Dark matter capture in neutron stars with exotic phases

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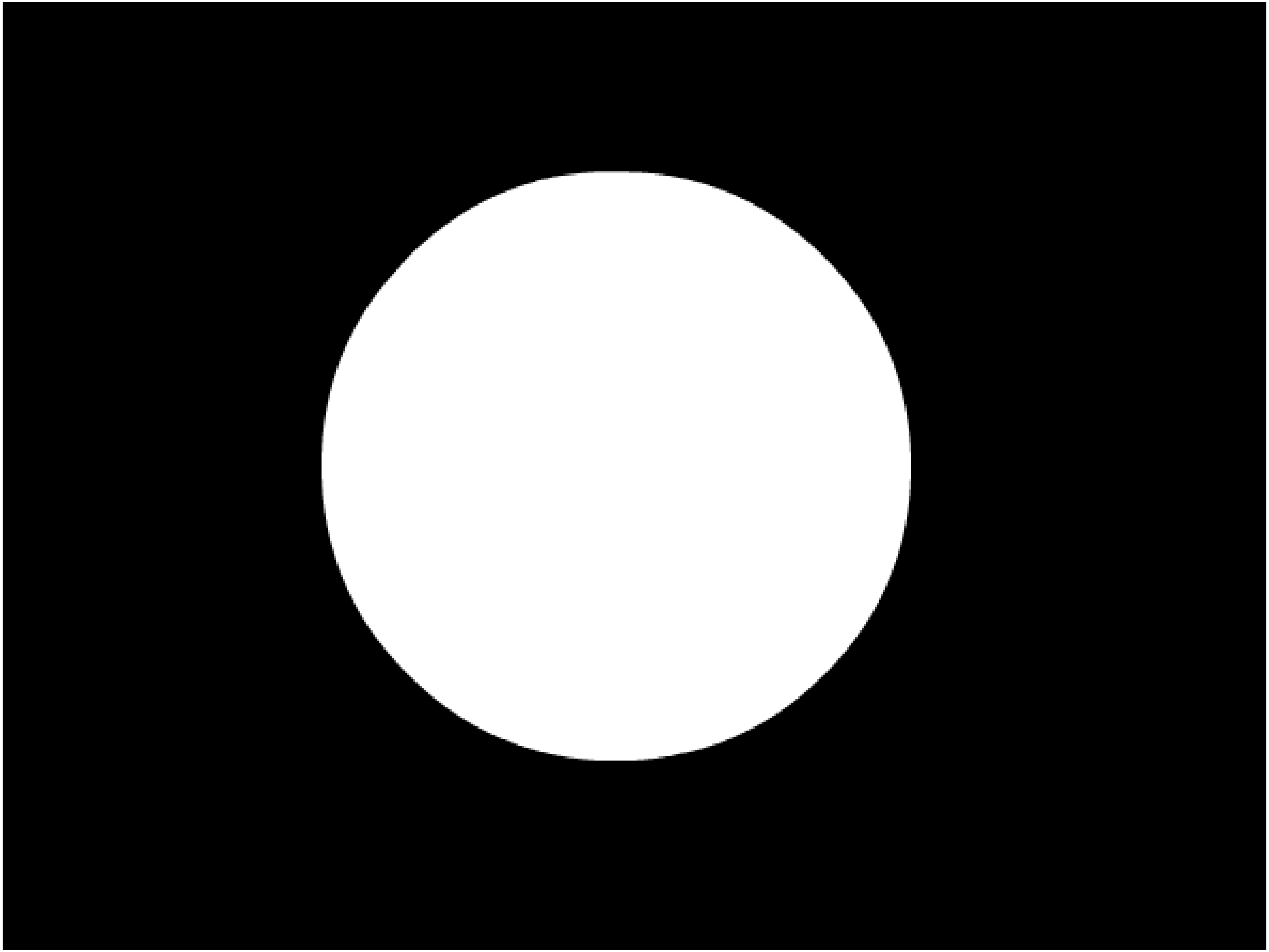
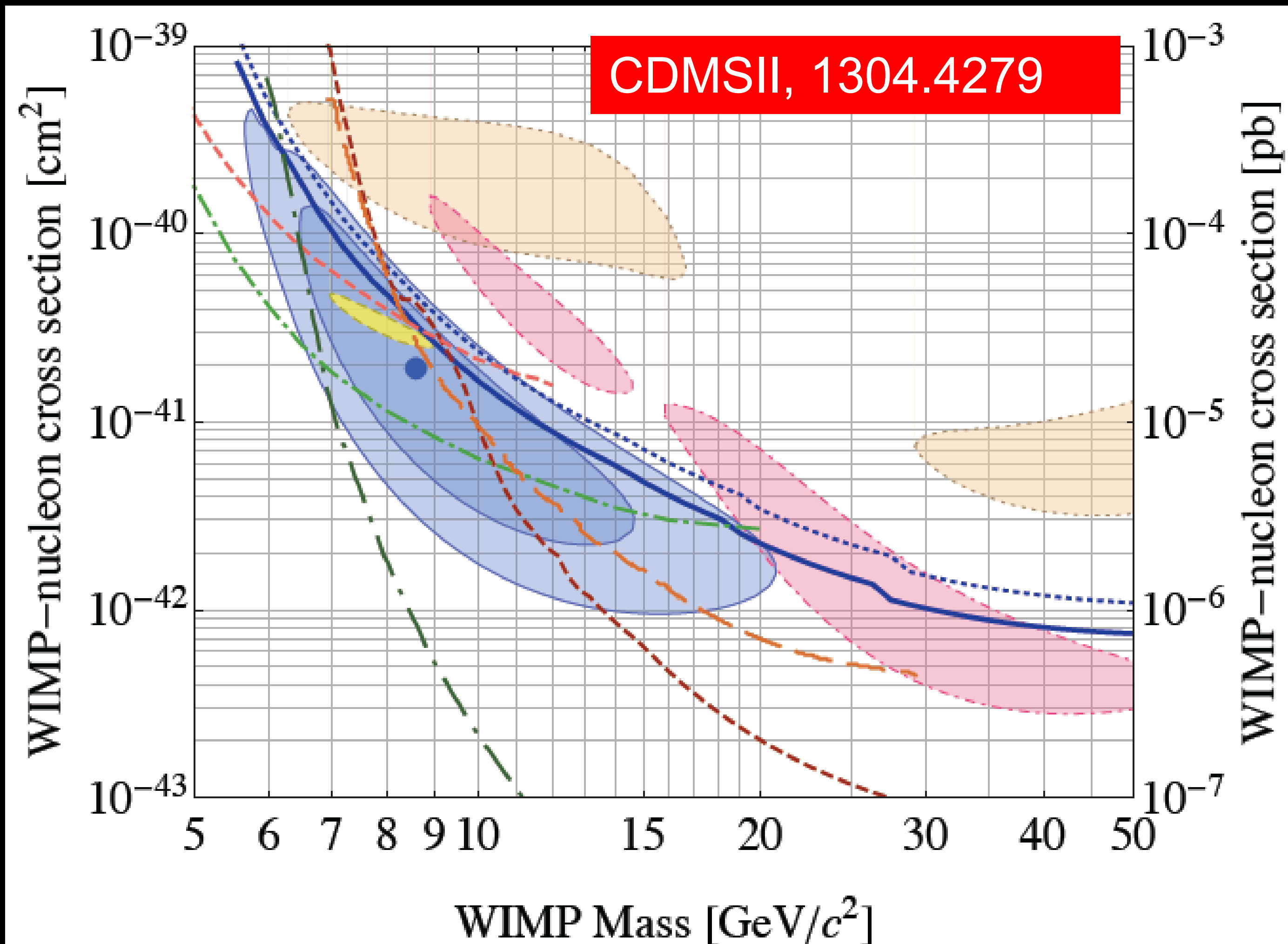


Why the connection between DM and NS?

Possibly constraining WIMP-DM properties via NS



Impacts of dark matter on NS

- NS mass-radius relation with dark matter EOS
- NS heating via dark matter annihilation

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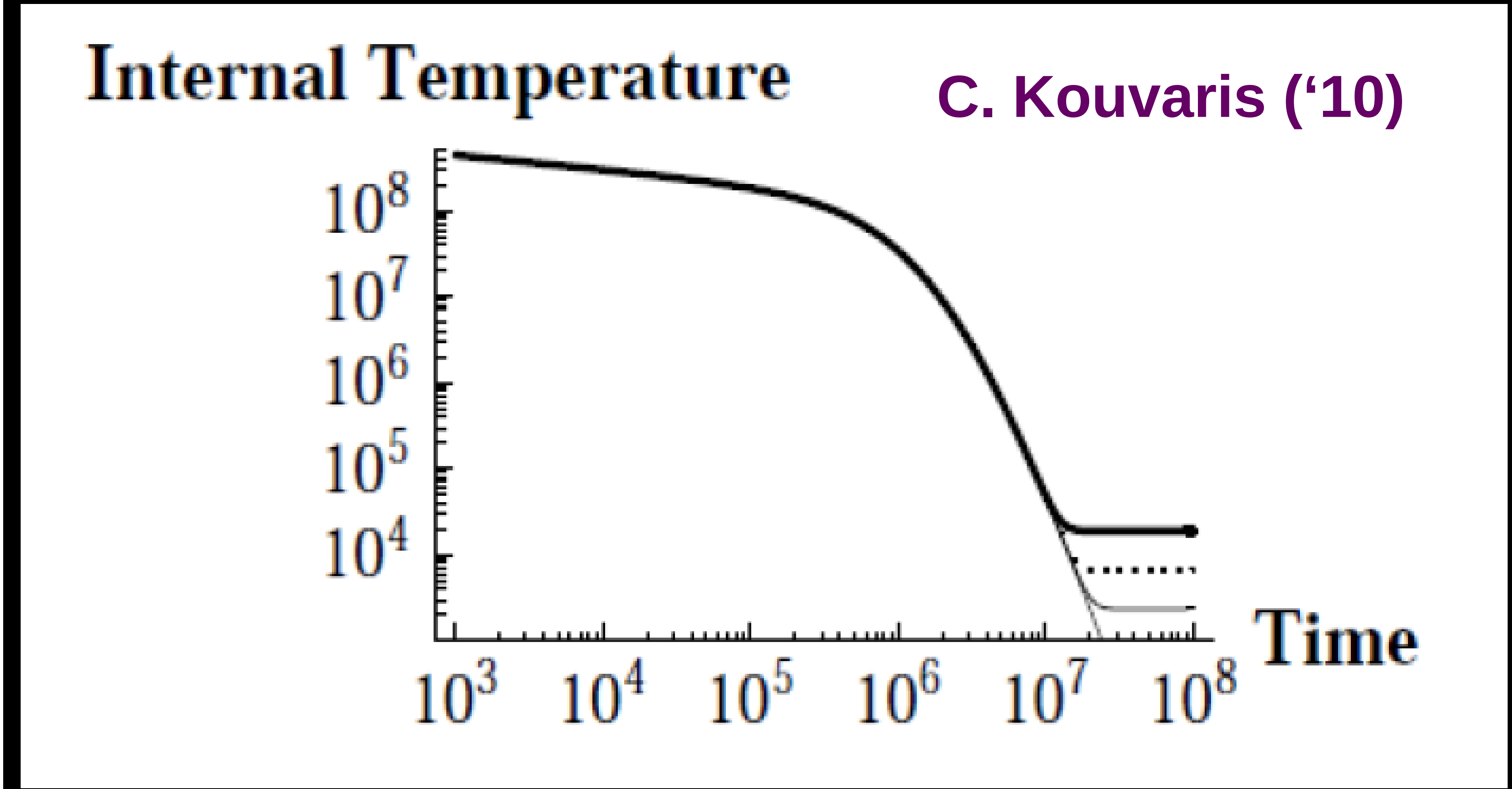
- Dark matter capture in NS and formation of black-hole to collapse host neutron stars

cf) This is not so a new idea. People have considered the DM capture by Sun and the Earth since 80's.

cosmion W. Press and D. Spergel (1984)

Application to NS : Goldman-Nussinov (1989)

Cooling curves of Neutron Star



DM capture in NS *

*Ref.) McDermott-Yu-Zurek (2012)

(1) Accretion of DM

$$\frac{dN_\chi}{dt} = C_B\left(N_\chi\right) \quad C_B : DM\ \ capture\ rate$$

(1) Thermalization of DM (energy loss)

$$\frac{dE}{dt} = -\xi n_B \sigma_{N\chi} v \delta E \quad \sigma_{N\chi} : DM - nucleon\ cross\ \ section$$

(2) BH formation and destruction of host NS

$$\frac{N_{self} m_\chi}{4\pi r_{th}^3 / 3} = \rho_B \quad r_{th} : thermal\ \ radius$$

condition of
self-gravitation

Capturable number of DMs in NS

$$\frac{dN_\chi}{dt} = C_{\chi N} + C_{\chi\chi} N_\chi - C_{\chi a} N_\chi^2$$

Capture rate due to DM-nucleon scattering

Self-capture rate due to DM-DM scattering

DM self-annihilation rate

$$C_{\chi\chi} = C_{\chi a} = 0$$ (no self-capture/annihilation)

$$N_{\chi} = C_{\chi N} t$$

Just linearly grows and $C_{\chi N}$ the growth rate.

Realized when DM carries a conserved charge,

analogous to baryon number.

Below we consider this case

① DM capture rate

The accretion rate (A. Gould, 1987)

$$C_{\chi N} = 4\pi \int_0^{R_n} r^2 \frac{dC_{\chi N}(r)}{dV} dr$$

neutron-DM elastic cross section

$$\frac{dC_{\chi N}(r)}{dV} = \sqrt{\frac{6}{\pi}} n_\chi(r) n_B(r) \xi \frac{v(r)^2}{\bar{v}^2} (\bar{v}\sigma_{N\chi}) \left[1 - \frac{1 - e^{-B^2}}{B^2} \right]$$

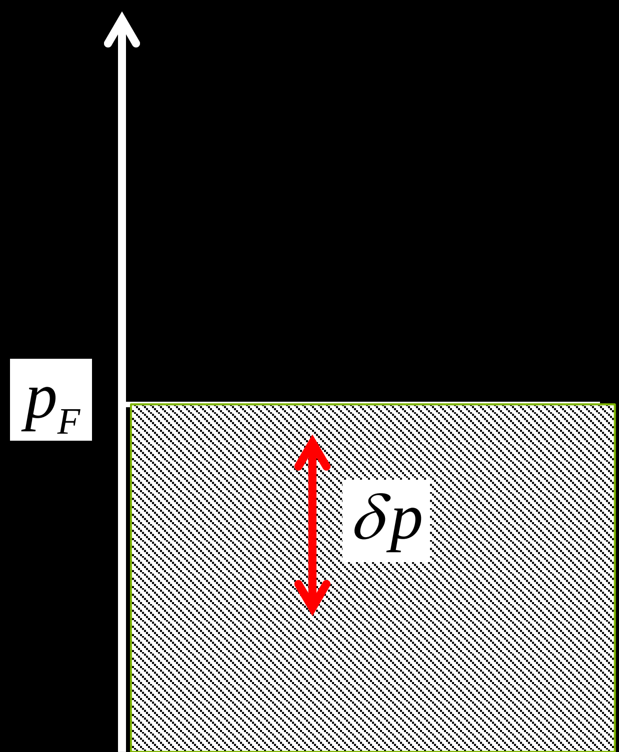
$n_\chi(r)$: *DM density* $\quad n_B(r)$: *baryon density*

$\bar{v} = 220\, km/s$: *DM velocity* $\quad v(r)$: *escape velocity*

$$B^2 = \frac{3}{2} \frac{v(r)^2}{\bar{v}^2} \frac{4\mu}{(\mu - 1)^2}, \quad \mu = \frac{m_\chi}{m_B}, \quad m_r = \frac{m_\chi m_B}{m_\chi + m_B}$$

Capture efficiency factor ξ

In NS, neutrons are highly degenerated



(i) If momentum transfer δp is less than p_F, only neutrons with momentum larger than $p_F - \delta p$ can participate in

(ii) If not, all neutrons can join

$$\xi = Min\left[\frac{\delta p}{p_F},\ 1\right]$$

② Thermalization of DM

After the capture, DMs lose energy via scattering with neutrons and eventually get thermalized

DM mass ≦ 1GeV,

$$t_{th} \approx 7.7\times10^{-5} yrs \left(\frac{2.1\times10^{-45} cm^2}{\sigma_{N\chi}}\right)\left(\frac{0.1GeV}{m_\chi}\right)\left(\frac{10^5 K}{T}\right)$$

DM mass ≧ 1GeV,

$$t_{th} \approx 0.054 yrs \left(\frac{2.1\times10^{-45} cm^2}{\sigma_{N\chi}}\right)\left(\frac{m_\chi}{100GeV}\right)^2\left(\frac{10^5 K}{T}\right)$$

③ Self-gravitation of DM

Then, the DM gets self-gravitating once the total # of DM particles is larger than a critical value

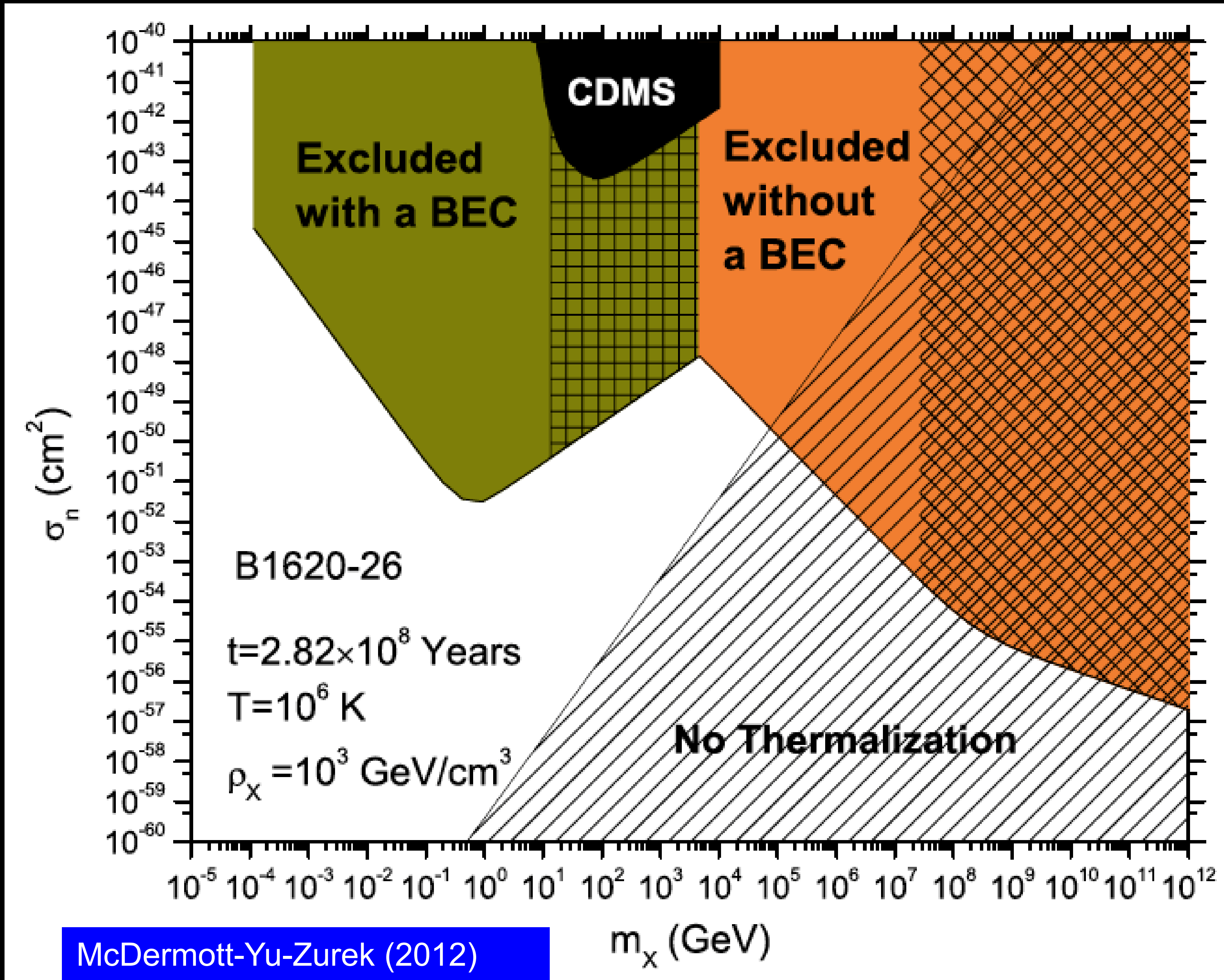
$$\frac{GN_\chi m_\chi^2}{r} > \frac{4\pi G\rho_B m_\chi}{3} r^2$$

$$\Rightarrow \quad \frac{N_{self} m_\chi}{4\pi r_{th}^3/3} = \rho_B$$

If this condition is met, gravitational collapse takes place.

Condition

$$N_{\chi} < N_{self}$$


CDMS
Excluded with a BEC
Excluded without a BEC
B1620-26
t=2.82×10^8 Years
T=10^6 K
ρ_X =10^3 GeV/cm^3
No Thermalization
σ_n (cm^2)
m_X (GeV)
McDermott-Yu-Zurek (2012)

However…

Hadrons inside NS are in EXTREME, and exotic matter states could appear.

(e.g.) neutron superfluidity
meson condensation
superconductivity of quarks

What if those effects are incorporated?

Brief ideas

M. Ruggieri and M.T. (2013)

① Modification of capture efficiency via energy gap
(e.g.) color-flavor-locked (CFL) quark matter

$$\xi = Min\left[\delta p / \left(p_F - \Delta_{CFL}\right),\ 1\right]$$

sizable effect?

② Modification of low-energy effective field theory
(e.g.) neutron superfluidity
dominant d.o.f. is a superfluid phonon.

Some work in progress

w/ T. Hatsuda

① DM thermalization

(Ref.) Bertoni-Nelson-Reddy (2013)

Hyperon degrees of freedom?

② NS mass-radius relation

(Ref.) Ciarcelluti-Sandin (2011)

TOV eq. w/ dark star core

Summary

Stellar constraints on dark matter properties

Dark matter capture in neutron stars
--Accretion, thermalization and BH formation—

Models for DM, but not considering NS seriously

Proposal of medium effects for hadrons in NS
--modified vacuum structures and collective modes--

DM study via NS is interesting!

Thank you！

感謝