Evaporating Primordial Black Holes:

Reformation and Isocurvature Perturbations

THK, Philip Lu, arXiv:2411.07469 (accepted to PLB)

THK, Jinn-Ouk Gong, Donghui Jeong, Dong-Won Jung, Yeong Gyun Kim, and Kang Young Lee, arXiv:2503.14581

Speaker: TaeHun Kim (School of Physics, KIAS, Korea)

Abstract

- Light mass primordial black holes (PBHs) with $M \lesssim 10^9\ \mathrm{g}$ all evaporated before Big Bang Nucleosynthesis (BBN) and hence not constrained.
- Their impact on cosmology :
  - If they have dominated the Universe, they can undergo a **reformation** process and form much heavier PBHs which survives much longer (arXiv:2411.07469).
  - If they remained subdominant, they induce **isocurvature perturbations** at evaporation and can be constrained by CMB observations (arXiv:2503.14581).

Outline

- Introduction: PBHs
- PBH reformation (arXiv:2411.07469)
  - Cosmic timeline of eMD by PBHs / PBH reformation / Gravitational wave signals
- Isocurvature perturbations from evaporating PBHs (arXiv:2503.14581)
  - PBHs as an isocurvature source / Isocurvature constraints on PBH
- Summary & Conclusion

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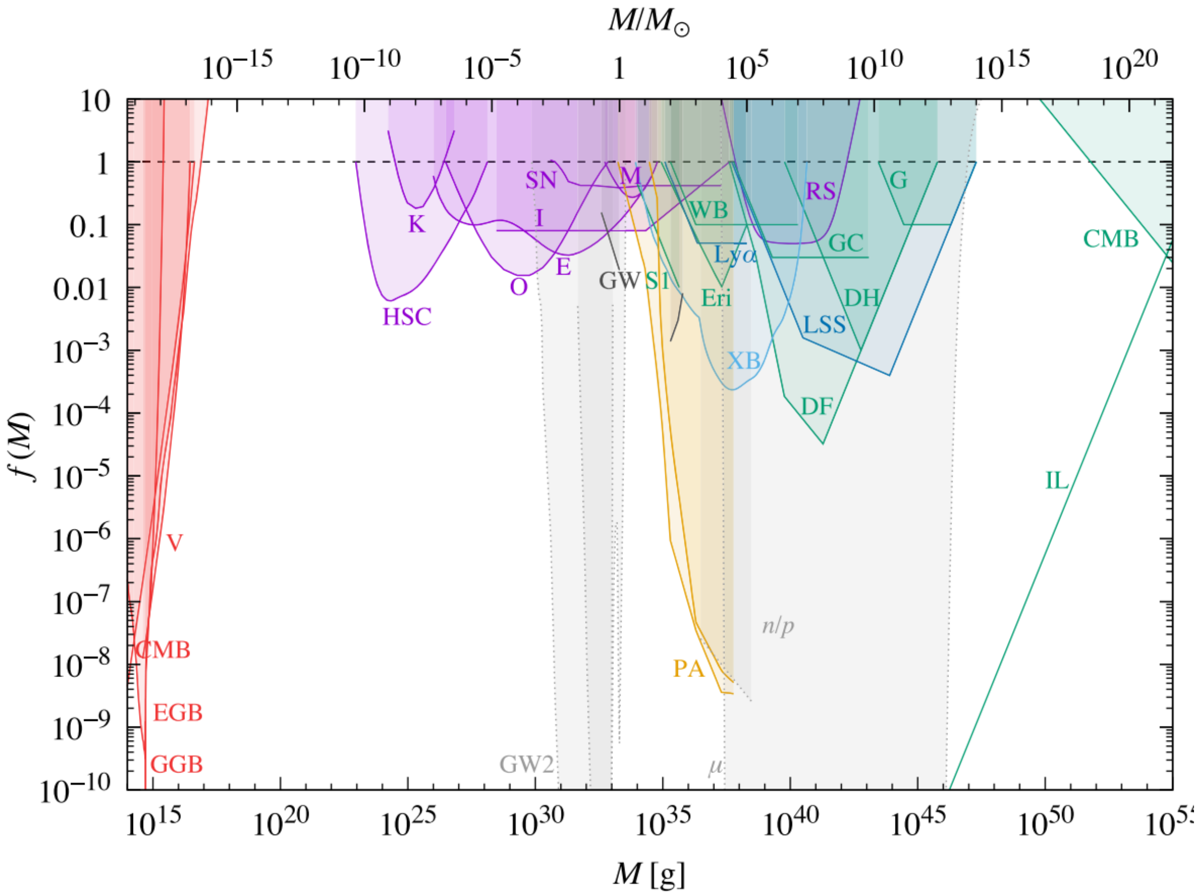
Introduction

- $1\,M_\odot \sim 10^{33}$ g

Carr et. al. (2021)

- PBHs: Black holes formed in the early Universe. Inflation, FOPTs, …



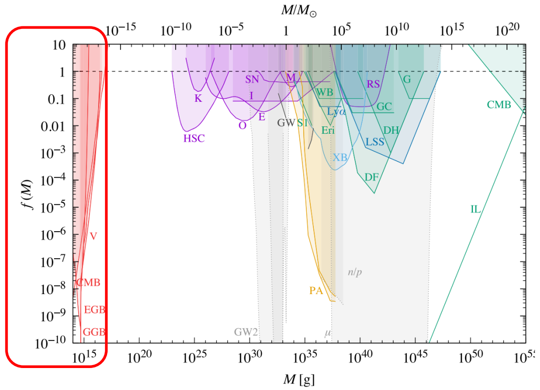
- Constraints
  - Evaporation
  - Lensing
  - Gravitational waves
  - CMB
  - Dynamical
- Candidates of
  - Dark matter
  - Microlensing event
  - Binary black hole mergers

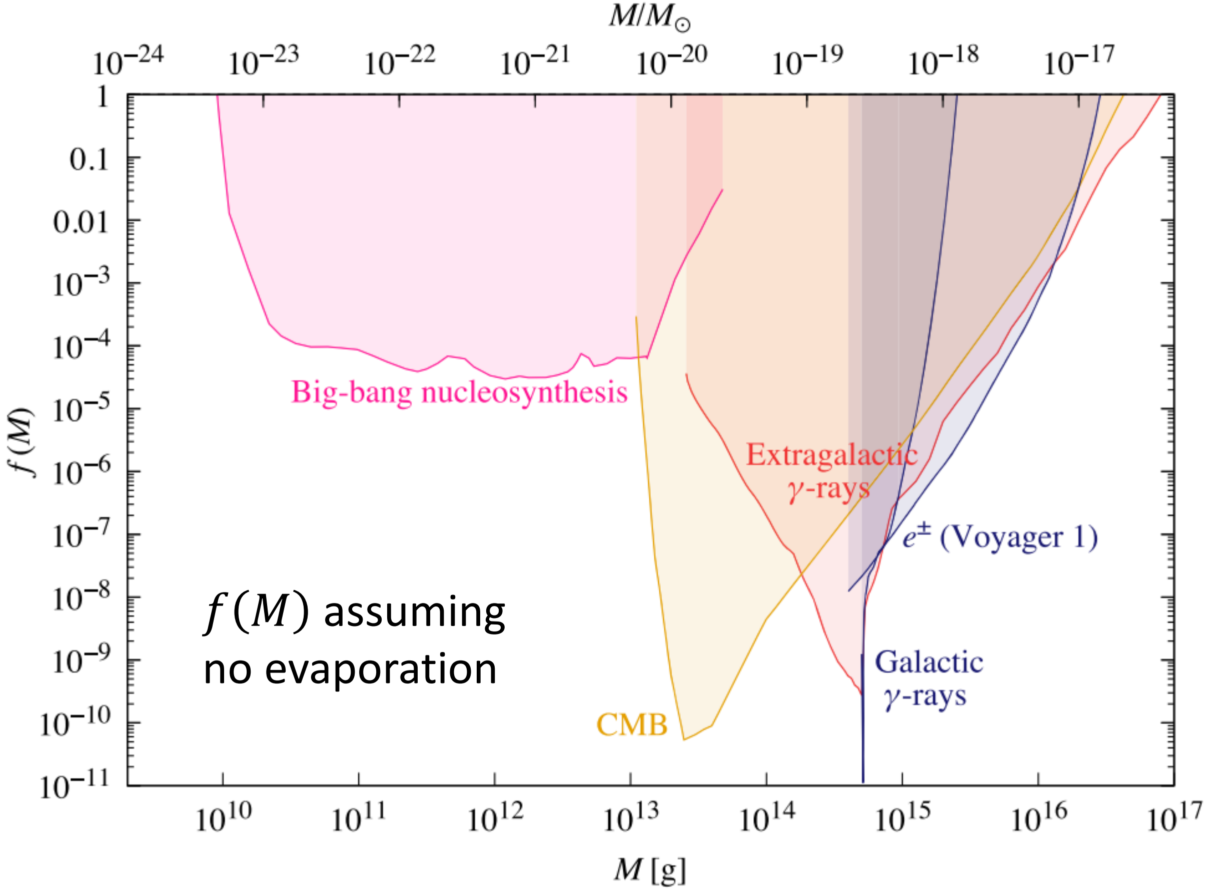
Introduction

- $1\,M_\odot \sim 10^{33}$ g

Carr et. al. (2021)

- Below $\sim 10^{15}$ g





- $M \sim 10^{14}$g evaporates now
- $M \sim 10^{9}$g evaporates at BBN
  - Light element abundances
- **$M \lesssim 10^{9}$g: no constraints**

  → We see their impact on cosmology depending on their dominance.

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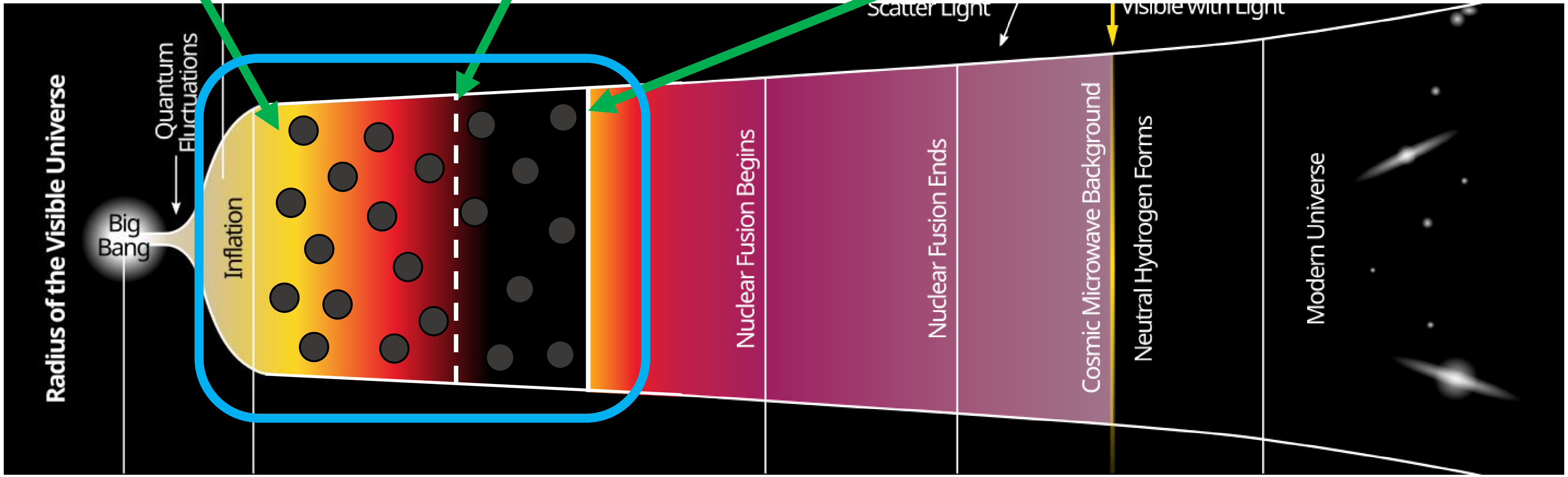
Cosmic timeline of eMD by PBHs

= PBHs

Copious production of PBHs

eMD starts:
$\rho_{\rm PBH} \propto 1/a^3$
$\rho_r \propto 1/a^4$

Reheating by PBH evaporation:
Standard timeline resumes



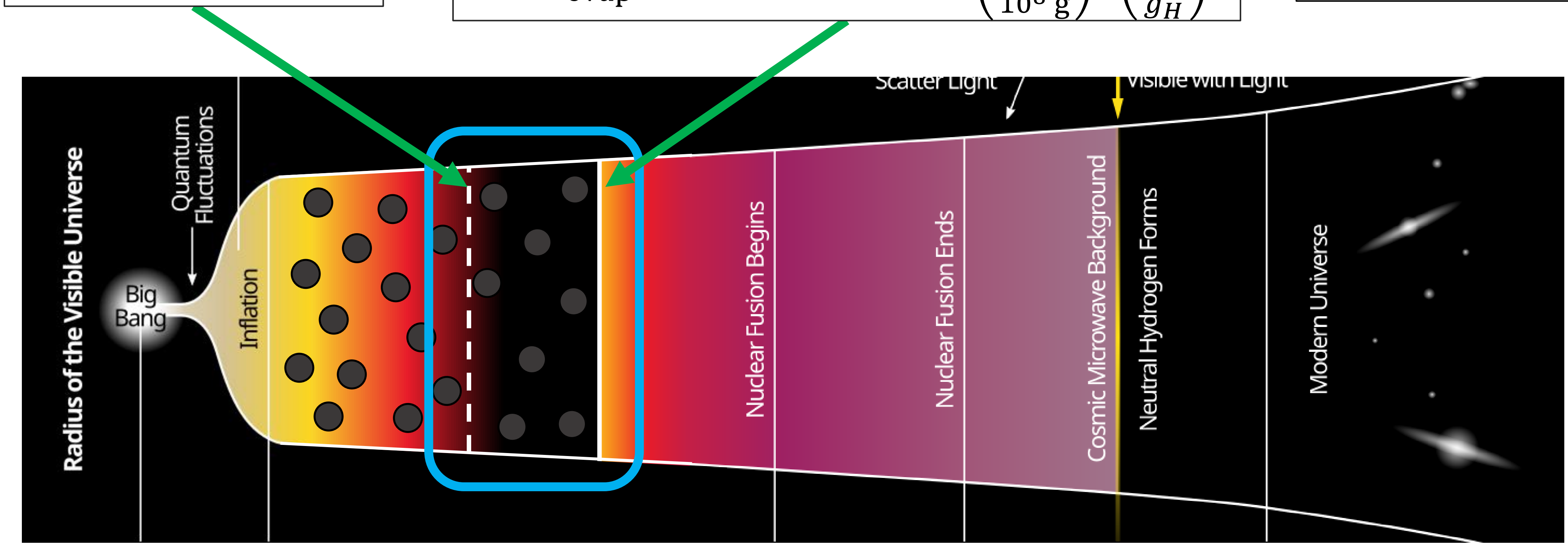
Cosmic timeline of eMD by PBHs

- $\beta_{\rm if}$: Initial PBH energy fraction
- $M_{\rm PBH}$: Initial PBH mass

Onset: $a_{\rm eq} = a_{\rm if}/\beta_{\rm if}$

End: $\tau_{\rm evap} = 4.0 \times 10^{-4}\ {\rm sec} \times \left(\frac{M_{\rm PBH}}{10^8\ {\rm g}}\right)^3 \left(\frac{108}{g_H}\right)$

"$a_{\rm evap}/a_{\rm eq} \gg 1$ → eMD"



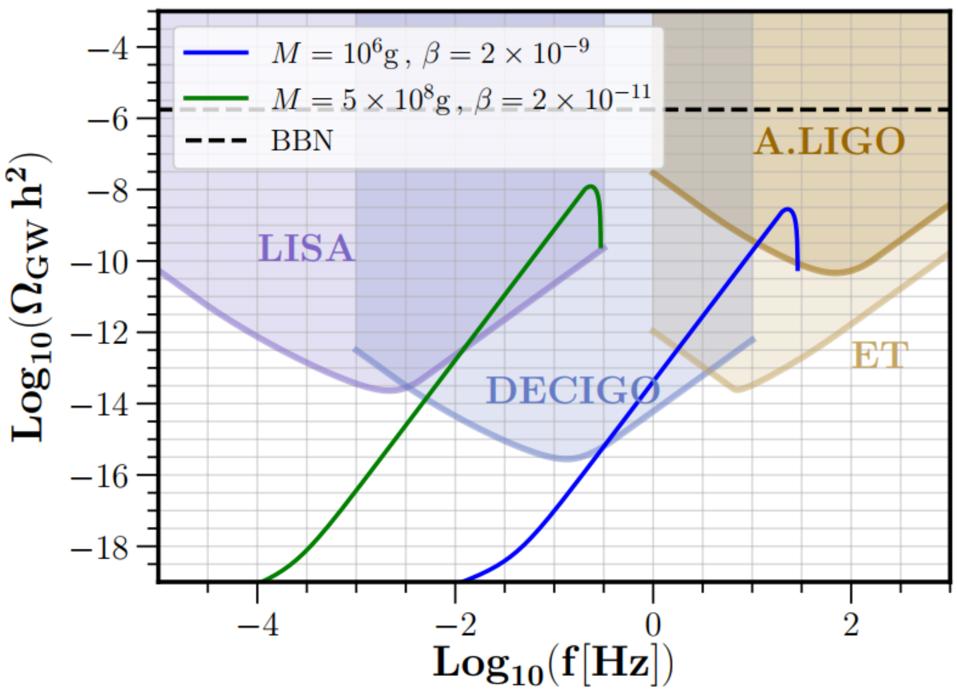
Cosmic timeline of eMD by PBHs

Inomata et. al. (2021)
Domenech et. al. (2021)
…

- Stochastic GW emission at the reheating
  - Oscillating gravitational potential

    → scalar-induced GW

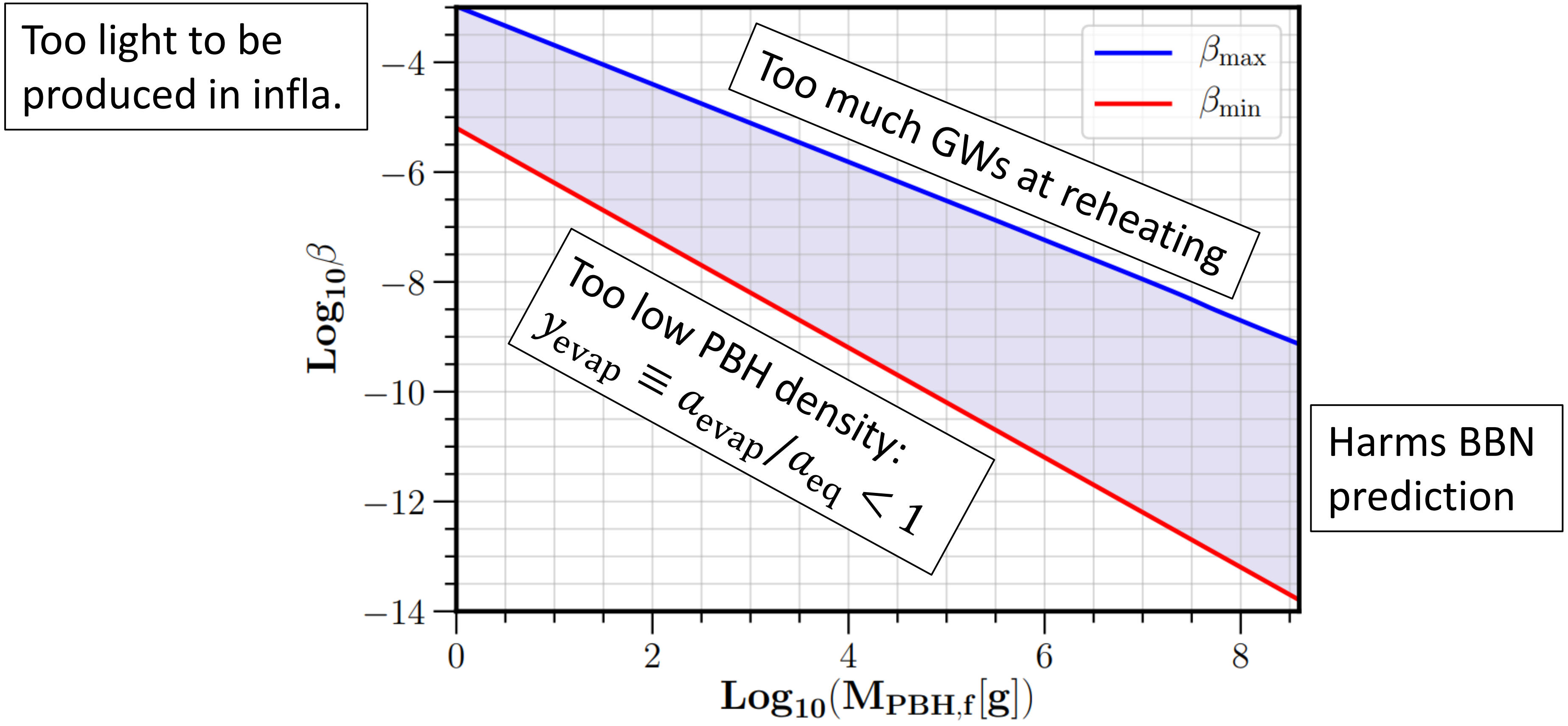
- This free streaming energy density is constrained by $\Delta N_{\rm eff} \lesssim 0.5$ at CMB



Cosmic timeline of eMD by PBHs

Domenech et. al. (2021)

- Allowed region of $(M_{\rm PBH}, \beta_{\rm if})$ for PBH eMD



PBH reformation during eMD

- PBH reformation
  - PBH "gas" can gravitationally collapse and produce much heavier PBHs
- This can happen during eMD, because
  - Gravitational collapse of overdensities is easier in MD then RD
  - Matter density perturbation grows during MD

PBH reformation during eMD

Khlopov, Polnarev (1980)
Polnarev, Khlopov (1981)
Harada et. al. (2016)
Harada et. al. (2017)
Kokubu et. al. (2018)

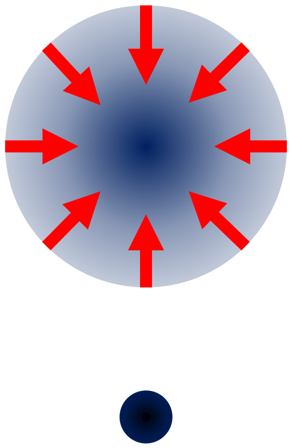
- Gravitational collapse in MD
  - No pressure : Eventually any overdensity will collapse
  - But what really happens during the collapse?
  - Spatial profile of an overdensity should be homogeneous and isotropic enough
    - The entire overdensity should successfully fall into its own Schwarzschild radius during the collapse

$\sigma \ll 1$: size of overdensity at horizon scale

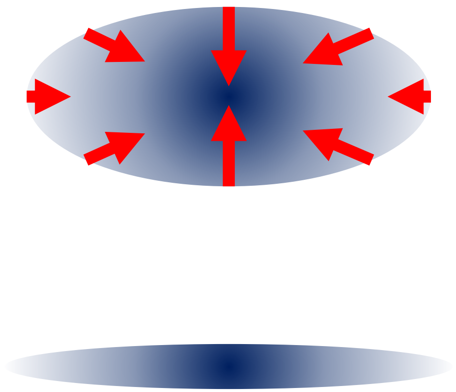
PBH reformation during eMD

Before

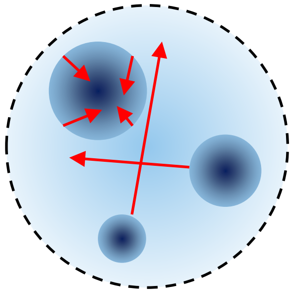
After



BH formation



"Pancake" collapse → virialized configuration



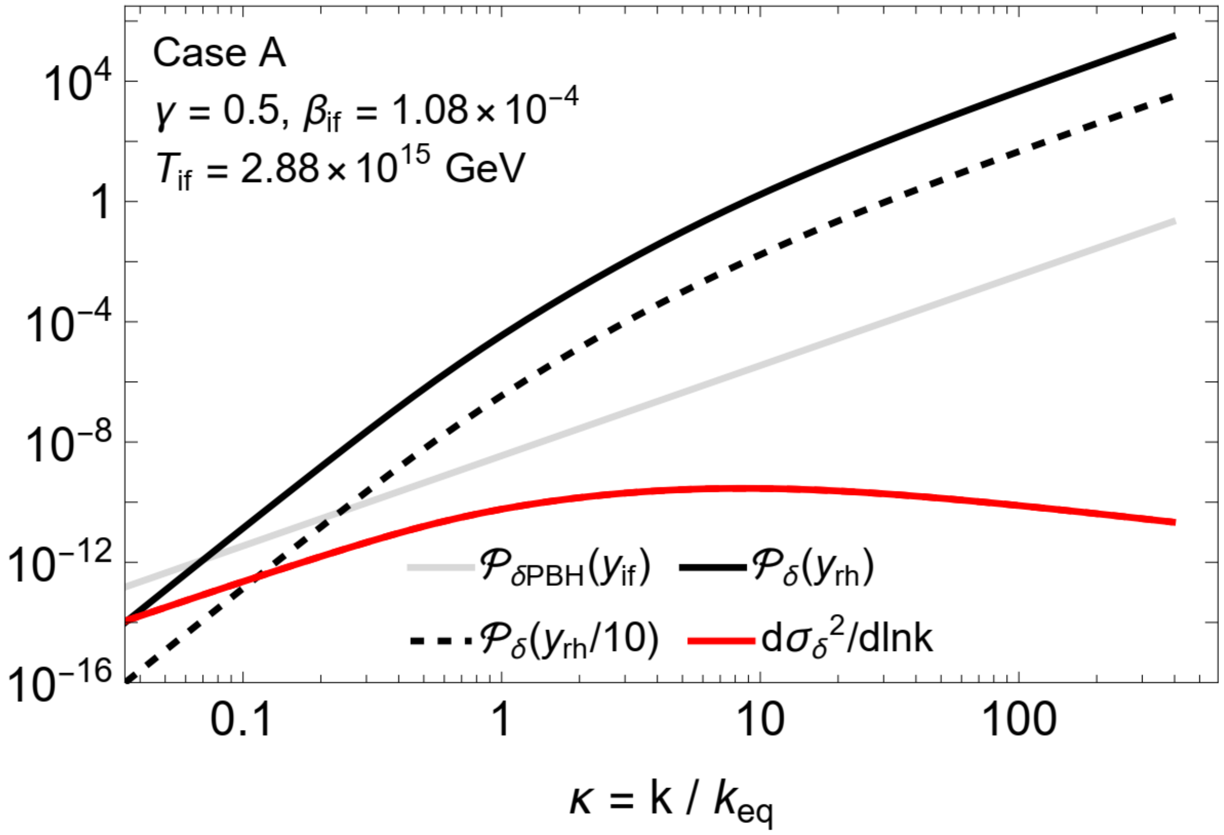
??? (not well known)

- Naked singularity
- Virialized
- Becomes radiation and stop by pressure
- ...

- Estimation of collapse probability : $\beta \simeq 0.05556 \times \sigma^5$
  - Only power-law suppressed.

PBH reformation during eMD

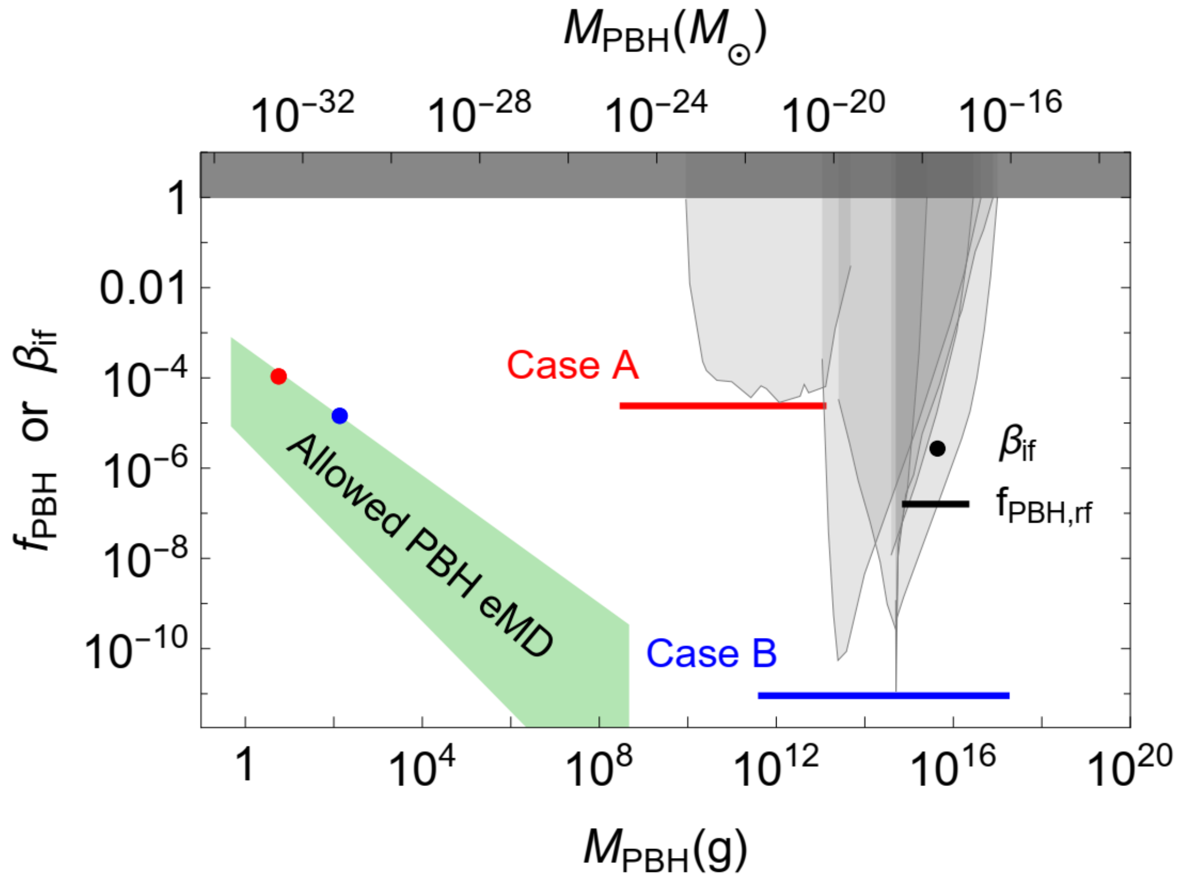
- Density power spectrum during eMD and resulting σ



- Gray = Randomly placed initial PBHs
  - Poisson noise
- Black = Growth by transfer function
  - $\mathcal{P}_\delta(t) = \mathcal{P}_\delta(t_{\rm if}) \times \mathcal{T}^2(t)$
- Red = $\dfrac{d\sigma^2}{d\ln k} = \mathcal{P}_\delta(t) \times W^2(kr)$
  - $\sigma \sim 10^{-3} - 10^{-4}$
  - $\beta \sim 10^{-20}$
  - $f_{\rm PBH} \sim \left(M_{\rm PBH,if}\,/\,1\ {\rm g}\right)^{-3/2}$

PBH reformation during eMD

- Reformed PBH population case study

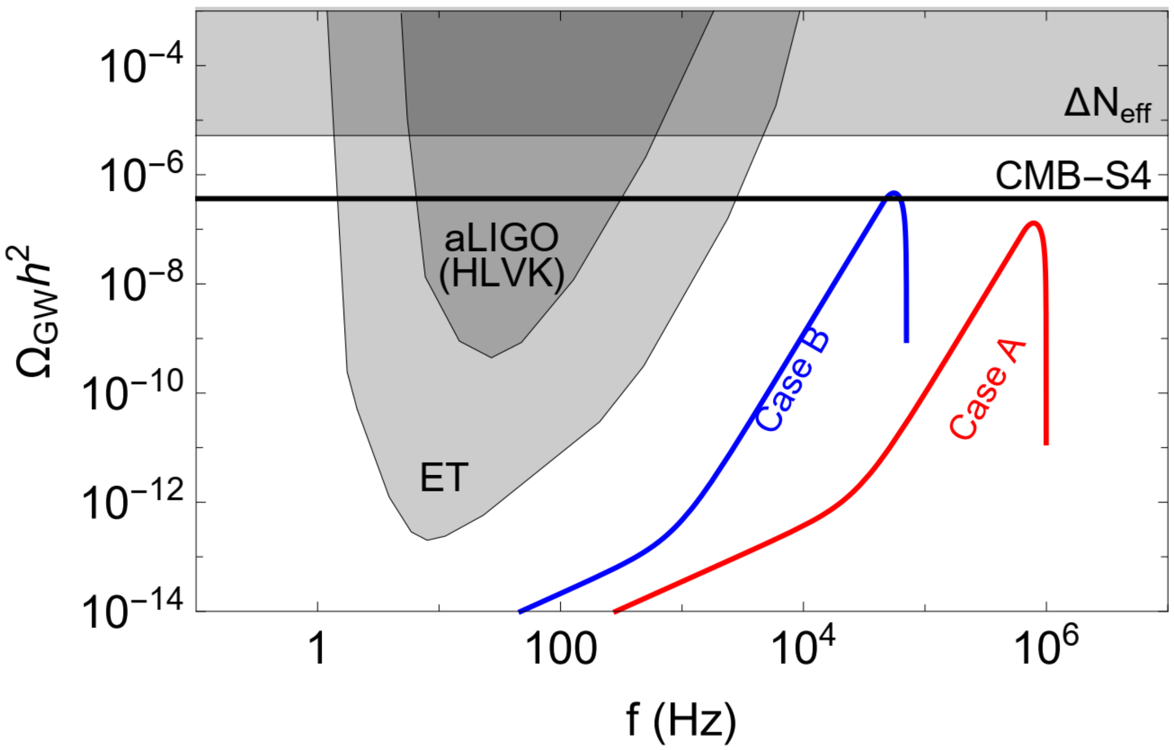


Case	T_{if} (GeV)	β_{if}	γ	f_{PBH}
A	2.88×10^{15}	1.08×10^{-4}	0.5	2.40×10^{-5}
B	5.89×10^{14}	1.45×10^{-5}	0.5	9.05×10^{-12}

- Case A: Reformed PBH population right below the current **BBN bound**
- Case B: Reformed PBH population right below the current **γ-ray bound**
- "PBHs with observable signals are reformed from much lighter PBHs produced in the early Universe"
  - Population decoupling

Correlated GW signal

- Remaining majority of original PBHs evaporate and emit GWs



- High frequency GWs are emitted
  - $\sim 10\ \mathrm{kHz}\ - 1\ \mathrm{MHz}$
- Could be detected by the next generation CMB-S4 experiment through ΔN_{eff}
- Correlated GW signal. "Possible **multi-messenger detection of PBH reformation**"

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Cosmological perturbations

- Cosmological perturbations describe inhomogeneity of the Universe

- Gauge-invariant curvature perturbation ζ

$$\zeta \equiv \psi - H\frac{\delta\rho}{\dot{\bar{\rho}}}, \qquad \zeta_X = \psi - H\frac{\delta\rho_X}{\dot{\bar{\rho}}_X}$$

  - X = $\boldsymbol{\gamma}$ (includes symmetric SM), $\boldsymbol{b}$ (asymmetric part only), and $\boldsymbol{d}$.

- Adiabatic condition : Single source

$$\zeta_\gamma = \zeta_b = \zeta_d$$

Cosmological perturbations

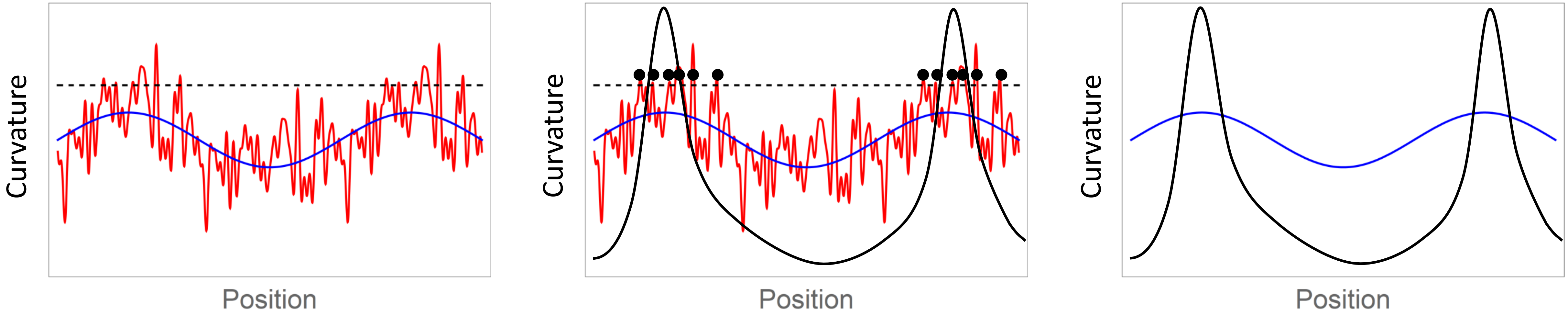
- Isocurvature perturbations : Difference between ζ_X and ζ_Y

$$S_{XY} \equiv 3(\zeta_X - \zeta_Y) = -3H\left(\frac{\delta\rho_X}{\dot{\bar{\rho}}_X} - \frac{\delta\rho_Y}{\dot{\bar{\rho}}_Y}\right)$$

  - Constrained by CMB observation (Planck 2018).

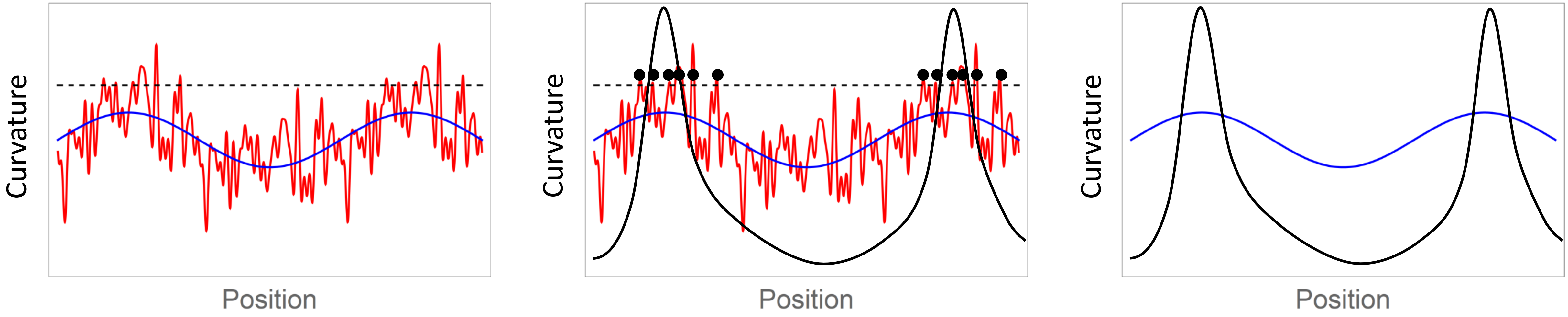
- PBH evaporation generates isocurvature perturbations → bound on PBH
  - PBH bias
  - Branching ratio of Hawking radiation

PBHs as an isocurvature source



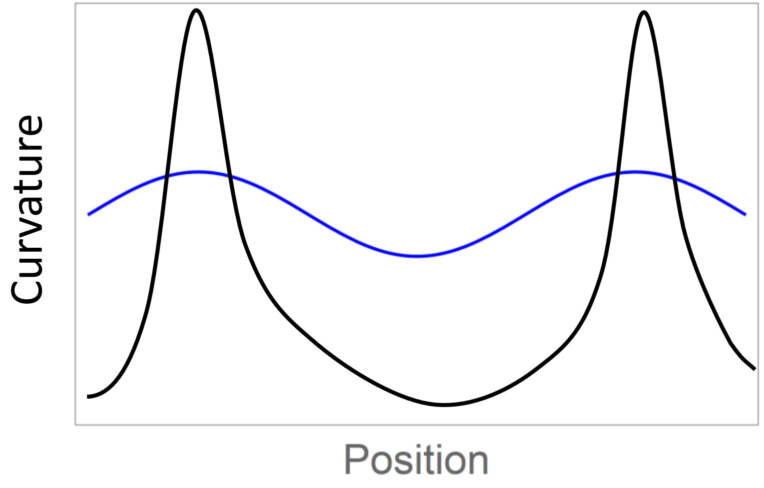
- PBH bias: $\zeta_{\mathrm{PBH}} \sim \mathcal{O}(10^2)\zeta$
  - Uniform density slicing, leading order : linearly added curvature → PBH clustering.
  - Natural consequence of PBHs being formed at the high curvature peaks.

PBHs as an isocurvature source

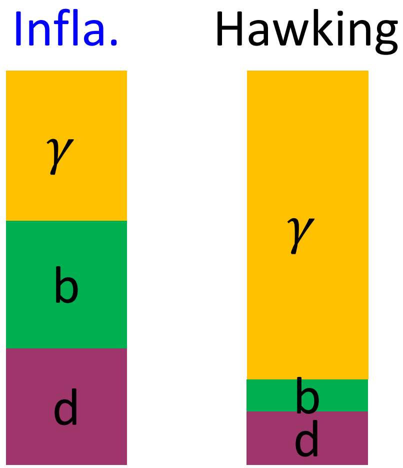


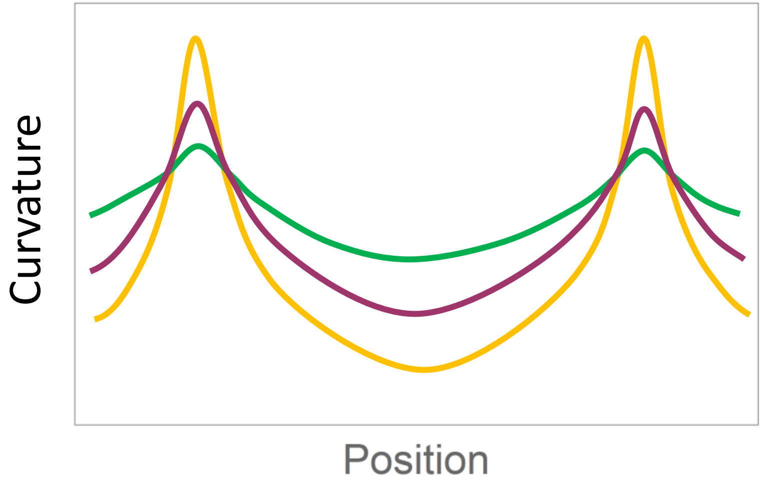
- PBH bias: $\zeta_{\rm PBH} \sim \mathcal{O}(10^2)\zeta$
  - Gauge ambiguity if we use δ instead of ζ
  - We use ζ to evaluate the PBH bias ($\simeq \delta$ at Newtonian gauge).

PBHs as an isocurvature source



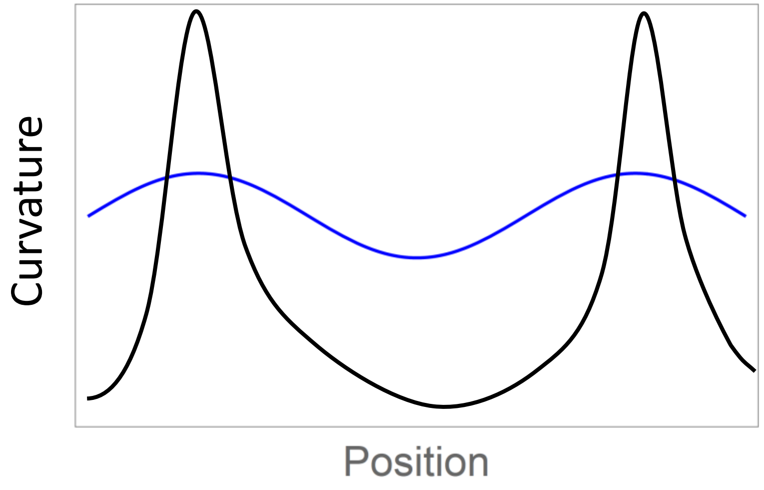
Example particle composition:





- After evaporation, each of γ, b, and d gets different perturbation
  - Isocurvature perturbations are generated.

PBHs as an isocurvature source



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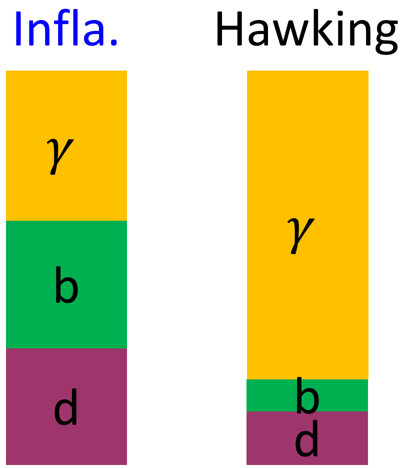
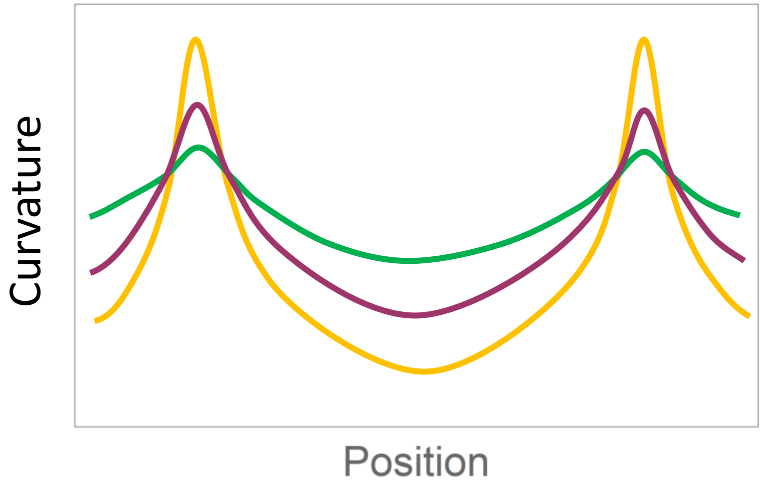




- Two conditions are simultaneously required:
  - PBHs are biased ("black curve should be different from the blue curve").
  - Branching ratio should be different. (Otherwise, they sum up as a single source.)

PBHs as an isocurvature source

- The key equation : Isocurvature between X and Y is

$$S_{XY,0} = 3\left(\frac{\bar{\rho}_{X\mathrm{PBH},0}}{\bar{\rho}_{X,0}} - \frac{\bar{\rho}_{\mathrm{YPBH},0}}{\bar{\rho}_{Y,0}}\right)(\zeta_{\mathrm{PBH}} - \zeta)$$

PBH contribution to the present X and Y should be different

↓

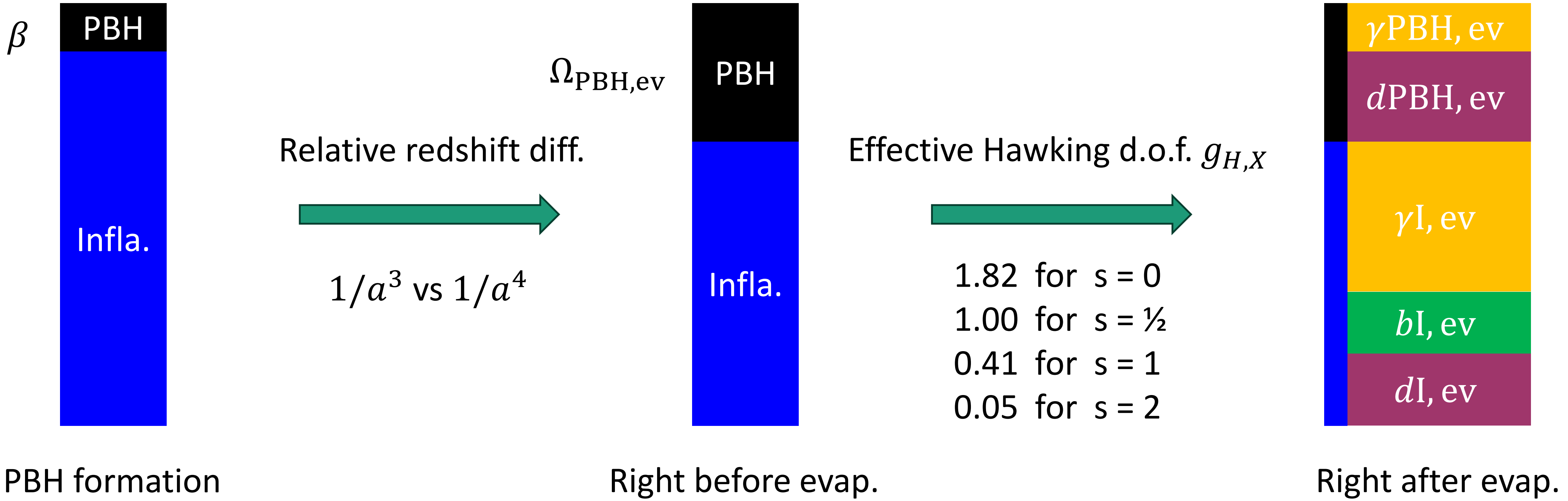
Branching ratio :
Hawking radiation ≠ Inflationary reheating

PBHs are biased.
$\zeta_{\mathrm{PBH}} \sim \mathcal{O}(10^2)\zeta$

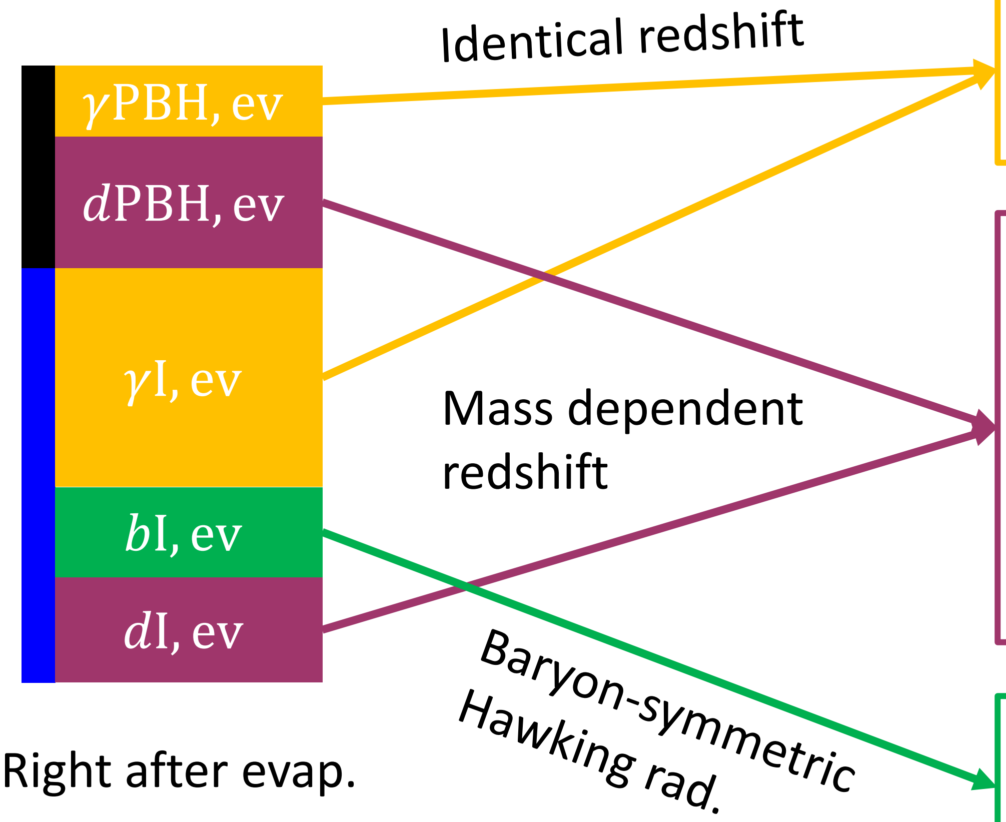
Particle abundances from PBH evaporation

- Calculate $\bar{\rho}_{X\mathrm{PBH},0}$ / $\bar{\rho}_{X,0}$ for $X = \gamma, b, d$
- Focus on a simplified case
  - Baryon-symmetric Hawking radiation. No net baryons from PBHs; $\bar{\rho}_{b\mathrm{PBH},0} = 0$
  - Single scalar DM, out of equilibrium (no longer converts to SM)

Particle abundances from PBH evaporation



Particle abundances from PBH evaporation



Right after evap.

- $\frac{\bar{\rho}_{\gamma\mathrm{PBH},0}}{\bar{\rho}_{\gamma,0}} = \frac{\bar{\rho}_{\gamma\mathrm{PBH,ev}}}{\bar{\rho}_{\gamma\mathrm{PBH,ev}}+\bar{\rho}_{\gamma\mathrm{I,ev}}}$

THK et.al. (2024)

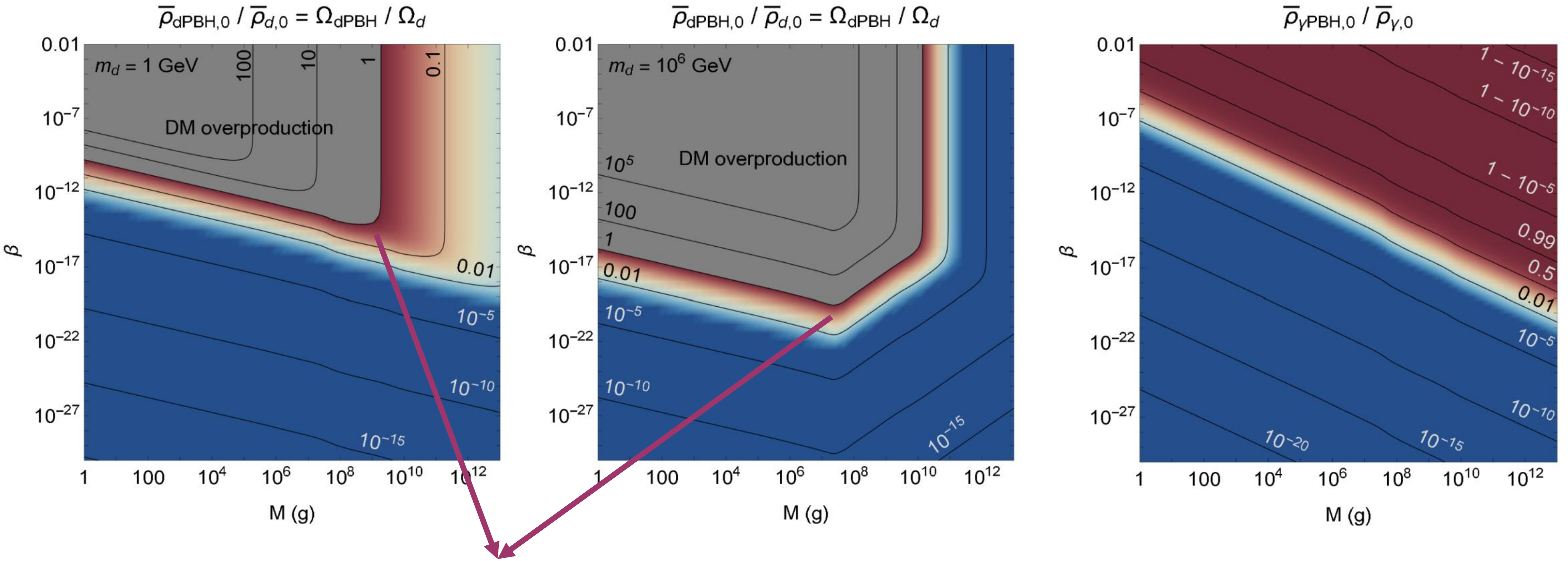
- $\Omega_{d\mathrm{PBH}} \propto \Omega_{\mathrm{PBH,ev}} \times g_{H,d} \times \begin{cases} m_d^{-1}\, M_{\mathrm{PBH}}^{-\frac{5}{2}}, & m_d > T_{\mathrm{PBH}} \\ m_d\, M_{\mathrm{PBH}}^{-\frac{1}{2}}, & m_d < T_{\mathrm{PBH}} \end{cases}$
- $\frac{\bar{\rho}_{d\mathrm{PBH},0}}{\bar{\rho}_{d,0}} \simeq \frac{\Omega_{d\mathrm{PBH}}}{0.26}$; peaks at $m_d \sim T_{\mathrm{PBH}}$

- $\frac{\bar{\rho}_{b\mathrm{PBH},0}}{\bar{\rho}_{b,0}} = 0$

At present.

- $\frac{\bar{\rho}_{b\mathrm{PBH},0}}{\bar{\rho}_{b,0}} = 0$

Particle abundances from PBH evaporation



$\frac{\bar{\rho}_{d\mathrm{PBH},0}}{\bar{\rho}_{d,0}}$ peaks at $m_d \sim T_{\mathrm{PBH}}$

$\frac{\bar{\rho}_{\gamma\mathrm{PBH},0}}{\bar{\rho}_{\gamma,0}}$ is nearly the same as $\Omega_{\mathrm{PBH,ev}}$

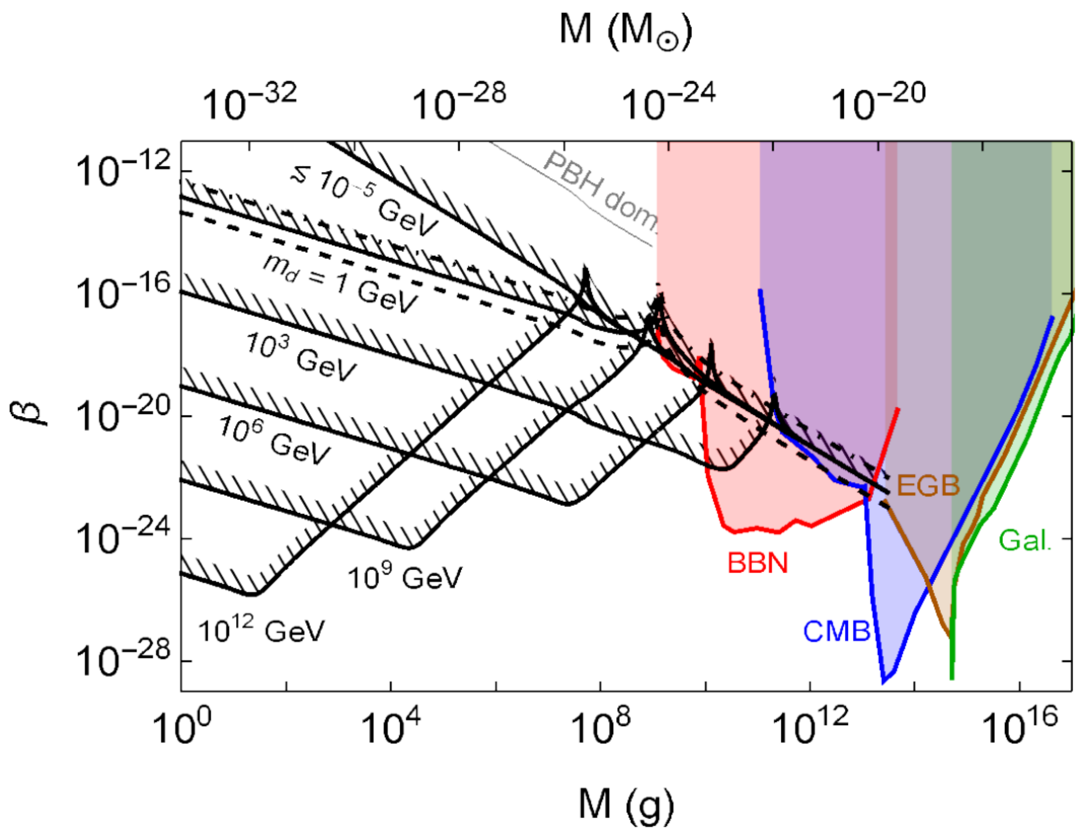
Isocurvature constraints on PBH

- $S_{XY,0} = 3\left(\frac{\bar{\rho}_{X\mathrm{PBH},0}}{\bar{\rho}_{X,0}} - \frac{\bar{\rho}_{Y\mathrm{PBH},0}}{\bar{\rho}_{Y,0}}\right)(\zeta_{\mathrm{PBH}} - \zeta) \neq 0.$

- Observed quantity : Isocurvature fraction

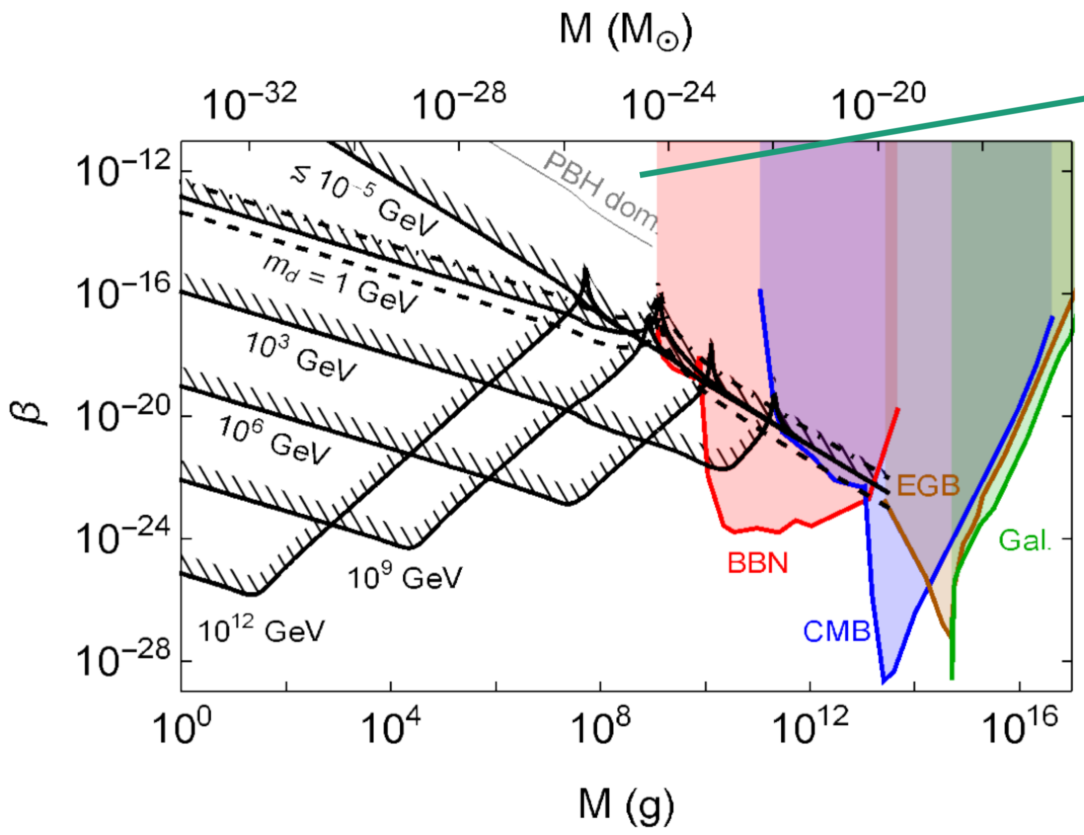
$$\beta_{\mathrm{iso}} = \frac{\mathcal{P}_S}{\mathcal{P}_\zeta + \mathcal{P}_S} = \frac{\left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2}{\zeta^2 + \left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2} < 0.025$$

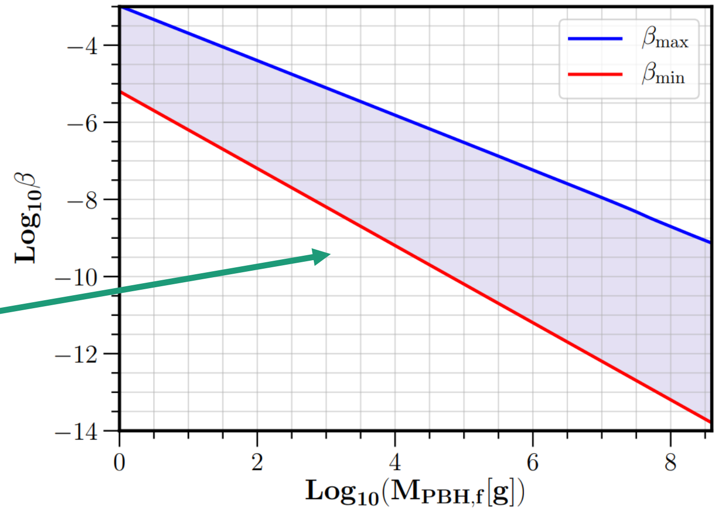
Isocurvature constraints on PBH



- $\beta_{\rm iso} < 0.025$ (Planck 2018) gives bounds on evaporating PBHs
- Depending on the DM mass, $\beta(M)$ for $M \lesssim 10^9$ g can be observationally constrained

Isocurvature constraints on PBH





- If PBH domination happens, the Universe is effectively a single fluid; no constraints above the gray line

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Summary & Conclusion

- PBHs with $M \lesssim 10^9\,\mathrm{g}$ are currently not constrained by observations
- If they dominated the Universe, they could have undergone reformation
  - Reformed PBHs are much heavier and could be detected by future BBN light element abundances / γ-ray observations.
  - Evaporation of original PBHs gives SGWB. Possible multi-messenger observations.

"PBH reformation provides an interesting possibility to decouple the PBH population today and the one from the early Universe physics."

Summary & Conclusion

- If they remained subdominant, they generate isocurvature perturbations
  - Particle composition of Hawking radiation is different from the one from the inflationary reheating
  - PBHs are biased. Formation happens at the high curvature tail of the distribution.

“CMB observation can constrain the past abundances of evaporating PBHs. This is the first observational constraint up to our knowledge.”

THE END. Thank you!