Low-mass black holes from dark core collapse

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Thanks to my collaborators: Anupam Ray and Basudeb Dasgupta

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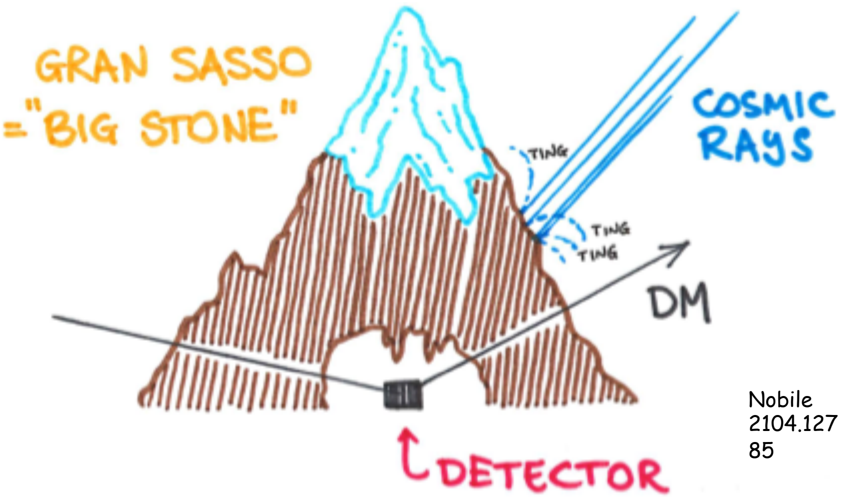
Dark matter direct detection

Direct detection



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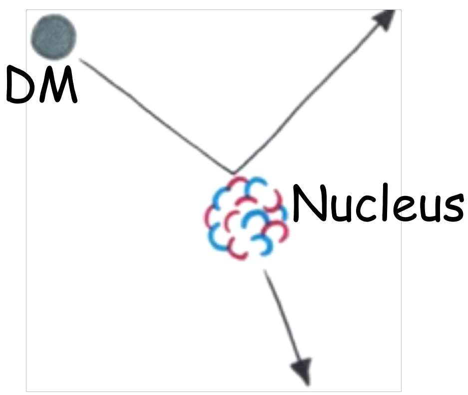
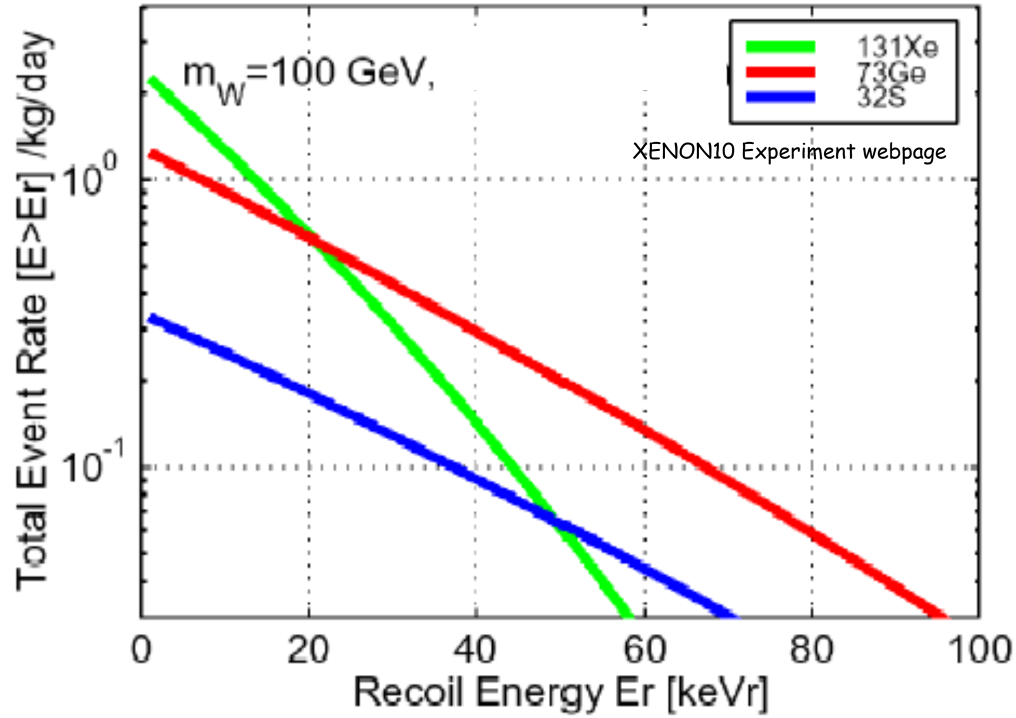
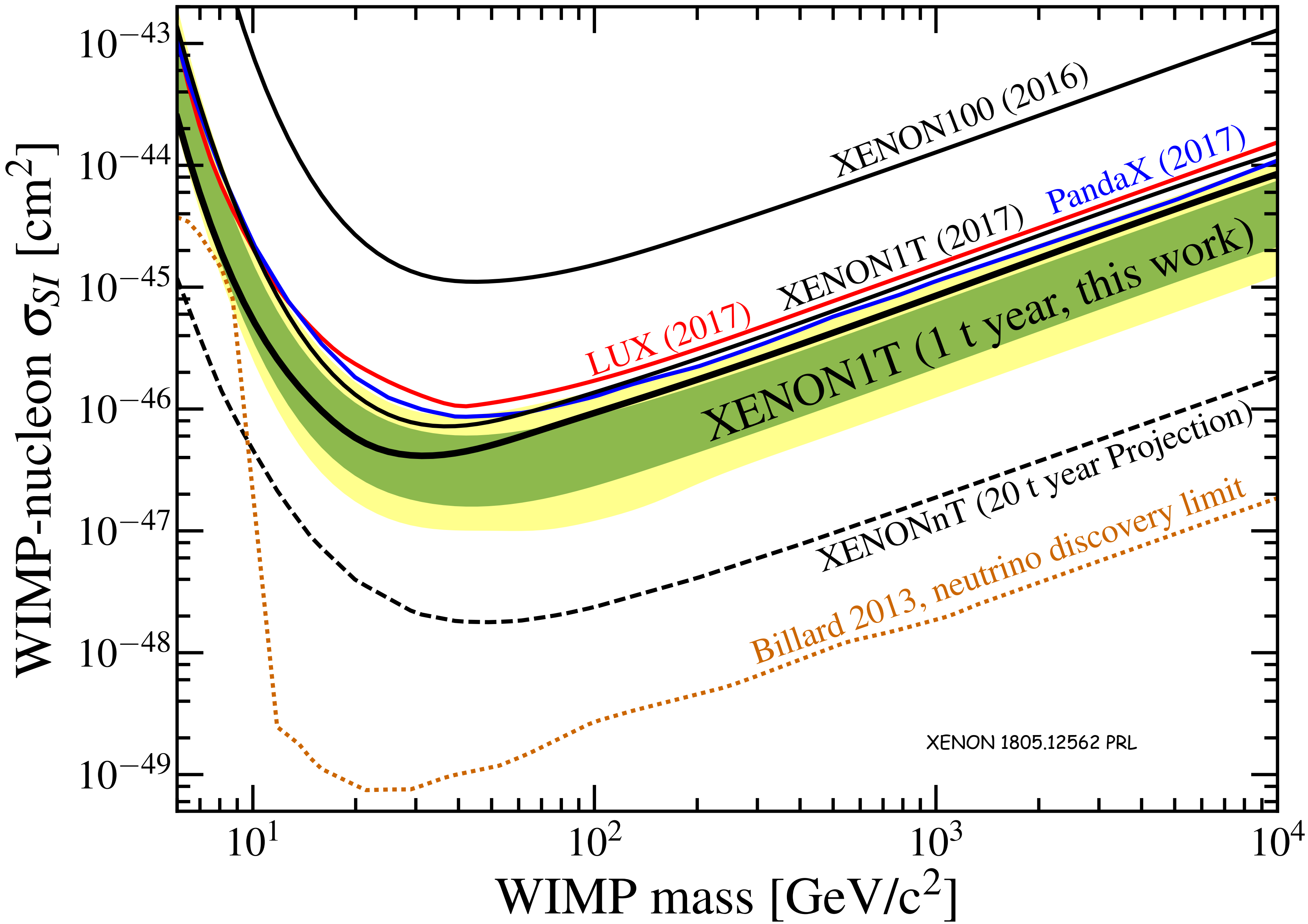




$$\mathrm{DM} + \mathrm{SM} \to \mathrm{DM} + \mathrm{SM}$$

- Search for interaction of dark matter particles with Standard Model particles
- Directional detection experiments can detect the incoming direction of the dark matter particle

Direct detection limits



Direct detection limits

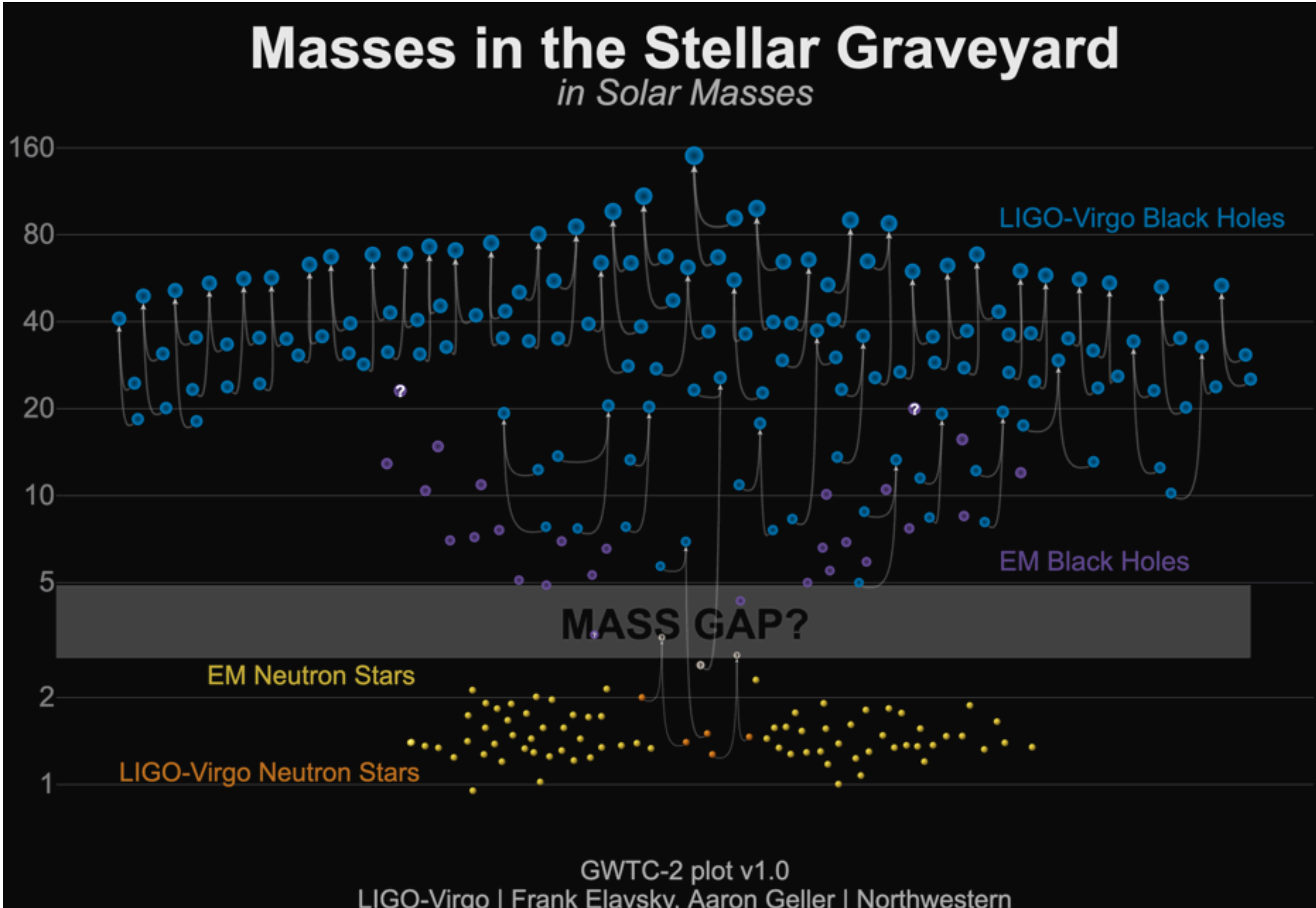
Main questions:

(1) How to improve the limits (besides building newer detectors) ?

(2) Can we go below the neutrino floor to probe discovery space?

Low mass black hole discovery

Black hole discoveries via gravitational waves



Low mass black hole/ compact object discoveries

(1) GW190814: Merger of (22.2 - 24.3) $M_\odot$ black hole with a compact object of mass (2.5 - 2.67) $M_\odot$ (LIGO Virgo Coll. 2006.12611 ApJL)

(2) Thompson et al. discovery of a $3.3^{+2.8}_{-0.7}\,M_\odot$ black hole (Science Vol. 366 Issue 6465 pp 637 to 640)

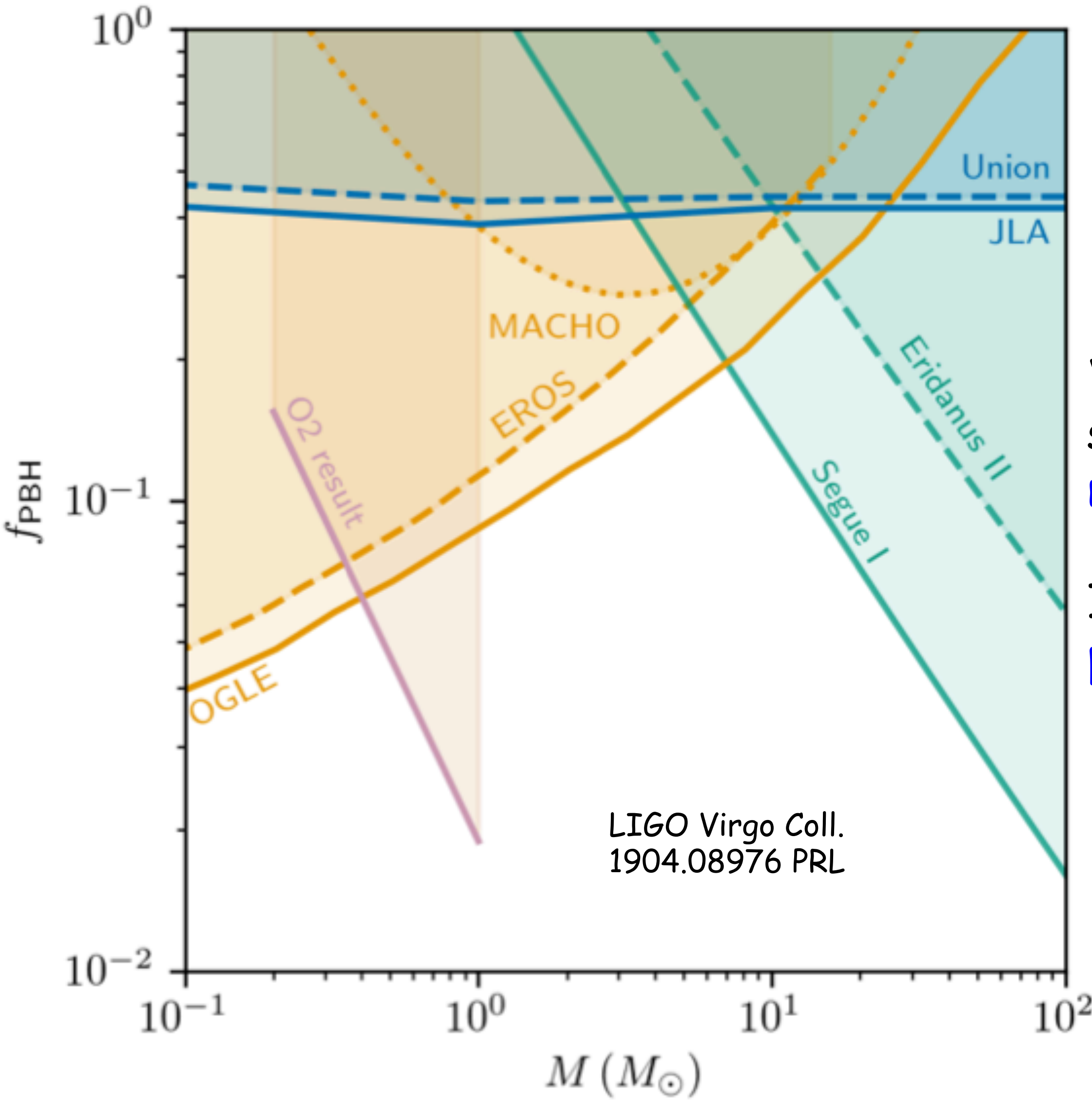
(3) GW190425: Compact binary merger with a total mass ~ 3.4 $M_\odot$ (component masses range from (1.12 - 2.52) $M_\odot$ (LIGO Virgo Coll. 2001.01761 ApJL)

(4) GW200105 and GW200115: neutron star - black hole merger with the mass of the lighter component being $1.9^{+0.3}_{-0.2}\,M_\odot$ and $1.5^{+0.7}_{-0.5}\,M_\odot$ respectively (although most probably these are neutron stars) (LIGO Virgo Coll. 2106.15163 ApJL)

Crucial questions: What are the origins of these black holes? Are they astrophysical black holes or primordial black holes? (astrophysical black holes born from death of stars; primordial black holes born due to new physics in the early Universe)

Crucial question: What happens if we detect a lower mass black hole?

Search for sub-solar mass black holes



What will be the implications of such a discovery of a sub-solar mass black hole?

Is it guaranteed to be of primordial origin?

Transmuted black holes from dark core collapse

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Low Mass Black Holes from Dark Core Collapse

Basudeb Dasgupta, Ranjan Laha, and Anupam Ray

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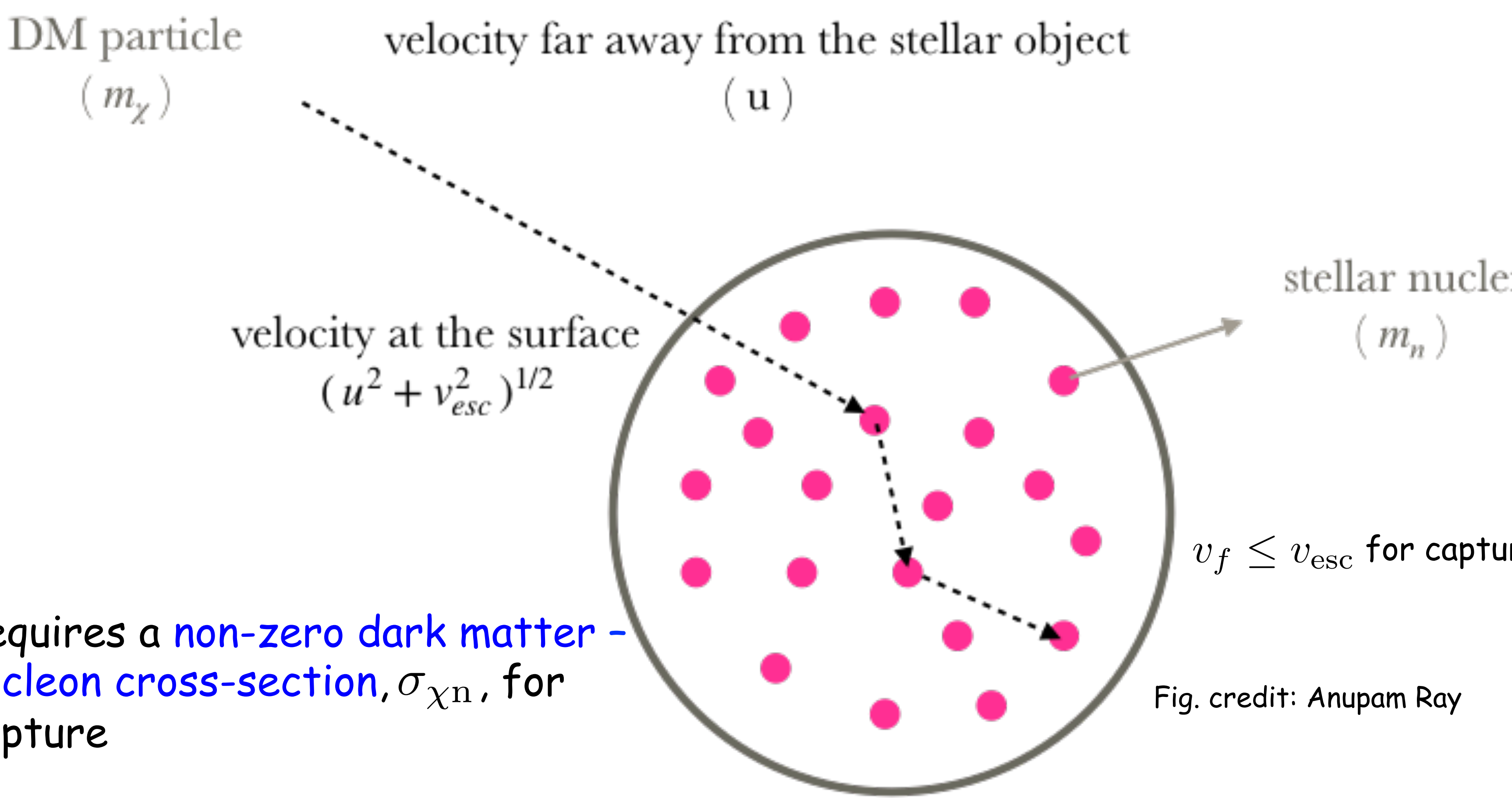
ABSTRACT

Unusual masses of black holes being discovered by gravitational wave experiments pose fundamental questions about the origin of these black holes. Black holes with masses smaller than the Chandrasekhar limit $\approx 1.4\ M_{\odot}$ are essentially impossible to produce through stellar evolution. We propose a new channel for production of low mass black holes: stellar objects catastrophically accrete nonannihilating dark matter, and the small dark core subsequently collapses, eating up the host star and transmuting it into a black hole. The wide range of allowed dark matter masses allows a smaller effective Chandrasekhar limit and thus smaller mass black holes. We point out several avenues to test our proposal, focusing on the redshift dependence of the merger rate. We show that redshift dependence of the merger rate can be used as a probe of the transmuted origin of low mass black holes.

Dark matter accretion in compact astrophysical objects



$v_f \leq v_{\rm esc}$ for capture

Requires a non-zero dark matter – nucleon cross-section, $\sigma_{\chi \rm n}$, for capture

Fig. credit: Anupam Ray

Press and Spergel (1985), Gould (1987), Goldman and Nussinov (1989), … …. , Garani, Genolini, and Hambye (2019), Dasgupta, Gupta, & Ray (2020), Garani, Gupta, and Raj (2020), Bell et al (2021), and many others

Dark matter accretion and collapse in compact astrophysical objects

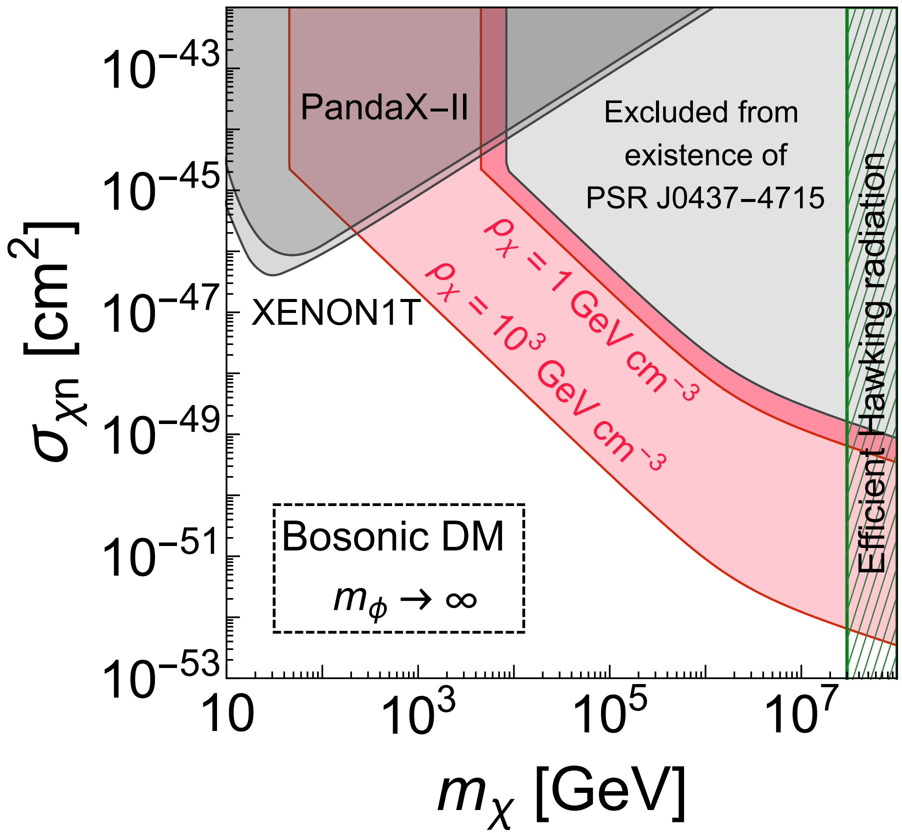
$$\underbrace{C_{\rm single}}_{\text{capture rate of a dark matter particle in an astrophysical object (most efficient for neutron stars)}} = \underbrace{\frac{\rho_\chi}{m_\chi}\int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2)}_{\text{incoming dark matter flux}} \underbrace{N_n}_{\text{no. of targets}} \min(\sigma_{\chi \rm n}, \underbrace{\sigma_{\chi \rm n}^{\rm sat}}_{\text{Geometrical saturation cross-section}}) \underbrace{g_1(u)}_{\text{Capture probability}}$$

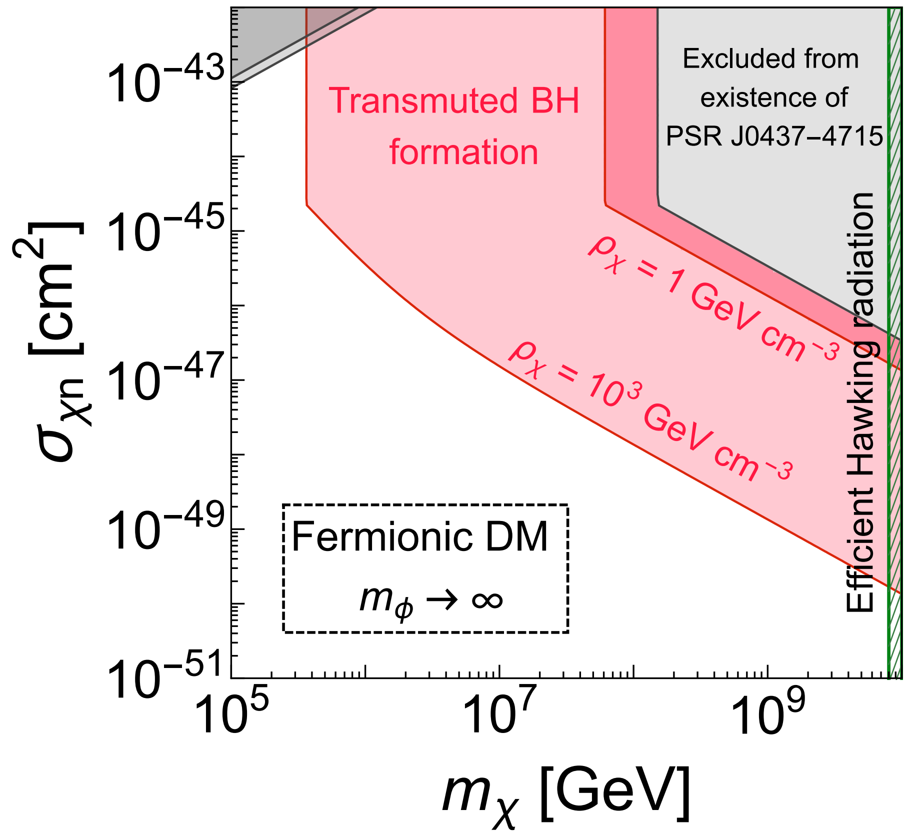
Dasgupta, Gupta, & Ray (2020)

- Assume non-annihilating dark matter particles
- Dark matter core collapse: total number of captured dark matter particles ≥ number of particles required for black hole formation
- The small black hole formed at the center of the star can increase in mass by accreting the entire stellar material: transmuted black hole

See also Kouvaris & Tinyakov 1804. 06740, Shandera et al 1802.08206

Transmuted black holes as probe of particle dark matter

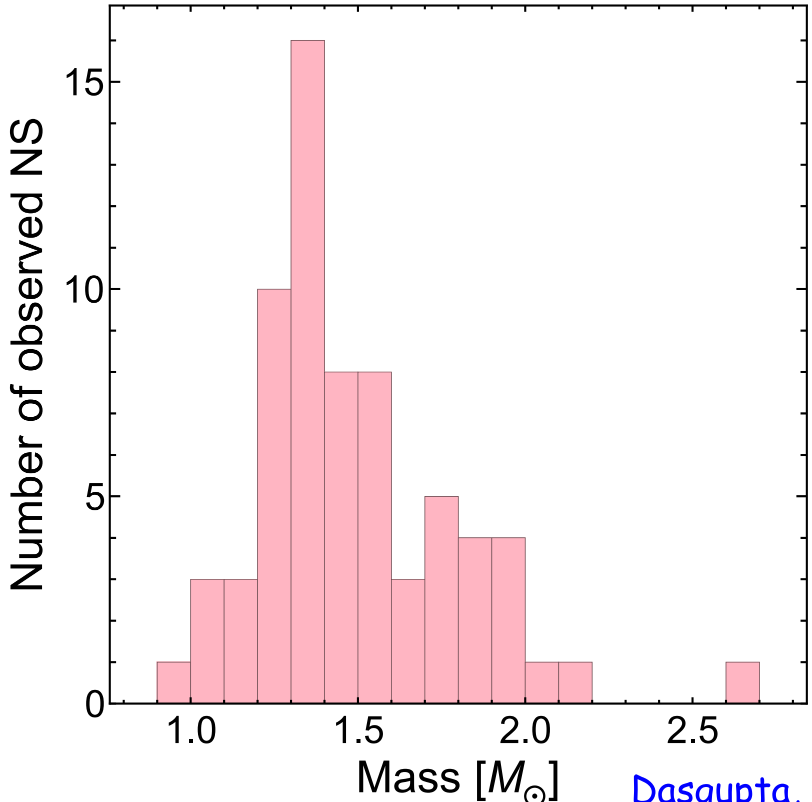


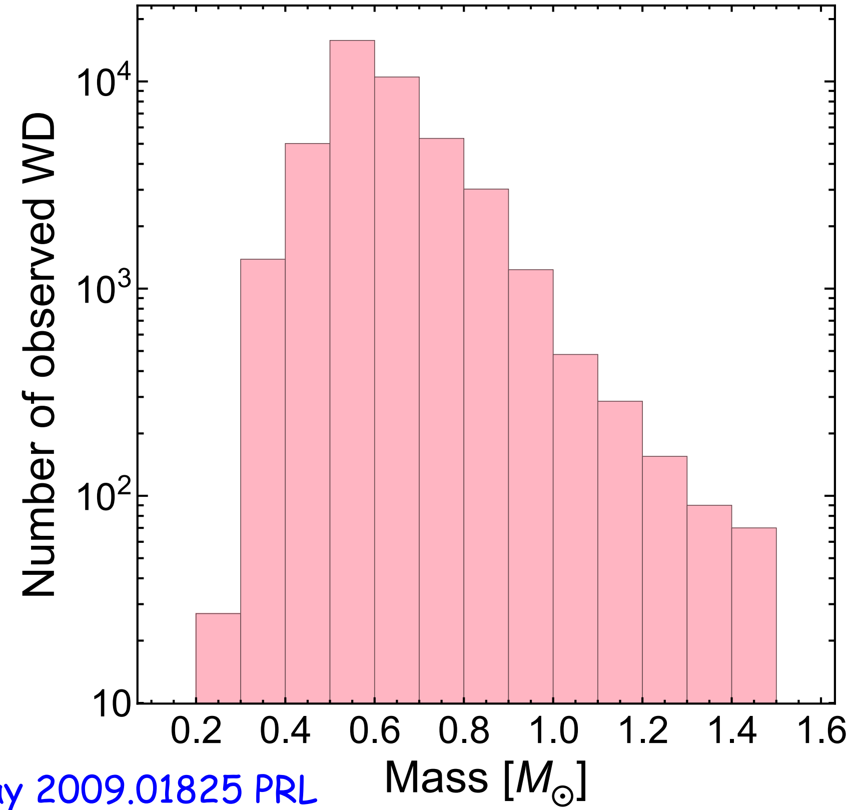


Dasgupta, Laha, and Ray 2009.01825 PRL

Mass function of transmuted black holes

- Two classes of astrophysics targets: neutron stars (NS) and white dwarfs (WD)
- These transmuted black holes can be detected
- Sub-Solar mass black holes need not be primordial in origin





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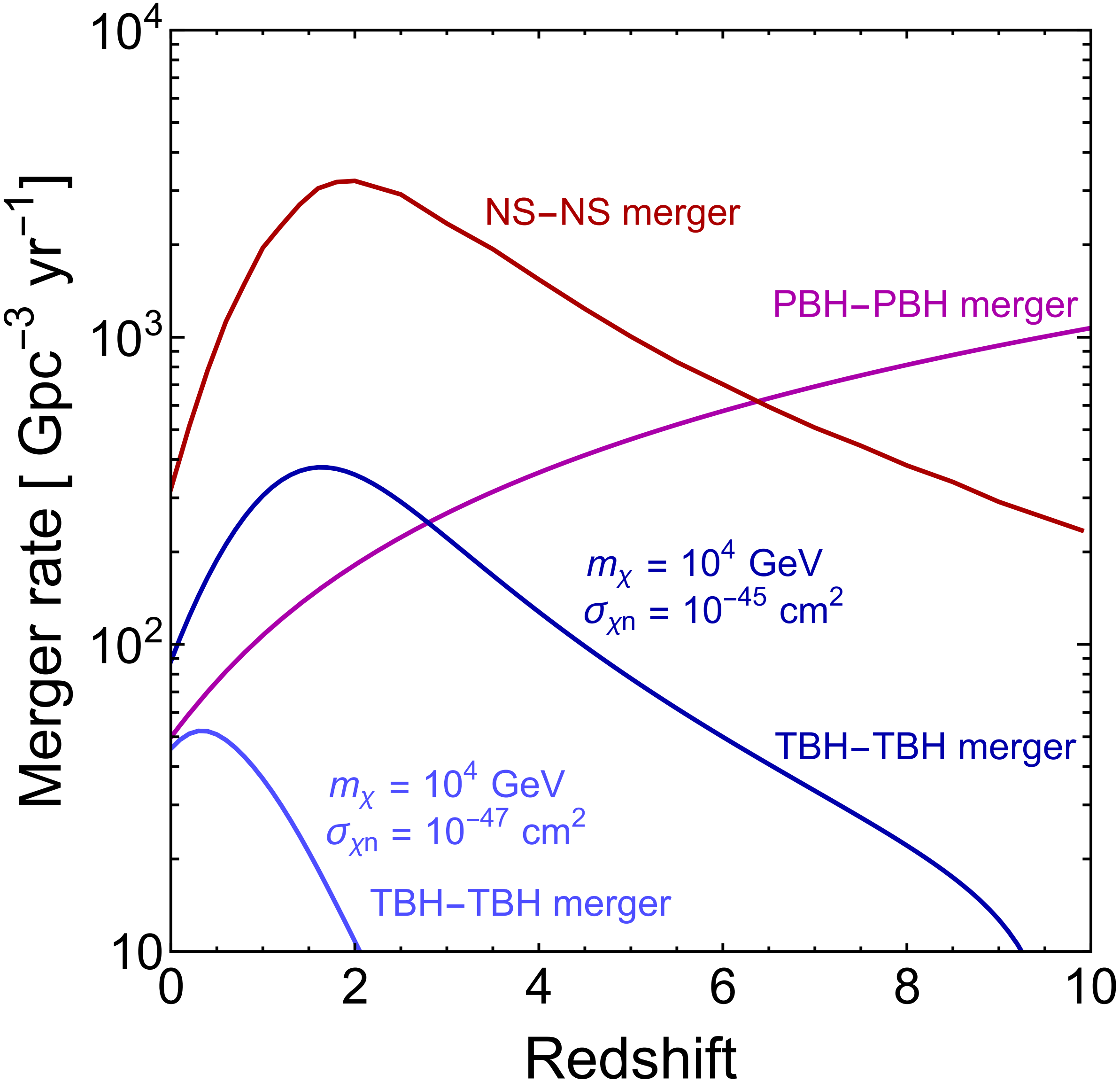
See also Takhistov et al 2008. 12780

Red-shift distribution of transmuted black holes



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

Some event numbers

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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

for $z \leq 1$ for $z > 1$ total

Possible detection rate of TBH binaries for aLIGO and ET

The three numbers in the last two columns correspond to detection rates for $z \leq 1$, $z > 1$, and the total

Some event numbers for advanced LIGO and Einstein Telescope

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

Conclusions

- Dark matter accumulation inside compact astrophysical objects can produce low mass transmuted black holes
- This is a compelling alternative to primordial black holes (for sub-Chandrasekhar/ sub-solar masses)
- Redshift dependence and mass dependence of the detections can distinguish between the various alternatives

Dasgupta, Laha, and Ray 2009.01825 PRL

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