Evolution of tau-neutrino lepton number in proto-neutron stars for active-sterile neutrino mixing

arXiv: 2306.08209

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Work in collaboration with: Yong-Zhong Qian

Astrophysical neutrinos and the origin of the elements, INT
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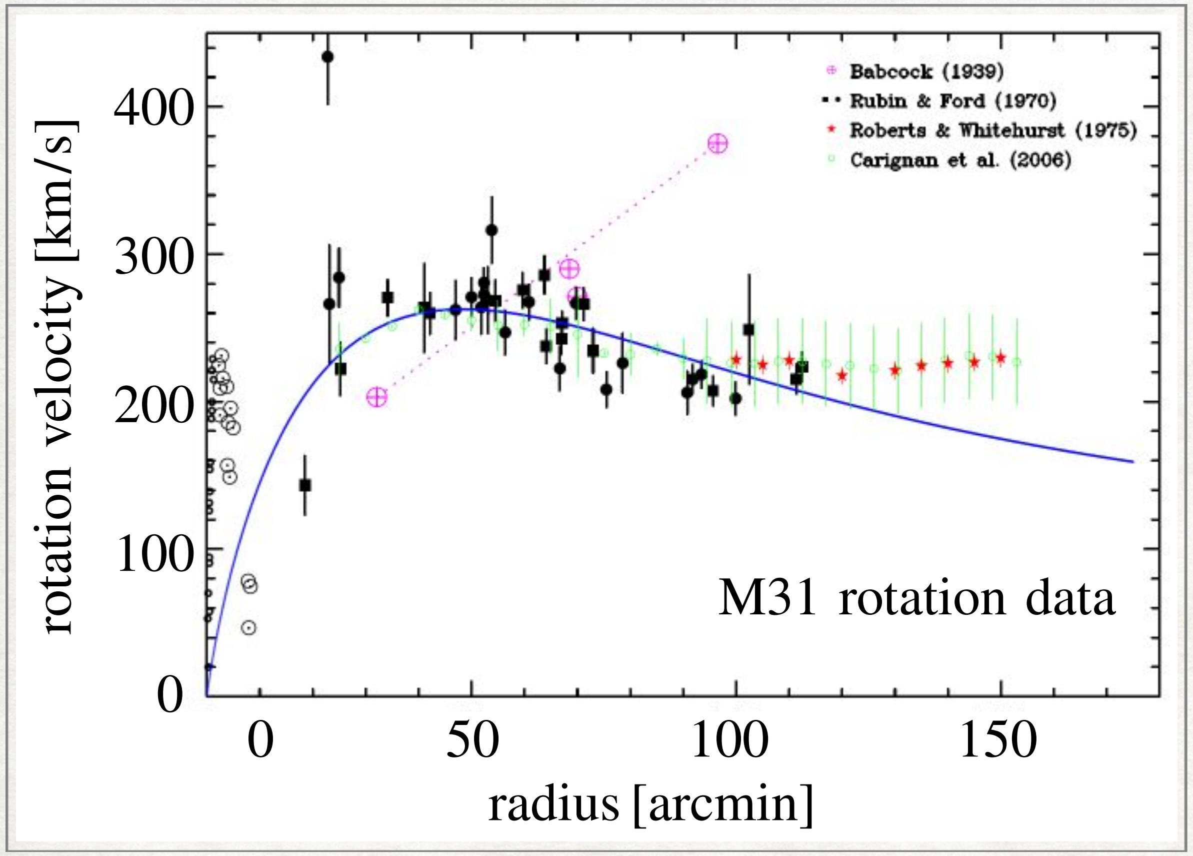
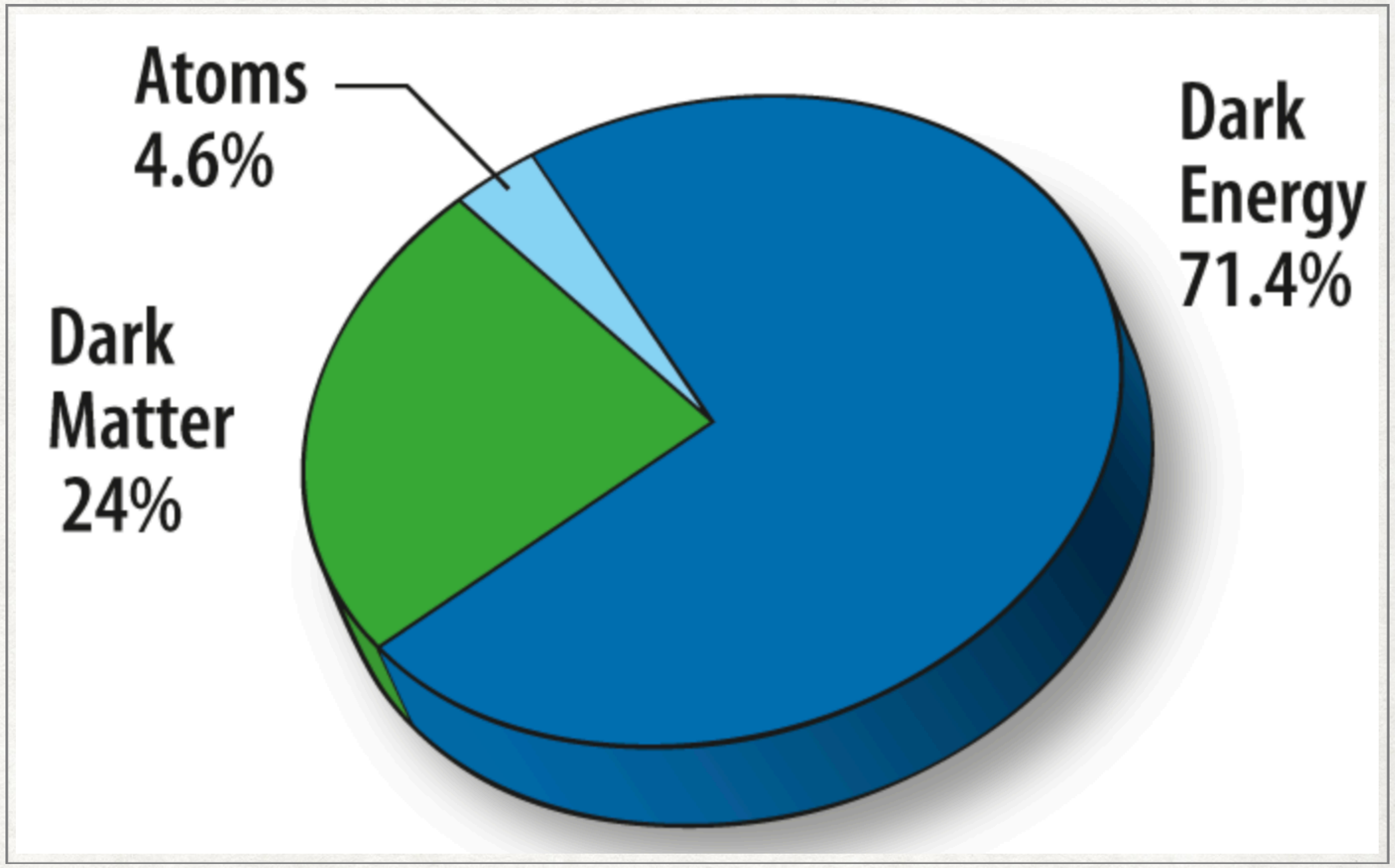
Dark Matter (DM)



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

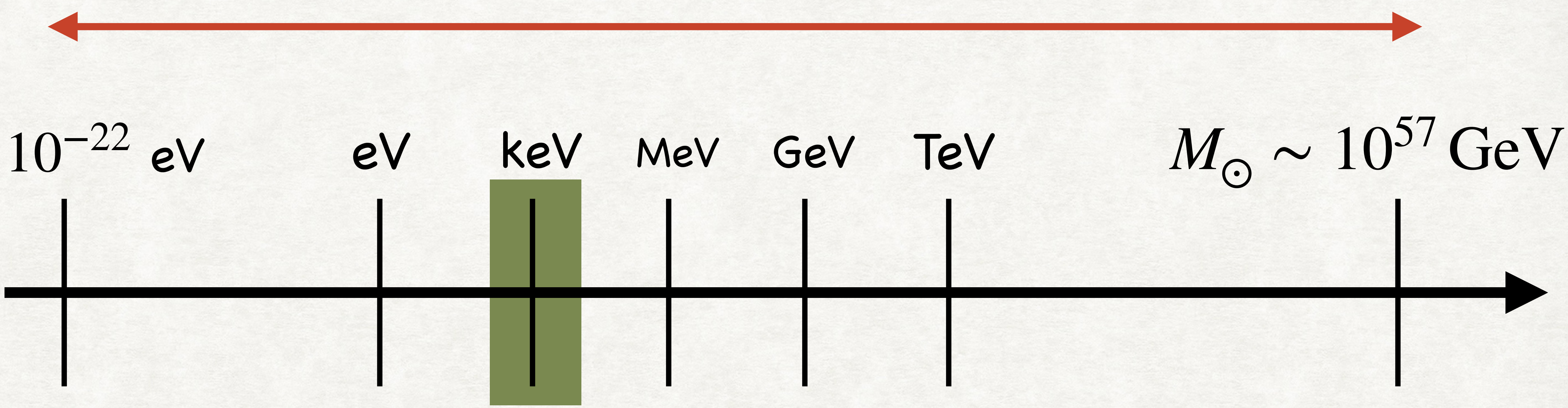


https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- DM is omnipresent in our Universe.

• What is DM?

More than 80 orders of magnitude!

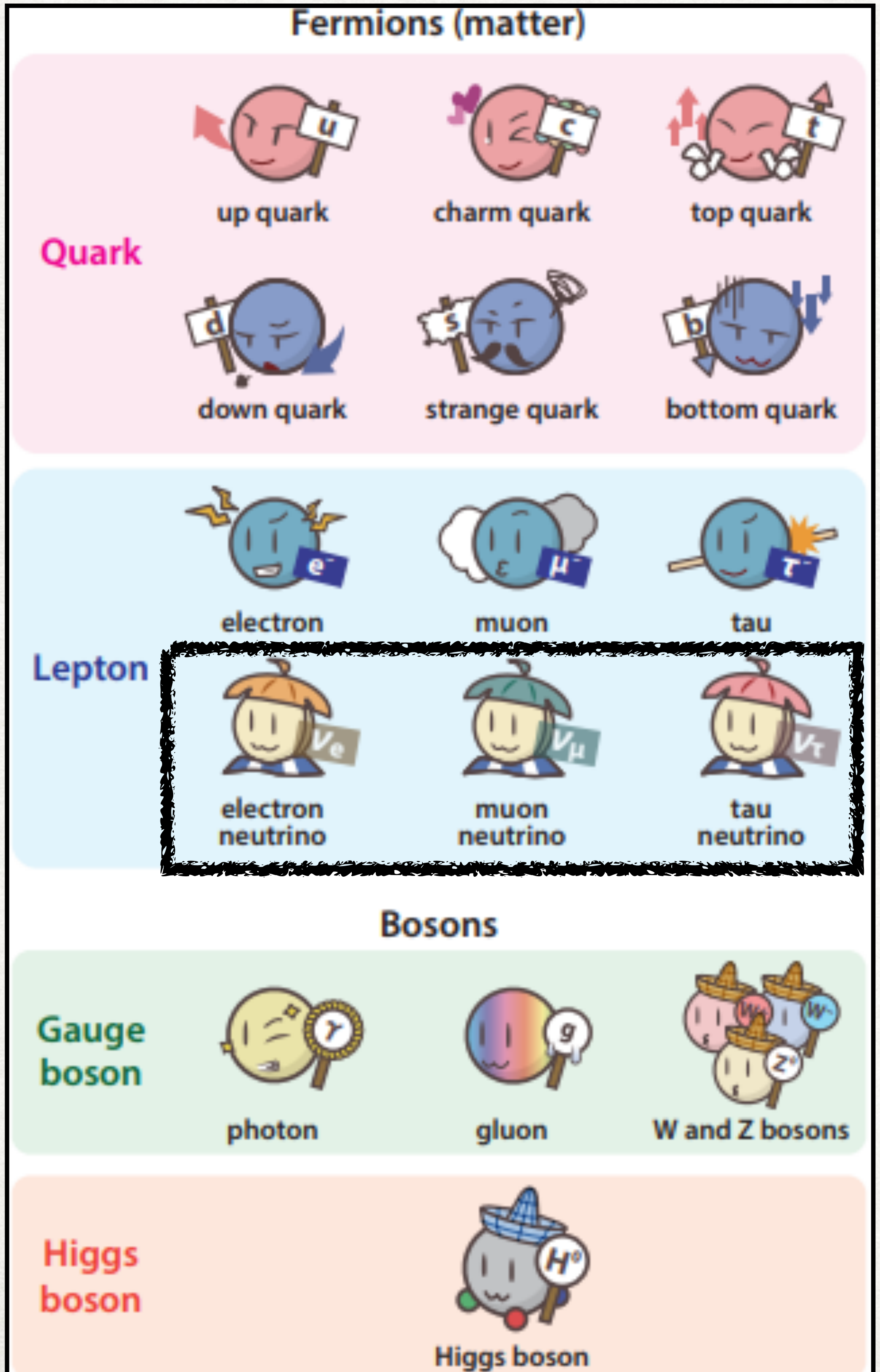


- We will consider : Sterile neutrinos of $\mathcal{O}(10)$ keV mass

- Take Away: Significant amount of tau-neutrino lepton number creation in proto-neutron stars.

"Zero" otherwise

Neutrinos in Standard Model (SM)



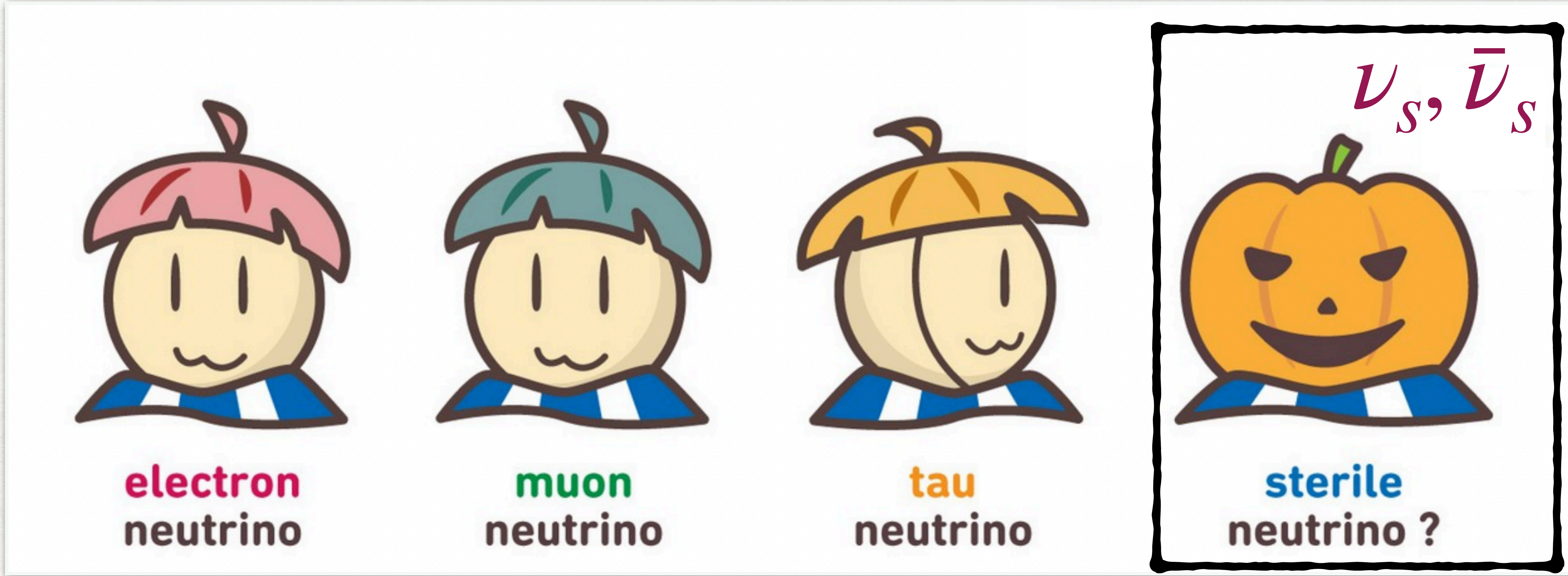
- Neutrinos are neutral leptons, interacts only via the weak force.
- In SM, three known flavours, each of them has a charged partner.

  "Active" neutrinos
- In SM, neutrinos have zero mass. But, in reality, they have non-zero masses, and they can mix with each other.

  BSM Physics

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en neutrino.html

Sterile Neutrinos

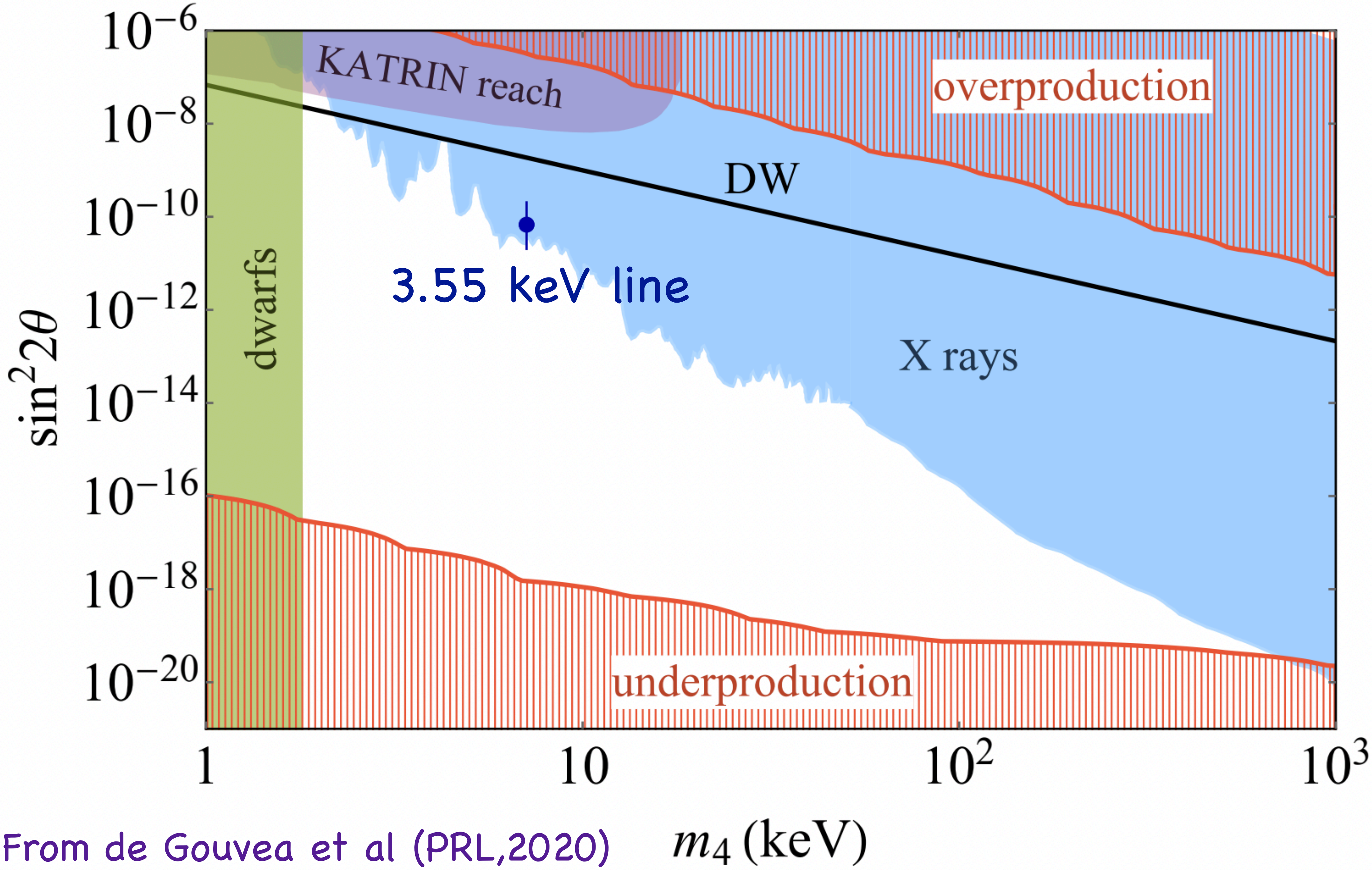


4th kind of neutrino, not in SM, can mix with the active neutrinos.

- Sterile neutrinos of keV mass are viable DM candidate.

See recent reviews: Kusenko (2009), Abazajian (2017), Boyarsky et al. (2017),...., Dasgupta et al. (2023)

keV Sterile Neutrinos as DM

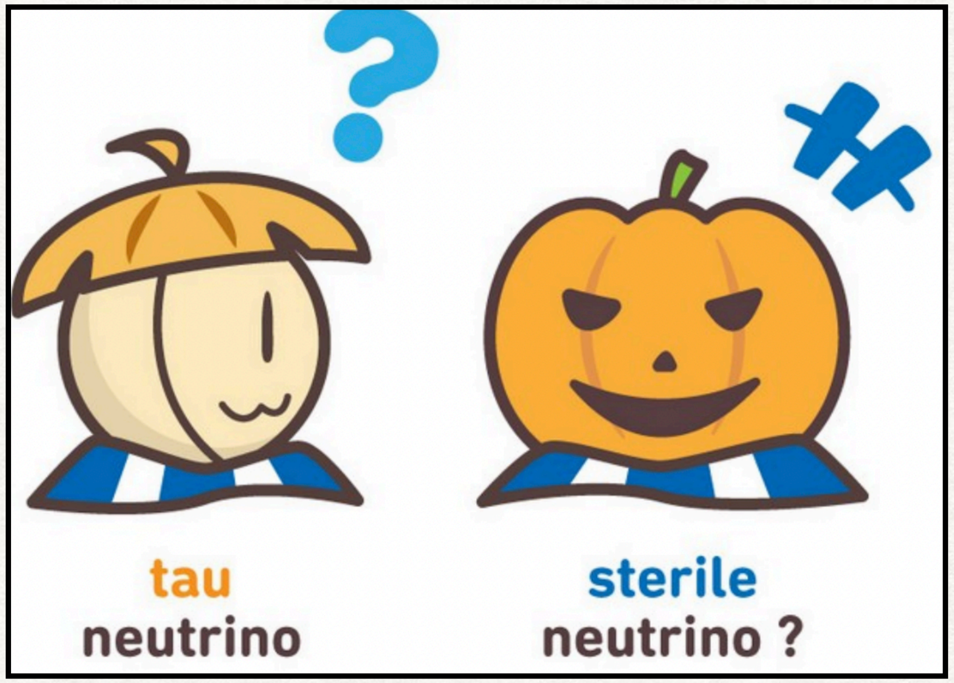


From de Gouvea et al (PRL,2020)

Constraint on Sterile neutrino mass and mixing angle

keV Sterile in proto-neutron star

- We consider mixing between sterile-tau states.



$$\nu_\tau, \bar{\nu}_\tau \longrightarrow \nu_s, \bar{\nu}_s$$

Two unknown parameter: m_s and θ

- Production of Sterile neutrinos in proto-neutron stars:
  - MSW production of $\bar{\nu}_s$
  - Collisional production of $\bar{\nu}_s$
  - Collisional production of ν_s

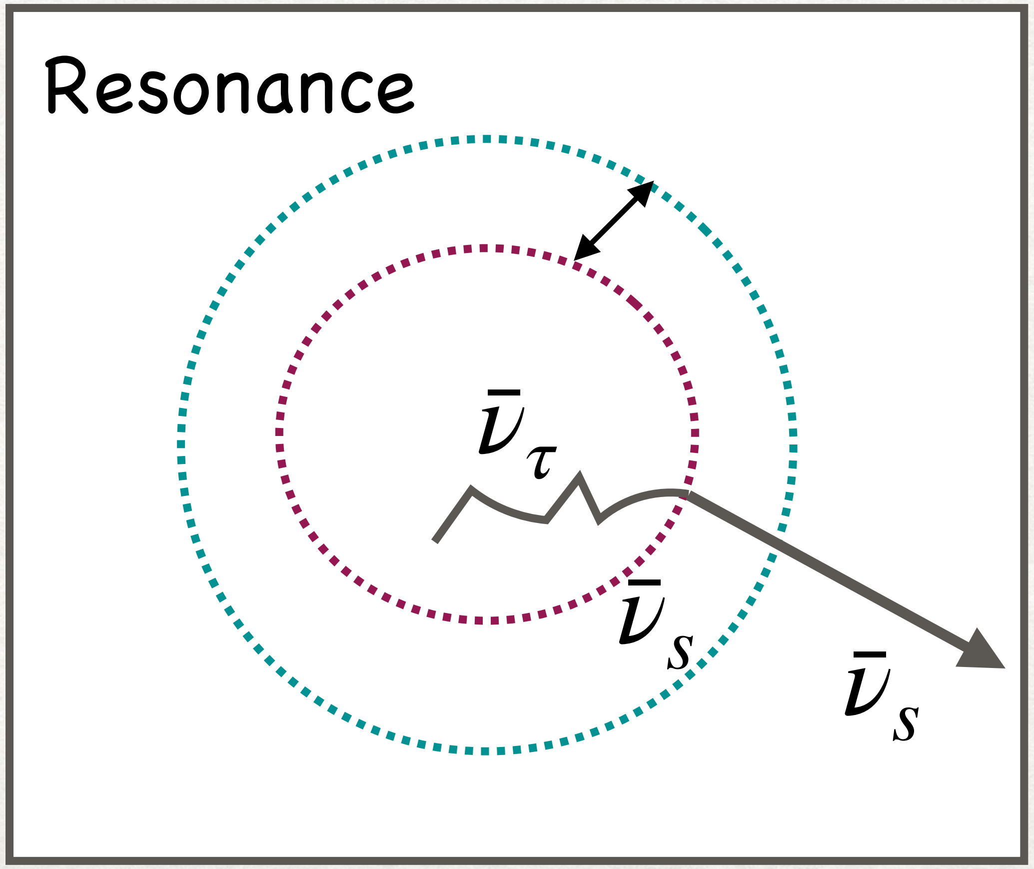
MSW Production

- MSW potential

$$V_\nu = \pm\sqrt{2}G_F n_b \left[-\frac{1-Y_e}{2} + Y_{\nu_e} + Y_{\nu_\mu} + 2Y_{\nu_\tau}\right]$$

For (anti)-neutrinos, the sign is (negative) positive.

- In typical proto-neutron stars: $V_\nu < 0$ and $V_{\bar\nu} > 0$



No MSW for tau-neutrinos.

Resonance Energy: $E_R \approx \dfrac{m_s^2}{2V_{\bar\nu}}$

MSW Production

$$Y_{\nu_\alpha} = (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})/n_b$$

- $\bar{\nu}_\tau$ undergoes MSW resonance inside proton-neutron stars, and is converted to $\bar{\nu}_s$

- Width of the MSW resonance region: $\delta r = 2\tan 2\theta \, |\partial \ln V_{\bar{\nu}}/\partial r|^{-1}_{E_R}$

- MSW production occurs: $\lambda_R > \delta r$

mean free path of the resonant neutrinos have to exceed the width of the MSW region.

- MSW production rate:

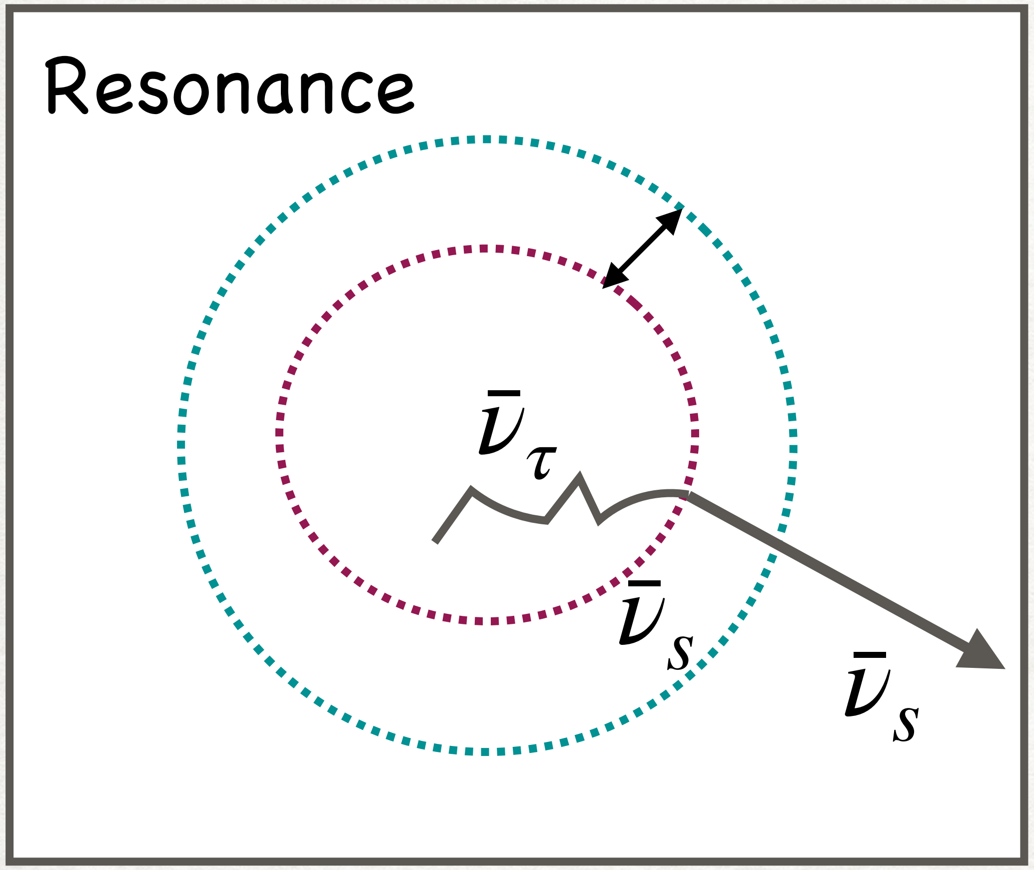
Ray and Qian (2023)

$$\dot{Y}^{\rm MSW}_{\nu_\tau} = \Theta(\lambda_R - \delta r) \frac{\pi E_R (1 - P^2_{\rm LZ})}{n_b(r)\, |\partial \ln V_{\bar{\nu}}/\partial r|^{-1}_{E_R}} \left. \frac{d^2 n_{\bar{\nu}_\tau}}{dE d\Omega} \right|_{E_R}$$

Landau-Zener probability $P_{\rm LZ} = \exp\left(-\frac{\pi^2 \delta r}{2 L_{\rm res}}\right)$ where $L_{\rm res} = \frac{4\pi E_R}{m_s^2 \sin 2\theta}$

MSW Production

$$Y_{\nu_\alpha} = (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})/n_b$$



$$\delta E = E_R \,|\, \partial \ln V_{\bar{\nu}} / \partial r \,|_{E_R} \delta r$$

$$\dot{Y}^{\rm MSW}_{\nu_\tau} = \frac{\Phi^{\rm MSW}_{\bar{\nu}_s}}{n_b\, \delta r}$$

$$\Phi^{\rm MSW}_{\bar{\nu}_s} = \Theta(\lambda_R - \delta r)(1 - P_{\rm LZ}) \frac{d^2 n_{\bar{\nu}_\tau}}{dE d\Omega}\Big|_{E_R} \delta E \times \left[\int_{\rm out} d\Omega \cos\vartheta + P_{\rm LZ} \int_{\rm in} d\Omega \,|\cos\vartheta\,| \right]$$

Previous literatures neglects the direction of propagation, which is an over-estimation in the MSW production rate.

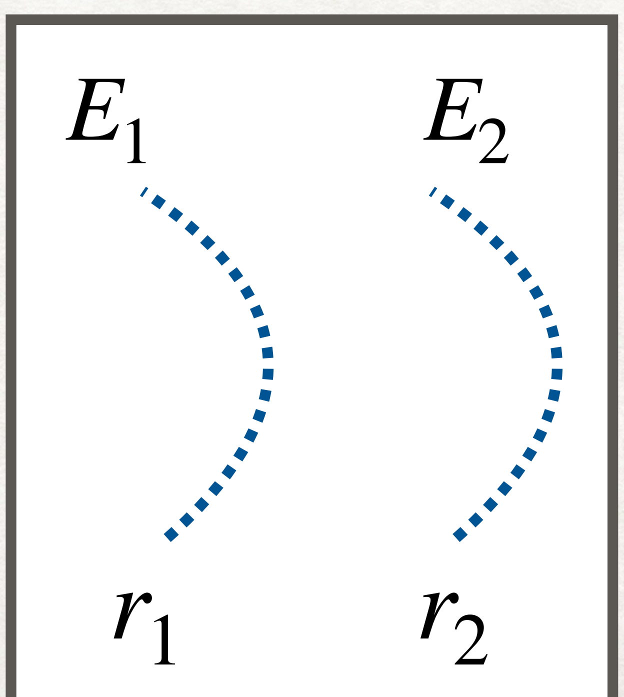
e.g. Arguelles et al (2019, PRD), Suliga et al. (2019, JCAP),…

Collisional Production

- Sterile neutrinos can also be produced via collisions of $\nu_\tau/\bar{\nu}_\tau$ with the proto-neutron star constituents. Raffelt and Zhou (PRD, 2011)

- Collisional production rate: Ray and Qian (2023)

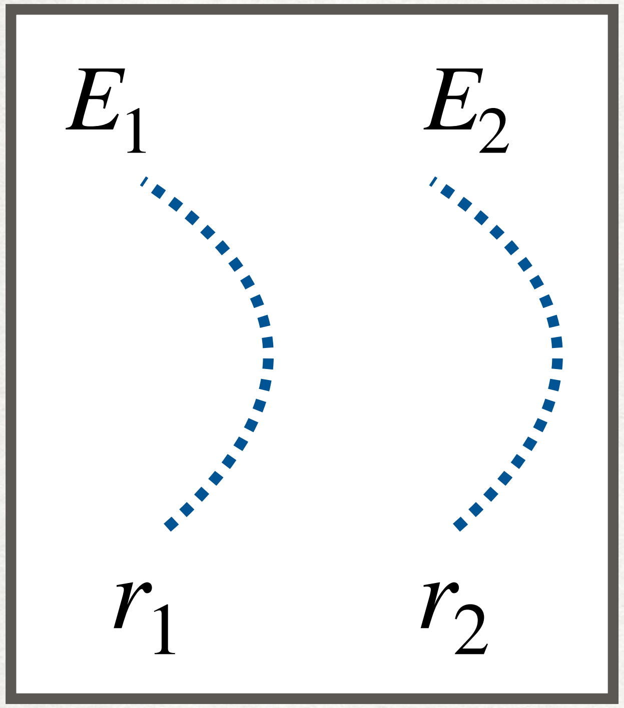
$$\dot{Y}^{\rm coll}_{\nu_\tau} = G_F^2 \left(\int_{E_{\bar{\nu}_\tau}} dE\, E^2 \sin^2 2\theta_{\bar{\nu}} \frac{d^2 n_{\bar{\nu}_\tau}}{dE d\Omega} - \int_0^\infty dE\, E^2 \sin^2 2\theta_\nu \frac{d^2 n_{\nu_\tau}}{dE d\Omega} \right)$$

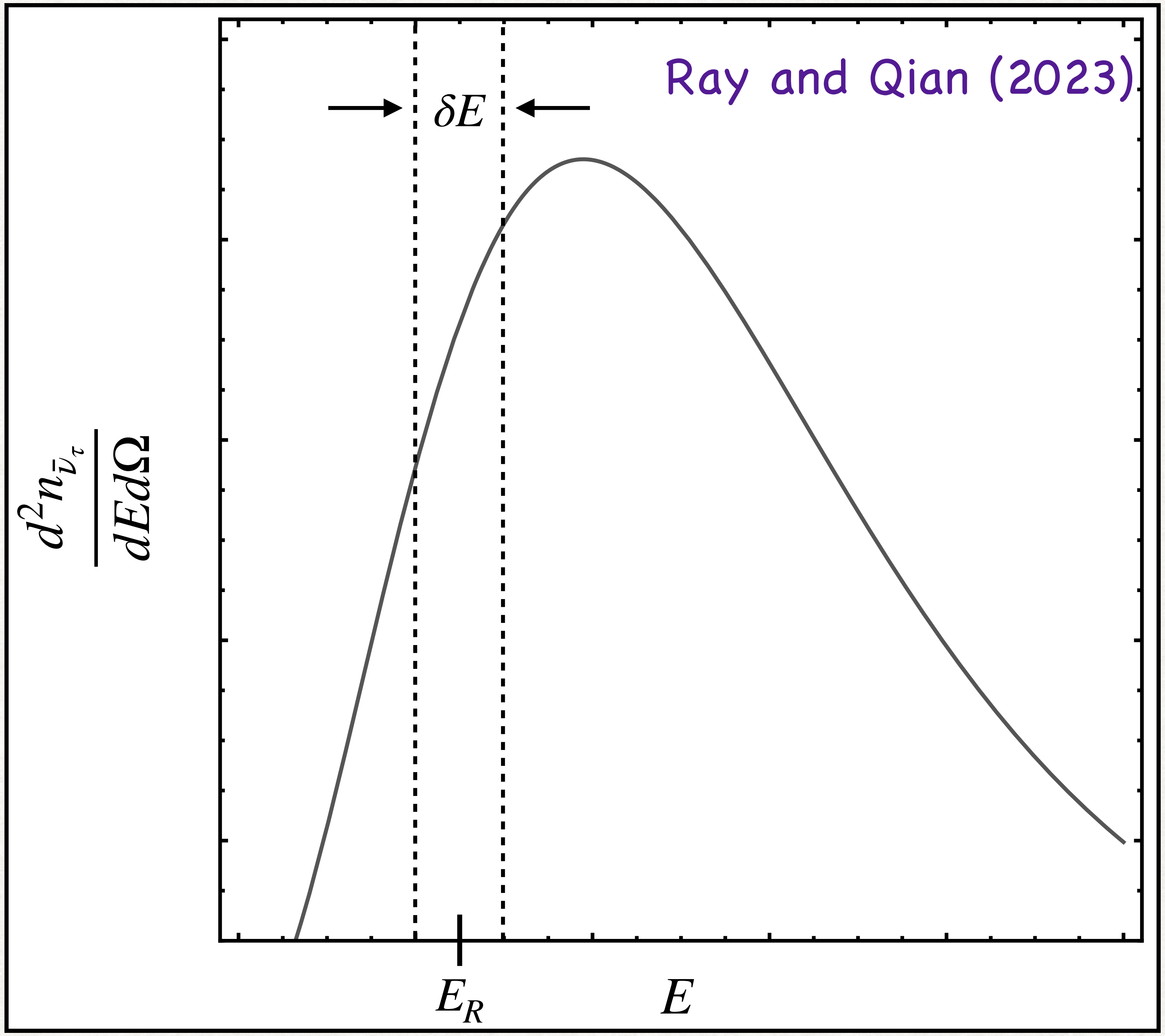


For $\bar{\nu}_\tau$: $E_{\bar{\nu}_\tau}$ excludes the resonant energy range (say $[E_1, E_2]$).

For ν_τ : E_{ν_τ} includes all energies.

MSW/Collisional Production





For a given neutrino spectra, the resonant production is shown within the dashed lines, whereas, rest of the neutrino energies will undergo collisional production.

Diffusion

- Along with the MSW (resonant) and collisional (non-resonant) production, $\nu_\tau/\bar{\nu}_\tau$ can also diffuse across various zones.

Syvolap et al. (PRD, 2022)

- Rate of diffusion:

Ray and Qian (2023)

$$\dot{Y}^{\rm diff}_{\nu_\tau} = \frac{1}{6\pi G_F^2 n_b r^2}\frac{\partial}{\partial r}\left(\frac{r^2}{n_b}\frac{\partial \mu_{\nu_\tau}}{\partial r}\right)$$

- The evolution of tau-neutrino lepton number is therefore determined by

$$\frac{\partial Y_{\nu_\tau}(r,t)}{\partial t} = \dot{Y}^{\rm MSW}_{\nu_\tau} + \dot{Y}^{\rm coll}_{\nu_\tau} + \dot{Y}^{\rm diff}_{\nu_\tau}$$

**MSW production is the dominant.

Evolution of Y_{ν_τ}

- The evolution of tau-neutrino lepton number is governed by

$$\frac{\partial Y_{\nu_\tau}(r,t)}{\partial t} = \dot{Y}^{\rm MSW}_{\nu_\tau} + \dot{Y}^{\rm coll}_{\nu_\tau} + \dot{Y}^{\rm diff}_{\nu_\tau}$$

  - At t=0, we first compute these rates.
  - At the next time-step $t=\Delta t$, we obtain

$$Y_{\nu_\tau}(t=\Delta t) = Y_{\nu_\tau}(t=0) + \dot{Y}_{\nu_\tau}\Delta t$$

  - Y_{ν_τ} reduces the MSW potential.

(Feedback of the MSW potential)

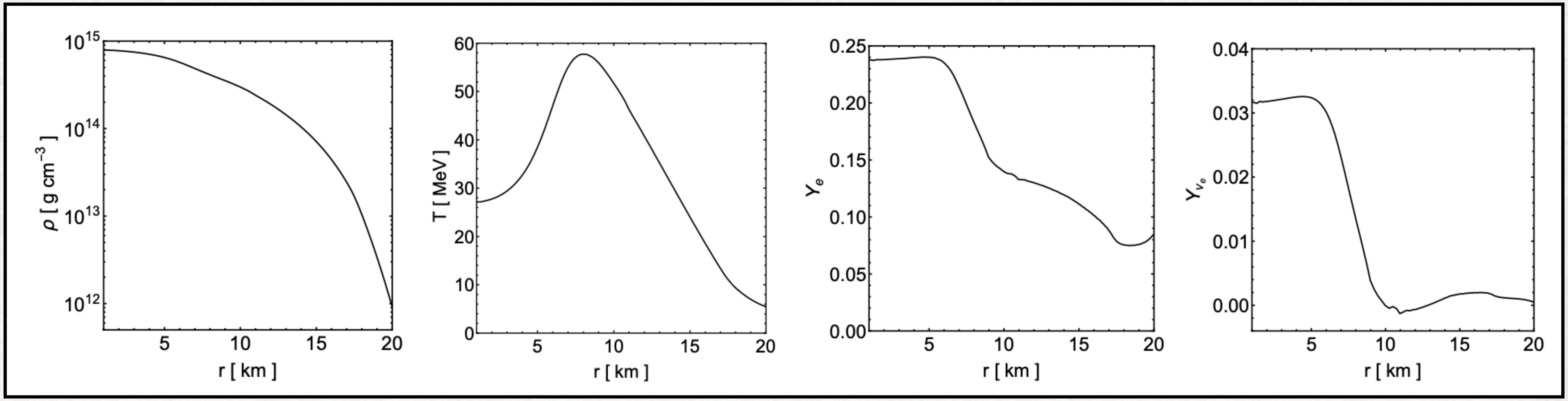
Suliga et al. (JCAP, 2019)

  - From Y_{ν_τ}, we calculate μ_{ν_τ} which further modifies the neutrino energy distribution.

SN Model

- We use a 20.0 $M_\odot$ Supernovae model with SFHo nuclear equation of state for our numerical computations.

https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/



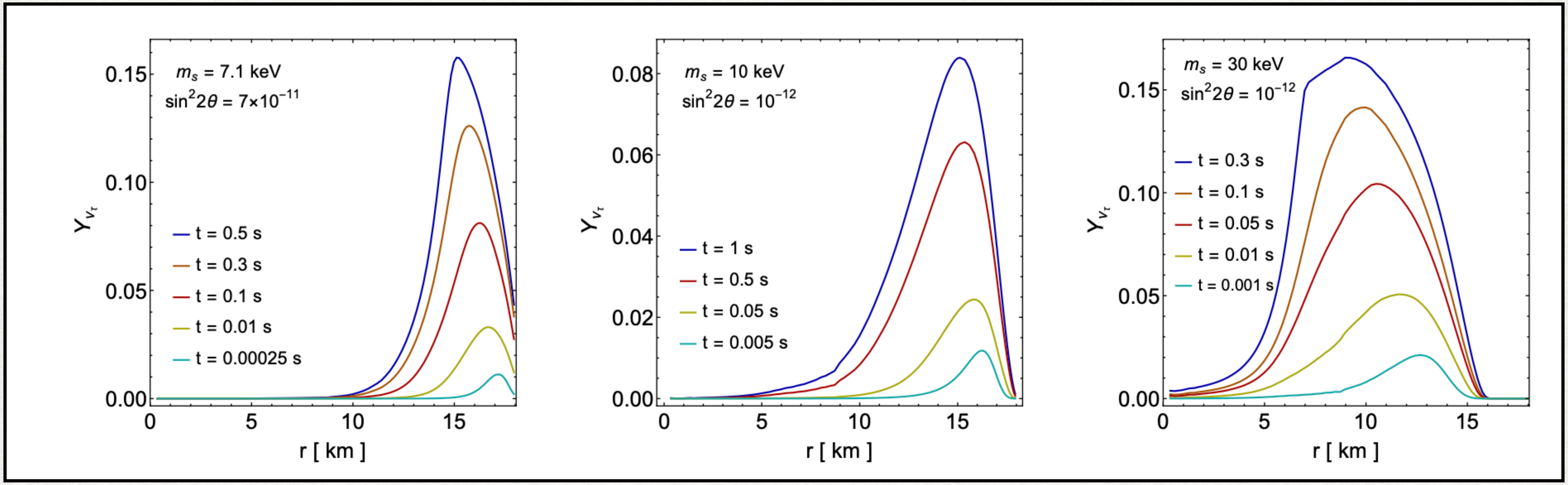
The radial profiles of the proto-neutron star conditions at 1 sec of post-bounce time.

Results

- Radial profiles:

At $t = 0$, $Y_{\nu_\tau} = 0$

Ray and Qian (2023)



(Left) 3.55 keV line explanation (Middle) 100% of DM (Right) <1% of DM

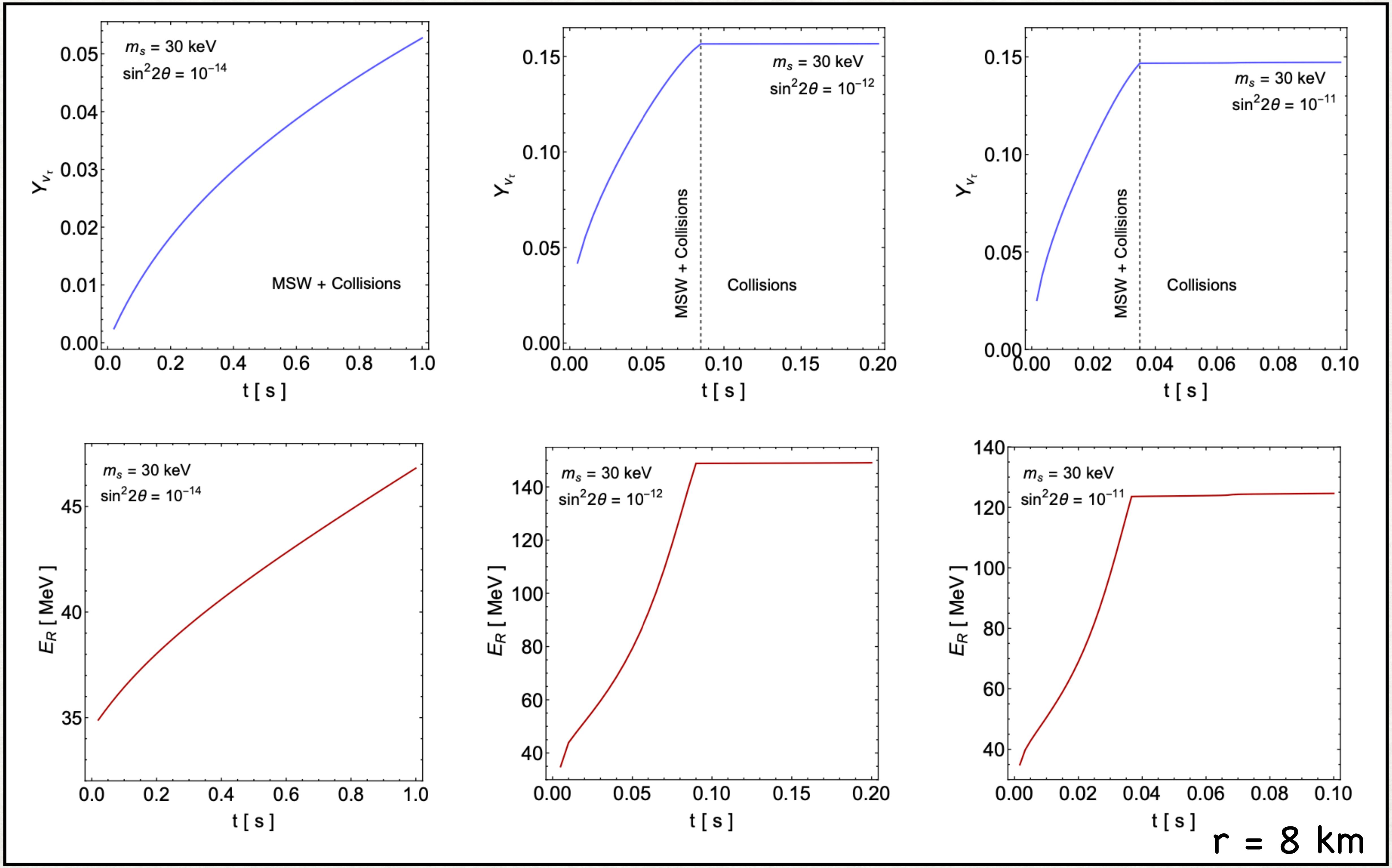
- In each panel, the peak shifts inwards with time. (With time, Y_{ν_τ} increases, leading to larger resonance energy)

- With increase in m_s, the peak shifts inwards. (Larger m_s leads to higher resonance energy)

Results

- Time evolution of a single zone

Ray and Qian (2023)



Summary & Conclusions

- keV mass Sterile neutrino, a viable DM candidate, have a major impact on Supernovae physics.
- We present a self-consistent analytical understanding of the problem by carefully examining all the relevant processes.
- We found a significant amount of tau-neutrino lepton number creation in typical proto-neutron stars which has a major impact on SN cooling and explosion mechanisms.

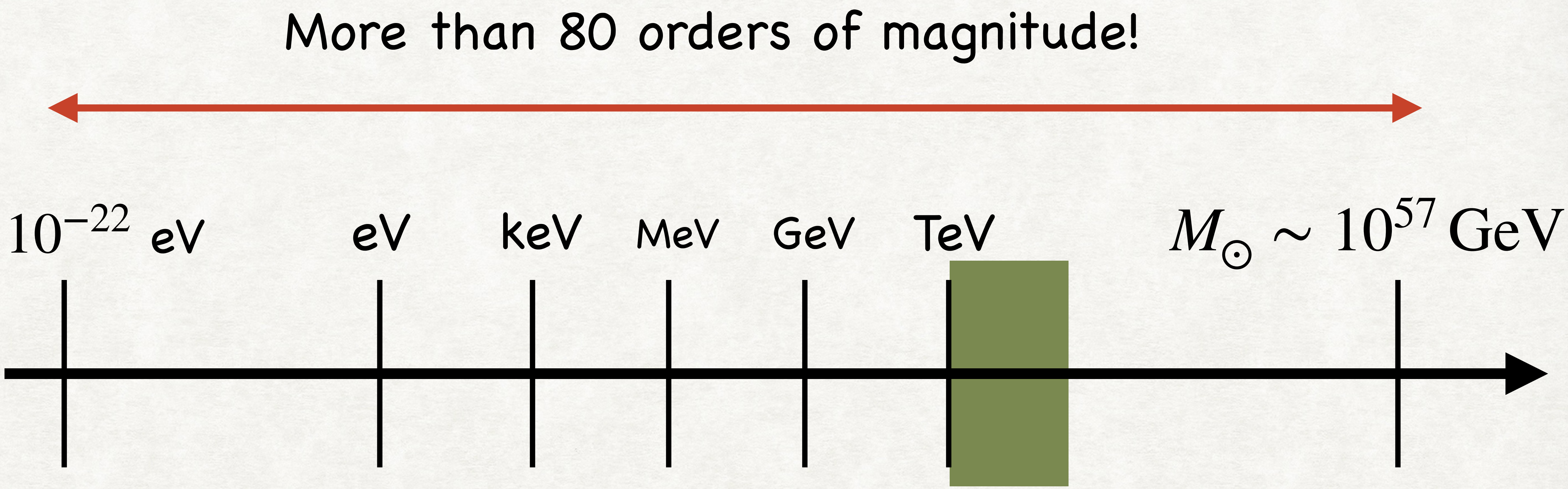
Weakly interacting Heavy DM

Searching DM with LIGO

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

(Accepted in PRL, in press)

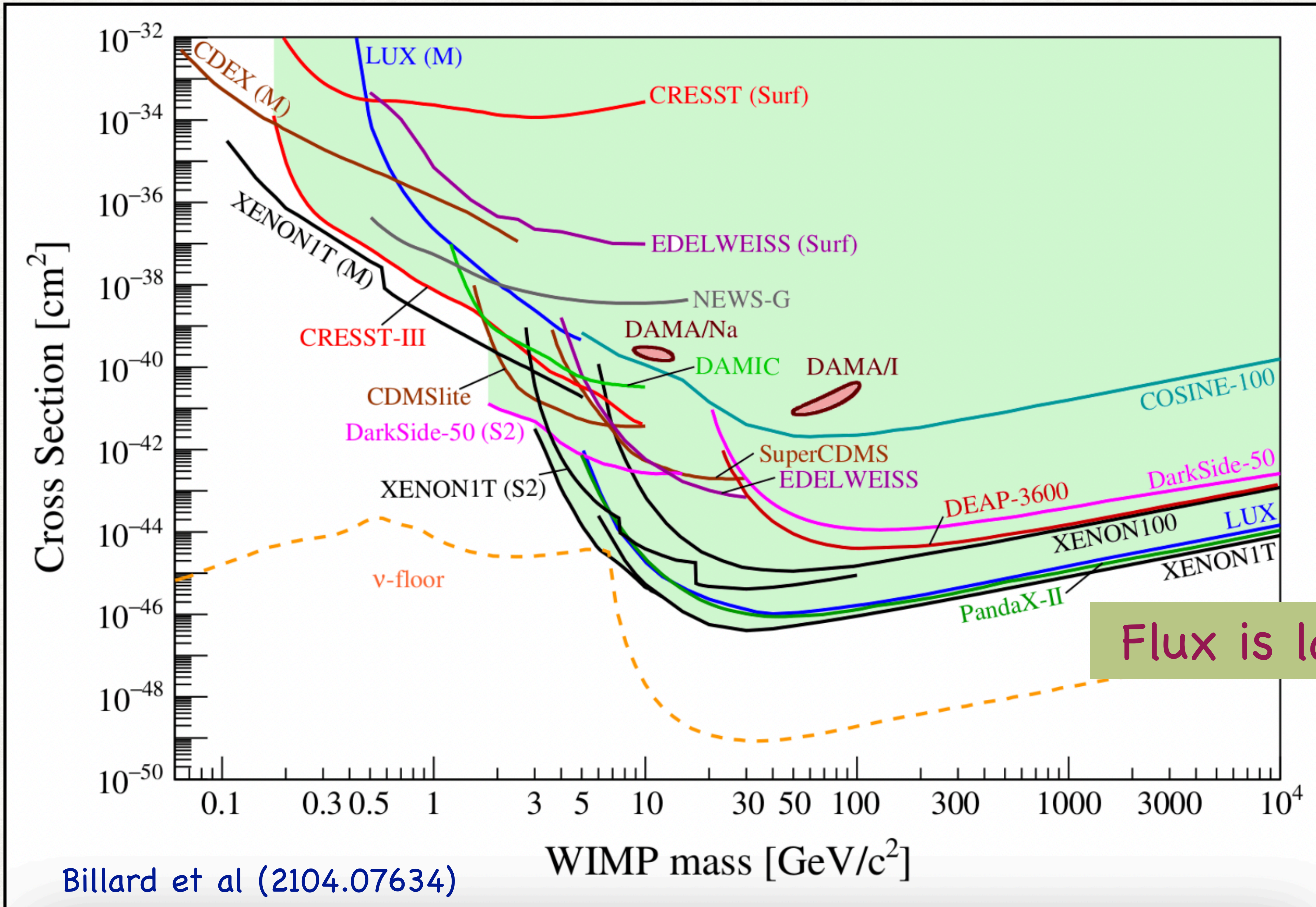
• What is DM?



- We will consider : Non-annihilating WIMPs of TeV-PeV mass

- Take Away: GW detectors, such as LIGO can be used for probing DM interactions

Results: Underground Detectors



Flux is low

- Heavy DM — a blind-spot to the underground detectors

Outline

- 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

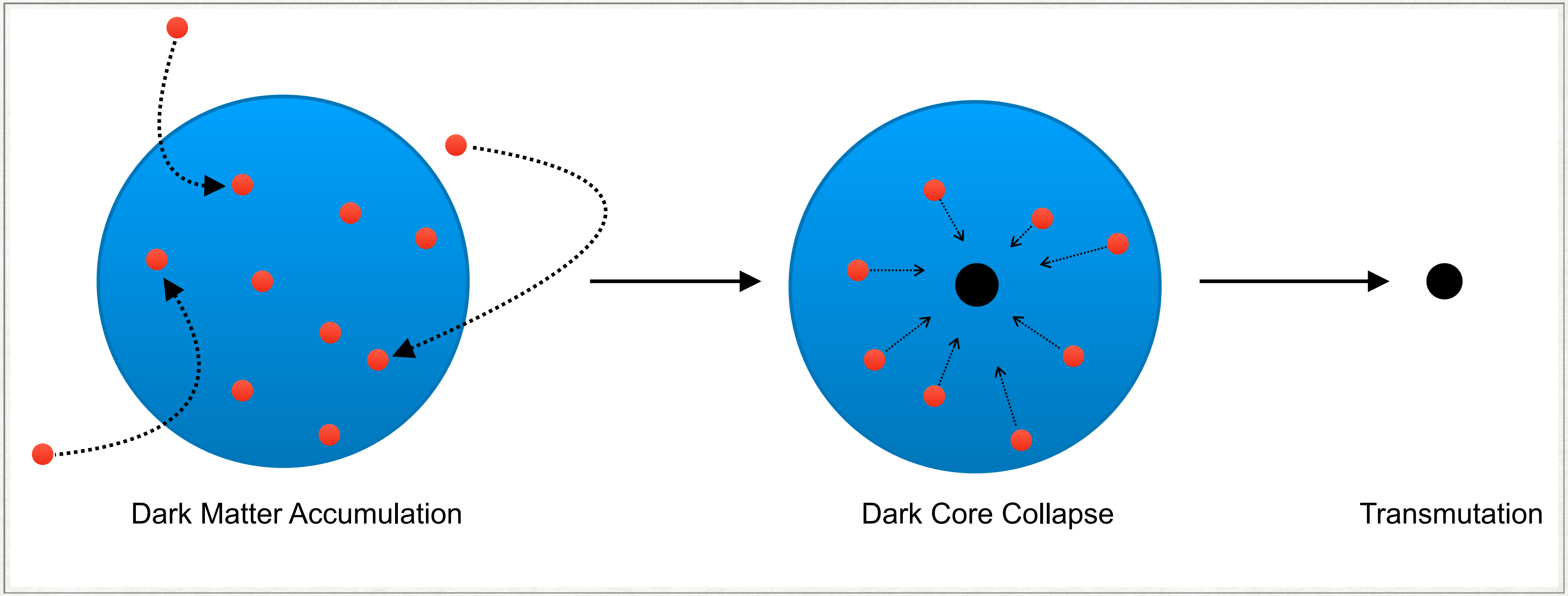
- In the weakly interacting regime, DM can be trapped in a significant number inside compact stars.

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

Goldman (PRD 1989), 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.

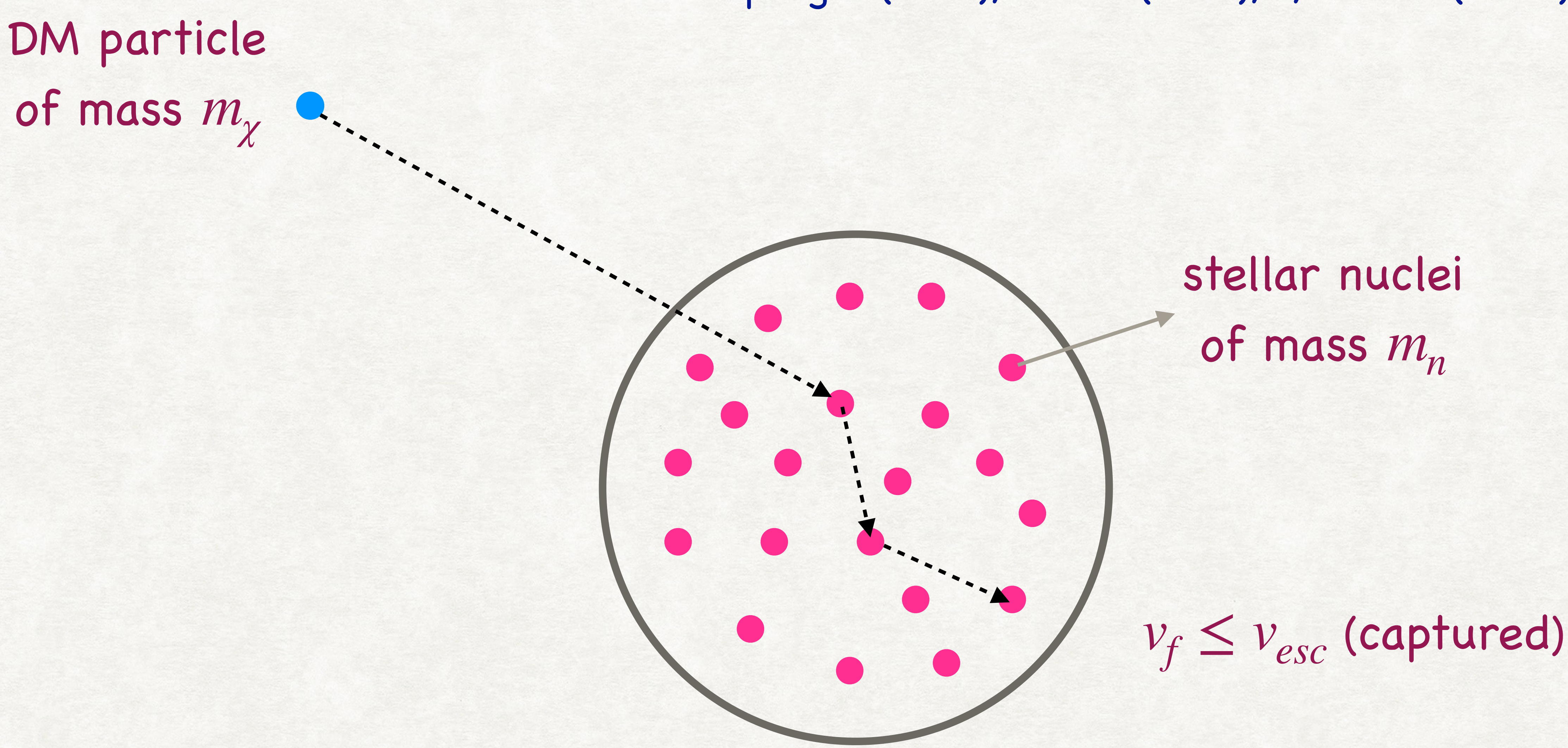
DM-induced Collapse



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

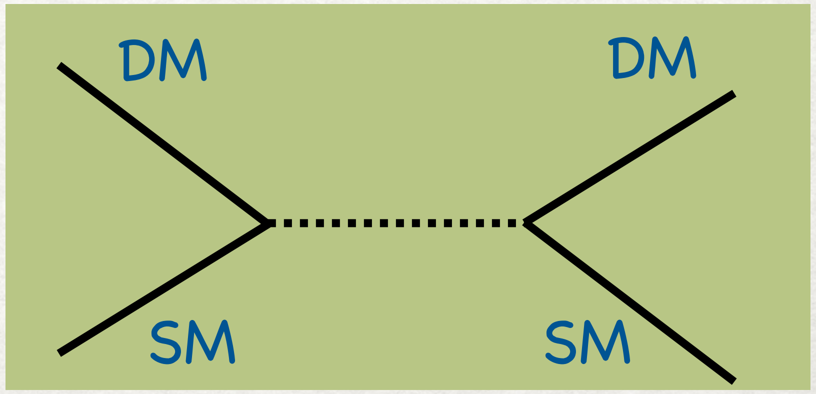
DM Accretion in Stellar Objects

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



v_f : final velocity of the DM particles

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



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! Thermalization radius decrease further with larger m_χ

Dark Core Collapse

Goldman (PRD, 1989), Kouvaris et al. (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),…, Dasgupta, Gupta, **Ray** (JCAP 2020),…

- Results in a huge core density.

For DM mass of 10^5 GeV, the core density is $\sim 10^{34}\,\mathrm{cm}^{-3}$, and it further increases as $m_\chi^{1/2}$.

- Undergoes Jeans Instability and overcomes the quantum degeneracy pressure.

Bosonic DM and fermionic DM has different collapse criterion.

- The mass of the nascent BH is small.

Heavier DM leads to favourable collapse criterion, however, BH becomes smaller in mass.

Growth and Evaporation of BH

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

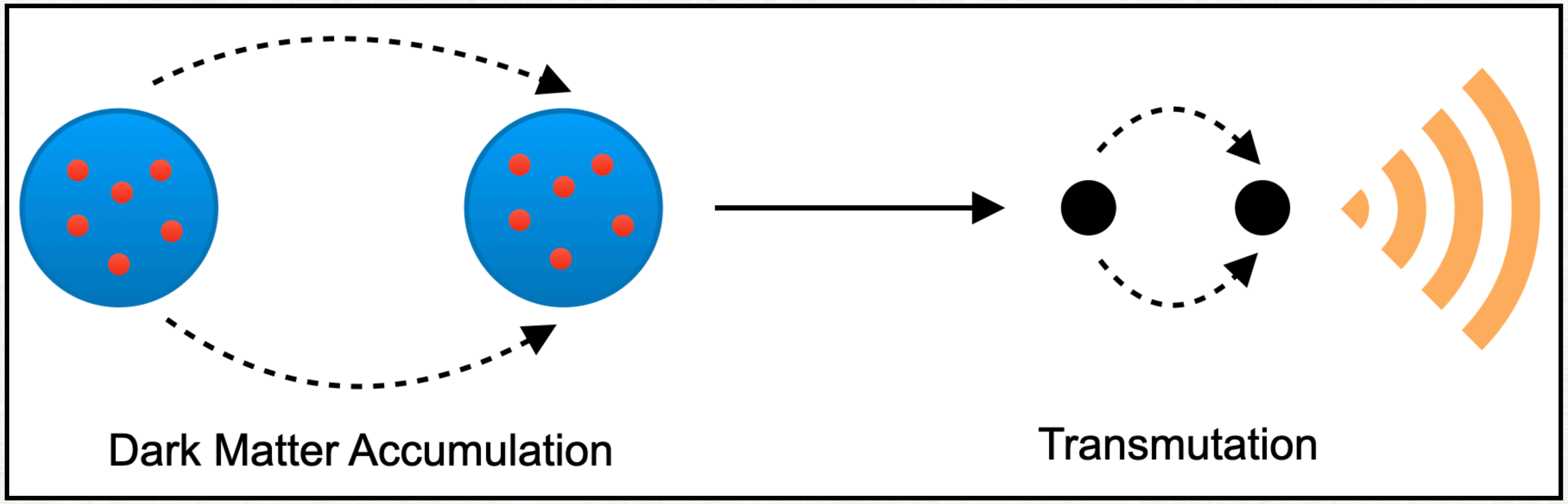
- For sufficiently small BH, accretion (M^2) becomes inefficient and Hawking evaporation dominates ($1/M^2$). This is relevant for very heavy DM mass, ceasing the implosion.

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

$P(M_{\rm BH})$: 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 $1/11360\pi$.

Outline



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

Transmuted Black Holes (TBHs)

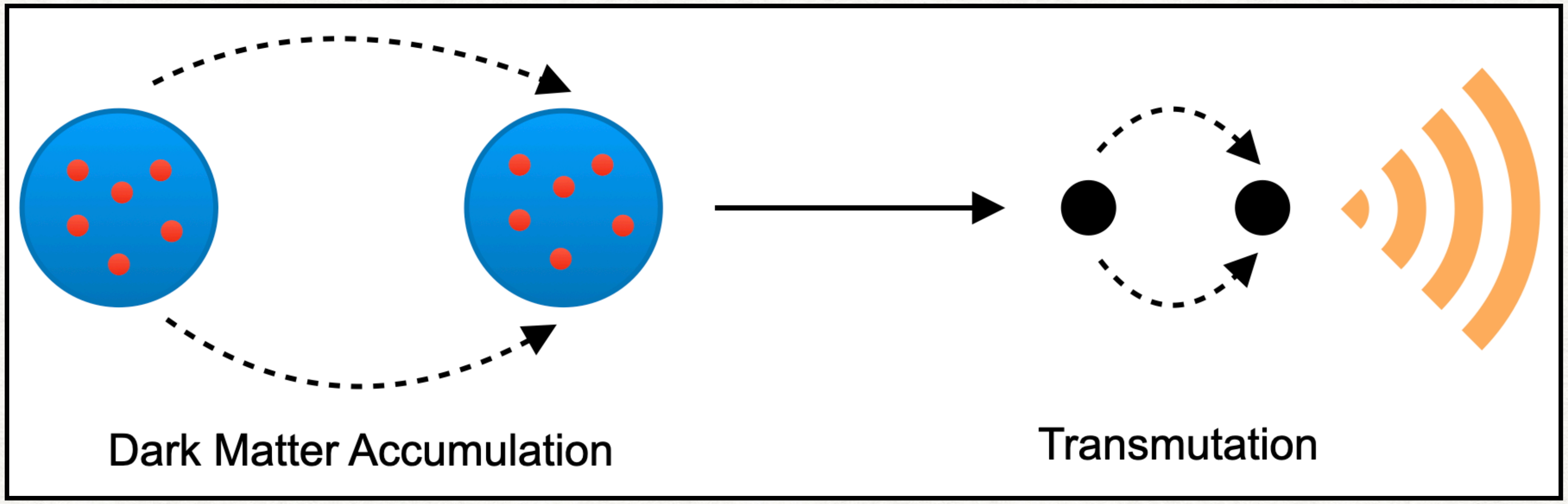
Dasgupta, Laha, Ray (PRL, 2022)

- 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 (PRL, in press)

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]

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

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

t_f : Binary formation time

t_0 = 13.79 Gyr = Present day

- 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.

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),...

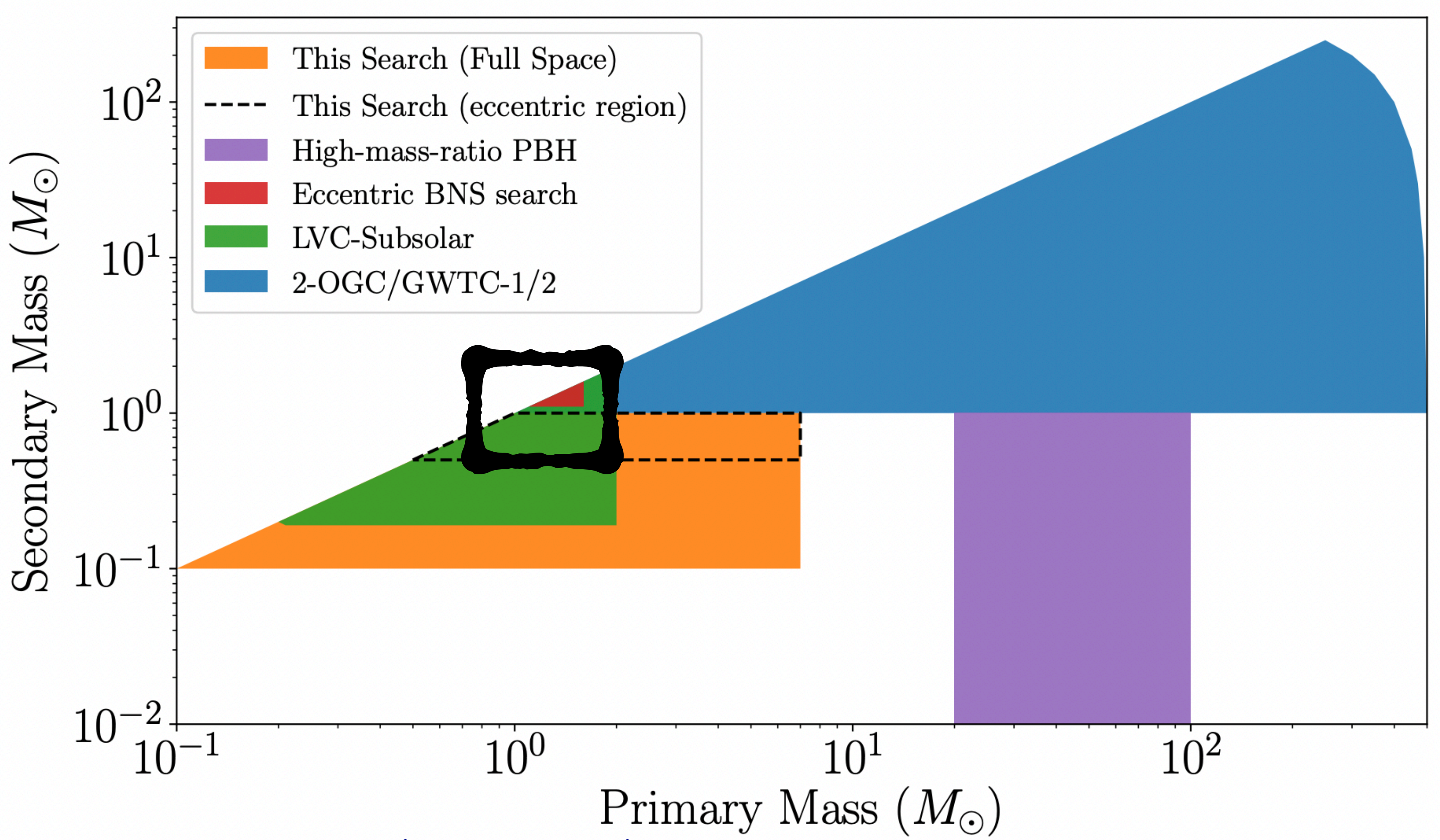


Fig: Nitz & Wang (APJ 2021)

GW Data & Statistics

- Merger rate upper limits:

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

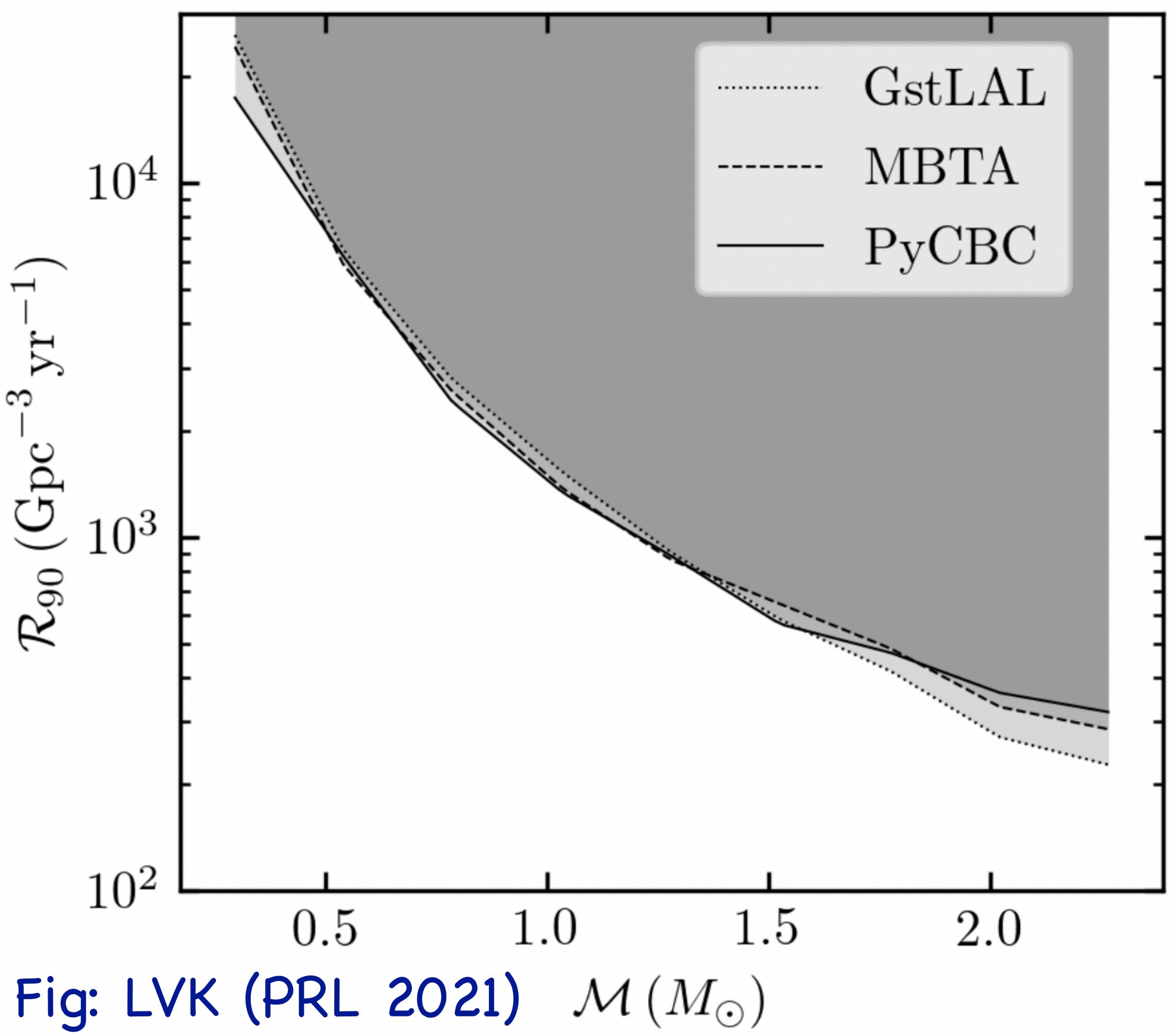


Fig: LVK (PRL 2021)

*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:

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

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

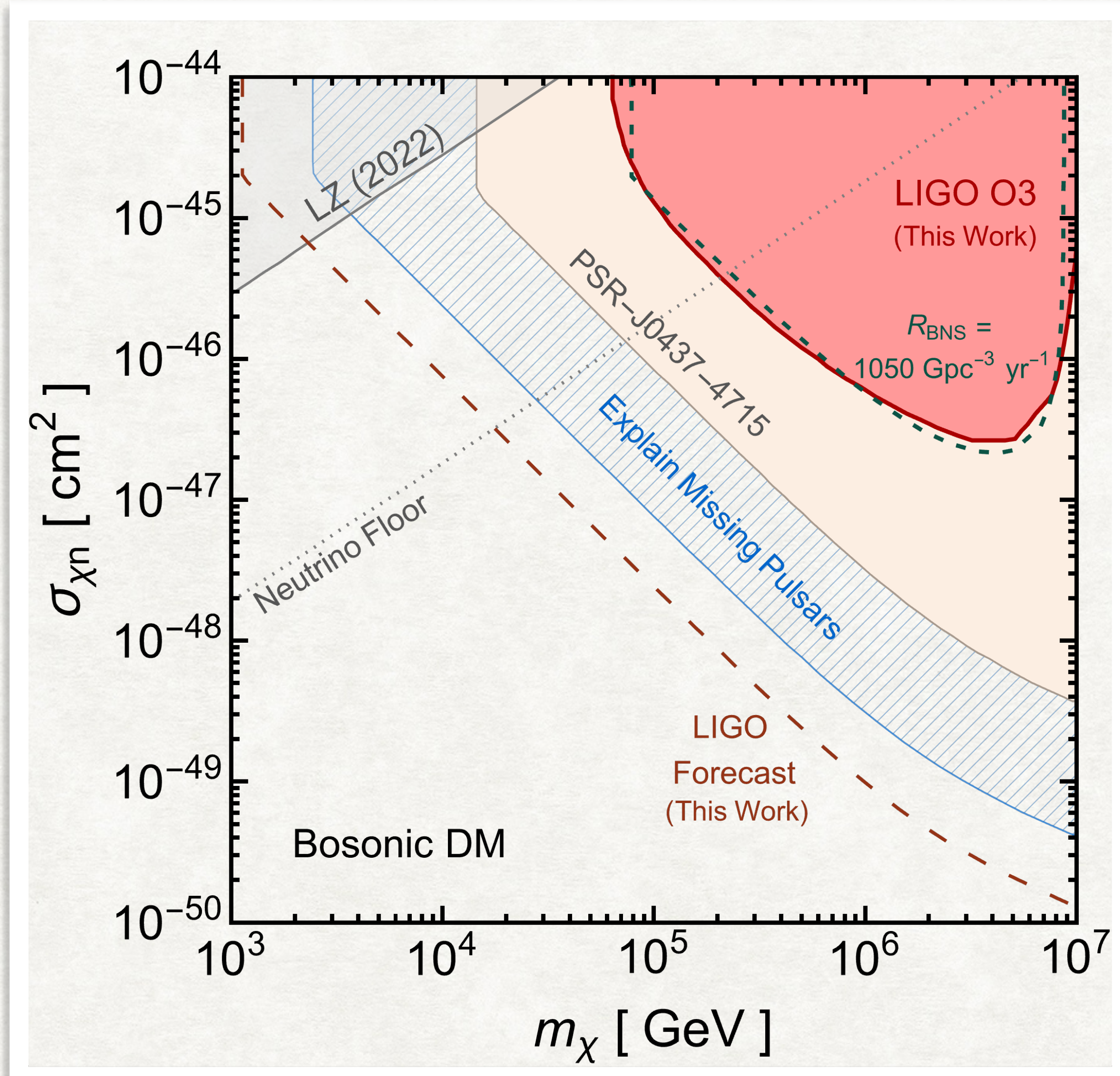
Ozel & Freire (Ann. Review of Astronomy and Astrophysics, 2016)

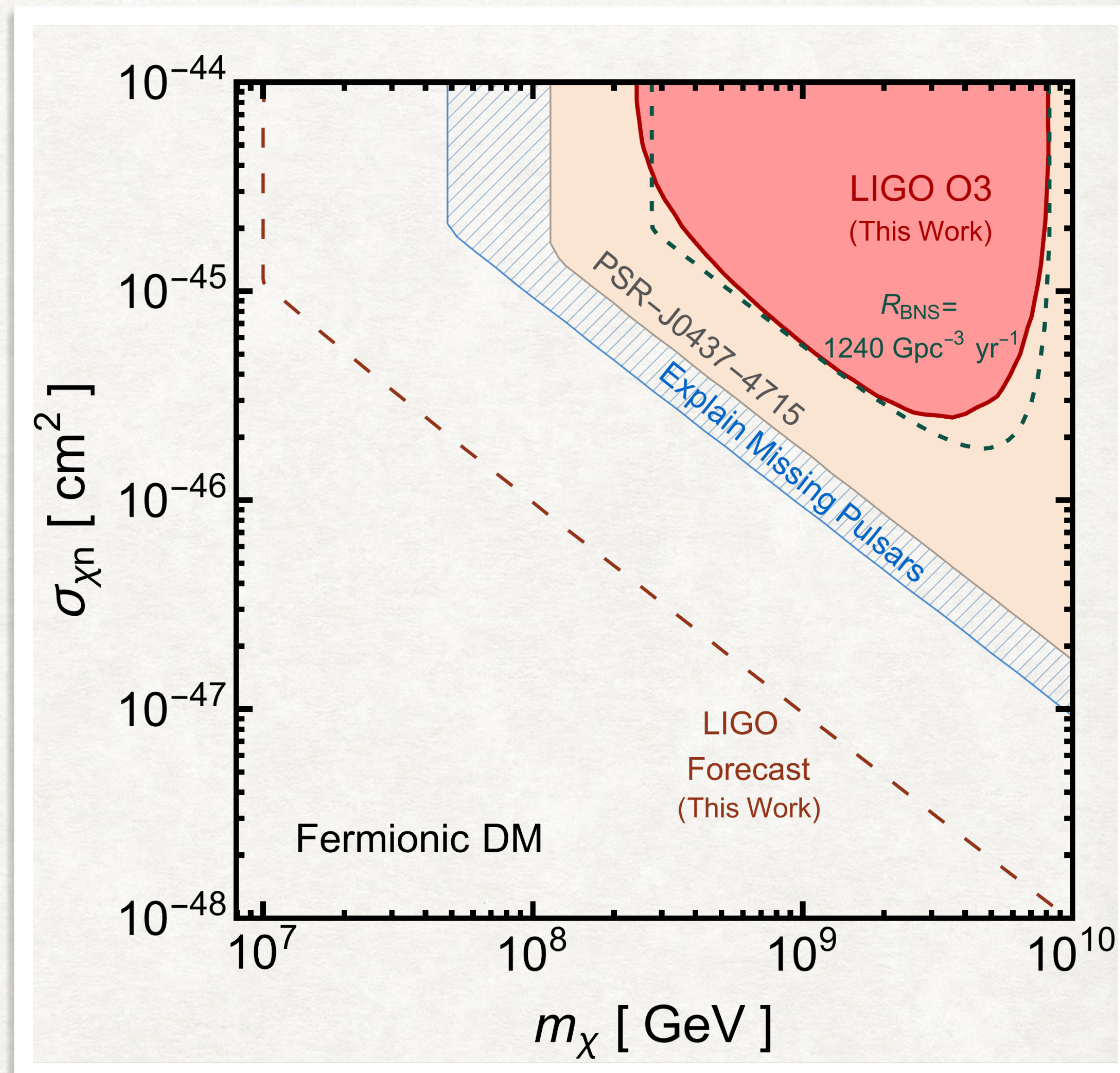
Conservative: LIGO can not distinguish low mass compact objects as BHs. With tidal deformation & EM counterpart, our analysis can be improved.

Results

(PRL, in press)

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





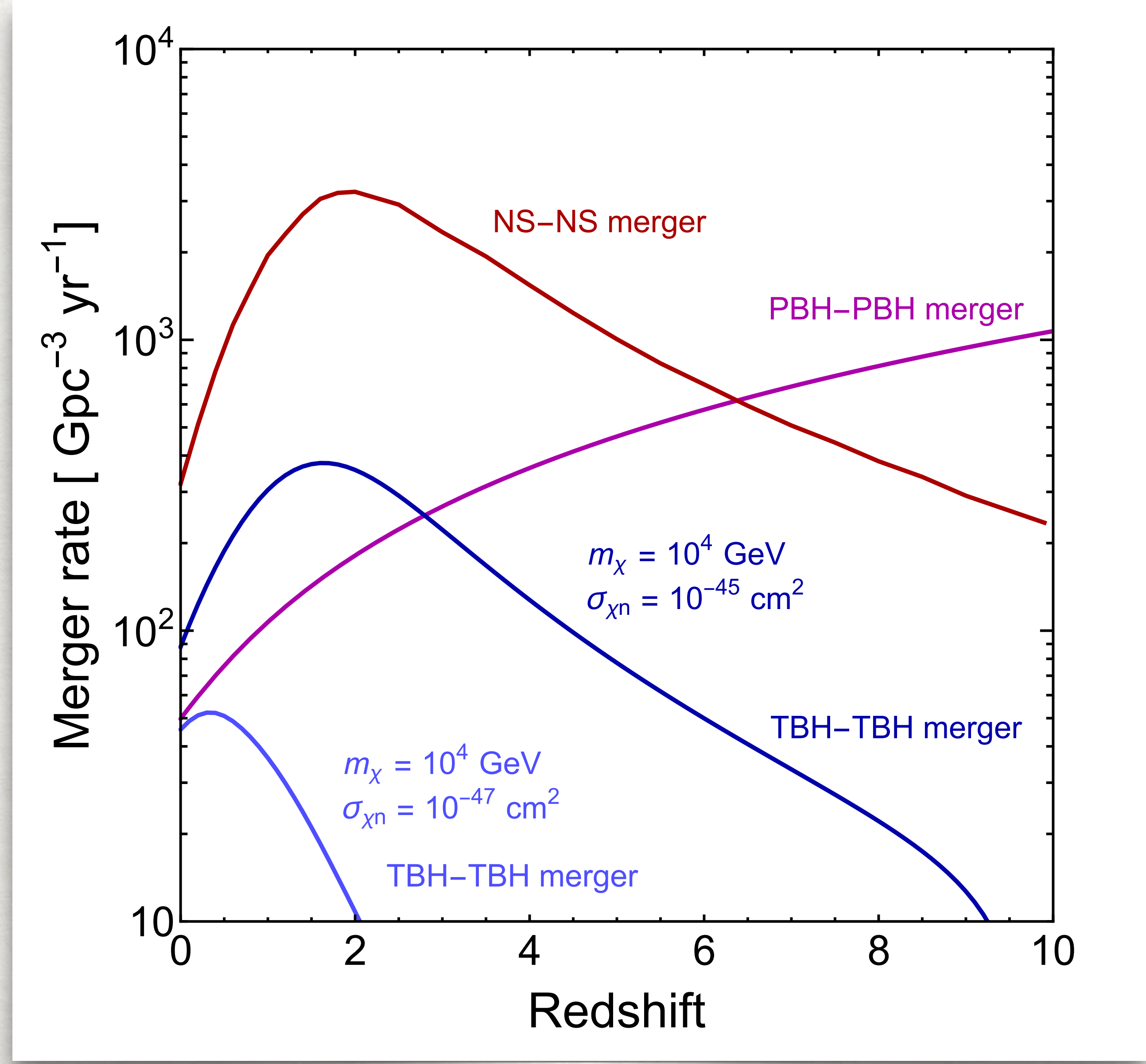
(Left) Bosonic DM (Right) Fermionic DM

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

Cosmic evolution of the binary merger rates

- 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 of the binary NS, PBH and transmuted BH (TBH) merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments (Pre-DECIGO, Einstein Telescope).

Dasgupta, Laha, and **Ray** (PRL, 2021)

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!

Extra Slides

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)

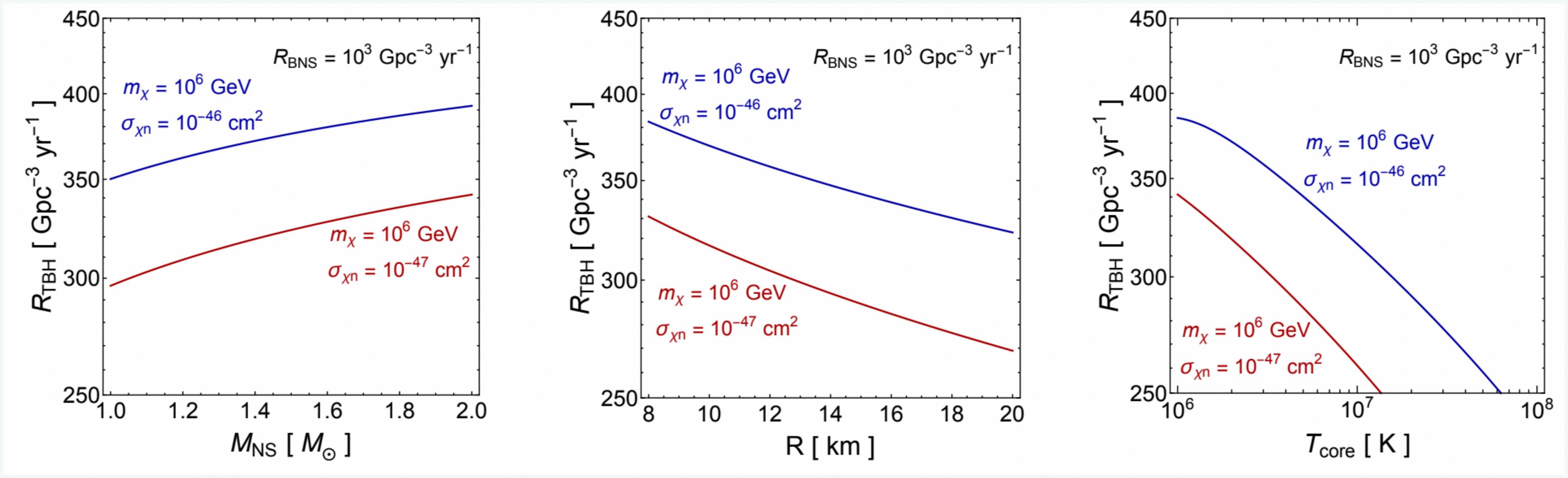
vi) Uncertain normalization parameter.

(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

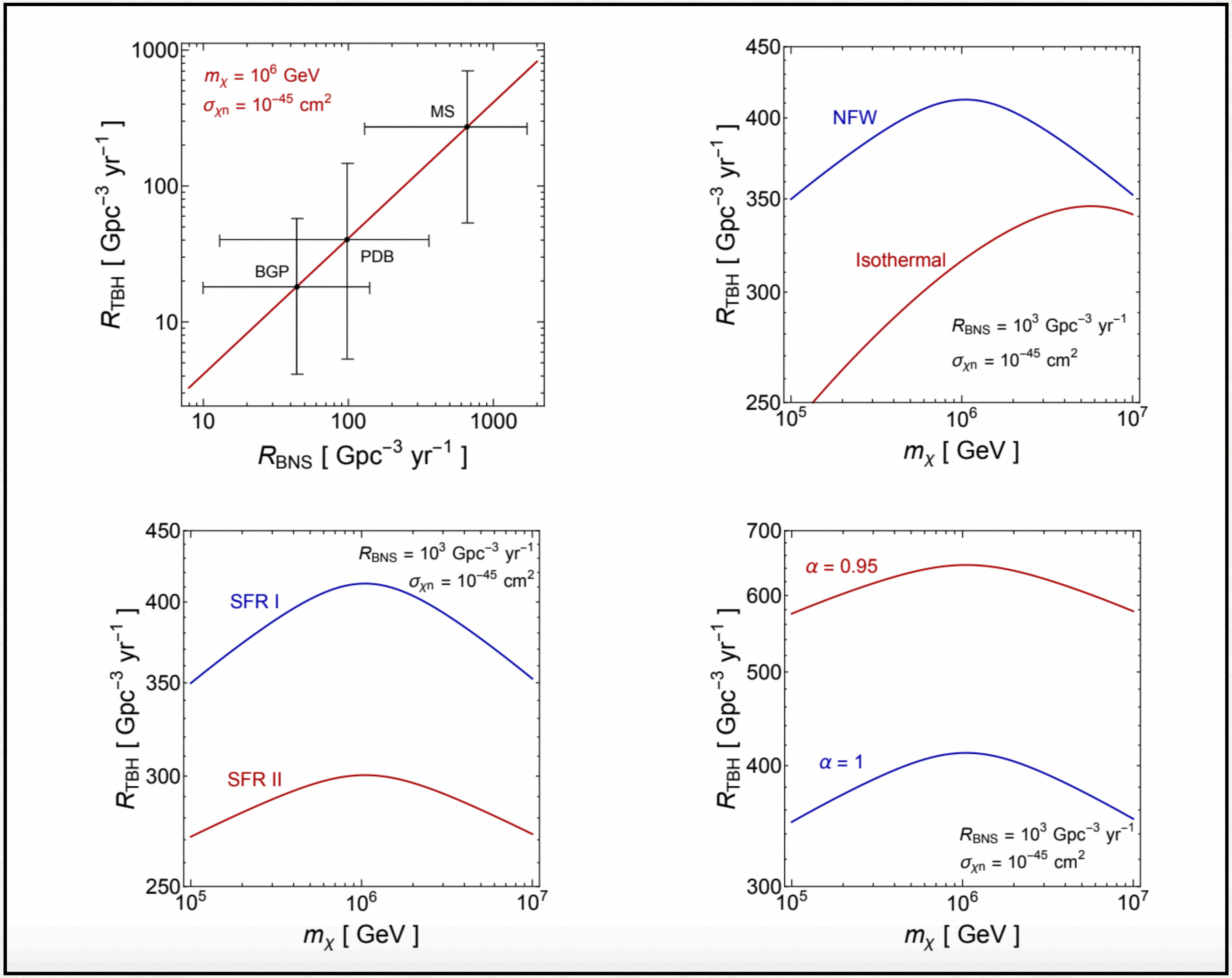


(Left) Mass (Middle) Radius (Right) Core-temperature

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.

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_{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 $\sigma_{\chi n} \in \left(10^{-50}, 10^{-44}\right)\ \mathrm{cm}^2$ for bosonic DM and $\sigma_{\chi n} \in \left(10^{-48}, 10^{-44}\right)\ \mathrm{cm}^2$ for fermionic DM.

— Uniform prior on the uncertain normalization parameter $R_{\mathrm{BNS}} \in (10, 1700)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ 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 $(m_\chi, \sigma_{\chi n})$.

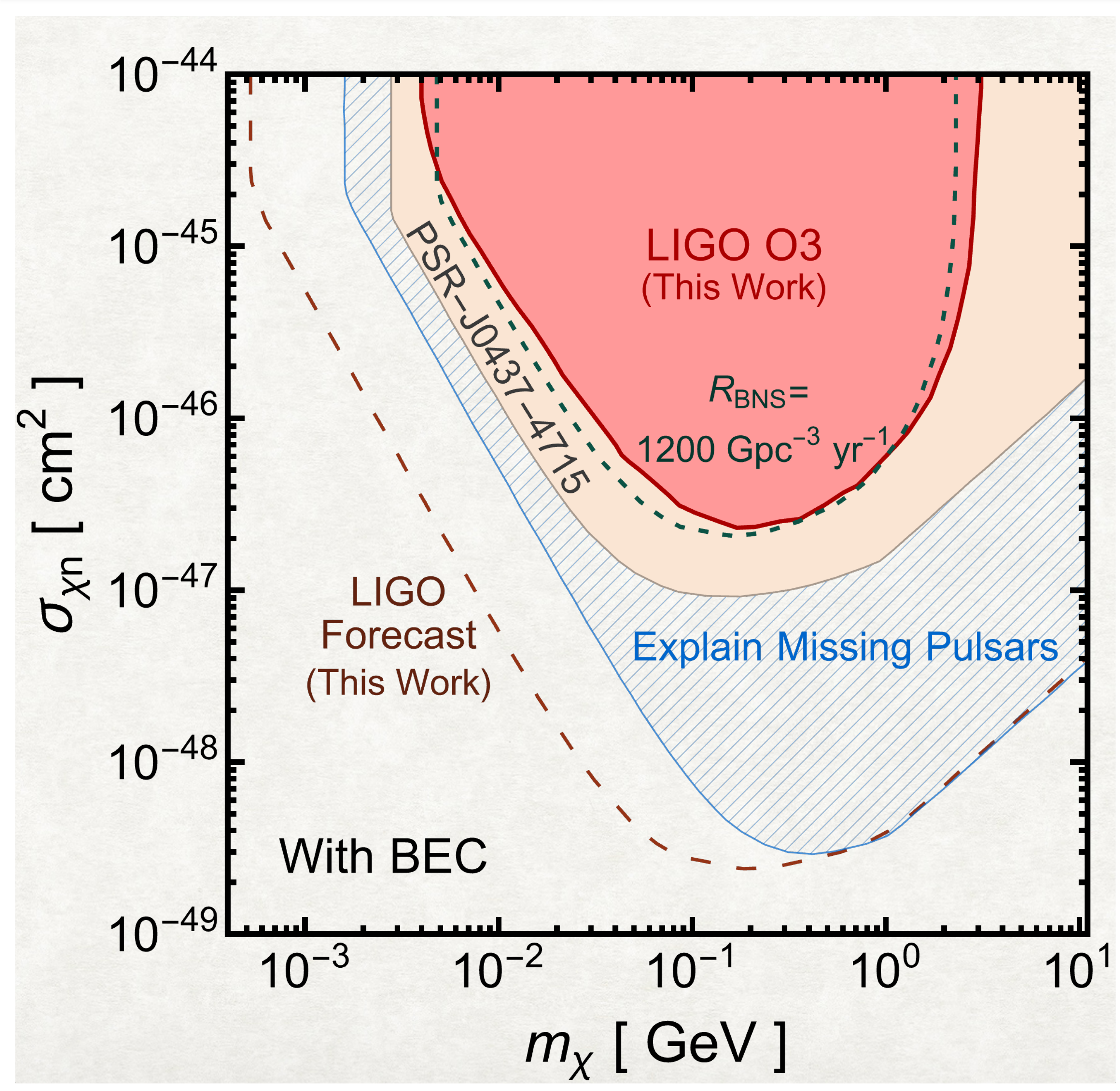
  — Marginalizing over the normalization parameter by assuming a uniform prior.

  — 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),...

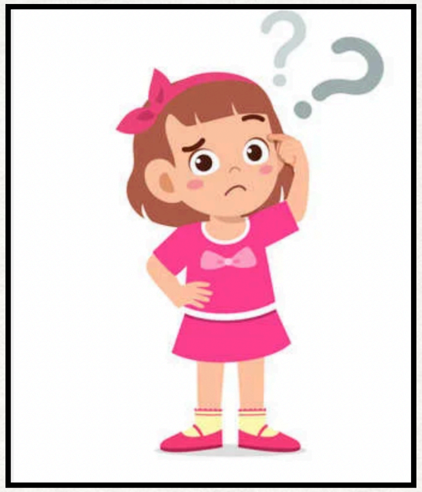


(PRL, in press)

Ray++, arXiv: 2302.07898

GW-inferred constraints for a possible BEC formation scenario

Going Underground or Listening to the Sky?



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