Do we need fine-tuning to create primordial black holes?: Nakama & Wang, arXiv:1811.01126

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Outline

- Fine tuning in cosmology
- Present Limits on abundance of PBHDM
- PBH formation: toy spherical collapse model
- Tuning of primordial fluctuations to get PBHDM

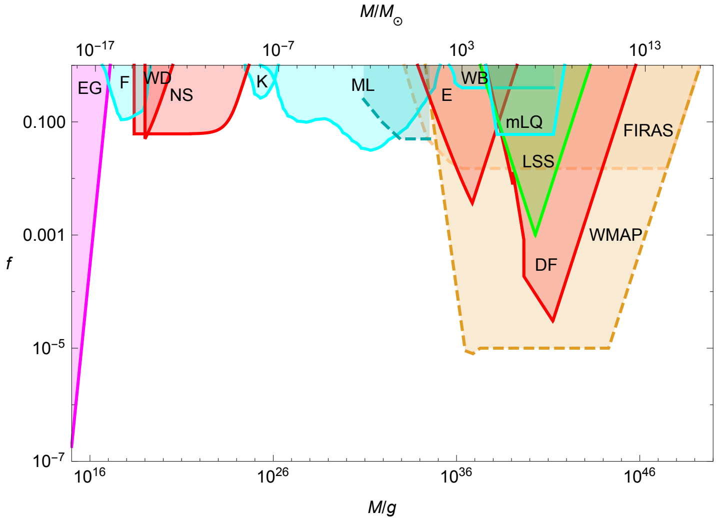
Some numbers that might be fine-tuned

- $\rho_{\mathrm{CDM}}/\rho_{\Lambda} \approx 0.5$ (today)
- $\rho_{\mathrm{B}}/\rho_{\mathrm{CDM}} \approx 0.2$ (since barygenesis and cdmgenesis)
- $\rho_{He}/\rho_{\mathrm{B}} \approx 0.05$ (since nucleosynthesis, $T \approx 60 keV$)
- $\rho_{stars}/\rho_{\mathrm{B}} \approx 0.01$ (since $z \approx 1$)

A time-independent CDM-to-baryon ratio of order unity is especially peculiar because baryogenesis (CP violation) and CDMgenesis (e.g. wimp freezout) are unrelated in most models.

Baryonic structures are not formed if $\rho_b > \rho_{cdm}$ (Silk damping destroys galaxy-size perturbations) or if $\rho_b < \rho_{cdm}/300$ (no radiative cooling to form disks). So if ρ_b/ρ_{cdm} is a random variable (e.g. on the string landscape), then anthropic selection plays a role.

Limits: B.Carr et al: 1607.06077



dashed: model dependent limits

$M < 10^{-17} M_\odot$: Hawking rad; $10^-7 < M < 10 M_\odot$: Microlensing
$M > 10^2 M_\odot$: disruption of stellar systems (binaries, disks...).

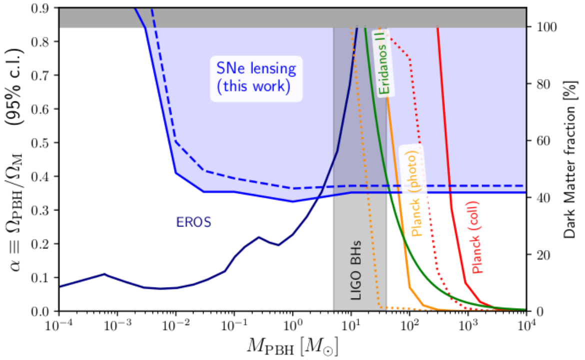
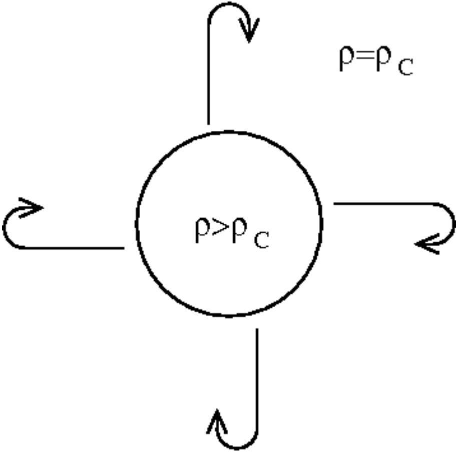


FIG. 3. Bounds on the abundance of PBHs as a function of the mass (95 % confidence level). The analysis of SNe lensing using the JLA (solid) and Union 2.1 compilations (dashed) constrain the PBH fraction in the range $M \gtrsim 0.01 M_\odot$. This range includes the masses of black hole events observed by the Laser Interferometer Gravitational-Wave Observatory (gray), only weakly constrained by previous data including microlensing (EROS [29]), the stability of stellar compact systems (Eridanus II [30, 31]) and CMB [32, 33]. The CMB excluded regions correspond to Planck-TT (solid), Planck-full (dotted) for the limiting cases of collisional (red) and photo-ionization (orange) (see [33] for details).

Lack of SN microlensing

Zumalacárregui & Seljak arXiv:1712.02240

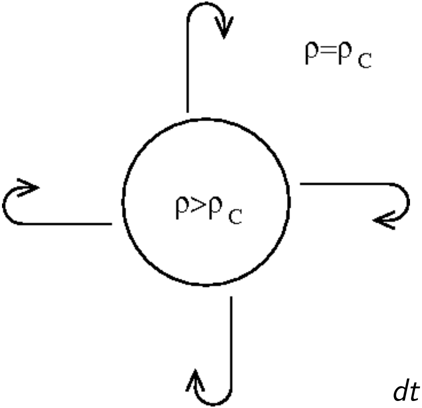
Spherical collapse model



A critical matter-only universe with a small spherical expanding region with $\rho > \rho_c$.

Overdense region acts like a mini-closed universe:
Gravity excess stops the its expansion starting a contraction phase

Spherical collapse model



Spherical symmetry ⇒ dynamics of $R(t)$ independent of rest of universe. Conservation of energy of test particle a boundary:

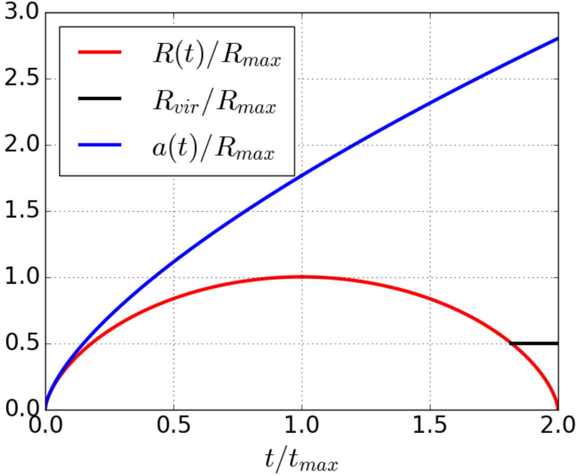
$$(1/2)\dot{R}^2 - \frac{GM}{R} = -\frac{GM}{R_{max}}$$

M = mass contained in spherical region (time-independent)

$$dt = \frac{dR}{\sqrt{2\Phi_g}\sqrt{R_{max}/R - 1}} \Rightarrow t(R)$$

Model characterized by R_{max} and $\Phi_g = GM/R_{max} <\sim 10^{-5}$)

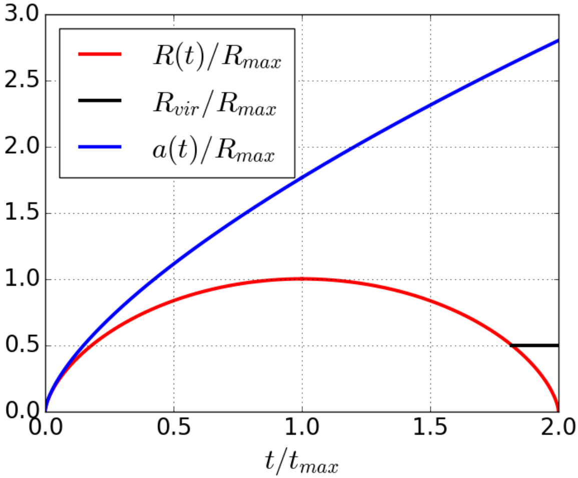
$R(t)$: expansion, collapse, virialization



At t_{max}, small density contrast:

$$\frac{M}{\frac{4\pi}{3}R(t_{max})^3} \approx 5.5\bar{\rho}(t_{max})$$

Gravitational potential



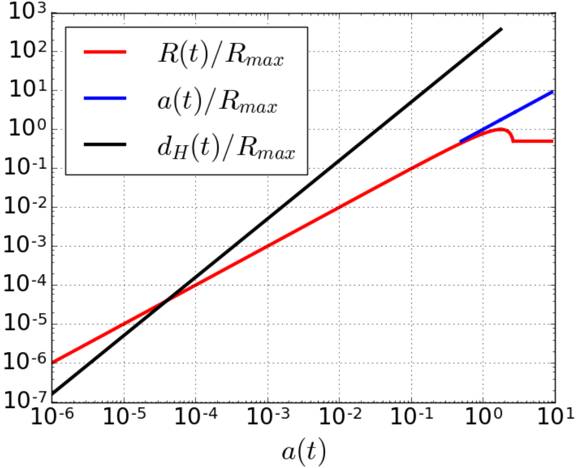
Potential fluctuation at $t \ll t_{max}$ equals potential at maximum expansion:

$$\frac{G(4\pi R^3/3)\Delta\rho}{R(t)} = \frac{GM}{R_{max}}$$

and $\approx$depth of virialized potential well:

$$\frac{GM}{R_{vir}} \approx 2\frac{GM}{R_{max}}$$

$R(a)$: Hubble entry



$R(t) \propto a$

$d_H(t) \propto a^{1.5}$
$= \sqrt{3/8\pi G\bar{\rho}}$

$\Rightarrow R_{max} \approx R_{enter}/\Phi_g$
$\approx \sqrt{\Phi_g} d_H(t_{max})$

The only bound structures that can be formed during the radiation epoch are black holes ($\Phi_g \sim 1$): they form fast enough to avoid dispersal by acoustic waves after entry (since $R_{enter} \sim R_{max}$)

Primordial Black Holes as DM

- Should form before nucleosynthesis
  (since nucleosynethesis $\Rightarrow \Omega_b h^2 = 0.02 < \Omega_m h^2$ from CMB)
- Form at Hubble entry:

$$
\begin{aligned}
M_{BH}(t_{enter}) &\approx d_H^3(t_{enter})\rho(t_{enter}) \\
&\approx (GT_{enter}^4)^{-3/2} T_{enter}^4 \\
&\approx m_{pl}^3 / T_{enter}^2
\end{aligned}
$$

- Fraction, f_{col}, of space that must collapse in order to make a fraction f_{BH} of today's darkmatter:

$$
\begin{aligned}
\rho_{BH} &\approx f_{BH} 10^4 \rho_\gamma \approx f_{BH} 10^4 T_0^4 \text{ (today)} \\
&\approx f_{col} T_{enter}^4 \times (T_0 / T_{enter})^3 \\
&\Rightarrow f_{col} \approx f_{BH} 10^4 T_0 / T_{enter} \approx f_{BH} 10^4 T_0 M_{BH}^{1/2} / m_{pl}^{3/2}
\end{aligned}
$$

$T_{enter} = 1 GeV \qquad M_{BH} = 1 M_\odot \qquad f \approx f_{BH} 10^{-9}$

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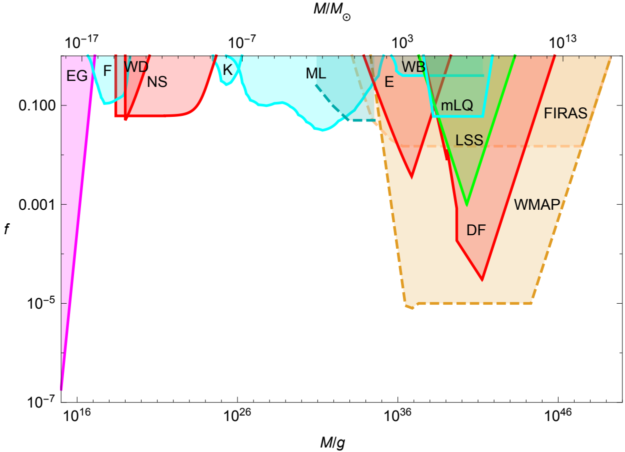

dashed: model dependent limits

$$T_{enter} = 1 MeV \qquad M_{BH} = 10^6 M_\odot \qquad f \approx f_{BH} 10^{-6}$$
$$T_{enter} = 1 GeV \qquad M_{BH} = 1 M_\odot \qquad f \approx f_{BH} 10^{-9}$$
$$T_{enter} = 10^8 GeV \qquad M_{BH} = 10^{-16} M_\odot \qquad f \approx f_{BH} 10^{-17}$$

Collapse fraction for Gaussian perturbations

$P(\phi) \sim \exp(-\phi^2/2\sigma_\phi^2)$

$f_{col} \sim P(\phi = 1) \sim \exp(-1/2\sigma_\phi^2) \approx f_{BH} T_{eq} M_{BH}^{1/2}/m_{pl}^{3/2} \approx f_{BH} 10^{-9}$

$\Rightarrow$ need $\sigma_\phi \approx 0.1$ if $f_{BH} \sim 1$

- No PBH if $\sigma_\phi \approx 10^{-5}$
  $\Rightarrow$ new physics needed if $f_{BH} \sim 1$
  e.g. a second inflationary scalar field to give large k dependence to power spectrum
- σ_ϕ is a logarithmic function of $(f_{BH},\ T_{eq},\ M_{BH}...)$
  Loose constraints on $(f_{BH}.....)$ imply tight constraints on σ_ϕ.

Nakama and Wang: $1 > \rho_{\rm B}/\rho_{\rm CDM} > 1/300 \Rightarrow 0.083 < \sigma_\phi < 0.091$
Degree of fine-tuning $= (0.091 - 0.083)/0.87 \approx 0.08$