Neutron Stars as Dark Matter Refrigerators

Hai-Bo Yu

University of Michigan, Ann Arbor

Pheno 2010, 05/10/2011

Sam McDermott, HBY and Kathryn Zurek, arXiv:1103.5472 [hep-ph]

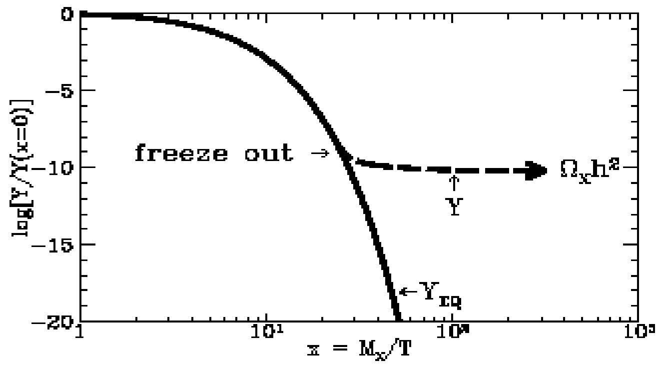
Outline

- Introduction and motivation
  - Thermal WIMP VS. Asymmetric Dark Matter

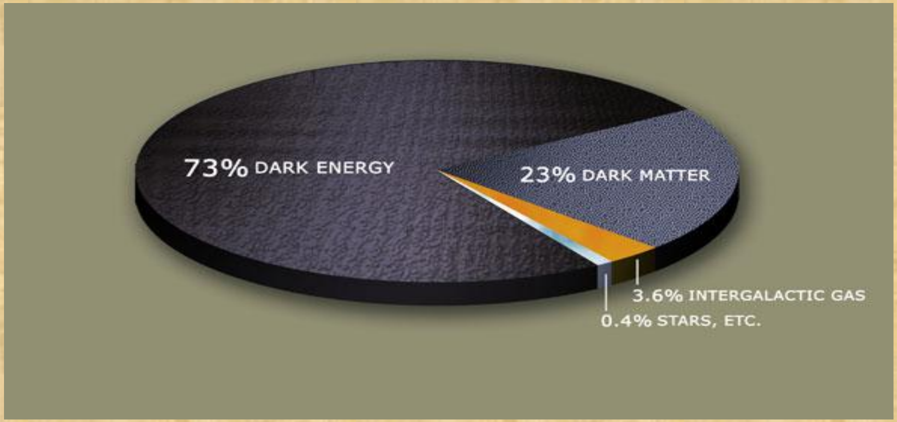
- A journey of scalar asymmetric dark matter (ADM) particles in neutron stars.

- Constraints on DM-neutron scattering cross section from the observed old neutron stars.

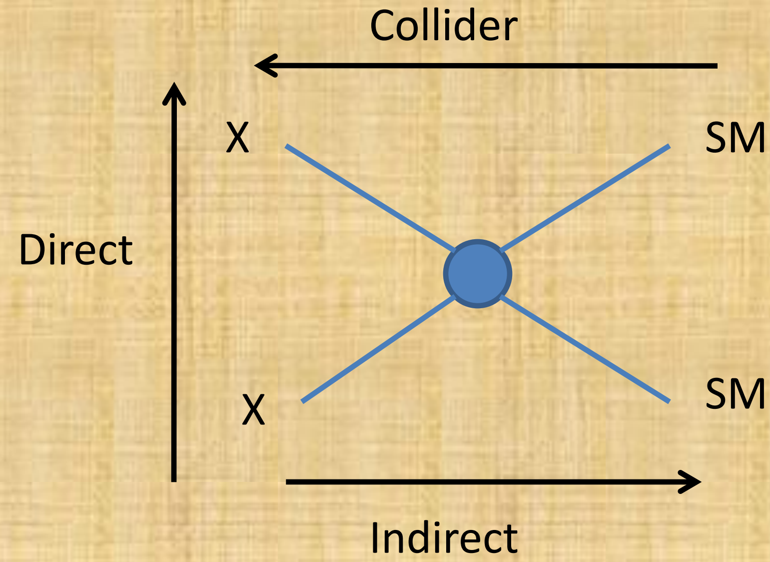
WIMP (WIMPless) VS ADM

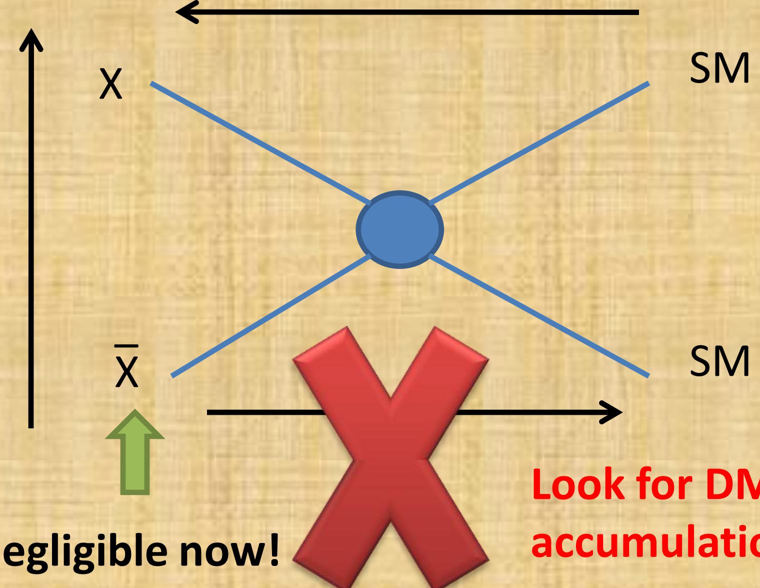


$$\Omega_X \simeq 0.23 \left(\frac{3.0 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle} \right)$$



$$\frac{\rho_{DM}}{\rho_b} \approx 5$$





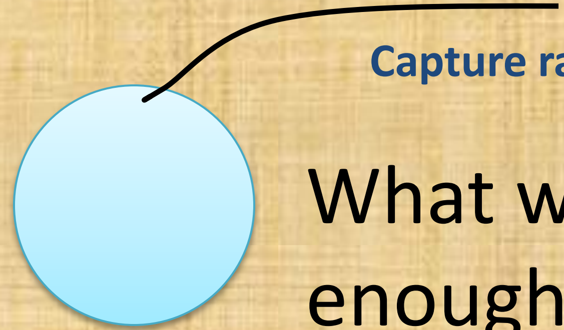
Negligible now!

Look for DM accumulation!

WHY NEUTRON STARS?

- Mass: Msun~10^{57} p
- Density: 1408 kg/m^3
- Ve: 0.002c
- T: 1.57×10^{7} K

- Mass: ~1.44 Msun
- Density: 1×10^{18} kg/m^3
- Ve: 0.6-0.7c
- T: 10^5-10^6 K



Capture rate:

$$C_B \simeq \sqrt{\frac{6}{\pi}}\,\frac{\rho_X}{m_X}\,\frac{v_{esc}^2}{\bar{v}^2}(\bar{v}\sigma_{XB})\xi N_B$$

What will happen if neutron stars capture enough ADM particles?

SPECULATIONS VS. REALITIES

Captured DM particles form a black hole at the center of neutron stars.

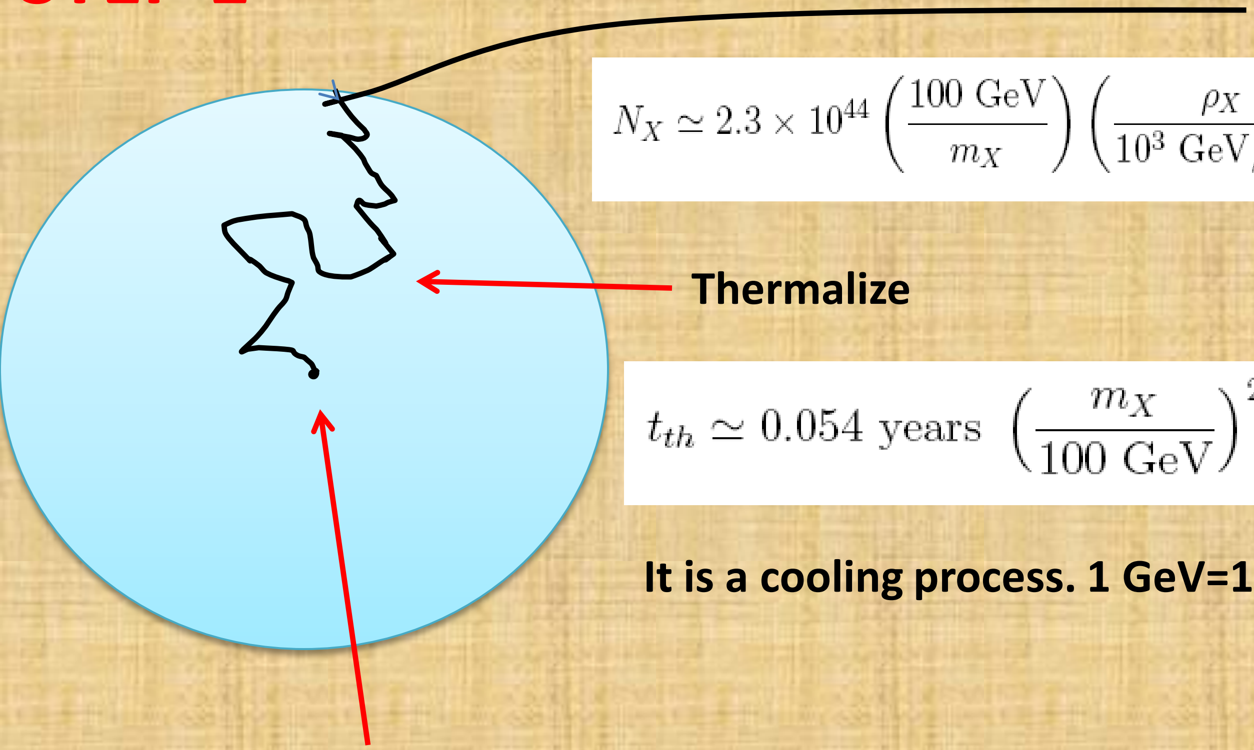
The black hole is hungry, eats everything and destroys the host neutron stars.

Realities:

We have observed many old neutron stars. What speculated does not happen!

CAPTURE AND THERMALIZATION

STEP 1



Capture

$$N_X \simeq 2.3 \times 10^{44} \left(\frac{100\ \mathrm{GeV}}{m_X}\right) \left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm^3}}\right) \left(\frac{\sigma_{XB}}{2.1 \times 10^{-45}\ \mathrm{cm}^2}\right) \left(\frac{t}{10^{10}\ \mathrm{years}}\right)$$

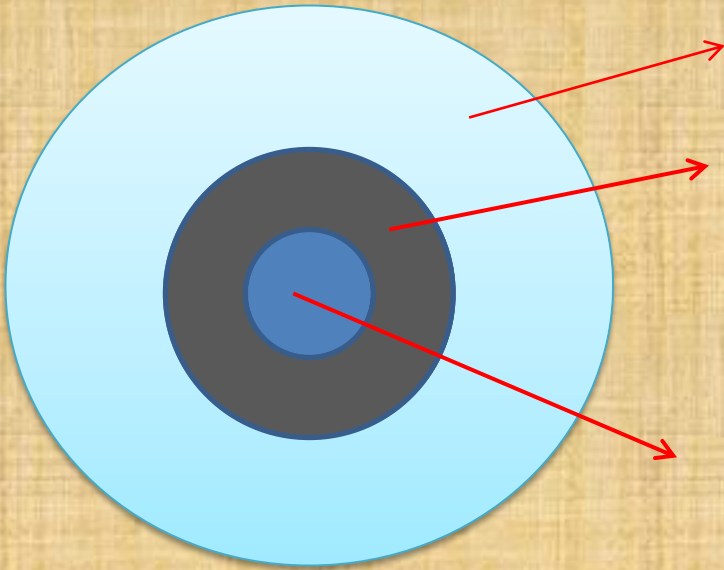
Thermalize

$$t_{th} \simeq 0.054\ \mathrm{years} \left(\frac{m_X}{100\ \mathrm{GeV}}\right)^2 \left(\frac{2.1 \times 10^{-45}\ \mathrm{cm}^2}{\sigma_n}\right) \left(\frac{10^5\ \mathrm{K}}{T}\right)$$

It is a cooling process. 1 GeV=1.2*10^{13} K

Drift to the center

BOSE-EINSTEIN CONDENSATION



$$R_n = 10.6\ \text{km}$$

DM in the thermal state

$$24\ \text{cm}\left(\frac{T}{10^5\ K}\cdot\frac{100\ \text{GeV}}{m_X}\right)^{1/2}$$

DM in the BEC ground state

$$1.5\times10^{-5}\ \text{cm}\left(\frac{100\ \text{GeV}}{m_X}\right)^{1/2}$$

STEP 2

Self-gravitation

$$\frac{3N_X m_X}{4\pi r^3} > \rho_B$$

$$N_{self} \simeq 4.8\times10^{41}\left(\frac{100\ \text{GeV}}{m_X}\right)^{5/2}\left(\frac{T}{10^5\ \text{K}}\right)^{3/2}$$

Without a BEC

$$1.0\times10^{23}\left(\frac{100\ \text{GeV}}{m_X}\right)^{5/2}$$

With a BEC

DM particles collapse. But we need to check another condition.

CHANDRASEKHAR LIMIT

Bosons: gravity VS. zero point energy

$$E \sim -\frac{GNm^2}{R} + \frac{1}{R}$$

Above this limit, the system collapses to a black hole.

$$N_{Cha}^{boson} \simeq \left(\frac{M_{pl}}{m}\right)^2 \simeq 1.5 \times 10^{34} \left(\frac{100\ \mathrm{GeV}}{m}\right)^2$$

Fermions: gravity VS. Fermi pressure

Fermi pressure

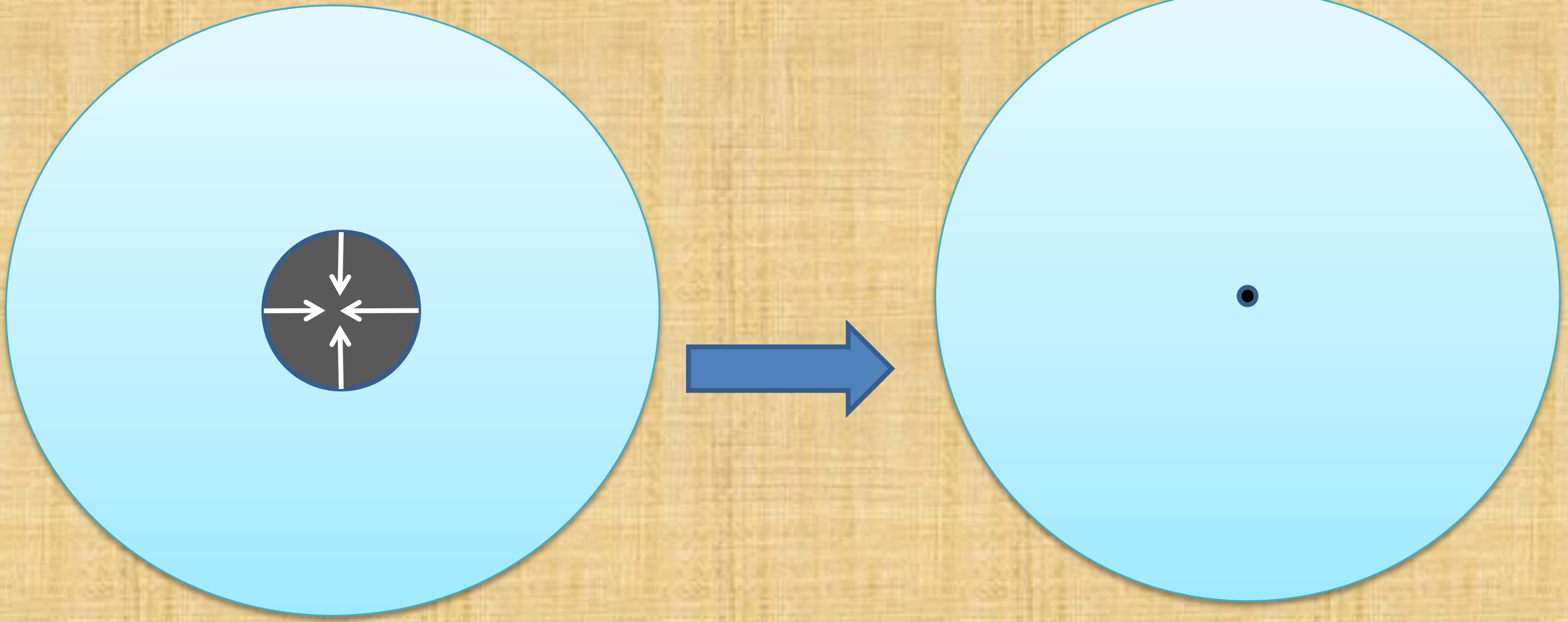
$$E \sim -\frac{GNm^2}{R} + \frac{N^{1/3}}{R}$$

$$N_{Cha}^{fermion} \sim \left(\frac{1}{Gm^2}\right)^{3/2} = \left(\frac{M_{pl}}{m}\right)^3 \simeq 1.8 \times 10^{51} \left(\frac{100\ \mathrm{GeV}}{m}\right)^3$$

Bosons are more ready to collapse.

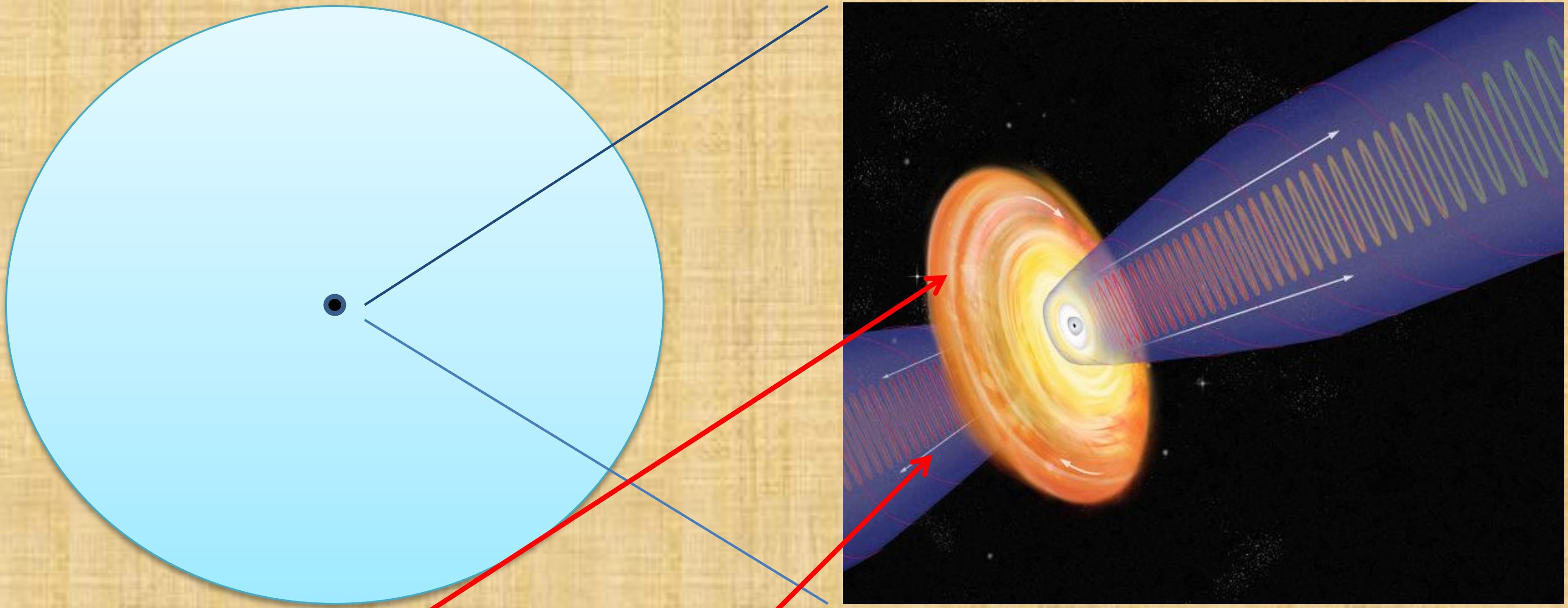
GRAVITATIONAL COLLAPSE AND BLACK HOLE FORMAION

STEP 3



$$N_X > N_{self} > N_{Cha}^{boson}$$

BARYON ACCRETION AND HAWKING RADIATION



$$\frac{dM_{BH}}{dt} \simeq 4\pi\lambda_s \left(\frac{GM_{BH}}{v_s^2}\right)^2 \rho_B v_s - \frac{1}{15360\pi G^2 M_{BH}^2}$$

Baryon accretion

Hawking radiation

Hawking wins if the BH initial mass is less than

$$M_{BH}^{crit} \simeq 1.2 \times 10^{37}\ \mathrm{GeV}$$

DESTRUCTION OF THE HOST STAR

- The formation of the mini black hole can destroy the host neutron star with the following time scale.

STEP 4

$$t \sim \frac{v_s^3}{\pi G^2 \rho_B M_i}$$

$$t \sim 17 \text{ years} \left(m_X/100 \text{ GeV}\right)^{3/2} \left(10^5 \text{ K}/T\right)^{3/2}$$

Without a BEC

$$5.4 \times 10^6 \text{ years } \left(m_X/\text{GeV}\right)$$

With a BEC

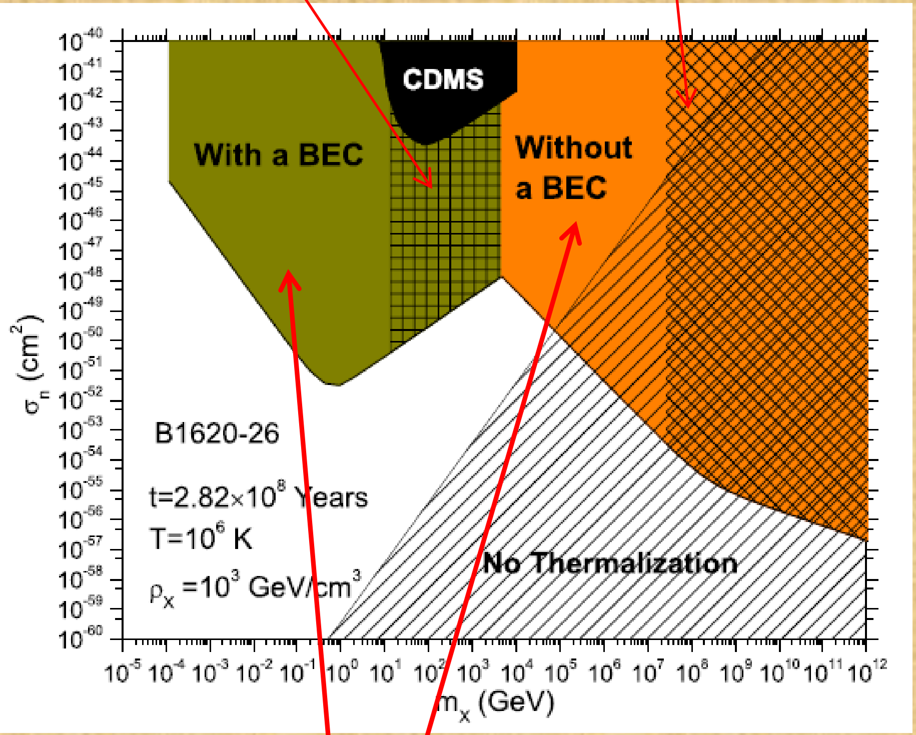
- Observations of old neutron stars put constraints on the DM-neutron scattering cross section.

CONSTRAINTS FROM PULSARS IN M4

The initial black hole mass is too small and it evaporates due to Hawking radiation.

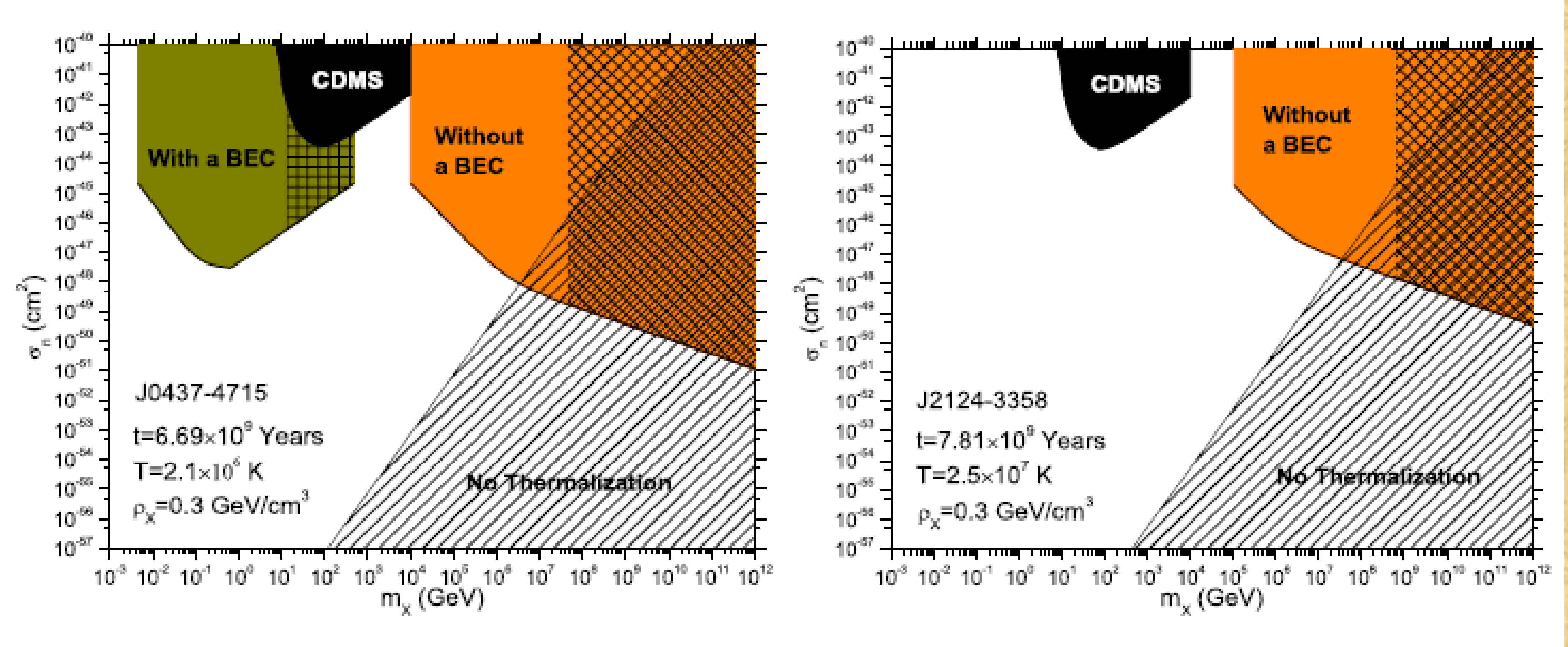
$$M_{BH}^{crit} \simeq 1.2 \times 10^{37}\ \mathrm{GeV}$$

Valid only if Hawking radiation does not heat DM and destroy the BEC.



Hawking radiation is not important.
Excluded by observations of the neutron star.

CONSTRAINTS FROM NEARBY PULSARS



CONCLUSIONS

- Neutron stars are very good refrigerators for dark matter particles.

- The observed old neutron stars put tight constraints on the DM-neutron scattering cross section in a wide DM mass range.