Equation of States of Nuclear Matter and Tidal deformation of Neutron Stars

by

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Equation of States of Nuclear Matter
Nuclear Matter and Neutron Star?

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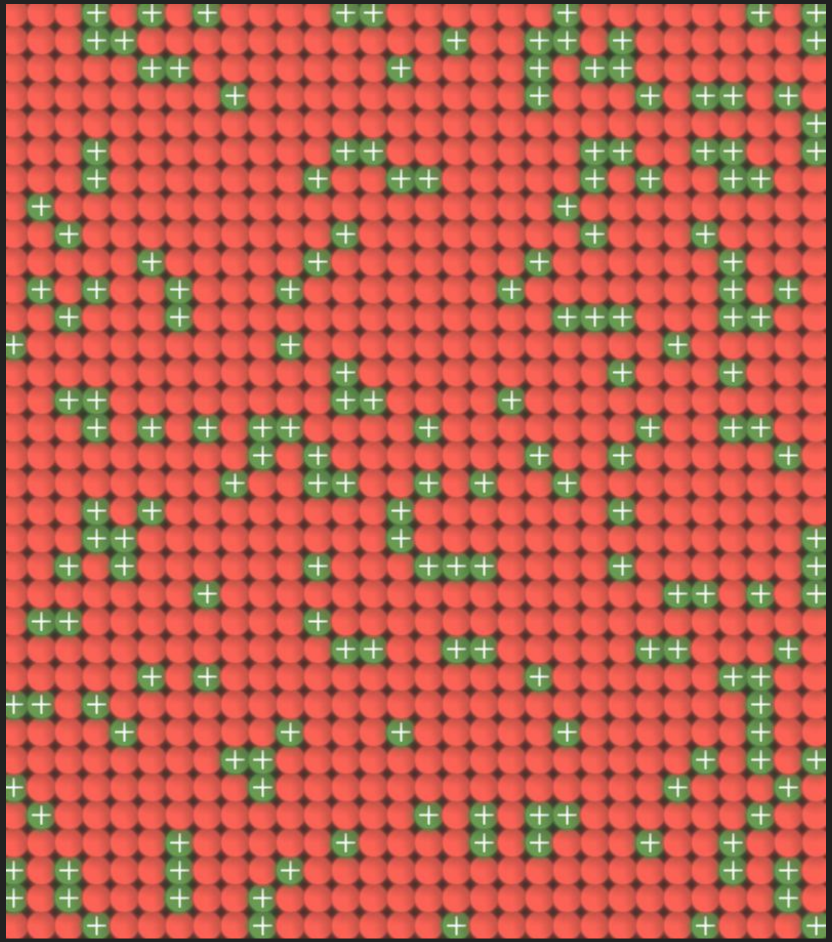
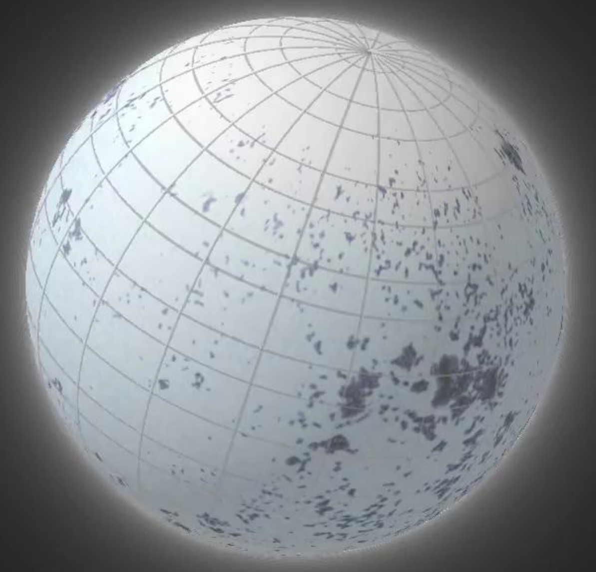


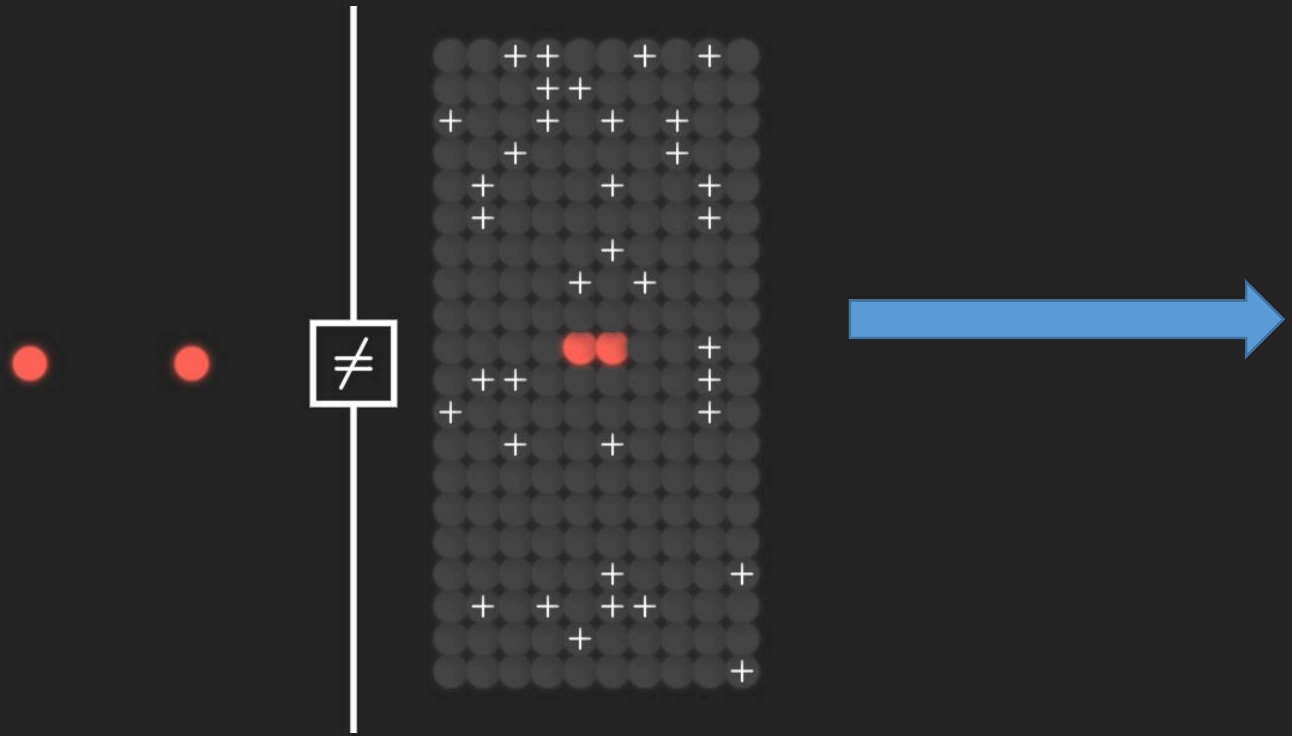
1993

Tolman-
Oppenheimer-
Volkoff equation



Equation of States of Nuclear Matter
Effective interactions

- Two-body nucleon-nucleon interaction in medium is different with that for free NN



Due to the lack of a proper theory in describing nuclear interaction in medium, *effective interaction* models were adopted, i.e. CDM3Yn

Equation of States of Nuclear Matter

CDM3Yn interactions

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- CDM3Yn interaction has the form

$$v(n_b, r) = F_{00}(n_b)v_{00}(r) + F_{01}(n_b)v_{01}(r)(\boldsymbol{\sigma_1} \cdot \boldsymbol{\sigma_2}) + F_{10}(n_b)v_{10}(r)(\boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2}) + F_{11}(n_b)v_{11}(r)(\boldsymbol{\sigma_1} \cdot \boldsymbol{\sigma_2})(\boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2})$$

- The central terms are inherited from M3Y-Paris interaction

known

$$v_{\sigma\tau}^{D(EX)}(r) = \sum_{k=1}^{3} Y_{\sigma\tau}^{D(EX)}(k) \frac{e^{-\mu_k r}}{\mu_k r}$$

Asymmetry: $\delta = \frac{n_n - n_p}{n_b}$

Polarization: $\Delta = \frac{n_{\uparrow\tau} - n_{\downarrow\tau}}{n_\tau}$

- The density-dependent form factors are

$$F_{\sigma\tau}(n_b) = C_{\sigma\tau}[1 + \alpha_{\sigma\tau} e^{-\beta_{\sigma\tau} n_b} + \gamma_{\sigma\tau} n_b] \longrightarrow \text{to be adjusted}$$

Equation of States of Nuclear Matter

Hartree-Fock energy

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- Total energy of system of nucleons

$$E_{HF} = \sum_{\boldsymbol{k}\sigma\tau} \frac{\hbar^2 k^2}{2m_\tau} + \frac{1}{2} \sum_{\boldsymbol{k}\sigma\tau} \sum_{\boldsymbol{k}'\sigma'\tau'} \left[\langle \boldsymbol{k}\sigma\tau, \boldsymbol{k}'\sigma'\tau' | v^D | \boldsymbol{k}\sigma\tau, \boldsymbol{k}'\sigma'\tau' \rangle + \langle \boldsymbol{k}\sigma\tau, \boldsymbol{k}'\sigma'\tau' | v^{EX} | \boldsymbol{k}'\sigma\tau, \boldsymbol{k}\sigma'\tau' \rangle \right]$$

Kinetic energy

Potential energy

- Baryonic pressure

$$P_b = n_b^2 \frac{\partial (E_{HF}/A)}{\partial n_b}$$

Equation of States of Nuclear Matter

β-stable nuclear matter

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- Aside from nucleons, leptons (e^- and μ^-) are also included, since

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

- **β-stable conditions** must be fulfilled
  - Charge balance

$$n_p = n_e + n_\mu$$

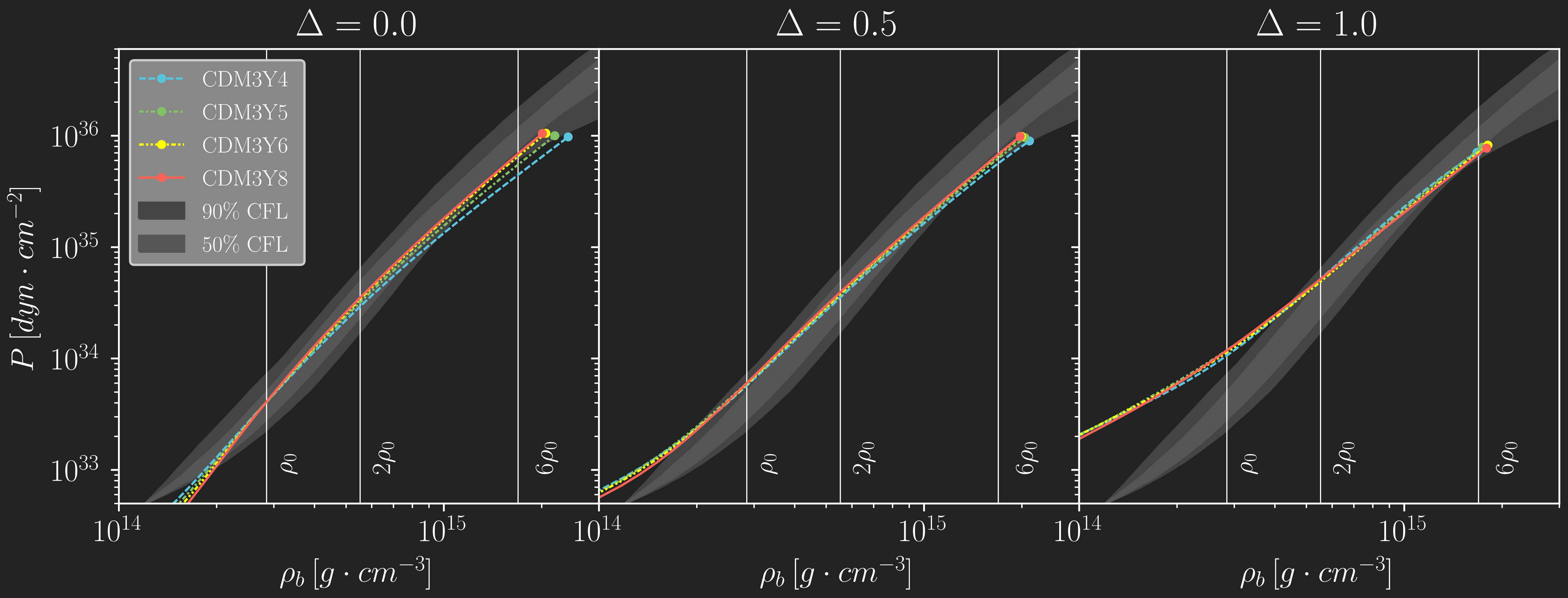
  - Energy balance

$$\mu_n - \mu_p = \mu_e = \mu_\mu$$

$$EoS(n_b, \delta, \Delta) \mapsto EoS(n_b, \Delta)$$

Equation of States of Nuclear Matter

Result

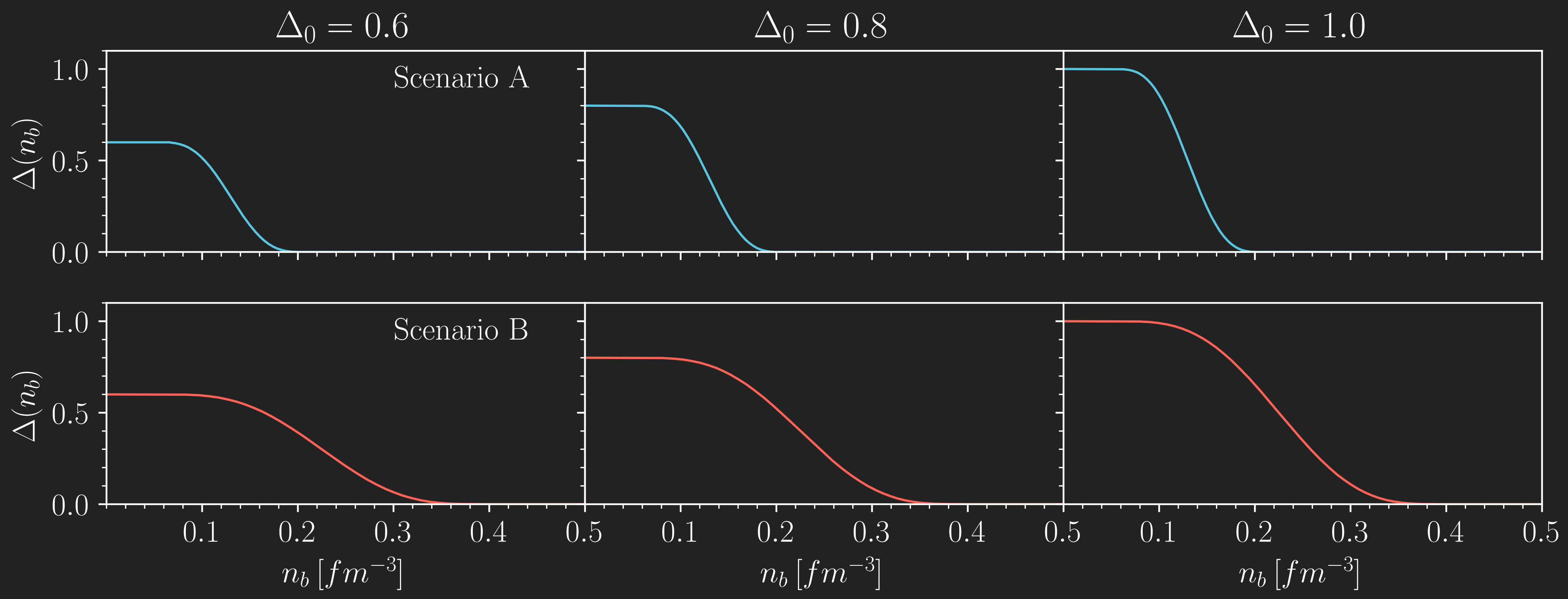


Tidal deformation of Neutron Star

Neutron Star configuration

In a highly magnetized Neutron star (a *magnetar*), the polarization Δ is expected to be

- high at lower density
- reduce to zero at high density



Tidal deformation of Neutron Star

Tolman-Oppenheimer-Volkoff equation

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The macroscopic properties of neutron star are determined from the equation of states using the TOV equation

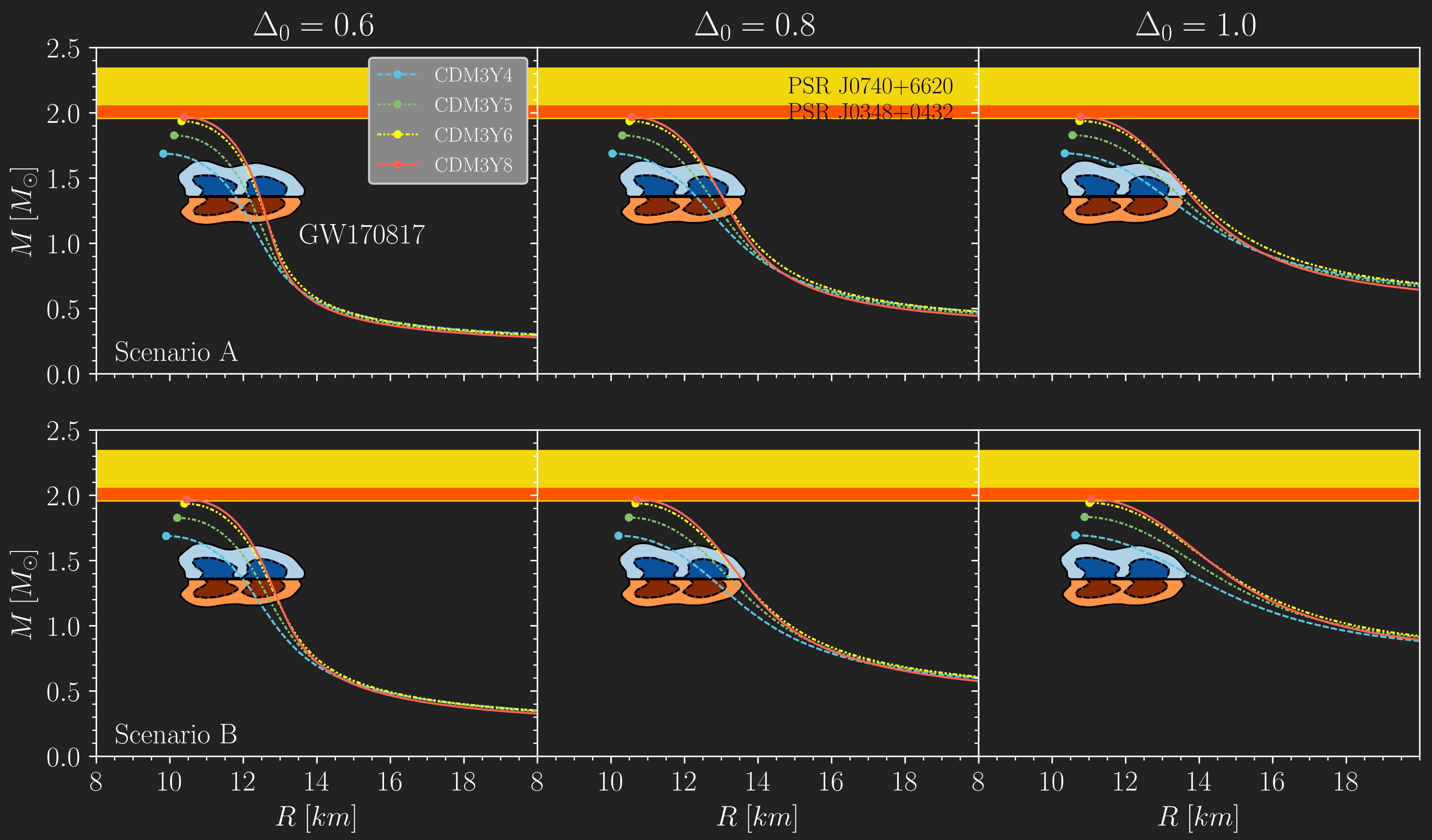
$$\frac{dP}{dr} = -\frac{G\rho\mathcal{M}}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{c^2\mathcal{M}}\right)\left(1-\frac{2G\mathcal{M}}{c^2 r}\right)^{-1}$$

↓

Mass-Radius M(R)

Tidal deformation of Neutron Star

Mass-Radius relation



Only models with high values of K (CDM3Y6 and CDM3Y8) at partial polarization ($\Delta < 1$) are plausible

Tidal deformation of Neutron Star

Tidal effect in a binary system

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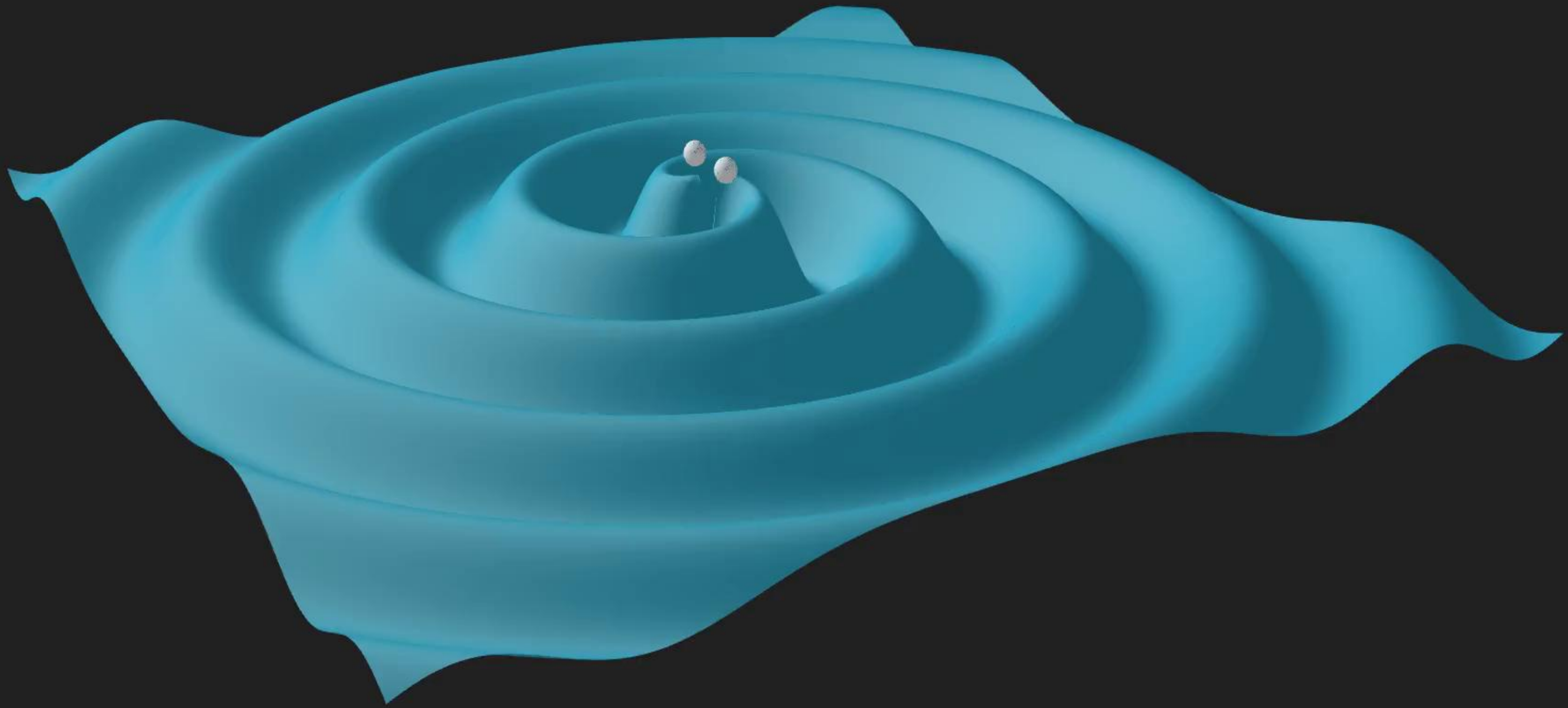
In a binary system of neutron stars, one is subjected to strong tidal effect caused by the other



Tidal deformation of Neutron Star

Tidal Love numbers

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- The tidal properties of a neutron star are expressed in order ℓ as

Body's reaction

- *Gravito-electric:*

$$M_L = \lambda_\ell G_L$$

- *Gravito-magnetic:*

$$S_L = \sigma_\ell H_L$$

Tidal field strength

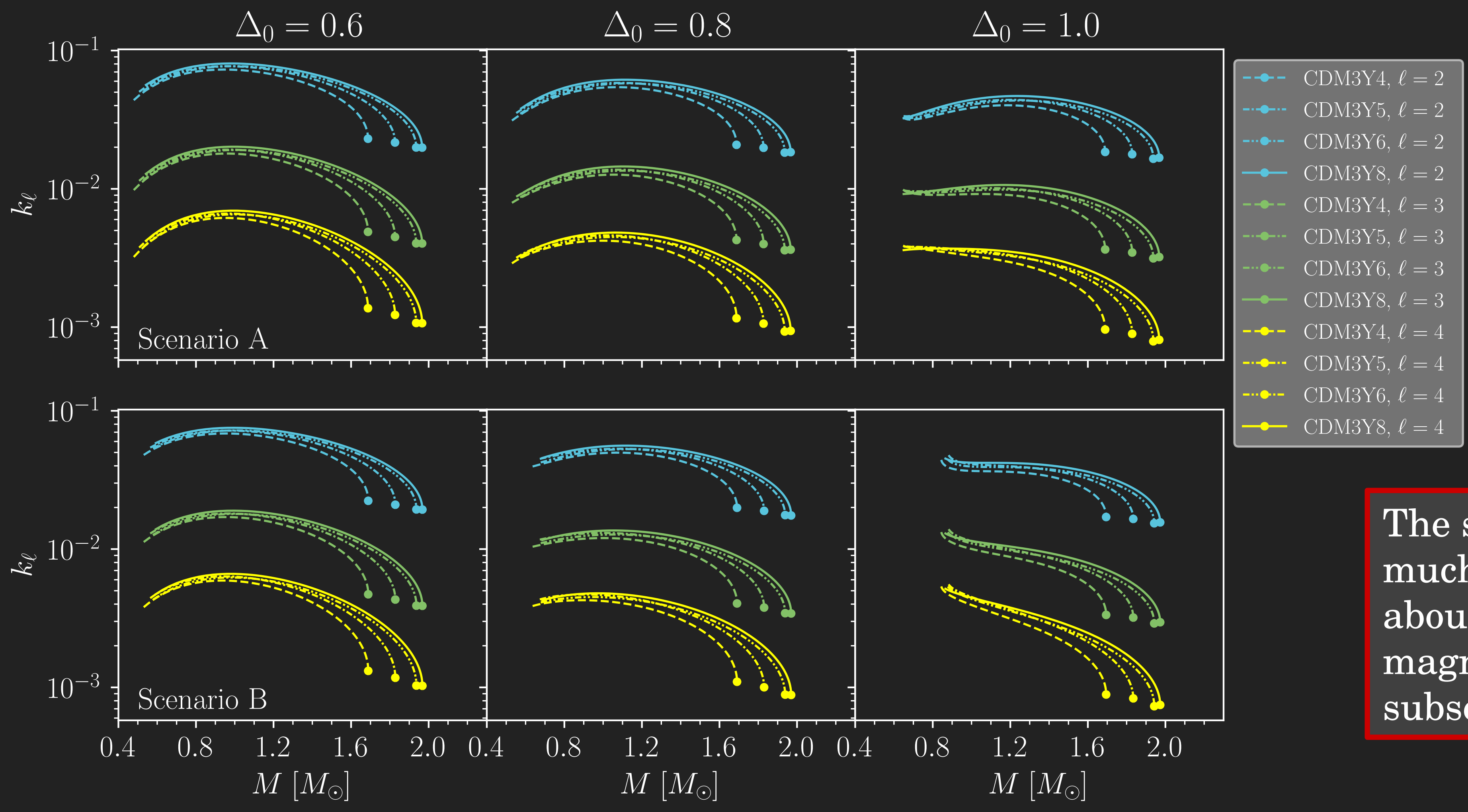
- Equivalently, they can also be described by the tidal Love numbers of order ℓ

$$k_\ell = \frac{1}{2}(2\ell - 1)!! \frac{G\lambda_\ell}{R^{2\ell+1}}$$

$$j_\ell = 4(2\ell - 1)!! \frac{G\sigma_\ell}{R^{2\ell+1}}$$

Tidal deformation of Neutron Star

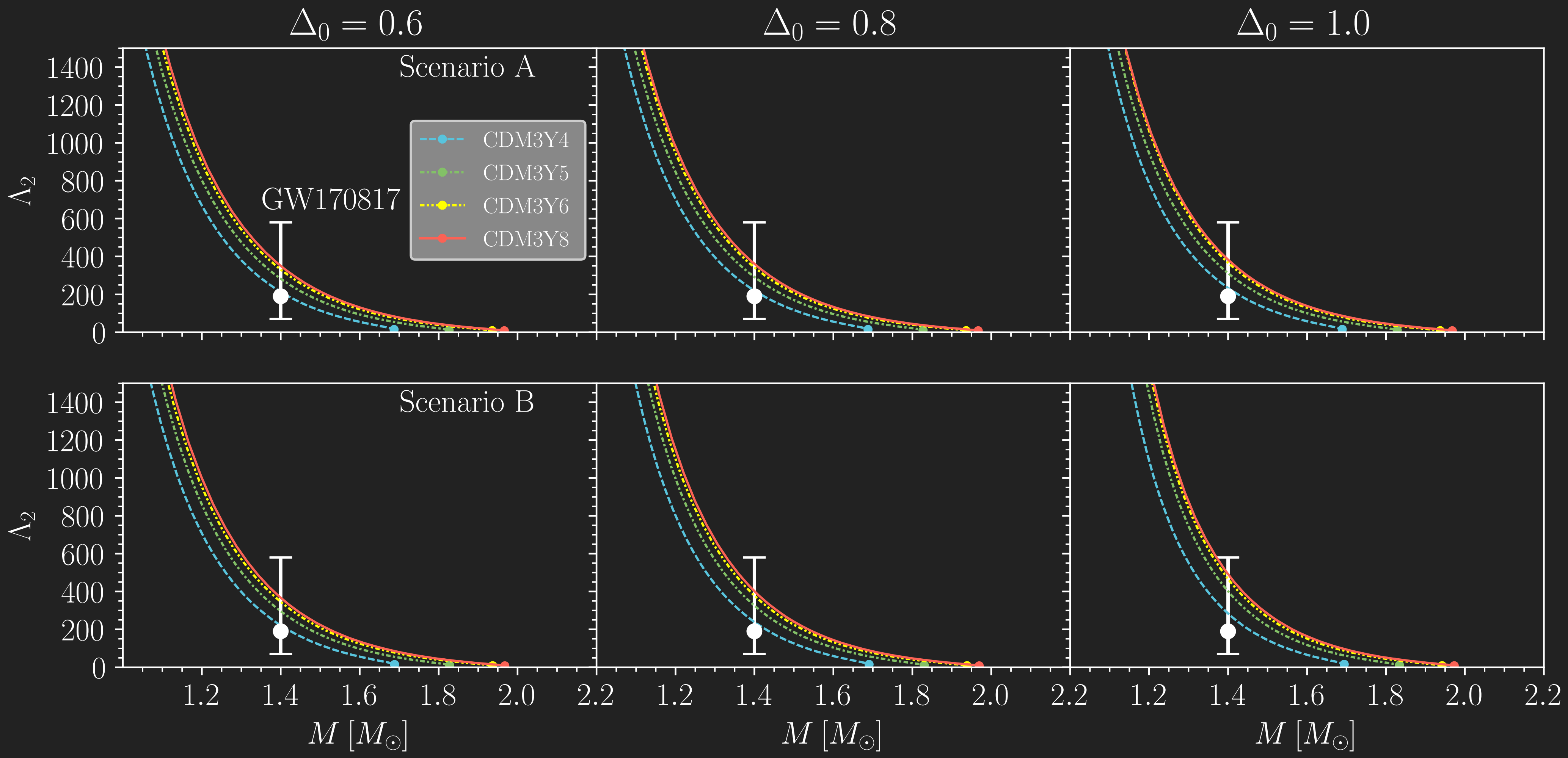
Tidal Love numbers



The second order ($\ell = 2$) is much more dominant, at about an order of magnitude larger than the subsequent order

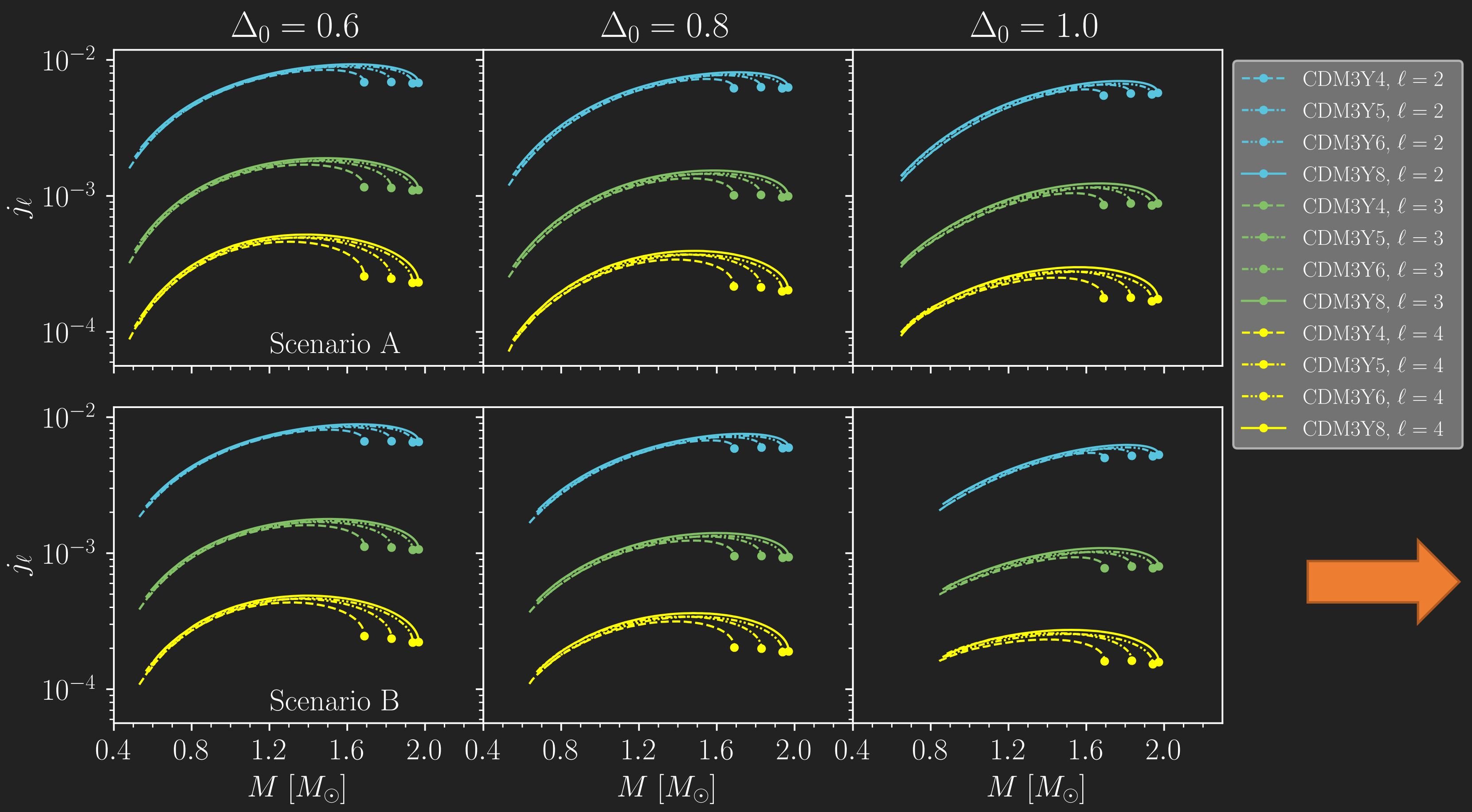
Tidal deformation of Neutron Star

Dimensionless tidal parameter



Tidal deformation of Neutron Star
Tidal Love numbers

➢ Static fluid



The same trend is found in gravito-magnetic Love numbers. However, they appear to be 1 order of magnitude lower than their GE counterparts.

Tidal deformation of Neutron Star

Tidal Love numbers

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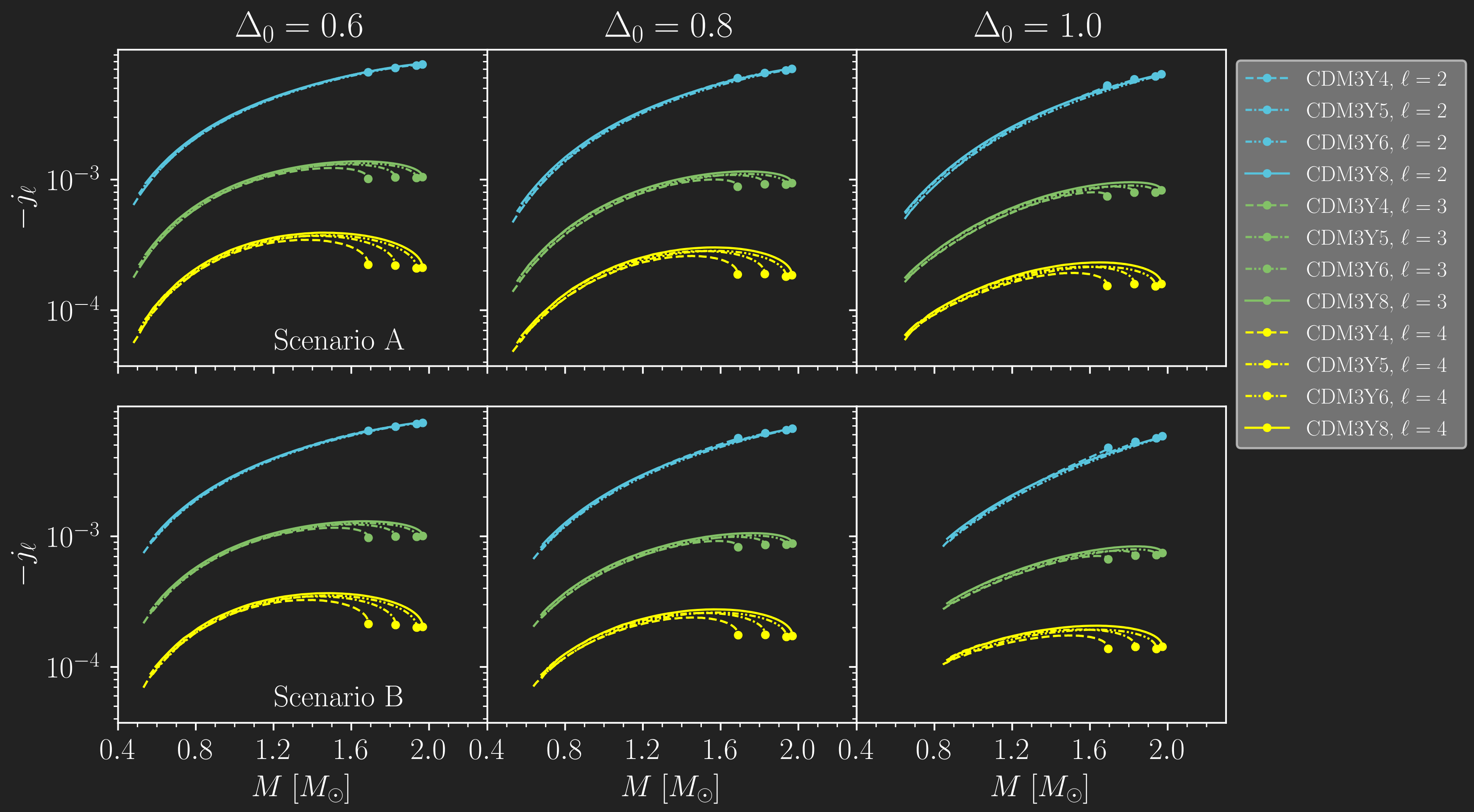
➢ Irrotational fluid



Conclusions

- The case of total polarization at the outer core and crust is ruled out as expected.
- Higher values of K are favored as only CDM3Y6 and CDM3Y8 come close to the lower mass limit of the heaviest pulsars observed.
- The tidal properties of the neutron star are also investigated with assumptions and up to fourth order in contribution, which returns a close result with those obtained in recent study.

Thank you for your attention!