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for Advanced Study

UNIVERSITY OF SOUTHERN DENMARK

The Dark Side of Stars

Chris Kouvaris

CP^3 - Origins

Particle Physics & Origin of Mass

DARK2012

What is the nature of Dark Matter?

WIMP-nucleus cross section:

- Spin-Independent
- Spin-dependent
- Inelastic cross section

WIMP-WIMP cross section:

- Self-Interacting dark matter

WIMP-WIMP annihilation:

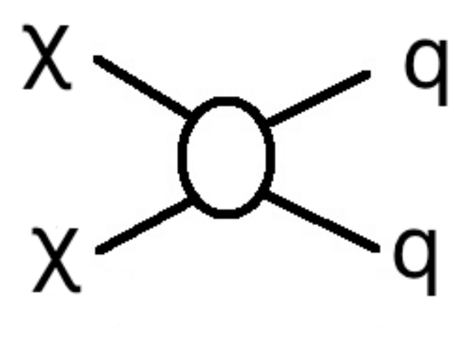
- Thermally produced WIMPs
- Nonthermally, asymmetric dark matter

Decaying WIMPs:
possible explanation of PAMELA results

Detection of Dark Matter

Detection of Dark Matter

Direct detection



Inconclusive!
DAMA. CoGeNT, CRESST have
signals compatible with dark matter.
Xenon, CDMS, Picasso null results.

Detection of Dark Matter

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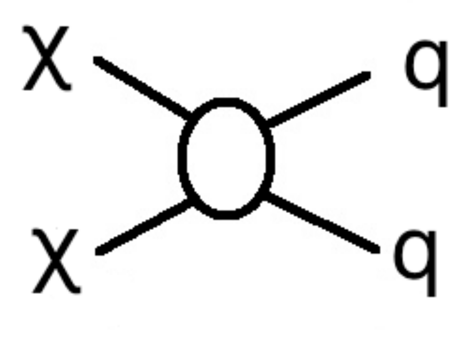

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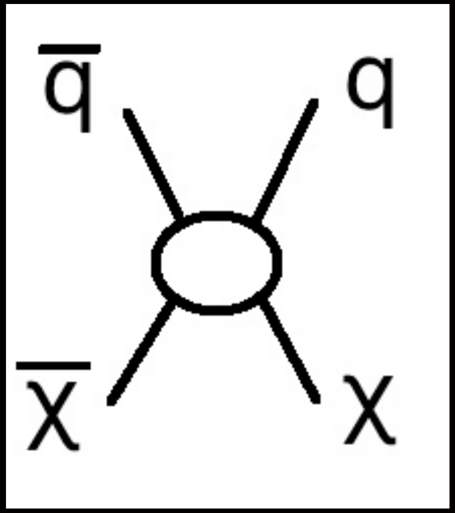

Inconclusive!
PAMELA positron excess, FERMI 130 GeV line?

Detection of Dark Matter

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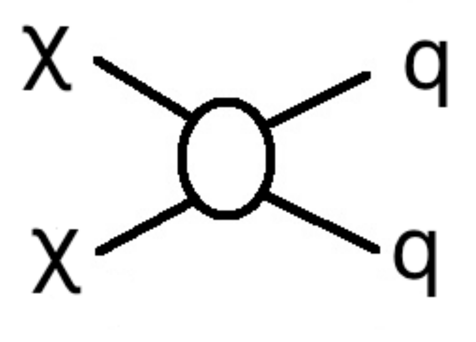

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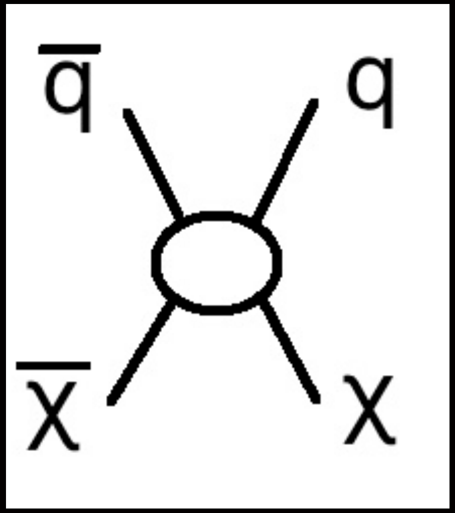

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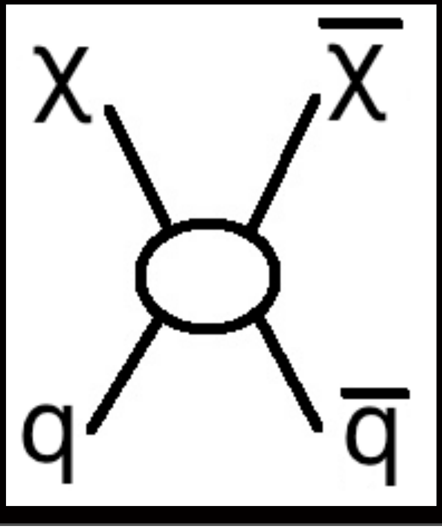
Production



Inconclusive!
LHC monophoton, monojet production and missing energy signal... nothing yet

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Astrophysical Observations of Compact Stars

Astrophysical Observations of Compact Stars

WIMP annihilation and Cooling of Stars

WIMP annihilation as a heating mechanism for

- neutron stars (CK ’07, CK Tinyakov ’10, Lavallaz Fairbairn ’10)
- white dwarfs (Bertone Fairbairn ’07, McCullough ’10)

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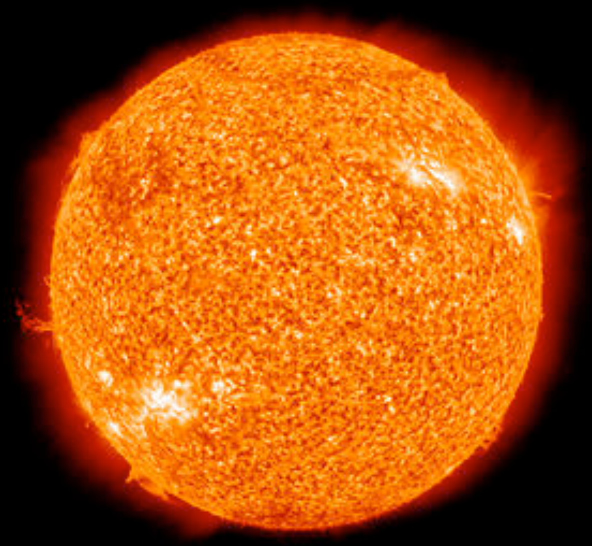
WIMP collapse to a Black Hole

WIMPs can be trapped inside stars and later collapse forming a black hole that destroys the star
(Goldman Nussinov '89, CK Tinyakov '10, '11, McDermott Yu Zurek '11, CK'11,
Guver Erkoca Reno Sarcevic '12, Fan Yang Chang '12)

WIMP capture in Stars

Condition: The energy loss in the collision should be larger than the asymptotic kinetic energy of the WIMP far out of the star.

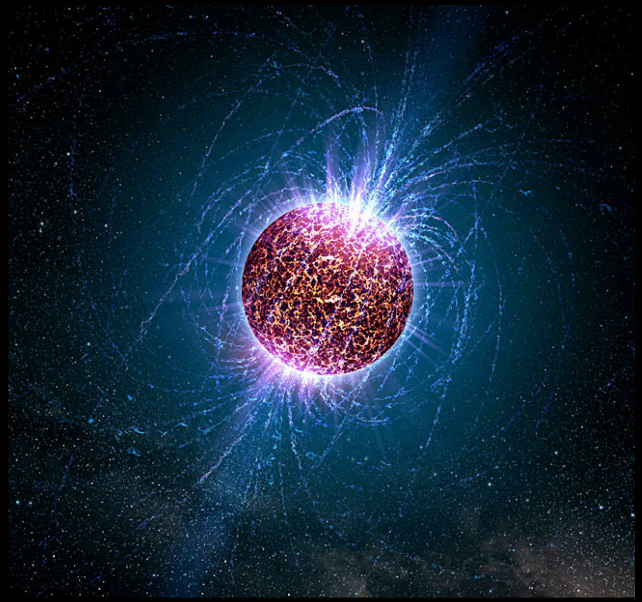


Example: Sun

WIMP mean free path inside the sun $\xi \approx \frac{1}{n\sigma}, \quad n \approx \frac{M_{solar}}{(4/3)\pi R_{solar}^3 m_n} \approx 8 \cdot 10^{23} \quad particles/cm^3$

Even if current limit of CDMS $\sigma < 10^{-41} cm^2, \quad \xi \approx 10^{17} cm, \quad \frac{R_{solar}}{\xi} \approx 10^{-6}$

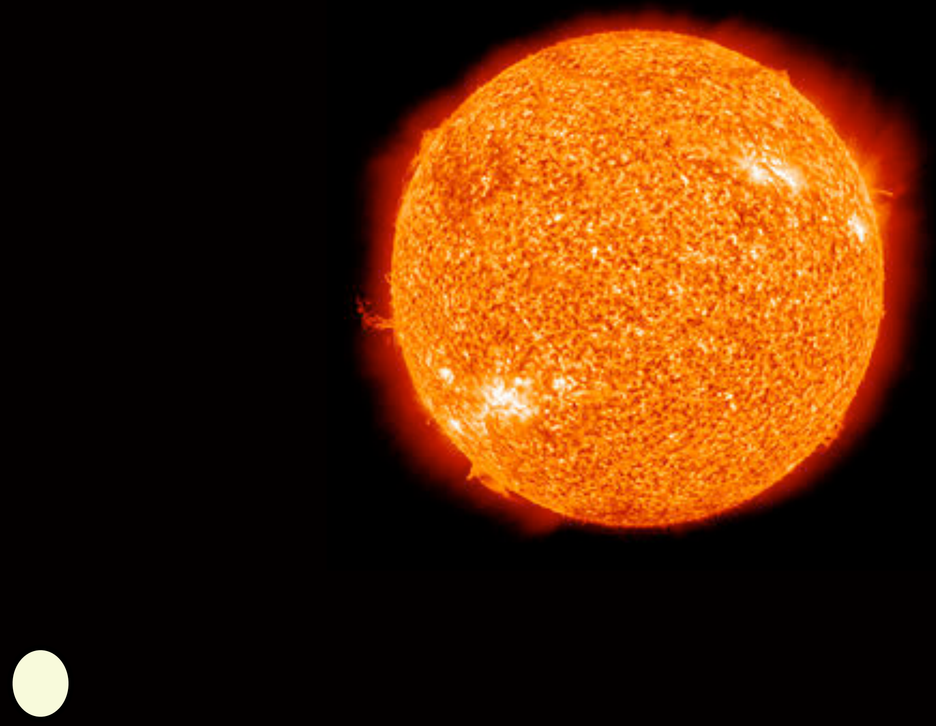
Only one out of a million WIMPs scatters!

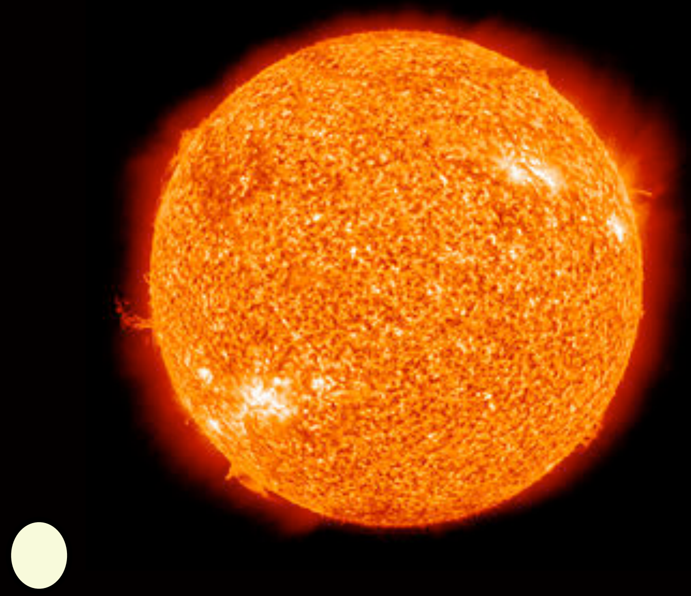


For a typical neutron star $M_{NS} \approx 1.4 M_{solar}, \quad R \approx 10km$

$$\sigma > \sigma_{critical} \approx 5 \cdot 10^{-46} cm^2$$ CK'07

For cross section larger than the critical one, every WIMP passing through the neutron star will be on average interact inside the star.





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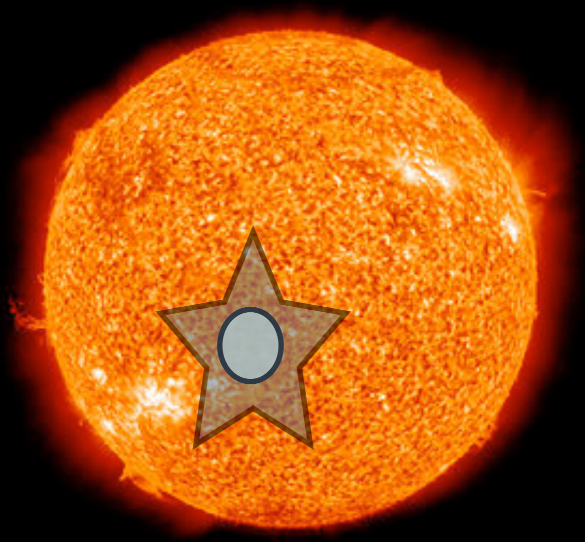

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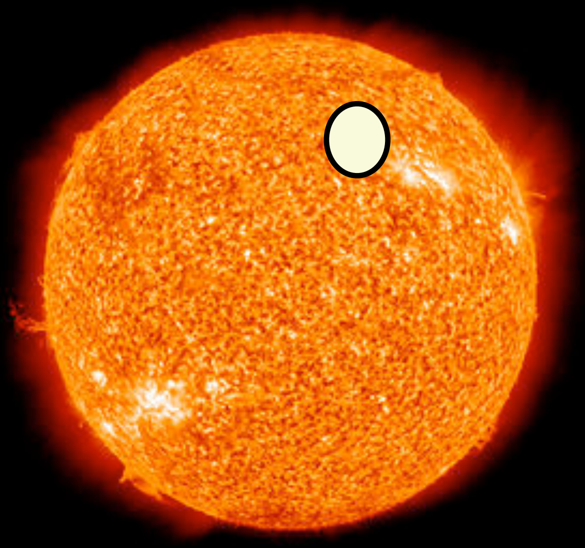

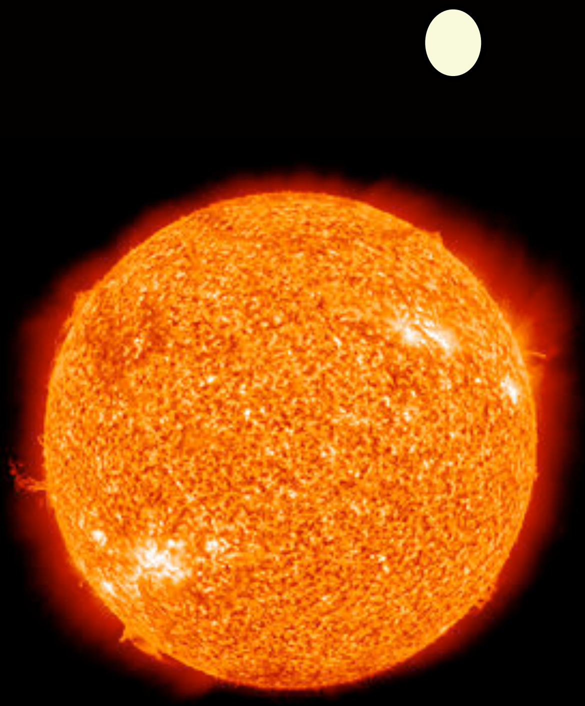

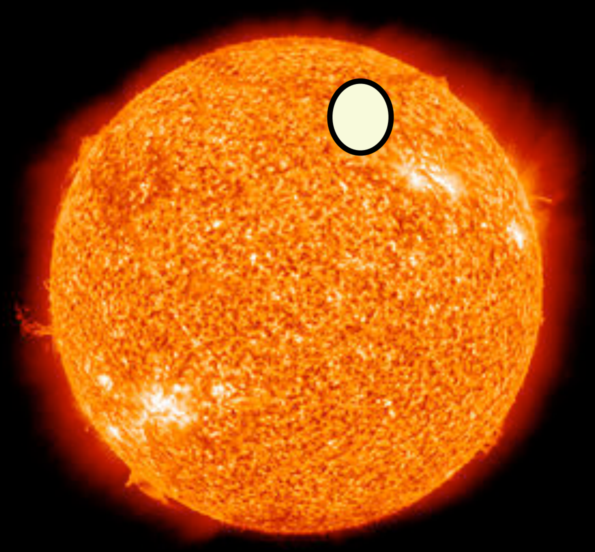

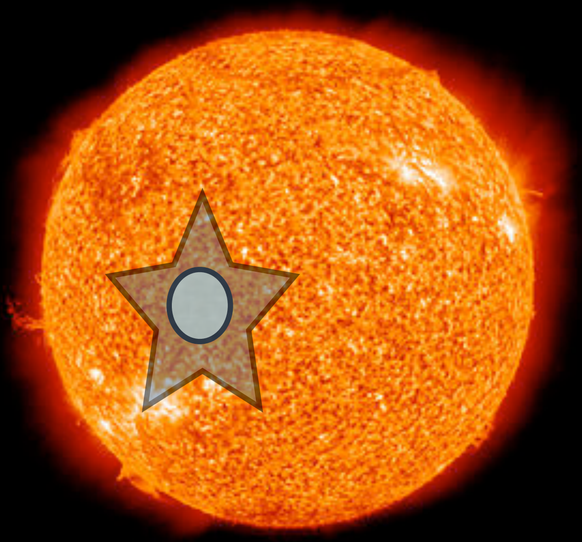

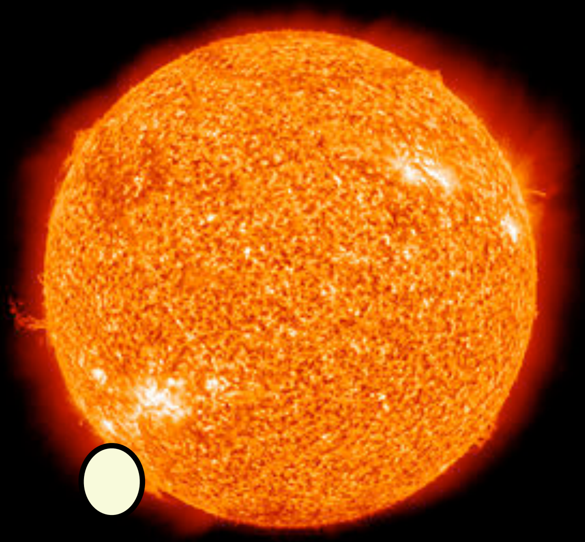

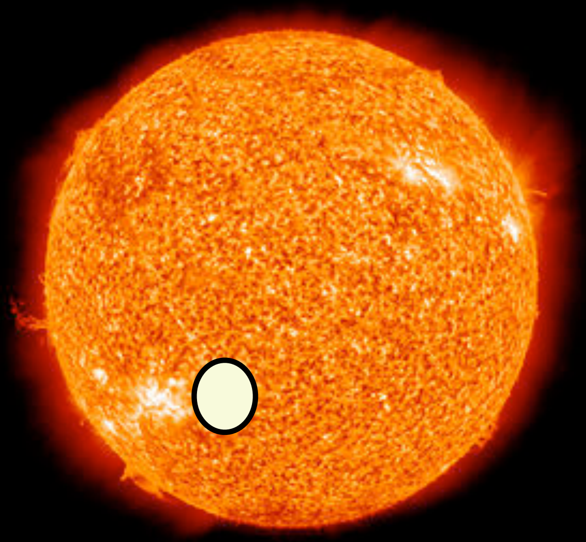

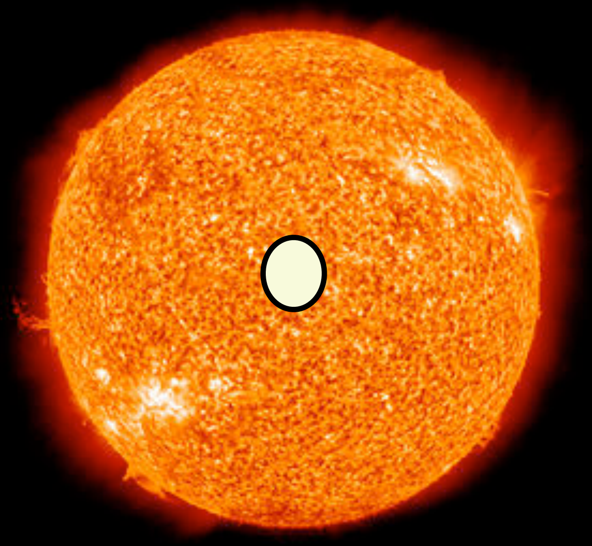

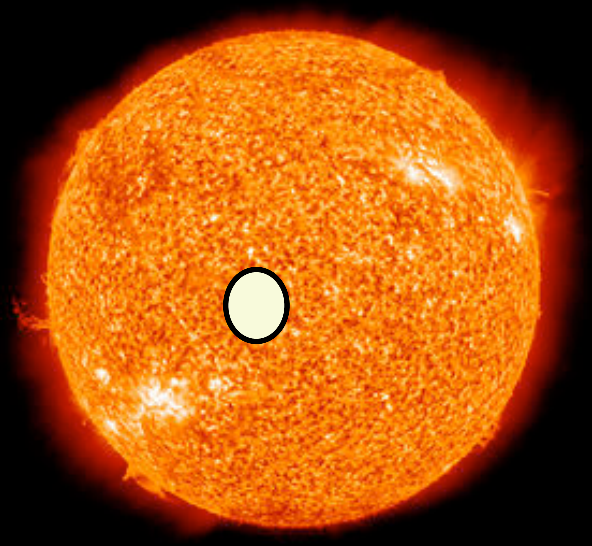

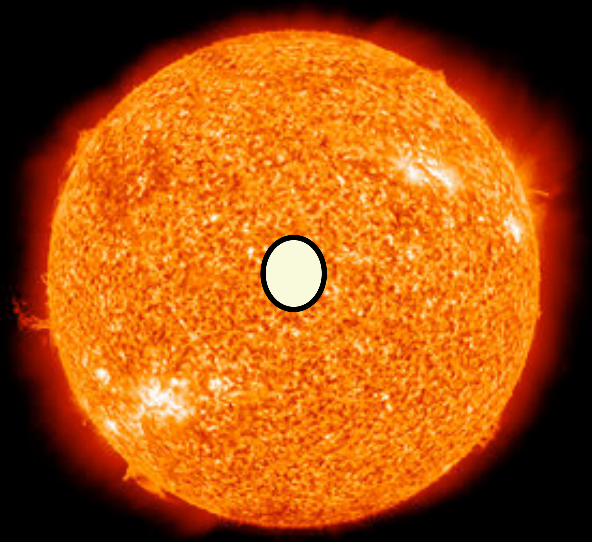

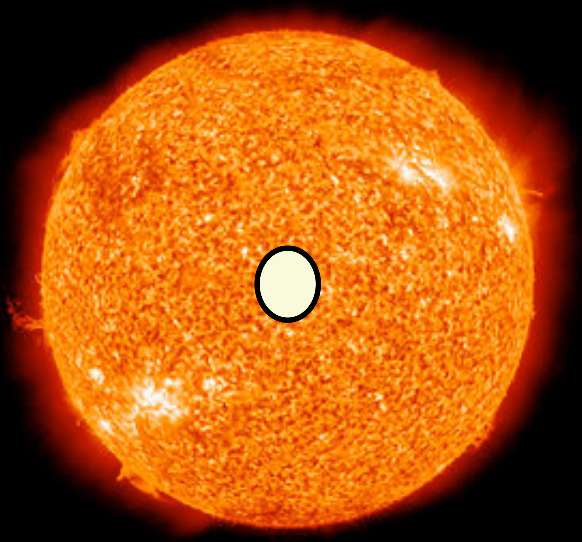

WIMP capture in Stars

$$F = \frac{8}{3}\pi^2 \frac{\rho_{\rm dm}}{m}\left(\frac{3}{2\pi v^2}\right)^{3/2} \frac{GMR}{1-\frac{2GM}{R}} v^2 (1-e^{-3E_0/v^2}) f$$

Press Spergel ’85, Gould ’86,
Nussinov Goldman ’89,
CK’07, CK Tinyakov ’10

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higher local DM density
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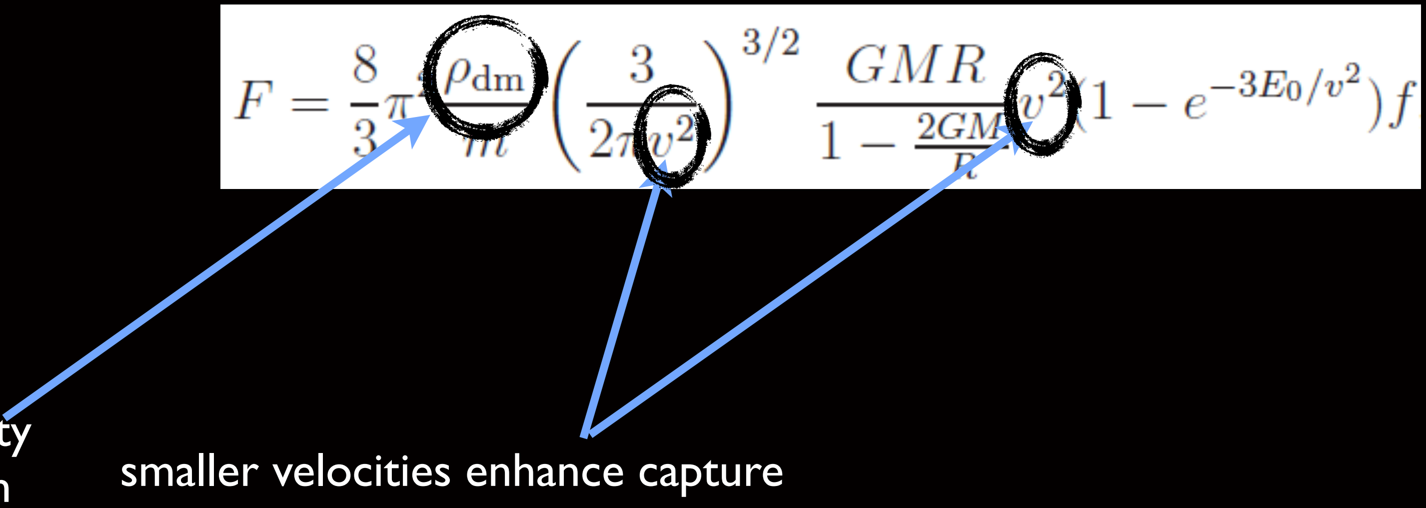

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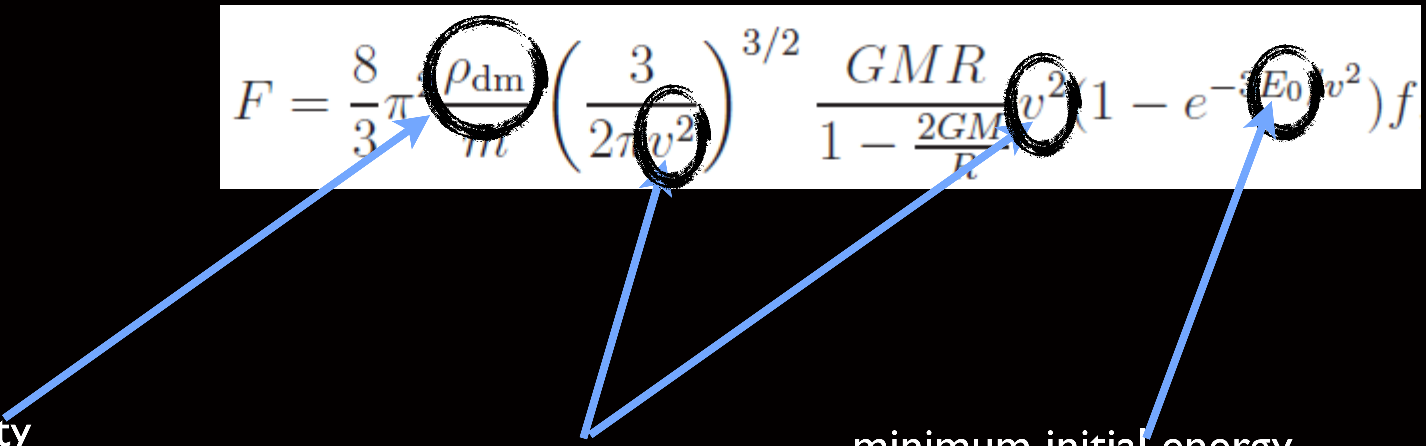

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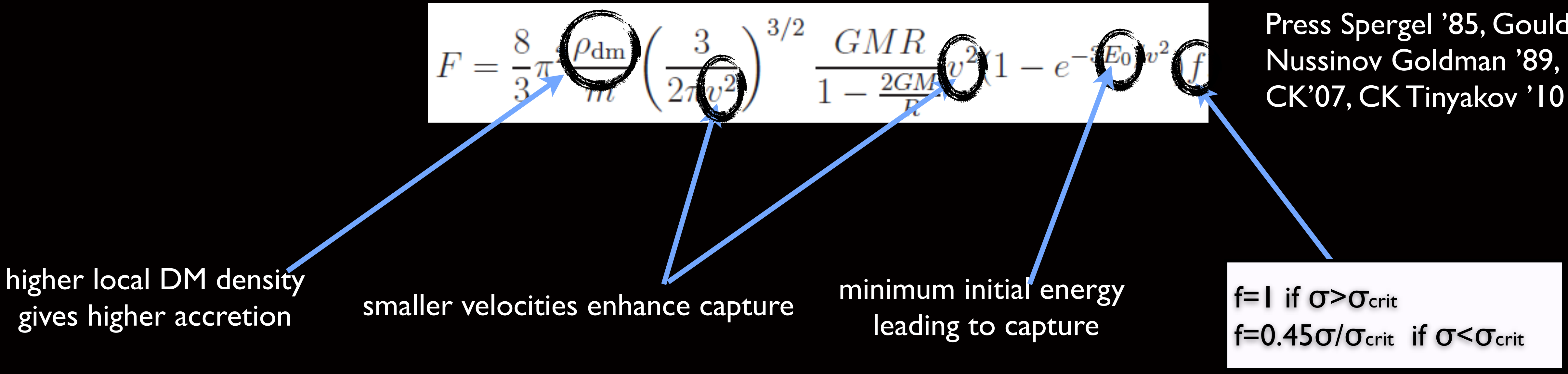

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$f=1$ if $\sigma > \sigma_{\rm crit}$
$f=0.45\sigma/\sigma_{\rm crit}$ if $\sigma < \sigma_{\rm crit}$

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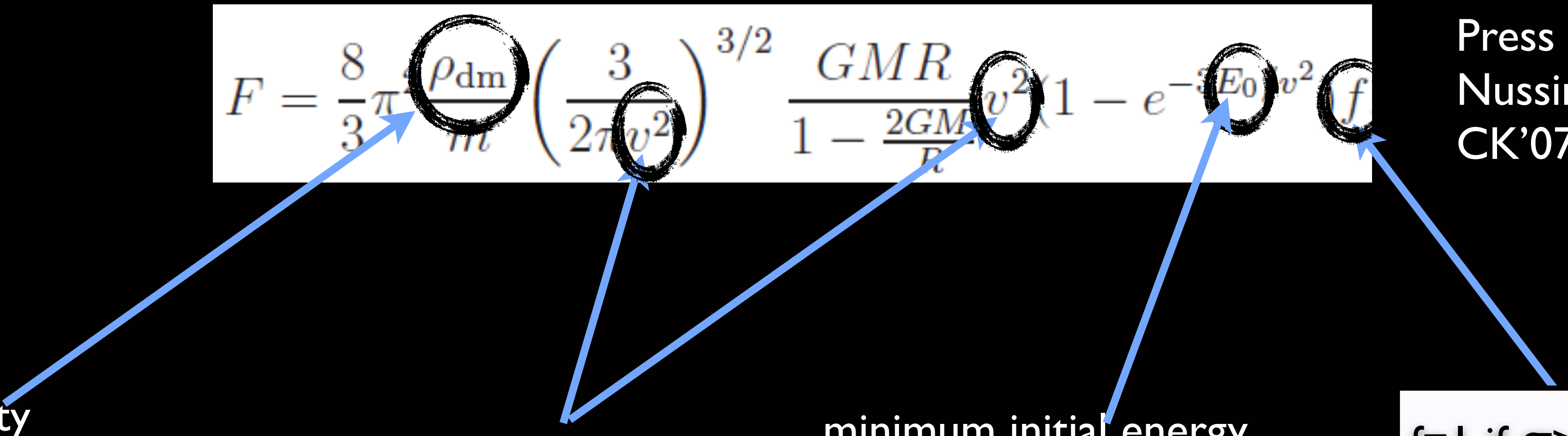
WIMP capture in Stars



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$$f \simeq \frac{\sigma_\chi}{\sigma_{\rm crit}} \left\langle \int \frac{\rho}{M/R^3}\frac{dl}{R} \right\rangle$$

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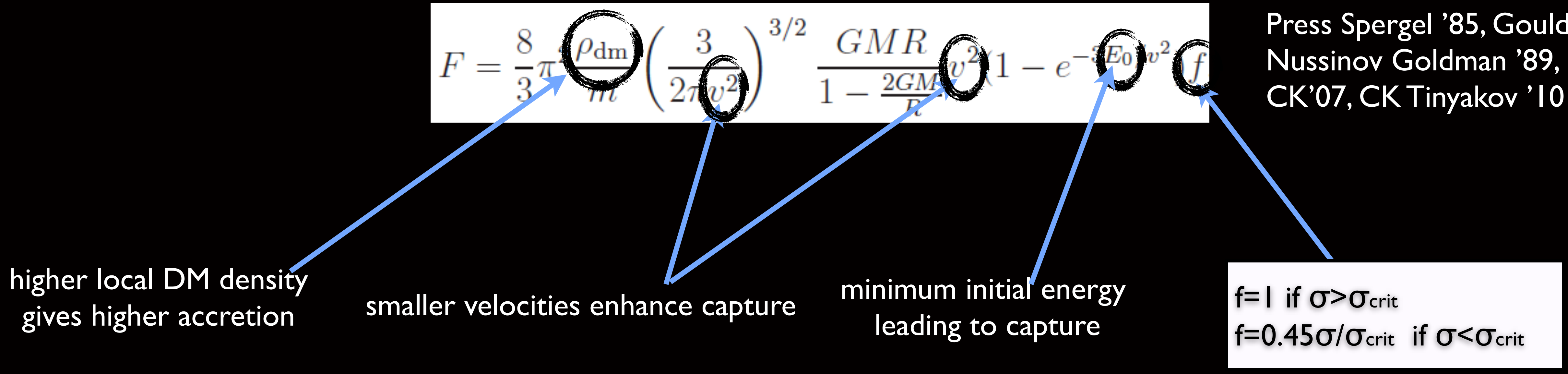

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For typical NS

$$F = 1.25\times 10^{24}{\rm s}^{-1}\left(\frac{\rho_{\rm dm}}{{\rm GeV/cm^3}}\right)\left(\frac{100{\rm GeV}}{m}\right) f$$

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Thermalization

$$t_{\rm th} = 0.2{\rm yr}\left(\frac{m}{\rm TeV}\right)^2\left(\frac{\sigma}{10^{-43}{\rm cm}^2}\right)^{-1}\left(\frac{T}{10^5{\rm K}}\right)^{-1}$$

Goldman
Nussinov'89,
CK Tinyakov '10

$$r_{\rm th} = \left(\frac{9T}{8\pi G\rho_c m}\right)^{1/2} \simeq 22{\rm cm}\left(\frac{T}{10^5{\rm K}}\right)^{1/2}\left(\frac{100{\rm GeV}}{m}\right)^{1/2}$$

Evaporation

$$F = n_s\left(\frac{T}{2\pi m}\right)^{1/2}\left(1+\frac{GMm}{RT}\right)\exp\left(-\frac{GMm}{RT}\right)$$

Krauss Srednicki
Wilczek '86

for WIMPs with mass larger than ~2 keV evaporation can be ignored

WIMP Annihilation in Neutron Stars

$$C_A = \langle \sigma_A v \rangle / V$$

$$\tau = 1/\sqrt{F C_A}$$

$$\tau = 3.4 \times 10^{-5}\mathrm{yr} \left(\frac{100}{m}\right)^{1/4} \left(\frac{\mathrm{GeV/cm^3}}{\rho_{\mathrm{dm}}}\right)^{1/2} \left(\frac{10^{-36}\mathrm{cm}^2}{\langle \sigma v \rangle}\right)^{1/2} \left(\frac{T}{10^5\mathrm{K}}\right)^{3/4} f^{-1/2}$$

Energy Release $W(t) = F m \,\mathrm{Tanh}^2 \frac{t+c}{\tau}$

we have to compare with other heating/cooling mechanisms

Basics of Neutron Star Cooling

Urca process

Direct Urca

$$n \rightarrow p + e + \bar{\nu}_e$$
$$p + e \rightarrow n + \nu_e$$

However for nuclear matter triangle inequalities are not satisfied

For quark matter it holds!

Emissivity: $\propto T^6$

Modified Urca presence of bystander

$$n + n \rightarrow n + p + e + \bar{\nu}_e$$
$$p + e + n \rightarrow n + n + \nu_e$$

Emissivity: $\propto T^8$

Photon Emission Emissivity: $\propto T^4$

$$T_{\text{surface}} = (0.87 \times 10^6\ \text{K}) \left(\frac{g_s}{10^{14}\text{cm/s}^2}\right)^{1/4} \left(\frac{T}{10^8\text{K}}\right)^{0.55}$$

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… more cooling mechanisms

- Nucleon Pair Bremsstrahlung

$$n+n \rightarrow n+n+\nu+\bar{\nu}$$

$$n+p \rightarrow n+p+\nu+\bar{\nu}$$

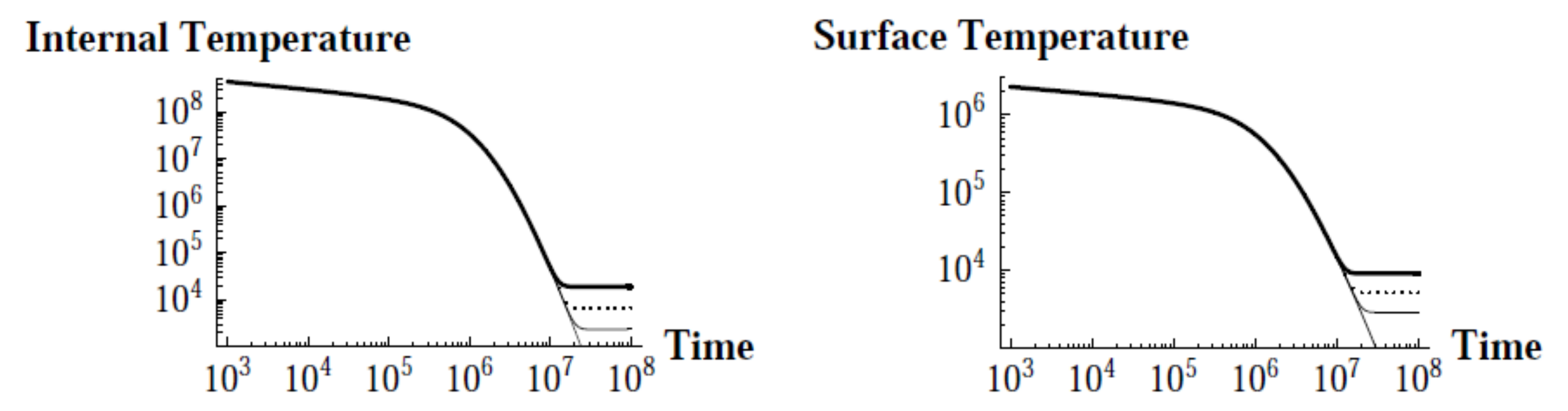
- Neutrino Pair Bremsstrahlung

$$e+(A,Z) \rightarrow e+(A,Z)+\nu+\bar{\nu}$$

- Pionic Reactions
- Superfluidity
- Color Superconductivity

Cooling of Neutron Stars

$$\frac{dT}{dt} = \frac{-L_\nu - L_\gamma + L_{\rm dm}}{V c_V} = \frac{V(-\epsilon_\nu - \epsilon_\gamma + \epsilon_{\rm dm})}{V c_V} = \frac{-\epsilon_\nu - \epsilon_\gamma + \epsilon_{\rm dm}}{c_V}$$



CK’07

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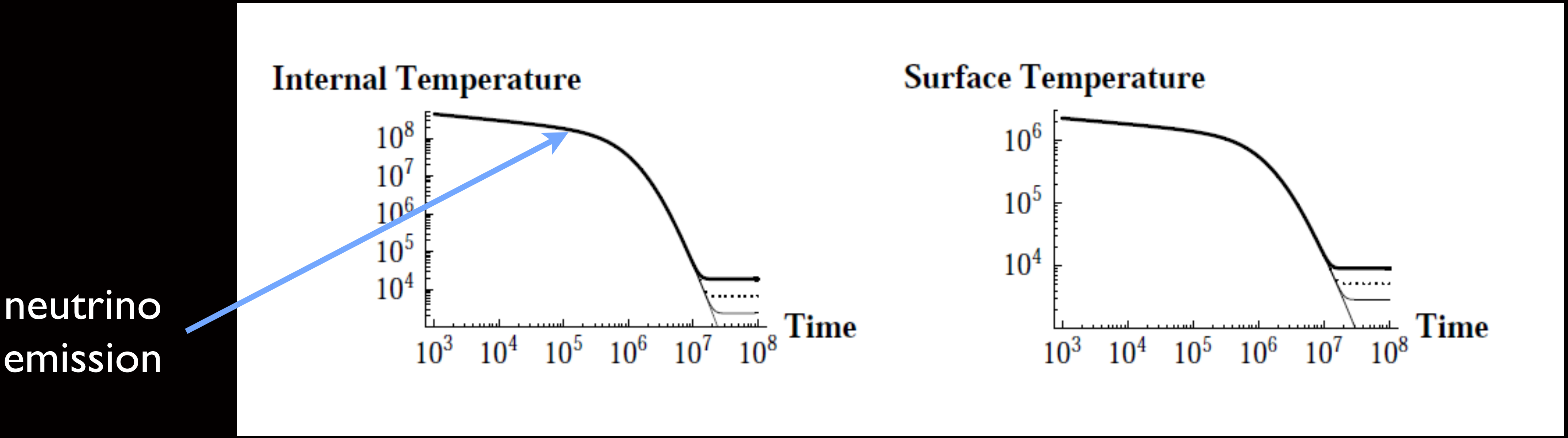

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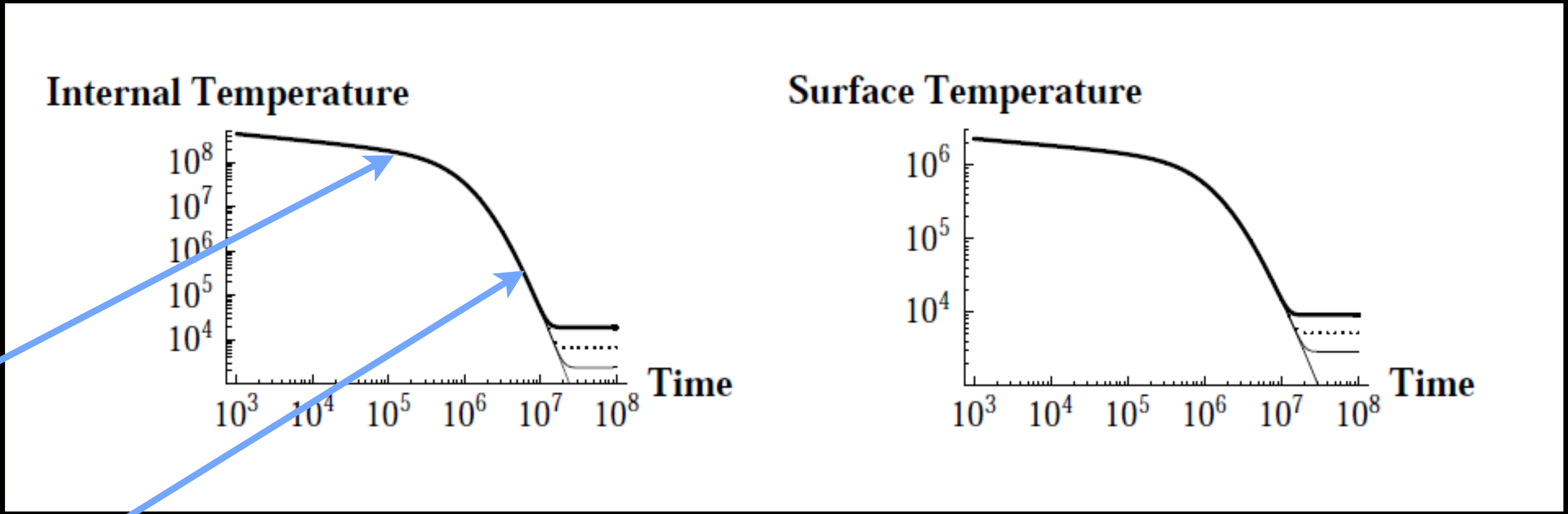

neutrino
emission

photon
emission

CK’07

Cooling of Neutron Stars

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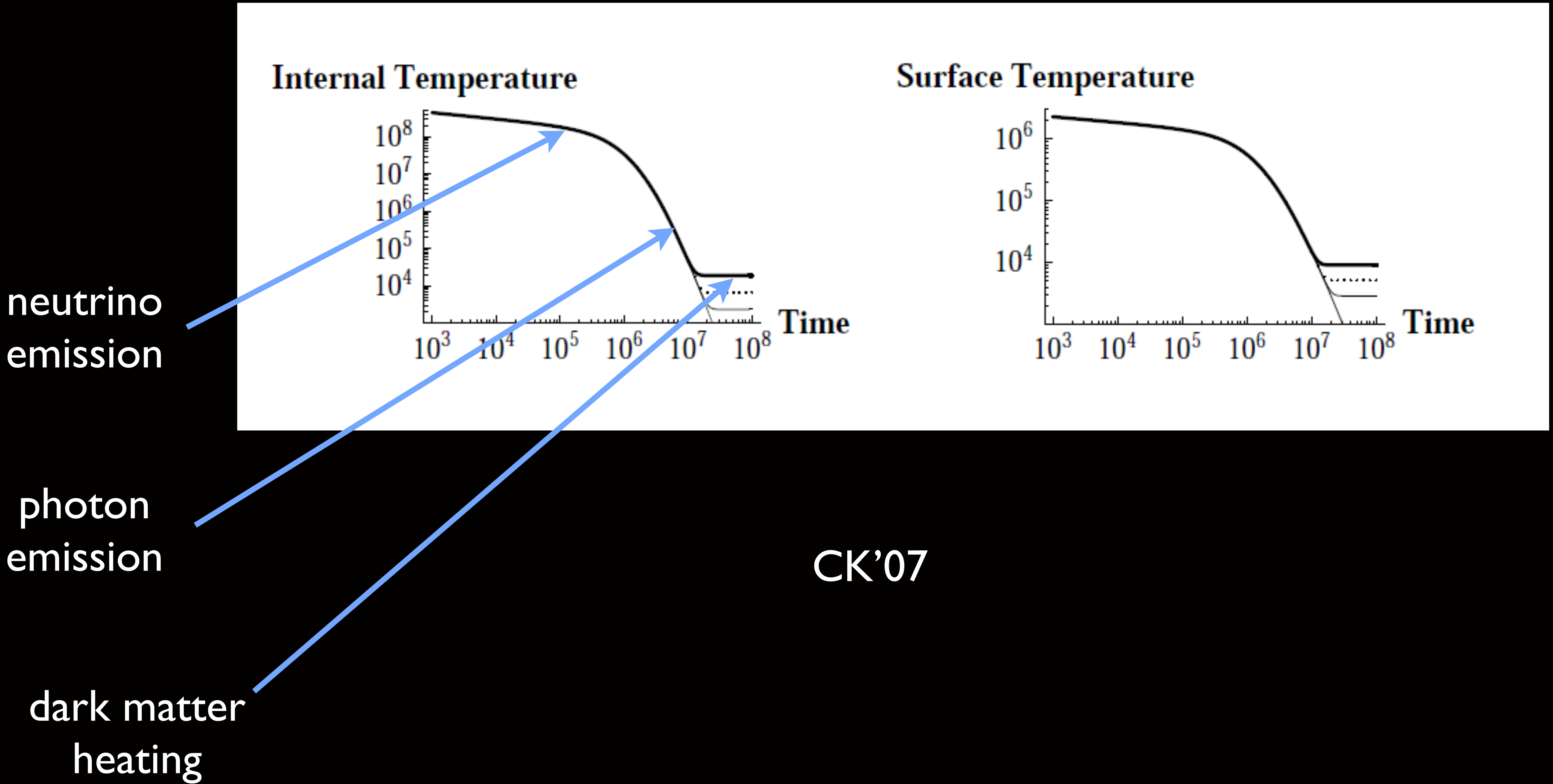

CK’07

Cooling of Neutron Stars

Galactic Center

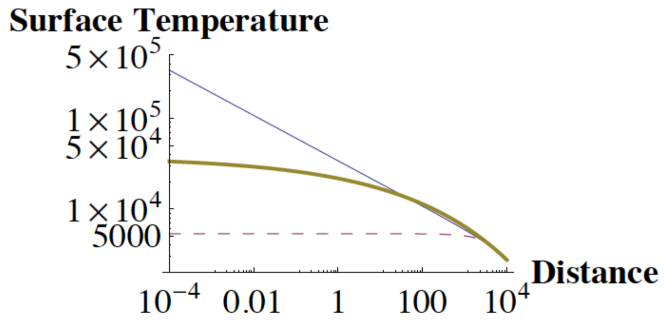

FIG. 3: The surface temperature of a typical old neutron star in units of K as a function of the distance of the star from the galactic center in pc, with the dark matter annihilation taken into account. The three curves correspond to three different dark matter profiles: NFW (thin solid line), Einasto (thick solid line), and Burkert (dashed line).

Globular Cluster

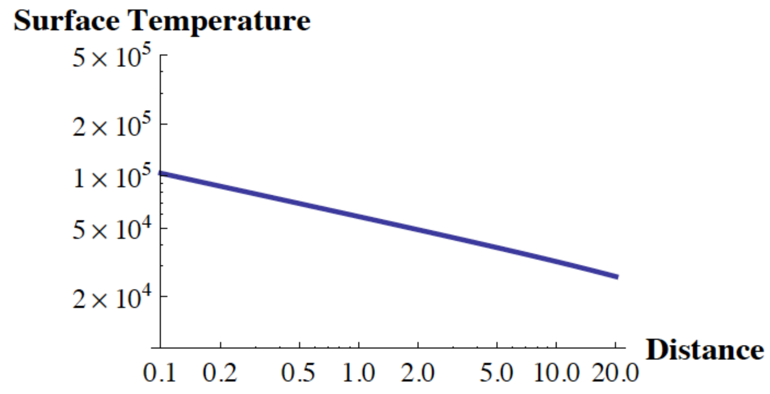

FIG. 5: The surface temperature of a typical old neutron star in units of K as a function of the distance in pc for a NFW profile of the globular cluster $M4$.

$$\rho_{\rm NFW} = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$\rho_{\rm Ein} = \rho_s \exp\left[-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right]$$

$$\rho_{\rm Bur} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$$

CK, Tinyakov '10
Fairbairn Lavallaz'10

Nearby old neutron stars

J0437-4715 temperature ~10^5 K
J2124-3358 temperature ~10^5 K
130-140 pc away

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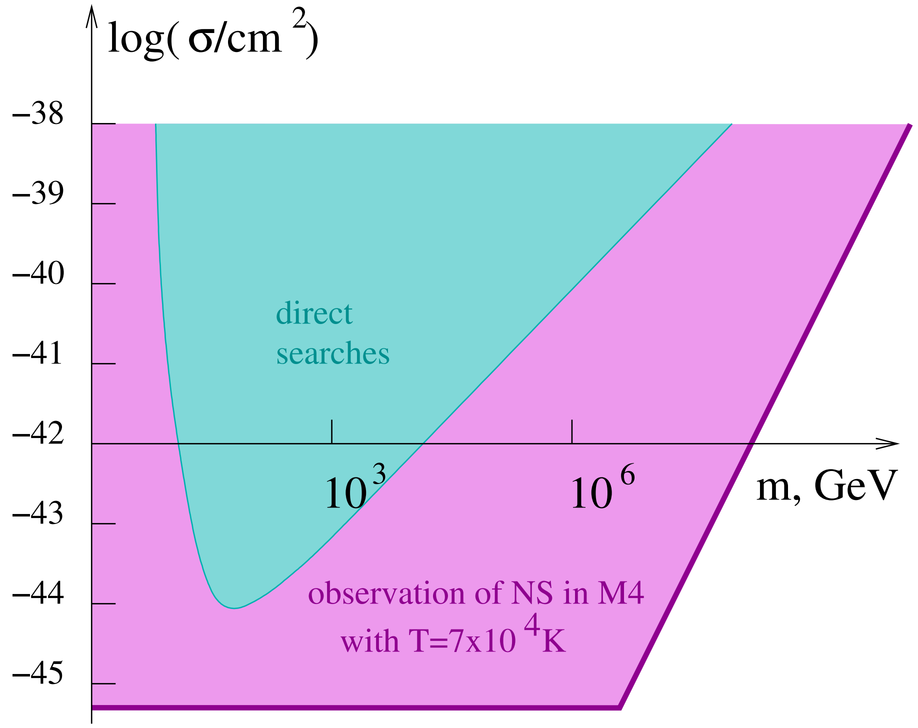
Cooling of Neutron Stars



Old neutron stars in Globular Clusters

X7 in 47 Tuc
1620-26 in M4

both have temperatures roughly 10^6 K

Bosonic Asymmetric Dark Matter

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No Fermi pressure but Heisenberg uncertainty keeps bosons from collapse

Bosonic Asymmetric Dark Matter

No Fermi pressure but Heisenberg uncertainty keeps bosons from collapse

$$\frac{GNm^2}{r} \simeq \frac{\hbar}{r} \longrightarrow M_{crit} = \frac{2M_{\rm Pl}^2}{\pi m}\sqrt{1+\frac{M_{\rm Pl}^2}{4\sqrt{\pi}m}\sigma^{1/2}} \qquad \sigma = \lambda^2/(64\pi m^2)$$

Bosonic Asymmetric Dark Matter

No Fermi pressure but Heisenberg uncertainty keeps bosons from collapse

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repulsive interactions

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repulsive interactions

BEC accelerates collapse

$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.31\,\frac{\hbar^2 n^{2/3}}{mk_B}$$

$$N_{\rm BEC} \simeq 2 \times 10^{36}$$

$$r_{\rm th} \simeq 2\ {\rm m}\left(\frac{T_c}{10^5 {\rm K}}\right)^{1/2}\left(\frac{m}{\rm GeV}\right)^{-1/2} \longrightarrow r_c = \left(\frac{8\pi}{3}G\rho_c m^2\right)^{-1/4} \simeq 1.6\times 10^{-4}\left(\frac{\rm GeV}{m}\right)^{1/2} {\rm cm}$$

Bosonic Asymmetric Dark Matter

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$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3}\frac{2\pi\hbar^2}{mk_B} \approx 3.31\,\frac{\hbar^2 n^{2/3}}{mk_B}$$

$$N_{\rm BEC} \simeq 2\times 10^{36}$$

$$r_{\rm th} \simeq 2\ {\rm m}\left(\frac{T_c}{10^5{\rm K}}\right)^{1/2}\left(\frac{m}{\rm GeV}\right)^{-1/2} \longrightarrow r_c = \left(\frac{8\pi}{3}G\rho_c m^2\right)^{-1/4} \simeq 1.6\times 10^{-4}\left(\frac{\rm GeV}{m}\right)^{1/2}\ {\rm cm}$$

Evolution of the Black Hole

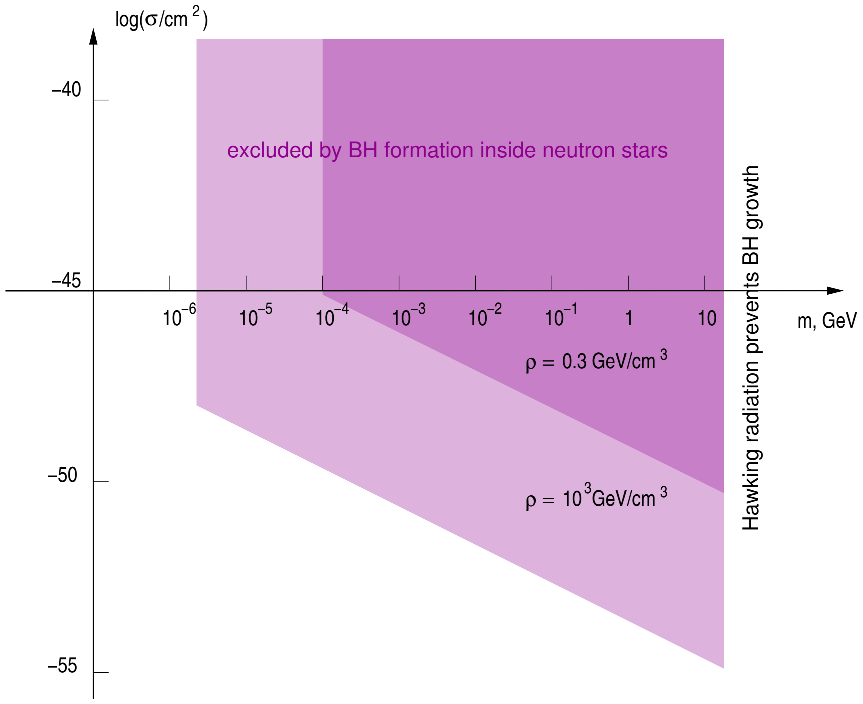
$$\frac{dM}{dt} = \frac{4\pi\rho_c G^2M^2}{c_s^3} - \frac{1}{15360\pi G^2M^2}$$

Bondi accretion

Hawking Radiation

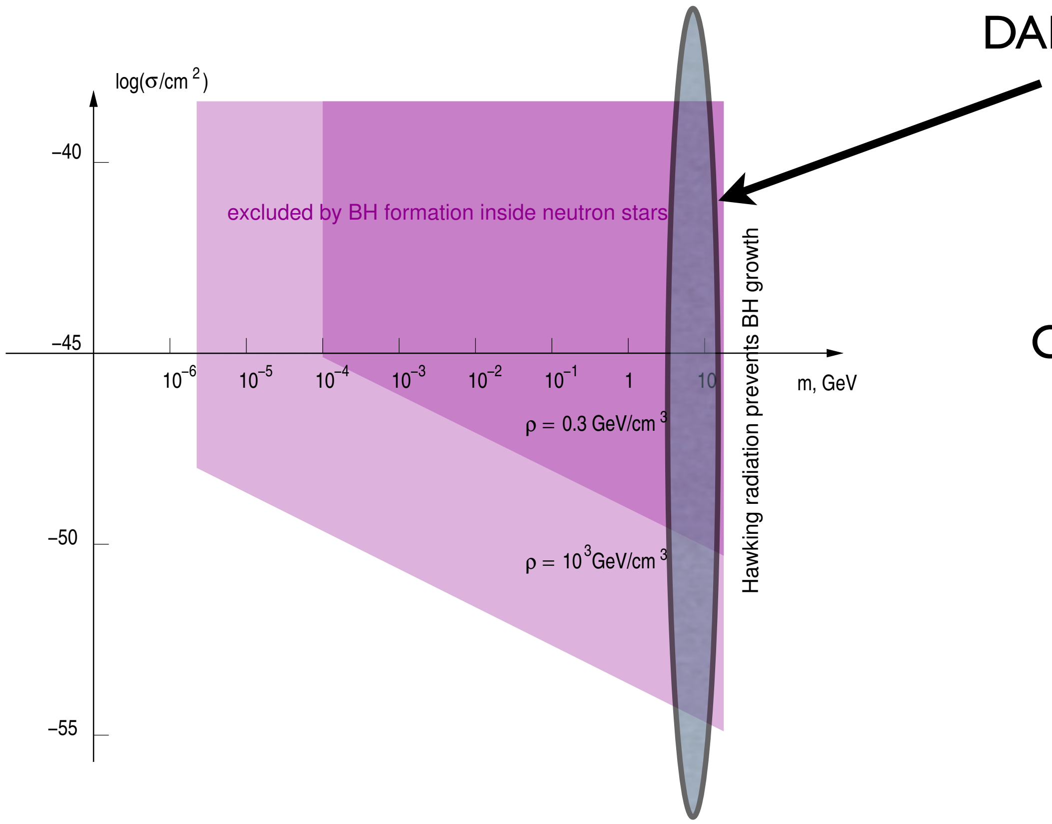
Bosonic Asymmetric Dark Matter

Bosonic Asymmetric Dark Matter



CK, Tinyakov PRL '11

Bosonic Asymmetric Dark Matter



DAMA/CoGeNT

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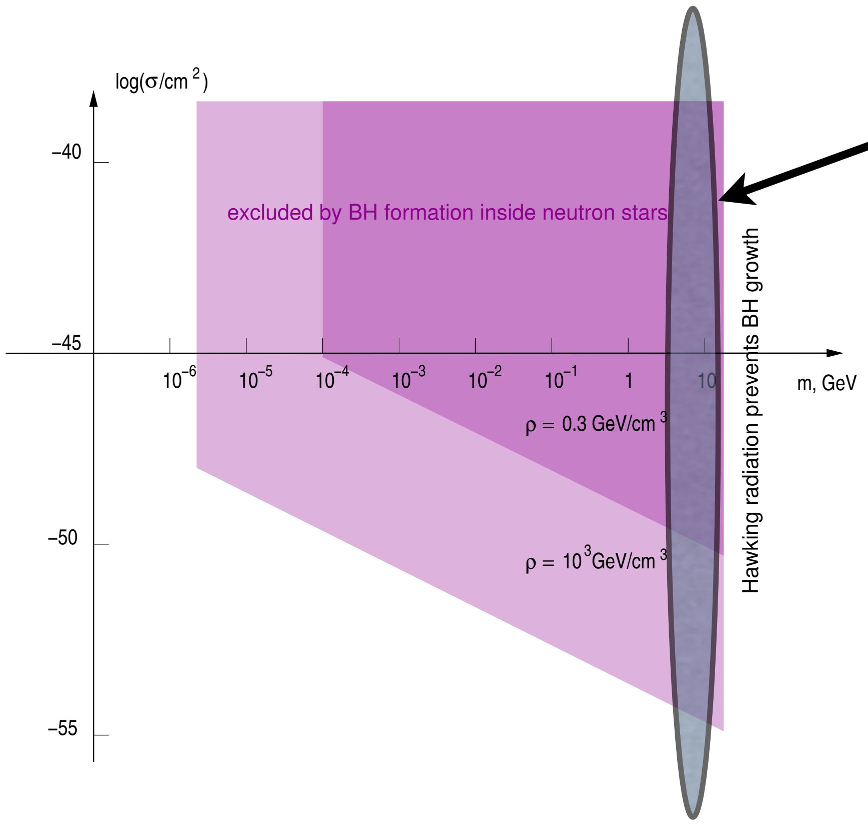
Bosonic Asymmetric Dark Matter



DAMA/CoGeNT

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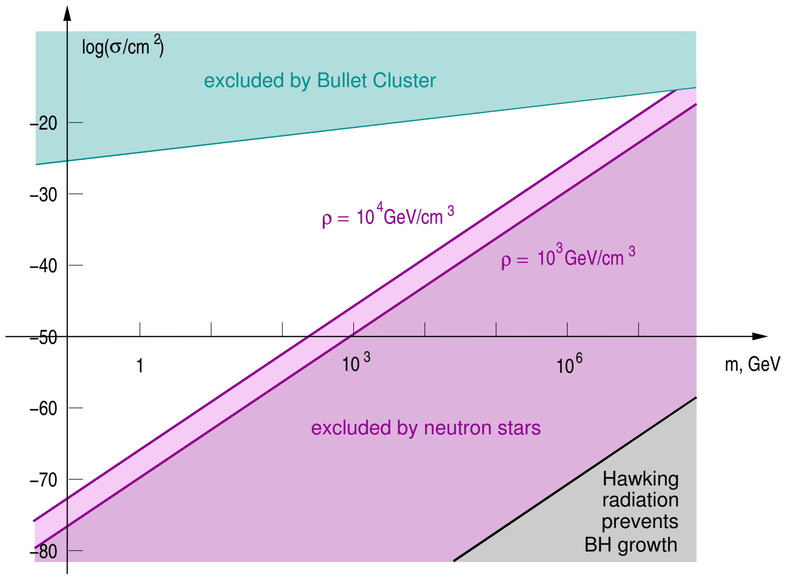

Self-Interacting DM

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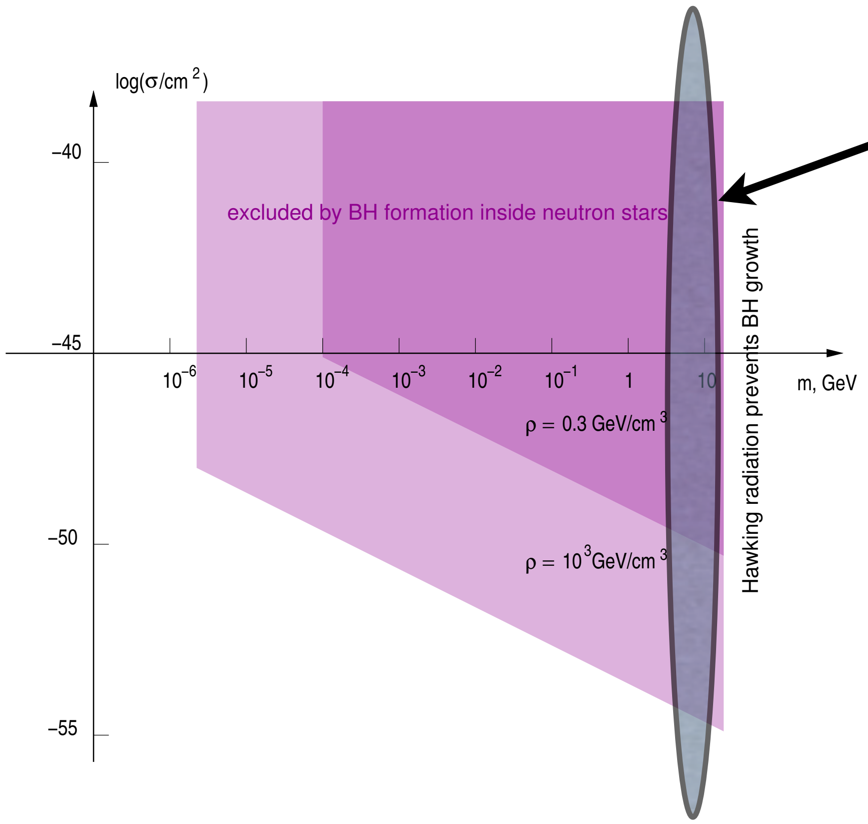
Bosonic Asymmetric Dark Matter



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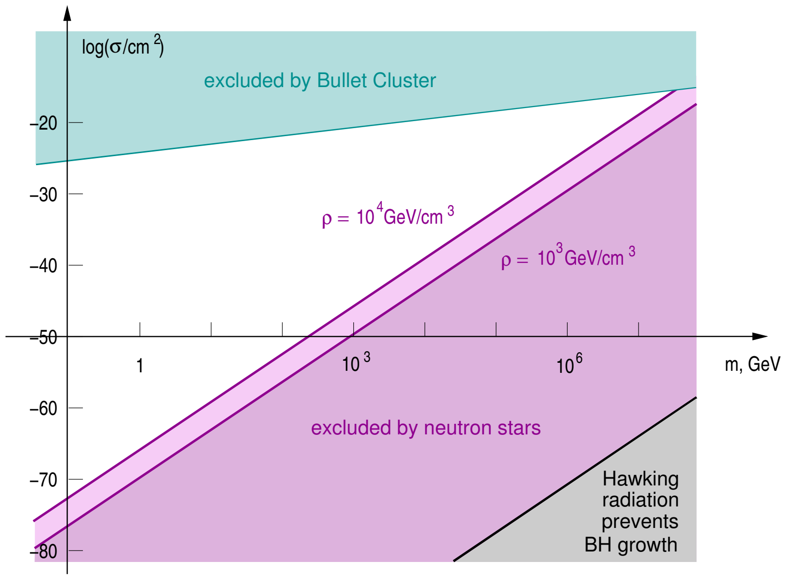


Self-Interacting DM

If WIMP is a composite of fermions

$$\Lambda_{crit} = m^{1/3} M_{\rm Pl}^{2/3} \left(1 + \frac{\lambda m_{pl}^2}{32 \pi m^2} \right)^{-1/3}$$

If WIMP is a composite of fermions above that scale, the bosonic constraints still hold

Self-Interacting Dark Matter

“Chandrashekhar Limit for WIMPs”

$$\frac{GNm^2}{r} > k_F = \left(\frac{3\pi^2 N}{V}\right) = \left(\frac{9\pi}{4}\right)^{1/3}\frac{N^{1/3}}{r}$$

N=10^57/m^3!!!

Yukawa-type WIMP self-interactions can explain the flatness of dwarf galaxies Spergel-Steinhardt ’99, Loeb-Weiner ’11

$\alpha\phi\bar{\psi}\psi$

$V(r) = -\alpha\exp[-\mu r]/r$

Yukawa self-interactions can alleviate the effect of the Fermi pressure, leading to a gravitational collapse with dramatically lower amount of captured WIMPs

Self-Interacting Dark Matter

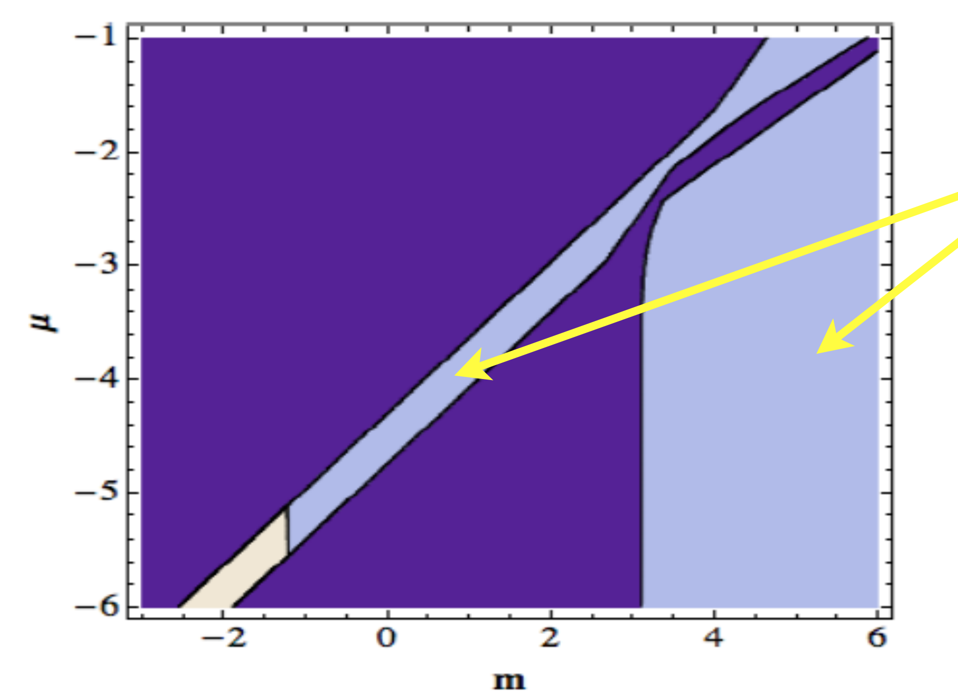
Virial Theorem

$$2\langle E_k\rangle = \frac{8}{3}\pi G\rho m r^2 + \frac{GNm^2}{r} + \left\langle \sum_j \alpha \frac{e^{-\mu r_{ij}}}{r_{ij}} + \alpha\mu e^{-\mu r_{ij}} \right\rangle$$

- Self-attraction before degeneracy
- Self-attraction after degeneracy

Yukawa potential energy once saturated it scales as 1/r^3

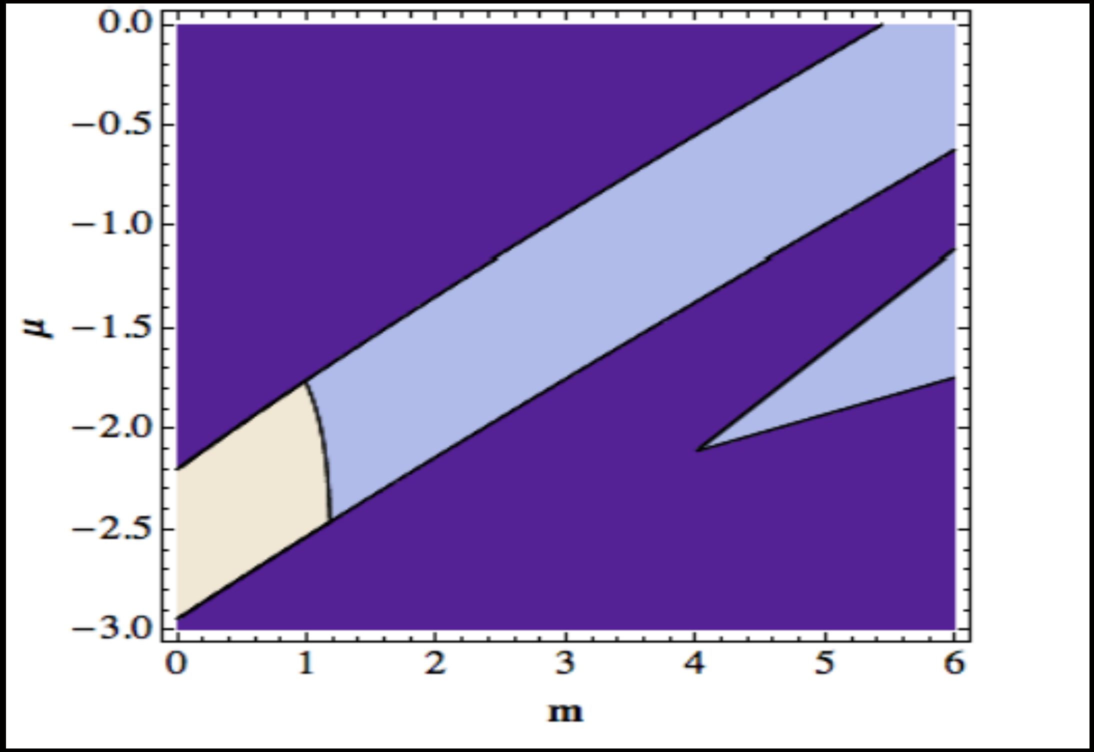
Self-Interacting Dark Matter



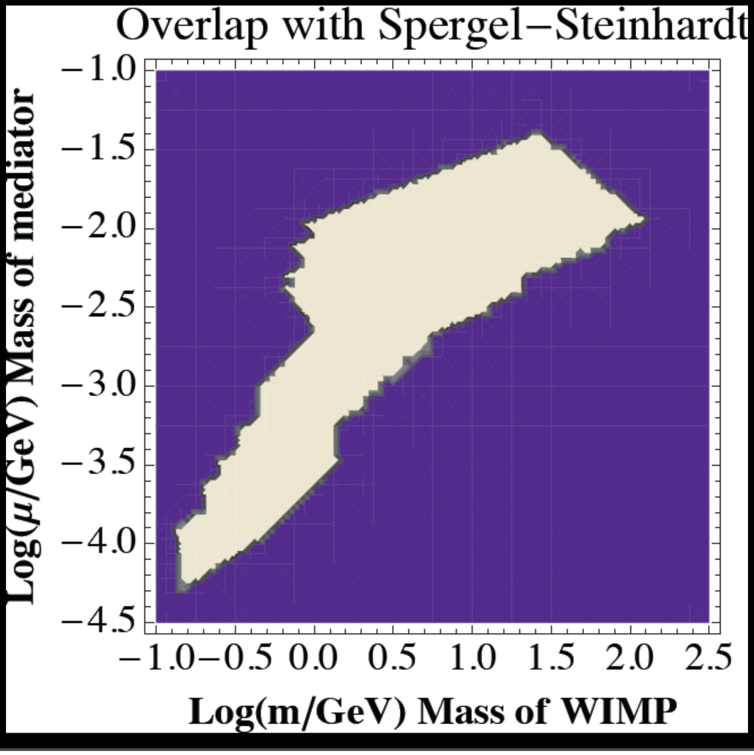
$\alpha = 10^{-5}$

Exclusion regions

CK PRL'12



$\alpha = 0.1$



Loeb-Weiner

$$(m_\chi/10\mathrm{GeV})(m_\phi/100\mathrm{MeV})^2 \sim 1$$

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Spin-Dependent Asymmetric Dark Matter

Spin-Dependent Asymmetric Dark Matter

A regular star accumulates WIMPs with spin-dependent WIMP-nucleon interactions and collapses to a white dwarf after the hydrogen and helium burning stages

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The WIMP population is inherited by the white dwarf and gets thermalized inside it due to the presence of C13-WIMP spin-dependent interactions

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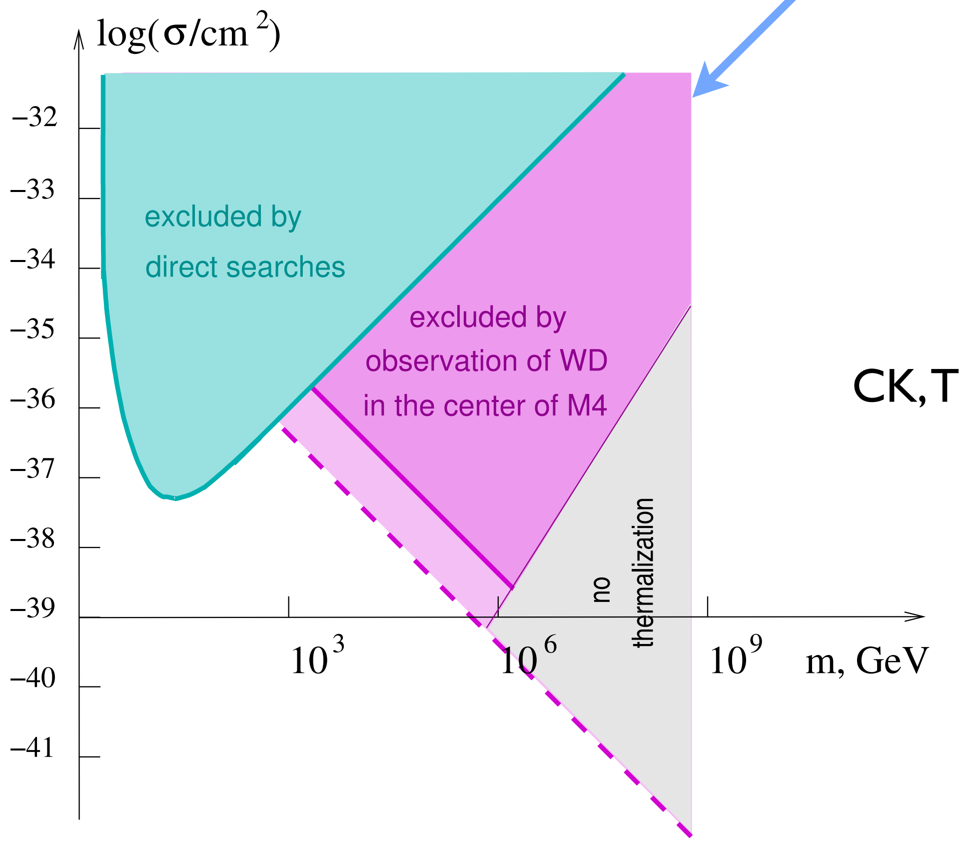
Formation of a Black Hole



CK, Tinyakov '10

The Dark Side of the Stars

Compact stars can reveal a lot of information about the nature of DM putting constraints on its properties complementary to direct searches.

- Observation of cold neutron stars can exclude thermally produced dark matter.

- Asymmetric dark matter:

1. keV to ~16GeV bosonic dark matter is excluded.
2. Part of fermionic WIMP self-interactions excluded.
3. Constraints on WIMP-nucleon spin-dependent interactions.