Constraining decaying DM with Neutron Stars

(arXiv 1403.6111)

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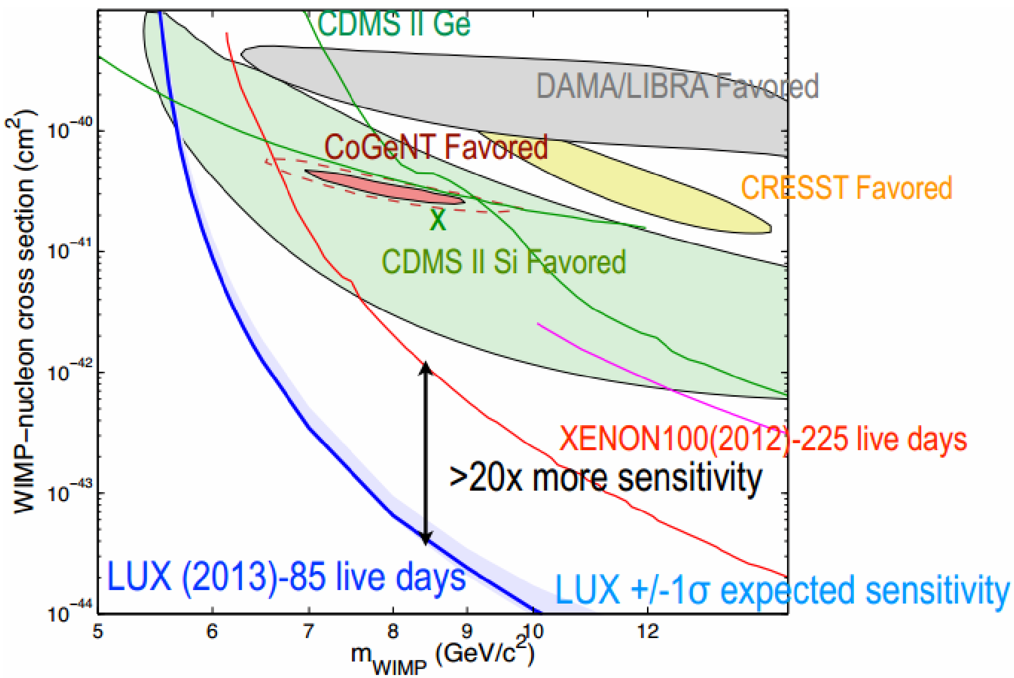
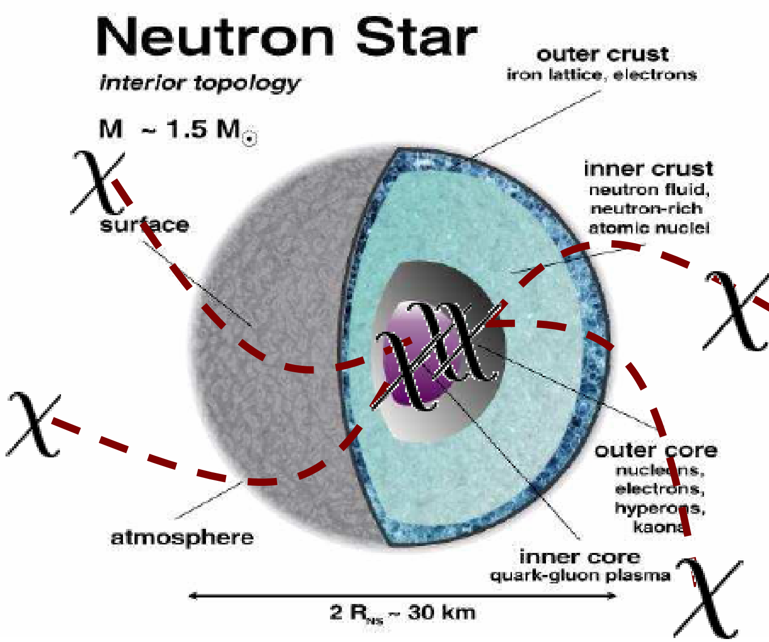
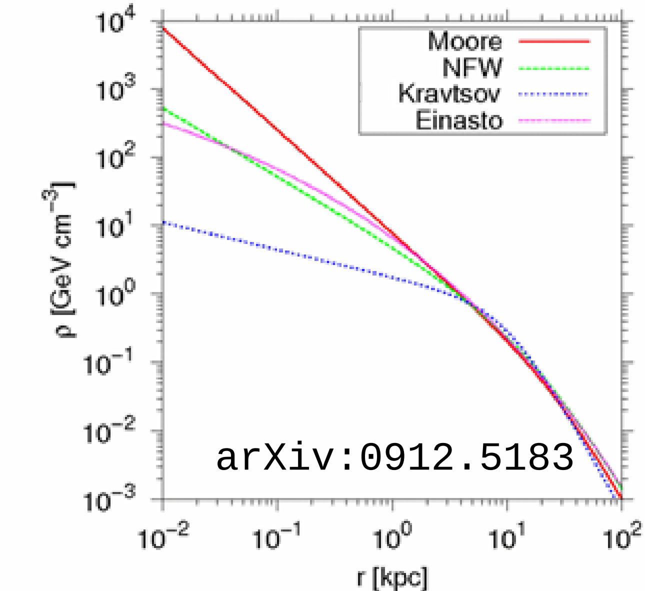
Dark matter trapped inside NSs







$$R/\lambda_\chi \simeq 8.5\left(\frac{R}{10\,\mathrm{km}}\right)\left(\frac{\sigma_{\chi n}}{10^{-44}\,\mathrm{cm}^2}\right)\left(\frac{\rho_n}{5\rho_0}\right)$$

Building up an internal DM distribution

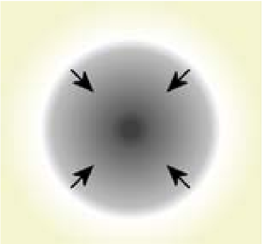
We consider a model where DM *only* decays

$$\frac{dN_\chi}{dt} = C_\chi - \Gamma N_\chi,$$

NS Capture rate [Gould' 87]

$$C_\chi \simeq 3.25 \times 10^{22} f_{GR} \left(\frac{M}{R}\right) \left(\frac{M}{1.5 M_\odot}\right) \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right) \left(\frac{\rho_\chi^{ambient}}{0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right) \mathrm{s}^{-1},$$

yields a solution



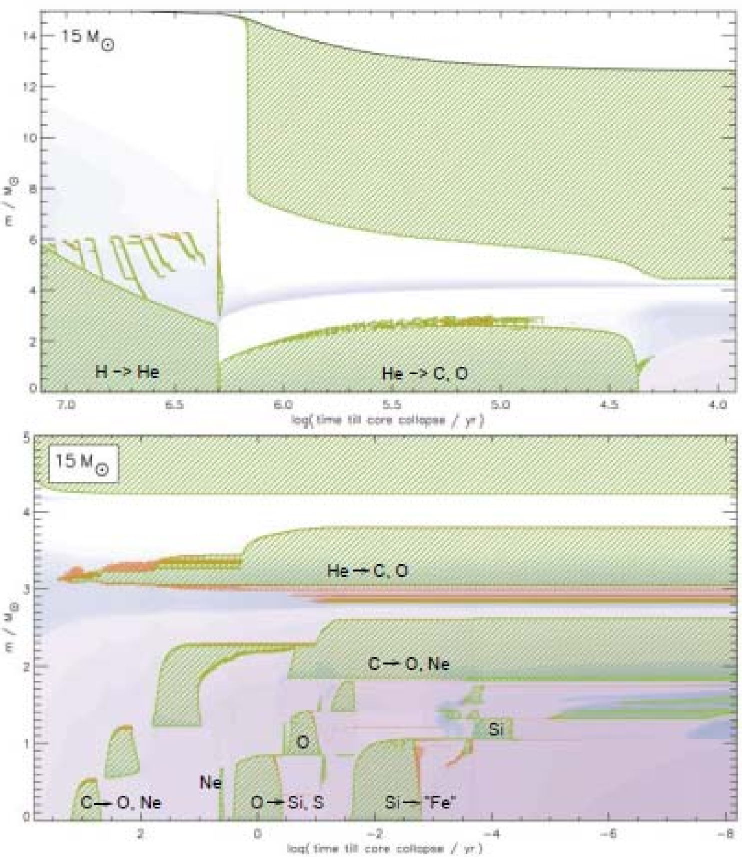
$$N_\chi(t) = \frac{C_\chi}{\Gamma} + \left(N_\chi(t_{\mathrm{col}}) - \frac{C_\chi}{\Gamma}\right) e^{-\Gamma(t - t_{\mathrm{col}})}, \quad t > t_{\mathrm{col}}.$$

with a DM population partially inherited from the progenitor $N_\chi(t_{\mathrm{col}})$

The capture rate in the progenitor depends on the burning stages

Perez-Garcia, Silk
arXiv:1403.6111

DM in the progenitor phase



Woosley et al'02

Main contribution comes from time duration and density in each phase

$$C_\chi^{\mathrm{He}\to\mathrm{CO}} t_{\mathrm{He}\to\mathrm{CO}} \simeq 3.35 \times 10^{39} \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)\left(\frac{\rho_\chi^{ambient}}{0.3\,\mathrm{GeV/cm^3}}\right)$$

along with coherence effects due to nuclei

$$\sigma_{\chi N} \simeq A^2 \left(\frac{\mu}{m_n}\right)^2 \sigma_{\chi n}$$

And DM thermalization times can follow dynamical timescales

$$t_{\mathrm{th}}/t_{\mathrm{He}\to\mathrm{CO}} \simeq 10^{-5}$$

$$t_{\mathrm{th}}/t_{\mathrm{Si}\to\mathrm{FeNi}} \simeq 10^{-7}$$

After this, collapse ms timescale causes that the proton-NS only retains those already inside the inner 10 km

Retained DM inside the Proto-NS

The number of DM particles inside is related to the gravitationally accreted distribution

$$n_\chi(r,T) = n_{0,\chi} e^{-(r/r_{\rm th})^2}$$

$$n_\chi(r,T) = \frac{\rho_\chi}{m_\chi} = n_{0,\chi} e^{-\frac{m_\chi}{k_B T}\Phi(r)},$$

$$r_{\rm th} = \sqrt{\frac{3 k_B T}{2\pi G \rho_n m_\chi}}$$

In this way a fraction ($r<R_{\rm PNS}$)

$$f_\chi = N_\chi^{-1} \int_0^{R_{\rm PNS}} n_{0,\chi} e^{-(r/r_{\rm th})^2} dV,$$

The final number of DM particles inside the PNS is

$$N_\chi = N_\chi(t_{\rm col}) f_\chi \simeq 6.7 \times 10^{36} \left(\frac{f_\chi}{2\times 10^{-3}}\right)\left(\frac{1\,\rm TeV}{m_\chi}\right)$$

Depletion of DM from Decays

The number of internal decays is recovered in the linear limit since we expect

$$\Delta t = t - t_{\rm col} << \Gamma^{-1}$$

Typical time scales >$10^{6\text{-}8}$ yr

Similar to Proton decay searches

In this way $N_{D,\chi} = N_\chi(t_{\rm col}) f_\chi \Gamma \Delta t.$

$$N_{D,\chi} = 4.2 \times 10^{26} \left(\frac{f_\chi}{2\times 10^{-3}}\right)\left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)\left(\frac{10^{26}\,s}{\tau_{e^+e^-}}\right)\left(\frac{\Delta t}{\tau_{\rm old\,NS}}\right)$$

The number of particle decays inside the NS assuming interpretations of e+e- data in terms of decaying DM $\tau_{e^+e} \simeq 10^{26} s$ in the context of GUT

$$\tau_{\rm GUT} \sim 10^{27}\,s \left(\frac{\mathrm{TeV}}{m_\chi}\right)^5 \left(\frac{M_{\rm GUT}}{2\times 10^{16}\,\mathrm{GeV}}\right)^4$$

Dark matter decay and data

A variety of sources provide limits if interpreted as decaying DM:

e+e- data [Ibarra et al, JCAP01 (2010) 009,Ibarra et al, arXiv: 1307.6434]

Antiprotons [M. Garny et al, JCAP 1208, 025 (2012)]

Galaxy clusters [X. Huang, G. Vertongen and C. Weniger, JCAP 1201, 042 (2012)]

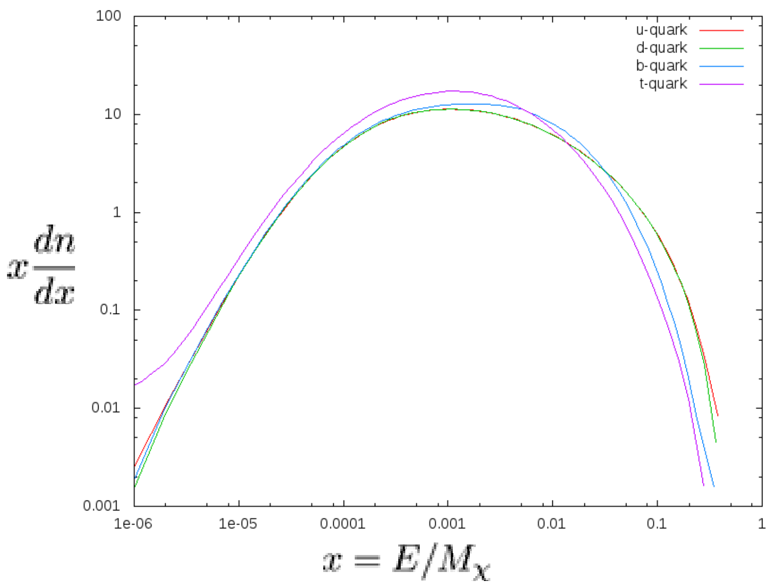
Gamma ray observation [L. Dugger et al, JCAP 1012, 015 (2010)]

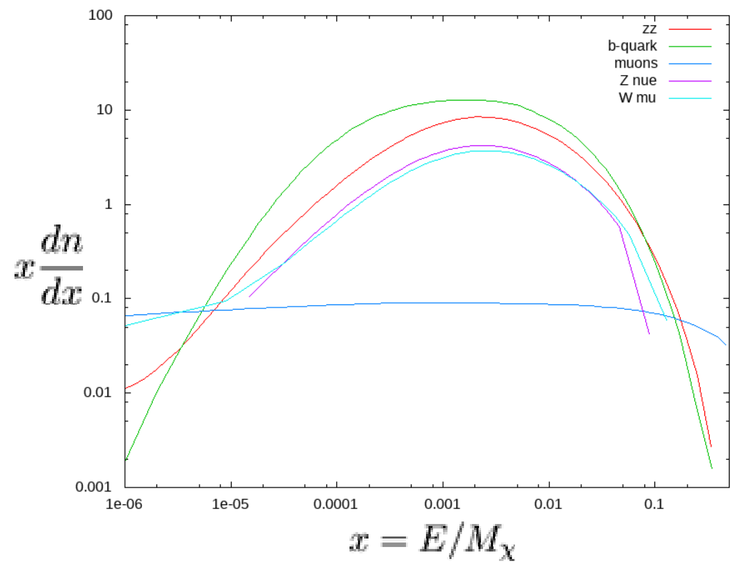
IceCube, SuperK [L. Covi et al JCAP 1004, 017 (2010)]

Decay channels

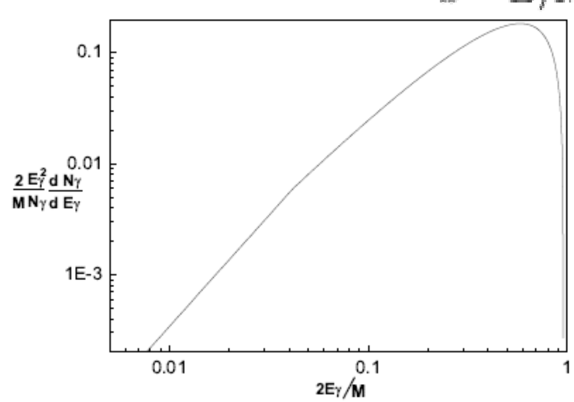
We have considered an scenario with bosonic and fermionic channels with different decay products and a generic channel with bosons into pions and photons

$$\chi \to \Phi_w l, \chi \to \Phi_w \Phi_w, \chi \to l^+ l^-, \chi \to q^+ q^-, \chi \to \Phi\gamma,$$





$$\chi \to 2\Phi, \Phi \to 2\pi, \pi \to 2\gamma$$



Energy deposit from DM decays

The energy deposit rate from decays $$\frac{dE}{dt} = \int\int EQ(E,r)dEdV.$$

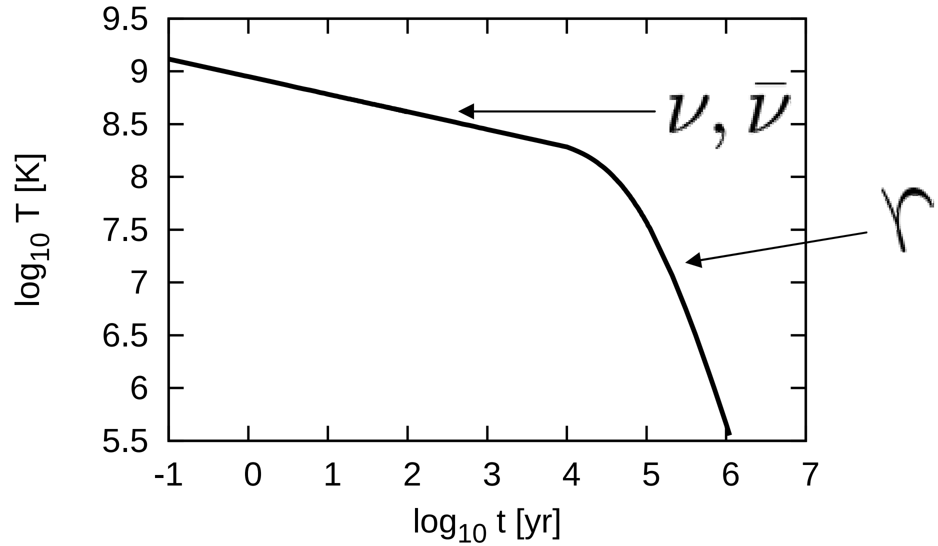
with $$Q(E,r) = n_\chi(r)\sum_i \Gamma_i \frac{dN_\gamma^i}{dE}$$

and a photon spectrum for different channels $$\frac{dN_\gamma^i}{dE}$$

Typically this energy deposit is injected in the thermal volume $$V_{\rm th} = \frac{4}{3}\pi r_{\rm th}^3,$$

$$r_{\rm th} = \sqrt{\frac{3k_BT}{2\pi G\rho_n m_\chi}}$$

$$\langle u_{\rm decay}\rangle \simeq \Delta t \int EQ(E,r)dE.$$



Energy deposit and bubble formation

Work to create a quantum bubble has been estimated
(Landau 1980, Alcock and Olinto 1989)

$$W = [n_q(\mu_q - \mu_n) - (P_q - P_n)]\frac{4\pi}{3}r^3 + 4\pi\sigma r^2 + 8\pi\gamma r + E_c,$$

For liquid-vapor phases in the superheated classical liquids $W \simeq E_{th}$

$$\frac{\partial W}{\partial r} = 0, R_c = \frac{2\sigma}{P_q - P_n}$$

The energy density to create such a bubble is

$$W_c = \frac{16\pi}{3}\sqrt{\frac{2\gamma^3}{\Delta P}}, \ \Delta P = P_q - P_n$$

It has been estimated that a few MeV Temperature fluctuation can cause a quark deconfinement transition able to nucleate stable bubbles in a cold system i.e. $\delta r \simeq \sqrt{\frac{T}{4\pi\sigma}}$

$$u_{\rm bub} \simeq W_c/V_d \simeq 5.4 \times 10^{35} {\rm erg/cm}^3$$

DM searches..and bubbles

Current searches with bubble chambers try to detect bubbles generated in superheated liquid from nuclear recoils

Much experience e.g. PICASSO, COUPP, SIMPLE

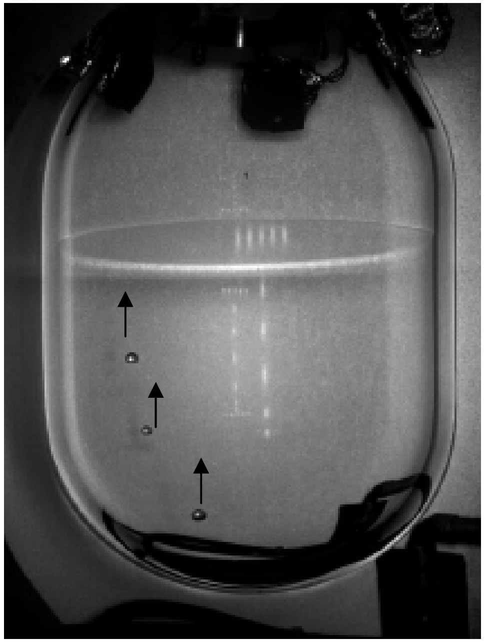
They are based on the hot-spike model of Seitz

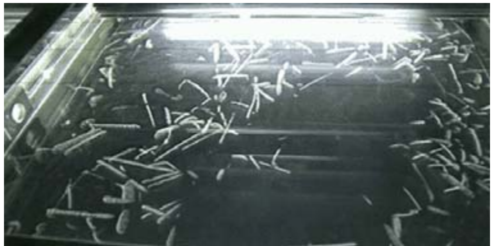
Considering a “classical liquid” a bubble survives to be detected if

-superheated liquid state

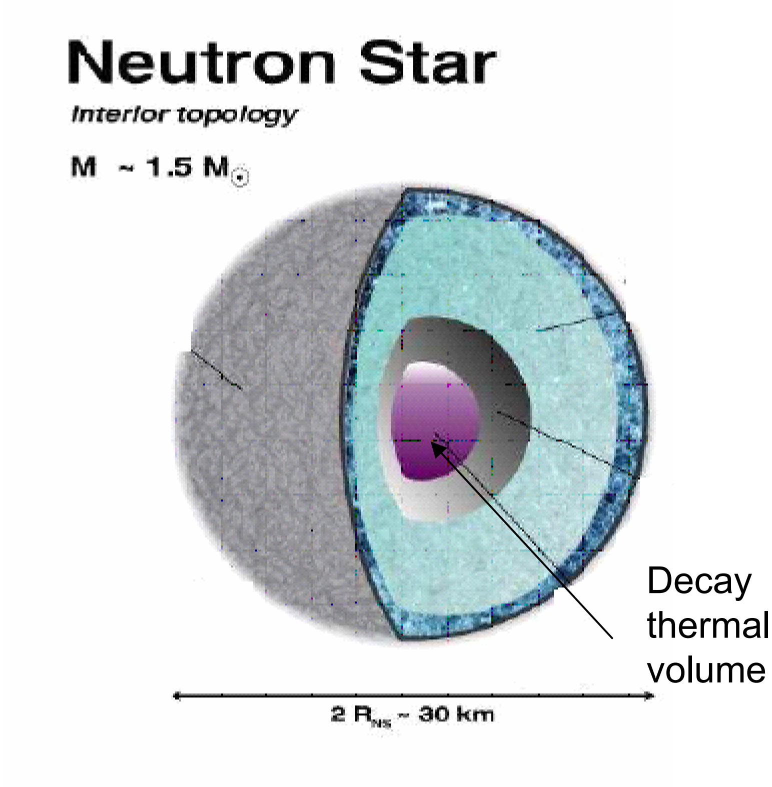
-radius is larger than critical radius r>Rc

-energy to nucleate the bubble is large enough

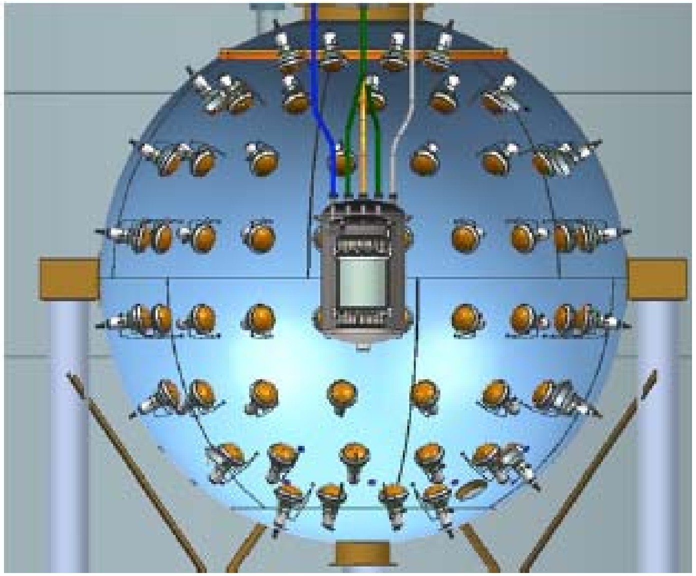




NS core as an indirect DM detector



$$r_{th} \leq 10^2 m$$



DarkSide-50 experiment liquid argon TPC and scintillation 4π coverage veto 30 tons

Bubble instability

If DM is heavy enough and decays this behavior is capable of producing additional indirect effects

Bubble formation can trigger changes in the Equation of State (EoS) by altering the pressure-energy density relation $P(\epsilon, T)$

Number of stable bubbles created is $N_{\rm bub} \simeq \int \frac{dN_{\rm bub}}{dE}\frac{dE}{dt}dt \geq N_0.$

If created large (R>Rc) they will not decay.

Harko et al. ApJ 608 (2004) 945 demostrate one single bubble may trigger macroscopic conversion NS→QS emittig sGRB.

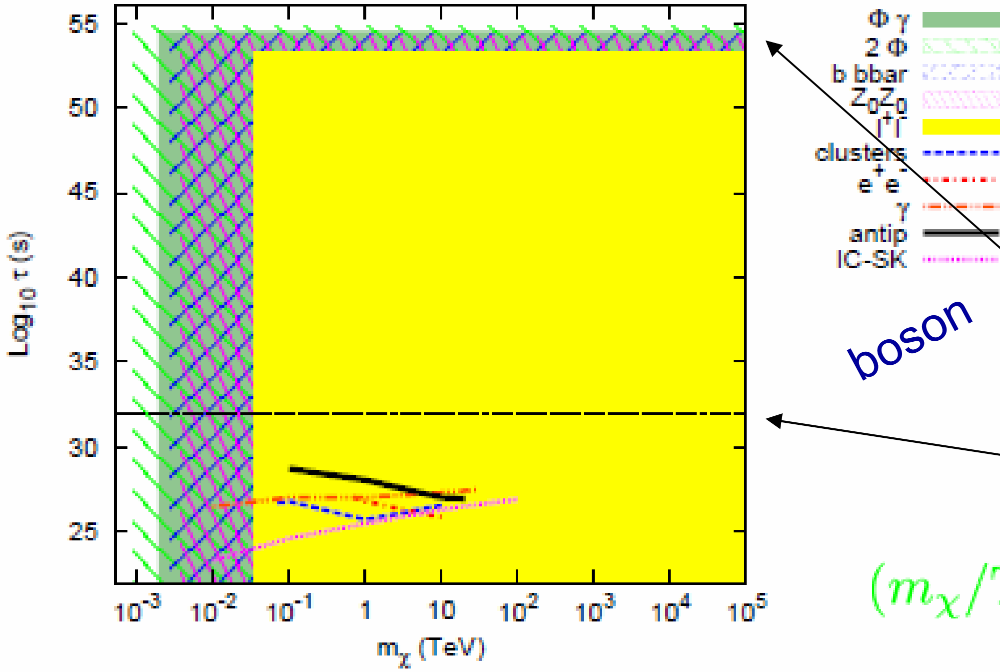
Perez-Garcia,Silk,Stone, PRL 105 141101 (2010)
Perez-Garcia, Daigne, Silk, ApJ 768 145 (2013)

Conservatively one may assume a "mechanical instability" in the GC ensamble

$$\delta P \simeq \left[\frac{\partial P}{\partial N_{\rm bub}}\right]_0 \delta N_{\rm bub} \quad \delta N_{\rm bub} \simeq N_0 \simeq \sigma_{A_{th}}/A_{min} \simeq \sqrt{V_{\rm th} n_n}/A_{\rm min} \simeq 10^{20}$$

Upper Limits on DDM

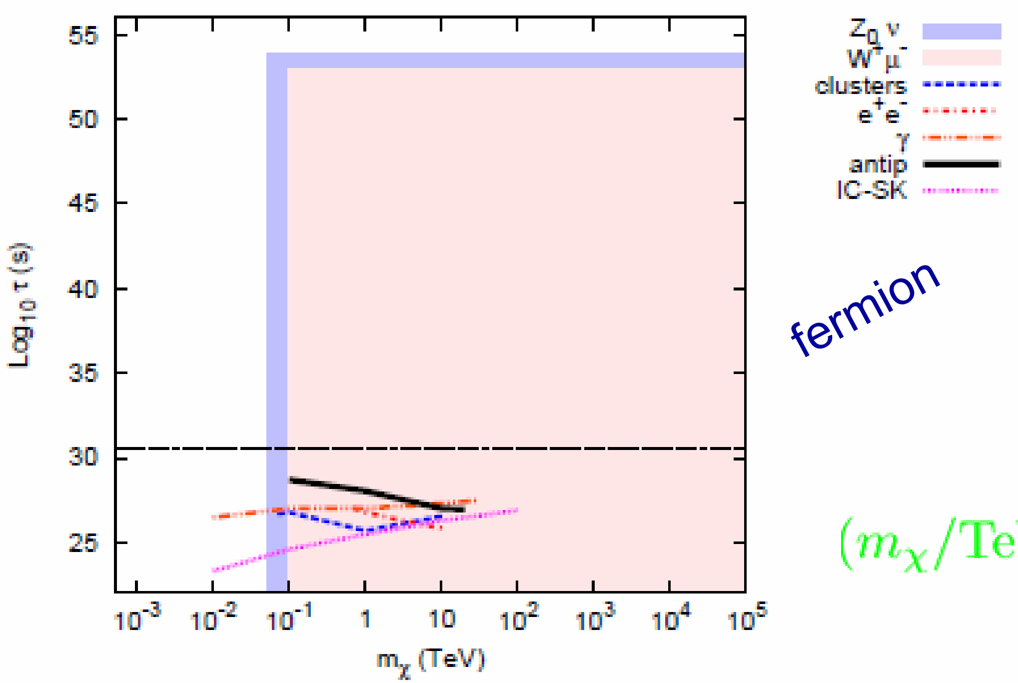
Pérez-García, Silk
1403.1611



Optimistic limit

Pessimistic limit

$$(m_\chi/\text{TeV}) > 9\times 10^{-4} \rightarrow \tau_\chi < 10^{55}\,\text{s}$$
$$\rightarrow \tau_\chi < 10^{32}\,\text{s}$$



excluded

$$(m_\chi/\text{TeV}) > 5\times 10^{-2} \rightarrow \tau_\chi < 10^{53}\,\text{s}$$
$$\rightarrow \tau_\chi < 10^{31}\,\text{s}$$

Conclusions

- We have discussed the possibility that NSs can constrain decaying Dark matter .
- DM mass-lifetime phase space is restricted from current abundance of NSs.
- Improvement of current DM lifetime limits by orders of magnitude even if pessimistic assumptions on the micro-physics efficiency.
- Rapidly decaying DM is tightly restricted in fermionic/bosonic channels.
- Quark bubble formation inside NSs may constitute an indirect probe of decay of DM if heavy enough to inject nucleation energy.
- NSs inner core may be another type of “bubble based” DM detector.