Axion-Like-Particle dark matter from kinetic fragmentation.

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CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Nieri, Fabrizio This talk .

Based on collaboration with

am Erar \bullet \leftarrow **Lin Carone** Collider phenomenology **Sato, Ryosuke Cem Eroncel, Philip Sørensen, Ryosuke Sato** **to appear**

as well as

Peera Simakachorn Yann Gouttenoire

ArXiv: 2108.10328 + [2111.01150](https://arxiv.org/abs/2111.01150)

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

Axion-Like-Particles (ALPs). 1 Symmetry Breaking and Non-Perturbative Particles (ALPs). 3 Production Axion-Like-Particles model as a second Higgs doublet. One Higgs field gives mass to the *u*-type quarks, while **VH** is a Maxion-Like-Particles (ALPs). The model is the choice of which \mathbf{A}

 \mathcal{L} idex expredicts explore field holder complex scalar field
 $i\theta$ ' in *SU*(2) ⇥ *U*(1). The whole Lagrangian is then taken to be invariant under a global **Consider complex scalar field consider complex scalar field**

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

charged under anomalous U(1) global symmmetry (Peccei-Quinn symmetry) Let's briefly review the general picture for axions given in the previous section, highlighting how this is relevant to axion cosmology in the very early Universe. Two important physical physical physical p
In the very early Universe. Two important physical physical physical physical physical physical physical physic) global symr where the *U*(1) symmetry acts as a shift symmetry for \mathcal{Y} . We consider our the homogeneous part of \mathcal{Y}

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

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

The PQW model introduces a single additional complex scalar field, α single scalar field, α

doublet, if not a third field, gives mass to the leptons). This fixes the representation of

$$
\langle \phi \rangle = f_a / \sqrt{2}
$$

in Axion as Goldstone boson

in perturbation theory. Non-perturbative electrons, "switch on "switch" and "switch on" at "switch" and "switch on" at "switch" and "switch on" at "switch on" at "switch on" at "switch on" at as Goldstone boson

as Goldstone boson the Goldstone boson of the spontaneously broken *U*(1)PQ symmetry.

 $s_{\rm s}$ some particular energy scale and break this shift symmetry, induction $s_{\rm s}$ a
D (*D* (*C*) correct $\Theta \rightarrow \Theta + \text{const.}$ $\theta \rightarrow \theta + \text{const.}$ *mq*(*/fa*)*iq*¯5*q*. The chiral anomaly [34] then induces couplings to gauge bosons via fermion $A \rightarrow A + const.$

 θ = a/f_a θ = a/f_a loops⁴ / *GG/f* ˜ *^a* and / *FF /f* ˜ *^a*, where *^F* is the EM field strength. The gluon term is θ = a/**f** a θ =a/f_a

ALPs.

Non-perturbative effects at energy $\Lambda_b \ll f_a$ **break the**
 • At if cummatry, and generate a notential/mass for the ex shift symmetry and generate a potential/mass for the axion

$$
\mathbf{V} = m_{\mathbf{a}}^2(T) f_{\mathbf{a}}^2 [1 - \cos(\theta)]
$$

 m_{a} $m_a = \Lambda_b^2 / f_a$ $m_a = \Lambda_b^2 / f_a$

> $\overline{\mathbf{a}}$ \overline{D} **T**

 \sim One of the strongest BSM candidates: Strongest BSM candidates: Strong CP problem, \sim

1 *A***credit AL QCD axion Generic ALP**

>: 1 *, T < T^c* $m_a^2 f_a^2 \approx (76 \text{ MeV})$

≈ (76 MeV)⁴ **ma** and f_{a:} free parameters

The hunt for axions.

Mainly through Axion-photon coupling

If long-lived: Dark Matter candidate

E

[~] *· ^B*

 $\mathcal{L}(\mathcal{L})$

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

 $\frac{f_7}{f_a} \approx 0.5 \times 10^3$
 $\frac{1}{2}$ (*x*, $\frac{1}{2}$ *x*, $\frac{1}{2}$ *x* **b** f^a **b** assuming KSVZ-like coupling $\frac{1}{7}$

The hunt for axions.

Which of these axions can make Dark Matter ?

Axions from the misalignment mechanism. $\mathcal{A}_\mathcal{A}$ field whose Lagrangian is given by $\mathcal{A}_\mathcal{A}$ is given by $\mathcal{A}_\mathcal{A}$ *L* = 1 *^g^µn∂µf∂nf ^V*(*f*) = ¹ *^g^µn∂µf∂nf ^m*2(*T*)*^f* ² <u>inent inechann</u> misalignm (2*p*)³ **ent mechanism.**

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

 \overline{M} **Define homogeneous zero-mode** $\overline{\mathbf{a}}(t) \equiv f\Theta(t)$ where the latter can be expanded into the latter can be expanded into the \mathcal{A} **Define homogeneous zero-mode** $\frac{1}{\sqrt{2}}$ a

 U allows, it satisfies $U + JUV + H_2(I)$ since $U = I - I$ Neglecting fluctuations, it satisfies $\ddot{\Theta} + 3H\dot{\Theta} + m_{\rm a}^2(T)\sin(\Theta) = 0$, \mathbf{F} \mathbf{F} (\mathbf{F}) \mathbf{F} \math a

With initial conditions:

nital conditions:

\n
$$
\Theta(t_i) = \Theta_i, \quad \Theta(t_i) = 0, \quad \text{assumption}
$$

$$
\sum_{a < 3H} m_a \ll 3H \iff \rho_a \propto a^0 \text{ (Frozen)}
$$

\n
$$
\sum_{a < 3H} m_a \gg 3H \iff \rho_a \propto a^{-3} \text{ (Oscillating)}
$$

 $\bigwedge^{m_a > 3H}$ // standard misalignement mechanism Fournan a misang noment moonanism **-> standard misalignement mechanism** $\overline{}$ = *F*
tandard misalignement med *i* <u>besy.</u>
Itandard misalignement mechanism: ⇠ *^m*² **ESY.**
 T₂> standard misalignement DESYª | Opening up the axion dark matter window with axion fragmentation | Philip Sørensen | Hamburg, 01.06.2020 **Page 6 DESY.** ⁴ Redshift as ⇢*^a* / *^a*³

$$
\begin{array}{ll}\n\text{PSR} & \text{PQ} \\
\text{PSR} & \text{PQ} \\
\text{PSR} & \text{PQ} \\
\text{PQ} & \text{
$$

10

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.

dark matter from ALPs: Misalignment mechanisms and the Misalignment mechanisms and the Misalignment mechanisms
Alps: Misalignment mechanisms and the Misalignment mechanisms and the Misalignment mechanisms and the Misalign **Standard versus kinetic Misalignment.**

ALP DM parameter space.

(KSVZ-like coupling)

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

ALP DM parameter space.

Constant axion mass

Conventional misalignement makes too little DM for low fa .

A way out: switch on initial velocity for the axion

case I: $\psi_{\text{ini}} \gg f_a$

Kinetic misalignment.

$$
H_a^{\text{osc}} \ll m_a
$$

$$
\dot{\theta}^2 f_a^2 \propto a^{-6} \qquad \dot{\theta} \simeq m_a
$$

ρ_{ESY} \rightarrow ALP can be DM for low f_a

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

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

Axion cosmology.

"Usual" story:

Starts at $\textless p\textgreater 0$

Studies axion cosmology ignoring the radial mode

Alternative:

Starts at < ϕ **>>** ϵ **=** ϵ

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 \rightarrow mexican nat potential is thied

If radial mode of PQ field starts at large VEV, the angular mode gets a large is included and allows the field with early universe in the early universe part of the PQ field obtains a large kick in early universe. This is known as the *kinetic misalignment* α netu starts at large v_L v, the angular mode gets a large is L_L *breaking, potential, assuming the initial rotation is generated via the explicit breaking term. The corresponding parameters defining each stages are as table of 1. Moreover, the U*(1)*-conserving interaction*

With initial conditions:

Delayed axion oscillations !

-> kinetic misalignment mechanism energy such that it goes over \blacksquare [Co, Harigaya, Hall'19] **1910.14152**

trapping of the energy of the energy of the 2004.00629_{18} **1910.14152 2004.00629** 18

ALP DM parameter space.

Axion fragmentation. $\mathcal{I}(\mathcal{A})$ is $\mathcal{I}(\mathcal{A})$ is $\mathcal{I}(\mathcal{A})$ is $\mathcal{I}(\mathcal{A})$ is constant. the weak interaction? The Peccei-Quinn (PQ) mechanism [4, 5] provides a simple and elegant answer: the

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.

> **Chatrchyan et al, [1903.03116,](https://arxiv.org/abs/1903.03116) 2004.07844 Greene, Kofman, Starobinsky, hep-ph/9808477 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.

> **Fonseca,Morgante,Sato, Servant'19 Chatrchyan et al, [1903.03116,](https://arxiv.org/abs/1903.03116) 2004.07844 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 **Example in the pre-inflations in the Fourier space. the mode functions in the Fourier space. on top of the homogeneous background, which can be described by**

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

These fluctuations are seeded by adiabatic and/or isocurvature perturbations: [~]k*·*~^x + h.c.

• Due to the energy density perturbations of the Adiabatic perturbations (This work)

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

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

• If ALPs exist during inflation and are light 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 *•* Can be avoided/suppressed if ALP has a large mass during inflation, or $f_{\text{inf}} \gg f_{\text{today}}$.

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.

Axion fragmentation in kinetic misalignment.

Fragmentation regions on the ALP parameter space **parameter space.Fragmentation regions in ALP**

Constant axion mass

Fragmentation regions on the ALP parameter space **Fragmentation regions in ALP parameter space.**

Constant axion mass

Temper**a**ture -dependent axion mass with $y=8$

Experimental reach.

Observational prospects ?

Lifetime of a fluctuation . Lifetime of a fluctuation model with $\mathcal{L}_{\mathcal{A}}$ fluctuation model with $\mathcal{L}_{\mathcal{A}}$

Lifetime of a fluctuation .

Observational tests: compact axion halos.

axion fragmentation-> structure formation enhancement

Scale density of axion compact structures

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 .

Requirements

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

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

2. Large initial scalar VEV

4. Damping of radial motion

Ingredients 1 & 2 : scalar potential

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

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

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

stabilization

(motivated by supersymmetric setups)

Ingredient 3 : large initial VEV ϕ_{ini}

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

example I: complex scalar feld dynamics Kination from a spinning axion.

circle $\omega \phi = f_a$

The conserved $U(1)$ -charge is *d dt* $(a^3 \phi^2 \dot{\theta}) = 0 \Rightarrow \dot{\theta} \propto a^{-3}$

Kinetic energy dominates $\rho_{\Phi} = KE \propto \dot{\theta}^2 \propto a^{-6}$ **in rotation**

and behaves as kination.

Impact of kination on Inflationary Gravitational Waves.

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

and the control of the second the second terms of the second terms of the second terms of the second terms of
And the second terms of the sec 10-15 *h* f [Hz] **fluctuations during inflation. Fraction energy density in GW** 2 **radiation era = fat Irreducible GW bgd from quantum**

Spectral distorsions of the printiple distributionary GW: Pectral distortion of the cosmological history. The primordial distortion of the cosmological history. The cosmological history. $10-10$ **frequency [Hz]**

Kination-enhanced GW signal from primordial inflation.

8 Signature in infationary GW: "Peak" Model-independent predictions.

$$
\text{Peak frequency: } f_{\text{peak}} \approx 10 \text{ Hz} \left(\frac{E_{\text{KD}}}{10^8 \text{ GeV}} \right) \left[\frac{\exp(N_{\text{KD}}/2)}{10} \right]
$$
\n
$$
\text{Peak amplitude: } \Omega_{\text{peak}} h^2 \approx 10^{-12} \left(\frac{E_{\text{inf}}}{1.6 \times 10^{16} \text{ GeV}} \right)^4 \left[\frac{\exp(2N_{\text{KD}})}{10^4} \right]
$$

Gravitational Waves and Axion Dark Matter.

QCD Axion Dark Matter. QCD Axion Dark Matter

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

via kinetic misalignment & axion fragmentation

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

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

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

GW peak & axion DM abundance $\Omega_{\rm peak}h^2 \approx 10^{-18} \, \bigg($ *f* KD $_{\rm Hz}$) \backslash *E*inf $\overline{10^{16} \text{ GeV}}$ 4 $\sqrt{}$ GeV $\overline{m_a f_a}$ $\Omega_{a,0}$ $\Omega_{{\rm DM},0} \left. \right/ \right.$ $f_{\rm peak} \approx 21 \text{ Hz}$ GeV $\overline{m_a f_a}$ 2/3 $\overline{\mathcal{L}}$ *E*KD 10^9 GeV $/$ 4/3 $\overline{ }$ $\Omega_{a,0}$ $\Omega_{{\rm DM},0} \left. \right/ \right.$ 1/3 10^{-8} 10^{-4} 1 10^{4} 10^{-13} 10^{-9} Peak frequency f_{KD} [Hz] Peak amplitude GW,KD $\boldsymbol{\mathscr{L}}$ $\mathbf{\sim}$ LISA ET **ZE B SKA** 5 yrs 10 yrs NANOG_{ra} O2 δ ⁴ O5 **PLOMA** =**10.7** DM CLDM = \rightarrow **axion** =Generic **ALP DM: ** *ma ^f a* \overline{L} L MOCD **QCD axion**

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]

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Gravitational Waves and Axion Dark Matter.

If the axion is Dark Matter:

[Gouttenoire,GS, Simakachorn 2111.01150] 46

Detectability of rotating axion models. LETTER with radial decay (philip)

Impact of kination on Gravitational Waves from Cosmic Strings.

Kination-enhanced GW from local cosmic strings.

Peak frequency: Peak frequency:

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

Kination-enhanced GW from local cosmic strings.

GW from global strings. Gravitational waves from global cosmic strings VEV means one could have large *¥*, but this will depend on when the cosmic strings is generated. If this happens during inflation, all defects during inflation, all defects \mathbf{q}

VEV means one could have large *¥*, but this will depend on when the cosmic strings is generated. If

, $\overline{3}$

 $\epsilon_{\text{R}} \approx (0.916 \text{ Hz}) \left(\frac{0.1}{\text{K}} \right) \left(\frac{E_{\text{KD}}}{\text{K}} \right) \left(\frac{e \text{xp}(N_{\text{KD}}/2)}{\text{p} \cdot \text{p} \cdot \text{p$ **GeW is defining by Eq. (3.42)** *and* (3.42) *and* (3.42) *and* (3.43). The black data is defined by the black data is defined by α /(10⁵ GeV/[**and** 10 $F_{\text{R}} \approx (0.916 \text{ Hz}) \left(\frac{0.1}{\text{ EVD}} \right) \left[\frac{\text{exp}(N_{\text{KD}}/2)}{\text{exp}(N_{\text{KD}}/2)} \right]$ **Activy.** $\binom{100}{000}$ (colored region) and $\binom{100}{000}$ and \binom $f_{\text{KD}} \simeq (0.916 \text{ Hz}) \left(\frac{0.1}{\gamma} \right)$ *Æ* $\left(\frac{E_{\text{KD}}}{10^5 \text{ GeV}}\right) \left(\frac{\exp(N_{\text{KD}}/2)}{10}\right)$ **Peak frequency:**

GW from primordial inflation + local cosmic strings. not abruptly relax to the new scaling regime. In this section, we point-out the possibility of a two-peak

 $E_{KD} = 1 \text{ TeV}, G\mu = 10^{-15}$

 $E_{KD} = 10^8$ GeV, $G\mu = 10^{-15}$

[Gouttenoire,GS, Simakachorn 2111.01150]

blue region. For large enough *¥*, the first condition is satisfied while the second is violated. This is when the global-string peak dominations depend on the kinations of the kinations of the kinations of the kination energy of the kinations of the kination energy of the kination energy of the kination energy of the kination ab^{al-se} **GW from primordial inflation + global cosmic strings. GW from inflation + global cosmic strings**

 \mathbf{h} is satisfied, the second is satisfied, the inflationary peak over the string peak over the string peak, shown in \mathbf{h}

*one another. On the right, the spectra with two-peak signature originated from the inflation of E*inf *=* **[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* e.g. iniiationary 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. B** munvalud by extribution complete the complete state of the scalar motor complete.
The process of front and low-scale kination during the pre-RRN enoch **can generate a short and low-scale kination during the pre-BBN epoch.**

 10^{-15}

*N*KD

 10^{-12}

Thank you !

 $\sqrt{2}$

 $\frac{1}{2}$

3

 \mathbf{r}

 \mathcal{L}

*N*KD =

" Peaked GW signature: "Peaked GW signature"

*ρ*tot

tion

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

w amplitude $\alpha \propto \kappa$ mation duratign **" GW amplitude** ∝ **kination duration**

BBO on ene DECES_O ET /CE inflation. Peak Position energy scale & duration ∝ **• Peak frequency**∝ kination duration & kination energy scale $\frac{1}{2}$

Kination from

 $\mathcal{L}% _{M_{1},M_{2}}^{\alpha,\beta}(-\varepsilon)=\mathcal{L}_{M_{1},M_{2}}^{\alpha,\beta}(-\varepsilon)$ ω $\frac{1}{\sqrt{2}}$ scalar Φ
Applies to any ALP in particular **era** radian dia axior 4 **Examplies to any ALP, in particular to QCD axion**

Annexes.

The axion production mechanism landscape. ⇢⇤ ˙ ⇤*/f^a* \blacksquare \overline{a} ⇤ ˙ ⇤*/f^a* **scape.**

The axion production mechanism landscape.

Evolution of ALP energy density.

Equations of motion.

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

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

it describes a Keplerian motion in a rotationally-invariant potential *V*,
, , , **in the presence of small wiggles and Hubble friction.**

Origin of the kick.

mann equation for the *Angular* equation \overline{u} *Angular equation of motion:*

$$
ni_{\theta} + 3Hn_{\theta} = \left(-\frac{\partial V_{U\{+\}}}{\partial \theta}\right)
$$
 with $n_{\theta} \equiv \phi^2 \dot{\theta}$.
comoving Noether
charge of the restored

with $n_{\theta} \equiv \phi^2 \dot{\theta}$.

In App. G.1, we show that the field restored received received received at the ones that the only and the restored $\mathcal{L}(t)$ *r*, eff(*; y*, is given by *U*(1) and *l* µ 4, is given by *L* α field value of the restored value $U(1)$ symmetry. **comoving Noether** *U* **(1) symmetry.**

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

In absence of *U*(1)-breaking:
$$
\frac{d}{dt}\left(a^3n_{\theta}\right) = 0,
$$

charge conservation equation

Figure radial damping i[†] *µFination era. PHEREE COMPLEX SCALAR field is reduced to a circular orbit density of the universe, and the longer the kination era. Obtained after numerically integrating the equations of* **Kination era.**

once again. For a fixed mr , the smaller fa, the longer the matter era, the larger the domination of the energy

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

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

More precisely, in App. G.4 we compute the evolution of the complex scalar field © *⁼ ¡ei^µ* after radial damping **in aps** *2 a b* and *i absence of radial mode kinetic energy 1998 -> kin*

motion in Eqs. (7.16)*,* (7.17) *and* (7.18)*.*

motion in Eqs. (7.16)*,* (7.17) *and* (7.18)*.*

2 \overline{a} **-> kination equation of state**

Rotating axion models.

A peaked GW signature. Fig. 6. Hence, it induces the step-liked suppression which might be observable signature for a large matter era without kination lead to the today horizon which is larger than the standard cosmology, the total energy density before the matter era is smaller than the standard case after the rescaling, cf.

matter era without kination lead to the today horizon which is larger than the standard cosmology,

lasting sources. The above argument using Eq. (3.72) applies for the rescaled scale factor. Since the

Fig. 6. Hence, it induces the step-liked suppression which might be observable signature for a large

A peaked GW signature. Fig. 6. Hence, it is induced suppression which might be observed suppression which might be observed signature for a large signature f Gw signal such as cosmic-string SGWB [37]. The such as cosmic-string SGWB [37]. The such as cosmic such as cos
SGWB [37]. The such as cosmic such matter era without kination lead to the today horizon lead to the today horizon which is larger than the standard cosmology, which is larger than the standard cosmology, which is larger than the standard cosmology, which i the total energy density before the matter era is smaller than the standard case after the rescaling \sim Fig. 6. Hence, it induces the step-liked suppression which might be observable signature for a large

lasting sources. The above argument using Eq. (3.72) applies for the rescaled scale factor. Since the

Inflationary GW: \blacksquare Figure 6: *The left panel shows that the energy density in GW is enhanced by the period of matter-kination era.* Figure 6: *The left panel shows that the energy density in GW is enhanced by the period of matter-kination era. This is true for long-lasting sources that produce GW as a fraction of the total energy density. The right panel*

Frequency of today GW: $f_{today}^{GW} \simeq H_k a_k/a_0 \propto a_k^{-2}$ (kination), a_k^{-1} (radiation), $a_k^{-1/2}$ (matter) \overline{S} shows \overline{S} peak position \overline{S} rescaling \overline{S} res t_{k} (in the scale factor) t_{k} and t_{k} (in the single t_{k} (in the single t_{k} (in the single t_{k}

spectral tilt: $\Omega_{\rm GW} \simeq$ $H_k^2a_k^4$ $\overline{H^2_0}$) $\big\backslash$ *E*inf $\overline{M_{\text{Pl}}}\,\int$ 4 $\propto f_{\text{today}}$ (kination), f_{today}^0 (radiation), f_{today}^{-2} (matter) *the scale factor, the matter era without kination leads to the universe that has smaller energy density at earlier* $\sum_{k=1}^{\infty} \int H_k^2 a_k \int f E_{\text{inf}}$ $t = 3.4$ km signal. **3.1 Inflationary Gravitational Waves**

Summary of prospects.

Standard Cosmology Radiation Era → Matter Era *T*⁰ *T*eq *T* ! 1 **MD RD Gravitational Waves from Cosmic strings.**

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: $\mathscr{L} \supset y_{\psi} \phi \psi_{I}^{\dagger} \psi_{R} + h.c. + g \bar{\psi} \gamma^{\mu} \psi A_{\mu}$

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

?

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_w or lowering T_{reh}

Thermal damping of radial mode.

