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

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IFIN-HH

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Neutron stars

- NSs are residues of supernovas
  - ▷ NS are born hot $T \approx 10-100$ MeV $\approx 10^{11}-10^{12}$ K $\qquad T_{M_\odot} \approx 1.57 \cdot 10^7$ K
  - ▷ $t(1\ \mathrm{h}) \approx 10^9\ \mathrm{K} \approx 100\ \mathrm{keV}$; cooling by ν and γ emission
- mass range: $1\mathrm{M}_\odot \lesssim M \lesssim 2\mathrm{M}_\odot$
  - ▷ M_{min}, M_{max} inform on formation, EoS and composition
- radii $R \approx 10-15$ km $\qquad R_{M_\odot} = 6.96 \cdot 10^5$ km
- average density $\approx 2 \cdot 10^{14}\ \mathrm{g/cm^3} \approx \rho_0$ $\qquad \rho_{M_\odot} \approx 1.4\ \mathrm{g/cm^3}$
- highly non-uniform $0 \lesssim \rho \lesssim 5-10\rho_0$ $\qquad$ what are NS made of?
- compactness $0.1 \lesssim GM/c^2R \lesssim 0.35$ $\qquad C_{BH} = 0.5$
- surface gravity is $7 \cdot 10^{12}\ \mathrm{m/s^2}$ $\qquad g_{Earth} = 9.8\ \mathrm{m/s^2}$
- fast spinning: $\nu = 716$ Hz (PSR J1748-2446)
- huge magnetic fields: $B = 10^{15}$ G $\qquad B_{Earth;core} = 25$ G, $B_{RMN} = 10^5$ G

NS are labs for dense matter, General Relativity, physics of magnetic fields ...

Structure and Composition

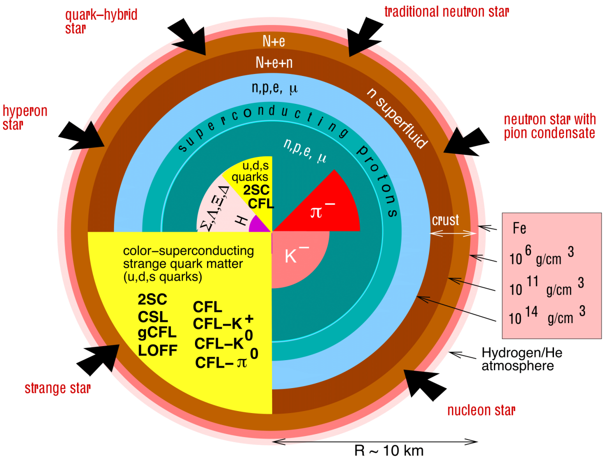


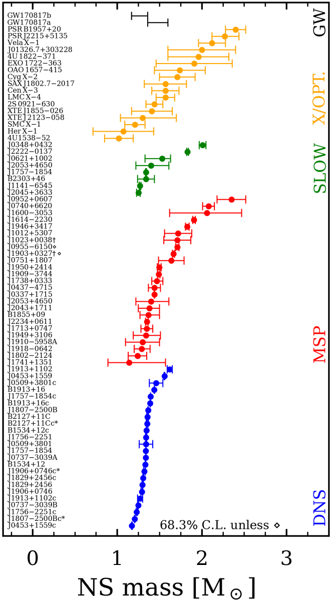
Image credit: F. Weber

CRUST - A. Fantina's talk
crystal struct. + pasta
inhomogeneous
nuclei, neutrons, electrons
uncertainties: inner crust, due to $E_{sym}(n)$

CORE - This talk
homogeneous struct.
uncertain composition: nucleons, hyperons, pions, quarks, electrons, muons, due to $E(n, Y_e)$

Equation of State $P(e)$
key for struct. and compo.

Observables: Masses



[Suleiman et al., PRC104, 015801]

DNS: binaries with two neutron stars,

MSP: millisecond pulsars with $f > 50$ Hz ,

SLOW: slowly rotating pulsars with $f < 50$ Hz ,

X/OPT measurement via X-ray or optical obs. ,

GW: measurements using detection of GW

Massive NS

PSR J1614-2230 ($M = 1.908 \pm 0.016 \mathrm{M}_\odot$) [Demorest+, 2010; Arzoumanian+, 2018]; PSR J0348+0432 ($M = 2.01 \pm 0.04 \mathrm{M}_\odot$) [Antoniadis+, 2013]; MSP J0740+6620 ($M = 2.08^{+0.07}_{-0.07} \mathrm{M}_\odot$) [Fonseca+, 2021]; PSR J1810+1744 ($M = 2.13 \pm 0.04 \mathrm{M}_\odot$ [Romani+, 2021]

Relevant for the composition of the core

Observables: Radii

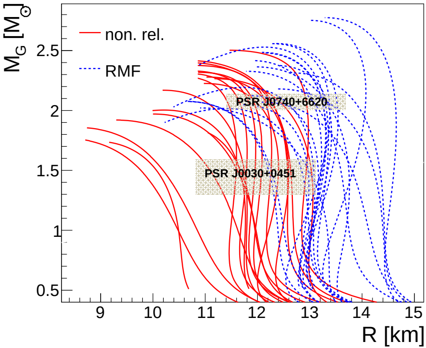
Two measurements:

▷ **PSR J0030+0451** by NICER
$R(1.44^{0.15}_{-0.14}\mathrm{M}_\odot) = 13.02^{+1.24}_{-1.06}$ km [Miller+, 2019]
$R(1.34^{+0.15}_{-0.16}\mathrm{M}_\odot) = 12.71^{+1.14}_{-1.19}$ km [Riley+, 2019]

▷ **J0740+6620** by NICER+XMM Newton
$R(2.08 \pm 0.07\mathrm{M}_\odot) = 13.7^{+2.6}_{-1.5}$ km [Miller+, 2021]
$R(2.072^{+0.067}_{-0.066}\mathrm{M}_\odot) = 12.39^{+1.30}_{-0.98}$ km [Riley+, 2021

• uncertainties still large but enough to rule out a number of EOS

• more measurements from NICER and future LOFT, Athena missions



Data from CompOSE,
`https://compose.obspm.fr/`

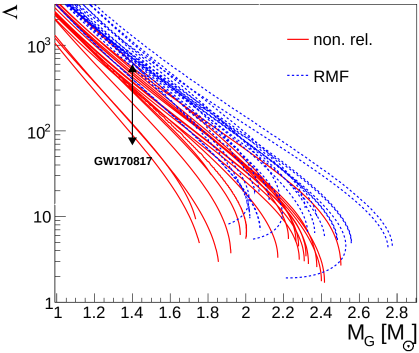
Observables: Tidal deformabilities

▷ the tidal deformability, Λ, describes how much body is deformed by tidal forces, which arise wher two massive bodies orbit each other;

▷ GW170817 - detection of GW emitted by the merging of two NS with $M_T = 2.73^{+0.04}_{-0.01}$ $M_\odot$ and $0.72 \leq q = M_2/M_1 \leq 1$

▷ tidal deformability $70 < \Lambda_{1.4} \leq 580$ [Abbott+, P 2018], constraint on the NS EOS over $2n_{sat} \lesssim n \lesssim 3n_{sat}$

• enough to rule out a number of realistic EOS



Data from CompOSE, `https://compose.obspm.fr/`

Equations of state: Cold nuclear matter

$E/A(n,\delta)$ is Taylor expanded in terms of deviation from isospin asymmetry, $\delta = (n_n - n_p)/n$, and saturation density, $\chi = (n - n_{\rm sat})/3n_{\rm sat}$, with $n = n_n + n_p$.

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

energy SNM — symmetry energy

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

i=0, 2, ... binding energy per nucleon $E_{\rm sat}$, incompressibility $K_{\rm sat}$, etc. at $n_{\rm sat}$

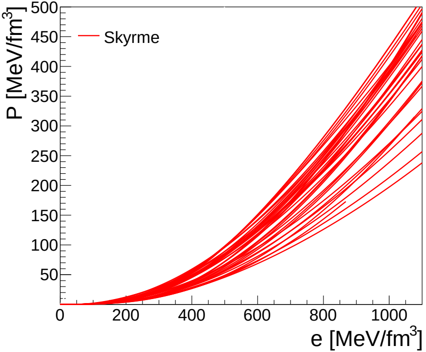
j=0, 1, 2, ... symmetry energy $J_{\rm sym}$ and its slope $L_{\rm sym}$, curvature $K_{\rm sym}$, etc. at $n_{\rm sat}$

▷ EOS exist for phenomenological and microscopic models

▷ **large uncertainties away from** $(n_{\rm sat}, \delta \approx 0)$

Equations of state: Neutron Stars

- may be built from any model of eff. interactic
- NS EOS are 1D, $P(e)$
- composition determined by β-equilibrium, $\mu_n = \mu_p + \mu_e$
- correlations among properties of NS, NM and nuclei
- correlations are best investigated by Bayesian-like analysis, talks by A. Fantina and M. Beznogov
- how to build a NS? talk by A. Fantina
- at $n \gtrsim 2n_{\rm sat}$, extra particles, hyperons, Δs, π, quarks, can appear; onset densities depend of the effective interactions



- uncertainties away $(n_{\rm sat}, \delta \approx 0)$
- dominated by $E_{\rm sym}(n)$, which is poorly known
- largely different NS properties

Exotica in the core

• at $n \approx 2-3 n_{\rm sat}$ extra particle degrees of freedom may be populated: hyperons, $\Delta(1232)$, quarks, condensates [Glendenning, PLB, 1982]

Baryon	B	Q	S	I_3	J^Π	rest mass (MeV)		mean life (s)
Λ	1	0	-1	0	$1/2^+$	1115.683	uds	$2.60 \cdot 10^{-10}$
Σ^+	1	1	-1	-1	$1/2^+$	1189.37	uus	$8.02 \cdot 10^{-11}$
Σ^0	1	0	-1	0	$1/2^+$	1192.642	uds	$7.4 \cdot 10^{-20}$
Σ^-	1	-1	-1	1	$1/2^+$	1197.449	dds	$1.48 \cdot 10^{-10}$
Ξ^0	1	0	-2	-1/2	$1/2^+$	1314.83	uss	$2.90 \cdot 10^{-10}$
Ξ^-	1	-1	-2	1/2	$1/2^+$	1321.31	dss	$1.64 \cdot 10^{-10}$
Δ^{++}	1	2	0	-3/2	$3/2^+$	1232	uuu	$5.63 \cdot 10^{-24}$
Δ^+	1	1	0	-1/2	$3/2^+$	1232	uud	$5.63 \cdot 10^{-24}$
Δ^0	1	0	0	1/2	$3/2^+$	1232	udd	$5.63 \cdot 10^{-24}$
Δ^-	1	-1	0	3/2	$3/2^+$	1232	ddd	$5.63 \cdot 10^{-24}$

• few hundreds scattering events for $N\Lambda$ and $N\Sigma$

• spectroscopic data of single- and double-hypernuclei [$U_\Lambda^{(N)} \approx -28\mathrm{MeV}$, $U_\Xi^{(N)} \approx -18\mathrm{MeV}$ $U_\Sigma^{(N)} \approx 30\mathrm{MeV}$], [Millener et al., 1998];

• pion-nucleus scattering and pion photo-production, electron scattering on nuclei and electromagnetic excitations of the Δs provided $-30~\mathrm{MeV} + U_N^{(N)} \leq U_\Delta^{(N)} \leq U_N^{(N)}$ [Drago+, 2014; Kolomeitsev+, 2017]

How to "build" a NS?

- "choose" the particles: baryons (n, p, Λ, $\Xi^{-,0}$, $\Sigma^{-,0,+}$, $\Delta^{-,0,+,++}$), mesons ($\pi^{-,0,+}$, $K^{-,0,+}$), and leptons (e^-, μ^-)
- choose the approach and the nucleonic effective EOS
- tune the coupling constants of all exotic species
- for each n_B solve the equil. eqs.
  - $n_B = \sum_{i \in B} n_i$,
  - local net charge neutrality: $\sum_{i \in B} n_i + \sum_{\alpha \in L} n_\alpha = 0$,
  - chemical equilibrium for baryons: $\mu_i = Q_B \mu_B + Q_Q \mu_Q + Q_S \mu_s$,
  - chemical equilibrium for leptons $\mu_\alpha = Q_Q \mu_Q + Q_L \mu_L$

    [strangeness not conserved $\mu_S = 0$; ν are not trapped $\mu_L = 0$]
  - "switch-on" particles with $\mu_i > m_i c^2$, $\mu_\alpha > m_\alpha c^2$
  - repeat until converged
- loop over n_B; result: $n_i(n_B)$, $n_L(n_B)$, $P(n_B)$, $e(n_B)$, etc.
- with $P(e)$ solve Tolman-Oppenheimer-Volkoff (TOV) eqs.
- check causality, compliance with astrophys. data ($M_{max} \gtrsim 2\mathrm{M}_\odot$, $R_{1.4}$, $R_{2.08}$, $\Lambda_{1.4}$)

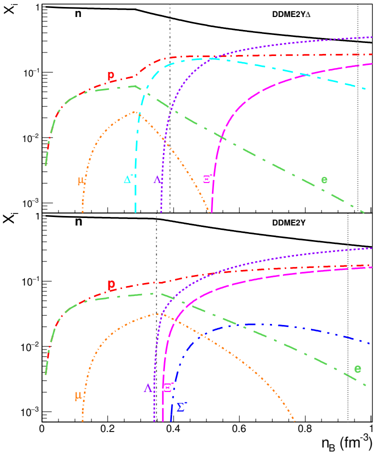
NS with exotic cores: composition

- particles' onset and abundances are decided upon rest mass, interaction potential, charge

- uncertainties in NN, NY, $N\Delta$ entail uncertainties in composition, especially at high n_B

- not all "allowed" species are present
  - hyperonic NS: only Λ, Ξ^- and Σ^-
    $n_\Lambda \approx 2 n_{\rm sat}$, $M_\Lambda \approx 1.5 {\rm M}_\odot$
    $n_{\Xi^-} \approx 2.5 n_{\rm sat}$, $M_{\Xi^-} \approx 1.6 - 1.8 {\rm M}_\odot$
  - Δ-admixed hyperonic NS: only Δ^-, Λ, Ξ^-

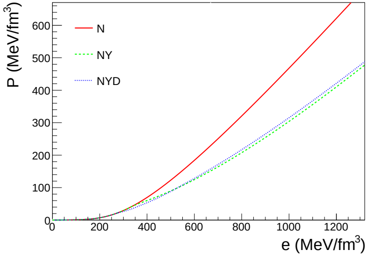
- change in abundances will impact $P(e)$, NS properties



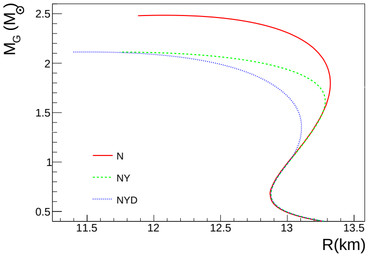
[Raduta+, MNRAS (2020)]

NS with exotic cores: EOS softening, reduction of M_{max}

- exotic species soften the EOS



- exotic NS have lower M_{max}
  compliance with $\approx 2M_\odot$ constraints
  composition and interaction potentials
- exotic NS have smaller R, Λ
  compliance with GW170817 constraints
  interaction potentials



CompOSE

online repository for EOS (`https://compose.obspm.fr/`)

- stores thermodyn., composition, microscopic, transport properties in standardized format
- tabulation with respect to temperature (T), charge fraction (Y_Q), part. number density (n_B)
- wide ranges: $0.1 \leq T$ [MeV] ≤ 100; $0.01 \leq Y_Q \leq 0.6$; $10^{-10} \leq n_B$ [fm^{-3}] $\leq 1-2$
- fine mesh; allows interpolation
- various types of EOS: cold neutron stars; neutron matter; "general purpose", ready for input in simulations; from microscopic, phenomenological, schematic models; various particle d.o.f.

provides tools

- to sort by type; approach; particle composition; prop. of NM; group of authors
- to compute thermodyn. quantities, thermal coefficients,
- to extract information for arbitrary thermodyn. conditions,

modular; constantly upgrading

[Typel, Oertel, Klaehn, Phys.Part.Nucl. (2015); Typel et al., Eur.Phys.J.A (2022)]

CompOSE

https://compose.obspm.fr/table/fam=3/part=3/homo=3

CompOSE — CompStar Online Supernovae Equations of State

- Home
- EoS
  - All families
  - Cold Neutron Star EoS
    - Models with hyperons and Delta-resonances
    - hybrid (quark-hadron) model
    - models with hyperons
      - Holographic models
      - Non-relativistic density functional models
      - Microscopic calculations
      - Relativistic density functional models
        - Thomas-Fermi calculation
        - Non unified models (crust model matched)
        - NSE models
        - Unified models
        - SNA models
        - All
      - All
    - Models with kaon condensate
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EoS

Family : Cold Neutron Star EoS
Particles : models with hyperons
C.M. Homogeneous Matter : Relativistic density functional models

Show 25 entries

Nparam	Name	Family	Particles Content	C.M. Homogeneous	C.M. Inomogeneous	Particles	T min MeV	T max MeV	T pts	nb min fm^{-3}	nb max fm^{-3}	nb pts
1	DS(CMF)-5	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npeBs	0	0	1	0.03	1.9	187
1	DS(CMF)-1 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeNBs	0	0	1	1e-07	3	1191
1	DS(CMF)-4 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeN	0	0	1	1e-07	3	1129
1	DS(CMF)-5 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeNBs	0	0	1	1e-07	1.9	1023
1	DS(CMF)-1	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npeBs	0	0	1	0.03	3	301
1	OPGR(GM1Y5) (with hyperons)	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeBs	0	0	1	7.9e-15	1.3	347
1	DS(CMF)-2	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npe	0	0	1	0.03	3	301
1	DS(CMF)-4	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npe	0	0	1	0.03	3	301
1	DS(CMF)-6 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeN	0	0	1	1e-07	1.9	1023
1	OPGR(GM1Y4) (with hyperons)	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeBs	0	0	1	7.9e-15	1.2	303
1	DNS(CMF) hadronic (cold neutron stars) with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npemBs	0	0	1	1e-07	3	1191
1	DS(CMF)-3 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeNBs	0	0	1	1e-07	3	1129
1	DS(CMF)-6	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npe	0	0	1	0.03	1.9	187
1	DS(CMF)-3	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npeBs	0	0	1	0.03	3	301
1	DS(CMF)-2 with crust	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeN	0	0	1	1e-07	3	1191
1	OPGR(GM1Y6) (with hyperons)	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeBs	0	0	1	7.9e-15	1.1	338
1	DNS(CMF) Hadronic (cold neutron stars)	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	—	npem Bs	0	0	1	0.03	3	301
1	OPGR(DDHdeltaY4) (with hyperons)	Cold Neutron Star EoS	models with hyperons	Relativistic density functional models	Non unified models (crust model matched)	npeBs	0	0	1	7.9e-15	0.99	307

EOS for CCSN and BNS

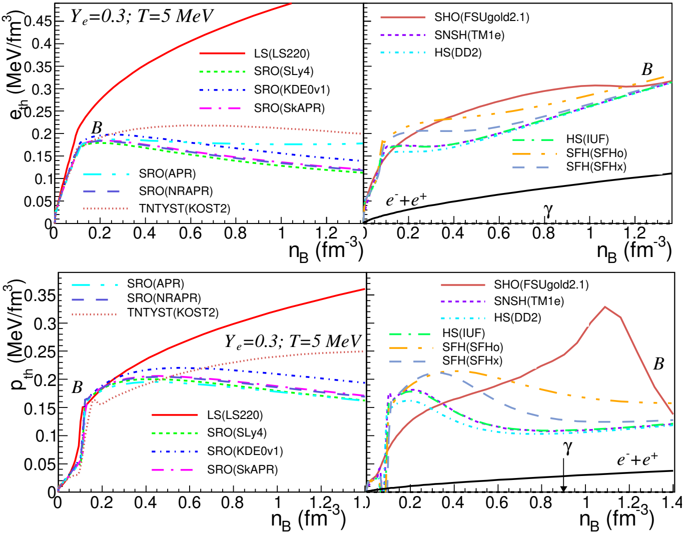
- from 1991 to 2010 only two EoS:

  (1) Lattimer & Swesty (LS) [NPA 535, 331 (1991)];
  (2) Shen, Toki, Oyamatsu & Sumiyoshi (STOS) [NPA 637, 435 (1998)]

- in June, 2021
  - about 100 EOS models are now available,
  - 36 EOS with exotic d.o.f. (Λ, hyperons, hyperons and Δ, π, K, quarks)
  - different features:
    - effective interactions: Skyrme, Covariant Density Functionals, ab-initio;
    - various NM properties, i.e. n_{sat}, E_{sat}, K_{sat}, J_{sym}, L_{sym}, K_{sym}, m_{eff} [not always in accord with constraints];
    - still far from exhausting the parameter space

Finite temperature - nucleonic models

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

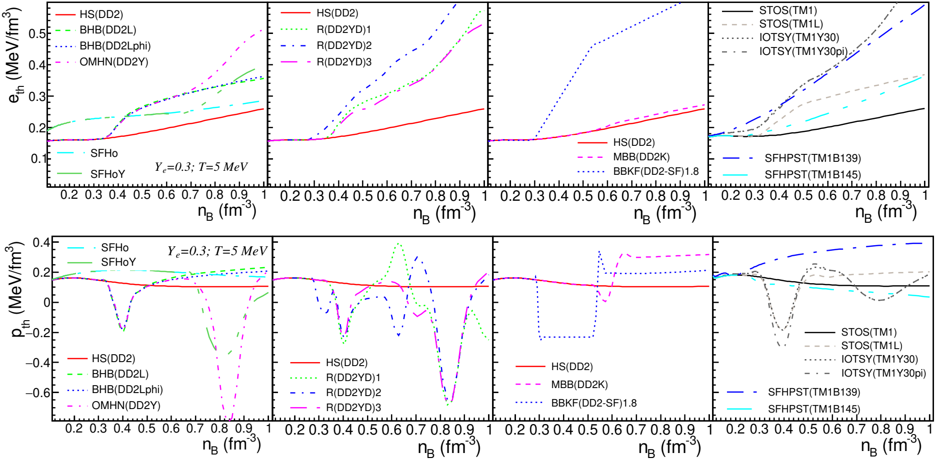


- non-rel. and RMF models behave differently; strong model dependence; so far unexplored
- in Skyrme-like models thermal effects are determined by m^*

[Raduta+, EPJA (2021)]

Thermal energy and pressure: models with exotica

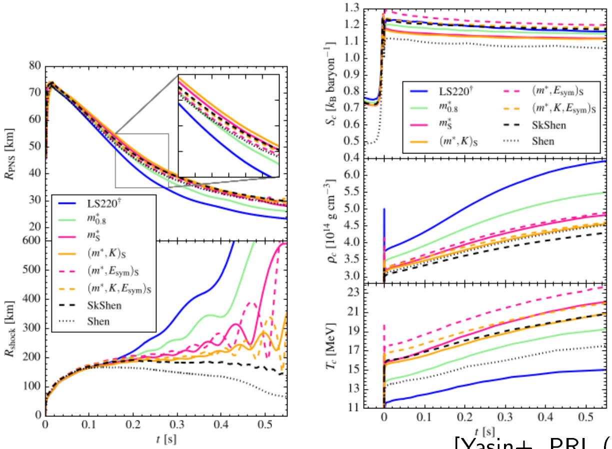
Thermal contrib.: $X_{th} = X(n_B, Y_e, T) - X(n_B, Y_e, 0)$



- 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 $p_{\rm th} < 0$

Early post-bounce evolution

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

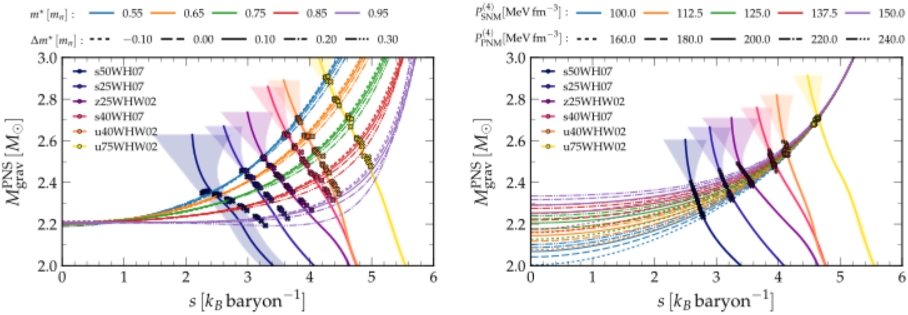


[Yasin+, PRL (2020)]

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; large E_ν, L_ν [Schneider+, ApJ(2020)]

BH formation in failed CCSN



[Schneider et al., ApJ (2020)]

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 important ingredients: progenitor and m^*

Conclusions

- Neutron Stars: definition, structure, composition, observables
- Equation of State: constraints, exotic particle d.o.f.
- `CompOSE`: an online repository of EOS
- Finite-temperature EOS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