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)


ODEON

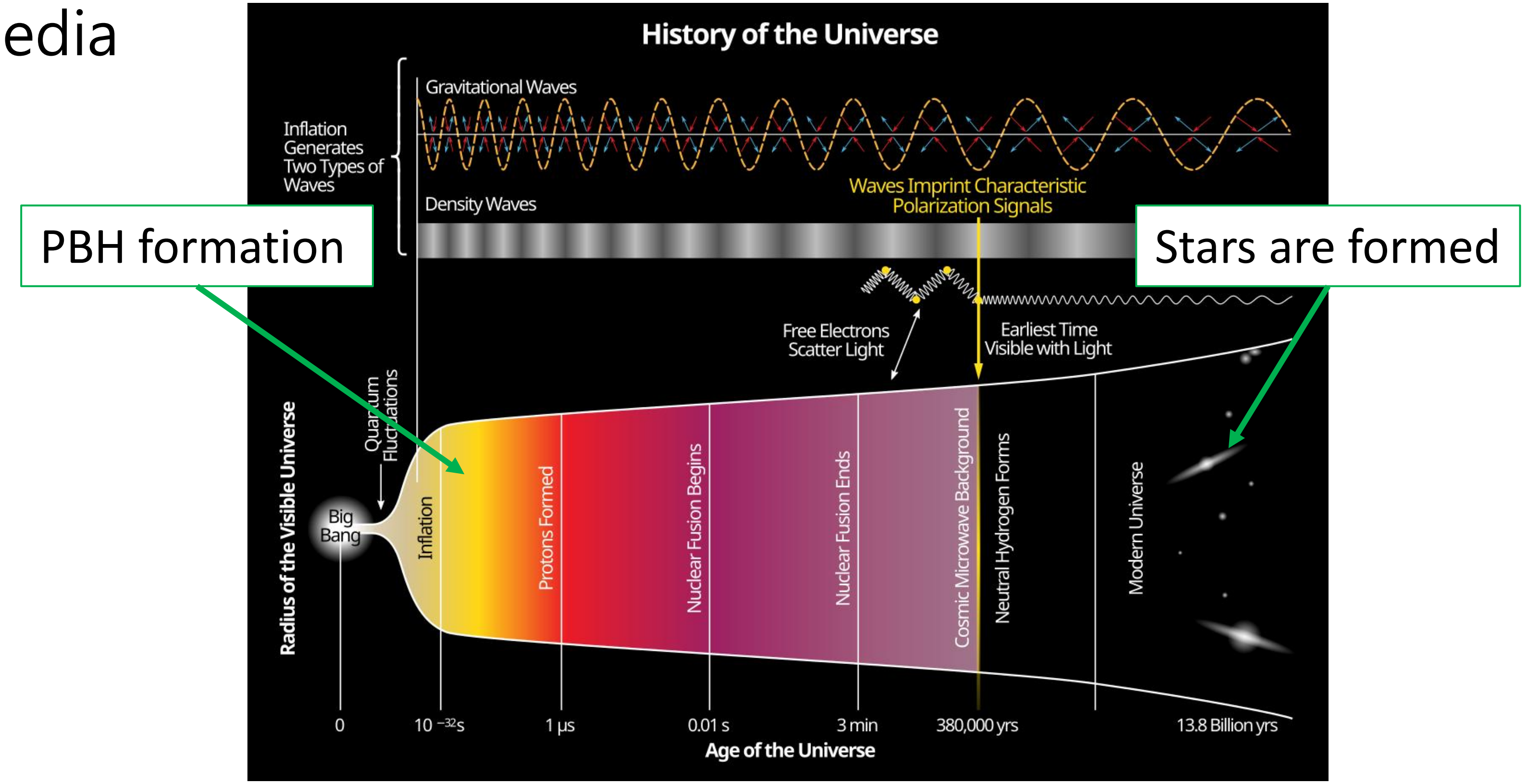
Abstract

"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

Introduction: PBHs

- “PBHs are *hypothetical* black holes that formed soon after the Big Bang”
  - Wikipedia



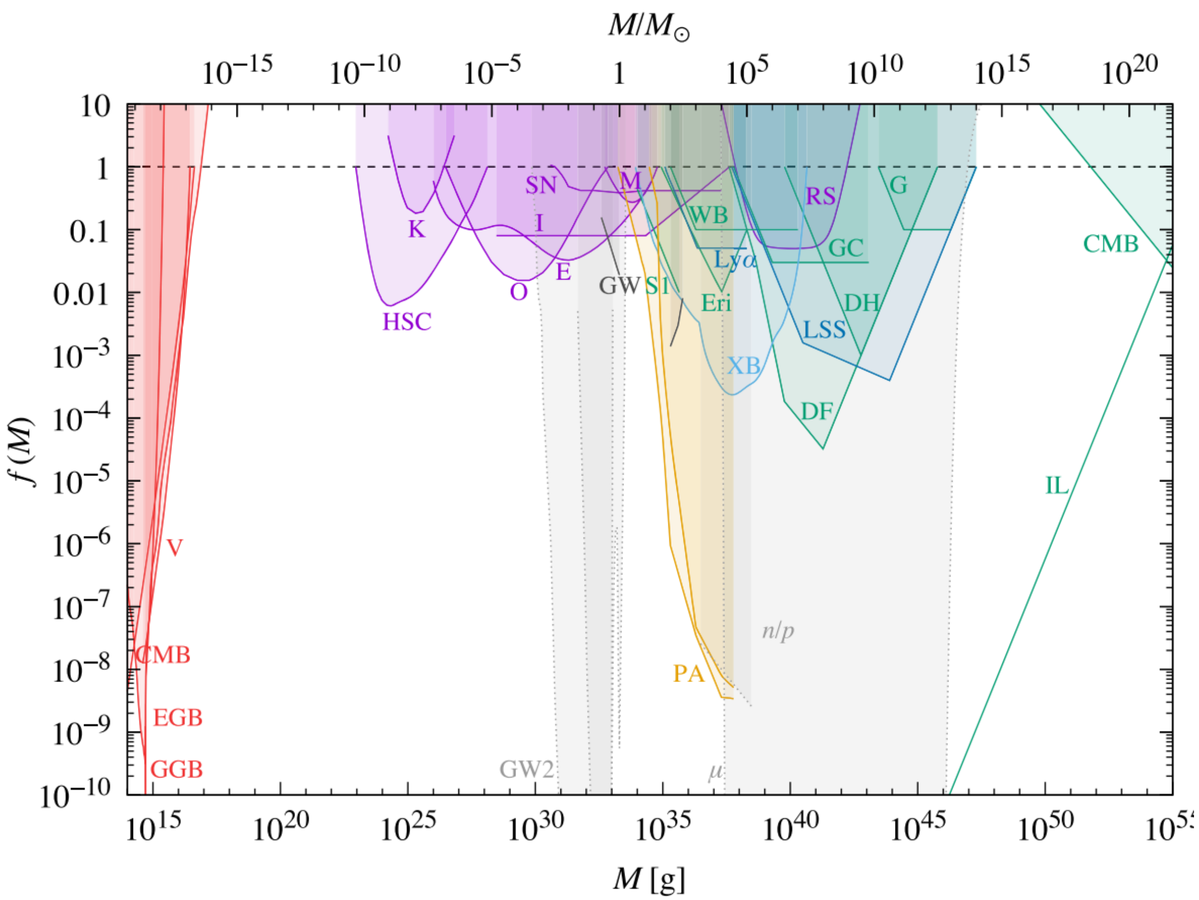
https://en.wikipedia.org/wiki/Cosmic_inflation#/media/File:History_of_the_Universe.svg

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

Introduction: PBHs

Carr et. al. (2021)

- Constraint plot for wide range of masses



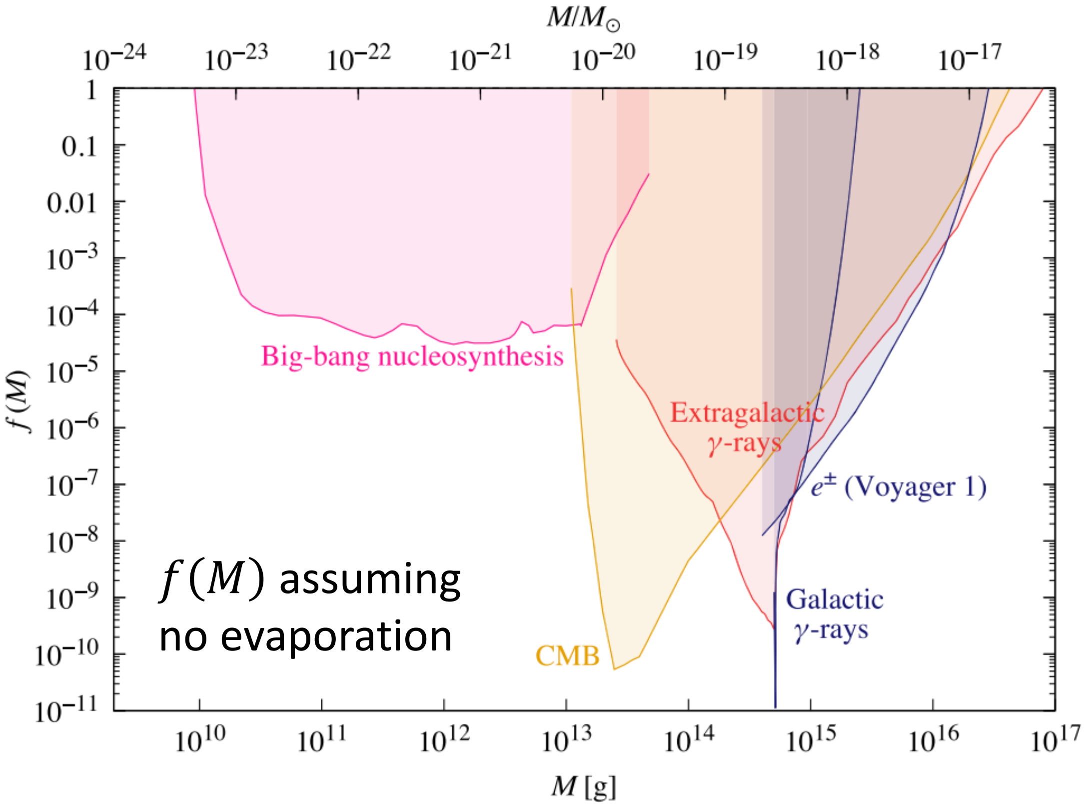
- Constraints
  - Evaporation
  - Lensing
  - Gravitational waves
  - CMB polarization (accretion)
  - Dynamical
  - CMB dipole
- Candidates of
  - Dark matter
  - Microlensing event
  - Binary black hole mergers
  - Super massive black holes

Introduction: PBHs

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

Carr et. al. (2021)

- 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.

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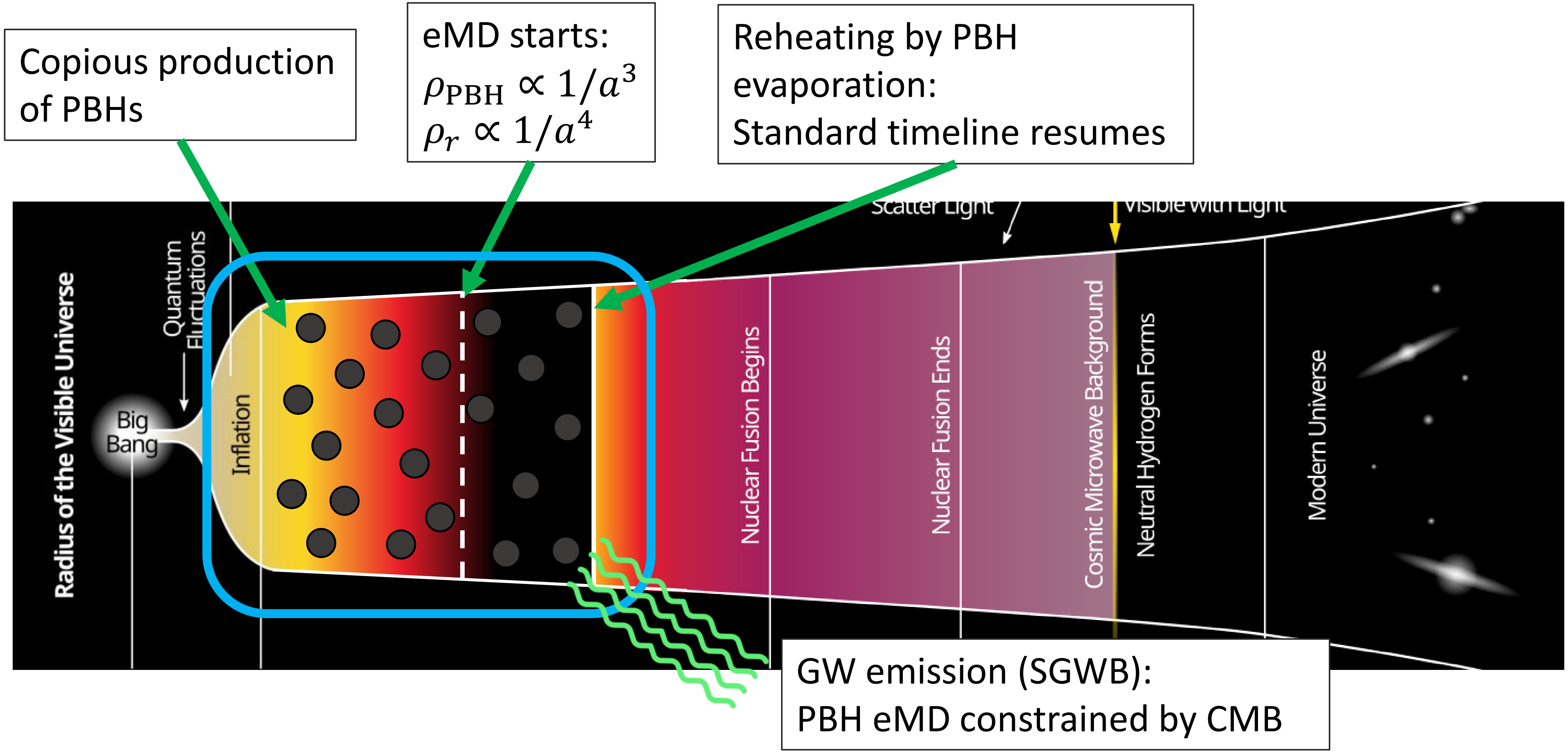
Cosmic timeline of eMD by PBHs

= PBHs



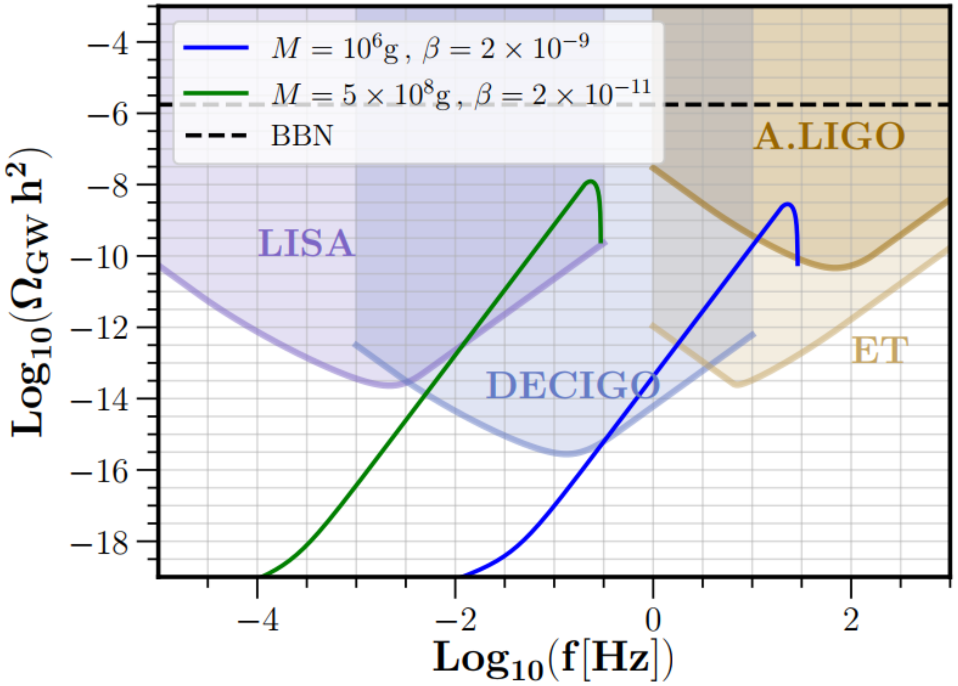
Cosmic timeline of eMD by PBHs

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

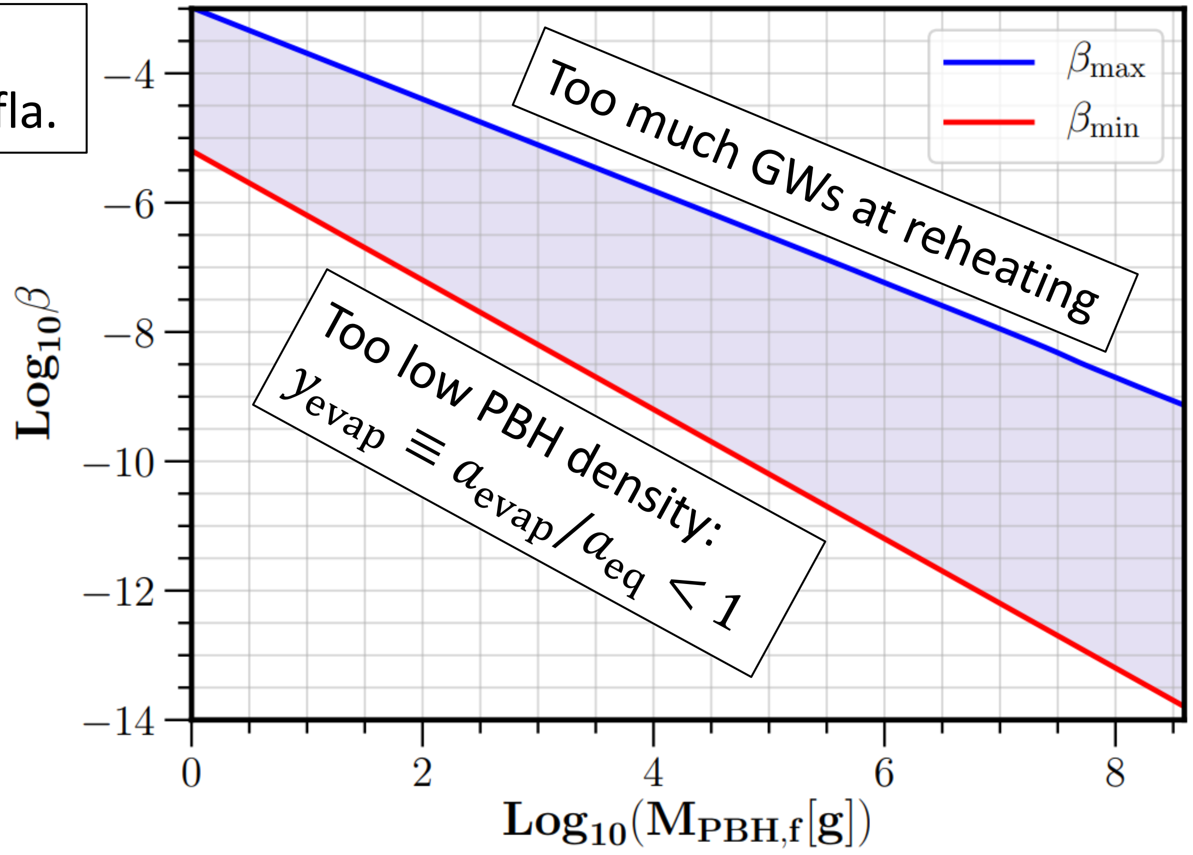


Cosmic timeline of eMD by PBHs

Domenech et. al. (2021)

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

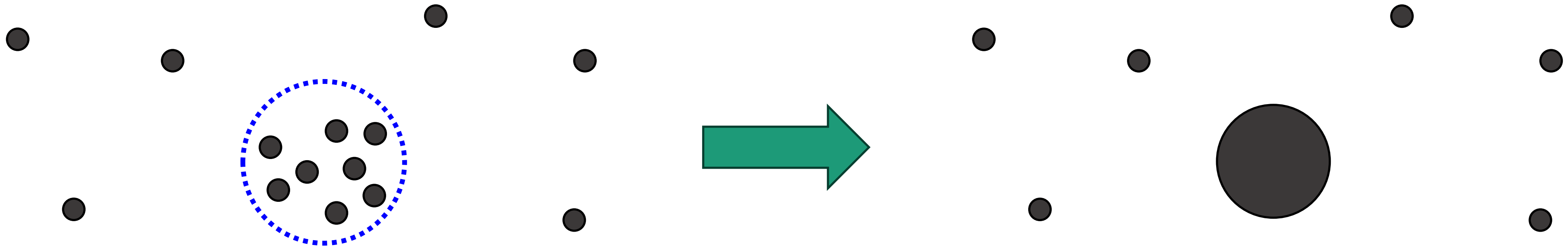
Too light to be produced in infla.



Harms BBN prediction

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

PBH reformation during eMD

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

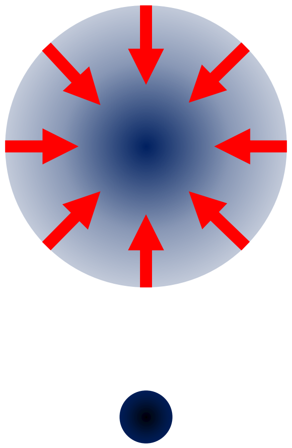
- Gravitational collapse in MD
  - No pressure : Eventually any overdensity will collapse
  - But what really happens during the collapse?
  - Spatial profile of an overdensity should be homogeneous and isotropic enough
    - To fall into its own Schwarzschild radius without virialization

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

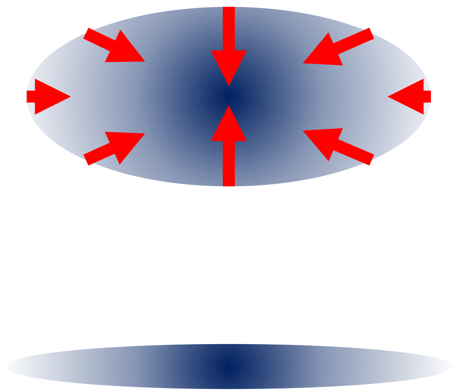
PBH reformation during eMD

Before

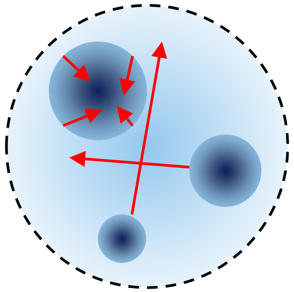
After



BH formation



“Pancake” collapse → virialized configuration



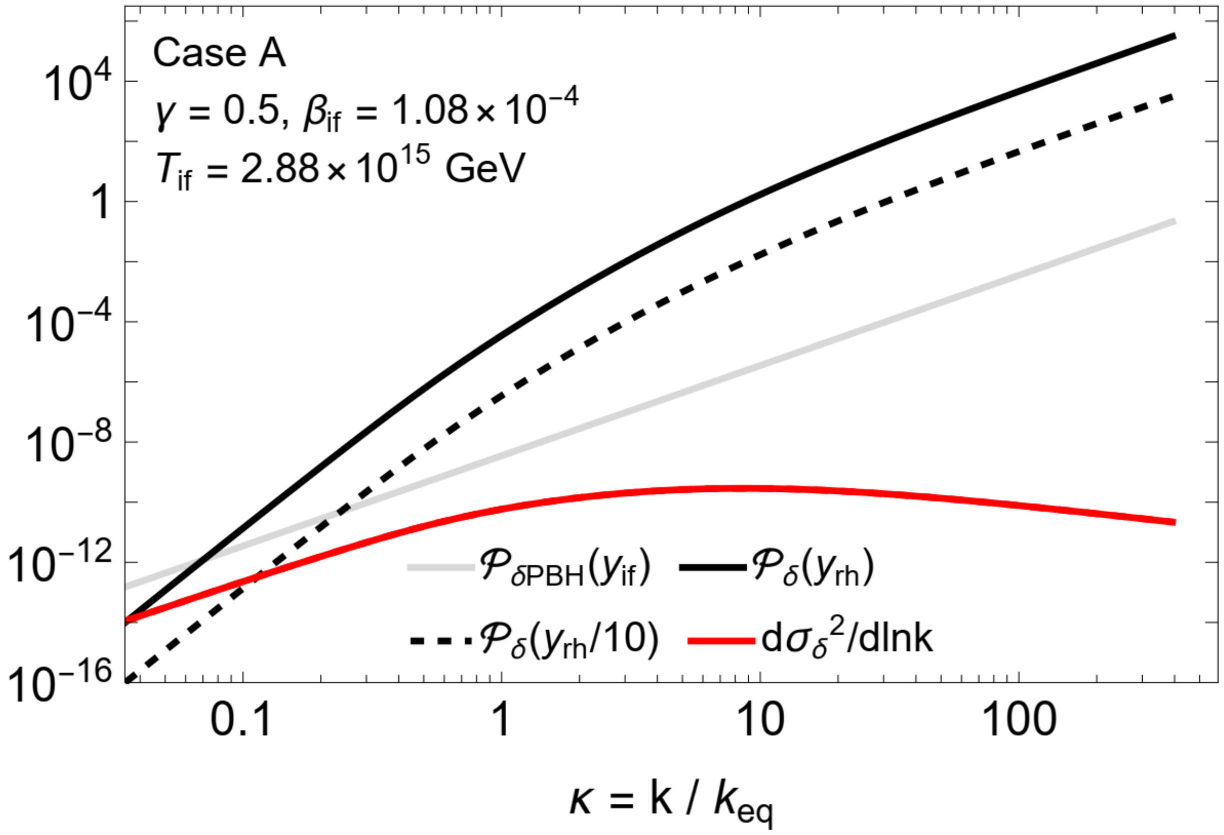
??? (not well known)

- 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

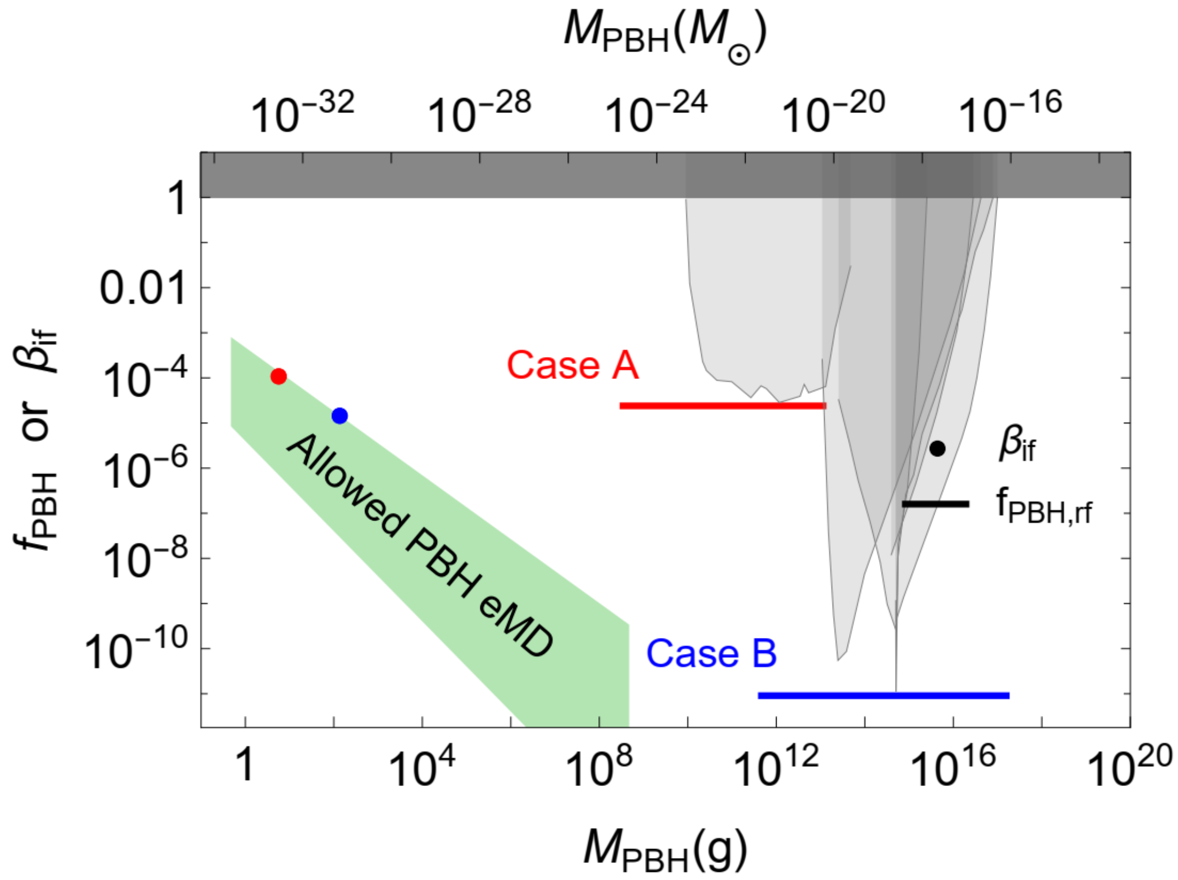
- Density power spectrum during eMD and resulting σ



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

PBH reformation during eMD

- Reformed PBH population case study

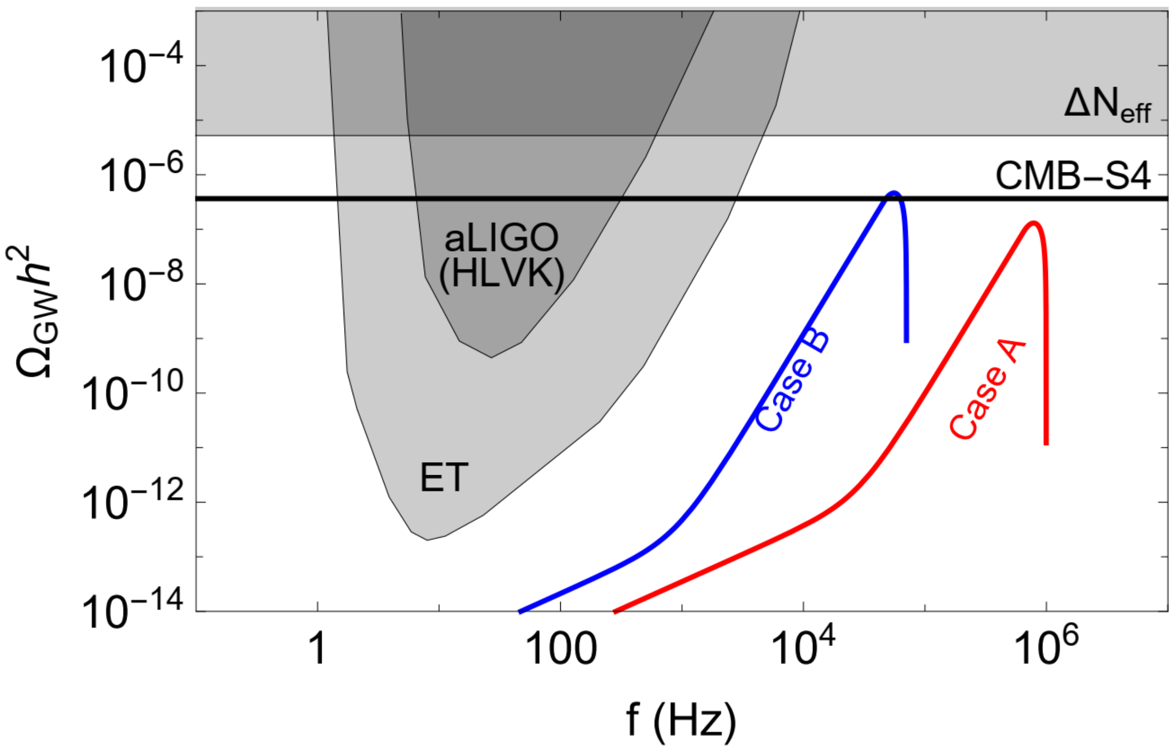


Case	T_{if} (GeV)	β_{if}	γ	f_{PBH}
A	2.88×10^{15}	1.08×10^{-4}	0.5	2.40×10^{-5}
B	5.89×10^{14}	1.45×10^{-5}	0.5	9.05×10^{-12}

- 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

- Smooth 0th order FLRW Universe + 1st order perturbations

- Gauge-invariant combination: 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 $\boldsymbol{\nu}$ and symmetric $\boldsymbol{b}$), $\boldsymbol{b}$ (asymmetric part only), and $\boldsymbol{d}$.

- Adiabatic condition : Single source

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

Cosmological perturbations

- Isocurvature perturbations : Multiple sources (PBHs in this work)

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

  - Constrained by CMB observation (Planck 2018).

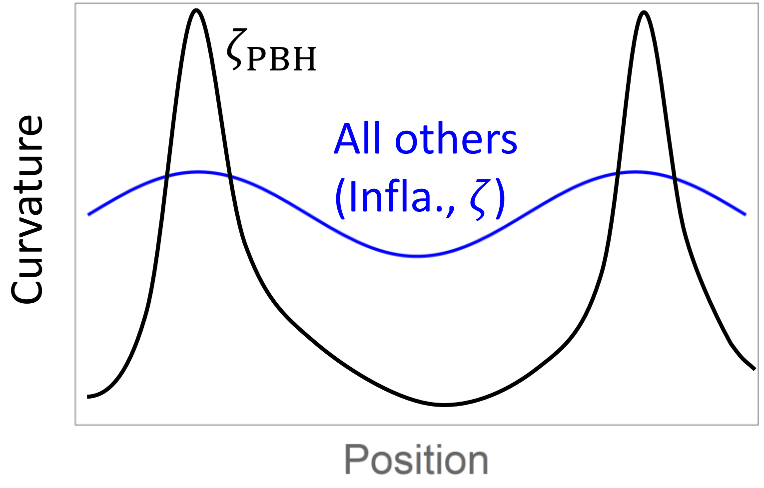
- This work : "PBH evaporation generates isocurvature perturbations"

  → **<u>CMB constrains evaporating PBHs through isocurvature perturbation.</u>**

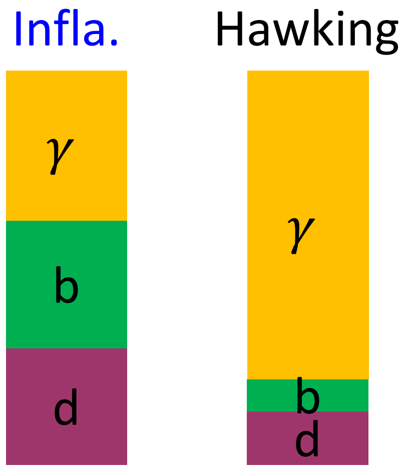
  - PBH distribution ≠ Average (adiabatic mode) : "PBHs are biased"
  - Composition : Hawking radiation ≠ Inflationary reheating products (background)

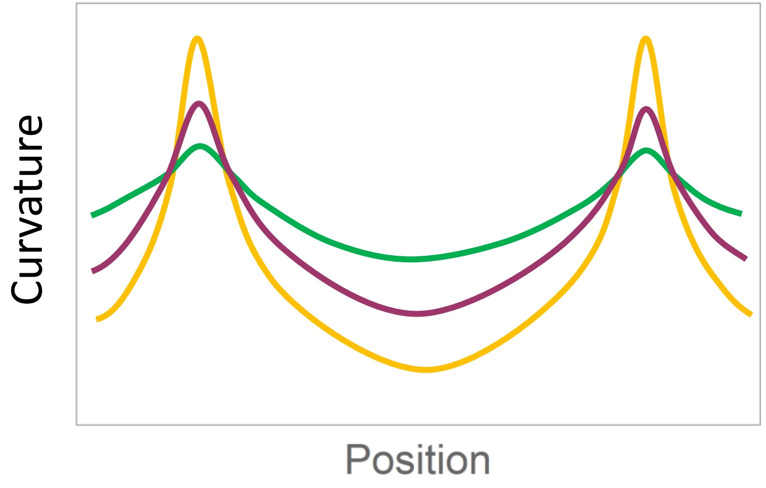
PBHs as an isocurvature source

Distribution at cosmological scale



Example particle composition:

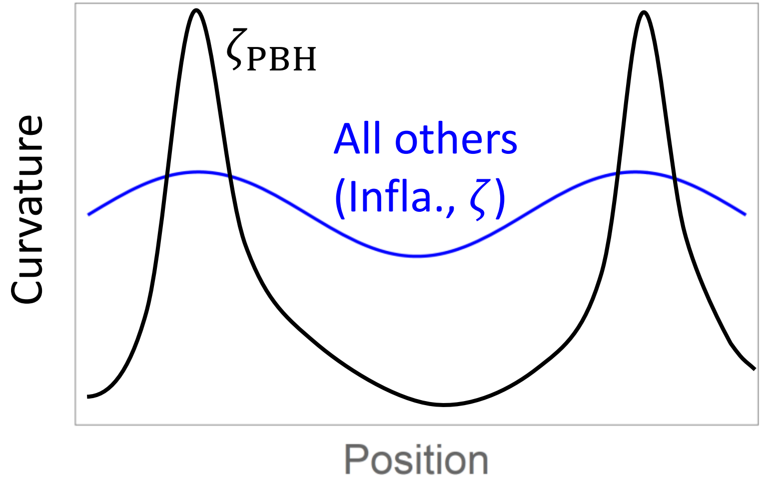




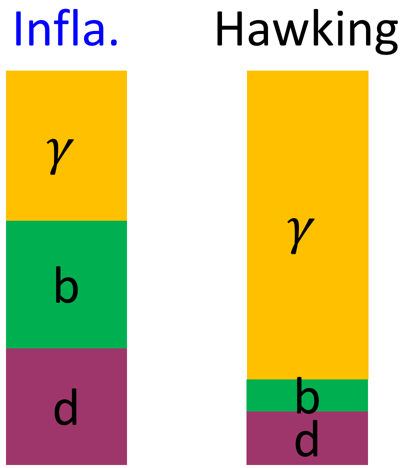
- After evaporation, each of γ, b, and d gets different perturbation
  - Isocurvature perturbations are generated.

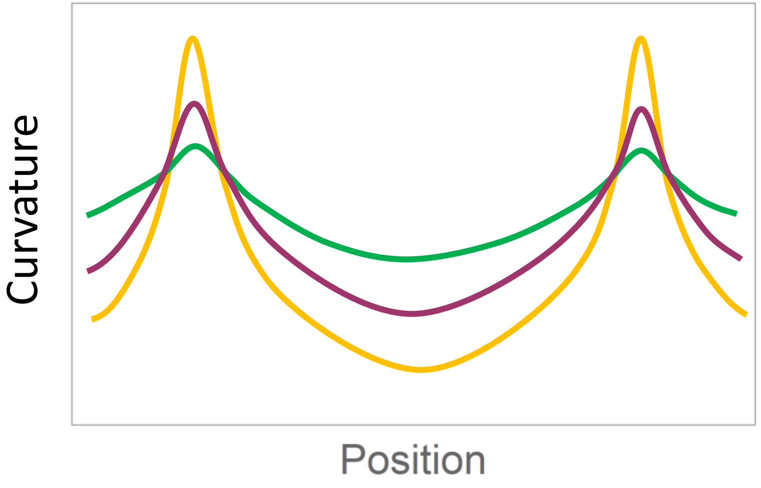
PBHs as an isocurvature source

Distribution at cosmological scale



Example particle composition:





- Again, required two conditions are :
  - PBHs are biased ("black curve should be different from the blue curve")
  - Particle composition should be different ("two curves should not sum up as one")

PBHs as an isocurvature source

- The key equation : Isocurvature between X and Y is

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

PBH contribution to the present X and Y should be different

PBHs are biased.

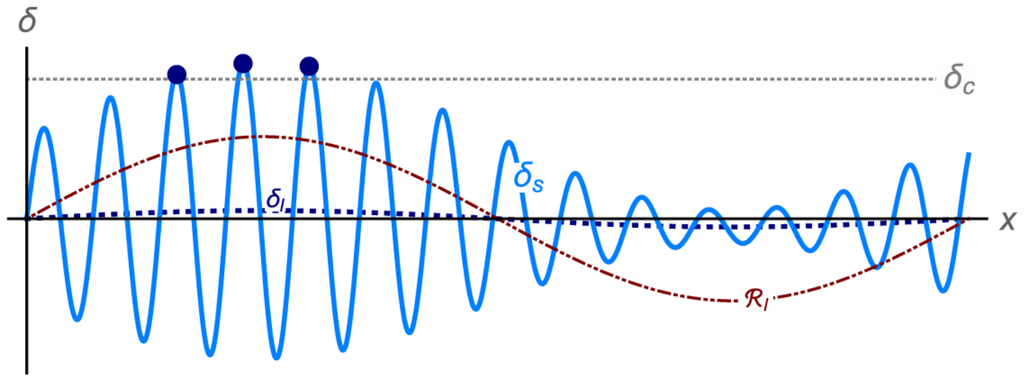
Branching ratio :
Hawking radiation $\neq$ Inflationary reheating

Simplified case study

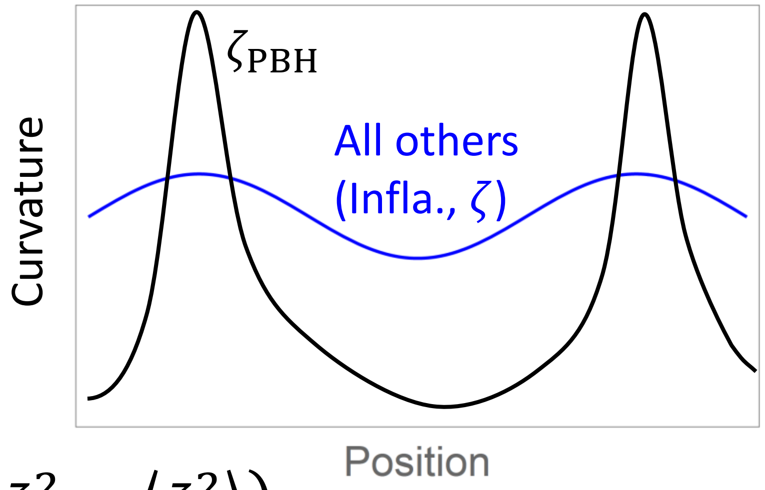
- Concrete demonstration : Example constraint for evaporating PBHs
  - PBH bias
    - Primordial non-Gaussianity of $f_{\mathrm{NL}} \sim \mathcal{O}(0.01 - 0.1)$
  - Particle model
    - Baryon-symmetric Hawking radiation. No net baryons from PBHs; $\bar{\rho}_{b\mathrm{PBH},0} = 0$
    - Single scalar DM, out of equilibrium (no longer converts to SM)

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

Simplified case study – PBH bias

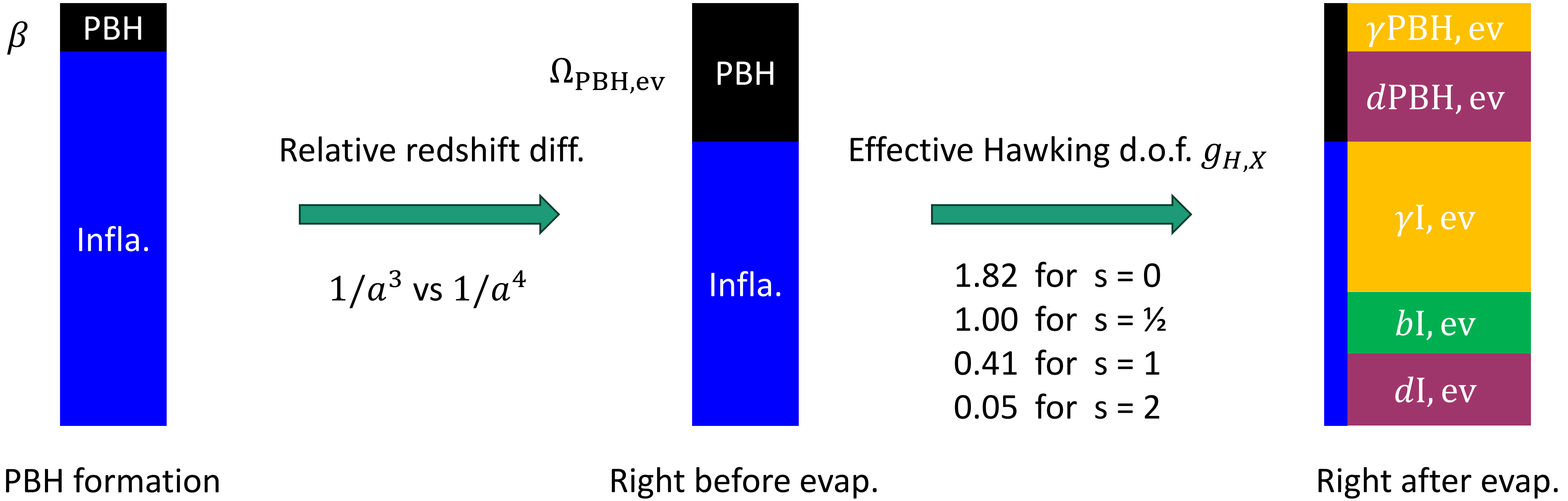


Distribution at cosmological scale

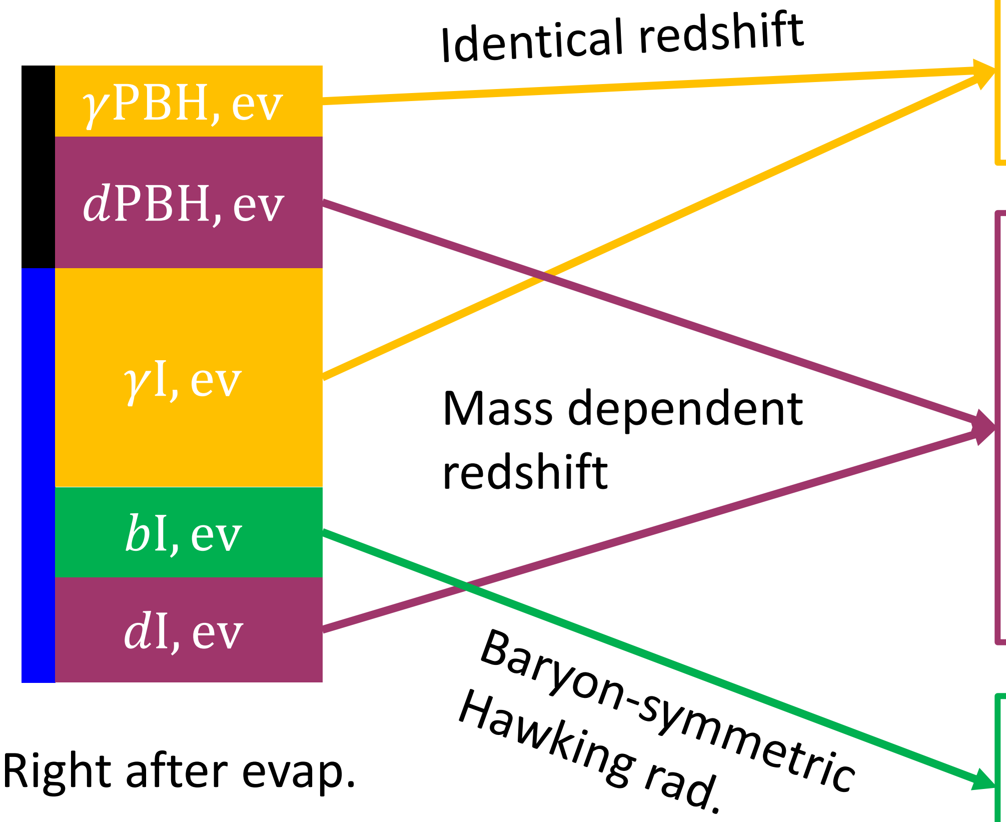


- Primordial non-Gaussianity : $\zeta = \zeta_G + (3/5) f_{\rm NL} \left(\zeta_G^2 - \langle \zeta_G^2 \rangle\right)$
  - Peak-background separation : $\zeta_s = \left(1 + 2 f_{\rm NL} \zeta_{l,G}\right) \zeta_{s,G} + f_{NL} \left(\zeta_{s,G}^2 + \langle \zeta_{s,G}^2 \rangle\right)$
    - Long mode 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 – Particle composition



Simplified case study – Particle composition



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)

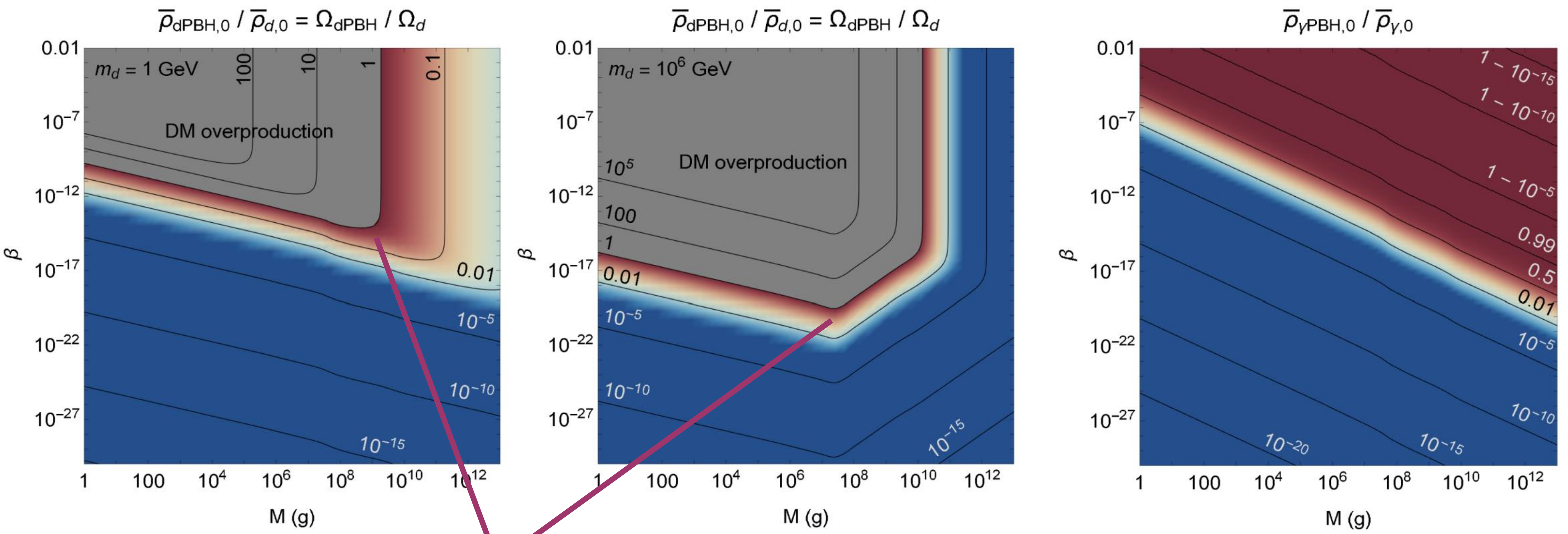
- $$\Omega_{d\mathrm{PBH}} \propto \Omega_{\mathrm{PBH,ev}} \times g_{H,d} \times \begin{cases} m_d^{-1} M_{\mathrm{PBH}}^{-\frac{5}{2}}, & m_d > T_{\mathrm{PBH}} \\ m_d M_{\mathrm{PBH}}^{-\frac{1}{2}}, & m_d < T_{\mathrm{PBH}} \end{cases}$$
- $\frac{\bar{\rho}_{d\mathrm{PBH},0}}{\bar{\rho}_{d,0}} \simeq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

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

At present.

Simplified case study – Particle composition

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



$\frac{\bar{\rho}_{d\mathrm{PBH},0}}{\bar{\rho}_{d,0}}$ 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

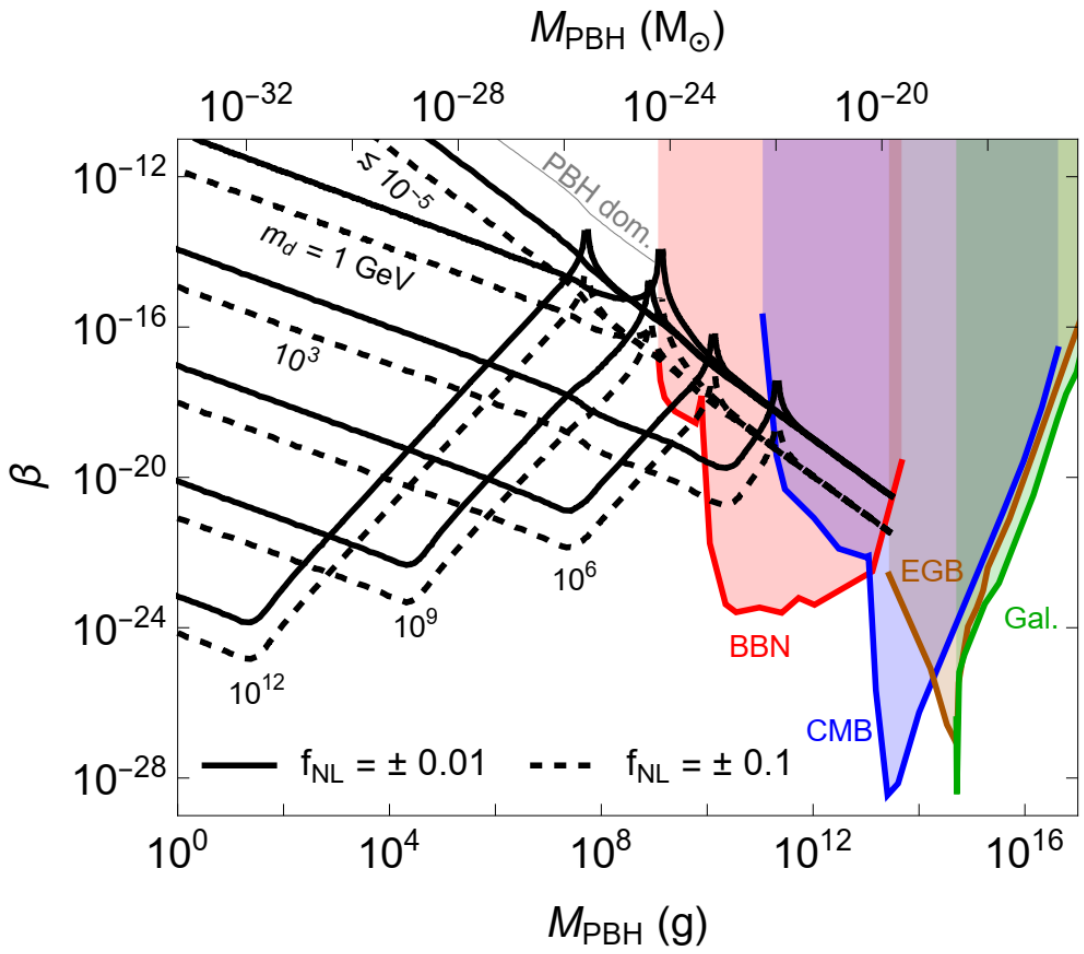
- PBH-generated isocurvature perturbation

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

- Observed quantity : Isocurvature fraction

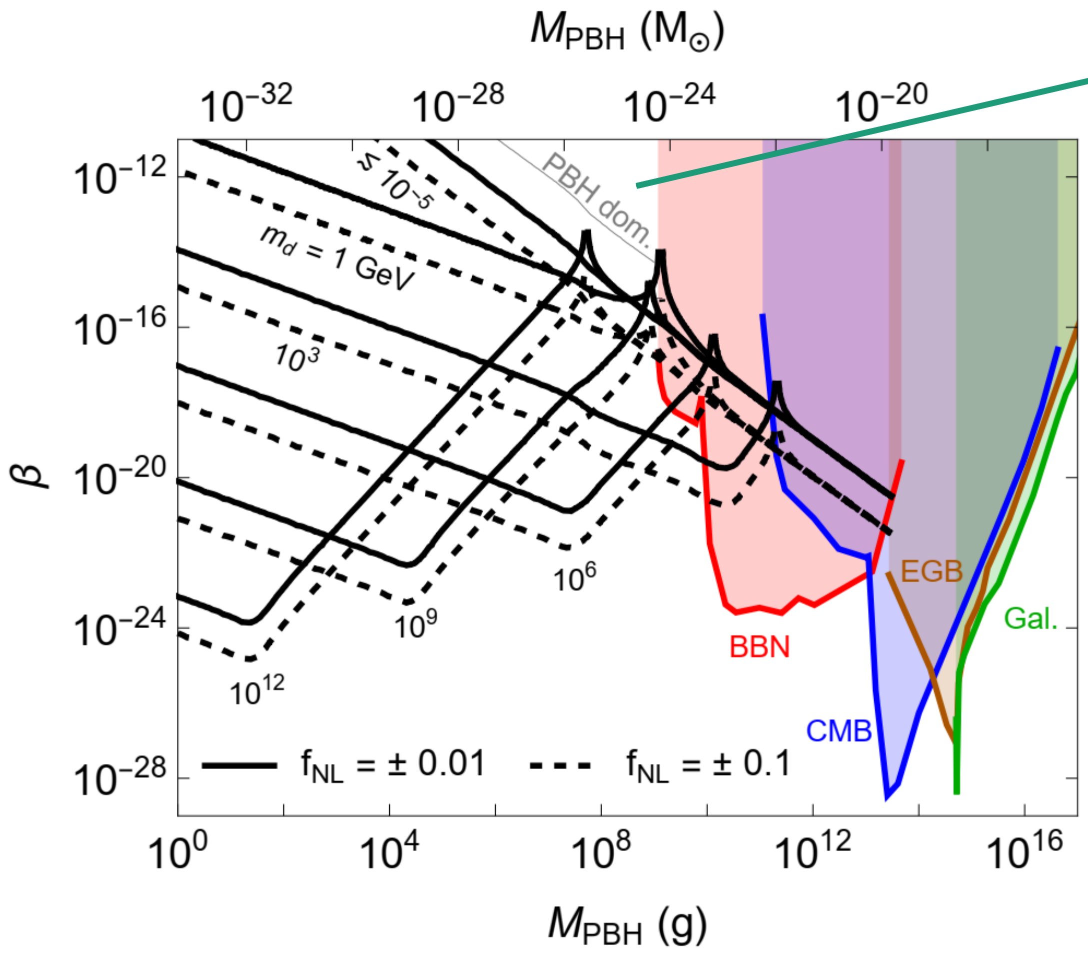
$$\beta_{\mathrm{iso}} = \frac{\mathcal{P}_S}{\mathcal{P}_\zeta + \mathcal{P}_S} = \frac{\left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2}{\zeta^2 + \left(S_{\gamma d,0} + \frac{\Omega_b}{\Omega_d} S_{\gamma b,0}\right)^2} < 0.001 \text{ (Planck 2018)}$$

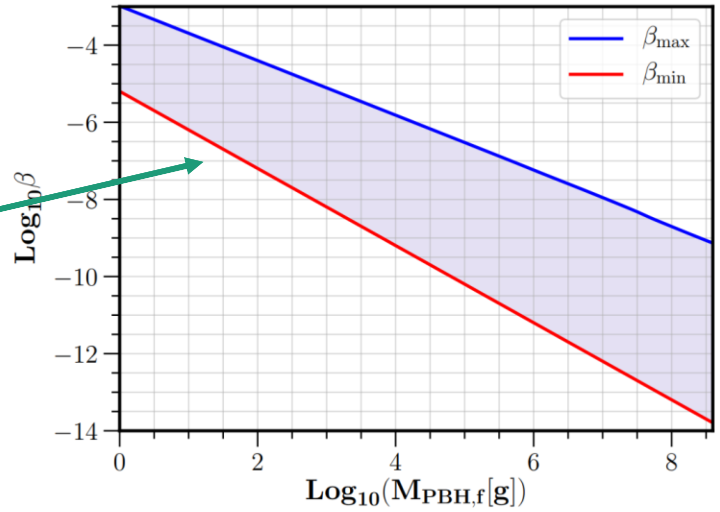
Isocurvature constraints on PBH



- Isocurvature bound on PBHs
- Past abundance for $M \lesssim 10^9$ g can now be observationally constrained
  - Depends on DM model and f_{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

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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

"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

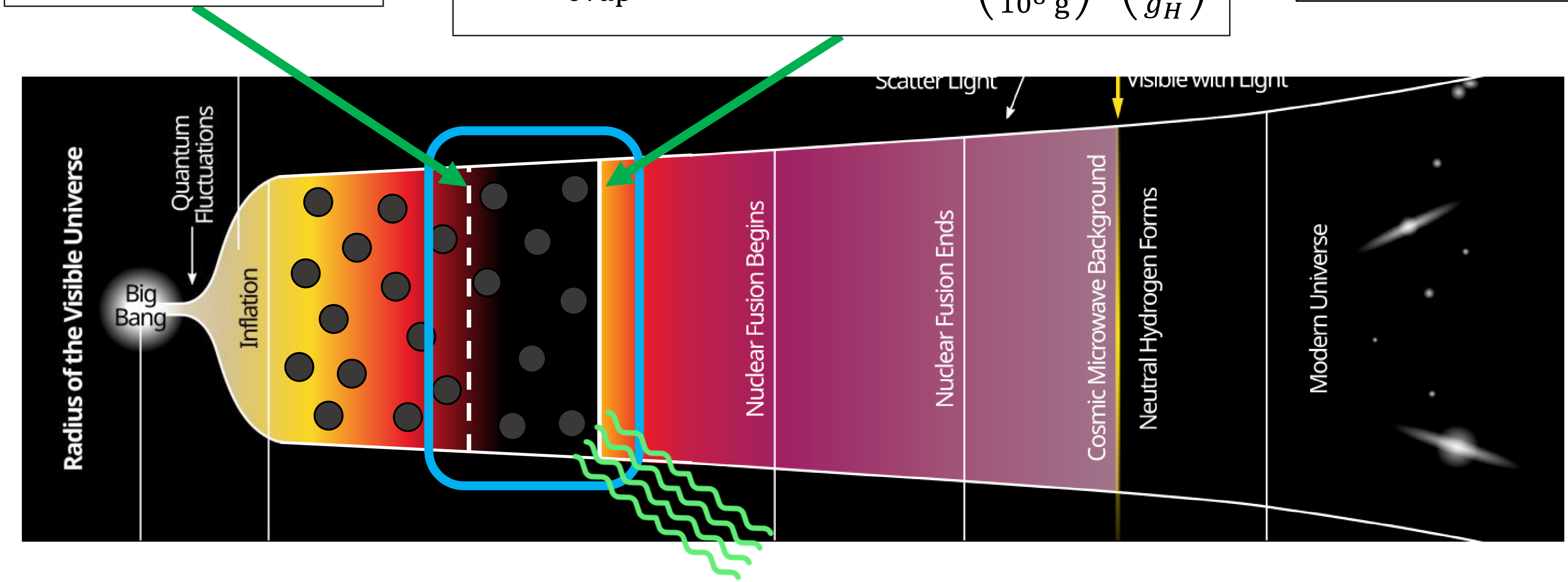
Cosmic timeline of eMD by PBHs

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

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

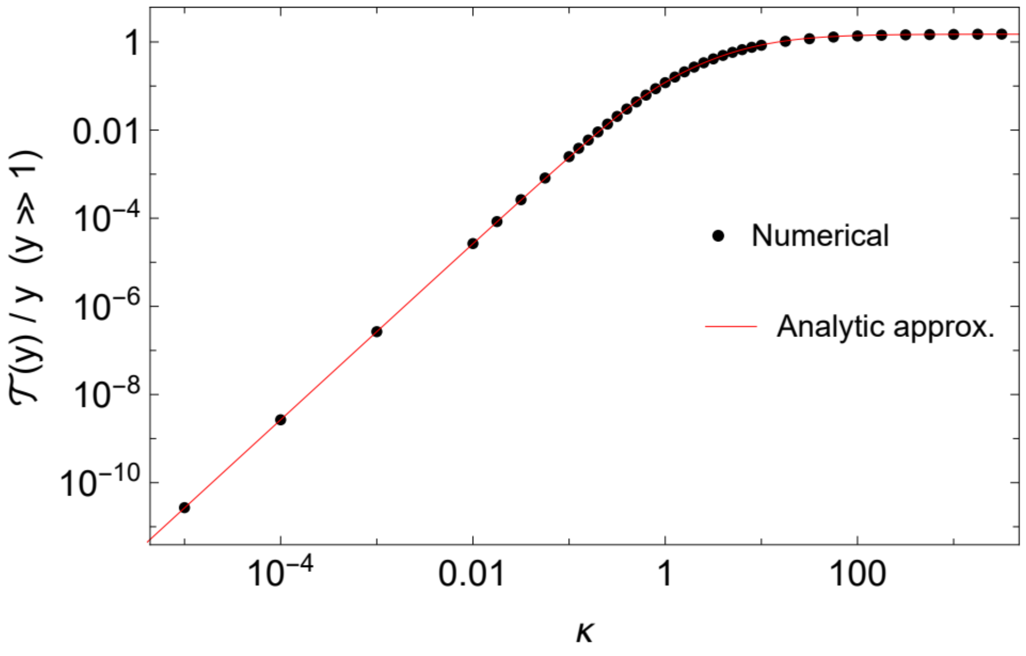
End: $\tau_{\rm evap} = 4.0 \times 10^{-4}\ {\rm sec} \times \left(\frac{M_{\rm PBH}}{10^8\ {\rm g}}\right)^3 \left(\frac{108}{g_H}\right)$

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



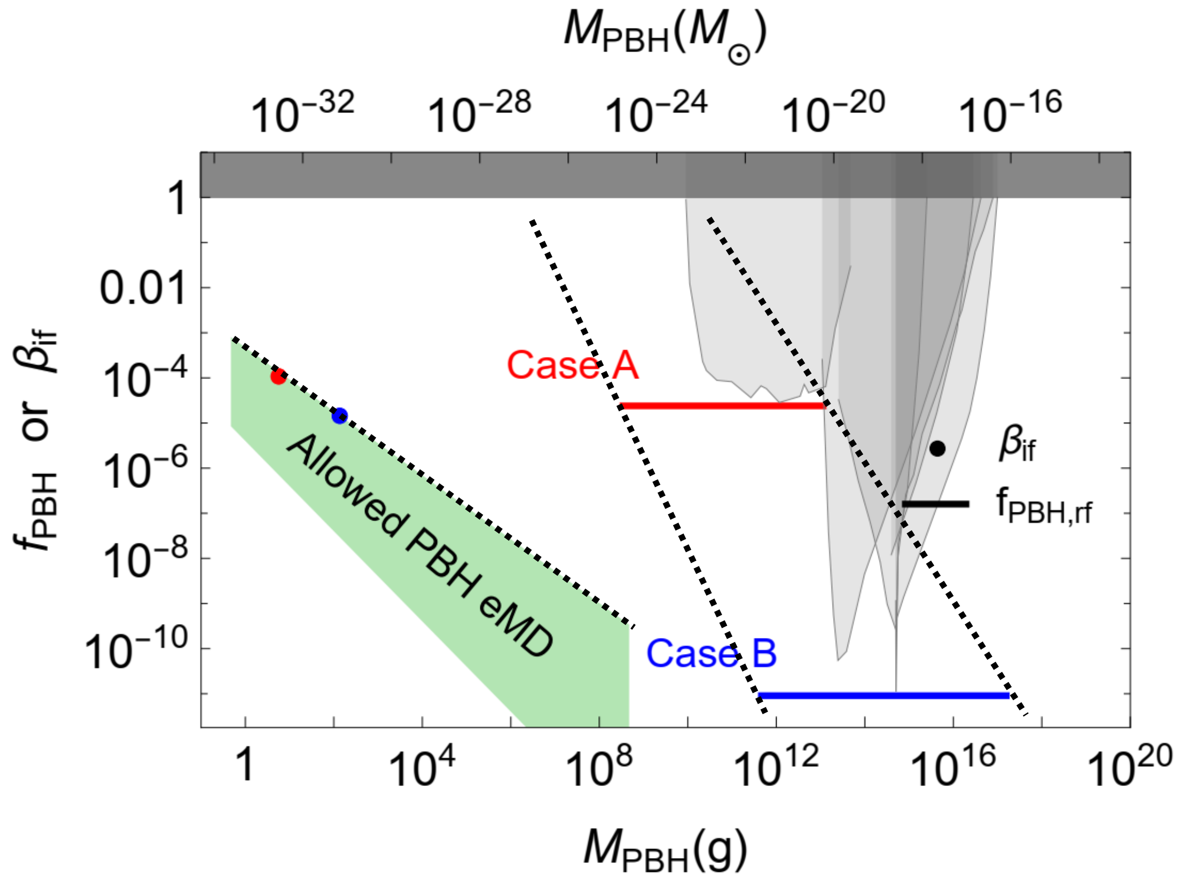
PBH reformation during eMD

- Transfer function at a given time
  - $y = a/a_{eq}$ ($\gg 1$ is shown), $\kappa = k/k_{\mathrm{eq}}$
  - At a given time, $\mathcal{T}$ is constant for $k > k_{eq}$ and decreases for smaller k.
    - $k > k_{eq}$: Short modes start to grow simultaneously when eMD starts
    - $k < k_{eq}$: Growth is delayed until they enter the horizon during eMD



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}

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