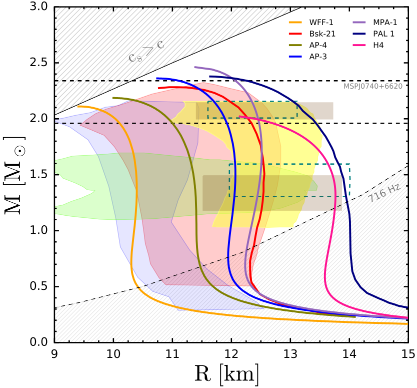
Thermalize DM
in
Neutron Stars

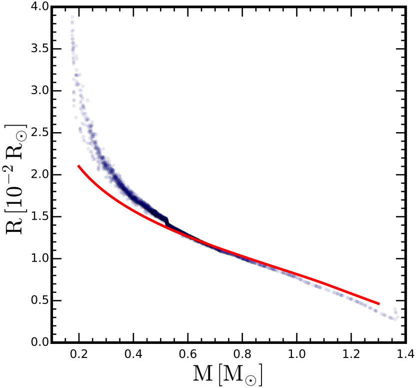
Raghuveer Garani

Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Degenerate celestial objects in the Universe

RG, Palomares-Ruiz '21



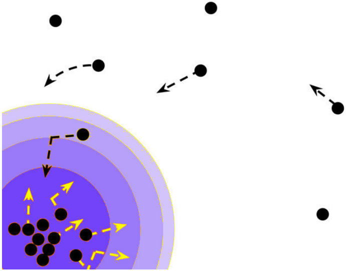


Capture of DM

Schematic

- If DM (χ) has a non vanishing $\sigma_{\chi T}$, it can be captured in celestial objects. Press and Spergel '85, Griest and Seckel '86, Gould '87, Goldman et.al. '89
- Dynamics governed by the equation

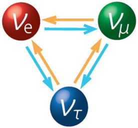
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\,\mathrm{N}_\chi - A\,\mathrm{N}_\chi^2$$

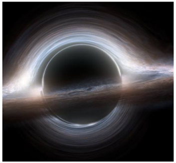


Capture of DM

Possible signals

Neutrinos Press and Spergel '85, Griest and Seckel '86, Gould '87 + +



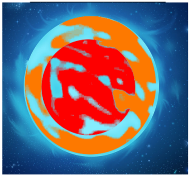


Black Hole formation

Goldman et al. '89, Kouvaris et al.'10 '11 '12,

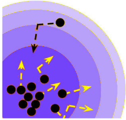
McDermott et al. '12 + +

Heating cold and old objects



Kouvaris '07, '10, Bertone et al. '08,

McCullough et al. '10, Baryakhtar et al.



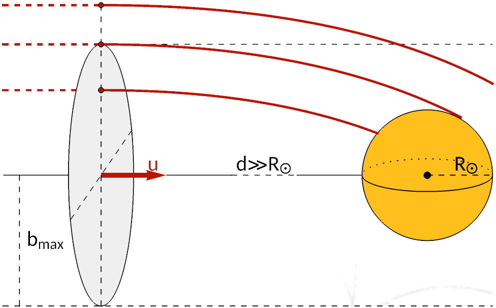
Outline

- Basic DM capture
- DM thermalization in NS
- Can we see faint NS with JWST?
- Conclusions & Outlook

DM Capture in celestial bodies

General picture

- All particles that intersect the celestial body is captured if $\frac{\Delta E}{E} \gtrsim \frac{u^2}{u^2+v_e^2}$

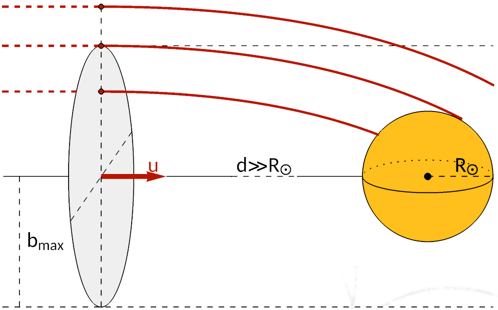


$$\mathcal{C}_{\max} \approx \pi R_\star^2 \left(1+\frac{v_e^2}{v_d^2}\right)\left(\frac{\rho_\chi}{m_\chi}\right) v_\infty$$

DM Capture in celestial bodies

General picture

- All particles that intersect the celestial body is captured if $\frac{\Delta E}{E} \gtrsim \frac{u^2}{u^2+v_e^2}$
- Estimate simple when $\sigma n_\star R_\star \gtrsim 1$. In this limit the rate is independent of σ



$$\mathcal{C}_{\max} \approx \pi R_\star^2 \left(1 + \frac{v_e^2}{v_d^2}\right)\left(\frac{\rho_\chi}{m_\chi}\right) v_\infty$$

Capture of DM

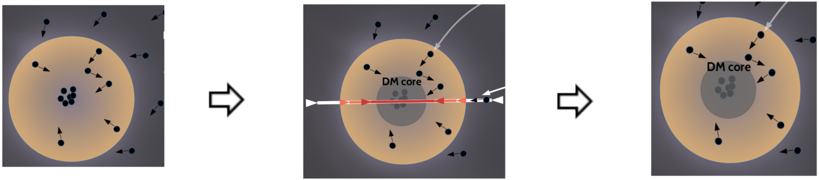
Comparison

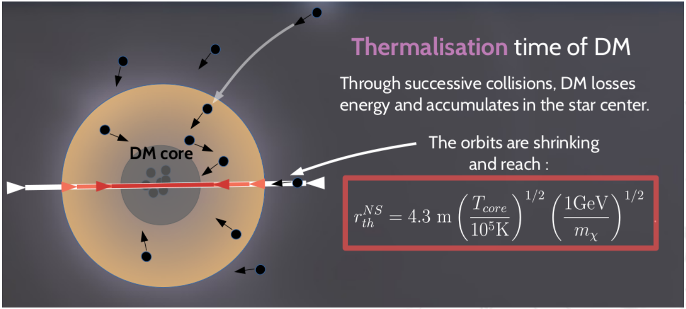
- Sufficiently weak, $\sigma n_\star R_\star \sim 1$
- Geometric cross section, $\sigma_\star = \pi R_\star^2/N$
- The maximal capture rate

$$\mathcal{C}_{\max} \approx \pi R_\star^2 \left(1 + \frac{v_e^2}{v_d^2}\right)\left(\frac{\rho_\chi}{m_\chi}\right) v_\infty$$

	$\sigma_\star$ [cm^2]	$\sim M_{\max}$/Gyr
Sun	10^{-35}	$10^{-11}\mathrm{M}_\odot$
White Dwarf	10^{-39}	$10^{-19}\mathrm{M}_\odot$
Neutron Star	10^{-45}	$10^{-15}\mathrm{M}_\odot$

Thermalization





Thermalisation time of DM

Through successive collisions, DM losses energy and accumulates in the star center.

The orbits are shrinking and reach :

$$\boxed{r_{th}^{NS} = 4.3\ \mathrm{m} \left(\frac{T_{core}}{10^5\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2}}$$

Thermalization

- $\chi(k) + T(p) \to \chi(k') + T(p')$
- Fermi's golden rule: Bertoni, Nelson, Reddy '13 and RG, Genolini, Hambye '18

$$d\Gamma = 2\frac{\mathrm{d}^3k'}{(2\pi)^3} S(q_0, q) \ ,$$

$$S(q_0, q) = \int \frac{\mathrm{d}^3p'}{(2\pi)^3 2E_{p'} 2E_{k'}} \int \frac{\mathrm{d}^3p}{(2\pi)^3 2E_p 2E_k} \times$$

$$(2\pi)^4 \delta^4 \left(k + p - k' - p'\right) |\mathcal{M}|^2 f(E_p) \left(1 - f(E_{p'})\right) \ ,$$

- The rate of energy loss:

$$\Phi = \int \mathrm{d}\Gamma \times (E_i - E_f) \ ,$$

- Thermalization time

$$\tau_{\rm therm} = - \int_{E_0}^{E_f} \frac{\mathrm{d}E_i}{\Phi}.$$

Thermalization: response function

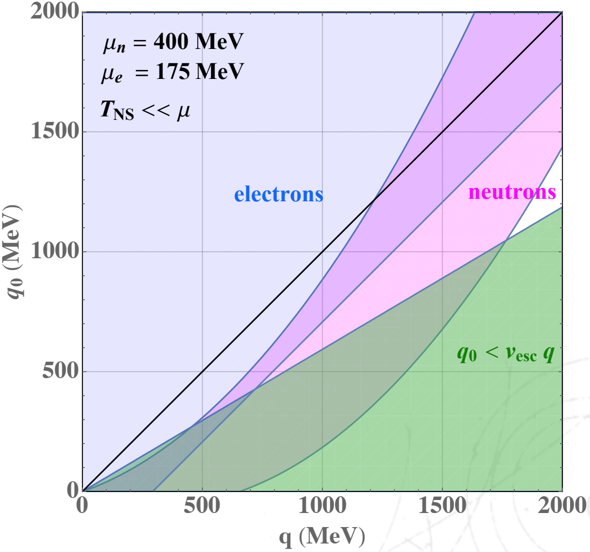
- Reminder: $S(q_0,q) = \int \frac{\mathrm{d}^3p'}{(2\pi)^3 2E_{p'} 2E_{k'}} \int \frac{\mathrm{d}^3p}{(2\pi)^3 2E_p 2E_k} \times (2\pi)^4 \delta^4\left(k+p-k'-p'\right) |\mathcal{M}|^2 f(E_p)\left(1-f(E_{p'})\right)$
- Integrable in rel. and non-rel. limit, for most cases
- Non-relativisitic limit

$$S^{\text{non-rel}}(q_0,q) = \frac{|\mathcal{M}|^2}{16\pi m_\chi^2}\frac{q_0}{q}\Theta\left(\mu - \frac{1}{4}\frac{(q_0 - q^2/2m_T)^2}{q^2/2m_T}\right)$$

- Rel. limit

$$S^{\text{rel}}(q_0,q) = \frac{|\mathcal{M}|^2}{16\,\pi\,m_\chi^2}\frac{q_0}{q}\Theta(2\mu + q_0 - q).$$

Thermalization: response function RG, Gupta, Raj '21



Number of scatterings needed RG, Gupta, Raj '21

- Average energy loss, neutron targets: RG, Genolini, Hambye '18

$$\langle \Delta E \rangle^{\rm non-rel} = \frac{\int_0^k d\Gamma(E_i)\,(E_i - E_f)}{\int_0^k d\Gamma(E_i)} \approx \frac{4}{7} E_i \ ,$$

- Average energy loss, electron targets:

$$\langle \Delta E \rangle^{\rm rel} \approx \frac{2}{3} E_i \ .$$

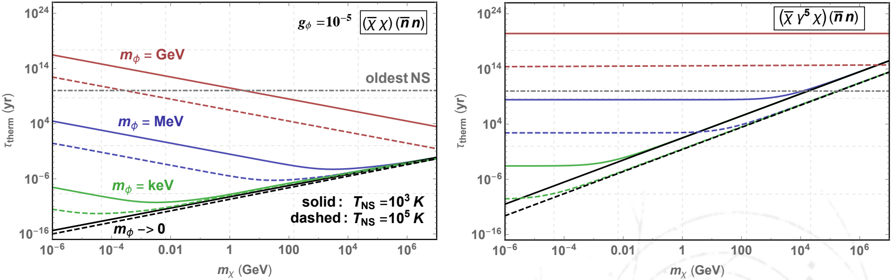
- Energy losses HUGE! $\implies$ we can expect DM to thermalize after a small number of scatters. This is obtained as the sum of a geometric series:

$$\mathcal{N}_{\rm T} = \frac{\log(E_{\rm th}/E_0)}{\log\,(1-\alpha_{\rm T})} = \mathcal{O}(10-100) \ .$$

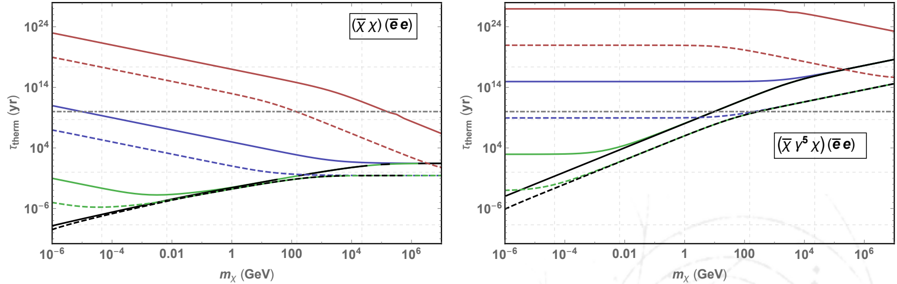
Model dependence

Name	Operator	$\sum_{\text{spins}} \lvert\mathcal{M}\rvert^2$
$\mathcal{O}_1^{\mathrm{F}}$	$(\bar{\chi}\chi)\left(\bar{\xi}\xi\right)$	$\Lambda^{-4}\ \left(4m_\chi^2 - t\right)(4m_T^2 - t)$
$\mathcal{O}_2^{\mathrm{F}}$	$(\bar{\chi}i\gamma^5\chi)\left(\bar{\xi}\xi\right)$	$\Lambda^{-4}\ t\,(t - 4m_T^2)$
$\mathcal{O}_3^{\mathrm{F}}$	$(\bar{\chi}\chi)\left(\bar{\xi}i\gamma^5\xi\right)$	$\Lambda^{-4}\ t\left(t - 4m_\chi^2\right)$
$\mathcal{O}_4^{\mathrm{F}}$	$(\bar{\chi}i\gamma^5\chi)\left(\bar{\xi}i\gamma^5\xi\right)$	$\Lambda^{-4}\ t^2$
$\mathcal{O}_1^{\mathrm{S}}$	$\left(\chi^\dagger\chi\right)\left(\bar{\xi}\xi\right)$	$\Lambda^{-2}\ (4m_{\mathrm{T}}^2 - t)$
$\mathcal{O}_2^{\mathrm{S}}$	$\left(\chi^\dagger\chi\right)\left(\bar{\xi}i\gamma^5\xi\right)$	$\Lambda^{-2}\ (-t)$

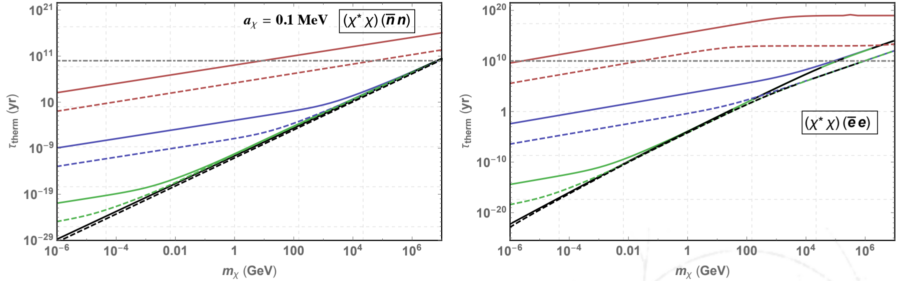
Examples: Fermion DM scattering with neutrons RG, Gupta, Raj '21



Examples: Fermion DM scattering with electrons RG, Gupta, Raj '21

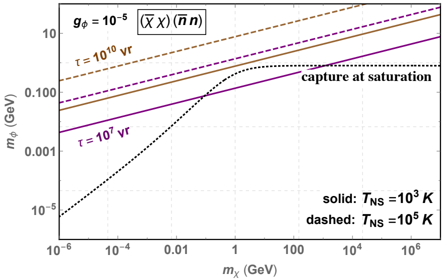


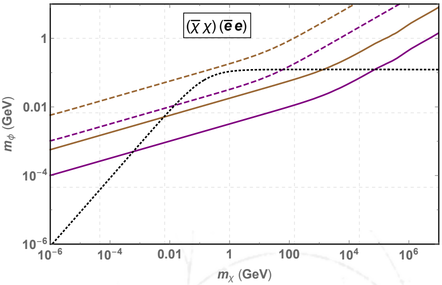
Scalar DM


a_χ = 0.1 MeV
$(\chi^* \chi)(\bar{n} n)$
$(\chi^* \chi)(\bar{e} e)$
$\tau_{\rm therm}$ (yr)
10^{21}
10^{11}
10
10^{-9}
10^{-19}
10^{-29}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
10^{-6}
10^{-4}
0.01
1
100
10^{4}
10^{6}
m_χ (GeV)

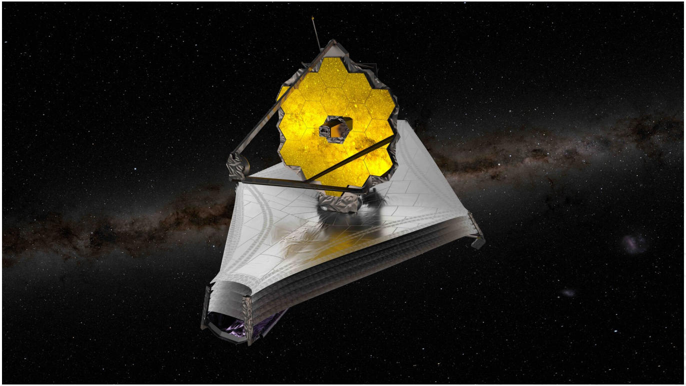
Testable parameterspace

RG, Gupta, Raj '21

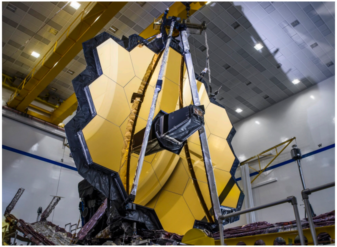




JWST and DM in Neutron stars



Renewed Interest



- In anticipation of James Webb space telescope science program
- Successor of Hubble telescope. Very good infra-red capabilities
- Find/study cold neutron stars, exoplanets ...
- Implications for DM from heating of cold objects?

Heating of NS due to DM capture

Ways to heat up cold and old NS

- Kinetic Heating: Infalling DM heats up the neutron star. Potentially observable by James Webb Space Telescope Baryakhtar et.al. '17, Raj et.al. '17, Bell et.al. '18, RG, Heeck '19
- Equate kinetic energy deposited to Stefan-Boltzmann law

$$m\,(\gamma - 1)C = 4\pi R^2 \sigma_b T^4$$

$$T_{\text{kin}}^{\text{max}} \simeq 1700K \left(\frac{C}{C_\star}\right)^{1/4} \left(\frac{\rho_{\text{DM}}}{0.4\text{GeV}/\text{cm}^3}\right)^{1/4} .$$

Heating of NS due to DM capture

Ways to heat up cold and old NS

- Annihilations: If DM capture and annihilation are in equilibrium Kouvaris '07, Kouvaris et.al. '10
- Equate annihilation energy deposited to Stefan-Boltzmann law

$$m\,C = 4\pi R^2 \sigma_b T^4$$

$$T^{\rm max}_{\textsf{ann}} \simeq 2480K\,[\rho_{\textsf{DM}}/(0.4\mathrm{GeV/cm^3})]^{0.25}$$

- Maximal heating: Kinetic+annihilation (KA) at geometric values of cross section $\sim 10^{-45}$ cm^2

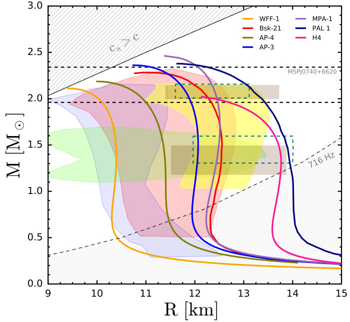
$$T^{\infty}_{\rm KA} \quad \approx \quad 2518\ \mathrm{K}\left[\frac{\alpha_{\rm KA}}{0.33}\left(\frac{\rho_\chi}{0.42\,\mathrm{GeV/cm^3}}\right)\left(\frac{220\,\mathrm{km/s}}{\mathrm{v}_\star}\right)\mathrm{Erf}\left(\frac{270\,\mathrm{km/s}}{\mathrm{v_d}}\frac{\mathrm{v}_\star}{220\,\mathrm{km/s}}\right)\right]^{1/4},$$

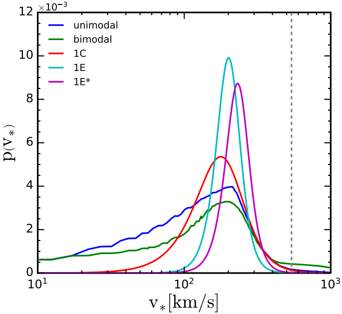
with,

$$\alpha_{\rm KA} = \frac{\gamma(\gamma^2-1)}{\gamma^4}$$

Heating of NS due to DM capture

Inputs RG+(2205.05048)





Ofek '09, Sartore et.al. '10, Taani '16

- Average over environmental parameters

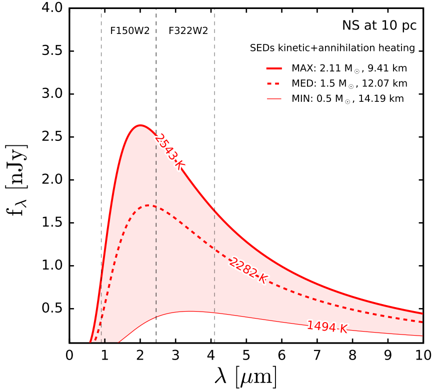
$$C^{\rm g}_{i,j}(M,R) = \kappa \sum_{k,l} \int dv_\star p_j(v_\star) C^{\rm g}_\star(i, v_\star, v_d^k, \rho_\chi^l) \ ,$$

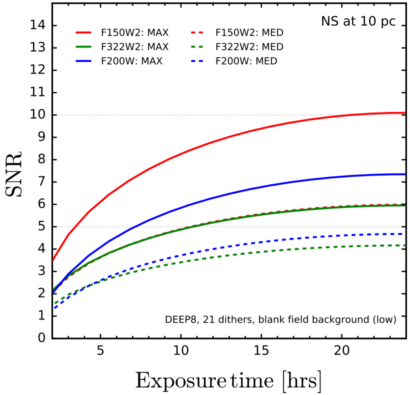
- Estimate blackbody spectrum

$$f_\lambda(M,R) = \frac{4\pi^2}{\lambda^3}\left(e^{\frac{2\pi}{\lambda T^\infty}} - 1\right)^{-1}\left(\frac{R\,\gamma}{d}\right)^2 \ .$$

Heating of NS due to DM capture

Signals at James Webb Space Telescope with exposure time calculator (2205.05048)





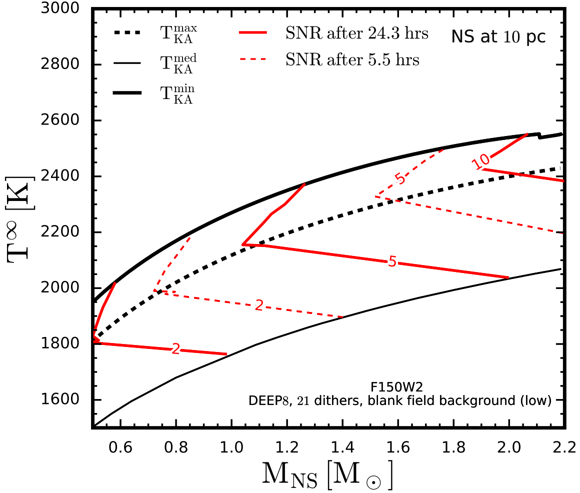
RG, S.Chatterjee, R.K.Jain, B.Kanodia, M.S.N.Kumar and S.K.Vempati

SNR > 10 achievable within 15 hrs of exposure!

Best sensitivity for broad band filter F150W2

Heating of NS due to DM capture

The whole range (2205.05048)



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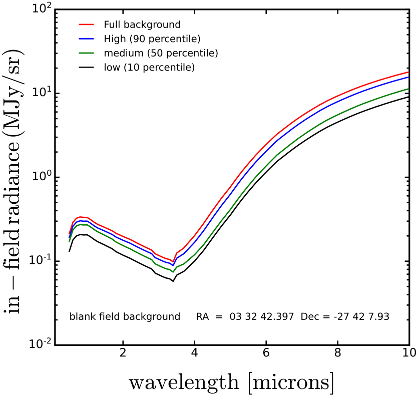
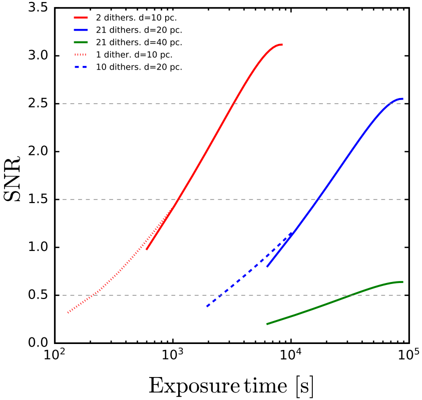
Heating of NS due to DM capture

Further comments





RG, S.Chatterjee, R.K.Jain, B.Kanodia, M.S.N.Kumar and S.K.Vempati

Heating of NS due to DM capture

The way forward

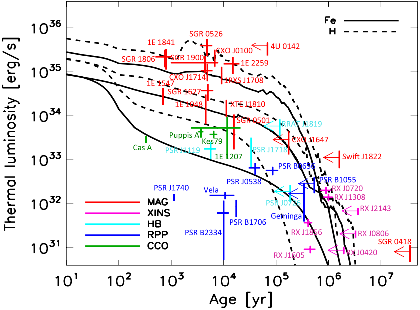
- How many old NS do we expect close to us?
- Spatial distribution of NS in galaxy from Monte-Carlo simulations Blaes et.al. '93, Treves et.al. '00, Ofek '09, Sartore et.al. '10, Gonzalez et.al. '10, Taani '16.
- 1-2 (100-200) with 10 (50) pc.
- Need list of candidates from other surveys.

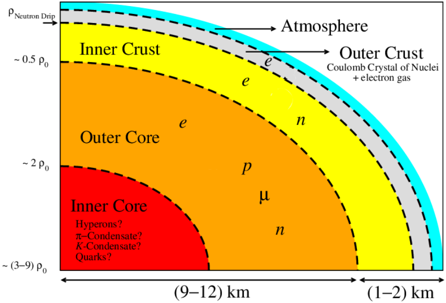
Conclusions and Outlook

- Thermalization crucial before DM annihilation and/or black-hole formation.
- Thermalization depends weakly NS equation of state.
- In several cases almost analytic.
- Using JWST exposure time calculator we demonstrate warm NS in the local bubble ~ 2500 K detectable by JWST. Corresponds to DM-neutron cross section $\sim 10^{-45}$ cm^2 (best case).
- Observation of cold NS $\implies$ constraints on DM $+$ better understanding of NS evolution.

Thank you!

NS luminosity and composition





Viganó et al. '13 & Potekhin '12

Much about NS interiors unknown

Most measurements of surface properties till date are from X-ray telescopes.

Possible exotic phases

in the NS core

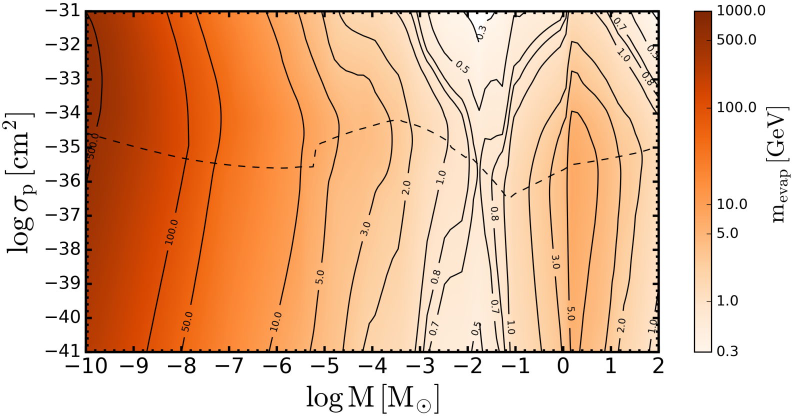
- Color superconductivity review: Alford et al. '08
- Mass-radius relation: only the M-R information insufficient
- Tidal deformability: GW wave form different if there is a step in the density profile. Depends on surface tension at interface.
- Cooling: Early times dominated by exotic phases. Need to observe proto-neutron stars in the neutrino channel.
- Pulsar spins: r-mode instabilities

More data

multi-messenger approach could lead the way

Evaporation mass

as a function of cross section RG, Palomares-Ruiz '21



Evaporation mass

as a function of cross section RG, Palomares-Ruiz '21