Uniwersytet Wrocławski

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Two-fluid formalism and phenomenology of the dark matter admixed neutron stars

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Spanish & Portuguese Relativity Meeting 2024

1 2 9 0
UNIVERSIDADE D COIMBRA

- **Credits**

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Edoardo Giangrandi

Ilidio Lopes

Constança Providência

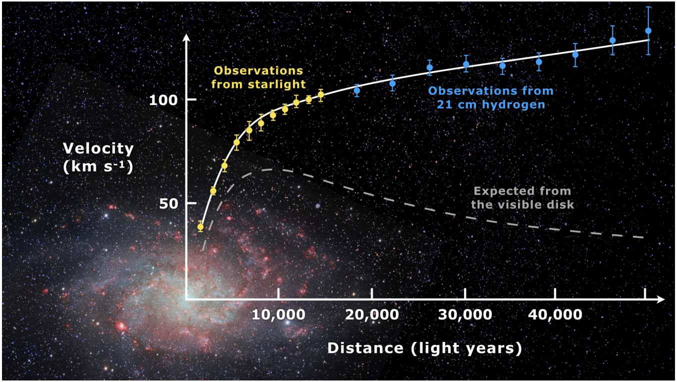
Violetta Sagun

- **References**

OI, V. Sagun, I. Lopes, PRD 102, 063028 (2020)
E. Giangrandi, V. Sagun, OI, C. Providência, T. Dietrich, ApJ 953 1, 115 (2023)
V. Sagun, E. Giangrandi, T. Dietrich, OI, R. Negreiros, C. Providência, ApJ 958, 49 (2023)
A. Ávila, E. Giangrandi, V. Sagun, OI, C. Providência, MNRAS 528, 6319 (2024)
E. Giangrandi, A. Ávila, V. Sagun, OI, C. Providência, Particles 7(1), 179 (2024)

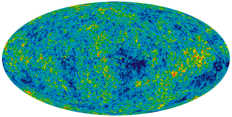
Galaxy rotation curve

$$v(r) = \left(r \frac{d\Phi(r)}{dr} \right)^{1/2}, \quad \Phi(r) - \text{gravitational potential}$$

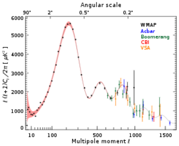


flat rotation curve $\Rightarrow$ invisible extra mass

Standard model of Big Band cosmology



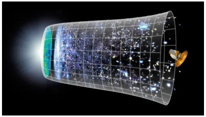
Assumption: GR is correct



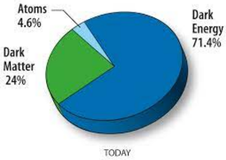
Components:

- baryon matter
- cosmological constant
- invisible "**dark**" matter

Predictions:



- CMB
- large-scale structure
- abundances of hydrogen
- accelerating expansion



The Universe is mostly Dark

Dark matter profile

Our Galaxy (not DM dominated):

- simulation of the rotation curve
- Navarro–Frenk–White profile

$$\rho(r) = \rho_0 \Big/ \frac{r}{r_0}\left[1 + \frac{r}{r_0}\right]^2$$

J.F.Navarro, C.S.Frenk, S.D.M.White, Astrophys. J. 462, 563 (1996)

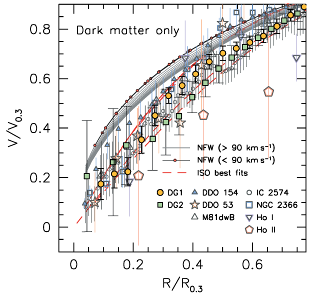
Significant amount of DM in the Galaxy

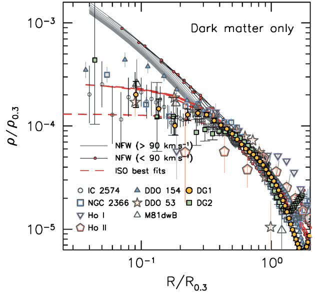
Dwarf galaxies (DM dominated):

- observation of the rotation curves
- tension with NFW - **core-cusp problem**

A. Del Popolo et al., Phys.Dark Univ. 33, 100847 (2021)

DM self-repulsion?



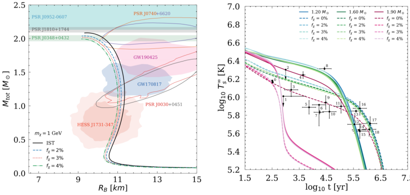


Dark matter in neutron stars?

- **Neutron stars - strong gravitational field**

$$\begin{array}{l} M \simeq 2M_\odot \\ R \simeq 10\ km \end{array} \quad \Rightarrow \quad g_{tt} = 1 - \frac{2M}{R} \simeq 0.5$$

Accumulation of DM in NS?



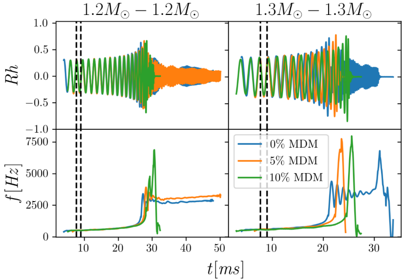
Avila+ 2024

- **Dark matter fraction in neutron stars**

$$f_D = \frac{M_D}{M_{tot}}, \quad M_{tot} = M_B + M_D$$

- **Sizable amount of dark matter affects**
  - mass radius relation
  - cooling dynamics
  - merger dynamics

A formalism for DM admixed NSs is needed

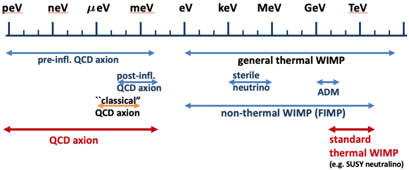


M. Emma et al., Particles 5, 273 (2022)

Scenario

Cold asymmetric DM in MeV-TeV range

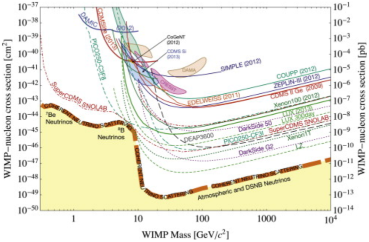
- particle≠antiparticle ⇒ no self-annihilation
- consistent with the ΛCDM model



No DM interaction with baryon matter

$$\sigma_{BD} \ll \sigma_{BB}$$

J. Cooley, Phys. Dark Univ 4, (2014)



Repulsive self-interaction of DM

- simulations of the Bullet Cluster dynamics

$$\frac{\sigma_{DD}}{m_D} < 0.7\frac{\text{cm}^2}{\text{g}}$$

S. Randall et al, Astrophys. J., (2008)

- minimal setup: non-interacting fermionic DM
  or self-repulsive bosonic DM

- **Spherical symmetry**

$$ds^2 = e^{\nu} dt^2 - e^{\lambda} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right)$$

ν, λ - metric functions

- **Perfect fluid approximation** (valid in the absence of flows)

$$\text{no BM} - \text{DM interaction} \quad \Rightarrow \quad \mathrm{T}^{\mu\nu} = \mathrm{T}^{\mu\nu}_{\mathrm{B}} + \mathrm{T}^{\mu\nu}_{\mathrm{D}}$$

$$\text{perfect fluid} \quad \Rightarrow \quad \mathrm{T}^{\mu\nu}_{\mathrm{i}} = \mathrm{diag}(\varepsilon_{\mathrm{i}}, -\mathrm{p}_{\mathrm{i}}, -\mathrm{p}_{\mathrm{i}}, -\mathrm{p}_{\mathrm{i}}), \quad \mathrm{i} = \mathrm{B}, \mathrm{D}$$

$$\text{equaion of state} \quad \Rightarrow \quad \mathrm{p}_{\mathrm{i}} = \mathrm{p}_{\mathrm{i}}(\varepsilon_{\mathrm{i}})$$

- **Relativistic hydrostatics**

$$-8\pi T^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu} \quad \Rightarrow \quad \begin{cases} e^{\lambda} = 1 - \frac{2m}{r} \\ \frac{dm}{dr} = 4\pi r^2 (\varepsilon_B + \varepsilon_D) \\ \frac{d\nu}{dr} = 2e^{\lambda} r^{-2} \left(m + 4\pi r^2 (p_B + p_D) \right) \\ \sum_i \frac{dp_i}{dr} = \frac{1}{2} \frac{d\nu}{dr} \sum_i (p_B + p_D) \end{cases}$$

5 independent variables ν, λ, m, ε_{B}, ε_{D} vs 4 equations?

Two-fluid formalism

$$\sum_i \frac{dp_i}{dr} = \frac{1}{2}\frac{d\nu}{dr}\sum_i (p_B + p_D)$$

- **Grand canonical ensemble** (μ_i - chemical potential=energy deposit per particle)

$$\begin{cases} p_i = p_i(\mu_i) \\ \varepsilon_i = \mu_i \frac{dp_i}{d\mu_i} - p_i \end{cases} \Rightarrow \sum_i \mu_i \frac{dp_i}{d\mu_i}\left[\frac{d\ln\mu_i}{dr} + \frac{1}{2}\frac{d\nu}{dr}\right] = 0$$

holds for any BM-DM composition, $\mu_i \frac{dp_i}{d\mu_i} > 0$

$$\frac{d\ln\mu_B}{dr} = \frac{d\ln\mu_D}{dr} = -\frac{1}{2}\frac{d\nu}{dr} \Leftrightarrow \frac{dp_i}{dr} = -(p_i + \varepsilon_i)\frac{m + 4\pi r^2(p_B + p_D)}{r^2 - 2mr}$$

OI+ (2020)

- **Gravitational "red shift" of chemical potentials**

$$\mu_i(r) = \mu_i(0)e^{-\nu(r)/2} \Rightarrow \frac{\mu_B(r)}{\mu_D(r)} = \frac{\mu_B(0)}{\mu_D(0)} = const$$

full analogy with $\omega = \omega_\infty/\sqrt{g_{tt}}$

Quadrupole deformations

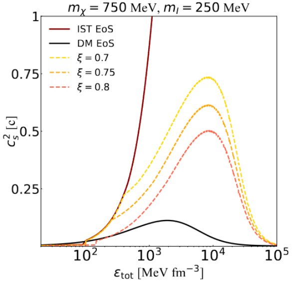
$$\int d\vec{x}\ \varepsilon(\vec{x})\left(x_i x_j - \frac{\vec{x}^2}{3}\delta_{ij}\right) \equiv Q_{ij} = \Lambda\varepsilon_{ij}$$

ε_{ij} - quadrupole external field, Λ - tidal deformability

- **Density perturbations**
  - unperturbed system: $\varepsilon = \varepsilon(r) \quad \Rightarrow \quad Q_{ij} = 0$
  - perturbations: $T^{00} = \varepsilon(r) + \delta p / \frac{dp}{d\varepsilon}(r)$
    $T^{11} = T^{22} = T^{33} = -p(r) - \delta p$
- **Effective "speed of sound"** ($\frac{dp_i}{d\varepsilon_i} = c_i^2$ - speed of sound)

$$\frac{dp}{d\varepsilon} \quad \rightarrow \quad \zeta c_B^2 + (1-\zeta)c_D^2$$

$$\zeta^{-1} = 1 + \frac{\mu_D(0)}{\mu_B(0)} \cdot \frac{d\varepsilon_D}{d\mu_D} \Big/ \frac{d\varepsilon_B}{d\mu_B}$$



Giangrandi+ (2023)

Internal structure: fermionic DM

$$\frac{d\ln\mu_i}{dr} = -\underbrace{\frac{m+4\pi r^2(p_B+p_D)}{r^2-2mr}}_{\text{increases with growth of the DM amount}}$$

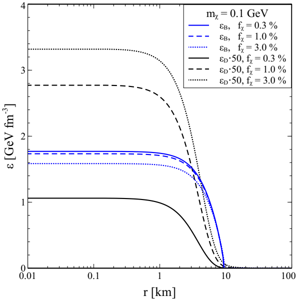
Light DM particles

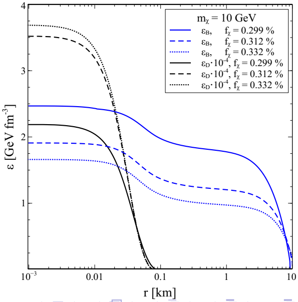
- small central density of DM
- extended DM halo ($R_D > R_B$)
- gradual decrease of the BM density

Heavy DM particles

- high central density of DM
- compact DM core ($R_B > R_D$)
- steep decrease of the BM density

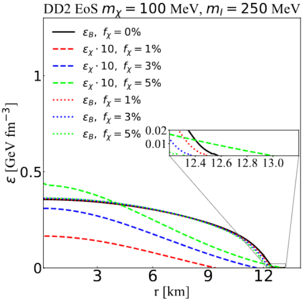
Ol+ (2020)





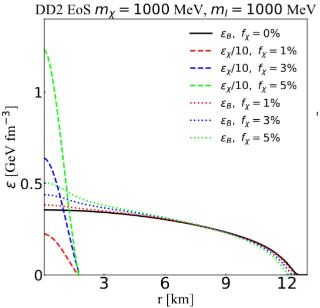
Internal structure: bosonic DM

$$\frac{d \ln \mu_i}{dr} = -\underbrace{\frac{m + 4\pi r^2 (p_B + p_D)}{r^2 - 2mr}}_{\text{increases with growth of the DM amount}}$$



Light DM particles

- small central density of DM
- extended DM halo ($R_D > R_B$)
- gradual decrease of the BM density



Heavy DM particles

- high central density of DM
- compact DM core ($R_B > R_D$)
- steep decrease of the BM density

E. Giangrandi+ (2023)

Mass-radius relation: fermionic DM

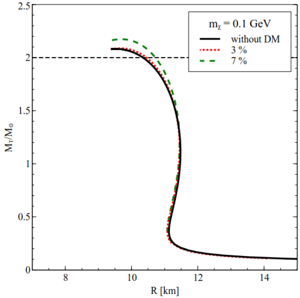
Light DM particles

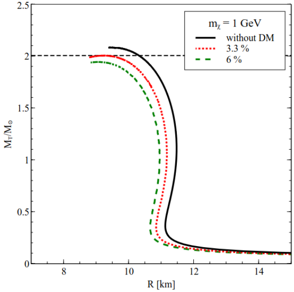
- increases total mass
- does not impact observed radius R_B

Heavy DM particles

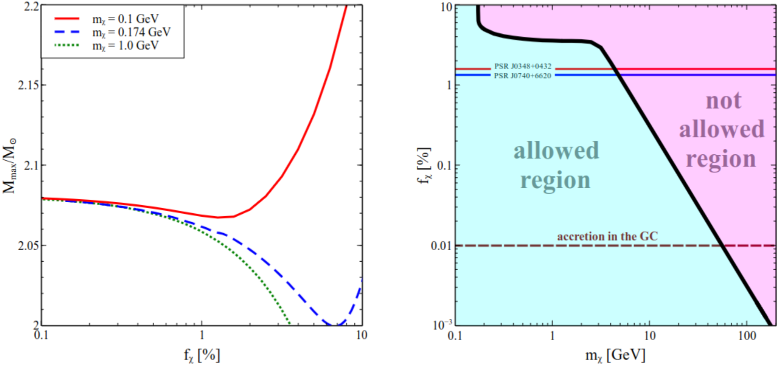
- decreases total mass
- decreases observed radius R_B

OI+ (2020)





Constraint on the particle mass (fermionic DM)



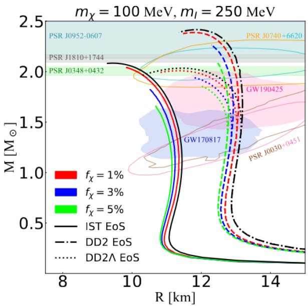
OI+ (2020)

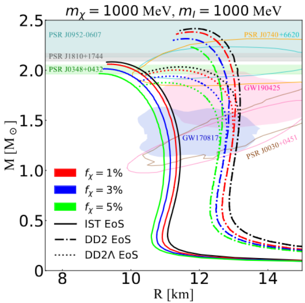
- **PSR J0348-0432/J0740-6620** - estimated from the NFW profile of DM
- **Accretion in the Galaxy center**

Mass-radius relation: bosonic DM

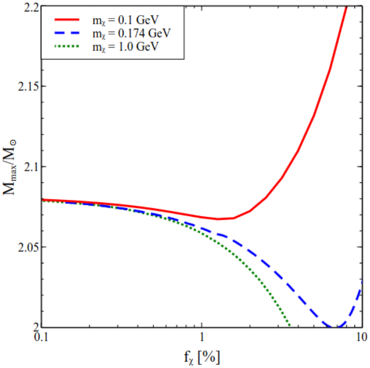
- DM decreases total mass
- DM decreases observed radius R_B

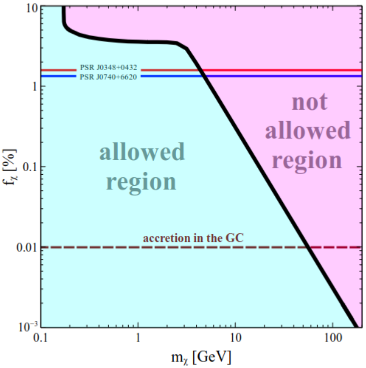
E. Giangrandi+ (2023)





Constraint on the particle mass (fermionic DM)





- **PSR J0348-0432/J0740-6620** - estimated from the NFW profile of DM
- **Accretion in the Galaxy center**

HESS J1731-347

- Ultra light and compact object
- Tensions with hadronic scenario

nature astronomy

Article

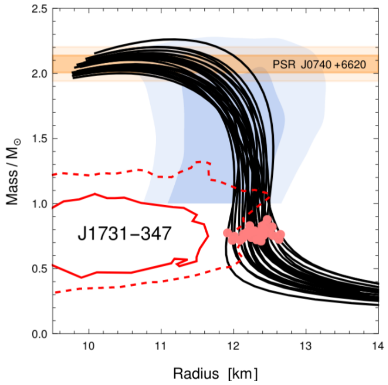
https://doi.org/10.1038/s41550-022-01800-1

A strangely light neutron star within a supernova remnant

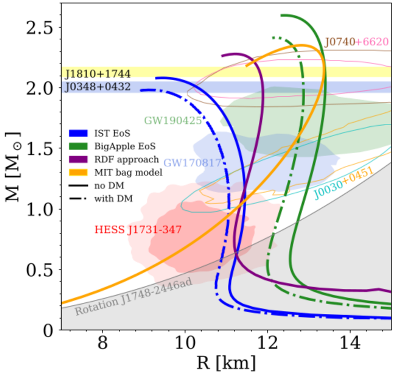
Received: 31 March 2022

Accepted: 1 September 2022

Victor Doroshenko, Valery Suleimanov, Gerd Pühlhofer and Andrea Santangelo



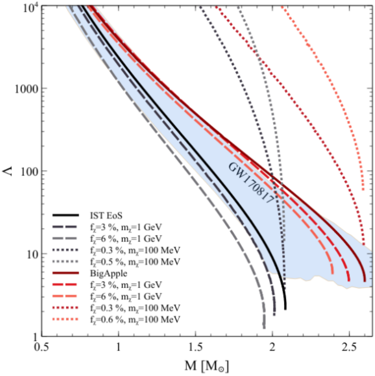
Brodie+ (2023)



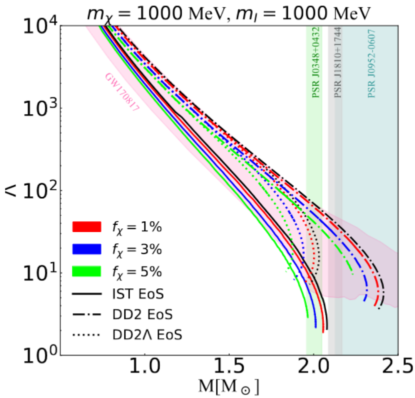
Sagun+ (2023)

Tidal deformability

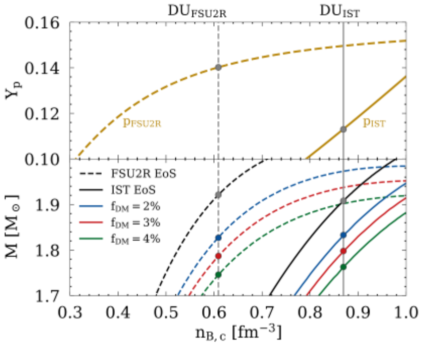
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R_{outermost}}{M_{tot}} \right)^5$$



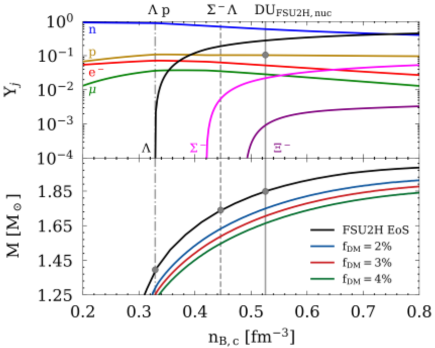
Giangrandi+ (2022)



Giangrandi+ (2023)



nucleonic Direct Urca process



Λ p and $\Sigma^-\Lambda$ Direct Urca processes

$$\begin{cases} n \to p + \ell + \overline{\nu}_\ell \\ p + \ell \to n + \nu_\ell \end{cases}$$

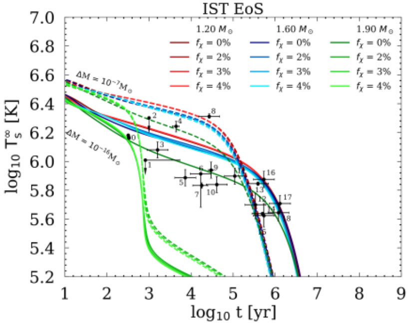
The triangle condition on Fermi momenta of particles, reads as $p_{Fp} + p_{Fe} \geq p_{Fn}$

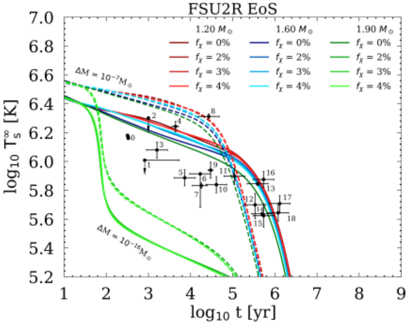
$$\begin{cases} \Lambda \to p + \ell + \overline{\nu}_\ell \\ p + \ell \to \Lambda + \nu_\ell \end{cases} \qquad \begin{cases} \Sigma^- \to \Lambda + \ell + \overline{\nu}_\ell \\ \Lambda + \ell \to \Sigma^- + \nu_\ell \end{cases}$$

Avila+ (2024), Giangrandi+ (2024)

DM vs cooling of neutron stars

- New born NSs are thermal
- Cooling by neutrino emission controlled by particle composition
- DM impacts composition $\Rightarrow$ affects cooling of NS

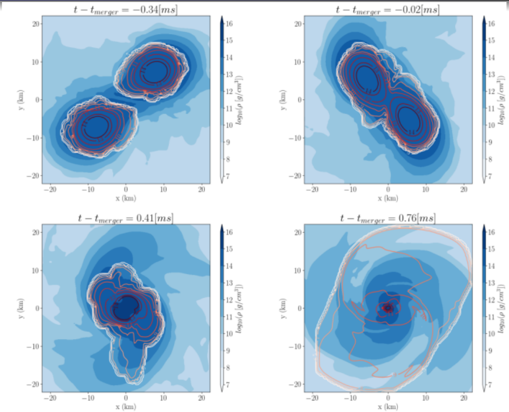




Avila+ (2024), Giangrandi+ (2024)

DM vs merger of neutron stars

- DM impacts inspiral
- DM modifies matter ejecta
- ...



M. Emma et al., Particles 5, 273 (2022)

More in Edoardo Giangrandi's talk on Tue 23/07 @ 14.45-15.00

Conclusions

- Two-fluid approach for DM admixed NSs
- DM increases compactness of NSs
- DM fastens cooling of NSs

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