Accretion of self-interacting dark matter onto neutron stars

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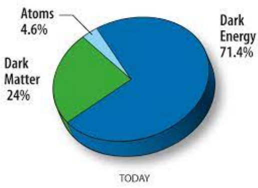
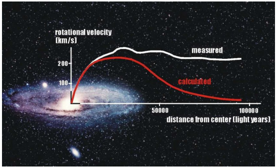
Dark matter and Stars

Lisbon, 5 May 2023

- **The Universe is mostly Dark**





- **Suggested by**
    - Rotation curves of Andromeda
    - Bullet cluster
    - ...

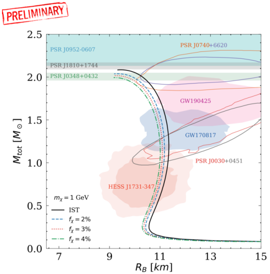
Dark matter in neutron stars

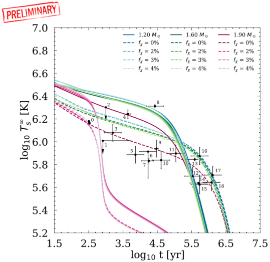
- **Dark matter fraction in neutron stars**

$$f_D = \frac{M_D}{M_{tot}}, \quad M_{tot} = M_B + M_D$$

- **Sizable amount of dark matter affects**
  - mass radius relation
  - cooling dynamics
  - merger dynamics

How to accumulate a sizable amount of dark matter?





credits to Afonso Avila for figures

Accretion of dark matter

- **Accretion rate without self-interaction of dark matter**

$$\mathcal{F} = \frac{3.042 \times 10^{25}}{m_\chi(\mathrm{GeV})} \times A \times 0.45\sigma_\chi/\sigma_{\mathrm{crit}}$$

A - local mass density of dark matter in units of 0.3 GeV/cm^3

C. Kouvaris, Phys. Rev. D 77 023006 (2008)

$$m_\chi(GeV) = 0.45\sigma_\chi/\sigma_{crit} = 1, \quad A(0.3GeV/cm^3) = 10^{15}$$

$$\Downarrow$$

$$\mathcal{F} \cdot 1\ Gyr \sim 10^{-10} M_\odot$$

Does the dark matter self-interaction make any difference?

Scenario

- Massive dark matter to exclude evaporation
- Zero amount of dark matter at the initial moment
- Multiple scatterings are ignored $\Rightarrow$ single scattering $=$ accretion
- Dark matter - baryon matter induces accretion
- Accumulated dark matter enhances accretion due to self-interaction

What to expect? (toy model)

$$\frac{dN_D}{dt} = I\left[N_B\sigma_{BD} + N_D\sigma_{DD}\right]$$

I - flux of dark matter
$N_{B,D}$ - number of baryonic and dark matter particles
$\sigma_{B,D}$ - interaction cross sections

- **Non-self-interacting dark matter ($\boldsymbol{\sigma_{BD}} = 0$)**

$$N_D(t) = IN_B\sigma_{BD}t, \quad accretion\ rate = \mathcal{O}(1)$$

- **Self-interacting dark matter ($\boldsymbol{\sigma_{BD}} \neq 0$)**

$$N_D(t) = n_B\frac{\sigma_{BD}}{\sigma_{DD}}\left[e^{I\sigma_{DD}t} - 1\right], \quad accretion\ rate = \mathcal{O}(e^t)$$

Self-interaction induces fast accretion of dark matter?

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Dark matter cross section

- **Very conservative estimate of the dark matter-baryon matter cross section**

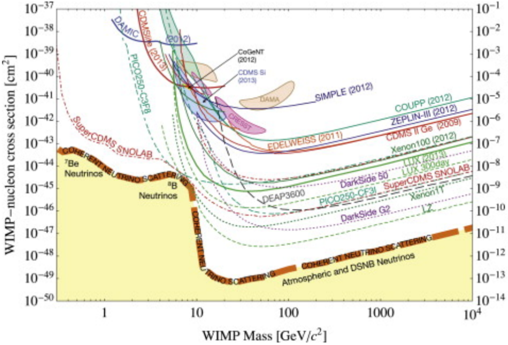
$$\sigma_{BD} = 10^{-30}\ fm^2$$

- **Numerical simulations of the Bullet Cluster dynamics**

S. Randall et al, Astrophys. J., (2008)

$$\frac{\sigma_D}{m_D} < 0.7\ \frac{cm^2}{g} \simeq 0.2 \frac{fm^2}{MeV}$$

More conservative values are used below



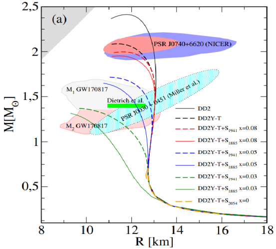
J. Cooley, Phys. Dark Univ 4, (2014)

- **Baryon matter - DD2Y-T**

  M. Shahrbaf et al., PRD 2022

  - type: relativistic density functional theory
  - degrees of freedom: nucleons & hyperons
  - fitted to: normal nuclear matter properties

  ask **Mahboubeh Shahrbaf** to know more



- **Dark matter - non-interacting spin-1/2 massive fermions at T=0**

$$p_D = 2\int \frac{d\mathbf{k}}{(2\pi)^3}(\mu_D - E)\theta((\mu_D - E)), \quad E = \sqrt{\mathbf{k}^2 + m_D^2}$$

$$\varepsilon_D = \mu_D \frac{\partial p_D}{\partial \mu_D} - p_D$$

m_D - mass of the dark matter particles, the only parameter

Boltzmannian energy distribution of interstellar DM

$$\phi_D(E) = C\exp(-\beta E), \quad E \geq m_D$$

- **Number density and mass density**

$$n_D = \int_{m_D}^{\infty} dE\ \phi_D(E), \quad \rho_D = m_D n_D$$

- **Mean energy of the DM particles**

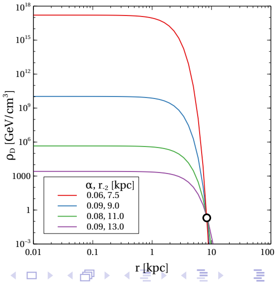
$$\overline{E}_D = \frac{1}{n}\int_{m_D}^{\infty} dE\ \phi_D(E)\ E$$

$$\Rightarrow \quad C = C(n_D, \overline{E}), \qquad \beta = \beta(n_D, \overline{E})$$

- **Einasto profile**

$$\rho_D(r) = \rho_{-2}\exp\left[\frac{2}{\alpha}\left(1 - \frac{r^2}{r_{-2}^2}\right)\right]$$

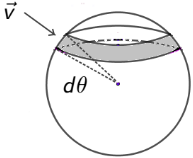
$$r_\oplus = 8.3\ \text{kpc}, \quad \rho_D(r_\oplus) = 0.3\ \text{GeV/cm}^3$$



ρ_D can cover many orders of magnitude

DM flux and parameter space

- **Flux**



$$dF = \underbrace{\phi_D(E)dE}_{\text{DM particle density}} \cdot \underbrace{|\vec{v}|cos\theta}_{\text{projection of velocity}} \cdot \underbrace{\frac{2\pi \sin\theta d\theta}{4\pi}}_{\text{part of the area}}$$

- **Angular momentum of the accreted particle**

$$L = m_D|\vec{v}|R\cos\theta \quad \Rightarrow \quad dF = \frac{\phi_D(E)dEdL^2}{4m_D^2|\vec{v}|R^2}$$

- **Geodesic (M(r) - enclosed mass profile)**

$$\left(\frac{dr}{d\theta}\right)^2 = \frac{r^2 m_D^2}{L^2}\left[\frac{E^2}{L^2} - \left(1 - \frac{2M(r)}{r}\right)\left(\frac{L^2}{r^2 m_D^2} + 1\right)\right]$$

$\frac{dr}{d\theta} = 0 \quad \Rightarrow \quad r = r_{min}$ - perihelion, only particles with $r_{min} \leq R$ can accrete

$$L^2 \leq L_{max}^2 = R^2\left[E^2\left(1 - \frac{2M(r)}{r}\right)^{-1} - m_D^2\right]$$

Derivation in **W. Press & D. N. Spergel, Astrophys. J. (1985)**

Accretion rate

- **Probability of at least one scattering**

$$P = 1 - \exp\left[- \int dl \sum_{i=BD} n_i \sigma_{iD} \right]$$

$dl =$ - element of the dark matter particle path in NS
$n_{B,D}$ - number density of the baryon and dark matter particles in NS

$$P = 1 - \exp\left[-2 \int_{r_{min}}^{R} dr \sum_i n_i(r) \sigma_{iD} \sqrt{1 + \frac{L^2}{E^2 r^2 - \left(1 - \frac{2M(r)}{r}\right)(m_D^2 r^2 + L^2)}} \right]$$

- **Accretion rate**

$$R = 4\pi R^2 \int dF \; P = \frac{1}{\pi m_D^2} \int_0^{\infty} dE \, \frac{\phi_D(E)}{|\vec{v}|} \int_0^{L^2_{max}} dL^2 \; P(E, L)$$

Accretion rate

- **Dark matter particle mass**

$$m_D = 1 GeV$$

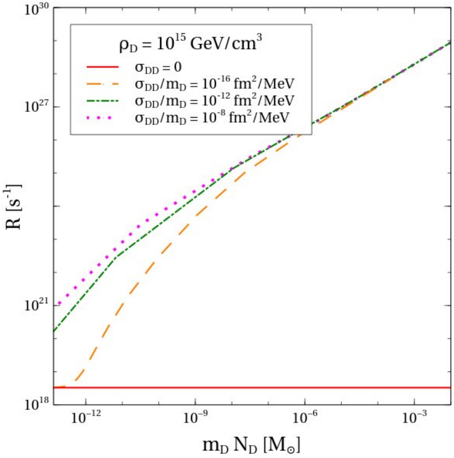
- **Accretion rate grows with σ_D**

Self-interaction enhances accretion

- **Accretion rate grows with amount of dark matter**

Non-linear time dependence
Fast accretion?

$$M_{tot}(M_D = 0) = 1.4\ M_{\odot}$$



Evolution

$$\frac{dN_D}{dt} = R(t) \quad with \quad N_D(0) = 0$$

comment: a speculative scenario with $N_D(0) > 0$ is possible

- **Comparison to the Toy model with $\mathbf{R_{Toy} = I(N_B\sigma_{BD} + N_D\sigma_{DD})}$**

$$\frac{dR}{dN_D} > 0 \quad and \quad \frac{dR_{Toy}}{dN_D > 0}$$

$$\Downarrow$$

Enhanced accretion due to self-interaction?

- **Complication due to $\mathbf{R = R[n_B(r,t), n_D(r,t)]}$**

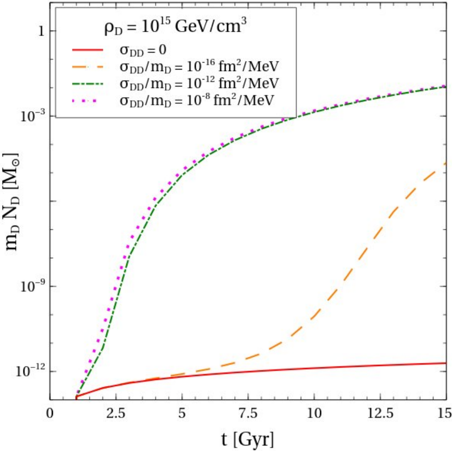
Solving a system of two coupled TOV-like equations along the time axis is required

Accreted mass

- **Nearly exponential accretion at early times**
- **Power law accretion at late times**

Due to saturation of the scattering probability?

$M_{tot}(t=0) = 1.4\ M_\odot$



Conclusions

- Dark matter self-interaction induces positive back reaction on the accretion rate
- Fastening of the accretion: exponential accretion at early times, power law accretion at later times
- Up to $\sim 1\%$ of self-interacting dark matter can be accreted during the Universe lifetime