Closest Pulsars For Dark Matter Searches

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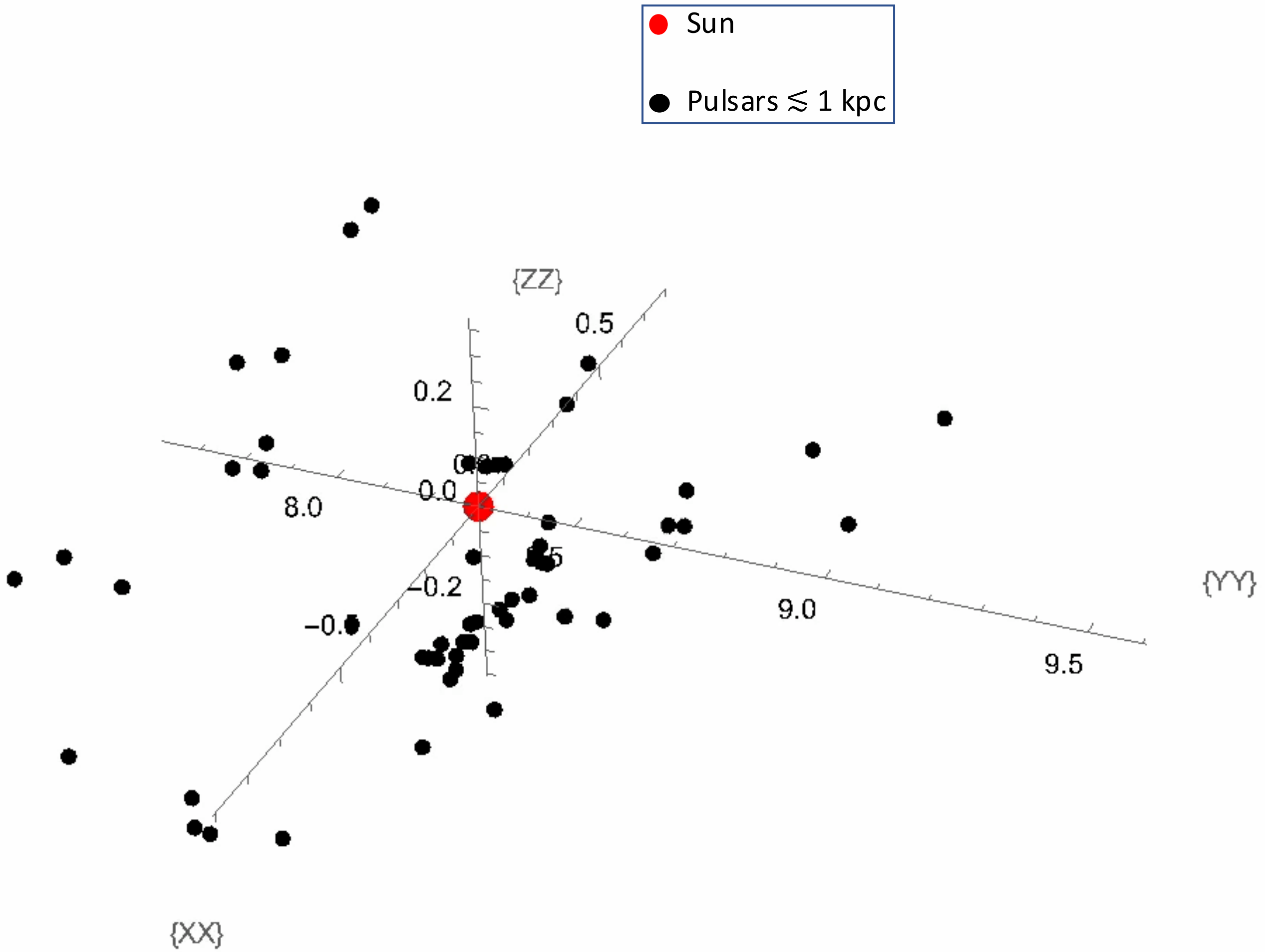
Pulsars in the Milky Way



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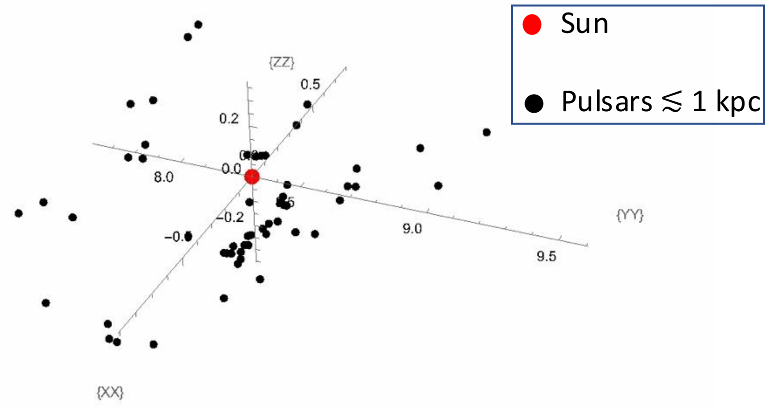

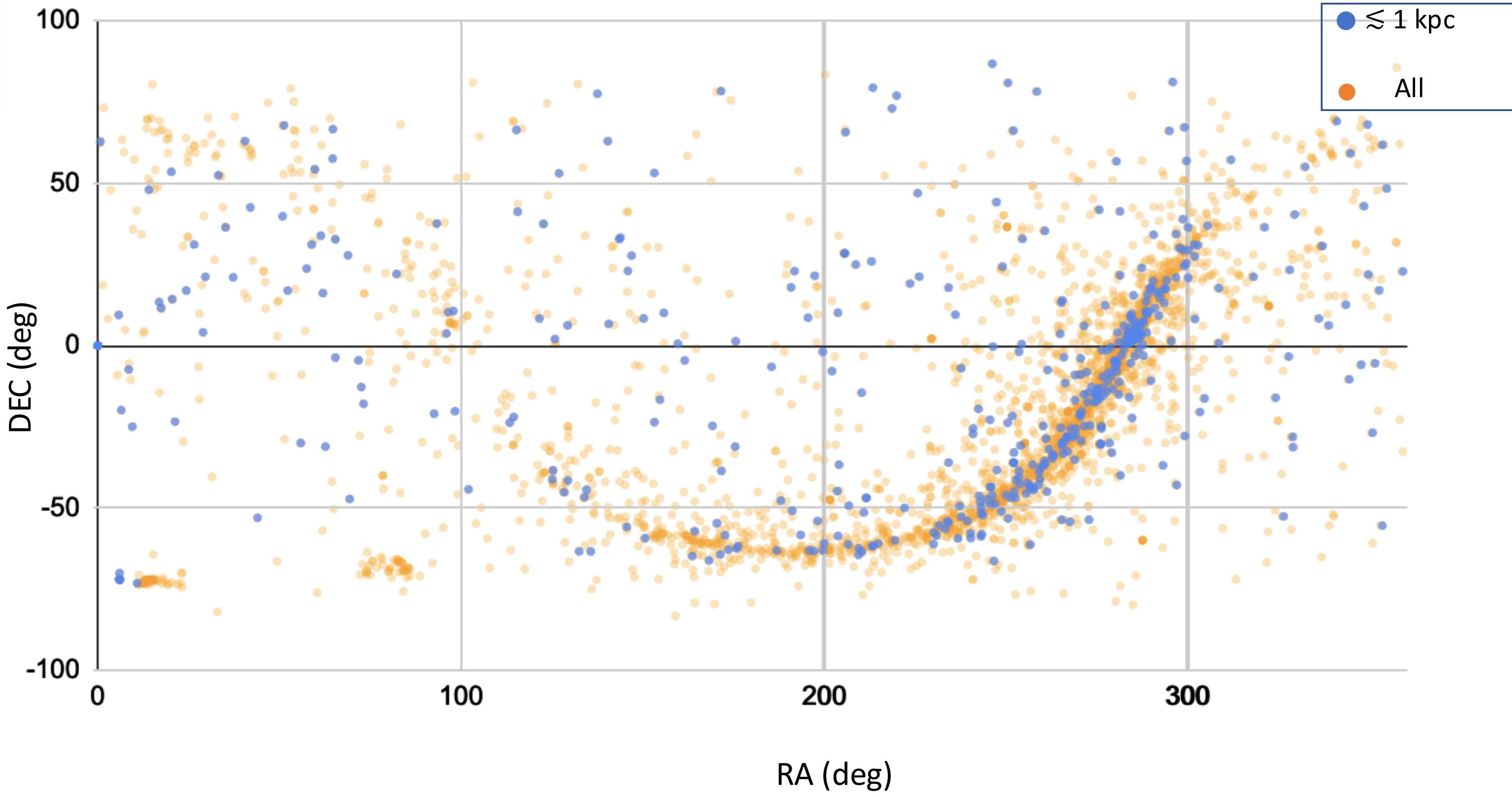

Pulsar Distances

- Measurements of absorption by neutral hydrogen combined with a model for differential rotation of the Galaxy

- **Parallax**

  → Based on annual parallax measurement of another object(e.g., optical binary companion) .

$$d(kpc) \simeq \frac{1}{PX(mas)}$$

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- **Dispersion Measure**

  → Pulsar's 'pulse' experiences temporal broadening that scales as $\Delta\tau \sim 1\ s\left(\frac{GHz}{\nu}\right)^2$

  → Dispersion Measure manifests as this pulse broadening over a finite bandwidth

$$DM = \frac{t_2 - t_1}{\kappa_{DM}(\nu_2^{-2} - \nu_1^{-2})} = \int_0^L n_e\, dl$$

L → Length of the LOS

κ_{DM} → dispersion constant = 4.149 $GHz^2\ pc^{-1}\ cm^3$ ms

n_e → Electron density

Galactic Electron Density Model

Several galactic electron column density exist:

- LMT85 model (Manchester & Taylor 1981;
  Lyne, Manchester, & Taylor 1985)
- VK82 model (Vivekanand & Narayan 1982)
- TC93 model (Cordes et al. 1991 ; Taylor & Cordes 1993)
- NE2001 (Cordes & Lazio 2002,2003)
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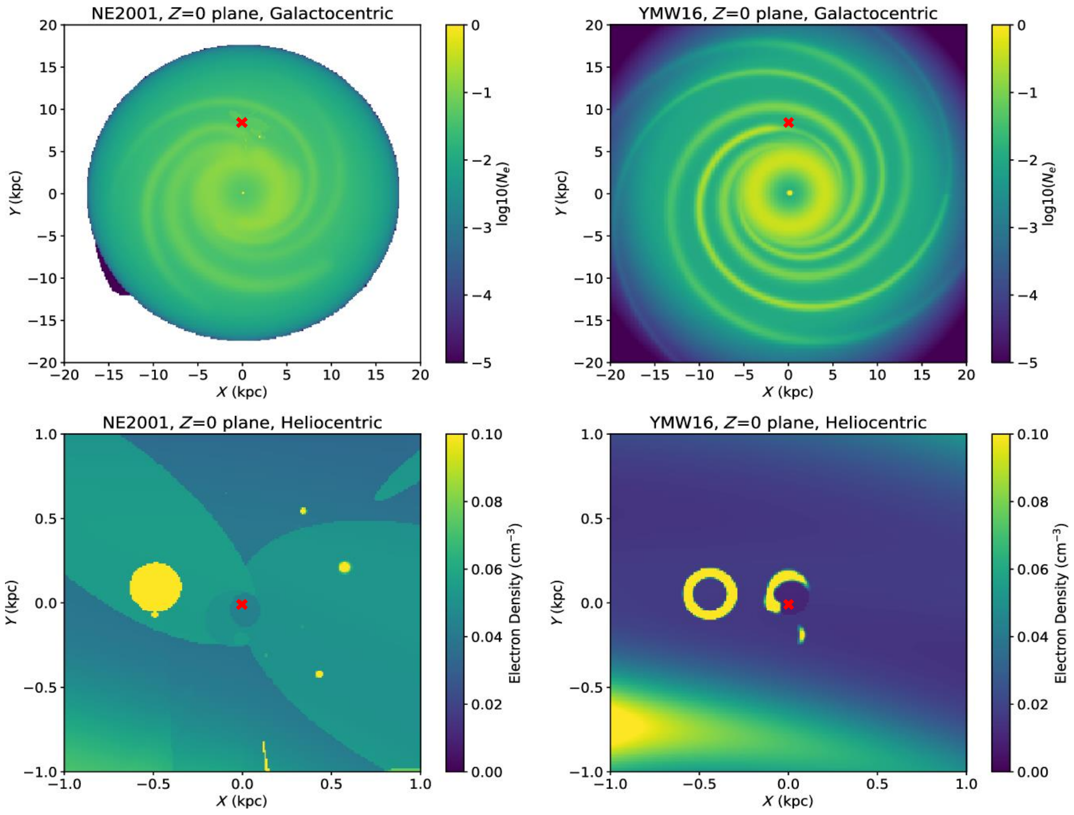
Price, Flynn & Deller (2021)



Electron density of NE2001(left) and YMW16(right) models, in the Galactic plane (z=0). The top panels show large-scale Galactic structure. The bottom panels show the local ISM in a ±1 kpc region centered about the Sun (red cross).

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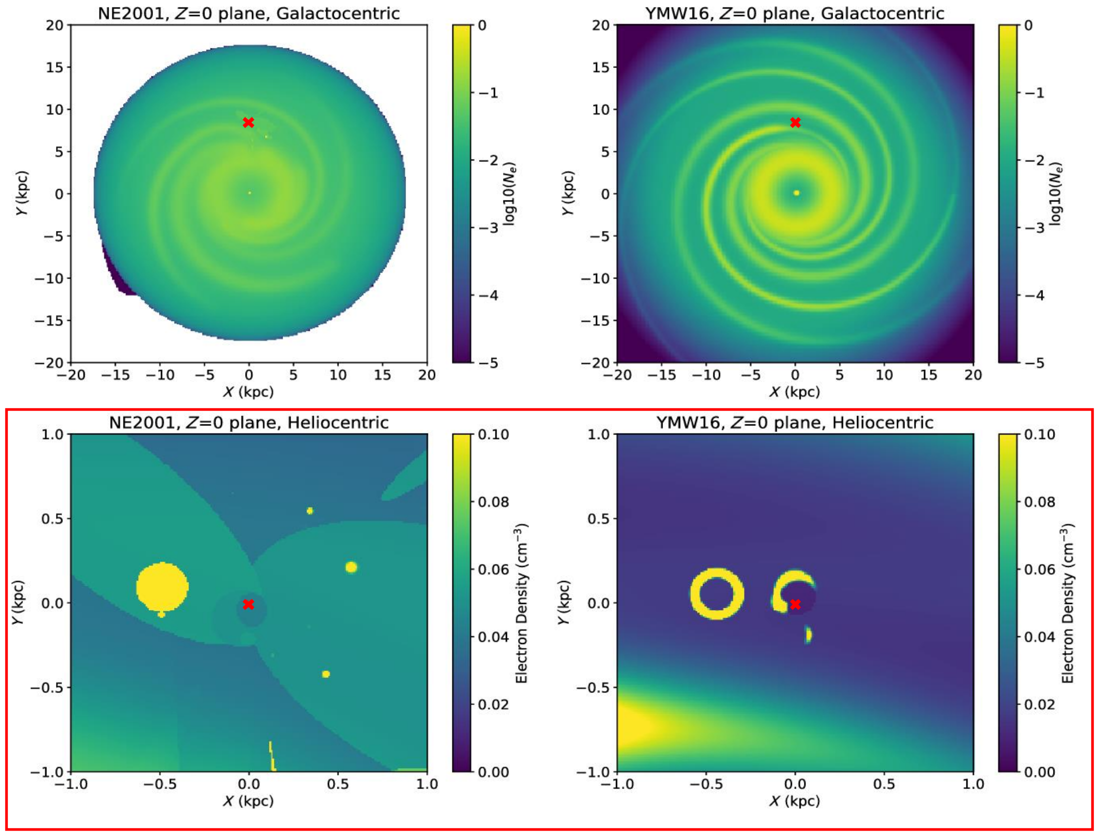

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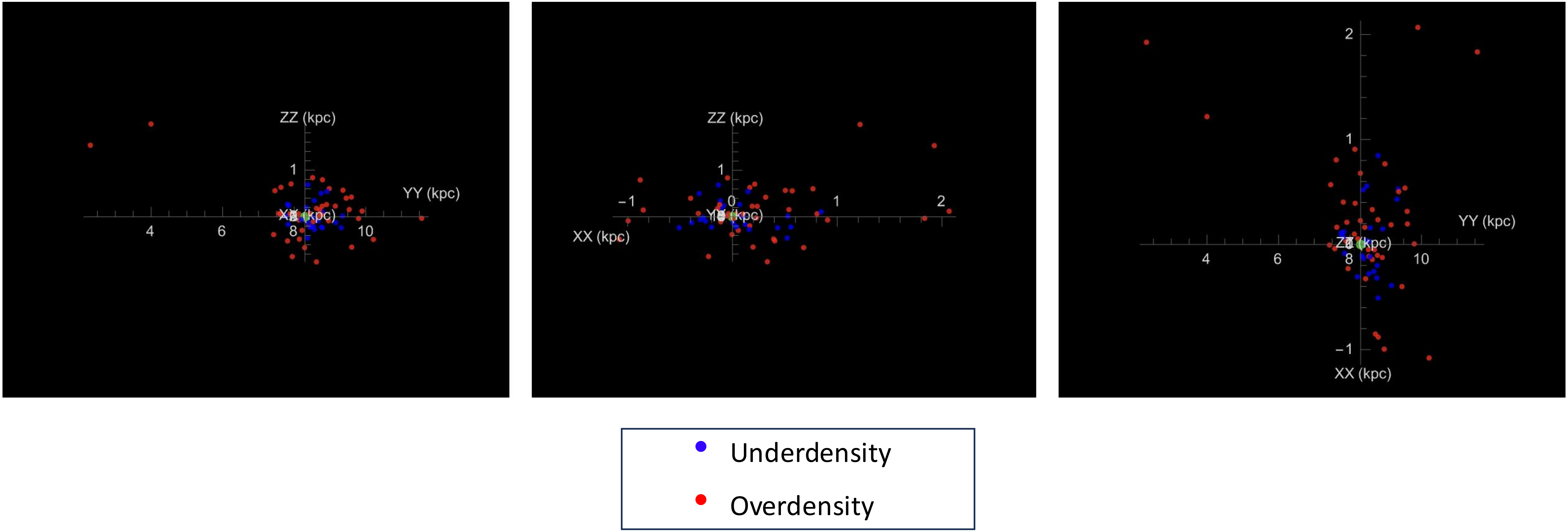
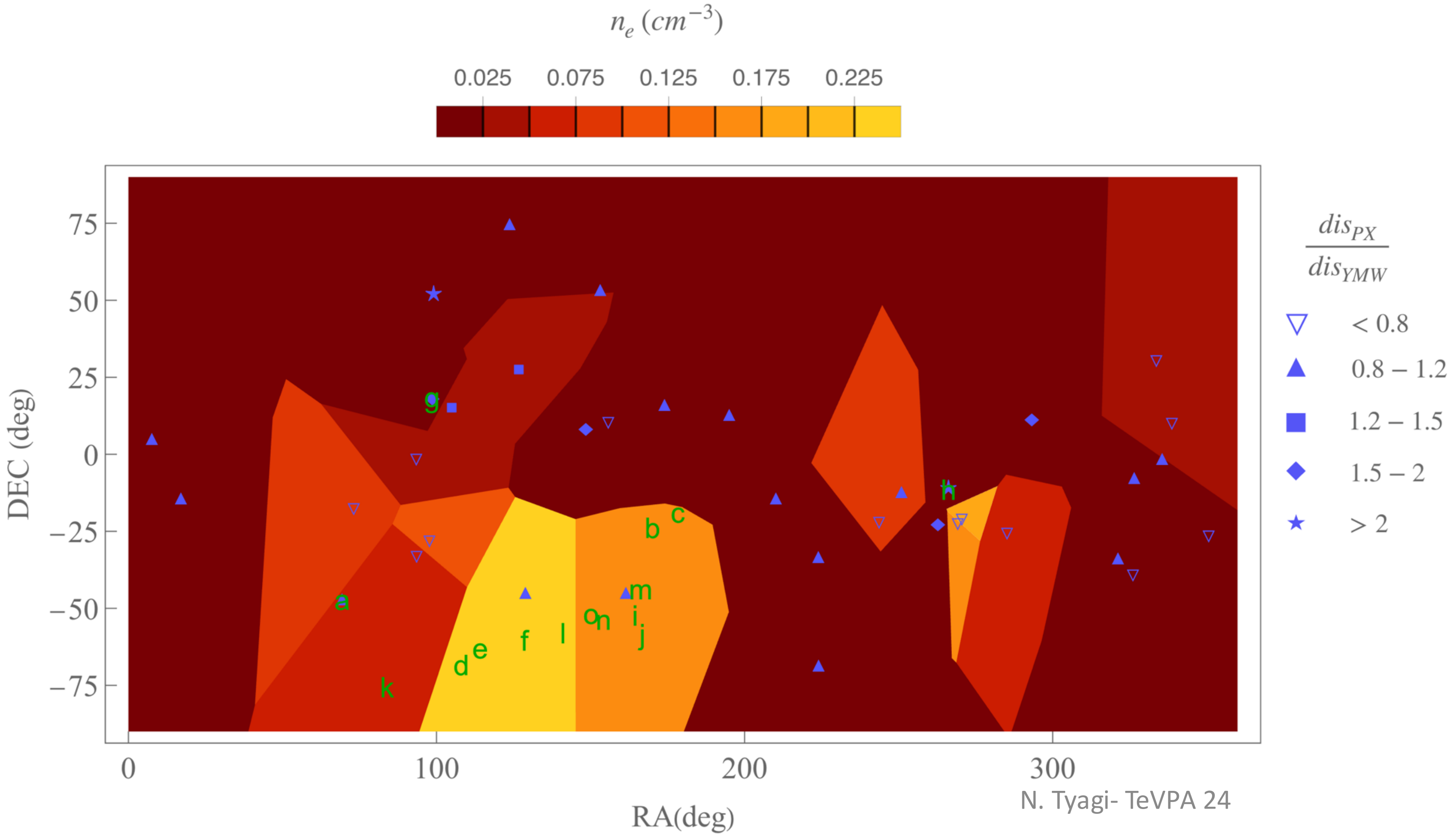
Quest for better Pulsar Distances



Local Electron Density Model

A linear relation between the Dispersion Measure and the distance is a reasonable approximation in the LISM[4]

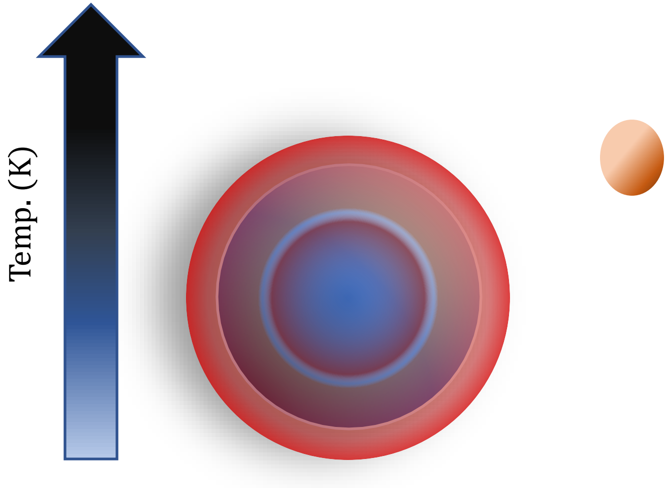


	PSRJ	YMW dis(pc)	Predicted dis(pc)
a.	J0437-4715	156	35 ± 20
b.	J1120-24	98	56 ± 14
c.	J1154-19	121	61 ± 15
d.	J0711-6830	106	82 ± 15
e.	J0736-6304	104	86 ± 16
f.	J0834-60	95	89 ± 43
g.	J0633+1746	138	116 ± 195
h.	J1744-1134	148	126 ± 211
i.	J1057-5226	93	132 ± 25
j.	J1107-5907	115	233 ± 56
k.	J0536-7543	143	248 ± 139
l.	J0924-5814	107	255 ± 49
m.	J1105-4353	127	257 ± 62
n.	J1016-5345	117	382 ± 102
o.	J1000-5149	127	416 ± 102

Dark Kinetic Heating

- DM flux through a NS depends on
  - NS size → M_{NS} , R_{NS}
  - Ambient DM density → $\boldsymbol{\rho_\chi}$
  - Maximum impact parameter → $b_{max} \propto \frac{v_{esc}}{v_\chi}$

For NS near earth → $\dot{m} \sim 4 \times 10^{25}\ GeV\ s^{-1}$



- Scattering results in kinetic energy deposition → heats the NS

- NSs become isothermal and cool to $T \lesssim 10^3\ K$ within 20 Myr and $T \sim 100\ K$ after a Gyr[1][2].

- Following thermalization, the apparent NS luminosity

$$L_\infty^{dark} = \dot{E}_k\left(1 - \frac{2GM}{R}\right) = 4\pi\sigma_B R^2 T_s^4\left(1 - \frac{2GM}{R}\right)$$

where $T_s \rightarrow$ blackbody temp of NS as would be seen on its surface

For a NS near Earth → $T_\infty^{dark} \sim 1750\ K$ (only Dark Kinetic heating)
$T_\infty^{dark} \sim 2480\ K$ (Dark Kinetic heating + annihilation)

[1] D.Page, J.M.Lattimer, M.Prakash, and A.W.Steiner, "Minimal cooling of neutron stars: A New paradigm," Astrophys. J. Suppl. 155, 623–650 (2004), arXiv:astroph/0403657.
[2] Dima G.Yakovlev and C.J.Pethick, "Neutron star cooling," Ann. Rev. Astron. Astrophys.42,169–210 (2004), arXiv:astro-ph/0402143.

Detecting Dark Kinetic Heating

Spectral Flux Density

For $\rho_{\chi_\odot} \simeq 0.42\ GeV\ cm^{-3}$

$\rightarrow T_\infty^{dark} \sim 1750\ K$

$\rightarrow \lambda_{peak} \sim 1 - 2\ \mu\text{m}$

Blackbody spectral flux density of NS[1] is given by

$$f_\nu = \pi B\left(\nu, T_\infty^{dark}\right)\frac{4\pi(R\gamma)^2}{4\pi d^2}$$

where $B(\nu, T) = 4\pi\nu^3\left(e^{2\pi\nu/k_b T} - 1\right)^{-1}$

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Exposure Time Calculation

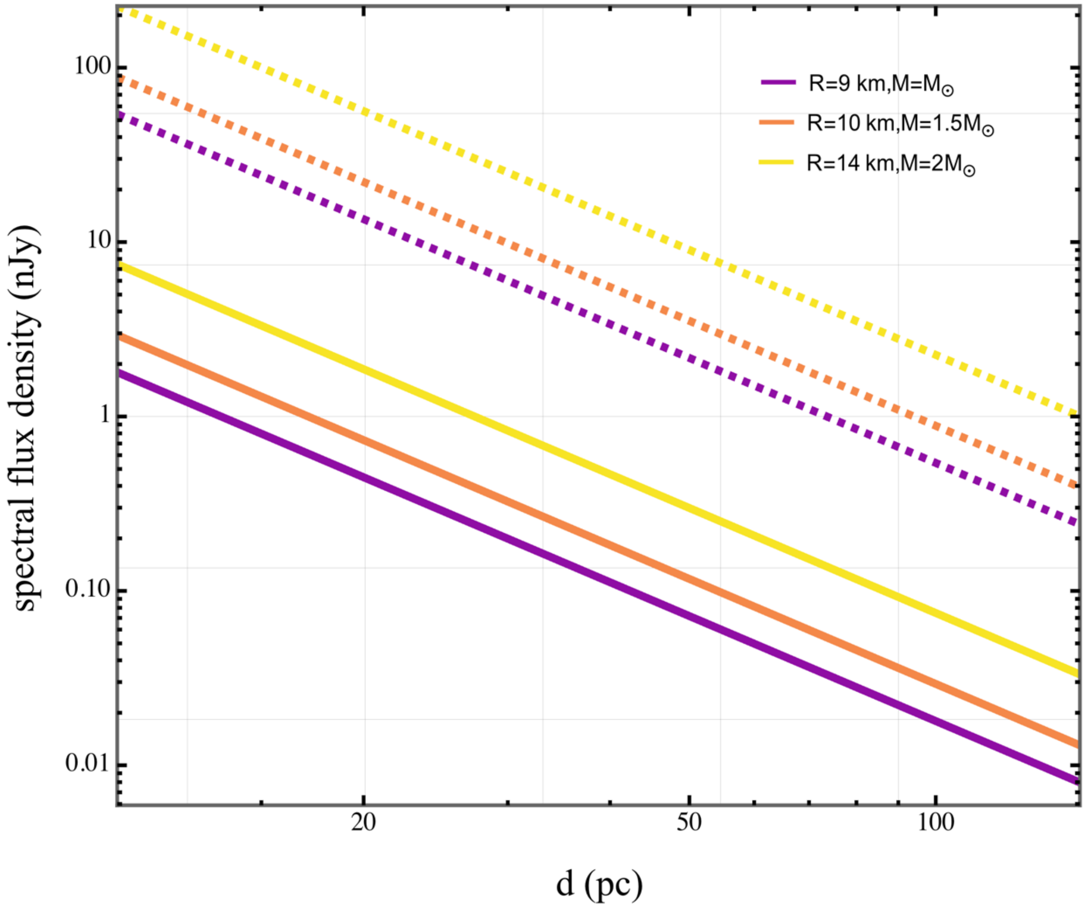
[TMT(IRIS), ELT]

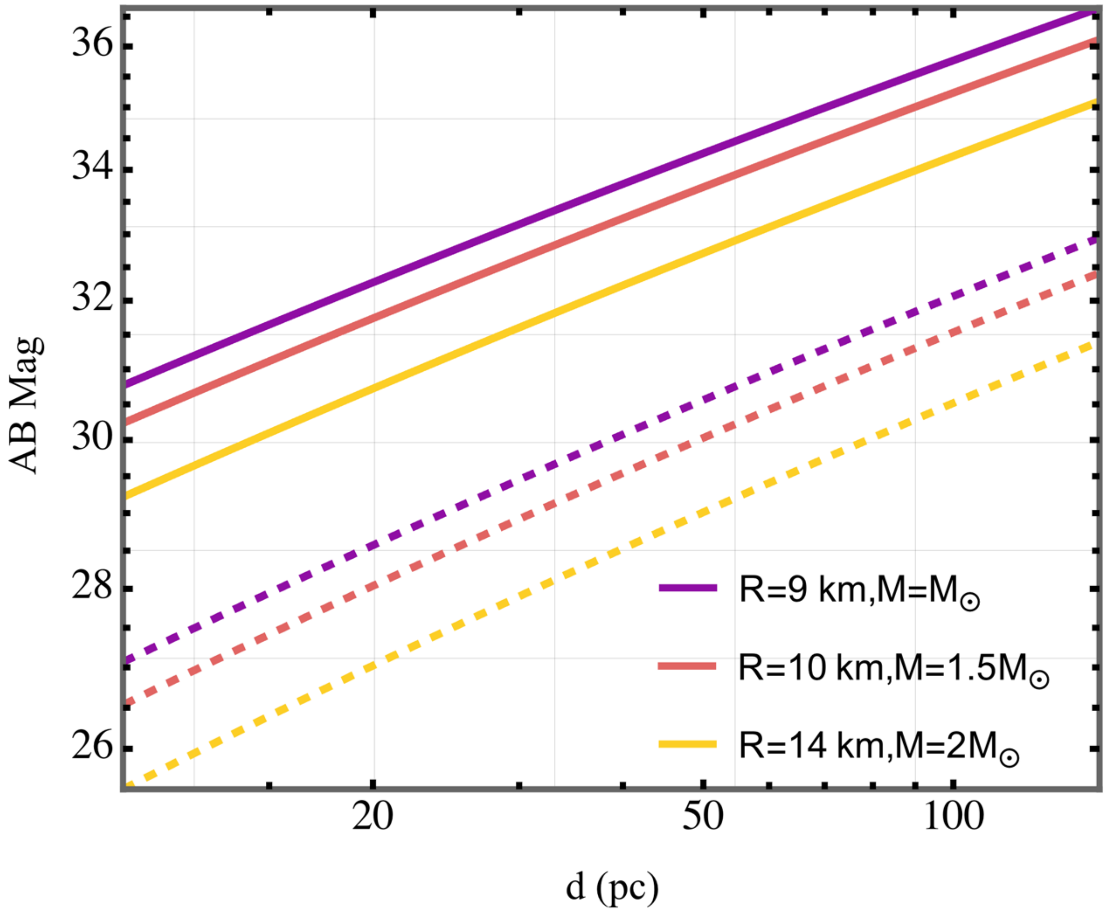
For NS at a distance d, we can find the spectral flux density in nJy units.

→ Depending upon the ETC format, we can determine the AB Magnitude/Vega Magnitude

→ Once determined, we can select the Filter/Band and the required SNR for calculating the Exposure Time for the NS in question.

Calculating Exposure Times for Pulsar Detection with TMT and ELT





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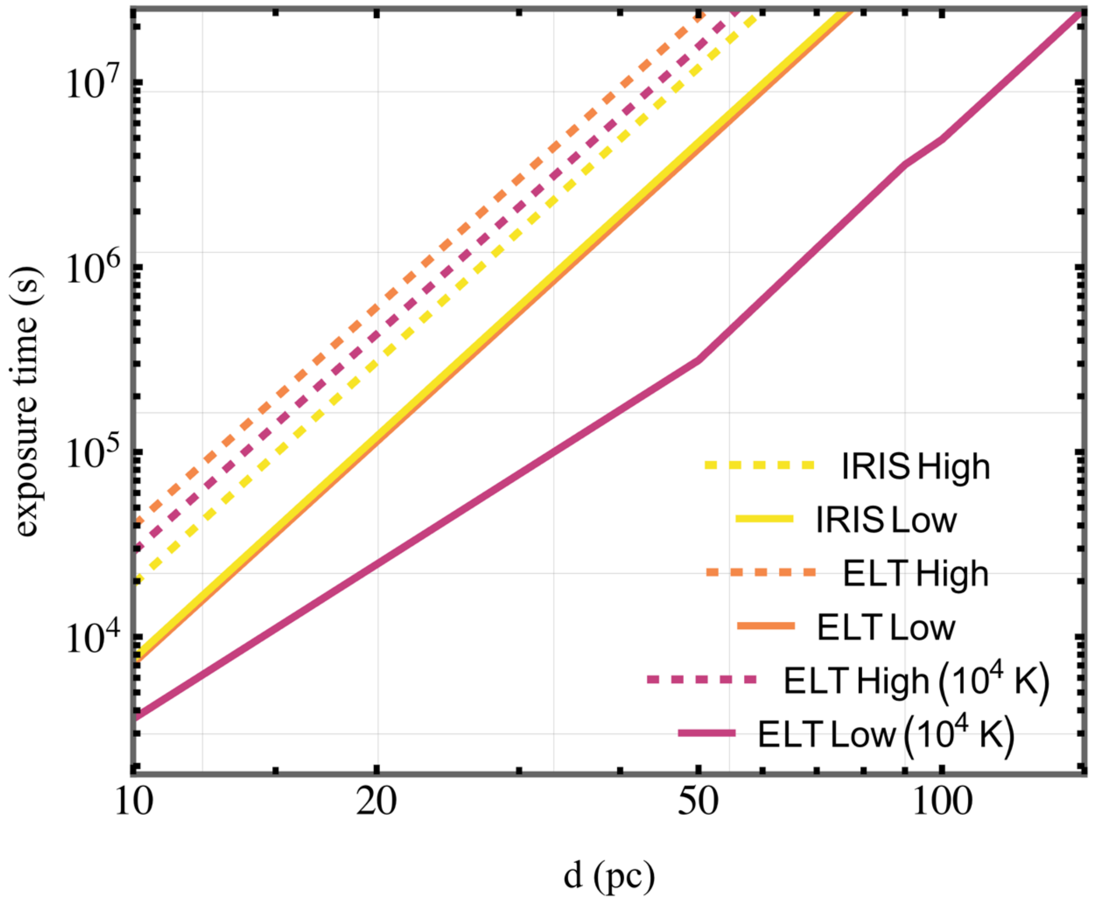
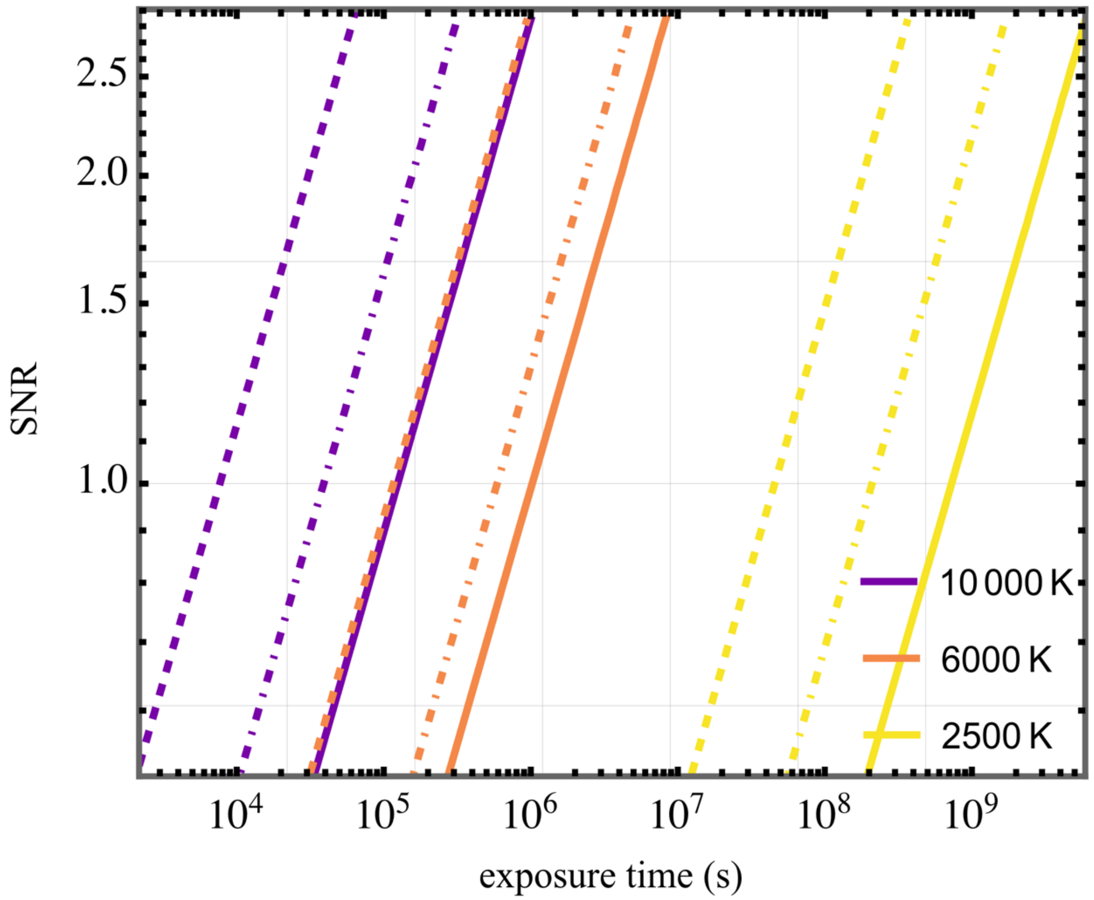


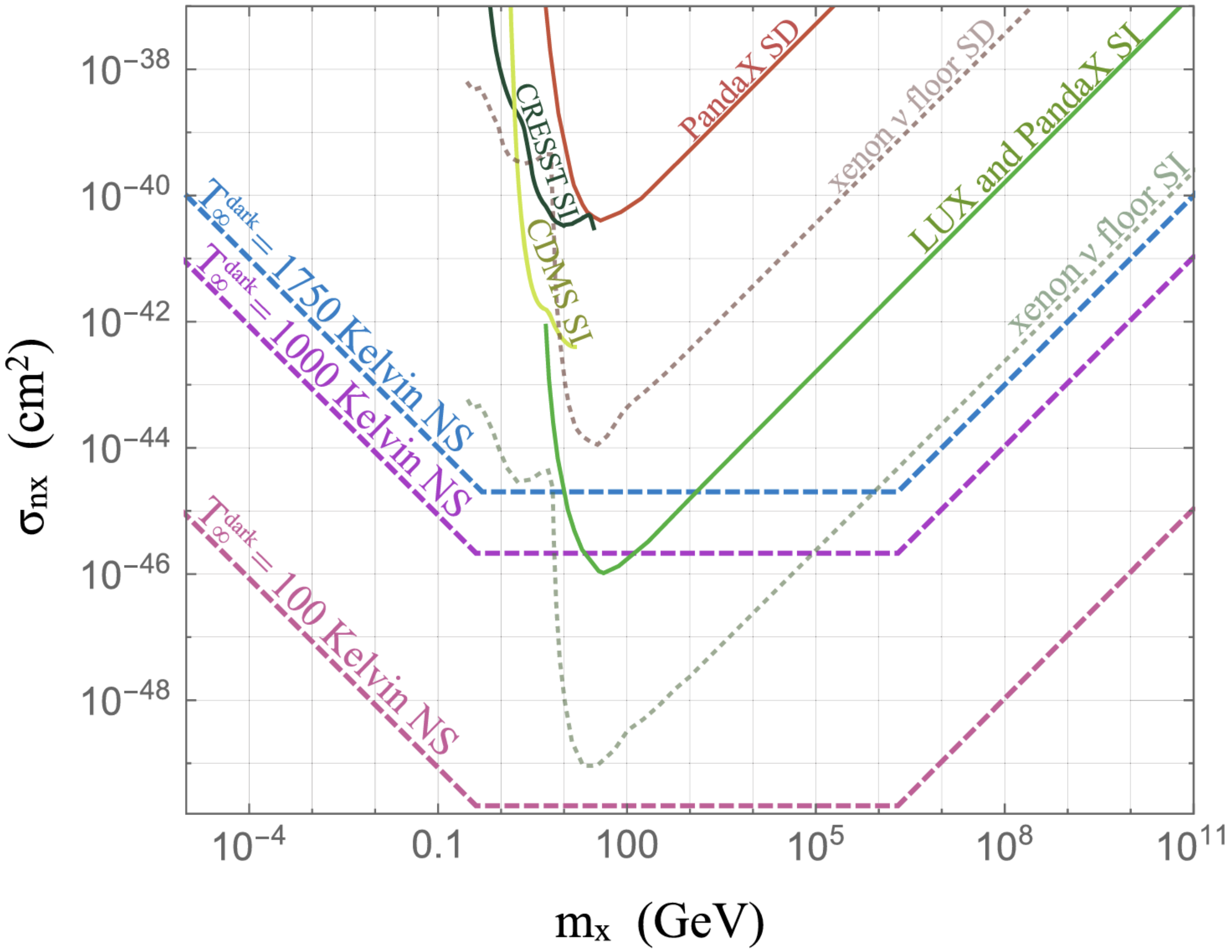


Dark Kinetic Heating Sensitivity[3]

- Saturation cross-section
  $$\sigma_{sat} \stackrel{\text{def}}{=} \sigma_{n\chi}$$
  for which all transiting dark matter is captured.

- Size and scaling of σ_{sat} depends on the dark matter mass m_χ.

- Dark kinetic heating will decrease linearly with $\sigma_{n\chi} < \sigma_{sat}$.



[3] Baryakhtar, M., Bramante, J., Li, S. W., Linden, T., and Raj, N., "Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos", doi:10.1103/PhysRevLett.119.131801.

Thank you !

Questions?

Backup Slides

NS Cooling Mechanisms

Neutron stars are incredibly hot when they are formed, but they cool down over time through various mechanisms:

- **Neutrino Cooling**: Neutron stars initially cool mainly through the emission of neutrinos. Neutrino emission carries away a significant amount of energy, causing the star to cool down over time.

- **dUrca and mUrca Process**: The modified Urca process is given by

$$n + n \rightarrow n + p + e + \bar{\nu}_e\,,$$
$$n + p + e \rightarrow n + n + \nu_e\,.$$

This process leads to the transfer of energy from the interior to the outer layers of the star, facilitating cooling.

- **Photon Cooling**: As the neutron star's interior cools down and becomes less dense, photons can escape more easily. Photon cooling becomes significant as the temperature decreases, allowing the star to lose thermal energy.

$\Bigg\}\ \mathcal{O}(100\ \mathrm{K})$

Then the possible background to dark kinetic heating is ISM accretion onto NS, which is fortunately discernible from dark kinetic heating (magneto-thermal heating effects damp out after a Myr).

Exposure Time Calculation

For NS at a distance d, we can find the spectral flux density in nJy units.

→ Depending upon the ETC format, we can determine the AB Magnitude/Vega Magnitude

→ Once determined, we can select the Filter/Band and the required SNR for calculating the Exposure Time for the NS in question.

Example estimations for

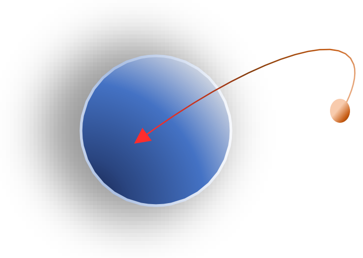
$$d = 130\ pc$$
$$f_{(2\ \mu m, 1750\ K)} \sim 0.003\ nJy$$
$$f_{(2\ \mu m, 2480\ K)} \sim 0.01\ nJy$$

$$On\ \boldsymbol{TMT}(\boldsymbol{IRIS}) \rightarrow Y\ band, SNR = 10\ \rightarrow Exposure\ Time \rightarrow \boldsymbol{\mathcal{O}(10^6)s}$$

DM scattering in NS

DM can recoil against neutrons in the NS → losing energy

For capture, the dark matter must lose enough of its energy through collisions with scattering sites in the star



GeV $< m_\chi <$ PeV

↓

a single scatter is enough for the DM particle to lose enough energy to get completely captured.

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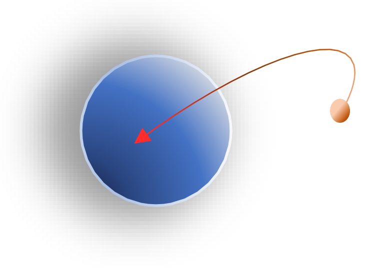

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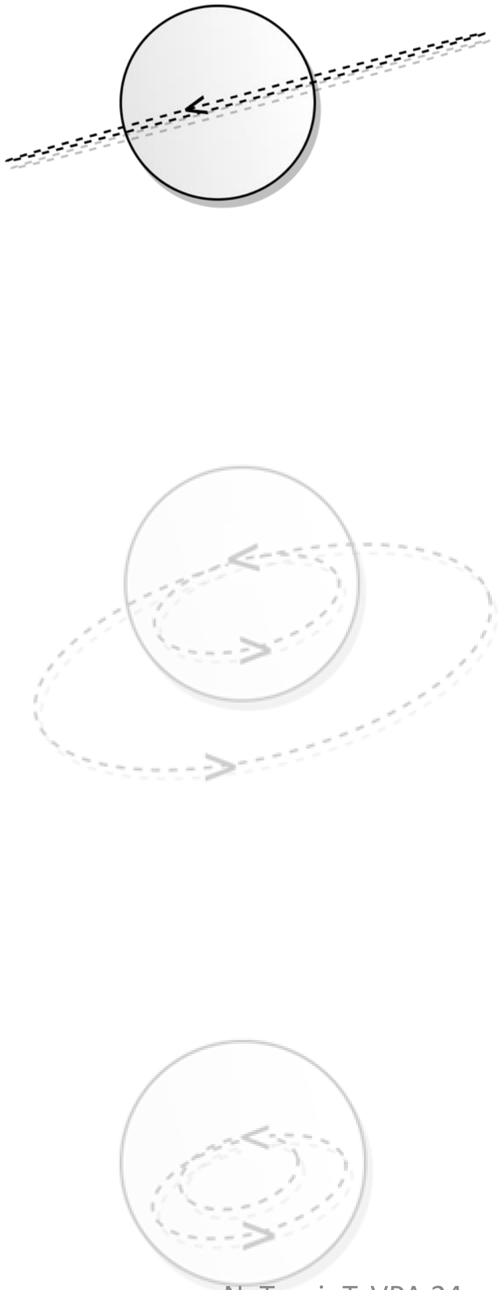
$m_\chi > \mathrm{PeV}$

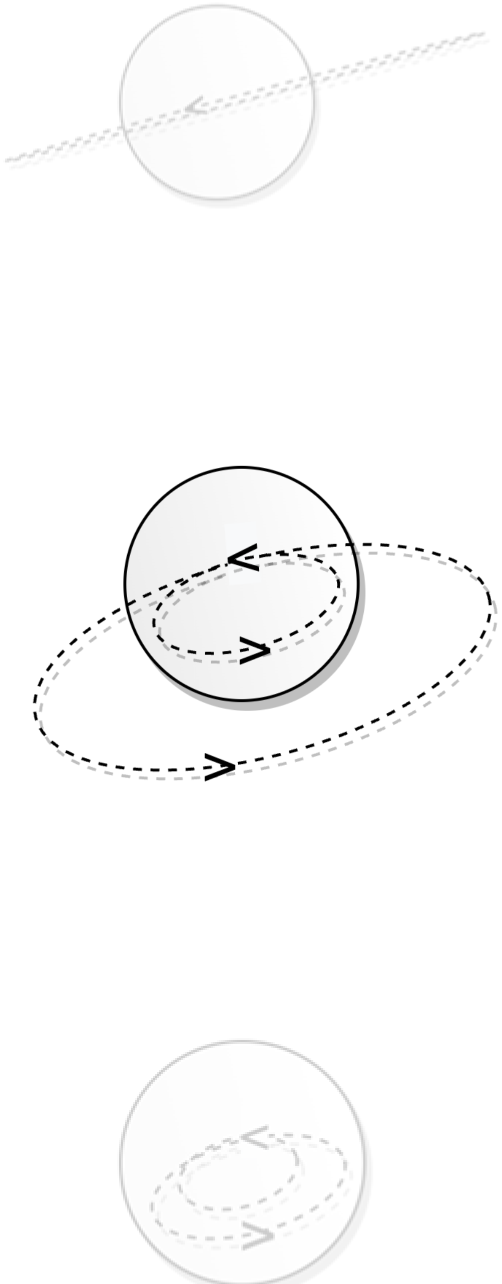
↓

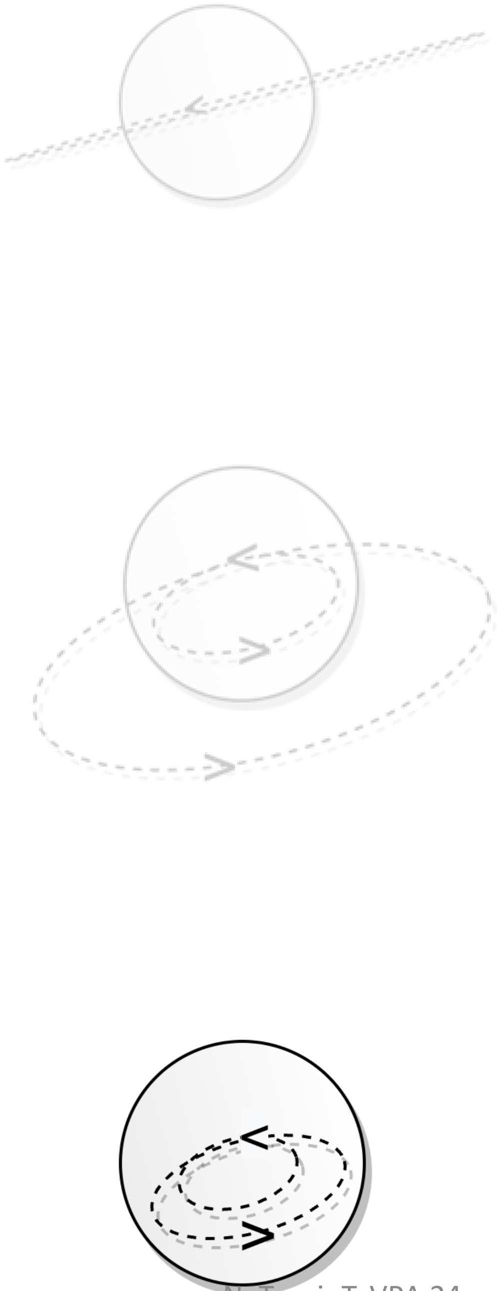
Heavier dark matter has more initial kinetic energy in the halo.
∴ it needs to lose more energy to be captured, i.e., it needs to scatter more.

Capture- Annihilation equilibrium



Orbit shrinks --> contained in NS





Thermal equilibrium