NUSDAF 2025 - 1st Collaboration Meeting on NUclear Structure, Dynamics and Astrophysics at FRIB

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

Symmetry Energy and Compact Stars : an Overview

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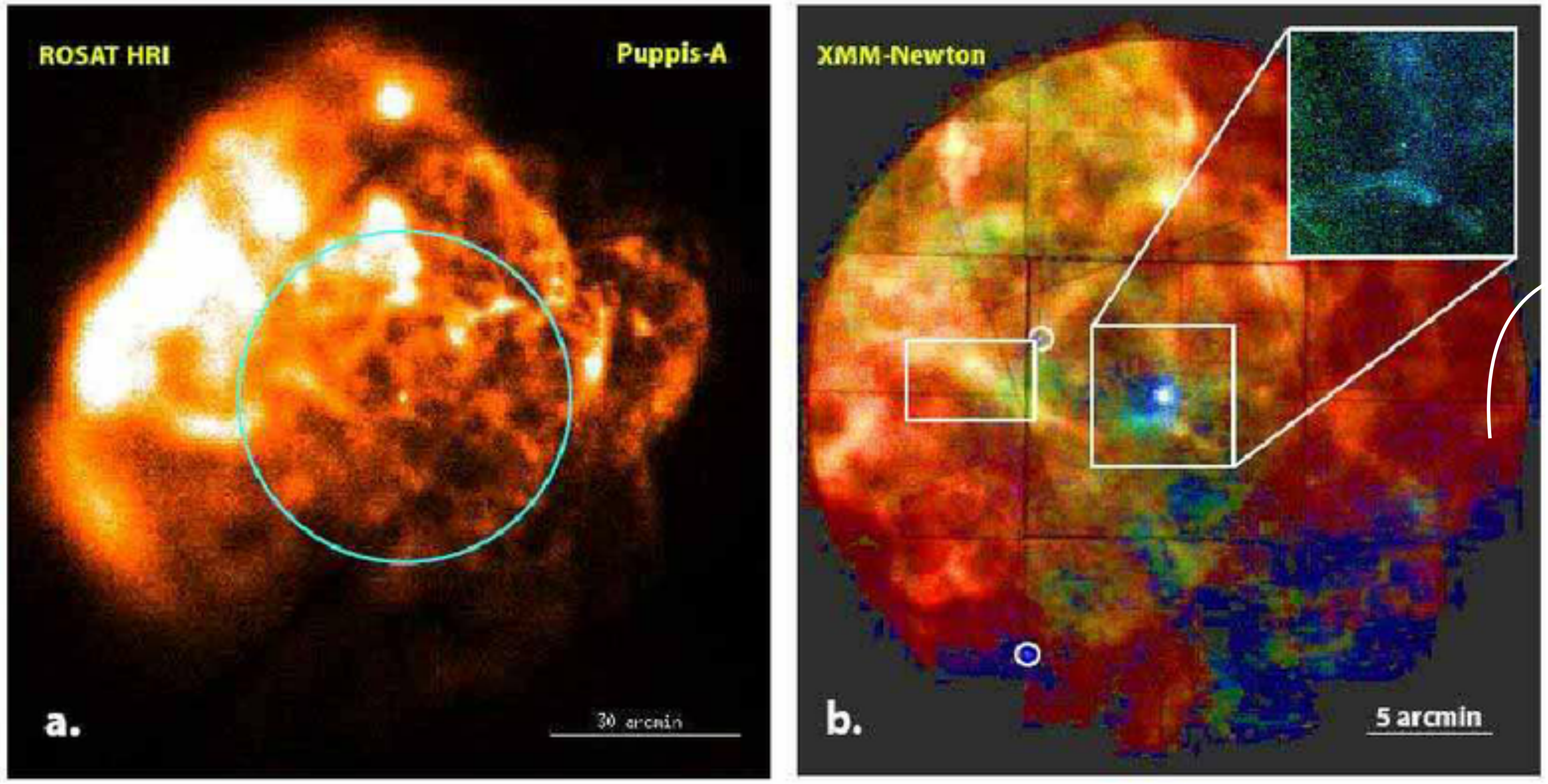
22-24 October 2025, Catania

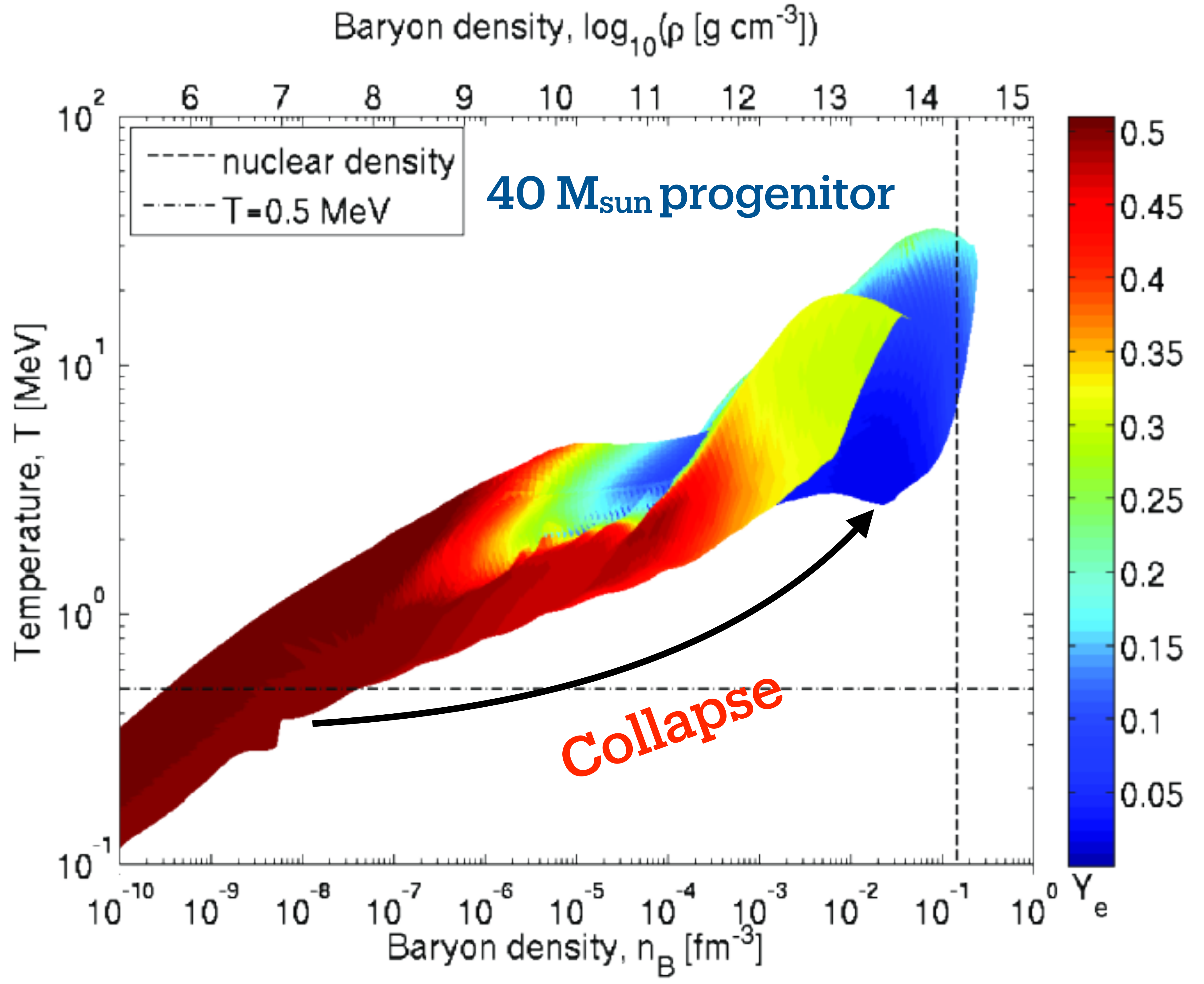
Dense matter in the Universe : SNe

T. Fischer et al., 2011 ApJS 194 39

Supernova remnant in Puppis A



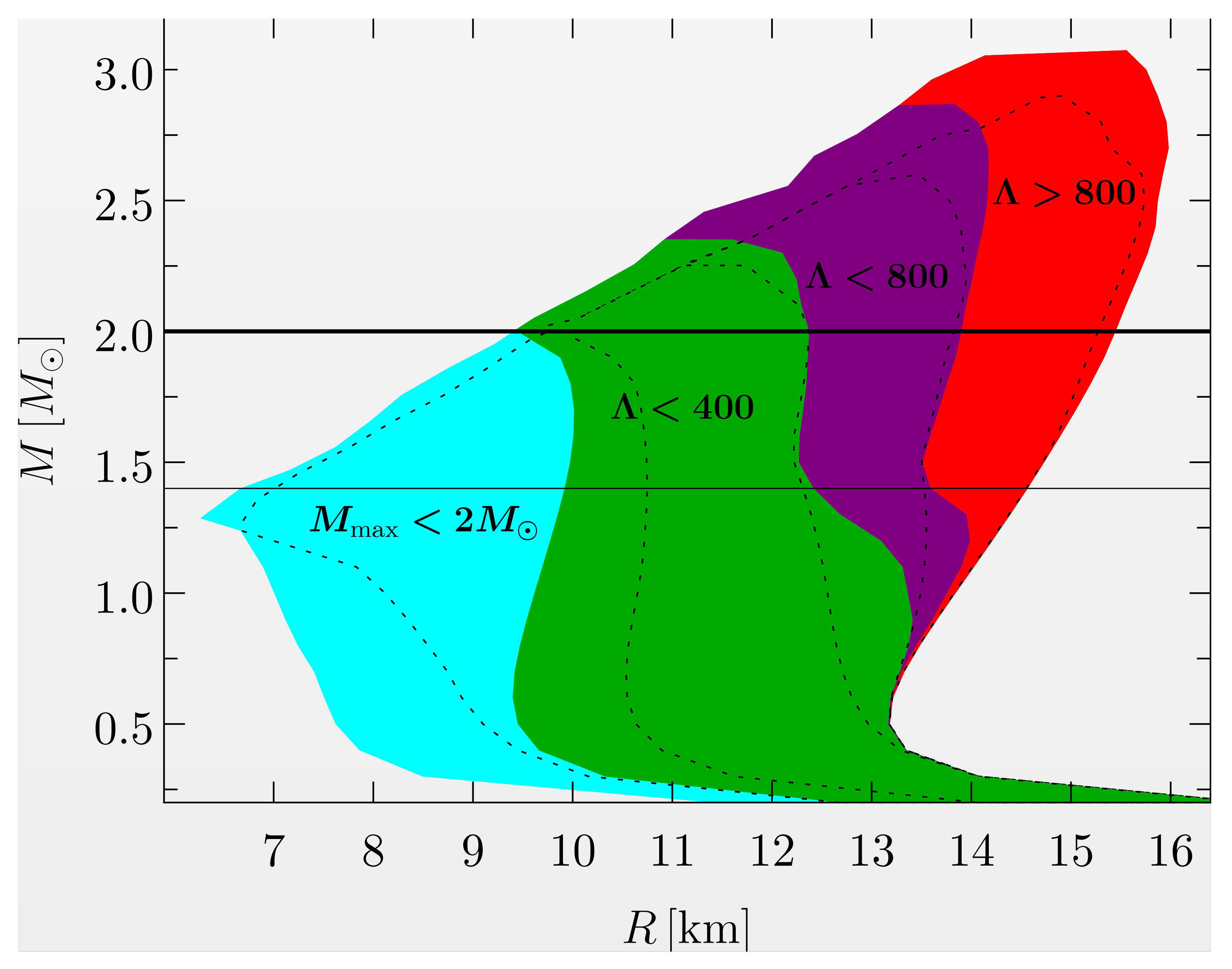
Credit: NASA



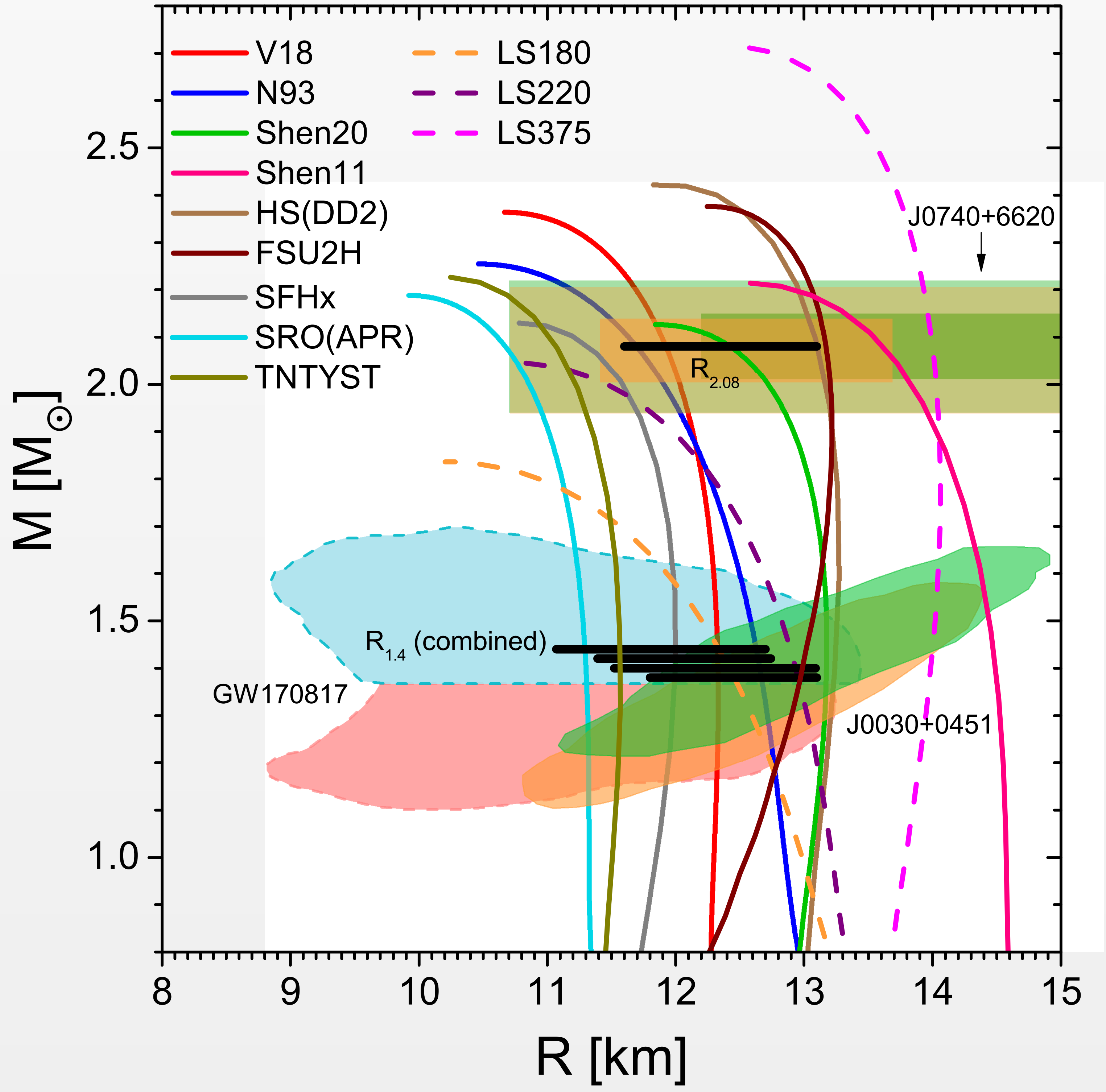
Temperature and density reached during a standard core-collapse supernova simulation at 100 ms post bounce.

Dense matter in the Universe : GW170817, BNS mergers & NICER obs. data

$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$ $\Lambda_{1.4} < 800$ at 90% confidence level

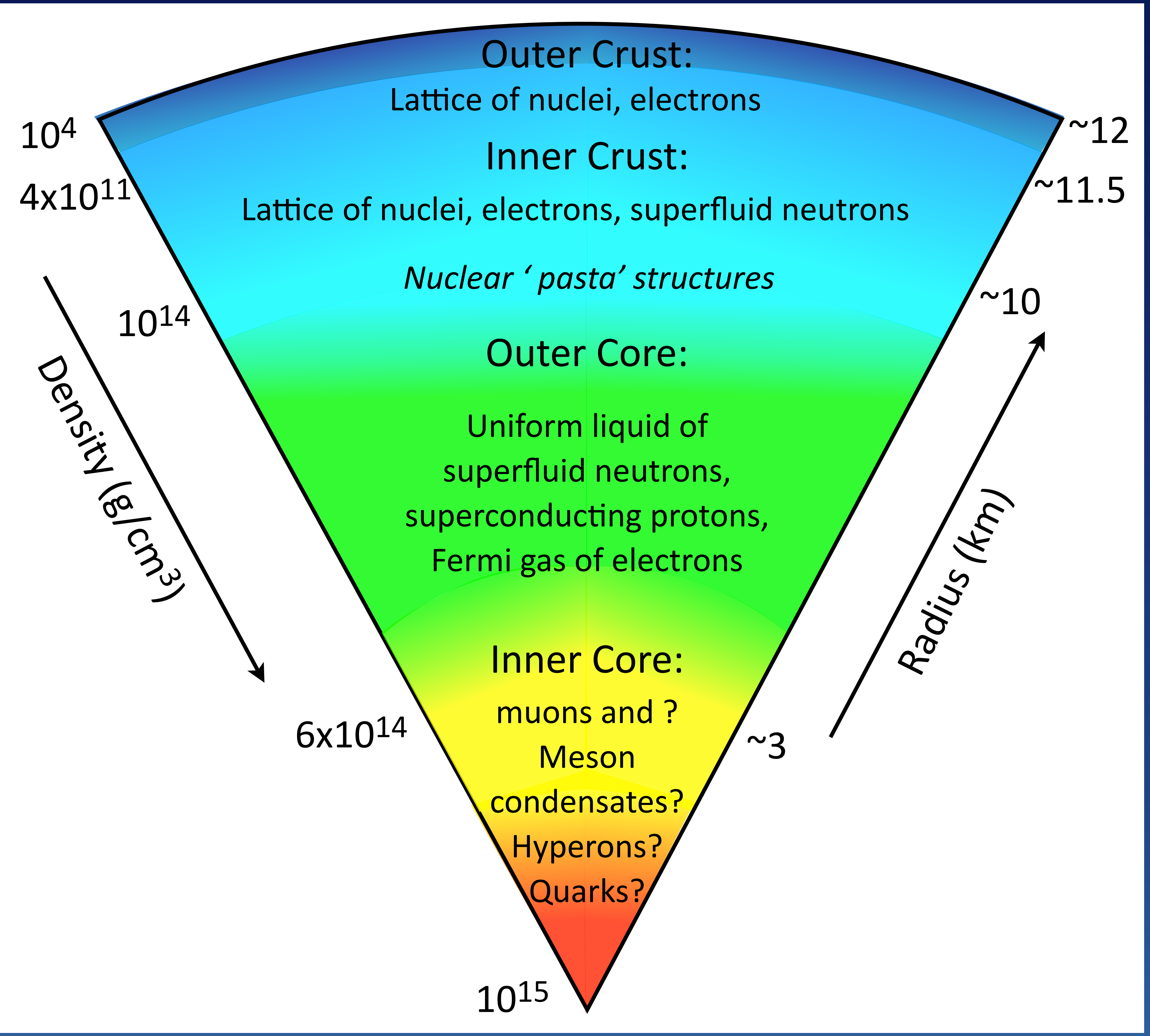


- Very stiff EoS are excluded (large radii)
- Limit for the radius $R_{1.4} < 13.6$ km



The mass of the most heavy pulsar PSR J0740+6620 observed together with the constraints from the GW170817 event and the mass-radius constraints on the pulsars J0030+0451 and J0740+6620 of the NICER mission. The black bars indicate the limits on R2.08 and R1.4 obtained in combined data analyses.

Dense matter in the Universe : NS



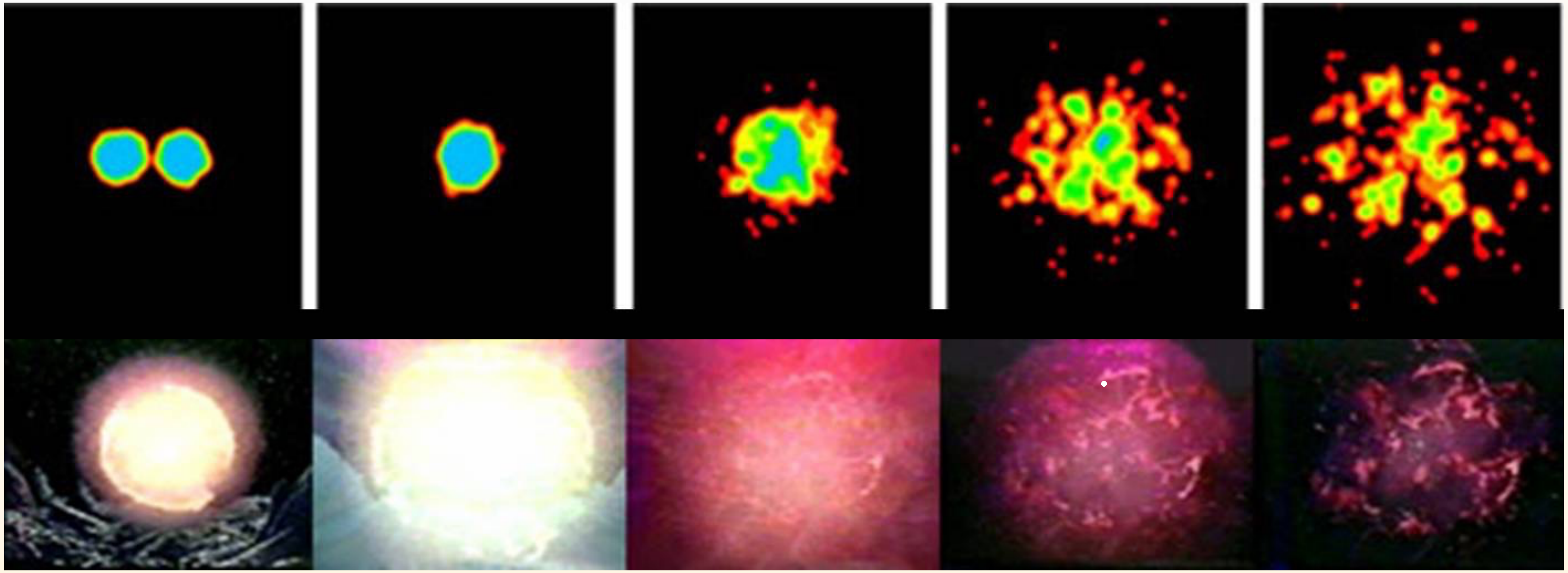
Outer crust *A few hundred m's thick*, $\rho = (10^4 - 10^{11})g/cm^3$. *Ions in an electron gas.*

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. Free neutrons gas. Nuclei melting down and nuclear matter formation 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. Is it all ?*

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 !

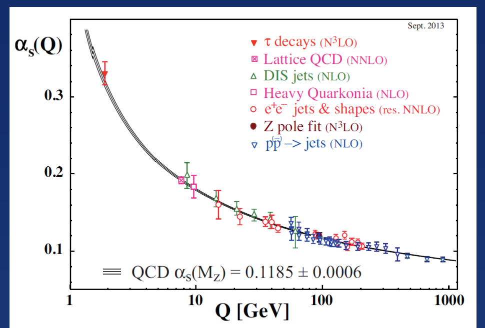
A nuclear matter theory must be able to treat all these physical situations.

What do we need ?

An exact theory to deal with

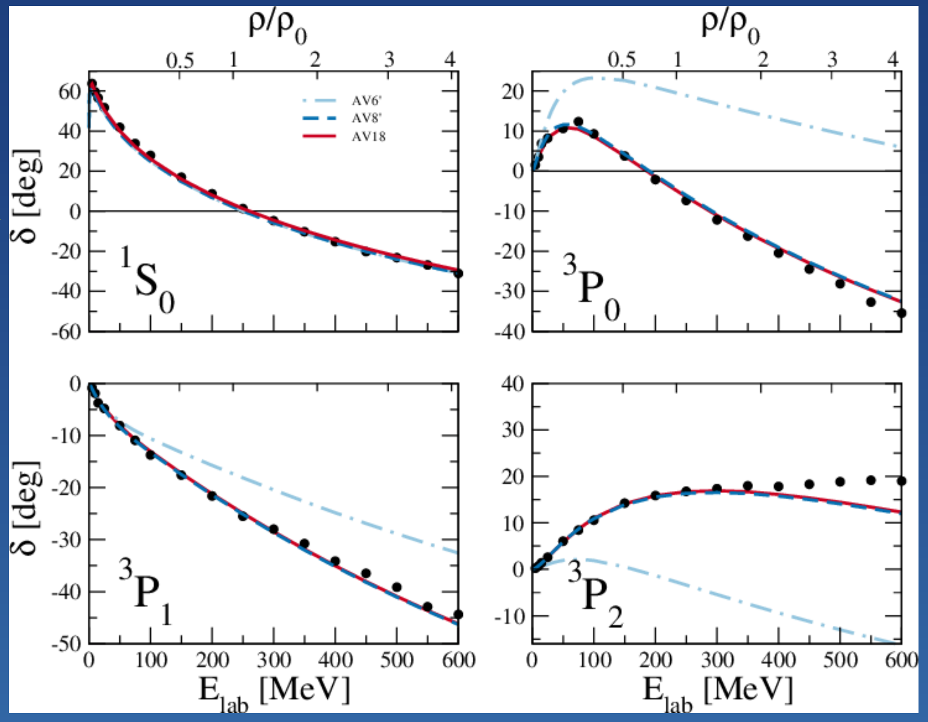
- Many-body effects in dense matter
- Strong interactions of particles of different species

- **Hadronic Hamiltonian ——> quark-gluon dynamics in QCD.**
- **Non-perturbative character of QCD —-> *the infamous "sign problem".***



Solution : **to adopt models where the <u>hadronic degrees of freedom</u> are the relevant ones. Meson exchange and potential models. Functional form dictated by fundamental symmetries.**

Essential requirement : Fit of the NN phase shifts



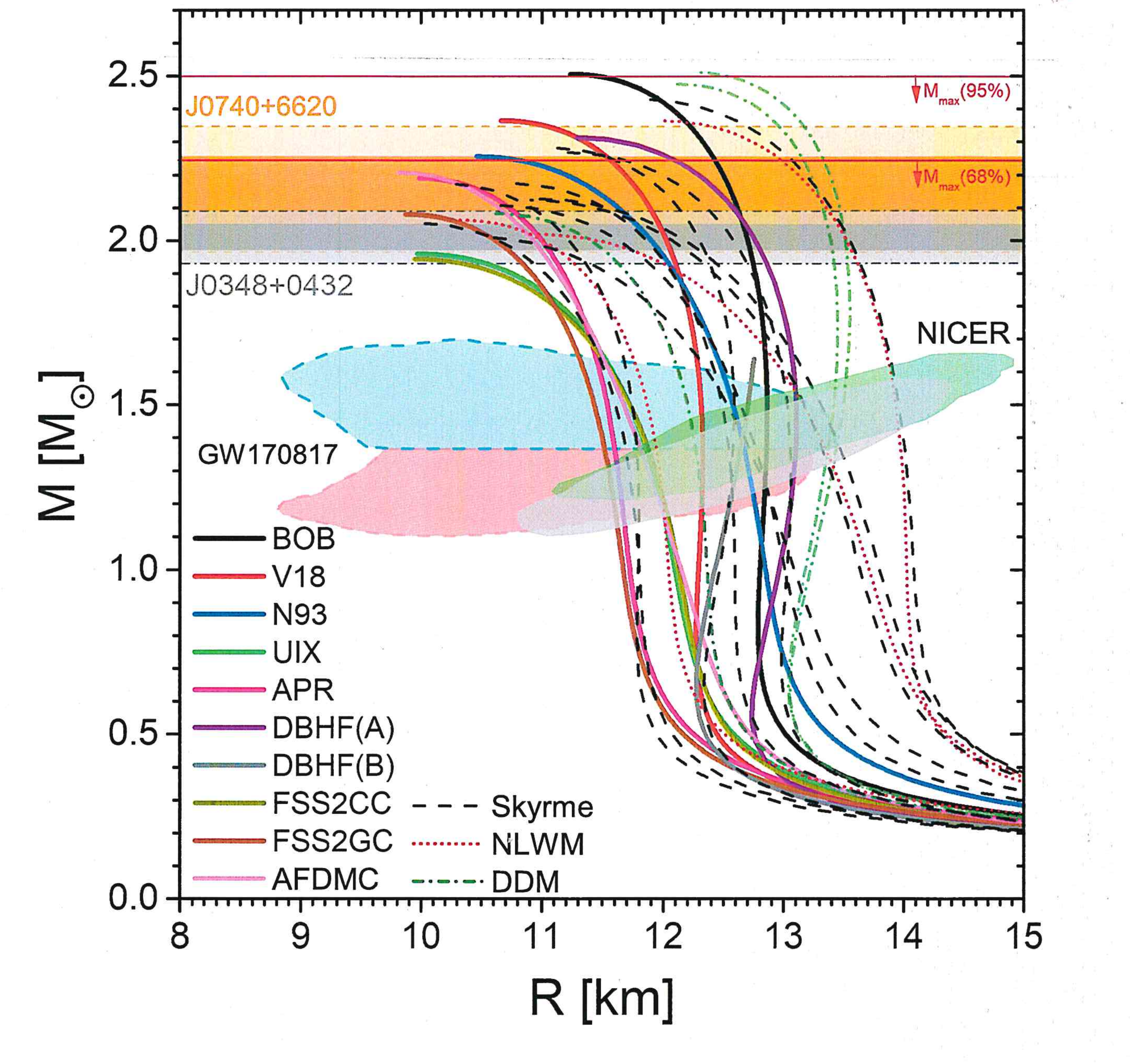
Workman et al., PRC94, 065203 (2016)

What do we have ?

Many different theoretical models!

Neutron stars and the nuclear equation of state

G.F. Burgio, H.-J. Schulze, I. Vidaña, J.-B. Wei , PPNP **120** (2021) 103879.



From NN interaction to EoS : Phenomenological vs. ab initio approaches

Phenomenological approaches

Based on effective density-dependent NN force with parameters fitted to reproduce nuclear observables and compact stars observables.

- Non-relativistic models: Skyrme and Gogny
- Relativistic mean-field models (RMF)

For clusterized matter

- SN approximation models : Liquid Drop models, Thomas-Fermi models, Self-consistent mean field models.
- NSE models. NSE, virial EoS.

Ab initio approaches

Based on two- and three-nucleon realistic interaction which reproduces scattering data and deuteron properties. The EoS is found by solving the complicated many-body problem.

- Diagrammatic: (Dirac)-Brueckner-Hartree-Fock, SCGF
- Variational : APR, FHNC, LOCV, CBF.
- Quantum Monte Carlo : VMC, GFMC, AFDMC.
- Chiral approaches : χEFT.

more in : Neutron stars and the nuclear equation of state,

F.B., HJ Schulze, I. Vidana, JB Wei, PPNP 120 (2021) 103879,

Check wrt χEFT and nuclear physics constraints

<u>Microscopic EoS</u>

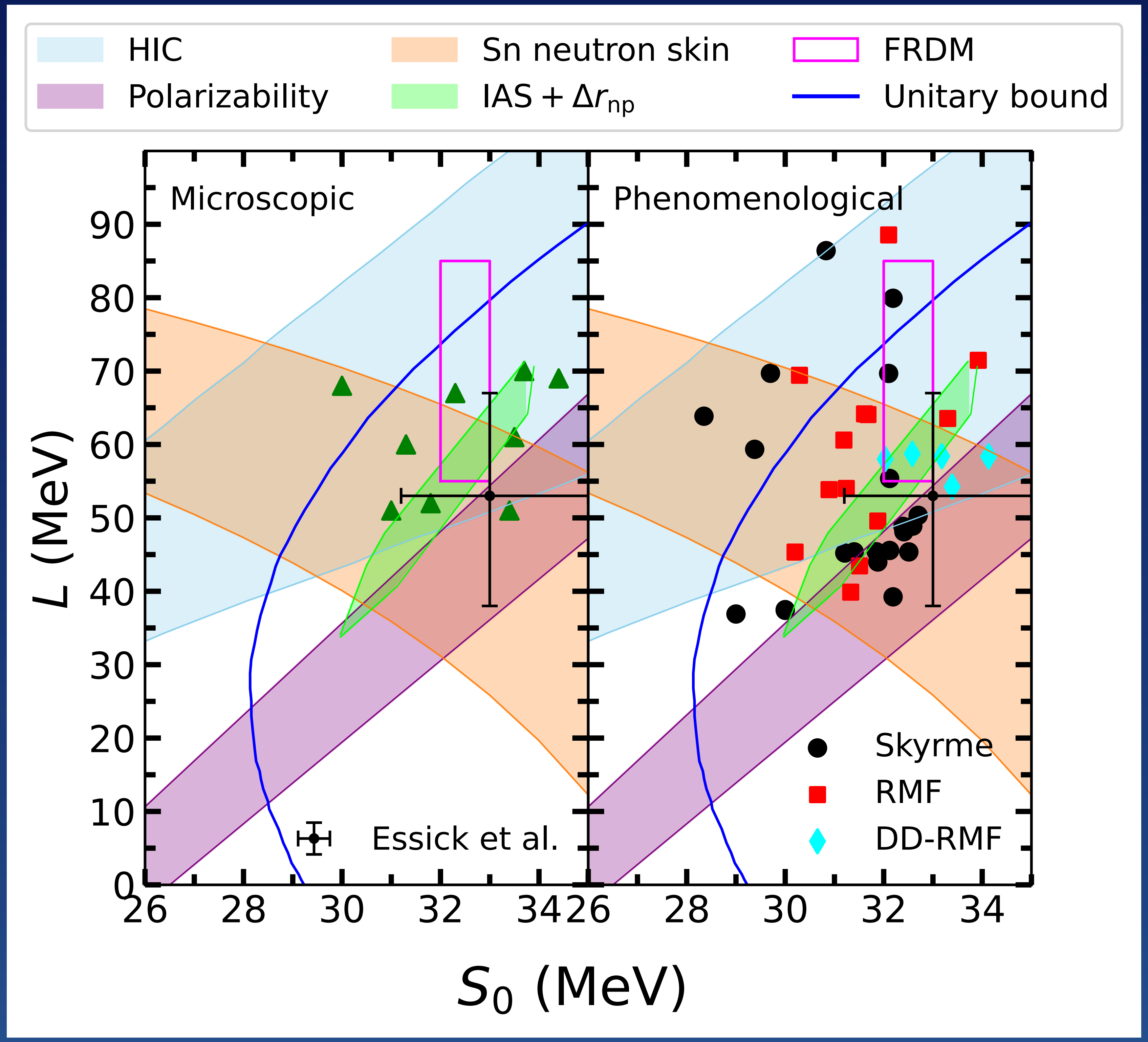
- BHF with Argonne V18 or Nijmegen 93 2NF and microscopic 3NF (BOB,V18, N93,UIX)
- BHF with FSS2 NN interaction (quark d.o.f. explicitly taken into account)
- Variational APR with Argonne V18 and 3NF of Urbana UIX type
- Relativistic DBHF (Bonn A)
- AFDMC with modified V18

<u>Phenomenological EoS</u>

- Skyrme forces (Gs,Rs,SLy4,SV etc…)
- Brussels-Montreal group BSk22,24,26
- RMF models with different parameterizations.
- DDM, RMF model with density dependent coupling constants.

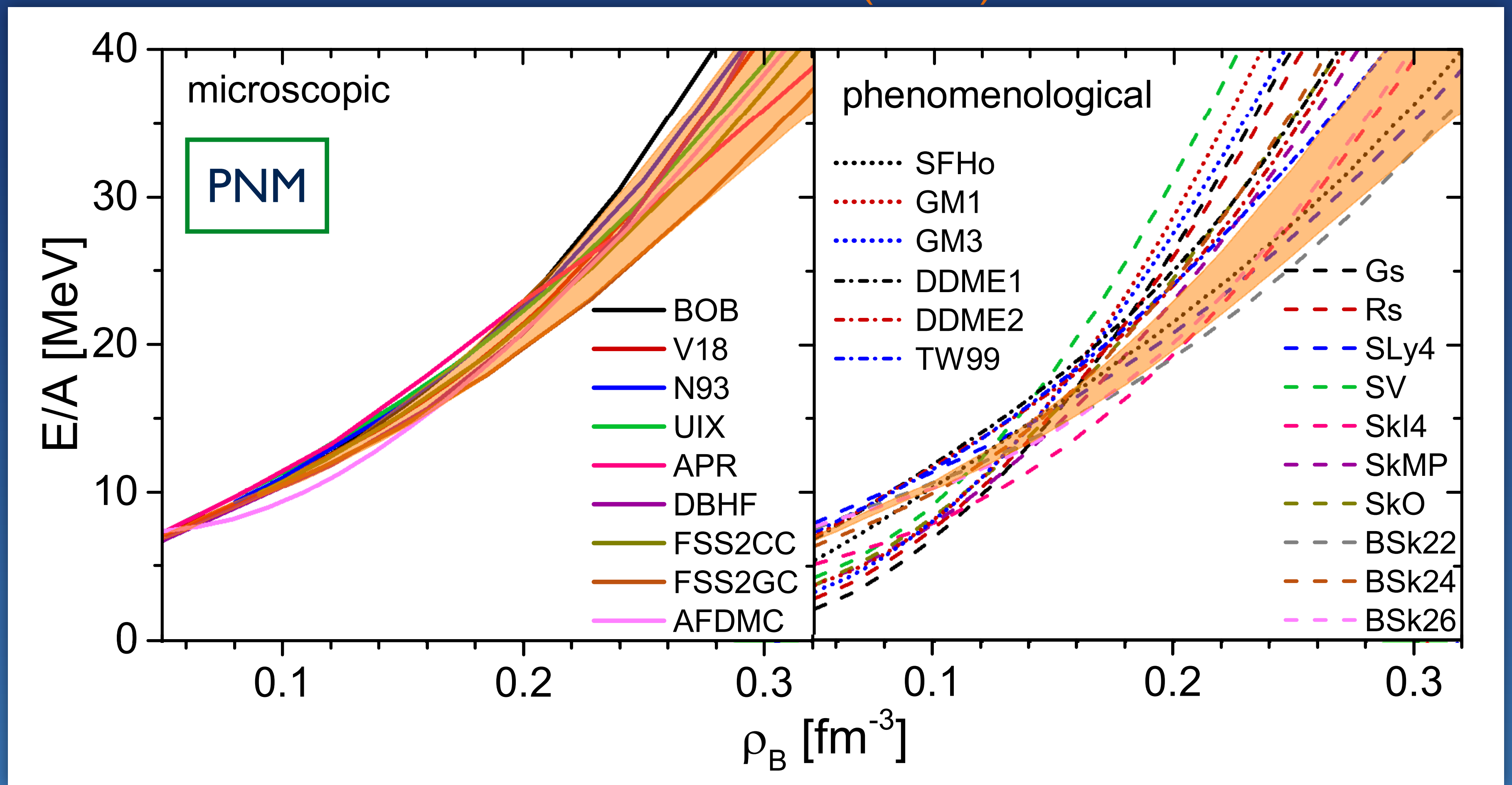
$$L \equiv 3\rho_0 \frac{dS(\rho)}{d\rho}\bigg|_{\rho_0}$$

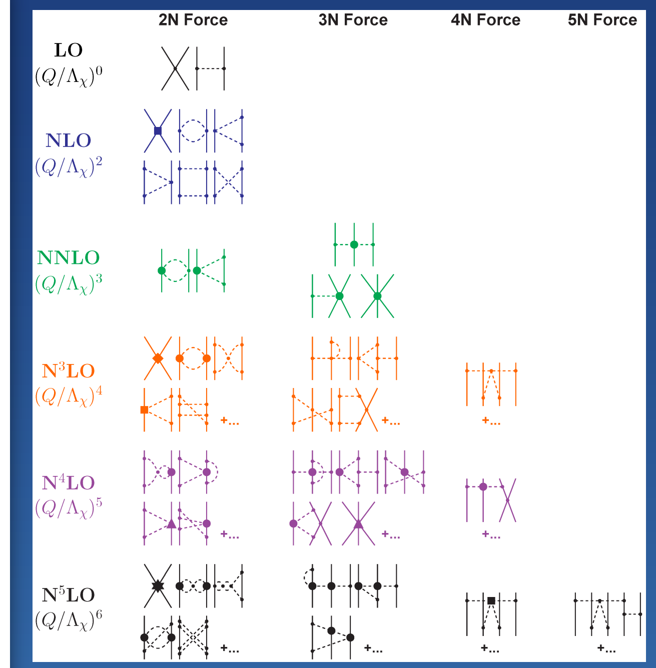
Tsang et al., PRL 102 (2009), 122701.
Roca-Maza et al., PRC 92 (2015), 064304.
Chen et al, PRC 82 (2010), 024321.
Moller et al., PRL 108(2012) 052501.
Danielewicz et al., NPA 922(2014) 1.
Tews et al., ApJ 848(2017) 105.



F.B., H.C. Das and I. Vidaña, Front. Astron. Space Sci. 11 (2024) 1505560

χEFT up to N3LO order
C. Drischler et al., PRL 125, (2020) 202702





Weinberg, PLB 251, 288 (1990); NPB 363, 3 (1991)
Entem & Machleidt, PRC 68, 041001(R) (2003)
Epelbaum et al., NPA 747, 363 (2005)

No overlap region !
Uncertainties in the expts. and in the models used for the data interpretation.
No model can be excluded a priori !

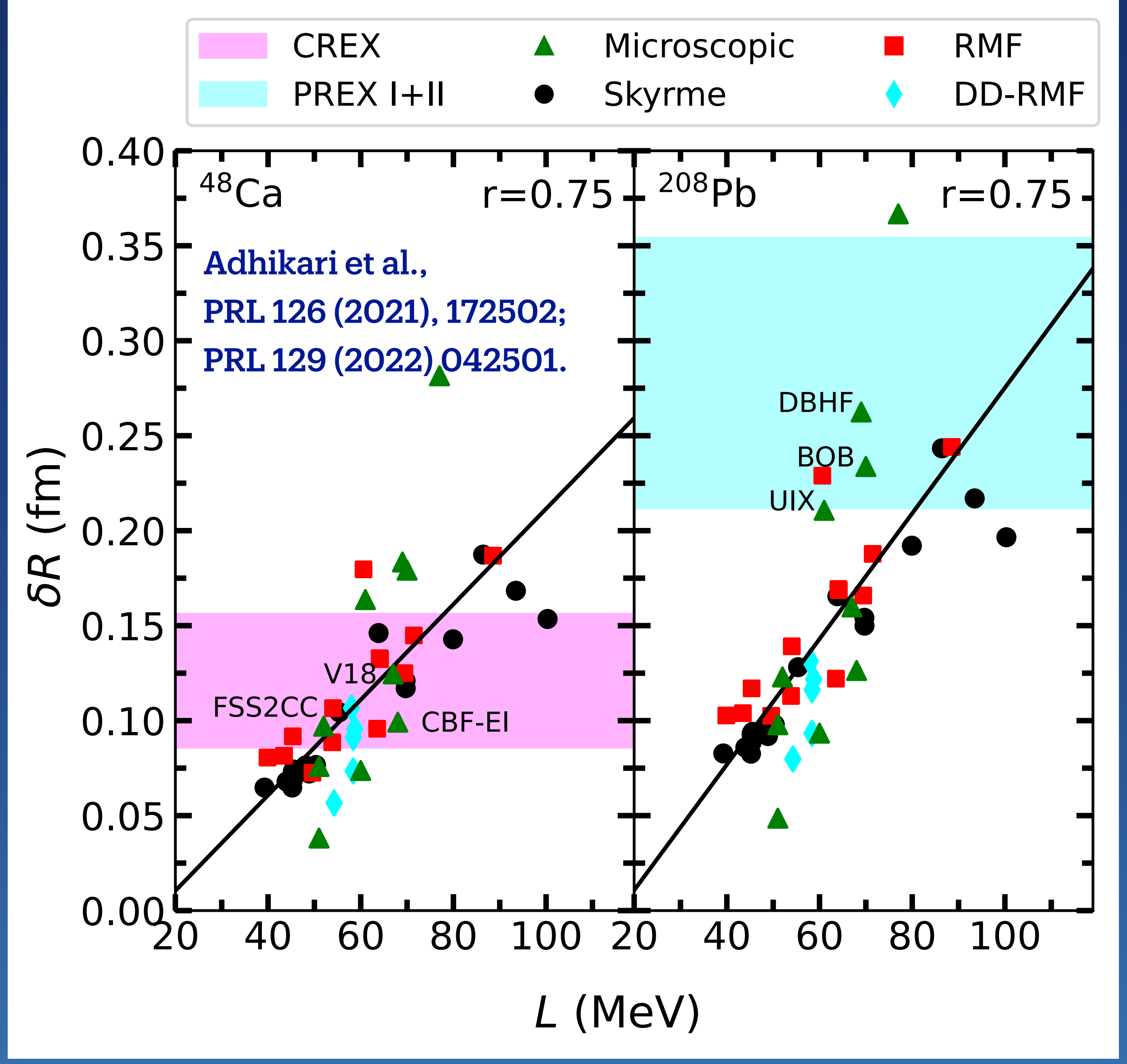
Check wrt neutron skin thickness

$$\delta R = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

To lowest order in the diffuseness corrections —-> $\delta R \approx \sqrt{\frac{3}{5}} t$ t : thickness of semi-infinite asymmetric nuclear matter

Brown et al., PRL 85 (2000), 5296
Steiner et al., PR 411 (2005), 411.
Vidaña et al., PRC 80 (2009), 045806.

$$t = \frac{\delta_c}{\rho_0(\delta_c)(1-\delta_c^2)} \frac{E_s}{4\pi r_0^2} \frac{\int_0^{\rho_0(\delta_c)} \rho^{1/2}[S_0/E_{sym}(\rho) - 1][E_{SNM}(\rho) - E_0]^{-1/2} d\rho}{\int_0^{\rho_0(\delta_c)} \rho^{1/2}[E_{SNM}(\rho) - E_0]^{1/2} d\rho}$$



- Some degree of correlation (r=0.75).
- Micro vs. Pheno—-> different slope.
- Tension with exp. data : no unique theoretical frame.
- Similar results for finite nuclei, see Lattimer, Particles (2023).
- Needed more experiments on medium size nuclei.

Any correlations with GW ? *Weak ...*

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

	ρ_0	BE	K_0	S_0	L	$\Lambda_{1.4}$	M_{max}	$\delta R(^{208}Pb)$	$\delta R(^{48}Ca)$
ρ_0	1	0.24	0.36	0.4	0.17	0.36	0.08	0.38	0.35
BE	0.24	1	0.09	0.2	0.22	0.1	0.24	0.1	0.11
K_0	0.36	0.09	1	0.25	0.11	0.22	0.37	0.17	0.15
S_0	0.4	0.2	0.25	1	0.39	0.07	0.05	0.36	0.33
L	0.17	0.22	0.11	0.39	1	0.55	0.06	0.75	0.75
$\Lambda_{1.4}$	0.36	0.1	0.22	0.07	0.55	1	0.4	0.44	0.45
M_{max}	0.08	0.24	0.37	0.05	0.06	0.4	1	0.03	0.04
$\delta R(^{208}Pb)$	0.38	0.1	0.17	0.36	0.75	0.44	0.03	1	1
$\delta R(^{48}Ca)$	0.35	0.11	0.15	0.33	0.75	0.45	0.04	1	1

The Symmetry Energy $S_2(\rho)$

$$\delta = \frac{n_n - n_p}{n} = 1 - 2x_p \qquad E(\rho,\delta) = E(\rho,0) + S_2(\rho)\,\delta^2,$$

$$S_2(\rho) = E_{PNM}(\rho) - E_{SNM}(\rho)$$

Composition of neutron star matter

"Recipe" for neutron star structure calculations

Brueckner results : $\epsilon\,(\rho_i)\,; i = n, p, e, \mu, \Lambda, \Sigma, u, d, s.....$

Chemical potentials : $\mu_i = \dfrac{\partial \epsilon}{\partial \rho_i}$

$$\mu_e = \mu_\mu = \mu_n - \mu_p = 4\,S_2(\rho)\,(1 - 2x_p)$$
$$\mu_{\Sigma^-} = 2\mu_n - \mu_p$$
$$\mu_{\Sigma^0} = \mu_\Lambda = \mu_n$$
$$\mu_{\Sigma^+} = \mu_p$$

Beta-equilibrium : $\mu_i = b_i \mu_n - q_i \mu_e$

Charge neutrality : $\sum_i x_i q_i = 0$

Composition : $x_i(\rho)$

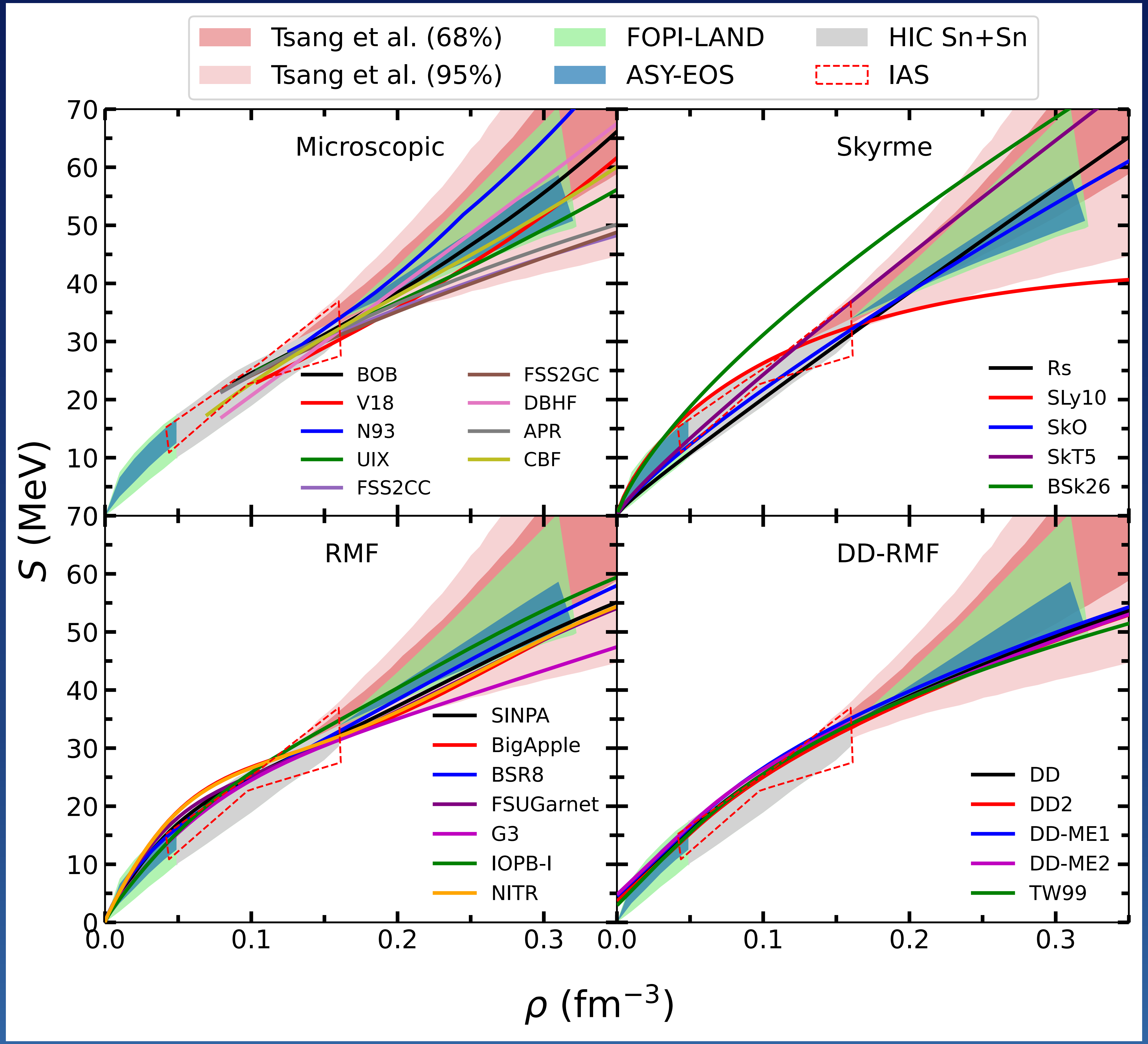
Equation of State : $p(\rho) = \rho^2 \dfrac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$

TOV equations :

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

$$\frac{dm}{dr} = 4\pi r^2 \epsilon(r)$$

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



NS cooling in a nutshell

- Stars of mass $(8 - 20\ M_\odot)$ collapse → newly formed Neutron Star ($\sim 10^{10-11}\ K$) .
- It cools very fast due to huge amount of neutrino emission.
- NS cooling is over vast domain of time $(10^{-10} - 10^5\ \mathrm{yr})$ dominated by several macroscopic processes.
- Processes → (i) direct URCA $(n \to p + e + \bar{\nu}_l, \dots)$

  (ii) modified URCA $(n + N \to p + N + l + \bar{\nu}_l, \dots)$

  (iii) Bremsstrahlung $(N + N \to N + N + \nu + \bar{\nu})$ …
- The temperature at the surface of the NS can be detectable.
- The emitted surface temperature depends on the internal structure, density profiles, particle types, …
- One of the main ingredient is the equation of state $p(\rho), \epsilon(\rho)$.

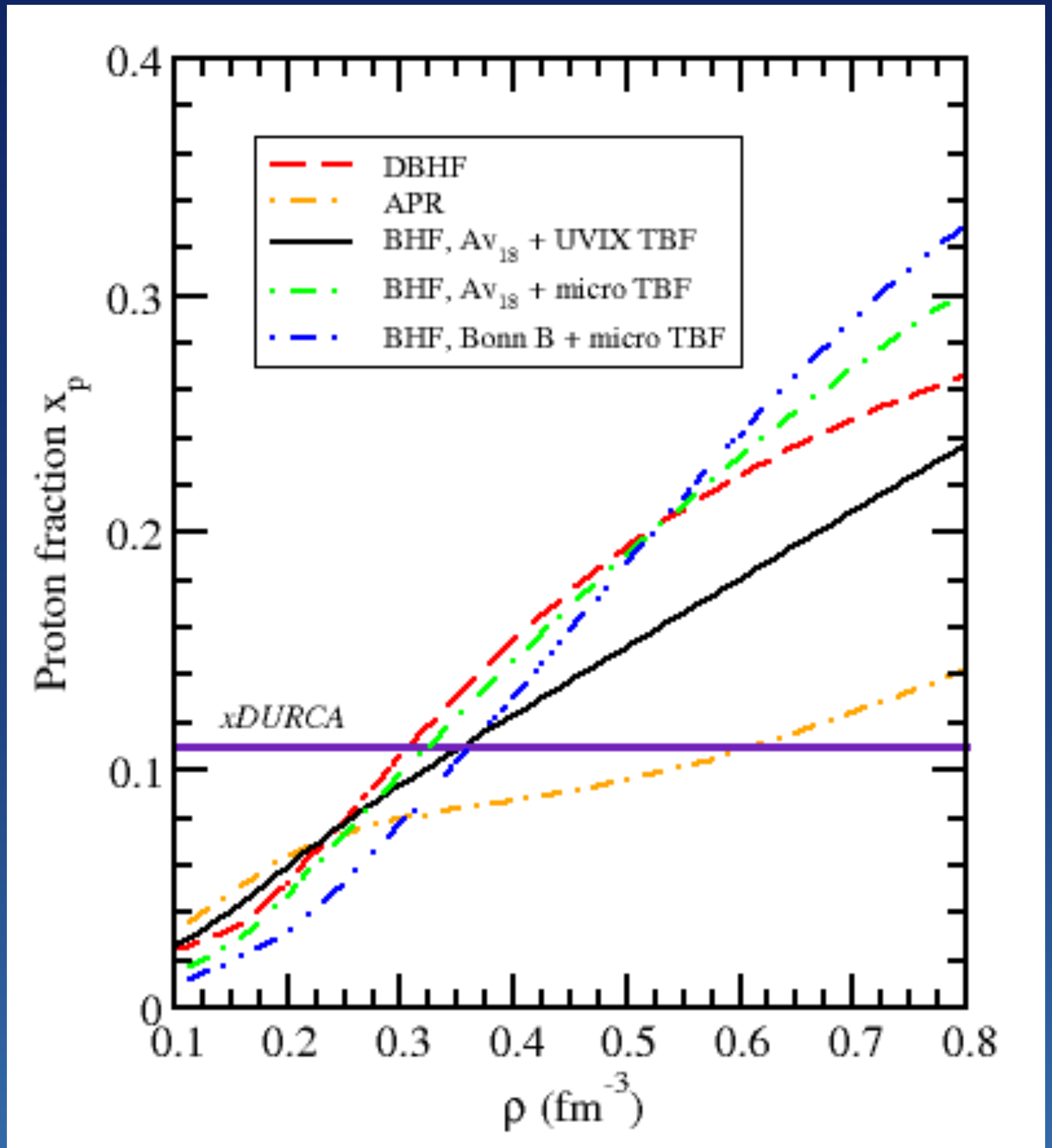
Direct URCA processes in NS

$$n \longrightarrow p + e + \overline{\nu}_e \ , \qquad p + e \longrightarrow n + \nu_e \ ,$$
$$n \longrightarrow p + \mu + \overline{\nu}_\mu \ , \qquad p + \mu \longrightarrow n + \nu_\mu \ .$$

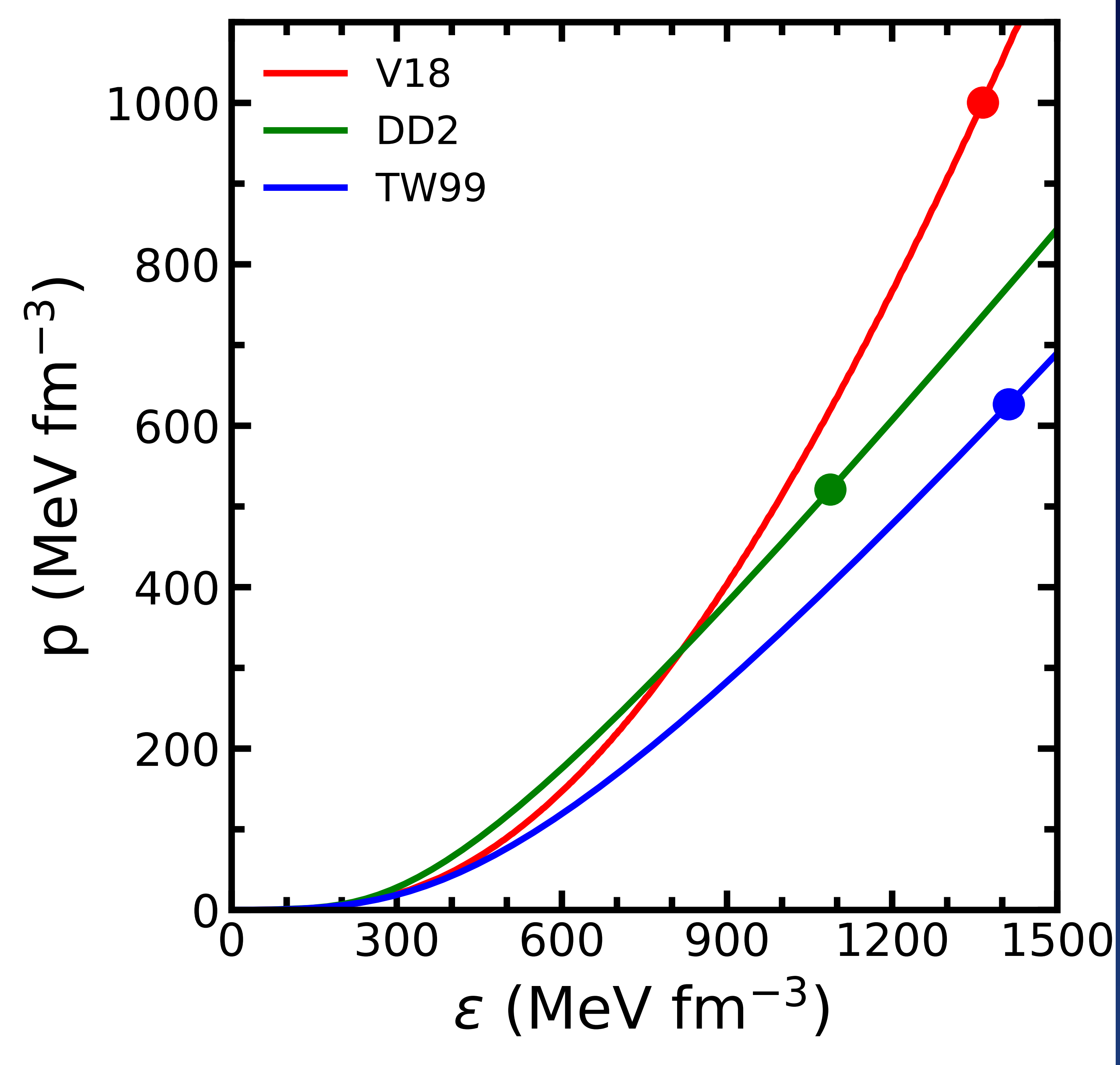
- They are allowed only at a rather high density at which the proton fraction $x_D > 0.11$-0.14 (Lattimer et al. 1991).

- If Direct URCA operate, then a non-superfluid NS core cools to 10^9 K in a minute, and to 10^8 K in a year. If they are not allowed, the time scales will be one year and 10^5 years respectively.

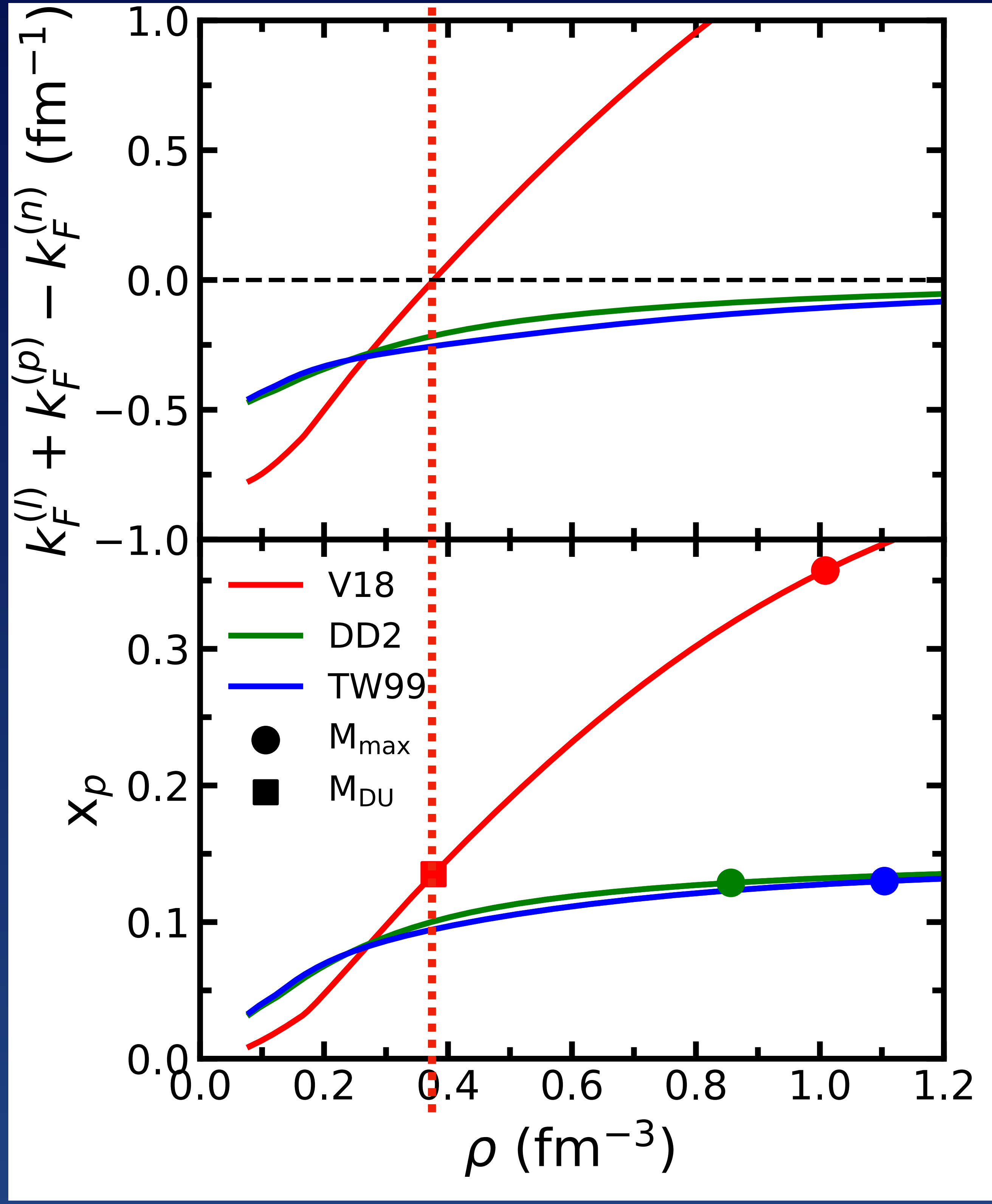
- The symmetry energy is crucial for determining the proton fraction.



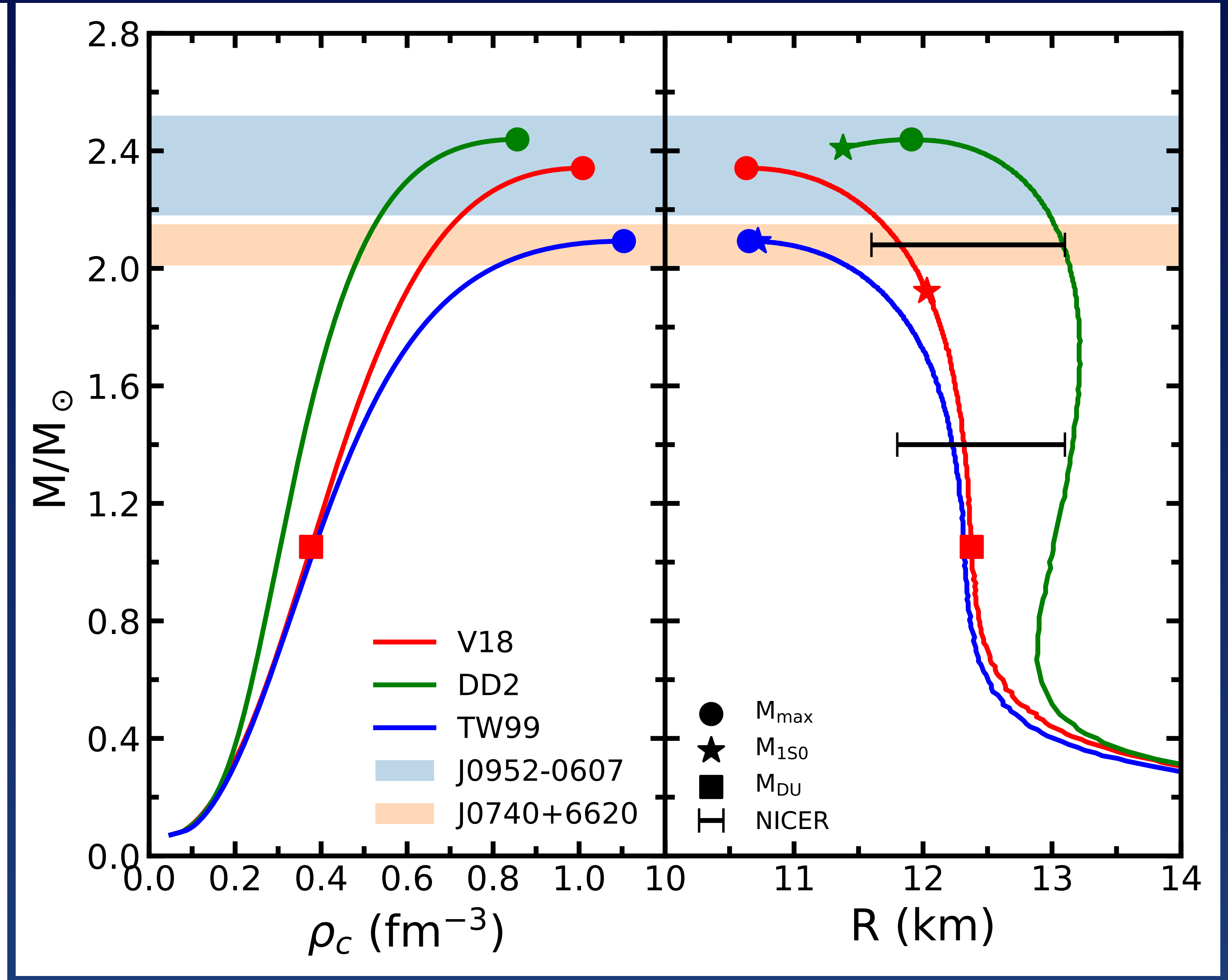
EoS



URCA process

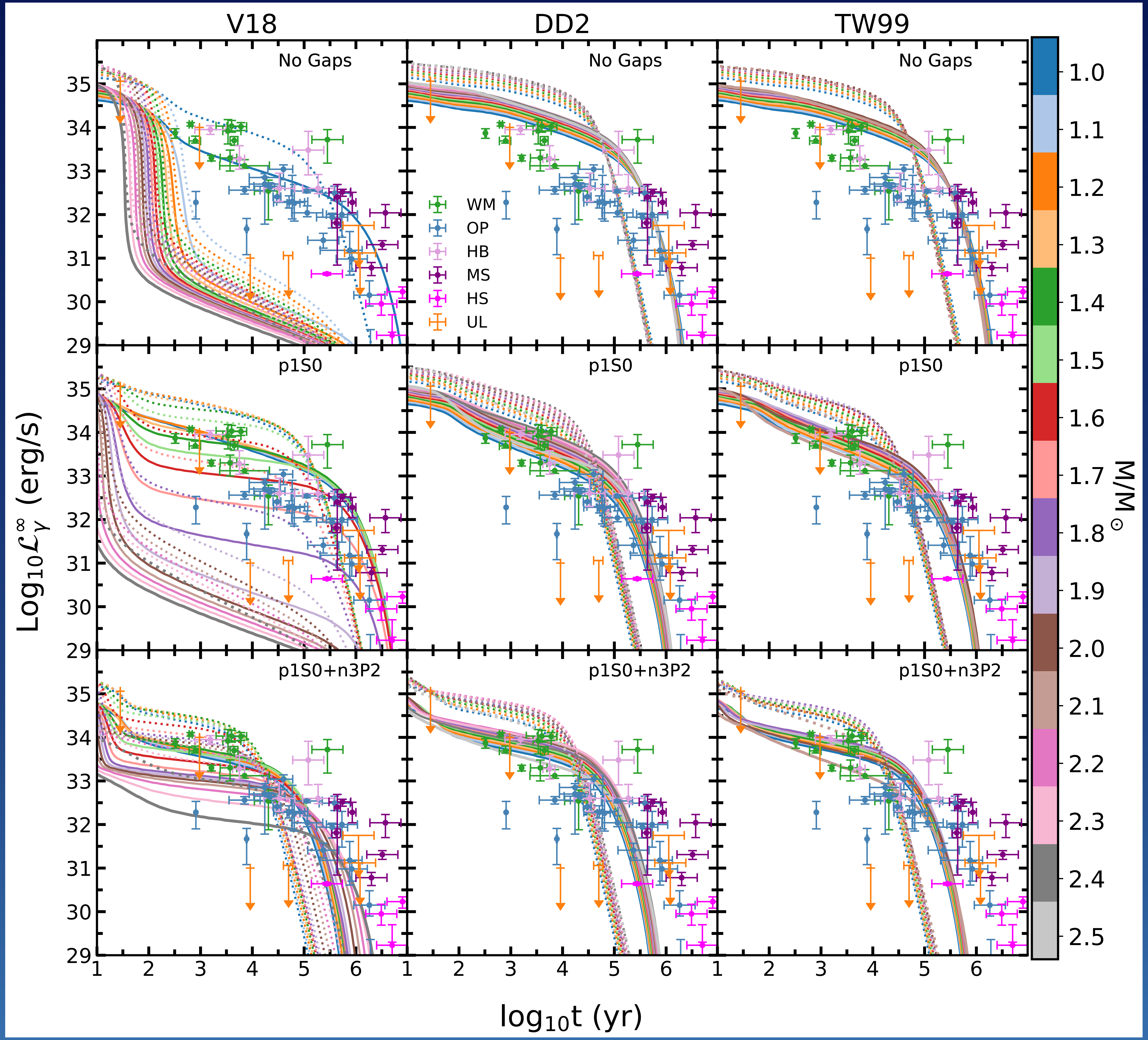


M-R relations



EOS	ρ_0 (fm^{-3})	$-E_0$ (MeV)	K_0 (MeV)	S_0 (MeV)	L (MeV)	x_{DU}	ρ_{DU} (fm^{-3})	M_{max} ($M_\odot$)	$\Lambda_{1.4}$	$R_{1.4}$ (km)
V18	0.178	13.9	207	32.3	63	0.135	0.37	2.36	440	12.3
DD2	0.149	16.0	243	31.7	55	–	–	2.42	680	13.2
TW99	0.153	16.2	240	32.8	55	–	–	2.08	400	12.3
Exp.	0.14–0.17	14–16	200–260	28–35	30–90			$> 2.35 \pm 0.17$	70–580	11.8–13.1

Cooling curves and observational data



H.C. Das et al., PRD109, 123018 (2024)

Type of Neutron Stars

- Weakly Magnetized (WM): 12
- Ordinary Pulsars (OP): 22
- High-B Pulsars (HB): 5
- The Magnificent Seven (MS): 7
- Small Hot Spots (HS): 5
- Upper Limits (UL): 6

Total = 57

https://www.ioffe.ru/astro/NSG/thermal/cooldat.html

Neutrons, protons, electrons, muons … is it all ?

Observation of $\sim 2\, M_\odot$ ***neutron stars***
<——> strangeness content

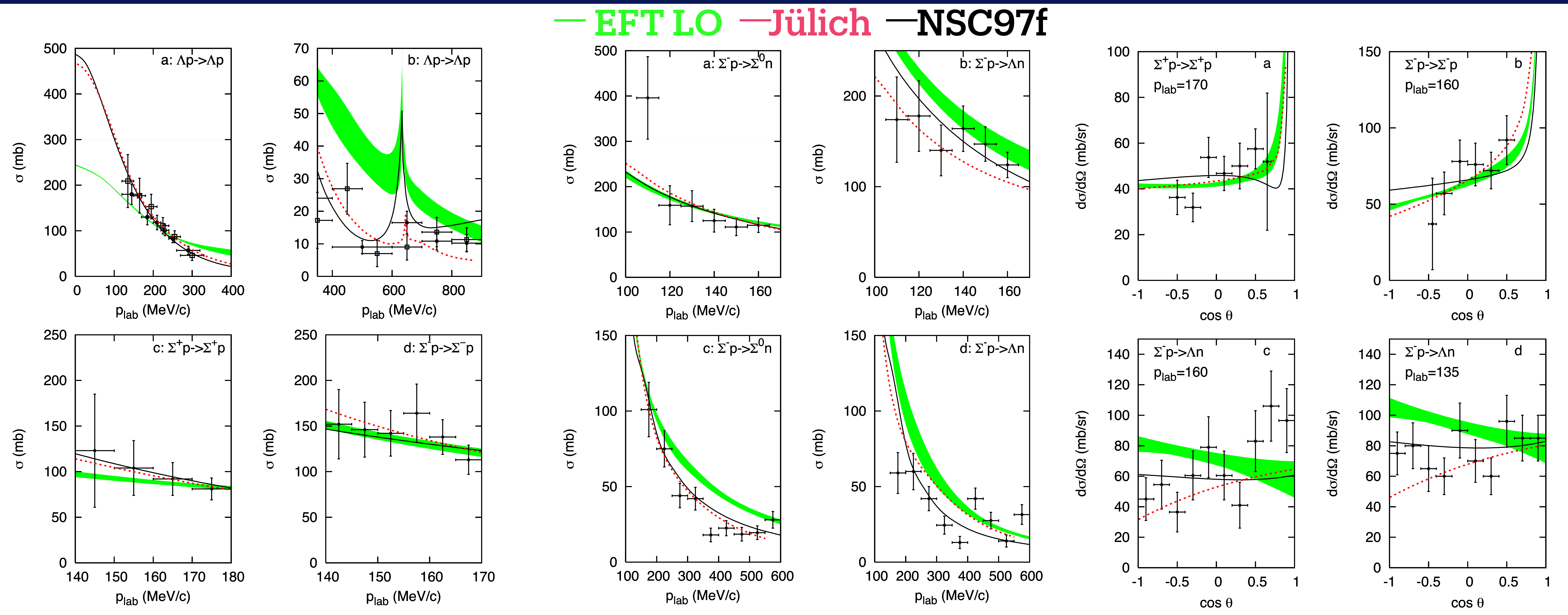
Can hyperons, or strangeness in general, still be present in neutron stars interiors ?

Probably <u>yes</u>, 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 ignorance of the nucleon-hyperon (NY) and hyperon-hyperon (YY) interaction.

Available NY Cross Sections Data :



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

- Very few NY scattering data due to hyperon short lifetimes and low intensity beam fluxes
- 35 data points, all from 1960’s
- No YY scattering data exist (cf. > 4000 NN data points available !)

Need more data. J-PARC ? FAIR ?

Including hyperons in BHF approach

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

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,

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

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

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

and similar expressions of the form

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

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

with

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

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

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

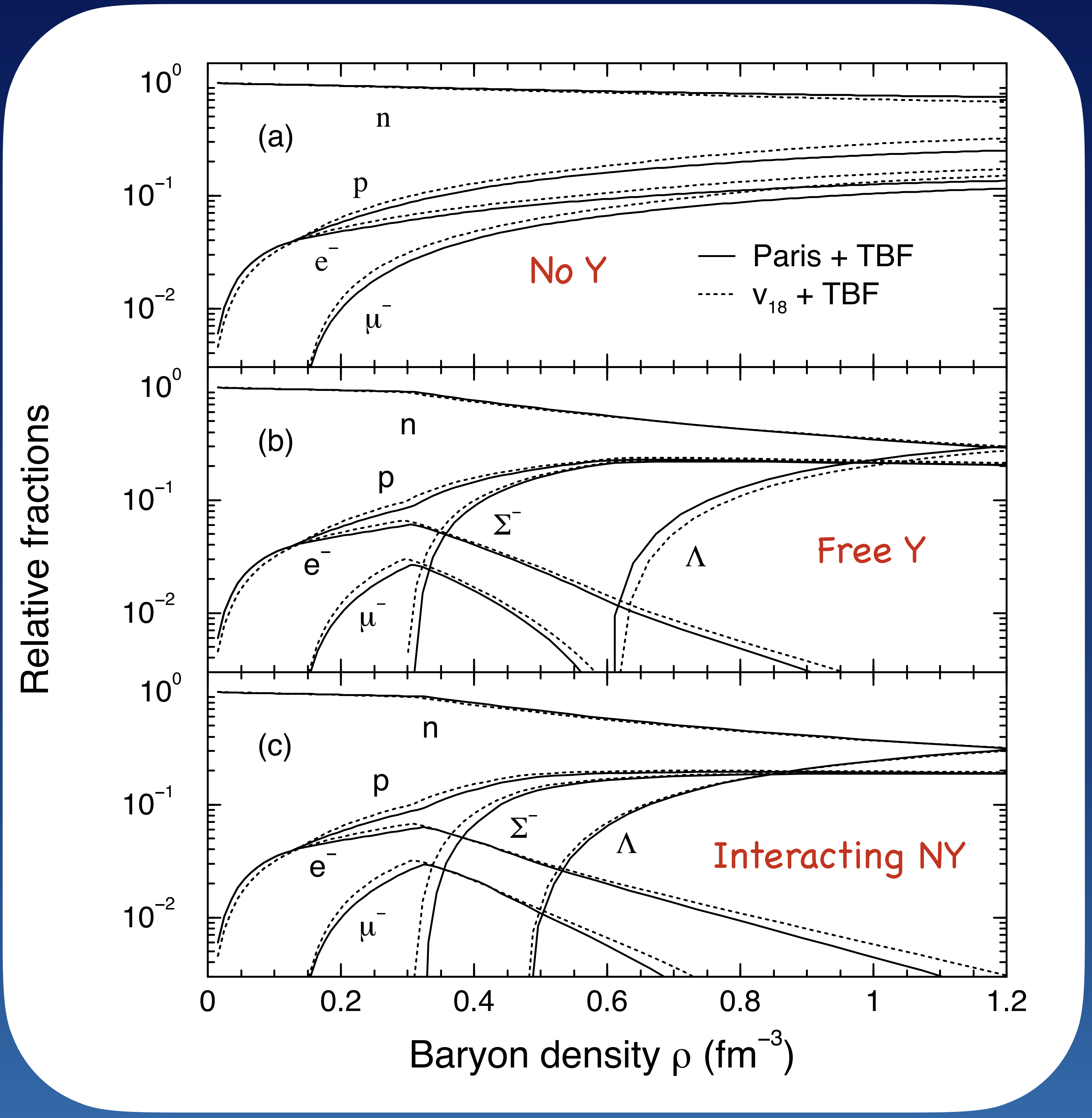
- NN force and effective NNN interactions only input required

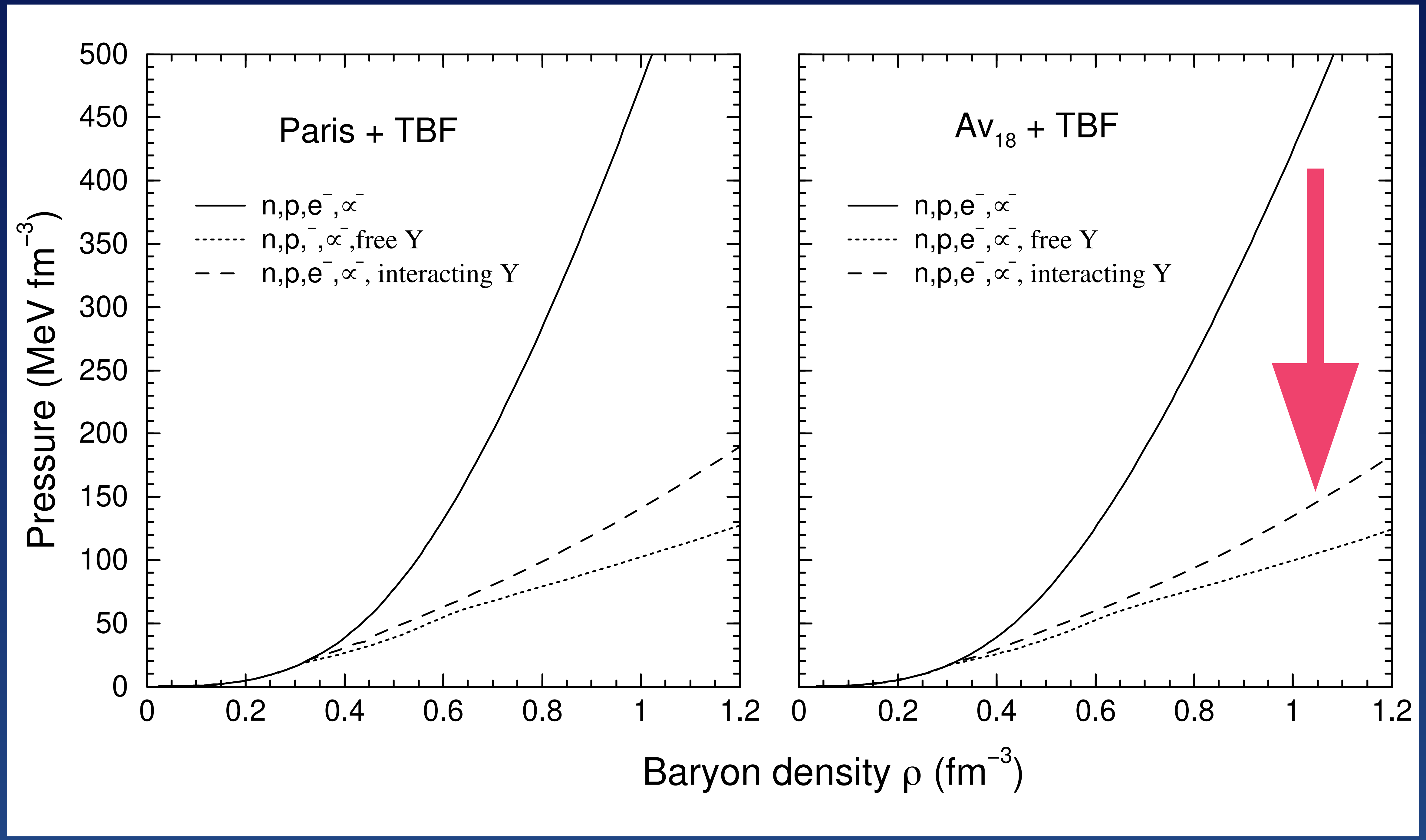
Technical difficulty :
coupled channel calculation !

- 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

Composition and EoS of hypernuclear matter





- Hyperon onset occurs at $\rho \sim (2-3)\,\rho_0$
- <u>Strong softening due to hyperon onset</u>

BRIDGES : a New Proposal submitted to European COST

PI : D. Blaschke (Wroclaw University and DFZ Goerlitz)

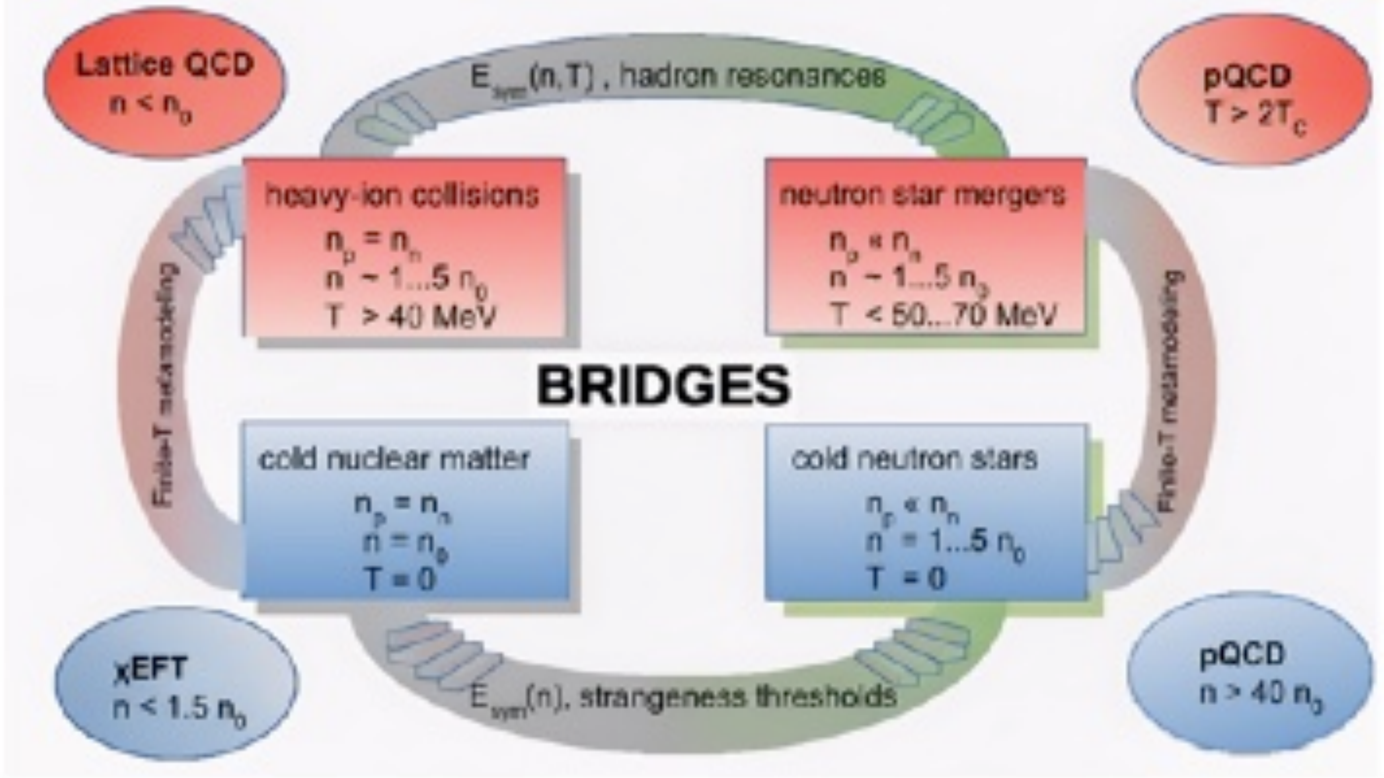


Figure 3: Bridges between the four corner states addressed in this project: cold and hot symmetric and asymmetric nuclear matter found in: atomic nuclei, HIC, cold NS and binary NSM, respectively. Further bridges (not shown) connect these states with ab-initio calculations at asymptotically low and high densities.

Working Group 1 Multi-messenger observation and simulation of NS and their mergers
Working Group 2 HIC experiments and their dynamical simulation
Working Group 3 Theory of warm, dense nuclear matter with phase transitions
Working Group 4 Common analysis tools for HIC and NS
Working Group 5 Training, Communication and Dissemination

98 participants from 28 COST full member countries, plus 2 near neighbour (Egypt and Tunisia), and 6 international partners (Argentina, China, India, Japan, Mexico, USA)

END OF REVIEW PROCESS : MAY 2026