Neutron Stars
versus
Scalar Asymmetric Dark Matter

Sam McDermott

with Hai-Bo Yu and Kathryn Zurek

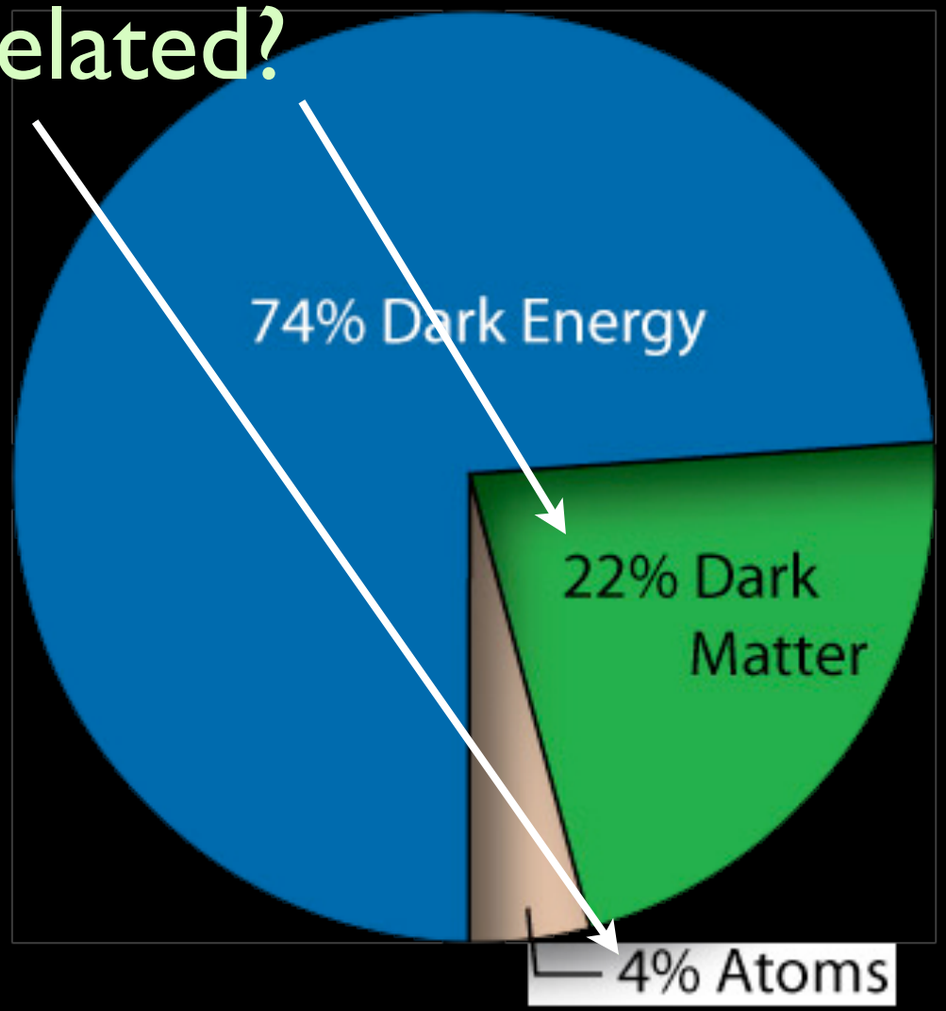
arXiv:**1103.5472 [hep-ph]**

Outline

- Introduction and Motivation
  - WIMP DM vs. Asymmetric DM
- Asymmetric DM in Neutron Stars
  - capture, thermalization, and...
- Constraints

Asymmetric Dark Matter

Maybe the abundances are related?

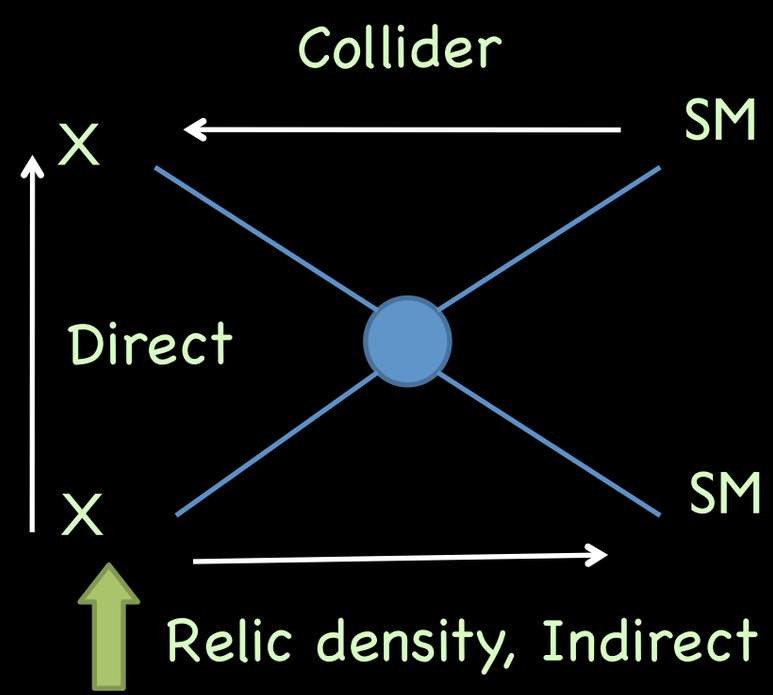


- Some mechanism generates DM and anti-DM number asymmetry. It may connect to the baryon asymmetry.
- DM is a Dirac fermion or complex scalar.

$$\frac{n_{\rm DM}}{n_{\rm SM}} \sim 1 \Rightarrow \frac{\Omega_{\rm DM}}{\Omega_{\rm SM}} \sim \frac{m_{\rm DM}}{m_{\rm SM}}$$

Nussinov (1985); Kaplan, Luty, Zurek (2009); Graesser, Shoemaker, Vecchi (2011); Bell, Petraki, Shoemaker, Volkas (2011)...

WIMPS vs. ADM

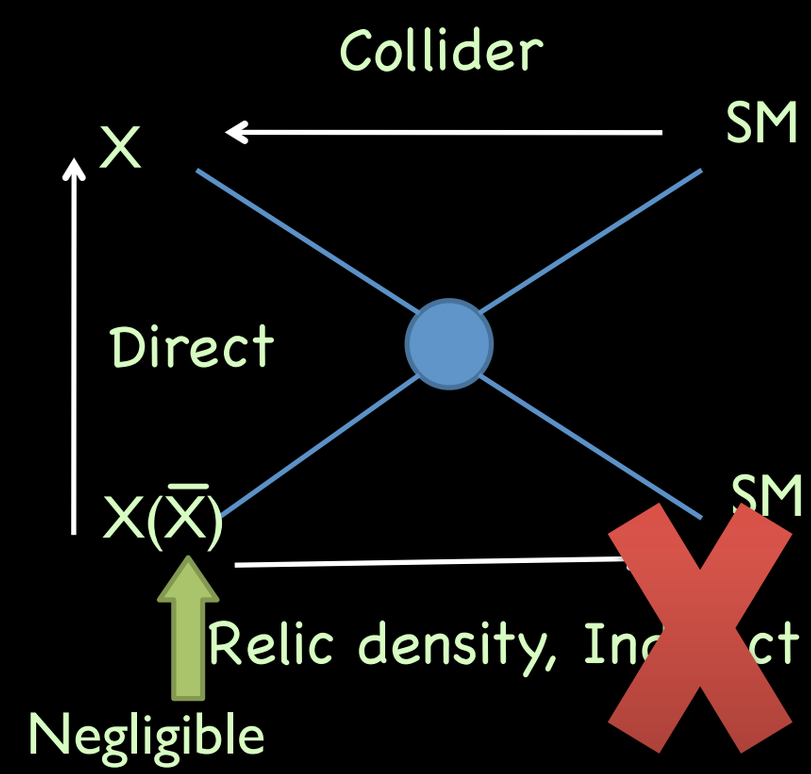


WIMPS

- Three different and well-explored routes to discovery

ADM!

- Production mechanism (hence, the relic population) is asymmetric, like the SM
- No annihilations leads to accumulation



Accumulation of ADM

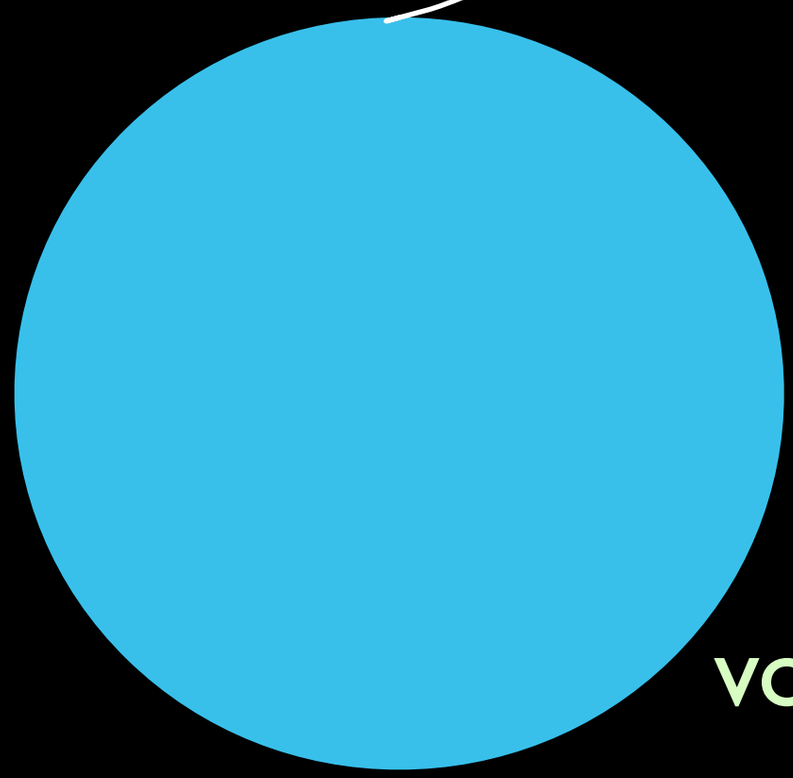
- ADM encounters SM particles off of which it may scatter
- Over time, very dense environments will accumulate many ADM particles
- Stars are very dense, and neutron stars are the densest stars

$M_\odot$	Mass	$1.4 M_\odot$
$1.4 \times 10^3 \ \mathrm{kg/m^3}$	density	$10^{18} \ \mathrm{kg/m^3}$
$\sim 2 \times 10^{-3} \ c$	v_{esc}	$\sim .6 \ c$

Easier to just pass through

Much more likely to be trapped, and much harder to escape!

ADM in the Neutron Star
1 : Capture

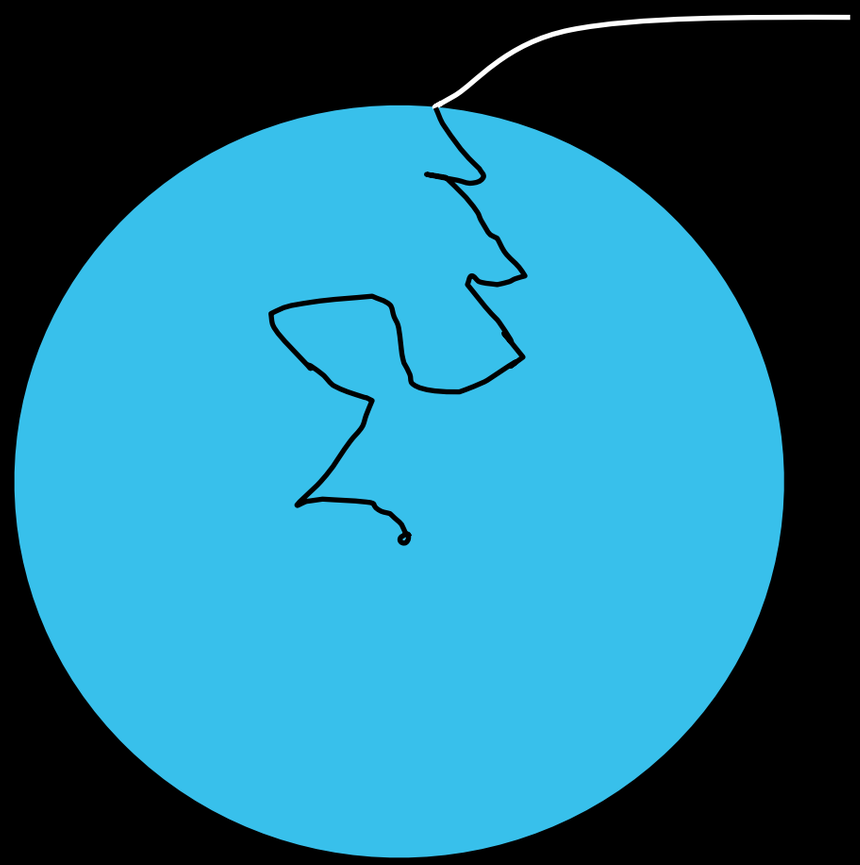


$$\frac{dC_B(r)}{dV} \simeq \sqrt{\frac{6}{\pi}} n_X(r) n_B(r) \xi \frac{v(r)^2}{\bar{v}^2} (\bar{v}\sigma_{XB})$$

The differential capture rate per unit volume sets the total number of particles

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

ADM in the Neutron Star II : Thermalization



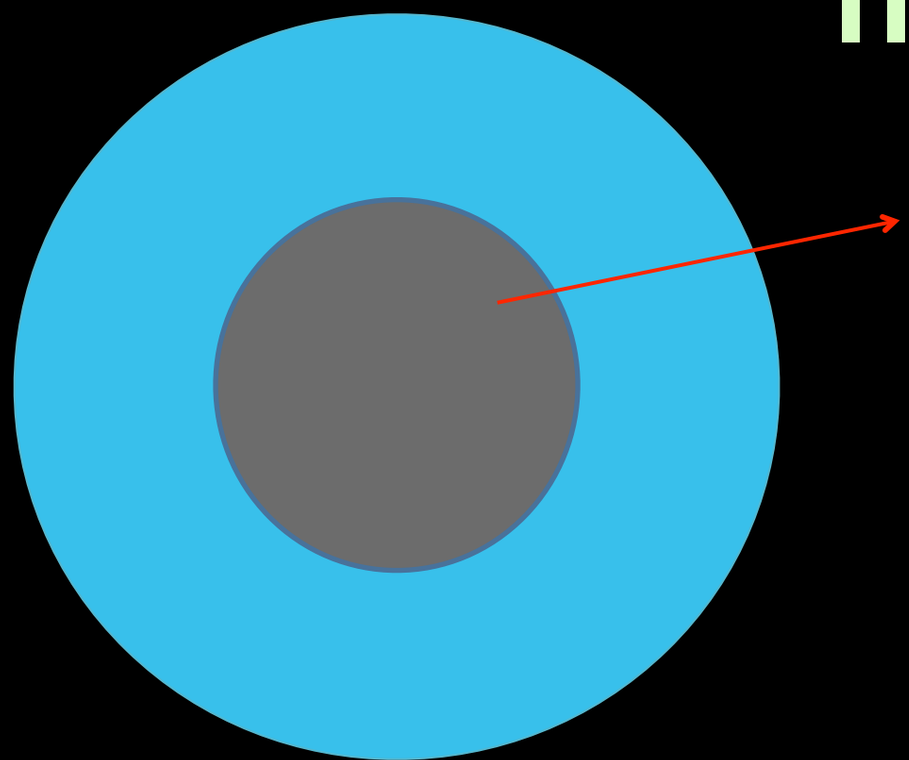
$$\frac{dE}{dt} = -\xi n_B \sigma_n v \; \delta E$$

The ADM particle will scatter many times with SM particles, eventually attaining thermal equilibrium

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

$$r_{th} = \left(\frac{9T}{4\pi G \rho_B m_X}\right)^{1/2} \simeq 24 \text{ cm} \left(\frac{T}{10^5 \; K} \cdot \frac{100 \text{ GeV}}{m_X}\right)^{1/2}$$

ADM in the Neutron Star III : Self-Gravitation



$$\frac{3N_X m_X}{4\pi r_{th}^3} \gtrsim \rho_B$$

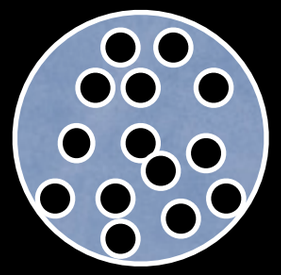
Self-gravity sets in when the density of ADM particles within the thermal radius exceeds the baryon density

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

Too many particles leads to gravitational collapse!

The Chandrasekhar Limit

- Fermions: gravity vs. Fermi pressure $$E \sim -\frac{GNm^2}{R} + \frac{N^{1/3}}{R}$$



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

- Bosons: gravity vs. zero point energy $$E \sim -\frac{GNm^2}{R} + \frac{1}{R}$$

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

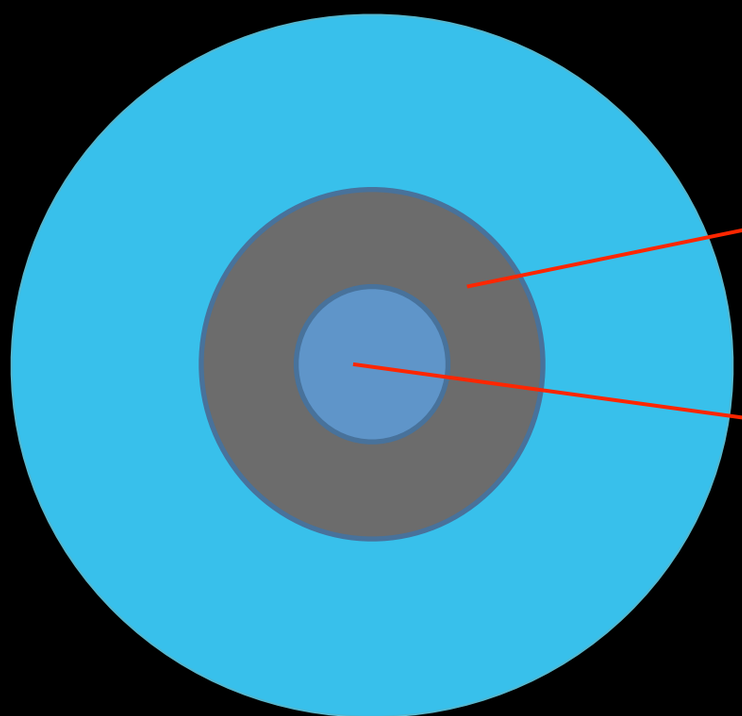
This is less than the number for self-gravity!

(in passing, note that: $M_i^{BH} = m_X N_{Cha}^{boson} = \frac{1}{G m_X}$)

Cool...

- So we've found that neutron stars are good at trapping ADM
- Once it becomes self-gravitating it can collapse to form a black hole
- A few questions remain:
  - can collapse happen more quickly?
  - what happens after collapse?
  - what are the constraints?

ADM in the Neutron Star IV : Condensation



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

$$r_{BEC} \simeq 1.5 \times 10^{-5} \text{ cm} \left(\frac{100 \text{ GeV}}{m_X} \right)^{1/2}$$

The Bose-Einstein condensate (BEC) that forms due to the extreme pressure is very very dense!

$$N_{BEC} \simeq 1.5 \times 10^{34} \left(\frac{100 \text{ GeV}}{m_X} \right)^2 + 1.0 \times 10^{36} \left(\frac{T}{10^5 \text{ K}} \right)^3$$

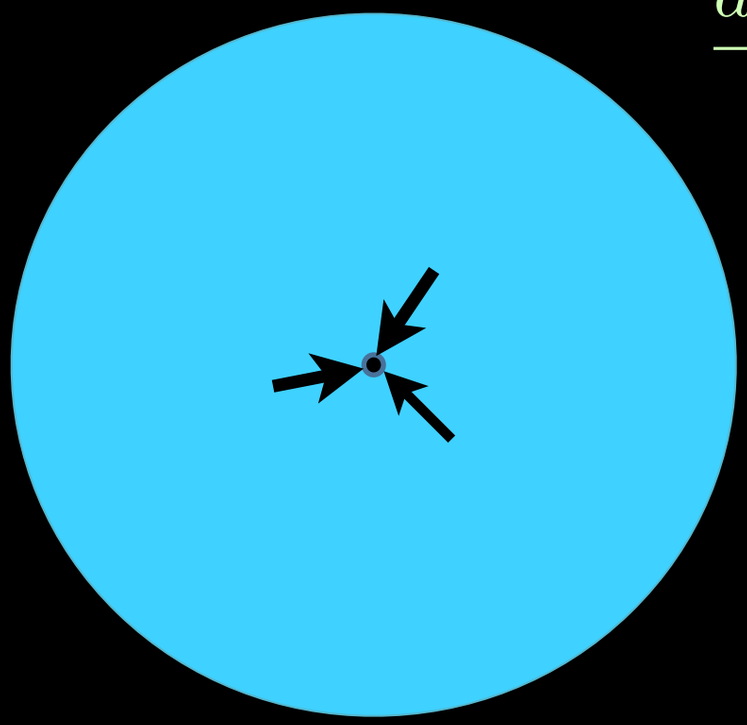
Black Hole Mass Accretion

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

Eating baryons

Eating ADM

Hawking Evaporation



With no BEC,
ADM term negligible.
Critical mass for BH
to survive in this case:

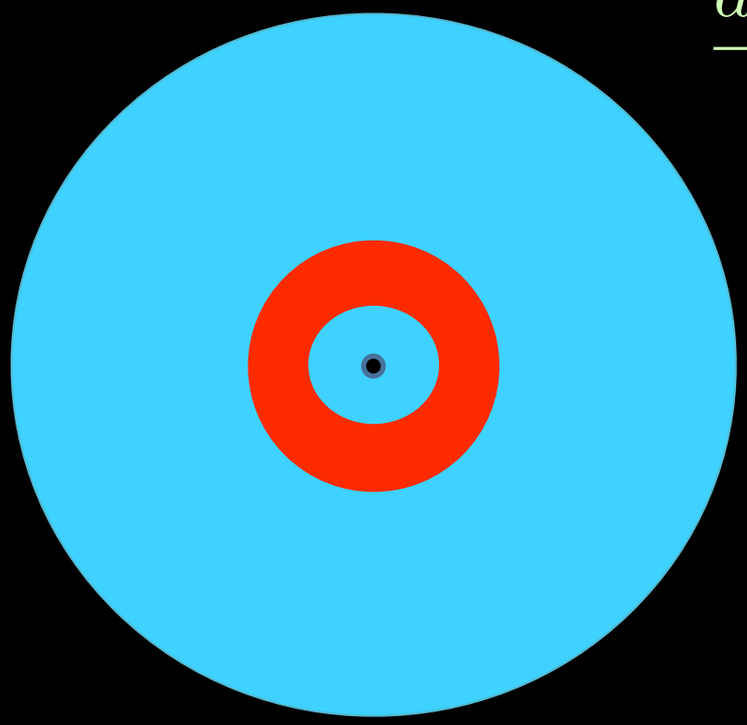
$$M_{BH}^{crit} \simeq 1.2 \times 10^{37}\ \mathrm{GeV}$$

$$m_X \lesssim 2.6 \times 10^6\ \mathrm{GeV}(\mathrm{T}/10^5\mathrm{K})$$

With BEC, ADM term dominates

$$t \sim \frac{v_s^3}{\pi G^2 \rho_B M_i} \simeq 2.3 \times 10^{-5}\ \mathrm{s} \left(\frac{M_\odot}{M_{BH}^i}\right)$$

Black Hole Heating



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

Eating baryons

Eating ADM

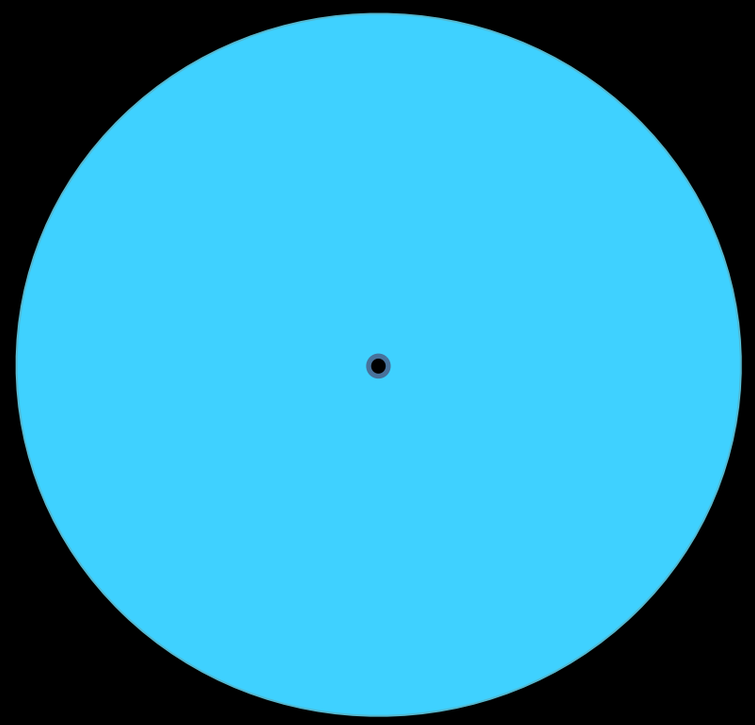
Hawking Evaporation

If the thermal energy from evaporation gets transmitted to....

i) ...the baryons, not much happens

ii) ...the ADM, the phase space can be altered

Black Hole Timescales



The timescales can obey two orderings to form a black hole:

$$t_{\rm BEC} < t_{\rm self} < t_{\rm Cha}$$

$$t_{\rm self} < t_{\rm BEC} < t_{\rm Cha}$$

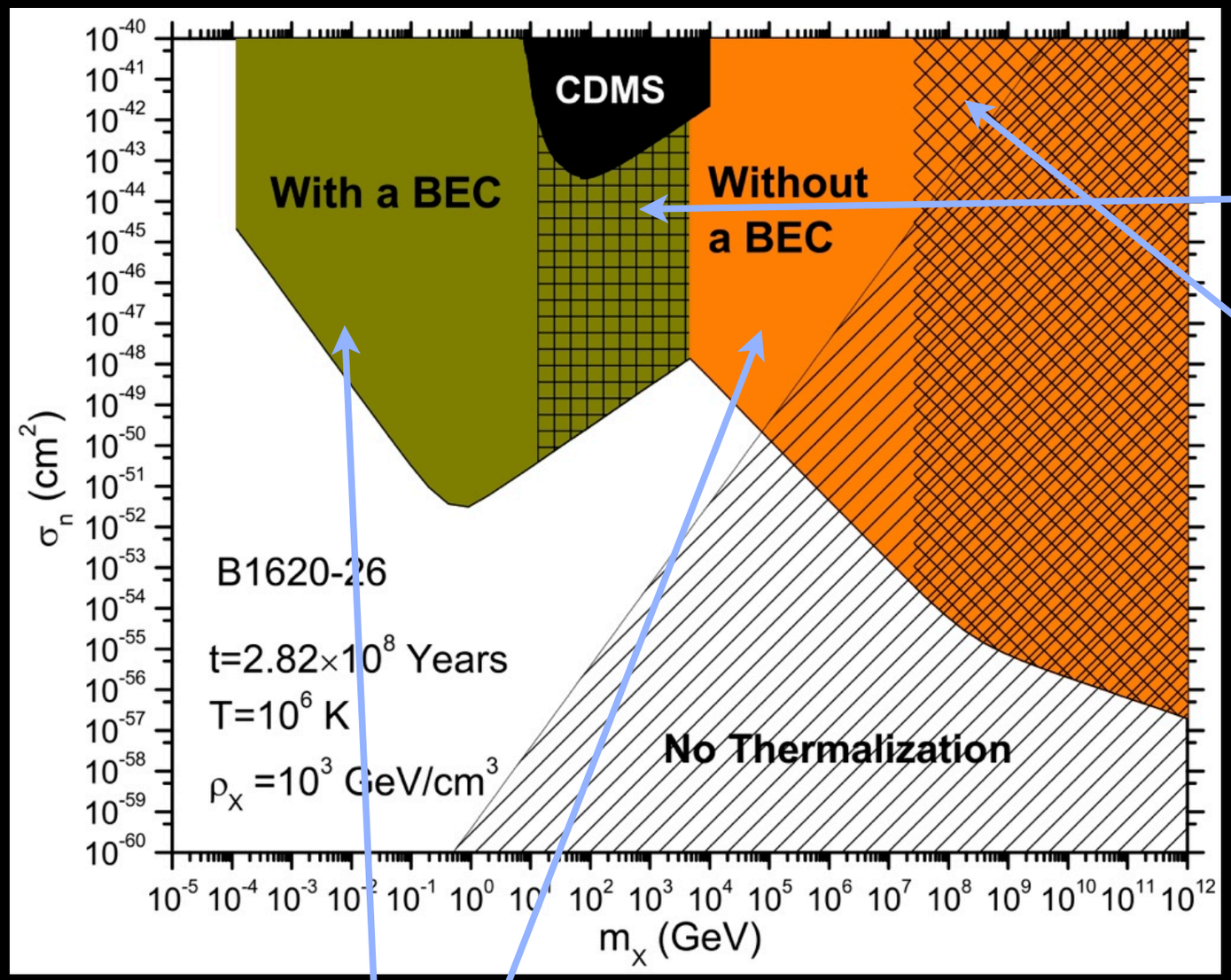
BEC black hole (typically stronger for low mass ADM)

$$t_{\rm Cha} < t_{\rm self} < t_{\rm BEC}$$

conventional black hole (typically stronger for high mass ADM)

Collapse happens for a wide range of masses!

Constraints from M4



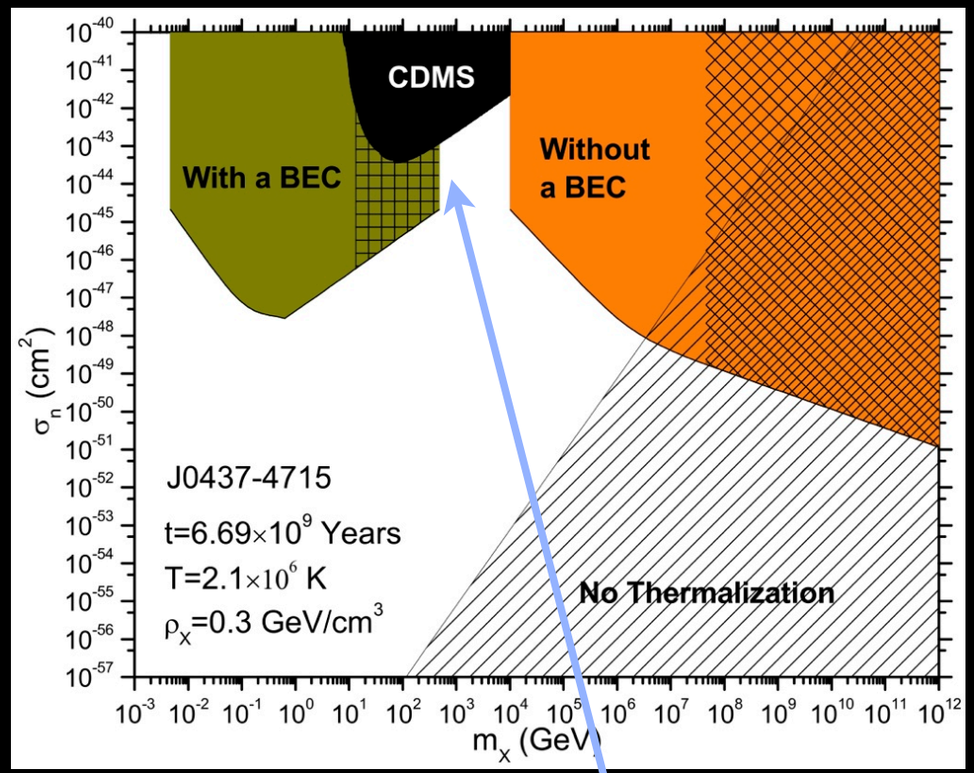
Hawking radiation may be important

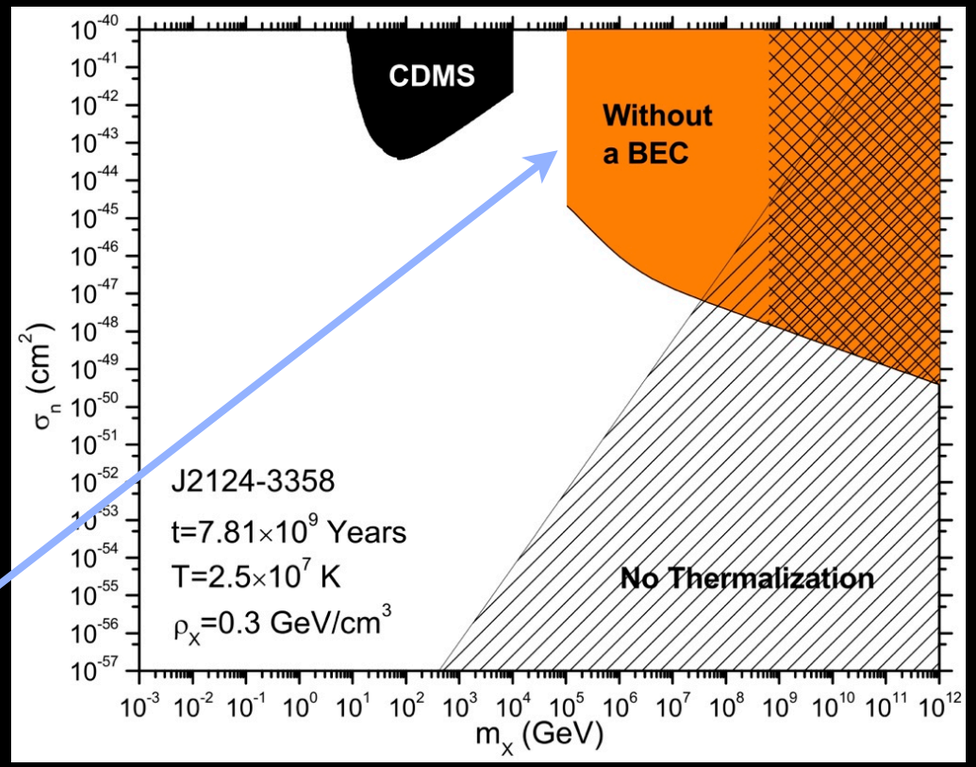
initial black hole mass below critical value

These regions excluded with or without other effects

Very strong constraints, but slightly uncertain local values

Constraints from nearby pulsars





Discontinuities where total cross-section saturates with geometrical cross-section of NS

Conclusions

- ADM has novel phenomenology
- It can accumulate and trigger gravitational collapse in old neutron stars
- Observations of neutron stars in high density environments allow us to constrain the scattering cross-section of the ADM