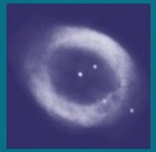
# Neutron Stars as Laboratories



# for Fundamental Dark Matter Physics

Current Topics in Astroparticle Physics — In Honor of Georg G. Raffelt
Max Planck Institute for Physics, 10 Nov 2022

Basudeb Dasgupta

# The Georg Connection


15+ years ago

ISAPP 2006
@ MPP Munich

# The Georg Connection


15+ years ago

@ TIFR Mumbai

# The Georg Connection

Many papers,
Many visits,
...

Jan 2020
@ TIFR Mumbai

THE ASTROPHYSICAL JOURNAL, 352:654–668, 1990 April 1
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## THERMAL CONDUCTION BY MASSIVE PARTICLES

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*Received 1989 April 19; accepted 1989 September 21*

ABSTRACT

We discuss thermal conduction by a dilute gas of elementary particles, mass $m_x$, in a background of nuclei, mass $m_n$. We present a formal solution to the linear Boltzmann collision equation, analyzing carefully the symmetry assumptions that enter our approach. These symmetries arise from approximations which are motivated by the problem of thermal conduction in stars by weakly interacting massive particles, but the results are of more general validity. For the special case of hard-sphere interactions, applicable to many "cosmion" candidates that have been proposed to solve the solar neutrino problem, we derive new explicit results by analytic and numeric techniques. In contrast to previous work, our results are valid for general values of the mass ratio $\mu \equiv m_x/m_n$. For $\mu \gg 1$, a subtle cancellation renders the inverse collision operator nearly singular, so that the thermal conduction coefficient scales with $\mu^{1/2}$ while it is nearly constant for $\mu \lesssim 4$. We also find that the optimal cross section for energy transfer by cosmions in the Sun is $(7\text{–}10) \times 10^{-36}$ cm$^2$, a factor of 2–10 larger than had been thought previously.

*Subject headings:* dark matter — elementary particles — stars: interiors

# Dark Matter Captured in Stars

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## COSMION ENERGY TRANSFER IN STARS: THE KNUDSEN LIMIT

ANDREW GOULD[1] AND GEORG RAFFELT[2]
*Received 1989 June 19; accepted 1989 September 21*

ABSTRACT

We discuss energy transfer in stars by a dilute gas of elementary particles ("cosmions" or weakly interacting massive particles ["WIMPs"]), an effect that has been proposed to solve the solar neutrino problem. We focus on the limit of large mean free paths (Knudsen limit) where the particles orbit many times in the stellar interior between their interactions with nuclei. By means of a Monte Carlo integration of the Boltzmann collision equation, we compute the energy transfer for simple model stars, and we compare these exact results with an analytic approximation previously proposed by Press and Spergel. We investigate in detail the sources of the discrepancy between the two methods and find that it is due largely to the deviation from isotropy of the WIMP distribution function. The Press-Spergel approximation overestimates the energy transfer typically by a factor of a few. This factor is a sensitive function of radius, so that it is impossible to correct for it globally.

*Subject headings:* elementary particles — radiative transfer — stars: interiors

# 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 Collaboration

(Dated: June 22, 2020)

ABSTRACT

We report the observation of a compact binary coalescence involving a $22.2 - 24.3\, M_\odot$ black hole and a compact object with a mass of $2.50 - 2.67\, M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal, GW190814, was observed during LIGO's and Virgo's third observing 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 $\mathrm{deg}^2$ 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 spin of the primary black hole is tightly constrained to $\leq 0.07$. Tests of general relativity reveal no measurable deviations from the theory, and its prediction of higher-multipole emission is confirmed at high confidence. We estimate a merger rate density of 1–23 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for the new class of binary coalescence sources that GW190814 represents. Astrophysical models predict that binaries with mass ratios similar to this event can form through several channels, but are unlikely to have formed in globular clusters. However, the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models for the formation and mass distribution of compact-object binaries.

The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20
https://doi.org/10.3847/2041-8213/ab75f5
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# GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

## Abstract

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 origins of the system based on its inconsistency with the known Galactic BNS population. Under the assumption that the signal was produced by a BNS coalescence, the local rate of neutron star mergers is updated to 250–2810 $\mathrm{Gpc^{-3}\,yr^{-1}}$.

THE ASTROPHYSICAL JOURNAL LETTERS, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e
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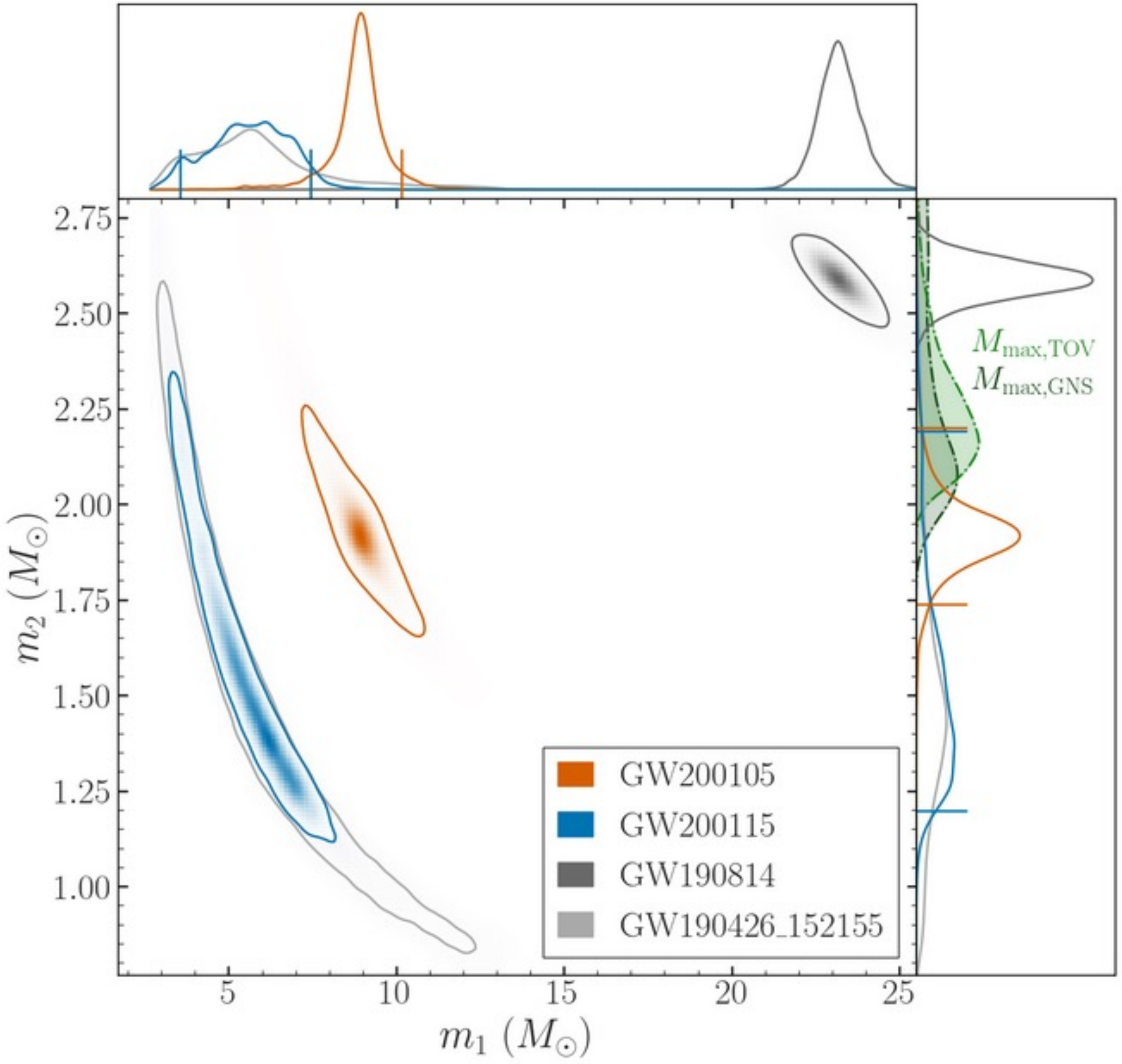
# Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

## Abstract

We report the observation of gravitational waves from two compact binary coalescences in LIGO's and Virgo's third observing run with properties consistent with neutron star–black hole (NSBH) binaries. The two events are named GW200105_162426 and GW200115_042309, abbreviated as GW200105 and GW200115; the first was observed by LIGO Livingston and Virgo and the second by all three LIGO–Virgo detectors. The source of GW200105 has component masses $8.9^{+1.2}_{-1.5}$ and $1.9^{+0.3}_{-0.2}\,M_{\odot}$, whereas the source of GW200115 has component masses $5.7^{+1.8}_{-2.1}$ and $1.5^{+0.7}_{-0.3}\,M_{\odot}$ (all measurements quoted at the 90% credible level). The probability that the secondary's mass is below the maximal mass of a neutron star is 89%–96% and 87%–98%, respectively, for GW200105 and GW200115, with the ranges arising from different astrophysical assumptions. The source luminosity distances are $280^{+110}_{-110}$ and $300^{+150}_{-100}$ Mpc, respectively. The magnitude of the primary spin of GW200105 is less than 0.23 at the 90% credible level, and its orientation is unconstrained. For GW200115, the primary spin has a negative spin projection onto the orbital angular momentum at 88% probability. We are unable to constrain the spin or tidal deformation of the secondary component for either event. We infer an NSBH merger rate density of $45^{+75}_{-33}$ Gpc$^{-3}$ yr$^{-1}$ when assuming that GW200105 and GW200115 are representative of the NSBH population or $130^{+112}_{-69}$ Gpc$^{-3}$ yr$^{-1}$ under the assumption of a broader distribution of component masses.




# Is it possible that there are new kinds of compact objects close to the Chandrasekhar Limit?

# What Can This Be?

- No new physics

  Occam's razor solution!

Image: Warner Bros.

- Primordial black holes

  Zeldo'vich (1966), Hawking (1970), ... Carr, ... Recent interest due to Bird et al. (2016)

- Neutron star converted to a black hole due to PBH transit

  Capela et al. (2013), Takhistov et al. (2017), ...
  But rate too low : Montero-Camacho et al. (2019), Genolini et al. (2020)

- Core collapse of dark matter blob

  Kouvaris et al. (2018) : Asymmetric DM with Self Interactions
  Shandera et al. (2018) : Dark Atoms

- Neutron star converted to BH due to dark matter

  Dasgupta, Laha, and Ray (2020) : This Talk

Image: Warner Bros.

# This Talk

Dark matter captured in a neutron star can collapse into a tiny black hole, which can eat up the host star from inside.

This predicts a new class of black holes, that we call "Transmuted Black Holes".

How to look for them?

Dasgupta, Laha, and Ray (PRL, 2020)

# Main Assumption

**Dark matter is a new particle with largeish mass $m_\chi$ and infrequent (but nonzero) interactions $\sigma_{\chi n}$**

$$m_\chi \sim 10^4 \, \mathrm{GeV}$$

$$\sigma_{\chi n} \sim 10^{-45} \, \mathrm{cm}^2$$

# Galactic DM is Attracted to Stars

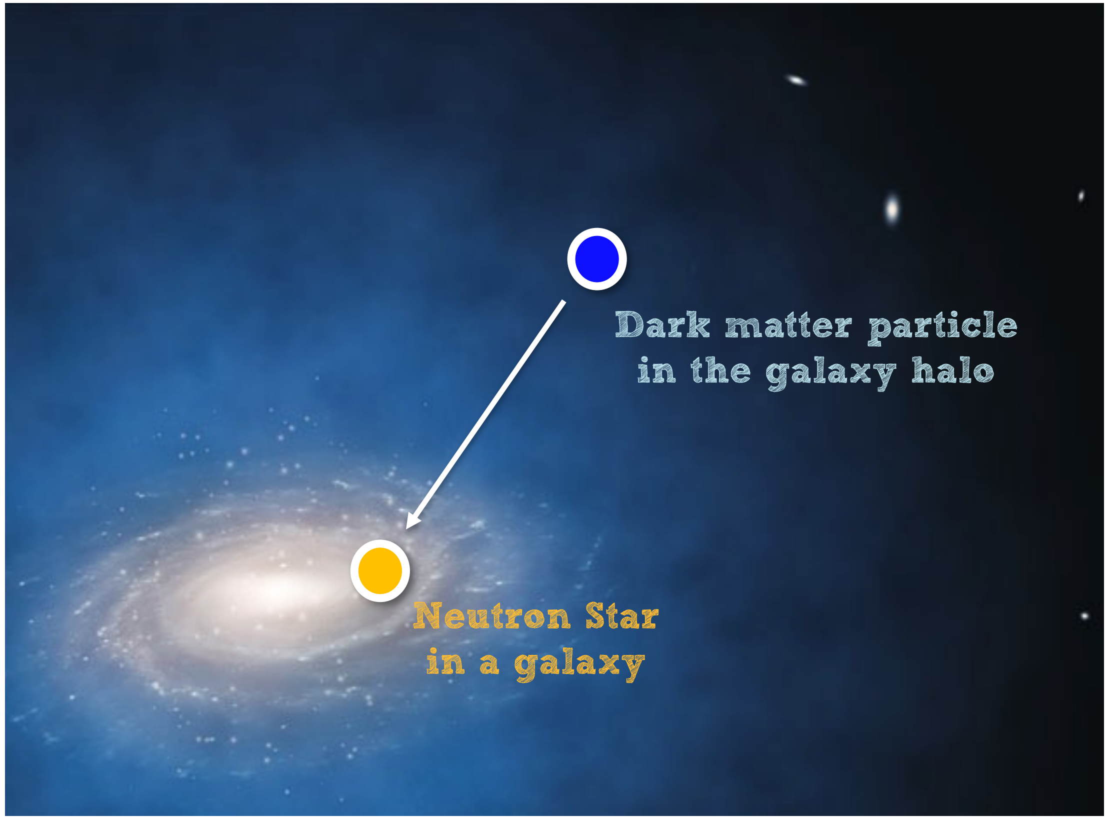
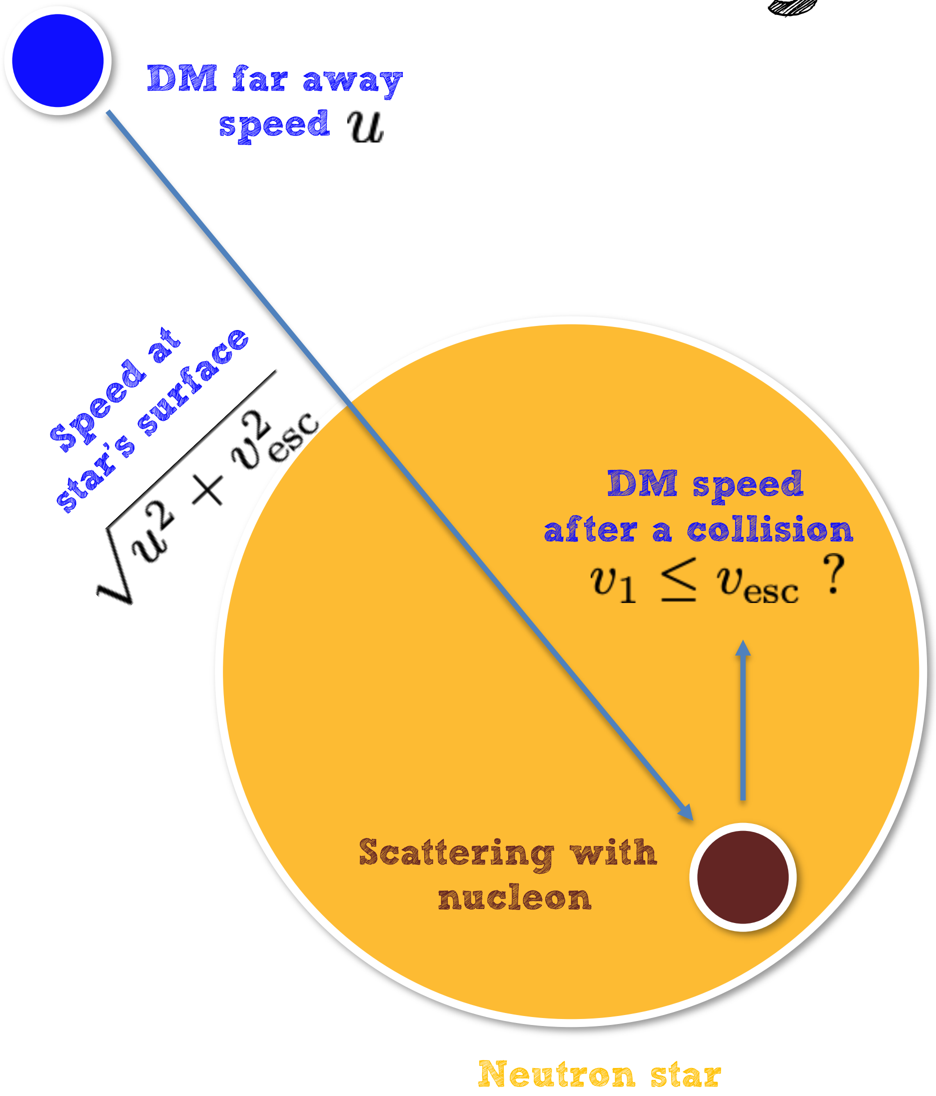



Image: Artist's composition of Hubble image and Via Lactea simulation

- The DM particles have speeds of about 200-300 km/s
- The escape velocity of neutron star is about $10^5$ km/s, and about $10^3$ km/s for white dwarf
- DM particles are gravitationally attracted to a star (speed increases due to energy conservation) and they can "zip through" the star

# DM gets Captured in Stars




- Unless the incoming DM scatters with the material of the star, it simply "slingshots" away
- Scattering on the stellar matter reduces kinetic energy of DM
- If the energy-loss is sufficient, i.e., velocity < escape velocity, then it is captured

Press and Spergel (1985), Gould (1987)

# What we did …

- An analytical calculation of the capture rate in stars, including the possibility that the DM is not always captured after a single collision but rather it requires several collisions to get captured

Dasgupta, Gupta and Ray (2019)

- Analytical treatment of the energy-loss distribution for each collision, and possible interactions between the captured DM particles, etc.

Dasgupta, Gupta and Ray (2020)

# In more detail ...

$$\underbrace{C}_{\text{capture rate}} = \underbrace{\frac{\rho_\chi}{m_\chi} \int \frac{f(u)du}{u} (u^2 + v_{\rm esc}^2)}_{\text{DM flux}} N_{\rm n} \underbrace{{\rm Min}\left[\sigma_{\chi{\rm n}}, \sigma_{\chi{\rm n}}^{\rm sat}\right]}_{\text{cross section}} \underbrace{g_1(u)}_{\text{capture probability}}$$

**where**

$$g_1(u) = \frac{m_\phi^2 \left(1 - \frac{1}{\beta} \frac{u^2}{u^2 + v_{\rm esc}^2}\right)}{\left(m_\phi^2 + \frac{4\mu^2 u^2}{\beta c^2}\right)} \Theta\left(v_{\rm esc}\sqrt{\frac{\beta}{1-\beta}} - u\right)$$

Mediator mass

Theta function decides how much energy lost on average

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

Dasgupta, Gupta and Ray (2020)

# Thermalization after Capture

- Once captured, many more collisions can occur bringing the DM particle to near-rest
- Eventually the DM "sinks" to the center of the star forming a thermalized sphere of radius

$$r_{\rm th} = \sqrt{9k_{\rm B}T_{\rm NS}/4\pi G\rho_{\rm NS}m_\chi}$$

- This process is quick, relative to stellar lifetime and the DM capture-time itself

# Self-gravitation Condition


The thermalized sphere of DM at the center of the star can start self gravitating if DM density exceeds that of ordinary stellar material therein

# Chandrasekhar Limit for Collapse

$$M_\chi^{\rm CL} \approx \frac{2m_{\rm Pl}^3}{\pi m_\chi^2}$$

vs.

$$M^{\rm CL} \approx \frac{2m_{\rm Pl}^3}{\pi m_p^2}$$

The Chandrasekhar limit for a sphere of DM-like particles is different from that of the same limit for ordinary atoms

Can be much smaller for heavy dark matter

If
mass captured > mass to self gravitate
&&
mass captured > mass needed to collapse
a small BH forms

# Accretion of the Star into the BH

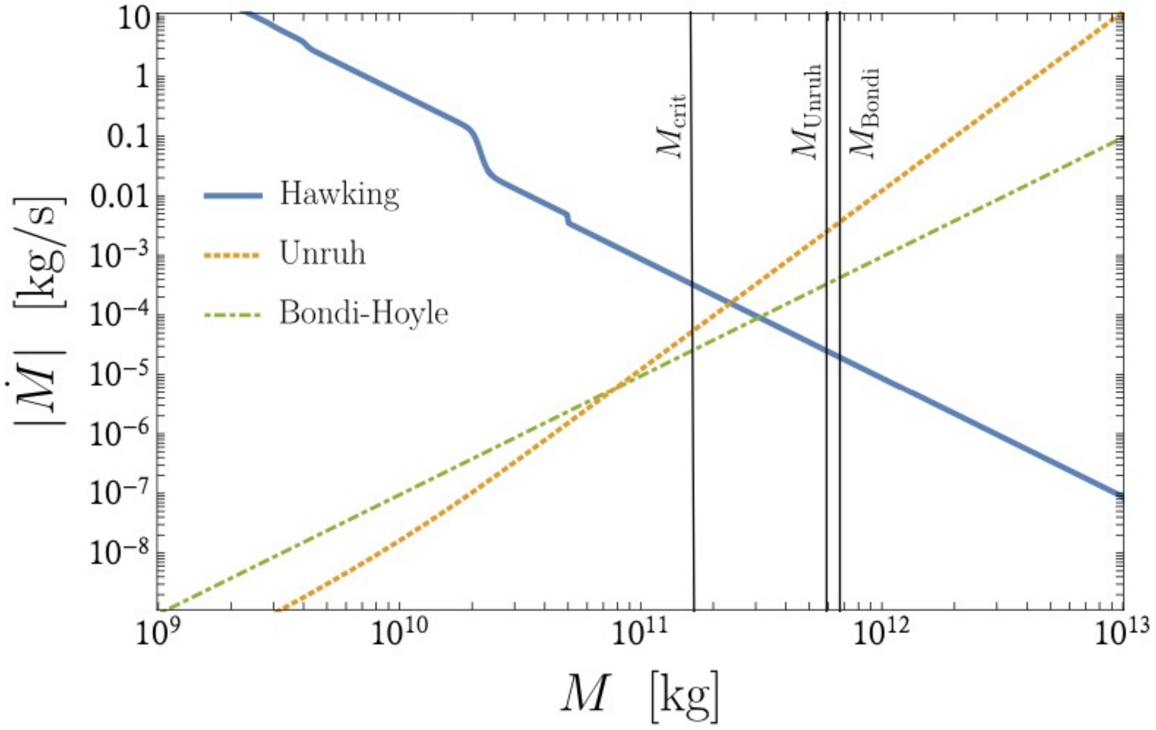


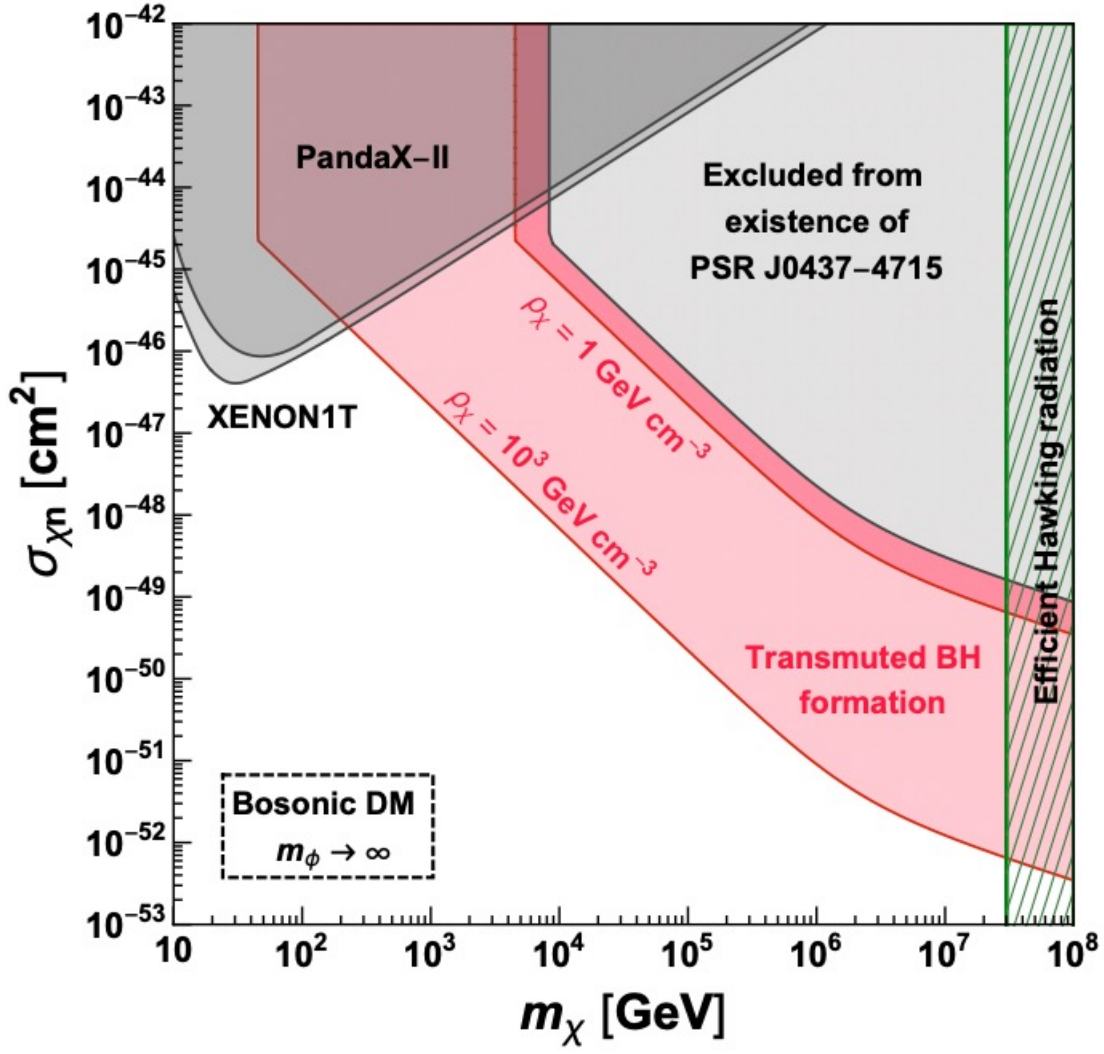

Fig. from Giffin et al. (2021)

- It can accrete material from the star efficiently
- The tiny BH can evaporate through Hawking evaporation
- Unless initial black hole is lighter than about $10^{12}$ kg, accretion wins and the star transmutes into a BH

# A quick recap

- DM is assumed to be a particle with mass and has cross section on nucleons
- It is nonrelativistic in the galactic halo, and gets captured in stars owing to gravitational attraction followed by one or more scatterings in the star
- The DM blob can collapse into a black hole at the center of the star
- This proto-BH can be extremely small, but it eats up the whole star and we get a Transmuted Black Hole that's roughly the mass of the original star.

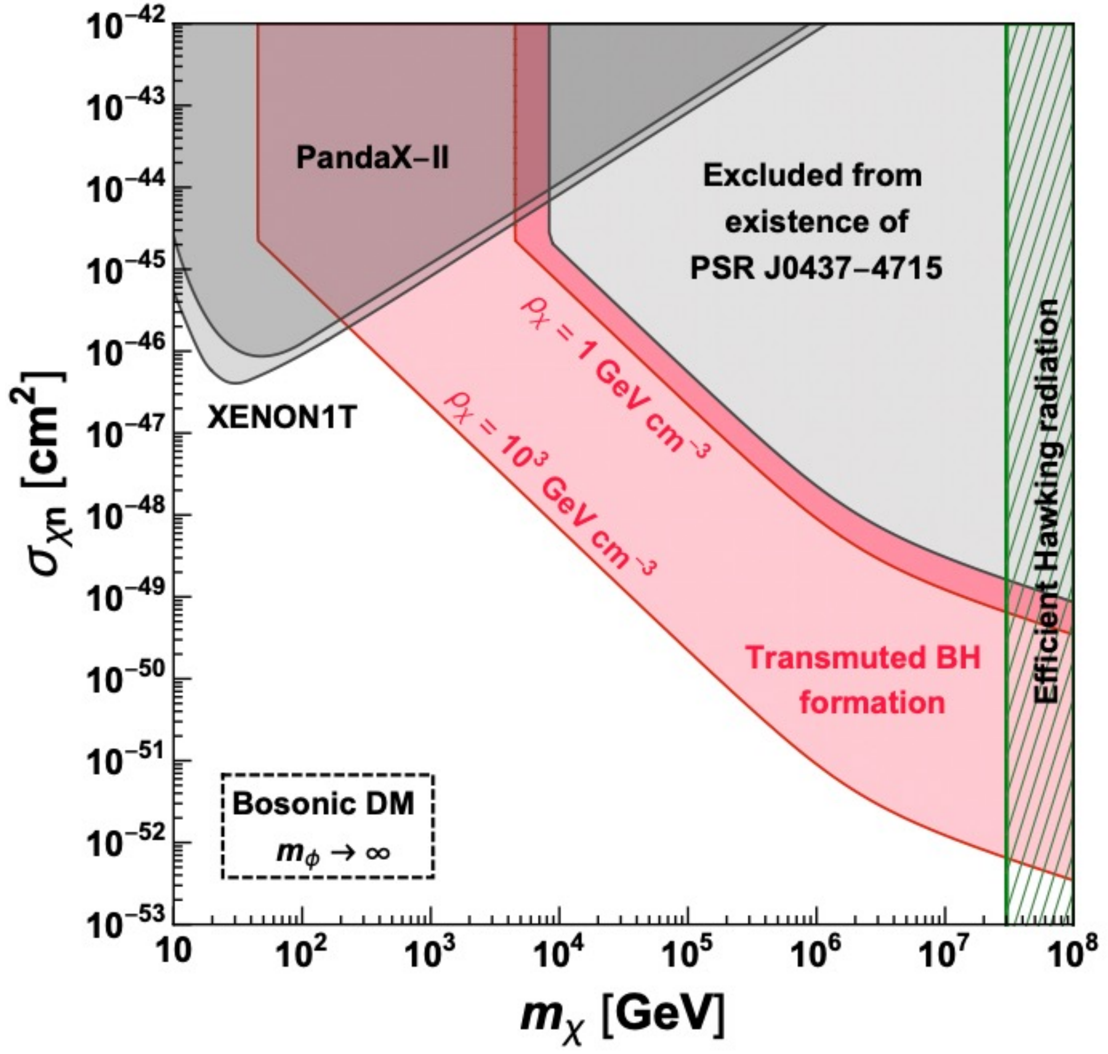
# Bosonic DM + 1.3 Msun Neutron Star




**TBH formation is not ruled out by present data**

Dasgupta, Laha, and Ray (2020)

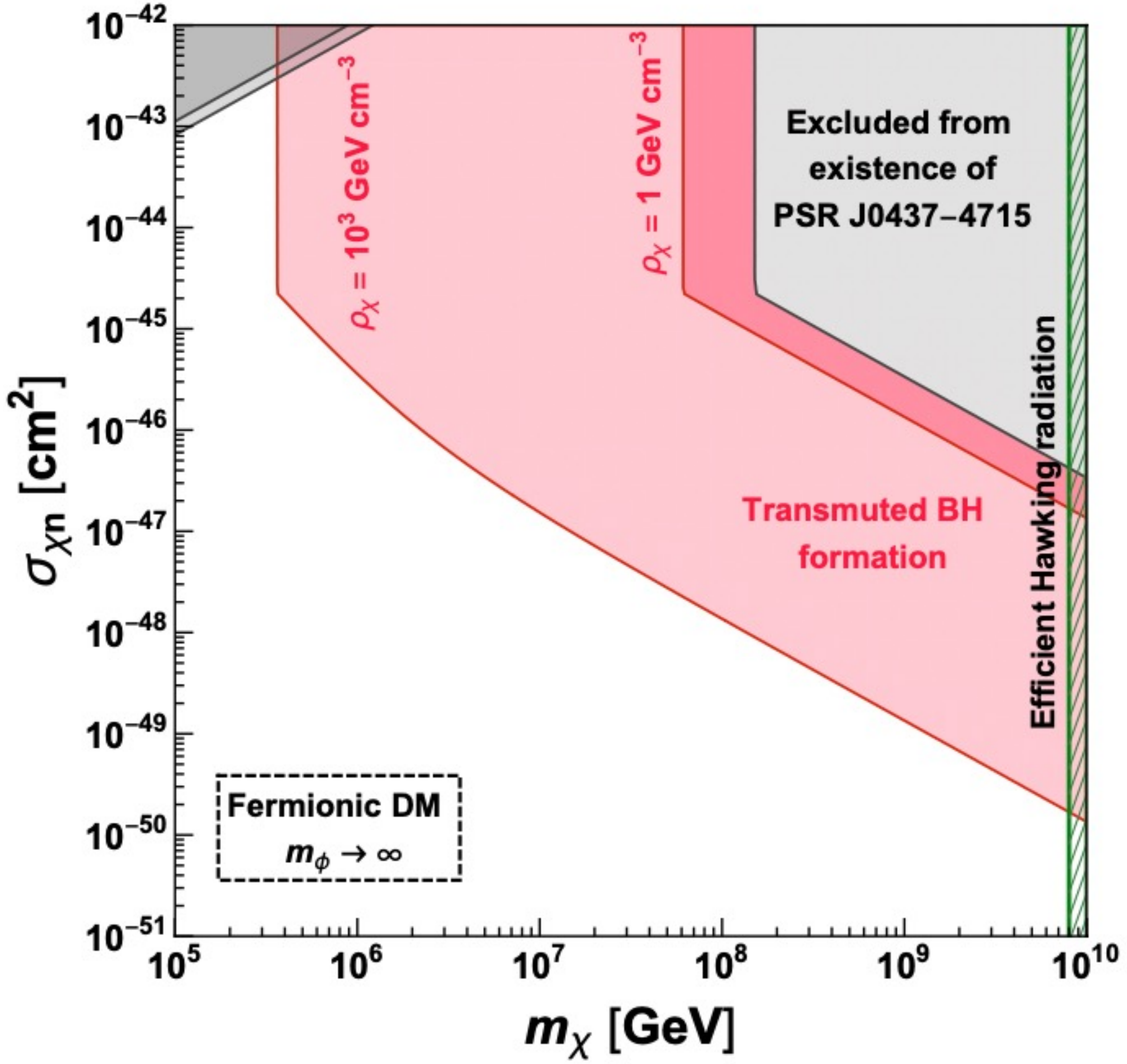
# Bosonic DM + 1.3 Msun Neutron Star




**Under some assumptions, strongest limits on DM**

Dasgupta, Laha, and Ray (2020)

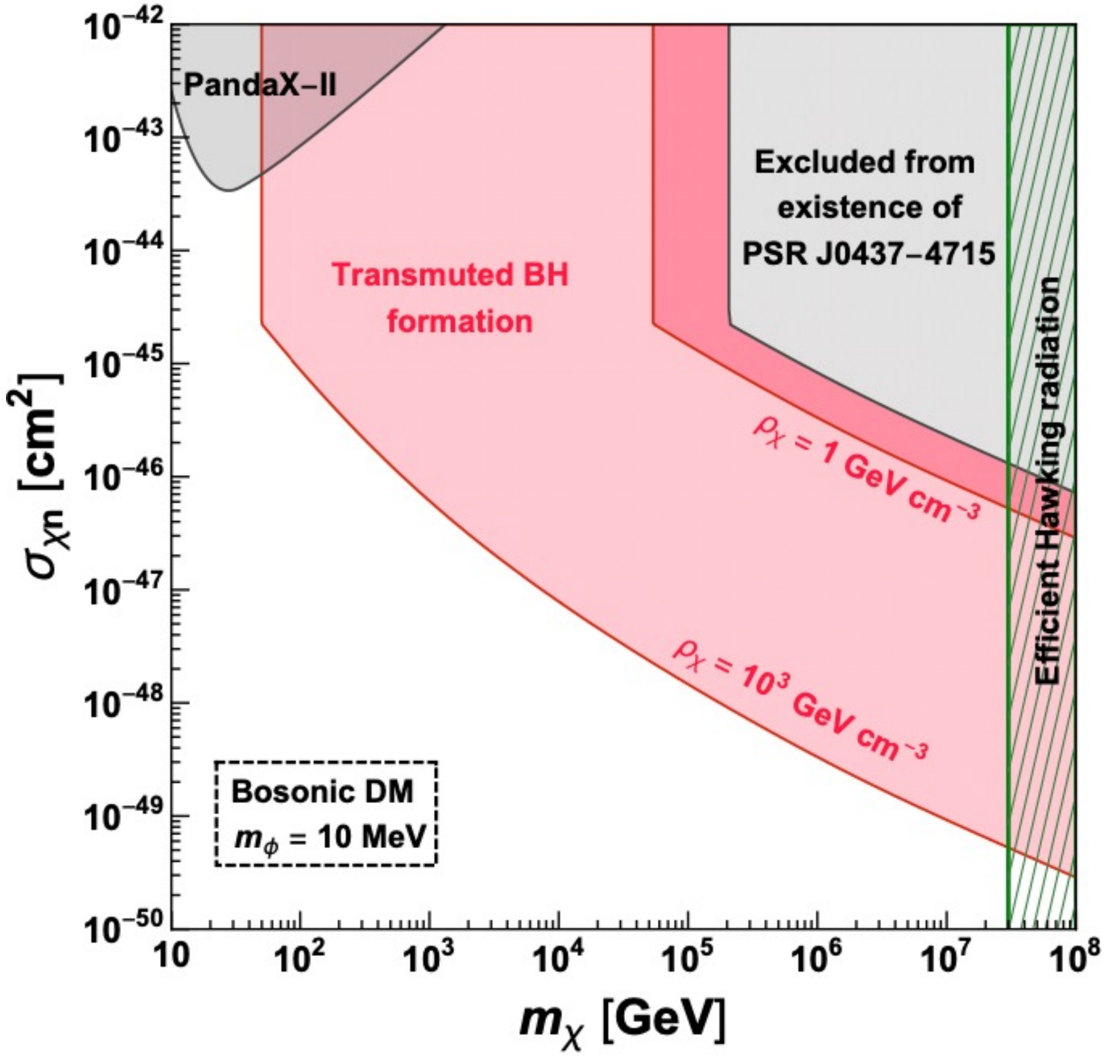
# Fermion DM + 1.3 Msun Neutron Star




**More parameter space unexplored**

Dasgupta, Laha, and Ray (2020)

# Light Mediator




**TBH formation is not ruled out by present data**

Dasgupta, Laha, and Ray (2020)

# What if DM has other interactions?

**Annihilation**

- no collapse
- Heating up of the star
- Can check using JWST!

**Self-interaction**

- $M^{CL}$ is larger
- Can resist collapse easier
- Can test using the existence of stars!

# How to Find these Fantastic Beasts?

- Regions of large DM density needed
- Typically compact stars such as NS are easier to transmute
- Can merge with a NS, another TBH or a BH, and emit gravitational waves

# Using Correlation with DM density

- Detection of a sub-Chandrasekhar BH in a low-DM-density region will disfavor its TBH origin

Improved localization of GW events needed

- Discovery of old neutrons stars in DM dense region will disfavor the TBH mechanism

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

- Coexistence of a sub-CS BH and NS will disfavor TBH

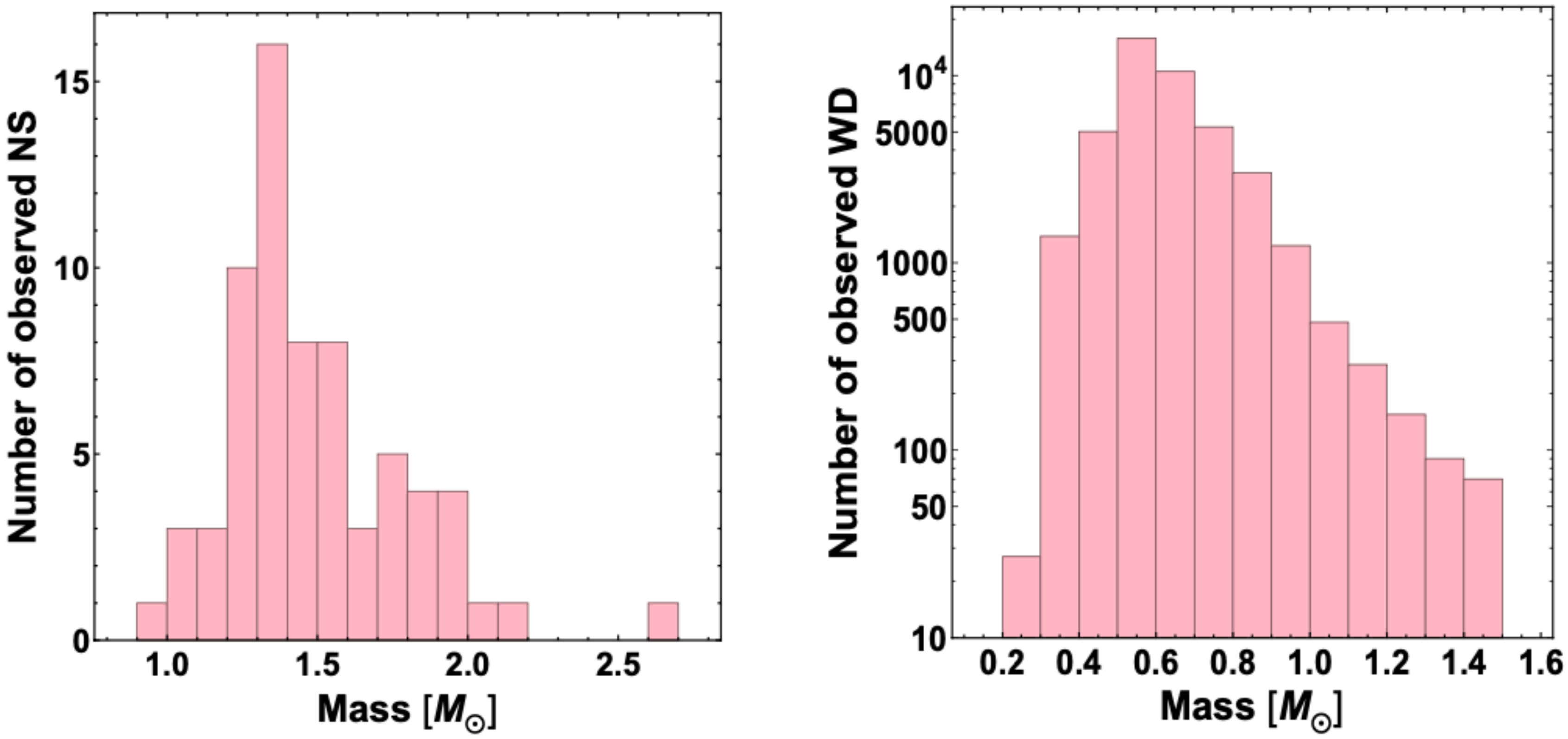
parameter space required for transmutation is disfavoured by the existence of companion NS

- Sudden disappearance of isolated neutron star or white dwarf in a DM-dense region will hint at TBH

Continuous monitoring of NS/WD needed

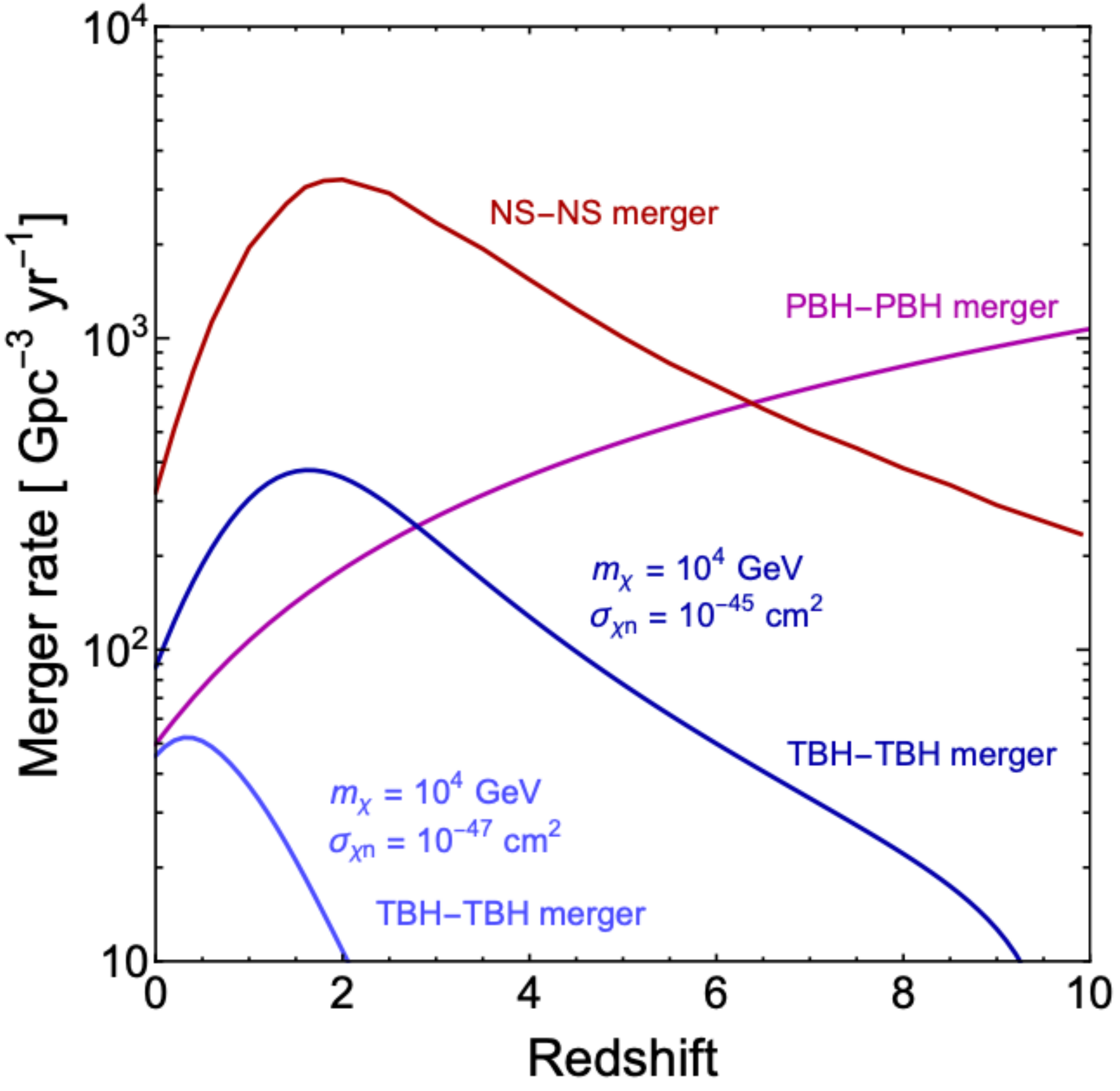
# Correlation with Mass Distributions

Dasgupta, Laha, and Ray (2020)




**The mass-function of observed TBH candidates can be compared with that of the parent neutron star or white dwarf populations**

# Redshift Evolution of Merger Rates




**The merger rate of TBHs is distinct from other candidates and 3rd-generation gravitational wave observatories can test it**

Dasgupta, Laha, and Ray (2020)

# Observable Mergers

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

| $M_{\rm NS}$ $[M_\odot]$ | $m_\chi$ [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 |

Dasgupta, Laha, and Ray (2020)

# A bit more detail … Neutron Stars

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

Merger Rate = Merger-time distribution x Binary Fraction x Star Formation Rate

Taylor et al. (2012)

The merger rate of binary neutron stars can be computed
This allows us to compute the TBH merger rate also

# A bit more detail … TBH

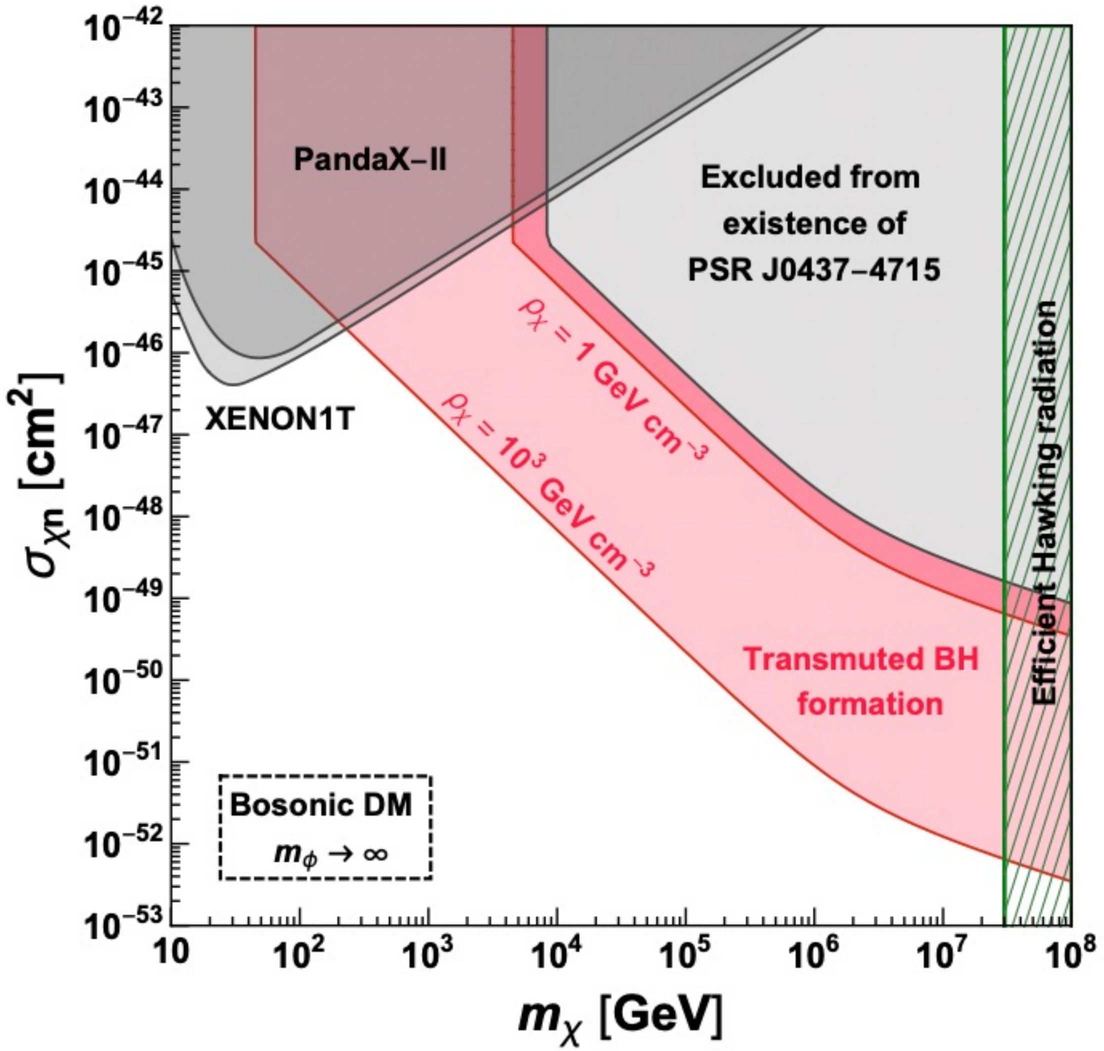
$$R_{\rm TBH}(t) = \sum_i f_i \int_{t_f=t_*}^{t} dt_f \frac{dP_m}{dt}(t-t_f)\lambda\frac{d\rho_*}{dt}(t_f)\times \;\; \Theta\left\{t - t_f - \tau_{\rm trans}\left[m_\chi, \sigma_{\chi n}, \rho_{{\rm ext},i}(t)\right]\right\}$$

Merger Rate = Merger-time distribution x Binary Fraction x Star Formation Rate x Delay due to Transmutation

Dasgupta, Laha, and Ray (2020)

TBH merger rate is systematically lower and cut off at larger red-shifts

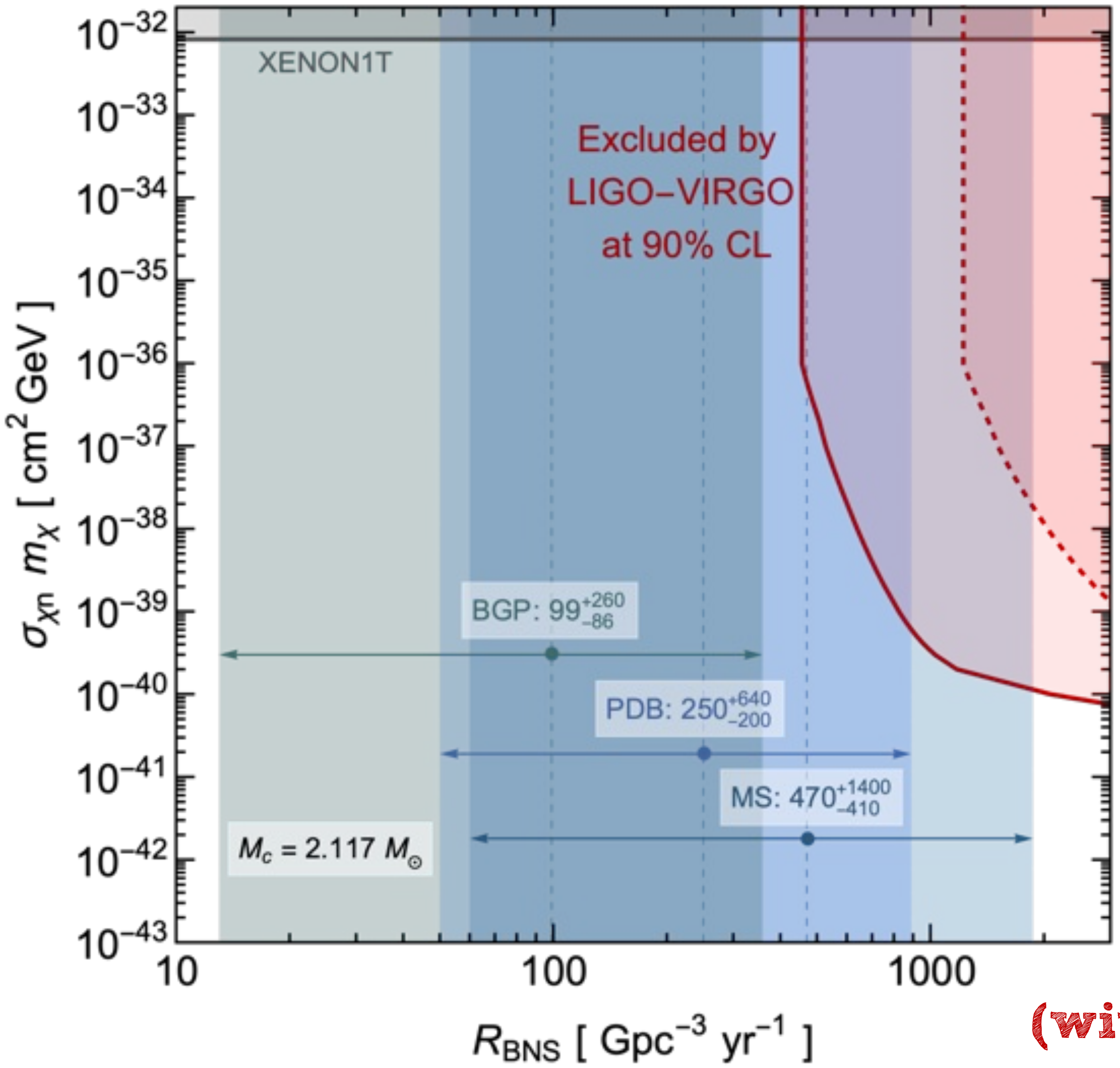
# Neutron Stars as a Dark Matter Lab




**Neutron Star existence can set strongest limits on DM interaction!**

Work in progress …
(with Sulagna Bhattacharyya and Anupam Ray)

# LIGO as Dark Matter Lab




**LIGO data already set the strongest limit on DM interactions under certain assumptions!**

Work in progress …
(with Sulagna Bhattacharyya and Anupam Ray)

# Take Home

- Dark Matter
  - How to find what it is? Several different approaches. None successful yet!
- Stellar and Black Hole Astrophysics
  - Can stars collect dark matter? Yes! Neutron Stars, WDs, …
  - How much? We can compute. Depends on dark matter's interactions.
  - What does it do? Can accumulate. Can collapse! Can annihilate …
- Phenomenology
  - What are the signatures of such dark matter collection? Black holes, Mergers, …

In this talk: NS-BH transmutation can be used to study DM interactions

# Cheers to many more years of fun and physics!