DM & COMPACT STARS

P. Tinyakov

Motivation

Capture of DM

After capture

Constraints on primordial BH

Summary

CONSTRAINTS ON DARK MATTER FROM COMPACT STARS

P. Tinyakov

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&
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Based on:

Kouvaris, P.T. PRD 82 (2010) 063531
Kouvaris, P.T., PRD 83 (2011) 083512
Kouvaris, P.T., PRL 107 (2011) 091301
Brayeur, P.T., PRL 109 (2011) 061301
Capela, Pshirkov, P.T. [arXiv:1209.6021]

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Outline

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  Annihilating DM
  Non-annihilating DM

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Motivation

- ► Many (indirect) arguments suggest the existence of dark matter
    - ► Rotation curves of galaxies
    - ► Gas temperature in clusters
    - ► Gravitational lensing
    - ► Structure formation

- ► Combined data from CMB anisotropies, SNe Ia and dynamics of clusters give $\Omega_{DM} \simeq 0.22$

- ► An attractive DM candidate is a weakly interacting massive particle, or WIMP.

- ► From phenomenological point of view, there are three key parameters: m, σ_N, σ_A. We will treat these quantities as free parameters.

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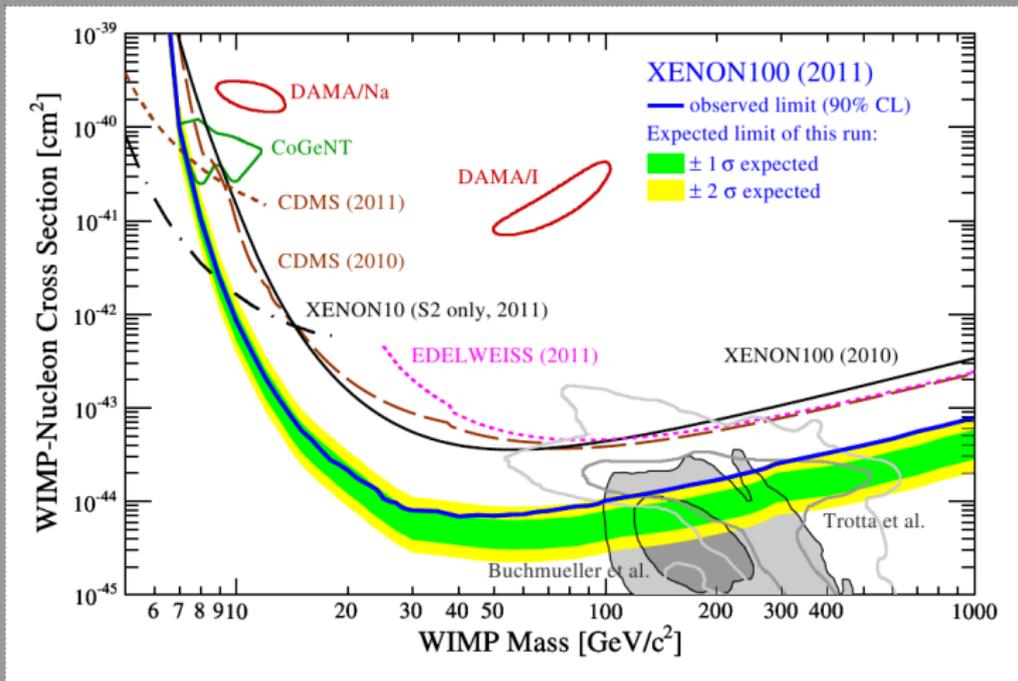
Direct constraints: spin-independent case

XENON100 Collaboration, arXiv:1104.2549

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

Direct constrains: spin-dependent case

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SD elastic, $a_p=0$, $a_n=1$

- CDMS 08+09
- XENON 09
- DAMA (90%/3σ)
- DAMA (90%/3σ) (no channeling)
- CoGeNT
- CoGeNT (90%/3σ) (no exponential BG)
- CDMS Si
- COUPP
- PICASSO

90% C.L.
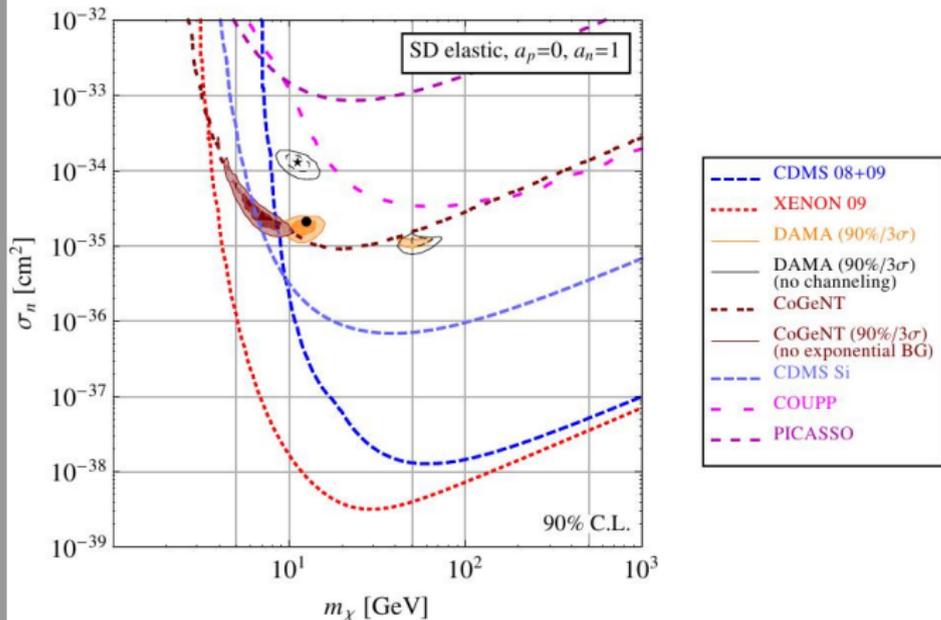
Kopp, Schwetz, Zupan, JCAP 1002 (2010) 014 [arXiv:0912.4264]

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

Possible detection?
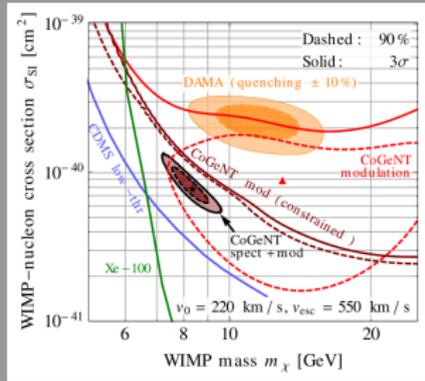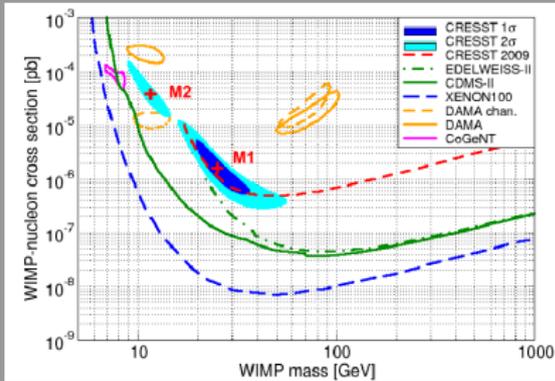
CRESST @ TAUP2011

Fox et al, arXiv:1107.0717

▶ DAMA, CoGeNT and CRESST results inspire models with a light DM with mass around 10 GeV

▶ 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

Constraints on DM may be derived from observations of stars

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▶ 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

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Summary

► More compact objects capture more

▸ Probability of collision during a single star crossing:

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

Critical cross section:

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

▸ Energy loss in a single collision

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

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▶ Assembling everything together, the general expression for capture rate is

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

$$\simeq \begin{cases} \sqrt{6\pi} \dfrac{\rho_D R_g R_*}{m_D v_\infty} f \dfrac{3E_{\mathrm{loss}}}{m_D v_\infty^2} & \text{at } E_{\mathrm{loss}} \ll m_D v_\infty^2 \\[4mm] \sqrt{6\pi} \dfrac{\rho_D R_g R_*}{m_D v_\infty} f & \text{at } E_{\mathrm{loss}} \gg m_D v_\infty^2 \end{cases}$$

▶

Sun: $E_{\mathrm{loss}} \sim 10 \text{ keV} \ll m_D v_\infty^2$ for $m_D \gtrsim 100 \text{ GeV}$

NS : $E_{\mathrm{loss}} \sim 300 \text{ MeV} \gg m_D v_\infty^2$ for $m_D \lesssim 10^6 \text{ GeV}$

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▶ Final capture rate:

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

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

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

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Digression: enhancement of capture rate in binary systems

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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
4h	3.5
8h	4.3
16h	2.8
32h	1.5

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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

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

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

▸ Subsequent evolution depends on whether WIMPS are annihilating or non-annihilating. *Note: because of a very high density, the annihilation may be efficient even for very small σ_A up to 10^{-60} cm^2.*

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Annihilating DM

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▶ 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

$$W = F m_D$$

It should balance the thermal emission

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

▶ $\Longrightarrow$ Minimum temperature of NS

$$T = \left(\frac{F m_D}{4\pi R_*^2 \sigma_B} \right)^{1/4} = 4 \cdot 10^3 \text{ K} \left(\frac{\rho_D}{\text{GeV/cm}^3} \right)^{1/4}$$

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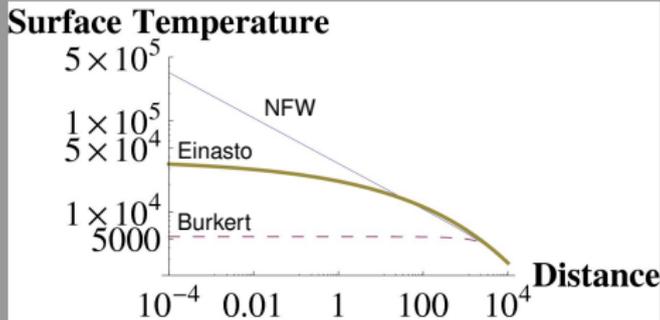**Capture of DM**

After capture
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Constraints on primordial BH

Summary

- The temperature is too low unless NS is in a DM-reach environment. Another factor which helps is small velocity v_∞.

- Galactic center

- Globular clusters [Bertone, Fairbairn, PRD77,043515 (2008)]

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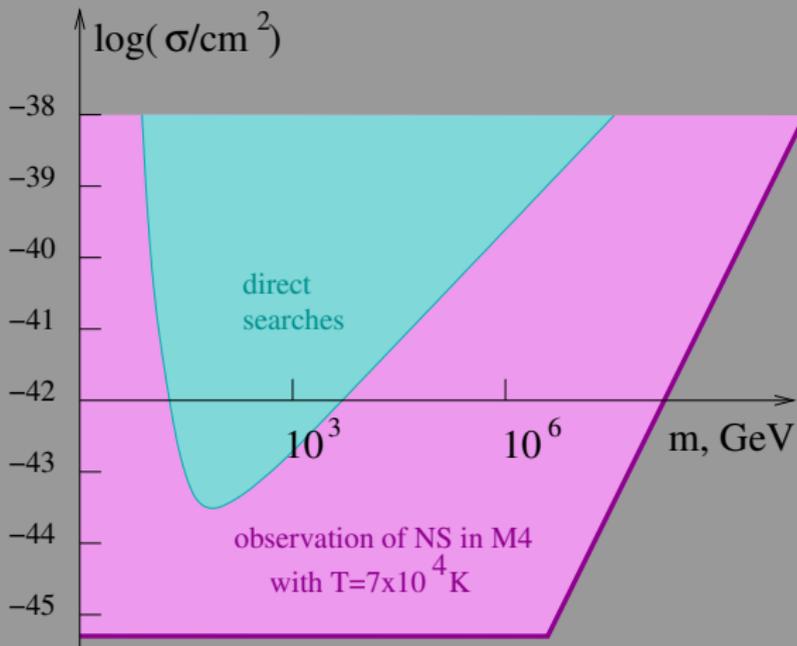
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NFW

Einasto

Burkert

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Surface Temperature

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

Caveats

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Summary

▶ 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.

▶ One has to be sure of high DM density at the location of a NS.

▶ The places where high DM density is expected are far (Galactic center, centers of globular clusters), while the DM density around Earth is not sufficient.

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NON-ANNIHILATING DM

▶ In some models WIMPs cannot annihilate (e.g., asymmetric DM models)

▶ If there is no annihilation, DM may become self-gravitating and collapse into a black hole inside the star, destroying it

▶ The collapse happens differently for fermions and bosons:

  ▶ Fermi pressure makes the collapse more difficult
  ▶ the formation of Bose-Einstein condensate helps the collapse

NON-ANNIHILATING DM

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- If there is no annihilation, DM may become self-gravitating and collapse into a black hole inside the star, destroying it

- The collapse happens differently for fermions and bosons:

  - Fermi pressure makes the collapse more difficult
  - the formation of Bose-Einstein condensate helps the collapse

NON-ANNIHILATING DM

DM & COMPACT
STARS

P. Tinyakov

Motivation

Capture of DM

After capture
Annihilating DM
Non-annihilating DM

**Constraints on
primordial BH**

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▶ The collapse occurs when the Fermi pressure cannot sustain the gravity. The number of DM particles should exceed

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

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

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Constraints from white dwarfs

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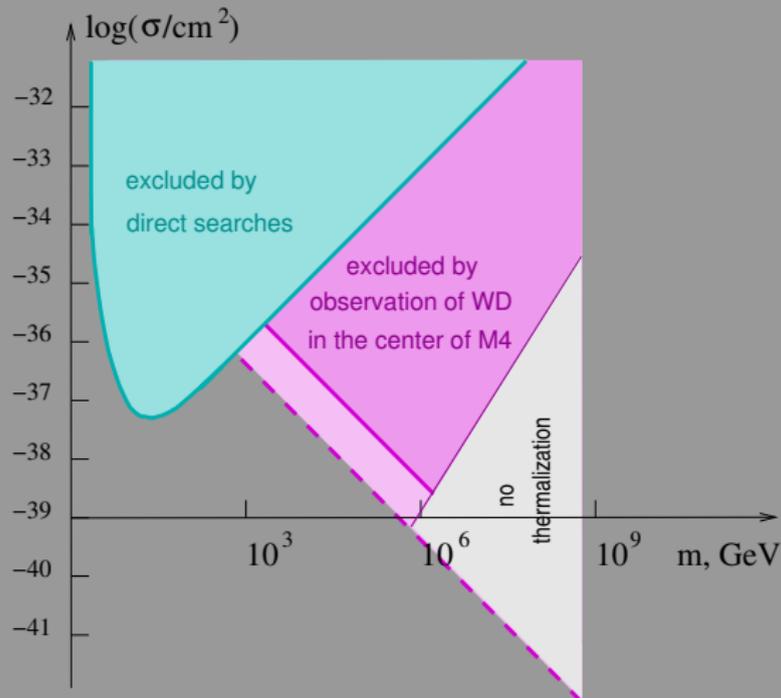
Constraints from neutron stars

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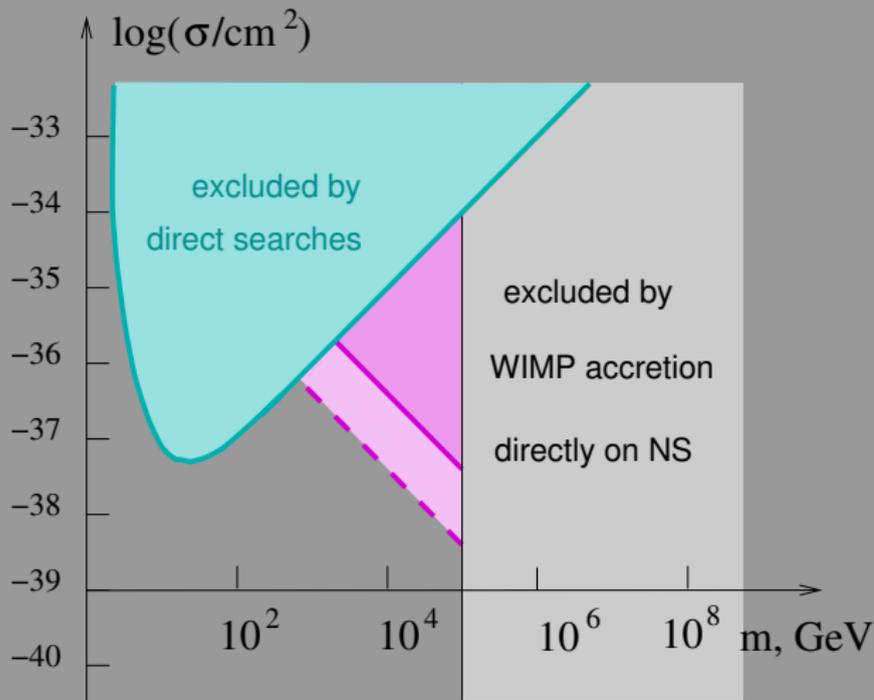
Purple region is excluded by finding a NS in a region with DM density 10^3GeV/cm^3

BOSONS

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▶ Gravitational collapse of bosons requires smaller
number of particles:

$$M_{\text{crit}} = \frac{2M_{\text{Pl}}^2}{\pi m_D}$$

▷ Self-gravitation sets in earlier because of the
formation of Bose-Einstein condensate, which
requires the DM density

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

▷ Condensed WIMPs occupy small region

$$r_{\text{BC}} = \left(\frac{8\pi}{3} G\rho_c m^2\right)^{-1/4} \simeq 1.6 \times 10^{-4} \left(\frac{\text{GeV}}{m_D}\right)^{1/2} \text{cm}.$$

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► Once the critical mass in the condensed state is reached, it collapses into a BH, which destroys the host star in a short time

► No dependence on the WIMP-nucleon cross section as long as it is larger than $\sim 10^{-46}$ cm^2

► At small masses the capture competes with evaporation. Evaporation can be ignored for $m_D \gtrsim 2$ keV

► The heavier the DM particles, the earlier the collapse occurs $\Longrightarrow$ the resulting BH is lighter for larger m_D. For masses $m_D \gtrsim 16$ GeV the Hawking evaporation of the BH starts to compete with its growth due to accretion.

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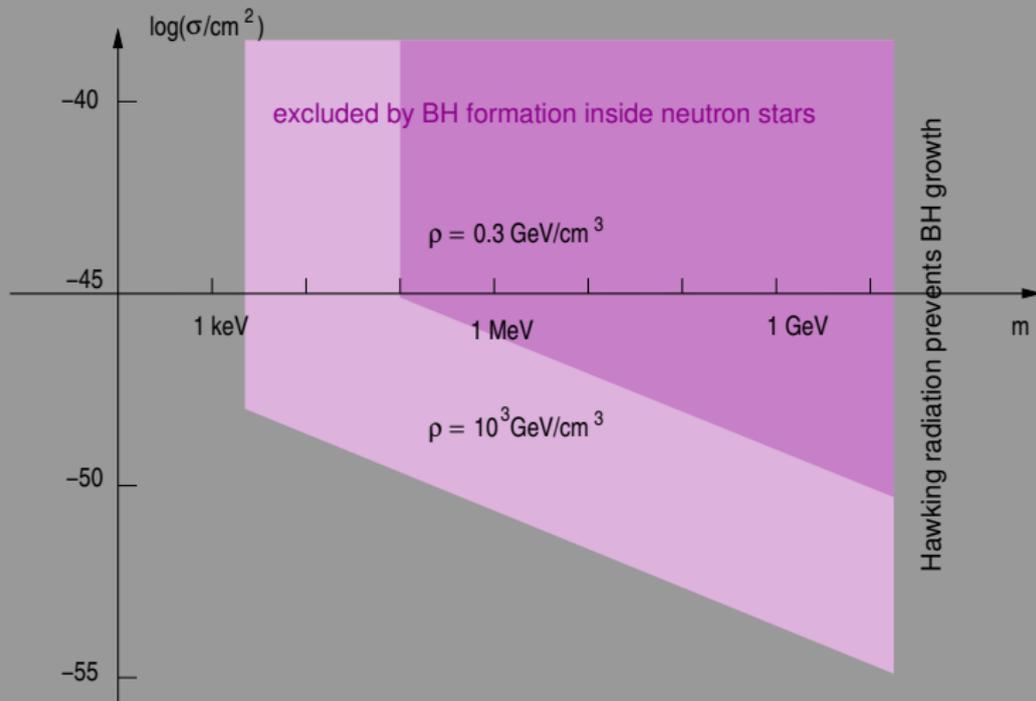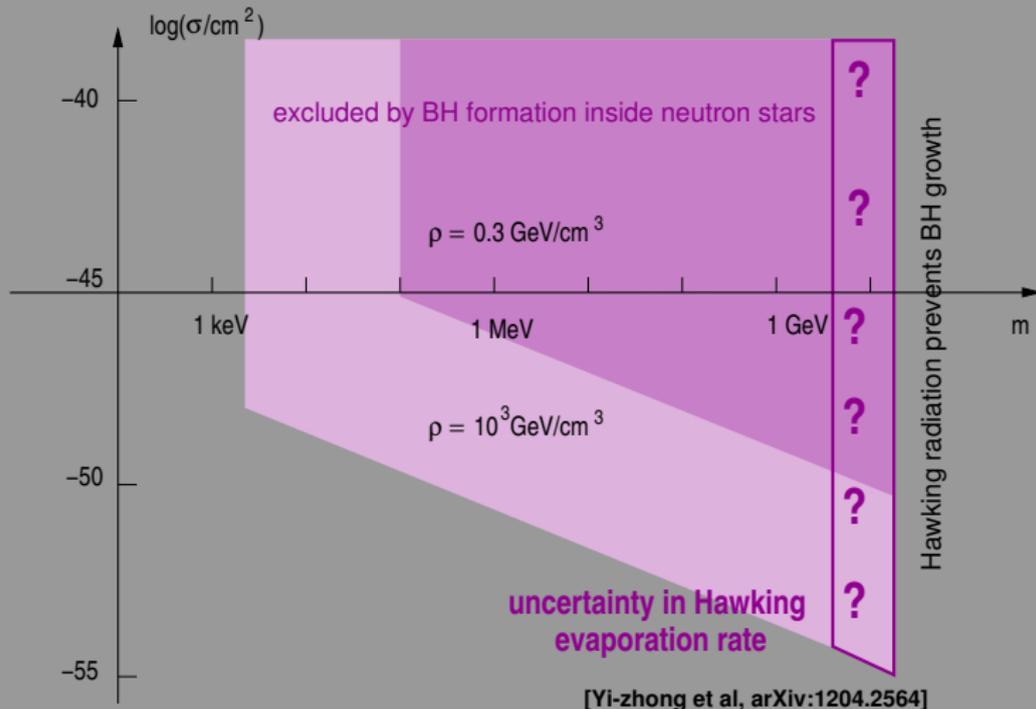**Motivation**

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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.

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Constraints at higher masses?

▸ If the WIMP mass is higher than $\sim$ 10 TeV the self-gravitation of the WIMP cloud may start before the BEC is formed.

▸ One may wonder if in this case the whole WIMP cloud may collapse into a big BH which would not evaporate but instead grow and destroy the whole star.

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▸ No, this does not work! The reason is that the collapse of the WIMP cloud takes time. In this process the cloud gets denser and unavoidably passes through BEC formation at some point. Then small BHs get formed which evaporate very fast with no consequences.

Kouvaris, PT, in preparation

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▶ An interesting possibility (not requiring new particles!) is that DM is composed of the primordial black holes

▷ This possibility is already severely constrained

   ▷ $M_{BH} \lesssim$ (a few) $\times 10^{16}$ g — excluded by Hawking evaporation

   ▷ 10^{26} g $\lesssim M_{BH} \lesssim 3 \times 10^{34}$ g — excluded by microlensing

   ▷ 10^{32} g $\lesssim M_{BH} \lesssim 3 \times 10^{40}$ g — excluded by CMB observations (X-rays produced by accreting matter modify recombination)

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▷ This range of masses can be probed by observations of compact stars

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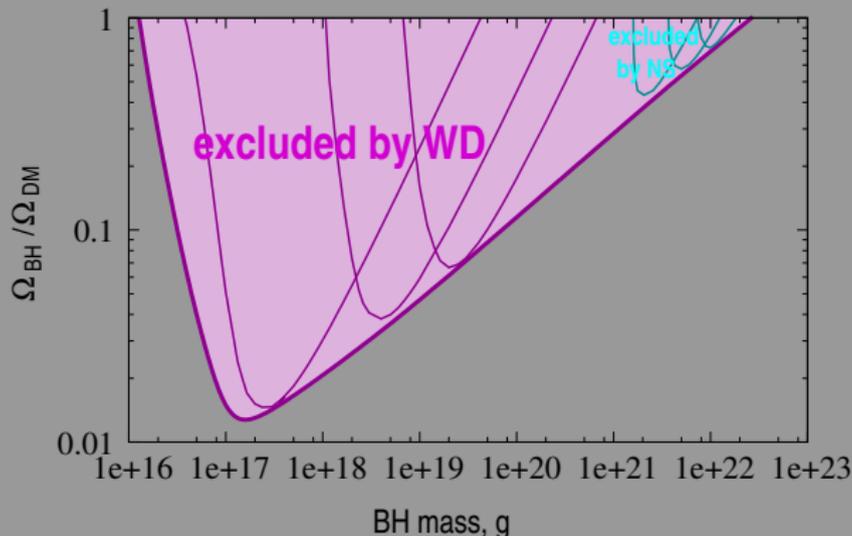
PRIMORDIAL BLACK HOLES

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- ▶ Observations of neutron stars and white dwarfs can give competitive constraints on DM models

- ▶ Bosonic asymmetric DM with no self-interaction are excluded by the already existing observations of NS in the mass range

$$2\,\mathrm{keV} \lesssim m_\mathrm{DM} \lesssim (5-10)\,\mathrm{GeV}$$

- ▶ Primordial black holes as DM are excluded in the mass range

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