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Gravitational Waves as a Probe of Particle Dark Matter

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Department of Theoretical Physics

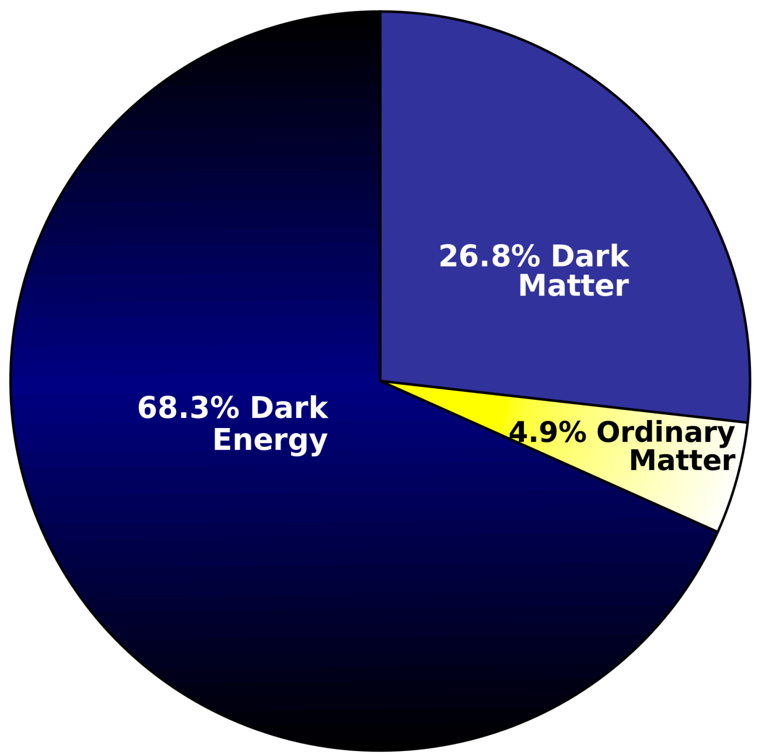
Tata Institute of Fundamental Research, Mumbai

02/01/2025

HEARING BEYOND THE STANDARD MODEL WITH COSMIC SOURCES OF GRAVITATIONAL WAVES

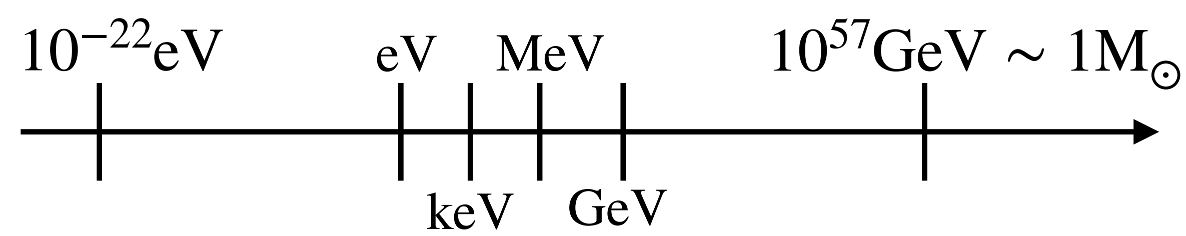
30/12/2024—10/01/2025

Dark Matter (DM-χ)



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

Candidates



Ultra-Light Fuzzy Wave like…GeV particles….black holes & macroscopic

Direct Detection

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

Indirect Detection

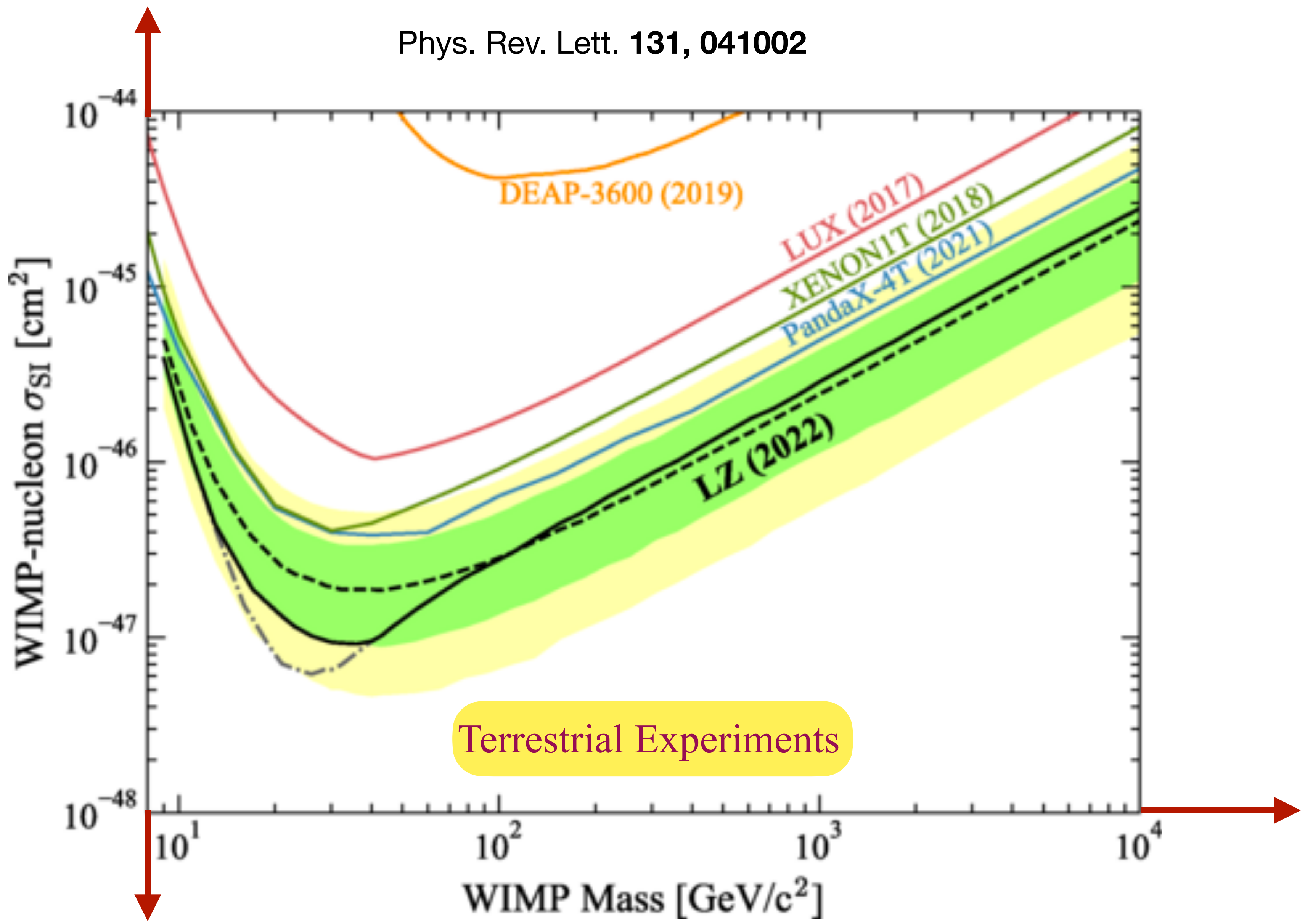
$$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$$

Collider Search

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

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

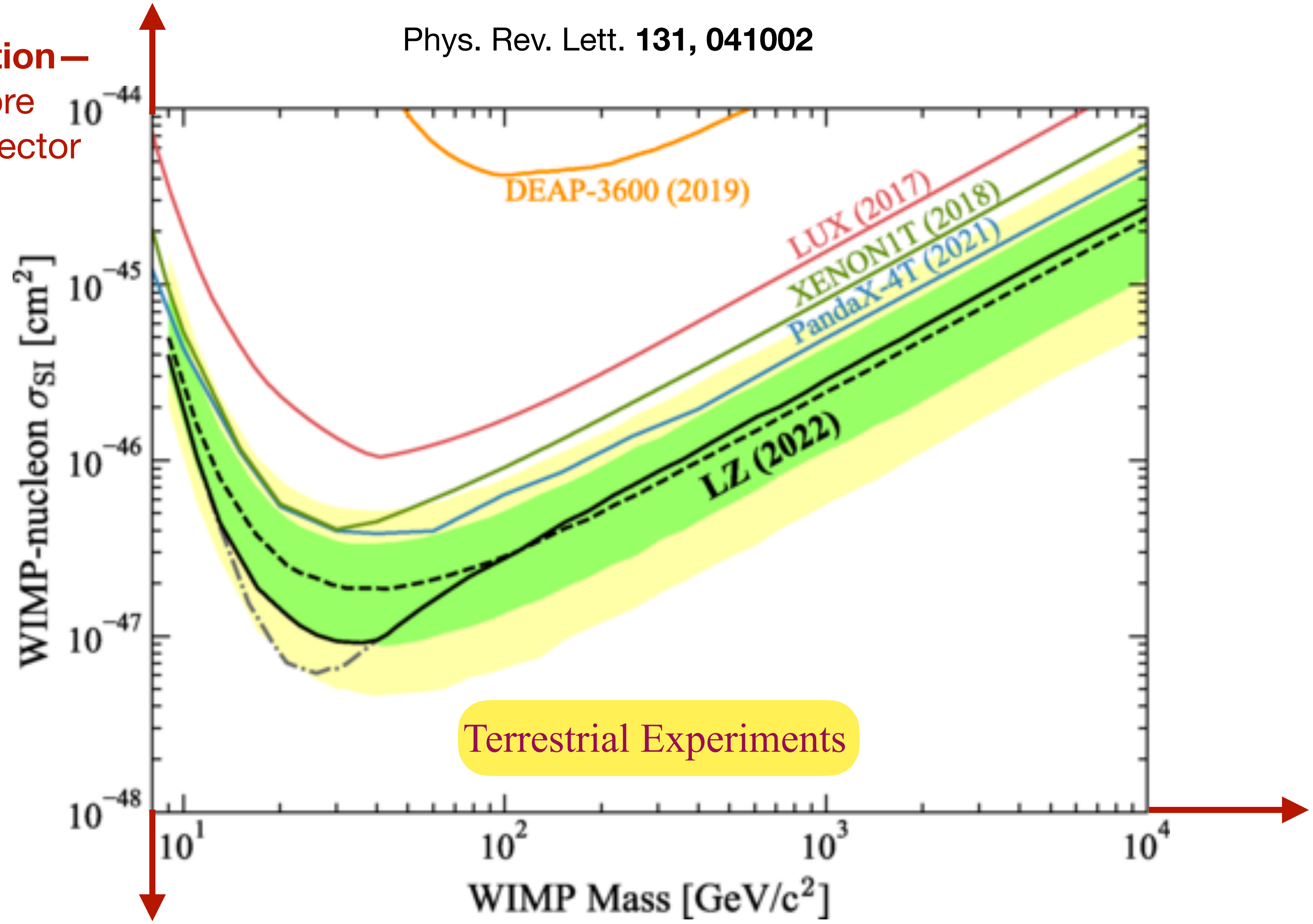
Direct Detection



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



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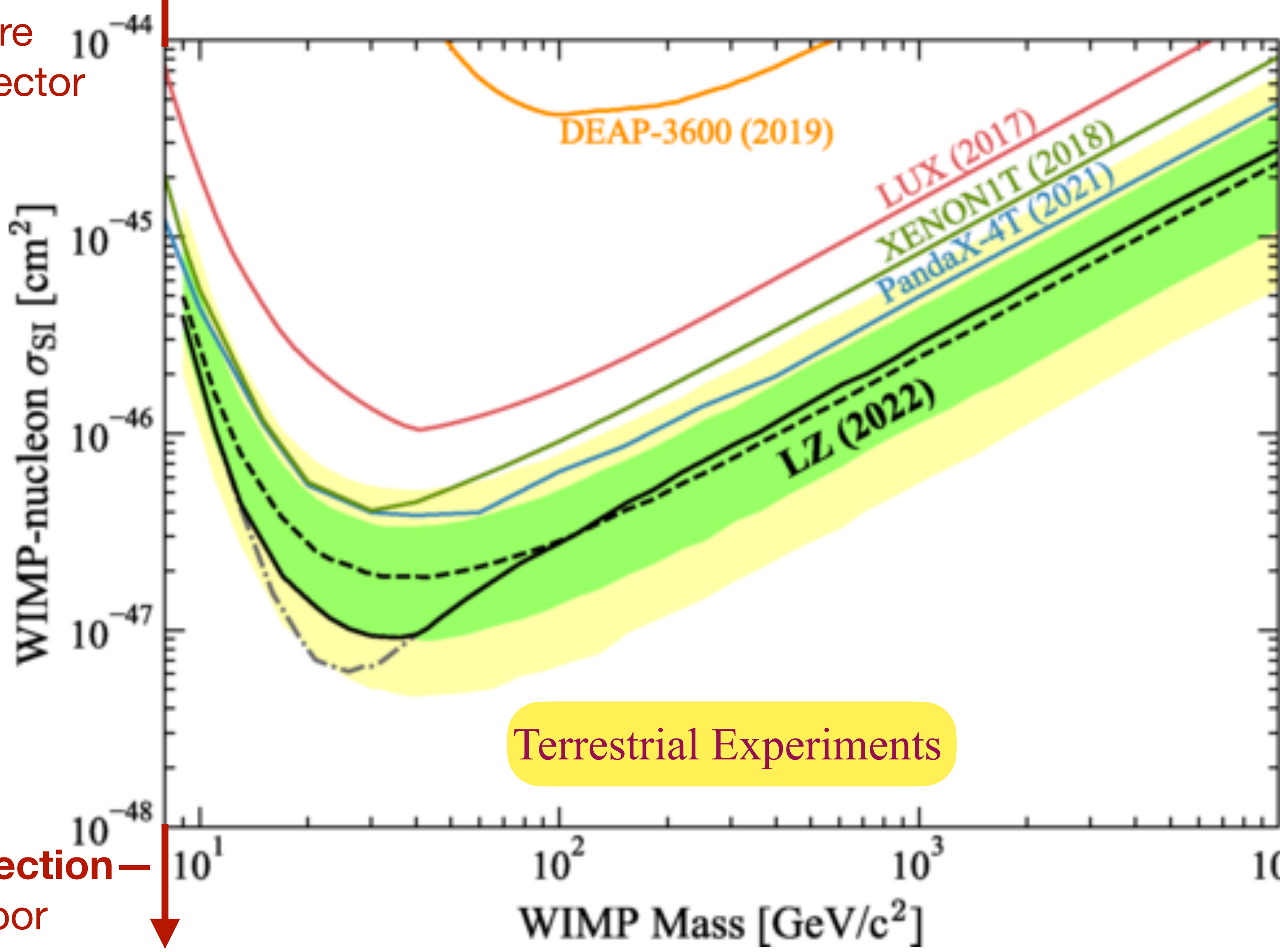
Phys. Rev. Lett. **131, 041002**



Smaller Cross-section— Neutrino Floor

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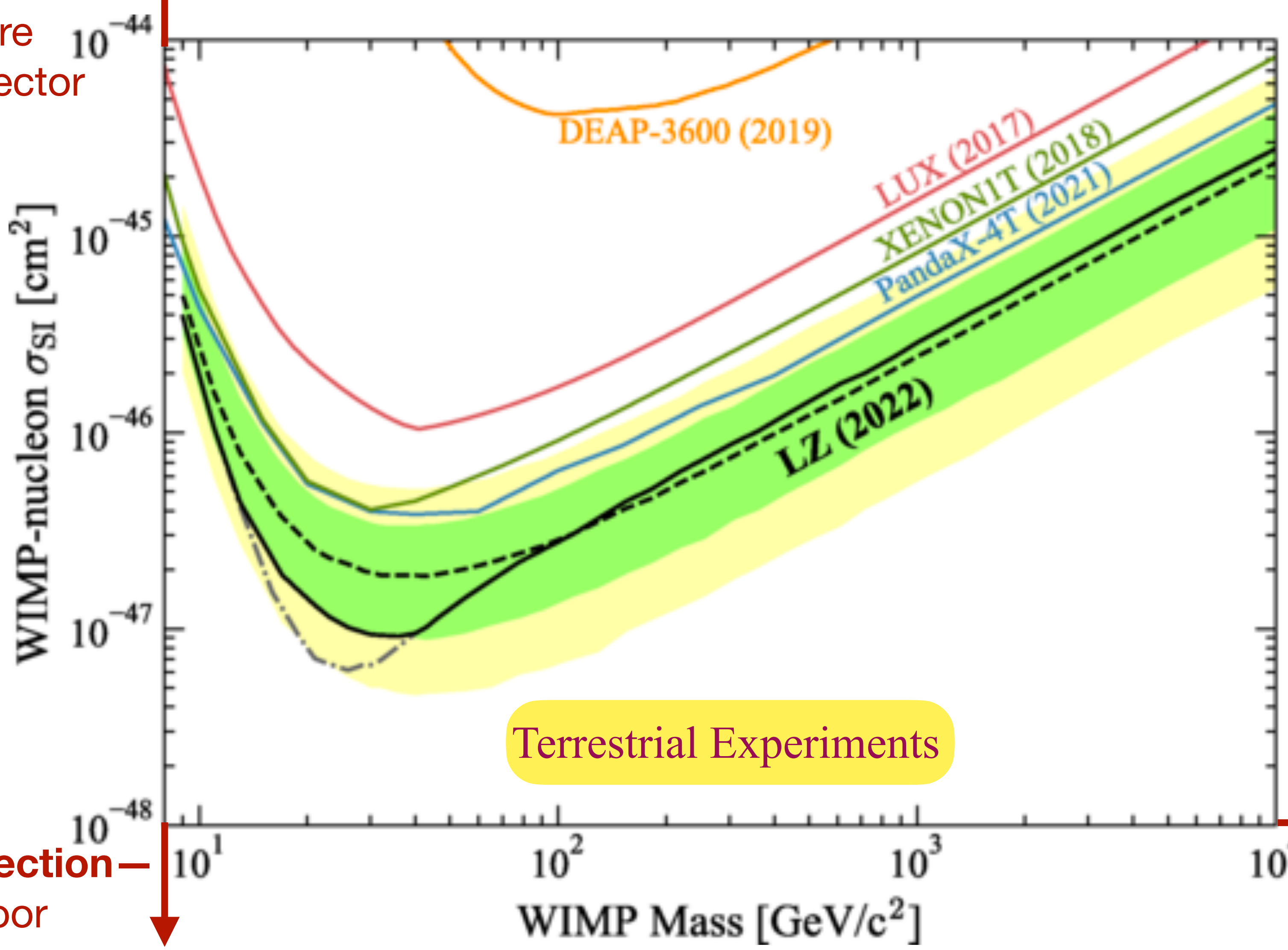

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Heavy DM— smaller flux

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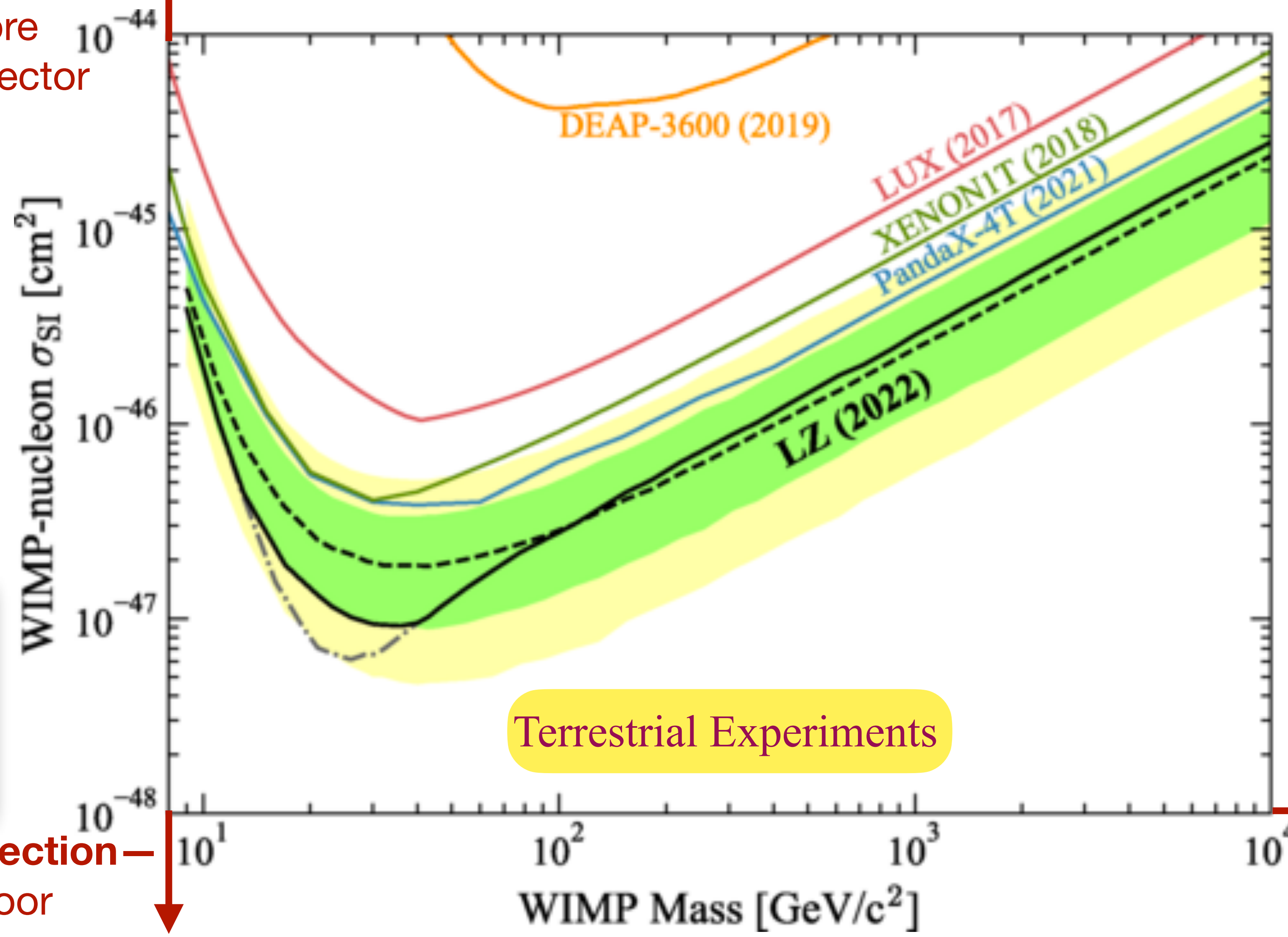

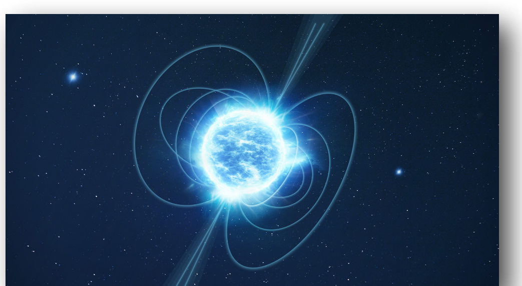

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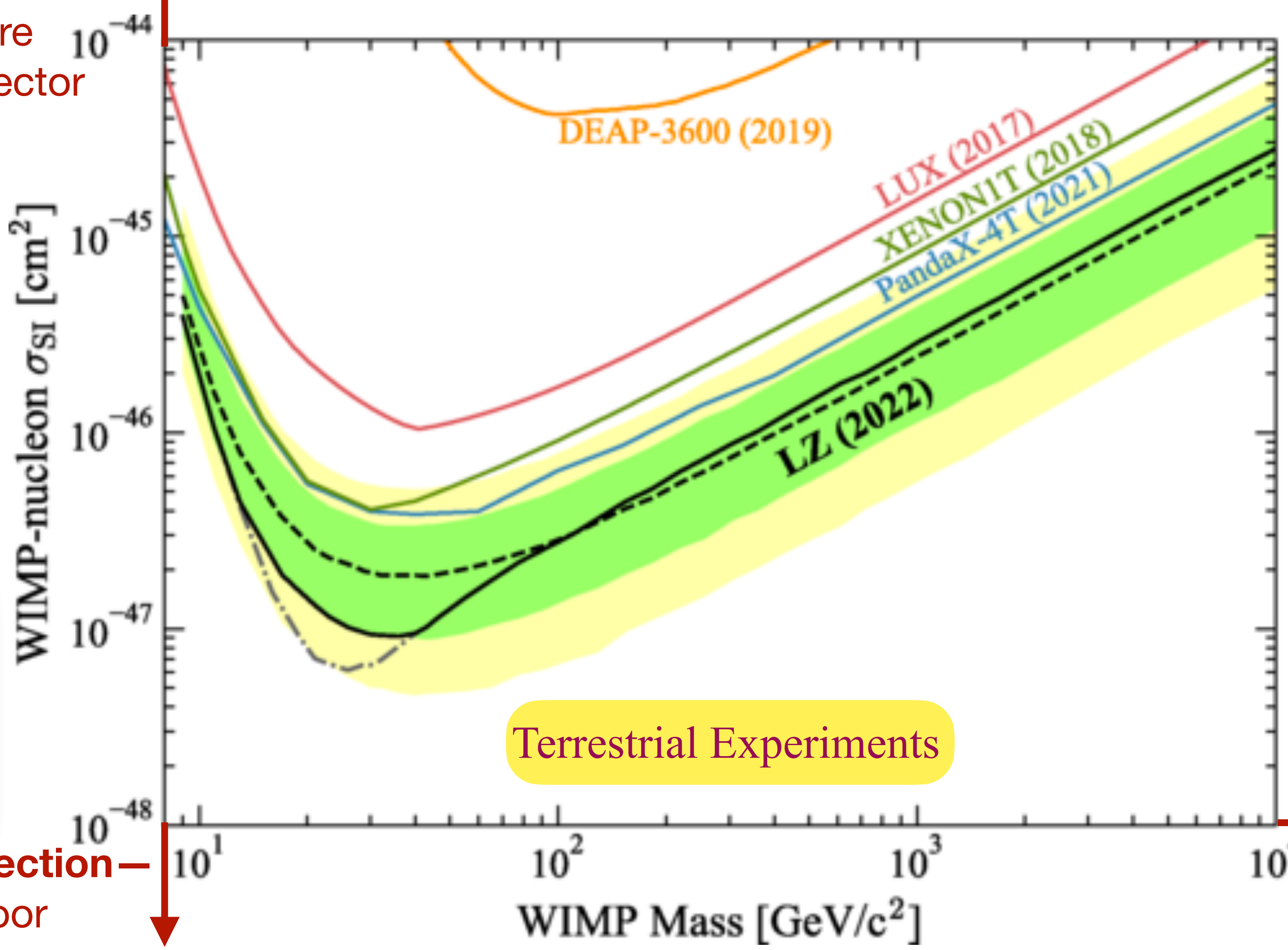

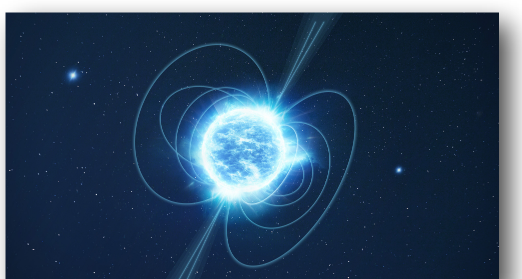

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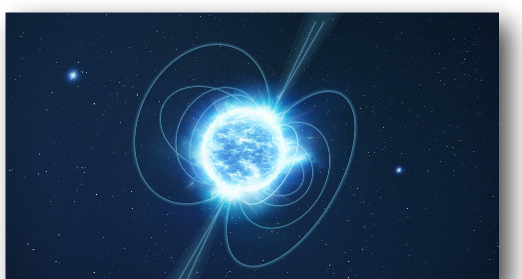

Smaller Cross-section—
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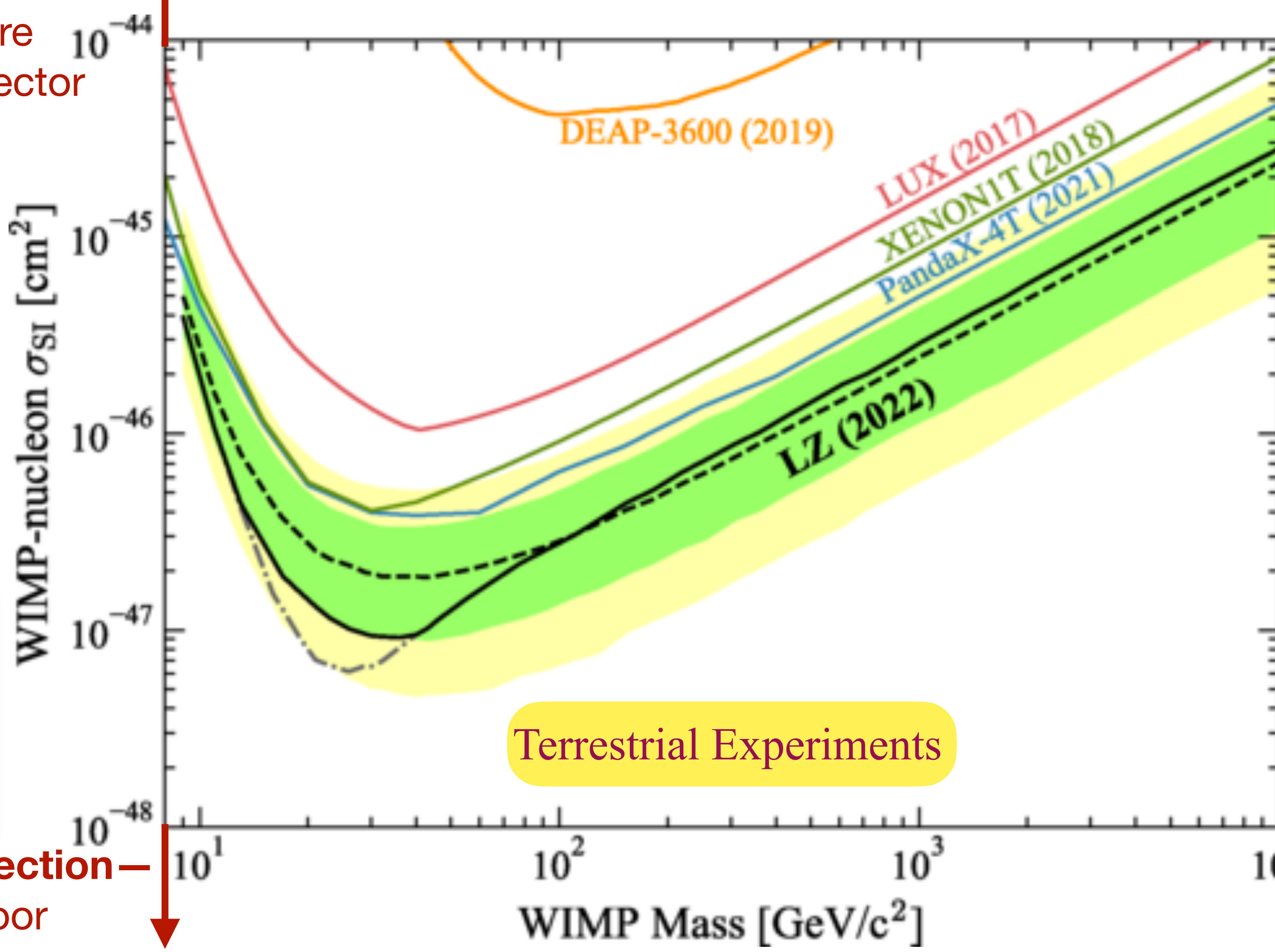
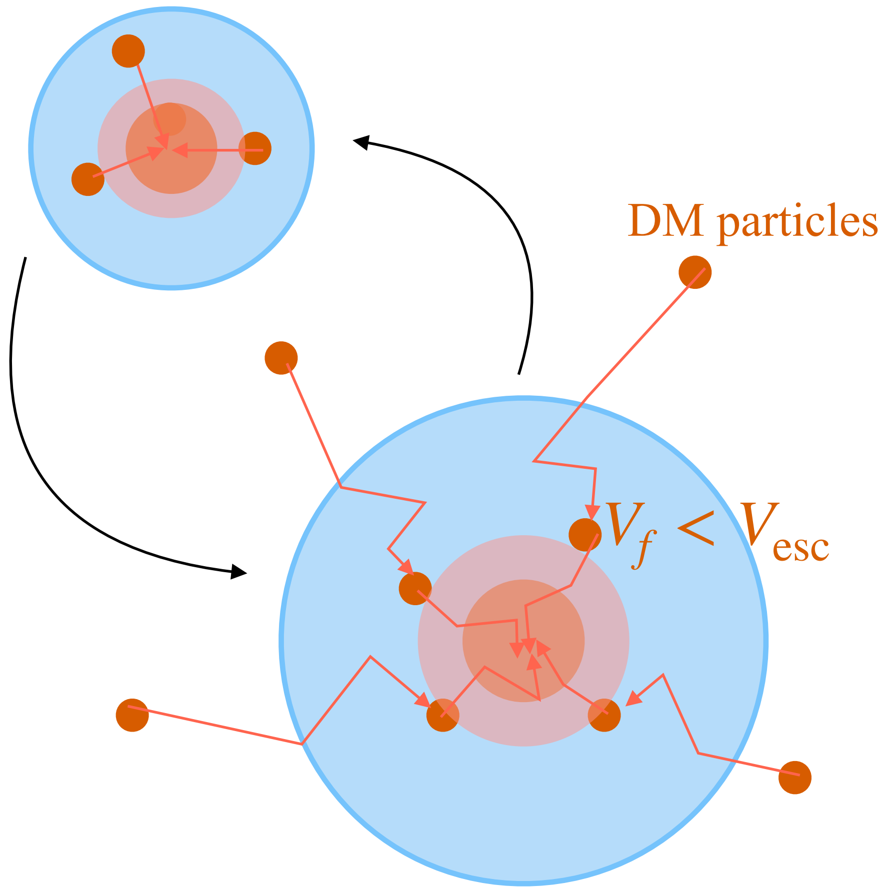


Heavy DM—
smaller flux

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

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

DM Capture

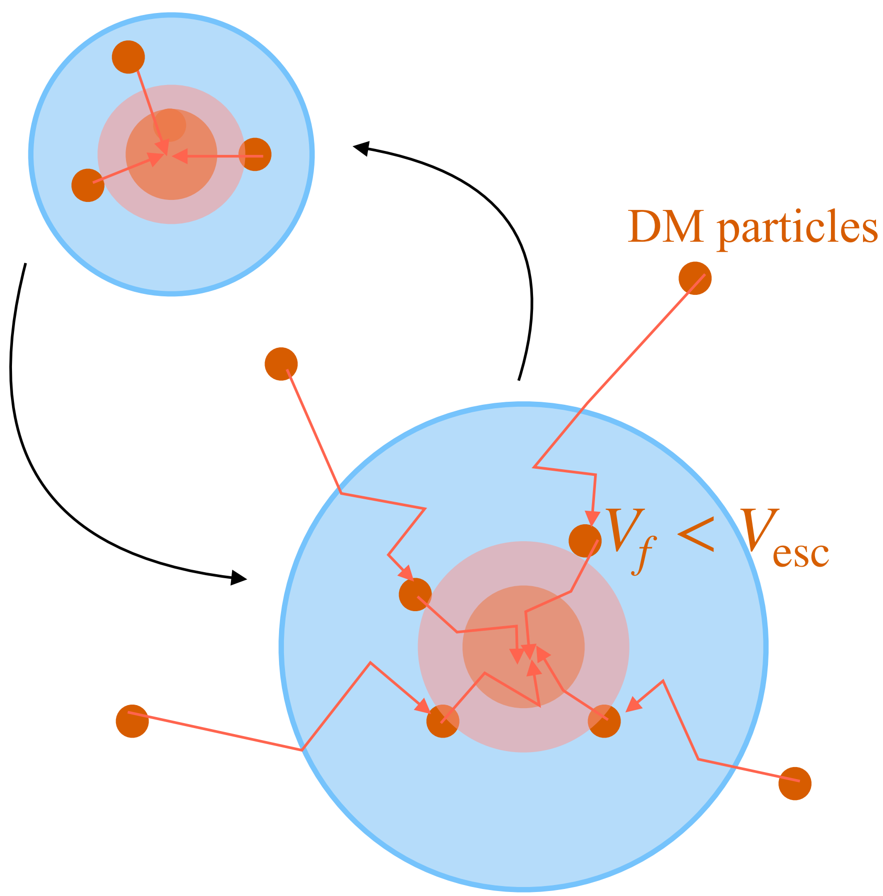


$$\mathbf{C} = \underbrace{\frac{\rho_\chi}{m_\chi} \int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2)}_{\text{Flux}} \times N_n \times \mathrm{Min}[\sigma_{\chi \rm n}, \sigma_{\rm sat}] \times \mathrm{g}_1(\mathrm{u})$$

N_n → Stellar Targets

$\mathrm{g}_1(\mathrm{u})$ → Probability of getting Captured after single collision

DM Capture



$m_\chi = 10^5\,\mathrm{GeV}, \sigma_{\chi \mathrm{n}} = 10^{-45}\,\mathrm{cm}^2, \mathrm{T} = 2.1 \times 10^6\,\mathrm{K},\ \mathrm{M_{NS}} = 1.35\mathrm{M}_\odot$

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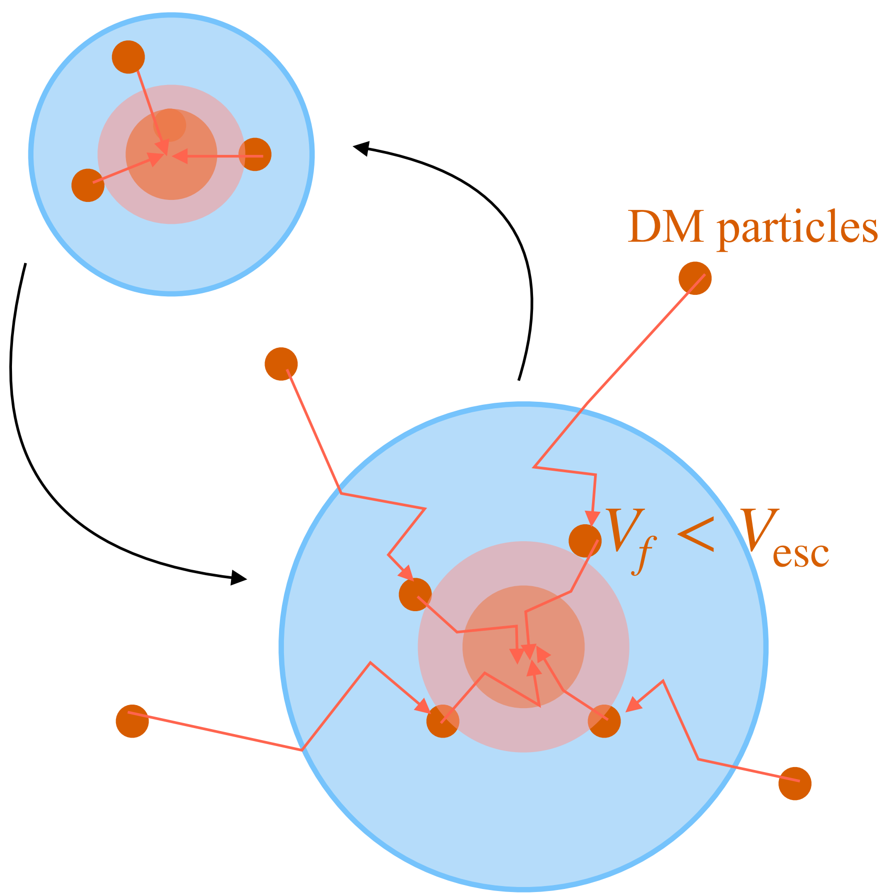

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Captured DM mass $\approx 4.9 \times 10^{42}\,\mathrm{GeV} \approx 10^{-15}\,\mathrm{M}_\odot$

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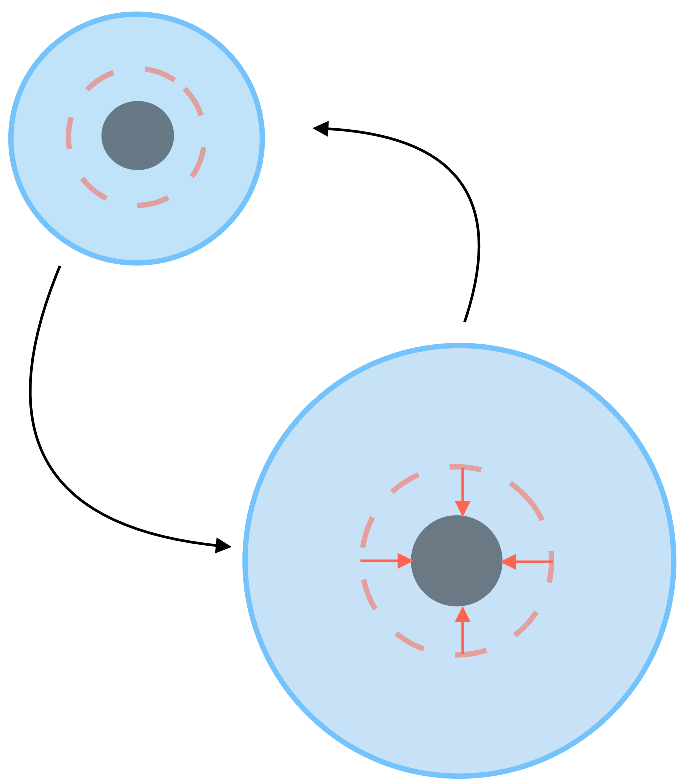
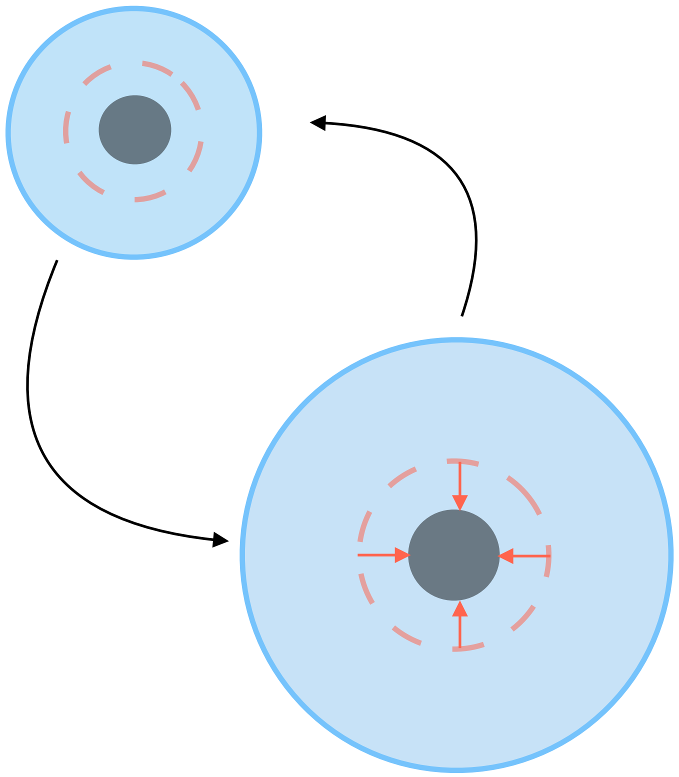
Dark Core Formation



The dark core collapses and forms a tiny black hole

Dark Core Formation



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DM thermalisation

$$r_{\rm th} \propto \sqrt{\frac{T_{\rm NS}}{m_\chi}} \sim 5\,{\rm cm}$$

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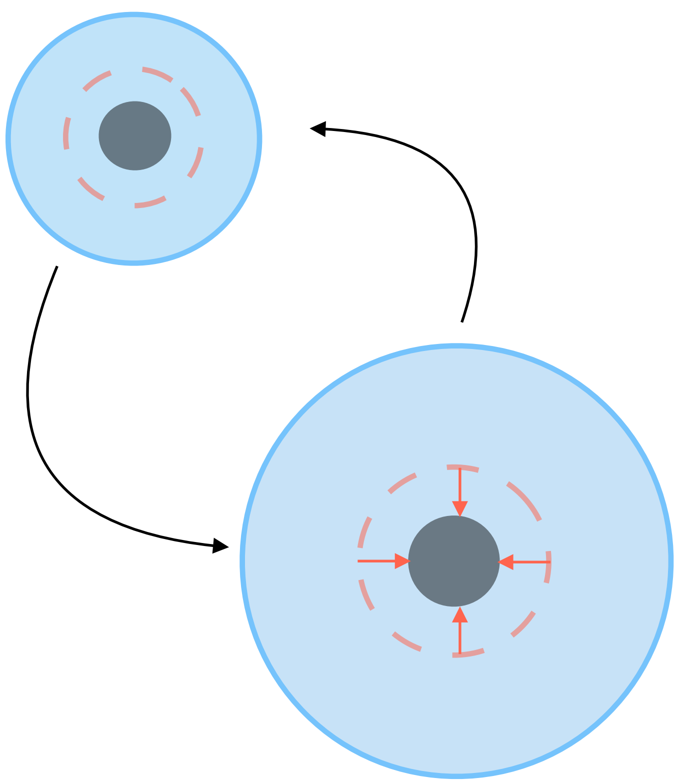

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Dark core collapse & micro-BH formation

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

$$N^{\text{Cha}}_{\chi-\text{fermion}} = \left(\frac{M_{\text{pl}}}{m_\chi}\right)^3 \;\&\; N^{\text{Cha}}_{\chi-\text{boson}} \simeq \left(\frac{M_{\text{pl}}}{m_\chi}\right)^2$$

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

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

$$\tau_{\text{collapse}} = 4.8 \times 10^8\,\text{years} = C^{-1} N_\chi^{\text{BH}}$$

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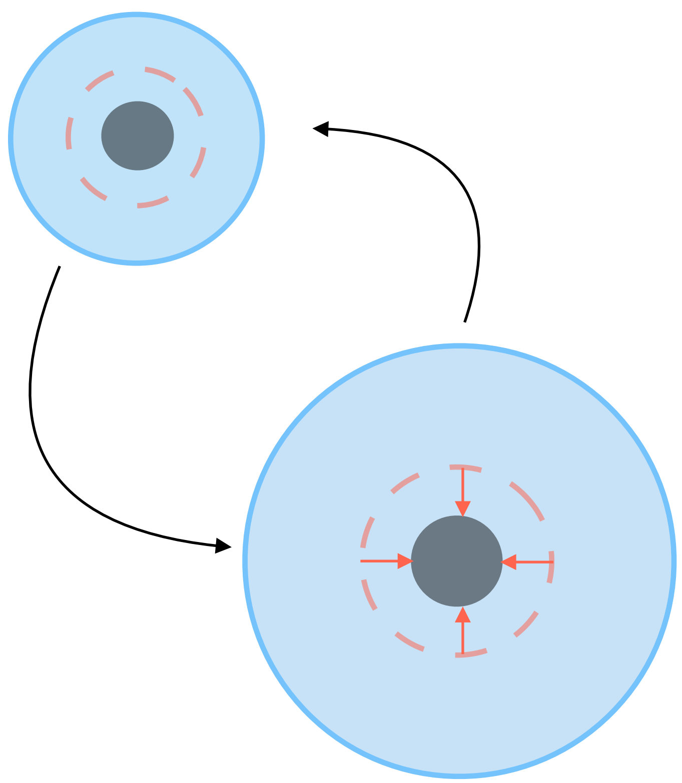

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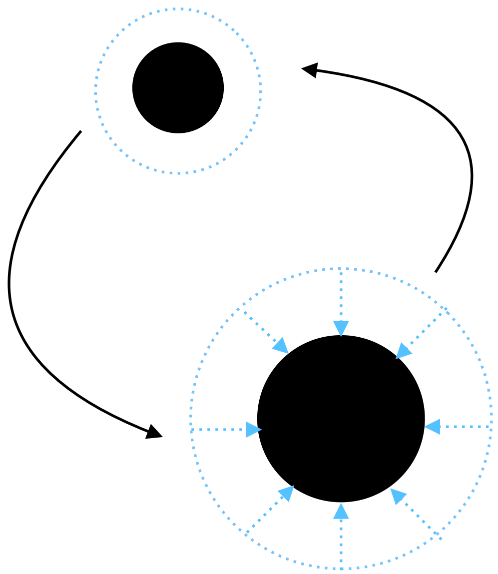
Heavy DM particles are the reason for this minuscule BH!!

Low Mass BH Formation



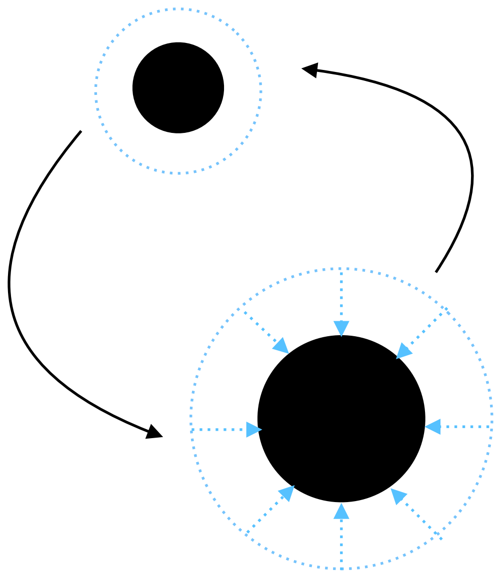
Seed black hole eats up the host star and forms Transmuted black hole

Low Mass BH Formation

Growth of the micro BH & it eats the host star

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

$$\tau_{\rm swallow} = 3 \times 10^{4}\ {\rm years}$$



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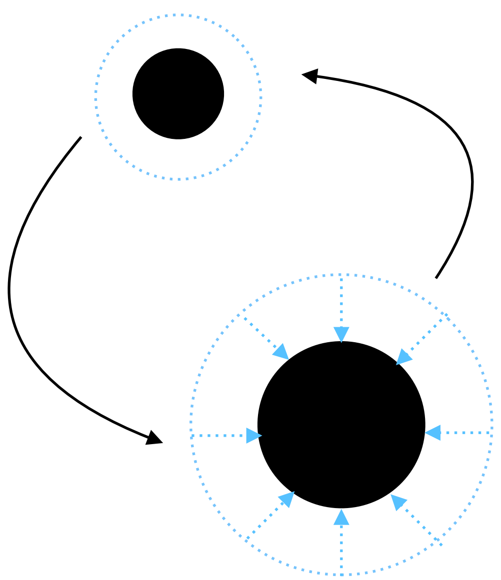

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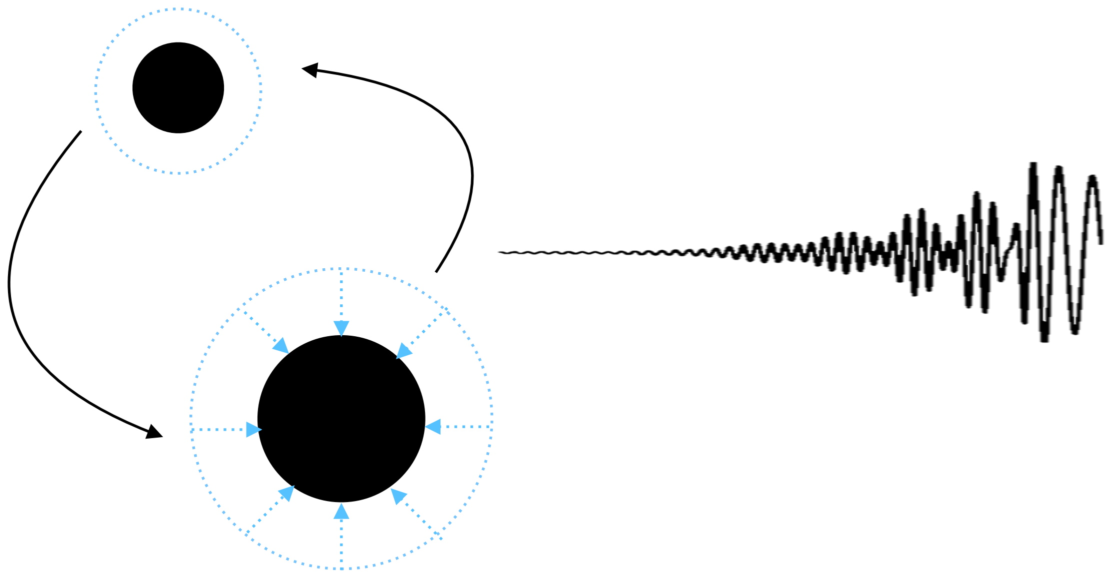

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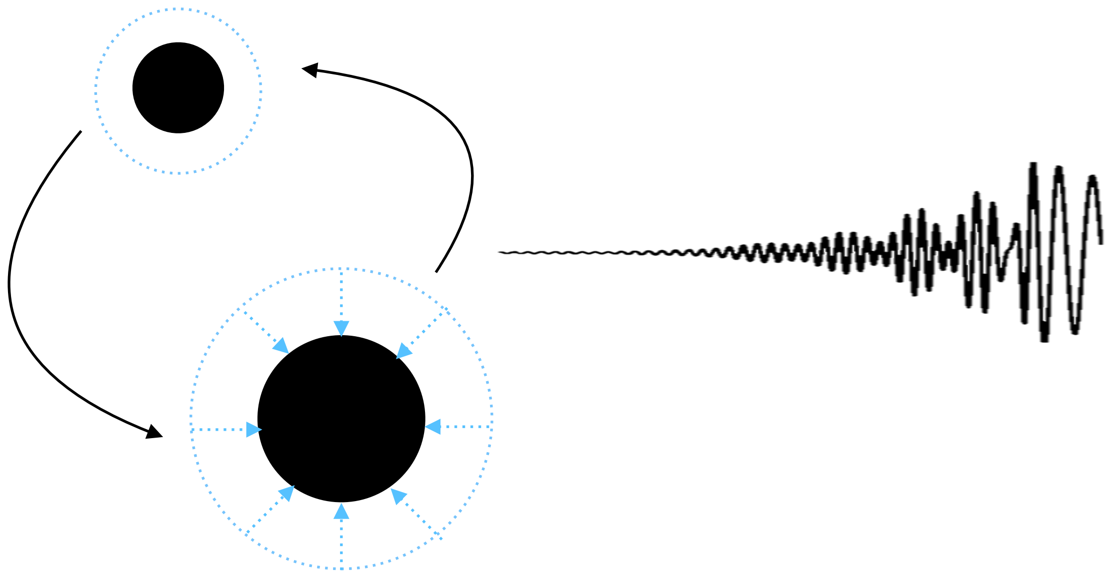

Non detection of these low mass black hole mergers sets constraints on DM parameter space.

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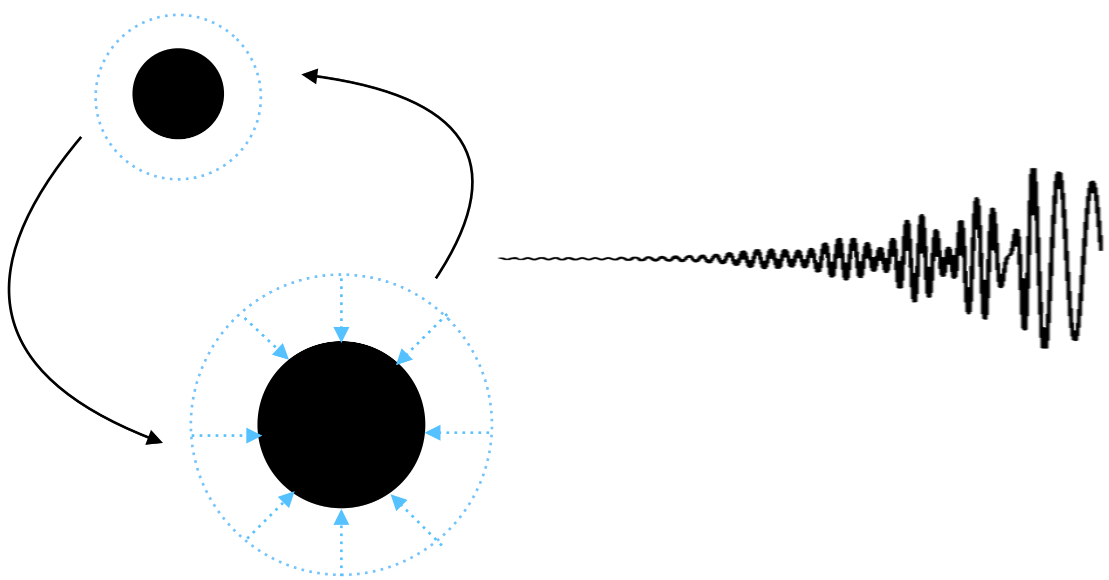

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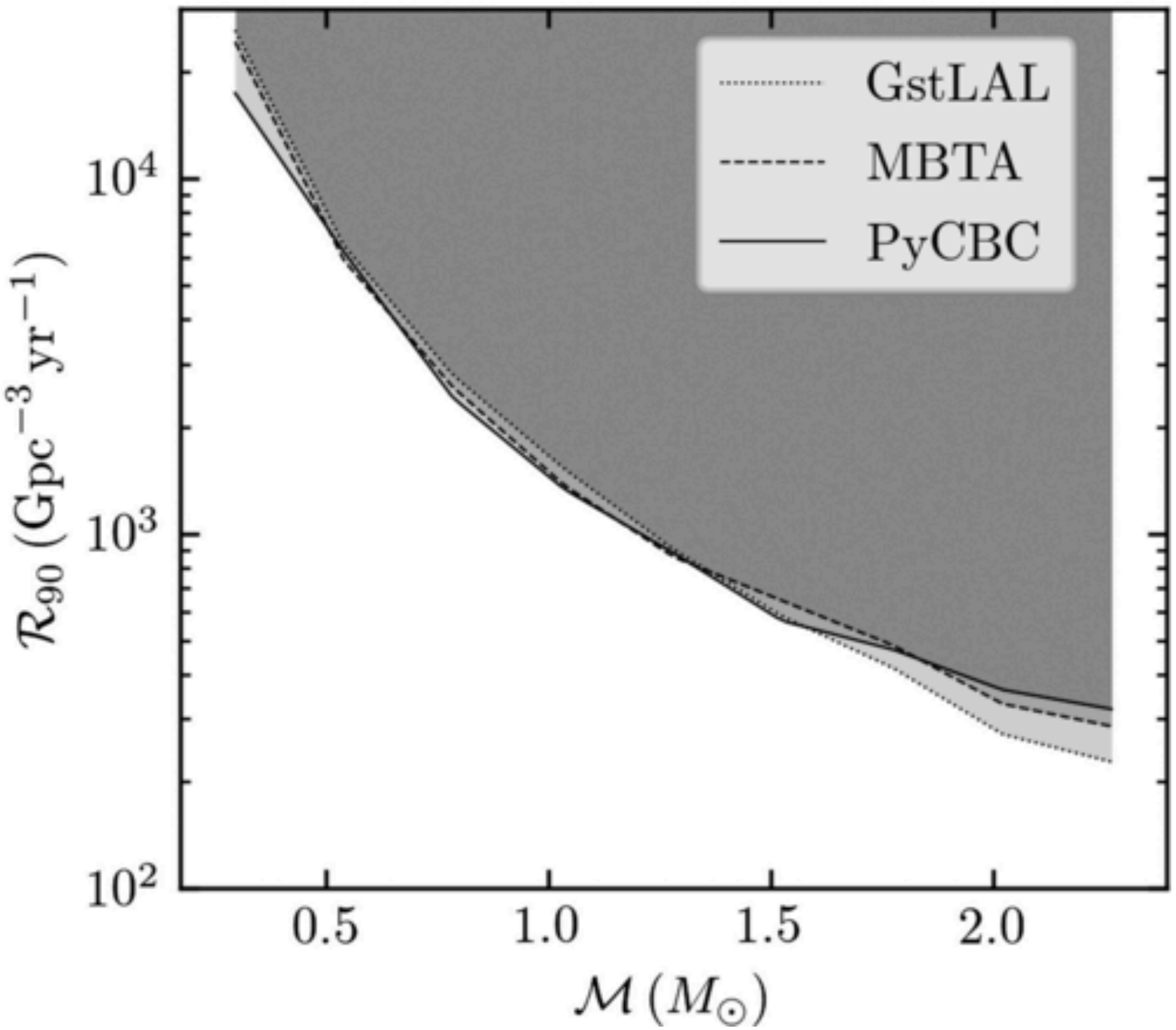
Non detection of these low mass black hole mergers sets constraints on DM parameter space.

These are termed as Transmuted Black Hole (TBH)

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.

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

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

TBH Merger Rate

Dasgupta, Laha, Ray, PRL(2021)

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

BNS Merger rate & its spatial distribution

Assures transmutation happens within the age of the universe

t_f = binary formation time

t_* = time at z = 10

$\tau_{\rm trans}$ = transmutation time of the BNS

$\frac{dR_{\rm BNS}}{dt_f}$ = differential BNS merger rate

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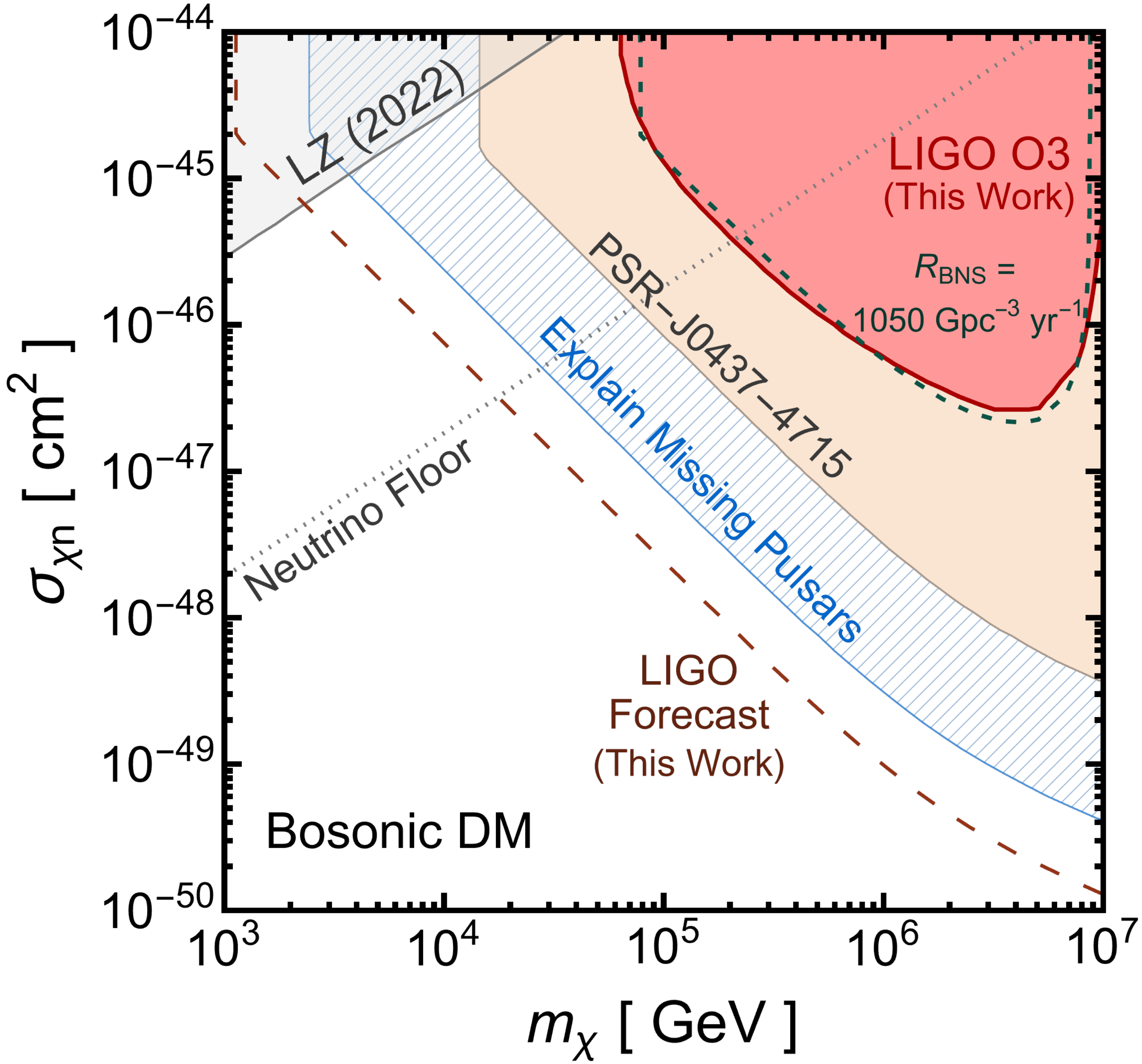
DM parameters for which,
$R_{\rm TBH}(m_\chi, \sigma_{\chi n}, R_{\rm BNS}, m_c)\langle {\rm VT}\rangle > 2.303$ are excluded.

Results



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

Priors for Bayesian Analysis

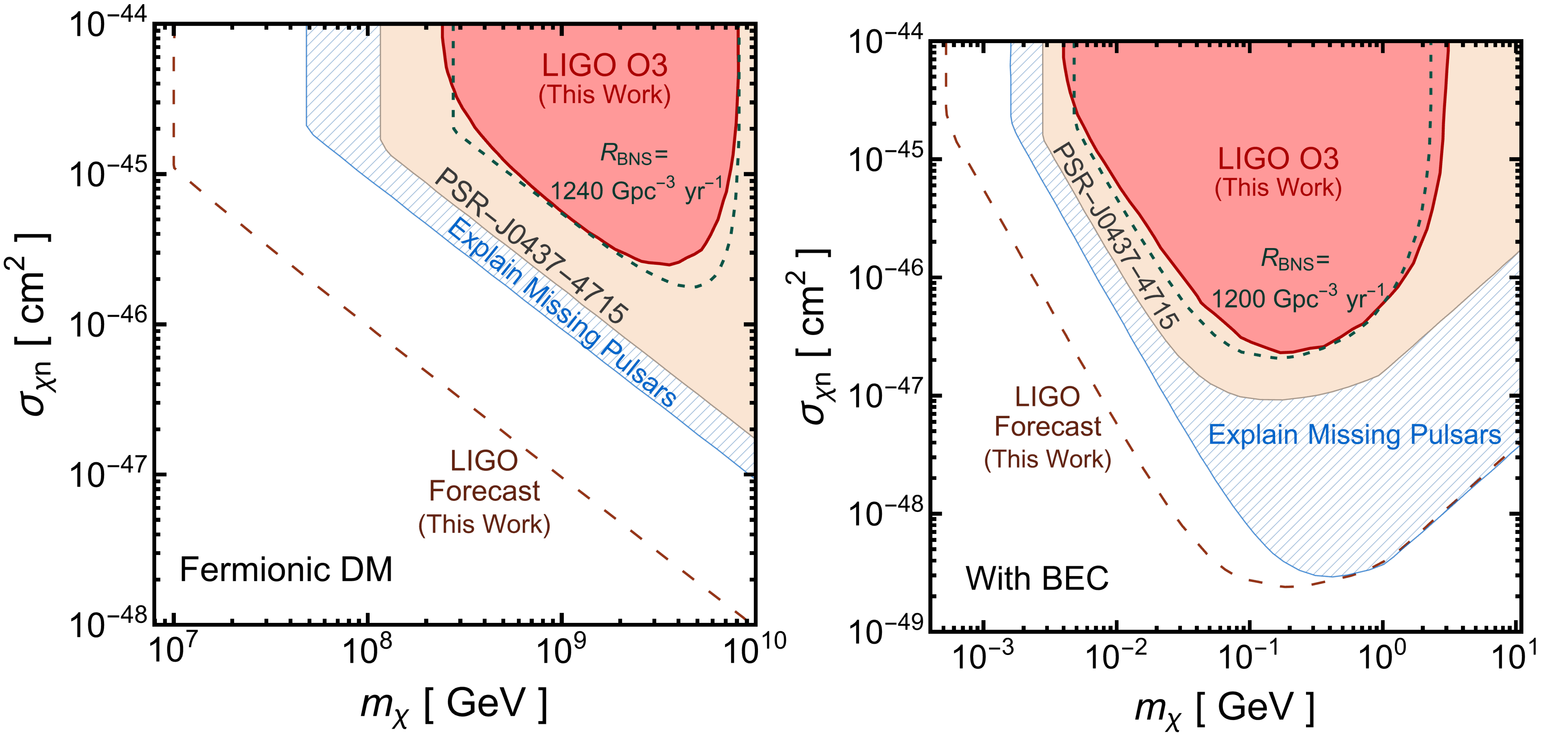
$$m_\chi \in \left[10^4 - 10^8\,\mathrm{GeV}\right]$$
$$\sigma_{\chi n} \in \left[10^{-50} - 10^{-44}\,\mathrm{cm}^2\right]$$
$$R_{\rm BNS} \in \left[10 - 1700\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}\right]$$

Hybrid Analysis

No priors on DM parameters.

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

Results



$m_\chi \in [10^8 - 10^{11}\,\mathrm{GeV}]$

$\sigma_{\chi n} \in [10^{-48} - 10^{-44}\,\mathrm{cm}^2]$

$m_\chi \in [10^{-3} - 10^3\,\mathrm{GeV}]$

$\sigma_{\chi n} \in [10^{-49} - 10^{-44}\,\mathrm{cm}^2]$

$R_{\mathrm{BNS}} \in [10 - 1700\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}]$

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

BNS Vs Low-Mass BBH

	BNS	NSBH	BBH	NS-Gap	BBH-gap	Full
	$m_1 \in [1, 2.5] M_\odot$	$m_1 \in [2.5, 50] M_\odot$	$m_1 \in [2.5, 100] M_\odot$	$m_1 \in [2.5, 5] M_\odot$	$m_1 \in [2.5, 100] M_\odot$	$m_1 \in [1, 100] M_\odot$
	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 100] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 5] M_\odot$	$m_2 \in [1, 100] M_\odot$
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	$10 - 1700$	$7.8 - 140$	$16 - 61$	$0.02 - 39$	$9.4 \times 10^{-5} - 25$	$72 - 1800$

LVK—arXiv:2111.03634

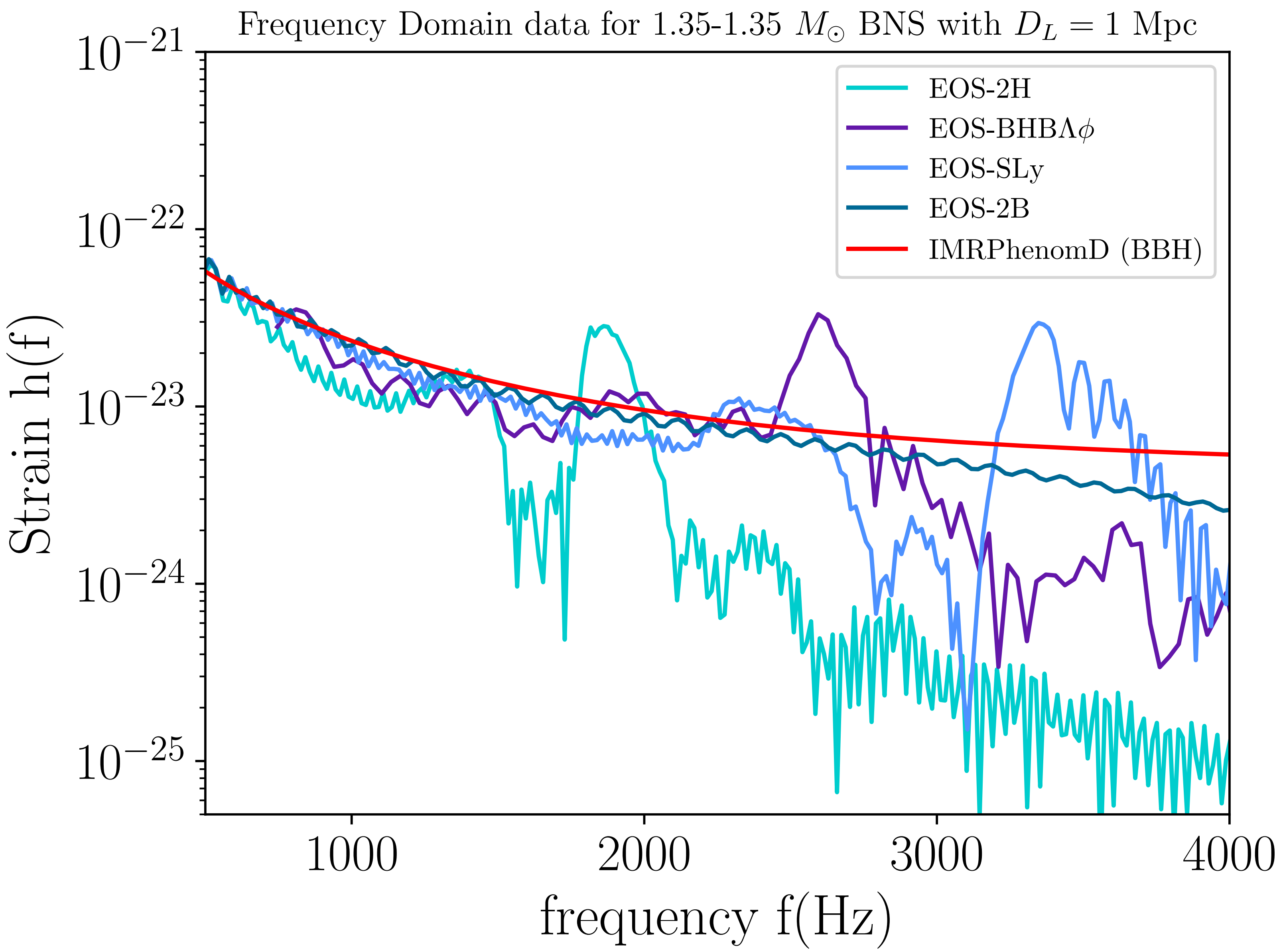
To distinguish low-mass BH mergers from Neutron Star mergers

Possible Approach

1) Tidal Deformability (Singh et.al. PRD(2023))

2) Waveform Analysis (With Basudeb Dasgupta, Shasvath Kapadia)

Waveform Analysis



$$h_+ - ih_\times = D_L^{-1} \sum_{l=2}^{\infty} \sum_{m=-l}^{l} h_{lm}(t)\, {}_{-2}Y_{lm}(\iota, \phi)$$

$$h_{lm}(t) = A_{lm}(t) e^{-i\phi_{lm}(t)}$$

ι, ϕ = polar and azimuthal angles

D_L = Luminosity distance

BNS waveforms from CoRe Database

In Preparation with Dasgupta, Kapadia

Fitting Factor

Noise-Weighted Inner Product, $\langle h_1(f) | h_2(f) \rangle = 2 \int_{f_{\min}}^{f_{\max}} \frac{\left(h_1^*(f) h_2(f) + h_1(f) h_2^*(f)\right)}{S_n(f)} df$

$S_n(f)$ is the power spectral density of the detector.

Fitting factor = $\langle \hat{h}_{\mathrm{BBH}}(f) | \hat{h}_{\mathrm{BNS}}(f) \rangle$ lies between 0 and 1

EOS	norm (Ins)	norm (PM)	$\mathrm{FF}^{\mathrm{BBH/BNS}}_{\mathrm{Ins}}$	$\mathrm{FF}^{\mathrm{BBH/BNS}}_{\mathrm{PM}}$	$\mathrm{FF}^{\mathrm{BBH/BNS}}_{\mathrm{total}}$	$\mathrm{BF}_{\mathrm{Ins}}$	$\mathrm{BF}_{\mathrm{PM}}$
2H	14.76	3.05	0.974	0.603	0.96	2414	20.7
MS1b	15.45	2.96	0.983	0.82	0.978	138.9	4.6
H4	16.07	3.64	0.986	0.738	0.975	65.85	8.72
BHB$\boldsymbol{\Lambda\phi}$	9.41	3.2	0.77	0.83	0.76	too large	4.2
ALF2	16.5	2.9	0.992	0.788	0.986	11.05	6.06
SLy	17.35	2.74	0.9949	0.8815	0.992	4.63	2.89
2B	17.87	2.71	0.9971	0.995	0.997	2.39	1.04

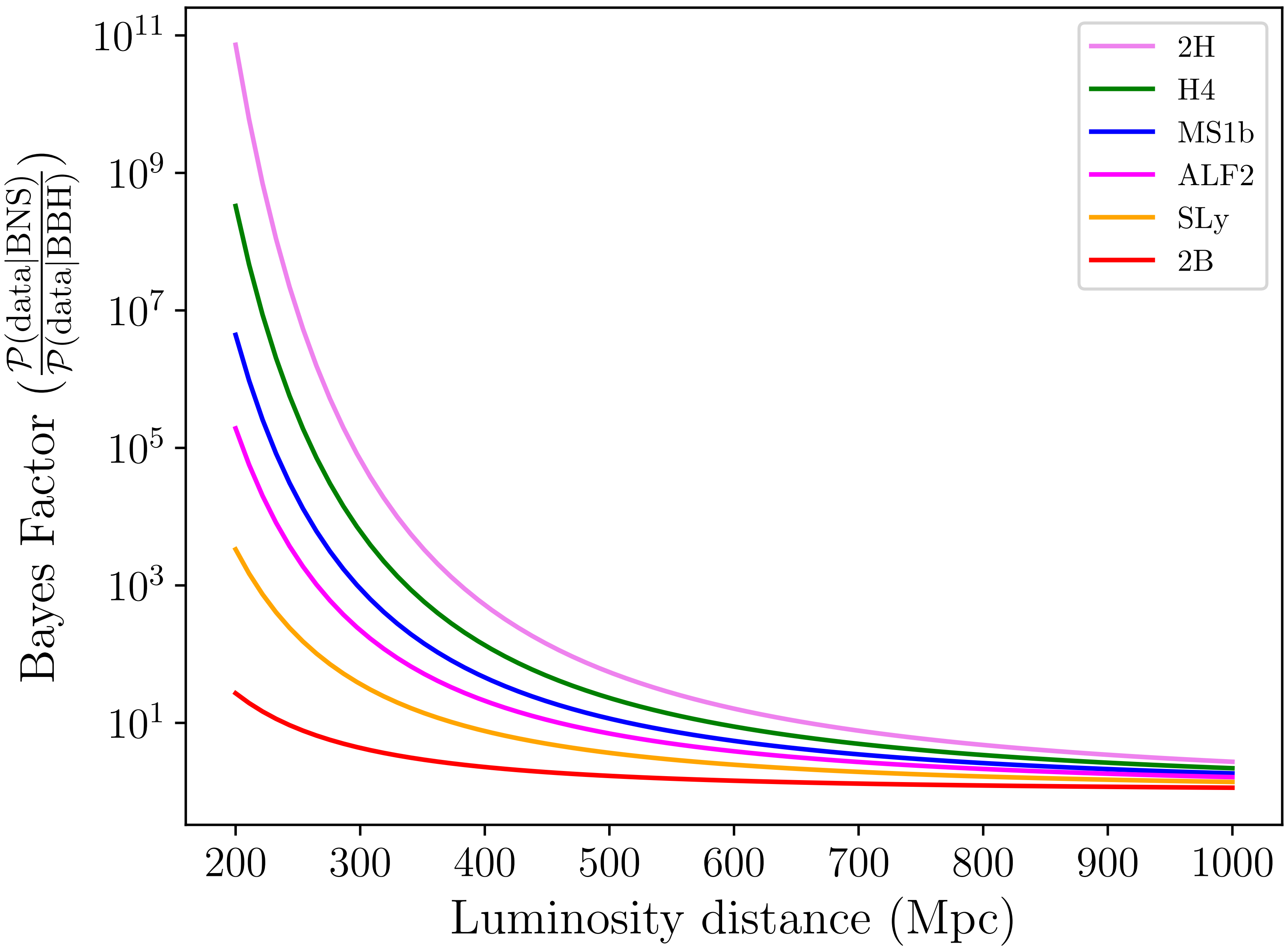
With Einstein Telescope, $D_L = 350$ Mpc, $m_1 = m_2 = 1.35\, M_\odot$

In Preparation

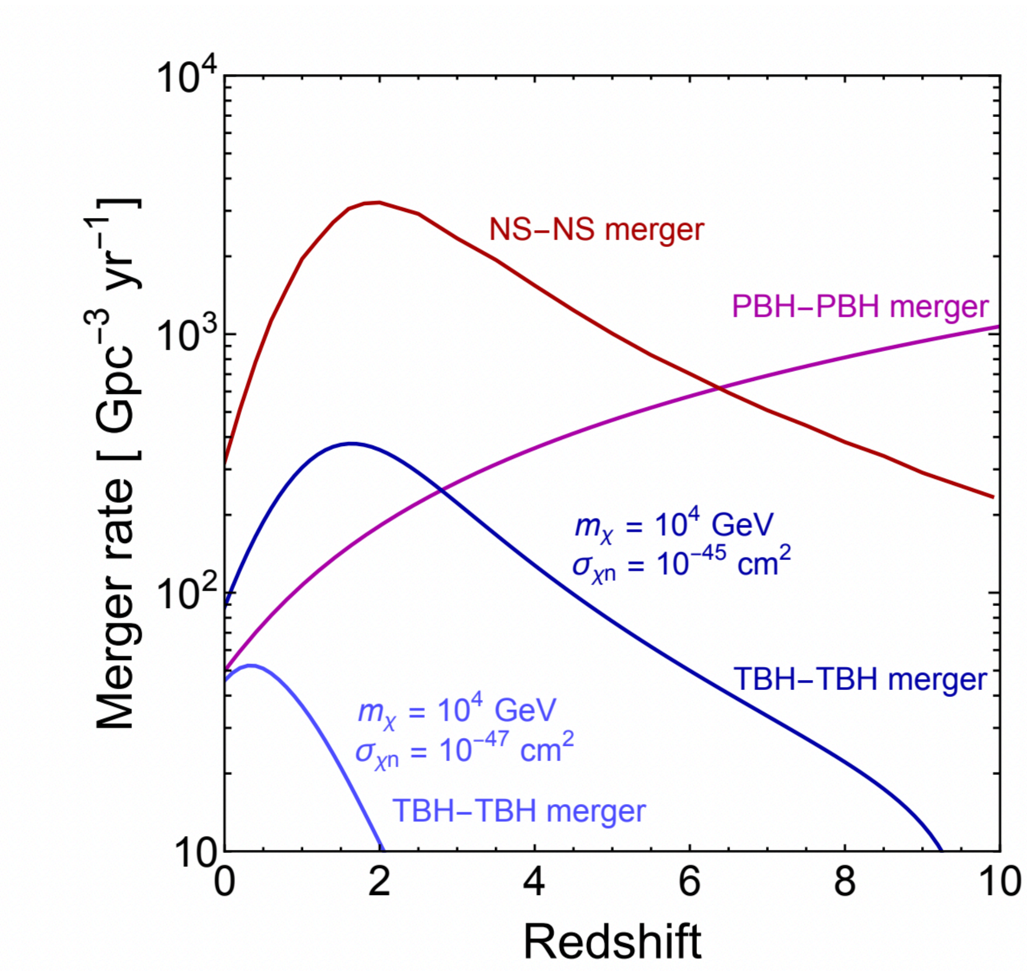
Bayes Factor

$$BF^{\mathrm{BNS}}_{\mathrm{BBH}} = \frac{\mathscr{P}(\mathrm{data}\,|\,\mathrm{BNS})}{\mathscr{P}(\mathrm{data}\,|\,\mathrm{BBH})} = e^{0.5(1-FF^2)\rho^2_{\mathrm{BNS}}}$$

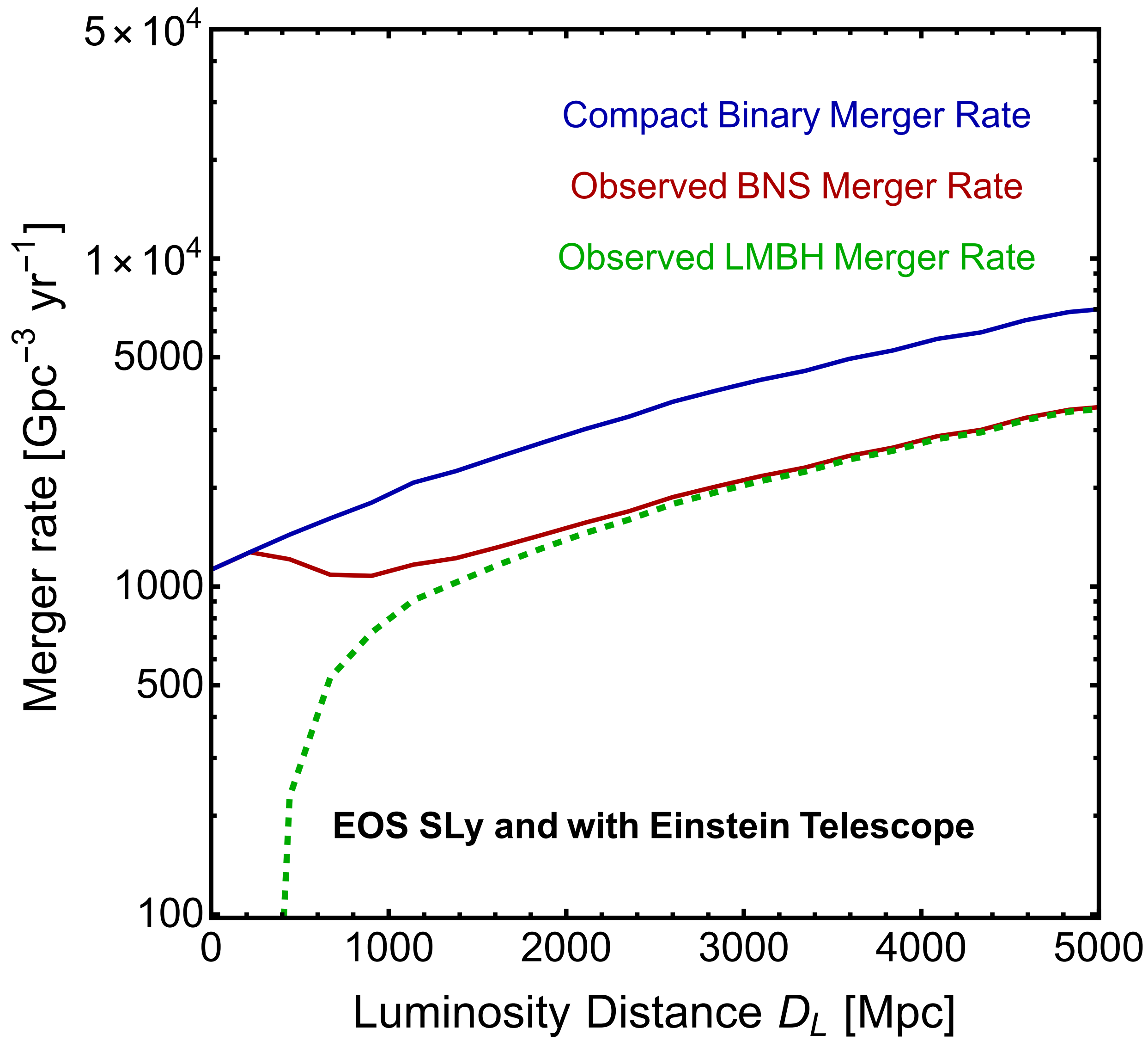
Cornish et. al PRD (2011)



Modified Merger Rates



Dasgupta, Laha, Ray PRL(2021)



Assuming no true LMBH mergers in the theoretical compact binary merger rate calculation.

Upto 400 Mpc BNS mergers can be identified with strong evidences but with higher luminosity distances bayesian evidence decreases and it becomes inconclusive.

In Preparation

Take Home

- **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 full waveform (Inspiral + Postmerger).**

Questions & Comments

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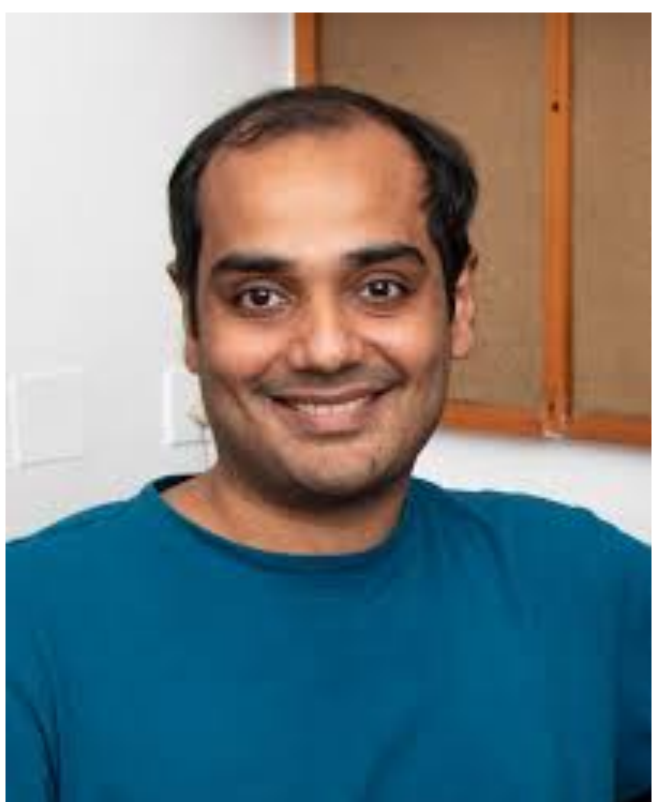

Prof. Shasvath J. Kapadia

Useful References

This work is based on Bhattacharya, Dasgupta, Laha, Ray PRL(2023)

The other one is in preparation with Dasgupta, Kapadia

✤McDermott, Hai-Bo-Yu, Zurek, PRD(2012)

✤Garani, Genolini, Hambye, JCAP(2018)

✤ Dasgupta, Laha, Ray PRL(2021)

✤ Takhistov, Fuller, Kusenko, PRL(2021)

✤ GW190425 ApJL(2020)

✤ GW190814 ApJL(2020)

✤ GW230529

✤ Singh, Gupta, Berti, Reddy, Sathyaprakash PRD(2023)


THANKS !