Neutron Stars : composition and observation

Débora Peres Menezes (UFSC)

01/10/2021

Existing models

- Parameter dependent nuclear models should satisfy some **nuclear bulk properties:**

- Saturation density, binding energy , symmetry energy (and its derivatives), (in)compressibility

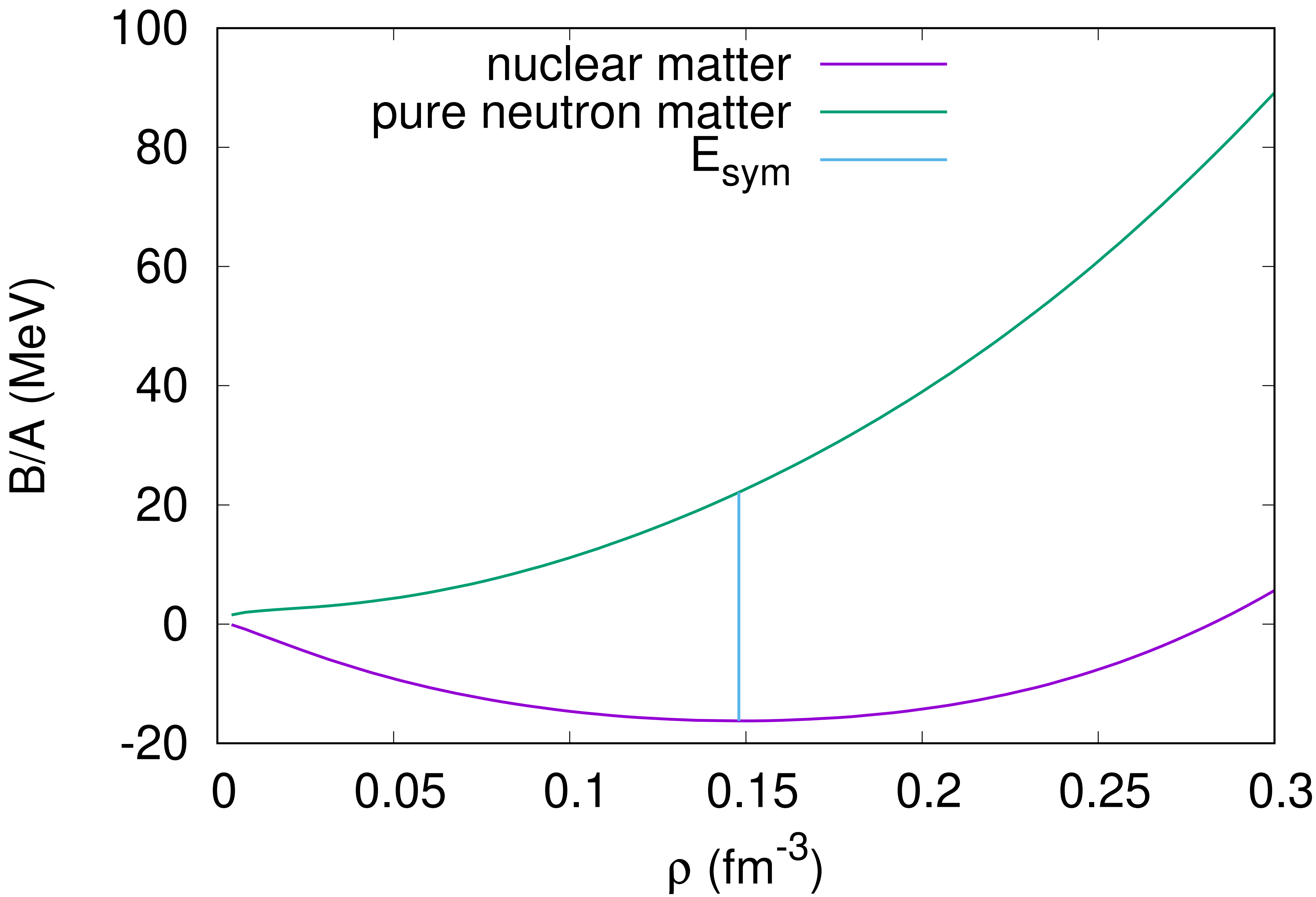
- Many parameters lead to many different models that satisfy them, both **non-relativistic** (Skyrme-type) and **relativistic** ones.

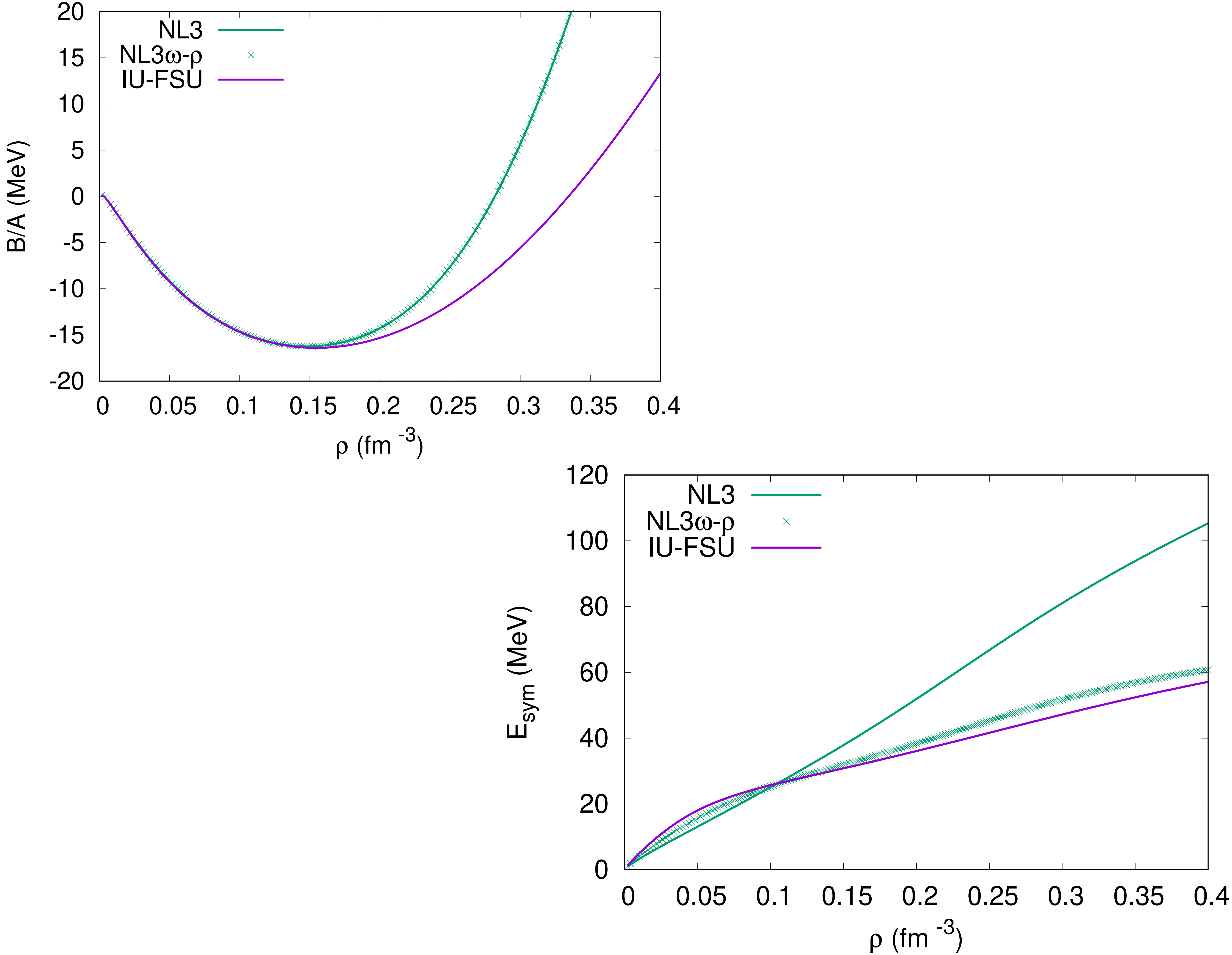
- How to choose?

$$E(\rho_B,\delta) \simeq E(Y_p = 0.5, \rho_B) + E_{sym}(\rho_b)\delta^2$$

$$E_{sym}(\rho_b) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2}|_\delta = 0$$

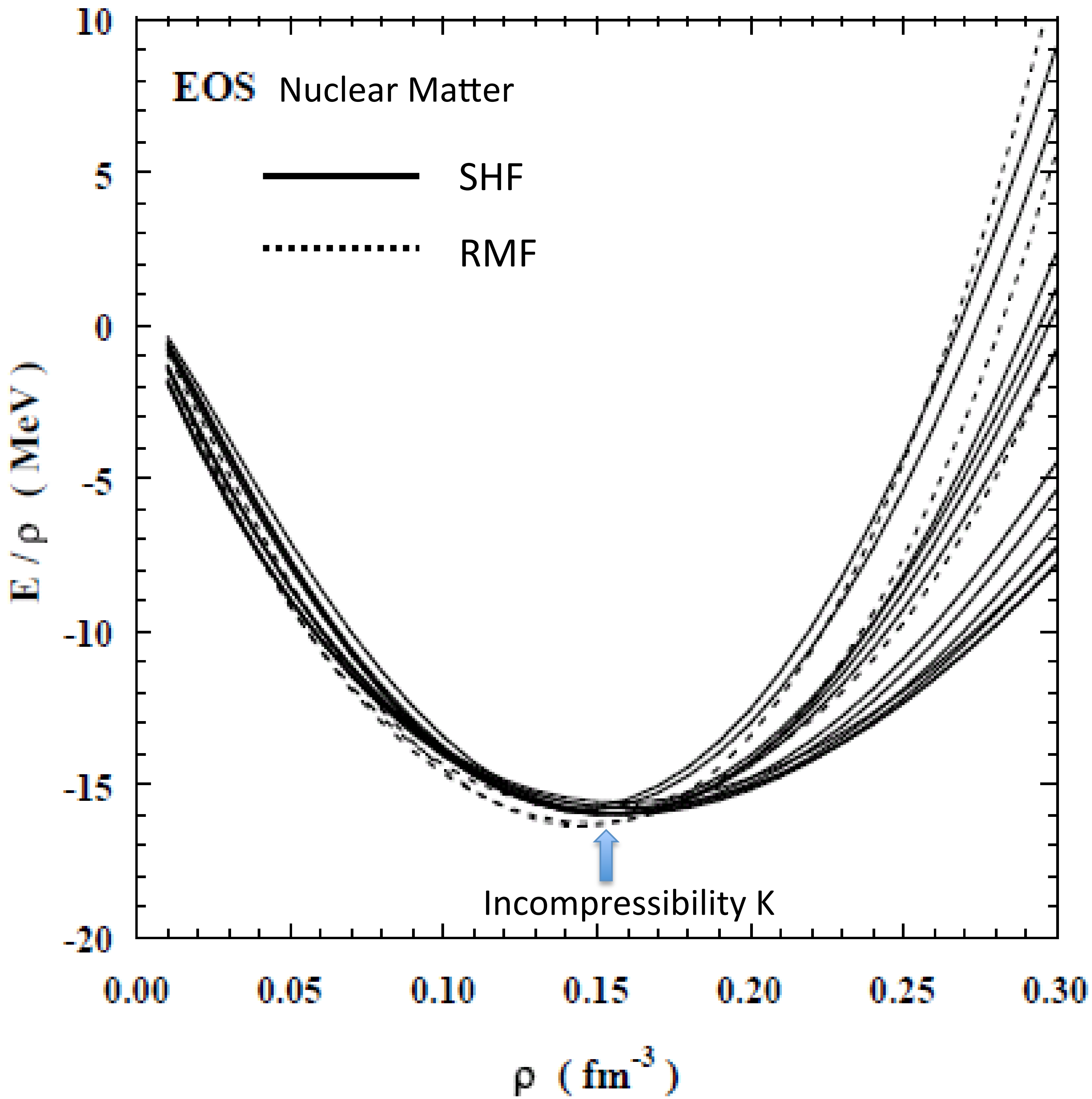
$$\delta = \frac{\rho_n - \rho_p}{\rho_B}, \quad \delta = 0 \rightarrow Y_p = 0.5$$





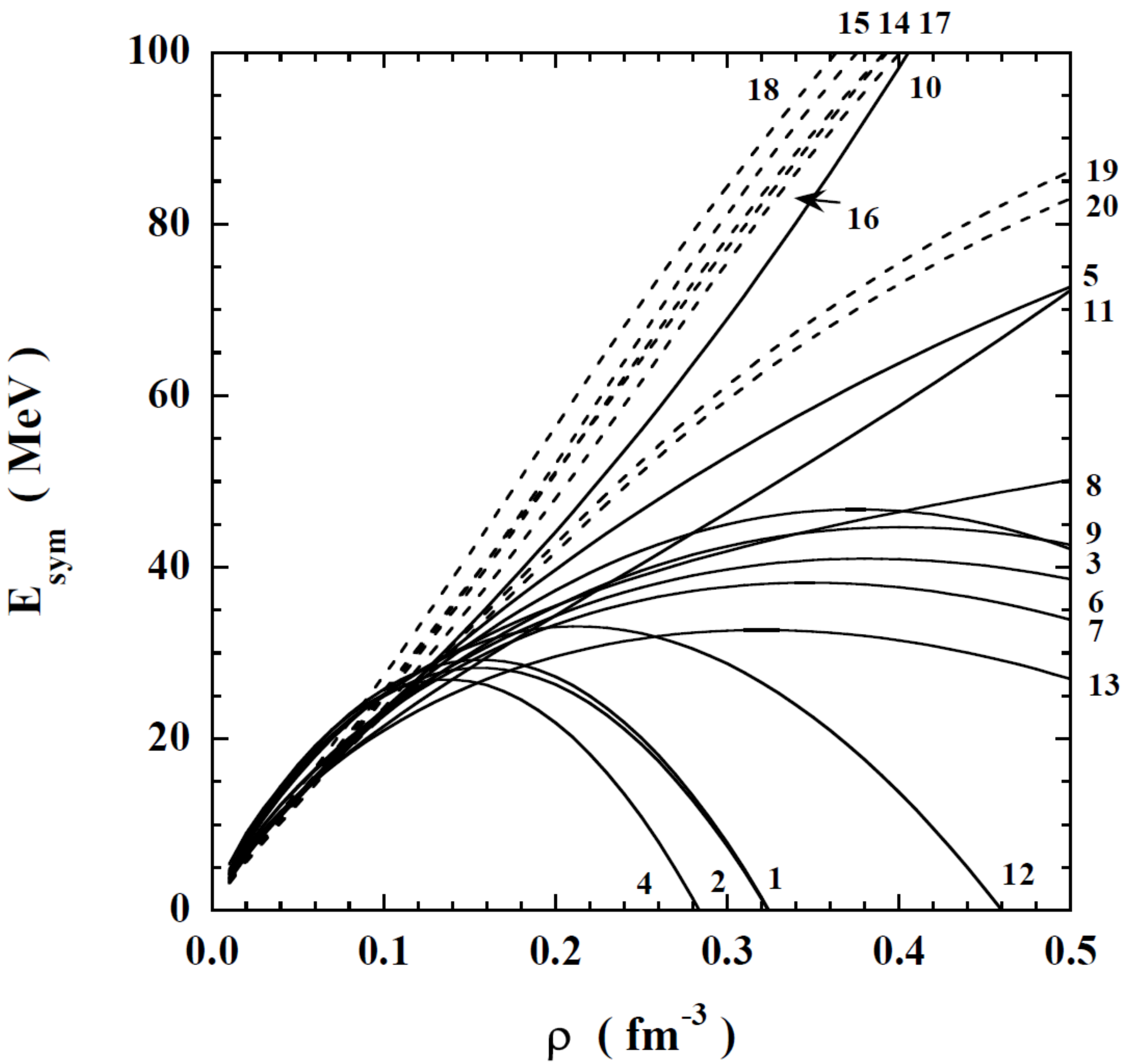
NL3
NL3ω-ρ
IU-FSU
B/A (MeV)
ρ (fm -3)
NL3
NL3ω-ρ
IU-FSU
E_sym (MeV)
ρ (fm -3)

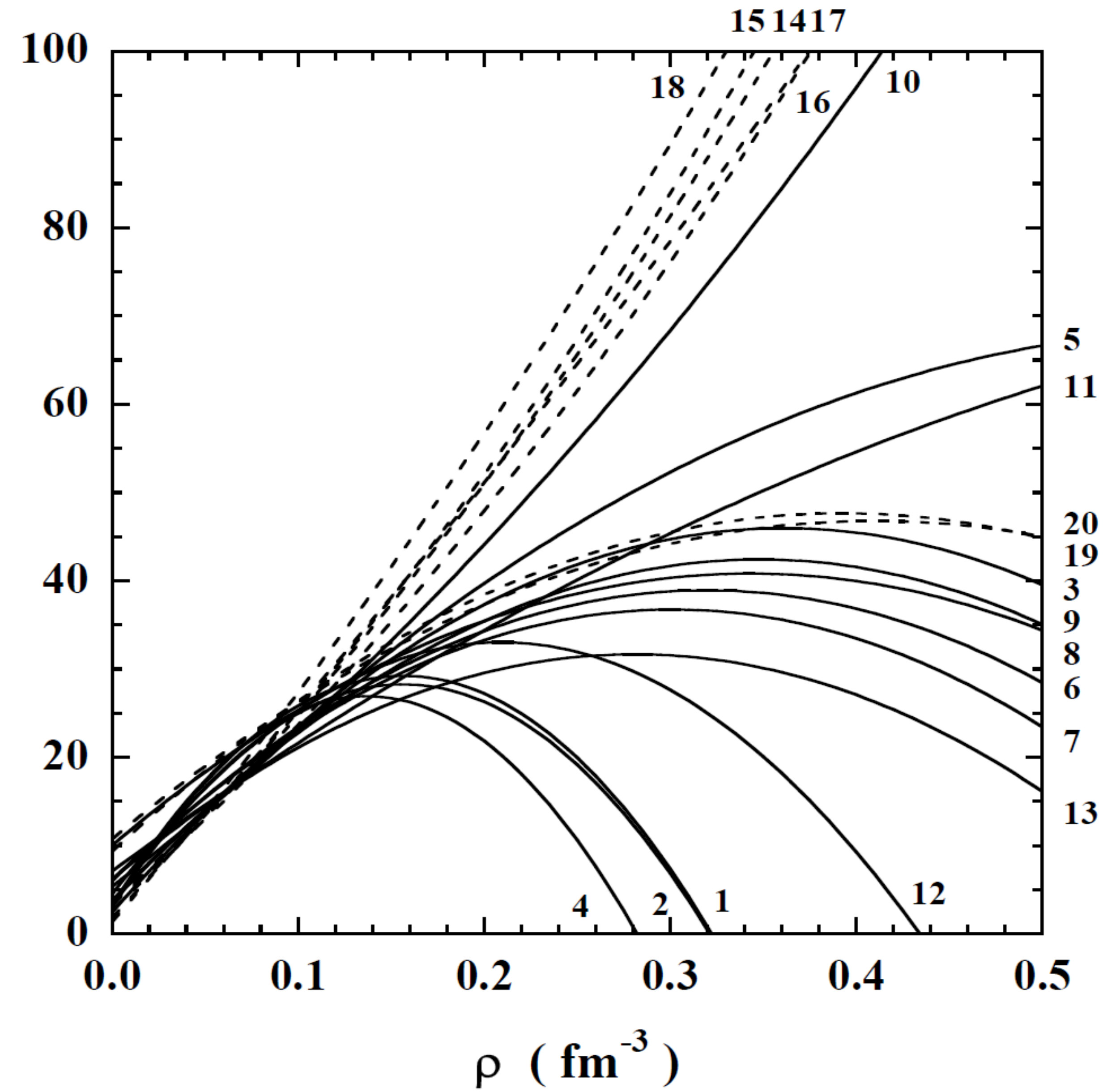
What happens when we move to higher densities? What about finite temperature?



$$\varepsilon_\delta(\rho) = \frac{1}{2} \lim_{I \to 0} \frac{\partial^2}{\partial I^2} \left(\frac{H_{nm}}{\rho} \right)$$

$$\varepsilon_\delta(\rho) = J + \frac{L}{3}\frac{\rho - \rho_{nm}}{\rho_{nm}} + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_{nm}}{\rho_{nm}}\right)^2.$$





$$E_{sym} = J + L(\frac{\rho - \rho_0}{3\rho_0}) + \frac{K_{sym}}{2}(\frac{\rho - \rho_0}{3\rho_0})^2 + \mathcal{O}(3)$$

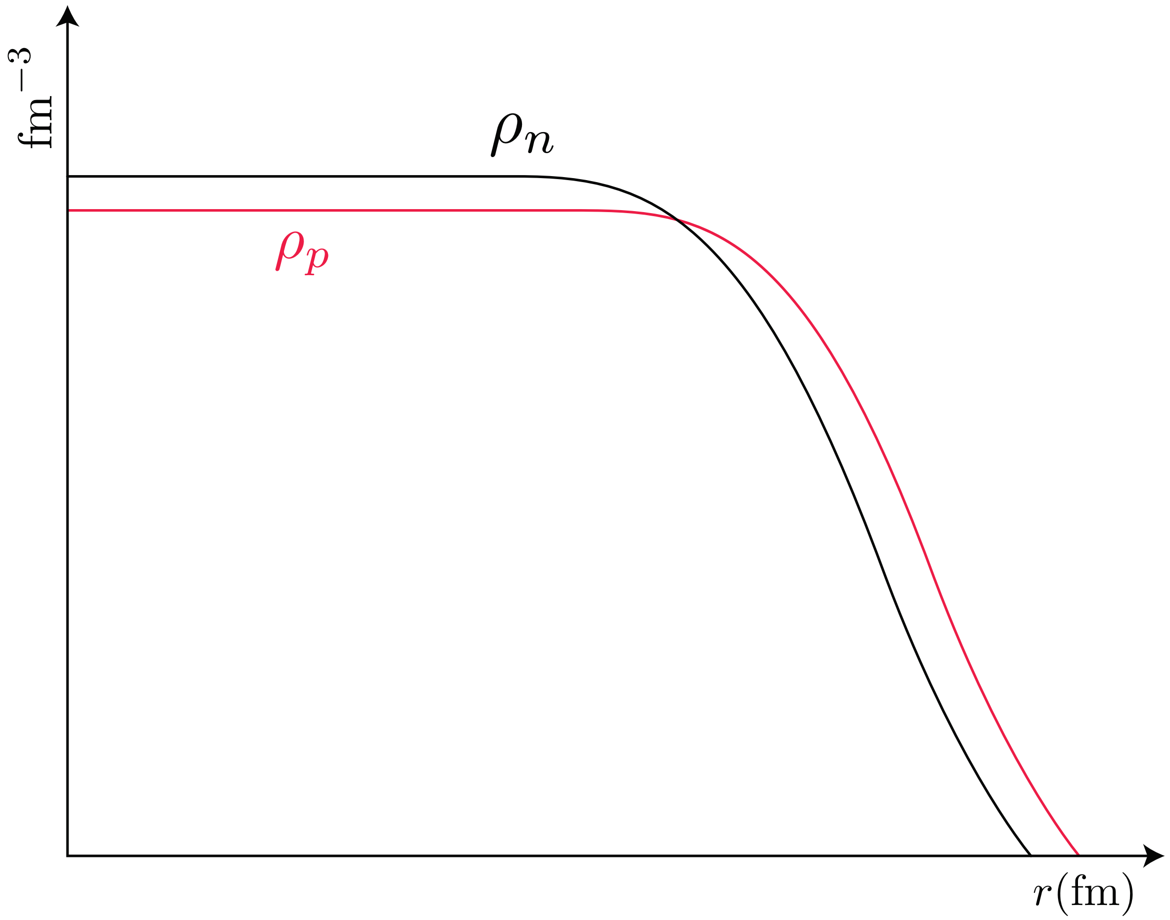
$$L = 3\rho_0 \left(\frac{\partial E_{sym}(\rho)}{\partial \rho} \right)_{\rho=\rho_0}$$

Phys. Lett. B 727, 276 (2013) $25 < L_0 < 115\ \mathrm{MeV}$

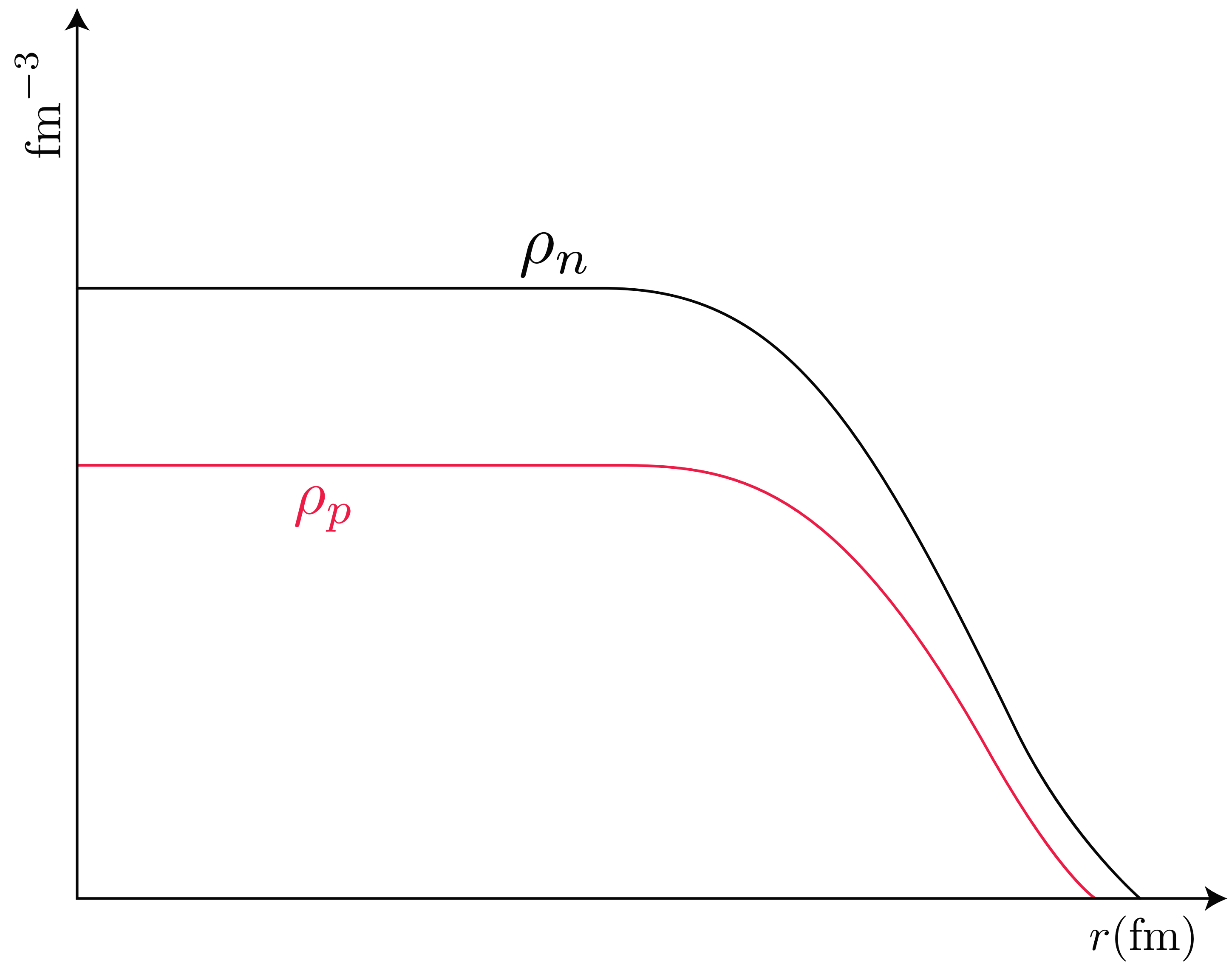
PRC 90, 055203 (2014) $30.6 < L_0 < 80.6\ \mathrm{MeV}$

Slope está correlacionado com a pele de nêutrons e raio da estrela de nêutrons

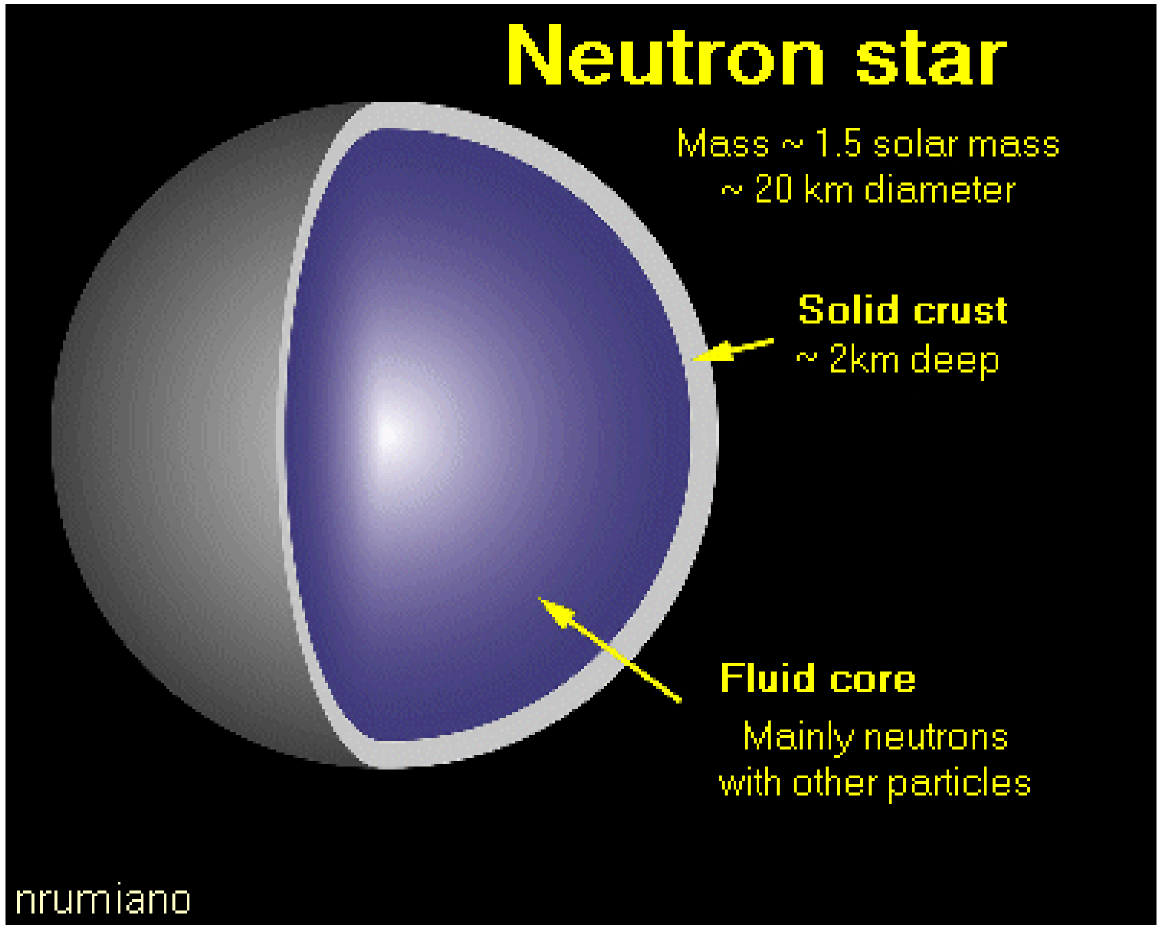
Pele de nêutrons

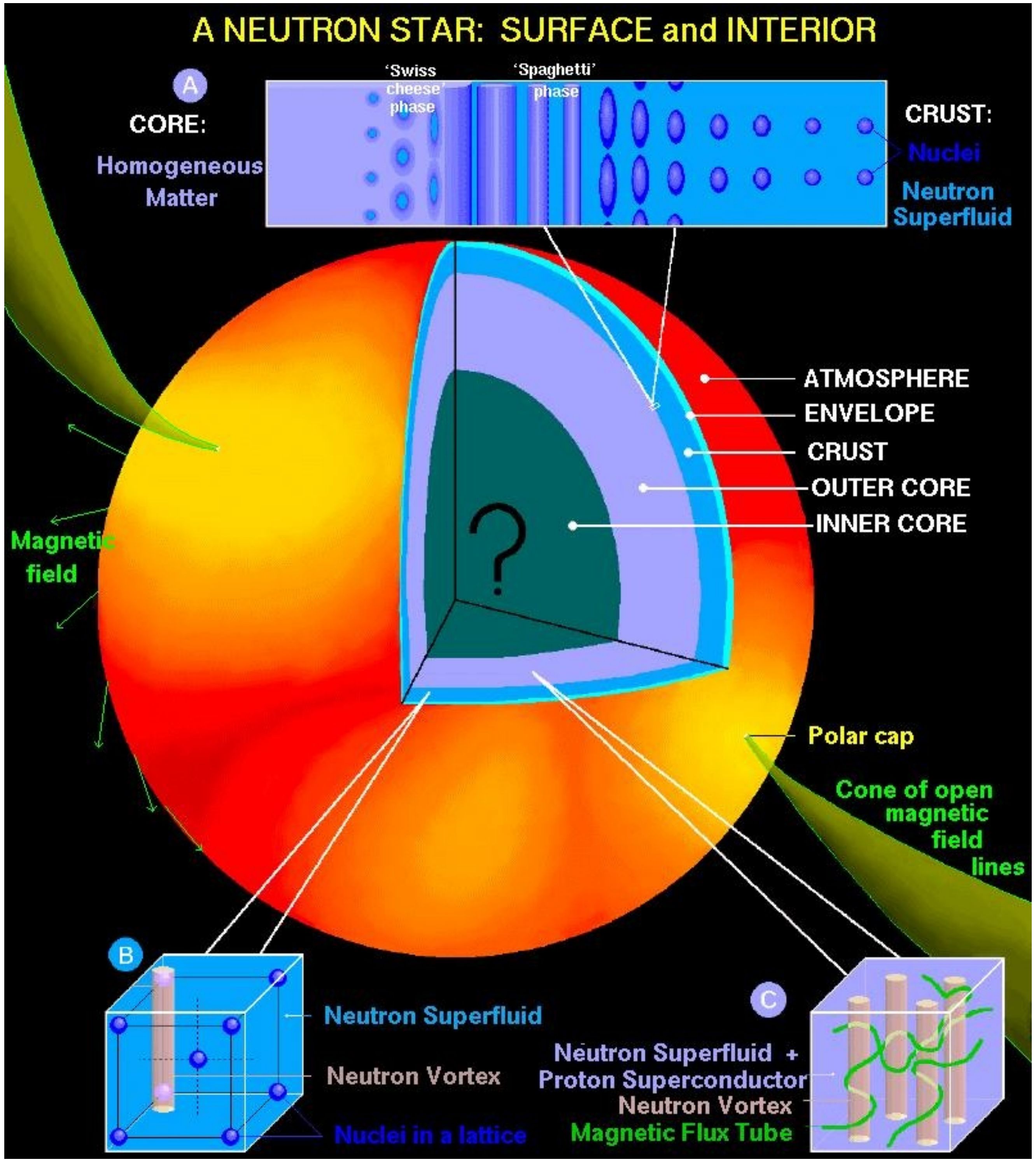


$$R_{\rm skin} = R_n - R_p$$



Structure of a NS





Non-linear models

$$\mathcal{L}_{\rm nm} = \overline{\psi}(i\gamma^\mu\partial_\mu - M)\psi + g_\sigma\sigma\overline{\psi}\psi - g_\omega\overline{\psi}\gamma^\mu\omega_\mu\psi - \frac{g_\rho}{2}\overline{\psi}\gamma^\mu\vec{\rho}_\mu\vec{\tau}\psi + g_\delta\overline{\psi}\vec{\delta}\vec{\tau}\psi,$$

$$\mathcal{L}_\sigma = \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) - \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4,$$

$$\mathcal{L}_\omega = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{C}{4}(g_\omega^2\omega_\mu\omega^\mu)^2,$$

$$\mathcal{L}_\rho = -\frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu,$$

$$\mathcal{L}_\delta = \frac{1}{2}(\partial^\mu\vec{\delta}\partial_\mu\vec{\delta} - m_\delta^2\vec{\delta}^2),$$

$$\mathcal{L}_{\sigma\omega\rho} = g_\sigma g_\omega^2\sigma\omega_\mu\omega^\mu\left(\alpha_1 + \frac{1}{2}{\alpha_1}'g_\sigma\sigma\right) + g_\sigma g_\rho^2\sigma\vec{\rho}_\mu\vec{\rho}^\mu\left(\alpha_2 + \frac{1}{2}{\alpha_2}'g_\sigma\sigma\right) + \frac{1}{2}{\alpha_3}'g_\omega^2 g_\rho^2\omega_\mu\omega^\mu\vec{\rho}_\mu\vec{\rho}^\mu$$

Baryon	M (MeV)	q content	J	$\vec{\tau}$	τ_3	S	electric charge
p	938.28	uud	$1/2$	$1/2$	$+1/2$	0	1
n	939.57	udd	$1/2$	$1/2$	-1/2	0	0
Λ	1115.6	uds	$1/2$	0	0	-1	0
Σ^+	1189.4	uus	$1/2$	1	$+1$	-1	$+1$
Σ^0	1192.5	uds	$1/2$	1	0	-1	0
Σ^-	1197.3	dds	$1/2$	1	-1	-1	$+1$
Ξ^0	1314.9	uss	$1/2$	$1/2$	$+1/2$	-2	0
Ξ^-	1321.3	dss	$1/2$	$1/2$	-1/2	-2	-1

Stellar matter is subjet to **chemical equilibrium** and **charge neutrality** conditions:

$$\mu_{\Sigma^+} = \mu_p = \mu_n - \mu_e, \quad \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_\Lambda = \mu_n, \quad \mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_n + \mu_e$$

$$\sum_B q_B \rho_B + \sum_l q_l \rho_l = 0$$

RMF - usual steps:

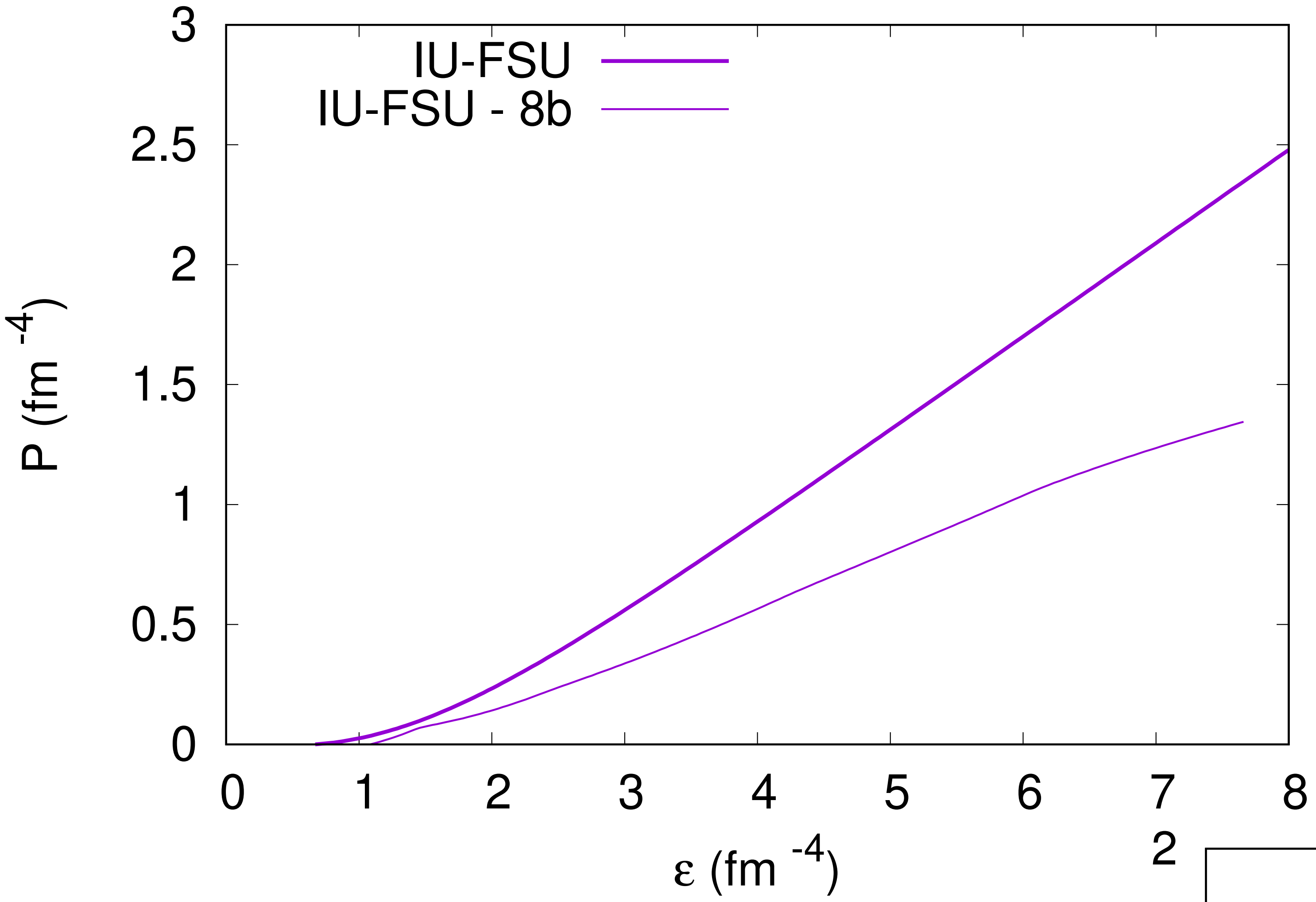
Mean-field approximation (the meson fields are treated as classical fields)

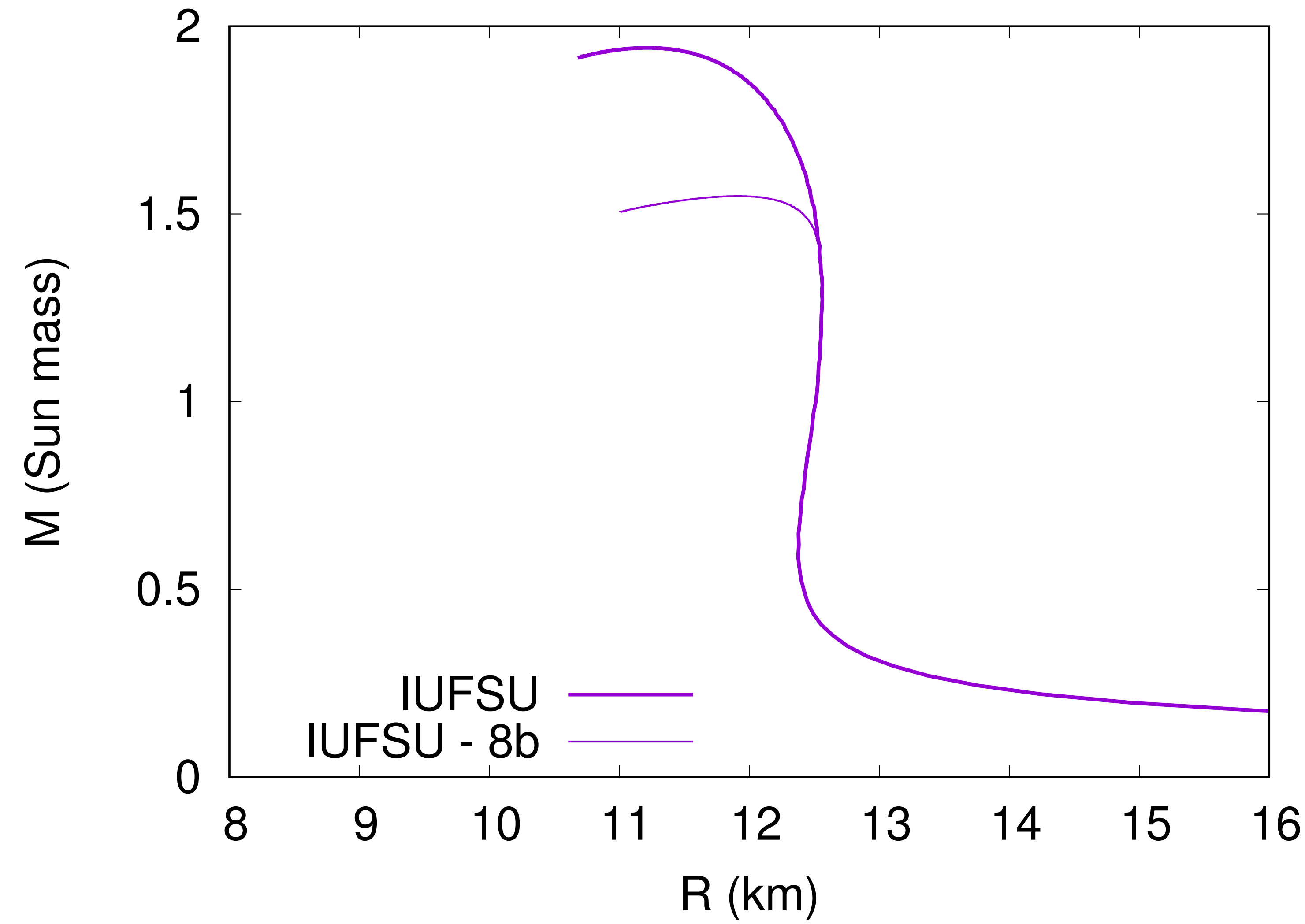
Euler-Lagrange equations → equations of motion (translational and rotational invariance) → energy-momentum tensor → EoS

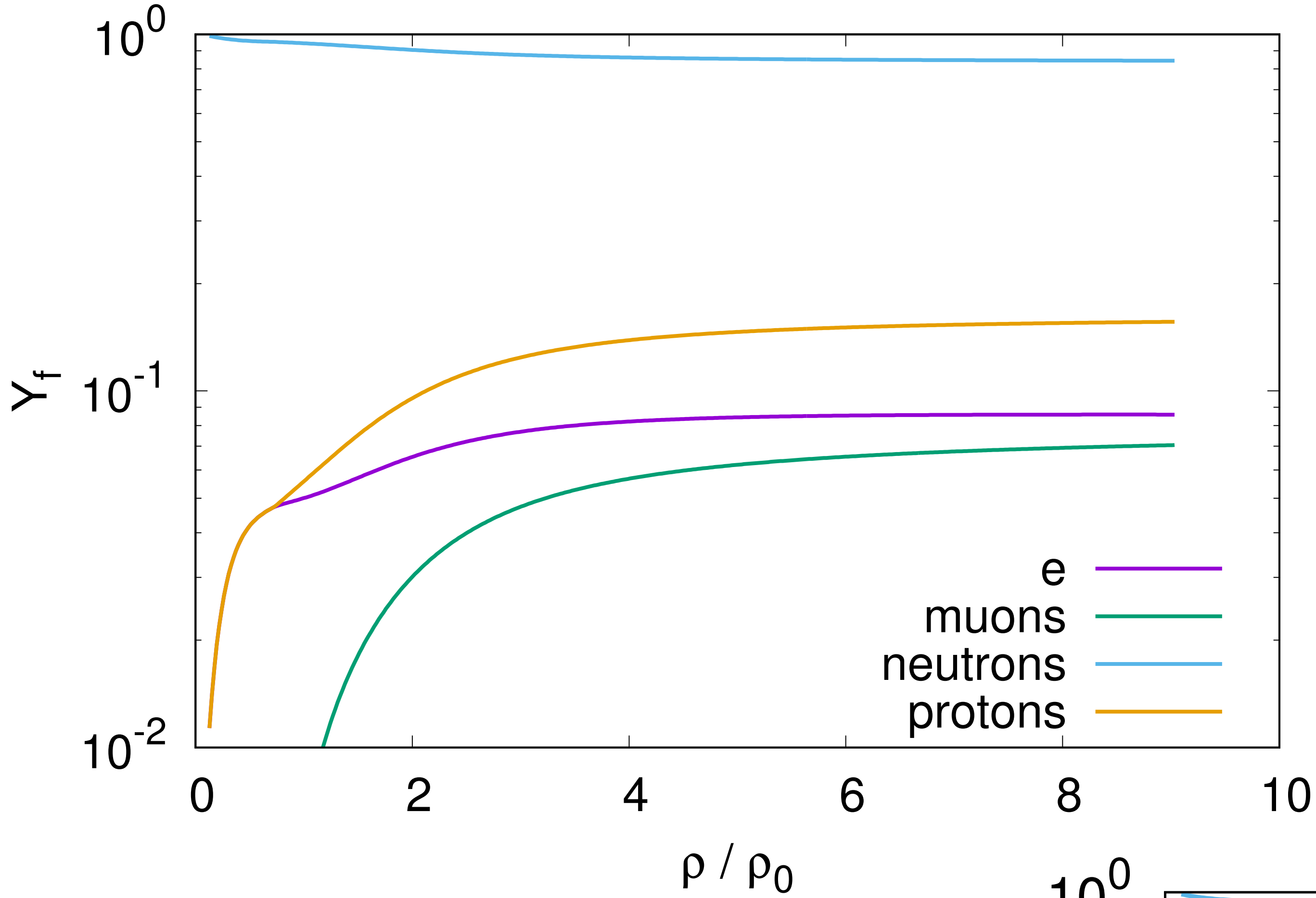
EoS is input to the Tolman-Oppenheimer-Volkoff equations:

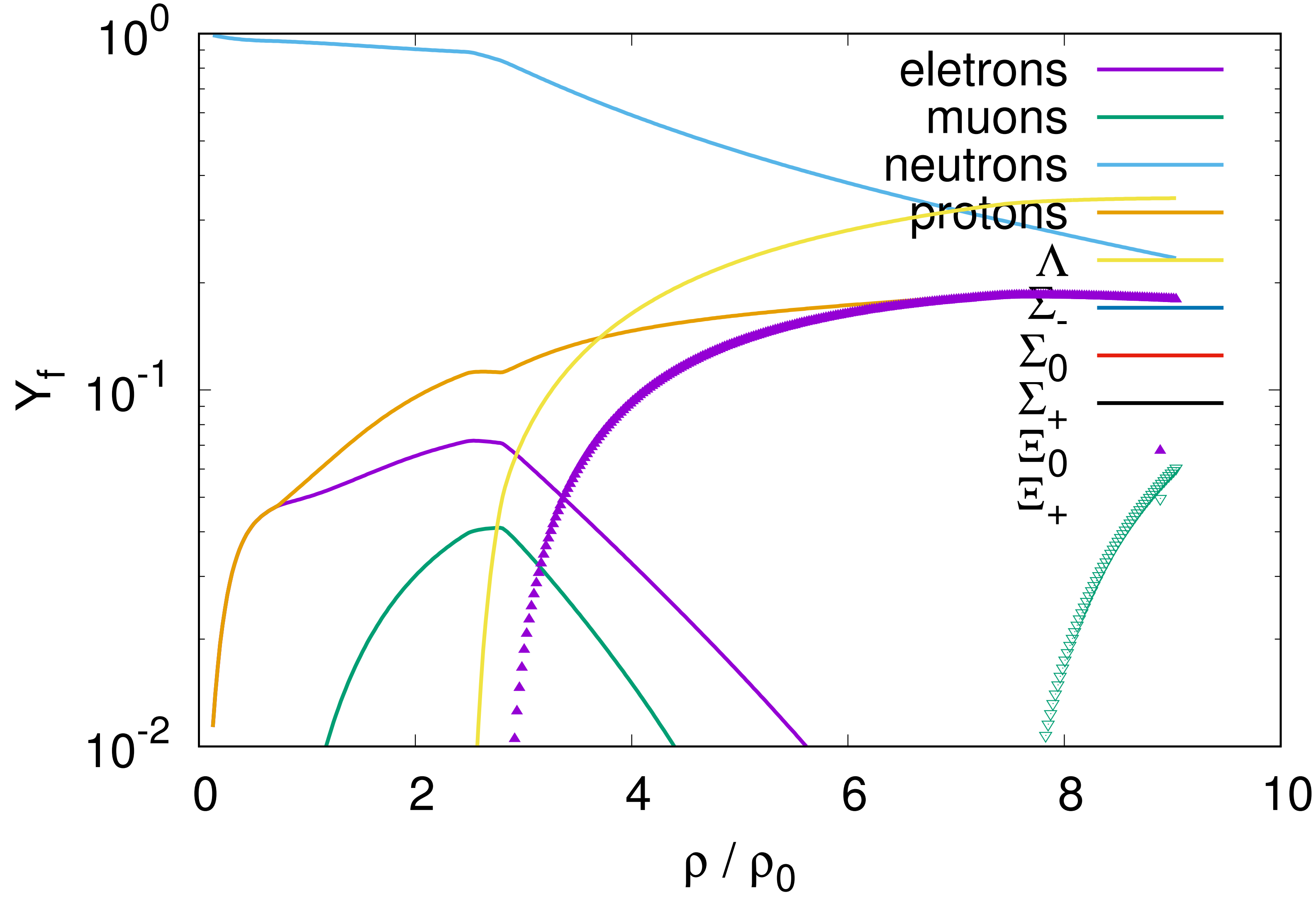
$$\frac{dP}{dr} = -\frac{G}{r}\frac{[\varepsilon + P]\left[M + 4\pi r^3 P\right]}{(r - 2GM)}$$

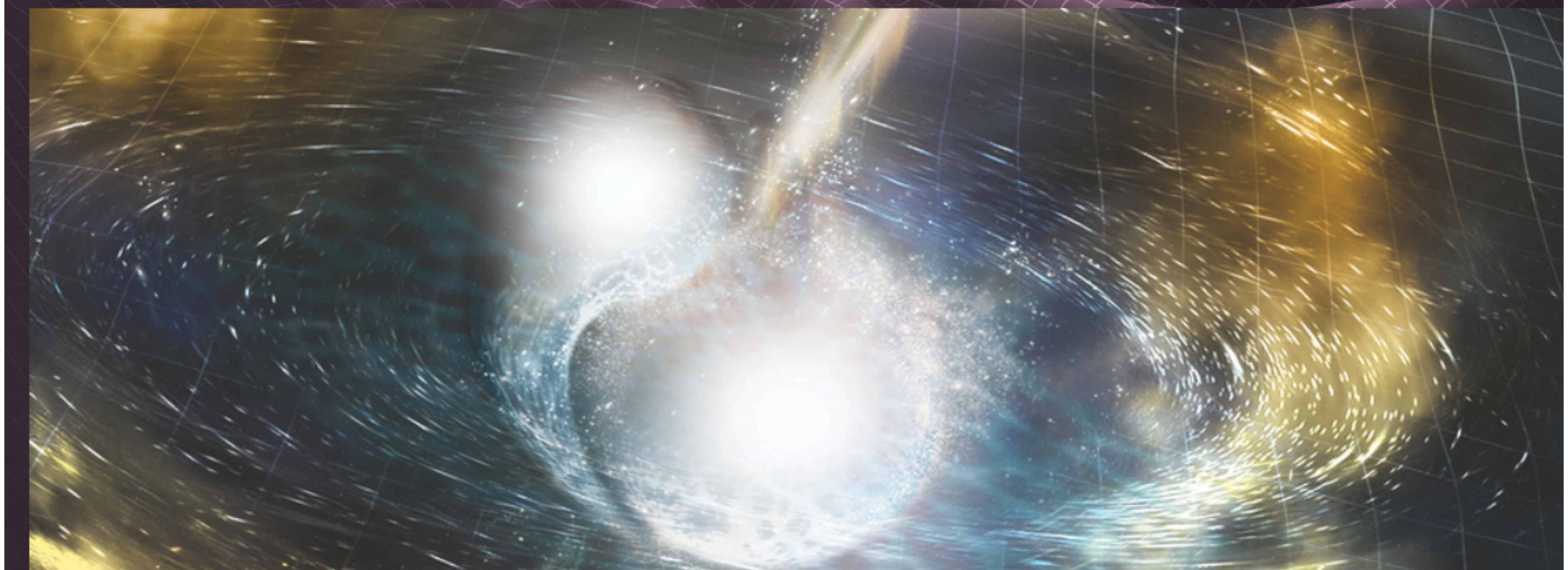
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon$$


IU-FSU
IU-FSU - 8b
P (fm -4)
ε (fm -4)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6
7
8


IUFSU
IUFSU - 8b
M (Sun mass)
R (km)
0
0.5
1
1.5
2
8
9
10
11
12
13
14
15
16


Y_f
ρ / ρ_0
e
muons
neutrons
protons


Y_f
ρ / ρ_0
eletrons
muons
neutrons
protons
Λ
Σ-
Σ0
Σ+
Ξ0
Ξ+



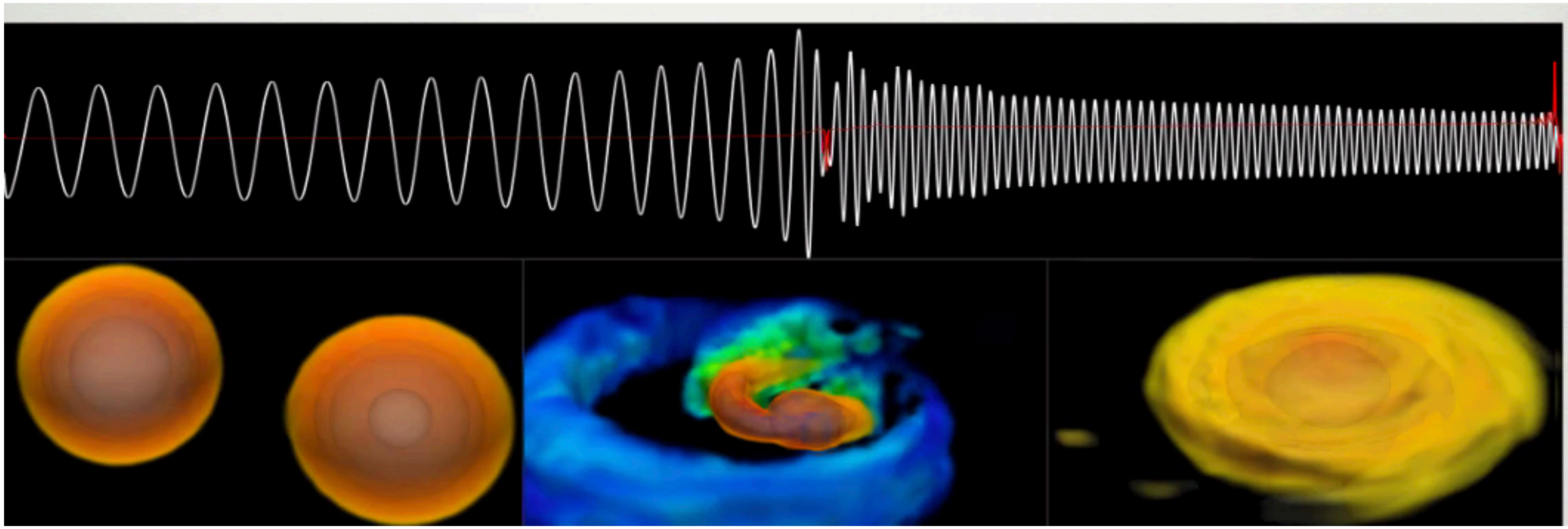
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

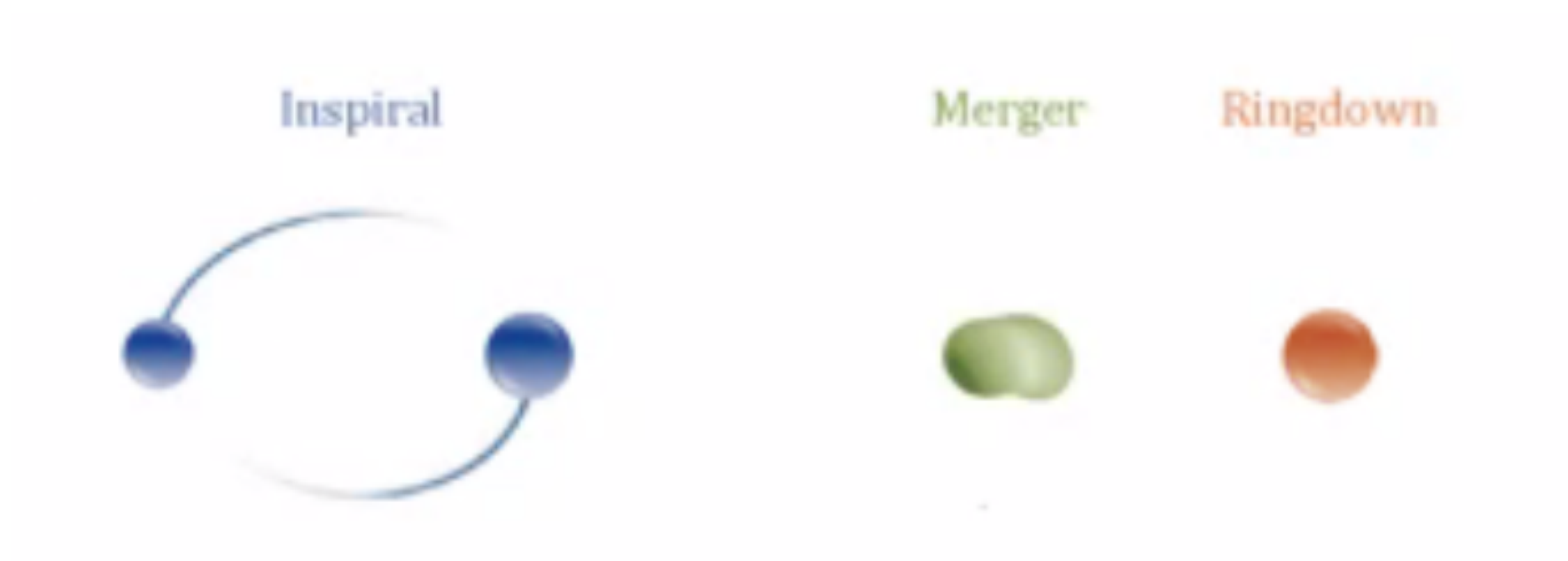
GW170817 Press Release

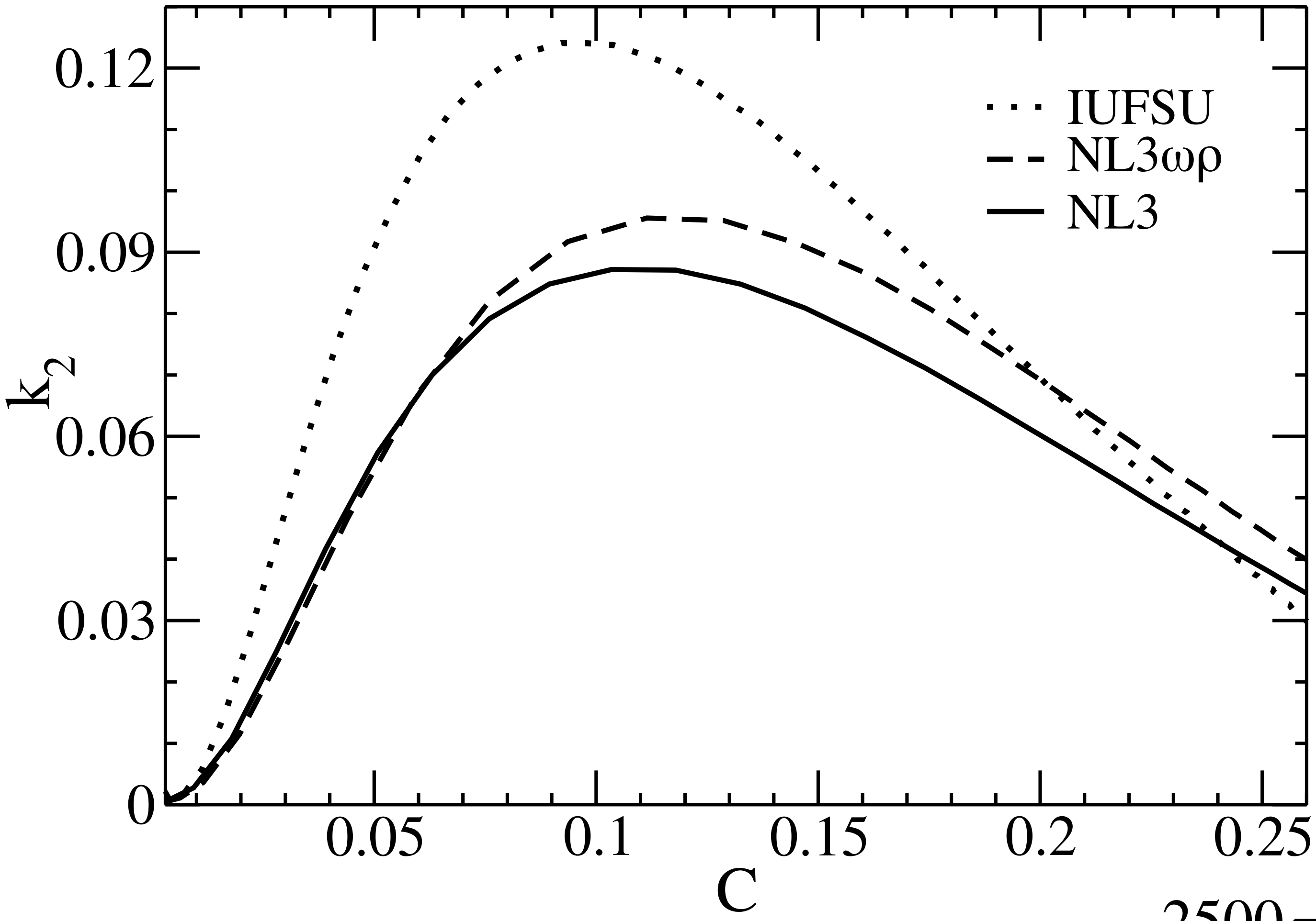
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.

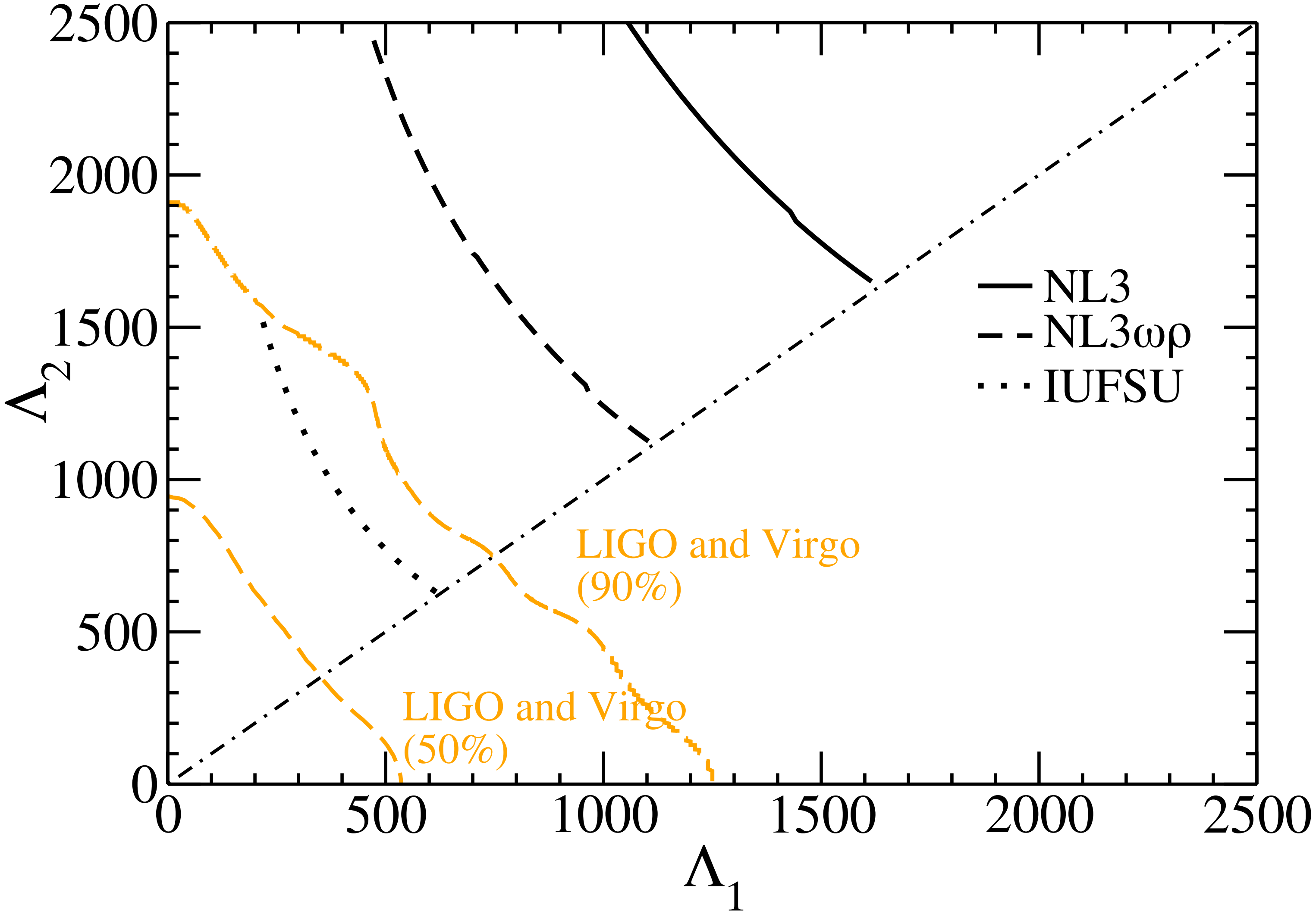
Watch the recording of a press conference announcing the discovery, at the National Press Club in Washington, DC:




Inspiral
Merger
Ringdown



IUFSU
NL3ωρ
NL3
k2
C
0.12
0.09
0.06
0.03
0
0.05
0.1
0.15
0.2
0.25



NL3
NL3ωρ
IUFSU
LIGO and Virgo
(90%)
LIGO and Virgo
(50%)
Λ2
Λ1
2500
2000
1500
1000
500
0

RMF Models - (relativistic) :

263 tested - nuclear bulk properties

M. Dutra et al, PRC 90, 055203 (2014)

35 approved

34 tested - astrophysical constraints

M. Dutra, O.Lourenço, DPM, PRC 93, 025806 (2016)

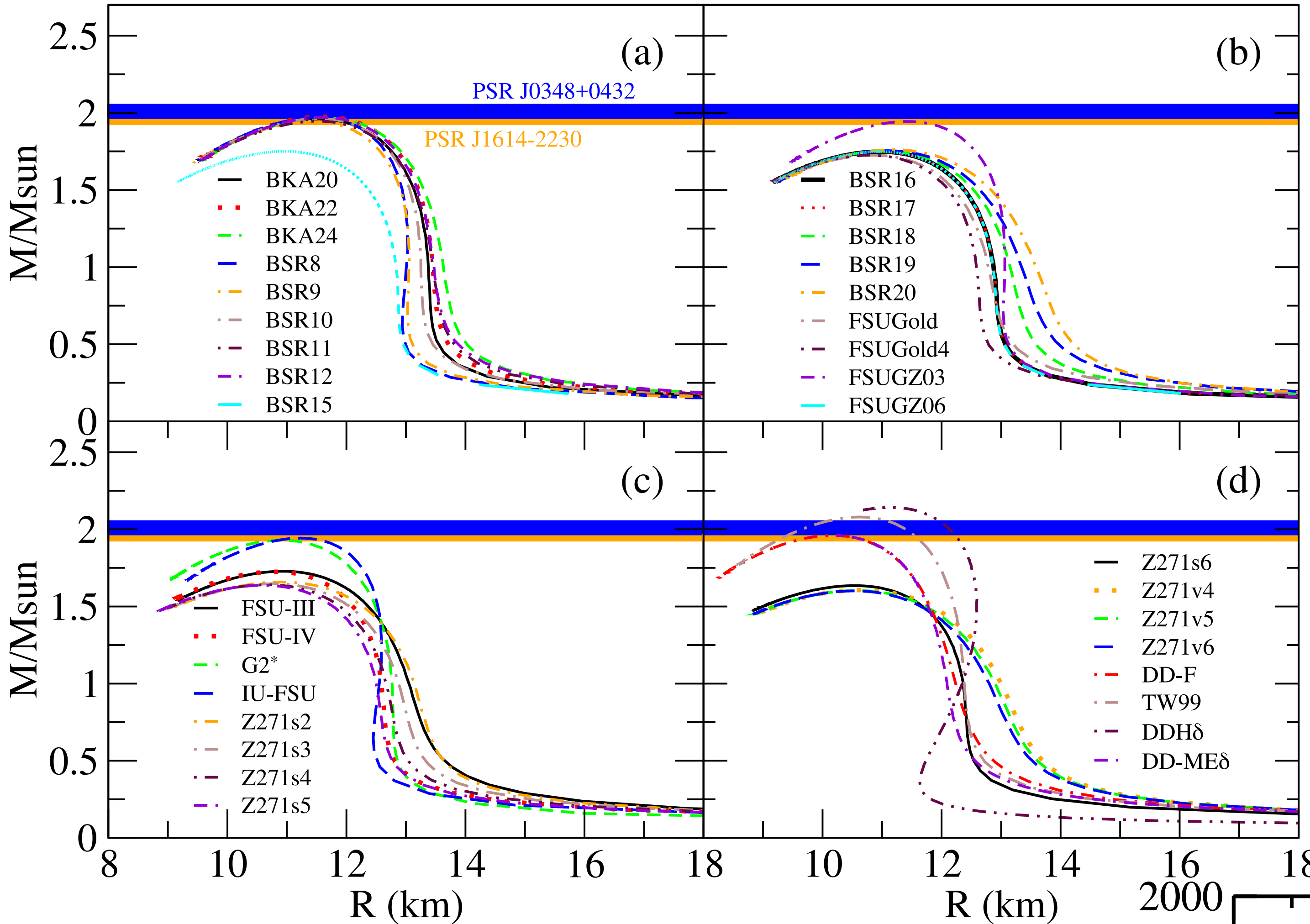
15 approved - can sustain massive NS

34 tested - GW170817

O. Lourenço, M. Dutra, C. Lenzi, C. V. Flores, DPM, PRC 99, 045202 (2019)

24 approved - lie inside tidal polarizabilities confidence lines

Only 5 can describe massive NS and satisfy GW170817



But now…

PSR J0740+6620

$$2.07 \pm 0.08\ M_\odot$$

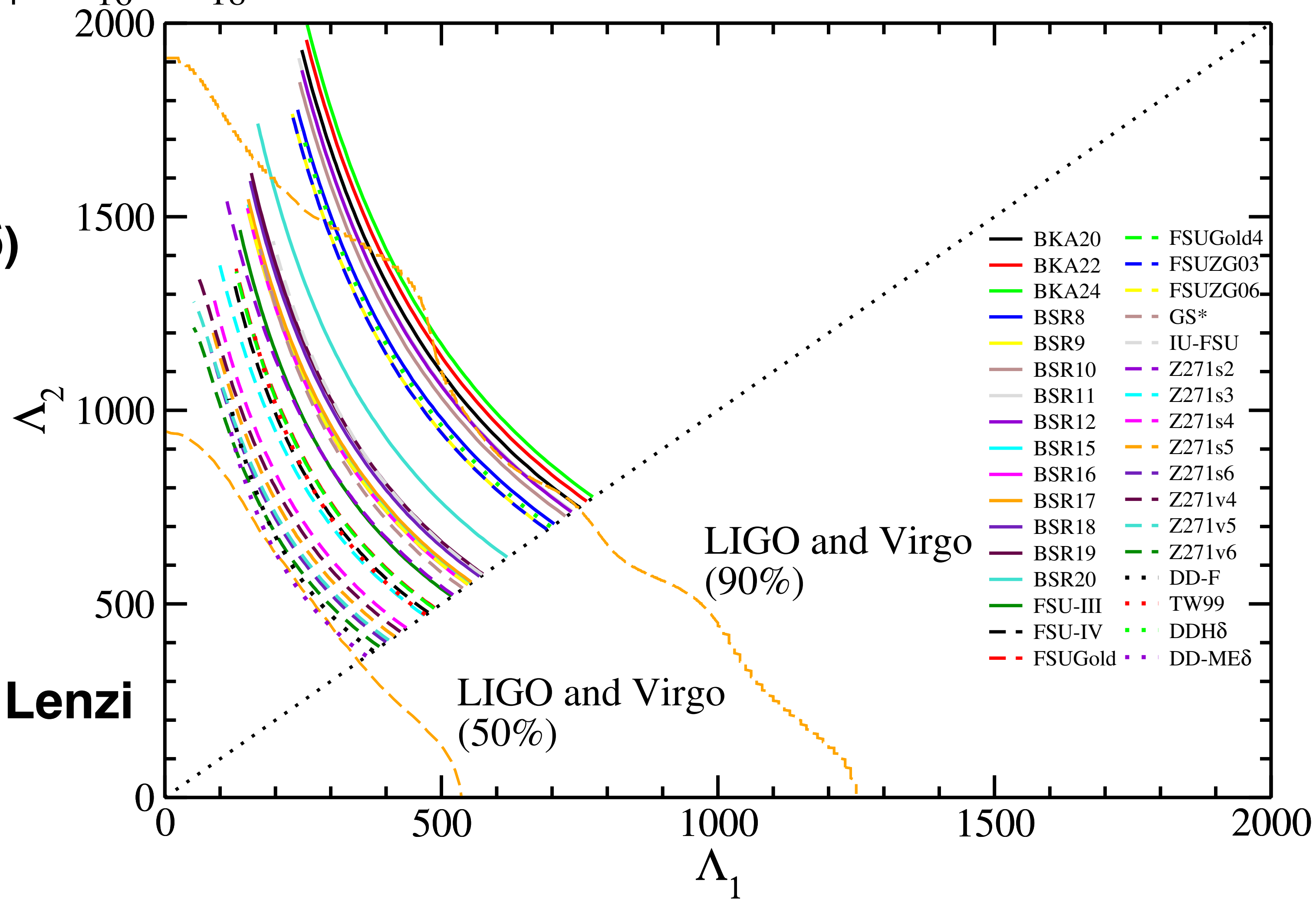
H.~Cromartie et al: Nat. Astr. (2019)
M.C.Miller et al, arXiv: 2105.06979

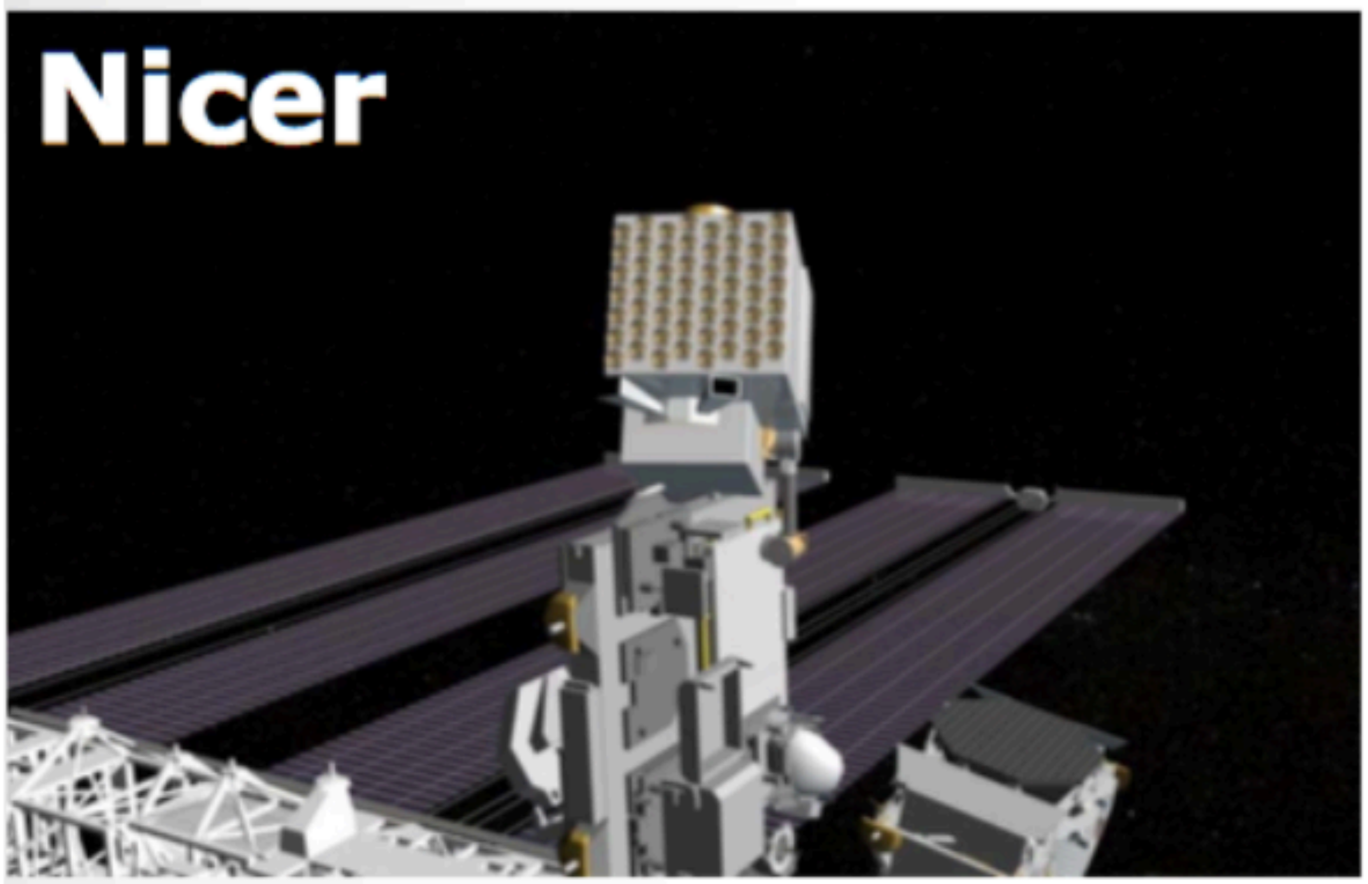
Not mentioning the hyperon puzzle

Mariana Dutra, Odilon Lourenço, DPM, Phys. Rev. C 93, 025806 (2016)

5 modelos satisfazem ambos

Odilon Lourenço, Mariana Dutra, César H. Lenzi Cesar V. Flores and DPM, Phys. Rev. C 99, 045202 (2019).





Main NS manifestations:

- Pulsars - powered by rotation energy (1900 observed in radio-frequency)

- Accreting X-Ray Binaries powered by gravitational energy rotation periods 0.0015-1000 s)

$$M = M_\odot \simeq 10^{30}\ Kg$$

$$\rho = M/R^3 \simeq 10^{18} Kg/l$$

$$R \simeq 10Km$$

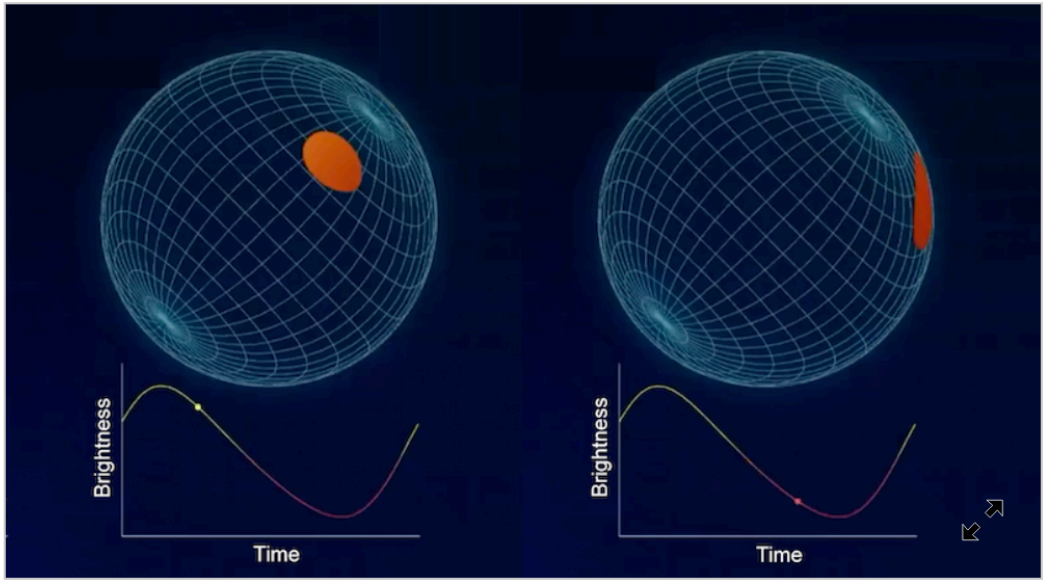
NS interior composition explorer - 06/2017

RESEARCH NEWS

Sizing Up the Most Massive Neutron Star

April 29, 2021 • *Physics* 14, 64

A satellite experiment has revealed that the heaviest known neutron star is unexpectedly large, which suggests that the matter in the star's inner core is less "squeezable" than some models predict.



Goddard Space Flight Center

NICER measures the size of a neutron star by tracking the x-ray emission from "hot spots" on the surface as the star rotates. These spots occur at the magnetic poles of the star, where the field slams particles onto the star surface.

Neutron stars are "cosmic zombies"—corpses of massive stars that collapsed in violent explosions after running out of fuel. By studying these ultradense objects, researchers hope to understand the behavior of matter under extreme conditions, which might help in cracking some of the biggest mysteries in physics. As announced at a press conference during the 2021 APS April meeting, NASA's Neutron star Interior Composition Explorer (NICER), an x-ray telescope on the International Space Station, has measured the size of the heaviest known neutron star. The surprisingly large radius measured for this star implies a stiffer-than-expected state of matter in the core, disfavoring models that predict a "squishy" center.

E os raios? Quais os vínculos?

GW170817

$$70 < \Lambda_{1.4} < 580$$

$$10.5 \text{ km} \leq R_{1.4\ M_\odot} \leq 13.4 \text{ km}$$

Capano et al, Nat. Astr. (2020)

$$R_{1.4\ M_\odot} \leq 11.9 \text{ km}$$

NICER

Miller et al, arXiv 2105.06979

PSR J0740+6620

$$2.07 \pm 0.08 \text{ M}_\odot$$

$$11.6 \text{ km} < R < 13.1 \text{ km}$$

PSR J0030+0451

$$11.8 \text{ km} < R_{1.4\ \text{M}_\odot} < 13.1 \text{ km}$$

PHYSICAL REVIEW LETTERS **126,** 172502 (2021)

Editors' Suggestion   Featured in Physics

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K. Aniol,[4] D. S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S. Barcus,[6] V. Bellini,[7] R. S. Beminiwattha,[8] J. F. Benesch,[6] H. Bhatt,[9] D. Bhatta Pathak,[8] D. Bhetuwal,[9] B. Blaikie,[10] Q. Campagna,[5] A. Camsonne,[6] G. D. Cates,[11] Y. Chen,[8] C. Clarke,[12] J. C. Cornejo,[13] S. Covrig Dusa,[6] P. Datta,[14] A. Deshpande,[12,15] D. Dutta,[9] C. Feldman,[12] E. Fuchey,[14] C. Gal,[12,11,15] D. Gaskell,[6] T. Gautam,[16] M. Gericke,[10] C. Ghosh,[17,12] I. Halilovic,[10] J.-O. Hansen,[6] F. Hauenstein,[18] W. Henry,[19] C. J. Horowitz,[20] C. Jantzi,[11] S. Jian,[11] S. Johnston,[17] D. C. Jones,[19] B. Karki,[21] S. Katugampola,[11] C. Keppel,[6] P. M. King,[21] D. E. King,[22] M. Knauss,[23] K. S. Kumar,[17] T. Kutz,[12] N. Lashley-Colthirst,[16] G. Leverick,[10] H. Liu,[17] N. Liyange,[11] S. Malace,[6] R. Mammei,[24] J. Mammei,[10] M. McCaughan,[6] D. McNulty,[1] D. Meekins,[6] C. Metts,[5] R. Michaels,[6] M. M. Mondal,[12,15] J. Napolitano,[19] A. Narayan,[25] D. Nikolaev,[19] M. N. H. Rashad,[18] V. Owen,[5] C. Palatchi,[11,15] J. Pan,[10] B. Pandey,[16] S. Park,[12] K. D. Paschke,[11,*] M. Petrusky,[12] M. L. Pitt,[26] S. Premathilake,[11] A. J. R. Puckett,[14] B. Quinn,[13] R. Radloff,[21] S. Rahman,[10] A. Rathnayake,[11] B. T. Reed,[20] P. E. Reimer,[27] R. Richards,[12] S. Riordan,[27] Y. Roblin,[6] S. Seeds,[14] A. Shahinyan,[28] P. Souder,[22] L. Tang,[6,16] M. Thiel,[29] Y. Tian,[22] G. M. Urciuoli,[30] E. W. Wertz,[5] B. Wojtsekhowski,[6] B. Yale,[5] T. Ye,[12] A. Yoon,[31] A. Zec,[11] W. Zhang,[12] J. Zhang,[12,15,32] and X. Zheng[11]

(PREX Collaboration)

$$R_{\text{skin}} = 0.283 \pm 0.071\text{fm}$$

PHYSICAL REVIEW LETTERS 126, 172503 (2021)

Editors' Suggestion

Implications of PREX-2 on the Equation of State of Neutron-Rich Matter

Brendan T. Reed,[1,2,*] F. J. Fattoyev,[3,†] C. J. Horowitz,[2,‡] and J. Piekarewicz[4,§]
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[2]Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA
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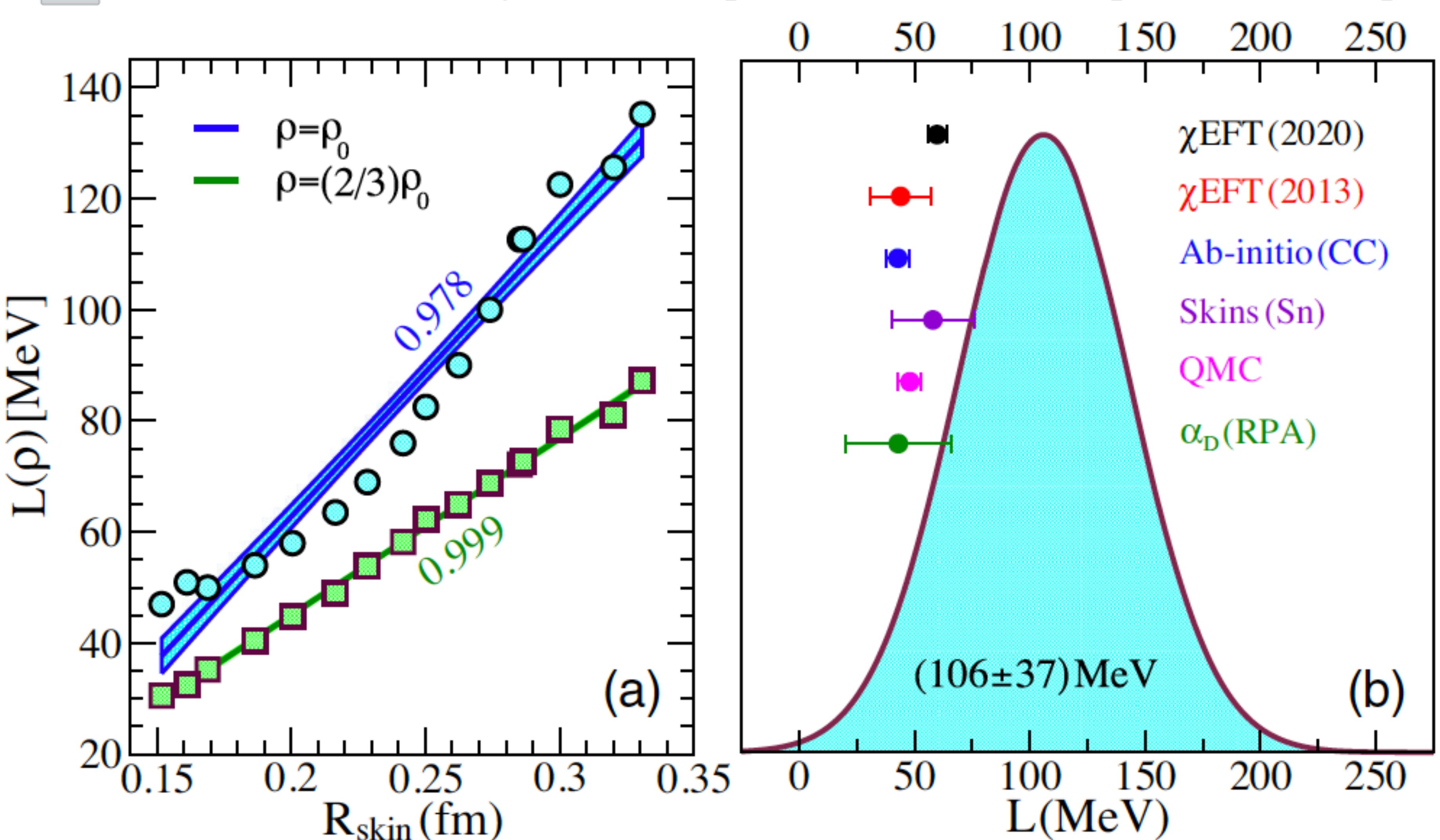
(Received 24 February 2021; accepted 31 March 2021; published 27 April 2021)



$$E_{sym} = J + L(\frac{\rho - \rho_0}{3\rho_0}) + \frac{K_{sym}}{2}(\frac{\rho - \rho_0}{3\rho_0})^2 + \mathcal{O}(3)$$

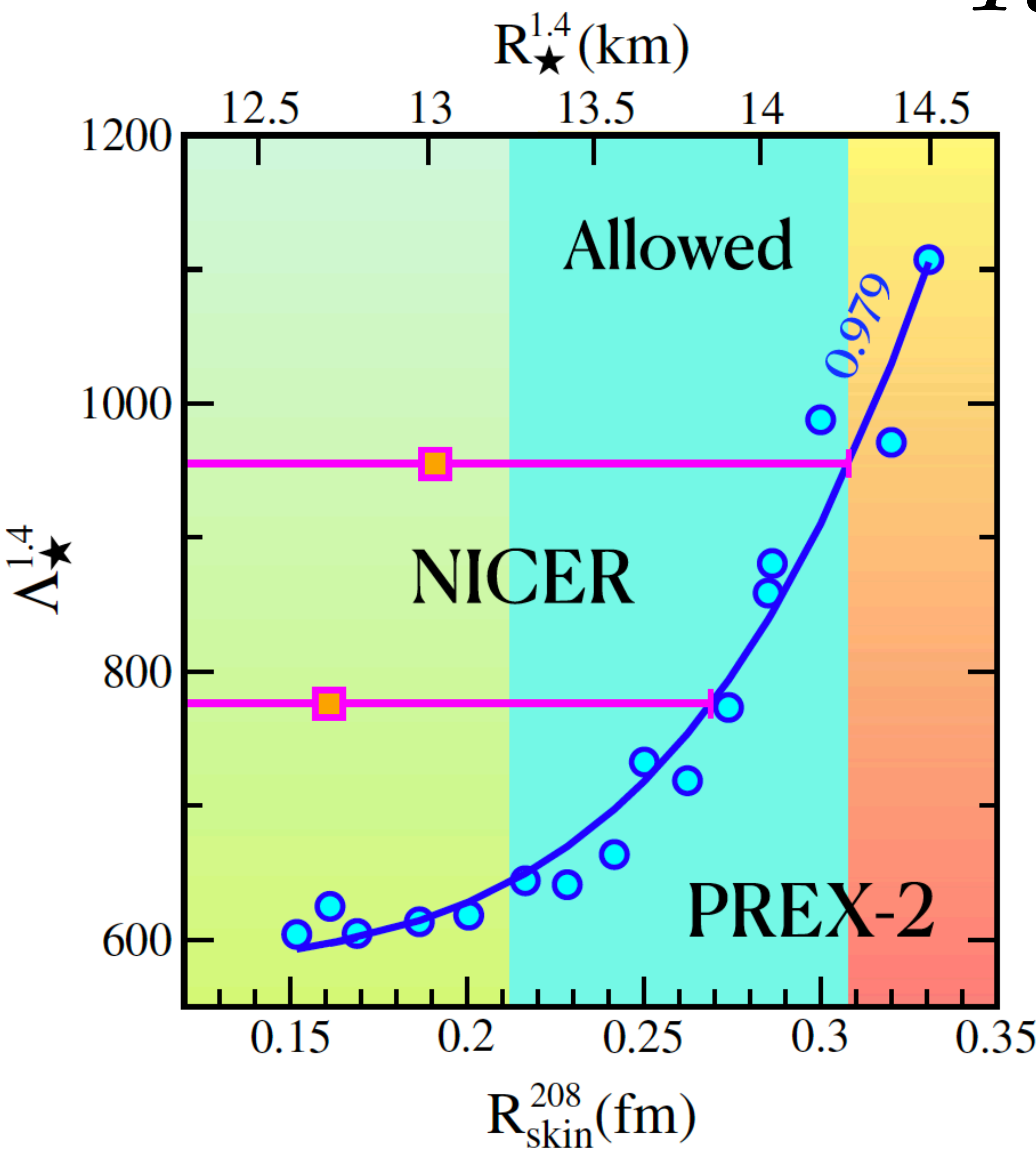
$$L = 3\rho_0 \left(\frac{\partial E_{sym}(\rho)}{\partial \rho} \right)_{\rho = \rho_0}$$

Phys. Lett. B 727, 276 (2013) $25 < L_0 < 115 \text{ MeV}$

PRC 90, 055203 (2014) $30.6 < L_0 < 80.6 \text{ MeV}$

PRL 126, 172503 (2021) $69 < L_0 < 143 \text{ MeV}$

$$R_{1.4\ \mathrm{M}_\odot} \geq 13.25\ \mathrm{km}$$

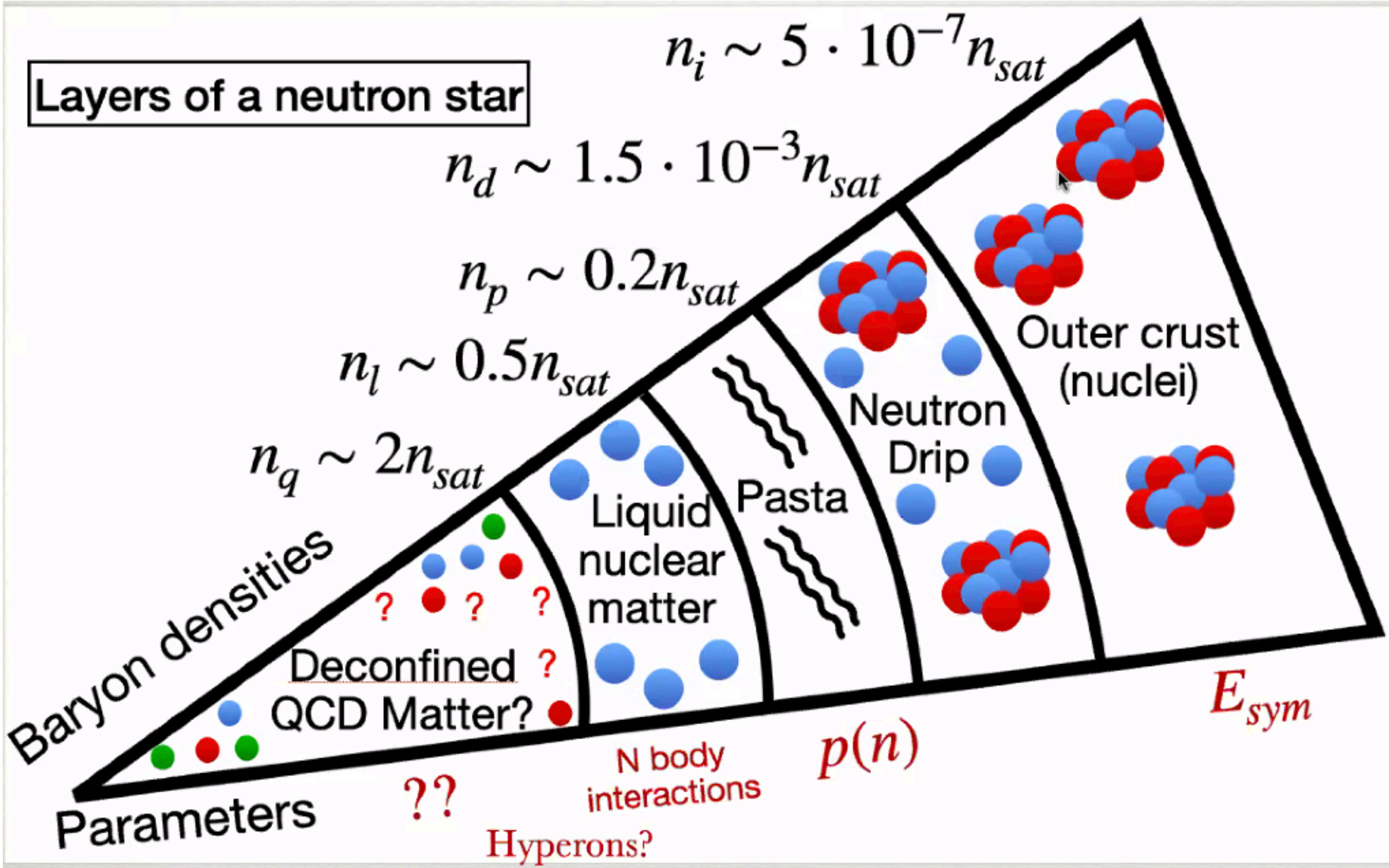


$$0.21 \lesssim R_{\mathrm{skin}}(\mathrm{fm}) \lesssim 0.31,$$

$$13.25 \lesssim R_\star^{1.4}(\mathrm{km}) \lesssim 14.26,$$

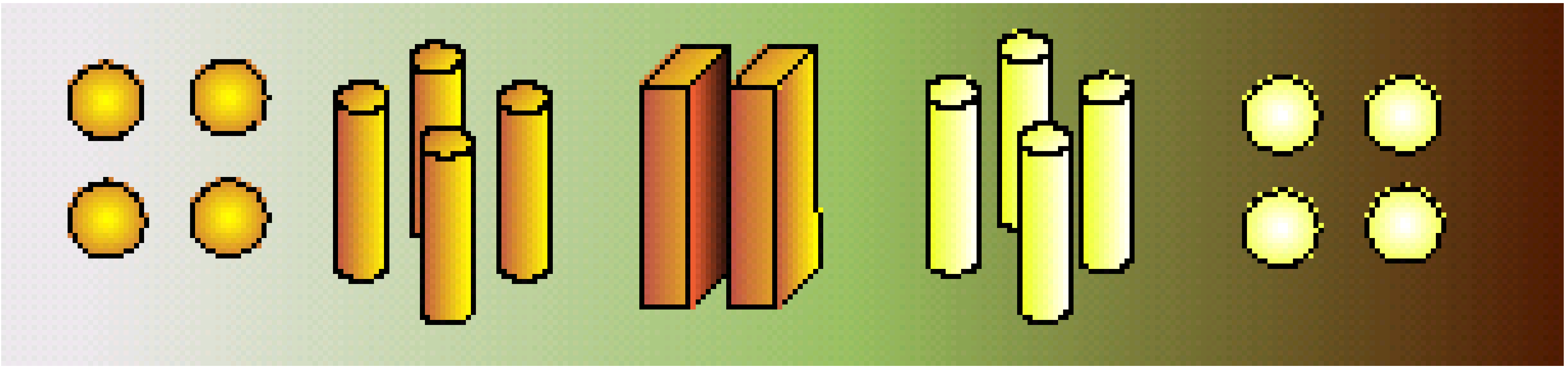
$$642 \lesssim \Lambda_\star^{1.4} \lesssim 955.$$

Moreover, a precise knowledge of the EOS of the crust is needed to minimize possible systematic uncertainties

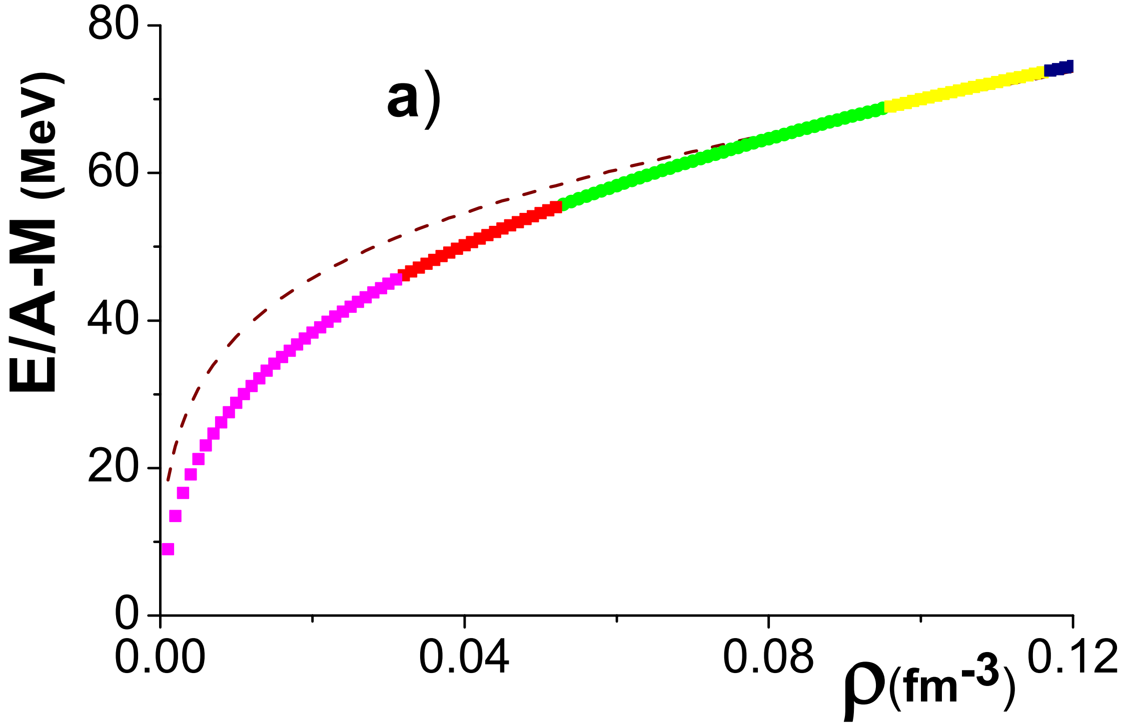

Layers of a neutron star
$n_i \sim 5 \cdot 10^{-7} n_{sat}$
$n_d \sim 1.5 \cdot 10^{-3} n_{sat}$
$n_p \sim 0.2 n_{sat}$
$n_l \sim 0.5 n_{sat}$
$n_q \sim 2 n_{sat}$
Baryon densities
Outer crust (nuclei)
Neutron Drip
Pasta
Liquid nuclear matter
Deconfined QCD Matter?
Parameters
??
Hyperons?
N body interactions
$p(n)$
E_{sym}

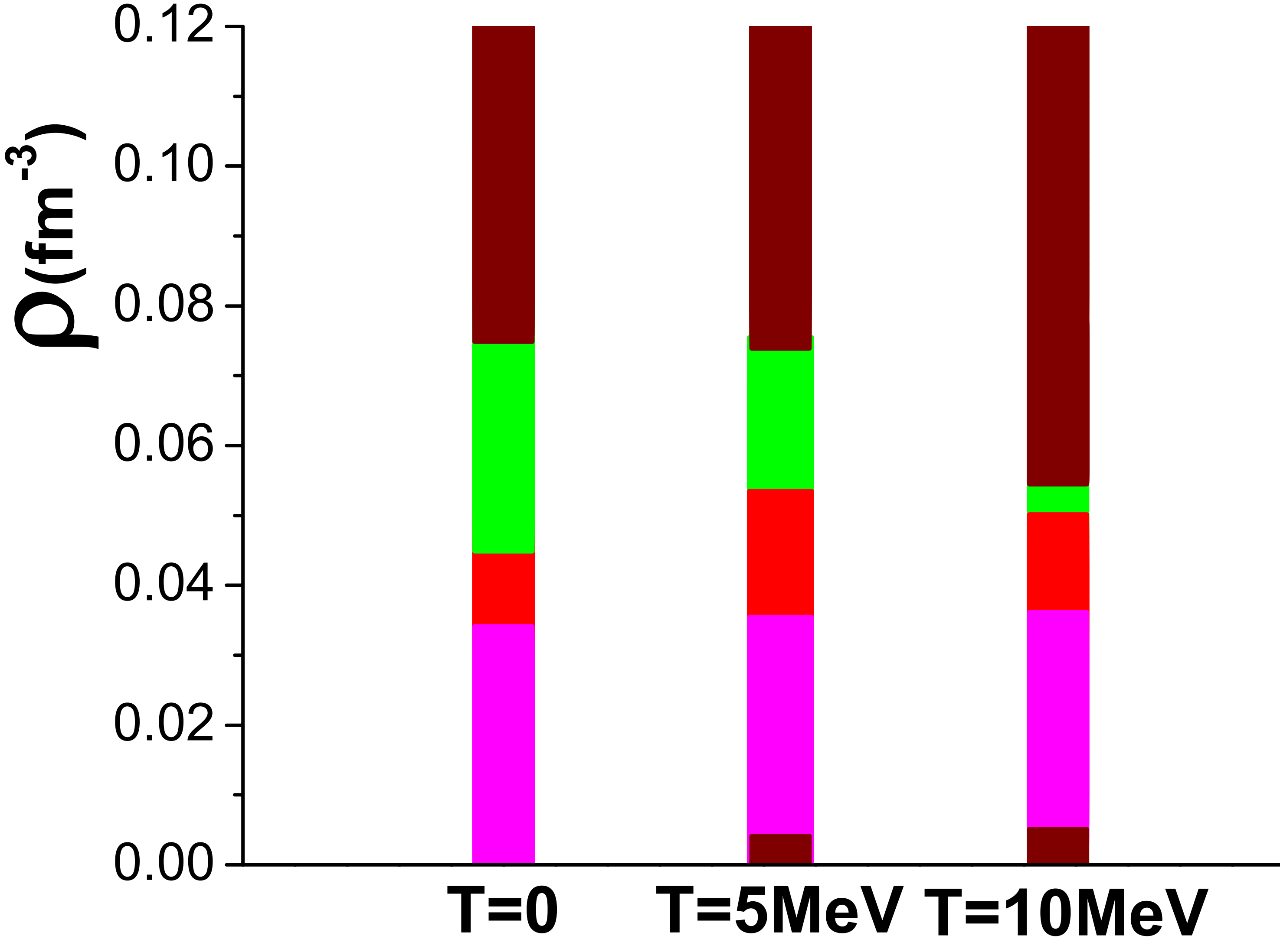
Pasta phase (inner crust)

It is the result of a **frustrated** system. Normally the short and large distance scales related to the nuclear and Coulomb interactions are well separated so that nucleons bind into nuclei but at very low densities, these length scales are comparable and a variety of complex structures exist: **droplet** (meatball, 3D), **rod** (spaghetti, 2D), lazagna (**slab,** 1D), penne (**tube**, 2D), Swiss cheese (**bubble**, 3D).

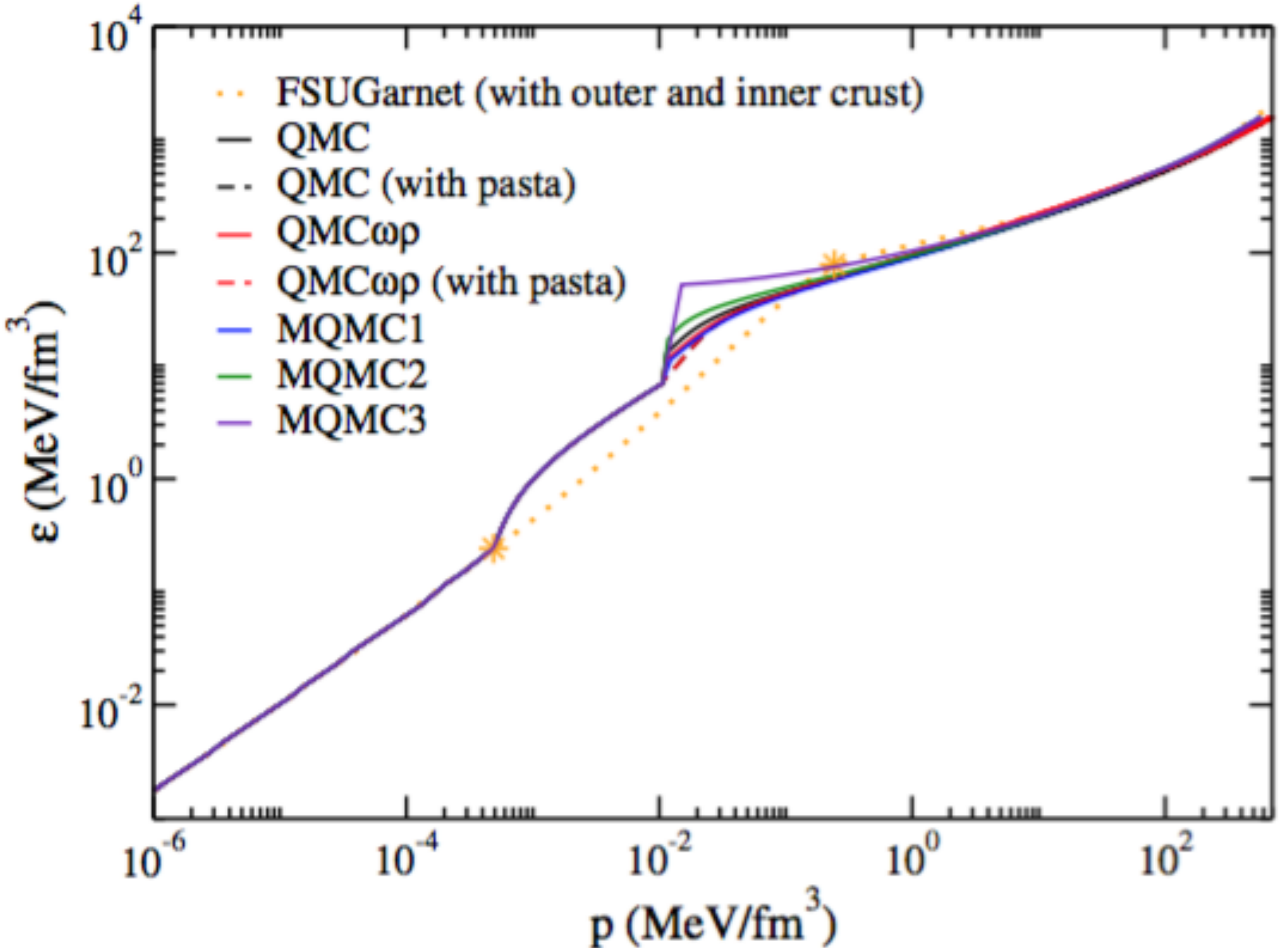


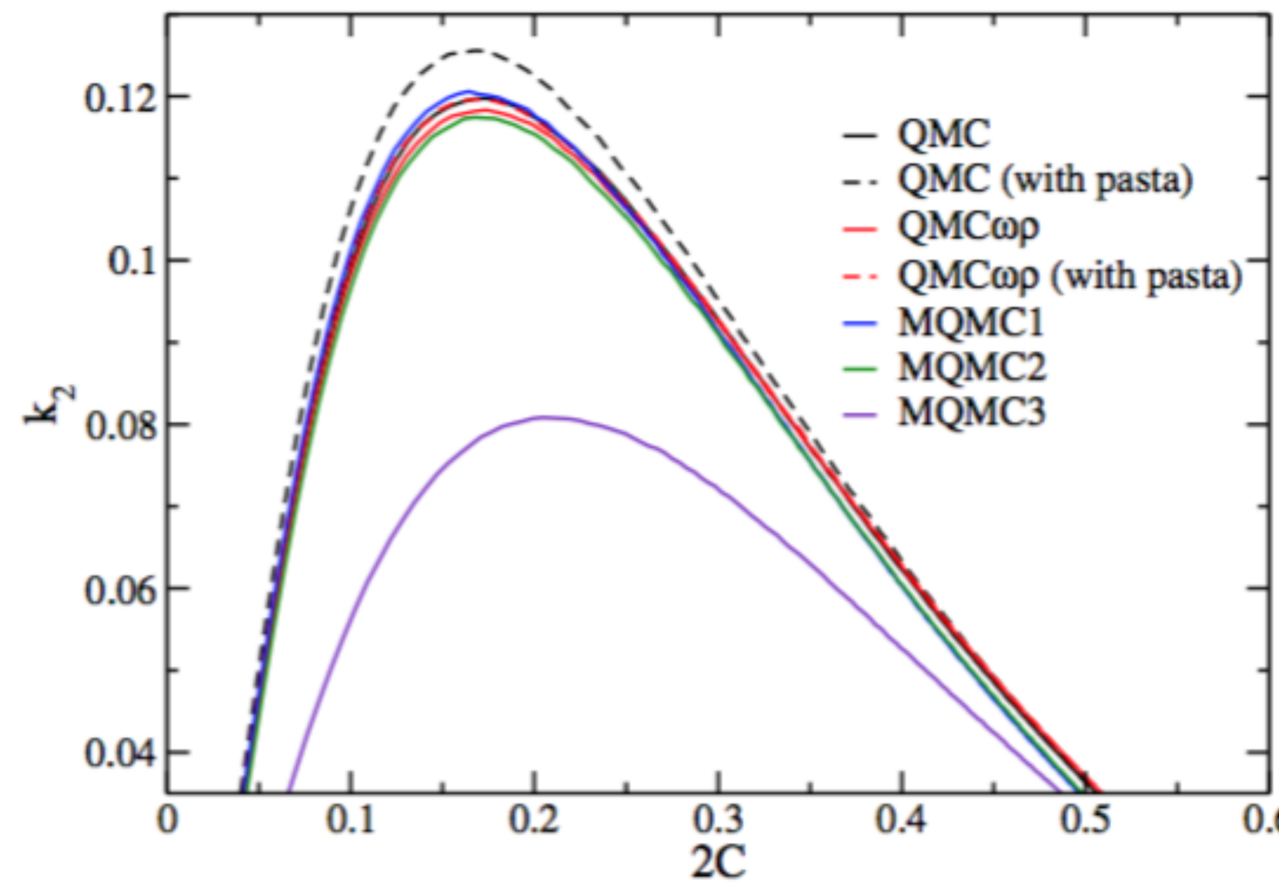
The pasta phase is the ground state configuration if its free energy is lower than the corresponding homogeneous phase.

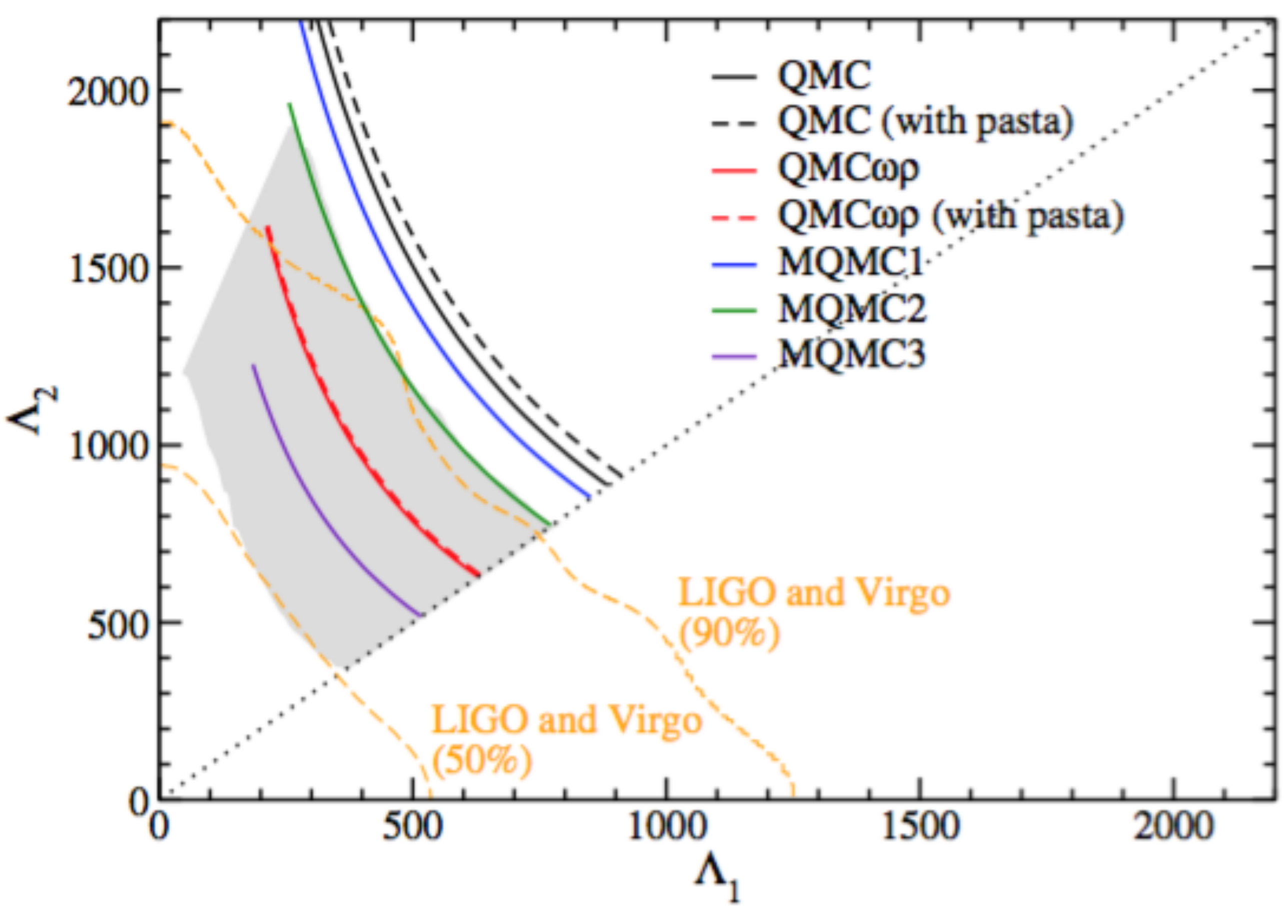




Effects of the inner (pasta) and outer (BPS) crusts







O. Lourenço, C. Lenzi, M. Dutra, T. Frederico, M.Bhuyan, R. P. Negreiros, C.V. Flores, G. Grams, DPM, Chinese Phys. C 45,025101 (2021); arXiv 1905. 07308

But the pasta phase can indeed be important:

shear and bulk viscosities (transport equations);

electrical + thermal conductivities (magnetic evolution of NS);

quasi-periodic oscillations (observed in SGR);

Our previous approximation was poor
(no fluctuations, one geometry at each density)

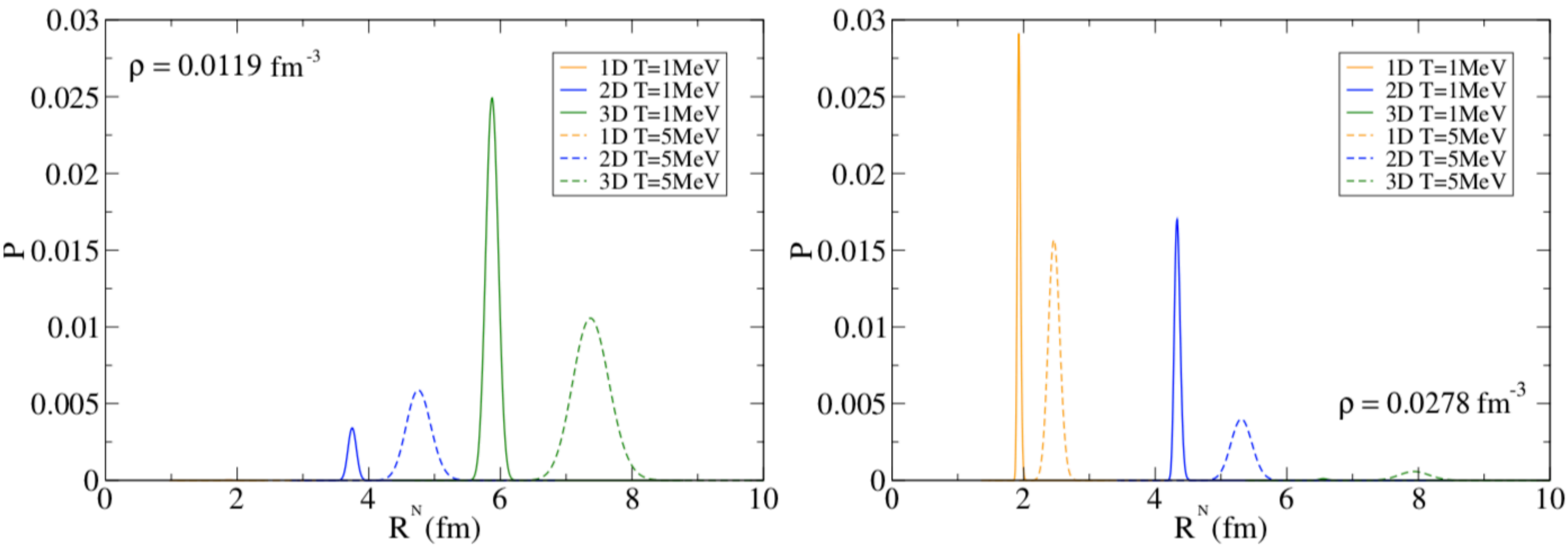
Fluctuations are confirmed in numerical simulations;
MDS is computationally very expensive

A.S.Schneider, M.E.Caplan, D.K.Berry, C.J.Horowitz,
Phys. Rev. C 98, 055801 (2018)

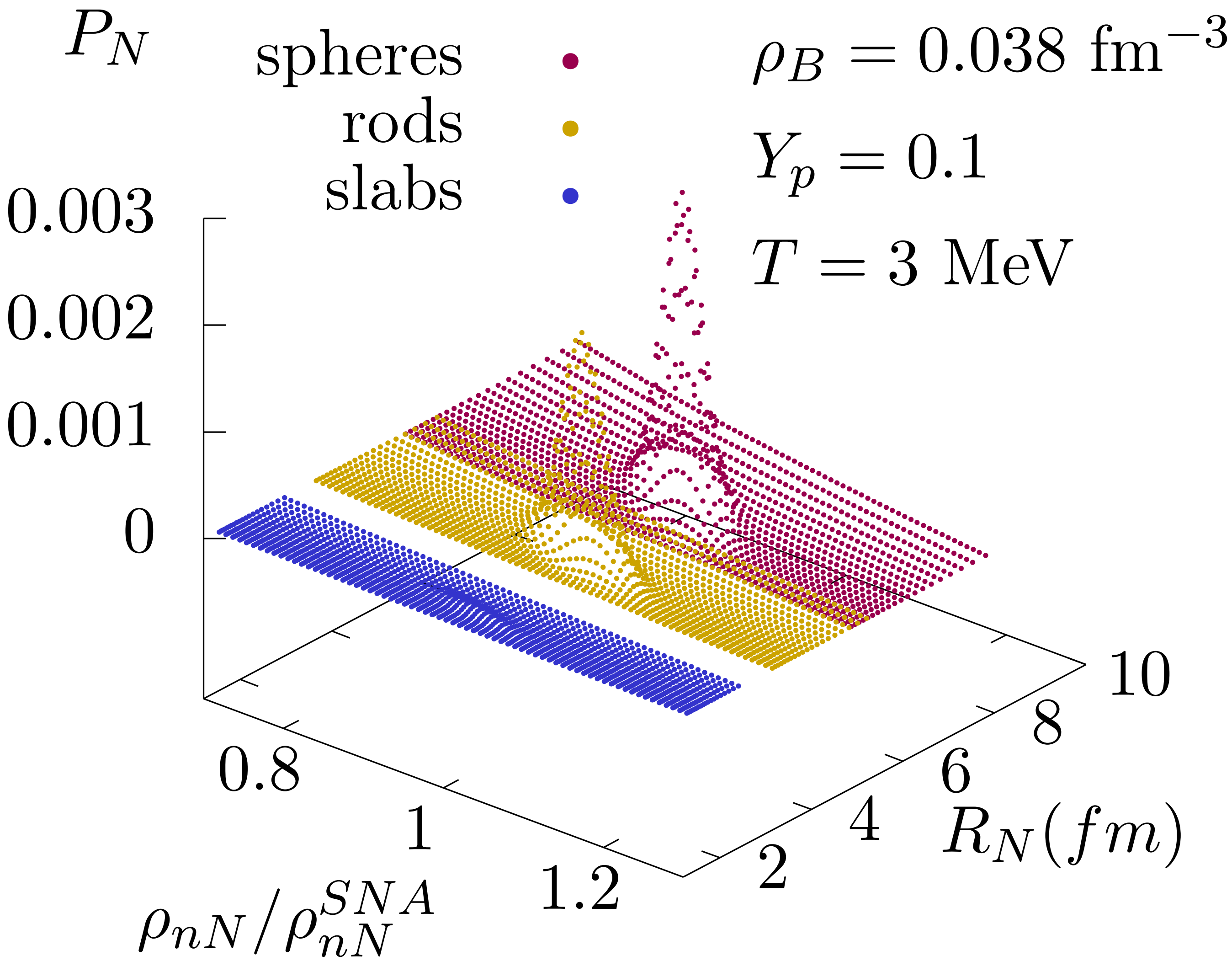
$$\tilde{\Omega}_D(A^N) = \tilde{F}_D(A^N) - \mu^N$$

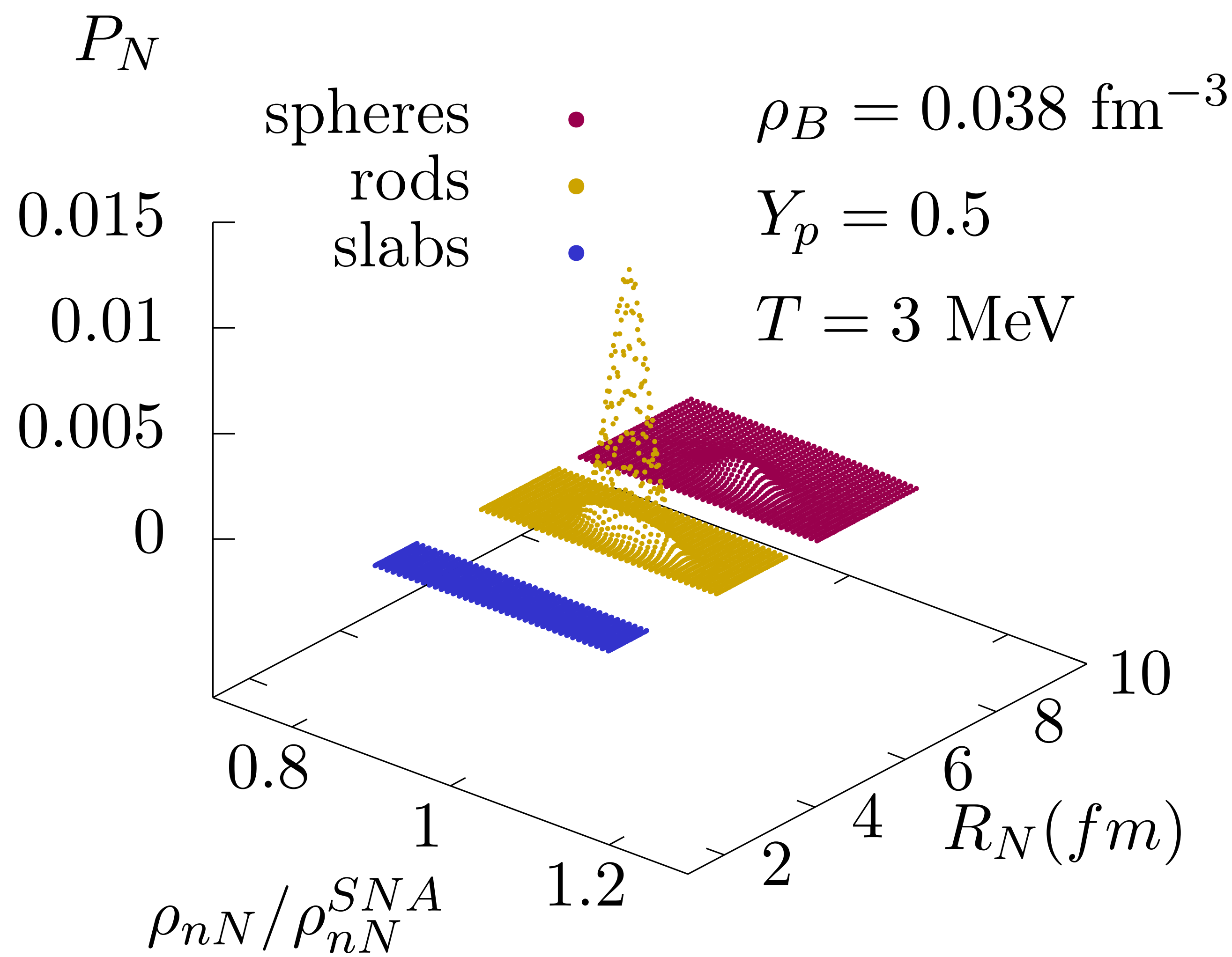
$$P_D(A^N) = \frac{\exp(-\beta\tilde{\Omega}_D(A^N))}{\sum_D \sum_A \exp(-\beta\tilde{\Omega}_D(A))}$$

$$P^N = \sum_D P_D(A^N)$$



Celso C. Barros Jr., DPM, Francesca Gulminelli,
PRC 101, 035211 (2020), arXiv: 1911.02863





Mateus R. Pelicer, DPM,
C.C. Barros Jr, F. Gulminelli
Phys. Rev. C 104, L022801 (2021)
arXiv: 2105.03318

Can NS be described by quark matter ?

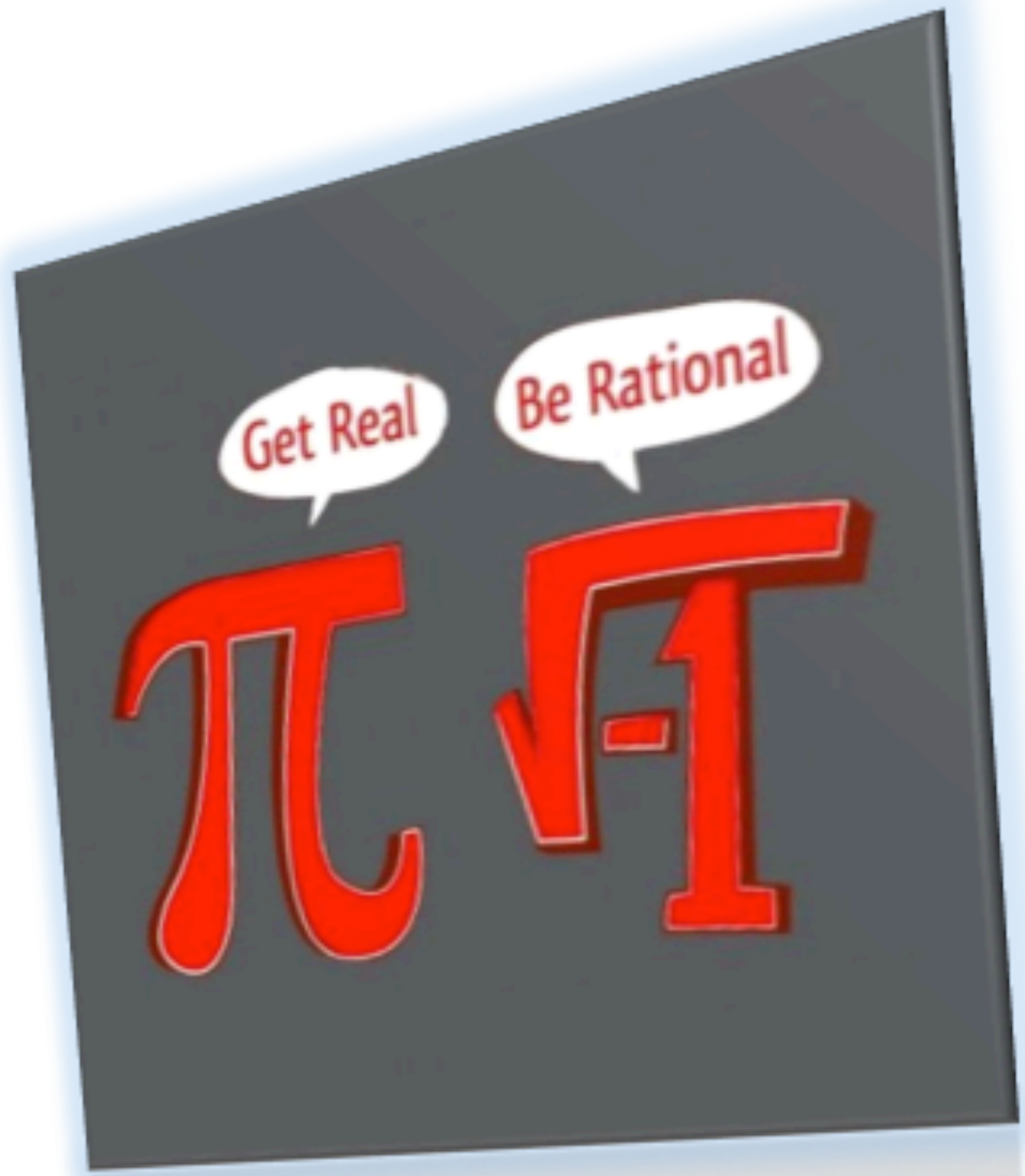
Are there hybrid stars ?

Astrophysical constraints:

Maximum mass > 2 solar masses

GW170817 - tidal polarisability and the Love number

radius of canonical stars : uncertain…
(PREX2, GWs)



Thank you !