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Fiorella Burgio

The Hyperon Puzzle in Neutron Stars : status and possible solutions

In collaboration with :
M. Baldo & U. Lombardo & H.-J. Schulze & I. Vidaña & J. Wei : Catania
H. Chen & A. Li & Z.H. Li & H.Q. Song & X.R. Zhou & W. Zuo : China
E. Hiyama & T. Maruyama & T. Tatsumi & N. Yasutake : Japan
T. Rijken : Nijmegen

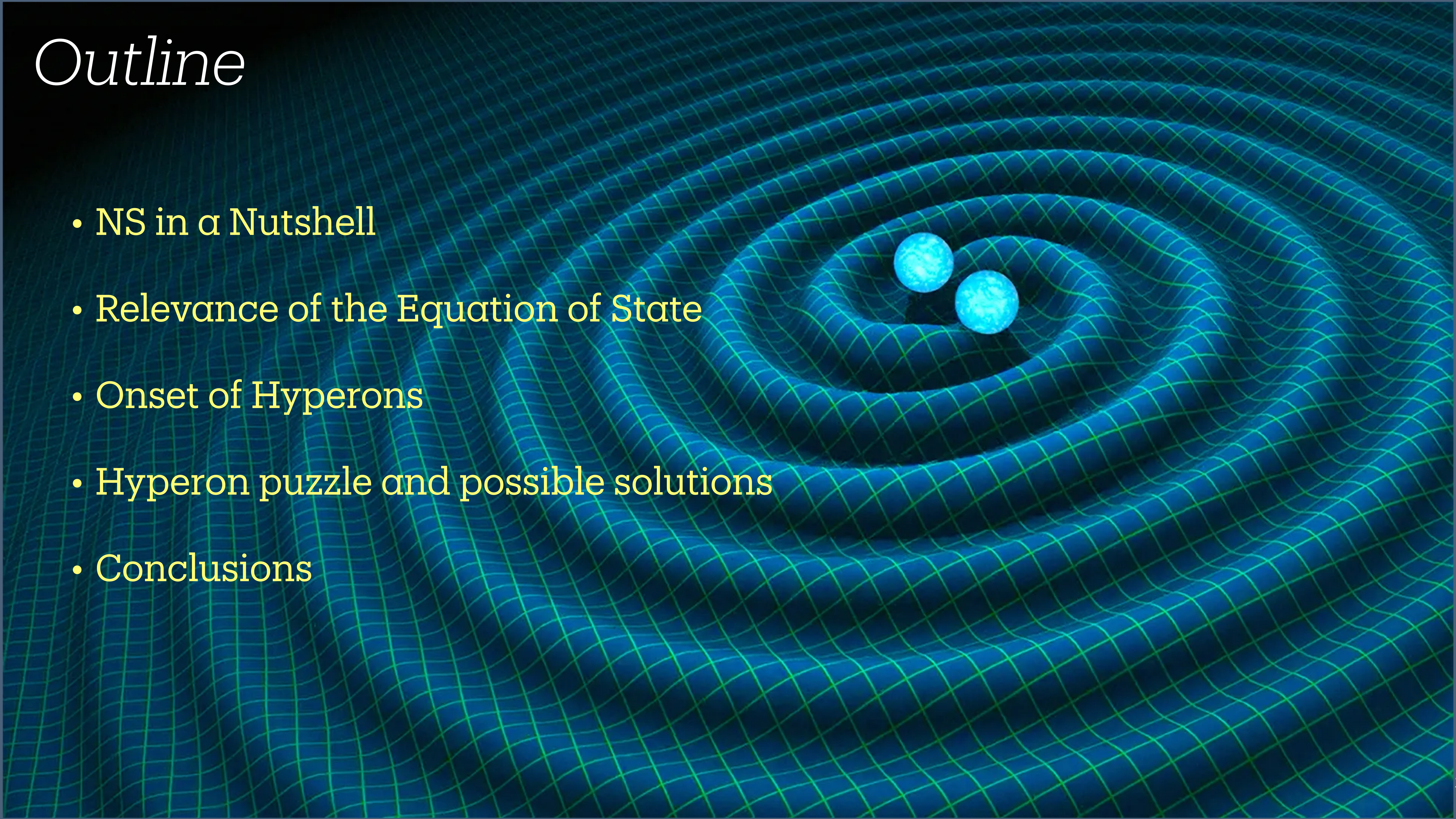
More in :

PRC 61, 055801 (2000), PRD 70, 043010 (2004), PRC 73, 058801 (2006),
PRC 74, 047304 (2006), PRD 76, 123015 (2007),PRC 78, 028801 (2008),
PRC 83, 025804 (2011),PRC 84, 035801 (2011), PRD 84, 105023 (2011),
PRC 88, 024322 (2013), EPJA 52, 21 (2016),PRC 96, 044309 (2017),
PRC 98, 064322 (2017),APJ 860, 139 (2018), JPG 46, 034001 (2019)

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

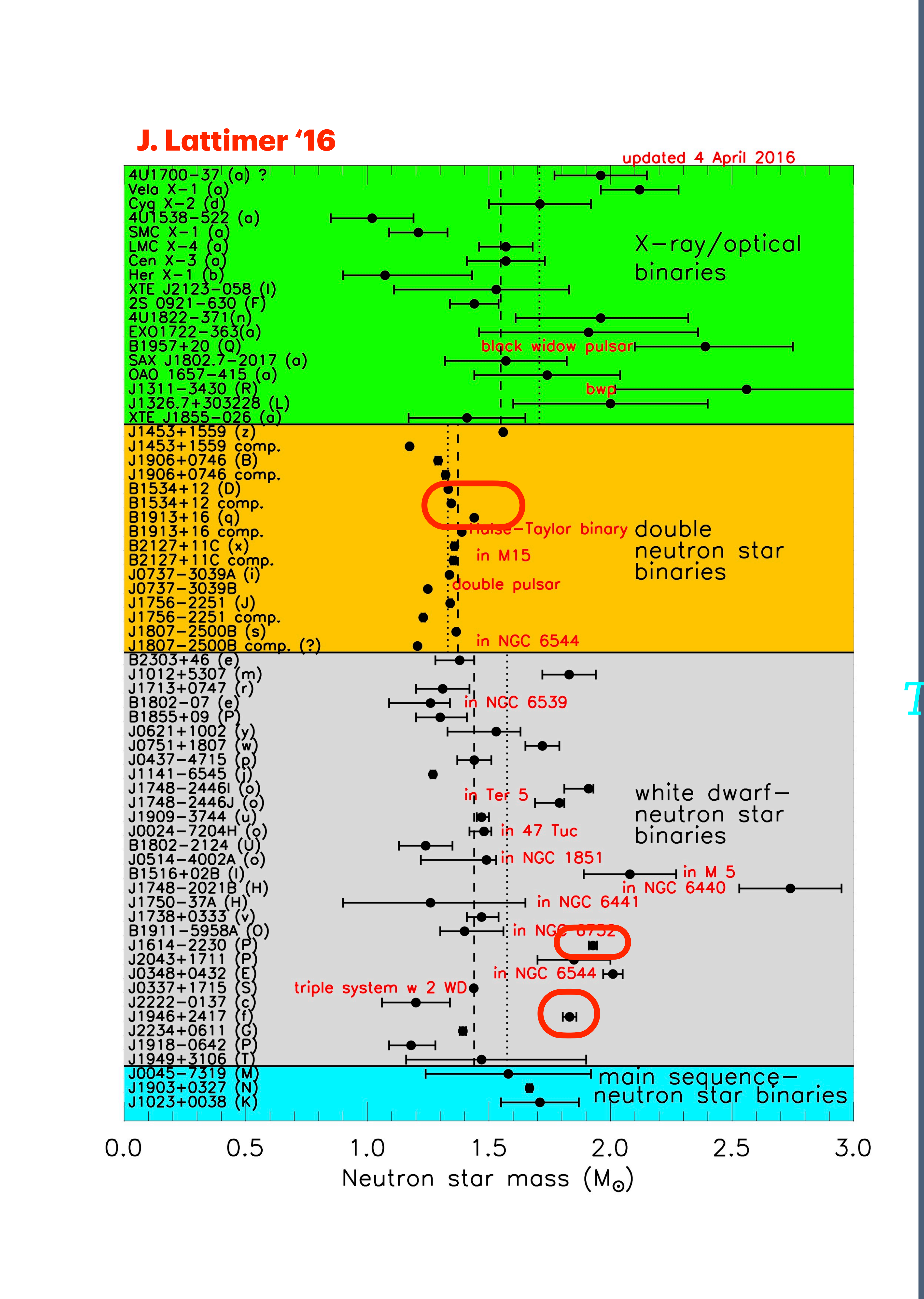
Outline

- NS in a Nutshell
- Relevance of the Equation of State
- Onset of Hyperons
- Hyperon puzzle and possible solutions
- Conclusions




$M = 1\text{-}2\ M_0\ (M_0 \sim 2 \times 10^{33}\ g)$
$R \sim 10\ km$
$\rho \sim M/R^3 \sim 2 \times 10^{15}\ g/cm^3$
Capo d'Orlando
Parco dei Nebrodi
Cesarò
Maletto
Randazzo
Bronte, Sicily
Parco dell'Etna
Barcellona Pozzo di Gotto
Messina
Santa Teresa di Riva
Castiglione di Sicilia
Taormina
E45
Giarre
E45
Zafferana Etnea
Adrano
Biancavilla
Centuripe
Acireale
San Giovanni La Punta
Paterno
Aci Castello
Terre Nere
Misterbianco
Catania
Sferro
DID YOU KNOW?
A teaspoon of a Neutron star would weigh more than 300 Great Pyramids of Giza.

Observational facts : the Mass



Observed mass range: $M \sim 1 - 2M_\odot$

Best determined masses in a narrow interval $M \sim (1.25 - 1.45)\, M_\odot$

Hulse-Taylor pulsar: PSR 1913+16 = 1.4411±0.0035 $M_\odot$

Values $M > 2M_\odot$ are strong constraints for the theory !

Theoretical model rejected if predicted maximum mass smaller than obs data.

- PSR J1614-2230, $\mathrm{M} = (1.97 \pm 0.04)\,\mathrm{M}_\odot$ (P. Demorest et al., Nature, 2010)
- PSR J0348+0432, $\mathrm{M} = (2.01 \pm 0.04)\,\mathrm{M}_\odot$ (J. Antoniadis et al., Science, 2013)
- MSP J0740+6620, $\mathrm{M} = (2.14^{+0.2}_{-0.18})\,\mathrm{M}_\odot$ (H. Cromartie et al., Nature Astronomy, 2019)
- PSR J0952-0607, $\mathrm{M} = (2.35 \pm 0.17)\,\mathrm{M}_\odot$ (R. Romani et al., ApJ Lett. 2022)

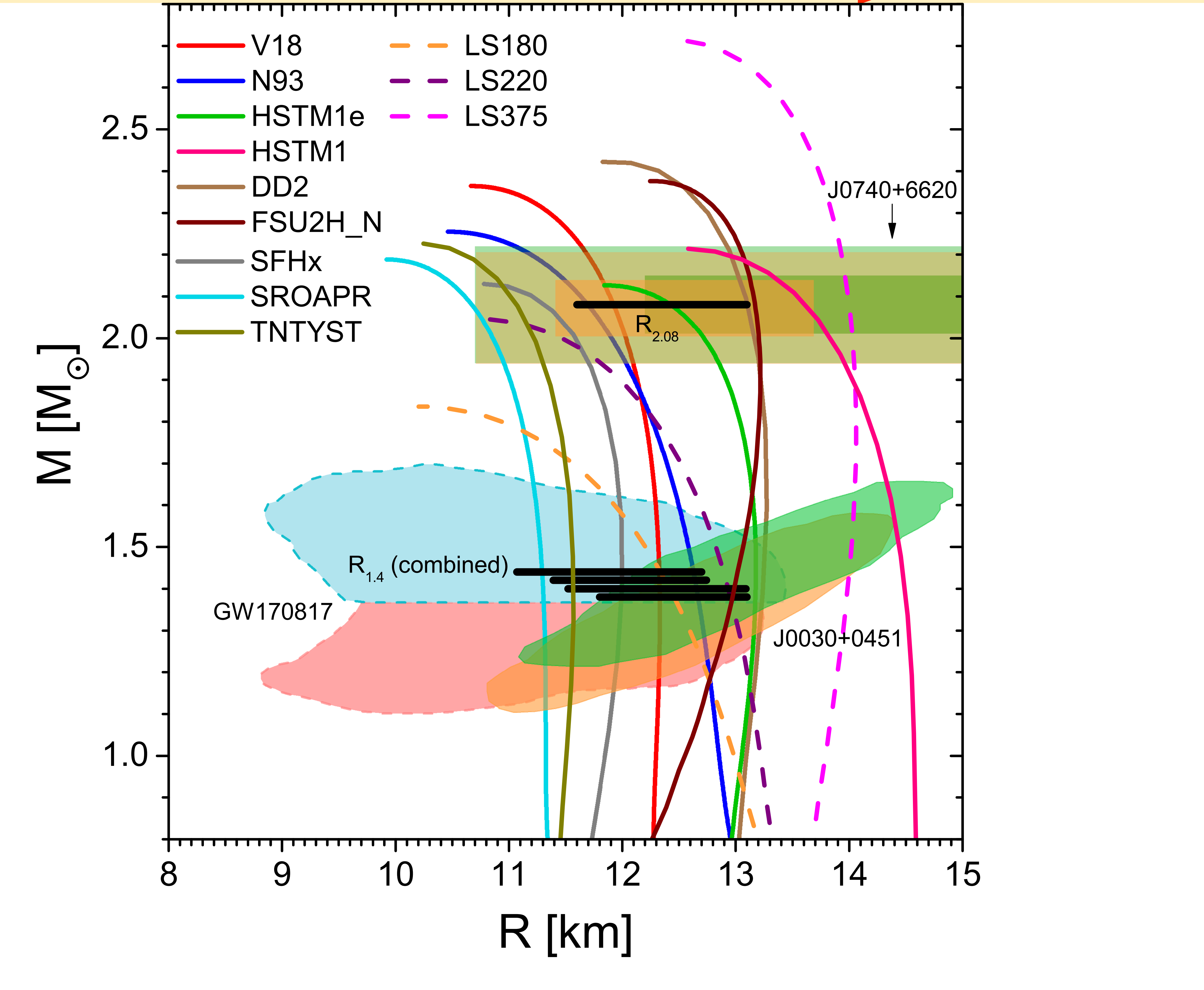
Observational facts : the Radius

Possible measure through the thermal emission of low-mass X-ray binaries.

The observed X-ray flux F and estimated surface temperature T, together with the distance D and M the mass of the NS, can be used to obtain the radius R_{NS}

$$R_\infty = \sqrt{\frac{FD^2}{\sigma T^4}} \rightarrow R_{NS} = \frac{R_\infty}{1+z} = R_\infty \sqrt{1 - \frac{2GM}{Rc^2}}$$

Major uncertainties → a) temperature, b) atmospheric model, c) star distance



NICER : a new technique to measure M & R from rapidly spinning compact stars with a hot spot, based on Doppler effect (R) and GR corrections of the signal (M/R) .

Combined analysis of PSR J0030+0451, PSR J0740+6620 with GW170817 yields :

$$R_{2.08} = 12.35 \pm 0.75\, km$$

$$R_{1.4} = 12.45 \pm 0.65\, km$$

$$R_{1.4} = 11.94^{+0.76}_{-0.87}\, km$$

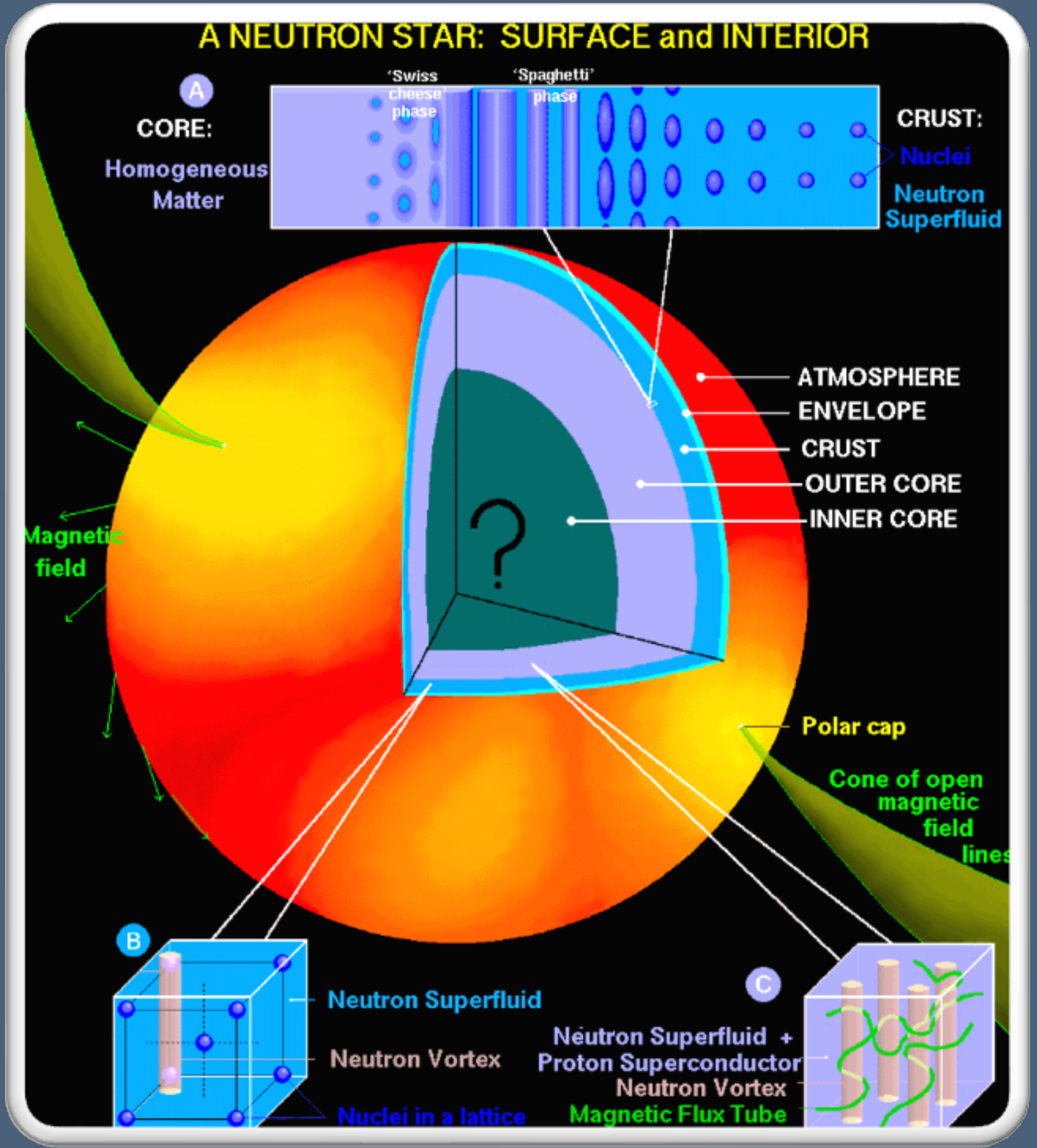
$$R_{1.4} = 12.33^{+0.76}_{-0.81}\, km$$

$$R_{1.4} = 12.18^{+0.56}_{-0.79}\, km$$

Miller, Riley, 2019, 2021

Schematic view of a neutron star

by Dany Page, UNAM Mexico City



Atmosphere A few tens of cm, $\rho \leq 10^4 g/cm^3$ made of atoms.

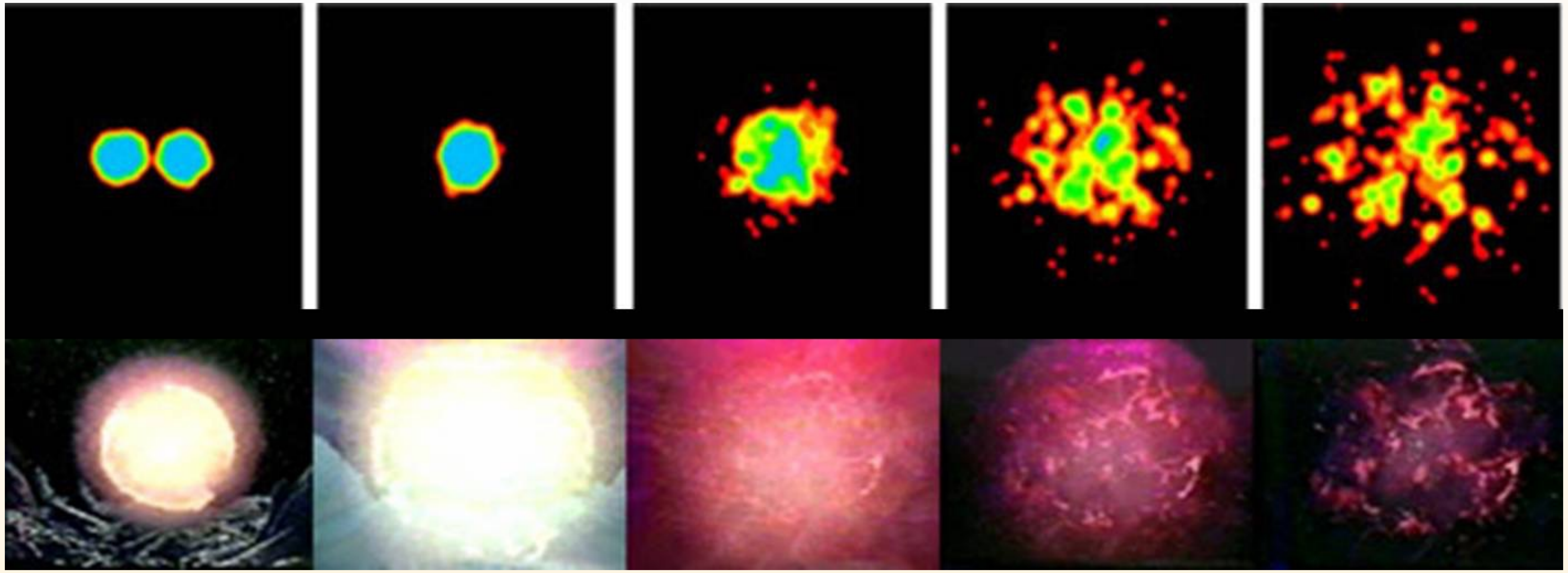
Outer crust A few hundred m's thick, $\rho = (10^4 - 10^{11}) g/cm^3$. Ions immersed in an electron gas.

Inner crust 1-2 km, $\rho = 4 \times 10^{11} - 10^{14} g/cm^3$. Electrons beta-captured by nuclei $\rightarrow$ neutron-rich nuclei $\rightarrow$ drip point . Gas of free neutrons. Nuclei melt down and nuclear matter sets in from drip up to $\rho \approx \rho_0/2$: uniform fluid of n, p, e^-

Outer core $\rho \approx \rho_0/2 - 2\rho_0$. Asymmetric nuclear matter above saturation. Composition made by neutrons, protons, and leptons.

Inner core $\rho \approx 2\rho_0 - (8 - 10)\rho_0$ The most unknown region. "Exotic matter" . Hyperons ? Quarks ?

Relevance of the EoS



1. Heavy ion collisions (small N/Z, high T)
2. Supernovae and Neutron Stars
   (high N/Z, high (small) T in SN (NS))
3. Binary NS merger and GW emission
   (high density, high N/Z and T)

Quite different physical conditions in each case !

A nuclear matter theory must be able to treat all these physical situations.

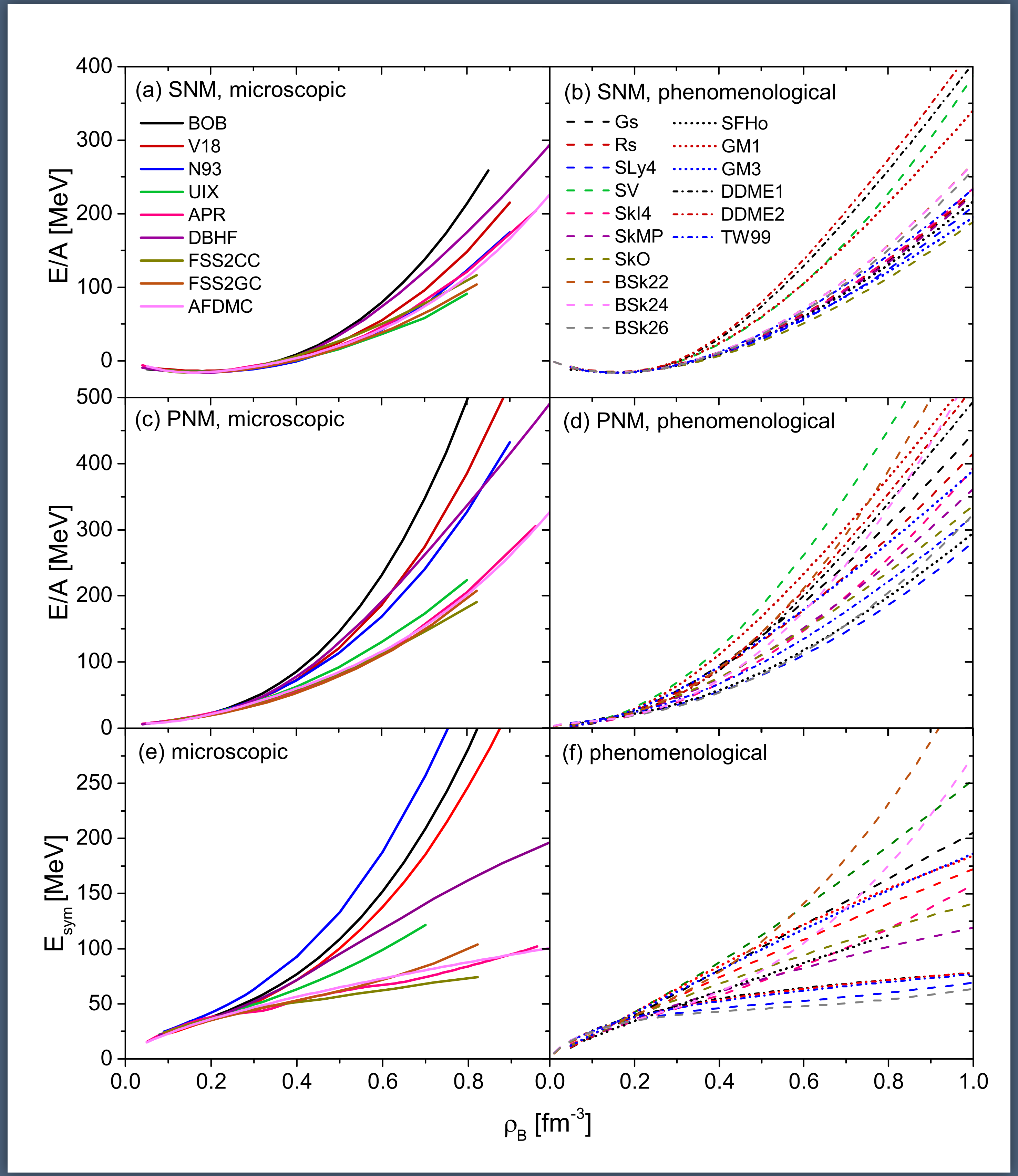
What do we need ?

An exact theory to deal with

- Strong interactions of particles of different species
- Many-body effects in dense matter

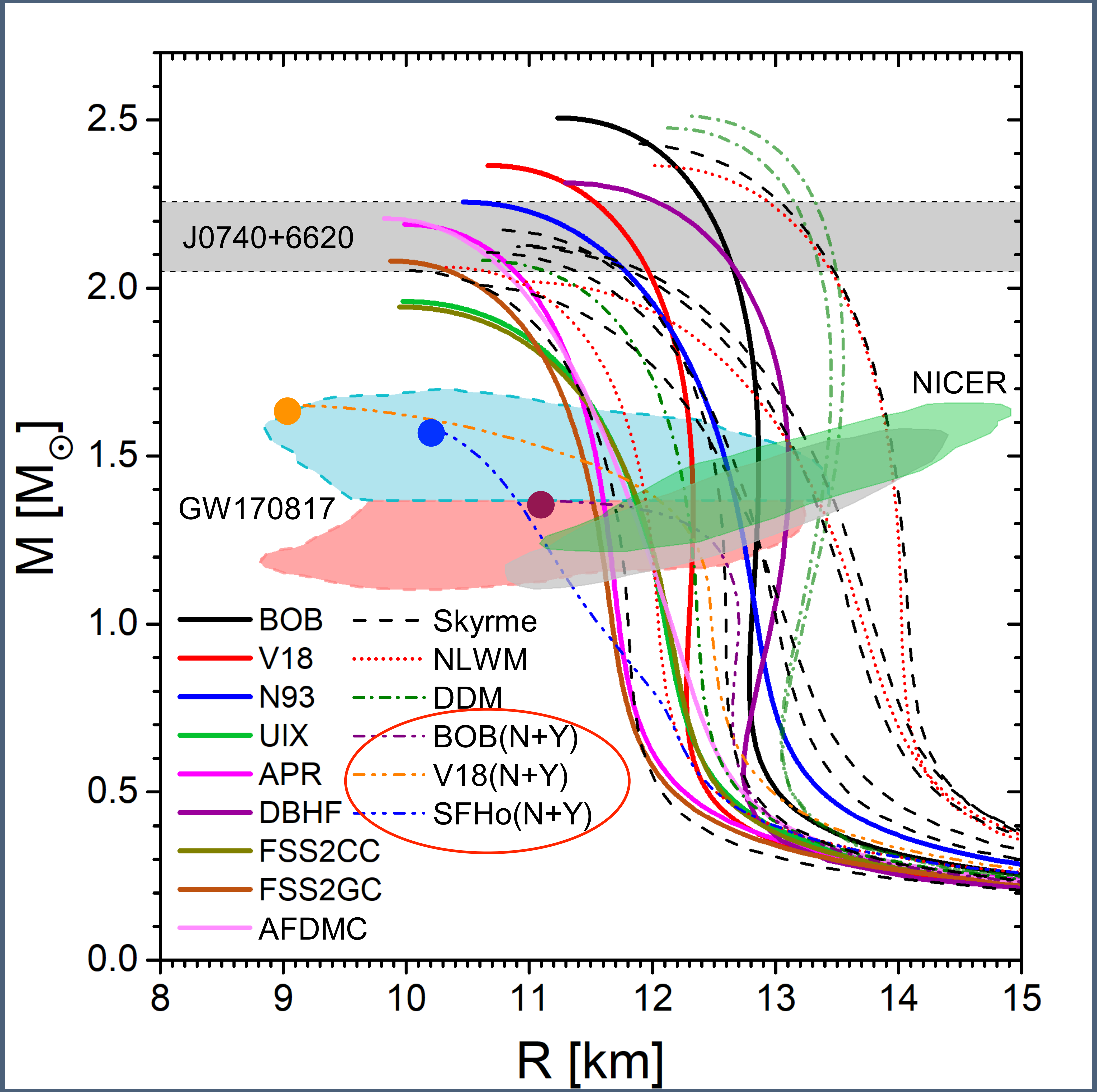
What do we have ?

- Many drastically different theoretical models!



Neutron stars and the nuclear equation of state

G.F. Burgio, H.-J. Schulze, I. Vidaña, J.-B. Wei , Progress in Particle and Nuclear Physics 120 (2021) 103879.



Given that constraint, can hyperons, or strangeness in general, still be present in neutron stars interiors ?

Probably yes, due to the high value of density at the center and the rapid increase of the nucleon chemical potential with density.

What do we know to include hyperons in the EoS ?

Unfortunately much less than in the nucleonic sector.
Hard to draw strong conclusions given our limited knowledge of the nucleon-hyperon (NY) and hyperon-hyperon (YY) interaction.

Theoretical models

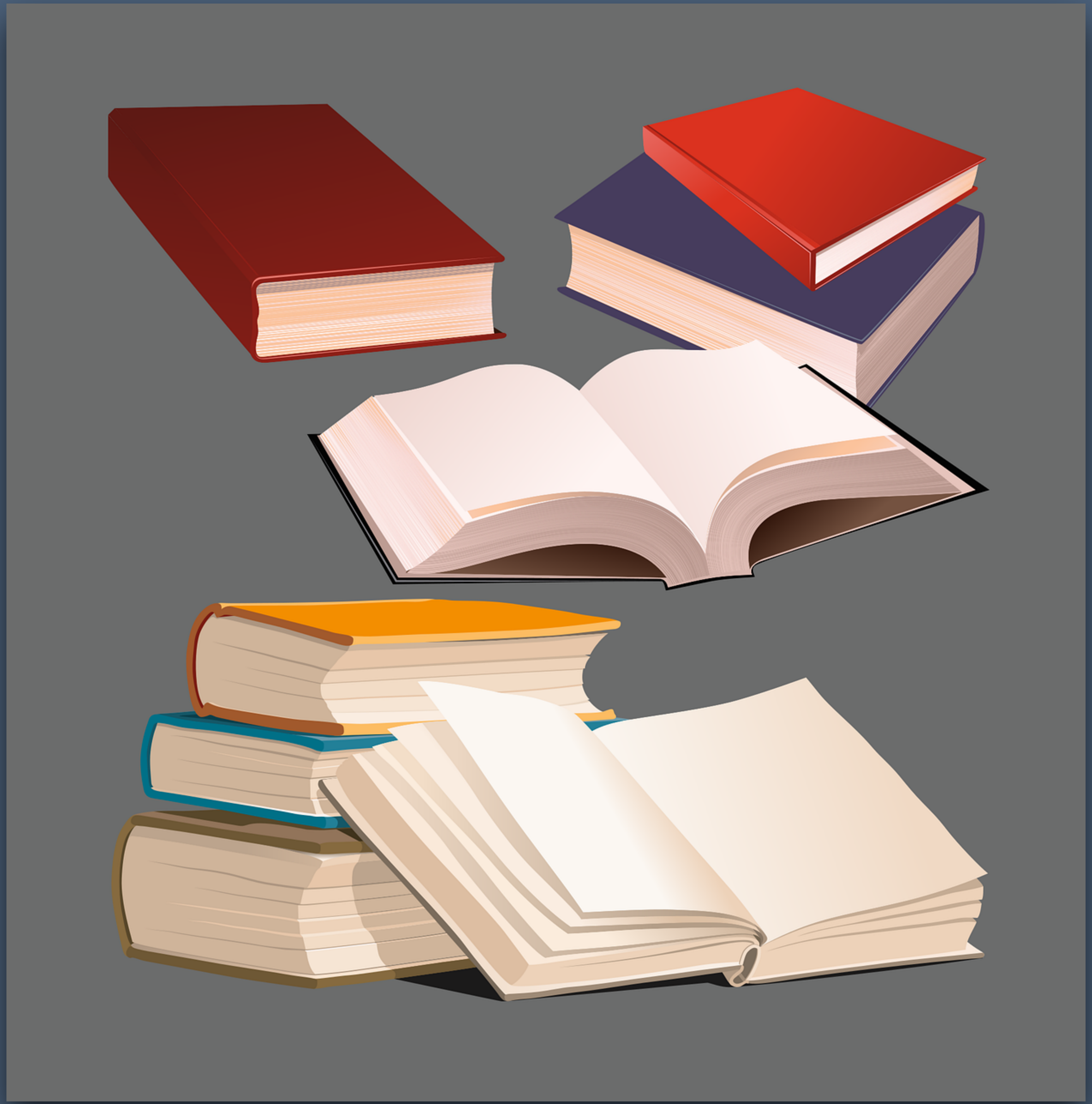
First considered by Ambartsumyan and Saakyan (1960)

➡ Microscopic approaches

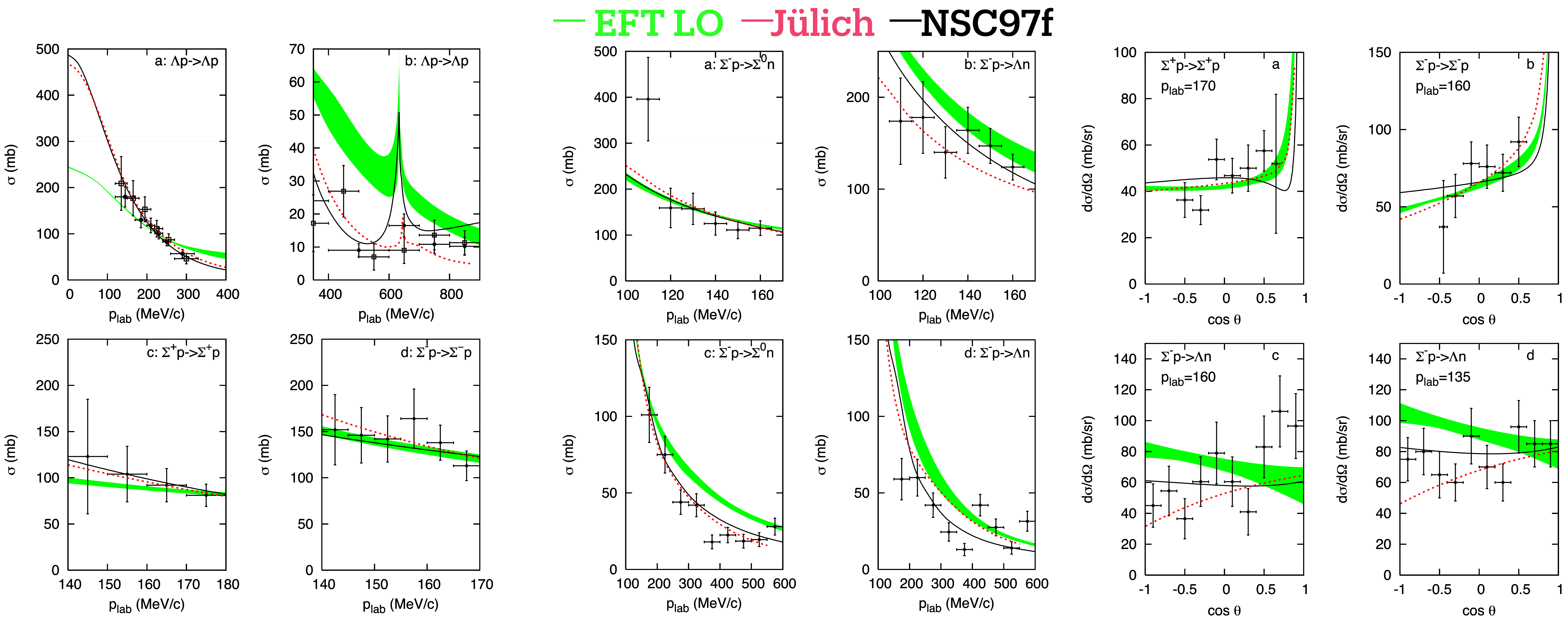
- Brueckner-Hartree-Fock theory : Baldo et al. 1998, Vidaña et al. 2000, Schulze et al. 2006, Schulze & Rjiken 2011
- DBHF : Sammarruca (2009), Katayama and Saito (2014)
- $V_{low\text{-}k}$: Djapo, Schaefer & Wambach (2010)
- Quantum Monte Carlo : Lonardoni et al. (2014)

➡ Phenomenological approaches

- Relativistic mean field models : Glendenning '85; Knorren et al. '95; Schaffner & Mishustin '96
- Non-relativistic potential model : Balberg & Gal '97
- Quark-meson coupling model : Pal et al. '99
- Chiral effective Lagrangians : Hanauske et al 2000
- Density dependent hadron field models : Hofmann et al. 2001



Available NY Cross Sections Data :



Polinder, Haidenbuer, Meissner, NPA 779, 244 (2006)

- 35 data points (1960), and 10 new points (2000) from KEK-PS E251 collaboration
- No *YY* scattering data exist (cf. > 4000 *NN* data points available !)

Need more data. J-PARC ?

Including hyperons in many-body Brueckner-Hartree-Fock approach

$$G_{ab}[W] = V_{ab} + \sum_c \sum_{p,p'} V_{ac} \left| pp' \right\rangle \frac{Q_c}{W - E_c + i\epsilon} \left\langle pp' \right| G_{cb}[W] \,, \quad (1)$$

where the indices a, b, c indicate pairs of baryons and the angle-averaged Pauli operator Q and energy E determine the propagation of intermediate baryon pairs. In a given nucleon-hyperon channels $c = (NY)$ one has, for example,

$$E_{(NY)} = m_N + m_Y + \frac{k_N^2}{2m_N} + \frac{k_Y^2}{2m_Y} + U_N(k_N) + U_Y(k_Y) \,. \quad (2)$$

The hyperon single-particle potentials within the continuous choice are given by

$$U_Y(k) = \sum_{N=n,p} U_Y^{(N)}(k) = \mathrm{Re} \sum_{N=n,p} \sum_{k'<k_F^{(N)}} \left\langle kk' \right| G_{(NY)(NY)} \left[E_{(NY)}(k,k') \right] \left| kk' \right\rangle \quad (3)$$

and similar expressions of the form

$$U_N(k) = \sum_{N'=n,p} U_N^{(N')}(k) + \sum_{Y=\Sigma^-,\Lambda} U_N^{(Y)}(k) \quad (4)$$

$$\frac{B}{A} = \frac{\epsilon}{\rho_n + \rho_p + \rho_{\Sigma^-} + \rho_\Lambda} \,,$$

$$\epsilon = \sum_{i=n,p,\Sigma^-,\Lambda} \int_0^{k_F^{(i)}} \frac{dk\, k^2}{\pi^2} \left(m_i + \frac{k^2}{2m_i} + \frac{1}{2} U_i(k) \right) = \epsilon_{NN} + \epsilon_{NY}$$

with

$$\epsilon_{NN} = \sum_{N=n,p} \int_0^{k_F^{(N)}} \frac{dk\, k^2}{\pi^2} \left(m_N + \frac{k^2}{2m_N} + \frac{1}{2} \left[U_N^{(n)}(k) + U_N^{(p)}(k) \right] \right) \,,$$

$$\epsilon_{NY} = \sum_{Y=\Sigma^-,\Lambda} \int_0^{k_F^{(Y)}} \frac{dk\, k^2}{\pi^2} \left(m_Y + \frac{k^2}{2m_Y} \right) + \sum_{N=n,p} \int_0^{k_F^{(N)}} \frac{dk\, k^2}{\pi^2} \left[U_N^{(\Sigma^-)}(k) + U_N^{(\Lambda)}(k) \right]$$

$$= \sum_{Y=\Sigma^-,\Lambda} \int_0^{k_F^{(Y)}} \frac{dk\, k^2}{\pi^2} \left(m_Y + \frac{k^2}{2m_Y} + \left[U_Y^{(n)}(k) + U_Y^{(p)}(k) \right] \right) \,.$$

- BHF based on in-medium scattering G-matrix
- Two-body force V only input required
- Effective three-body force ⟶ correct NM saturation point

Technical difficulty :

coupled channel calculation !

- Only NN and NY interactions are included. No YY potentials.
- The nucleons feel direct effects of the other nucleons and the hyperons.
- For the hyperons only nucleonic contributions are included.

Baldo et al., Phys.Rev.C61:055801,2000

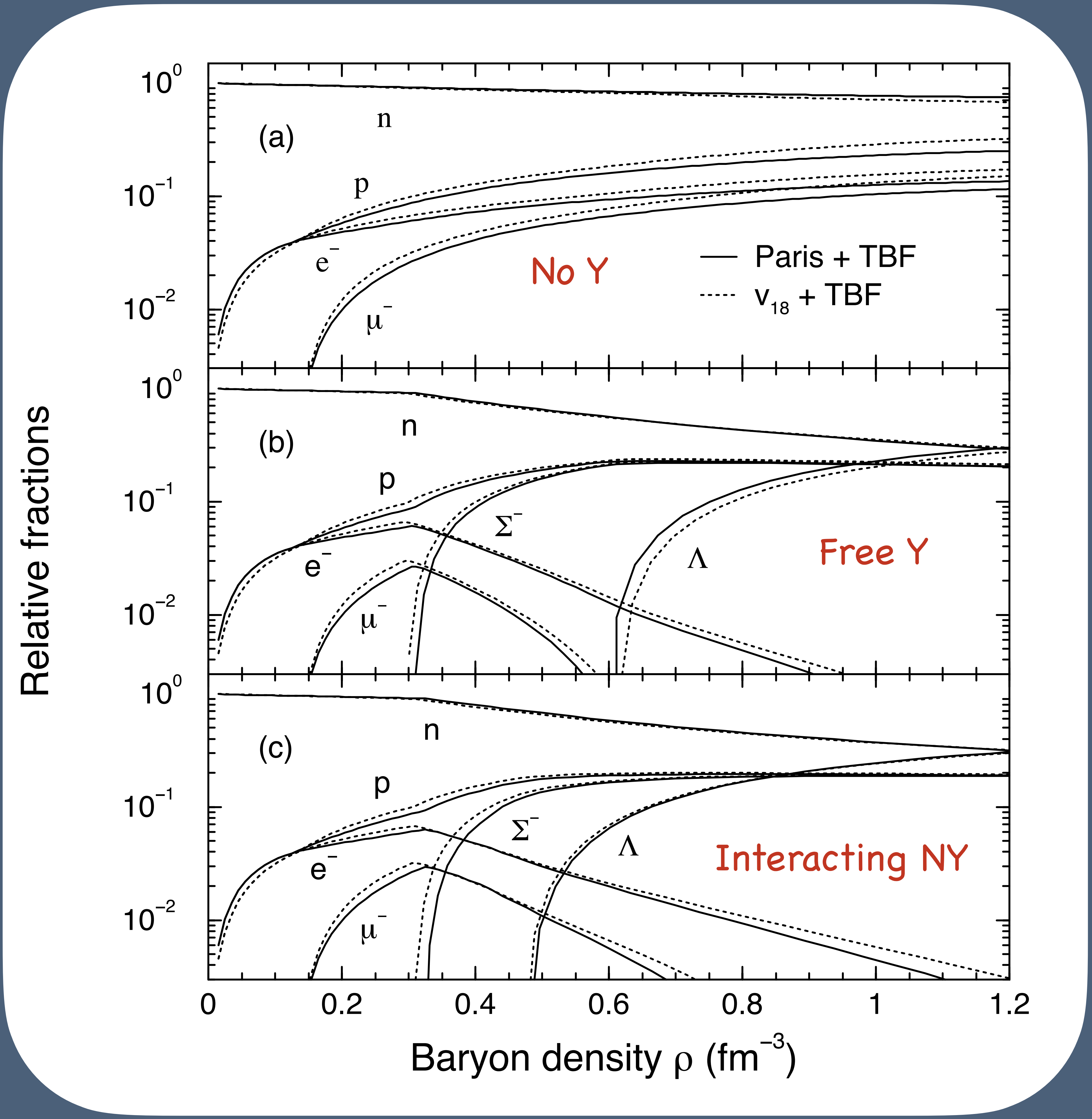
"Recipe" for neutron star structure calculations

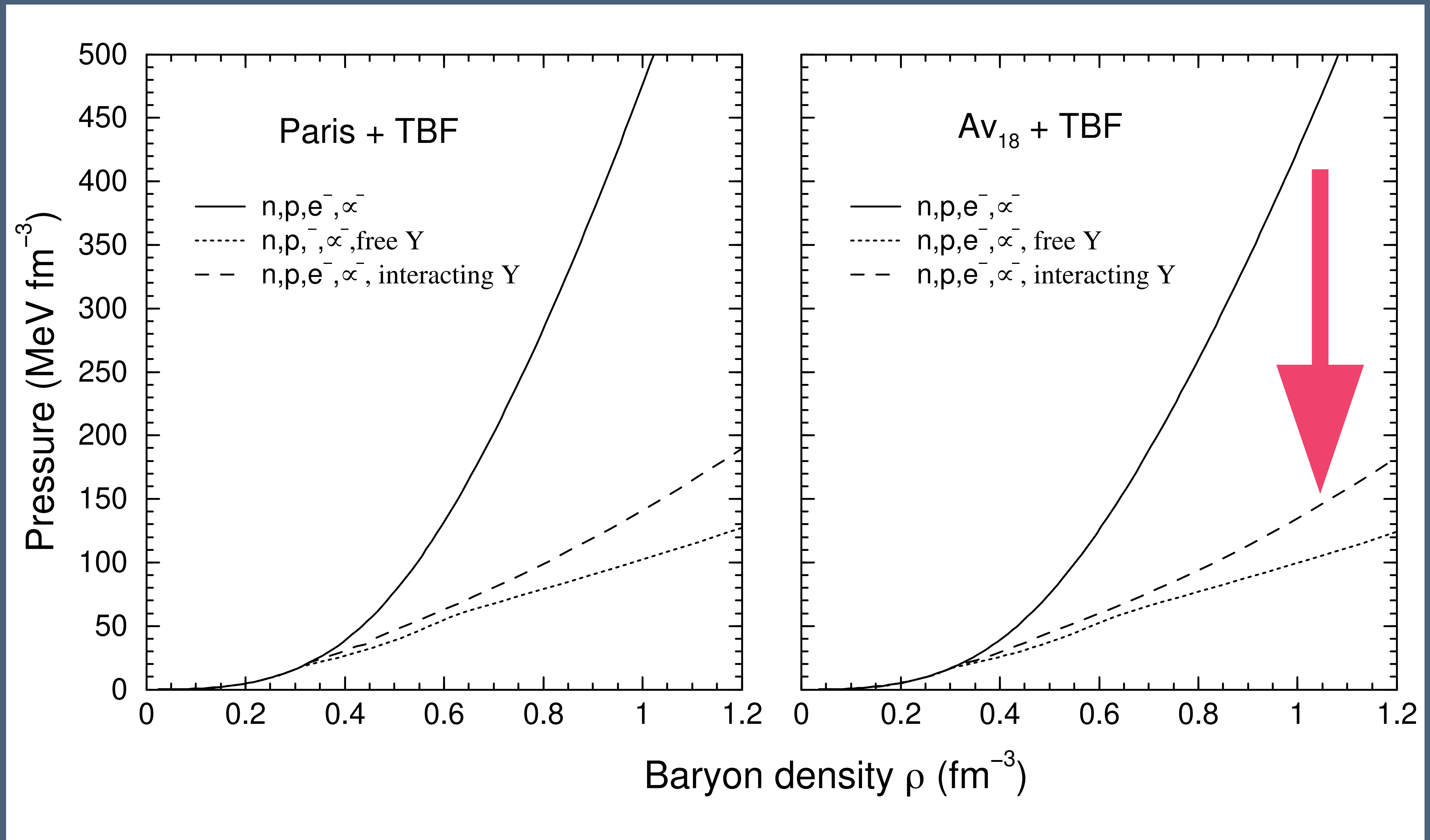
- Brueckner results : $\epsilon(\rho_i); i = n, p, e^-, \mu^-, \Lambda, \Sigma, u, d, s \ldots$
- Chemical potentials : $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$
- Beta-equilibrium : $\mu_i = b_i \mu_n - q_i \mu_e$
- Charge neutrality : $\sum_i x_i q_i = 0$
- Composition : $x_i(\rho)$
- Equation of State : $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$
- TOV equations :

$$\begin{cases} \frac{dP}{dr} = -\frac{Gm}{r^2}\frac{(\epsilon + P)(1 + 4\pi r^3 P/m)}{1 - \frac{2Gm}{r}} \\ \frac{dm}{dr} = 4\pi r^2 \epsilon(r) \end{cases}$$

Structure of the star: ϱ(r), ***M(R)*** etc.

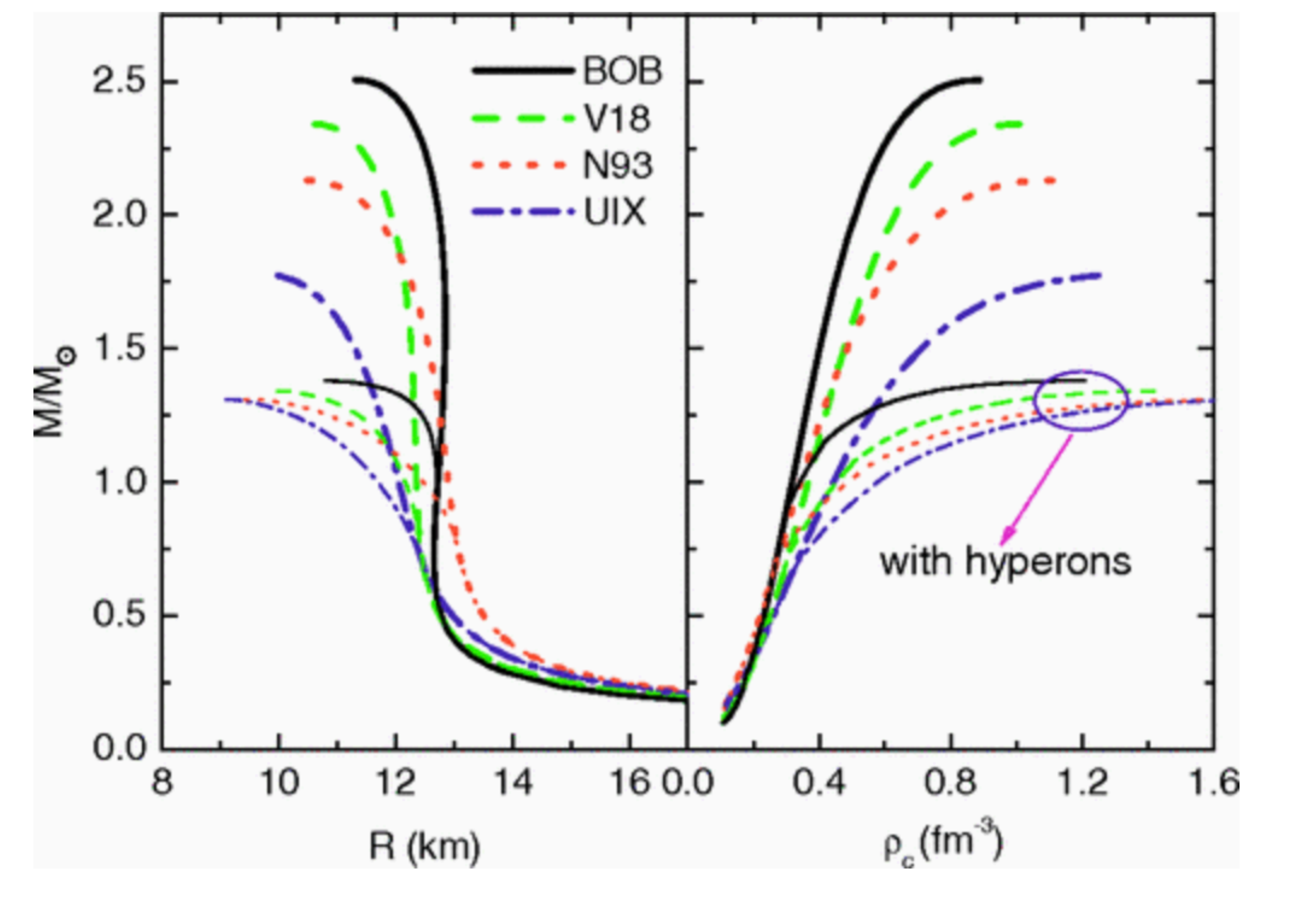
Composition and EoS of hypernuclear matter





- NSC89 NY potential
- No (YY, YYY) potential
- Hyperon onset occurs at $\rho \sim (2-3)\,\rho_0$
- Strong softening due to hyperon onset

Mass-Radius relation with different NN interactions



BOB : Bonn B + microscopic TBF

V18 : Argonne v_{18} + microscopic TBF

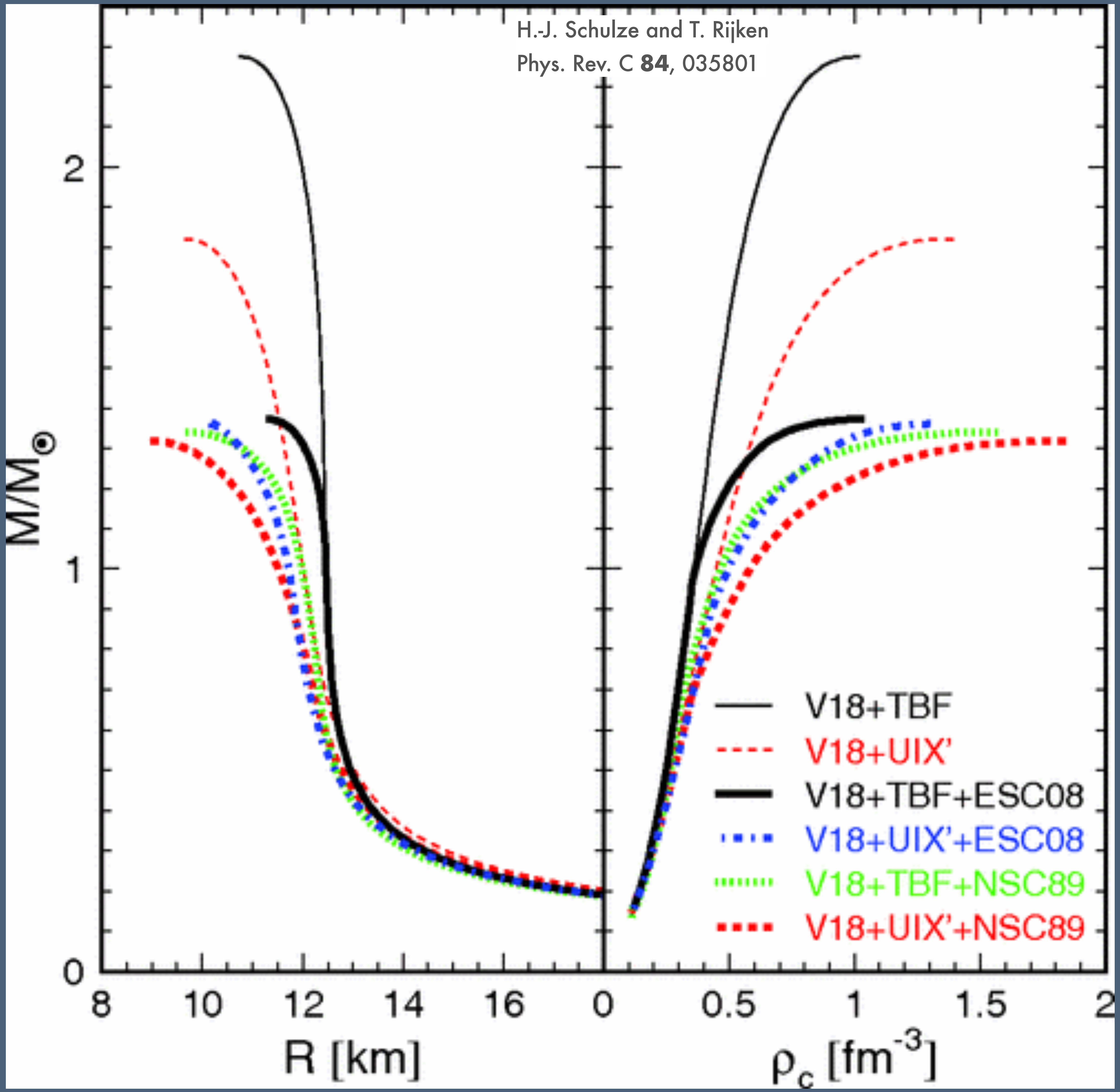
N93 : Nijmegen + microscopic TBF

UIX : Argonne v_{18} + phenom. TBF (Urbana model)

- Only small effect required [$\delta(B/A) \approx 1$ MeV at ϱ_0]
- TBF are model dependent, no final theory yet
- Use and compare microscopic and phenomenological TBF…
  - Microscopic TBF of P. Grangé et al., PRC 40, 1040 (1989): Exchange of $\pi, \varrho, \sigma, \omega$ via $\Delta(1232)$, R(1440), $N\bar{N}$
    Parameters compatible with two-nucleon potential (Paris,V_{18},…)
  - Urbana IX phenomenological TBF:
    2π-TBF + phenomenological repulsion Fit saturation point

- *Large variation of M_{max} with the NN interaction*
- *Softening due to hyperon appearance*
- *Stiffer EoS → earlier hyperon onset*

Mass-Radius relation with different NY potentials



- Nijmegen ESC08b YN potentials features a more repulsive $\Sigma^{-}N$ interaction, in contrast to the previously used NSC89, NSC97 YN potentials.
- Smaller Σ^{-} fraction expected in β-stable matter.
- Maximum mass independent of potentials !

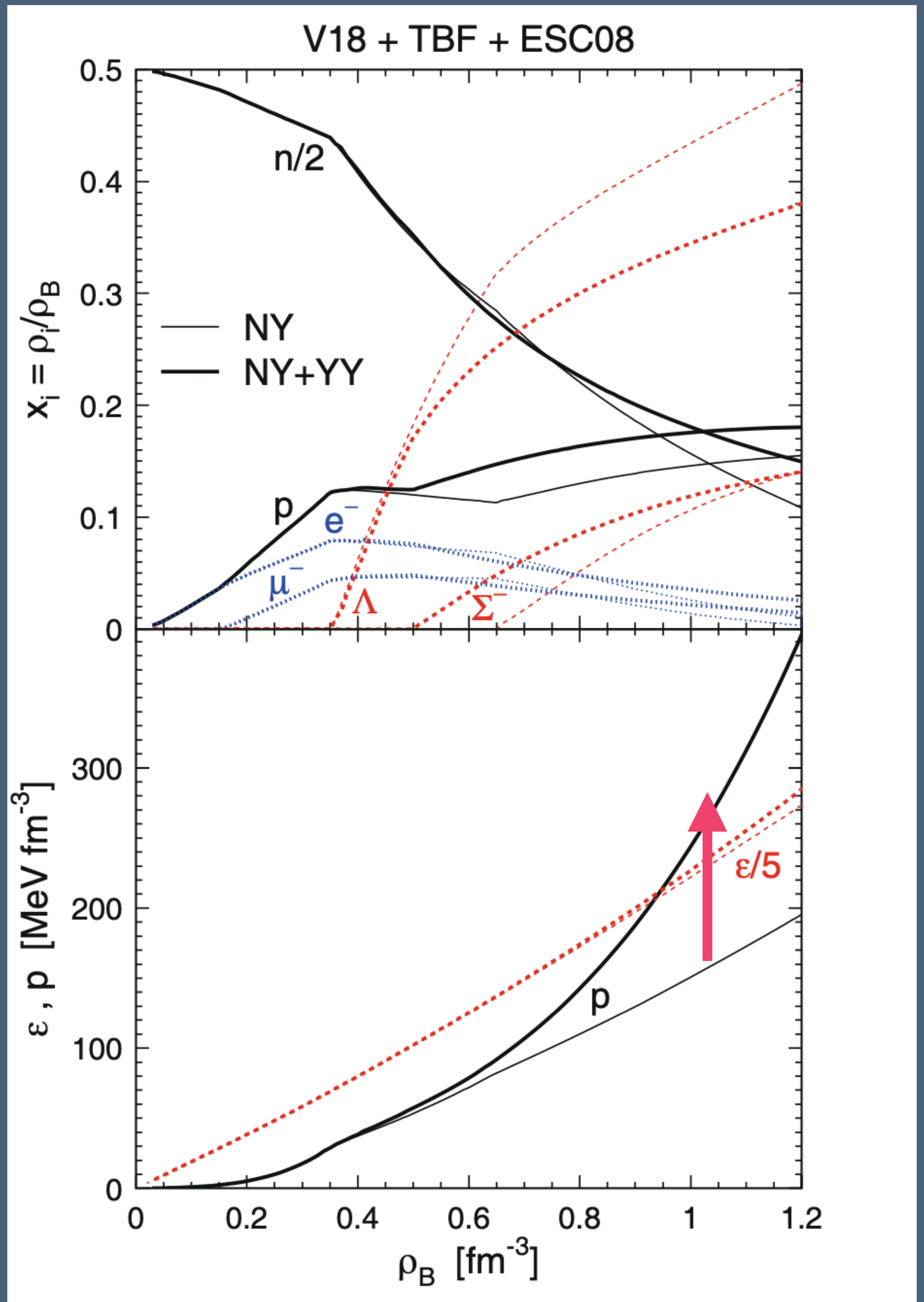
M_{max} too low ($< 1.4\ M_{\odot}$) !

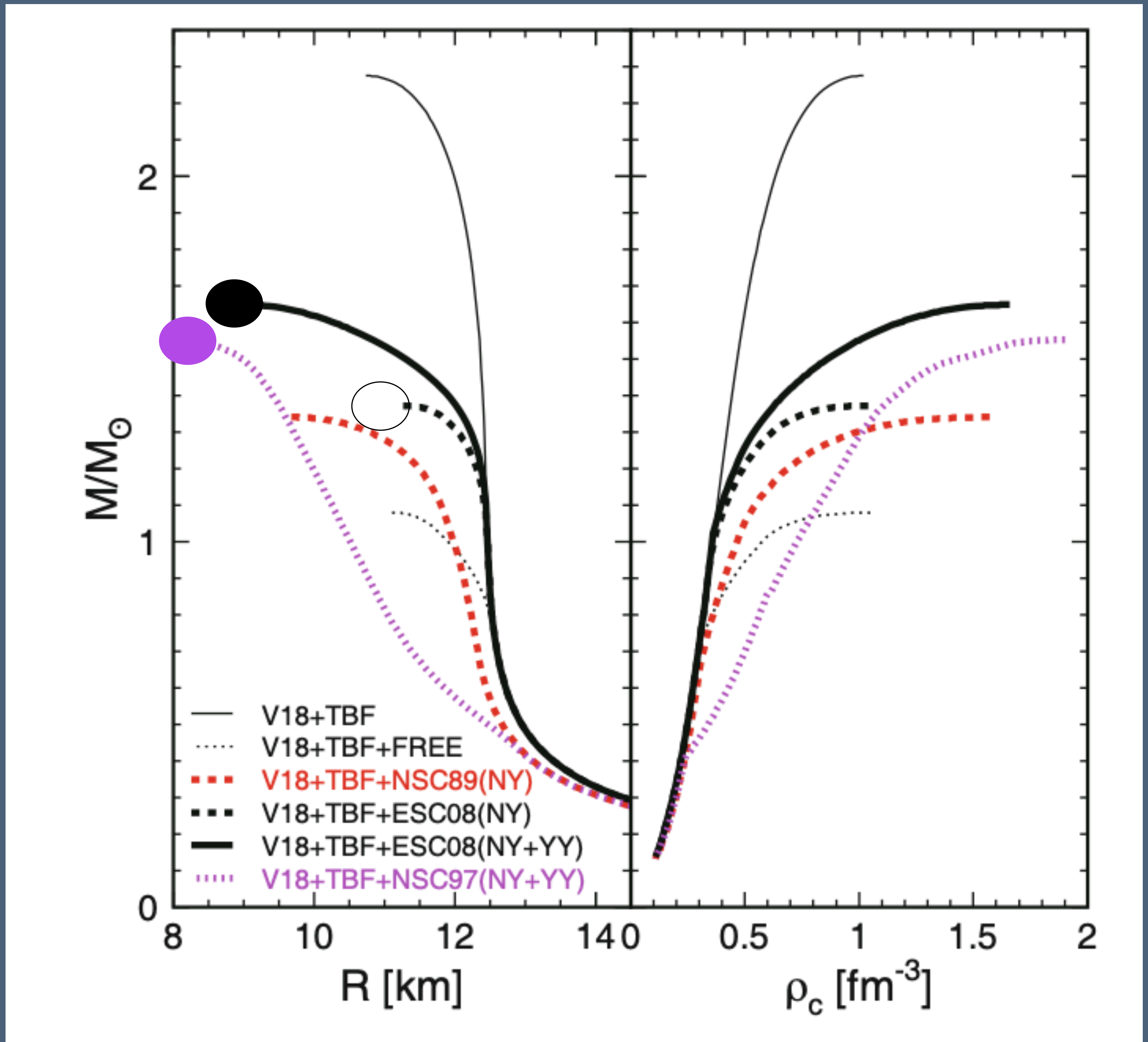
Possible effects of the YY potentials

Th. A. Rijken & H. -J. Schulze, EPJA 52, 21 (2016)

ESC08 model : inclusion of the (S = −2) ΛΛ, NΞ, ΣΛ, ΣΣ channels

- ΛΛ, $\Sigma^-\Sigma^-$ repulsive
- $\Lambda\Sigma^-$ attractive
- Stiffer EoS
- Expected larger M_{max}





M_{max} increase to about 1.7 $M_\odot$

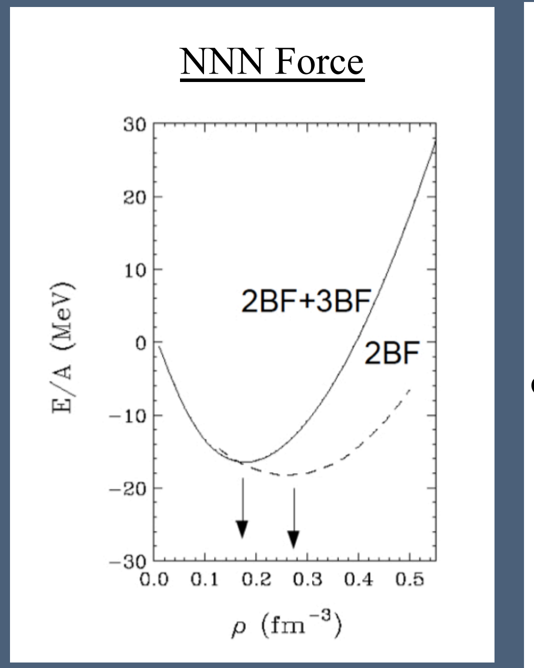
Hyperon puzzle

Hyperons → too soft EoS not compatible with measured NS masses.

CAVEAT : the presence of hyperons in the NS core seems to be unavoidable !

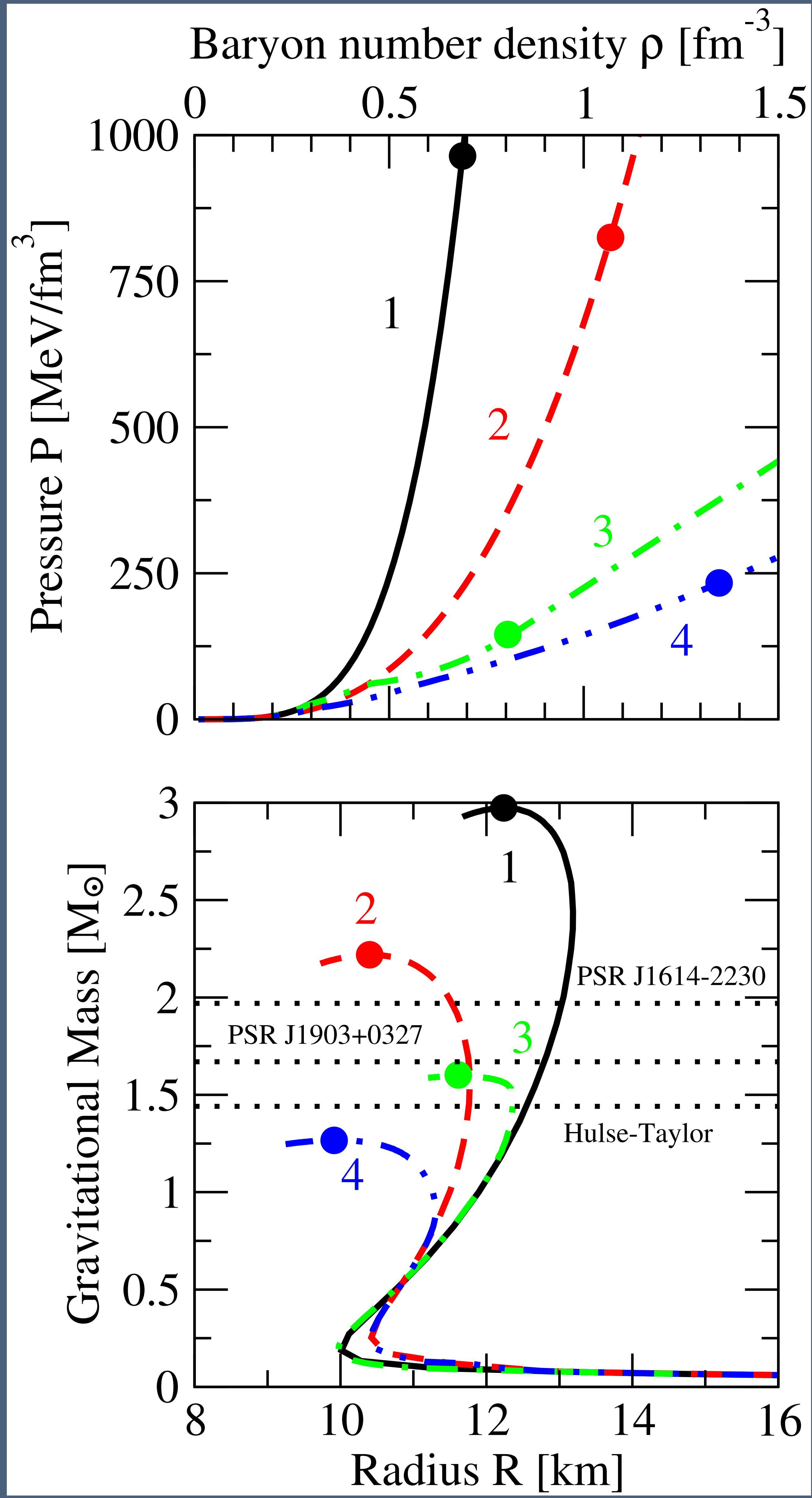
Possible solutions of the hyperon puzzle

Solution I : Hyperonic TBF



- Importance of TBF in Nuclear Physics
- Correct saturation point in microscopic approaches
- Can hyperonic TBF solve the puzzle ?
- Introduction of a simple phenomenological density dependent contact term. Parameters fitted on NM saturation point.
- No general consensus regarding the results.
- Hyperonic 3-body forces in χEFT might solve the hyperon puzzle ??

$1.27 < M_{max} < 1.6 M_\odot$



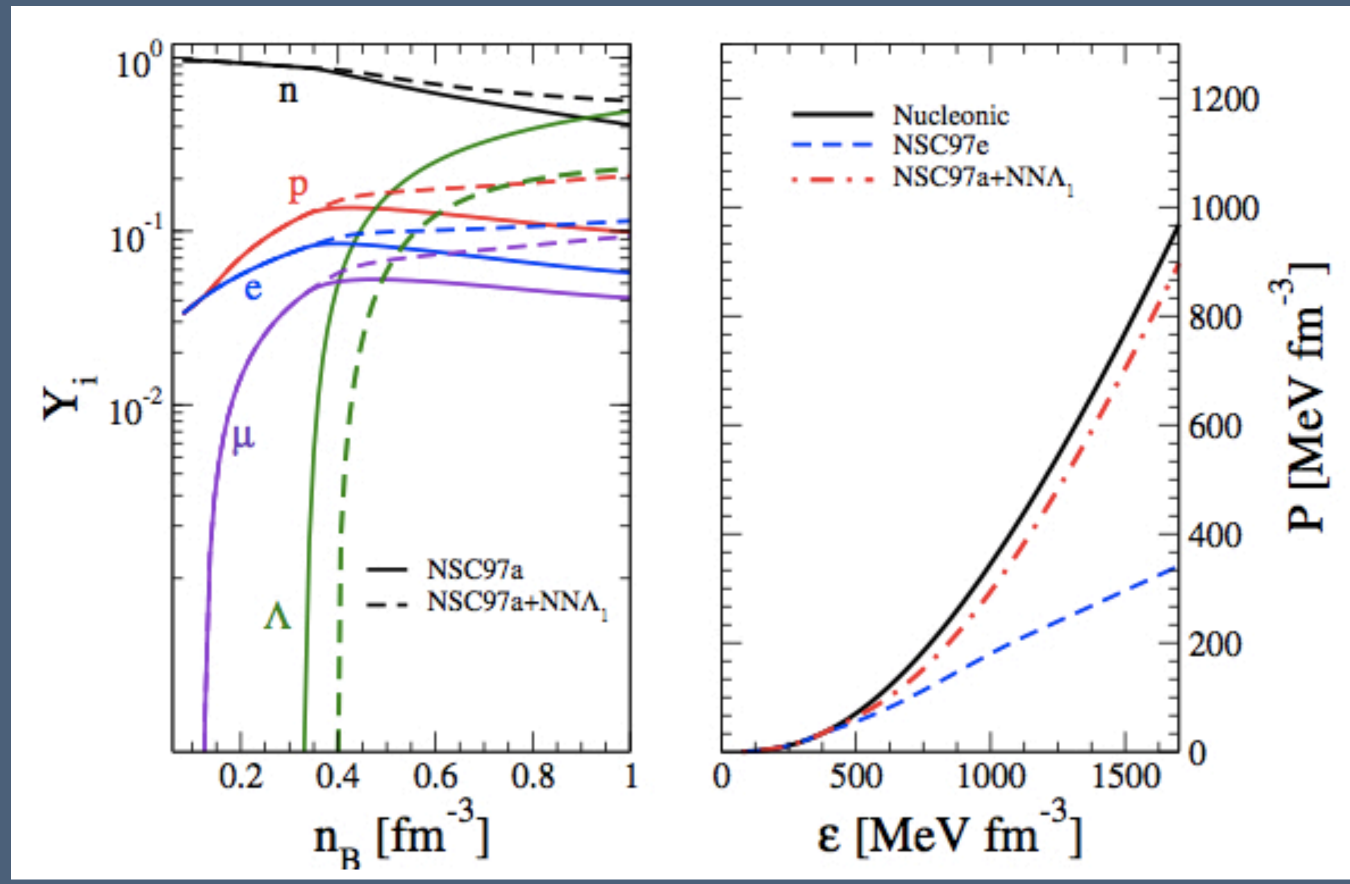
Solution II : the NNΛ chiral forces

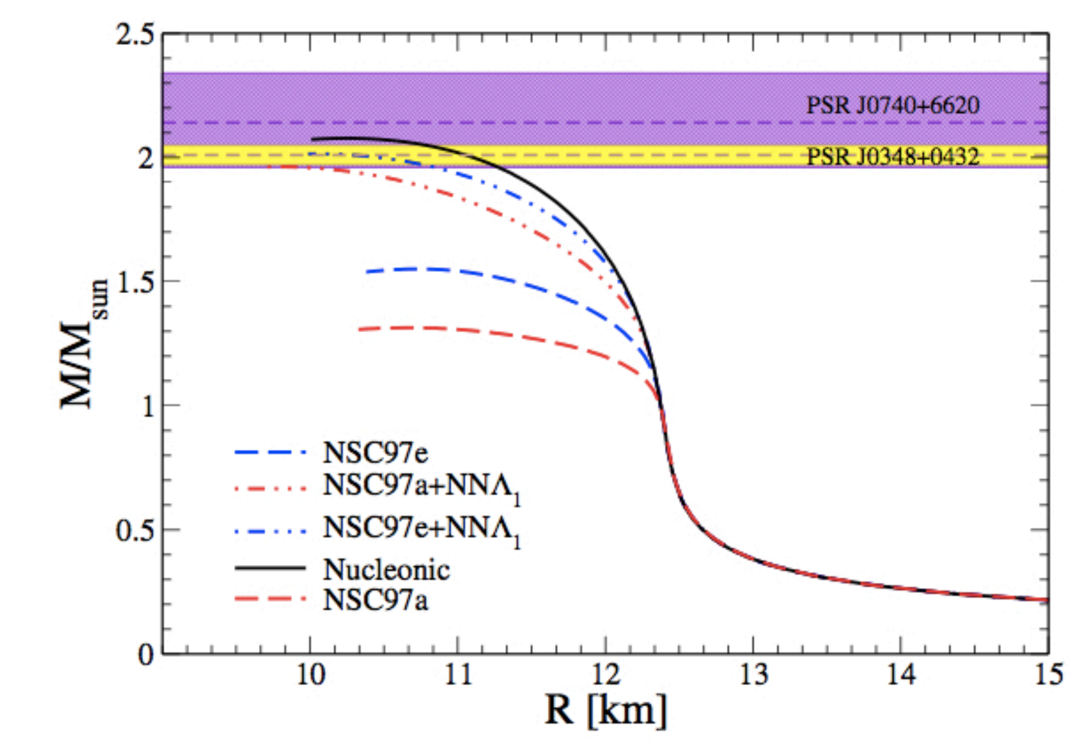
- Preliminary exploratory work by Logoteta, Vidaña & Bombaci on the role of NNΛ interaction. Eur. Phys. J. A (2019) 55:207.

- The chiral NNΛ shifts the onset of Λ to slightly larger densities and largely reduces the concentration, thus stiffening the EoS.

- Maximum mass “almost” compatible with the 2 $M_\odot$ limit, but *other hyperons* should be included.

Hyperon puzzle cannot be considered as solved !

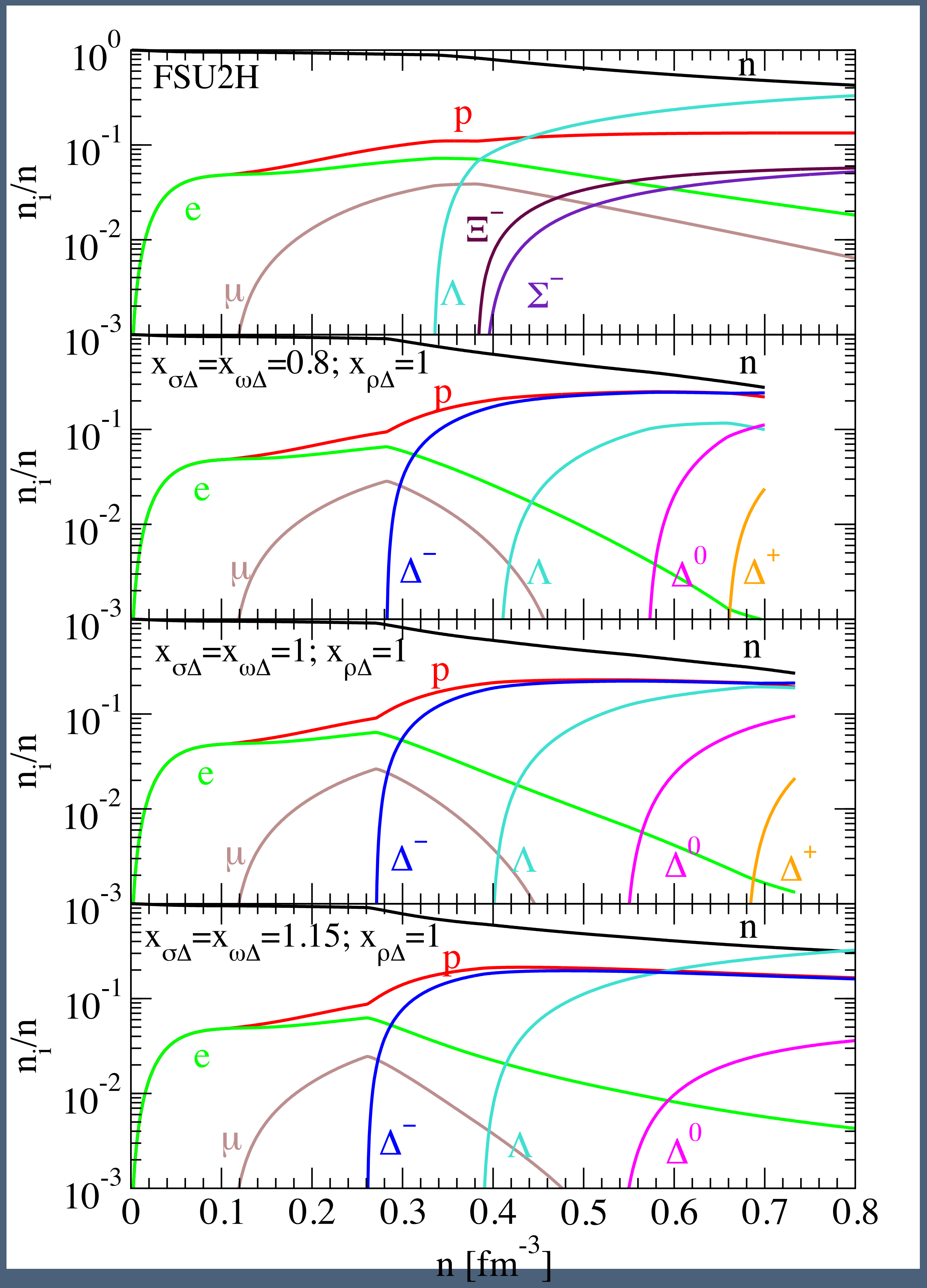


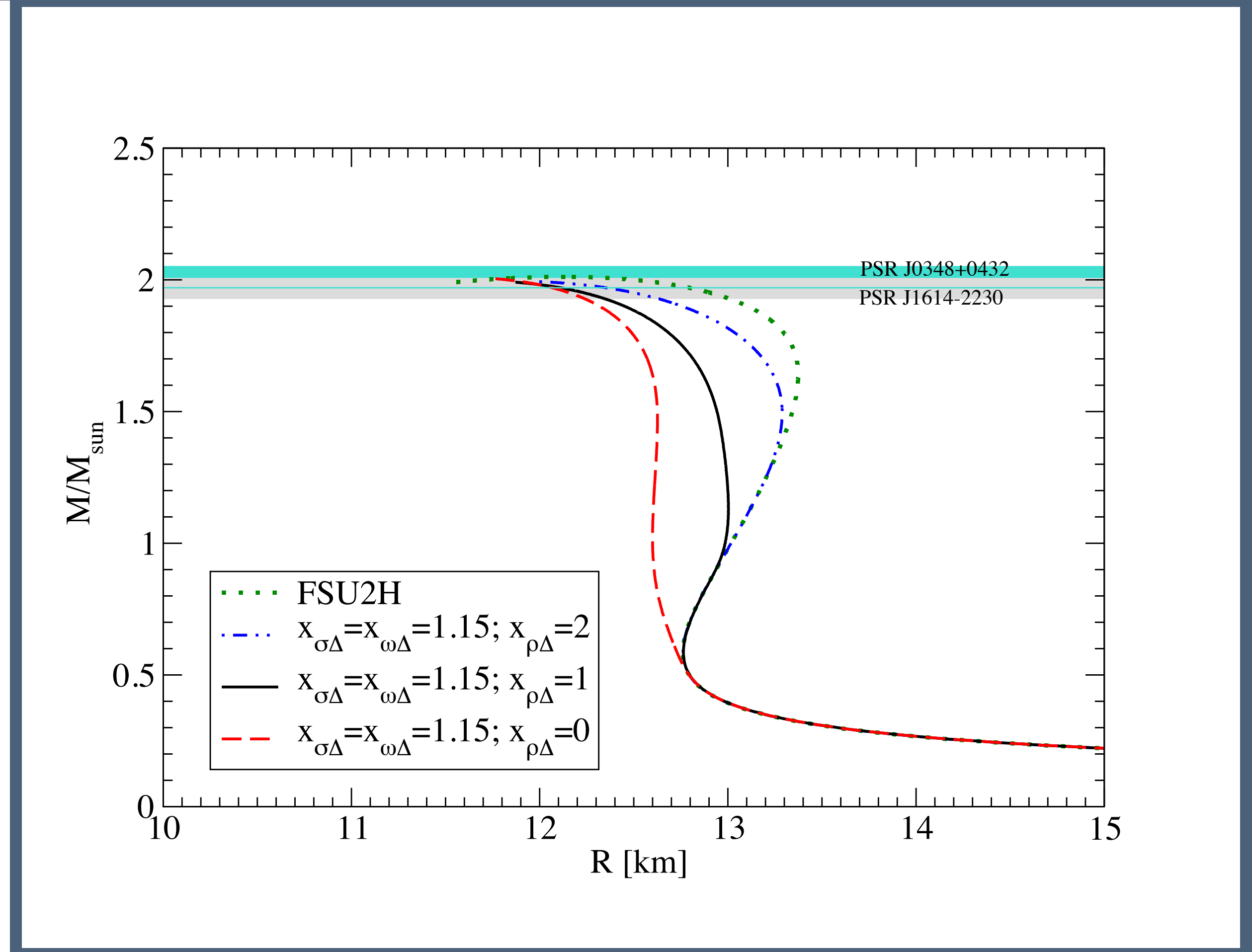


	$M_{max}(M_\odot)$	R (km)	n_c (fm^{-3})
Nucleonic	2.08	10.26	1.15
NSC97a	1.31	10.60	1.40
NSC97a+NNΛ$_1$	1.96	9.80	1.30
NSC97a+NNΛ$_2$	1.97	9.87	1.28
NSC97e	1.54	10.81	1.18
NSC97e+NNΛ$_1$	2.01	10.10	1.20
NSC97e+NNΛ$_2$	2.02	10.15	1.19

Solution III : Appearance of Δ-isobars

- Mainly in RMF models.
- Couplings of the Δ isobars with the meson fields $x_{\sigma\Delta}$, $x_{\omega\Delta}$, $x_{\rho\Delta}$ are poorly constrained due to the limited experimental data.
- Imposing an attractive Δ-nucleus potential of a few tenths of MeV thus containing the range.
- Push of the Y onset to higher densities, even disappearing !
- The 2Mo limit might be reached for some choices of the meson fields.





Ribes, Ramos, Tolos, Gonzalez-Boquera, Centelles, ApJ (2019)

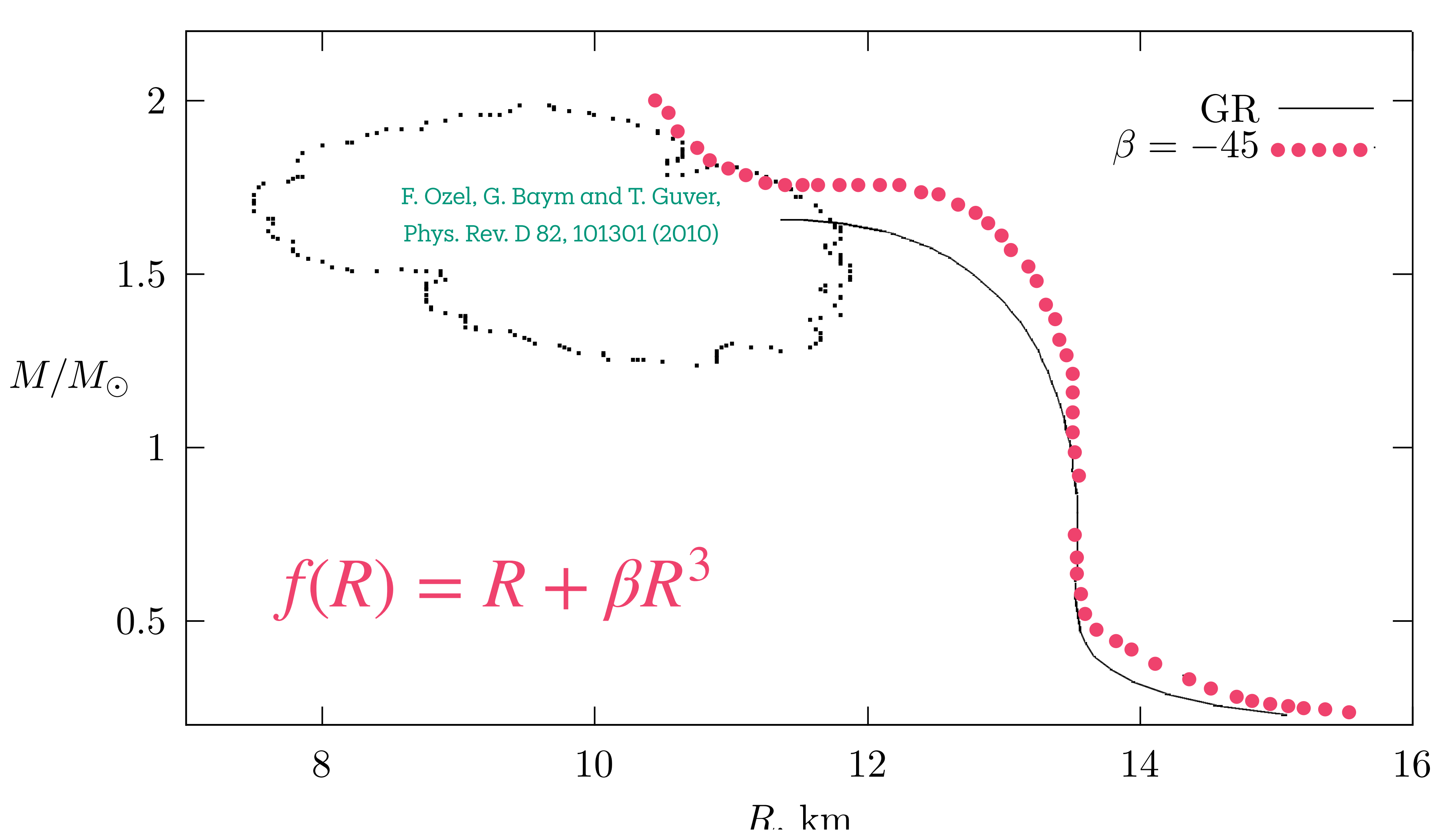
Drago et al '14 '15, Jie Li et al '19...

Unconventional Solutions

Solution IV : Modified gravity

- Modified TOV eqs. in f(R) gravity.
- It depends on the chosen f(R).

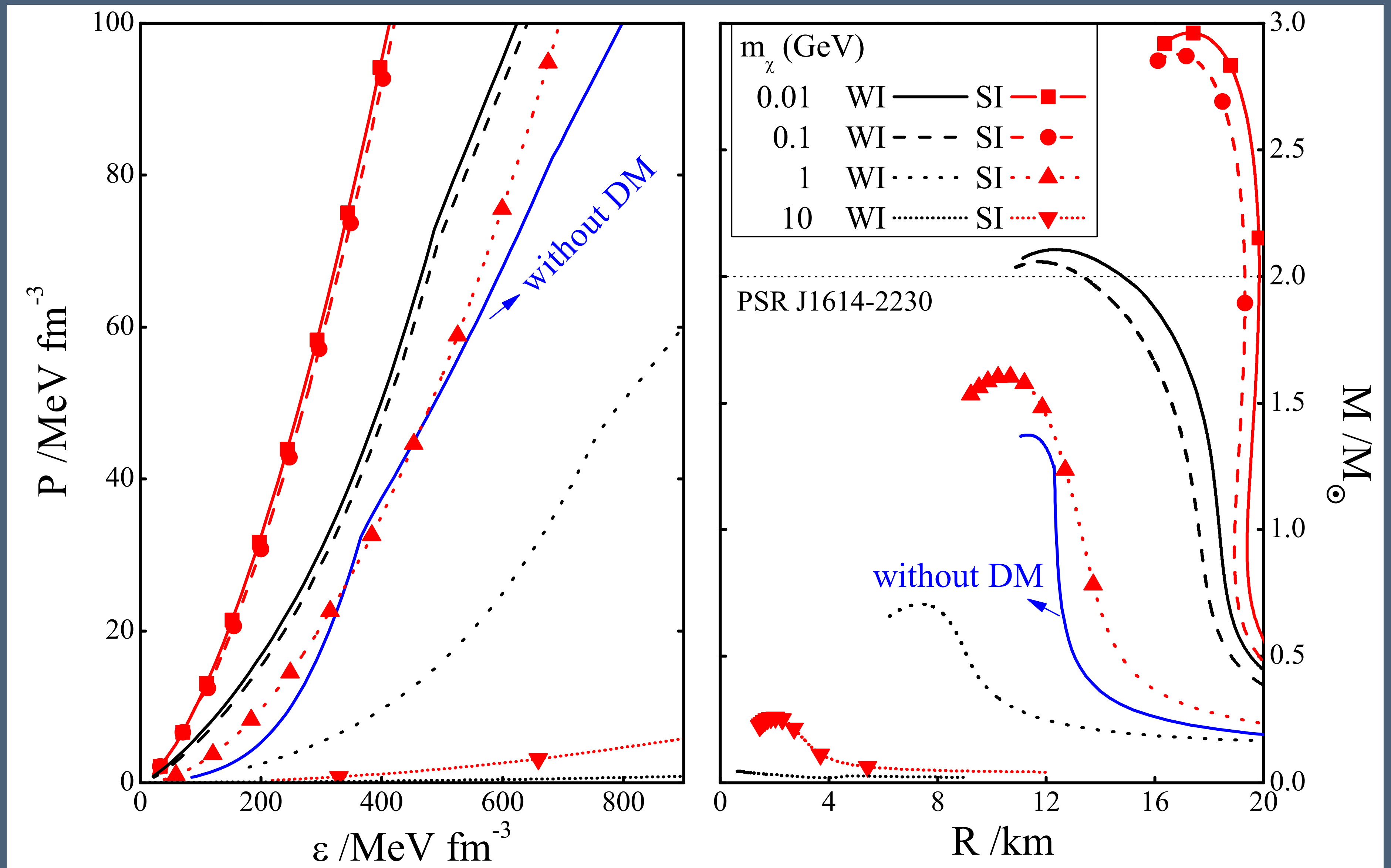
Astashenok, Capozziello, Odintsov '10, '11, '14 ...



Solution V : DM-admixed NS

- DM particle nature and mass
- DM interaction strength
- DM fraction in NS interior
- Large parameter space to explore
- Possible solution of the hyperon puzzle but strong parameter dependence.

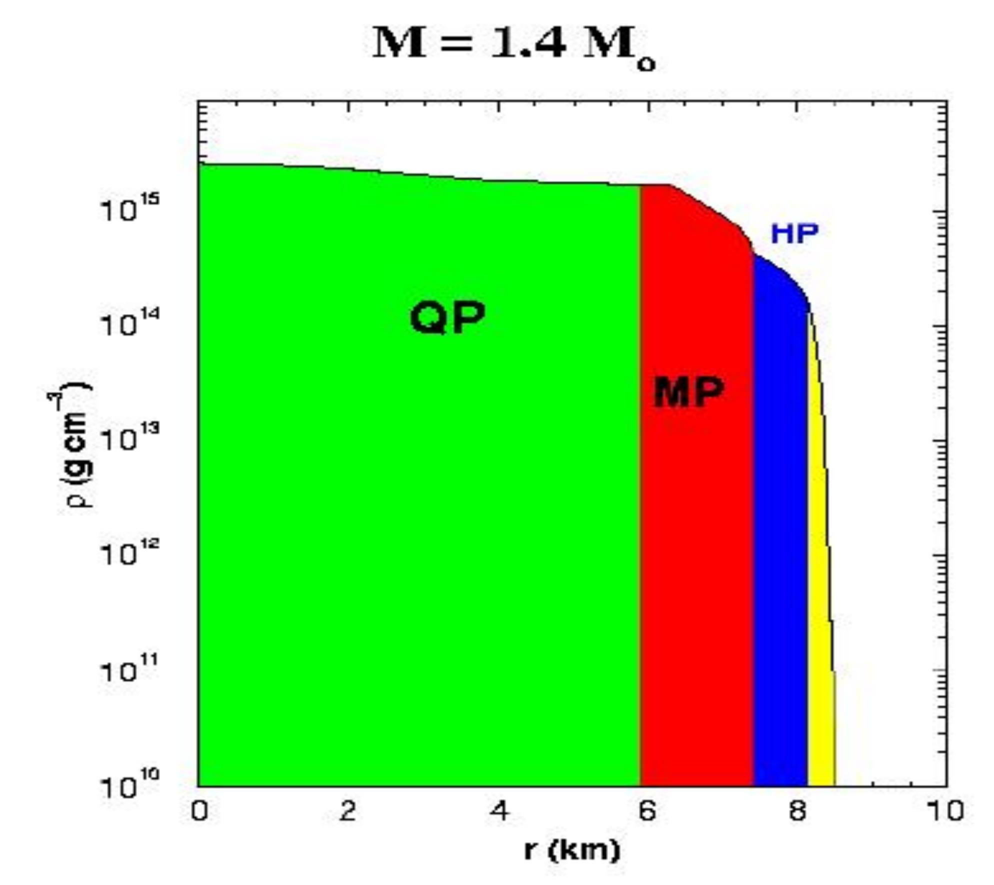
Li, Huang, Xu, Astroparticle Physics 37 (2012) 70–74



Solution VI : Quark matter core

- Problem : no exact result from QCD. Large theoretical uncertainties.
- Use of available quark models in combination with the baryonic matter EoS. Maxwell/Gibbs phase transition.
- MIT bag model, Nambu—Jona-Lasinio, Dyson-Schwinger, Color-Dielectric model, Field Correlator method.
- Important constraint from HIC : in Symmetric matter no phase transition below $\sim 3\rho_0$
- They all give different hybrid star structure and maximum mass limits.

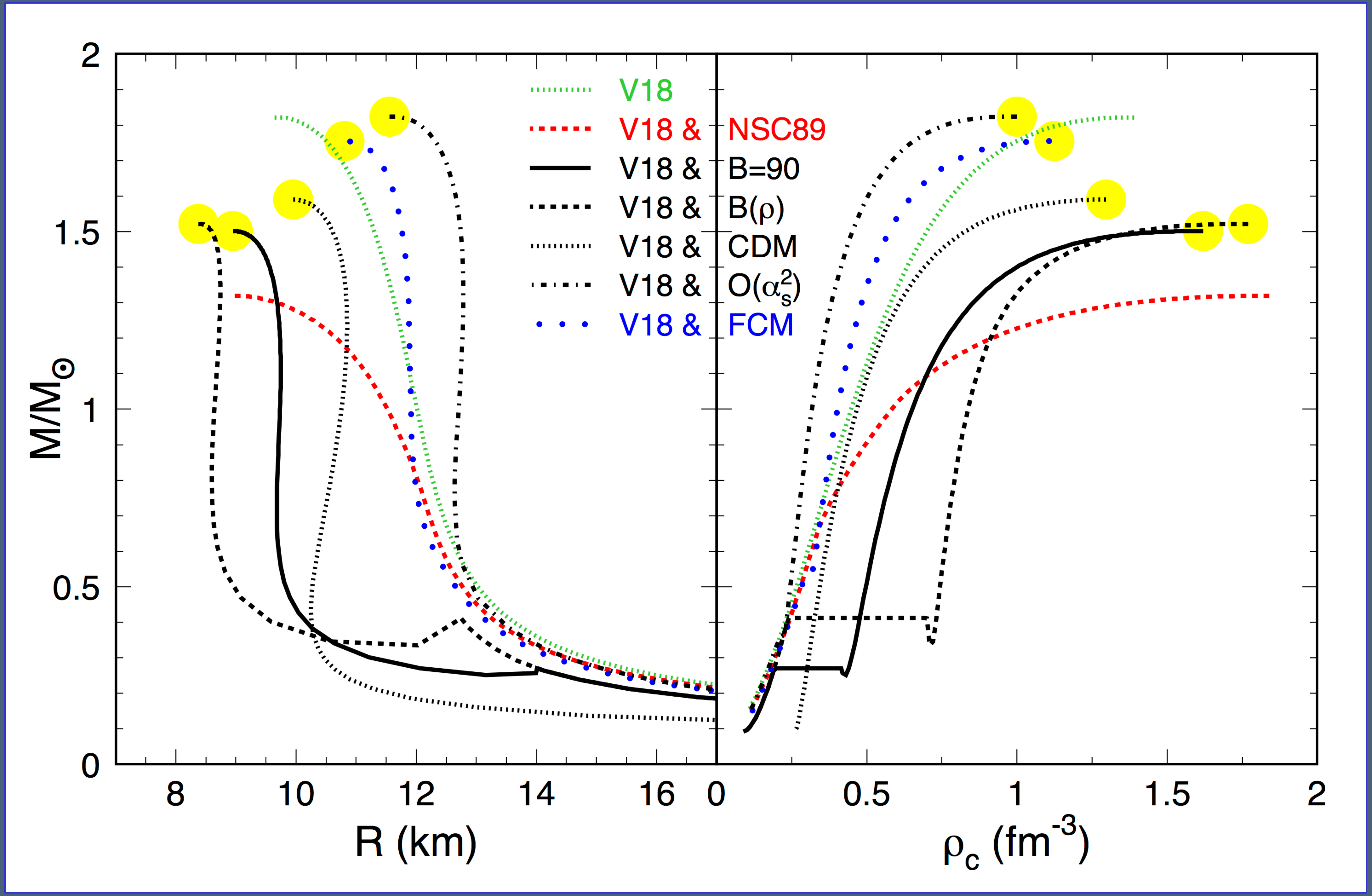
- MIT bag model (Chodos (1974), Fahri (1984), Baym (1985), Glendenning (1990))
- MIT bag wt. phen. corr. (Alford et al., ApJ**629** (2005), 969)
- NJL models (Buballa et al., Nucl. Phys. A703 (2002) 770)
- PNJL models (Blaschke et al., arXiv:1302.6275)
- Color Dielectric model (Maieron et al, PR**D70** (2004) 043010)
- Dyson-Schwinger model (Chen et al, PR**D84** (2011) 105023)
- 2-loop perturbation theory of the cold QCD EoS (Kurkela PR**D81**(2010) 105021)



Density profiles of different phases
MIT bag model

Stable configurations of Hybrid Stars

- The value of the maximum mass lies in a range 1.5…1.9 $M_\odot$
- The value of the maximum mass is mainly determined by the quark component and relative EoS.
- Neutron stars with quark matter core may have smaller radii than purely hadronic stars.
- Additional repulsion in QM EoS is required in order to reach 2$M_\odot$

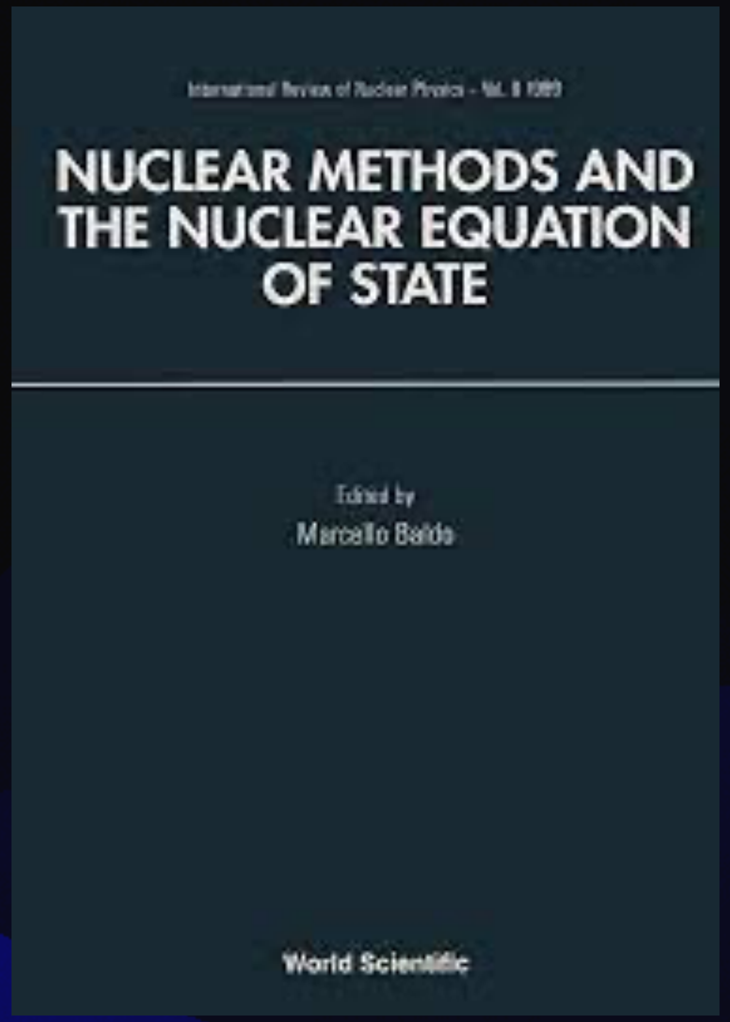


Conclusions

- On the *NN + NNN + NY* level, the prediction of very low NS maximum masses is rather robust.
- Reliable *YY*, *YNN*, *YYN*, *YYY* forces are not available (probably in the future ?).
- Only simultaneous repulsion in all relevant *YY*, *YNN*,… channels could substantially increase the maximum mass.

Need quark matter to reach higher masses of hybrid stars !

A big theoretical challenge for the future.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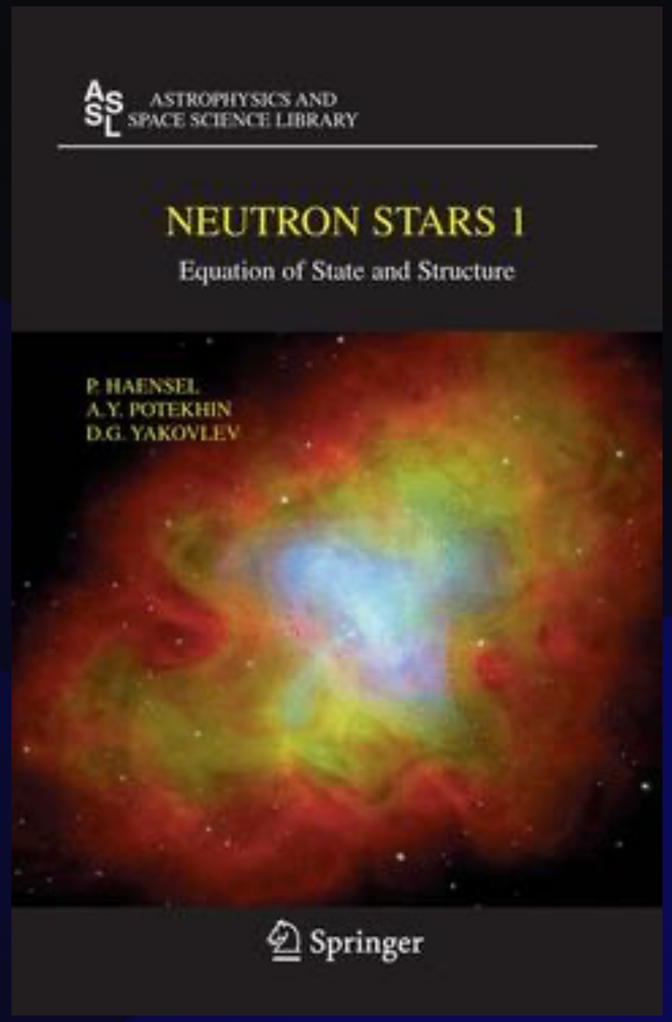
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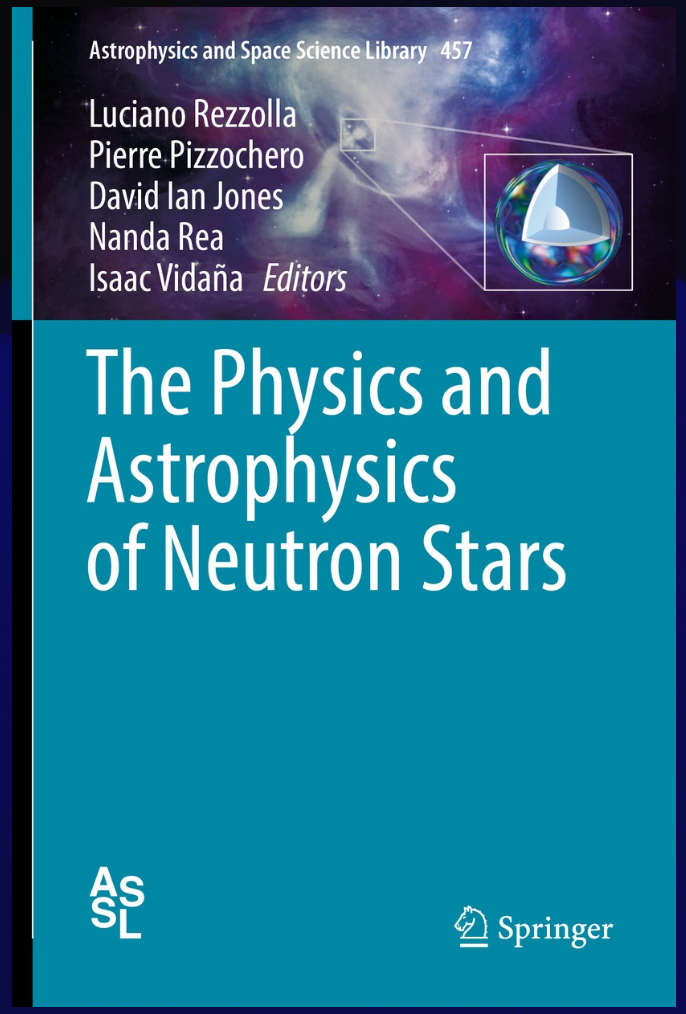
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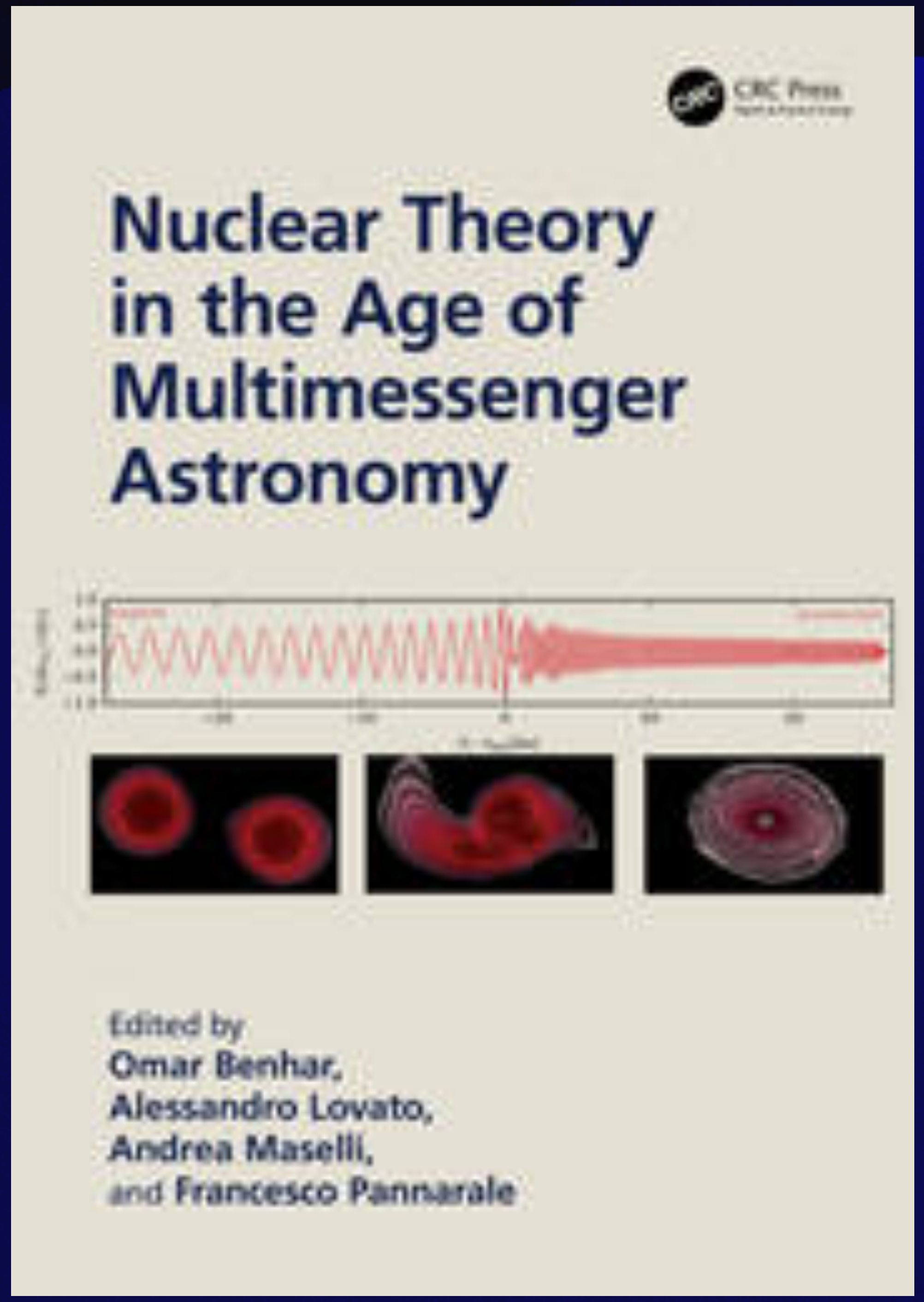
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