Dark Matter Interactions with Muons in Neutron Stars

Raghuveer Garani

Université Libre de Bruxelles

Based on
JCAP 1905 (2019) no.05, 035 (1812.08773)
in collaboration with Y. Genolini and T. Hambye

and

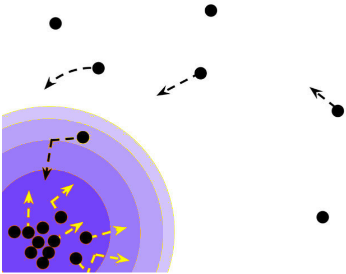
Phys. Rev. D 100, 035039 (1906.10145)
in collaboration with J. Heeck

12.09.2019

Prelude

- 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

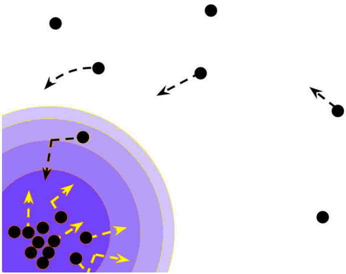
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\mathrm{N}_\chi - A\mathrm{N}_\chi^2$$



Prelude

- 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

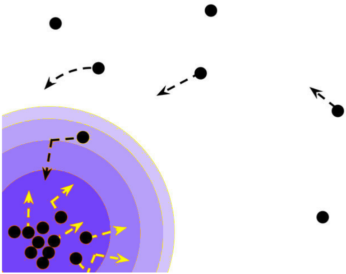
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\mathrm{N}_\chi - A\mathrm{N}_\chi^2$$



Prelude

- 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

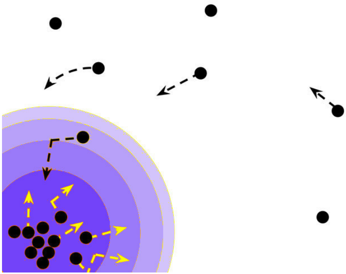
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\,\mathrm{N}_\chi - A\,\mathrm{N}_\chi^2$$



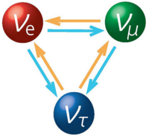
Prelude

- 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

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

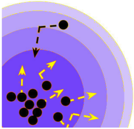


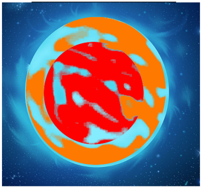
Neutrinos Press and Spergel '85, Griest and Seckel '86, Gould '87...



Black Hole formation

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





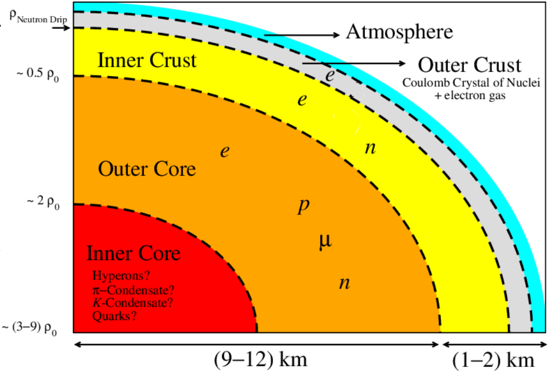
Heating cold and old objects Kouvaris '07, '10, Bertone et.al. '08, McCullough et.al. '10, Baryakhtar et.al. '17...

Outline

- Introduction
- Dark Matter in Neutron Stars: Theory
  - Dark Matter Elastic Scattering off Fermi-Degenerate gas: Capture, Thermalisation and Annihilation
- Neutron Star Heating Constraints on Dark Matter
  - Implications for muonphilic WIMP Dark Matter
- Conclusions & Outlook

Introduction: Neutron Stars

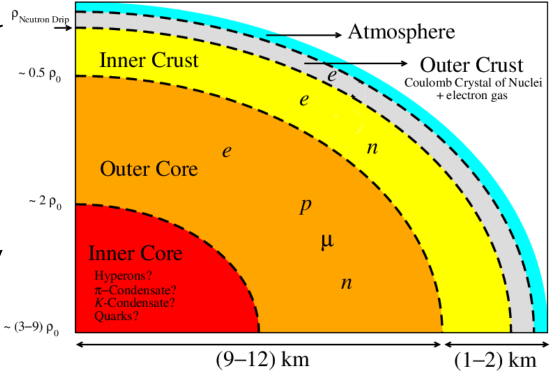
- Much about neutron star interiors unknown
- We consider a phenomenological NS profile. Exotic phases not considered. Brussels-Montreal energy density functionals which are fitted to APR Potekhin et.al. '13, Goriely et.al. '13



- $M = 1.52\,\mathrm{M}_\odot$, $R = 11.6\,\mathrm{km}$. $\mu_n = 350\,\mathrm{MeV}$, $Y_\mu = 2\times10^{-2}$, $\mu_\mu = 65\,\mathrm{MeV}$
- Consistent with observation of GW from NS-NS merger Abbott et.al. '18, Most et.al. '18

Introduction: Neutron Stars

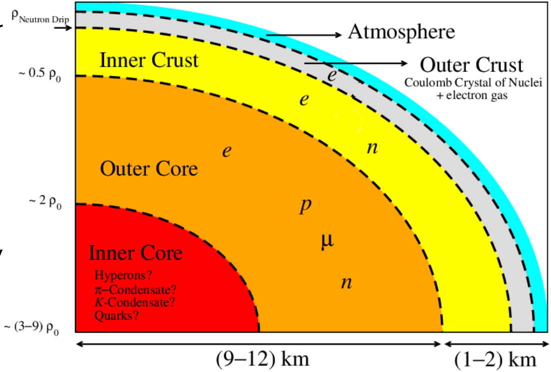
- Much about neutron star interiors unknown
- We consider a phenomenological NS profile. Exotic phases not considered. Brussels-Montreal energy density functionals which are fitted to APR Potekhin et.al. '13, Goriely et.al. '13



- $M = 1.52\,\mathrm{M}_\odot$, $R = 11.6\,\mathrm{km}$. $\mu_n = 350\,\mathrm{MeV}$, $Y_\mu = 2 \times 10^{-2}$, $\mu_\mu = 65\,\mathrm{MeV}$
- Consistent with observation of GW from NS-NS merger Abbott et.al. '18, Most et.al. '18

Introduction: Neutron Stars

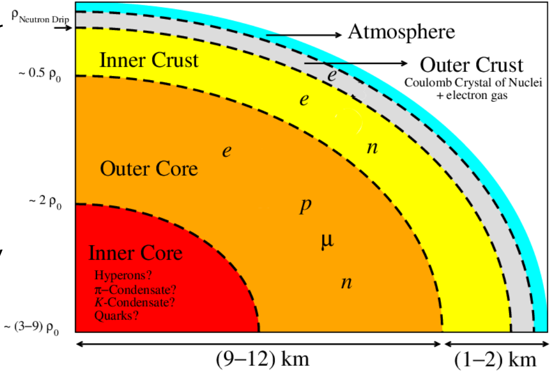
- Much about neutron star interiors unknown
- We consider a phenomenological NS profile. Exotic phases not considered. Brussels-Montreal energy density functionals which are fitted to APR Potekhin et.al. '13, Goriely et.al. '13



- $M = 1.52\,\mathrm{M}_\odot$, $R = 11.6\,\mathrm{km}$. $\mu_n = 350\,\mathrm{MeV}$, $Y_\mu = 2\times10^{-2}$, $\mu_\mu = 65\,\mathrm{MeV}$
- Consistent with observation of GW from NS-NS merger Abbott et.al. '18, Most et.al. '18

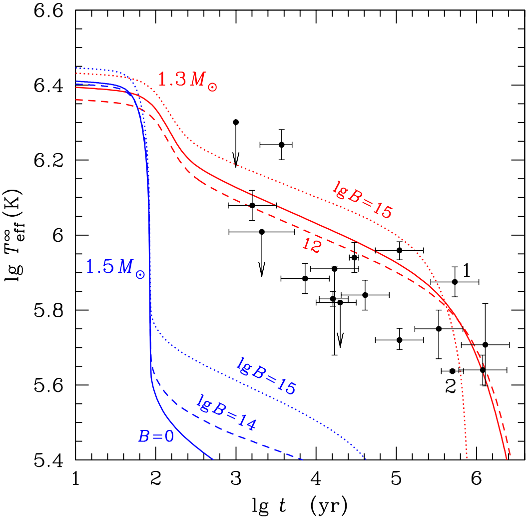
Introduction: Neutron Stars

- 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

Introduction: Neutron Stars Temperature



Potekhin '11

NS Heating Constraints on Dark Matter: General Picture

Two ways to heat-up

- Kinetic Heating: Infalling 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

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

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

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

Introduction: Dark Matter in Celestial Objects

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

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

	$\sigma_\star\ [\mathrm{cm}^2]$	$M_{\max}\ [\mathrm{M}_\odot]/\mathrm{Gyr}$
Sun	10^{-35}	10^{-21}
Earth	10^{-33}	10^{-26}
Moon	10^{-32}	10^{-27}
White Dwarf	10^{-39}	10^{-19}
Neutron Star	10^{-45}	10^{-15}

- We consider DM-neutron cross section of the form

$$\frac{d\sigma(v_{\rm rel}, \cos\theta_{\rm cm})}{d\cos\theta_{\rm cm}} = \frac{\sigma_{\chi-n}}{2}.$$

- The rate of DM accretion is

$$C_{\odot}^{w} = \int_0^{R_\odot} 4\pi r^2 dr \int_0^\infty du \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_\odot(u)}{u} \omega(r) \int_0^{\nu_e} R^-(\omega \to \nu) d\nu,$$

with

$$R^{\pm}(\omega \to v) = 16\,\mu_+^4 n(r) N_{fd} \frac{v}{w} \int_0^\infty ds \int_0^\infty dt\, t\, f_2(E)(1 - f_4(E')) \frac{d\sigma}{d\cos\theta_{cm}} H^{\pm}(s, t, \omega, v).$$

Dark Matter in Neutron Stars: Capture

- We consider DM-neutron cross section of the form

$$\frac{d\sigma(v_{\rm rel}, \cos\theta_{\rm cm})}{d\cos\theta_{\rm cm}} = \frac{\sigma_{\chi-n}}{2}.$$

- The rate of DM accretion is

$$C_{\odot}^{w} = \int_0^{R_\odot} 4\pi r^2 dr \int_0^{\infty} du \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_\odot(u)}{u} \omega(r) \int_0^{\nu_e} R^{-}(\omega \to \nu) d\nu,$$

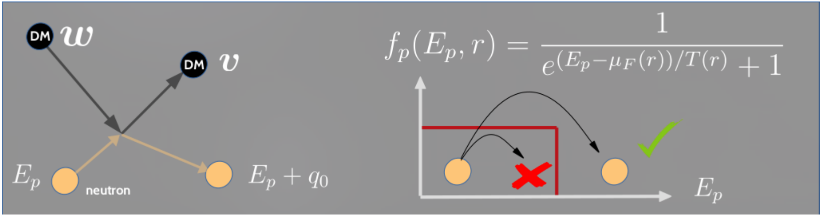
with

$$R^{\pm}(\omega \to v) = 16\, \mu_+^4 n(r) N_{fd} \frac{v}{w} \int_0^{\infty} ds \int_0^{\infty} dt\, t\, f_2(E)(1 - f_4(E')) \frac{d\sigma}{d\cos\theta_{cm}} H^{\pm}(s, t, \omega, v).$$

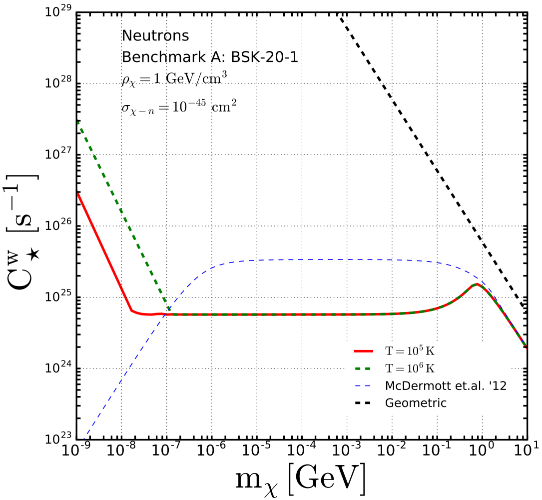
Dark Matter in Neutron Stars: Capture [RG, Y.Genolini and T. Hambye]

$$R^{\pm}(\omega \to v) = 16\, \mu_+^4\, n(r) N_{fd} \frac{v}{w} \int_0^\infty \mathrm{d}s \int_0^\infty \mathrm{d}t\, t\, f_2(E)(1 - f_4(E'))$$

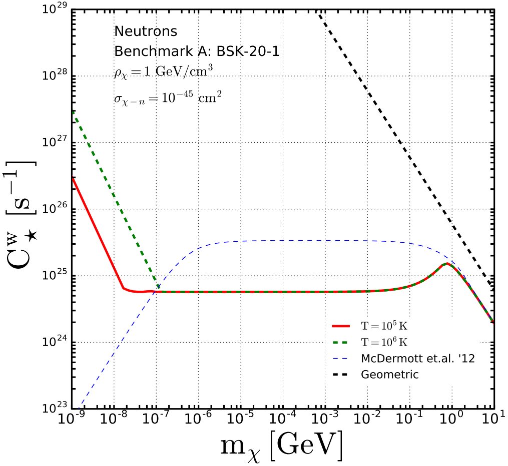
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{cm}} H^{\pm}(s, t, \omega, v).$$

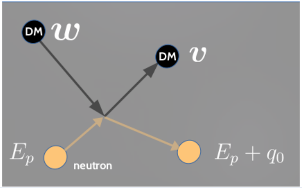


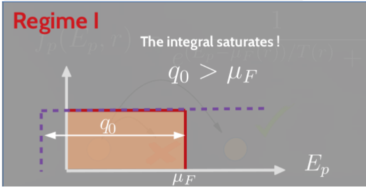
Capture Rate for Const. $\sigma_{\chi n}$ [RG, Y.Genolini and T. Hambye]



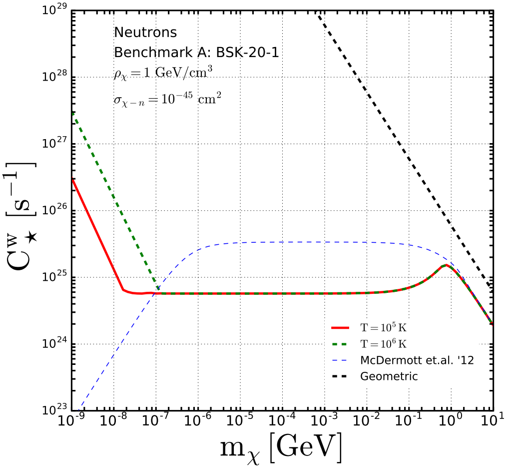
Capture Rate for Const. $\sigma_{\chi n}$ [RG, Y.Genolini and T. Hambye]

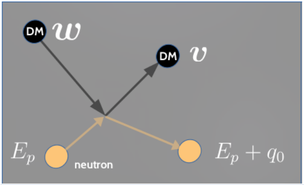


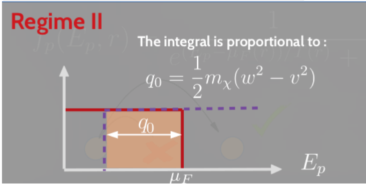




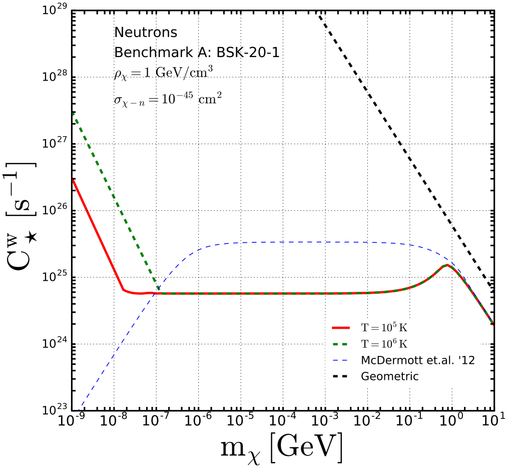
Capture Rate for Const. $\sigma_{\chi n}$ [RG, Y.Genolini and T. Hambye]

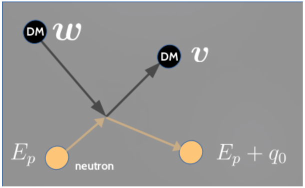


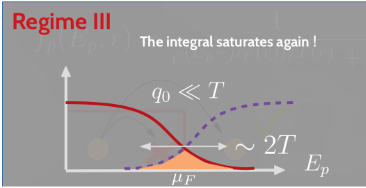




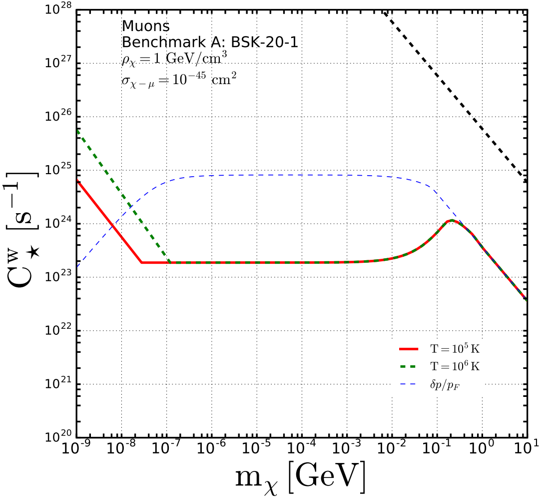
Capture Rate for Const. $\sigma_{\chi n}$ [RG, Y.Genolini and T. Hambye]



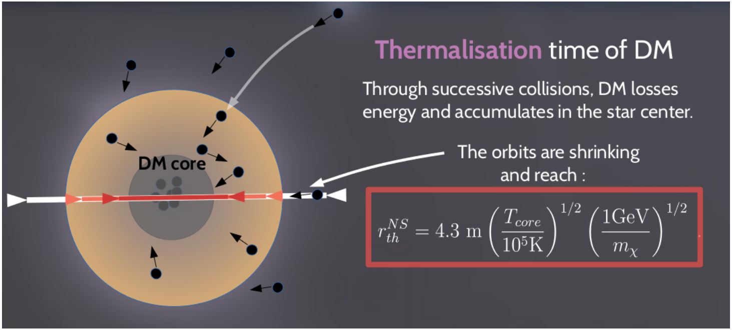




Capture Rate for Const. $\sigma_{\chi\mu}$ [RG, Y.Genolini and T. Hambye]



Thermalisation I



Two novelties:

- Average of differential energy loss along orbits
- A better estimation of the number of thermalised particles

Thermalisation II: Energy loss [RG, Y.Genolini and T. Hambye]

- DM orbits in the neutron star: characterise an orbit we use the maximal kinetic energy

$$E \equiv E_{\rm kin}^{\rm max} = \begin{cases} -\dfrac{GM_\star m_\chi}{r_0} + 3\,\dfrac{GM_\star m_\chi}{2R_\star} & \text{for } r_0 > R_\star\,, \\ \dfrac{GM_\star m_\chi}{2R_\star}\left(\dfrac{r_0^2}{R_\star^2}\right) & \text{for } r_0 \leq R_\star\,. \end{cases}$$

- Differential energy loss in Fermi degenerate medium Bertoni et.al. '13

$$\frac{d\Gamma}{dE'_k} = \sigma_\chi \frac{m_n^2 m_\chi}{2\pi^2 m_r^2}\sqrt{\frac{E'_k}{E_k}}\,(E_k - E'_k).$$

- Energy lost per collison

$$\langle \Delta E \rangle = E_i - E_0 = \frac{\int_0^k d\Gamma(E_i)\,(E_i - E_f)}{\int_0^k d\Gamma(E_i)} = \frac{4}{7}E_i\,,$$

Thermalisation III: time

- Average over orbits

$$\frac{d\Gamma_2}{dE'} = \left\langle \frac{d\Gamma}{dE'_k} \right\rangle_{r_0} = \sigma_\chi \frac{m_n^2 m_\chi}{2\pi^2 m_r^2} \left(1 - \sqrt{1 - \frac{E'}{E}}\right)(E - E')$$

-

$$b_2(E) = \int_0^E \frac{d\Gamma_2}{dE'}(E - E')dE' = \frac{\sigma_\chi}{42\pi^2} \frac{m_n^2 m_\chi}{m_r^2} E^3$$

- Thermalisation time: $t_2 = \int_{E_{\rm surf}}^{E_{\rm th}} \frac{dE}{b_2(E)}$

$$t_2 \approx \frac{21\pi^2 m_r^2}{\sigma_\chi m_n^2 m_\chi} \frac{1}{E_{th}^2} \approx 10700 \text{ yrs} \frac{\gamma}{(1+\gamma)^2} \left(\frac{10^5 \text{ K}}{T}\right)^2 \left(\frac{10^{-45}\text{cm}^2}{\sigma_\chi}\right)$$

Annihilation

- Recall

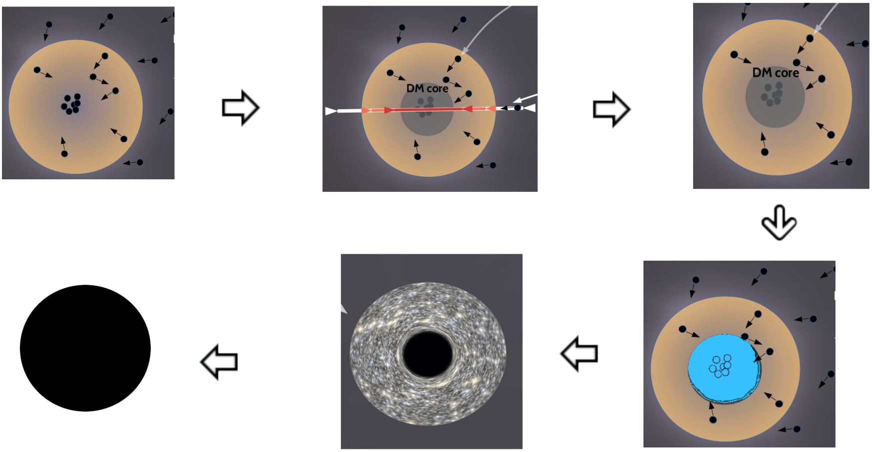
$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C - E\,\mathrm{N}_\chi - A\,\mathrm{N}_\chi^2$$

$$\mathrm{N}_\chi = \left(\frac{C}{A}\right)^{1/2} \tanh\left(t/\tau\right) \quad \text{with} \quad \tau = \frac{1}{\sqrt{C\,A}}$$

- Once thermalised DM can efficiently annihilate:

$$\frac{t}{\tau} \approx 10^2 \left(\frac{m_\chi}{\mathrm{GeV}}\right)^{1/4} \left(\frac{10^5\,\mathrm{K}}{T}\right)^{3/4} \left(\frac{t}{10\,\mathrm{Gyrs}}\right) \left(\frac{\langle\sigma v\rangle}{10^{-45}\,\mathrm{cm}^3/\mathrm{s}} \cdot \frac{\rho_\chi}{0.4\,\mathrm{GeV}/\mathrm{cm}^3} \cdot \frac{\sigma_{\chi\mu}}{10^{-43}\,\mathrm{cm}^2}\right)^{1/2}$$

Summary so far and the way forward



A Muonphilic Dark Matter Model?

- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.
  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\implies$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\text{new}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi}\left(i\not{D} - m^2_\psi\right)\psi$$

$$\mathcal{L}^s_{\text{new}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

A Muonphilic Dark Matter Model?

- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.
  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\implies$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\text{new}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi}\left(i\not{D} - m^2_\psi\right)\psi$$

$$\mathcal{L}^s_{\text{new}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

A Muonphilic Dark Matter Model?

- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.

  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\implies$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi}\left(i\not{D} - m^2_\psi\right)\psi$$

$$\mathcal{L}^s_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

A Muonphilic Dark Matter Model?

- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.
  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\implies$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi}\left(i\not{D} - m^2_\psi\right)\psi$$

$$\mathcal{L}^s_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

A Muonphilic Dark Matter Model?

- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.
  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\Longrightarrow$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi}\left(i\not{D} - m^2_\psi\right)\psi$$

$$\mathcal{L}^s_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

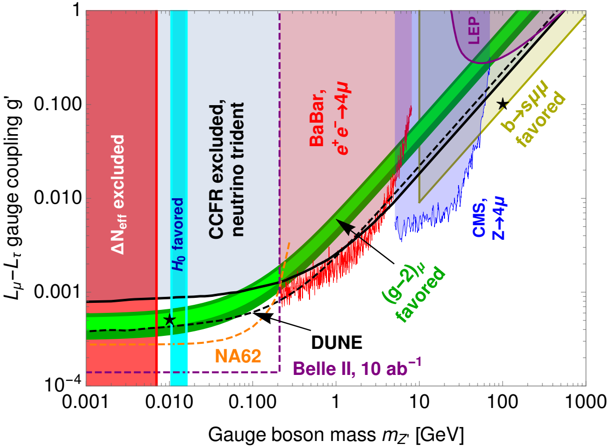
A Muonphilic Dark Matter Model?

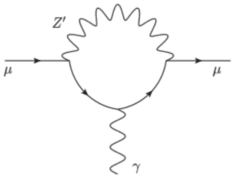
- DM interactions with first generation particles highly constrained.
- Easily evade the constraints by making DM charged under $U(1)_{L_\mu - L_\tau}$.
  Cirelli et.al. '09, Baek et.al. '09
- Simple WIMP model!
- Z' can be light $\implies$ interesting phenomenology. Possible solution to anomalies in the muon sector. He et.al. '91, Foot '91, Heeck et.al. '11, Altmannshofer et.al. '14 '16, Crivellin et.al. '15

$$\mathcal{L}^f_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \bar{\psi} \left(i\not{D} - m^2_\psi \right) \psi$$

$$\mathcal{L}^s_{\rm new} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \phi^* D^\mu \phi - \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2$$

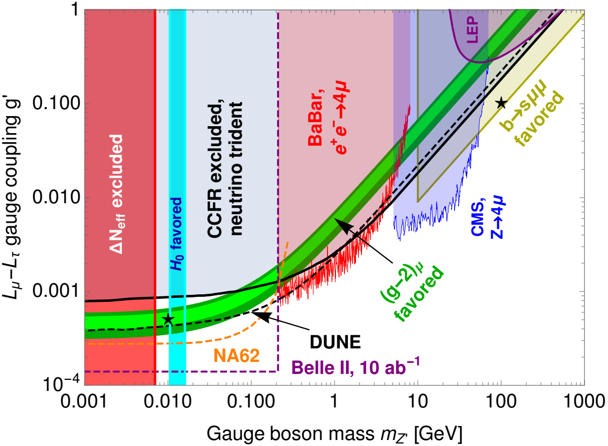
A Muonphilic Dark Matter Model: $U(1)_{L_\mu - L_\tau}$ [RG and J. Heeck]

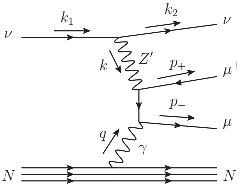




He et.al. '91, Foot '91, Heeck et.al. '11

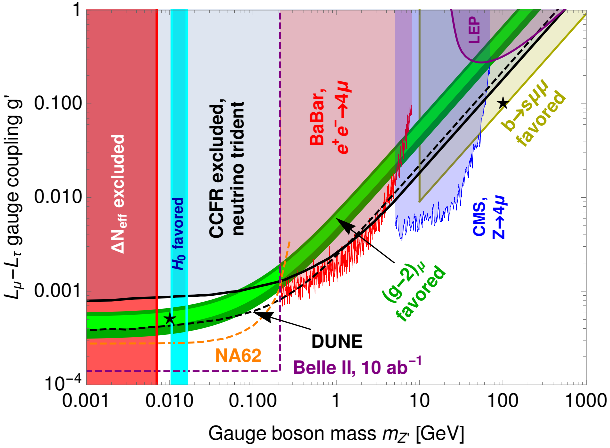
A Muonphilic Dark Matter Model: $U(1)_{L_\mu - L_\tau}$ [RG and J. Heeck]

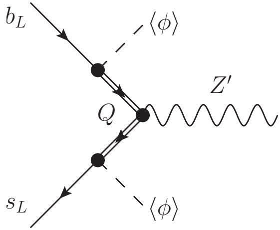




Altmannshofer et.al. '14 '16

A Muonphilic Dark Matter Model: $U(1)_{L_\mu - L_\tau}$ [RG and J. Heeck]





Altmannshofer et.al. '14 '16, Crivellin et.al. '15 .....

Capture of Muonphilic Dark Matter with light Mediator

[RG and J. Heeck]

- Maximal accretion

$$C_\star \simeq \frac{5.6 \times 10^{25}}{\mathrm{s}} \frac{\rho_\chi}{\mathrm{GeV/cm^3}} \frac{\mathrm{GeV}}{m_\chi} \frac{R_\star}{11.6\,\mathrm{km}} \frac{M_\star}{1.52\,\mathrm{M_\odot}}$$

- Interactions between DM particles χ and muons are mediated by a potentially light gauge boson Z' with vector coupling $g' q_\mu$ to muons and coupling $g' q_\chi$ to χ.

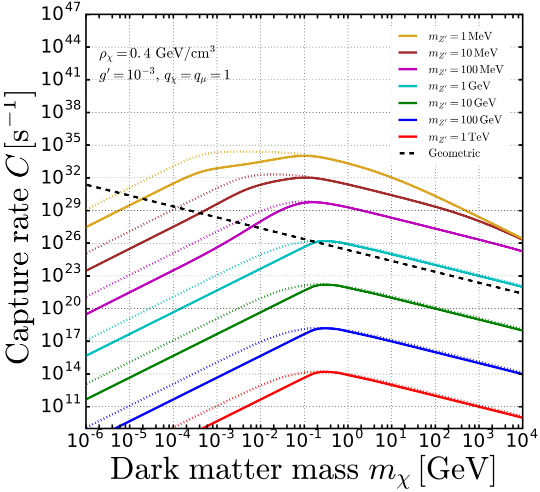
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}(\chi\mu \to \chi\mu) = \frac{(g')^4 q_\chi^2 q_\mu^2}{2\pi} \frac{m_\mu}{w^2(2m_\mu E_R + m_{Z'}^2)^2}$$

- 1-loop interactions with protons

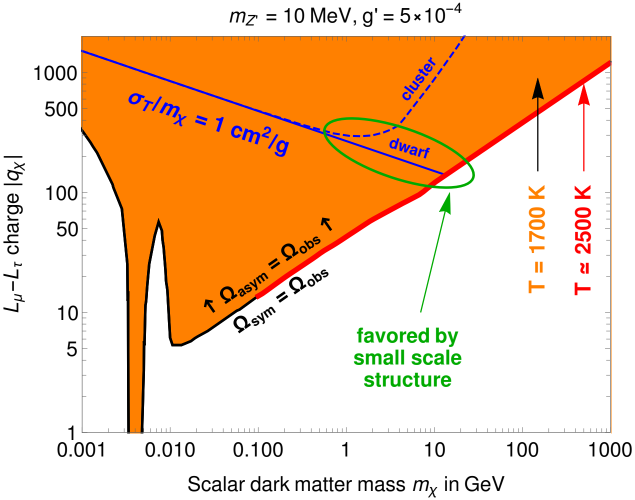
$$\sigma_{\chi N} = \frac{Z^2}{A^2} \frac{m_{\mathrm{red},\chi N}^2}{\pi m_{Z'}^4} \left(g' q_\chi\right)^2 \left[e\epsilon + \frac{\alpha g'}{3\pi} \log\left(\frac{m_\tau^2}{m_\mu^2}\right)\right]^2$$

Capture of Muonphilic Dark Matter with light Mediator

[RG and J. Heeck]

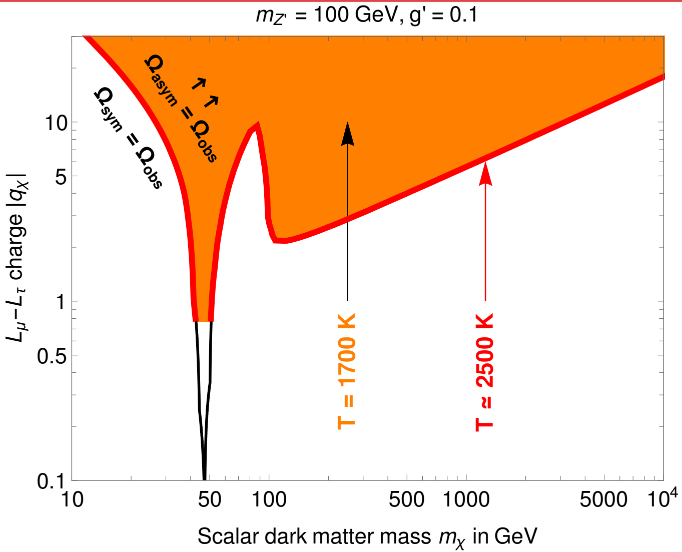


Constraining Muonphilic DM: Light med [RG and J. Heeck]



Kaplinghat, Tulin, Yu, 1508.03339

Constraining Muonphilic DM: Heavy med [RG and J. Heeck]



Conclusions and Outlook

- Considered realistic Neutron Star profile and developed formalism for DM scattering in Fermi-degenerate medium for arbitrary degeneracy.
- Direct detection severely constrain DM interactions with 1st generation particles $\implies$ perhaps DM interacts with second generation particles !
- $U(1)_{L_\mu - L_\tau}$ models well motivated by several anomalies in muon sector.
- Old Neutron stars are expected to contain 10^{57} neutrons and about 10^{55} Muons.
- Heating of old Neutron stars can constrain muonphilic DM scenario. Potentially testable by future infrared telescopes.

Thank You !

Capture of Majorana muonphilic DM