Primordial Black Hole Reformation in the Early Universe

TaeHun Kim & Philip Lu, arXiv: 2411.07469

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Abstract

- Light mass primordial black holes (PBHs) can undergo a **reformation** process if they induce an early matter-dominated phase (eMD).
- Reformation produces much heavier PBHs by gravitational collapse of PBH "gas". Reformed PBHs survive after the Hawking evaporation of original PBHs.
- This provides a possibility of **decoupling the current PBH population from the initial formation in the early Universe**.

Outline

- Introduction
- Cosmic timeline of eMD by PBHs
- PBH reformation during eMD & Gravitational wave signals
- PBH reformation after reheating
- Summary & Conclusion

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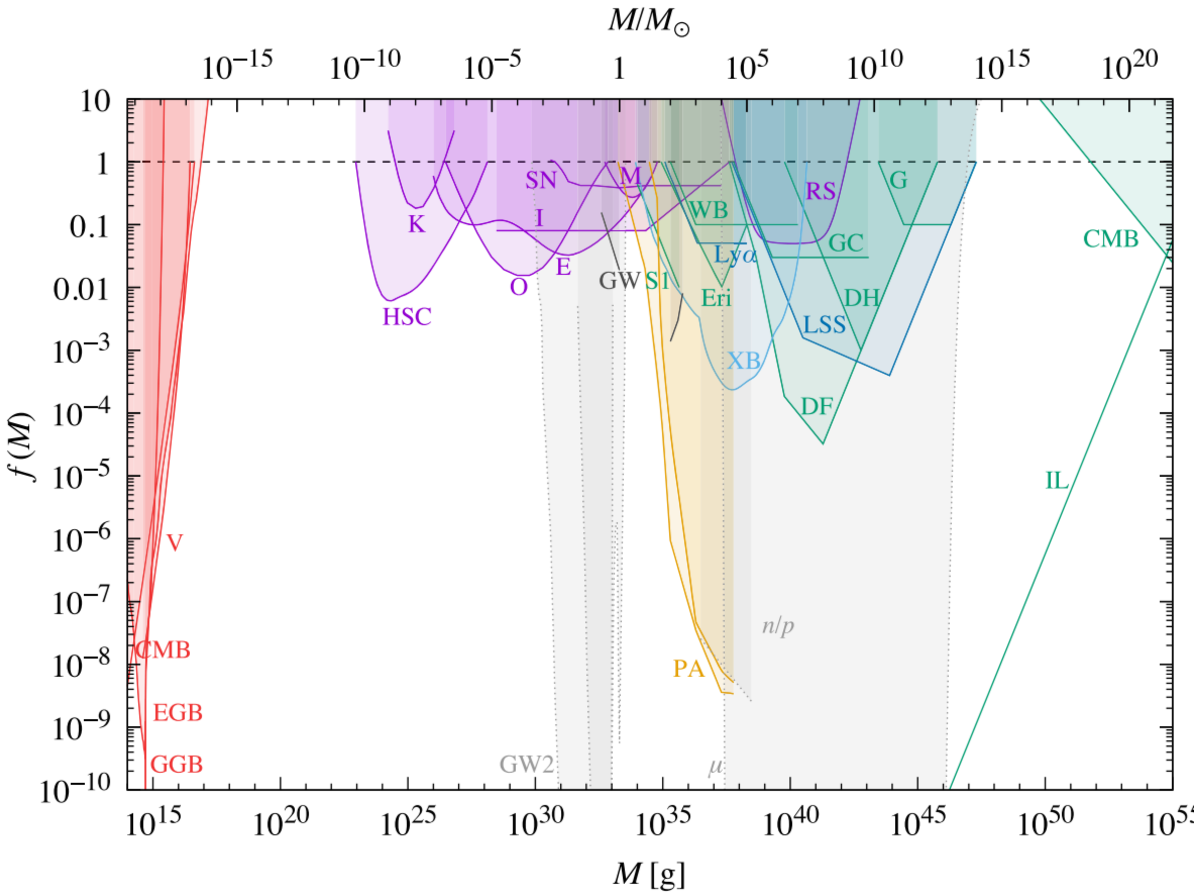
- $1\,M_\odot \sim 10^{33}$ g

Introduction

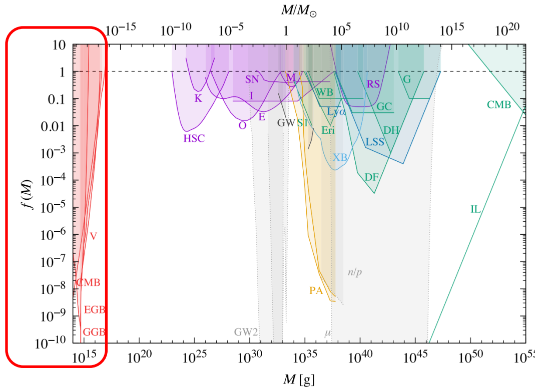
Carr et. al. (2021)

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



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

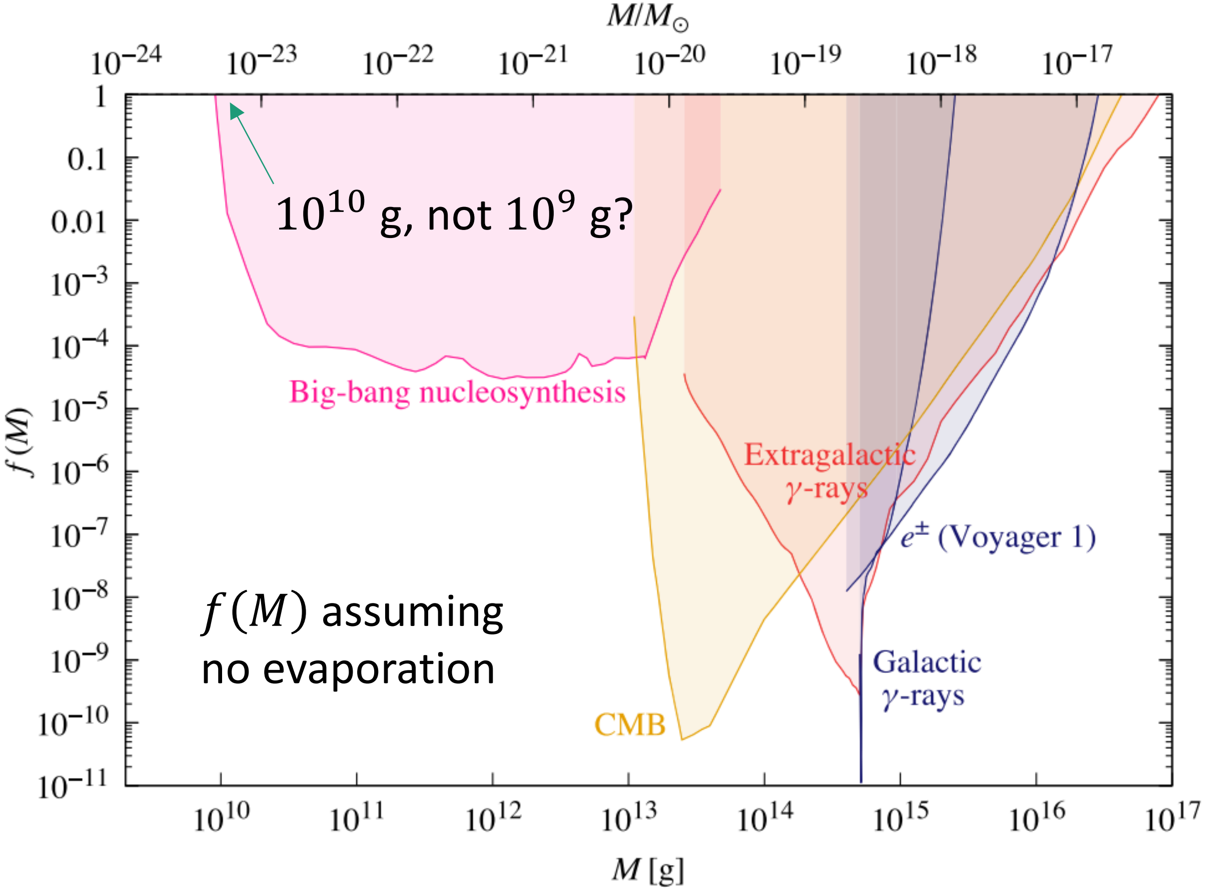
Introduction



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

Introduction

Carr et. al. (2021)

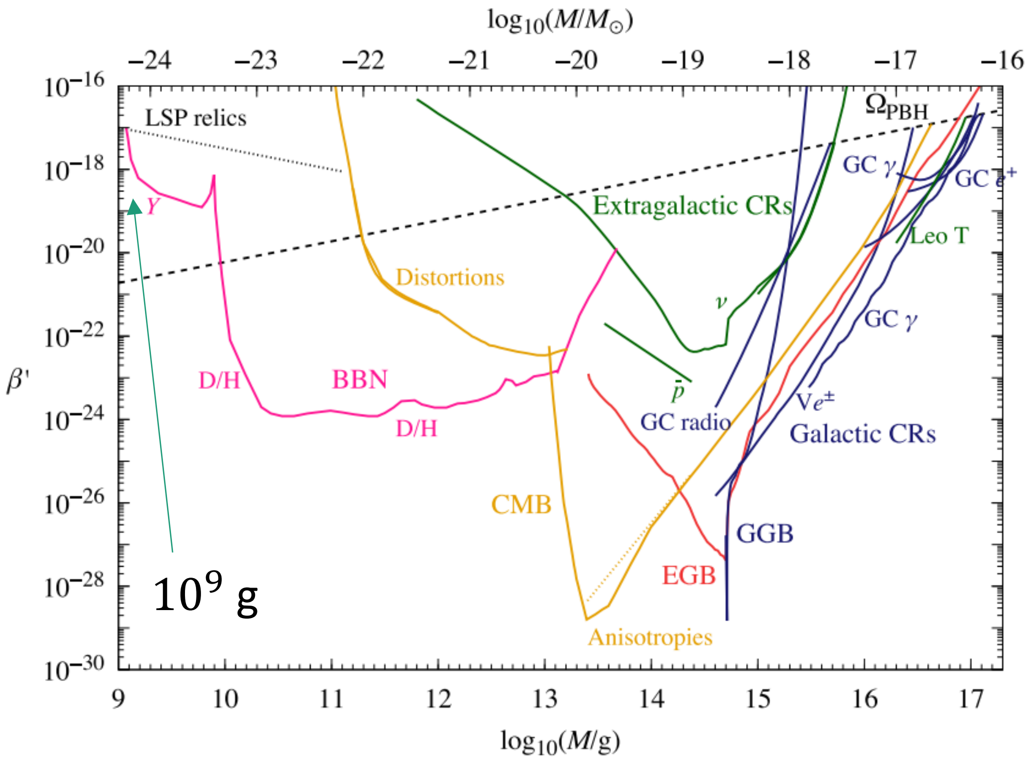
- $f(M)$ is not meaningful for light mass PBHs. They have all been evaporated.
- $\beta(M)$ = energy fraction at the formation $\simeq$ collapse probability

$$\beta'(M) = \gamma^{1/2}\left(\frac{g_{*i}}{106.75}\right)^{-1/4}\left(\frac{h}{0.67}\right)^{-2}\beta(M)$$

PBHs with $\boldsymbol{M \lesssim 10^9}$ g are unconstrained.

They could even once **dominated the Universe**.

Let's see the impact on cosmology.



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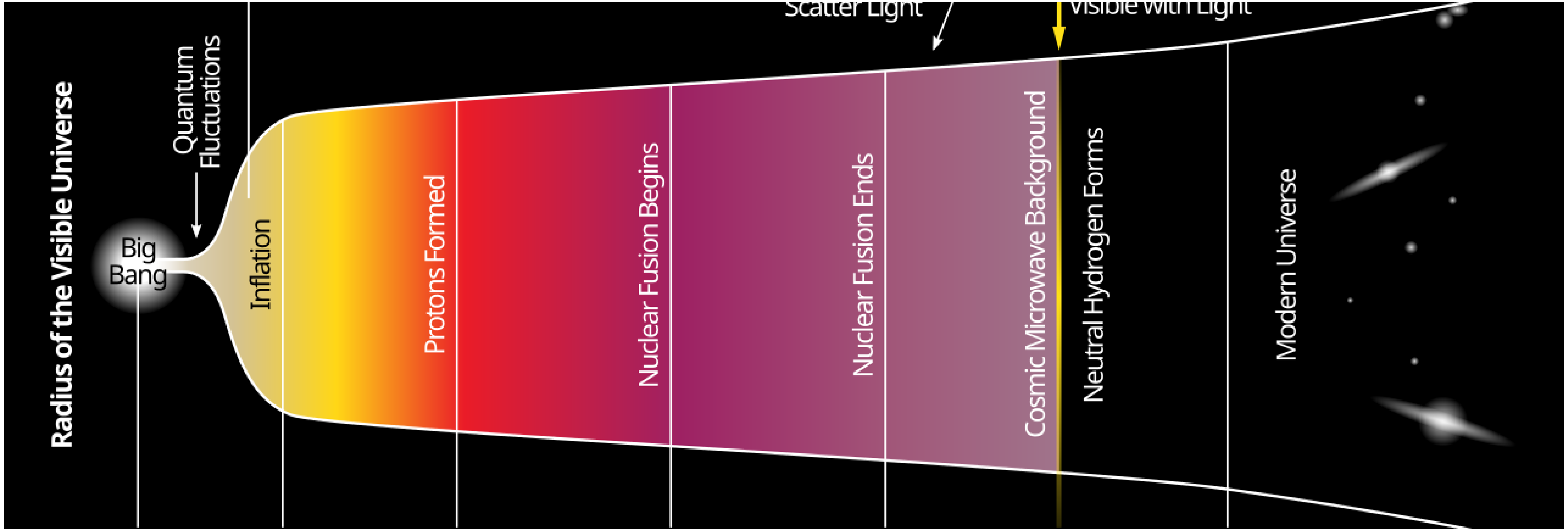
Cosmic timeline of eMD by PBHs

- Standard cosmic timeline



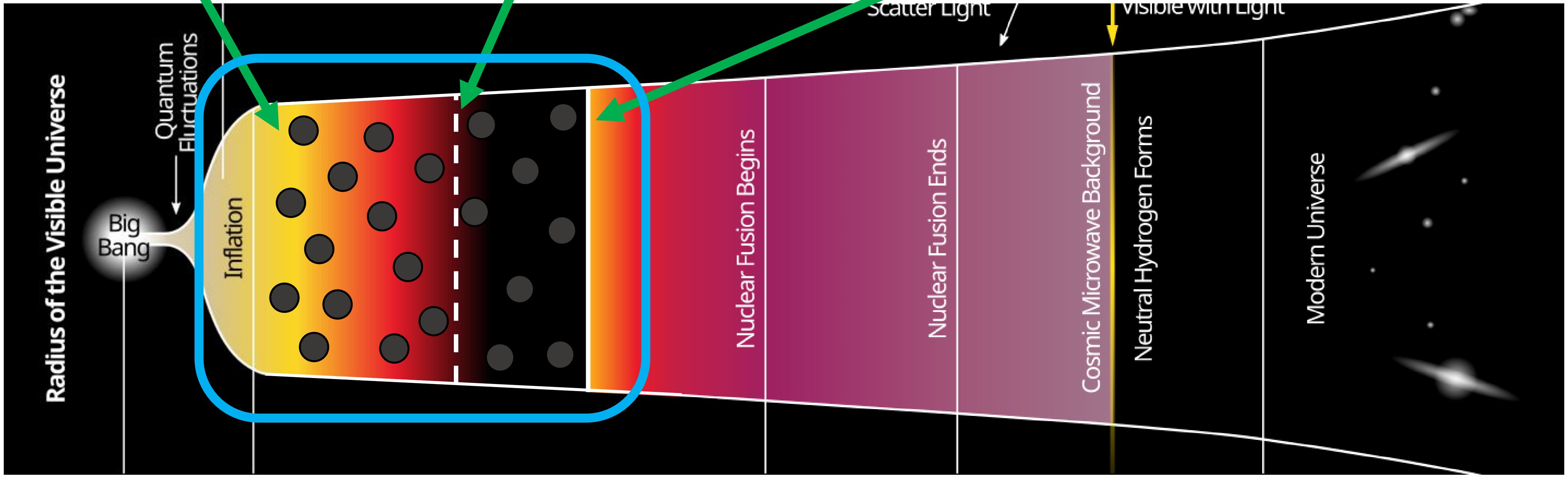
Cosmic timeline of eMD by PBHs

= PBHs

Copious production of PBHs

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

Reheating by PBH evaporation:
Standard timeline resumes



Cosmic timeline of eMD by PBHs

- "if" = Initial formation (opposed to reformation)
- "eq" = PBH-radiation equality
- g_H = eff. Hawking d.o.f.

- eMD by PBH is characterized by:
  - $\beta_{\rm if}$: Energy fraction of PBHs at the initial formation ($\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}$ at formation)
    - Determines how fast eMD starts. $\rho_{\rm PBH} \propto 1/a^3$ vs. $\rho_r \propto 1/a^4$

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

  - $M_{\rm PBH}$: Mass of initially formed PBHs
    - Determines how late eMD ends (lifetime of PBH).

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

  - $y_{\rm evap} \equiv a_{\rm evap}/a_{\rm eq} \gg 1$ characterizes a successful eMD.

Cosmic timeline of eMD by PBHs

- “RH” = Reheating
- g_* = eff. energy d.o.f.
- g_H = eff. Hawking d.o.f.

- Reheating by PBH evaporation

$$T_{RH} \simeq 2.8 \times 10^{10}\mathrm{GeV} \times \left(\frac{M_{\mathrm{PBH}}}{1\ g}\right)^{-3/2} \left(\frac{g_*(T_{\mathrm{RH}})}{106.75}\right)^{-1/4} \left(\frac{g_H}{108}\right)$$

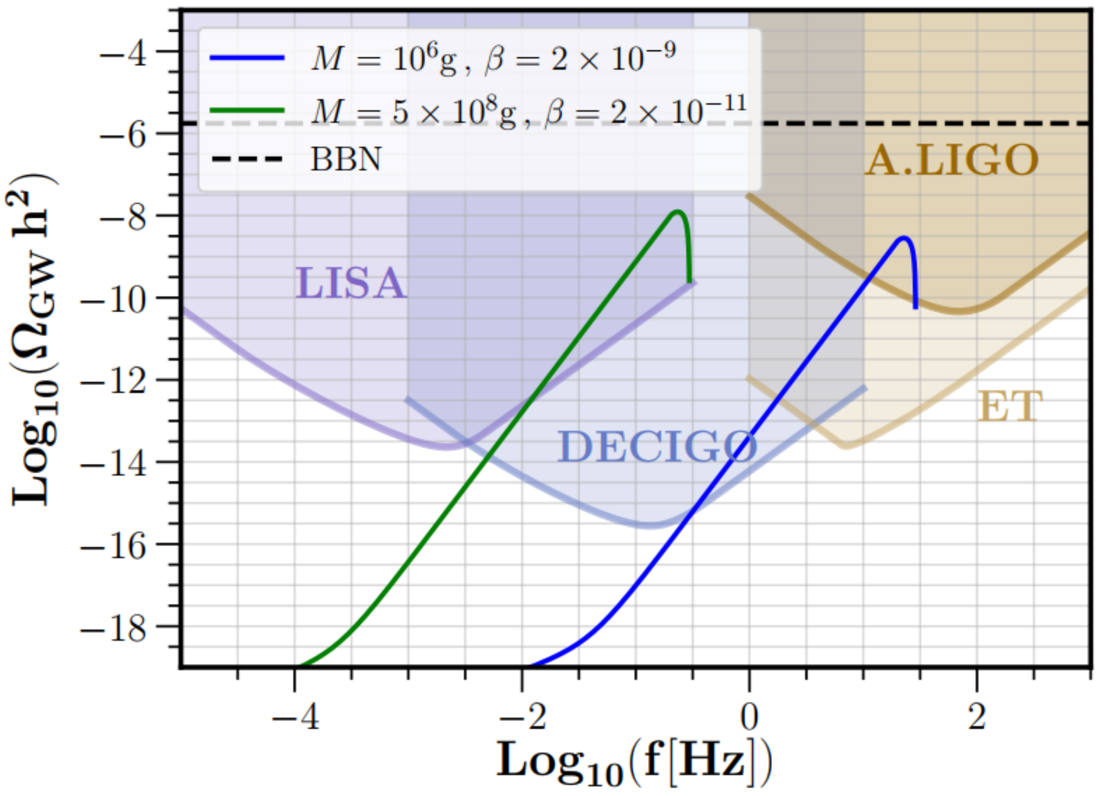
Inomata et. al. (2021)
Domenech et. al. (2021)
…

- GW emission at the reheating
  - Gravitational potential held by each PBH begin to oscillate once PBHs disappear and become radiations. Propagating scalar-induced GWs → SGWB.

Cosmic timeline of eMD by PBHs

Domenech et. al. (2021)

- GW spectrum
  - Highly blue tilted; peaks at the wavelength corresponding to the average separation of PBHs
- This free streaming energy density is constrained by $\Delta N_{\rm eff} \lesssim 0.5$ at CMB

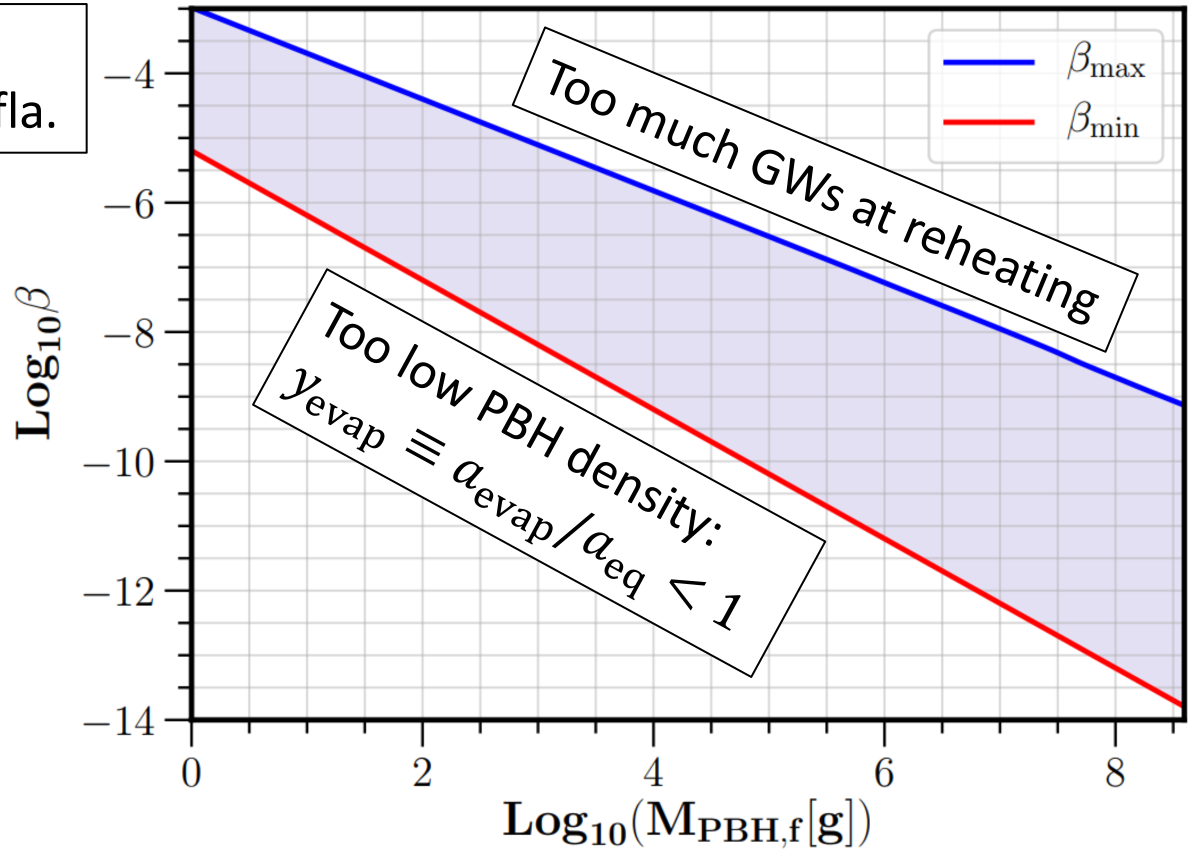


Cosmic timeline of eMD by PBHs

Domenech et. al. (2021)

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

Too light to be produced in infla.



Harms BBN prediction

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PBH reformation during eMD

- “PBH “gas” can gravitationally collapse and produce much heavier PBHs”
    - We call this PBH reformation.
- PBH reformation 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 in to its own Schwarzschild radius during the collapse

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

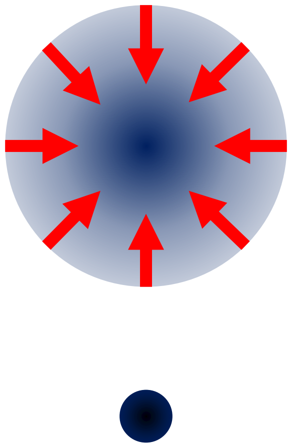
$$\sigma^2(r) = \int_0^\infty \mathcal{P}_\delta(k) W^2(kr) \frac{dk}{k}$$

PBH reformation during eMD

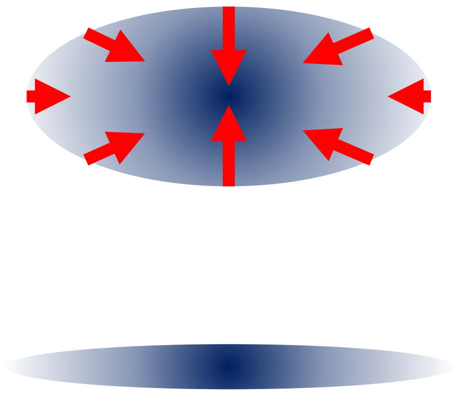
- Probability to be isotropic enough : $\beta_{\text{iso}} \simeq 0.05556 \times \sigma^5$
- Probability to be homogeneous enough : $\beta_{\text{hom}} \simeq 3.6979 \times \sigma^{3/2}$

Before

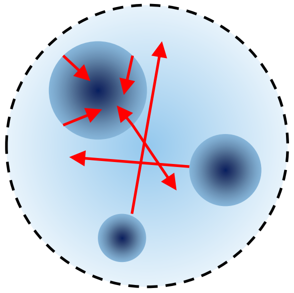
After



BH formation



“Pancake” collapse → virialized configuration



??? (not well known)

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

PBH reformation during eMD

- Both conditions are more easily satisfied for large overdensities.

  ∴ They are correlated.

  - Larger overdensities, larger Schwarzschild radius, easier to satisfy both

- Optimistic $\beta = \min(\beta_{\mathrm{iso}}, \beta_{\mathrm{hom}}) = \beta_{\mathrm{iso}} \simeq 0.05556 \times \sigma^5$

- Pessimistic $\beta = \beta_{\mathrm{iso}} \times \beta_{\mathrm{hom}} \simeq 0.2055 \times \sigma^{6.5}$

We take this in our analysis

PBH reformation during eMD

- Collapse probability β follows a power law in σ
  - c.f. Exponentially suppressed probability (erfc) in RD
  - $\sigma \sim 10^{-4} - 10^{-3}$ during eMD gives appreciable reformed PBH population
- Then, what is the value of σ for given eMD parameters?

$$\sigma^2(r) = \int_0^\infty \mathcal{P}_\delta(k) W^2(kr) \frac{dk}{k} \quad \text{for} \quad W(kr) = 3\frac{\sin kr - kr\cos kr}{(kr)^3}$$

  - $\mathcal{P}_\delta(k)$: Dimensionless density power spectrum
  - $W(kr)$: Top-hat window function for volume with radius r (should be the horizon)

PBH reformation during eMD

- Then, what is $\mathcal{P}_\delta(k)$ during eMD?

"Initial × growth"

$$\mathcal{P}_\delta(k,t) = \mathcal{T}^2(t)\mathcal{P}_\delta(t_{\rm if})$$

$$\mathcal{P}_\delta(t_{\rm if}) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3, \qquad k_{\rm UV} = \frac{a}{\bar{r}}$$

Poisson noise power spectrum:
Initial PBHs are randomly distributed

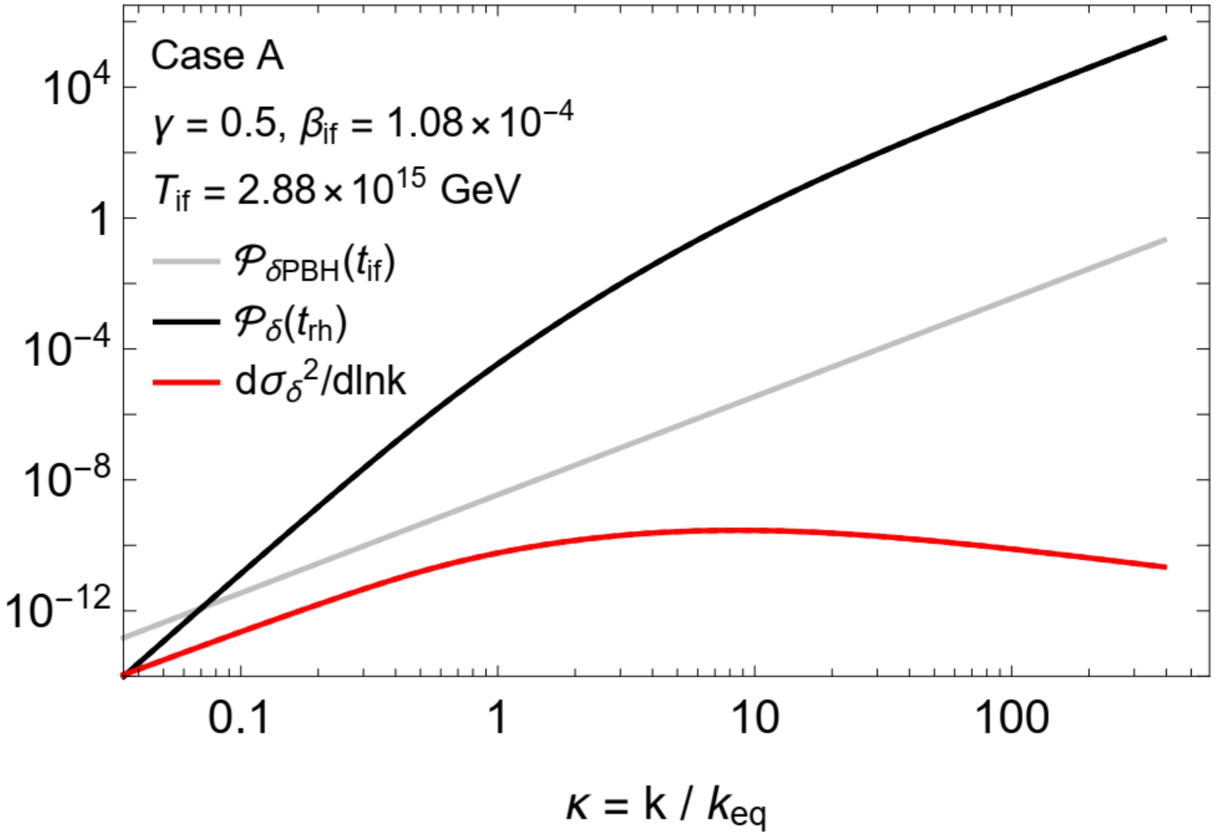
$$\mathcal{T}(t) \simeq \frac{a}{a_{\rm eq}} \times \begin{cases} \frac{3}{2}, & k \gg k_{eq} \\ \frac{4}{15}\left(\frac{k}{k_{eq}}\right)^2, & k < k_{eq} \end{cases} \quad \rightarrow \quad \mathcal{T}(t) \propto a$$

Transfer function:
"Subhorizon perturbation grows in $\propto a$ during MD"

- $k_{\rm UV}$ is the inverse of the mean separation of PBHs (UV cutoff)
- We use linear perturbation theory (being conservative by neglecting nonlinear effects)

PBH reformation during eMD

- Growth of perturbation and resulting σ



- Gray = Initial power spectrum:

  $\mathcal{P}_\delta(t_{\text{if}}) \propto k^3$

  - Poisson noise of initial PBHs

- Black = Grown power spectrum:

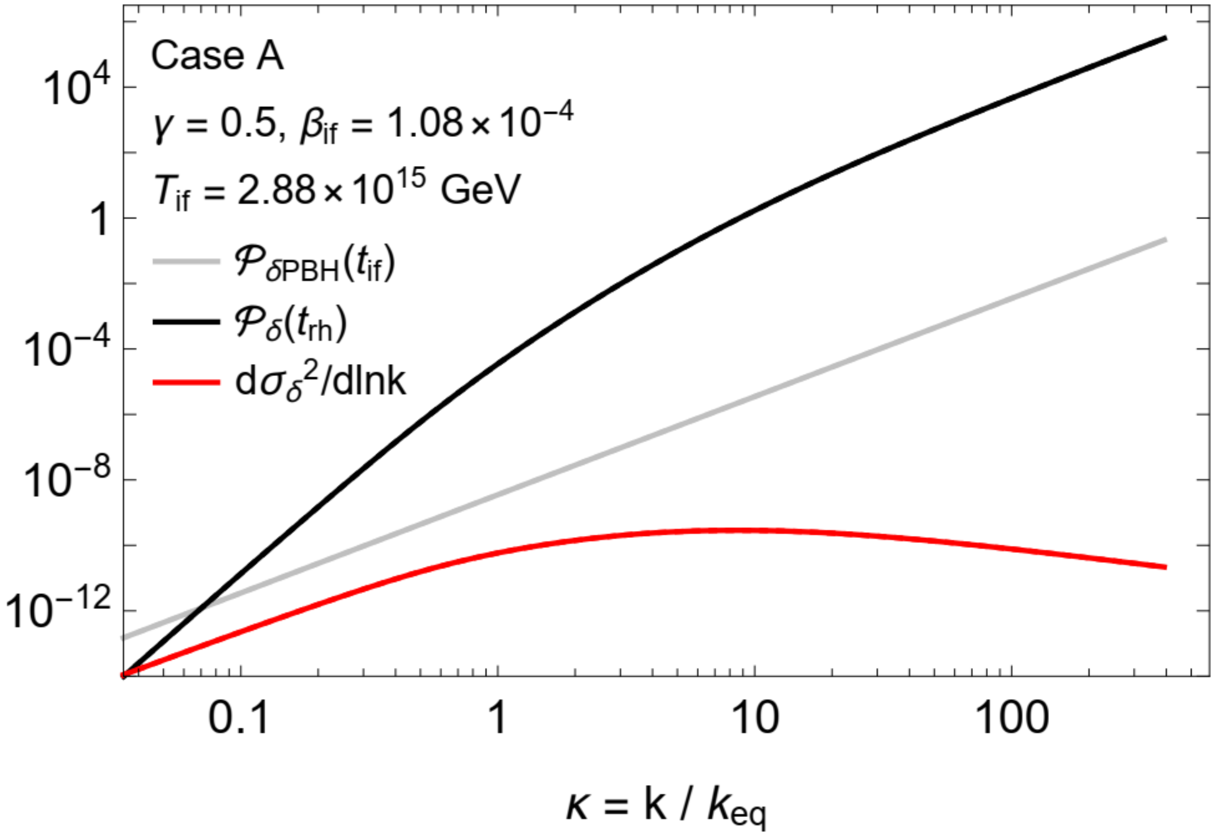
  $\mathcal{P}_\delta(t) = \mathcal{P}_\delta(t_{\text{if}}) \times \mathcal{T}^2(t)$

  - $\mathcal{T} \propto a$

- Red = $\dfrac{d\sigma^2}{d\ln k} = \mathcal{P}_\delta(t) \times W^2(kr)$

PBH reformation during eMD

- Growth of perturbation and resulting σ



- Integrating the red curve gives $\sigma \sim 10^{-3} - 10^{-4}$.
- $\beta \simeq 0.05556 \times \sigma^5 \sim 10^{\sim -20}$.
- Small β is enhanced to significant $f(M)$ after long RD
  - Redshift difference

PBH reformation during eMD

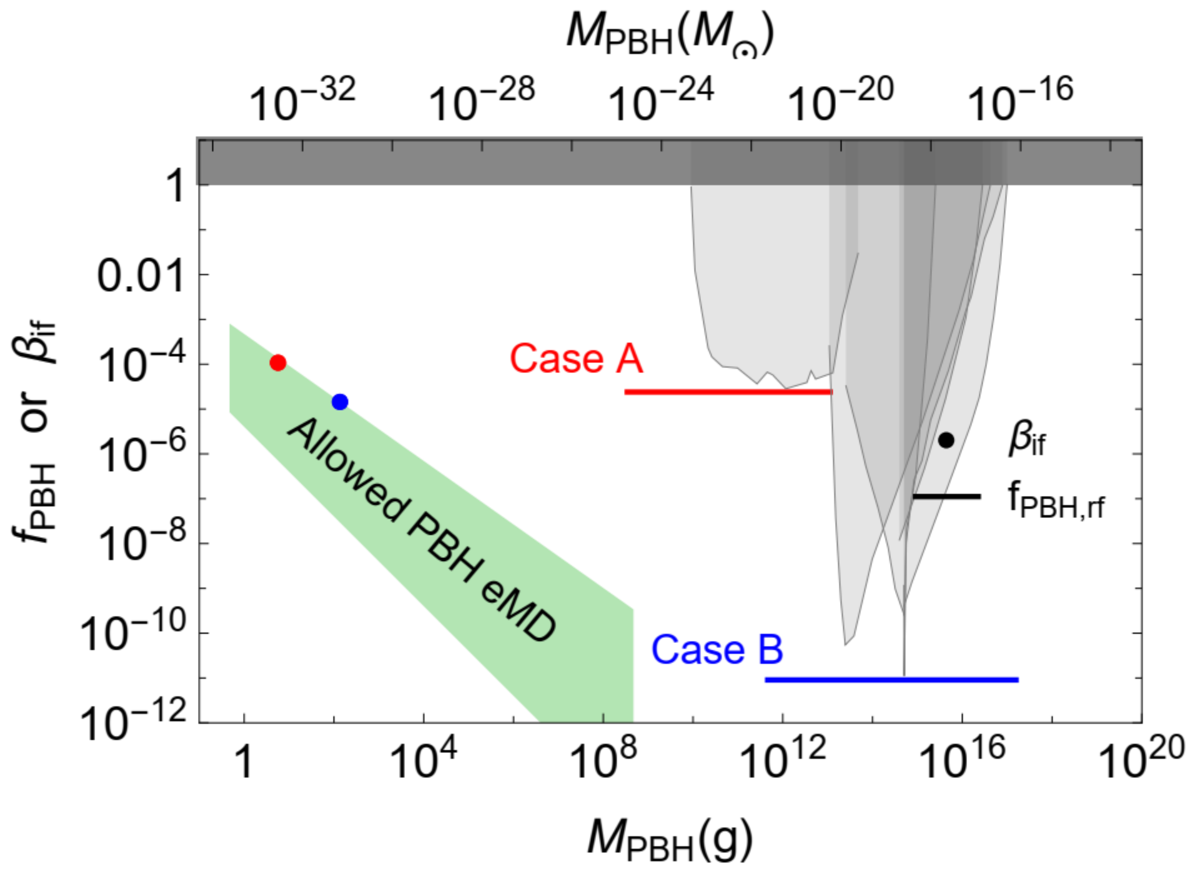
- σ remains a constant during eMD (from equality to the evaporation)
  - Growth by $\mathcal{T}(t) \propto a$ is cancelled by the window function for growing horizon size
- Continuous PBH reformation during eMD
  - The collapse probability β also remains as a constant value
  - The resultant mass function given by the cosmic expansion history:

$$f_{\mathrm{PBH}} = 4.0 \times 10^{20} \beta \times \left(\frac{M_{\mathrm{PBH,if}}}{1\ \mathrm{g}}\right)^{-3/2} \left(\frac{g_*(T_{\mathrm{RH}})}{106.75}\right)^{1/12}$$

  - $\beta \sim 10^{\sim -20}$ gives $f_{\mathrm{PBH}} \sim \left(M_{\mathrm{PBH,if}} \,/\, 1\ \mathrm{g}\right)^{-3/2}$ (although with “some” error)

PBH reformation during eMD

- Reformed PBH population case study

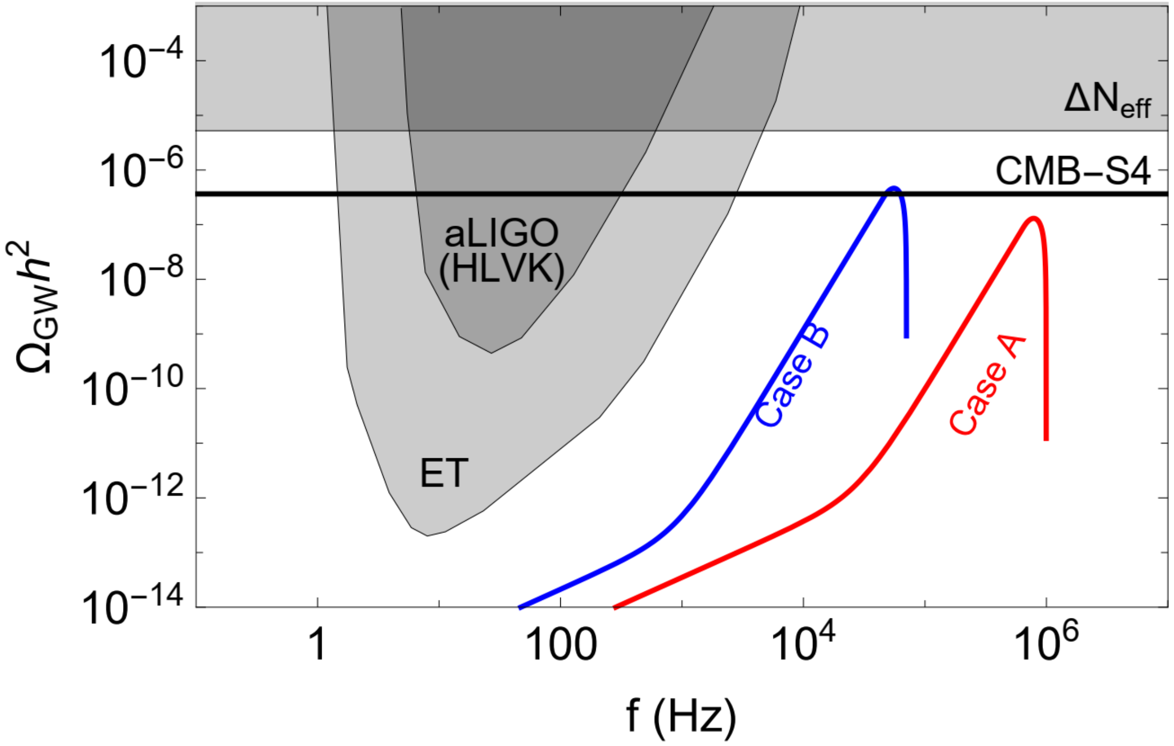


Case	T_{if} (GeV)	β_{if}	γ	f_{PBH}
A	2.88×10^{15}	1.08×10^{-4}	0.5	2.40×10^{-5}
B	5.89×10^{14}	1.45×10^{-5}	0.5	9.05×10^{-12}

- 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"

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.
  "Multi-messenger detection of PBH reformation"

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PBH reformation after reheating

- Reformation can also happen after evaporation, in RD

$$\beta \simeq \mathrm{erfc}\left(\frac{\delta_c(\simeq 0.45)}{\sqrt{2}\sigma}\right) \sim \frac{e^{-\left(\delta_c/\sqrt{2}\sigma\right)^2}}{\sqrt{\pi}\left(\delta_c/\sqrt{2}\sigma\right)}$$

  - Exponentially suppressed for small σ; practical formation only for $\sigma \gtrsim 10^{-2}$
    - This is not reachable with naïve evolution during eMD, giving $\sigma \sim 10^{-3} - 10^{-4}$.

- Any significant reformation after reheating needs initial PBH clustering
  - e.g., Enhanced non-Gaussianity at intermediate scales

Chisholm (2006)
Ali-Haimoud (2018)
Desjacques, Riotto (2018)
Suyama, Yokoyama (2019)
...

PBH reformation after reheating

Domenech et. al. (2021)

- Phenomenological parameterization of initial PBH clustering

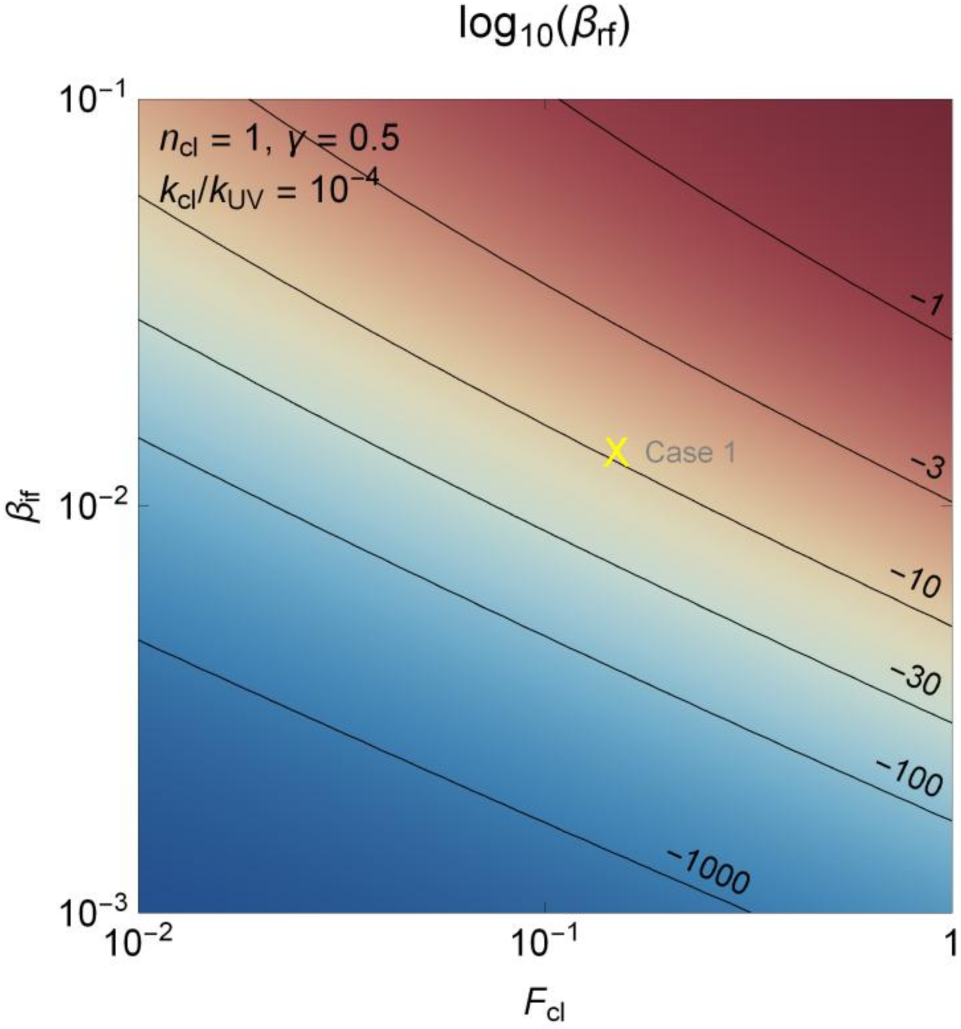
$$\mathcal{P}_{\delta,\mathrm{cl}}(t_{\mathrm{if}}) = \mathcal{P}_{\delta}(t_{\mathrm{if}}) \left(1 + F_{\mathrm{cl}} \left(\frac{k}{k_{\mathrm{cl}}}\right)^{n_{\mathrm{cl}}}\right)$$

  - F_{cl} : Strength of clustering
  - k_{cl} : Scale of clustering
  - n_{cl} : Scale dependence of clustering

- Clustering enhances power spectrum at small scales, $k_{\mathrm{cl}} < k < k_{\mathrm{UV}}$

PBH reformation after reheating

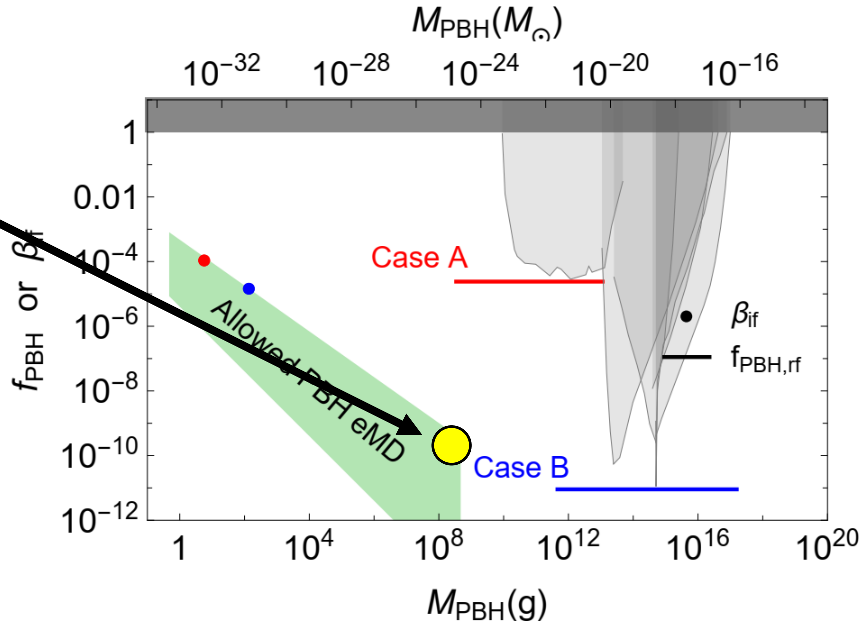
- β_{rf} as a function of β_{if} and F_{cl}
- Depending on clustering, an initial PBH fraction of $\beta_{\mathrm{if}} \gtrsim 10^{-2}$ induces an appreciable reformation after reheating



PBH reformation after reheating

- But clustering enhances GW production too
  - Should not have clustering in the last eMD. Too much GWs affecting ΔN_{eff}.
  - But allowed when it induces a 2nd eMD, which dilutes GWs from the 1st eMD

Case	$T_{\rm if}$ (GeV)	$\beta_{\rm if}$	γ	$F_{\rm cl}$	$k_{\rm cl}/k_{\rm UV}$	$n_{\rm cl}$
1	2×10^{16}	0.0136	0.5	0.15	10^{-4}	1
2	5×10^{15}	0.0214	0.0311	1.0	10^{-4}	1



- Two cases that induces allowed 2nd eMD through the reformation after reheating
- "Cascade PBH reformation" might be possible

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Summary & Conclusion

- PBH reformation is a process where light mass PBHs form much heavier PBHs through gravitational collapse, when they have an eMD.
  - Matter density perturbation grows during MD.
- Reformation during eMD can give a PBH population that can be detected by future BBN light element abundances / γ-ray observations.
- Reformation after reheating relies on initial PBH clustering, and can give a PBH population that can induce 2nd eMD.

Summary & Conclusion

- Evaporation of original PBHs gives a correlated GW signal.
  - Reformation (during eMD) can be tested by multi-messenger observations.

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

THE END. Thank you!