

Dark side of black holes or can primordial black holes be DM?

P. Tinyakov

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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

... work in progress ...

February 20, 2018, Lake Louise

Outline

- 1 Introduction
- 2 PBH production and constraints
 - Production
 - Existing astrophysical constraints
- 3 Constraints from compact stars
 - Capture of PBH in stars
 - during lifetime
 - at star formation
 - Constraints on PBH
- 4 Can LIGO events be due to DM PBH?
- 5 Summary

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INTRODUCTION

- Many (indirect) arguments suggest the existence of dark matter with $\Omega_{DM} \simeq 0.26$

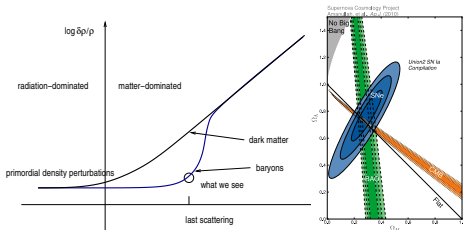
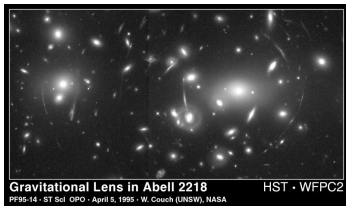
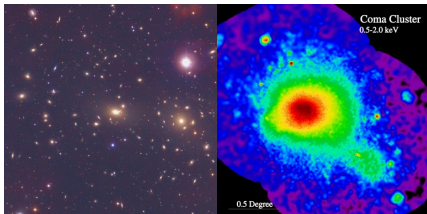
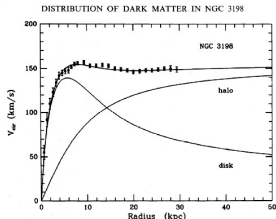
Introduction

PBH production and constraints

Constraints from compact stars

Can LIGO events be due to DM PBH?

Summary



INTRODUCTION

- Despite we are sure of the DM existence, its mass is uncertain to ~ 95 (!) orders of magnitude.
 \implies ample room for imagination!
- The DM is often assumed to be a new stable particle: axion-like particle, sterile neutrinos, WIMPs, ...
- What about 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 \implies good DM candidate
 - Bonus1: no new stable particles are needed.
 - Bonus2: connection to LIGO GW detection?

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PRODUCTION OF PHB

PRODUCTION OF PHB: BASICS

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

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

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

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,

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

- For the production at temperature T one has to have

$$f = \frac{T_{\text{eq}}}{T} \sim \frac{\text{eV}}{T} \ll 1$$

- \Rightarrow Easy to have overproduction

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 then

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

- 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 $M_{\text{PBH}} \sim M_{\odot}$ the relevant $l \sim 10^8$.

PRODUCTION MECHANISMS

- Soft equation of state at some period of evolution

Carr, ApJ 201 (1975) 1

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

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

- This gets rid of the pressure that opposes the collapse. Smaller amplitude initial perturbations may collapse into BH.
- Typically period of “softness” is limited \implies 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 rare and never collide

⇒ One gets a **compact spectrum** with

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

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

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

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

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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

⇒ NO REAL CONSTRAINTS FROM THEORY

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EXPERIMENTAL CONSTRAINTS

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

Niikura et al, 1701.02151

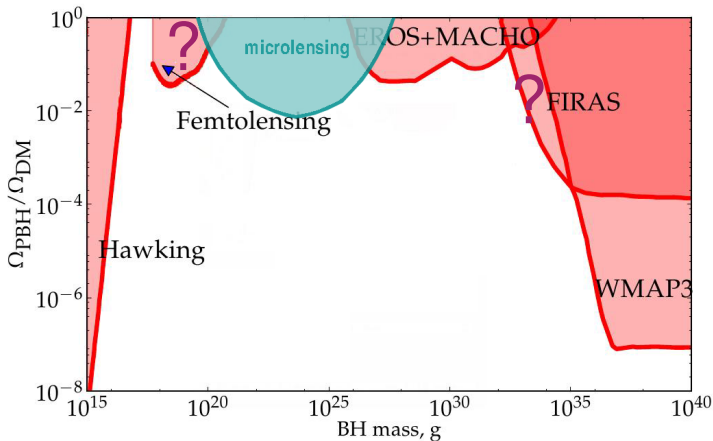
- CMB distortions

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

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EXPERIMENTAL CONSTRAINTS



Introduction

PBH production and constraints

Production
Existing astrophysical constraints

Constraints from compact stars

Can LIGO events be due to DM PBH?

Summary

- In the 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

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

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

Kouvaris Phys. Rev D77, 023006 (2008);

Sadin, Ciarcelluti, Astropart. Phys. 32 (2009) 278-284;

Bertone, Fairbairn, Phys. Rev. D77, 043515 (2008);

McCullough, Fairbairn, Phys. Rev. D81 (2010) 083520.

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Capture of PBH in
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- during lifetime
- at star formation

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CONSTRAINTS FROM COMPACT STARS

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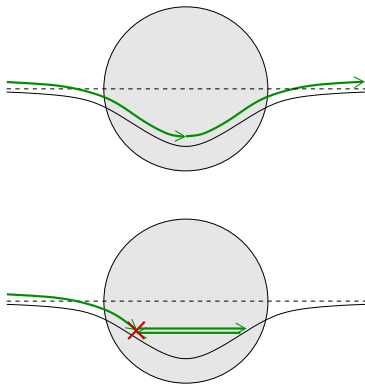
Summary

Capture of PBH in stars

Two different mechanisms:

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

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

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Energy loss: dynamical friction approximation

Chandrasekhar '1949

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

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

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 (in case of NS)

$$E_{\text{loss}} \sim \frac{2Gm_{\text{BH}}^2}{R_*} \ln(R_*/r_g)$$

- **Complication** in case of NS: **degeneracy of nuclear matter**
- The integral over impact parameters has to be cut when momentum transfer becomes smaller than Fermi momentum
- Taking into account accreted matter and realistic star density profile

$$E_{loss} \simeq \frac{2Gm_{BH}^2}{R_*} \frac{2GM_*}{R_*} \left\langle \frac{\ln \Lambda}{v^2} \right\rangle$$

where, numerically

$$\left\langle \frac{\ln \Lambda}{v^2} \right\rangle \simeq 14.7$$

\Rightarrow smaller by a factor ~ 5 than non-degenerate case

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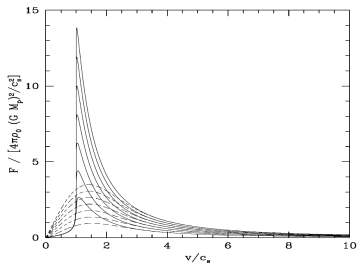
Can LIGO events be due to DM PBH?

Summary

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

E.Ostriker '1999



⇒ DF is good approximation in the supersonic case

From E_{loss} to capture rate

- The cross section of the star crossing

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

- Average with Maxwellian distribution

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

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

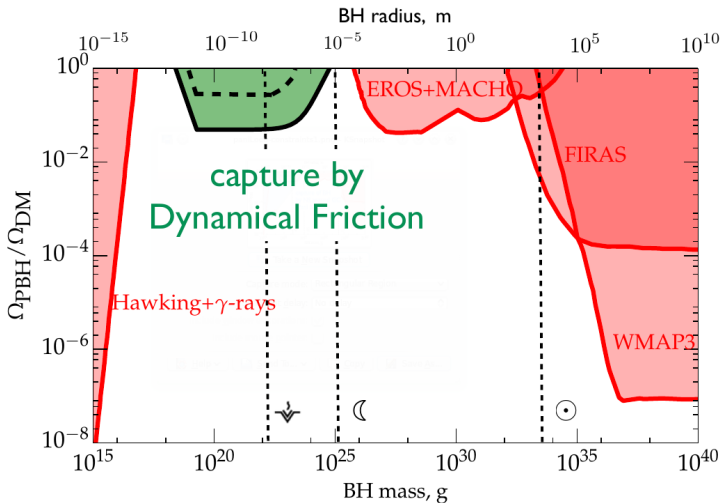
- Best conditions for capture:
 - Large DM density ρ_D
 - Small DM velocity v_∞

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Constraints from DF

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



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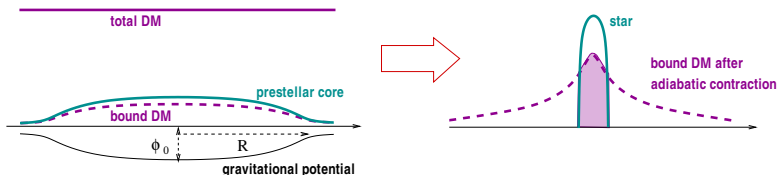
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II. Capture at star formation

- 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

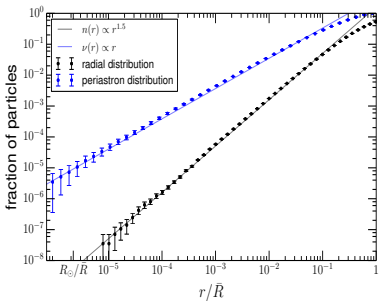


- When the star evolves into a compact remnant (NS or WD), some of these PBHs may be inherited by the latter.

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

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

- DM after the adiabatic contraction:

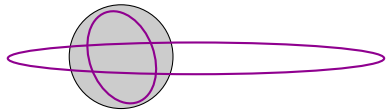


- Number of particles within r ,

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

- Number of particles with periastron $< r$,

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



Time scales

- Two stages
 - When PBH is mostly outside the star

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

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

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

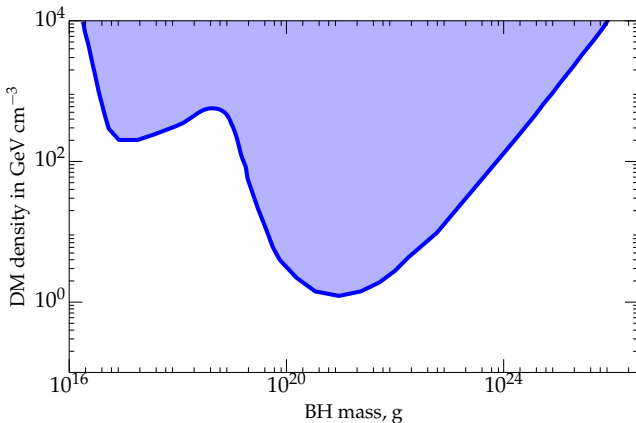
- \Rightarrow Insufficient time at small m_{BH}

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RESULTING CONSTRAINTS

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



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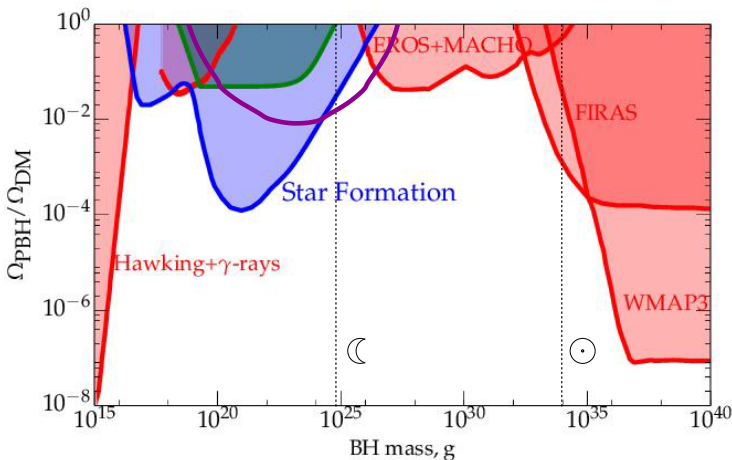
Where to look?

- 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 $\rho_D \sim 2 \times 10^3 \text{ GeV cm}^{-3}$.
- Bertone, Fairbairn, PRD77,043515 (2008)*
- Another candidate — dwarf spheroidals
 - similar to GC in size; DM-dominated: densities $\sim 200 \text{ GeV/cm}^3$ have been inferred from modeling
 - But: no NS have been observed in dSph's (yet)

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



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CAN LIGO EVENTS BE DUE TO DM PBH?

Two subtleties:

- How solid are the constraints around $M_{\text{PBH}} = \mathcal{O}(10M_{\odot})$?
- Are the constraints weaker for an **extended** PBH mass function?

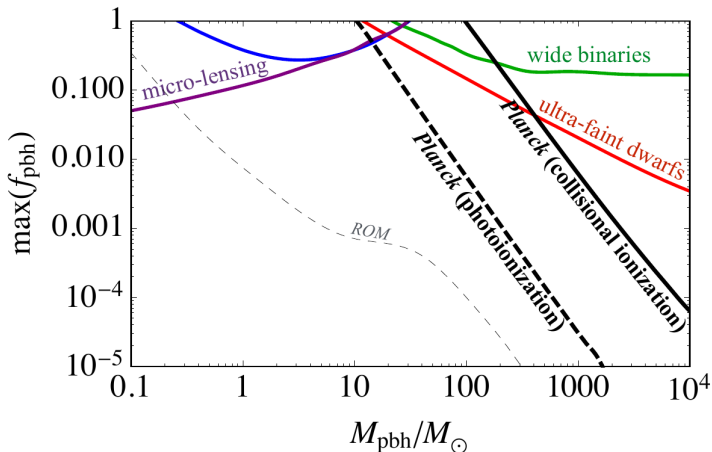
Although the answer to both questions may appear favorable, they turn out to be irrelevant as there is a **bigger problem**.

So, the idea of **combined** DM and LIGO explanation is **unlikely to work**.

REVISITING CONSTRAINTS

Ali-Haimoud, Kamionkowski, 1612.05644

Region around $10M_{\odot}$ reconsidered:

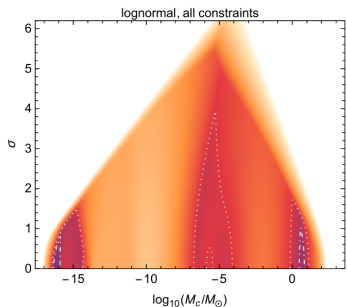
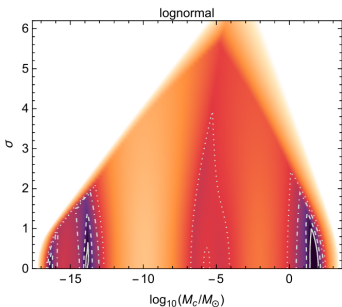


REVISITING CONSTRAINTS

Carr et al, 1705.05567

Extended mass function (e.g., log-normal):

$$\psi(M) = M \frac{dn}{dM} = \frac{f}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$



Key point for LIGO — formation of binaries

Two competitive ways to form binaries:

- Pair collisions with emission of GW in halos of galaxies

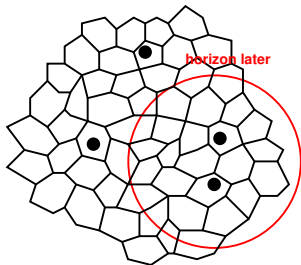
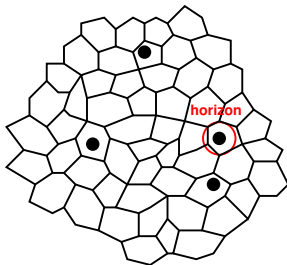
Bird et al, PRL 116 (2016) 201301

Very inefficient: hardly makes it even if all DM is in PBH

- In the early Universe

Nakamura et al, ApJ 487 (1997) L139

- PBH are created much less than one per horizon
- After some time they enter each other horizon and start interacting gravitationally



Formation of binaries

- If the distance between BH is large, cosmological expansion drives them even further away.
- Before equality, radiation energy density drops faster than PBH density \implies at some point 2 sufficiently close PBH may happen to dominate the energy density in the local region, so they **decouple from expansion and form a bound pair**.
- Probability peaks at equality time.
- Once two PBH are gravitationally bound, they starts to orbit each other and loose energy to GW

Formation of binaries

- In the absence of perturbations, two PBH just fall on each other and merge \implies not interesting: no LIGO events today
- If the orbit is perturbed and becomes elliptical, the lifetime of the pair depends on the orbit parameters

$$\tau = 10^{33} \text{ yr} \left(\frac{x}{x_{\text{mean}}} \right)^4 (1 - e^2)^{7/2}$$

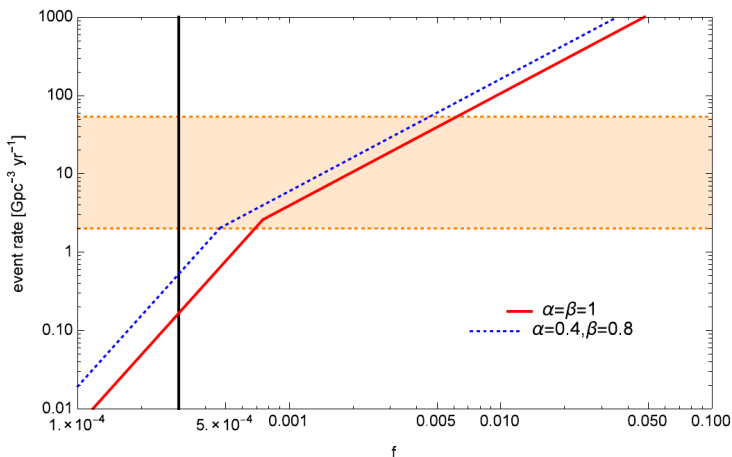
and can easily be very long

- In the case of perturbations by a third PBH the distribution over lifetimes is very flat

$$dP = \text{const} \left(\frac{10^{33} \text{ yr}}{t} \right)^{1/7} f^2 \frac{dt}{t}$$

Formation of binaries

Normalizing to the LIGO rate:



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
- The whole of the DM is **unlikely** to be explained by the PBH of masses $O(10M_{\odot})$ that are responsible for LIGO events.

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BACKUP SLIDES

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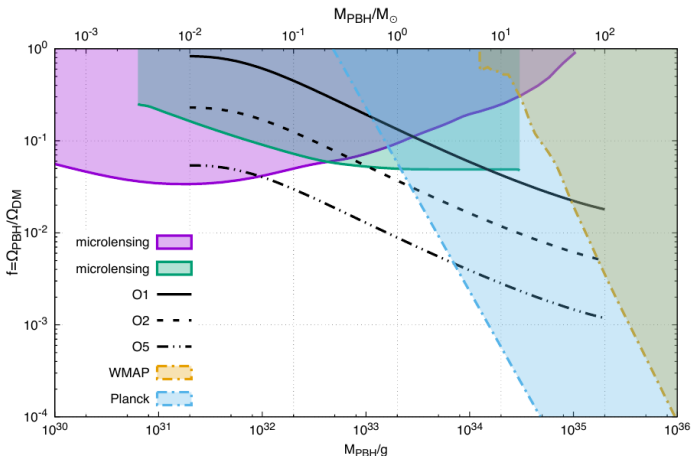
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Constraints on PBH from stochastic GW



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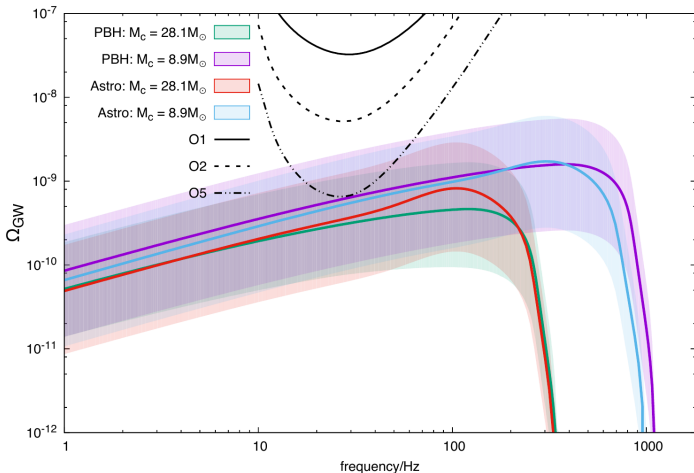
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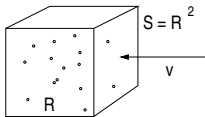
BACKUP: Compact stars capture more efficiently

- Cross section of hitting the star:

$$\pi R_*^2 \left(1 + \frac{2GM_*}{R_* v_\infty^2} \right) \sim \frac{\pi R_* R_g}{v_\infty^2}$$

Second term dominates.

- No gravity:



$$\text{rate} \propto R^2 \cdot R \sigma n = R^3 \sigma \frac{N}{R^3} \propto \sigma N$$

- With gravity

$$\text{rate} \propto R_* \cdot R_* \sigma n = R_*^2 \sigma \frac{N}{R_*^3} \propto \sigma \frac{N}{R_*}$$

⇒ Compact objects capture more

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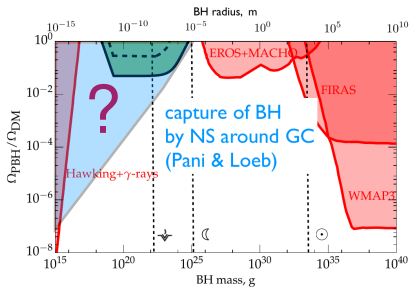
DIGRESSION: surface waves

- 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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PBH production and constraints

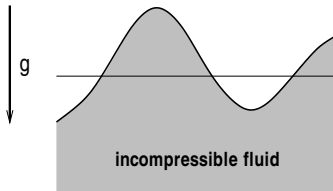
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MODEL: flat incompressible fluid in gravitational field

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



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

$$\Delta\phi = 0$$

$$\phi_{tt} + g\phi_z = 0 \quad @ \text{ surface}$$

- \implies surface waves with dispersion

$$\omega^2 = gk$$

$$v_s^2 = g/k$$

- solution for displacement is

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

Energy loss in incompressible fluid

- Calculate 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
- Total energy loss is parametrically the same as in Dynamical friction

$$\frac{G^2 m_{\text{BH}}^2 \rho}{g} \sim \frac{G m_{\text{BH}}^2}{R}$$

CONCLUSION on tidal approach:

- No divergency at small wavelengths
- Suppression of the surface wave contribution by $v_s^2/v^2 \lesssim 10^{-3}$
- Thus, “tidal” approach is just a different way to calculate the same quantity which, when done correctly, gives the same answer