Mergers as a Probe of Particle Dark Matter

arXiv: 2009.01825 [astro-ph.HE]

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- Recent discoveries of unusually low mass black holes (BHs) pose fundamental questions about their origin.

(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

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Science 01 Nov 2019:
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BH mass: $3.3^{+2.8}_{-0.7}\,M_\odot$

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 ($< 1.4\ \mathrm{M}_\odot$) BH is usually thought as a smoking gun signature of its primordial origin.

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

Carr et al. 2002.12778, Green et al. 2007.10722...

- One of the earliest proposed DM candidates and recently received a renewed attention after the GW detection by LIGO collaboration.

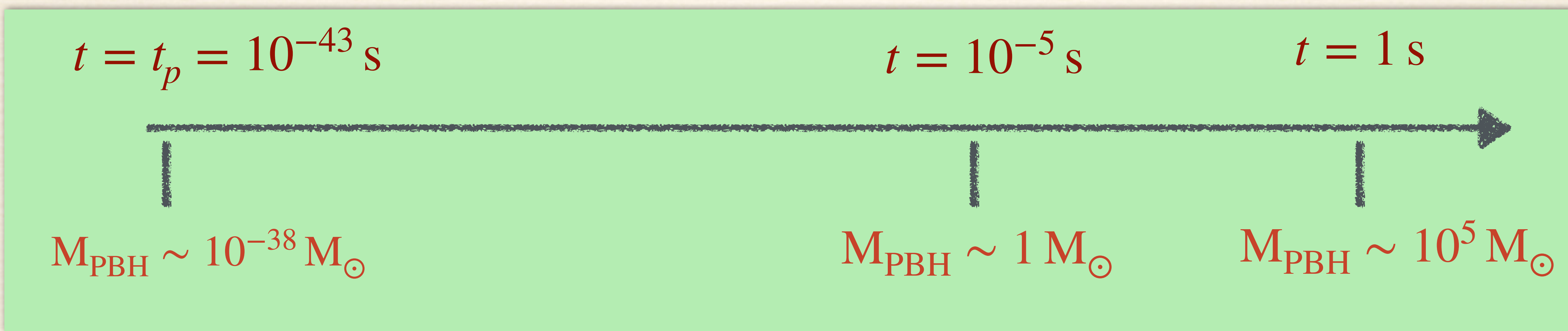
Zel'dovich (1966), Hawking (1971), Chapline (1975), Bird (2016)...

- Wide range of masses depending on their time of formation

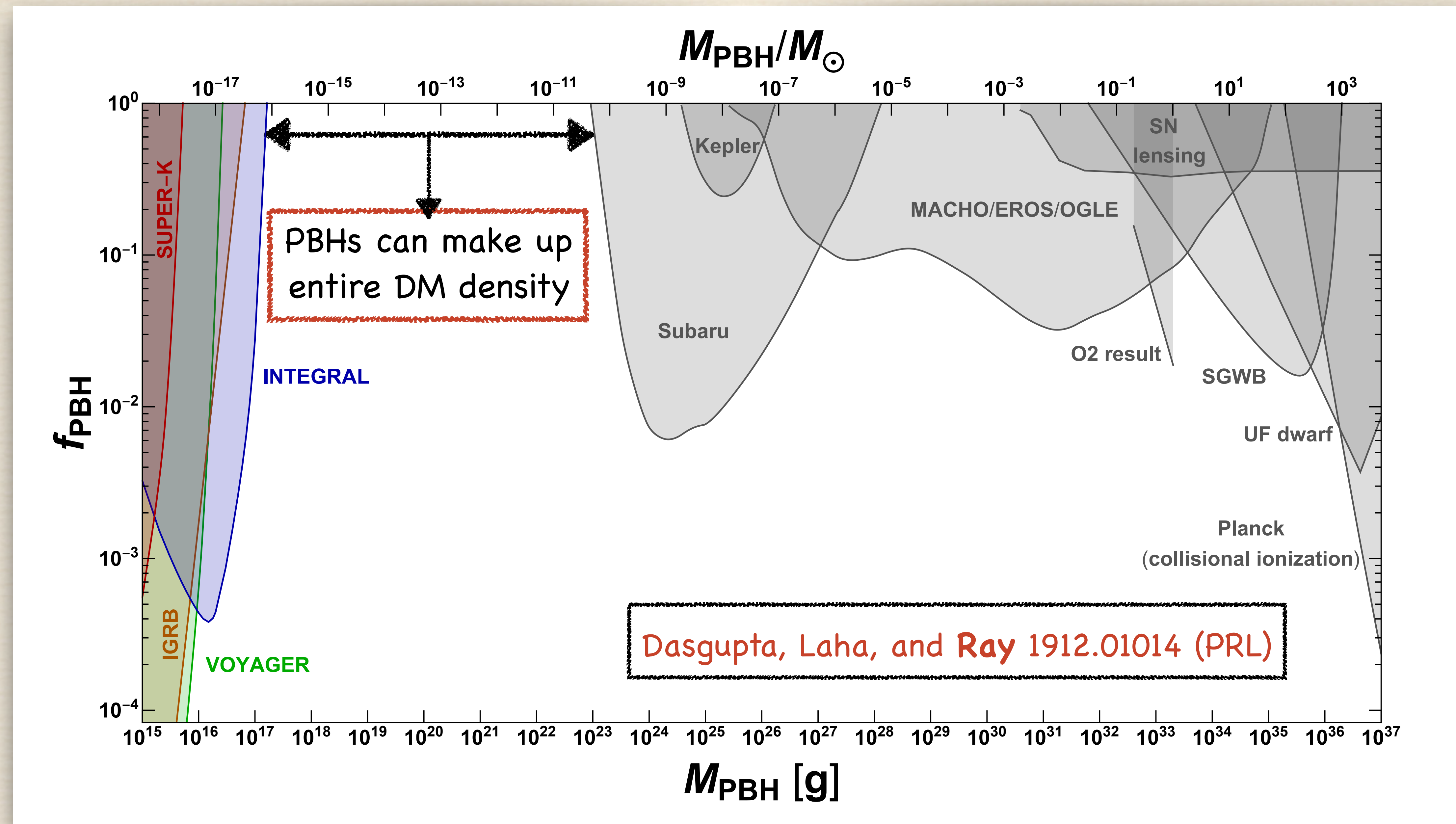
$$M_{PBH} \sim \frac{c^3\,t}{G}$$

time of formation

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



- PBHs that are formed before $\sim 10^{-5}$ s are naturally sub-Solar.



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 well-established formation mechanisms.

Carr et al. 2002.12778,...

Summary of the work

- We study a simple and elegant formation mechanism of low mass BHs which can be a viable alternative of fine-tuned PBHs.

- Dark matter (DM) with non-zero interaction strength with nuclei is sufficient to produce sub-Chandrasekhar mass non-primordial BHs.

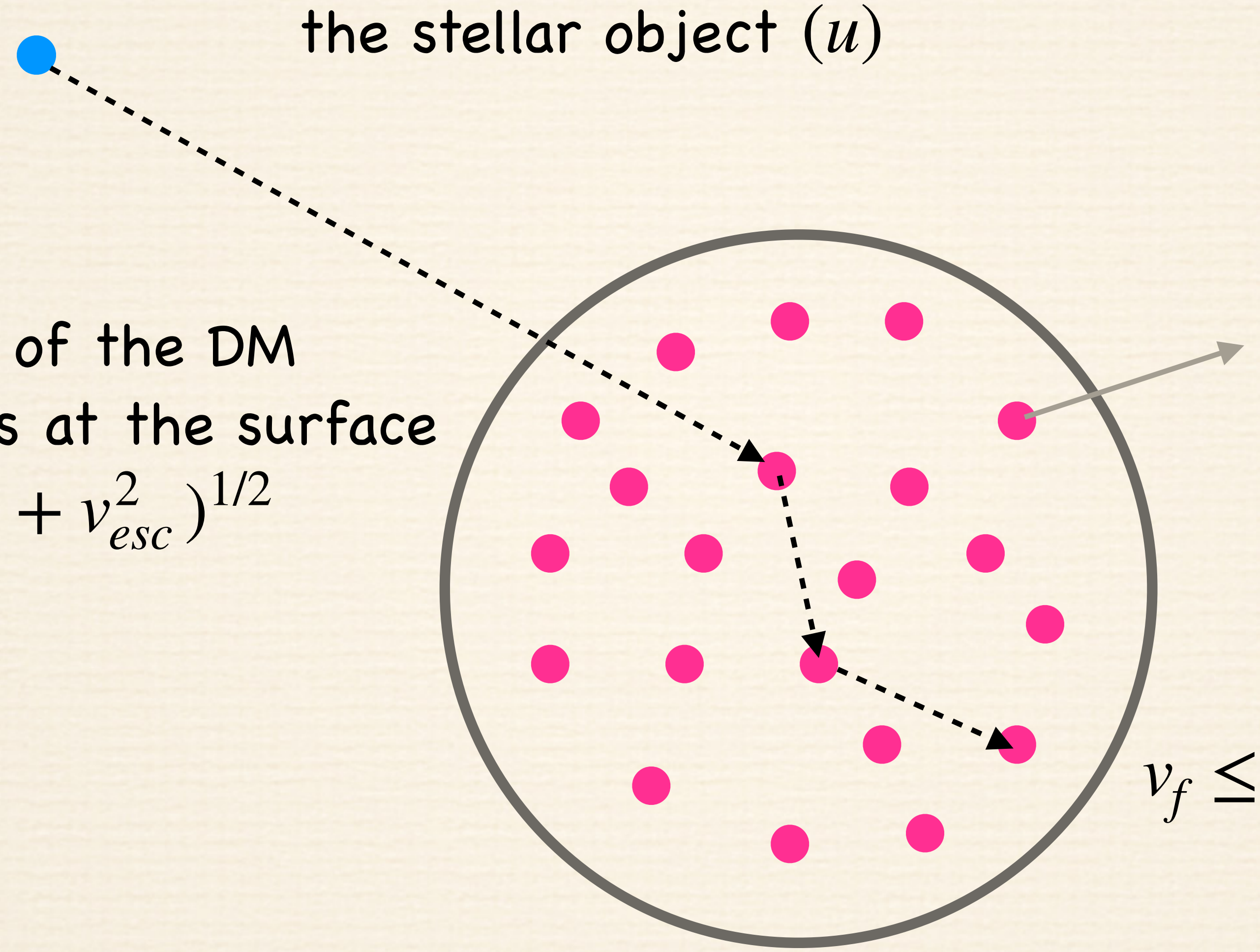
- Origin of a low mass BH (transmuted or primordial) can easily be tested via several simple yet powerful probes.

- 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.

Formation of low mass transmuted BHs

$\boxed{\text{Dark Core Collapse}}$

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

$$\underbrace{C}_{\text{Capture rate (assumes single scattering)}} = \underbrace{\frac{\rho_\chi}{m_\chi}\int \frac{f(u)du}{u}\left(u^2+v_{\rm esc}^2\right)}_{\text{Incoming DM flux}} \underbrace{N_n}_{\text{Number of targets}} \,\mathrm{Min}\left[\sigma_{\chi \rm n}, \underbrace{\sigma_{\chi \rm n}^{\rm sat}}_{\text{geometrical cross section}}\right] \mathrm{g}_1(\mathrm{u})$$

Capture rate (assumes single scattering)

Incoming DM flux

Number of targets

geometrical cross section

$\boxed{\text{Capture Probability } P\left(v_f \le v_{\rm esc}\right)}$

*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.

- Dark core collapse:

Goldman (1989), McDermott (1103.5472), Kouvaris (1104.0382),..., Dasgupta (2006.10773),...

Total number of captured DM particles $\geq$ Number of particles required for black hole formation

$$t_{\rm age}\, C\left(m_\phi, m_\chi, \sigma_{\chi \rm n}\right)$$

age of the stellar object

$$\mathrm{Max}\left[N_\chi^{\rm self}, N_\chi^{\rm cha}\right]$$

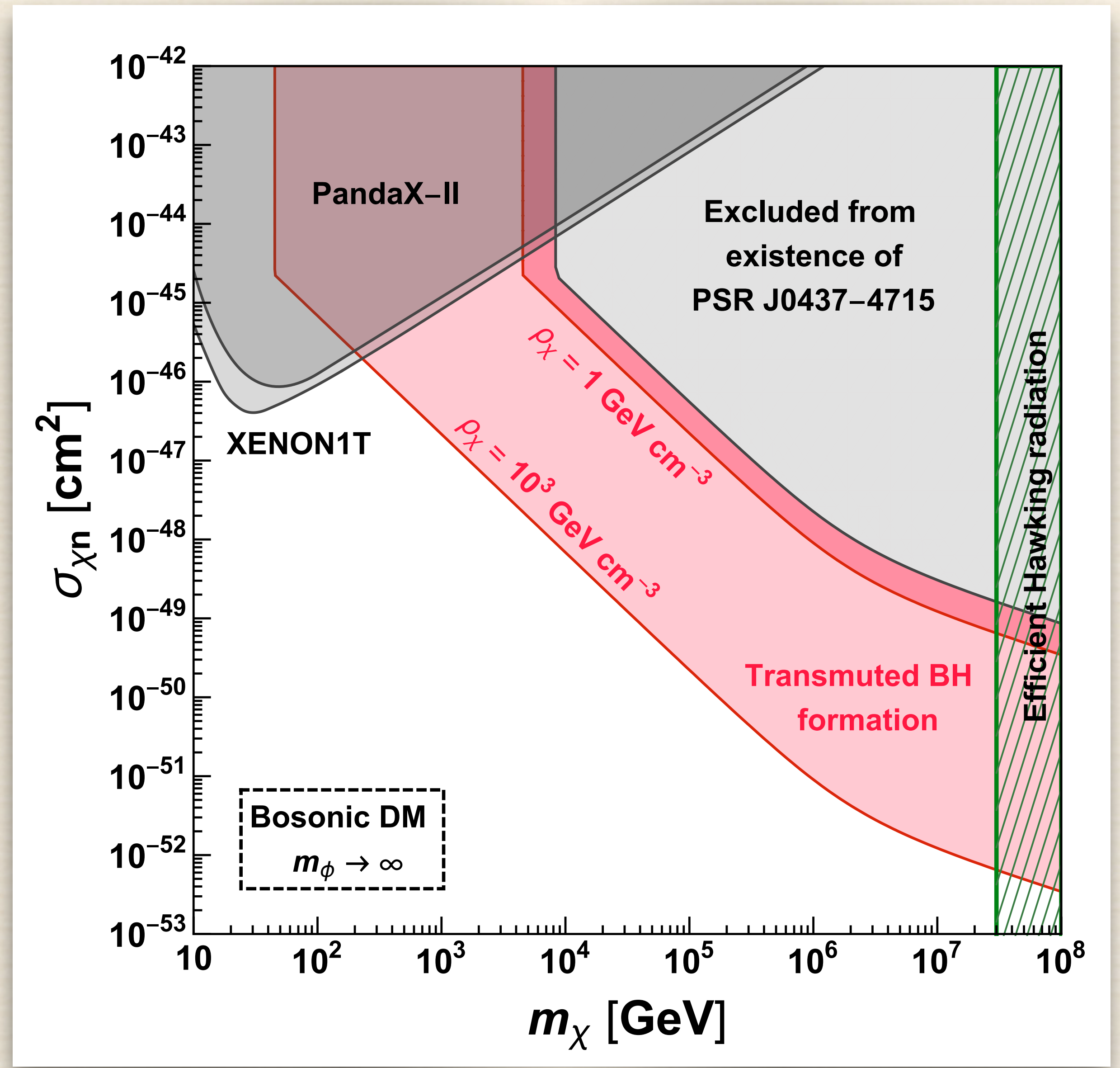
required number of DM particles for self-gravitating collapse

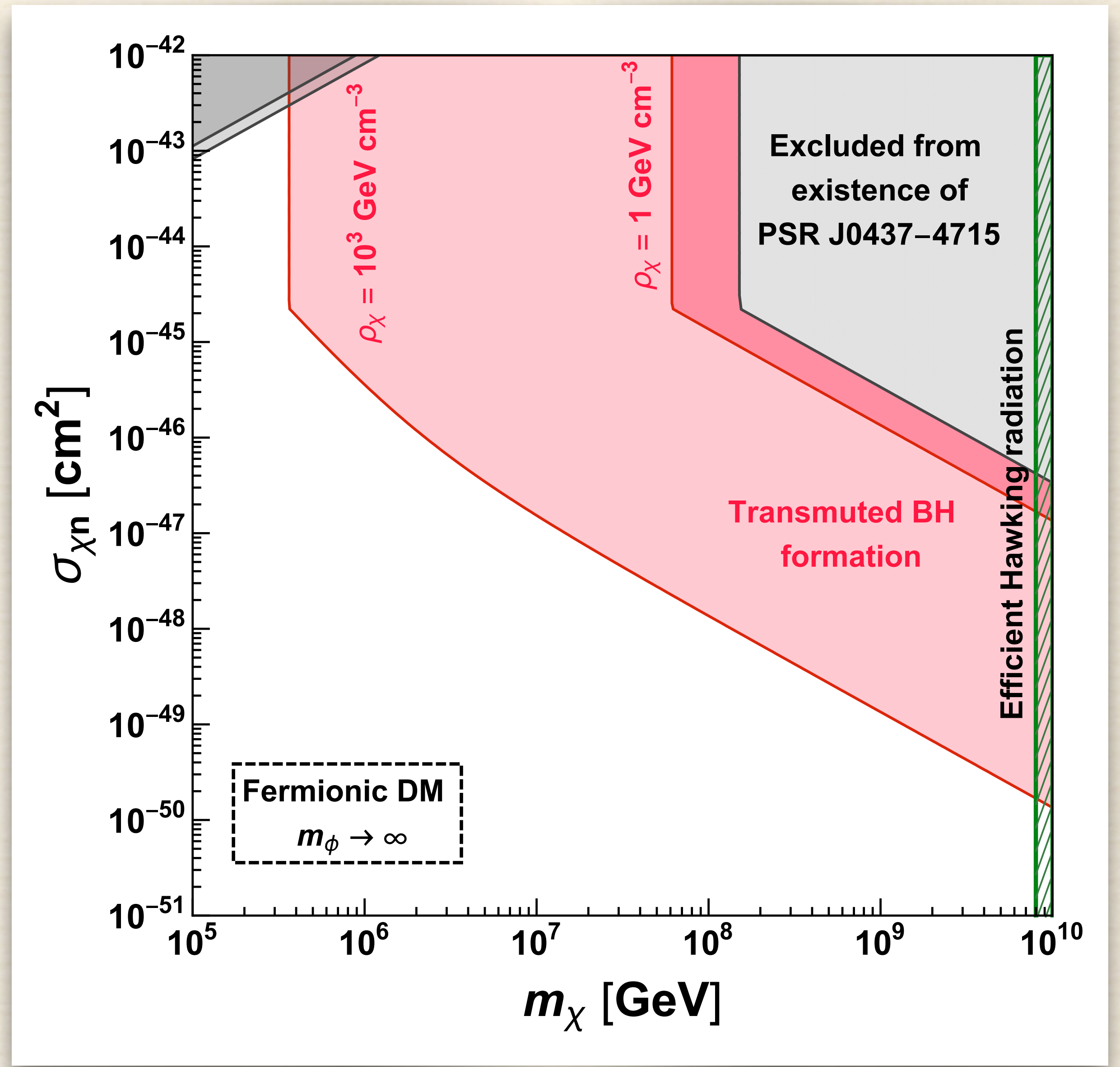
Chandrasekhar limit

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

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

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.

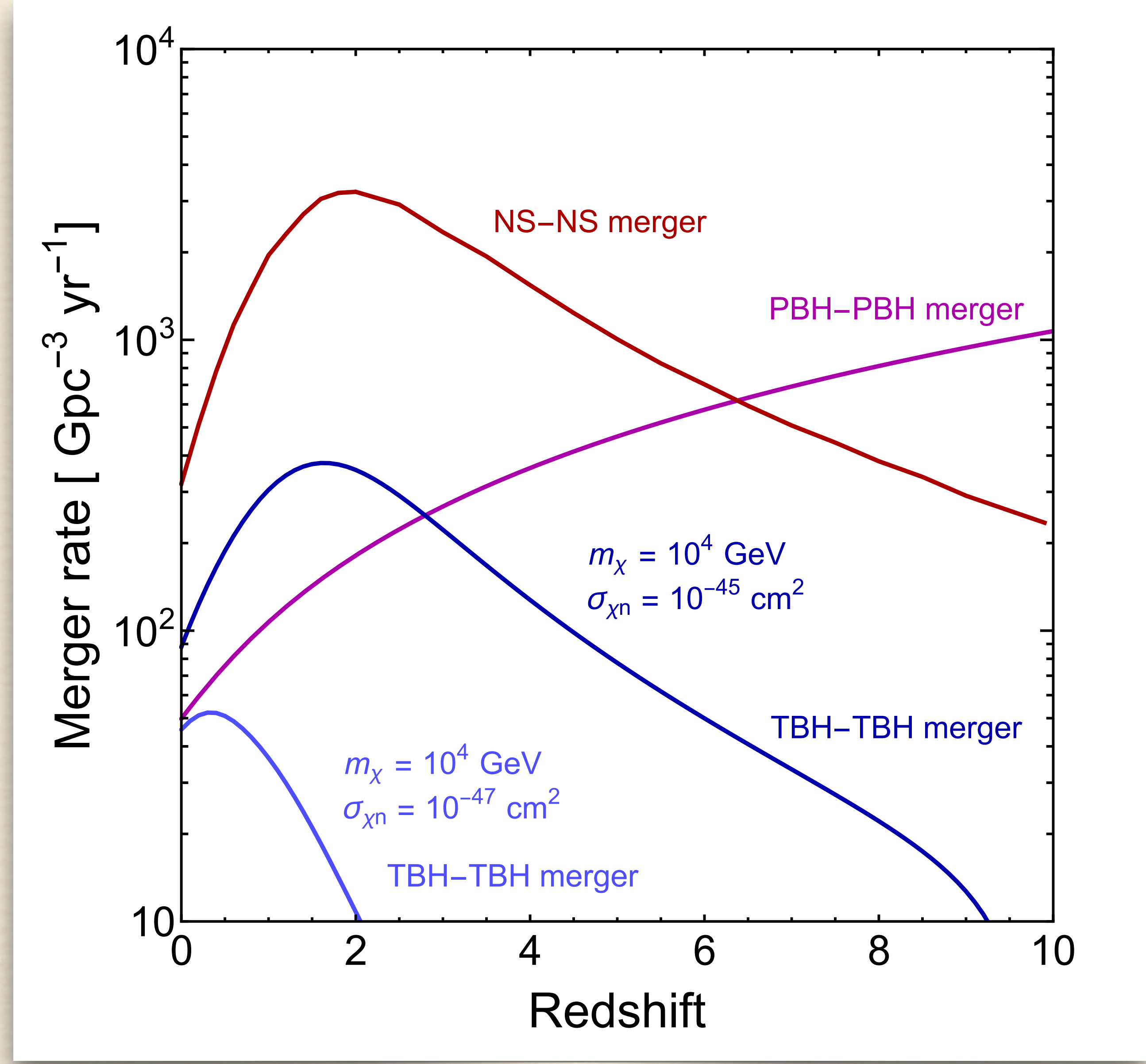
Tests for the origin of low mass BHs

(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

- Cosmic evolution of the binary merger rates can be used as a probe to determine the origin of low mass BHs/test the particle DM hypothesis.



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)

- Expected detection rate of TBH binaries:

Taylor et al. 1204.6739 (PRD)

$$N_D = \int_{z=0}^{\infty} dz \frac{4\pi D_c^2(z)}{(1+z)H(z)} R_{\mathrm{TBH}}(z) \times C_\theta \left[\frac{\rho_0}{8} \frac{D_L(z)}{r_0} \left(\frac{1.2 M_\odot}{(1+z)\mathcal{M}_c} \right)^{5/6} \right]$$

M_{NS} $[M_\odot]$	m_χ [GeV]	$\sigma_{\chi n}$ [cm^2]	aLIGO [yr^{-1}]	ET [yr^{-1}]
1.0	10^4	10^{-47}	0.2; 0; 0.2	672; 3; 675
1.0	10^4	10^{-45}	0.3; 0; 0.3	2982; 32; 3014
1.3	10^4	10^{-47}	0.4; 0; 0.4	1451; 84; 1535
1.3	10^4	10^{-45}	0.8; 0; 0.8	5916; 880; 6796

Possible detection rate of TBH binaries for aLIGO and ET. The three numbers in the last two columns imply the detection rate for low redshift ($z \leq 1$); high redshift ($z > 1$); and total respectively.

Transmuted BH mergers can also be searched in the LIGO/VIRGO data, and non-detection pose a stringent exclusion on the DM parameters.

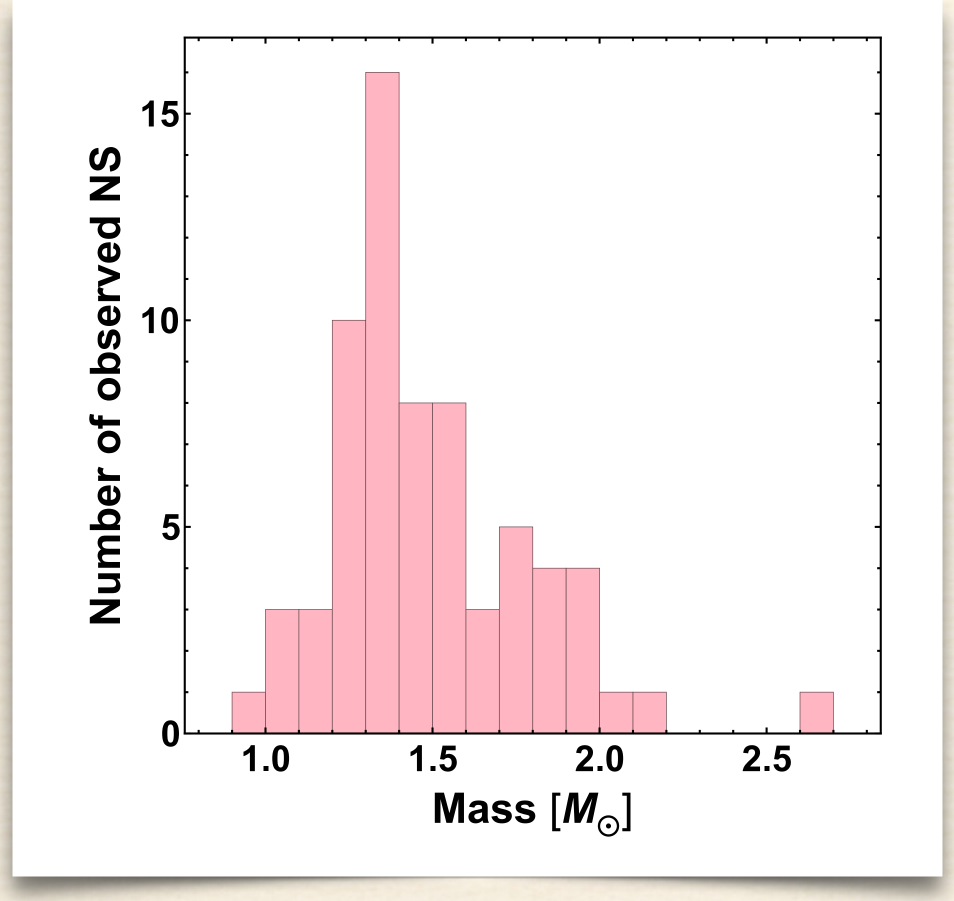
Dasgupta, Laha, and **Ray** (in prep.)

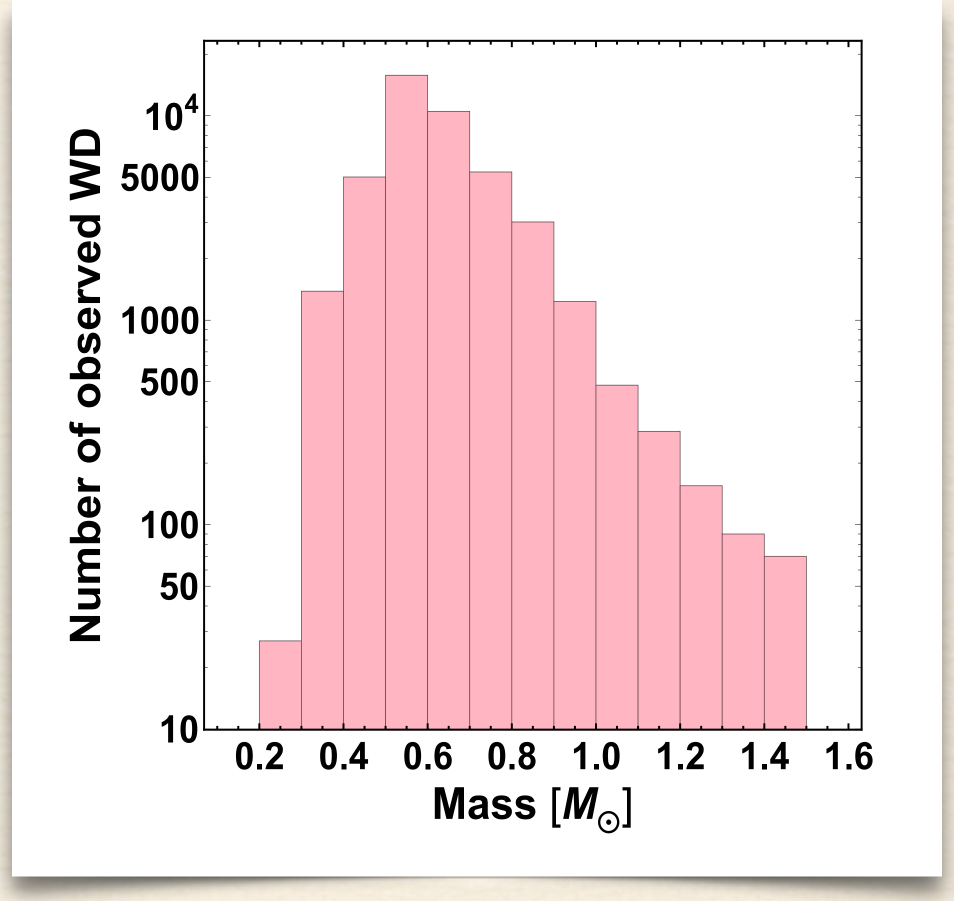
Mass distribution as a probe of low mass BHs

- 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.

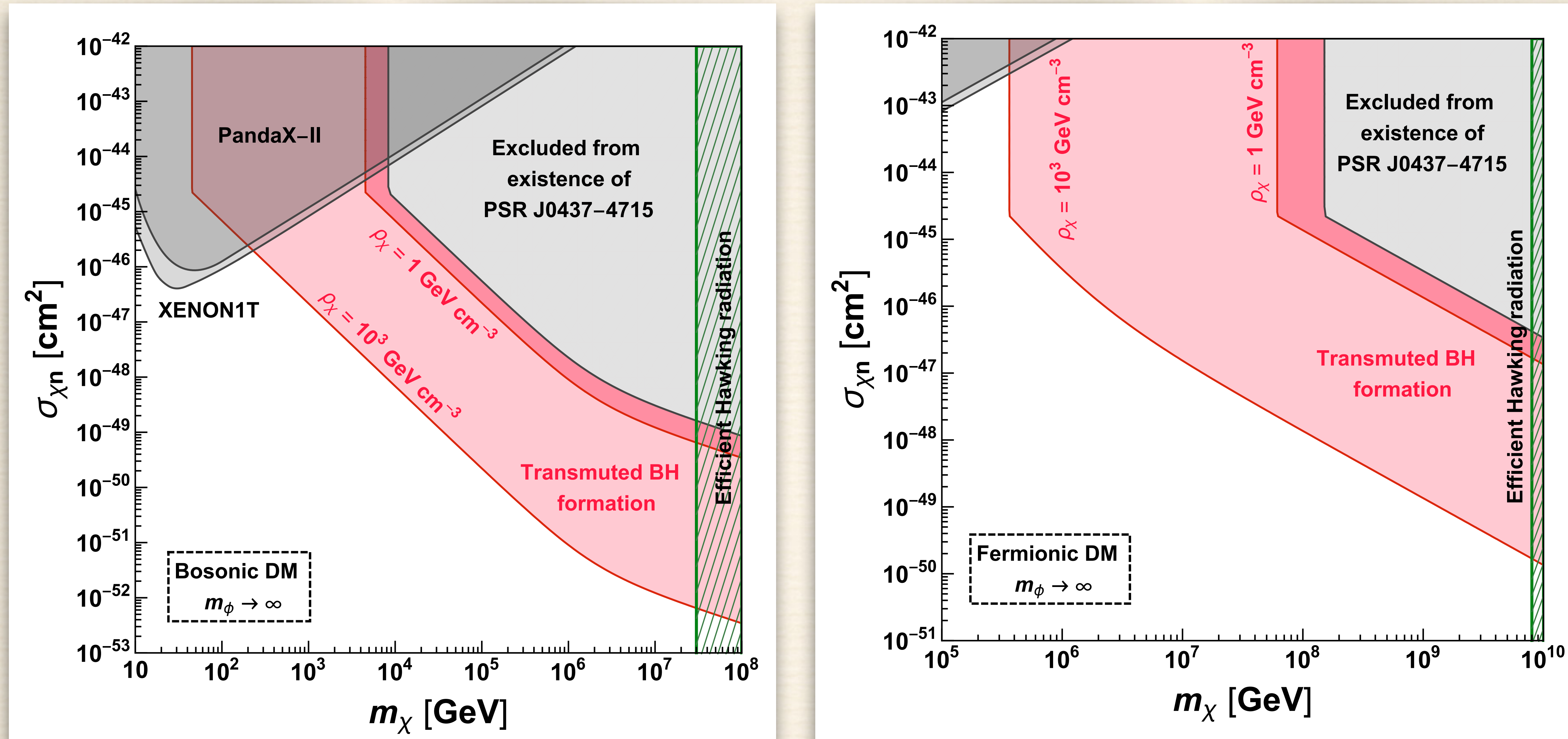
See also Takhistov et al. 2008.12780 (PRL)





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

Ambient DM density as a probe of low mass BHs



Parameter space for transmuting a 1.3 $M_\odot$ neutron star to a comparable mass ($\lesssim$ 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.

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

- Detection of a sub-Chandrasekhar mass BH in low (high) DM dense regions favours its primordial (stellar) origin.

improved sky localization of the GW events with multi-detector networks, GW lensing

- Observation of a cold and old NS in DM dense environments by the imminent radio telescopes (SKA, FAST) favours the primordial hypothesis.

exclusion limits from the existence of compact objects will strengthen

- Co-existence of a sub-Chandrasekhar mass BH and a NS of comparable age can be a strong evidence of its primordial origin.

parameter space required for transmutation is disfavoured by the existence of companion NS

- Disappearance of an isolated NS/WD can also be a smoking gun of its transmuted stellar origin.

continuous monitoring of NS/WD can test the origin

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

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 $\rho_{\mathrm{ext},\,i}$ does evolve with time by maintaining its NFW universality (i.e. DM halos are NFW halos at all redshifts).

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

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.