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Primordial black hole formation in a matter-dominated early universe

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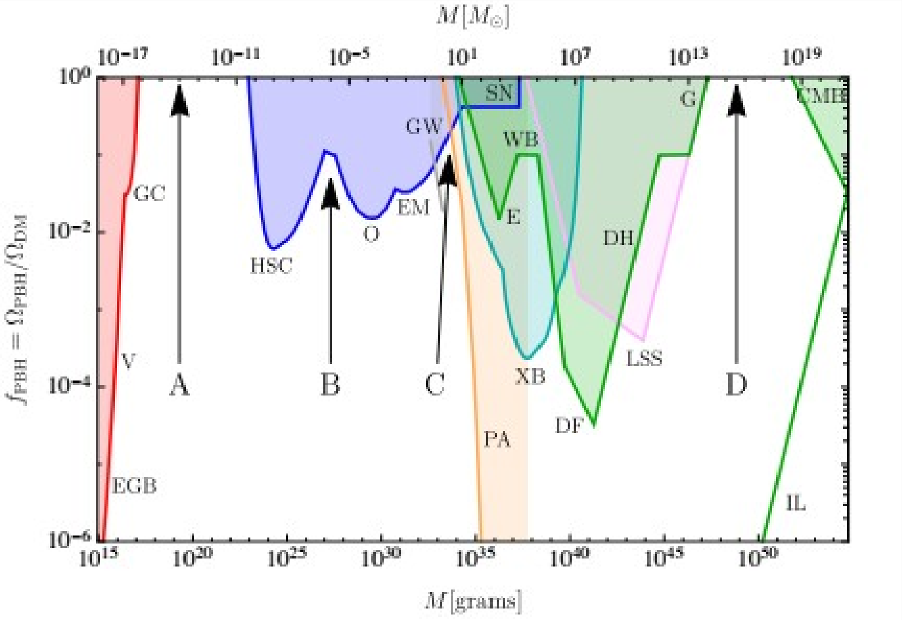
Main results

- Non-linear initial perturbations, both sub- and superhorizon
- At formation $M_{\mathrm{PBH}} H \sim 10^{-2}$
- Rapid post-collapse accretion
- Maximum final PBH mass with rapid accretion + self-similar growth $10^5 M_\odot$
- With slower accretion, potentially LVK PBHs

Primordial black holes (PBHs)

- Black holes that form in the early universe
- PBHs were first considered by Zeldovich/Novikov (1967) and Hawking (1971)
- PBHs could make up part of dark matter
- Many PBH formation mechanisms

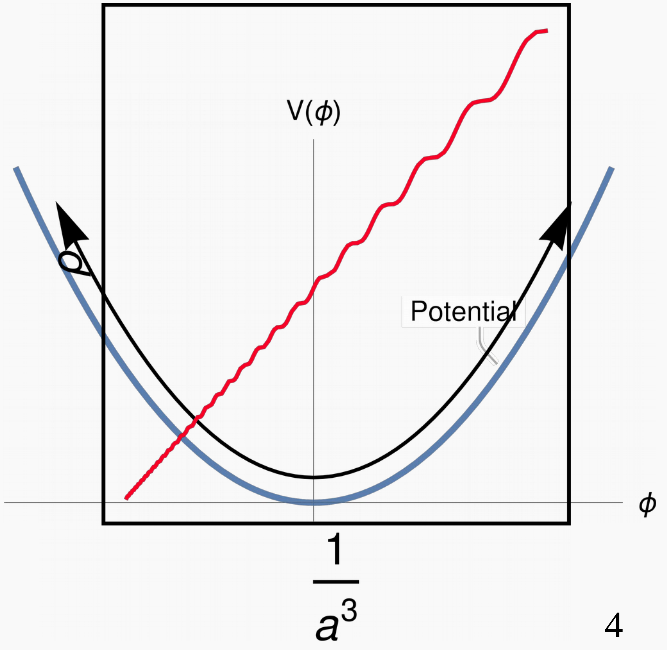


From: Carr & Kuhnel, arXiv:2006.02838

Matter domination

- Mostly radiation domination in PBH literature
- We choose matter-dominated universe
- Expansion driven by scalar field in quadratic potential
- Need $m \gg H$

$$\mathcal{L}_\phi = \frac{1}{2}\nabla^\mu\phi\nabla_\mu\phi + \frac{1}{2}m^2\phi^2$$

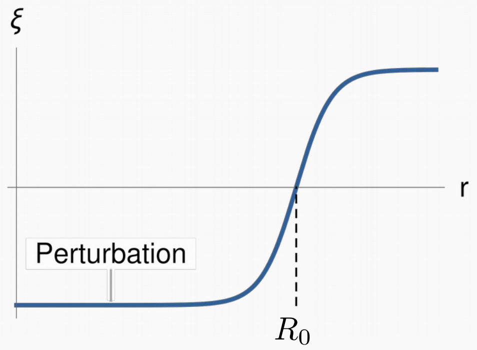


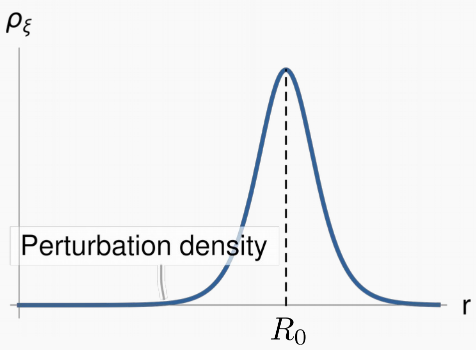
Energy perturbation

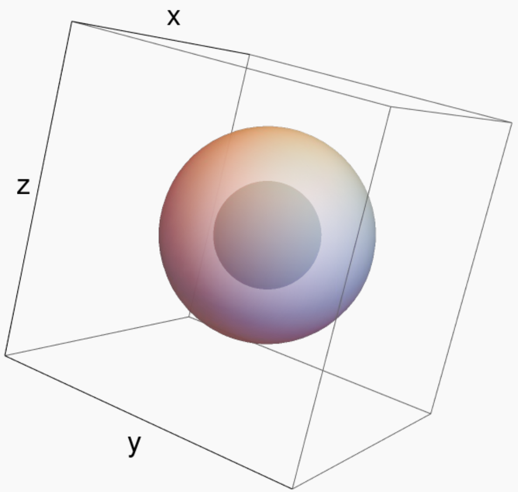
- 2nd massless scalar field

$$\rho_\xi(t=0) = \frac{1}{2}\left(\partial_i \xi\right)^2$$

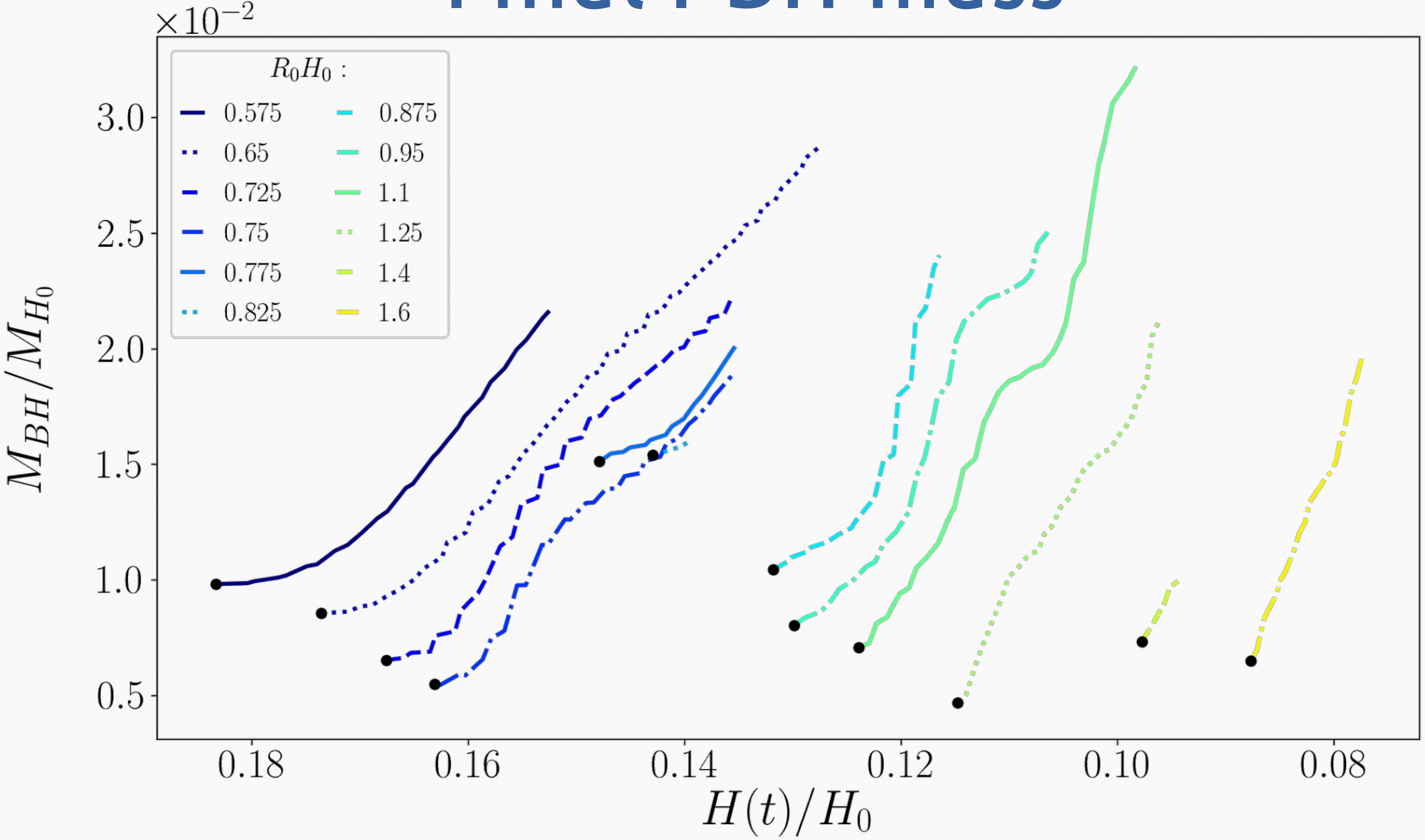
- Fixed amplitude and width, varying radius
- Spherically symmetric perturbation "shells", sub- and superhorizon
- We have $M_{\mathrm{shell}} \ll M_{\mathrm{Hubble}}$







Final PBH mass



PBH accretion

- Rapid initial accretion
- Naive argument (Z&N 1967):

$$\frac{dM_{\text{PBH}}}{dt} \sim R_{\text{PBH}}^2 \rho_{\text{background}} v_{\text{infall}}$$

$$\frac{dM_{\text{PBH}}}{dt} \sim M_{\text{PBH}}^2 \rho_{\text{background}} v_{\text{infall}}$$

  – if $\rho_{\text{background}} \sim H^2, v \lesssim 1$

$$\frac{dM_{\text{PBH}}}{dt} \sim M_{\text{PBH}}^2 H^2$$

  – integrating:

$$M_{\text{PBH}} H \sim \text{C}$$

- Upper limit: expansion makes self-similar growth impossible (Carr 1974)

Final PBH mass

- PBH mass can catch up with horizon mass
- However, $M_{\rm PBH} H \lesssim 1$
- BBN at T = 1MeV

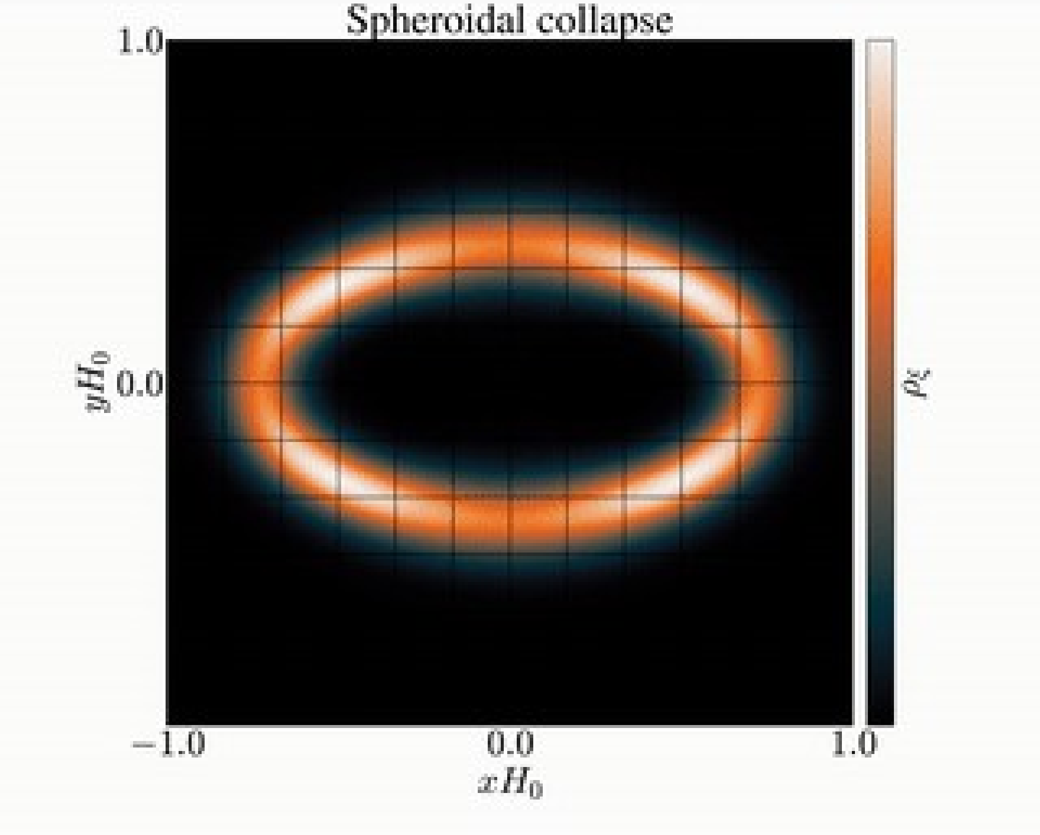
  $M_{\rm PBH} \lesssim 10^5 M_\odot$

- If PBH accretion slows down earlier,

  $M_{BH} \gtrsim 10^{-2} H^{-1}$

- For formation around T = 5MeV, LIGO/Virgo/KAGRA PBHs can be formed

Why 3+1: beyond spherical symmetry



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Accretion/direct collapse