Mergers as a Probe of Particle Dark Matter

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Motivation & Summary

- Recent discoveries of unusually low mass black holes (BHs) pose fundamental questions about their origin.
- BHs below Chandrasekhar limit (1.4 $M_\odot$) are usually thought as a smoking gun signature of their primordial origin.
- We study a simple and elegant formation mechanism of low mass BHs which can be a viable alternative of fine-tuned primordial black holes (PBHs).
- Non-annihilating Dark matter (DM) owing to their non-zero interaction strength with the stellar nuclei can gradually accumulate inside compact objects, and eventually transmute them to low mass 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 the binary merger rates at high redshifts can conclusively determine the origin of low mass BHs.

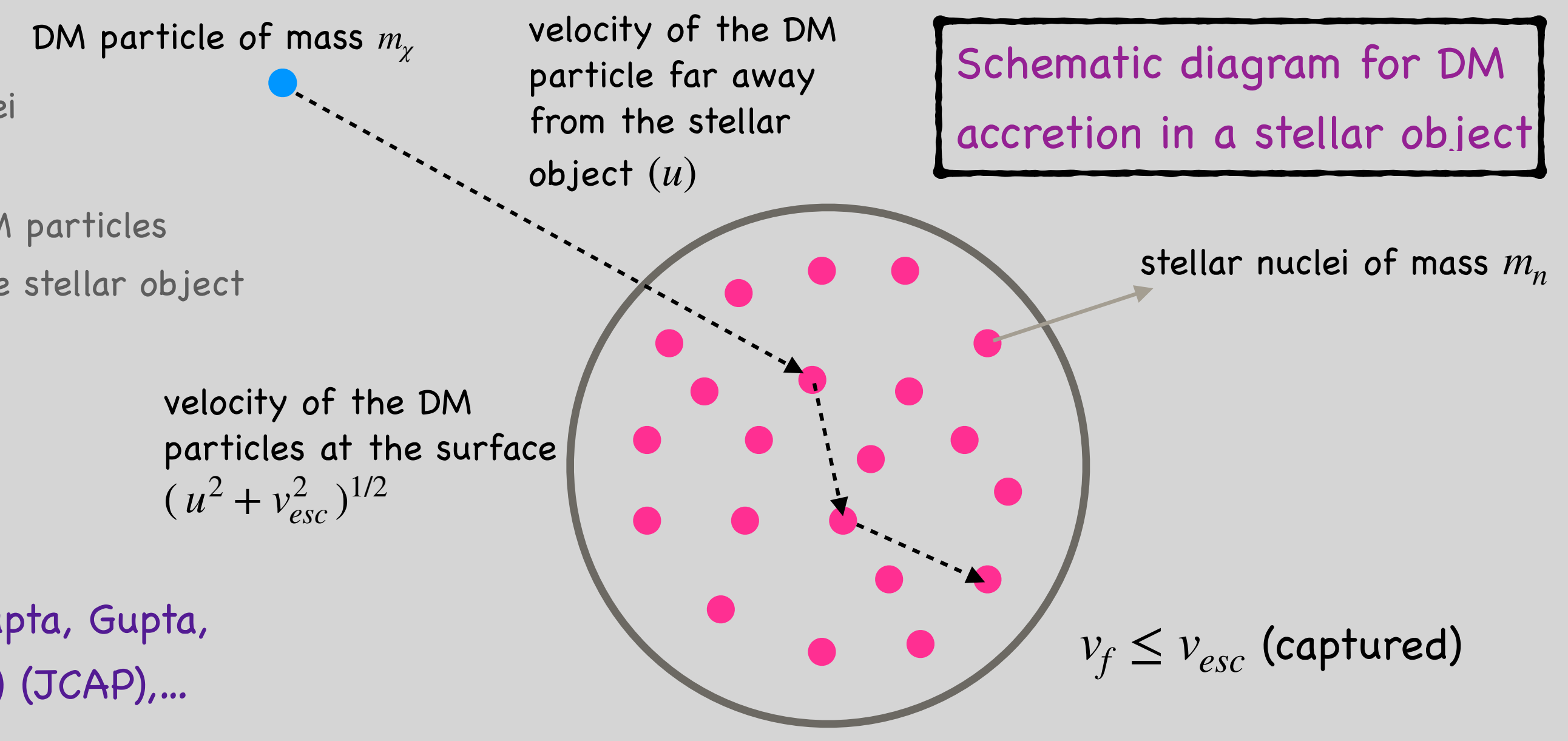
$\sigma_{\chi n}$: interaction strength between DM and nuclei

m_ϕ : mass of the mediator

v_f : final velocity of the DM particles

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

ρ_χ : ambient DM density



DM particle of mass m_χ

velocity of the DM particle far away from the stellar object (u)

Schematic diagram for DM accretion in a stellar object

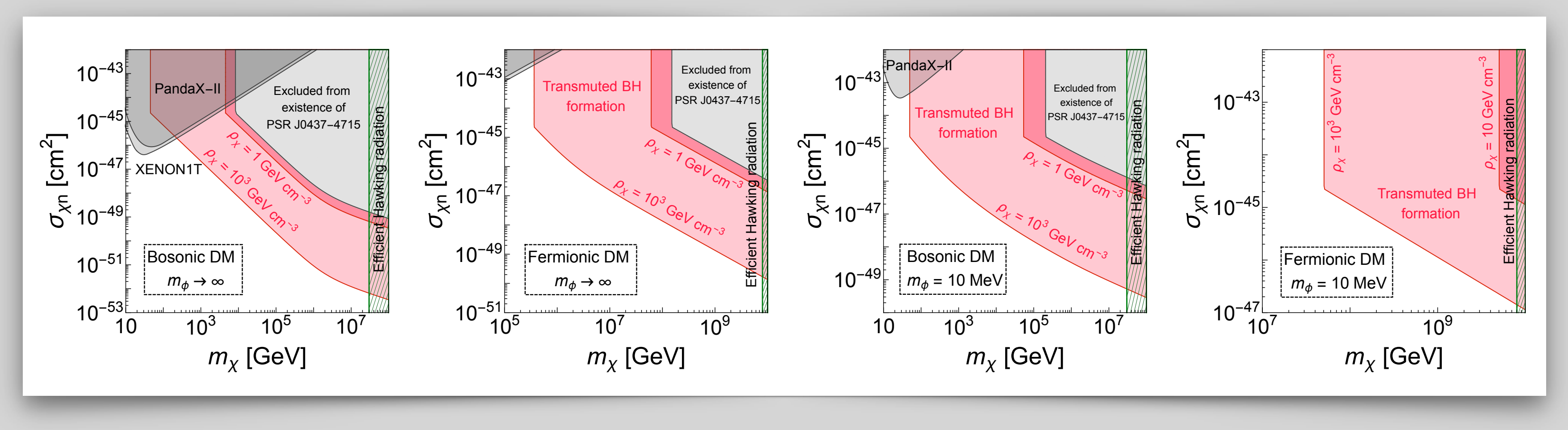
stellar nuclei of mass m_n

velocity of the DM particles at the surface $(u^2 + v_{esc}^2)^{1/2}$

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

Gould (1987),..., Dasgupta, Gupta, and **Ray** (2006.10773) (JCAP),...

Parameter space for TBH formation



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/fermionic DM. Contact interaction is assumed for the left two panels, and a scalar mediator of mass 10 MeV is assumed for the right two panels.

TBH merger rate & possible detection rate

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

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

increase in transmutation time → lower TBH merger rate

- Expected detection rate of TBH binaries for current (aLIGO) and future (Einstein Telescope) GW detectors.

$M_{\rm NS}$ [$M_\odot$]	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

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

Formation of low mass transmuted BHs (TBHs): Dark core collapse

- DM particles in the galactic halo, owing to their non-zero interaction strength with the stellar nuclei, scatter, deposit energy, and eventually get captured as they traverse through the stellar body.
- If the DM particles are non-annihilating in nature, due to the continued accumulation of DM particles in the stellar core, the dark core collapses, subsequently swallows the host star and transmutes it into a comparable mass BH.

Total number of captured DM particles ≥ Number of particles required for black hole formation

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

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

C : baryonic capture rate

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

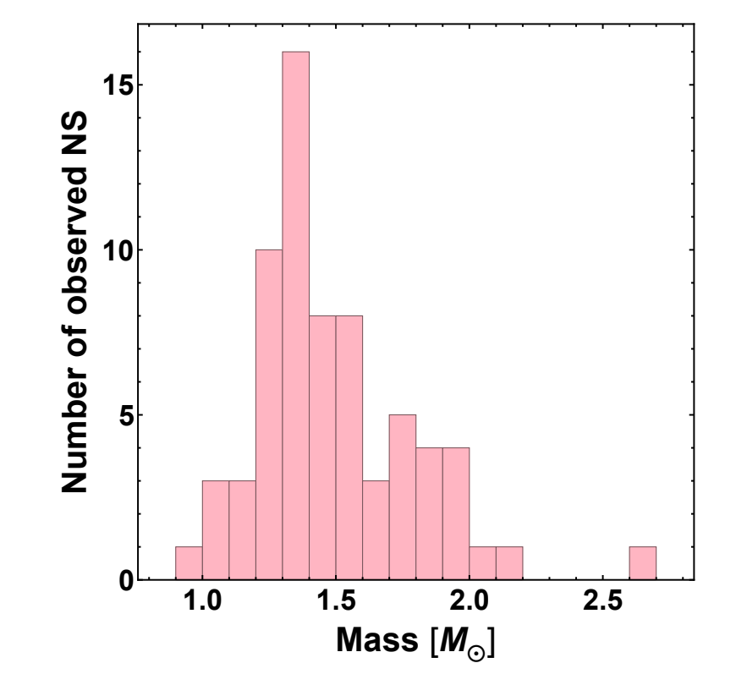
$N_\chi^{\rm cha}$: Chandrasekhar limit

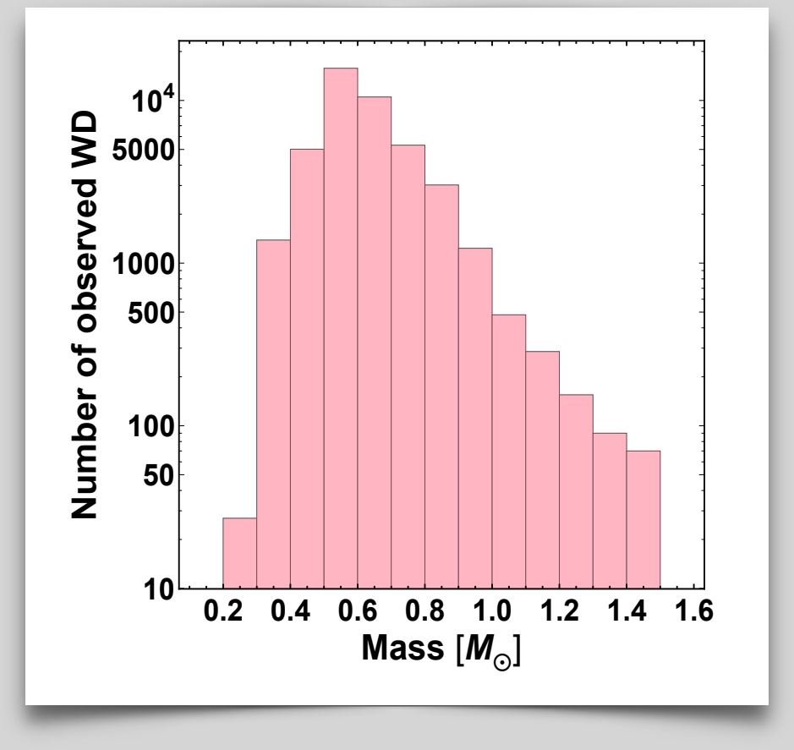
$$C = \underbrace{\frac{\rho_\chi}{m_\chi} \int \frac{f(u)du}{u} (u^2 + v_{\rm esc}^2)}_{\text{Incoming DM flux}} \underset{\substack{\downarrow \\ \text{Number of targets}}}{N_n} \underbrace{{\rm Min}\left[\sigma_{\chi{\rm n}}, \sigma_{\chi{\rm n}}^{\rm sat}\right]}_{\text{Scattering cross section}} \underset{\substack{\downarrow \\ \text{Capture probability}}}{g_1(u)}$$

Test for the origin of low mass BHs

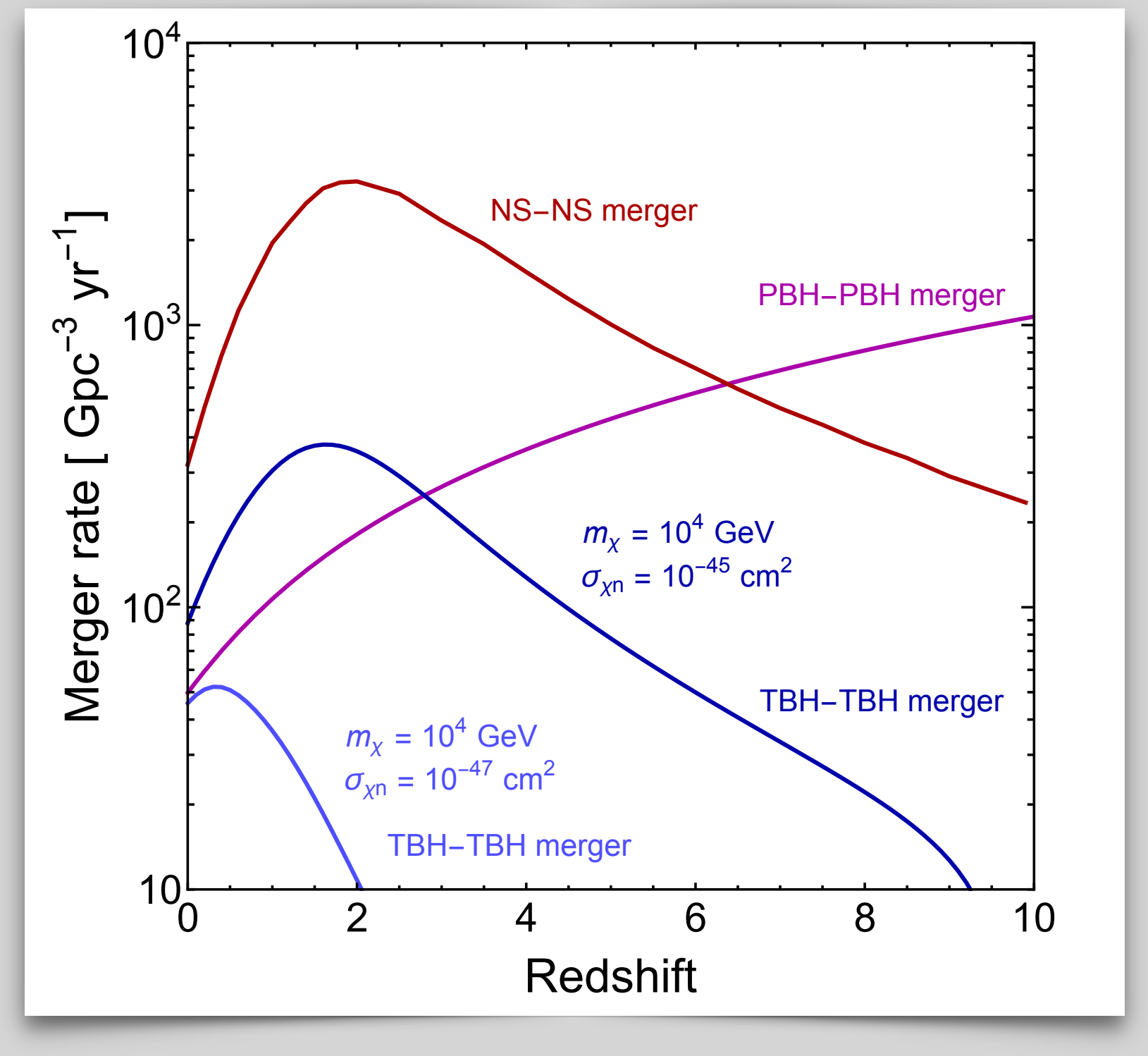
- Transmuted BHs track the mass distribution of their progenitors (Neutron Star/White Dwarf). Mass distribution of the compact objects can be statistically compared against some well motivated PBH mass distributions to examine the origin of low mass BHs.

See also Takhistov et al 2008.12780 (PRL)





- Cosmic evolution of the binary merger rates can be used as a probe to determine the origin (transmuted/primordial) of low mass BHs.



Distinct redshift dependence of the binary merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments, and hence, can conclusively determine the origin of low mass BHs.

Questions & comments :
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