Primordial Black Holes

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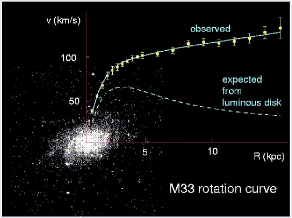
CAP Theory, Montreal
June 19, 2026

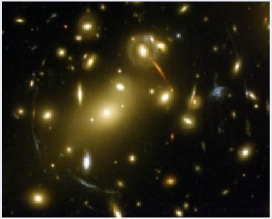
Based on

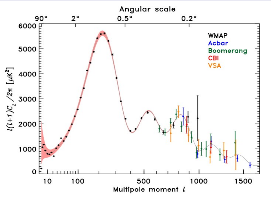
JCAP03(2026)082 [arXiv:2508.01896]
JCAP11(2024)005 [arXiv:2308.04642]
JCAP09(2022)034 [arXiv:2205.08906]
MNRAS505(2021)1787 [arXiv:2101.07812]

Outline

Evidences

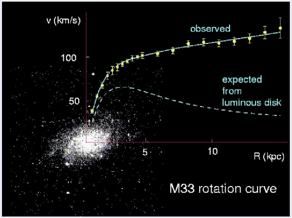

v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

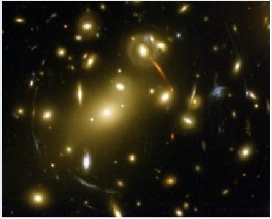


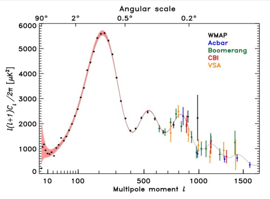

Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
WMAP
Acbar
Boomerang
CBI
VSA
$l(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
1500
Multipole moment l

Dark Matter

Evidences







How much DM?

Planck.XIII

$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$$

Properties

- stable
- neutral
- weakly interacting
- right relic density

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Candidates

- Axions
- Sterile neutrinos
- WIMPs
- ...

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- ...

Any candidate in Standard Model?

Primordial Black Holes (PBHs)

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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.

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Mass: $M_{\rm BH} = 10^{15}\left(\frac{t}{10^{-23}\,{\rm s}}\right)\,{\rm g}$ $\qquad M_{\odot} \simeq 2\times 10^{33}\,{\rm g}$

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$$\begin{aligned} \text{Planck scale} &\longrightarrow 10^{-5}\,\rm g \\ \text{GUT scale} &\longrightarrow 10^{3}\,\rm g \\ \text{EW scale} &\longrightarrow 10^{28}\,\rm g \\ \text{QCD scale} &\longrightarrow 10^{32}\,\rm g \end{aligned}$$

Hawking radiation

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

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

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

$M_{\rm BH}$	$\tau_{\rm BH}$
A man	$10^{-12}\,\rm s$
A building	$1\,\rm s$
$10^{15}\,\rm g$	$10^{10}\,\rm y$
The Earth	$10^{49}\,\rm y$
The Sun	$10^{66}\,\rm y$
The Galaxy	$10^{99}\,\rm y$

Why PBHs are useful?

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

How PBHs form?

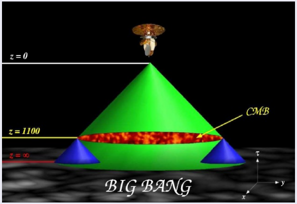
- Soft equation of state
- Bubble collisions
- Collapse of cosmic loops
- Fluctuations by inflation ✓

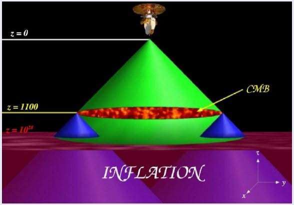
Inflation

Accelerated expansion of the Universe $\ddot{a} > 0$

Why inflation?

- Flatness problem
- Horizon problem





$$\frac{\ddot{a}}{a} = -\frac{4\pi\, G}{3}\,(\rho + 3\,p) \xrightarrow{\ddot{a}>0} w < -\frac{1}{3}$$

Scenario

Equation of motion $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \xrightarrow{V(\phi) \gg \dot{\phi}^2} 3H\dot{\phi} \simeq -V'(\phi)$

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Inflation Parameters

Power Spectrum

$$\mathcal{P}_{\mathcal{R}_c} = \frac{1}{12\pi^2 M_{\rm P}^6}\frac{V^3}{V'^2}$$

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

$$n_s(k_0) \equiv \frac{d\ln\mathcal{P}_{\mathcal{R}_c}}{d\ln k}$$

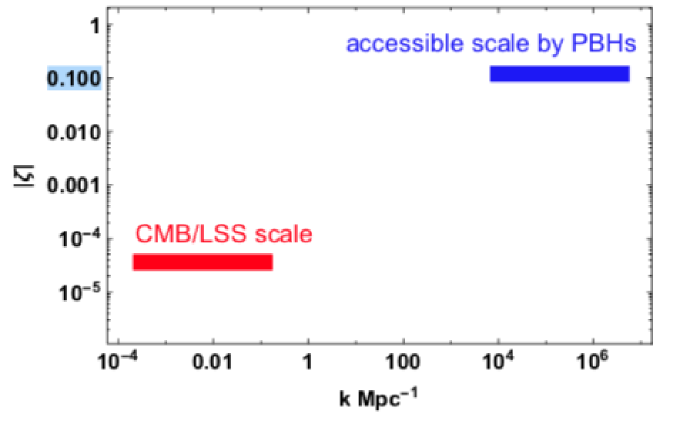
$$n_s = 1 - 3\left(\frac{V'}{V}\right)^2 + 2\frac{V''}{V}$$

Observation Results Planck XX

$\ln(10^{10}\mathcal{P}_{\mathcal{R}_c}(k_0)) = 3.094 \pm 0.034$

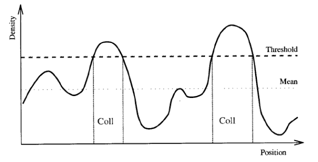
$n_s = 0.9645 \pm 0.0049$

$k_0 = 0.05\ \mathrm{Mpc}^{-1}$



Press-Schechter Formalism

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



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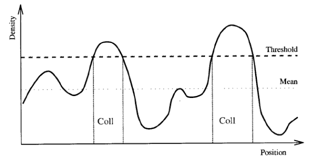

$f(\geq M) = \int_{\delta_{\rm th}}^{\infty} P(\delta;\, M(R))$

$\delta_{\rm th} = 0.47$

Gaussian PDF: $P_{\rm G}(\delta;\, R) = \dfrac{1}{\sqrt{2\pi}\sigma_\delta(R)} \exp\left(-\dfrac{\delta^2(R)}{2\sigma_\delta^2(R)}\right)$

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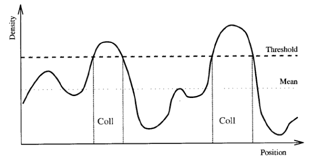

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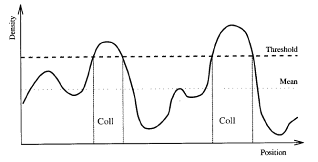

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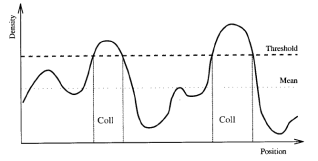

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$\sigma_\delta^2(R) = \int_0^\infty W^2(kR)\mathcal{P}_\delta(k)\dfrac{\mathrm{d}k}{k}$ $\qquad W(kR) = \exp\left(-k^2R^2/2\right)$

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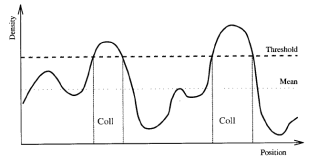

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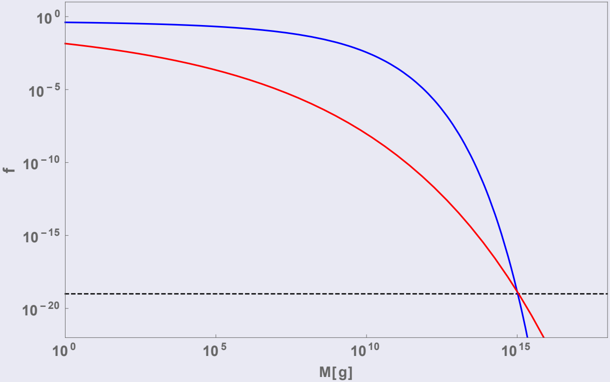
$$M_{\rm PBH} \simeq M_{\rm PH} \to \frac{R}{1\,{\rm Mpc}} = 5.5\times 10^{-24}\left(\frac{M_{\rm PBH}}{1\,{\rm g}}\right)^{1/2}\left(\frac{g_*}{3.36}\right)^{1/6}$$

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

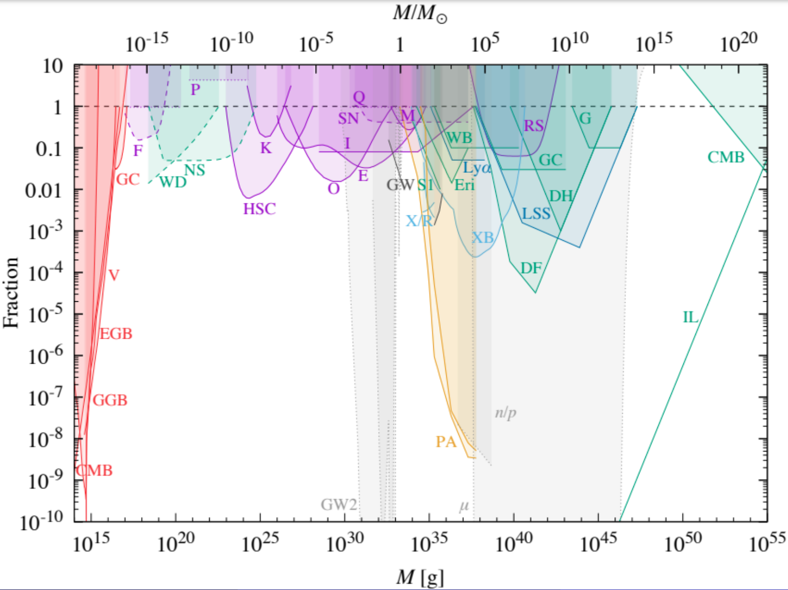


Result

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

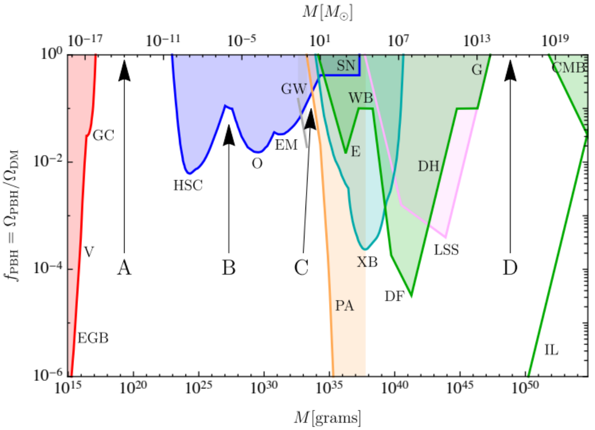
$n_s(k_{\mathrm{PBH}}) \geq 1.418 \quad \Rightarrow \quad \mathcal{P}_{\mathcal{R}_c} \simeq 2 \times 10^{-2}$ for Gaussian PDF

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



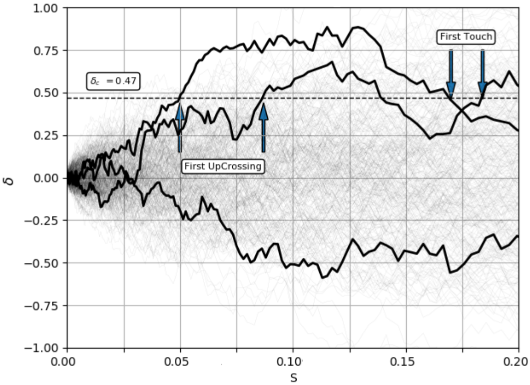
No constraints

arXiv:2002.12778



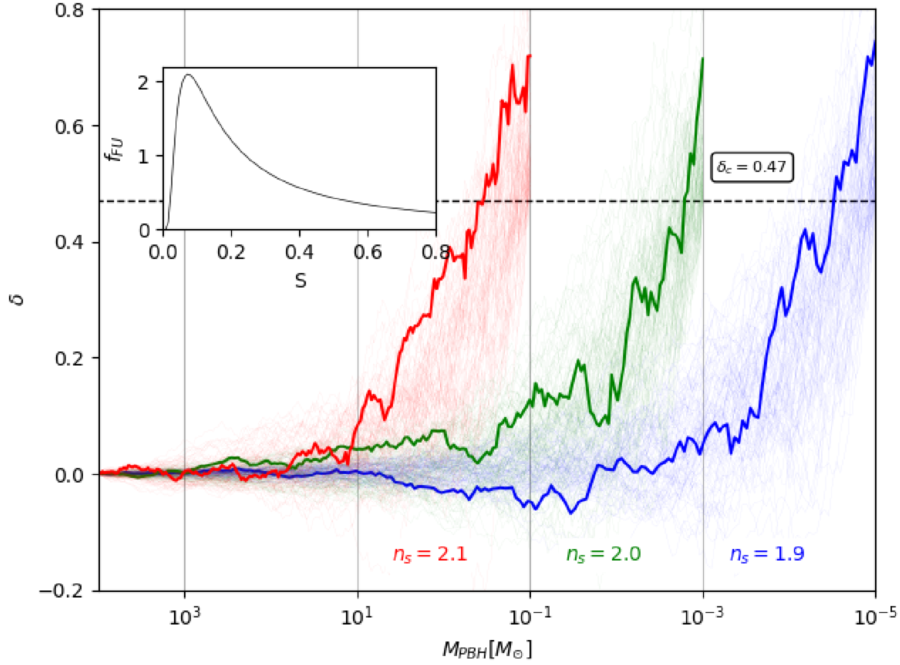
- asteroid mass range $10^{16}\,\mathrm{g} \lesssim M_{\rm PBH} \lesssim 10^{17}\,\mathrm{g}$,
- sublunar mass range $10^{20}\,\mathrm{g} \lesssim M_{\rm PBH} \lesssim 10^{24}\,\mathrm{g}$,
- intermediate mass range $10\,M_\odot \lesssim M_{\rm PBH} \lesssim 10^{3}\,M_\odot$,
- stupendously large black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

Excursion Set Theory



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

$$S = \sigma^2(R) = \int \frac{dk}{k}\,\mathcal{P}_\delta(k)\,W^2(k,\,R)$$


0.8
0.6
0.4
0.2
0.0
−0.2
δ
f_{FU}
2
1
0
0.0
0.2
0.4
0.6
0.8
S
$\delta_c = 0.47$
$n_s = 2.1$
$n_s = 2.0$
$n_s = 1.9$
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
$M_{PBH}[M_\odot]$

Results

	mass range	f_{PBH}	lower bound of mass range	spectral index EST	spectral index PS
asteroid mass range	$(10^{16}-10^{17})$ g	1	10^{16} g	1.490	1.616
sublunar mass range	$(10^{20}-10^{24})$ 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

Hierarchical Merger of PBHs in Dwarf Galaxies

Dwarf Galaxies

Dwarf Galaxies (DGs) are DM dominated, with mass-to-light ratios $\sim 1000\, M_\odot / L_\odot$

Mass: $M_{\rm DG} = 10^9\, M_\odot$ Radius: $R_{\rm DG} \sim 10$ pc

core of DGs: $M_{\rm c} = 10^5\, M_\odot$ $R_{\rm c} = 0.9$ pc

number of PBHs:

$$N_{\rm PBH} = \frac{4\pi}{3} \frac{\rho_{\rm DM}\, R_{\rm c}^3}{m_{\rm PBH}}$$

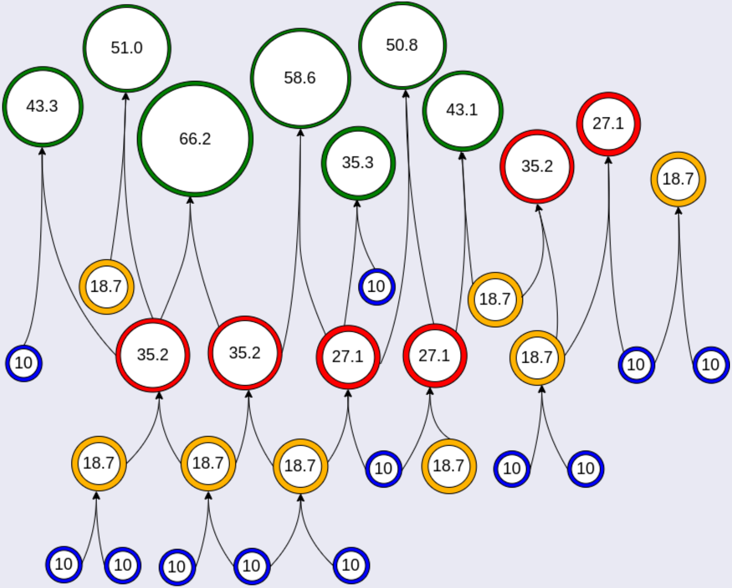
central densities of DGs: $\sim (0.08 - 2.1)\, M_\odot / {\rm pc}^3$

Generations

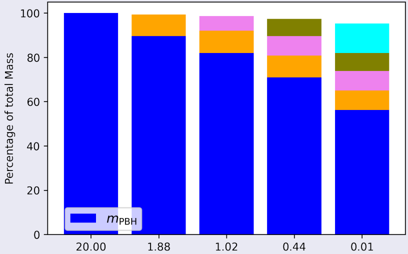
four different initial masses for PBHs (1st Generation):
1G: $10^{-14}\, M_\odot$ $10^{-2}\, M_\odot$ $1\, M_\odot$ $10\, M_\odot$

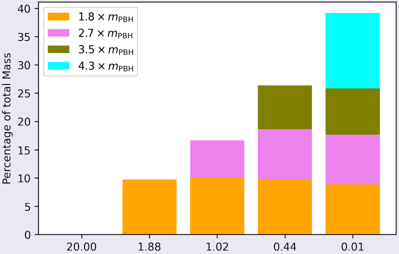
2G: 1G + 1G

3G: 1G + 2G & 2G + 2G


51.0
50.8
58.6
43.3
66.2
43.1
27.1
35.3
35.2
18.7
18.7
10
18.7
10
35.2
35.2
27.1
27.1
18.7
10
10
18.7
18.7
18.7
10
18.7
10
10
10
10
10
10
10

First Epoch $(z = 20 - 1.88)$											
m_i	10										
N_i	10^4										
v_i	~ 13										
Second Epoch $(z = 1.88 - 1.02)$											
m_i	10	**18.7**									
N_i	6434	1783									
v_i	~ 10.6	~ 7.5									
Third Epoch $(z = 1.02 - 0.44)$											
m_i	10	18.7	**27.1**	**35.2**							
N_i	4955	994	1092	43							
v_i	~ 9	~ 5.6	~ 7	~ 1.5							
Fourth Epoch $(z = 0.44 - 0.0)$											
m_i	10	18.7	27.1	35.2	**35.3**	**43.1**	**43.3**	**50.8**	**51.0**	**58.6**	**66.2**
N_i	3154	266	526	12	833	281	19	12	17	7	~ 0
v_i	~ 7.5	~ 2.8	~ 4.8	~ 1	~ 6.8	~ 4.4	~ 1.1	~ 1	~ 1.1	~ 0.77	-





GWs from Merger of PBHs

$$\left\langle \frac{dE}{dt} \right\rangle = -\frac{32}{5} \frac{G^4 (m_i m_j)^2 (m_i + m_j)}{a^5} F(e)$$

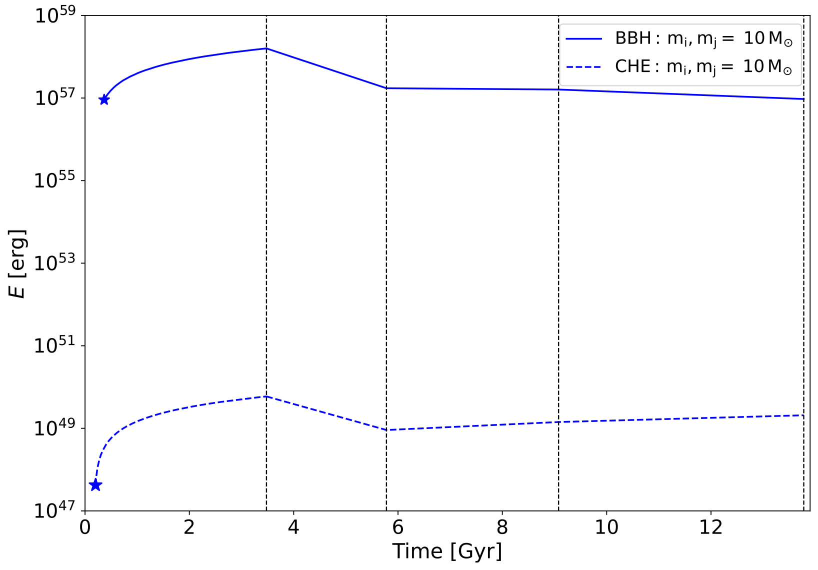
$$F(e) = \frac{1}{(1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

$$\Delta E_{\rm BBH} = \frac{1}{2} m_i m_j \left(\frac{1}{a_{\rm merge}} - \frac{1}{a_{\rm i}} \right)$$

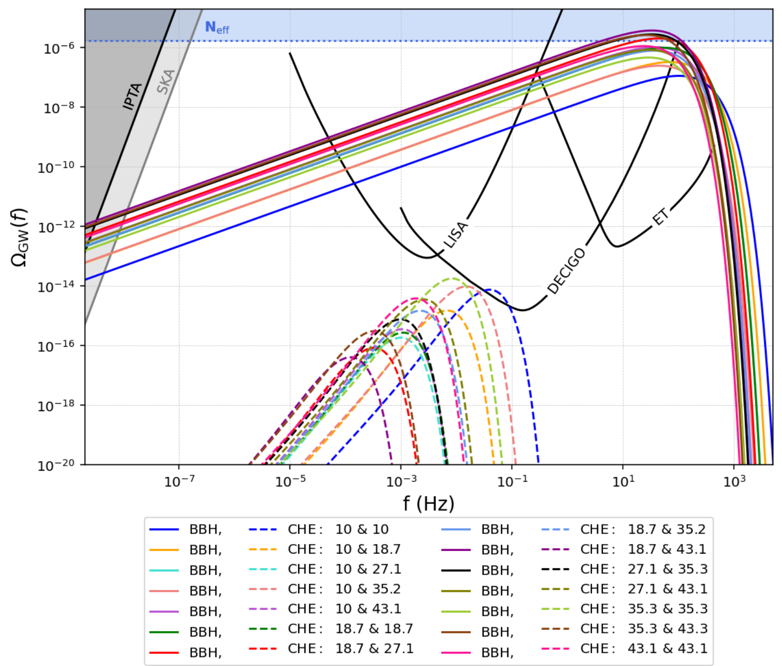
GWs from Close Hyperbolic Encounters of PBHs

$$\sigma_{\rm CHE}(m_i,\, m_j) = \pi b^2 = \pi \left(\frac{G\,(m_i + m_j)}{v_0^2} \right)^2 (e^2 - 1)$$

$$\Delta E_{\rm CHE} = -\frac{8}{15} \frac{G^{7/2}}{c^5} \frac{(m_i + m_j)^{1/2} m_i^2 m_j^2}{r_{\rm min}^{7/2}} f(e)$$



10^{59}
10^{57}
10^{55}
10^{53}
10^{51}
10^{49}
10^{47}
E [erg]
0
2
4
6
8
10
12
Time [Gyr]
BBH : $m_i, m_j =$ 10 $M_\odot$
CHE : $m_i, m_j =$ 10 $M_\odot$



N_{eff}
IPTA
SKA
LISA
DECIGO
ET
$\Omega_{GW}(f)$
f (Hz)
BBH, CHE: 10 & 10
BBH, CHE: 10 & 18.7
BBH, CHE: 10 & 27.1
BBH, CHE: 10 & 35.2
BBH, CHE: 10 & 43.1
BBH, CHE: 18.7 & 18.7
BBH, CHE: 18.7 & 27.1
BBH, CHE: 18.7 & 35.2
BBH, CHE: 18.7 & 43.1
BBH, CHE: 27.1 & 35.3
BBH, CHE: 27.1 & 43.1
BBH, CHE: 35.3 & 35.3
BBH, CHE: 35.3 & 43.3
BBH, CHE: 43.1 & 43.1

Conclusions

- 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.
- Lowering the collapse threshold increases clustering probability and shifts its peak toward higher PBH masses.
- In DM PBHs dominated DGs, the total mass loss at the DG core from GW emission, and the mass fraction of BH that undergo collisions are mostly independent of the initial PBH mass.


mount Everest mass ~ 10^15 g
Thank you