Neutron Star in the presence of Dark Matter

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"Gravitational waves: a new messenger to explore the universe"
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What is Dark Matter ?

- Dark matter:- ~85% of the matter, ~27% of its total mass-energy density.
- Dark matter interaction:- no interaction with EM field, absorb, reflect or emit EM radiation
- Dark matter particles:- WIMPs, FIMPs, Axions etc.
- WIMPs:- thermal relics, most abundant
- Experimental set up :- XENON100, CDMS, PANDA, CRESST, DAMA etc.
- Observational evidences:-
    - Galaxy rotation curves
    - Velocity dispersions
    - Galaxy clusters
    - Gravitational lensing
    - Bullet cluster

Motivation

- There is possibility of accretion of dark matter (DM) inside the compact objects like NS, which may affects some properties of the NSs.
- Type of DM:- non-annihilating DM (WIMP)
- Formalism: RMF, SHF, DBHF etc.
- Predicted NS properties by RMF : X-ray, GW170817 and NICER data.
- RMF parameter set: NL3, G3 and IOPB-I
- We fixed the DM percentage.

Relativistic mean-field Model (RMF)

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

nucleons

σ-meson

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

ω^4

Higher order of σ

ω-meson

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

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

$\sigma - \rho^2$

ρ-meson

$\omega^2 - \rho^2$

δ-meson

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

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

RMF Model

No of coupling constants

NL3: 5 G3: 11 IOPB-I: 7

Parameter	NL3	G3	IOPB-I
$m_\sigma/M_{\text{nucl.}}$	0.541	0.559	0.533
$m_\omega/M_{\text{nucl.}}$	0.833	0.832	0.833
$m_\rho/M_{\text{nucl.}}$	0.812	0.820	0.812
$m_\delta/M_{\text{nucl.}}$	0.0	1.043	0.0
$g_\sigma/4\pi$	0.813	0.782	0.827
$g_\omega/4\pi$	1.024	0.923	1.062
$g_\rho/4\pi$	0.712	0.962	0.885
$g_\delta/4\pi$	0.0	0.160	0.0
k_3	1.465	2.606	1.496
k_4	−5.688	1.694	−2.932
ζ_0	0.0	1.010	3.103
η_1	0.0	0.424	0.0
η_2	0.0	0.114	0.0
η_ρ	0.0	0.645	0.0
Λ_ω	0.0	0.038	0.024

$$\mathscr{E}_{NM} = \frac{\gamma}{(2\pi)^3}\sum_{j=p,n}\int_0^{k_j} d^3k E_j^\star(k_j) + \rho_b W + \frac{1}{2}\rho_3 R - \frac{1}{4!}\frac{\zeta_0 W^4}{g_\omega^2}$$
$$+\frac{m_s^2\Phi^2}{g_s^2}\left(\frac{1}{2}+\frac{\kappa_3}{3!}\frac{\Phi}{M_{nucl.}}+\frac{\kappa_4}{4!}\frac{\Phi^2}{M_{nucl.}^2}\right) - \Lambda_\omega(R^2\times W^2)$$
$$-\frac{1}{2}m_\omega^2\frac{W^2}{g_\omega^2}\left(1+\eta_1\frac{\Phi}{M_{nucl.}}+\frac{\eta_2}{2}\frac{\Phi^2}{M_{nucl.}^2}\right) - \frac{1}{2}\left(1+\frac{\eta_\rho\Phi}{M_{nucl.}}\right)\times\frac{m_\rho^2}{g_\rho^2}R^2$$
$$+\frac{1}{2}\frac{m_\delta^2}{g_\delta^2}D^2,$$

$$P_{NM} = \frac{\gamma}{3(2\pi)^3}\sum_{j=p,n}\int_0^{k_j} d^3k\frac{k^2}{E_j^\star(k_j)} + \frac{1}{4!}\frac{\zeta_0 W^4}{g_\omega^2} + \Lambda_\omega(R^2\times W^2)$$
$$-\frac{m_s^2\Phi^2}{g_s^2}\left(\frac{1}{2}+\frac{\kappa_3}{3!}\frac{\Phi}{M_{nucl.}}+\frac{\kappa_4}{4!}\frac{\Phi^2}{M_{nucl.}^2}\right) + \frac{1}{2}m_\omega^2\frac{W^2}{g_\omega^2}\left(1+\eta_1\frac{\Phi}{M_{nucl.}}+\frac{\eta_2}{2}\frac{\Phi^2}{M_{nucl.}^2}\right)$$
$$+\frac{1}{2}\left(1+\frac{\eta_\rho\Phi}{M_{nucl.}}\right)\frac{m_\rho^2}{g_\rho^2}R^2 - \frac{1}{2}\frac{m_\delta^2}{g_\delta^2}D^2.$$

$$E_j^\star(k_j) = \sqrt{k_j^2 + M_*^2}$$

Neutron star equation of state

- Inside NS, the neutron decays to proton, electron and anti-neutrino called as β-equilibrium process.

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

- The inverse β-equilibrium process is also happening to maintain both β-equilibrium and charge neutrality which stable the neutron star.

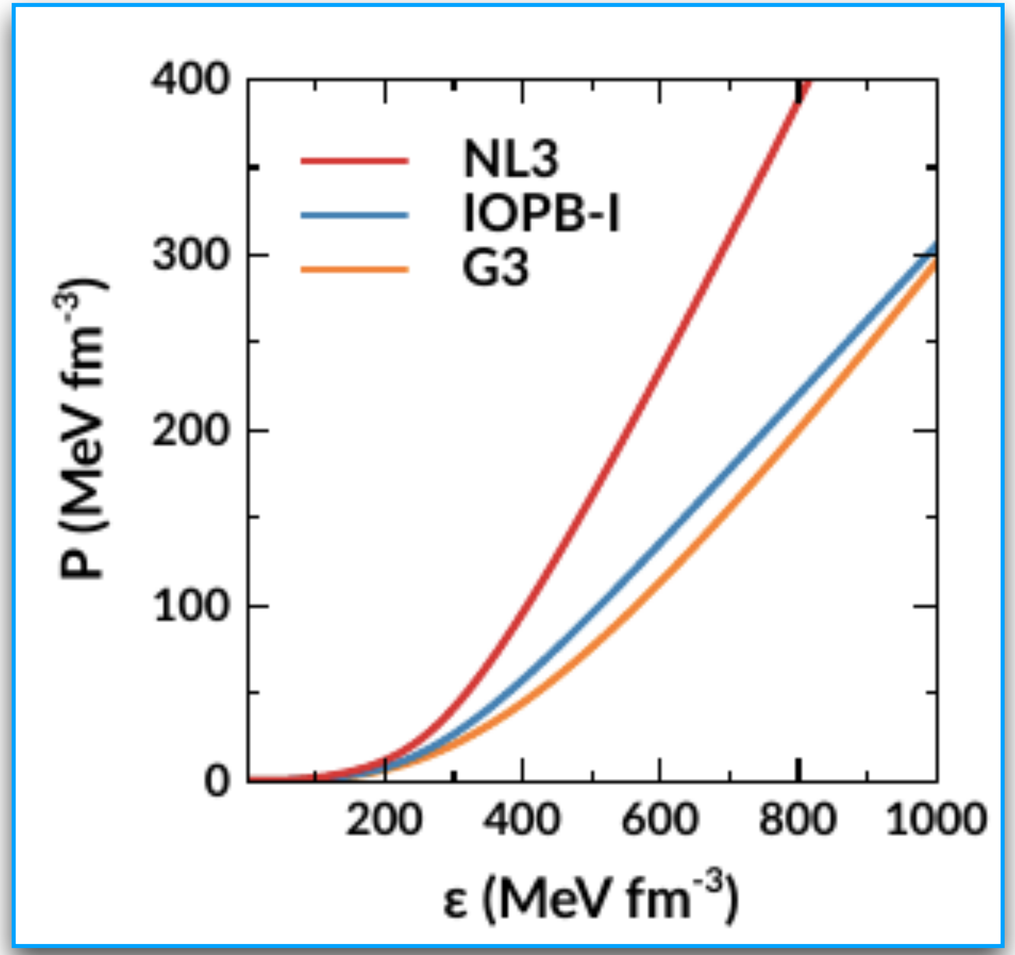
$$p + e^- \rightarrow n + \nu_e$$

- The total equation of state is the addition of both nucleons and leptons.

$$\mathscr{E} = \mathscr{E}_{NM} + \mathscr{E}_l, P = P_{NM} + P_l,$$

where $\mathscr{E}_l = \sum_{l=e,\mu} \frac{2}{(2\pi)^3} \int_0^{k_l} d^3k \sqrt{k^2 + m_l^2},$

$$P_l = \sum_{l=e,\mu} \frac{2}{3(2\pi)^3} \int_0^{k_l} \frac{d^3k\ k^2}{\sqrt{k^2 + m_l^2}}.$$



Dark Matter inside the Neutron Star

- Dark matter (DM) particles are accreted inside the NS due to its high gravitational potential and enormous baryon density.
- Neutralino as DM candidate which is interacting with nucleons via standard model Higgs.
- The DM density is 1/3 rd of the total baryon density.
- All the coupling constants are constraints using both direct/indirect experiments and LHC searches.

$$\text{DM mass}, M_\chi = 200 \text{ GeV}$$
$$\text{DM} - \text{Higgs coupling}, y = 0.07$$
$$\text{Proton} - \text{Higgs form factor}, f = 0.35$$
$$\text{Mass of the Higgs}, M_h = 125 \text{ GeV}$$

MNRAS 495,4893(2020)
JCAP 01,007(2021)

$$\mathscr{L} = \mathscr{L}_{NS} + \bar{\chi}\left[i\gamma^\mu\partial_\mu - M_\chi + yh\right]\chi + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{2}M_h^2 h^2 + f\frac{M_{nucl.}}{v}\bar{\psi}h\psi,$$

$$\mathscr{E} = \mathscr{E}_{NS} + \frac{2}{(2\pi)^3}\int_0^{k_f^{DM}} d^3k\sqrt{k^2 + (M_\chi^\star)^2} + \frac{1}{2}M_h^2 h_0^2,$$

$$P = P_{NS} + \frac{2}{3(2\pi)^3}\int_0^{k_f^{DM}} \frac{d^3k\ k^2}{\sqrt{k^2 + (M_\chi^\star)^2}} - \frac{1}{2}M_h^2 h_0^2,$$

where k_f^{DM} is DM momentum.

$M_\chi^* = M_\chi - yh_0$

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EOS, M-R relation

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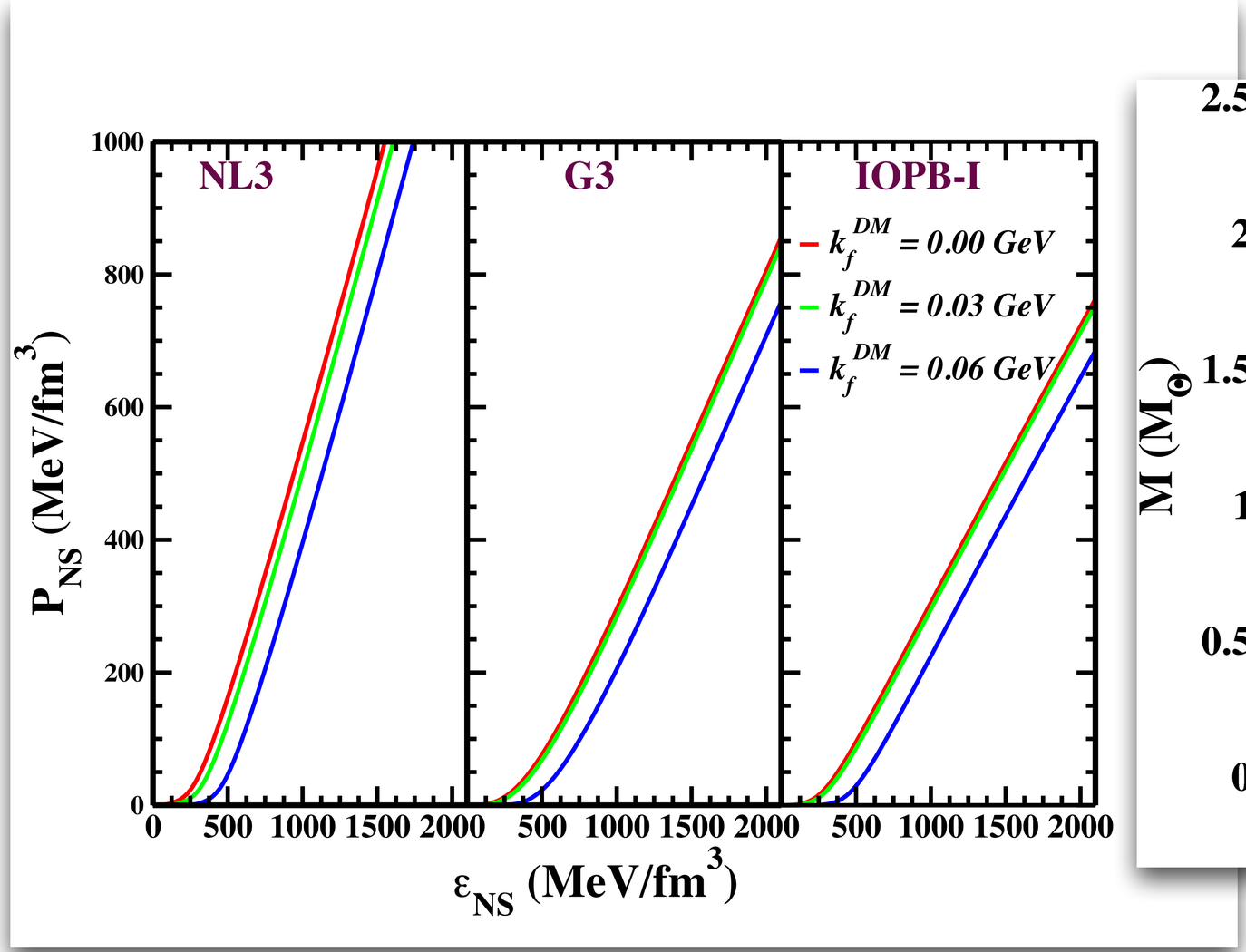
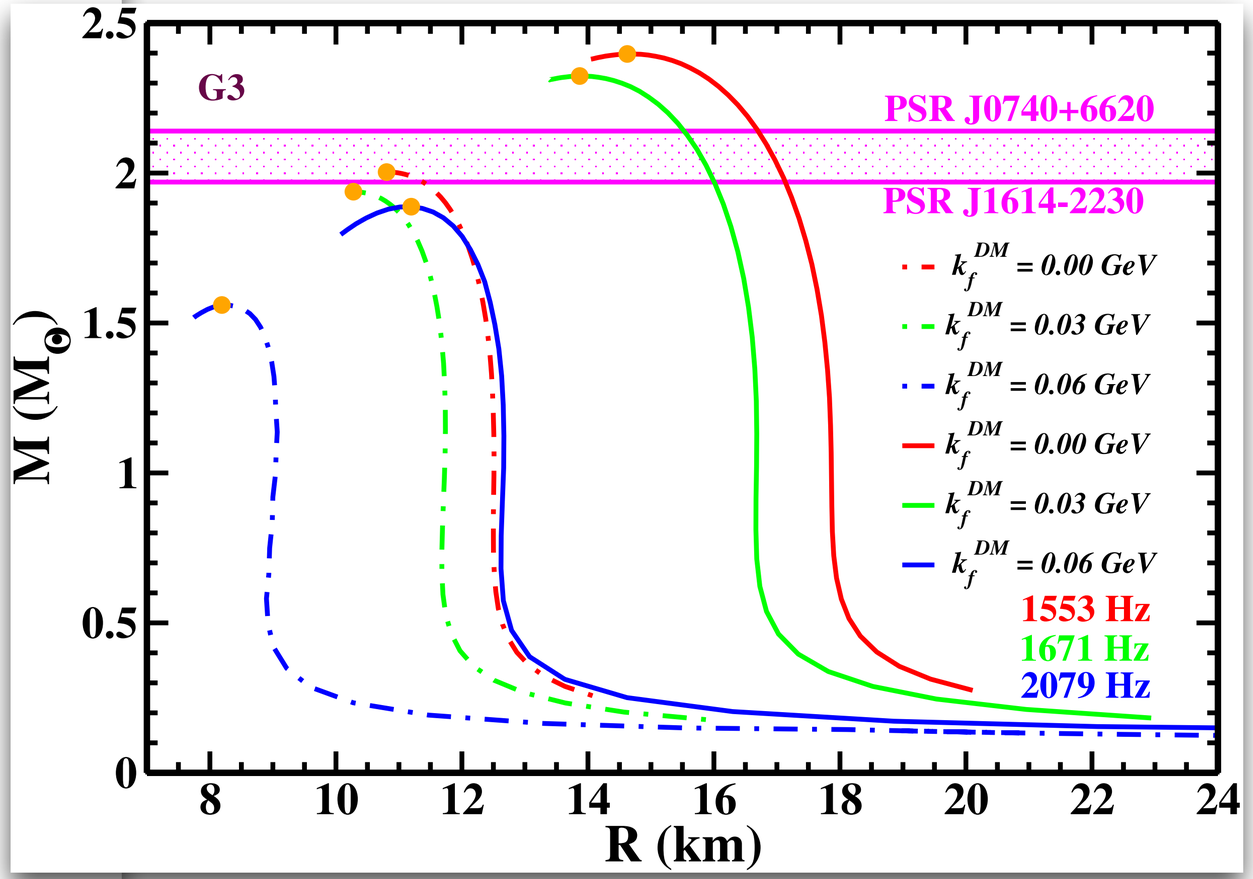
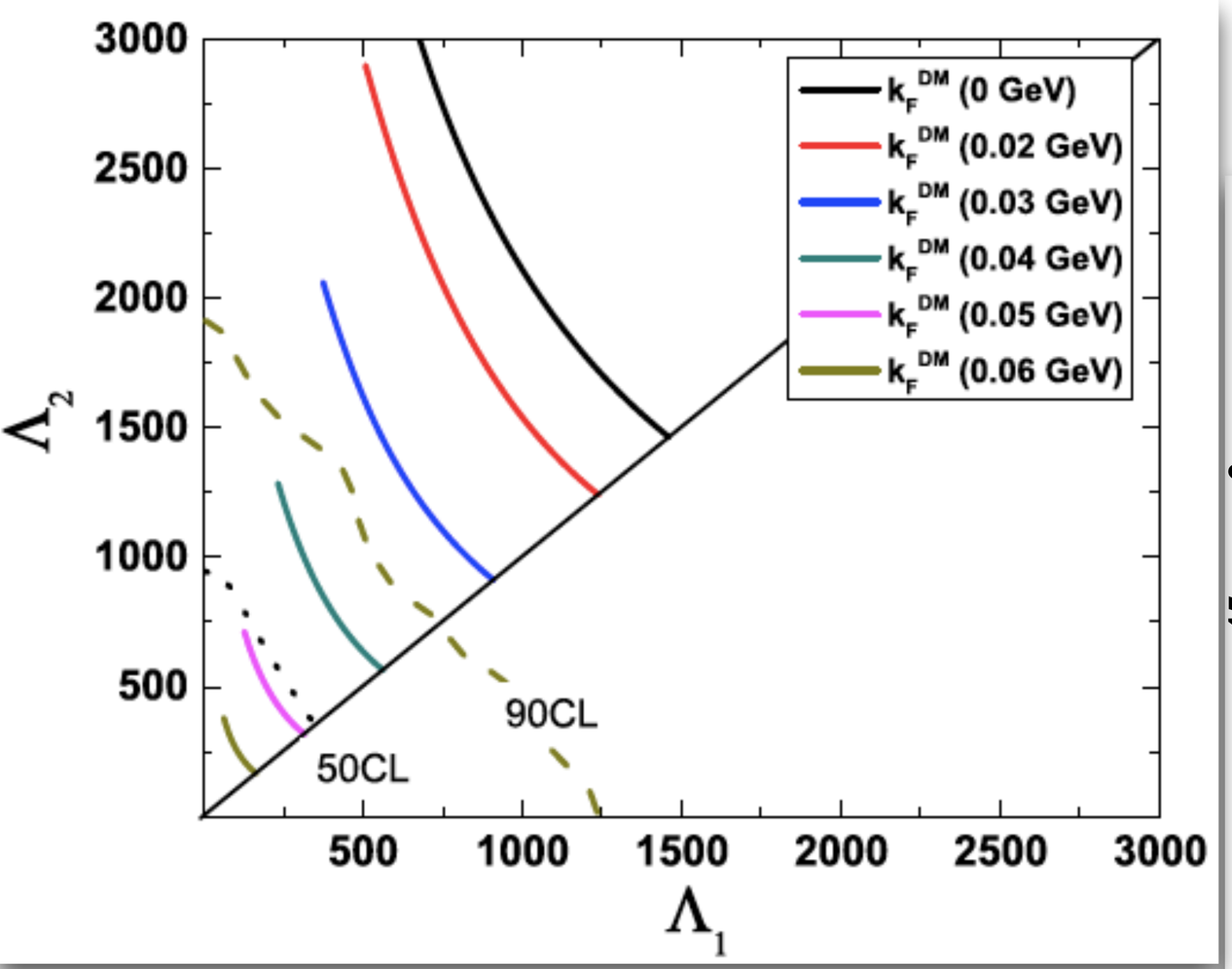
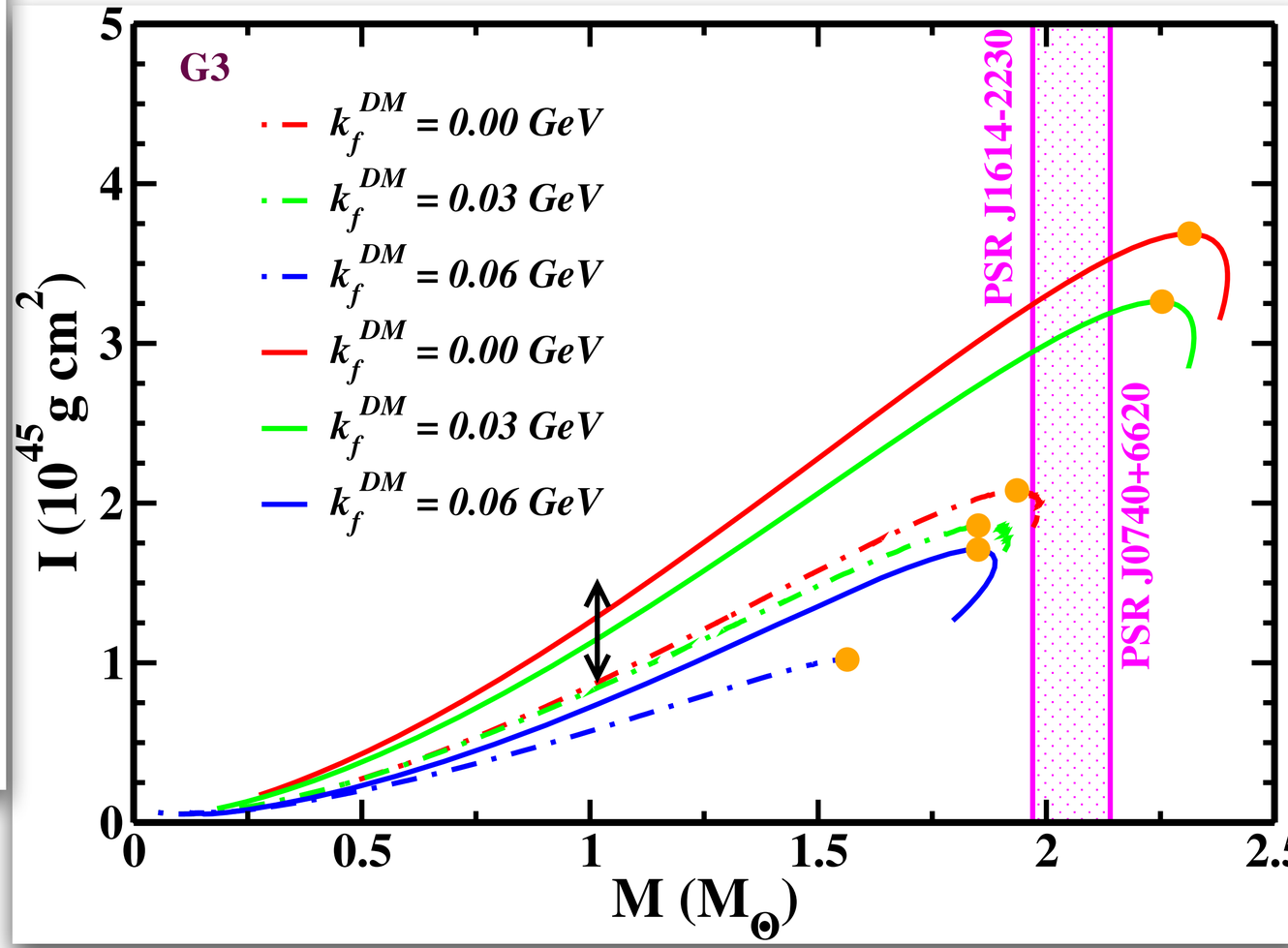




Tidal Deformability and Moment of Inertia





Phys. Rev. D 99, 043016 (2019)

MNRAS 495,4893(2020)

Curvature quantities

To study the curvature of the space-time , some quantities are derived in Phys. Rev. D 89 (2014) 063003

- The Ricci scalar

$$\mathscr{R}(r) = 8\pi\left[\mathscr{E}_{tot.}(r) - 3P_{tot.}(r)\right]$$

- The full contraction of the Ricci tensor

$$\mathscr{J}(r) \equiv \sqrt{\mathscr{R}_{\mu\nu}\mathscr{R}^{\mu\nu}} = 8\pi\left[\mathscr{E}^2_{tot.}(r) + 3P^2_{tot.}(r)\right]^{1/2}$$

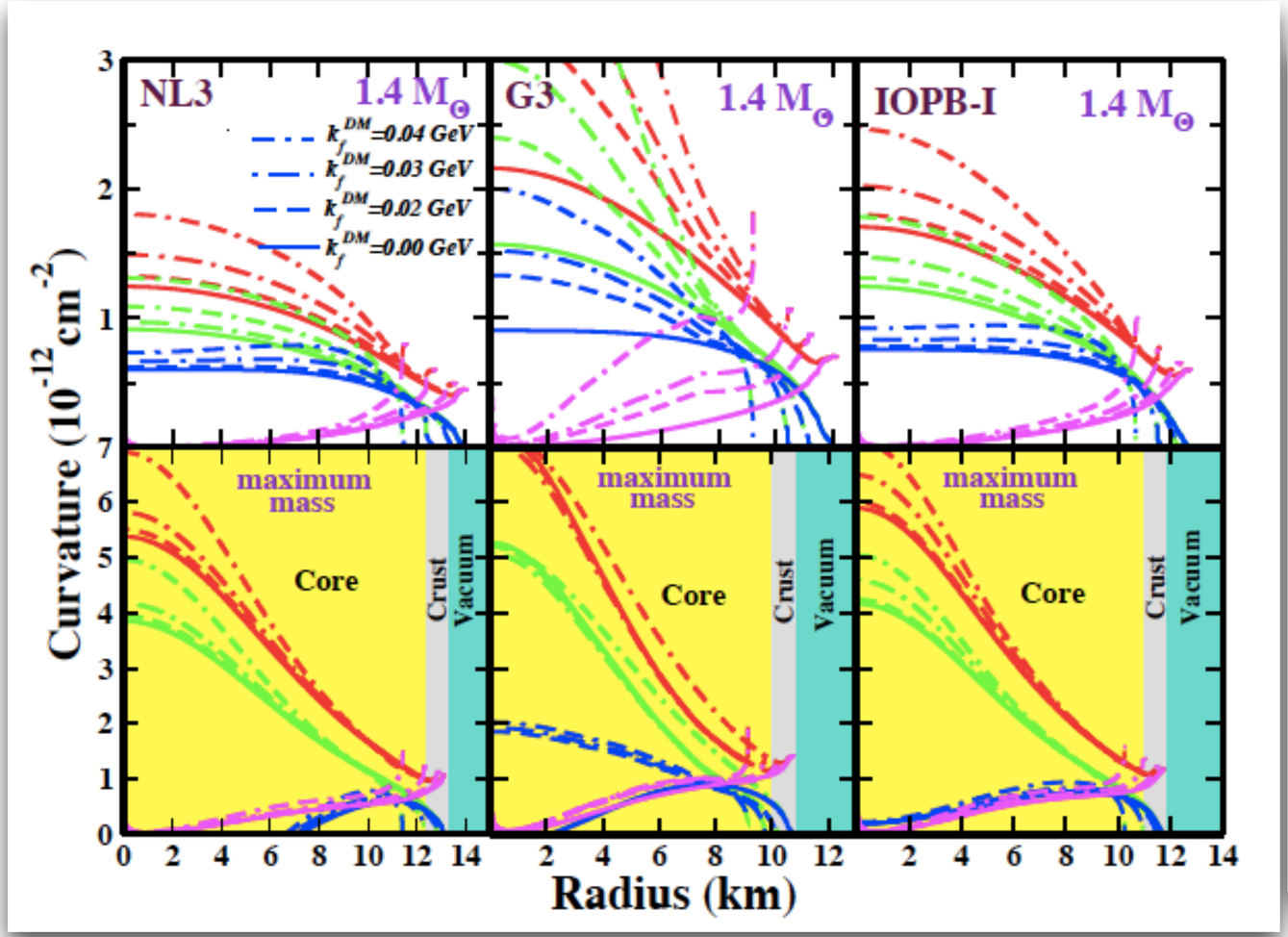
- The Kretschmann scalar (full contraction of the Riemann tensor)

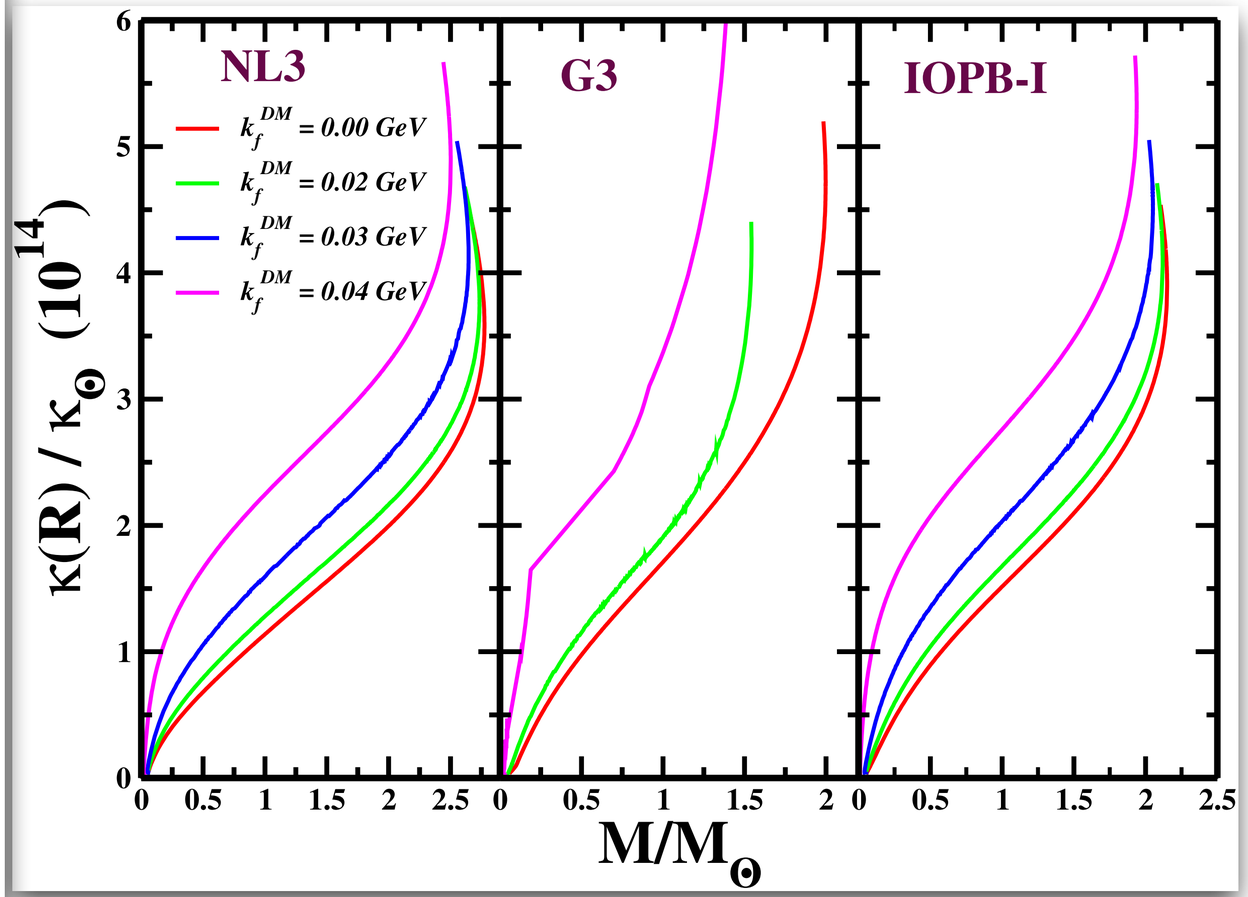
$$\mathscr{K}(r) \equiv \sqrt{\mathscr{R}^{\mu\nu\rho\sigma}\mathscr{R}_{\mu\nu\rho\sigma}} = (8\pi)\left\{\left[3\mathscr{E}^2_{tot.}(r) + 3P^2_{tot.}(r) + 2P_{tot.}(r)\mathscr{E}_{tot.}(r)\right] - \frac{128\mathscr{E}_{tot.}(r)m(r)}{r^3} + \frac{48m^2(r)}{r^6}\right\}^{1/2}$$

- The full contraction of the Weyl tensor

$$\mathscr{W}(r) \equiv \sqrt{\mathscr{C}^{\mu\nu\rho\sigma}\mathscr{C}_{\mu\nu\rho\sigma}} = \left[\frac{4}{3}\left(\frac{6m(r)}{r^3} - 8\pi\mathscr{E}_{tot.}(r)\right)^2\right]^{1/2}$$

Curvature in the presence of DM





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Summary

- The RMF formalism are adopted and three well-known parameter sets such as NL3, G3 and IOPB-I are taken for calculation of the EOS, M-R relations, tidal deformability, moment of inertia and curvature of the NS.
- Neutralino is DM candidates which interact with the nucleons by Higgs.
- EOS becomes softer with the addition of DM.
- The mass-radius, tidal deformability and moment of inertia decreases with the addition of DM both for static and rotating NS.
- One can constrain the percentage of the DM by observational data.
- The surface curvature of the NS increases with the increasing of DM percentage.
- Some percentage of the DM for which NS is stable, more than this the NS becomes unstable.
- The DM has significant changes the properties of the NS.

Collaborators

- Prof. S. K. Patra, IOP, Bhubaneswar, India (supervisor)
- Mr. Ankit Kumar, IOP, Bhubaneswar, India
- Dr. S. K. Biswal, Xiamen University, China
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THANK YOU