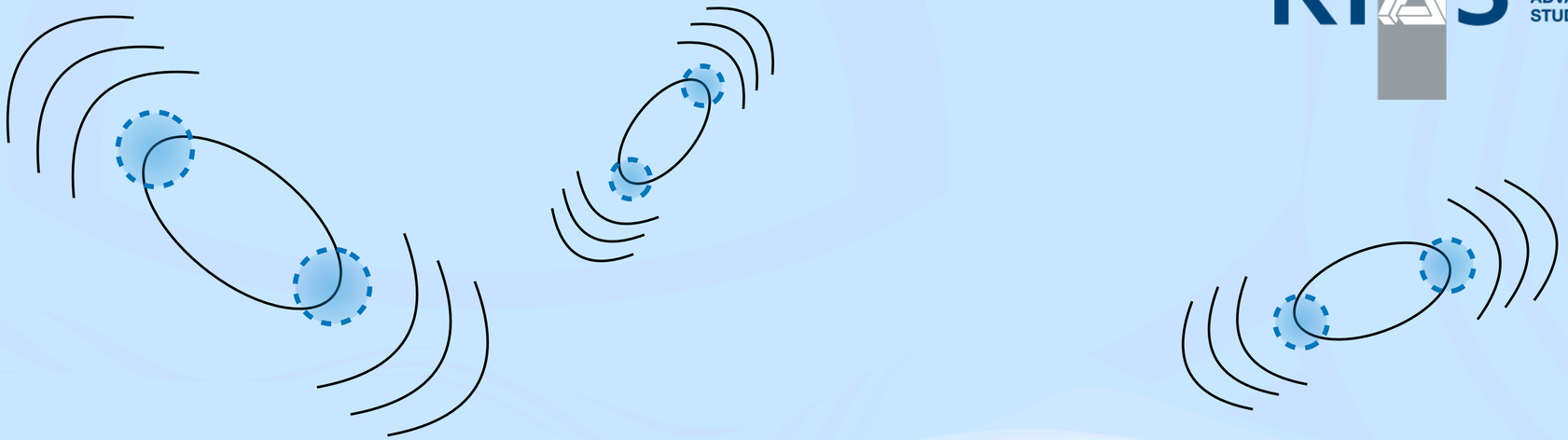


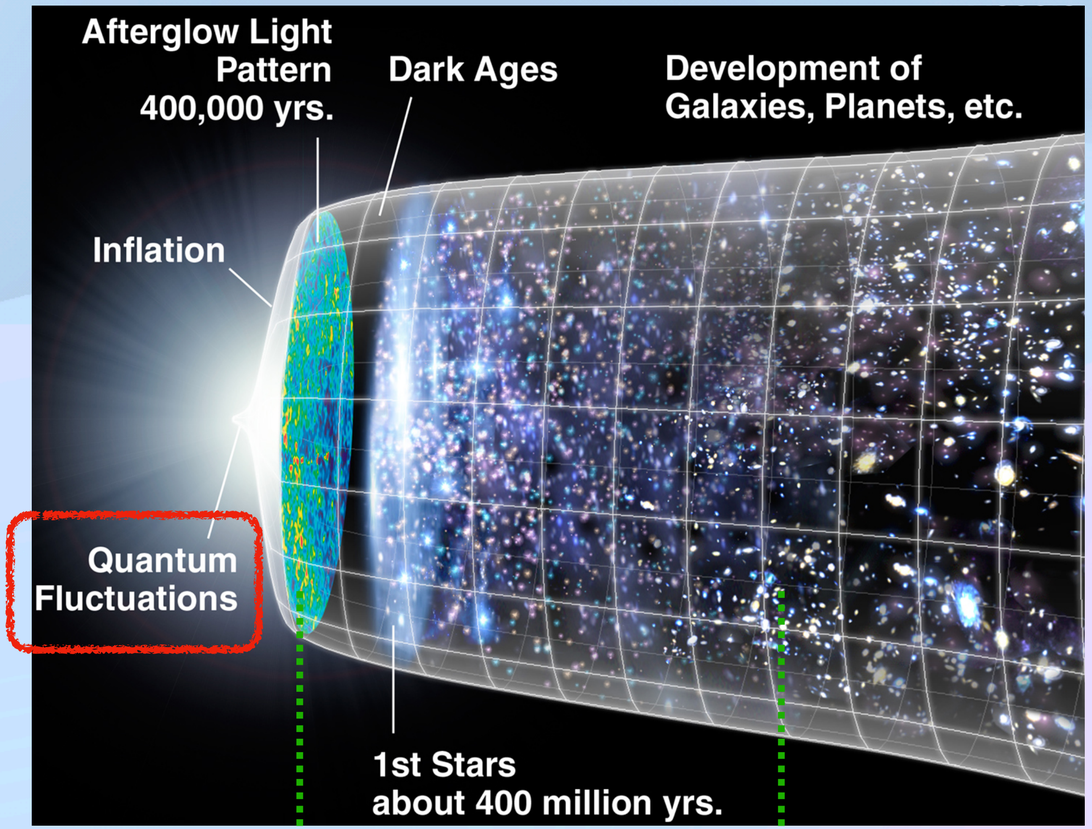
Gravitational Waves from the Early Universe:

A Primordial Black Hole Perspective

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

O. A Brief Introduction to Inflation and Primordial Black Holes

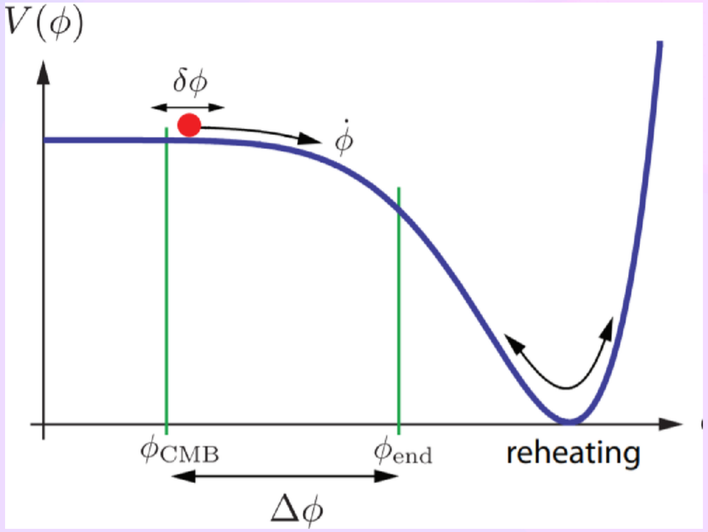
Inflation



Cosmic Microwave Background (z=1100) Isotropic & Homogeneous

Large Scale Structure (z<10)

Inflation (A primordial phase before Big Bang)
A phase of <u>semi-exponential accelerating expansion of space</u> solving the monopole, horizon, and flatness problems.

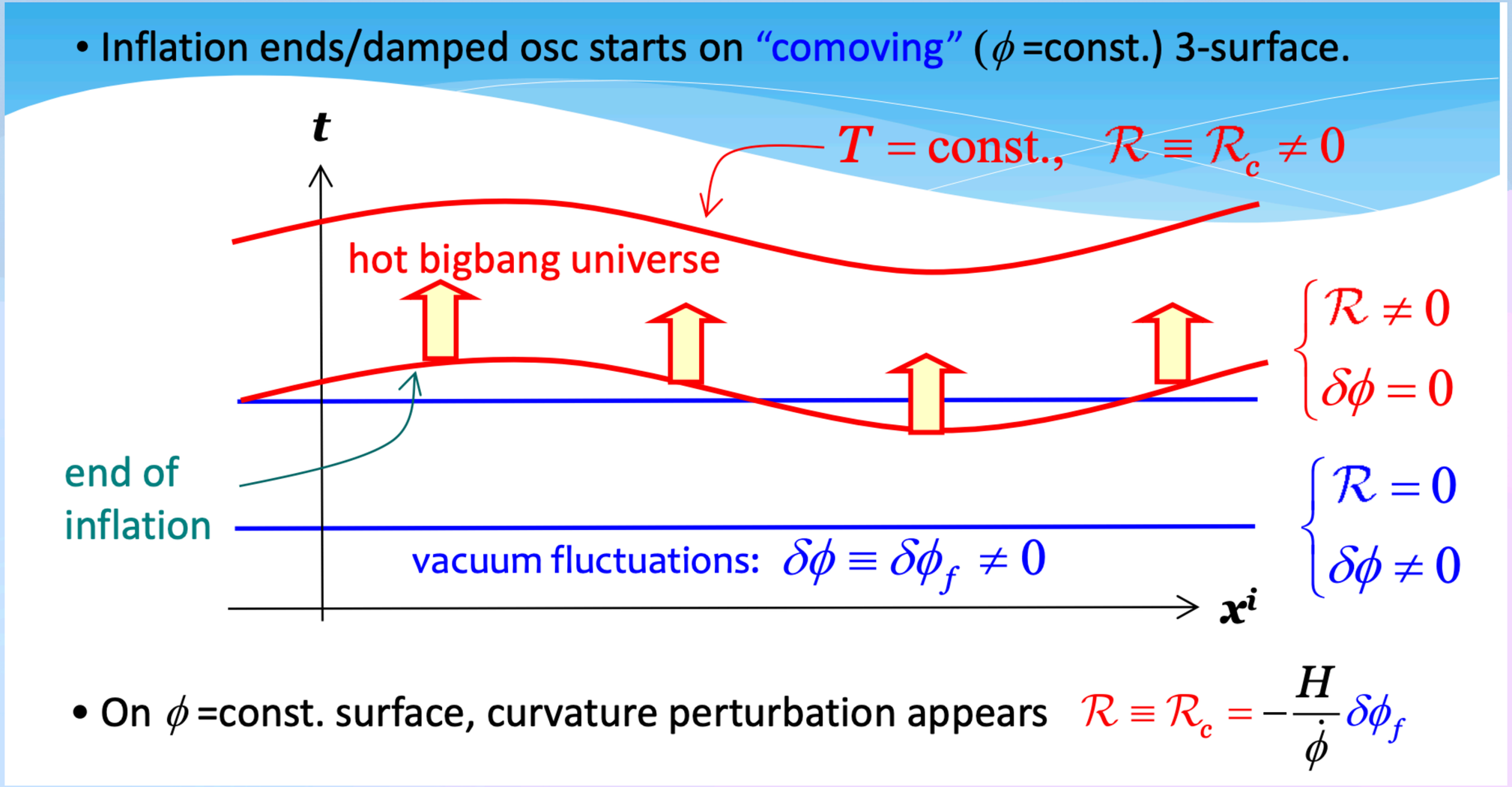


Growth of scale factor

$$\frac{a_{\rm end}}{a_{\rm CMB}} = e^{50\sim60}$$

Single field slow-roll inflation (Linde, 1983, ….)

From field perturbation $\delta\phi$ to curvature perturbation

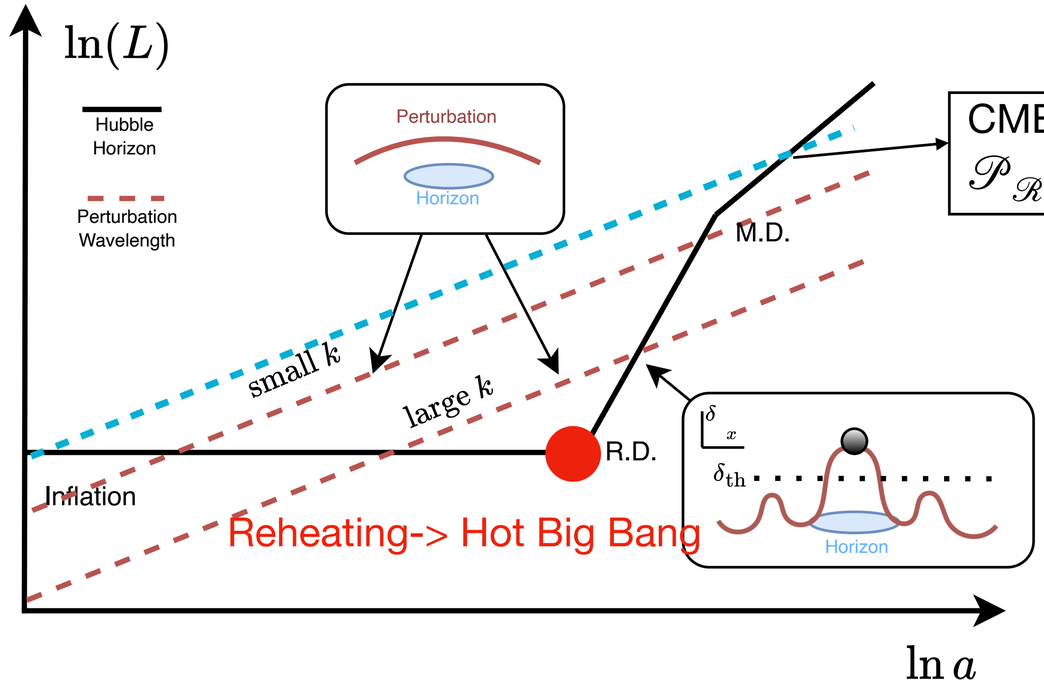


Credit. Misao Sasaki

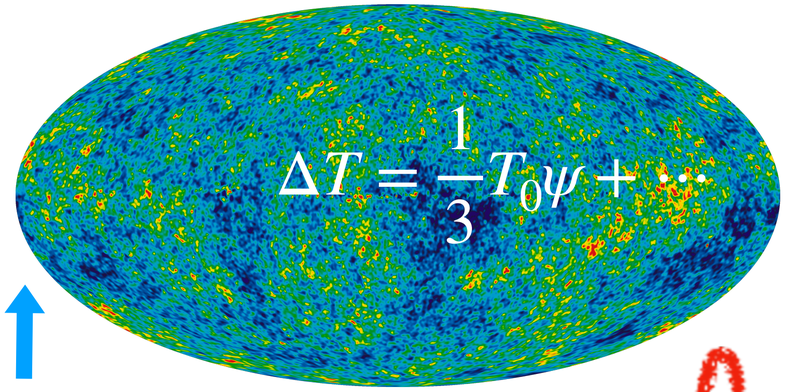
Xinpeng Wang (Kavli IPMU)

Primordial Black Hole seeded from Inflation

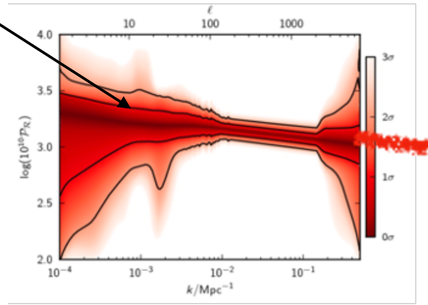
Hubble Radius VS scale factor

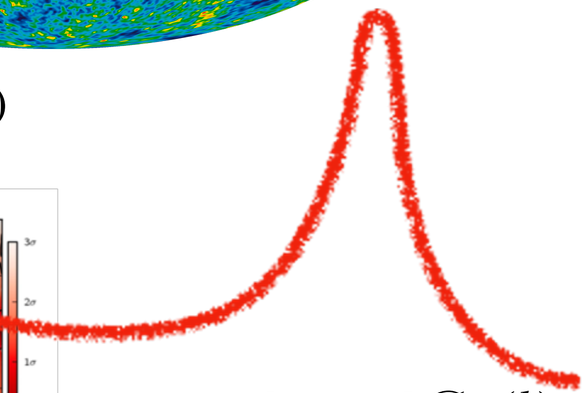


CMB
$\mathscr{P}_{\mathscr{R}}(k) \sim 10^{-9}$



Observed $\mathscr{P}_{\mathscr{R}}(k)$ @ Large scale





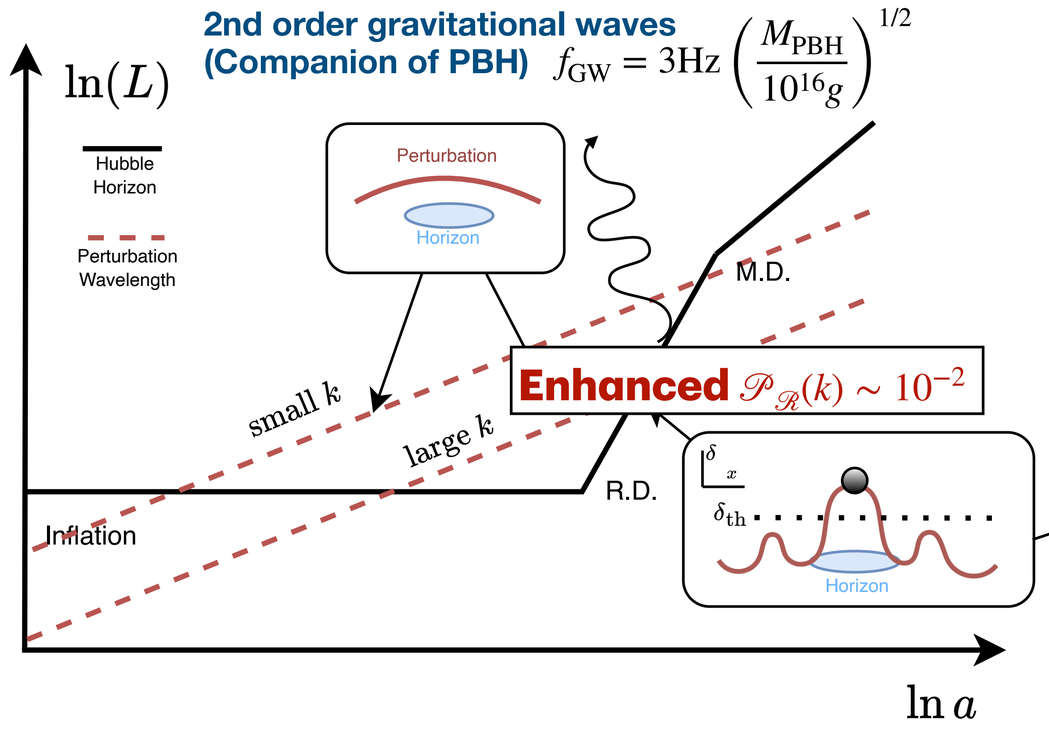
Enhanced $\mathscr{P}_{\mathscr{R}}(k)$ @Small scale

The Planck Collaboration, 2018 (1807.06209)

Xinpeng Wang (Kavli IPMU)

Primordial Black Hole seeded from Inflation

Hubble Radius VS scale factor

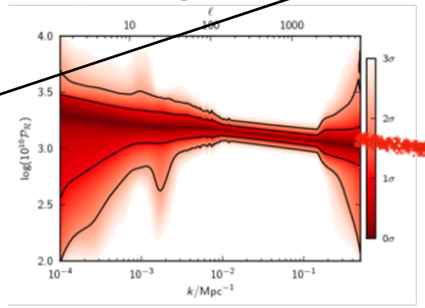


$$\delta \propto k^2 R^2 \mathcal{R} \gtrsim \delta_{\rm th}$$

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

Our Goal!!

Observed $\mathcal{P}_{\mathcal{R}}(k)$ @ Large scale



Enhanced $\mathcal{P}_{\mathcal{R}}(k)$ @Small scale

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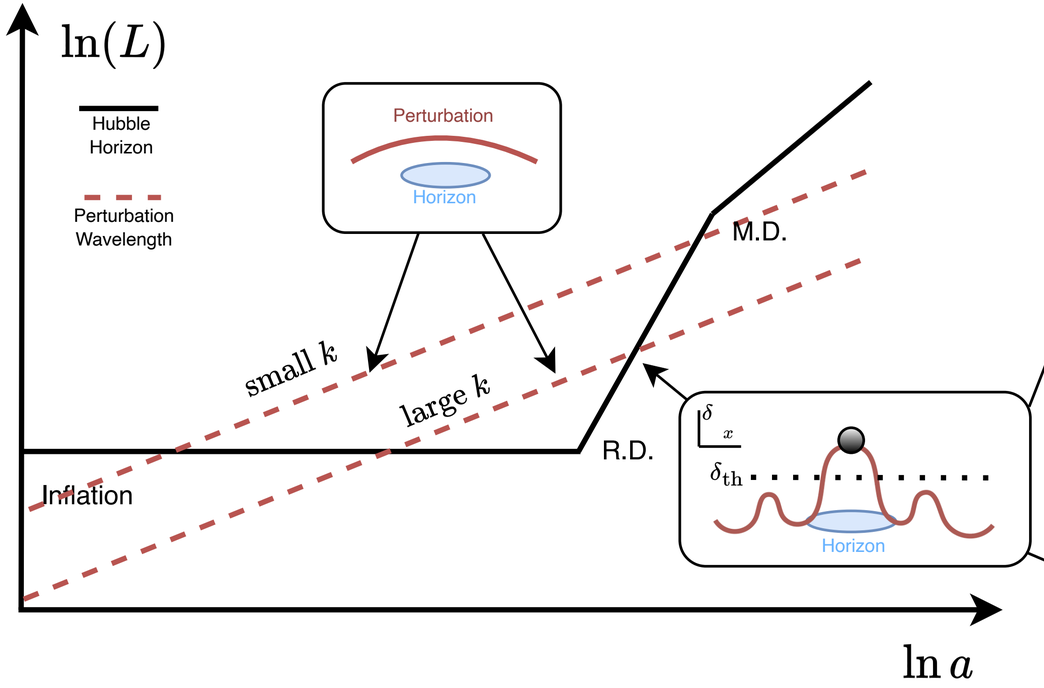
Xinpeng Wang (Kavli IPMU)

Primordial Black Hole seeded from Inflation

Hubble Radius VS scale factor



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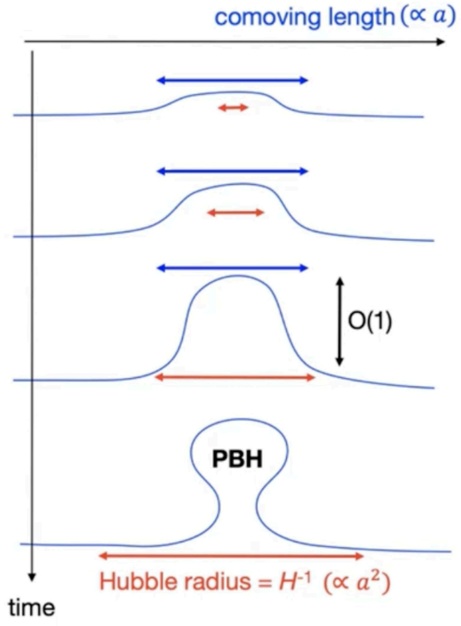
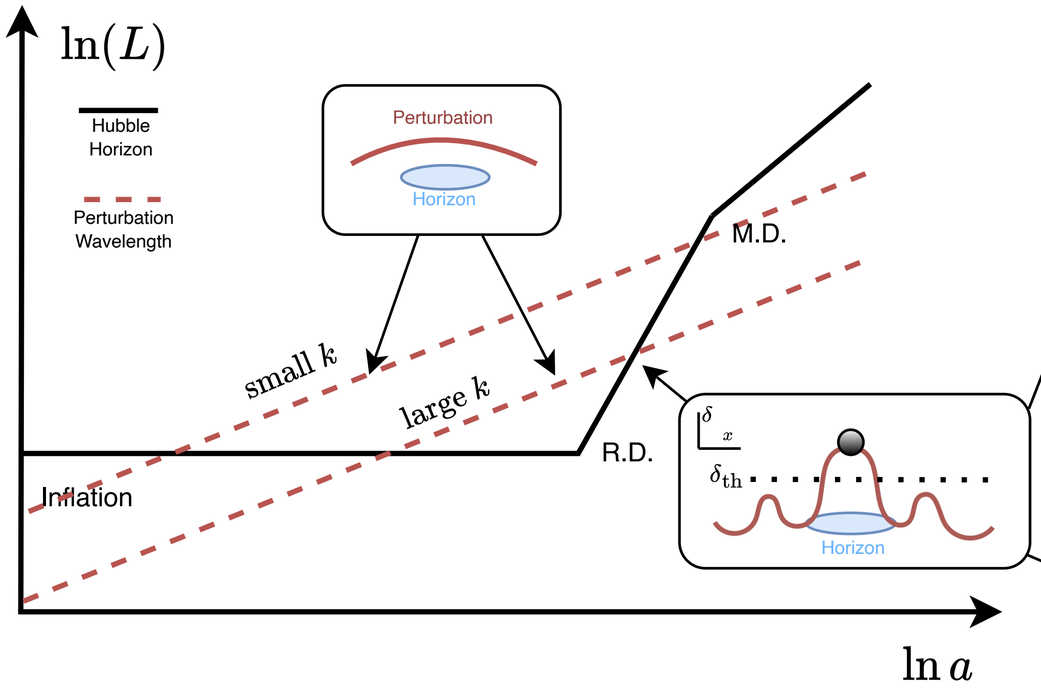


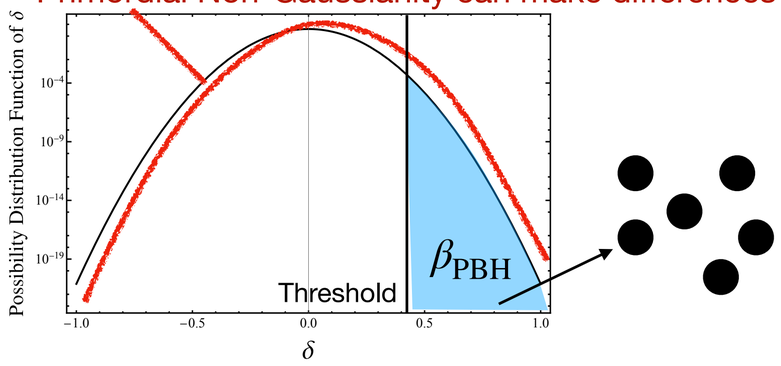
Xinpeng Wang (Kavli IPMU)

Primordial Black Hole seeded from Inflation

Hubble Radius VS scale factor



Primordial Non-Gaussianity can make differences

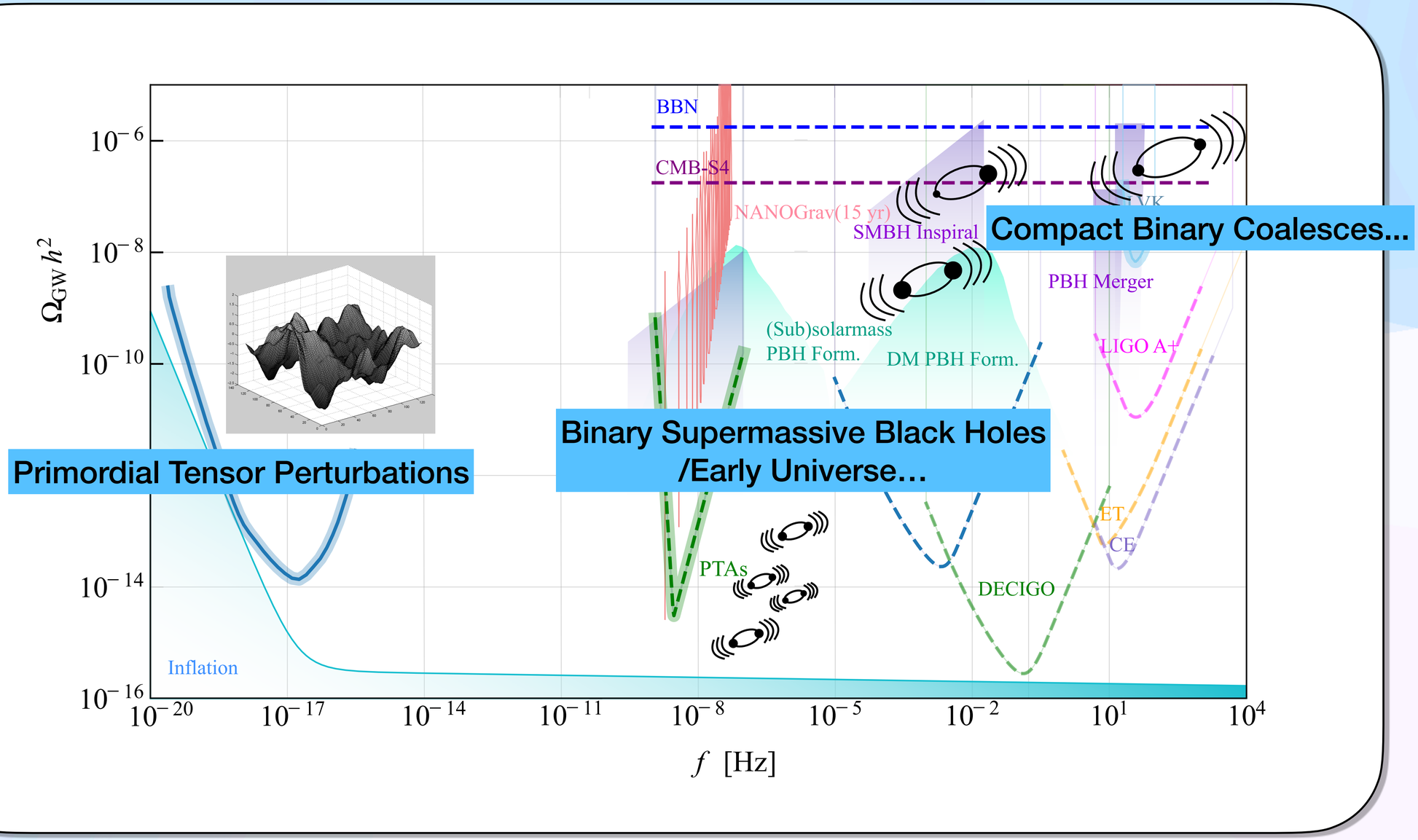


Using Press-Schecter method to estimate the PBH abundance β at formation (Gaussian case):

$$\beta(M_{\rm PBH}) \approx \frac{1}{\sqrt{2\pi\sigma_\delta^2}} \int_{\delta_{\rm th}}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right) d\delta$$

σ_δ^2———variance of δ (typical size of fluctuations)

Gravitational Waves : A Great Probe to the Dark

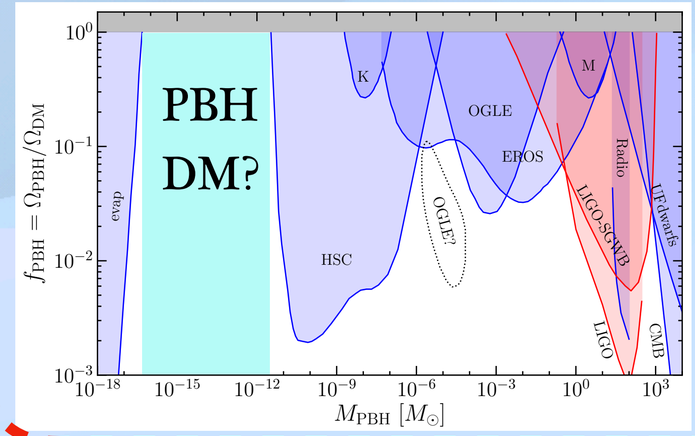


Xinpeng Wang (Kavli IPMU)

Primordial Black Holes and Gravitational Waves

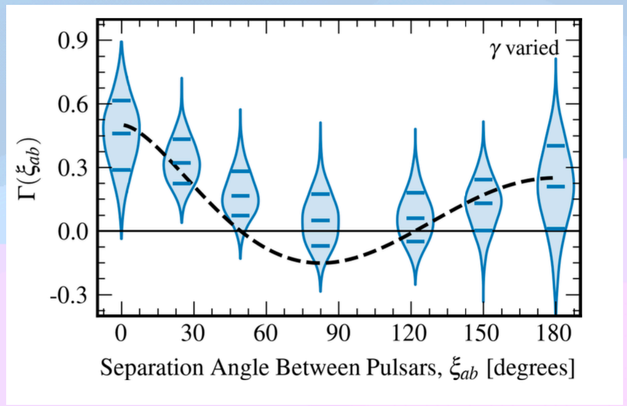
Companion: Deci hertz GW
Signals in LISA/LVK band (future)

Dark Matter PBH：$10^{17} \sim 10^{21}$g



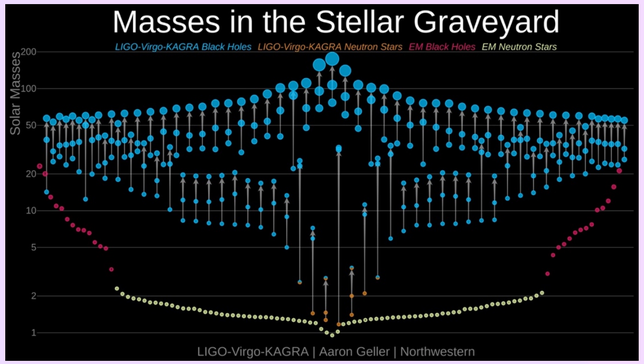
PBH

Stellar mass PBH： $\sim 10^{33}$g



Nanohertz GW Signals detected by Pulsar Timing Arrays (PTAs)

LIGO BH： $10 \sim 100 M_\odot$



10 hertz GW Signals detected by LIGO collaboration (LVK)

Seeds of Supermassive Black Holes $> 10^2 M_\odot$

Companion:
Nanohertz GW
Signals detected by
PTAs

I. Primordial Black Holes and Induced Gravitational waves from Inflation

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

Amplifying the Superhorizon Perturbations

Single field slow roll inflation: $\mathcal{R}'' + 2(z'/z)\mathcal{R}' + k^2\mathcal{R} = 0$

Several e-folds after horizon crossing, $k/(aH) \ll 1$,

the e.o.m of comoving curvature $\mathcal{R}$ at leading order of spatial gradient expansion:

$$\mathcal{R}_0'' + 2(z'/z)\mathcal{R}_0' = 0$$

We observe adiabatic constant mode and decaying mode.

$$\mathcal{R}_0(\eta_f) = \mathcal{R}(\eta_k) + \mathcal{R}'(\eta_k)\int_{\eta_k}^{\eta_f} \frac{z^2(\eta_k)}{z^2(\eta')} d\eta'$$

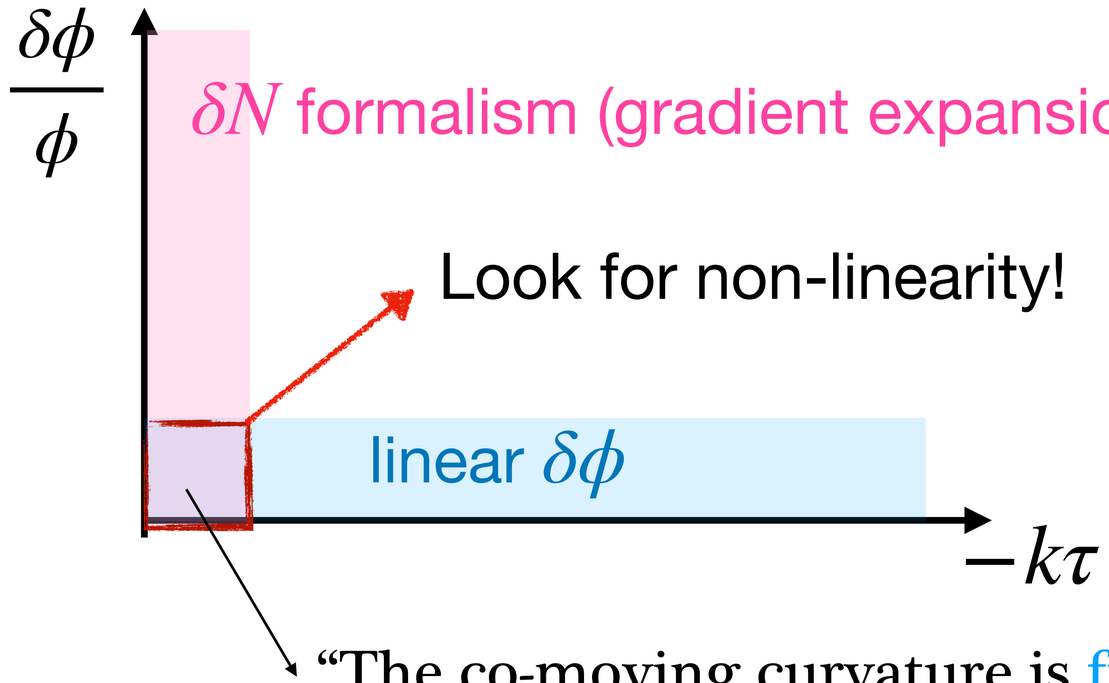
$\propto (a/a_k)^{-3}$ Negligible outside horizon

"The co-moving curvature is frozen after horizon crossing" ?

Not really!

Amplifying the Superhorizon Perturbations

Single field slow roll inflation:



The solution in small k limit: adiabatic constant mode and decaying mode.

$$\mathscr{R}_0(\eta_f) = \mathscr{R}(\eta_k) + \mathscr{R}'(\eta_k)\int_{\eta_k}^{\eta_f}\frac{z^2(\eta_k)}{z^2(\eta')}d\eta'$$

$$\propto (a/a_k)^{-3}$$

Negligible outside horizon

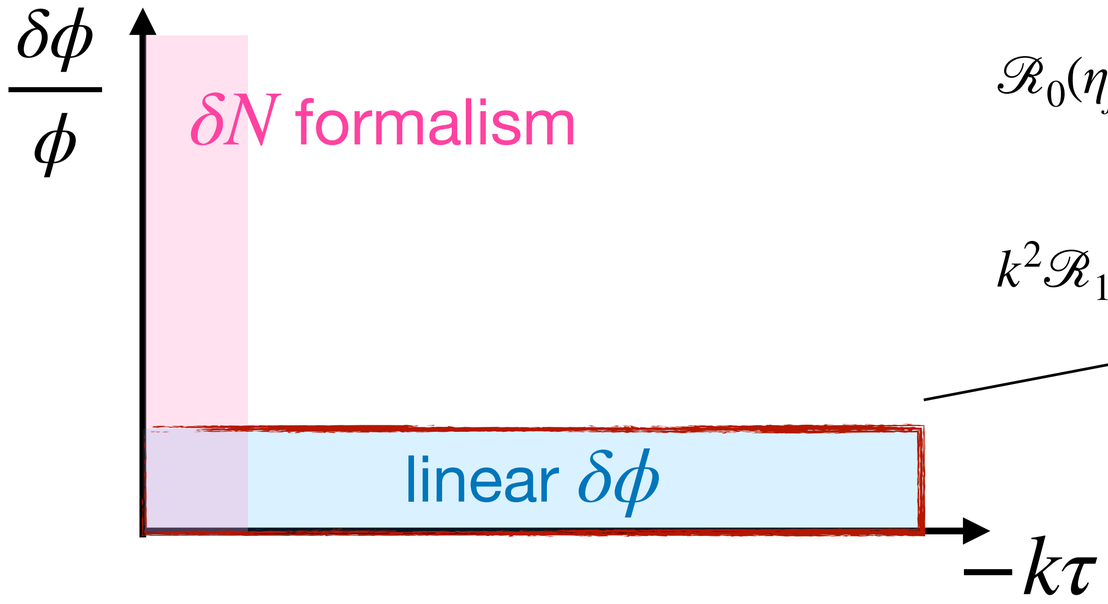
"The co-moving curvature is frozen after horizon crossing"

Amplifying the Superhorizon Perturbations

The super horizon behavior———Decay modes and k^2 correction

S.Leach , M. Sasaki, D. Wands and A. Liddle , 2001 (astro-ph/0101406)

Given $\mathscr{R}_k, \mathscr{R}'_k$ at(shortly after) horizon crossing $\eta = \eta_k$



Homogenous Decay mode

$$\mathscr{R}_0(\eta_f) = \mathscr{R}(\eta_k) + \mathscr{R}'(\eta_k)\int_{\eta_k}^{\eta_f}\frac{z^2(\eta_k)}{z^2(\eta')}d\eta'$$

$$k^2\mathscr{R}_1(\eta_f) = k^2\mathscr{R}(\eta_k)\int_{\eta_f}^{\eta_k}\int_{\eta_f}^{\eta'}\frac{z^2(\eta'')}{z^2(\eta')}d\eta''d\eta'$$

1st order k^2 correction

Superhorizon behavior can be important for single field inflation.

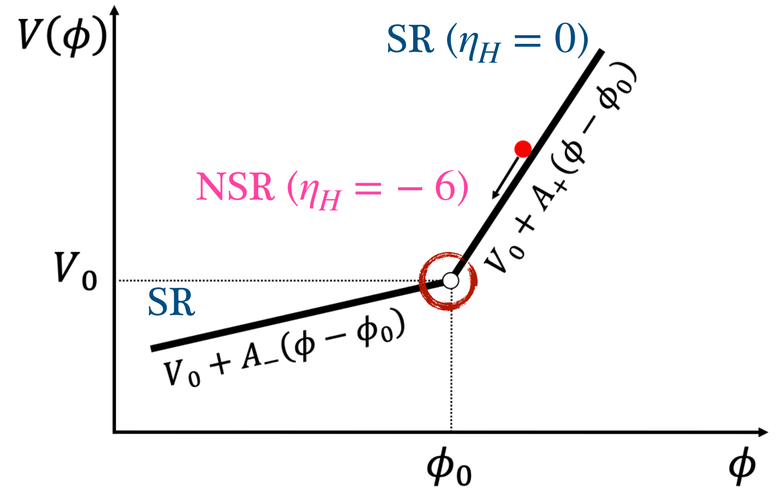
Amplifying the Superhorizon Perturbations (Single Field)

The super horizon behavior———Decay modes and k^2 correction

S.Leach , M. Sasaki, D. Wands and A. Liddle , 2001 (astro-ph/0101406), Shi Pi, Jianing Wang, 2022 (2209.14183);

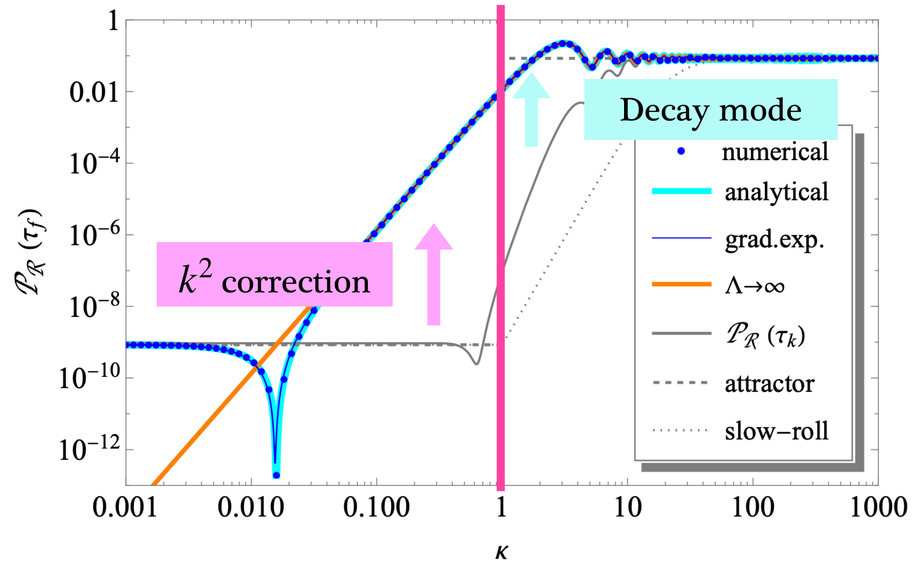
C. T. Byrnes, P. S. Cole, and S. P. Patil, 1811.11158 **The "Steepest" growth: $\mathcal{P}_{\mathcal{R}} \propto k^4$ for single field inflation**

Starobinsky's linear piece-wise model



$\eta \ll \epsilon$ during SR phases is assumed

$k_0 = a_0 H_0$



Specific features will appear in primordial power spectrum and full PDF, see 2412.16463

Amplifying the Superhorizon Perturbations (Multi Field)

Contributions of the iso-curvature fields

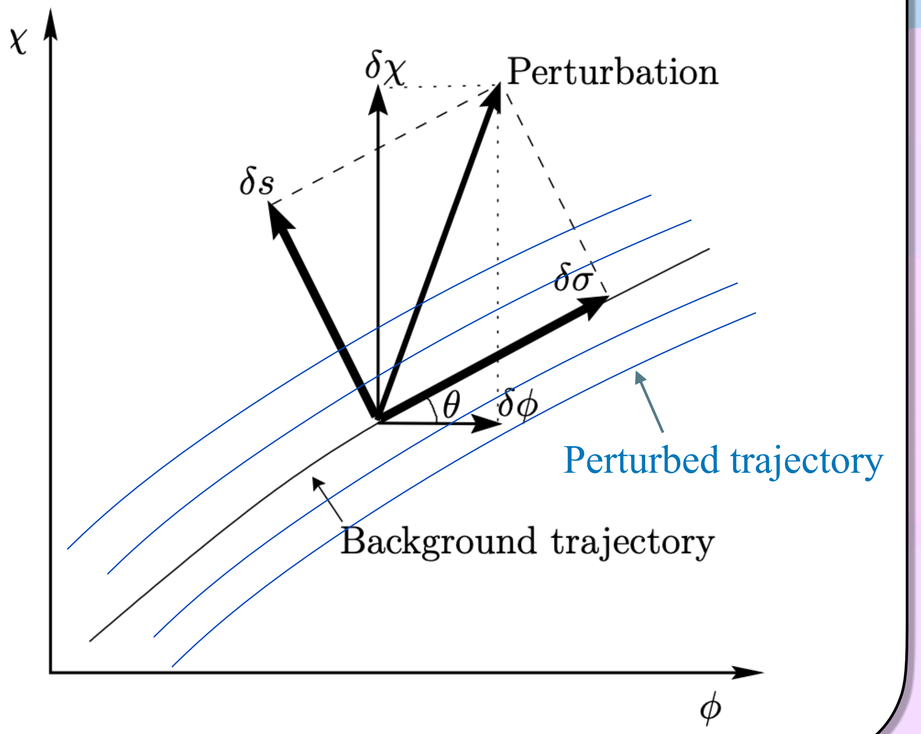
C. Gordon, D. Wands, B. Bassett and R. Maartens. 2000, (astro-ph/0009131)

$$\mathcal{S} = -3H\left(\frac{\delta p}{\dot{p}} - \frac{\delta\rho}{\dot{\rho}}\right)$$

$$\dot{\mathcal{R}} \approx -3H\frac{\dot{p}}{\dot{\rho}}\mathcal{S} \approx \sqrt{\frac{2}{\epsilon}}\dot{\theta}\delta s + \mathcal{O}\left(\frac{k^2}{a^2H^2}\right)$$

$$\propto \frac{\dot{\chi}\delta\phi - \dot{\phi}\delta\chi}{\epsilon_H}$$ "Field perturbations orthogonal to the background"

Isocurvature sources the time evolution of curvature perturbation



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)

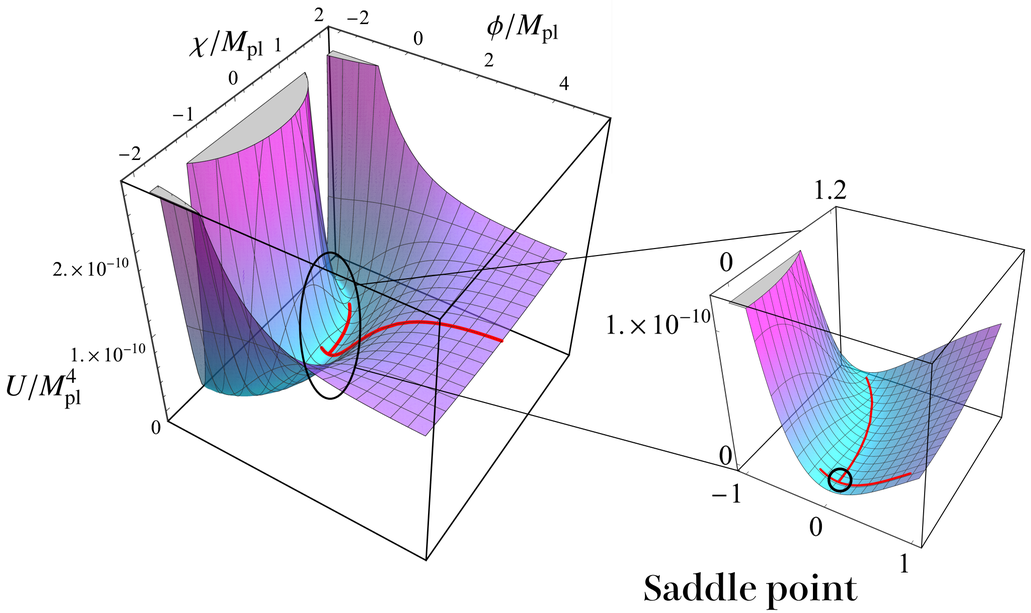
$$S_J = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}f(R,\chi) - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right],$$

$$f(R,\chi) = R + \frac{R^2}{6M^2} - \frac{\xi R}{M_{\rm pl}^2}(\chi - \chi_0)^2,$$ To break Z_2 symmetry

Avoid: 1)DW overproduction 2)eternal inflation

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

The potential is bounded from below



Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

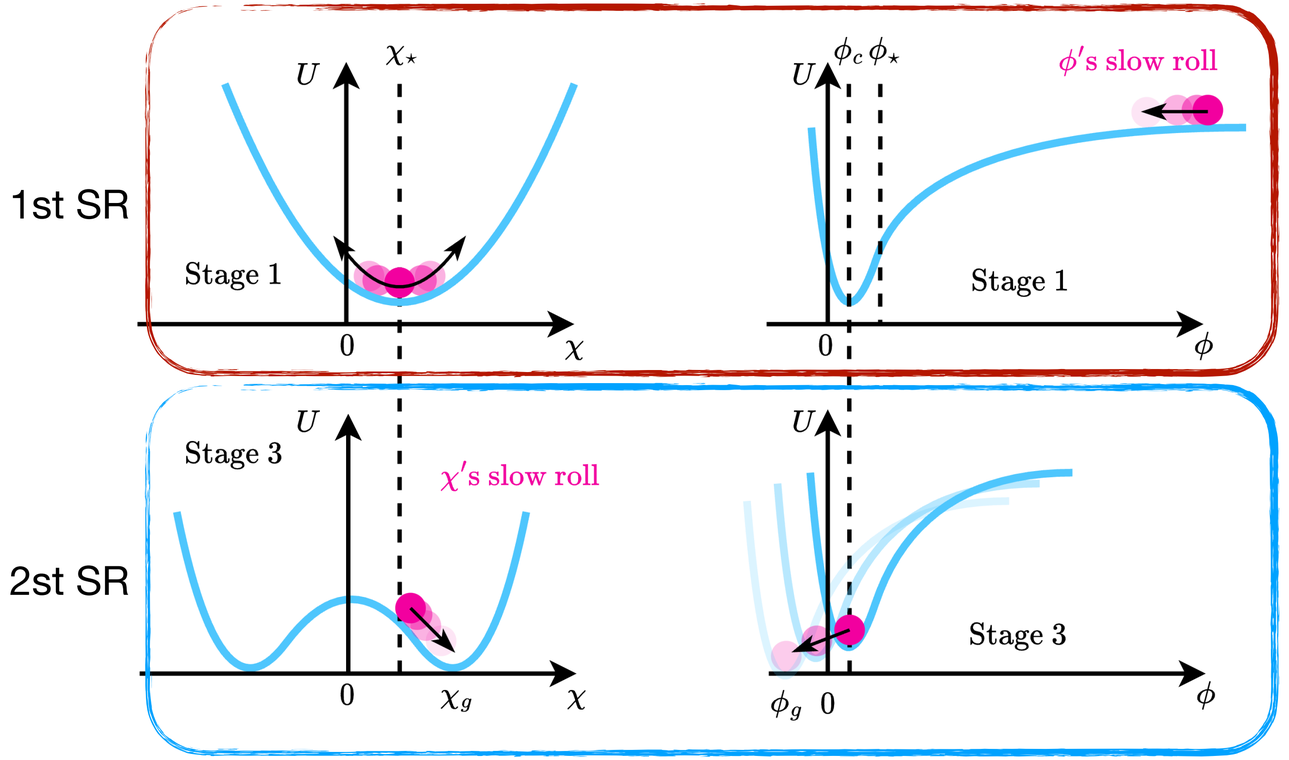
XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)

In Einstein frame

$$\phi \equiv M_{\rm pl}\sqrt{\frac{3}{2}}\ln F$$

$$U(\phi,\chi) \equiv \frac{3}{4}M^2M_{\rm pl}^2W^2(\phi,\chi) + \frac{V(\chi)}{F(\phi)^2}$$

$$W(\phi,\chi) \equiv 1 - \frac{1}{F(\phi)}\left[1 - \xi\left(\frac{\chi-\chi_0}{M_{\rm pl}}\right)^2\right].$$

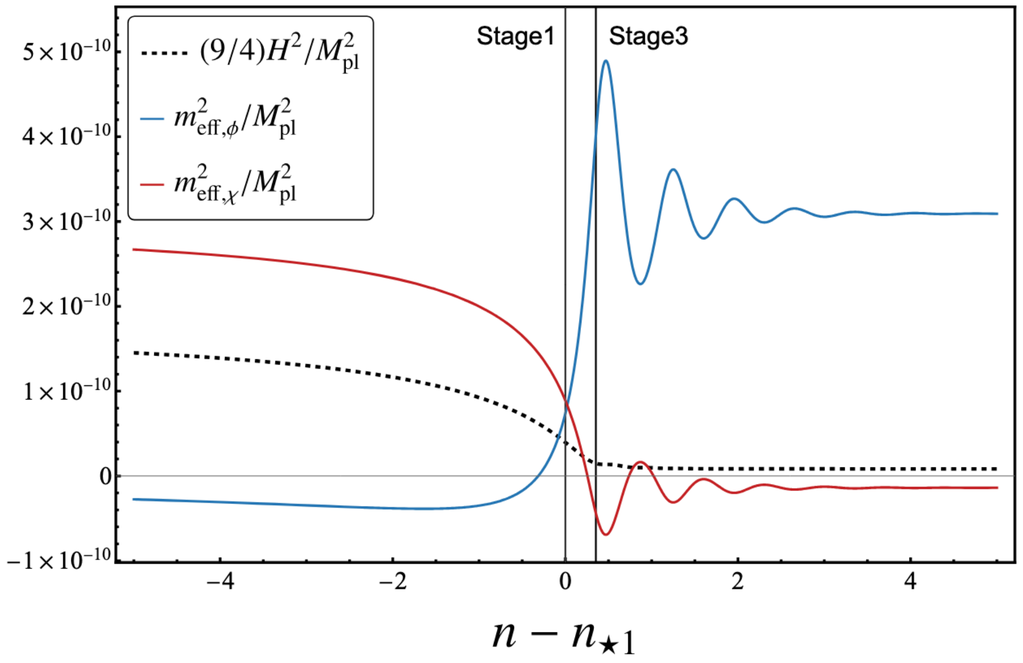


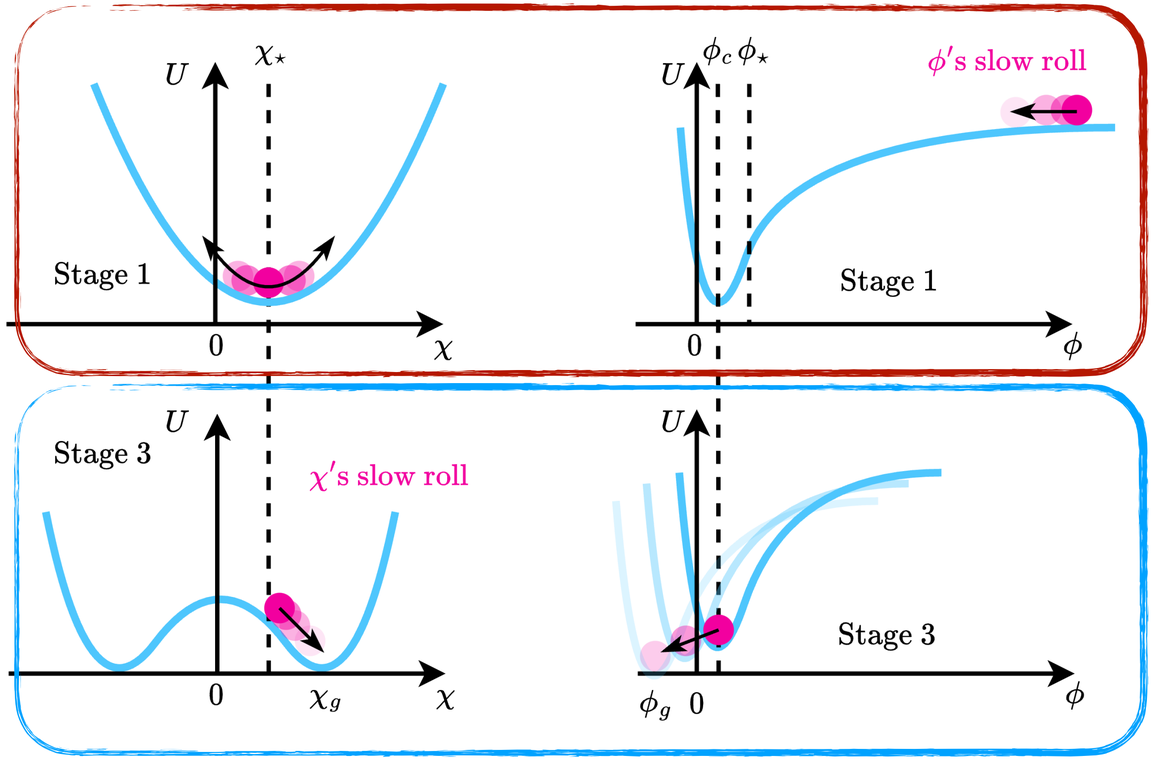
Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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

The effective mass of two fields

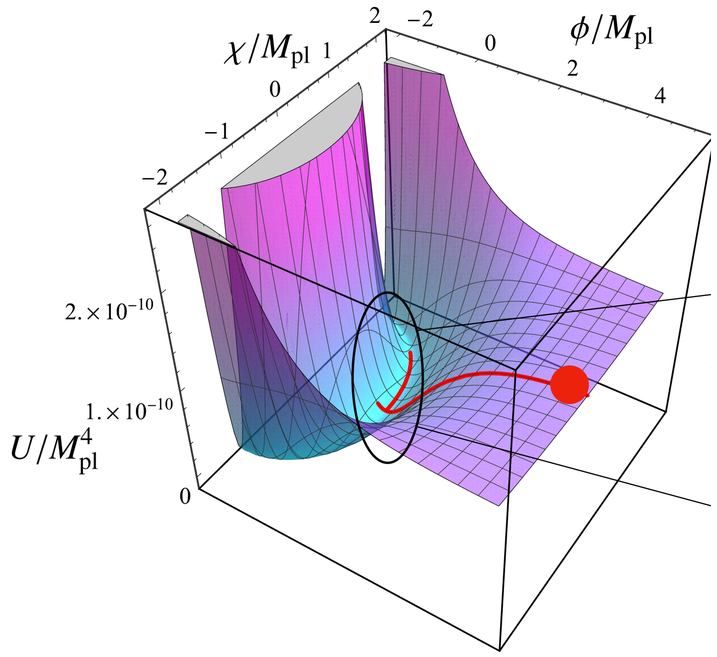


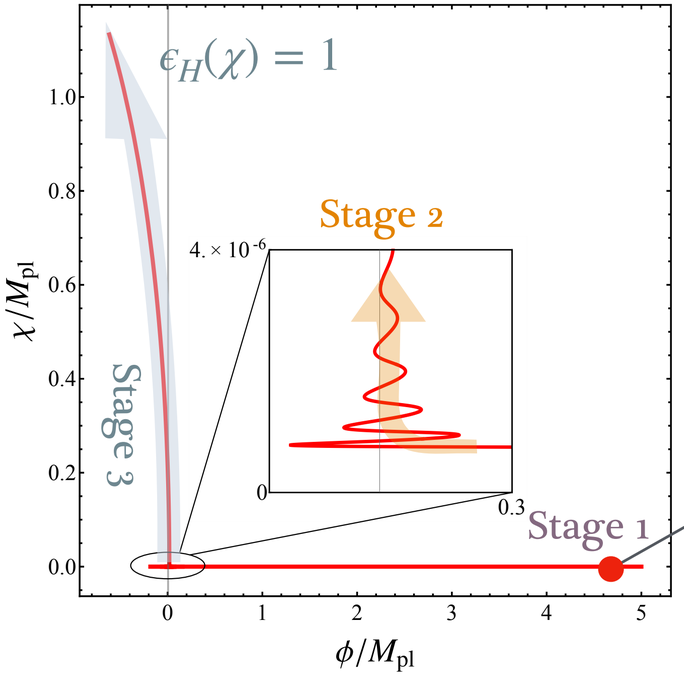


Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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





ϕ dominated inflation

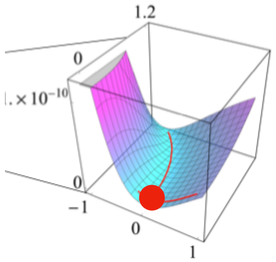
Inflaton rolls along ϕ direction (R^2 **inflation**),

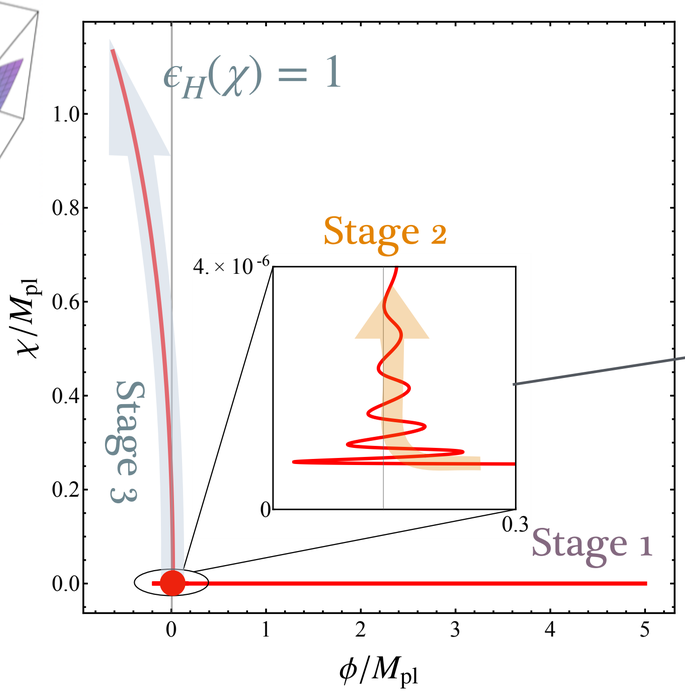
χ behaves like a damped* oscillator around χ_0.

Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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

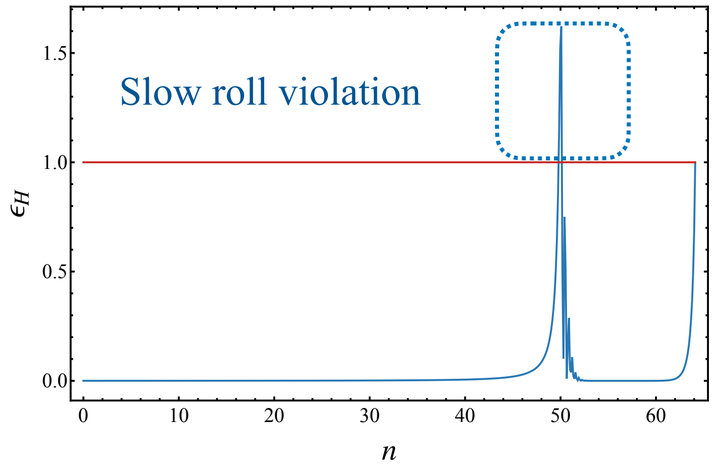




Baby R^2 reheating

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

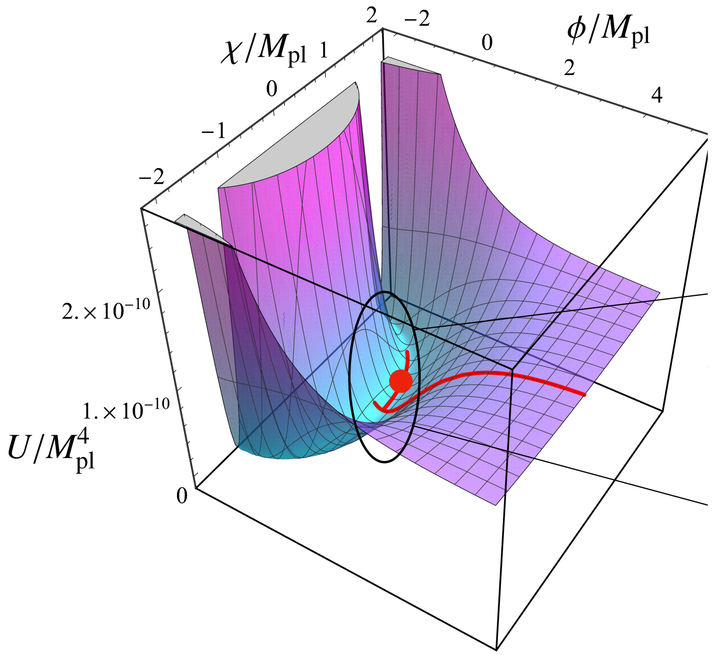
χ stays in the potential valley.

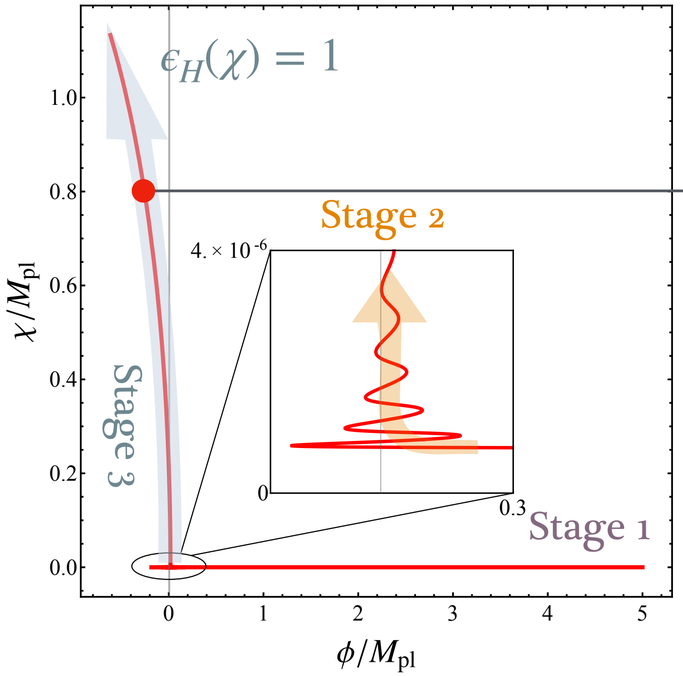


Amplifying the Superhorizon Perturbations (Multi Field)

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**),

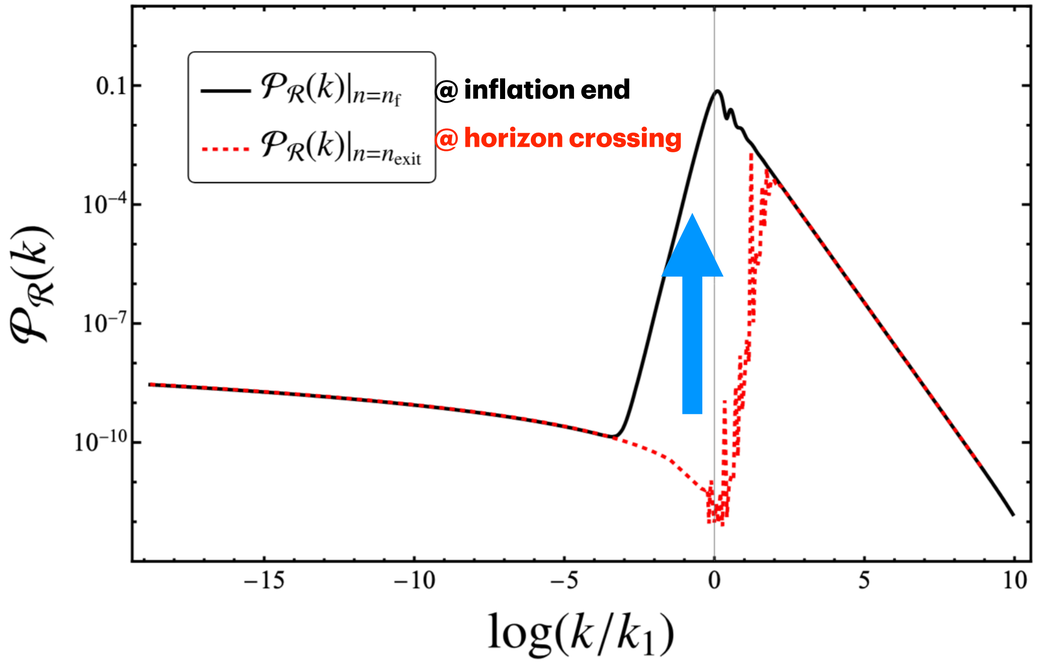
ϕ behaves like a under-damped oscillator around it's potential valley. The inflation ends when $\epsilon_H = 1$.

Amplifying the Superhorizon Perturbations (Multi Field)

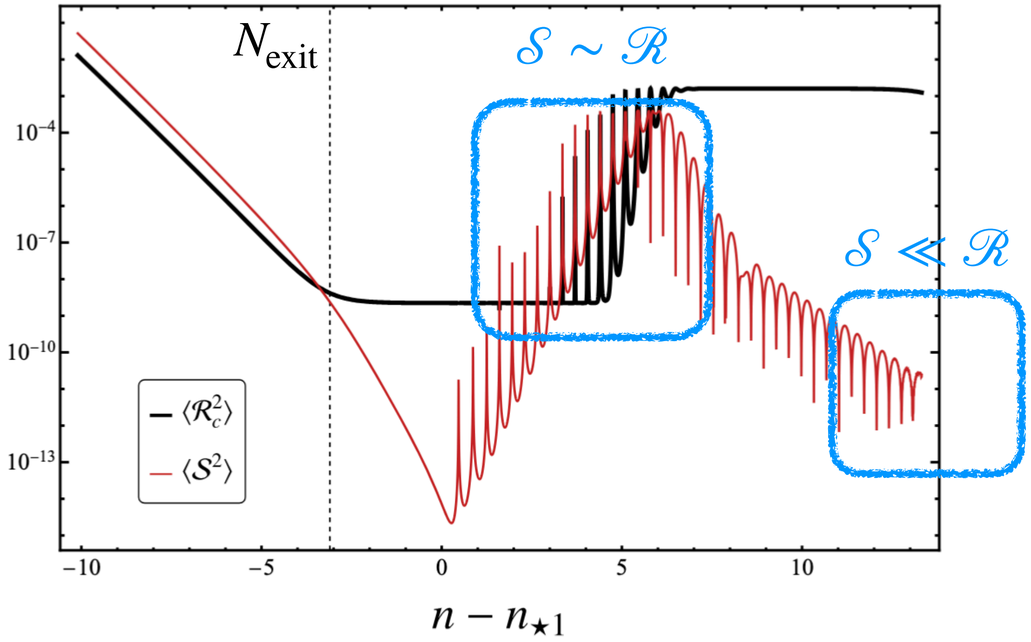
R^2 inflation + non-minimally coupled χ

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

Comparison between the power spectrum
@ inflation end and horizon crossing



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



A non-linear approach: δN formalism

Kodama & Sasaki, 1984 Sasaki & Stewart, 1995 (astro-ph/9507001)

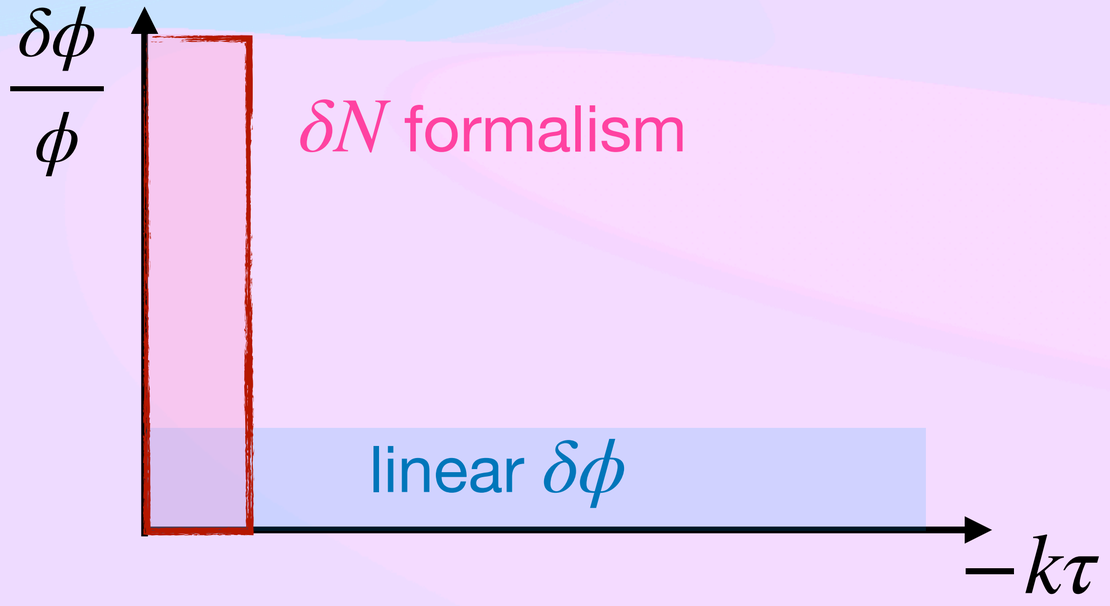
δN formalism is used to calculate the full possibility distribution function of $\mathscr{R}$,

*$\mathscr{R} = \delta N$ is based on separate universe approach, leading order of gradient expansion

Background solution $\phi = \phi(N)$

$$\mathscr{R} \equiv \delta N = \tilde{N}_{\rm tot} - N_{\rm tot}$$

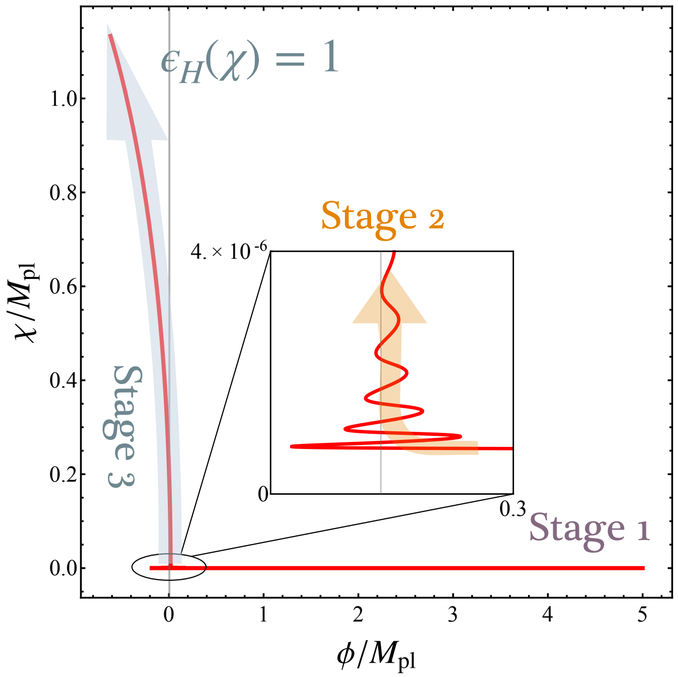
$$P[\mathscr{R}] \approx P[\mathscr{R}^{-1}(\delta\phi)]$$



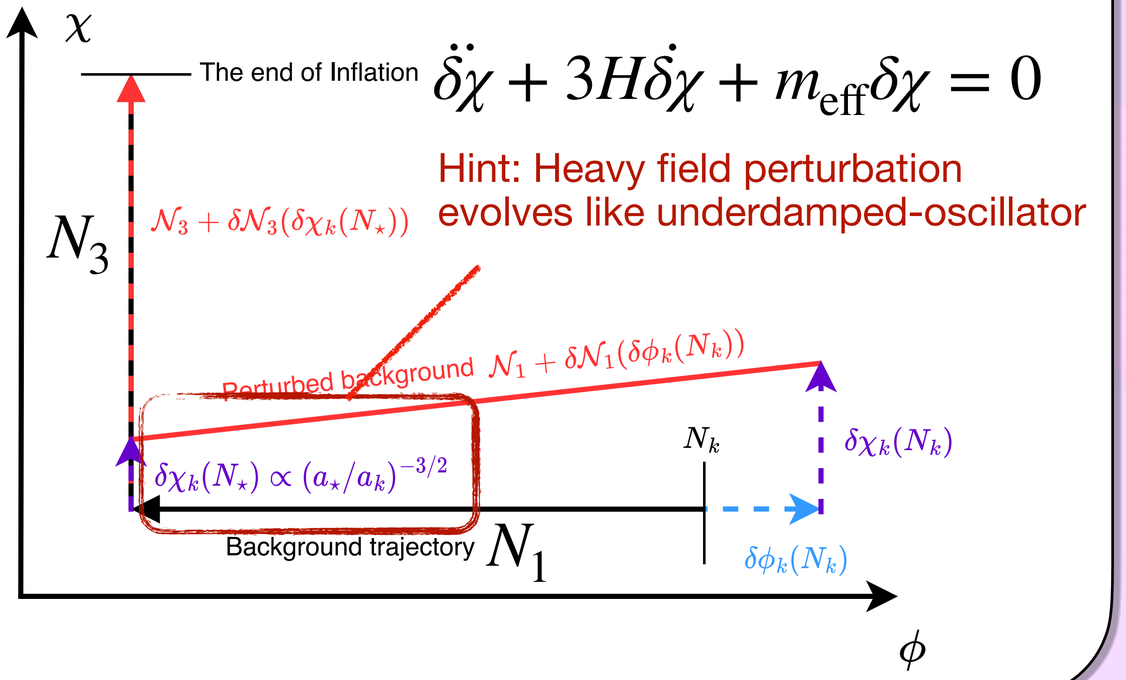
Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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



Simplified traj.

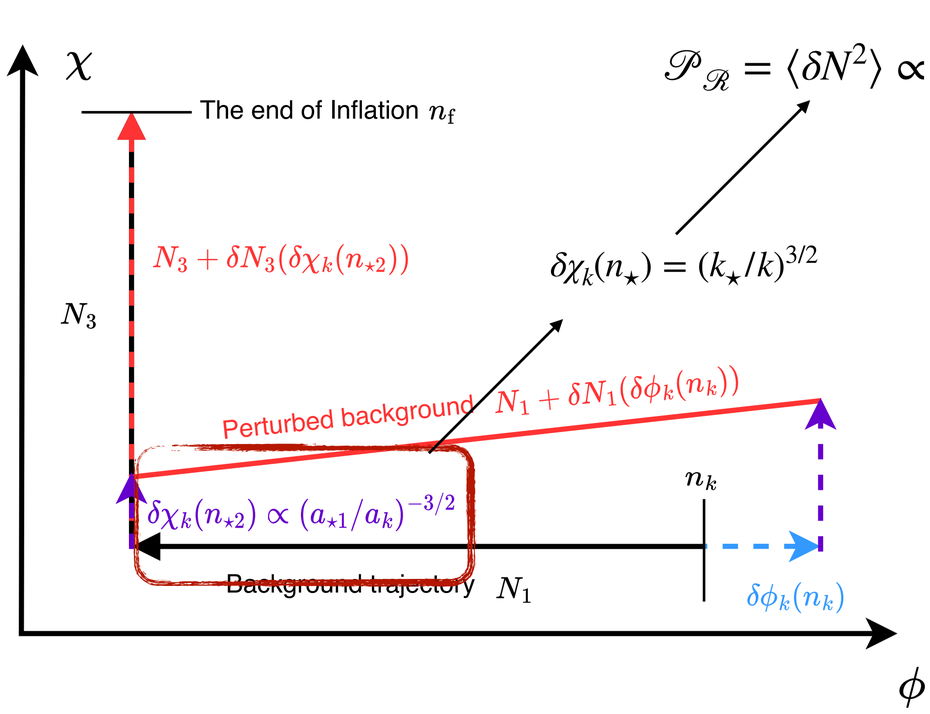


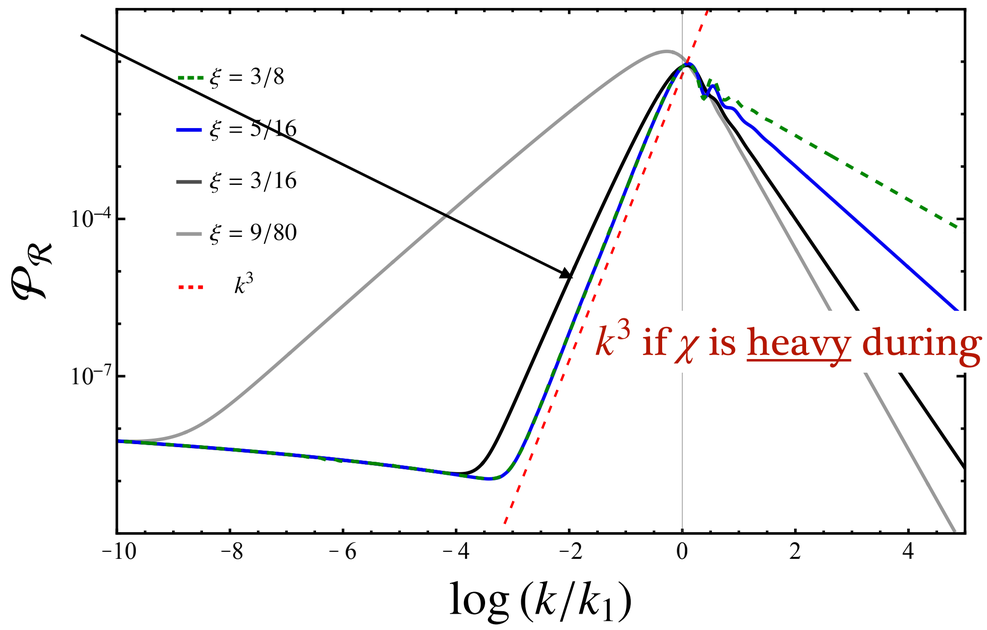
Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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

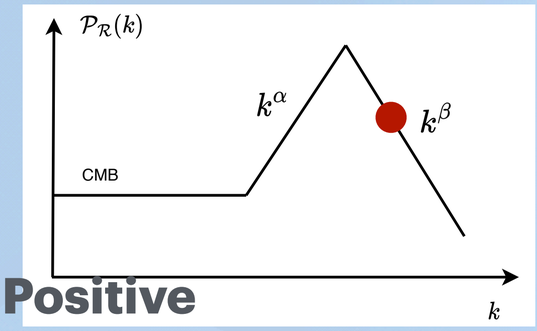
The growth rate depends on the effective mass of early isocurvature field (χ) that dominates the latter inflation.





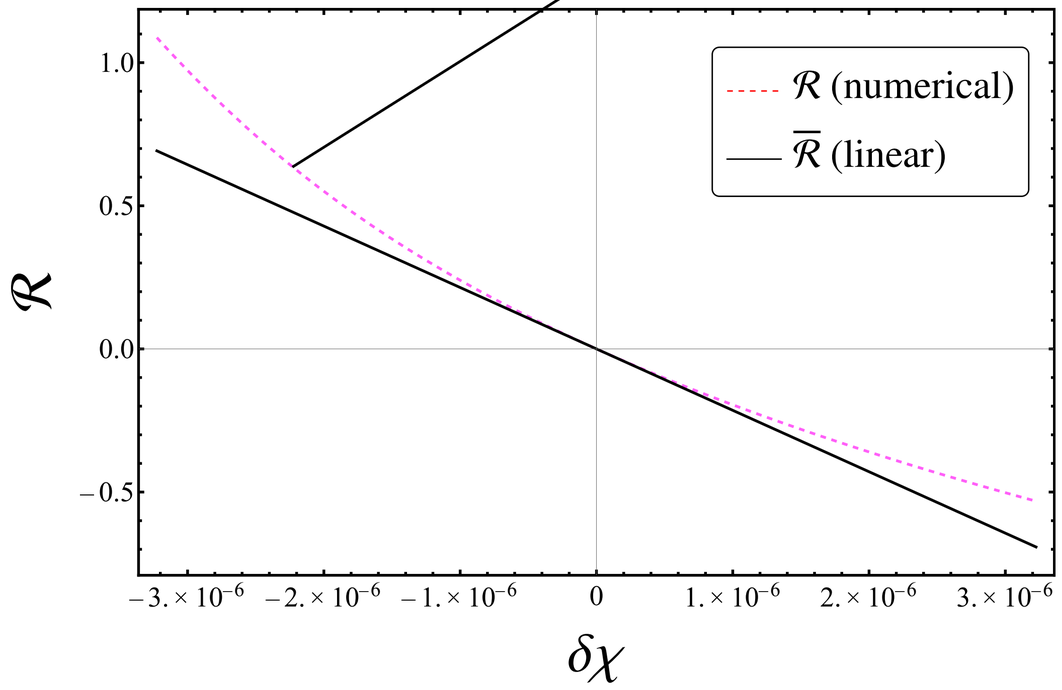
k^3 if χ is heavy during st-1.

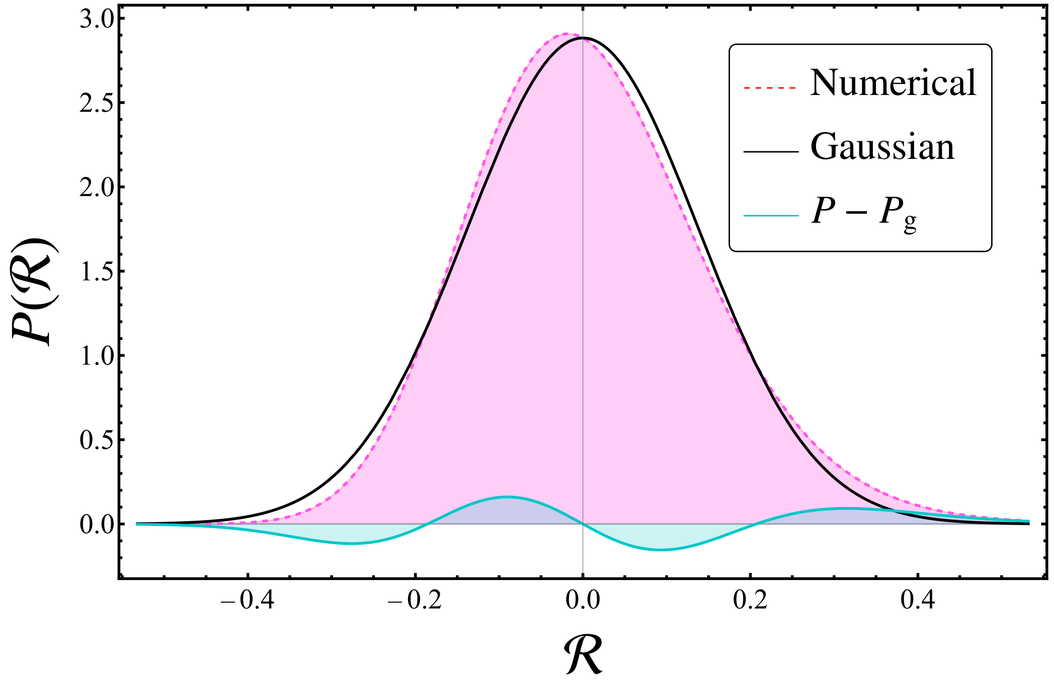
Non-Gaussianity ($k \gg k_1$)



$$\mathscr{R} \approx \delta N_3 = N_3' - N_3 \sim \frac{dN_3}{d\chi}\delta\chi + \frac{d^2N_3}{d\chi^2}\delta\chi$$

$f_{\rm NL}^{\rm local}$ **Small and Positive**

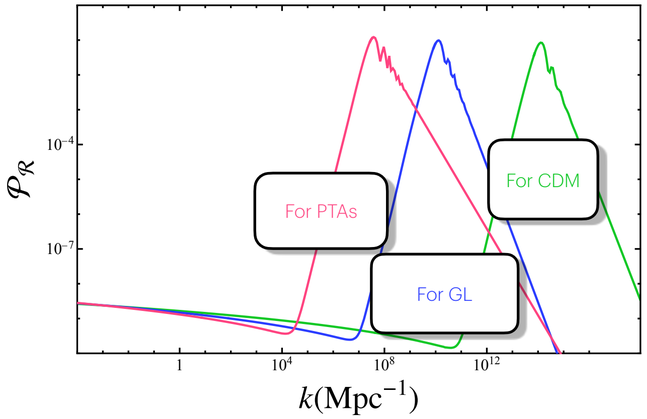




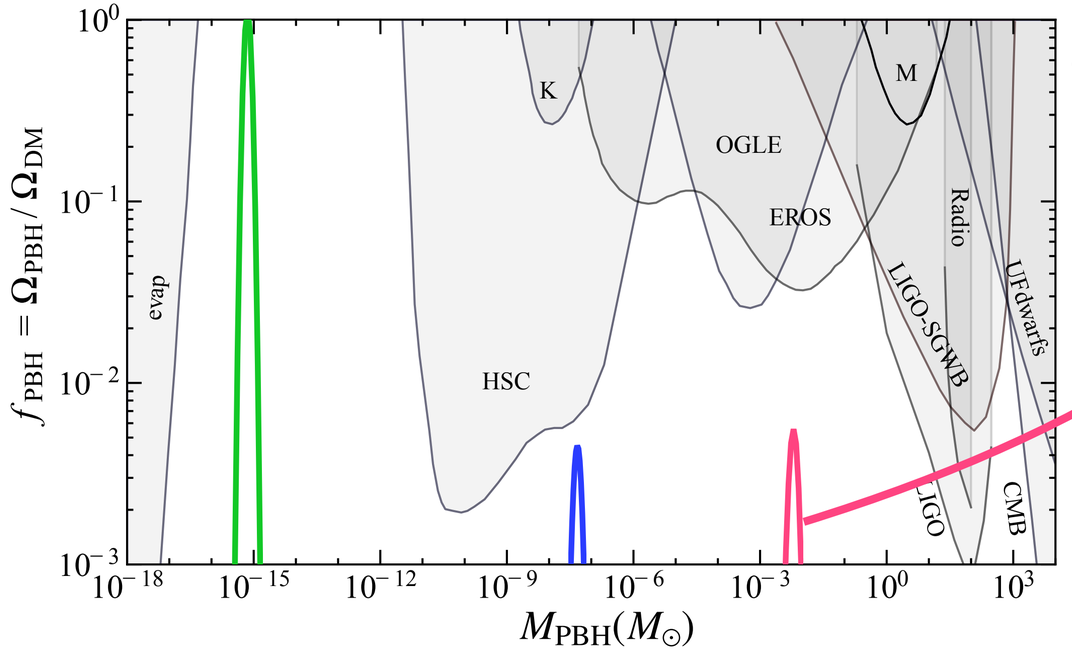
Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

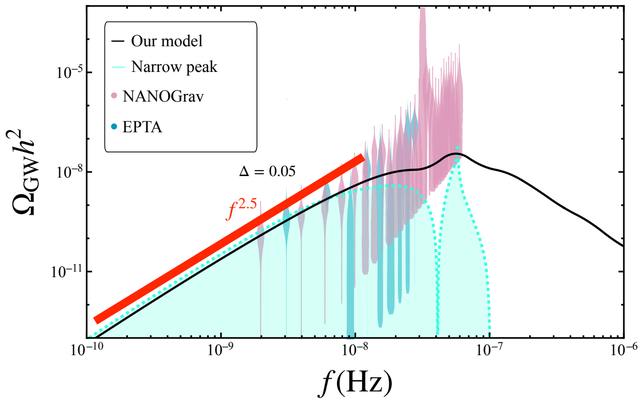
XW, YL. Zhang, M. Sasaki, 2024 (2404.02492)



Press-Schechter Formalism



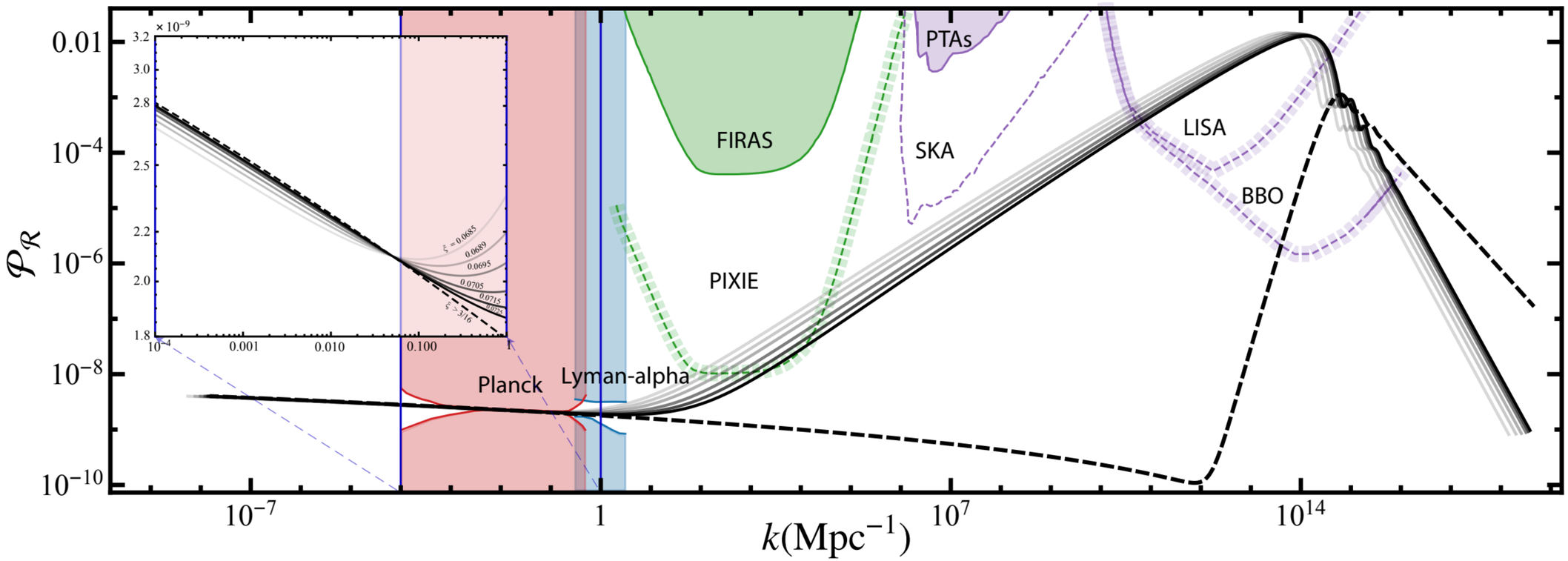
Scalar induced GW



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)



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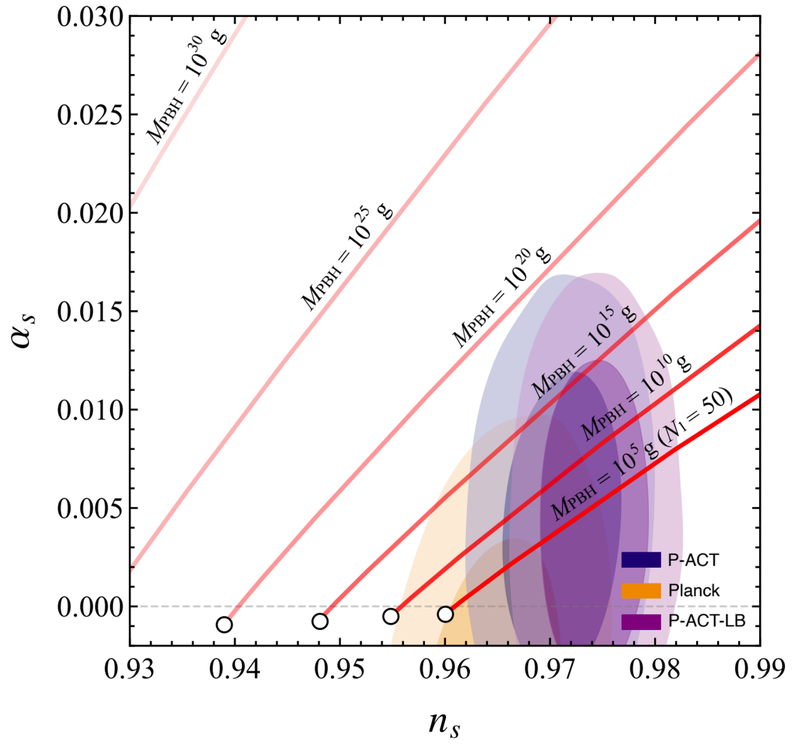
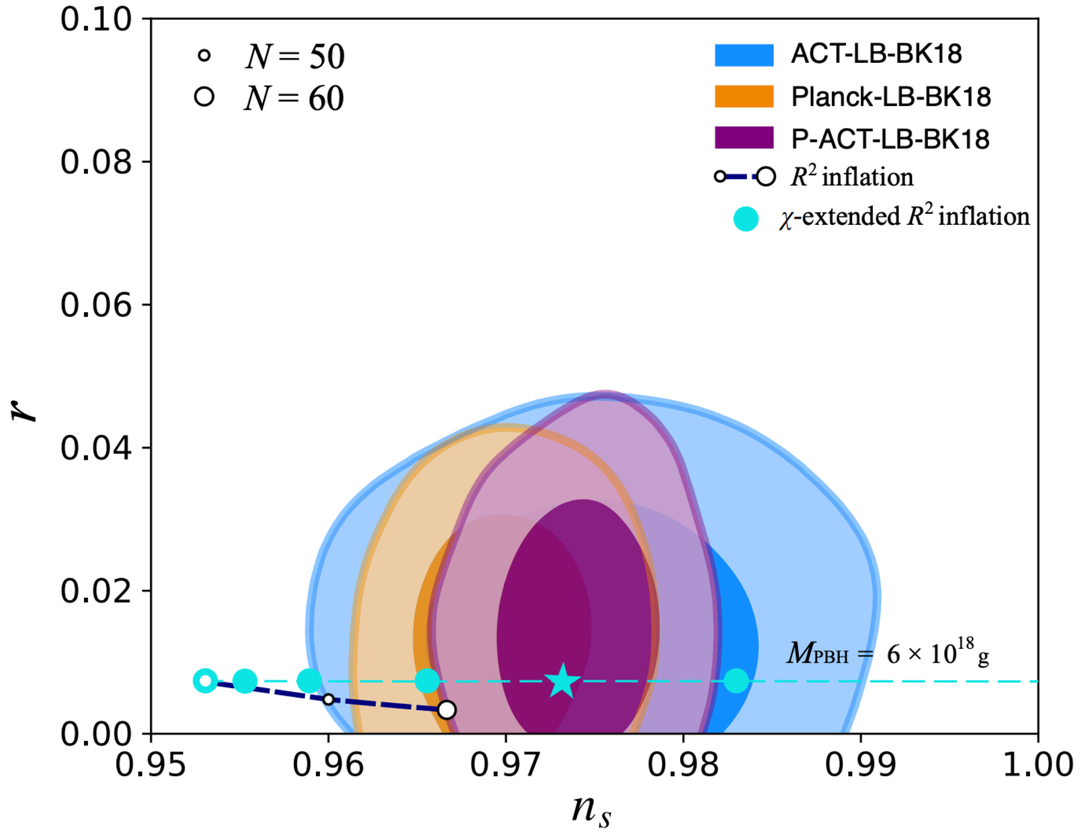


PBHDM scenario is consistent with P-ACT result

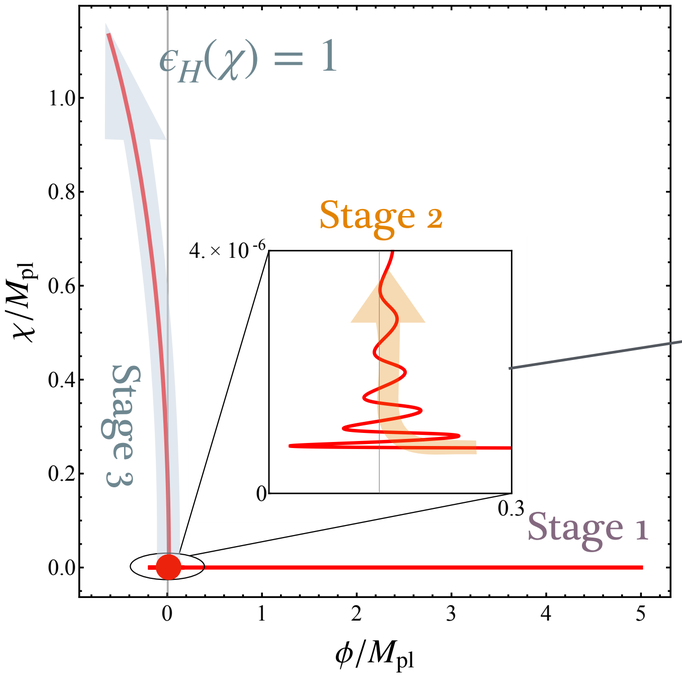


Whether there are other interesting and unique observables for two field models?

Amplifying the Superhorizon Perturbations (Multi Field)

R^2 inflation + non-minimally coupled χ

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

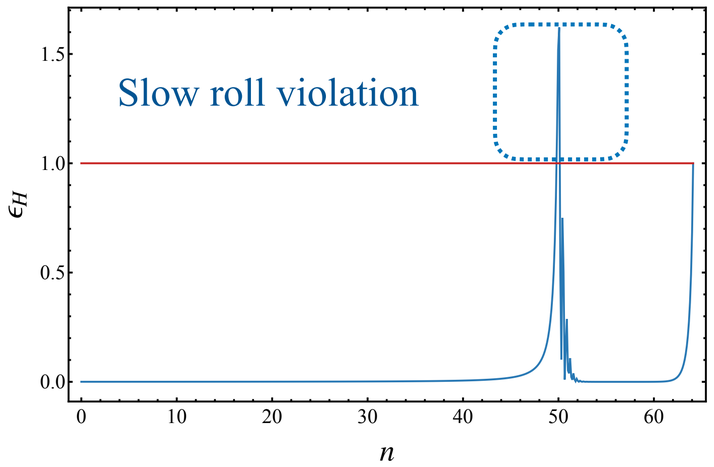


Baby R^2 reheating

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!

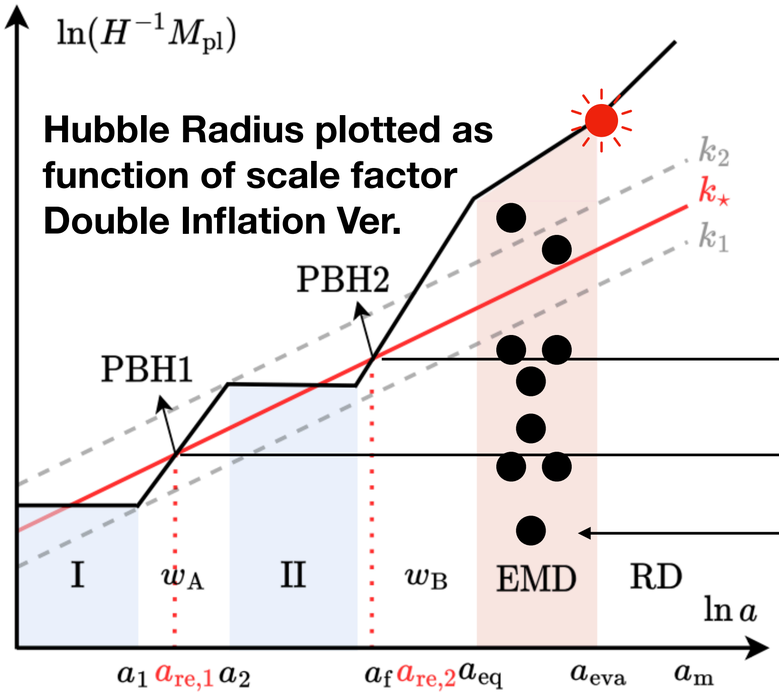


Inflation Break Stage: Dual PBH Formation

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)

Let's rewrite the thermal history of the early universe!



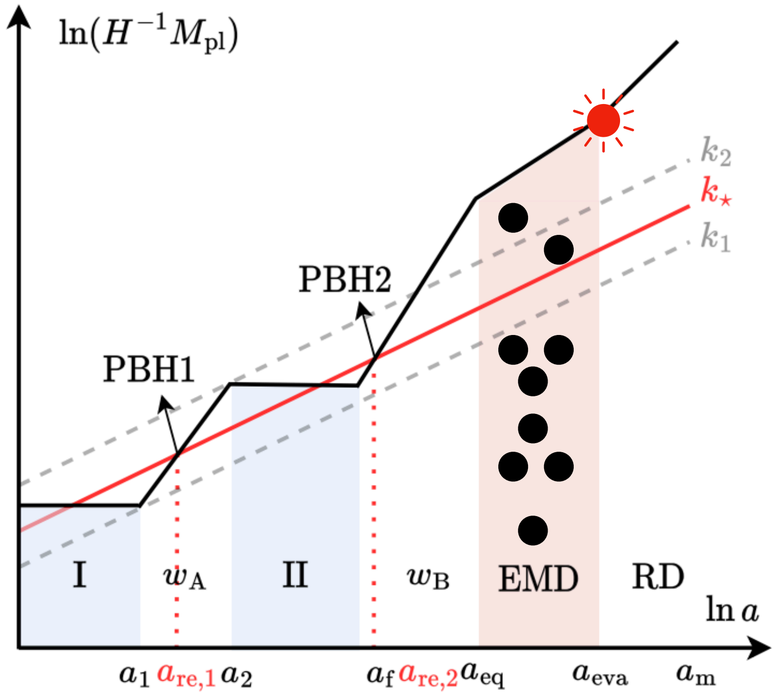
Hawking Radiation $t_{\rm eva} \propto M^3$

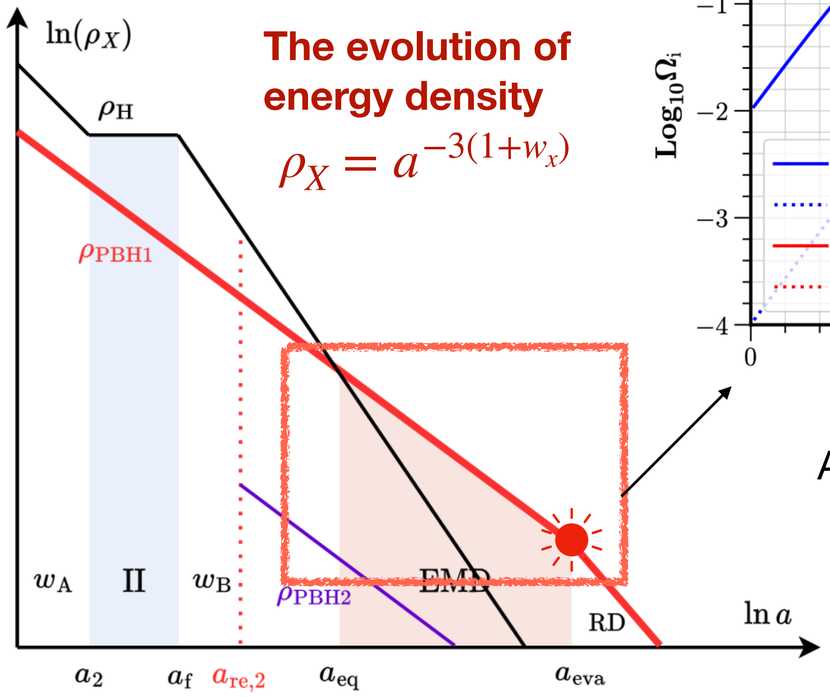
PBH2: Slowly Evaporating (remain till today->CDM)

PBH1: Rapidly Evaporating (disappeared before BBN)

Inflation Break Stage: Dual PBH Formation

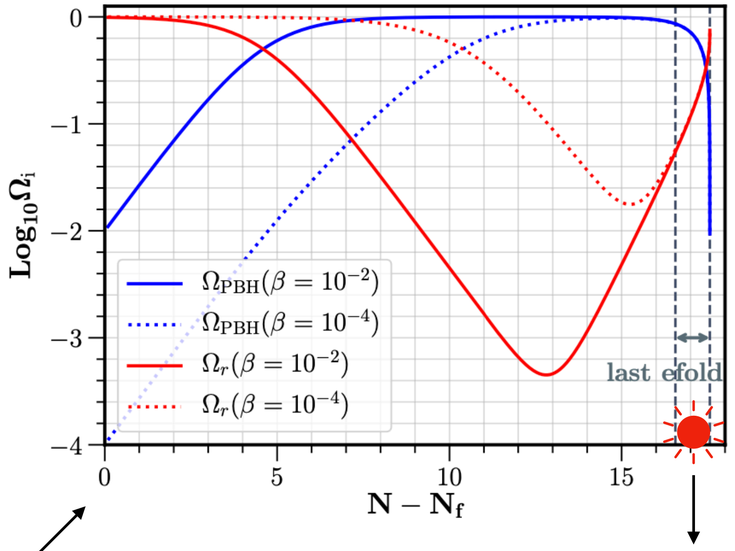
XW, M. Sasaki et al 2025, (2505.09337)





The evolution of energy density

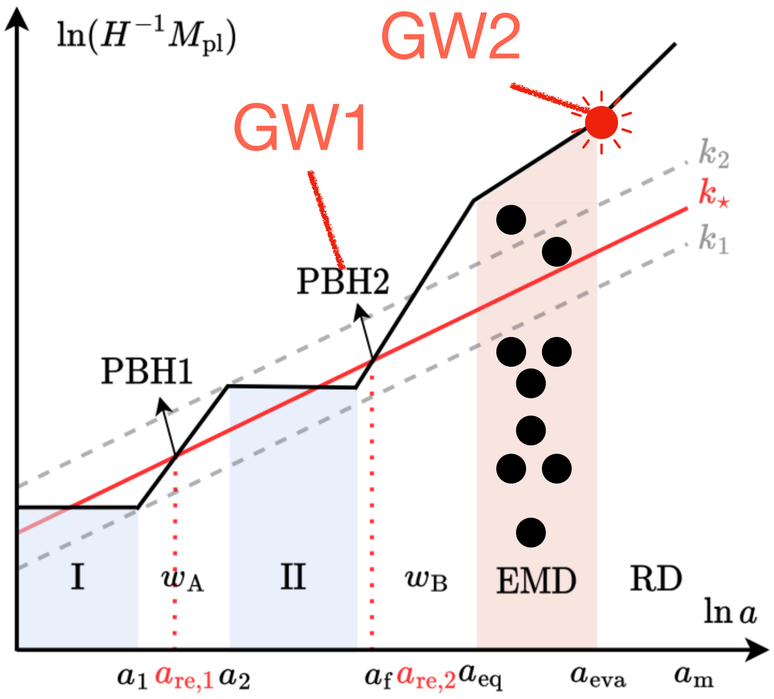
$$\rho_X = a^{-3(1+w_x)}$$



Almost instantaneous transition

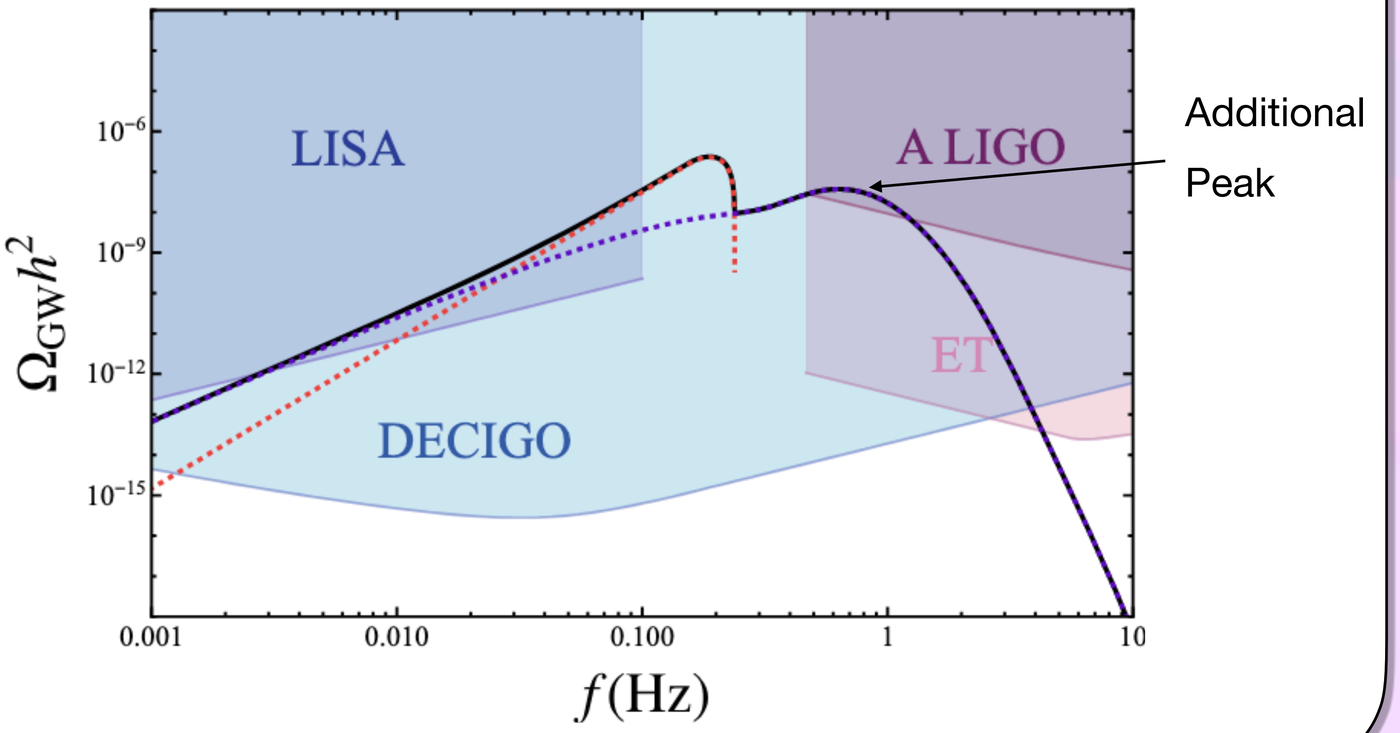
Inflation Break Stage: Dual PBH Formation

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 (Guillem 2020)



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

Based on 2510.12984

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 $\beta^{2\cdots} = F_y/F_g \gg 1$, can efficiently form structures, halos, and black holes in the very early universe.

The Basic Lagrangian

DM&DE Interaction?

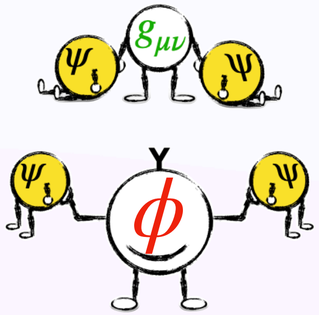
Credit. Domenech

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

For two fermions:

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

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



For fermions in the early universe with a conserved number density: $\dot{n}_{\psi} + 3Hn_{\psi} = 0,$

The δ *follows the continuity equation:* $\dot{\delta}_{\psi} + \theta_{\psi} = 0$, *where* $\dot{\theta}_{\psi} + 2H\theta_{\psi} = -\frac{1}{a^2}\nabla^2\phi,$

δ—number density perturbation of ψ fermions θ_{ψ}—divergence of the peculiar velocity $\phi = \phi_g + \phi_y$— potential of the forces

Xinpeng Wang (Kavli IPMU)

Early halo formation: Theory

Amendola, Rubio, and Wetterich, 2017
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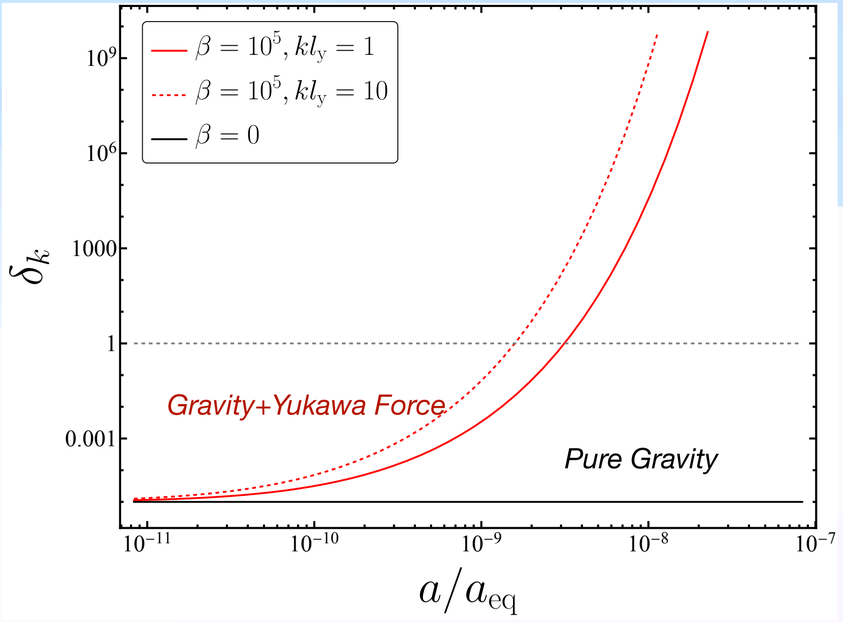
…

DM&DE Interaction?

Credit. Domenech

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

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



Solution (in R.D.)

$$\delta_k \propto c_1 I_0(\sqrt{6\alpha(a/a_{\rm eq})}) + c_2 K_0(\sqrt{6\alpha(a/a_{\rm eq})}),$$

$$\alpha = f_\psi\left[1+\frac{2\beta^2}{1+(kl_{\rm y})^{-2}}\right]$$

When $6\alpha(a/a_{\rm eq}) \ll 1$

(Pure Gravity/ Force Screened)

$$I_0(\sqrt{6\alpha(a/a_{\rm eq})}) \to \text{const}.$$

When $6\alpha(a/a_{\rm eq}) \gg 1$

(Strong Force)

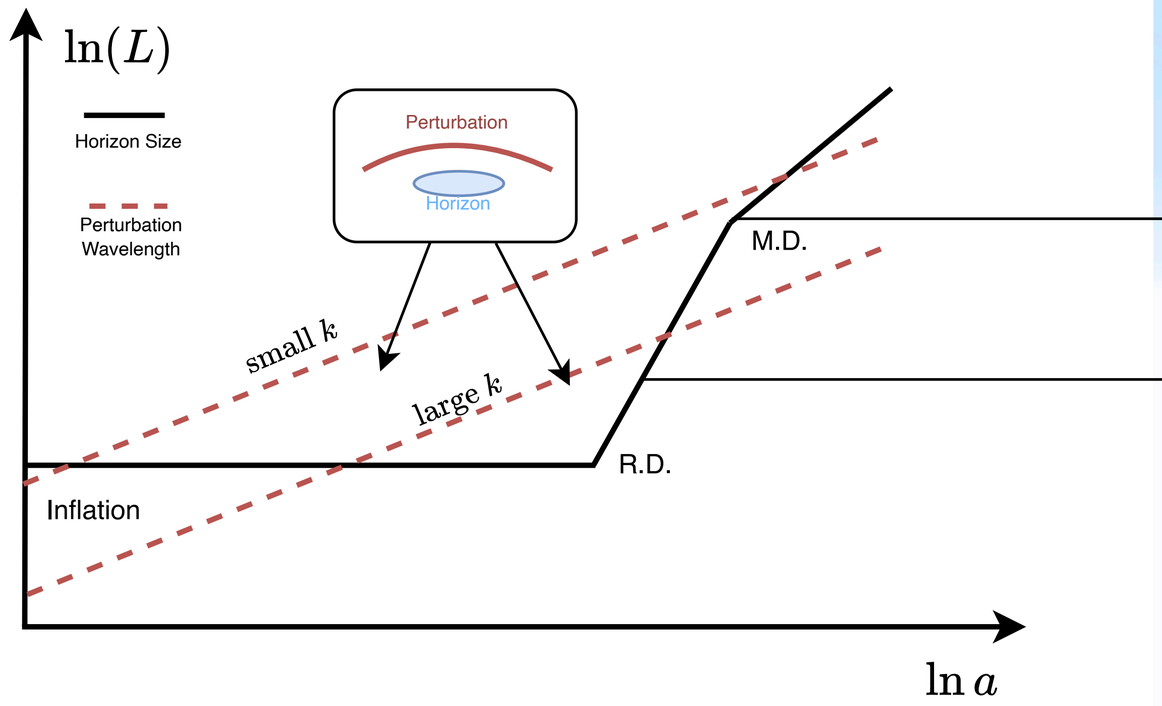
$$I_0(\sqrt{6\alpha(a/a_{\rm eq})}) \to \frac{e^{\sqrt{6\alpha(a/a_{\rm eq})}}}{\sqrt{2\pi\sqrt{6\alpha(a/a_{\rm eq})}}}$$

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 Only



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

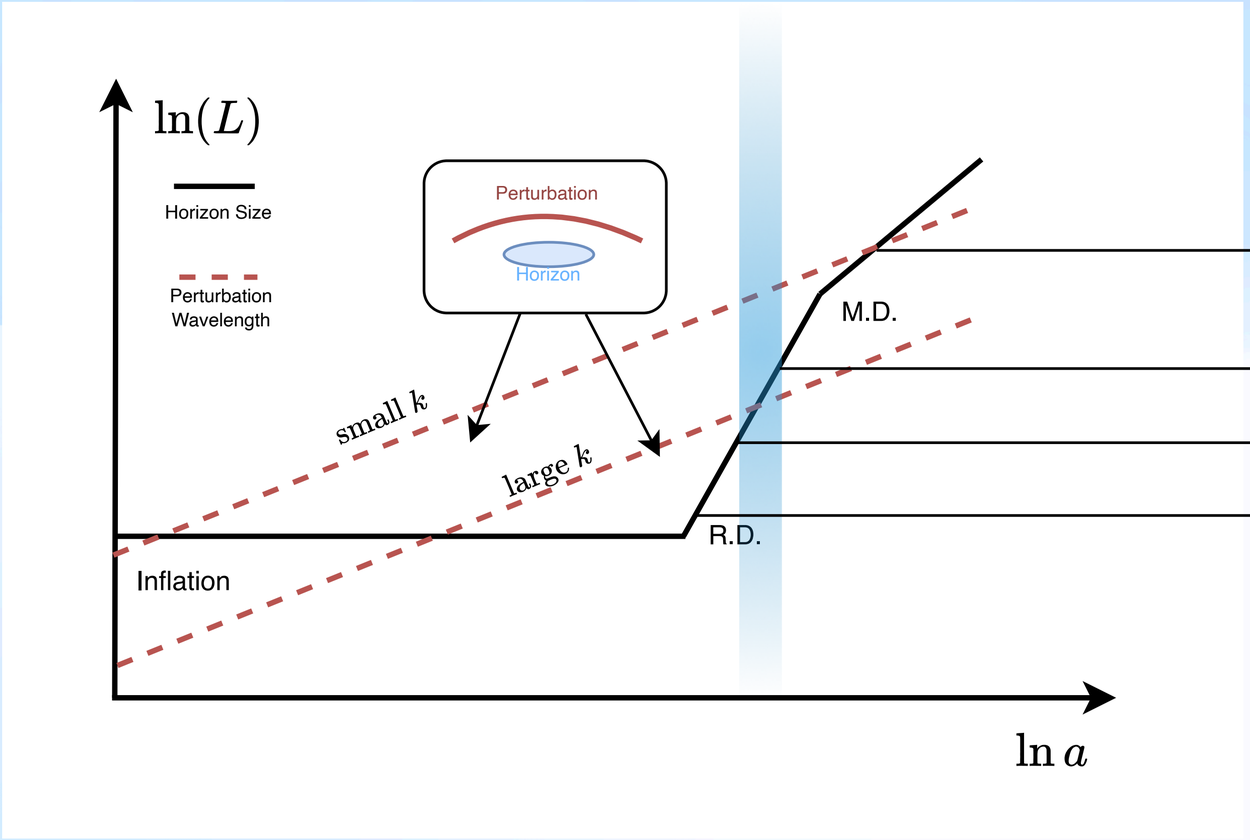
Density Perturbations Barely Grow

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 ($H^{-1} \gg \beta l_{\rm y}$)

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

Density Perturbations Barely Grow

Xinpeng Wang (Kavli IPMU)

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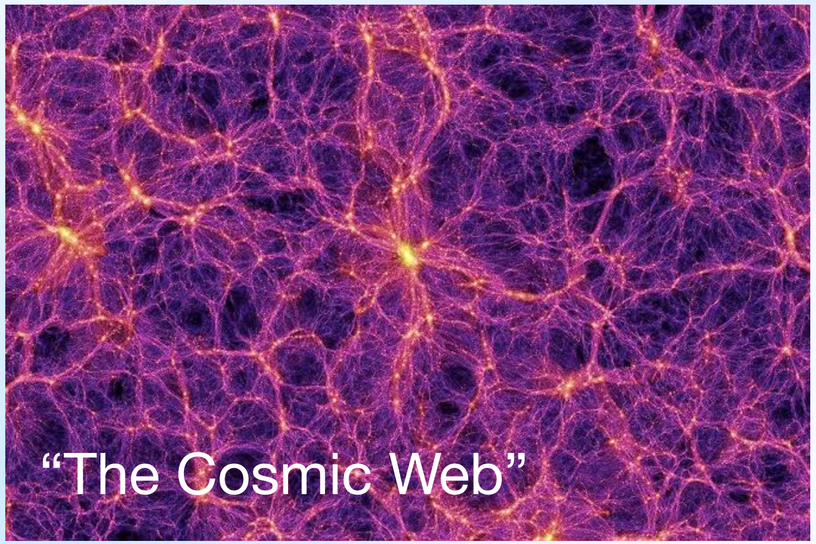
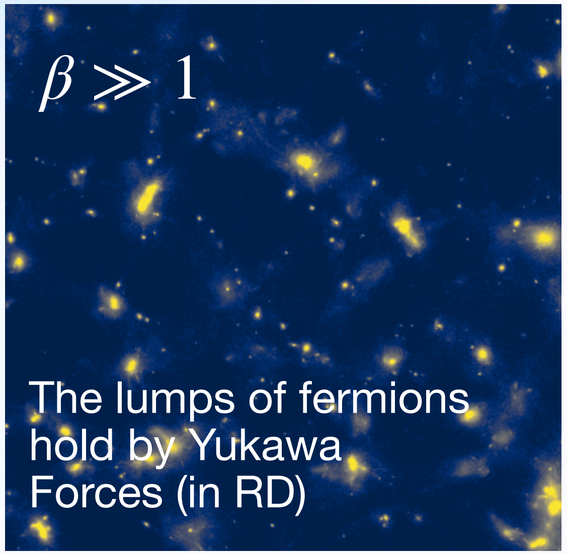
can efficiently form structures, halos, and black holes in the very early universe.

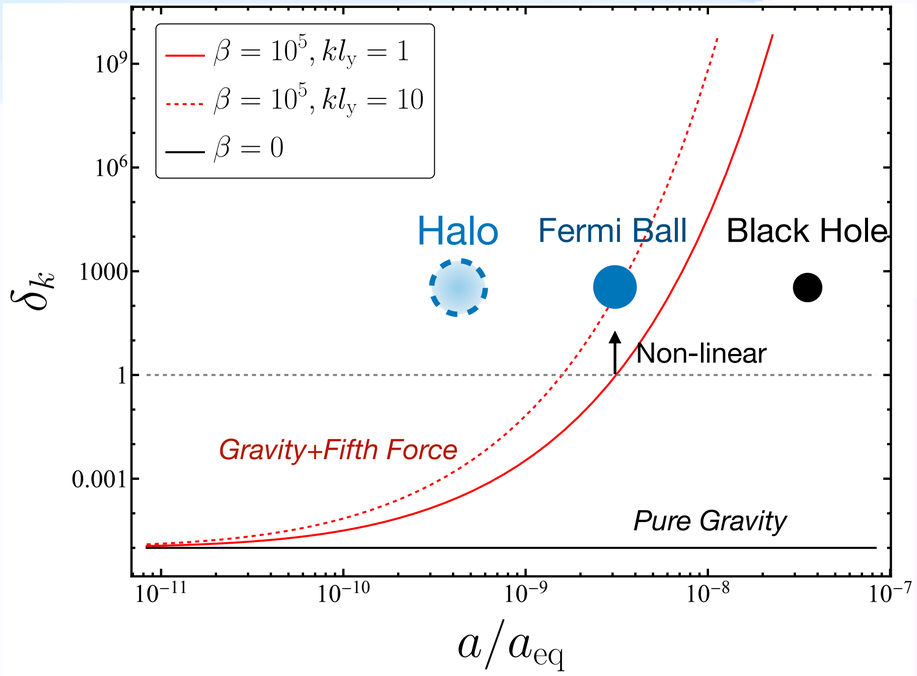
DM&DE Interaction?

Credit. Domenech

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



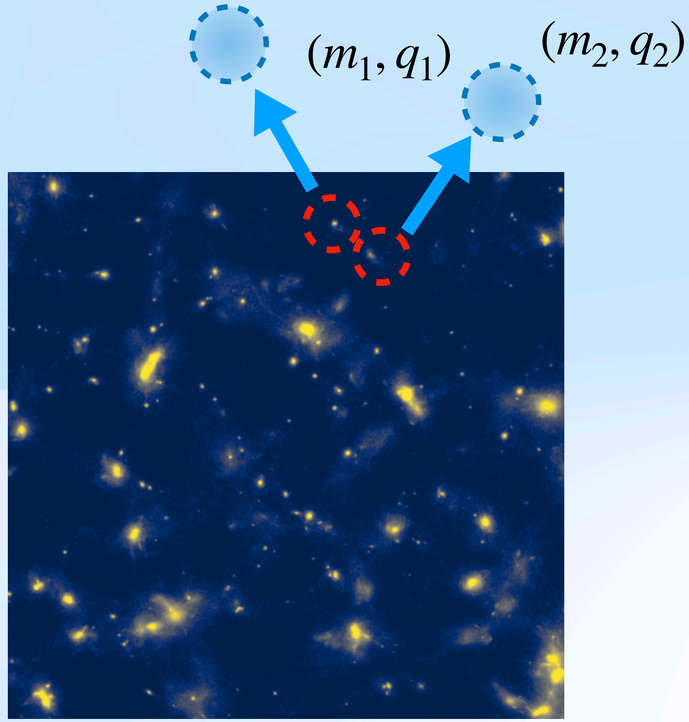




Domenech, Inman, Kusenko and Sasaki, 2023 & Inman, 2025

Early halo formation: Theory

Something is not yet considered..



For two fermionic minihalos:

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

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

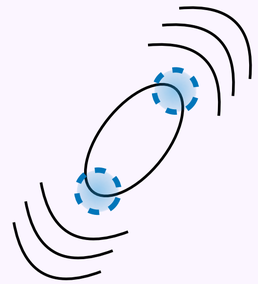
$$\frac{F_y}{F_G} \sim \frac{y^2}{G m_\psi^2} = 2\beta^2$$

Attractive Potential V.S. Hubble Flow

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

→ Isolated Bound System

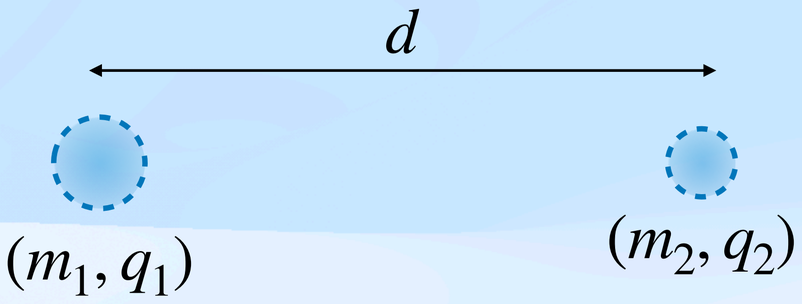
+ Tidal Force →



Radiations from halo binaries:

GW and SW from the Halo Inspirals

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



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

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

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

Detectability

Gravity V.S. Yukawa Forces

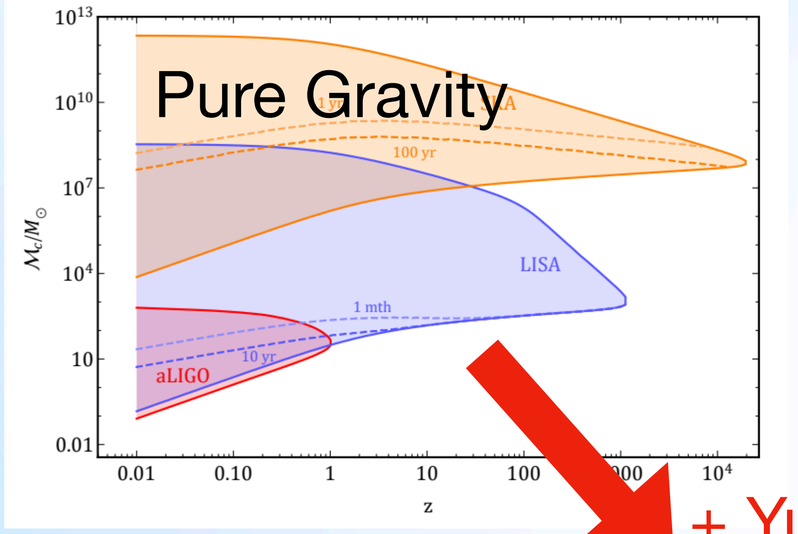
	Gravitationally-Bound	Yukawa-Bound
Strain h_z	$\frac{4}{d_L c^4}(\pi f_z)^{2/3}(G\mathcal{M}_z)^{5/3}$ $(\star)$	$(\star)\times\left(2\beta^2\right)^{2/3}$
Frequency $f_z = f/(1+z)$	$\frac{1}{\pi(1+z)}\sqrt{\frac{G(m_1+m_2)}{a^3}}$ $(\circ)$	$(\circ)\times\sqrt{2\beta^2}$
Orbital Evolution df_z/dt_z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

$d_L \propto (1+z)$

$f_z = f/(1+z)$

$\mathcal{M}_z = \mathcal{M}(1+z)$

Detectable CBC by LIGO/LISA/SKA (Credit. Qianhang)



High-redshift events are not detectable if BBH

1) Cut-off Frequency $\propto 1/\mathcal{M}_z$

2) Strain related to $\mathcal{M}$

+ Yukawa Force

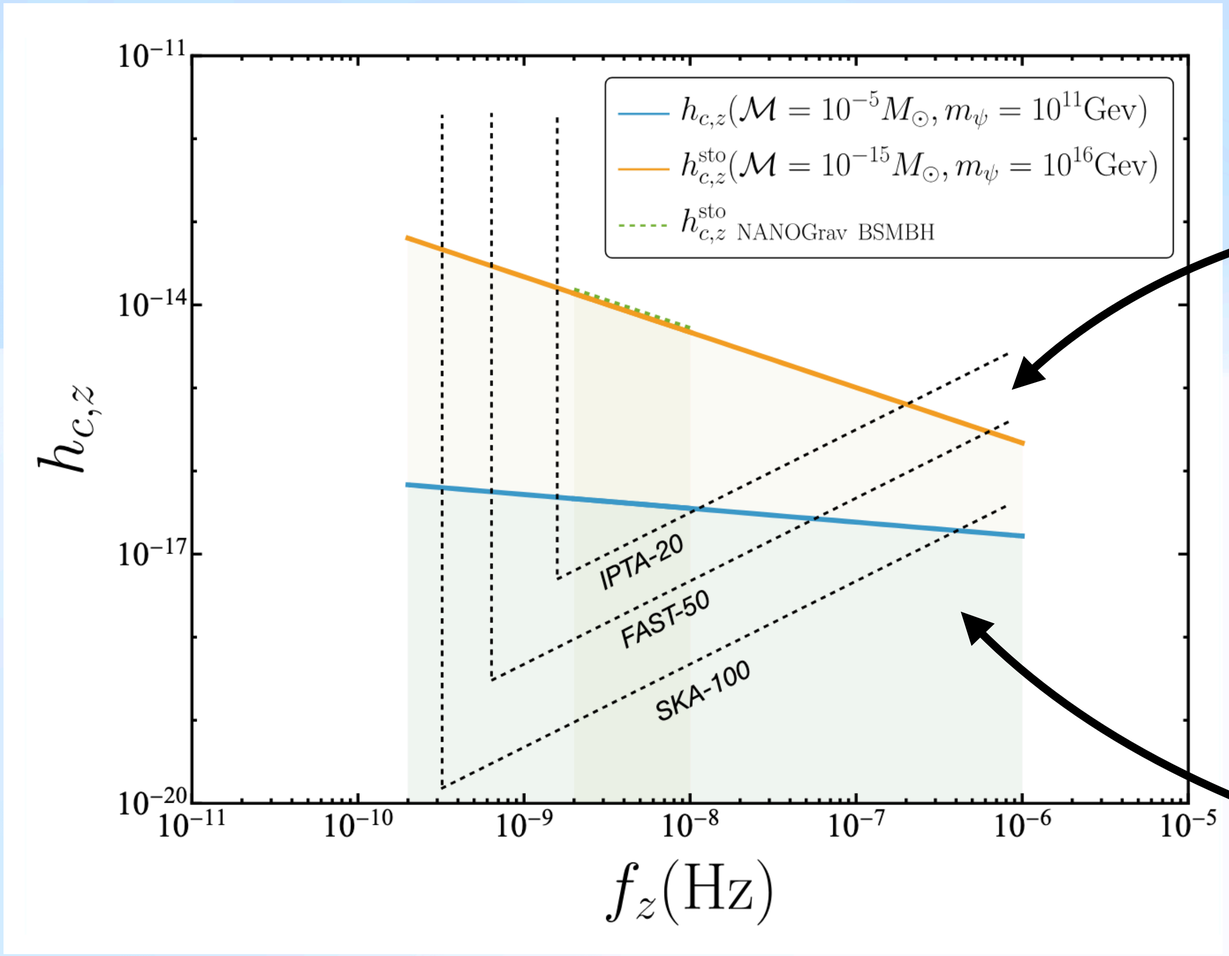
Xinpeng Wang (Kavli IPMU)

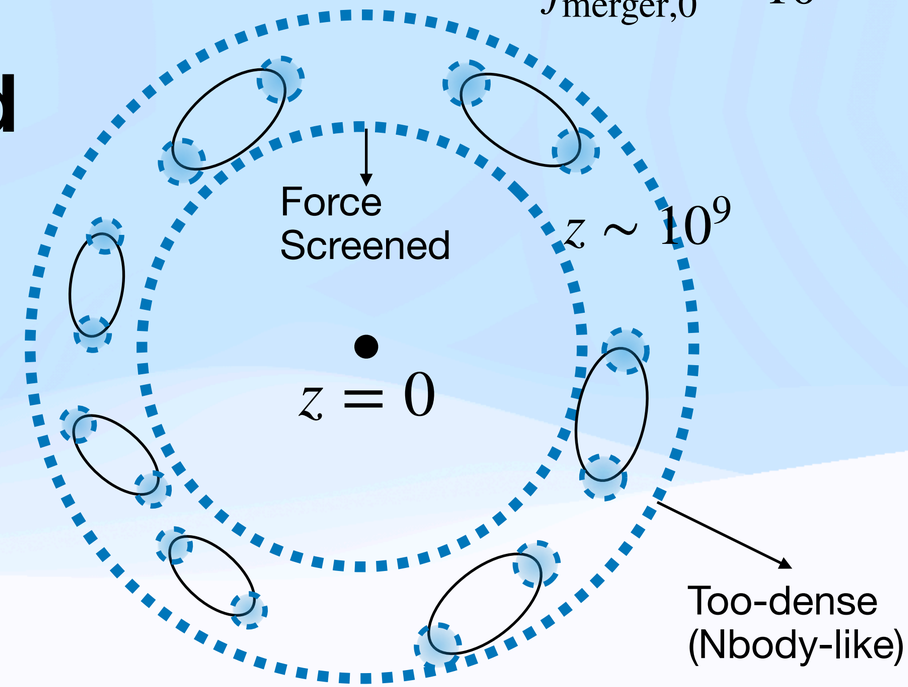
Radiations from halo binaries:

Individual event & stochastic background

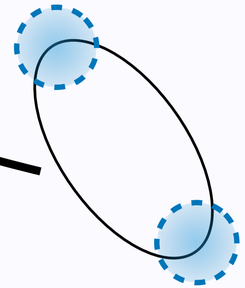
The fraction of merger relics in dark matter

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





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



Single Event @ $z = 10^9$

NANOGrav Collaboration, 2023

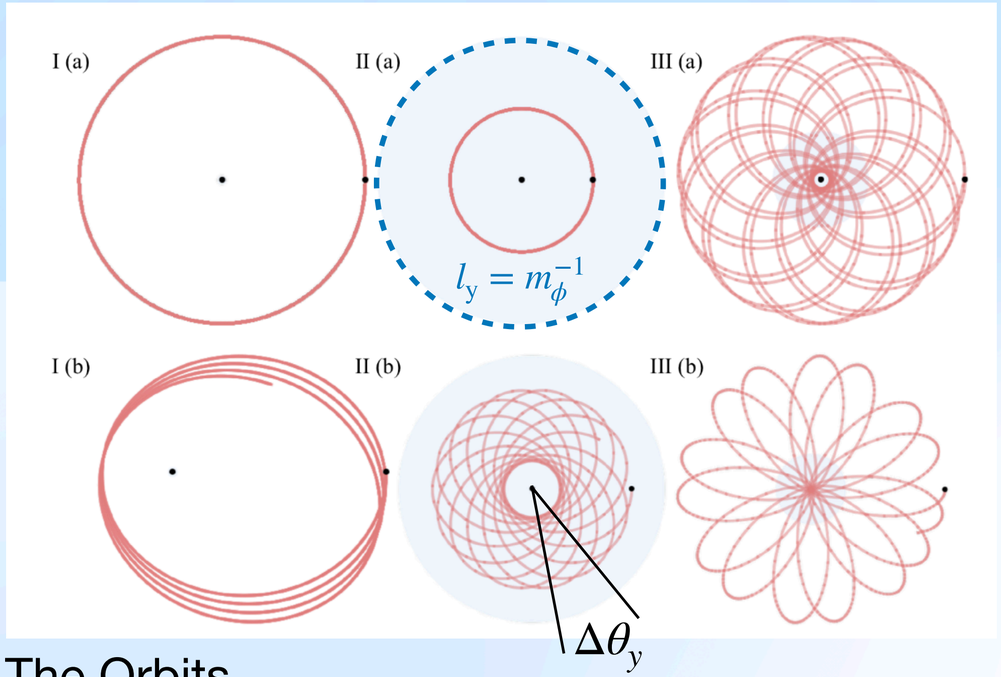
Xinpeng Wang (Kavli IPMU)

Radiations from halo binaries:

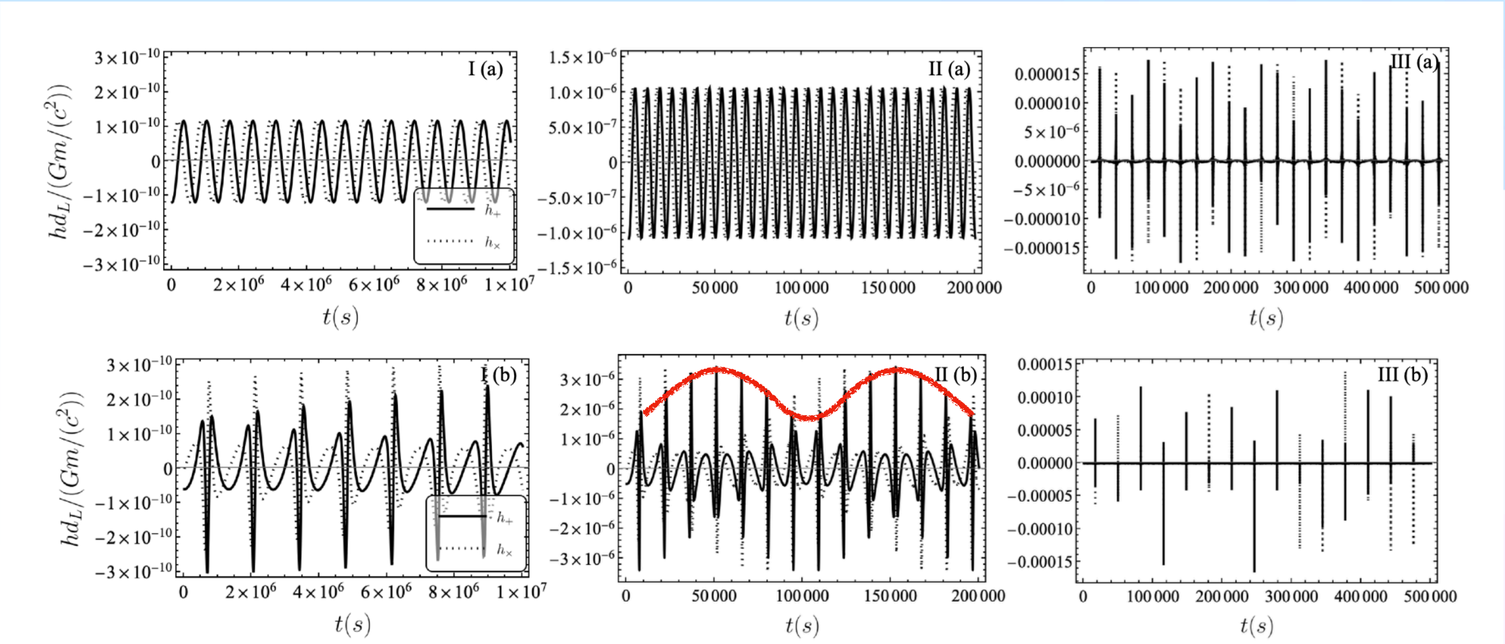
A Smoking Gun:
The Precession of the Orbit

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

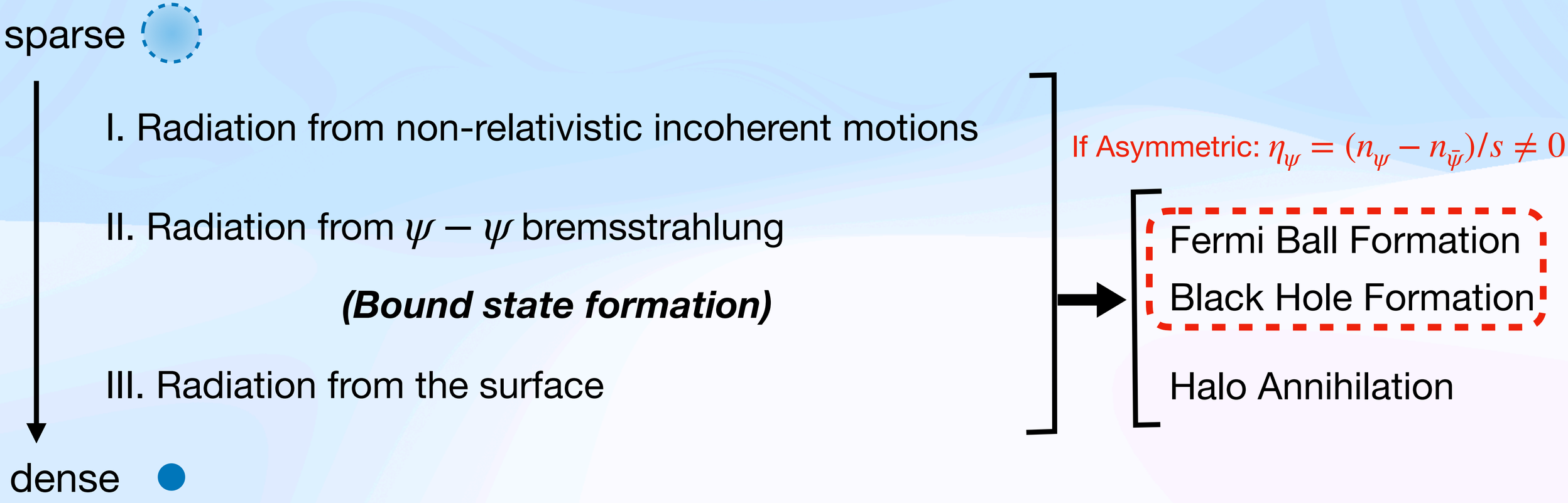
The Precession Angle per orbit $\Delta\theta_{\rm GR} \sim \dfrac{GM}{r(1-\epsilon^2)c^2}$ (1PN) $\Delta\theta_{\rm y} \sim 2\pi\left(\sqrt{\dfrac{1+r/l_{\rm y}}{1+r/l_{\rm y}-(r/l_{\rm y})^2}}-1\right)$ (0PN)

Cooling of the halo

Flores, Kusenko 2021
Flores, Lu, Kusenko 2023

After virialization…

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



The scalar charge of the halo

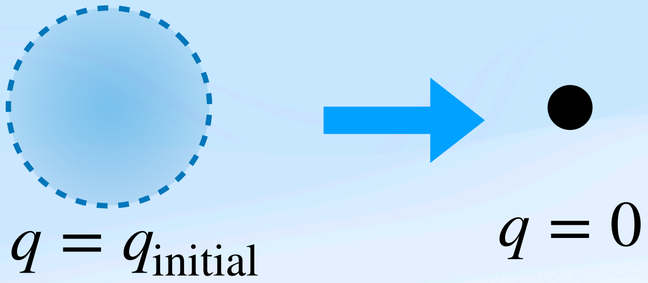
If the degeneracy pressure cannot support anymore…

The ‘Chandrasekhar Mass’ for strong force:

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

A black hole will form eventually!

“No hair theorem”



If the degeneracy pressure can still support the fermi ball…

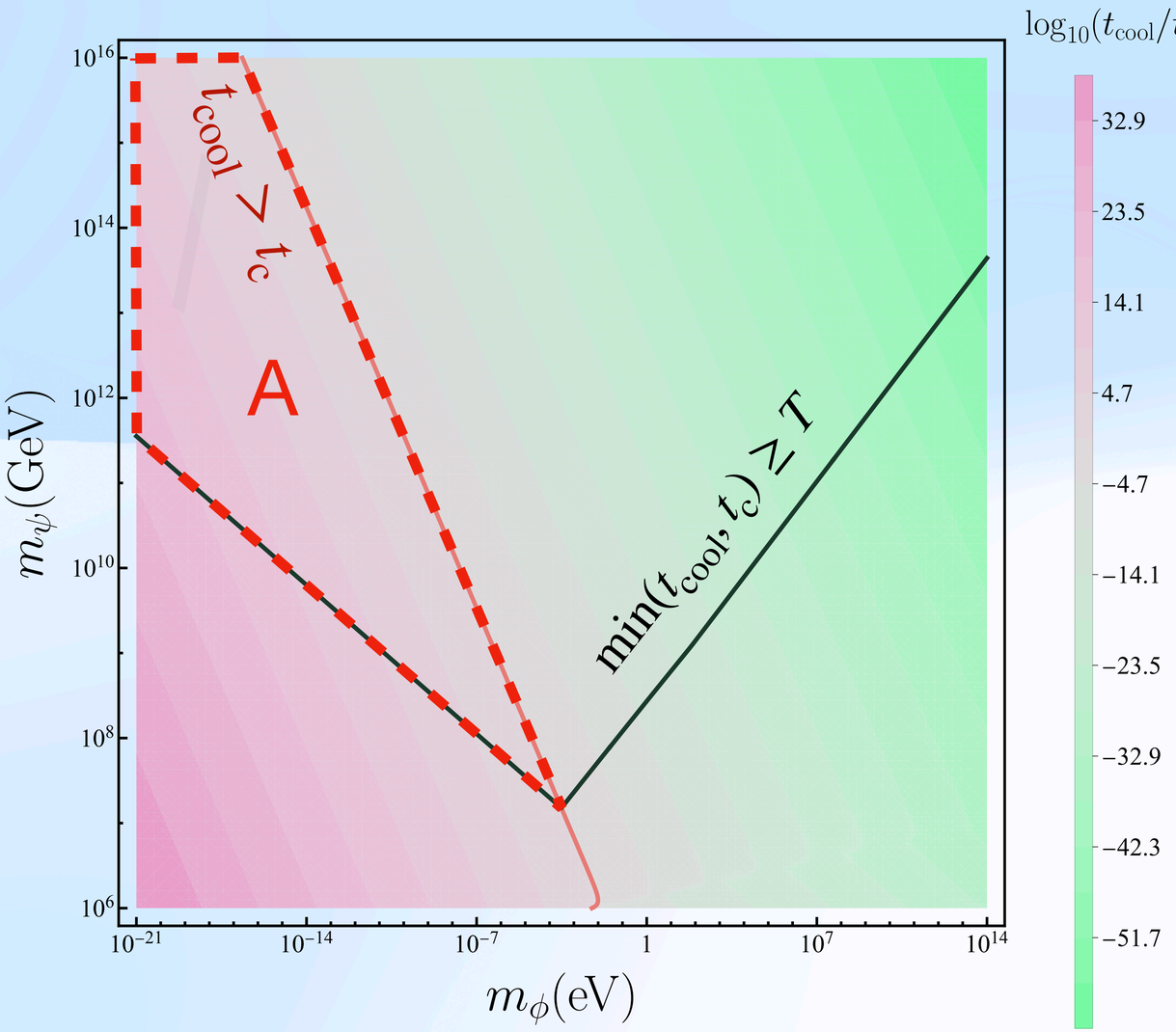
Scalar condensation →

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

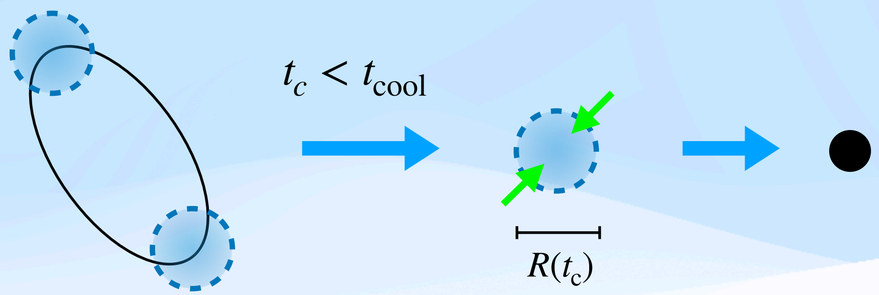
$\lambda\phi^4$ $\quad$ $m_{\psi,\rm eff}^2(\phi)$

→ Force/ Charge Screened

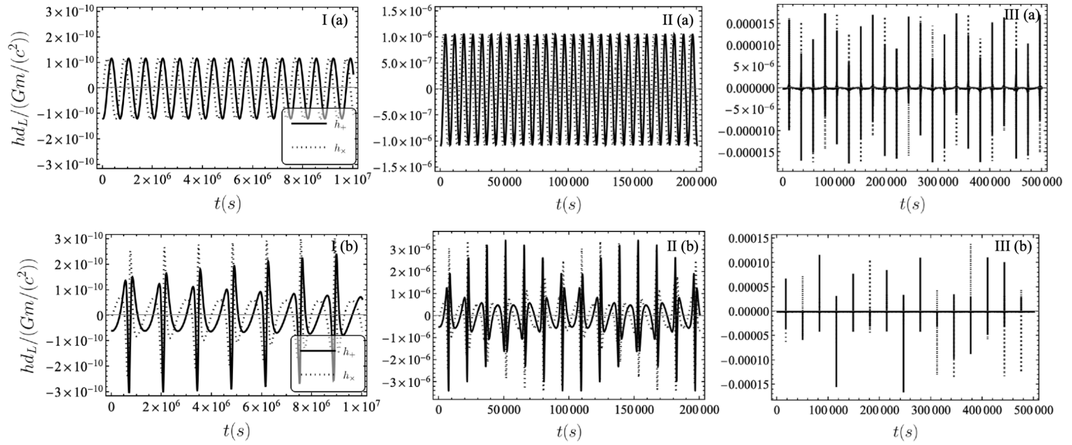
Comparing the time scale



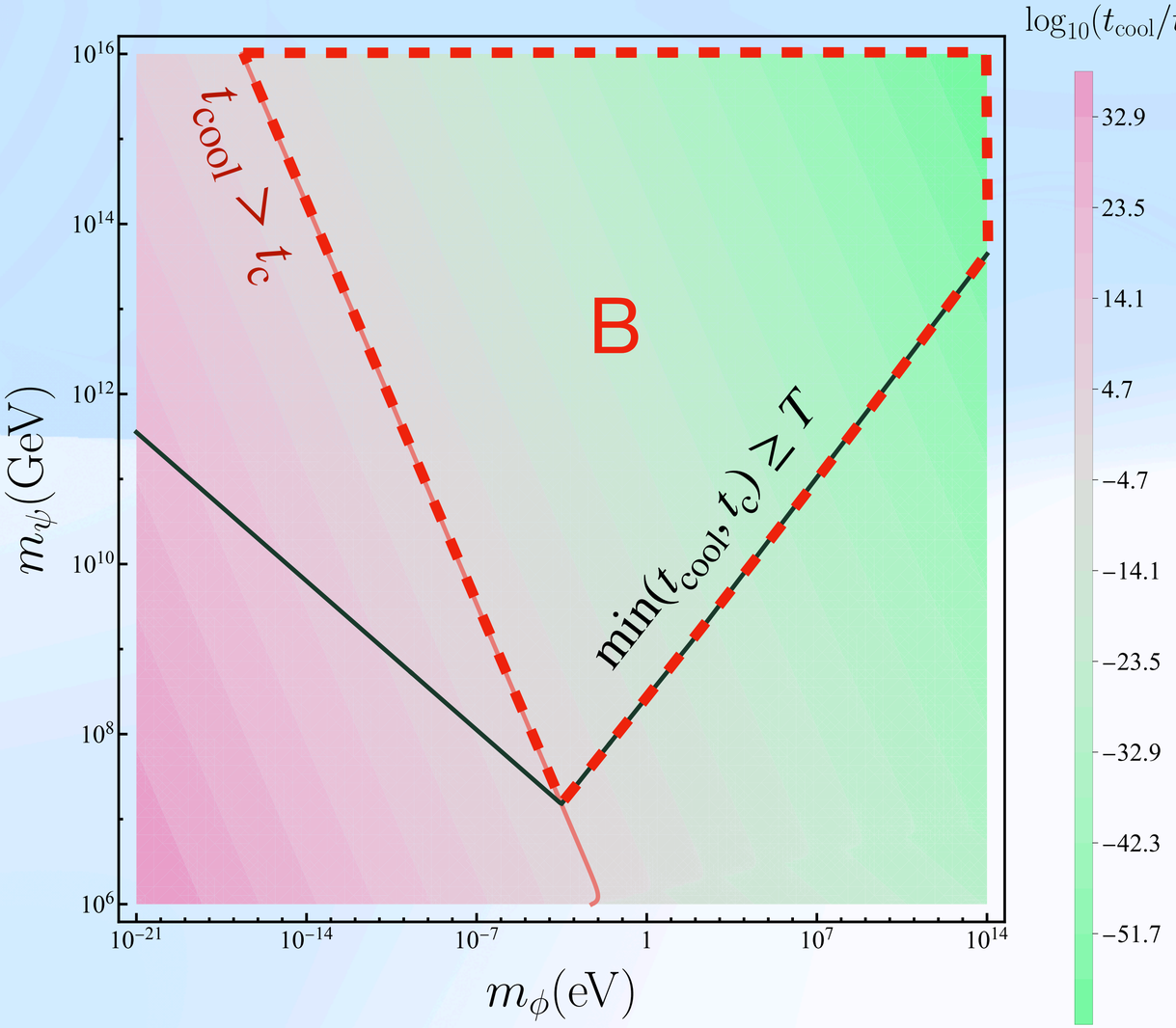
Complete Merger



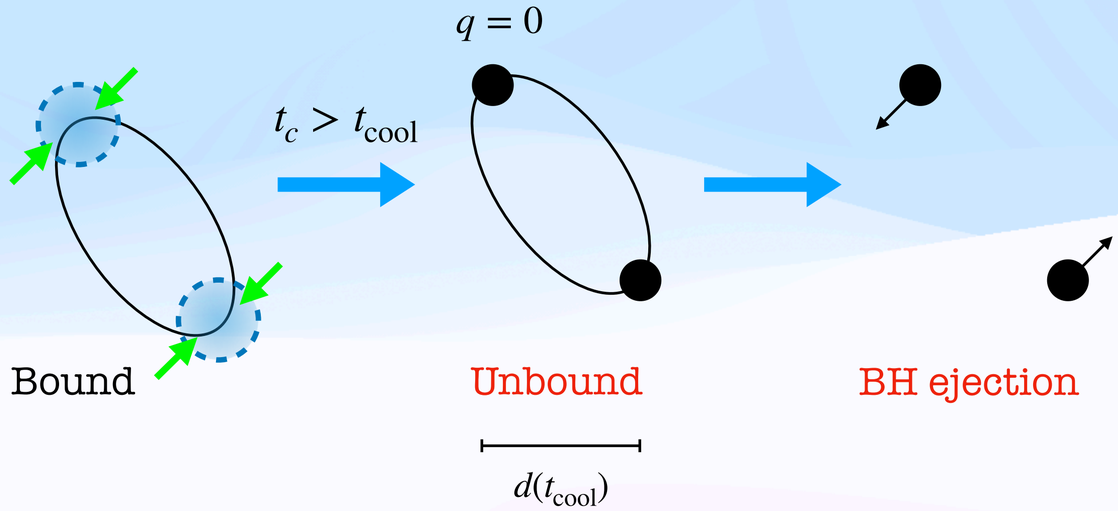
Gravitational Waves (Inspiral-Merger-Ringdown)



Comparing the time scale



Interrupted Merger

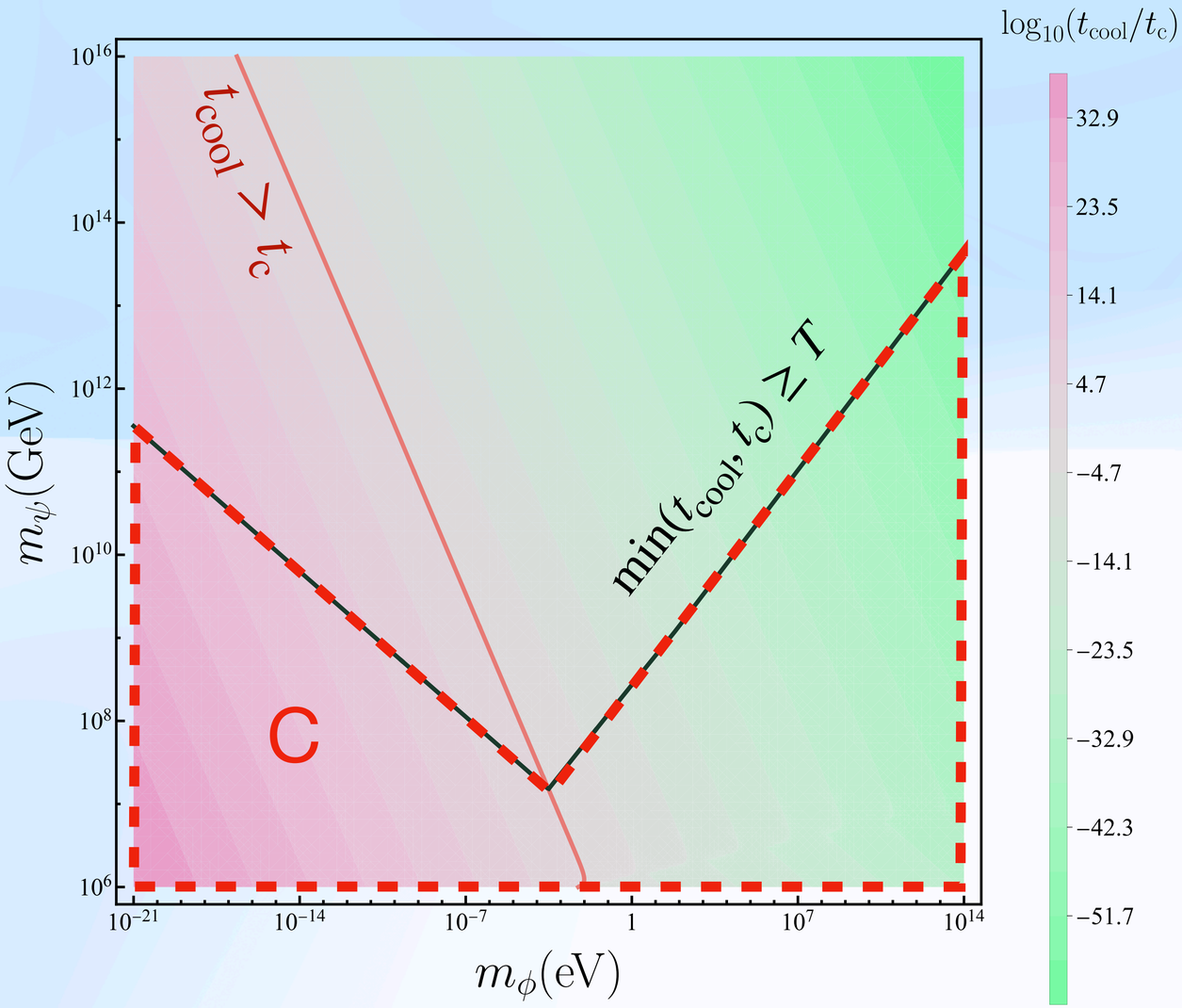


$E_{\rm y} \rightarrow E_{\rm k}$ Ejection @ $v_{\rm rel}$

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

Free-Floating Planets in Micro-lensing?

Comparing the time scale

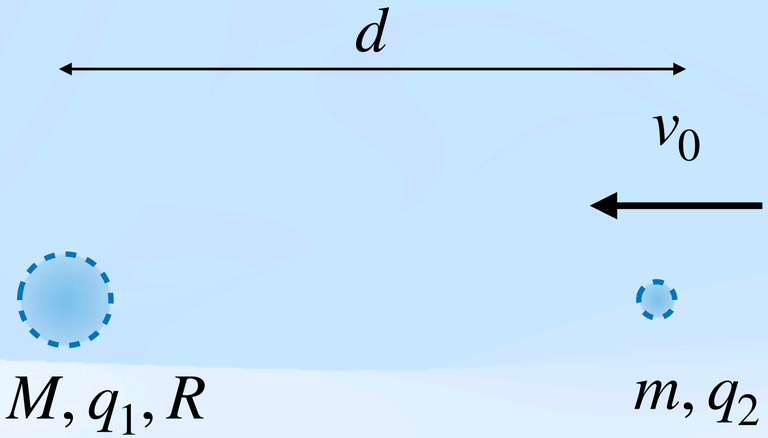


Prompt Merger

The merger concludes before completing a full orbital period.

Prompt Merger: Short-time GW Burst

When throwing a relativistic point-like charge to a halo…

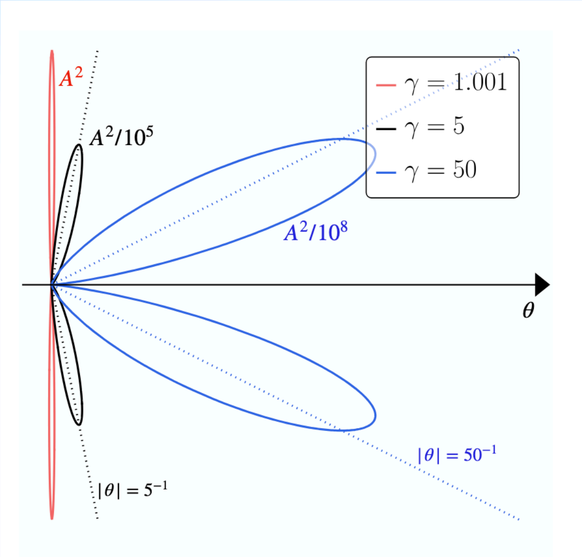


The Gravitational Wave Strain

$$h_{\theta\theta} = -h_{\phi\phi} = \frac{2m}{D_L}\left[\frac{\gamma \dot{d}^2 \sin^2\theta}{1-\dot{d}\cos\theta}\right]$$

Assuming $R \gg 2M$:

$$\ddot{d} = -\frac{y^2 q_1 q_2}{4\pi\gamma^3 d^2}$$

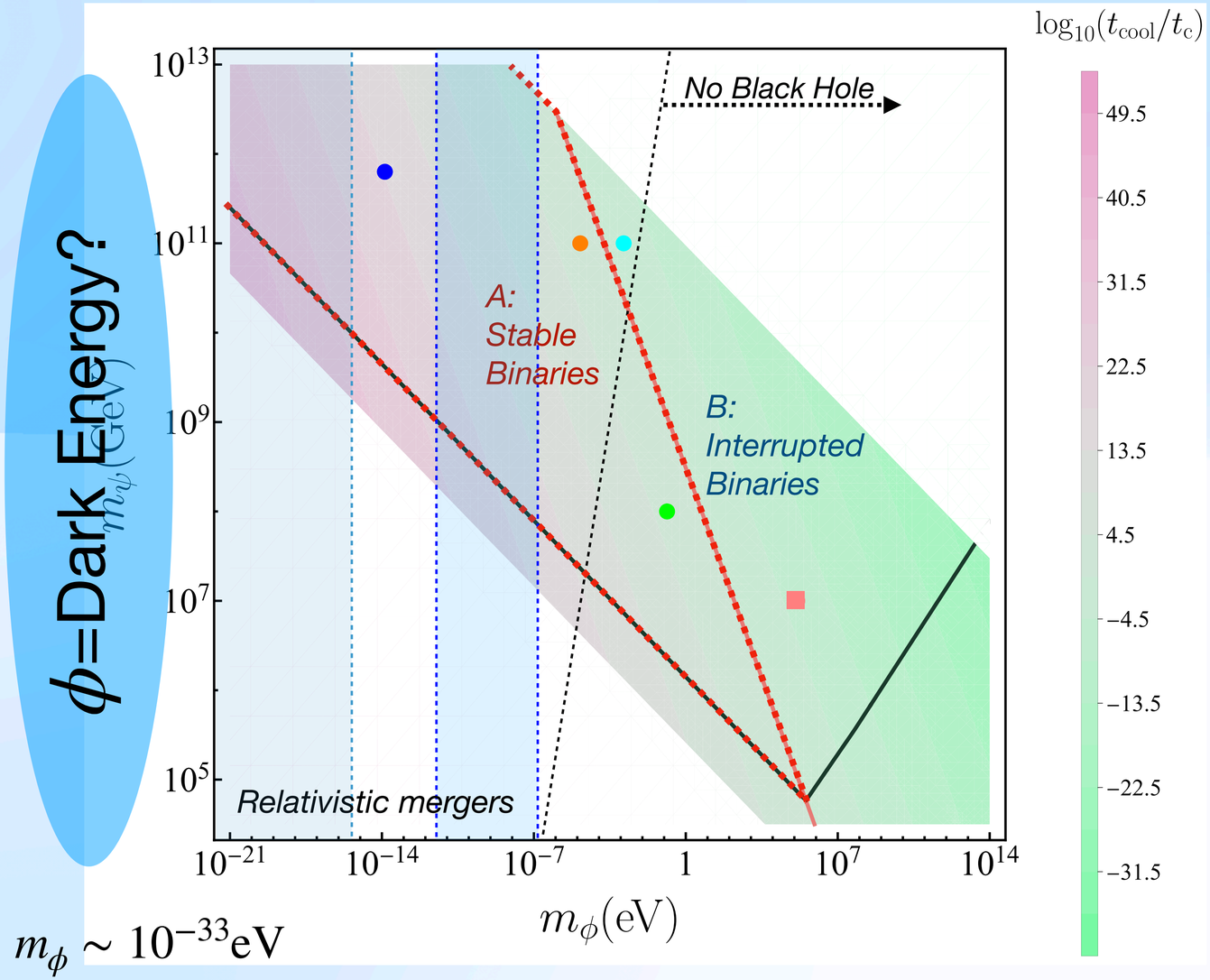


The energy emitted is concentrated in a opening angle γ^{-1}, just like a γ-ray burst.

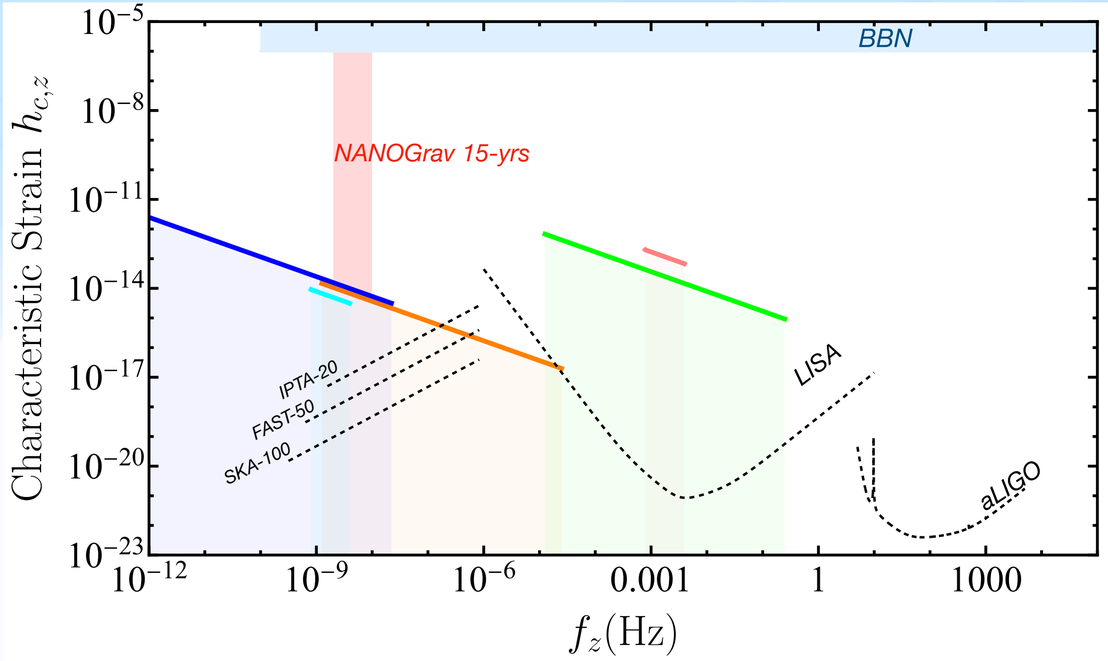
In the ultra-relativistic limit, $\Delta E_{\rm GW} \propto \gamma_0^2$

A plot of parameter space constraints

ϕ=Dark Energy?

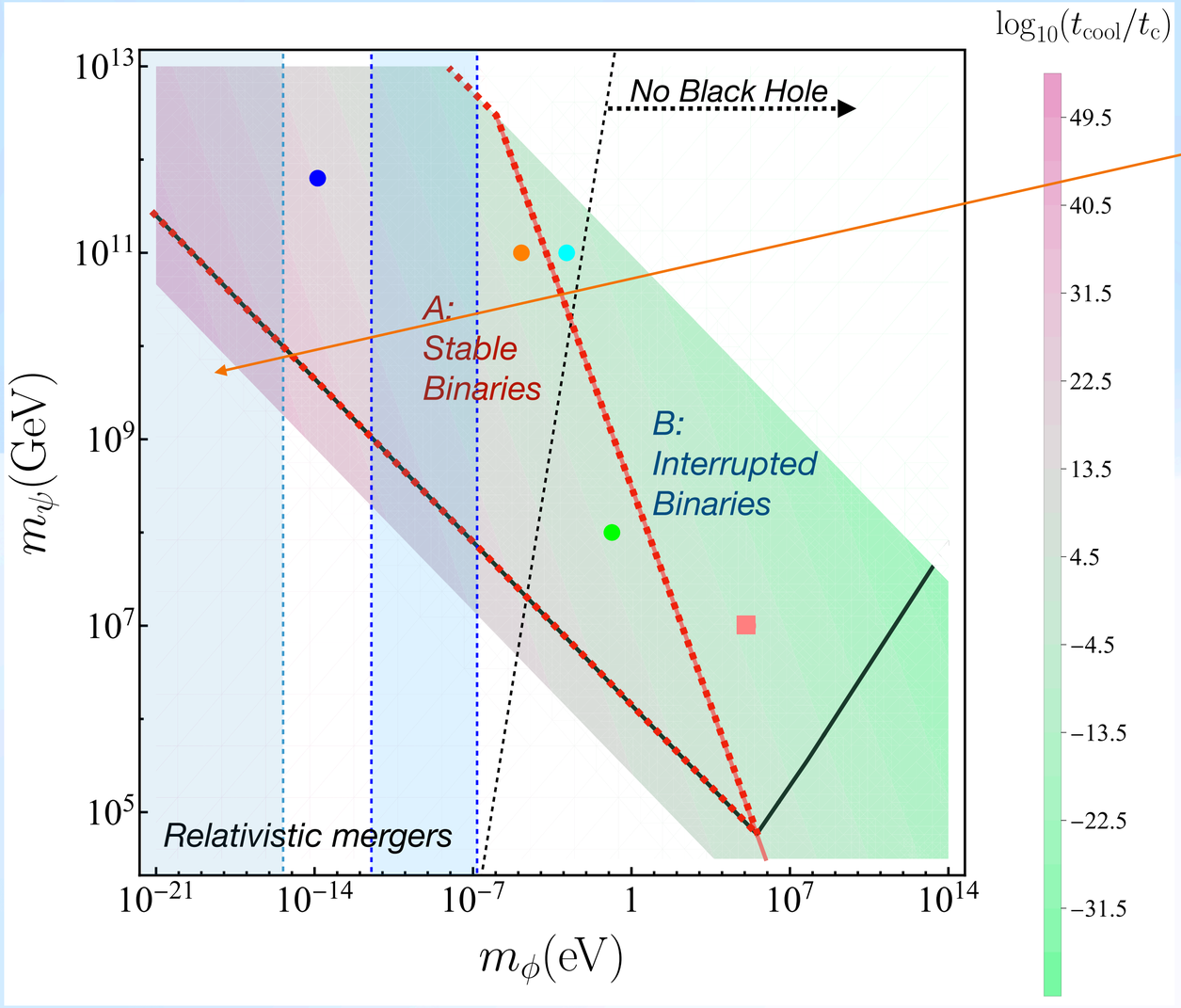


$m_\phi \sim 10^{-33}$eV



GWB comes from the minihalo Inspirals

A plot of parameter space constraints



Observational Constraints

if FB=DM (Bullet Cluster)

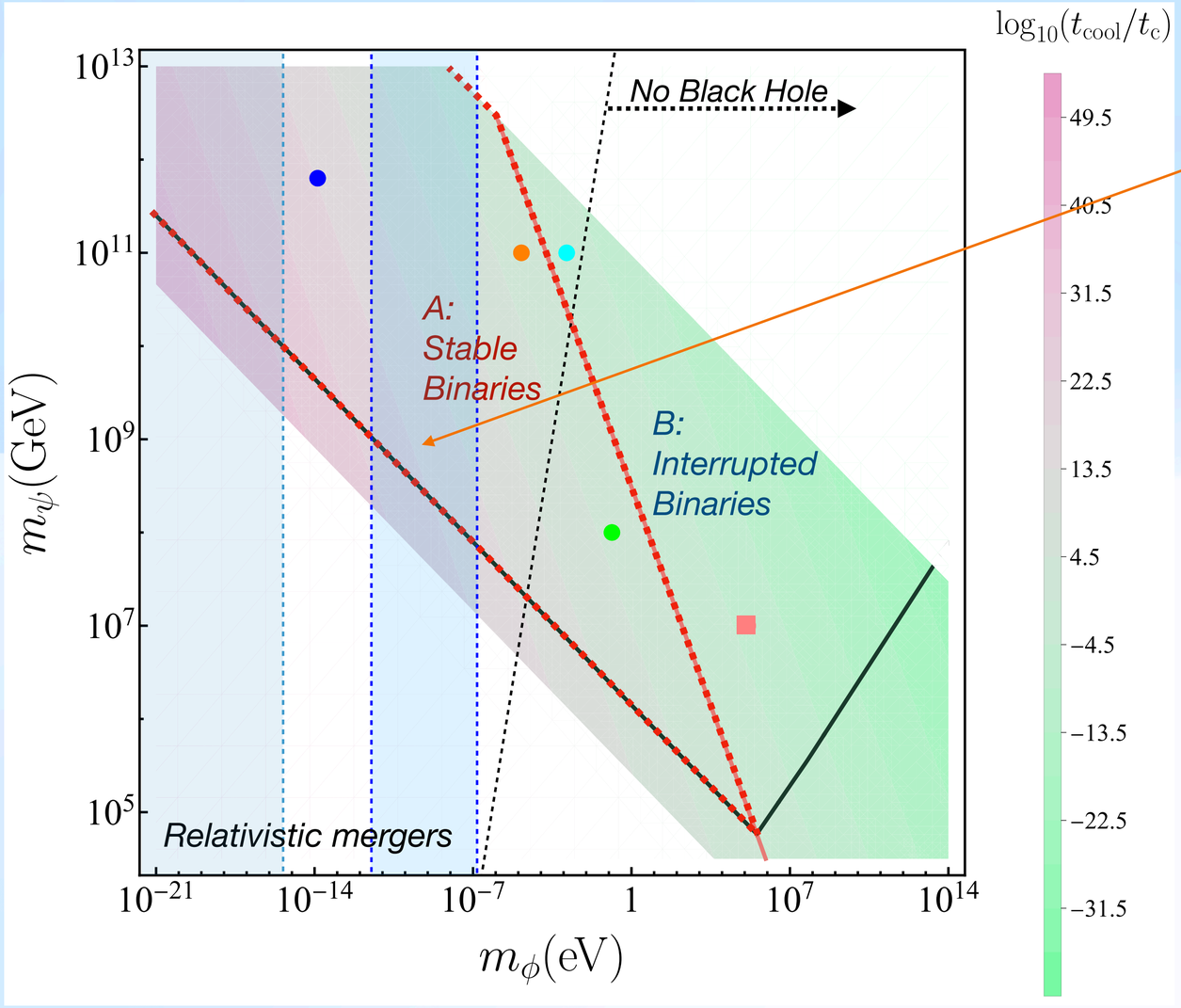
$$\sigma/m_{\rm FB} < 1{\rm cm}^2/{\rm g}$$

$$\sigma \sim \pi m_\phi^{-2}$$

if FB=small fraction of DM

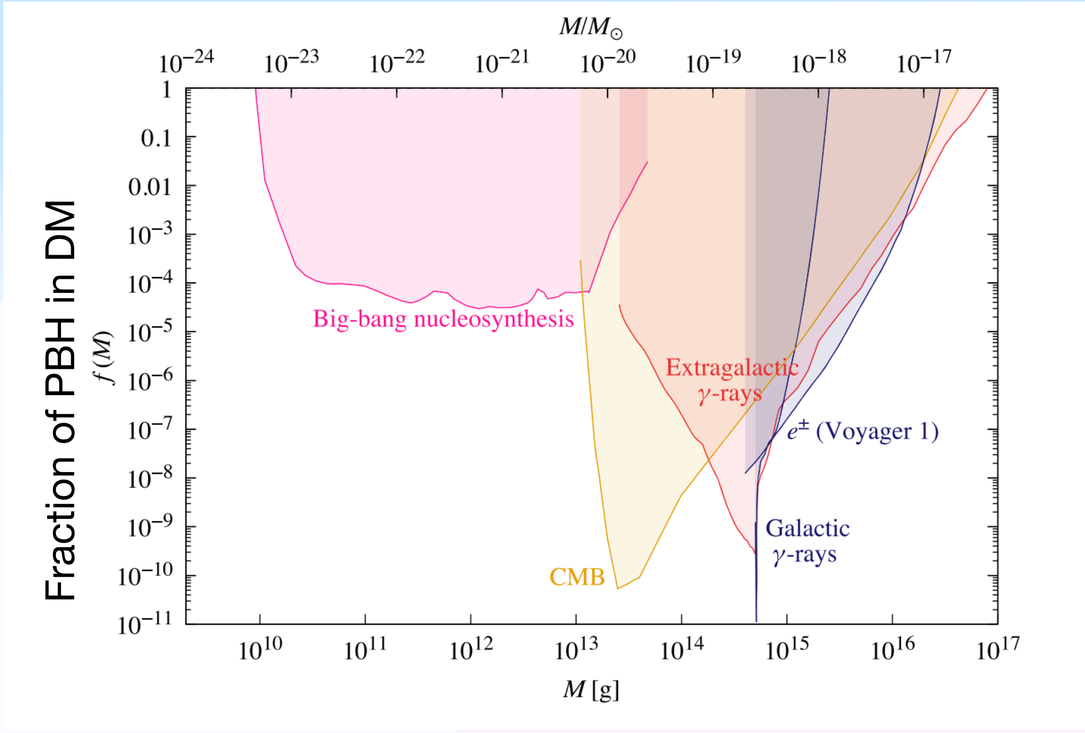
No Constraints!

A plot of parameter space constraints



Observational Constraints

if BH=DM (BBN & γ-ray)



Take Home

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.