IEAP CTU in Prague

EuCAPT
Astroneutrino Theory Workshop 2024
Prague, Czech Republic

Supra-massive dark objects with self interacting dark matter

Phys. Rev. D 109, 123006 (2024)

Dr. Vlasios Petousis
Institute of Experimental and Applied Physics (IEAP)
Czech Technical University in Prague (CTU)

vlasios.petousis@cvut.cz

Outline

Facts - Indications - Motivation - Method - Findings

Dark Matter Admixed Neutron Stars (DANS) - What we Know

Self-interacting Bosonic & Fermionic Dark Matter in Neutron Stars

The stability method

The "Two Fluid's Model"

The Supra-massive Compact Objects

Facts - Indications - Motivation – Method - Findings

Fact #1: we know that among the compact objects exist in galaxies, neutron stars (NS) considered as natural laboratories, where theories can be tested.

Fact #2: we know that Dark Matte (DM) exists and due to its gravity behavior could be accumulated in a NS

Indication #1: many models they have propose the presence of DM inside NS, studying how they accumulate and how they affect their structure and their basic properties.

Indication #2 : all the previous studies limited in a small amount of DM concentrated inside a NS and in many cases DM can extended out of it producing a halo.

Motivation:

- was to extend the region of the accumulated DM and to test “how far we can go”. First and foremost our main concern was to investigate that if these supra-massive hybrid objects can be stable and compact.

Method used:

- by employing two fluids model, we discovered a stable area in the M-R diagram of a celestial formation consisting of nuclear matter and DM that is substantial in size.

Findings:

- we found that these formation can span hundreds of km in diameter having a mass equivalent to 100 or more Solar masses. To elucidate, these entities resembles an enormous celestial body of DM, with a NS at its core.
- after many cross-checks we found that these new class of objects can exist are stable and compact.

Dark Matter and Neutron Stars – What we know

From literature so far we know that:

1) Dark Matter can be accumulated inside neutron stars due to gravitational attraction.
2) Dark Matter can extend the mass and radius of the neutron star producing a halo around it.
3) Dark Matter can interact (scattering) with neutron matter including also self interactions.
4) Dark Matter inside neutron stars can be annihilating (thermalization) or non annihilating.
5) Dark Matter can cause a collapse of the neutron star to a black hole.
6) Dark Matter can signals in gravitational waves from neutron star mergers.
7) Dark Matter can signals in pulsar timing.

Reference:
Bramante Joseph and Raj Nirmal, "Dark matter in compact stars" , Physics Reports, Volume 1052, p. 1-48 (2024)
doi.org/10.1016/j.physrep.2023.12.001

Neutron Stars – In brief

Bulk properties of Nuclear Matter

$$E(\rho,\delta) = E_{\mathrm{SNM}}(\rho) + E_{\mathrm{sym}}(\rho)\delta^2\,,$$
$$E_{\mathrm{SNM}}(\rho) = E_0 + \frac{K_0}{2}x^2\,,$$
$$E_{\mathrm{sym}}(\rho) = S_0 + Lx + \frac{K_{\mathrm{sym}}}{2}x^2\,,$$
$$x \equiv (\rho-\rho_0)/3\rho_0$$
$$\delta \equiv (\rho_n-\rho_p)/\rho$$

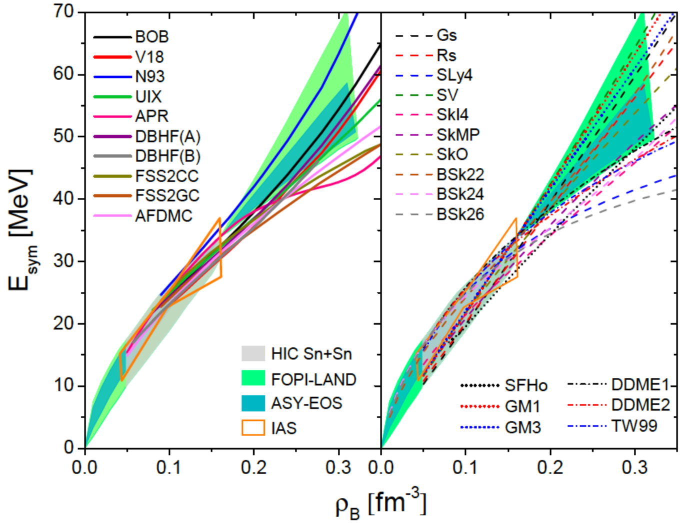
$$K_0 \equiv 9\rho_0^2 \frac{d^2E_{\mathrm{SNM}}}{d\rho^2}(\rho_0)\,,$$
$$S_0 \equiv \frac{1}{2}\frac{\partial^2 E}{\partial\delta^2}(\rho_0,0)\,,$$
$$L \equiv 3\rho_0 \frac{dE_{\mathrm{sym}}}{d\rho}(\rho_0)\,,$$
$$K_{\mathrm{sym}} \equiv 9\rho_0^2 \frac{d^2E_{\mathrm{sym}}}{d\rho^2}(\rho_0)\,.$$

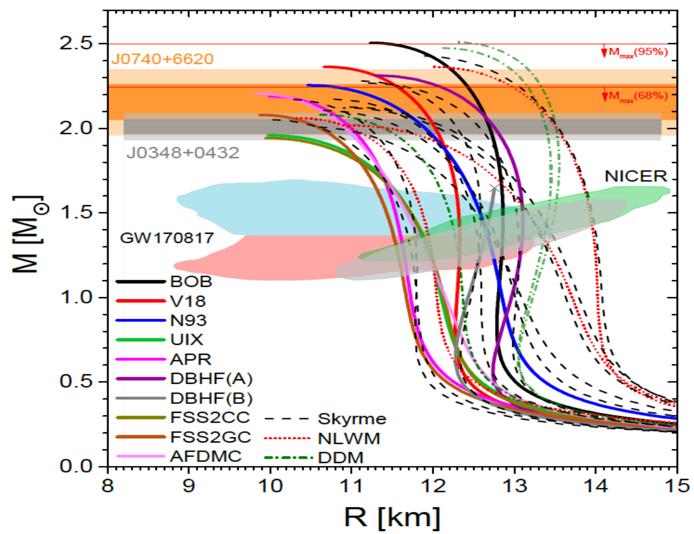
$$E_0 = -16 \pm 1\ \mathrm{MeV}$$
$$\rho_0 = 0.14 - 0.17\ \mathrm{fm}^{-3}$$

Model	EOS	ρ_0 [fm^{-3}]	$-E_0$ [MeV]	S_0 [MeV]	L [MeV]	K_0 [MeV]	$M_{\max}$ [$M_\odot$]	$\Lambda_{1.2}$	$\Lambda_{1.4}$	$\Lambda_{1.6}$
Skyrme	Gs	0.158	15.6	31.2	94	239	2.13	1769	659	253
	Rs	0.158	15.1	30.8	86	248	2.12	1652	618	238
	SLy4	0.160	16.0	31.8	45	232	2.05	756	287	111
	SV	0.155	16.0	33.0	97	305	2.43	2224	914	393

Tolman – Oppenheimer – Volkoff equations

$$\frac{dp}{dr} = -G\frac{\varepsilon m}{r^2}\left(1+\frac{p}{\varepsilon}\right)\left(1+\frac{4\pi p r^3}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}$$
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon\,,$$





Fermionic Dark Matter + Neutron Stars

Fermionic – Repulsive and Self Interacting Dark Matter

$$V(r) = \frac{g_\chi^2(\hbar c)}{4\pi r}\exp\left[-\frac{m_\phi c^2}{\hbar c} r\right]$$

Yukawa type interaction

m_ϕ in the range eV - MeV (vector gauge boson)

Self interaction energy density

$$\mathcal{E}_{SI}(n_\chi) = \frac{y^2}{2}(\hbar c)^3 n_\chi^2$$

Self interaction strength

$$y = g_\chi / m_\phi c^2$$

(in units MeV^{-1})

$$\mathcal{E}_{\rm DM}(n_\chi) = \frac{(m_\chi c^2)^4}{(\hbar c)^3 8\pi^2}\left[x\sqrt{1+x^2}(1+2x^2) - \ln(x+\sqrt{1+x^2})\right] + \frac{y^2}{2}(\hbar c)^3 n_\chi^2$$

$$P_{\rm DM}(n_\chi) = \frac{(m_\chi c^2)^4}{(\hbar c)^3 8\pi^2}\left[x\sqrt{1+x^2}(2x^2/3-1) + \ln(x+\sqrt{1+x^2})\right] + \frac{y^2}{2}(\hbar c)^3 n_\chi^2$$

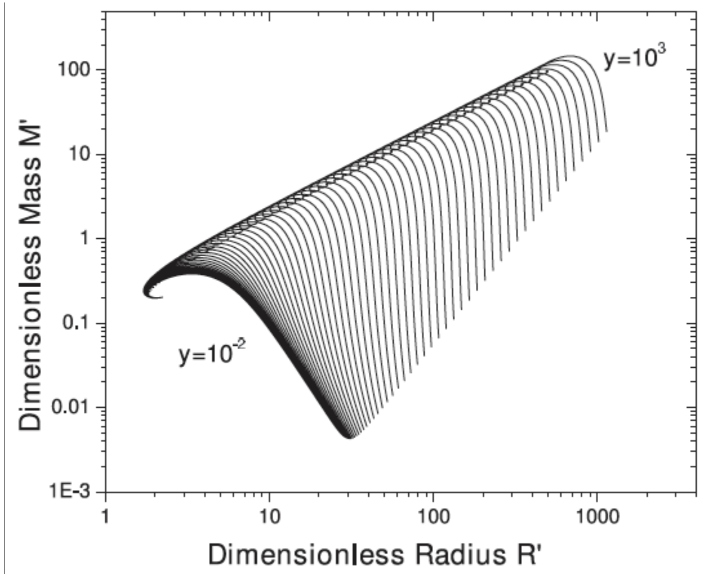
$$M_{\rm max} = (0.384 + 0.165\tilde{y}) \times \left(\frac{\rm GeV}{m_\chi}\right)^2 \times 1.632 M_\odot$$

$$R_{\rm min} = (3.367 + 0.797\tilde{y}) \times \left(\frac{\rm GeV}{m_\chi}\right)^2 \times 2.410 \ ({\rm km})$$

$$x = \frac{(\hbar c)(3\pi^2 n_\chi)^{1/3}}{m_\chi c^2}$$

$$\mathcal{E}(n_b, n_\chi) = \mathcal{E}_{\rm NS}(n_b) + \mathcal{E}_{\rm DM}(n_\chi)$$

$$P(n_b, n_\chi) = P_{\rm NS}(n_b) + P_{\rm DM}(n_\chi)$$



G. Narain, Jurgen Scha ner-Bielich, and Igor N. Mishustin, “Compact stars made of fermionic dark matter”, Phys. Rev. D 74, 063003 (2006).

Bosonic Dark Matter + Neutron Stars

Bosonic – Repulsive and Self Interacting Dark Matter

$$\mathcal{E}_{\rm DM}(n_\chi) = m_\chi c^2 n_\chi + \frac{u^2}{2}(\hbar c)^3 n_\chi^2$$

$$P_{\rm DM}(n_\chi) = \frac{u^2}{2}(\hbar c)^3 n_\chi^2$$

$$M_T = m_B(R_B) + m_D(R_D)$$

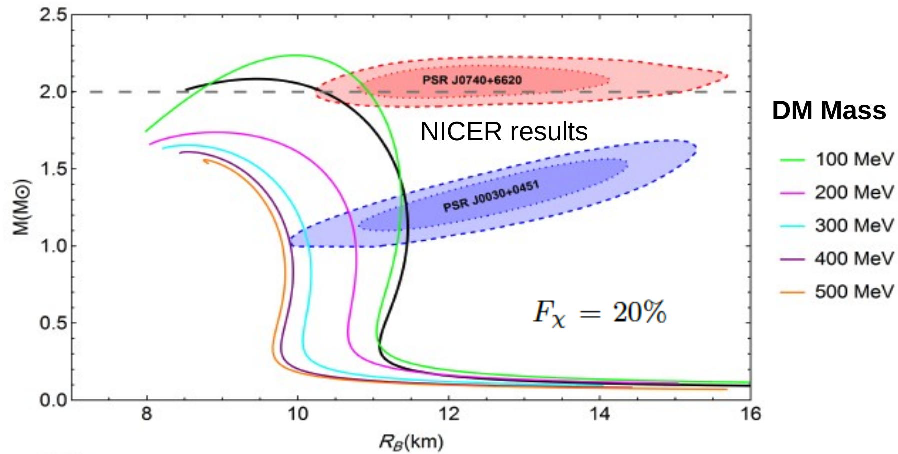
Self interaction strength

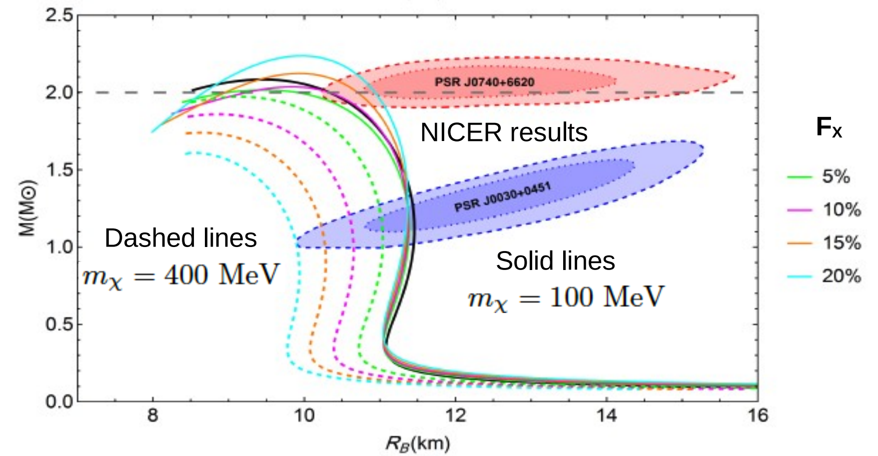
$$u = g_\chi / m_\phi c^2$$

(in units MeV^{-1})

DM Fraction

$$F_\chi = \frac{m_D(R_D)}{M_T}$$





Soroush Shakeri and Davood Rafiei Karkevandi, Phys. Rev. D 109, 043029 (2024)

The Stability Method

- We used the method developed in 1989 by Henriques-Liddle-Moorhouse for bosons and fermions.
- The method examining the behavior of baryons fixing the total mass M values.
- The stability curve is formed with a pair of central pressure values, exactly at the point where the number of particles reaches the min and max values.

$$\left(\frac{\partial N_b}{\partial P_c^{\rm NS}}\right)_{\rm M=const} = \left(\frac{\partial N_\chi}{\partial P_c^{\rm NS}}\right)_{\rm M=const} = 0$$

$$\left(\frac{\partial N_b}{\partial P_c^{\rm DM}}\right)_{\rm M=const} = \left(\frac{\partial N_\chi}{\partial P_c^{\rm DM}}\right)_{\rm M=const} = 0$$

$$\{P_c^{\rm NS}, P_c^{\rm DM}\}$$

$$f = P_{DM}^c / P_{NS}^c$$

DM fraction

$$N_i = 4\pi \int_0^{R_i} n_i(r) \frac{r^2 dr}{\sqrt{1 - 2GM(r)/rc^2}}, \quad i = b, \chi$$

A. Henriques, A. R. Liddle, and R. Moorhouse, “Combined boson-fermion stars”, Phys. Lett. B 233, 99 (1989).
A. Henriques, A. R. Liddle, and R. Moorhouse, “Combined boson-fermion stars: Configurations and stability”, Nucl. Phys. B 337, 737 (1990).
F. D. Giovanni, D. Guerra, S. Albanesi, M.M. Tenes, D. Tseneklidou, “Fermion-axion stars: Static solutions and dynamical stability”, Phys. Rev. D 106, 084013 (2022).

The "Two Fluids Model"

- A Two Fluids Model used in our study (1st Fluid DM - 2nd Fluid neutron star matter).
- We consider non-self annihilating DM particles admixed with neutron star matter.
- We consider that the total number of particles interact only gravitational.
- Solve the Tolman – Oppenheimer – Volkoff (TOV) 4 equations.

$$\frac{dP_{\rm NS}(r)}{dr} = -\frac{G\mathcal{E}_{\rm NS}(r)M(r)}{c^2r^2}\left(1+\frac{P_{\rm NS}(r)}{\mathcal{E}_{\rm NS}(r)}\right) \times \left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}$$

$$\frac{dM_{\rm NS}(r)}{dr} = \frac{4\pi r^2}{c^2}\mathcal{E}_{\rm NS}(r)$$

$$\frac{dP_{\rm DM}(r)}{dr} = -\frac{G\mathcal{E}_{\rm DM}(r)M(r)}{c^2r^2}\left(1+\frac{P_{\rm DM}(r)}{\mathcal{E}_{\rm DM}(r)}\right) \times \left(1+\frac{4\pi P(r)r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2r}\right)^{-1}$$

$$\frac{dM_{\rm DM}(r)}{dr} = \frac{4\pi r^2}{c^2}\mathcal{E}_{\rm DM}(r)$$

$$M(r)=M_{NS}(r)+M_{DM}(r)$$

$$P(r)=P_{NS}(r)+P_{DM}(r)$$

Supra-massive Compact Objects – Fermionic DM

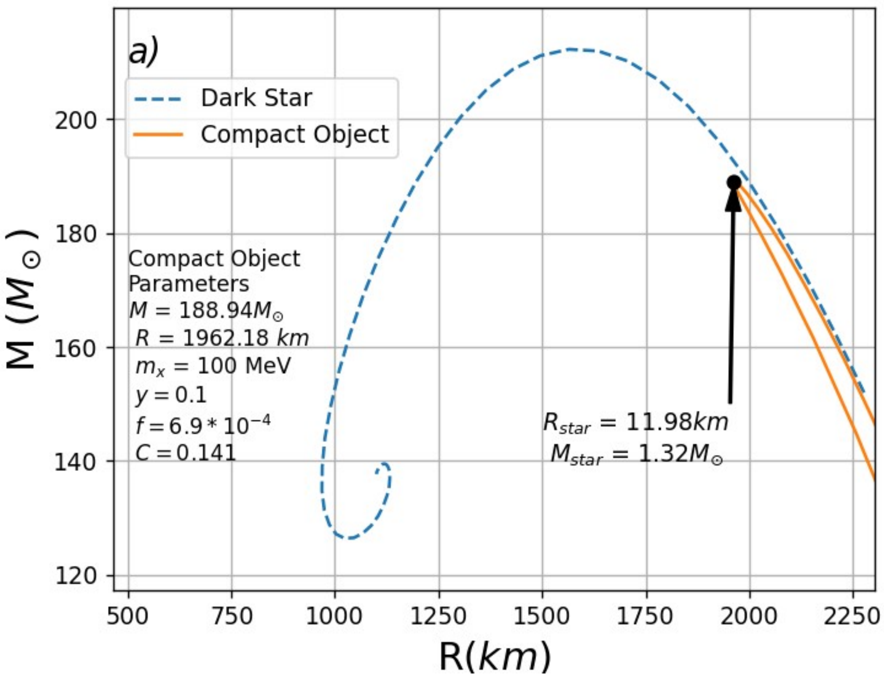
- **Fermionic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

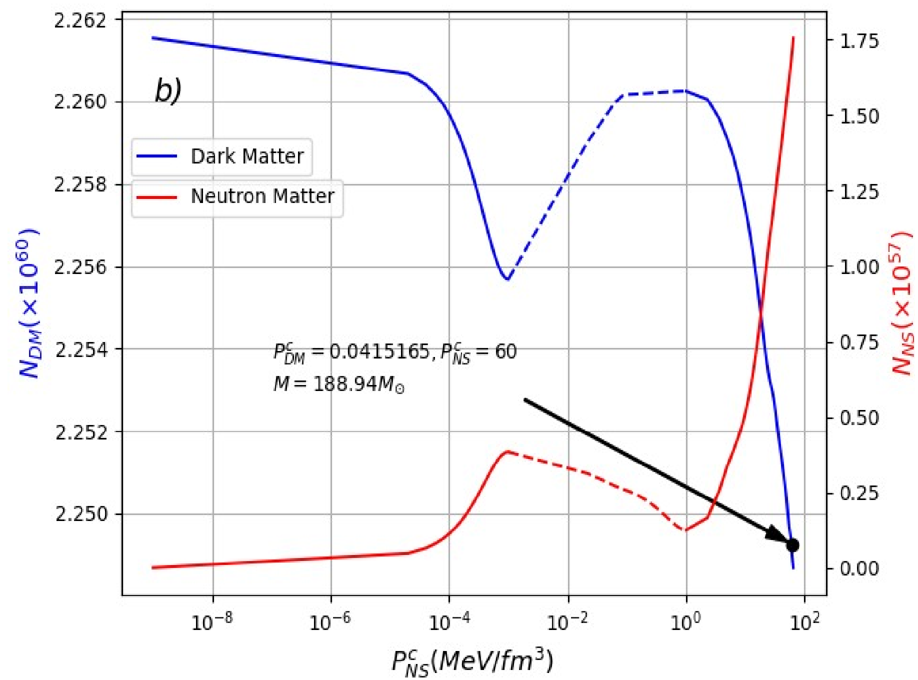
$$C = \frac{GM}{Rc^2}$$

C ∈[0.05 – 0.30]

Stability Region

Instability Region





Supra-massive Compact Objects – Fermionic DM

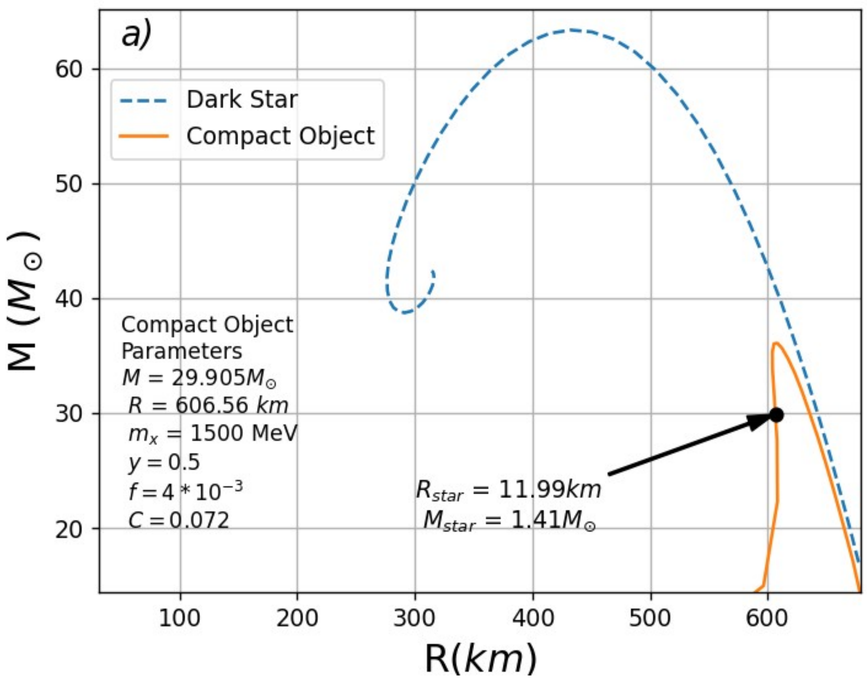
- **Fermionic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

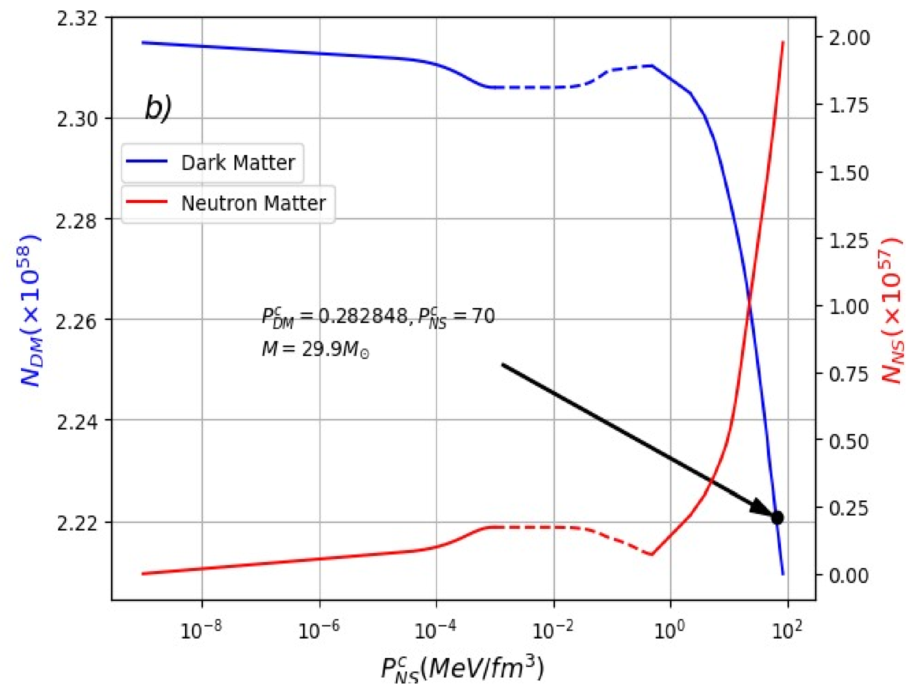
$$C = \frac{GM}{Rc^2}$$

$C \in [0.05 - 0.30]$

Stability Region ———

Instability Region - - -





Supra-massive Compact Objects – Fermionic DM

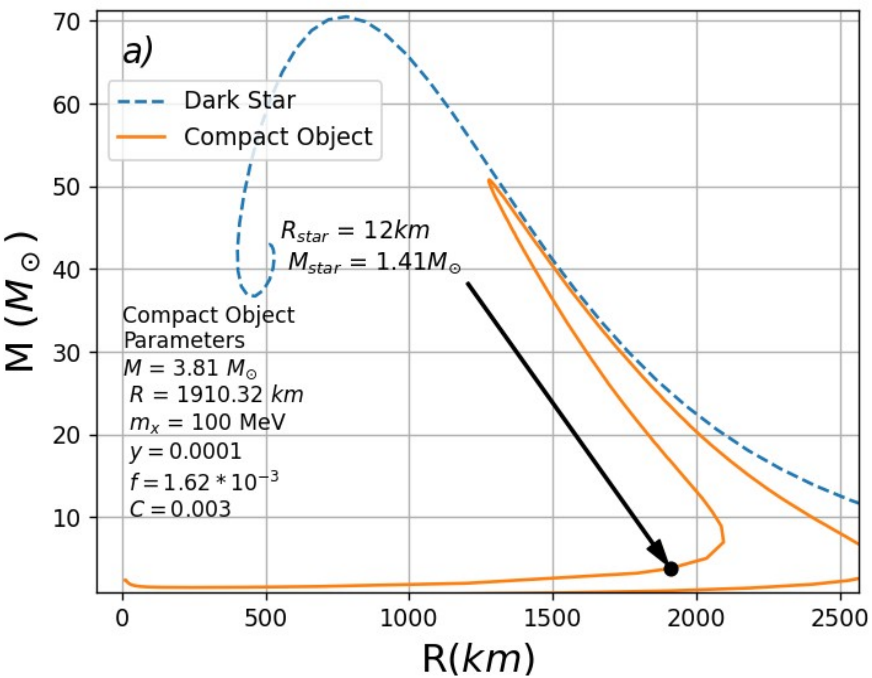
- **Fermionic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

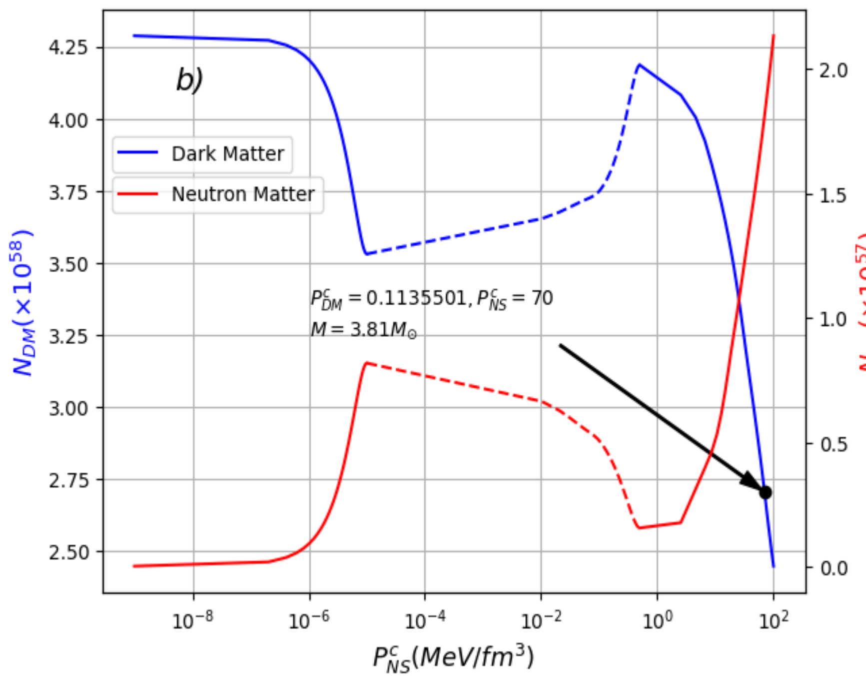
$$C = \frac{GM}{Rc^2}$$

$C \in [0.05 – 0.30]$

Stability Region ——

Instability Region - - -





Supra-massive Compact Objects – Fermionic DM

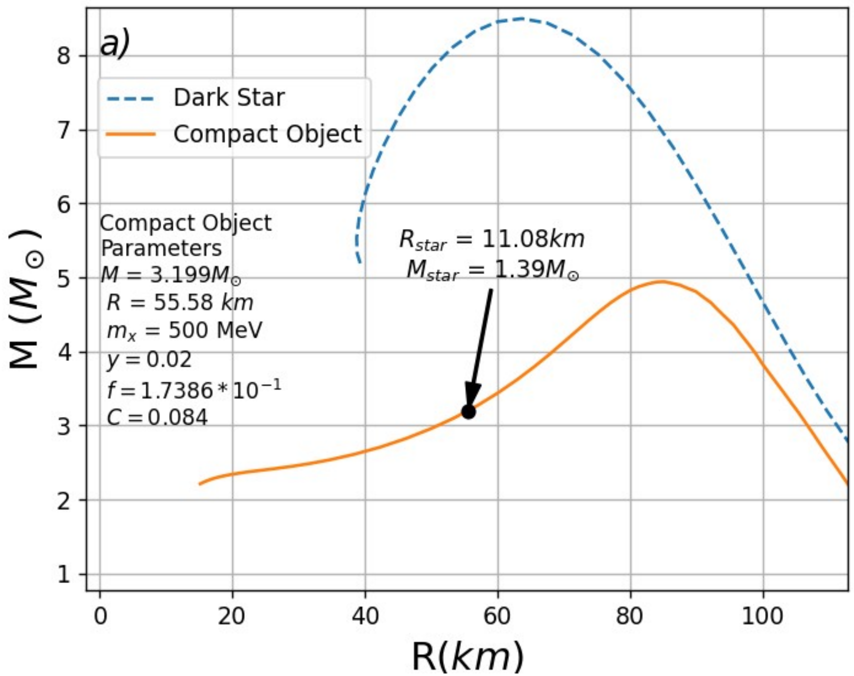
- **Fermionic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

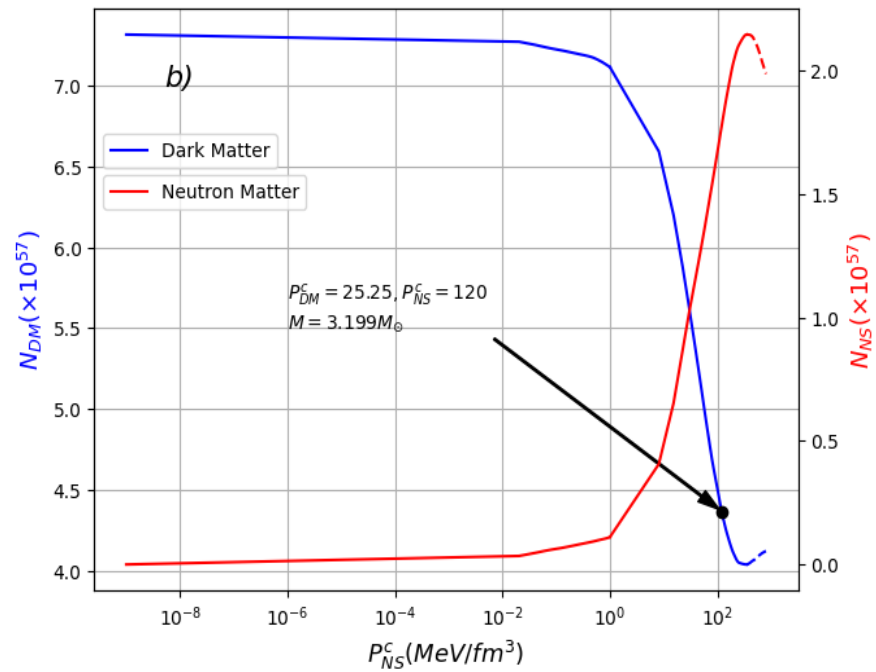
$$C = \frac{GM}{Rc^2}$$

C $\in$[0.05 – 0.30]

Stability Region

Instability Region





Supra-massive Compact Objects – Bosonic DM

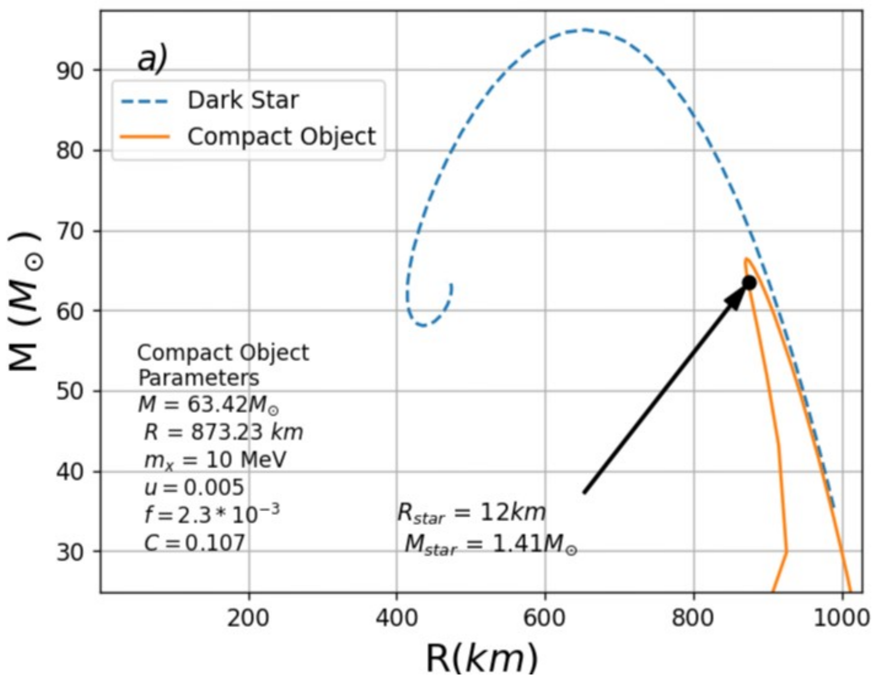
- **Bosonic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

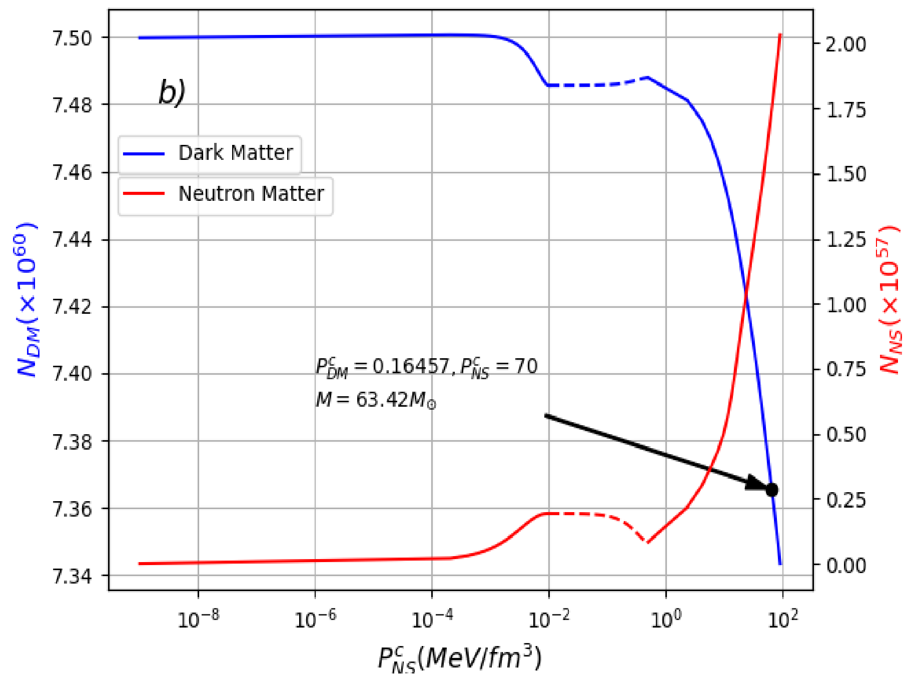
$$C = \frac{GM}{Rc^2}$$

$C \in [0.05 - 0.30]$

Stability Region ——

Instability Region - - -





Supra-massive Compact Objects – Bosonic DM

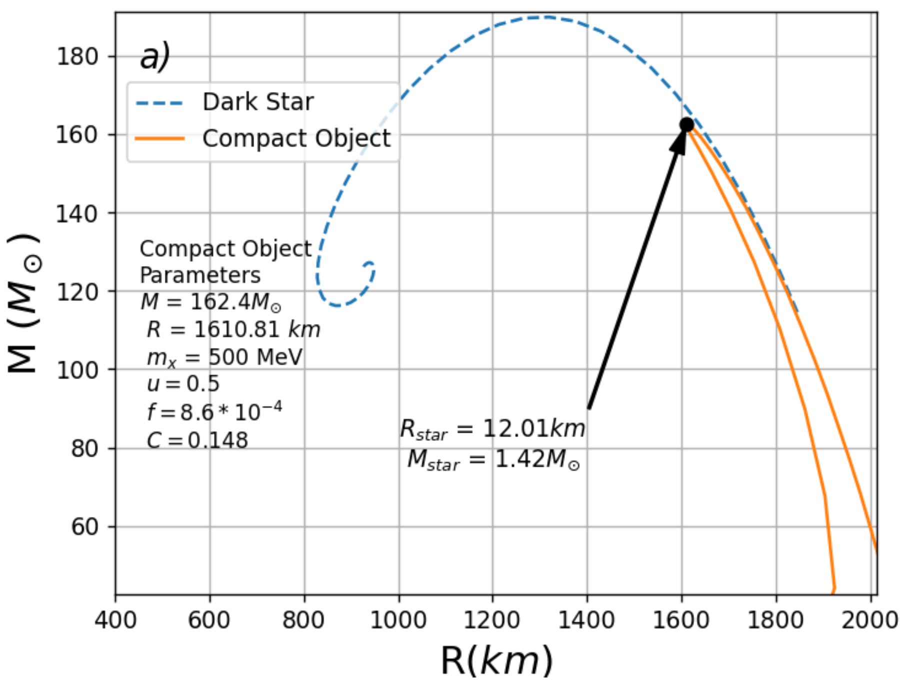
- **Bosonic Dark Matter**
- Non-self annihilating
- Self interacting DM
- Compactness C
- Stability Check

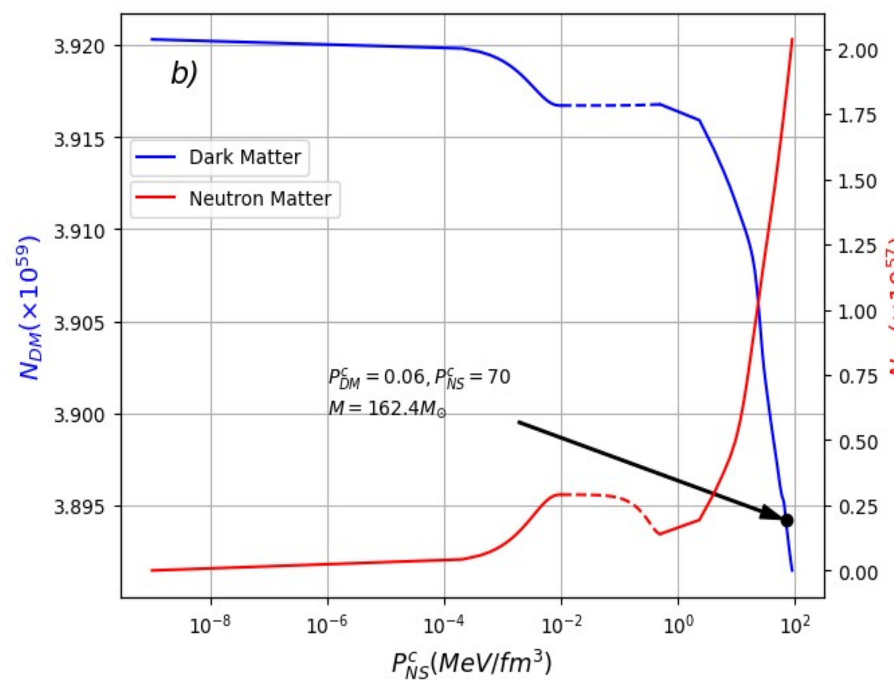
$$C = \frac{GM}{Rc^2}$$

C ∈[0.05 – 0.30]

Stability Region ———

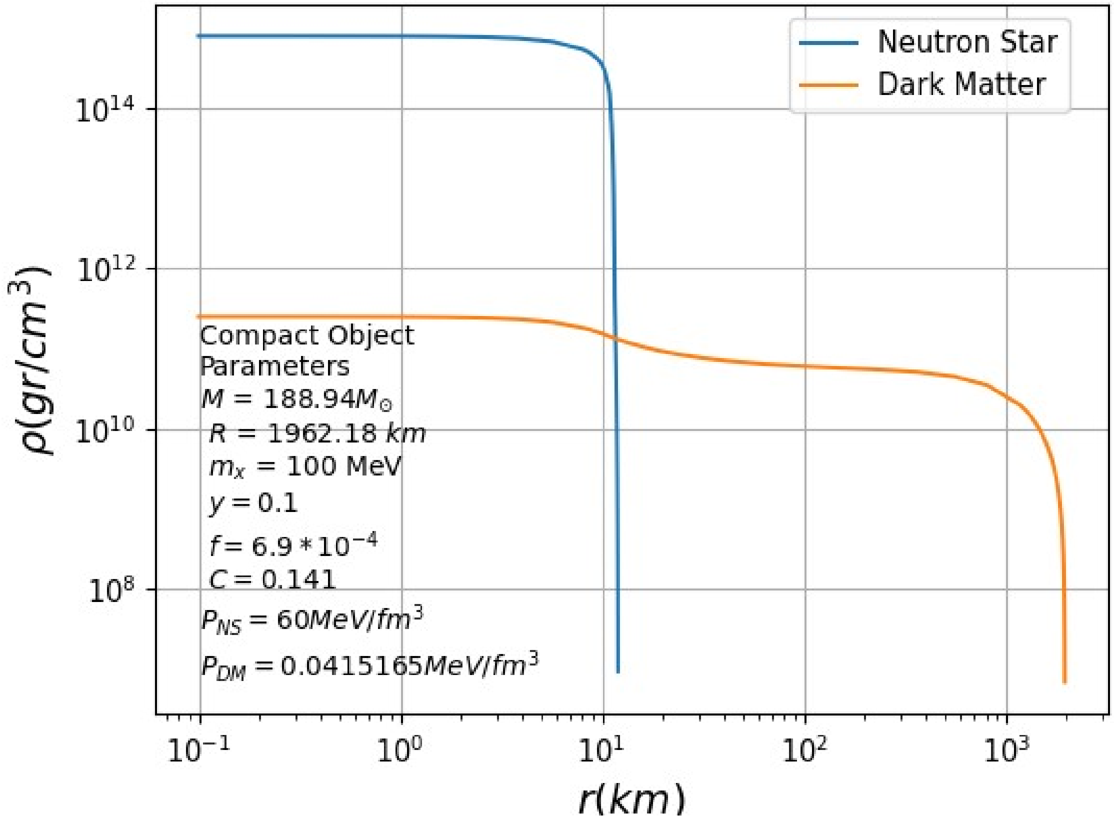
Instability Region - - -

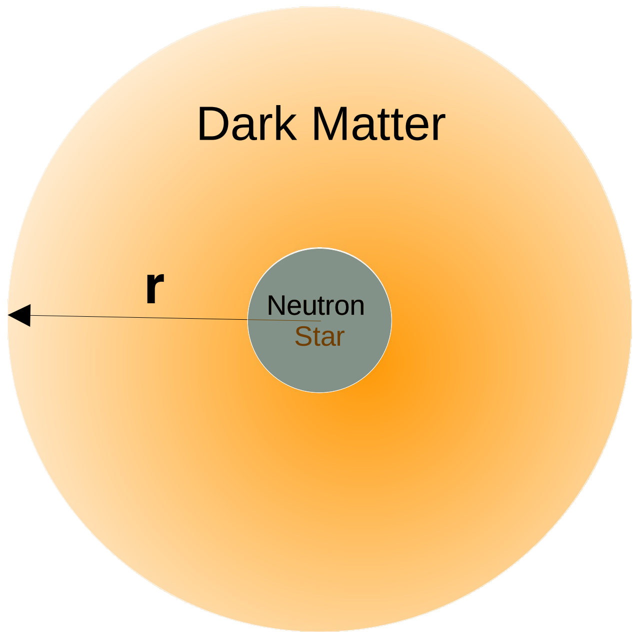




The Supra-massive Compact Objects

The **density** of DM and neutron star matter as a function of the radius **r** for the specific configuration (**D**ark Matter **A**dmixture **N**eutron **S**tars)





Not in scale

Concluding Remarks

- We investigated possible supra-massive dark objects stable configurations, with neutron star origin.
- We used EoS of self-interactive fermions and bosons and one of the most reliable EoS for the neutron star matter (Two Fluids Model).
- Unlike other similar studies, we did not focus on the cases of neutron stars surrounded by a DM halo of a few kilometers and low relative in mass contribution of DM.
- In the literature so far there is no any strong theoretical prediction which argues strongly against the creation of these supra-massive DM objects.
- We also explore the possibility that some of very massive neutron stars in the region of the “mass-gap” can be attributed to the proposed scenario with some modifications.
- **Creation:**

  (a) possible capture of a DM during the core-collapse supernova

  (b) accretion of DM due to gravity when the neutron star lives in a dense DM region inside the galaxy
- **Detection:**

  (a) by gravitational lensing (deviation from what is expected like the deviation observed in rotational curves)

  (b) from merger between two dark objects (LIGO-VIRGO-KARGA for possible “unexpected” signals recorded)

  (c) from merger between a dark object and another compact object including a pure neutron star or a black hole
- In any case, further theoretical studies and precise astrophysical observations will help to shed light on this open issue.

Collaborators

M. Vikiaris[1]
Ch. Moustakidis[1]
V. Petousis[2]
M. Veselsky[2]

(1) Department of Theoretical Physics, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
(2) Institute of Experimental and Applied Physics, Czech Technical University, Prague, 110 00, Czechia

- Czech Science Foundation - GAČR Contract No. 21-24281S
- Hellenic Foundation for Research and Innovation (HFRI No. 5657)

IEAP CTU in Prague

Thank you

Back Up Slides

Neutron Stars – In brief

Neutron stars are the densest objects in the Universe.

Naturally, the matter inside of them is exotic and unlike anything on Earth - imagine squashing the mass of our Sun into a star only 11 - 12 km across !!

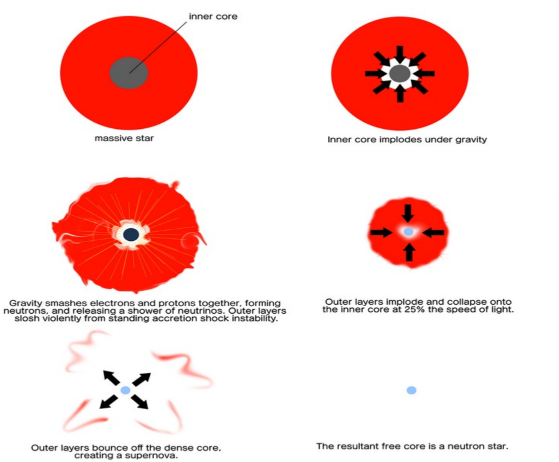
As one might guess from their name, neutron stars are comprised of mostly neutrons, with a small fraction of electrons and protons also contributing to their mass.

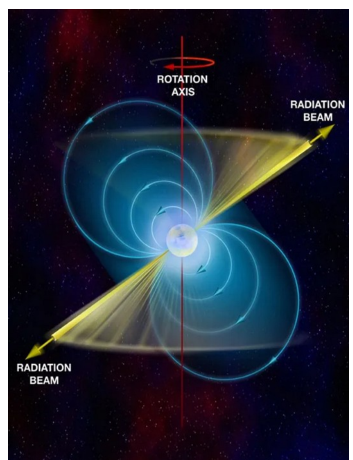
A neutron star can be thought of as analogous to a giant atomic nucleus, bound by gravitational forces rather than the strong force.

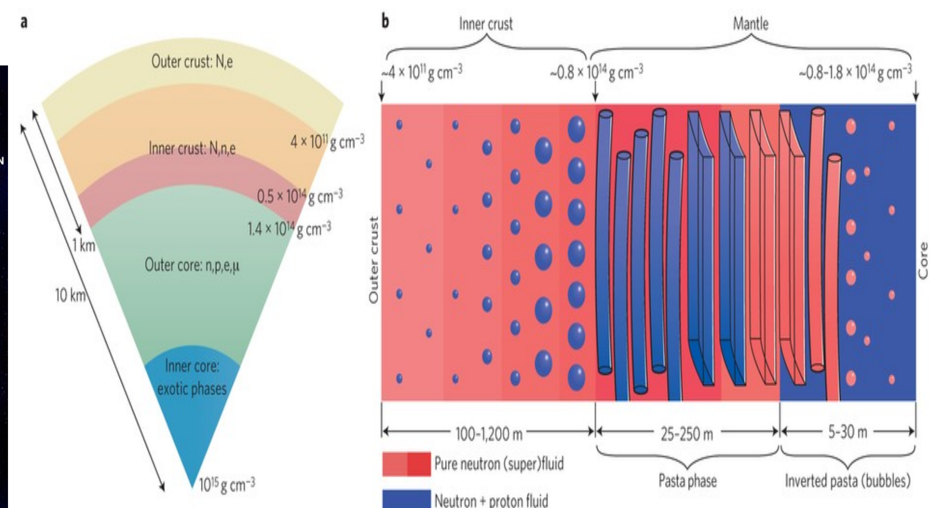
Under the pressure exerted by gravity, matter is compressed to the same density as the nuclei of atoms.

Jocelyn Bell Burnell – PhD
Pulsar Discovery 1967

Prof. Antony Hewish
Nobel Prize 1974 for pulsars

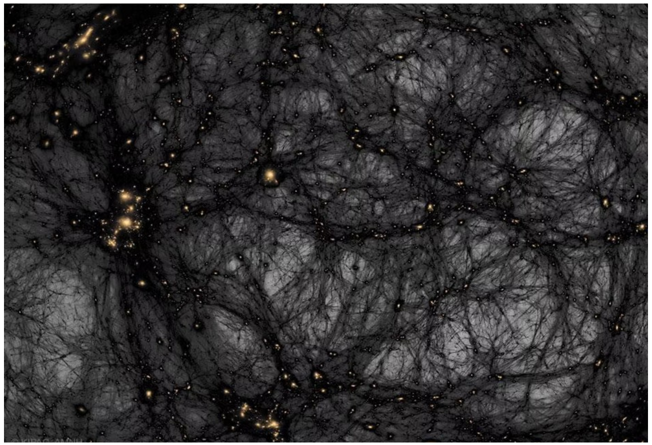


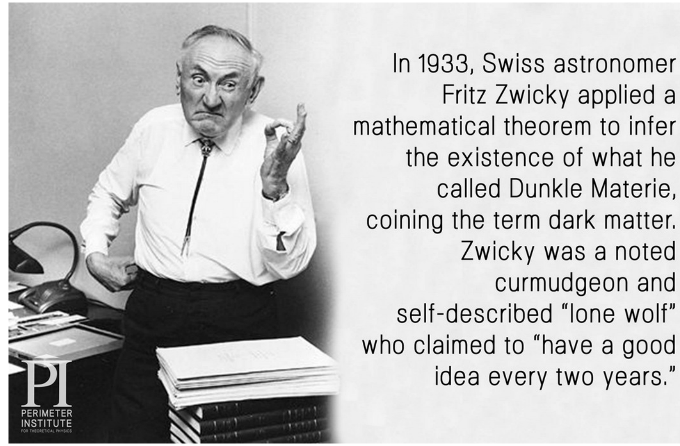




Dark Matter – In brief

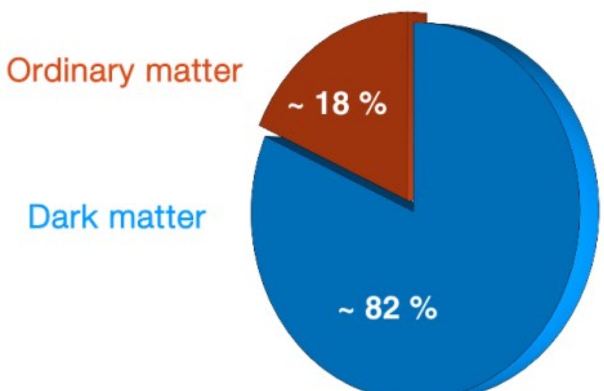
Is a HYPOTHETICAL form of matter which appears to not interact with normal matter except only gravitational

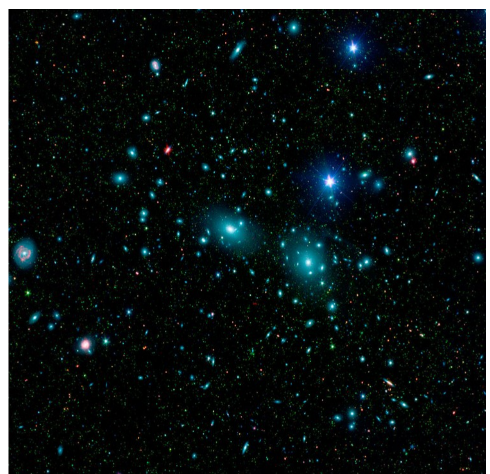


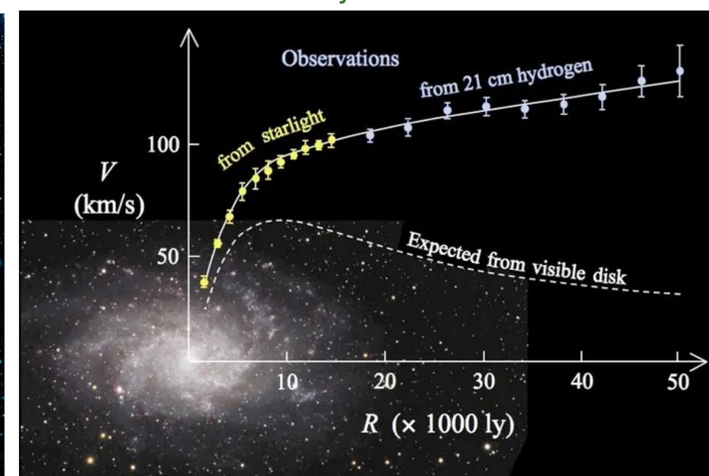


Fritz Zwicky – Dark Matter - 1933
Coma Cluster

Vera Rubin – Dark Matter
Galaxy rotation curves - 1976



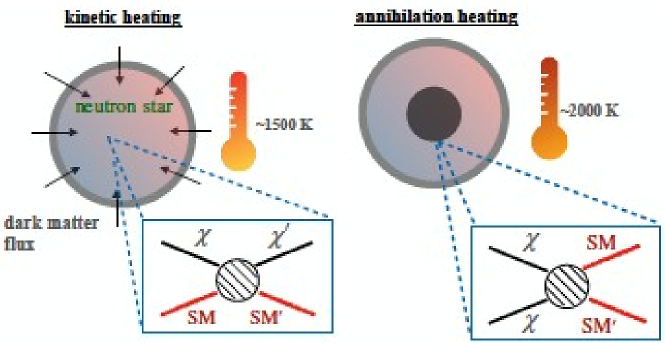


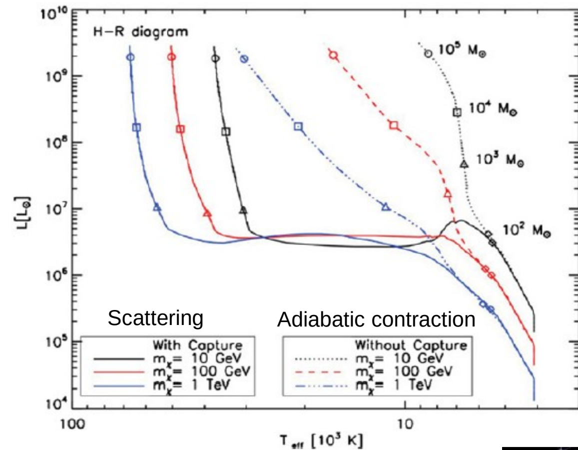


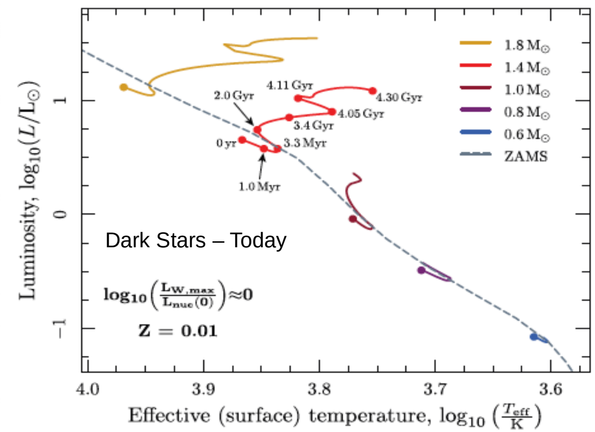
Dark Stars – In brief

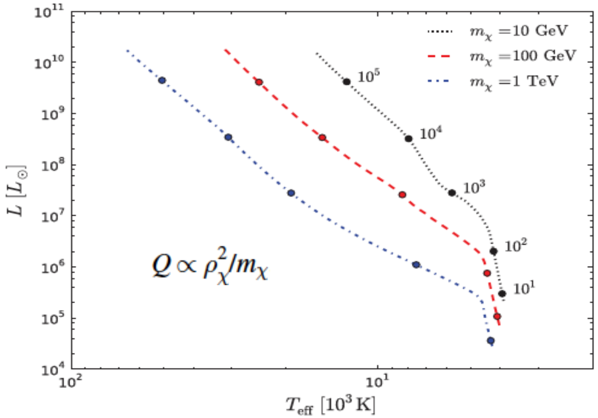
Dark stars are stellar objects made (almost entirely) of hydrogen and helium, but powered by the heat from dark matter annihilation, rather than by fusion. They are in hydrostatic and thermal equilibrium, but with an unusual power source.

Katherine Freese, Tanja Rindler-Daller, Douglas Spolyar and Monica Valluri, “Dark Stars: a review”, Rep. Prog. Phys. 79, 066902 (2016)









Luminosity sources

$$L_{\rm tot} = L_{\rm DM} + L_{\rm grav} + L_{\rm nuc} + L_{\rm cap}$$

$$L_{\rm DM} = \frac{2}{3}\frac{1}{m_\chi}\int \rho(r)^2_{\rm DM}\langle\sigma v\rangle dV$$