LIGO as a Non-Annihilating Dark Matter Detector

i) arXiv: 2302.07898

ii) Phys. Rev. Lett. **126**, 141105 (2021)

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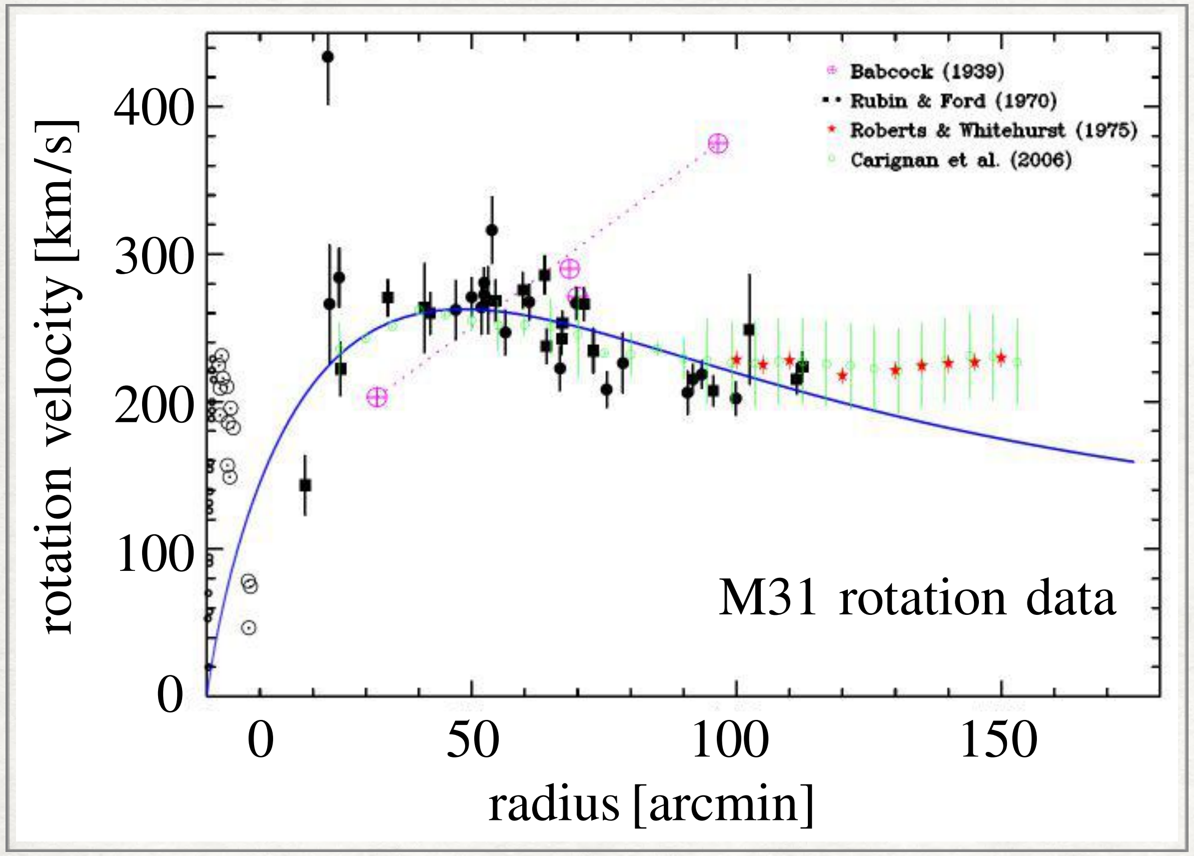
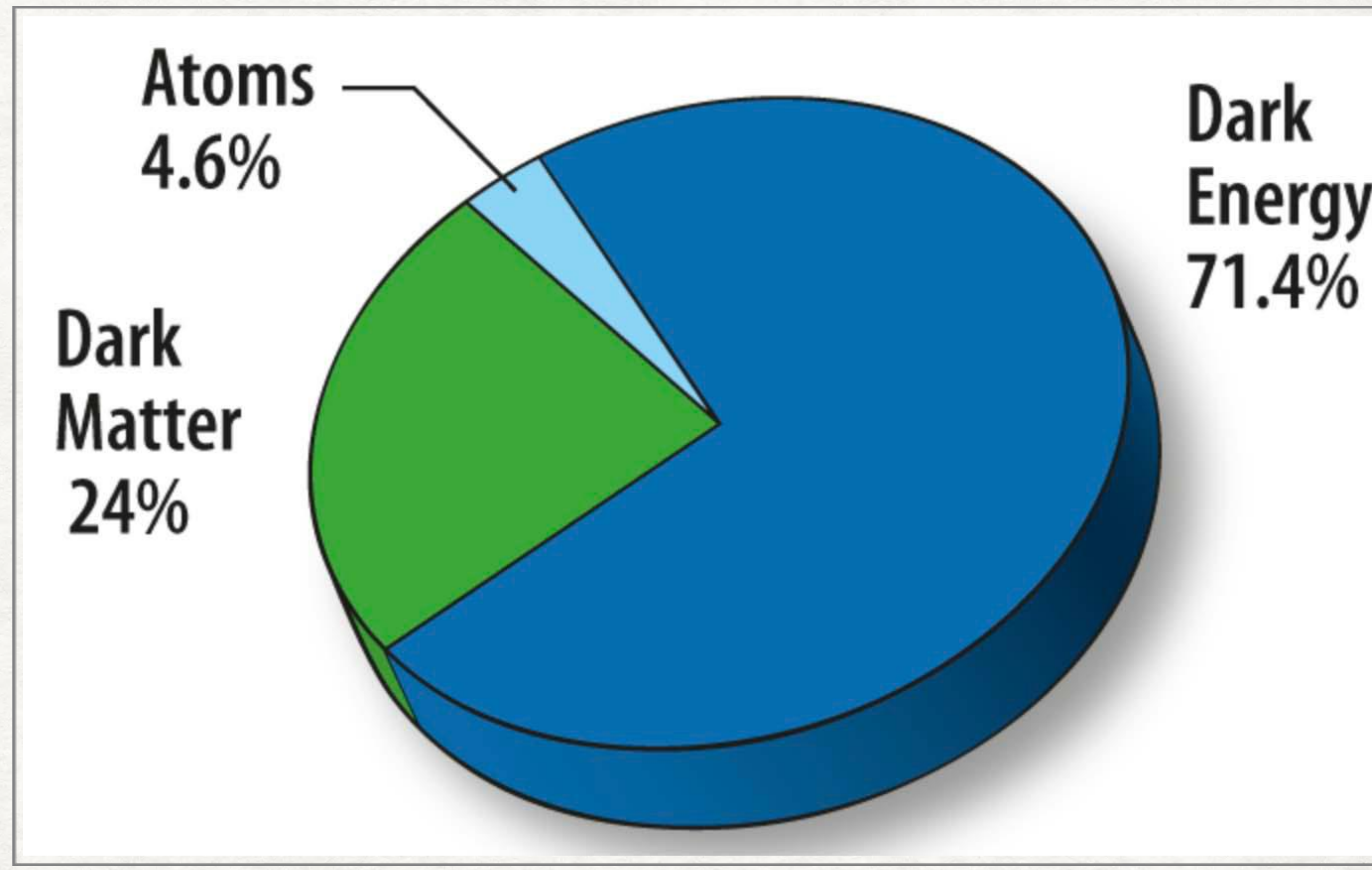
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Dark Matter (DM)



From: Bertone and Hooper, Rev. Mod. Physics (2016)



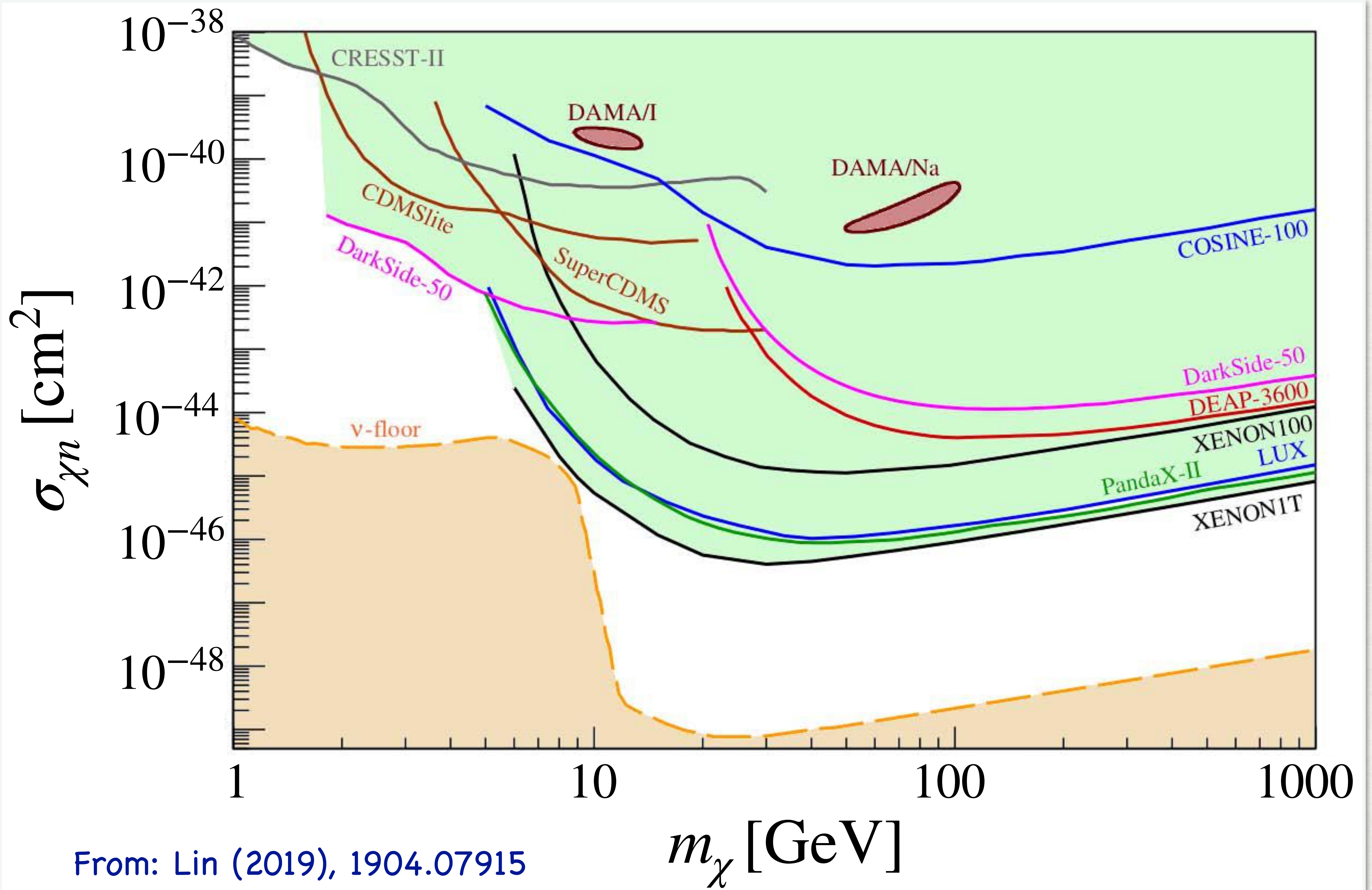
https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- DM mass?
- DM interactions with baryons?

Underground Detectors

https://www.symmetrymagazine.org/article/dark-matters-newest-pursuer

Results: Underground Detectors



From: Lin (2019), 1904.07915

- Exclusion limit weaken linearly for heavy DM interactions.

— Blind-spots to the underground detectors.

Weakly interacting Heavy DM

LIGO as a DM Detector

Bhattacharya, Dasgupta, Laha, **Ray** (2023) arXiv: 2302.07898

- How to probe heavy non-annihilating DM with feeble interactions?

Use existing GW detectors.

Also, EM observation of old neutron stars

Kouvaris et al (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...

Summary

- Celestial objects because of their large size and cosmologically long lifetime naturally act as gigantic DM detectors.

  naturally providing sensitivity to the tiny flux of heavy DM

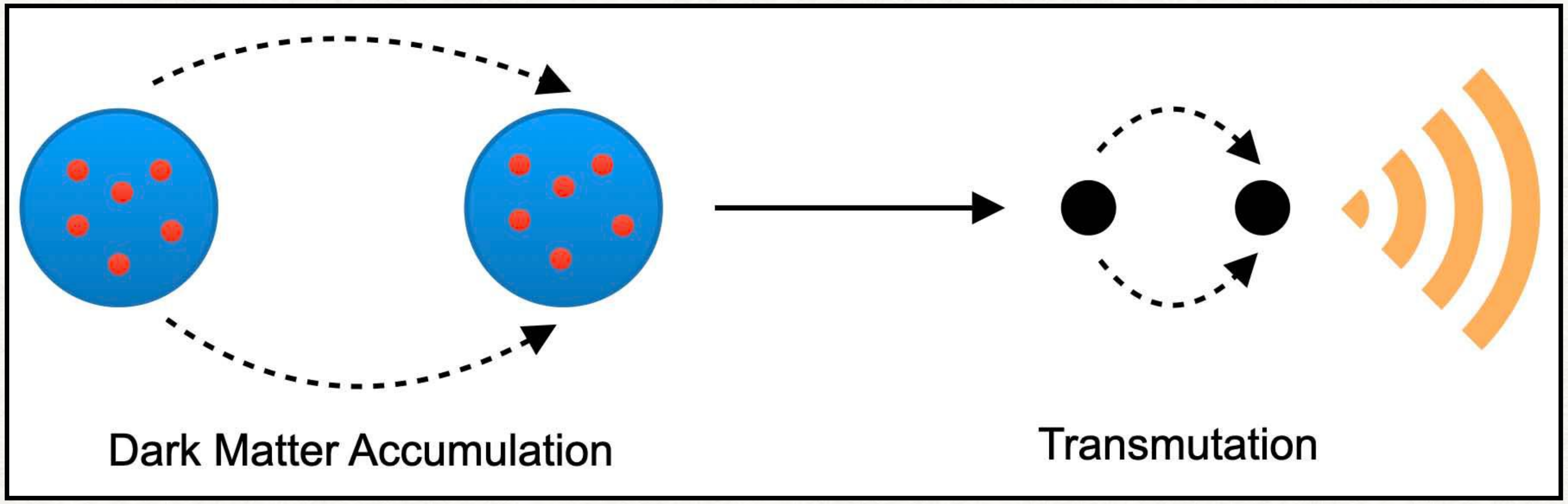
- In the weakly interacting regime, DM can be trapped in a significant number inside compact stars.

- EM observations of neutron stars provide the leading exclusions on weakly interacting heavy non-annihilating DM.

  Kouvaris et al. (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),…, Dasgupta, Gupta, **Ray** (JCAP 2020),…

- We explore GW observations of low mass compact objects to probe non-annihilating heavy DM interactions.

Summary



- Binary neutron stars can be transmuted to anomalously low mass binary BHs via gradual accumulation of non-annihilating DM.

Transmuted Black Holes (TBHs)

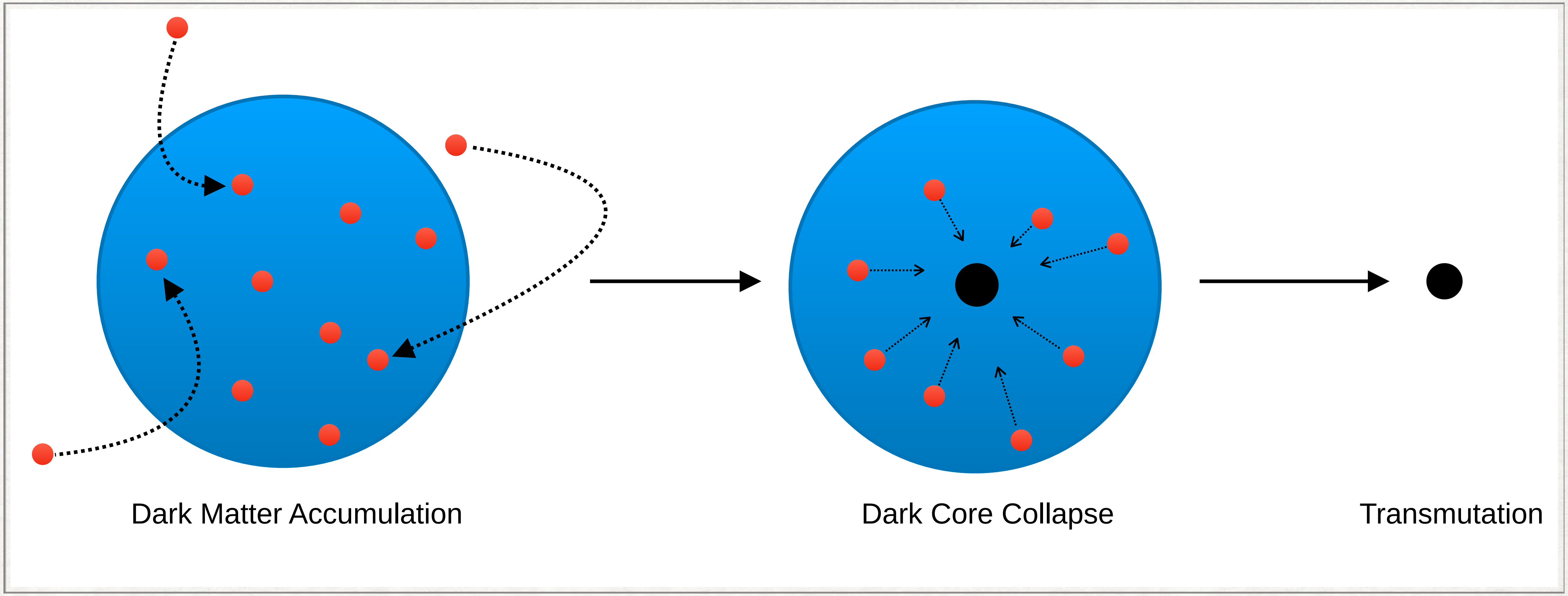
Dasgupta, Laha, Ray (PRL, 2022)

- Non detection of such binary BHs in the existing GW data provide novel constraints on weakly-interacting heavy DM interactions.

LIGO as a novel DM detector

Bhattacharya, Dasgupta, Laha, Ray (2023) arXiv: 2302.07898

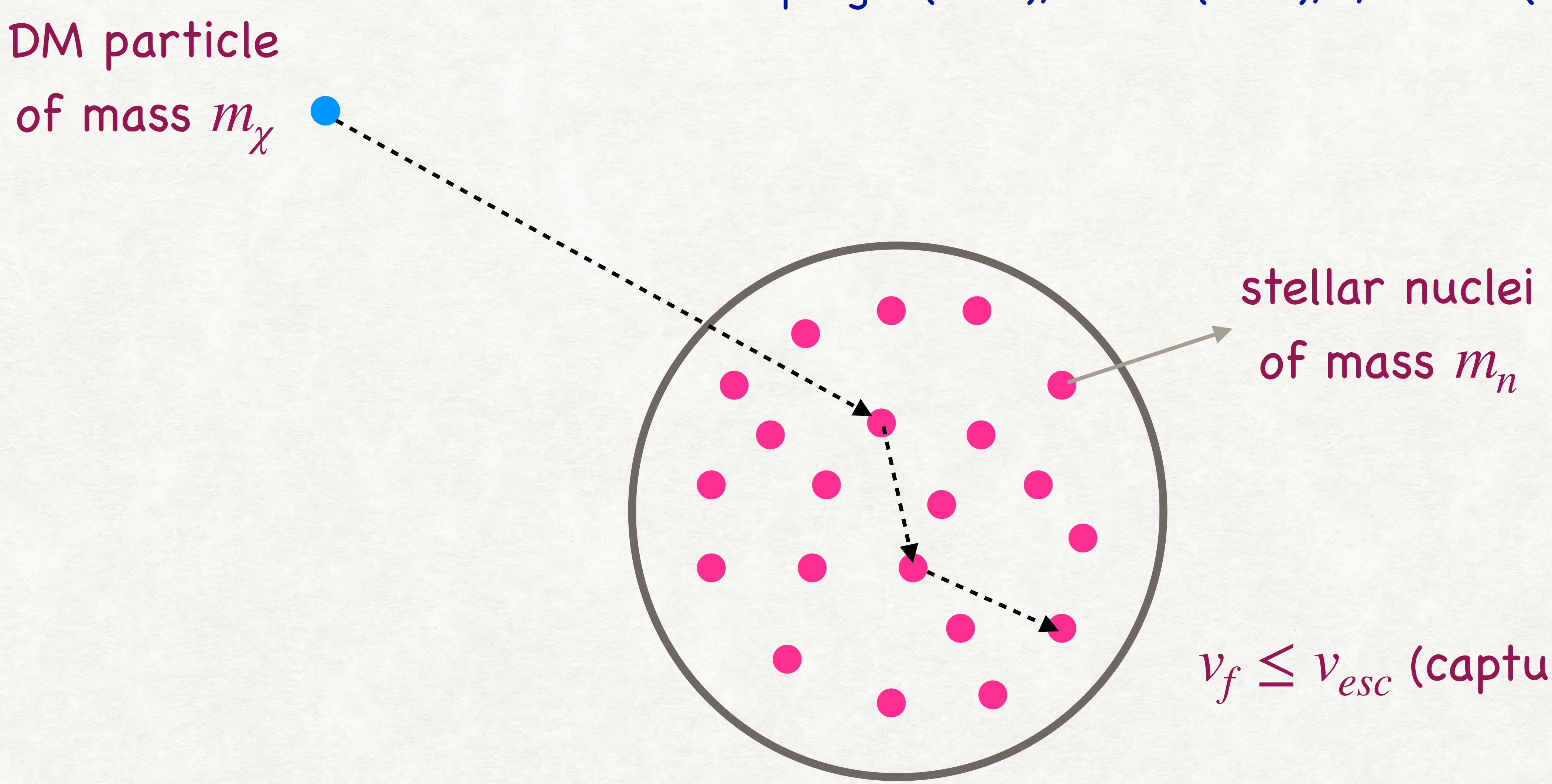
DM-induced Collapse



1. DM accumulation
2. DM thermalisation
3. DM distribution
4. Dark Core Collapse
5. Growth of micro-BH
6. Destruction of host

DM Accretion in Stellar Objects

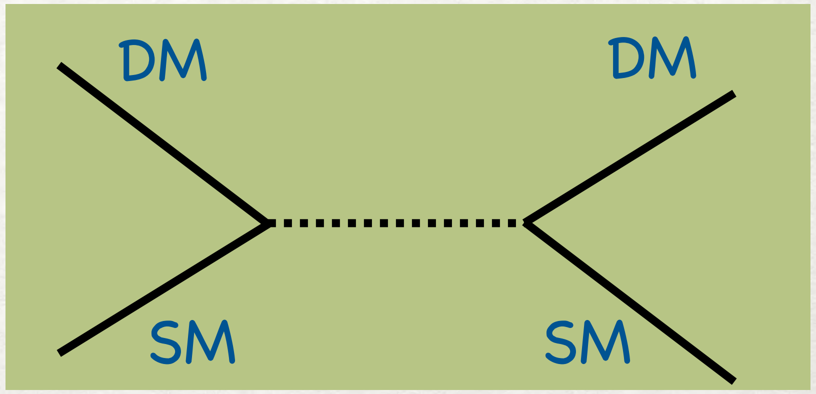
Press & Spergel (1985), Gould (1987),…., AR+++ (2020),…



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

v_f : final velocity of the DM particles

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



DM Accretion in Stellar Objects

- In the weakly interacting regime, DM typically scatters once while transiting thorough the stellar object.

  long mean free path

- Single-collision capture rate scales as M/R (compactness)

  - Neutron stars are the most optimal targets in the weakly interacting regime.

  - Non-compact objects are the most optimal targets in the strongly interacting regime.

$$C = 1.4 \times 10^{20}\,\mathrm{s}^{-1} \left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{10^5\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\sigma_{\chi n}}{10^{-45}\,\mathrm{cm}^2}\right)\left(1 - \frac{1-e^{-A^2}}{A^2}\right) \times \left(\frac{v_{\mathrm{esc}}}{1.9\times 10^5\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{220\,\mathrm{km\,s^{-1}}}{\bar{v}_{\mathrm{gal}}}\right)^2$$

Gould (1987),...

DM Distribution in Stellar Objects

- DM distribution inside the celestial objects depends on the effects of diffusion and gravity.

Gould and Raffelt 1990 (APJ), ..., Leane et al (2209.09834)

- For heavy DM, the effect of gravity ($\sim m_\chi$) dominates over the diffusion processes ($\sim m_\chi^{-3/2}$), and they gravitate towards the stellar core.

$$\frac{\nabla n_\chi(r)}{n_\chi(r)} + (\kappa + 1)\frac{\nabla T(r)}{T(r)} + \frac{m_\chi g(r)}{T(r)} = \frac{\Phi}{n_\chi(r) D_{\chi n}(r)} \frac{R_\oplus^2}{r^2}$$

For a typical NS, DM particles of mass 10^5 GeV settle within ~5 cm radius, and decreases further for larger DM mass!

Growth and Evaporation of BH

- The micro BH accumulates matter from the host and also evaporates via Hawking radiation.

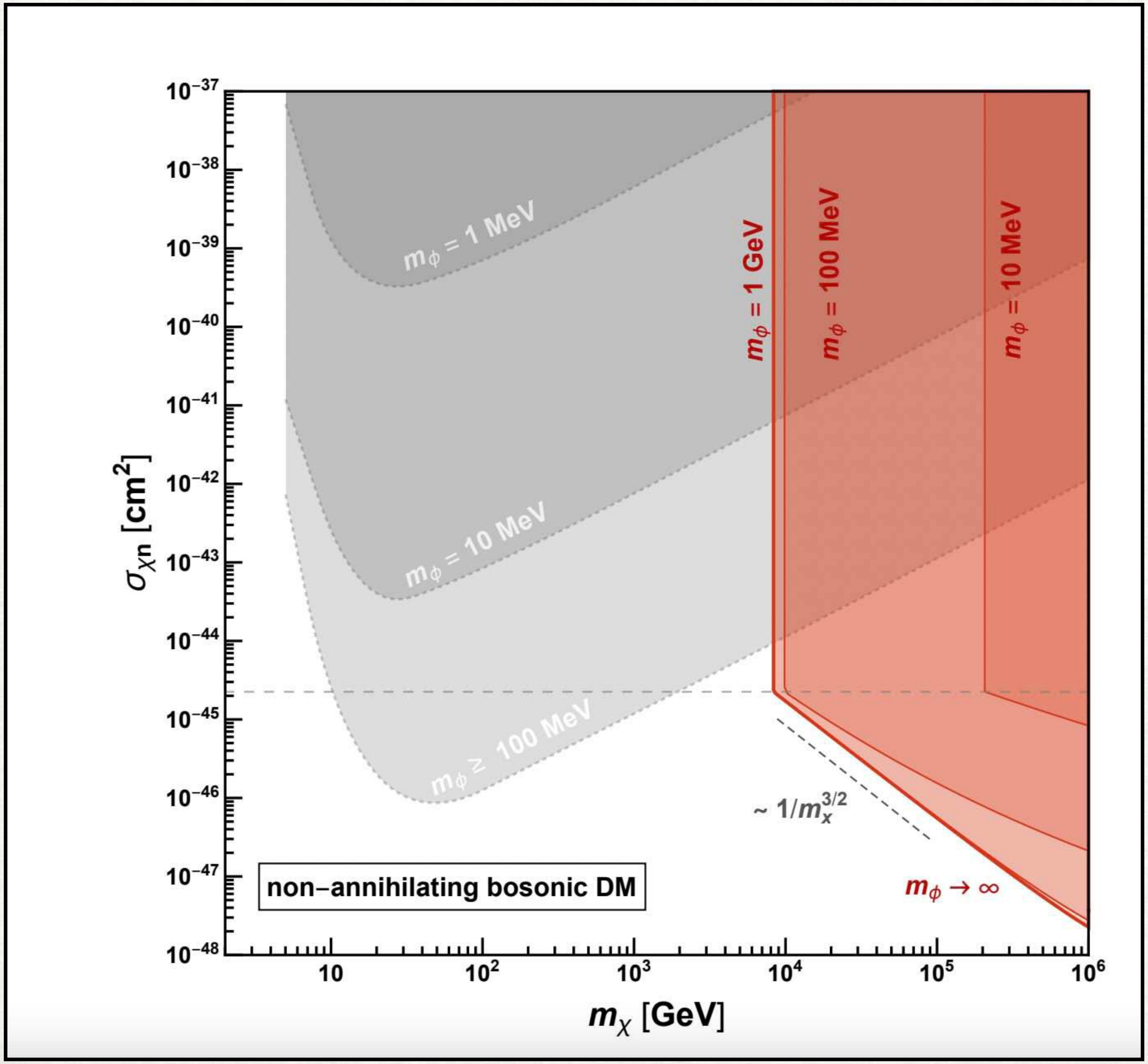
- For sufficiently small BH, accretion (M^2) becomes inefficient and Hawking evaporation dominates ($1/M^2$). This is relevant for very heavy DM mass, ceasing the implosion.

$$\frac{dM_{\rm BH}}{dt} = \frac{4\pi\rho_{\rm core}G^2M_{\rm BH}^2}{c_s^3} - \frac{P\left(M_{\rm BH}\right)}{G^2M_{\rm BH}^2}$$

$P(M_{\rm BH})$: Page factor which takes into account the grey-body spectrum and importantly, the number of emitted SM species. It ranges from $1/74\pi$ to $1/1135\pi$.

Classical limit is $1/11360\pi$.

Exclusion from EM observations



Kouvaris et al. (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),…, Dasgupta, Gupta, **Ray** (JCAP 2020),…

What about GW observations?

Constraints from existence of an old nearby Pulsar PSR-J0437-4715.

TBH formation & Mergers

- Captured DM particles, because of the **strong gravitational potential** of the neutron stars, **sink** towards the stellar core, undergo a dark core-collapse, and form a micro-BH.

Kouvaris et al (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...

- Transmutation time: [Collapse time + Swallow time]

$$\tau_{\rm collapse} = C^{-1} \max\left[N_\chi^{\rm self}, N_\chi^{\rm Cha}\right]$$

$$\tau_{\rm collapse}|_{\rm boson} = 4.8\times 10^8\,{\rm years}\left(\frac{T_{\rm core}}{2.1\times10^6\,{\rm K}}\right)^{3/2}\left(\frac{10^5\,{\rm GeV}}{m_\chi}\right)^{3/2}\left(\frac{0.4\,{\rm GeV\,cm^{-3}}}{\rho_\chi}\right)\left(\frac{10^{-45}\,{\rm cm^2}}{\sigma_{\chi n}}\right),$$

$$\tau_{\rm collapse}|_{\rm fermion} = 1.9\times 10^9\,{\rm years}\left(\frac{10^9\,{\rm GeV}}{m_\chi}\right)\left(\frac{0.4\,{\rm GeV\,cm^{-3}}}{\rho_\chi}\right)\left(\frac{10^{-45}\,{\rm cm^2}}{\sigma_{\chi n}}\right).$$

$$\tau_{\rm swallow} = 10^4\,{\rm years}\left(\frac{10^{-15}\,M_\odot}{M_{\rm BH}}\right)$$

Baumgarte et al. (PRD 2021), Richards et al (PRD 2021),...

TBH formation & Mergers

- For TBH mergers at present time:

$$t_f + \tau_{\rm trans} < t_0$$

t_f : Binary formation time

t_0 = 13.79 Gyr = Present day

- We track each progenitors (NS binaries) from their binary formation time till present day to compute the present day TBH merger rate.

Dasgupta, Laha, Ray (PRL, 2022)

$$R_{\rm TBH}(z=0) = \int dr \frac{df}{dr} \int_{t_*}^{t_0} dt_f \frac{dP_m}{dt}[t_0 - t_f] \times \lambda \times \frac{d\rho_*}{dt}[t_f] \times \Theta\left[t_0 - t_f - \tau_{\rm trans}\left[m_\chi, \sigma_{\chi n}, \rho_{\rm ext}(r, t_0)\right]\right]$$

TBH merger rate depends on DM mass and DM-nucleon scattering cross-section via transmutation time with an uncertain normalization parameter.

TBH Merger Rate

- TBH merger rate depends on:

i) Spatial distribution of Binary NS in the Galaxies.

(uniform distribution in 1d)

ii) DM density profile in the Galactic halos.

(NFW profile)

iii) Cosmic star formation rate.

(Madau-Dickinson model)

iv) Merger delay time distribution. $\propto 1/(t_0 - t_f)$

v) Progenitor properties (mass, radius, core temperature of the progenitors).

(Typical NS parameters)

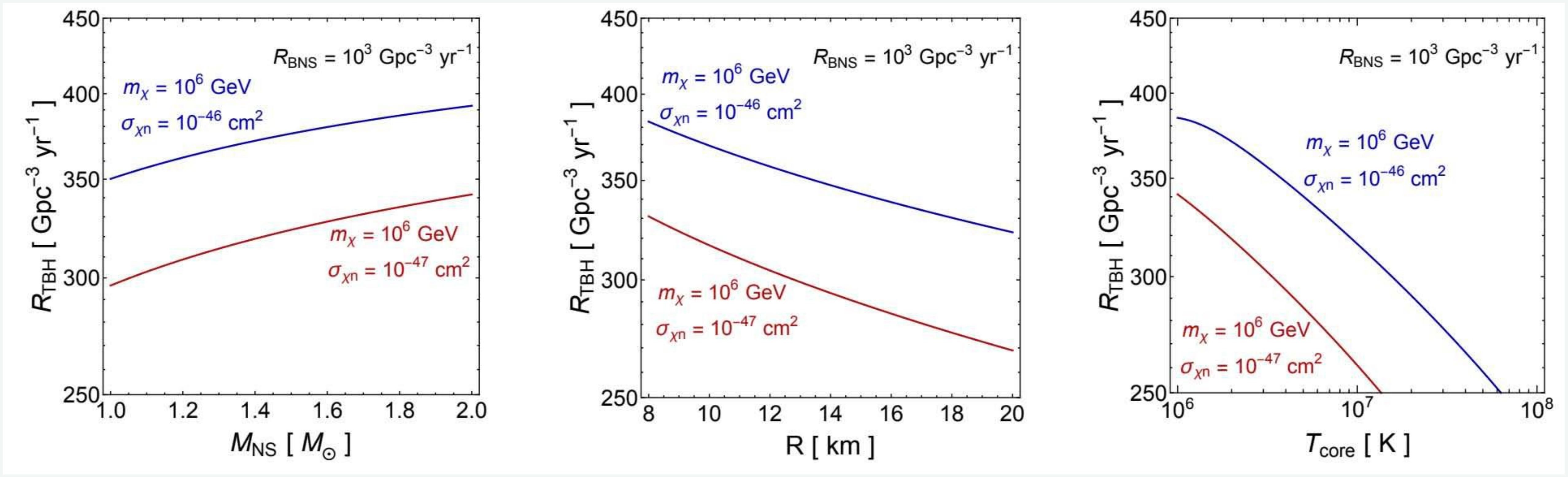
vi) Uncertain normalization parameter.

(10-1700 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ from LVK measurement)

Systematic exploration is required.

TBH Merger Rate

Bhattacharya, Dasgupta, Laha, **Ray** (2023) arXiv: 2302.07898

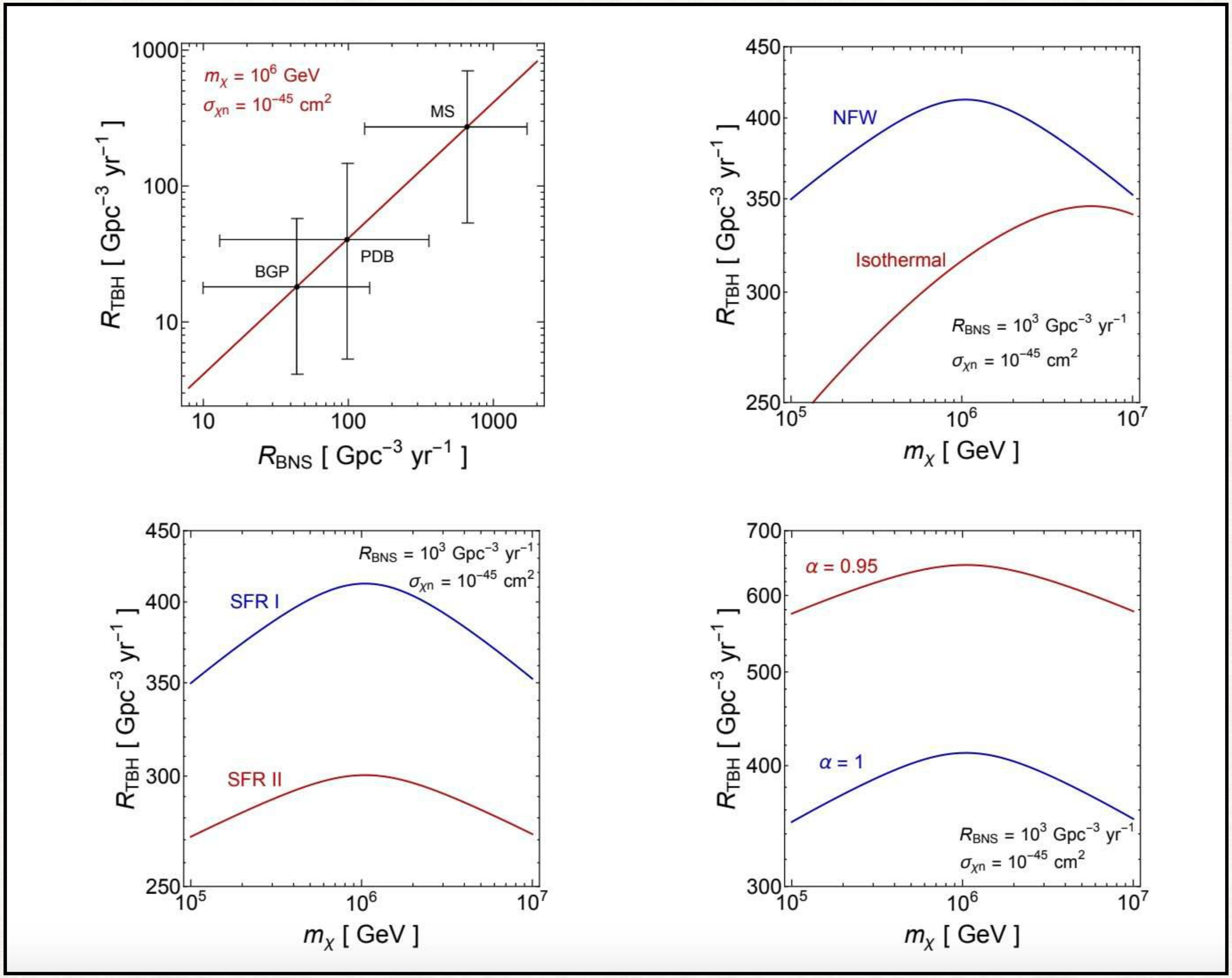


(Left) Mass (Middle) Radius (Right) Core-temperature

Possible variations in the progenitor properties have a negligible impact on the TBH merger rate. Quantitatively, TBH merger rate varies at most 20% because of progenitor properties.

TBH Merger Rate

Ray++, arXiv: 2302.07898



Cosmic star formation and delay time distribution models have an insignificant impact.

However, the uncertain normalization parameter has the most prominent impact.

GW Data & Statistics

- We use the **null-detection of low mass BH searches** in the LIGO data to infer constraints on non-annihilating DM interactions.

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (APJ 2021, PRL 2021),...

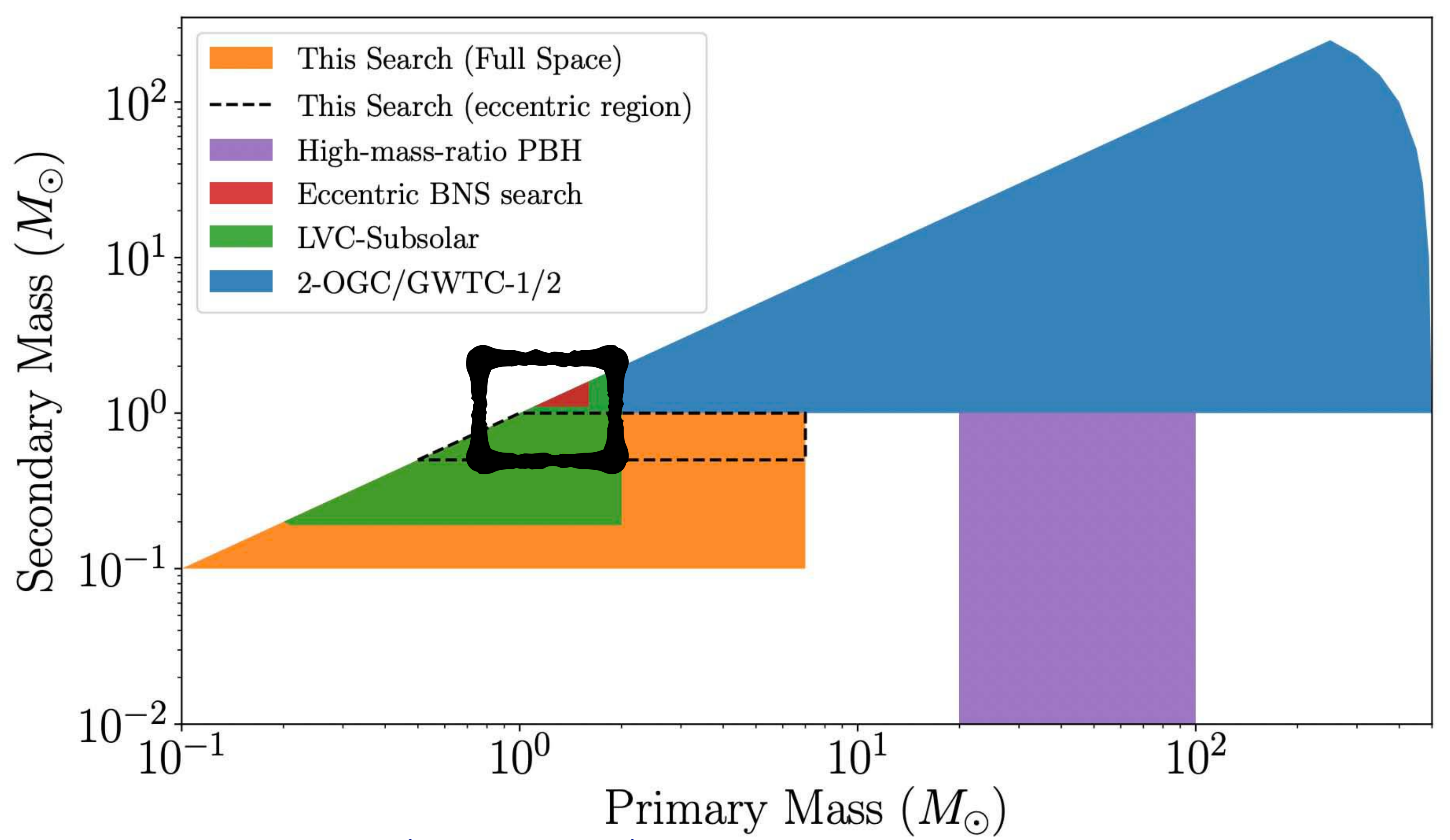


Fig: Nitz & Wang (APJ 2021)

GW Data & Statistics

- Merger rate upper limits:

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (APJ 2021, PRL 2021),...

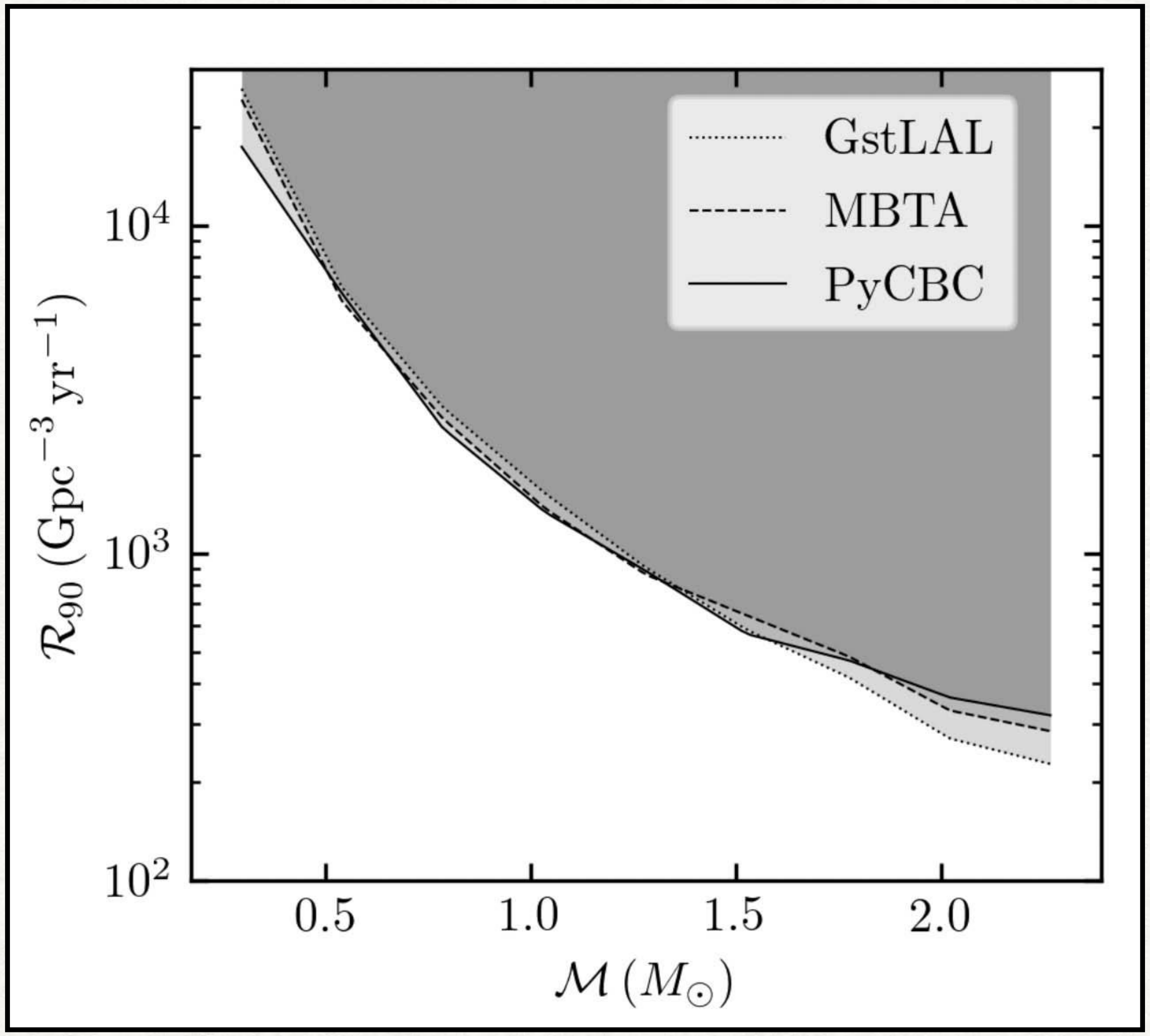


Fig: LVK (PRL 2021)

*These searches have recently been used to put constraints on PBHs as DM as well as an atomic DM model. For the first time, we use them to probe particle DM interactions.

GW Data & Statistics

- For 1.32 - 1.32 $M_\odot$ binary = Chirp mass of 1.15 $M_\odot$, LIGO collaboration (O3 run) provides a merger rate upper limit of $R_{90} = 389\,\mathrm{Gpc^{-3}\,yr^{-1}}$.

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (PRL 2021),...

- Our "Conservative" exclusion limit:

$$R_{\rm TBH}(z=0)\,[m_c = 1.15\,M_\odot] \leq 389\,\mathrm{Gpc^{-3}\,yr^{-1}}$$

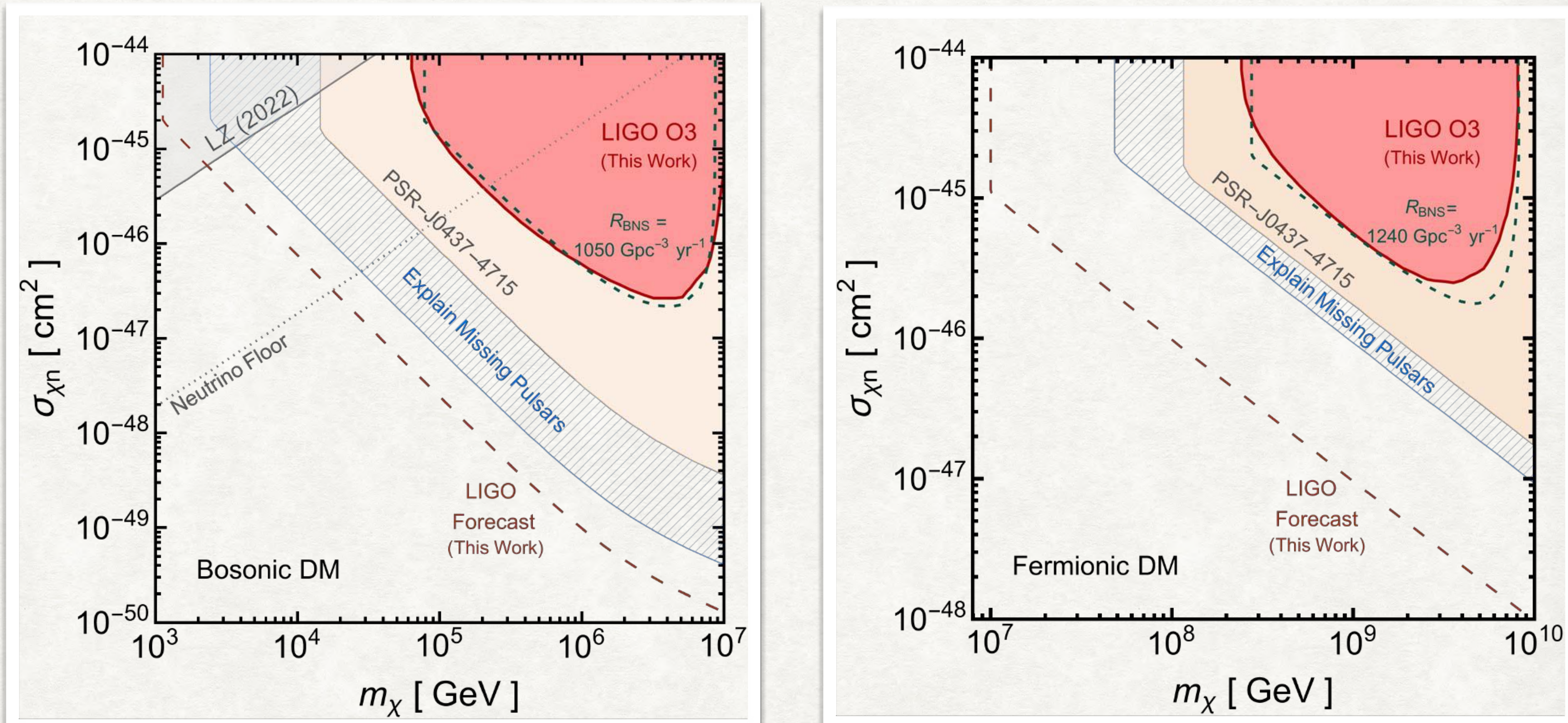
Chirp mass distribution of BNS is sharply peaked peaked at 1.15 $M_\odot$, which can be approximated as a Dirac-delta mass distribution.

Ozel & Freire (Ann. Review of Astronomy and Astrophysics, 2016)

Conservative: LIGO can not distinguish low mass compact objects as BHs. With tidal deformation & EM counterpart, our analysis can be improved.

Results

Bhattacharya, Dasgupta, Laha, **Ray** (2023) arXiv: 2302.07898



(Left) Bosonic DM (Right) Fermionic DM

Heavier DM masses, the nascent BH becomes smaller, Hawking evaporation becomes significant, ceasing the TBH formation.

More on Statistics

- We employ three different statistical methods to estimate the GW-inferred constraints on DM interactions.

In order to bracket the uncertainty on the normalization parameter of $R_{\rm TBH}$

- Benchmark Bayesian analysis:

[Prior-dependent]

— Log-uniform priors on $m_\chi \in \left(10^4, 10^8\right)$ GeV for bosonic DM and $m_\chi \in \left(10^8, 10^{11}\right)$ for fermionic DM.

— Log-uniform priors on $\sigma_{\chi n} \in \left(10^{-50}, 10^{-44}\right)\ {\rm cm}^2$ for bosonic DM and $\sigma_{\chi n} \in \left(10^{-48}, 10^{-44}\right)\ {\rm cm}^2$ for fermionic DM.

— Uniform prior on the uncertain normalization parameter $R_{\rm BNS} \in (10, 1700)\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$ LVK 2111.03634

More on Statistics

- **Frequentist analysis:**

  — Normalization parameter of R_{TBH} needs to be assumed.

  — For lower values of the normalization parameter, we obtain "no" exclusions.

  — For relatively higher values of the normalization parameter (consistent with the LVK measurement), we obtain stringent exclusion limits.

- **Hybrid-Frequentist analysis:**

  — No assumption of priors for the DM parameters $(m_\chi, \sigma_{\chi n})$.

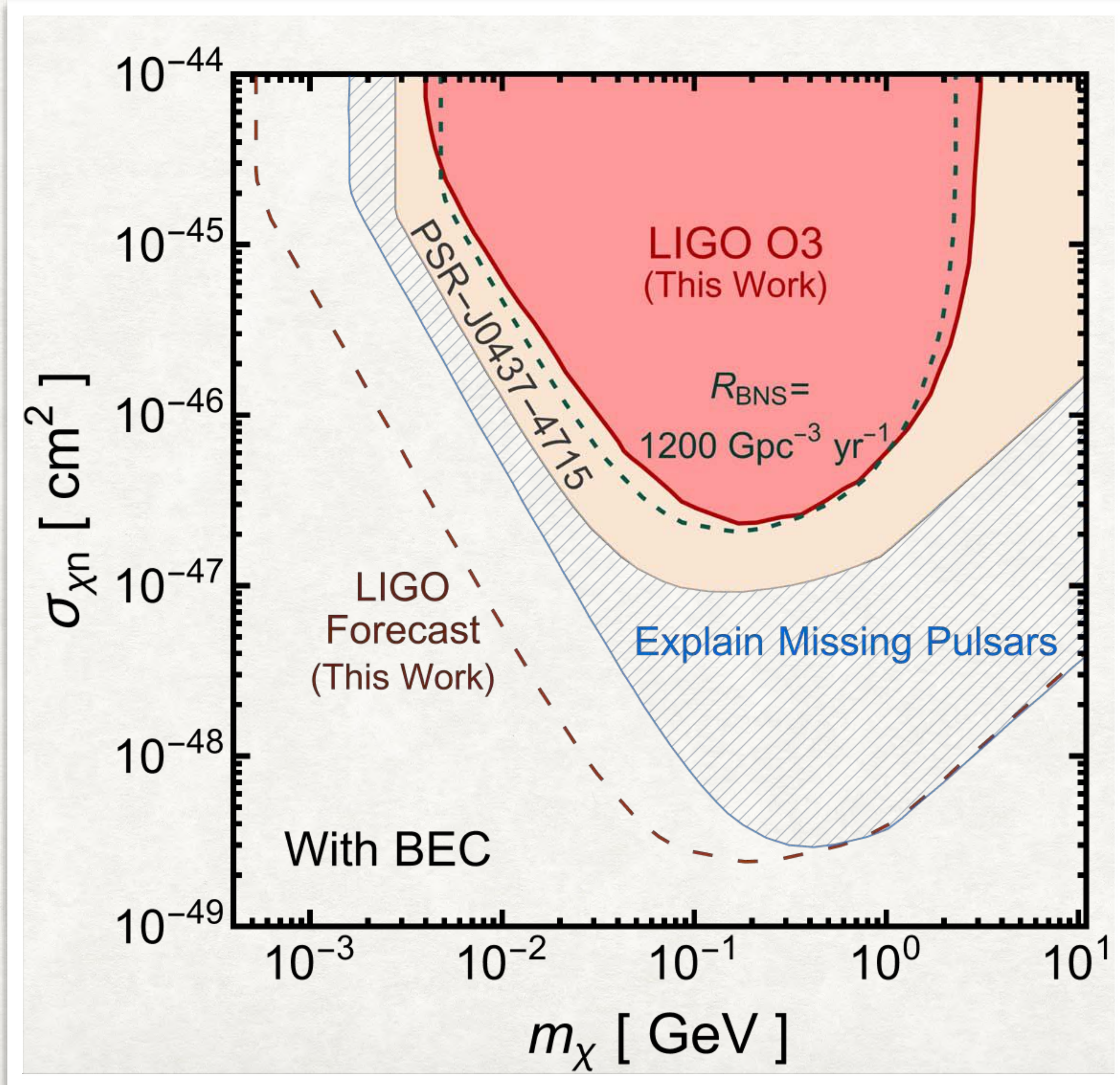
  — Marginalizing over the normalization parameter by assuming a uniform prior.

  — For any value (even the lowest) of the normalization parameter, we obtain an exclusion limit 25 times weaker than the Bayesian exclusion.

BEC Formation

- Bosonic DM can form a Bose-Einstein condensate inside NSs

Kouvaris et al (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...



Ray++, arXiv: 2302.07898

GW-inferred constraints for a possible BEC formation scenario

Conclusion

- Existing GW detectors can be used to probe the particle nature of DM.

- For weakly interacting heavy DM, LIGO provides novel constraints on DM interactions, much more stringent as compared to the direct DM searches.

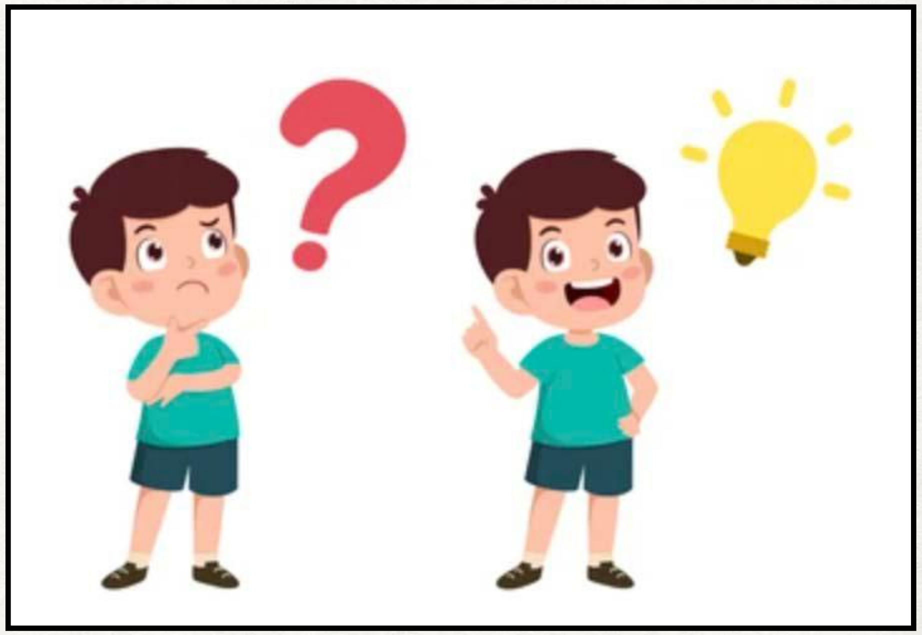
  with increased exposure, LIGO provides world-leading sensitivity within a decade

- Owing to a different systematics, GW-inferred exclusions has the potential to beat the EM-inferred exclusions.

(LZ 2022) (spin-independent) excludes DM-nucleon scattering cross-section of $2.8 \times 10^{-43}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$.

LIGO excludes DM-nucleon scattering cross-section of $2 \times 10^{-47}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$. **"Impossible"** to reach by these underground detectors!

For Heavy non-annihilating DM interactions, Listening to the sky seems the best way forward!



Thanks!

Questions & Comments: anupam.ray@berkeley.edu