CONSTRAINTS ON DARK MATTER FROM COMPACT STARS

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Kouvaris, P.T., PRL 107 (2011) 091301

Capela, Pshirkov, PT, PRD87 (2013) 023507

Capela, Pshirkov, PT, PRD87 (2013) 123524

Hot topics in GR
July-August 2013, Quy Nhan, Vietnam

Outline

MOTIVATION

- Many (indirect) arguments suggest the existence of dark matter with $\Omega_{\text{DM}} \simeq 0.26$
  - Rotation curves of galaxies
  - Gas temperature in clusters
  - Gravitational lensing
  - Structure formation
- The DM was hypothesized to be a new stable “particle”.
- From a phenomenological point of view, the DM sector has three key parameters: m_D, σ_N, σ_A.
- There are many different DM candidates: axion-like particles, sterile neutrinos, WIMPs, primordial BHs, ... In this talk:
  - Weakly-interacting massive particles (WIMPs)
  - Primordial black holes (PBH)

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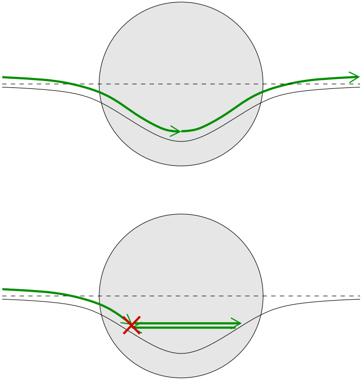
Capture of DM in stars



- With no energy loss there is no capture
- $\Longrightarrow$ Collisions with nucleons of the star are necessary to lose energy

- Cross section of hitting the star:

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

  Second term dominates.

- No gravity:

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

- With gravity

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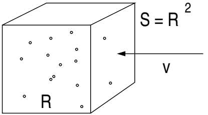

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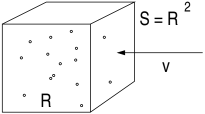

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$$\eta = R_* \sigma_N n = \frac{\sigma_N}{\sigma_\mathrm{crit}}; \qquad \sigma_\mathrm{crit} \equiv \frac{m_p R_*^2}{M_*}$$

Critical cross section:

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

- Energy loss in a single collision (for WIMPs)

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

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- Averaging with Maxwellian distribution, the capture rate is

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

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- Final capture rates:

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

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

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

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

$$\eta_{\mathrm{NS}} = 1 \quad \text{unless } \sigma_N < 6\cdot 10^{-46}\ \mathrm{cm}^2$$

$$N_{\mathrm{tot}} = 3\cdot 10^{39} \quad \text{(over 5 Gyr)}$$

Compare to $M_\odot \sim 10^{57}$ GeV

AFTER CAPTURE

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

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

  - Sun: $r_{\rm th} = 0.01 R_\odot$
  - WD: $r_{\rm th} = 2 \cdot 10^6$ cm
  - NS: $r_{\rm th} = 20$ cm
- What happens next:
  - Annihilating DM: produce heat, neutrinos, ...
  - Non-annihilating DM: may collapse into BH and destroy the star
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Non-annihilating case: asymmetric DM

- An interesting model of DM is an asymmetric DM model where it is assumed that there is an asymmetry in the DM sector similar to the baryon asymmetry (therefore, DM is non-annihilating)
- It is assumed that DM and baryonic asymmetries are created by the same mechanism and are of the same order $\Longrightarrow$ the DM has a mass of a few GeV
- Note that this is close to the mass region favored by DAMA and CoGeNT results
- An additional bonus in these models is that one naturally explains a coincidence $\Omega_{\rm DM} \sim \Omega_B$.

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- Non-annihilating DM (like asymmetric DM) accumulates and eventually becomes self-gravitating and may collapse into a BH.
- The collapse happens differently for fermions and bosons:
  - Fermions:

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

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- Bosonic DM accumulated by NS forms a Bose-Einstein condensate which occupies very small region

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$\Longrightarrow$ Self-gravitation sets in very early.

- At small DM masses the capture competes with the DM evaporation from the NS. Evaporation can be ignored for $m_D \gtrsim 2$ keV
- The heavier the DM particles, the earlier the collapse into BH occurs $\Longrightarrow$ the resulting BH is lighter for larger m_D.
- For masses $m_D \gtrsim 15$ GeV the Hawking evaporation of the BH starts to compete with its growth due to accretion.

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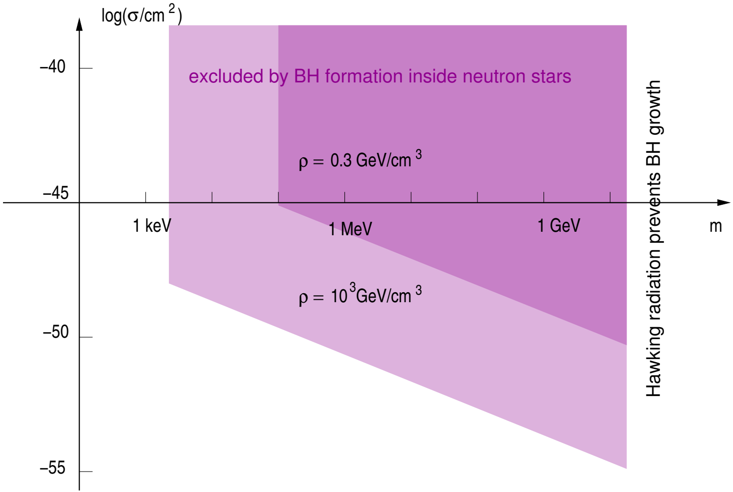

The dark purple region is excluded by the already observed NS.

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- Good candidate for DM (no new particles!)
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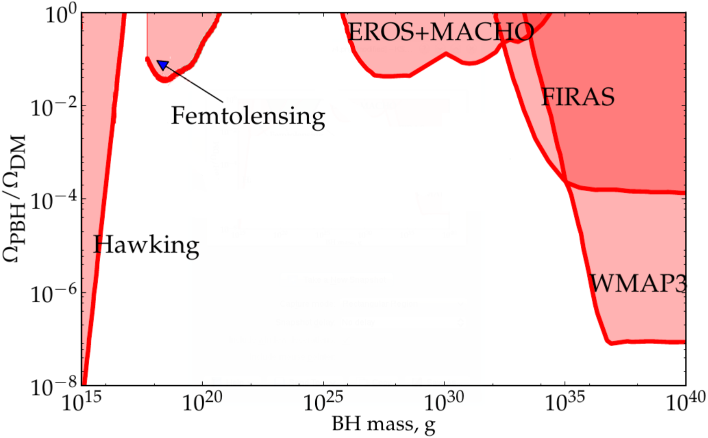

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- There are two ways PBH – if they exist – may end up in compact stars:
    - during star formation
    - during subsequent evolution of a star
- If even a single PBH is captured by NS or WD, it will destroy it in a short time.
- Requiring that the probability to have a PBH inside a NS or WD is much less than 1 imposes constraints on the abundance of PBH with a given mass

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CAPTURE AT STAR FORMATION

Capela, Pshirkov, PT, PRD87 (2013) 023507

- The stars are formed in the collapse of baryonic matter in giant molecular clouds. These clouds have some DM density gravitationally bound to them.
- Collapsing baryons gravitationally drag the DM along (the adiabatic contraction), so some PBHs end up inside the star
- When the star evolves into a compact remnant (NS or WD), some of these PBHs may be inherited by the latter.

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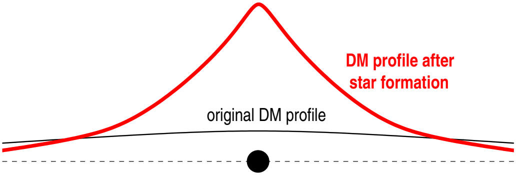

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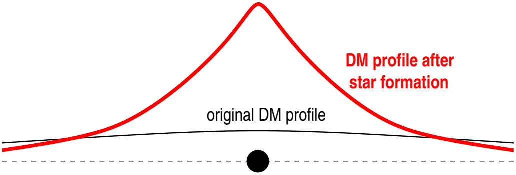

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Capela, Pshirkov, PT, PRD87, 123524 (2013)

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- Energy loss is due to two effects:
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  - Direct accretion of star matter onto a PBH
- Additional complication: high degeneracy of the NS matter. Its effect can be calculated by using the NS models; gives the reduction by a factor ~ 5

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Where to look?

- Best constraints come from sites where the DM density is largest and the DM velocity is smallest
- One such site could be Globular Clusters (GC)
  - GC are gravitationally bound compact systems containing $10^4 - 10^7$ stars, very old $\gtrsim$ 10 Gyr
  - GC are not DM-dominated systems
  - There are two suggested mechanisms of the GC formation: primordial and 'recent'
  - recently formed GC carry little DM — not enough for constraints
  - primordial GCs must have DM cores
  - The evolution of DM in GC can be simulated taking into account adiabatic contraction, tidal stripping and heating by moving stars. One finds $\rho_D \sim 2 \times 10^3\ \mathrm{GeV\,cm^{-3}}$.

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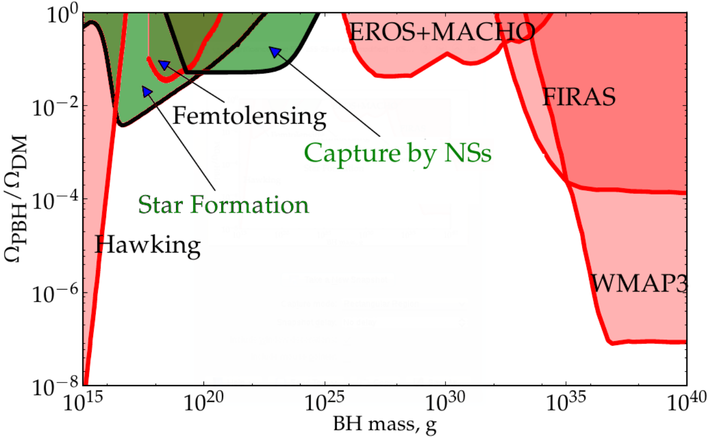
RESULTING CONSTRAINTS

Assuming $\rho_D = 2 \times 10^3$ GeV cm^{-3} in the core of GC, and DM velocity $v = 7$ km/s



Summary

- Observations of neutron stars and white dwarfs in dark-matter-rich environments can give competitive constraints on DM models
- Already existing observations of NS near Earth exclude a large range of parameters of bosonic asymmetric DM, in particular the regions relevant for DAMA and CoGeNT excesses.
- If (some) GC will be shown to have primordial origin, observations of NS and WD in their centers will exclude PBHs as DM in almost entire remaining allowed mass range.

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Summary

- Observations of neutron stars and white dwarfs in dark-matter-rich environments can give competitive constraints on DM models
- Already existing observations of NS near Earth exclude a large range of parameters of bosonic asymmetric DM, in particular the regions relevant for DAMA and CoGeNT excesses.
- If (some) GC will be shown to have primordial origin, observations of NS and WD in their centers will exclude PBHs as DM in almost entire remaining allowed mass range.