Low Mass Black Holes from Dark Core Collapse

2009.01825

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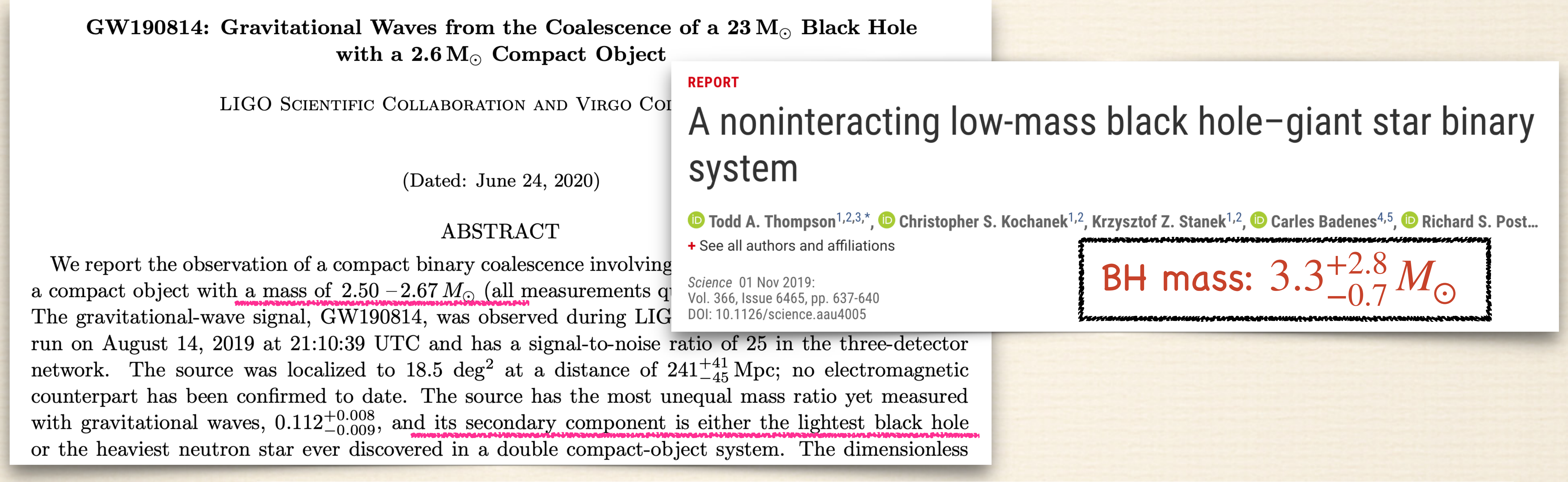
- Recent discoveries of unusually low mass black holes (BHs) pose fundamental questions about their origin.

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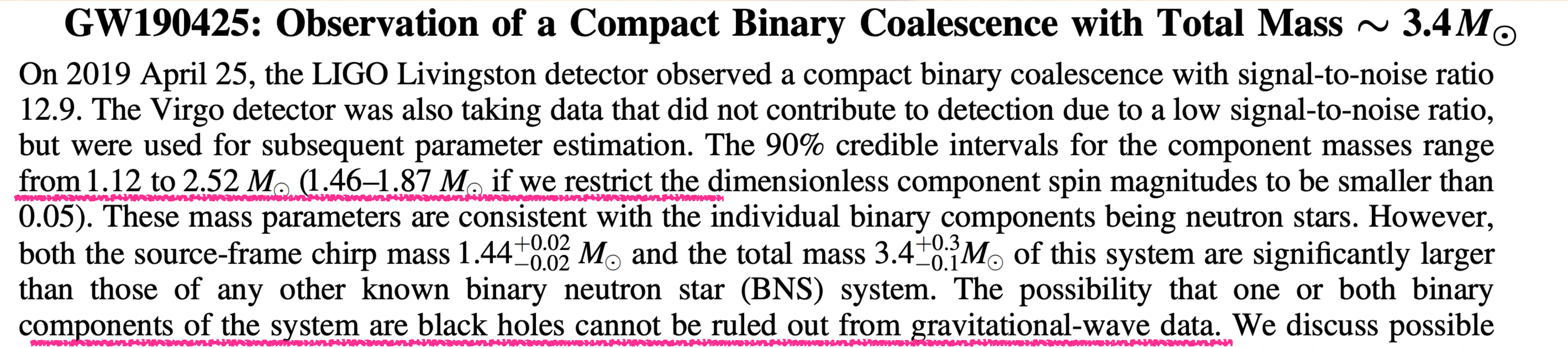
BH mass: $3.3^{+2.8}_{-0.7}\,M_\odot$



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 $M_\odot$) 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.

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.

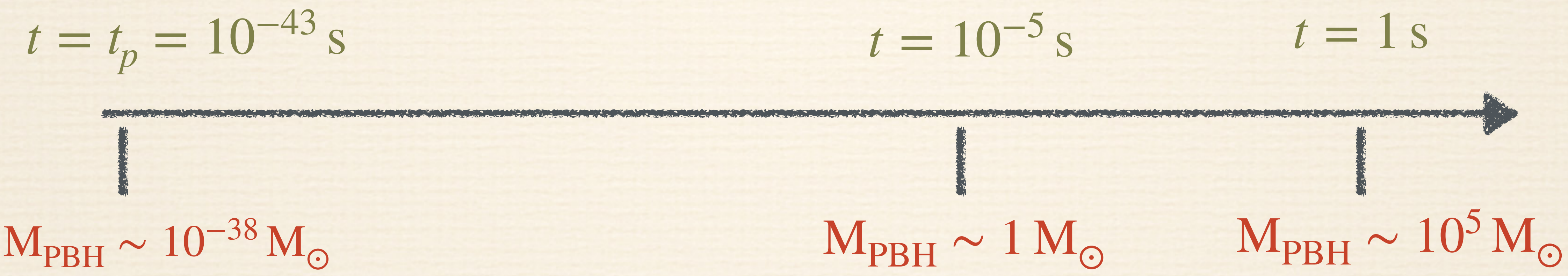
Zel'dovich (1966), Hawking (1971), Chapline (1975), Bird (2016)…

- Wide range of masses depending on the time of formation.

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

time of formation

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



$t = t_p = 10^{-43}\,\mathrm{s}$

$M_{\mathrm{PBH}} \sim 10^{-38}\,M_\odot$

$t = 10^{-5}\,\mathrm{s}$

$M_{\mathrm{PBH}} \sim 1\,M_\odot$

$t = 1\,\mathrm{s}$

$M_{\mathrm{PBH}} \sim 10^{5}\,M_\odot$

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

- Initial abundance of PBHs from gravitational collapse is fine-tuned

threshold for collapse

$$\beta\left(M_{\mathrm{PBH}}\right) \sim \exp\left(\frac{-\delta_c^2}{2\,\sigma^2}\right)$$

Carr et. al. (1975),...

typical size of the
density fluctuation

- PBHs do not have any well-established formation mechanisms. A plethora of formation channels exist including

bubble collisions, domain wall collapse, scalar condensate fragmentation, and many more

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 a sub-Chandrasekhar mass non-primordial BH.

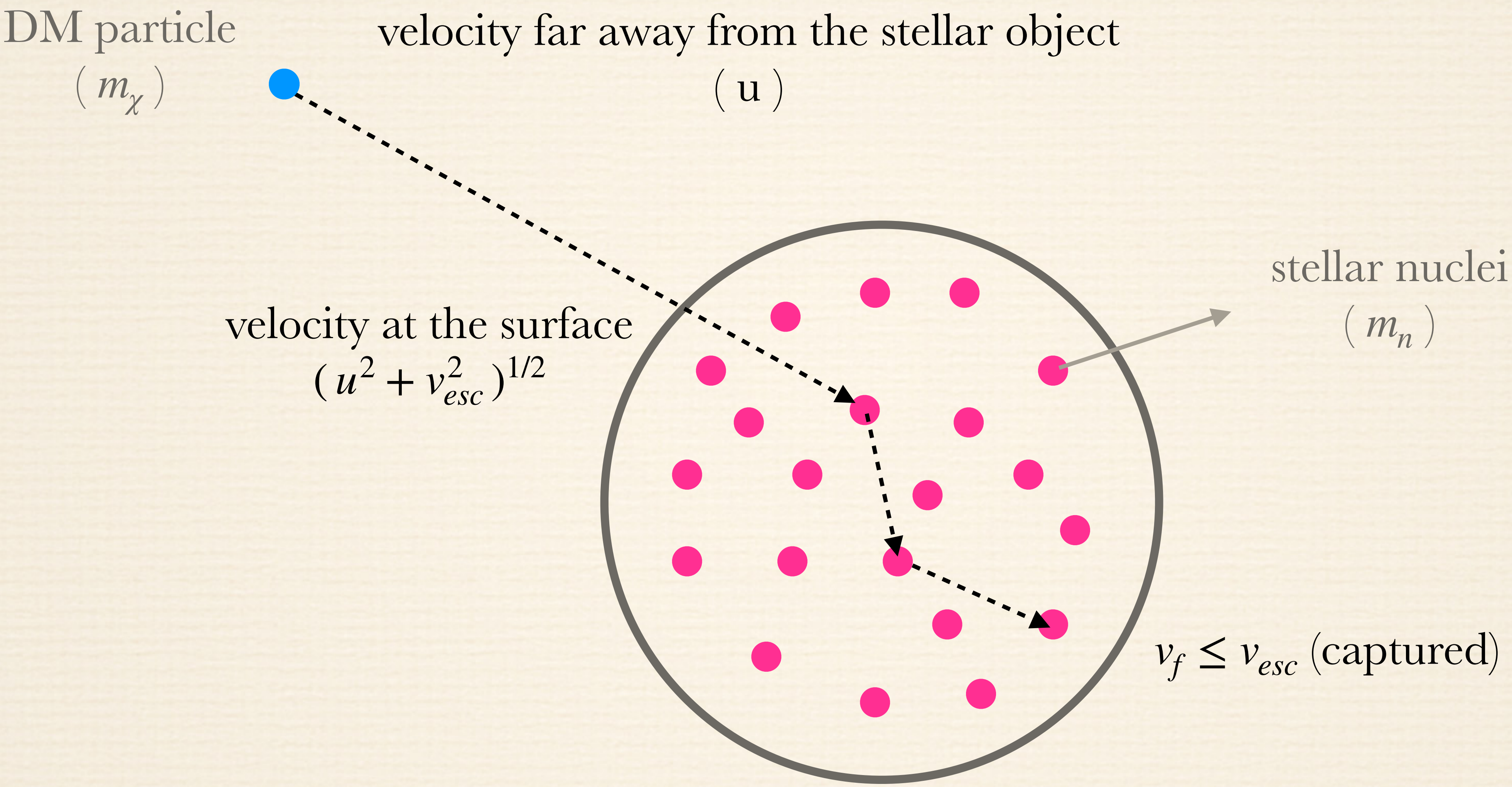
- Origin of a low mass BH (transmuted or primordial) can easily be tested via several simple yet powerful probes.

- Cosmic evolution of the binary merger rate can be used as a probe of the transmuted origin of low mass black holes.

Formation of low mass transmuted BHs

Dark Core Collapse

DM accretion in stellar objects



DM particle

(m_χ)

velocity far away from the stellar object

(u)

velocity at the surface

$(u^2 + v_{esc}^2)^{1/2}$

stellar nuclei

(m_n)

$v_f \leq v_{esc}$ (captured)

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

- Baryonic capture rate of incoming DM particles:

Scattering cross section

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

Number of targets

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

geometrical saturation cross section

Capture probability

$$P\left(v_f \le v_{\rm esc}\right)$$

***capture rate (C) assumes single scattering. For a detailed treatment of multiple scattering,

Dasgupta, Gupta, and **Ray** 1906.04204 (JCAP)

- Capture probability is computed in the contact interaction approximation over the decades.

$$g_1(u) = \left(1 - \frac{1}{\beta}\frac{u^2}{u^2 + v_{esc}^2}\right)\Theta\left(v_{esc}\sqrt{\frac{\beta}{1-\beta}} - u\right)$$

Gould (1987),...

$$\boxed{\beta = \frac{4\, m_\chi\, m_n}{(m_\chi + m_n)^2}}$$

prominent impact on the astrophysical exclusions obtained over the decades

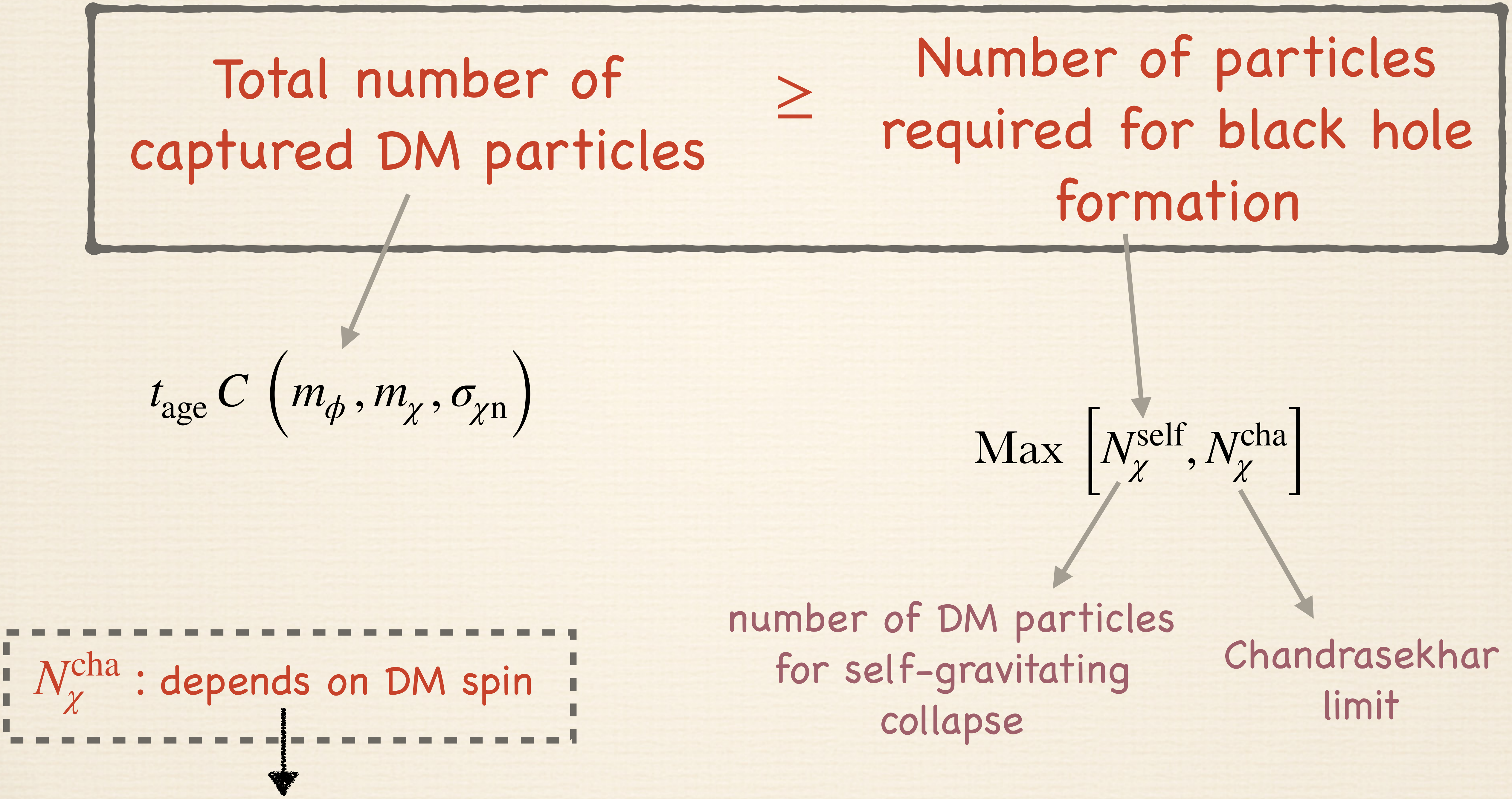
- Generalized capture probability to account for interactions via arbitrary mediator masses

$$g_1(u) = \frac{m_\phi^2\left(1 - \frac{1}{\beta}\frac{u^2}{u^2 + v_{esc}^2}\right)}{\left(m_\phi^2 + m_\chi m_n \frac{u^2}{c^2}\right)}\Theta\left(v_{esc}\sqrt{\frac{\beta}{1-\beta}} - u\right)$$

mass of the mediator

Dasgupta, Gupta, and **Ray** 2006.10773 (JCAP)

- Dark core collapse:



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

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

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

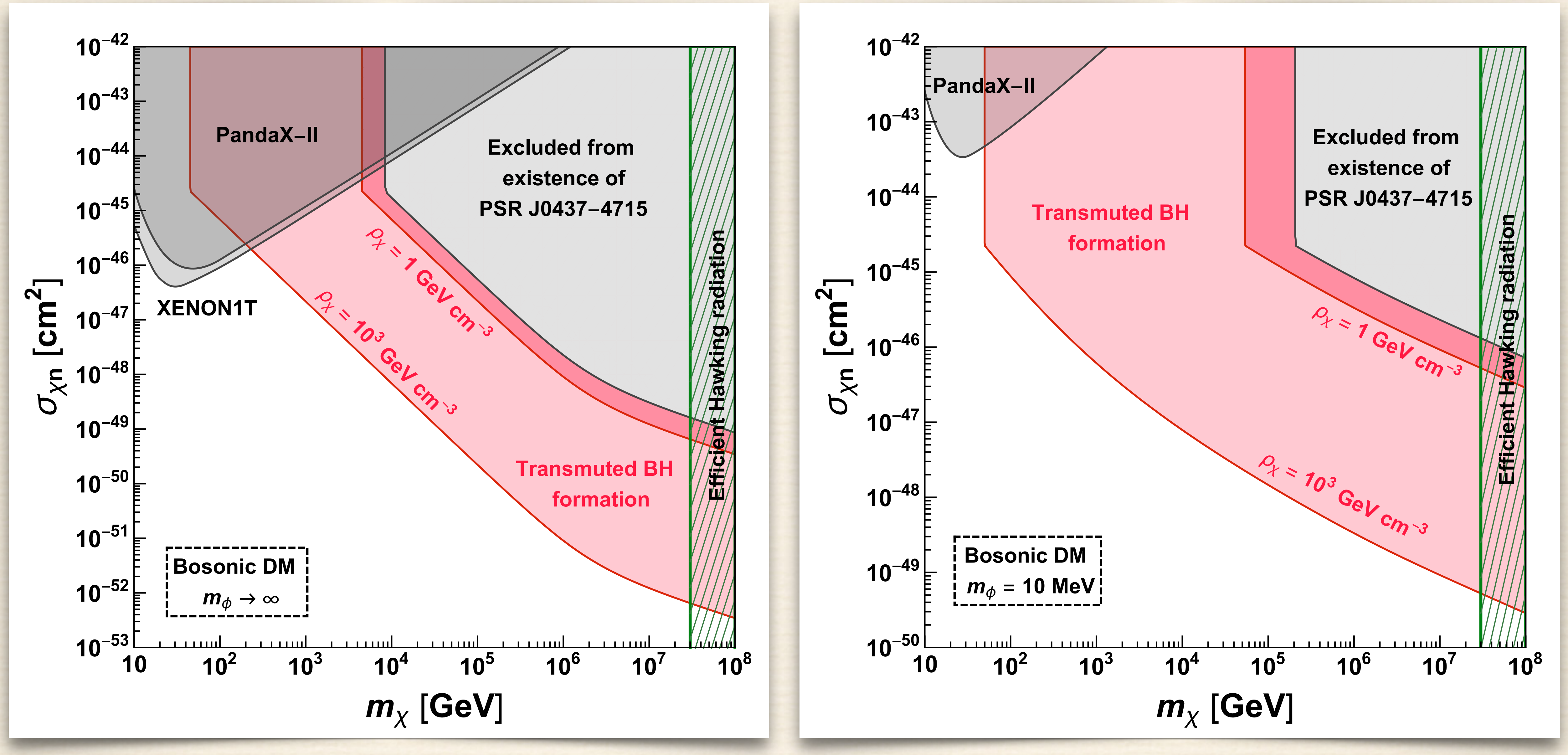
number of DM particles for self-gravitating collapse

Chandrasekhar limit

$N_\chi^{\rm cha}$: depends on DM spin

parameter space for Dark core collapse is different for bosonic and fermionic DM

Dasgupta, Laha, and **Ray** 2009.01825



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 DM. Contact interaction is assumed in the left panel, 10 MeV mediator is assumed in the right panel.

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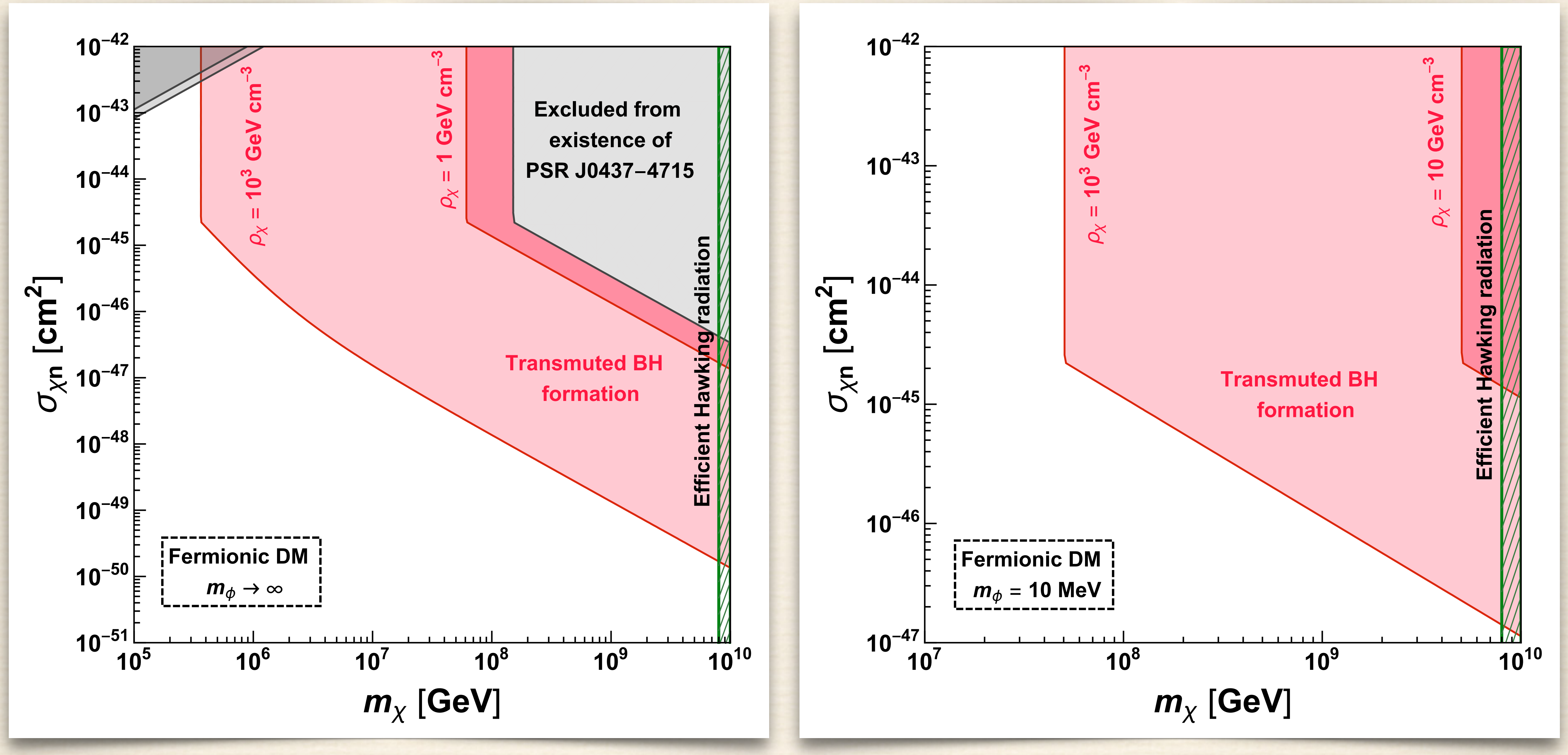

Parameter space for transmuting a 1.3 $M_\odot$ neutron star to a comparable mass ($\lesssim$ 1.3 $M_\odot$) BH for non-annihilating fermionic DM. Contact interaction is assumed in the left panel, 10 MeV mediator is assumed in the right panel.

Other non-primordial scenarios

- Conversion of a compact object (NS/WD) to a comparable mass BH due to a tiny PBH transit.

Capela et al. 1301.4984 (PRD), Takhistov et. al. 1707.05849 (PLB)

PBH transmit rate is over estimated by multiple orders of magnitude, impossible to convert a compact object residing in Milky Way like galaxy

Montero-Camacho et. al. 1906.05950 (JCAP),

Genolini et. al. 2006.16975

- Dark core collapse due to accumulation of self-interacting, non-annihilating fermionic DM (Kouvaris et. al. 1804.06740 (PRL)), exotic cooling channels of sufficiently complex dark sector (Shandera et. al. 1802.08206 (PRL)).

appeal to fairly baroque DM models, not generic

Tests for the origin of low mass BHs

(Transmuted or Primordial)

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

- 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 be a smoking gun of its transmuted stellar origin.

continuous monitoring of NS/WD can test the origin

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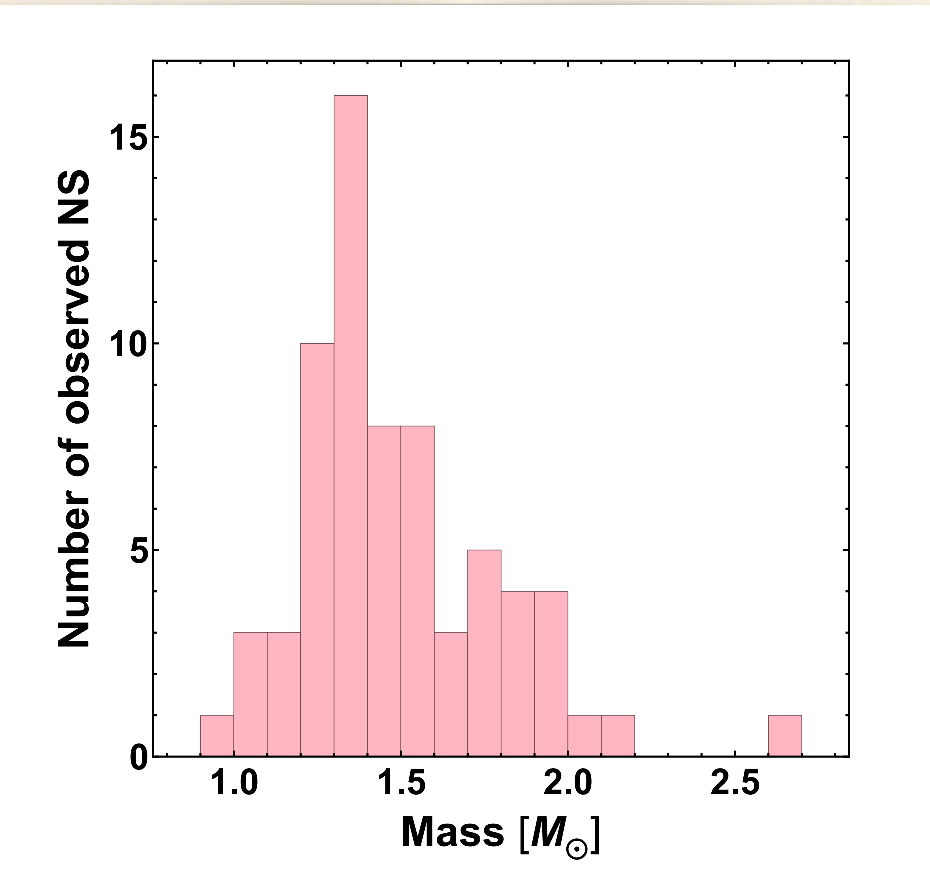
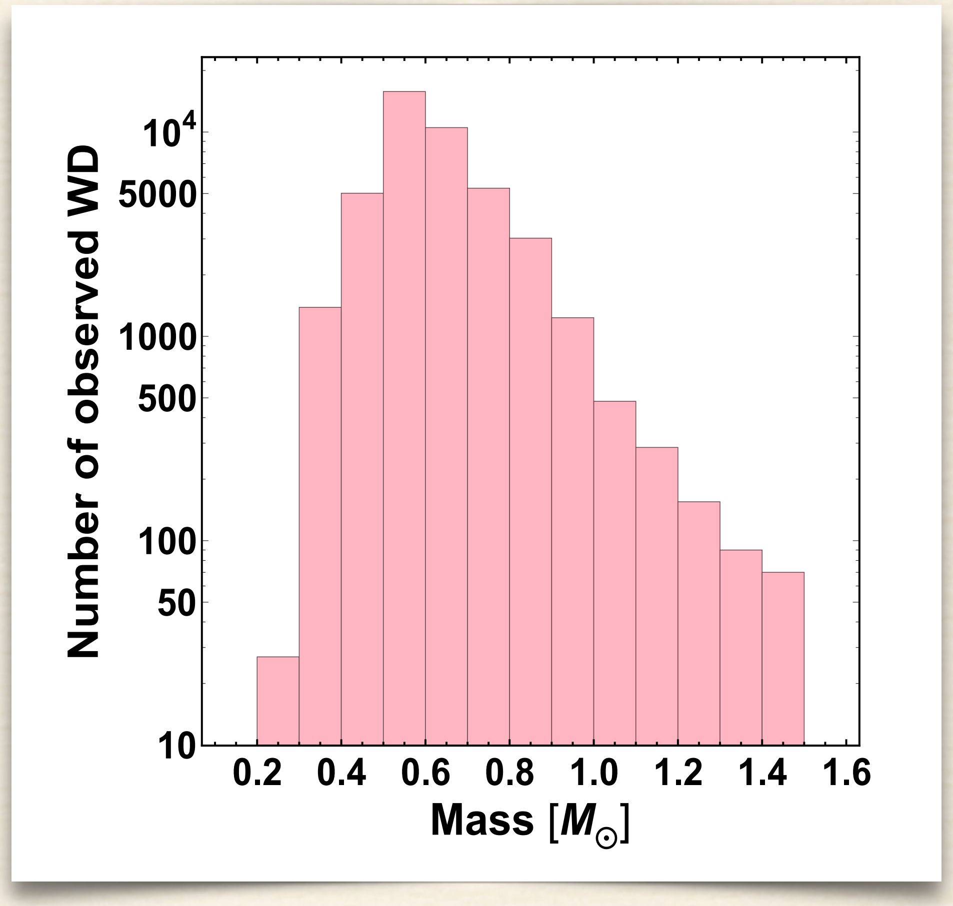
- Low mass BH from dark core collapse tracks the mass distribution of their progenitors (NS/WD).





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

See also Fuller et al. 2008.12780 (PRL)

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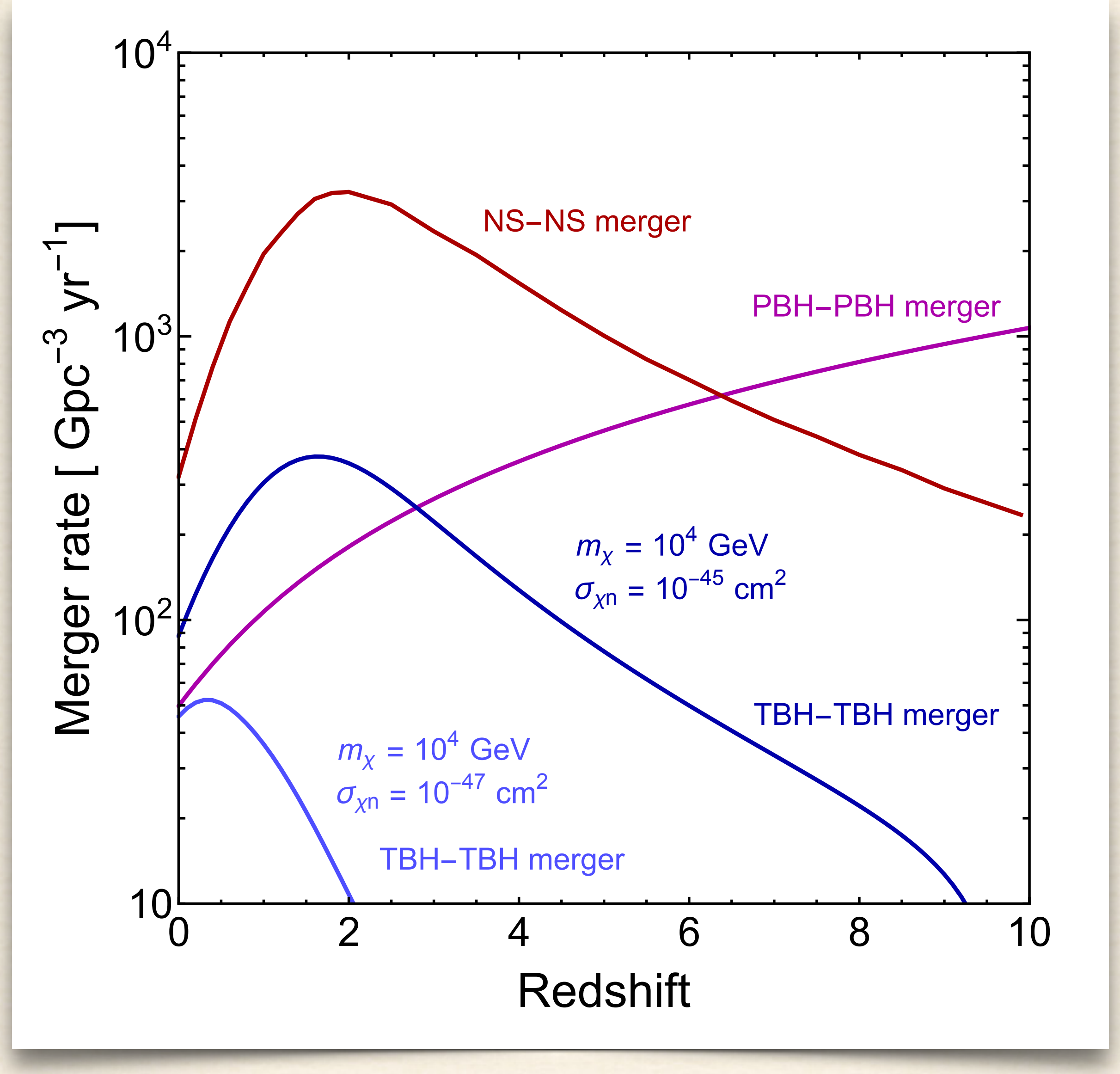
- Cosmic evolution of the binary merger rates can be used to determine the origin of sub-Chandrasekhar mass BHs.



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).

Cosmic evolution of the binary merger rates

- 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

Cosmic evolution of the binary merger rates

- 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)

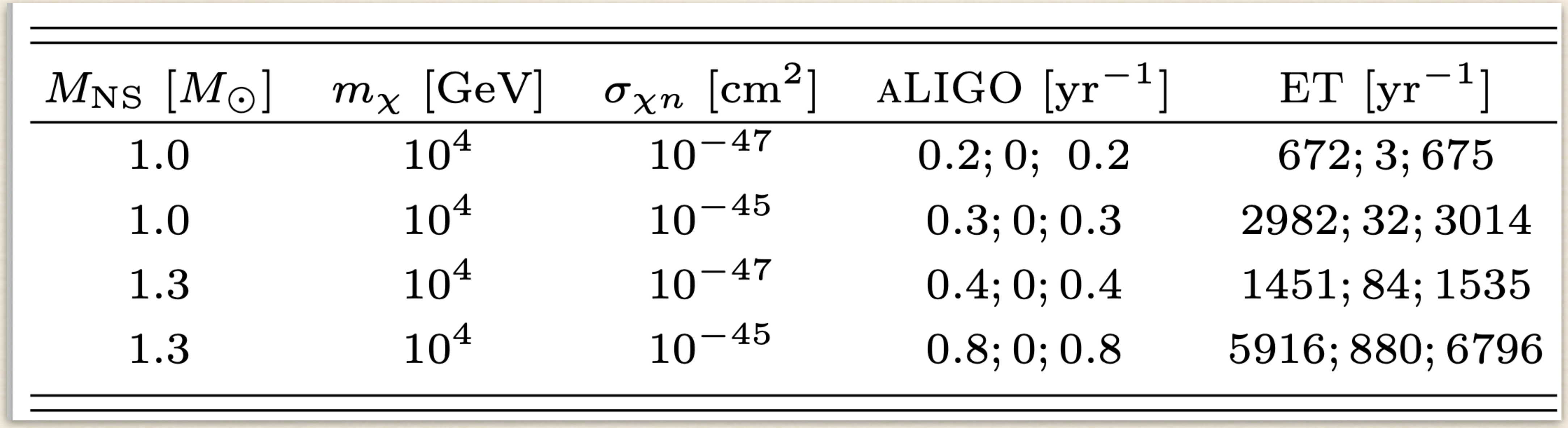
Raidal et al. 1812.01930 (JCAP),....

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

- 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.

aLIGO is already sensitive to the DM parameters (m_χ = 10 TeV, $\sigma_{\chi n} = 10^{-45}\,\mathrm{cm}^2$) that are not ruled out by any present data!

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, a vanilla DM model, is sufficient for dark core collapse, can naturally produce a viable alternative of fine-tuned PBHs.

- Ambient DM density around the compact objects, mass distribution of the compact objects, and cosmic evolution of the binary merger rate 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; enormous number of GW events with multi-detector networks, and measurement of binary merger rates at high redshifts by upcoming GW experiments will settle their origin. Stay tuned!

Stars can't make black holes this small. If astronomers find one here, it's likely it was made in the Big Bang.

Really!!??

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

Thanks!