Axion
Poltergeist

Axion-induced Stochastic Gravitational-Wave Background

Keisuke Harigaya, Keisuke Inomata, and Takahiro Terada, arXiv:2305.14242 [hep-ph]

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Peccei-Quinn and Axion(-like) Fields

QCD axion

Pseudo Nambu-Goldstone (NG) boson of the $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry, which solves the strong CP problem.

Strong CP problem: The only fine-tuning problem in the SM without anthropic solutions?

Axion-like particle (ALP)

Ubiquitous in supersymmetric theories & String Theory.

Both are Dark Matter candidates.

In this talk, we are interested in an axion(-like) field in the phase direction of a complex scalar ("PQ") field.

Axion Rotation Cosmology

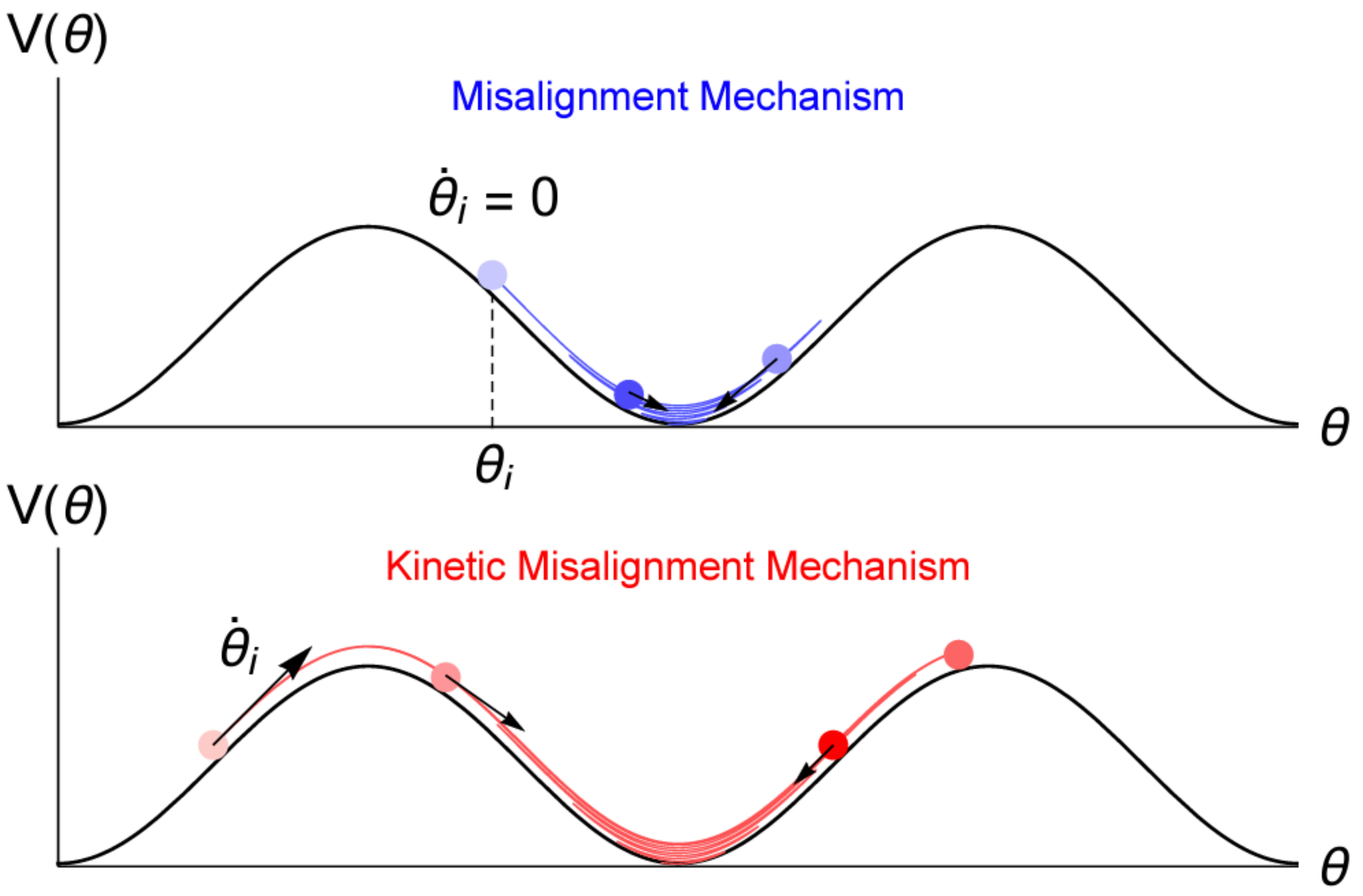


Figure from [Co, Hall, Harigaya, 1910.14152]

- Dark Matter — the *kinetic misalignment mechanism*

  [Co, Hall, Harigaya, 1910.14152]

- Baryon Asymmetry of the Universe

  — Axiogenesis (QCD axiogenesis, ALPgenesis)

  — Lepto-axiogenesis (QCD lepto-axiogenesis, lepto-ALPgenesis)

  [Co, Harigaya, 1910.02080]

  [Co, Fernandez, Ghalsasi, Hall, Harigaya, 2006.05687]

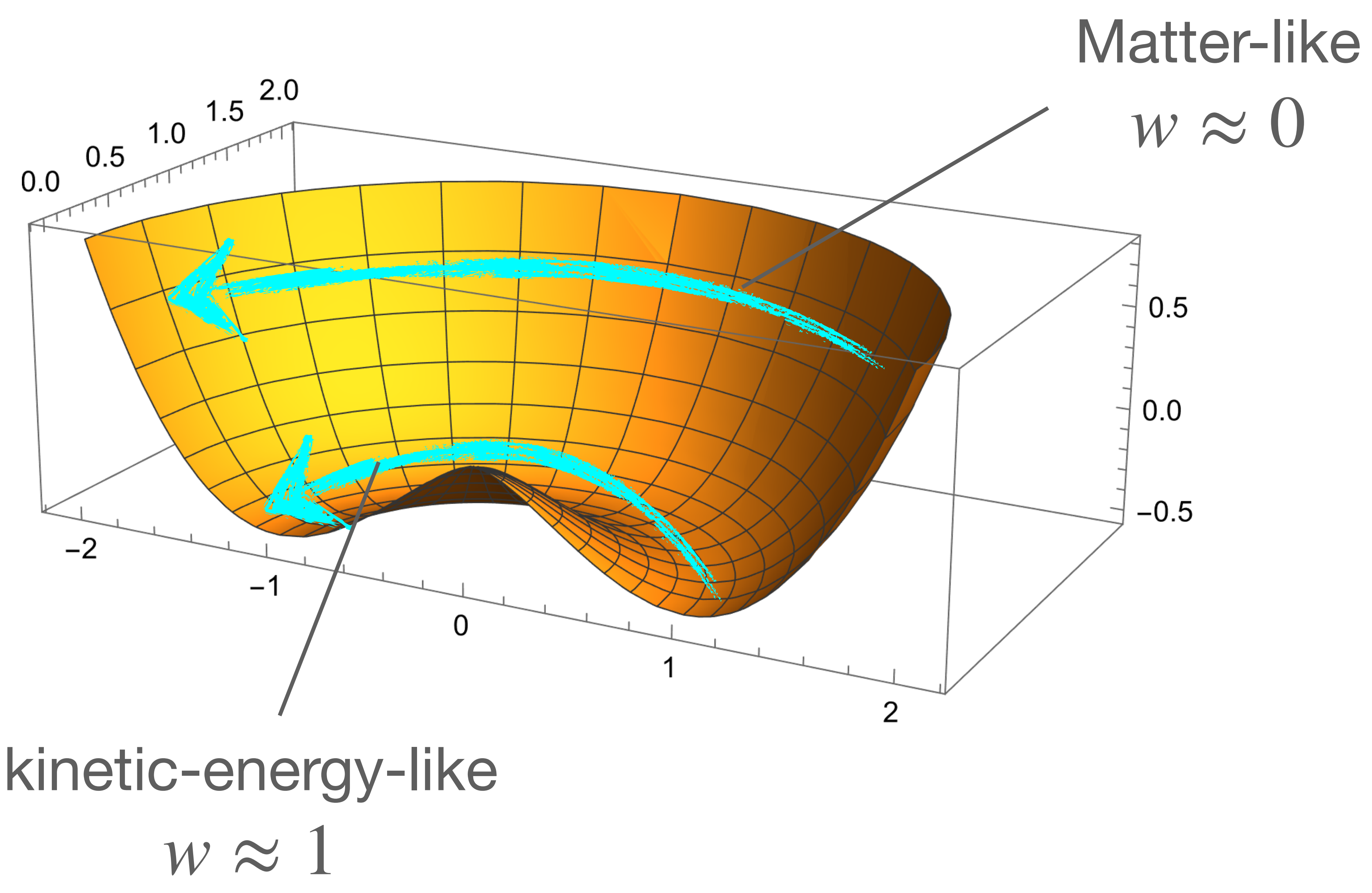
  [Co, Hall, Harigaya, 2006.04809], [Kawamura, Raby, 2109.08605]

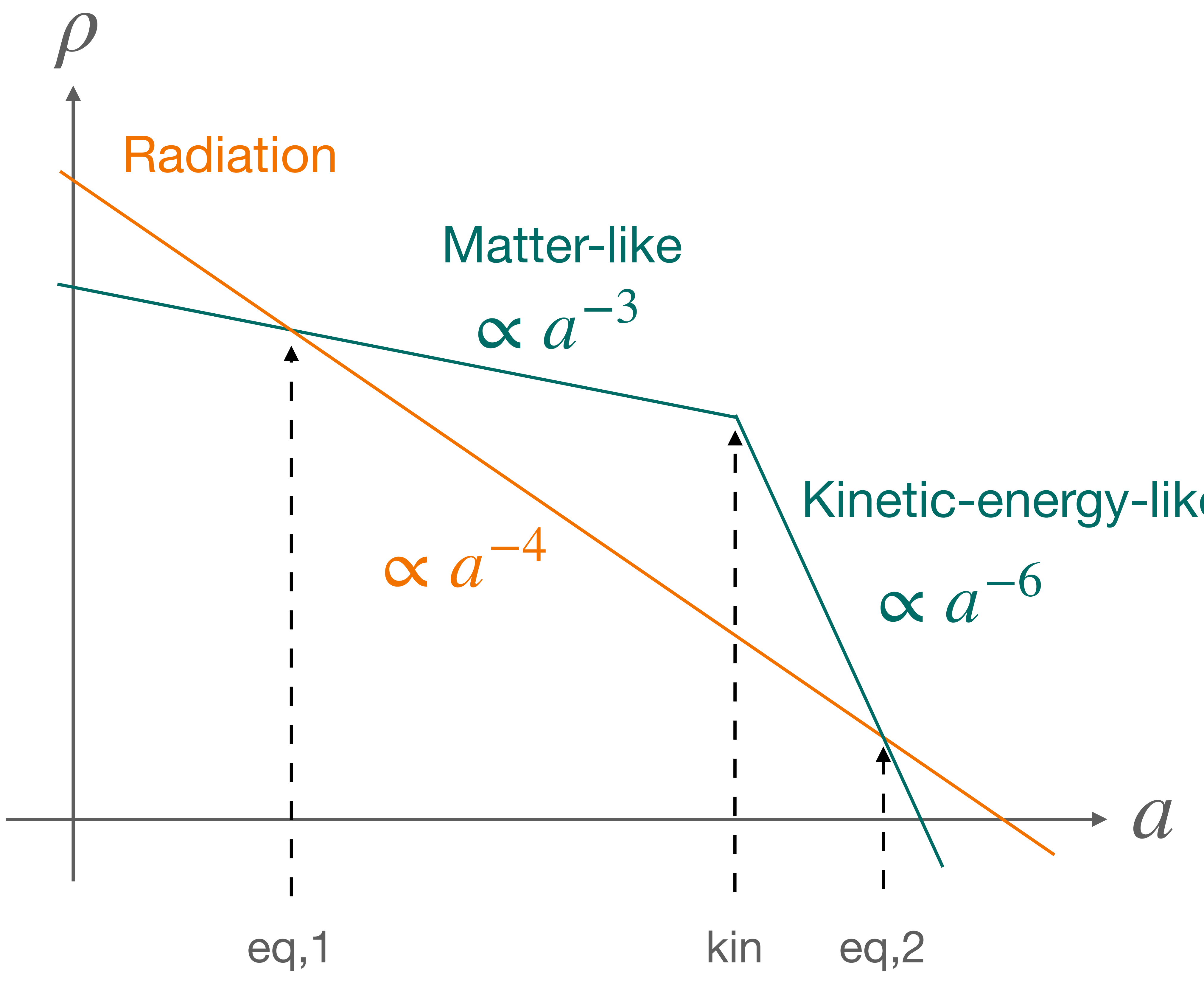
Axion Rotation Cosmology with Kination

[Co, Dunsky, Fernandez, Ghalsasi, Hall, Harigaya, Shelton, 2108.09299]
[Gouttenoire, Servant, Simakachorn, 2108.10328]

Example:

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





No Entropy Production neither at “kin” nor at “eq,2”!

Scalar-induced Gravitational Waves

(Induced GWs, Second-order GWs, Secondary GWs, ...)

[Ananda, Clarkson, Wands, gr-qc/0612013], [Baumann, Steinhardt, Takahashi, Ichiki, hep-th/0703290] For reviews, see [Yuan, Huang, 2103.04739], [Domènech, 2109.01398].

Density perturbations

$\delta\phi$

inflaton

δa

axion

$\delta\rho$

density perturbations in general

$\Longleftrightarrow$

gauge transf.
Einstein eqs.

Scalar modes in metric

gravitational potential Φ

curvature perturbations Ψ

$\Longleftrightarrow$

Einstein eqs.

Tensor modes in metric

$$h_{ij} = \mathcal{O}(\partial^2\Phi^2)$$

gravitational waves (GWs)

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Density perturbations		Scalar modes in metric		Tensor modes in metric
$\delta\phi$ inflaton	⟷	gravitational potential Φ	⟷	$h_{ij} = \mathcal{O}(\partial^2\Phi^2)$
δa axion	gauge transf. Einstein eqs.	curvature perturbations Ψ	Einstein eqs.	gravitational waves (GWs)
$\delta\rho$ density perturbations in general				

Need large perturbations δa for observables GWs? — Not necessarily: *The "Poltergeist" mechanism*

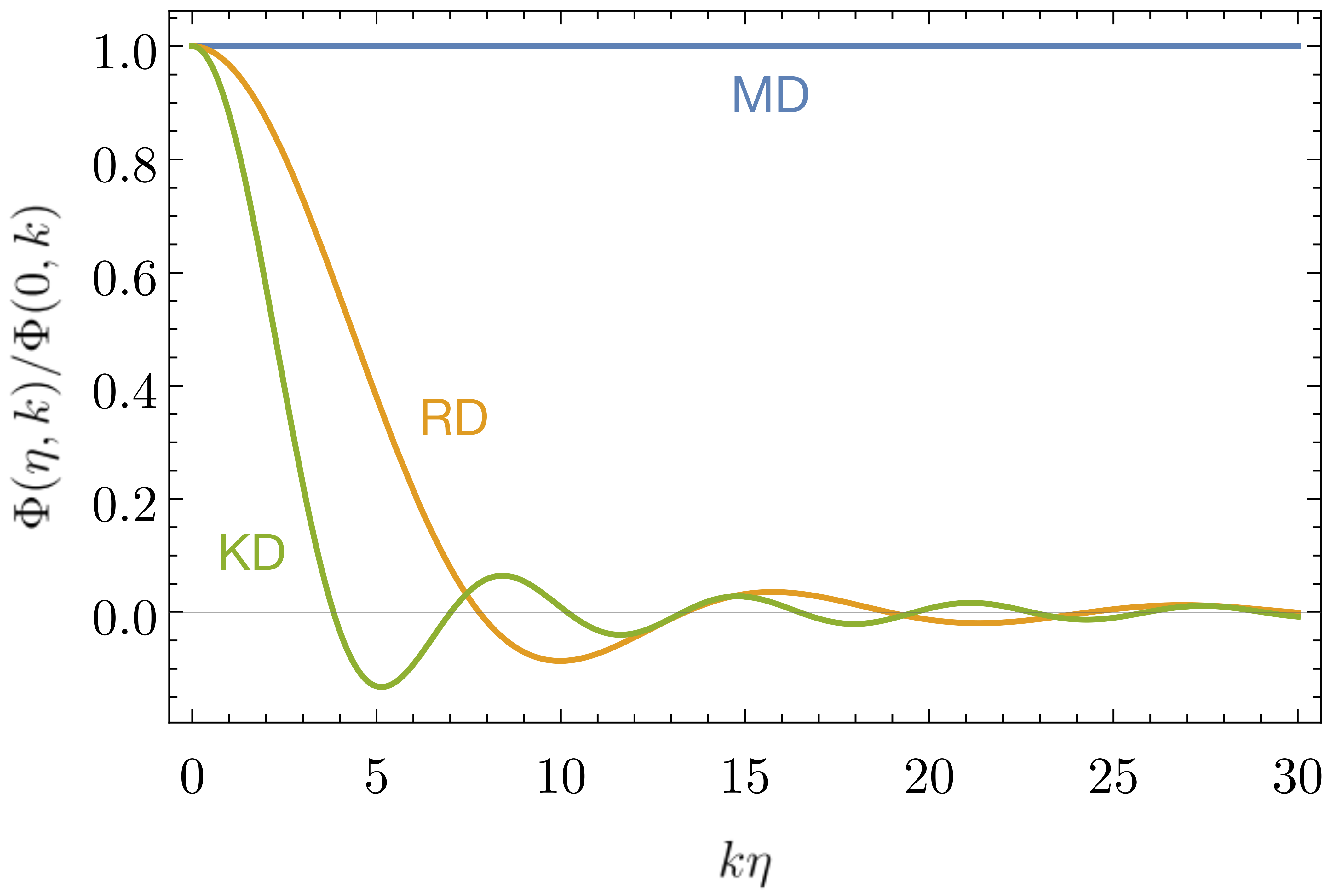
Poltergeist Mechanism

[Inomata, Kohri, Nakama, Terada, 1904.12879]
[Inomata, Kawasaki, Mukaida, Terada, Yanagida, 2003.10455]

Enhancement effects during a MD era

[Baumann, Steinhardt, Takahashi, Ichiki, hep-th/0703290], [Assadullahi, Wands, 0901.0989]

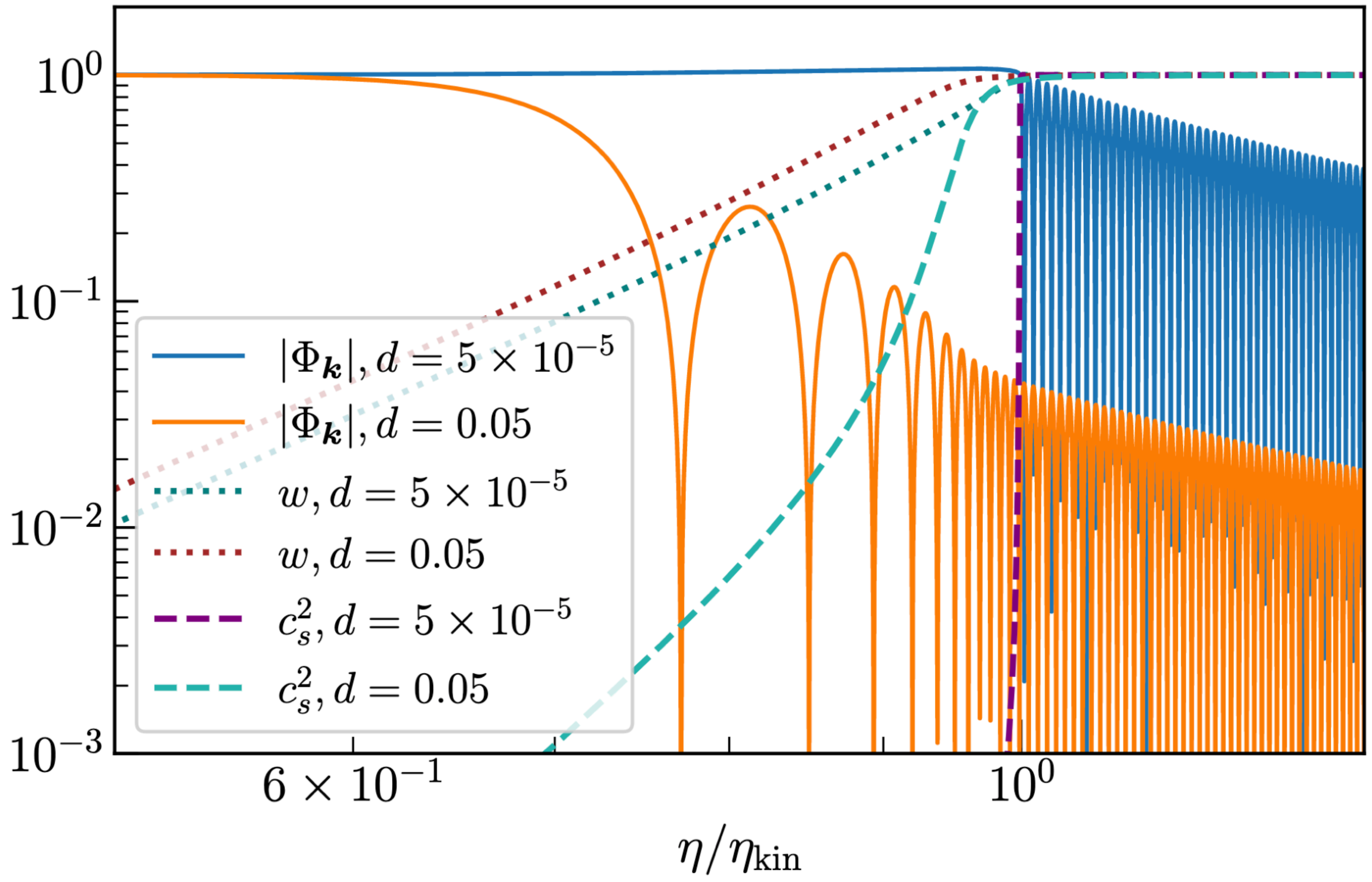
$$\frac{\delta\rho}{\rho} \propto a(\eta) \quad \Longleftrightarrow \quad \Phi = \text{const.}$$



Poltergeist Mechanism

[Inomata, Kohri, Nakama, Terada, 1904.12879]
[Inomata, Kawasaki, Mukaida, Terada, Yanagida, 2003.10455]

Time evolution of $|\Phi_k|$ $(k\eta_{\rm kin} = 450)$, w, and c_s^2



Degenerate limit: $d \equiv (m_{\bar{P}} - m_P)/m_P \to 0$

[Harigaya, Inomata, Terada, 2305.14242]

Rapid oscillations of Φ_k with the unsuppressed amplitude

→ Large $h_{ij} = \mathcal{O}(k^2 \dot{\Phi}_k^2 / H^2)$

Suppression in quasi-sudden case is important.

$$\mathcal{P}_h \propto \mathcal{P}_\Phi^2 \propto \Phi^4$$

Axion Model Setup

[Co, Dunsky, Fernandez, Ghalsasi, Hall, Harigaya, Shelton, 2108.09299]

Supersymmetric Two-field model

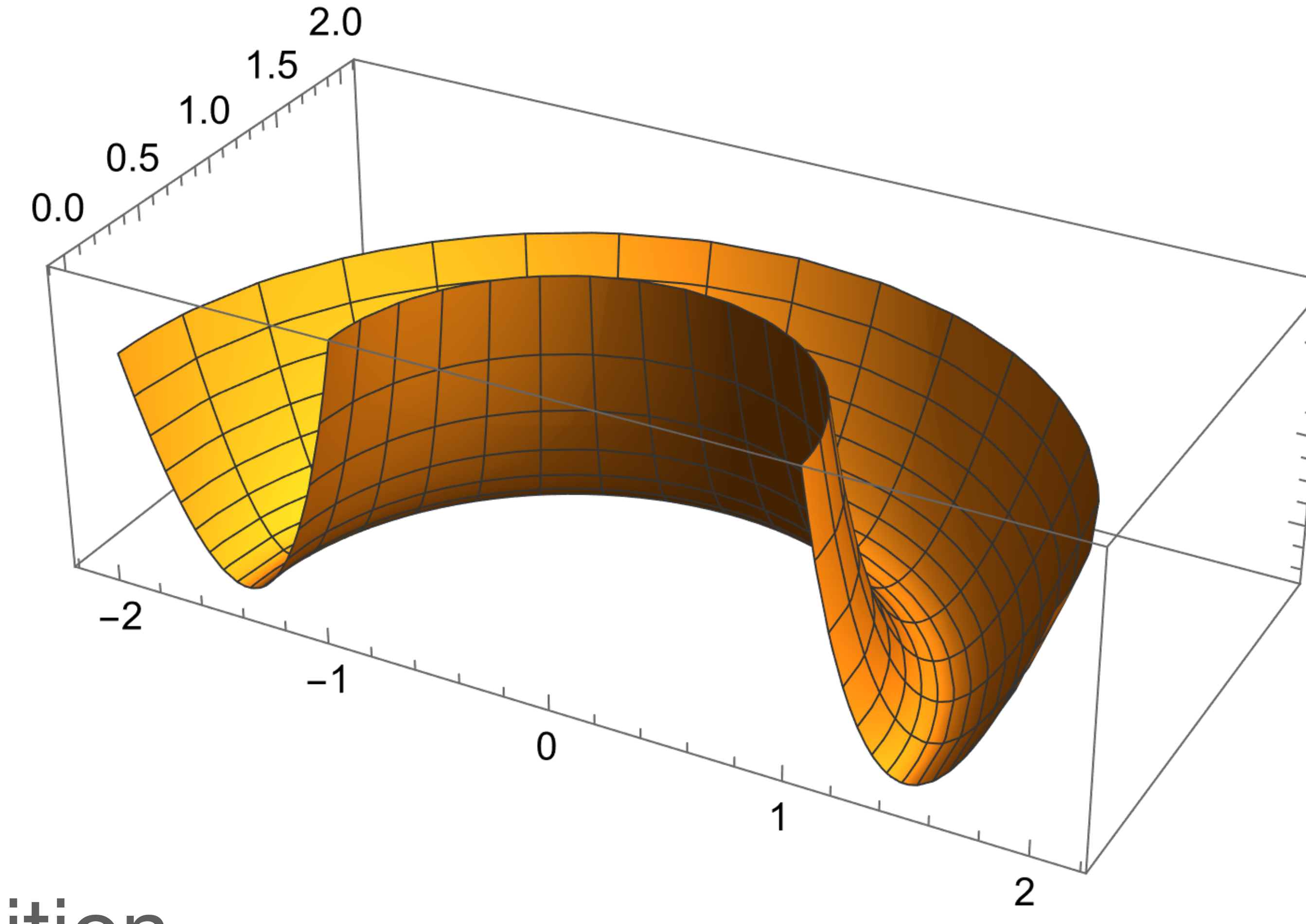
Kähler potential $K = |P|^2 + |\bar{P}|^2 + |X|^2$

Superpotential $W = \lambda X(P\bar{P} - v_P^2)$

Soft supersymmetry breaking mass terms $(v_P \gg m_P, m_{\bar{P}})$ $V_{\text{soft}} = m_P^2|P|^2 + m_{\bar{P}}^2|\bar{P}|^2$

X and a combination of P and $\bar{P}$ become heavy and can be integrated out.

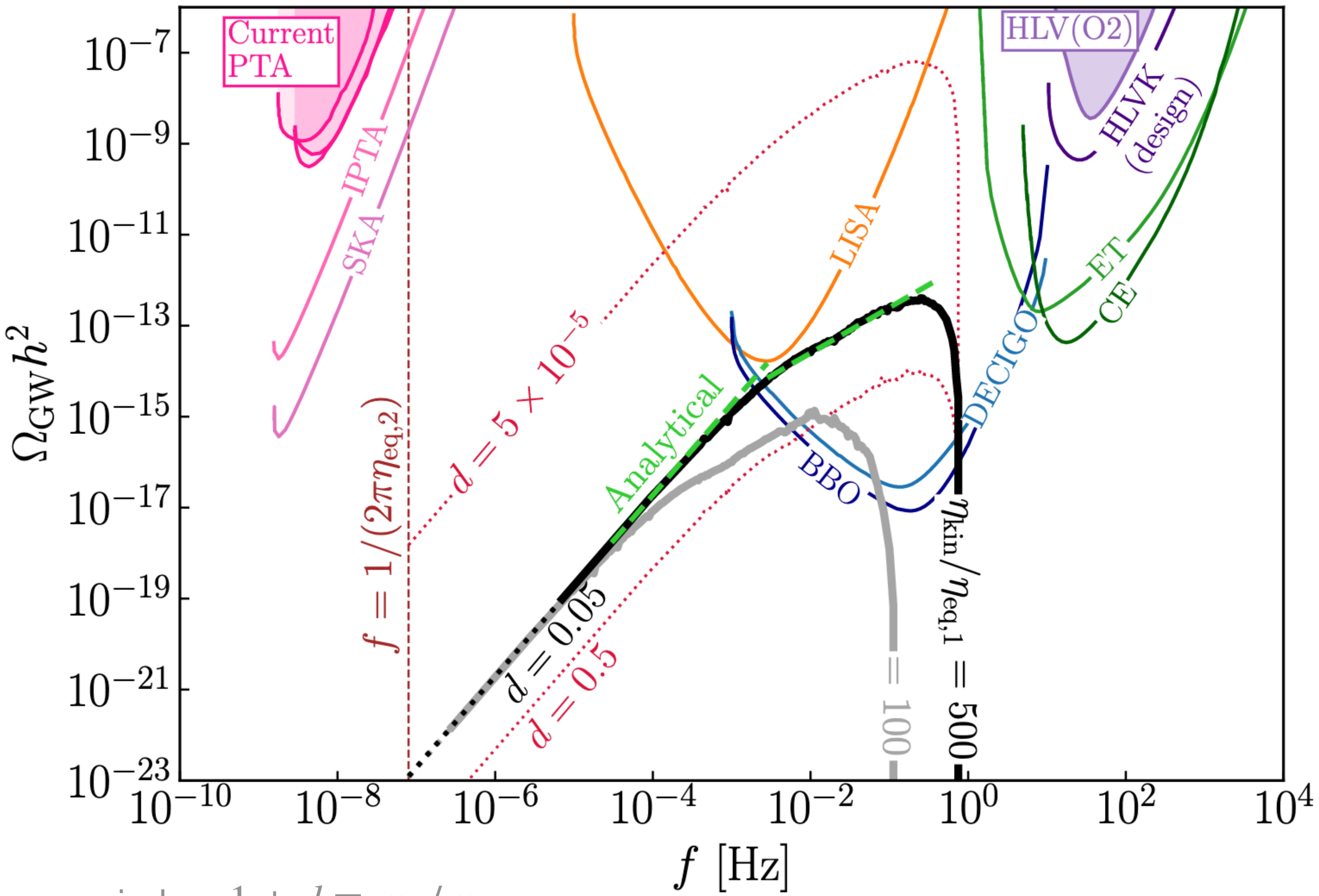
$$\mathscr{L} = -\left(1 + \frac{f_a^4}{16|P|^4}\right) g^{\mu\nu}\partial_\mu P^\dagger \partial_\nu P - \left(1 - \frac{(1+d)f_a^2}{4|P|^2}\right)^2 m_P^2|P|^2$$



The approximately $\mathbb{Z}_2$ symmetric limit $d \equiv (m_{\bar{P}} - m_P)/m_P \ll 1$ realizes a sudden transition.

Axion-Induced Gravitational Waves [Harigaya, Inomata, Terada, 2305.14242]

See our Supplemental Material, [Domènech, 1912.05583], and [Domènech, Pi, Sasaki, 2005.12314] for Induced GWs with a general equation-of-state parameter w.



reminder: $1 + d \equiv m_{\bar{P}}/m_P$

The dominant contribution (from the KD era by the Poltergeist mechanism) is plotted.

Assumed Curvature Spectrum:

$$\mathcal{P}_\zeta = A\,\Theta(k_{\rm max} - k)\,\Theta(k - 1/\eta_{\rm kin})$$

with $A = 2.1 \times 10^{-9}$, and $k_{\rm max}$ the nonlinear scale.

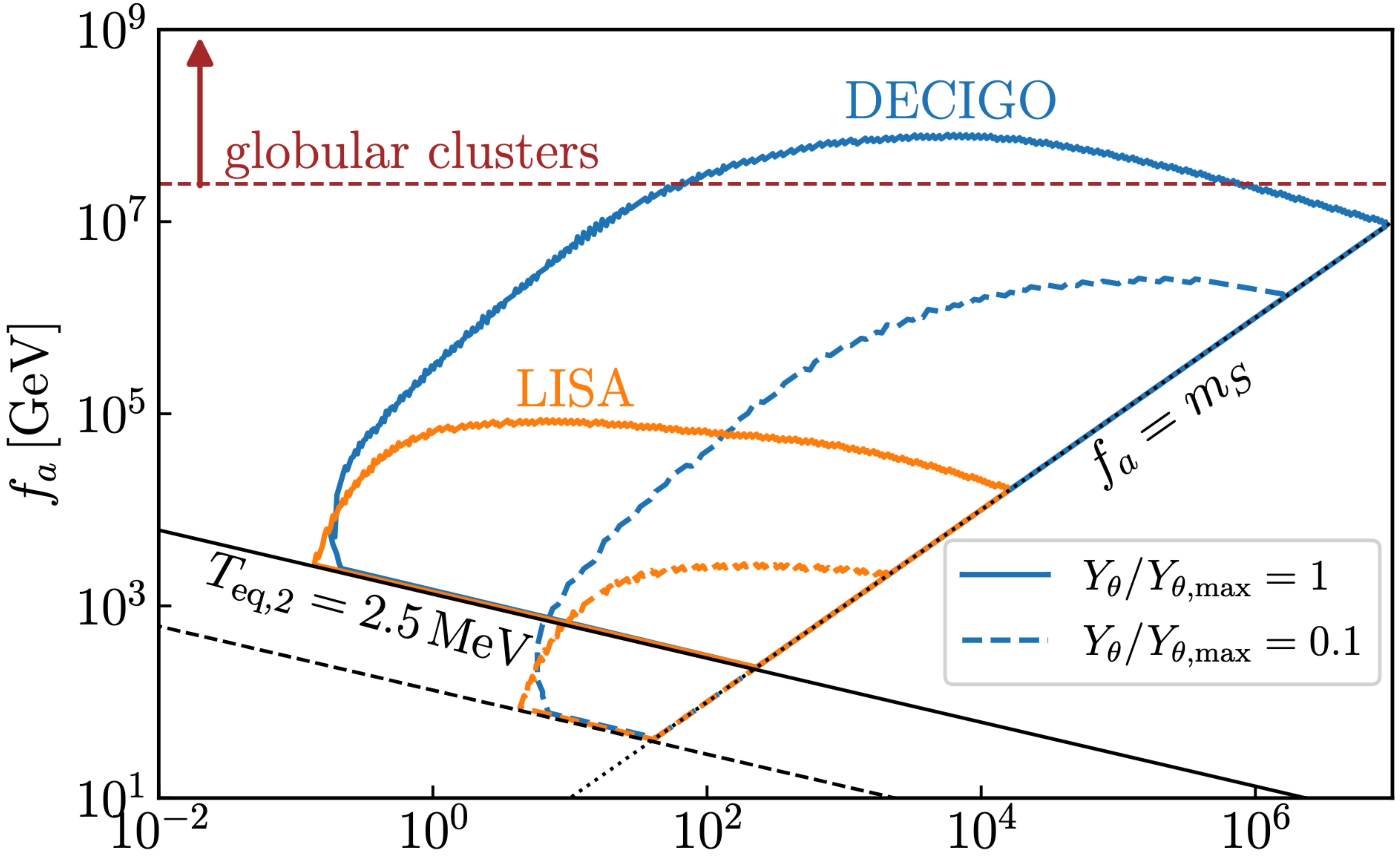
Analytic formula:

$$\Omega_{\rm GW}h^2 \simeq 2\times10^{-11}A^2Q^4\frac{\eta_{\rm kin}^2}{\eta_{\rm eq,1}^2}(k_*\eta_{\rm kin})^5\begin{cases} k\eta_{\rm kin} & (k\eta_{\rm kin}\geq 4) \\ 0.535\times(k\eta_{\rm kin})^2 & (k\eta_{\rm kin}<4)\end{cases}$$

where $k_* \equiv \min[k_{\rm max}, 1/\eta_{\rm eq,1}]$ and $Q \sim \Phi_{k_*}(\eta_{\rm kin})/\Phi_{k_*}(\eta_{\rm eq,1} \ll \eta \ll \eta_{\rm kin})$.

Testable Parameter Space 1: Saxion

[Harigaya, Inomata, Terada, 2305.14242]



($= m_P$; SUSY breaking scale)

$d = 0.05$ and $b = 0.1$

U(1) charge density

$$Y_\theta \equiv \frac{n_\theta}{s}, \quad n_\theta = 2\left(1 + \frac{f_a^4}{16|P|^4}\right)|P|^2\dot{\theta}$$

$$Y_{\theta,\max} = 100\left(\frac{m_S}{8.7\times 10^8\,\mathrm{GeV}}\right)^{-1/3}\left(\frac{b}{0.1}\right)^{1/3}$$

b: parametrizing the efficiency of thermalization

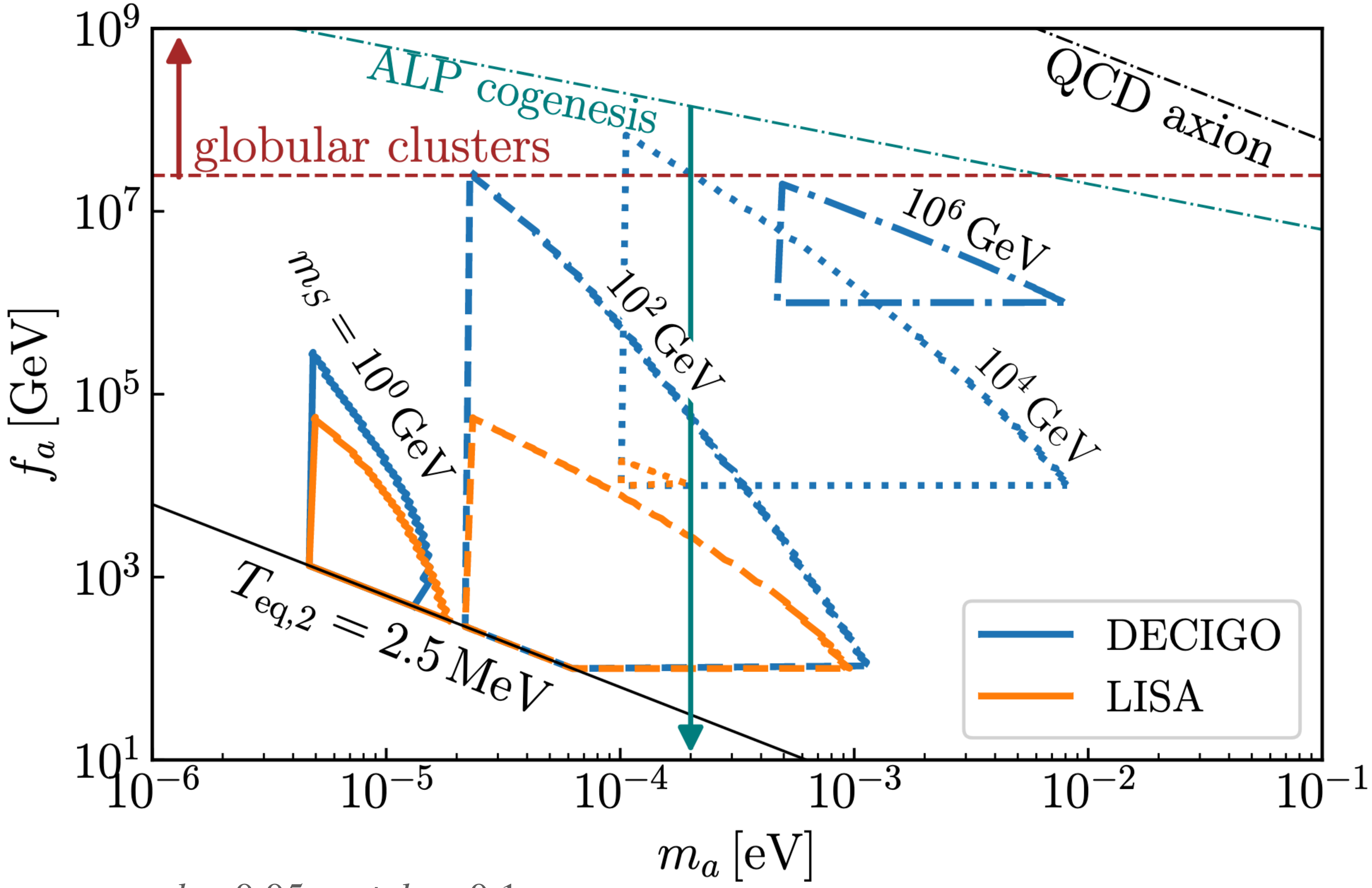
[Dolan, Hiskens, Volkas, 2207.03102]

Globular cluster constraint assumes

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}.$$

Testable Parameter Space 2: Axion

[Harigaya, Inomata, Terada, 2305.14242]



$d = 0.05$ and $b = 0.1$

Axion 100% dark matter is assumed.

$$m_a Y_\theta \simeq 0.44\,\mathrm{eV}$$

kinetic misalignment [Co, Hall, Harigaya, 1910.14152]

ALP cogenesis [Co, Hall, Harigaya, 2006.04809]

Conclusion

Axion rotation can explain **dark matter** abundance and/or **baryon asymmetry** of the universe.

We find that it can also produce the **observable** stochastic **gravitational-wave** background.

Axion
Poltergeist

Parameter Relations

Duration of the MD era: $$\frac{\eta_{\rm kin}}{\eta_{\rm eq,1}} = 3.8 \left(\frac{m_S}{10^5\,{\rm GeV}}\right)^{1/3} \left(\frac{f_a}{10^9\,{\rm GeV}}\right)^{-1/3} \left(\frac{Y_\theta}{100}\right)^{2/3}$$

Temperature at the second equality: $$T_{\rm eq,2} = 1.8 \times 10^6\,{\rm GeV} \left(\frac{f_a}{10^9\,{\rm GeV}}\right) \left(\frac{Y_\theta}{100}\right)^{-1}$$

Frequency corresponding to the second equality: $$\frac{1}{2\pi\eta_{\rm eq,2}} = 0.11\,{\rm Hz} \left(\frac{T_{\rm eq,2}}{1.8 \times 10^6\,{\rm GeV}}\right)$$

Maximal charge yield: $$Y_{\theta,{\rm max}} = 100 \left(\frac{m_S}{8.7 \times 10^8\,{\rm GeV}}\right)^{-1/3} \left(\frac{b}{0.1}\right)^{1/3}$$

Scalar-induced Gravitational Waves

(Induced GWs, Second-order GWs, Secondary GWs, ...)

[Ananda, Clarkson, Wands, gr-qc/0612013], [Baumann, Steinhardt, Takahashi, Ichiki, hep-th/0703290] For reviews, see [Yuan, Huang, 2103.04739], [Domènech, 2109.01398].

Conformal Newtonian gauge (There are some variants of its name.)

$$ds^2 = -a^2(1+2\Phi)d\eta^2 + a^2\left((1-2\Psi)\delta_{ij} + \frac{1}{2}h_{ij}\right)dx^i dx^j$$

Gravitational potential Curvature perturbations GW (tensor mode)

(In the absence of anisotropic stress, $\Phi = \Psi$.)

Graviton mode expansion

$$h_{ij}(\eta, \mathbf{x}) = \int \frac{d^3k}{(2\pi)^{3/2}}\left(e^{+}_{ij}(\mathbf{k})h^{+}_{\mathbf{k}}(\eta) + e^{\times}_{ij}(\mathbf{k})h^{\times}_{\mathbf{k}}(\eta)\right)e^{i\mathbf{k}\cdot\mathbf{x}}$$

Equation of motion

$$h''_{\mathbf{k}}(\eta) + 2\mathcal{H}h'_{\mathbf{k}}(\eta) + k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta)$$

where $\mathcal{H} = aH$ is the conformal Hubble, and the source term is $S_{\mathbf{k}} = \int \frac{d^3q}{(2\pi)^{3/2}} e_{ij}(\mathbf{k})q_i q_j \left(2\Phi_{\mathbf{q}}\Phi_{\mathbf{k}-\mathbf{q}} + \frac{4}{3(1+w)}(\mathcal{H}^{-1}\Phi'_{\mathbf{q}} + \Phi_{\mathbf{q}})(\mathcal{H}^{-1}\Phi'_{\mathbf{k}-\mathbf{q}} + \Phi_{\mathbf{k}-\mathbf{q}})\right)$

GW energy density on subhorizon scales [Maggiore, gr-qc/9909001]

$$\rho_{\rm GW}(\eta) = \frac{1}{16a^2}\langle\overline{h'_{ij}h'_{ij}}\rangle = \frac{1}{16a^2}\langle\overline{h_{ij,k}h_{ij,k}}\rangle = \int d\ln k\, \rho_{\rm GW}(\eta, k)$$

where an overline denotes the oscillation average.

Dimensionless Power spectrum

$$\langle h^{\lambda}_{\mathbf{k}}(\eta)h^{\lambda'}_{\mathbf{k}'}(\eta)\rangle = \delta_{\lambda\lambda'}\delta^3(\mathbf{k}+\mathbf{k}')\frac{2\pi^2}{k^3}\mathcal{P}_h(\eta, k)$$

$$\Omega_{\rm GW}(\eta, k) = \frac{\rho_{\rm GW}(\eta, k)}{\rho_{\rm total}(\eta)} = \frac{1}{24}\left(\frac{k}{aH}\right)^2 \overline{\mathcal{P}_h(\eta, k)}$$

Scalar-induced Gravitational Waves
Cosmological relevance

Why does the second-order effect matter?

Simple perturbative series: $\mathcal{O}(\epsilon) + \mathcal{O}(\epsilon^2) + \mathcal{O}(\epsilon^3) + \cdots$ (ϵ : small quantity)

Situation for induced-GWs: $\mathcal{O}(\epsilon_T) + \mathcal{O}(\epsilon_S^2) + \mathcal{O}(\epsilon_S \epsilon_T) + \mathcal{O}(\epsilon_T^2) + \cdots$

$$h''_{\mathbf{k}}(\eta) + 2\mathcal{H} h'_{\mathbf{k}}(\eta) + k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta)(= \mathcal{O}(\mathcal{P}_\zeta))$$

Curvature perturbations are measured to be very small, aren't they?

Yes, on the CMB scale.

When can the induced-GWs be cosmologically relevant?

Relevant if the curvature perturbations are enhanced on smaller scales.

Possibility 1: Initial condition

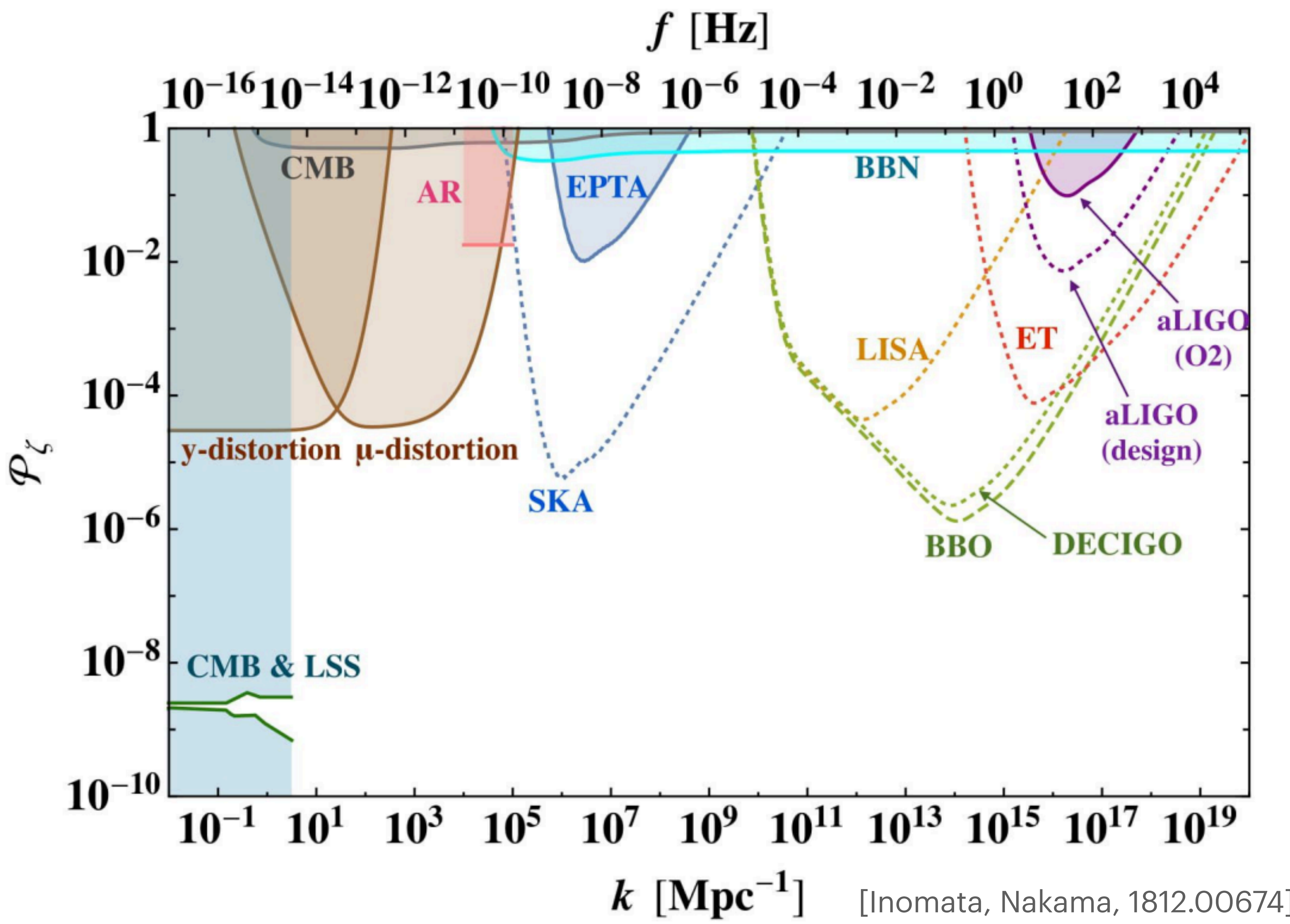
- ultra-slow-roll (USR) inflation, (multi-field) inflation with features, etc.
- relevant in primordial-black-hole (PBH) scenarios

[Saito, Yokoyama, 0812.4339; 0912.5317]

Possibility 2: Growth (more precisely, non-decay)

- growth of density perturbations in a MD era

  → non-decaying curvature perturbations even after horizon entry
- main interest in this talk



[Inomata, Nakama, 1812.00674]

Poltergeist Mechanism
Previous works

[Inomata, Kohri, Nakama, Terada, 1904.12879]
[Inomata, Kawasaki, Mukaida, Terada, Yanagida, 2003.10455]

comparison of the behavior of Φ in sudden/gradual transitions

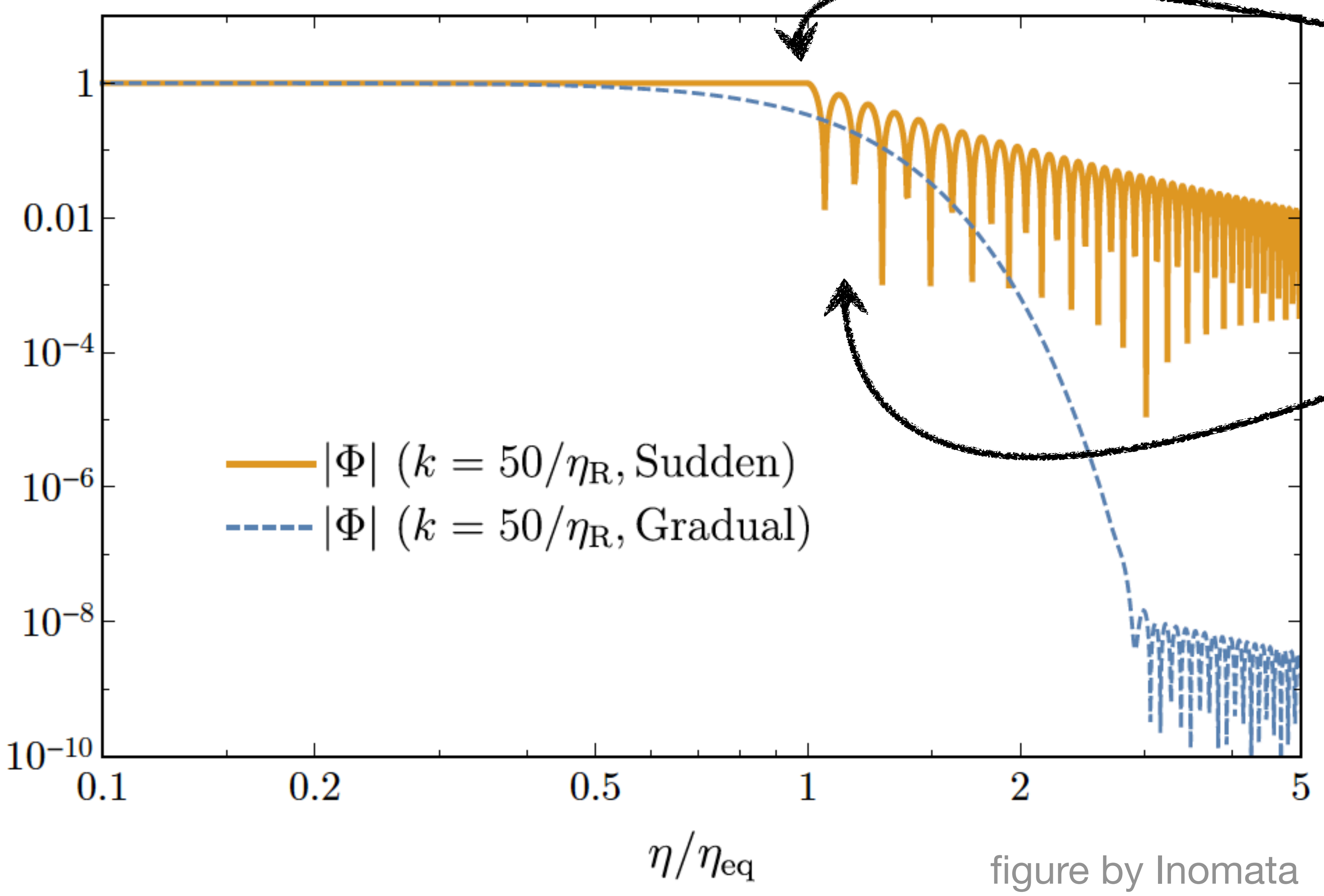


figure by Inomata

No Decay until reheating

Enhanced contribution of GWs from the MD era (known effect).

Fast oscillations due to a hierarchical ratio

$$\frac{k}{\mathcal{H}(\eta)} \gg 1$$

Enhanced contribution of GWs from the RD era (new effect).

(Quasi-) Sudden Reheating Examples

- "Triggeron" model (kinematic blocking)
  [Inomata, Kohri, Nakama, Terada, 1904.12879]
- Dark sector 1st-order phase transition
  [Inomata, Kohri, Nakama, Terada, 1904.12879]
- Black-hole domination & evaporation
  [Inomata, Kawasaki, Mukaida, Terada, Yanagida, 2003.10455]
- Q-ball domination & evaporation
  [White, Pearce, Vagie, Kusenko, 2105.11655]
  [Kasuya, Kawasaki, Murai, 2212.13370]
- I-ball/oscillon domination & evaporation
  [Lozanov, Takhistov, 2204.07152]
- Reheating by some higher-dim. operators
  [Co, Gonzalez, Harigaya, 2007.04328]

Poltergeist

mechanism for gravitational wave production

Poltergeist

Article Talk

From Wikipedia, the free encyclopedia

For other uses, see Poltergeist (disambiguation).

In ghostlore, a **poltergeist** (/ˈpoʊltərˌɡaɪst/ or /ˈpɒltərˌɡaɪst/; German for "rumbling ghost" or "noisy spirit") is a type of ghost or spirit that is responsible for physical disturbances, such as loud noises and objects being moved or destroyed. Most claims or fictional descriptions of poltergeists show them as being capable of pinching, biting, hitting, and tripping people. They are also depicted as capable of the movement or levitation of objects such as furniture and cutlery, or noises such as knocking on doors. Foul smells are also associated with poltergeist occurrences, as well as spontaneous fires and different electrical issues such as flickering lights. [1]

They have traditionally been described as troublesome spirits who haunt a particular person instead of a specific location. Some variation of poltergeist folklore is found in many different cultures. Early claims of spirits that supposedly harass and torment their victims date back to the 1st century, but references to poltergeists became more common in the early 17th century.

as if "ghost" of matter
is shaking the bath

Matter for MD era → reheating → Sound waves in Thermal Bath → Induced GWs