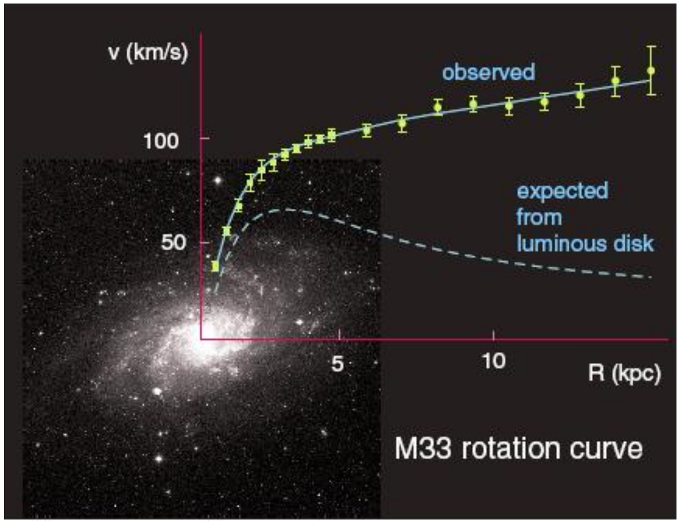
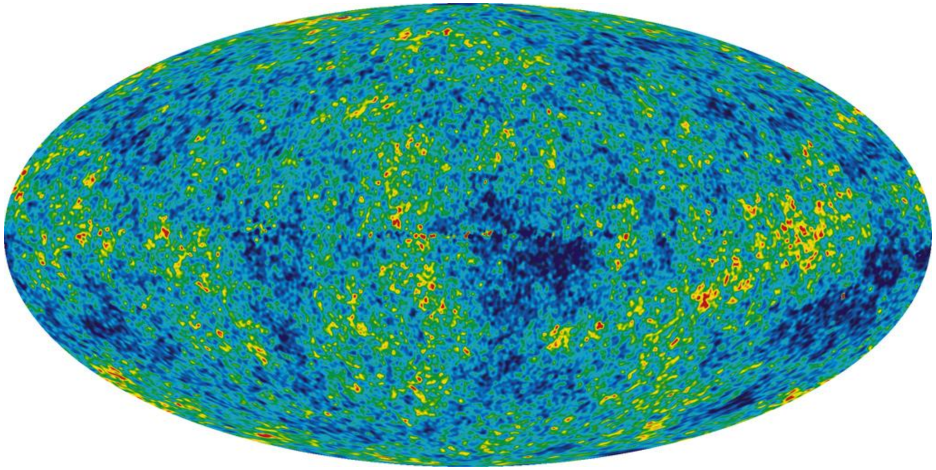
Can Neutron Stars Constrain Dark matter?

Chris Kouvaris
Université Libre de Bruxelles

Dark Matter


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve



Dark Matter Candidates

- Supersymmetric (neutralino, gravitino etc)
- Hidden Sectors
- Technicolor Candidates
- Kaluza Klein
- Axions
- … and many other

Candidates can have:

Spin independent cross section
Spin Dependent cross section
Inelastic Scattering
Self-Interacting cross section
Thermal annihilation cross section
Non-thermal annihilation cross section

Can Stars impose constraints on Dark Matter?

Neutrino production from WIMP annihilation

IceCube & Super-Kamiokande can impose constraints on the WIMP-nucleon cross section

WIMP accumulation and formation of Black Holes

In neutron stars at rich dark matter regions, WIMPs can cause gravitational collapse (Goldman, Nussinov '89, CK Tinyakov '10)

WIMP annihilation and cooling of stars

WIMP annihilation as a heating mechanism

- **for neutron stars (CK '07, CK, P. Tinyakov, Lavallaz, Fairbairn '10)**
- **for white dwarfs (Bertone, Fairbairn '07, McCullough '10)**

Why look at compact stars?

Example: Sun

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

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!

The number of accumulated WIMPs is even smaller because not all the scattered WIMPs get trapped.

<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.

Same Exercise for a White Dwarf

$$M_{WD} \approx M_{solar}, \quad R_{WD} \approx 5500km \quad n \approx \frac{M_{WD}}{(4/3)\pi R_{WD}^3 m_n} \approx 1.7 \cdot 10^{30} \ particles / cm^3$$

If we want one collisions per WIMP passing the cross section

$$\sigma > \sigma_{critical} = 10^{-39} cm^2$$

This is an improvement!!!

Since for the sun $\sigma_{critical} = 10^{-35} cm^2$

However still above the CDMS limit!!!

If $M_{WD} \approx 0.5 M_{solar}$, $R_{WD} \approx 10000km$ $\sigma > \sigma_{critical} = 7 \cdot 10^{-39} cm^2$

Could Coherent Scattering help???

Coherent Scattering WIMP-Nucleus

Dirac (non-Majorana) type of candidates can interact coherently with the whole nucleus

$$\sigma \propto N_1^2, \; N_1 = (A - Z) + \epsilon Z \qquad \epsilon = (1 - 4\sin^2\theta_W) \sim 0.08$$

This effect is taken into account in earth based experiments, where WIMPs are passing through with velocities 220 km/s putting tight constraints on these candidates.

However loss of coherence occurs when

the momentum transfer $q,= (2M_T E_R)^{1/2}$, is such that the wavelength h/q is no longer large compared to the nuclear radius

$$\sigma(qr_n) = \sigma_0 F^2(qr_n)$$

$$F^2(qr_n) = e^{-\alpha(qr_n)^2}$$

Helm factor ⟶ $F(qr_n) = 3\,\dfrac{j_1(qr_n)}{qr_n} \times e^{-(qs)^2/2}$

Studies so far were assuming coherence in the scattering between WIMP-nucleus in the White Dwarfs….

…but this not true (CK, Tinyakov '10) because the potential energy is much larger than the asymptotic kinetic energy of the WIMP. WIMPs are almost relativistic while entering the Whit Dwarf.

$$\frac{GM}{R} > E_0$$

The de Broglie wavelength is much shorter than the size of the nuclei and the form factor kills the enhancement of the cross section due to the coherence.

Neutron Stars

even more compact objects! Fermi pressure of neutrons and/or quark matter??? balances gravity.

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

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

Way below the CDMS limit!!!

WIMPs are relativistic while entering the NS, and therefore also here coherence is lost, but this is not important since for cross sections larger than the critical one, every WIMP passing the NS will scatter at least once on average.

Neutron Stars seem to be the objects with the best efficiency in capturing WIMPs!

… furthermore

Inelastic Dark Matter

since $$\sigma_{\rm inelastic} = \sigma_{\rm elastic}\sqrt{1-\frac{2\delta}{\mu v^2}}$$

the two cross sections become almost identical for a NS and therefore the same constraints apply

Self-Interacting Dark Matter

Strong WIMP-WIMP cross section

$$\frac{{\rm d}N_{\rm x}}{{\rm d}t} = C_{\rm c} + C_{\rm s}N_{\rm x} - C_{\rm a}N_{\rm x}^2$$

For a Neutron star as long as the WIMP-nucleon cross section is above the critical value, self-interactions make no difference in the accretion and capture of the the WIMPs

Capture of WIMPs in Neutron Stars

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

CK '07

For a typical NS

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

Thermalization

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

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

Annihilation of WIMPs inside the Neutron Stars

$$\frac{dN(t)}{dt} = F - C_A N(t)^2 \qquad C_A = \langle \sigma_A v \rangle / V \qquad N(t) = \sqrt{\frac{F}{C_A}} \mathrm{Tanh} \frac{t+c}{\tau}$$

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

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

Energy Release

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

We must compare it with the other heating/cooling mechanisms

Basics of Neutron Star Cooling

Urca Process

Direct Urca

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

Energy release through escaping neutrinos

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: $\propto T^4$

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

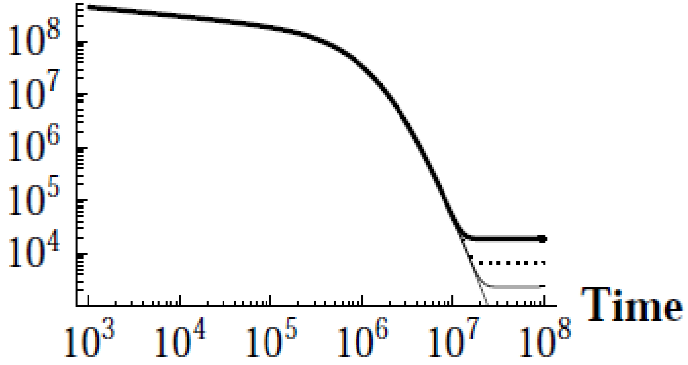
Cooling Curves

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

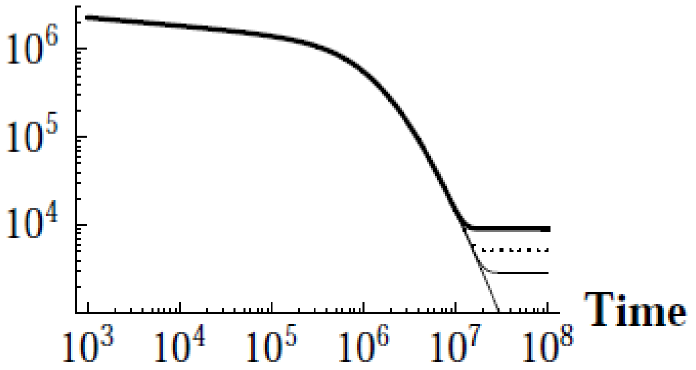
$$\epsilon_{\rm dm} = \frac{E}{4\pi R^3/3} = \frac{3\mathcal{F} m_\chi}{4\pi R^3} = A\ 1.16 \times 10^4\ {\rm erg\ cm^{-3} s^{-1}}$$

$$\epsilon_\gamma = \frac{L_\gamma}{(4/3)\pi R^3} = 1.8 \times 10^{14} \left(\frac{T}{10^8{\rm K}}\right)^{2.2} {\rm erg\ cm^{-3}\ s^{-1}}$$

Internal Temperature



Surface Temperature



CK '07

Galactic Center

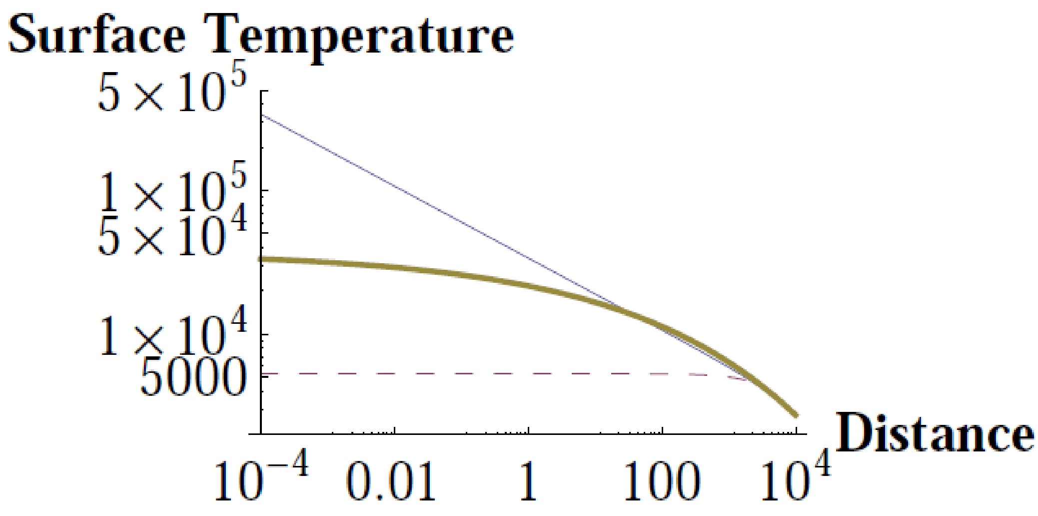


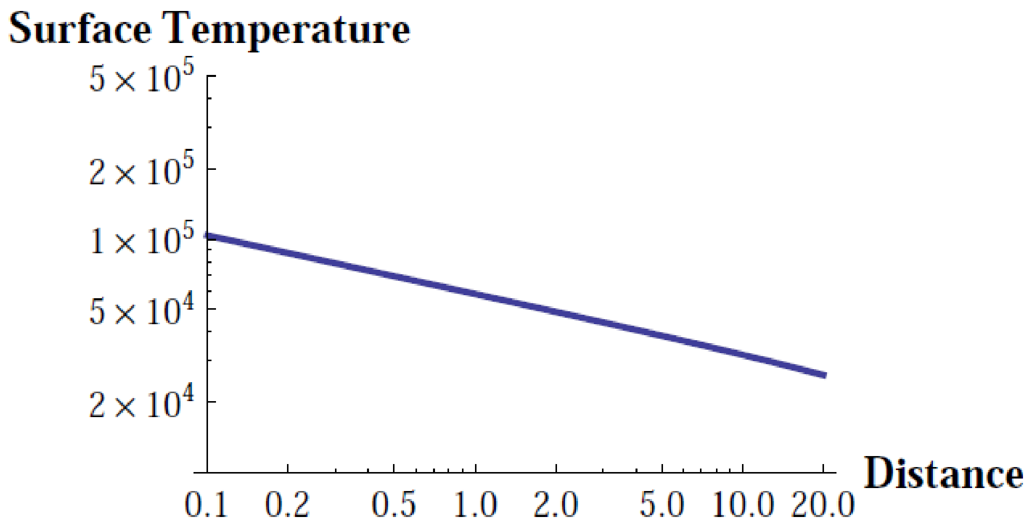
FIG. 3: The surface temperature of a typical old neutron star in units of K as a function of the distance of the star from the galactic center in pc, with the dark matter annihilation taken into account. The three curves correspond to three different dark matter profiles: NFW (thin solid line), Einasto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

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

CK , Tinyakov '10

Globular Clusters

NFW for M4



Baryonic contraction might reduce the temperature up to 30%

Examples: X7 in 47 Tuc
1620-26 in M4 both have temperatures roughly 10^6 K

Observed temperatures smaller than the ones predicted, excludes the dark matter candidate.

Isolated Neutron Stars

…maybe the best candidates for the constraints
•No accretion from bystander white dwarf or other star
•Probably better knowledge of the local dark matter candidate

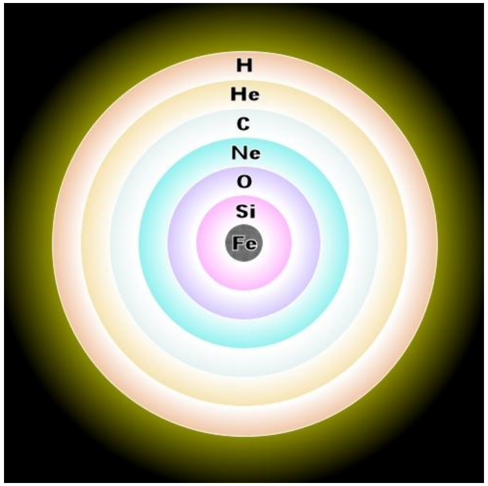
Examples: J0437-4715 temperature 10^5 K
J0108-1431 temperature 9 x 10^4 K

Both of them are old
… only problem their distance from the earth is 130-140 pc
•The local dark matter density should be small (or maybe not)
•Other heating mechanisms can take place

Reisenegger '94 (chemical energy converted to thermal),
Alford, CK, Kundu, Rajagopal '04 (color superconducting matter)

Can A Progenitor change the picture??

A supermassive star can collapse to a neutron star via a Supernova II explosion



The pre-existence of the star increases the local dark matter density in the vicinity of the newly born neutron star

The effect in principle can be large!

Total number of accumulated particles

$$N_0 = 5 \times 10^{37} \left(\frac{\rho_{\rm dm}}{\rm GeV/cm^3} \right) \left(\frac{100\ \rm GeV}{m} \right) \left(\frac{\sigma_N}{10^{-43}\ \rm cm^2} \right)$$

Same order of magnitude as for a neutron star!
Compactness and small WIMP mean free path is counterbalanced by huge mass and radius

After the explosion…

$$\frac{dN_c}{dt} = -F = -1.25 \times 10^{26}\mathrm{s}^{-1} \left(\frac{\mathrm{cm}^3}{V}\right) f \times N_c$$

The mean free path of the WIMPs is too large for them to be carried away from the shock wave, however the WIMPs are “sucked” inside the neutron star very fast (exponentially)

Neutron star kicks up to several thousands of km/s do not alter the picture. WIMPs remain gravitationally bound to the neutron star within the thermal radius of the last stage of the star (silicon).

…still the annihilation cannot compete with the Urca process

however…

Non-thermally produced WIMPs can have extremely small annihilation cross section (supersummetry etc.)
In that case:

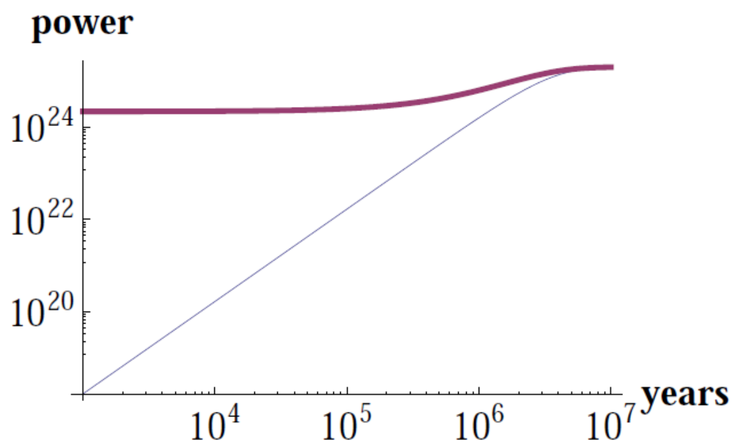


FIG. 2: Power due to WIMP burning in erg/sec as a function of the time. The thick line assumes the pre-existence of a massive star, where in the thin one, the neutron star starts accreting at $t = 0$. We assumed an annihilation cross section of 10^{-60}cm^2 and $\rho_{\text{dm}} = 100\ \text{GeV/cm}^3$.

It can change the temperature estimate by 50%

Neutron Stars as Giant Detectors!

CDMS	NS
Density 5 g/cm^3	10^14g/cm^3
1% Light production	100% Light Production
Local dark matter density	
0.3 GeV/cm^3	up to 10^10!? GeV/cm^3
Cryogenic detectors	low temperature

Black Hole formation

Neutron Stars close to the galactic center might accrete to many WIMPs, and gravitational collapse might occur

For fermionic WIMPs there is a Chandrasekhar limit by setting

$$\frac{GNm^2}{r} > k_F, \quad k_F = (3\pi^2 N/(4\pi r^3/3))^{1/3}$$ Fermi momentum

For gravitational collapse, it takes

10^{51} (10^{48}) particles for a WIMP mass of 100 GeV (1 TeV).

If the dark matter density is smaller than $10^7 \, GeV/cm^3$

The time needed for collapse exceeds the age of the universe!

Conclusions

- Neutron Stars are the only objects that have efficient accretion of WIMPs for WIMP-nucleon cross section below the current experimental limits.
- The constraints apply to thermally and non-thermally produced WIMPs with extremely small annihilation cross section (as low as 10^-57 or even 10^-61 cm^2 depending on the local DM density).
- Although observing neutron stars at the galactic center is an extremely difficult task, globular clusters or isolated neutron stars can impose constraints.
- We set lower bounds on the surface temperature of a NS. If a NS is observed with a temperature lower than what we predict, a huge class of candidates is ruled out!