Did LIGO detect dark matter:
S. Bird et al., 1603.00464

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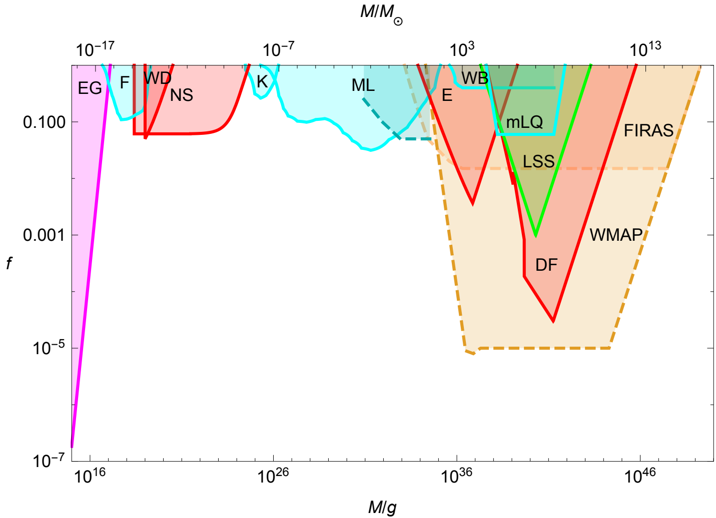
Primordial black holes as dark matter

- “primordial” $\Rightarrow$ formed before $T \sim MeV$ to avoid nucleosynthesis bounds on $\Omega_b \sim 0.04$.
- Scale-invariant inflationary fluctuations produce gravitationally bound objects with $\langle v^2/c^2 \rangle \sim \Delta\phi_{grav} \leq \Delta T/T \sim 10^{-5}$
- Black holes have $\Delta\phi_{grav} \sim 1$ so PBHs require a new source of primordial fluctuations at small scale.
- Without new fluctuations, non-primordial black holes formed later by radiative processes.)

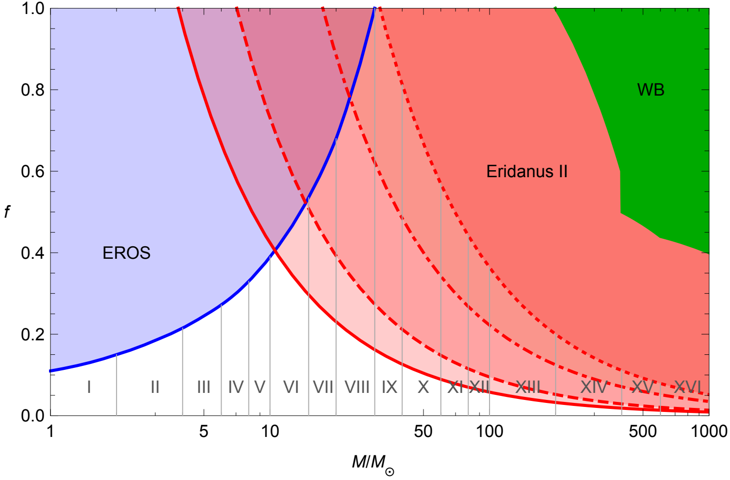
Limits: B.Carr et al: 1607.06077



dashed: model dependent limits

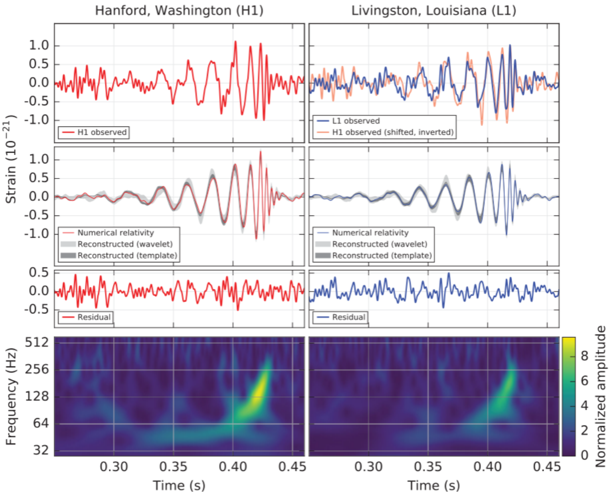
$M < 10^{-17} M_\odot$: Hawking rad; $10^-7 < M < 10 M_\odot$: Microlensing $M > 10^2 M_\odot$: disruption of stellar systems (binaries, disks...).

Limits weak for $20 < M < 100 M_\odot$



EROS: Tisserand et al (2007) 254 citations to date.
Eridanus II: model dependent

Ligo event: coalescence of BH-BH binary



$M_{BH1} - (36 \pm 5) M_\odot$
$M_{BH2} - (29 \pm 4) M_\odot$

(where limits on PBH are weak)

$D = 410 \pm 170 \mathrm{Mpc}$

rate:
$2 \rightarrow 400 \ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Did LIGO detect dark matter? (S. Bird et al.)

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter.

Capture cross section: $BH + BH \rightarrow binary + grav.wave$

$$\begin{aligned}\sigma &= \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7} \\ &= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2, \end{aligned} \qquad (1)$$

Black holes captured at a distance $\sim (c/v)^{9/7} R_s$

$\Rightarrow$ short merger time (compared to Hubble time).

$R_s(30M_\odot) = 88.6$ km

PBHs in halos of mass M_{halo}

Simple halo model: halos characterized by M_{halo} and velocity dispersion $v^2 \sim GM_{halo}/r_{halo}$. $\Rightarrow \rho_{halo} \sim v^6/(G^3 M_{halo}^2)$.
Binary formation rate, τ^{-1}, per black hole:

$$\tau^{-1} = \frac{\rho_{halo}}{M_{bh}} \langle \sigma v \rangle \ \sim \rho_{halo} M_{bh} v^{-11/7} \ G^2$$

Total binary formation rate in one halo:

$$\Gamma_{1\,halo} \sim \frac{M_{halo}}{M_{bh}} \tau^{-1} \sim M_{halo} \rho_{halo} v^{-11/7} G^2$$

Total binary formation rate per Gpc^3 if all BHs in one type of halo:

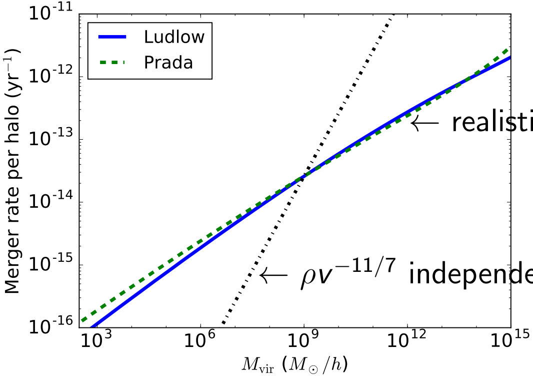
$$\Gamma \sim \frac{\Omega_m \rho_c}{M_{halo}} \Gamma_{1\,halo} \sim 10^{-4} \frac{\rho_{halo}}{0.002 M_\odot \mathrm{pc}^{-3}} \left(\frac{v}{200 \mathrm{km\,s}^{-1}} \right)^{11/7} \mathrm{Gpc}^{-3} \mathrm{yr}^{-1}$$

$\Rightarrow$ galaxy-size halos give $\Gamma \ll \Gamma_{LIGO}$

Binary formation rate in one halo

$$\Gamma_{1\,halo} \sim \frac{M_{halo}}{M_{bh}}\tau^{-1} \sim M_{halo}\rho_{halo}v^{-11/7}G^2$$

In real halos, $\rho_{halo}v^{-11/7}$ decreases with increasing mass:



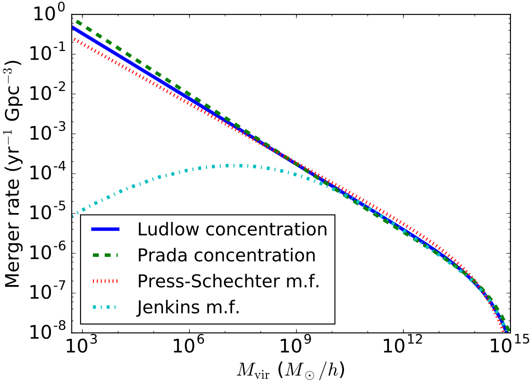
← realistic halo (NFW)

← $\rho v^{-11/7}$ independent of M_{halo}

Total merger rate

$$\Gamma \sim \frac{\Omega_m \rho_c}{M_{halo}} \Gamma_{1\,halo} \sim 10^{-4} \frac{\rho_{halo}}{0.002 M_\odot \mathrm{pc}^{-3}} \left(\frac{v}{200 \mathrm{km\,s}^{-1}} \right)^{11/7} \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

$\Rightarrow$ total rate dominated by lowest mass halos



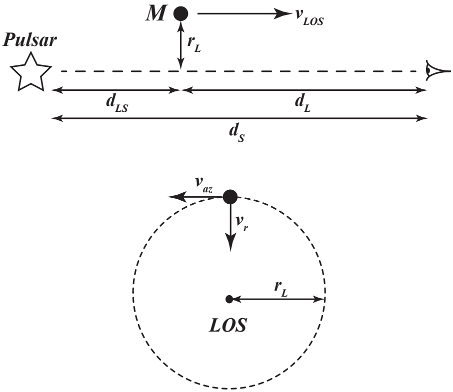
Integrated rate:
$\Gamma \sim 2\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

$2 < \Gamma_{LIGO} < 53 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Comments

- rate insensitive to cusp problem.
  Most events in cusples halos $< 10^9 M_\odot$.
- LIGO rate is also consistent with that expected from BH's from stellar evolution
  arXiv:1602.04531; 1003.2480
  Events in $M > 10^9 M_\odot$ halos
- no electromagnetic component for PBH
- PBHs detectable/identifiable by pulsar-timing arrays
  arXiv:1610:04234

Pulsar-timing arrays: 1610:04234



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Pulsing frequency varies as pulsar and BH move across line-of-sight.

Pulsar period and derivative, $P, \dot{P}$;

Pulse arrival times t_n

$$t_n - t_0 \approx nP\left(1+\frac{4GMv_r}{c^3 r_{L,0}}\right)+\frac{n^2P^2}{2}\left(\frac{\dot{P}}{2P}+\frac{4GMv_r^2}{c^3 r_{L,0}^2}\right)+n^3P^3\frac{4GMv_r^3}{3c^3 r_{L,0}^3}+\ldots$$

Only the n^3P^3 term signals presence of BH (assuming $\ddot{P}=0$!).

Rate for measurable time delay

$$t_n - t_0 \approx nP\left(1+\frac{4GMv_r}{c^3 r_{L,0}}\right)+\frac{n^2P^2}{2}\left(\frac{\dot{P}}{2P}+\frac{4GMv_r^2}{c^3 r_{L,0}^2}\right)+n^3P^3\frac{4GMv_r^3}{3c^3 r_{L,0}^3}+\ldots$$

Only the n^3P^3 term signals presence of BH (assuming $\ddot{P} = 0$!).
Minimum detectable shift: $\Delta t_{min} \sim 0.05\ \mu$sec after 30 years (!).
$\Rightarrow$ "cross section" for such a shift is

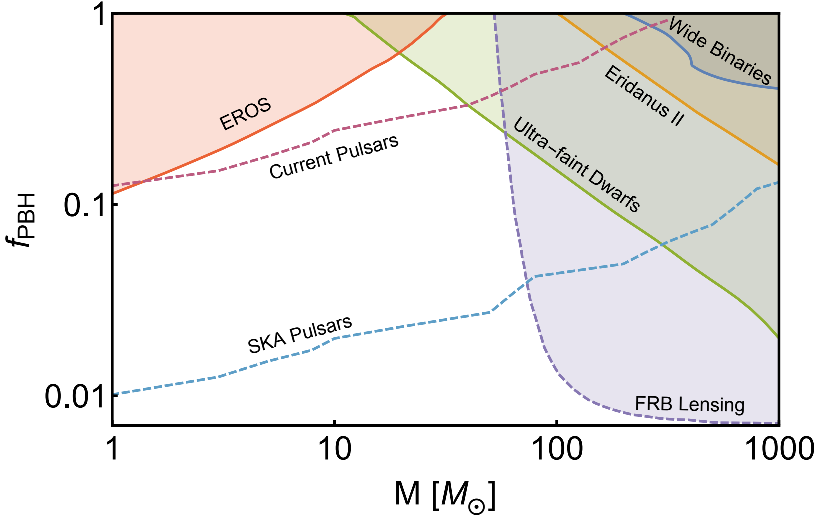
$$r_{max}^2 \sim \frac{(GM_{BH})^{2/3} T_{obs}^2 v^2/c^2}{(\Delta t_{min})^{2/3}}$$

(Impact parameters $< r_{max} \Rightarrow \Delta t > \Delta t_{min}$ after a time T_{obs}.)

To be compared with cross-section for microlensing (amp > 1.34):

$$R_E^2 \sim \frac{GM_{BH}D_{BH}}{c^2} \qquad \text{Not obvious who wins!}$$

Limits on PBH DM Abundance



143 current pulsars; 2000 SKA pulsars over 30 years.

FRB Lensing: Double pulsing of Fast Radio bursts.