CONSTRAINTS ON DARK MATTER FROM COMPACT STARS

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Based on:

Kouvaris, P.T. PRD 82 (2010) 063531 [arXiv:1004.0586]
Kouvaris, P.T., PRD 83 (2011) 083512 [arXiv:1012.2039]
Kouvaris, P.T., PRL 107 (2011) 091301
Brayeur, P.T., arXiv:1111.3205

Outline

Motivation

Many (indirect) arguments suggest the existence of dark matter

- Rotation curves of galaxies
- Gas temperature in clusters
- Gravitational lensing
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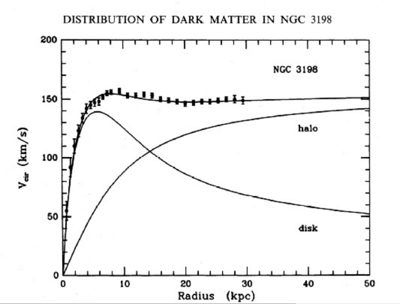

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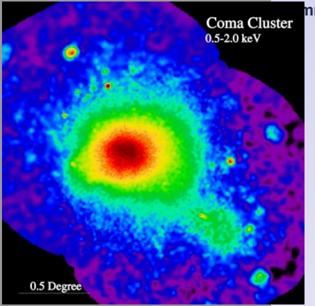

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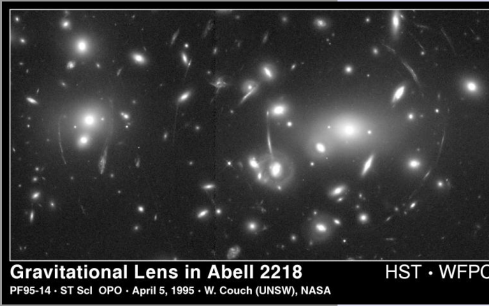

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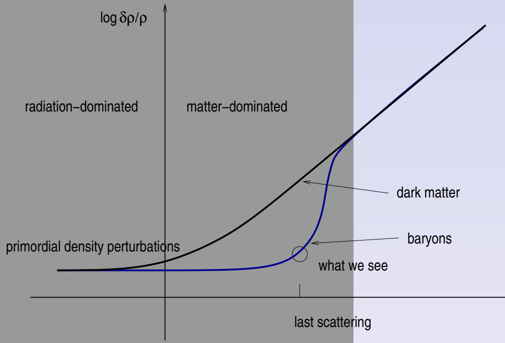


- Combined data from CMB anisotropies, SNe Ia and dynamics of clusters give $\Omega_M \simeq 0.27$ while primordial nucleosynthesis limits the baryonic contribution to $\Omega_B \simeq 0.045$

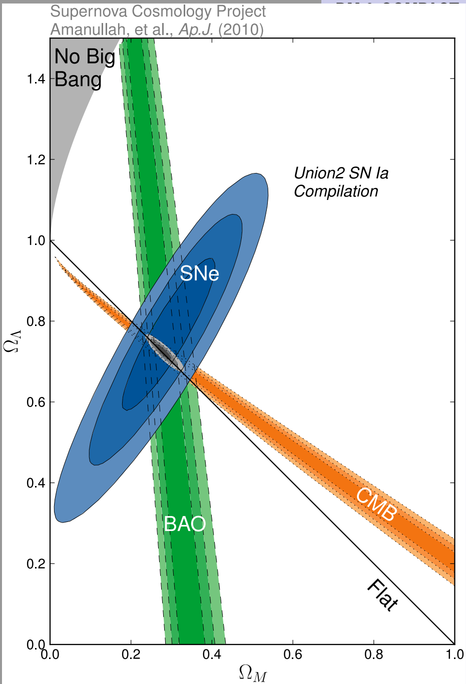
$\Longrightarrow$ $\Omega_{\mathrm{DM}} \simeq 0.22$

Note, however:
all the existing evidence for dark matter is indirect and of gravitational origin

$\Longrightarrow$

Non-gravitational detection is required

Key parameters: m, σ_N, σ_A



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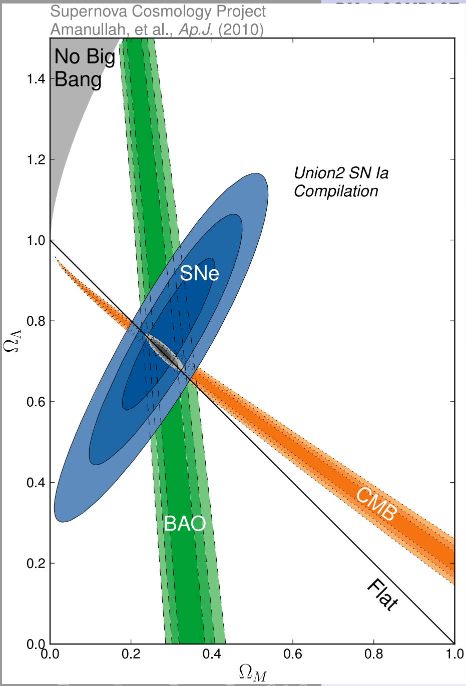

WIMPs

An attractive particle-physics candidate for DM is weakly interacting massive particle (WIMP)

- WIMPs are inspired by the “WIMP miracle”: the WIMP annihilation cross section of order weak cross section automatically gives right DM abundance. However, if a non-thermal production mechanism is assumed, the annihilation cross section is a free parameter
- WIMP masses are essentially unconstrained if heavier than ~ 10 keV. Typical SUSY-inspired candidates have masses of order 100 GeV and larger.
- If WIMPs can decay or annihilate into SM particles, these processes can be used in indirect DM detection through, e.g., γ-ray signals.
- WIMPs may also scatter off nucleons, in which case they would produce recoils that may be detected. This is a way to directly detect DM particles.

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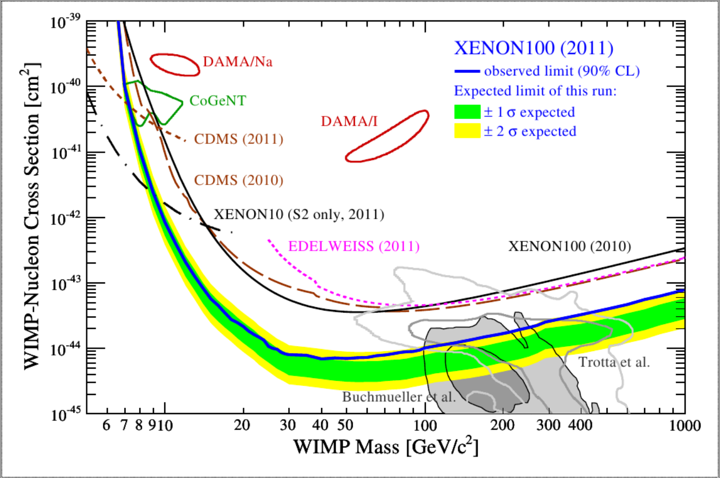
Direct constraints: spin-independent case



XENON100 Collaboration, arXiv:1104.2549

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

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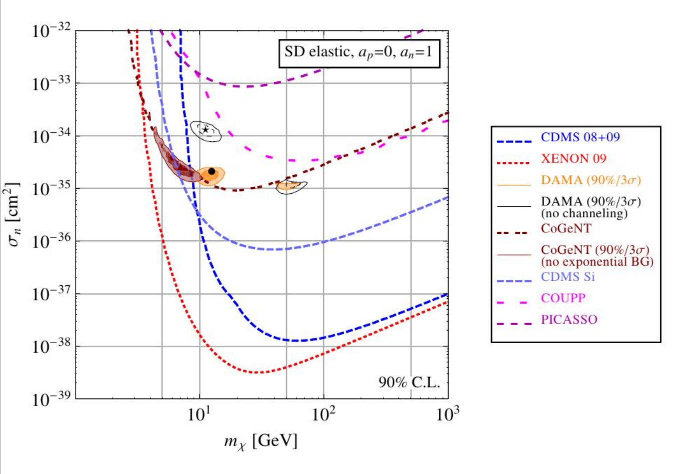
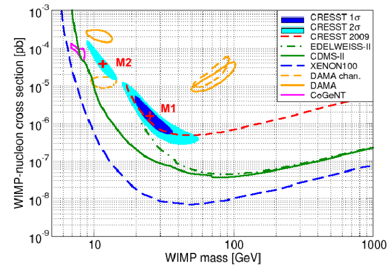


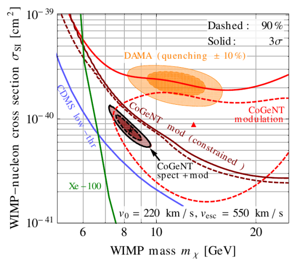
Kopp, Schwetz, Zupan, JCAP 1002 (2010) 014 [arXiv:0912.4264]

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

Positive detection?



CRESST @ TAUP2011



Fox et al, arXiv:1107.0717

- DAMA, CoGeNT and CRESST results inspire models with a light DM with mass around 10 GeV
- Models were constructed where such DM can apparently be reconciled with exclusions from XENON and CDMS
- An additional bonus in these models is the possibility to explain the coincidence, within a factor of 5, of the DM and baryon abundance. DM is assumed to have an asymmetry *à la* baryons, and is therefore non-annihilating

Can one use stars to search for DM?

- DM may be accumulated by stars and produce detectable effects. Their non-observation thus would constrain 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.

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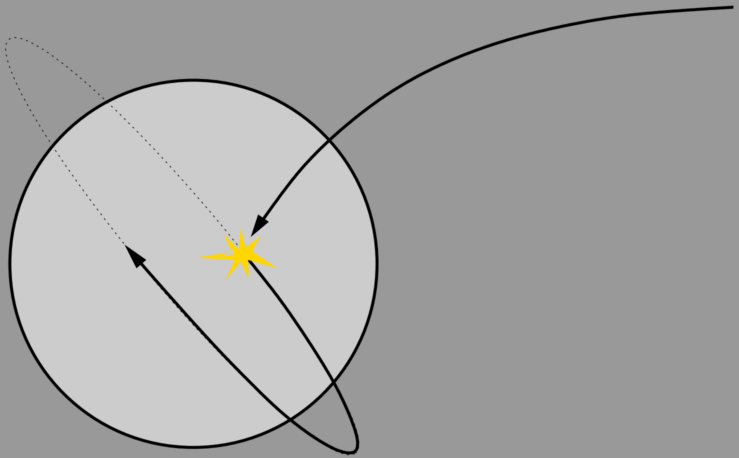
Capture of DM in stars



More compact objects capture more

- Cross section of hitting the star:

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

- For the Sun:

$$\frac{R_g}{R_* v_\infty^2} \sim \frac{3\ \text{km}}{7 \cdot 10^5\ \text{km}} \frac{1}{v_\infty^2} \gtrsim 1$$

- If there were no gravity:

$$\text{rate} \propto R^2 \cdot R \sigma_N n = R^3 \sigma_N \frac{N}{R^3} \propto \sigma_N N$$

With gravity capture rate is larger for compact objects

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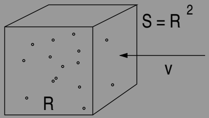

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- Probability of collision during a single star crossing:

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

- Critical cross section:

Sun: $\sigma_{\rm crit} = 4 \cdot 10^{-36} {\rm cm}^2$
WD: $\sigma_{\rm crit} = 4 \cdot 10^{-40} {\rm cm}^2$
NS: $\sigma_{\rm crit} = 6 \cdot 10^{-46} {\rm cm}^2$

- Energy loss in a single collision

$$E_{\rm loss} \sim \frac{2m_p}{m_D} E_{\rm kin} \sim \frac{m_p}{m_D} \frac{R_g m_D}{R_*} \sim m_p \frac{R_g}{R_*}$$

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- General expression for capture rate, assuming Maxwellian distribution of DM in velocity v_∞:

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

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$$f_{\mathrm{Sun}} = 7 \cdot 10^{-8} \left(\frac{\sigma_N}{3 \cdot 10^{-43}\mathrm{cm}^2}\right)$$

$$N_{\mathrm{tot}} = 2 \cdot 10^{35} \quad \text{(over 5 Gyr)}$$

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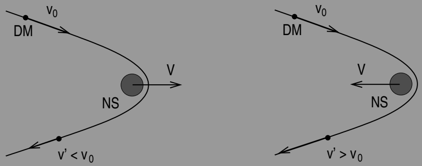
Brayeur, P.T., arXiv:1111.3205

- Additional mechanism of energy loss: gravitational slingshot



- Efficient in binaries where the NS velocity is comparable to that of DM particles

period	amplification factor
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8h	4.3
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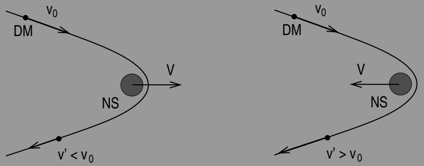

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AFTER CAPTURE

- DM particles continue to interact with the nucleons and thermalize to a small cloud in the center
- Thermal radius

$$r_{\mathrm{th}} = \left(\frac{9 T_{\mathrm{core}}}{8\pi G \rho_{\mathrm{core}} m_D} \right)^{1/2}$$

  - Sun: $r_{\mathrm{th}} = 0.01 R_{\odot}$
  - WD: $r_{\mathrm{th}} = 2 \cdot 10^6$ cm
  - NS: $r_{\mathrm{th}} = 20$ cm (!)
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Annihilating DM

- The dark matter annihilation inside the star is governed by the equation

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

- Solution to this equation

$$N(t) = N_0 \mathrm{th} \left(\frac{t - t_0}{\tau} \right)$$

$$N_0 = \sqrt{\frac{VF}{\langle \sigma_A v \rangle}}, \qquad \tau = \sqrt{\frac{V}{F \langle \sigma_A v \rangle}}$$

- The stationary regime is reached in less than Gyr for annihilation cross sections as low as $\langle \sigma_A v \rangle \gtrsim 10^{-61} \mathrm{cm}^2$.
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- 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

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

- $\Longrightarrow$ Minimum temperature of NS

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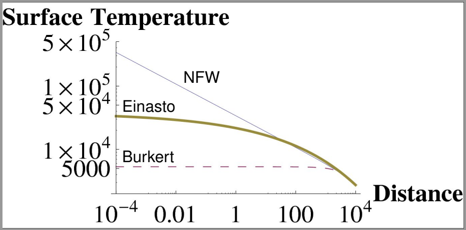

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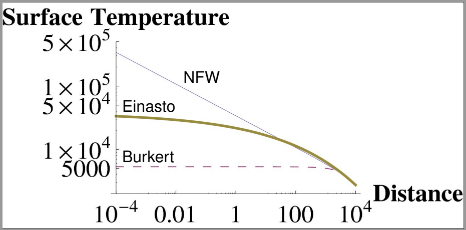

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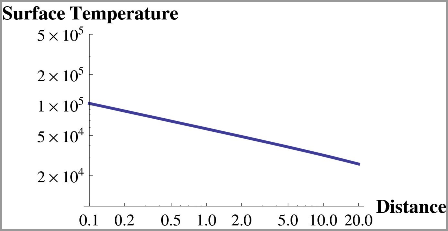
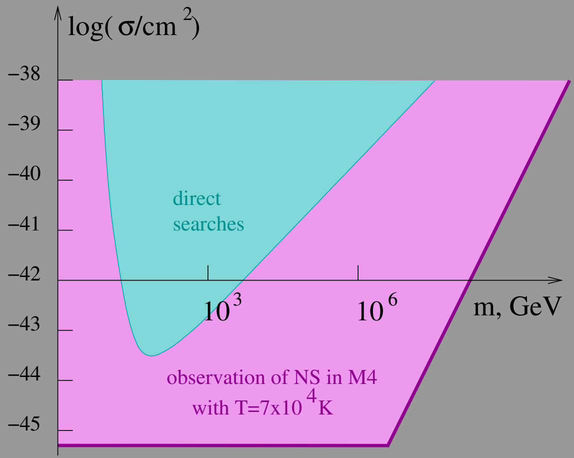


- For instance, observation of a cold NS close to the center of M4 would give the following constraints:



Caveats

- Neutron stars are difficult to observe, and even more difficult is to establish their temperature.
- The temperature of interest — $T \sim 10^5$ K — falls into UV band. Galactic center is not transparent in this band.
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- In some models WIMPs cannot annihilate (e.g., asymmetric DM models)
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White Dwarfs

- White dwarfs are formed from solar-mass stars which are not heavy enough to ignite next chain of nuclear reactions at some stage.
- The white dwarf progenitor accumulates WIMPs for long time of order 10 Gyr. The WIMPs thermalize and form the cloud in the center of the star. WIMPs with spin-dependent cross section may accumulate faster because the constraints on the cross section are weaker.
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- Once the black hole is formed, it starts accreting matter. It has been argued *[Giddings, Mangano, PRD78, 035009 (2008)]* that this happens in the Bondi regime. The BH mass changes according to

$$\frac{dM}{dt} = \frac{4\pi \rho_c G^2 M^2}{c_s^3} - \frac{1}{15360\pi G^2 M^2}$$

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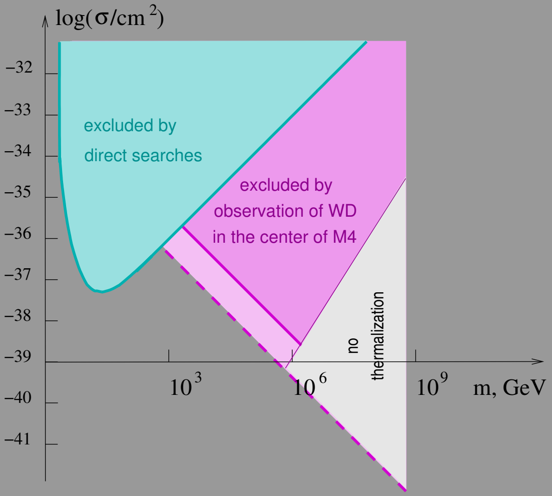
log(σ/cm 2)
−32
−33
−34
−35
−36
−37
−38
−39
−40
−41
10 3
10 6
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m, GeV
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Neutron Stars

- Neutron star progenitors are massive stars with mass $M_* \sim 15 M_\odot$. Such stars capture WIMPs by the spin-dependent cross section during the hydrogen burning stage which lasts ~ 11 Myr.
- This process can compete, in the amount of DM accumulated, with the direct capture by NS considered previously in *[Goldman, Nussinov PRD40, 3221,(1989)]*.
- A substantial part of the DM accumulated by the massive star can be sucked in by the NS after supernova explosion, provided WIMP velocities are mixed sufficiently well by the WIMP-WIMP interaction or by the companion.
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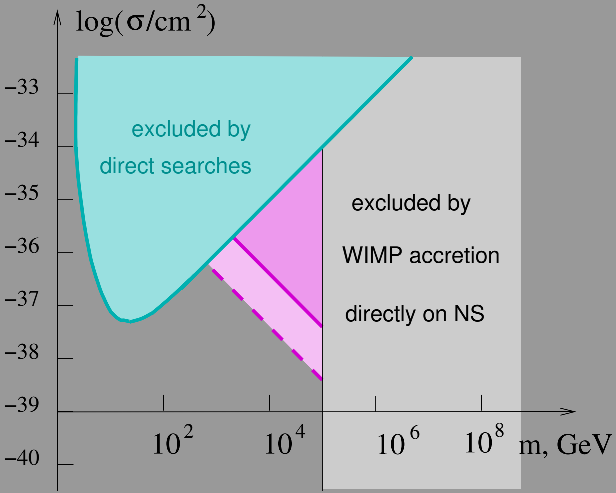

Purple region is excluded by finding a NS in a region with DM density 10^3GeV/cm^3 like it may be present in the centers of globular clusters.

BOSONS

- Gravitational collapse of bosons requires smaller number of particles:

$$M_{\rm crit} = \frac{2M_{\rm Pl}^2}{\pi m_D}\sqrt{1 + \frac{M_{\rm Pl}^2}{4\sqrt{\pi}\, m_D}\sigma_{\rm si}^{1/2}}$$

- Self-gravitation sets in earlier because of the formation of BEC, which requires the DM density

$$n_{\rm BEC} \simeq 4.7\times 10^{28}{\rm cm}^{-3}\left(\frac{m_D}{\rm GeV}\right)^{3/2}\left(\frac{T_c}{10^5{\rm K}}\right)^{3/2}$$

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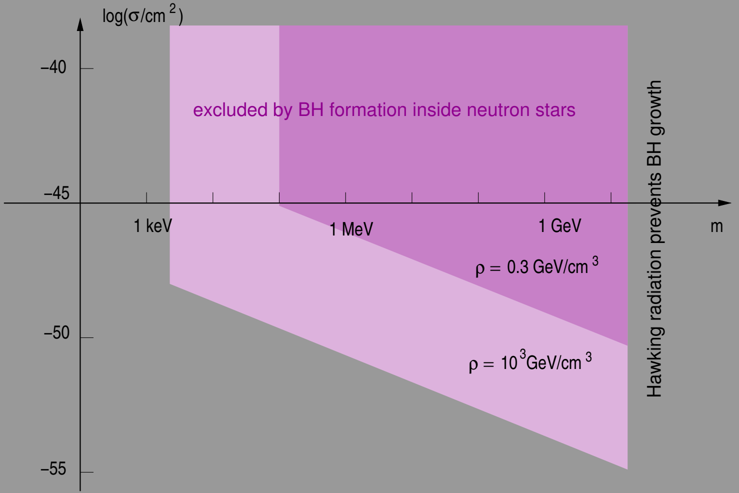
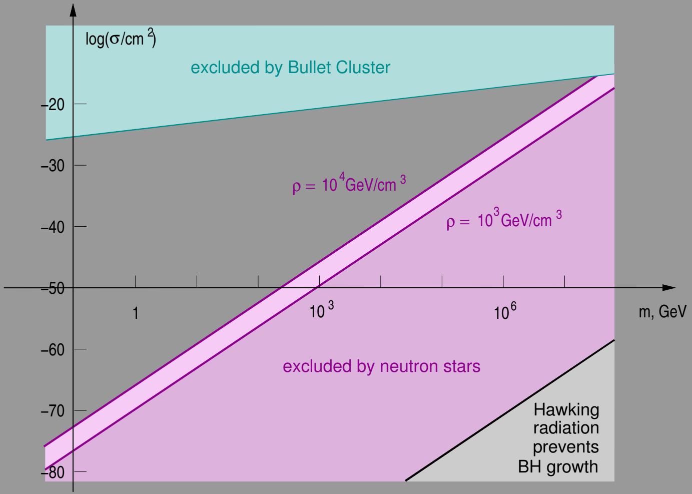


The exclusion regions of the $\sigma_N - m_D$ plane for different ρ_D. The dark purple region is excluded by the already observed NS.



Excluded region in case of the repulsive self-interaction parameterized by the cross section $\sigma_{\rm si}$

Summary

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