Thermal history of Neutron Stars admixed with self-annihilating Light Dark Matter

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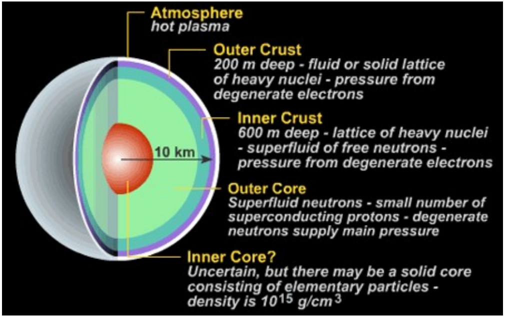
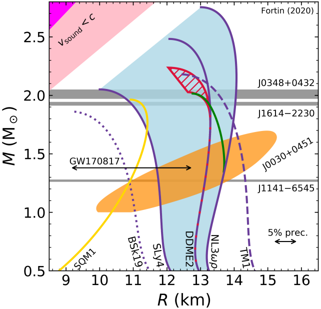
September 14, 2021

Basics on Neutron stars





- Neutron stars (NS): compact and dense astrophysical objects appearing in aftermath Supernovae events. Typically quantum relativistic neutron-rich matter populates the core.
- Characterized on macroscopic properties: mass and radius
- Multimessenger signals: GW in mergers, EM associated Kilonovae, neutrinos from first cooling stages.

Cooling of NSs

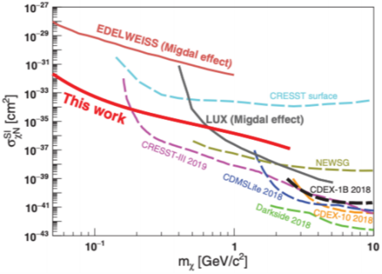
- Cooling Neutron stars can be described in terms of spherical coordinates (`Thorne ApJ 1977`) in GR geometry:

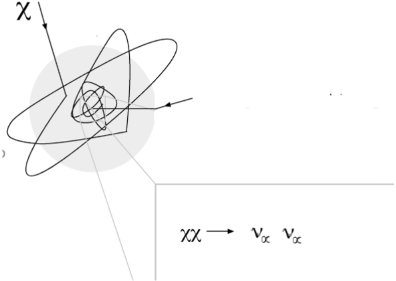
$$\frac{e^{-\lambda-2\Phi}}{4\pi r^2}\frac{\partial}{\partial r}\left(e^{2\Phi}L\right) = -Q + Q_{\mathrm{h}} - \frac{c_V}{e^{\Phi}}\frac{\partial T}{\partial t}, \tag{1}$$

$$\frac{L}{4\pi\kappa r^2} = e^{-\lambda-\Phi}\frac{\partial}{\partial r}\left(Te^{\Phi}\right) \tag{2}$$

- κ, c_V describe matter microscopic properties: thermal conductivity, heat capacity
- Q, Q_h are emittivities (energy released/injected per unit volume unit time)
- $\Phi(r)$ specifies the gravitational redshift, $\lambda(r)$: gravitational distortion of radial scales, $e^{-\lambda} = \sqrt{1 - 2Gm(r)/r}$, where $m(r)$ is the gravitational mass enclosed within a sphere of radius r. At the stellar surface, $\Phi(R) = -\lambda(R)$.
- Our assumption: DARK MATTER may provide external energy source in Q_h

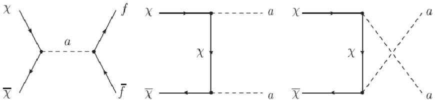
Dark Matter: status of Light DM searches





- Progenitor stars and NS are efficient at accretion of LDM. `CDEX, PRL 2021`
- Cross-section opacity above critical value $\sigma_0 \sim 10^{-46}\,\mathrm{cm}^2$, evaporation is negligible for $m_\chi > 1$ MeV.

LDM self-annihilation



$$\mathcal{L}_{\mathcal{I}} = -i\frac{g_\chi}{\sqrt{2}}a\bar{\chi}\gamma_5\chi - ig_0\frac{g_f}{\sqrt{2}}af_5f \quad (3)$$

- pseudoscalar a as in `Cermeño, PG and Lineros, ApJ 2018`. $\chi\chi \to \nu\nu$ or $\chi\chi \to aa$ with subsequent decay $a \to \nu\nu$
- DM local emissivities are obtained in-medium at finite density and T

$$Q_{\chi\chi} = Q_h = 4\int d\Phi\,(E_1 + E_2)\,|\bar{\mathcal{M}}|^2\mathcal{F}, \quad (4)$$

- phase space factor given by $\mathcal{F} = f_\chi(E_1)\,f_\chi(E_2)\,(1 - f_f(E_3))\,(1 - f_f(E_4))$. $f_\chi \sim f_{MB}, f_\nu \sim 1$ are the local stellar distribution function.

Energy input LDM heating

- LDM number inside NS obtained aprox $N_\chi(t) \simeq N_{\chi,0} + \frac{dN_\chi}{dt}(t - t_0)$
- capture and self-annihilation inside the dark core compete

$$\frac{dN_\chi}{dt} = C_\chi - C_a N_\chi^2. \tag{5}$$

- capture

$$C_\chi \simeq 5.6 \times 10^{26} \left(\frac{M}{1.5 M_\odot}\right) \left(\frac{R}{14 \text{ km}}\right) \left(\frac{0.1\text{GeV}}{m_\chi}\right) \left(\frac{\rho_\chi}{0.4 \frac{\text{GeV}}{\text{cm}^3}}\right) \text{s}^{-1}, \tag{6}$$

- self-annihilation rate is $C_a \simeq \frac{\langle \sigma v \rangle}{R_\chi^3}$, and $\langle \sigma v \rangle \sim 3 \times 10^{-26}\, \text{cm}^3 \text{s}^{-1}$.
- thermalized local LDM distribution has a radius based on the constant density inner core $R_\chi \sim 0.8\,\text{km} \left(\frac{0.1\,\text{GeV}}{m_\chi} \frac{2\rho_0}{\rho_N} \frac{T}{0.1\,\text{MeV}}\right)^{1/2}$

$$C_a \simeq 2 \times 10^{-42} \left(\frac{0.1 \text{ GeV}}{m_\chi} \frac{2\rho_0}{\rho_N} \frac{T}{0.5\,\text{MeV}}\right)^{-3/2} \text{s}^{-1}. \tag{7}$$

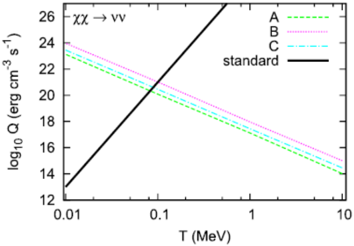
Fitting LDM emissivity

- LDM emissivity

$$Q_{\chi\chi}(T) = 10^{\alpha} \left(\frac{T}{0.1\,\mathrm{MeV}} \right)^{-3} \mathrm{erg\,cm^{-3}\,s^{-1}}, \quad (8)$$

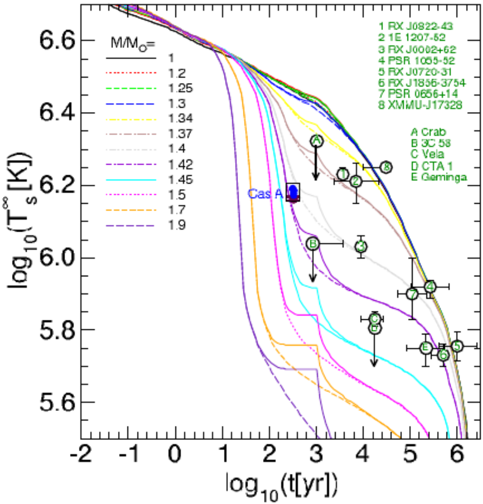
($19 < \alpha < 21$.)

- Standard Model microphysics $Q_E^{\mathrm{MURCA}} \sim 10^{21} \mathcal{R} \left(\frac{T}{0.1\,\mathrm{MeV}} \right)^8 \mathrm{erg\,cm^{-3}\ s^{-1}}$
- We also consider LDM conduction contribution (before self-annihilation): $\kappa = \sum_f \kappa_f + \kappa_\chi$ and $\kappa_\chi \sim v_\chi \lambda_\chi n_\chi$.
- $v_\chi = \sqrt{3T/m_\chi}$ and $\lambda_\chi \sim (\sigma_{\chi N} n_N)^{-1}$



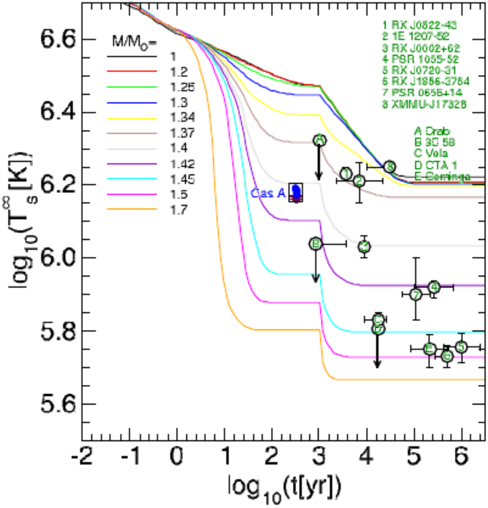
Cermeño, PG and Lineros, ApJ 2018

Results: $m_\chi = 0.1$ GeV



PG, Grigorian, Albertus, Barba and Silk, submitted 2021

Results: $m_\chi = 0.1$ GeV, Q_h enhanced a factor $\times$ 5



PG, Grigorian, Albertus, Barba and Silk, submitted 2021

Concluding remarks

- NS admixed with self-annihilating LDM may temporarily halt cooling in the context of enhanced emissivities for the DM model studied.
- Cooling history can be greatly affected with the presence of one or more *plateaus* shifting them towards higher T, larger duration, for enhanced emissivities.
- Degeneracies in NS mass and age must be resolved. Complementary constraints on *individual* masses may help resolve the true cooling path.
- Thank you (mperezga@usal.es)