Quantum Gravity and Cosmology 2024

Primordial Black Holes seeded during Inflation

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Tongji University

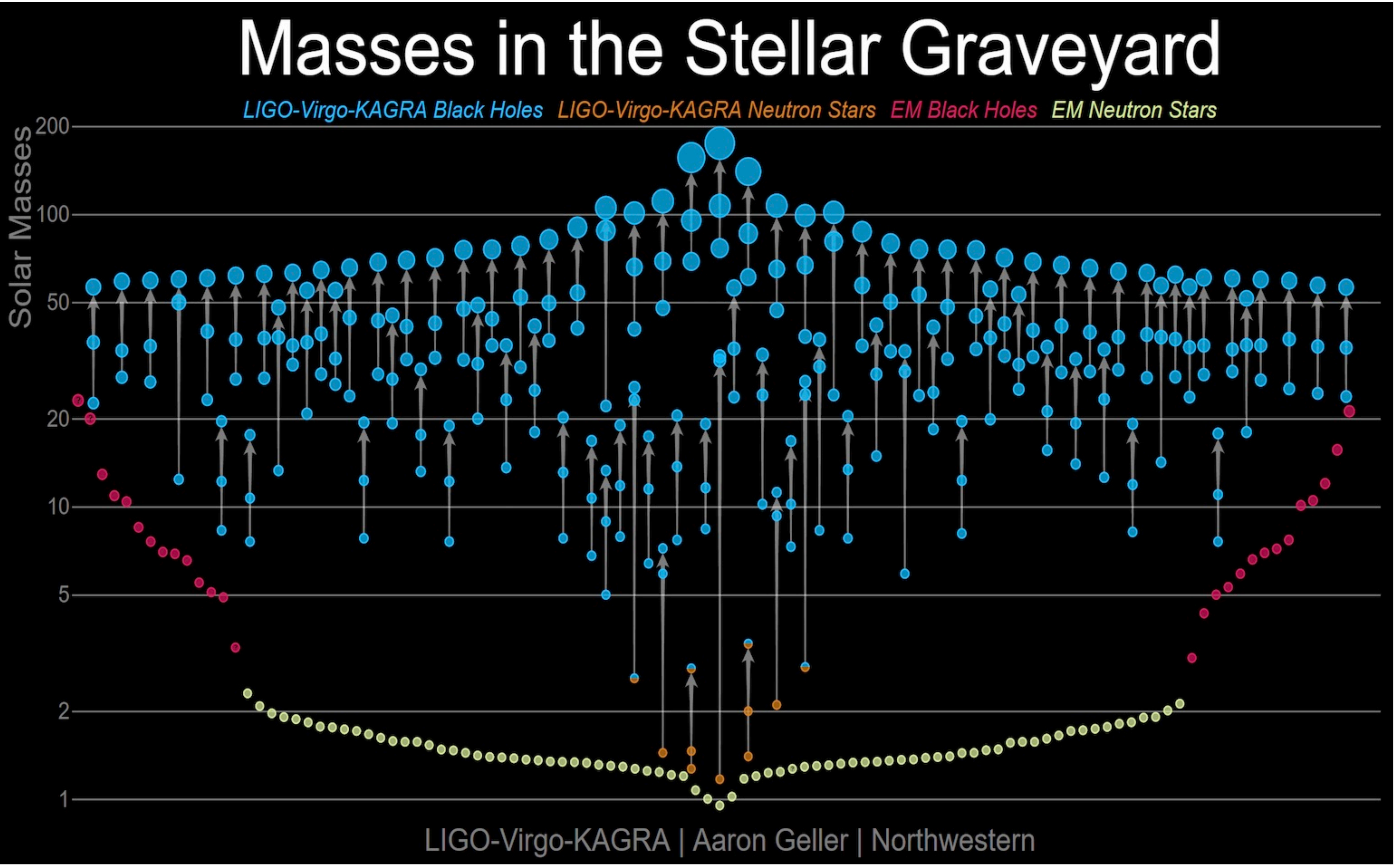
2024. 7. 2

Based on:
X. Wang, YZ, M. Sasaki, [arXiv: 2404.02492]
S. Pi, YZ, Q. Huang, M. Sasaki, JCAP 05 (2018) 042 [arXiv: 1712.09896]
X. Wang, YZ, Kimura and M. Yamaguchi, SCPMA 6 (2023) 66 [arXiv: 2209.12911]
R. Kimura, T. Suyama, M. Yamaguchi and YZ, JCAP 04 (2021) 031 [arXiv: 2102.05280]
H. Wang, YZ, T. Suyama, in preparation

Why Primordial Black Hole (PBH)?

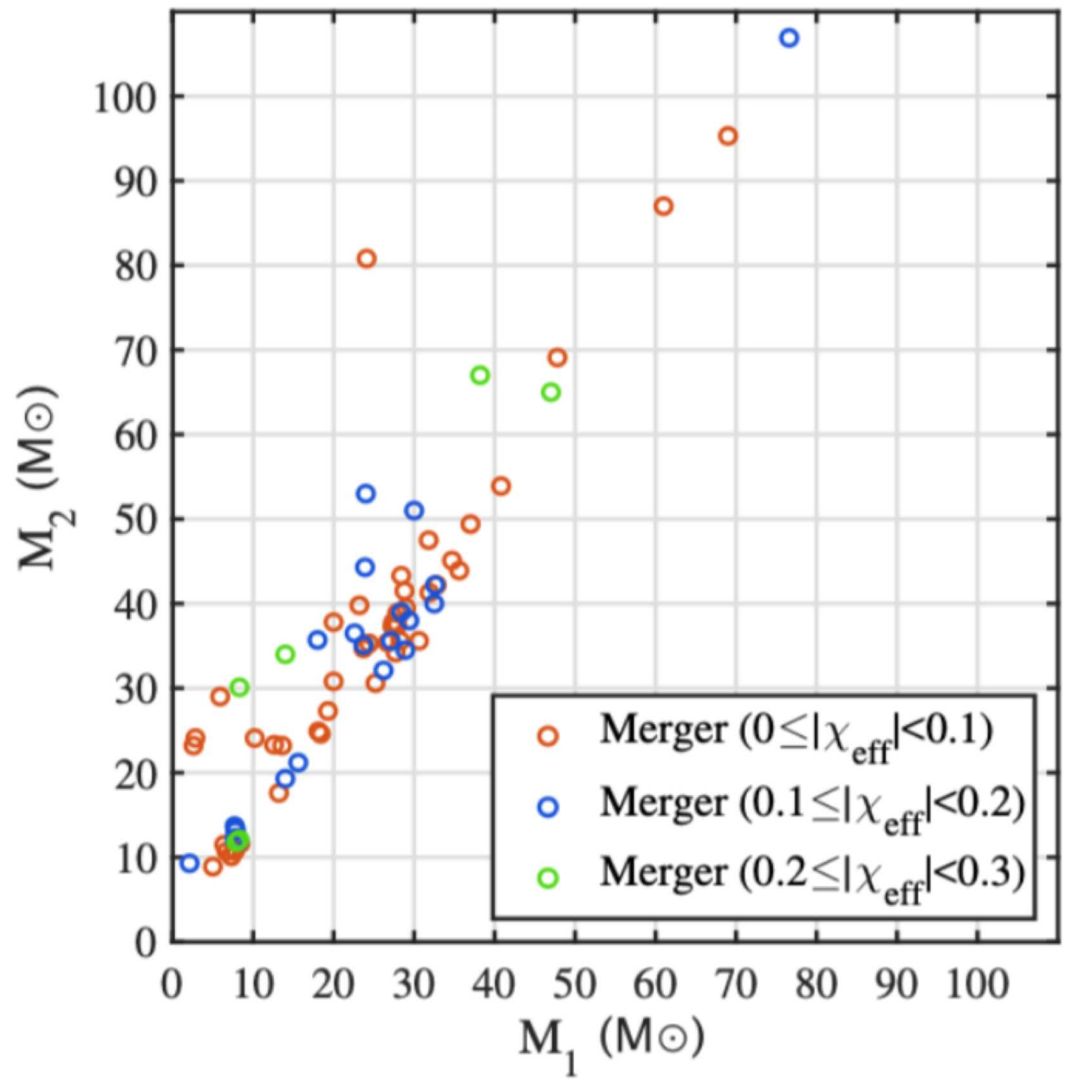
- BHs exist in the universe
- No need for new physics
- PBHs may dominate Dark Matter
- Detected GW events from LIGO may originate from the merger of PBH binaries

  M. Sasaki, T. Suyama, T. Tanaka, S. Yokoyama, PRL 117, no. 6, 061101 (2016)
- A possible way to probe the primordial power spectrum of curvature perturbation on small scales
- …



https://media.ligo.northwestern.edu

According to LIGO/Virgo O3 data



X. Wang, YZ, Kimura and M. Yamaguchi, SCPMA 6 (2023) 66

91 BBH candidates, 76 of them satisfy $m \gtrsim 1.5 M_{\odot}$ and $|\chi_{\rm eff}| \lesssim 0.3$

1. Merging BHs are Massive

2. Spin of BH is small

Contradiction ⟷ BHs from collapse of Stars

↑ satisfy

Primordial BHs

Massive BHs ?

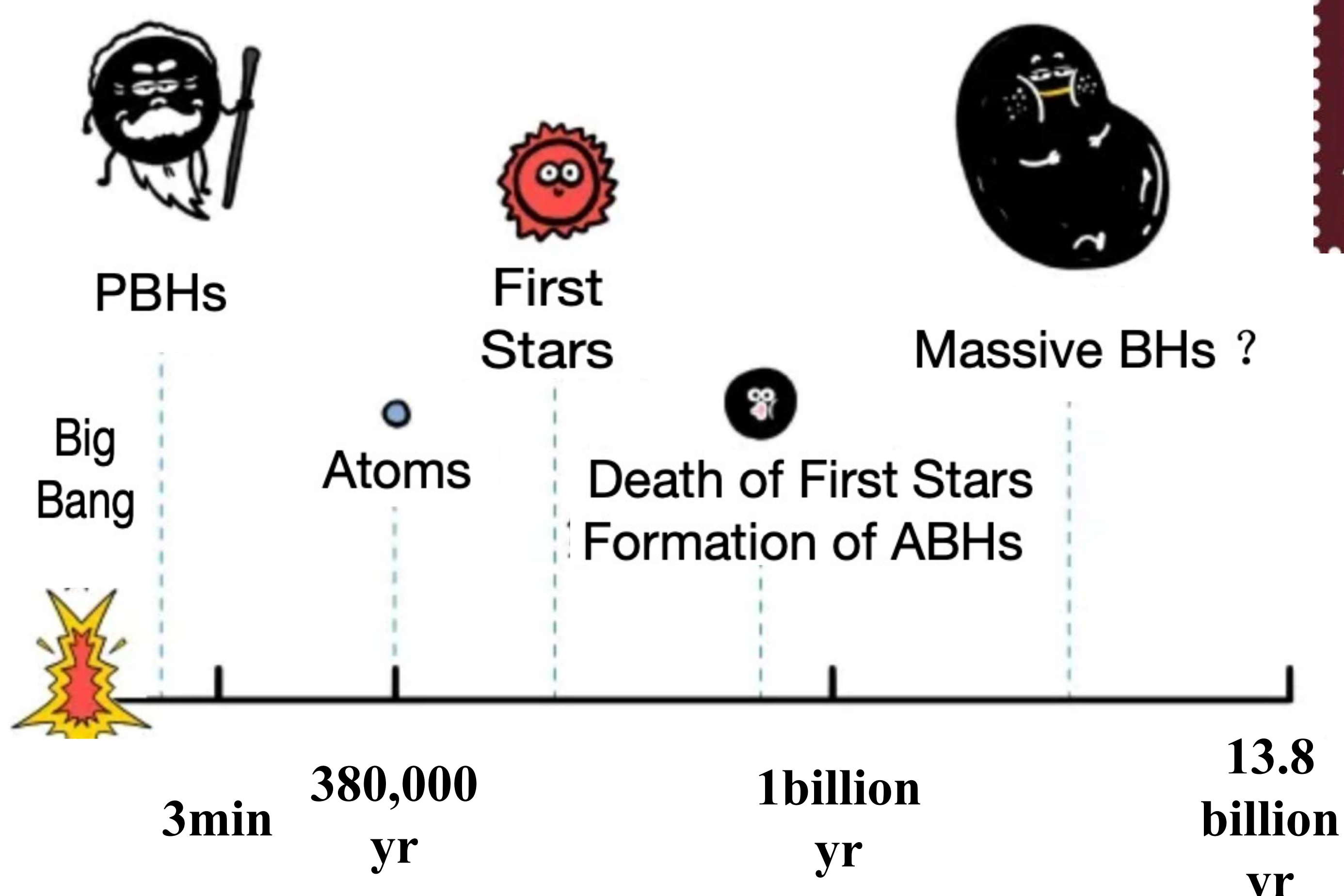
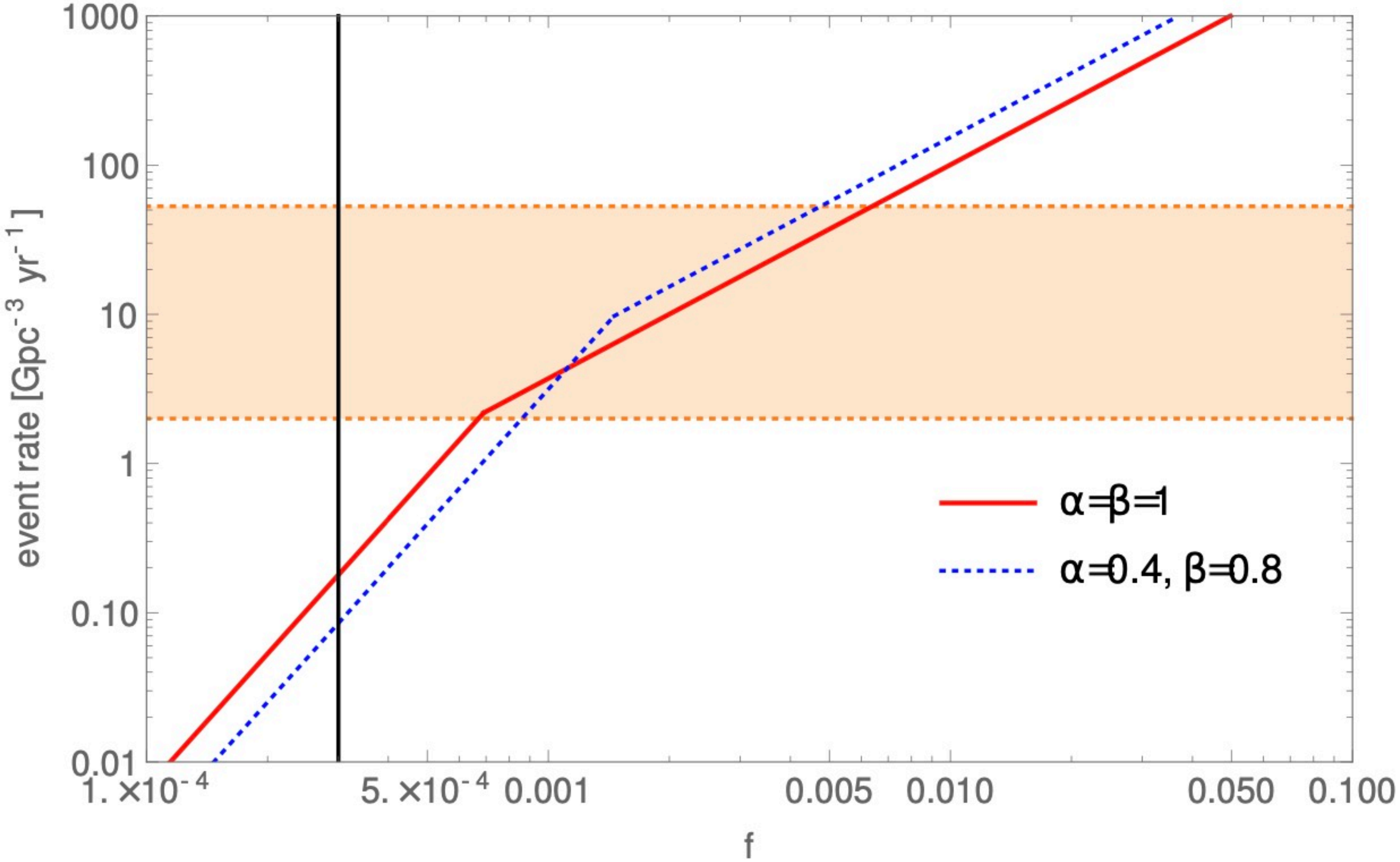


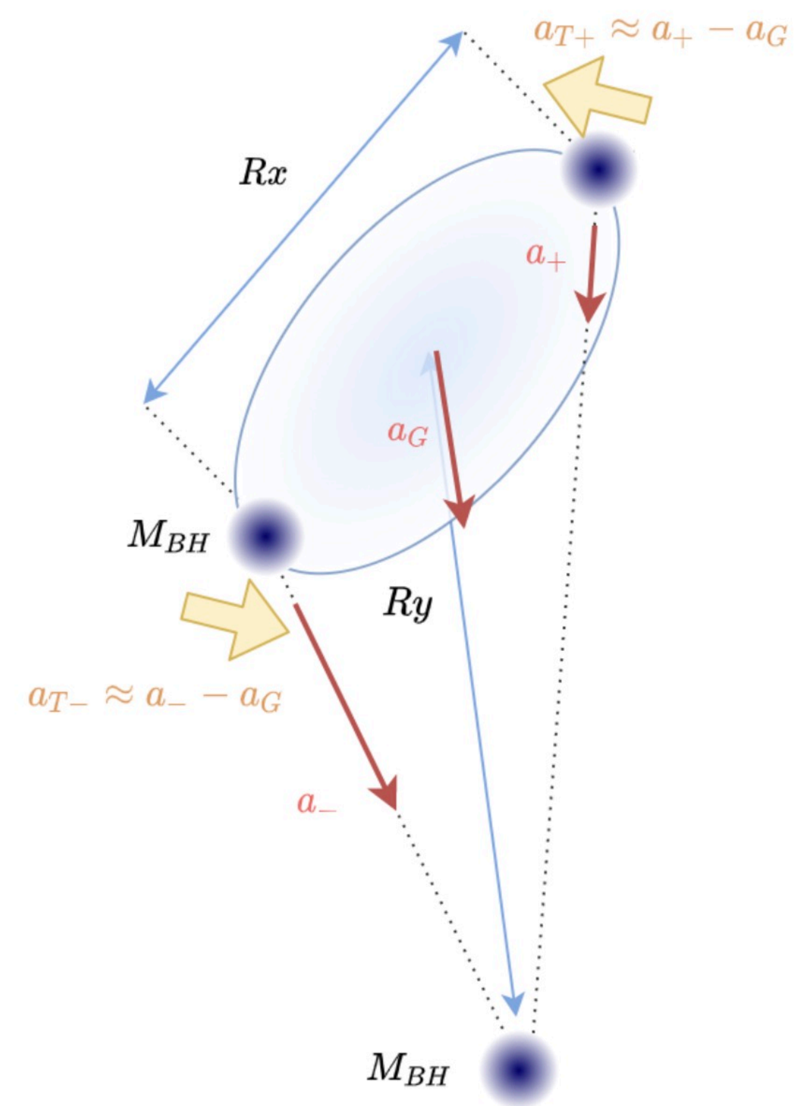
Illustration from “墨子”

Y. B. Zel’dovich, I. D. Novikov, Soviet Astronomy 10, 602 (1967)

S. Hawking, Mon. Not. Roy. Astron. Soc. 152, 75 (1971)

Massive PBHs for explanation of LIGO events

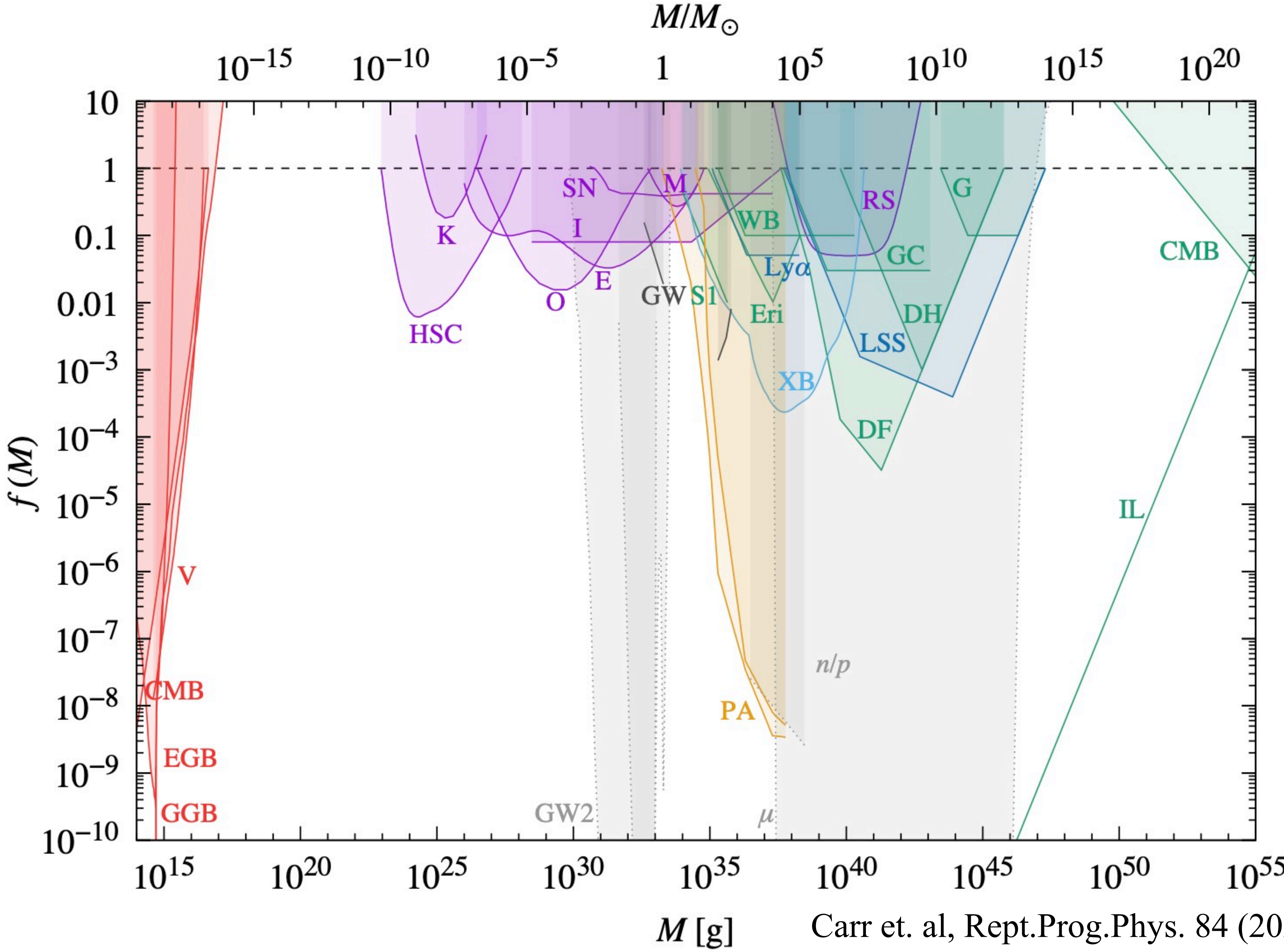




Sasaki, Suyama, Tanaka, Yokoyama, PRL 117 (2016) 6, 061101

Illustrated by Xinpeng

Moreover, small PBHs are candidate for DM



Carr et. al, Rept.Prog.Phys. 84 (2021) 11, 116902

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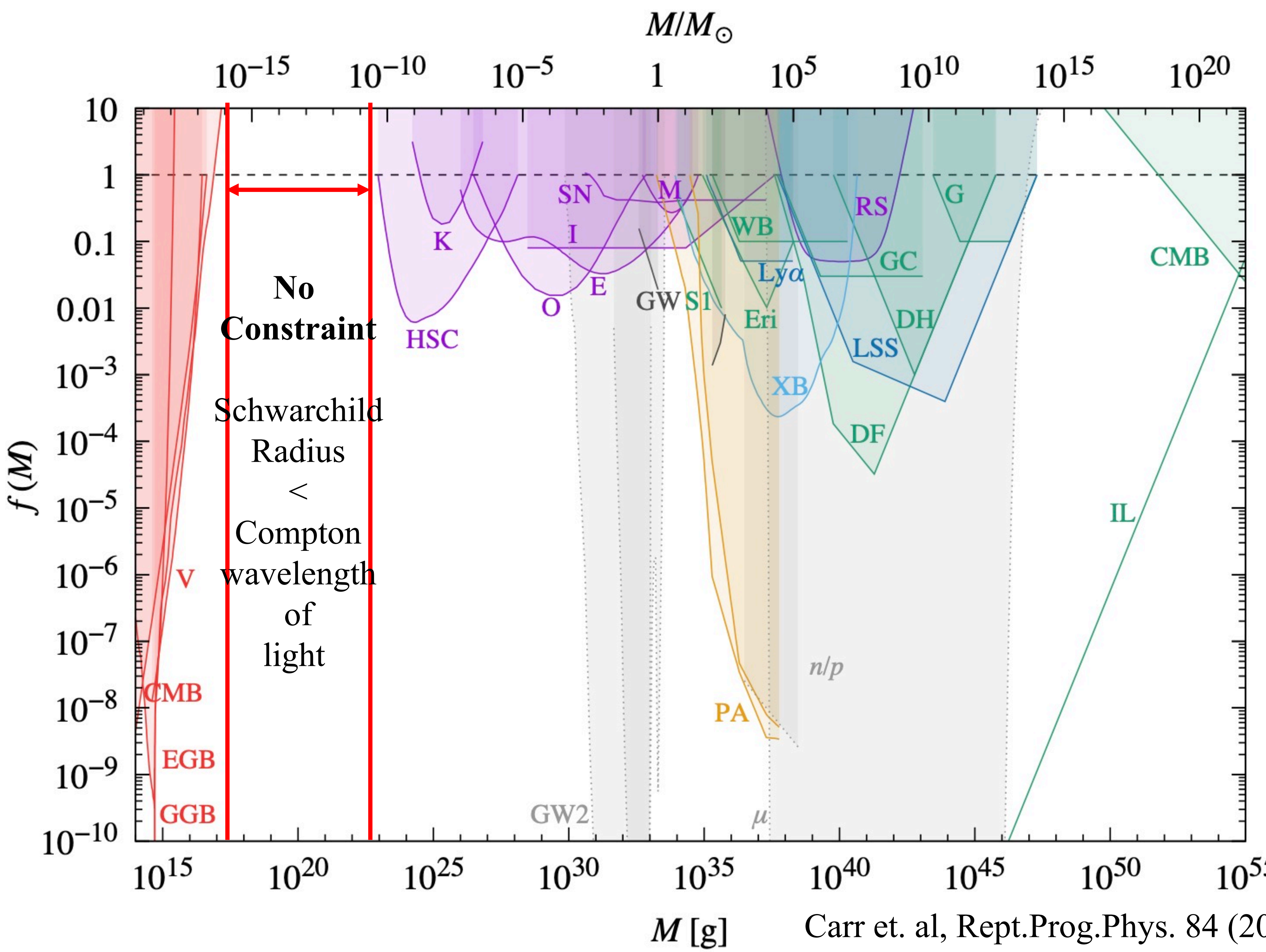

Carr et. al, Rept.Prog.Phys. 84 (2021) 11, 116902

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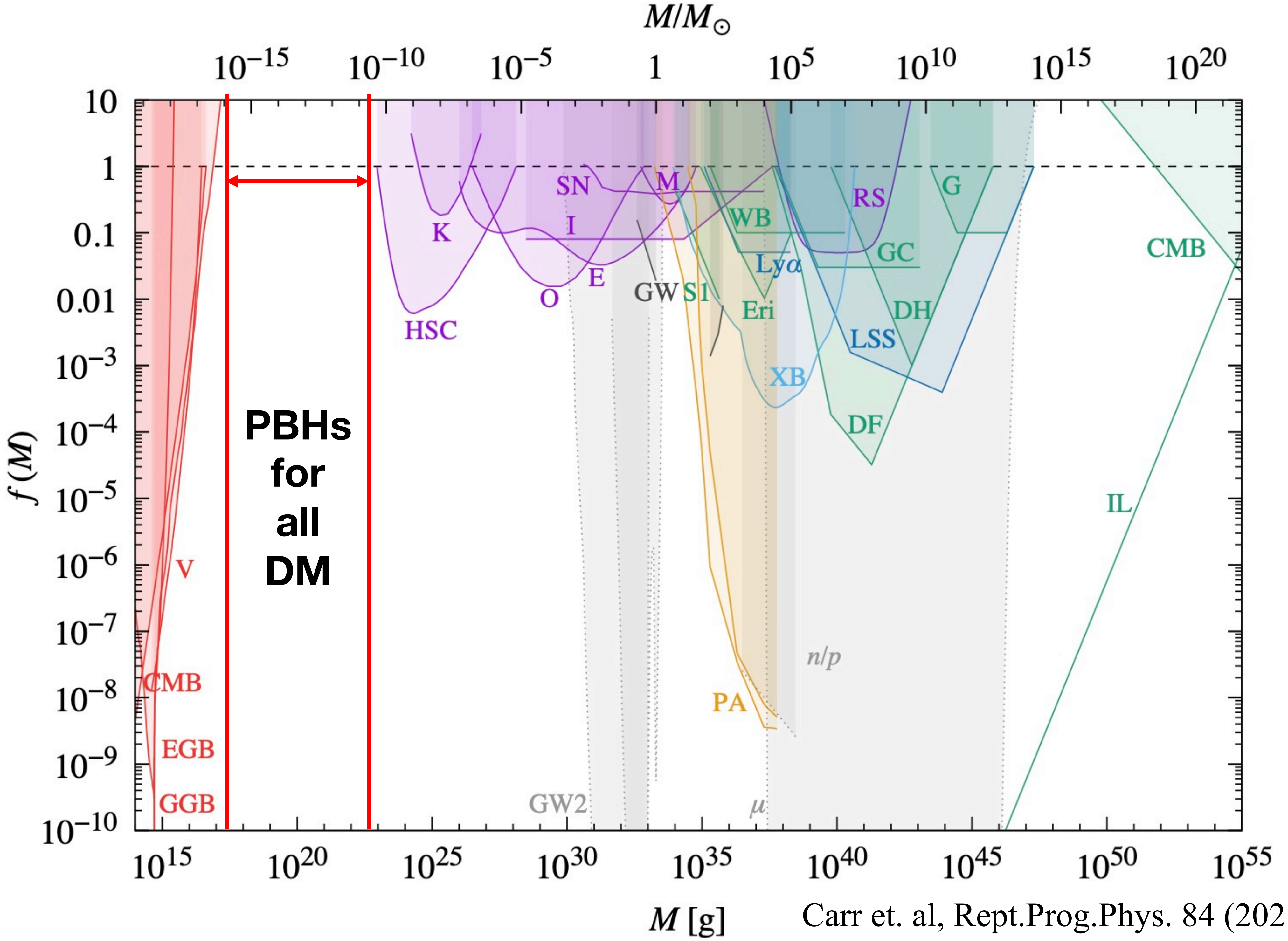
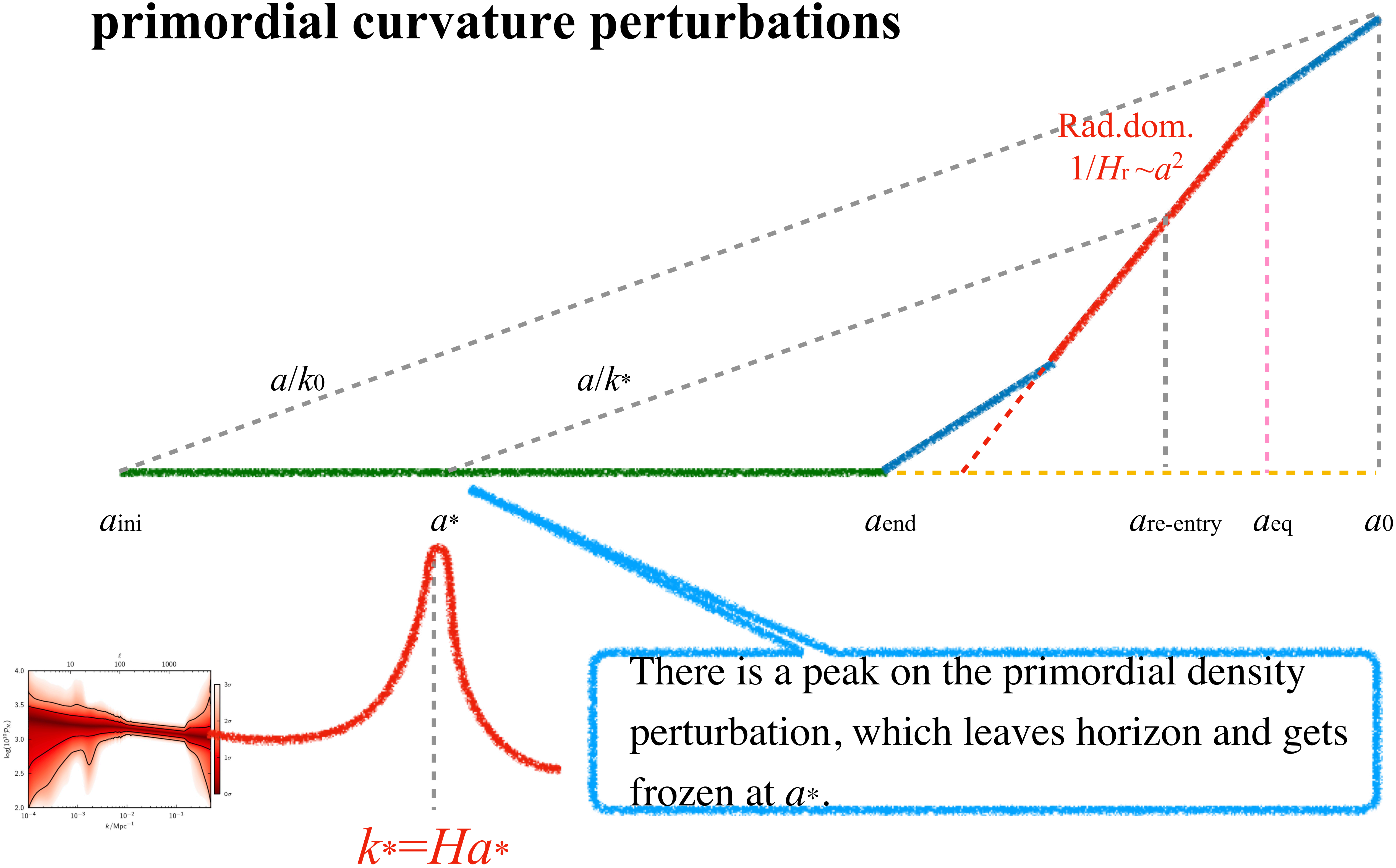
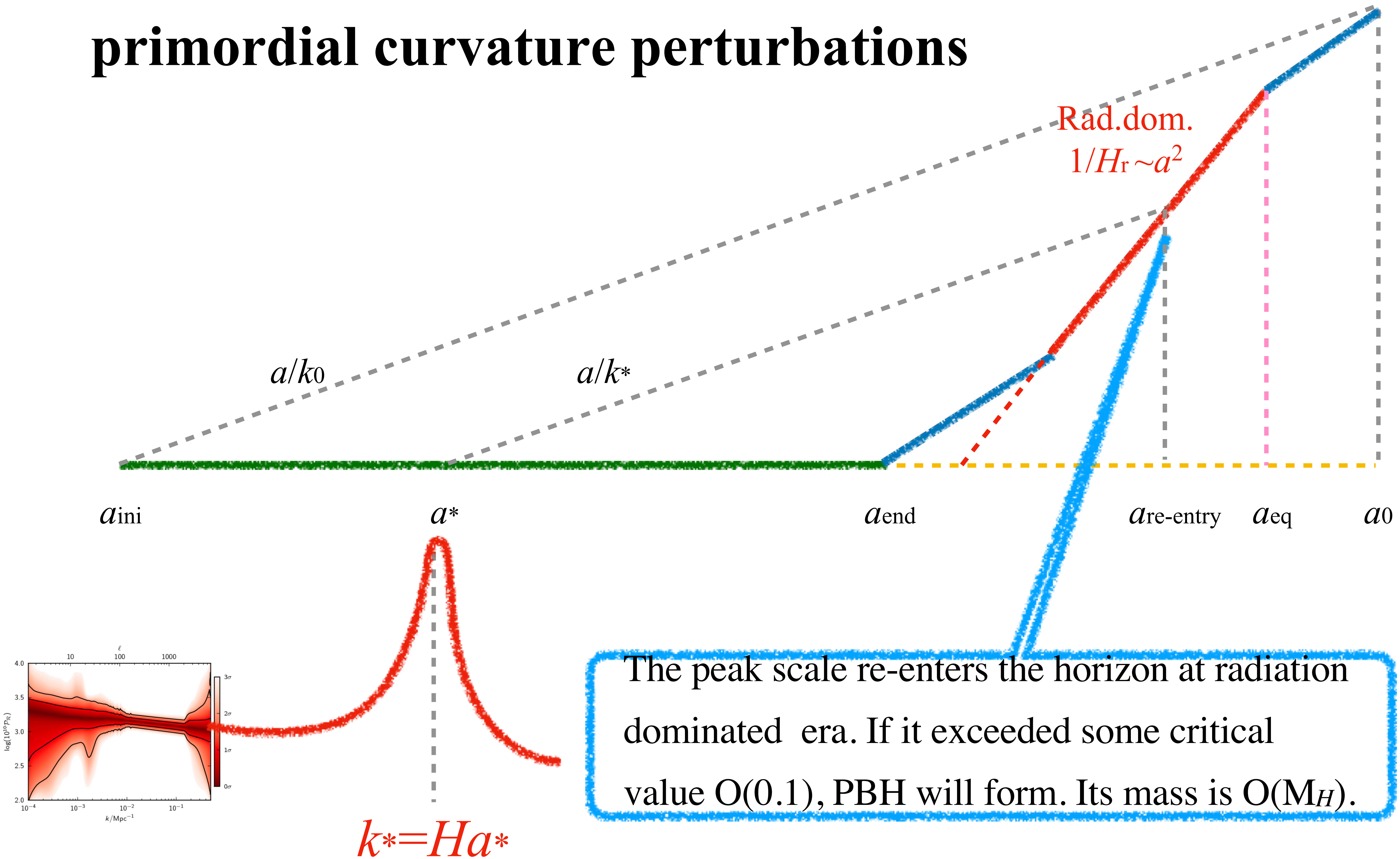


Carr et. al, Rept.Prog.Phys. 84 (2021) 11, 116902

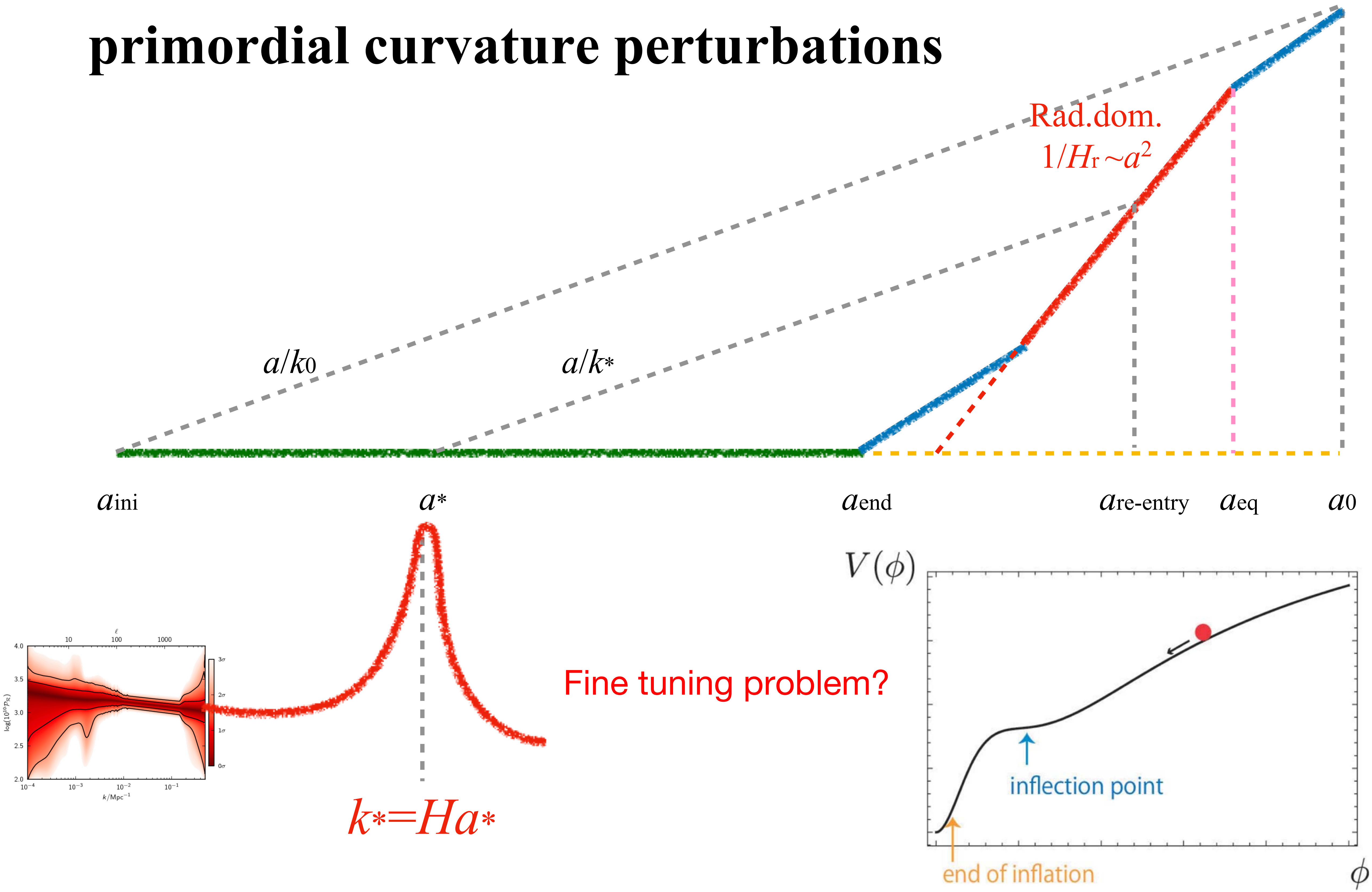
Formation of PBHs from enhancement of primordial curvature perturbations



Formation of PBHs from enhancement of primordial curvature perturbations



Formation of PBHs from enhancement of primordial curvature perturbations

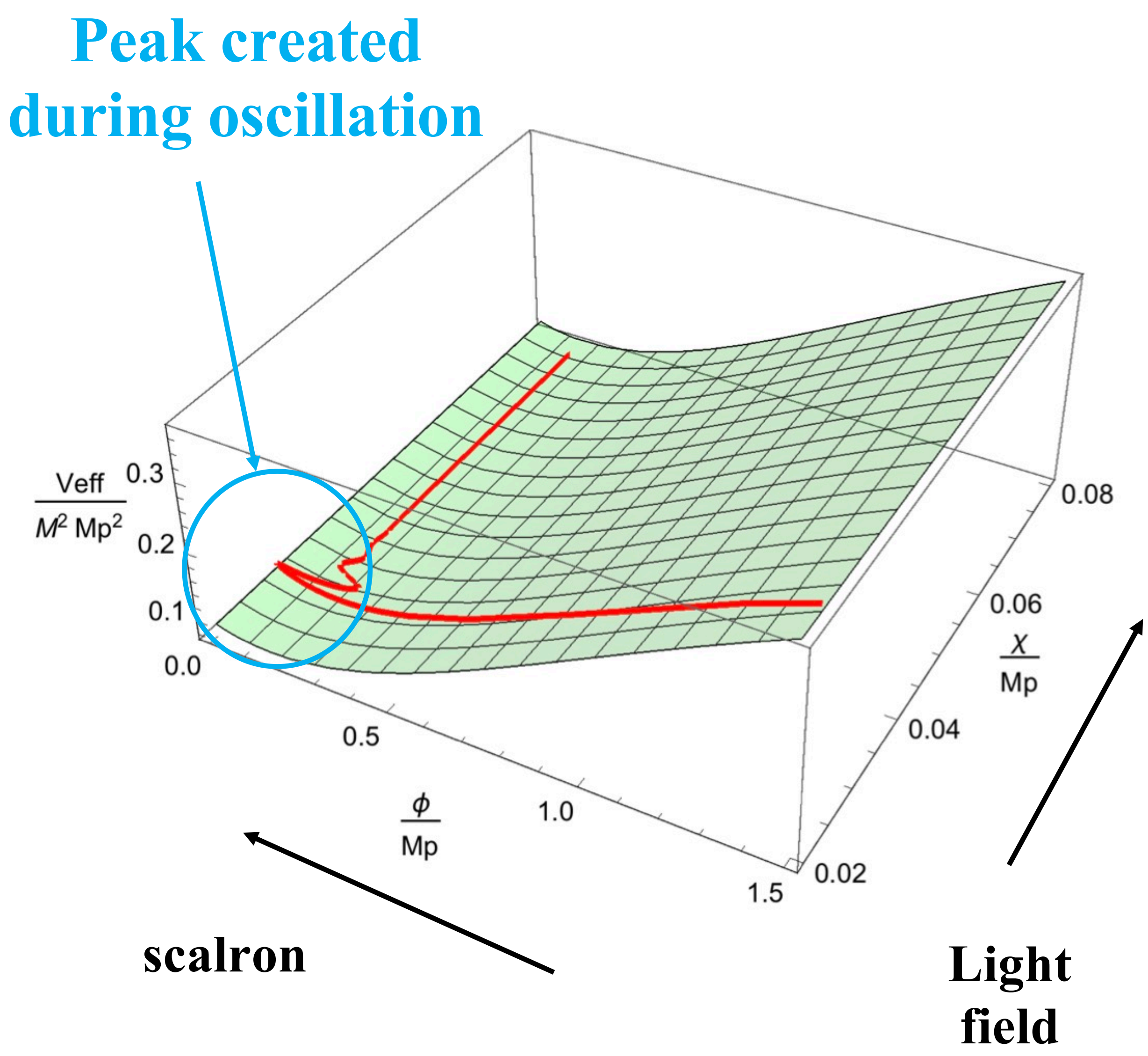


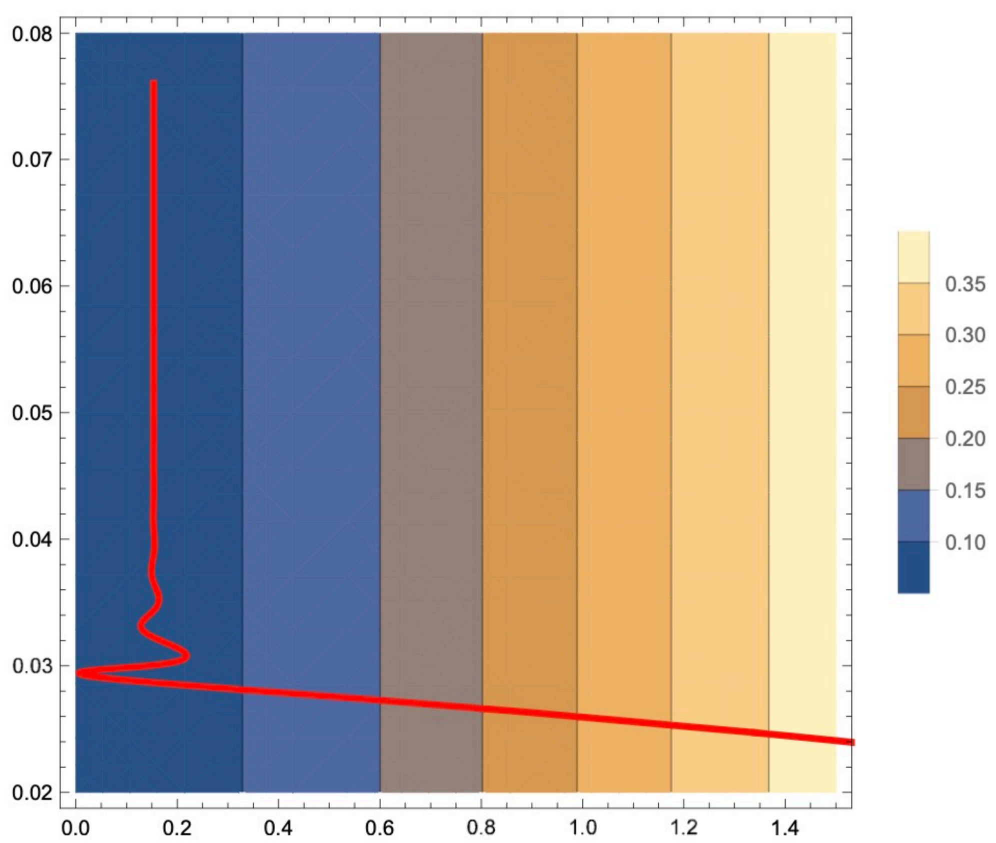
We proposed a model driven by Starobinsky model with a non-minimally coupled field

$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right)-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi) - \frac{1}{2}\xi R\chi^2\right\}$$

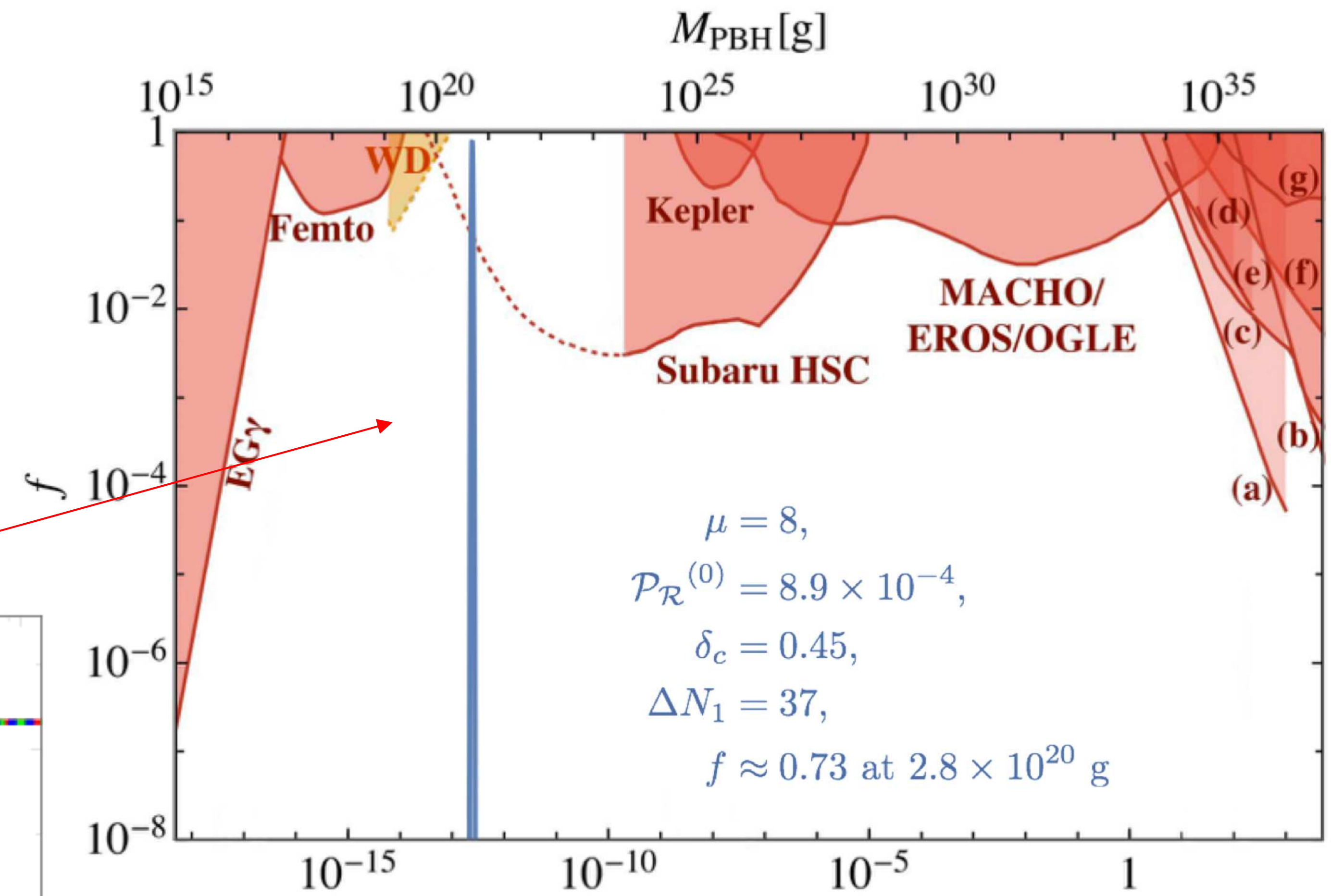
$$V(\chi) = V_0 - \frac{1}{2}m^2\chi^2$$

Pi, YZ, Huang, Sasaki, JCAP 05 (2018) 042 [arxiv:1712.09896]

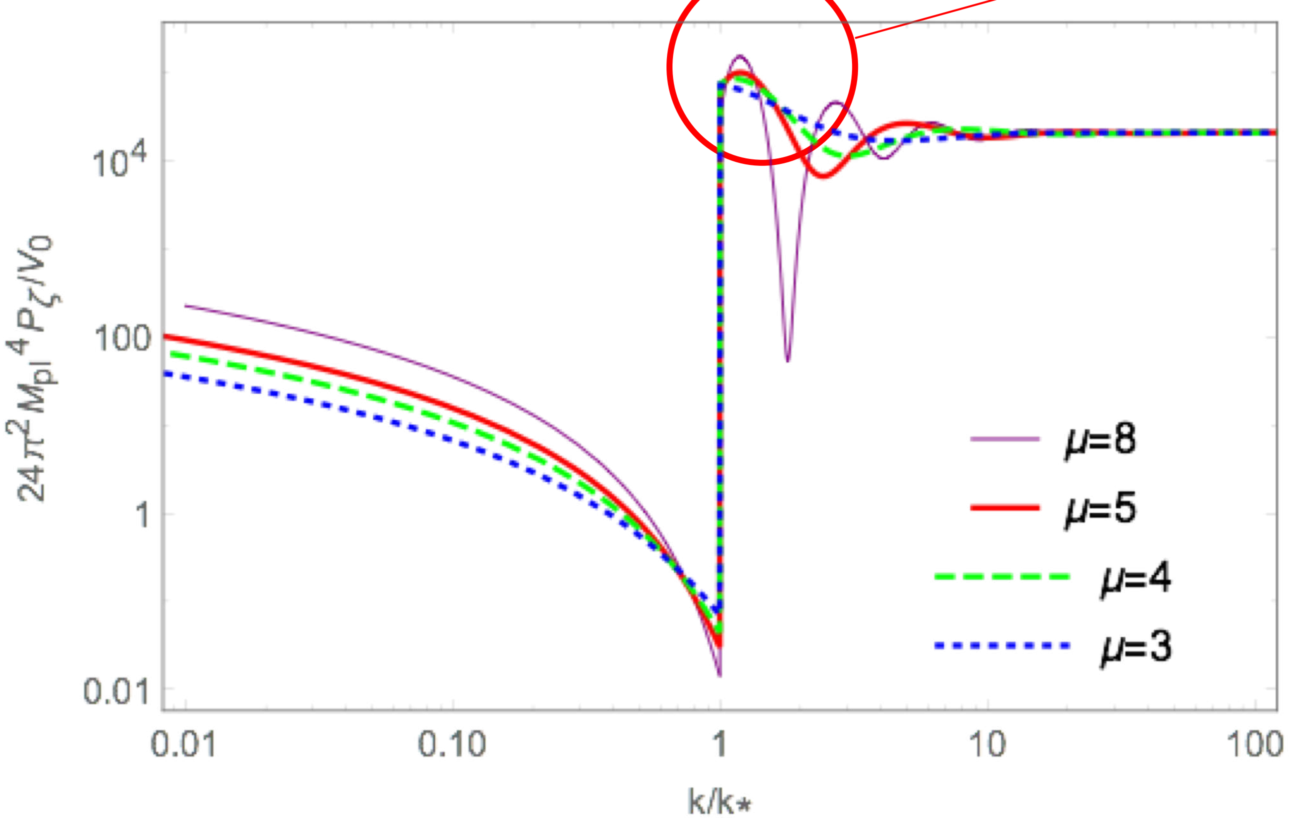




$$f \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{CDM}}} \propto \exp\left[-\frac{1}{\mathscr{P}(k)}\right]$$



Peak



Spike

Defects: (1) No exit from inflation

(2) Incomplete interpretation on enhancement mechanism

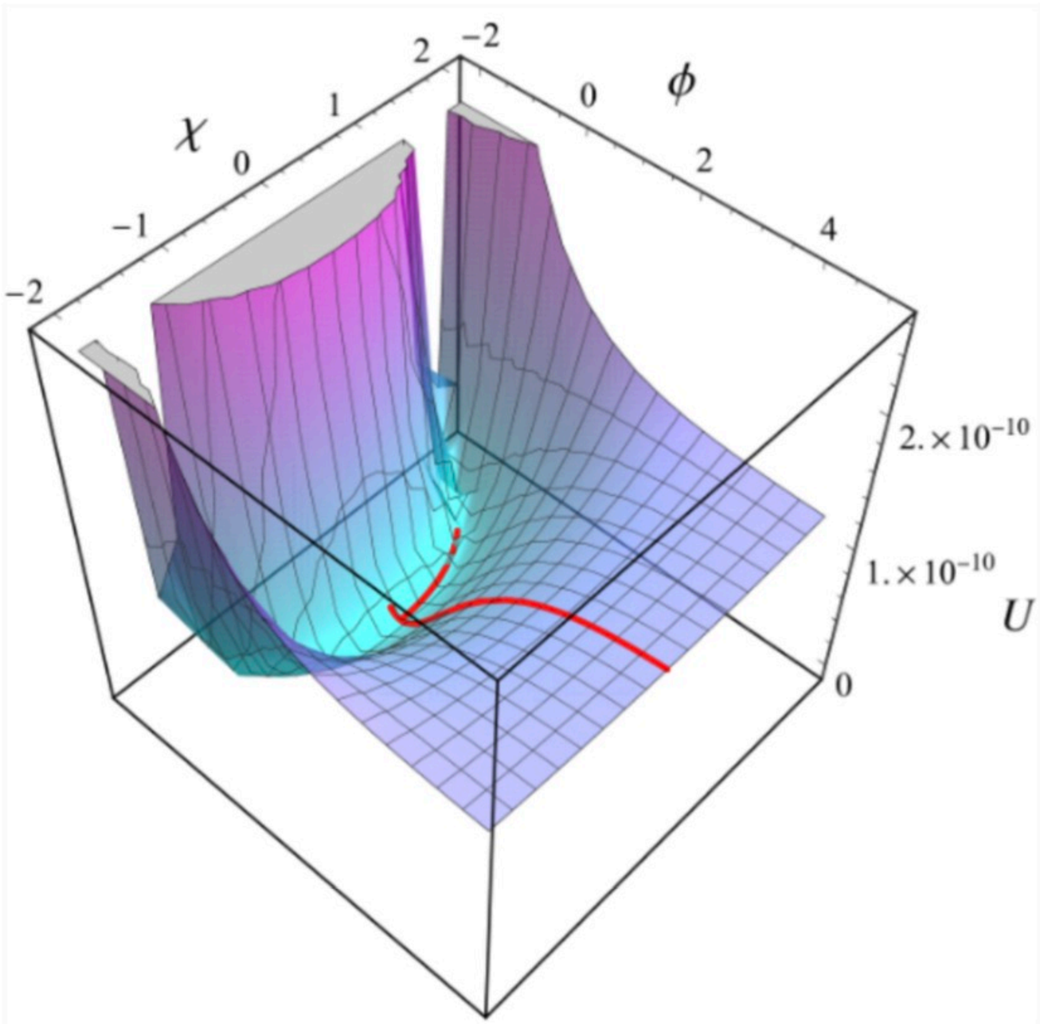
Avoid huge perturbations:

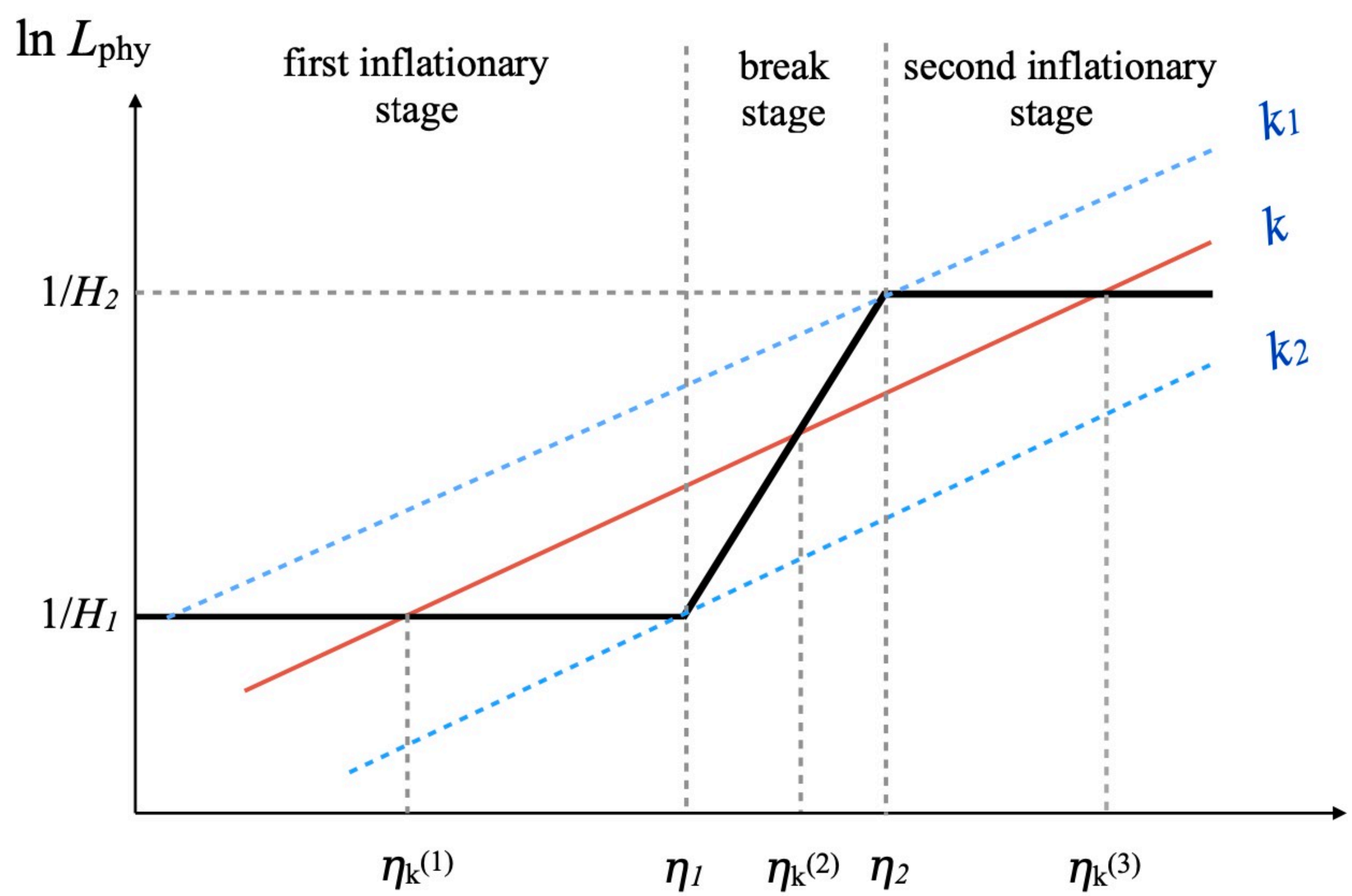
$$f(R) = R + \frac{R^2}{6M^2} - \frac{\xi R}{M_{\rm pl}^2}(\chi - \chi_0)^2$$

Expand the potential to 4-th order:

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

X. Wang, YZ, M. Sasaki, [2404.02492]





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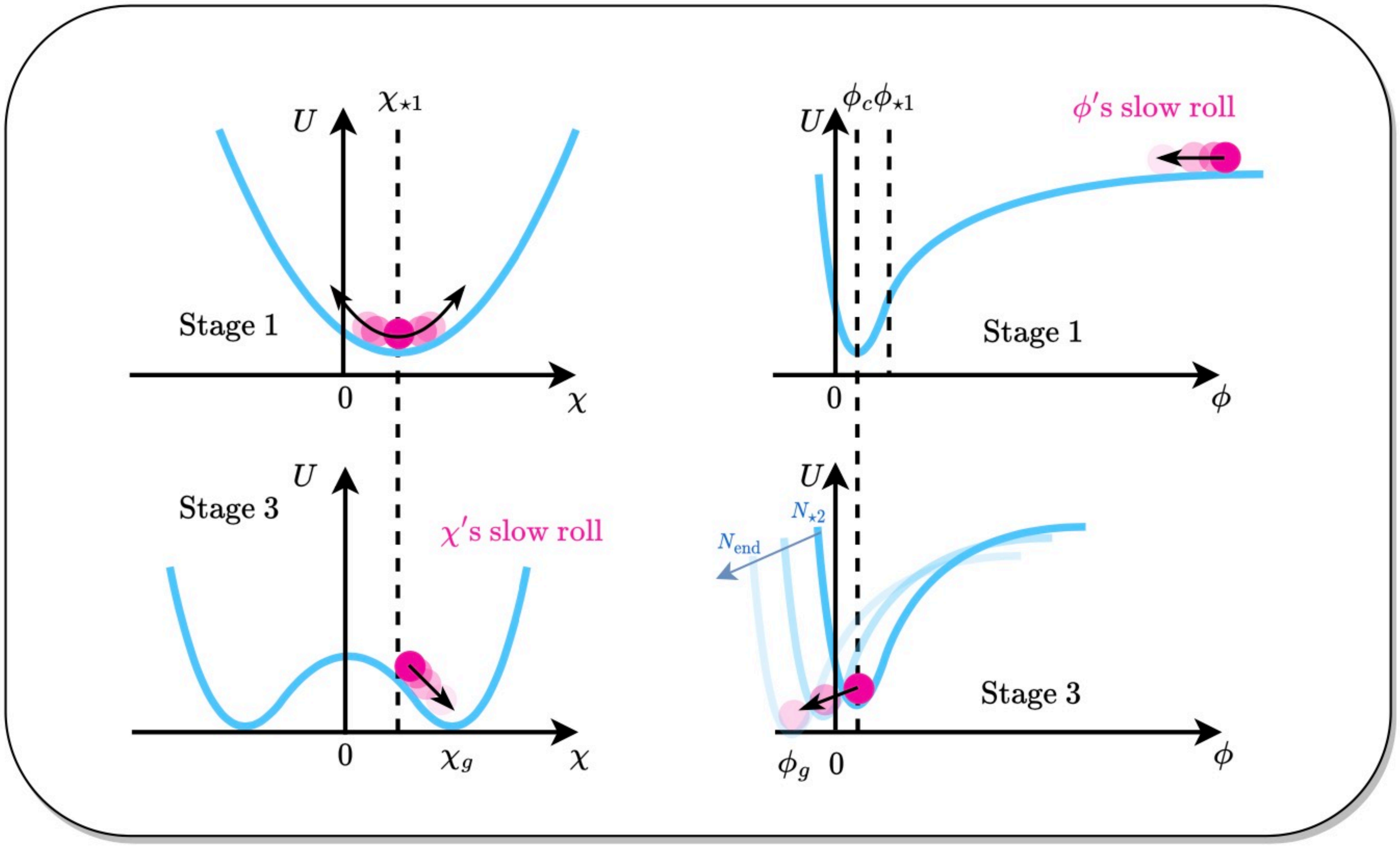

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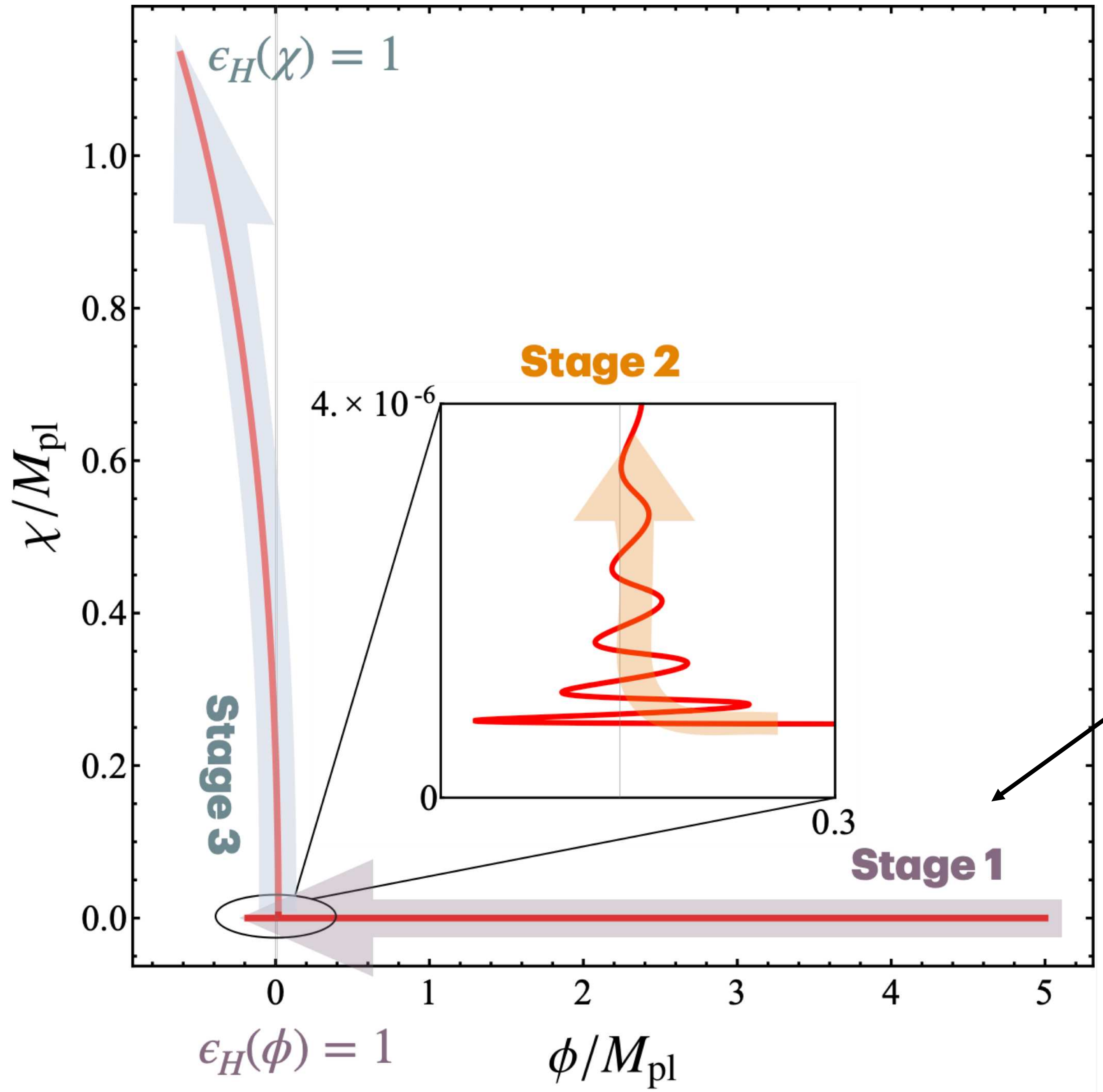


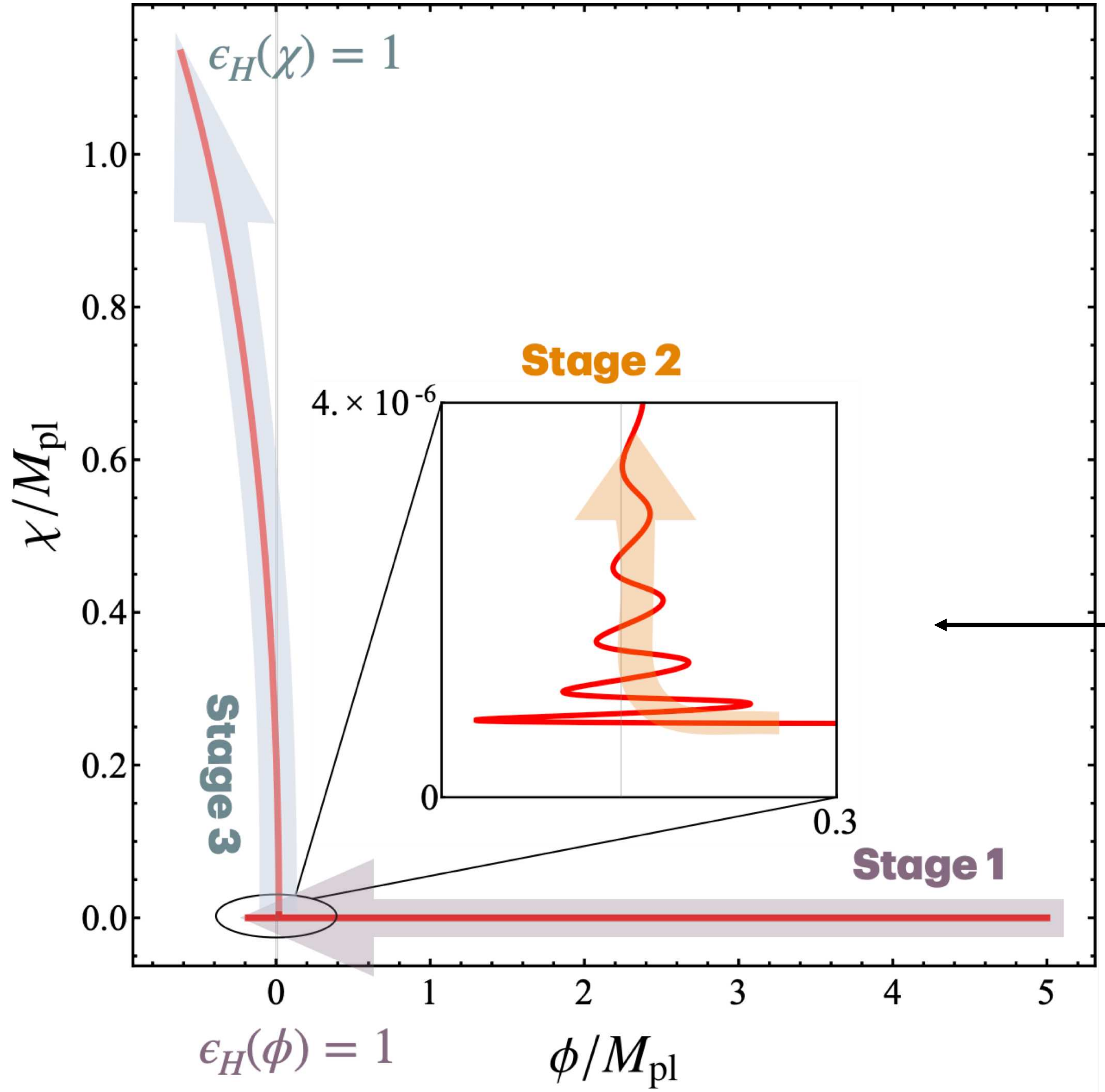
Inflaton rolls along $\boldsymbol{\phi}$ direction ($\boldsymbol{R}^2$ inflation), $\boldsymbol{\chi}$ behaves like a damped oscillator around $\boldsymbol{\chi_0}$.

Avoid huge perturbations:

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

Expand the potential to 4-th order:

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



The slow roll is shortly violated by inflaton's oscillation along ϕ direction.

χ accelerates to attractor phase.

Avoid huge perturbations:

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

Expand the potential to 4-th order:

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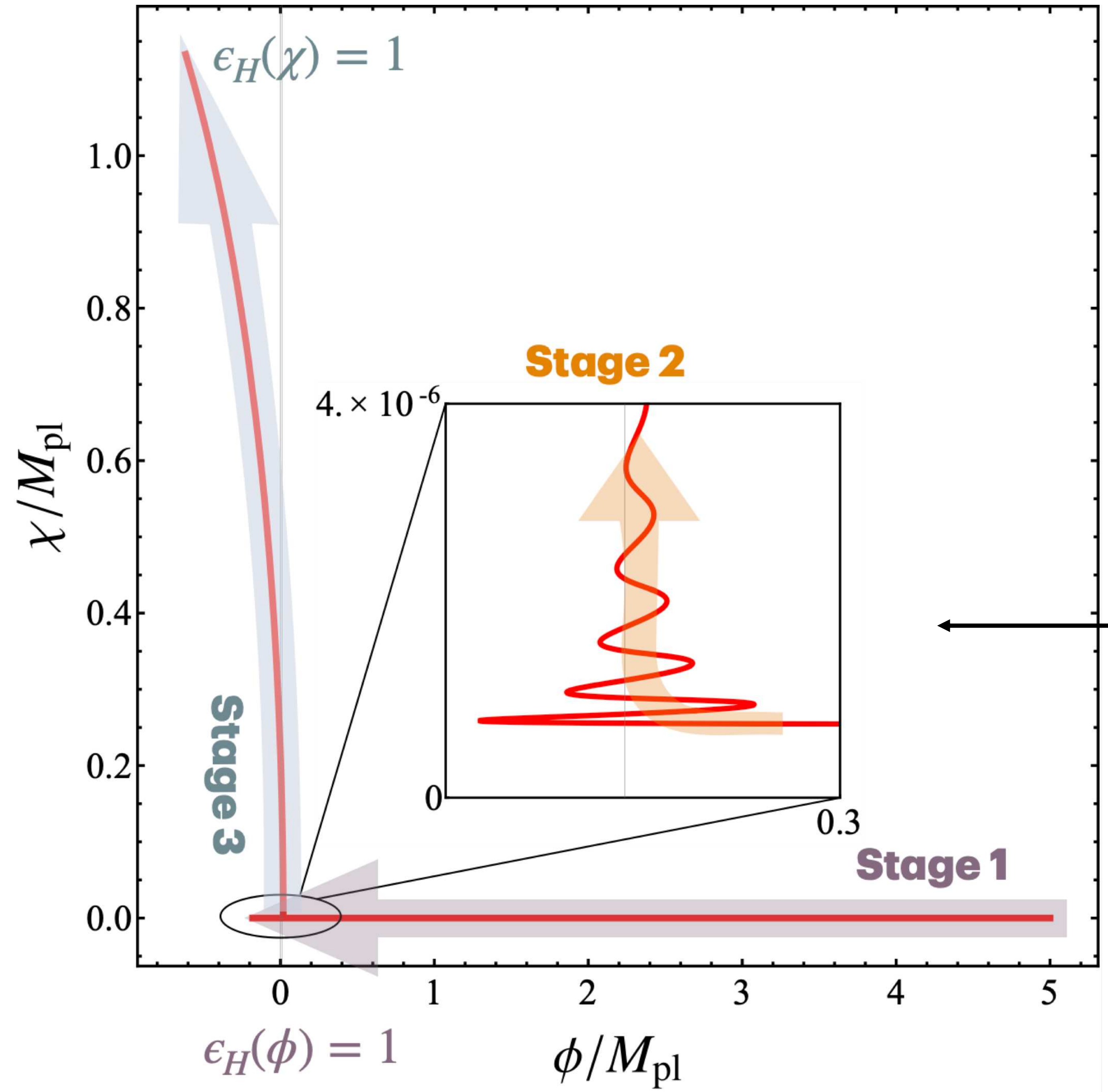

The slow roll is shortly violated by inflaton's oscillation along $\boldsymbol{\phi}$ direction.

$\boldsymbol{\chi}$ accelerates to attractor phase.

Avoid huge perturbations:

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

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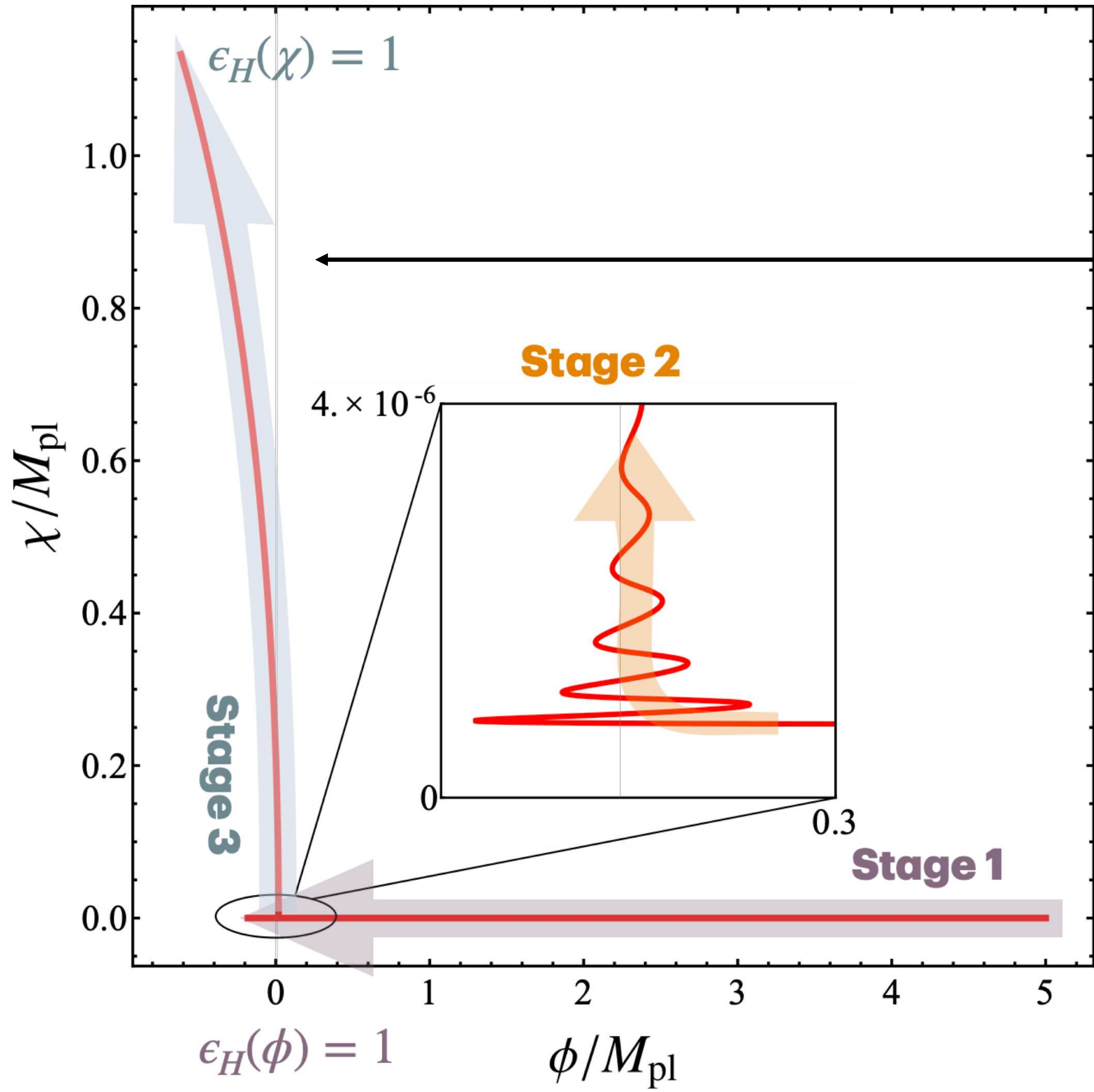


Inflaton rolls along χ direction,

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

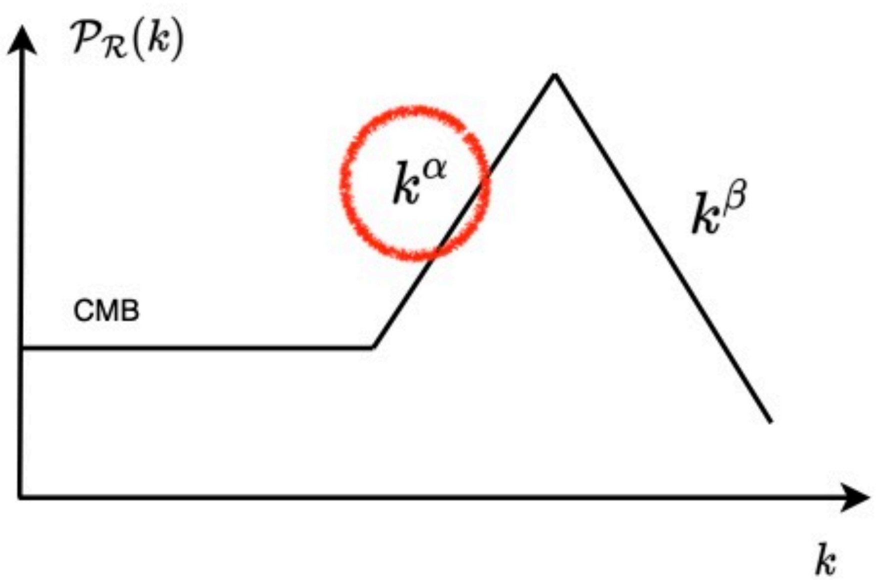
The Primordial Power Spectrum can be analytically approximated as

$$\mathcal{P}_\mathcal{R}(k) \approx \frac{M^2}{16\pi^2} \times \begin{cases} \left[\frac{2}{3}\left(\ln\frac{k_1}{k}+\frac{3}{4}F_\star\right)^2 + \left(\frac{g_1 h}{\chi_0}\right)^2 \left(\frac{k}{k_1}\right)^{\alpha}\right]\left[1+\left(\ln\frac{k_1}{k}+\frac{3}{4}F_\star\right)^{-1}\right], & \text{for } k < k_1 \\ \frac{g_2^2 h^2}{\chi_0^2 \mu^2}\left(\frac{k}{k_1}\right)^{\beta}, & \text{for } k \geq k_1 \end{cases}$$

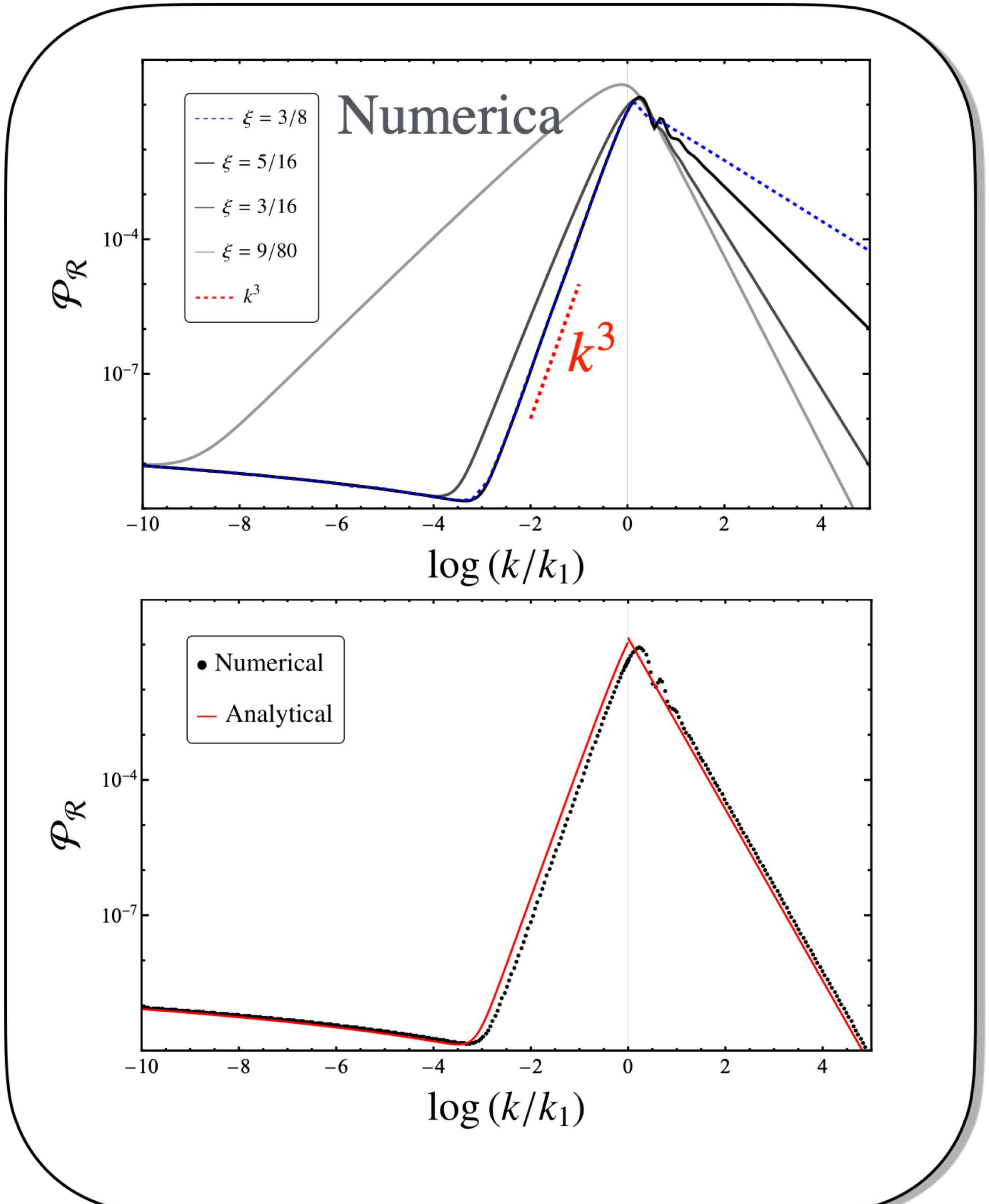
Broken power-law!

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

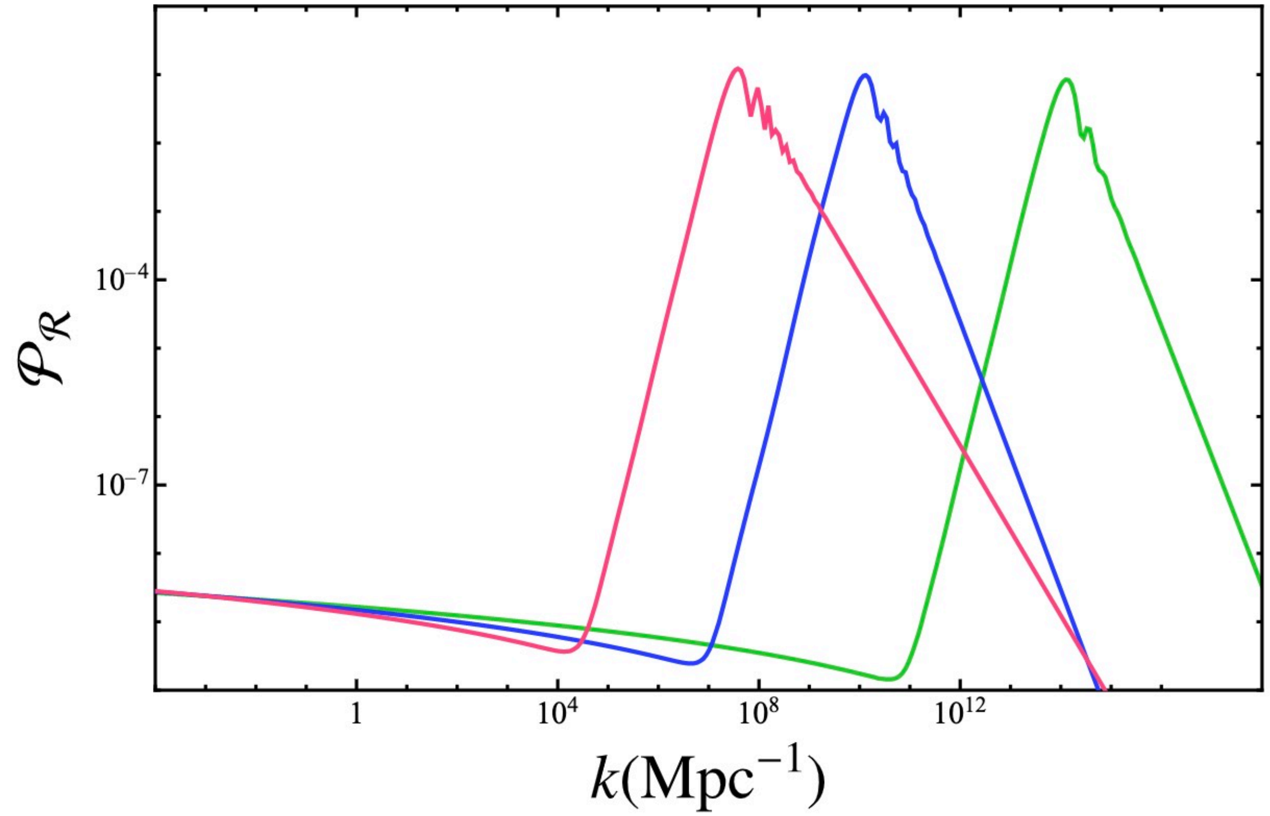
$$\beta \equiv 3 - \sqrt{3 + \frac{48\xi(A-1)}{1+1/\mu^2}},$$



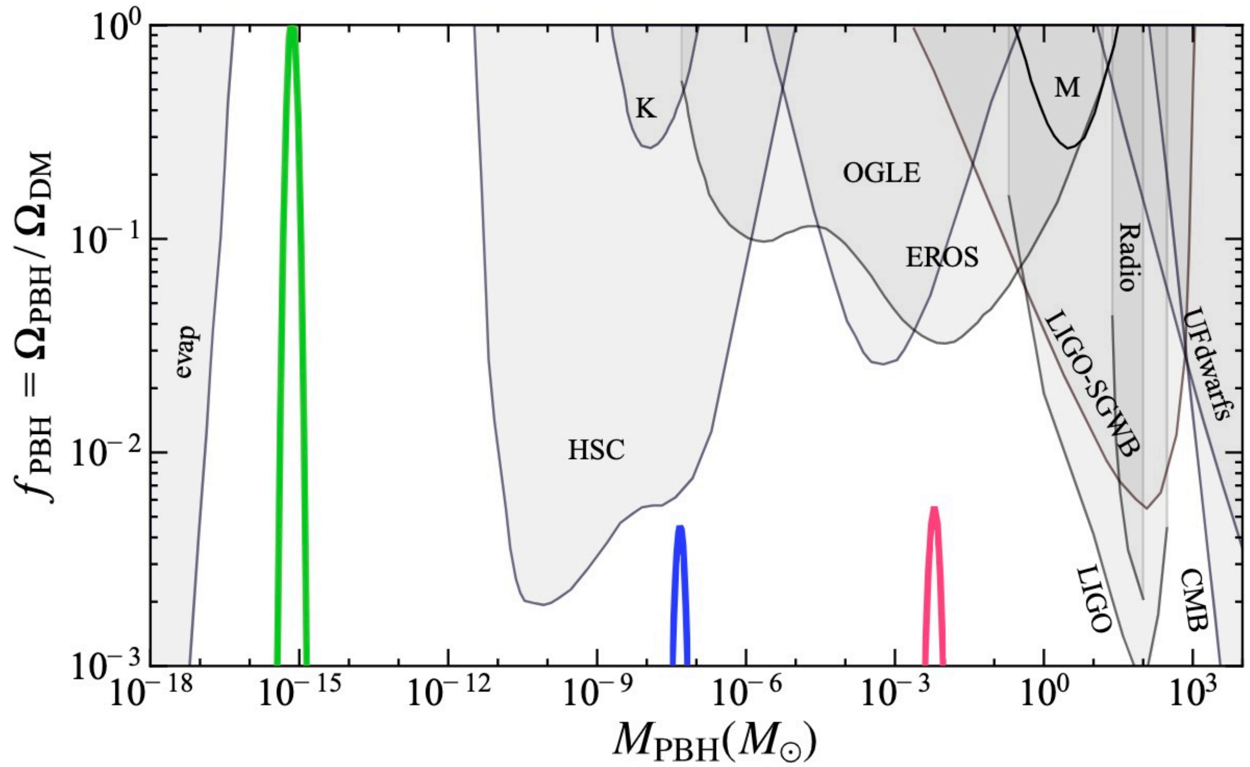
α is determined by the behavior of χ during late 1st stage



Numerica
ξ = 3/8
ξ = 5/16
ξ = 3/16
ξ = 9/80
k³
$\mathcal{P}_\mathcal{R}$
10^{-4}
10^{-7}
−10 −8 −6 −4 −2 0 2 4
$\log(k/k_1)$
Numerical
Analytical
$\mathcal{P}_\mathcal{R}$
10^{-4}
10^{-7}
−10 −8 −6 −4 −2 0 2 4
$\log(k/k_1)$



$\mathcal{P}_\mathcal{R}$
10^{-4}
10^{-7}
1
10^{4}
10^{8}
10^{12}
$k(\mathrm{Mpc}^{-1})$



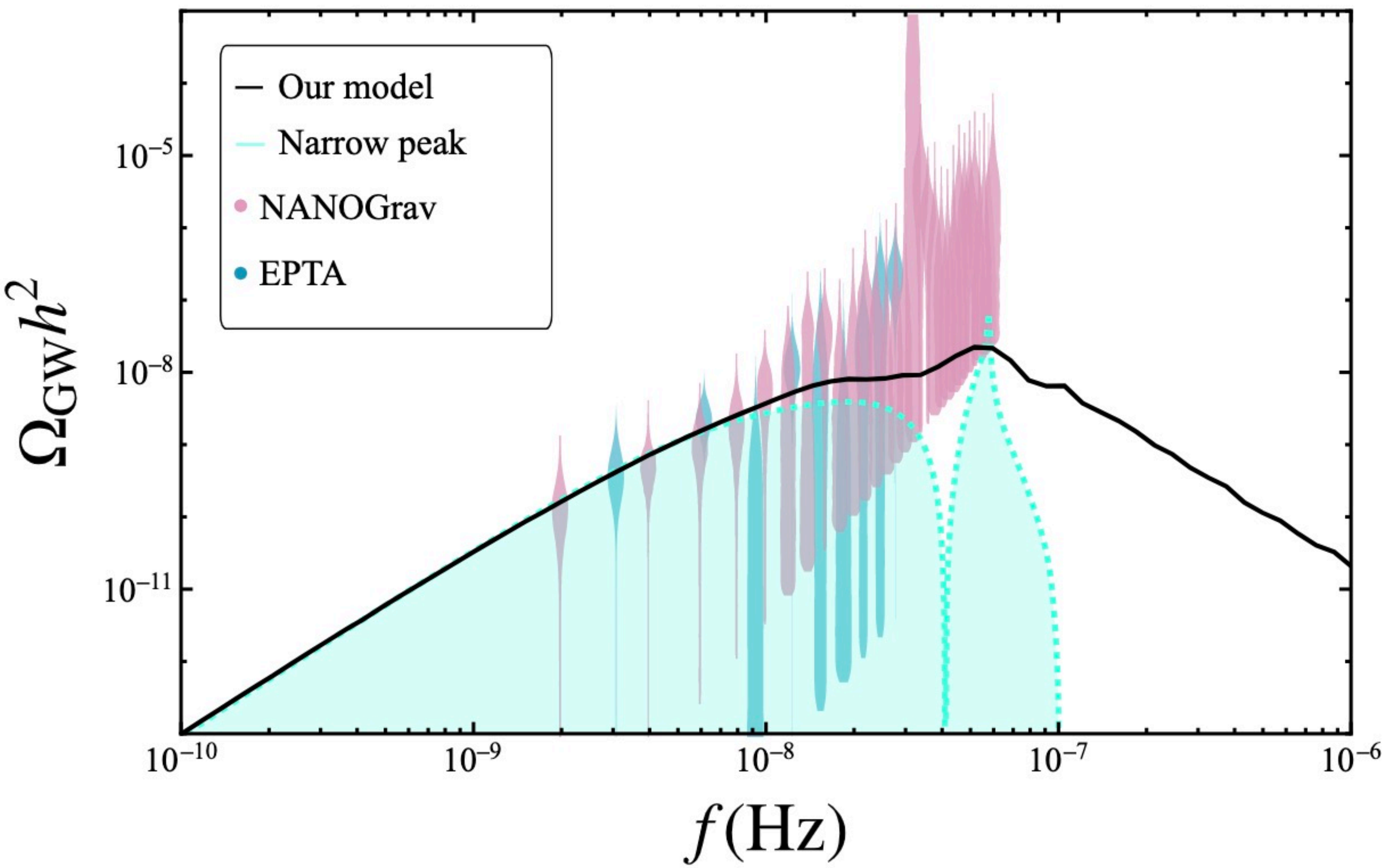
$f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3}
$M_{\mathrm{PBH}}(M_\odot)$
evap
HSC
K
OGLE
EROS
M
Radio
LIGO-SGWB
UFdwarfs
LIGO
CMB

Induced Gravitational Wave (IGW)

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\hat{\mathcal{T}}_{ij}{}^{lm}\mathcal{S}_{lm}$$

$$\mathcal{S}_{ij} \;=\; 4\Phi\Phi_{|ij} + 2\Phi_{|i}\Phi_{|j} - \frac{3}{\kappa^2 a^2 \rho}\left[\mathcal{H}^2\Phi_{|i}\Phi_{|j} + 2\mathcal{H}\Phi_{|i}\Phi'_{|j} + \Phi'_{|i}\Phi'_{|j}\right]$$

K. Ananda,
C. Clarkson,
D. Wands,
Phys.Rev.D 75
(2007) 123518

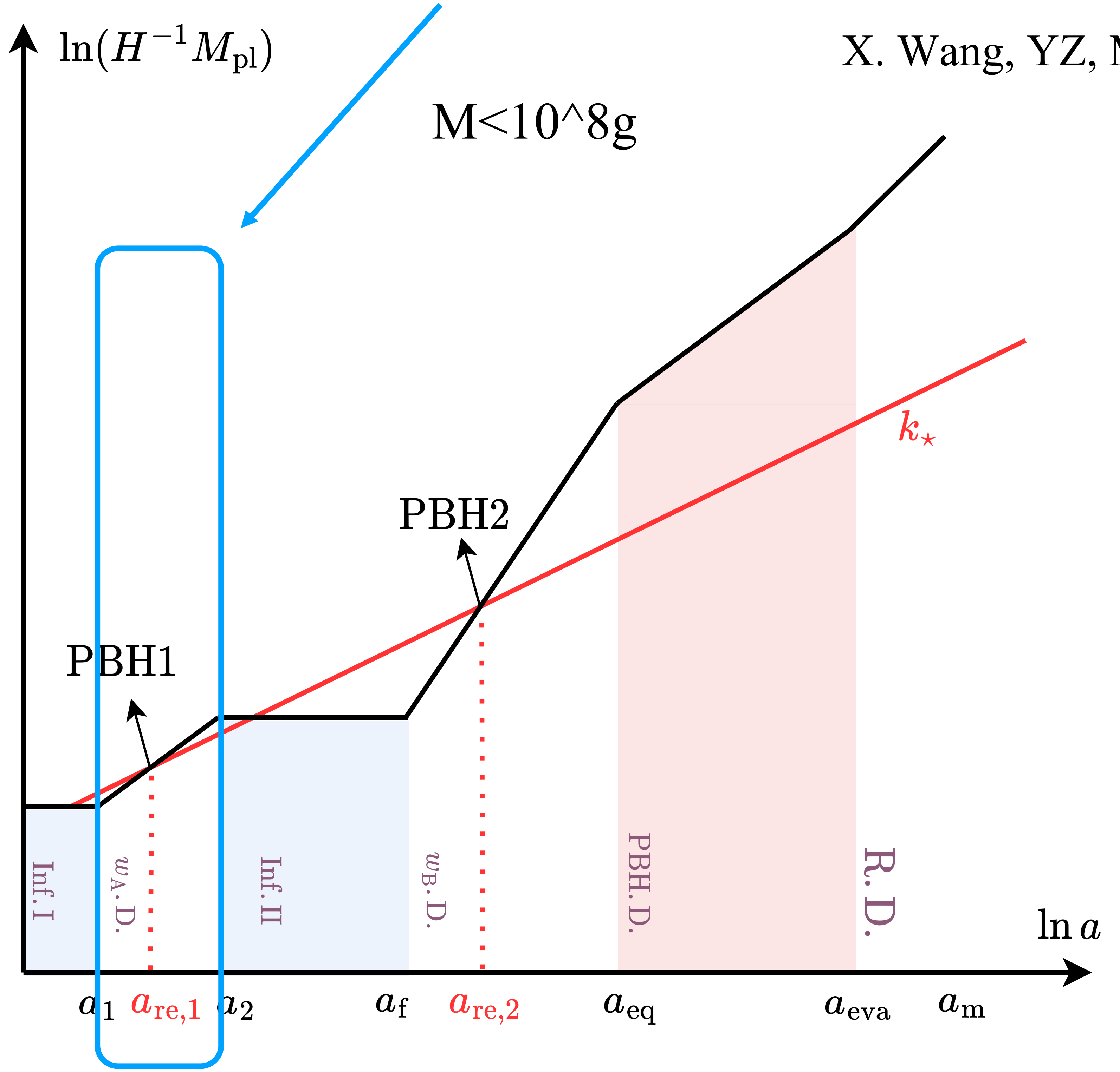


Data from: NANOGrav, 2023 (2306.16219), EPTA, 2023 [2306.16227]

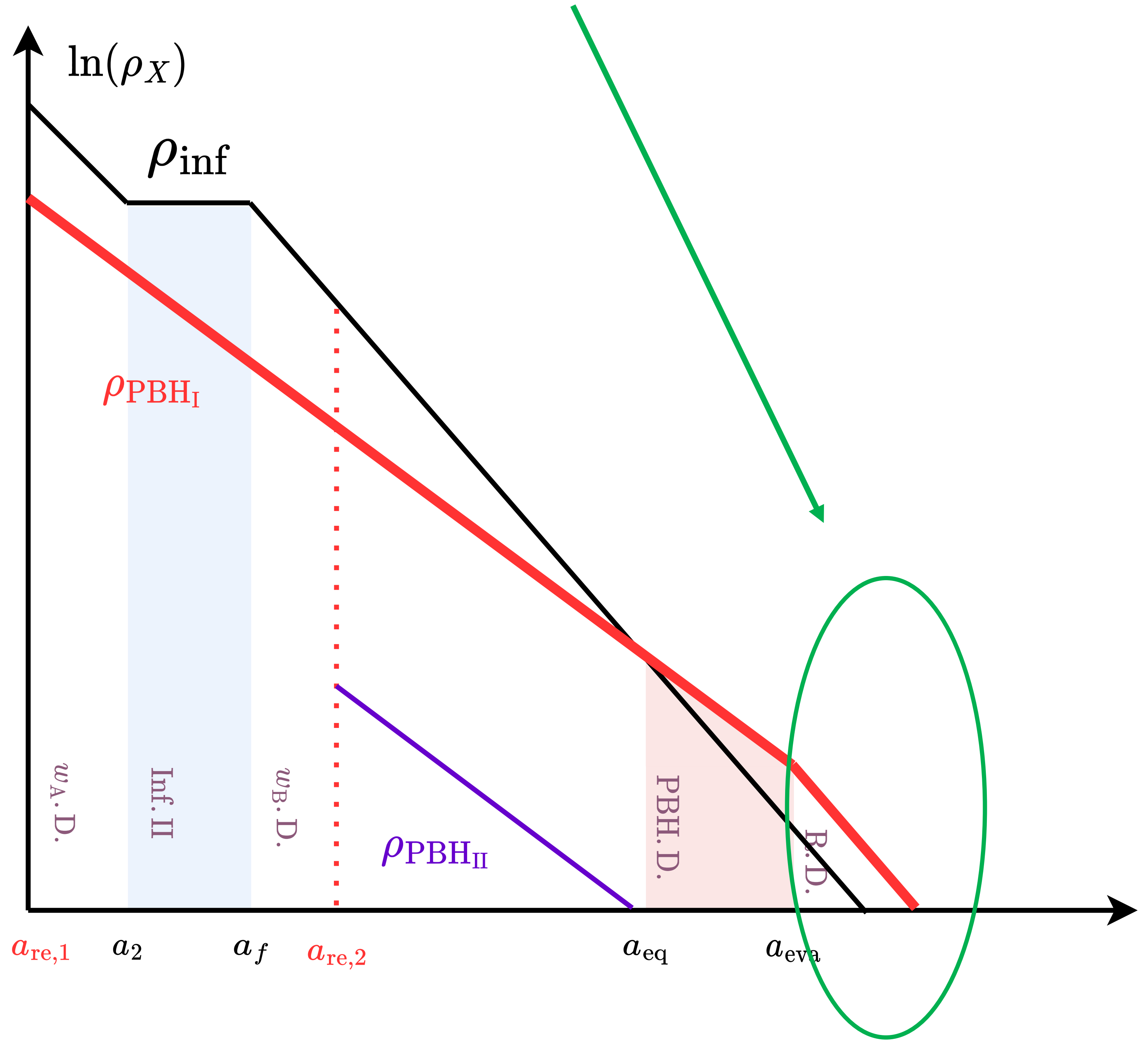
An interesting scenario: Light PBH formation during break stage

X. Wang, YZ, M. Sasaki, in prep

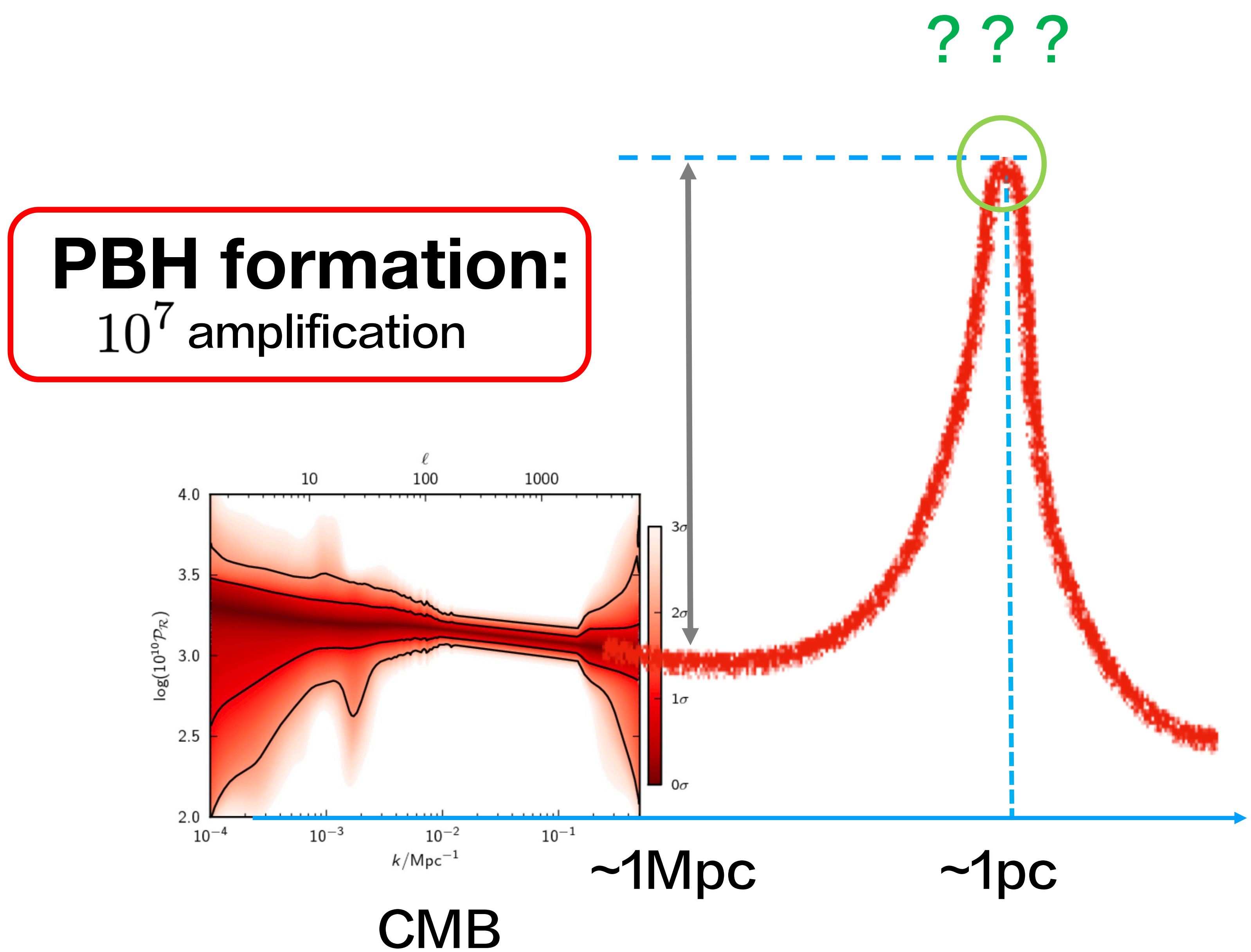
M<10^8g



Radiation-dominated Era from Evaporation of PBHs



Question： Any hints on such huge amplification?



Idea

PBHs from large curvature perturbations

+ LIGO data from mergers of PBH binaries

↓

Primordial Power Spectrum of
curvature perturbations?
(on small scales)

Assumptions

0. At least some of the BBH LIGO events are PBHs

   merger rate from observations

1. PBHs formed out of high peaks of curvature perturbations

   the simplest case

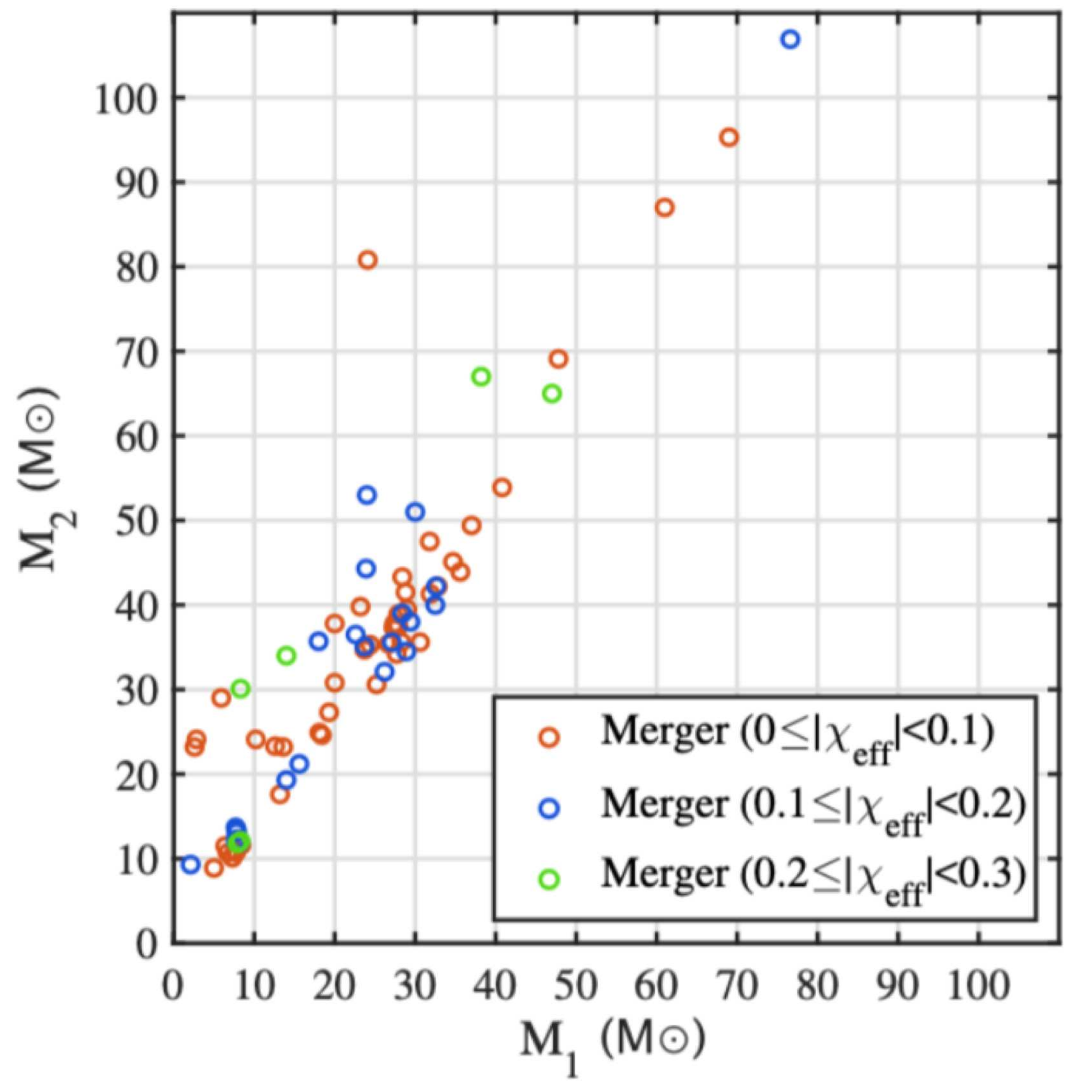
2. Window function: top-hat form

   semi-analytic expression for calculation of merger rate

3. Gaussian distribution of density perturbation

   simple relation between between power spectrum and the variance

The LIGO/Virgo released data $\mathcal{R}(m_i, m_j) = \mathcal{R}_0 N(m_i, m_j)\,, \quad \mathcal{R}_0 \equiv \frac{R_{\rm total}}{N_{\rm total}}$



91 BBH candidates, 76 of them satisfy $m \gtrsim 1.5 M_\odot$ and $|\chi_{\rm eff}| \lesssim 0.3$

We simply identify these events as PBH mergers

WARN: The largest Uncertainty comes from here!

Merger rate is given by

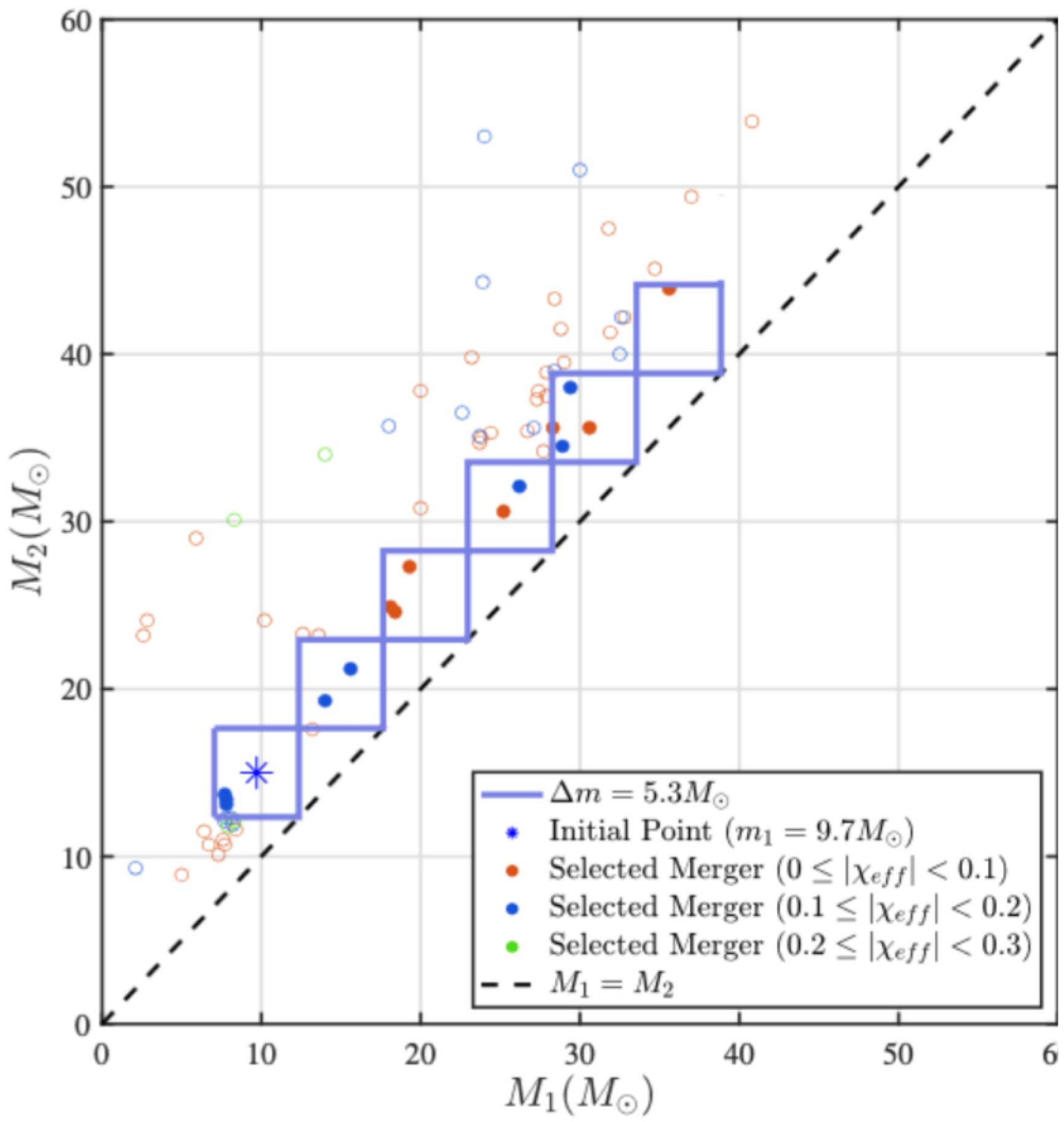
$$\mathscr{R}\left(m_1, m_2, t\right) = \frac{1.6 \times 10^6}{\mathrm{Gpc}^3\mathrm{yr}} S[f \mid f_{PBH}, m_t] f_{\mathrm{PBH}}^{\frac{53}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \left(\frac{m_1 + m_2}{M_\odot}\right)^{-\frac{32}{37}} \left(\frac{(m_1 + m_2)^2}{m_1 m_2}\right)^{\frac{34}{37}} m_1 m_2 f\left(m_1\right) f\left(m_2\right)$$

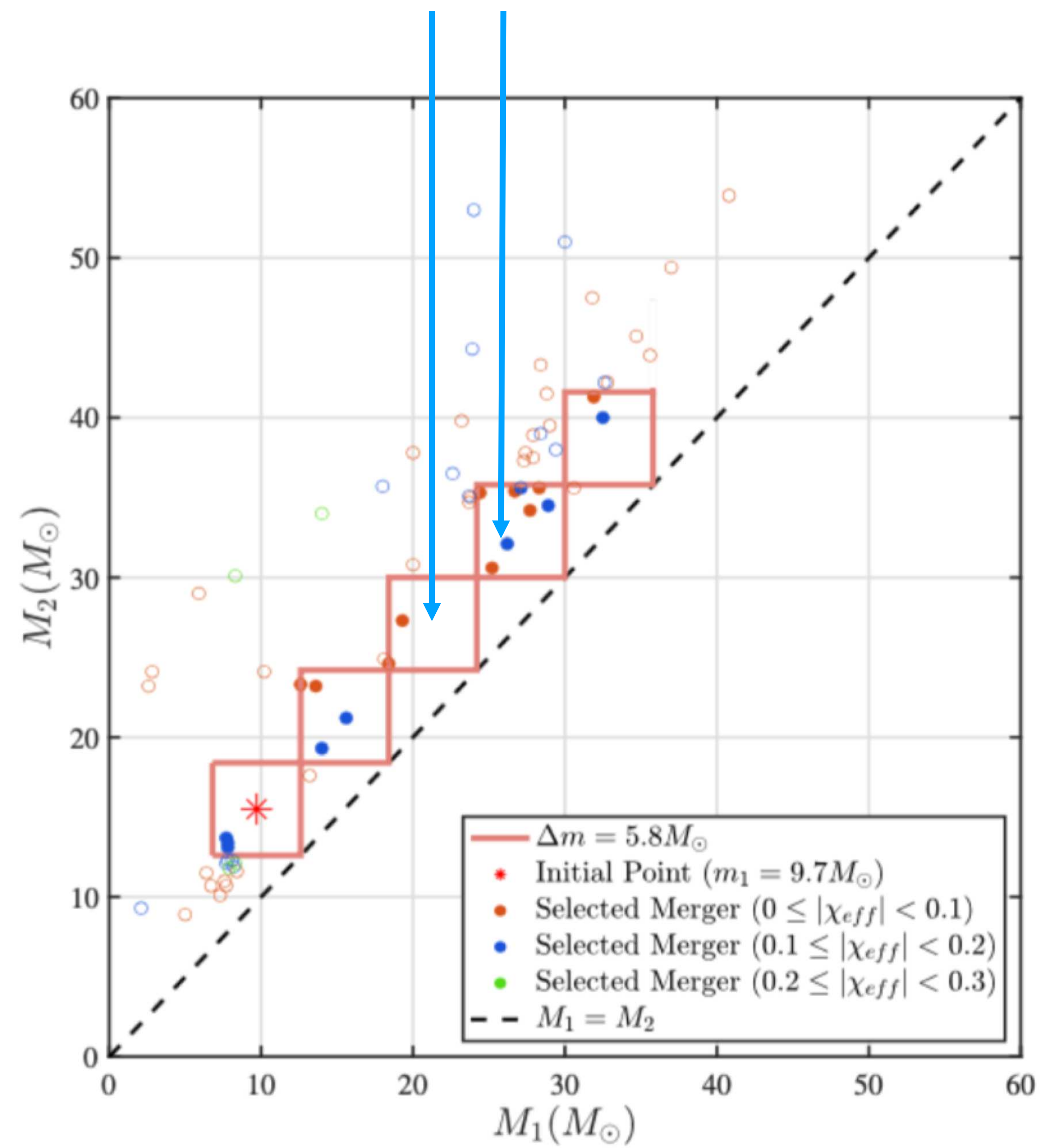
$$\begin{cases} \dfrac{f(m_1)}{f(m_3)} = \dfrac{f(m_1)f(m_2)}{f(m_2)f(m_3)} = \dfrac{\mathscr{R}\left(m_1, m_2, t\right)}{\mathscr{R}\left(m_2, m_3, t\right)} \left(\dfrac{m_2 + m_3}{m_1 + m_2}\right)^{36/37} \left(\dfrac{m_3}{m_1}\right)^{3/37} \\ \dfrac{f(m_1)}{f(m_2)} = \dfrac{f(m_1)f(m_1)}{f(m_1)f(m_2)} = \dfrac{\mathscr{R}\left(m_1, m_1, t\right)}{\mathscr{R}\left(m_1, m_2, t\right)} \left(\dfrac{m_1 + m_2}{m_1 + m_1}\right)^{36/37} \left(\dfrac{m_2}{m_1}\right)^{3/37} \end{cases}$$

If $f(m_1)$ is fitted, to obtain $f(m_n)(n = 2,3,4...)$,

we need to get $\mathscr{R}\left(m_1, m_1, t\right), \mathscr{R}\left(m_n, m_{n+1}, t\right)(n = 1,2,3...)$

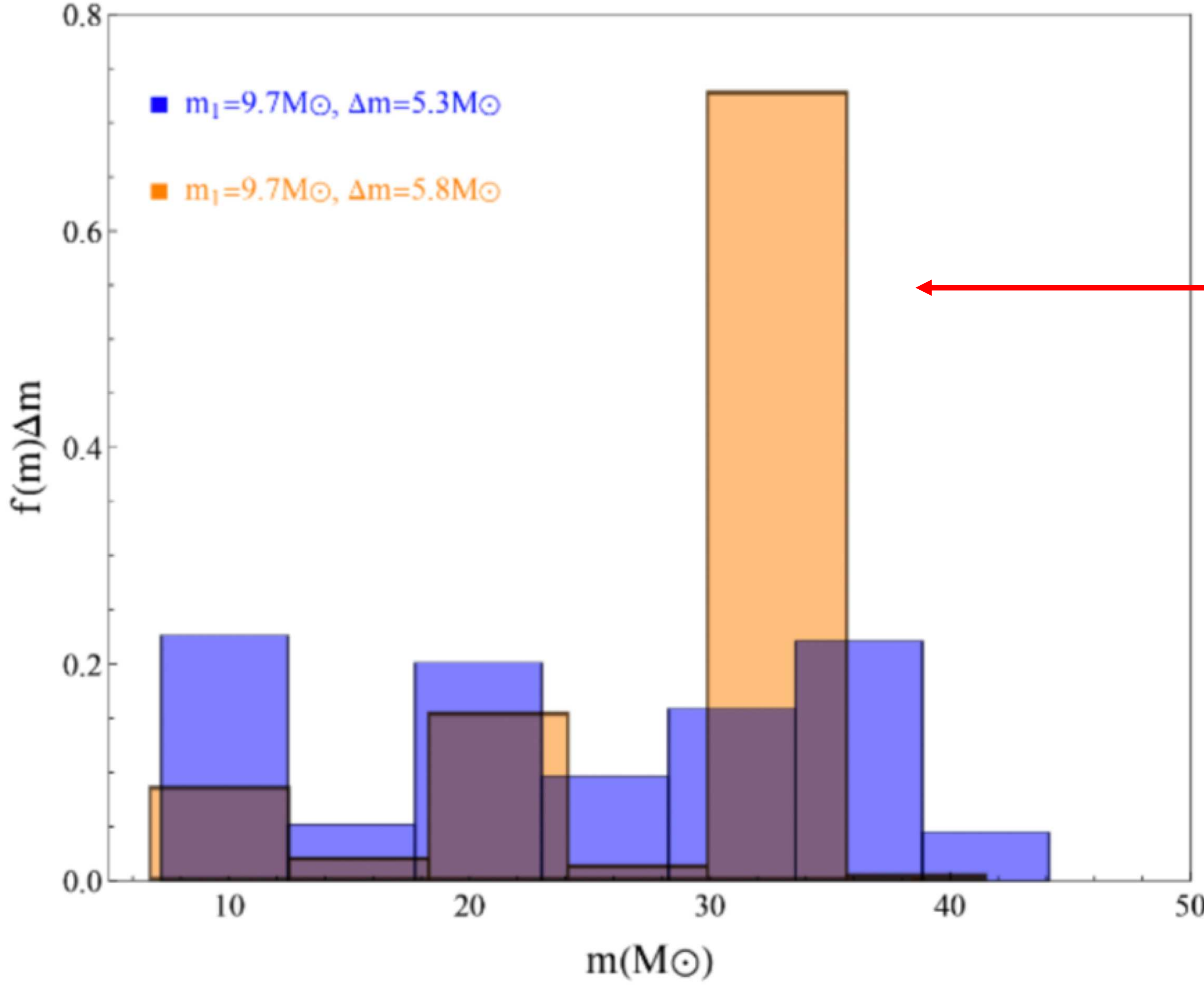
Large difference of # of points included





Two typical ways of division

Then it is straightforward to obtain the mass function



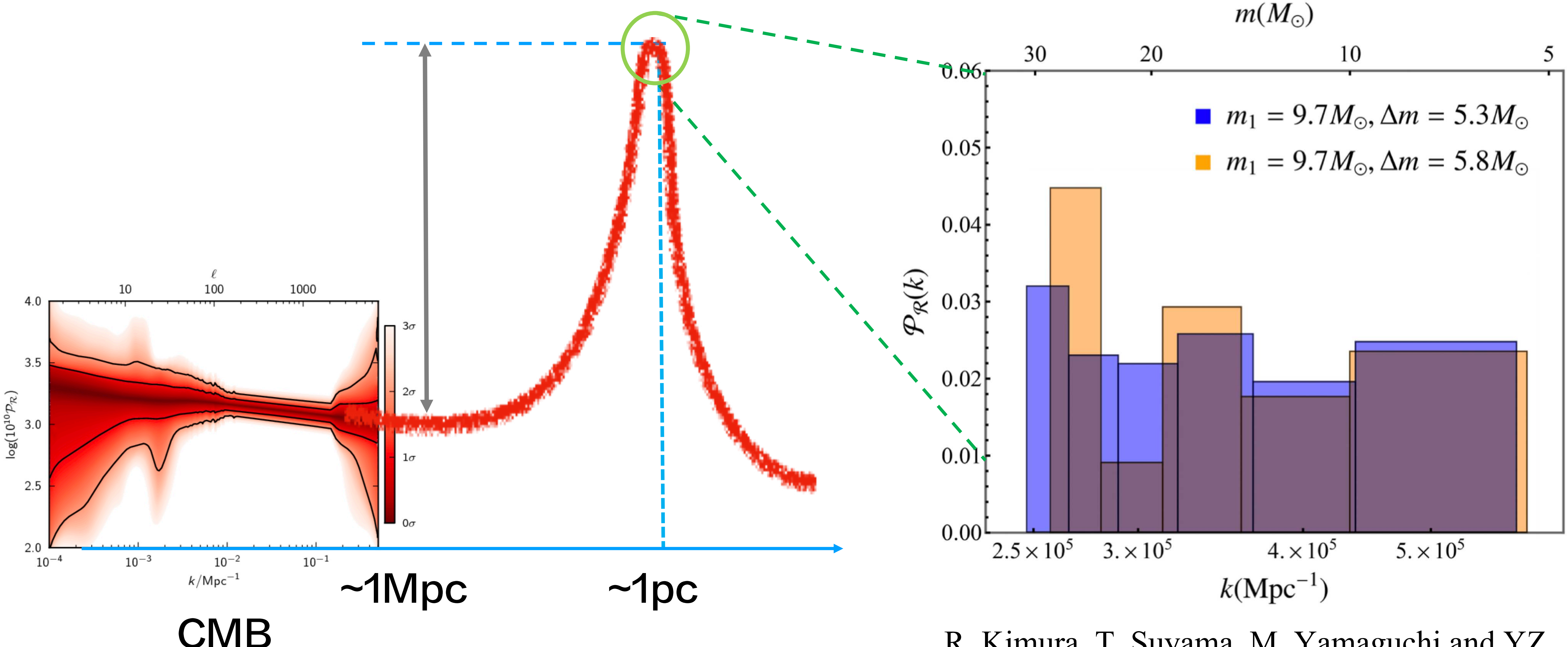
"Artificial" peak

Common feature:

Amplitude of order 0.01

Consistent with PBH scenario

10^7 amplification !



R. Kimura, T. Suyama, M. Yamaguchi and YZ, JCAP 04 (2021) 031 [arXiv: 2102.05280]

X. Wang, YZ, Kimura and M. Yamaguchi, SCPMA 6 (2023) 66 [arXiv: 2209.12911]

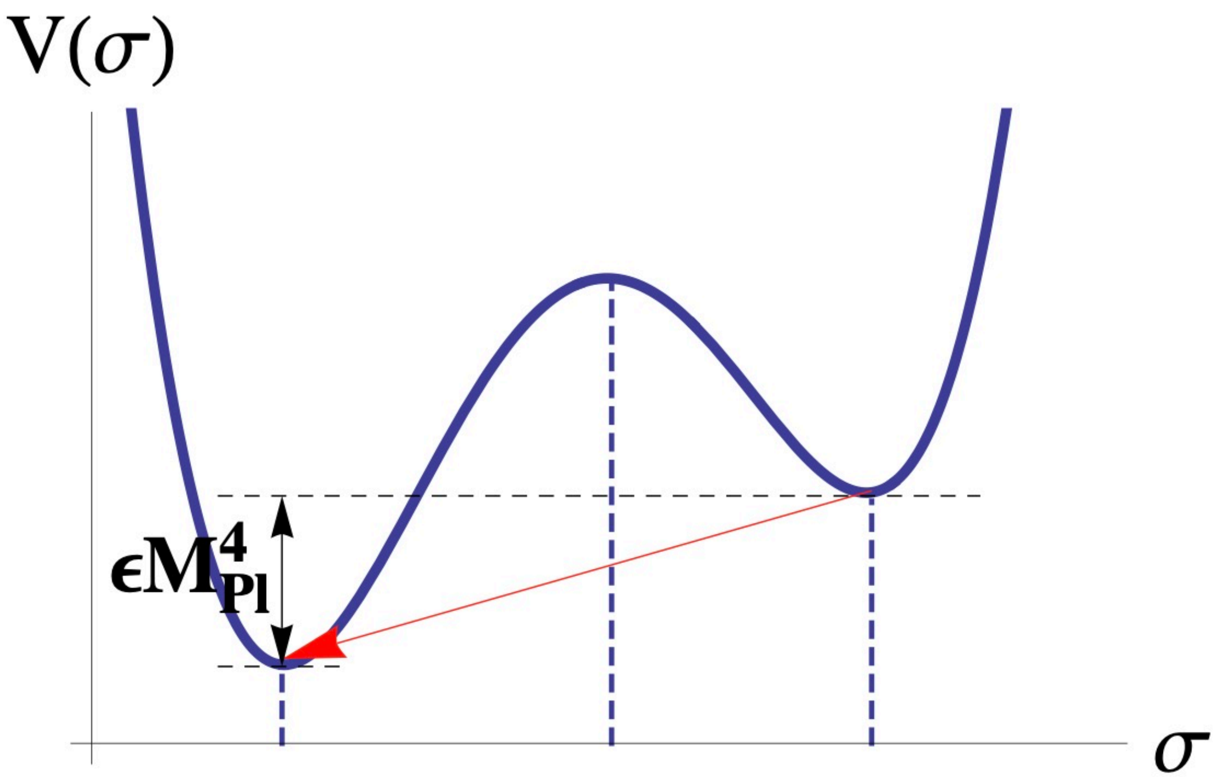
Question: If no IGW observed, can we rule out PBH scenario?

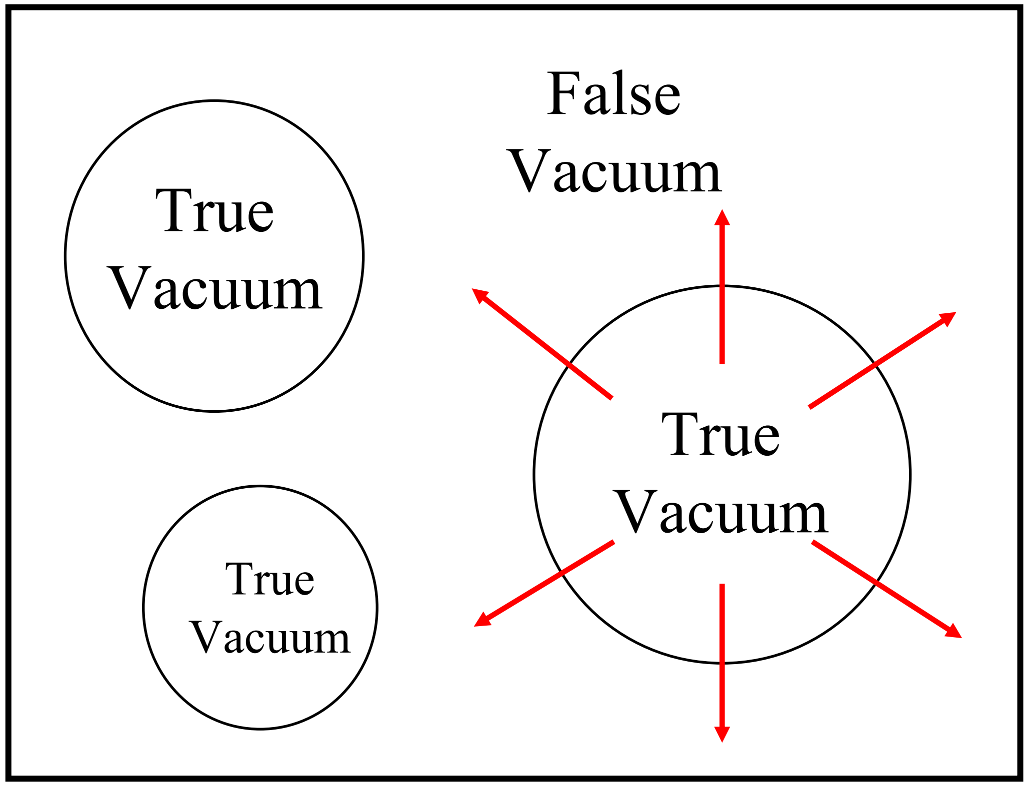
↕

Question: Is there any PBH scenario without amplification of primordial power spectrum?

Another mechanism: The Bubble Nucleation

Bubble will be nucleated via tunneling process in early universe





During Inflation

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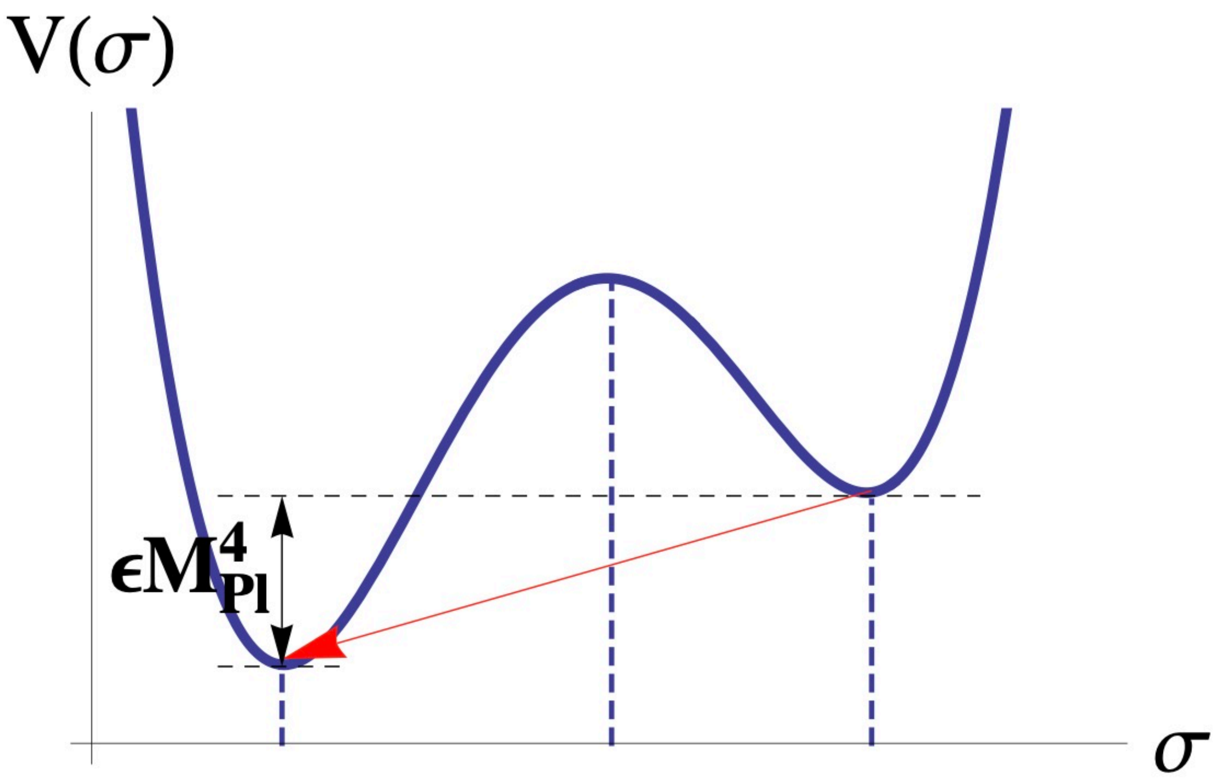

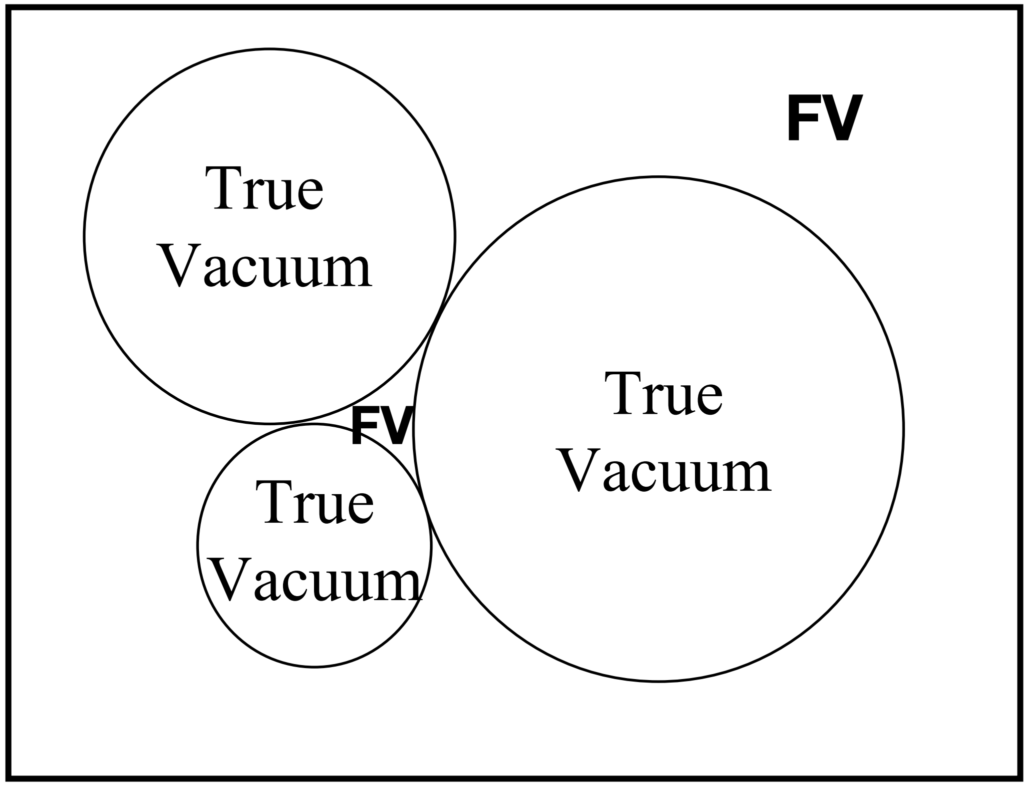

During Inflation

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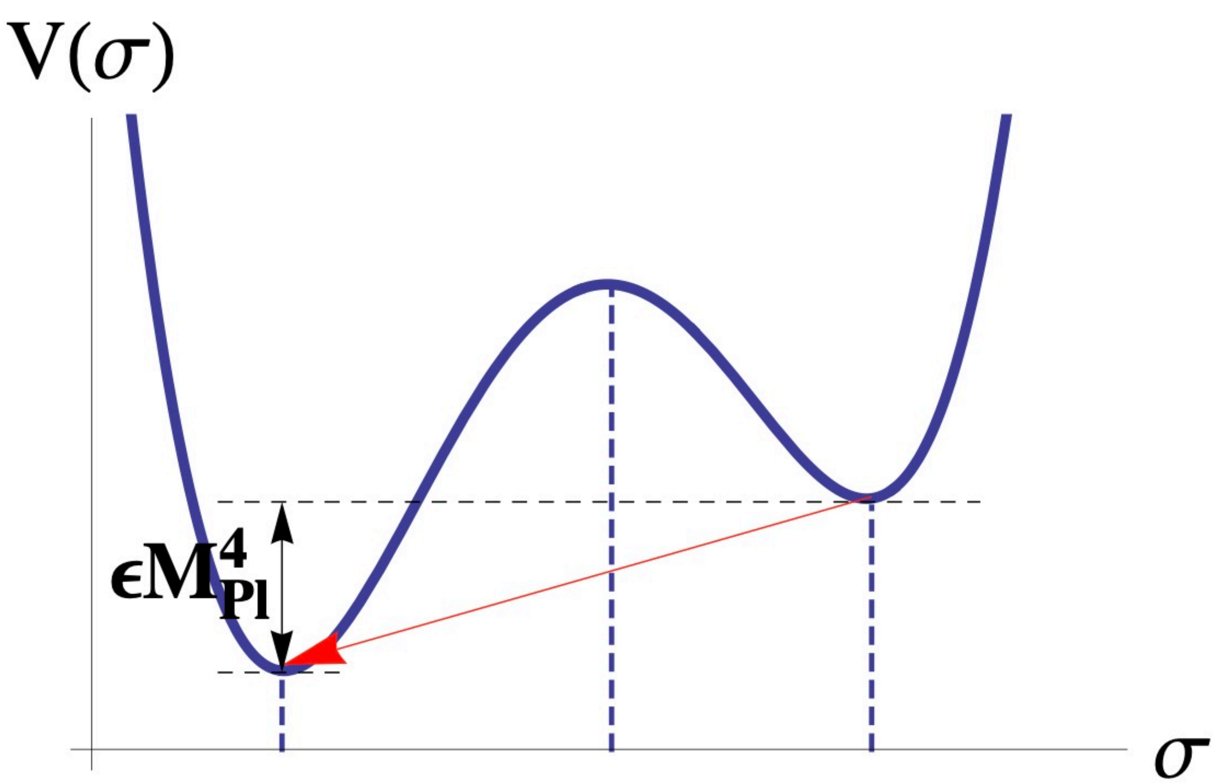
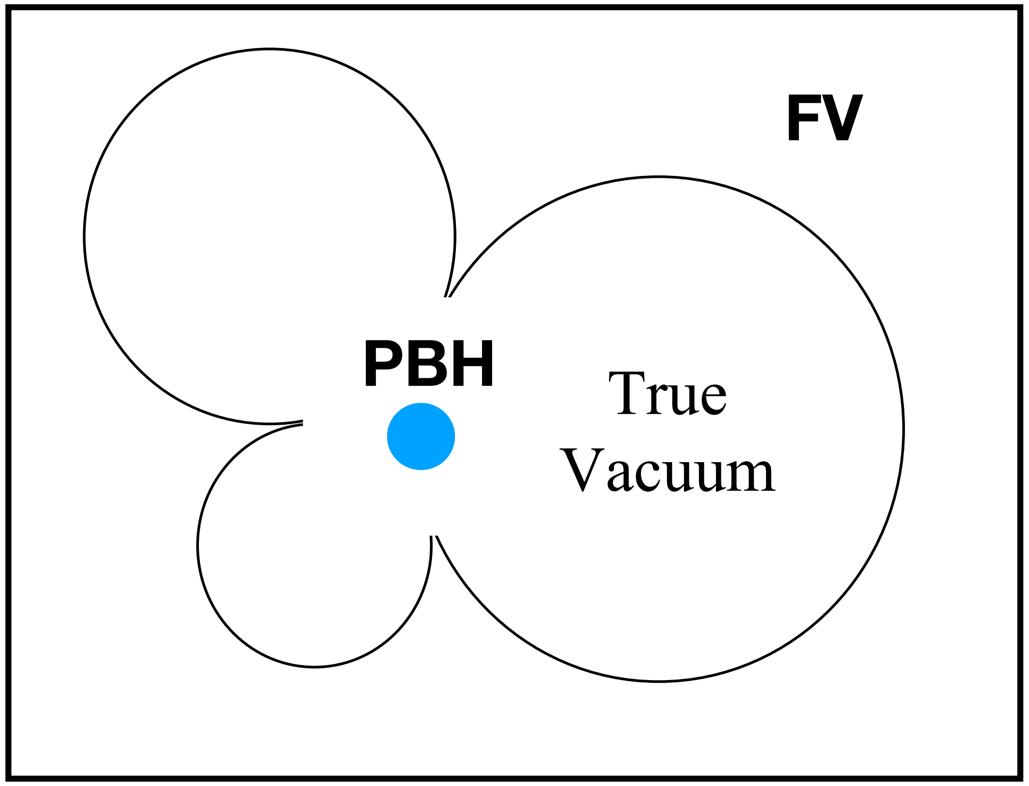
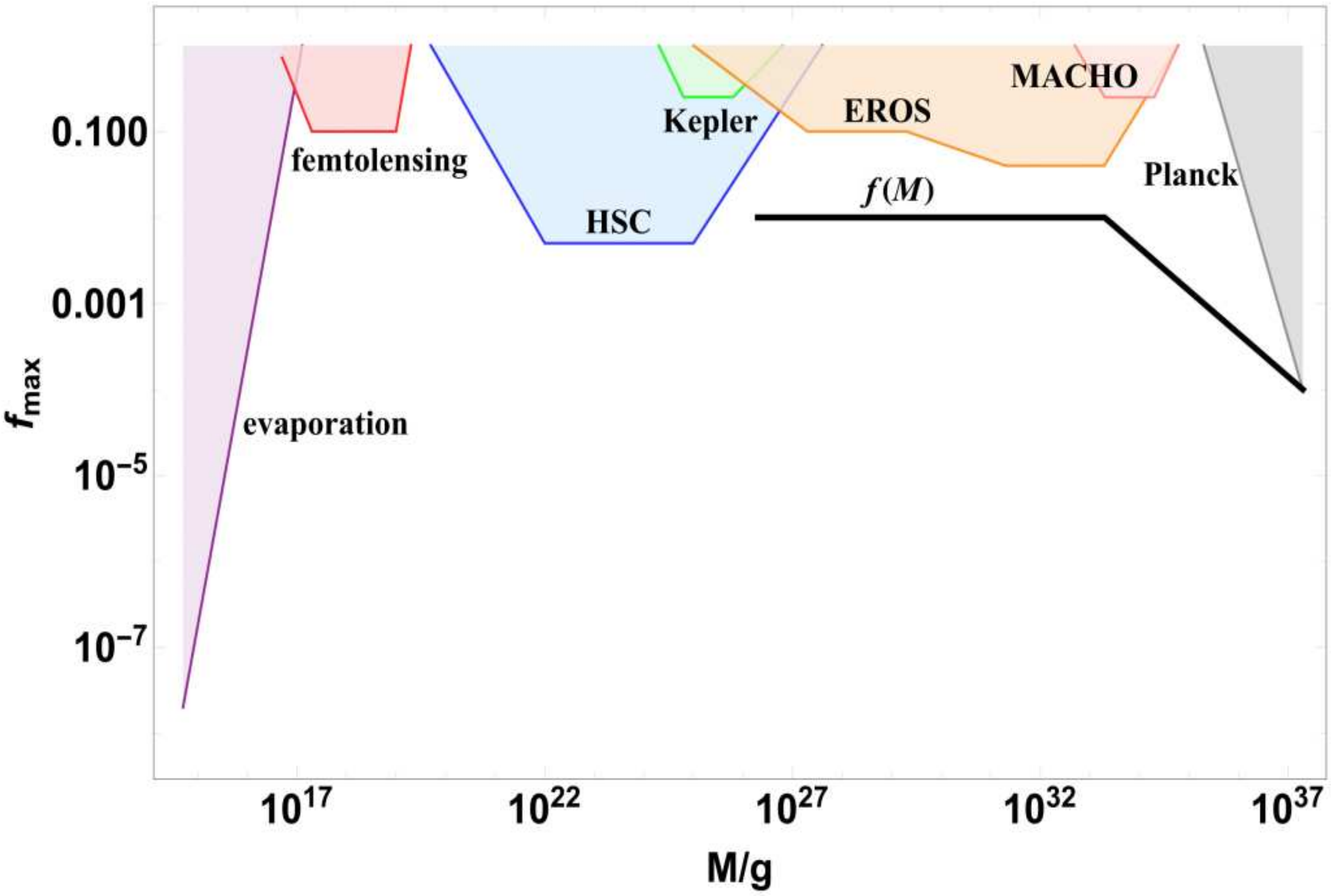




During Inflation

Case of a constant tunneling rate

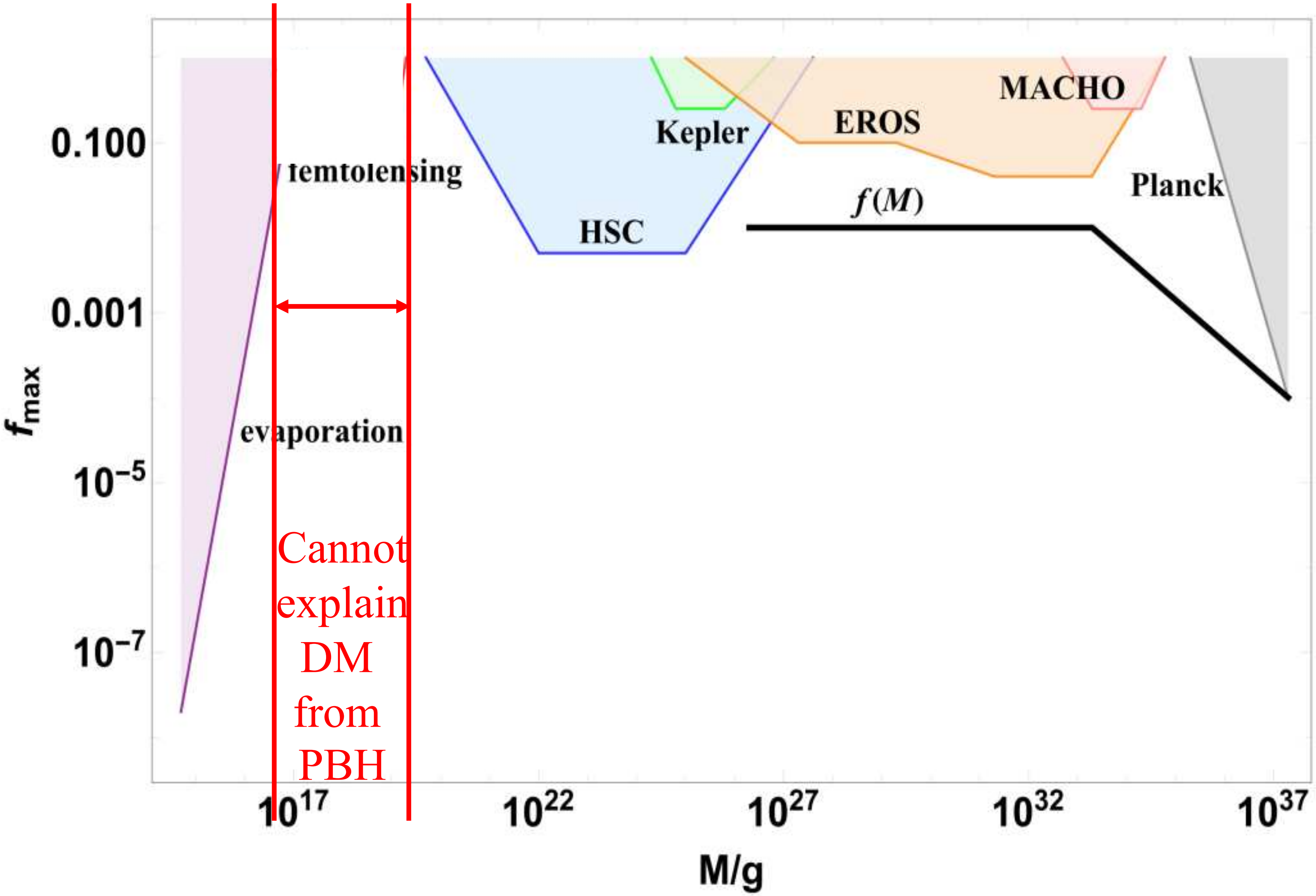
H. Deng, A. Vilenkin, JCAP 2017(12): 044.



We need a varying tunneling rate to explain DM

Case of a constant tunneling rate

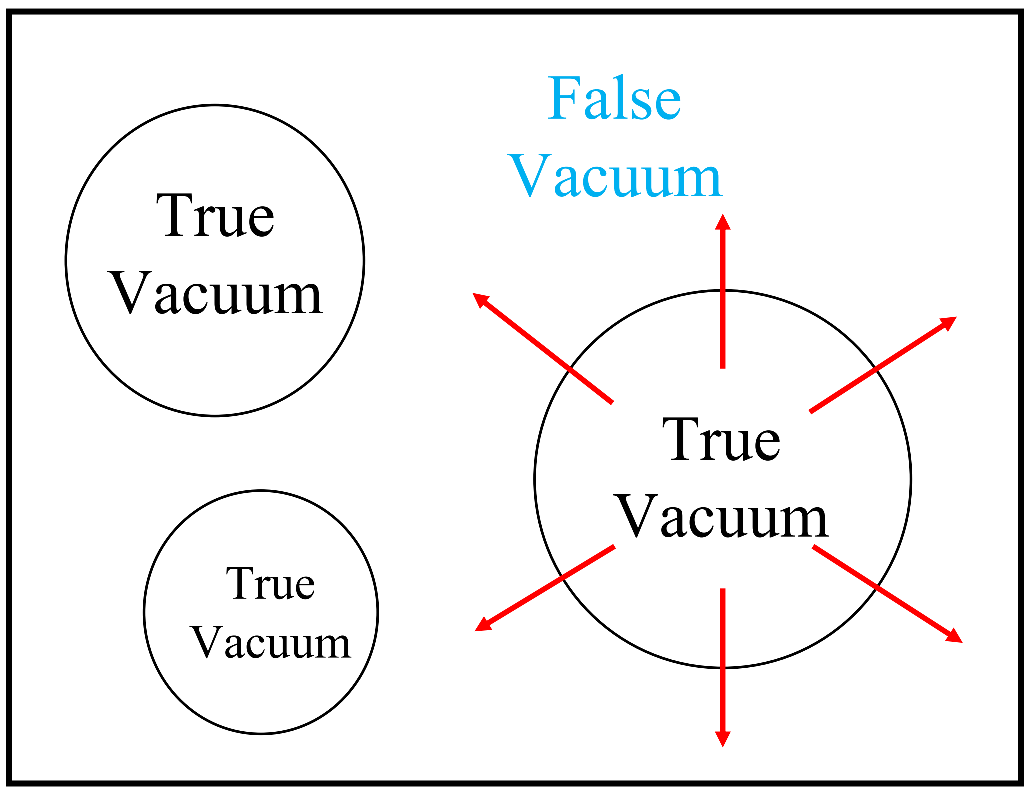
H. Deng, A. Vilenkin, JCAP 2017(12): 044.



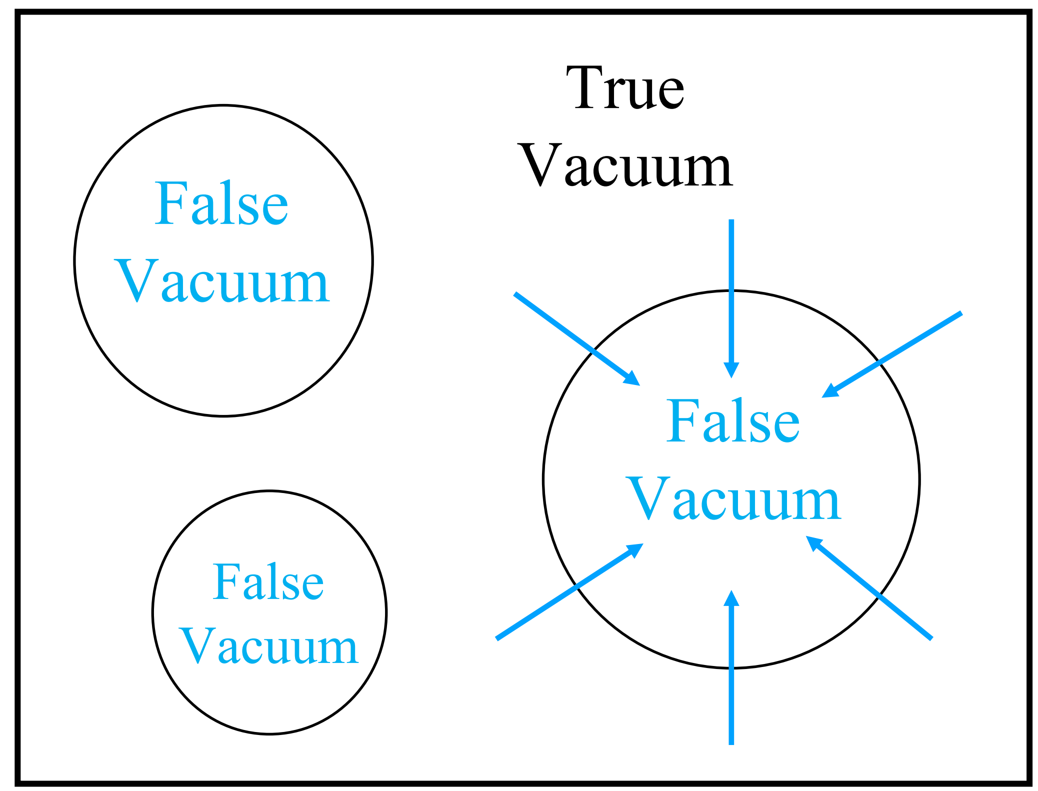
We need a varying tunneling rate to explain DM

The Bubble Nucleation

Bubble will be nucleated via tunneling process in early universe



During Inflation



After Inflation

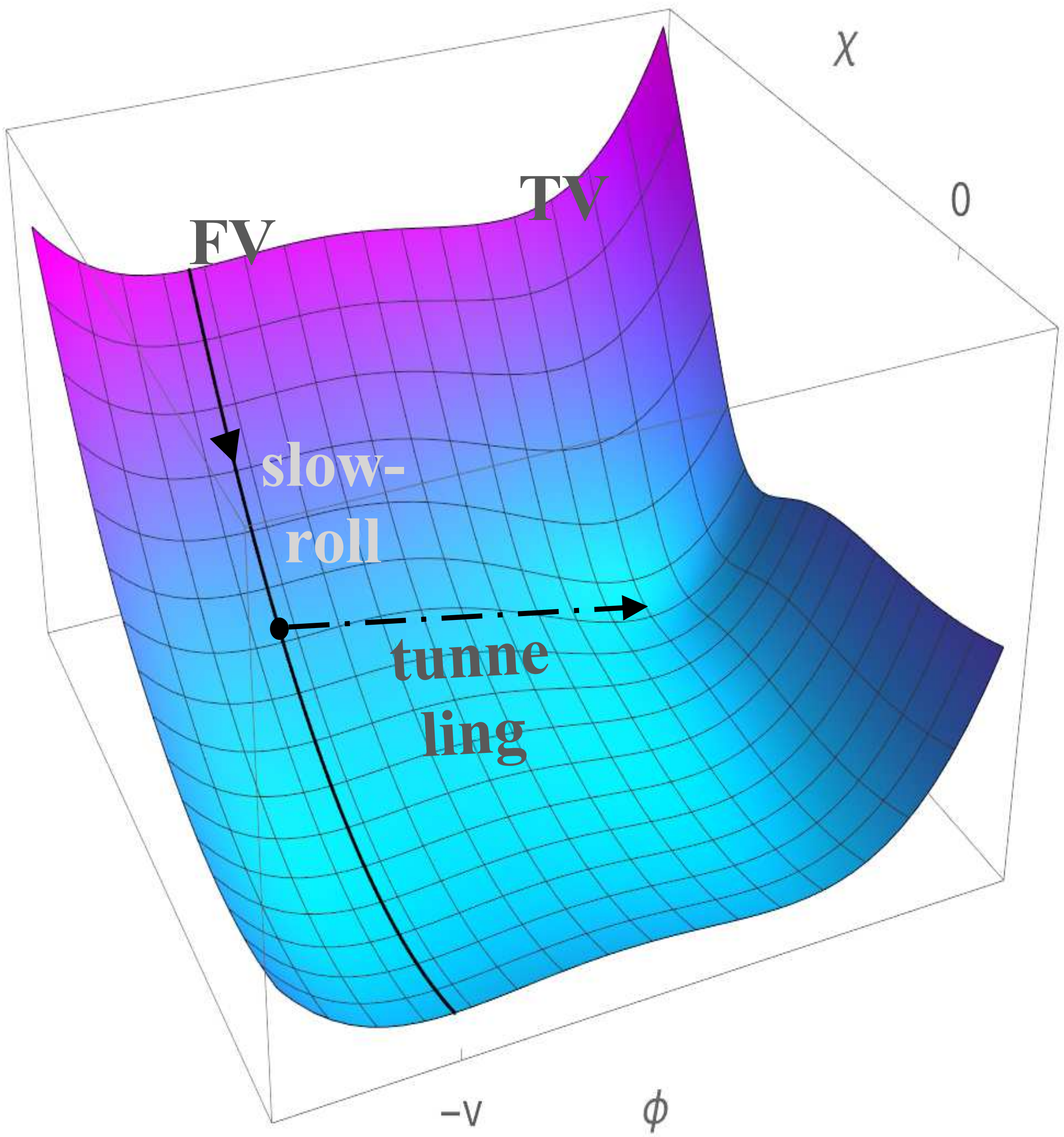
Question: How to realize this scenario?

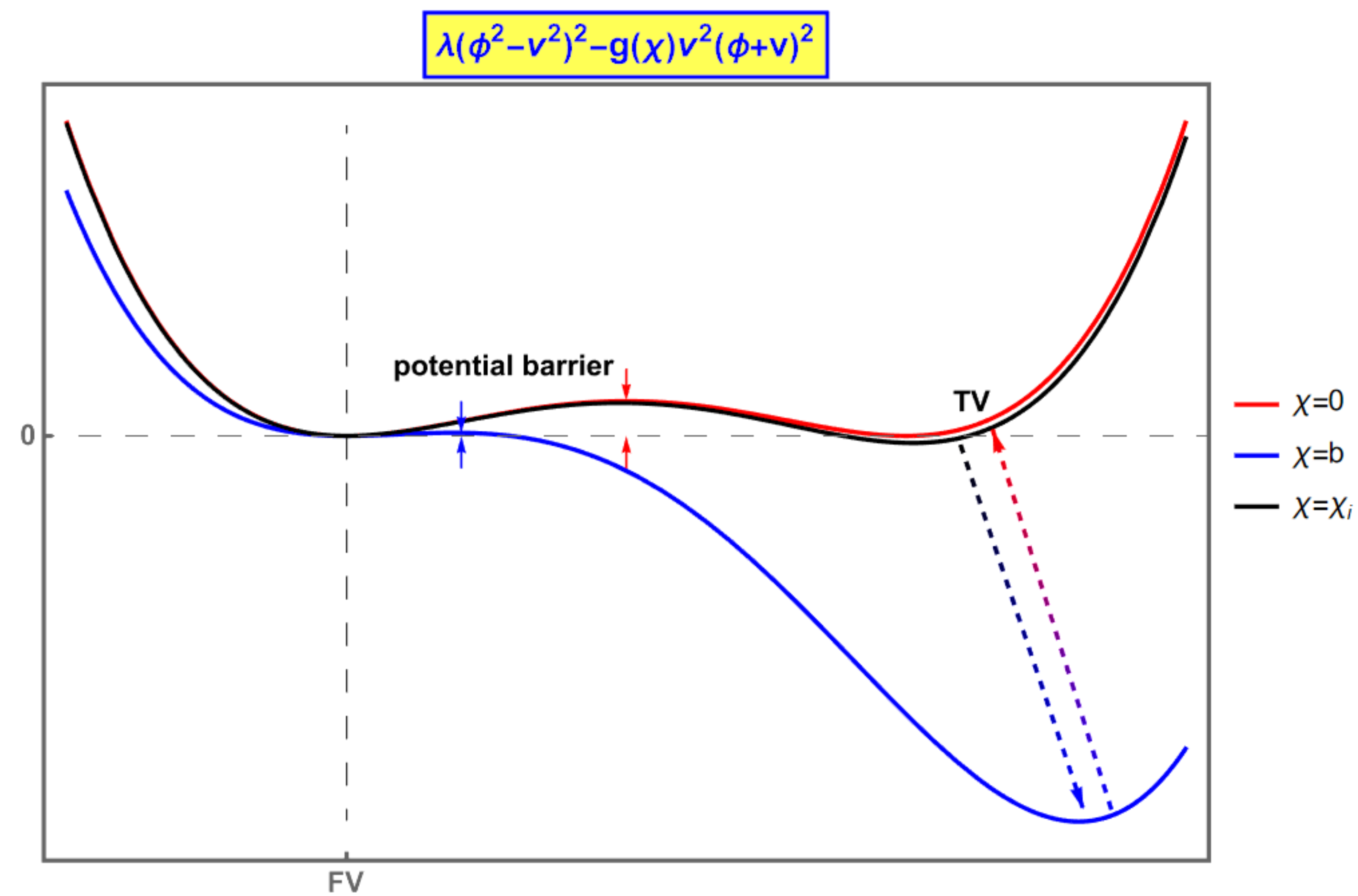
Running of local minima

$$V(\chi,\phi)=\frac{1}{2}m^2\chi^2+\lambda(\phi^2-v^2)^2-g(\chi)v^2(\phi+v)^2$$

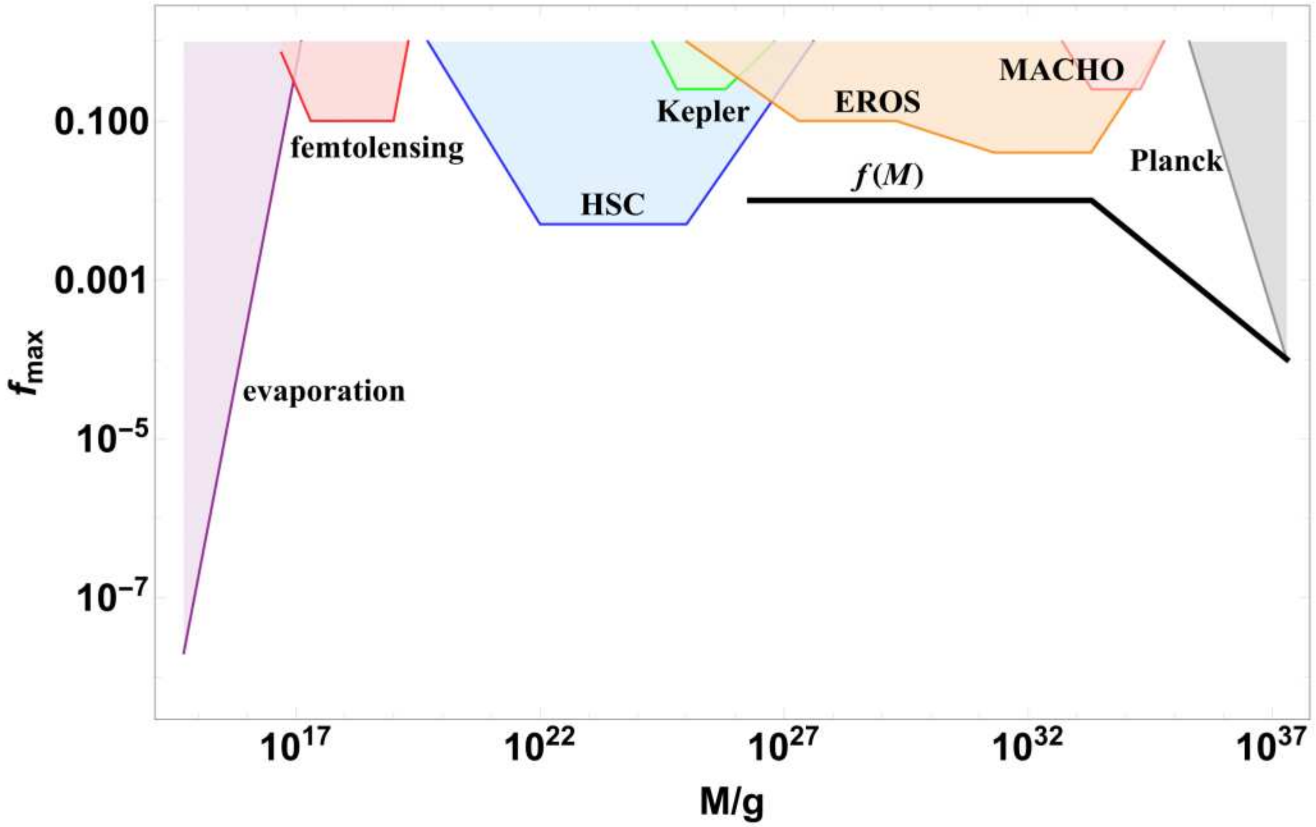
inflaton

instanton



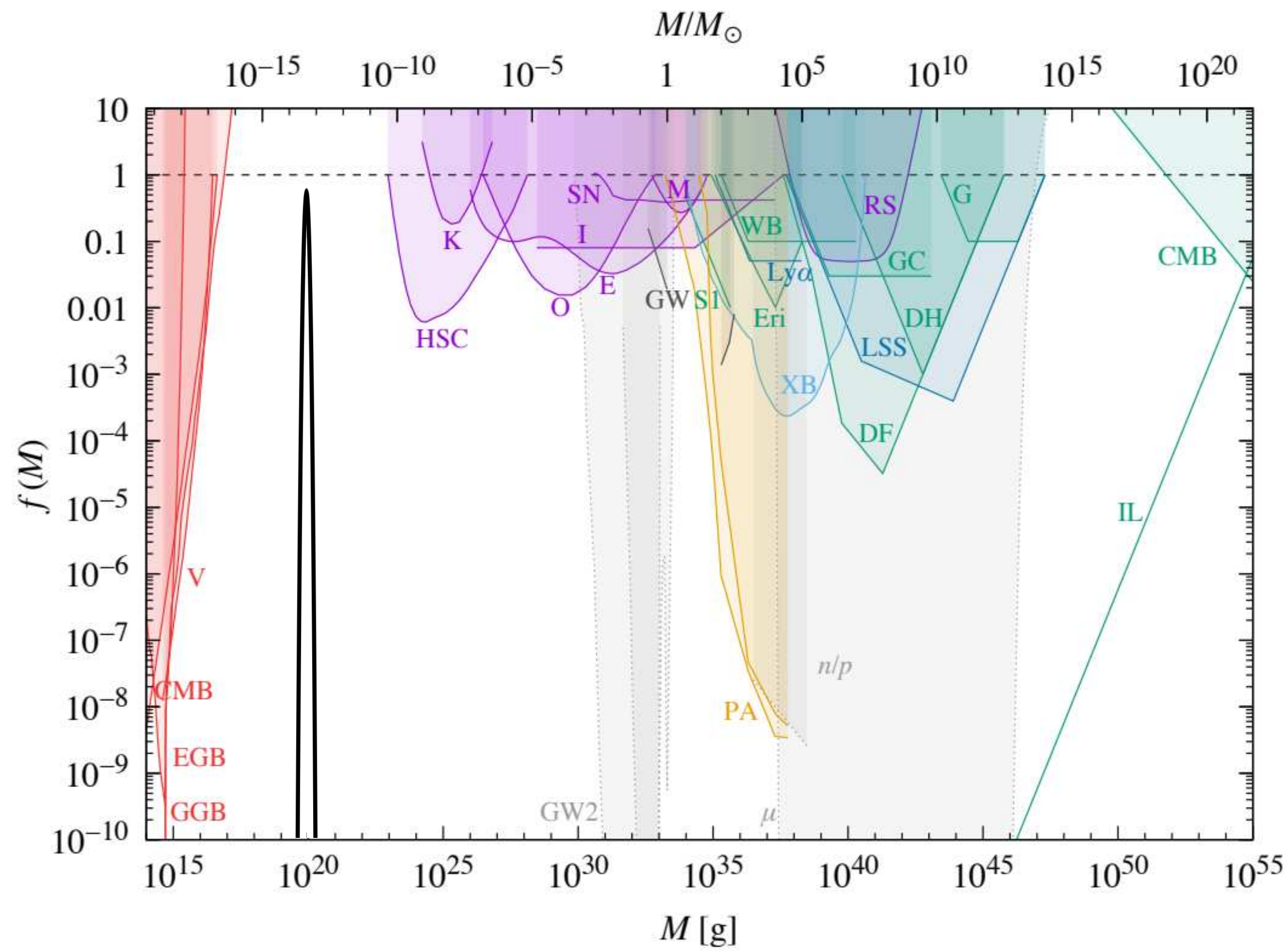


H. Wang, YZ, T. Suyama, in preparation



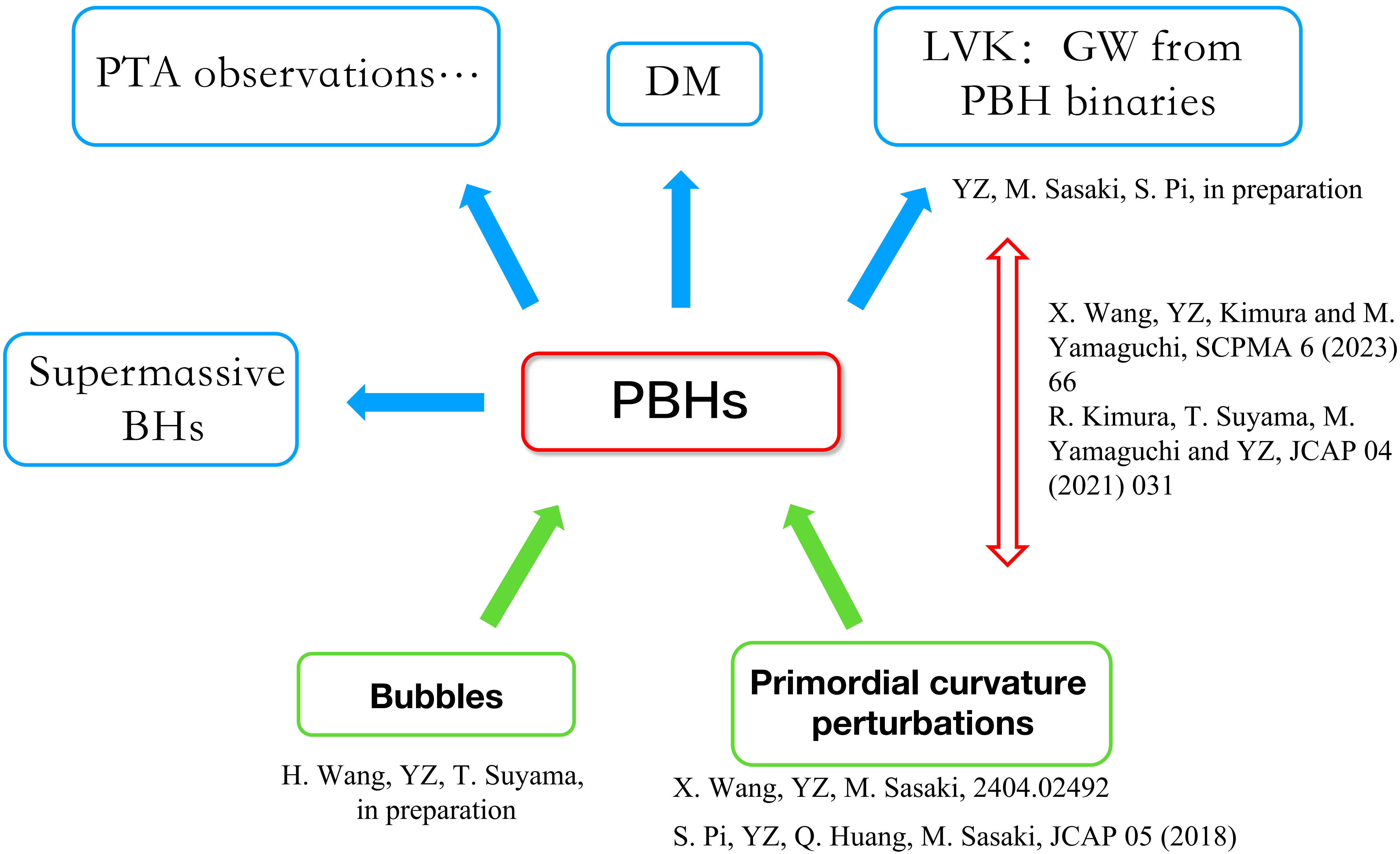
Single Field case

H. Deng, A. Vilenkin, JCAP 2017(12): 044.



Two field with nonminimally coupling

Summary


PTA observations…
DM
LVK： GW from PBH binaries
YZ, M. Sasaki, S. Pi, in preparation
Supermassive BHs
PBHs
X. Wang, YZ, Kimura and M. Yamaguchi, SCPMA 6 (2023) 66
R. Kimura, T. Suyama, M. Yamaguchi and YZ, JCAP 04 (2021) 031
Bubbles
Primordial curvature perturbations
H. Wang, YZ, T. Suyama, in preparation
X. Wang, YZ, M. Sasaki, 2404.02492
S. Pi, YZ, Q. Huang, M. Sasaki, JCAP 05 (2018)