Evaporating Primordial Black Holes:
Reformation and Isocurvature Perturbations

THK, Philip Lu, Phys.Lett.B 865 (2025) 139488, arXiv:2411.07469

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 PBHs with $M \lesssim 10^9$ g can impact the cosmology depending on their early Universe abundance.”

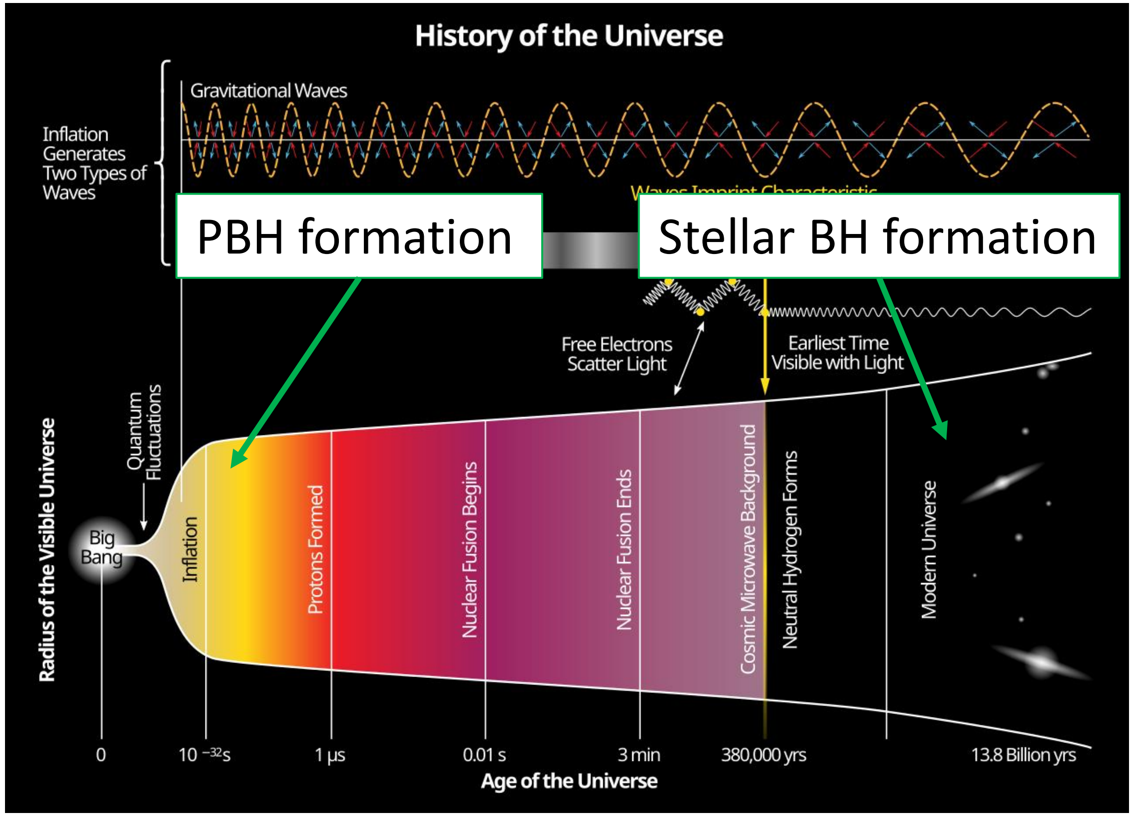
- Outline
  - Introduction : Evaporating PBHs
  - PBH reformation (Dominating; arXiv:2411.07469)
  - Isocurvature perturbation generation (Not dominating; arXiv:2503.14581)
  - Summary & Conclusion

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

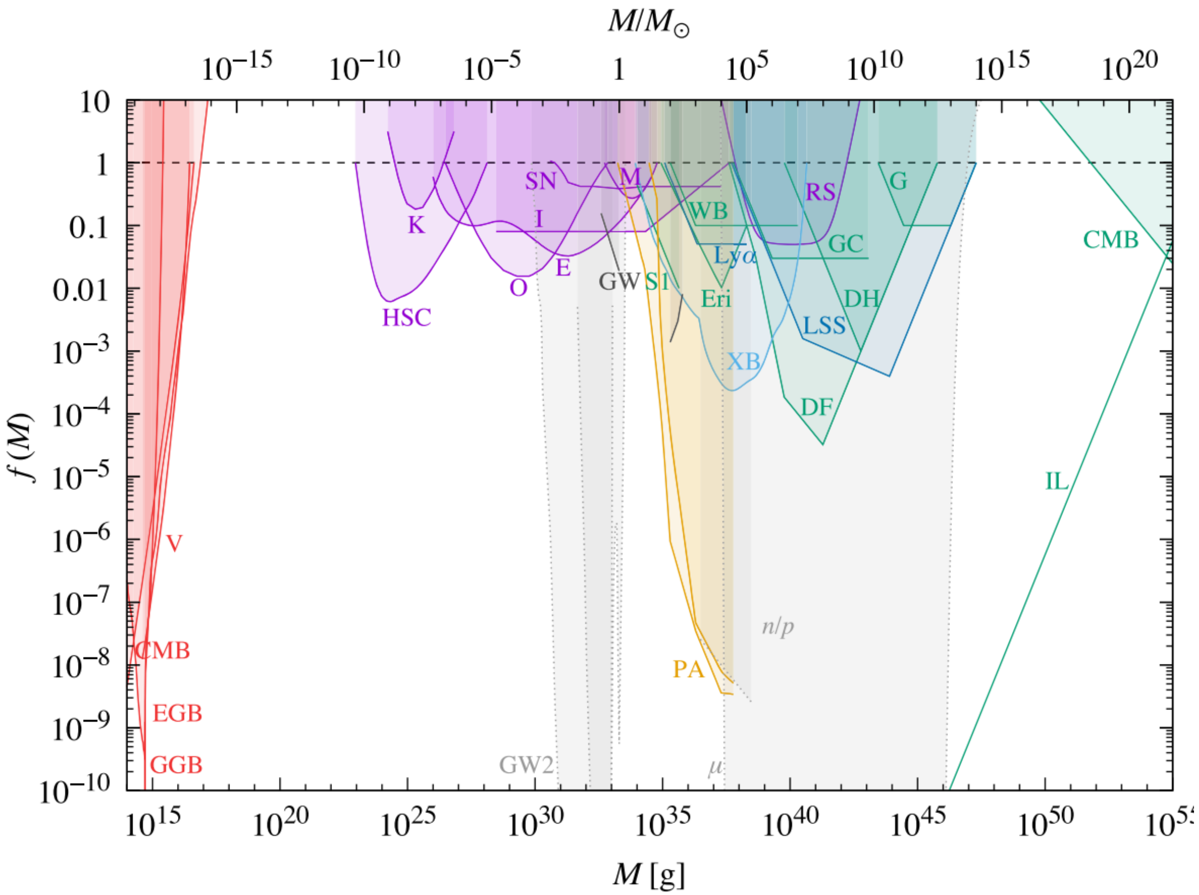
Carr et. al. (2021)

Introduction: PBHs

- "PBHs are hypothetical BHs that formed soon after the Big Bang"



https://en.wikipedia.org/wiki/Cosmic_inflation#/media/File:History_of_the_Universe.svg

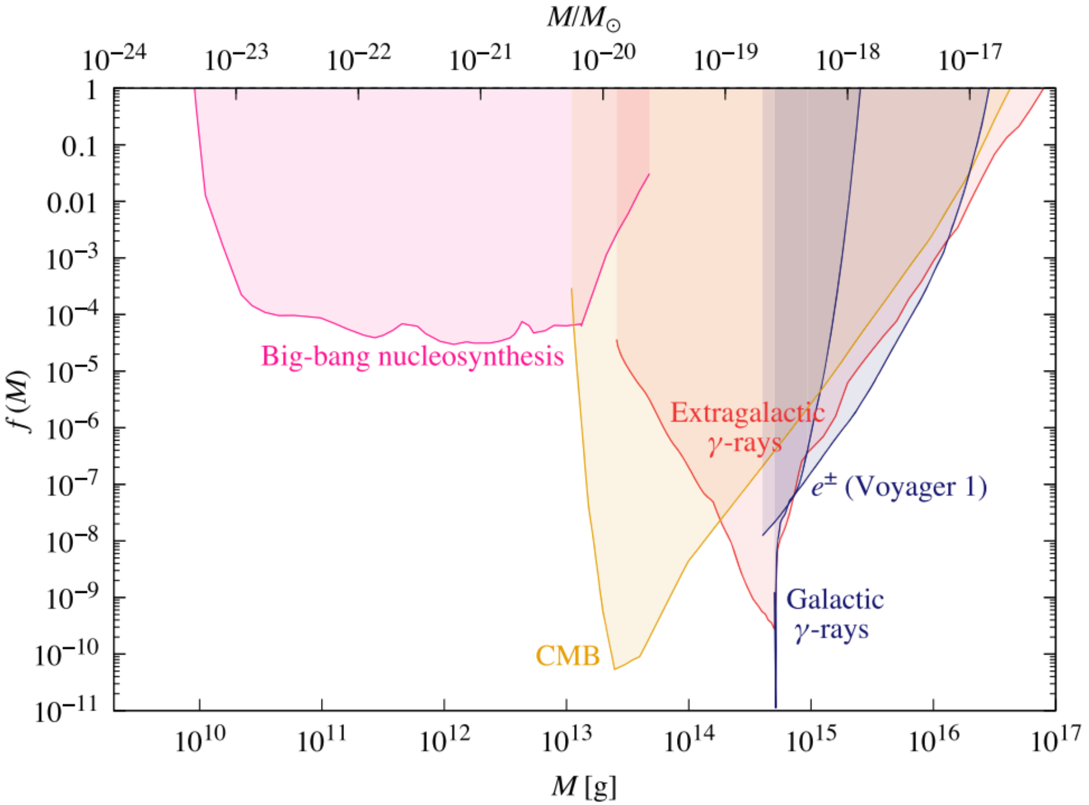


- $1\, M_\odot \sim 10^{33}$ g

Carr et. al. (2021)

Introduction : Evaporating PBHs

- Particularly interested below $\sim 10^{15}$ g : Evaporation



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

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

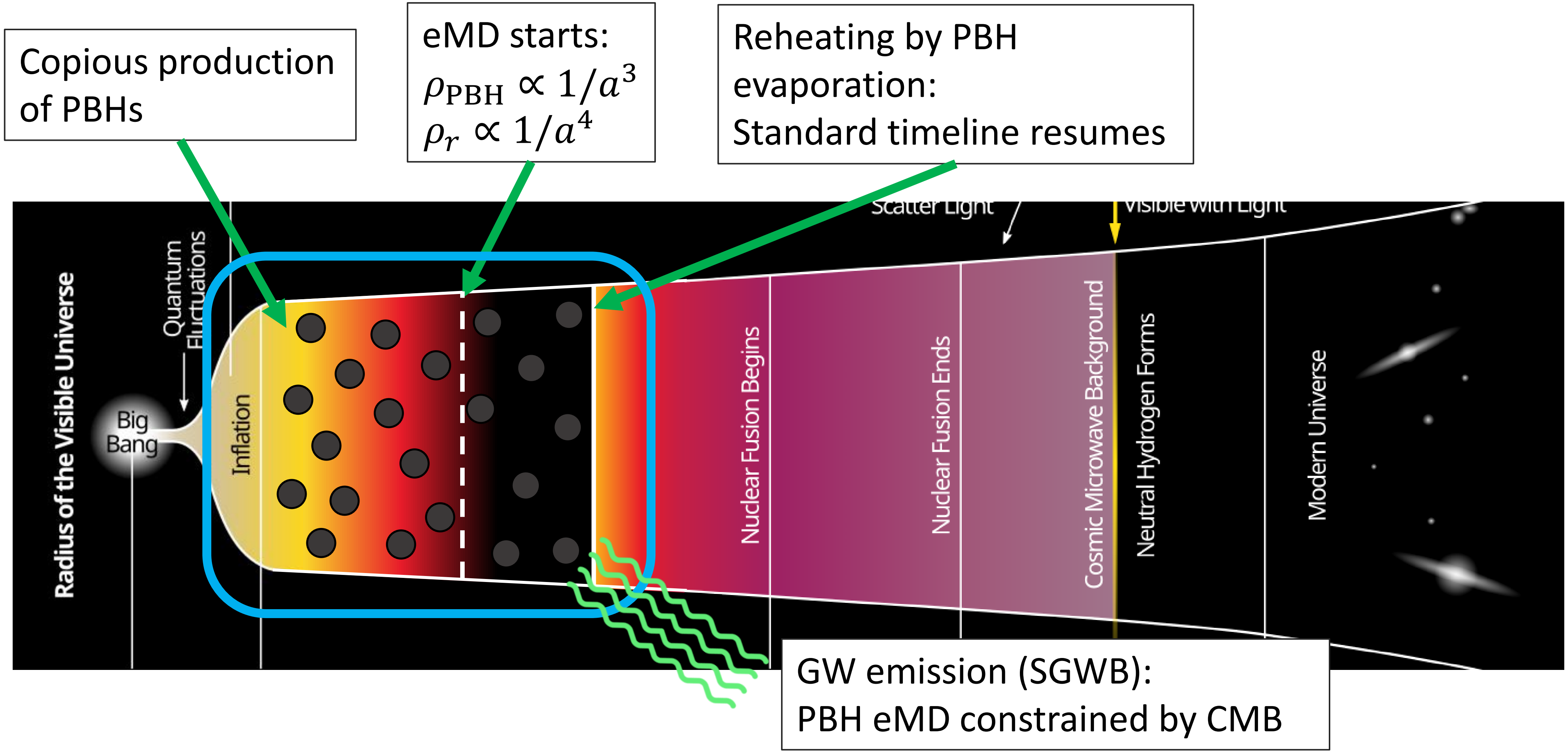
Abstract

“Light mass PBHs with $M \lesssim 10^9$ g can impact the cosmology depending on their early Universe abundance.”

- Outline
  - Introduction: PBHs
  - PBH reformation (Dominating; arXiv:2411.07469)
  - Isocurvature perturbation generation (Not dominating; arXiv:2503.14581)
  - Summary & Conclusion

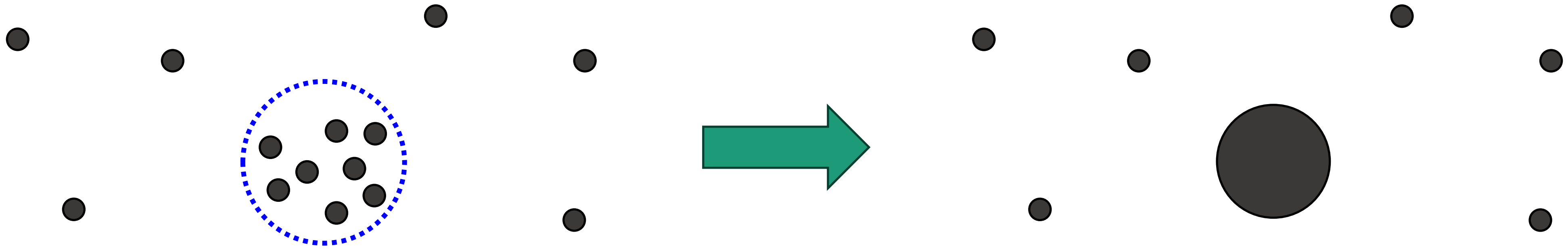
Cosmic timeline of eMD by PBHs

= PBHs



PBH reformation during eMD

- PBH reformation
  - Random overdensities in PBH distribution → collapse → 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

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

PBH reformation during eMD

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

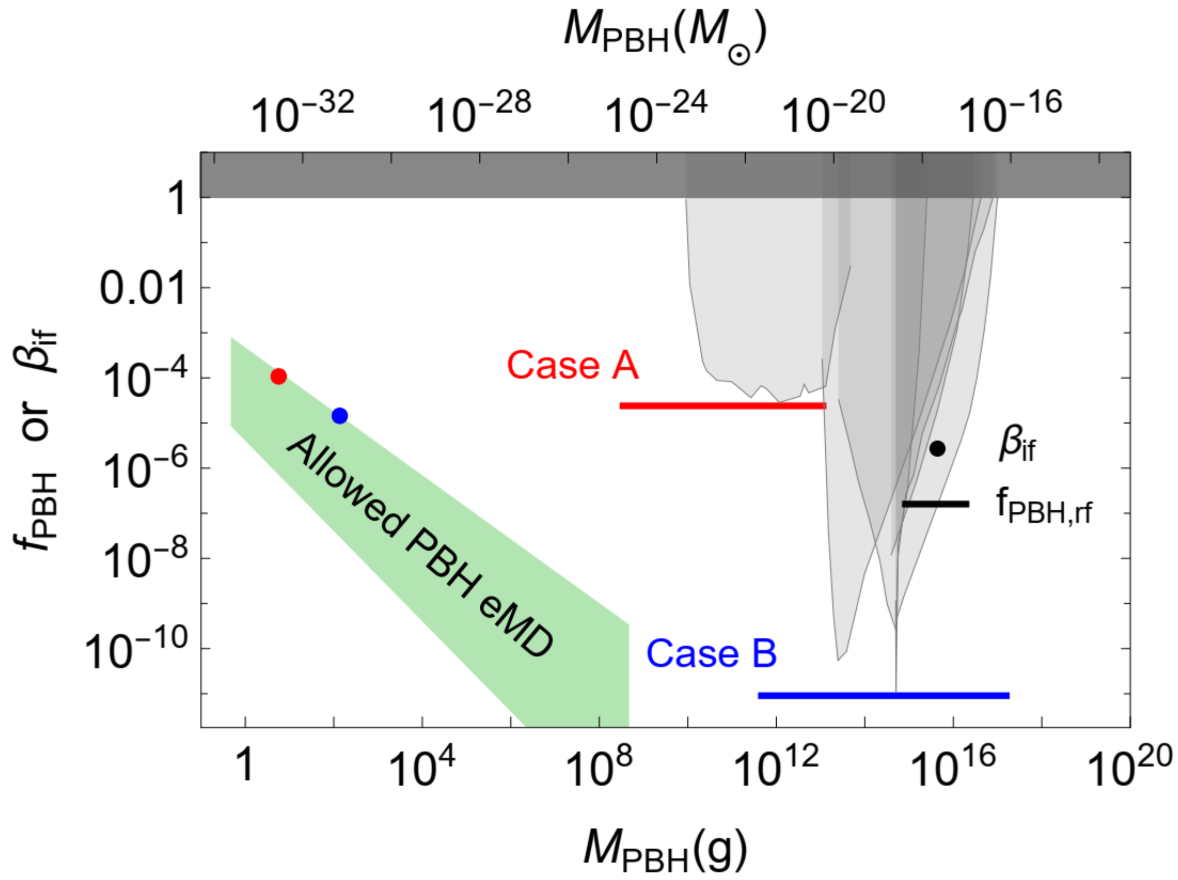
- Gravitational collapse in MD
  - No pressure : Eventually any overdensity will collapse?
  - Spatial profile of an overdensity should be homogeneous and isotropic enough
    - To fall into its own Schwarzschild radius without virialization
  - Collapse probability : $\beta \simeq 0.05556 \times \sigma^5$
- Poisson noise → Transfer function → $d\sigma^2/d\ln k$ → σ → β → $f_{\rm PBH}$

Initial PBH (Poisson noise) | eMD (Transfer function → $d\sigma^2/d\ln k$ → σ) | Reformation (β → $f_{\rm PBH}$)

PBH reformation during eMD

- Reformed PBH population case study

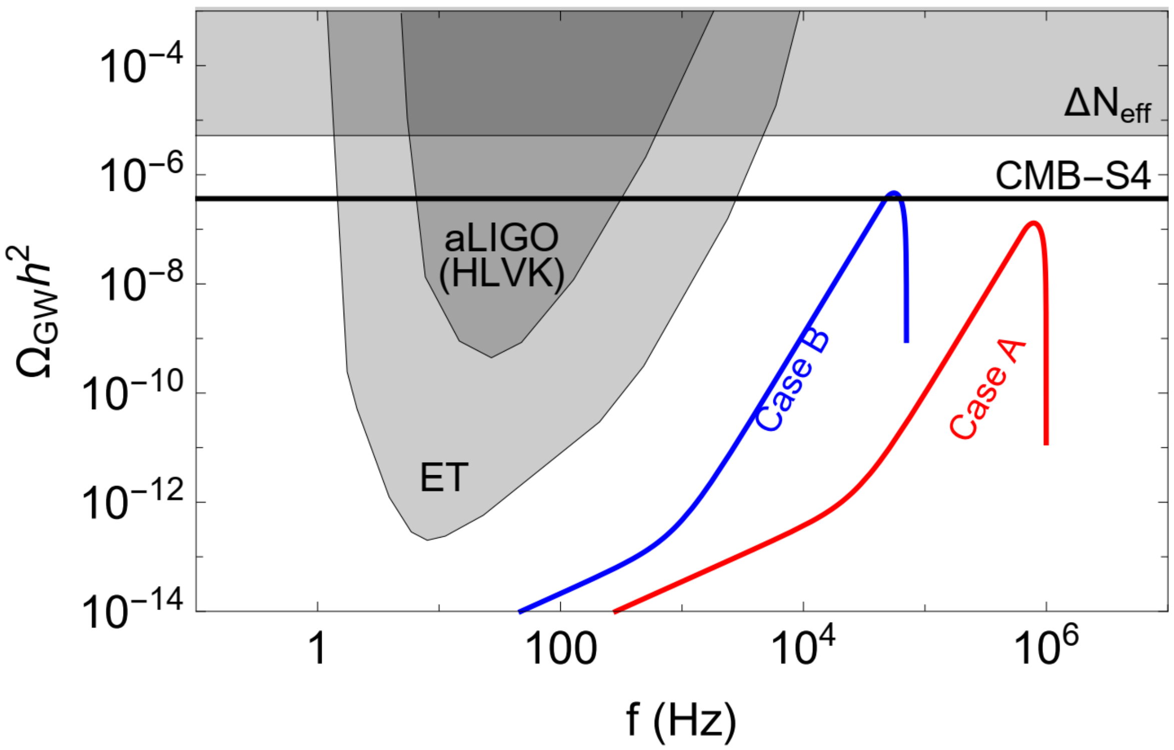
Case	$T_{\rm if}$ (GeV)	$\beta_{\rm if}$	γ	$f_{\rm PBH}$
A	2.88×10^{15}	1.08×10^{-4}	0.5	2.40×10^{-5}
B	5.89×10^{14}	1.45×10^{-5}	0.5	9.05×10^{-12}



- 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**"

Abstract

"Light mass PBHs with $M \lesssim 10^9$ g can impact the cosmology depending on their early Universe abundance."

- Outline
  - Introduction: PBHs
  - PBH reformation (Dominating; arXiv:2411.07469)
  - Isocurvature perturbation generation (Not dominating; arXiv:2503.14581)
  - Summary & Conclusion

Isocurvature perturbations

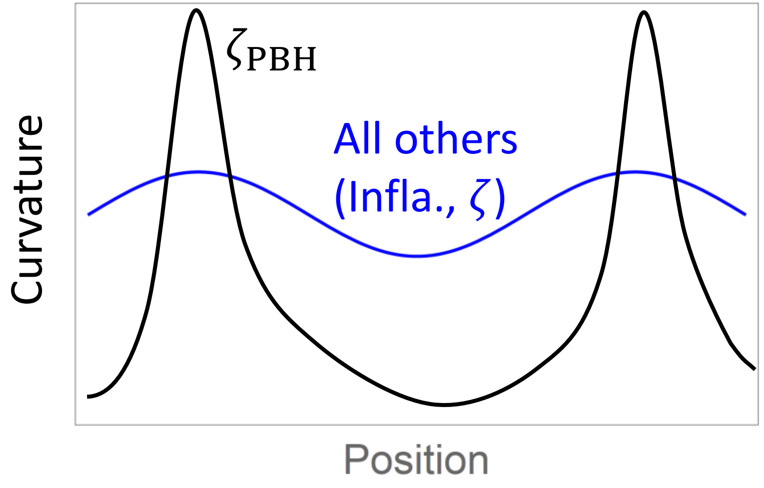
- Isocurvature perturbations : $S_{XY} \equiv 3(\zeta_X - \zeta_Y)$ $(X, Y = \gamma, b, d)$
  - Cosmological perturbation; difference between different energy components
  - Constrained by CMB observation
- This work : "PBH evaporation generates isocurvature perturbations"

  → **CMB constrains evaporating PBHs through isocurvature perturbation.**

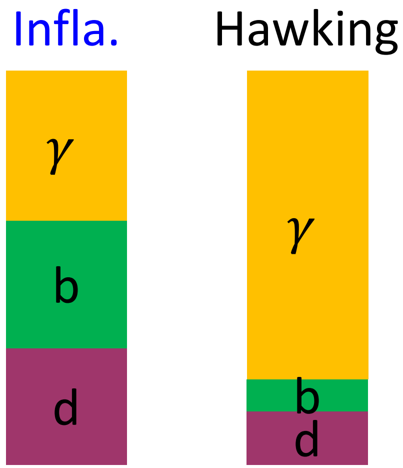
  - PBH distribution ≠ Average (adiabatic mode) : "PBHs are biased"
  - Composition : Hawking radiation ≠ Inflationary reheating products (background)

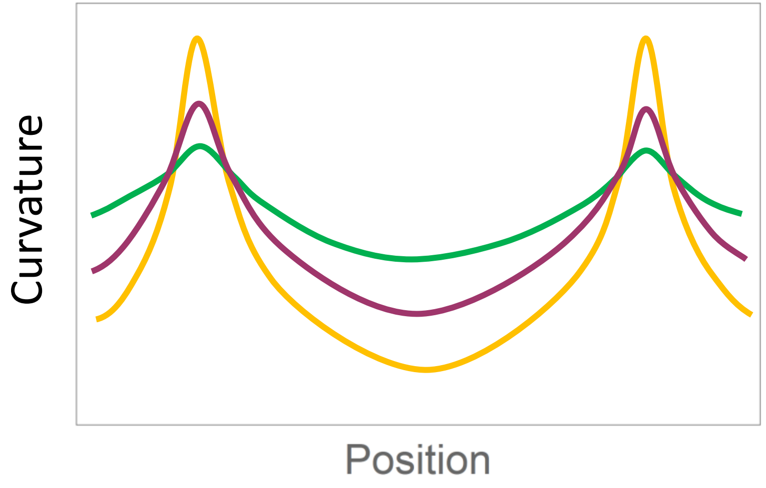
PBHs as an isocurvature source

Distribution at cosmological scale



Example particle composition:





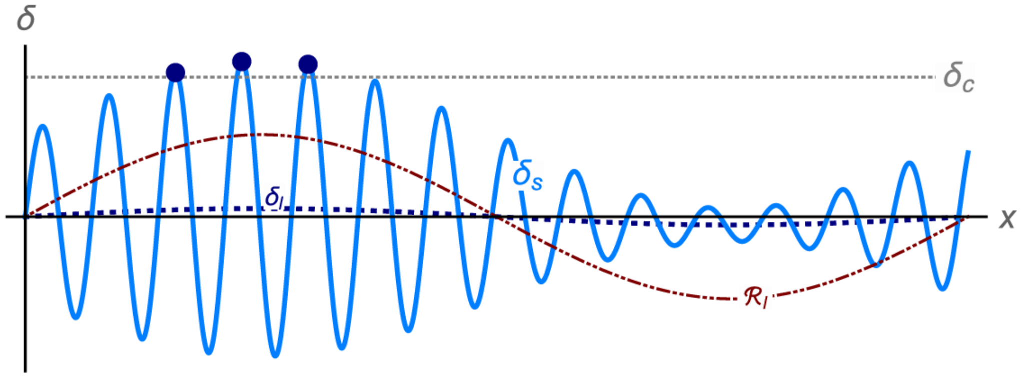
- After evaporation, each of γ, b, and d gets different perturbation
  - Isocurvature perturbations!
  - PBH bias & Particle composition

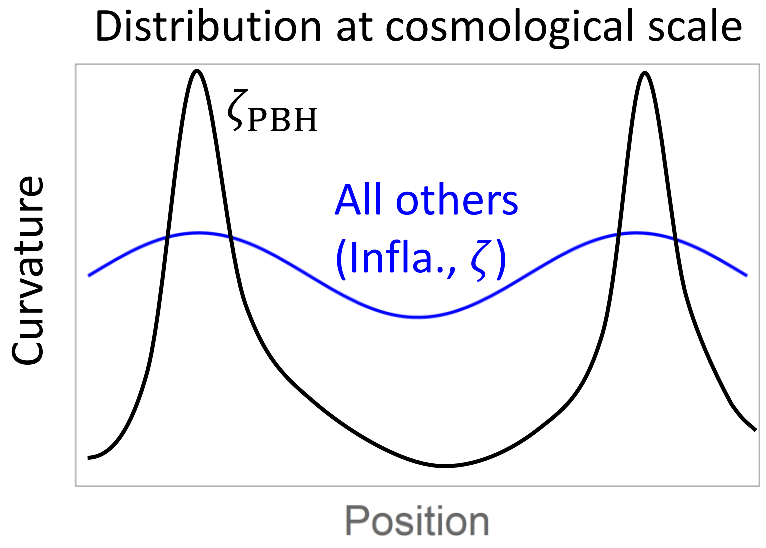
$$S_{XY,0} = 3\left(\frac{\bar{\rho}_{X\mathrm{PBH},0}}{\bar{\rho}_{X,0}} - \frac{\bar{\rho}_{Y\mathrm{PBH},0}}{\bar{\rho}_{Y,0}}\right)(\zeta_{\mathrm{PBH}} - \zeta)$$

Simplified case study

Tada, Yokoyama (2015)
Young, Byrnes (2015)
van Laak, Young (2023)

- Concrete demonstration : Example constraint for evaporating PBHs
  - PBH bias : Local type primordial non-Gaussianity : $\zeta = \zeta_G + (3/5) f_{\rm NL} \left(\zeta_G^2 - \langle \zeta_G^2 \rangle \right)$
    - Long mode enhances short mode's amplitude → Enhanced PBH clustering
  - PBH bias : $\zeta_{\rm PBH} \sim \mathcal{O}(10^2) f_{\rm NL} \times \zeta$

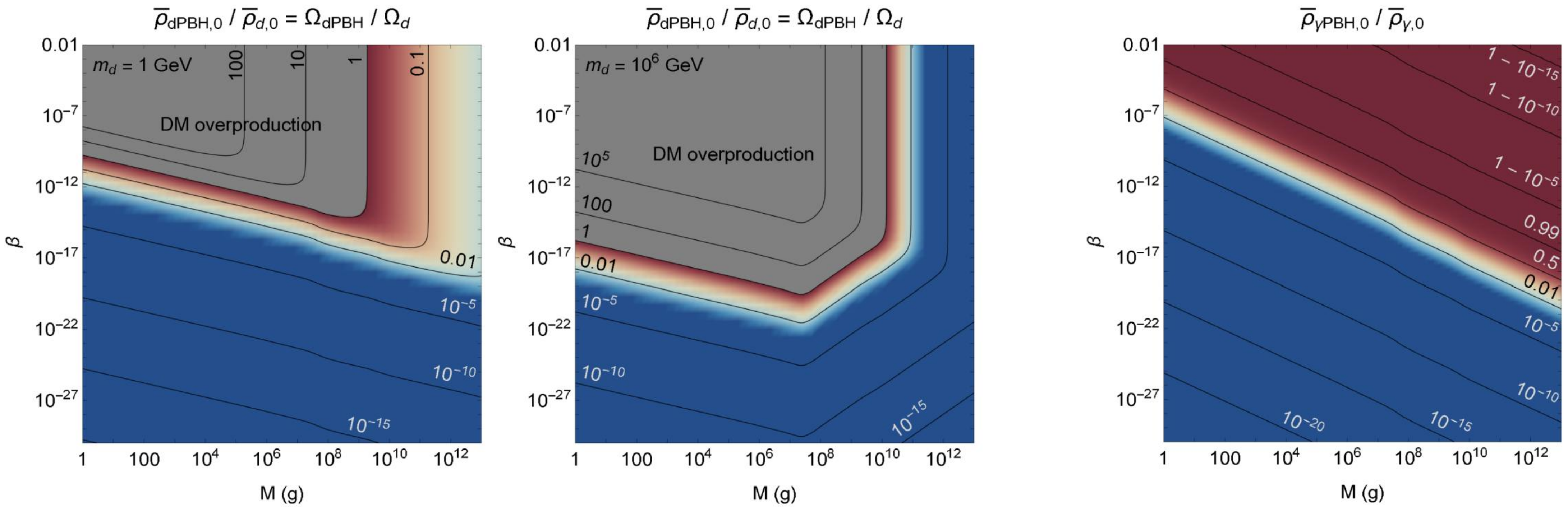




Simplified case study

- PBH energy fraction
- Branching ratio → PBH contribution to γ, b, d
- Subsequent redshift

- Particle model
  - Baryon-symmetric Hawking radiation. No net baryons from PBHs.
  - Single scalar DM, out of equilibrium (no longer converts to SM)



Isocurvature constraints on PBH

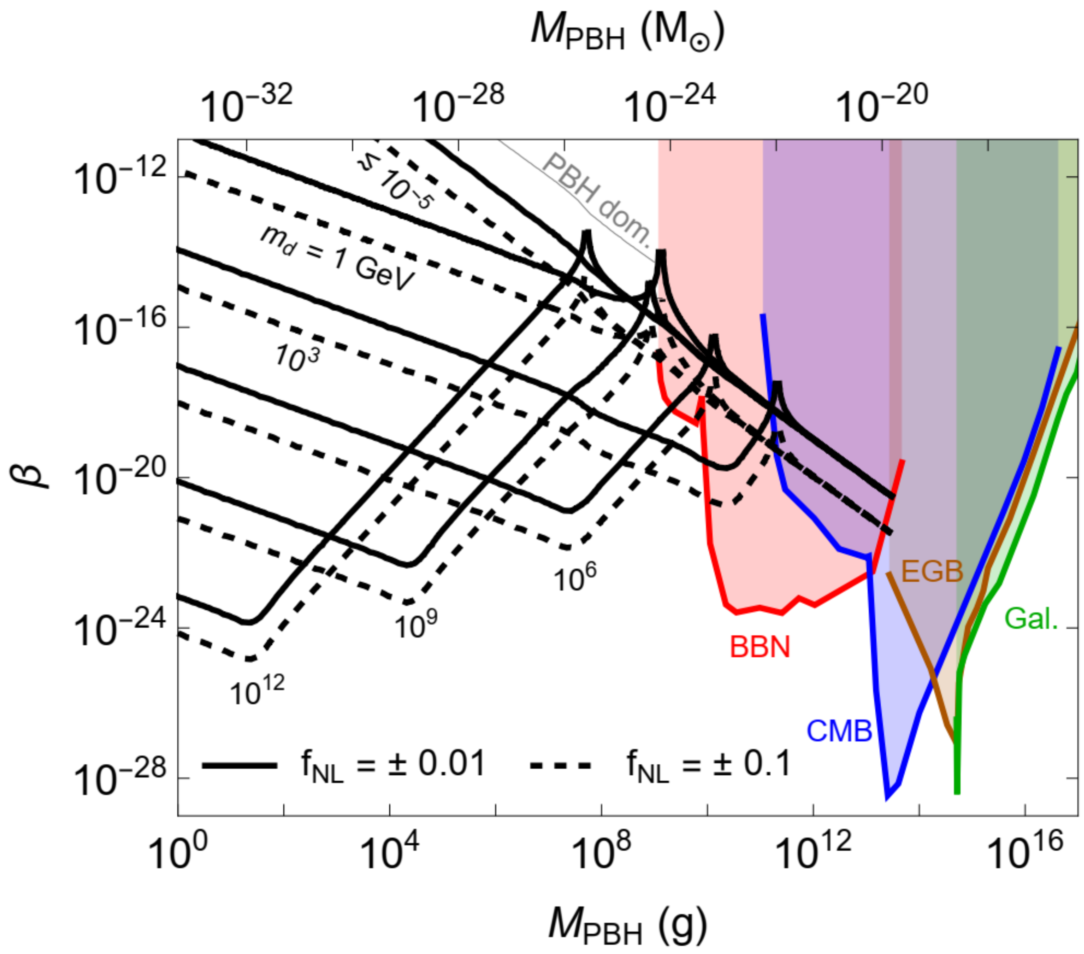
- PBH-generated isocurvature perturbation

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

- Observed quantity : Isocurvature fraction

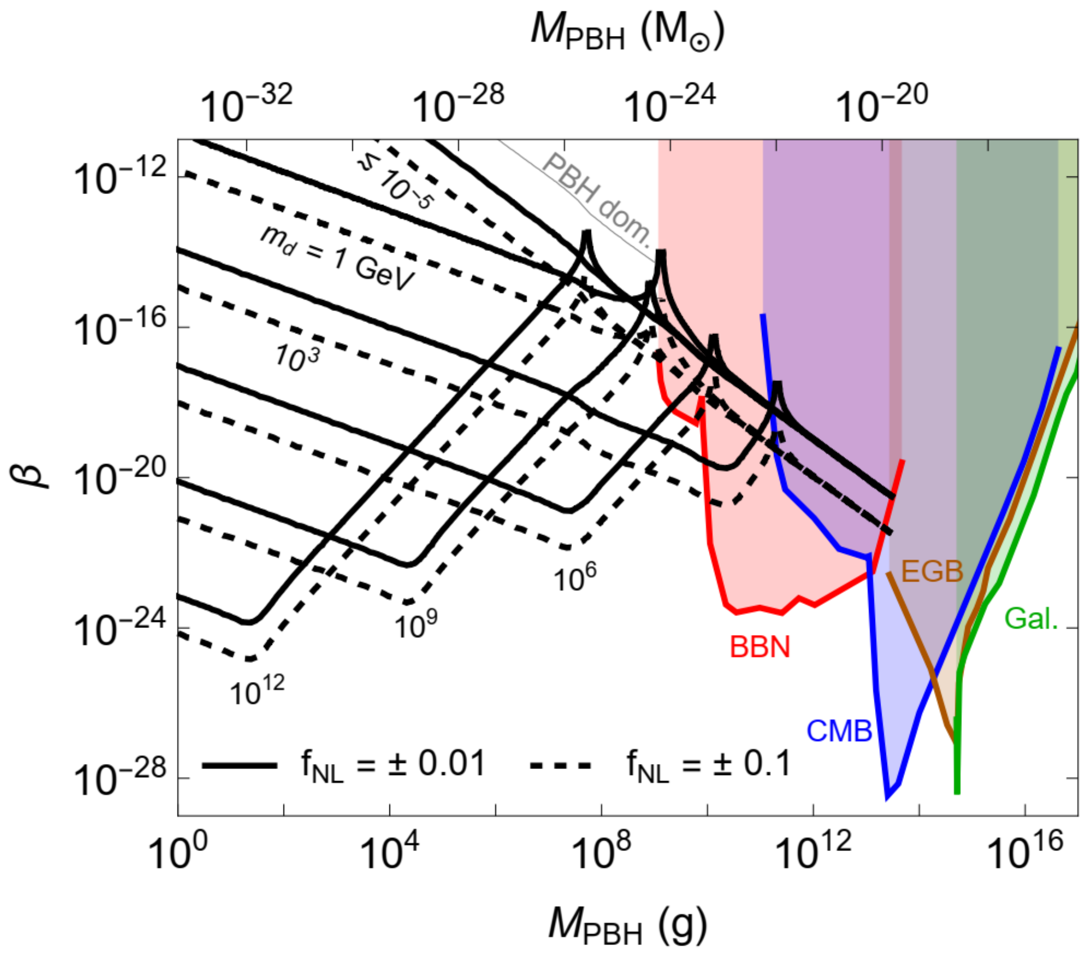
$$\beta_{\mathrm{iso}} = \frac{\mathcal{P}_S}{\mathcal{P}_\zeta + \mathcal{P}_S} = \frac{\left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2}{\zeta^2 + \left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2} < 0.001 \text{ (Planck 2018)}$$

Isocurvature constraints on PBH



- Isocurvature bound on PBHs
- Past abundance for $M \lesssim 10^9$ g can now be observationally constrained
  - Depends on DM model and $f_{\rm NL}$
  - But the first observational constraints for PBHs with $M \lesssim 10^9$g (up to our knowledge)

Isocurvature constraints on PBH



- Above the gray line, PBH domination happens
  - Universe is effectively a single fluid
  - No isocurvature constraints above the gray line

Abstract

"Light mass PBHs with $M \lesssim 10^9\ \mathrm{g}$ can impact the cosmology depending on their early Universe abundance."

- Outline
  - Introduction: PBHs
  - PBH reformation (Dominating; arXiv:2411.07469)
  - Isocurvature perturbation generation (Not dominating; arXiv:2503.14581)
  - Summary & Conclusion

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

"PBH reformation can decouple PBH populations in the late Universe and in the early Universe."

- If they remained subdominant, they generate isocurvature perturbations

"CMB can observationally constrain the evaporating PBHs."

THE END. Thank you!

Backup slides

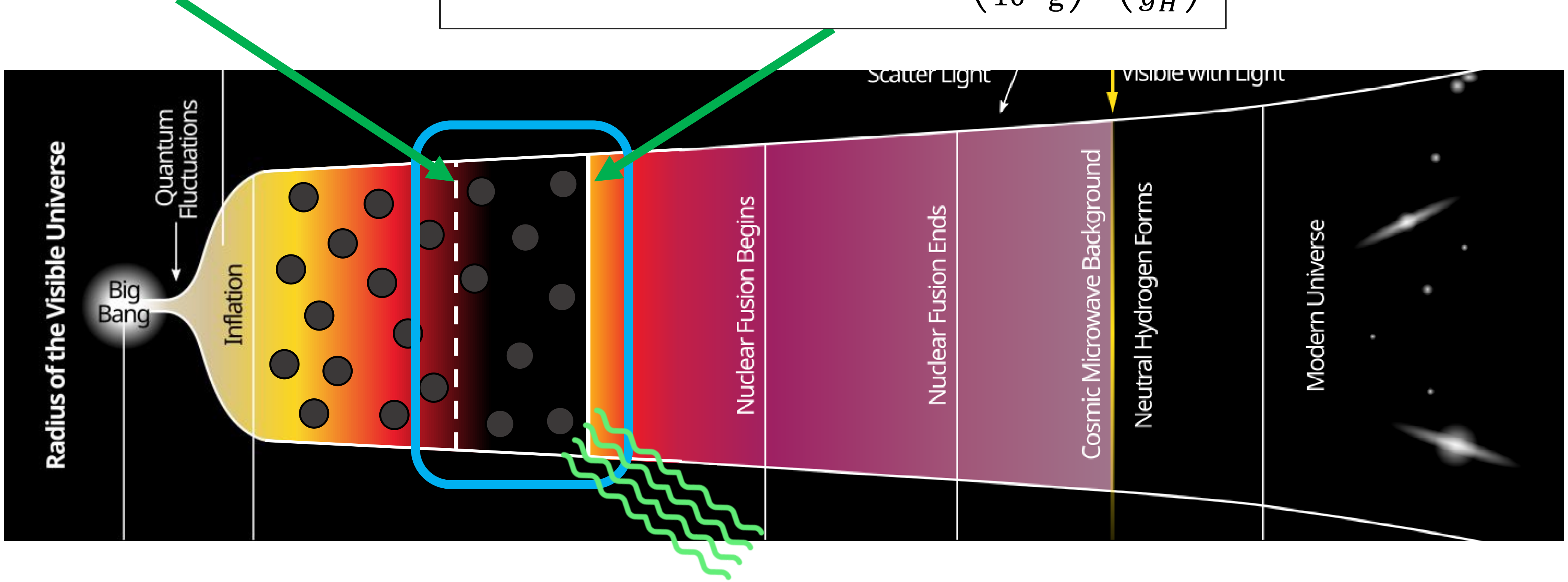
Cosmic timeline of eMD by PBHs

- $\beta_{\rm if}$: 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"

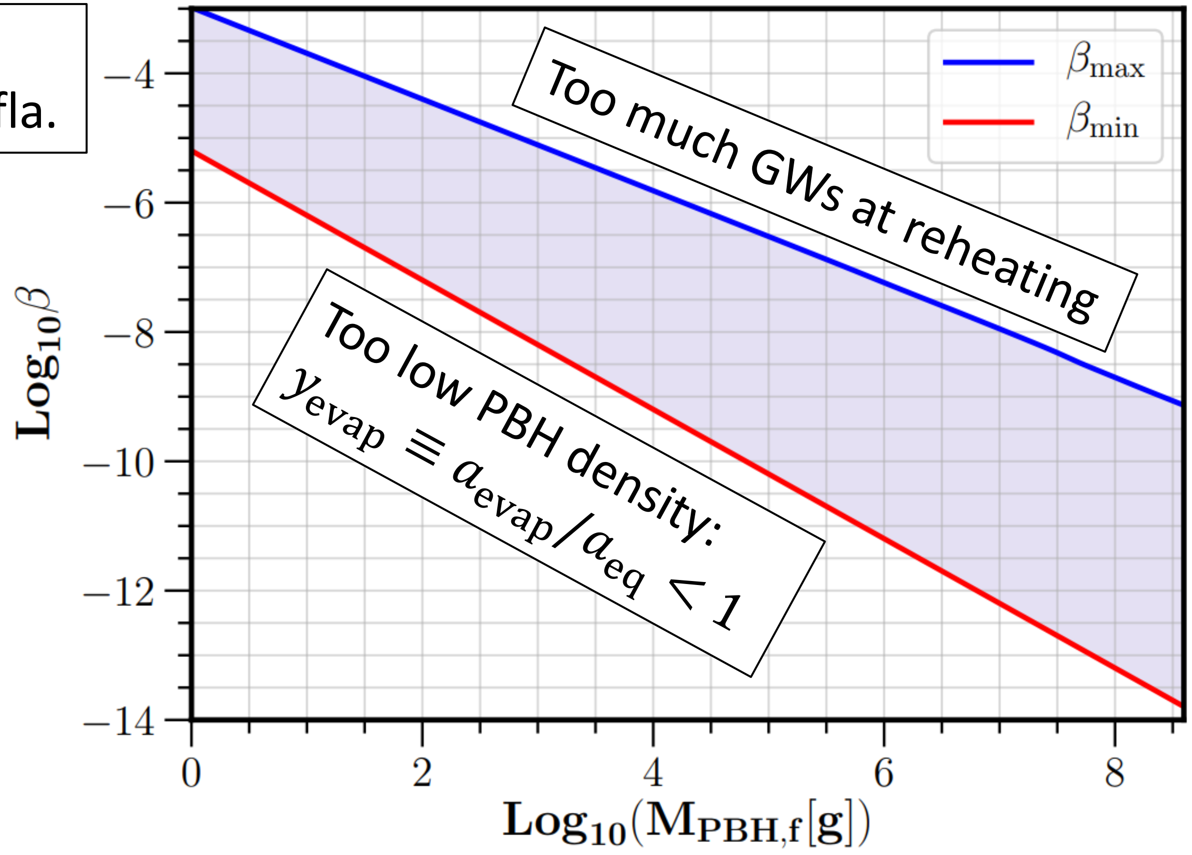


Cosmic timeline of eMD by PBHs

Domenech et. al. (2021)

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

Too light to be produced in infla.

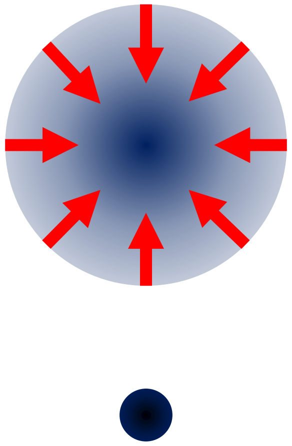


Harms BBN prediction

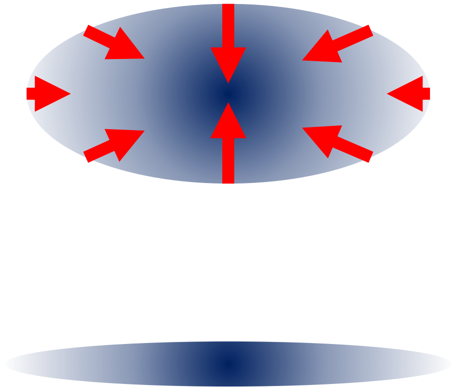
PBH reformation during eMD

Before

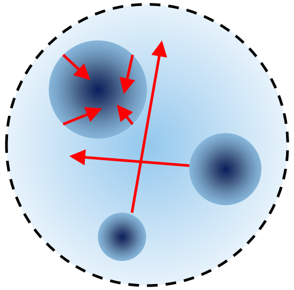
After



BH formation



“Pancake” collapse → virialized configuration

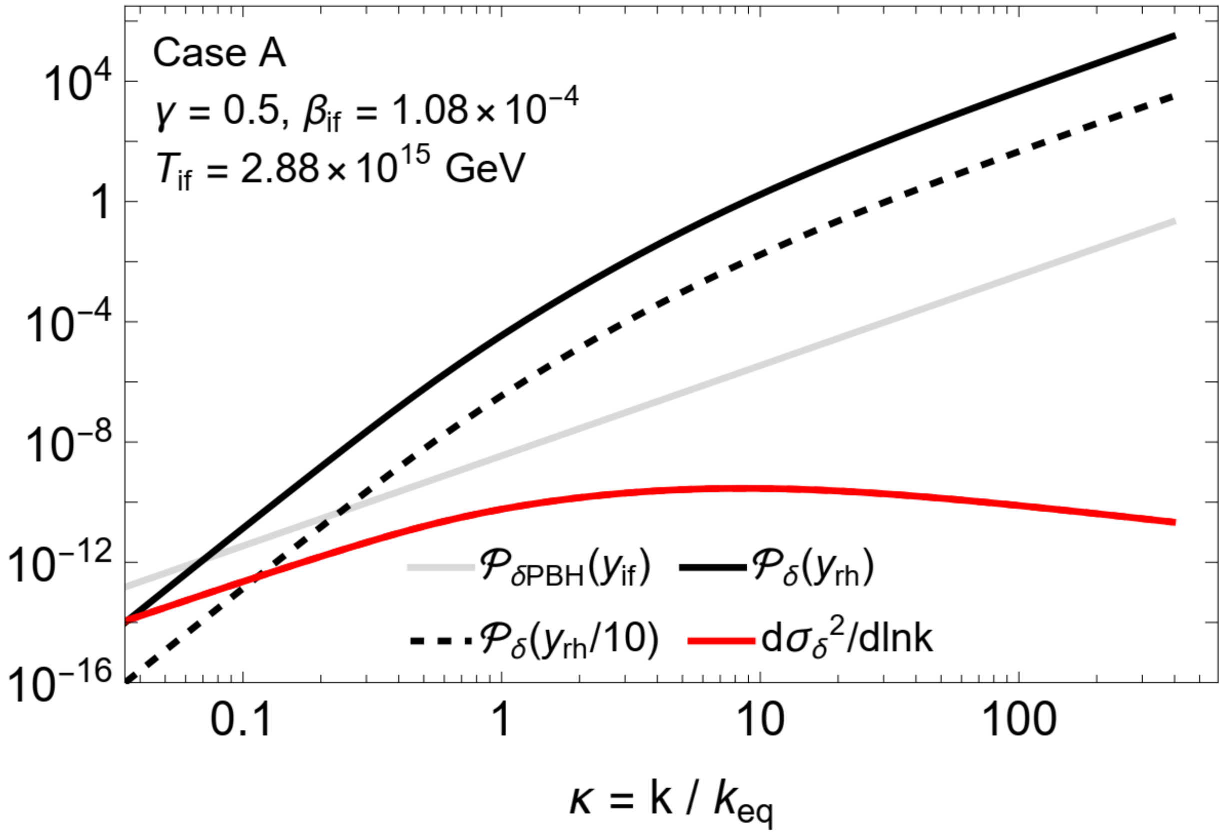


??? (not well known)
- Naked singularity
- Virialized
- Becomes radiation and stop by pressure
- ...

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

PBH reformation during eMD

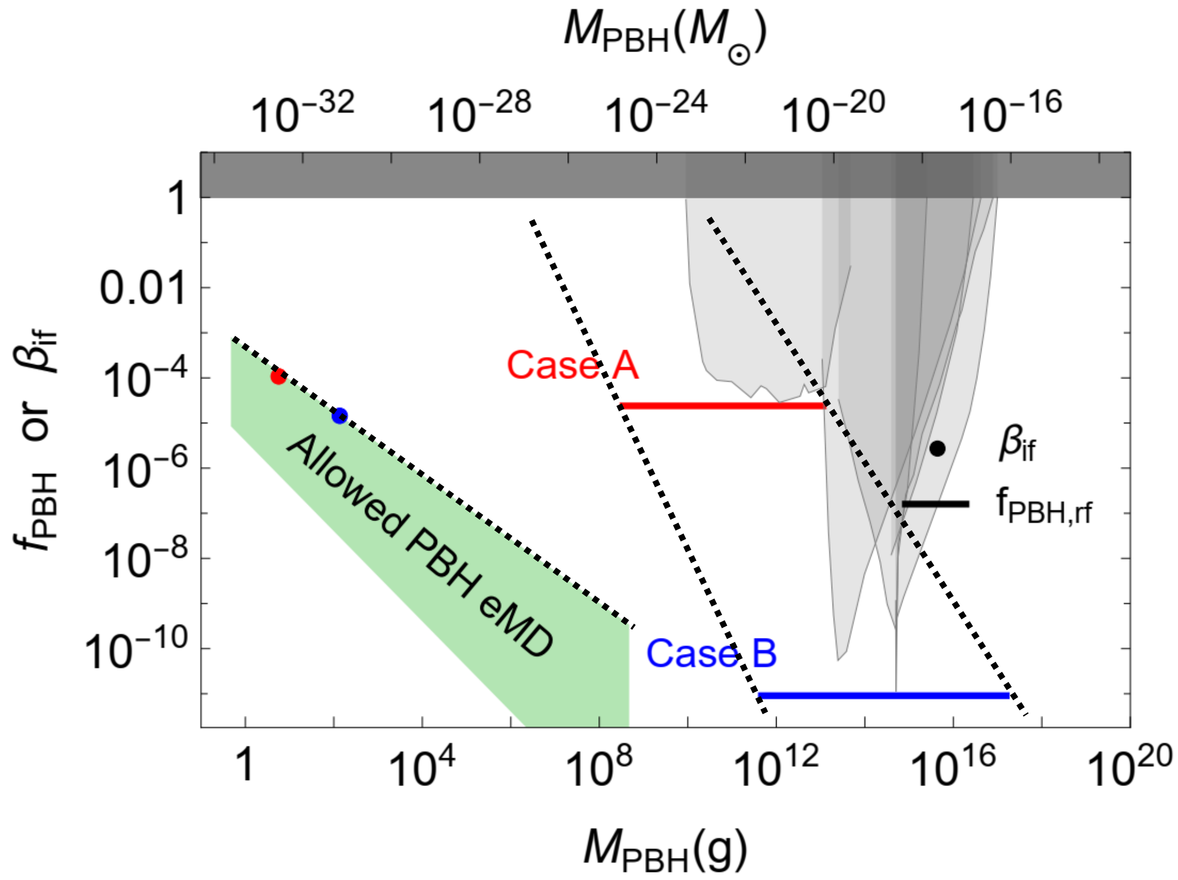
- Density power spectrum during eMD and resulting σ



- 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 = $\frac{d\sigma^2}{d\ln k} = \mathcal{P}_\delta(t) \times W^2(kr)$
  - $\sigma \sim 10^{-3} - 10^{-4}$
  - $\beta \sim 10^{-20}$
  - $f_{\rm PBH} \sim \left(M_{\rm PBH,if} / 1\ {\rm g}\right)^{-3/2}$

PBH reformation during eMD

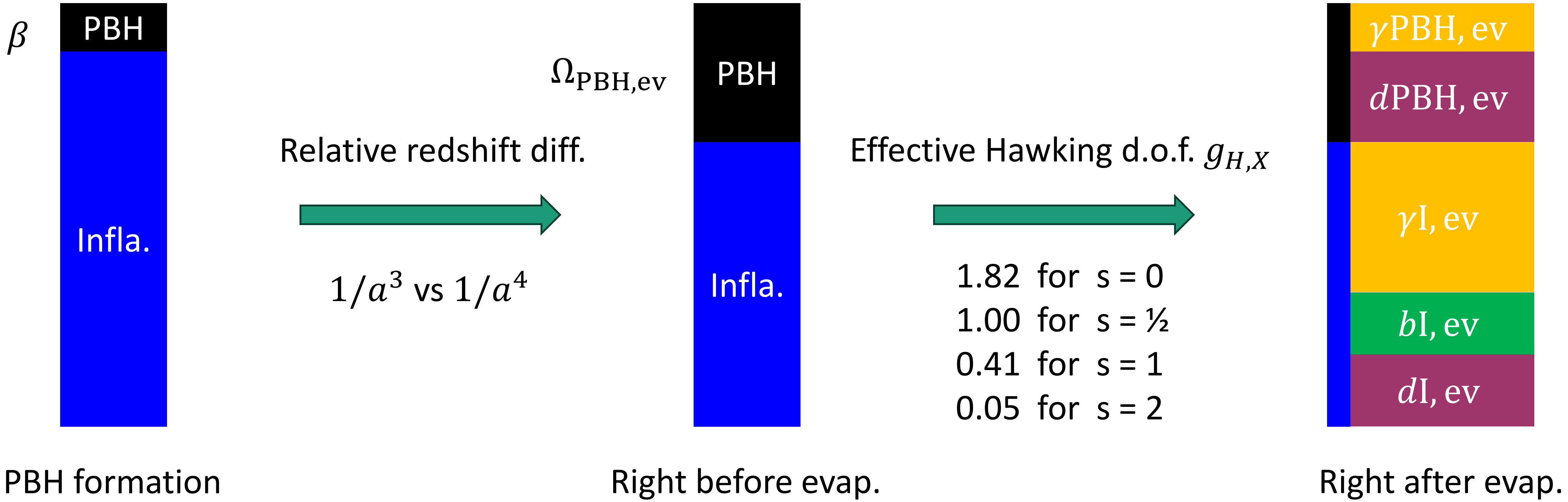
- Reformed PBH population case study



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}

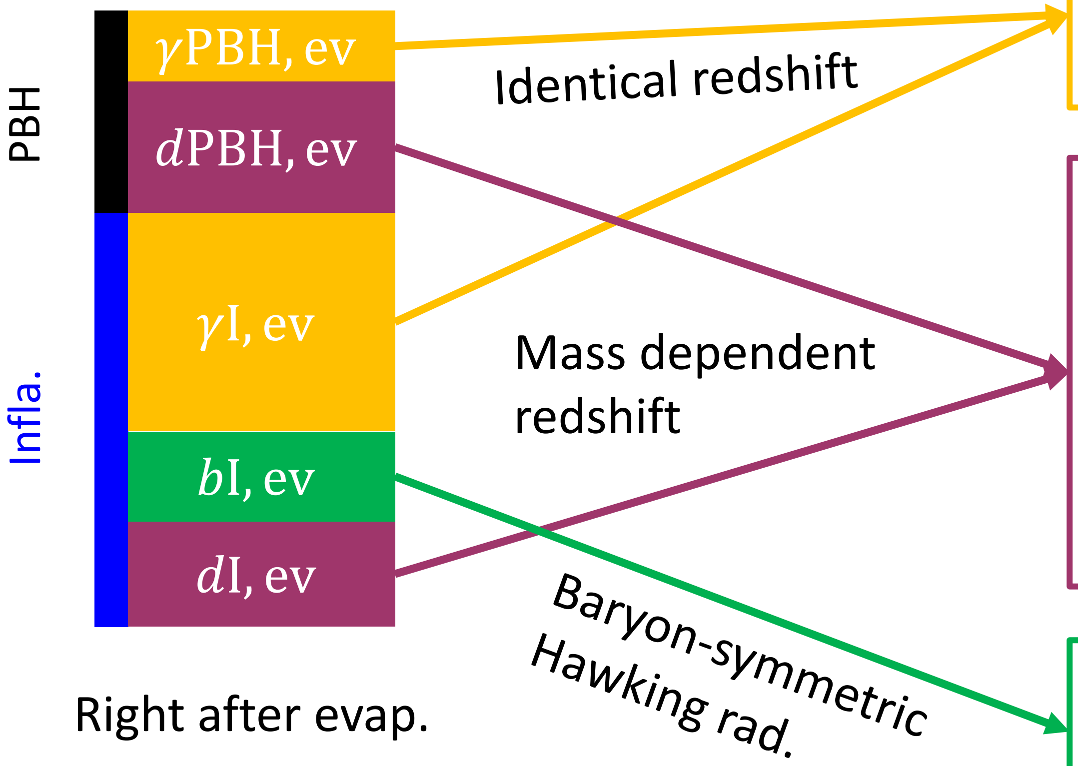
- $f_{PBH} \propto \beta \times M_{PBH,if}^{-3/2}$
  - Steeply decreasing f_{PBH} for larger $M_{PBH,if}$
- Practical reformation happens only for $M_{PBH,if} \lesssim 10^2$ g
  - High scale inflation
  - Fragmented PBHs from FOPT
- Cannot cover the DM window ☹

Simplified case study – Particle composition



Simplified case study – Particle composition

Effective Hawking d.o.f. $g_{H,X}$



Right after evap.

THK et.al. (2024)

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

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

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

At present.