Cosmology 2018 in Dubrovnik

The effects of scalar meson interactions on Symmetry Energy in RMF theory

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SYMMETRY ENERGY DEF.

Important for Nuclear Physics and Astrophysics

- Neutron skin thickness in finite nuclei
- Stable nuclei
- Heavy-Ion collisions
- Giant Resonance
- …

- Supernova explosions
- Neutron emission and cooling of the protoneutron stars
- Mass-Radius relations in NS
- Composition of the crust of NS
- …

Describes the increase of Energy with increasing asymmetry of matter.

$$E_{sym}(n) = \frac{1}{8} \frac{\partial^2 \epsilon\,(n, x)}{\partial x^2}\bigg|_{x=\frac{1}{2}}$$

EOS of NS matter

Basic inputs:

- $\epsilon\,(n, x)$ – energy density
- x – proton fraction

Empirical parabolic law:

Its validity within 1 MeV has been verified by using microscopic many –body theories and phenomenological models + various effective interactions.

$$\epsilon\,(n, x) = \epsilon\left(n, x = \frac{1}{2}\right) + \boldsymbol{E_{sym}(n)}(1 - 2x)^2 + O((1 - 2x)^4)$$

SNM
Symmetric Nuclear Matter
(relatively well-determined)

ANM
Asymmetric Nuclear Matter
(uncertained)

(poorly-known)

IMPORTANCE OF SYMMETRY ENERGY

- Tells us about the structure and composition of a NS outer crust.
- The faster E_{sym} increases with n, the more exotic the composition. *
- The high-density behavior of the E_{sym} is currently the most uncertain part of the EOS of dense neutron-rich matter.

E_{sym} around saturation density:

$$\boldsymbol{E_{sym}(n)} = (\mathrm{J} + \mathrm{L}\,\mathrm{x} + \frac{1}{2}\,\mathrm{K}\,\mathrm{x}^2 + \mathrm{O}(\mathrm{x}^3)), \qquad \mathrm{J} = \mathrm{E_{sym}}(\mathrm{n_0})$$

Governs many nuclear physics and astrophysics observables

* Physical Review C 78, 025807 (2008).

EMPIRICAL VALUES

Significant progress have been made recently in constraining the $E_{sym}(\mathrm{n})$ around and below n_0.

$$E_{sym}(n) = (\mathrm{J} + \mathrm{L}\,\mathrm{x} + \frac{1}{2}\mathrm{K}\,\mathrm{x}^2 + \mathrm{O}(\mathrm{x}^3))$$

- Saturation density:

$$n_0 = 0.16\ \mathrm{fm}^{-3}$$

- Binding Energy for SNM:

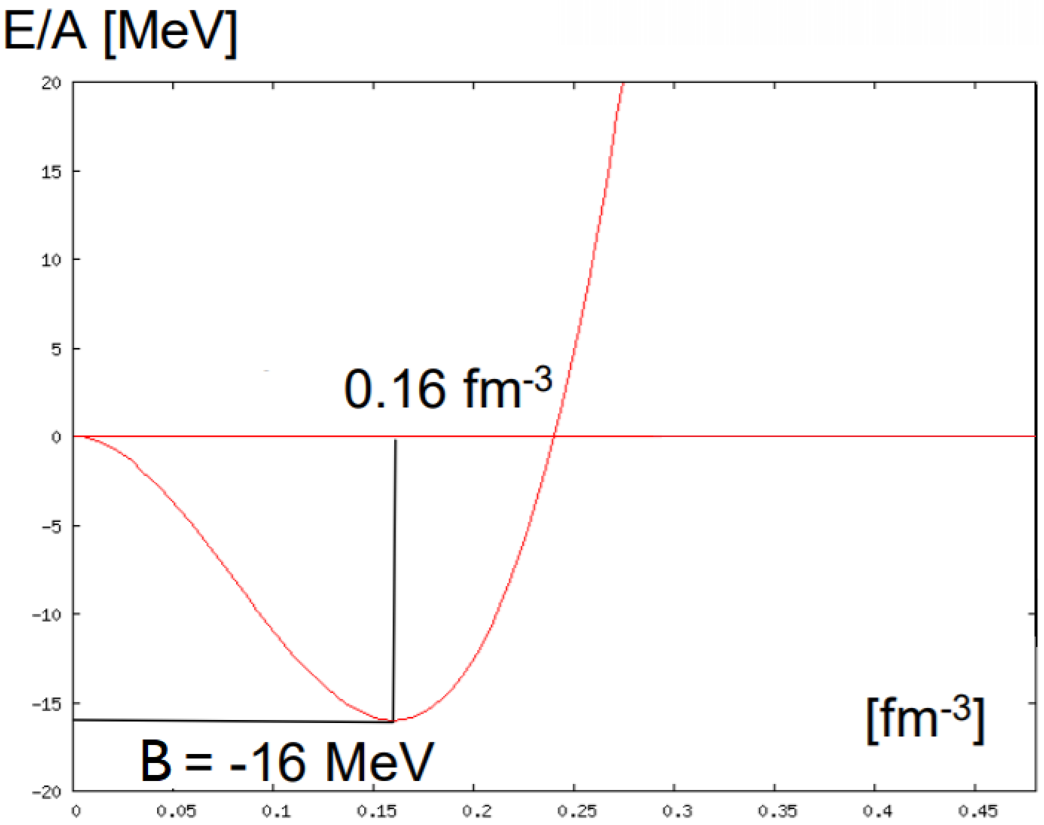
$$B = \epsilon\left(n_0, \frac{1}{2}\right) / n_0 - \mathrm{m} = -16\ \mathrm{MeV}$$

- Incompressibility:

$$K = 230\ MeV$$

- Slope:

$$L = 40 - 70\ MeV\ *$$



* B. A. Li and X. Han, Phys. Lett. B 727, 276 (2013).

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- Binding Energy for SNM:

$$B = \epsilon\left(n_0, \frac{1}{2}\right) / \, n_0 - \mathrm{m} = -16\ \mathrm{MeV}$$

- Incompressibility:

$$K = 230\ MeV \longleftrightarrow K = 9\, n^2 \frac{\partial^2 E_{sym}}{\partial n^2}\bigg|_{n_0}$$

K: quantity in the study of nuclei, supernova collapse, neutron stars, and heavy-ion collisions - it is directly related to the curvature of nuclear matter EOS.

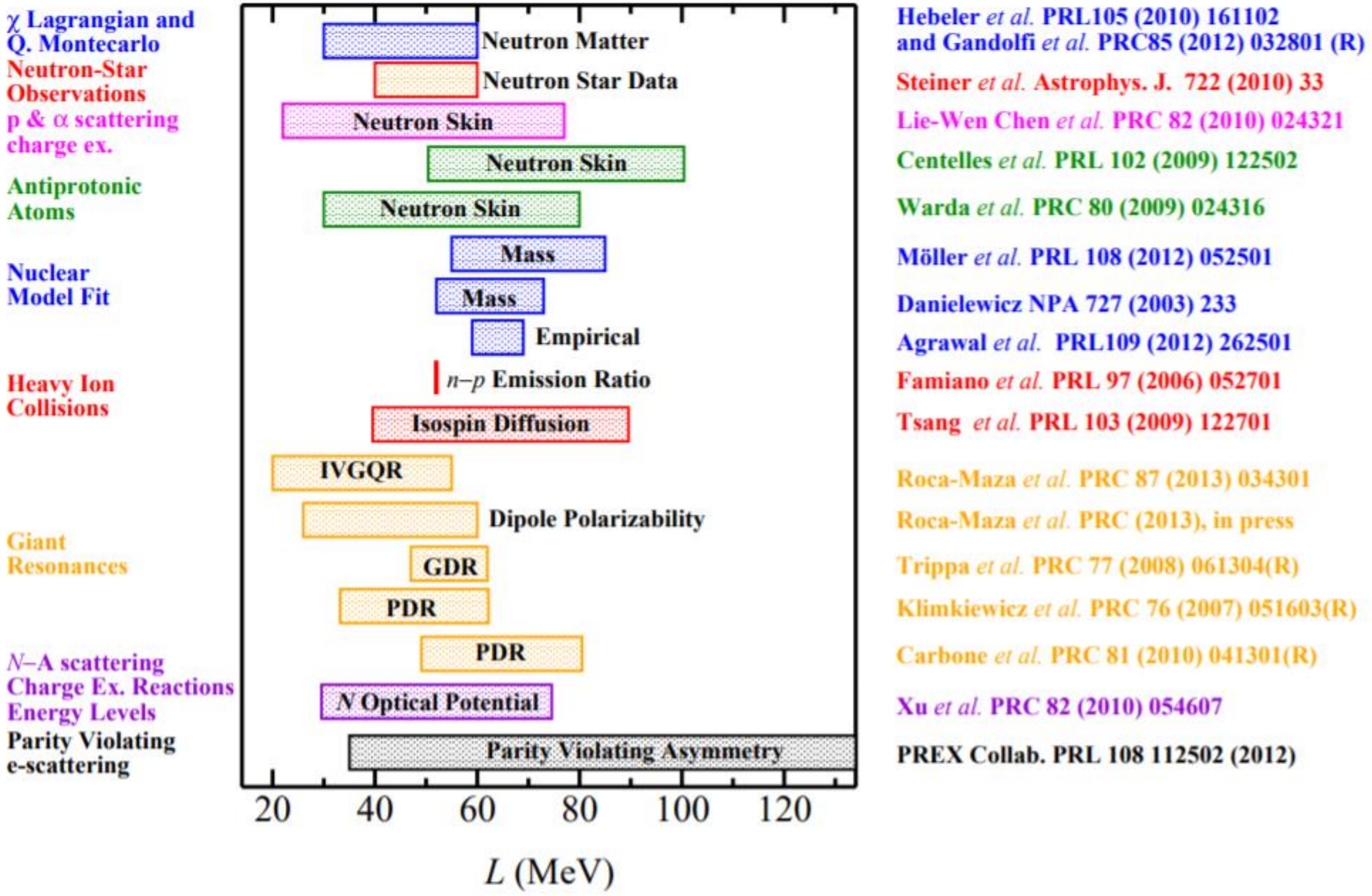
- Slope:

$$L = 40 - 70\ MeV\ * \longleftrightarrow L = 3n \frac{\partial E_{sym}}{\partial n}\bigg|_{n_0}$$

L is important for : the size of the neutron skin in heavy nuclei, location of the neutron drip line, core-crust transition density and gravitational binding energy of neutron stars.

* B. A. Li and X. Han, Phys. Lett. B 727, 276 (2013).

Slope from various studies



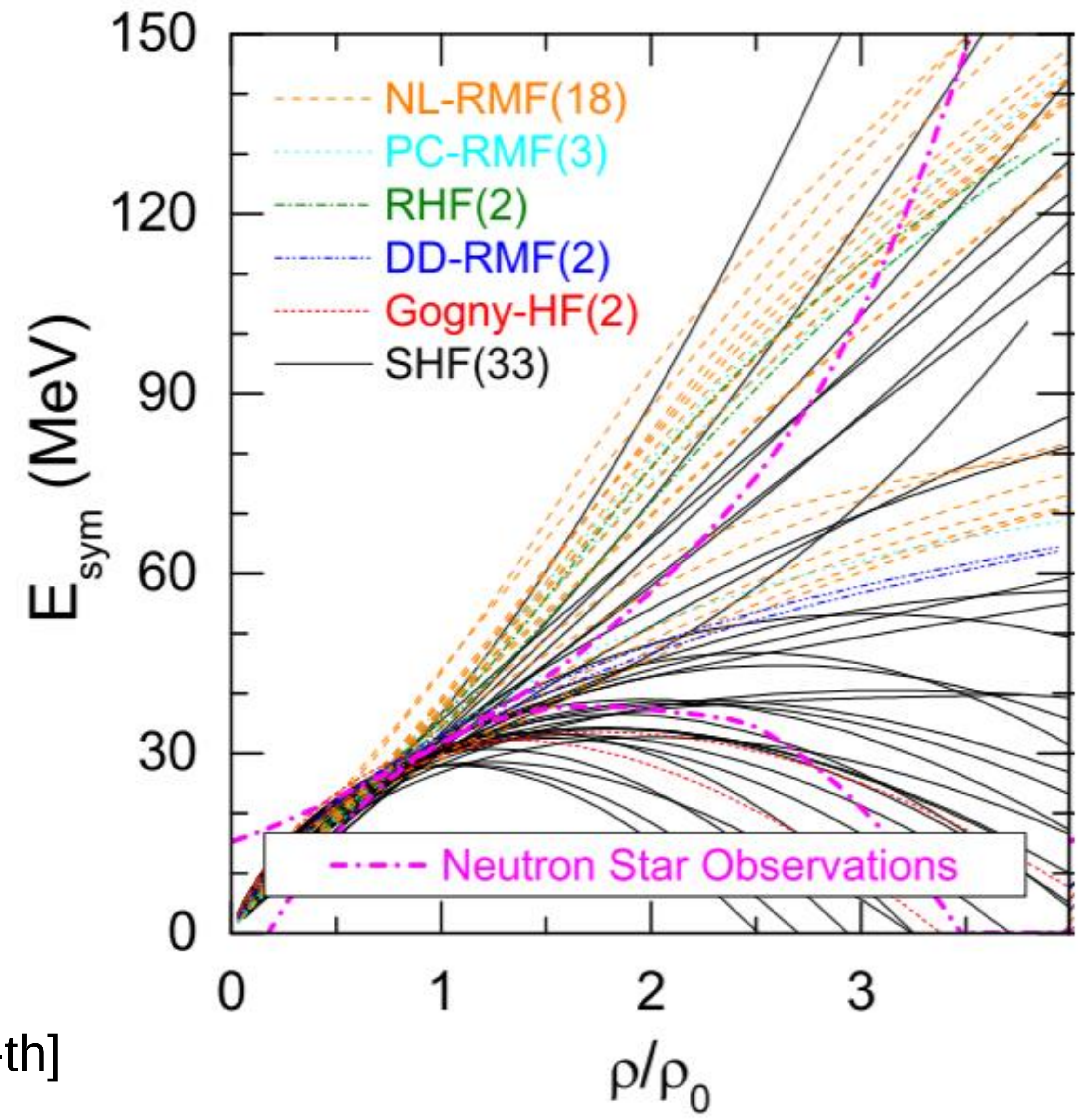
* Adopted from X. Vinas (2014).

RELATIVISTIC MEAN FIELD THEORY (RMF)

- Good description of the nuclear matter in higher densities.
- Contains both: nucleonic and mesonic degrees of freedom.

Fig. 60 selected representatives from 6 classes of phenomenological models and/or energy density functional theories including:

- Relativistic Mean Field (RMF) using 3 different kinds of coupling schemes,
- Relativistic Hartree-Fock (RHF),
- Gogny Hartree-Fock (HF) Skyrme Hartree-Fock



* N. B. Zhang and B. A. Li, arXiv:1807.07698 [nucl-th]

RELATIVISTIC MEAN FIELD THEORY (RMF)

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STANDARD RMF $+$ scalar mesons interaction

$\sigma, \omega, \rho, \delta$

$\sigma - \delta$ interaction

linear $g_1 \sigma \delta^2$

quadratic $g_2 \sigma^2 \delta^2$

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\left(\partial_\mu\omega_\nu - \partial_\nu\omega_\mu\right)\left(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu\right) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\left(\partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu\right)\left(\partial^\mu\vec{\rho}^\nu - \partial^\nu\vec{\rho}^\mu\right) + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu$$

$$+ \frac{1}{2}\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - \frac{1}{2}m_\delta^2\vec{\delta}^2 + \bar{\psi}\left(i\partial_\mu\gamma^\mu - m\right)\psi + g_\sigma\sigma\bar{\psi}\psi - g_\omega\omega_\mu\bar{\psi}\gamma^\mu\psi - \frac{1}{2}g_\rho\vec{\rho}_\mu\bar{\psi}\gamma^\mu\vec{\tau}\psi + g_\delta\vec{\delta}\bar{\psi}\vec{\tau}\psi - U(\sigma) + \mathcal{L}_{\sigma\delta},$$

RELATIVISTIC MEAN FIELD THEORY (RMF)

Step 1. Lagrangian $\mathcal{L} = \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2\right) - \frac{1}{4}\left(\partial_\mu \omega_\nu - \partial_\nu \omega_\mu\right)\left(\partial^\mu \omega^\nu - \partial^\nu \omega^\mu\right) + \ldots$

Step 2. Energy density (in effective masses language)

$$\epsilon = \frac{2}{(2\pi)^3}\left(\int_0^{k_p} d^3k \sqrt{k^2 + m_p^{*2}} + \int_0^{k_n} d^3k \sqrt{k^2 + m_n^{*2}}\right) + \frac{1}{2}\frac{1}{C_\sigma^2}(m - \bar{m}^*)^2 + \frac{1}{2}C_\omega^2 n^2 + \frac{1}{8}C_\rho^2(2x - 1)^2 n^2 + \\ + \frac{1}{8}\frac{1}{C_\delta^2}(\Delta m^*)^2 + 2g_\alpha(\Delta m^*)^2(m - \bar{m}^*)^\alpha + U(m - \bar{m}^*)$$

- Coupling constants of each meson $\left(C_i^2 = \frac{g_i^2}{m_i^2},\ i = \sigma, \omega, \rho, \delta\right)$
- Effective masses

$$m_p^* = m - g_\sigma \bar{\sigma} - g_\delta \bar{\delta}_3,$$
$$m_n^* = m - g_\sigma \bar{\sigma} + g_\delta \bar{\delta}_3.$$

- Proton fraction $\left(x = \frac{n_p}{n}\right)$

SYMMETRY ENERGY

Step 1. Lagrangian $\mathcal{L} = \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\left(\partial_\mu\omega_\nu - \partial_\nu\omega_\mu\right)\left(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu\right) + \ldots$

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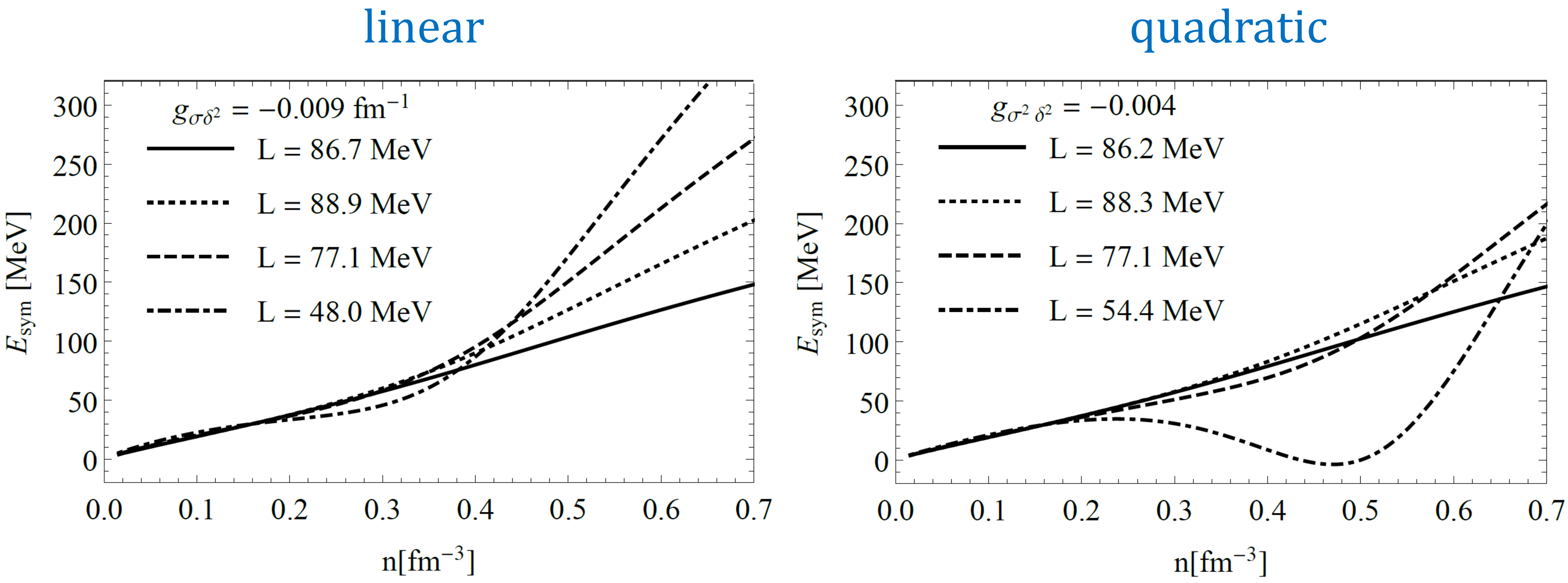
Step 3. Symmetry energy

$$E_{sym}(n) = \frac{1}{8}C_\rho^2 n + \frac{k_0^2}{6\sqrt{k_0^2 + m_0^{*2}}} - C_\delta^2\frac{m_0^{*2}n}{2(k_0^2 + m_0^{*2})\left(1 + C_\delta^2 A - 8\,g_\alpha C_\delta^2\,(m - m_0^*)^\alpha\right)}$$

Step 4. Slope *L*

Step 5. Precedure: $C_\delta^2 = 0.5, 1.5, 2.5, 3.5 \quad \rightarrow \quad C_\rho^2 \quad \rightarrow \quad L$

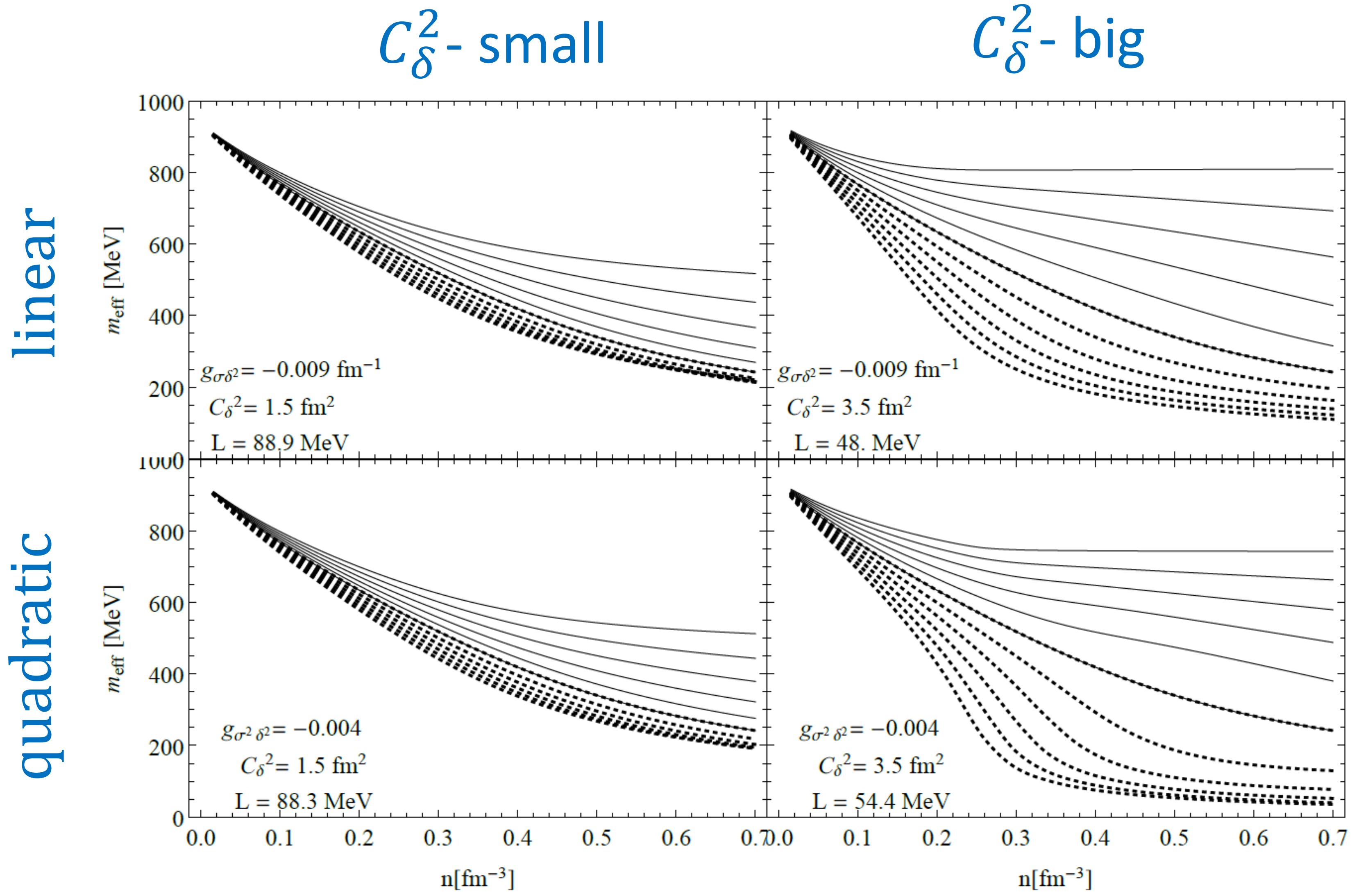
RESULTS



With $\sigma - \delta$ interaction the E_{sym} can be close to zero.

Better control of the slope (negative g_α gives sufficiently small L)

RESULTS



The presence of δ-meson makes the Effective nucleon mass splitting.

↓

m_p i m_n are no longer the same!

STARS

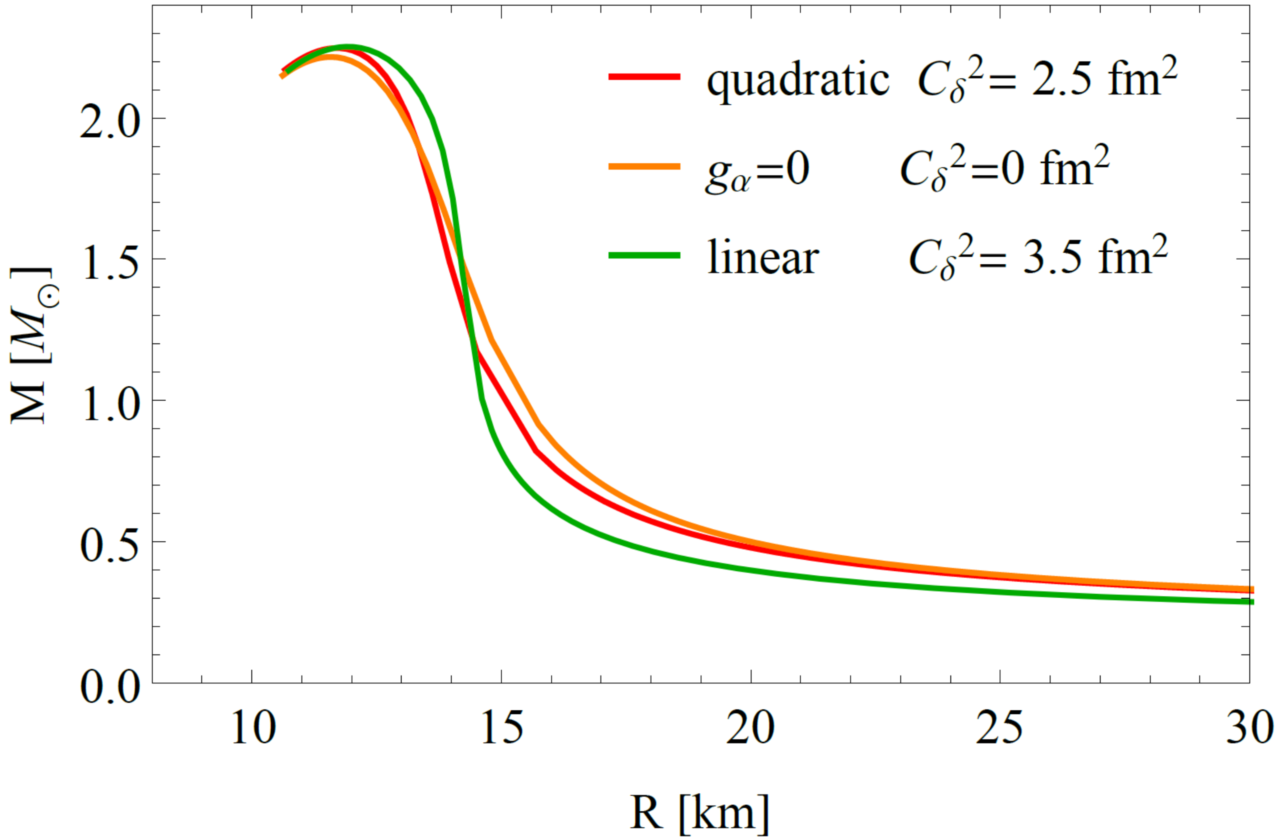
Step 1. EOS (β-equilibrium + charge neutrality)

Step 2. TOV $P'(x) = -G(P(R) + \rho(R))\frac{M(R) + 4\pi r^3}{R(c^4 - 2GM(R))}$

$M'(R) = 4\,\pi r^2 \rho(R)$

Structure of the star:

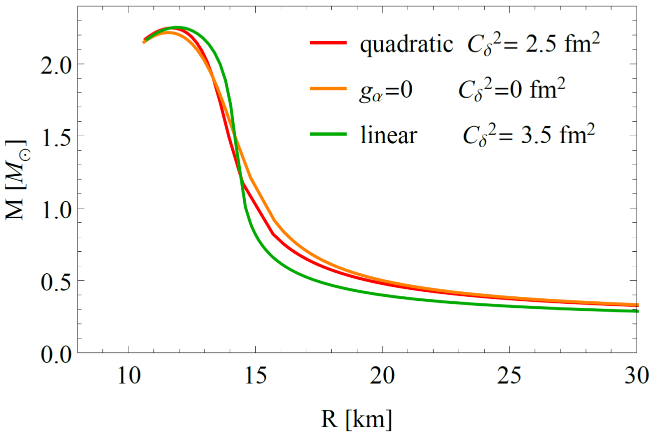
- M vs R
- M(ρ)
- ρ(R)
- …



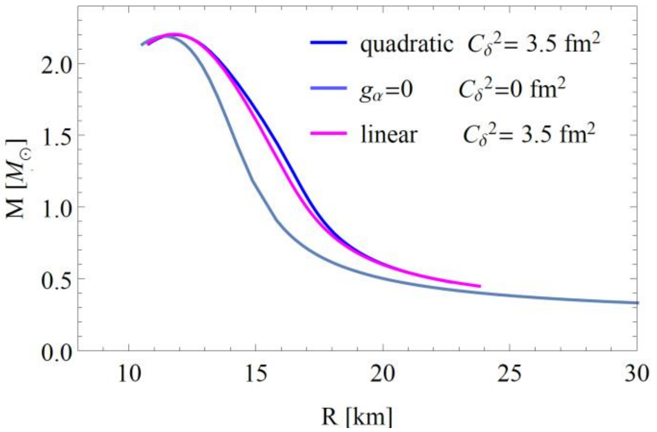
STARS

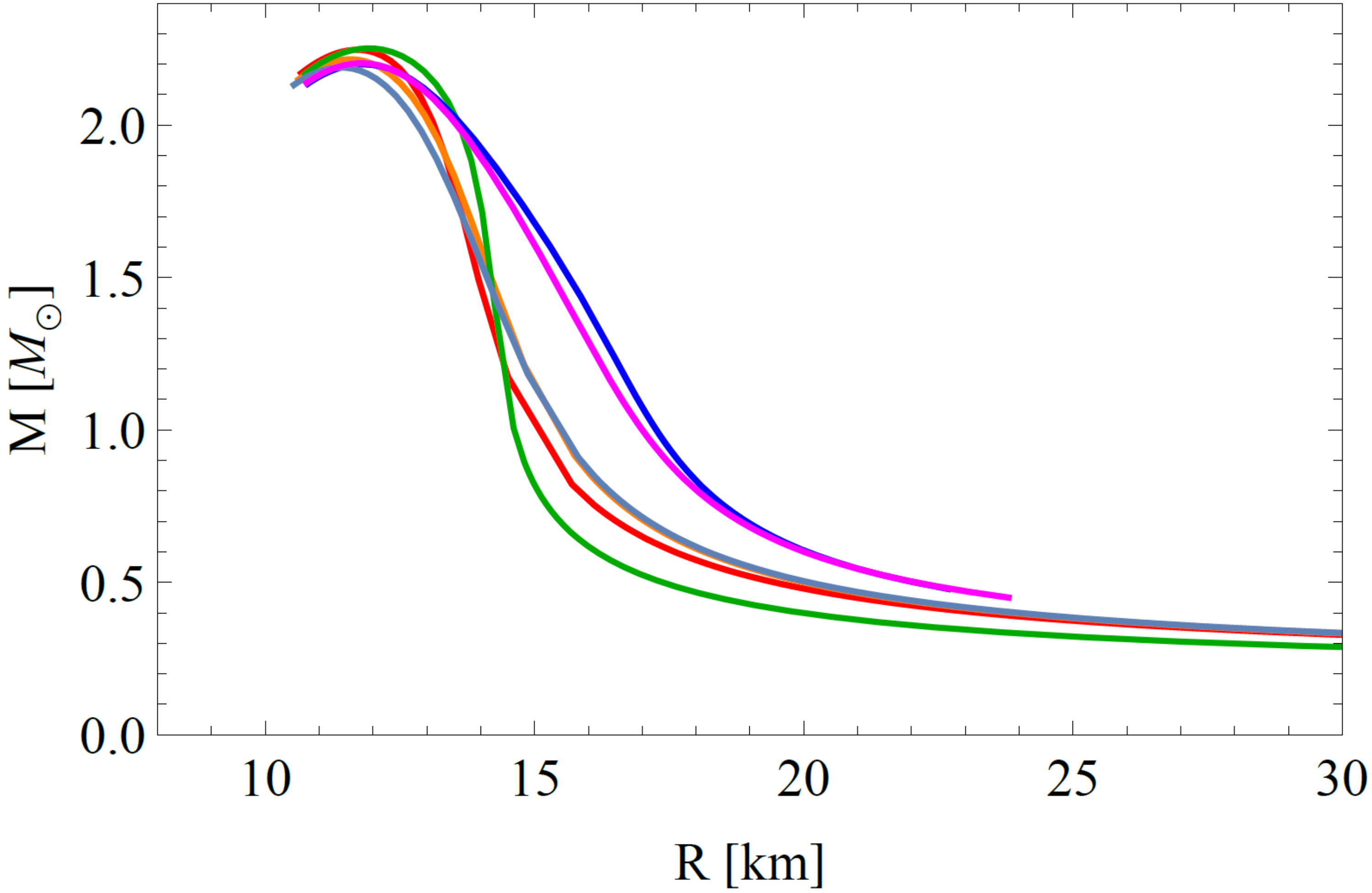
Maximum masses: $M = 2.19 - 2.25\ M_{\odot}$
Radius: $R = 11.40 - 11.97\ km$

g_α - negative



g_α - positive





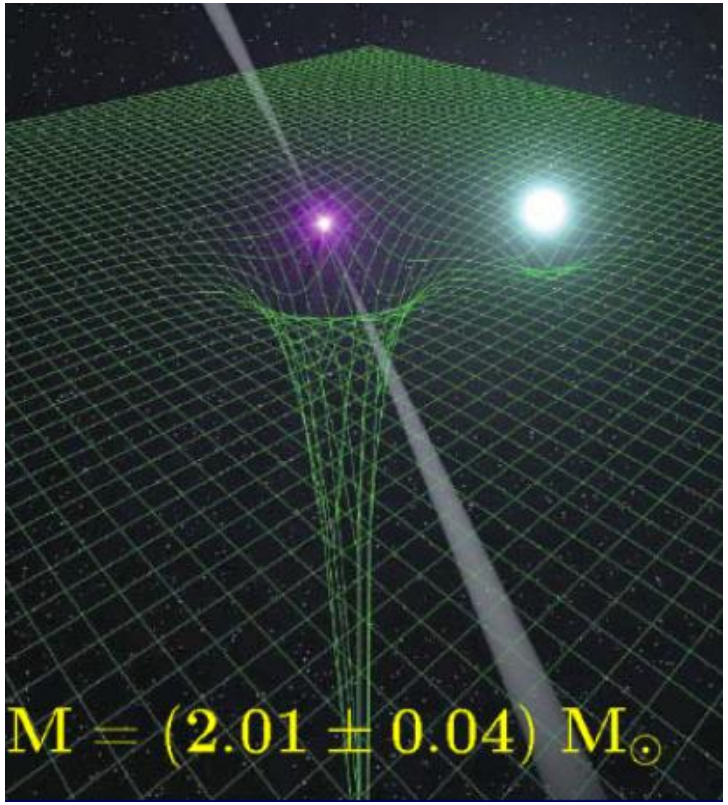
STARS

g-linear, $C_\delta^2 = 3.5\ fm^2 \rightarrow M = 2.25\ M_\odot$ & $R = 11.93\ km$

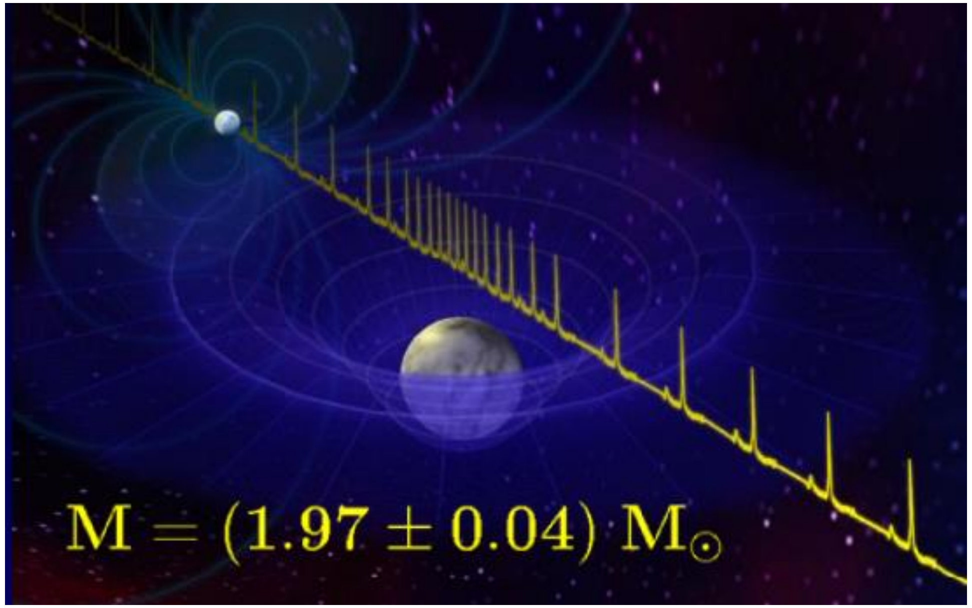
g-quadratic, $C_\delta^2 = 2.5\ fm^2 \rightarrow M = 2.24\ M_\odot$ & $R = 11.86\ km$

Highest well-known masses of NS

NS in a binary system with a WD



Pulsar J0348+0432



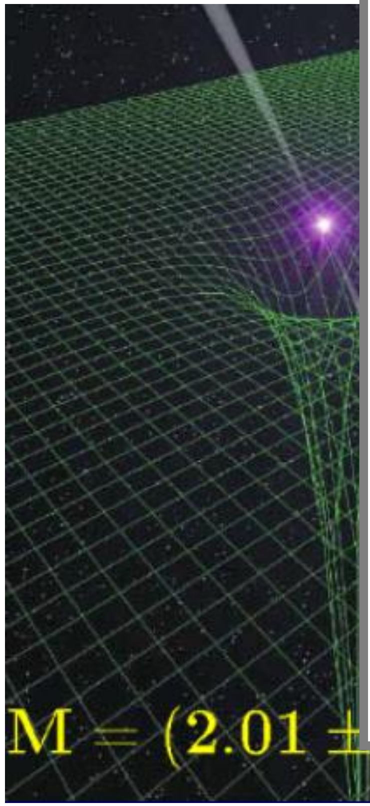
Pulsar J1614-2230

STARS

g-linear, $C_\delta^2 = 3.5\ fm^2 \rightarrow M = 2.25\ M_\odot$ & $R = 11.93\ km$

g-quadratic, $C_\delta^2 = 2.5\ fm^2 \rightarrow M = 2.24\ M_\odot$ & $R = 11.86\ km$

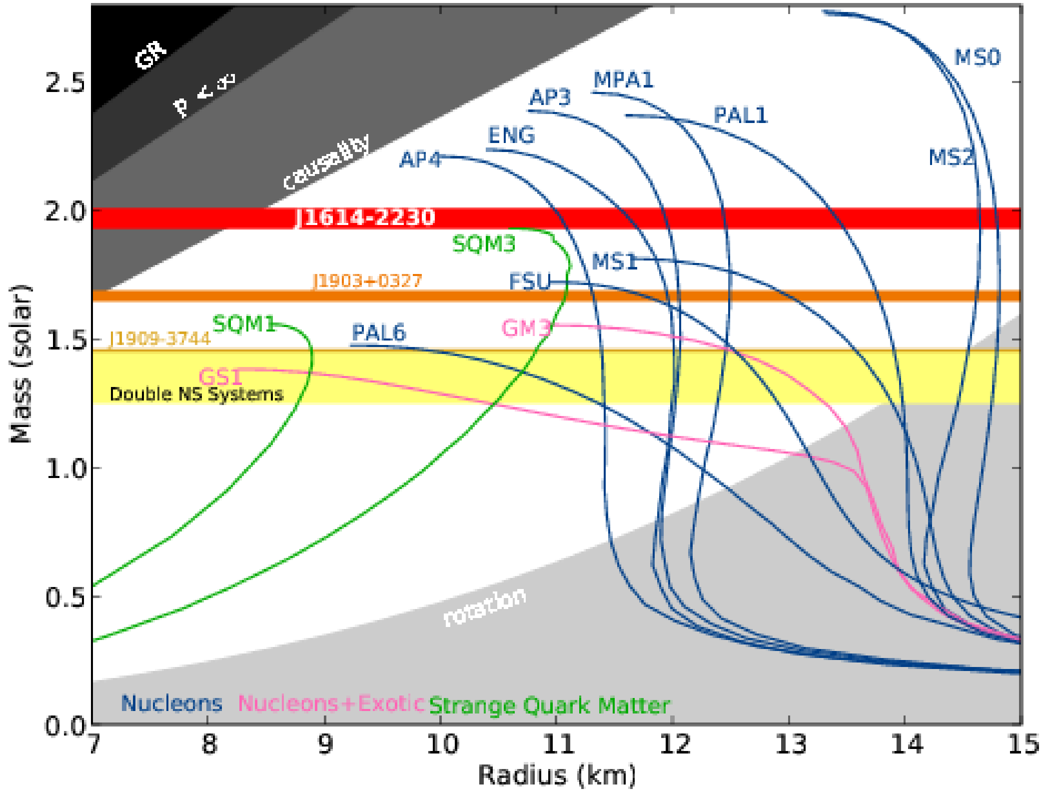
Highest well-known masses of NS



Neutron star (NS) mass-radius diagram for several typical NS equations of state.

Horizontal bands show the observational constraint:

- from J1614–2230 mass measurement,
- similar measurements for tw other millisecond pulsars
- and the range of observed masses for double NS binari



Pulsar J03448+0432

Pulsar J1614-2230

Thank You

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BACK-UP

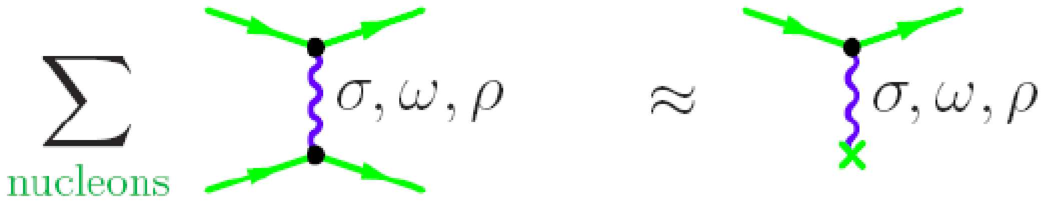
RMF THEORY

$$\mathcal{L} = \sum_N \bar{\mathrm{N}} \Big[i\,(\hat{\partial} + i\, g_{\omega\, N}\hat{\omega} + i\, g_{\rho\, N}\boldsymbol{\tau}\,\hat{\boldsymbol{\rho}}) \Big] - (m - g_{\sigma\, N}\,\sigma) \Big]\, \mathrm{N}$$

$$+ \underbrace{\frac{1}{2}(\partial_\mu \sigma\, \partial^\mu \sigma - m_\sigma^2\, \sigma^2) - U(\sigma)}_{\text{scalar}}$$

$$- \underbrace{\frac{1}{4}\omega_{\mu\nu}\,\omega^{\mu\nu} + \frac{1}{2} m_\omega\, \omega_\mu\, \omega^\nu}_{\text{vector}} - \underbrace{\frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\,\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}\boldsymbol{\rho}_\mu\,\boldsymbol{\rho}^\mu}_{\text{iso-vector}}$$

medium: mean-field approximation



$$\sigma(r,t) = \sigma$$

$$\omega_\mu(r,t) = \delta_{\mu,0}\,\omega_0$$

$$\rho^a_\mu(r,t) = \delta^{a,3}\,\delta_{\mu,0}\,\rho_0^{(3)}$$

constant fields