Primordial black holes as DM?

P. Tinyakov

ULB, Brussels

Original part is based on:

Capela, Pshirkov, PT, PRD87 (2013) 023507

Capela, Pshirkov, PT, PRD87 (2013) 123524

Capela, Pshirkov, PT, PRD90 (2014) 083507

Defillon, Granet, PT, Tytgat, PRD90 (2014) 103522

Trieste, April 13-17, 2015

Outline

INTRODUCTION

- Many (indirect) arguments suggest the existence of dark matter with $\Omega_{\rm DM} \simeq 0.26$
- Despite we are sure of the DM existence, we are ignorant of its mass to an amazing degree — the uncertainty is 95 (!) orders of magnitude.
- The DM is often assumed to be a new stable particle: axion-like particle, sterile neutrinos, WIMPs, ...

  We will discuss here another possibility — that DM is composed of primordial black holes (PBH)

  Hawking, MNRAS 152 (1971) 75

  - PBH interact very weakly with other matter and among themselves $\Longrightarrow$ good DM candidate
  - Bonus: no new stable particles are needed.

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PRODUCTION OF PHB: BASICS

- The mass of PBH $M_{\rm PBH}$ produced at a given time t (temperature T) is limited by the horizon mass at this time
- In most of the models this is also an estimate of the PBH mass
- Horizon mass at temperature T:

$$M_H \simeq 0.02 \frac{M_{\rm Pl}^3}{T^2}$$

T	MeV	100 MeV	100 GeV	10^8 GeV
M_H	$3 \times 10^4 \; M_\odot$ 6×10^{37} g	$3 \; M_\odot$ 6×10^{33} g	$3 \times 10^{-6} \; M_\odot$ 6×10^{27} g	$3 \times 10^{-18} \; M_\odot$ 6×10^{15} g

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PRODUCTION OF PHB: BASICS

- To have all of DM composed of PBH today, at a time of production only a small fraction f of the total energy density has to be converted into BH,

$$\text{at } T: \quad \rho_{\rm PBH} = f\, \rho_R$$

- For the production at temperature T one has to have

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PRODUCTION MECHANISMS

- From primordial density perturbations

Carr, ApJ 201(1975)1

  - Need overdensities of ~ 1. More precisely, for the equation of state

$$p = \gamma\rho$$

one needs

$$\delta\rho/\rho > \gamma$$

at scales L of the order of horizon size at the production epoch. One typically has

$$L \sim R_H$$

$$M_{\rm PBH} \sim M_H$$

  - In case of (approximately) flat spectrum of perturbations, the PBH mass spectrum is extended.
  - Note: one needs to modify the primordial perturbation spectrum at very high multipole l. For instance, to produce $M_{\rm PBH} \sim M_\odot$ the relevant $l \sim 10^8$.

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PRODUCTION MECHANISMS

- Soft equation of state at some period of evolution

Carr, ApJ 201 (1975) 1

Khlopov, Malomed, Zel'dovich, MNRAS 215 (1985) 575

$$p = \gamma\rho; \quad \gamma \to 0$$

  - This gets rid of the pressure that opposes the collapse. Smaller amplitude initial perturbations may collapse into BH.
  - Typically period of "softness" is limited $\Longrightarrow$ compact PBH mass spectrum centered at a value set by the corresponding horizon mass

PRODUCTION MECHANISMS

- Bubble collisions during phase transitions

Hall, Hsu, PRL64 (1990) 2848

Jedamzik, PRD55 (1997) 5871

Jedamzik, Niemeyer, PRD59 (1999) 124014

Bubble nucleation rate needs to be finely tuned

- if the rate is much larger than the expansion rate the whole Universe undergoes the transition at once and there is no time to form BHs
- if the rate is much smaller than the expansion rate the bubbles are rage and never collide

$\Longrightarrow$ One gets a compact spectrum with

$$M_{\rm BH} \sim M_H$$

For a QCD phase transition at $T \sim O(100\ \mathrm{MeV})$ one would get

$$M_{\rm BH} \sim M_\odot$$

PRODUCTION MECHANISMS

- Collapse of cosmic strings

Hawking, Phys.Lett. B231 (1989) 237

Polnarev, Zembowicz, PRD 61 (1991) 1106

- Collapse of closed domain walls

Rubin, Khlopov, Sakharov, Grav.Cosmol. 6 (2001)

Dokuchaev, Eroshenko, Rubin, Grav.Cosmol. 11 (2005) 99

- At reheating

Suyama et al, PRD71 (2005) 063507

- At preheating

Green, Malik, PRD64 (2001) 021301

- During inflation

Garsia-Bellido, Linde, Wands PRD54 (1996) 6040

TO SUMMARIZE:

- The mass of the PBH can be any
- The PBH mass spectrum can be extended or compact
- The PBH abundance can be any

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EXPERIMENTAL CONSTRAINTS

Arise from various arguments:

- Evaporation and γ-background

  Review in: Carr et al., PRD81 (2010) 104019

- Femtolensing

  Gould, ApJ Lett. 386 (1992) L5

  Barnacka et al., PRD86 (2012) 043001

- Microlensing

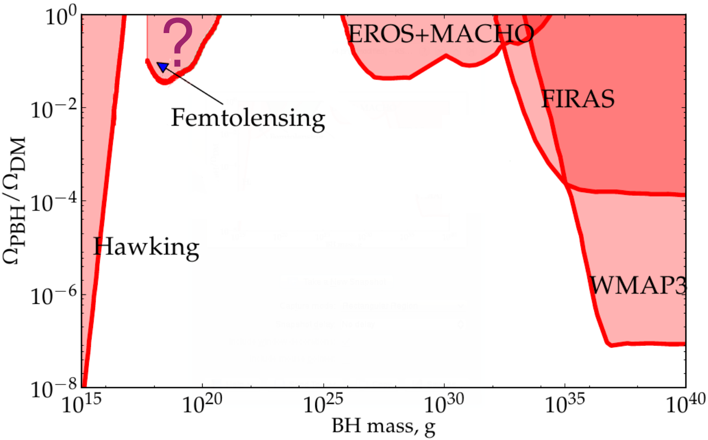
  Tisserand et al., Astron. Astrophys. 469 (2007) 387

  Alcock et al., ApJ Lett., 499 (1998) L9

- CMB distortions

  Ricotti, Ostriker, Mack, ApJ 680 (2008) 829

EXPERIMENTAL CONSTRAINTS



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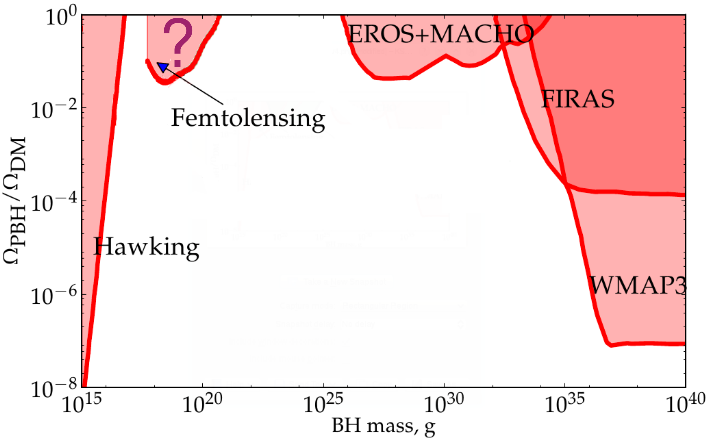

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CONSTRAINTS FROM COMPACT STARS

Constraints from compact stars

- 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 is destroyed. Requiring that the probability of such an event is $\ll 1$ imposes constraints on PBH abundance.

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Capture of PBH in stars

Two different mechanisms:

- Capture during lifetime
- Capture at the stage of star formation (turns out dominant)

- Some refs on DM capture in stars:

Press, Spergel Astrophys.J. 296 (1985) 679-684;

Goldman, Nussinov Phys. Rev. D40, 3221 (1989);

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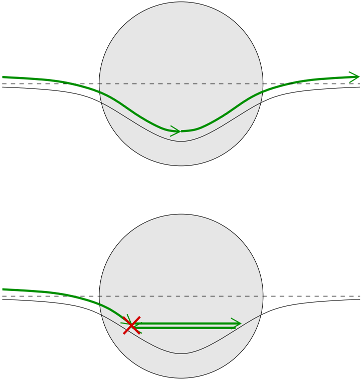
I. Capture during star lifetime



- For capture the energy loss is required
- In case of PBH, the energy loss occurs due to gravitational acceleration of star matter by the passing PBH, and by its accretion onto the PBH

Dynamical friction approximation

Chandrasekhar '1949

- Matter particles are considered as independent
- Individual particles are scattered off the BH

$$\phi(b) = -\pi + 2\tilde{b}\int_0^{x_{\max}} \frac{dx}{\sqrt{\gamma^2 - (1+\tilde{b}^2x^2)(1-x)}}$$

where $\tilde{b} = bv\gamma/R_g$ is the rescaled impact parameter

- momentum transfers are summed up

$$\Delta p = (mv\gamma^2(-1+\cos\phi), mv\gamma\sin\phi, 0)$$

- Total energy loss is

$$E_{loss} \simeq \frac{2Gm_{BH}^2}{R_*}\ln\left(R_*/r_g\right)$$

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BUT: is the DF a good approximation?

- Causality argument: supersonic motion
  PBH speed: $v \sim 0.6c$
  sound speed: $v_s \sim 0.2c$
- Has been verified in case of uniform medium

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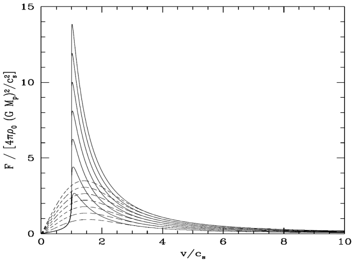

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DIGRESSION: surface waves

- Pani & Loeb: “tidal capture” is a lot much more efficient than DF

Pani & Loeb, JCAP’2014

- Alternative approach: excitation of star normal modes Tidal energy loss is dominated by excitation of large-k surface waves

$$E_{\text{loss}} \sim \frac{Gm_{\text{BH}}^2}{R} \sum_{l=1}^{\infty} \frac{1}{l^n} \sim \frac{Gm_{\text{BH}}^2}{R} \times 10^4 \quad ??$$

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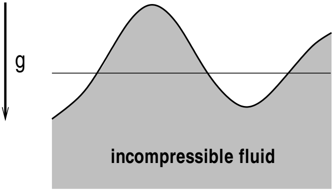
MODEL: flat incompressible fluid in gravitational field

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

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

- analytic solution for displacement is

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

Energy loss in incompressible fluid

- Calculate the energy of outgoing waves:

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

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

- Integral is convergent and saturated by the region where $v_s \gtrsim V$ in agreement with causality
- Total energy loss is parametrically the same as in dynamical friction

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CONCLUSION:

- No divergency at small wavelengths
- Suppression of the surface wave contribution by $v_s^2/v^2 \lesssim 10^{-3}$
- The "tidal" approach is just a different way to calculate the same quantity which gives the same answer.

$\Longrightarrow$ DF APPROXIMATION IS CORRECT

From $E_{\rm loss}$ to capture rate

- Take cross section of the star crossing

$$\sigma \sim \pi R_* R_g / v_\infty^2$$

- Average with Maxwellian distribution

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

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

- Best conditions for capture:
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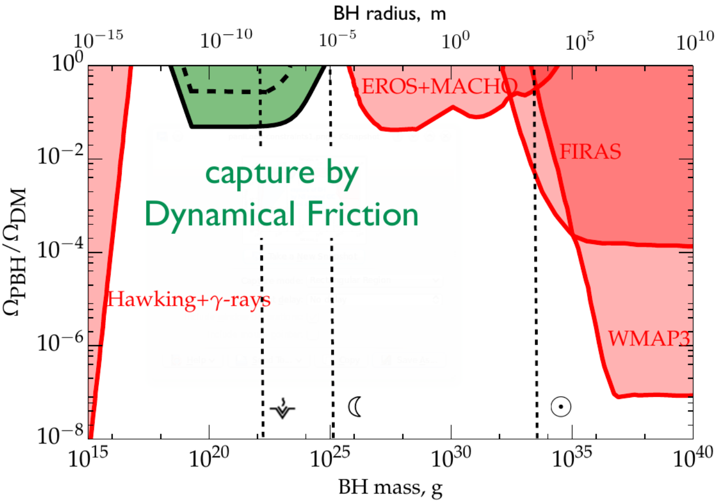
Constraints from DF

Assuming $\rho_D = 2 \times 10^3$ GeV/cm^3, velocity $v_\infty = 7$ km/s



II. Capture 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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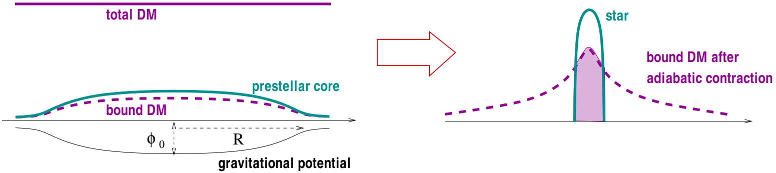

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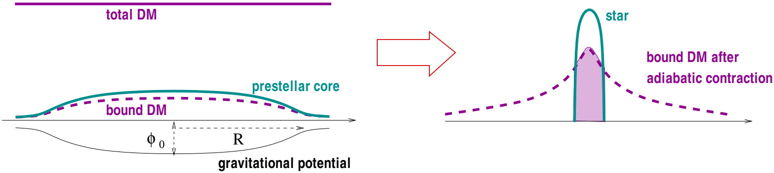

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- The density of bound DM, assuming Maxwellian parent distribution with $\bar{v}$:

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

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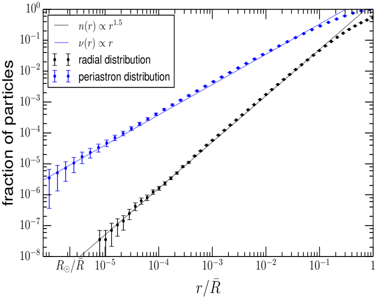
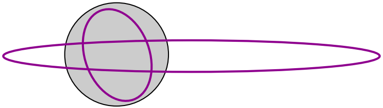


- Number of particles within r,

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

- Number of particles with periastron $< r$,

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



Time scales

- Two stages
  - When PBH is mostly outside the star

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

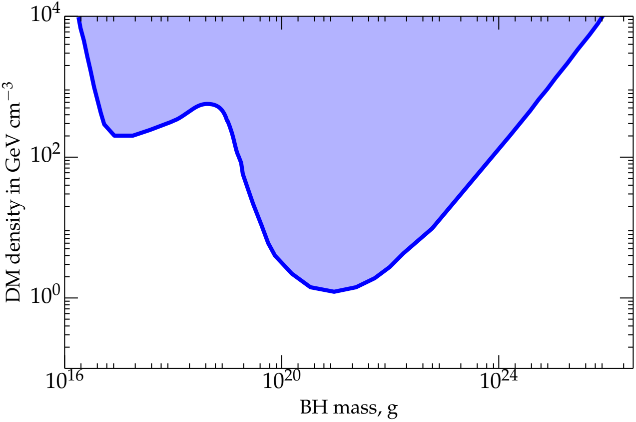
  - When PBH is completely inside the star: numerical calculation in a realistic density profile. Rough estimate:

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

  - $\Longrightarrow$ 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 $\rho_D \sim 2 \times 10^3$ GeV cm^{-3}.

Bertone, Fairbairn, PRD77,043515 (2008)

- Another candidate — dwarf spheroidals
  - similar to GC in size; DM-dominated: densities ~ 200 GeV/cm^3 have been inferred from modeling
  - But: no NS have been observed in dSph's (yet)

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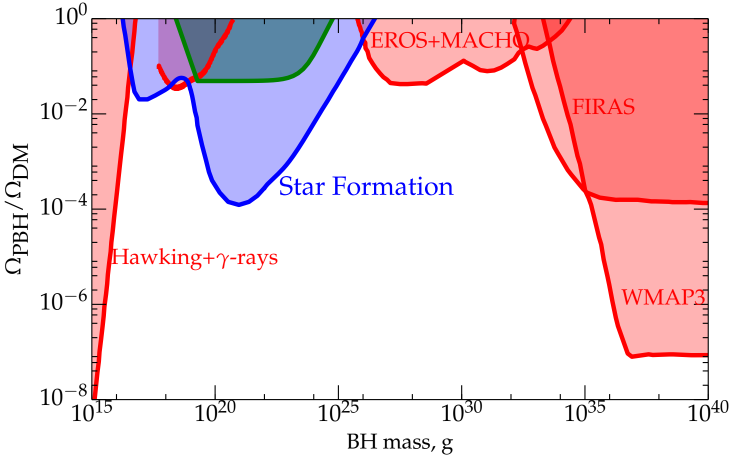
Assuming $\rho_D = 10^4$ GeV/cm^3 and $v = 7$km/s



Summary

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