Mergers as a Probe of Particle Dark Matter

arXiv: 2009.01825 [astro-ph.HE]

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Work in collaboration with: Basudeb Dasgupta, Ranjan Laha

AstroDark-2021,
07.12.2021

- Recent discoveries of unusually low mass objects in the GW detectors pose a very fundamental question about their origin.

$\boxed{\text{(Stellar or Primordial?)}}$

GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object

LIGO Scientific Collaboration and Virgo Co[...]

(Dated: June 24, 2020)

ABSTRACT

We report the observation of a compact binary coalescence involving [...] a compact object with a mass of $2.50 - 2.67\,M_\odot$ (all measurements q[...] The gravitational-wave signal, GW190814, was observed during LIG[...] run on August 14, 2019 at 21:10:39 UTC and has a signal-to-noise ratio of 25 in the three-detector network. The source was localized to 18.5 deg^2 at a distance of 241^{+41}_{-45} Mpc; no electromagnetic counterpart has been confirmed to date. The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$, and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. The dimensionless

REPORT

A noninteracting low-mass black hole–giant star binary system

Todd A. Thompson[1,2,3,*], Christopher S. Kochanek[1,2], Krzysztof Z. Stanek[1,2], Carles Badenes[4,5], Richard S. Post...

+ See all authors and affiliations

Science 01 Nov 2019:
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DOI: 10.1126/science.aau4005

$\boxed{\text{BH mass: } 3.3^{+2.8}_{-0.7}\,M_\odot}$

+also, secondary components of GW200105 & GW200115 can be low mass BHs!

GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4\,M_\odot$

On 2019 April 25, the LIGO Livingston detector observed a compact binary coalescence with signal-to-noise ratio 12.9. The Virgo detector was also taking data that did not contribute to detection due to a low signal-to-noise ratio, but were used for subsequent parameter estimation. The 90% credible intervals for the component masses range from 1.12 to 2.52 $M_\odot$ (1.46–1.87 $M_\odot$ if we restrict the dimensionless component spin magnitudes to be smaller than 0.05). These mass parameters are consistent with the individual binary components being neutron stars. However, both the source-frame chirp mass $1.44^{+0.02}_{-0.02}\,M_\odot$ and the total mass $3.4^{+0.3}_{-0.1}M_\odot$ of this system are significantly larger than those of any other known binary neutron star (BNS) system. The possibility that one or both binary components of the system are black holes cannot be ruled out from gravitational-wave data. We discuss possible

- Detection of a sub-Chandrasekhar mass (< 1.4 $M_\odot$) BH is usually thought as a smoking gun signature of its primordial origin.

- Non-annihilating DM with non-zero interaction strength with nuclei, a vanilla scenario, is sufficient to produce sub-Chandrasekhar mass non-primordial BHs.

- Origin of a low mass BH (transmuted or primordial) can easily be tested via several simple yet powerful probes.

- Cosmic evolution of the binary merger rates, especially, measurement of binary merger rates at higher redshifts can conclusively determine the origin of low mass BHs, and therefore, can test the particle DM hypothesis.

- **Primordial black holes (PBHs):** Exotic compact objects; formed in the early universe possibly by gravitational collapse of over dense regions.

$$\rho_{\rm PBH} \sim \frac{\rm M_{PBH}}{\left(\frac{2\,G\,M_{PBH}}{c^2}\right)^3} \sim 10^{18} \left(\frac{\rm M_\odot}{\rm M_{PBH}}\right)^2 \ {\rm g/cm^3}$$

Required density for PBH formation

average density of Sun $\sim 1.41\, g/cm^3$

$$\rho_c \sim \frac{1}{\rm G\,t^2} \sim 10^6 \left(\frac{1\,s}{\rm t}\right)^2 \ {\rm g/cm^3}$$

Cosmological density

PBH forming large density can only be achieved in the very early universe.

PBHs: sirens of the early universe

- Wide range of masses depending on their time of formation

$$M_{PBH} \sim \frac{c^3 t}{G}$$

time of formation

$$\sim 10^{15} \left(\frac{t}{10^{-23}\,\mathrm{s}} \right) \mathrm{g}$$

$t = t_p = 10^{-43}$ s | $t = 10^{-5}$ s | $t = 1$ s

$M_{PBH} \sim 10^{-38}\, M_\odot$ | $M_{PBH} \sim 1\, M_\odot$ | $M_{PBH} \sim 10^5\, M_\odot$

- PBHs that are formed before $\sim 10^{-5}$ s are naturally sub-Solar.
  - PBHs form much much earlier than the first stars.

PBHs as DM

- Primordial black holes (PBHs): One of the earliest proposed DM candidate.

- Detection of gravitational waves in LIGO followed by the subsequent proposals that these black holes can be primordial in nature rekindled the idea of PBHs as DM.

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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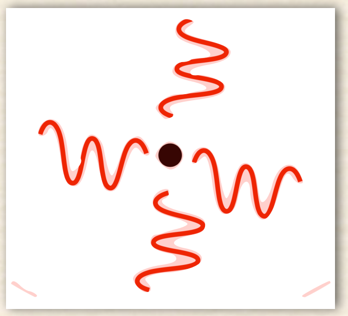
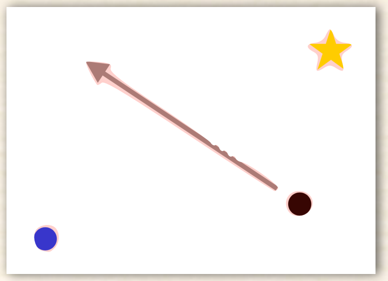
Abstract

We point out that the gravitational-wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO Scientific Collaboration and the Virgo Collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, > 2 events Gpc^{-3}yr^{-1}, roughly coincides with the existing upper limit set by the nondetection of the cosmic microwave background spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.

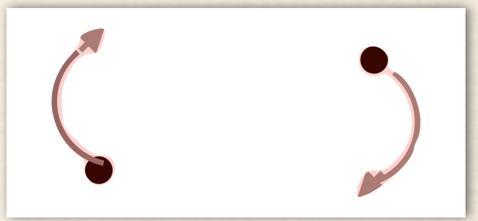
- Multiple techniques have been applied to probe PBHs as DM in various mass ranges.
  - Constraints from Hawking radiation.



  - Constraints from lensing.

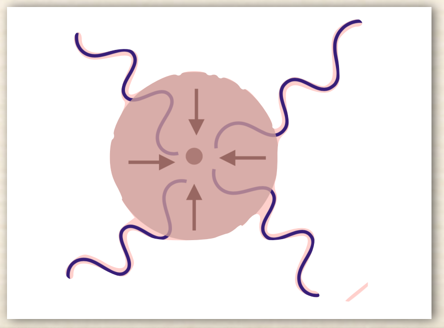


  - Constraints from gravitational waves searches.

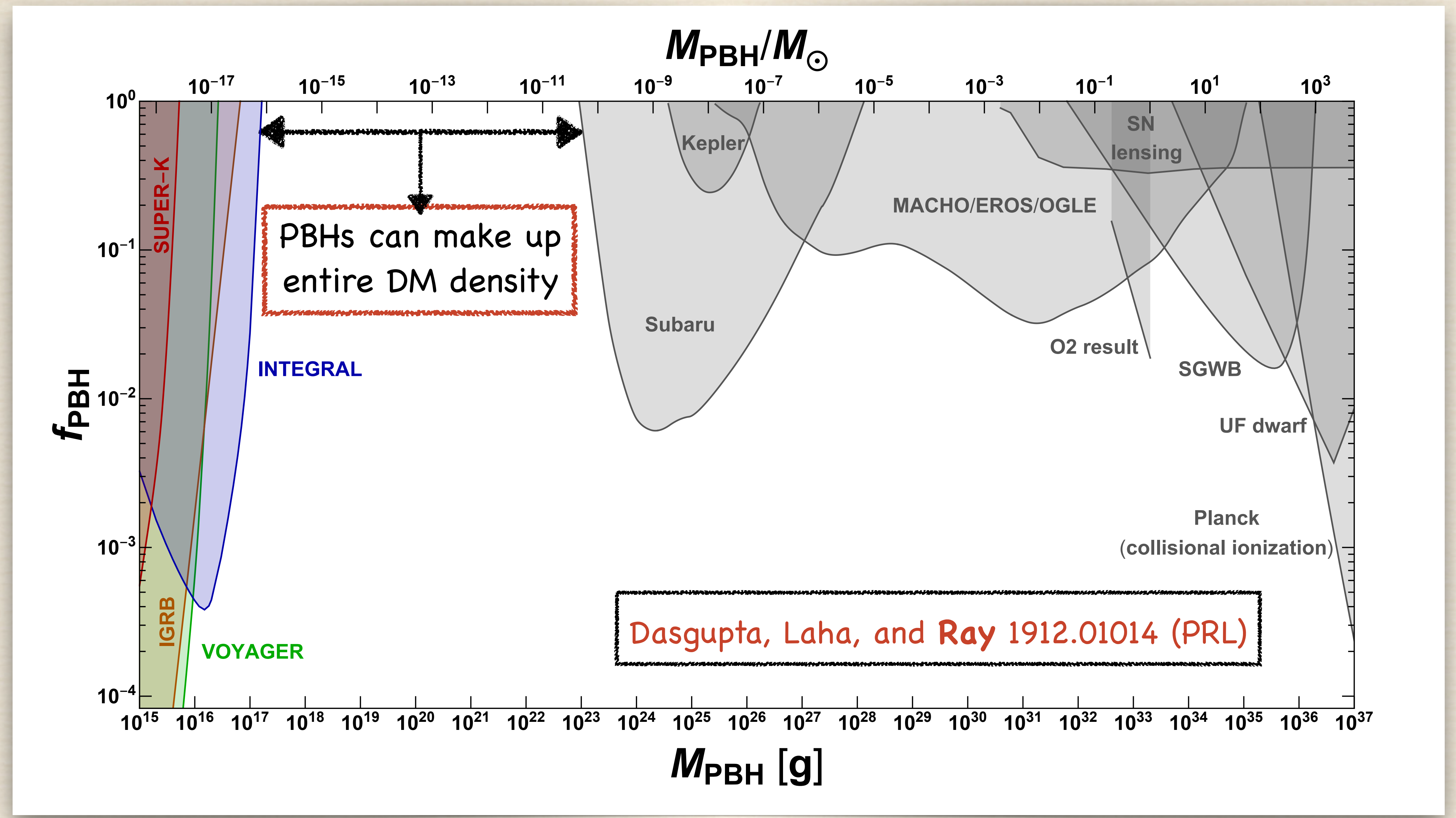


  - Constraints from dynamical effects.

  - Constraints from accretion.



Pic. Courtesy:
Anne Green



See also Carr et al. 2002.12778, Carr et al. 2006.02838, Green et. al. 2007.10722, and https://github.com/bradkav/PBHbounds.

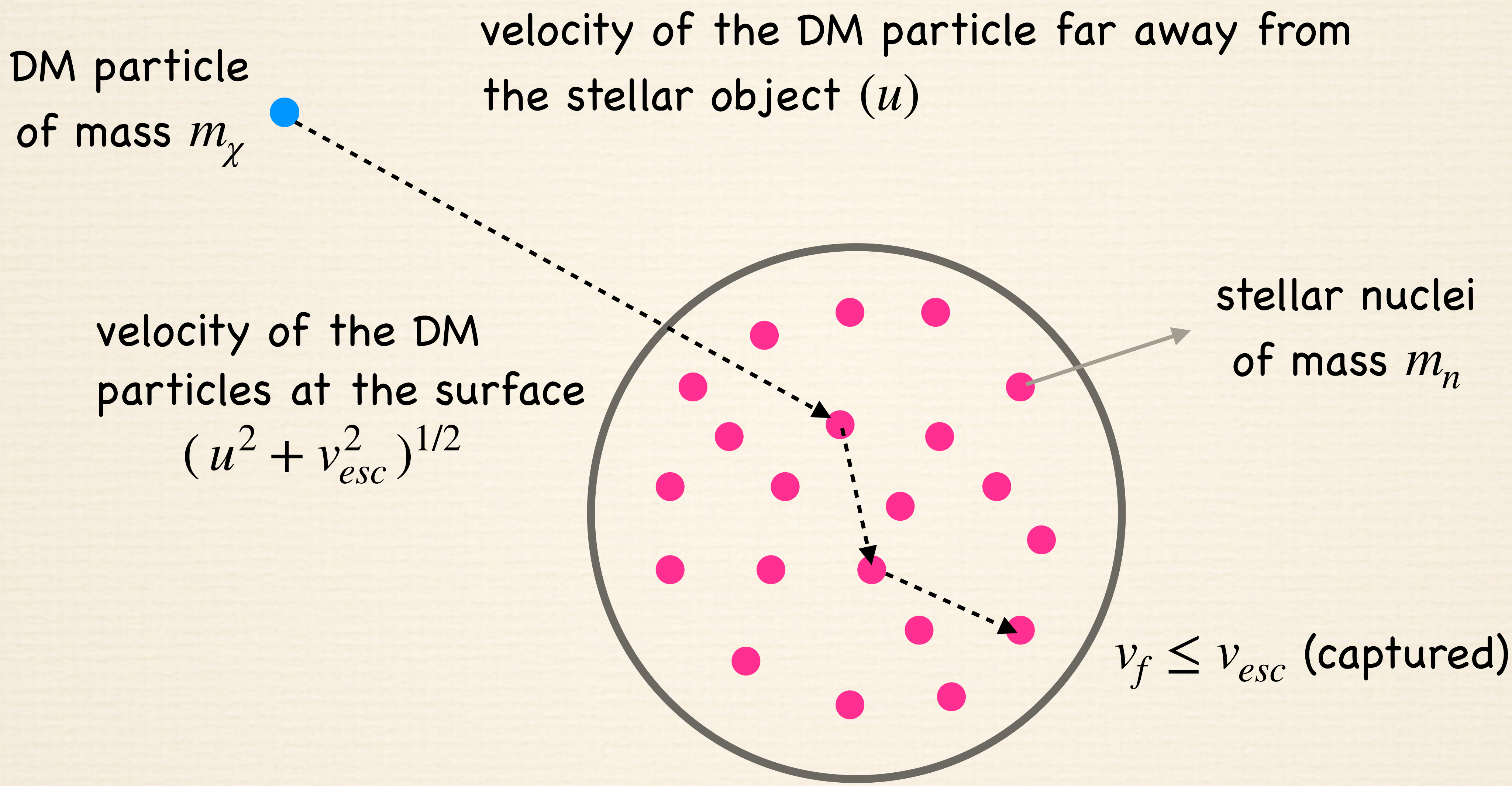
- Initial abundance of PBHs from gravitational collapse is fine-tuned.
- PBHs do not have any compelling formation mechanisms.

Carr et al. 2002.12778,...

Formation of low mass transmuted BHs

Dark Core Collapse

DM accretion in stellar objects



v_f : final velocity of the DM particles

$v_{\rm esc}$: escape velocity of the stellar object

Press & Spergel (1985), Gould (1987),...

Gould (1987),...

- Baryonic capture rate of incoming DM particles:

$$\sigma_{\chi n}^{\rm sat} = \frac{\pi R^2}{N_n}$$

Scattering cross section

$$C = \underbrace{\frac{\rho_\chi}{m_\chi}\int \frac{f(u)du}{u}(u^2+v_{\rm esc}^2)}_{\text{Incoming DM flux}}\, N_n\, {\rm Min}\left[\sigma_{\chi {\rm n}}, \sigma_{\chi {\rm n}}^{\rm sat}\right] {\rm g}_1({\rm u})$$

geometrical cross section

Capture rate (assumes single scattering)

Number of targets

*For a detailed treatment of multiple scattering, see Dasgupta, Gupta, and **Ray** 1906.04204 (JCAP)

*See Dasgupta, Gupta, and **Ray** 2006.10773 (JCAP) for estimation of the capture probability for interactions mediated via arbitrary mass mediators.

Capture Probability
$P\left(v_f \leq v_{\rm esc}\right)$

- Dark core collapse:

Goldman (1989), McDermott (1103.5472), Kouvaris (1104.0382),…, Kouvaris (1804.06740), Dasgupta (2006.10773),…

$$\boxed{\text{Total number of captured DM particles} \geq \text{Number of particles required for black hole formation}}$$

$$t_{\rm age}\, C\left(m_\phi, m_\chi, \sigma_{\chi n}\right) \qquad\qquad \mathrm{Max}\left[N_\chi^{\rm self}, N_\chi^{\rm cha}\right]$$

$t_{\rm age}$: age of the stellar object

$N_\chi^{\rm self}$: required number of DM particles for self-gravitating collapse

$N_\chi^{\rm cha}$: Chandrasekhar limit

$N_\chi^{\rm cha}$: depends on DM spin (boson/fermion)

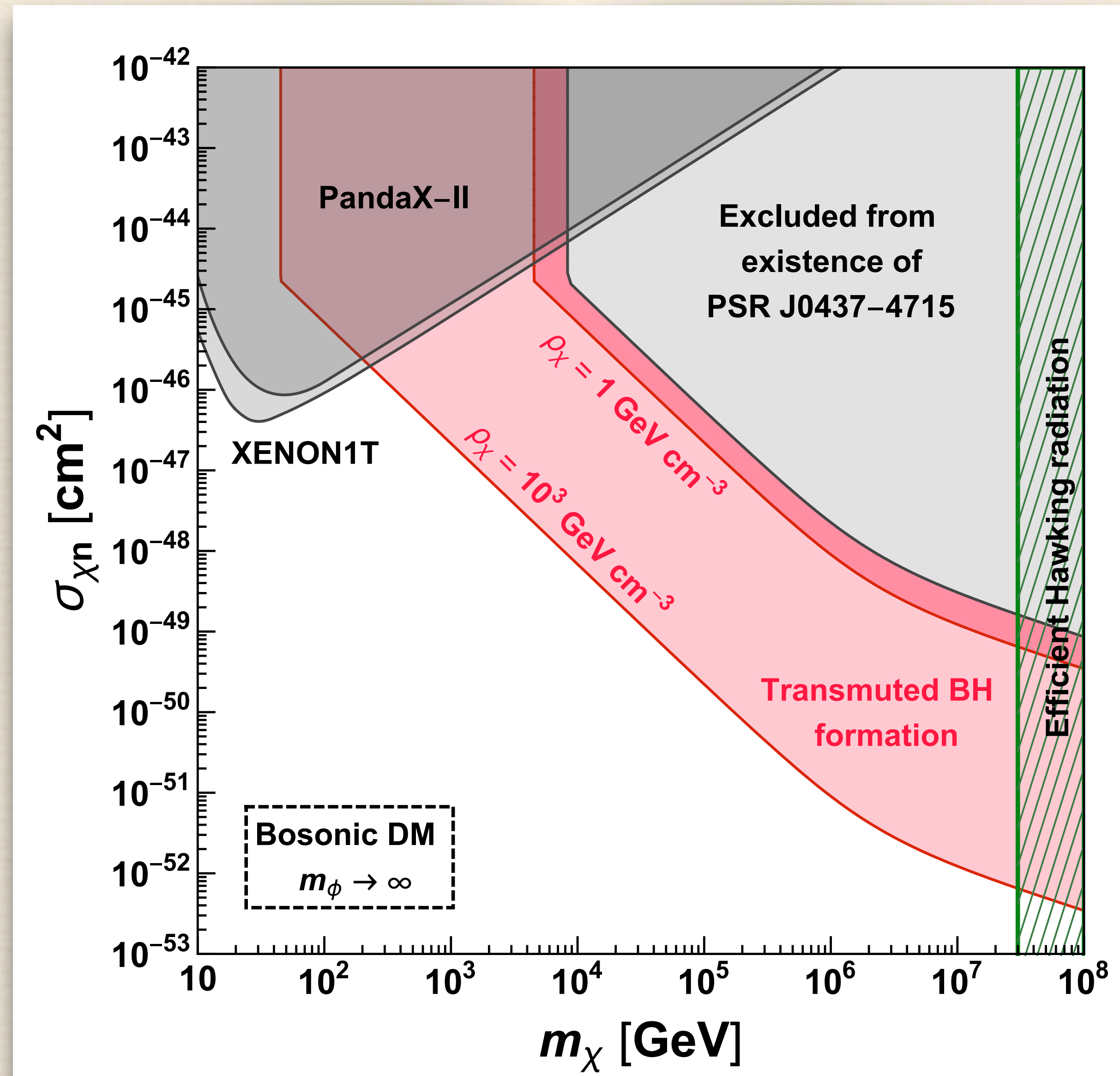
parameter space for transmuted BH formation is different for bosonic and fermionic DM

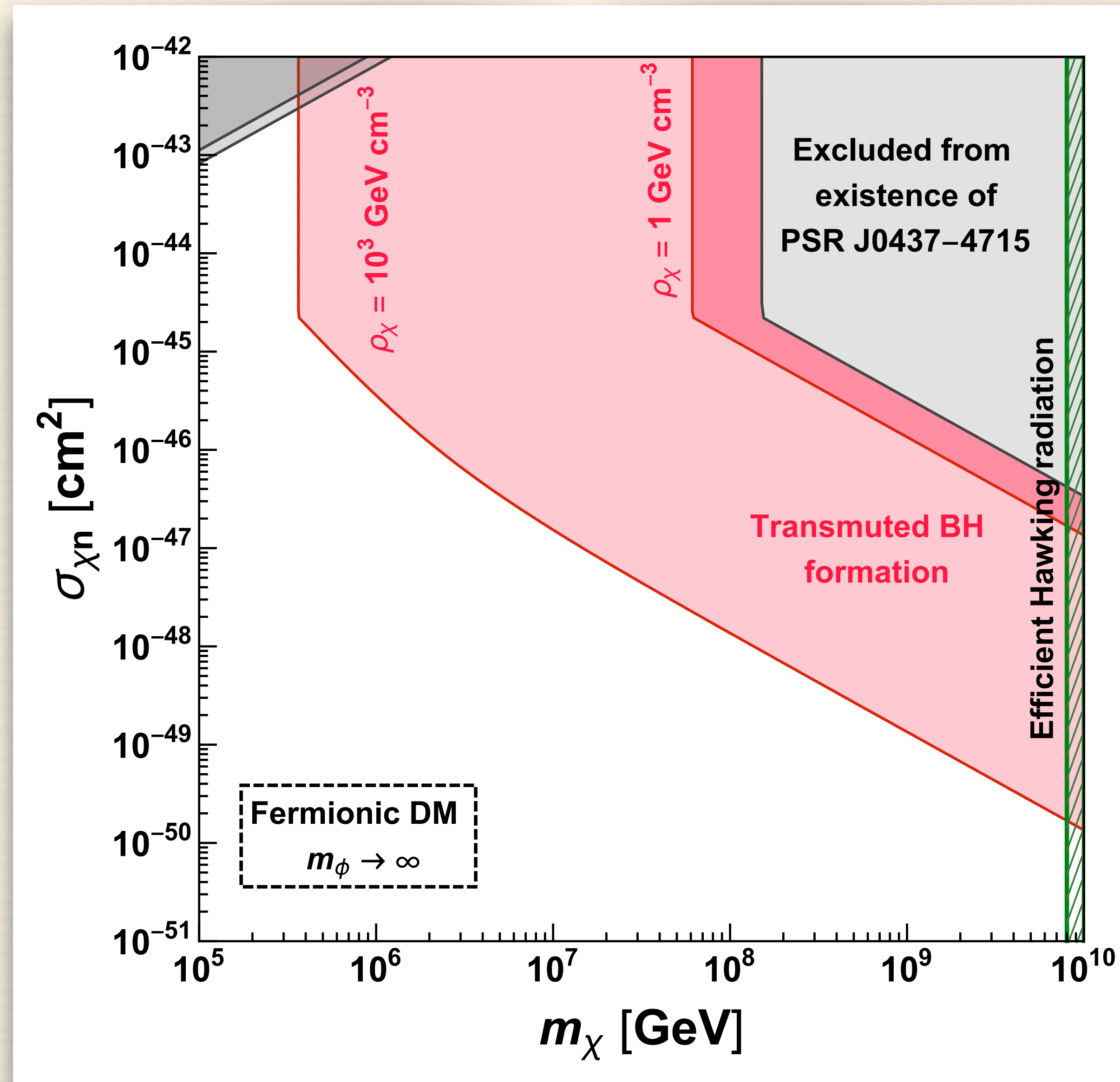
$$N_\chi^{\rm self} = 4.8\times 10^{41}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{5/2}\left(\frac{T}{10^5\,\mathrm{K}}\right)^{3/2}$$

$$N_\chi^{\rm cha} = 1.5\times 10^{34}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{2} \quad \text{Bosonic DM}$$

$$N_\chi^{\rm cha} = 1.8\times 10^{51}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{3} \quad \text{Fermionic DM}$$

Dasgupta, Laha, and **Ray** 2009.01825 (PRL)





Parameter space for transmuting a 1.3 $M_\odot$ neutron star to a comparable mass ($\leq$ 1.3 $M_\odot$) BH for non-annihilating bosonic (left)/fermionic (right) DM. Contact interaction between DM and stellar nuclei is assumed in these plots.

Tests for the origin of low mass BHs

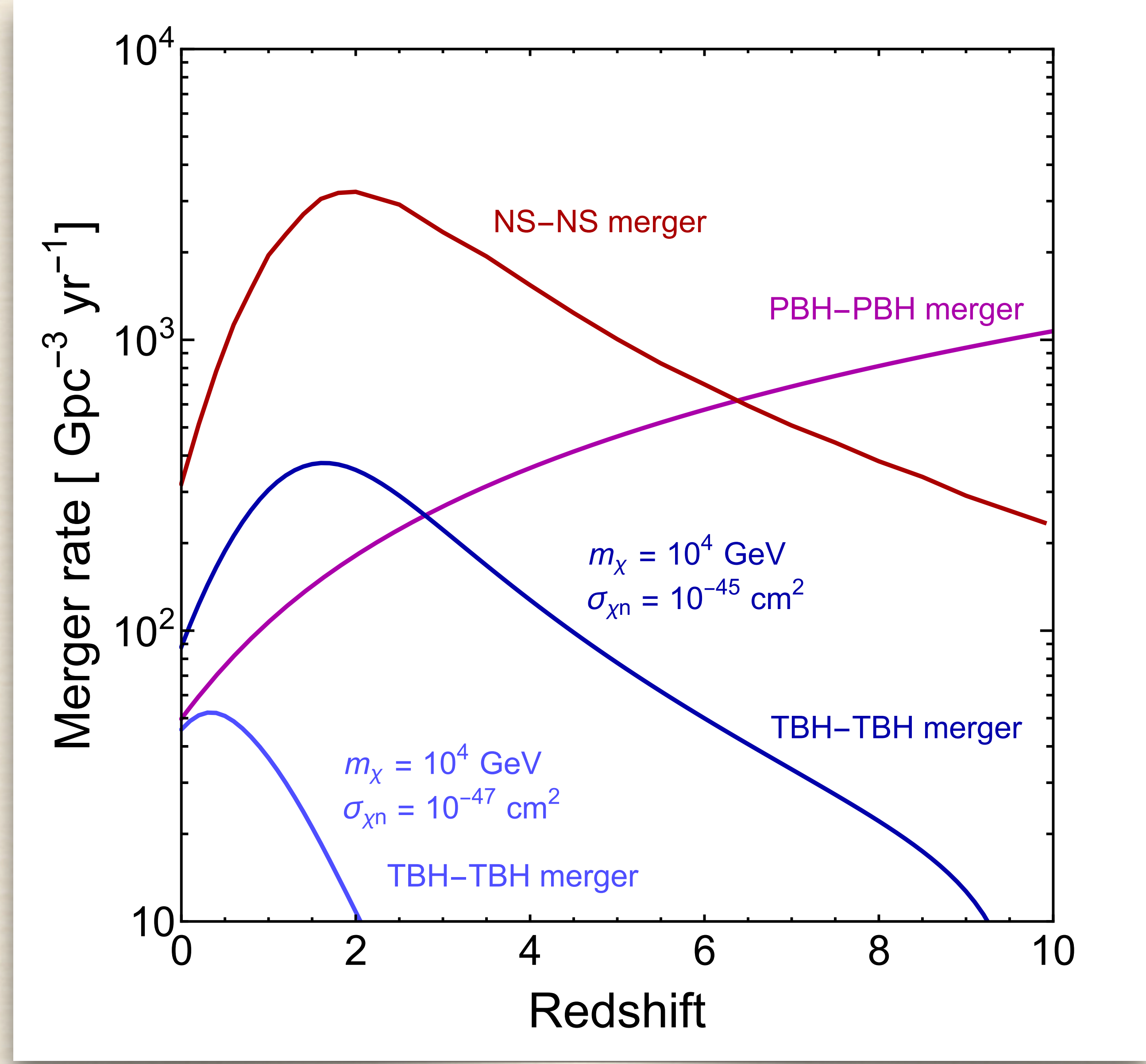
(Transmuted or Primordial)

- Cosmic evolution of the binary merger rates.
- Mass distribution of the compact objects.
- Ambient DM density around the compact objects.

Cosmic evolution of the binary merger rates

- Redshift dependence of the binary merger rates can be used as a probe to determine the origin of low mass BHs

Mergers as a probe of particle DM



Distinct redshift dependence of the binary NS, PBH and transmuted BH (TBH) merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments (Pre-DECIGO, Einstein Telescope).

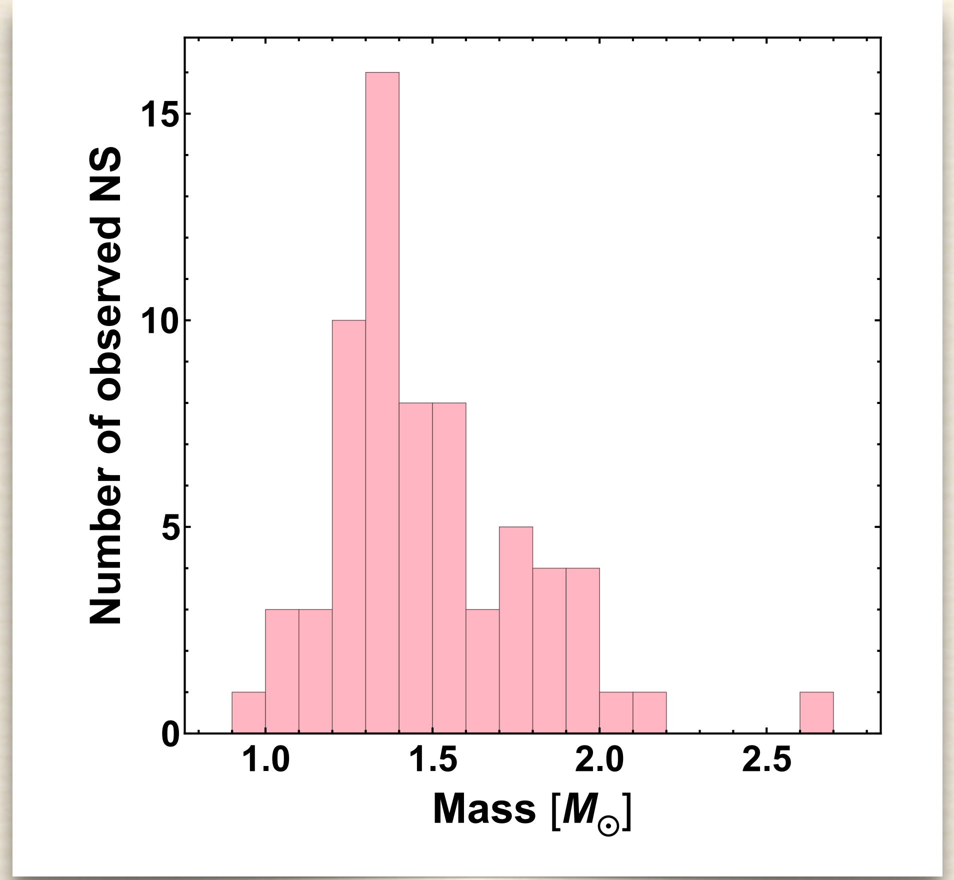
Dasgupta, Laha, and **Ray** 2009.01825 (PRL)

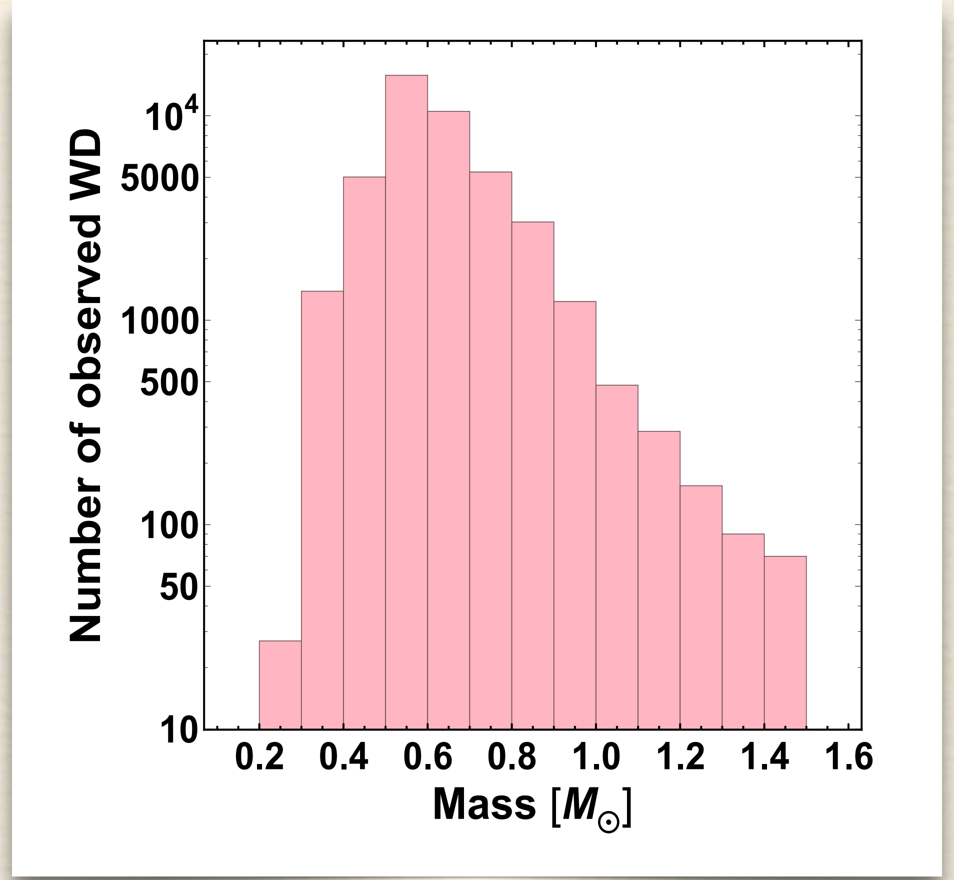
Mass distribution as a probe of low mass BHs

- Transmuted BHs track the mass distribution of their progenitors (Neutron Star/White Dwarf)

Mass distribution of the compact objects can be statistically compared against some well motivated PBH mass distribution to examine the origin of low mass BHs.

See also Takhistov et al. 2008.12780 (PRL)





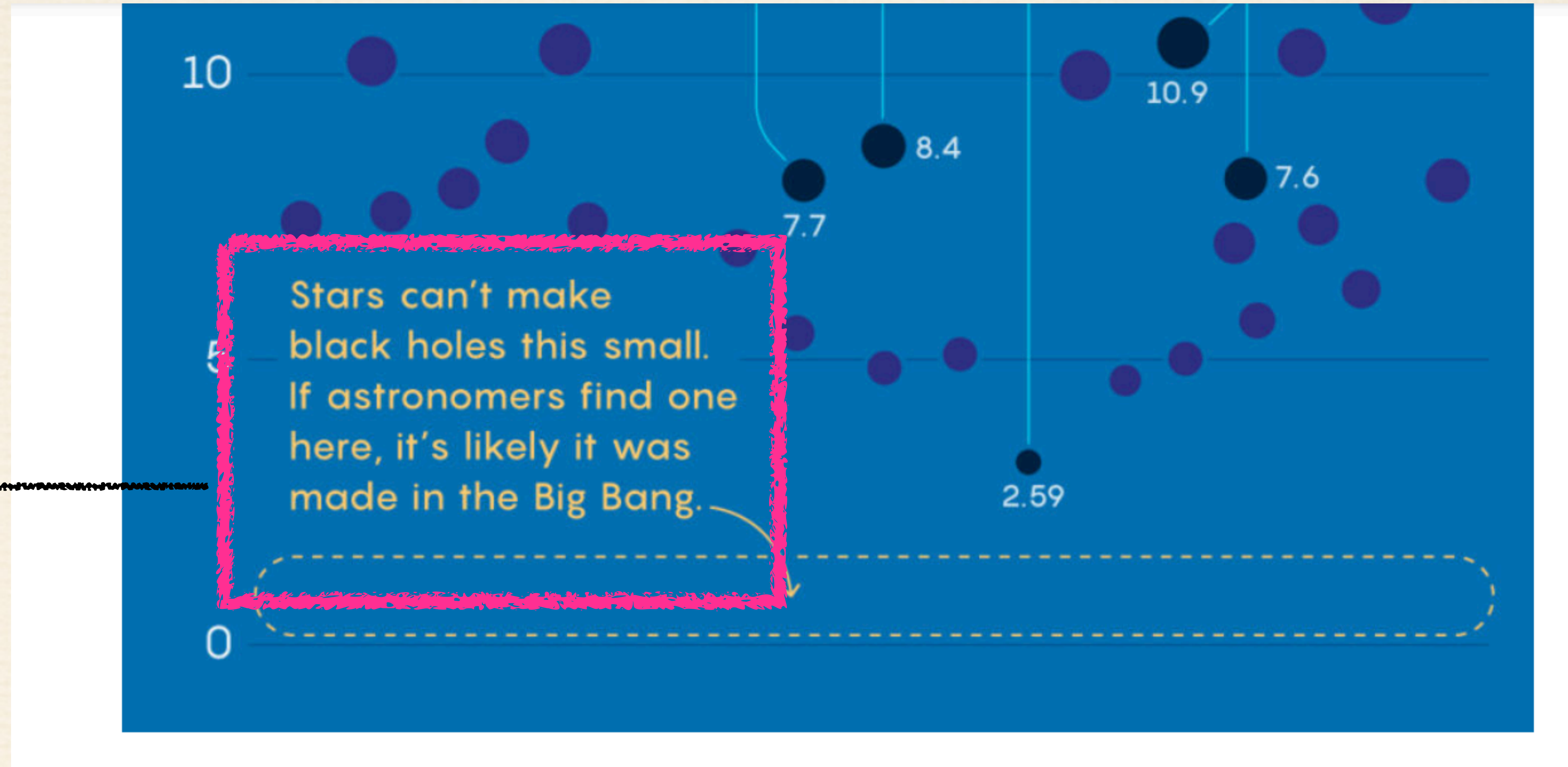
Dasgupta, Laha, and **Ray** 2009.01825 (PRL)

Conclusions

- sub-Chandrasekhar mass BH is not a smoking gun signature of its primordial origin.
- Non-annihilating DM with non-zero interaction strength with nuclei is sufficient to produce a sub-Chandrasekhar mass BH of non-primordial origin.
- Mass distribution of the progenitors, cosmic evolution of the binary merger rates are some simple yet novel probes to test the transmuted/primordial origin of low mass BHs.
- With remarkable advances in GW astronomy, we have already started to observe unusually low mass BHs; measurements of the binary merger rates, especially at high redshifts by the upcoming GW experiments will settle their origin, and test the particle DM hypothesis.

Stay tuned!

Really!!??



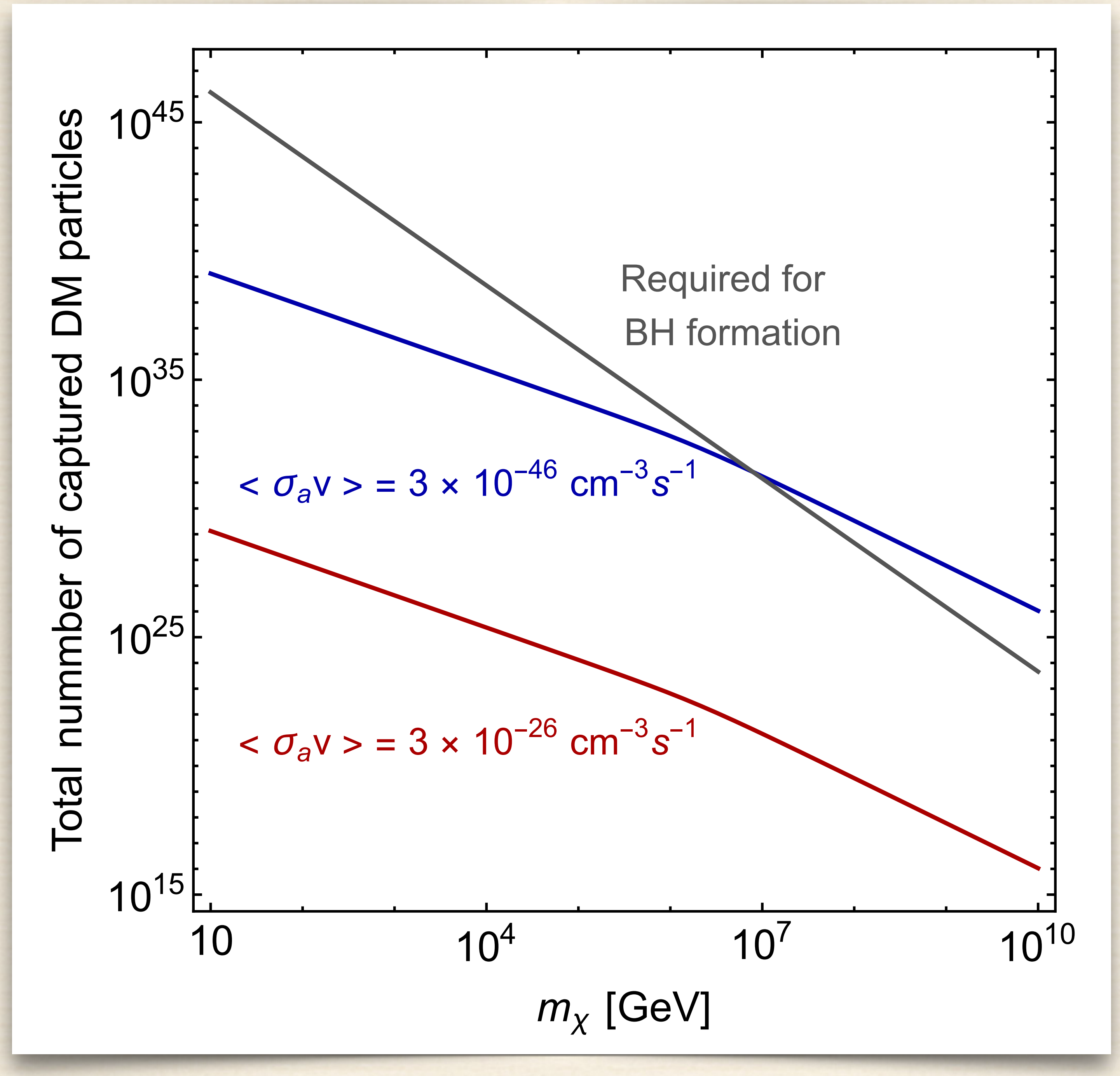
https://www.quantamagazine.org/black-holes-from-the-big-bang-could-be-the-dark-matter-20200923/

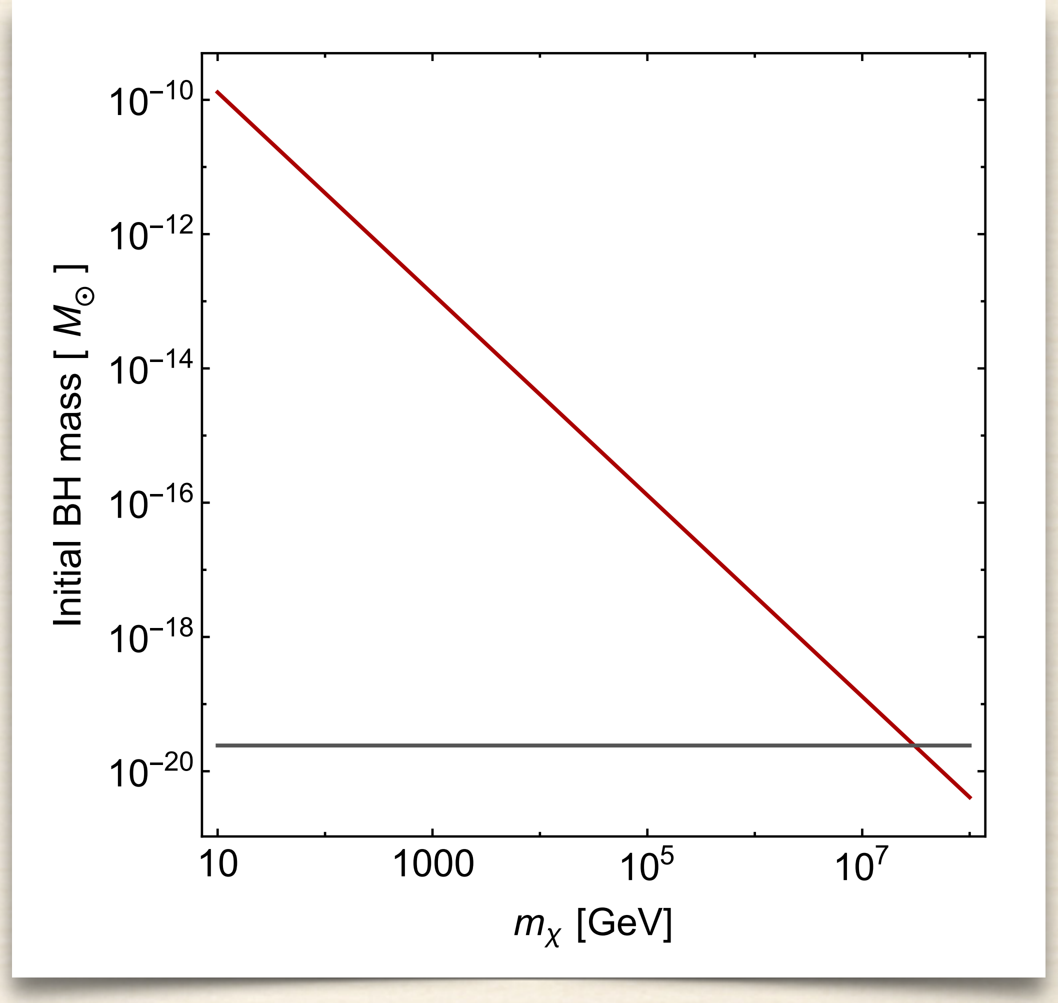
Thanks!

Questions & Comments: anupam.ray@theory.tifr.res.in

Extra Slides

Back Up Slides





Baumgarte et al 2101.12220,
Richards et al 2102.09574
Schnauck et al 2110.08285

$$\tau_{\mathrm{swallow,max}} = 10^6\,\mathrm{s}\left(\frac{10^{-10}\,\mathrm{M}_\odot}{\mathrm{M}_{\mathrm{init,BH}}}\right)$$

Merger rate of TBH binary

- Merger rate of TBH binaries depends on the NS population in the galaxies as well as evolution of DM density in the galaxies:
    - We assume NS binaries are uniformly distributed in r = (0.01, 0.1) kpc.
    - We assume fraction of NS binaries in i^{th} bin , f_i does not evolve with time, but the ambient DM density at i^{th} bin $\rho_{\text{ext},\,i}$ does evolve with time by maintaining its NFW universality (i.e. DM halos are NFW halos at all redshifts).

$$R_{\text{TBH}}(t) = \sum_i f_i \int_{t_*}^{t} dt_f \, \frac{dP_m}{dt}(t - t_f)\, \lambda \, \frac{d\rho_*}{dt}(t_f)\, \Theta\left(t - t_f - \tau_{\text{trans}}\left(m_\chi, \sigma_{\chi n}, \rho_{\text{ext},\,i}(t)\right)\right)$$

cosmic star formation rate density
Madau et al. 1403.0007

time required for transmutation

Increase in transmutation time → lower merger rate

- Binary NS merger rate traces the cosmic star formation rate and peaks at redshift of $\mathcal{O}(1)$:

$$R_{\rm NS}(t) = \int_{t_*}^{t} dt_f \, \frac{dP_m}{dt}(t - t_f)\, \lambda \, \frac{d\rho_*}{dt}(t_f)$$

Taylor et al. 1204.6739 (PRD)

- Merger rate of PBH binaries keeps rising with higher redshifts as PBH binaries can efficiently form in the early universe:

$$R_{\rm PBH}(t) \propto t^{-34/37}$$

Ali-Haimoud et al. 1709.06576 (PRD)

Chen et al. 1801.10327 (PRD)

Raidal et al. 1812.01930 (JCAP),...

Merger rate of TBH binaries is systematically less than merger rate of binary NSs, and distinctively different from merger rate of PBH binaries.