Equations of state of dense matter in the light of present and future nuclear physics and astrophysics constraints

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Overview

- Neutron Stars (NS): formation, properties, structure, composition
- Equation of State (EOS): definition, constraints, models, uncertainties
- NS with heavy baryons: particle abundances, maximum mass, radii, tidal deformabilities
- Core-Collapse SuperNovae (CCSN), Binary NS Mergers (BNS): domains of temperature, density, proton fraction
- Hot EOS: thermal energy density and pressure, entropy, specific heats, adiabatic and thermal index, speed of sound; CompOSE (`https://compose.obspm.fr/`)
- Model dependence; effective masses
- Nucleons, Heavy Baryons, Quarks
- Challenges and Future

What is a Neutron Star?

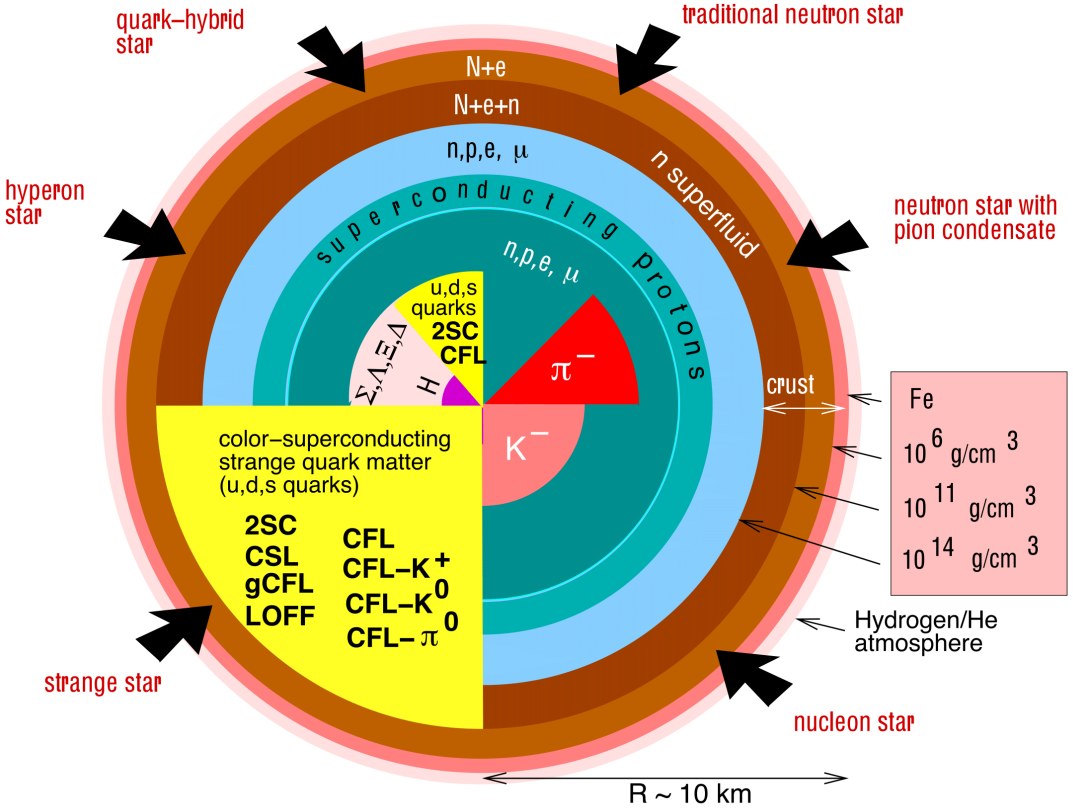


Image credit: F. Weber

- residue of core collapse supernova, usually observed as pulsars
- $1 \lesssim M/M_\odot \lesssim 2$, $10 \lesssim R$ [km] $\lesssim 12$
- average density $\approx n_{sat}$, usually referred to as compact objects
- highly non-uniform $0 \lesssim n \lesssim 5-10 n_{sat}$
- fast spinning: $\nu = 716$ Hz (PSR J1748-2446)
- magnetic field $10^6 \lesssim B$ [G] $\lesssim 10^{16}$
- temperature $10^6 \lesssim T$ [K] $\lesssim 10^{11}$

Chemical composition according to β-**equilibrium**: $\mu_n = \mu_p + \mu_e$

Astrophys. observations: masses, radii, rotation frequencies, gravitational waves, surface temperatures, etc.

Nuclear Equation of State (EOS)

EOS=thermodyn. concept. The nuclear EOS at $T=0$: $E/A(n_n,n_p)$;
Taylor expansion in terms of deviation from isospin asymmetry, $\delta=(n_n-n_p)/n$, and saturation density, $\chi=(n-n_{sat})/3n_{sat}$, with $n=n_n+n_p$.

$$
\begin{aligned}
E/A(n,\delta) &= E/A(n,0) + S(n)\ \delta^2 + \ldots \\
&= \sum_{i\geq 0}\frac{1}{i!}X_{sat}^{(i)}\chi^i + \sum_{j\geq 0}\frac{1}{j!}X_{sym}^{(j)}\chi^j\delta^2 + \ldots
\end{aligned}
$$

energy SNM symmetry energy

$$
X_{sat}^{(i)}=3^i n_{sat}^i\left(\frac{\partial^i(E/A)}{\partial n^i}\right)_{n=n_{sat},\delta=0};\quad X_{sym}^{(j)}=3^j n_{sat}^j\left(\frac{\partial^j S(n)}{\partial n^j}\right)_{n=n_{sat},\delta=0}
$$

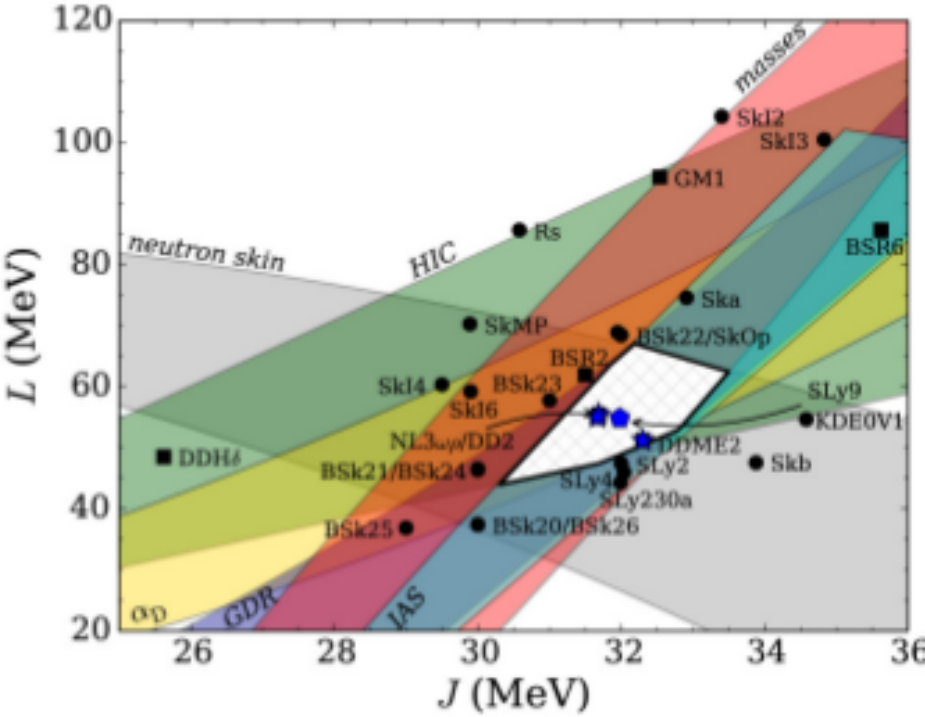
i=0, 2, 3, 4, ... binding energy per nucleon E_{sat}, incompressibility K_{sat}, skewness Q_{sat}, kurtosis Z_{sat}, etc. at n_{sat}

j=0, 1, 2, 3, 4, ... symmetry energy J_{sym} and its slope L_{sym}, curvature K_{sym}, etc. at n_{sat}

Constraints from nuclear physics experiments

- nuclear masses: $E_{sat} = -15.8 \pm 0.3$ MeV [Margueron+, PRC (2018)]
- isoscalar giant monopole resonances: $K_{sat} = 230 \pm 40$ MeV [Khan+, PRL (2012)]

- nuclear masses, isobaric analog state, neutron skin thickness, heavy ion collisions: $J_{sym} = 31.7 \pm 3.2$ MeV [Oertel+, RMP (2017)]
- neutron skin thickness, dipole polarizability, dipole resonance: $L_{sym} = 58.7 \pm 28.1$ MeV [Oertel+, RMP (2017)]



[Fortin+, PRC (2016)]

- higher order coefficients Q_{sat}, Z_{sat}, K_{sym}, Q_{sym}, Z_{sym} are highly uncertain

⚠ parameter values and their correlations are model dependent [Margueron+, PRC97 (2018)]

- extra constraints from neutron stars, in particular the isovector channel (L_{sym})

Constraints from NS measurements

- **masses** of **massive** NS, *e.g.* $M/M_\odot \geq 2.01 \pm 0.04$ [Antoniadis+ (2013)]; lower bound on M_{max}; **extra particle d.o.f.**

- **mass** and **radius** *accurately* [NICER, Athena, LOFT,...]

  - **intermediate mass** NS: isovector channel over $1 \lesssim n/n_{sat} \lesssim 2-3$
    e.g. PSR J0030 + 0451 [NICER]
    $R(1.44^{0.15}_{-0.14} M_\odot) = 13.02^{+1.24}_{-1.06}$ km [Miller+, 2019];
    $R(1.34^{+0.15}_{-0.16} M_\odot) = 12.71^{+1.14}_{-1.19}$ km [Riley+, 2019];
  - **massive NS**: EOS at high densities;
    e.g. PSR J0740 + 6620 [NICER]
    $R(2.08 \pm 0.07 M_\odot) = 13.7^{+2.6}_{-1.5}$ km [Miller+, 2021];
    $R(2.072^{+0.067}_{-0.066} M_\odot) = 12.39^{+1.30}_{-0.98}$ km [Riley+, 2021]

- **tidal deformability** from GW
  e.g. late inspiral of $1.36 \leq M_1/M_\odot \leq 1.6$, $1.16 \leq M_2/M_\odot \leq 1.36$: $\Lambda = 190^{+390}_{-120}$ [LIGO and VIRGO, PRL 119, 161101]; isovector channel over $1 \lesssim n/n_{sat} \lesssim 2-3$

- **thermal evolution**: dURCA: composition: isovector or extra particles;
- quasi-periodic **oscillations**, **moment of inertia**, etc.

Models of nuclear EOS

Phenomenological: density-dependent effective interactions adjusted to nuclear observables and neutron star observations; $0 \lesssim n/n_{sat} \lesssim 5-10$;

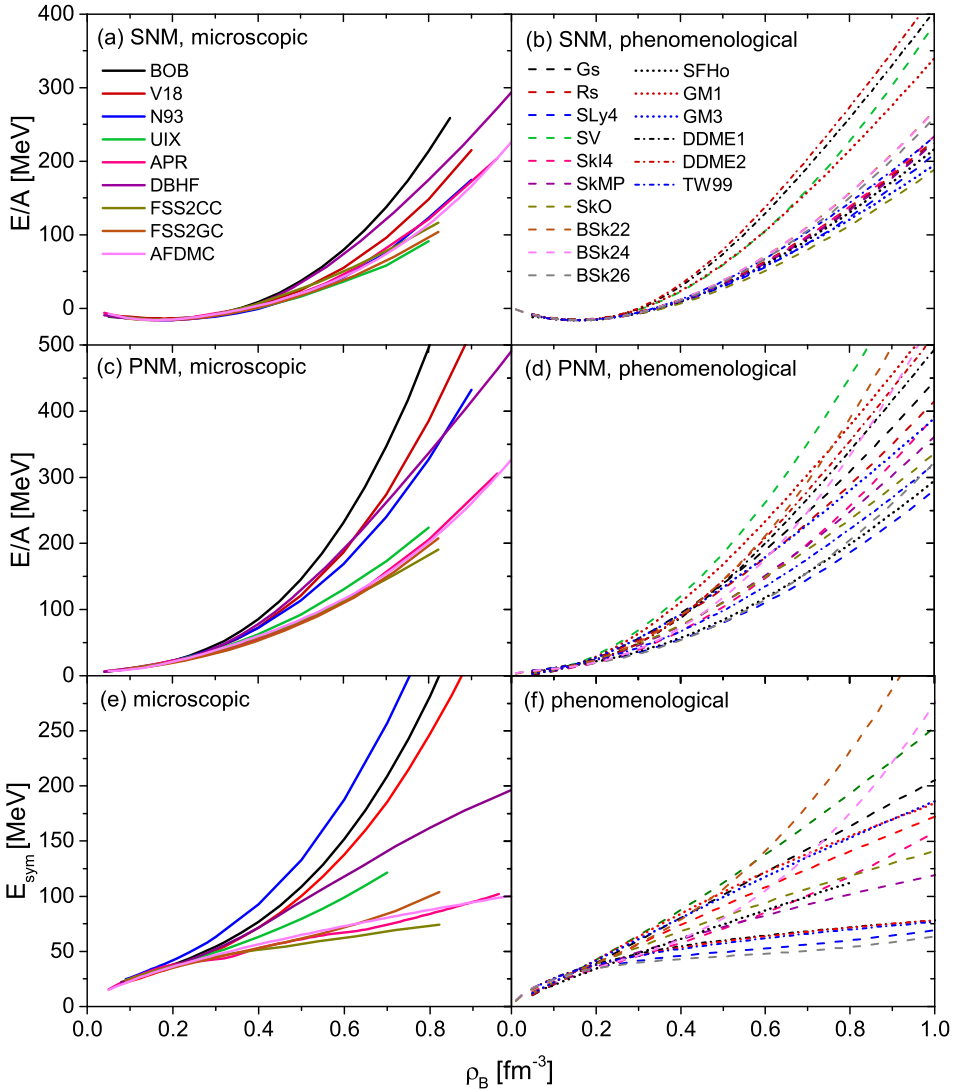
e.g.: non-relativistic EDF (Skyrme, Gogny), relativistic mean-field, relativistic Hartree-Fock [Dutra+, PRC 85, 035201; Dutra+, PRC 90, 055203]

Microscopic Ab-initio: the many-body problem is solved starting from two- and three-body interactions; $0 \lesssim n/n_{sat} \lesssim 1-2$;

e.g.: variational (APR, TNTYST), quantum Monte Carlo (VMC, AFDMC, GFDMC), coupled cluster expansion, diagrammatic: BBG (BHF), lattice, chiral effective, etc.

Agnostic: piecewise polytrops, parametrization of the speed of sound

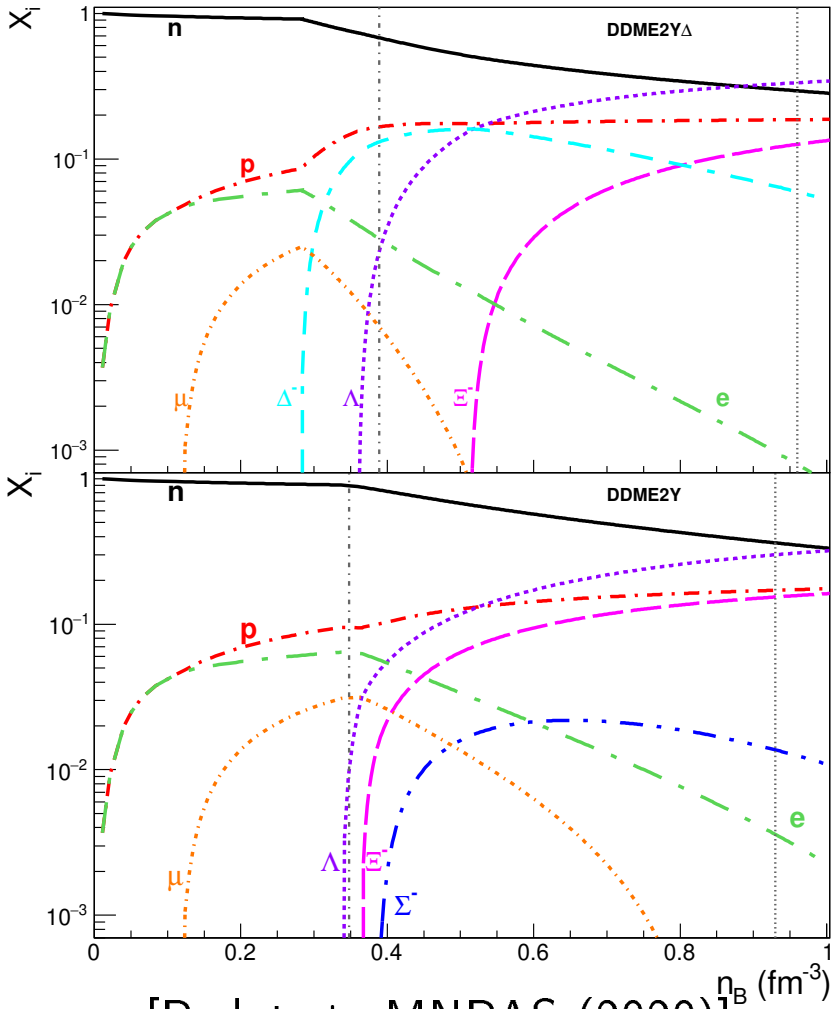
Large uncertainties for $n \gtrsim 2n_{sat}$ and $\delta \neq 0$



[Burgio+, PPNP (2021)]

Exotic d.o.f.: hyperons and Δs

- Onset of the X-species at $T=0$:
  $\mu_X = B_X\mu_B + Q_X\mu_Q \geq m_X$;
  B_X, Q_X, μ_X, m_X are baryon and charge quantum nr. chemical potential, rest mass
- exp. data on YN and YY eff. int. [Gal+, RMP (2016)]: $U_\Lambda^{(N)} \approx -28$ MeV, $U_\Xi^{(N)} \approx -18$ MeV, $U_\Sigma^{(N)} \approx 30$ MeV
- exp. data on ΔN eff. int. [Drago+, PRC (2014); Kolomeitsev+, NPA (2017)]:
  $-30\ \mathrm{MeV} + U_N^{(N)} \lesssim U_\Delta^{(N)} \lesssim U_N^{(N)}$
- composition determined from **baryon nr. cons.**, **net charge neutrality**, **β-equil.**



[Raduta+, MNRAS (2020)]

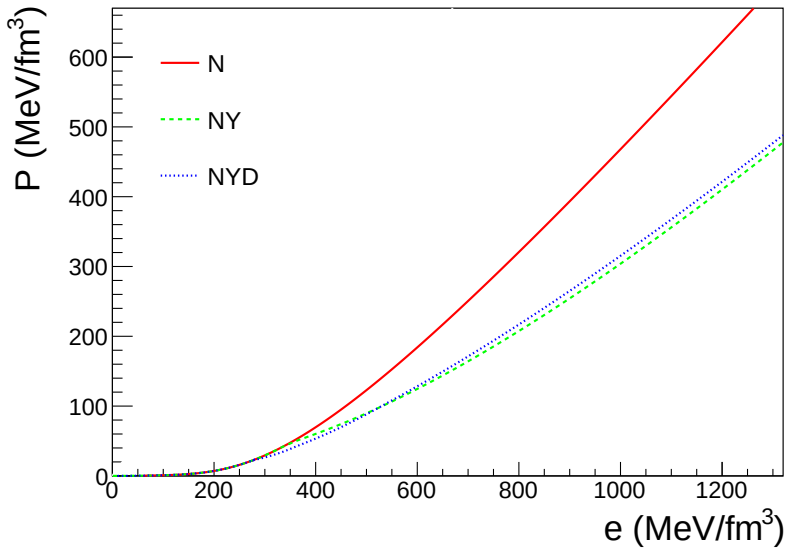
in cold NS only Λ, Ξ^- and Σ^- (Δ^-)

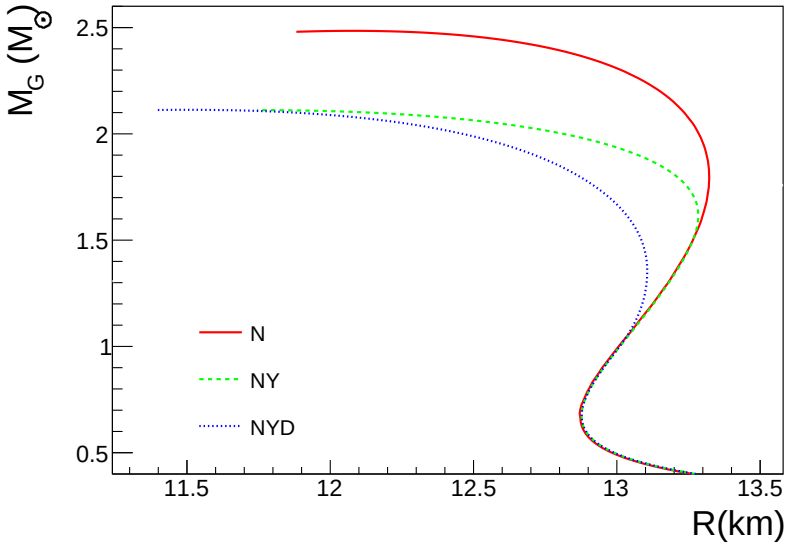
NS with heavy baryons: EOS softening and M_{max} decrease

- extra new species softens EOS

Compo.	P_1	n_{P_1} [fm^{-3}]	M_{max} [$M_\odot$]	$R_{1.4}$ [km]	$\Lambda_{1.4}$
N	-	-	2.485	13.24	723
NY	Λ	0.34	2.113	13.25	712
NYΔ	Δ^-	0.28	2.111	13.08	653

- Y diminishes M_{max}
- Δ diminishes $R_{1.4}$, $\Lambda_{1.4}$





Core-Collapse SuperNovae, Proto-NS evolution, Binary NS Mergers, stellar BH formation

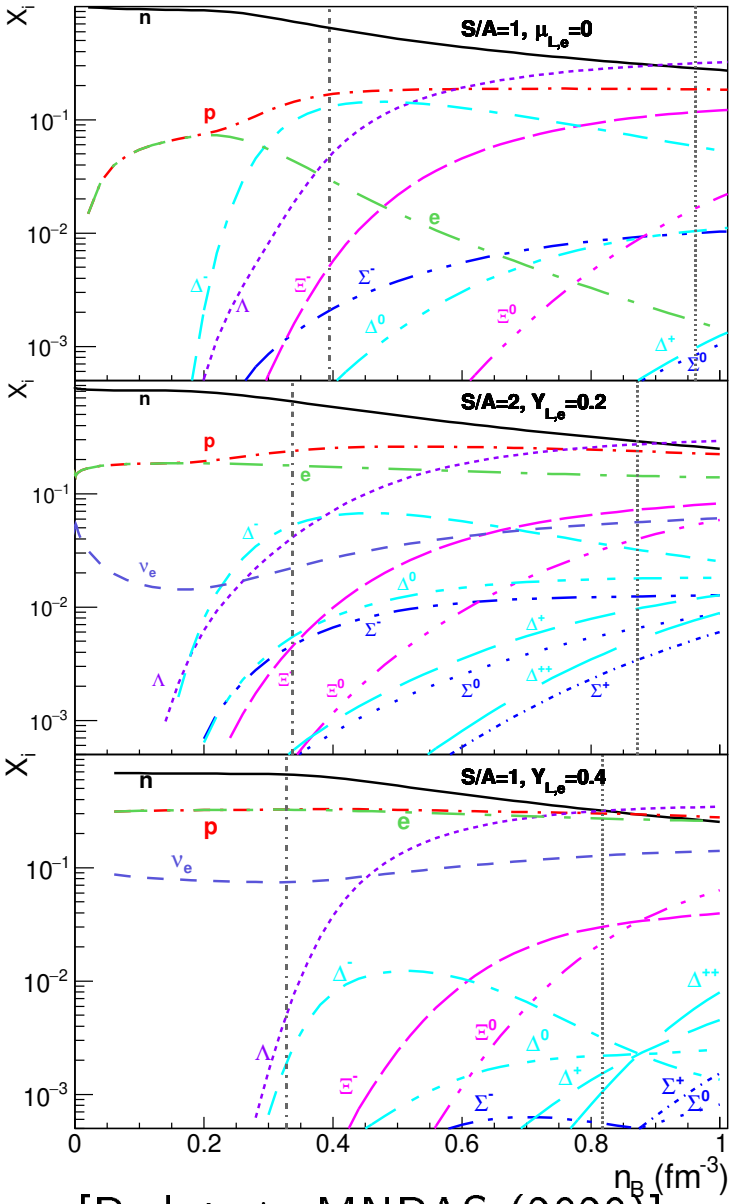
- wide ranges of
  - baryonic densities $[10^{-10} \leq n_B \leq 1-10\ \mathrm{fm}^{-3}]$,
  - temperature $[0 \leq T \leq 100\ \mathrm{MeV}]$,
  - charge fraction $[0 \leq Y_q \leq 0.6]$

  are populated

[Pons+, ApJ 667, 282; Janka+, Phys Rep 442, 38; Fischer+, AA 499, 1; Shibata+, Living Rev. Rel.14, 6; O'Connor+, ApJ 730, 70; Hempel+, ApJ 48, 70; Mezzacappa+, 1507.05680; Rosswog, Int J Mod Phys D24, 1530012; Baiotti+, Rep Prog Phys 80, 096901; O'Connor+, ApJ 865, 81; Burrows+, MNRAS 491, 2715; Ruiz+, PRD101, 064042; Janka, Ann Rev Nucl Part Phys 62, 407; Bauswein+, PRD86, 063001; Koppel+, ApJ872, L16; Bauswein+, PRL125]

- EOS: $X(n_B, Y_p, T)$, $X = e,\ P, \mu_B, \mu_Q, \ldots$
  also microscopic and composition info. is provided;
  3D tables, see CompOSE (`https://compose.obspm.fr/`)
- simulation results depend on effective interaction, particle d.o.f., modeling
- extra uncertainties due to **thermal** behavior; **model dependence**

Heavy baryons in hot and dense matter



[Raduta+, MNRAS (2020)]

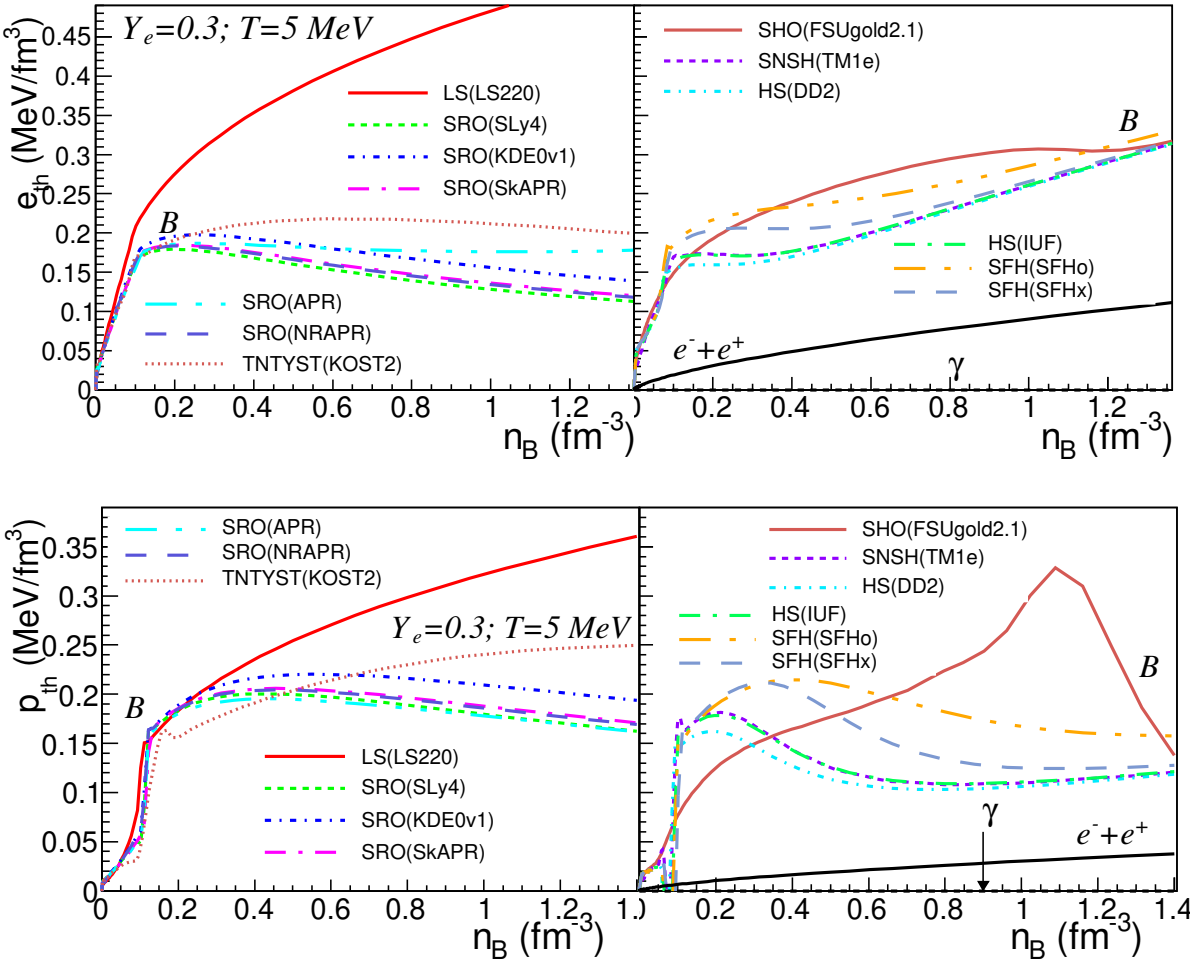
- thermal excitation of new d.o.f.
- ν_e trapping modifies the composition
- high T: hyperons and Δs appear at $n_B < n_{sat}$
- high T favor exotic species
- Λ and Δ^- dominate

- thermodyn. potentials, microscopic quantities will depend on T, $Y_{p/L}$, particle d.o.f. and nucleonic EOS

- effects on properties and stability of hot stars

Thermal energy and pressure: nucleonic models

Thermal contrib.: $X_{th} = X(n_B, Y_e, T) - X(n_B, Y_e, 0)$



- S/A, C_V have strong correl. with m_L^*

[Raduta+, EPJA (2021)]

- low n_B, high T: ideal gas
- high n_B: strong n_B-, T-dep.
  strong EoS-dep.
- qualitative differences among non-rel. and RMF models; due to single particle en.

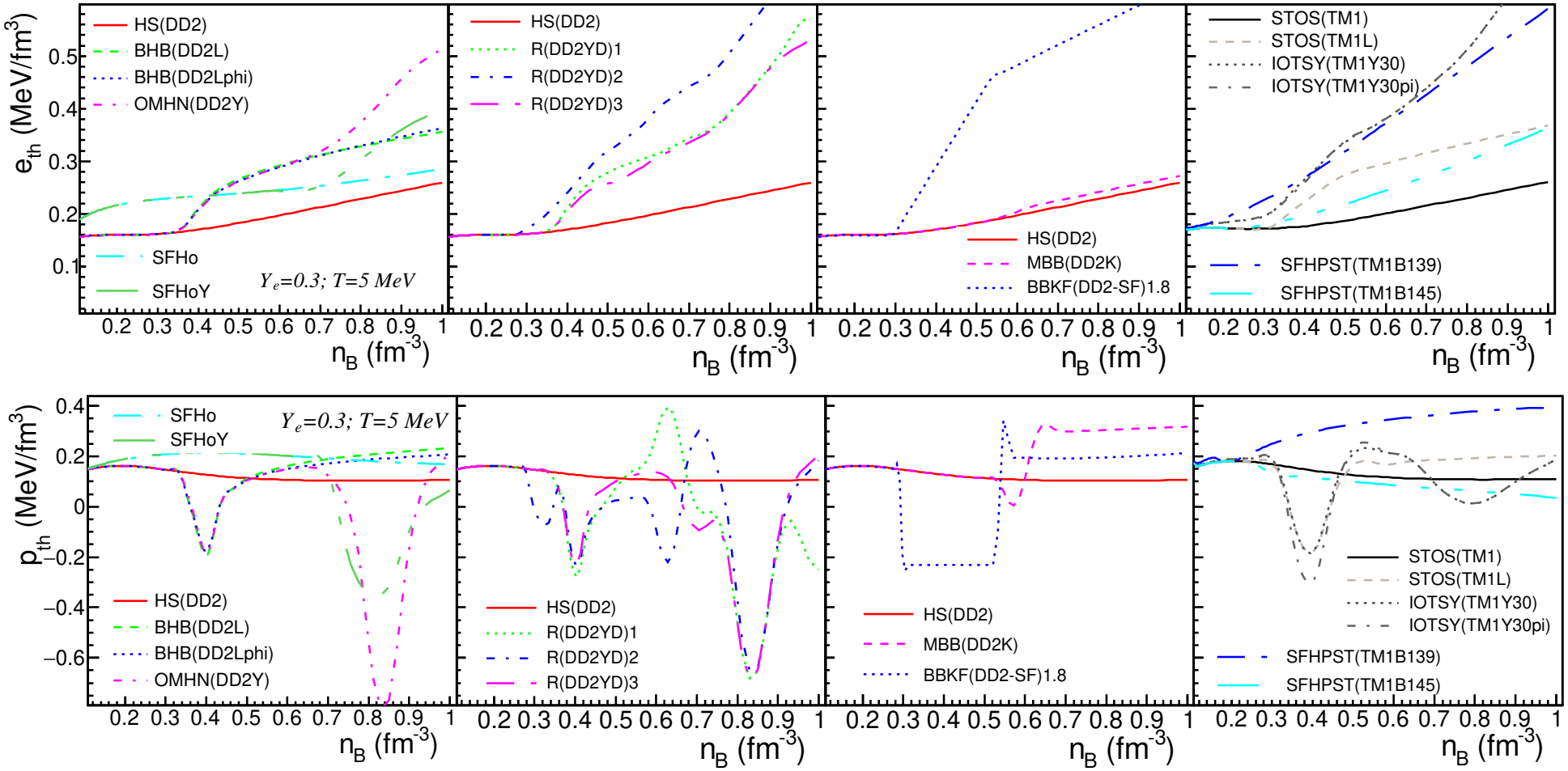
  RMF: $\epsilon(k) = \sqrt{k^2 + m_D^{*2}} + \Sigma_V$

  Skyrme:
  $\epsilon(k) = k^2/2m_L^* + V(n,\tau)$
  - e_{th}, p_{th} depend on m_L^*;
  - p_{th} depends on dm_L^*/dn
- different $\epsilon(k)$ and effective masses

  see also [Constantinou+, PRC (2014); PRC (2015)]

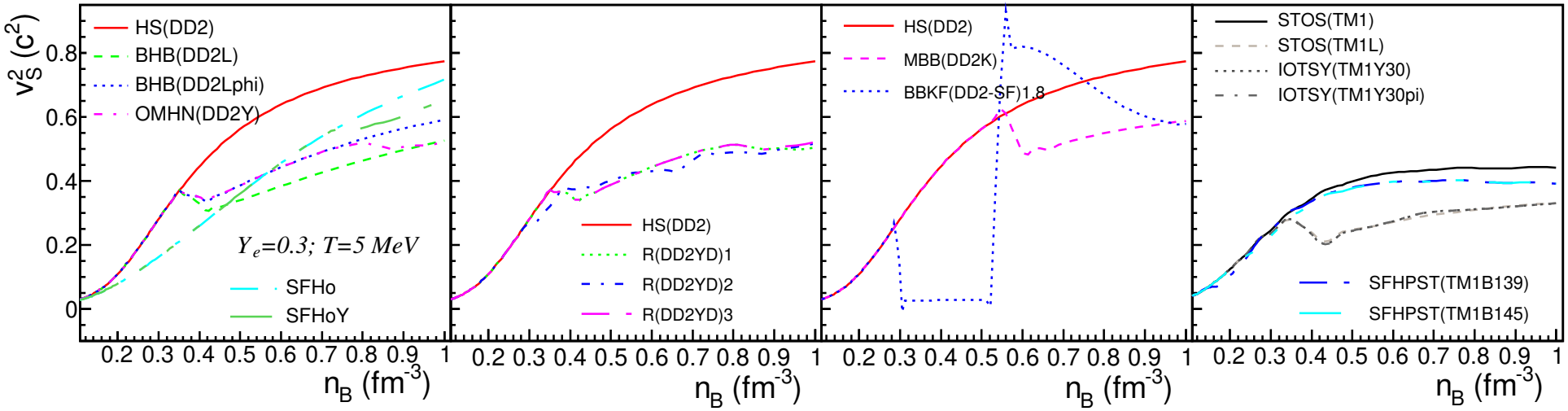
Thermal energy and pressure: nucleons vs. exotica

$X_{th} = X(n_B, Y_e, T) - X(n_B, Y_e, 0)$



- the larger the number of particle d.o.f. the larger $e_{\rm th}$; [Raduta, EPJA (2022)]
- nucleation of exotic d.o.f. diminishes $p_{\rm th}$; under specific conditions $p_{\rm th} < 0$
- Gibbs versus Glendenning construction for hadron to quark phase transition

Speed of sound: $c_S^2 = dP/de|_{S,A,Y_Q}$: nucleons vs. exotica

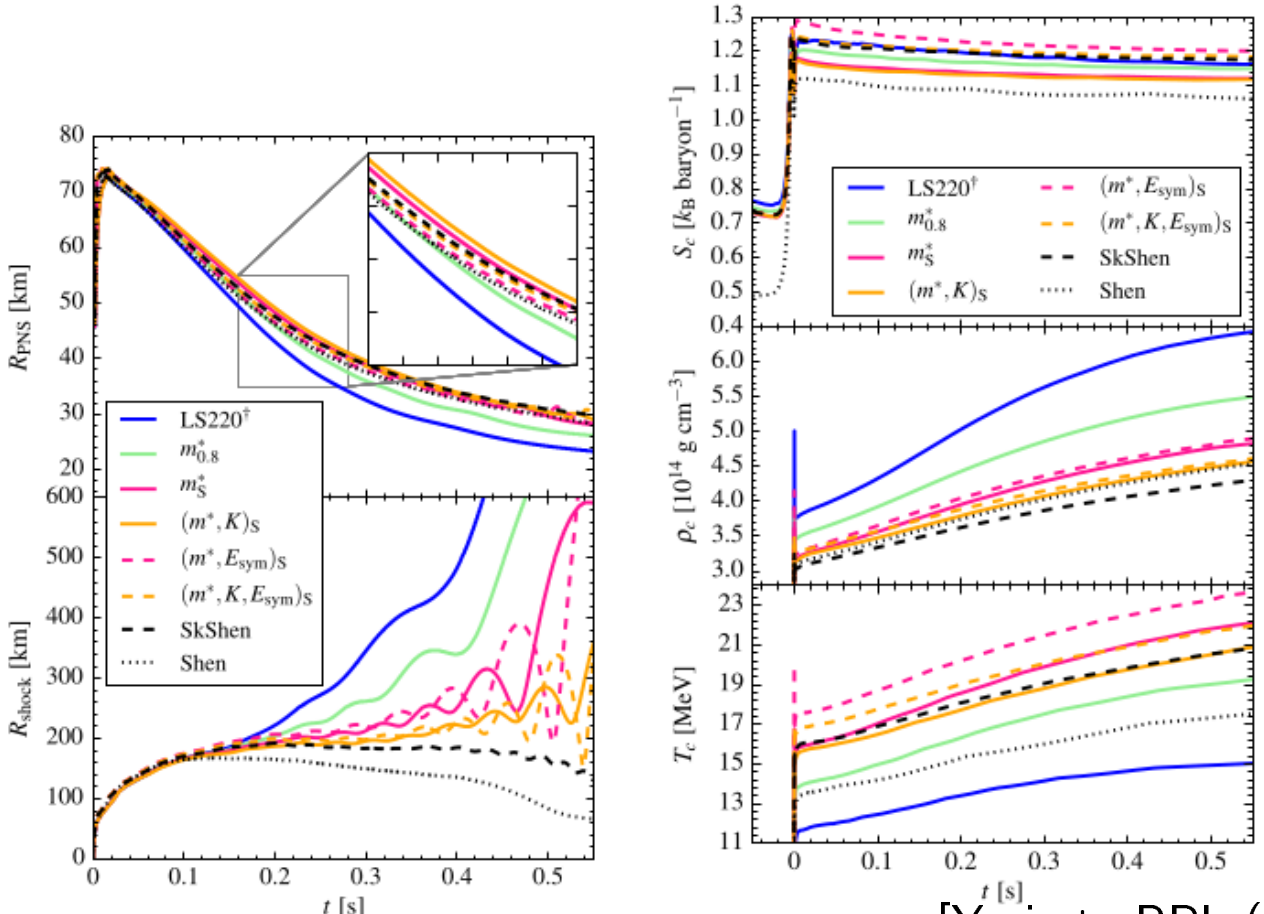


[Raduta, EPJA (2022)]

- strong n_B- and EOS- dependence;
- for Gibbs treatment of phase coex., $c_S^2 = 0$
- heavy baryons, mesons: c_S^2 decreases over a narrow n_B domain
- transition to quarks: c_S^2 decreases over large n_B domain

m^*-effect in early post-bounce evolution

$m^*/m = 1$ (LS220), 0.634 (Shen)

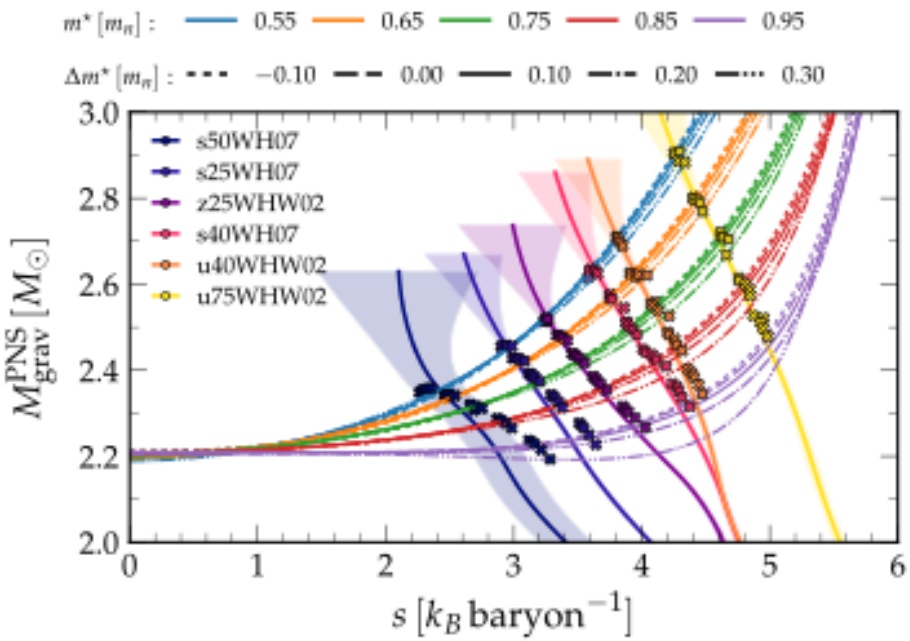


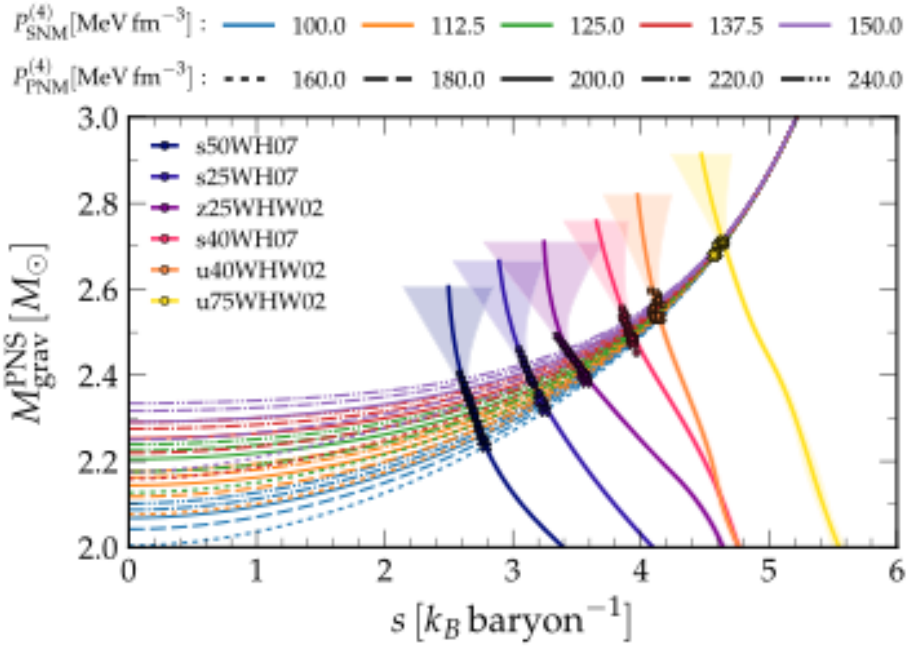
[Yasin+, PRL (2020)]

large m^* → fast explosion; fast contraction of PNS; high (low) ρ_c (T)

large m^* → high (low) T (n_B and R) in the ν-sphere;

m^*-effect in the onset of collapse





[Schneider et al., ApJ (2020)]
failed CCSN; stellar BH formation;

simulation results: collapse begins when hot core's gravitational mass exceeds the maximum gravitational mass predicted by the EoS under the specific thermo conditions;

most importnat ingredients: progenitor and m^*

Conclusions and Challenges

- EOS is essential for describing static and dynamic properties of NS and evolution of proto-NS, core-collapse supernovae, binary NS mergers, formation of stellar BH, etc.
  - isoscalar behavior at supra-saturation - role and treatment of three-body forces
  - isovector behavior in isopin asymmetric matter - the symmetry energy
  - exotic particles; density dependent effective interactions
  - finite-T behavior

- further constraints
  - ab-initio calculations
  - experimental data from nuclear and hypernuclear physics
  - multi-messenger astrophysics, including gravitational wave astronomy