Neutron Star Constraints on Dark Matter

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and
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Based on

2009.10728
in collaboration with A. Gupta and N. Raj

October 7, 2020

Prelude: Stellar Frontiers for Dark Sectors

- Energy losses $\implies$ significantly alter minimal cooling paradigm
- Energy transport $\implies$ modifications to stellar models
- Capture of weakly interacting particles $\implies$ neutrino fluxes/heating/black hole formation

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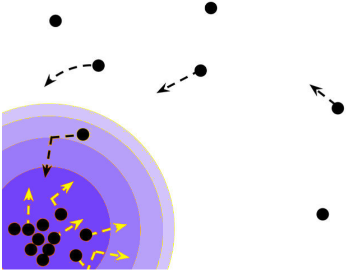
Prelude: Stellar Frontiers for Heavy Dark Sectors

- 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

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



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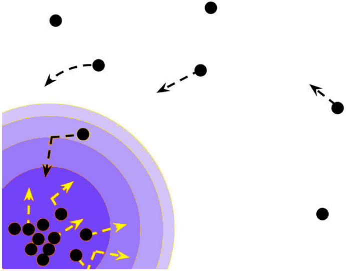

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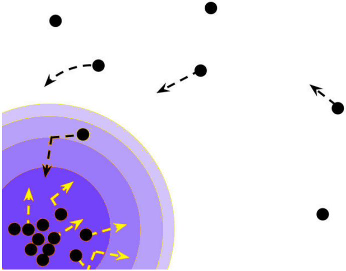

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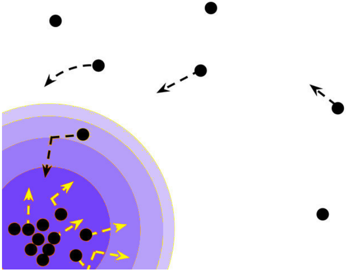
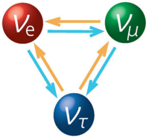
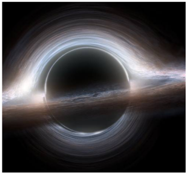


Prelude: Stellar Frontiers for Heavy Dark Sectors II

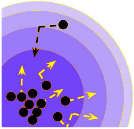
Neutrinos Press and Spergel '85, Griest et.al. '86, Gould '87,++, RG et.al.'17

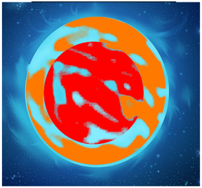




Black Hole formation

Goldman et.al. '89, Kouvaris et.al.'10 '11 '12, McDermott et.al. '12..., RG et.al. '18





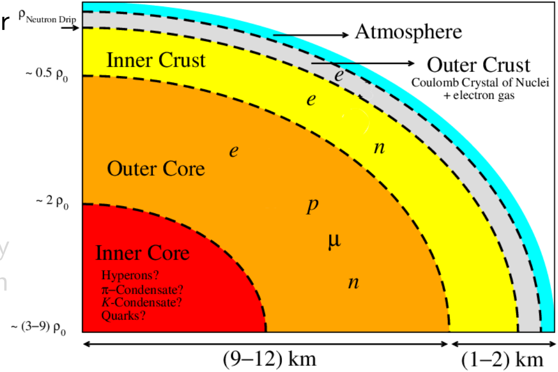
Heating cold and old objects Kouvaris '07, '10, Bertone et.al. '08, McCullough et.al. '10, Baryakhtar et.al. '17, Bell et.al. '18, RG and Heeck '19, RG and Tinyakov '19

Outline

- Introduction
- Dark Matter Thermalization in Neutron Stars
- Neutron Star Heating Constraints on Dark Matter
- Conclusions & Outlook

Introduction: Neutron Stars

- Much about neutron star interiors unknown



- We consider a phenomenological NS profile. Exotic phases not considered. Brussels-Montreal energy density functionals which are fitted to APR Potekhin et.al. '13, Goriely et.al. '13
  - $M = 1.52\,\mathrm{M}_\odot$, $R = 11.6\,\mathrm{km}$. $\mu_n = 350\,\mathrm{MeV}$, $Y_\mu = 2 \times 10^{-2}$, $\mu_\mu = 65\,\mathrm{MeV}$
  - Consistent with observation of GW from NS-NS merger Abbott et.al. '18, Most et.al. '18

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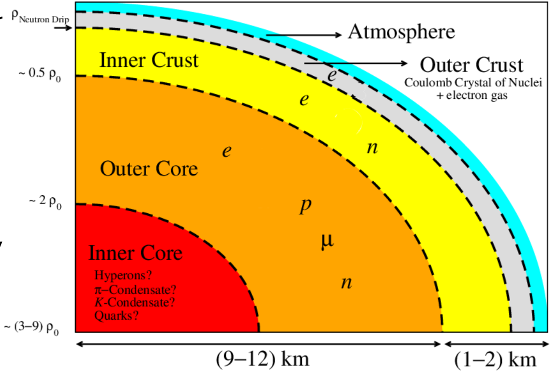

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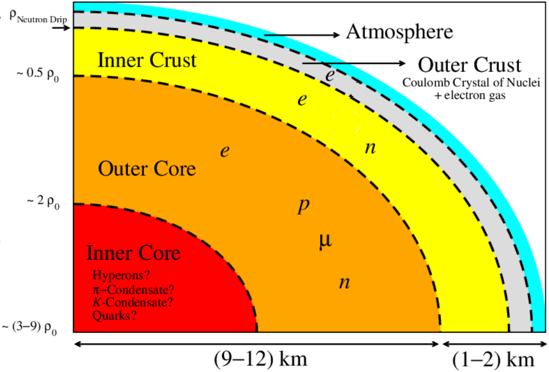

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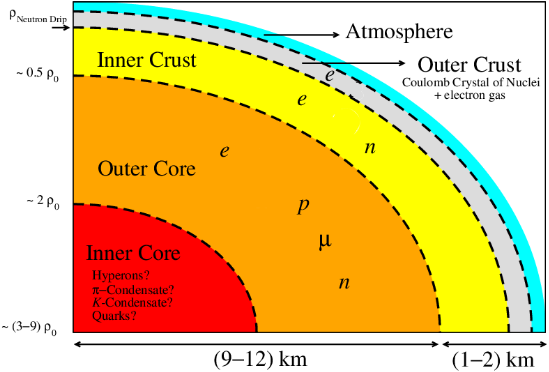

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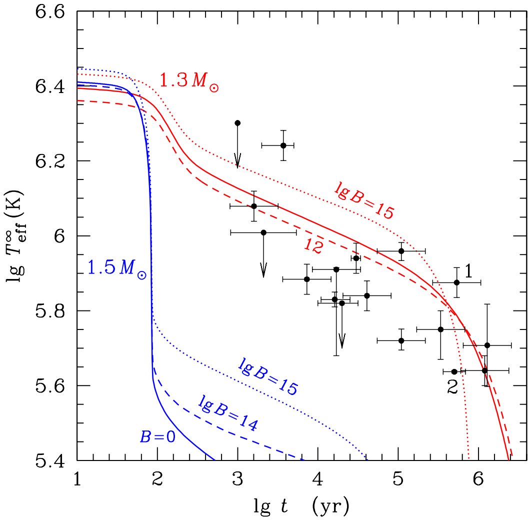
Introduction: Neutron Star Temperature



Potekhin '11

Introduction: Dark Matter in Celestial Objects

- Sufficiently weak, $\sigma n_\star R_\star \sim 1$
- The maximal capture rate

$$C_\star = \pi R_\star^2 \left(1 + \frac{v_e^2}{v_\infty^2}\right) \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right) v_\infty$$

	$\sigma_\star$ [cm^2]	$\sim M_{\rm max}$/Gyr
Sun	10^{-35}	$10^{-11}{\rm M}_\odot$
Earth	10^{-33}	$10^{-10}{\rm M}_{\rm E}$
Moon	10^{-32}	$10^{-9}{\rm M}_{\rm m}$
White Dwarf	10^{-39}	$10^{-19}{\rm M}_\odot$
Neutron Star	10^{-45}	$10^{-15}{\rm M}_\odot$

NS Heating Constraints on Dark Matter: General Picture

Two ways to heat-up

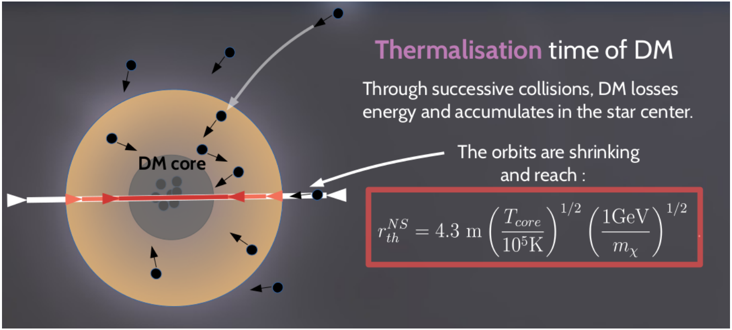
- Kinetic Heating: In-falling DM heats up the neutron star. Potentially observable by James Webb Space Telescope, the Thirty Meter Telescope, or the European Extremely Large Telescope Baryakhtar et.al. '17, Raj et.al. '17, Bell et.al. '18

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

- Annihilations: If DM capture and annihilation are in equilibrium Kouvaris '07, Kouvaris et.al. '10

$$T_{\rm ann}^{\rm max} \simeq 2480\,{\rm K}\,[\rho_{\rm DM}/(0.4\,{\rm GeV/cm^3})]^{0.45}$$

Dark Matter Thermalization in NS



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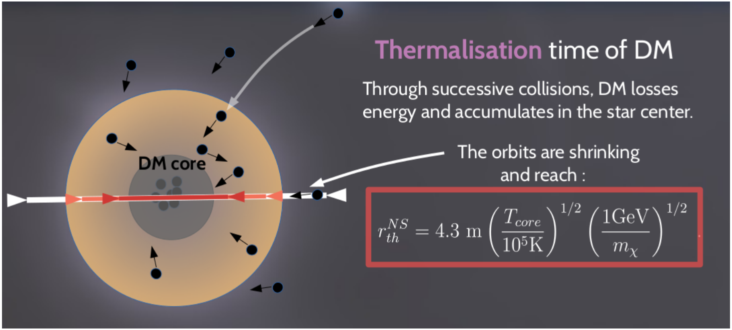

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Thermalization: phase space [RG, A. Gupta and N. Raj]

- Interaction rate in Fermi-degenerate medium is given by Fermi's golden rule

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

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

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

- Thermalization time is given by

$$\tau_{\rm therm} = -\int_{E_0}^{E_f} \frac{\mathrm{d}E_i}{\int \mathrm{d}\Gamma \times (E_i - E_f)}.$$

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Thermalization: response function

- For non-relativistic neutrons

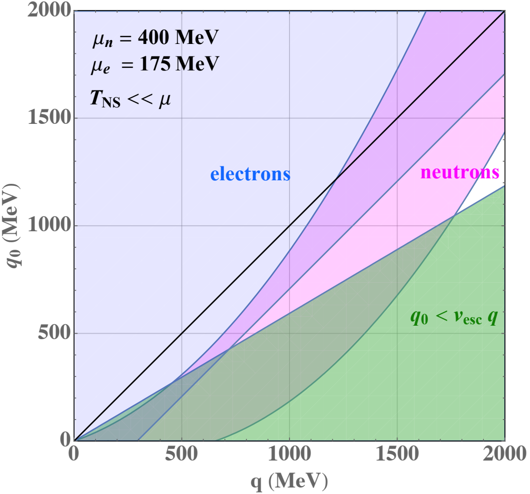
$$S^{\rm non-rel}(q_0, q) \quad = \quad \frac{|\mathcal{M}|^2}{16\pi m_\chi^2}\frac{q_0}{q}\Theta\left(\mu - \frac{1}{4}\frac{(q_0 - q^2/2m_T)^2}{q^2/2m_T}\right) \ ,$$

- For relativistic electrons inside NS

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

RG, A. Gupta and N. Raj

Thermalization: response function



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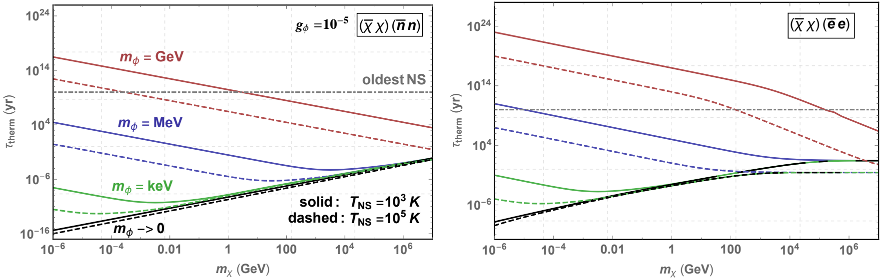
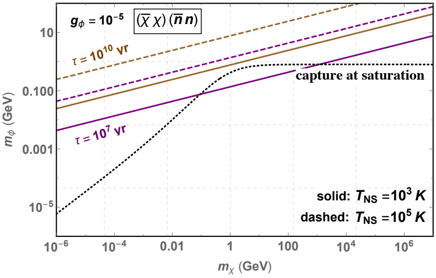
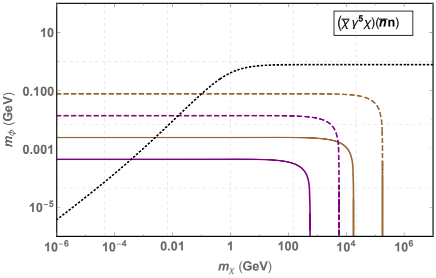
Example application: scalar operators

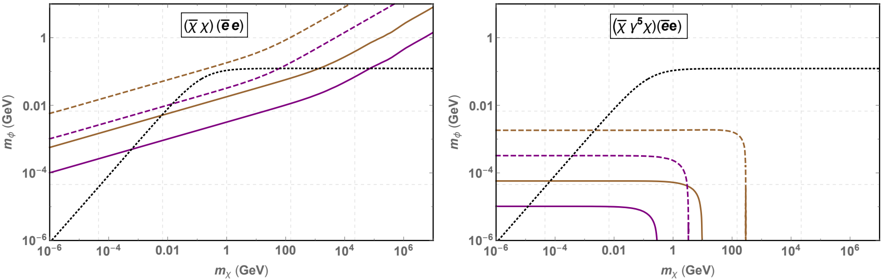


Parameter space for DM-neutron interactions





Parameter space for DM-electron interactions



Comments on the annihilation cross section

- After DM thermalizes with NS, does capture and annihilation equilibrate? Recall: annihilation heating heats NS up to 2400 K.
- The equilibration time is given by $\tau_{\rm eq} = (V_{\rm th}/C\langle\sigma v\rangle_{\rm ann})^{1/2}$.
- Parameterize $\langle\sigma v\rangle_{\rm ann} = a + b\,v^2$. For s-wave annihilation

$$a > 7.5\times10^{-54}\,{\rm cm^3/s}\left(\frac{\rm Gyr}{\tau_{\rm NS}}\right)^2\left(\frac{C_{\rm sat}}{C}\right)\left(\frac{\rm GeV}{m_\chi}\,\frac{T_{\rm NS}}{10^3\,{\rm K}}\right)^{3/2}$$

and for p-wave

$$b > 2.9\times10^{-44}\,{\rm cm^3/s}\left(\frac{\rm Gyr}{\tau_{\rm NS}}\right)^2\left(\frac{C_{\rm sat}}{C}\right)\left(\frac{\rm GeV}{m_\chi}\,\frac{T_{\rm NS}}{10^3\,{\rm K}}\right)^{1/2}$$

Conclusions and Outlook

- Neutron stars are unique laboratories to probe particle nature of dark matter.
- Considered realistic Neutron Star profile and developed formalism for DM scattering in Fermi-degenerate medium for arbitrary degeneracy.
- Heating of old Neutron stars can constrain several DM models. Kinetic heating can heat old NS up to 1700 K and heating from annihilation can lead to NS temperature of 2400 K. Decisively testable by future infrared telescopes such as JWST.
- For signals from annihilation heating: the requirement to thermalize is a strong criterion! DM-nucleon (electron) momentum dependent operators DO NOT thermalize with NS efficiently $\implies$ signals from kinetic heating the only way.

Thank You !