Detecting Dark Matter With Neutron Stars

i) Phys. Rev. Lett. 131, 091401 (2023)

ii) Phys. Rev. D. 111, 023005 (2025)

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Recontres de Moriond, EW, 2025

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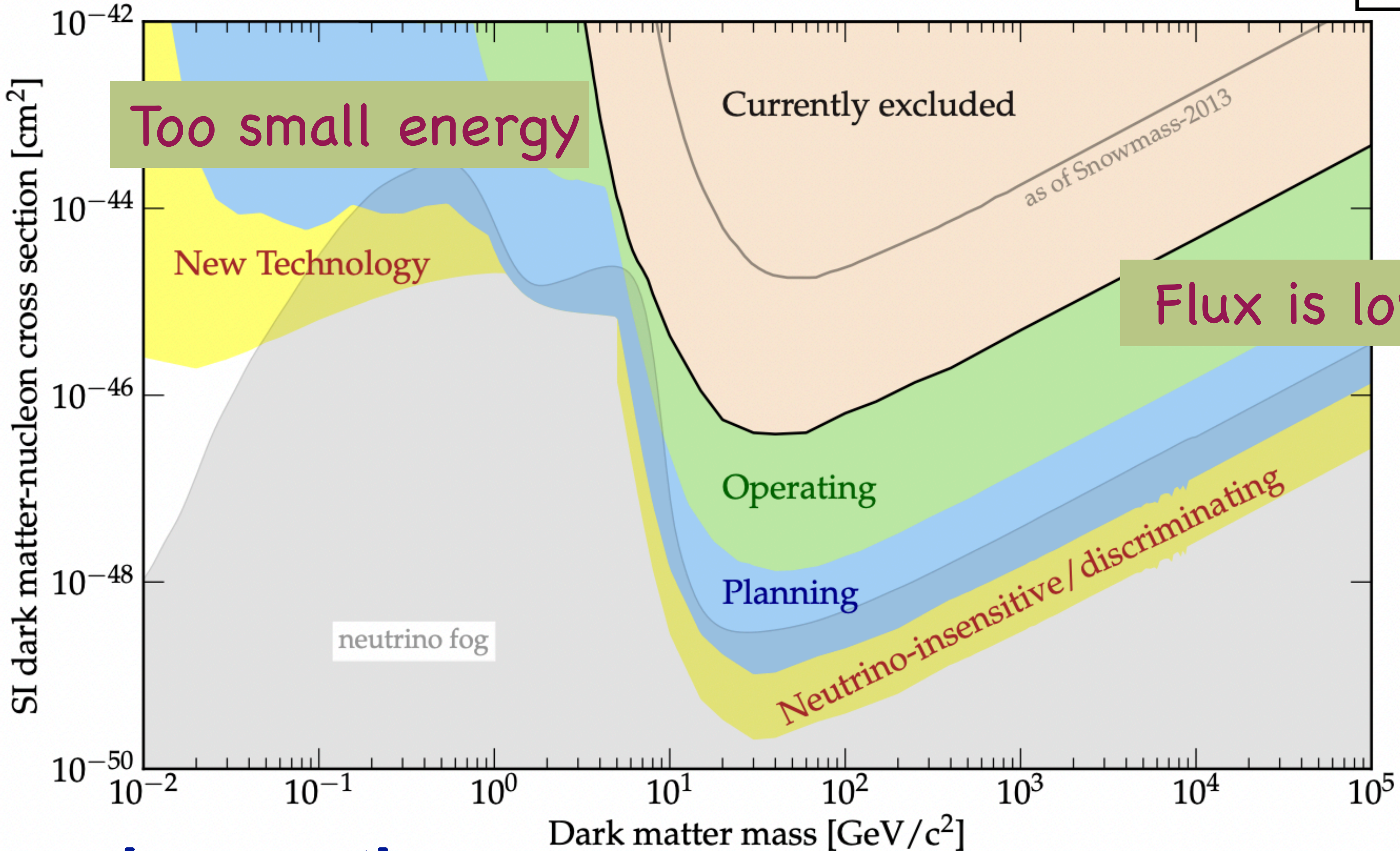
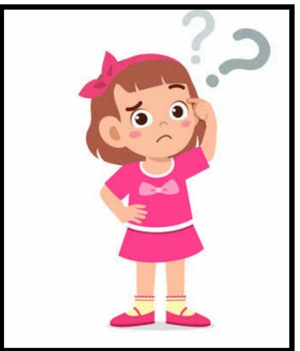
PHYSICS FRONTIER CENTER

Results: Underground Detectors





Snowmass [2209.07426]

Summary

- Celestial Objects are excellent DM detectors, especially for heavy DM searches.

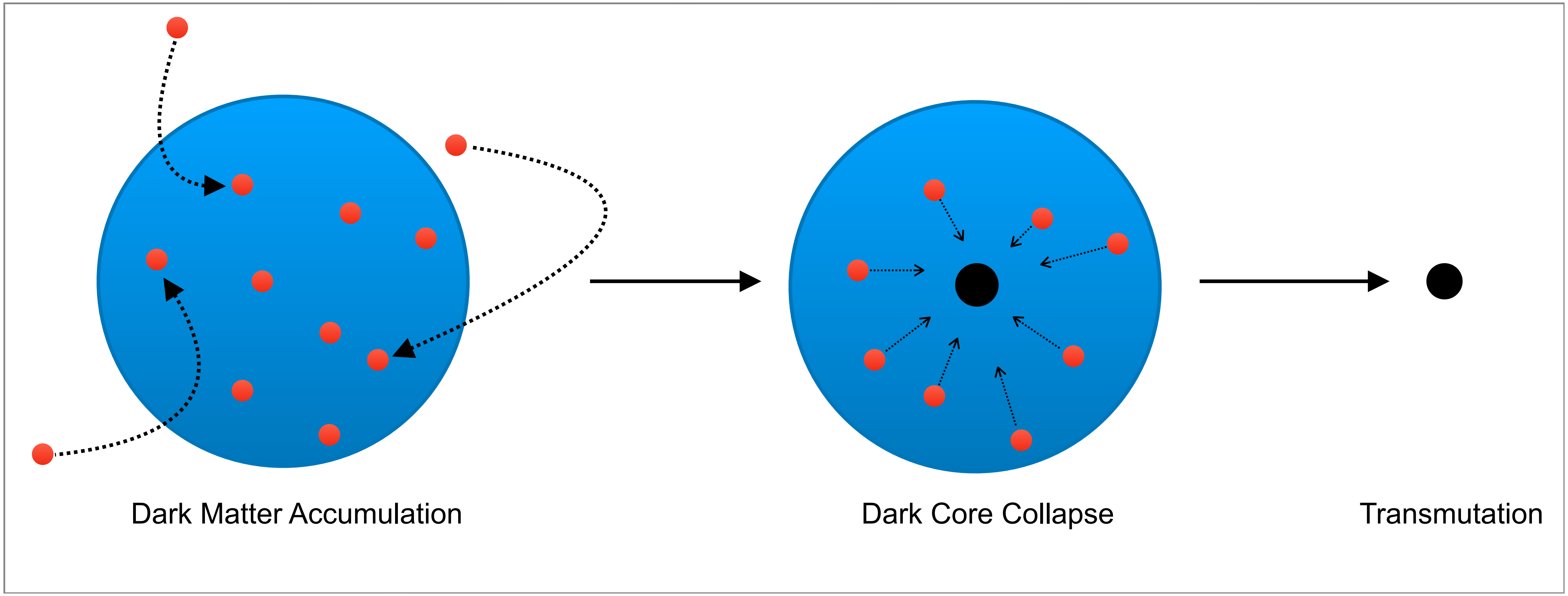
  Their "effective" exposures are much larger as compared to the human-made experiments.

- Neutron Stars are the most optimal objects.

  Far more trapping than any other celestial objects in the optically thin regime.

- Several phenomenological observables: (based on DM model).

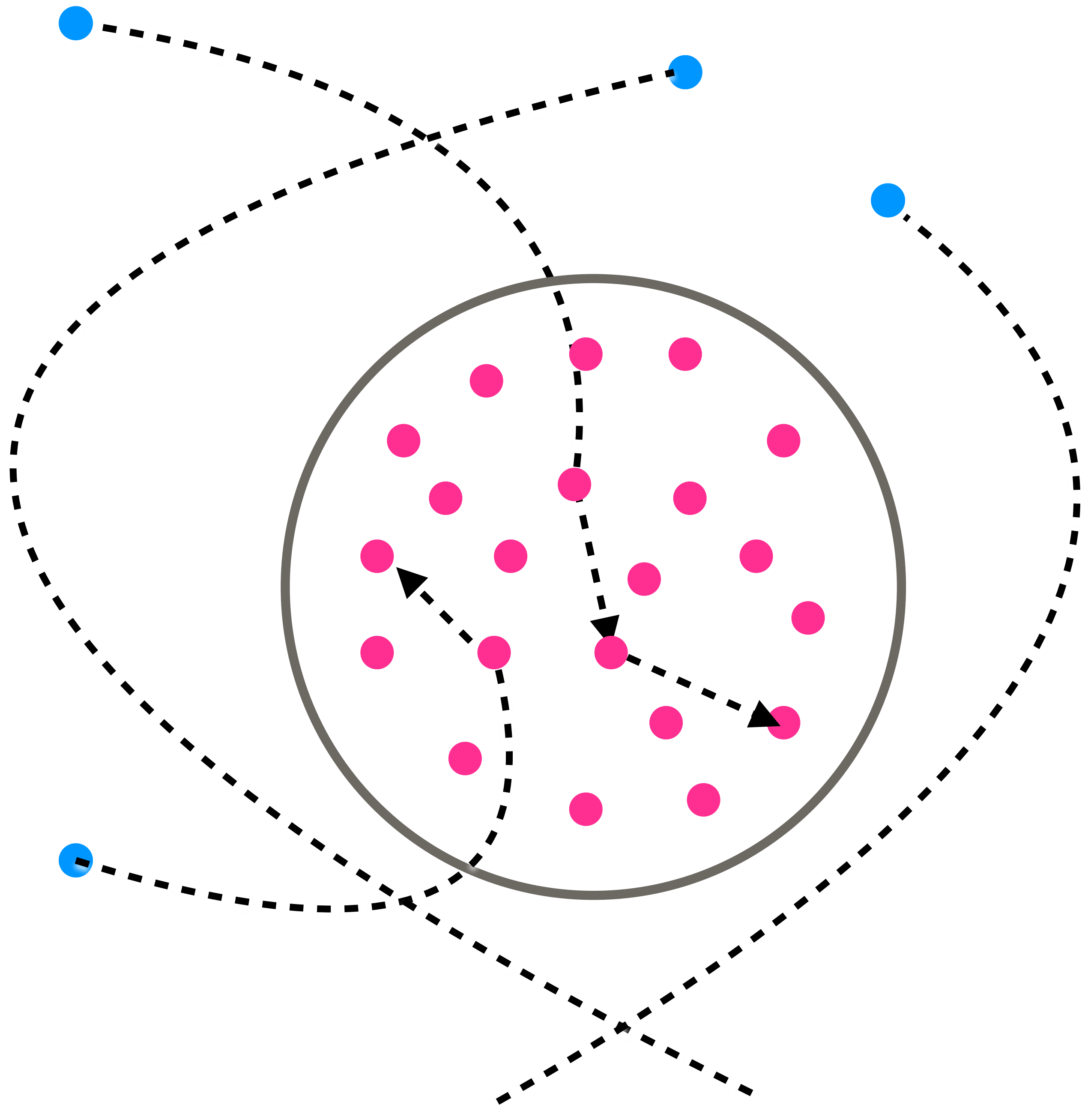
Non-Annihilating DM



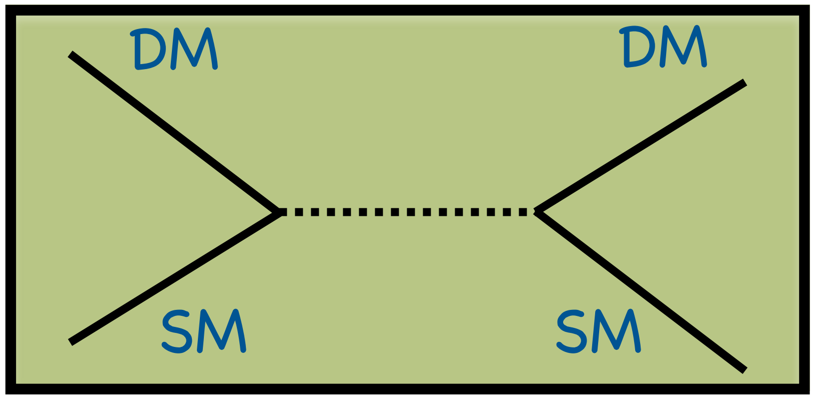
1. DM accumulation and its thermalisation
2. DM distribution
3. Dark Core Collapse
4. Growth of micro-BH and destruction of host

DM Accumulation

Press & Spergel (1985,ApJ), Gould (1987, ApJ),...



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



DM Accumulation

Press & Spergel (1985, ApJ), Gould (1987, ApJ),...

- Rate of DM particles transiting:

$$C_{\rm geo} \sim \pi R^2 \times \frac{\rho_\chi}{m_\chi} \times \bar{v} \times \left(1 + \frac{3v_{\rm esc}^2}{2\bar{v}^2}\right)$$

For typical NS parameters, transit rate is $10^{20}\,\mathrm{s}^{-1}$ for $m_\chi = 10^5$ GeV

- Fraction of these transiting DM particles gets captured depending on DM-nucleon scattering cross-section.

For $\sigma_{\chi n} = 10^{-45}$ cm^2 $\rightarrow f_c \sim 0.4$

(For Sun $\rightarrow f_c \sim 10^{-10}$)

Capture fraction (f_c) = $\dfrac{\sigma_{\chi n}}{\pi R^2 / N_n}$

*Capture rate scales linearly with compactness (M/R)

Distribution of Captured DM

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

Gould and Raffelt (APJ, 1990), …, Leane et al (JCAP, 2023)

- For heavy DM, the effect of gravity dominates over the diffusion processes, and they gravitate towards the stellar core.

For a typical NS, DM particles of mass 10^5 GeV settle within $\sim$5 cm radius!

- The core density of the captured DM particles become very large and eventually it collapses to a tiny BH at the core.

Core density of $10^{39}\,\mathrm{GeV/cm^3}$

Growth of Nascent BH

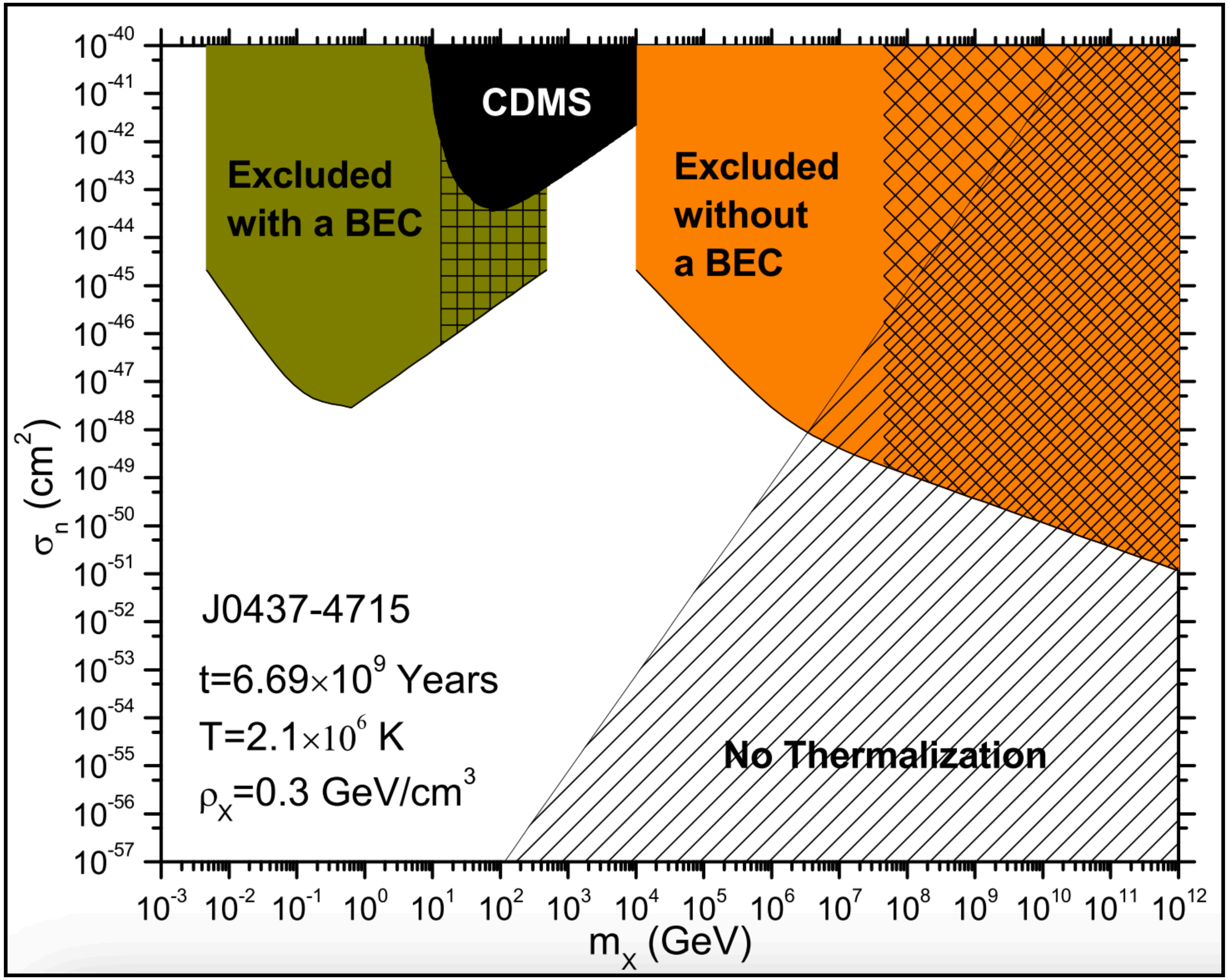
- The micro BH accumulates matter from the host and also evaporates via Hawking radiation.

- For sufficiently small BH, accretion (M^2) becomes inefficient and Hawking evaporation dominates ($1/M^2$), ceasing the implosion.

For micro-BHs smaller than $10^{-20}\,M_\odot$, Hawking evaporation dominates

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

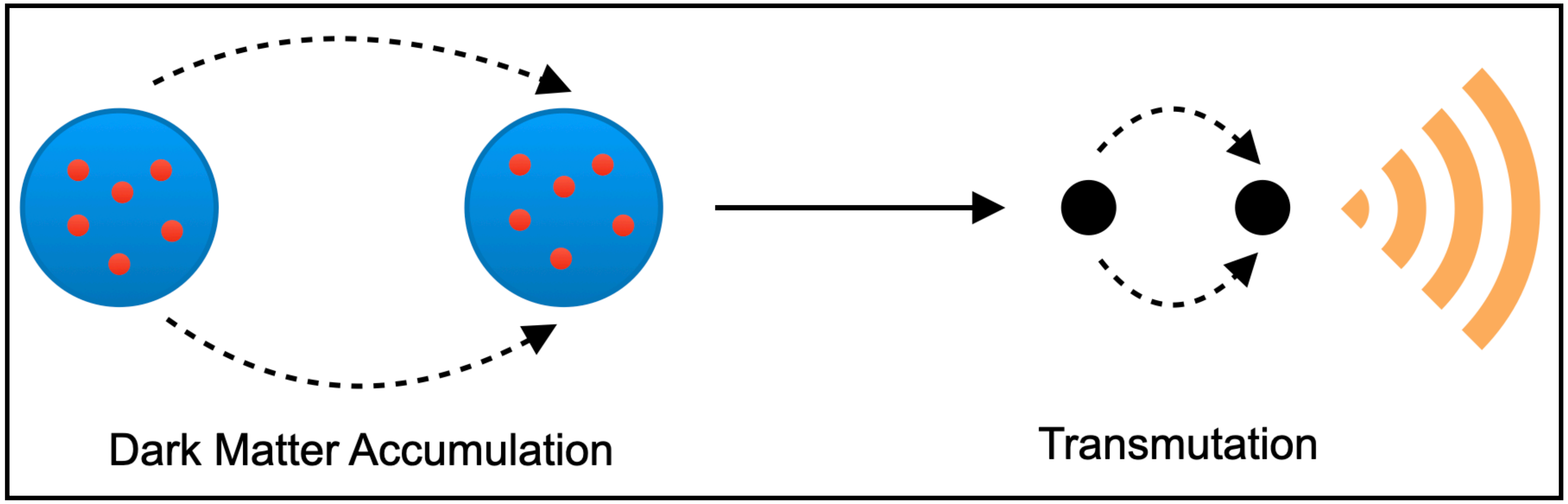
Exclusions on DM parameters



Existence of a nearby old Pulsar.

Mcdermott, Yu, Zurek (PRD, 2011), Kouvaris, Tinyakov (PRL, 2011),....

GW probes



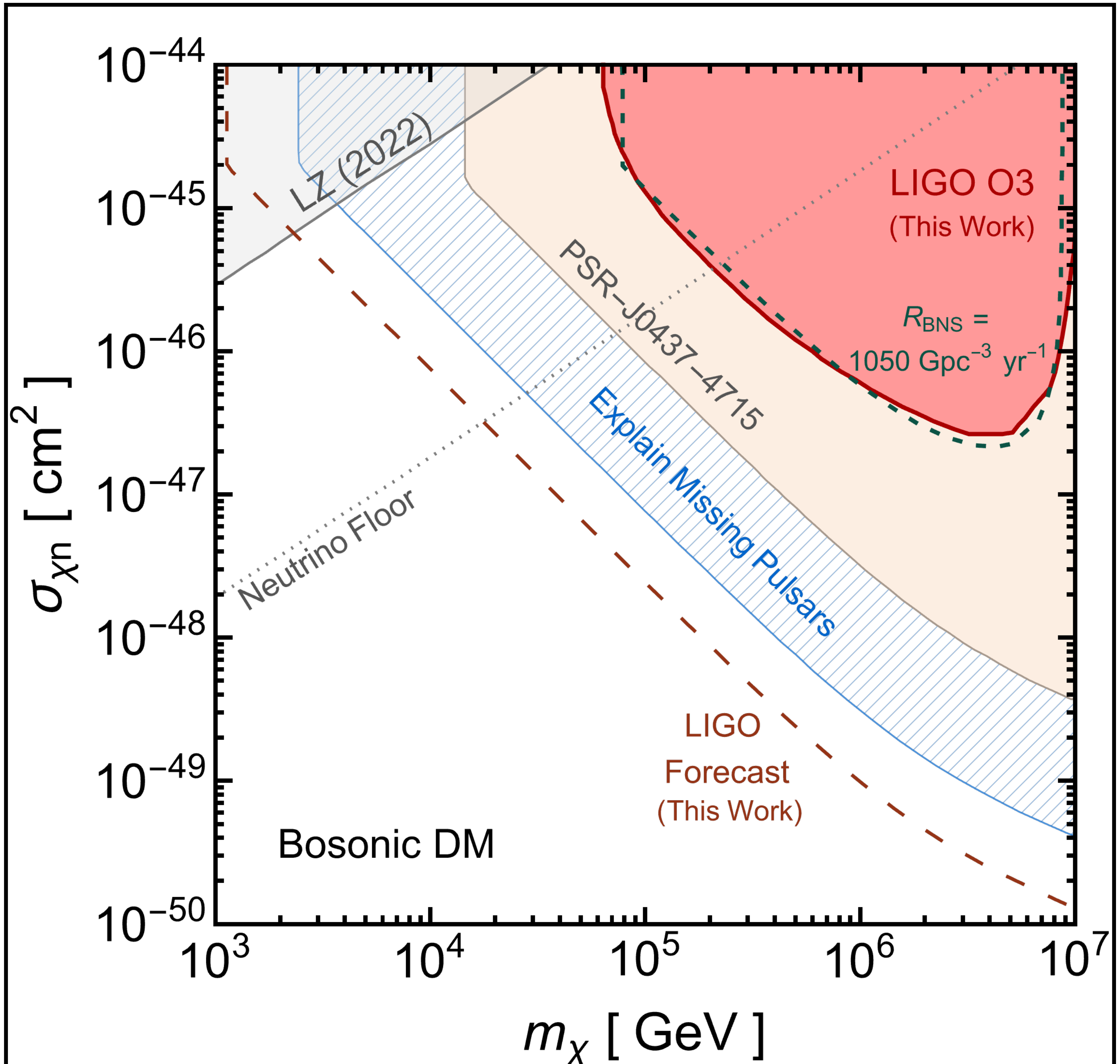
- GW from mergers of such low mass transmuted BH can also be searched in the LVK data.

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

Ray (with Bhattacharya, Dasgupta, Laha) [PRL, 2023]

Results

Ray (with Bhattacharya, Dasgupta, Laha) [PRL, 2023]



Heavier DM masses, the nascent BH becomes smaller, Hawking evaporation becomes significant, terminating the process.

Discovery Potential

- Transmuted black holes are exciting as they provide non-primordial solution to unusual low mass BHs.

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 24, 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

(Stellar or Primordial?)

+ few other

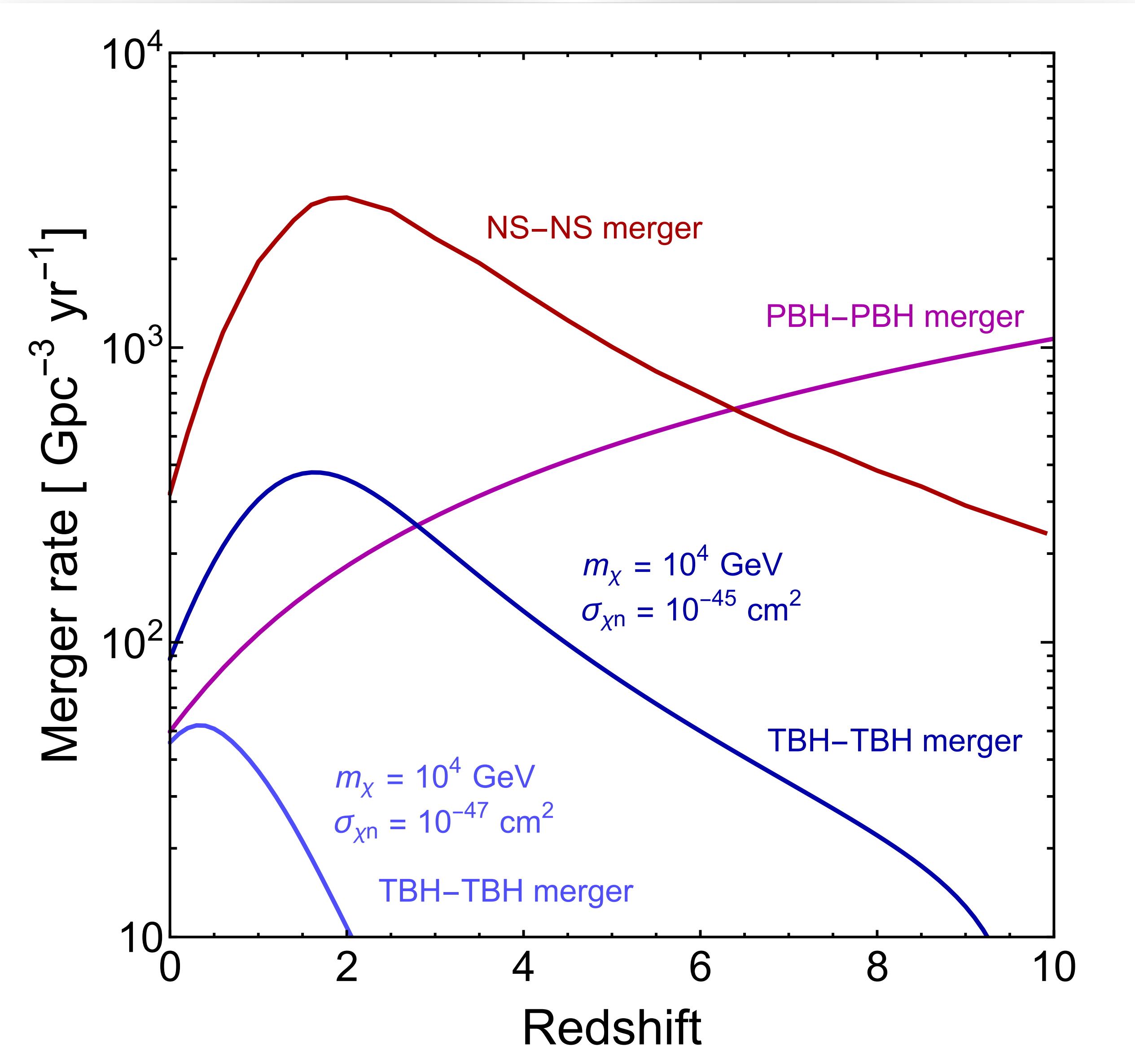
GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4\,M_\odot$

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

Discovery Potential

- Redshift dependence of the binary merger rates can be used as a probe to determine the origin of low mass BHs

Mergers as a probe of particle DM



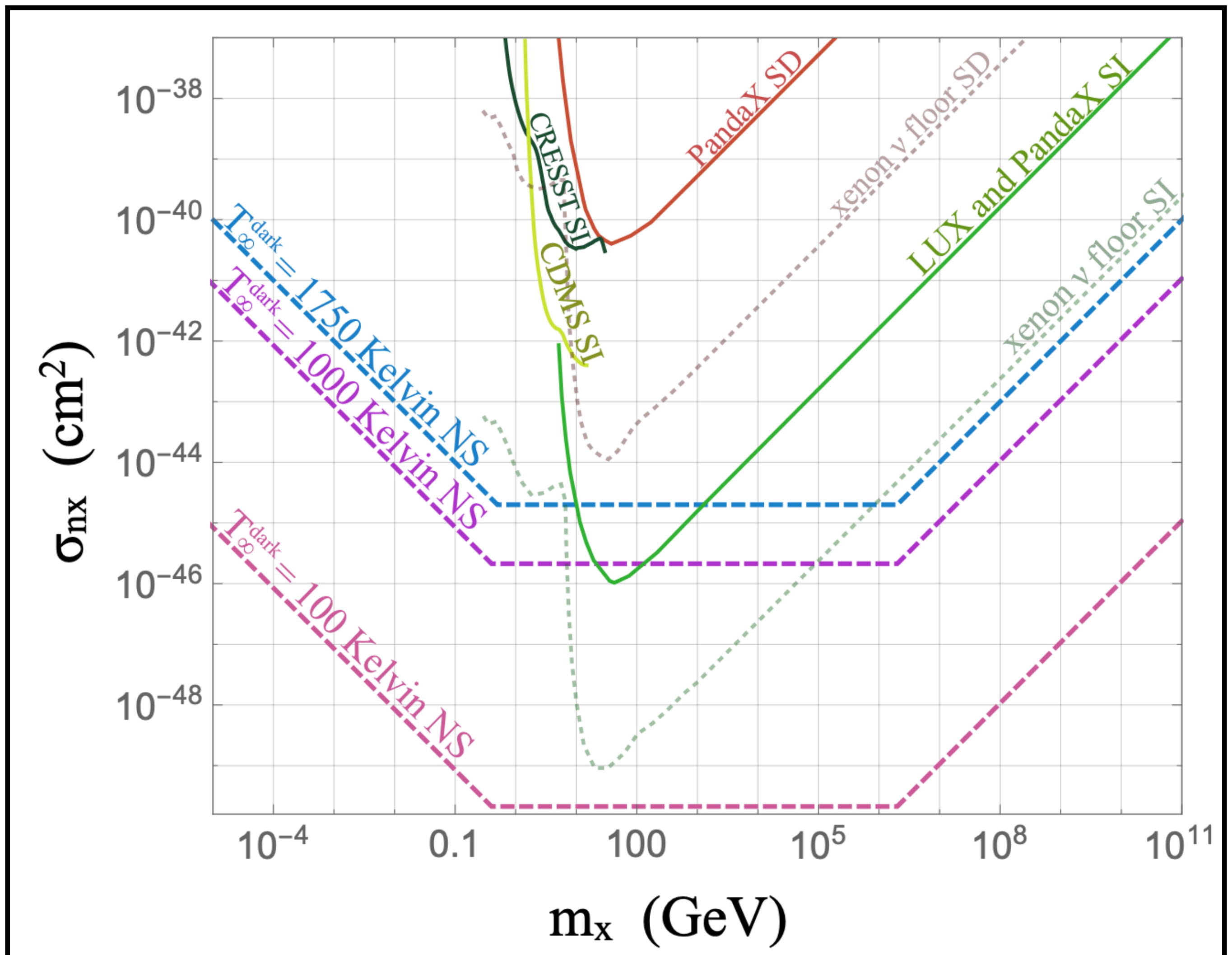
Distinct redshift dependence o merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments (Pre-DECIGO, Einstein Telescope).

Ray (with Dasgupta, Laha) [PRL, 2021]

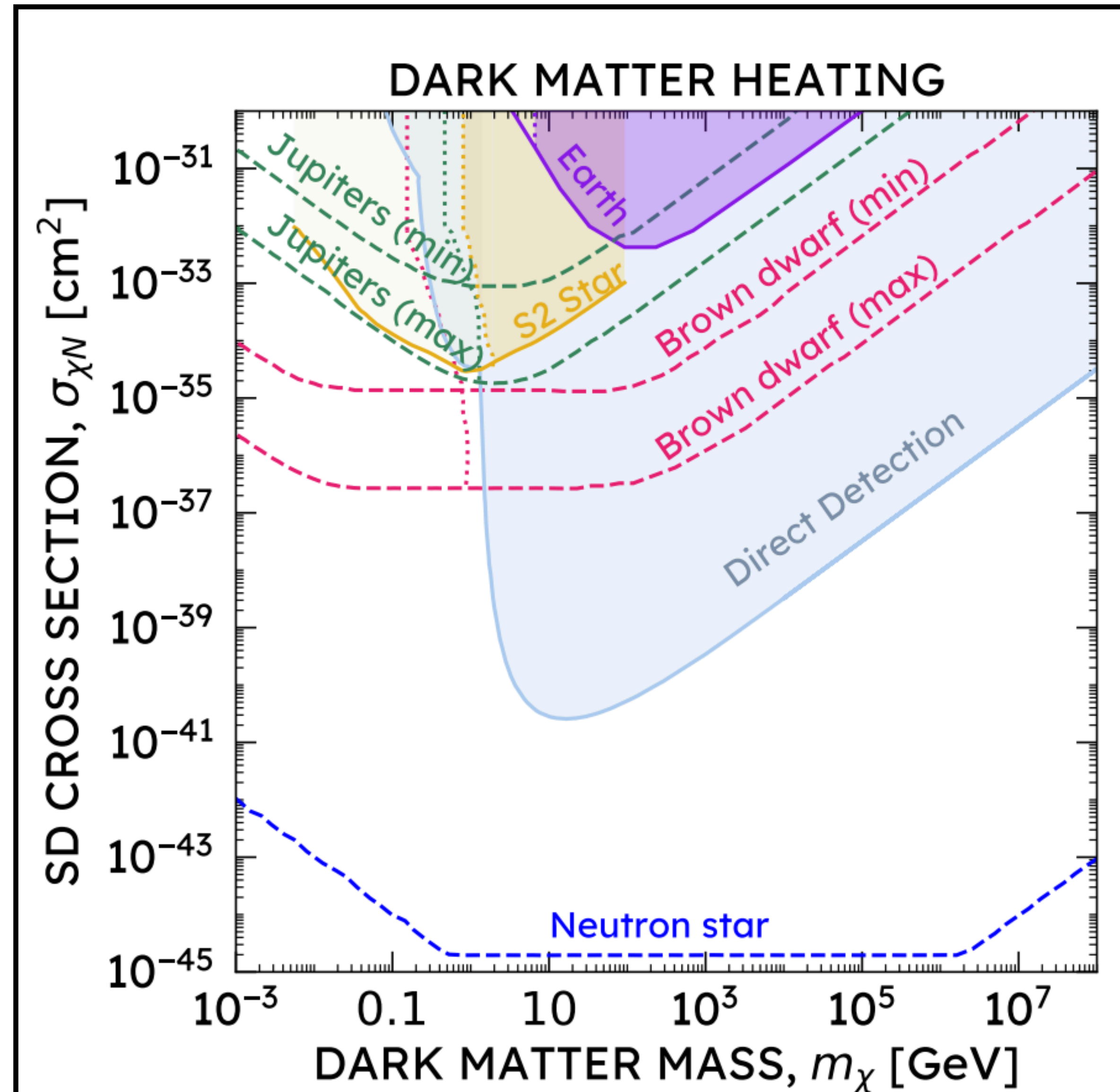
What about the Annihilating DM?

- Anomalous neutron star heating via captured DM annihilation (or via kinetic energy transfer).

Baryakhtar et al [PRL, 2017]



Leane et al [2405.05312]

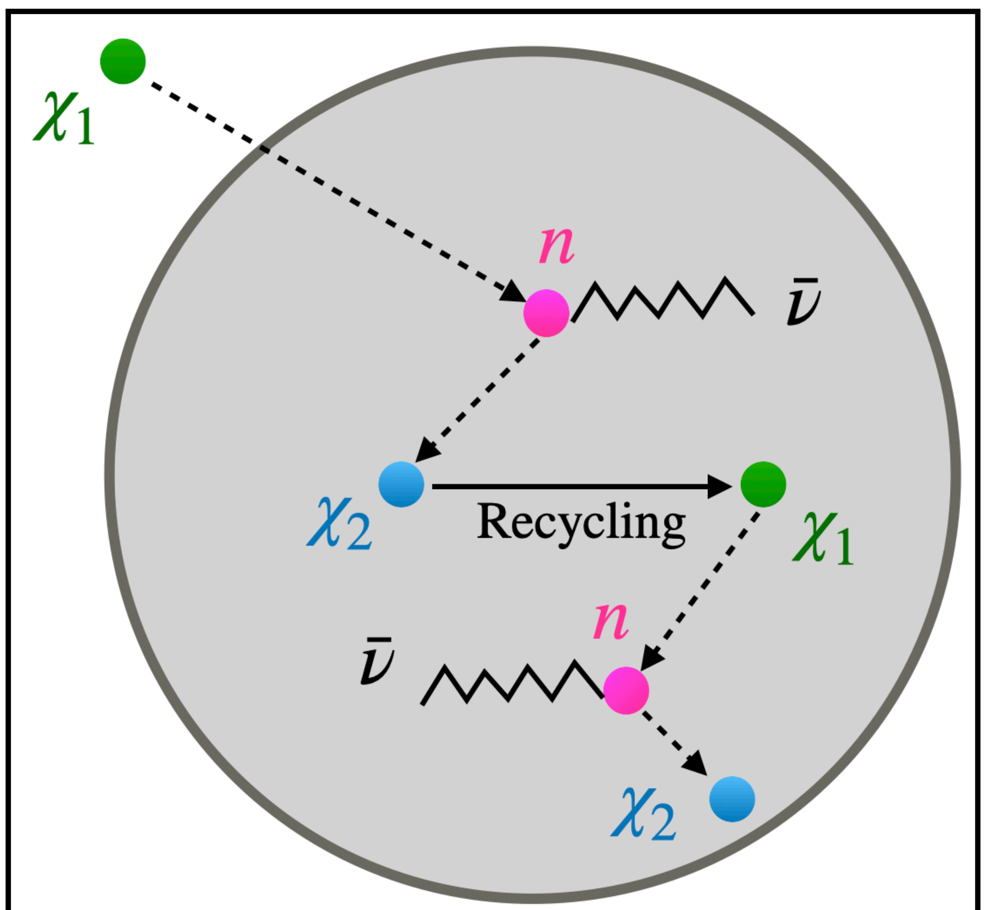


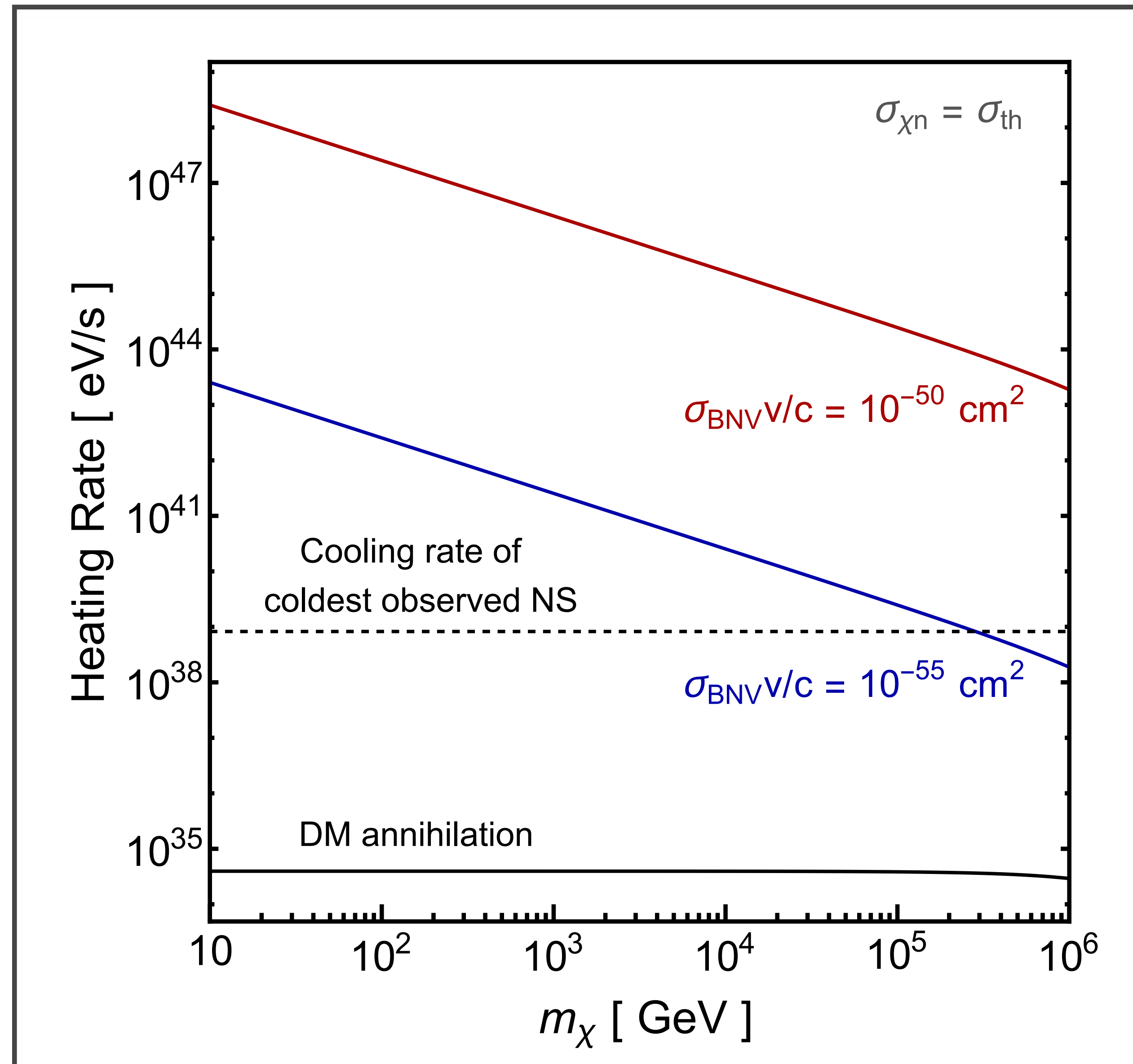
Coldest NS so far seen has $T \sim 40{,}000\,K$ $\rightarrow$ **(no actual constraint on vanilla models!)**

Baryon-Number-Violating Interactions

- WIMP-type DM with additional $\Delta B \neq 0$ interactions, can lead to novel heat generation mechanism in cold neutron stars.

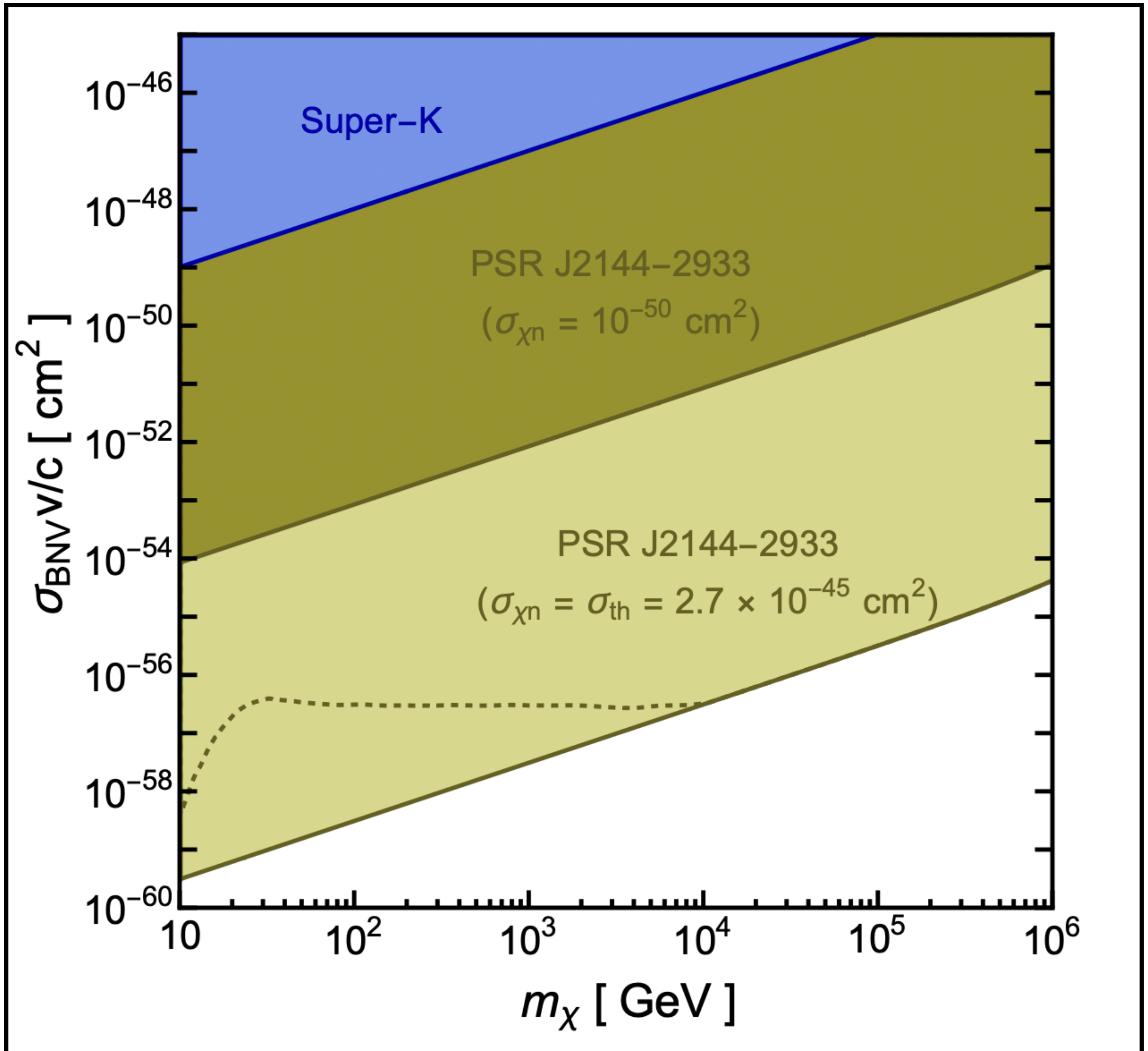
$$\chi_1 + n \to \chi_2 + \bar{\nu}$$
$$\chi_2 \to \chi_1$$





Ray, (with Ema, McGhee, Pospelov) [PRD, 2025]

Baryon-Number-Violating Interactions



Non-observation of any anomalous heating in a nearby cold pulsar.

Ray, (with Ema, McGhee, Pospelov) [PRD, 2025]

Conclusions

- Neutron stars are excellent DM detectors, especially for heavy DM searches.

- Owing to a different systematics, these exclusions has the potential to cover parameter space well-below the neutrino floor.

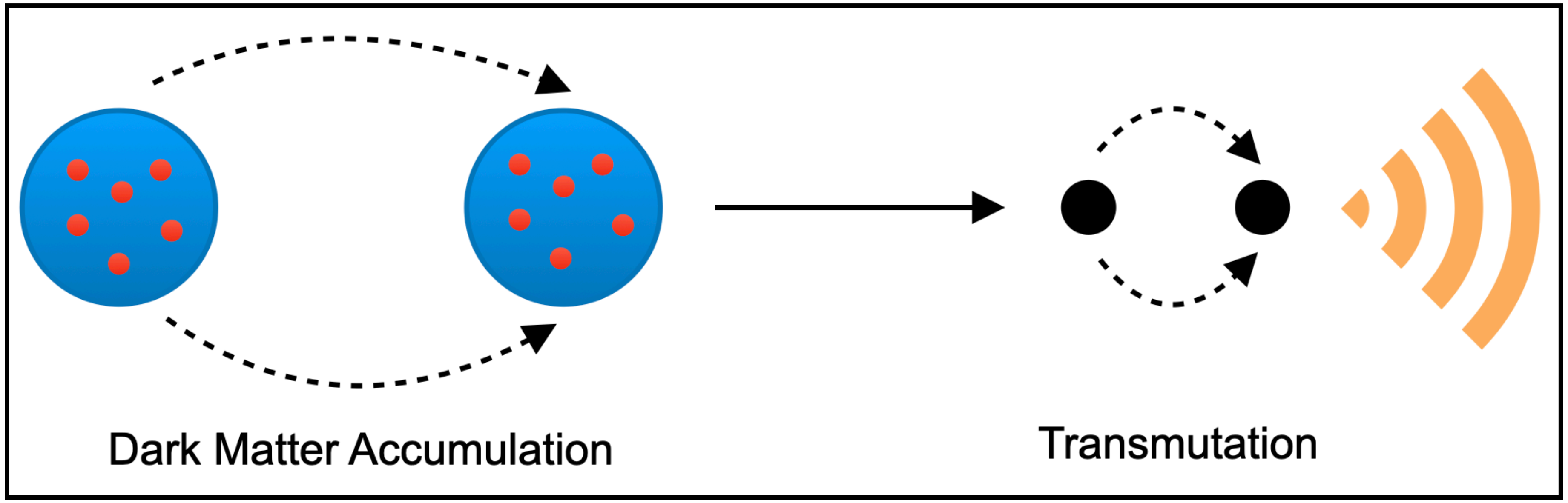
(LZ 2022) (spin-independent) excludes DM-nucleon scattering cross-section of $2.8 \times 10^{-43}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$.

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 annihilating DM models, vanilla scenarios are not currently excluded, but, significant constraints on $\Delta B \neq 0$ interactions.

Extra Slides

GW probes



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

Ray (with Dasgupta, Laha) [PRL, 2021]

Essentially, counting the number of NS binaries that undergoes a successful transmutation from its birth till the present day.

GW probes

- Transmutation time:

[Collapse time + Swallow time]

t_f : Binary formation time

t_0 = 13.79 Gyr = Present day

$$\tau_{\mathrm{trans}} < t_0 - t_f$$

Depends on DM parameters (DM mass and DM-nucleon scattering cross-section)

- Normalization (number of progenitors) is fairly uncertain and needs to be statistically marginalised. Normalization is based on “few” observed BNS events by LVK.

GW probes

- Other Uncertainties:

i) Spatial distribution of Binary NS in the Galaxies.

(uniform distribution in 1d)

ii) DM density profile in the Galactic halos.

(NFW profile)

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

(Typical NS parameters)

iv) Uncertain normalization parameter.

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

Systematic exploration is required.

GW Data & Statistics

- Merger rate upper limits:

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

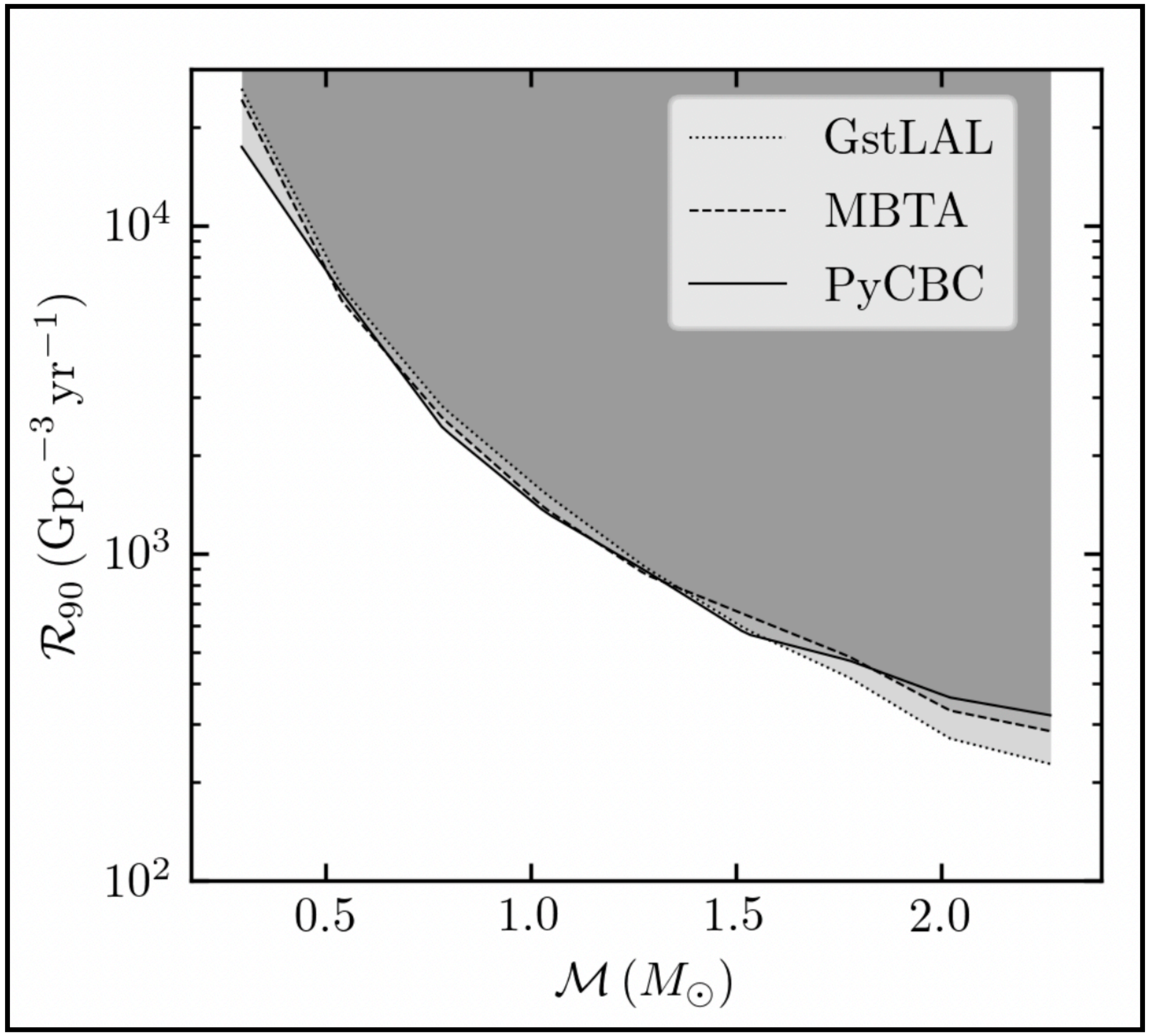


Fig: LVK (PRL 2021)

*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.