

曲率揺らぎに誘起された重力波

Curvature-induced Gravitational Waves

Probing Early Universe via Gravitational Waves

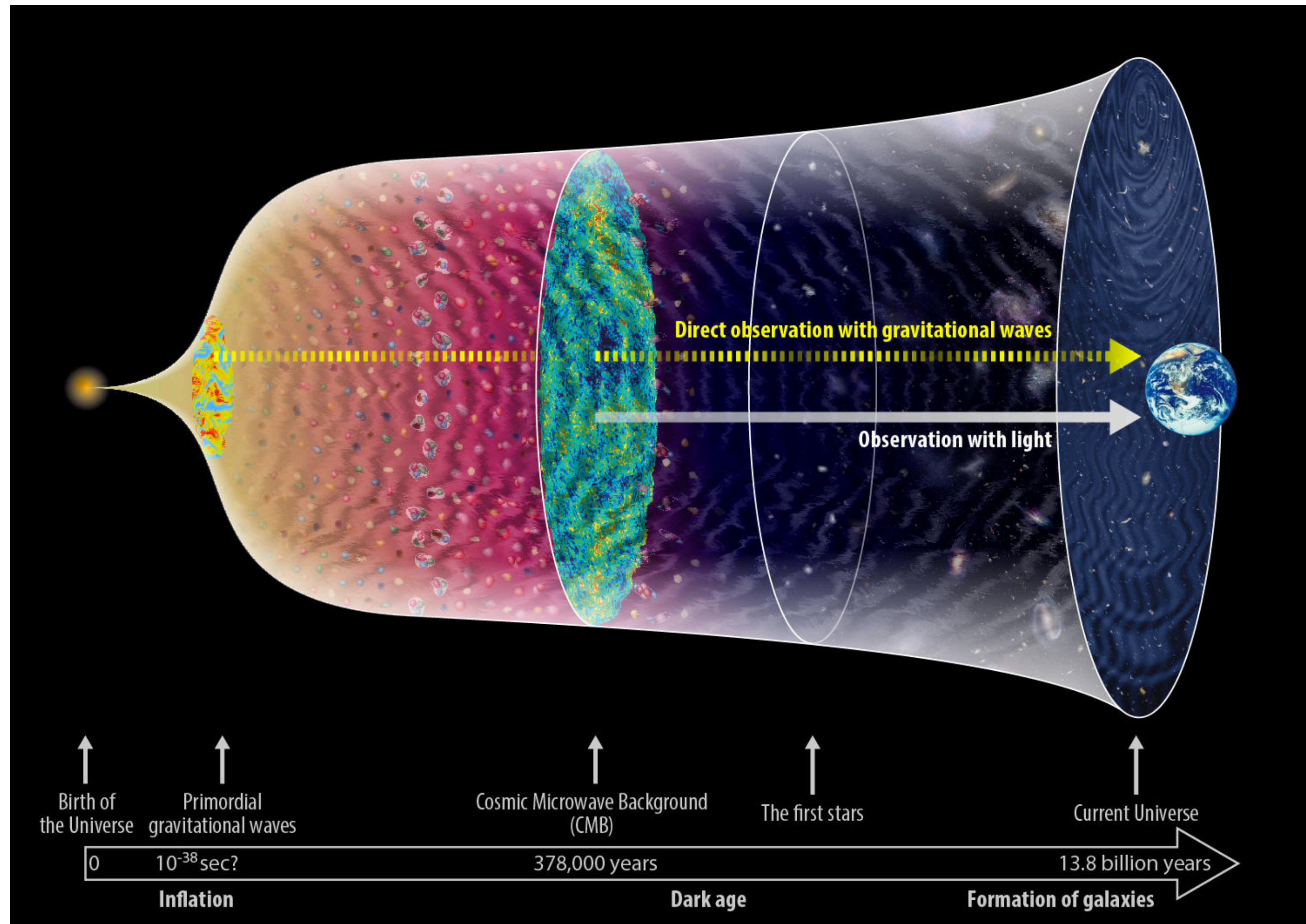


Image credit: NAOJ

Sources of GWs

- Inflation
- Preheating
- Phase transitions
- Curvature perturbations
- Hawking radiation
- Astrophysical sources
- ...

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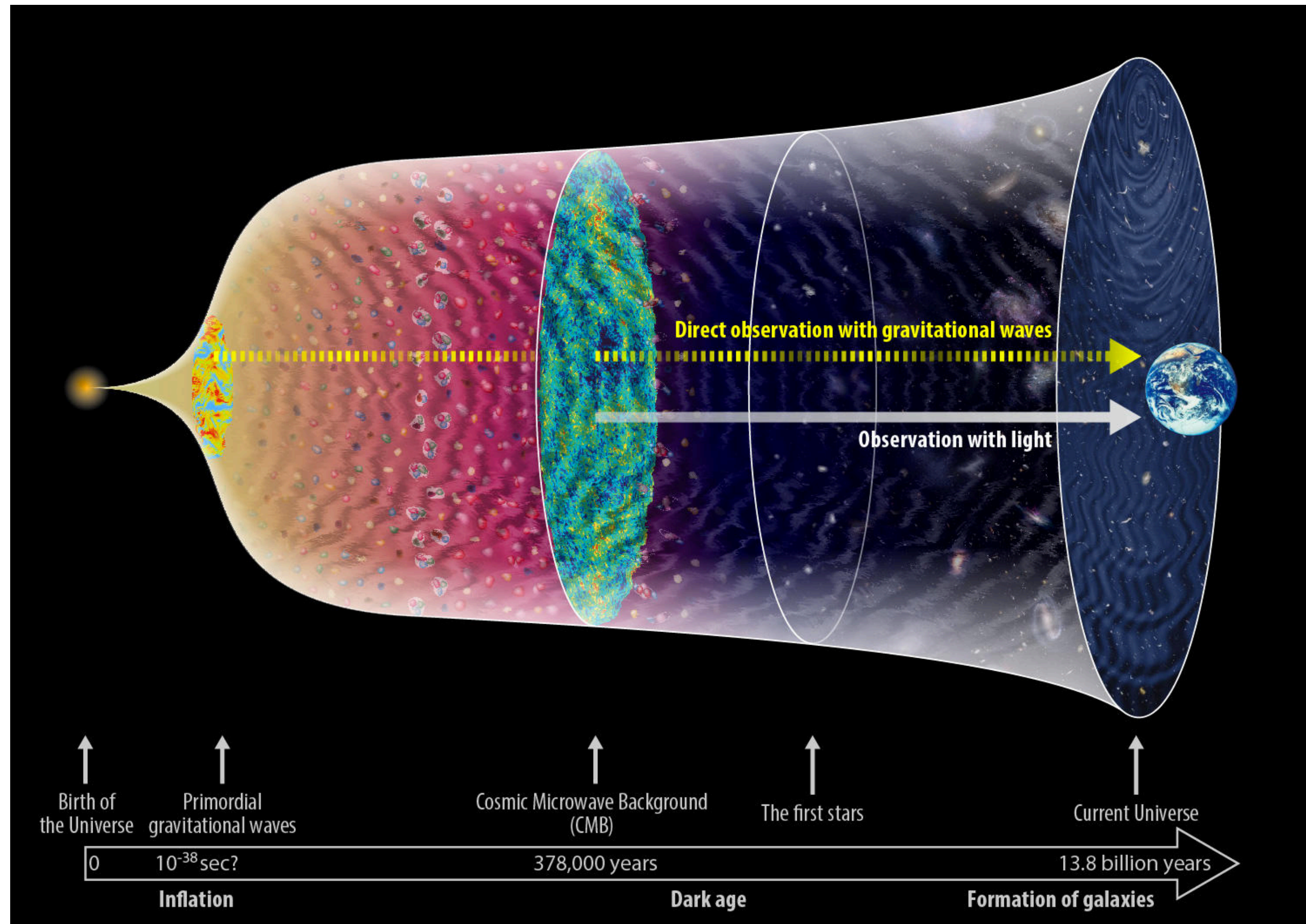


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Curvature-Induced Gravitational Waves

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

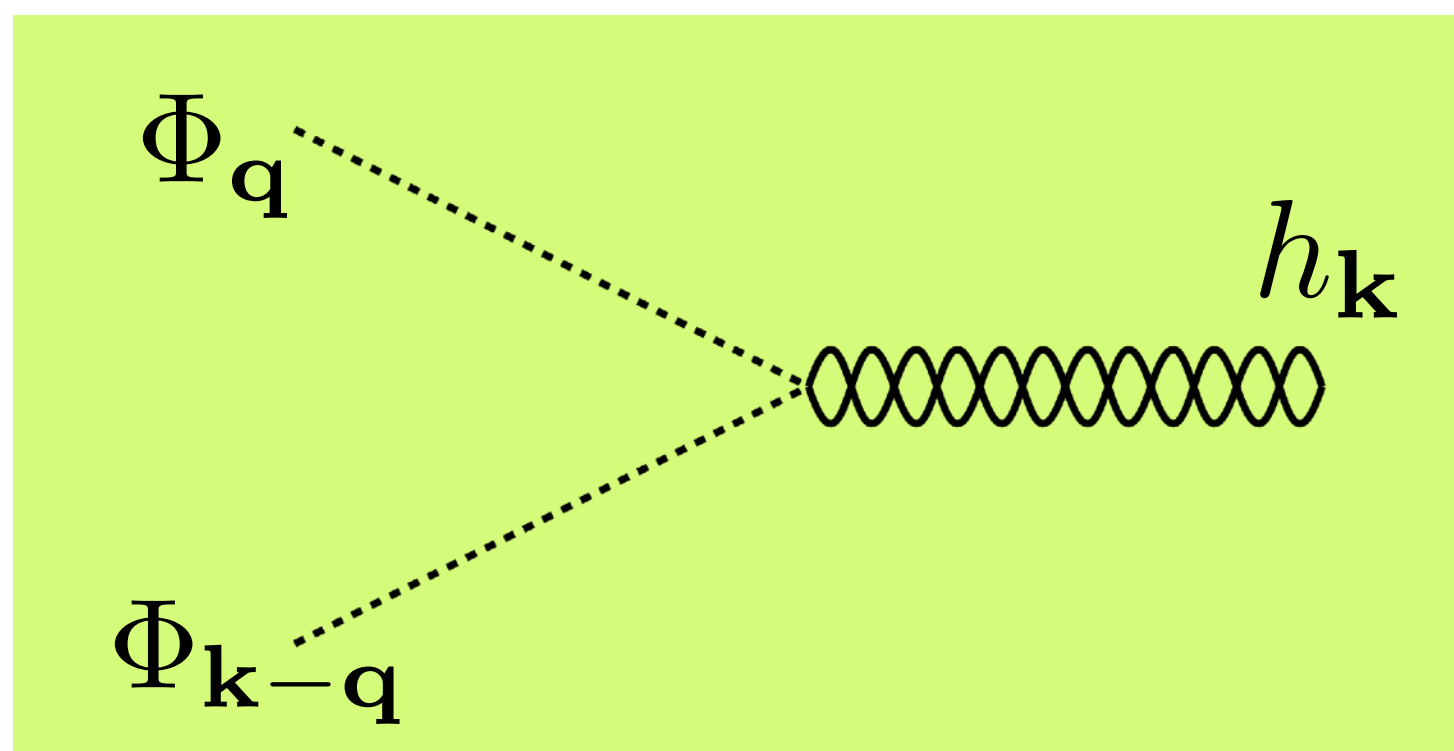
[Ananda, Clarkson, Wands, gr-qc/0612013], [Baumann, Steinhardt, Takahashi, Ichiki, hep-th/0703290] For reviews, see [Yuan, Huang, 2103.04739], [Domènech, 2109.01398].

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

Gravitational potential Curvature perturbations GW (tensor mode)

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

$$h_{\mathbf{k}}'' + 2\mathcal{H}h_{\mathbf{k}}' + k^2 h_{\mathbf{k}} = S_{\mathbf{k}}(\eta) \sim \Phi^2$$



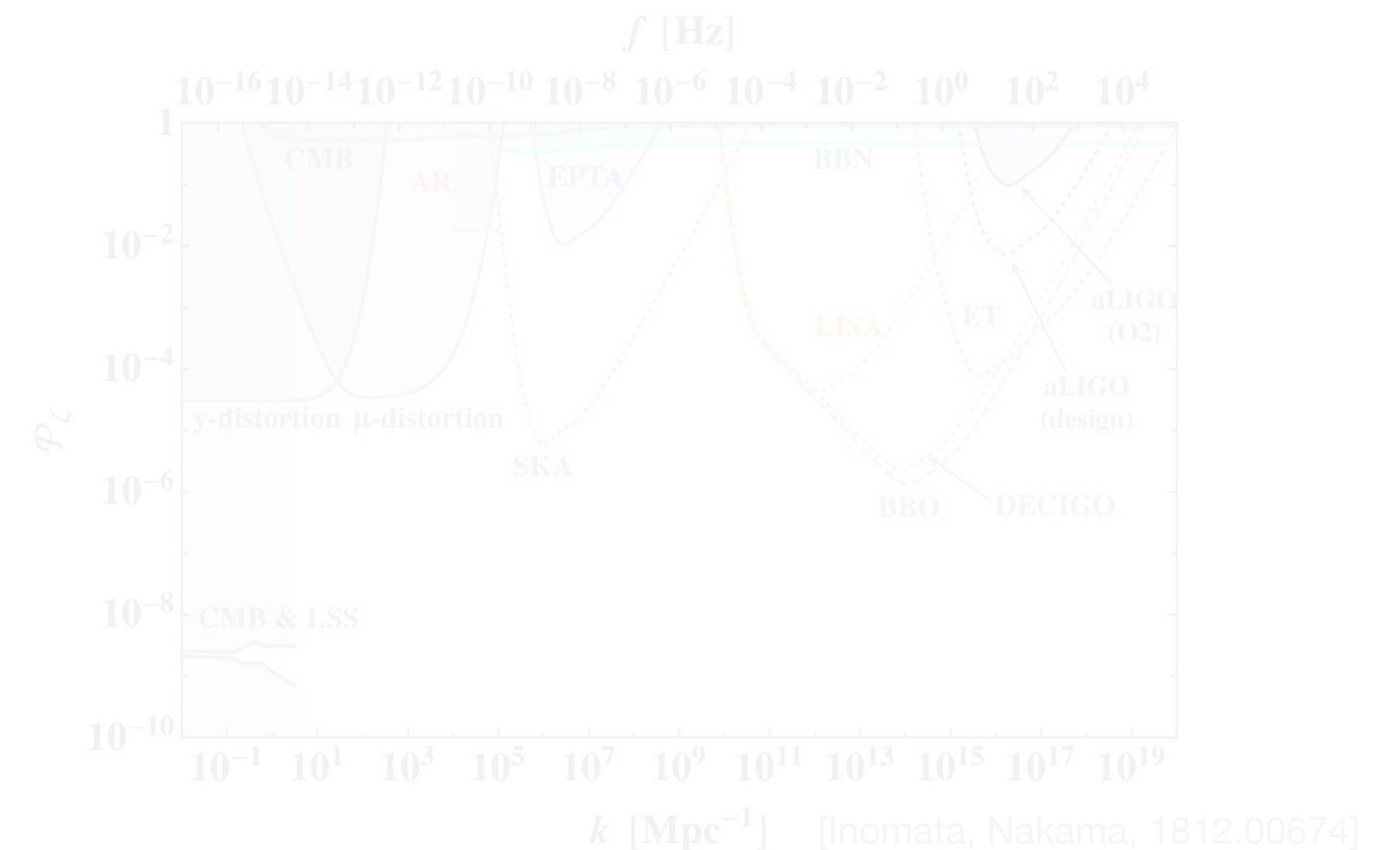
Analytic formulae for the integral kernel available:

[Espinosa, Racco, Riotto, 1804.07732], [Kohri, Terada, 1804.08577]

Can the source Φ be sufficiently large?

We know that $\mathcal{P}_{\Phi}(k_{\text{CMB}}) \simeq 2.1 \times 10^{-9}$ and $\Omega_{\text{GW}} \propto \mathcal{P}_{\Phi}^2 \dots$

1. May be large on smaller scales



2. May be enhanced by “non-standard” cosmological history

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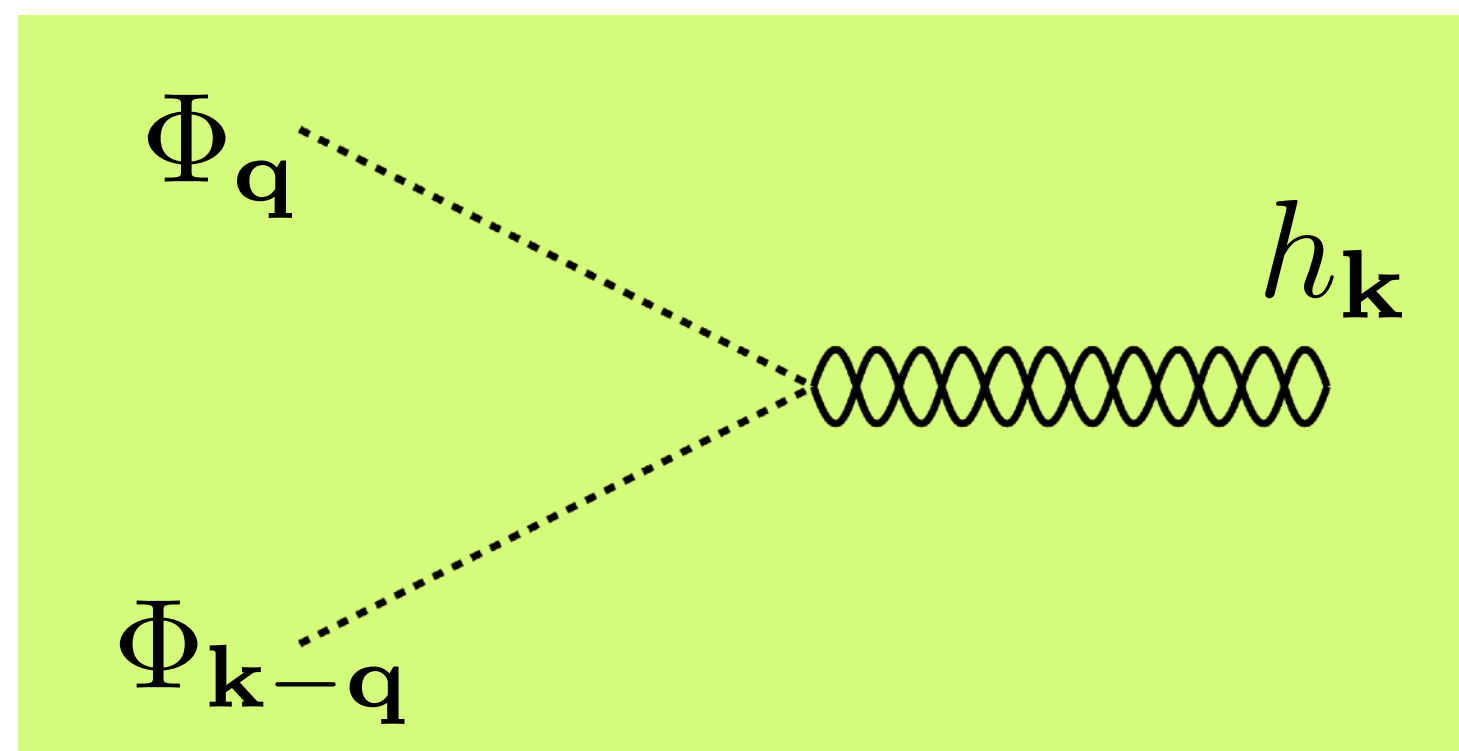
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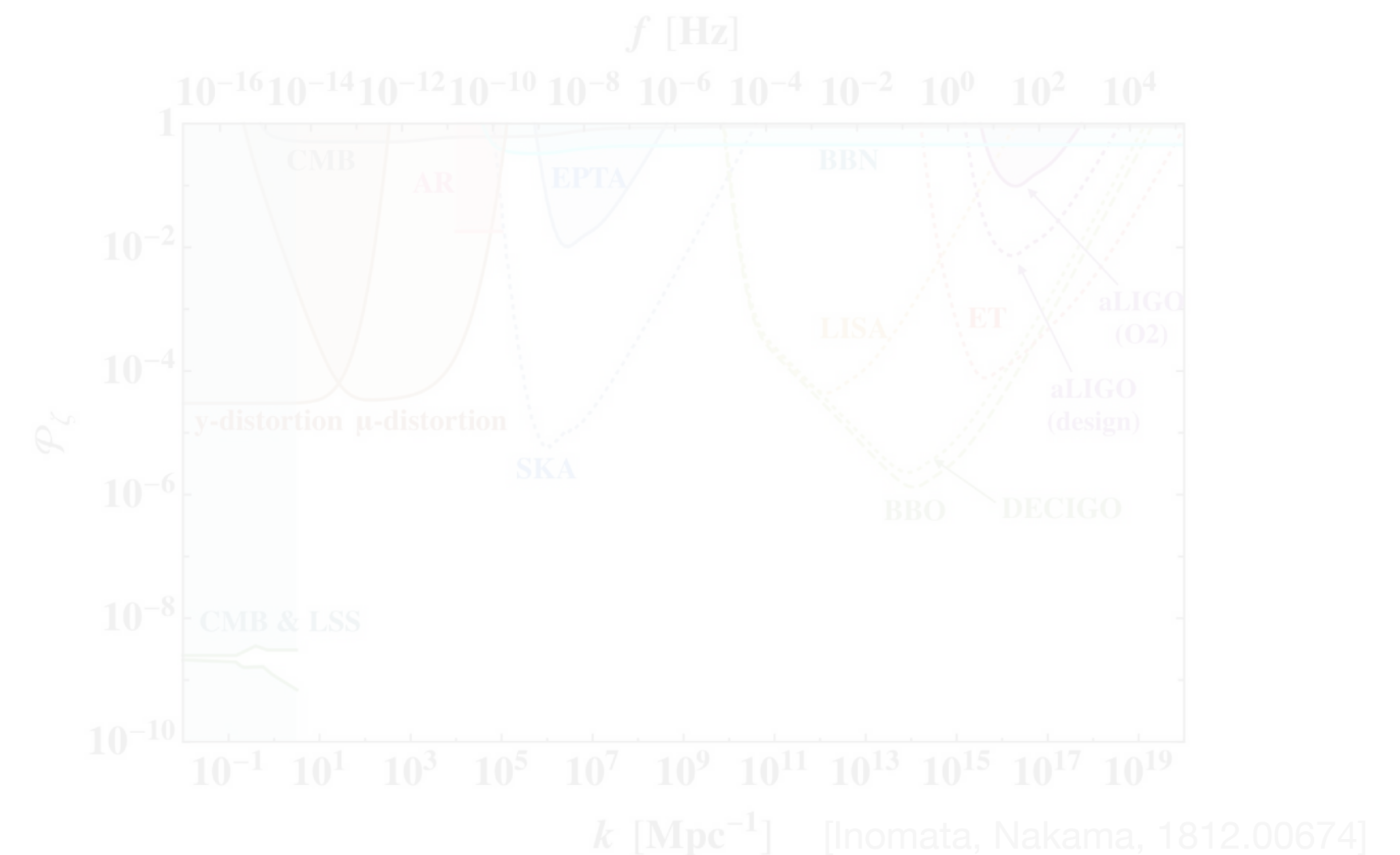
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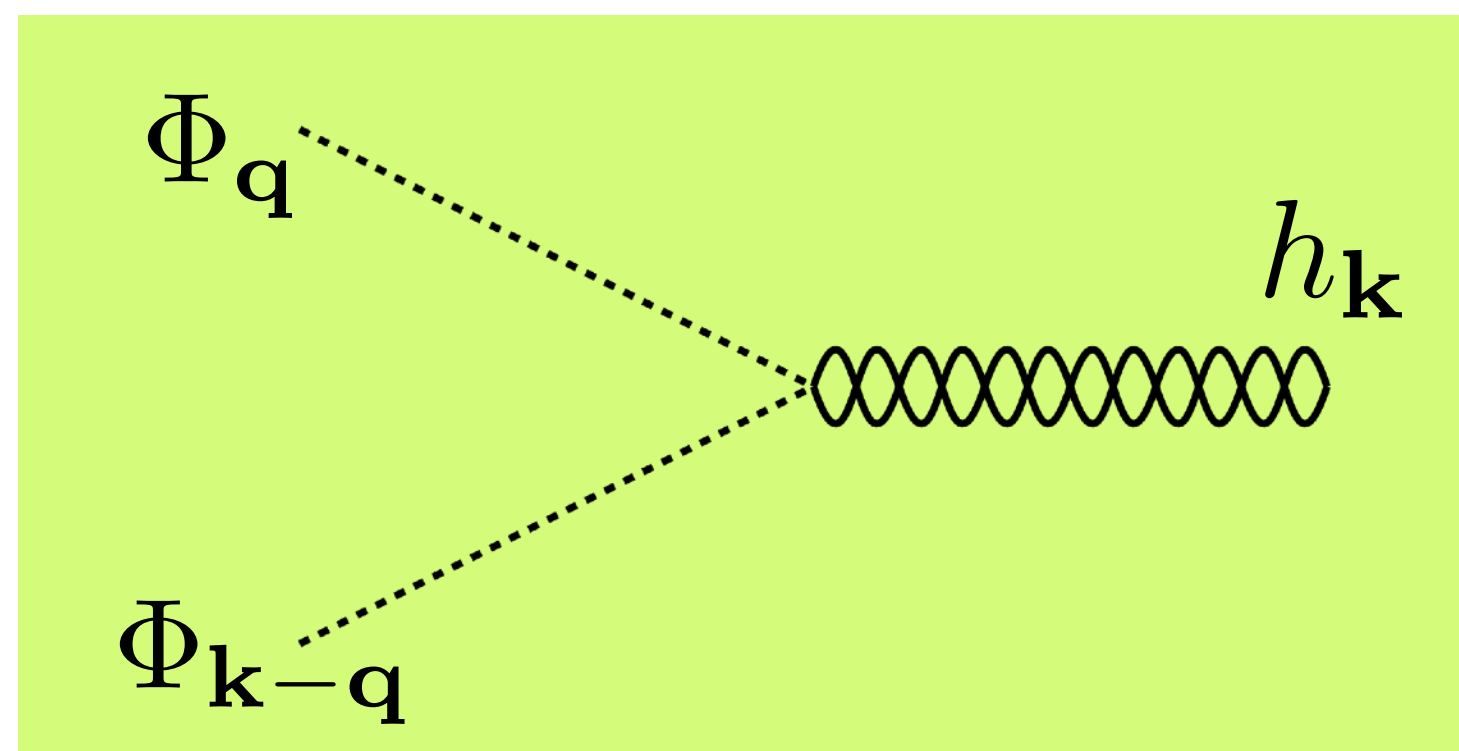
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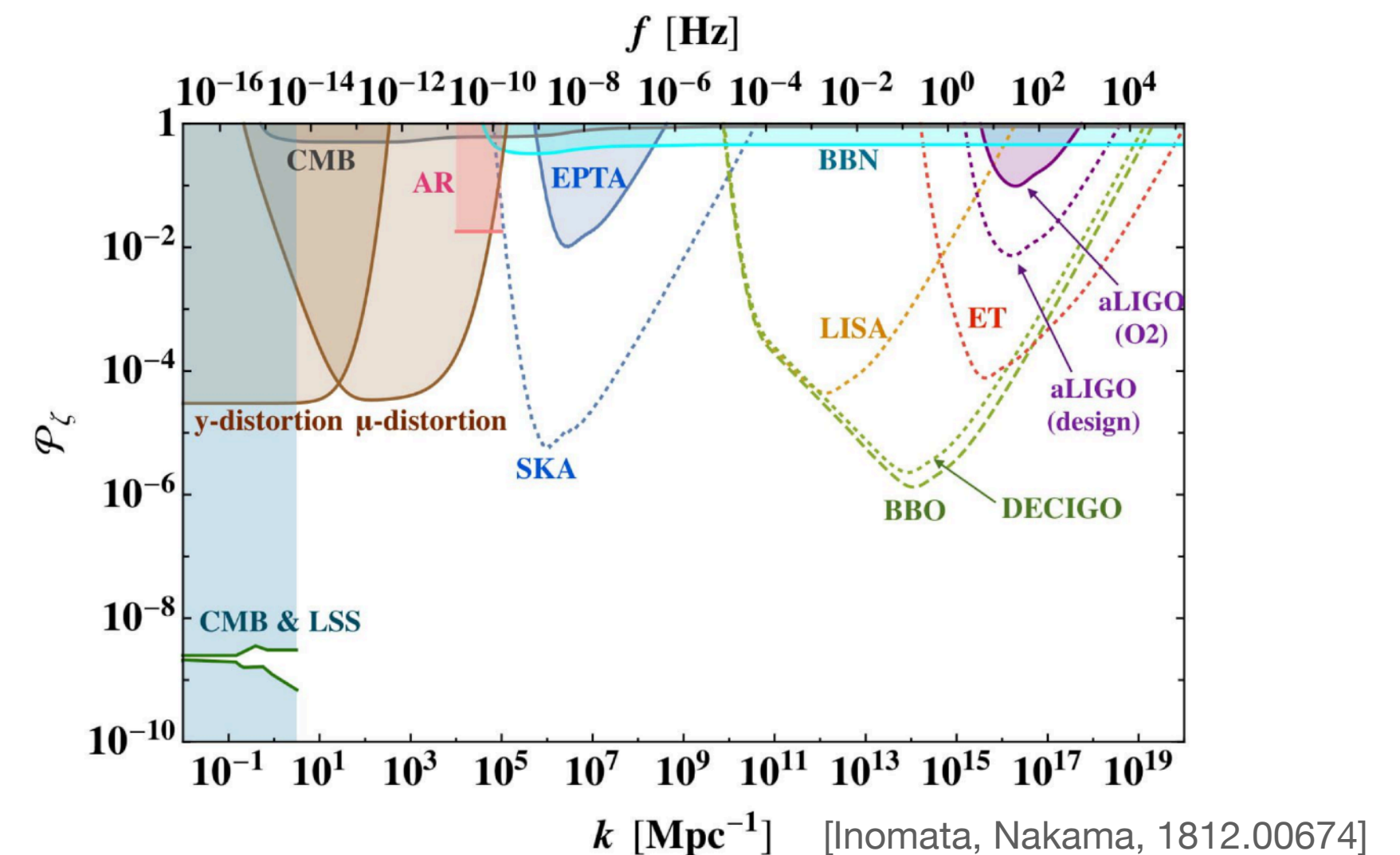
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Enhancement by Matter-Dominated Era?

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



$$\delta(\eta, k) \propto a(\eta) \quad \longleftrightarrow \quad \Phi = \text{const.}$$

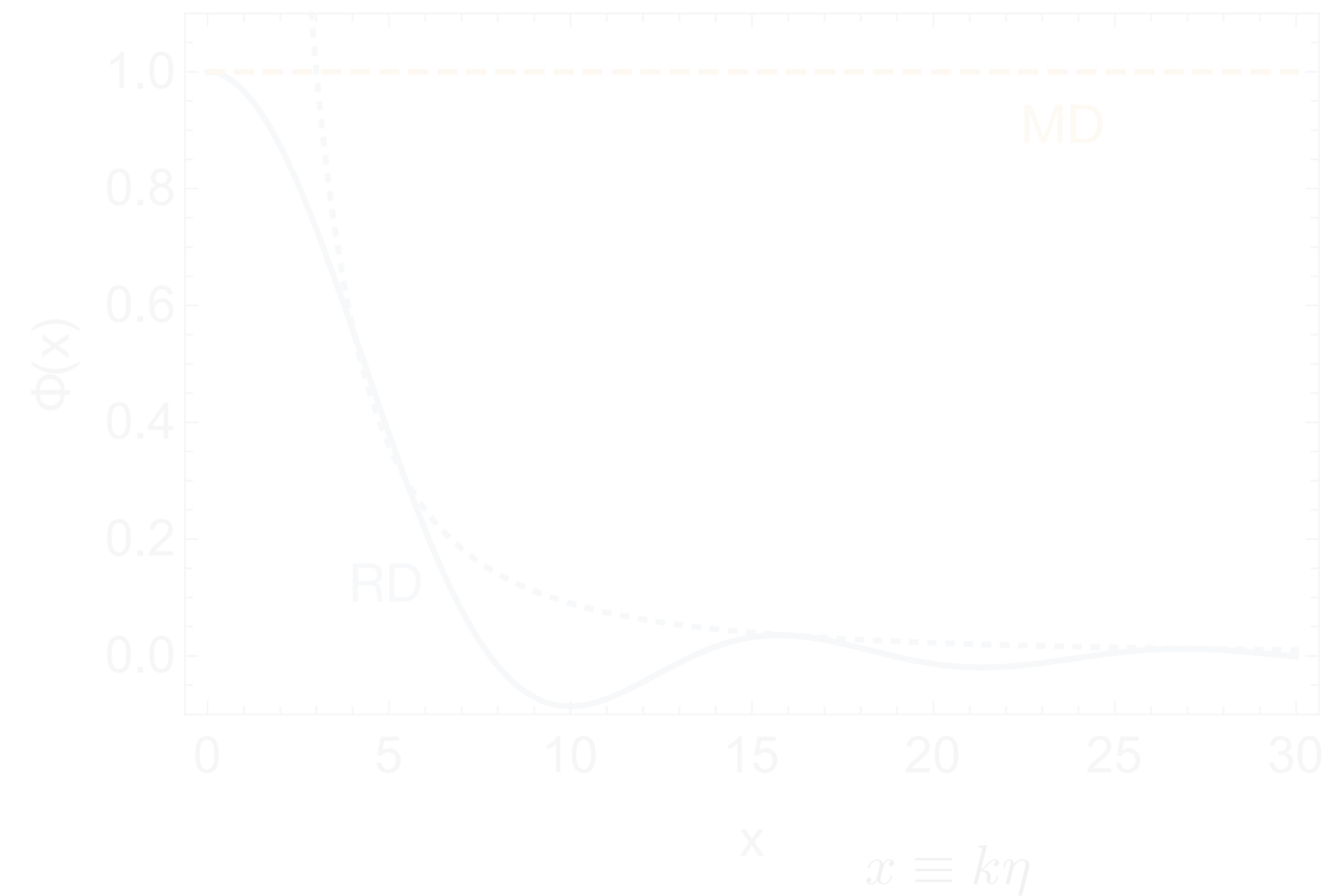
This makes the source term constant.

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

Constant metric distortion
(+ decaying mode)



Propagating GW



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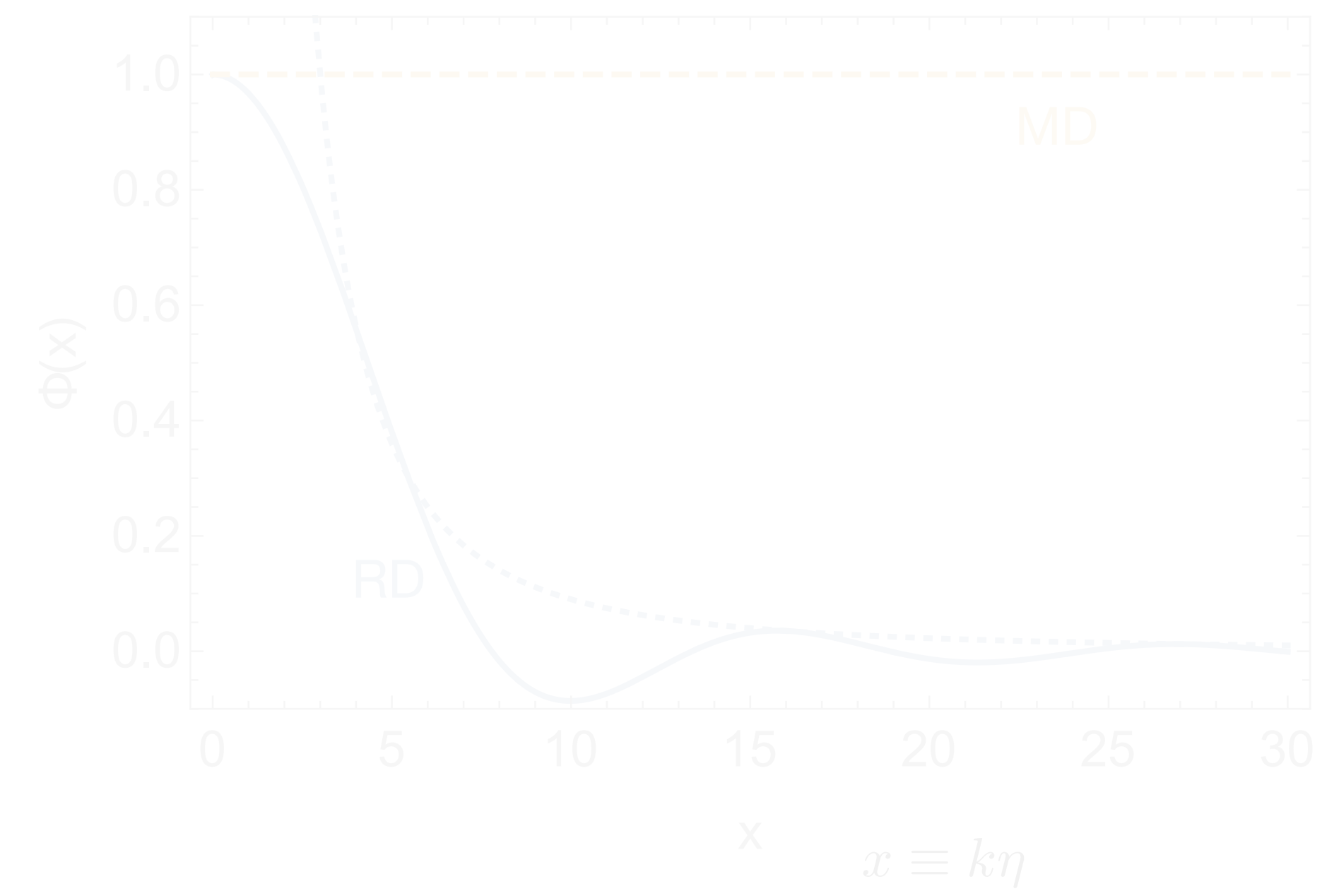
Coherent oscillations of scalar fields: inflaton, moduli, axion, curvaton, etc.
 Heavy (non-relativistic) matter: gravitino, modulino, PBH, Q-ball, etc.

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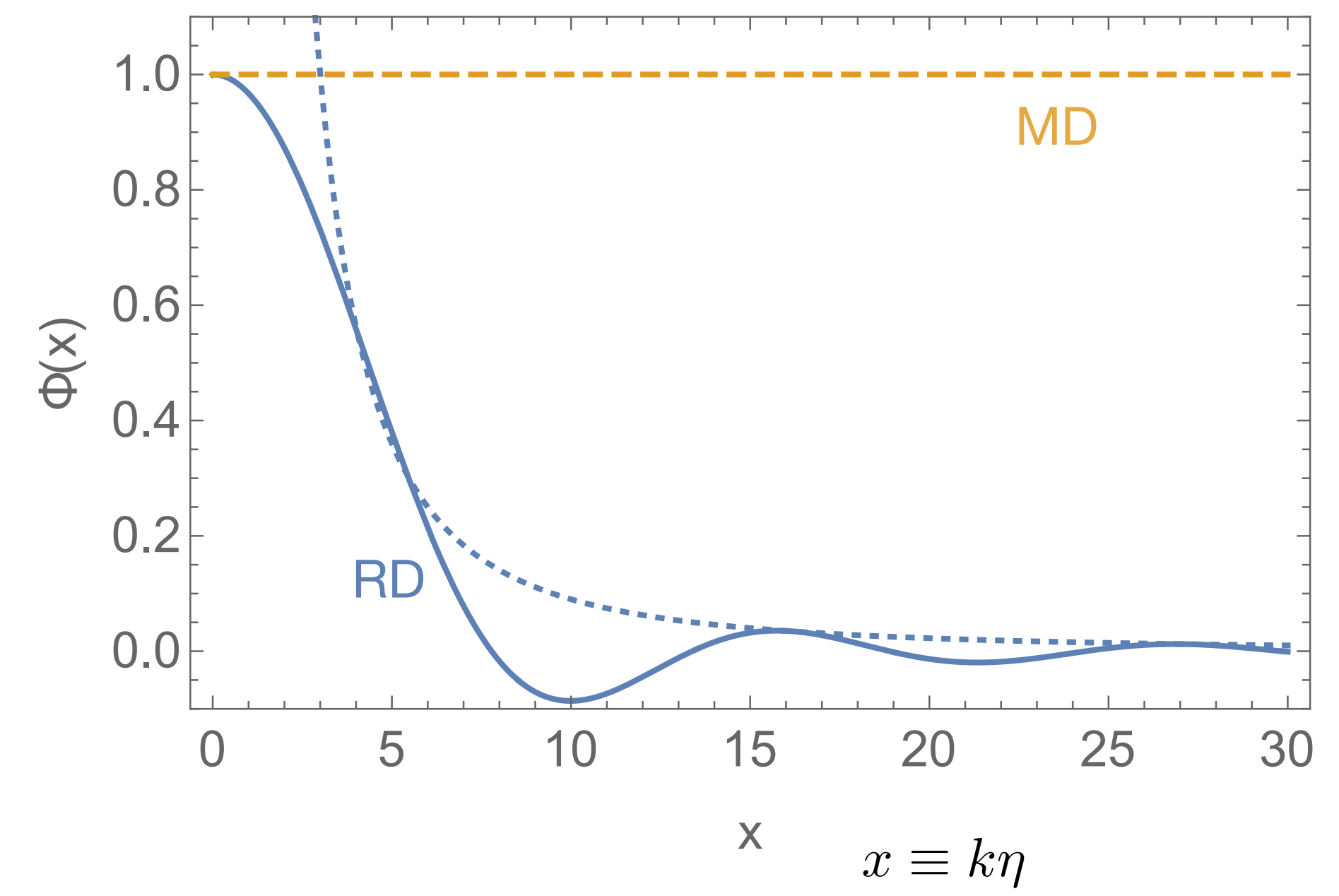
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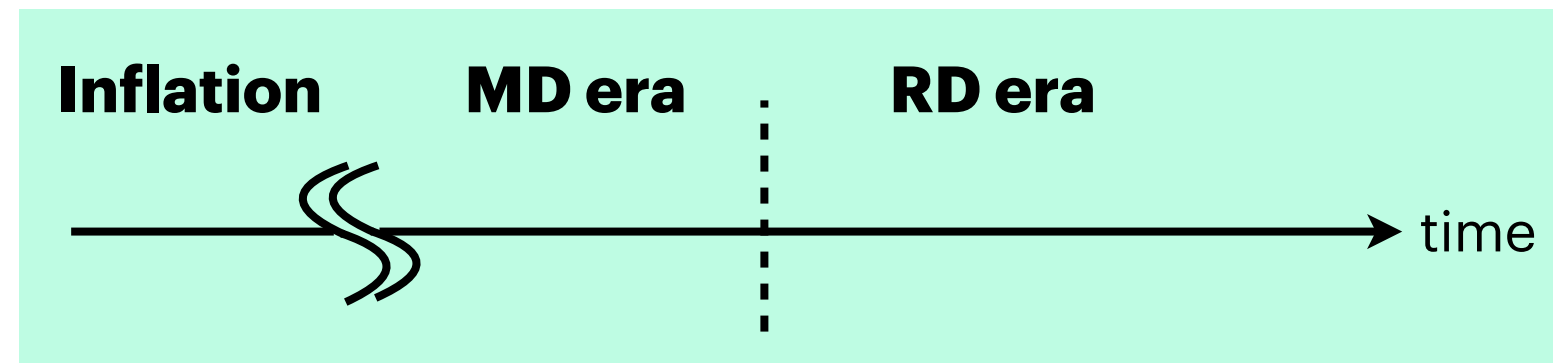
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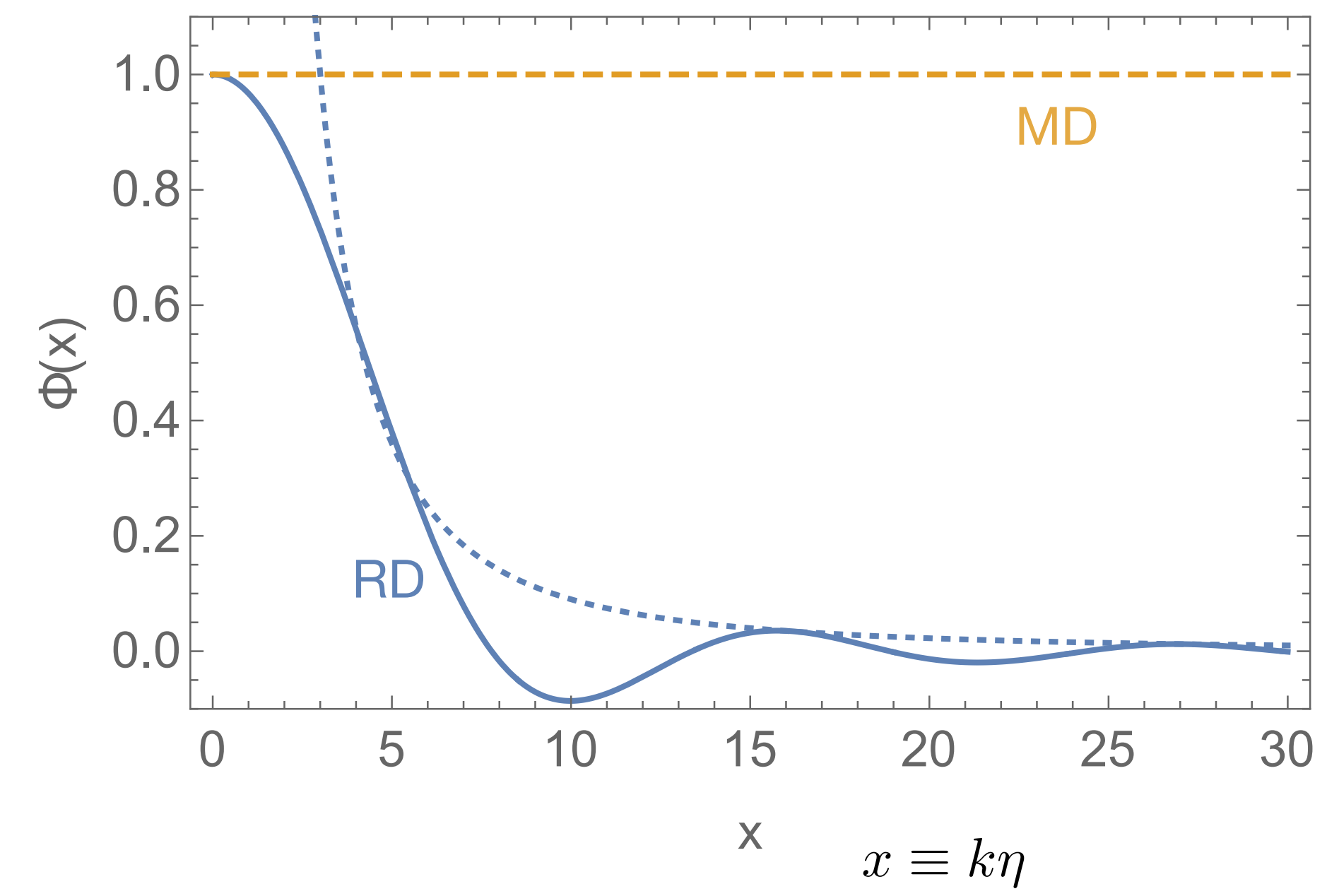
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We find that the conversion efficiency sensitively depends on the time-scale of the reheating transition!

Gradual (Standard) Reheating Transition

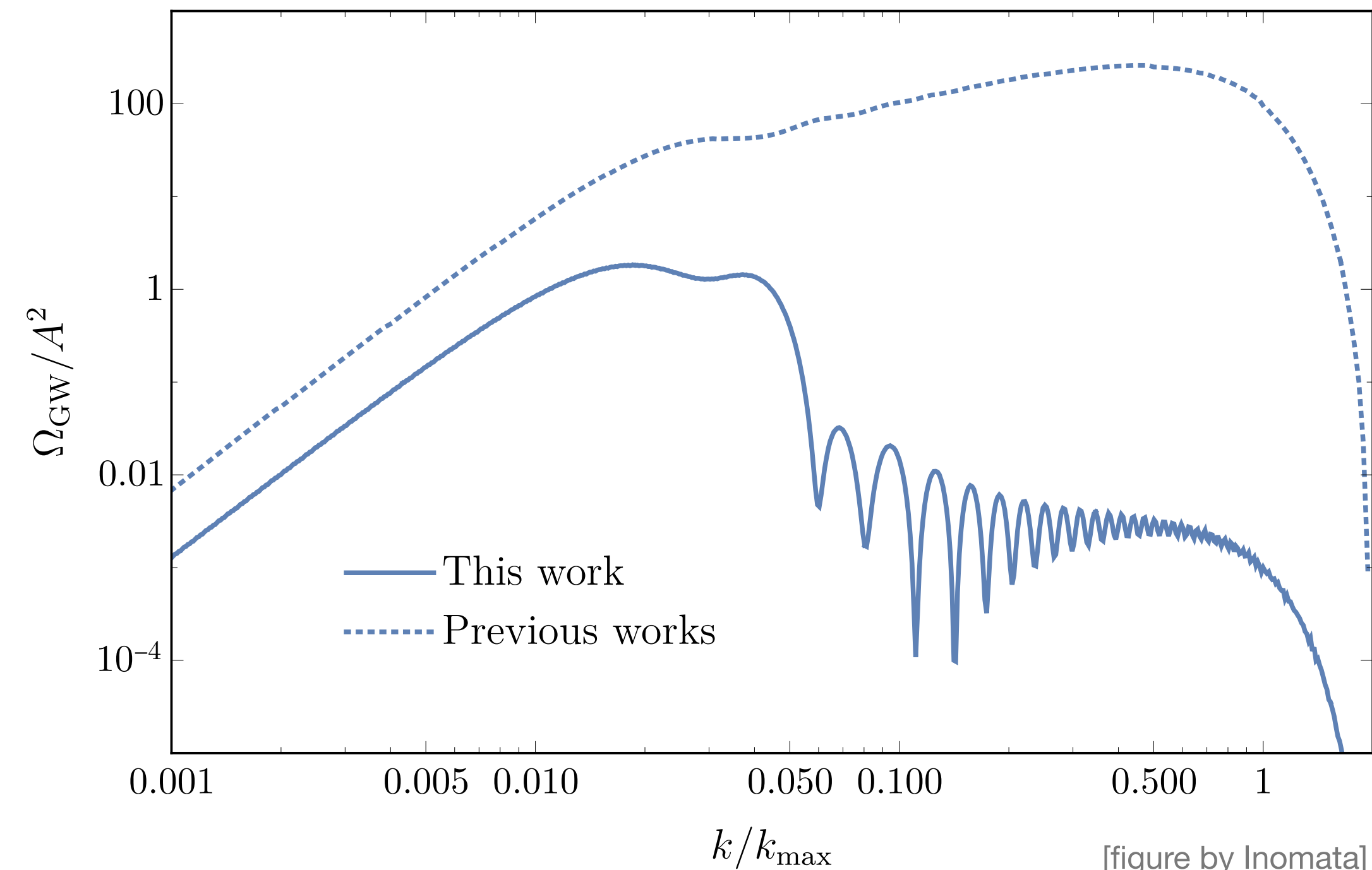
(Transition time scale) \gg (Period of relevant GW mode)

For the standard perturbative decay,

$$\Phi \sim \delta_{\text{matter}} \sim e^{-\Gamma t}$$

even after the matter-radiation equality for a while.

$$\Omega_{\text{GW}} \propto \mathcal{P}_h \propto \mathcal{P}_\Phi^2 \propto \Phi^4 \propto e^{-4\Gamma t}$$



Enhancement is spoiled significantly.

Sudden Reheating Transition

(Transition time scale) \ll (Period of relevant GW mode)

Just reproduce the previous results in the literature?

We find that [an omitted contribution](#) is actually dominant.

Produced **after** the MD era.

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Huge enhancement is possible.

Origin of the enhancement: $(k/\mathcal{H}_{\text{transition}}) \gg 1$

Interesting interplay between MD and RD eras!

- GWs are induced by fast oscillations of Φ .
- Φ is associated with the sound waves on the thermal bath.
- It is created by the decay of the field dominating in the MD era.

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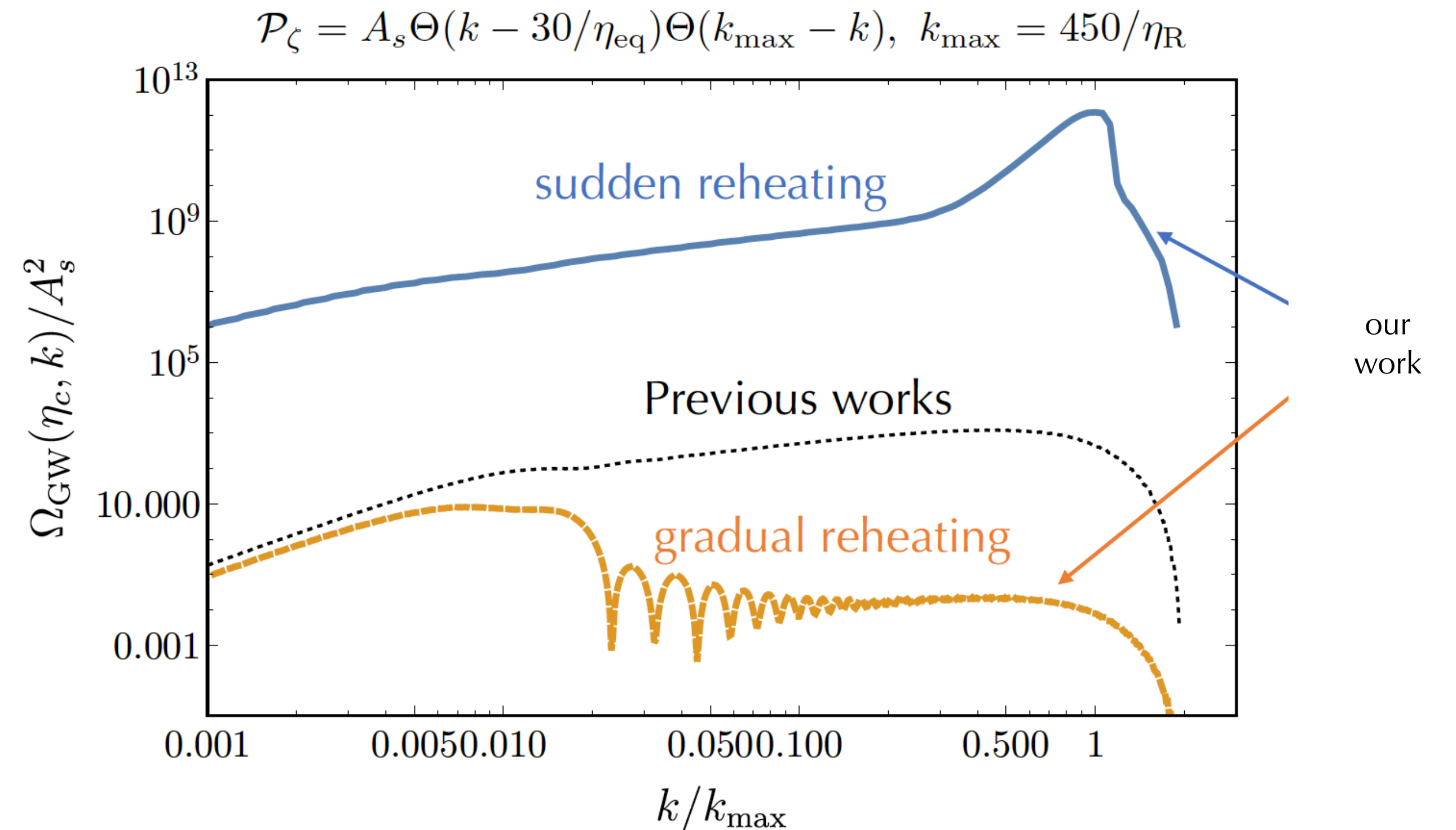
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[Modification of a figure by Inomata]

[Inomata, Kohri, Nakama, [Terada](#), 1904.12878]

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Poltergeist

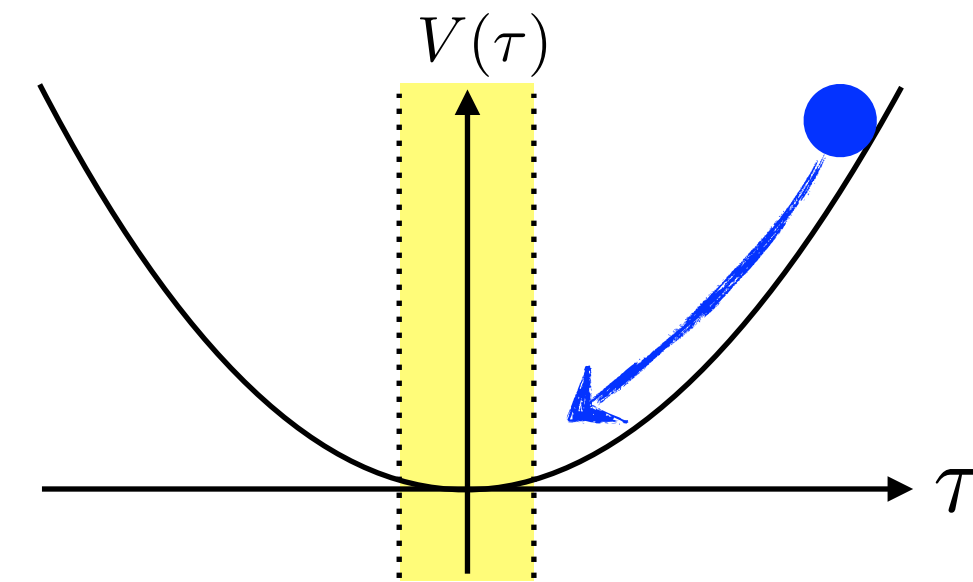
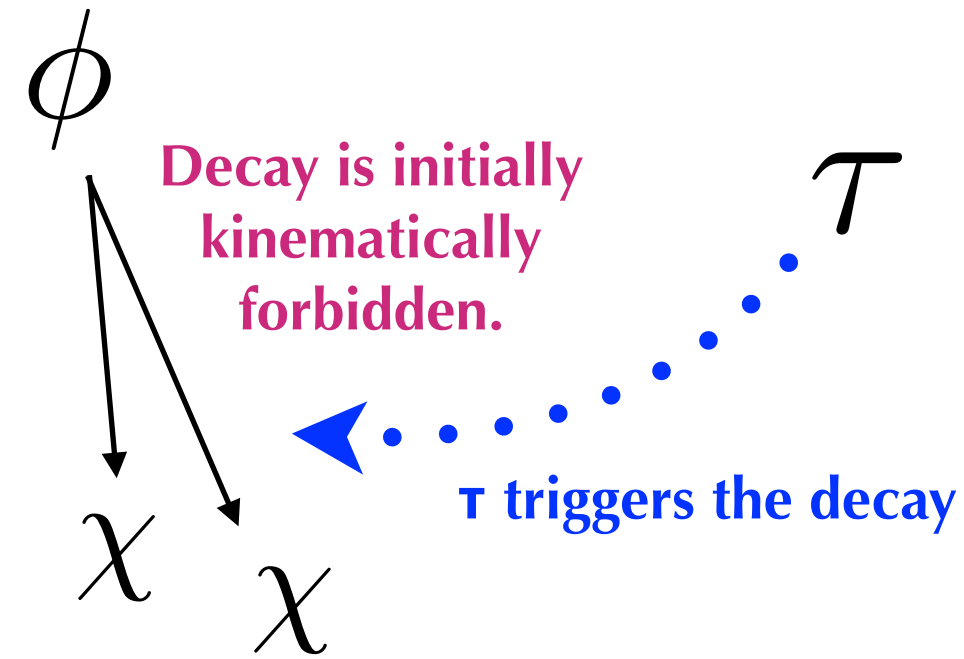
mechanism for gravitational wave production

• **Triggeron dynamics** (scalar-fields toy model)

[Inomata, Kohri, Nakama, Terada, 1904.12879]

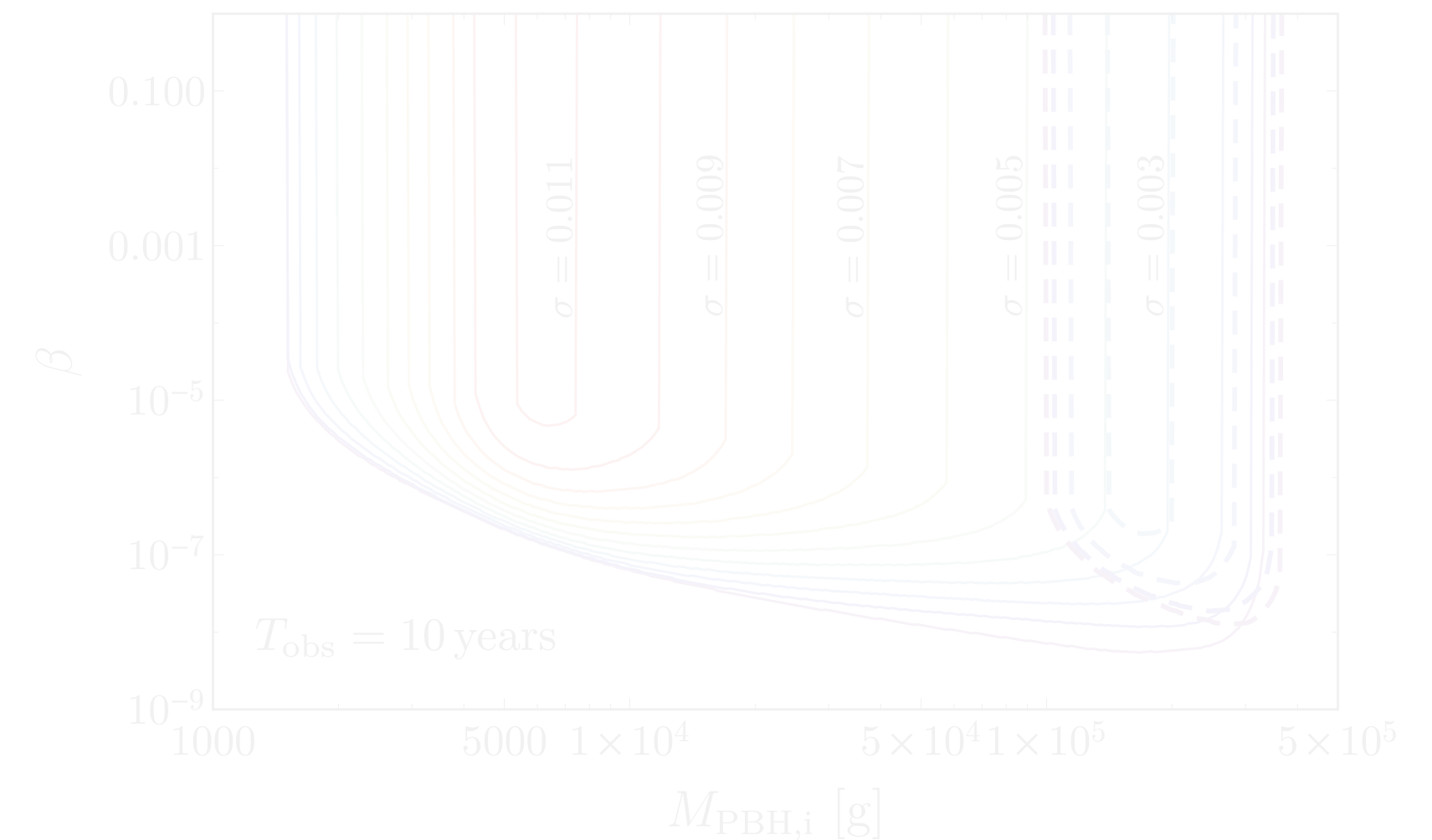
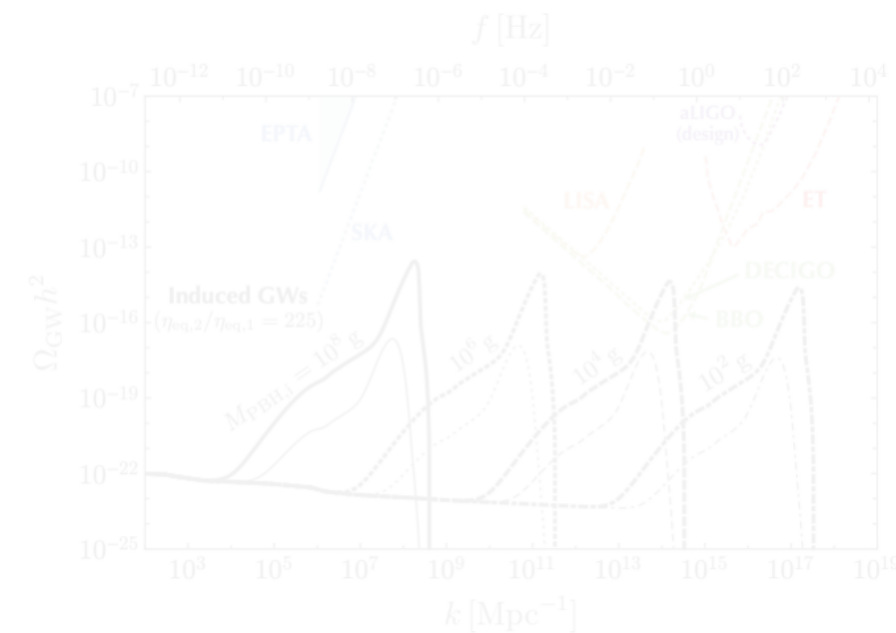
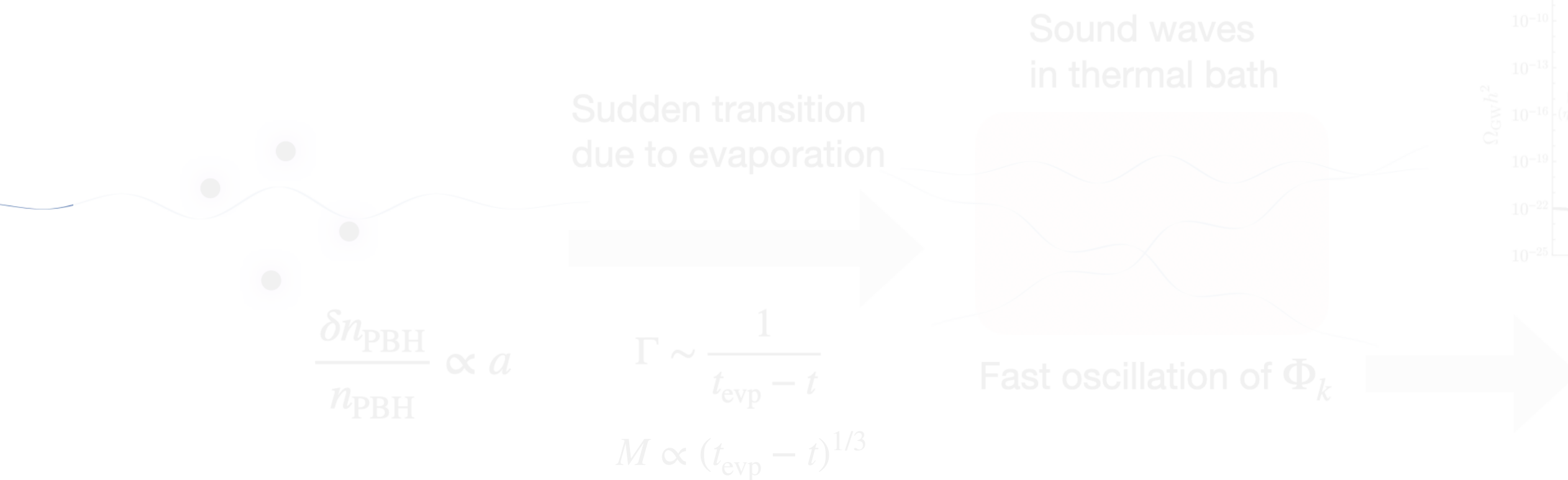
$$V = \frac{1}{2}M^2\phi^2 + \frac{1}{2}m^2\tau^2 + \frac{1}{4}\lambda\tau^2\chi^2 + \frac{c}{2}M\phi\chi^2$$

τ-dependent mass of χ



• **PBH domination scenario** (narrow mass function)

[Inomata, Kawasaki, Mukaida, Terada, Yanagida, 2003.10455]



Polttergeist

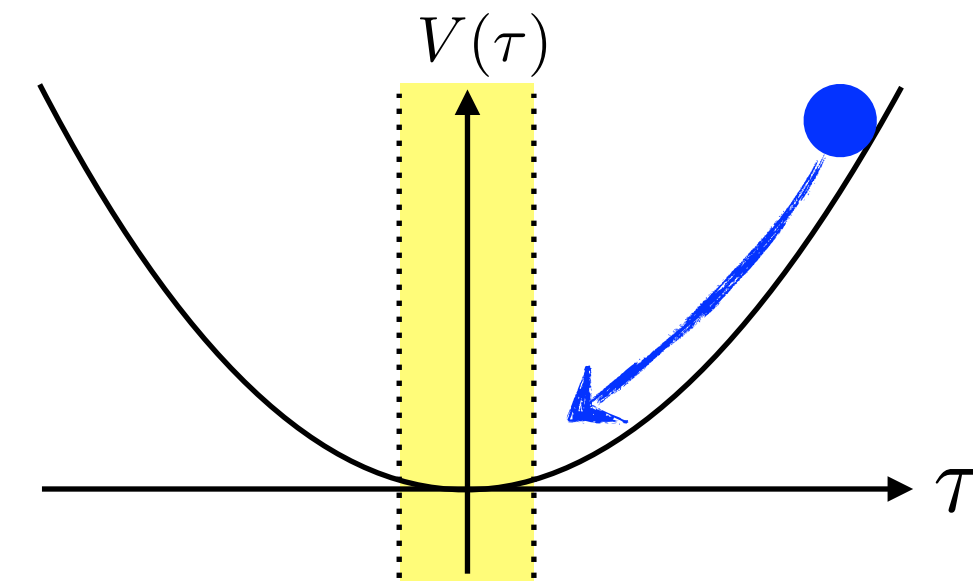
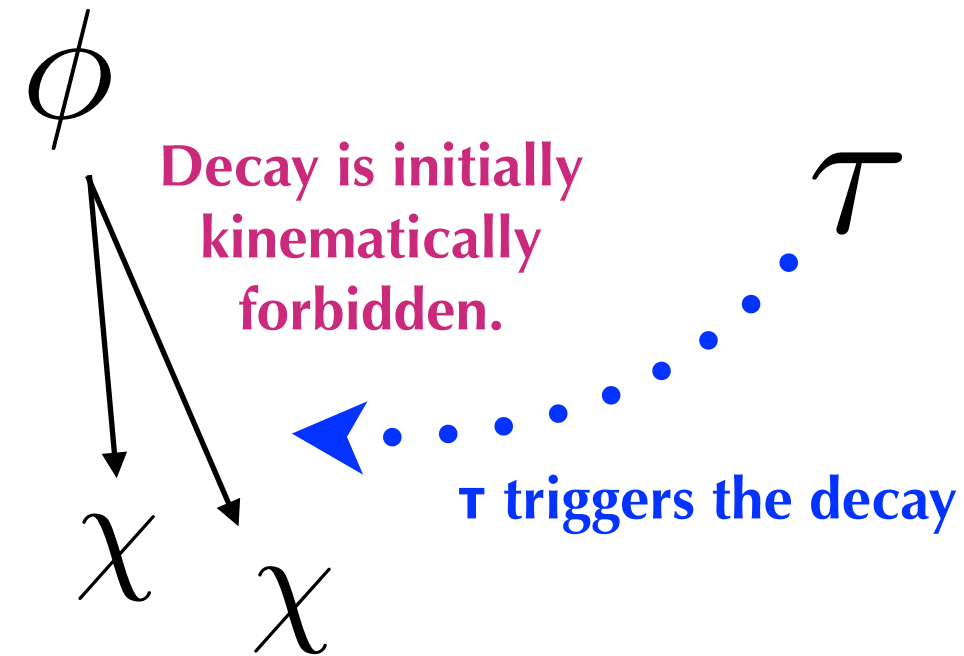
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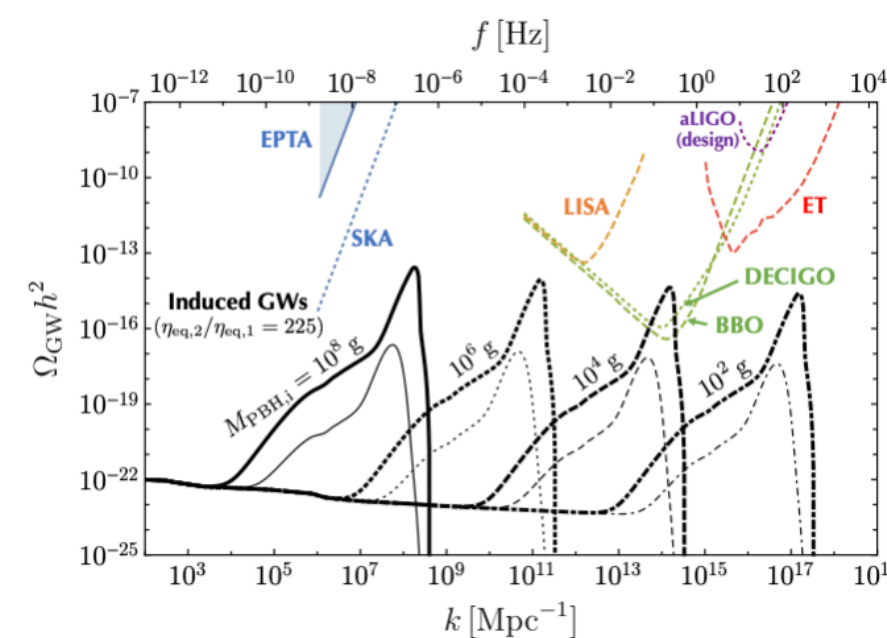
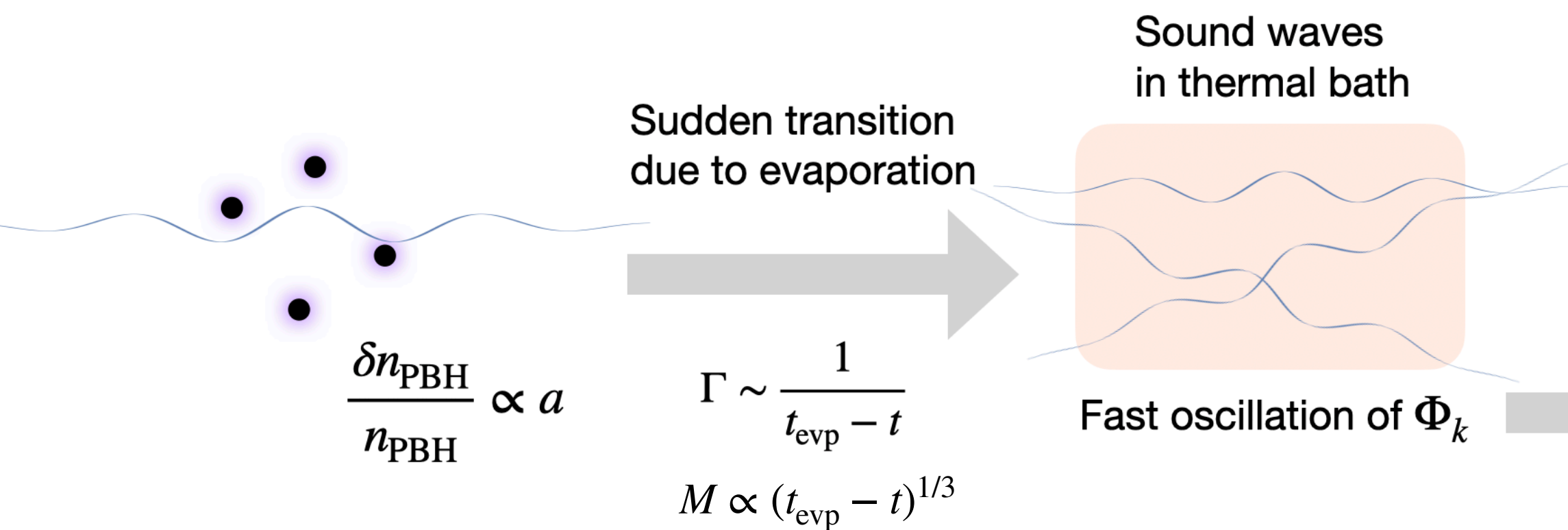
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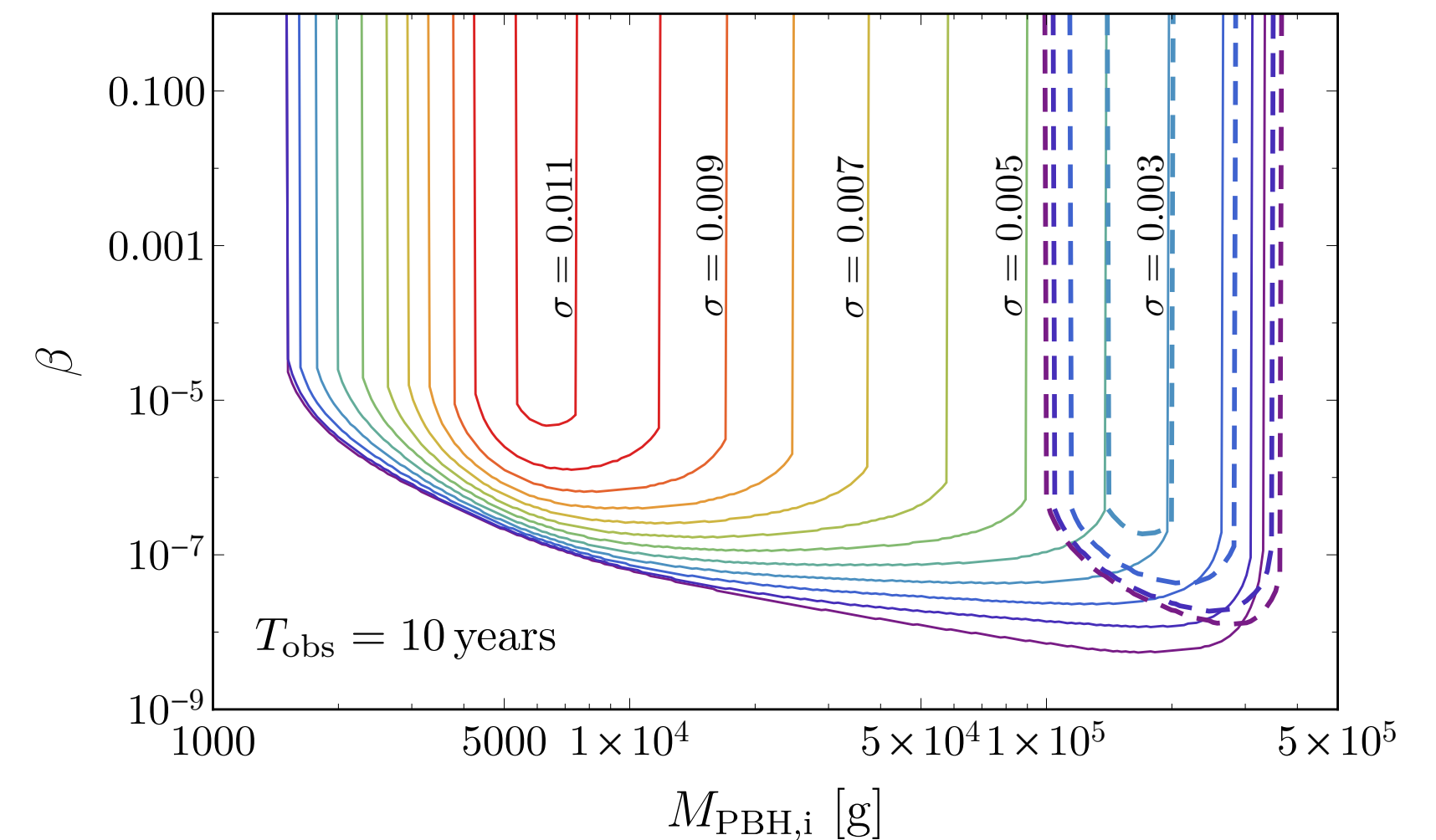


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(Resonant) production of 2nd-order GWs



Summary

- Curvature-induced gravitational waves (GWs) can probe
 - small-scale perturbations
(information on inflaton potential away from the CMB scale; relevant for PBH scenarios)
[Saito, Yokoyama, 0812.4339; 0912.5317]
 - dynamics of reheating transition as well as reheating temperature
- The strength of the induced GWs in a scenario with an early MD era sensitively depends on the time scale of the reheating transition.
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