Gravitational Wave Observations as a Probe of Heavy Non-Annihilating Dark Matter Particles

PPC 2024, IITH (14/10-18/10)

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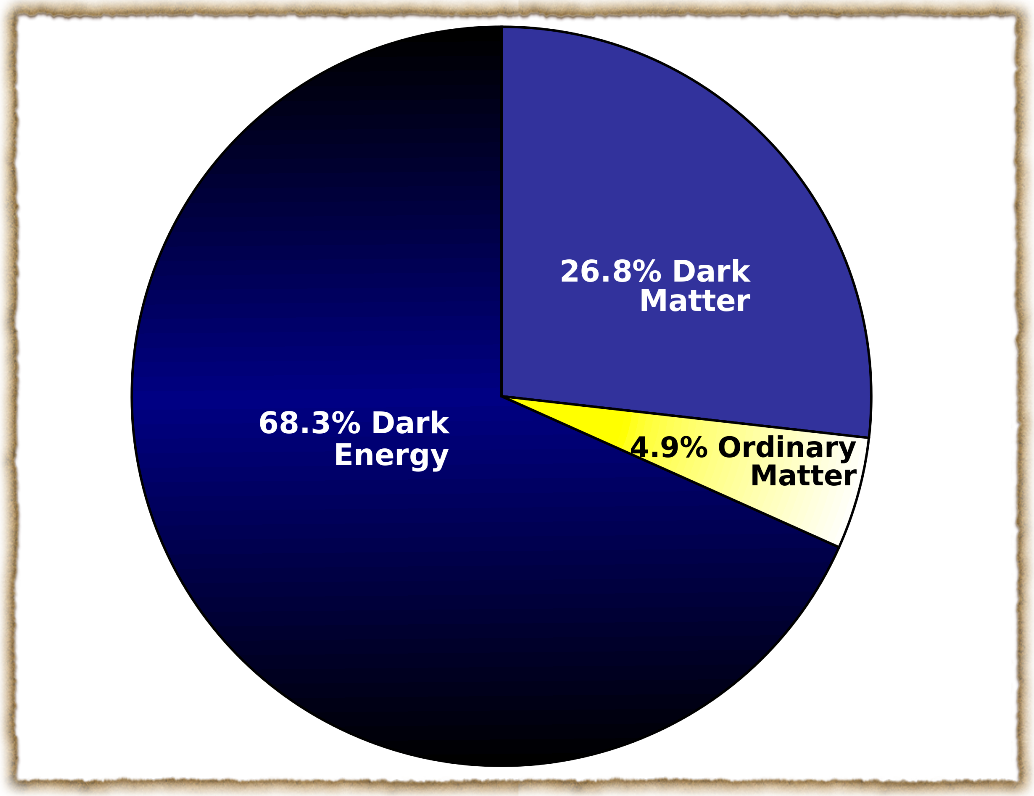
Tata Institute of Fundamental Research, Mumbai

16th Oct, 2024

1) Phys. Rev. Lett. **131**, 091401 (arXiv:2302.07898)
With Basudeb Dasgupta, Ranjan Laha, Anupam Ray

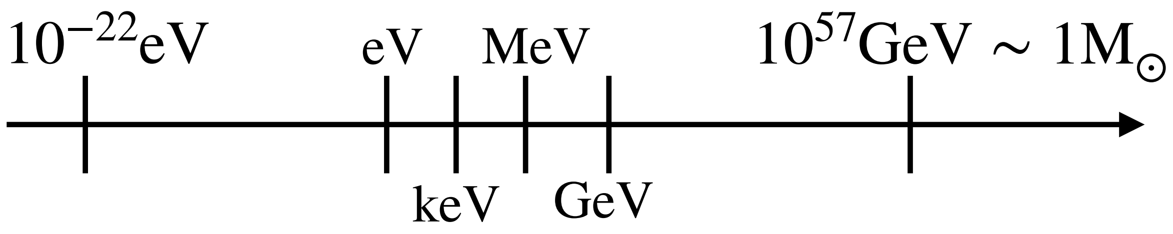
2) Phys. Rev. D 110 (2024), 043006 (arXiv:2403.13886)
With Andrew Miller, Anupam Ray

Dark Matter (DM-χ)



https://www.darkenergysurvey.org/the-des-project/science/

Candidates



ULTRA-LIGHT AXIONS….WIMPS….MASSIVE PRIMORDIAL BLACK HOLES

Direct Detection

$$\chi + \mathrm{SM} \rightarrow \chi + \mathrm{SM}$$

Indirect Detection

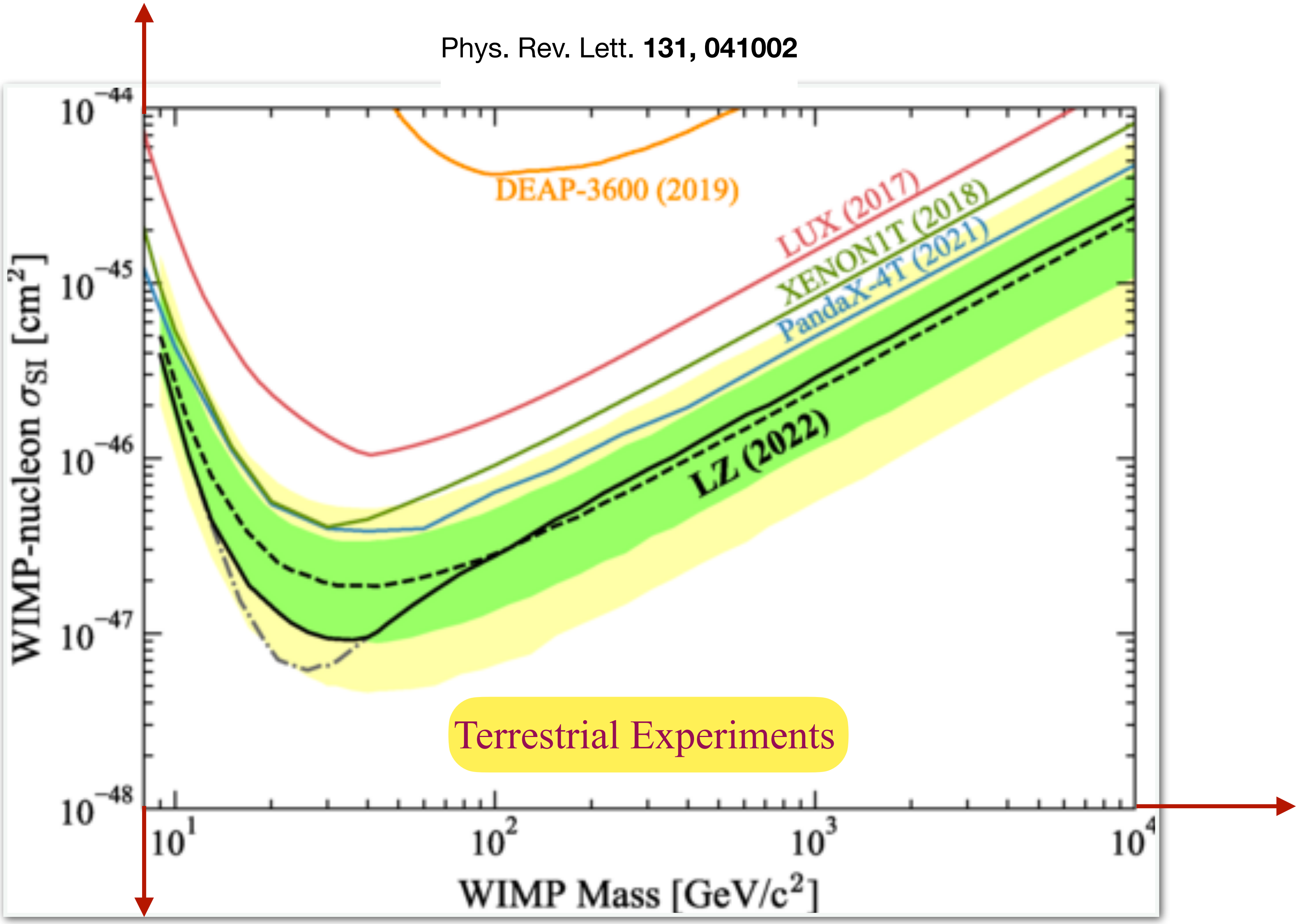
$$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$$

Collider Search

$$\mathrm{SM} + \mathrm{SM} \rightarrow \chi + \chi$$

Non-annihilating Heavy DM particles with some non-gravitational interaction with SM particles

Direct Detection



Phys. Rev. Lett. **131, 041002**

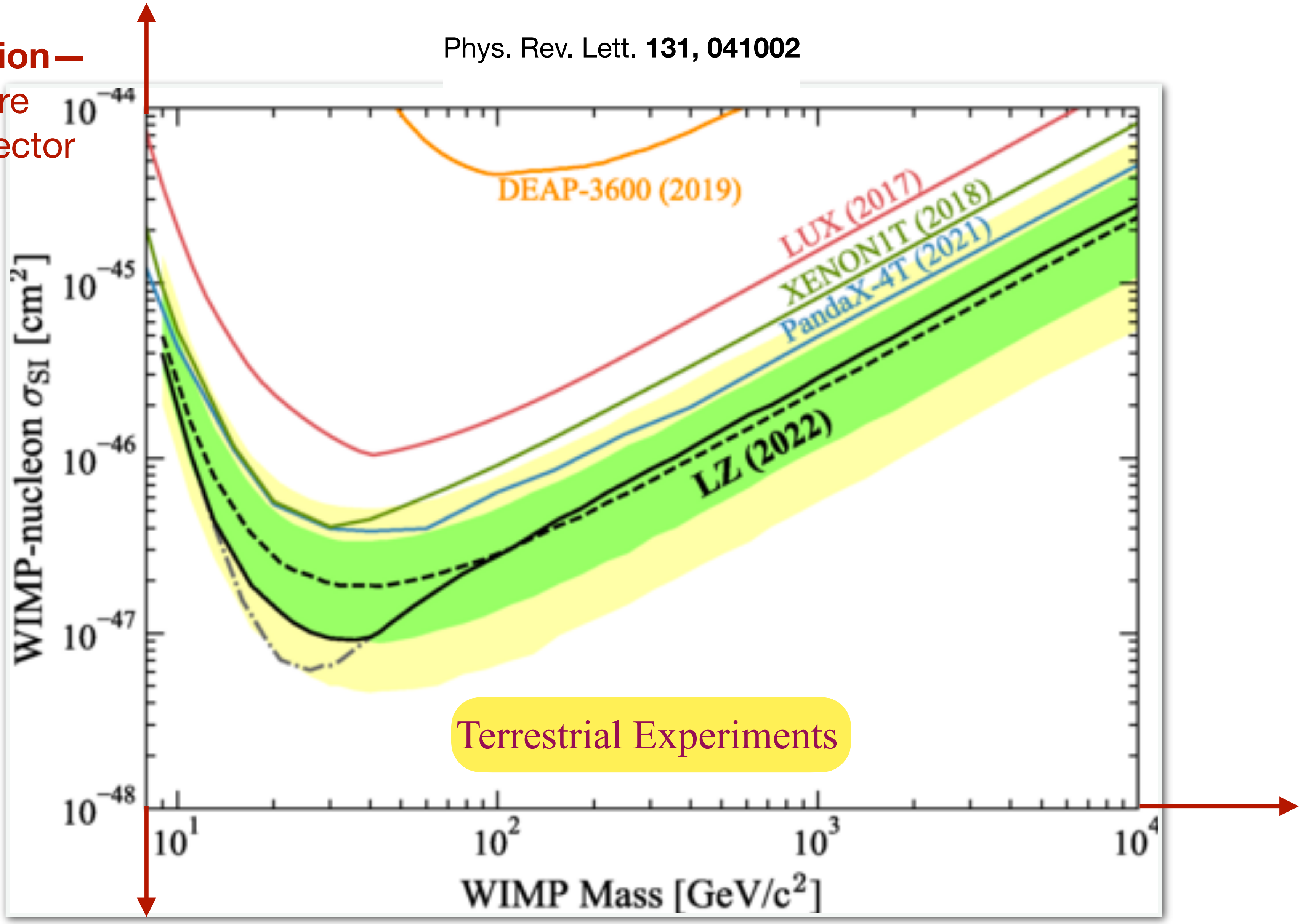
Exposure —

- Terrestrial Detector — kTon year
- Neutron Star as a detector — 10^{33-36} × kTon year

Direct Detection

High Cross-section—
Interacts before
reaching the detector

Phys. Rev. Lett. **131, 041002**



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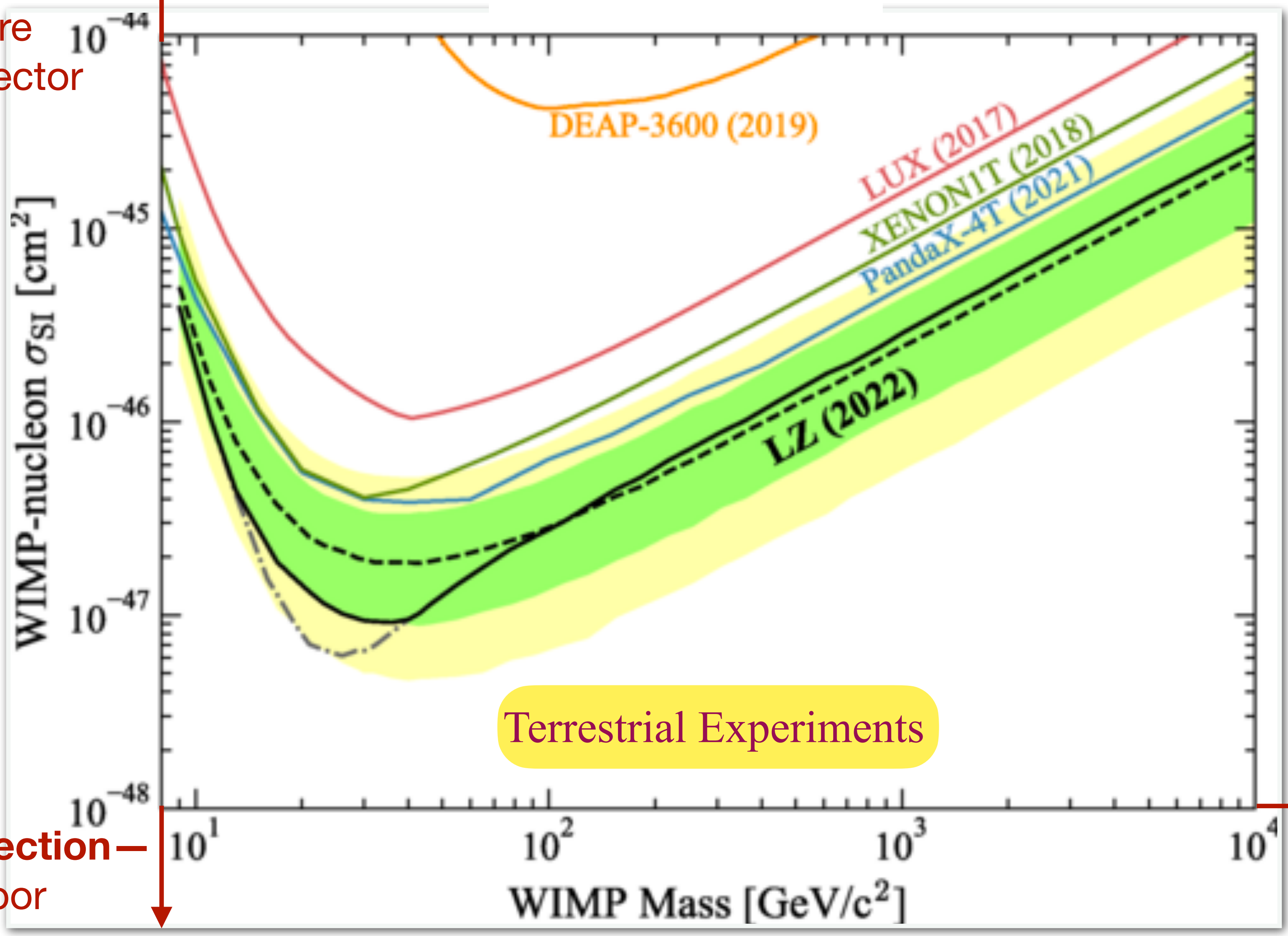

Phys. Rev. Lett. **131, 041002**

Terrestrial Experiments

Smaller Cross-section—
Neutrino Floor

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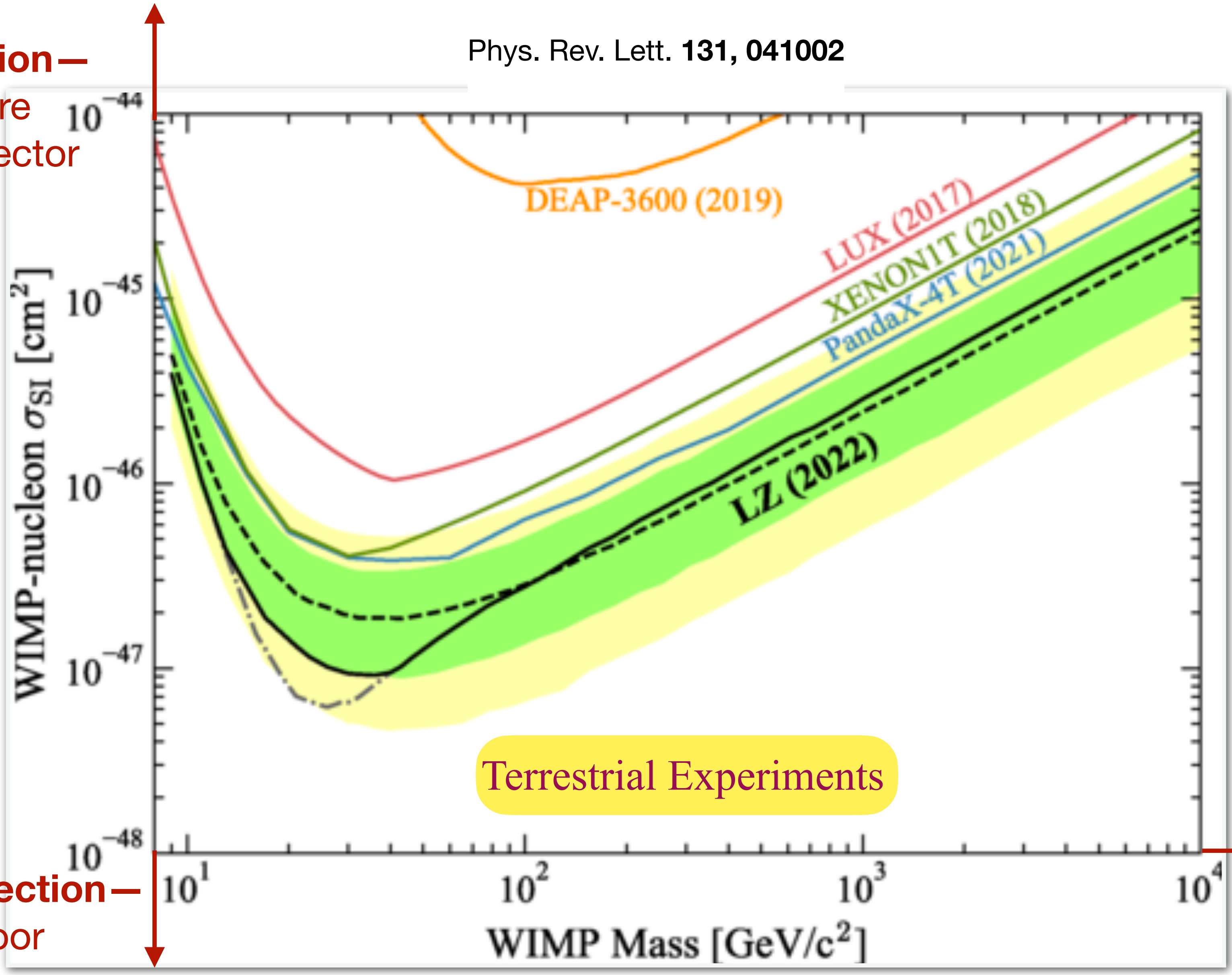

Smaller Cross-section—
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Heavy DM—
smaller flux

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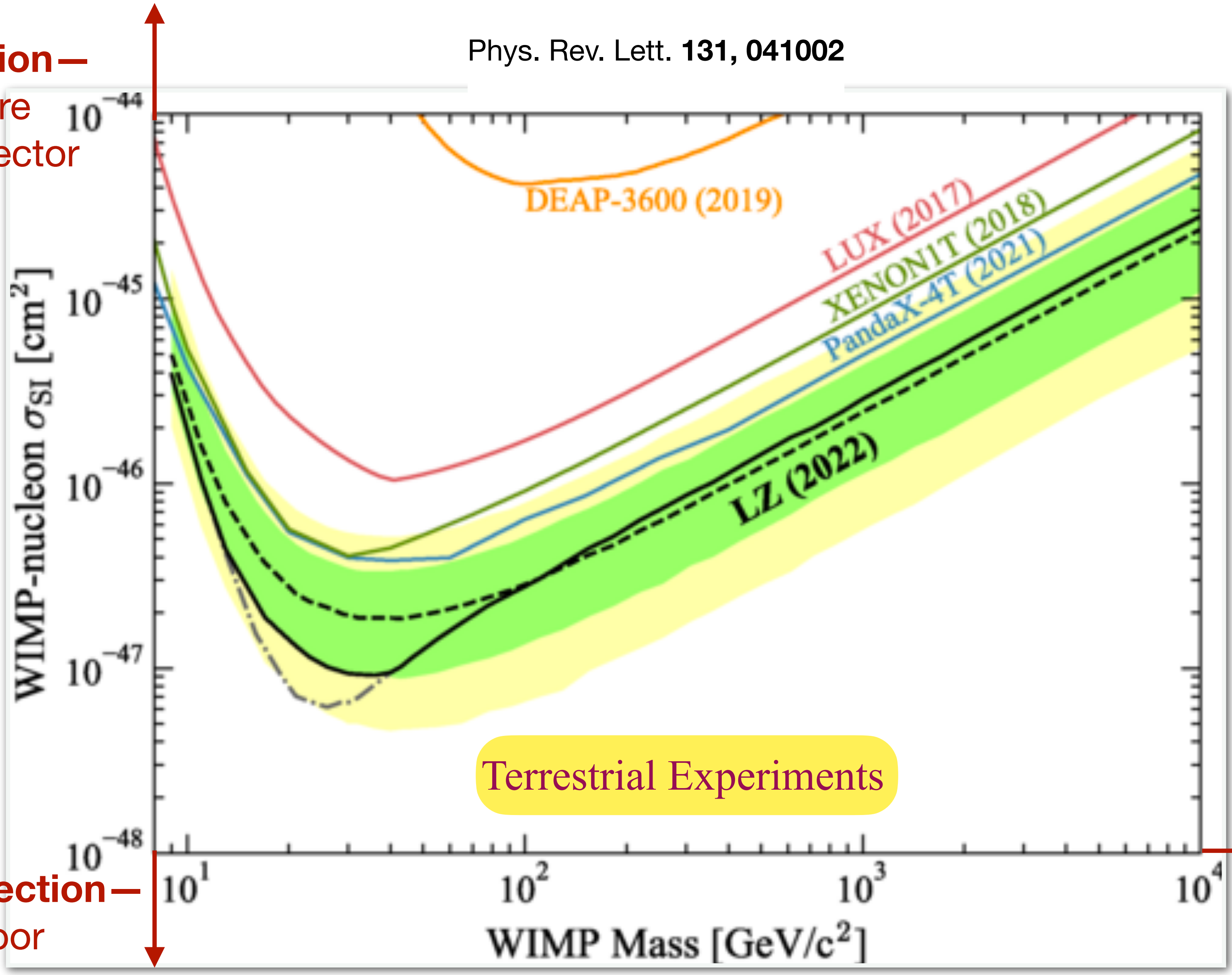

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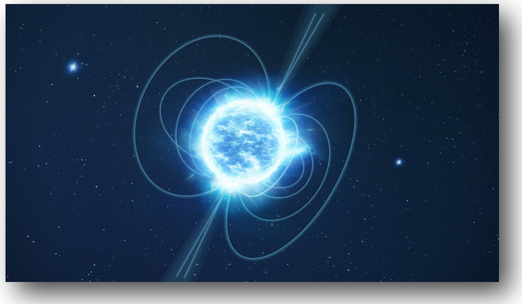

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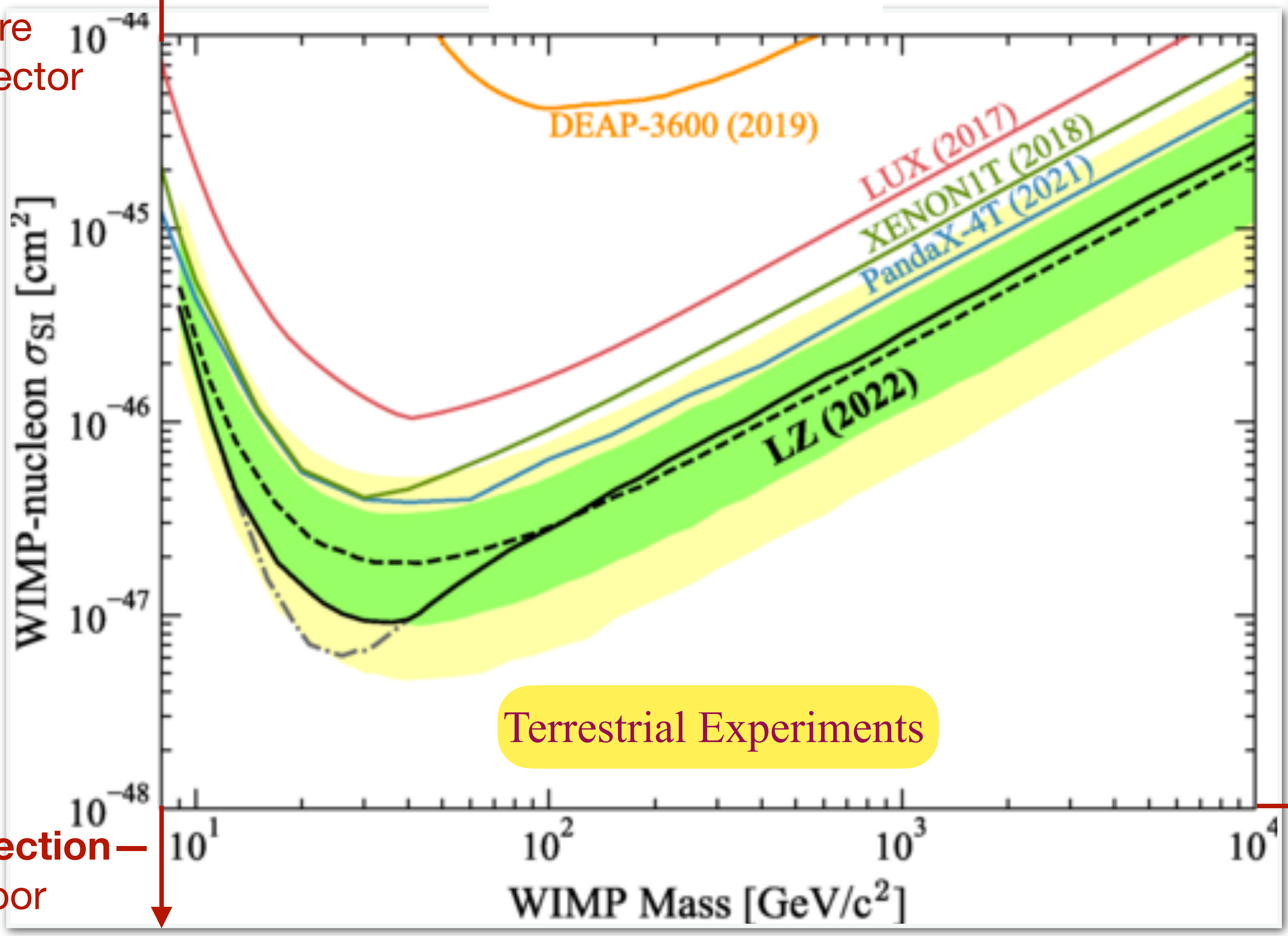

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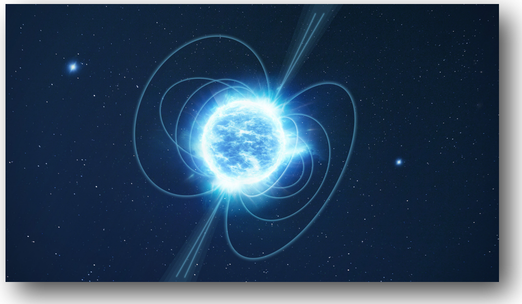

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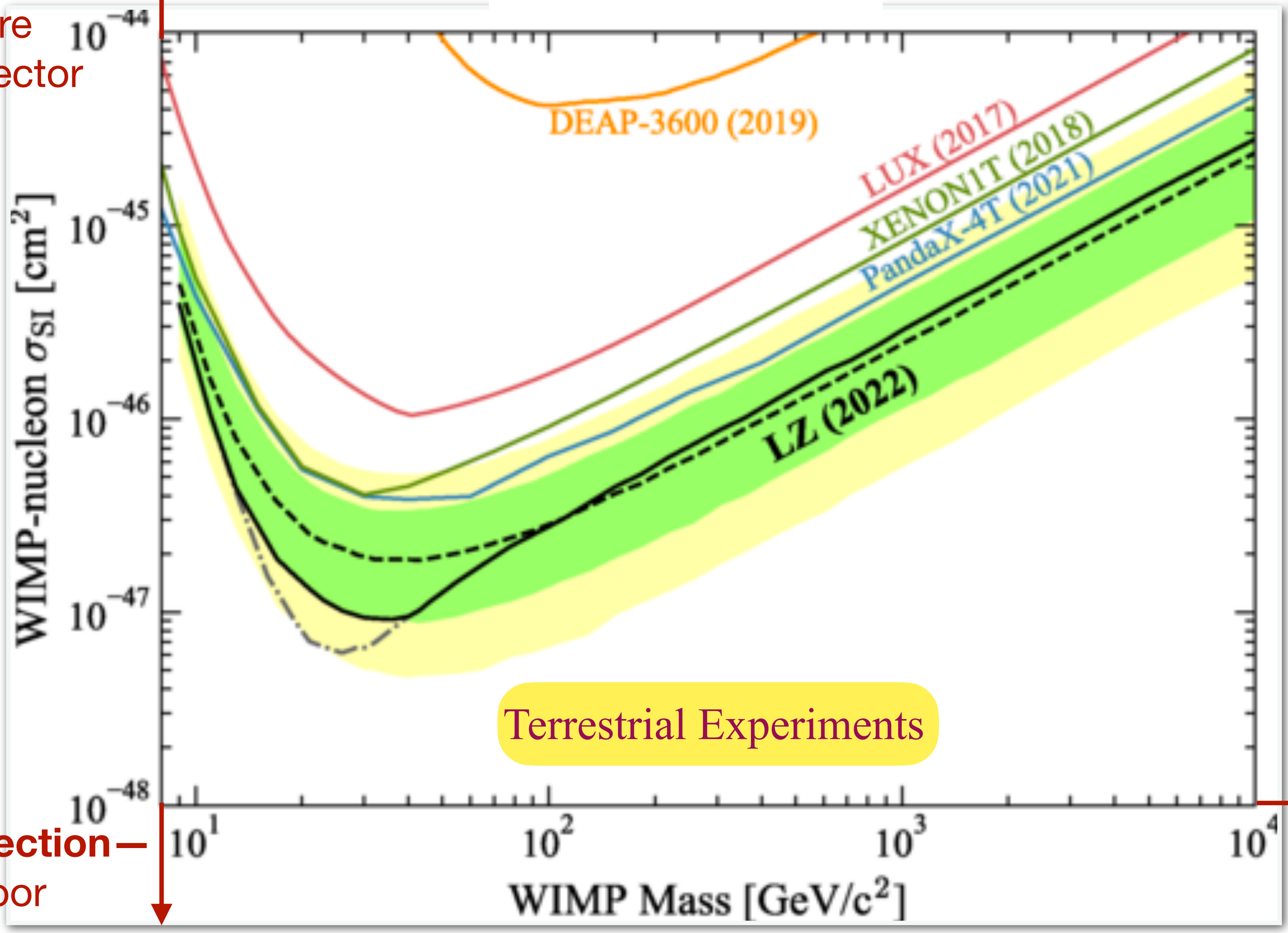

Smaller Cross-section —
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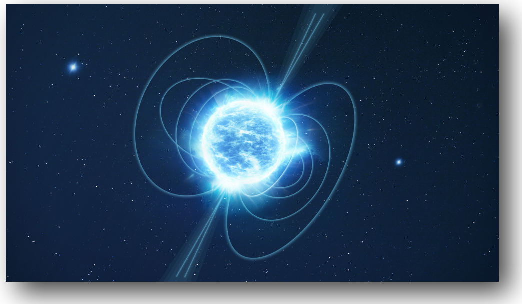


Exposure —
- Terrestrial Detector — kTon year
- Neutron Star as a detector — 10^{33-36} × kTon year

Another exciting probe can be **Gravitational Wave (GW) detectors !!**

The Scenario We Study

DM particles get captured after interacting with the stellar constituents ($V_{DM} < V_{esc}$)

↓

Eventually they lose their energy after successive interactions and thermalise

↓

The DM particles being heavy travel towards the core and forms a thermalised core

↓

The heavier the DM particle the denser the core

↓

Under specific circumstances the core starts to collapse and forms a mini BH
$\sim 10^{-17} M_{\odot}$ for 10^5 GeV DM particle

↓

That mini BH if not too small can eat up the whole progenitor and forms a similar mass BH
$\sim 10^{12}$s for 10^{-16}M$_{\odot}$ BH.

Non-observation of GW signatures from these low-mass BHs leads to stringent constraints in DM parameter space.

Transmuted Black Hole (TBH)

★ **DM capture in Sun-like stars**

$$m_\chi = 10^5\,\mathrm{GeV}, \sigma_{\chi \mathrm{n}} = 10^{-30}\,\mathrm{cm}^2, \mathrm{T}_{\mathrm{core}} = 1.5 \times 10^7\,\mathrm{K}$$

$$\text{Capture rate} \sim f_{\mathrm{cap}} C_{\mathrm{geom}} \sim 1.3 \times 10^{25}\, s^{-1}$$

★ **DM thermalisation**

$$r_{\mathrm{th}} \propto \sqrt{\frac{T}{m_\chi}} \sim 2.8 \times 10^5\,\mathrm{m}$$

★ **Dark core collapse & micro-BH formation**

$$\tau_{\mathrm{collapse}} = 2 \times 10^{11}\,\text{years}$$

★ **Growth of the micro BH & it eats the host star**

$$\text{Mass of the micro BH} \sim 7.8 \times 10^{-9} M_\odot$$

$$\tau_{\mathrm{swallow}} = 10.5\,\text{years}$$

★ **DM capture in Neutron stars**

$$m_\chi = 10^5\,\mathrm{GeV}, \sigma_{\chi \mathrm{n}} = 10^{-45}\,\mathrm{cm}^2, \mathrm{T} = 2.1 \times 10^6\,\mathrm{K}$$

$$\text{Capture rate} \sim f_{\mathrm{cap}} C_{\mathrm{geom}} \sim 2.3 \times 10^{20}\, s^{-1}$$

★ **DM thermalisation**

$$r_{\mathrm{th}} \propto \sqrt{\frac{T}{m_\chi}} \sim 5\,\mathrm{cm}$$

★ **Dark core collapse & micro-BH formation**

$$\tau_{\mathrm{collapse}} = 4.8 \times 10^8\,\text{years}$$

★ **Growth of the micro BH & it eats the host star**

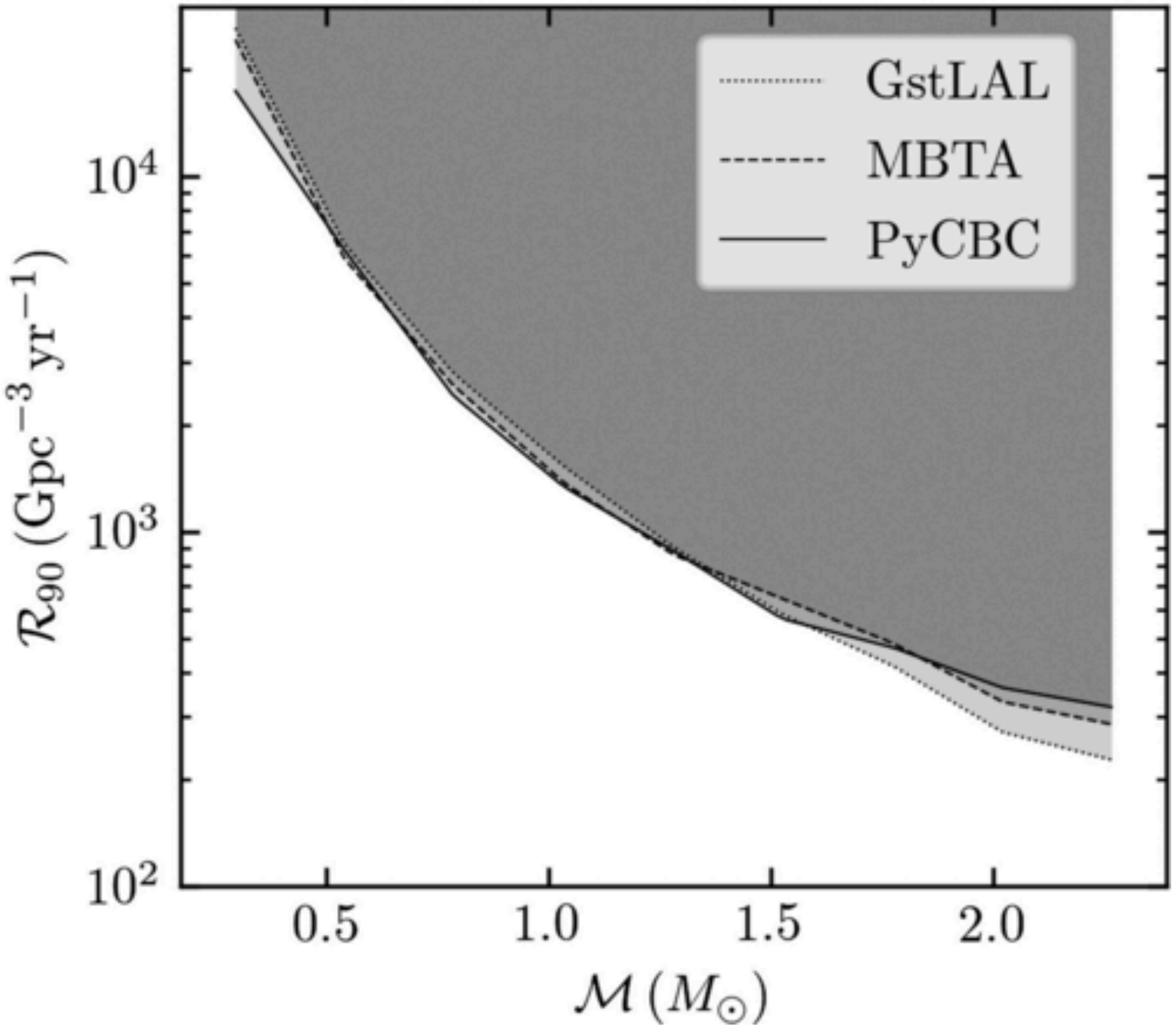
$$\text{Mass of the micro BH} \sim 10^{-16} M_\odot$$

$$\tau_{\mathrm{swallow}} = 3 \times 10^4\,\text{years}$$

$$\tau_{\mathrm{transmutation}} = \tau_{\mathrm{collapse}} + \tau_{\mathrm{swallow}}$$

LVK Search for Low-Mass BH

LVK Collaboration (arXiv:2212.01477)



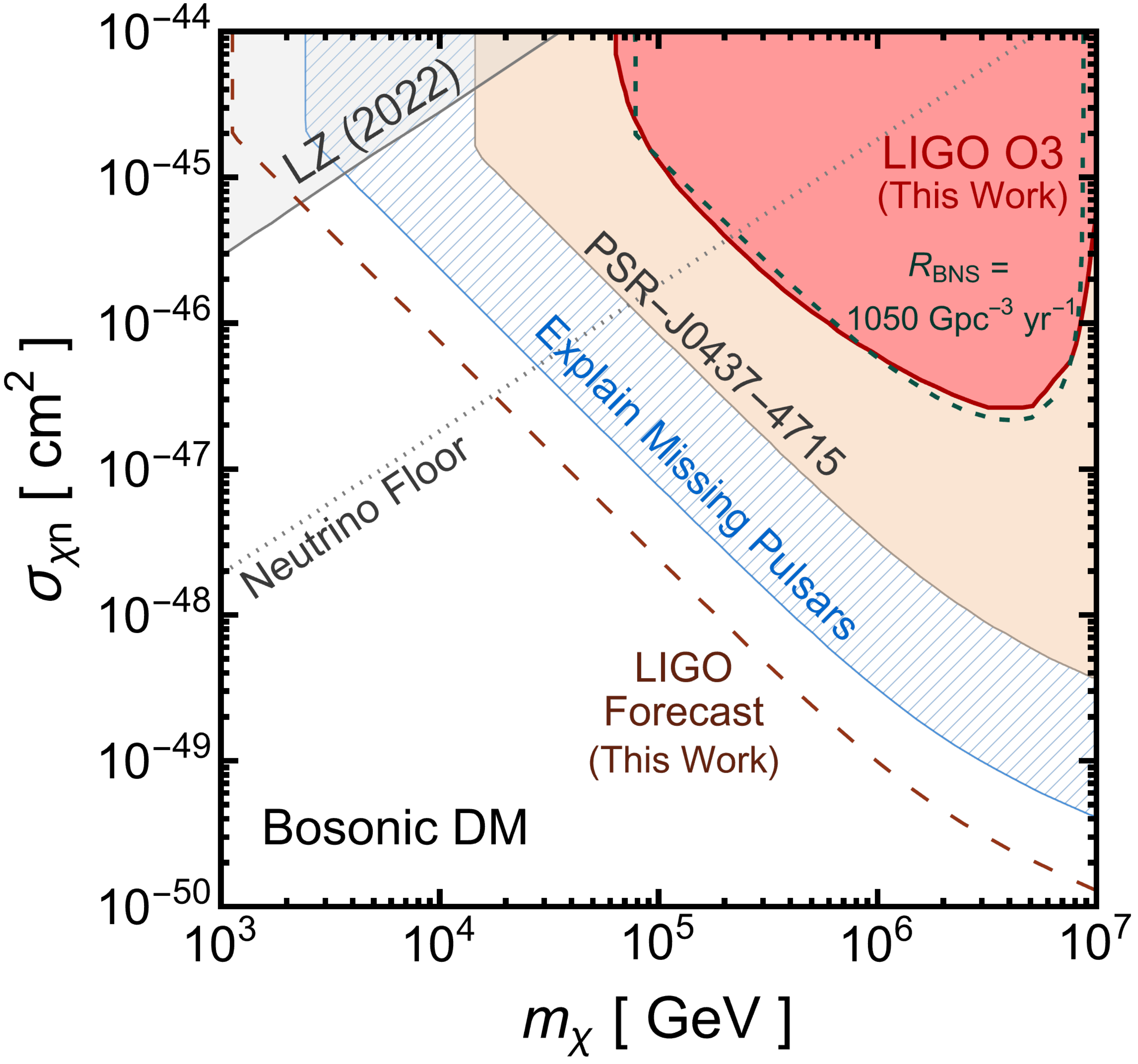
LVK concludes null detection of low mass BH mergers hence they put upper limits on the merger rate with 90% confidence.

$$\mu_{90} = R_{90}\langle \mathrm{VT}\rangle \geq 2.303 \text{ excluded}$$

$\langle \mathrm{VT}\rangle$ is the detector sensitivity.

We propose that DM parameters for which, $R_{\mathrm{TBH}}(m_c) > R_{90}(m_c)$ are excluded.

LIGO as a DM Detector?



Bhattacharya, Dasgupta, Laha, Ray (PRL, 2023)

Priors for Bayesian Analysis

$$m_\chi \in \left[10^4 - 10^8\,\mathrm{GeV}\right]$$
$$\sigma_{\chi n} \in \left[10^{-50} - 10^{-44}\,\mathrm{cm}^2\right]$$
$$R_{\rm BNS} \in \left[10 - 1700\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}\right]$$

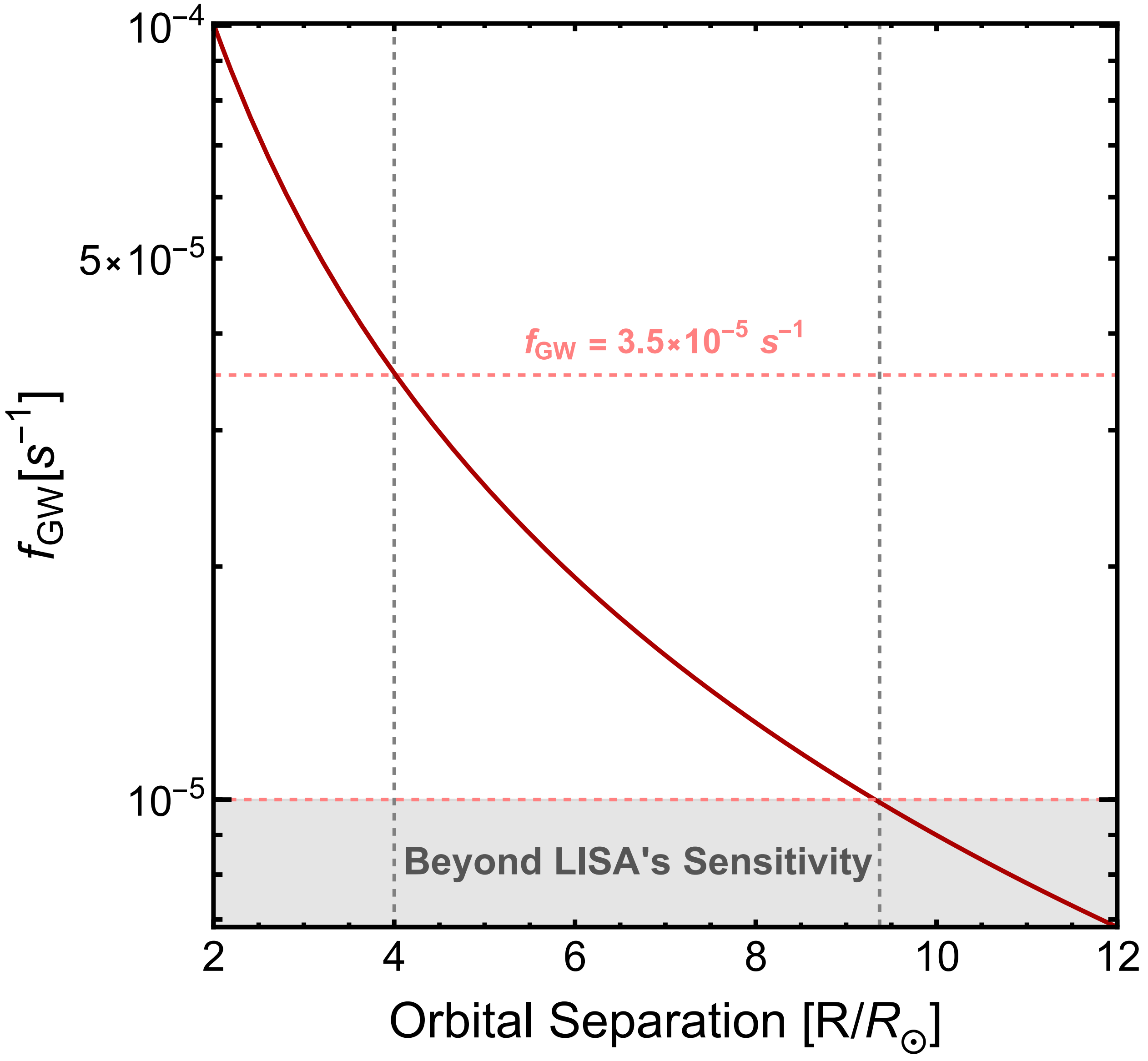
Hybrid Analysis

No priors on DM parameters.

Forecast with $50 \times \langle \mathrm{VT} \rangle$

LISA as a DM Detector?

Close stellar binaries can emit monochromatic continuous GW waves in their inspiral phase.
For sun-like symmetric stellar binaries, if their orbital separation is within $4R_\odot - 9.5R_\odot$, LISA will be sensitive in this frequency range.



Bhattacharya, Miller, Ray (PRD, 2024)

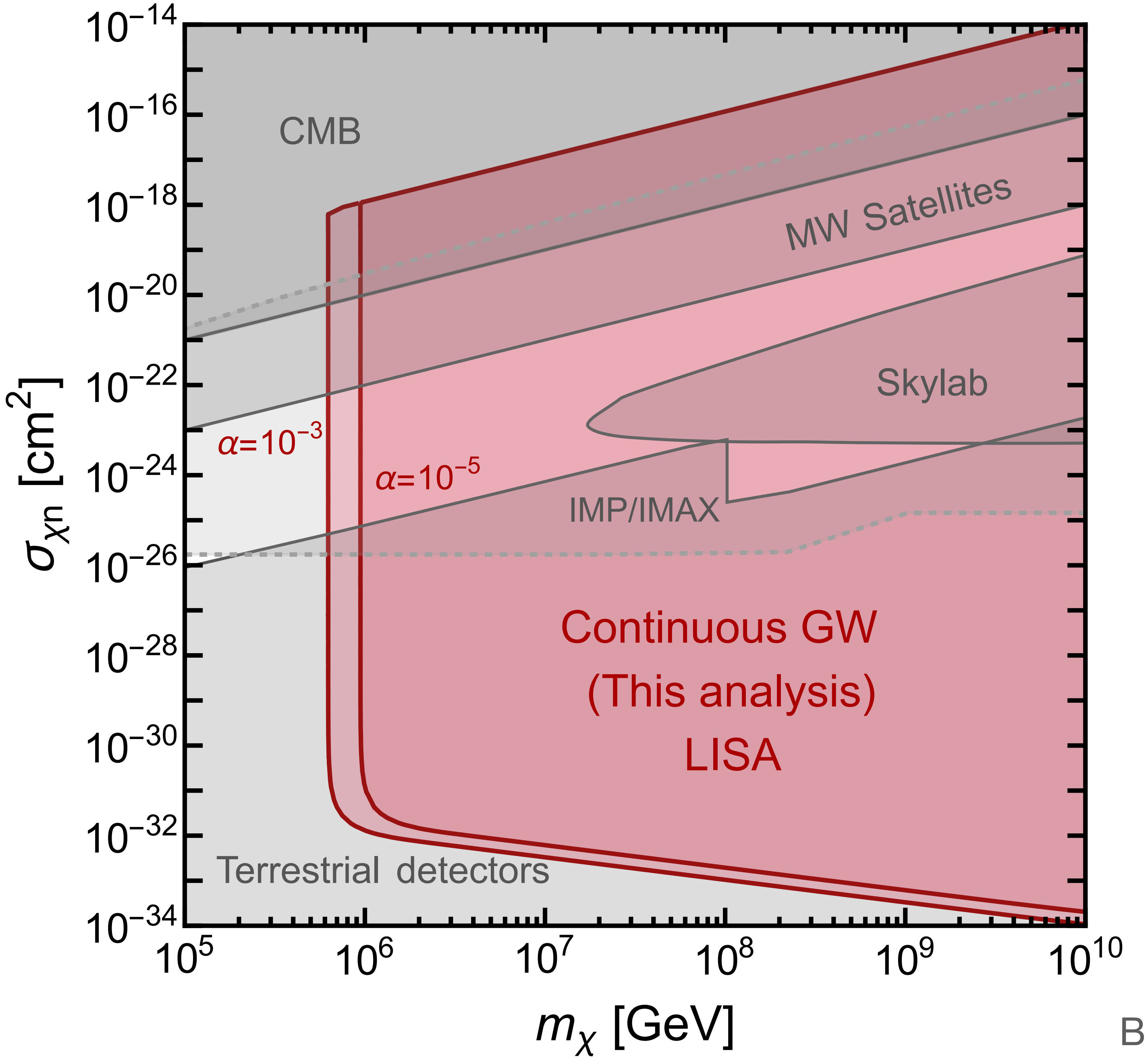
The frequency evolution of these GW signals are too low

$$\dot{f}_{\rm gw} \approx 10^{-23}\,{\rm Hz/s}\left(\frac{\mathscr{M}}{0.87M_\odot}\right)^{5/3}\left(\frac{f_{\rm GW}}{3.5\times10^{-5}\,{\rm Hz}}\right)^{11/3}$$

LISA as a DM Detector?

These sun-like stellar binaries can capture DM particles and eventually form a binary BH system within the age of the universe.

Non-observation of continuous GW signals from these inspiralling stellar binaries can put an upper limit on their occurrence rate density $\mathscr{R}$.



DM parameters for which,

$$R_{\text{occurrence}_{|\text{theo}}}(m_\chi, \sigma_{\chi n}, \alpha) > \mathscr{R}_{\text{occurrence}_{|\text{gw}}}$$

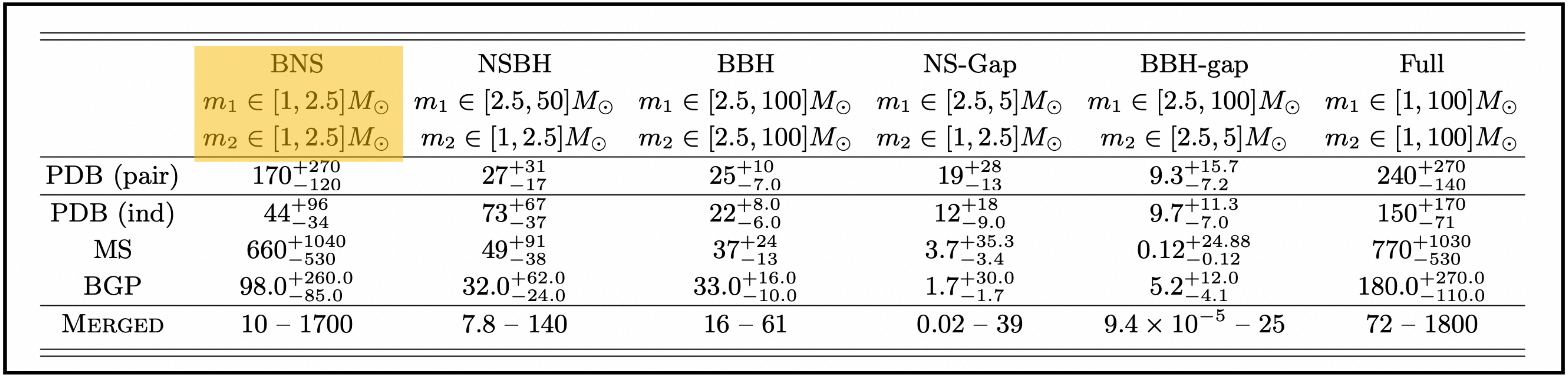
are ruled out.

Here α denotes the fraction of close stellar sun-like binaries.

Bhattacharya, Miller, Ray (PRD, 2024)

BNS vs Low Mass BBH

1) To distinguish low-mass BH mergers from Neutron Star mergers



	BNS $m_1 \in [1, 2.5] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	NSBH $m_1 \in [2.5, 50] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	BBH $m_1 \in [2.5, 100] M_\odot$ $m_2 \in [2.5, 100] M_\odot$	NS-Gap $m_1 \in [2.5, 5] M_\odot$ $m_2 \in [1, 2.5] M_\odot$	BBH-gap $m_1 \in [2.5, 100] M_\odot$ $m_2 \in [2.5, 5] M_\odot$	Full $m_1 \in [1, 100] M_\odot$ $m_2 \in [1, 100] M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$	19^{+28}_{-13}	$9.3^{+15.7}_{-7.2}$	240^{+270}_{-140}
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	770^{+1030}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
Merged	10 – 1700	7.8 – 140	16 – 61	0.02 – 39	9.4×10^{-5} – 25	72 – 1800

LVK—arXiv:2111.03634

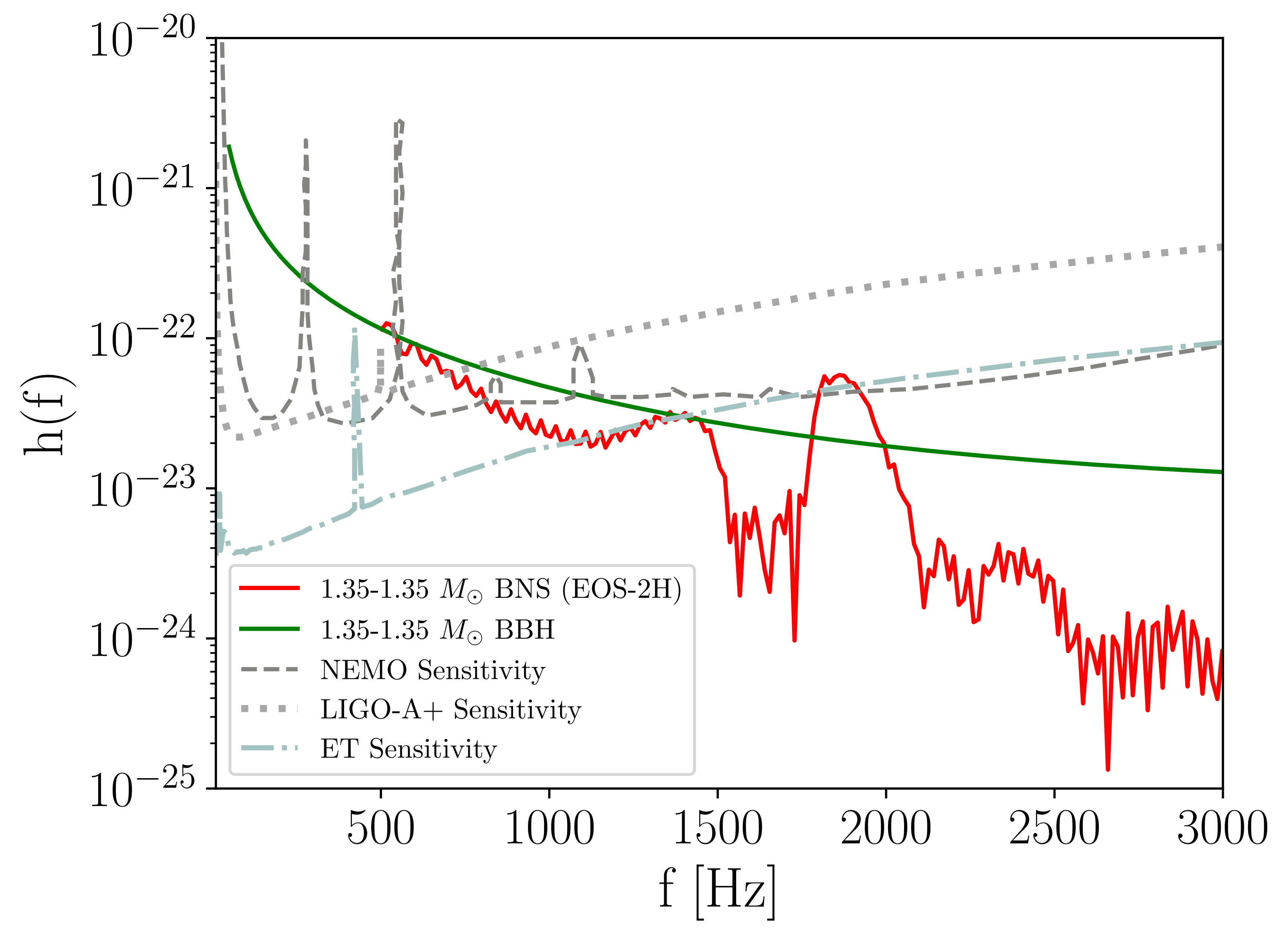
Possible Approaches

a) Tidal Deformability (Phys.Rev.D 107 (2023) 8, 083037)

b) **Post Merger Signals** (Matter effect for BNS systems may dampen the strain significantly)

BNS vs Low Mass BBH

Preliminary Result



Work in progress with Basudeb Dasgupta & Shasvath Kapadia

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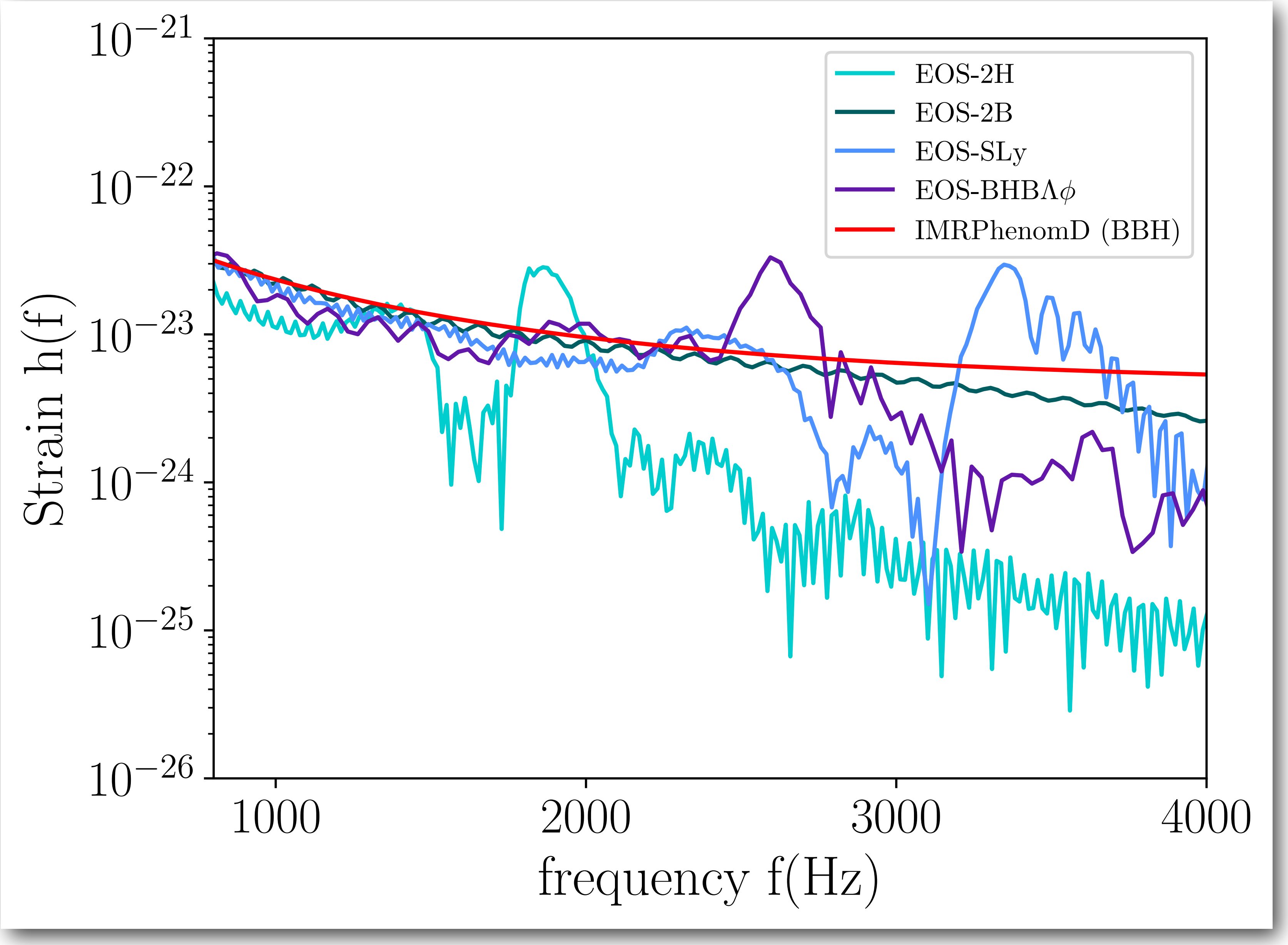

Work in progress with Basudeb Dasgupta & Shasvath Kapadia

Concluding Remarks

- GW observations can shed light into particle dark matter theory and can even do better than the terrestrial experiments in future.

- Given confirmed GW events like GW230529, GW190814, GW190425, low-mass BH scenario has become a viable explanation and hence needs to be explored.

- Without an electromagnetic counterpart it is still hard to conclude whether two Neutron stars or low-mass BHs merged. We are trying to distinguish BNS mergers from low-mass BBH merger by analysing their postmerger signal.

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THANKS!

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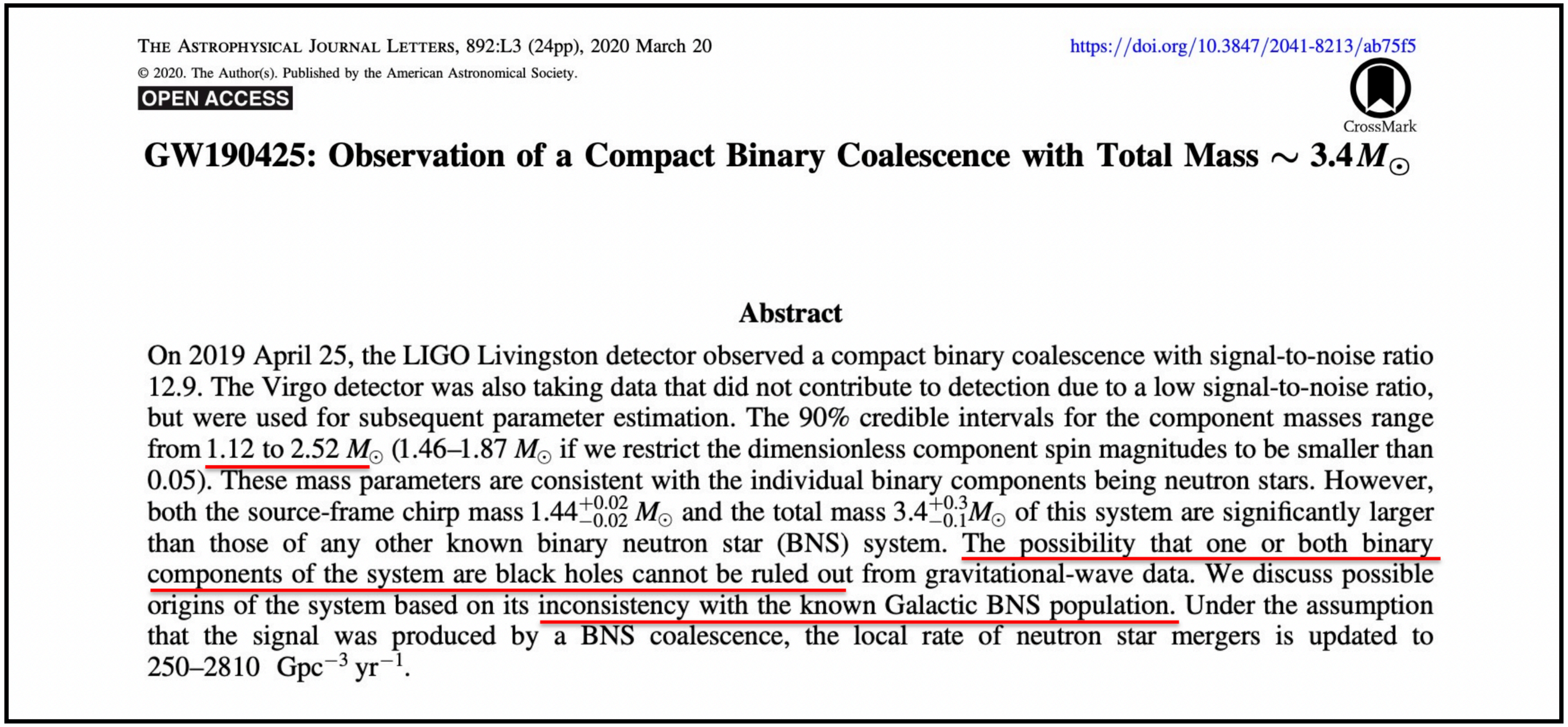
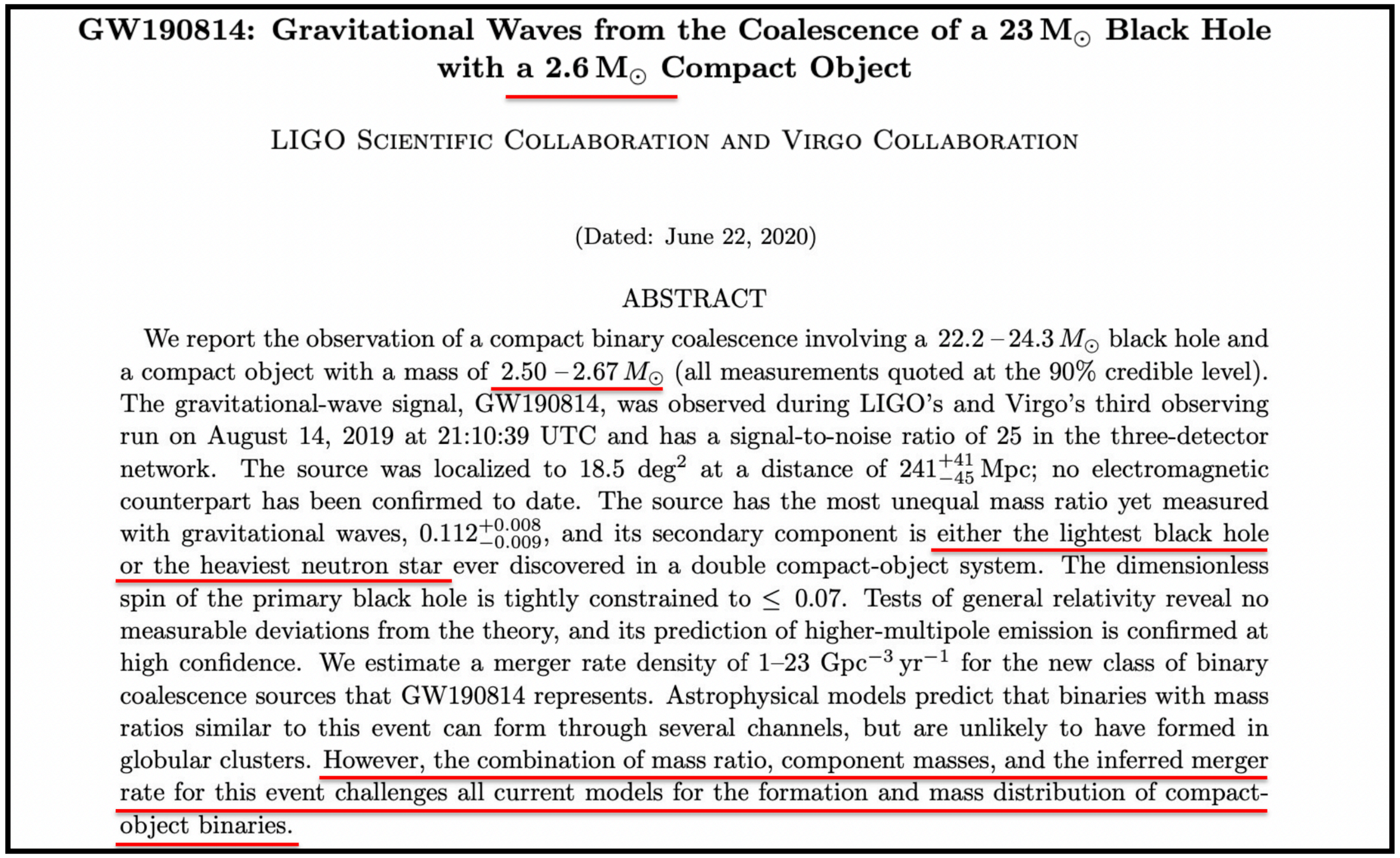


The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20
https://doi.org/10.3847/2041-8213/ab75f5

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 Gpc^{-3} yr^{-1}.



GW190814: Gravitational Waves from the Coalescence of a 23 $\mathrm{M}_\odot$ Black Hole with a 2.6 $\mathrm{M}_\odot$ Compact Object

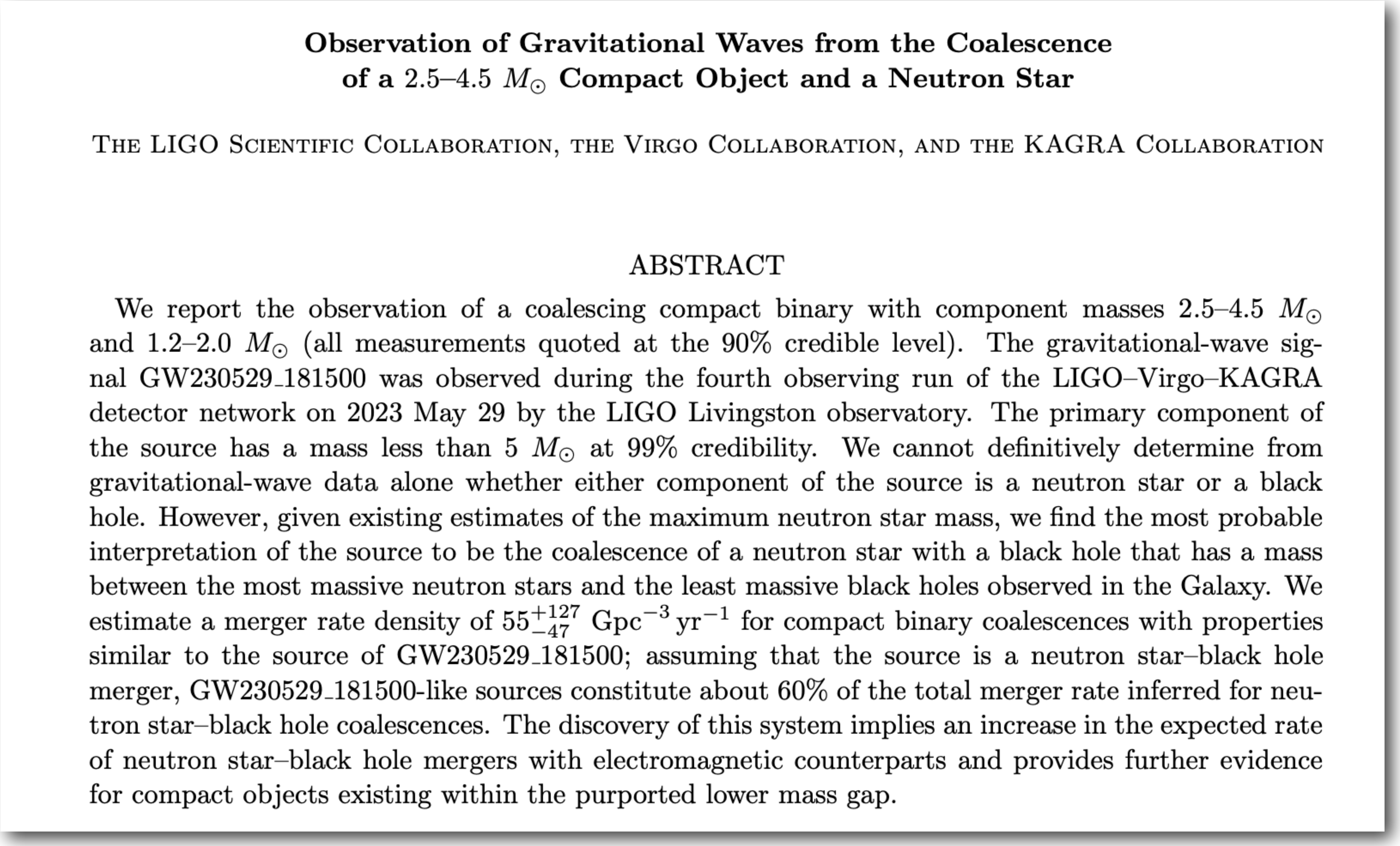
LIGO Scientific Collaboration and Virgo Collaboration

(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 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 ≤ 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 Gpc^{-3} 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.

Slide credit: Basudeb Dasgupta

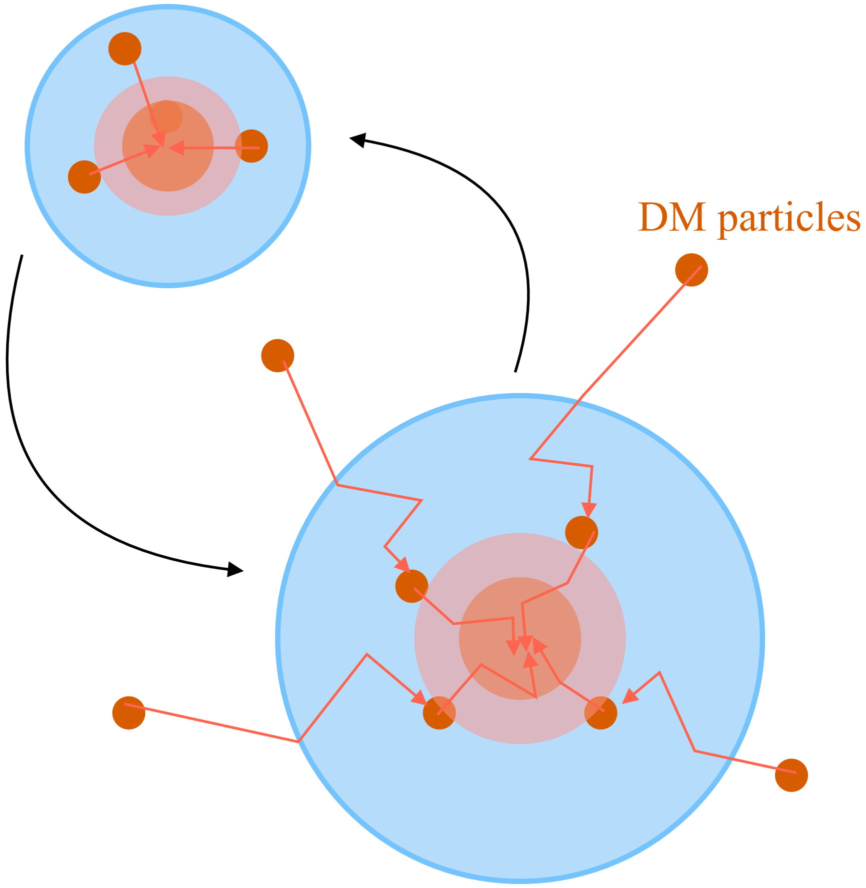


Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 $M_\odot$ Compact Object and a Neutron Star

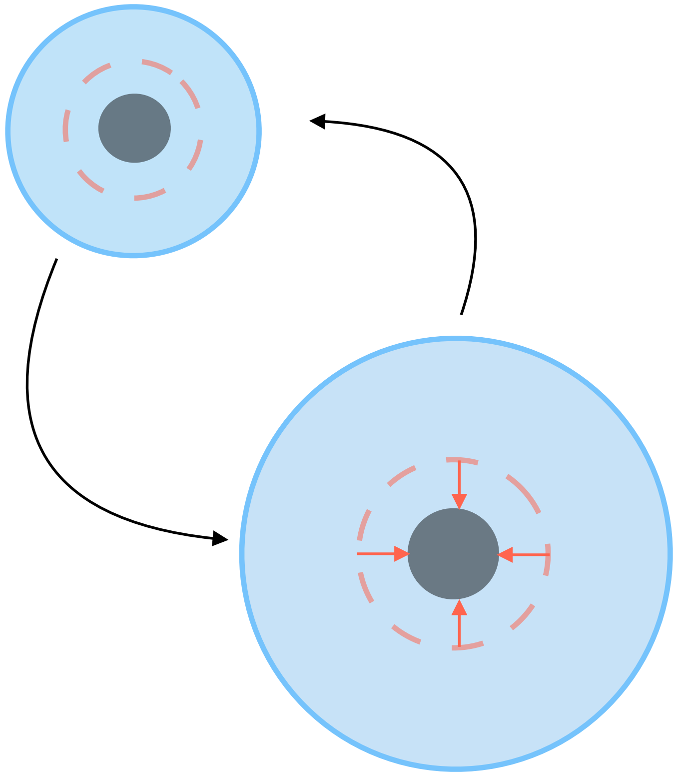
The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration

ABSTRACT

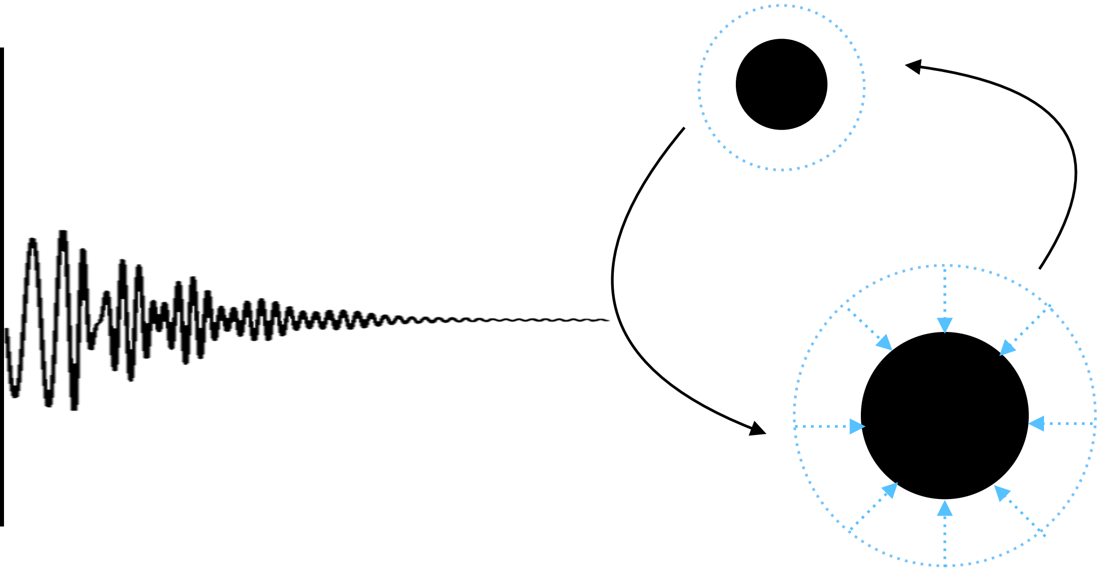
We report the observation of a coalescing compact binary with component masses 2.5–4.5 $M_\odot$ and 1.2–2.0 $M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal GW230529_181500 was observed during the fourth observing run of the LIGO–Virgo–KAGRA detector network on 2023 May 29 by the LIGO Livingston observatory. The primary component of the source has a mass less than 5 $M_\odot$ at 99% credibility. We cannot definitively determine from gravitational-wave data alone whether either component of the source is a neutron star or a black hole. However, given existing estimates of the maximum neutron star mass, we find the most probable interpretation of the source to be the coalescence of a neutron star with a black hole that has a mass between the most massive neutron stars and the least massive black holes observed in the Galaxy. We estimate a merger rate density of $55^{+127}_{-47}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for compact binary coalescences with properties similar to the source of GW230529_181500; assuming that the source is a neutron star–black hole merger, GW230529_181500-like sources constitute about 60% of the total merger rate inferred for neutron star–black hole coalescences. The discovery of this system implies an increase in the expected rate of neutron star–black hole mergers with electromagnetic counterparts and provides further evidence for compact objects existing within the purported lower mass gap.



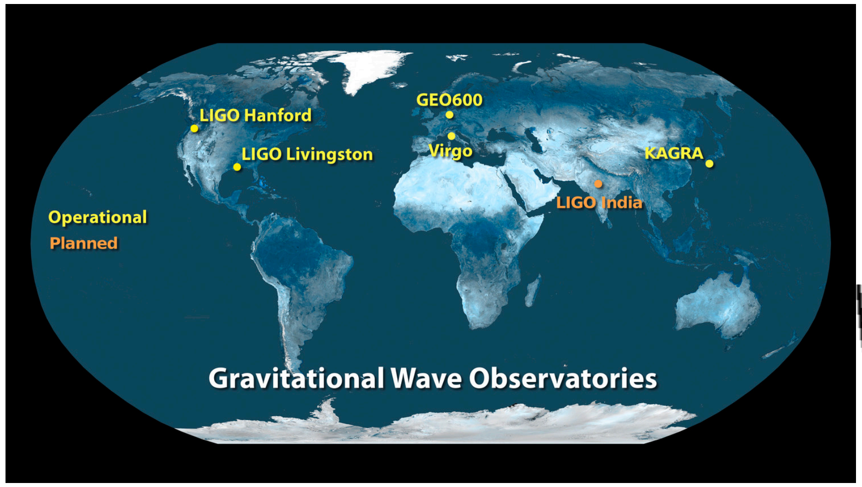
1. Galactic Dark Matter particles accumulate in the Neutron Star and form a dense core



2. The dark core collapses and forms a tiny black hole



3. Seed black hole eats up the host star and forms Transmuted black hole



Credit: Caltech/MIT/LIGO Lab

4. Non detection of these low mass black hole mergers sets constraints on DM parameter space.

TBH-TBH Merger Rate

Binary Neutron Star Merger Rate $t_0 = 13.79\,\mathrm{Gyr},\ t_f = \text{Binary formation time}$

$$R_{\mathrm{BNS}} = \int_{t_*}^{t_0} \frac{dR_{\mathrm{BNS}}}{dt_f} dt_f \approx \ (10 - 1700)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

arXiv:2111.03634v4 (LVK)
Taylor, Gair PRD.2012

In presence of DM parameters, a fraction of these BNS mergers will convert into TBH-TBH mergers and should be detected by GW detectors if,

$$t_0 > t_f + \tau_{\mathrm{transmutation}}$$

Dasgupta, Laha, Ray PRL. 2021+ This Work

Binary TBH Merger Rate

$$R_{\mathrm{BNS}} = \int \frac{df}{dr} dr \int_{t_*}^{t_0} \frac{dR_{\mathrm{BNS}}}{dt_f} dt_f \times \Theta\left[t_0 - t_f - \tau_{\mathrm{trans}}[m_\chi, \sigma_{\chi n}, \rho_{\mathrm{ext}}[r, t_0]]\right]$$

Spatial distribution of BNSs

DM parameters determine the fraction

Capture Rate

$$\mathbf{C} = \underbrace{\frac{\rho_\chi}{m_\chi}\int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2)}_{\text{Flux}} \times \underset{\substack{\big\downarrow \\ \text{Stellar Targets}}}{N_n} \times \text{Min}[\sigma_{\chi\rm n}, \sigma_{\rm sat}] \times \underset{\substack{\big\downarrow \\ \text{Probability of getting} \\ \text{Captured after} \\ \text{single collision}}}{\text{g}_1(\text{u})}$$

$$m_\chi = 10^5\,\text{GeV}, \sigma_{\chi\rm n} = 10^{-45}\,\text{cm}^2, \text{T} = 2.1\times 10^6\,\text{K}$$

$$\text{Capture rate} \sim \pi R^2 \frac{\rho_\chi}{m_\chi}\text{Min}[\frac{\sigma_{\chi\rm n}}{\sigma_{\rm sat}},1] \quad \approx 1.4\times 10^{20}\,\text{s}^{-1}$$

TBH Formation

$$\text{Thermalisation Radius, } r_{th} = \sqrt{\frac{9k_B T_{NS}}{4\pi G \rho_{NS} m_\chi}}$$

so massive DM particles accumulate to the extreme core.

TBH Formation

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Seed BH Formation Condition

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Seed BH Formation Condition

$$N_\chi^{BH} = \max\left[N_\chi^{self}, N_\chi^{Cha}\right]$$

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$$\text{Thermalisation Radius, } \mathrm{r_{th}} = \sqrt{\frac{9\mathrm{k_B T_{NS}}}{4\pi \mathrm{G}\rho_{\mathrm{NS}}\mathrm{m}_\chi}}$$

so massive DM particles accumulate to the extreme core.

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$$M_{\text{pl}} = 1.2 \times 10^{19}\,\text{GeV}$$

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Put, 1 GeV as neutron mass, neutron being fermion we get, $M_{\rm BH} \sim 10^{57}\,\rm GeV \simeq 1\,M_\odot$

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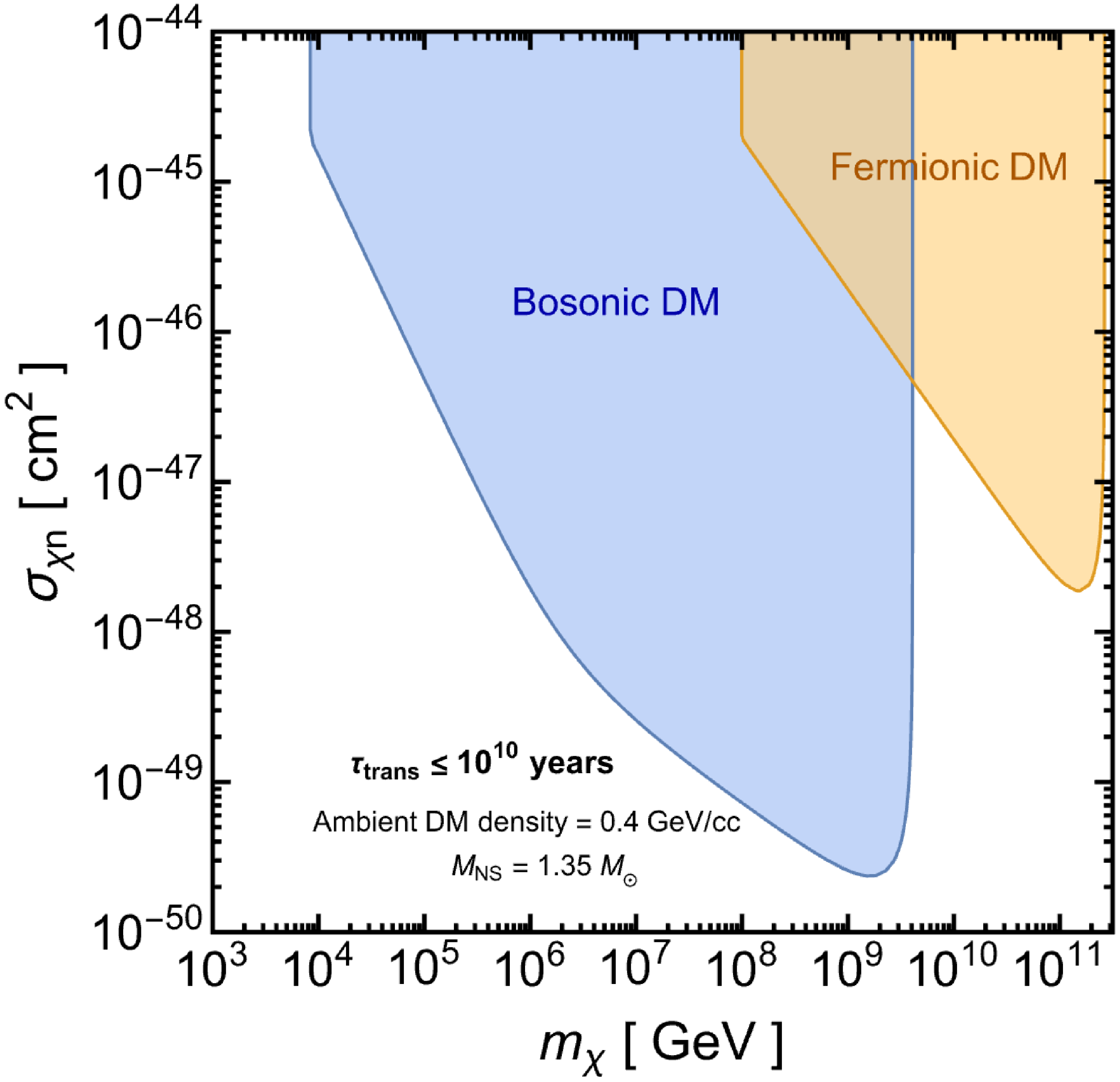
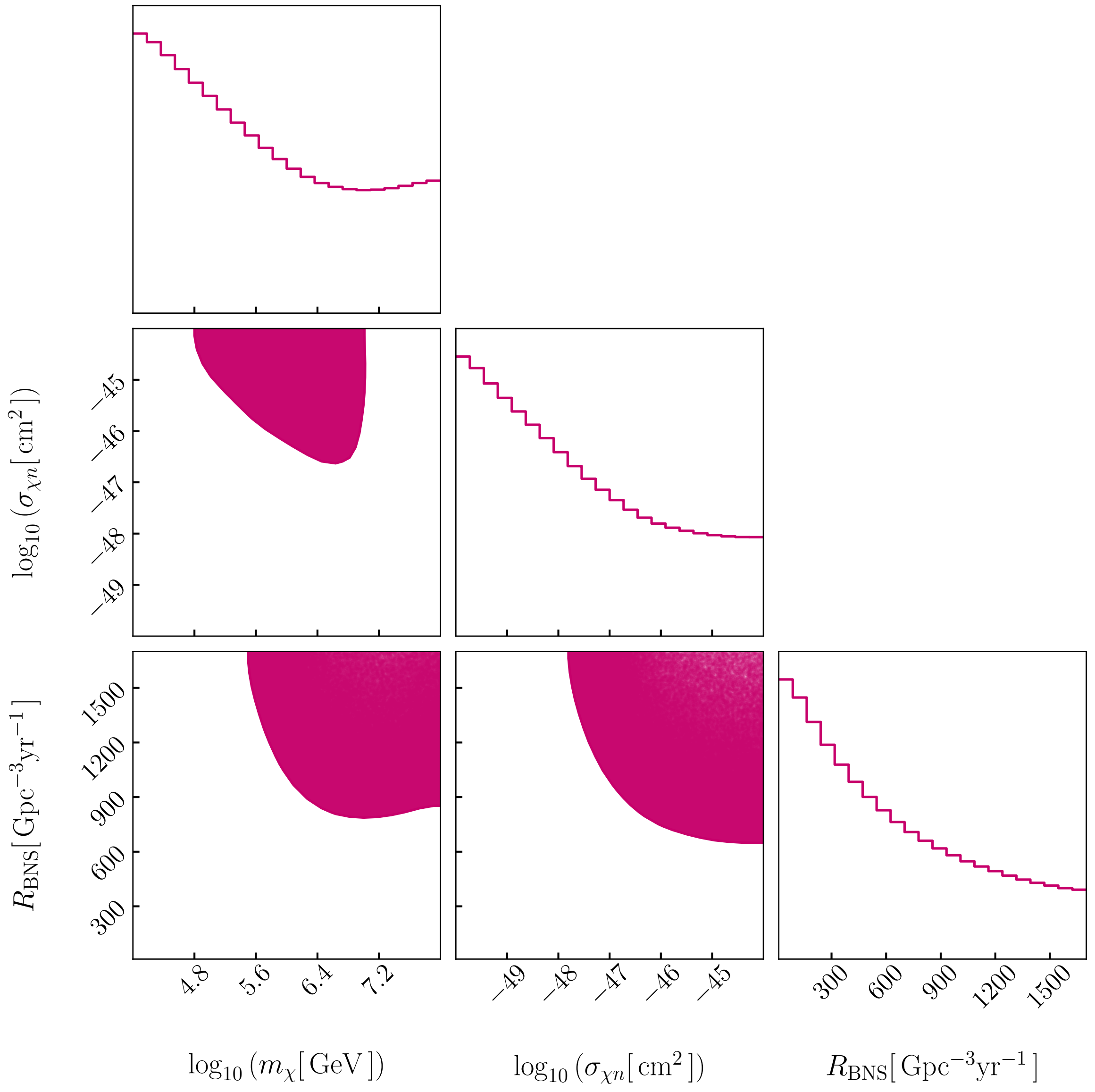
Put, 1 GeV as neutron mass, neutron being fermion we get, $M_{BH} \sim 10^{57}\,\text{GeV} \simeq 1\,\text{M}_\odot$

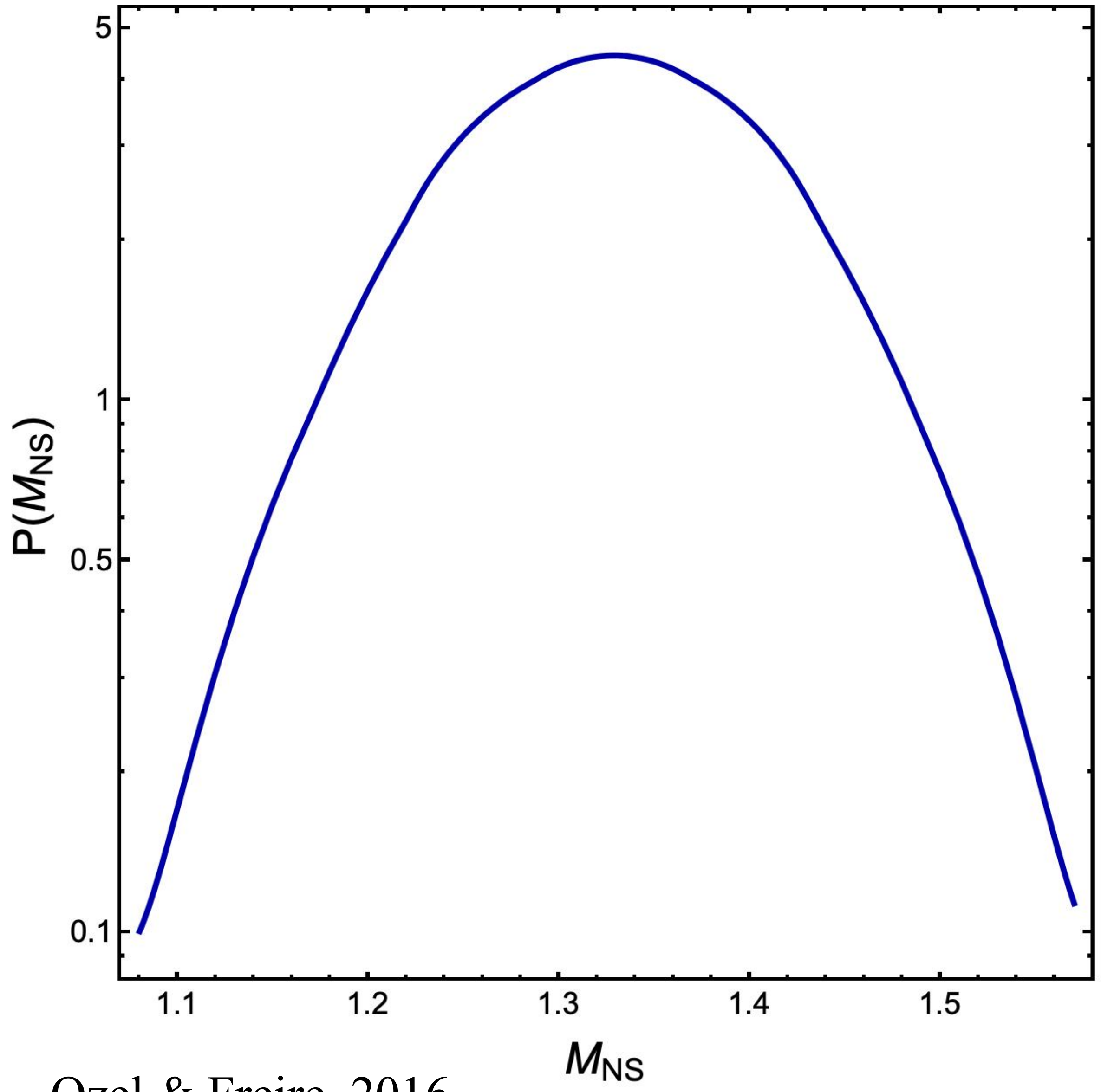
If the seed BH is $< 10^{-19}\, M_\odot$, efficient Hawking radiation leads to impossible transmutation

Priors are set from

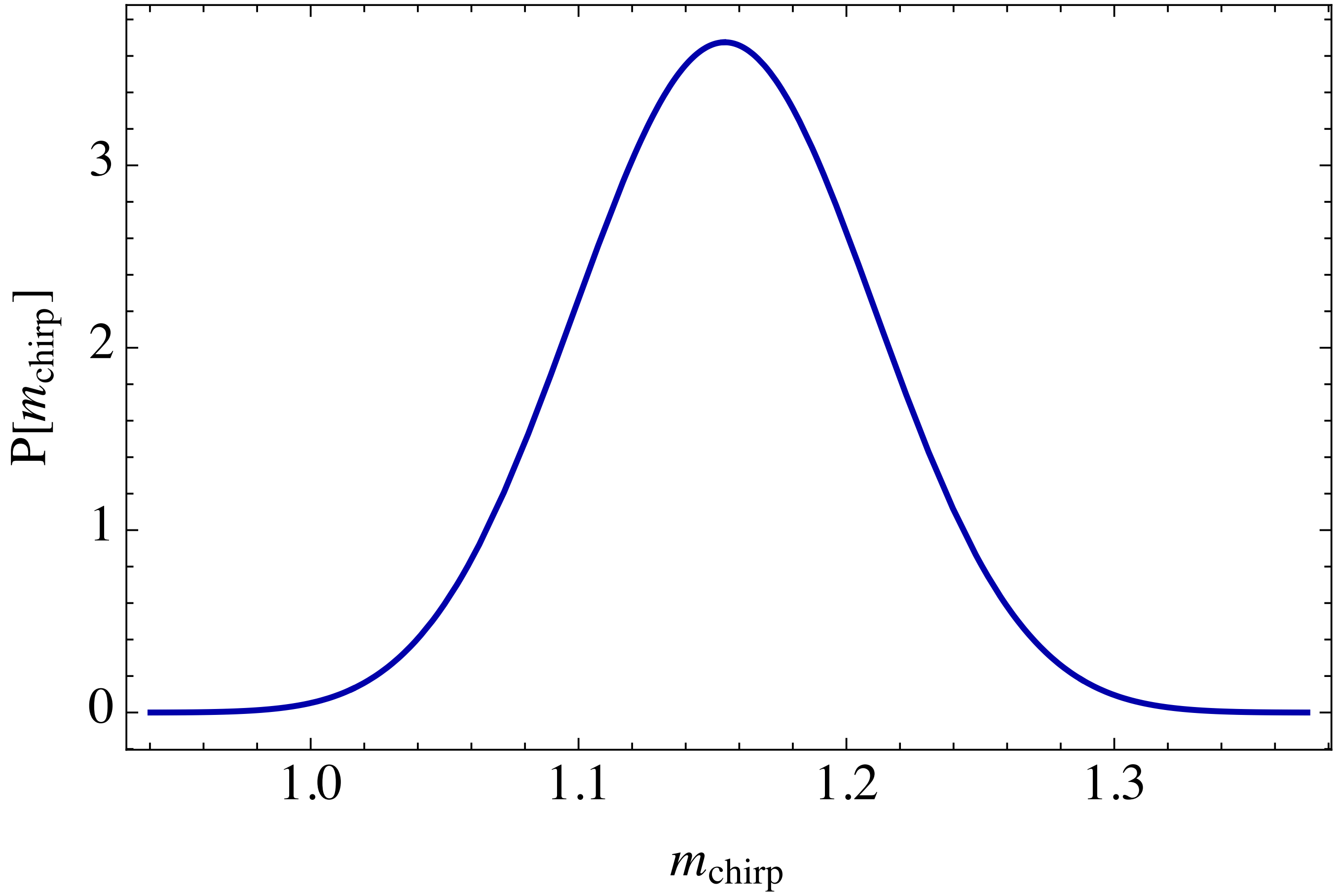




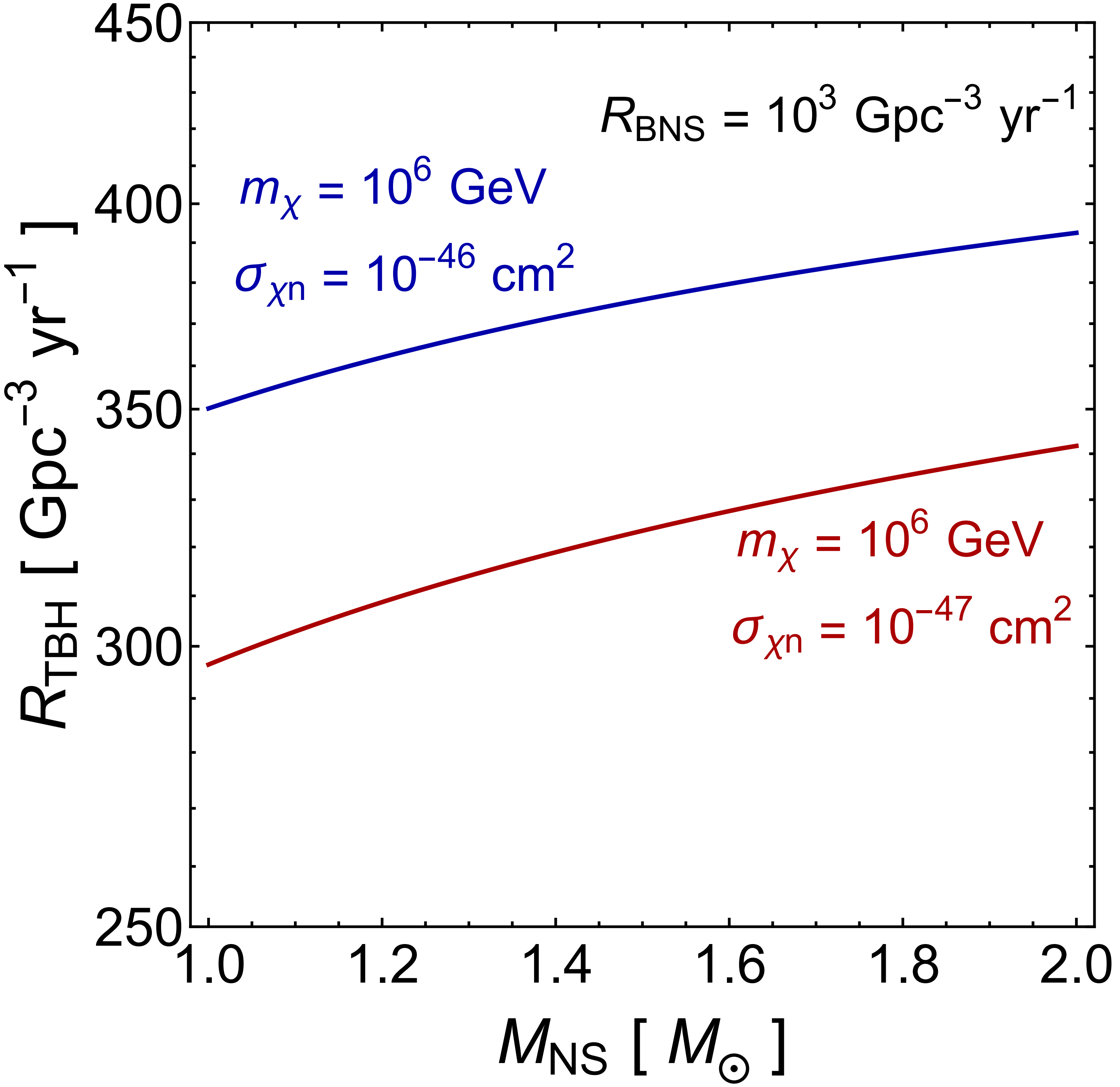
BNS and Chirp mass distributions



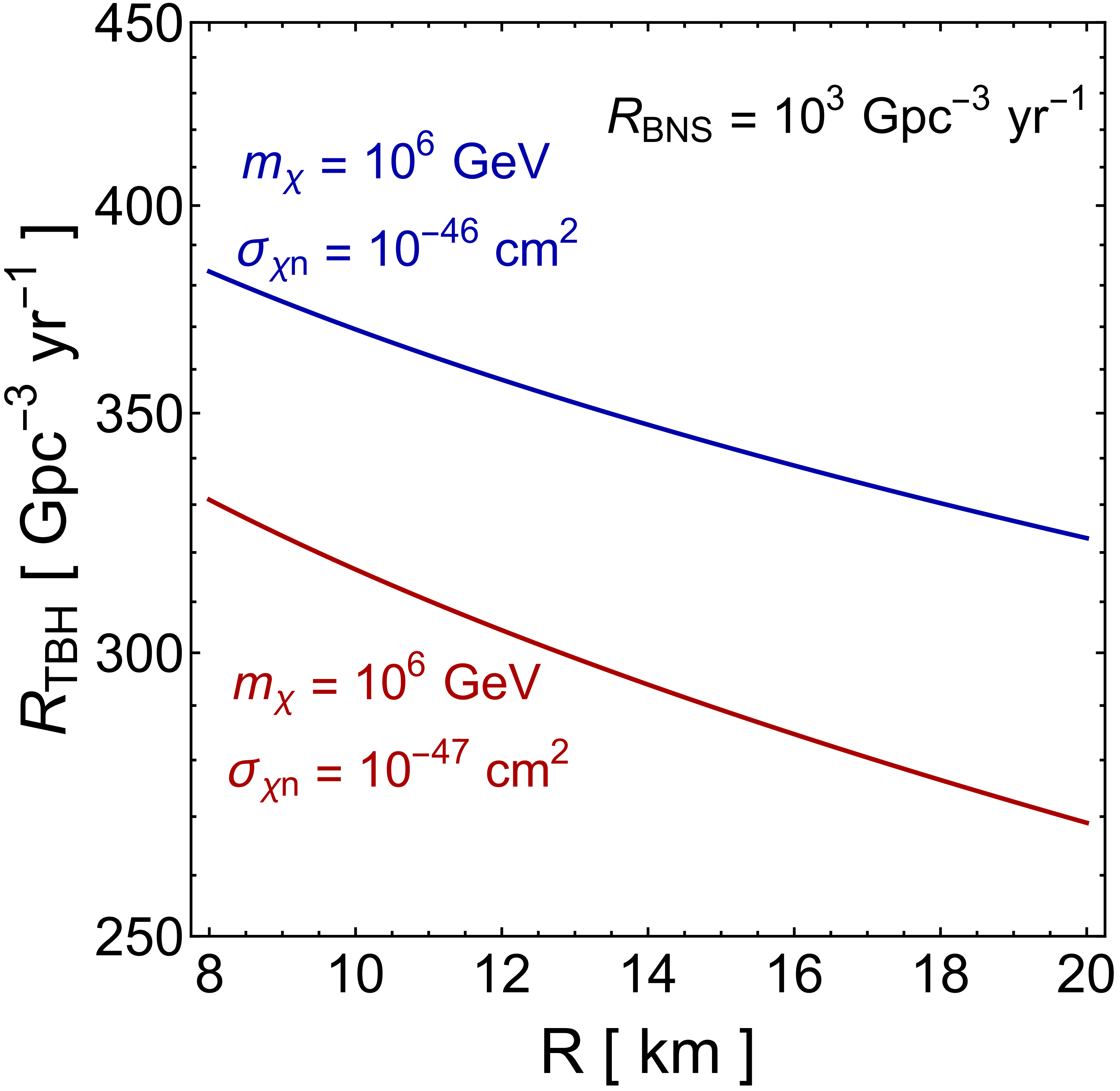
Ozel & Freire, 2016



Progenitor Properties—Mass of the NS



Progenitor Properties—Radius of the NS



Progenitor Properties—Temperature of the NS