Going Underground or Listening to the Sky?

i) arXiv: 2302.07898
ii) Phys. Rev. Lett. 126, 141105 (2021)
iii) Phys. Rev. D 107, 083012 (2023)

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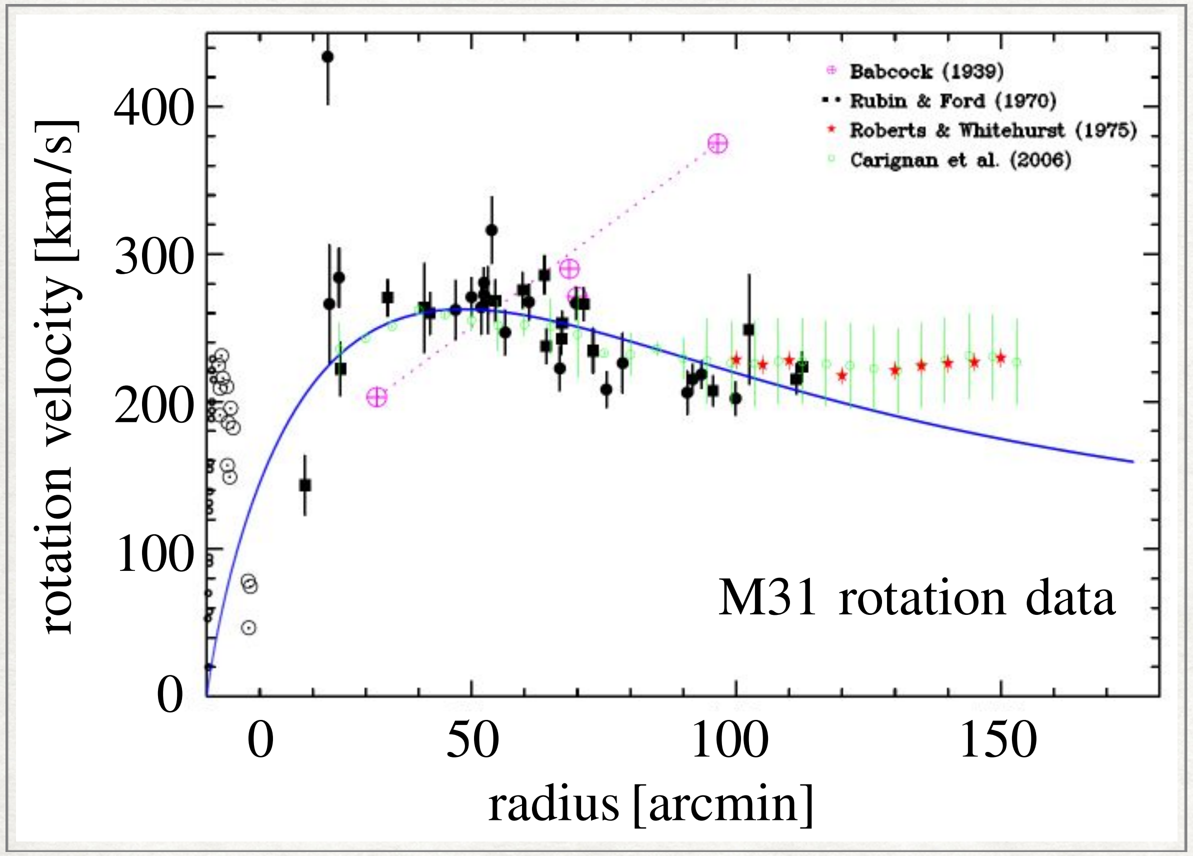
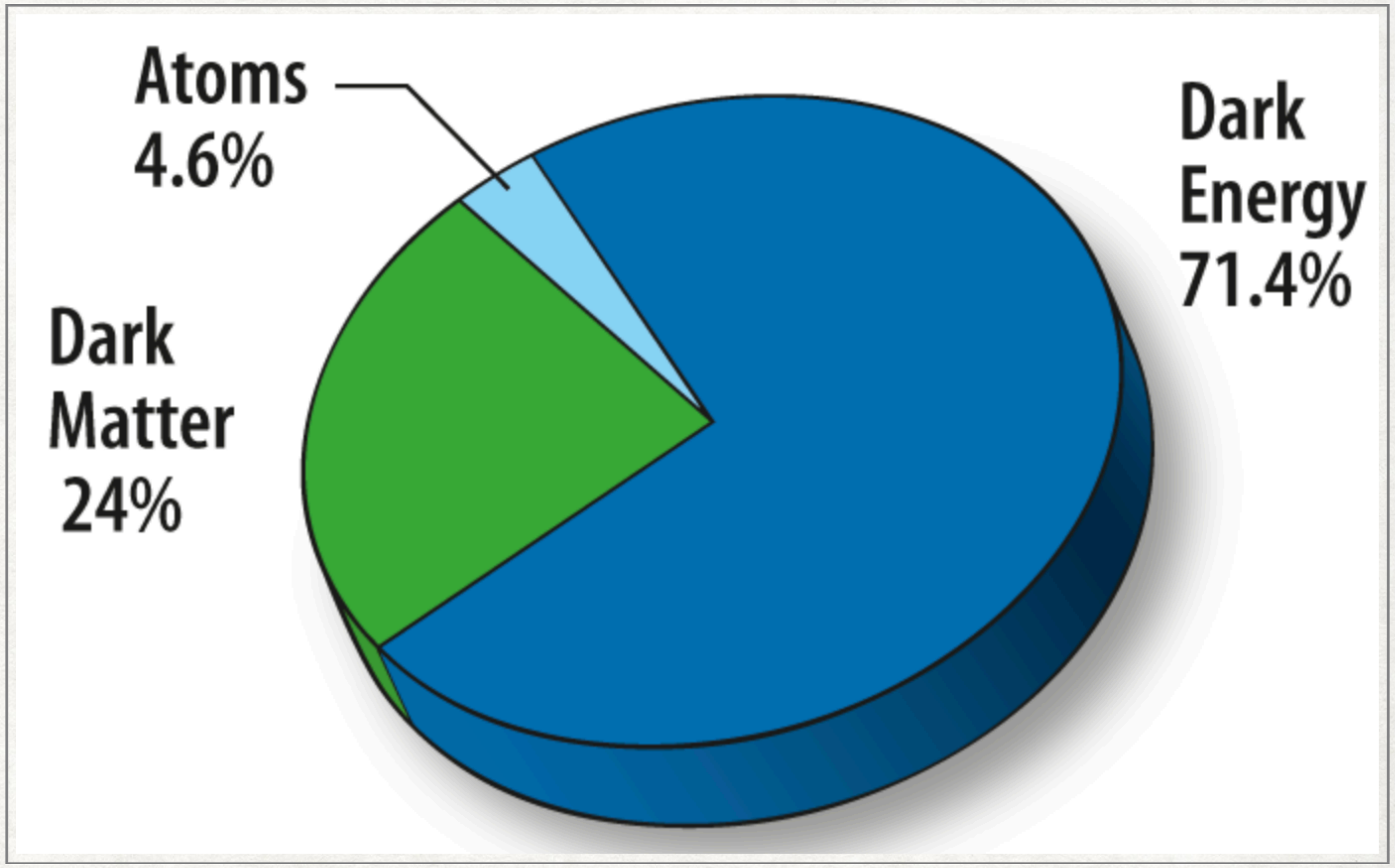
Dark Matter (DM)



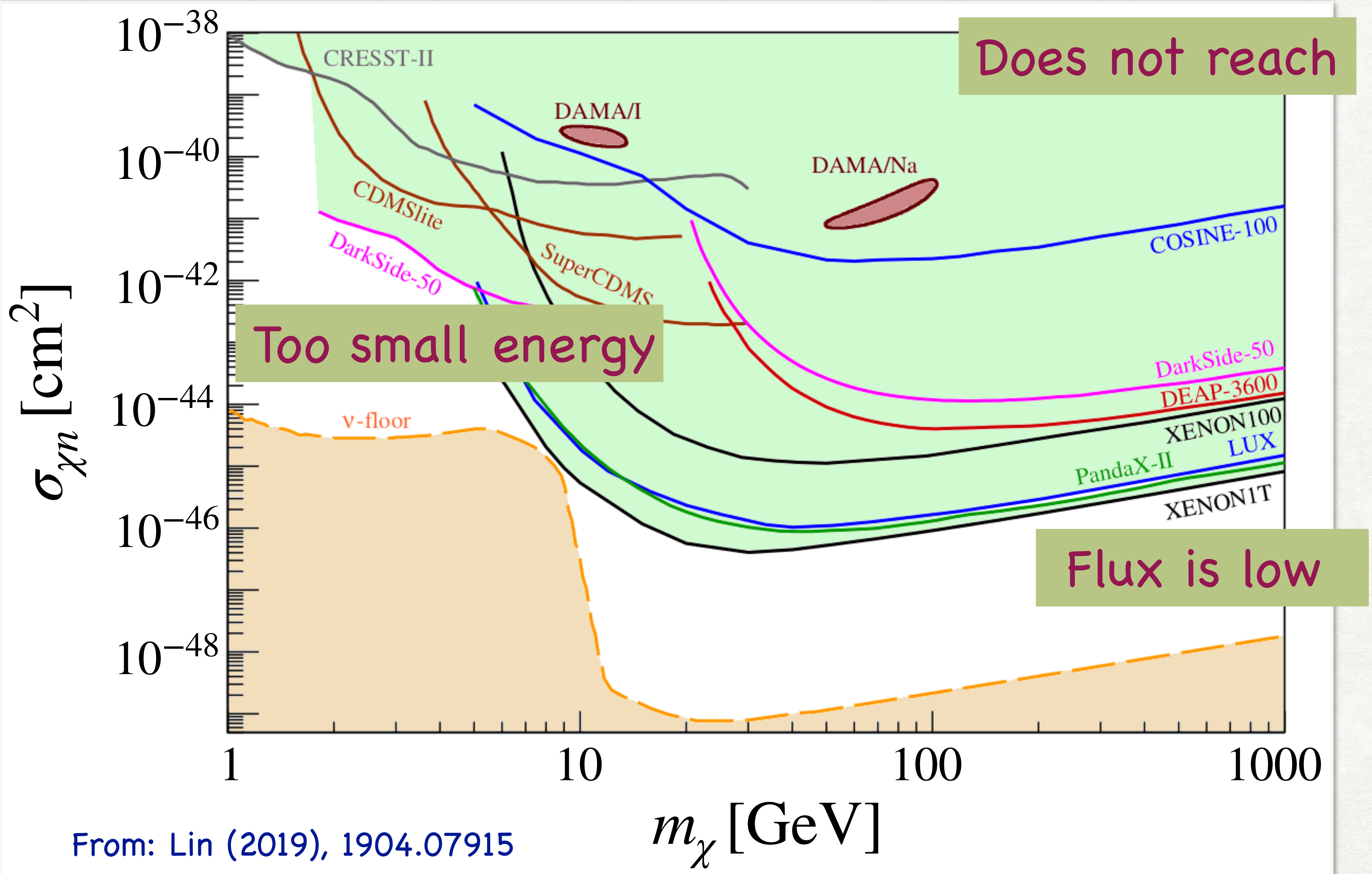
From: Bertone and Hooper, Rev. Mod. Physics (2016)



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

- DM mass?
- DM interactions with baryons?

Results: Underground Detectors



From: Lin (2019), 1904.07915

- Light DM, Heavy DM and Strongly-interacting DM

— "3" Blind-spots to the underground detectors.

Take Away

- We show DM capture in celestial objects can provide unprecedented sensitivity to these blind-spots.

GW Probe of DM:

- LIGO can act as a novel DM detector. It provides one of the leading constraints on weakly-interacting heavy DM.

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

EM Probe of DM:

- Continued existence of stellar objects, such as, Sun, Jupiter excludes strongly-interacting heavy DM.

Ray (2023), arXiv:2301.03625 (PRD 2023)

Can LIGO Detect Asymmetric Dark Matter?

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(Dated: February 17, 2023)

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.

Outline

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

$M_{\odot}$-Gyr >> kT-yr

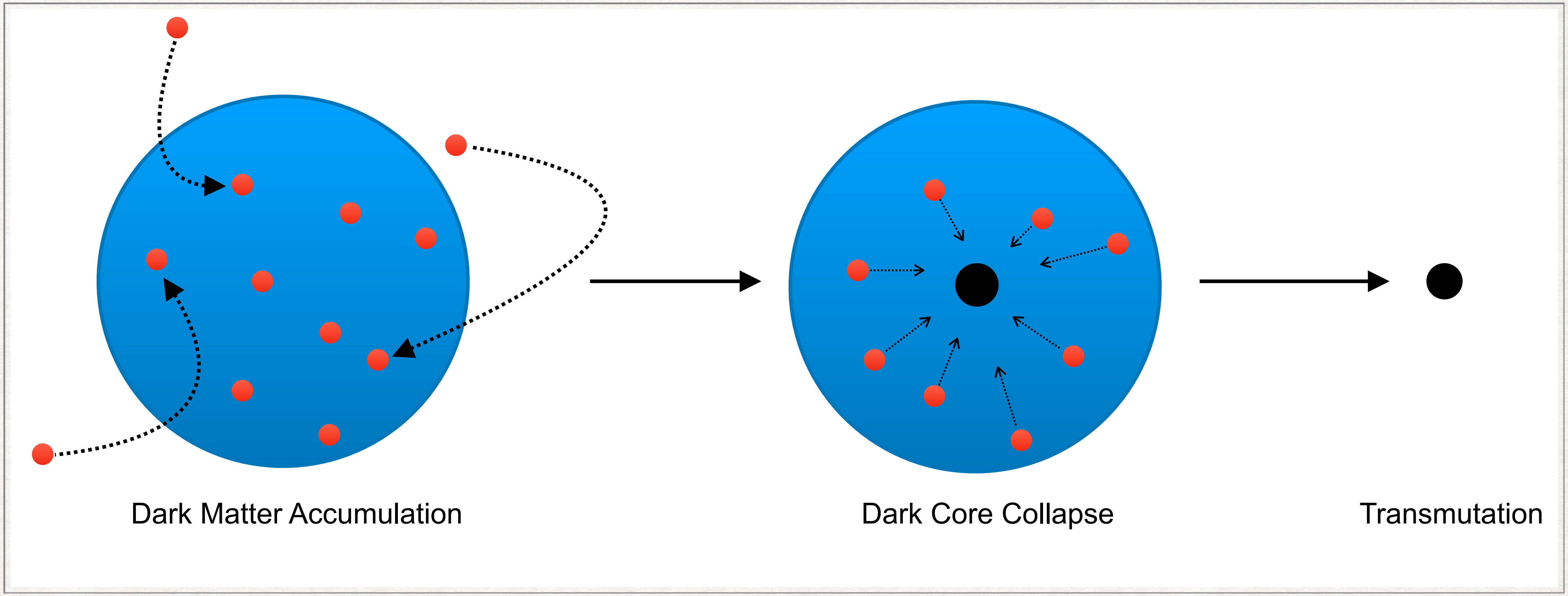
- In the weakly interacting regime, DM can be trapped in a significant number inside compact stars.

- 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),…

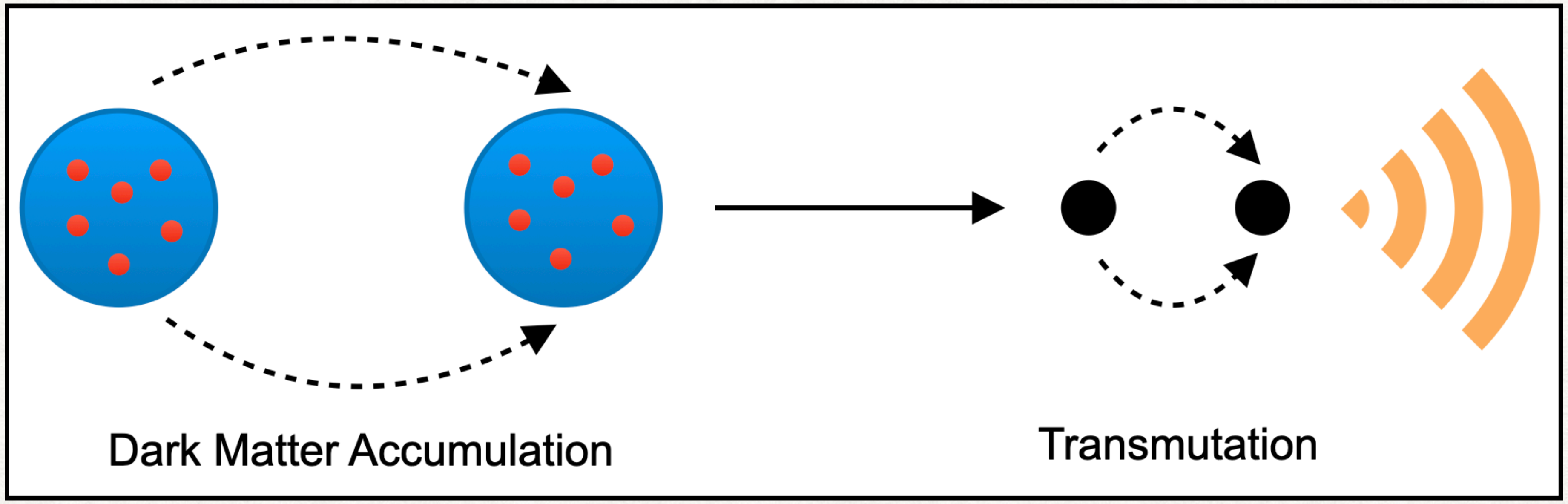
- We explore GW observations of low mass compact objects to probe non-annihilating heavy DM interactions.

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

Summary



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

Transmuted Black Holes (TBHs)

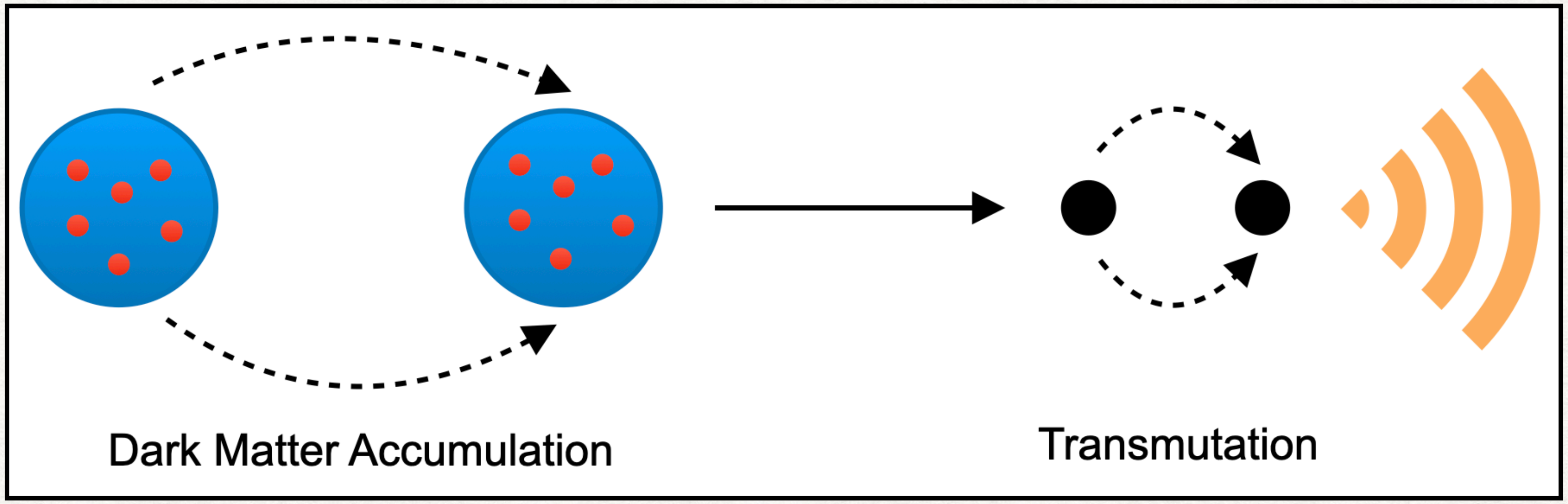
Dasgupta, Laha, Ray (PRL, 2022)

- 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

TBH formation & Mergers



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

- 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)

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

TBH formation & Mergers

- Transmutation time:

[Collapse time + Swallow time]

t_f : Binary formation time

t_0 = 13.79 Gyr = Present day

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

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.

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. → Insignificant 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),...

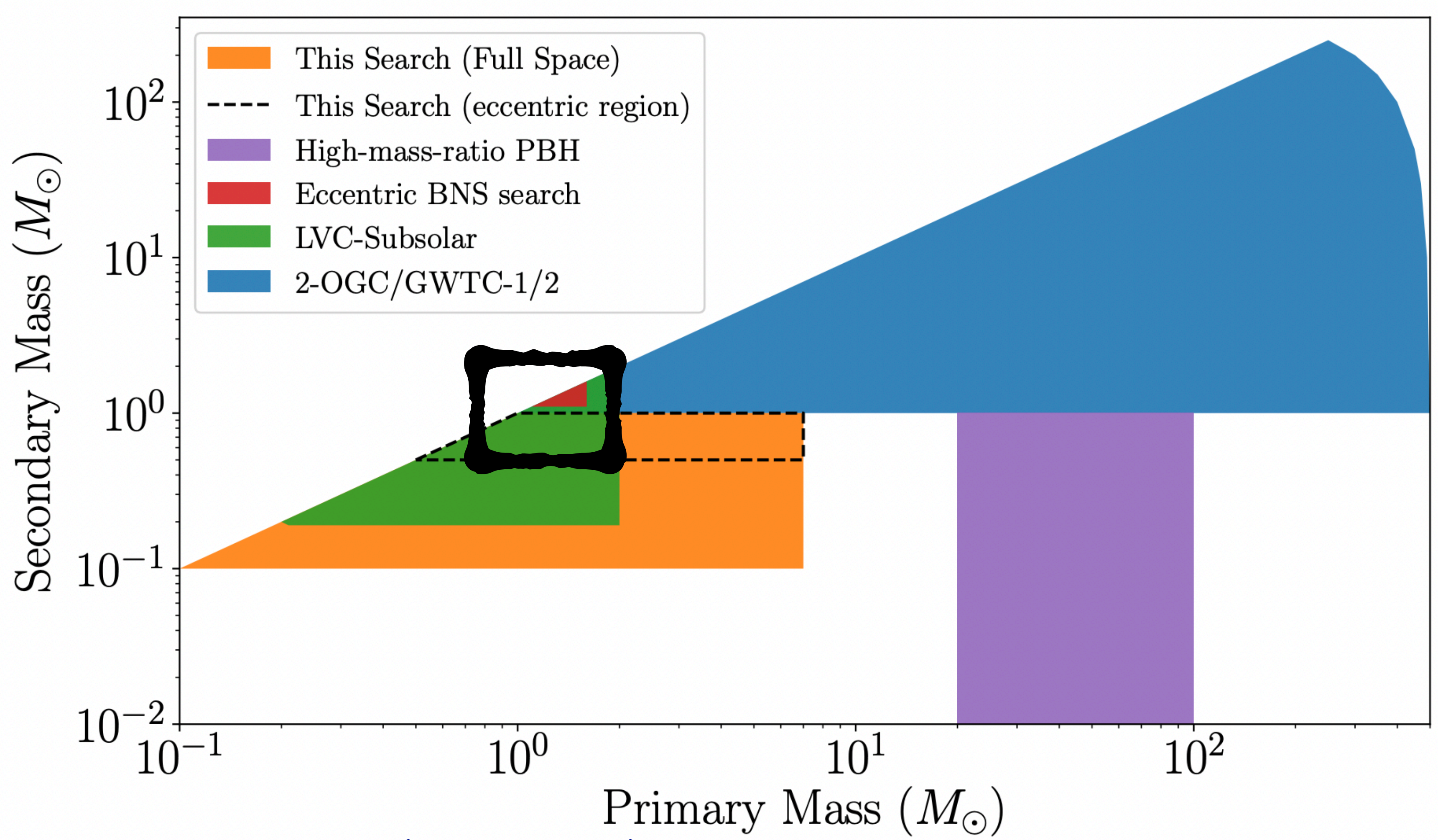


Fig: Nitz & Wang (APJ 2021)

GW Data & Statistics

- Merger rate upper limits:

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

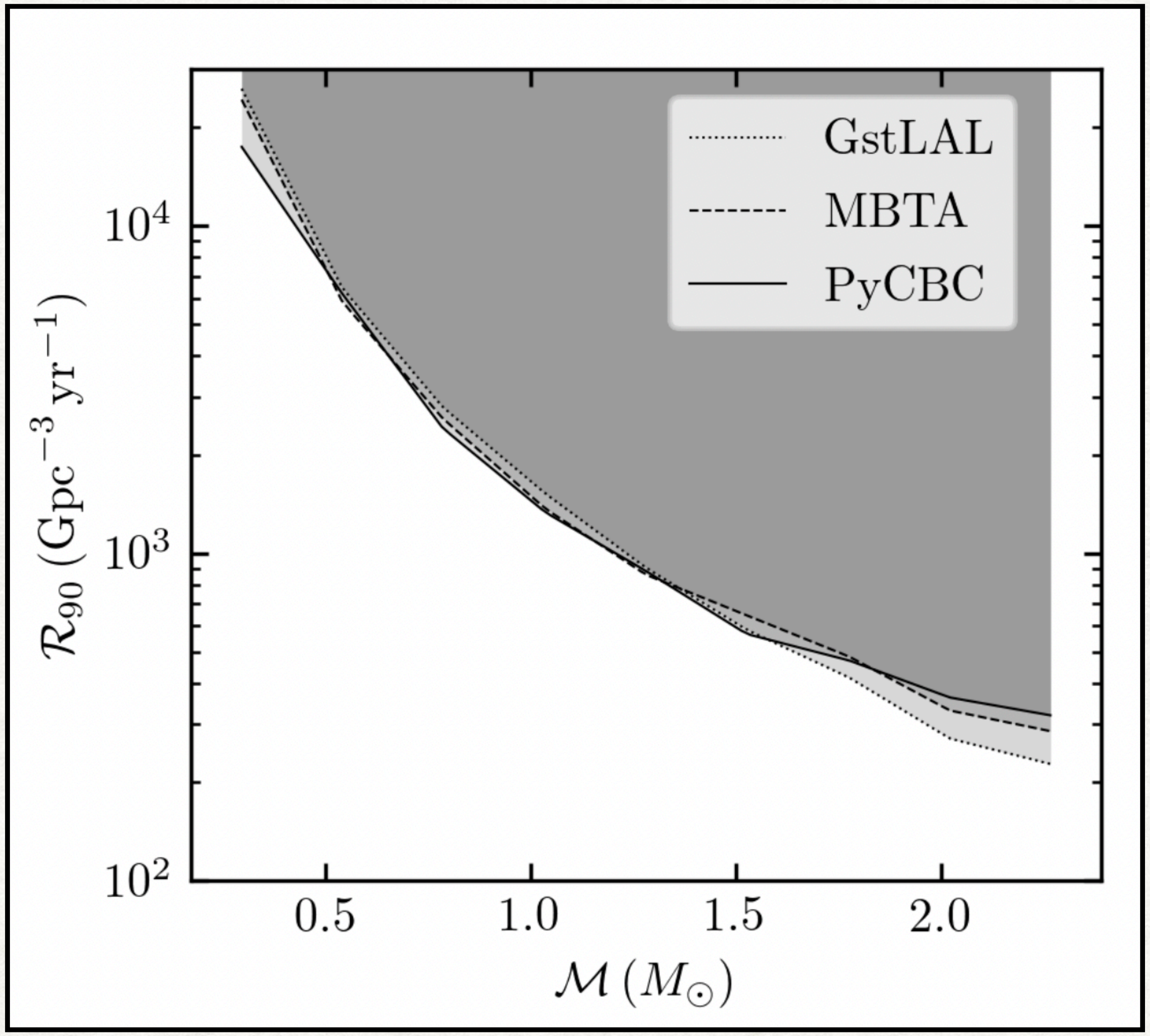


Fig: LVK (PRL 2021)

*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 $R_{90} = 389\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

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

- Our "Conservative" exclusion limit:

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

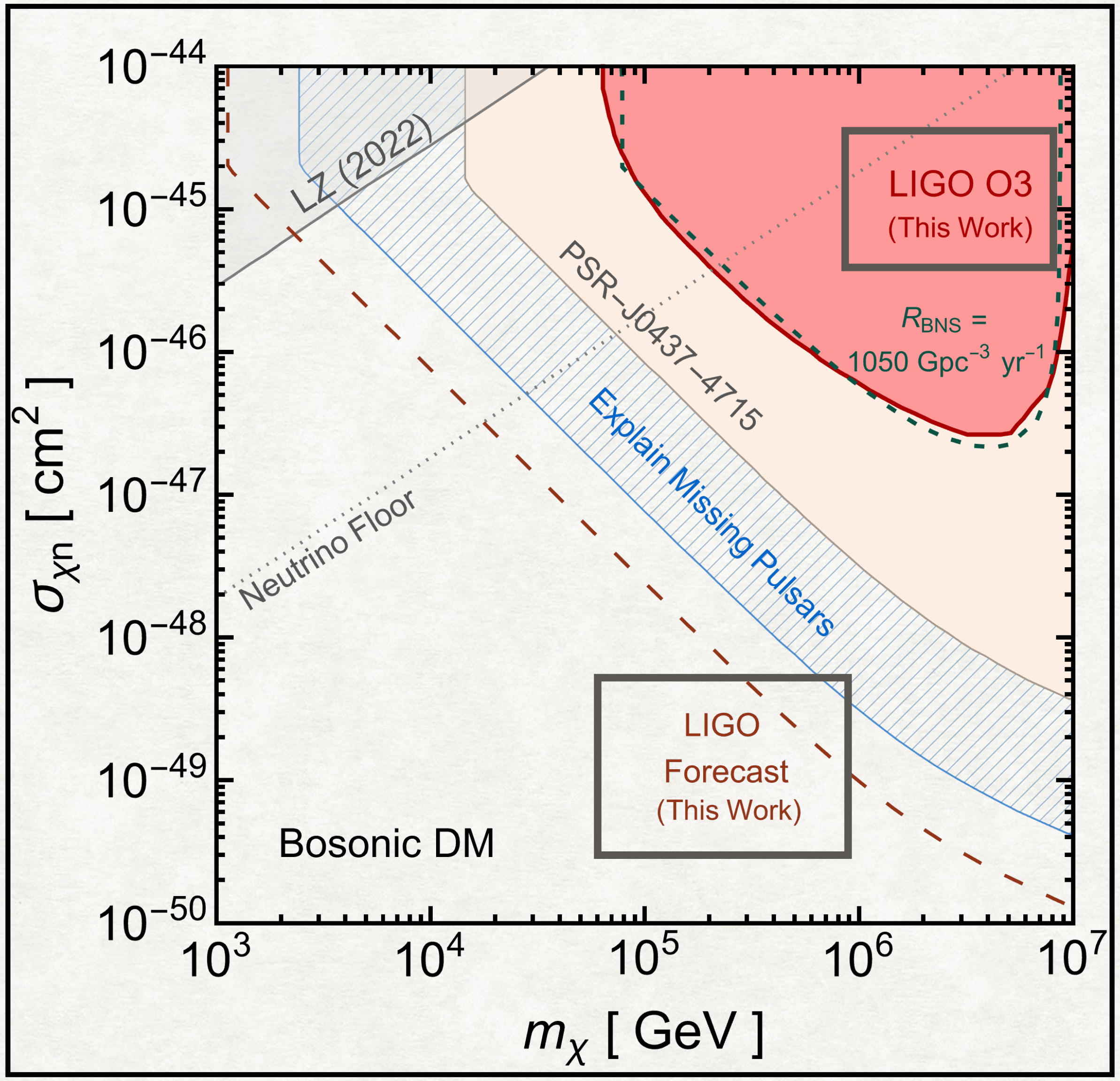
Chirp mass distribution of BNS is sharply peaked peaked at 1.15 $M_\odot$, which can be approximated as a Dirac-delta mass distribution.

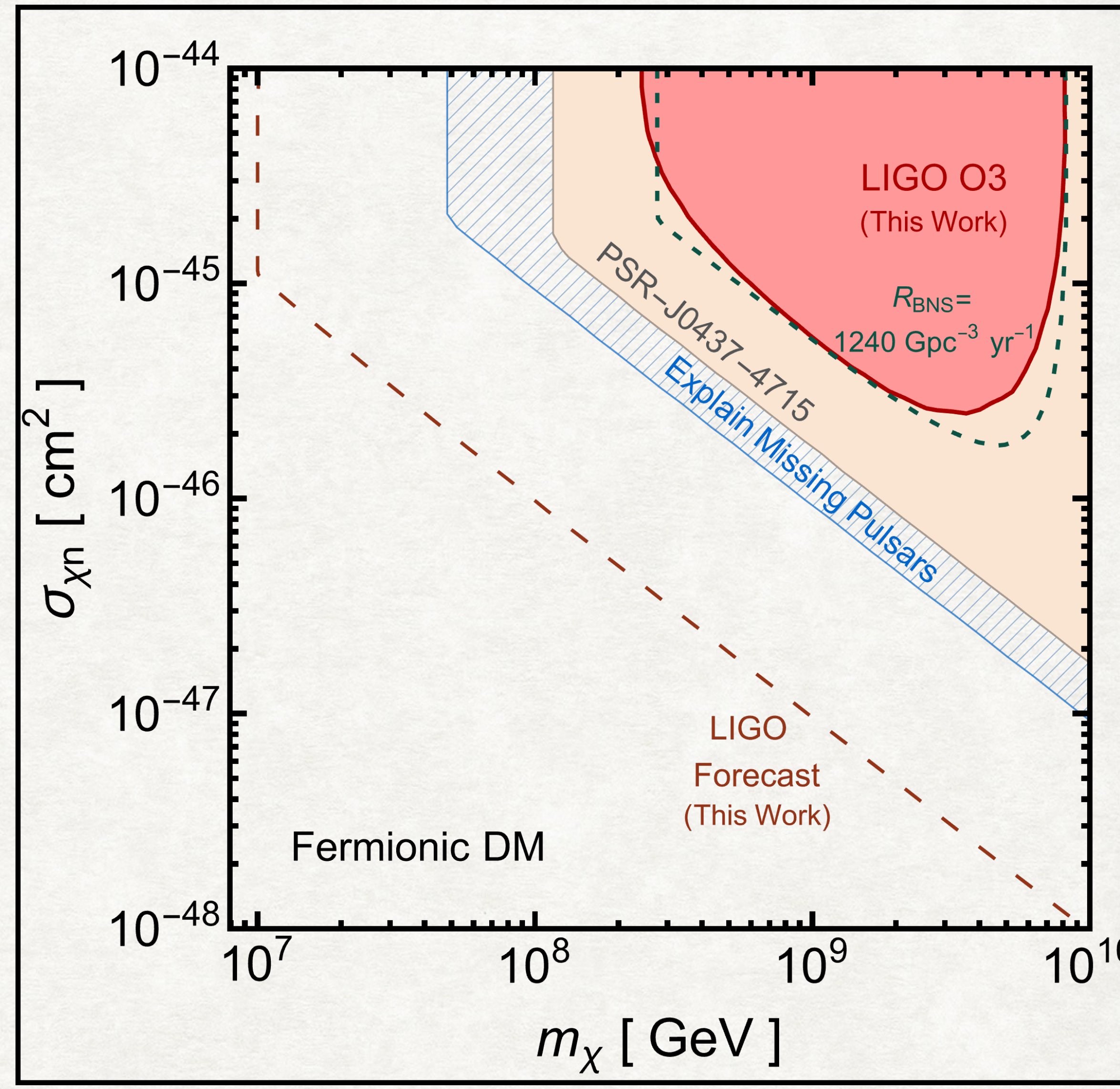
Ozel & Freire (Ann. Review of Astronomy and Astrophysics, 2016)

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.

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.

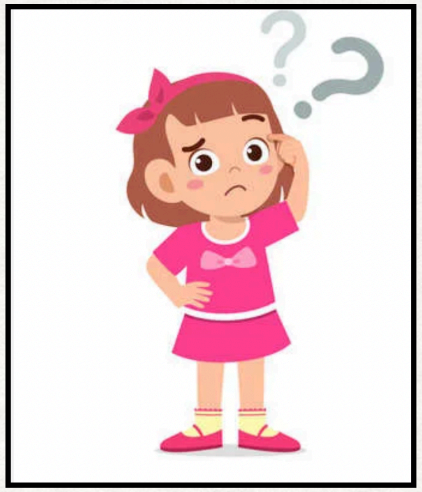
  with increased exposure, LIGO provides world-leading sensitivity within a decade

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

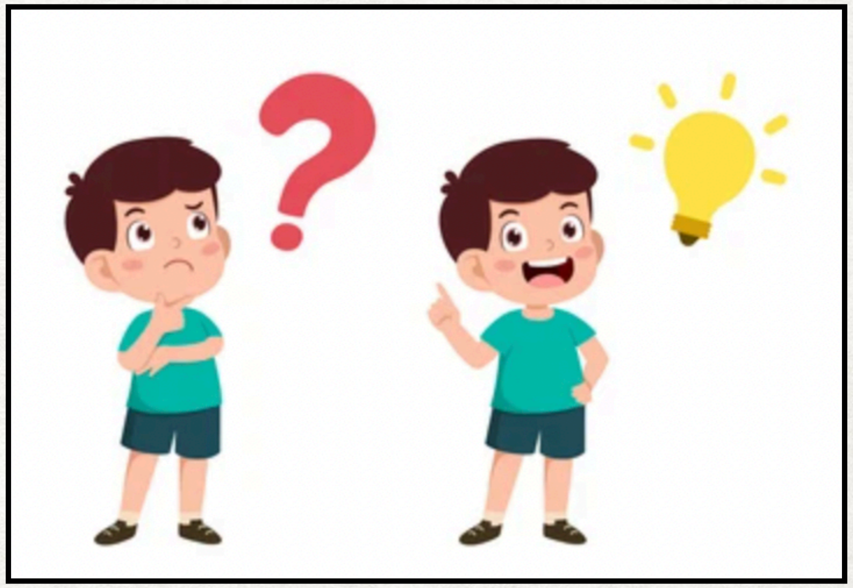
(LZ 2022) (spin-independent) excludes DM-nucleon scattering cross-section of $2.8 \times 10^{-43}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$.

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!

Going Underground or Listening to the Sky?



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



Thanks!

Questions & Comments: anupam.ray@berkeley.edu

Celestial Objects as Strongly-Interacting Asymmetric Dark Matter Detectors

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(Dated: January 11, 2023)

Strongly interacting Heavy DM

Celestial Objects as DM Detectors

Ray (2023), 2301.03625 (PRD 2023)

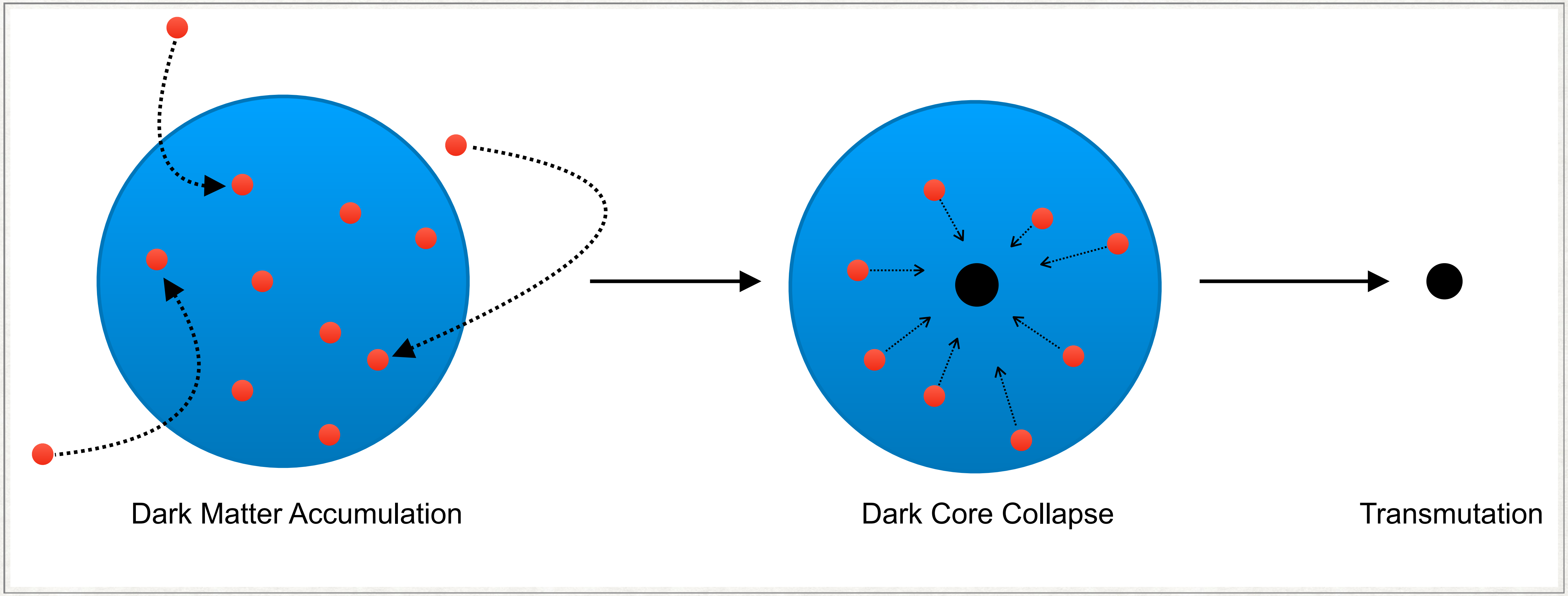
i) Why Celestial Objects are Novel DM detectors for heavy DM mass?

They are gigantic.

ii) Which Celestial Objects are the most optimal targets?

Systematic study is required

DM-induced Collapse

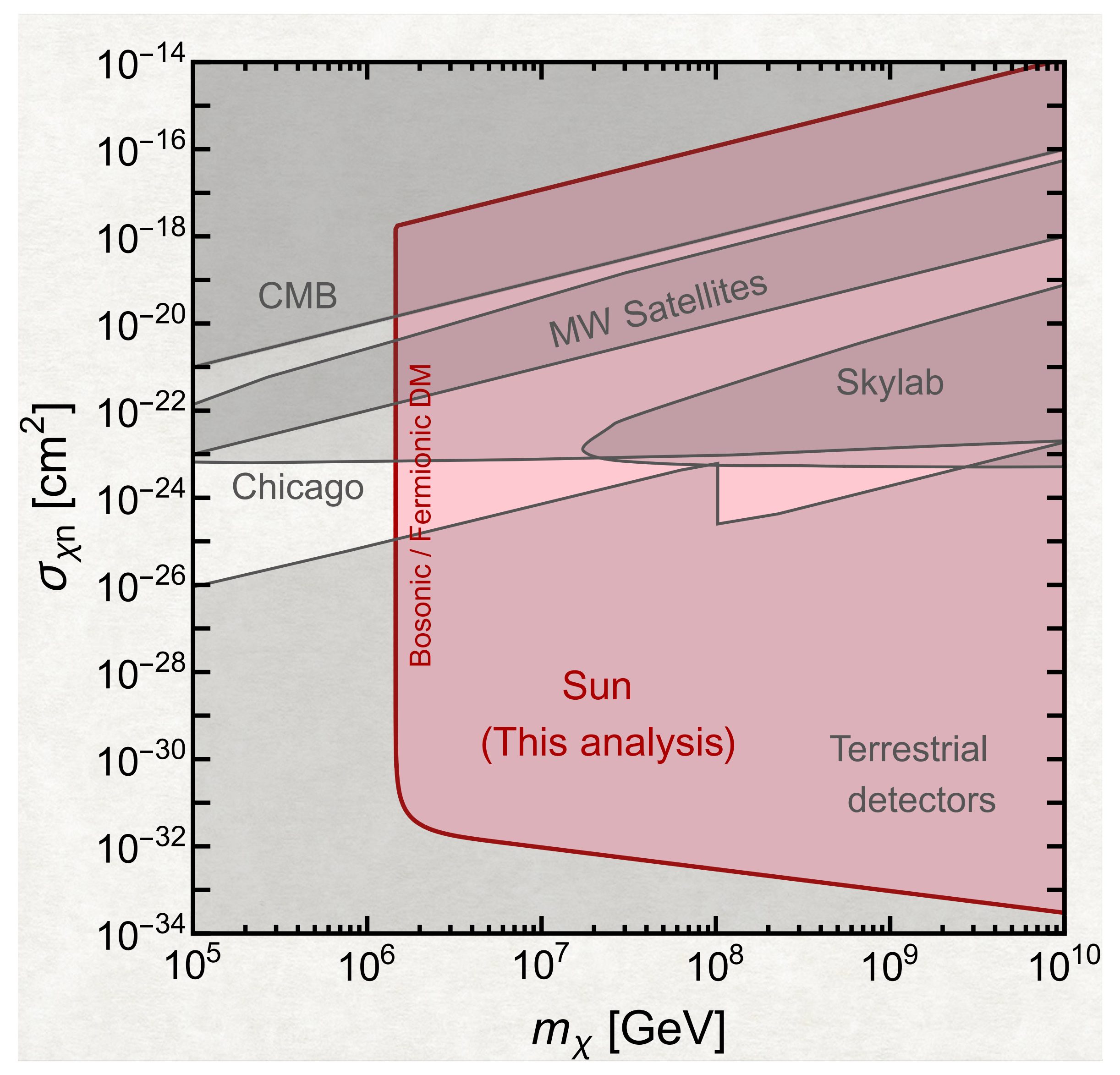


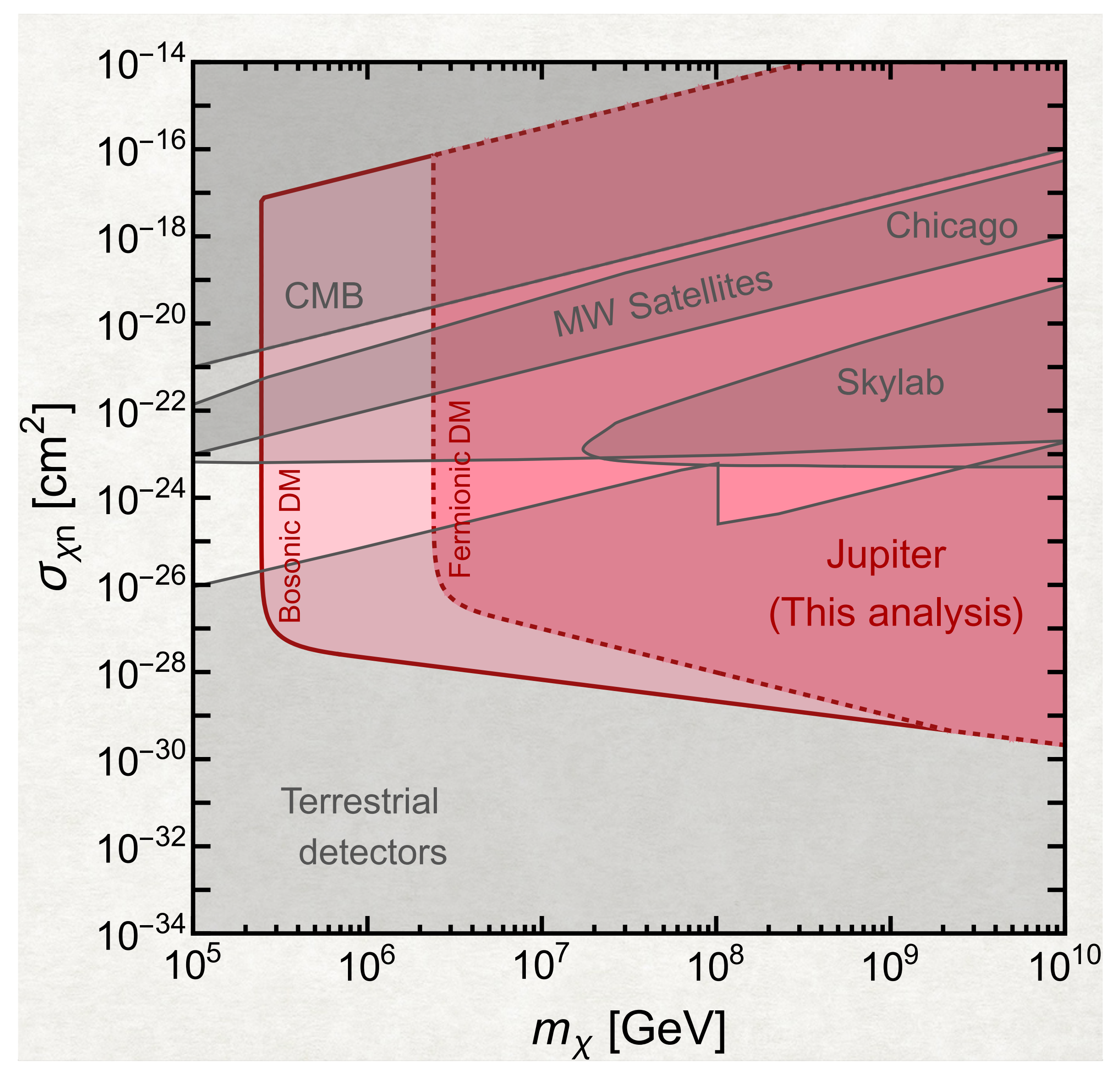
1. DM accumulation
2. DM thermalisation
3. DM distribution
4. Dark Core Collapse
5. Growth of micro-BH
6. Destruction of host

Results

- DM parameters which predicts successful BH formation are excluded because we see Sun, Jupiter, Earth, Moon!

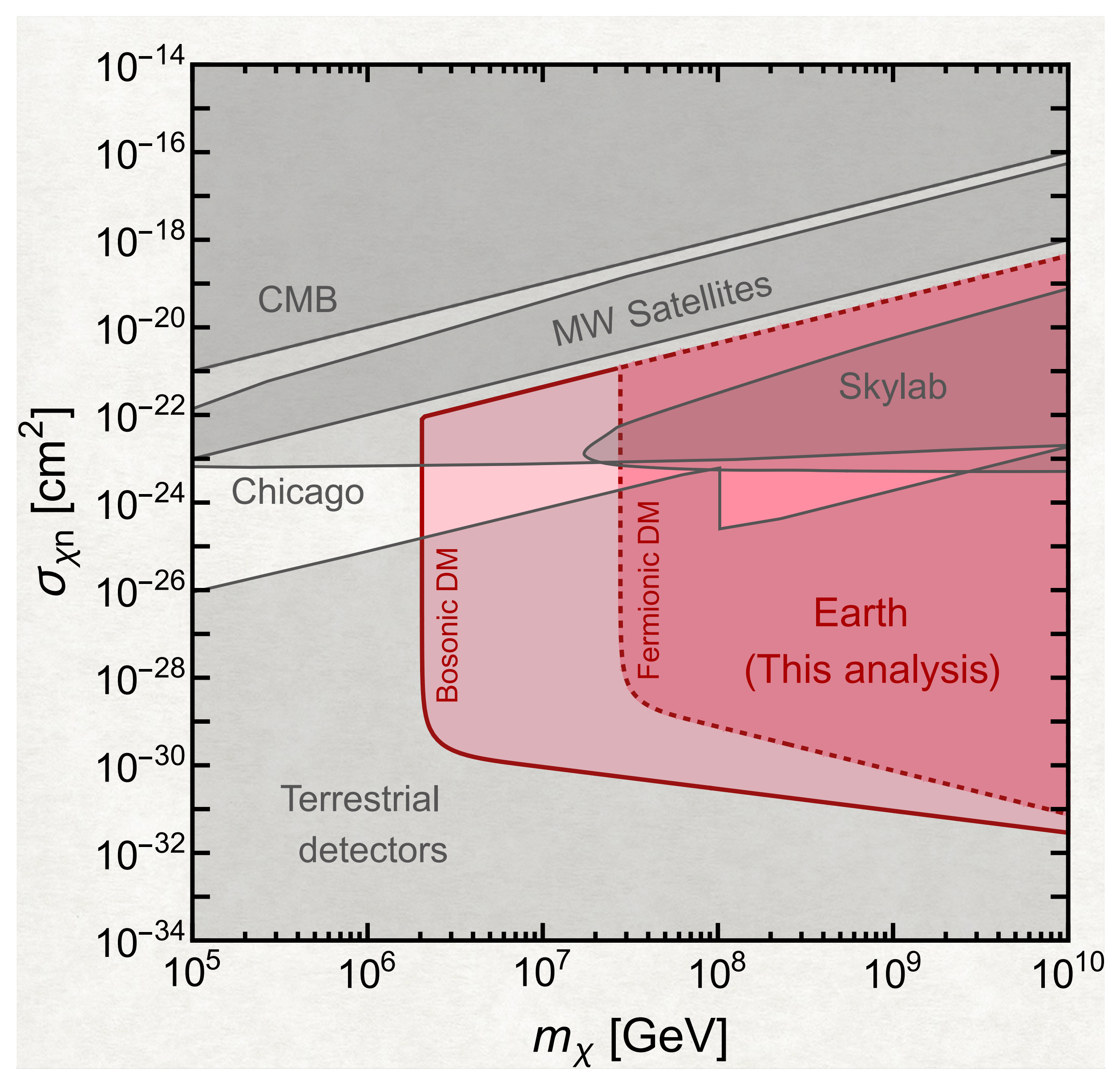
Ray (2023), 2301.03625 (PRD)

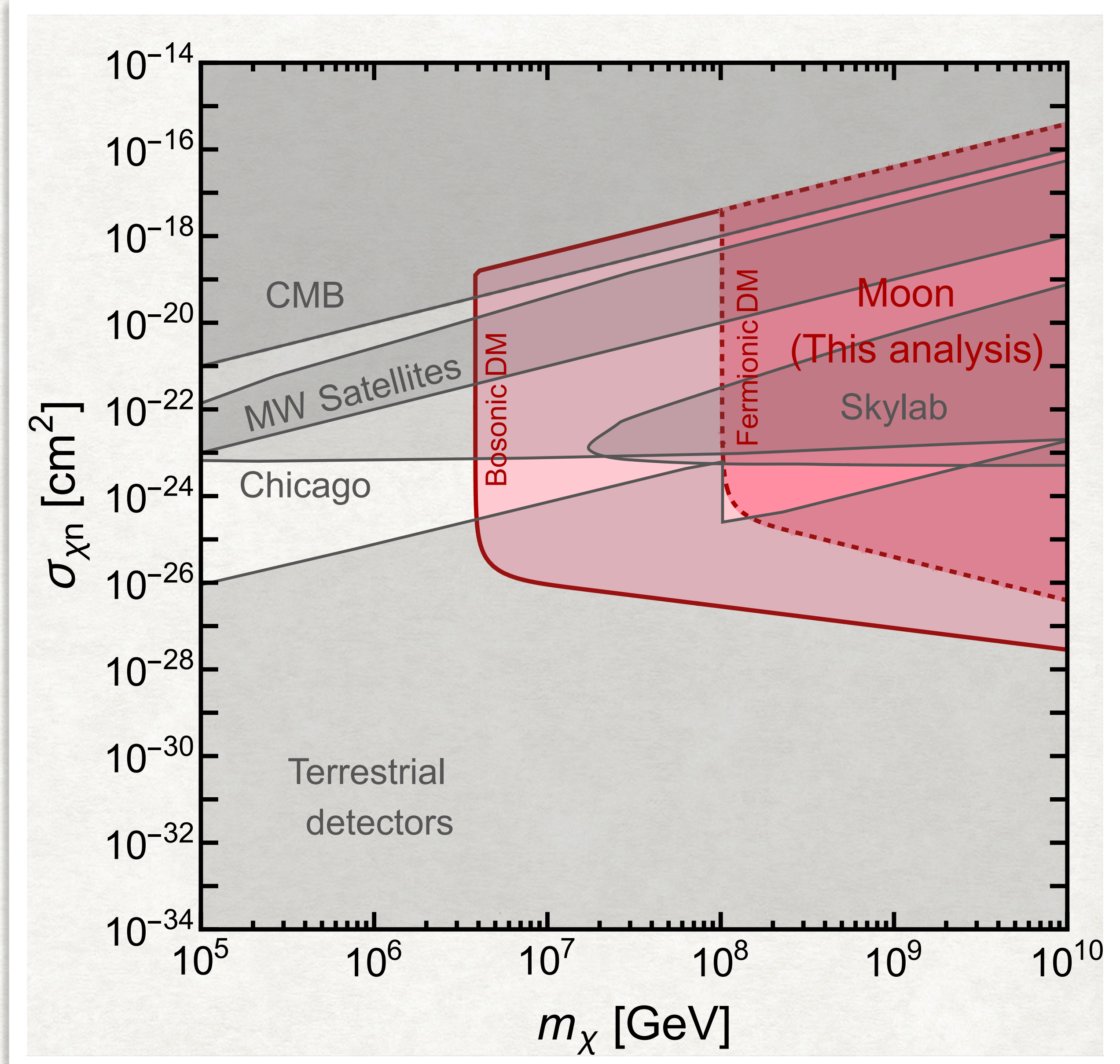




Results

Ray (2023), 2301.03625 (PRD)





*** Stellar objects with larger size and the low core-temperature (Jupiter) are the ideal targets. Larger size implies more DM capture, and lower temperature implies easier BH formation.

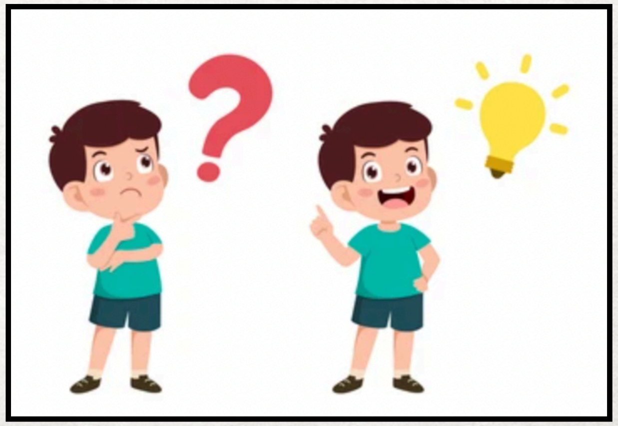
Conclusion

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

Underground detectors have typical exposure of kT-year, whereas, celestial objects have typical exposure of $M_{\odot}$- Gyr = 10^{33} kT-year, naturally providing sensitivity to the tiny flux of heavy DM.

- We show existence of stellar objects provides unprecedented sensitivity to the DM parameters and primarily bridges the gap between the terrestrial and cosmological probes.

Stellar objects with larger size and the low core-temperature (Jupiter) are the most optimal targets.



- As a by-product, this simple yet elegant mechanism naturally provides planet mass BHs.

Lots of interesting hints of planet mass BHs! (Planet-9, OGLE excess, NANOGrav detection of SGWB, etc!)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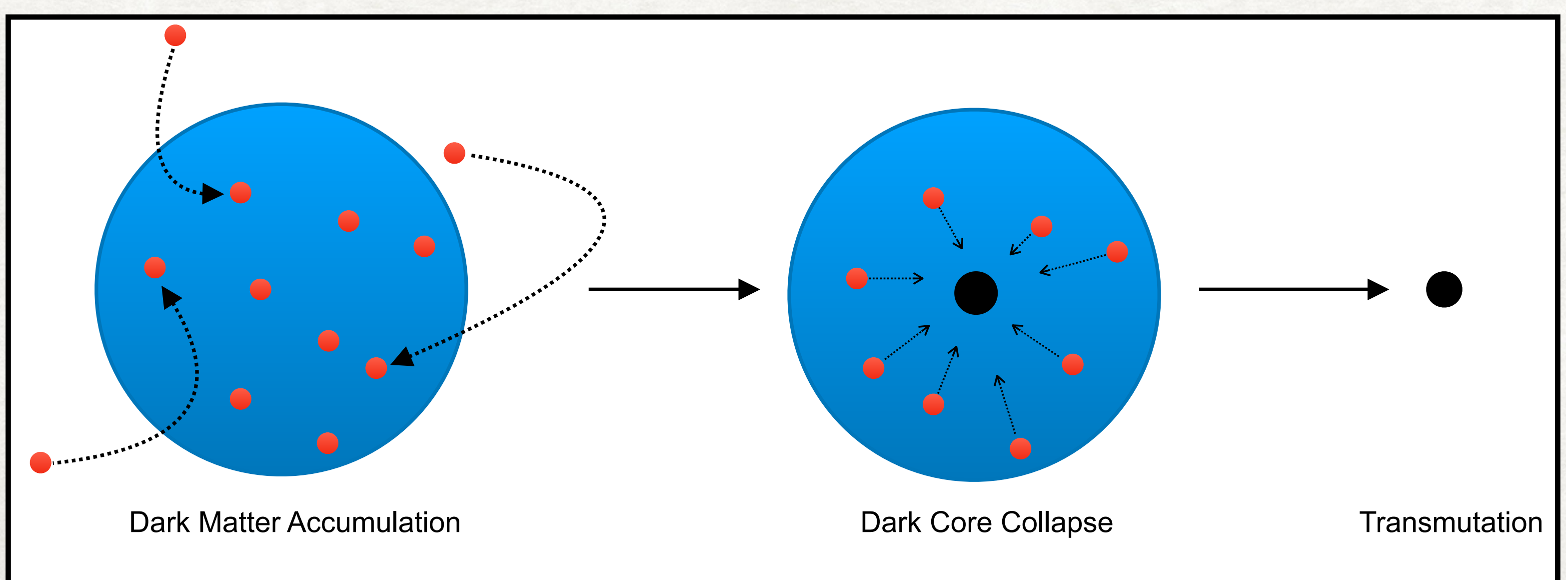


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