Primordial Black Holes

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4th year in Physics

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What are primordial black holes (PBH)?

02
Formation

How PBHs formed? What are the possible scenarios? How massive are they?

03
Abundance Constraints

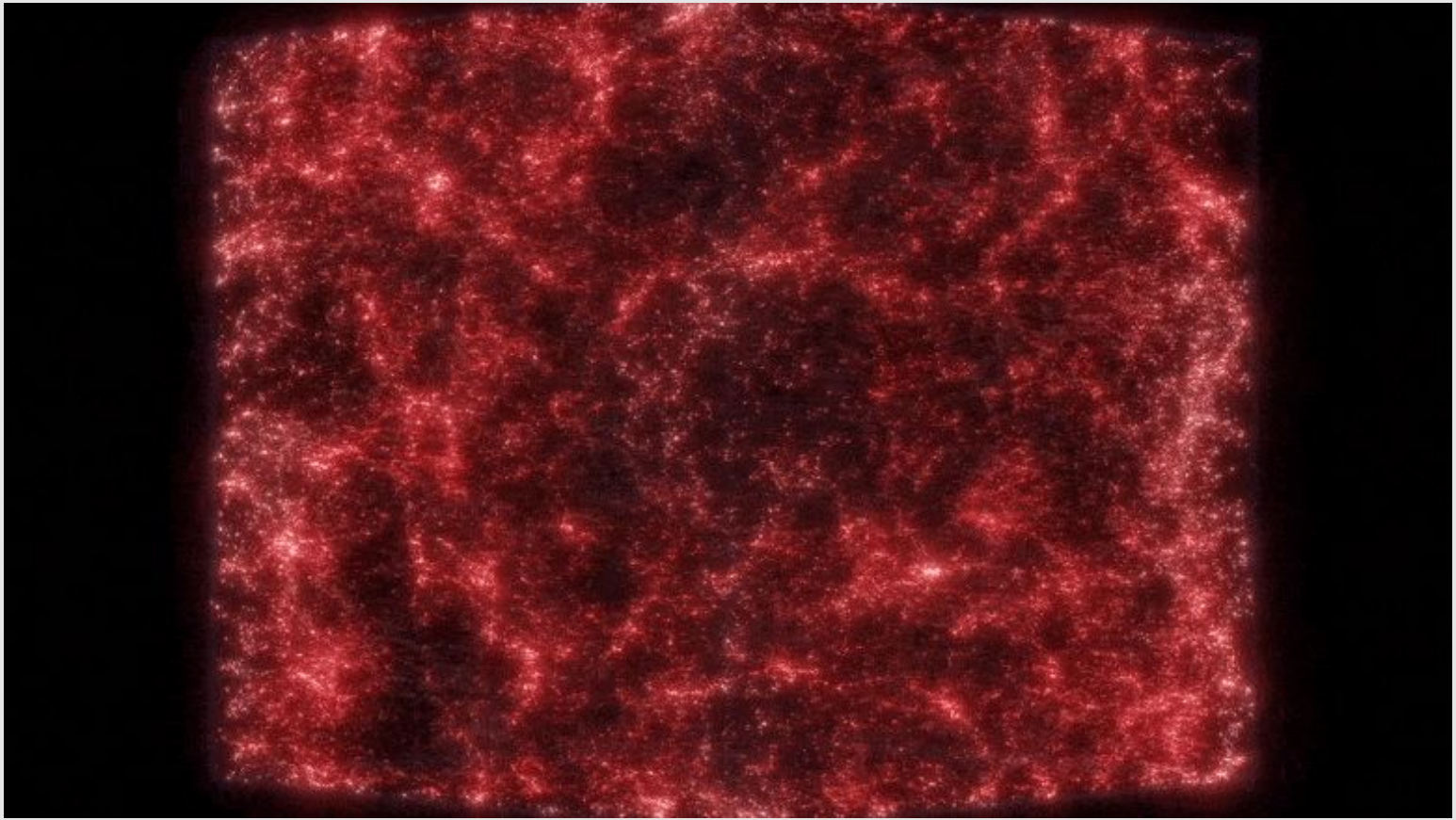
What's the current constraints on PBHs? And how people derive those constraints

04
Other Directions

How will people detect PBH in the future? Any interesting theories?

01. Overview

What are primordial black holes (PBH)?



About Primordial Black Hole

- Black holes formed via overdensity collapses in the early universe
- First proposed by Zel'dovich(1967) and Hawking(1971)
- One the potential Dark Matter candidates(Hawking(1971))
- Limited by Hawking Radiation(Hawking(1974)), those less massive PBHs($<5\times10^{14}$g) will be evaporated away, more massive ones could survive till today(Page(1976))
- LIGO-Virgo detection of solar mass BHs merger event(Abbott, et al. 2016) has intrigued research interests on PBHs

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

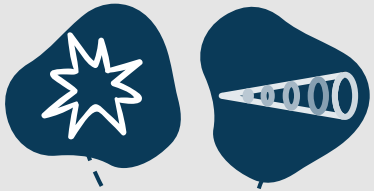
It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years.

02, Formation Theories

How PBHs formed? What are the possible scenarios? How massive are they?

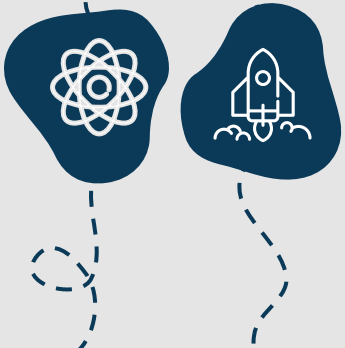
Formation Theories

1. Formed During Radiation Domination



3. Perturbation Generated by Inflation

2. Formed During Matter Domination



4. Other Mechanisms

Formation Theories

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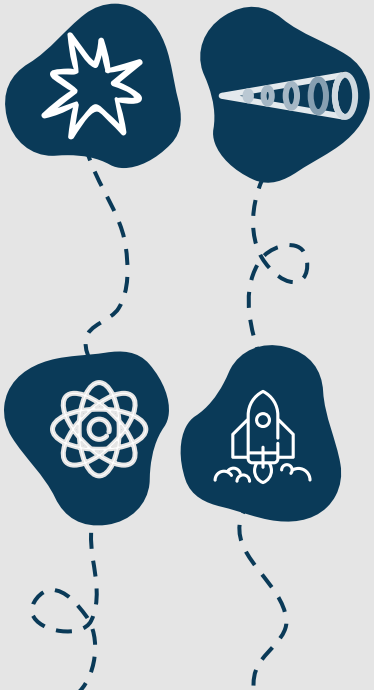
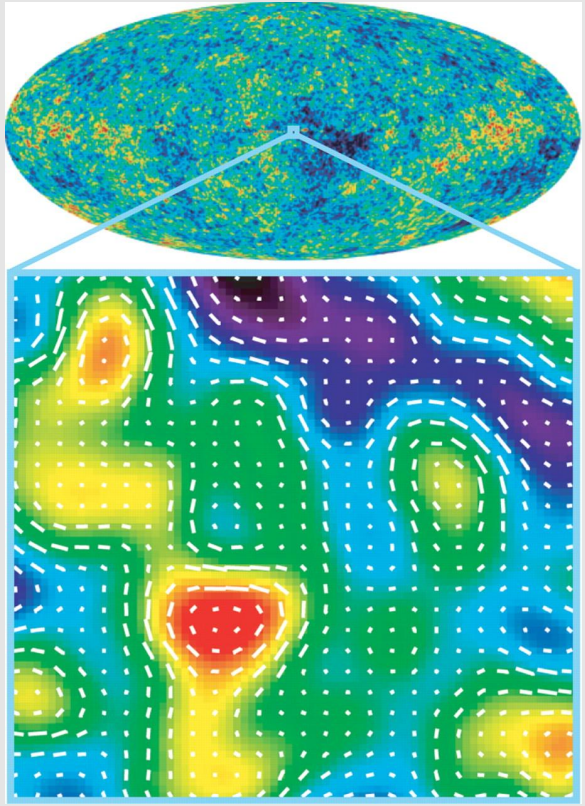


Formation during Rad-Domination

- Original calculation done by Carr(1975). When the density contrast $\delta \equiv \delta\rho/\rho > \delta_c = 1/3$, a PBH will form with mass~mass of the horizon(M_H).
- PBH mass depends on the amplitude and shape of the fluctuation:
- $$M_{\mathrm{PBH}} = \kappa M_{\mathrm{H}} (\delta - \delta_{\mathrm{c}})^{\gamma}$$
- Its mass fraction calculate by Press-Schechter theory(1974, refer to eq.(11)) as
- $$\beta(M_{\mathrm{H}}) \equiv \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}} = \int_{\delta_{\mathrm{c}}}^{\infty} P(\delta)\, \mathrm{d}\delta$$
- probability distribution of primordial density perturbations, $P(\delta)$



Formation Theories

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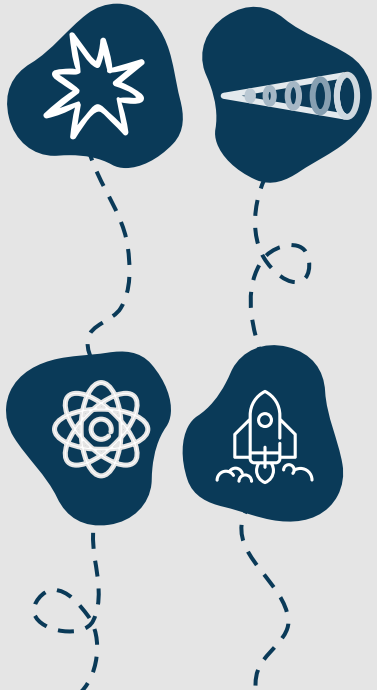


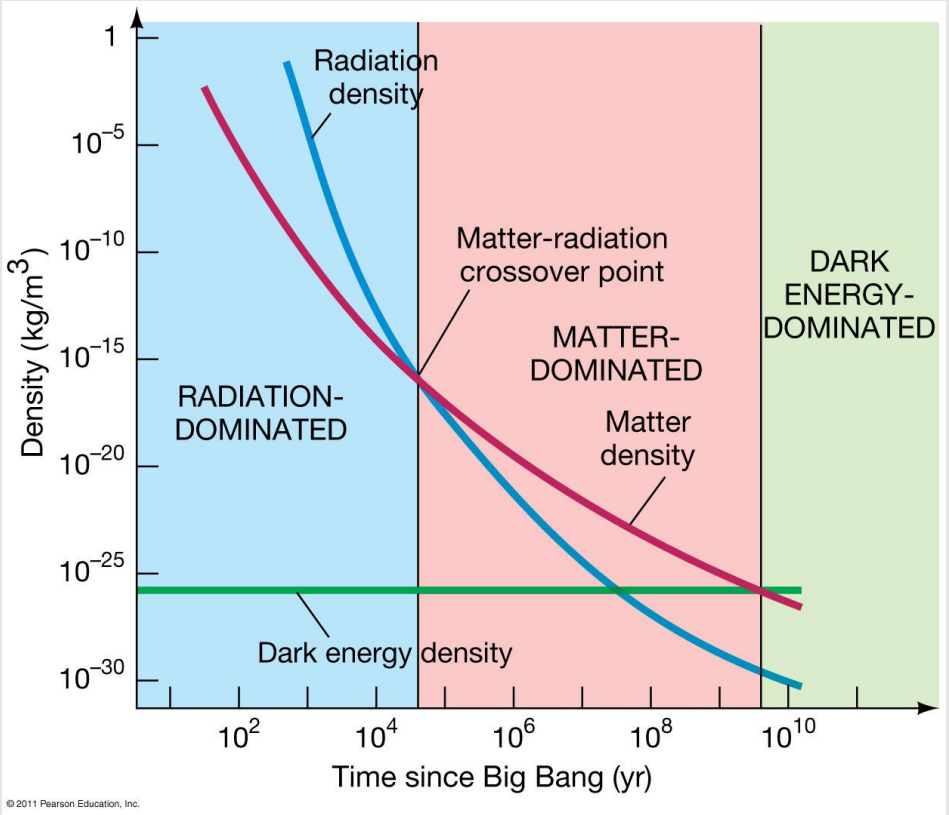
3. Perturbation Generated by Inflation

4. Other Mechanisms

Formation during Matter-Domination

- Recall rad-domination -> matter domination at t~1.7×10^{12}s
- GUT predicted matter domination before BBN(t~200s), where $\delta \propto a$, density contrast could grow
- Possibility first proposed by Khlopov and Polnarev in (1980), to get the astrophysical restriction on GUT.
- Mass fraction can be written as the product of inhomogeneity and anisotropy

$$\beta = \beta_{\mathrm{inhom}} \times \beta_{\mathrm{aniso}}$$



https://pages.uoregon.edu/jimbrau/astr123/Notes/Chapter27.html

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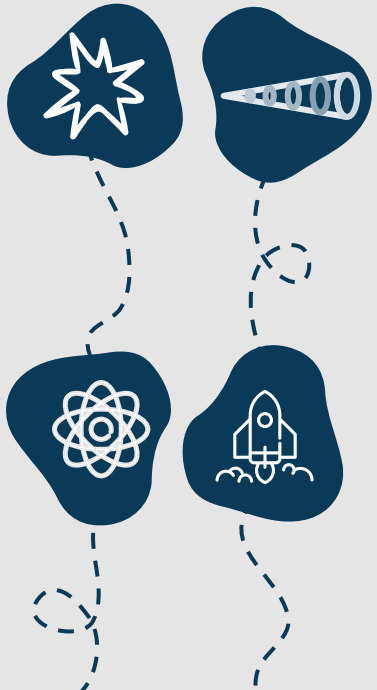
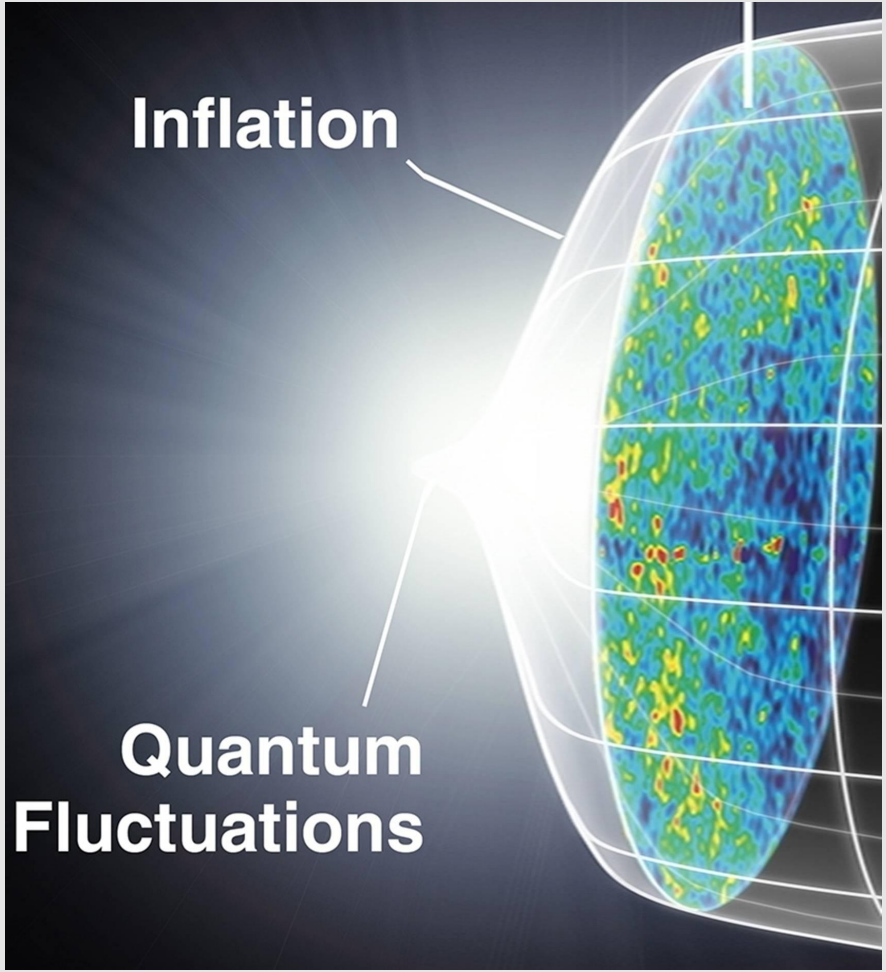


3. Perturbation Generated by Inflation

4. Other Mechanisms

Condition for Large Perturbations

- Ideas of inflation were covered in class. Quantum fluctuation->large scale density perturbation
- The Plank Collaboration(2018) measured the amplitude of the power spectrum, give constraints on inflation models/PBH mass fraction
- PBH forming perturbation from single-field inflation modes: dependence on potential shape, reheating era
- Multi-field inflation modes: hybrid inflation most commonly studied, leads to a large abundance of light PBHs



https://lecospa.ntu.edu.tw/theory-2/inflation-and-early-universe/

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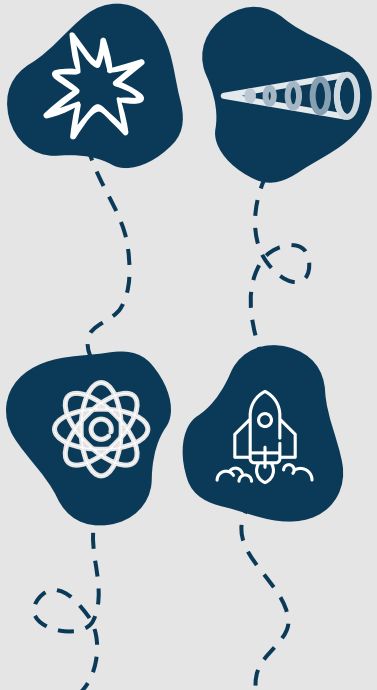

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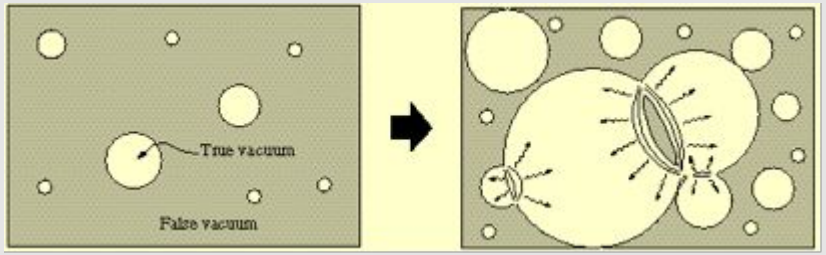
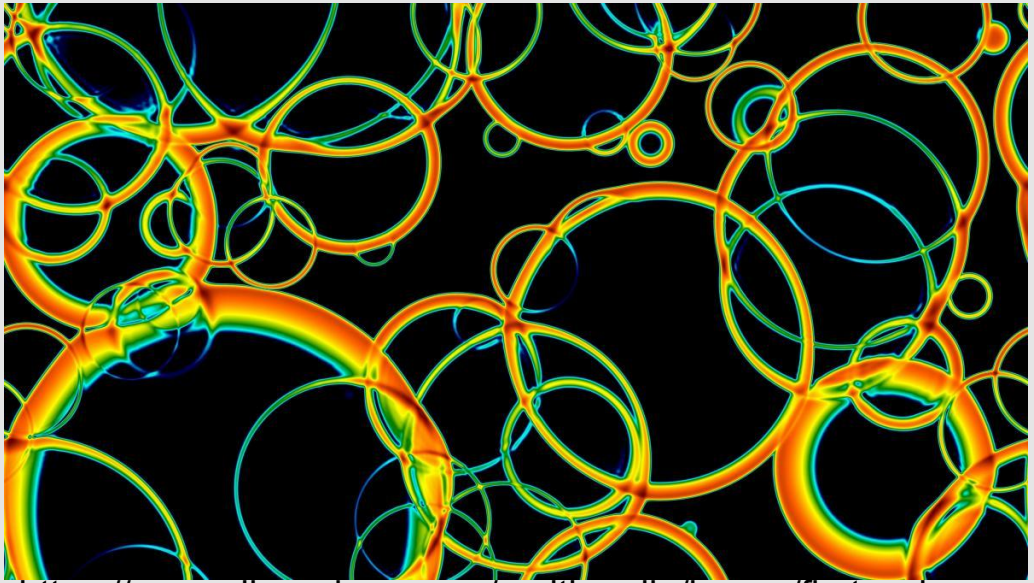
Other Mechanisms



- Bubble collisions: during first order phase transition
- Cosmic string-loop or cusp-collapse
- Domain wall collapse: during second order phase transition
- Scalar condensate fragmentation



https://www.elisascience.org/multimedia/image/first-order-phase-transition-early-universe

Text to image(AI created):

https://creator.nightcafe.studio/

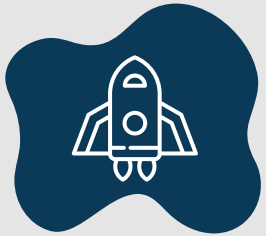
03, Abundance Constraint

What's the current constraints on PBHs? And how people derive those constraints?

Some defining parameters/assumptions:

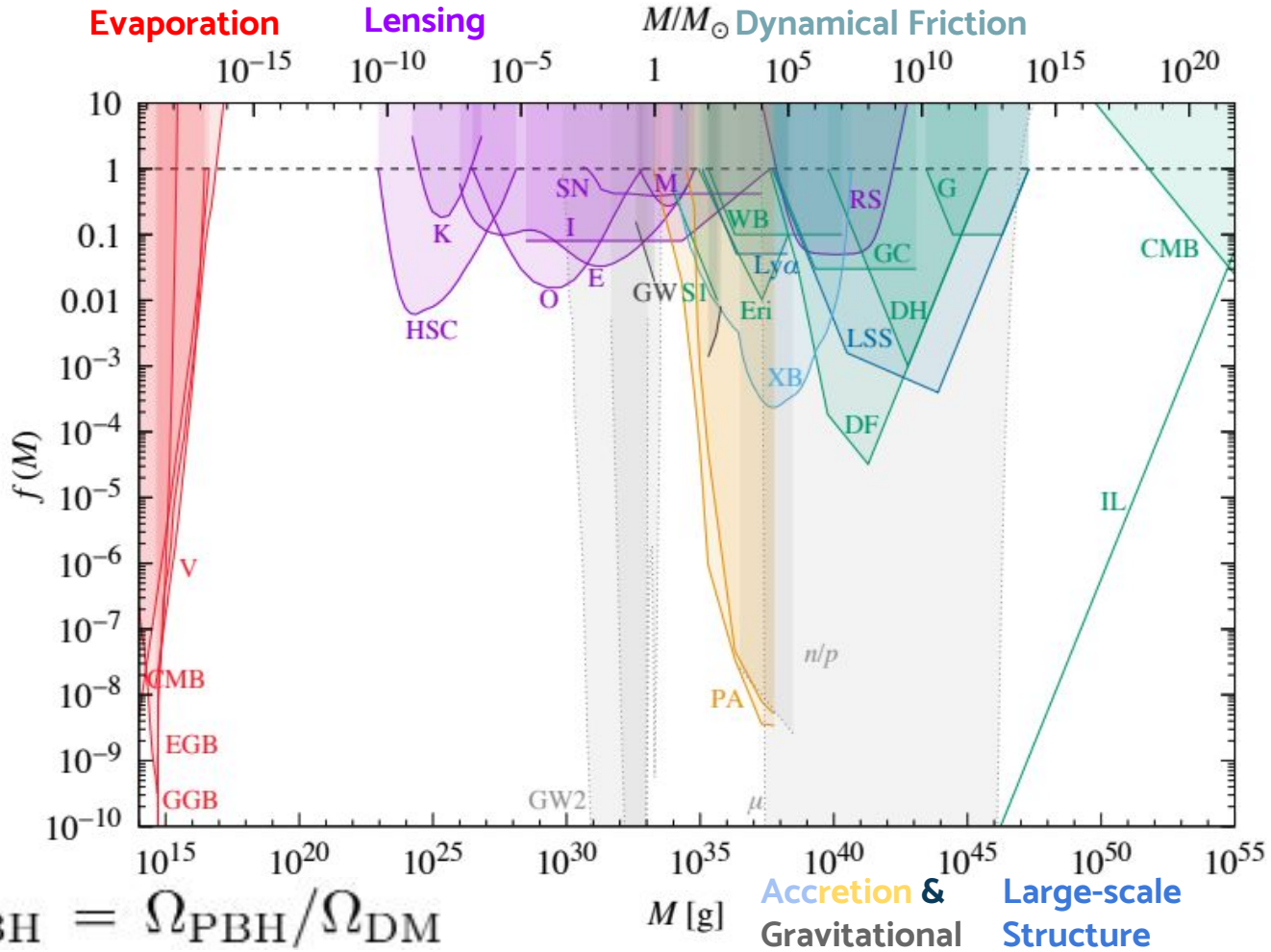
Mass Fraction

$$f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$$



Mass Range

Assume monochromatic distribution, all PBHs cluster in galactic halos



$$f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$$

Accretion & Gravitational wave

Large-scale Structure

Fig 10: Carr et al. (2021) ArXiv: [2002.12778]

Evaporation Constraints

- PBH smaller than $M_* = 10^{15}$g evaporated completely based on Hawking radiation, cannot contribute to DM
- Most stringent bound given by BBN, CMB and extragalactic γ-ray background (ECG)
- High energy particles emitted by PBH would modify standard BBN
- PBH emission will distort CMB spectrum, studied by Zel'dovich et al. (1977)
- The form of γ-ray spectrum from ECG rule out the PBHs as dominant contribution

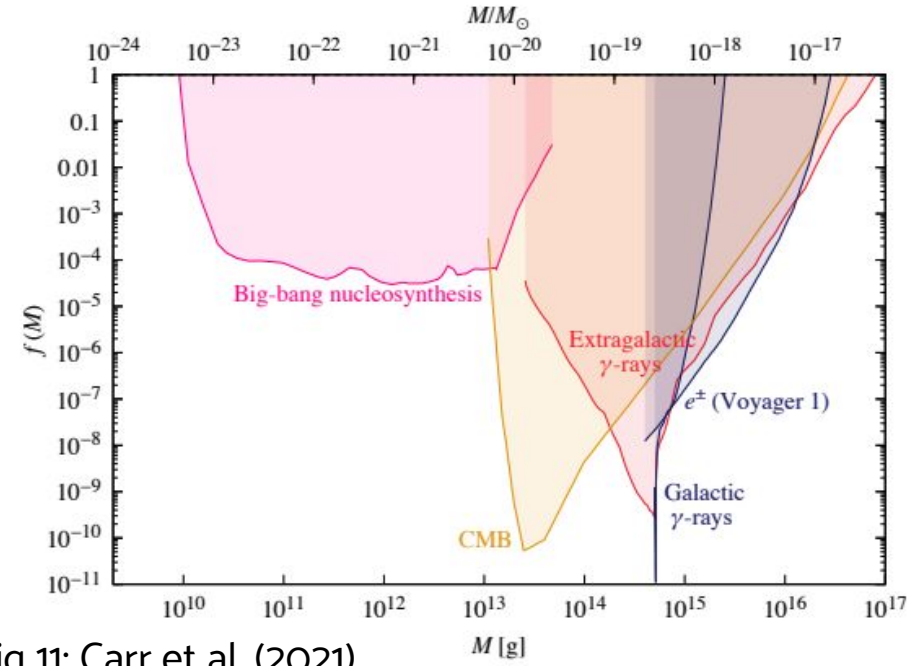


Fig 11: Carr et al. (2021)

Lensing Constraints

- Disputed/revised constraints in dashed: γ-ray bursts(GRB), Subaru Hyper Suprime-Cam(HSC)
- Microlensing of stars in the Magellanic Clouds: MACHO, EROS and OGLE
- Microlensing of supernovae(SNe): first applied to SNe by Metcalf and Silk(2007), more recent study ruled out PBH comprising all DMs
- In higher mass range: millilensing of compact radio sources(AGN)

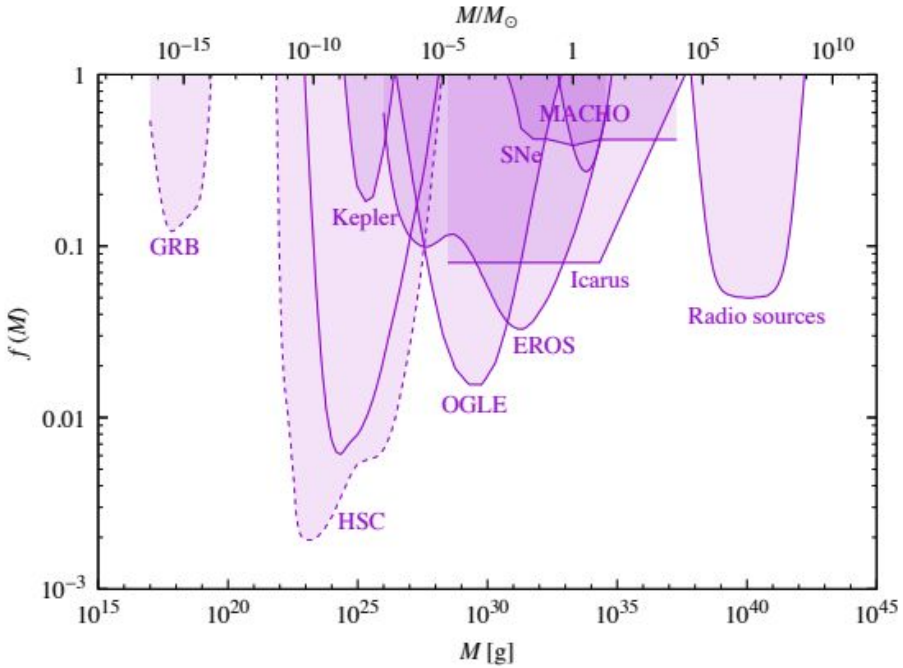


Fig 12: Carr et al. (2021)

Dynamical Friction

- Incredulity limit(at least 1 PBH given universe/cluster/galactic halo environment)
- Mostly in intermediate mass range 10-10^6 M_{sun}.
- Disputed: capture of light PBHs by stellar objects
- Disruption by passing PBH: wide binaries/ globular clusters/dwarf galaxies
- Tidal distortion of galaxies
- Dynamical friction: PBH been dragged to the nucleus of galaxy, leading to excessive nuclear mass

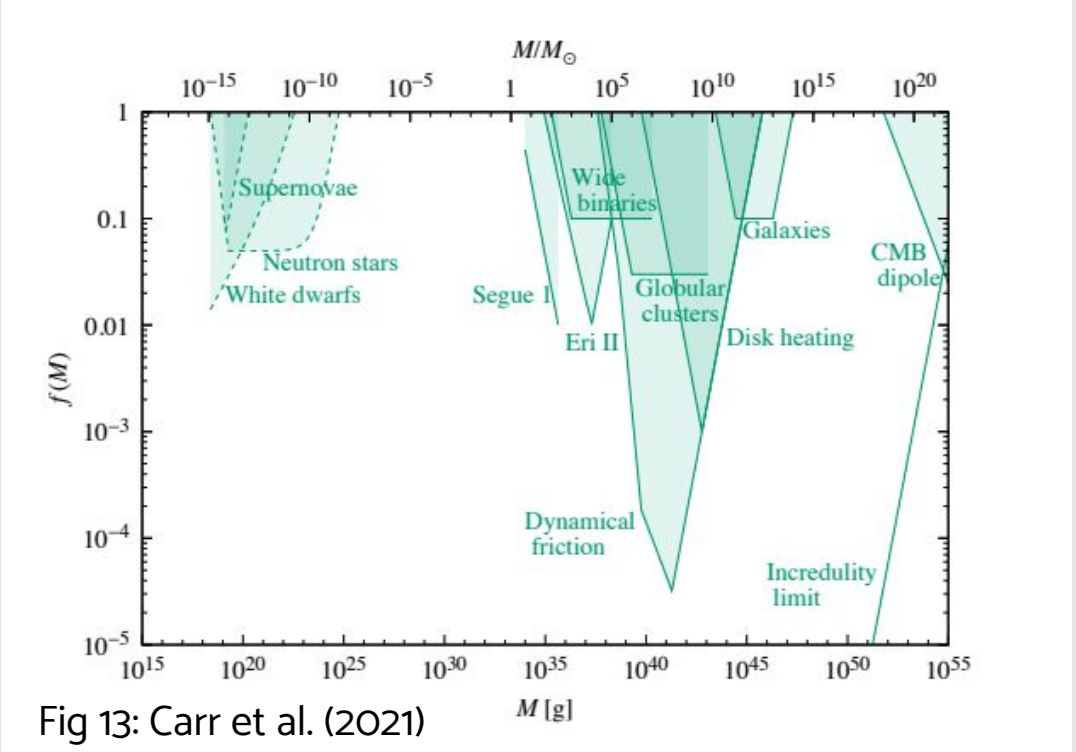


Fig 13: Carr et al. (2021)

Large Scale Structure Constraints

- Observation of Lyman-α alpha forest: constrain the Poisson noise in the matter density fluctuations.(Afshordi et al. (2003))
- Not to accelerate formation of Dwarf/Milky way/Clusters of galaxies by the 'seed' and 'Poisson' effect (Carr and Silk(2018))

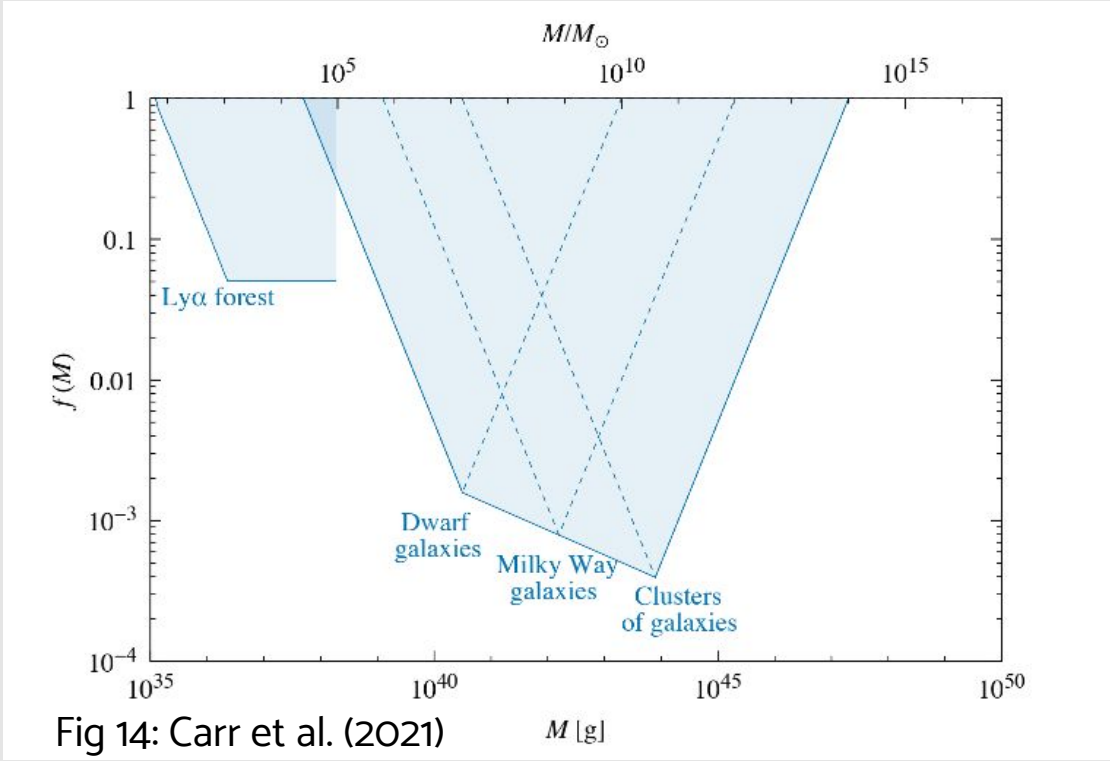


Fig 14: Carr et al. (2021)

Accretion and Gravitational Wave Constraints

- Most accretion studies assume Bondi accretion: could alter mass function, less secure. Constrains: Planck, Leo T, X-ray binaries
- Intensified by recent years of GW detection, possibility of PBH origin
- Stochastic GW background:LIGO/Virgo
- Stellar mass BH merger event: LIGO/Virgo O1 data

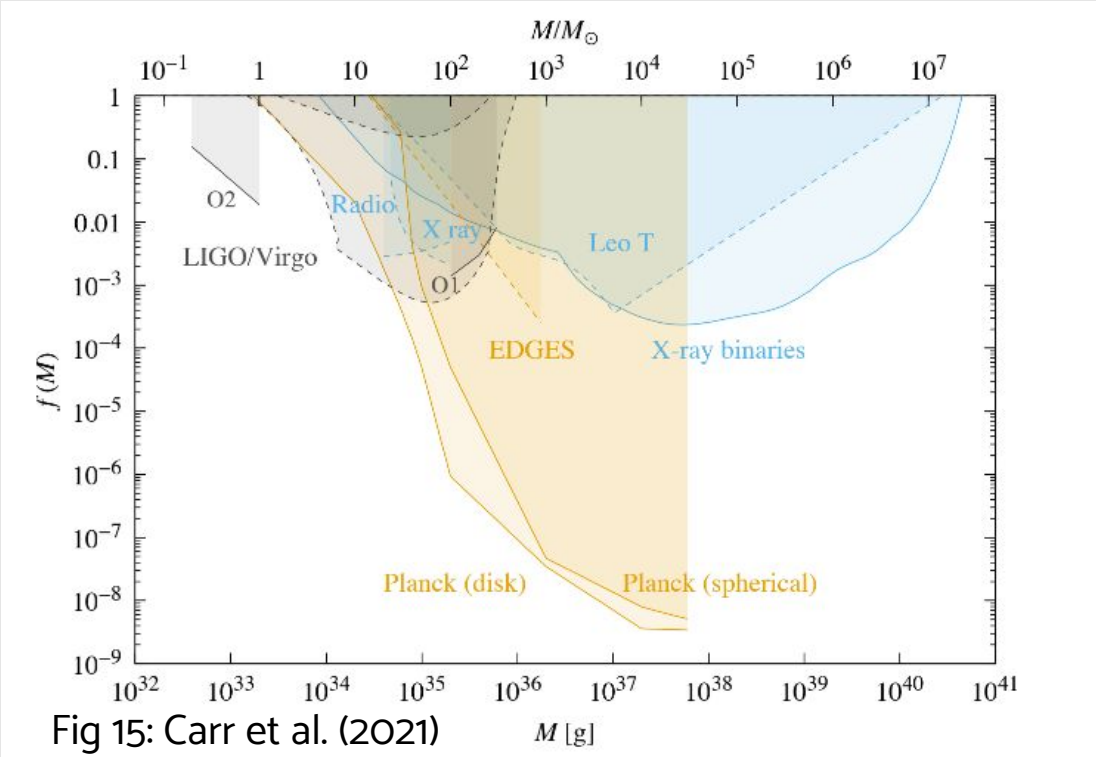


Fig 15: Carr et al. (2021)

04, Other Directions

How will people detect PBH in the future? Any interesting theories?

PBH mass Function

- For PBH span an extended range of masses:
- $$\rho(M) \equiv M^2 \frac{\mathrm{d}n}{\mathrm{d}M}\,, \quad f(M) \equiv \frac{\rho(M)}{\rho_{\mathrm{CDM}}}$$
- dn : # density of PBHs in (M, M+dM)
- f(M): integrated values for density fraction around M.
- Total PBH fraction in DM f_{PBH} is given by:
- $$f_{\mathrm{PBH}} \equiv \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{CDM}}} = \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M\, \psi(M)$$
- ψ(M): distribution density for log M, governed by different formation mechanisms

$$\psi(M) \propto M \frac{\mathrm{d}n}{\mathrm{d}M} \qquad \psi_{\mathrm{mon}}(M) \equiv f_{\mathrm{PBH}}(M_c)\, \delta(M - M_c)$$

Extended PBH mass-function Constraints

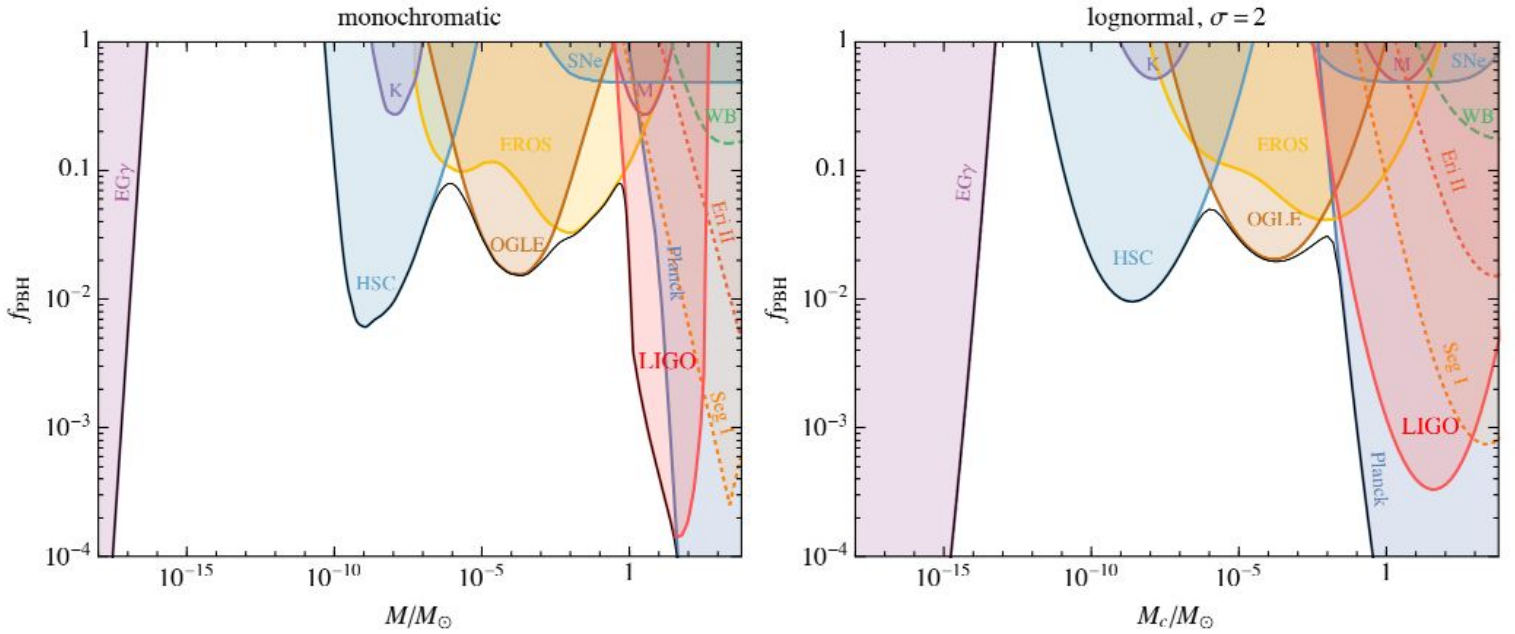
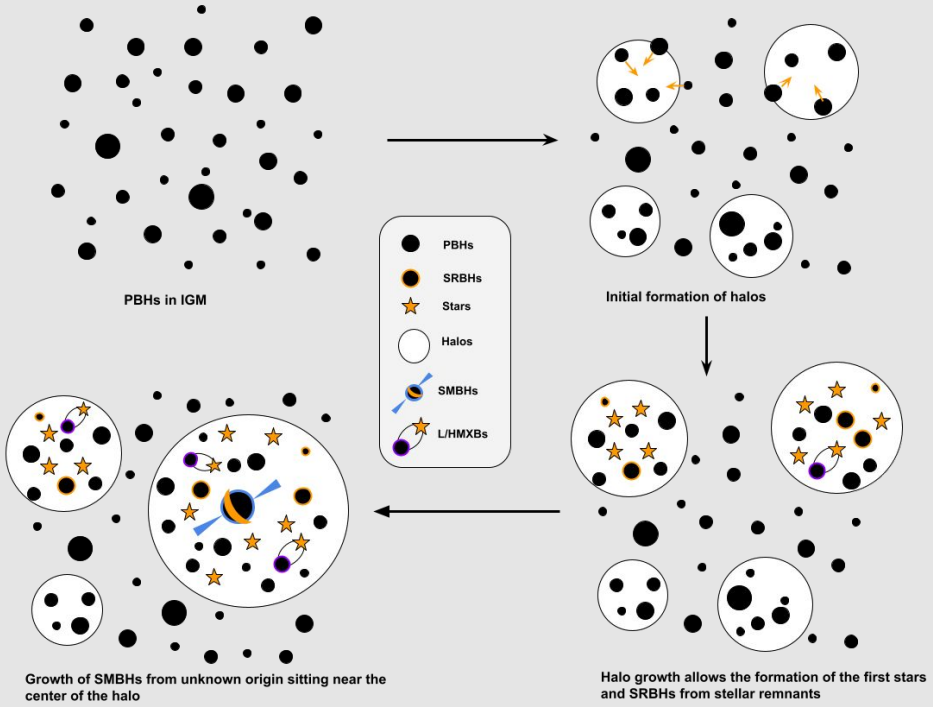


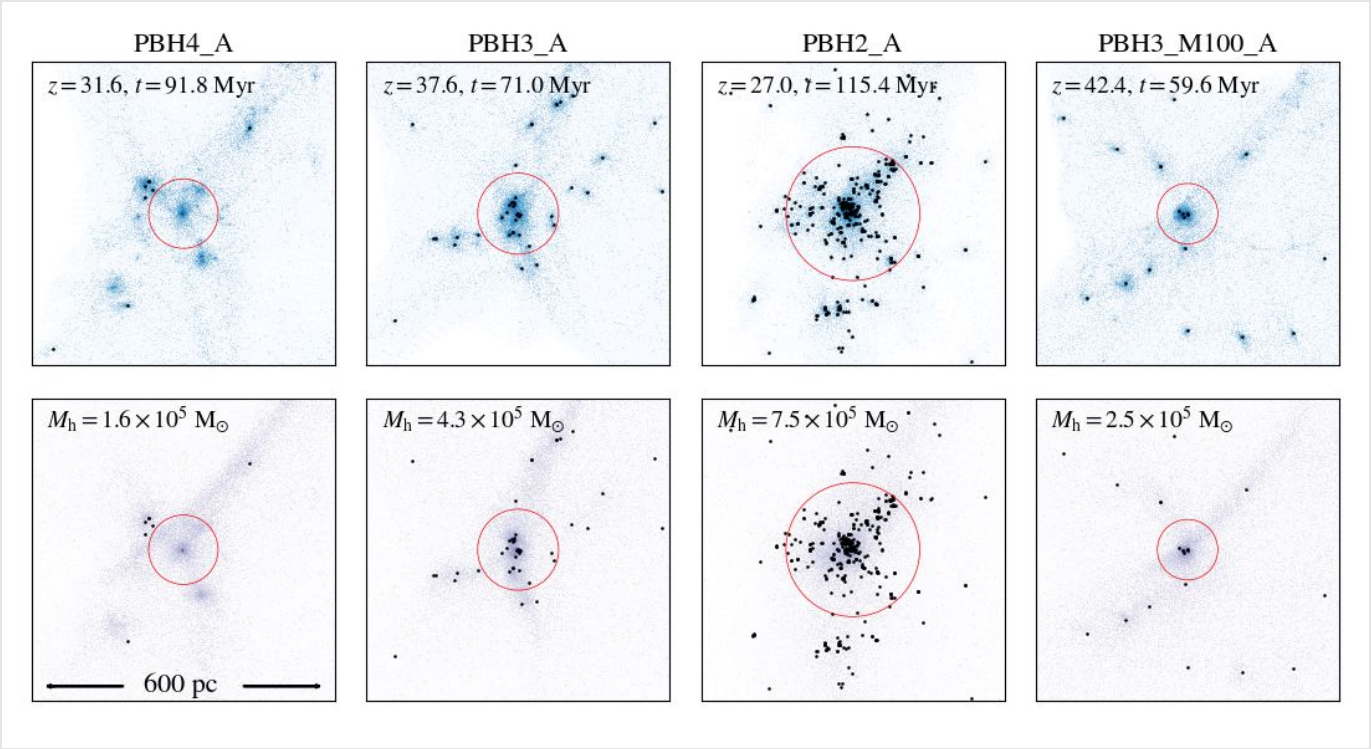
Fig 20: Carr et al. (2021)

How do I Approach PBHs

- Choose some PBH parameters
- Consider the initial configuration
- Consider the astrophysical effect of PBHs
- Simulations and simulations!



Cosmological Simulations w/ PBHs



Let's conclude with a video

Thank you!

References

[1]Green, A. M., & Kavanagh, B. J. (2021). Primordial Black Holes as a dark matter candidate. *Journal of Physics G: Nuclear and Particle Physics*, *48*(4), 043001.
[2]Carr, B., Kohri, K., Sendouda, Y., & Yokoyama, J. I. (2021). Constraints on primordial black holes. *Reports on Progress in Physics*, *84*(11), 116902.