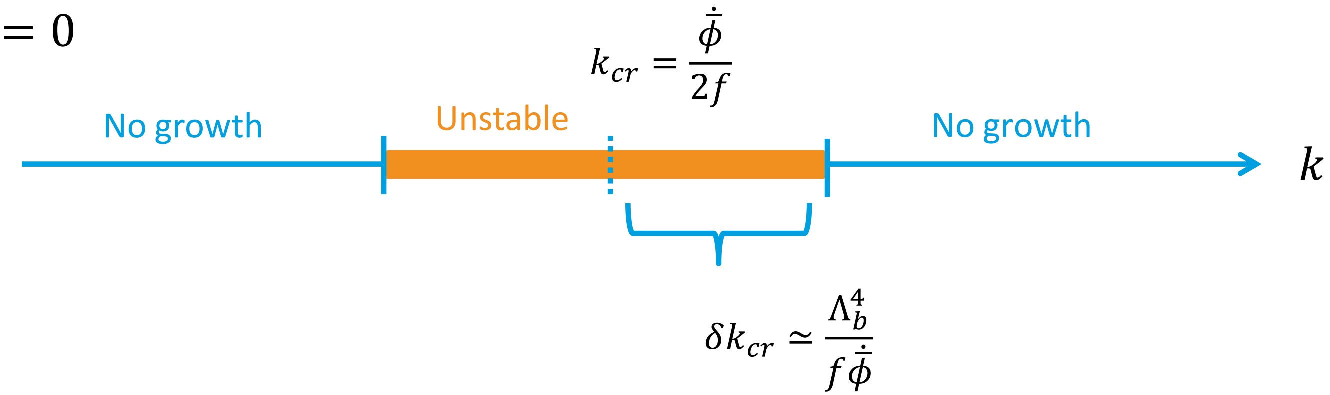
⇨

$$\begin{aligned}\frac{d^2\phi_{i,j,k}}{dt^2} =& \frac{1}{a^2}\left(\phi_{i+1,j,k} - 2\phi_{i,j,k} + \phi_{i-1,j,k}\right)\\ &+ \frac{1}{a^2}\left(\phi_{i,j+1,k} - 2\phi_{i,j,k} + \phi_{i,j-1,k}\right)\\ &+ \frac{1}{a^2}\left(\phi_{i,j,k+1} - 2\phi_{i,j,k} + \phi_{i,j,k-1}\right)\\ &+ \frac{\Lambda_b^4}{f}\sin\frac{\phi_{i,j,k}}{f}.\end{aligned}$$

Naïve estimation on back reaction

As long as $\dot{\phi}$ is constant, $\delta\phi_k \sim \exp\left(\frac{\Lambda_b^4 t}{f\dot{\phi}}\right)$ for $\left|k - \frac{\dot{\phi}}{2f}\right| < \frac{\Lambda_b^4}{2f\dot{\phi}}$

$t = 0$



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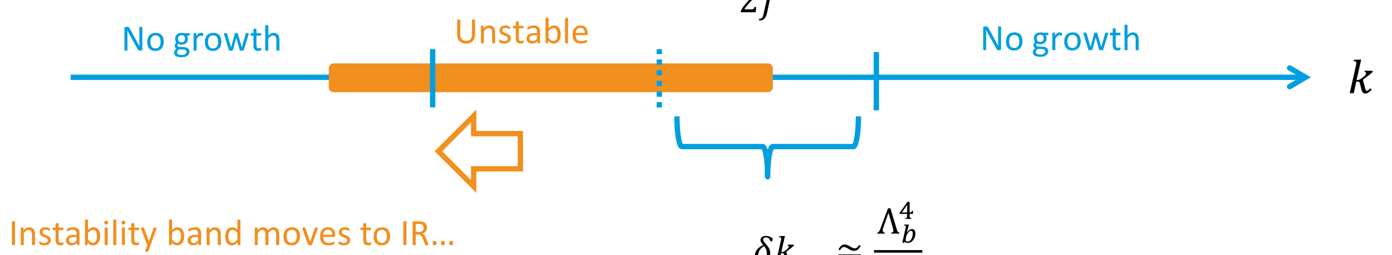
$t > 0$



$k_{cr} = \frac{\dot{\phi}}{2f}$

$\delta k_{cr} \simeq \frac{\Lambda_b^4}{f\dot{\phi}}$

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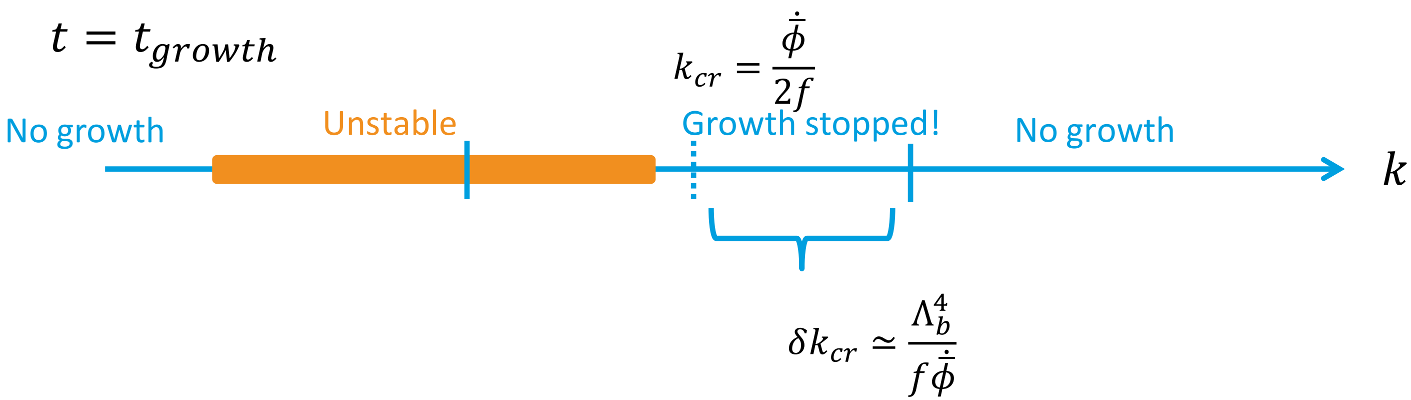

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1. ϕ rolls
2. Fluctuation w/ $k \simeq \dot{\phi}/2f$ grows
3. Fluctuation takes energy from ϕ
4. Instability band moves to IR
5. Back to 1. with smaller $\dot{\phi}$

This process repeats
and ϕ loses its kinetic energy!

Naïve estimation on back reaction

Time scale of growth of single mode :

$$t_{stop} \sim \frac{f\bar{\dot{\phi}}}{\Lambda_b^4}\log\frac{f^4}{\bar{\dot{\phi}}^2}$$

Energy stored in fluctuations :

$$\rho_{fluc}(t_{stop}) \sim \bar{\dot{\phi}}^2 \times \frac{\delta k_{cr}}{k_{cr}},$$

$$\Rightarrow \quad \frac{d}{dt}\dot{\phi}^2 \sim -\frac{\rho_{fluc}(t_{stop})}{t_{stop}} \sim -\frac{\Lambda_b^8}{f\dot{\phi}}\left(\log\frac{f^4}{\dot{\phi}^2}\right)^{-1}$$

$$\Rightarrow \quad \frac{d}{dt}\dot{\phi} \sim -\frac{\Lambda_b^8}{f\dot{\phi}^2}\left(\log\frac{f^4}{\dot{\phi}^2}\right)^{-1}$$

c.f.) WKB approx. with $\dot{\phi} \gg \Lambda_b^2$ gives $\quad \frac{d\dot{\phi}}{dt} = -\frac{\pi}{2}\frac{\Lambda_b^8}{f\dot{\phi}^2}\left(\log\frac{32\pi^2 f^4}{\dot{\phi}^2}\right)^{-1}$

(see 1911.08472 for details)

Time scale of fragmentation :

$$\Delta t_{frag} \sim f\frac{\dot{\phi}_0^3}{\Lambda_b^8}\log\frac{f^4}{\dot{\phi}_0^2}$$

Field excursion:

$$\Delta\phi_{frag} \sim \dot{\phi}_0\Delta t_{frag} \sim f\frac{\dot{\phi}_0^4}{\Lambda_b^8}\log\frac{f^4}{\dot{\phi}_0^2}$$

Non-zero slope & Hubble expansion

What happens for non-zero μ^3 & non-zero H?

- Fragmentation $\quad \ddot{\phi}_{frag} = -\frac{\pi\Lambda_b^8}{2f\dot{\phi}^2}\left(\log\frac{32\pi^2 f^4}{\dot{\phi}^2}\right)^{-1}$
- Acceleration by slope $\quad \mu^3$
- Hubble expansion $\quad 3H\dot{\phi}$

Fragmentation works if

- During inflation ($3H\dot{\phi} \sim \mu^3$)

  $3H\dot{\phi} < \sim|\ddot{\phi}_{frag}|$ If not, axion keeps rolling with slow-roll velocity

- Not during inflation ($3H\dot{\phi} \ll \mu^3$)

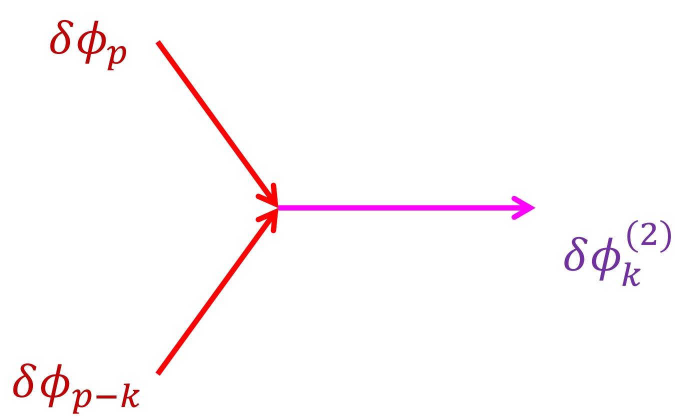
  $\mu^3 < \sim|\ddot{\phi}_{frag}|$ If not, axion is just accelerated by slope

2 to 1 process

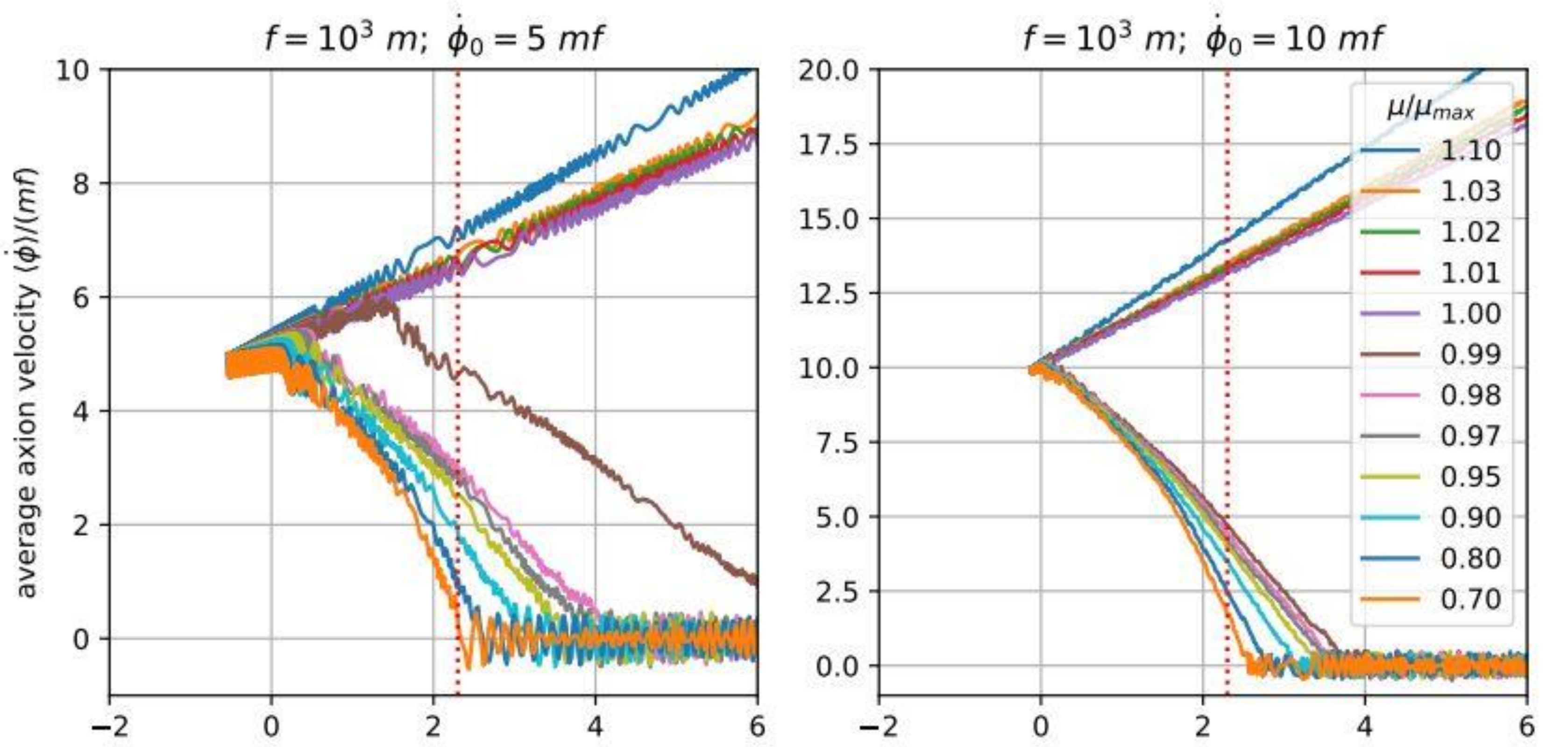
$$\phi(x,t) = \phi(t) + \delta\phi(x,t) + \delta\phi^{(2)}(x,t) + \ \ldots$$

$$\ddot{\phi} - \nabla^2\phi = V'(\phi) \quad \Rightarrow \quad \delta\ddot{\phi}^{(2)} + (k^2 + V'')\delta\phi^{(2)} = -\frac{1}{2}V'''\int d^3p\ \delta\phi_p\delta\phi_{k-p}$$

- $\delta\phi_p$ with $|p| = \dot{\phi}/2f$ is amplified by resonance
- $\delta\phi$ becomes source term for $\delta\phi^{(2)}$



Lattice calc. w/ slope term



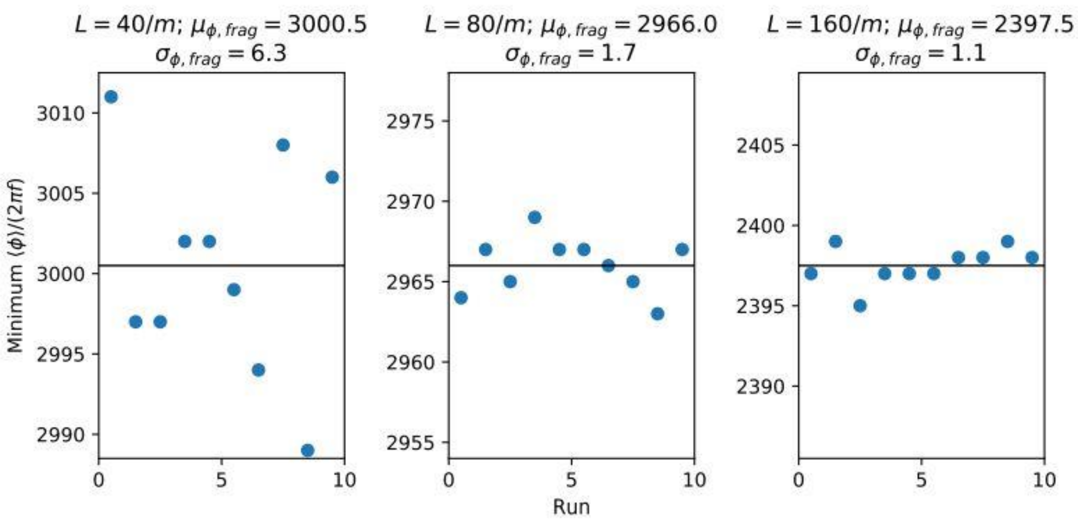
[Morgante, RS, Ratzinger, Stefanek (2021)]

Domain wall?

Field variance after fragmentation is not so small : $\delta\phi \sim f$

Multiple run with finite size box

- $\delta\phi$ in multiple run = $\delta\phi$ of causally disconnected area
- Extrapolation to $V^{1/3} \approx \delta t_{\rm frag}$



[Morgante, RS, Ratzinger, Stefanek (2021)]

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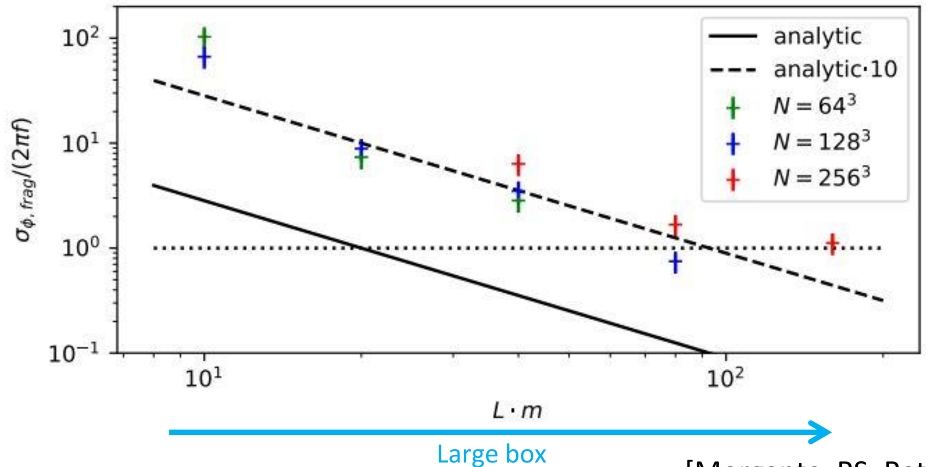


[Morgante, RS, Ratzinger, Stefanek (2021)]

Empirical formula of variance:

$$\frac{\delta\phi}{2\pi f} \sim O(10) \times V^{-1/2} \times \left(\frac{f\dot{\phi}_0}{\Lambda_b^2}\right)^{3/2}$$

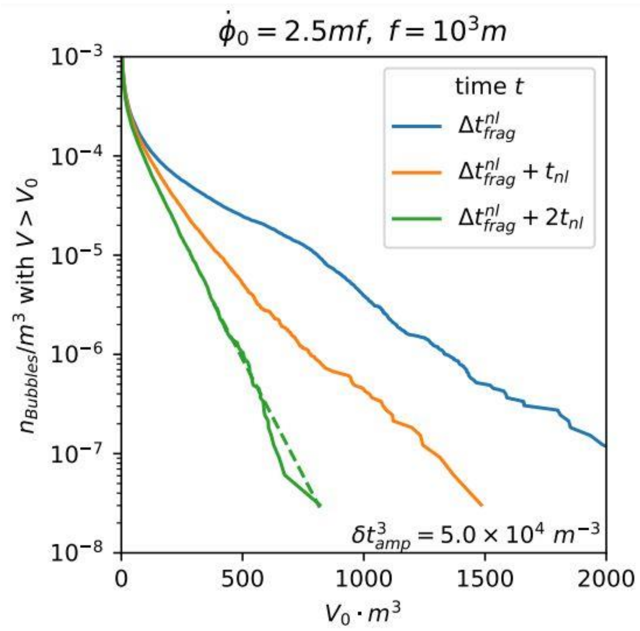
Naïve extrapolation to $V^{1/3} \sim t_{amp}$:

$$\frac{\sigma}{2\pi f} \sim O(10) \times \left(\log\frac{8\pi f^2}{\dot{\phi}_0}\right)^{-\frac{3}{2}} \sim 0.01 - 0.1$$

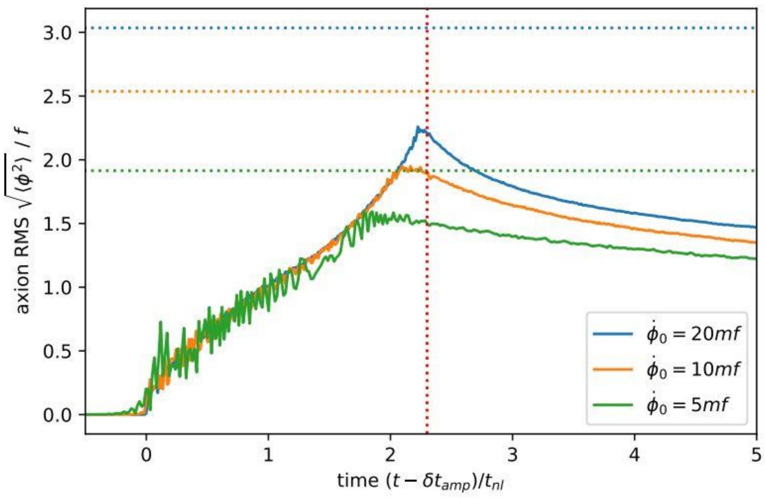
Domain wall formation probability is $\sim e^{-100} - e^{-10}$

Energy cascade into UV

Number counting of "bubble"



Time evolution of variance $\langle \delta\phi^2 \rangle$



[Morgante, RS, Ratzinger, Stefanek (2021)]

- Fluctuation with long wave-length is exponentially suppressed.
- The size of variance decreases in time.

Possible signals

Axion mini-cluster

See Eröncel-Servant (2207.10111)

Gravitational Wave (tensor perturbation in metric)

$$\nu \sim \frac{k}{a_{emit}} \frac{a_{emit}}{a_0}$$ (Typically, $k \sim m$)

Wave number at emission — Redshift

$$\Omega_{GW}^{peak} \sim \frac{64\pi^2}{3M_{pl}^4 H_{emit}^2} \frac{\rho_{\theta,emit}^2}{\left(k_{peak}/a_{emit}\right)^2} \frac{\alpha^2}{\beta}$$ (Typically, $\alpha < 1,\ \beta > 1$)

See [Chatrchyan, Jaeckel (2020)]

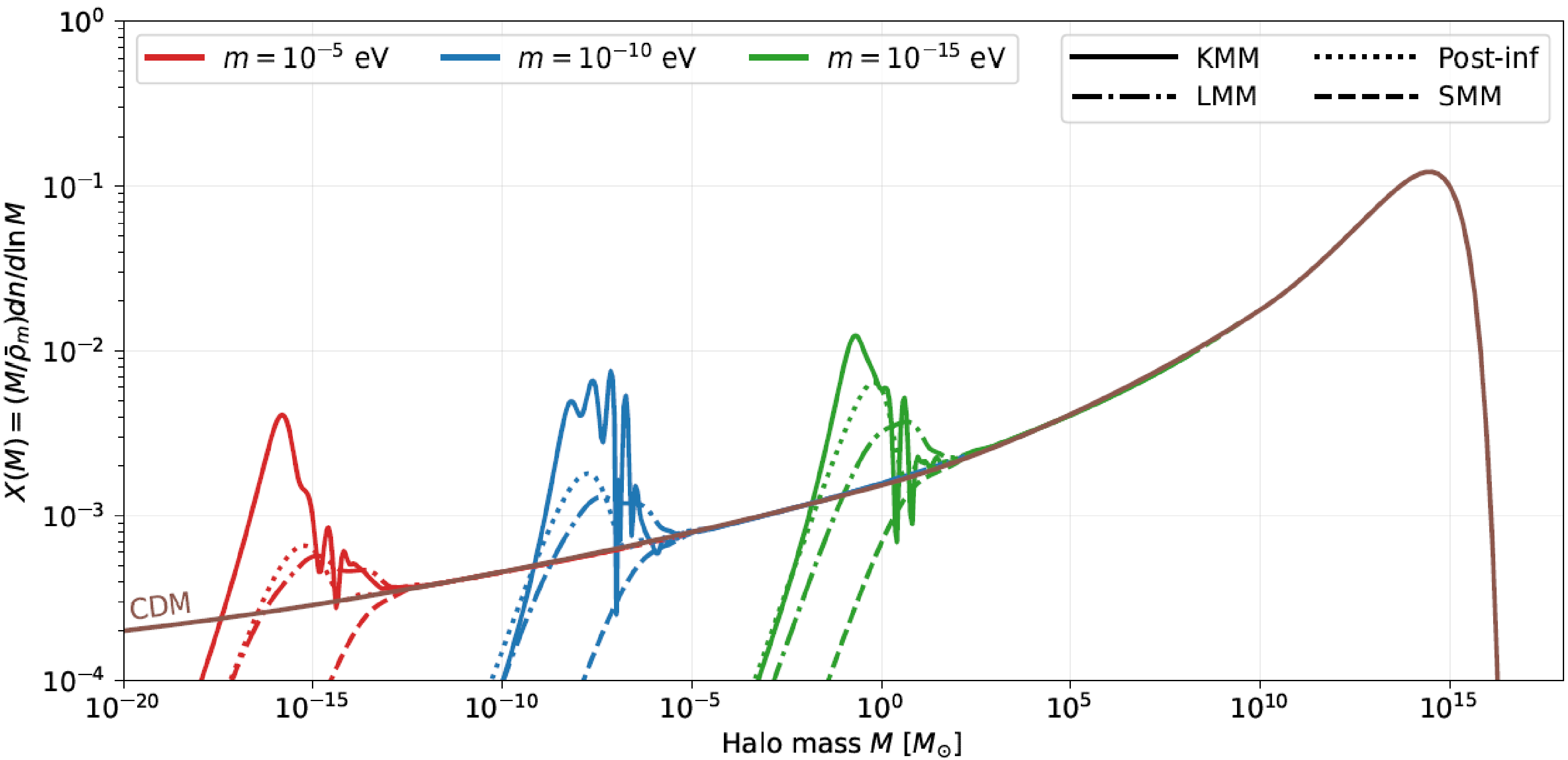
c.f.) $\ddot{h} + 3H\dot{h} \sim \frac{1}{M_{pl}^2}\rho_\phi, \quad \rho_{GW} \sim M_{pl}^2 \dot{h}^2$

Possible signals : ALP mini-cluster

clump of axion DMs

Small $m \rightarrow$ Large mini-cluster

Perturbative analysis + Press-Schechter formalism



[Eröncel, Servant (2022)]

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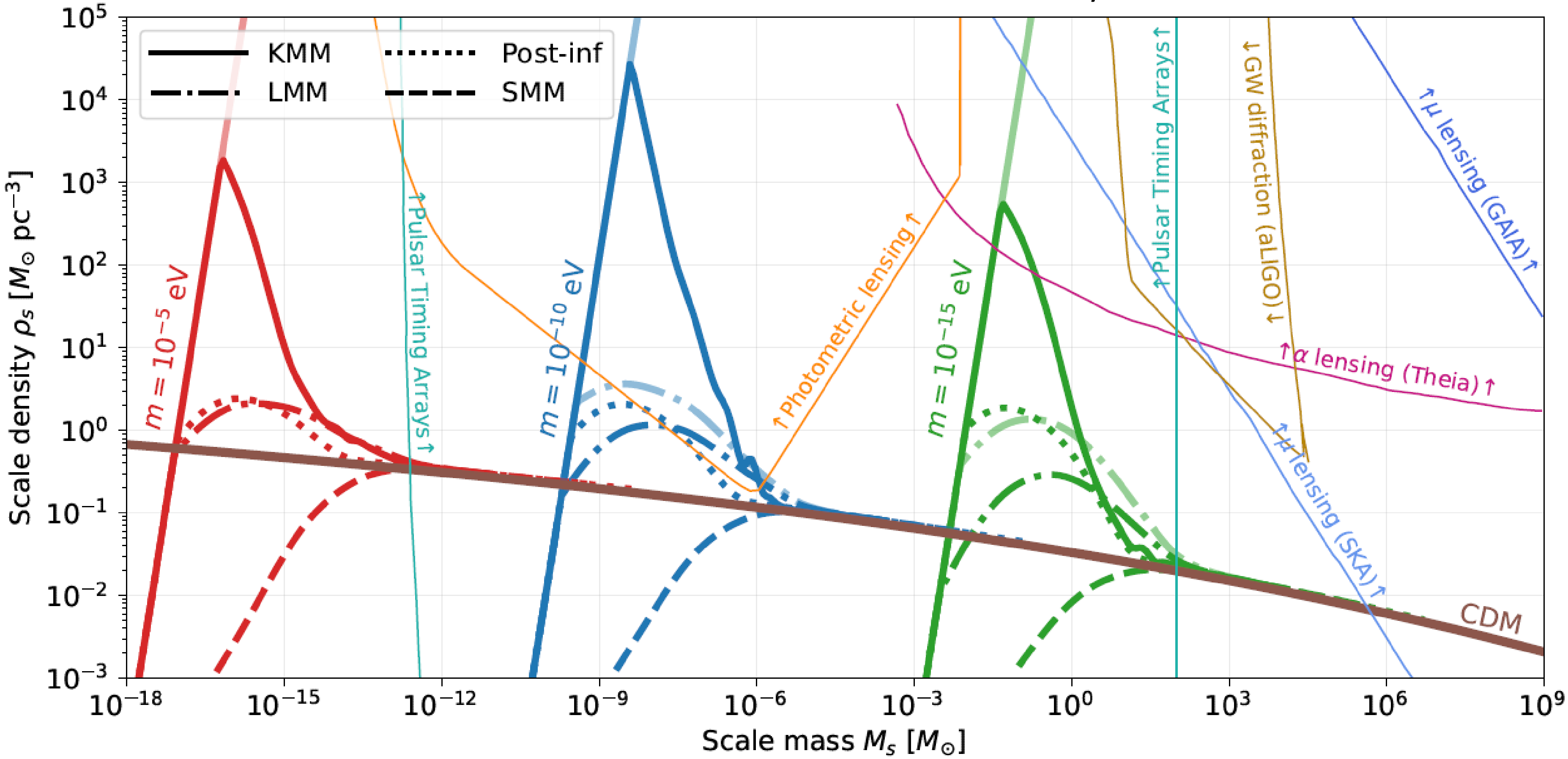
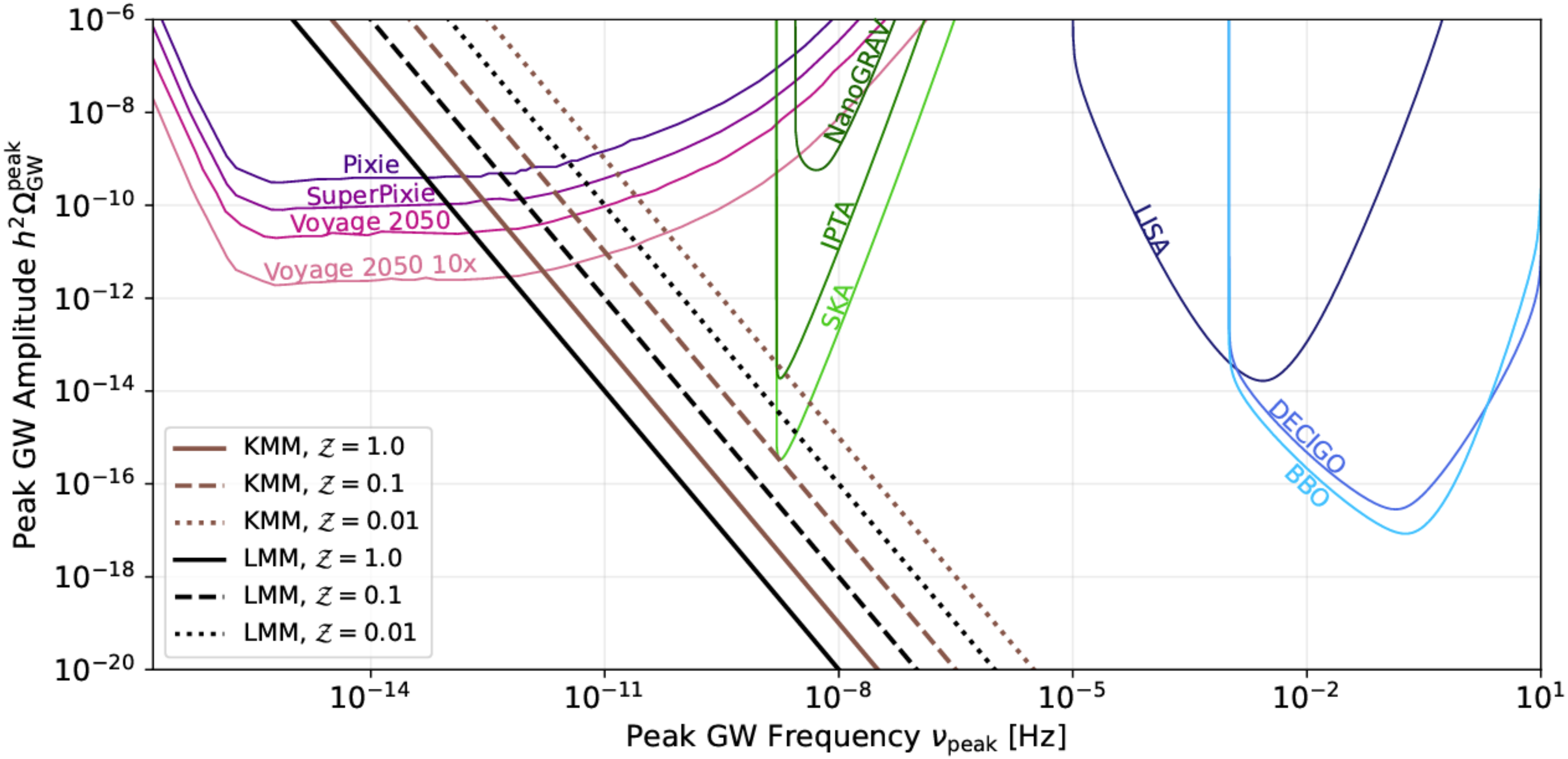


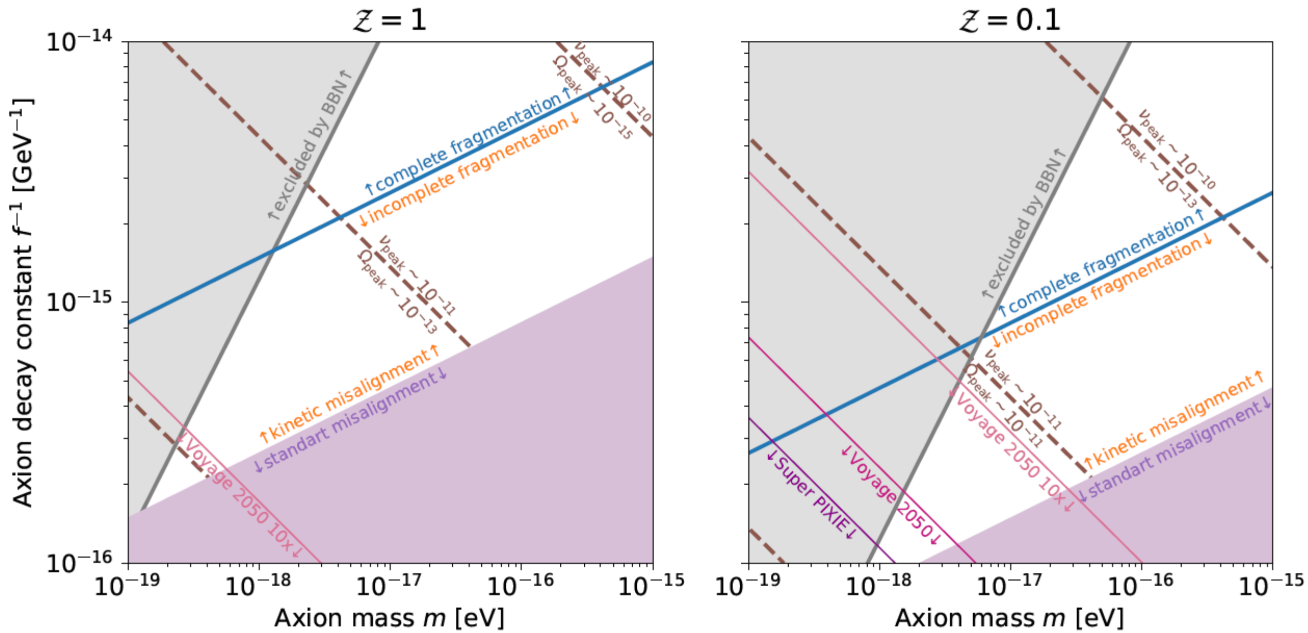
[Eröncel, Servant (2022)]

Possible signals : gravitational waves



[Eröncel, RS, Sørensen, Servant (2022)]

Possible signals : gravitational waves



Detailed analysis is future work

[Eröncel, RS, Sørensen, Servant (2022)]

$$\nu_{\rm peak} \sim 8 \times 10^{-11}\,{\rm Hz} \left(\frac{m_*}{m_0}\right)^{2/3} \left(\frac{m_0}{10^{-16}\,{\rm eV}}\right)^{1/3} \left(\frac{f}{10^{14}\,{\rm GeV}}\right)^{-2/3} \mathcal{Z}^{-1/3}.$$

$$\frac{a_*}{a_0} = \left(\frac{3\pi}{8}\frac{\Omega_{\rm DM}}{\mathcal{Z}}\frac{M_{\rm pl}^2 H_0^2}{m_0 m_* f^2}\right)^{1/3}.$$

$$\Omega_{\rm GW,0}^{\rm peak} \sim 1.5 \times 10^{-15} \left(\frac{m_*}{m_0}\right)^{2/3} \left(\frac{m_0}{10^{-16}\,{\rm eV}}\right)^{-2/3} \left(\frac{f}{10^{14}\,{\rm GeV}}\right)^{4/3} \mathcal{Z}^{-4/3}.$$

Fate of saxion

Saxion oscillation can overclose universe.

WHEN

before saxion dominates → no entropy production
after saxion dominates → entropy production

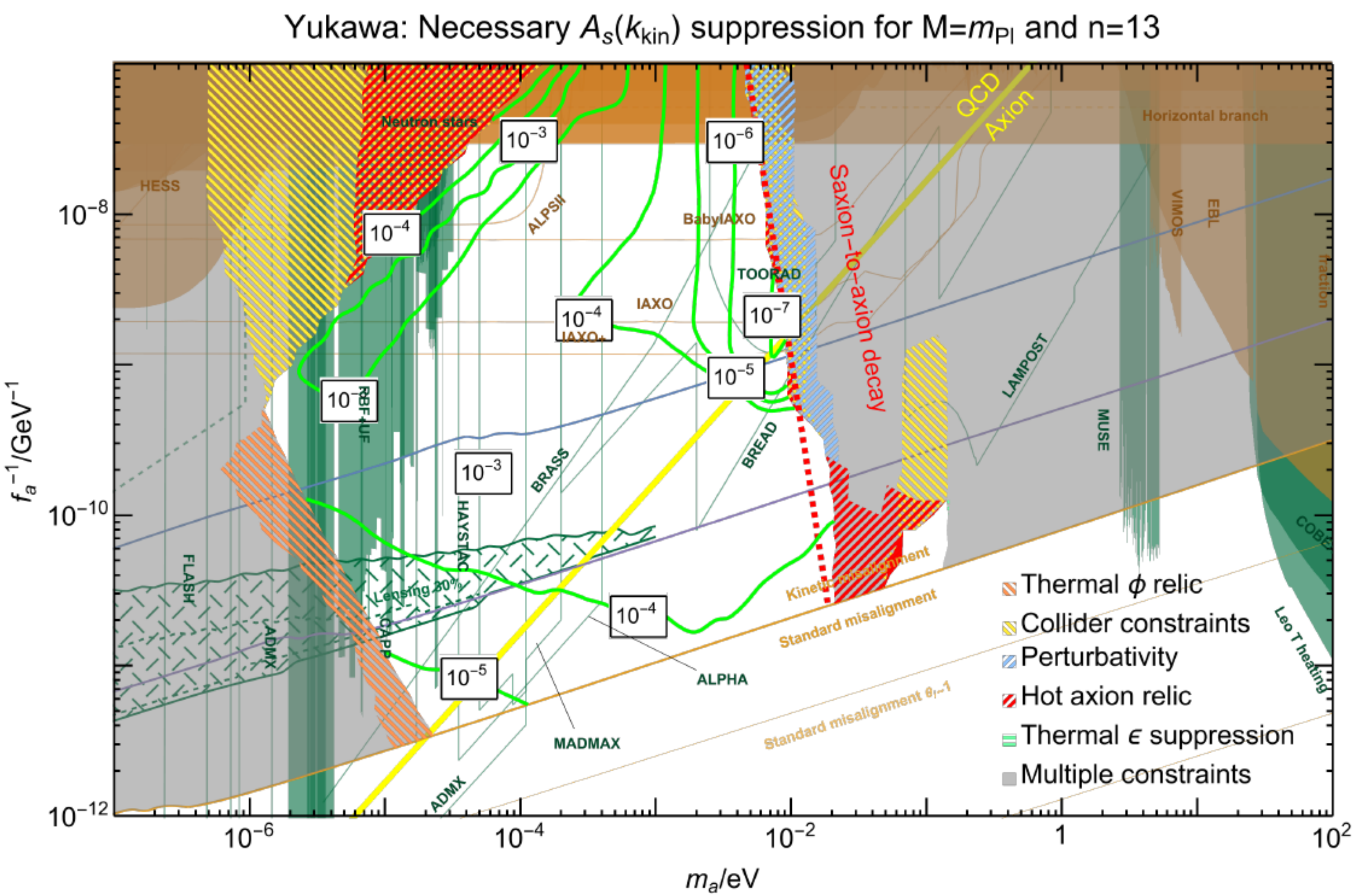
HOW

Coupling with fermion χ : $L \sim P\bar{\chi}\chi$

Coupling with Higgs : $L \sim |\mathrm{P}|^2|\mathrm{H}|^2$

Something else?

Necessary suppression of As



[Eröncel, RS, Sørensen, Servant, in preparation]

Implication to ALP dark matter

Possible two approaches:

Model independent analysis

- $V = -\Lambda_b^4 \cos(\phi/f)$
- Initial value of $Y = n_{PQ}/s = f\dot{\phi}/s$

($\dot{\phi}$ scales as $a^{-3} \propto s$ at the beginning)

Model dependent analysis

$$P = \frac{1}{\sqrt{2}} s \exp\left(\frac{i\phi}{f}\right)$$

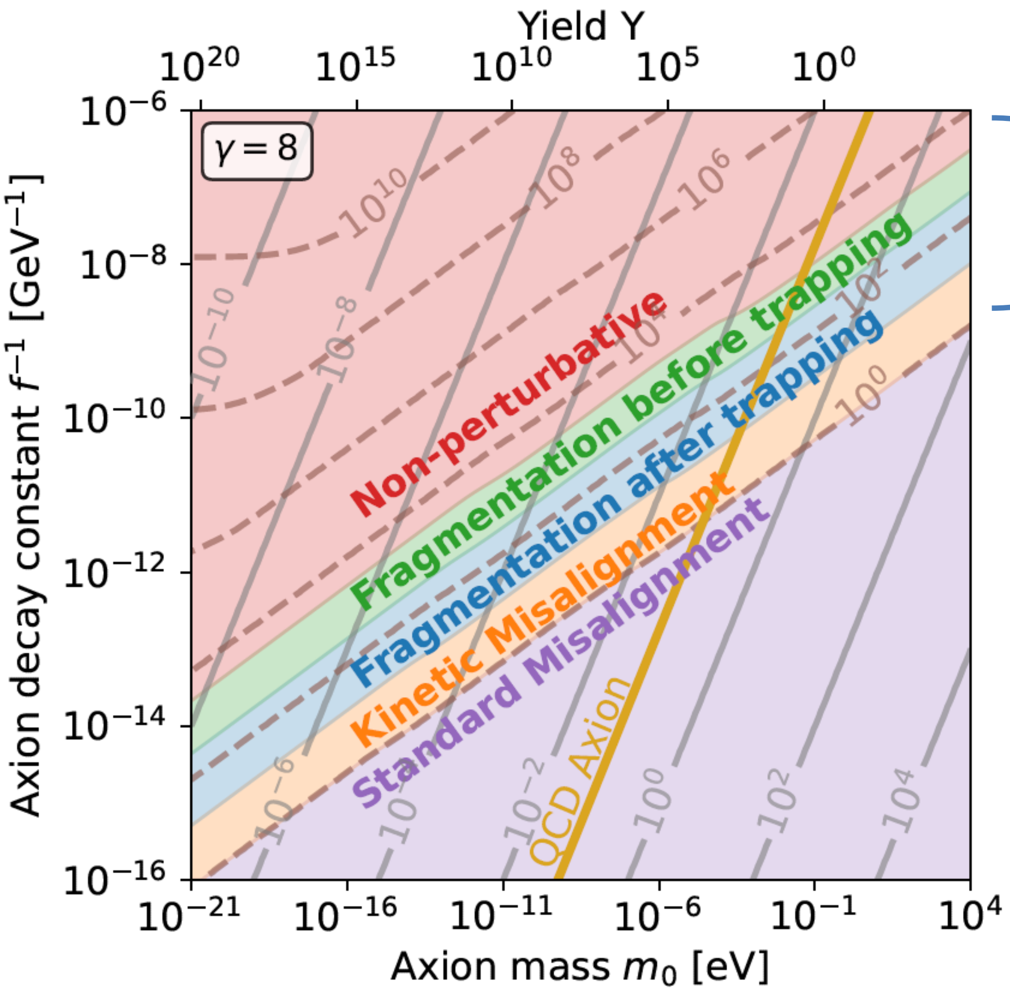
P : PQ charged scalar
s : saxion
ϕ : axion

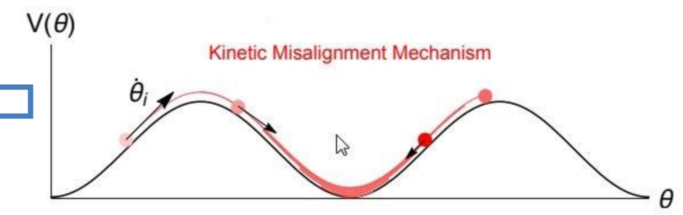
There are many possibility of UV models and thermal scenarios.

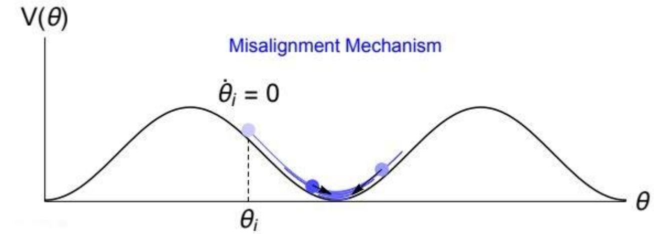
- Potential for PQ breaking
- How to get $\dot{\phi} \neq 0$?
- How to eliminate saxion oscillation?
- etc

Model independent analysis

ALP dark matter : Fragmentation could happen before axion starts to oscillate

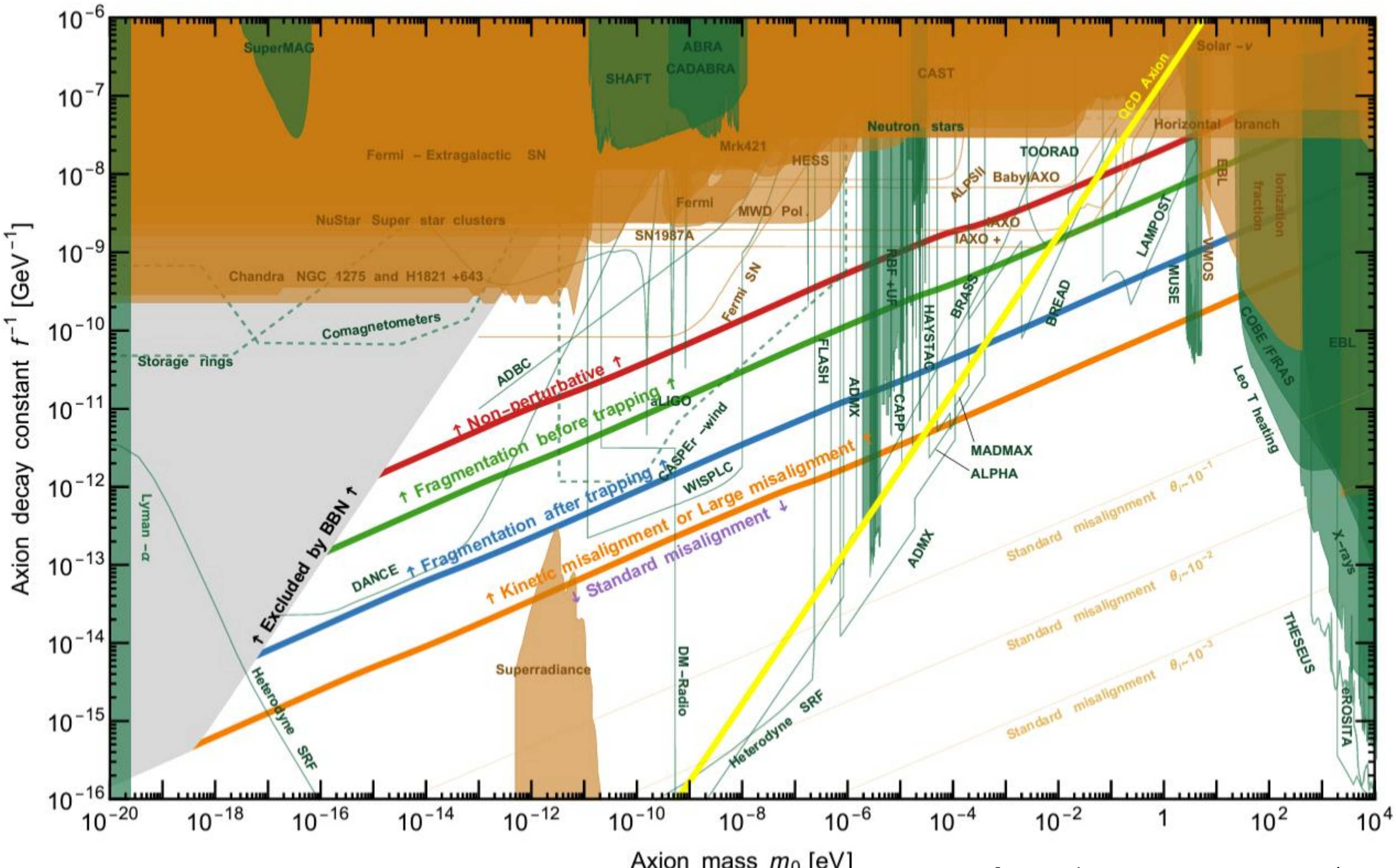




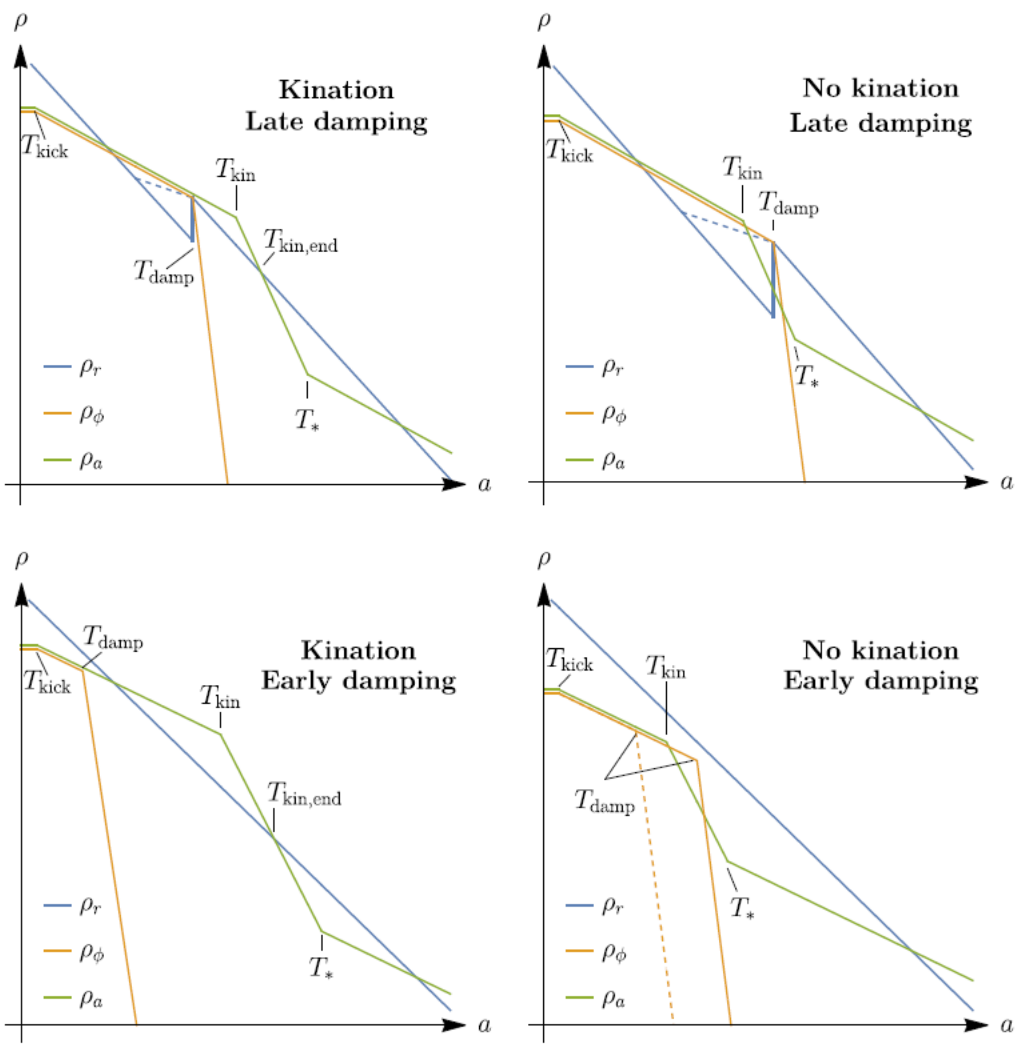


[Eröncel, RS, Sørensen, Servant (2022)]

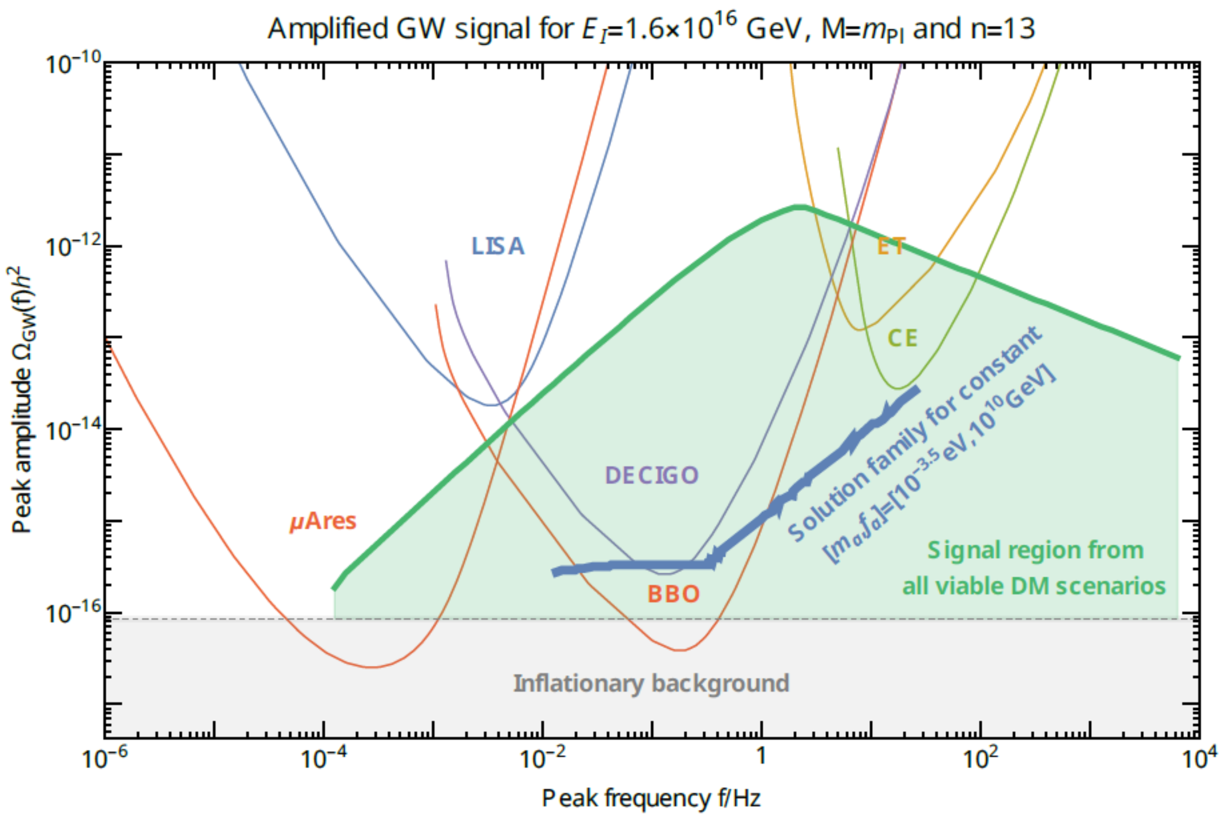
Model independent analysis



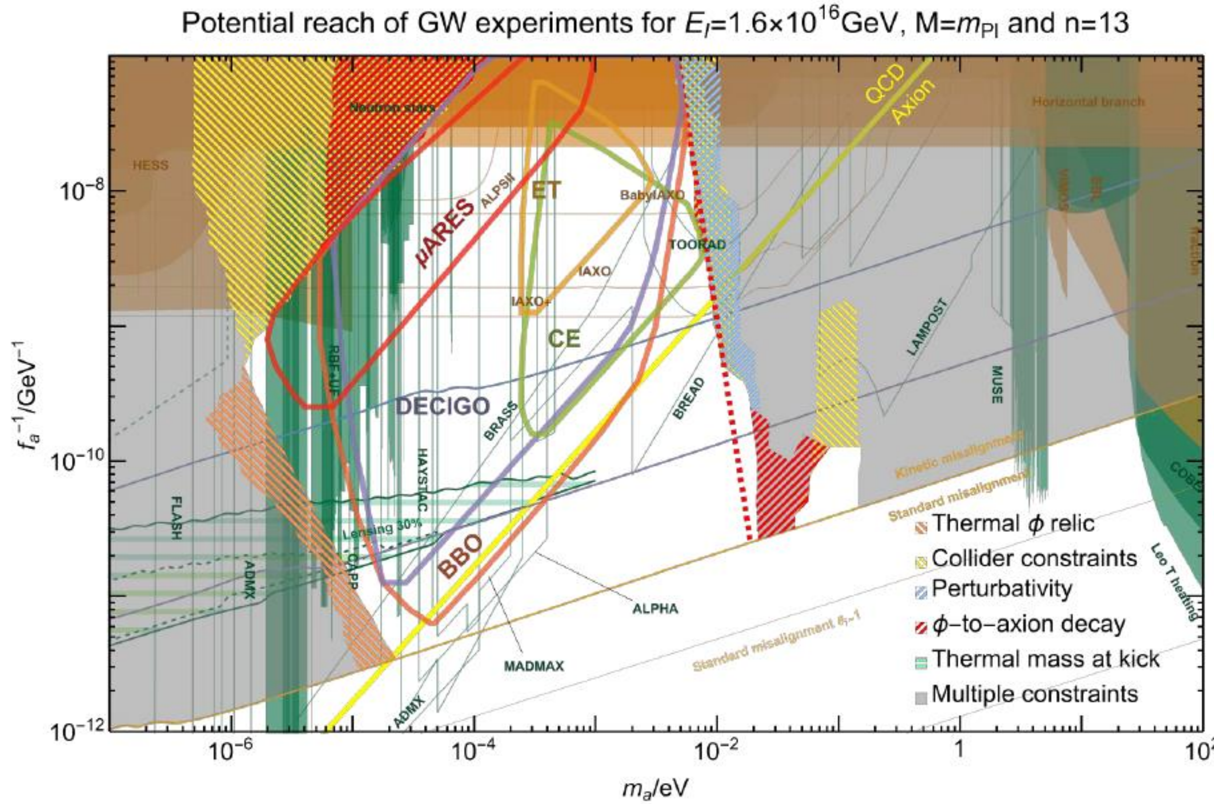
[Eröncel, RS, Sørensen, Servant (2022)]



Kination
Late damping
No kination
Late damping
Kination
Early damping
No kination
Early damping
ρ
a
$T_{\rm kick}$
$T_{\rm kin}$
$T_{\rm damp}$
$T_{\rm kin,end}$
T_*
ρ_r
ρ_ϕ
ρ_a



Amplified GW signal for E_I=1.6×10^16 GeV, M=m_{Pl} and n=13
Peak amplitude $\Omega_{GW}(f)h^2$
Peak frequency f/Hz
LISA
ET
CE
DECIGO
μAres
BBO
Solution family for constant $[m_a f_a]$=[10^−3.5 eV,10^10 GeV]
Signal region from all viable DM scenarios
Inflationary background



Potential reach of GW experiments for E_I=1.6×10^{16}GeV, M=m_{Pl} and n=13
f_a^{-1}/GeV^{-1}
m_a/eV
10^{-8}
10^{-10}
10^{-12}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
μARES
ET
CE
DECIGO
BBO
QCD Axion
HESS
Horizontal branch
BabyIAXO
IAXO
IAXO+
TOORAD
ALPSII
RBF+UF
HAYSTAC
BRASS
BREAD
LAMPOST
MUSE
FLASH
ADMX
CAPP
Lensing 30%
ALPHA
MADMAX
Kinetic misalignment
Standard misalignment
Leo T heating
Thermal ϕ relic
Collider constraints
Perturbativity
ϕ–to–axion decay
Thermal mass at kick
Multiple constraints

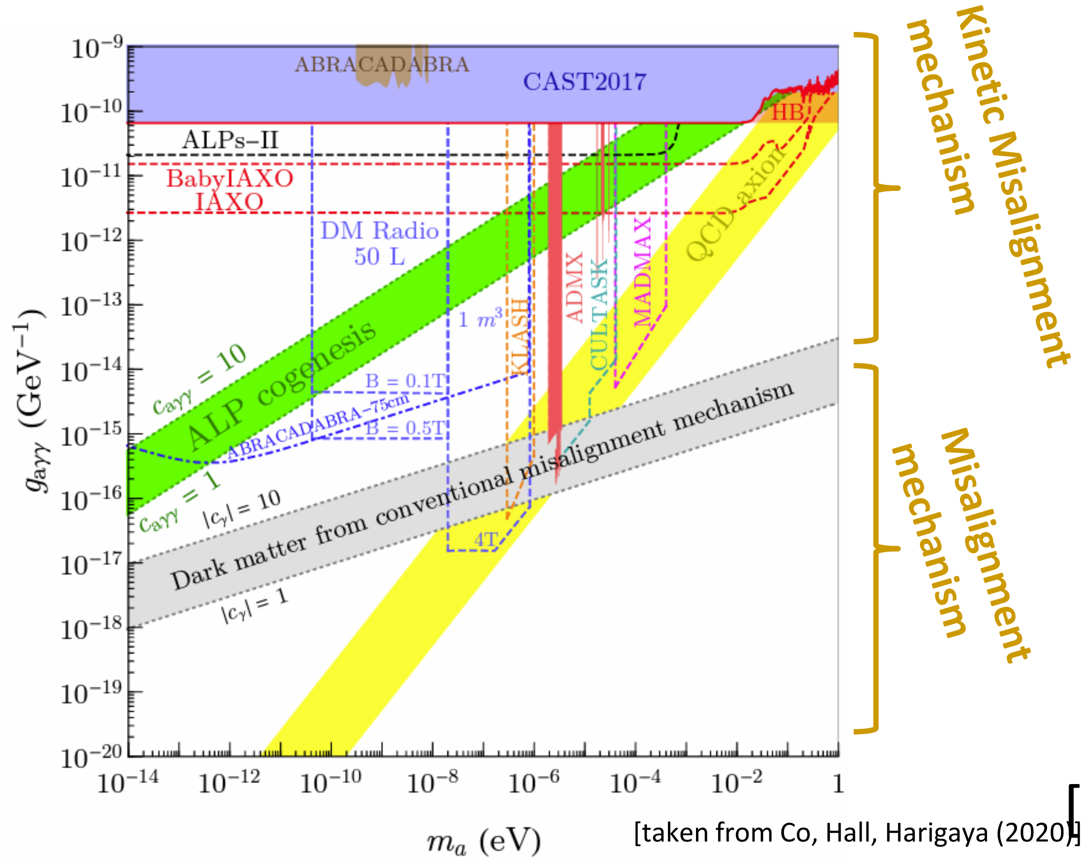
Why interesting?

For given axion mass,

- Conventional MM predicts smaller ρ_{DM} for smaller f_a
- KMM predicts larger ρ_{DM} than conventional MM

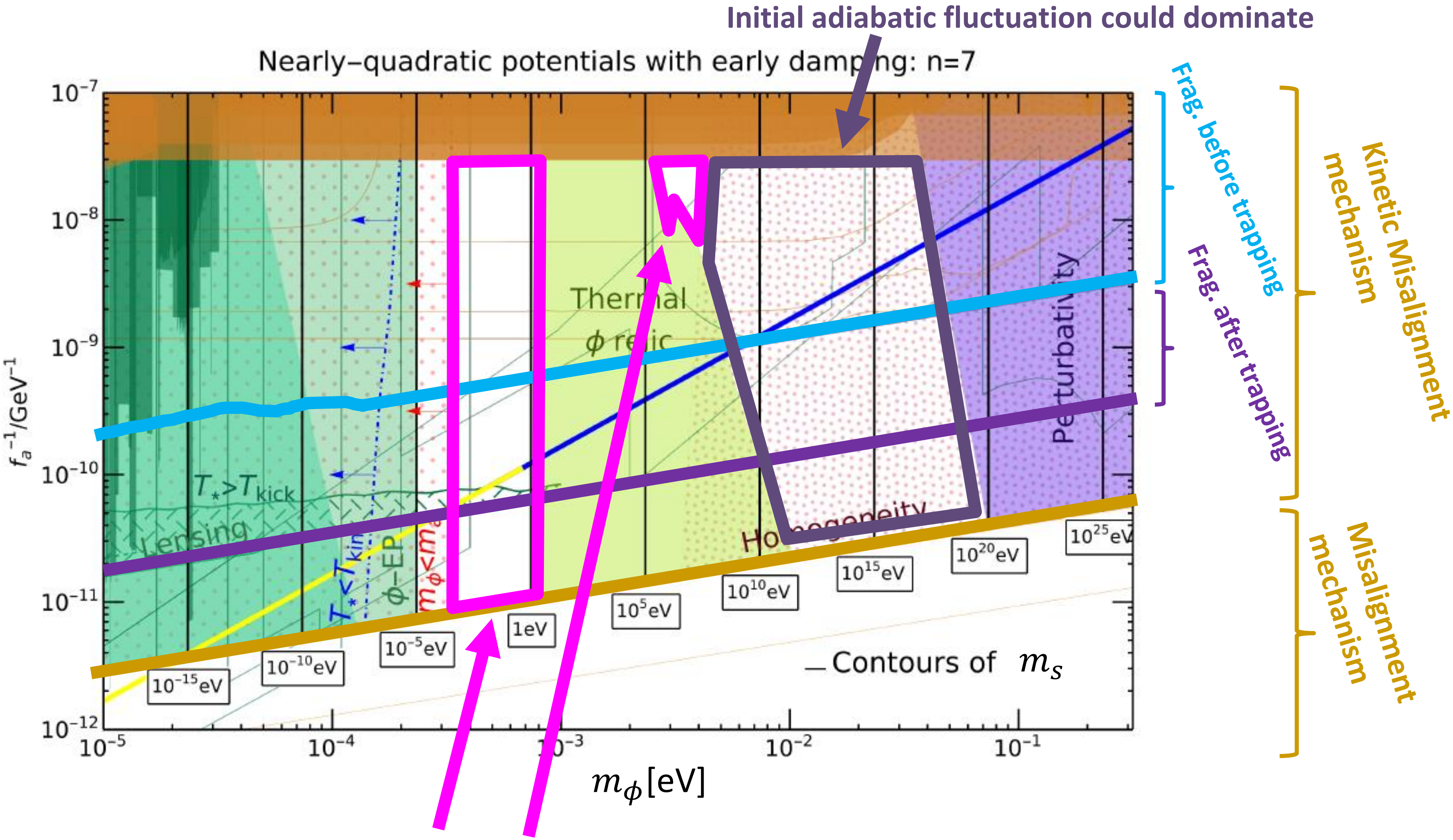
⇩

KMM tends to predicts smaller f_a (~ larger $g_{a\gamma\gamma}$)
motivates experiments!!



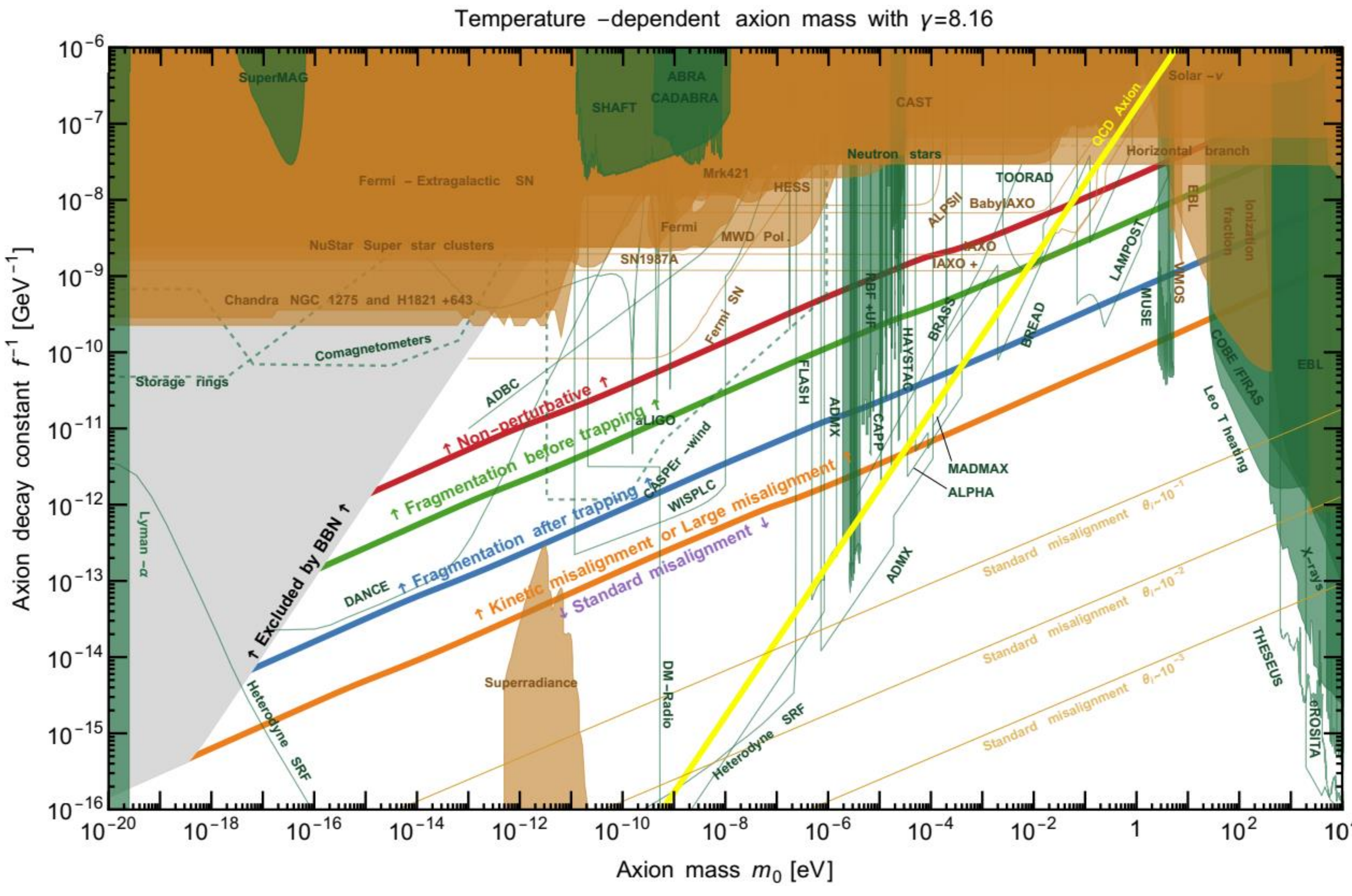
[taken from Co, Hall, Harigaya (2020)]

A parameter space



Kinetic misalignment (+ fragmentation)

[Eröncel, RS, Sørensen, Servant, in preparation]


Temperature -dependent axion mass with γ=8.16
Axion decay constant f^-1 [GeV^-1]
Axion mass m_0 [eV]
SuperMAG
SHAFT
ABRA
CADABRA
CAST
Solar -ν
QCD Axion
Horizontal branch
Neutron stars
Fermi - Extragalactic SN
Mrk421
HESS
TOORAD
BabyIAXO
IAXO
IAXO +
Fermi
MWD Pol.
NuStar Super star clusters
SN1987A
Chandra NGC 1275 and H1821 +643
Comagnetometers
Storage rings
Lyman -α
ADBC
↑ Non-perturbative ↑
↑ Fragmentation before trapping ↑
aLIGO
↑ Fragmentation after trapping ↑
↑ Kinetic misalignment or Large misalignment ↑
↓ Standard misalignment ↓
↑ Excluded by BBN ↑
DANCE
CASPEr -wind
WISPLC
Fermi SN
FLASH
ADMX
CAPP
HAYSTAC
BRASS
BREAD
LAMPOST
MUSE
VMOS
EBL
Ionization fraction
COBE /FIRAS
Leo T heating
MADMAX
ALPHA
X-rays
THESEUS
eROSITA
Standard misalignment θ_i~10^-1
Standard misalignment θ_i~10^-2
Standard misalignment θ_i~10^-3
Superradiance
DM -Radio
Heterodyne SRF