Primordial black holes as dark matter candidates: closing the remaining mass window

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Capela, Pshirkov, PT, PRD87 (2013) 023507

Capela, Pshirkov, PT, PRD87 (2013) 123524

Capela, Pshirkov, PT, arXiv:1403.7098

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Outline

INTRODUCTION

- Many (indirect) arguments suggest the existence of dark matter with $\Omega_{\rm DM} \simeq 0.26$
    - Rotation curves of galaxies
    - Gas temperature in clusters
    - Gravitational lensing
    - Structure formation
- The DM is often assumed to be a new stable particle. There are many different DM candidates: axion-like particles, sterile neutrinos, WIMPs, ...
- We will consider an alternative option — that DM is composed of primordial black holes (PBH)
    - PBH may have been produced in the early Universe. Many mechanisms have been considered (e.g., at phase transitions).
    - Attractive feature of this scenario is that no new particles are required.
    - From theory, the PBH masses are not constrained.

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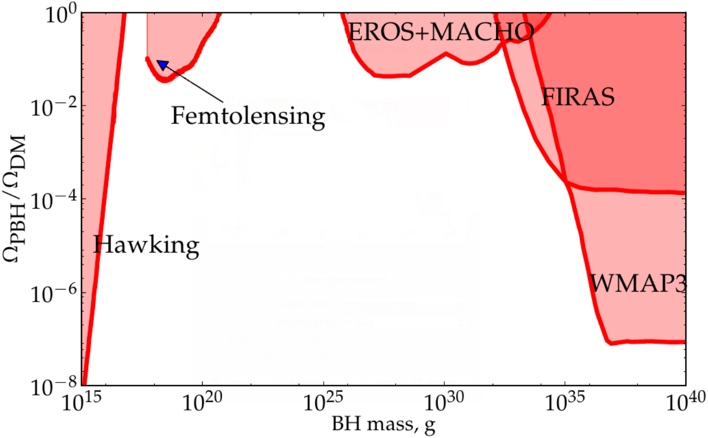
INTRODUCTION

- A large part of the parameter space is already constrained from various arguments



INTRODUCTION

- In the remaining mass window $10^{16} - 10^{26}$ g, the abundance of PBH may be constrained from observations of compact stars — WD and NS
- Compact stars are special because if a PBH gets inside such a star, the star gets destroyed. Requiring the probability of such event is $\ll 1$ imposes constraints on PBH abundance.
- DM capture in stars has been considered before

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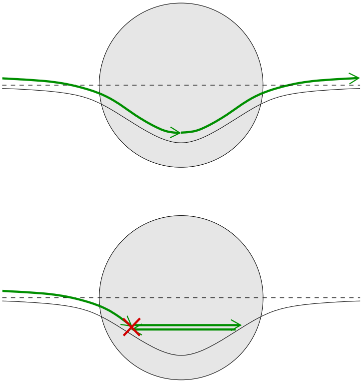
Two ways to capture a PBH: (I) during star lifetime



- For capture the energy loss is required
- In case of PBH, the energy loss occurs due to dynamical friction and accretion of star matter onto the PBH
- Total energy loss is

$$E_{loss} = \frac{4 m_{BH}^2 M_*}{M_{Pl}^4 R_*^2} \left\langle \frac{\ln \Lambda}{v^2} \right\rangle$$

- Averaging with Maxwellian distribution, the capture rate is

$$F = \sqrt{6\pi}\frac{\rho_{DM}}{v_\infty m_{BH}}\frac{R_g R_*}{1 - R_g/R_*}\left[1 - \exp\left(-\frac{3E_{\rm loss}}{m_{BH}v_\infty^2}\right)\right]$$

$$\simeq 3\sqrt{6\pi}\frac{\rho_{DM}}{v_\infty^3}\frac{R_g R_*}{m_{BH}^2}E_{\rm loss} \qquad \text{at } E_{\rm loss} \ll m_{BH}v_\infty^2$$

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  - Large DM density ρ_D
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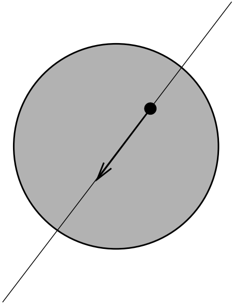

How to estimate $E_{\rm loss}$?

- Dynamical friction: treat NS particles as independent

$$E_{\rm loss} \sim \frac{Gm_{\rm BH}^2}{R}$$

- Tidal energy loss: dominated by excitation of surface waves [Pani & Loeb, JCAP'2014]

$$E_{\rm loss} \sim \frac{Gm_{\rm BH}^2}{R} \times 10^4$$

- P&L are WRONG: tidal loss is of the same order as DF.

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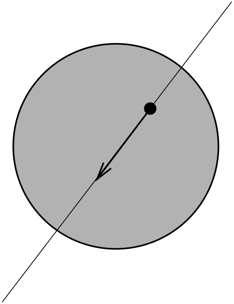

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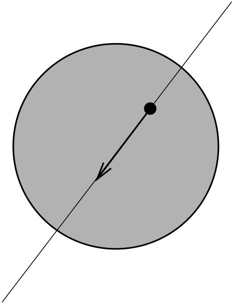

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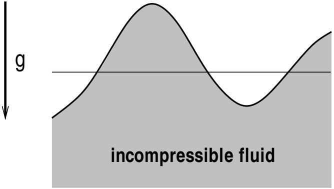
MODEL: incompressible fluid in gravitational field

G.Defillon, E.Garnet, M.Tytgat and P.T.



- Irrotational fluid: $\vec{v} = \vec{\nabla}\phi$

$$\begin{aligned} \Delta\phi &= 0 \\ \phi_{tt} + g\phi_z &= 0 \quad \text{@ surface} \end{aligned}$$

- $\Longrightarrow$ surface waves with dispersion

$$\begin{aligned} \omega^2 &= gk \\ v_s^2 &= g/k \end{aligned}$$

- solution for displacement is

$$\eta(x,t) = \frac{Gm_{\rm BH}}{g} \int_0^\infty dk \frac{J_0(kr)}{1 + V^2/v_s^2} \left\{ e^{-kVt} + 2\frac{V}{v_s} \sin(\omega t) \right\}$$

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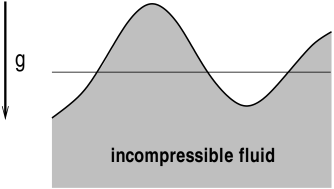

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Energy loss in incompressible fluid

- Calculate twice potential energy of outgoing waves:

$$E_{\text{loss}} = 2\int d^2x \frac{g}{2}\rho\eta^2(x,t) =$$

$$= 4\pi \frac{G^2 m_{\text{BH}}^2 \rho}{g} \int_0^\infty \frac{d(kV^2/g)}{(1+kV^2/g)^2}$$

- Integral is convergent and saturated by the region where $v_s \gtrsim V$ in agreement with causality
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Two ways to capture a PBH: (II) at star formation

- The stars are formed in the collapse of baryonic matter in giant molecular clouds. These clouds have some DM density gravitationally bound to them.
- Collapsing baryons gravitationally drag the DM along by adiabatic contraction, so some PBHs end up inside the star
- When the star evolves into a compact remnant (NS or WD), some of these PBHs may be inherited by the latter.

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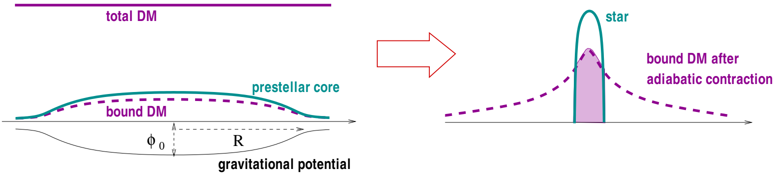

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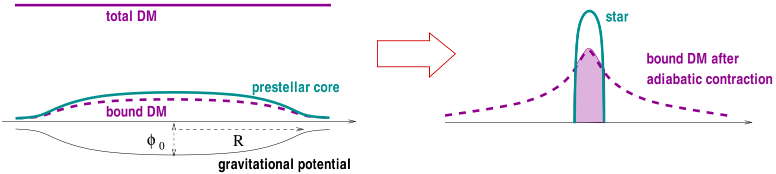

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- The density of bound DM, assuming Maxwellian parent distribution with $\bar{v}$:

$$\rho_{\rm bound} \sim \bar{\rho}_{DM} \left(\frac{\phi_0}{\bar{v}^2}\right)^{3/2} = \text{const} \cdot \frac{\bar{\rho}_{DM}}{\bar{v}^3}$$

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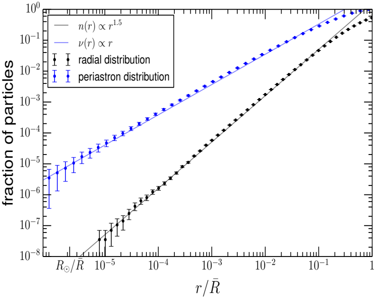
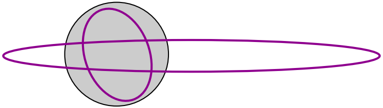


- Number of particles within r,

$$n(r) \propto r^{3/2}$$

- Number of particles with periastron $< r$,

$$\nu(r) \propto r$$



Time scales

- Two stages
  - When PBH is mostly outside the star

$$\tau_1 \simeq \frac{\sqrt{r_{max}} R_*^2 v_{esc}^2}{G\sqrt{R_g} m_{BH} \ln\Lambda} \sim 2 \times 10^8 \mathrm{yr} \left(\frac{10^{22}\mathrm{g}}{m_{BH}} \right)$$

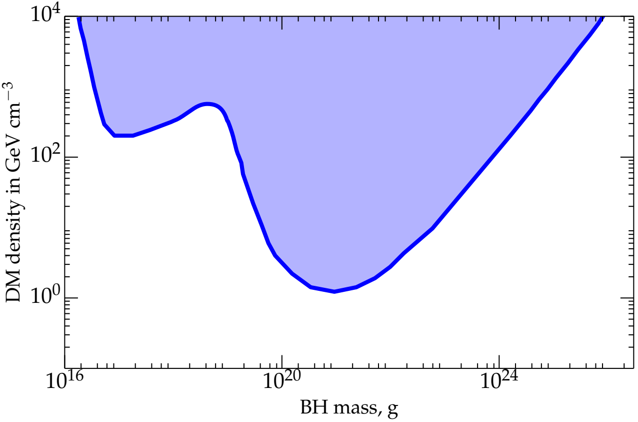
  - When PBH is completely inside the star: numerical calculation in a realistic density profile. Rough estimate:

$$\tau_2 \sim 10^2 \frac{M_*^{3/2}}{2\pi\sqrt{G}\rho(0) m_{BH} R_*^{3/2} \ln\Lambda}$$

  - $\Longrightarrow$ Insufficient time at small m_{BH}

RESULTING CONSTRAINTS

Assuming DM velocity dispersion $v = 7$ km/s



Where to look?

- Best constraints come from sites where the DM density is largest and the DM velocity is smallest
- One such site could be Globular Clusters (GC) — bound compact systems containing $10^4 - 10^7$ stars, very old $\gtrsim 10$ Gyr
  - There are two suggested mechanisms of the GC formation: primordial and 'recent'
  - recently formed GC carry little DM — not enough for constraints
  - primordial GCs should have DM cores with $\rho_D \sim 2 \times 10^3\ \mathrm{GeV\,cm^{-3}}$.

Bertone, Fairbairn, PRD77,043515 (2008)

- Another candidate — dwarf spheroidals
  - similar to GC in size; DM-dominated: densities $\sim 200\ \mathrm{GeV/cm^3}$ have been inferred from modeling
  - no NS have been observed in dSph's yet

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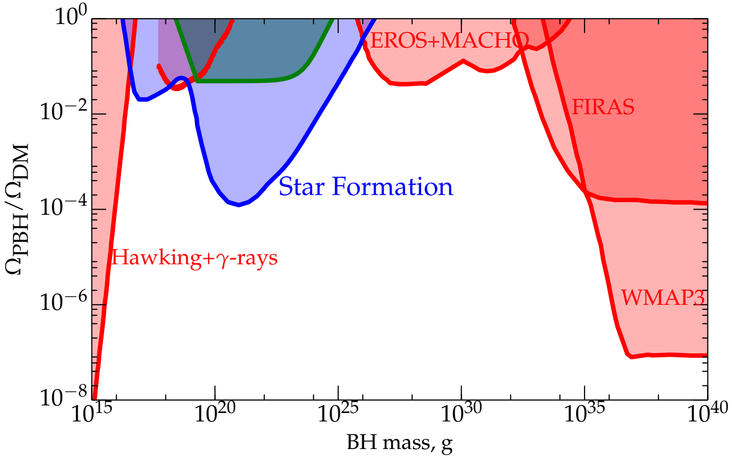

Summary

- Observations of NS and WD in dark-matter-rich environments can potentially exclude PBH as DM candidates of masses $\sim 10^{16} - 10^{26}$ g
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