CONSTRAINTS ON DARK MATTER FROM COMPACT STARS

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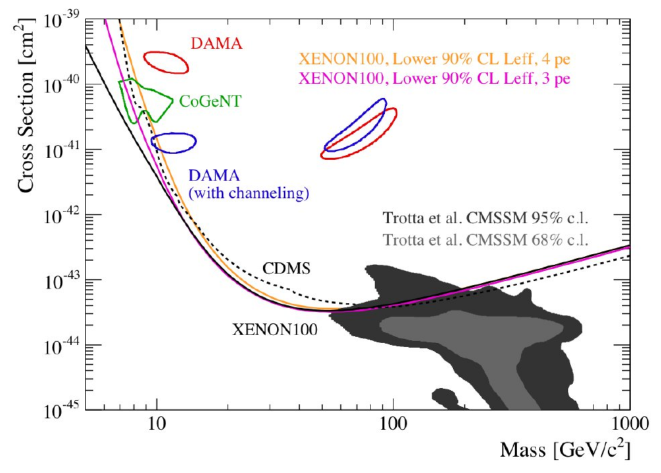
Based on:
Kouvaris, P.T. Phys.Rev. D82 (2010) 063531 [arXiv:1004.0586]
Kouvaris, P.T., in preparation

Motivation

- Dark matter is suggested by many indirect arguments, all of which are of a gravitational origin $\Longrightarrow$ A non-gravitational evidence is needed
- An attractive particle-physics candidate for DM is WIMP. This is the possibility we discuss here.
- In many DM models WIMPs scatter on nucleons and can decay/annihilate, which is used for their direct search. Small cross sections make it a difficult task.
- DM may be accumulated by stars and produce observable effects, thus constraining the DM models.
- This not a new idea:

  Press, Spergel Astrophys.J. 296 (1985) 679-684; Golgman, Nussinov Phys. Rev. D40, 3221 (1989); Kouvaris Phys. Rev D77, 023006 (2008); Sadin, Ciarcelluti, Astropart. Phys. 32 (2009) 278-284; Bertone, Fairbairn, Phys. Rev. D77, 043515 (2008); McCullough, Fairbairn, Phys. Rev. D81 (2010) 083520.

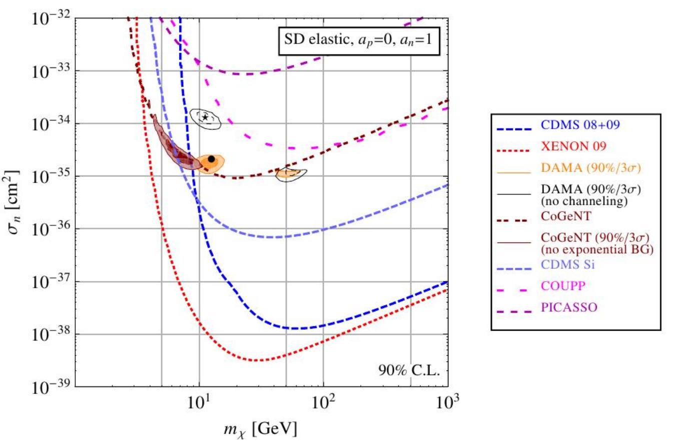
Direct constraints: spin-independent case



XENON100 Collaboration, arXiv:1005.2615

Large masses: $\sigma_{\rm SI} \leq 3 \times 10^{-43} {\rm cm} \left(\frac{m_{\rm DM}}{\rm TeV} \right)$

Direct constrains: spin-dependent case



Kopp, Schwetz, Zupan, JCAP 1002 (2010) 014 [arXiv:0912.4264]

Large masses: $\sigma_{\rm SD} \leq 10^{-37}{\rm cm}\left(\frac{m_{\rm DM}}{\rm TeV}\right)$

Can these constraints be improved by making use of DM accumulation in compact stars?

Capture of DM

More compact objects capture more

- Cross section of hitting the star:

$$\pi R_*^2 \left(1 + \frac{2GM_*}{R_* v_\infty^2}\right)$$

- Collision probability

$$f = \frac{\sigma_N}{\sigma_{\mathrm{crit}}}; \qquad \sigma_{\mathrm{crit}} = \frac{m_p R_*^2}{M_*}$$

- Critical cross section:

  Sun: $4{\cdot}10^{-36}\mathrm{cm}^2$; WD: $4{\cdot}10^{-40}\mathrm{cm}^2$; NS: $6{\cdot}10^{-46}\mathrm{cm}^2$

- Energy loss at a single collision

$$E_{\mathrm{loss}} \sim \frac{m_N}{m_D} E_{\mathrm{kin}} \sim \frac{m_N}{m_D} \frac{GM_* m_D}{R_*}$$

Capture of DM

- Final expression for capture rate:

$$F = \sqrt{6\pi}\frac{\rho_{\rm D}}{v_\infty m_D}\frac{2GM_* R_*}{1 - R_g/R_*}\left[1 - \exp\left(-\frac{3E_{\rm loss}}{mv_\infty^2}\right)\right] f$$

- In numbers:

$$\text{Sun:} \qquad F \sim 2 \cdot 10^{25}\,\mathrm{s}^{-1}\,\left(\frac{\rho_D}{0.3\mathrm{GeV/cm}^3}\right)\left(\frac{m_D}{TeV}\right)^{-1} f_{\rm Sun}$$

$$\text{NS :} \qquad F \sim 3 \cdot 10^{22}\,\mathrm{s}^{-1}\,\left(\frac{\rho_D}{0.3\mathrm{GeV/cm}^3}\right)\left(\frac{m_D}{TeV}\right)^{-1} f_{\rm NS}$$

Once captured

- DM particles continue to interact with the nucleons and thermalize to a small cloud in the center.
  - Sun: $r_{\rm th} = 0.01 R_\odot$
  - WD: $r_{\rm th} = 2 \cdot 10^6$ cm
  - NS: $r_{\rm th} = 20$ cm
- In case of annihilating DM it annihilates and produces heat. **Note:** because of a very high density, the annihilation is efficient even at a very small σ_A up to 10^{-60} cm^2.

$$\frac{dN}{dt} = F - \frac{\langle \sigma_A v \rangle}{V} N^2$$

- In the stationary regime, the rates of capture and annihilation are equal.

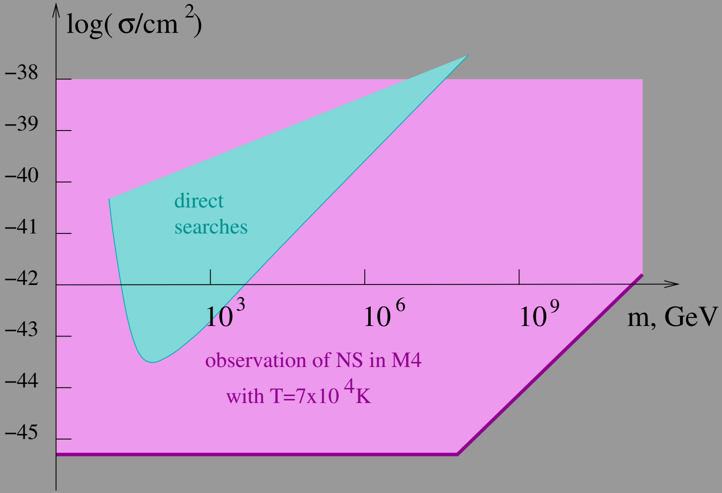
- In the absence of external heat sources (e.g., accretion) NS cools in a timescale of order $10^6 - 10^7$ yr to a temperature of order $10^5 - 10^4$ K.
- Annihilation of DM provides enough heat to stabilize the temperature somewhere in this range.
- The power created by DM annihilations is

$$W = Fm_D$$

It should balance the thermal emission

$$L = 4\pi R_*^2 \sigma_B T^4$$

Constraints from observations of cold NS



Caveats

- Neutron stars are difficult to observe, and even mode difficult is to establish their temperature
- The temperature of interest — $T \sim 10^5$ K — falls into UV band. Galactic center is not transparent.
- One has to be sure of high DM density at the location of a NS.
- The places where DM density is expected to be high are far (Galactic center, centers of globular clusters), while the DM density around Earth is not sufficient.

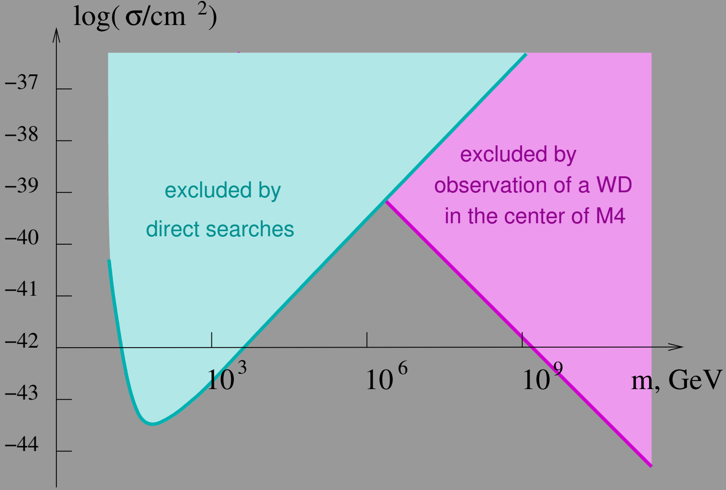
Constraints from collapse into a BH

- If there is no annihilation, DM may become self-gravitating and collapse into a black hole inside the star, destroying it.
- The collapse occurs when the Fermi pressure cannot sustain the gravity. The number of DM particles should exceed

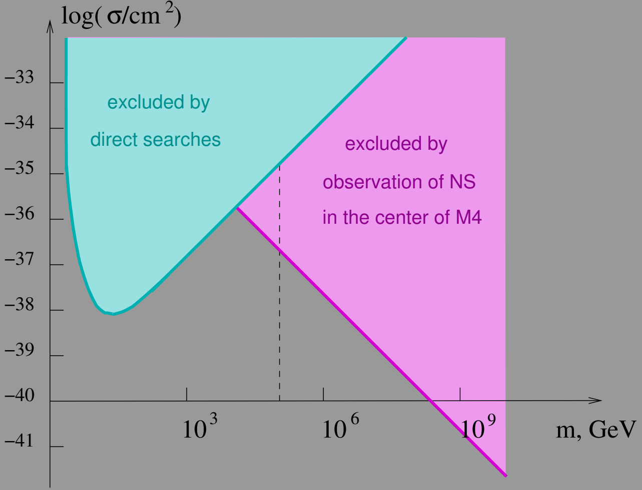
$$N = \left(\frac{9\pi}{4}\right)^{1/2} \left(\frac{M_{\rm Pl}}{m_D}\right)^3 \sim 5 \cdot 10^{48} \left(\frac{m_D}{\rm TeV}\right)^{-3}$$

- Best constraints come from the accumulation in the compact star progenitor (Sun-like stars for WD, supermassive stars for NS).

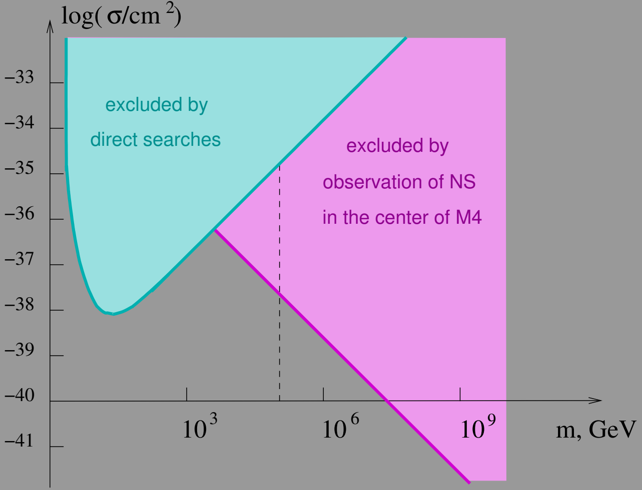
Collapse to BH: spin-independent case



Collapse to BH: spin-dependent case



Collapse to BH: spin-dependent case



Summary

Observations of neutron stars and white dwarfs in dark-matter-rich environments can give competitive constraints on DM models, provided:

- astronomical observational techniques improve further
- DM density in these environments is better known