Solar Mass Primordial Black Holes from Early Matter Domination

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Basics

What are PBHs?

• Formed in the early universe when the density fluctuations of high amplitude $(\delta > \delta_c)$ re-enter the Hubble horizon at post-inflationary epochs and collapse gravitationally. (Hawking, Carr, 1974)

• Large $\delta \propto \zeta$ be obtained from large scalar (curvature) fluctuations at $k \gg k_{\mathrm{CMB}}$ produced during inflation: inflection points/ bumps in single field models; multi-field dynamics.

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- **Why PBHs?**

  • Nonrelativistic, massive and collisionless: Can be a candidate for DM.

  • GW detectors (LIGO/Virgo) observed binary black hole mergers: Can LIGO/Virgo events $M \sim M_\odot$ be described by PBH? (Bird, 2016)

  • A tool to probe smaller scales of inflation. $\rightarrow$ Accommodate $P_\zeta(k_{\rm CMB}) \sim 10^{-9}$ and $P_\zeta(k \gg k_{\rm CMB}) \sim 10^{-2}$ together in an inflation model.

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- **Epoch of formation**

  • Mass-scale relation $M(k)$ varies for different EoS w.

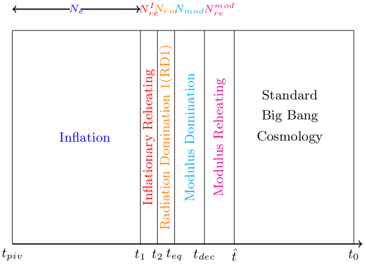
  • Critical condition for collapse varies for different w.

Motivation

- If early universe was matter dominated (EMD) due to moduli fields, what is PBH formation mechanism there?
- Can the constituent BHs in the mergers observed by LIGO/Virgo be PBHs formed in moduli dominated epoch?
- How does it contribute to the total DM density? If not 100% then what else forms rest of DM?

Modified Post-inflationary history

- Moduli vacuum misalignment in String theory inspired models of inflation $\rightarrow$ post-inflationary moduli domination + moduli reheating.$\rightarrow$ Parametrization of post-inflationary epoch in terms of inflationary model parameters.



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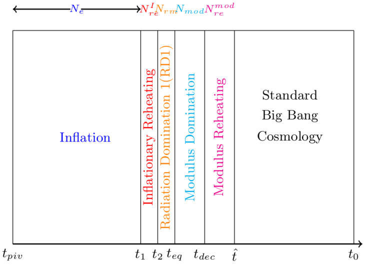

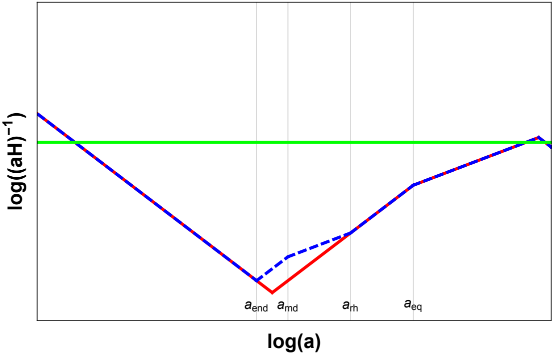

$$N_* = 55.75 - \log\left[\frac{10^{16}\text{Gev}}{V_{\text{pivot}}^{1/4}}\right] + \log\left[\frac{V_{\text{pivot}}^{1/4}}{V_{\text{end}}^{1/4}}\right] - \frac{1}{4}(1-3w_{\text{re}})N_{\text{re}}^{\text{mod}} - \frac{1}{4}N_{\text{emd}}$$

PBH formation in Radiation vs Matter Domination

RD (Carr et.al., 1975; Garcia-Bellido et. al., 1702.03901)

- Standard deviation of fluctuations is determined in the general relativistic perturbation theory. $\delta_c = 0.414$.
- $\beta(M) = \int_{\delta_c}^{\infty} d\delta P(\delta) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M)}\right)$.
- $\psi(M) = \frac{1}{M}\frac{\rho_{\rm PBH}(M)}{\rho_{\rm DM}}$.
- $f_{\rm PBH} = \int dM \psi(M)$
- $M_k \propto \frac{1}{H_k}$.

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EMD(Harada et. al., 1609.01588)

- Zel'dovich Approximation.
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- $M_{\text{rh}} \propto \frac{1}{\Gamma}$.
- $M_{\text{max}} \simeq M_{\text{rh}}\sigma_{\text{max}}^{3/2}$, $M_{\text{min}} = M_{\text{max}}\left(\frac{a_{\text{dom}}}{a_{\text{rh}}}\right)^{3/2}$.

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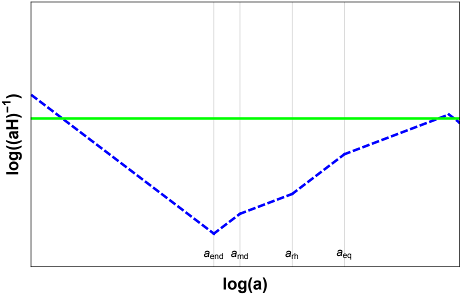
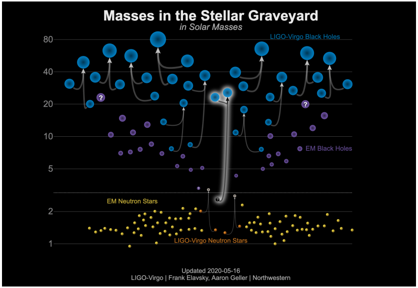
- In EMD: Horizon entry $\rightarrow$ Maximum Expansion $\rightarrow$ Collapse.
- $\frac{H_c}{H_{\rm h.e.}} = \sigma^{3/2}$. $\sigma_{\rm max} \equiv \sigma(k_{\rm max} \gtrsim k_{\rm rh}) < 1$.
- $H_{\rm dom} \simeq m_\phi(\phi_0/M_{\rm Pl})^4$.
- $N_{\rm emd} = \frac{1}{6}\ln\left(\frac{H_{\rm dom}}{H_{\rm rh}}\right) = \frac{1}{6}\ln\left(\frac{16\pi\phi_0^4}{m_\phi^2 M_{\rm Pl}^2}\right)$.
- Parameters entering from moduli domination: m_ϕ and $\phi_0 = M_{\rm Pl}/100$.
- σ is calculated from inflationary perturbations $\rightarrow$ Dependence on $P_\zeta(k)$.

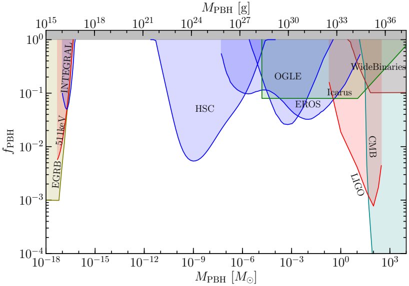
PBH mass function in EMD



$$\psi(M) = \begin{cases} 2.6 \times 10^8 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{m_\phi M_{\rm Pl}}{\phi_0^2}\right)^{1/3} \frac{\beta_{\rm RD}(M)}{M} , & M < M_{\rm min} , \\ 5.2 \times 10^{26} \left(\frac{m_\phi}{M_{\rm Pl}}\right)^{3/2} \frac{\beta_{\rm MD}(M)}{M} , & M_{\rm min} \leq M \leq M_{\rm max} , \\ 5 \times 10^8 \left(\frac{M_\odot}{M}\right)^{1/2} \frac{\beta_{\rm RD}(M)}{M} , & M > M_{\rm max} . \end{cases}$$

PBH mass range of interest





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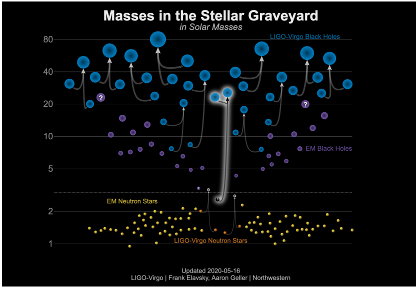

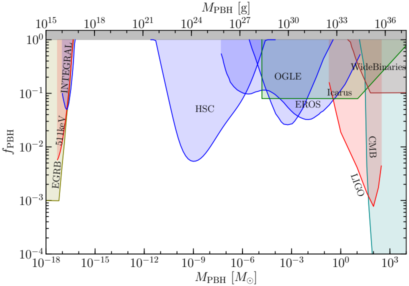

- Mass range of interest: $M \gtrsim M_\odot$.
- $M_{\rm RD}(T_{\rm BBN} = 10{\rm MeV}) \simeq 1000 M_\odot \leftrightarrow k \sim 10^6$ Mpc^{-1}.
- But, $M_{\rm max} = \sigma_{\rm max}^{3/2} M_{\rm rh} \leftarrow$ primordial physics inputs. $\sigma_{\rm max} \sim \frac{2}{5}\sqrt{P_\zeta^{\rm max}}$. We expect $M_{\rm max}/M_{\rm rh} \sim 10^{-3} - 10^{-2}$.

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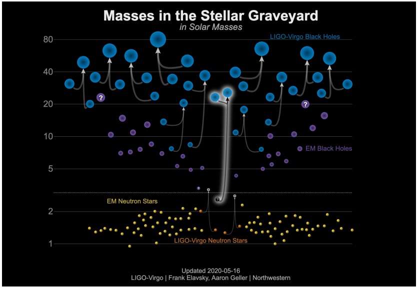

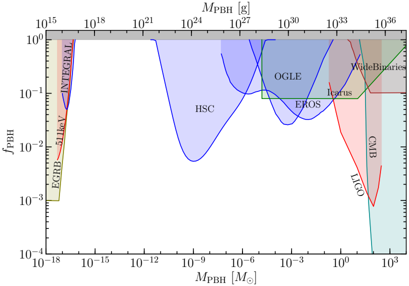

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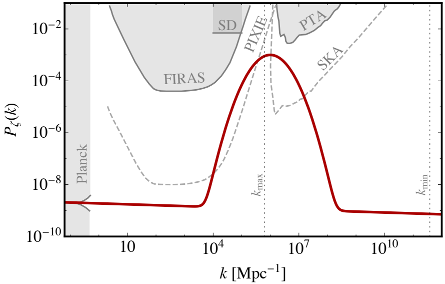
- $\Gamma = \frac{m_\phi^3}{M_P^2}$, $M_{\rm rh} \propto \frac{1}{\Gamma}$.
- $T_{\rm rh} = 2.75 \text{ MeV} \left(\frac{10.66}{g_*(T_{\rm rh})}\right)^{1/4} \left(\frac{m_\phi}{100{\rm TeV}}\right)^{3/2}$
- Smallest possible $T_{\rm rh} = 4.3{\rm MeV} \rightarrow m_\phi = 135$ TeV.

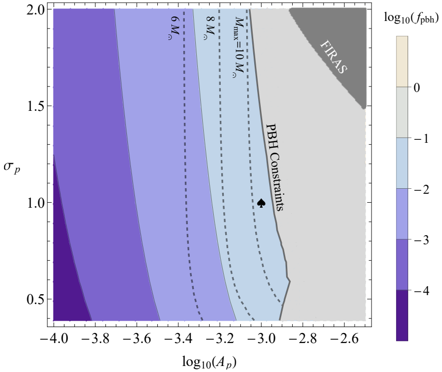
Primordial Power spectrum

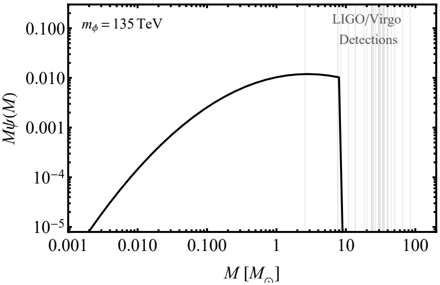
$$P_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} + A_p \exp\left[-\frac{(N_k - N_p)^2}{2\sigma_p^2}\right]$$

- Parameters from the primordial sector: A_p, σ_p, k_p.
- $A_p = 10^{-3}, \sigma_p = 1$, and $k_p = 10^6$ Mpc^{-1}.

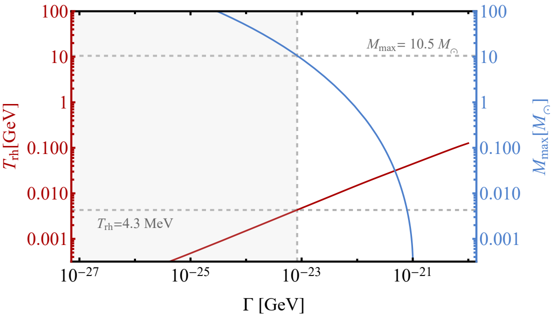


Bounds on primordial parameters





Maximum PBH mass



- $M_{\rm max}$ is such that a few (2-3) BBH events observed by the LIGO/Virgo detectors can be explained by PBHs.
- $f_{\rm PBH} \simeq 4\%$.

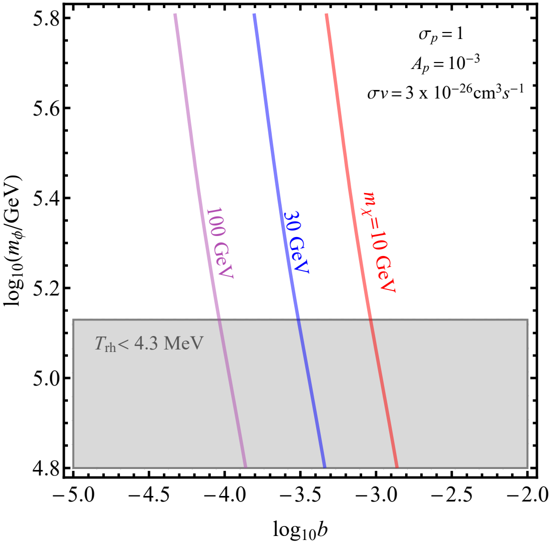
Particle DM content

- DM particle χ of mass m_χ: characterised by decay branching ratio b of the ϕ to χ and its thermally-averaged annihilation cross section $\langle\sigma v\rangle$.
- Due to direct decay: $f_{\rm decay} \simeq 0.28 \left(\frac{m_\chi}{10\ \rm Gev}\right)\left(\frac{b}{10^{-4}}\right)\left(\frac{m_\phi}{100\ \rm Tev}\right)^{1/2}$.
- Depending on the interaction stregth of DM particles:

$$\Omega_{\chi,\rm thermal}h^2 = 1.6\times 10^{-4}\frac{\sqrt{g_*(T_{\rm rh})}}{g_*(T_{\rm fo})}\left(\frac{m_\chi/T_{\rm fo}}{15}\right)^4\left(\frac{150}{m_\chi/T_{\rm rh}}\right)^3\left(\frac{3\times10^{-26}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle}\right).$$

$$\Omega_{\chi,\rm nonthermal}h^2 = 0.062\times\frac{g_*^{3/2}(T_{\rm rh})}{g_*^3(m_\chi/4)}\left(\frac{150}{m_\chi/T_{\rm rh}}\right)^5\left(\frac{T_{\rm rh}}{5\ \rm GeV}\right)^2\left(\frac{\langle\sigma v\rangle}{10^{-36}{\rm cm}^3{\rm s}^{-1}}\right).$$

χ particles as rest of the DM



- Can choose b for different values of m_χ.

Summary

- **If early universe was matter dominated (EMD) due to moduli fields, what is PBH formation mechanism there?**
- Mechanisms are fundamentally different due to subhorizon growth of perturbations in EMD.
- PBH production in non-RD epochs often lead to larger PBH abundance: EMD epoch due to moduli fields, early kinetic energy domination in quintessential inflation models (see 1912.01653).

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