

Primordial Black Holes in the Excursion Set Theory

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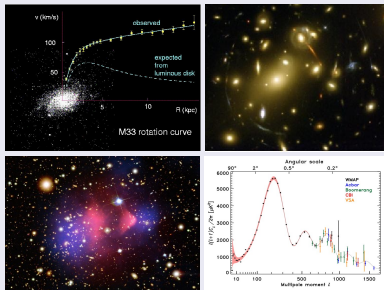
Based on

MNRAS 505 (2021) 1787 [arXiv:2101.07812]

- 1 Primordial Black Holes
- 2 PBHs Formation
 - Press-Schechter Formalism
 - Excursion Set Theory
- 3 Conclusion

Dark Matter

Evidences



Properties

- stable
- neutral
- weakly interacting
- right relic density

Candidates

- Axions
- Sterile neutrinos
- WIMPs
- Primordial Black Holes (PBHs)

Primordial Black Holes

Definition

A PBH is a type of black hole that is **not** formed by the gravitational collapse of a star, but by the extreme density of matter present during the Universe's early expansion.

PBHs properties

Mass: $M_{\text{BH}} = 10^{15} \left(\frac{t}{10^{-23} \text{ s}} \right) \text{ g}$

$$M_{\odot} \simeq 2 \times 10^{33} \text{ g}$$

$$\text{Planck scale} \longrightarrow 10^{-5} \text{ g}$$

$$\text{GUT scale} \longrightarrow 10^3 \text{ g}$$

$$\text{EW scale} \longrightarrow 10^{28} \text{ g}$$

$$\text{QCD scale} \longrightarrow 10^{32} \text{ g}$$

Hawking radiation

Temperature: $T_{\text{BH}} \approx 10^{-7} \left(\frac{M}{M_{\odot}} \right)^{-1} \text{ K}$

$M > 10^{17} \text{ g}$	massless particles
$10^{15} \text{ g} \lesssim M \lesssim 10^{17} \text{ g}$	electrons
$10^{14} \text{ g} \lesssim M \lesssim 10^{15} \text{ g}$	muons
$M < 10^{14} \text{ g}$	hadrons

Lifetime: $\tau_{\text{BH}} \approx 10^{64} \left(\frac{M}{M_{\odot}} \right)^3 \text{ y}$

M_{BH}	τ_{BH}
A man	10^{-12} s
10^{15} g	10^{10} y
Earth	10^{49} y
Sun	10^{66} y
Milky Way	10^{99} y

Why PBHs are useful?

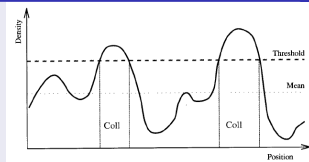
- PBHs as a probe of the early Universe ($M < 10^{15}$ g)
- PBHs as a probe of gravitational collapse ($M > 10^{15}$ g) ✓
DM candidates $\Omega_{\text{PBH}}^0 \lesssim \Omega_{\text{CDM}}^0 (= 0.23)$ Source of gravitational waves
- PBHs as a probe of High Energy Physics ($M \sim 10^{15}$ g)
- PBHs as a probe of quantum gravity ($M \sim 10^{-5}$ g)
(DM candidates)

How PBHs form?

- Soft equation of state
- Bubble collisions
- Collapse of cosmic loops
- Fluctuations by inflation

Press-Schechter Formalism

The Press-Schechter formalism is a model for predicting the number density of bound objects of a certain mass.



$$\beta(\geq M) = \gamma \int_{\delta_c}^{\infty} P(\delta; M(R))$$

$$\delta_c = 0.47$$

$$\text{Gaussian PDF: } P_G(\delta; R) = \frac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\frac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$$

$$\delta^2(k, t) \equiv \mathcal{P}_\delta(k, t) = \frac{4(1+w)^2}{(5+3w)^2} \left(\frac{k}{aH}\right)^4 \mathcal{P}_{\mathcal{R}_c}(k) \quad w = 1/3$$

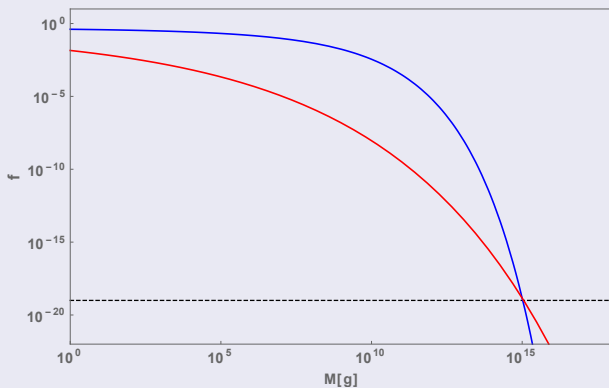
$$\mathcal{P}_{\mathcal{R}_c}(k) = \mathcal{P}_{\mathcal{R}_c}(k_0) \left(\frac{k}{k_0}\right)^{n(k)-1}$$

$$\sigma_\delta^2(R) = \int_0^\infty W^2(kR) \mathcal{P}_\delta(k) \frac{dk}{k}$$

$$W(kR) = \exp(-k^2 R^2 / 2)$$

$$M_{\text{PBH}}(k) \simeq 30 M_\odot \left(\frac{\gamma}{0.2}\right) \left(\frac{g_{*,i}}{10.75}\right)^{-1/6} \left(\frac{k_{\text{PBH}}}{2.9 \times 10^5 \text{ Mpc}^{-1}}\right)^{-2}$$

$f(\geq M)$ diagram for the mass range $10^0 - 10^{20}$ g

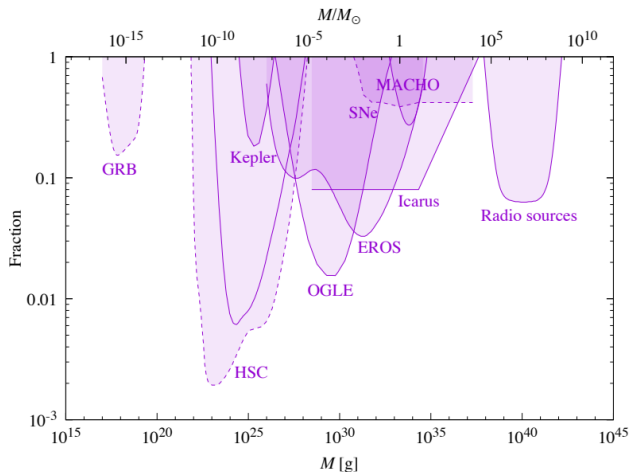


Result

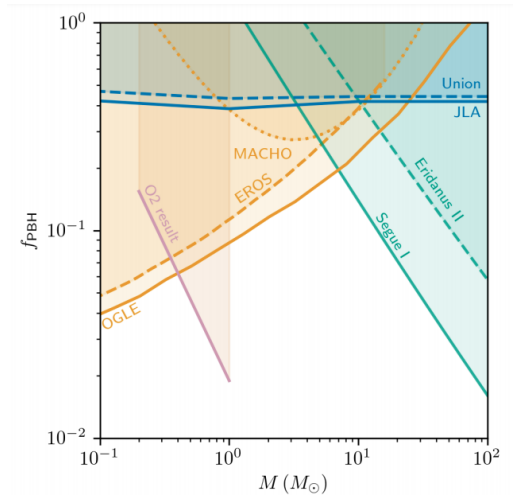
$$\beta = \frac{1}{2} \operatorname{erfc} \left(\delta_c / \sqrt{2\sigma_\delta^2(R)} \right)$$

$$n_s(k_{\text{PBH}}) \geq 1.418 \quad \Rightarrow \quad \mathcal{P}_\zeta \simeq 2 \times 10^{-2} \quad \text{for Gaussian PDF}$$

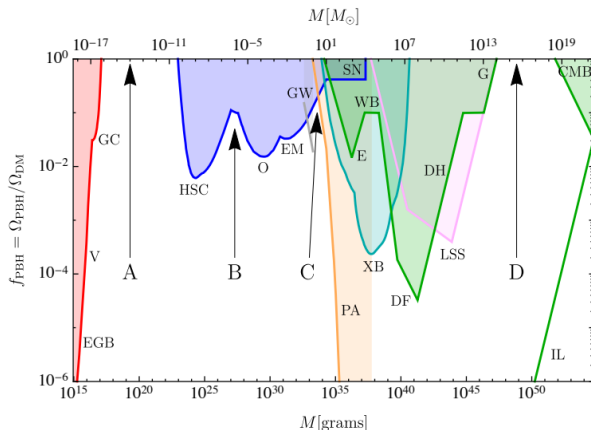
$$\beta \simeq 3.7 \times 10^{-9} \gamma^{-1/2} \left(\frac{g_{*,i}}{10.75} \right)^{1/4} \left(\frac{M_{\text{PBH}}}{M_\odot} \right)^{1/2} f_{\text{PBH}}, \quad f_{\text{PBH}} \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}}$$



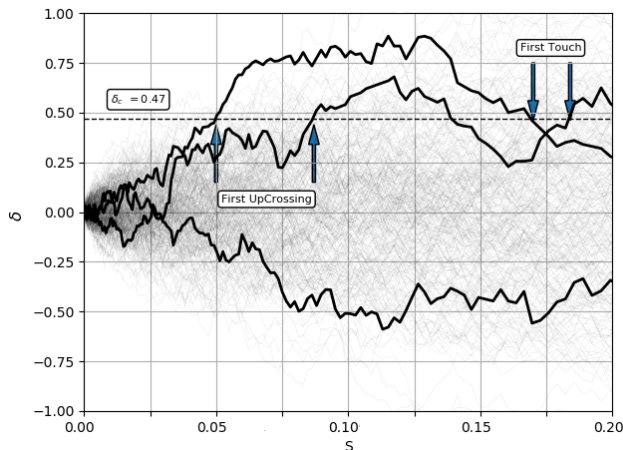
- $10^{-11} M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^{-6} M_{\odot}$ with $f_{\text{PBH}} \sim 10^{-3}$,
- $10^{-6} M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^{-3} M_{\odot}$ with $f_{\text{PBH}} \sim 10^{-2}$,
- $10^{-3} M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^{-1} M_{\odot}$ with $f_{\text{PBH}} < 0.04$.



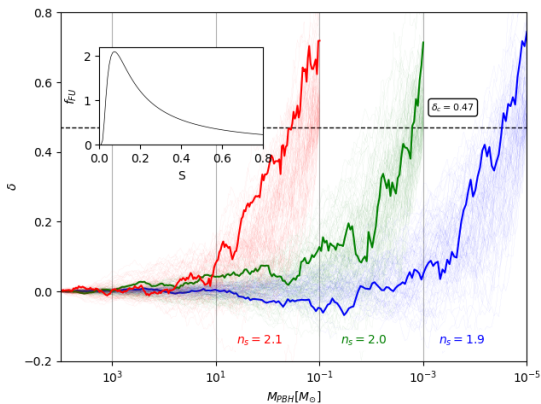
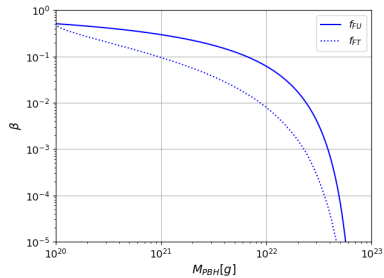
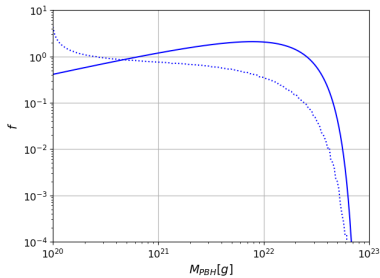
- $0.2 M_{\odot} \lesssim M_{\text{PBH}} \lesssim 1.0 M_{\odot}$, corresponding to at most 0.16 or 0.02 of the DM, respectively.



- asteroid mass range $10^{16} \text{ g} \lesssim M_{\text{PBH}} \lesssim 10^{17} \text{ g}$,
- sublunar mass range $10^{20} \text{ g} \lesssim M_{\text{PBH}} \lesssim 10^{24} \text{ g}$,
- intermediate mass range $10 M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^3 M_{\odot}$,
- stupendously large black holes (SLABs) $M_{\text{PBH}} \geq 10^{11} M_{\odot}$.



$$f_{\text{FU}}(S, \delta_c) = \frac{1}{\sqrt{2\pi}} \frac{\delta_c}{S^{3/2}} \exp\left(-\frac{\delta_c^2}{2S}\right)$$



Results

	mass range	f_{PBH}	lower bound of mass range	spectral index	
				EST	PS
asteroid mass range	$(10^{16} - 10^{17}) \text{ g}$	1	10^{16} g	1.490	1.616
sublunar mass range	$(10^{20} - 10^{24}) \text{ g}$	1	10^{20} g	1.540	1.703
			10^{22} g	1.600	1.756
Subaru HSC	$(10^{-11} - 10^{-6}) M_{\odot}$	10^{-3}	$10^{-10} M_{\odot}$	1.604	1.560
			$10^{-8} M_{\odot}$	1.666	1.605
OGLE	$(10^{-6} - 10^{-3}) M_{\odot}$	10^{-2}	$10^{-6} M_{\odot}$	1.729	1.757
			$10^{-4} M_{\odot}$	1.845	1.835
EROS/MACHO	$(10^{-3} - 10^{-1}) M_{\odot}$	0.04	$10^{-3} M_{\odot}$	1.862	1.947
			$10^{-2} M_{\odot}$	1.942	1.970
sub-Solar mass range	$(0.2 - 1.0) M_{\odot}$	0.02	$0.2 M_{\odot}$	2.018	2.046
			$0.6 M_{\odot}$	2.115	2.078
intermediate mass range	$(10^1 - 10^3) M_{\odot}$	1	$10 M_{\odot}$	2.130	2.408
			$10^2 M_{\odot}$	2.235	2.514
SLABs	$\geq 10^{11} M_{\odot}$	1	$10^{11} M_{\odot}$	5.220	5.598
			$10^{12} M_{\odot}$	6.660	6.891

- The fluctuation which arise at inflation are the most likely source of PBHs.
- The power spectrum at scale of PBHs formation should be much higher than the one in the observed scales.
- We can form PBHs in the EST with any mass.
- PBH cannot be the whole fraction of dark matter.

