Probing dark matter halo profile with primordial black hole mergers

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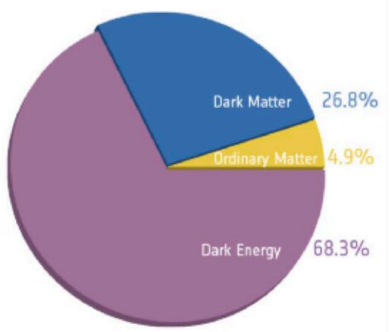
2025/08/19@TDLI-Shanghai

Qianhang Ding, MH, Volodymyr Takhistov, ApJ 981 (2025) 1, 62 [arXiv: 2410.02591]

Motivation



- Dark matter (DM)
  - Major component of matter contents
  - Cosmic evolution
  - Structure formation

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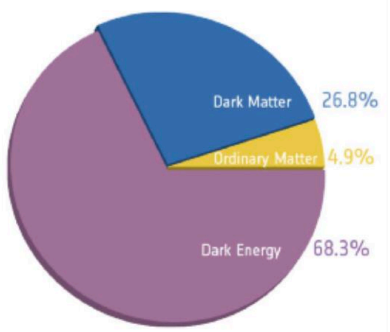

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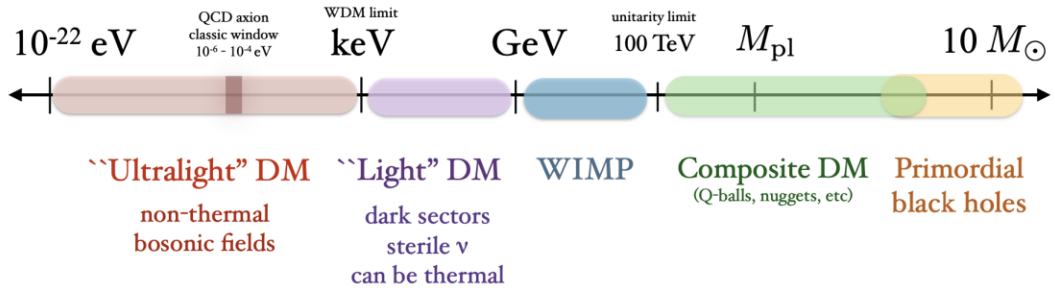
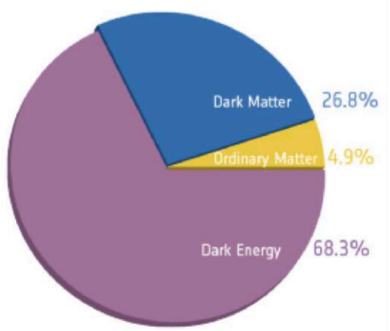
  - Major component of matter contents
  - Cosmic evolution
  - Structure formation
- DM models



Credit: Tongyan Lin

Motivation



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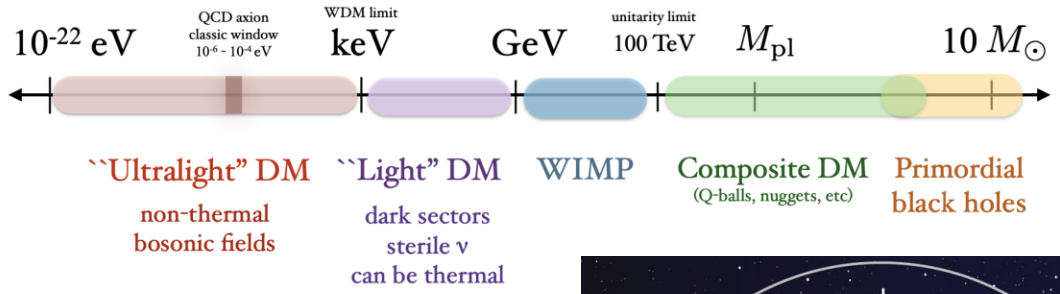
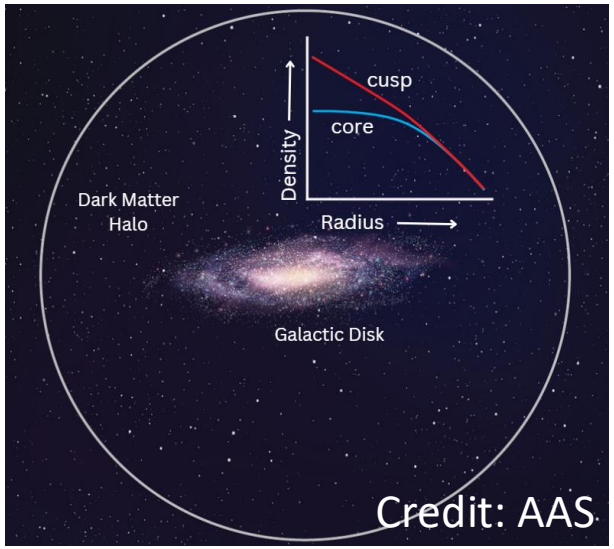


Credit: Tongyan Lin

- DM models

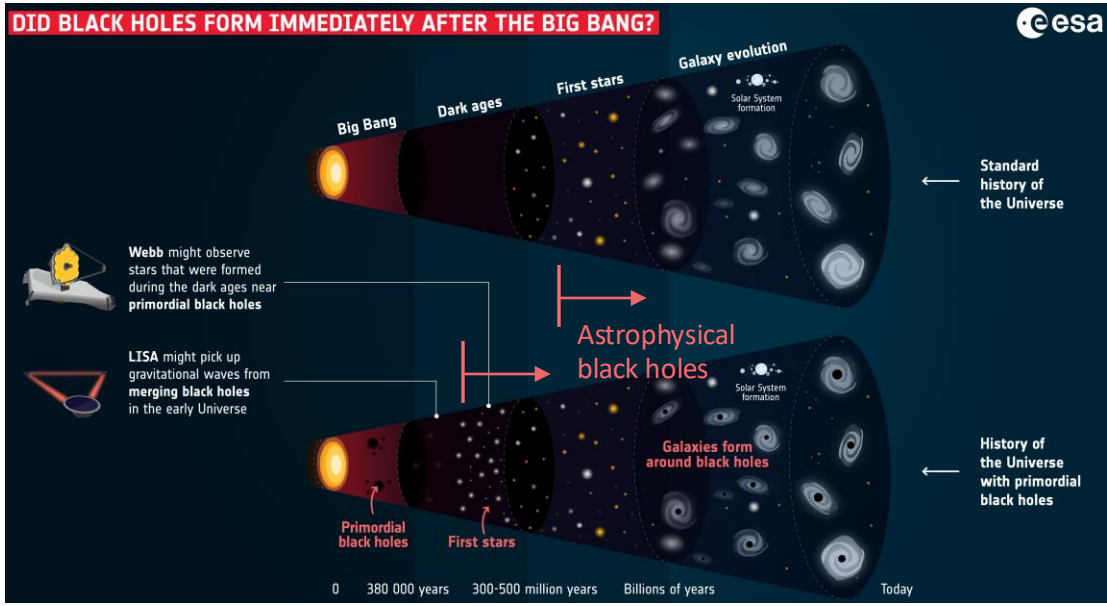
- Small-scale structures
  - E.g. central density profile of DM halo



Credit: AAS

Motivation

- Primordial black hole (PBH)
  - Formation in very early Universe
  - Mass range, abundance
  - Candidates for: DM, LVK events, seeds of supermassive black hole, Hawking radiation…



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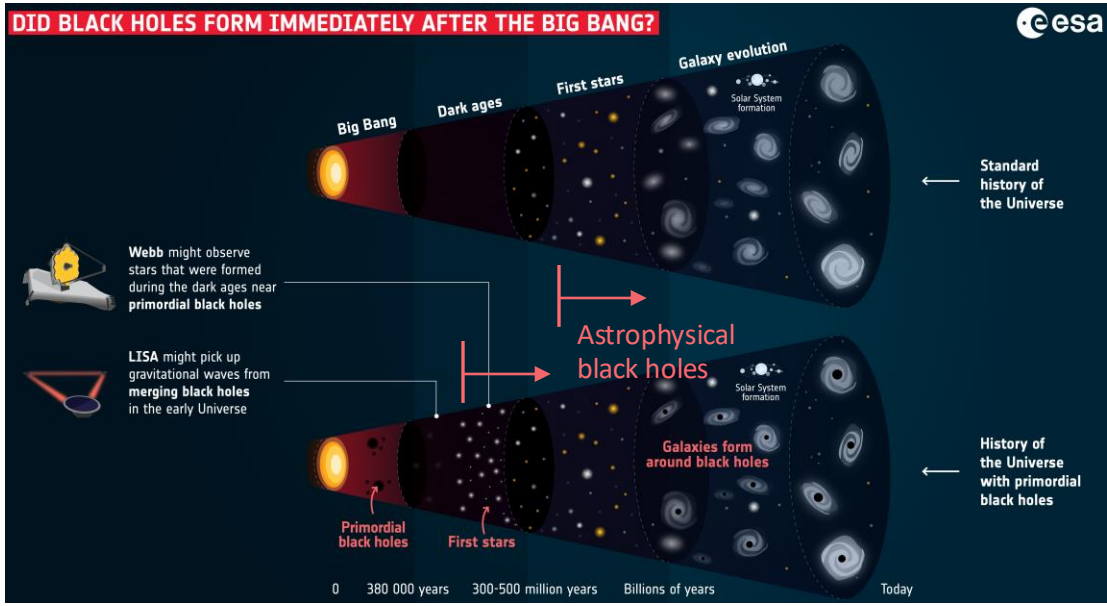
- Merger rate
  - Number density
  - PBH Mass



Plan of talk

- Dark matter (DM) halo profile
- Primordial black hole (PBH)
- PBH merger history as probe of DM
- Summary

Dark matter halo profile

Dark matter halo profile

- Cold DM
- NFW profile Navarro, Frenk, White 1996,1997

$$\rho_{\rm DM}(r) = \frac{\rho_0}{(r/r_0)(1+r/r_0)^2}$$

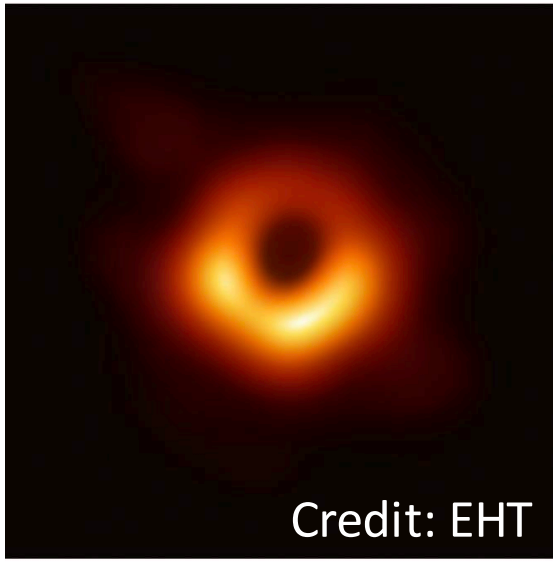
  - Milky way: $\rho_0 = 6.6 \times 10^6\ M_\odot/\mathrm{kpc}^3$, $r_0 = 19.1\ \mathrm{kpc}$

- Simplified power-law profile for inner region

$$\rho(r) \simeq \rho_0 (r_0/r)^\gamma$$

Dark matter halo profile

- Supermassive black holes (SMBHs)
  - At galactic center
  - Mass $\gtrsim 10^5\ M_\odot$
  - Origin (unknown)



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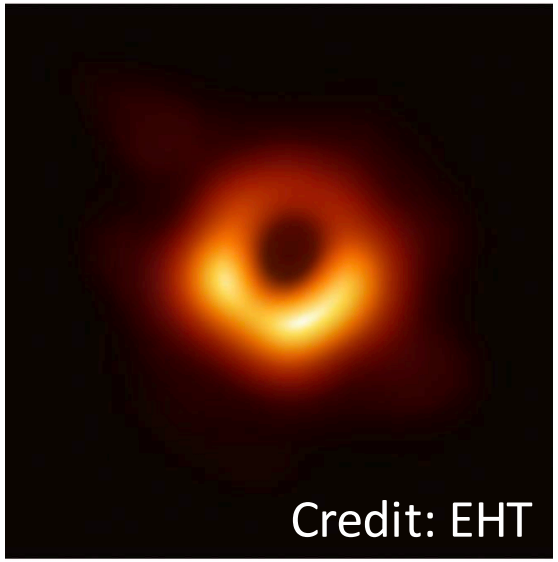
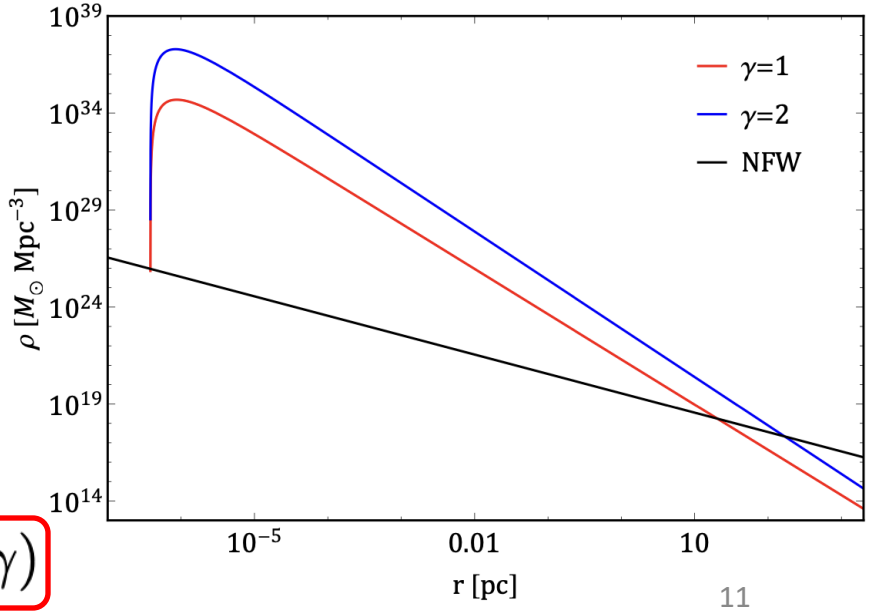


- DM spike Gondolo, Silk 1999

$$\rho(r) \simeq \rho_0 (r_0/r)^\gamma$$

$$\rho_{\rm sp}(r) = \rho_R \left(1 - \frac{4r_s}{r}\right)^3 \left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

$$\gamma_{\rm sp} = (9 - 2\gamma)/(4 - \gamma)$$



Dark matter halo profile

- Halo and SMBH
  - Velocity dispersion σ of halo

$$\sigma^2 = \frac{GM(c_m r_0)}{c_m r_0}$$

  - $M - \sigma$ relation

Robertson et al 2006, Gultekin et al 2009

$$\log_{10}\left(\frac{M_{\rm SMBH}}{M_\odot}\right) = a + b\log_{10}\left(\frac{\sigma}{200\,{\rm km\,s^{-1}}}\right) - \xi\log_{10}(1+z)\ ,$$

Relate SMBH with halo profile

$M_{\rm halo}(r_0, \rho_0)$

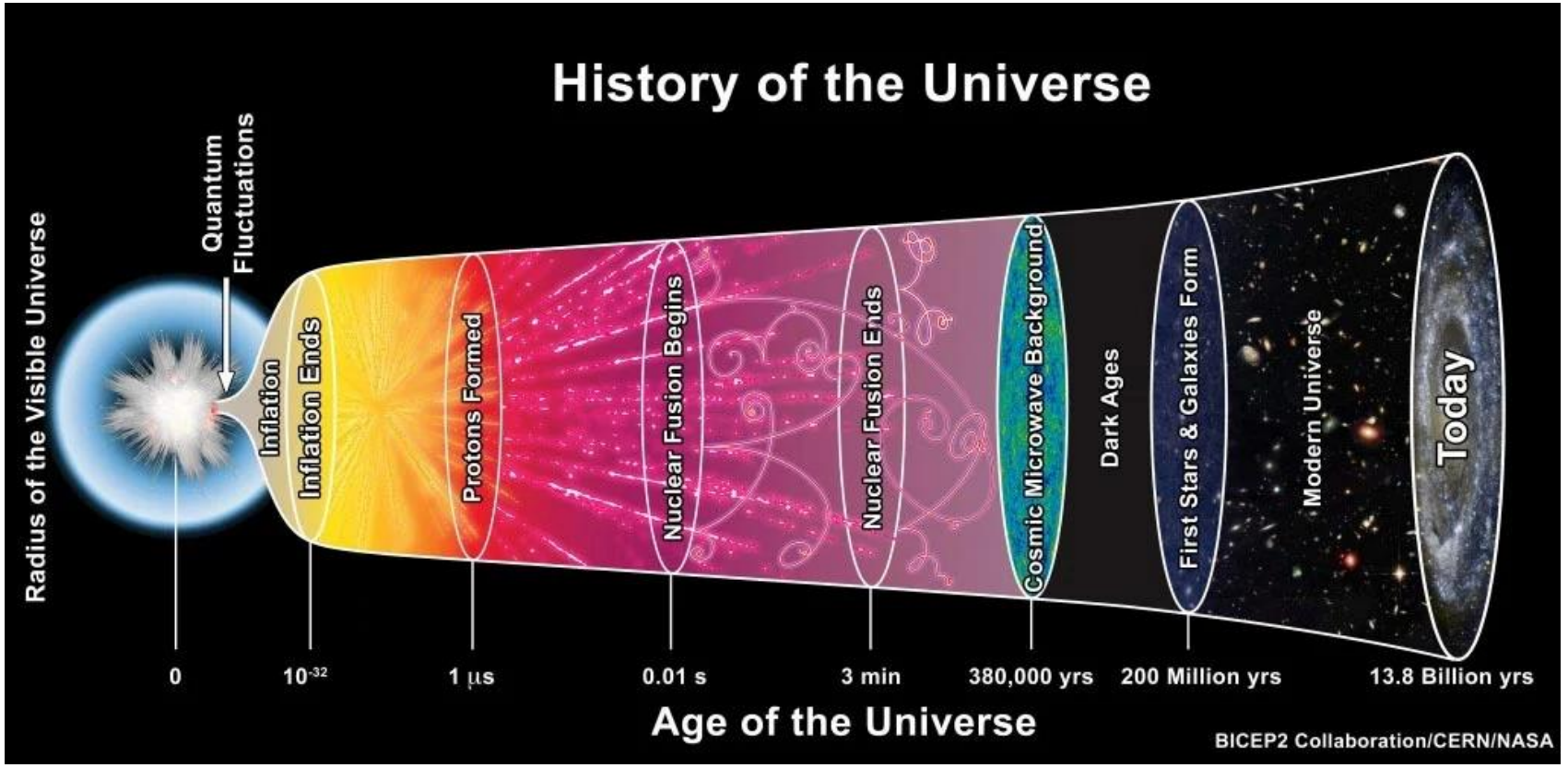
$a{\sim}8,\ b{\sim}4,\ \xi{\sim}0.2$

Primordial black hole

Primordial black hole

Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974; Carr 1975

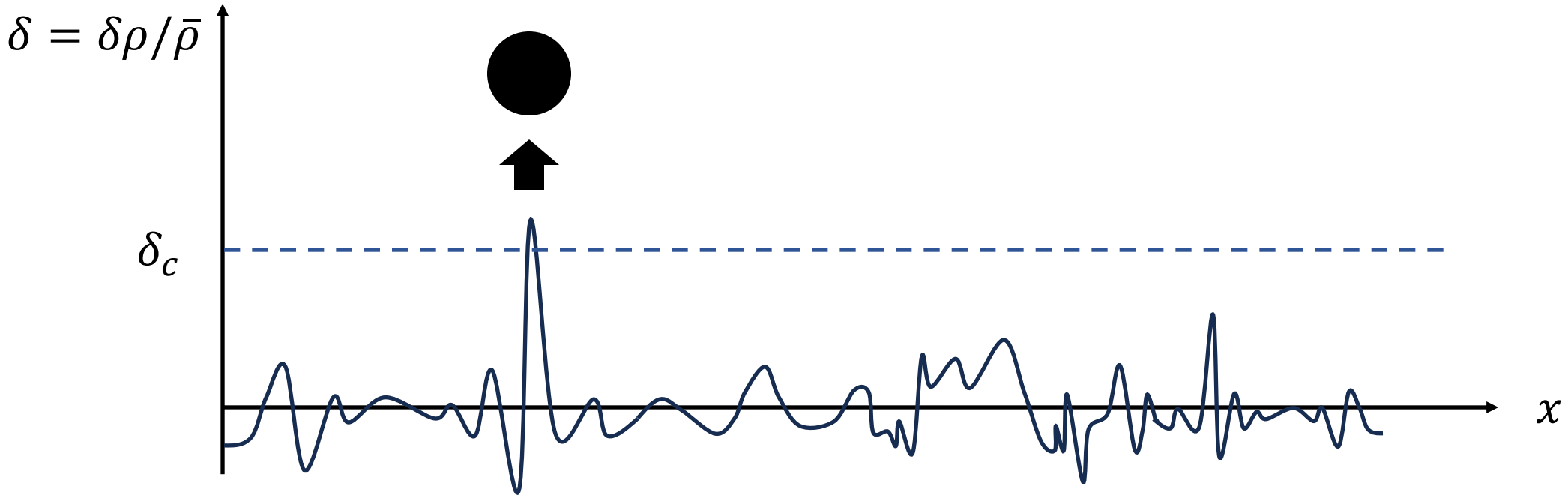
- Inflationary cosmology



Primordial black hole

Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974; Carr 1975

- Collapse of primordial density fluctuation



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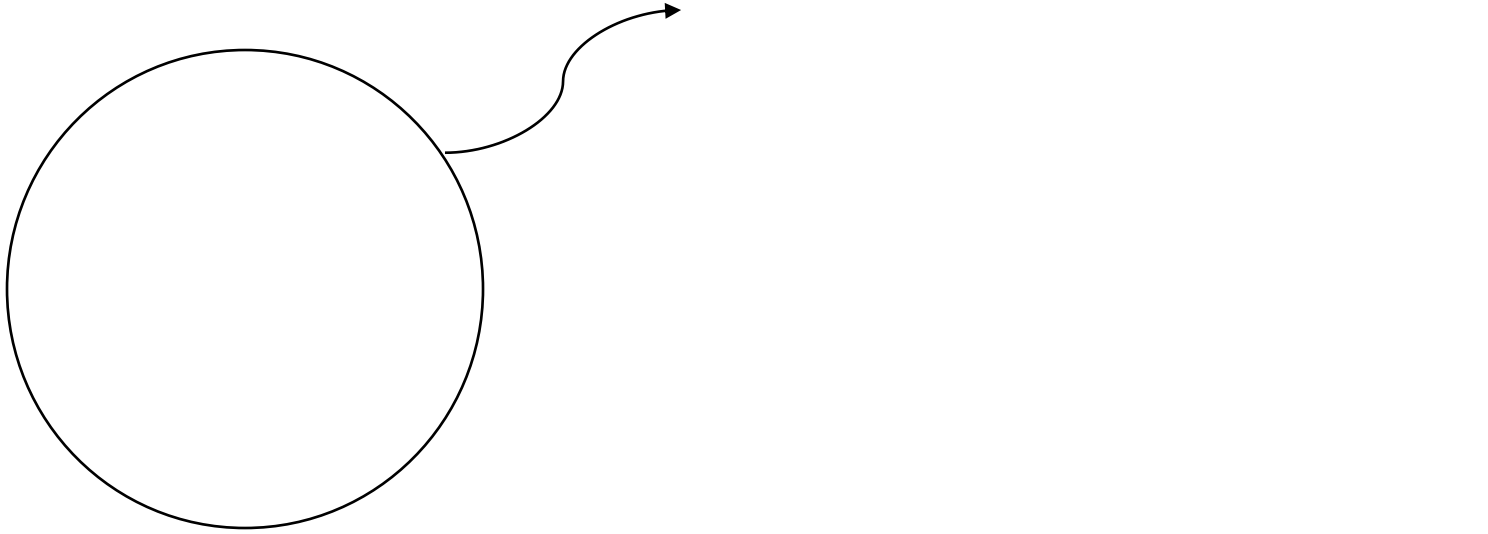

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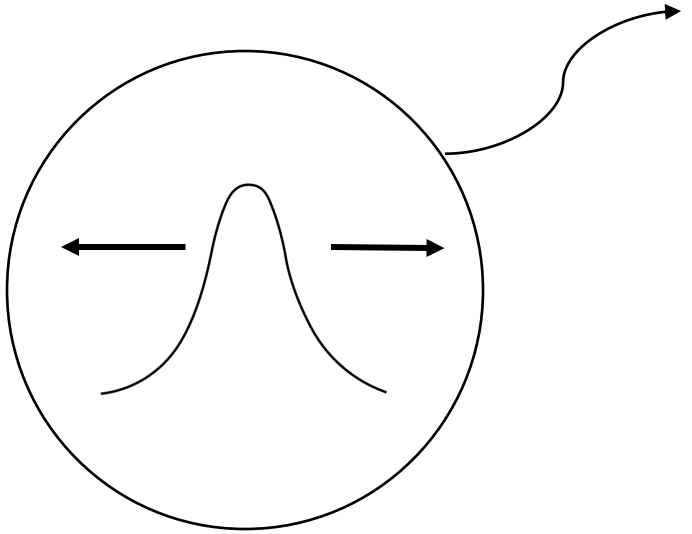

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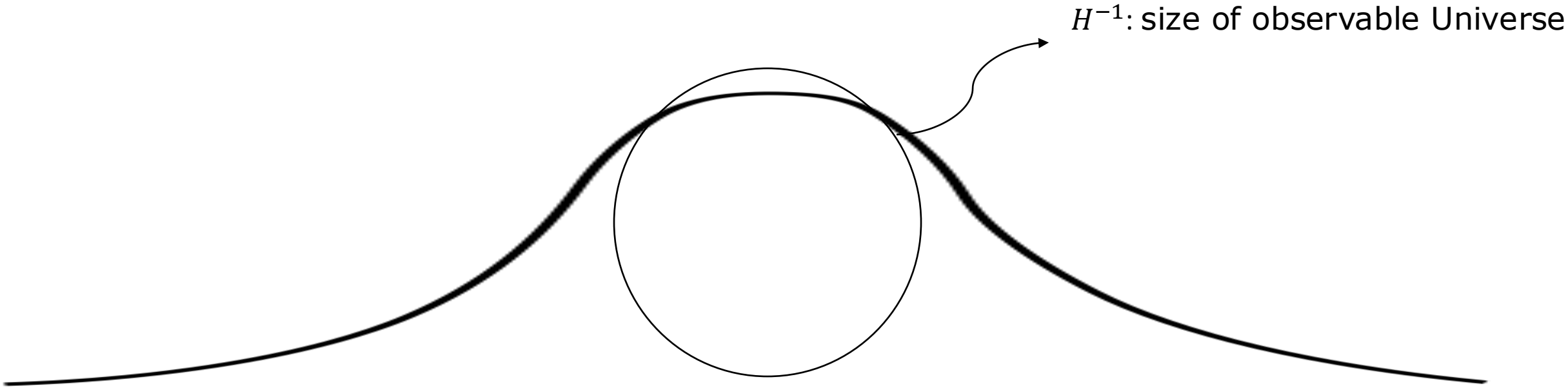

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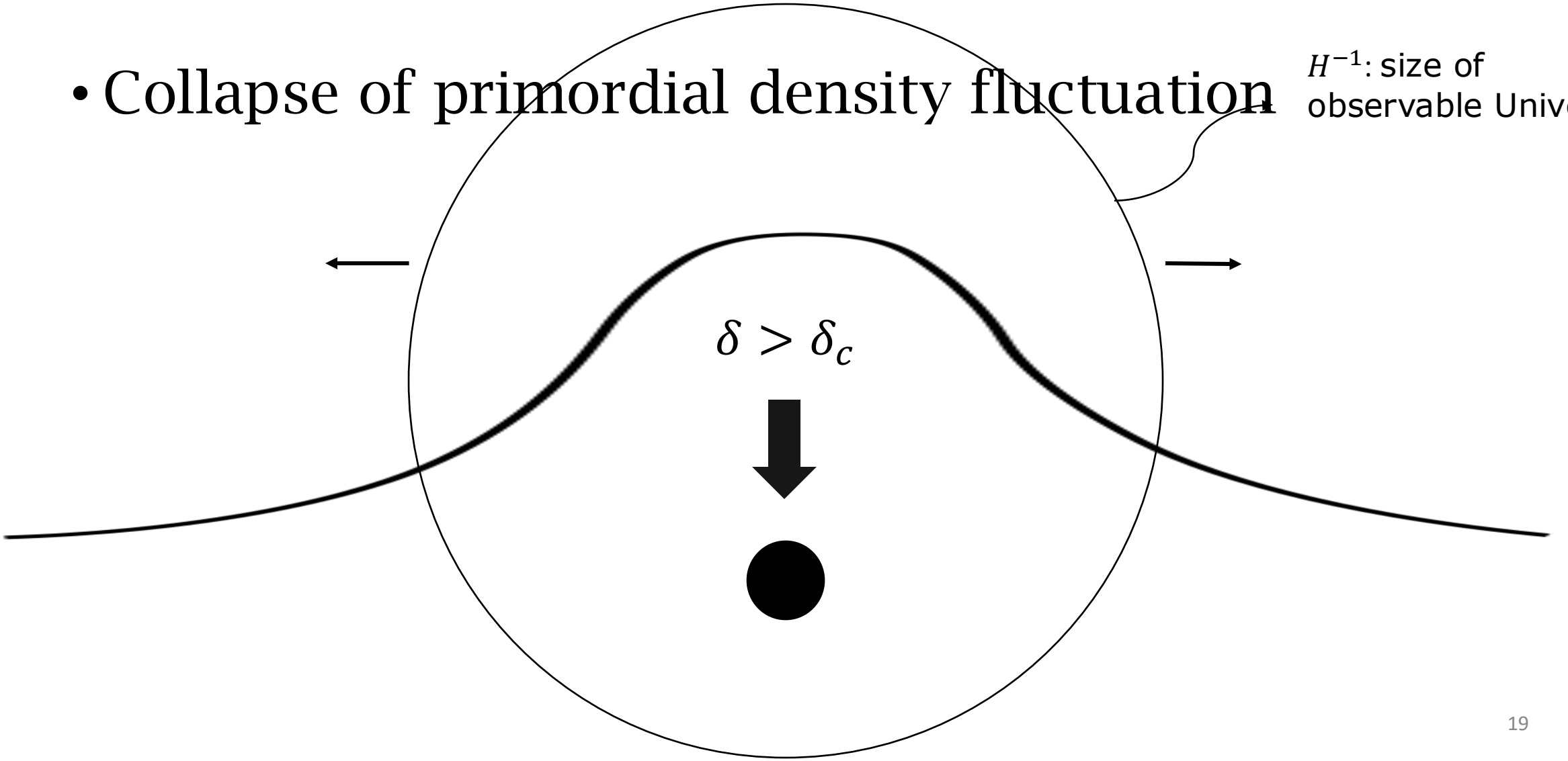

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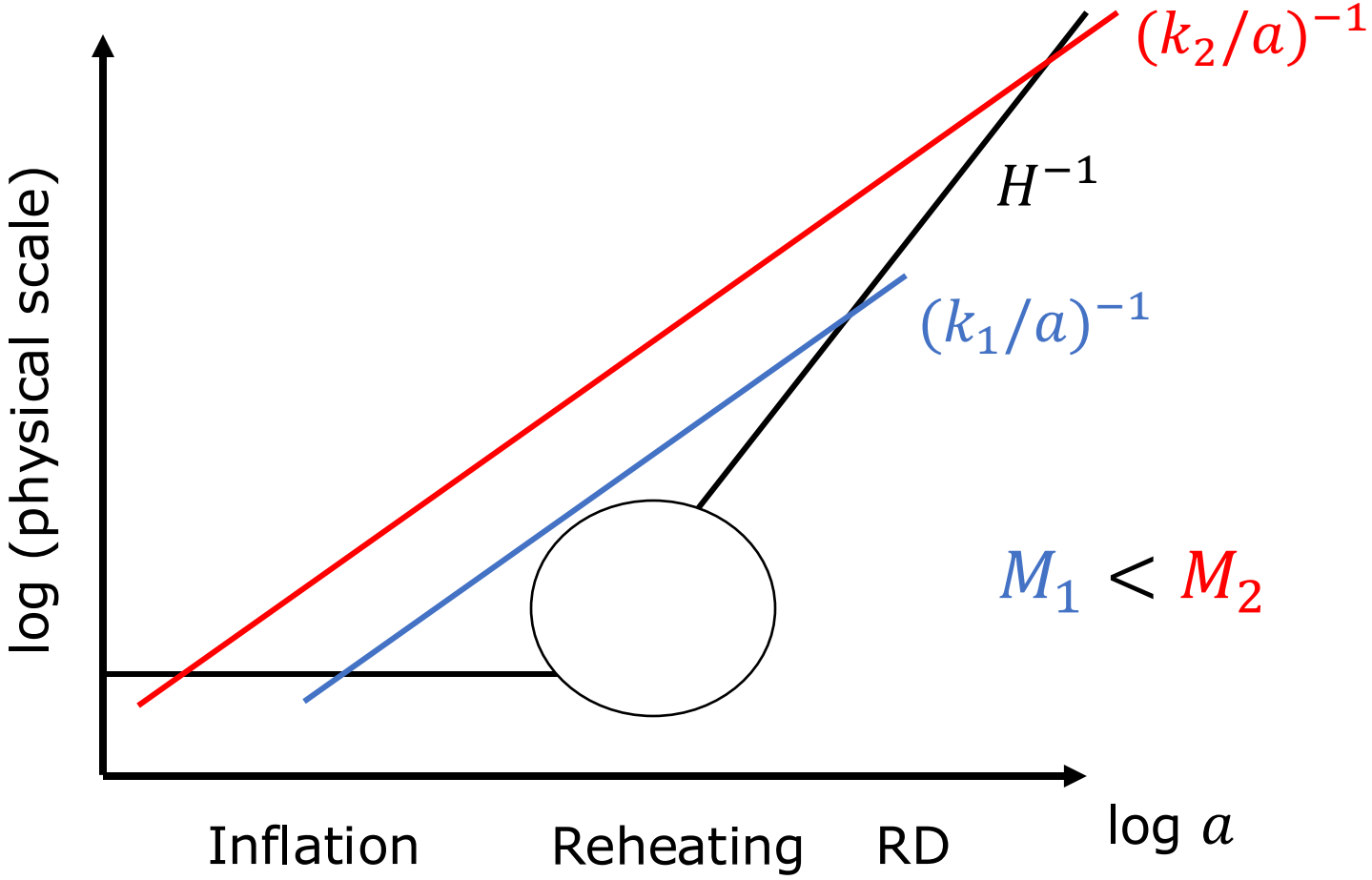


$$M_{\rm ini} = \gamma \frac{4\pi\rho_{\rm ini}}{3H_{\rm ini}^3}$$
$$= 4\pi\gamma \frac{M_{\rm pl}^2}{H_{\rm ini}}$$
$$\propto t_{\rm ini}$$

Primordial black hole

Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974; Carr 1975

- Collapse of primordial density fluctuation
  - PBH mass and formation time

$$M_{\rm ini} = \gamma \frac{4\pi\rho}{3H_{\rm ini}^3} = 4\pi\gamma \frac{M_{\rm Pl}^2}{H_{\rm ini}} \simeq 0.4\,{\rm g} \left(\frac{\gamma}{0.2}\right)\left(\frac{H_{\rm ini}}{6\times 10^{13}\,{\rm GeV}}\right)^{-1}$$

$m_{\rm pl}$ Lower bound from inflation $\gtrsim m_{\rm inf}$ $m_{\rm SMBH}$

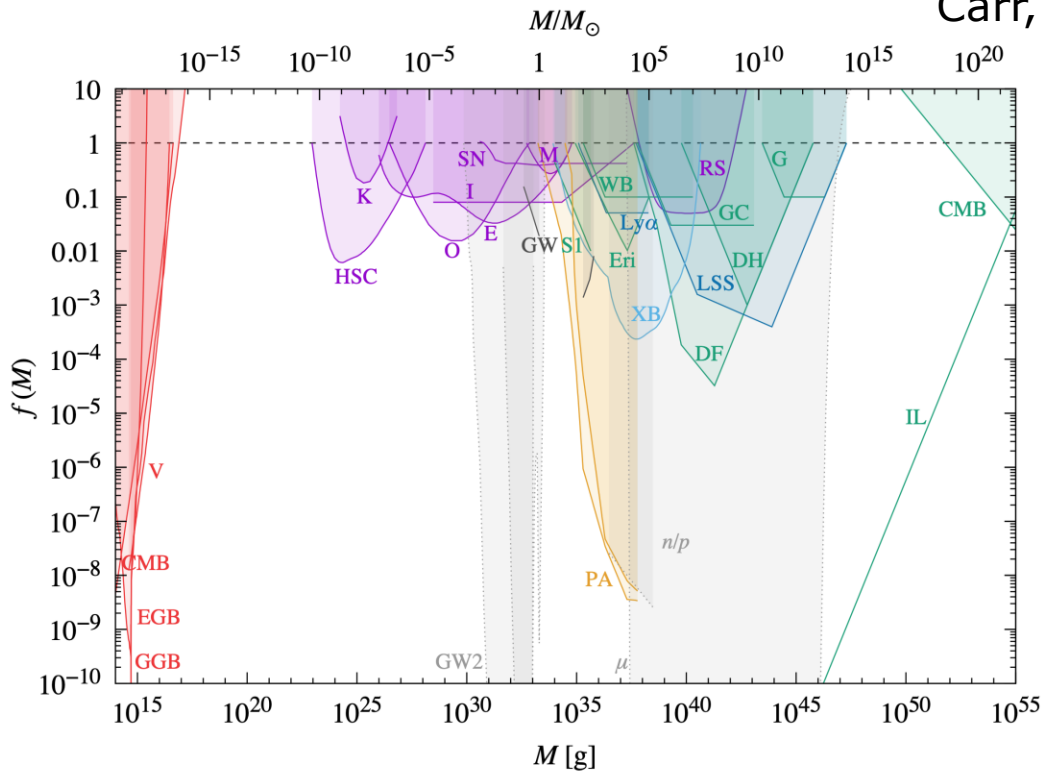
- $M_{\rm ini} = 10^9{\rm g}$: $H_{\rm ini}{\sim}10^5{\rm GeV} \implies t_{\rm ini}{\sim}10^{-30}{\rm s}$
- $M_{\rm ini} = 10^{15}{\rm g}$: $H_{\rm ini}{\sim}0.02\,{\rm GeV} \implies t_{\rm ini}{\sim}10^{-23}{\rm s}$

Primordial black hole

Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974; Carr 1975

- Collapse of primordial density fluctuation
  - PBH mass and formation time
- PBH as DM

Carr, Kohri, Sendouda, Yokoyama 2021



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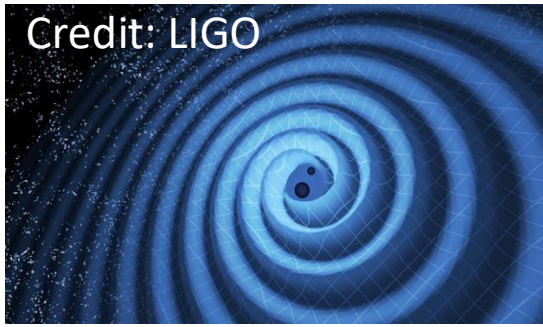
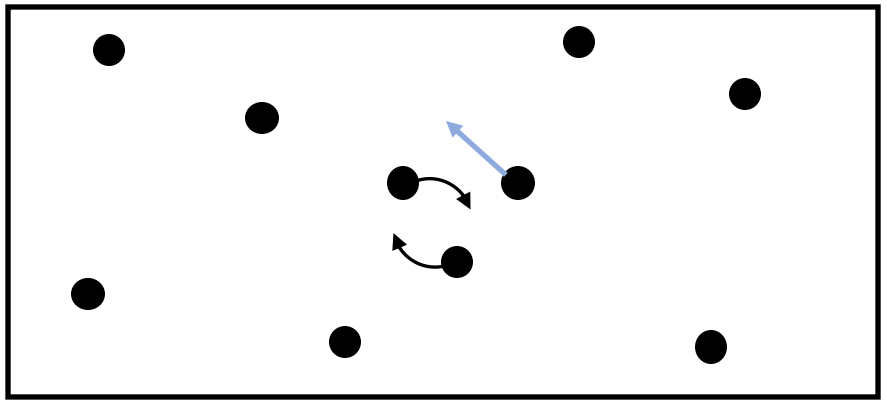


- PBH mergers
  - Early PBH merger

    Nakamura et al 1997
    Sasaki et al 2016
    Ali-Haïmoud et al 2017
    Raidal et al 2019
    Ng et al 2022

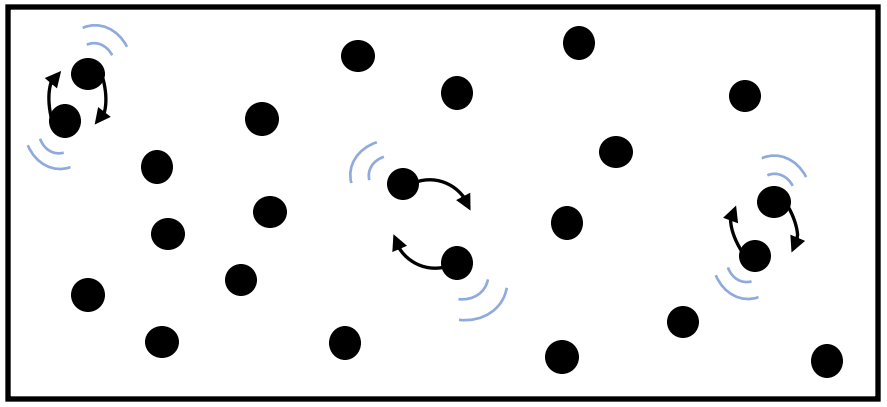


Differential merger rate per comoving volume:

$$\frac{\mathrm{d}R}{\mathrm{d}m_1\mathrm{d}m_2}(m_1, m_2, f_{\mathrm{PBH}}, z)$$

  - Mergers in halos

    Quinlan et al 1989
    Mouri, Taniguchi 2002
    Bird et al 2016



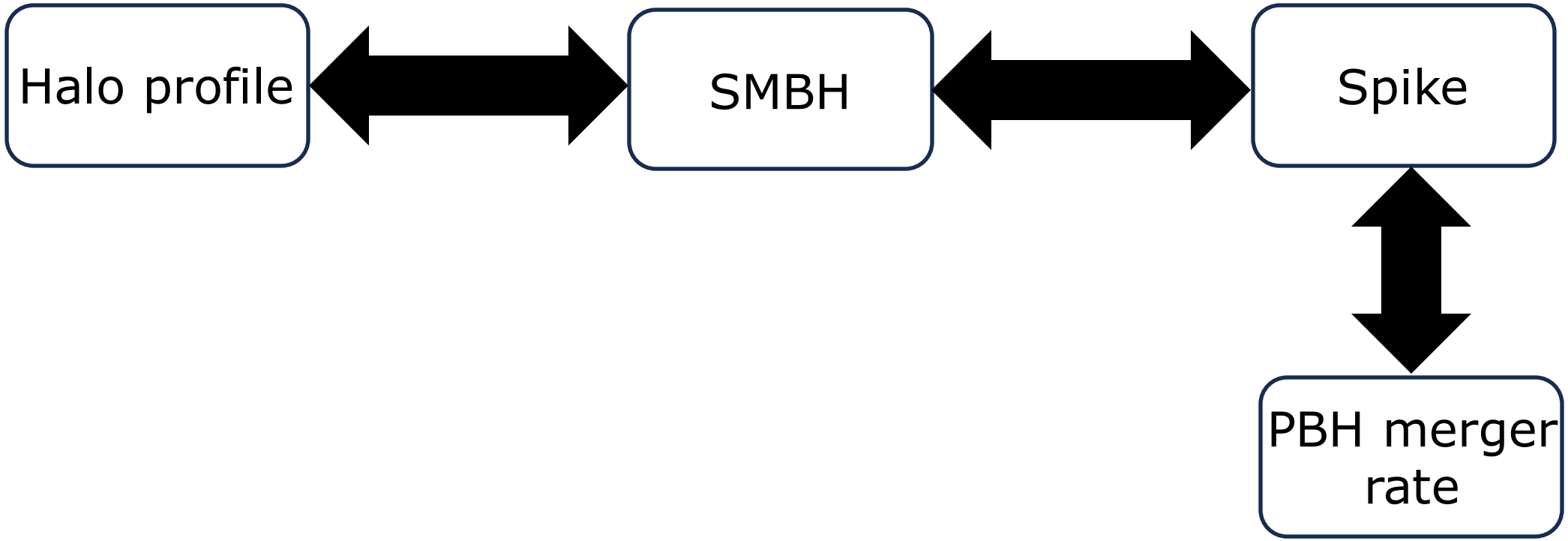
Equal mass case:

$$\sigma \propto m_{\mathrm{tot}}^2 v_{\mathrm{rel}}^{-18/7}$$

$$R = \int \left(\int \rho \sigma v \, \mathrm{d}V \right) \mathrm{d}n$$

PBH merger history as probe of DM

PBH merger history as probe of DM



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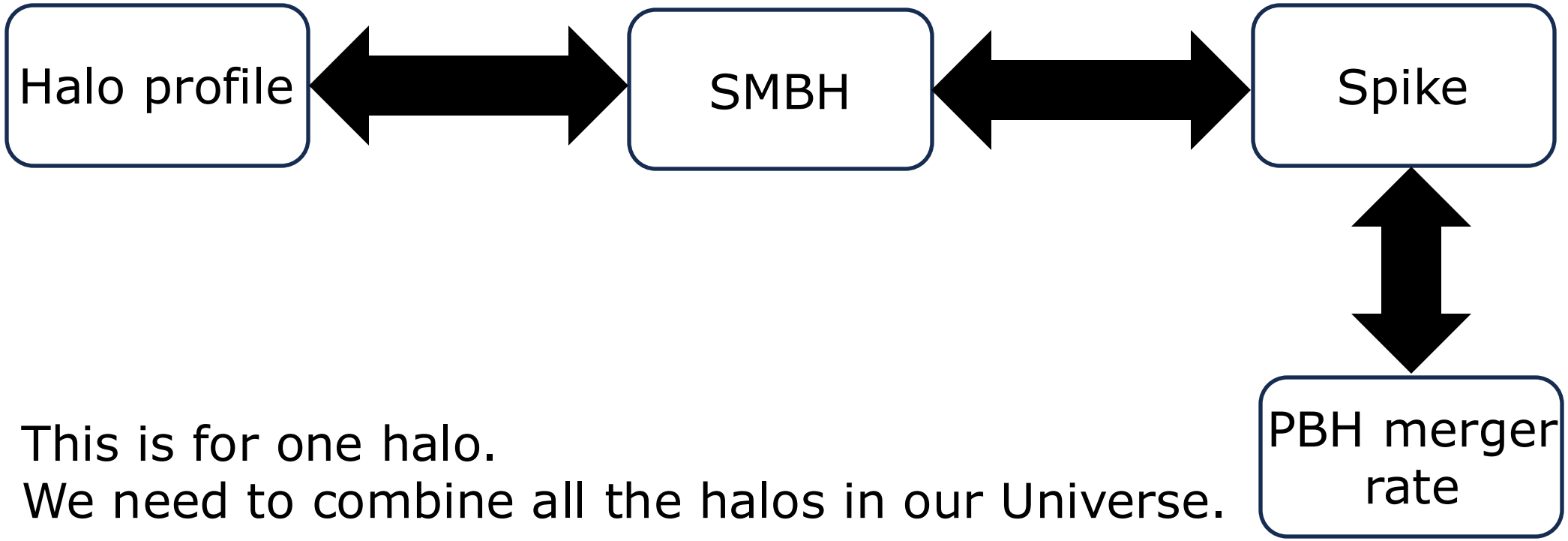
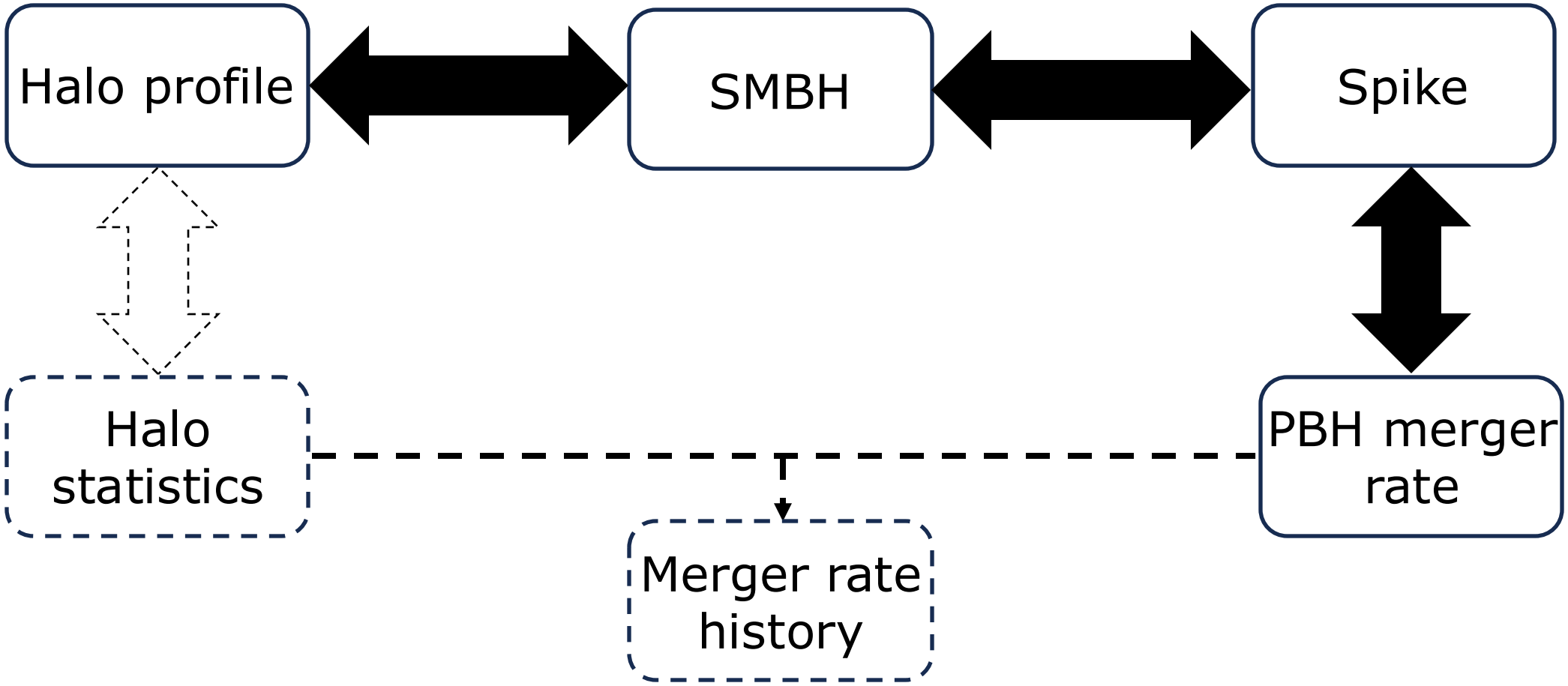


This is for one halo.
We need to combine all the halos in our Universe.

PBH merger history as probe of DM

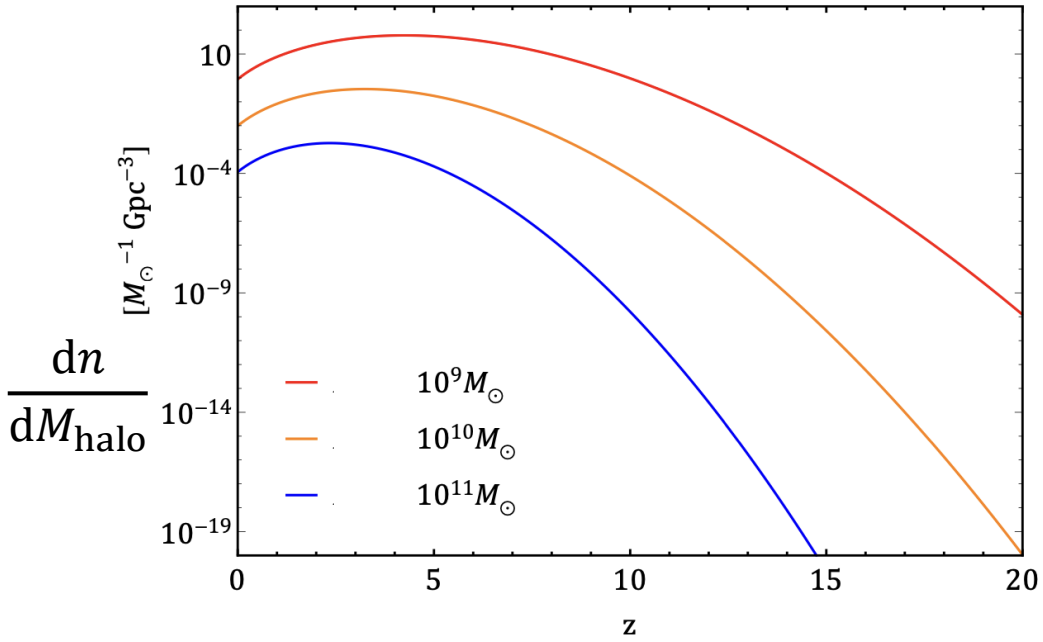


PBH merger history as probe of DM

- Halo distribution Prada et al 2012

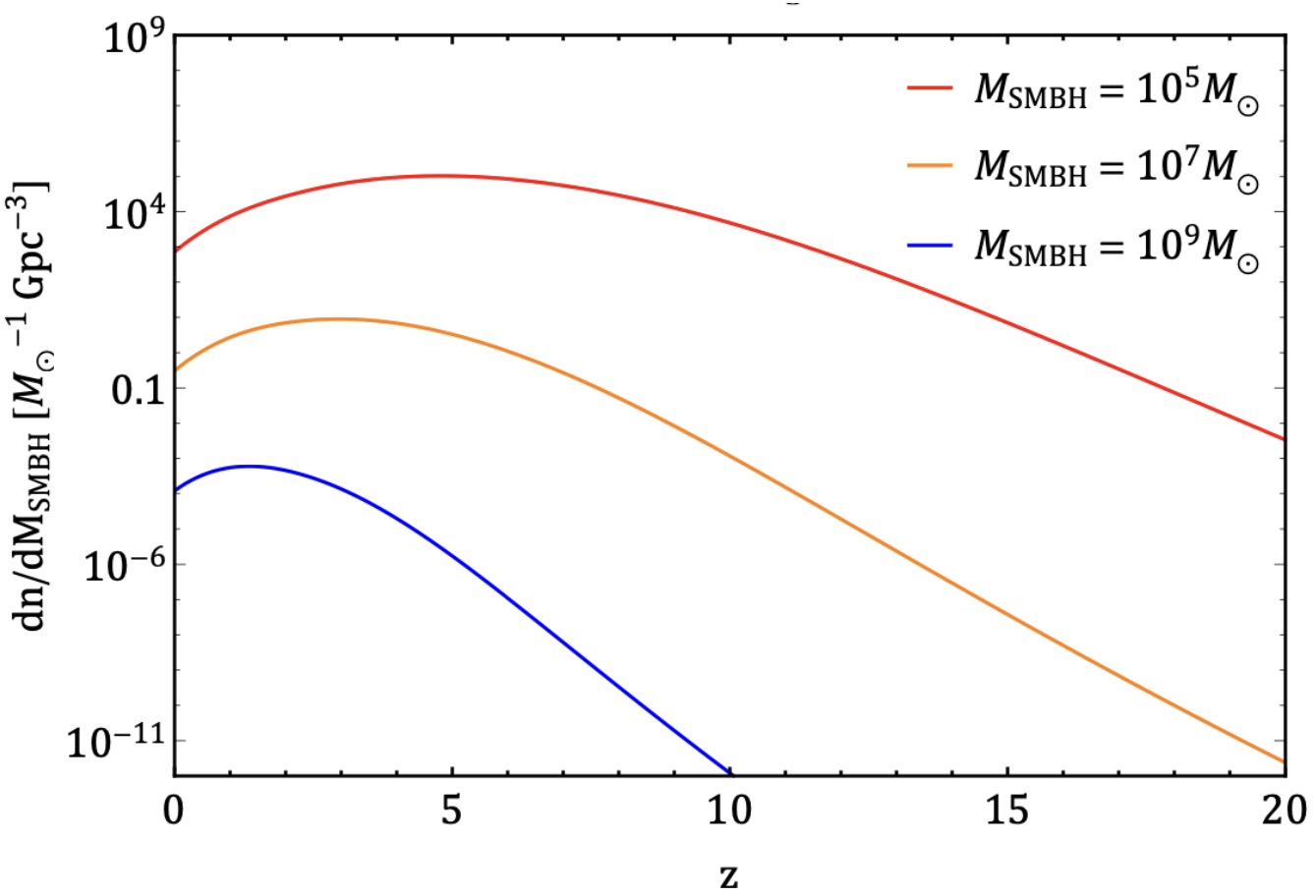
$$\frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{SMBH}}} = \frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{halo}}} \frac{\mathrm{d}M_{\mathrm{halo}}}{\mathrm{d}M_{\mathrm{SMBH}}}$$

Calculated by density power spectrum at different redshifts



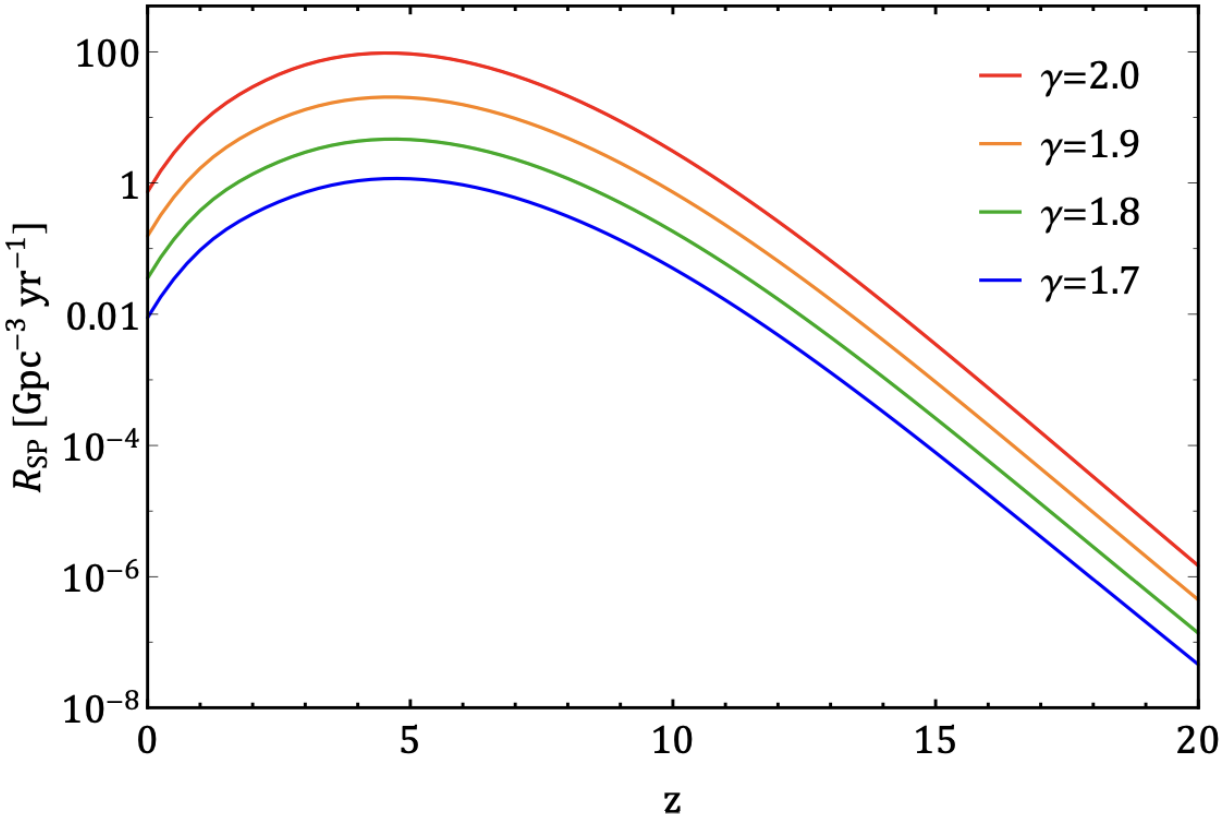
PBH merger history as probe of DM

- SMBH distribution



PBH merger history as probe of DM

- PBH merger rate in spikes as a function of redshift



$M_{\rm PBH} = 30\,M_\odot,\ f_{\rm PBH} = 10^{-3}$

PBH merger history as probe of DM

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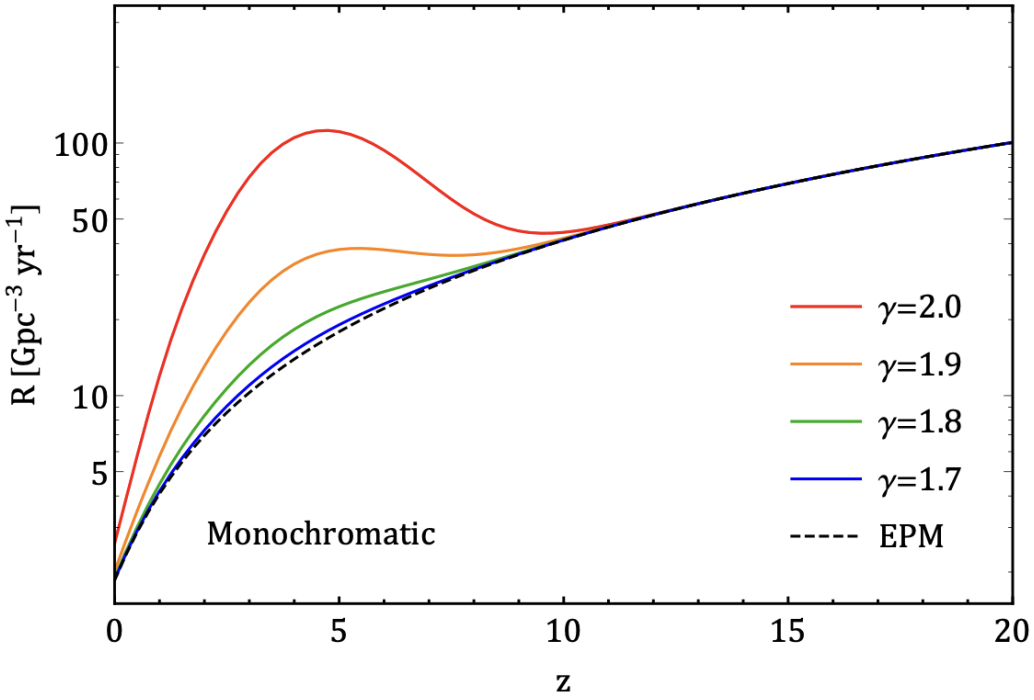
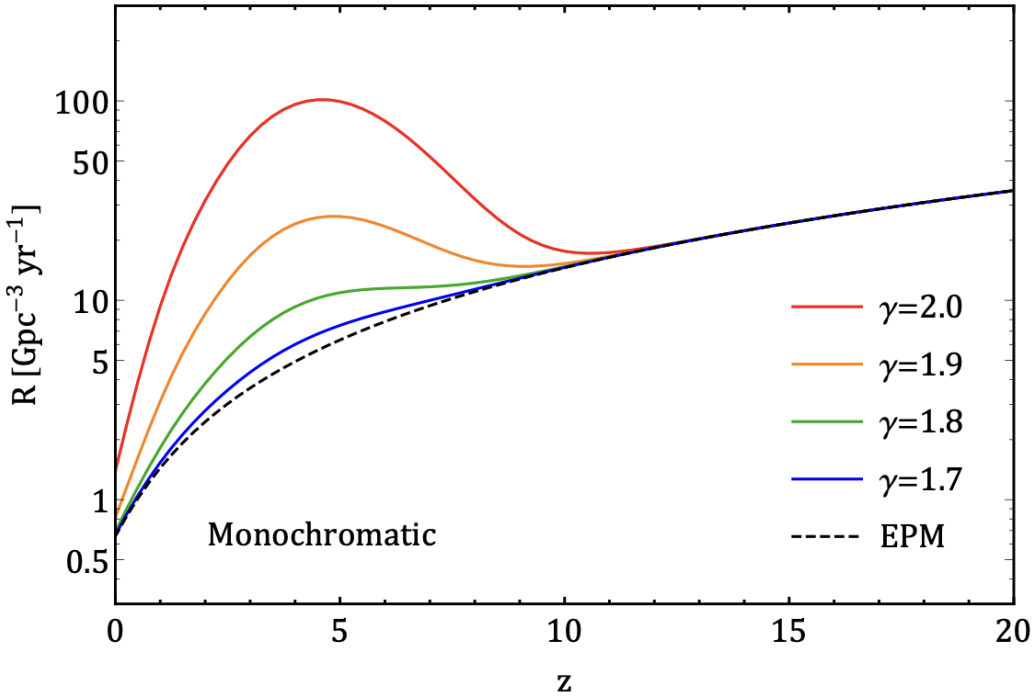
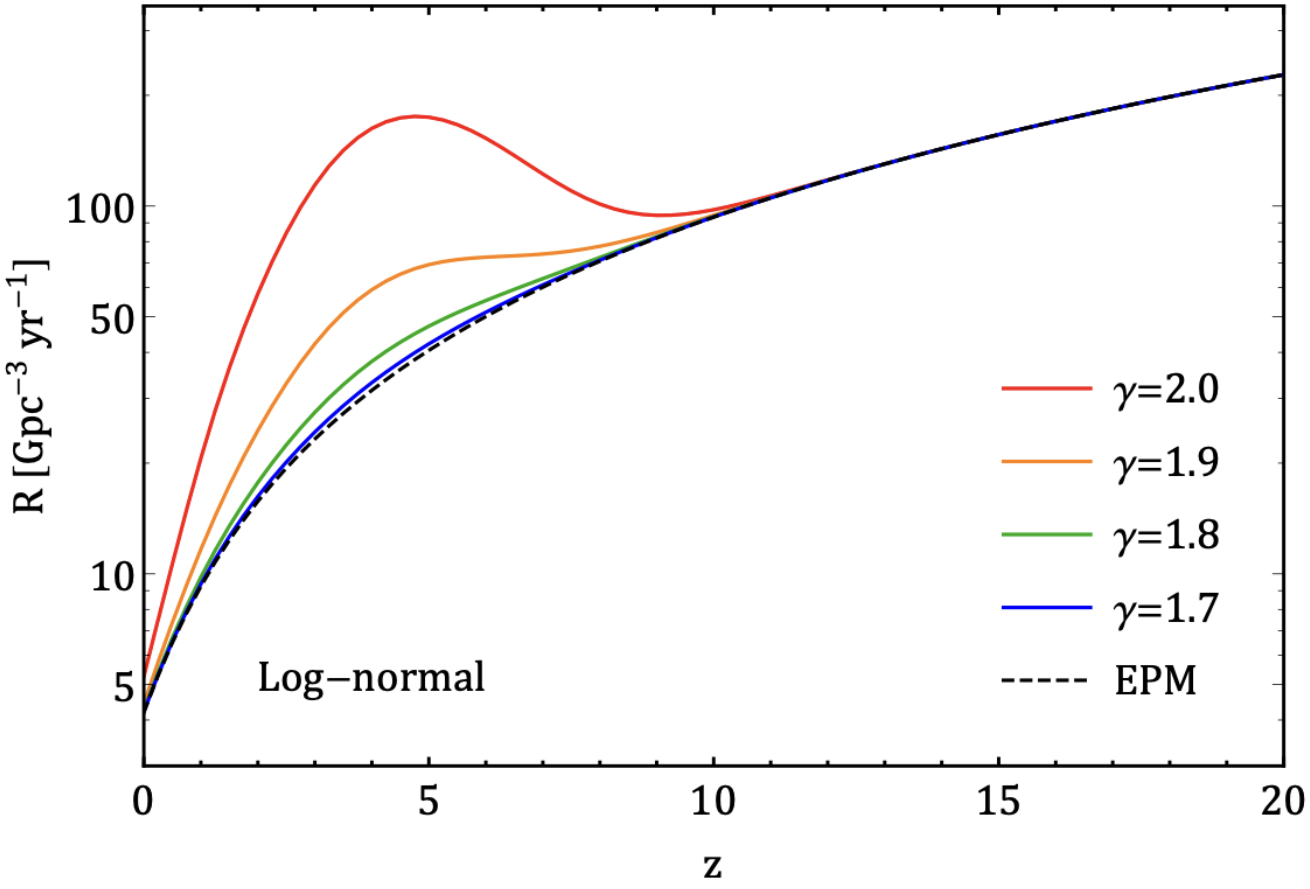




$M_{\rm PBH} = 30 M_\odot$ $f_{\rm PBH} = 10^{-3}$ $M_{\rm PBH} = 100 M_\odot$

PBH merger history as probe of DM

- PBH merger rate in spikes as a function of redshift



$$f_{\mathrm{PBH}} = 10^{-3}$$

Summary

- DM spike in the presence of SMBH
- PBH can be a fraction of DM
- PBH merger evolution can be a probe of DM spike because it shows a feature around $z \sim 5$

Thank you for your attention!