Neutron Stars as Particle Detectors: Probing the Nature of Dark Matter

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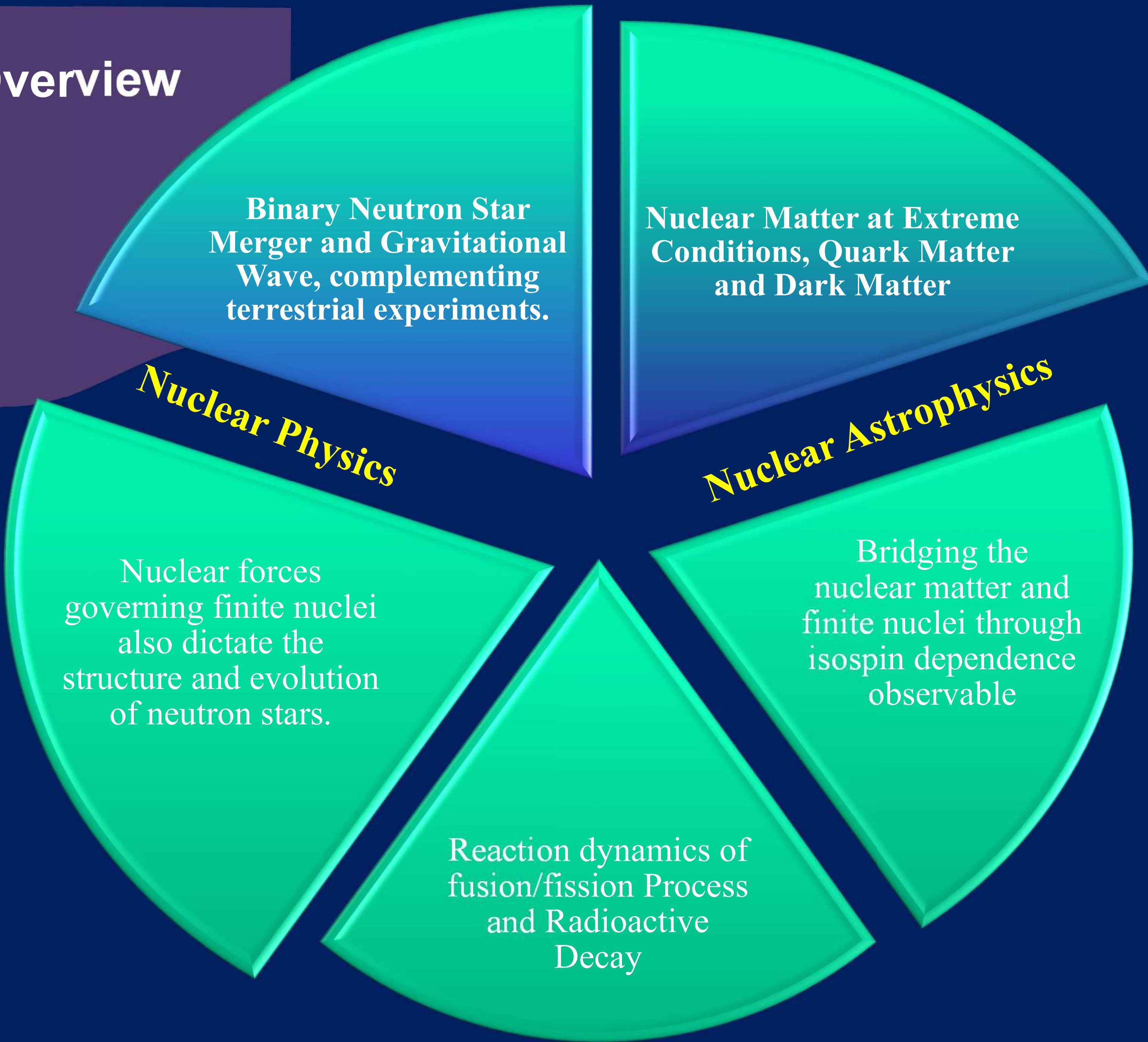
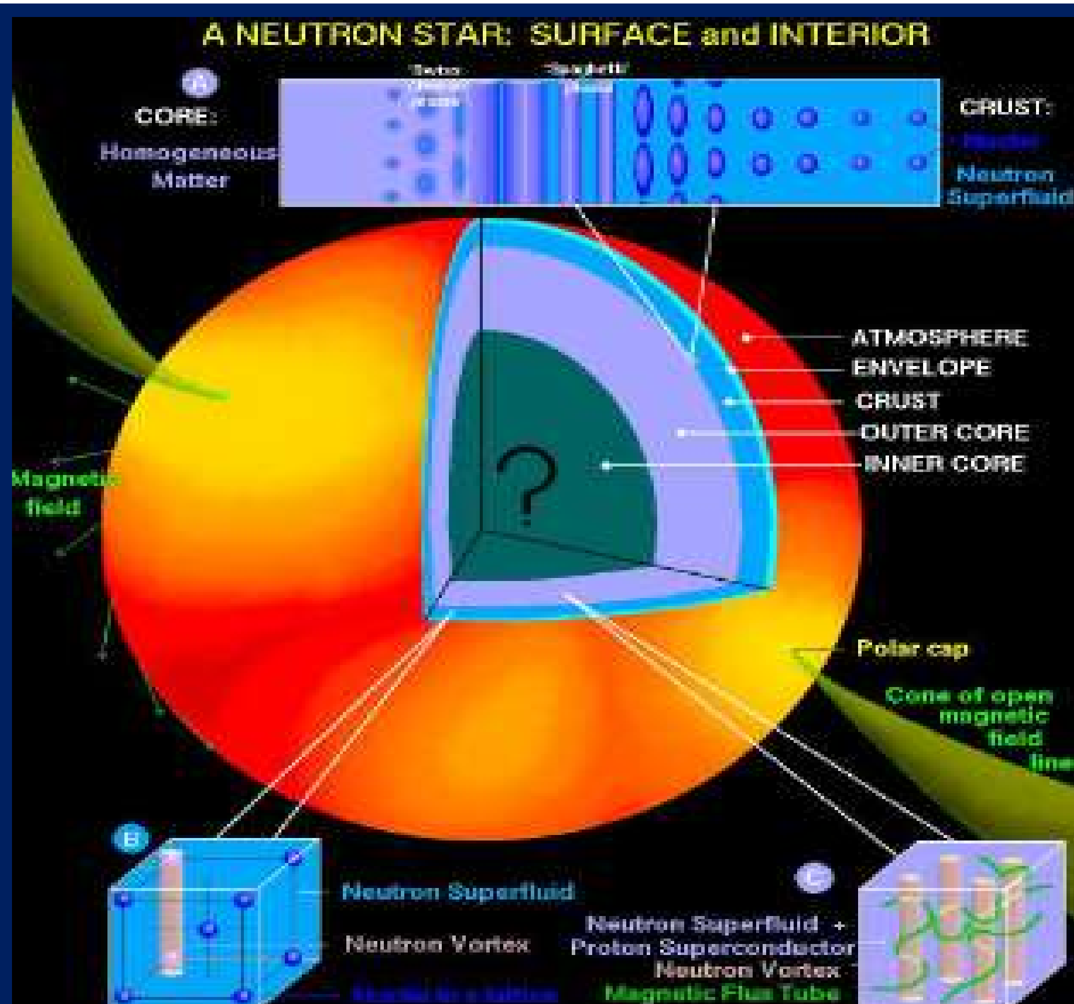
Overview



Binary Neutron Star Merger and Gravitational Wave, complementing terrestrial experiments.
Nuclear Matter at Extreme Conditions, Quark Matter and Dark Matter
Nuclear Physics
Nuclear Astrophysics
Nuclear forces governing finite nuclei also dictate the structure and evolution of neutron stars.
Bridging the nuclear matter and finite nuclei through isospin dependence observable
Reaction dynamics of fusion/fission Process and Radioactive Decay

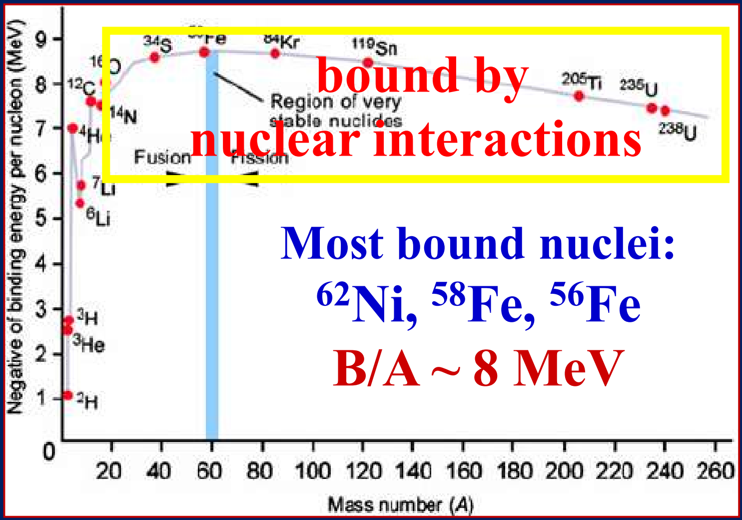
OUTLINE

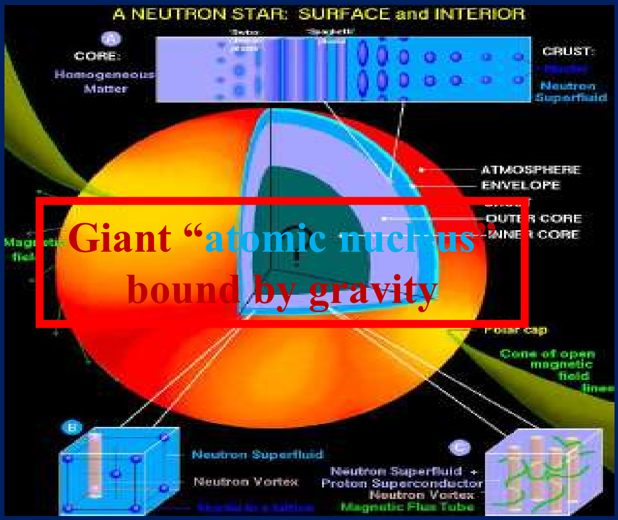


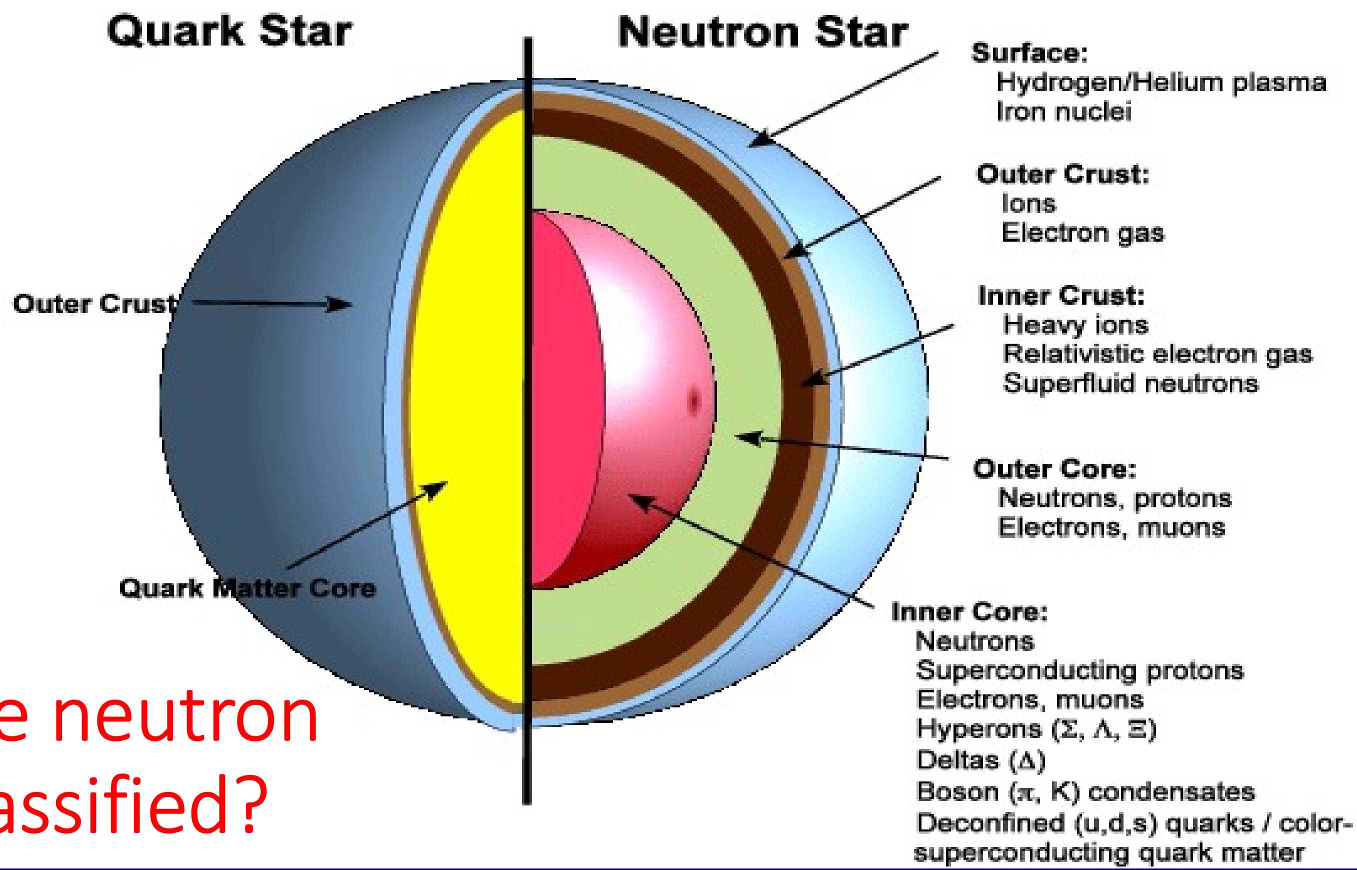
- **Observational Constraints for Dense Matter**
- **Dark Matter admixed Hybrid Star**
- **Nature of Dark Matter (DM) — Dirac or Majorana (Unsolved)**
- **Observable quantities and Correlations**

Atomic Nuclei ~ Neutron Star

Target system	Finite Nuclei	Neutron-Rich matter (crust/core)
Density range	$\sim \rho_0$	10^{-4} - 10 ρ_0
Asymmetry	Small δ	Large $\delta \sim 0.9$
Electrons/Muons	Ignored	Included (beta equilibrium)
Geometry	Spherical Nuclei	Pasta phases (slabs, rods, etc.)
Dealing with	Mass formula, Models	Crust modeling, EoS, TOV solution







How are neutron stars classified?

Classified into different types based on their characteristics, such as:

- **Magnetars:** Neutron stars that have extremely strong magnetic fields, up to 10^{11} tesla, which can cause violent bursts of gamma rays and X-rays, as well as starquakes and flares on their surfaces.
- **Quarkonic stars:** Hypothetical neutron stars that have such high density that their **neutrons break down into quarks**, the fundamental particles of matter, forming a strange state of matter called quark-gluon plasma.
- **Dark Matter Admix Neutron Stars:** Hypothetical neutron Star that have such **high density and gravity**, forming a star of nuclear, quarkonic and dark matter

Nucleon Stars

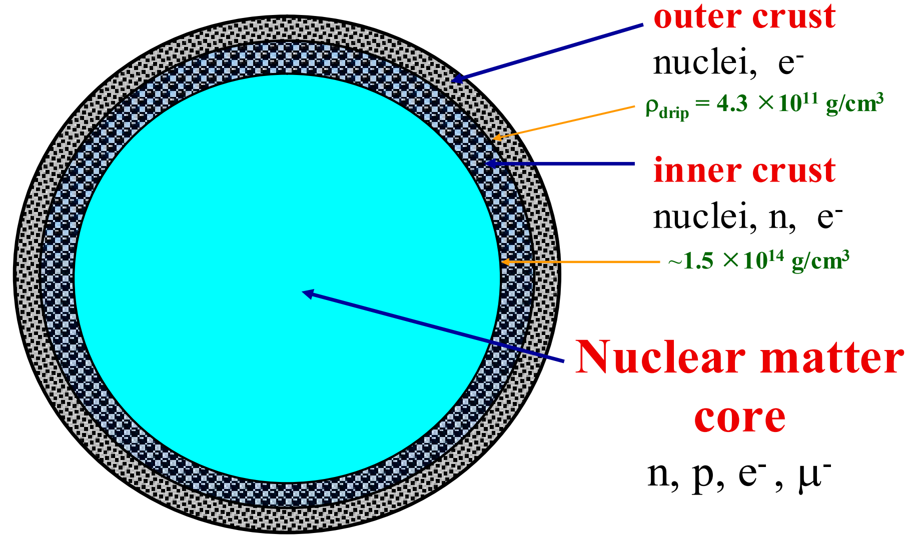
β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$\mu_e \geq m_\mu$$

$$e^- \rightarrow \mu^- + \nu_e + \bar{\nu}_\mu$$



Equilibrium with respect to the weak interaction processes

$$\mu_n - \mu_p = \mu_e$$

$$\mu_\mu = \mu_e$$

neutrino-free matter

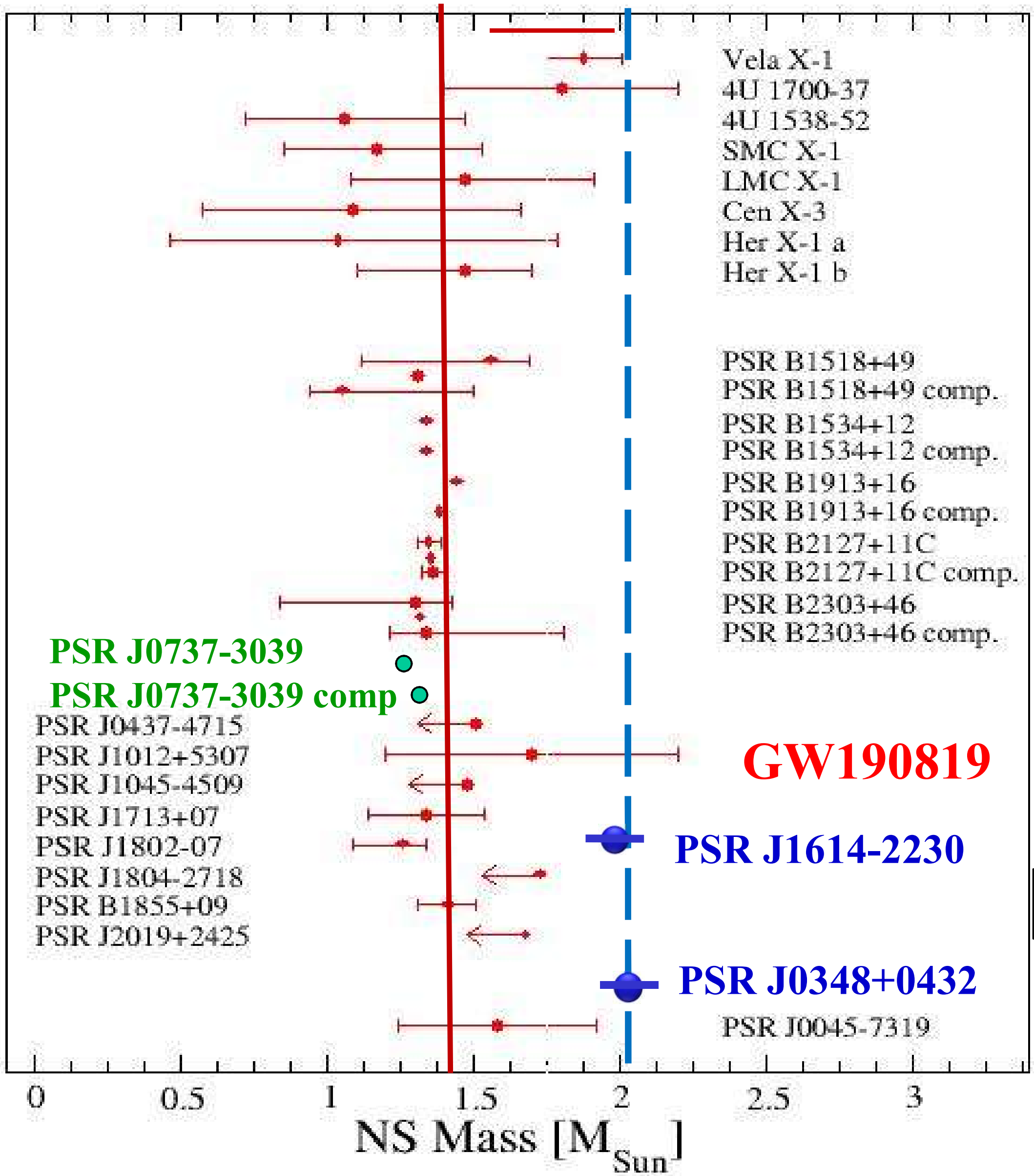
$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

Charge neutrality

$$n_p = n_e + n_\mu$$

To be solved for any given value of the total baryon number density ρ_B

Measured Neutron Star Masses



$M_{max} \geq M_{measured}$

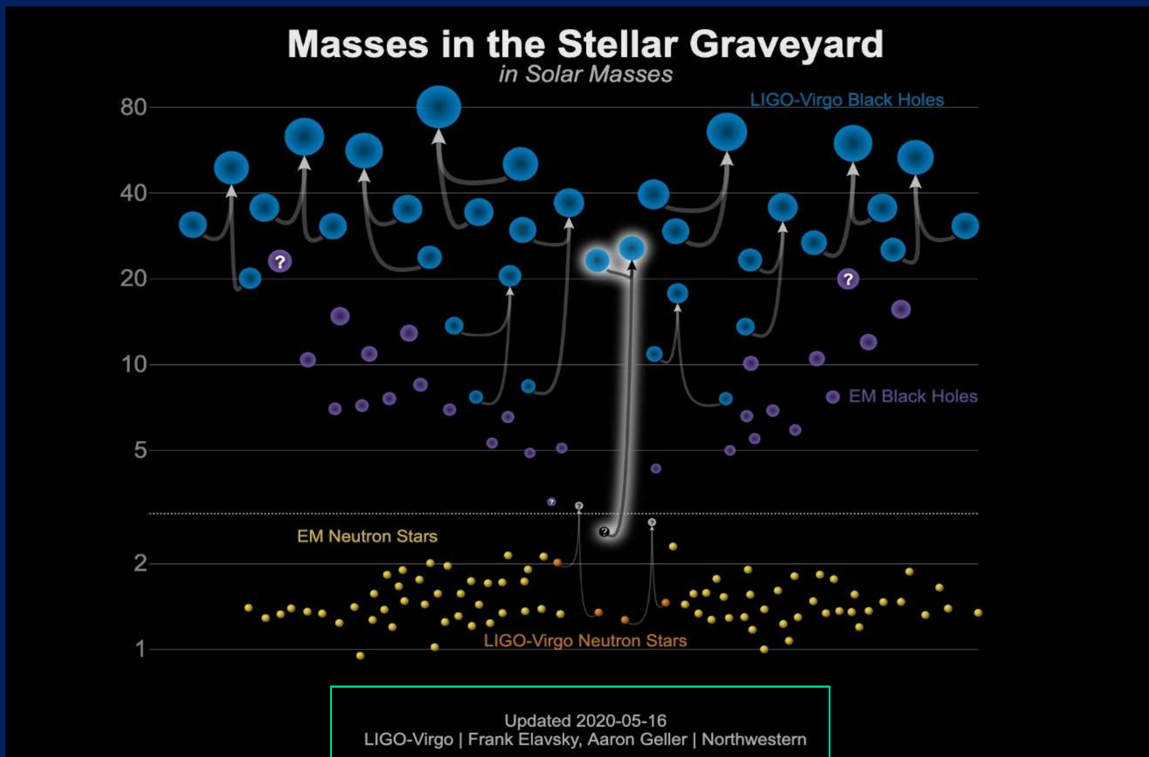
$M_{max} \geq 2\ M_{\odot}$

Very stringent constraint on the EOS

Feryal Özel *et al* (2010) *ApJL* 724 L199

Lynch, R. S et al (2013) *ApJL* 81 L783

GW190814 Observation and Possible Predictions

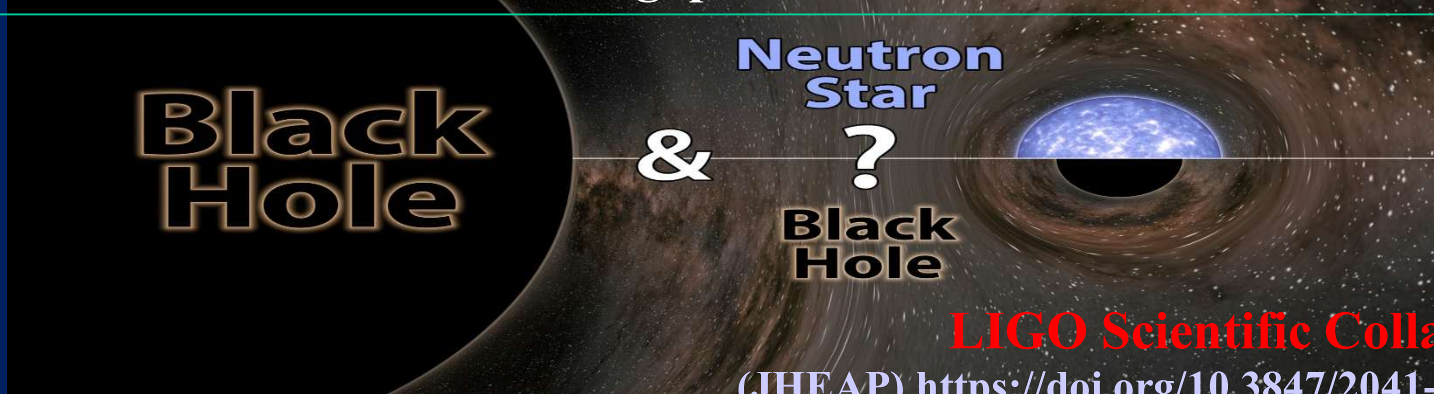


$M_{max} \geq M_{measured}$

$M_{max} \approx 2.6\ M_{\odot}$

Very stringent constraint on the EOS

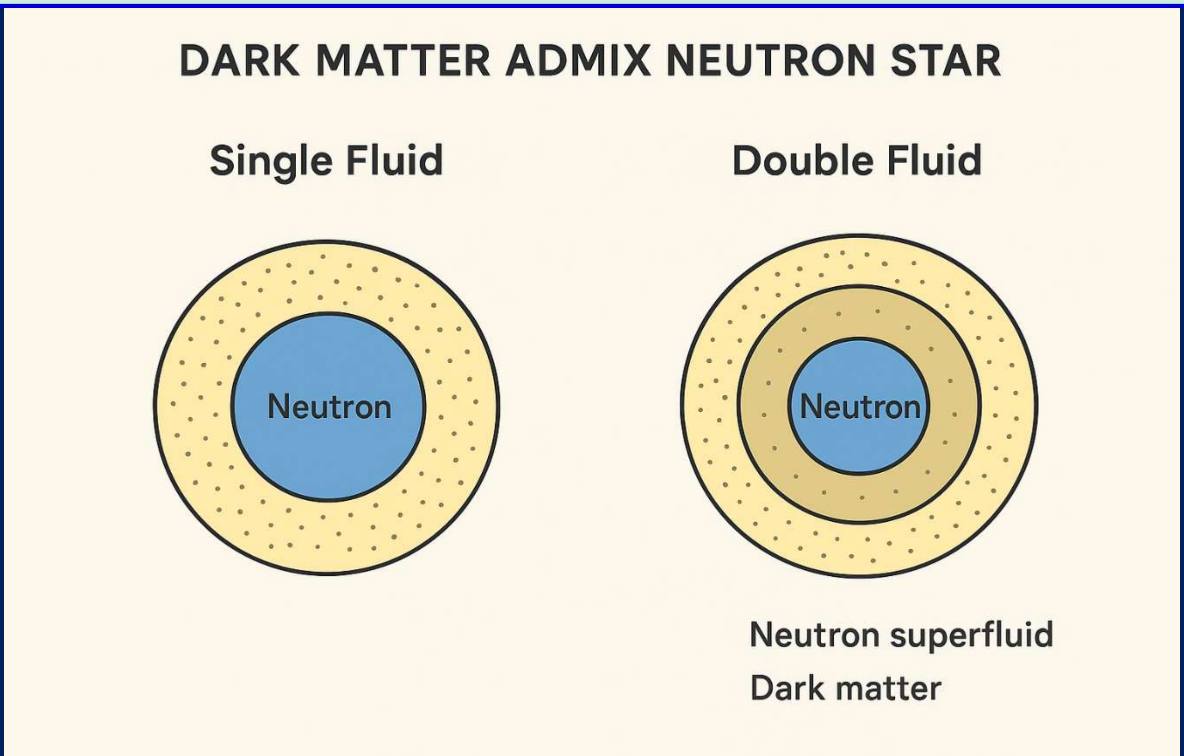
Object sits in the so-called "mass gap" between neutron stars and black holes



LIGO Scientific Collaboration

(JHEAP) https://doi.org/10.3847/2041-8213/ab960f

Where a Dark Matter Admix with a Neutron Star



Dark matter (DM) capture/admix mainly gravitationally,

And possibly weakly (if WIMPs exist)

Type of Dark Matter	Location in Neutron Star	Physical Behavior
Weakly Interacting Massive Particles (WIMPs)	Concentrated in the **core**	Thermalized and possibly form a small DM core
Bosonic DM (e.g. axion-like)	Can form a **Bose–Einstein condensate**	Quantum pressure can balance gravity
Self-interacting or asymmetric DM	May form a **co-existing fluid**	Creates a “double-fluid” structure

How to deal a Dark Matter Admix Neutron Star

Single-fluid approach:

The dark matter (DM) and baryonic (neutron) matter are treated as one combined fluid, they move together and share pressure and density relations.

Visible Matter + DM fully mixed

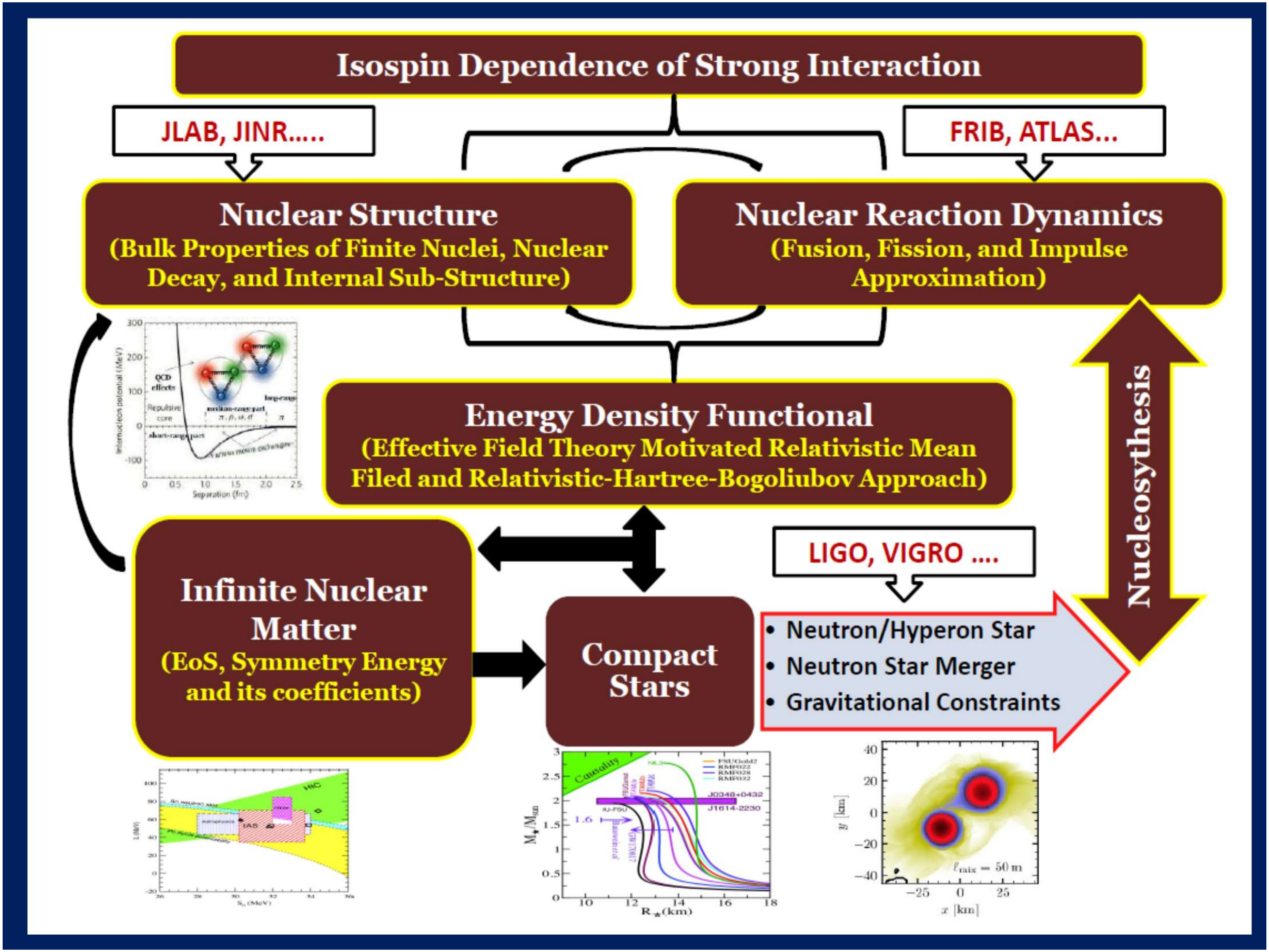
Double-fluid approach:

The DM and baryonic matter are treated as two separate fluids that interact only through gravity — each has its own density, pressure, and equation of state (EOS), and the total gravitational potential binds them.

Visible Matter and DM behave as two separate, gravitationally coupled fluids

Held mainly by gravity, not electromagnetic or strong forces

→ **Scalar (Higgs-like) Portal in RMF**

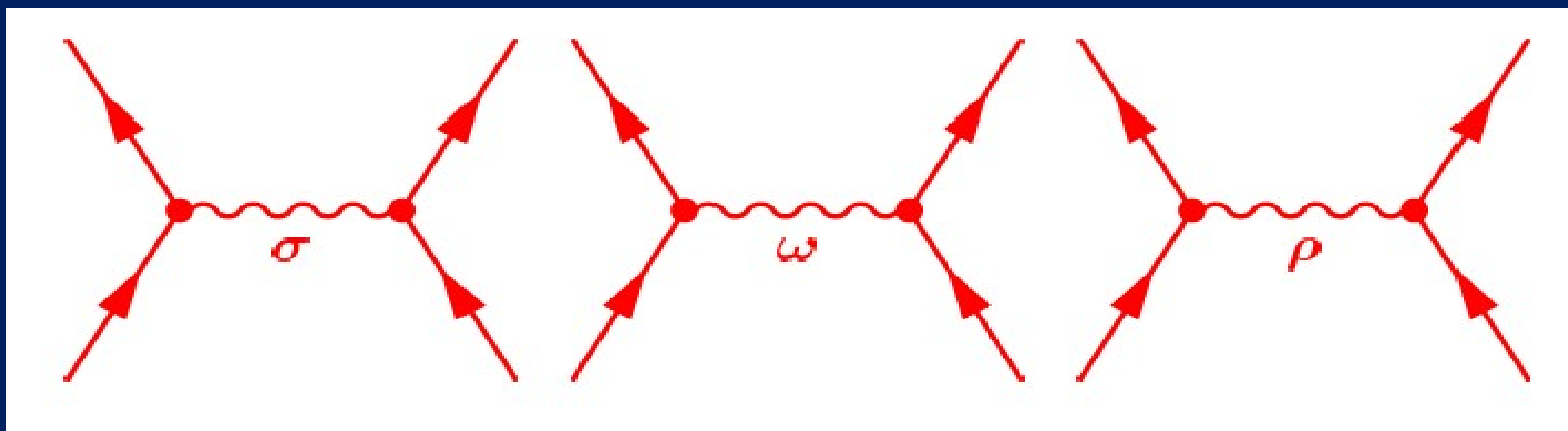


Isospin Dependence of Strong Interaction
JLAB, JINR.....
FRIB, ATLAS...
Nuclear Structure
(Bulk Properties of Finite Nuclei, Nuclear Decay, and Internal Sub-Structure)
Nuclear Reaction Dynamics
(Fusion, Fission, and Impulse Approximation)
Energy Density Functional
(Effective Field Theory Motivated Relativistic Mean Filed and Relativistic-Hartree-Bogoliubov Approach)
Nucleosynthesis
LIGO, VIGRO ....
Infinite Nuclear Matter
(EoS, Symmetry Energy and its coefficients)
Compact Stars
• Neutron/Hyperon Star
• Neutron Star Merger
• Gravitational Constraints

Relativistic mean field theory

i. Degrees of freedom for mesons and nucleon

ii. Dirac nucleons coupled to the exchange **mesons** and the **photon** field through an effective Lagrangian.



(J^{π} = 0^{+}) | (J^{π} = 1^{-}) | (J^{π} = 1^{-})

σ-meson: attractive scalar field

ω-meson: short-range repulsive field

ρ-meson: isovector field

Mathematically the modified Lagrangian,

$$\mathcal{L} = \mathcal{L}_{\mathcal{NM}} + \mathcal{L}_{\mathcal{QM}} + \mathcal{L}_{\mathcal{DM}}$$

JCAP: https://doi.org/10.1088/1475-7516/2025/08/003

Dark Matter Part

$$\mathcal{L}_{\rm DM} = \bar{\chi}\left[i\gamma^\mu\partial_\mu - M_\chi + yh\right]\chi + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}M_h^2 h^2 + f\frac{M_{\rm nucl./\mathit{u}/\mathit{d}}}{v}\bar{\psi}h\psi.$$

Scalar (Higgs-like) Portal in RMF

Energy Density,

$$\mathcal{E}_{\rm DM} = \frac{g_{DM}^{\rm deg}}{(2\pi)^3}\int_0^{k_f^{\rm DM}} d^3k\sqrt{k^2+(M_\chi^\star)^2} + \frac{1}{2}M_h^2 h_0^2$$

Pressure,

$$P_{\rm DM} = \frac{g_{DM}^{\rm deg}}{3(2\pi)^3}\int_0^{k_f^{\rm DM}} \frac{d^3k k^2}{\sqrt{k^2+(M_\chi^\star)^2}} - \frac{1}{2}M_h^2 h_0^2.$$

Dirac vs. Majorana Dark Matter Imprints on Neutron Star Observables

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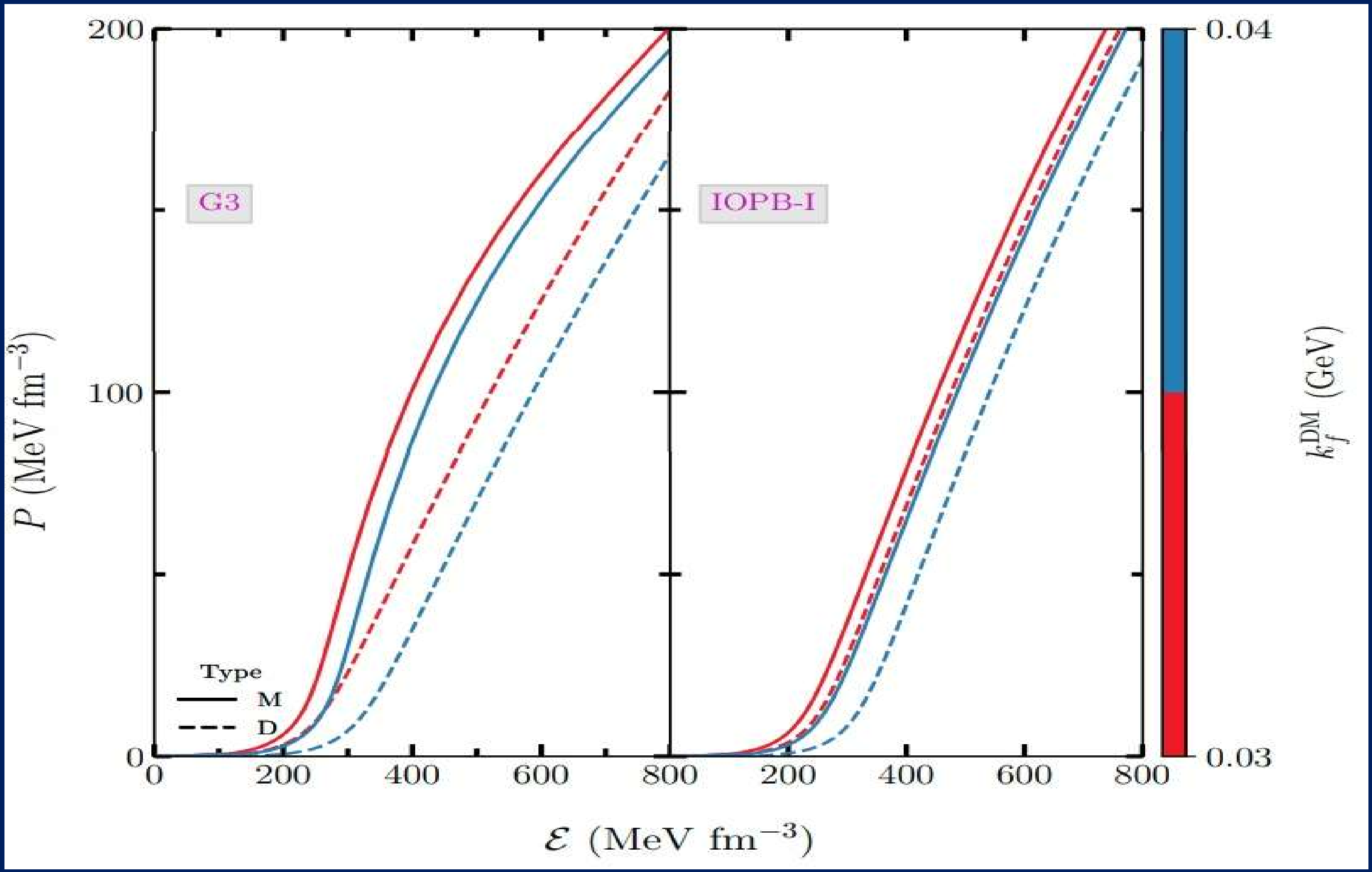
The microscopic nature of dark matter (DM), whether it is a Dirac or Majorana fermion—remains a central open question in particle physics and cosmology. Compact stars, particularly neutron stars (NSs), offer unique astrophysical laboratories for probing such fundamental properties under extreme densities. The presence of DM admixed with nuclear matter can modify the equation of state (EoS), thereby affecting observable quantities such as the mass–radius (M–R) relation and tidal deformability. In this work, we investigate how the intrinsic particle nature of fermionic DM influences neutron star structure. Within a relativistic mean-field (RMF) framework extended by a scalar (Higgs-like) portal coupling between DM and nucleons, we construct self-consistent EoSs for both Dirac and Majorana cases and solve the Tolman–Oppenheimer–Volkoff equations to obtain stellar configurations. Owing to the difference in internal degrees of freedom, Dirac DM ($g = 4$) generally softens the EoS more strongly than Majorana DM ($g = 2$), leading to smaller radii and lower maximum masses. We identify the parameter space consistent with current NICER and gravitational-wave constraints, highlighting the potential of compact-star observations to discriminate between Dirac and Majorana dark matter.

Submitted to Physics Letter B

Total Energy and Pressure Density,

$$\mathcal{E} = \mathcal{E}_{\rm BM} + \mathcal{E}_{\rm QM} + \mathcal{E}_{\rm DM},$$

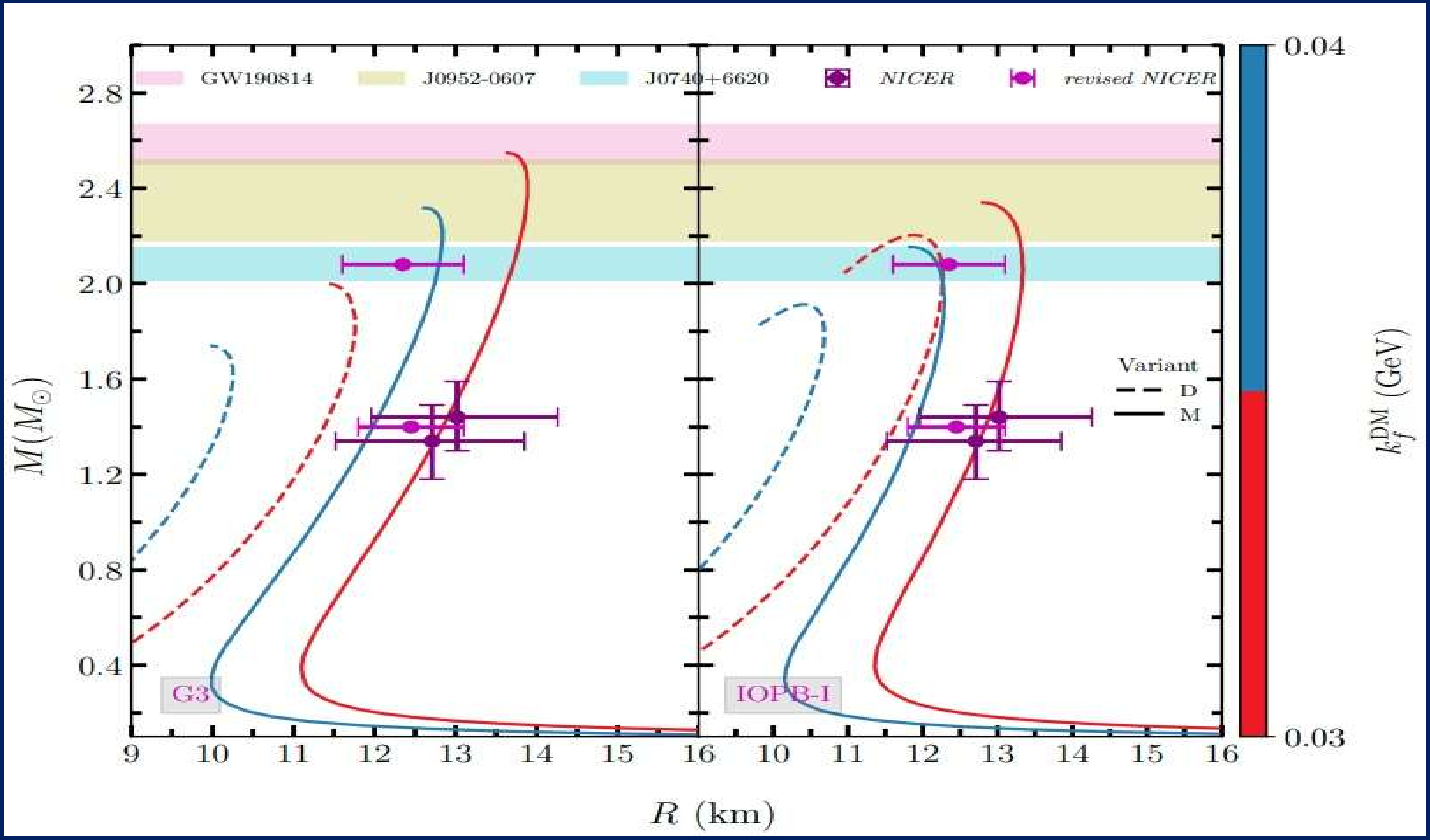
$$P = P_{\rm BM} + P_{\rm QM} + P_{\rm DM}.$$



Equation of state for dark matter–admixed quarkonic star
Transition Density $n_t = 0.3 fm^{-3}$, QCD confinement scale Λcs = 800MeV

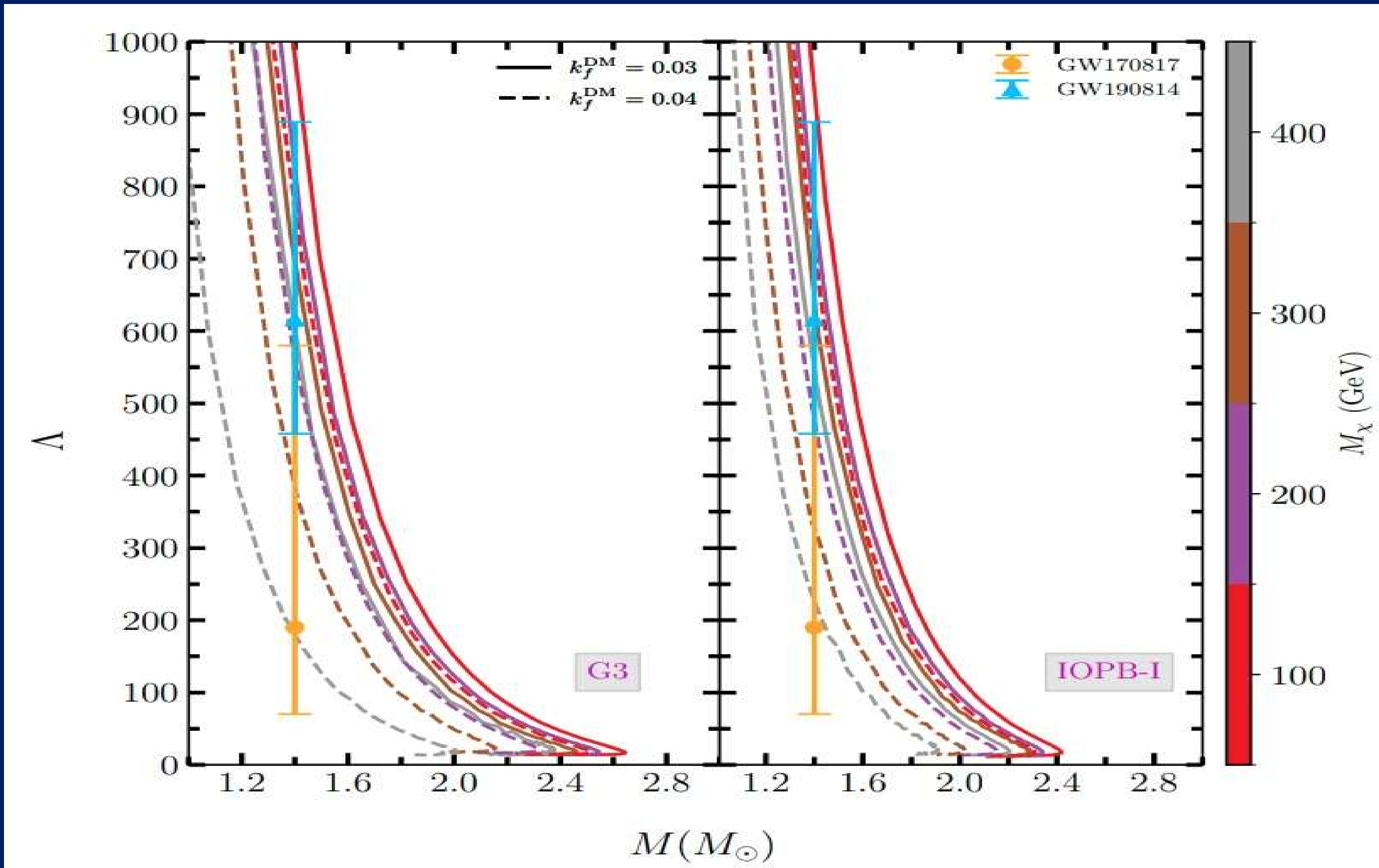
Solve in TOV

$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\frac{\left[\varepsilon(r)+P(r)\right]\left[M(r)+4\pi r^3 P(r)\right]}{1-2GM(r)/r},$$
$$\frac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r),$$

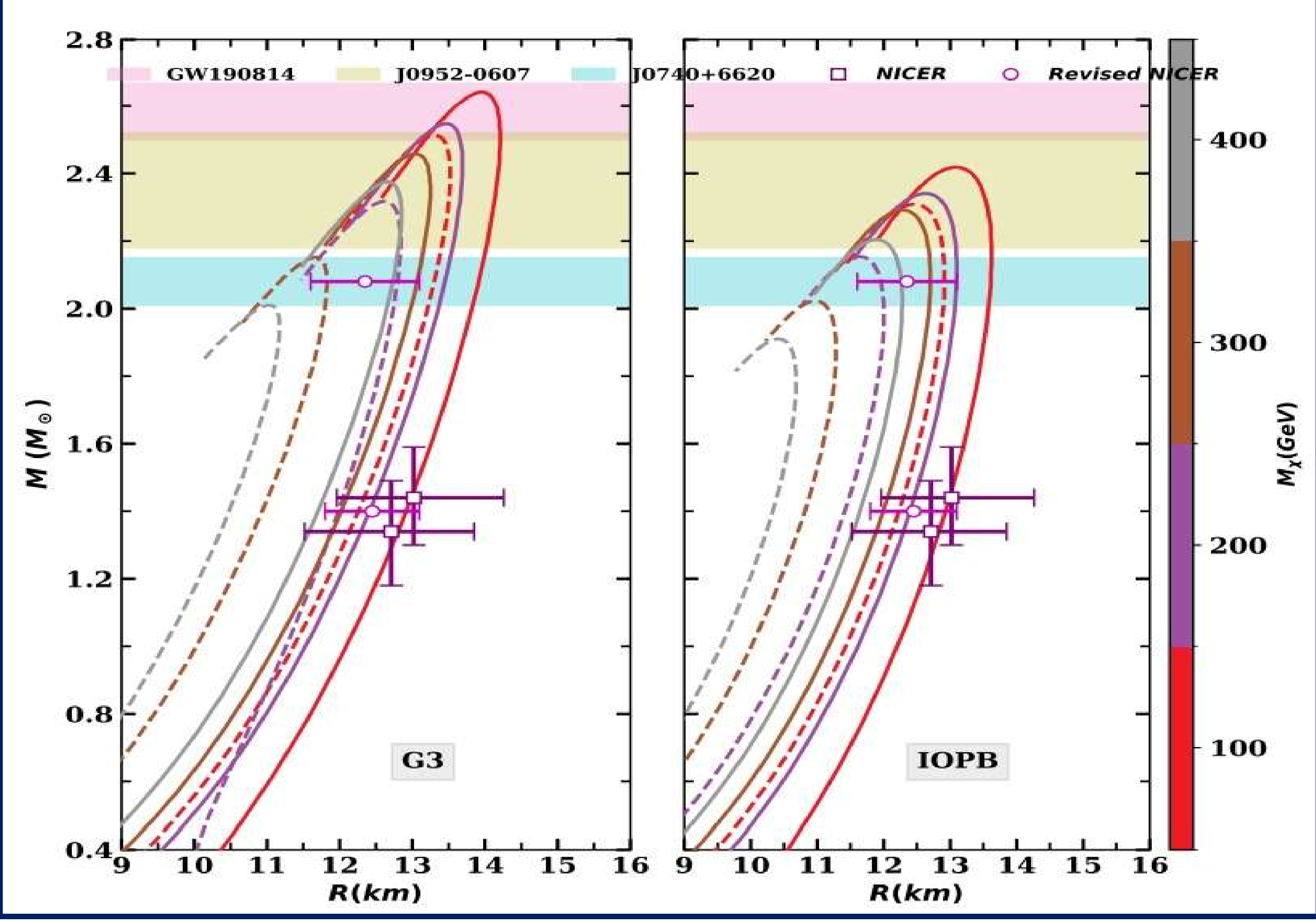


M-R relations for the EoSs

Λ - M relations for the majorona type EoSs having n_t = 0.3fm^{-3}, QCD confinement scale Λ_{cs} = 800MeV DM Fermi momentum k_{DM} = 0.03 GeV (solid) and 0.04 GeV (dashed) DM masses M_χ = 100,200,300,400 GeV



M-R relations for the majorona type EoSs
n_t = 0.3 fm^{-3}, QCD confinement scale Λ_{cs} = 800MeV and
DM Fermi momentum $k_{DMb\,f}$ = 0.03 GeV (solid) and 0.04 GeV
DM masses M_χ = 100,200,300,400 GeV



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