Dark Matter Admixed Quarkyonic Stars as the Secondary Object in GW190814: A Two-Fluid Analysis

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Outline of the Talk

1. Motivation

- Dark matter admixed quarkyonic neutron stars

2. Introduction

- Neutron stars, dense QCD matter, quarkyonic phase and dark matter

3. Formalism

- Two-fluid framework: visible and dark sectors coupled through gravity

4. Results and Discussion

- EOS, M–R relation, tidal deformability, and core–halo morphology

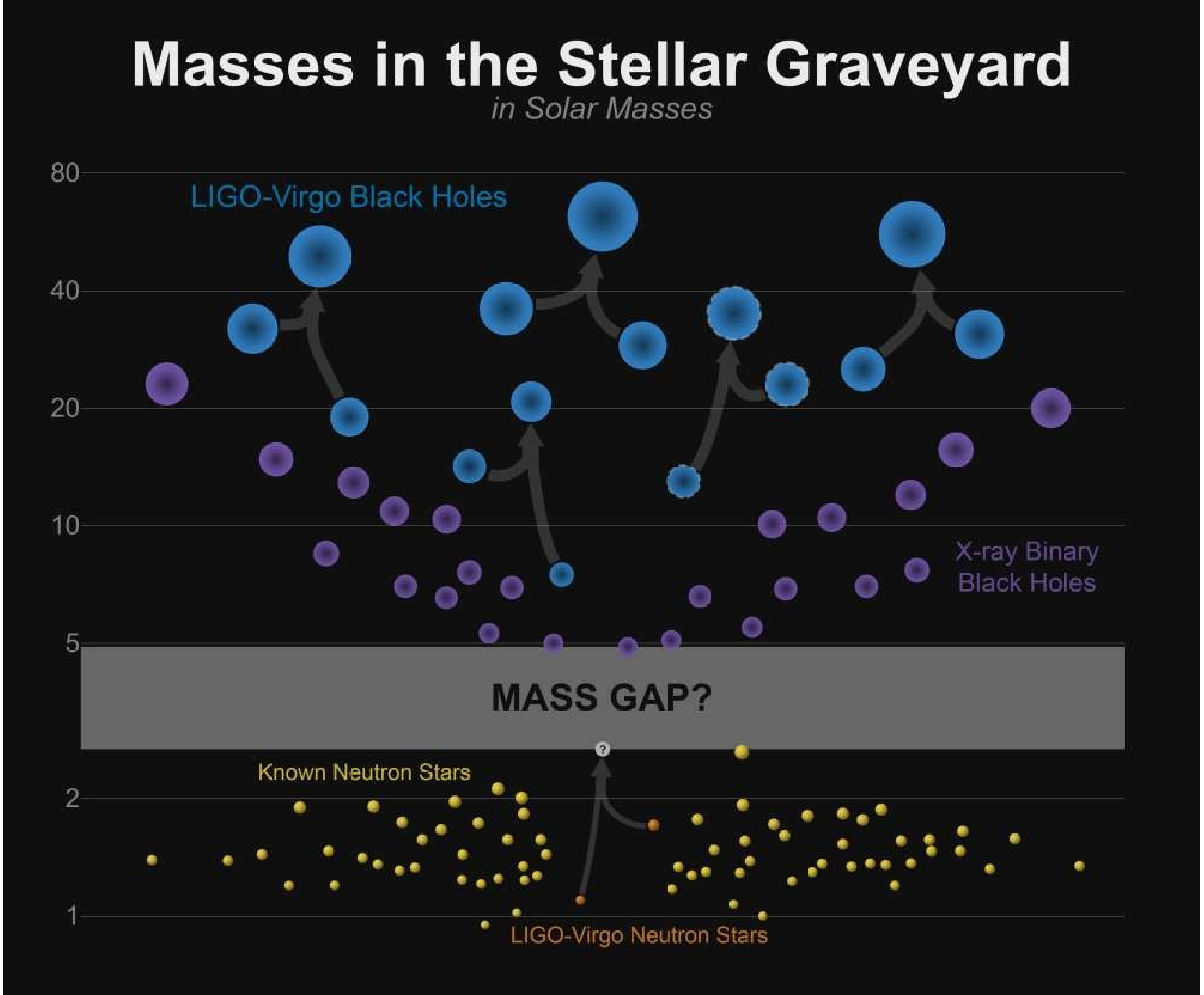
5. Conclusions

- DM-admixed quarkyonic stars explain GW190814 secondary mass

Introduction

Why Quarkyonic Stars?

Possibility of Presence of DM?



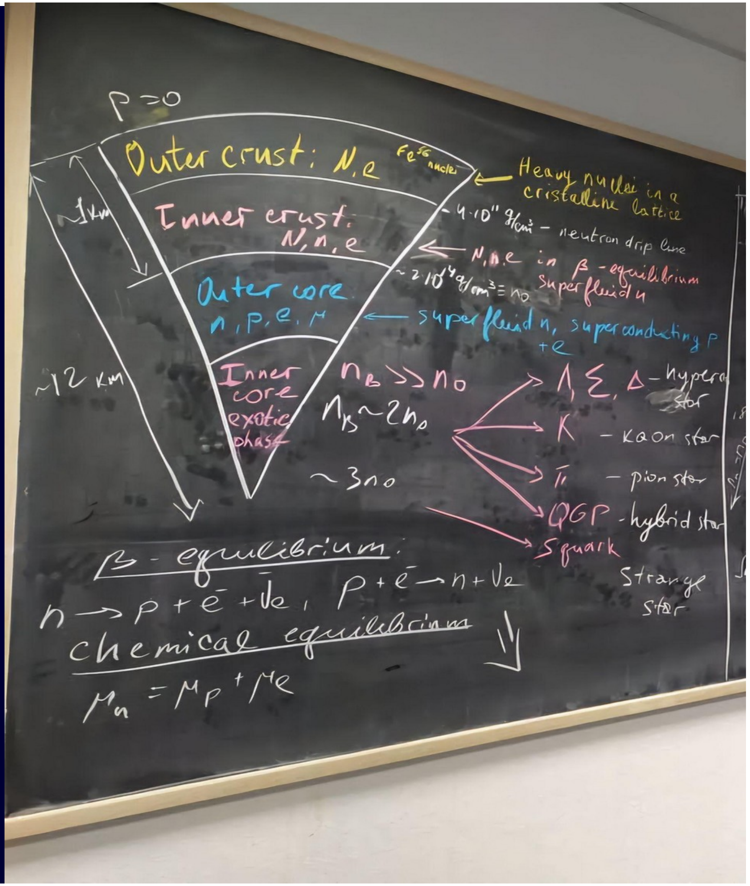
Zombies of the cosmos : Neutron star

- A compact object formed after supernovae explosion.

- It has mass around ~ 2 $M_\odot$ and radius ~ 10 km.
- PSR J1614-2230 $M = 1.97 \pm 0.04 M_\odot$ **ApJ 832 (2016)167**
- PSR J0348+0432 $M = 2.01 \pm 0.04 M_\odot$ **Science 340 (2013) 1233232**
- PSR J1810+1744 $M = 2.13 \pm 0.07 M_\odot$ **ApJL 908 (2021) L46**

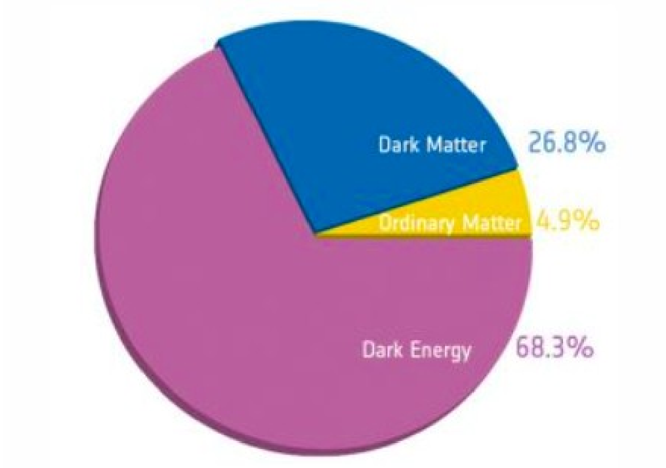
- Mainly composed of neutrons and few percentage of protons and leptons.

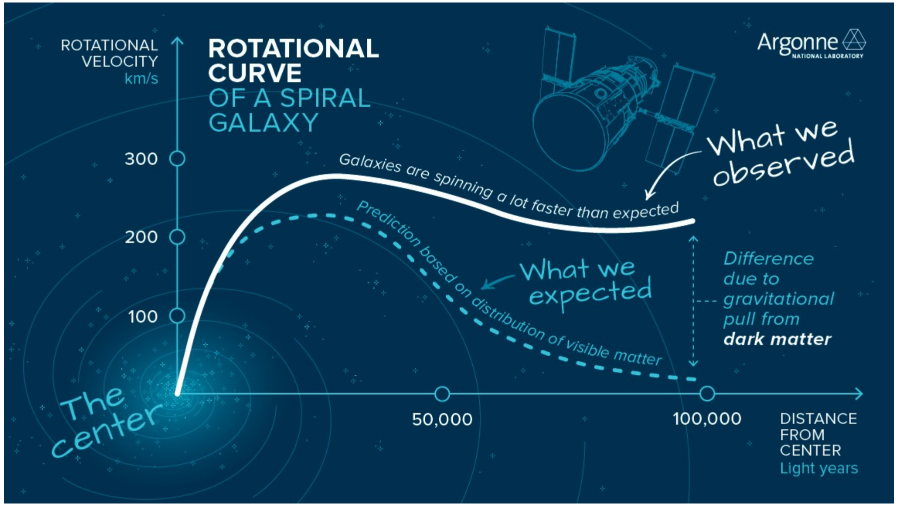
- Neutron degeneracy pressure and nuclear repulsive force support the star from gravitational collapse.



Dark Matter and NS

- Is all that we see all that there is in the universe?
- Why its dark?





- We cannot rule out the possibility of dark matter trapped inside the Neutron stars due to high density matter and extreme gravitational potential.

Source: Argonne National Laboratory

Nuclear Model with mean field interaction

- To study various neutron star properties we need a framework which incorporate the nuclear interaction.

- Here we use the Effective Relativistic Mean Field formalism (E-RMF).

- In E-RMF model, we consider that the interaction between nucleons with exchange of various mesons like σ, ω, ρ etc. Here we have considered two parameter sets, namely G3 and IOPB-I.

B. Kumar et al, NPA 966 (2017) 197

PRC 97 (2018) 045806.

Nuclear Model with mean field interaction

$$\mathscr{L}_{NM} = \boxed{\sum_{j=p,n} \bar{\psi}_j \left\{ \gamma_\mu \left(i\partial^\mu - g_\omega \omega^\mu - \frac{1}{2} g_\rho \vec{\tau}_j \cdot \vec{\rho}^{\,\mu} \right) - \left(M_{nucl.} - g_\sigma \sigma - g_\delta \vec{\tau}_j \cdot \vec{\delta} \right) \right\} \psi_j} + \frac{1}{2}\partial^\mu \sigma\, \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2$$

Nucleons part

σ-meson

$$+ \frac{\zeta_0}{4!} g_\omega^2 \omega^4 - \boxed{\frac{\kappa_3}{3!} \frac{g_\sigma m_\sigma^2 \sigma^3}{M_{nucl.}} - \frac{\kappa_4}{4!} \frac{g_\sigma^2 m_\sigma^2 \sigma^4}{M_{nucl.}^2}} + \frac{1}{2} m_\omega^2 \omega^2 - \frac{1}{4} W^{\mu\nu} W_{\mu\nu} + \boxed{\frac{\eta_1}{2} \frac{g_\sigma \sigma}{M_{nucl.}} m_\omega^2 \omega^2 + \frac{\eta_2}{4} \frac{g_\sigma^2 \sigma^2}{M_{nucl.}^2} m_\omega^2 \omega^2}$$

ω^4

Higher order of σ

ω-meson

$\sigma - \omega^2, \sigma^2 - \omega^2$

$$+ \boxed{\frac{\eta_\rho}{2} \frac{m_\rho^2}{M_{nucl.}} g_\sigma \sigma \vec{\rho}^{\,2}} + \frac{1}{2} m_\rho^2 \vec{\rho}^{\,2} - \frac{1}{4} \vec{R}^{\mu\nu} \cdot \vec{R}_{\mu\nu} - \boxed{\Lambda_\omega g_\omega^2 g_\rho^2 \vec{\omega}^{\,2} \vec{\rho}^{\,2}} + \frac{1}{2} \partial^\mu \vec{\delta}\, \partial_\mu \vec{\delta} - \frac{1}{2} m_\delta^2 \vec{\delta}^{\,2}.$$

$\sigma - \rho^2$

ρ-meson

$\omega^2 - \rho^2$

δ-meson

$$\boxed{W^{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu}$$

Phys. Rev. C 97, 045806, 2018

$$\boxed{\vec{R}^{\mu\nu} = \partial^\mu \vec{\rho}^{\,\nu} - \partial^\nu \vec{\rho}^{\,\mu}}$$

Quarkyonic Model

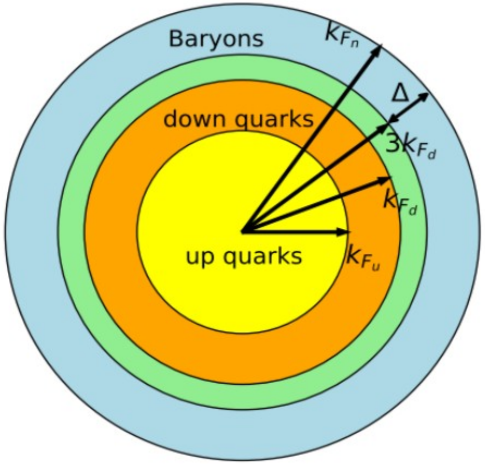


Figure 1. *The momentum space of the quarkyonic matter*

Describes a system with a two nucleon and two-flavor quark matter (u, d) along with chemical and beta equilibrium.

Minimum momentum of nucleon:

$$k_{0(n,p)} = (k_{f_{(n,p)}} - k_{t_{(n,p)}})\left[1 + \frac{\Lambda^2}{k_{f_{(n,p)}} k_{t_{(n,p)}}}\right]$$

Where,

$$k_{t(n,p)} = (3\pi^2 n_{t(n,p)})^{\frac{1}{3}}$$

<u>Free Parameters</u>

Λ (Confinement Scale)

n_t (Transition Density)

L. McLerran and S. Reddy, PRL 122 (2019) 122701.
T. Zhao and J. M. Lattimer, PRD 102 (2020) 023021.
D. Dey et al JCAP 01 (2025) 056.

Dark Matter Model

The dark matter candidate is treated as a fermion. The effective single-particle potential is:

$$V_{\text{eff}}(r) = \frac{g_v^2}{4\pi}\frac{e^{-m_v r}}{r} - \frac{g_s^2}{4\pi}\frac{e^{-m_s r}}{r}.$$

The energy density and pressure are then written as,

$$\mathcal{E}_{\text{DM}} = \frac{1}{\pi^2}\int_0^{k_D} dk\, k^2\sqrt{k^2+M_D^{*2}} + \frac{g_{DV}^2}{2m_{DV}^2}\rho_D^2 + \frac{m_{DS}^2}{2g_{DS}^2}(M_D - M_D^*)^2,$$

$$P_{\text{DM}} = \frac{1}{3\pi^2}\int_0^{k_D} dk\, \frac{k^4}{\sqrt{k^2+M_D^{*2}}} + \frac{g_{DV}^2}{2m_{DV}^2}\rho_D^2 - \frac{m_{DS}^2}{2g_{DS}^2}(M_D - M_D^*)^2.$$

The effective mass of the DM candidate is given as:

Xiang et al, PRC 89 (2014) 025803.

$$\mathrm{M}_D^* = M_D - g_{DS}\phi_D$$

The interaction strengths are characterized by two coupling constants:

Attractive scalar coupling: $\mathrm{C}_{DS} = g_{DS}/m_{DS}$

Repulsive vector coupling: $\mathrm{C}_{DV} = g_{DV}/m_{DV}$

Two-Fluid Approach

NM/VM and DM treated as independent fluids interacting via gravity.
The coupled TOV equations:

$$\frac{dP_1}{dr} = -(\varepsilon_1 + P_1)\frac{4\pi r^3(P_1 + P_2) + m(r)}{r\,[r - 2m(r)]},$$

$$\frac{dP_2}{dr} = -(\varepsilon_2 + P_2)\frac{4\pi r^3(P_1 + P_2) + m(r)}{r\,[r - 2m(r)]}$$

$$\frac{dm(r)}{dr} = 4\pi r^2[\,\varepsilon_1(r) + \varepsilon_2(r)\,].$$

At the stellar center (r = 0):
$m(0) = 0$, $P_1(0) = P_{c,1}$, $P_2(0) = P_{c,2}$

Integration continues outward until either $P_1(r)$ or $P_2(r)$ vanishes, defining the radii R_1 and R_2.

The total radius R corresponds to the outermost surface where both pressures vanish:
$P_1(R) = P_2(R) = 0$.

Here, P_1, ε_1 correspond to the pressure and energy density of baryonic matter, while P_2, ε_2 denote those for dark matter. m(r) is the total gravitational mass enclosed within radius r.

Sandin et al, APP, 32 (2009) 278.
Xiang et al, PRC 89 (2014) 025803.
A Das et al, PRD 105 (2022) 123034.
Routaray et al, PRD 111 (2025) 103045
Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

Advantages of Two-fluid approach

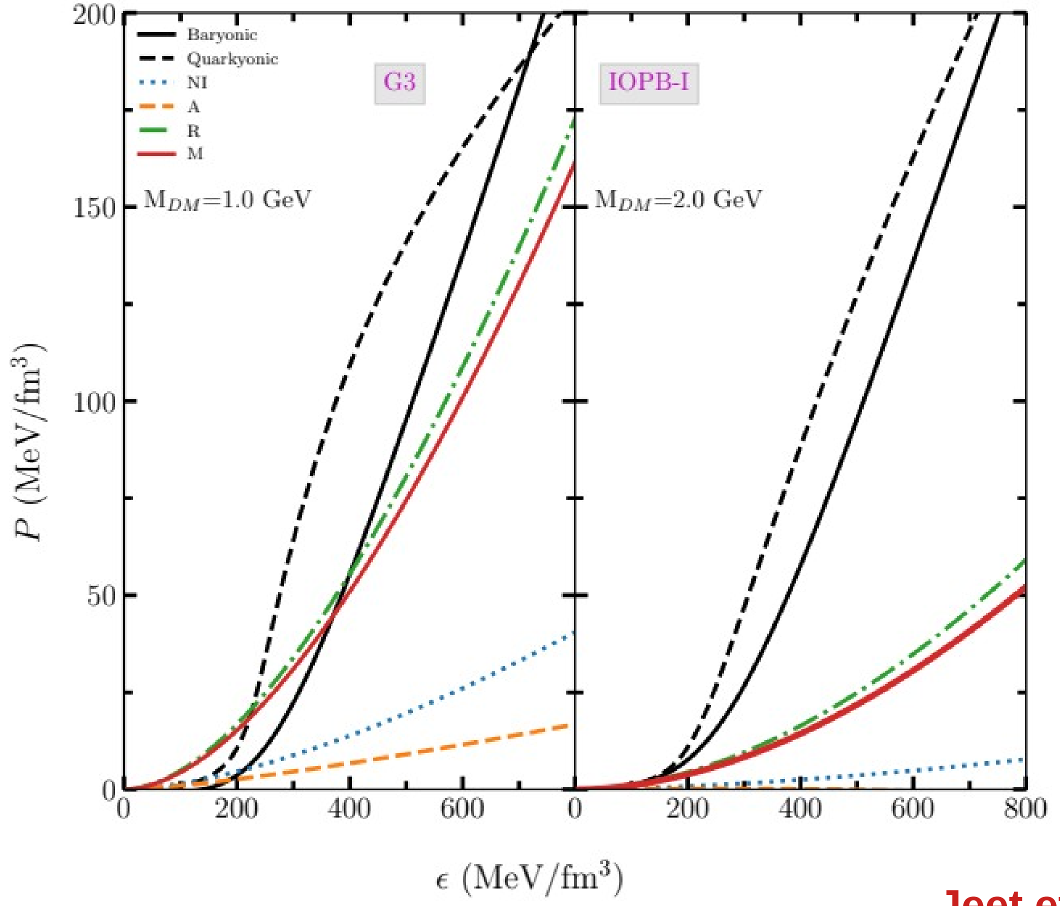
Treats normal matter (NM) and dark matter (DM) as separate fluids coupled only through gravity.

Each follows its own pressure-density profile with distinct EOS and particle properties.

Naturally produces DM cores or halos, unlike single-fluid models.

Captures realistic structural effects on mass-radius, moment of inertia, tidal deformability, and redshift.

Numerical Results: EOS



Visible Sector

Transition Density$\rightarrow$ n_t= 0.3 fm^{-3}

Confinement Scale$\rightarrow$ Λ_{cs} = 800 MeV

Dark Sector

R$\rightarrow$ Repulsion (C_{DV}=10 GeV^{-1}, C_{DS}=0)

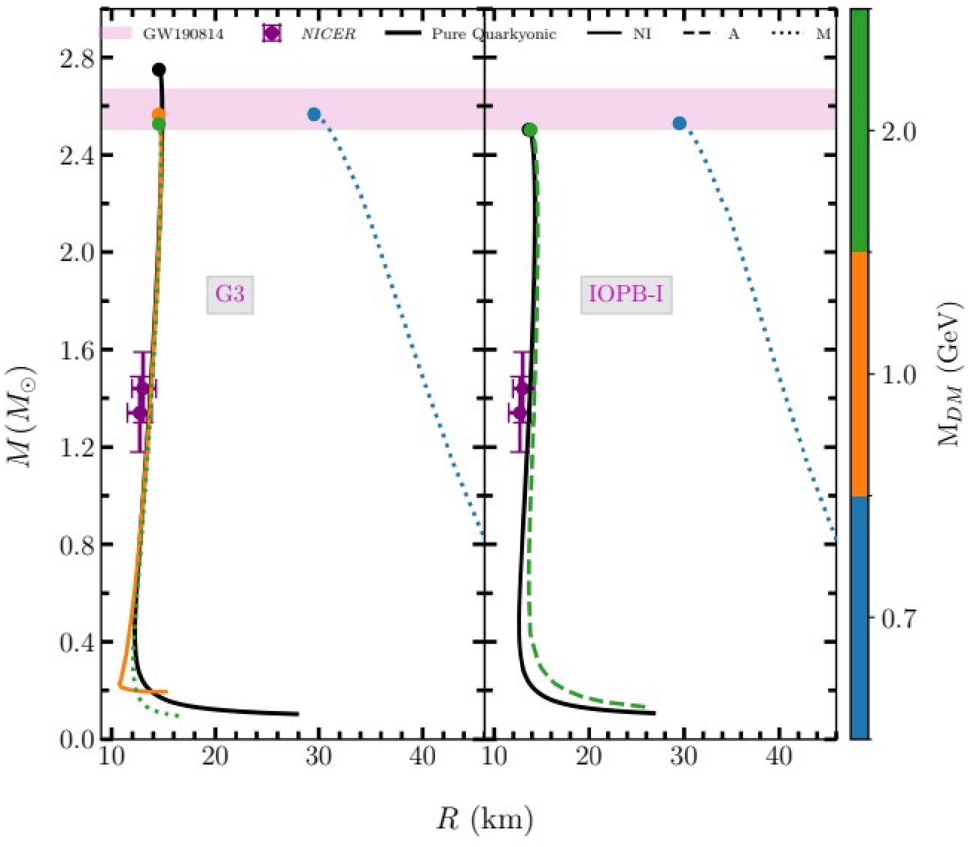
M$\rightarrow$ Mixed (C_{DV}=10 GeV^{-1}, C_{DS}=4 GeV^{-1})

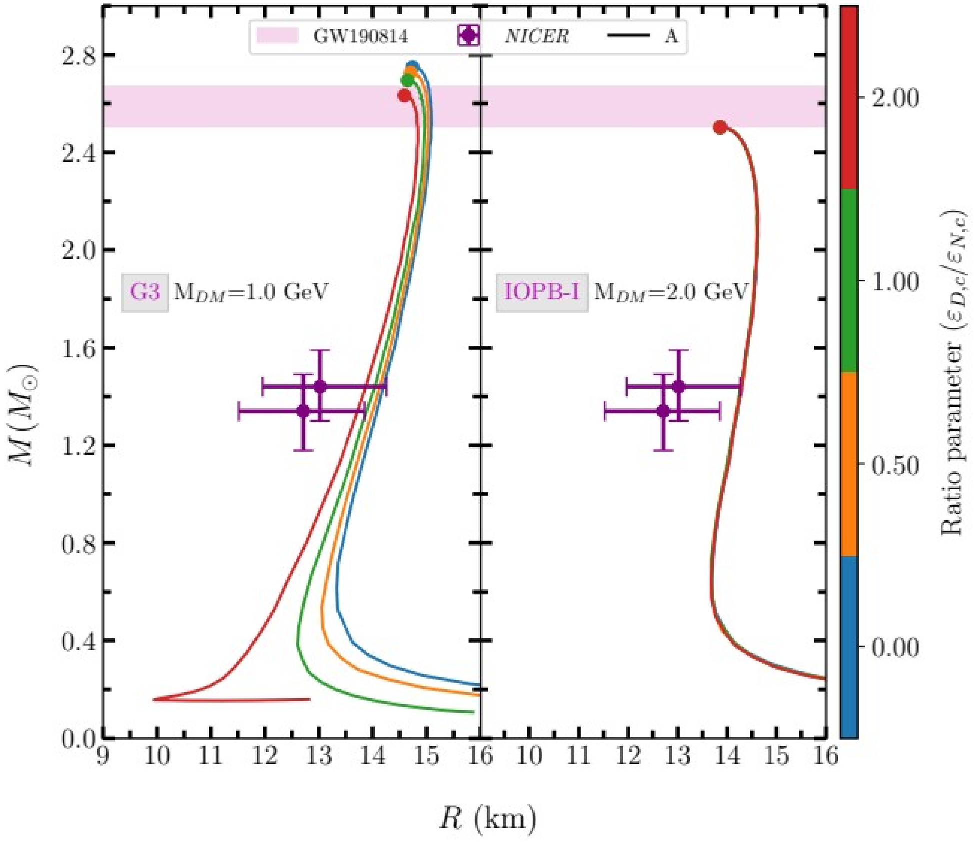
NI$\rightarrow$ No interaction (C_{DV}=0, C_{DS}=0)

A$\rightarrow$ Attraction (C_{DV}=0, C_{DS}=4 GeV^{-1})

Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

Numerical Results: M-R





Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

Numerical Results: Λ

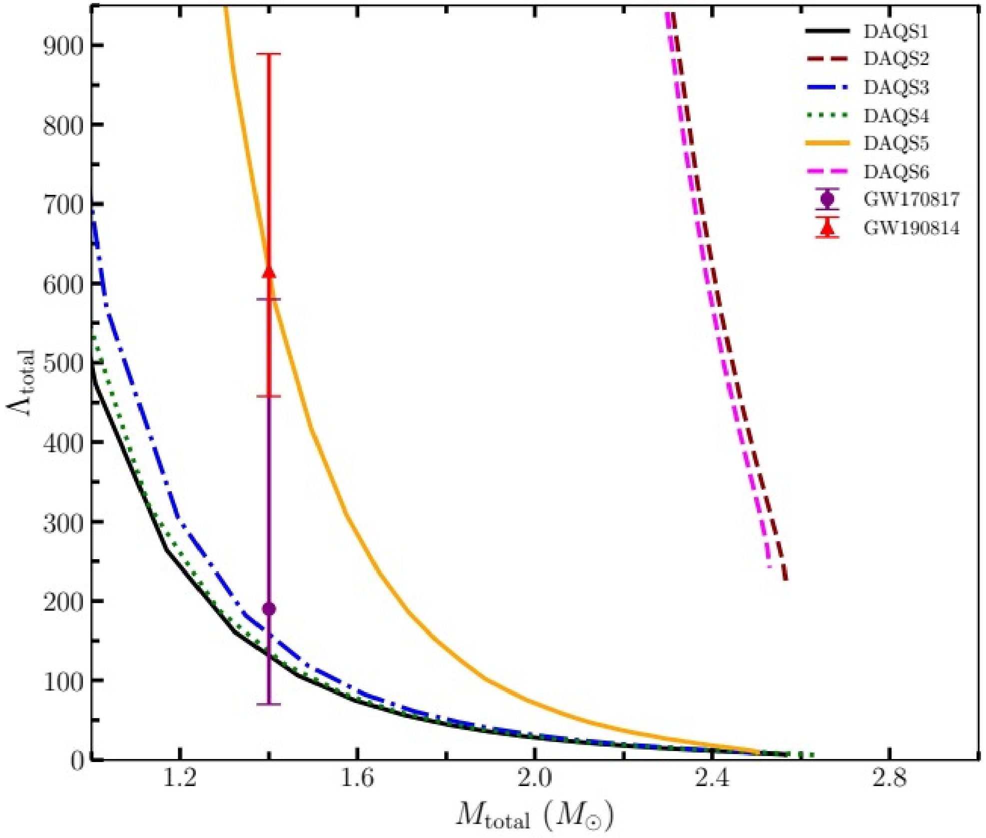


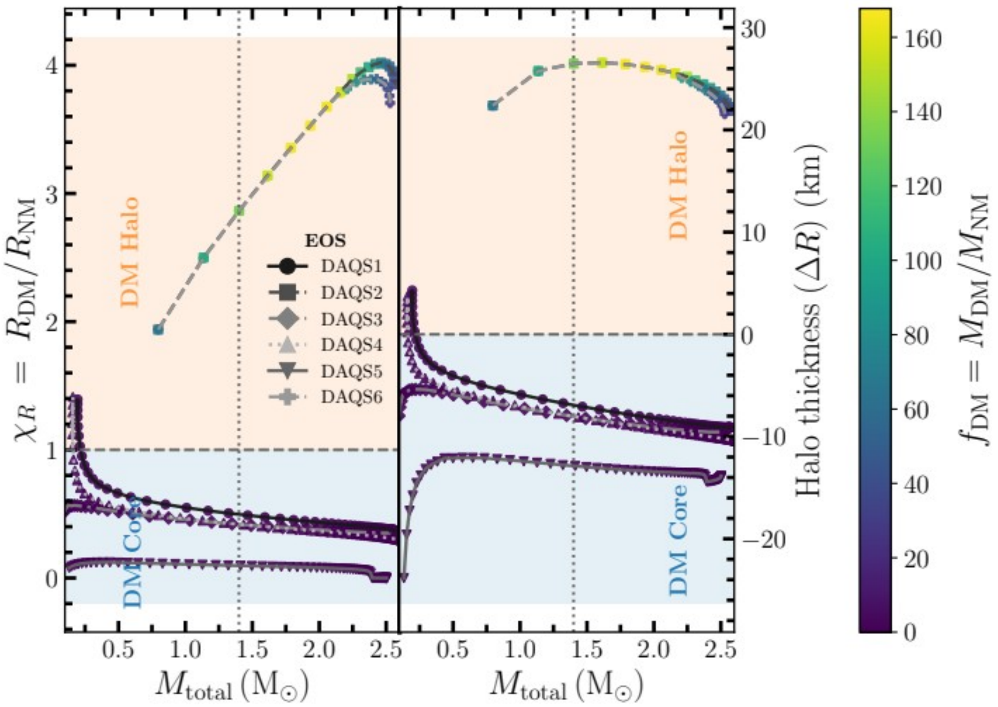
Table 1: EOS characteristics such as DM particle mass, interaction type, and ratio parameter $\epsilon_{D,c}/\epsilon_{N,c}$ are listed for the six DAQS configurations consistent with the GW190814 secondary mass range.

Star(s)	EOS	$M_{\rm DM}$ (GeV)	DM Interaction Type	Ratio
DAQS1	G3	1.0	No Interaction	1.0
DAQS2	G3	0.7	Mixed (Attr.+Repl.)	1.0
DAQS3	G3	2.0	Mixed (Attr.+Repl.)	1.0
DAQS4	G3	1.0	Attractive	2.0
DAQS5	IOPB-I	2.0	Attractive	1.0
DAQS6	IOPB-I	0.7	Mixed (Attr.+Repl.)	1.0

- **DAQS2, 6: nearly flat Λ–M curves → indicate DM halos**
- **Other DAQS sets agree with observed tidal deformability**
- **Confirms observational viability of DM-admixed quarkyonic stars**

Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

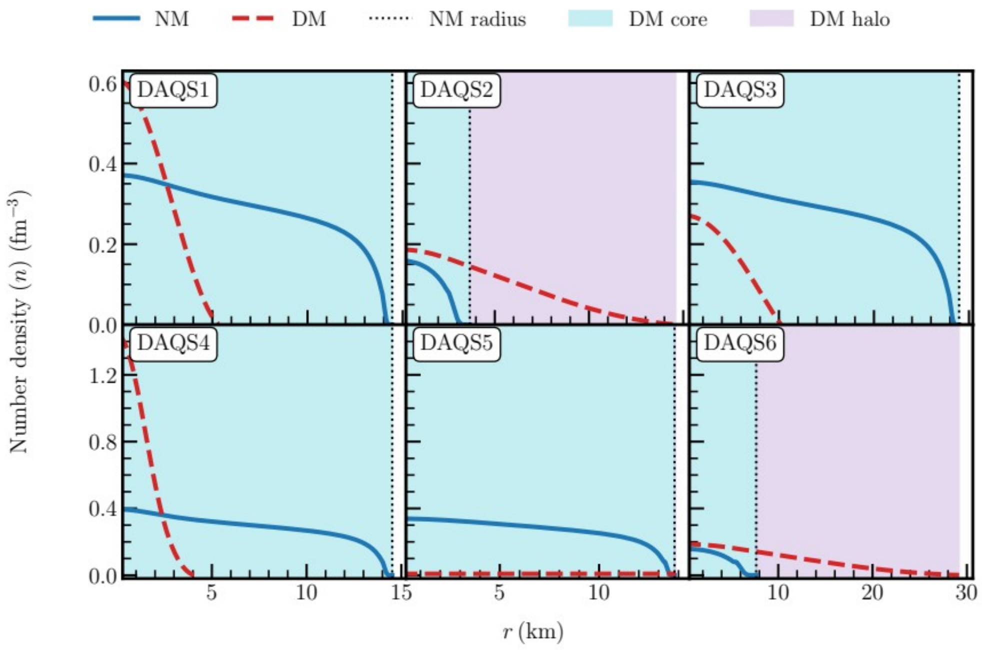
Numerical Results: Internal Morphology



- **Morphology indicators: χR = R_{DM}/R_{NM} and ΔR = $R_{DM} - R_{NM}$**
- **χR < 1: DM core; χR > 1: DM halo**
- **DAQS2, 6: strong DM halos; DAQS3, 5: compact DM cores**
- **DAQS1, 4: transition from halo → core with increasing mass**
- **DM fraction f_{DM} increases for halo-dominated stars**

Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

Numerical Results: Density Profiles



- **Plots show number-density profiles of NM (red) and DM (blue)**
- **DAQS2 & 6: DM extends beyond NM surface → thick halos**
- **DAQS1, 3, 4, 5: DM concentrated near center → compact cores**
- **DAQS4: strongest DM-core case ($n_{DM} \approx 1.4\ \mathrm{fm}^{-3}$)**
- **Density profiles directly support morphology classification from χR & ΔR**

Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).

Summary

- Six DAQS configurations constrained by GW190814 secondary mass
- Both core-dominated and halo-dominated stars can explain 2.5–2.6 $M_\odot$ objects
- Halo cases (DAQS2, 6): large Λ, extended DM distribution
- Core cases (DAQS1, 3, 4, 5): compact, observationally consistent
- Suggests GW190814 secondary may be either a DM core or DM halo quarkyonic star

Jeet et al, arXiv:2509.06684 [astro-ph.HE], (2025).


thank you
danke
gracias
obrigado
bedankt
dziękuję
sukriya
kop khun krap
go raibh maith agat
teşekkür ederim
mochchakkeram
eskerrik asko
terima kasih
dakujem
ngiyabonga
dank je
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