Primordial Black Holes

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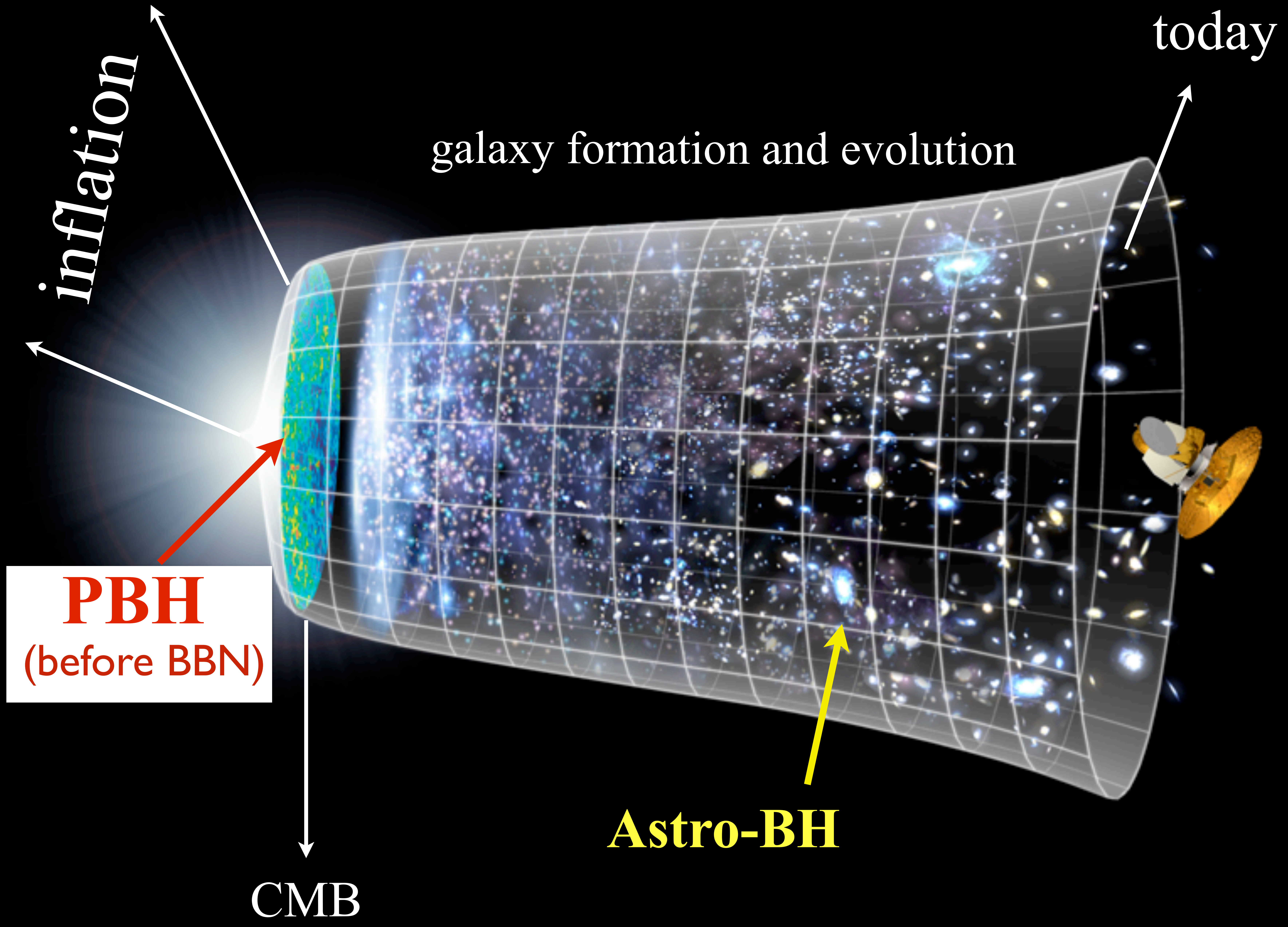
35th Rencontres de Blois on Particle Physics and Cosmology



inflation

galaxy formation and evolution

today

PBH
(before BBN)

CMB

Astro-BH

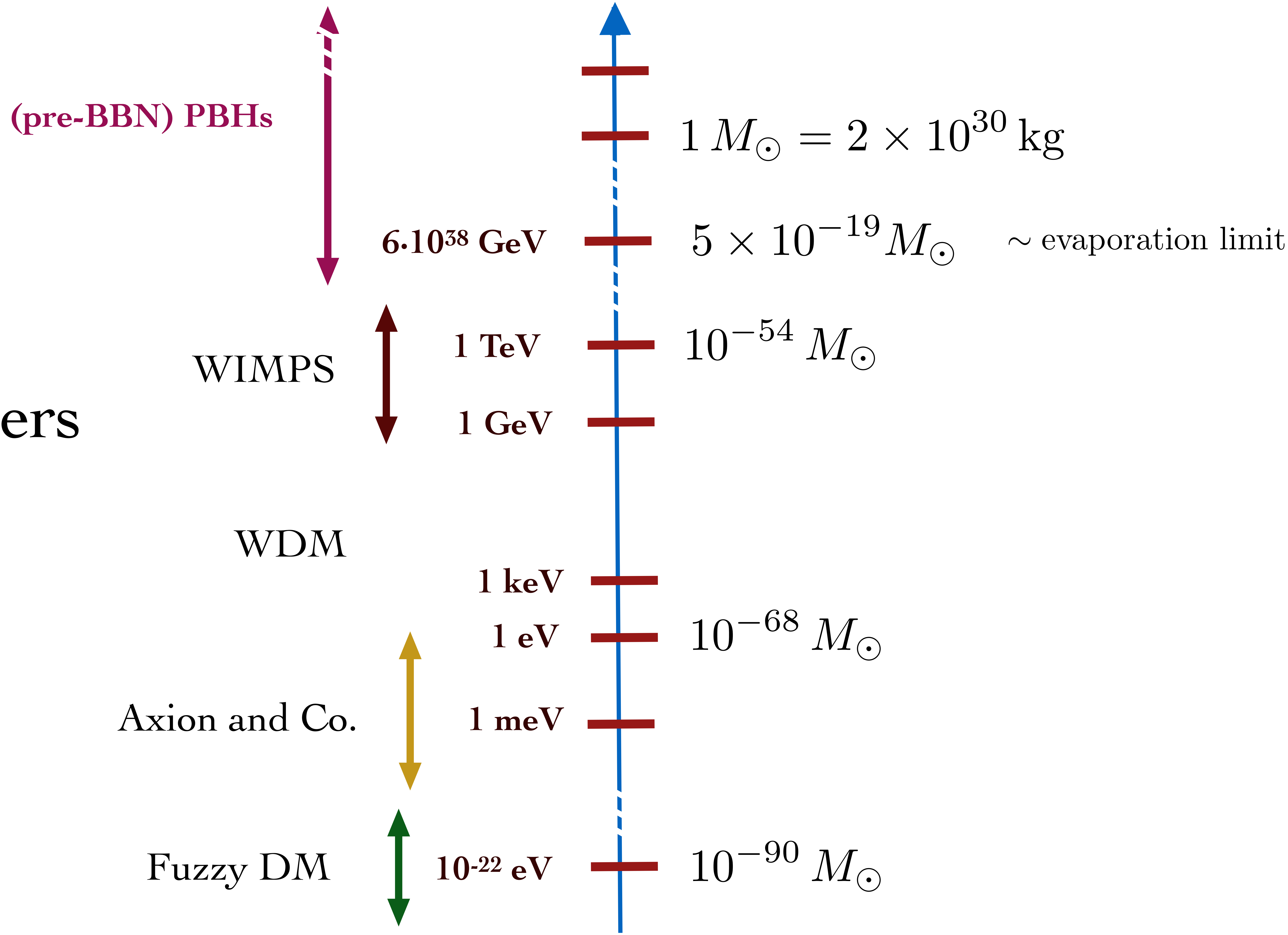
Adapted from NASA/WMAP Science Team

Primordial black holes

Zeldovich and Novikov 1967, Hawking 1971, Hawking & Carr 1974, …

- **Dark matter candidate**
- Reheat the universe after inflation
- Catalysers for particle dark matter or other BSM production
- Baryogenesis
- Seeds of supermassive black holes
- Possible BH merger outliers in LIGO/Virgo/Kagra
- Possible BH microlensing events
- PTA indications of a stochastic GW background
- Window into the early universe

Dark Matters



(pre-BBN) PBHs

$1\,M_\odot = 2 \times 10^{30}$ kg

6·10^{38} GeV

$5 \times 10^{-19} M_\odot$

~ evaporation limit

WIMPS

1 TeV

$10^{-54}\,M_\odot$

1 GeV

WDM

1 keV

1 eV

$10^{-68}\,M_\odot$

Axion and Co.

1 meV

Fuzzy DM

10^{-22} eV

$10^{-90}\,M_\odot$

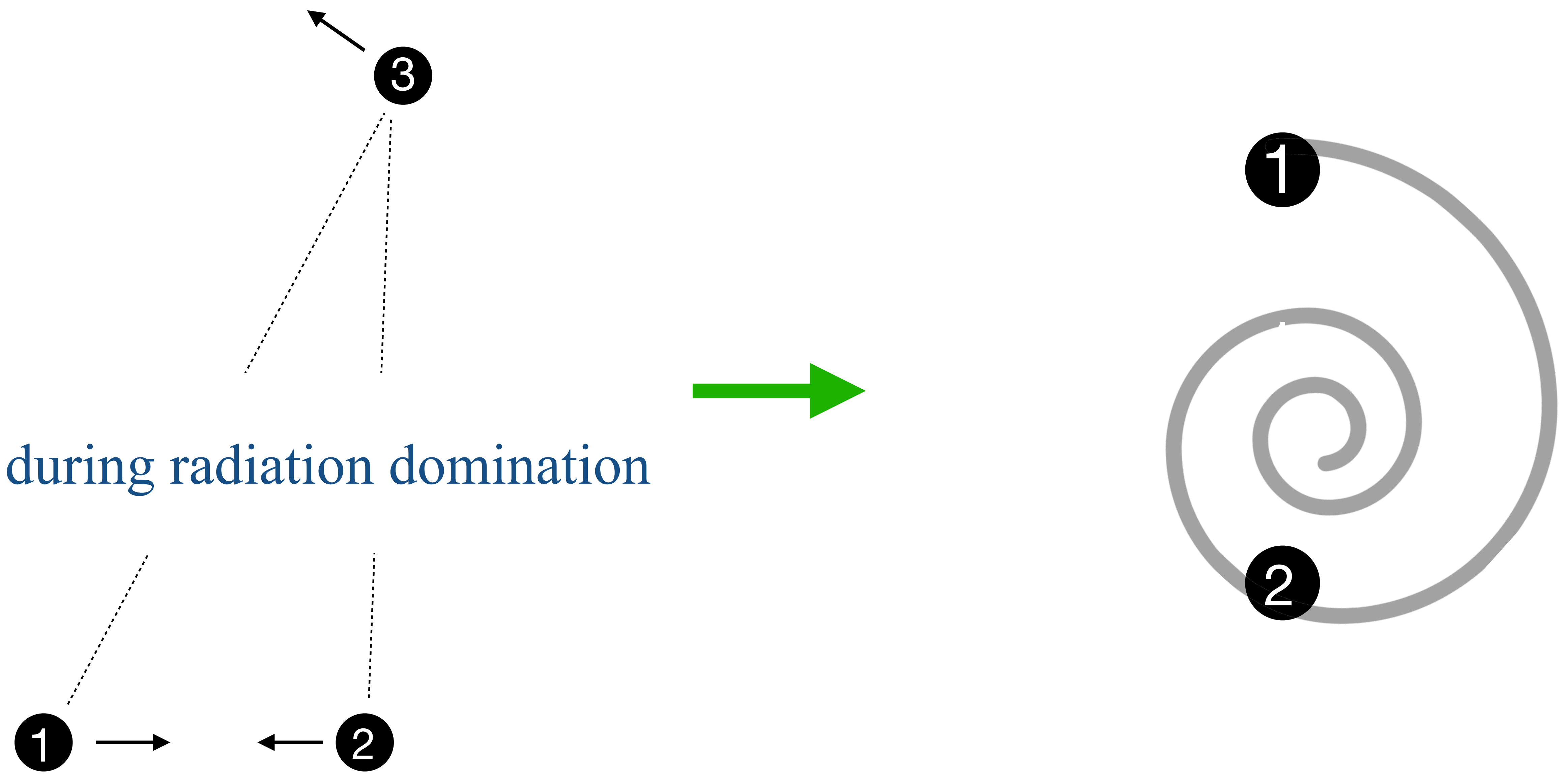
PBHs and other dark matter candidates

* WIMPs: possibly largely incompatible (absence of annihilation signals)

(e.g. Lacki+ 2018, Adamek+2019, Gaggero+2019)

* axions: no problem

- 2016: LIGO: merger with ~**30 Solar masses BH**
- Did **LIGO** detect **(THE)** dark matter? (Bird et al 2016…)
- Most likely **NO.** Or at least, most likely not the main component of it.
- Two mechanisms to form PBHs binaries:
  - Late Universe (in dark matter halos)
  - Early Universe (before matter radiation equality). **Nakamura et al 1997**
- **MAX 0.1%** – **1%** of the DM in the range **1-100 Solar Masses**



Form during radiation domination

Merge today. Observable by LIGO-Virgo if

$$M \sim 10\, M_{\odot}$$

binary BH mergers

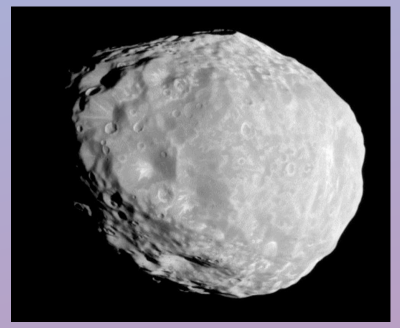
100 Hz

Courtesy
Caltech/MIT/LIGO Laboratory

M

$r_s = \frac{2GM}{c^2}$

$100\, M_\odot$ — $300\,\mathrm{km}$



$M_\odot$ — $3\,\mathrm{km}$

$0.1\, M_\odot$ — $0.3\,\mathrm{km}$

PTA ~ nHz

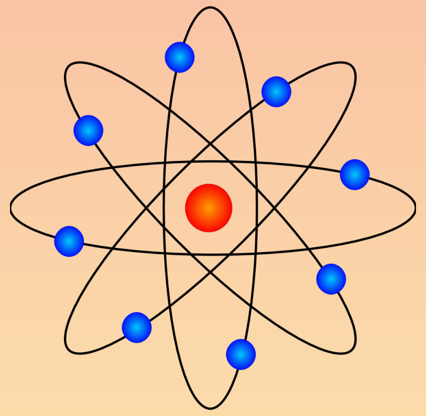
Possible Stochastic
GW backgrounds
from inflation

$0.03\,\mathrm{Hz} - 3\,\mathrm{Hz}$
e.g. LISA

100% of the
Dark Matter
possible

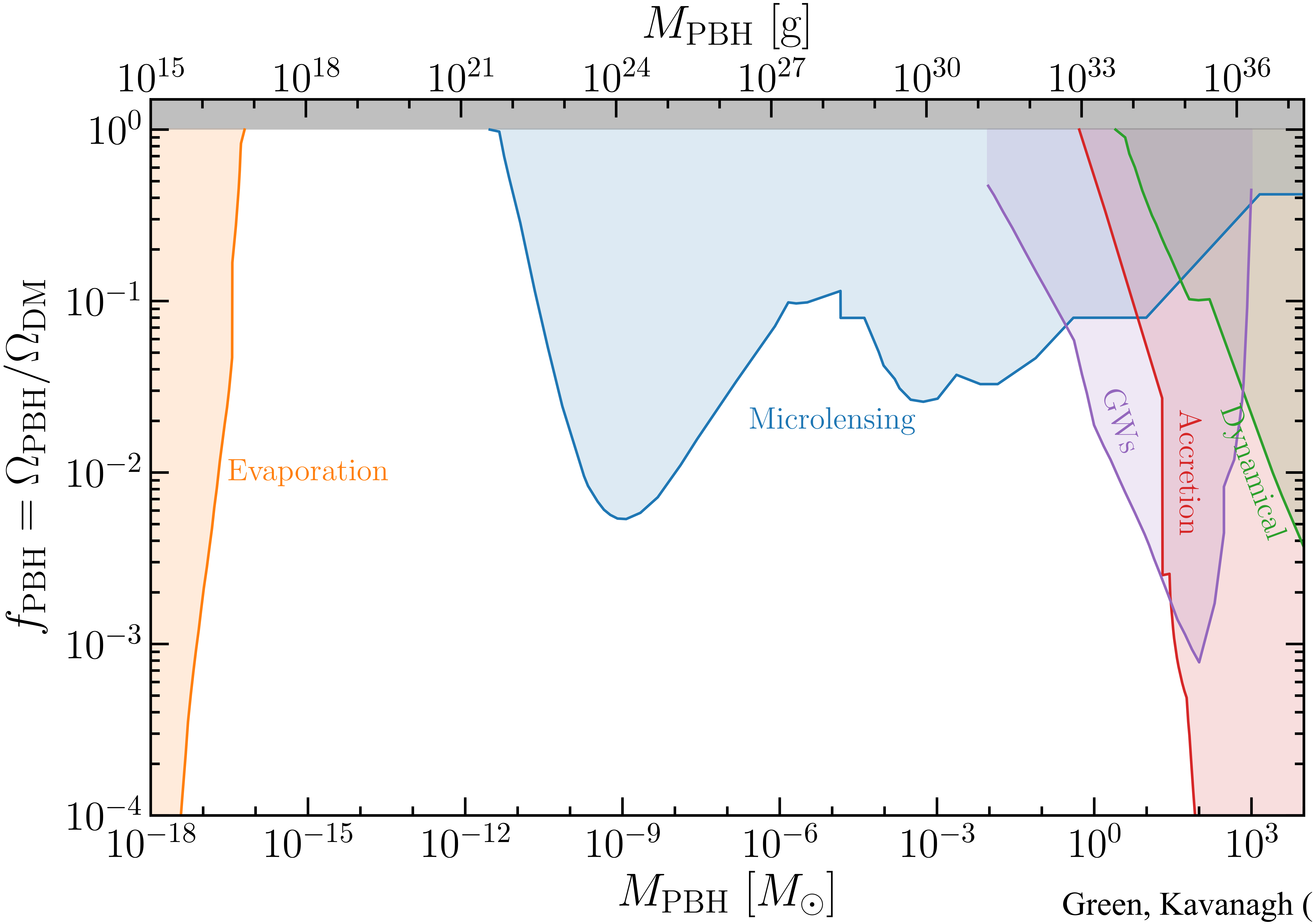
$10^{-12}\, M_\odot$ — $3\,\mathrm{nm}$

asteroid
mass
window



$\sim 0.1\,\mathrm{nm}$

$10^{-16}\, M_\odot$ — $3 \times 10^{-4}\,\mathrm{nm}$



Green, Kavanagh (review). 2020

Evaporation by Hawking radiation

$$T = \frac{\hbar c^2}{8\pi G\, k_B M} = 6 \times 10^{-8} \frac{M_\odot}{M} K$$

Bound for $M \lesssim 10^{17}\, g \simeq 5 \times 10^{-17} M_\odot$

Carr+ 2009

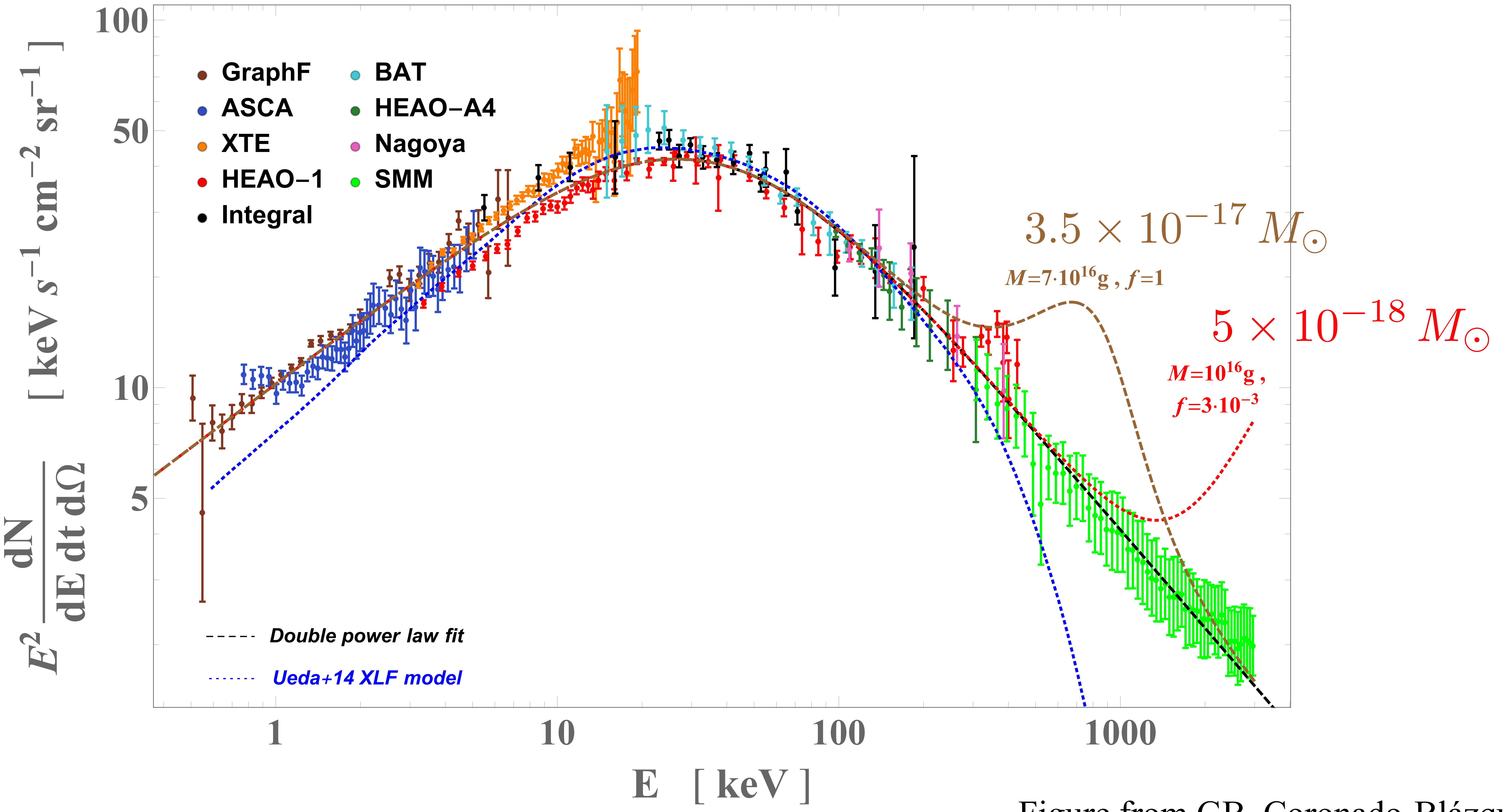


Figure from GB, Coronado-Blázquez, Gaggero, 2019

Situation before ~2019

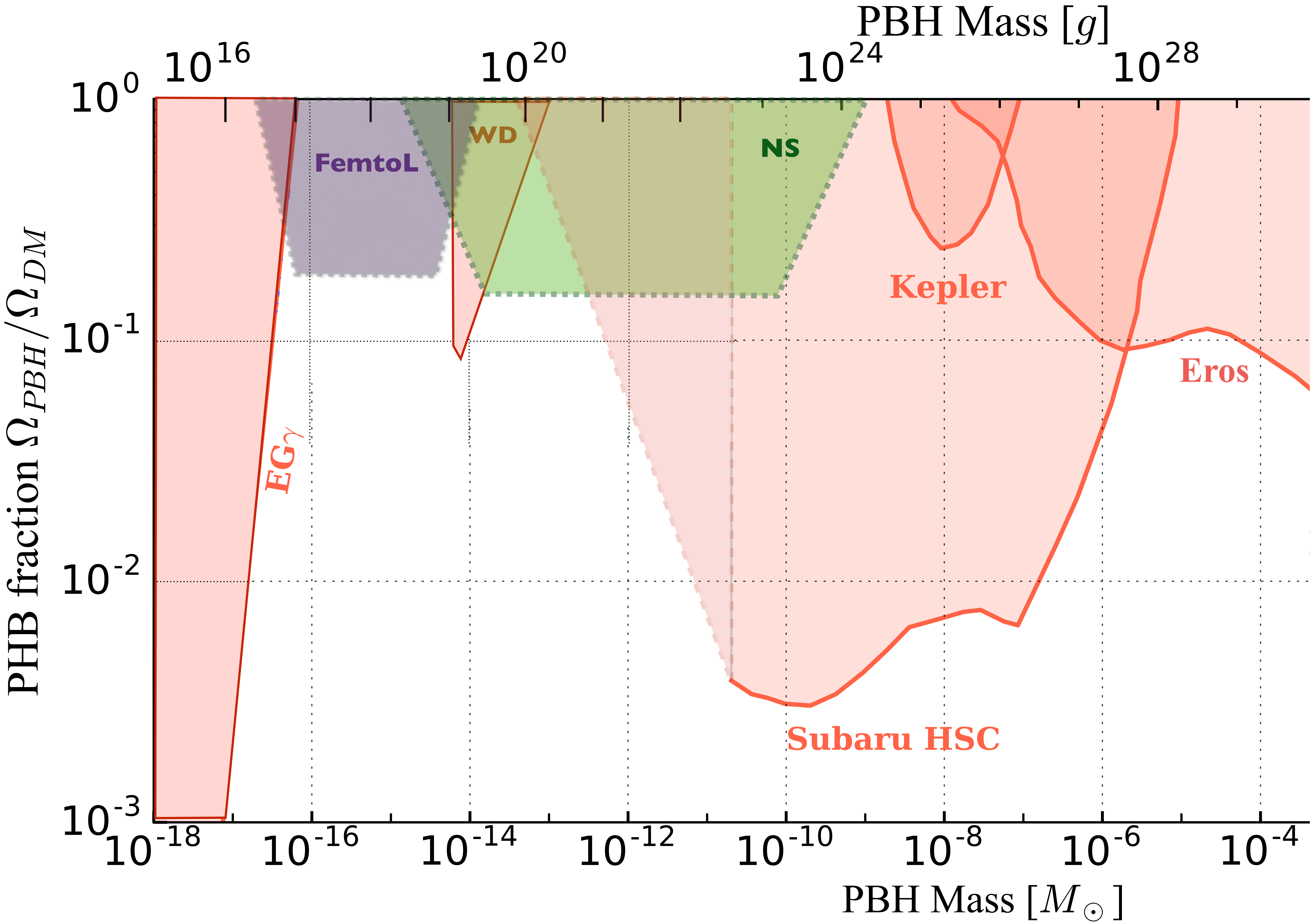


Figure from Katz et al. 2018
(modified)

See also Montero-Camacho et al. 2019
Smyth et al. 2019

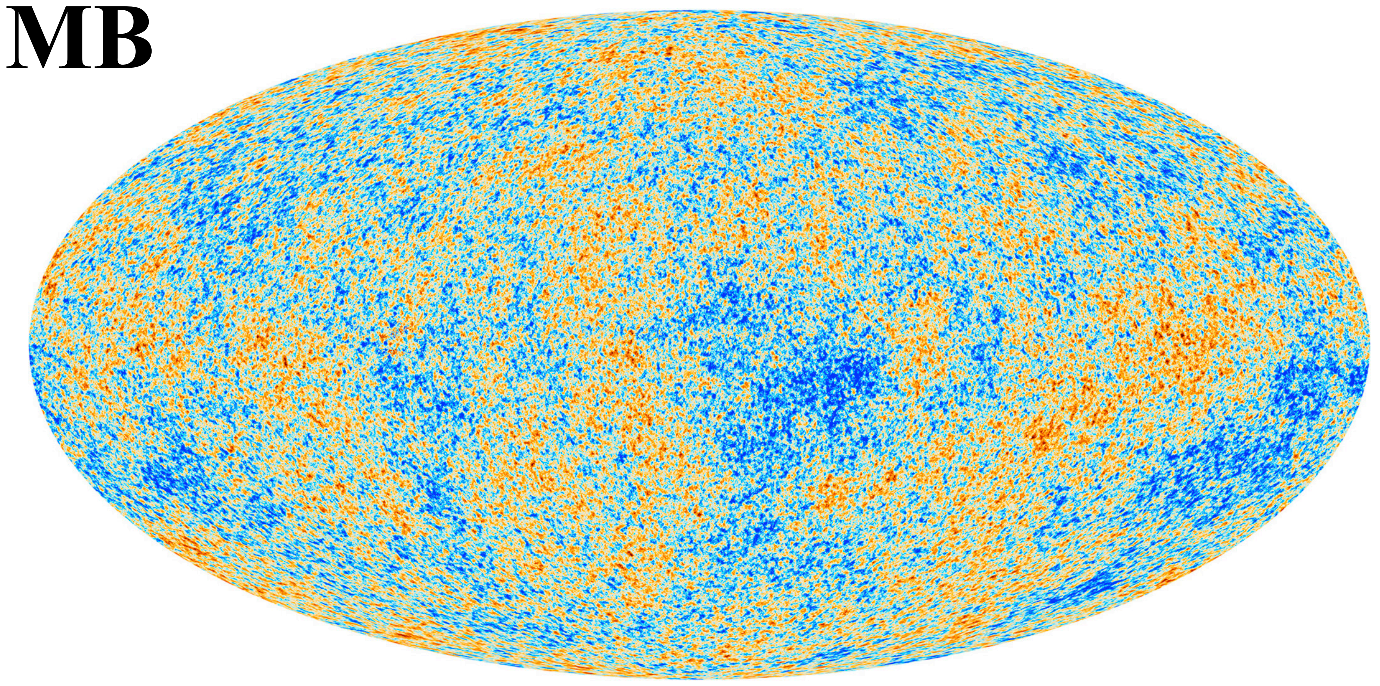
Mechanisms for PBH formation

- Large primordial fluctuations (inflation)
- Reheating after inflation
- 1st order phase transitions
- Collapse of topological defects
- False vacuum decay
- …

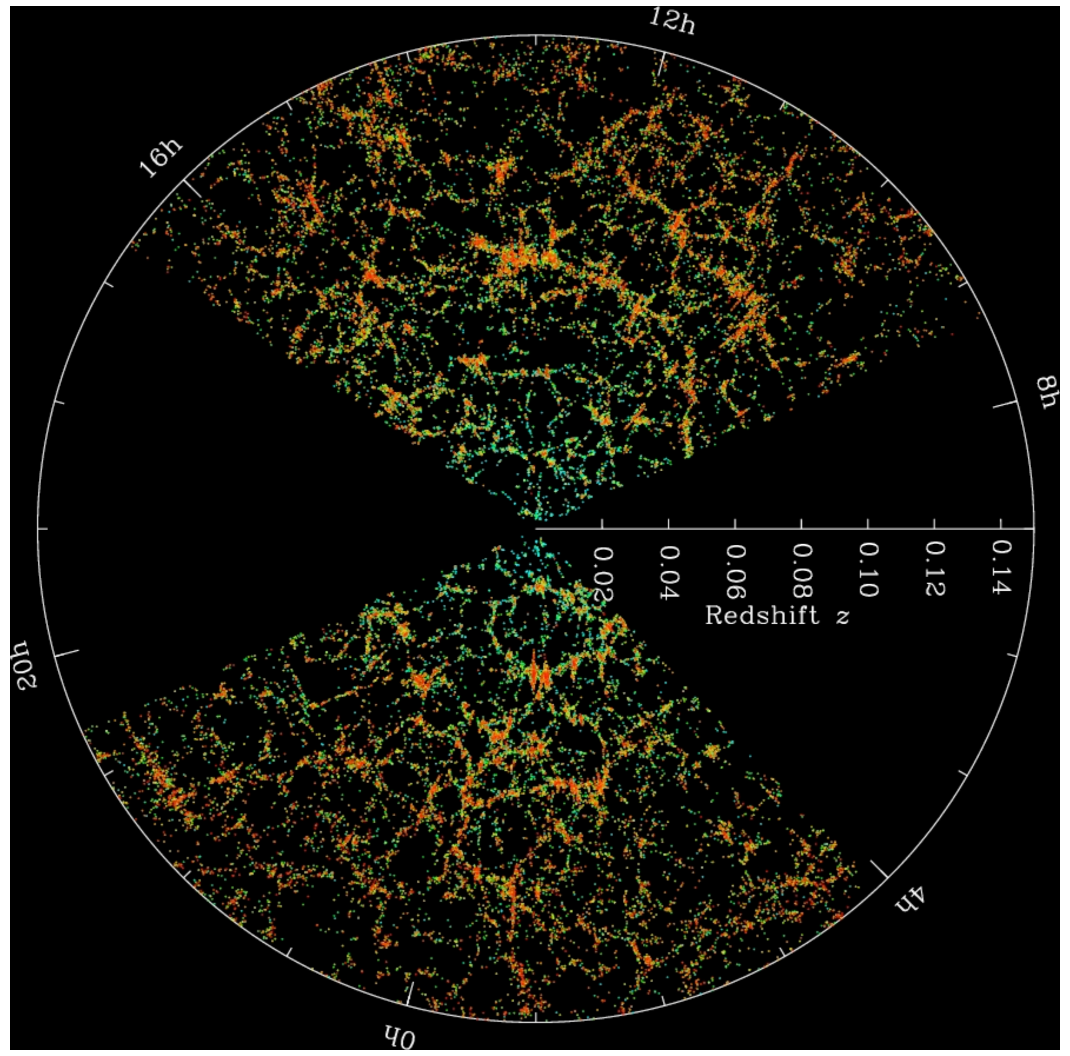
PBH dark matter (from inflation)

Credit: ESA/Planck

CMB

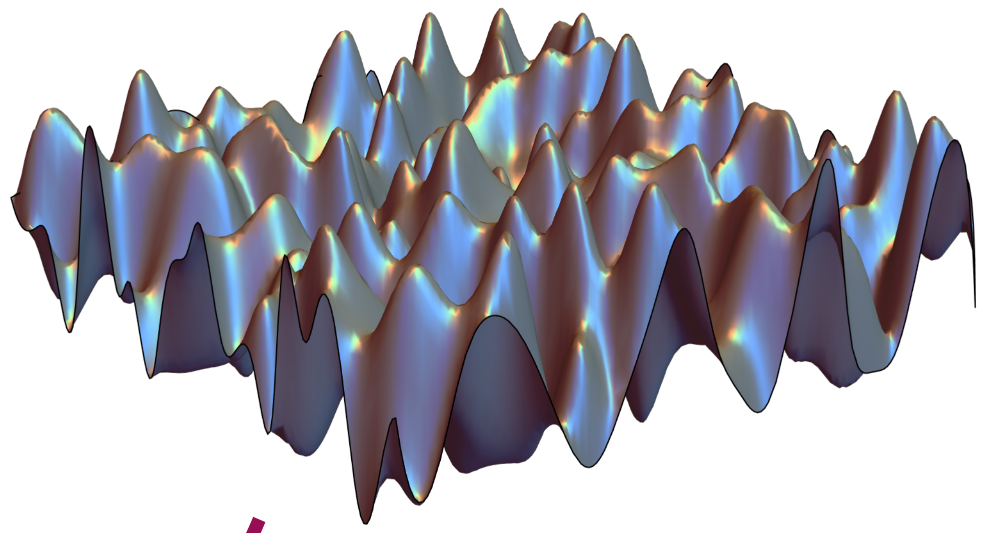


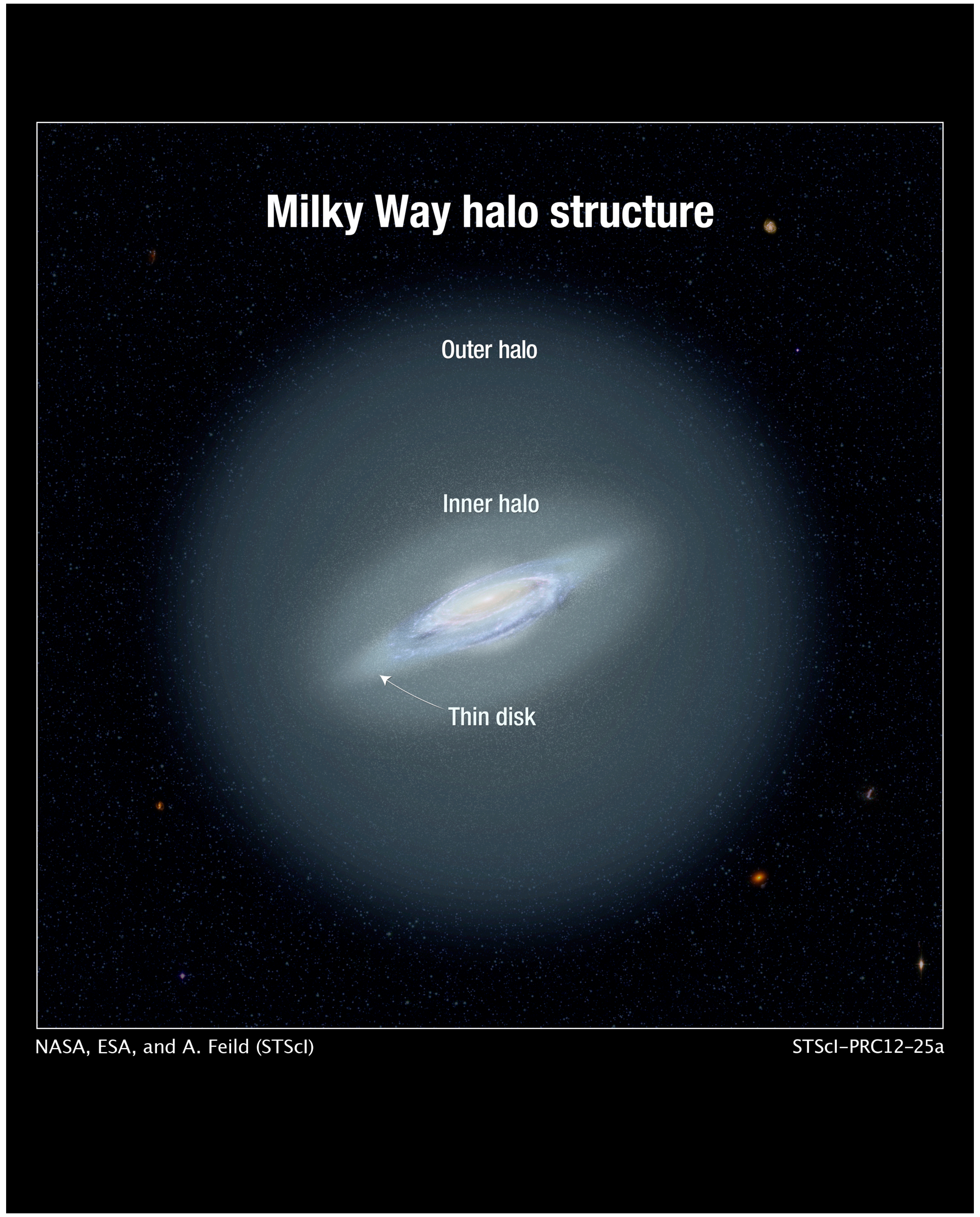
LSS



Credit: M Blanton
and SDSS

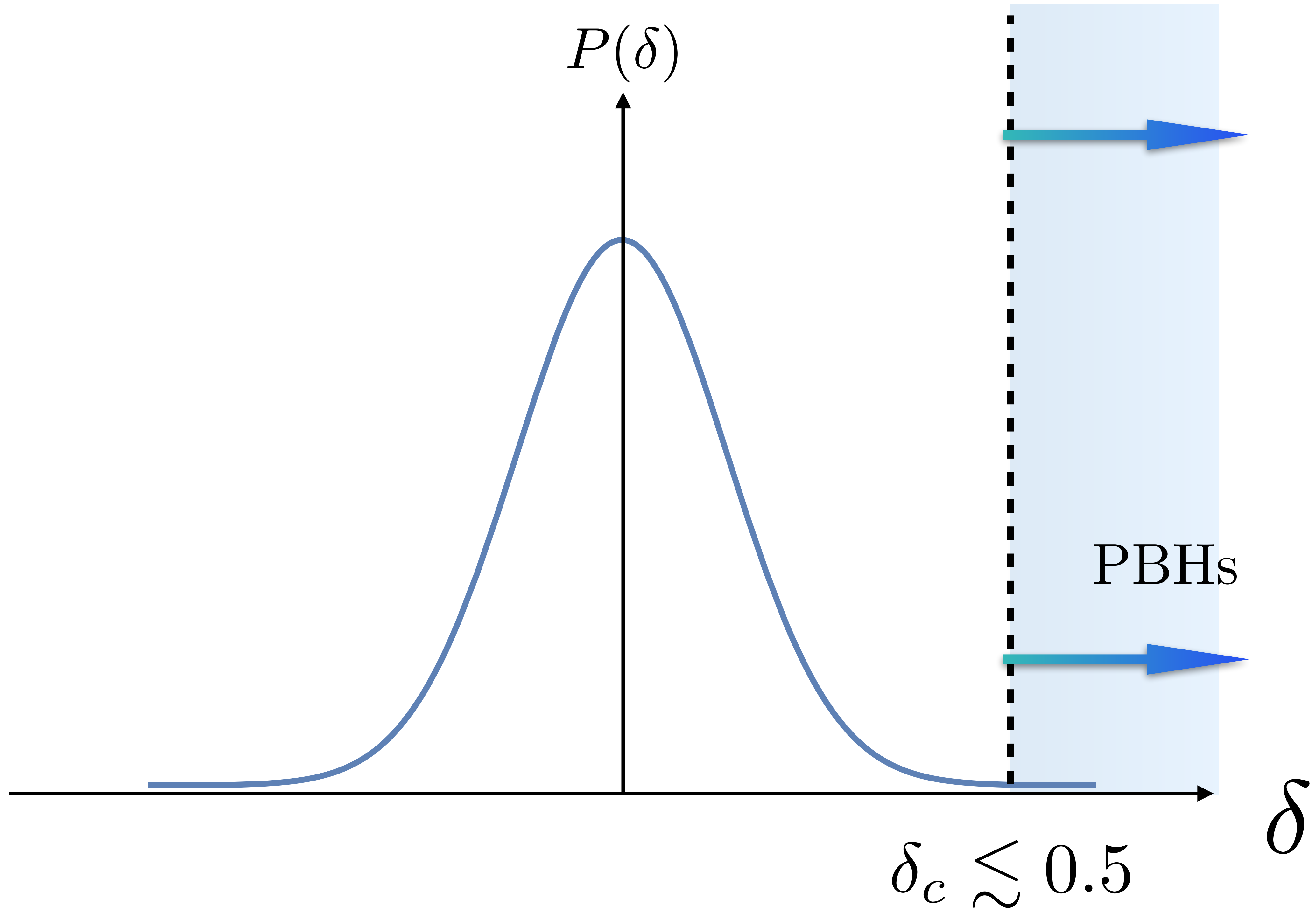
Quantum fluctuations
of space-time

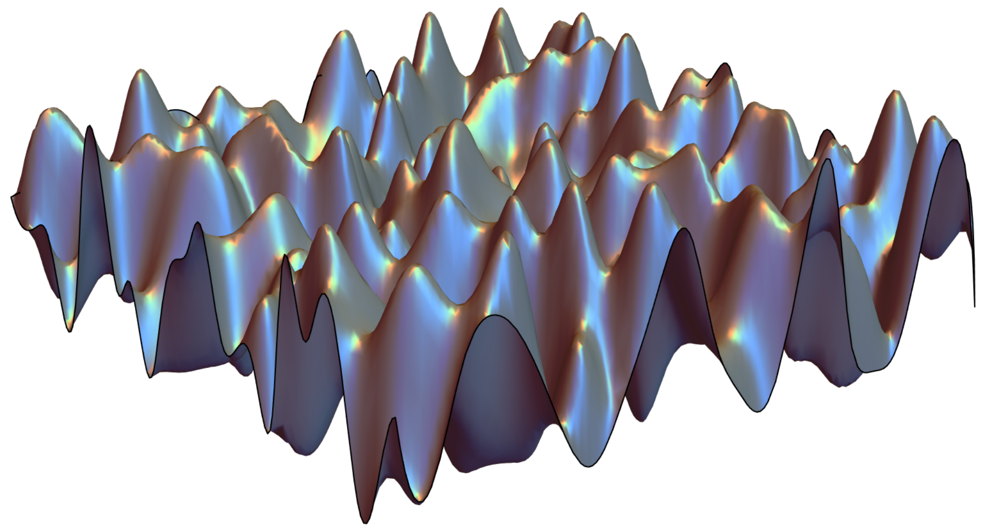




NASA, ESA, and A. Feild (STScI)

STScI-PRC12-25a





Mass:

$$M \sim 10^{-14} \left(\frac{10^{13}\,\mathrm{Mpc}^{-1}}{k} \right)^2 M_\odot$$

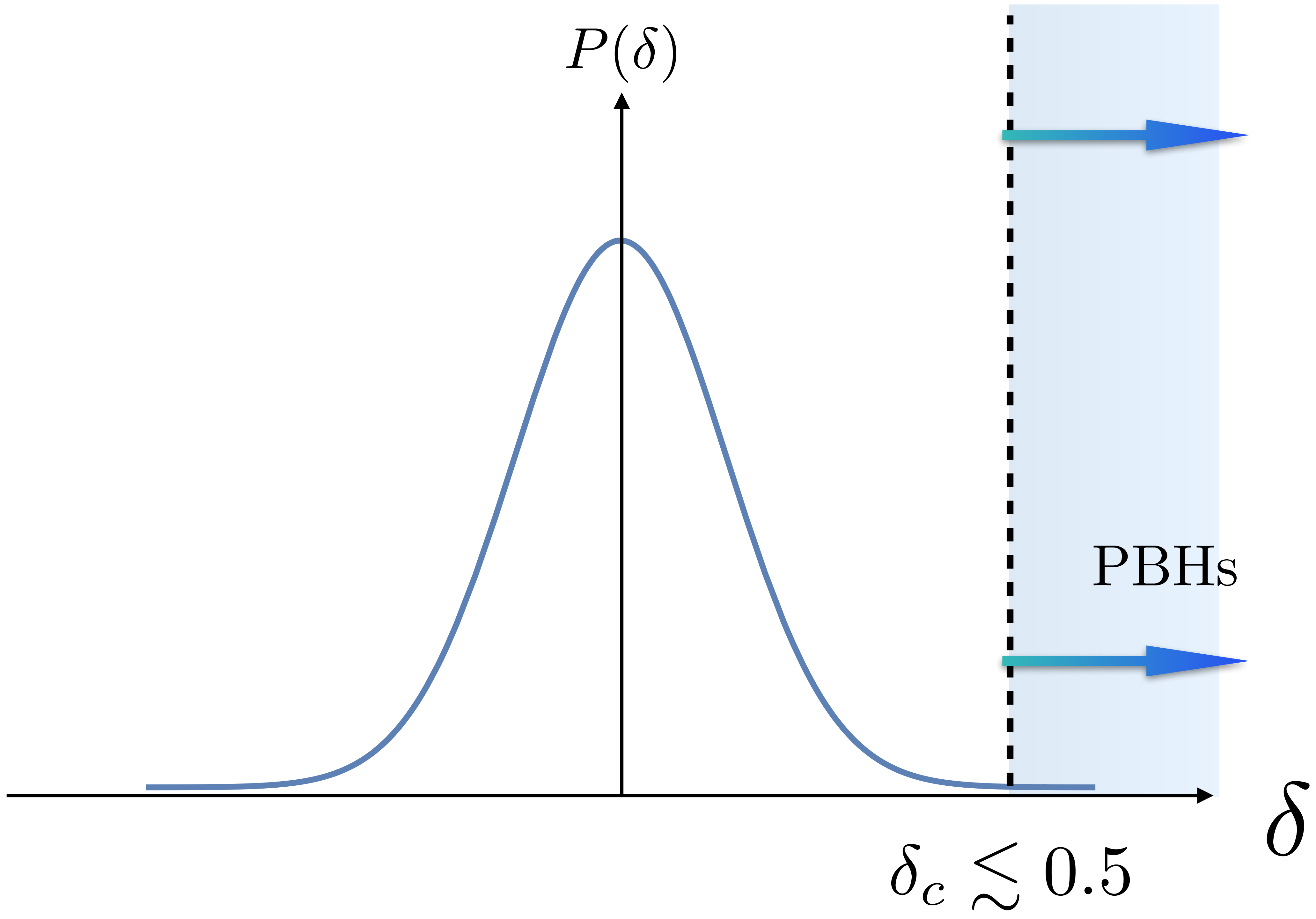
$$N_e \simeq 18 - \frac{1}{2} \log \frac{M}{M_\odot}$$

(for PBHs formed during radiation domination)

Abundance (naive Gaussian estimate):

$$f_{\mathrm{PBH}} = \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \propto \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma^2} \right) d\delta$$

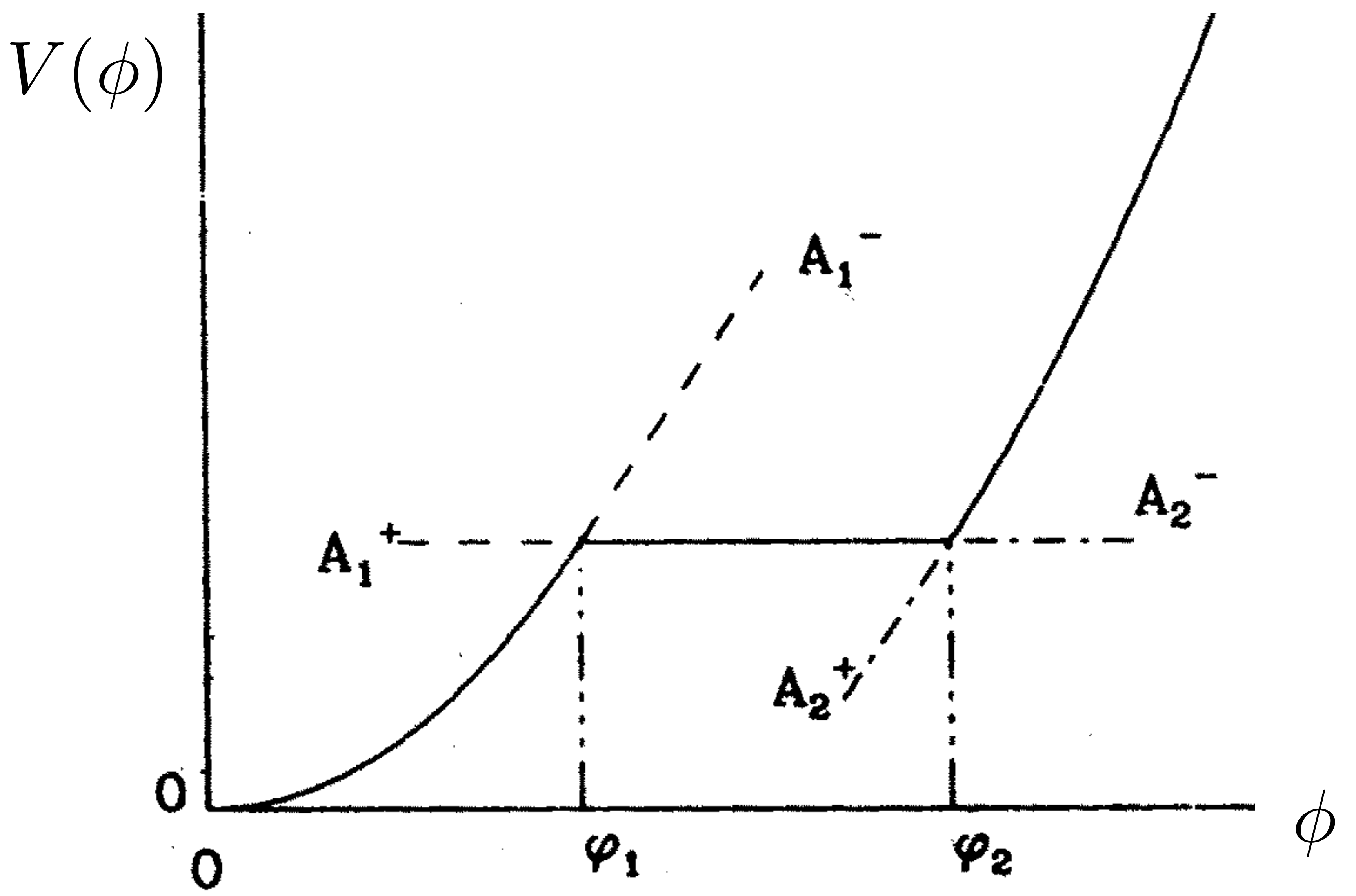
$$\sigma \sim \mathcal{P}_{\mathcal{R}} \sim 10^{-2} \quad \Longrightarrow \quad \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \sim 1$$



$$\mathcal{P}_{\mathcal{R}} \sim \left(\frac{H}{m_P}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 \sim \frac{1}{m_P^2}\left(\frac{V}{V'}\right)^2 \frac{V}{m_P^4}$$

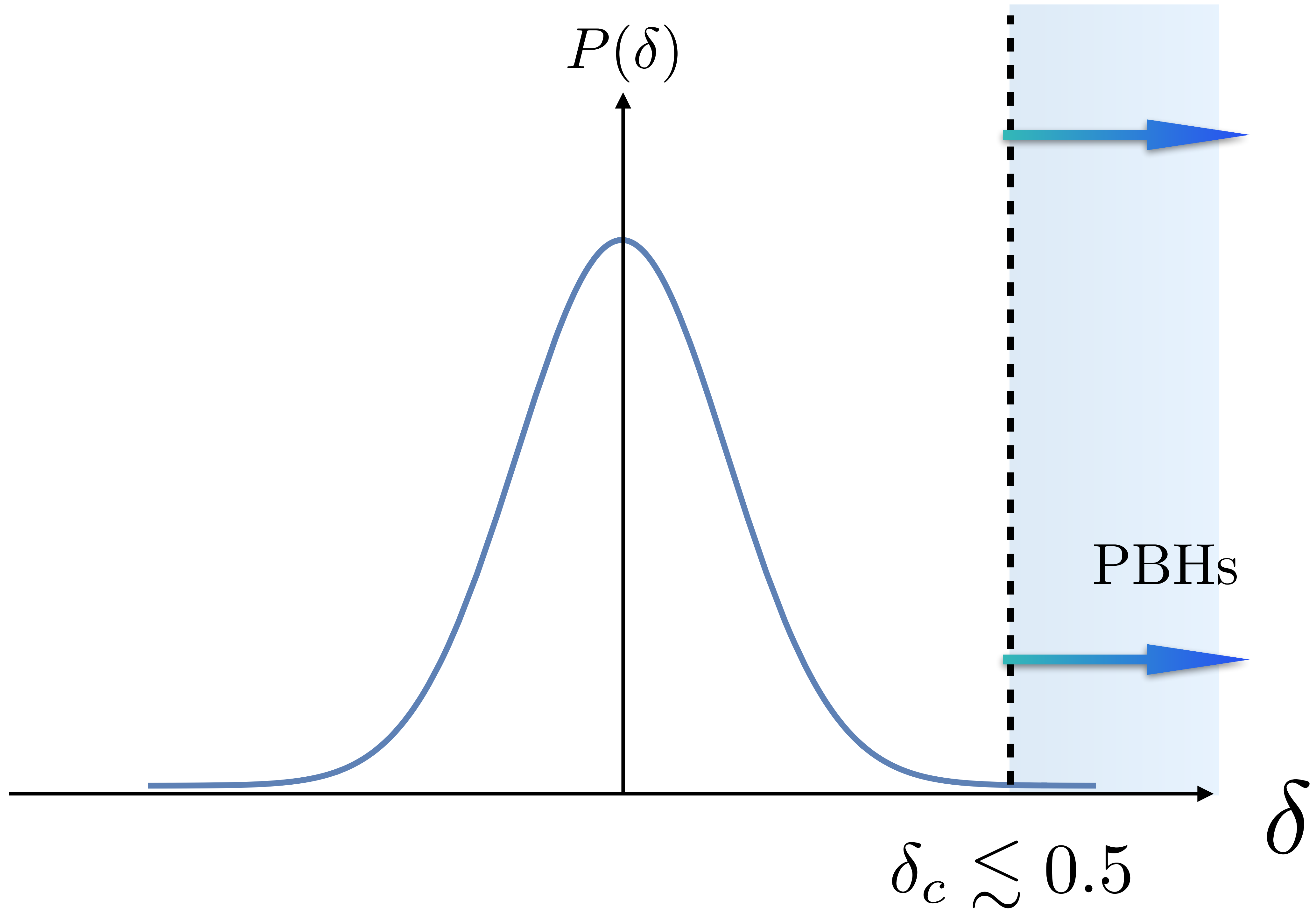
Inflation and primordial black holes as dark matter

Ivanov, Naselsky, Novikov. 1994



$$V(\phi) = \begin{cases} V_0 + A_+(\phi - \phi_0) & \text{for } \phi > \phi_0 \\ V_0 + A_-(\phi - \phi_0) & \text{for } \phi < \phi_0 \end{cases}$$

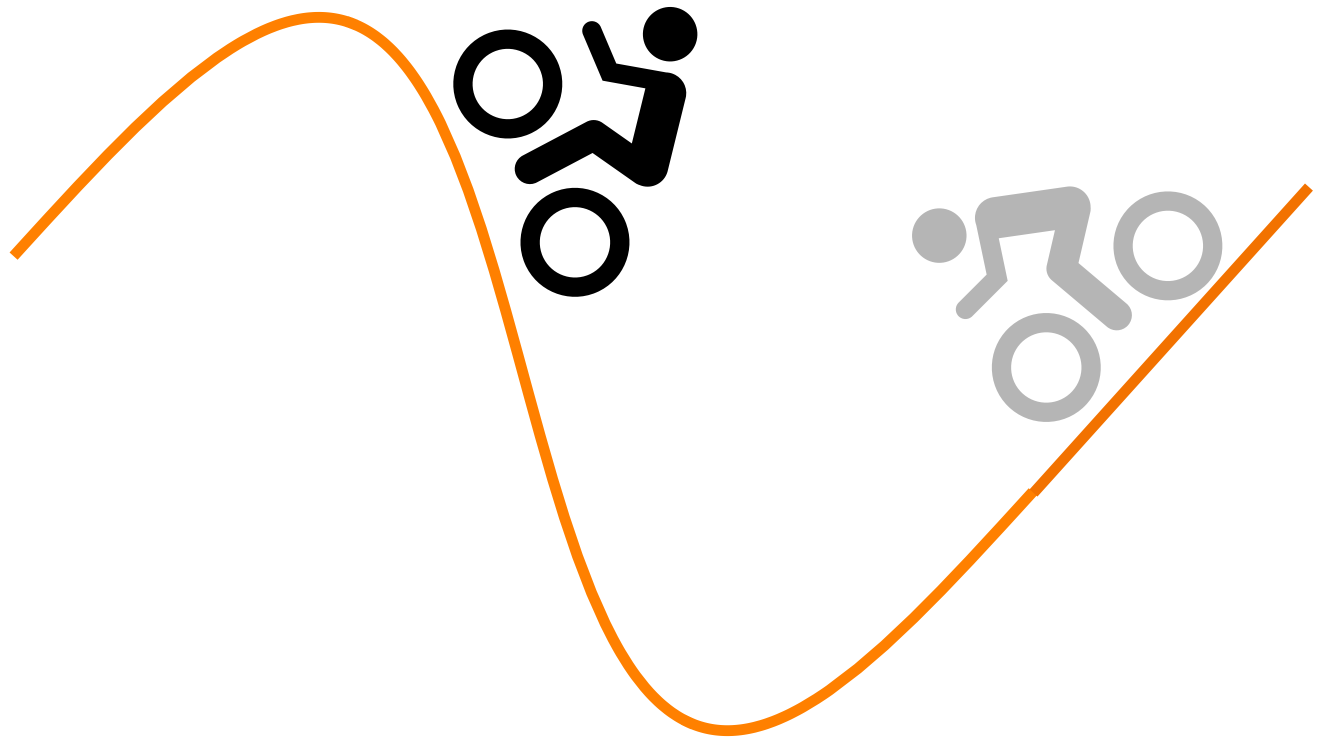
Starobinsky 1994



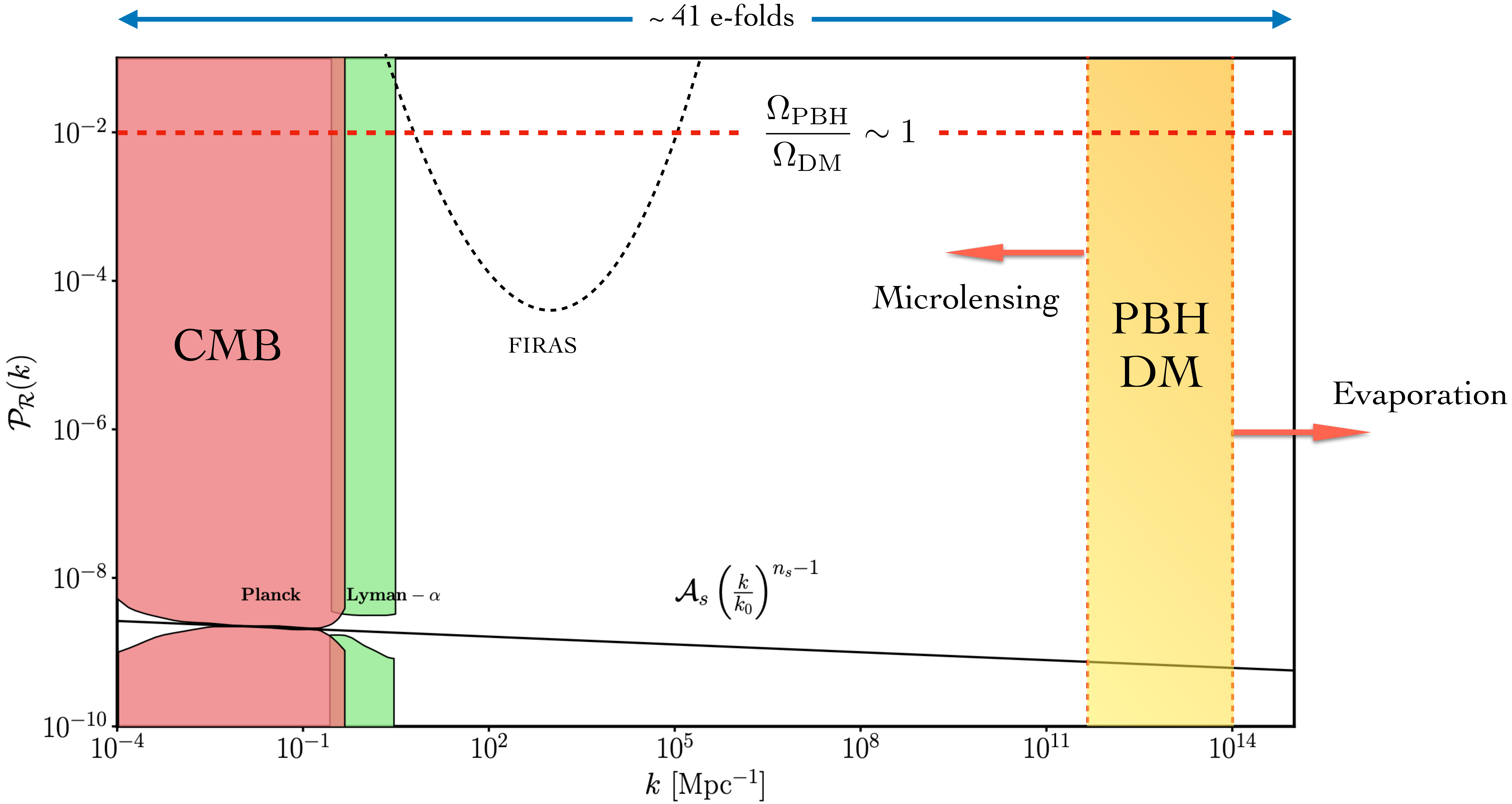
$$\mathcal{P}_\mathcal{R} \sim \left(\frac{H}{m_P}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 \sim \frac{1}{m_P^2}\left(\frac{V}{V'}\right)^2 \frac{V}{m_P^4}$$

Ultra Slow-Roll (USR)

$$\ddot{\phi} + 3H\dot{\phi} \simeq 0$$

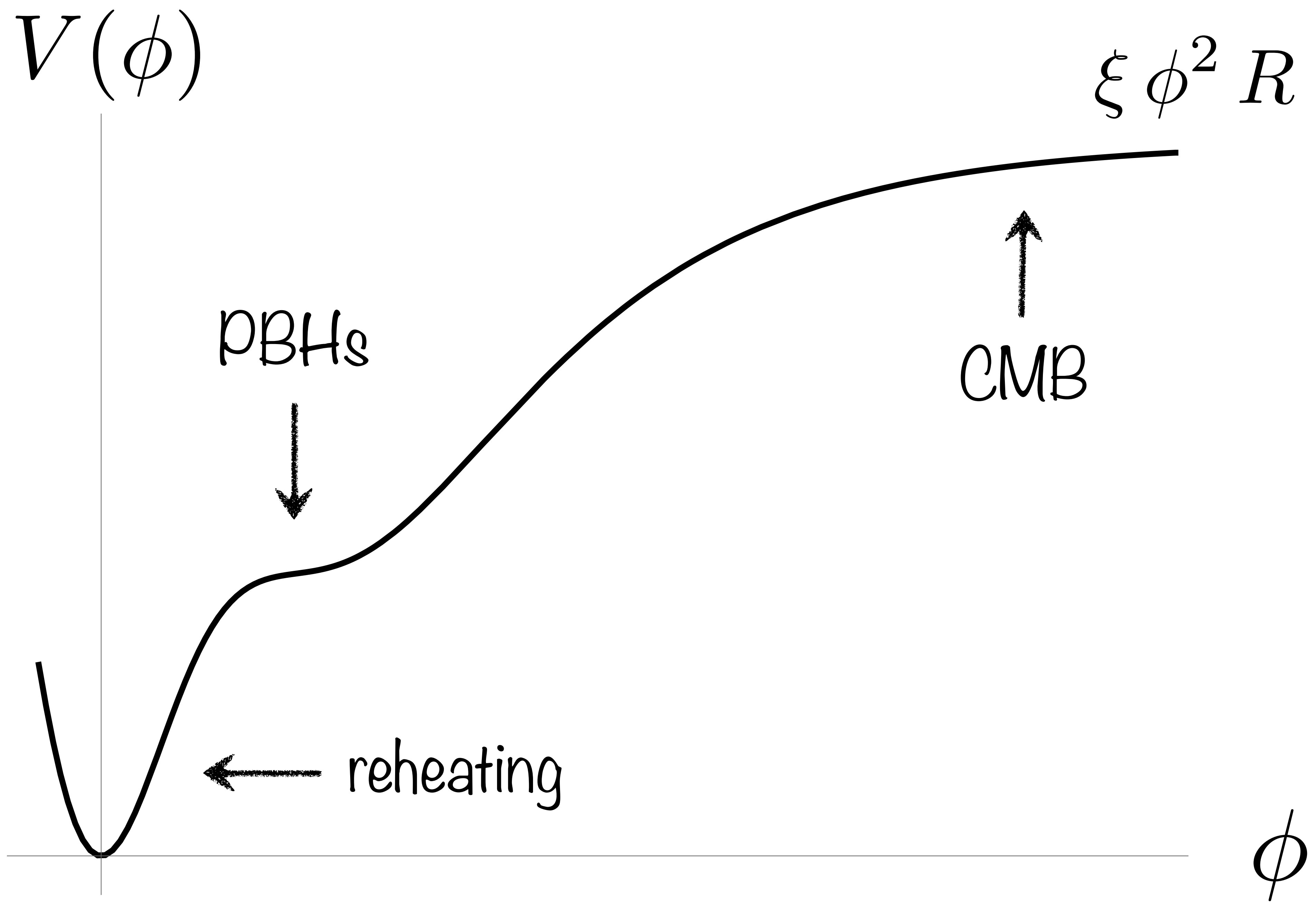


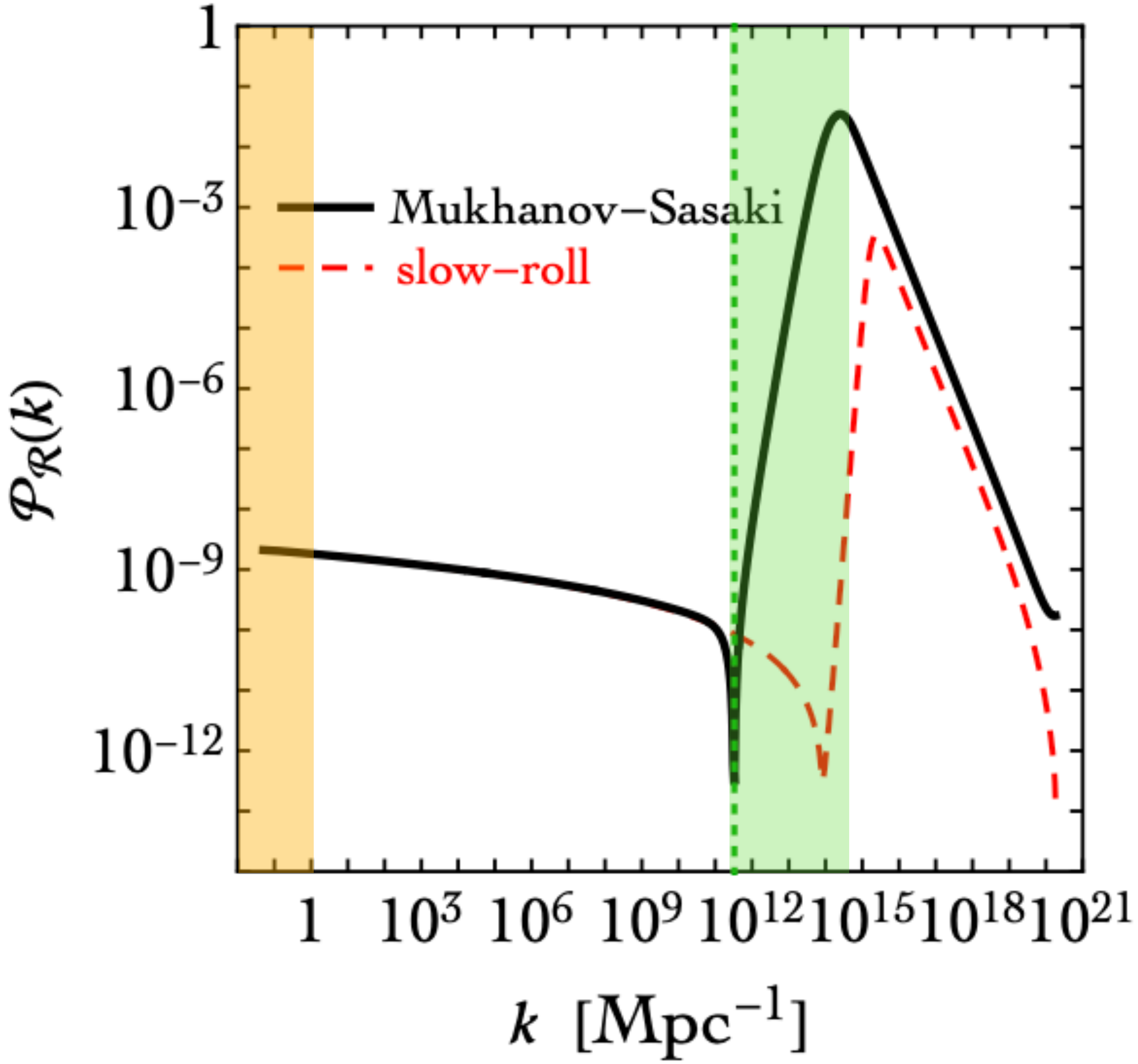
$$\eta \sim \frac{\ddot{\phi}}{\dot{\phi}\,H} \sim -3$$



Franco-Abellán, EUCAPT symposium 2023 (modified)

+ enough inflation & successful reheating





$$V = \sum_{n=2}^{4+\epsilon\,\mathcal{O}(5)} a_n \phi^n$$

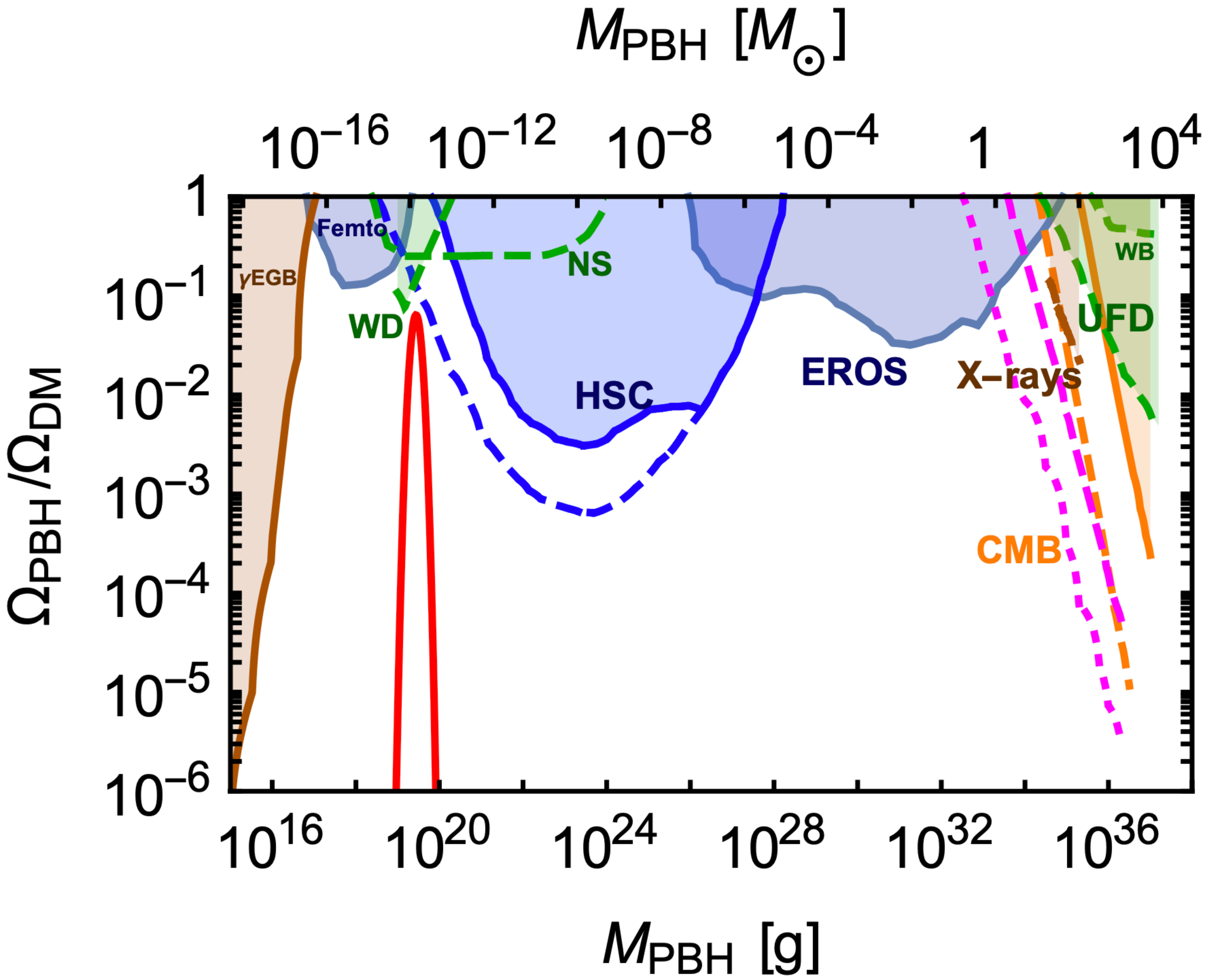
$$\frac{V(\phi)}{\phi^4} = \lambda(\phi_0) + \frac{1}{2}\beta_\lambda(\phi_0)\log\frac{\phi^2}{\phi_0^2} + \frac{1}{8}\beta'_\lambda(\phi_0)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2 + \cdots$$

GB, Taoso 2017

GB, Rey, Taoso, Urbano 2020

- Enough inflation
- Agreement with the CMB (n_s within 3σ)
- $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 1$ (Gaussian, RD)

$$\boxed{10^{-16} M_\odot \longleftrightarrow 10^{-12} M_\odot}$$



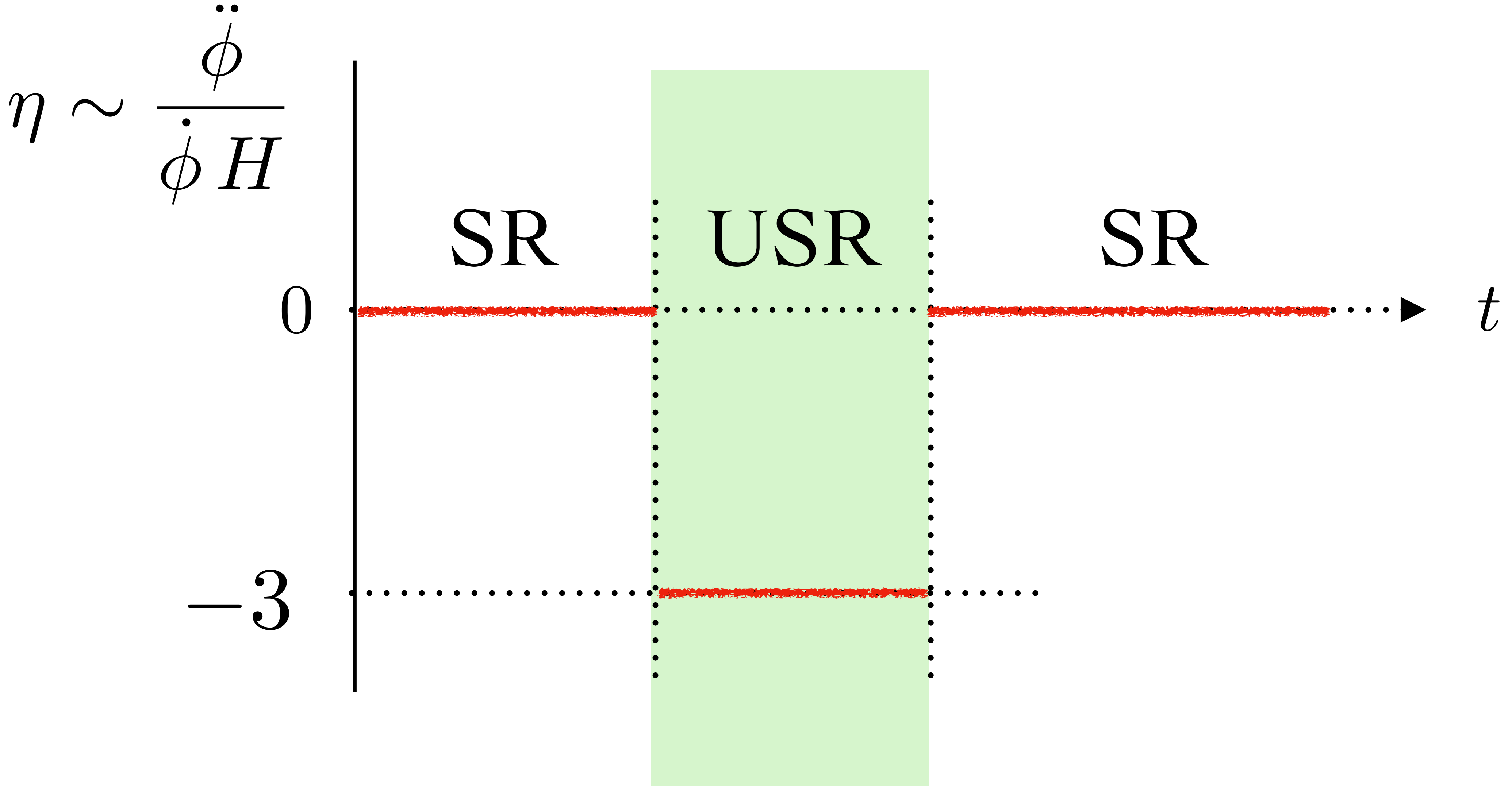
GB, Taoso 2017

Breakdown of perturbation theory in USR inflation?

Claim: *a large enough tree-level primordial spectrum for PBH DM implies perturbation theory breaks at CMB scales.*

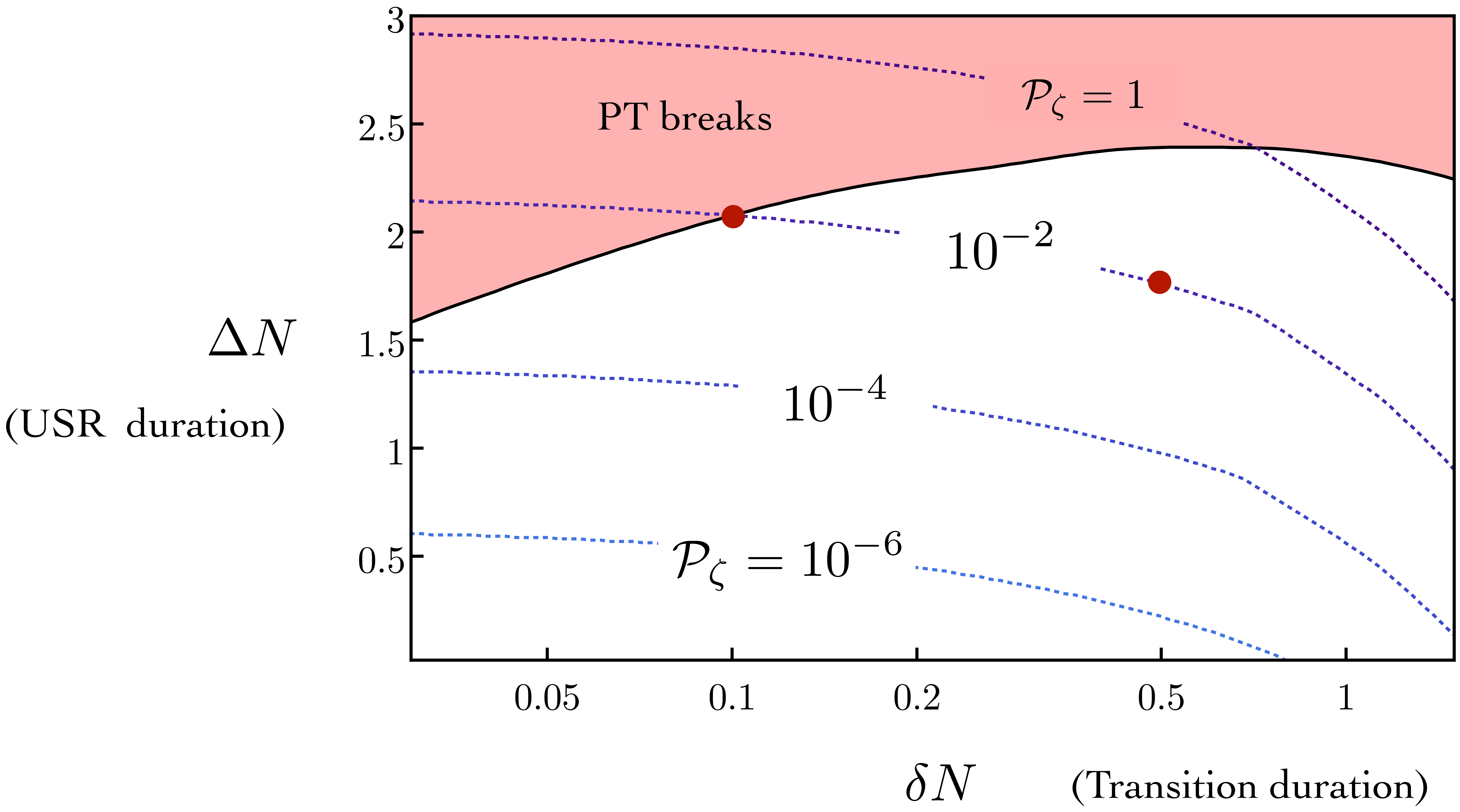
Kristiano and Yokoyama, 2022 & 2023

Toy model: SR –> USR –> SR (with sharp transitions)



$$\mathcal{P}_\zeta \ll \frac{1}{(\Delta\eta)^2} \simeq 0.03$$

(for perturbation theory to hold)



GB, Gambín Egea 2024

Other mechanisms to form PBH

- Single-field inflation other than USR
- Transient Dissipation during inflation

✳ Single-field inflation other than USR

$$\mathcal{S} = \int d^4x\, M\, \frac{a^3\epsilon}{c_s^2}\left(\dot{\mathcal{R}}^2 - \frac{c_s^2}{a^2}|\nabla\mathcal{R}|^2\right) \qquad \mathcal{R} \simeq C_1 + C_2 \int \frac{c_s^2}{a^3\, M^2\, \epsilon\, H} dN$$

Rate of change of ϵ

$$\frac{d\mathcal{R}}{dN} \propto \exp\left[-\int (3 + \epsilon - 2\eta - 2s + \mu)\right] dN$$

Rate of change of c_s

Rate of change of M

GB, Beltrán Jiménez, Pieroni. 2018
GB, Céspedes, Santoni. 2021

✳ (Transient) Dissipation during inflation

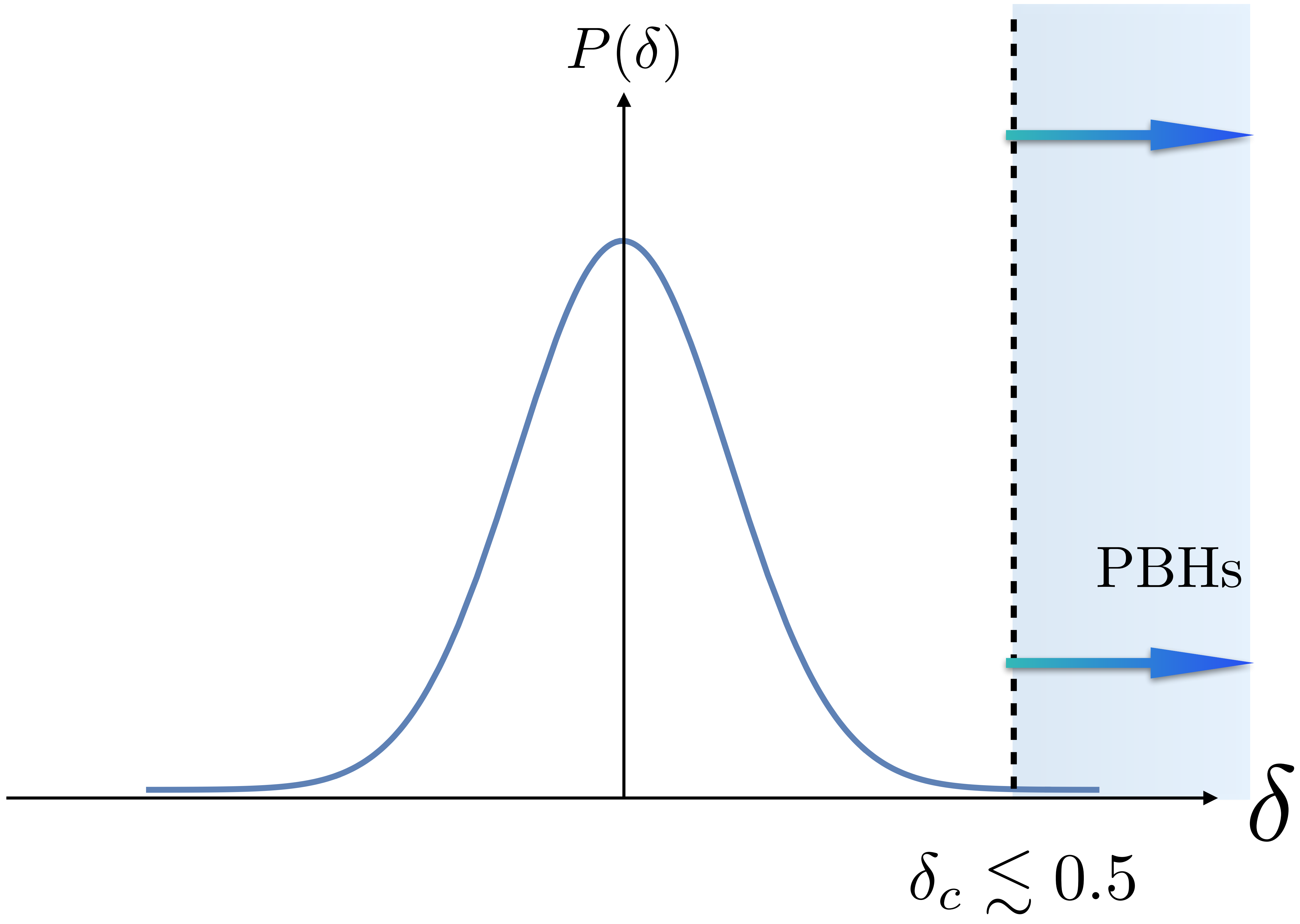
Background: $\ddot{\phi} + (3H + \boldsymbol{\Gamma})\dot{\phi} + V' = 0$

Fluctuations (schematically): $\delta\ddot{\phi}_{\boldsymbol{k}} + (3H + \Gamma)\delta\dot{\phi}_{\boldsymbol{k}} + \left(\frac{k^2}{a^2} + \dot{\phi}\,\Gamma_\phi\right)\delta\phi_{\boldsymbol{k}} \propto \sqrt{\frac{2\Gamma T}{a^3}}\,\xi_{\boldsymbol{k}}(t)$

(Stochastic thermal noise)

GB, García-García, Pérez Rodríguez, Pierre, Rey, 2022

The problem of the abundance



$$\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \int_{\delta_c}^{\infty} f(\delta)\, d\delta$$

How does the tail of the PDF look like?

- The relation between ζ and δ is non-linear

- ζ is, in general, intrinsically non-gaussian

- The abundance may require more than an integral

$$f(\delta) \sim \exp\left(-\frac{\zeta}{2\,\mathcal{P}_\zeta} + \frac{\langle\zeta\zeta\zeta\rangle}{{\mathcal{P}_\zeta}^3}\zeta^3 + \dots\right)$$ Small corrections for small ζ

Several indications of non-gaussian tails, for large ζ

Non-linear saddle point for $\dot{\zeta}^4$ Celoria, Creminelli, Tambalo, Yingcharoenrat 2021

USR {

- Stochastic inflation, numerically Figueroa, Raatikainen, Rasanen, Tomberg 2020
- Stochastic δN formalism Pattison, Vennin, Wands, Assadullahi 2021

$$\frac{\dot{\phi}}{H} \gg \frac{H}{2\pi} \longrightarrow \mathcal{P}_\zeta \ll 1$$ Quantum diffusion?

Non-Gaussian tails in the PDF of curvature perturbations arise
in USR inflation without invoking stochastic inflation.

GB, Konstandin, Pérez Rodríguez, Pierre, Rey 2024

Gravitational wave signatures of PBH DM

- Second order induced gravitational waves
- Gravitational wave emission from PBH mergers

✴ Second-order induced gravitational waves

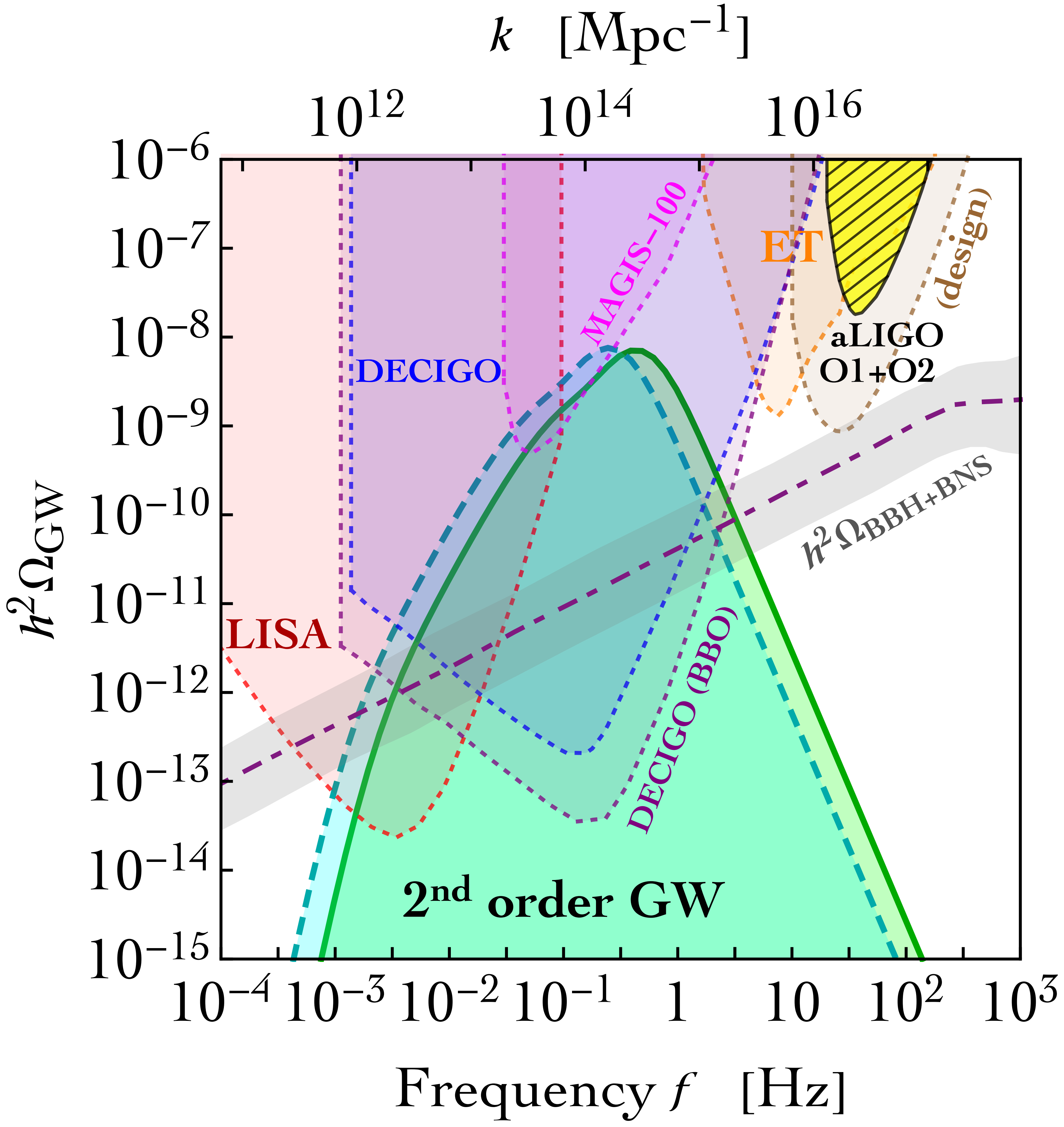
$$h''_{ij} + 2\frac{H\,'}{h\ _{ij}} - \nabla^2 h_{ij} = S_{ij} \sim \partial_i\mathcal{R}\,\partial_j\mathcal{R} \qquad \Longrightarrow \qquad \Omega_{\rm GW} \sim \mathcal{P}_h \sim (\mathcal{P}_\mathcal{R})^2$$

$$\left(\frac{M_{\rm PBH}}{10^{17}\,{\rm g}}\right)^{-1/2} \simeq \frac{k}{2\cdot 10^{14}\,{\rm Mpc}^{-1}} \simeq \frac{f}{0.3\,{\rm Hz}}$$

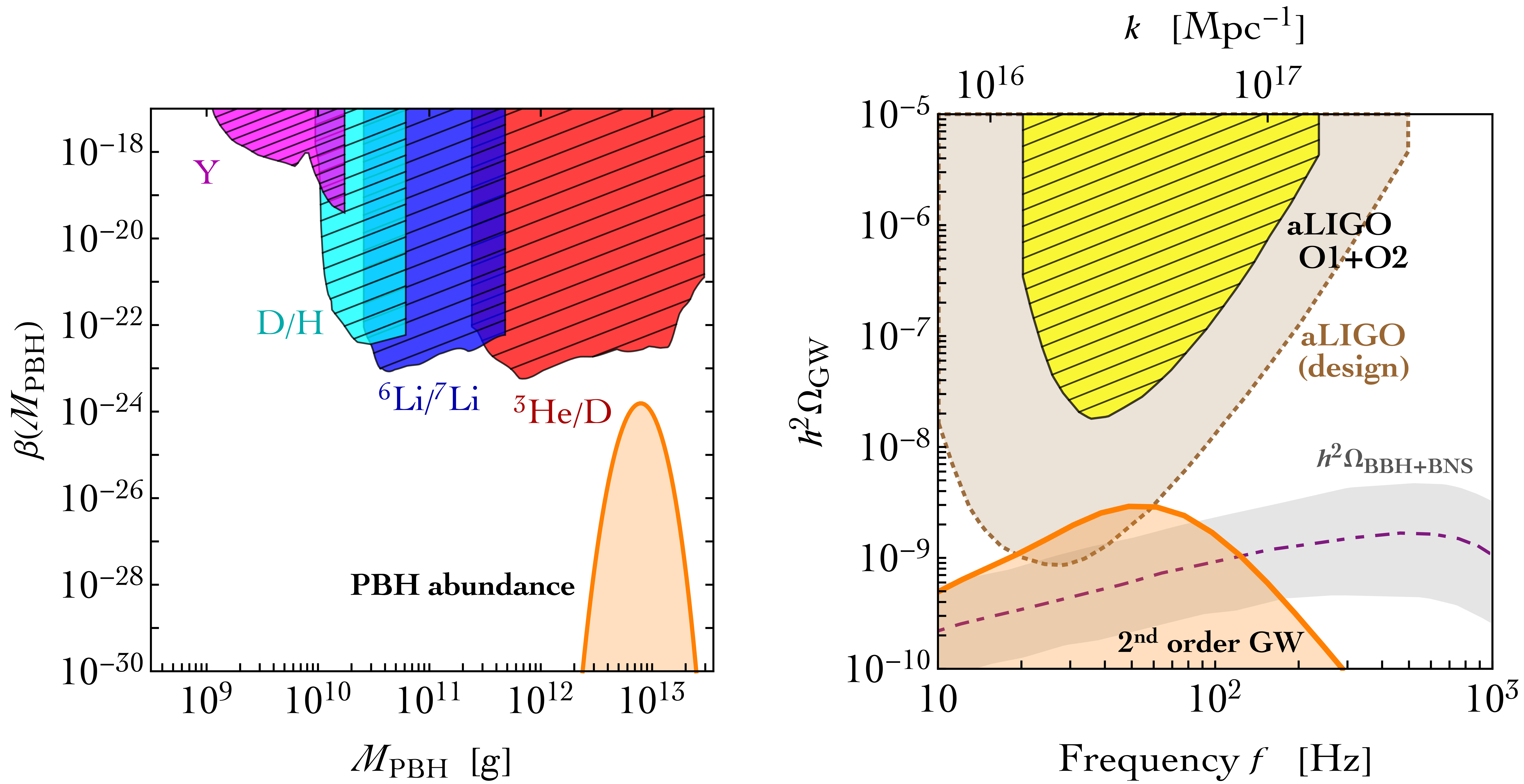
* LISA: for PBH DM

* LIGO/Virgo/KAGRA: if PBHs already evaporated

* PTA: if PBHs of ~ 0.1 Solar masses

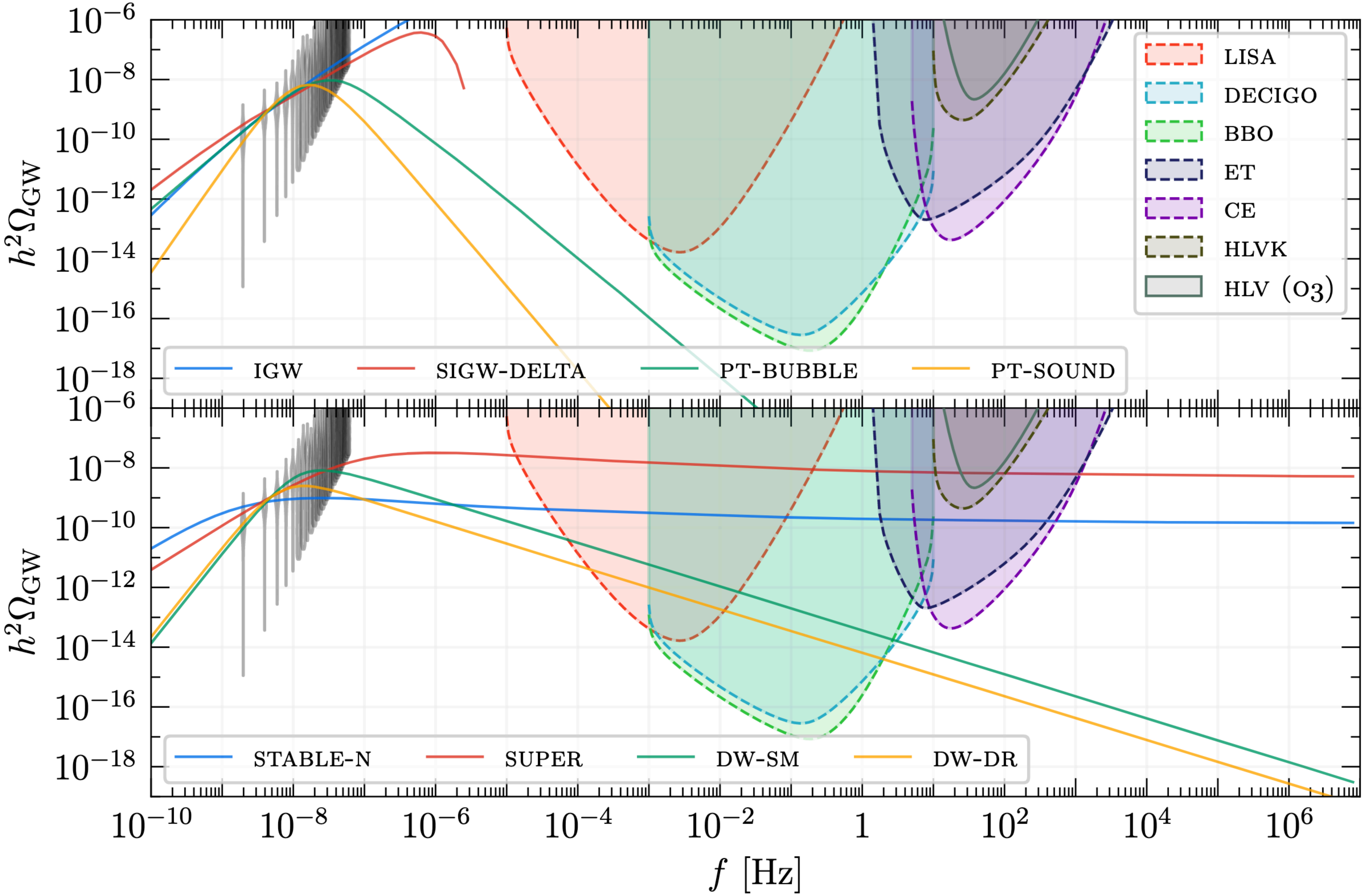


✴ Second-order induced gravitational waves



GB, Rey, Taoso, Urbano, 2020

✴ Second-order induced gravitational waves



PTA

~ NHz $\sim 10 M_\odot$

NANOGRAV, 2023

✳ High frequency GW from PBH DM mergers

No known astrophysical sources at GHz

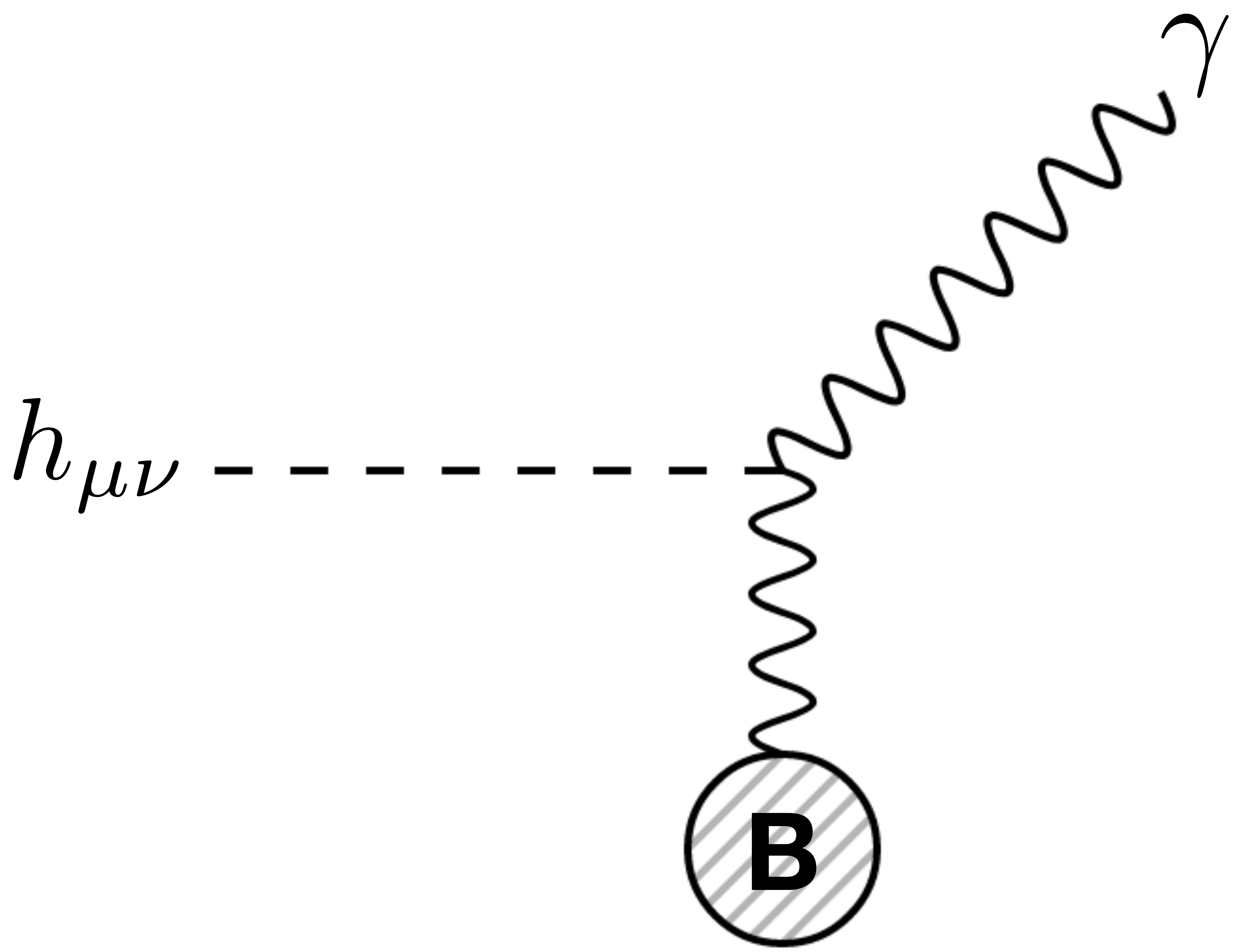
Asteroid mass PBH mergers. GW frequency $\gtrsim$ GHz

Small characteristic strain $\sim 10^{-25}$

- Very strong clustering
- Enhanced local DM density for ~ 10 Kpc

✳ High frequency GW from PBH DM mergers

Inverse Gertsenshtein effect. Connection with axion physics



ALPS II. DESY / Heiner Müller-Elsner

Summary

- Asteroid-mass PBHs are a strong contender to explain the DM.
- PBH from inflation. Interesting for phenomenology and theory playground
- GW: indirect probes of PBH DM. Technical challenges.
- Goal: detect subsolar BH with lensing, GW interferometry, etc.