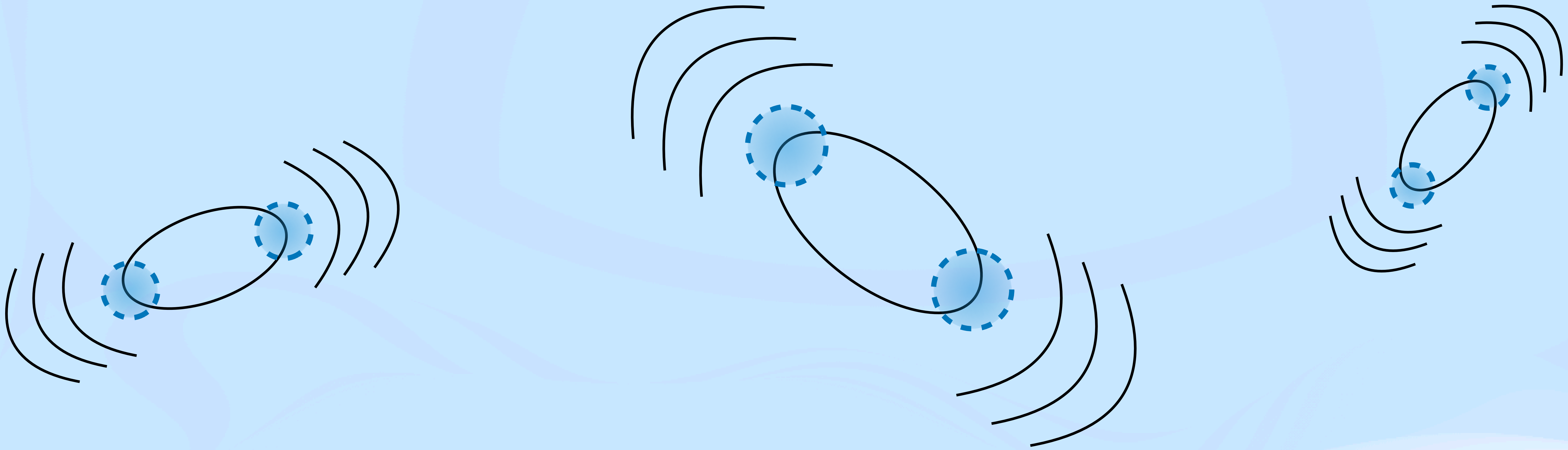


Gravitational Waves from the Early Universe:

A Primordial Black Hole Perspective

Xinpeng Wang (Kavli IPMU, The University of Tokyo)
In collaborations with:
MISAO SASAKI, Kazunori Kohri (KEK/NAOJ), Alexander Kusenko (UCLA), Yifan Lu (UCLA), Zachary S.C. Picker (UCLA), Masahide Yamaguchi (IBS), Tsutomu Yanagida (IPMU), Ying-li Zhang (Tongji).

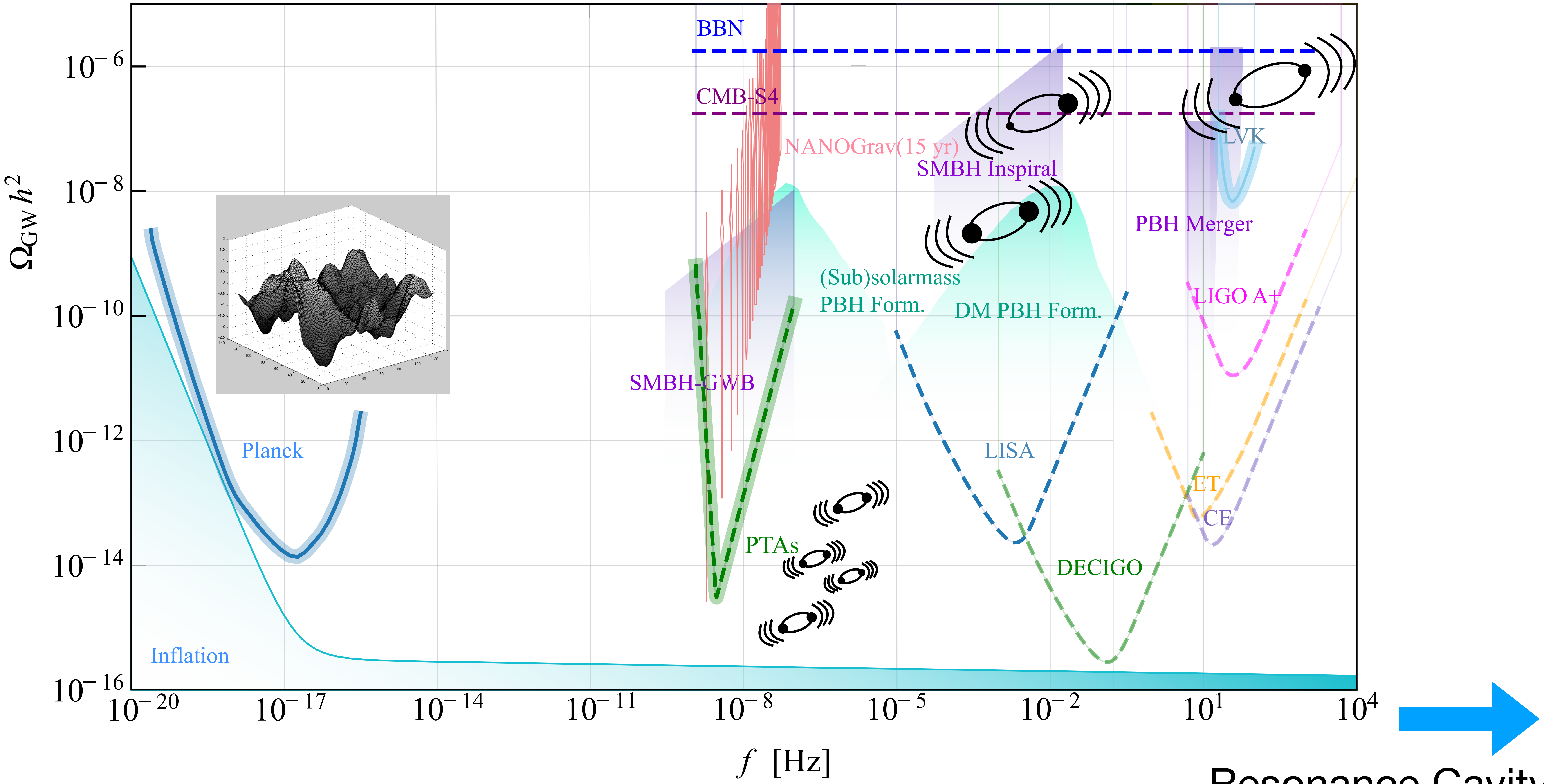
Xinpeng Wang (Kavli IPMU)

Gravitational Waves : A Great Probe to the Dark

Primordial Tensor Perturbations

Binary Supermassive Black Holes? Early Universe Cosmology?

Compact Binary Coalesces Astrophysical? Primordial?



Resonance Cavity

Xinpeng Wang (Kavli IPMU)

~~Gravitational Waves~~: A Great Probe to the Dark

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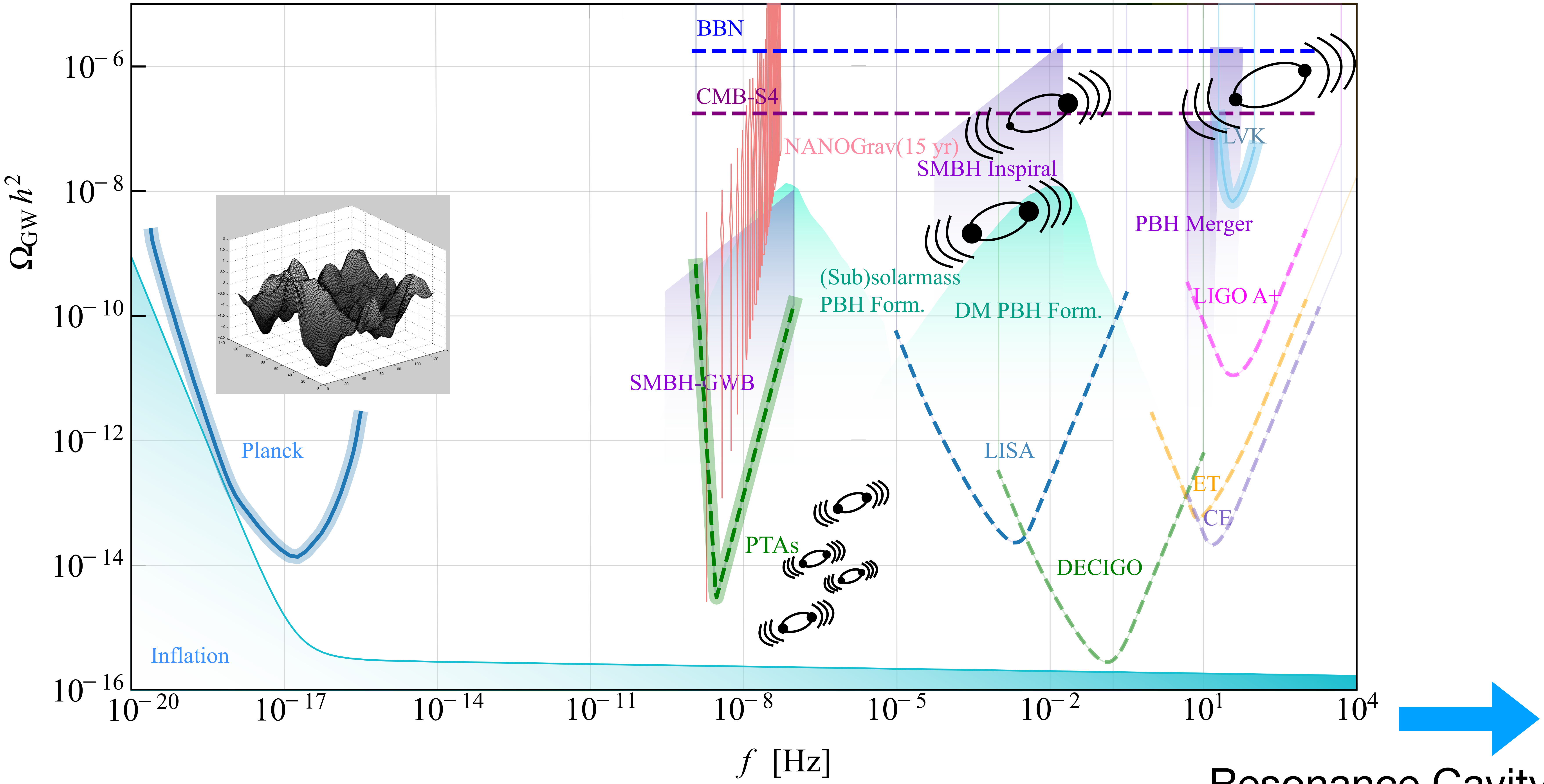
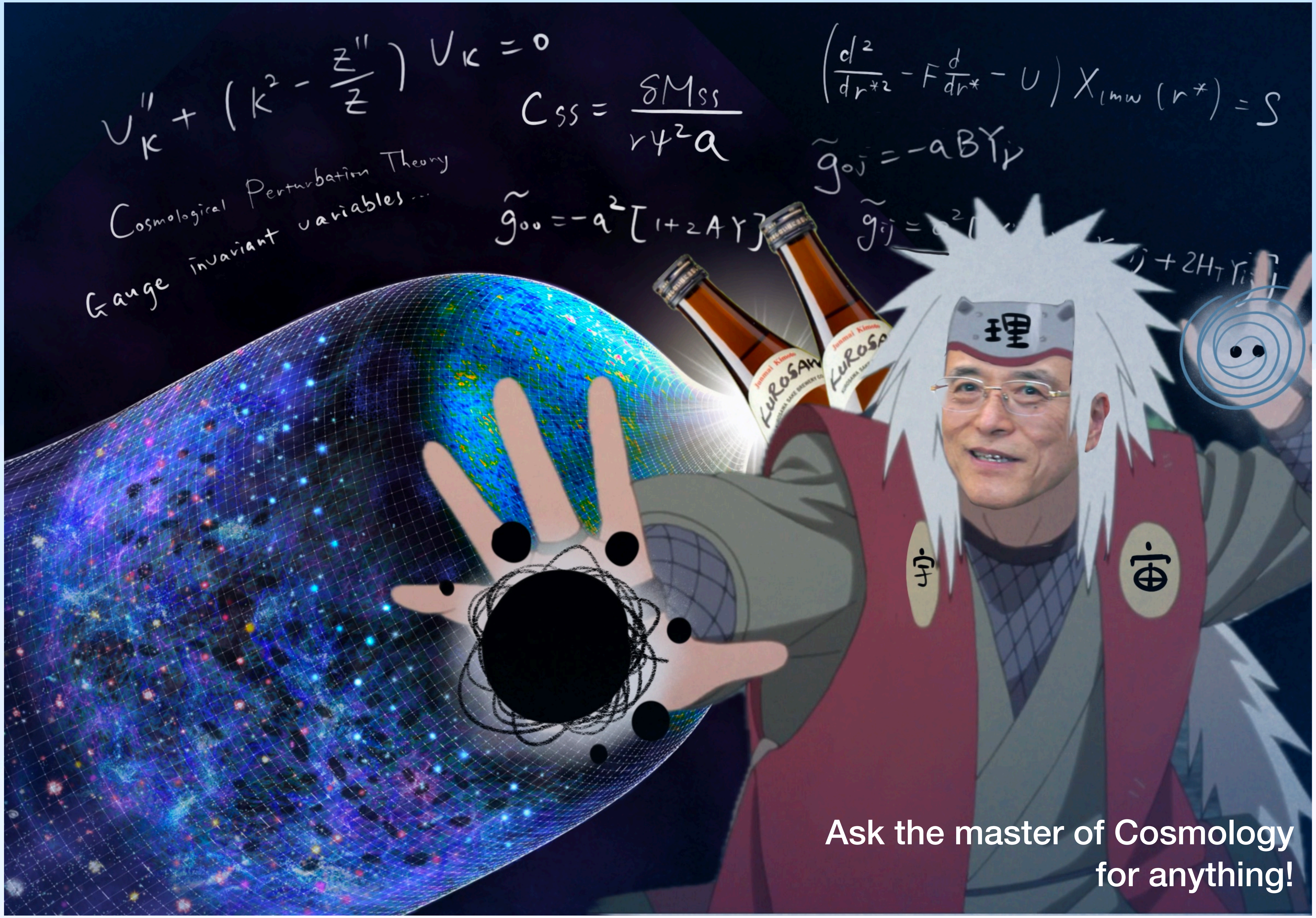


Resonance Cavity

Xinpeng Wang (Kavli IPMU)

MISAO SASAKI: A Great Probe to the Dark

- Cosmological Perturbation Theory
- (Primordial) Black Holes
- Gravitational Waves
- …
- Alcohol



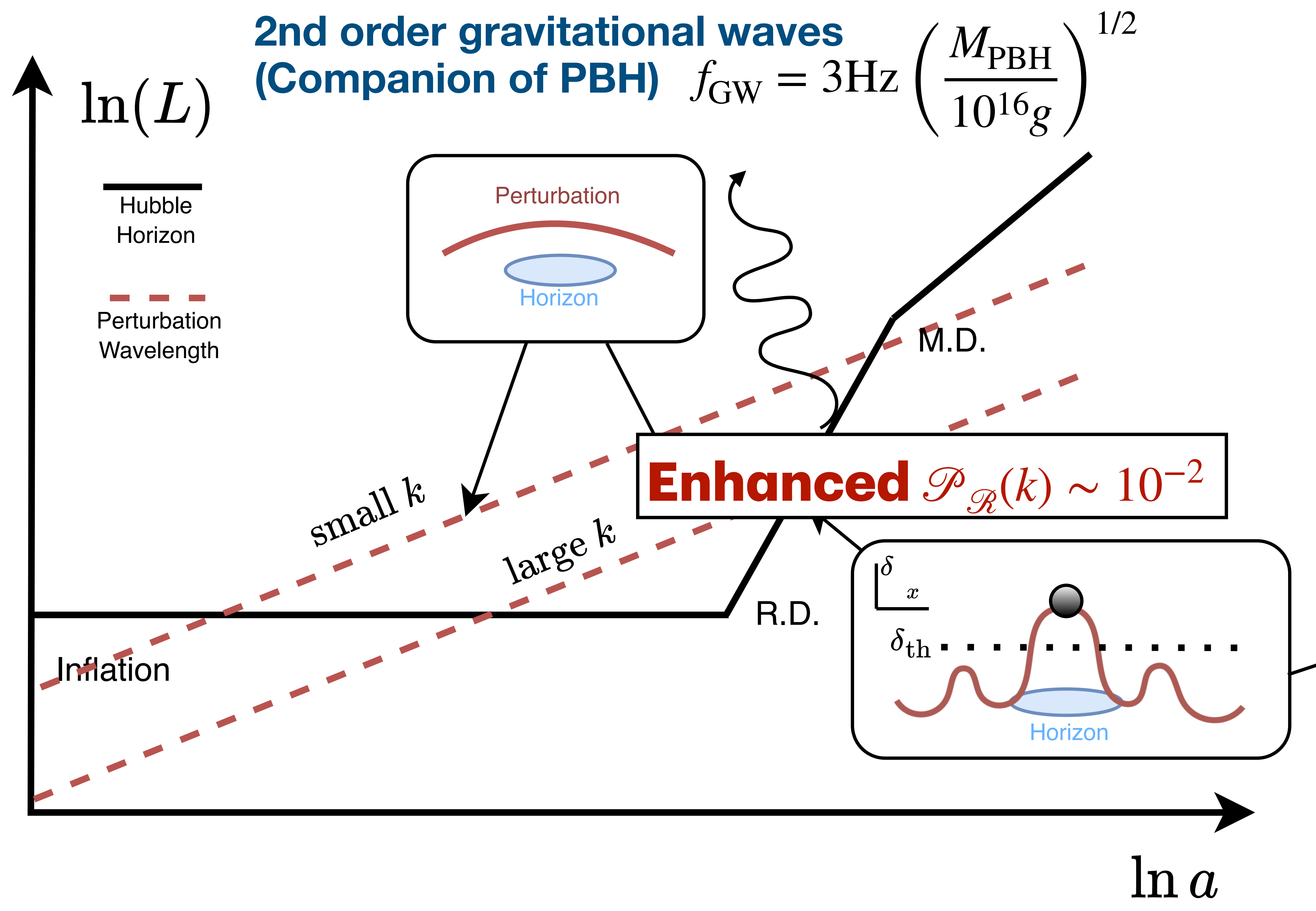
I. Primordial Black Holes and Induced Gravitational waves from Inflation

Based on 2404.02492, 2412.16463, 2504.12035, 2505.09337, 2506.06797 + upcoming works

Xinpeng Wang (Kavli IPMU)

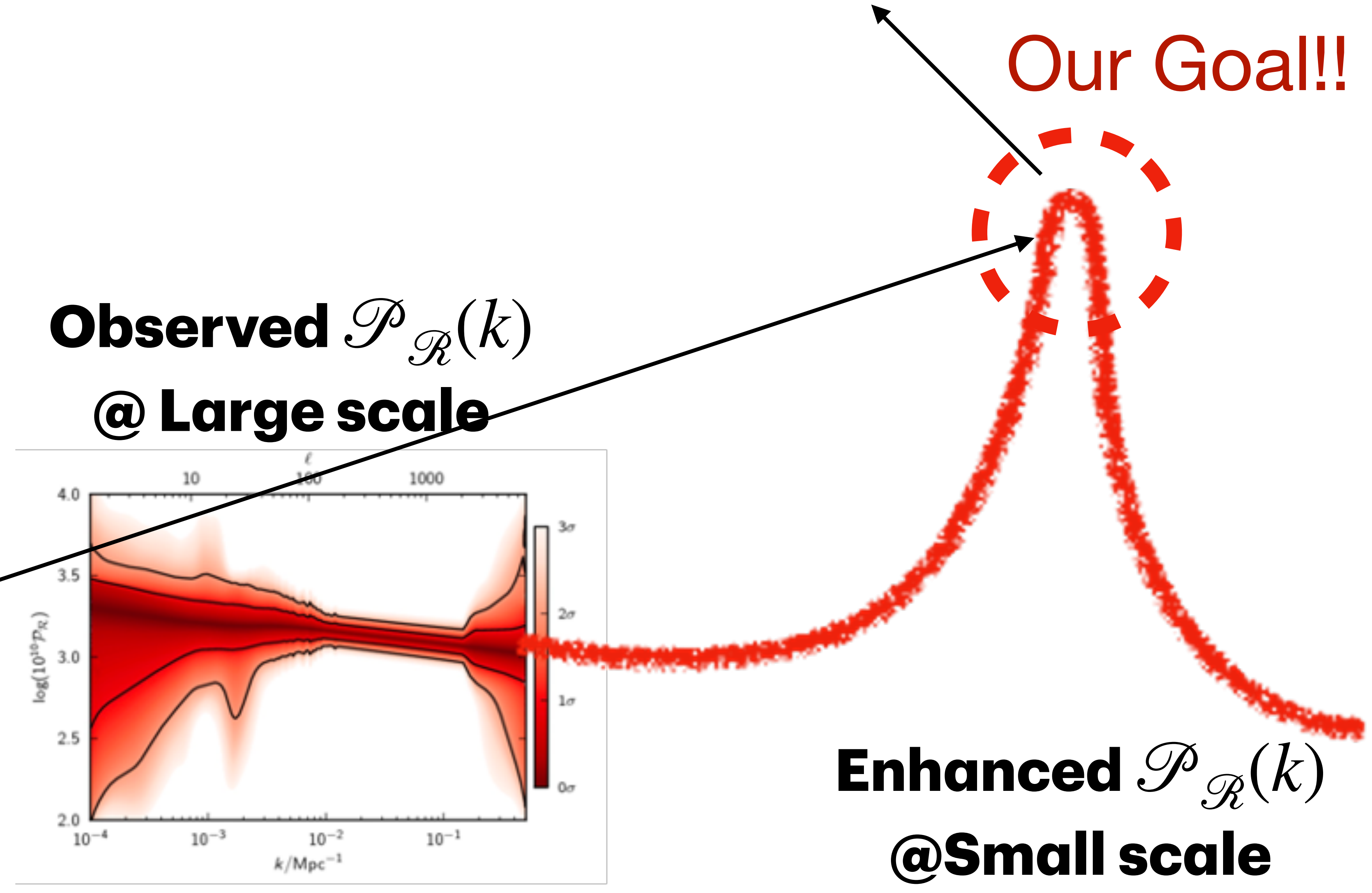
Primordial Black Hole seeded from Inflation

Hubble Radius VS scale factor



$$\delta \propto k^2 R^2 \mathscr{R} \gtrsim \delta_{\rm th}$$

Hubble size region with $\delta \sim \mathcal{O}(1)$ collapses to form BH



The Planck Collaboration, 2018 (1807.06209)

Amplifying the Superhorizon Perturbations (Multi Field)

Contributions of the iso-curvature fields

R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

$$S_J = \int d^4x\sqrt{-g}\,\left[\frac{M_{\rm pl}^2}{2}f(R,\chi) - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right],$$

$$f(R,\chi) = R + \frac{R^2}{6M^2} - \frac{\xi R}{M_{\rm pl}^2}(\chi - \boxed{\chi_0})^2,$$

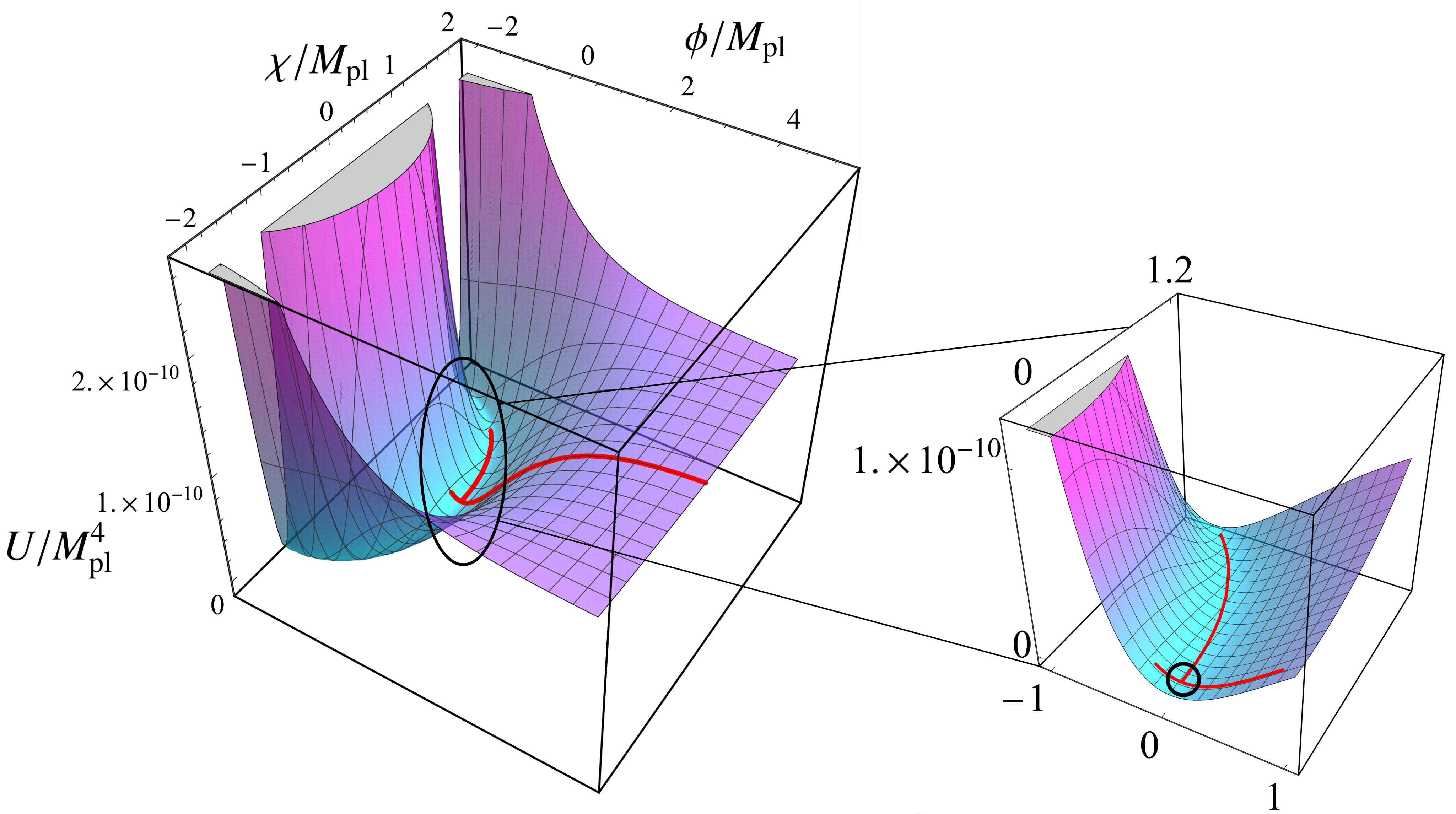
To break Z_2 symmetry

Avoid: 1)DW overproduction 2)eternal inflation

$$V(\chi) = V_0 - \frac{1}{2}m^2\chi^2 + \boxed{\frac{1}{4}\lambda\chi^4}.$$

To end inflation

The potential is bounded from below



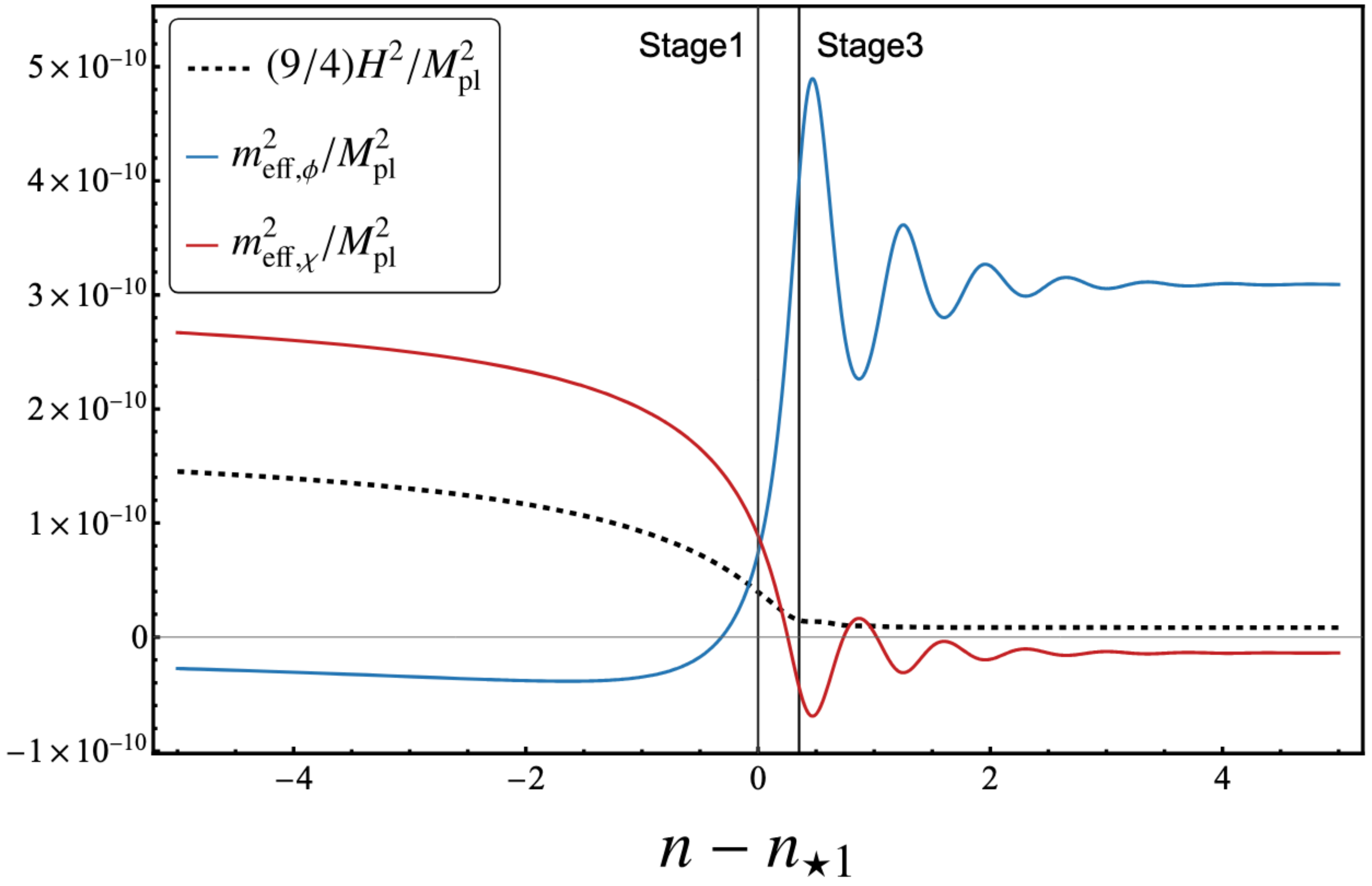
Saddle point

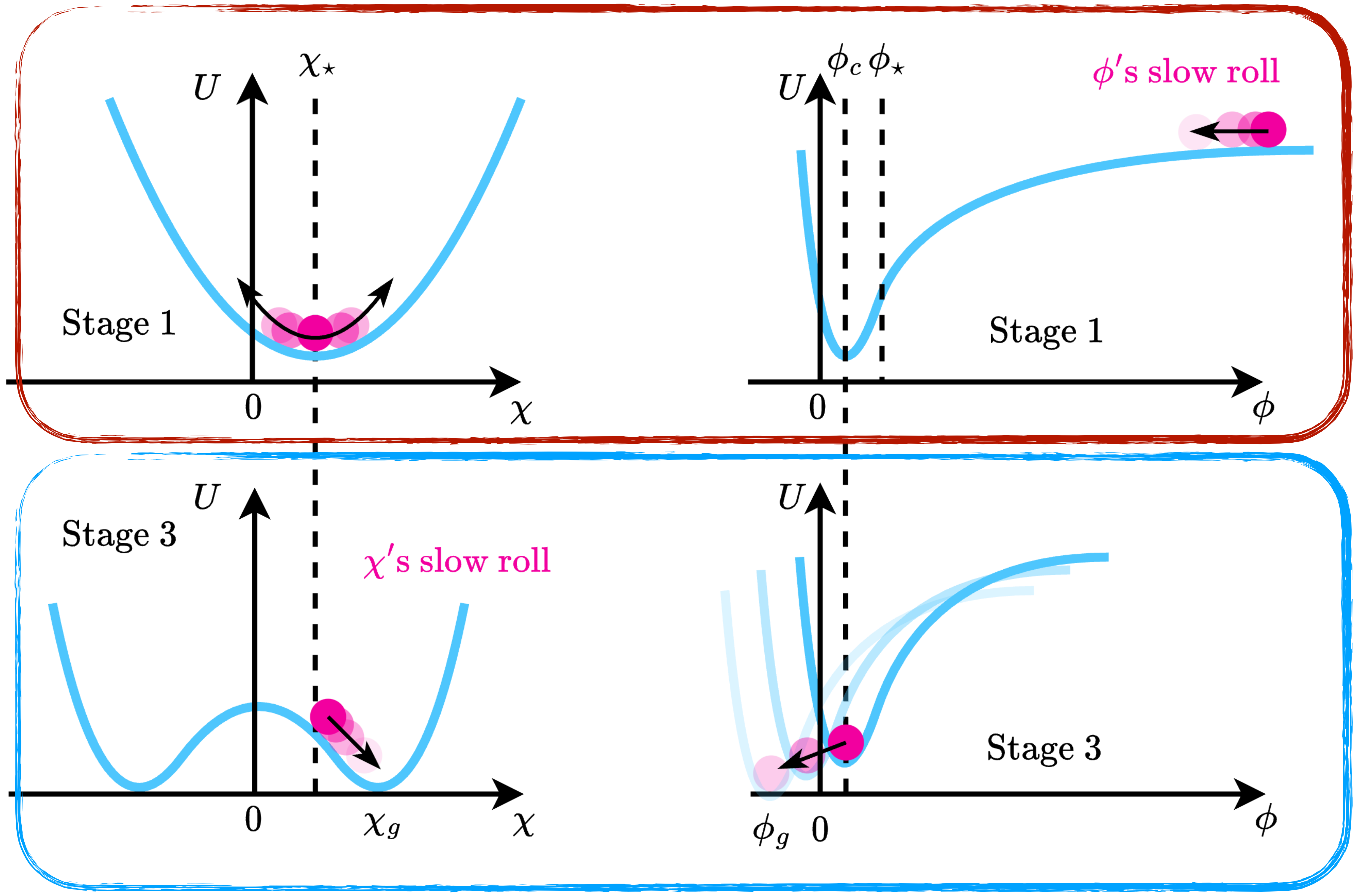
Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

The effective mass of two fields

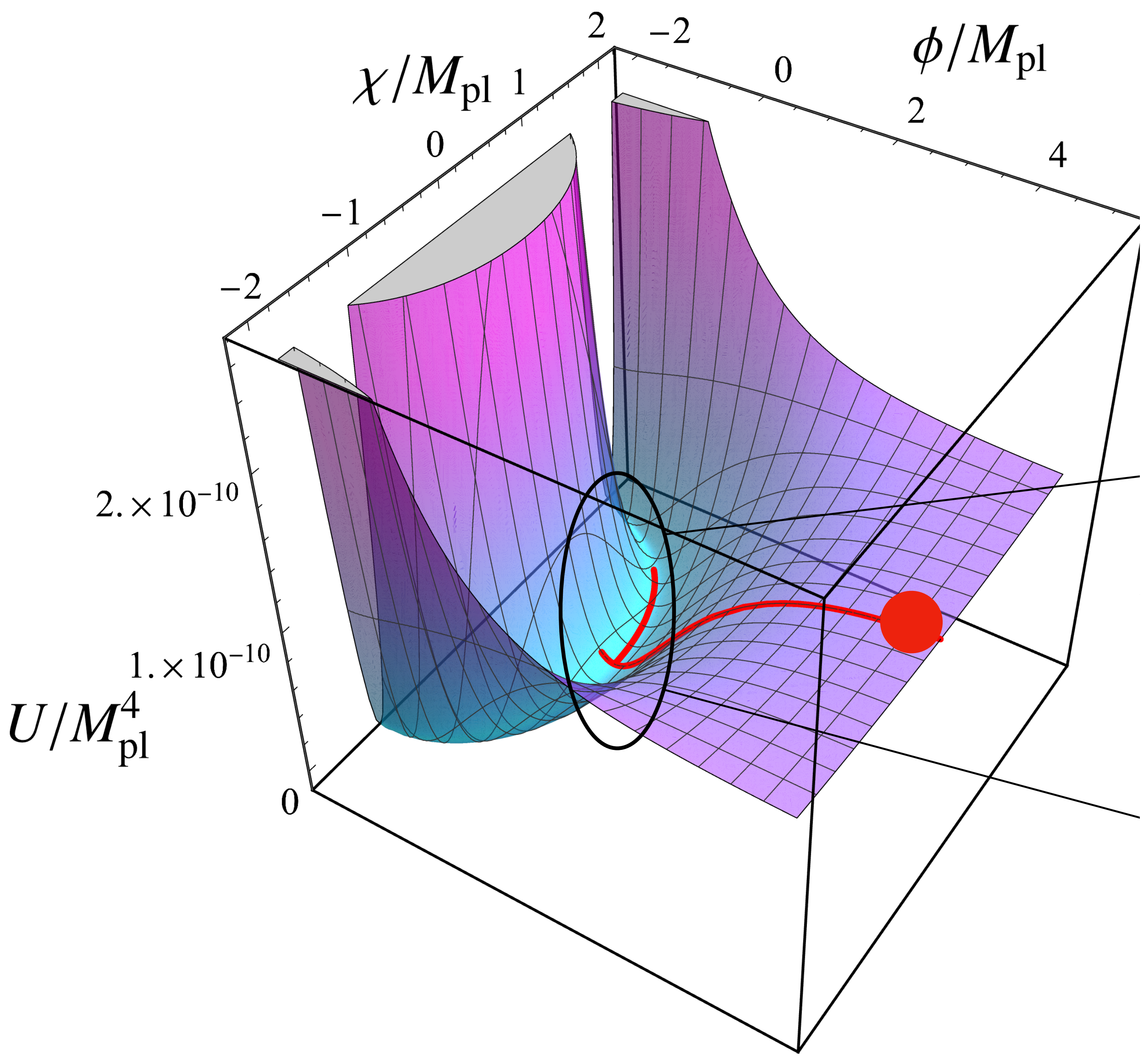


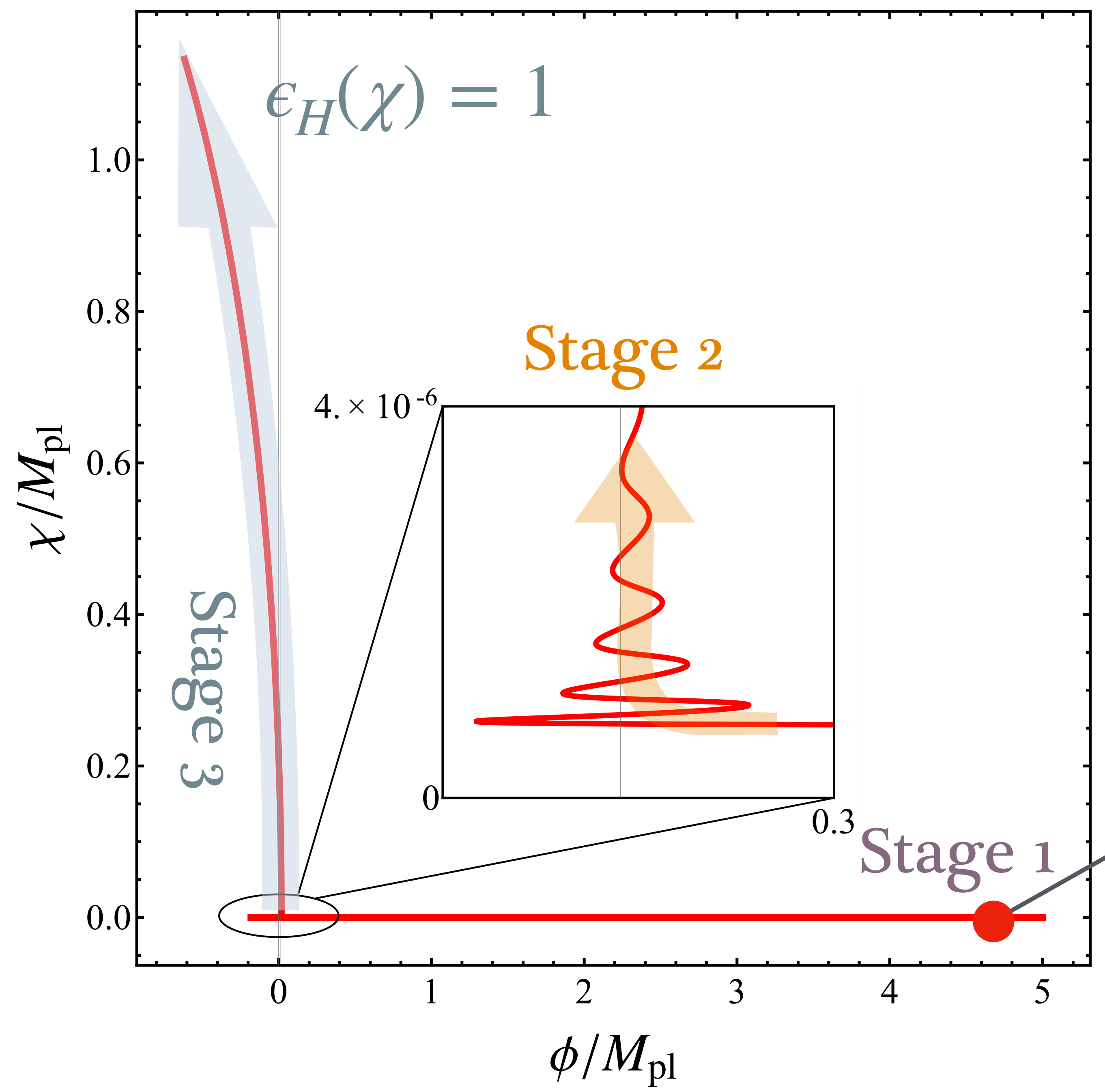


Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)





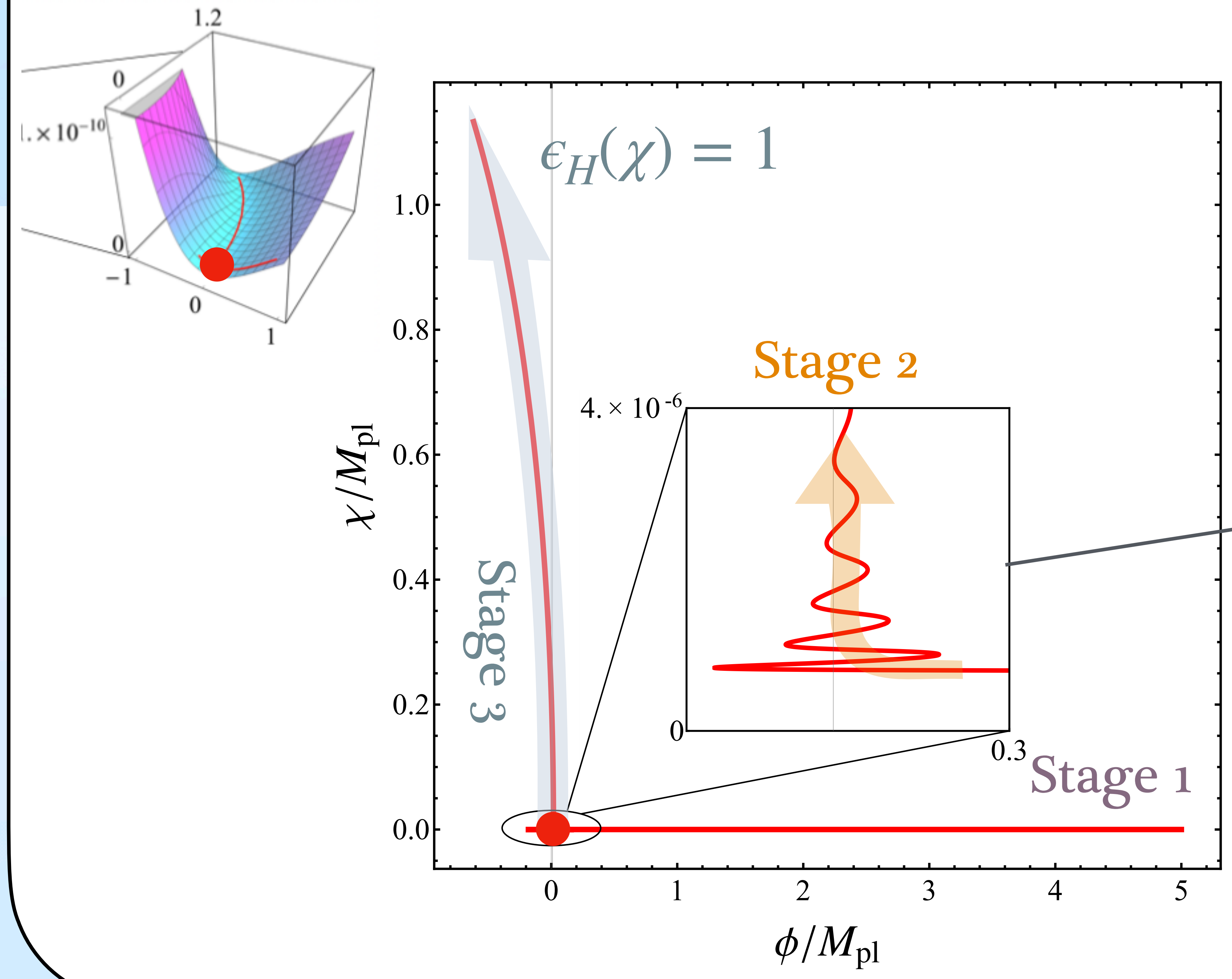
ϕ dominated inflation

Inflaton rolls along ϕ direction (R^2 **inflation**), χ behaves like a damped* oscillator around χ_0.

Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

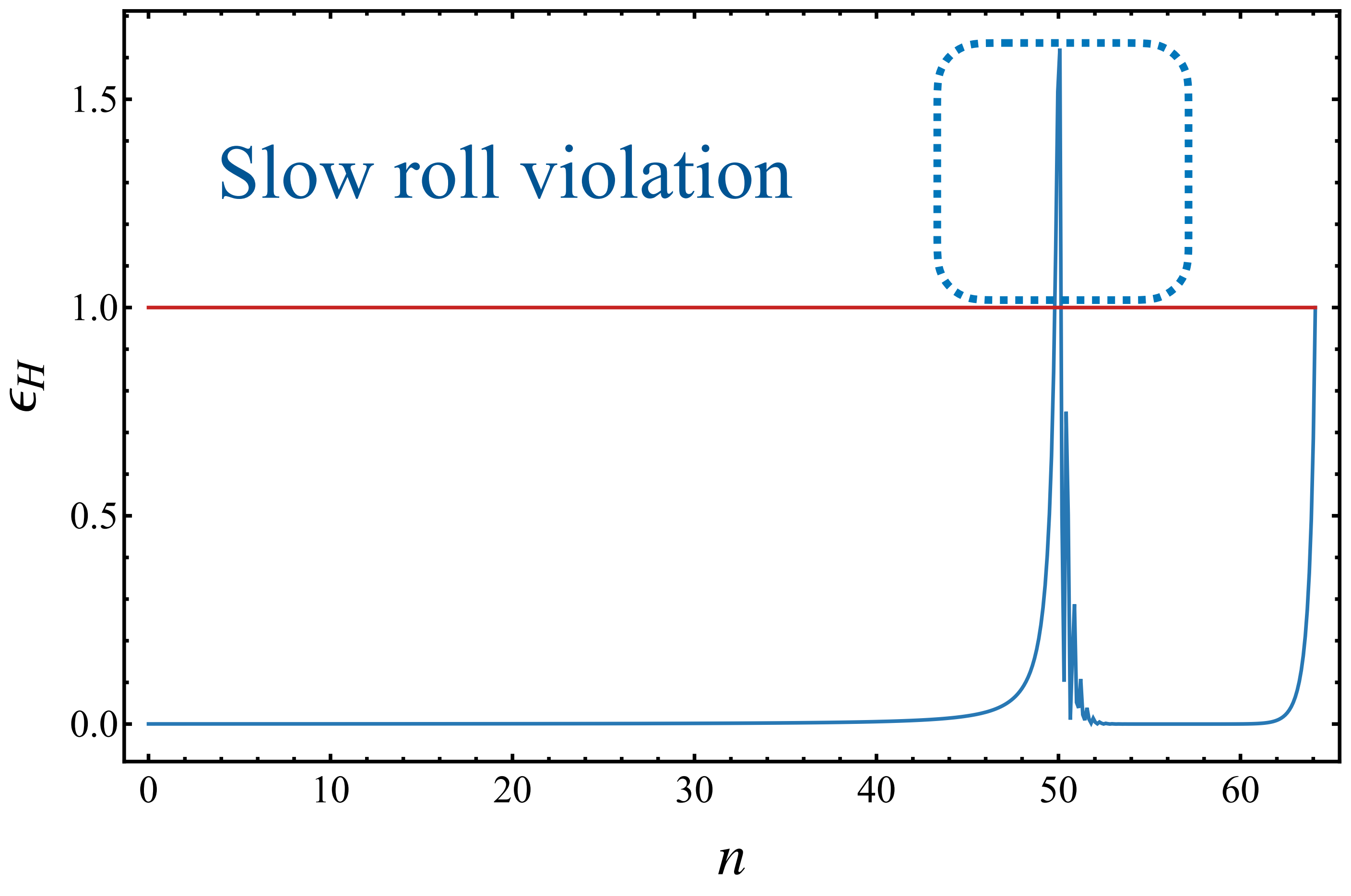
XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)



Baby R^2 reheating

The slow roll is shortly violated ($\epsilon_H > 1$) by inflaton's oscillation along ϕ direction.

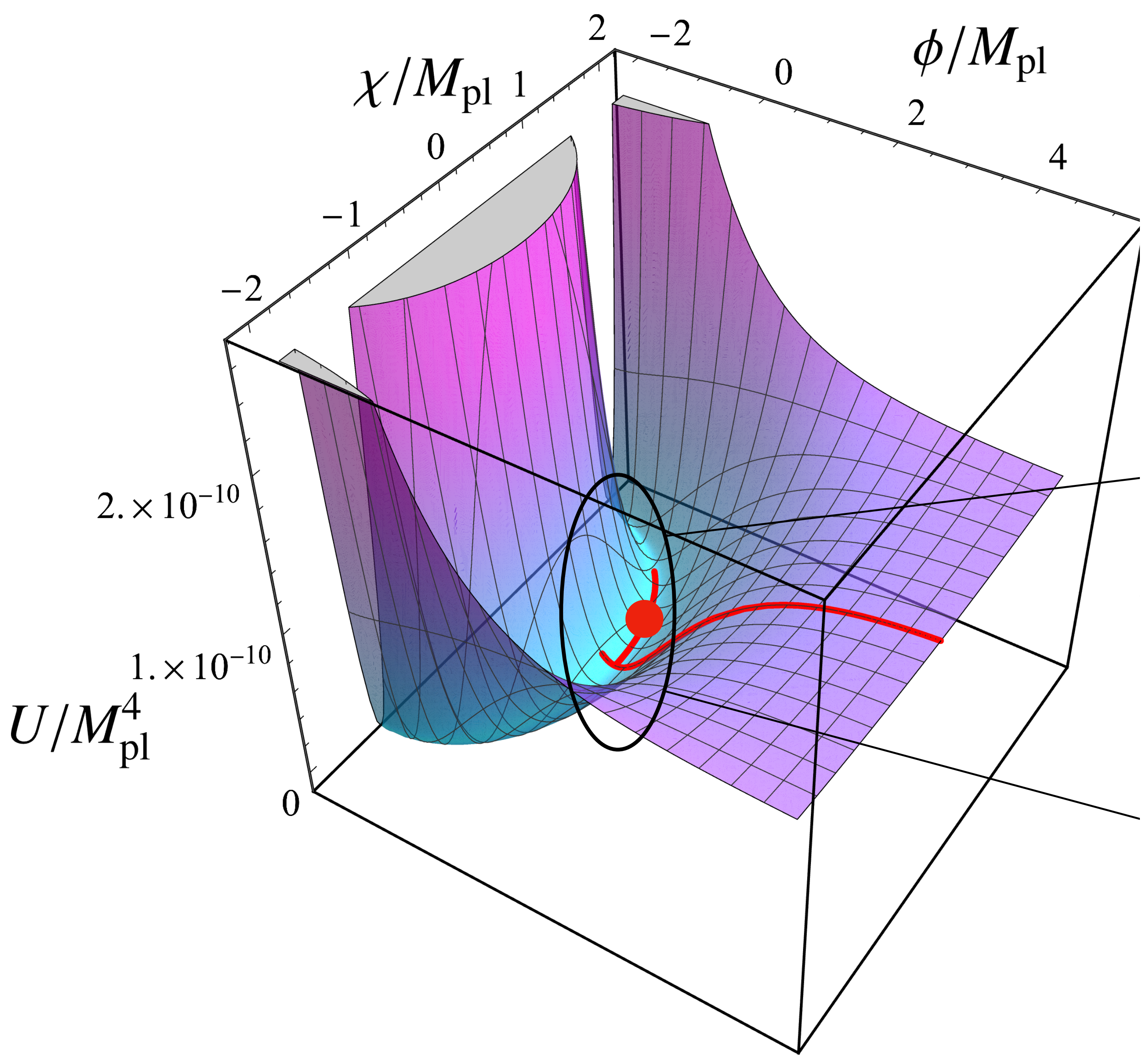
χ stays in the potential valley.

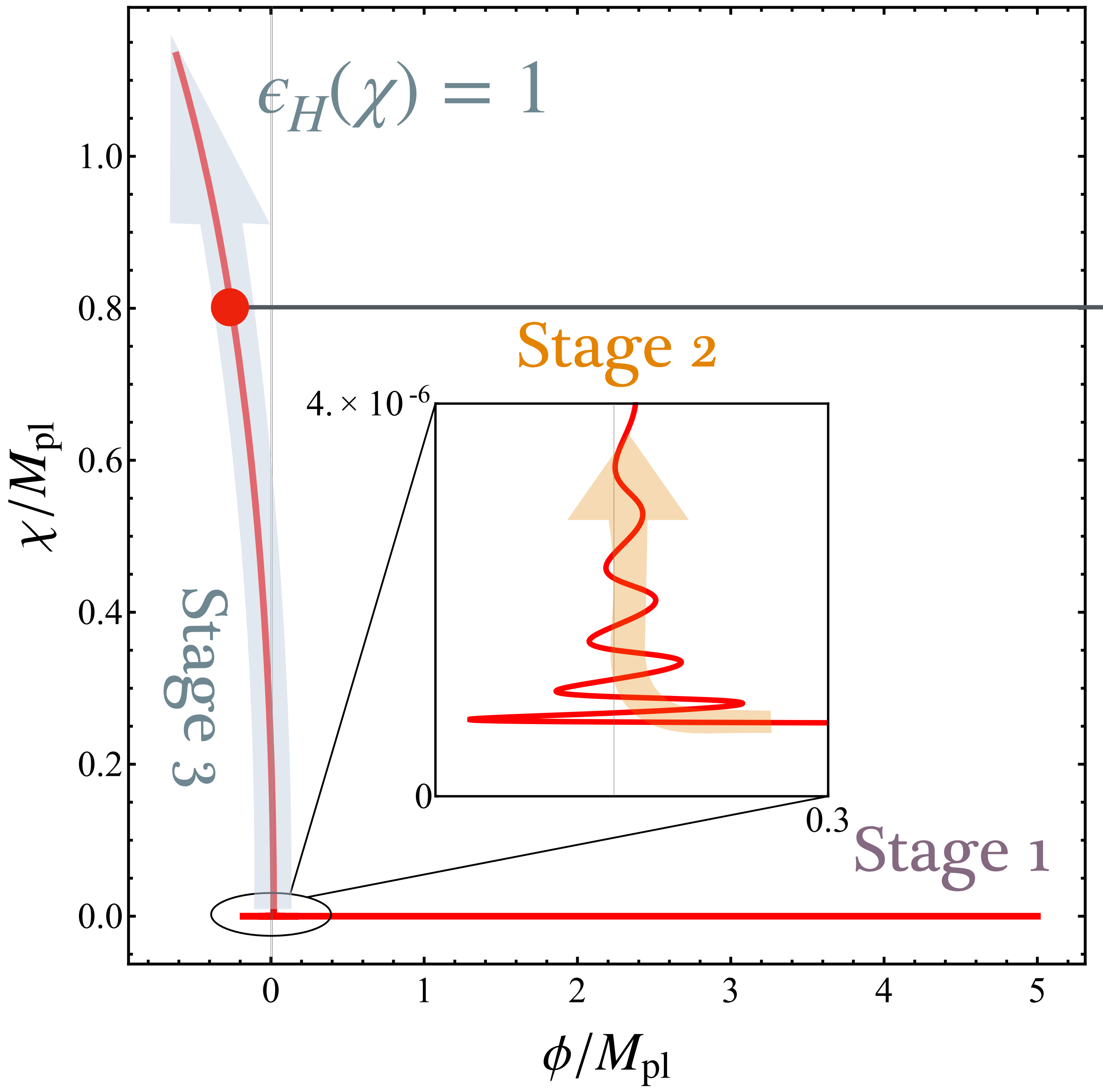


Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)





χ dominated inflation

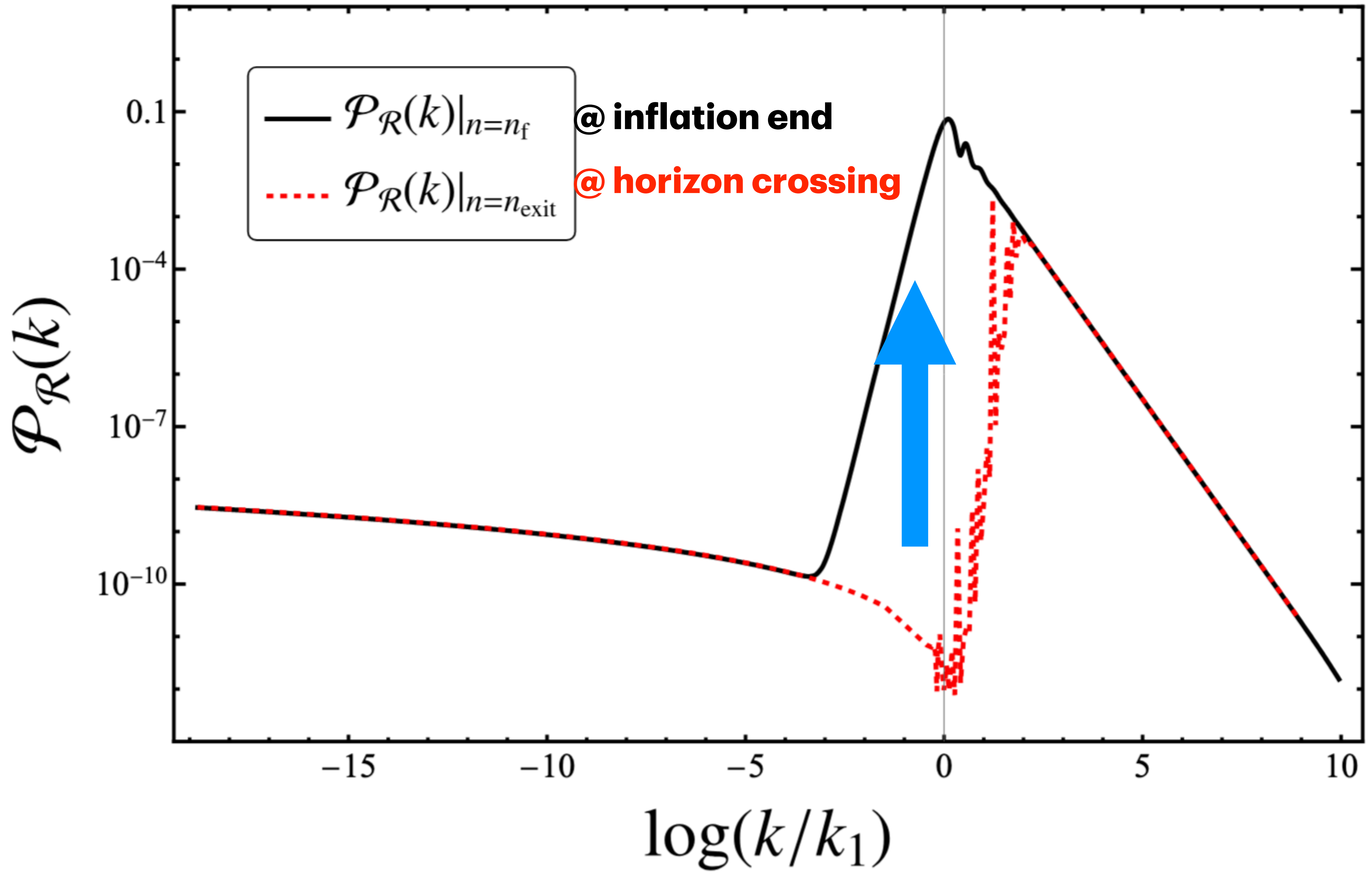
Inflation rolls along χ direction (**Higgs inflation**), ϕ behaves like a under-damped oscillator around it's potential valley. The inflation ends when $\epsilon_H = 1$.

Amplifying the Superhorizon Perturbations (Multi Field)

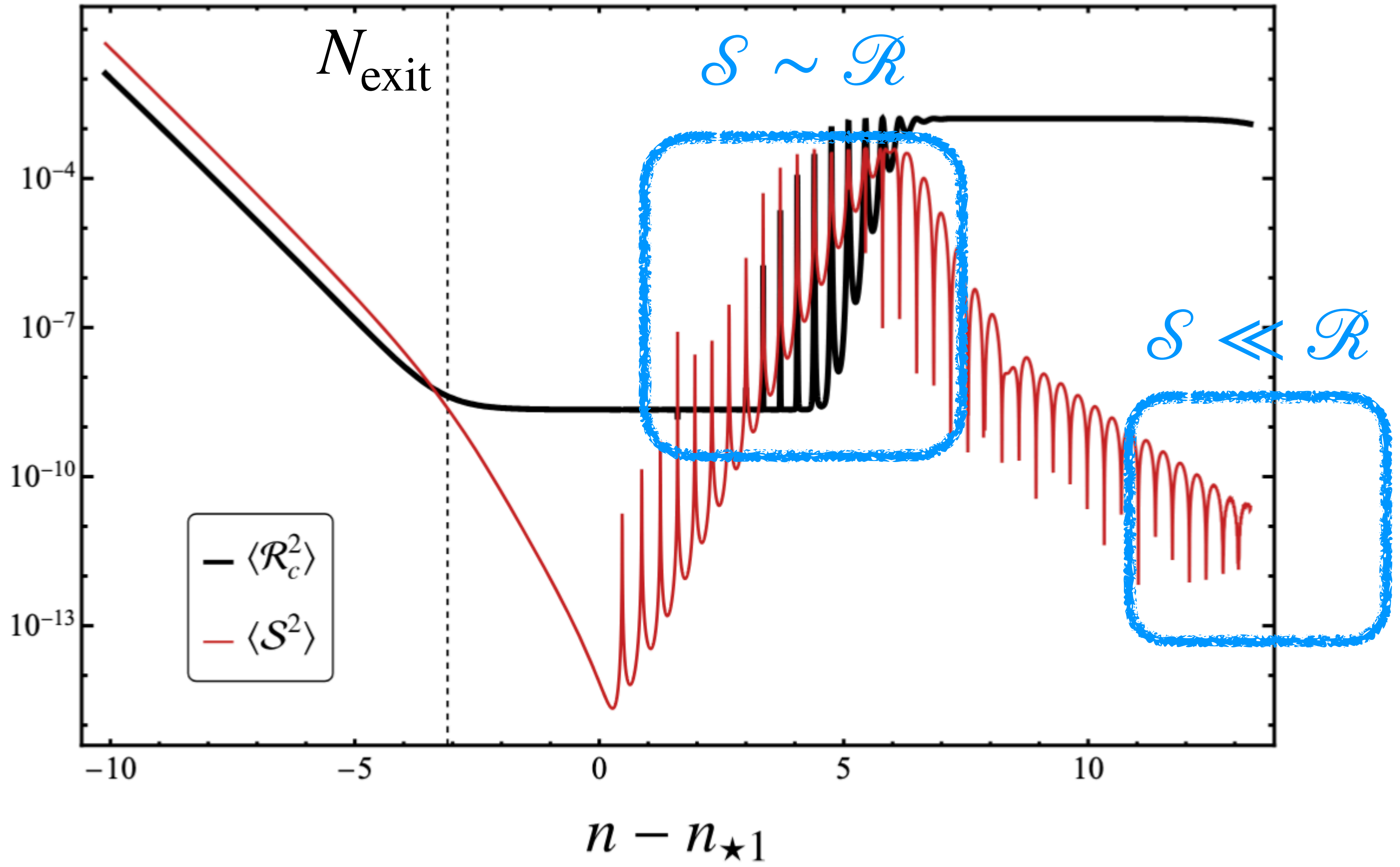
R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

Comparison between the power spectrum
@ inflation end and horizon crossing



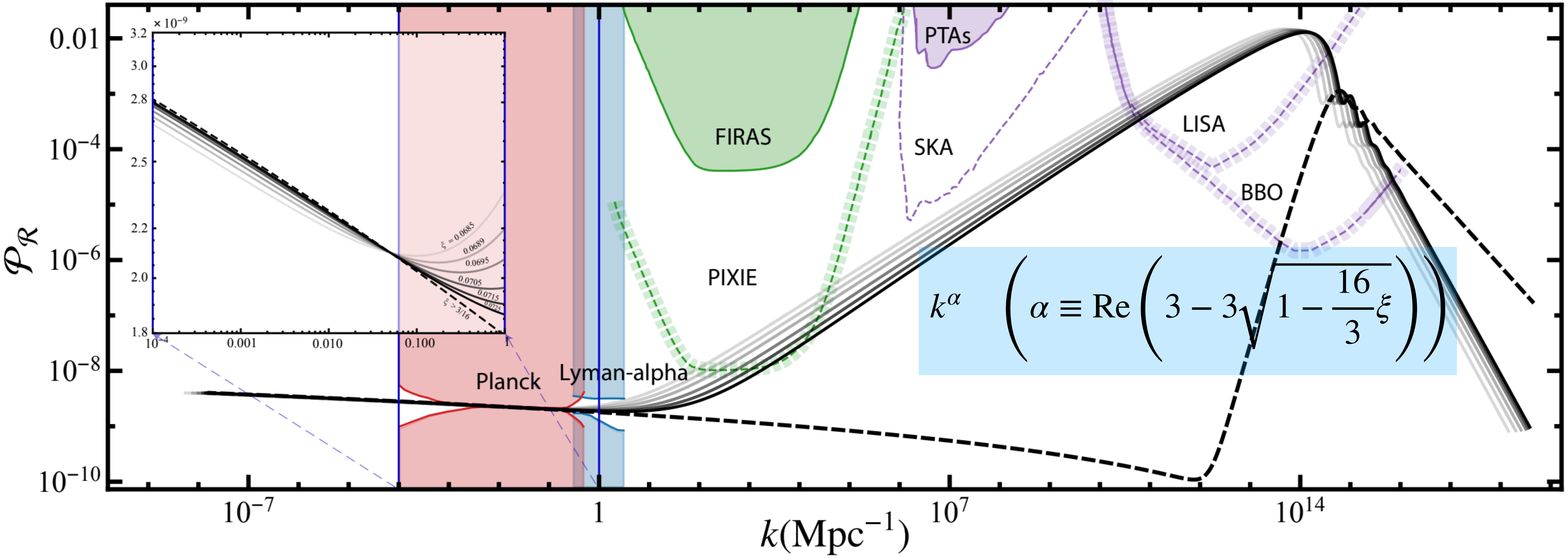
Evolution of $\mathscr{R}_c$ and $\mathscr{S}$



Large scale effect: a solution to the n_s tension

R^2 inflation + non-minimally coupled χ

XW, K. Kohri, Tsutomu T. Yanagida, 2025 (2506.06797)



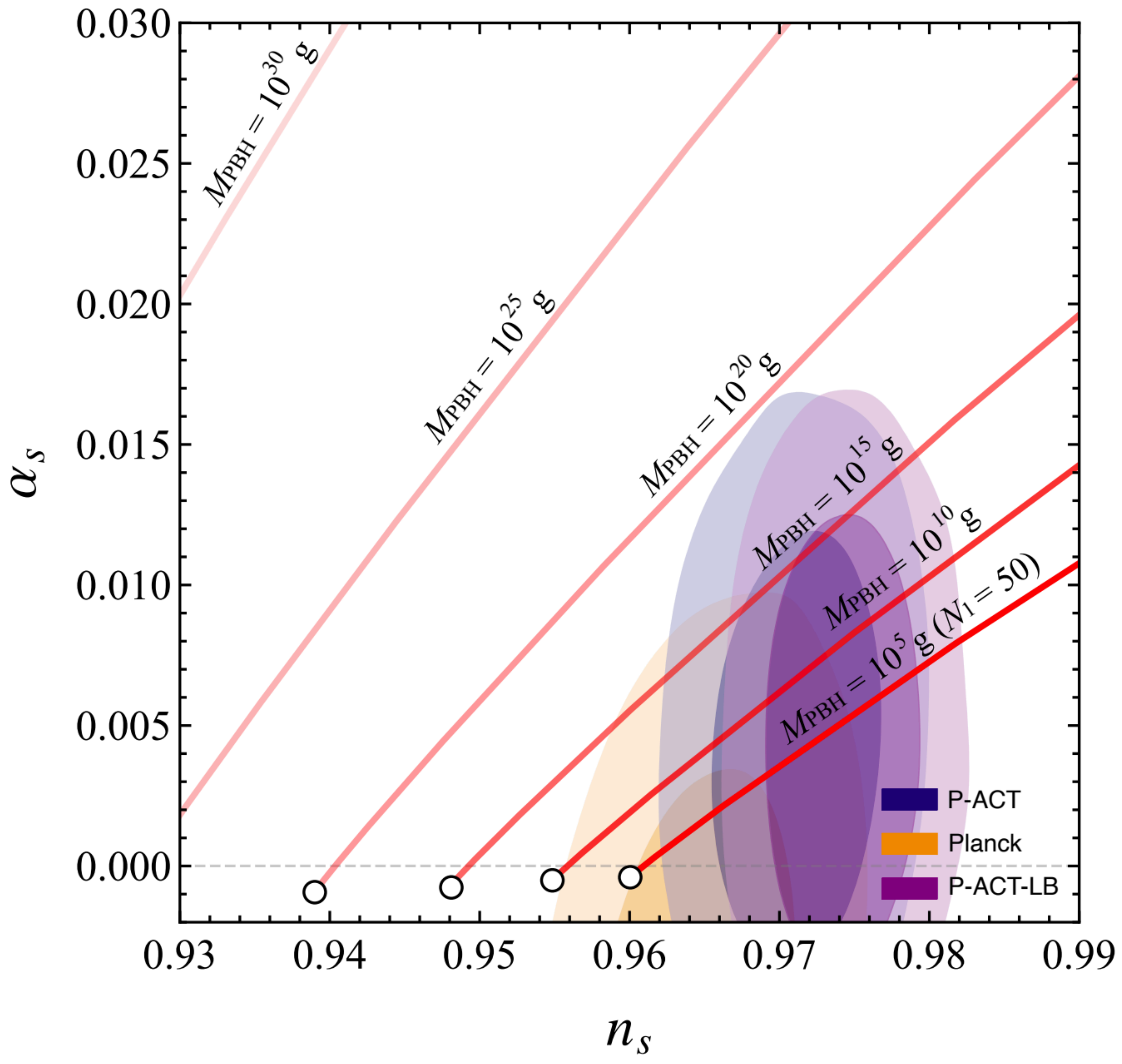
$k^\alpha \quad \left(\alpha \equiv \mathrm{Re}\left(3 - 3\sqrt{1 - \frac{16}{3}\xi}\right)\right)$

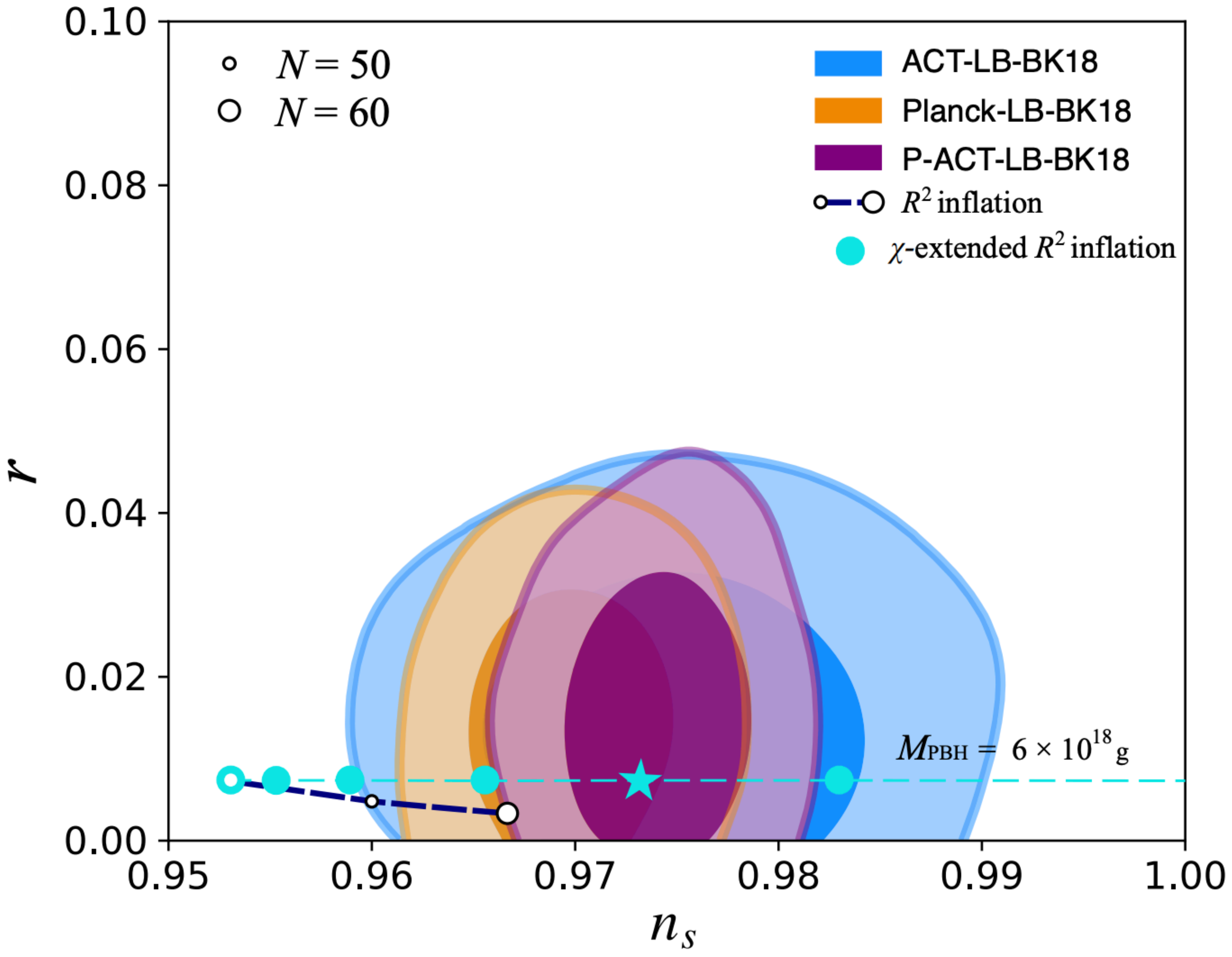
Large scale effect: a solution to the n_s tension

R^2 inflation + non-minimally coupled χ

XW, K. Kohri, Tsutomu T. Yanagida, 2025 (2506.06797)

PBHDM scenario is consistent with P-ACT result in $R^2 - \phi$ inflation.



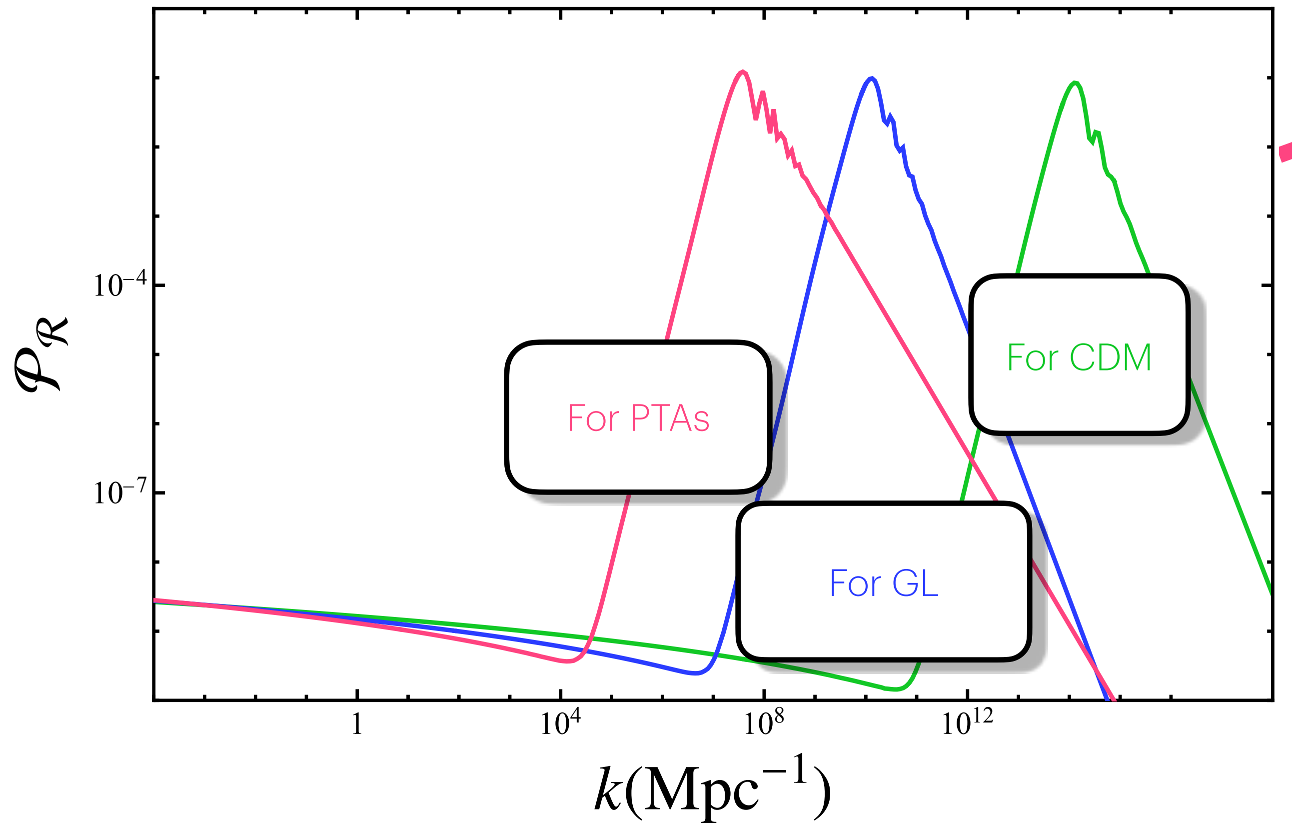


Amplifying the Superhorizon Perturbations (Multi Field)

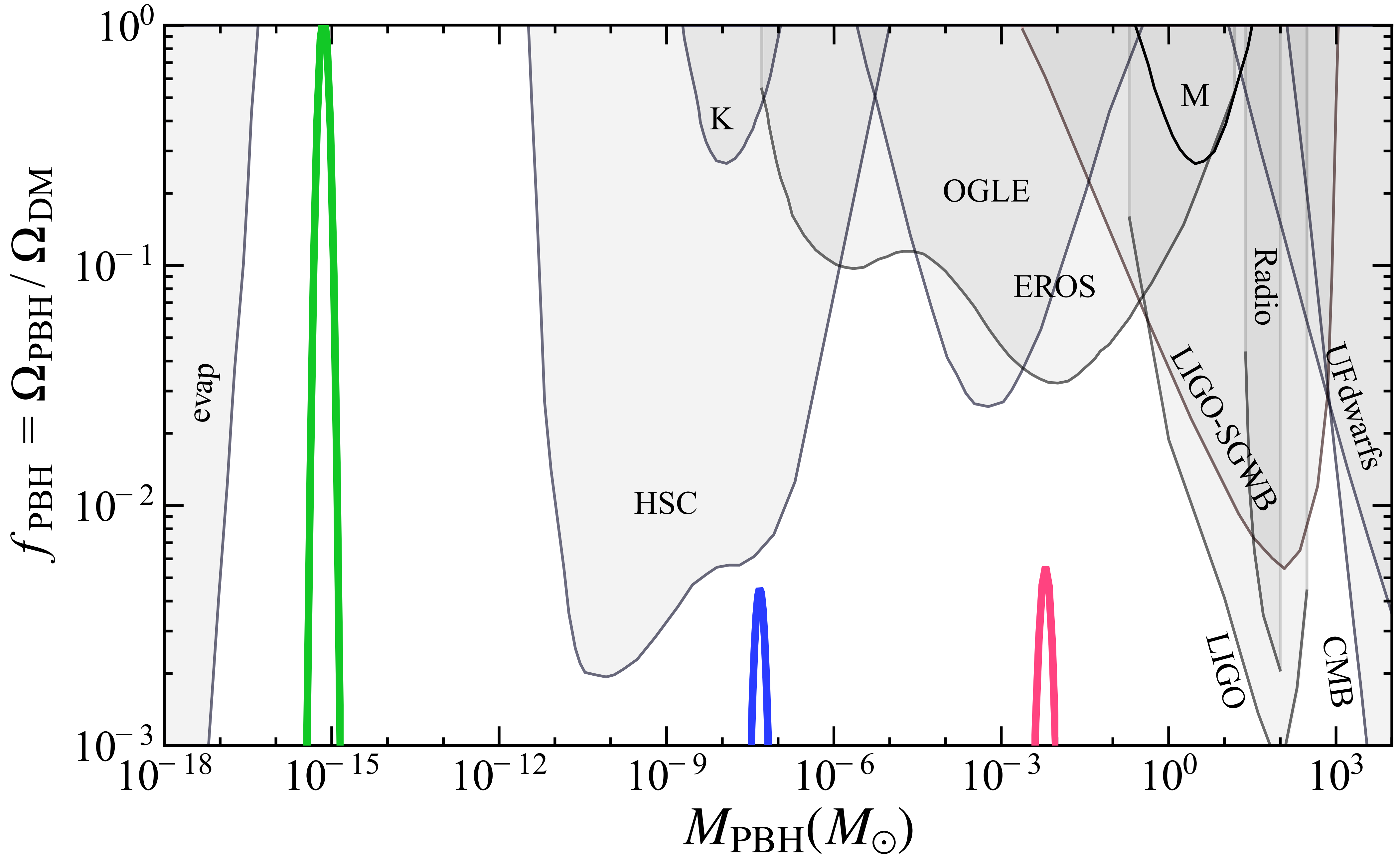
R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

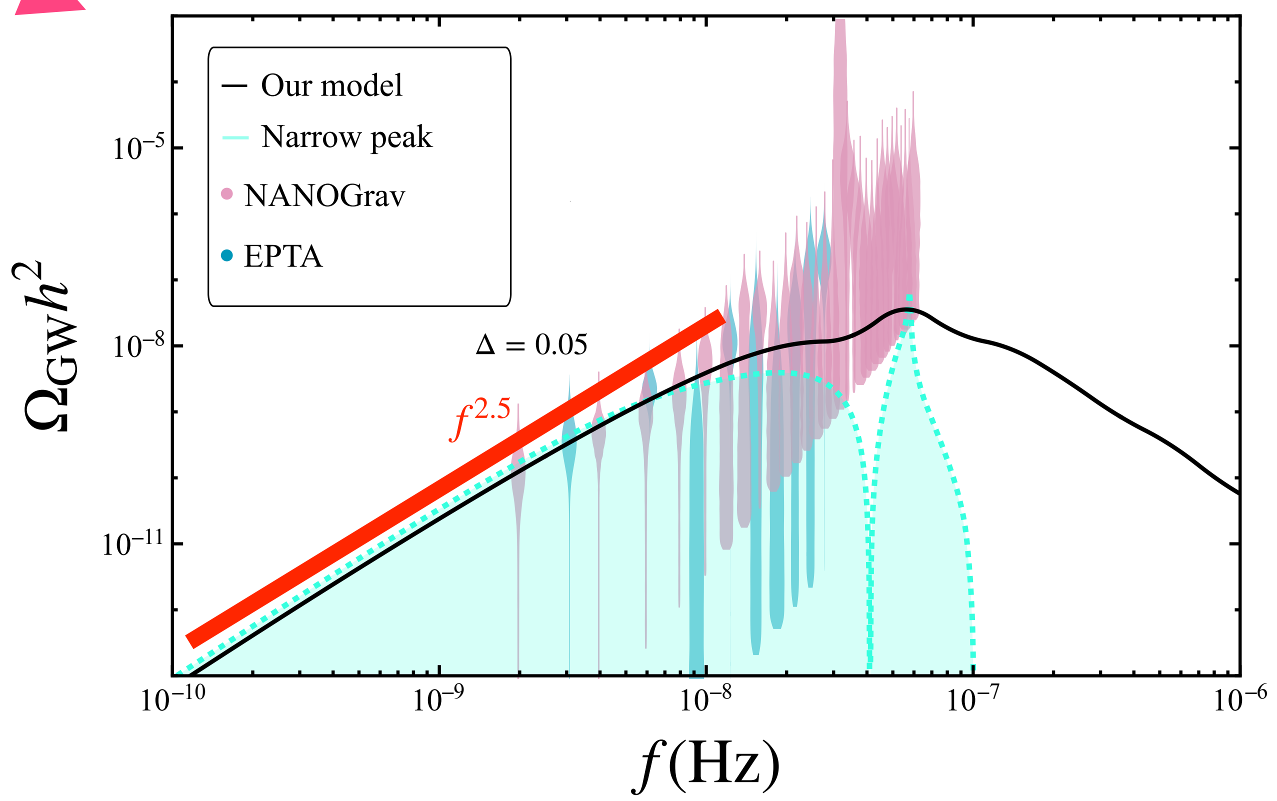
$$h''_{ij} + 2\mathscr{H} h'_{ij} - \partial_k \partial^k h_{ij} \approx P^{ab}{}_{ij} \left\{ \partial_a \delta\varphi \partial_b \delta\varphi \right\}$$



Primordial Black Holes

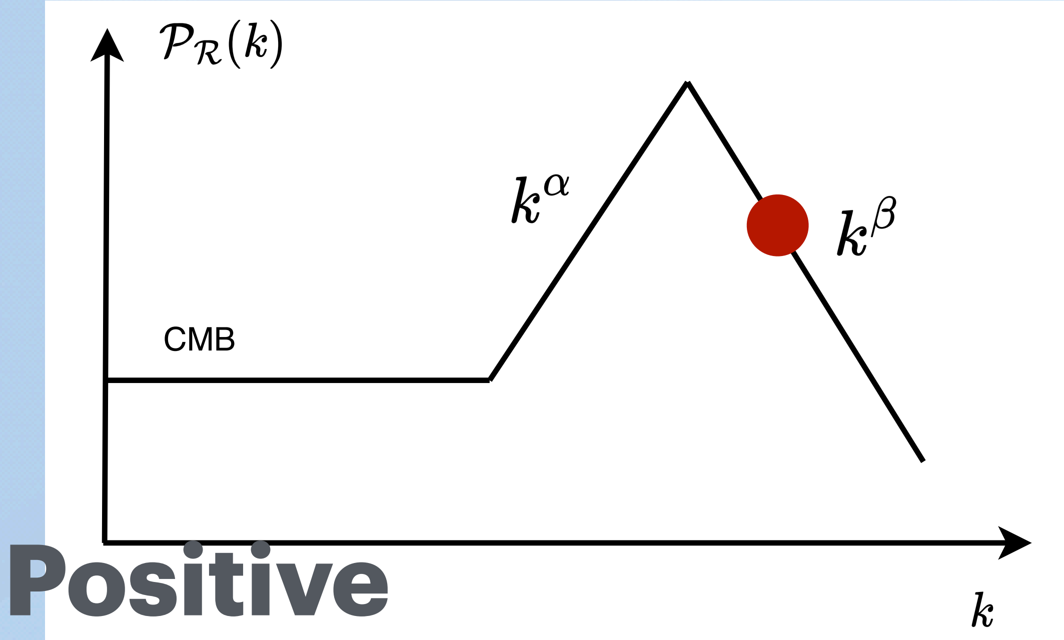


Scalar induced GW



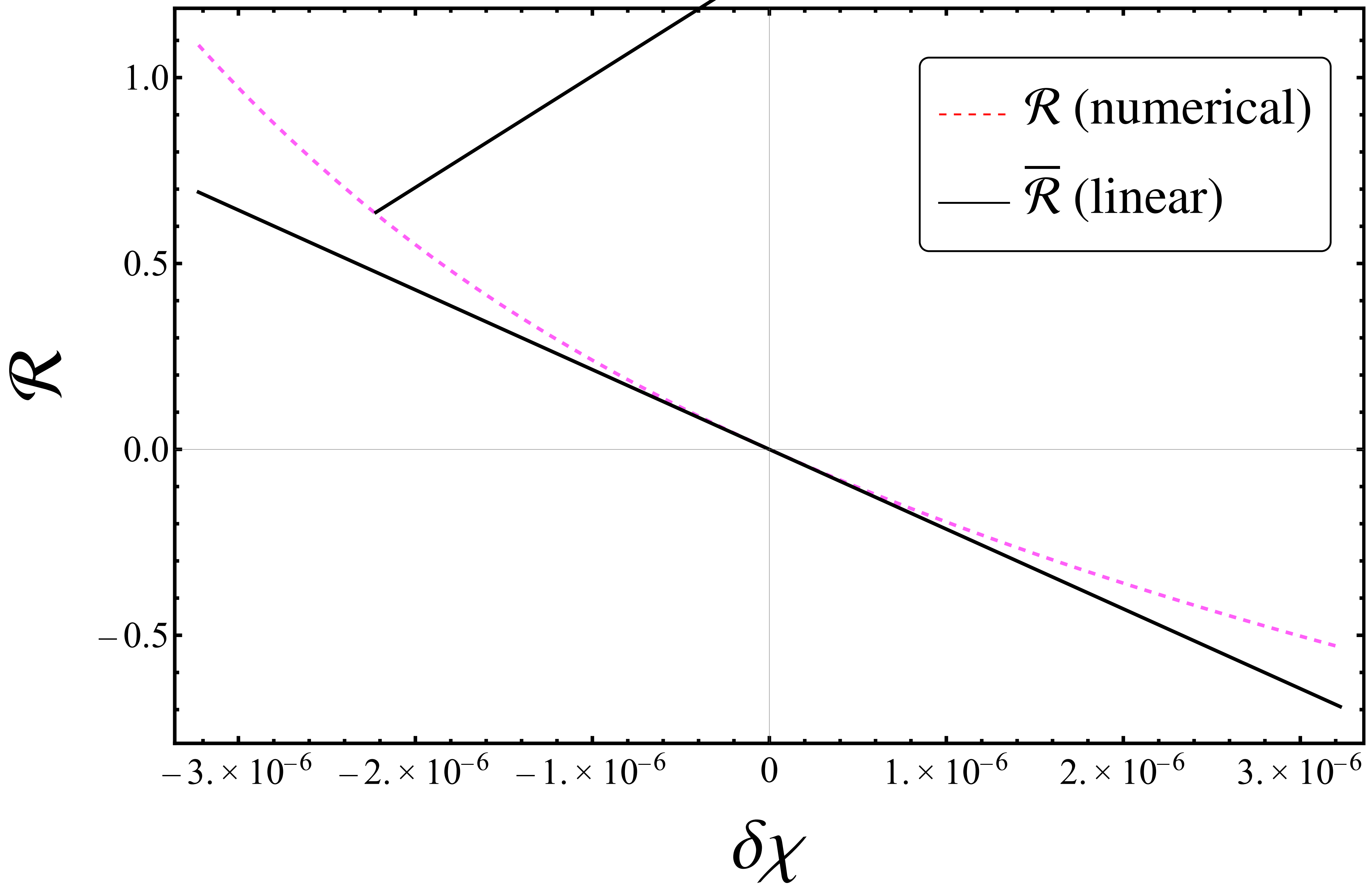
Xinpeng Wang (Kavli IPMU)

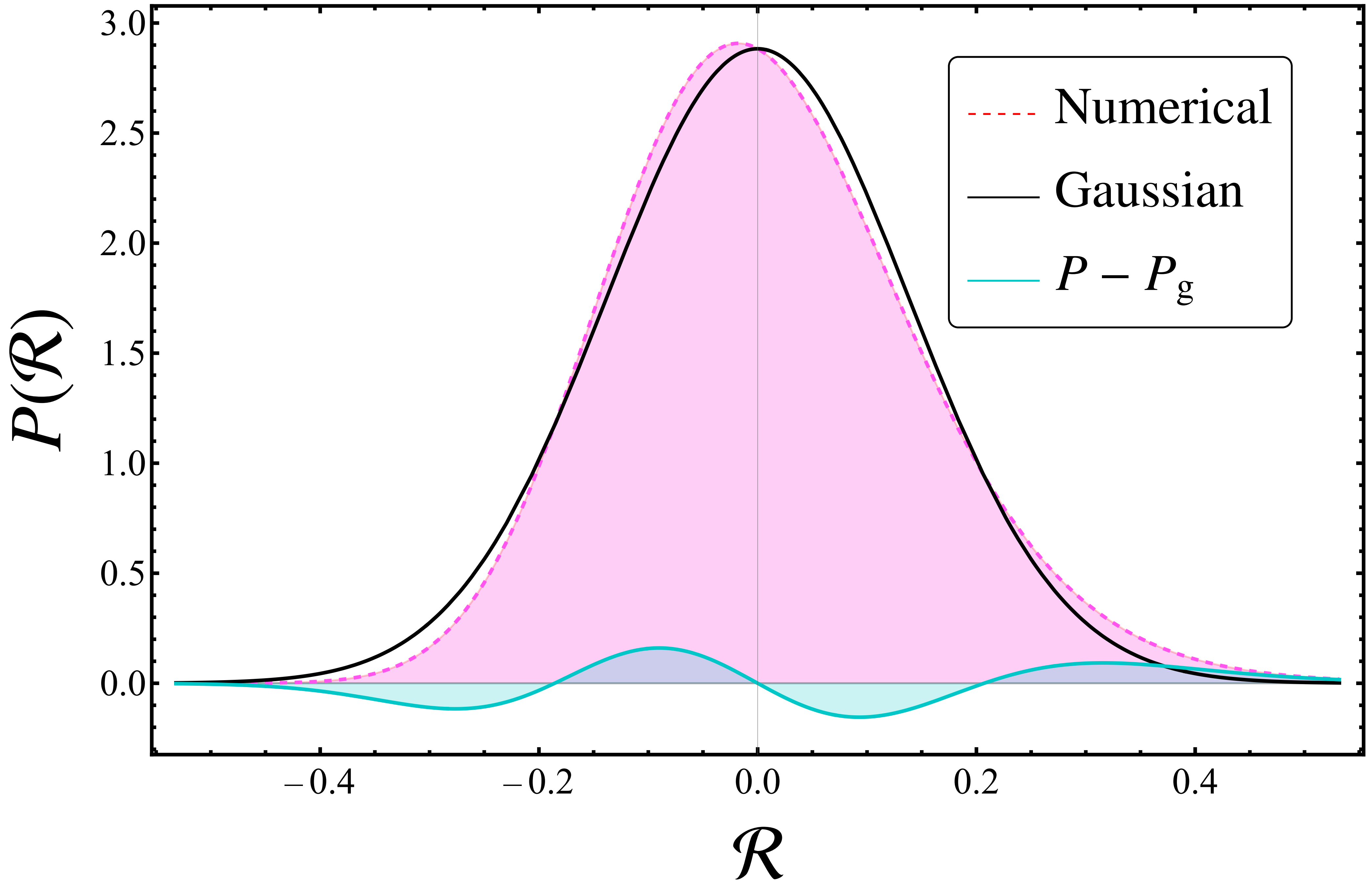
Non-Gaussianity ($k \gg k_1$)



$$\mathcal{R} \approx \delta N_3 = N_3' - N_3 \sim \frac{dN_3}{d\chi}\delta\chi + \boxed{\frac{d^2N_3}{d\chi^2}\delta\chi} \Rightarrow f_{\rm NL}^{\rm local}$$

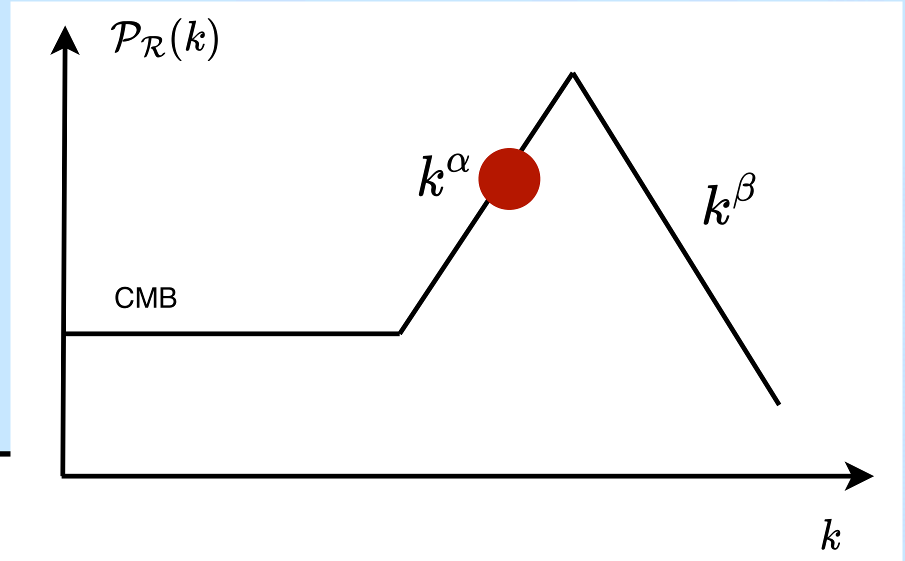
Small and Positive





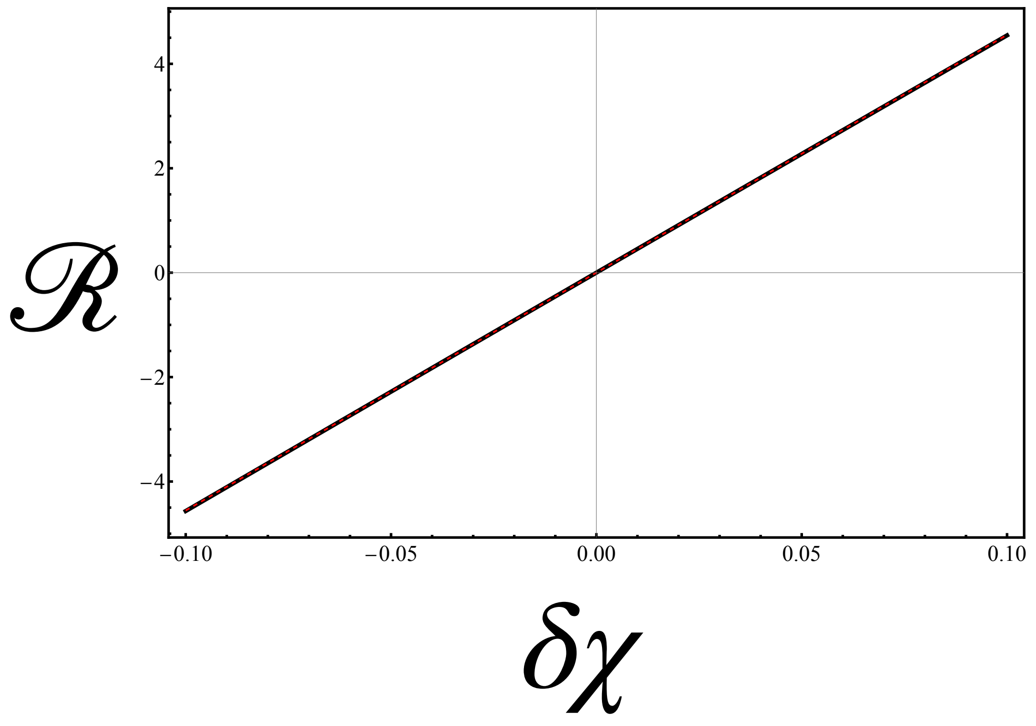
Xinpeng Wang (Kavli IPMU)

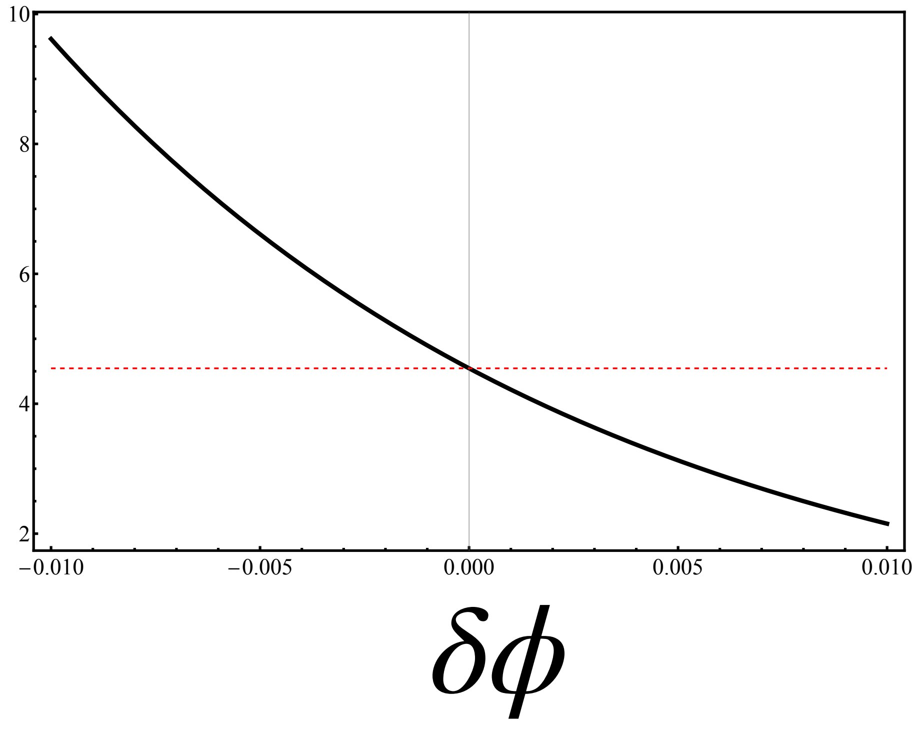
Non-Gaussianity ($k \gg k_1$)

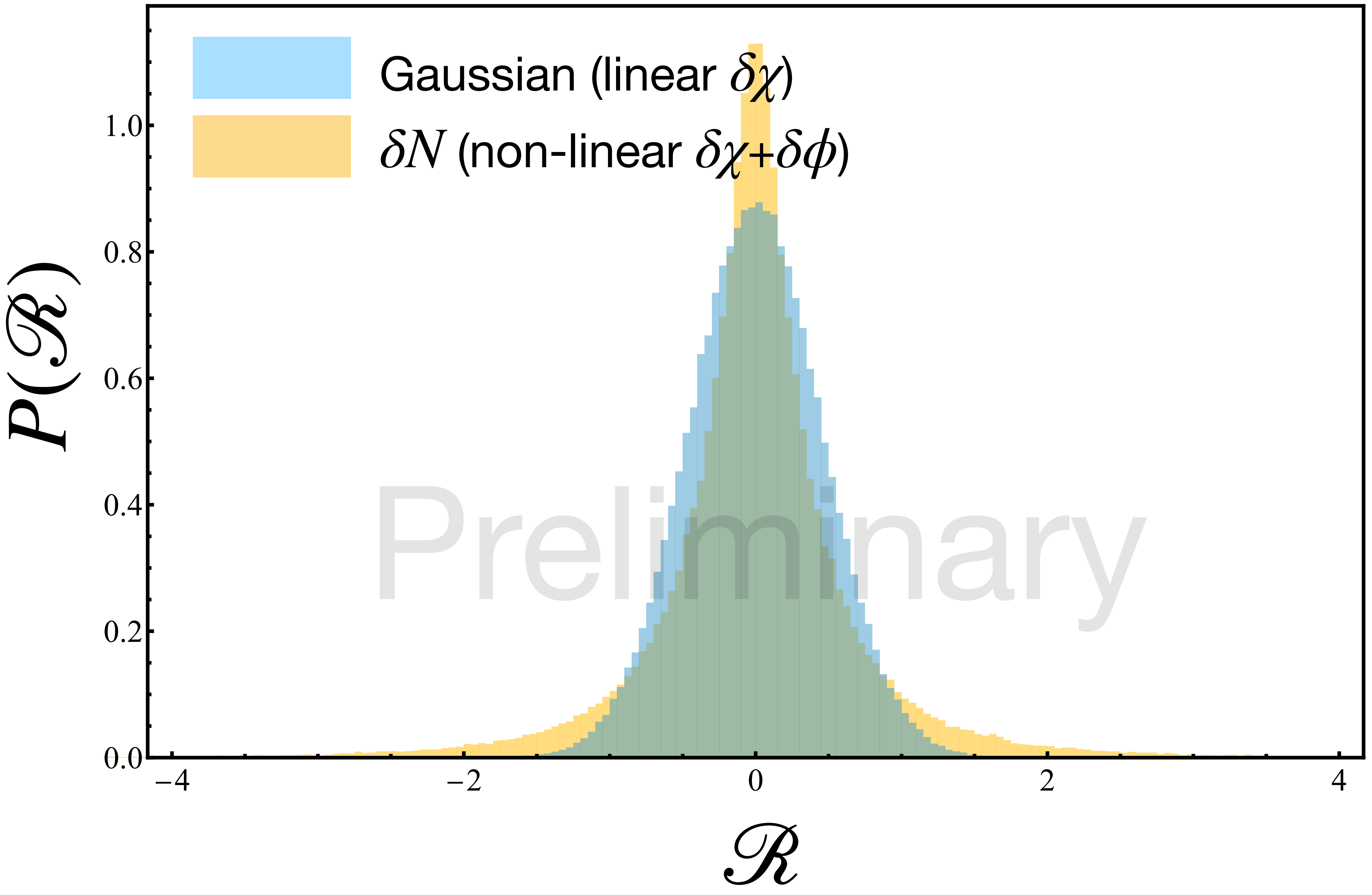


$$\mathscr{R} \approx N_3' - N_3 \approx \frac{2}{\beta} \ln \left[\frac{\chi_0}{\boxed{\delta\chi}(\phi_0/(\phi_i + \boxed{\delta\phi}))^{\alpha/(n_s-1)} + \chi_0} \right]$$

Non-negligible dependence on $\delta\phi$



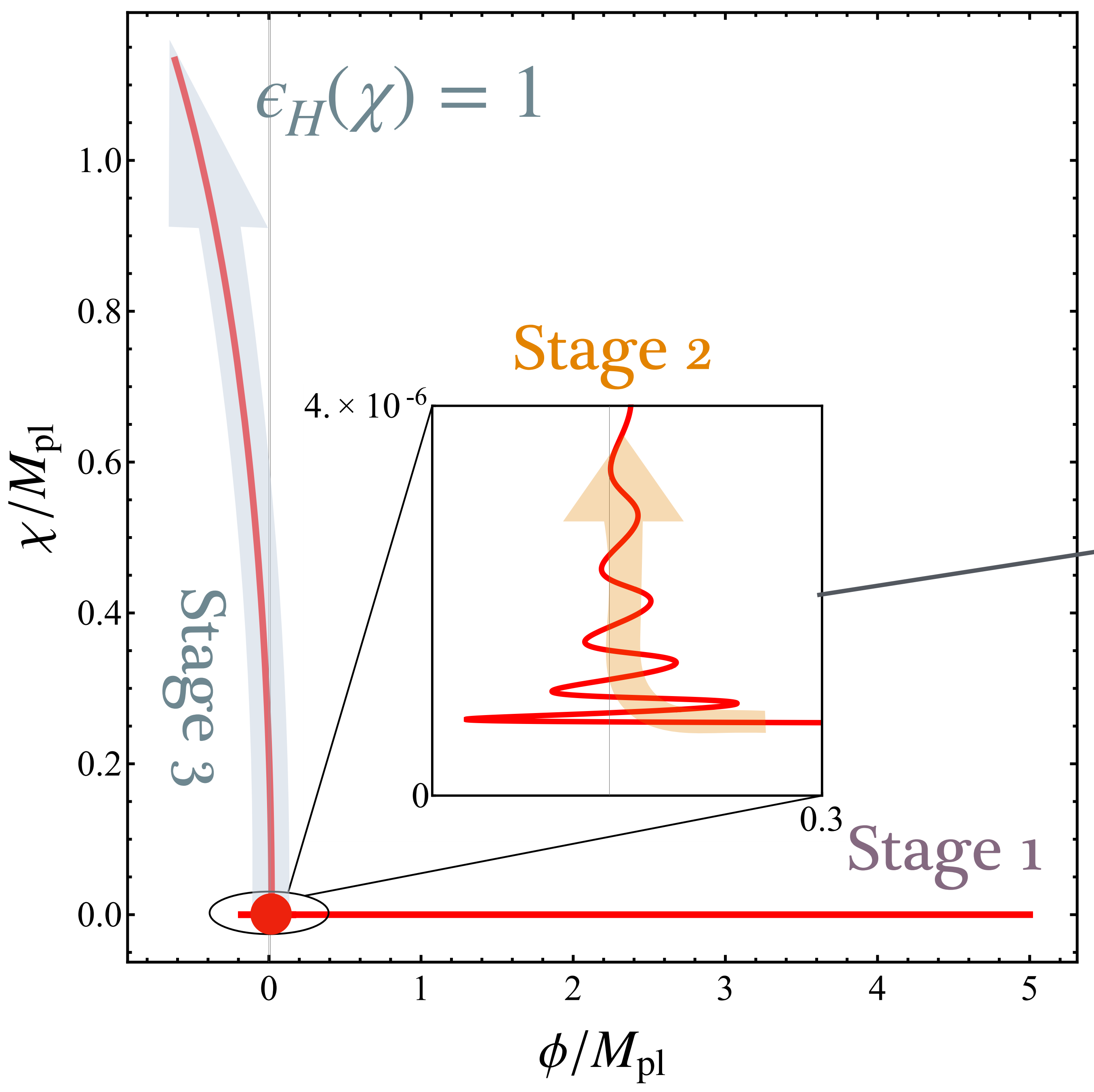




Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

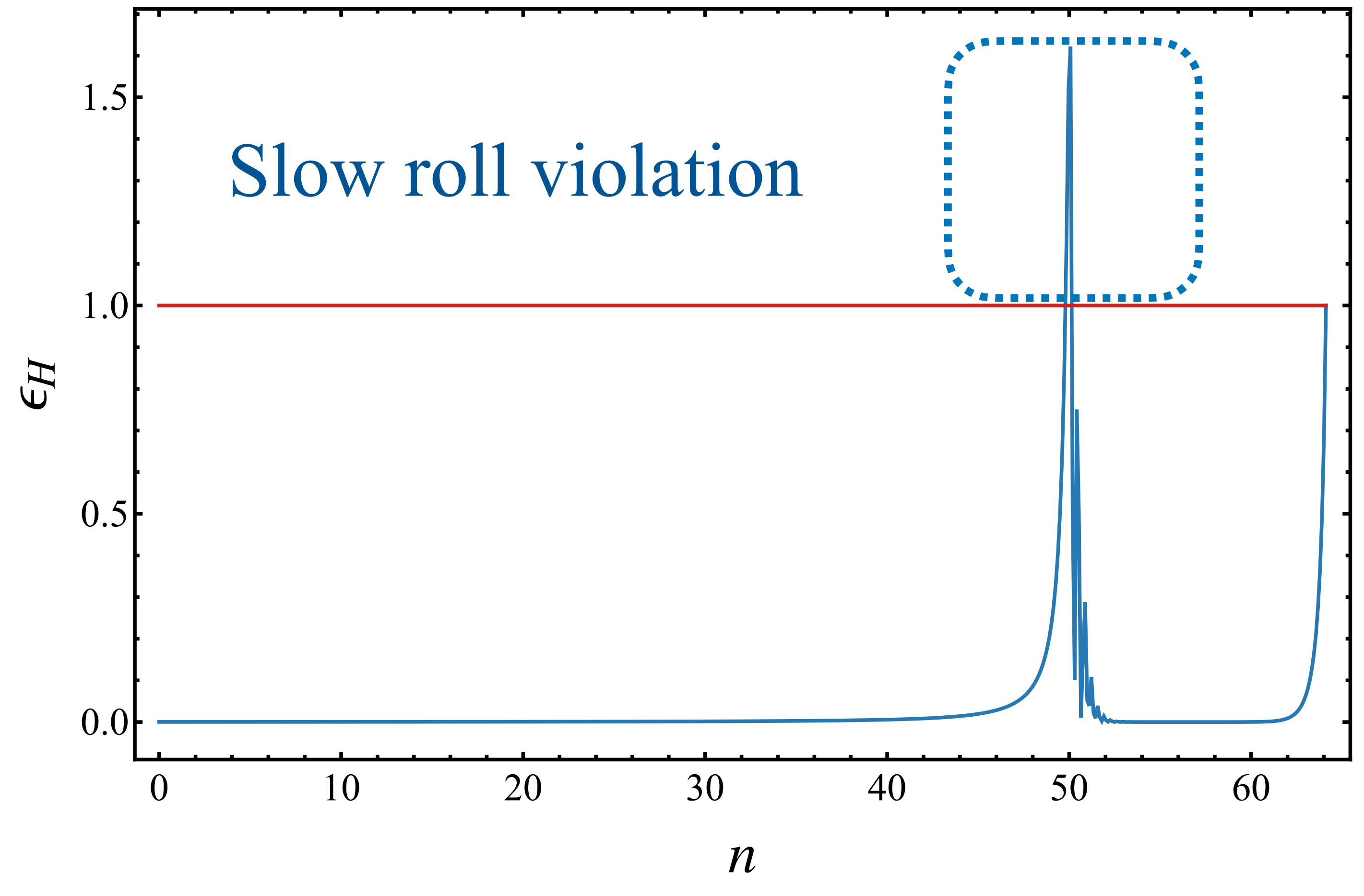


Baby R^2 reheating

The slow roll is shortly violated ($\epsilon_H > 1$) by inflaton's oscillation along ϕ direction.

χ stays in the potential valley.

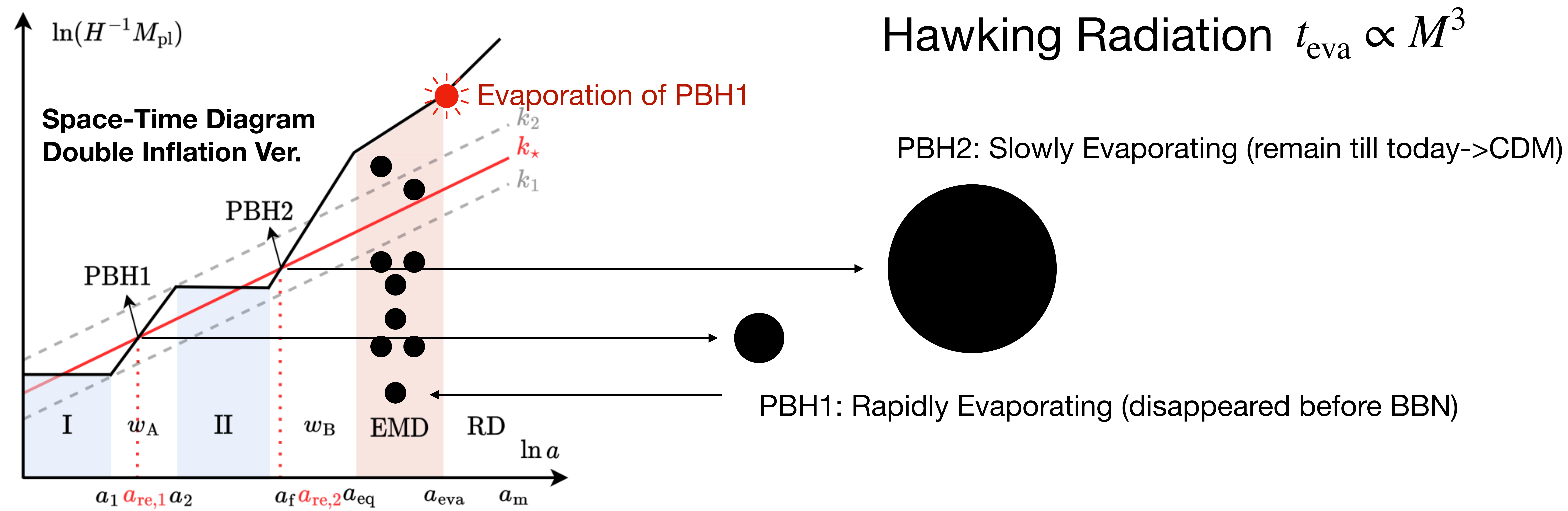
Interesting scenario happening
In hybrid-like inflationary models



Inflation Break Stage: Dual PBH Formation

Forming **two families** of PBH with at nearly the same comoving scales but **at two different epochs**.

XW, M. Sasaki et al 2025, (2505.09337)



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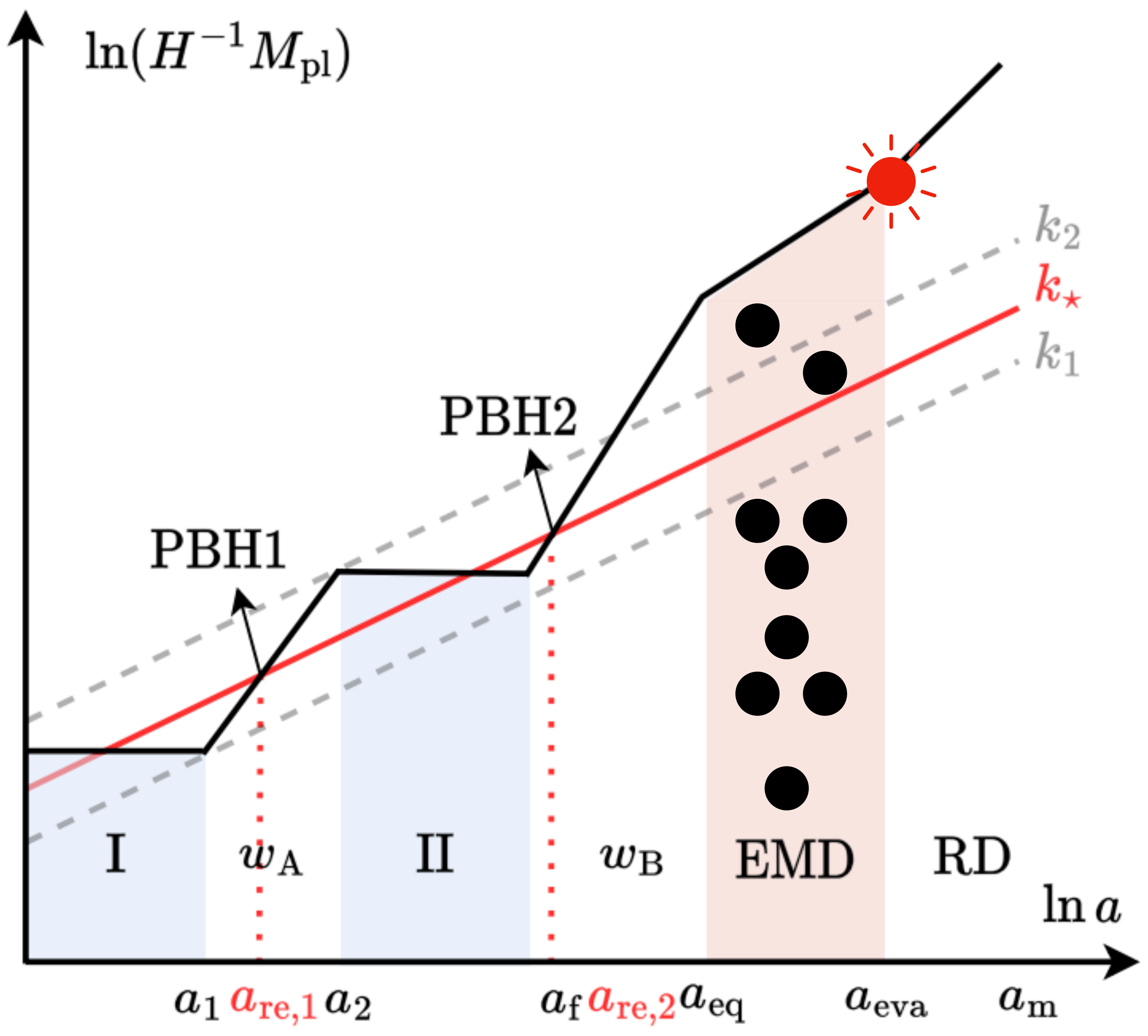
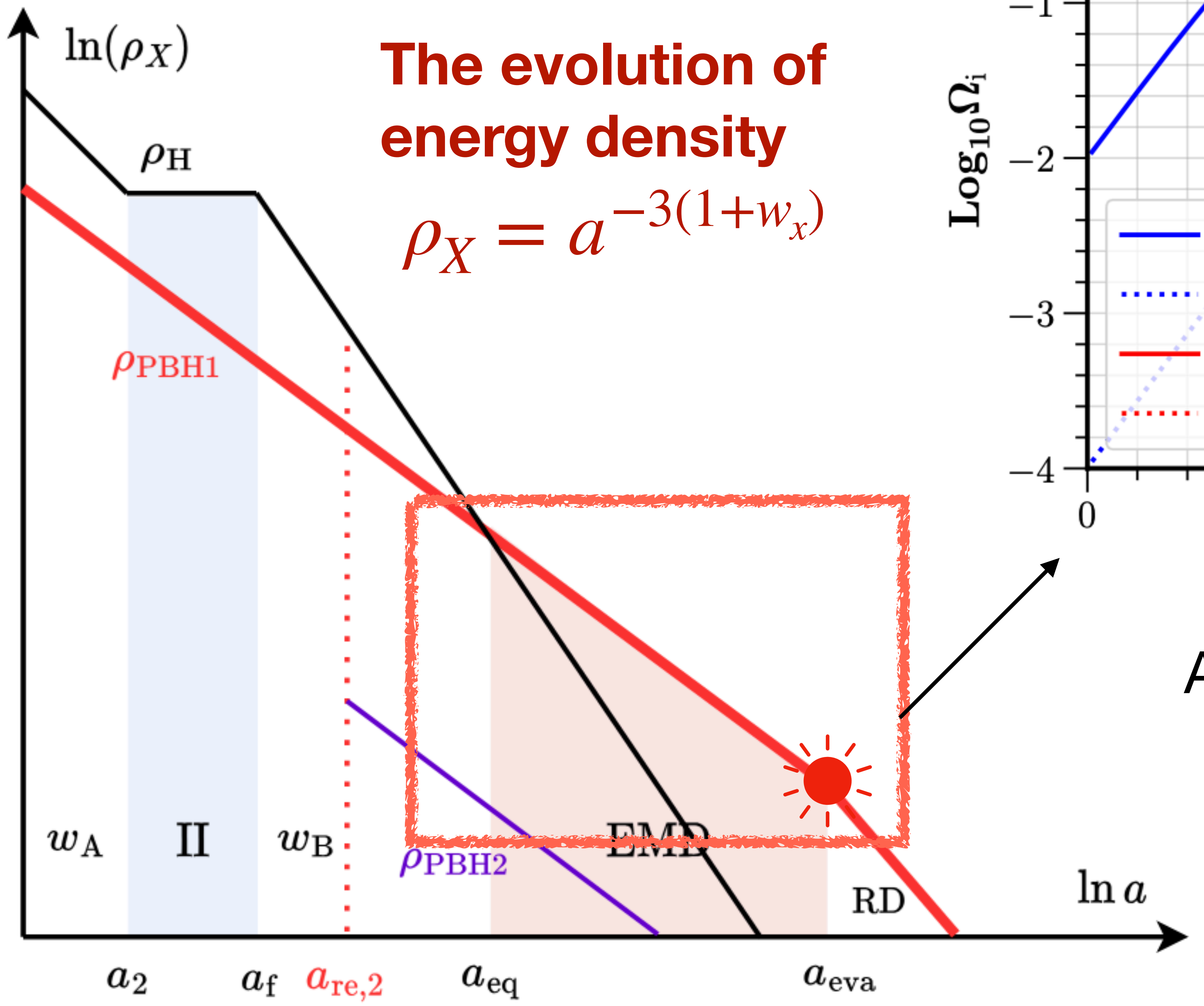
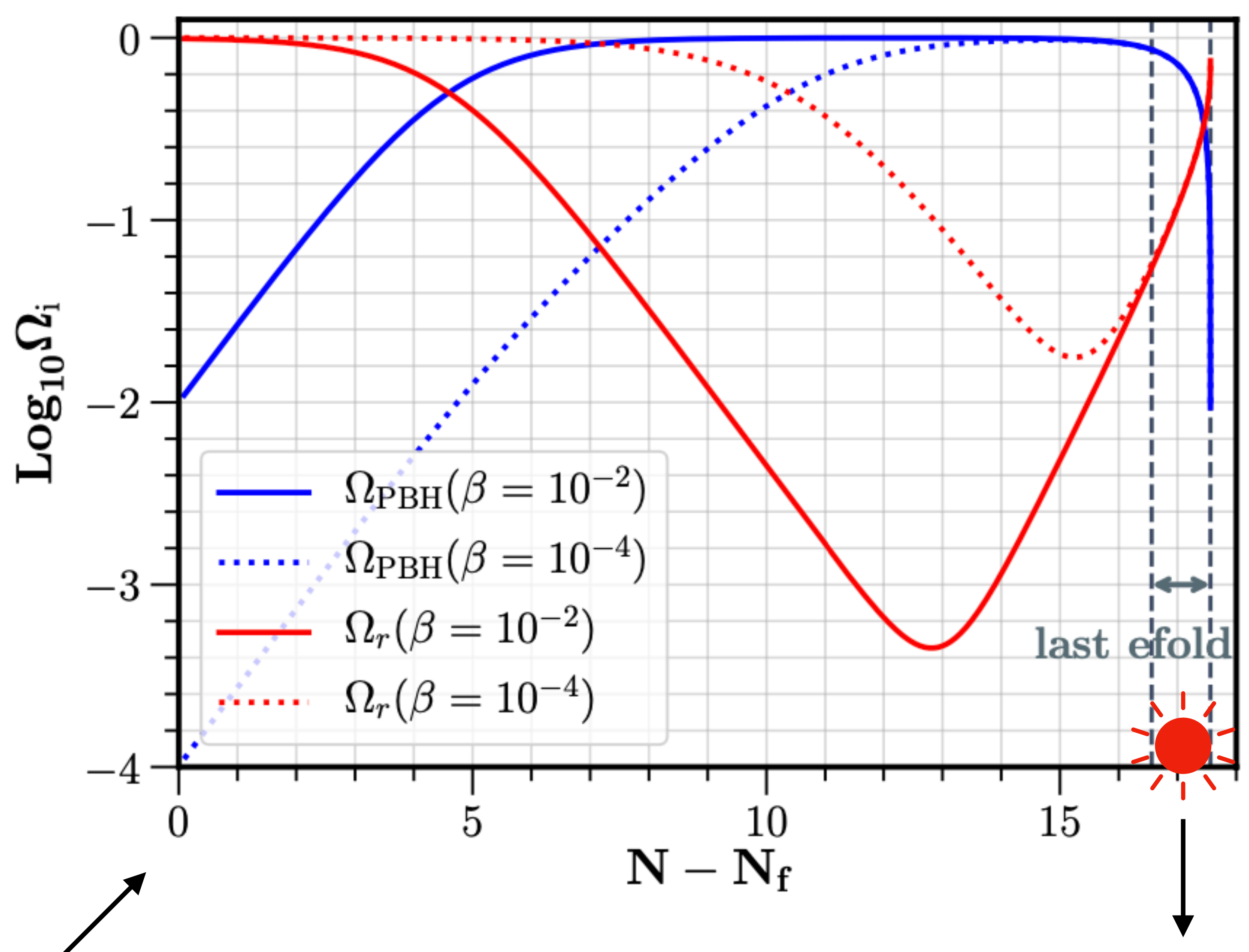




The evolution of energy density

$$\rho_X = a^{-3(1+w_x)}$$



Almost instantaneous transition

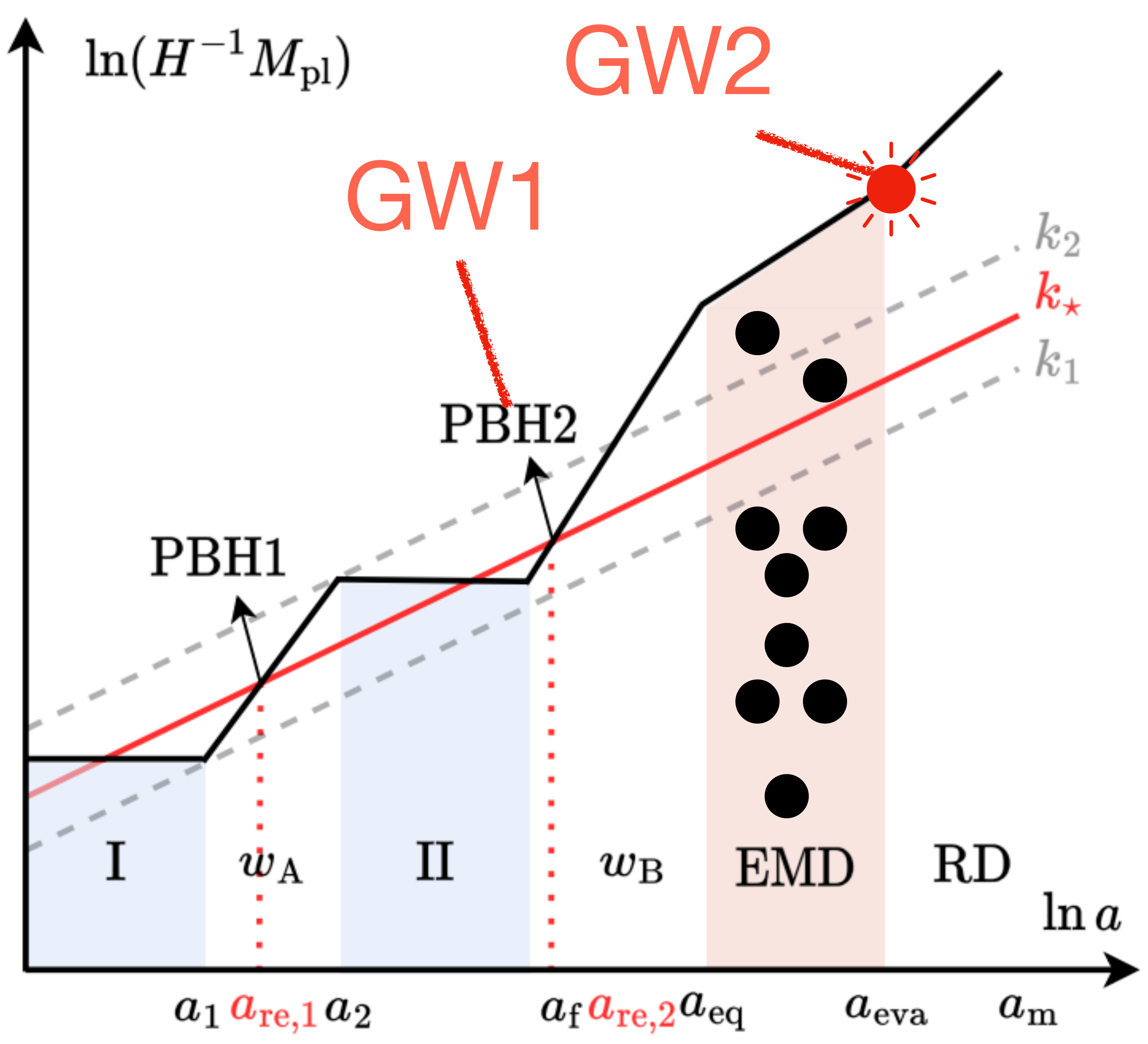
Inflation Break Stage: Dual PBH Formation

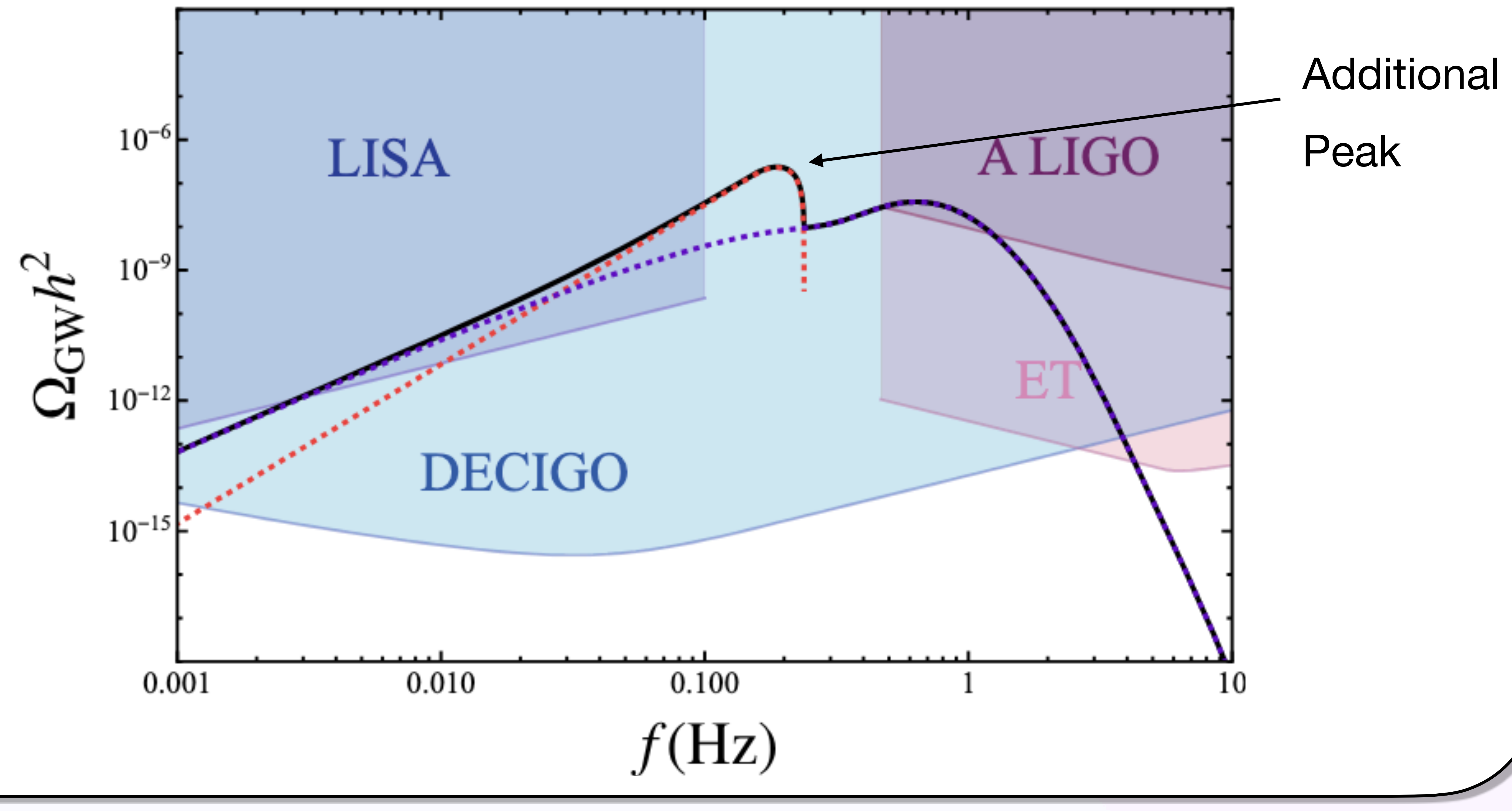
Forming **two families** of PBH with at nearly the same comoving scales but **at two different epochs**.

XW, M. Sasaki et al 2025, (2505.09337)

GW1: Companion of PBH2, might get enhanced during w_B

GW2: From fast transition from EMD to RD (Domènech 2020)





II. Gravitational Waves from Yukawa Force Mergers —An Alternative to Small Scale Perturbations

Based on 2510.12984

Xinpeng Wang (Kavli IPMU)

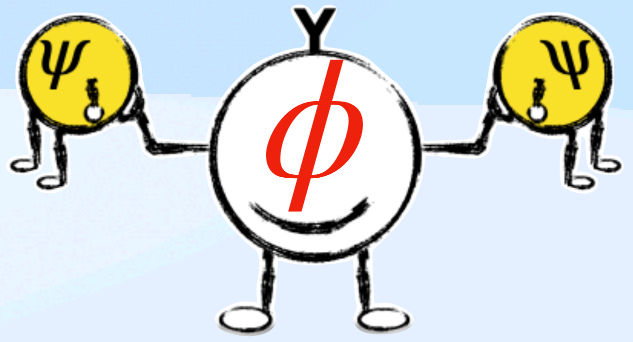
Early halo formation: Theory

Amendola, Rubio, and Wetterich, 2017
Savastano, Amendola, Rubio, and Wetterich, 2019
Flores, Kusenko 2021
Domenech and Sasaki, 2021
...

The long-range Yukawa forces, if much stronger than Gravity $\beta^2 = F_y / F_g \gg 1$,
can efficiently form structures, halos, and black holes in the very early universe.

The Basic Lagrangian

DM&DE Interaction?

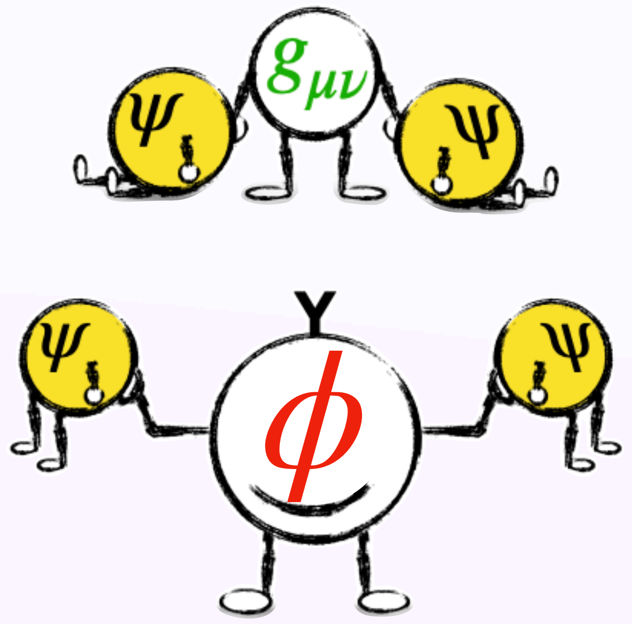


Credit. Domenech

$$\mathscr{L} \supset \bar{\psi} i \Gamma^\mu D_\mu \psi - (m_\psi + y\phi)\bar{\psi}\psi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi$$

For two fermions:

$$F_G = \frac{G m_\psi^2}{d^2} \qquad F_y = \frac{y^2}{4\pi d^2} e^{-m_\phi d} \qquad \boxed{\frac{F_y}{F_G} \sim \frac{y^2}{G m_\psi^2} = 2\beta^2}$$



The perturbation equation of motion for number density perturbation of ψ fermions:

$$\ddot{\delta}_k + 2H\dot{\delta}_k - \frac{3}{2} H^2 \Omega_\psi \left(1 + \frac{2\beta^2}{1 + (k l_y)^{-2}} \right) \delta_k = 0$$

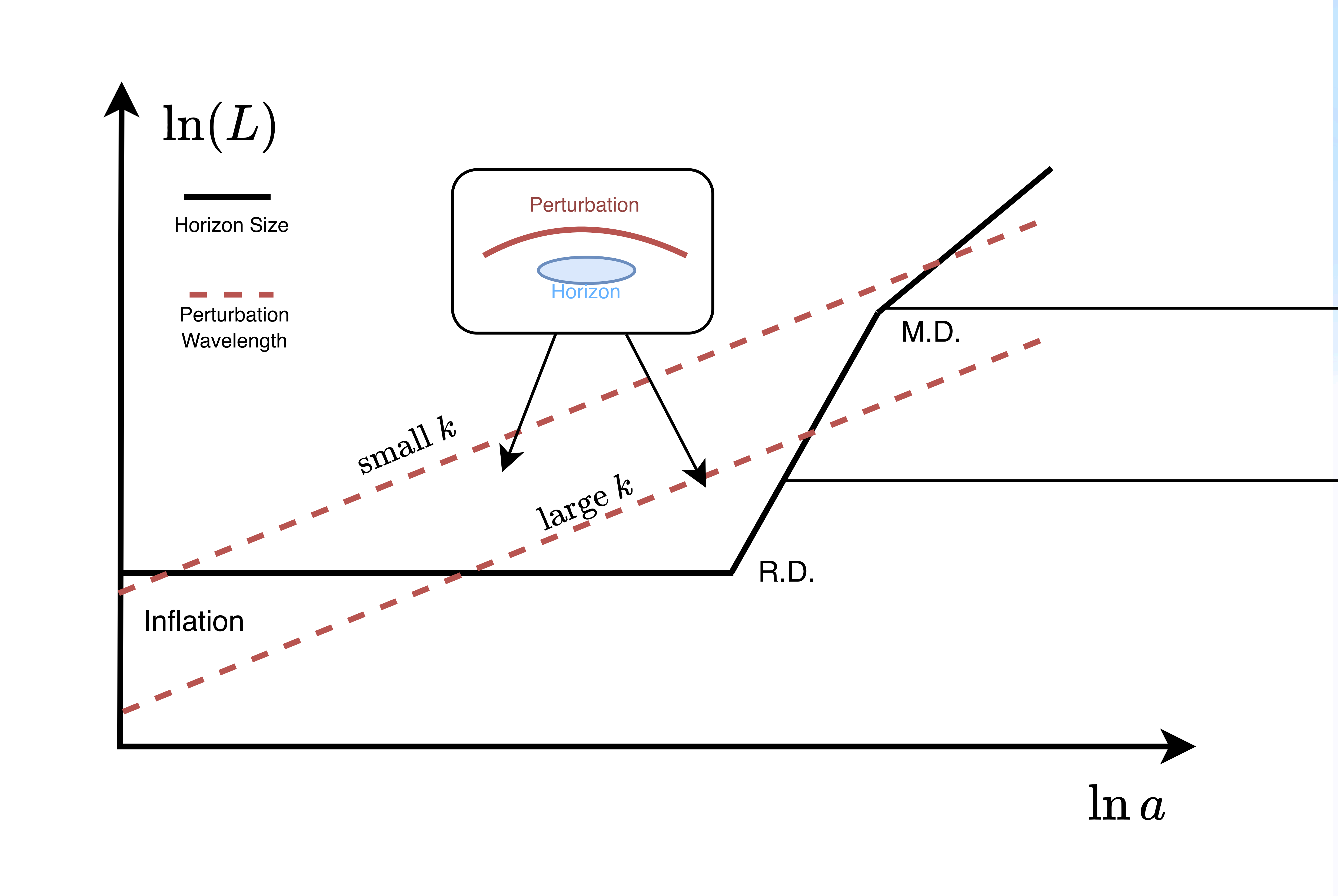
$\rightarrow$ Exponential Growth of δ_k during radiation domination.

Xinpeng Wang (Kavli IPMU)

Amendola, Rubio, and Wetterich, 2017
Savastano, Amendola, Rubio, and Wetterich, 2019
Flores, Kusenko 2021
Domenech and Sasaki, 2021
...

Early halo formation: Theory

Gravity Only



Structures Start to Form
(Large-scale, Gravitational Collapse)

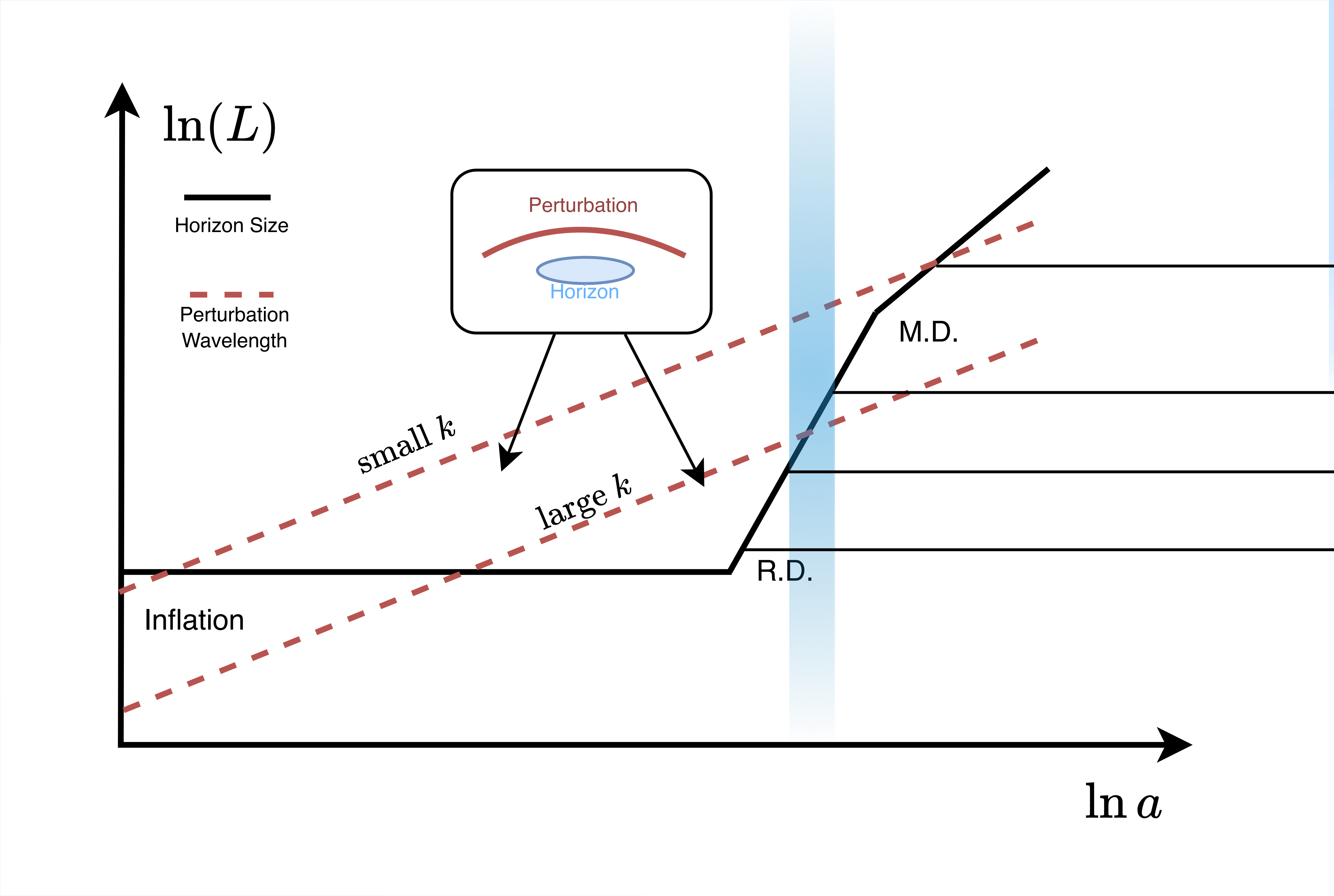
Density Perturbations Barely Grow

Xinpeng Wang (Kavli IPMU)

Early halo formation: Theory

Amendola, Rubio, and Wetterich, 2017
Savastano, Amendola, Rubio, and Wetterich, 2019
Flores, Kusenko 2021
Domenech and Sasaki, 2021
...

Gravity + Long-range force ($2\beta^2 \gg 1$)



Structures Start to Form
(Large-scale, Gravitational Collapse)

Long-range Forces are Screened ($H^{-1} \gg \beta l_y$)

Structures Start to Form
(Small-scale, Yukawa-driven Collapse)

Density Perturbations Barely Grow

Xinpeng Wang (Kavli IPMU)

Early halo formation: Theory

Amendola, Rubio, and Wetterich, 2017
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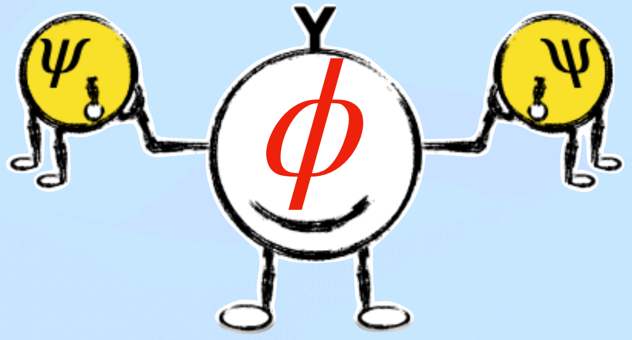
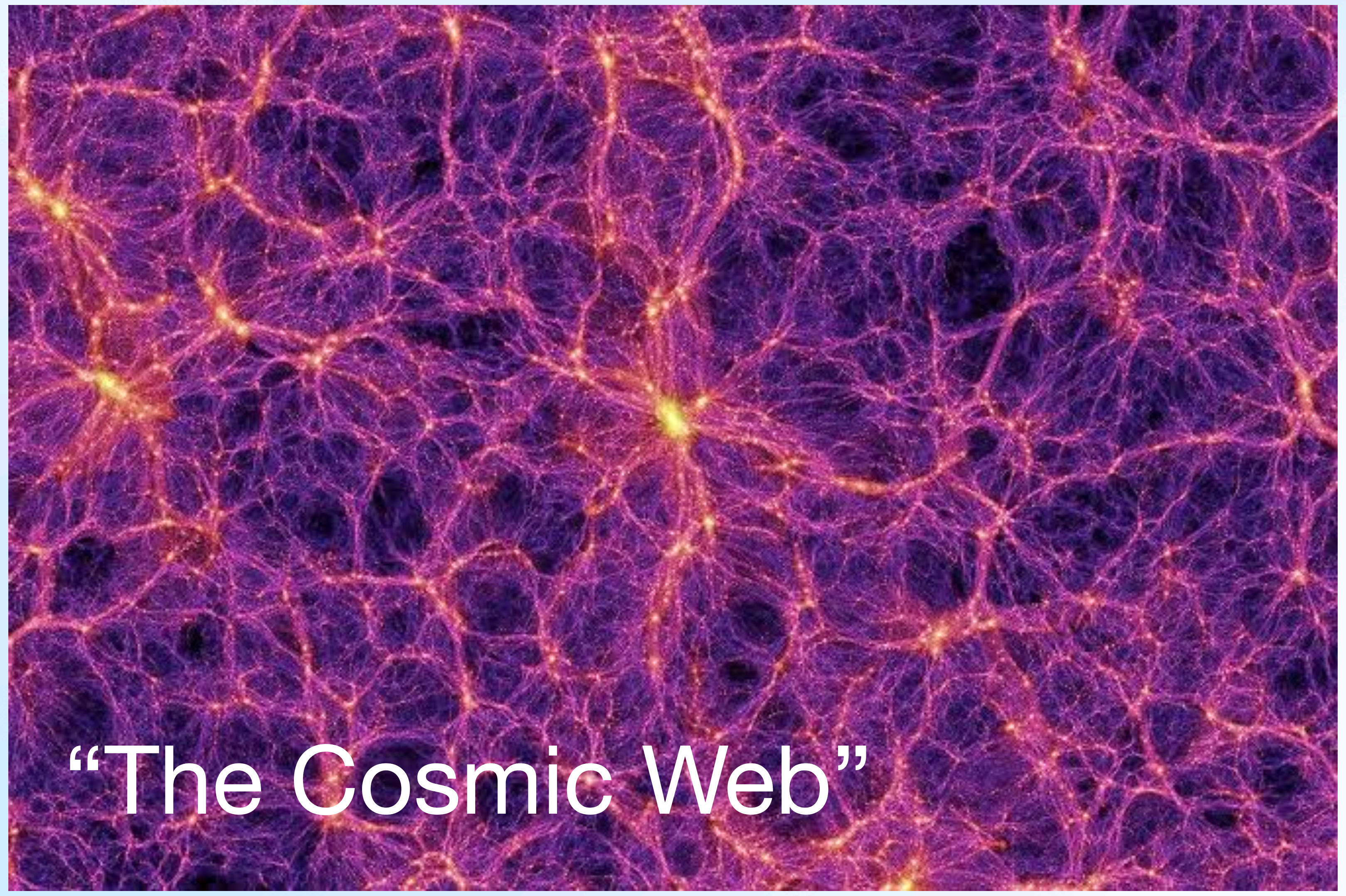
The long-range Yukawa forces, if much stronger than Gravity $\beta^2 = F_y/F_g \gg 1$, *can efficiently form structures, halos, and black holes in the very early universe.*

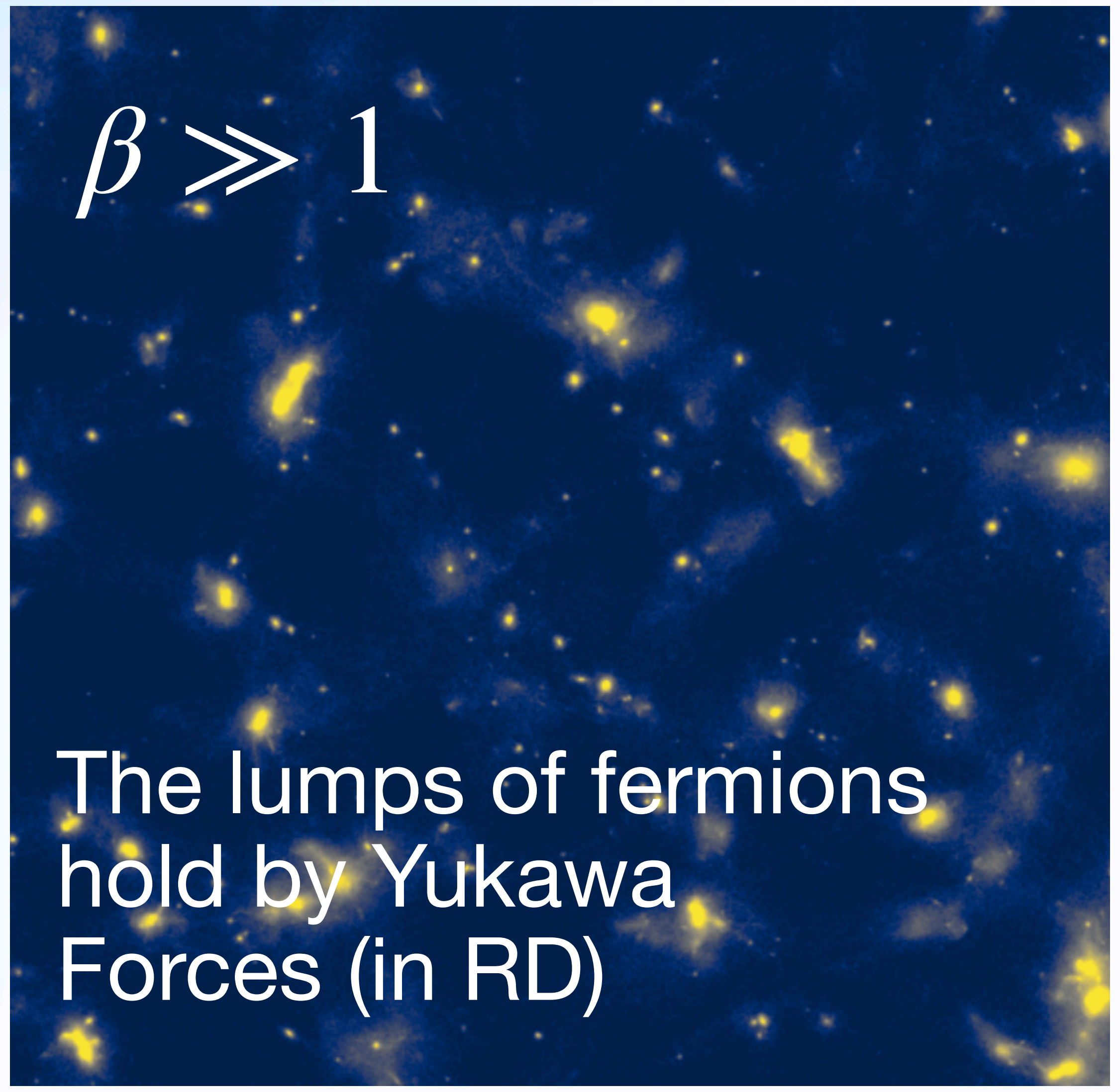
DM&DE Interaction?

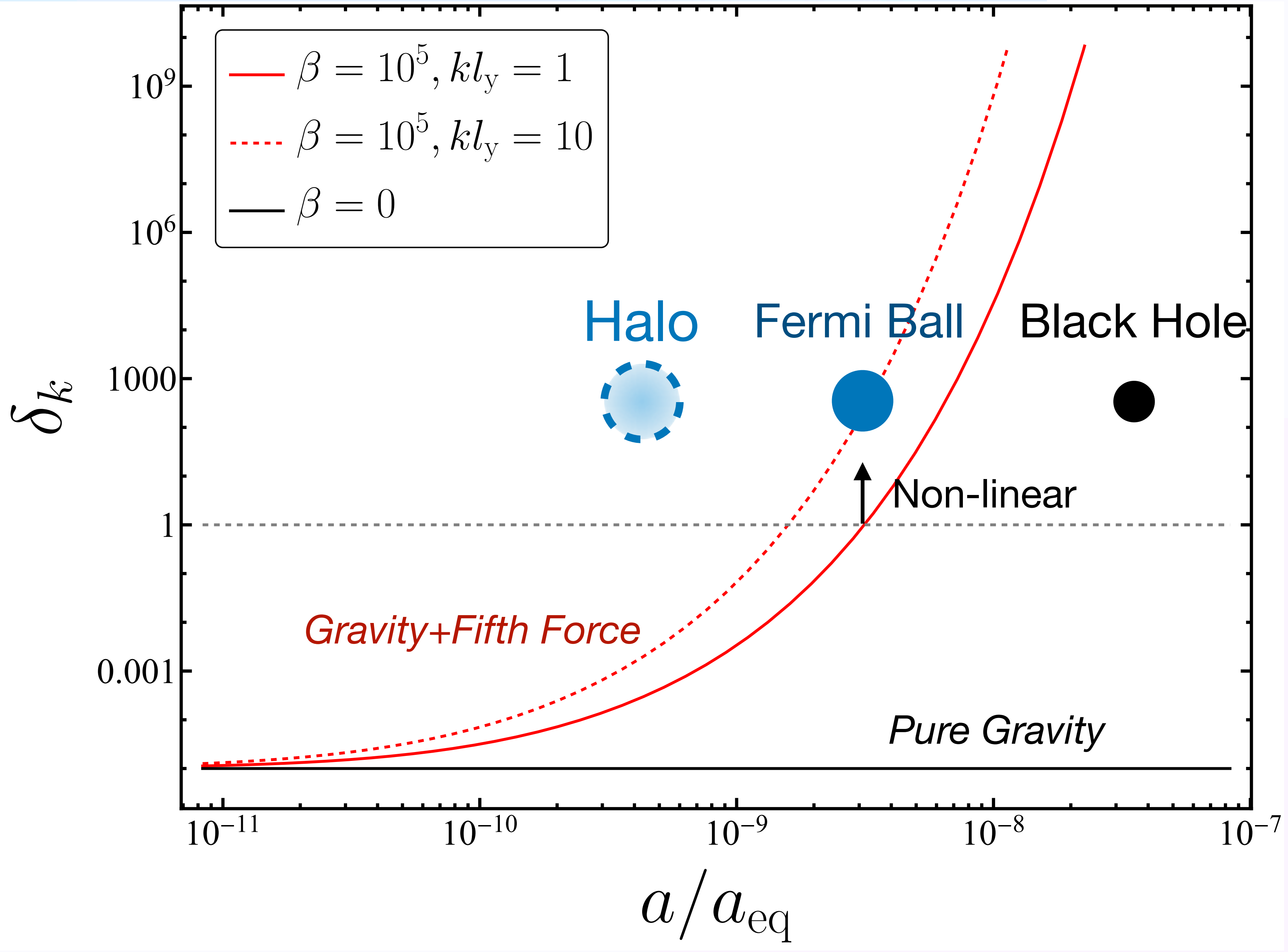


Credit. Domenech

$$\ddot{\delta}_k + 2H\dot{\delta}_k - \frac{3}{2}H^2\Omega_\psi\left(1 + \frac{2\beta^2}{1+(kl_y)^{-2}}\right)\delta_k = 0$$



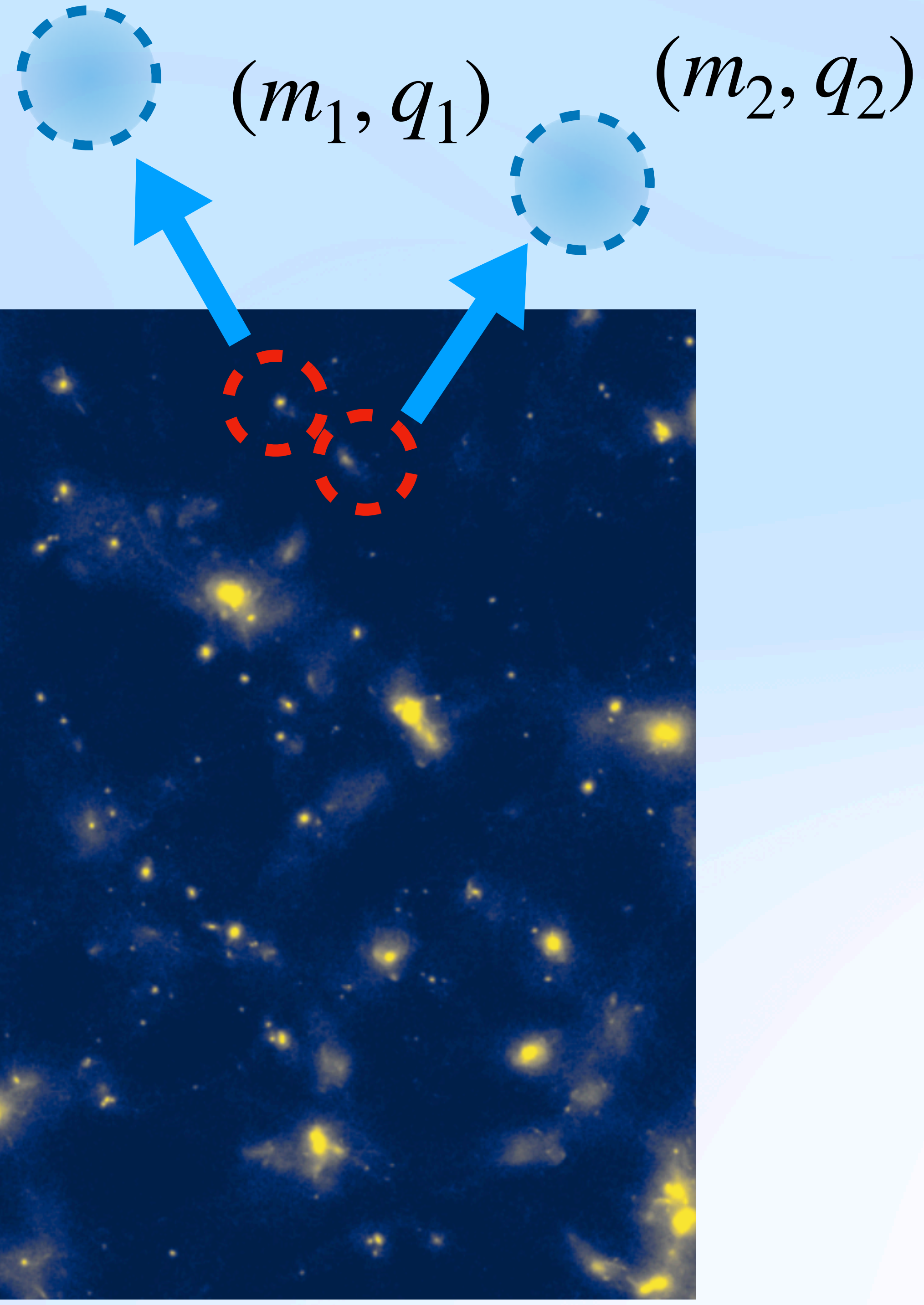




Domenech, Inman, Kusenko and Sasaki, 2023 & Inman, 2025

Early halo formation: Theory

Something is not yet considered..



For two fermionic minihalos:

$$F_G = \frac{G q_1 q_2 m_\psi^2}{d^2}$$

$$F_y = \frac{y^2 q_1 q_2}{4\pi d^2} e^{-m_\phi d}$$

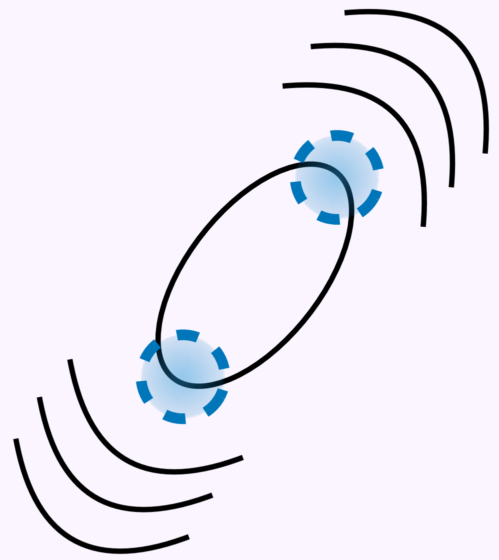
$$\frac{F_y}{F_G} \sim \frac{y^2}{G m_\psi^2} = 2\beta^2$$

Attractive Potential V.S. Hubble Flow

$$\mu H^2 d^2 - \frac{G m_1 m_2}{d} - \frac{y^2 q_1 q_2}{d} < 0$$

$\rightarrow$ Isolated Bound System

\+ Tidal Force $\rightarrow$

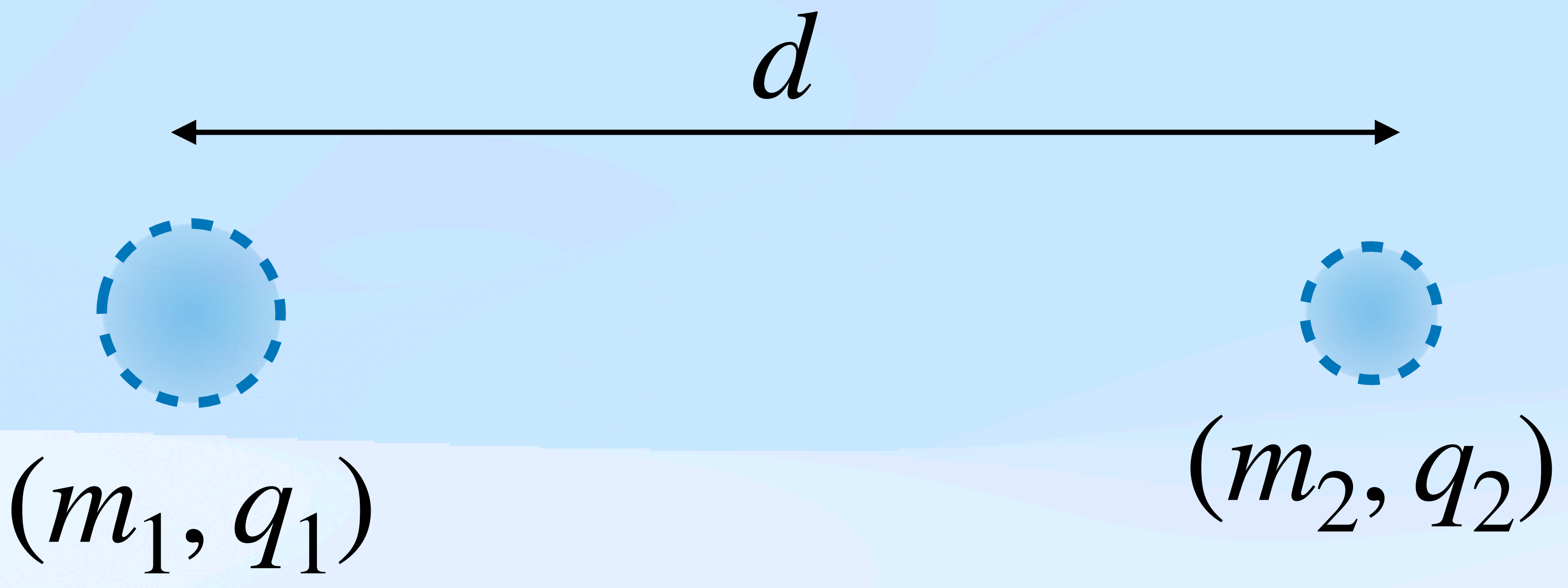


Xinpeng Wang (Kavli IPMU)

Radiations from halo binaries:

GW and SW from the Halo Inspirals

The simplest case: $dm_\phi \ll 1 \qquad \frac{F_y}{F_G} = 2\beta^2$



$$P_{\rm GW} \propto G\,|\dddot{Q}_g^{ab}|^2\,.$$

$$P_{\rm SW} \propto y^2\,|\dddot{Q}_q^{ab}|^2\,.$$

Quadrupole **Scalar Waves** and **Gravitational Waves** are radiated at the same time.

(Dipole momentum vanishes)

Gravity V.S. Yukawa Forces

	Gravitationally-Bound	Yukawa-Bound
Strain h_z	$\frac{4}{d_L c^4}\left(\pi f_z\right)^{2/3}\left(G\mathcal{M}_z\right)^{5/3} \quad (\star)$	$(\star) \times \left(2\beta^2\right)^{2/3}$
Frequency $f_z = f/(1+z)$	$\frac{1}{\pi(1+z)}\sqrt{\frac{G(m_1+m_2)}{a^3}} \quad (\circ)$	$(\circ) \times \sqrt{2\beta^2}$
Orbital Evolution df_z/dt_z	$\frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}_z}{c^3}\right)^{5/3} f_z^{11/3} \quad (\triangle)$	$(\triangle) \times \left(2\beta^2\right)^{5/3}$

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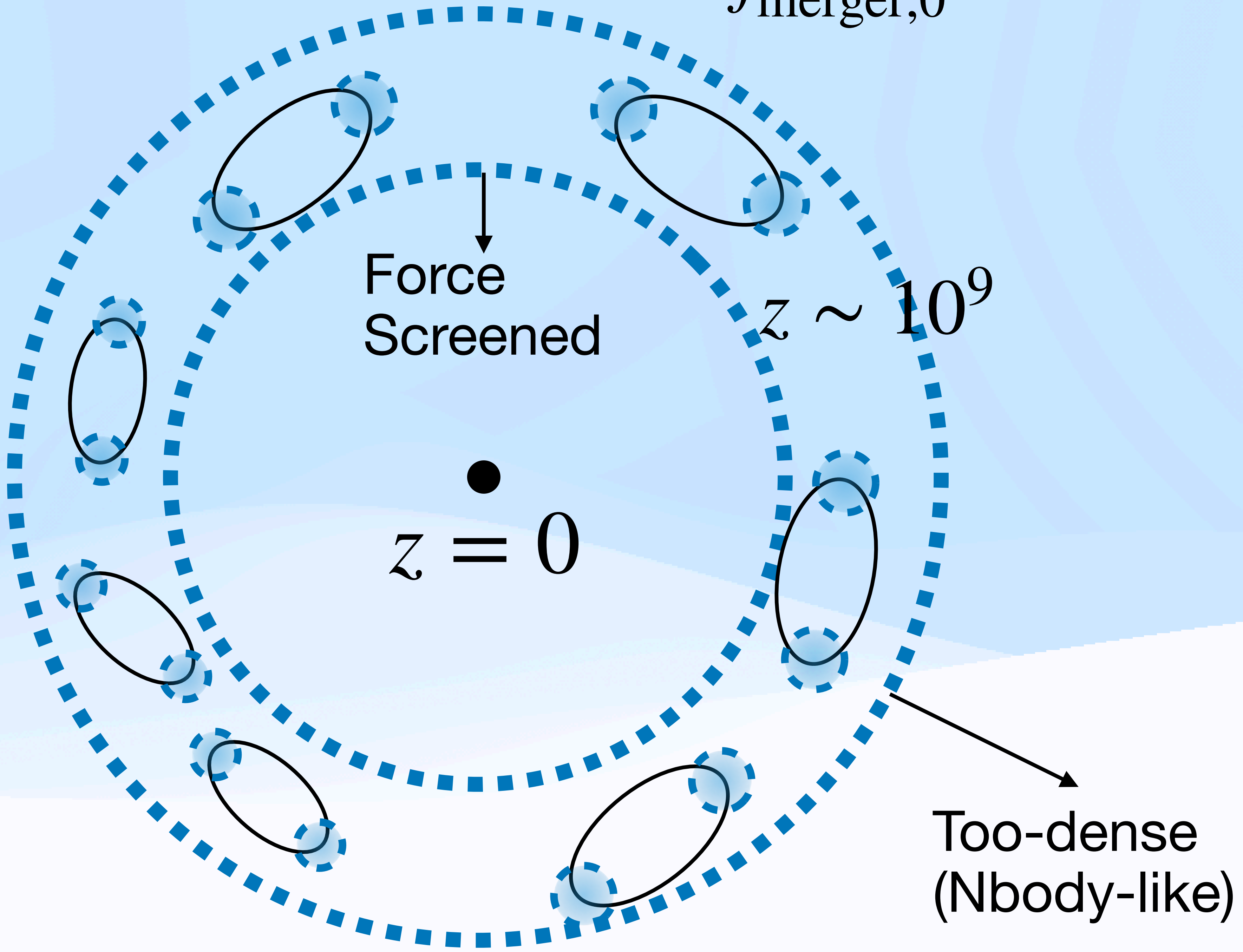
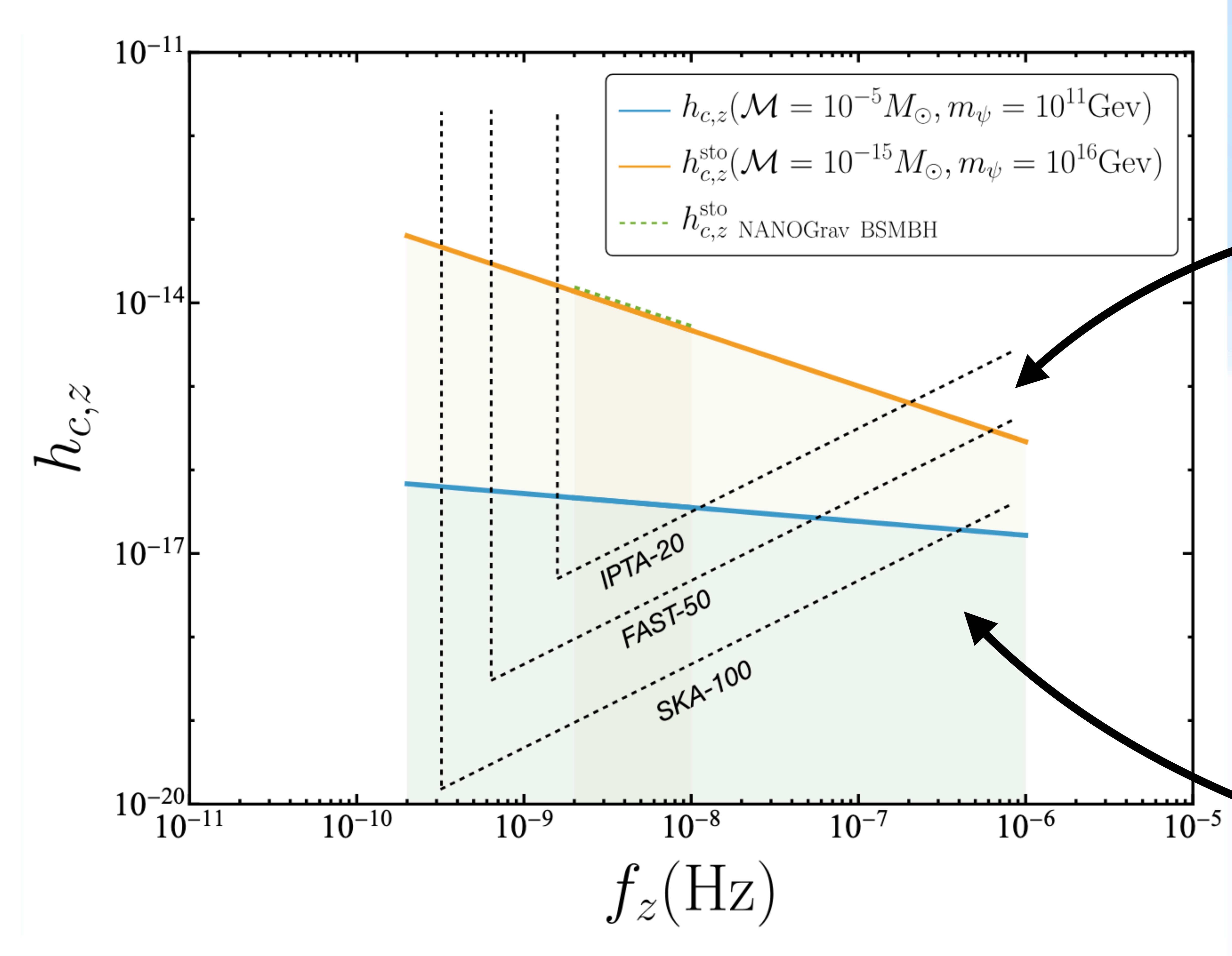
Radiations from halo binaries:

Individual event & stochastic background

The fraction of merger relics in dark matter

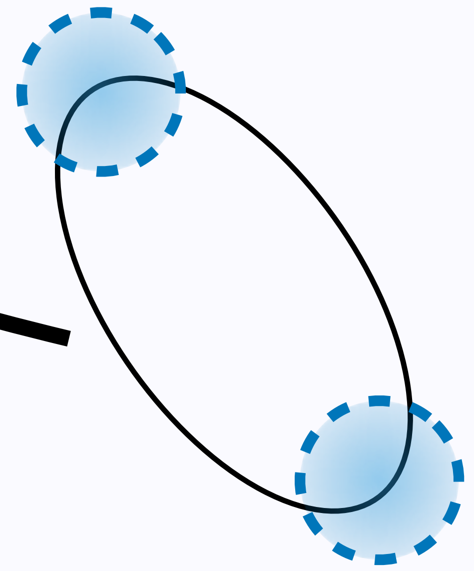
$f_{\text{merger},0} = 10^{-6}$





NANOGrav Collaboration, 2023

Stochastic GWB @ $z = 10^9 \pm \delta z$



Single Event @ $z = 10^9$

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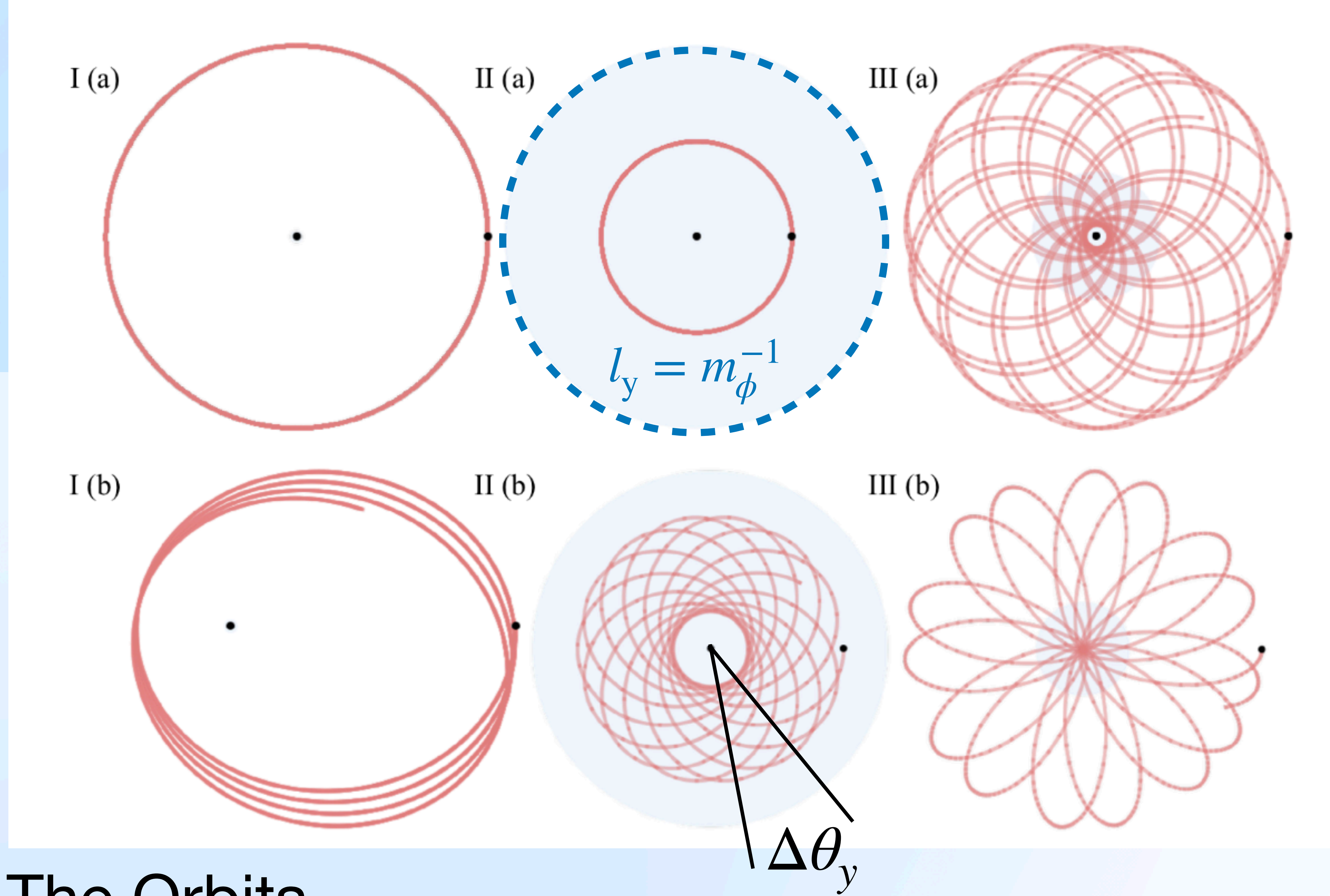
Radiations from halo binaries:

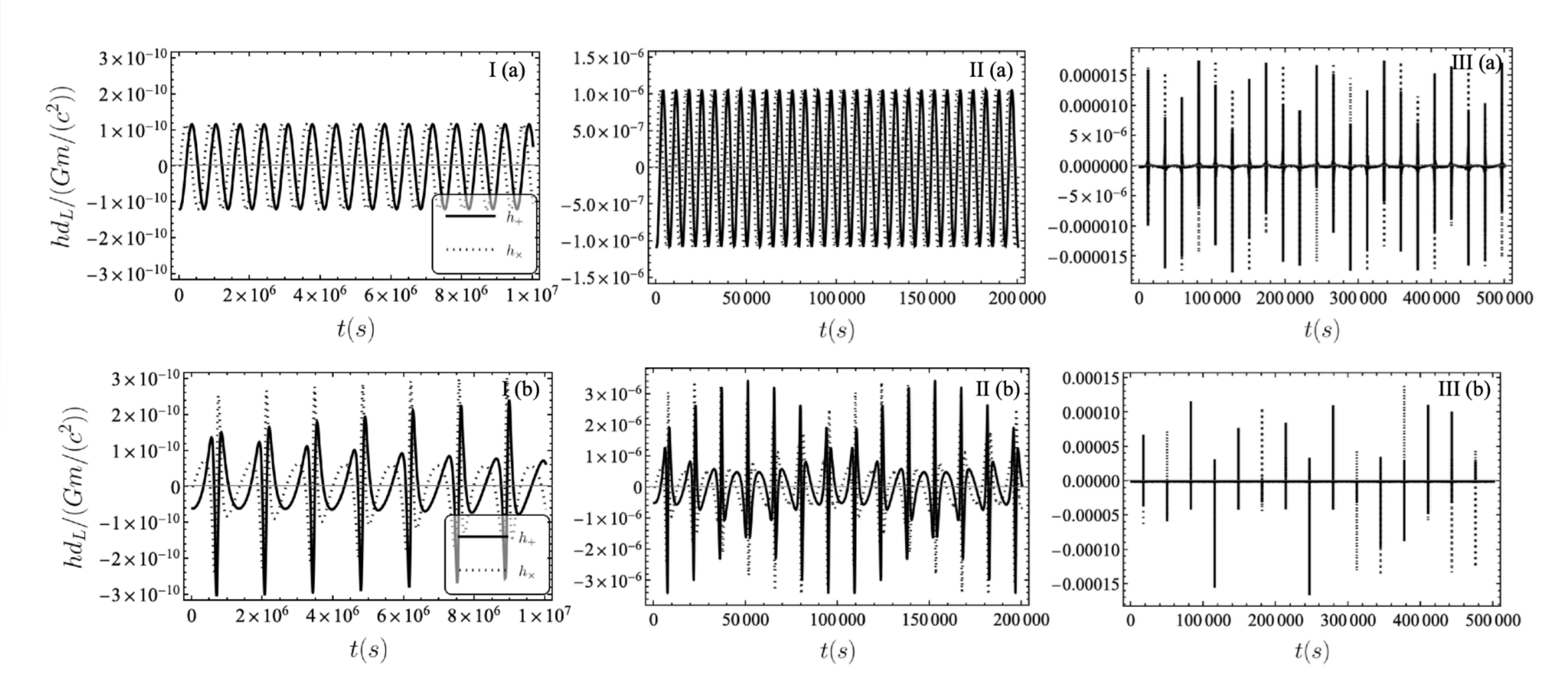
A Smoking Gun: The Precession of the Orbit

If we consider the potential with Screening:

$$V = -\frac{1}{r}\left(Gm_1m_2 + \frac{y^2q_1q_2}{4\pi}e^{-m_\phi r}\right).$$



The Orbits



The GW Strain

The Precession Angle per orbit $\Delta\theta_{GR} \sim \dfrac{GM}{r(1-\epsilon^2)c^2}$ (1PN) $\Delta\theta_y \sim 2\pi\left(\sqrt{\dfrac{1+r/l_y}{1+r/l_y-(r/l_y)^2}}-1\right)$ (0PN)

Cooling of the halo

Flores, Kusenko 2021
Flores, Lu, Kusenko 2023

After virialization…

Without dissipation, halos will remain virialized until the constituent particles decay…

sparse

I. Radiation from non-relativistic incoherent motions

II. Radiation from $\psi - \psi$ bremsstrahlung

(Bound state formation)

III. Radiation from the surface

dense

If Asymmetric: $\eta_\psi = (n_\psi - n_{\bar{\psi}})/s \neq 0$

Fermi Ball Formation

Black Hole Formation

Halo Annihilation

The loss of scalar charge of the halo

If the degeneracy pressure cannot support anymore…

The 'Chandrasekhar Mass' for strong force:

$$m_{\mathrm{h}} > m_{\mathrm{critical}} \sim \frac{M_{\mathrm{pl}}^2}{m_\psi}$$

A black hole will form eventually!

"No hair theorem"

$q = q_{\mathrm{initial}}$ $\qquad$ $q = 0$

If the degeneracy pressure can still support the fermi ball…

Scalar condensation

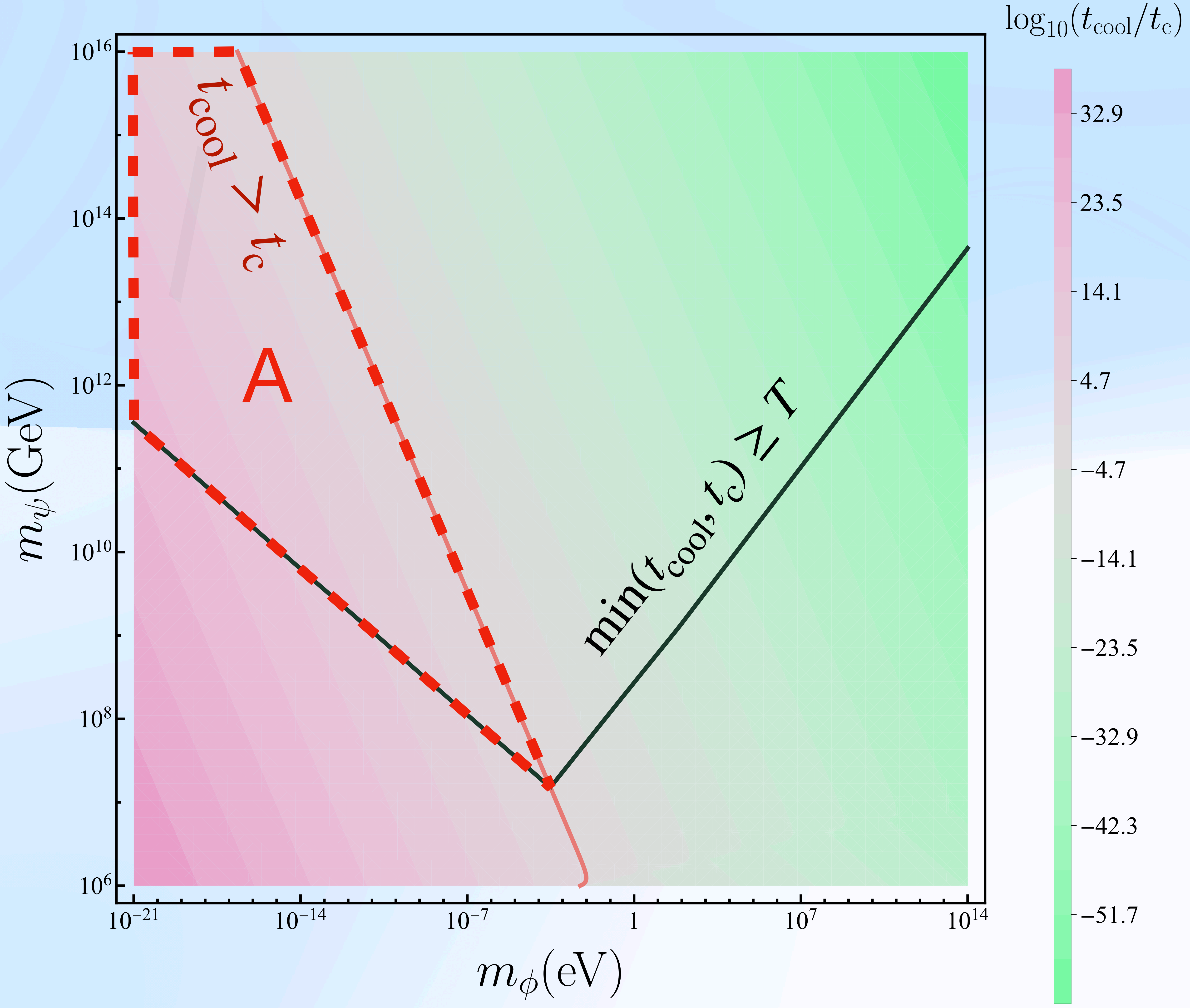
$$m_{\phi,\mathrm{eff}}^2 = V_{,\phi\phi} - y\frac{\partial\langle\bar{\psi}\psi\rangle}{\partial\phi} \uparrow$$

$\lambda\phi^4$ $\qquad$ $m_{\psi,\mathrm{eff}}^2(\phi)$

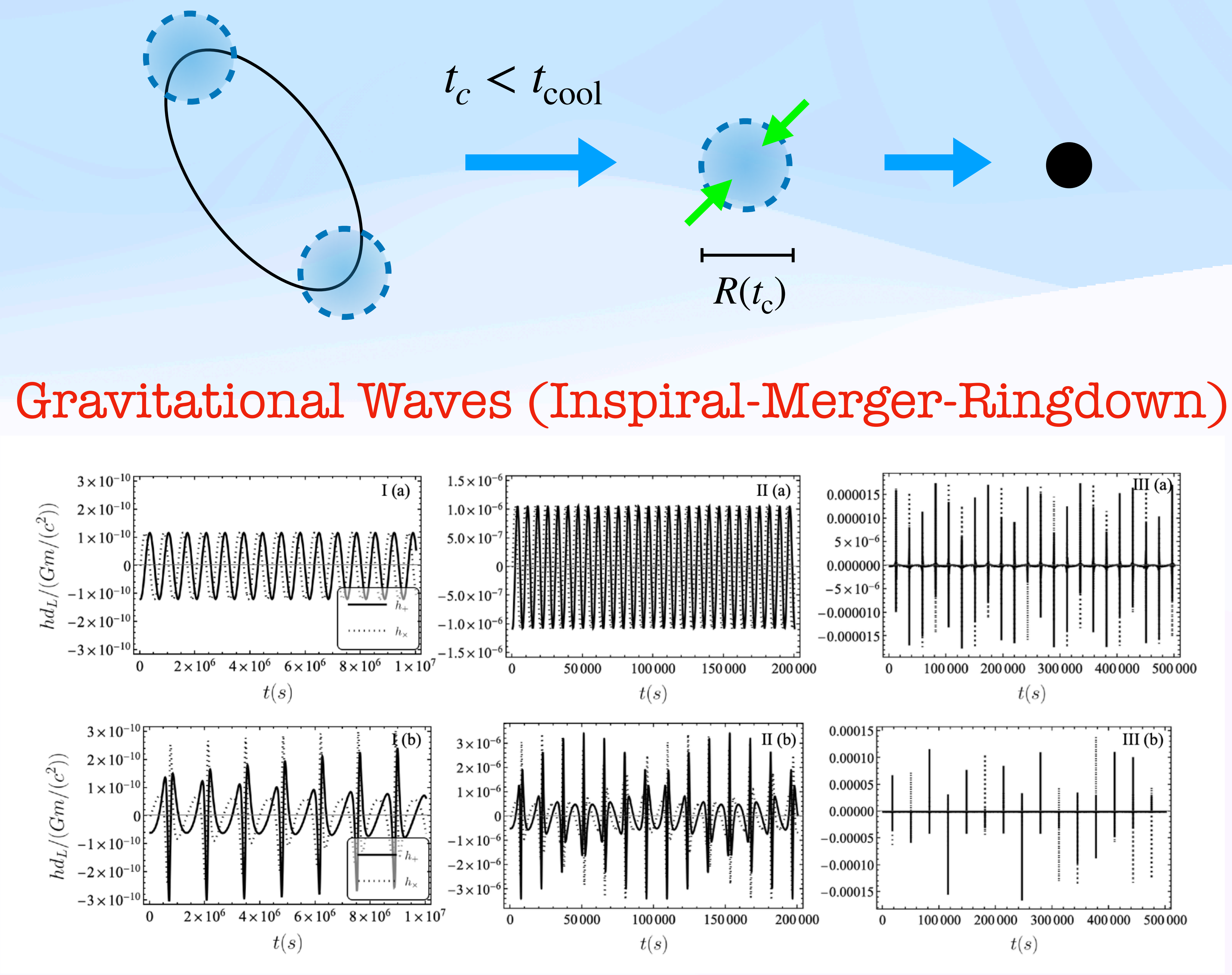
Force/ Charge Screened

Xinpeng Wang (Kavli IPMU)

Comparing the time scale

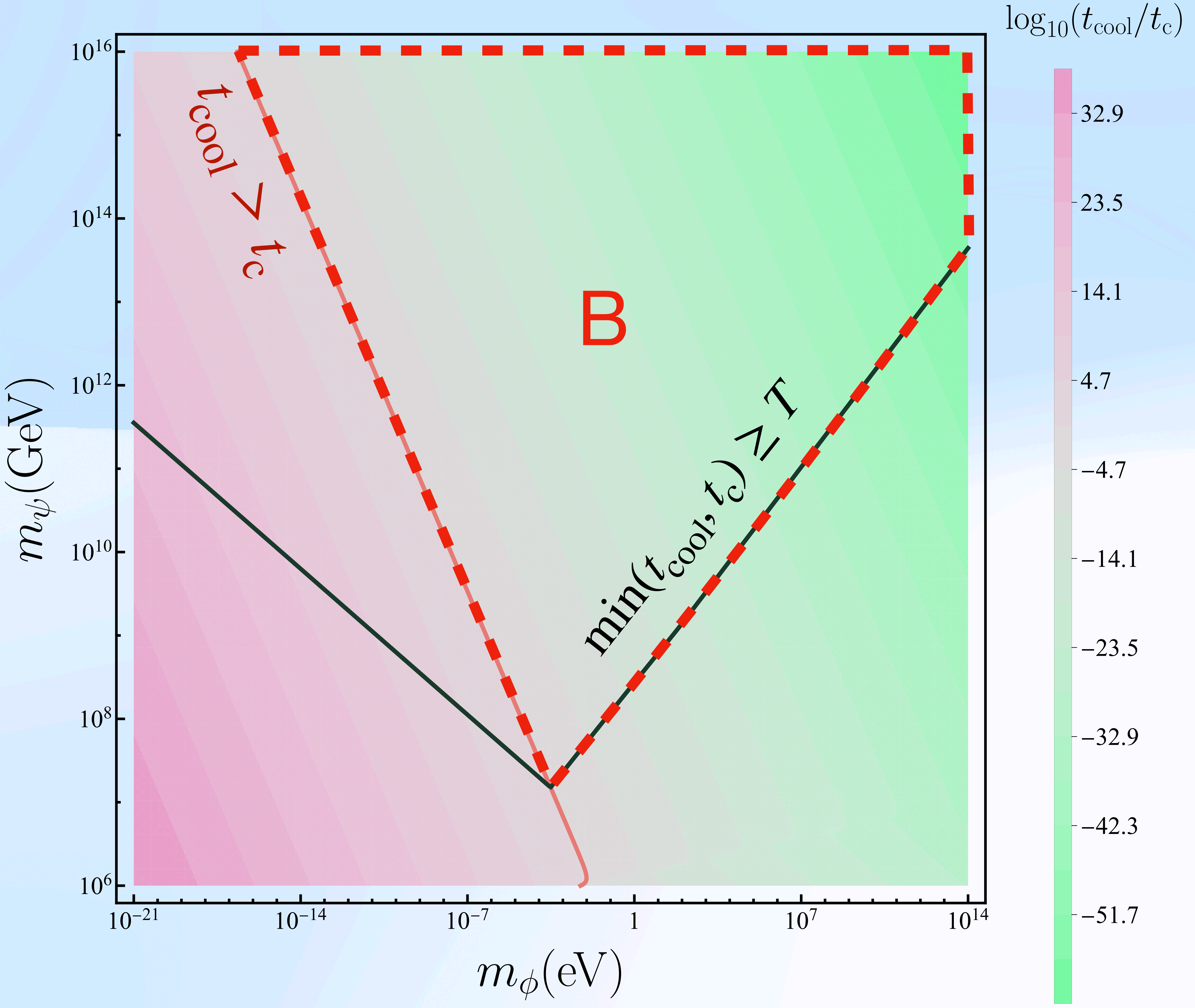


Complete Merger

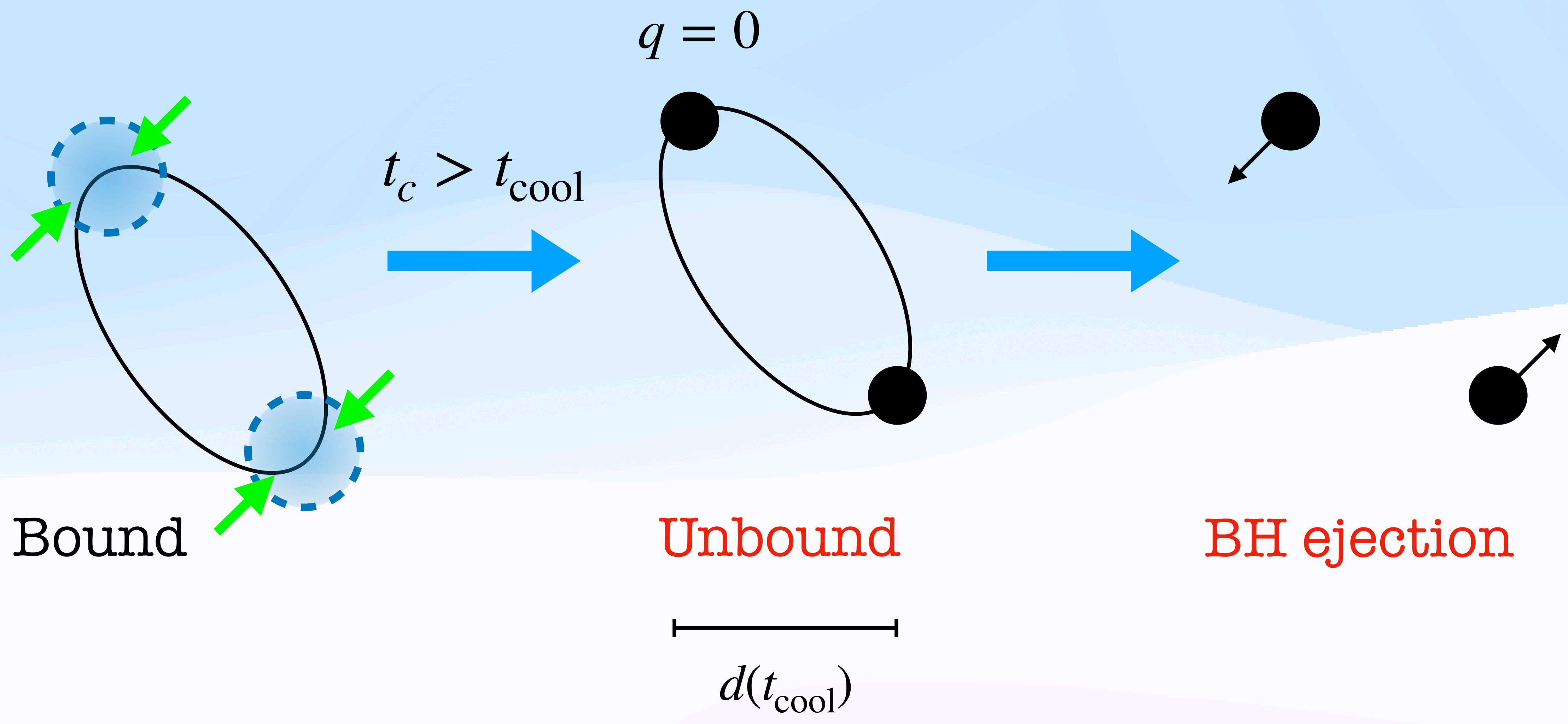


Xinpeng Wang (Kavli IPMU)

Comparing the time scale



Interrupted Merger

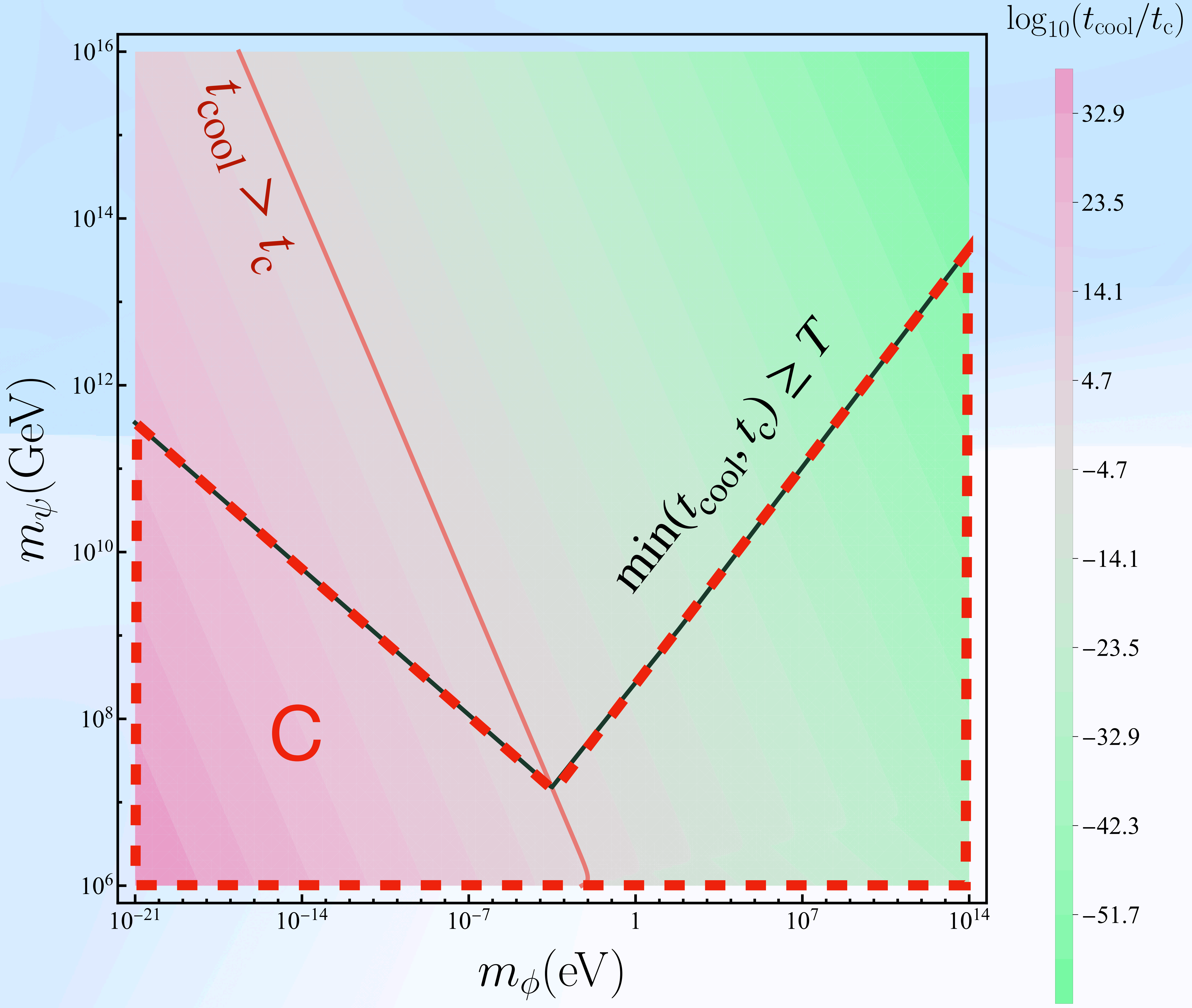


$E_y \rightarrow E_k$ Ejection @ $v_{\rm rel}$

$$v_{\rm rel} \sim \sqrt{\frac{4G(m_1+m_2)\beta^2}{d}} \rightarrow 1 \text{ when } y^2 \sim \frac{m_\psi}{m_\phi q}$$

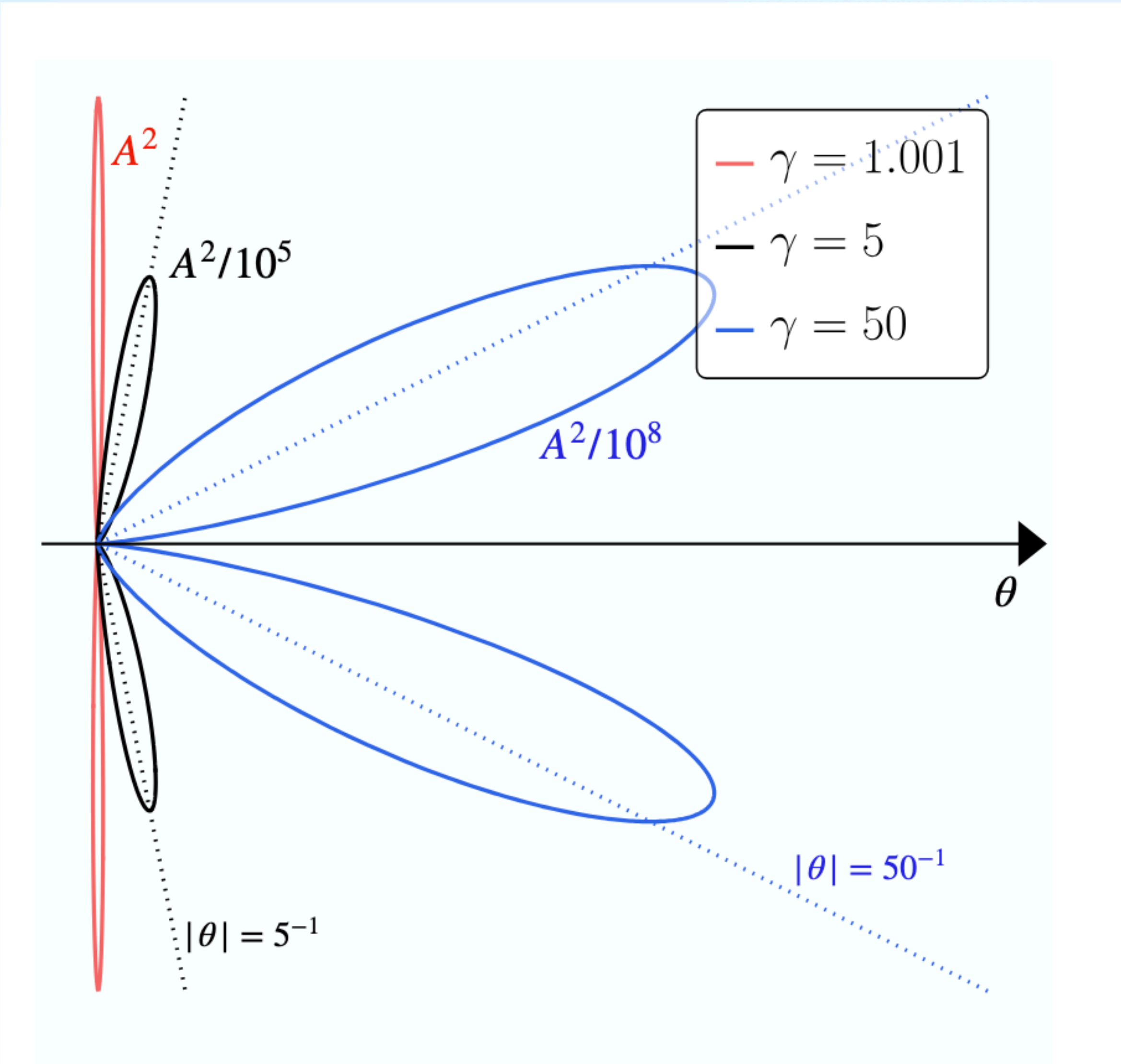
Free-Floating Planets in Micro-lensing?

Comparing the time scale



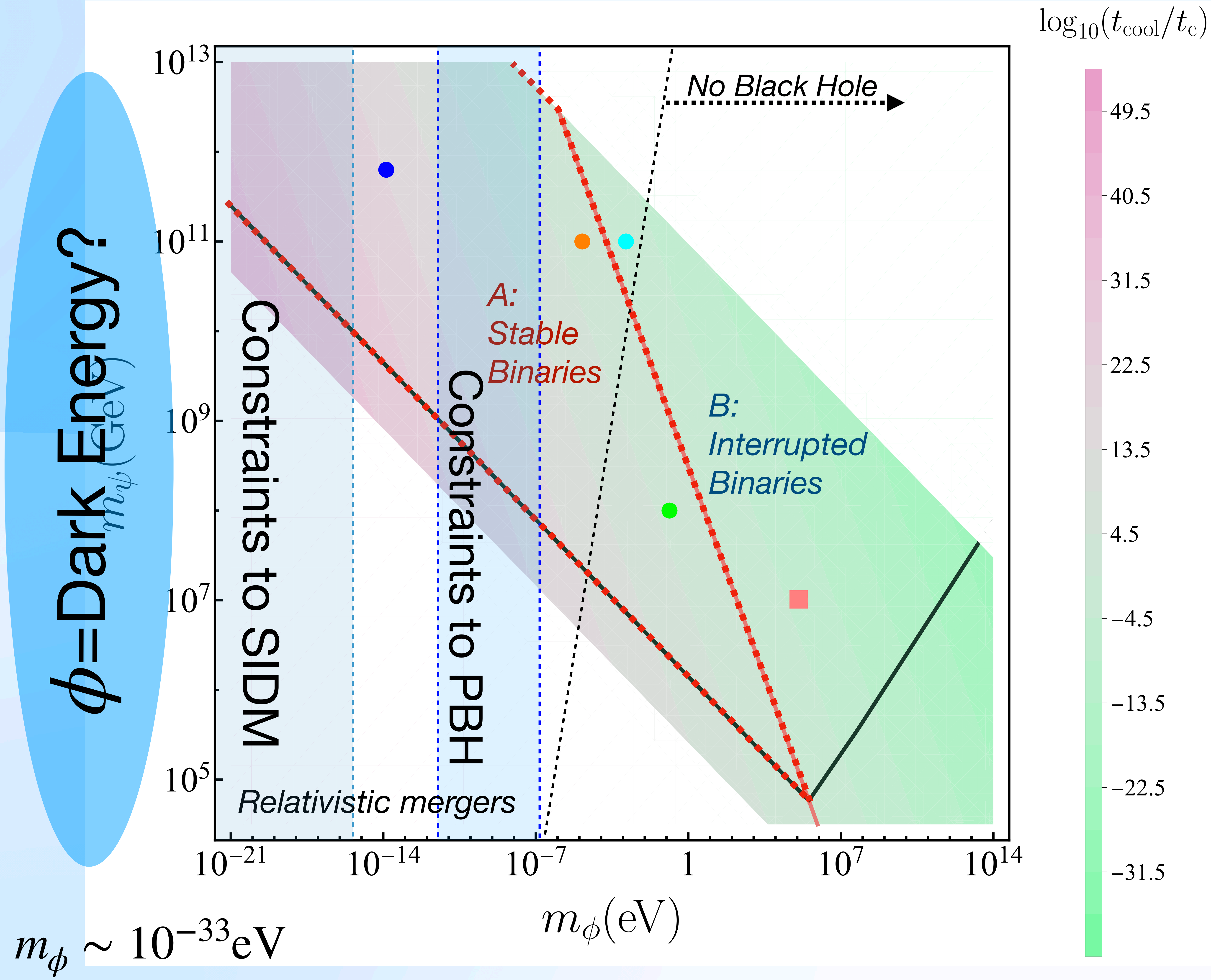
Prompt Merger

The merger concludes before completing a full orbital period.

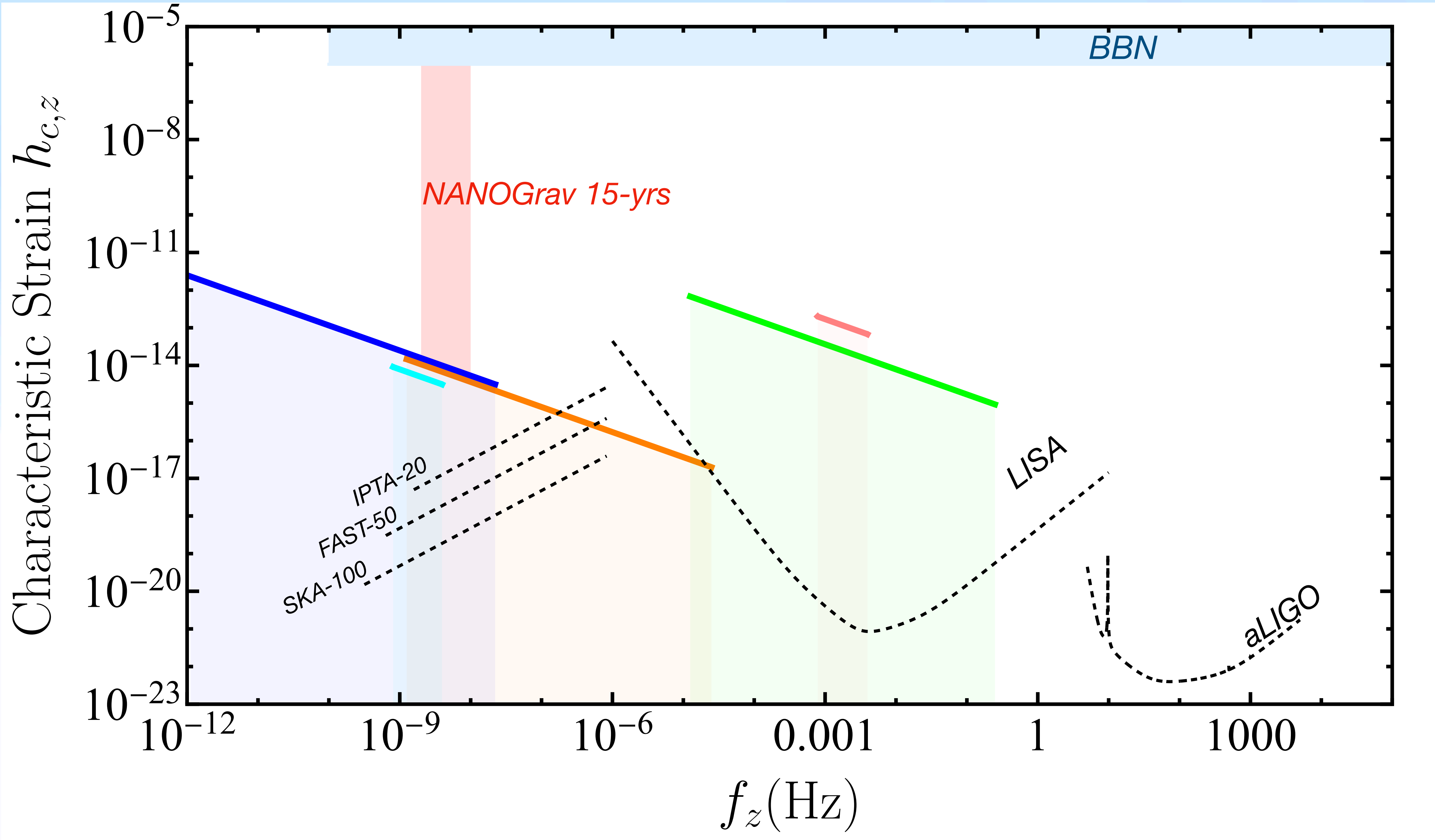


Gravitational Wave Burst

A plot of parameter space constraints



$m_\phi \sim 10^{-33}$eV



GWB comes from the minihalo Inspirals

Summary of the Summary

I. **Primordial Black Holes (PBHs)** are promising dark matter candidates.

II. They can form from enhanced small-scale primordial density perturbations, from attractive interactions among dark matter particles, or through other non-standard early-Universe mechanisms…

III. PBHs also act as sources of **gravitational waves** across a wide range of frequency bands, offering distinctive signals that can be probed by future experiments.