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University of Southern Denmark

Compact Stars & Dark Matter

Chris Kouvaris

CP3 - Origins

Particle Physics & Origin of Mass

Cosmovia March 28, 2014

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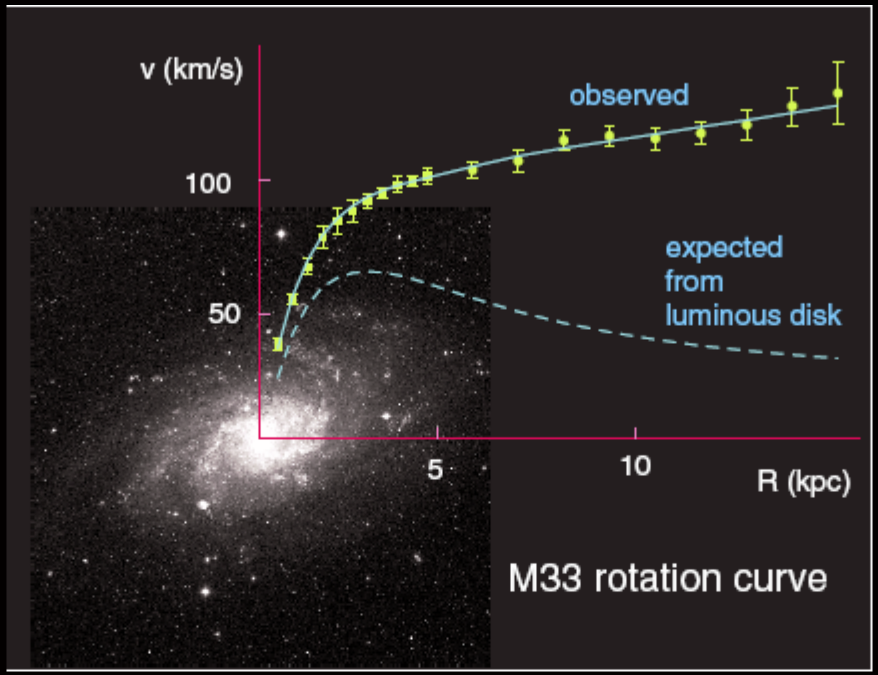
The Missing Mass of the Universe

A Mystery for 80 years!

Zwicky 1933:
Coma cluster



Vera Rubin 70's
Rotation curves of Andromeda are not falling according to Newton

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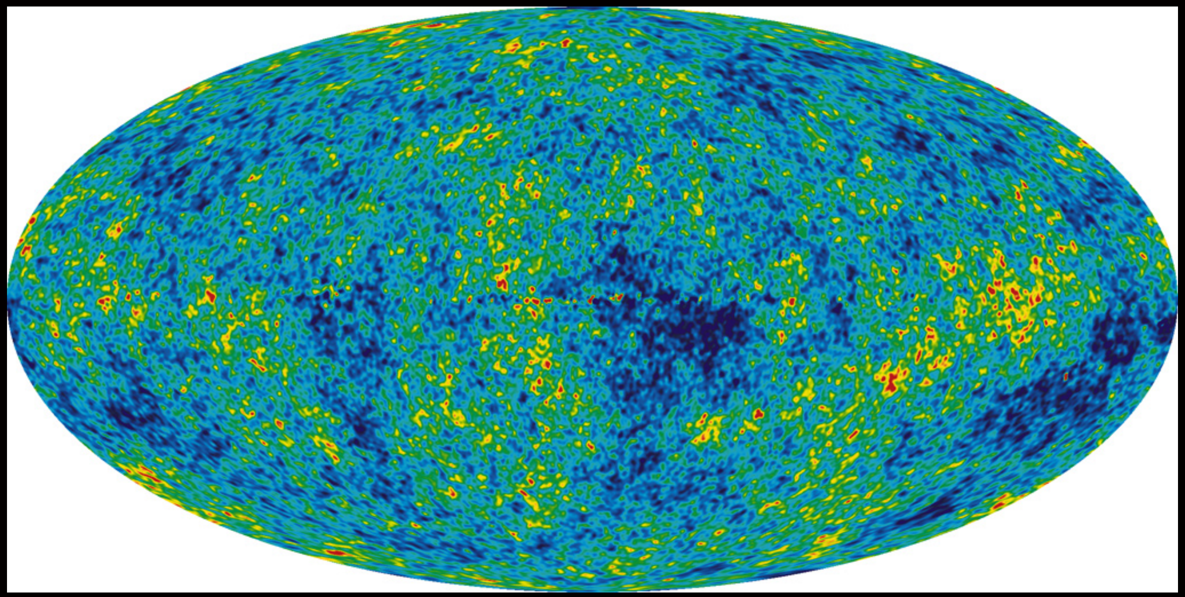
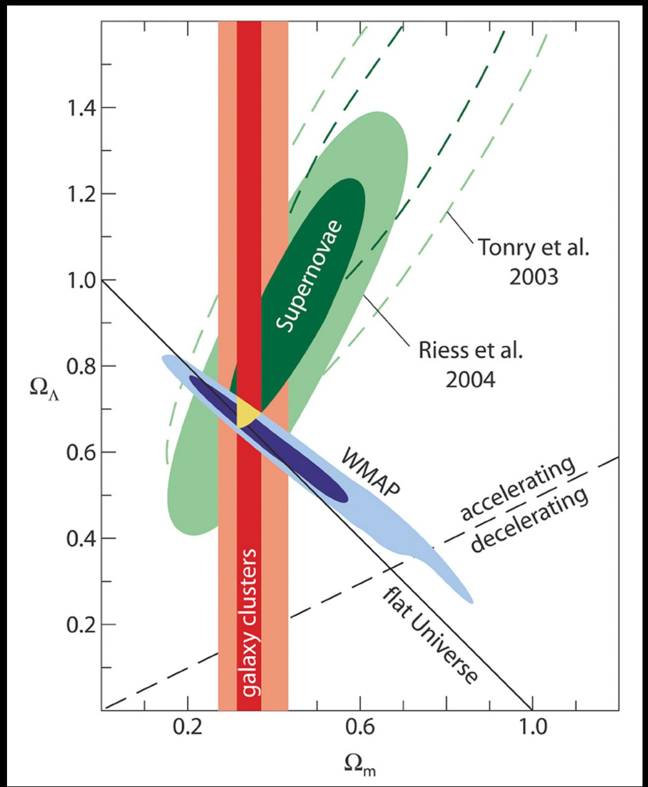
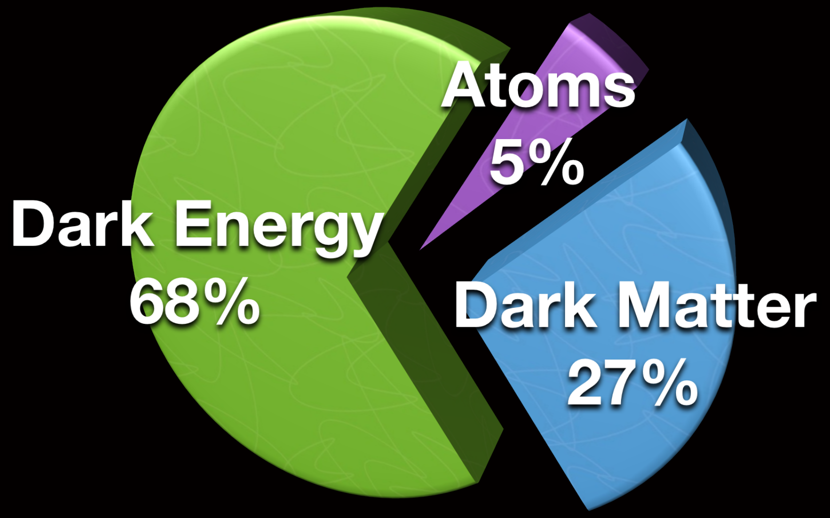
Dark Matter



Microwave Background Radiation

Bullet cluster





Dark Matter is NOT

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- Baryons!!!
- MACHOs ruled out by microlensing observations 10^{-7}–$30\ M_\odot$
- Neutrinos

Light neutrinos: are problematic in small scale structure
m>500 eV (Tremaine-Gunn) otherwise neutrinos violate Pauli blocking in dwarf galaxies. But for m>500 eV gives too much dark matter
Heavy Neutrinos: m> 2 GeV (Lee-Weinberg)
excluded by direct dark matter search experiments unless the mass is huge

- ChaMPs (Charged Massive Particles)
- SIMPs (Strongly Interacting Massive Particles)

ruled out by anomalous hydrogen isotope searches in ocean water*

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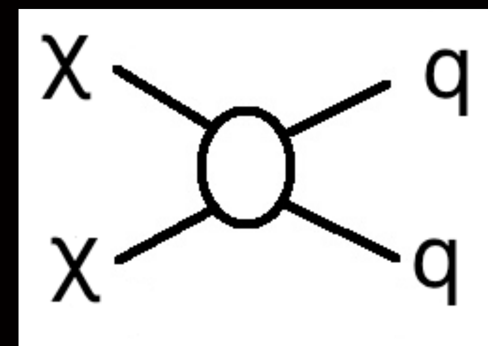
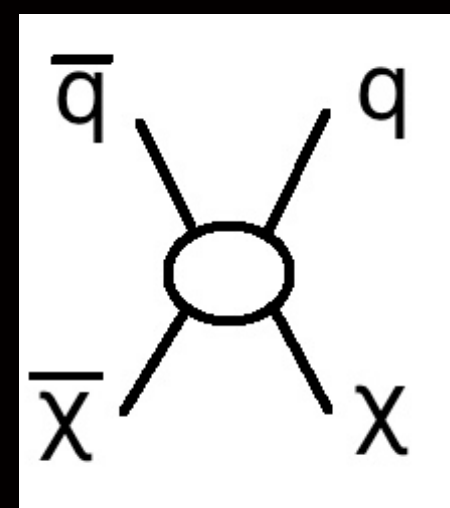
Detection of Dark Matter

Direct detection



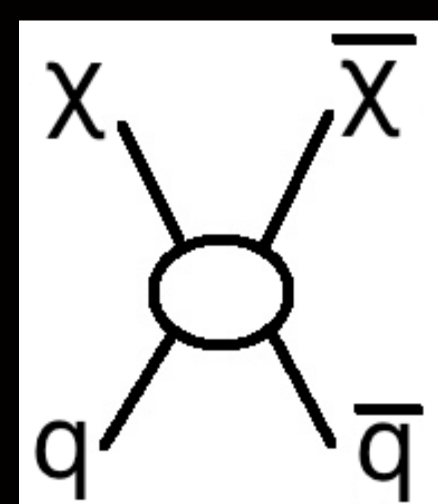
Inconclusive!
DAMA, CRESST, CDMS have signals compatible with dark matter.
Xenon, Picasso, LUX null results.

Indirect detection



Inconclusive!
PAMELA positron excess, FERMI 130 GeV line? New keV line?

Production



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

Astrophysical Observations

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)

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,’13 McDermott Yu Zurek ’11, CK’11,’12 Guver Erkoca Reno Sarcevic ’12, Fan Yang Chang ’12, Bell Melatos Petraki ’13, Bramante Fukushima Kumar Stopnitzky ’13)

New effects

WIMPs can slow down the rotation of a pulsar (Perez-Garcia,CK ’14)

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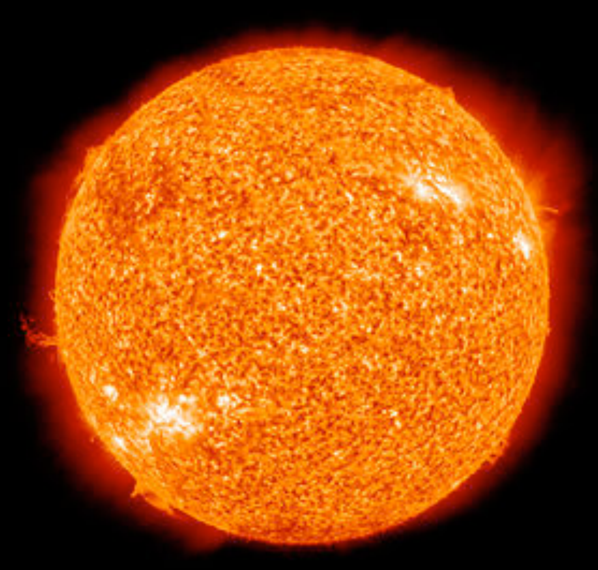
WIMP capture in Stars

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

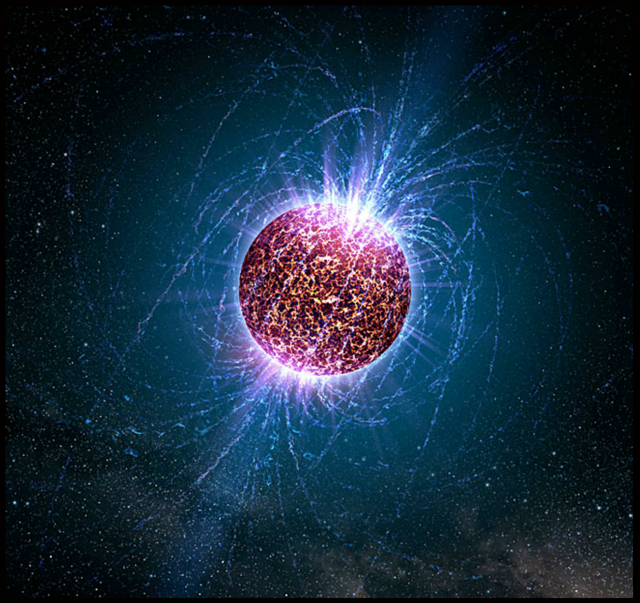


Example: Sun

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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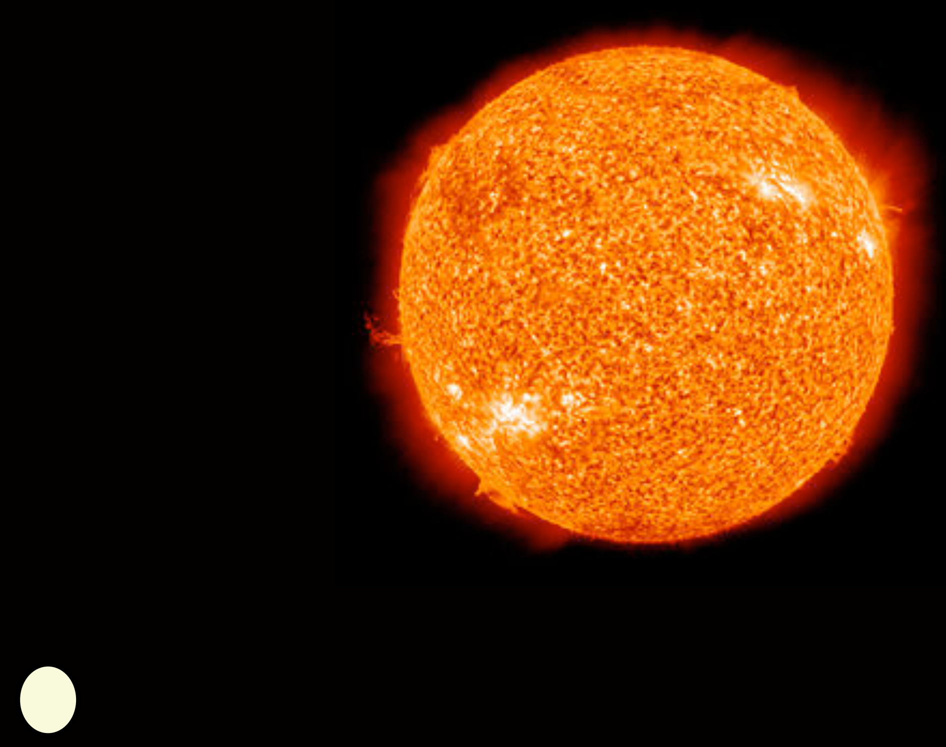

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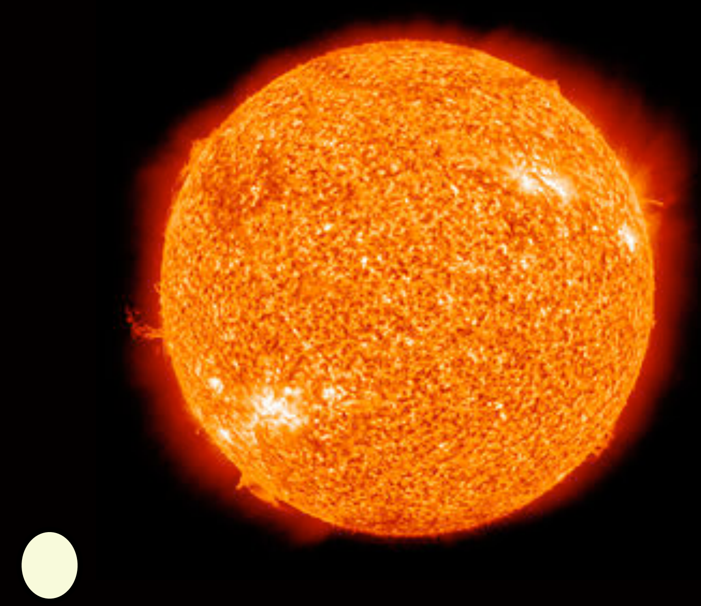

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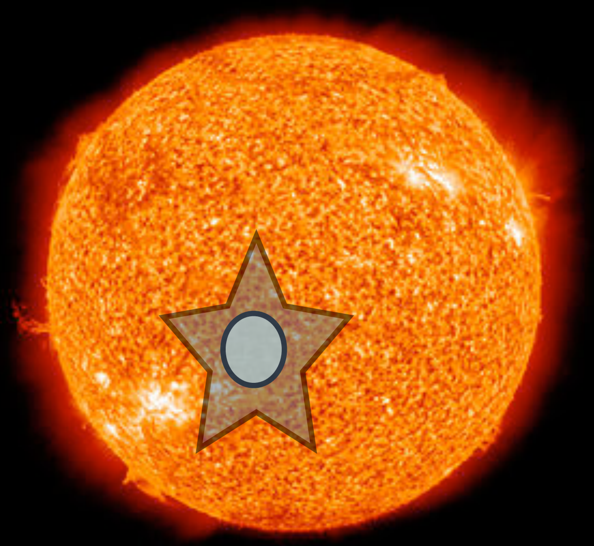

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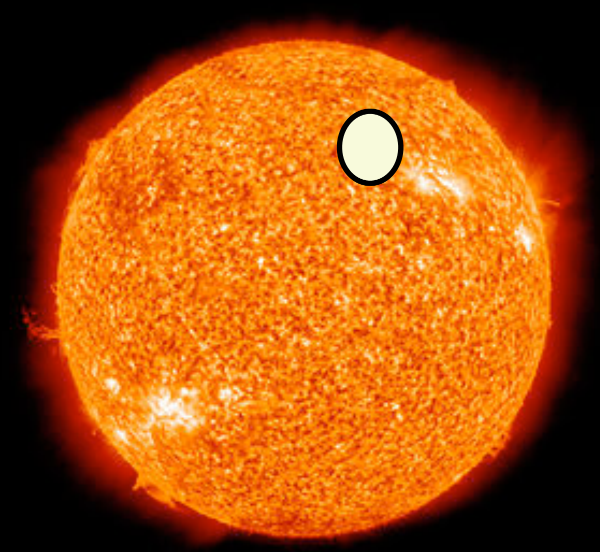

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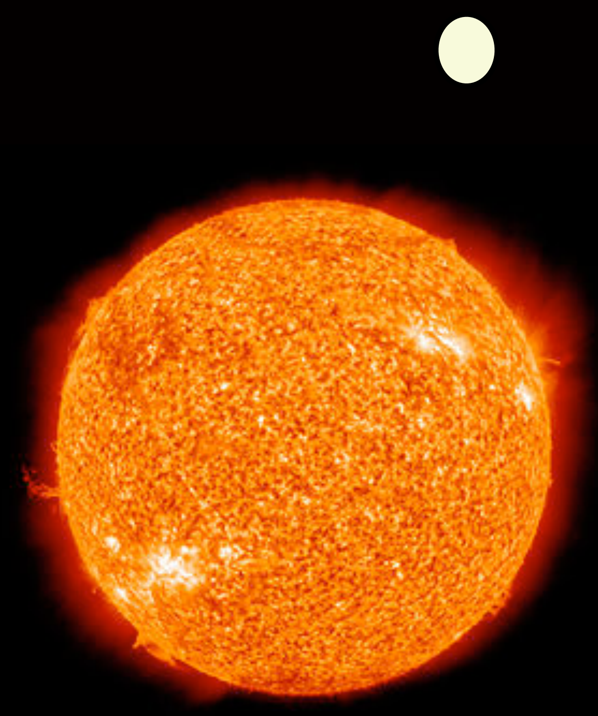

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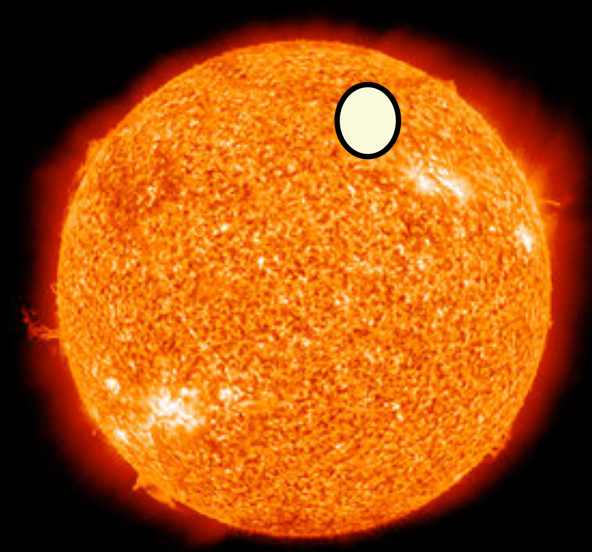

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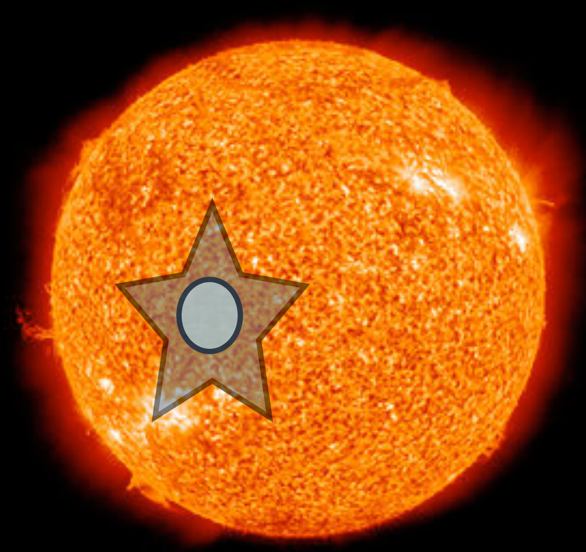

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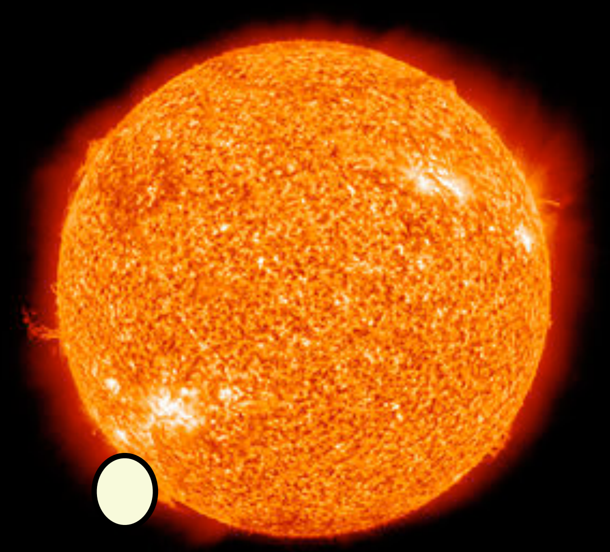

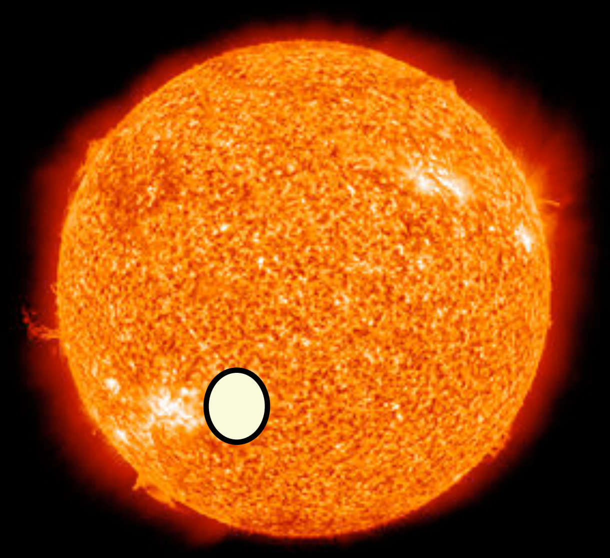

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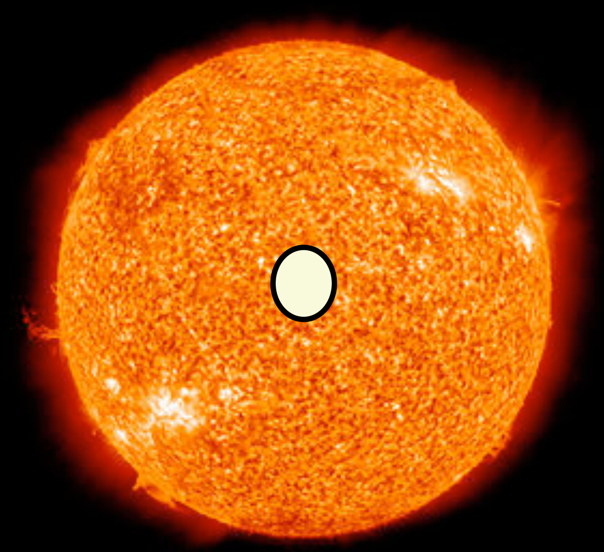

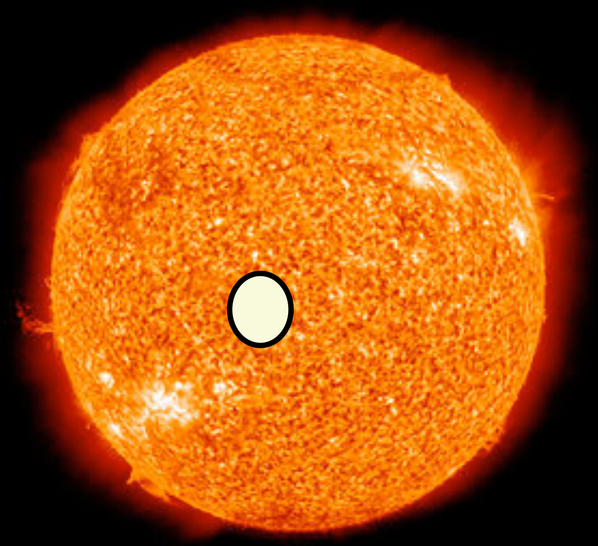

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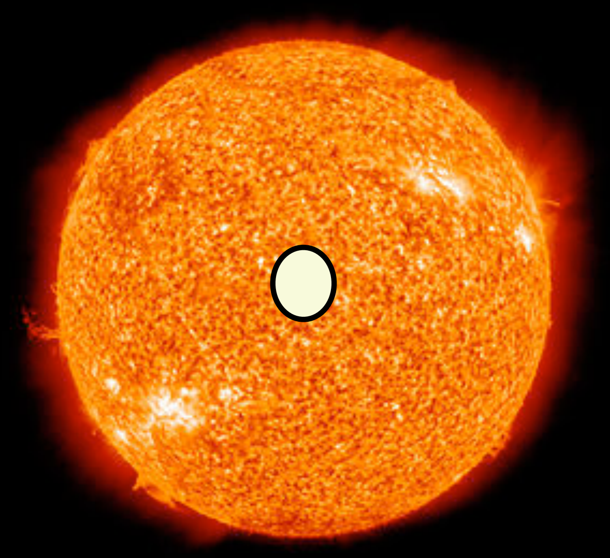

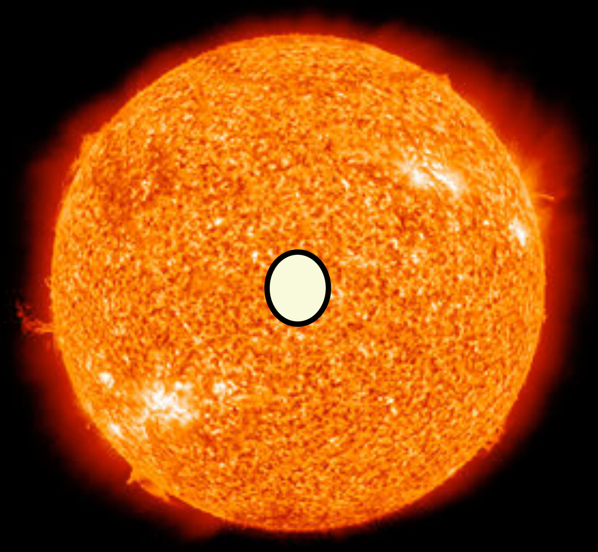

WIMP capture in Stars

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

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

higher local DM density gives higher accretion

smaller velocities enhance capture

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

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

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

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

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

Goldman Nussinov'89, CK Tinyakov '10 Bertoni Nelson Reddy '13

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

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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 $$W(t) = Fm\,\mathrm{Tanh}^2 \frac{t+c}{\tau}$$

we have to compare with other heating/cooling mechanisms

Basics of Neutron Star Cooling

Urca process

Direct Urca

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

However for nuclear matter triangle inequalities are not satisfied

For quark matter it holds!

Emissivity: $\propto T^6$

Modified Urca presence of bystander

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

Emissivity: $\propto T^8$

Photon Emission Emissivity: $\propto T^4$

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

... 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

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

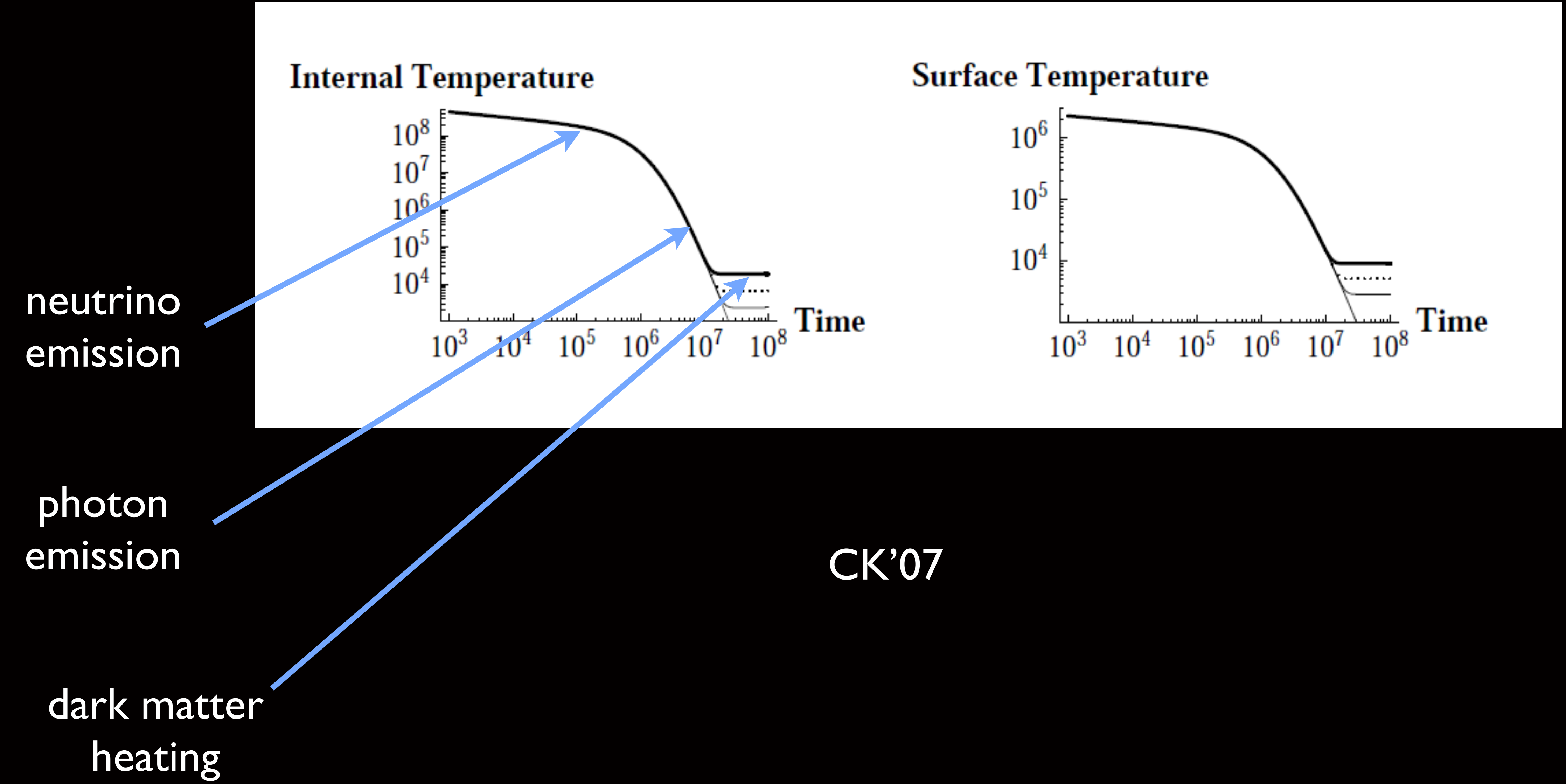
•Pionic Reactions

•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

Cooling of Neutron Stars

Galactic Center

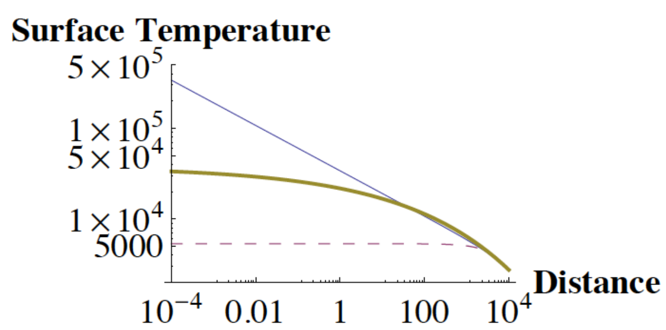


FIG. 3: The surface temperature of a typical old neutron star in units of K as a function of the distance of the star from the galactic center in pc, with the dark matter annihilation taken into account. The three curves correspond to three different dark matter profiles: NFW (thin solid line), Einasto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

Globular Cluster

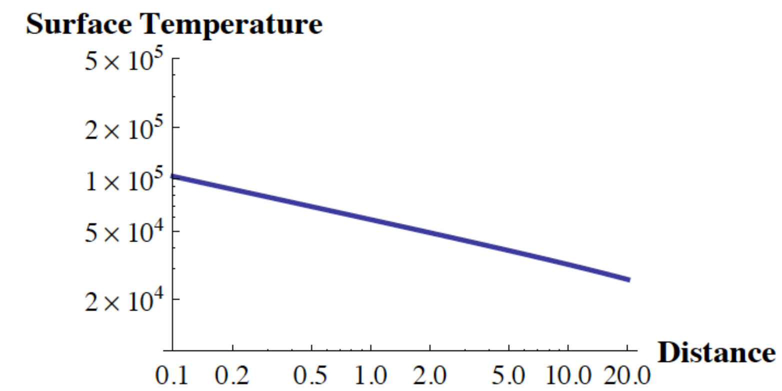


FIG. 5: The surface temperature of a typical old neutron star in units of K as a function of the distance in pc for a NFW profile of the globular cluster $M4$.

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

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

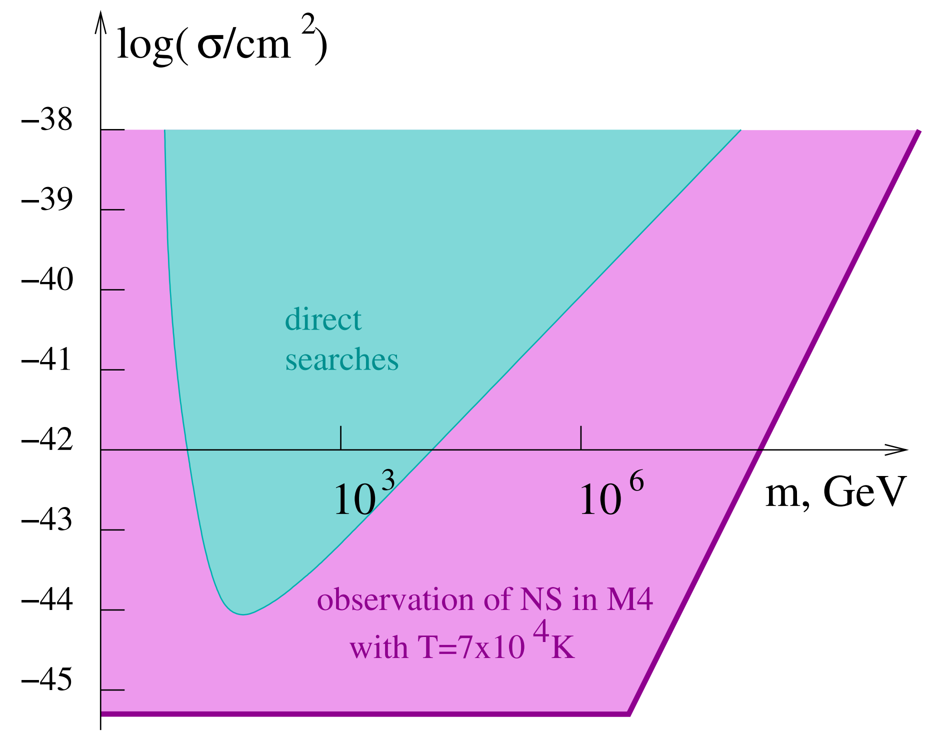
$$\rho_{\rm Bur} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$$

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

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

No Fermi pressure but Heisenberg uncertainty keeps bosons from collapse

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

repulsive interactions

BEC accelerates collapse

$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3}\frac{2\pi\hbar^2}{mk_B} \approx 3.31\,\frac{\hbar^2 n^{2/3}}{mk_B} \qquad N_{\rm BEC} \simeq 2\times 10^{36}$$

$$r_{\rm th} \simeq 2\ {\rm m}\left(\frac{T_c}{10^5{\rm K}}\right)^{1/2}\left(\frac{m}{\rm GeV}\right)^{-1/2} \longrightarrow r_c = \left(\frac{8\pi}{3}G\rho_c m^2\right)^{-1/4} \simeq 1.6\times10^{-4}\left(\frac{\rm GeV}{m}\right)^{1/2}{\rm cm}$$

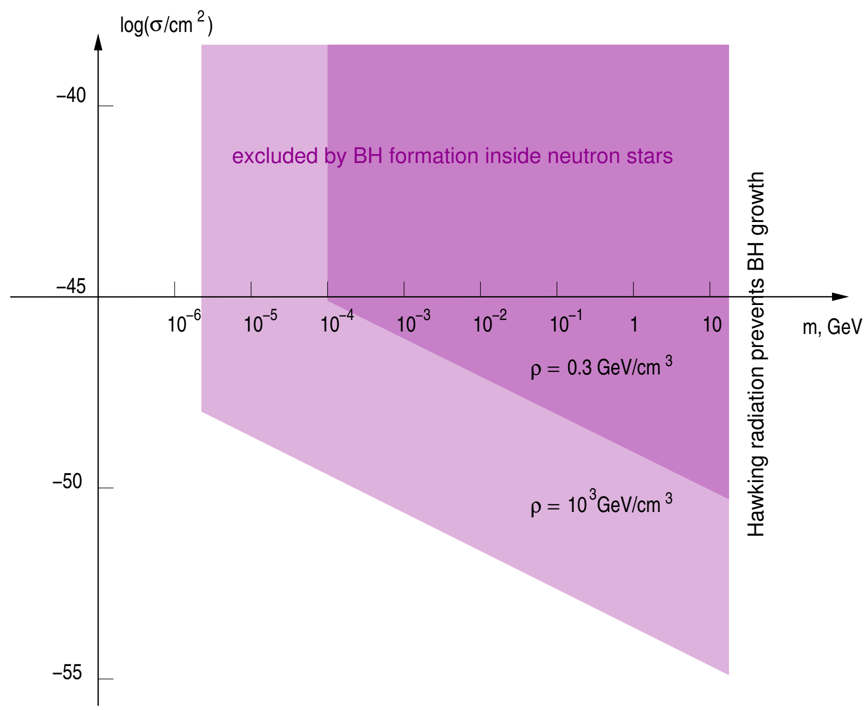
Evolution of the Black Hole

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

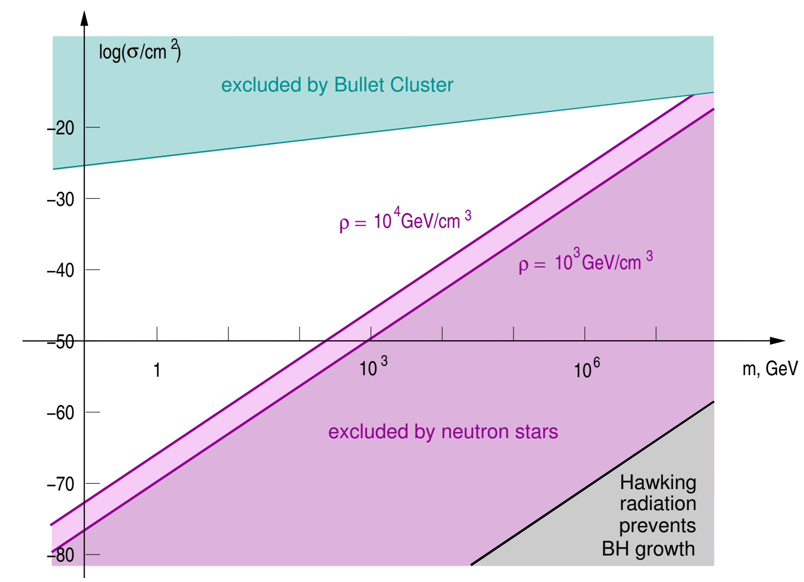
Bondi accretion

Hawking Radiation

Bosonic Asymmetric Dark Matter



CK, Tinyakov PRL '11



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

The effect of Rotation I

For the scenario to be realised one should make sure that all conditions are met!

The accretion is never perfectly spherical because the neutron star rotates usually with high frequencies.

Can rotation slow down the accretion to the point that invalidate the constraints?

The conditions for Bondi accretion are valid as long as the angular momentum of an infalling piece of matter is much smaller than the keplerian one in the last stable orbit

The mass of the black hole must be larger than

$$M_{\rm crit} = \frac{1}{12^{3/2}} \left(\frac{3}{4\pi\rho_c}\right)^2 \left(\frac{\omega_0}{G}\right)^3 \frac{1}{\psi^3}$$

$$M_{\rm crit} = 2.2 \times 10^{46} P_1^{-3}\ {\rm GeV}$$

CK, Tinyakov '13

viscosity of nuclear matter can help!

It subtracts angular momentum at the initial stage where the black hole is still small

in the final stages Bondi accretion is not valid but the star is seconds away from destruction!

The effect of Rotation II

A maximally spinning black hole will stop the accretion

$$a = J/GM^2$$

$$\frac{1}{a}\frac{da}{dt} = \frac{1}{J}\frac{dJ}{dt} - 2\frac{1}{M}\frac{dM}{dt}$$

$$\frac{1}{a}\frac{da}{dt} = \frac{1}{J}\omega_0 r_s^2 \frac{dM}{dt} - \frac{g(a)}{G^2M^3} - \frac{2}{M}\frac{dM}{dt}$$

After formation the black hole spins down, then it spins up and at the last stages it spins down again

$$a_{\max} = 2 \times 10^{-23} T_5^4 / P_1^{10}$$

Temperature Considerations

Radiation from in falling matter can in principle impede further accretion in two ways:

Reduce viscosity

Increase radiation pressure

e-e Bremsstrahlung close to the horizon is the dominant radiation mechanism

$$\epsilon = \frac{L_{ee}}{dM/dt} \simeq 5 \times 10^{-12} T_5 \left(\frac{M}{M_0}\right)$$

$$\delta T = \frac{L_{ee}}{4\pi k r} \simeq 458 \left(\frac{M}{M_0}\right)^2 \left(\frac{r_B}{r}\right) \mathrm{K}.$$

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Bosonic Asymmetric Dark Matter

For m>10 TeV, self-gravitation takes place before BEC formation

Could this lead to the collapse of the whole WIMP sphere into a single black hole?

The answer is no!

The WIMP sphere has to go through a BEC formation

Small black holes form one after the other

$$t_{\rm cool} \simeq 1.5 \times 10^3 {\rm s} \times \left(\frac{m}{10{\rm TeV}}\right)^{5/3} \left(\frac{T}{10^5{\rm K}}\right)^{-3} \left(\frac{\sigma}{10^{-43}\,{\rm cm}^2}\right)^{-1} \quad > \quad \tau = 5 \times 10^3 {\rm s} \left(\frac{10{\rm TeV}}{m}\right)^3$$

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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!!!

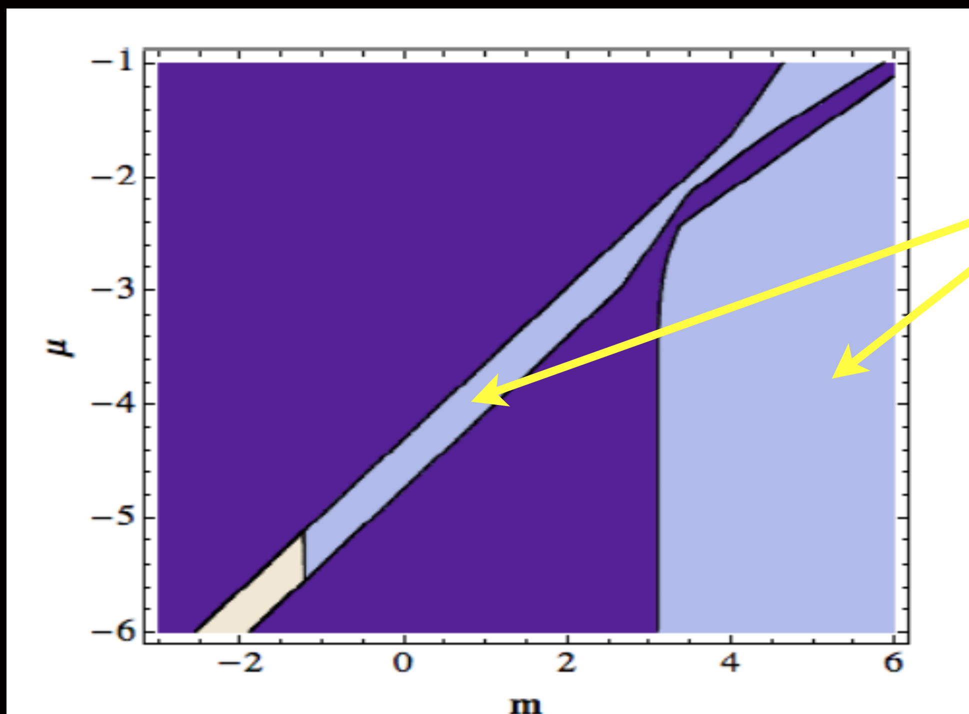
Yukawa-type WIMP self-interactions can explain the flatness of dwarf galaxies Spergel-Steinhardt '99, Loeb-Weiner '11

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

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

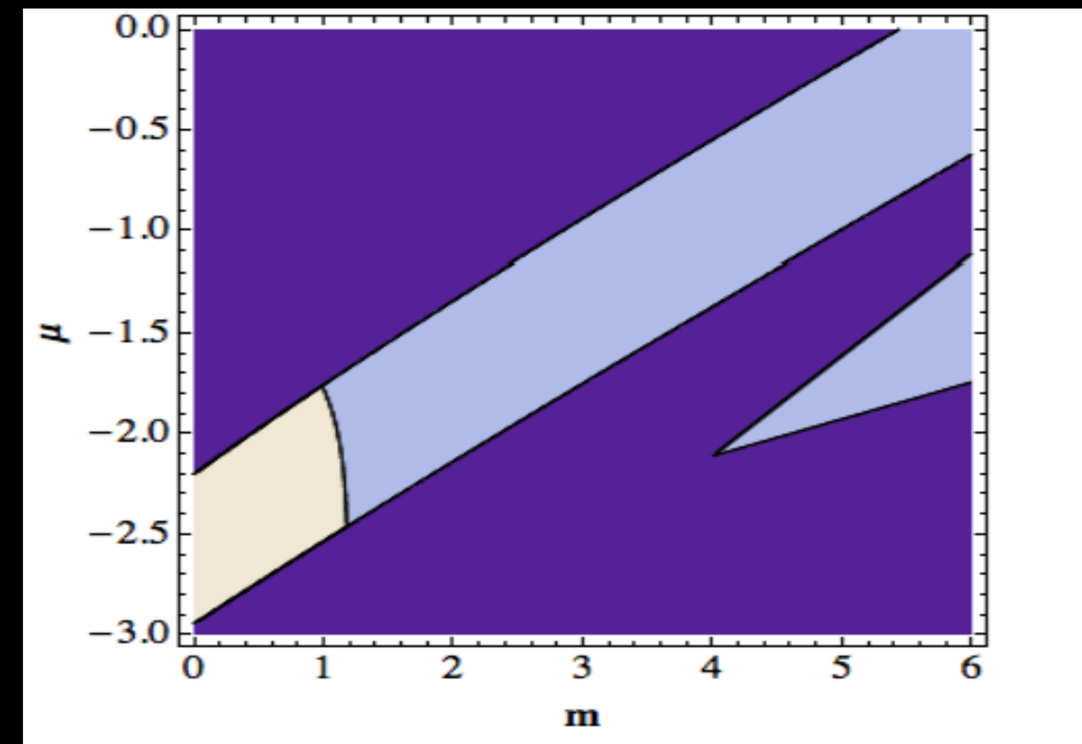
Yukawa self-interactions can alleviate the effect of the Fermi pressure, leading to a gravitational collapse with dramatically lower amount of captured WIMPs

Self-Interacting Dark Matter

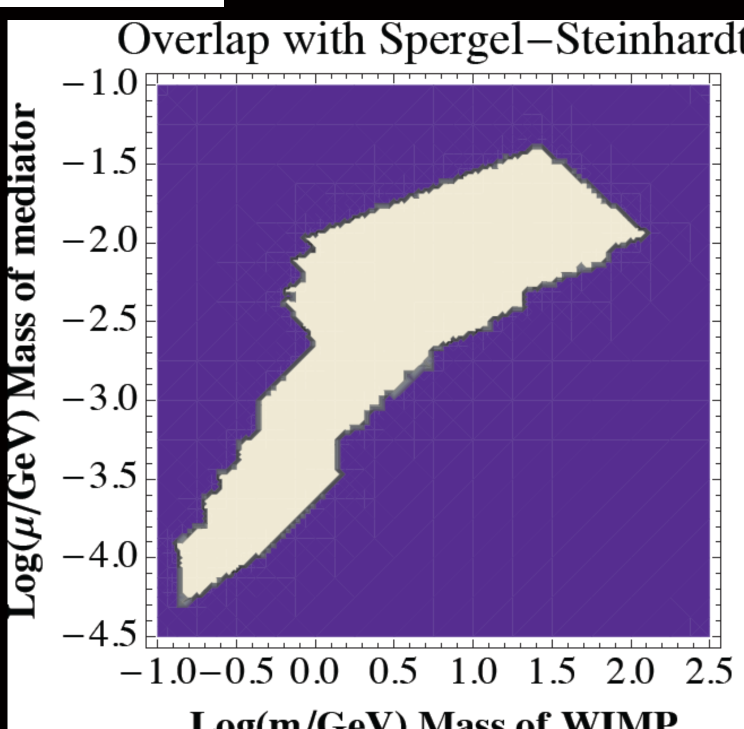


Exclusion regions

CK PRL'12



$\alpha = 10^{-5}$



$\alpha = 0.1$

Loeb-Weiner

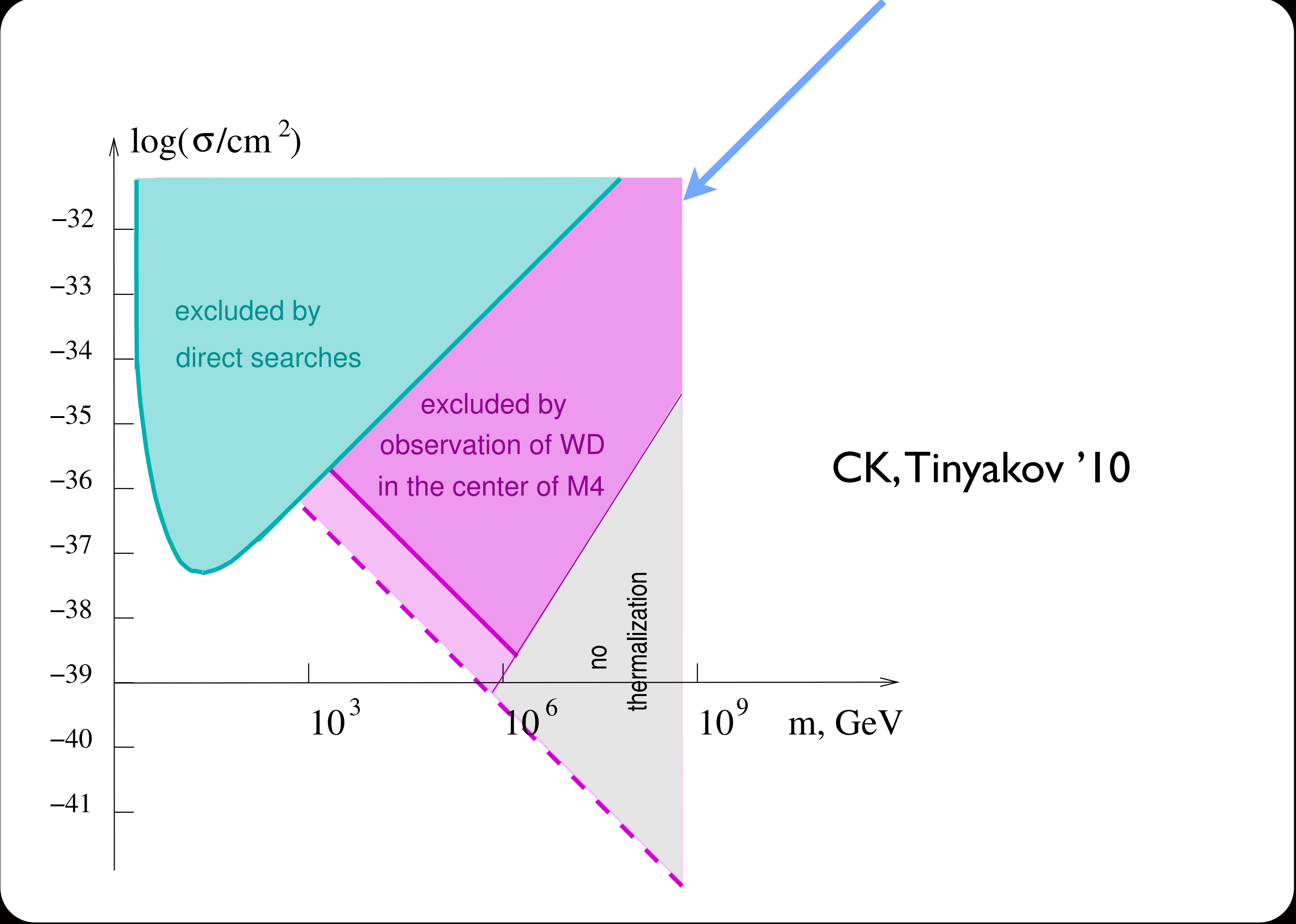
$$(m_\chi/10\mathrm{GeV})(m_\phi/100\mathrm{MeV})^2 \sim 1$$

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

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

Formation of a Black Hole



CK, Tinyakov '10

Pulsar Spindown

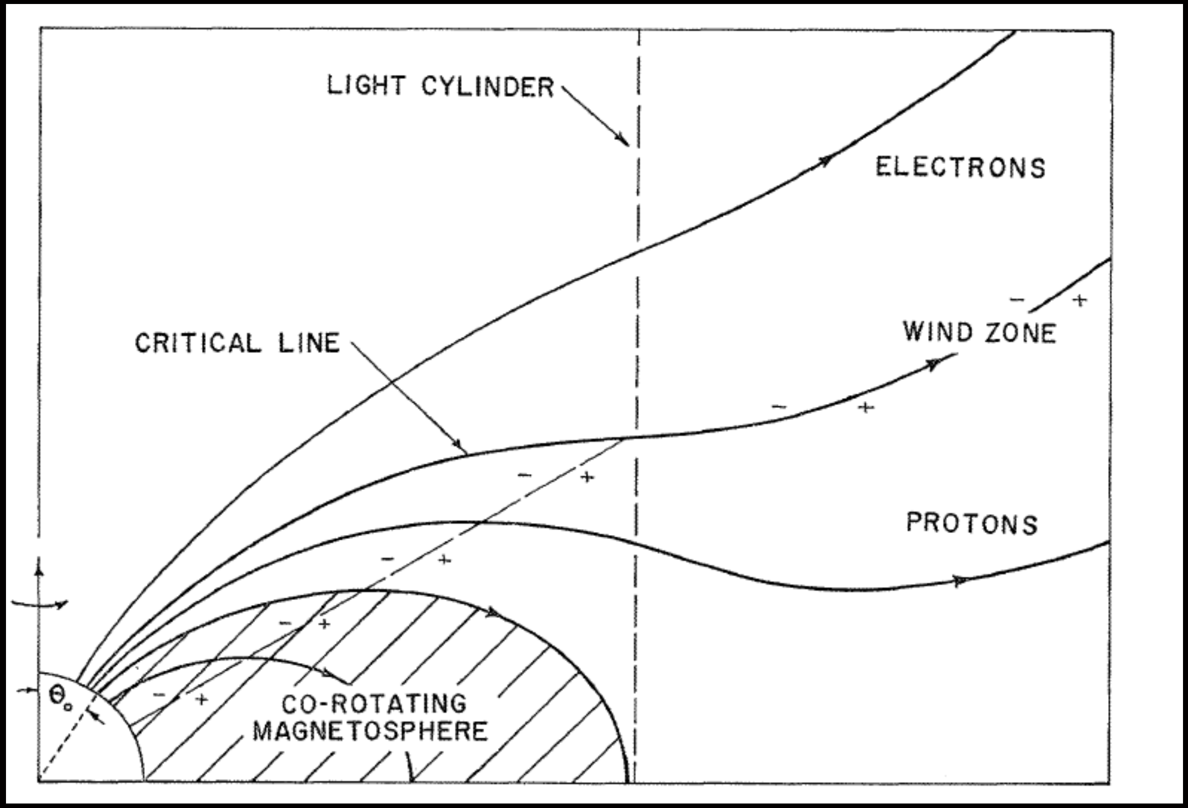
Pulsars spin down according to 2 basic mechanisms

- Magnetic Dipole Radiation
- Aligned Rotator

$$L = L_{\rm orth} \sin^2\theta + L_{\rm align} \cos^2\theta$$

$$L_{\rm orth} = \frac{B_0^2 \Omega^4 R^6}{4c^3}, \qquad L_{\rm align} = \frac{B_0 \Omega \Omega_F R^3 I}{2c^2}$$

Contopoulos, Spitkovsky '06



$$I = I_{\rm GJ} = \frac{B_0 R^3 \Omega^2}{2c} \simeq 1.4 \times 10^{30} e \left(\frac{B_0}{10^{12}\,G}\right)\left(\frac{s}{P}\right)^2 \; s^{-1}$$

$$\dot{E} = \mathcal{I}\Omega\dot{\Omega} = \tfrac{2}{5} M R^2 \Omega \dot{\Omega} = -L$$

Julian Goldreich '69

Danish Institute for Advanced Study

Pulsar Spindown

Can accretion of millicharged particles affect the spinning?

At steady state a NS should expel as much charge as it accumulates

$$\dot{\Omega} = -\frac{5B_0^2\Omega^3R^4}{8Mc^3}\left[\sin^2\theta + \left(1 - \frac{\Omega_{\rm death}}{\Omega}\right)\left(1 + \frac{I_{\rm DM}}{I_{\rm GJ}}\right)\cos^2\theta\right]$$

Observable independent of the magnetic field braking index

$$n = \ddot{\Omega}\Omega/\dot{\Omega}^2$$

$$n = 3 - \frac{2\lambda\cos^2\theta}{1+\lambda\cos^2\theta}$$

$$\lambda = \frac{I_{\rm DM}}{I_{\rm GJ}}$$

If the DM current is similar to the GJ current, the braking index can significantly different than 3

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Pulsar Spindown

TABLE 2

SPIN AND INFERRED PARAMETERS FOR PULSARS WITH MEASURED n, ORDERED BY SPIN-DOWN AGE

Pulsar	n[a]	ν (s^{-1})	$\dot{\nu}$ (10^{-11} s^{-2})	τ_c[b] (yr)	τ[c] (yr)	B_{di}[d] (10^{12} G)	$\dot{E}$[e] (10^{36} ergs s^{-1})	Reference
J1846−0258	2.65(1)	3.07	−6.68	723	884	49	8.1	1
B0531+21	2.51(1)	30.2	−38.6	1240	1640	3.8	460	2
B1509−58	2.839(3)	6.63	−6.76	1550	1690	15	18	3
J1119−6127	2.91(5)	2.45	−2.42	1610	1680	42	2.3	4
B0540−69	2.140(9)	19.8	−18.8	1670	2940	5.1	150	5
B0833−45[f]	1.4(2)	11.2	−1.57	11300	57000	3.4	6.9	6

[a] Uncertainties on n are in the last digit.
[b] Characteristic age is given by $\tau_c = \nu/2\dot{\nu}$.
[c] Inferred upper-limit timing age given n, $\tau = \nu/(n-1)\dot{\nu}$, assuming $\nu_i \gg \nu$.
[d] Dipole magnetic field estimated by $B_{di} = 3.2 \times 10^{19}(-\dot{\nu}/\nu^3)$ G, assuming $\alpha = 90°$ and $n = 3$.
[e] Spin-down luminosity, $\dot{E} \equiv 4\pi^2 I\nu\dot{\nu}$, where it is assumed that $I = 10^{45}$ g cm^2 for all pulsars.
[f] Braking index for the Vela pulsar was not determined from a standard timing analysis due to the large glitches experienced by this object. Instead, measurements of $\dot{\nu}$ were obtained from assumed "points of stability" 100 days after each glitch (see Lyne et al. 1996 for details).

REFERENCES.—(1) This work; (2) Lyne et al. 1993; (3) Livingstone et al. 2005b; (4) Camilo et al. 2000; (5) Livingstone et al. 2005a; (6) Lyne et al. 1996.

Dark Matter accretion

Electromagnetic

$$F_{\rm I} \simeq 1.0 \times 10^{29} \left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV cm^{-3}}}\right)\left(\frac{1{\rm GeV}}{m}\right)\left(\frac{P}{\rm s}\right)\ {\rm s}^{-1}$$

Gravitational

$$F_{\rm II} = 4.2 \times 10^{26} \left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV cm^{-3}}}\right)\left(\frac{1{\rm GeV}}{m}\right) f\ {\rm s}^{-1}$$

Condition

$$r_L << R_{\rm curv}$$

$$r_L = \frac{m v_\perp}{\epsilon e B}$$

$$R_{\rm curv}(r,\gamma) = \left|\frac{1}{B}\frac{dB}{dr}\right|^{-1}$$

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Pulsar Spindown

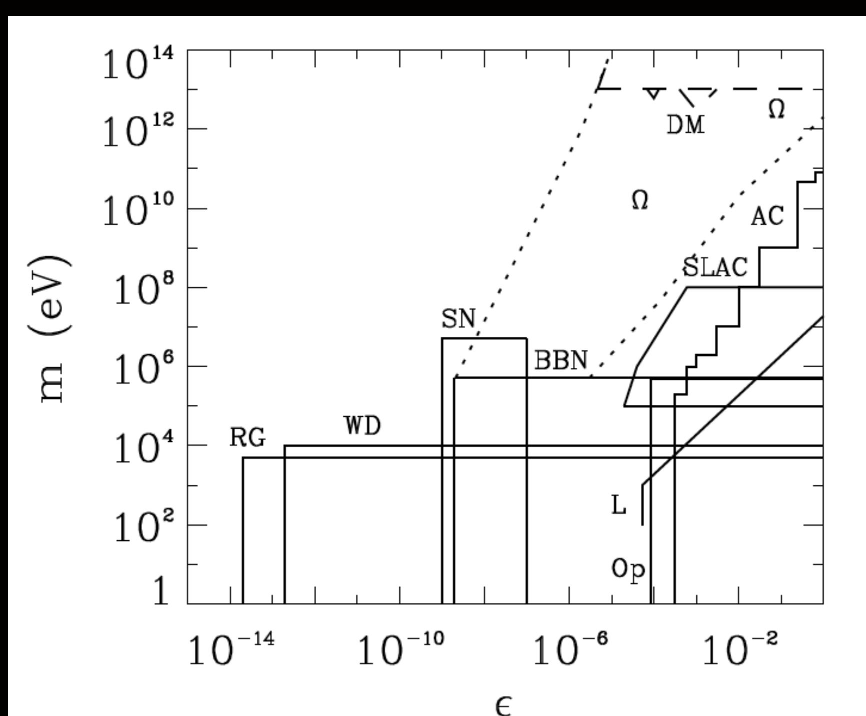
Electromagnetic

$$\epsilon \left(\frac{\mathrm{GeV}}{m}\right) \simeq 14 \left(\frac{0.3\,\mathrm{GeV cm^{-3}}}{\rho_{\mathrm{DM}}}\right) \left(\frac{\mathrm{s}}{P}\right)^3 \left(\frac{B_0}{10^{12}\,G}\right)$$

CK, Perez-Garcia '14

Gravitational

$$\epsilon \left(\frac{\mathrm{GeV}}{m}\right) \simeq \frac{3.3 \times 10^3}{f} \left(\frac{0.3\,\mathrm{GeV cm^{-3}}}{\rho_{\mathrm{DM}}}\right) \left(\frac{\mathrm{s}}{P}\right)^2 \left(\frac{B_0}{10^{12}\,G}\right)$$



Davidson,Hannestad, Raffelt '00

$$\epsilon^2 \gtrsim 5 \cdot 10^{-11}\,\mathrm{GeV}^{-1/2} \frac{m_X}{\sqrt{\mu_{X,e}} + \sqrt{\mu_{X,p}}}$$

Dolgov,Dubovsky,Rubtsov,Tkatchev '13

Can be satisfied for example for
MeV, ε~10^-6 and either higher DM density
or lower magnetic field

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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 few GeV non-interacting bosonic dark matter is excluded.
2. Part of fermionic WIMP self-interactions excluded.
3. Constraints on WIMP-nucleon spin-dependent interactions.

- Millicharged dark matter could slow down pulsars faster than other mechanisms predict.