Study of β-stable matter in proto-neutron star: impact of the nuclear symmetry energy at finite temperature

N. H. Tan, D.T. Loan, D. T. Khoa, J. Margueron
INST/VINATOM, VIETNAM
IPNLyon/CNRS, FRANCE

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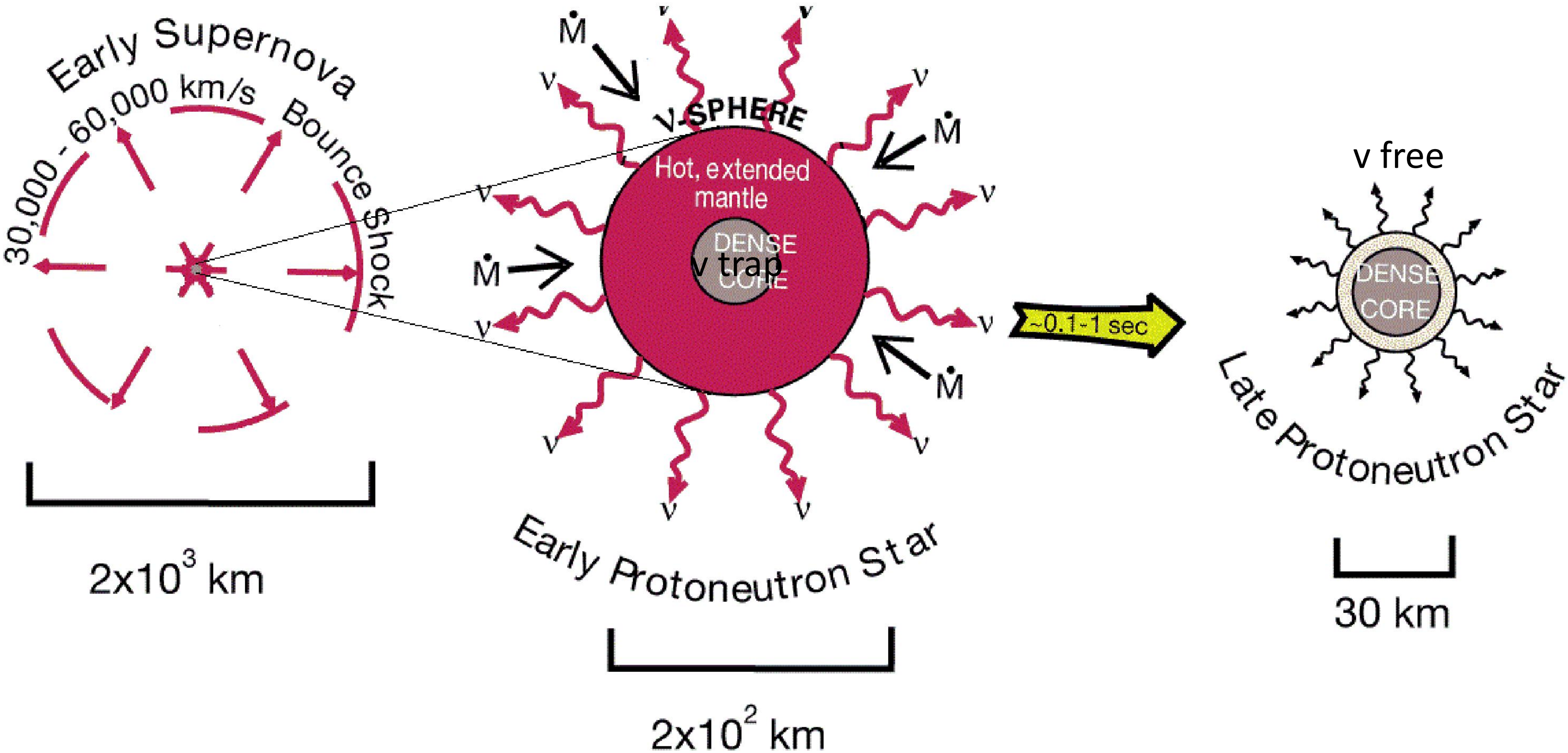
Core-collapse supernova and proto-neutron star



PNS: residual state after gravitational collapse of massive star.

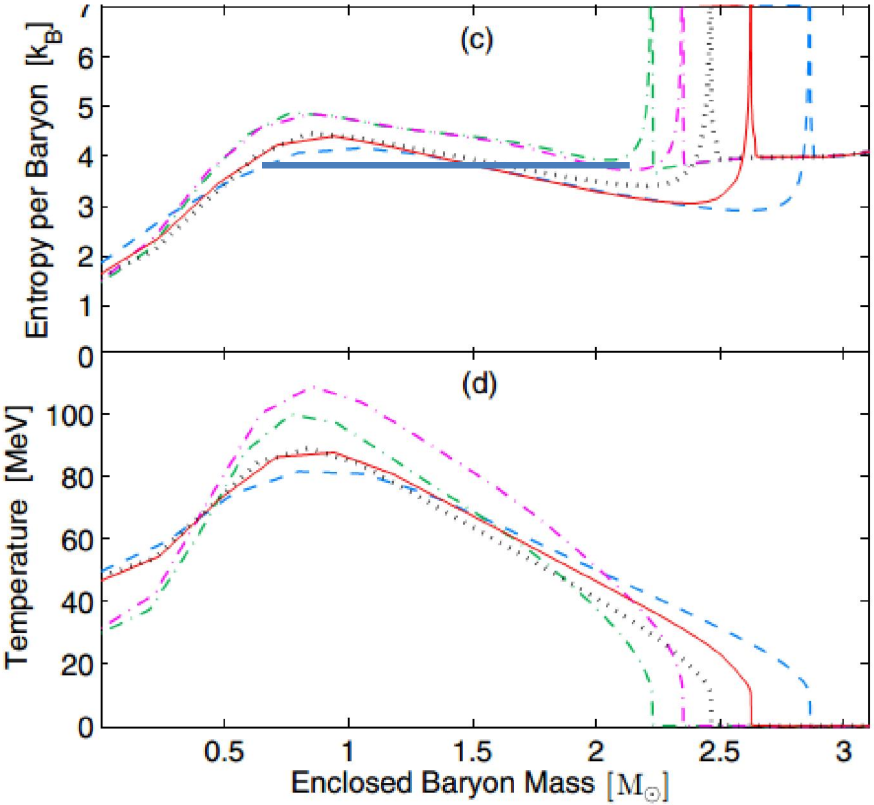
For massive stars ($M=8\text{-}30M_o$): PNS , S=2→ Neutron Star

For very massive stars ($M>30M_o$) PNS, S=4→ Black-Hole

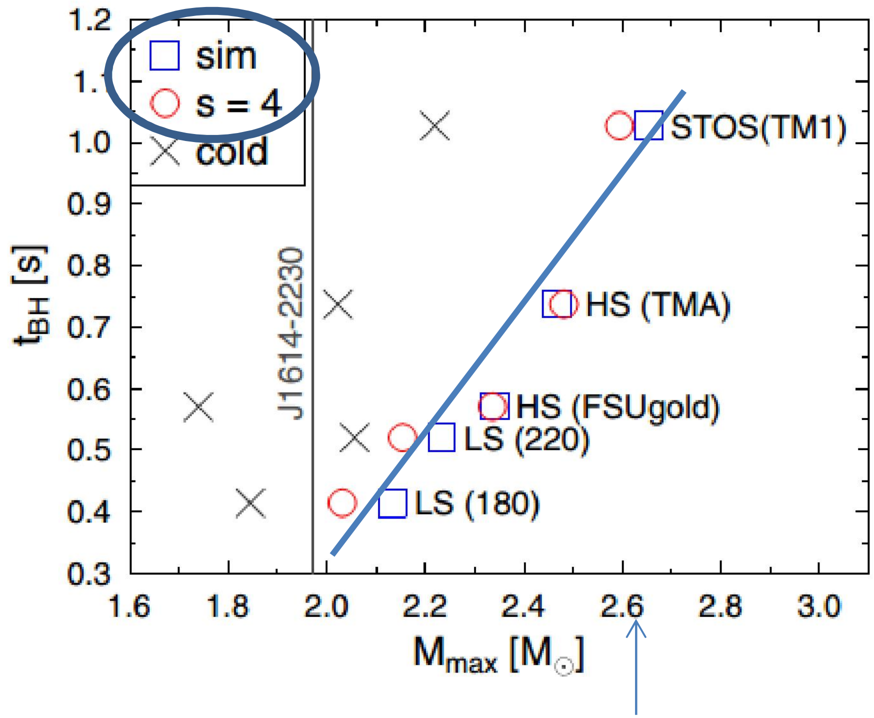
Evolution of 40 Mo star (numerical simulation)

Simulation of core-collapse supernova, Hempel et al., APJ 748 (2012)

T and s mass profiles at the onset of BH collapse



time before the PNS collapse to a black-hole t_{BH}



Maximum Mass of a s=4 beta stable matter

In the following, we study the s=1, 2 &4 EOS at ν-trapped and ν-free in beta stable with different nuclear interaction.

Nonrelativistic HF mean field with M3Y interaction for ANM

Model	n_0 fm^{-3}	E_0 MeV	K MeV	J MeV	L MeV	K_{sym} MeV	Ref.
CDM3Y3	0.17	-15.9	217	29.0	62.5	45	Khoa PRC 1997
CDM3Y6	0.17	-15.9	252	29.8	64.3	46	
CDM3Y6s	0.17	-15.9	252	32.0	49.14	-154	
CDM3Y3s	0.17	-15.9	217	32.0	49.14	-140	
M3Y-P5	0.16	-16.1	235	30.9	27.9	-229	Nakada, PRC 2003
M3Y-P7	0.16	-16.0	254	33.0	54.3	-138	Nakada PRC 2013
SLy4	0.16	-16.0	230	32.1	46.0	-120	Chabanat NPA 1998
D1N	0.16	-16.0	221	30.1	32.4	-182	E.Chappert, PLB 2008

Constrains on J: 30 < J < 34 MeV; constrains on K: 240 ± 30 MeV

CDM3Y*n*:
$$v^{\mathrm{D(EX)}}_{(\sigma\tau)}(\rho,r) = F_{(\sigma\tau)}(\rho)\sum_{\nu=1}^{3} Y^{\mathrm{D(EX)}}_{(\sigma\tau)}(\nu)\,\frac{\exp(-R_\nu r)}{R_\nu r}$$

M3Y-P*n*:
$$v^{\mathrm{D(EX)}}_{(\sigma\tau)}(\rho,r) = \sum_{\nu=1}^{3} Y^{\mathrm{D(EX)}}_{(\sigma\tau)}(\nu)\,\frac{\exp(-R_\nu r)}{R_\nu r} + t^d(r)\rho(r)^\alpha\,\delta(\boldsymbol{r})$$

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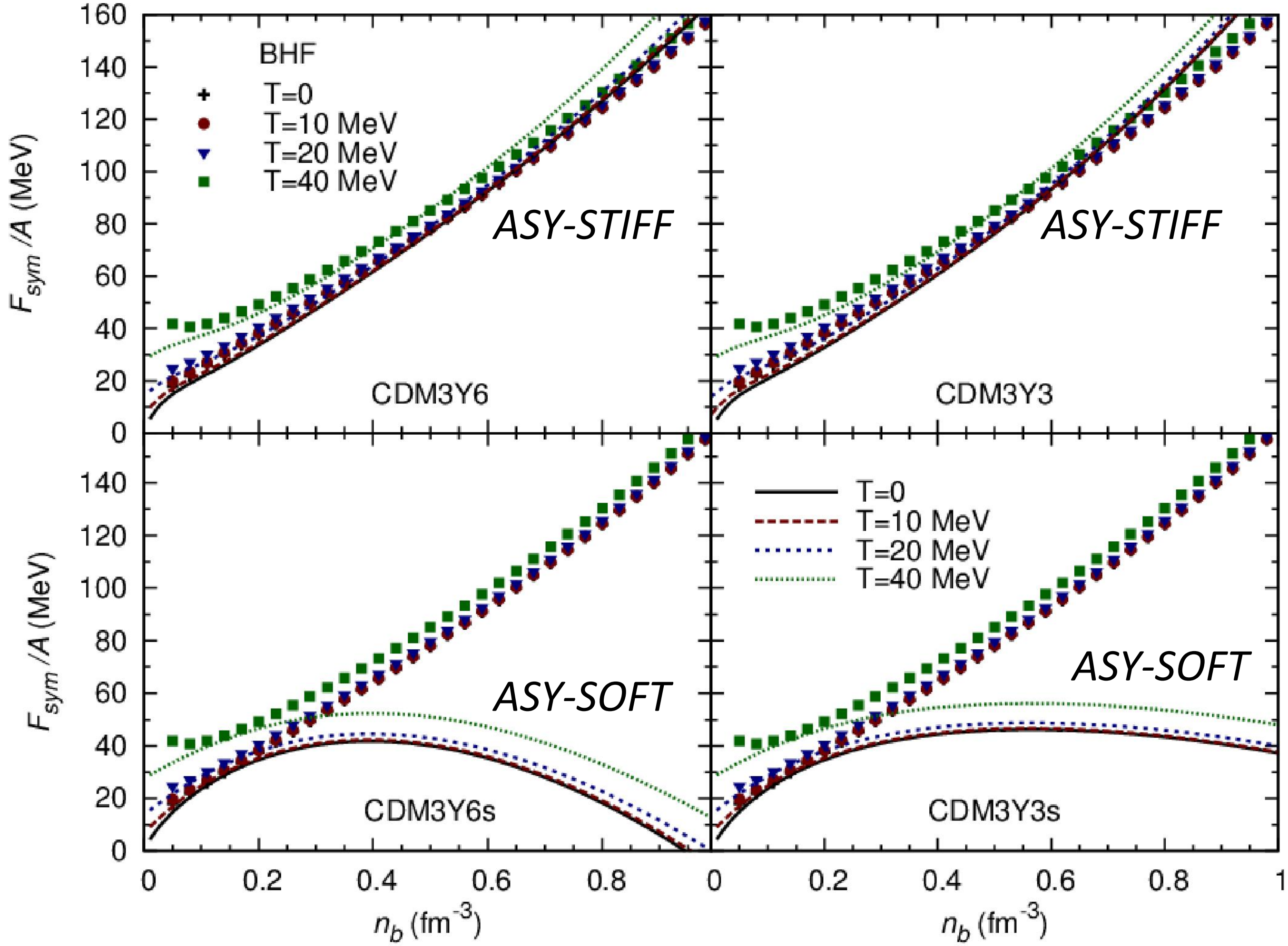

BHF: G.F. Burgio, A&A **518** (2010)

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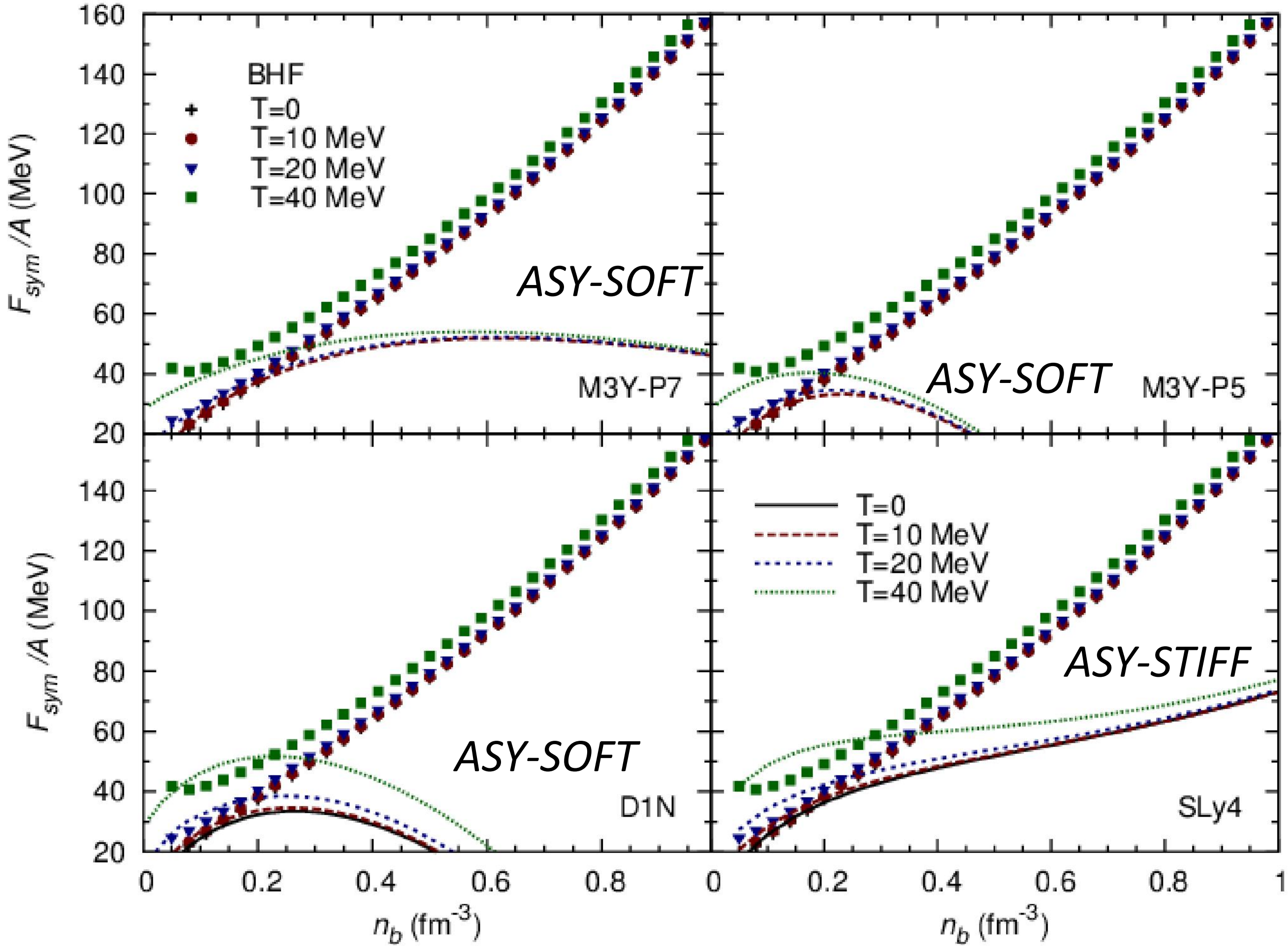

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Hot β-equilibrium matter of PNS

In the core: Homogeneus npeμν matter

β – equilibrium process

$$p + e \leftrightarrows n + \nu_e$$

$$p + \mu \leftrightarrows n + \nu_\mu$$

$$\mu_e > m_\mu c^2 \sim 105.6 \text{ MeV}$$

$$\rho_p = \rho_e + \rho_\mu$$

$$\mu_n - \mu_p = \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu}$$

$$\mu_{\nu_e} = -\mu_{\overline{\nu}_e}$$

$$\mu_{\nu_\mu} = -\mu_{\overline{\nu}_\mu}$$

$$Y_{Le} = x_e - x_{\overline{e}} + x_{\nu_e} - x_{\overline{\nu}_e} = 0.4$$

$$Y_{L\mu} = x_\mu - x_{\overline{\mu}} + x_{\nu_\mu} - x_{\overline{\nu}_\mu} = 0$$

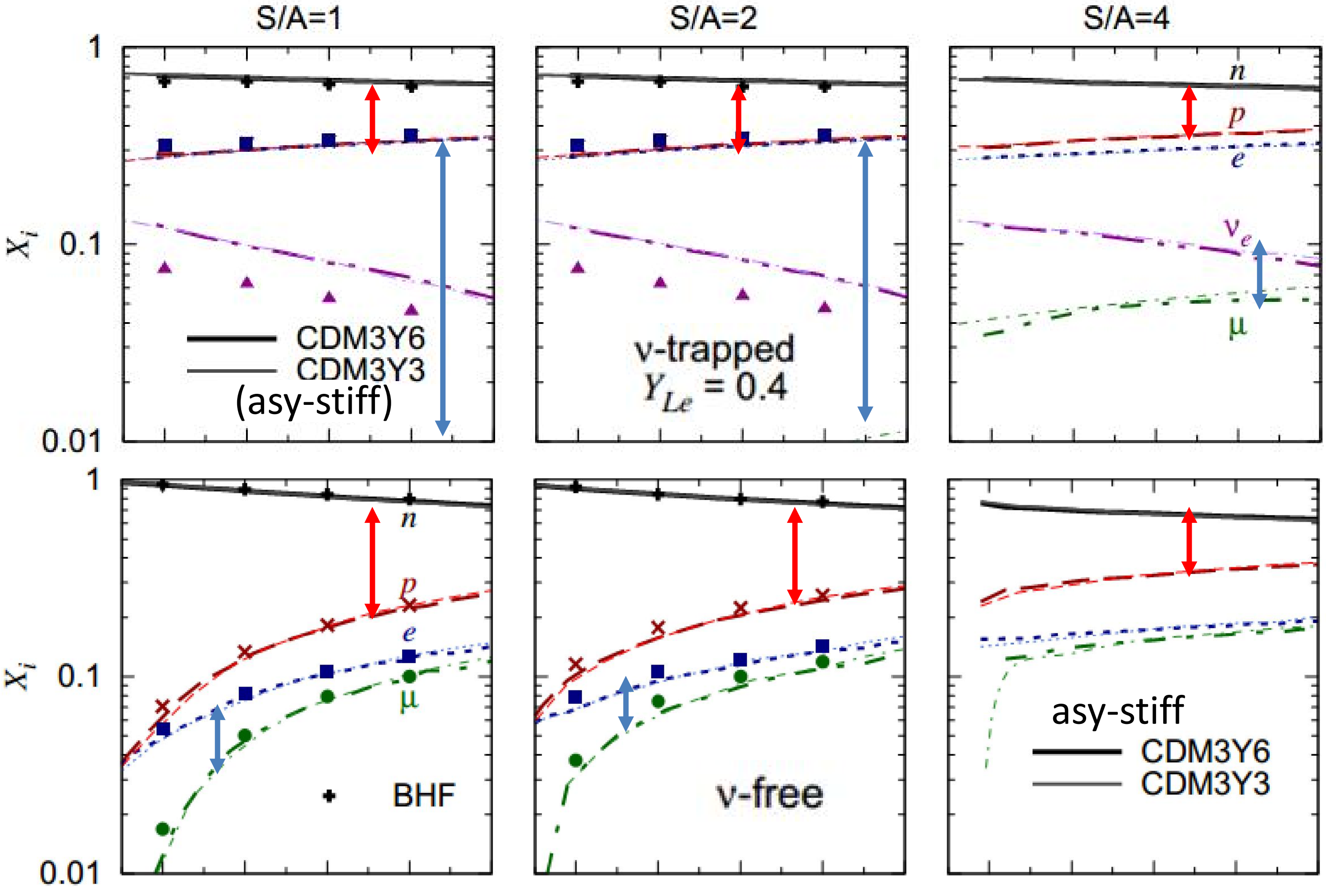
← ν trapped: x_e is larger

$$\rho_p = \rho_e + \rho_\mu$$

$$\mu_n - \mu_p = \mu_e - \mu_{\nu_e} = \mu_\mu - \mu_{\nu_\mu}$$

↑ ν free: more *n*-rich

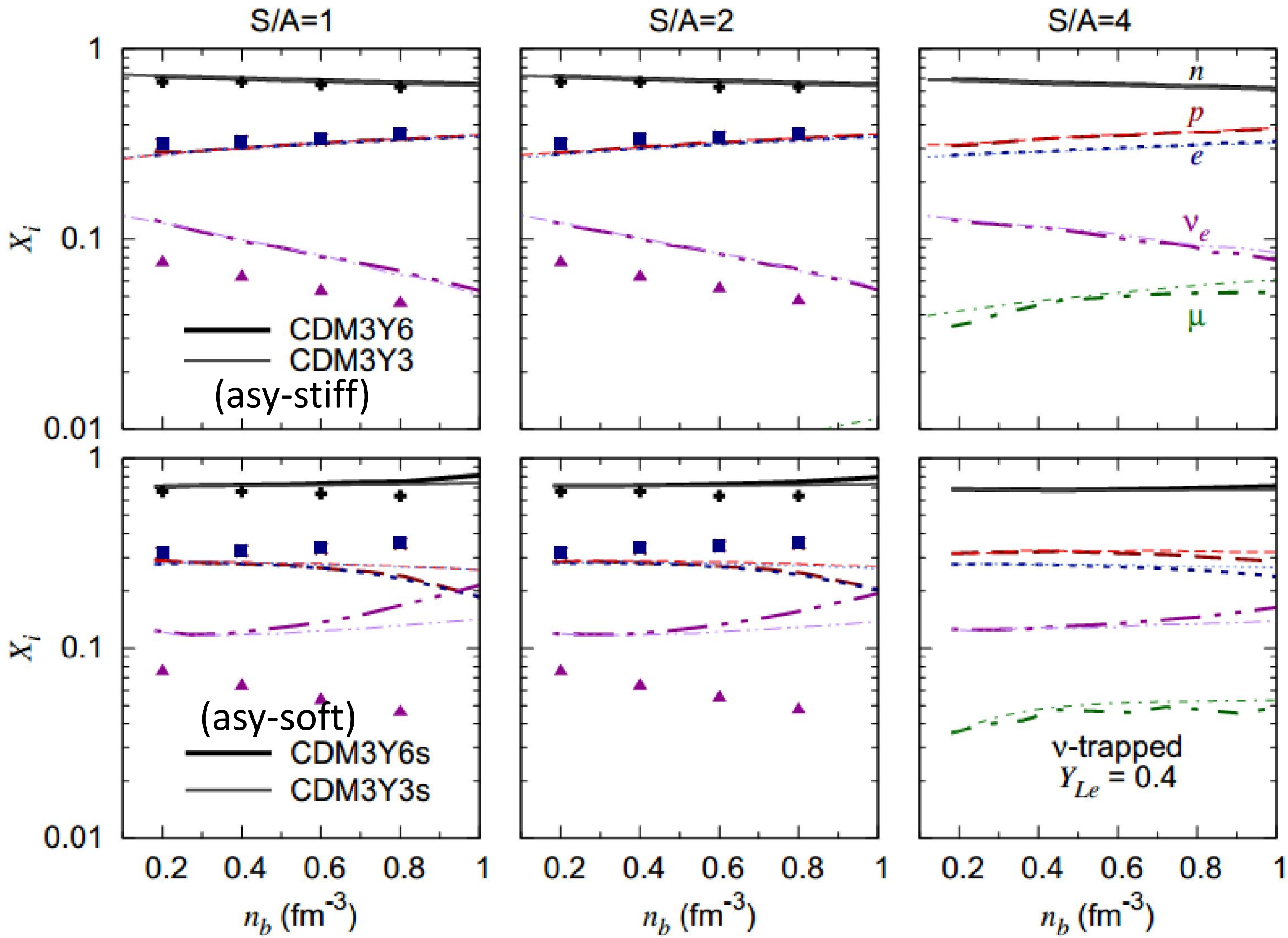
Isentropic particle fraction of PNS matter



→ ν-trapped is more symmetric and has larger x_e than ν-free matter.

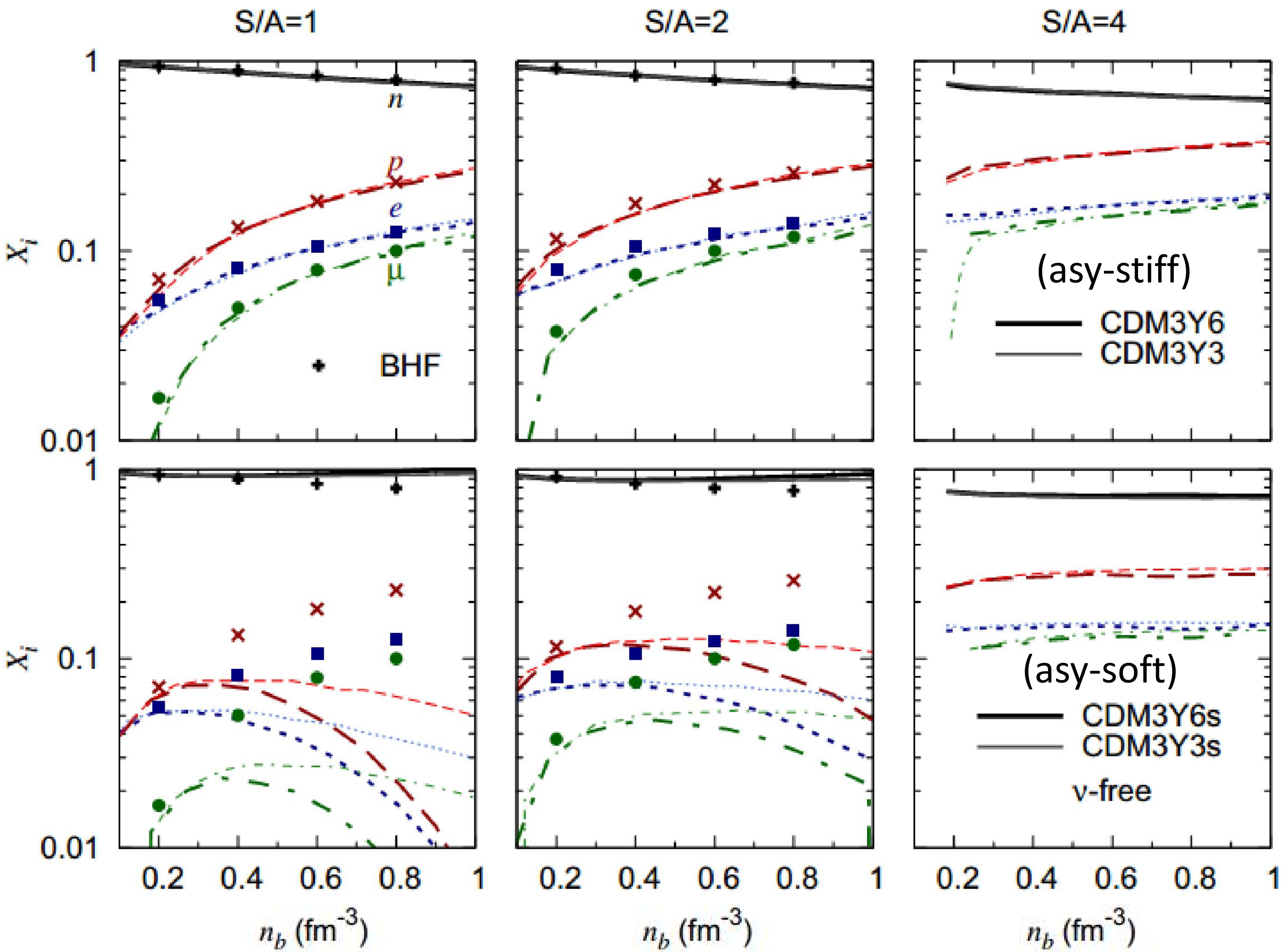
→ As entropy increases, x_e and x_μ get more and more close as well as x_n and x_p

Isentropic particle fraction of PNS matter



→ASY-STIFF produce more symmetric NM, higher x_e , decreasing x_ν
→ASY-STIFF models are closer to BHF than ASY-SOFT;

Isentropic particle fraction of PNS matter

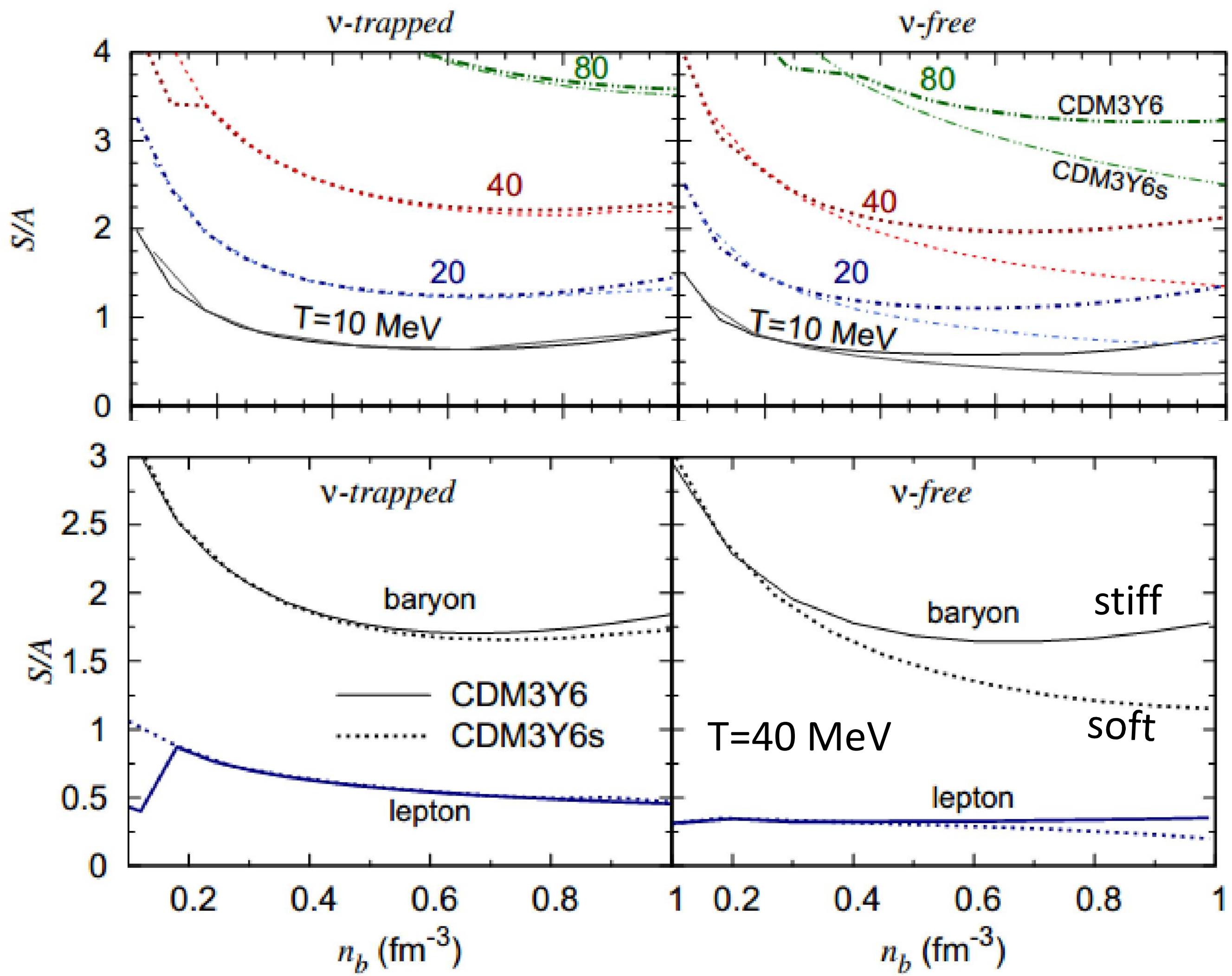


→The difference between ASY-STIFF and ASY-SOFT is more pronounced in ν –free matter

→ effect of temperature softening the effect of symmetry energy

→cooling of NS in Direct Urca process may not be describeb by ASY-SOFT interactions

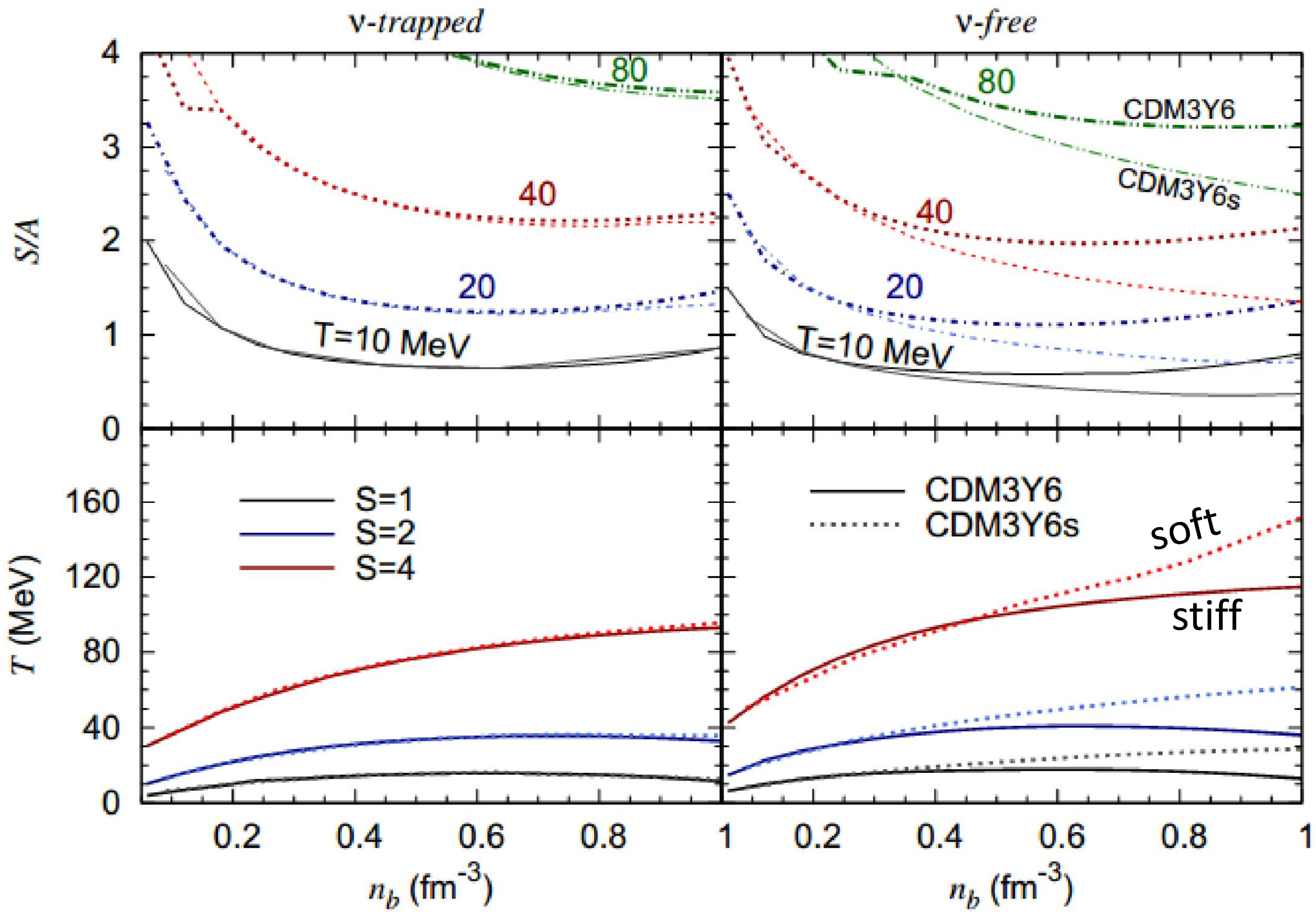
EOS of proto-neutron star matter – Entropy



→ASY-STIFF predict larger entropy than ASY-SOFT interactions

→ $S_{\nu\text{-trapped matter}}$ is larger than $S_{\nu\text{-free matter}}$

EOS of proto-neutron star matter – Entropy & Temperature

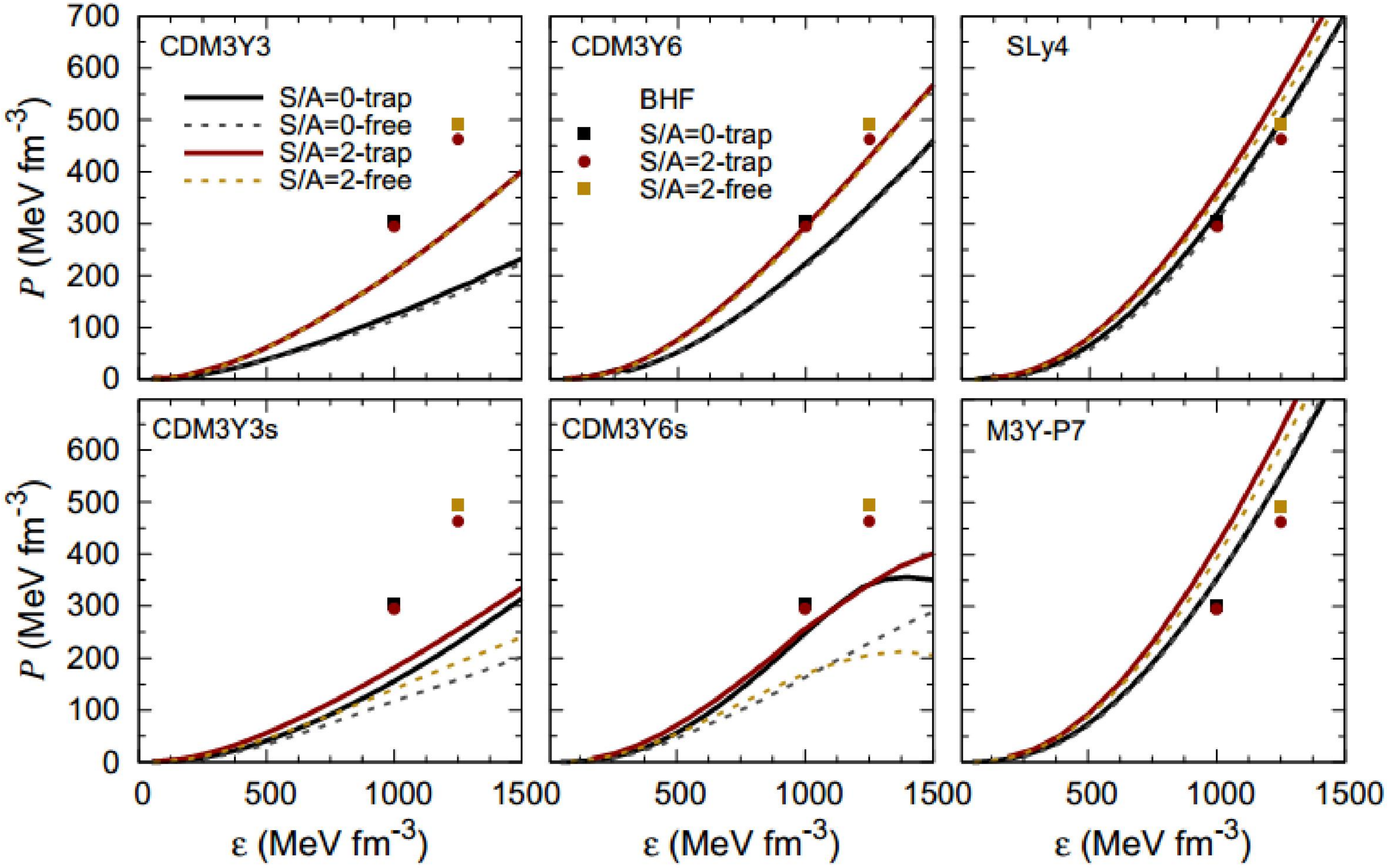


→ ASY-SOFT interactions predict higher temperature profile.

→At fix entropy, $T_{\nu\text{-trapped matter}}$ is less than $T_{\nu\text{-free matter}}$.

In an isentropic cooling of PNS, matter becomes hotter in the core of PNS

EOS of proto-neutron star matter – Pressure



→ $P_{S=2} > P_{S=0}$, different with BHF.

→ $P_{trap} > P_{free}$, different with BHF

Apply to core-collapse supernovae

EOS of proto-neutron star matter
P(ρ, r, S)

↓

TOV equation

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

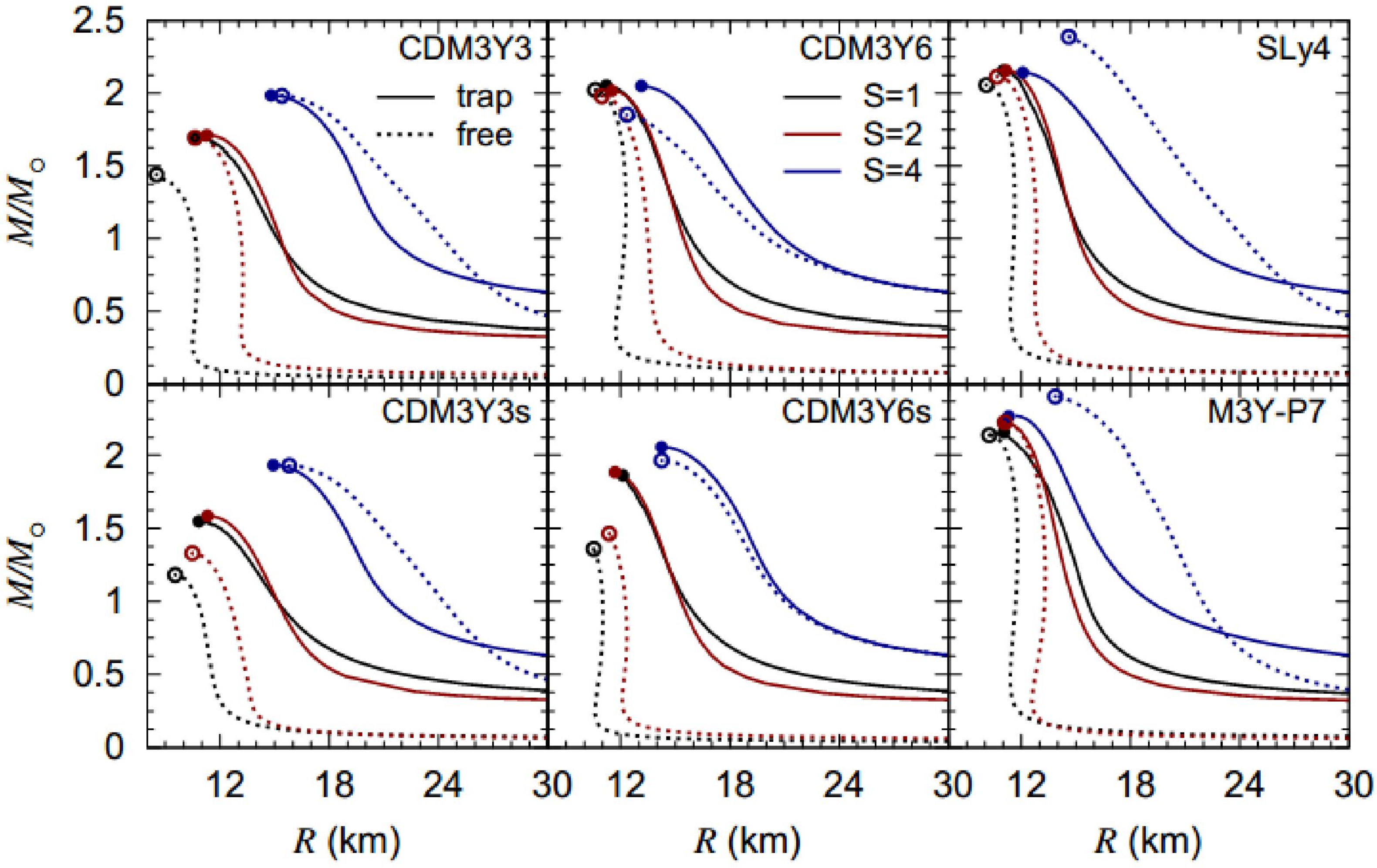
$P = P(\rho)$ Pressure (input of TOV eq.)

$\rho = \rho(r)$ Density at position r

$m = m(r) = \int_0^r 4\pi s^2 \rho(s) ds$ Enclosed mass

$M = m(R), \quad R = R(\rho \approx 0)$ total mass and radius.

Apply to core-collapse supernovae

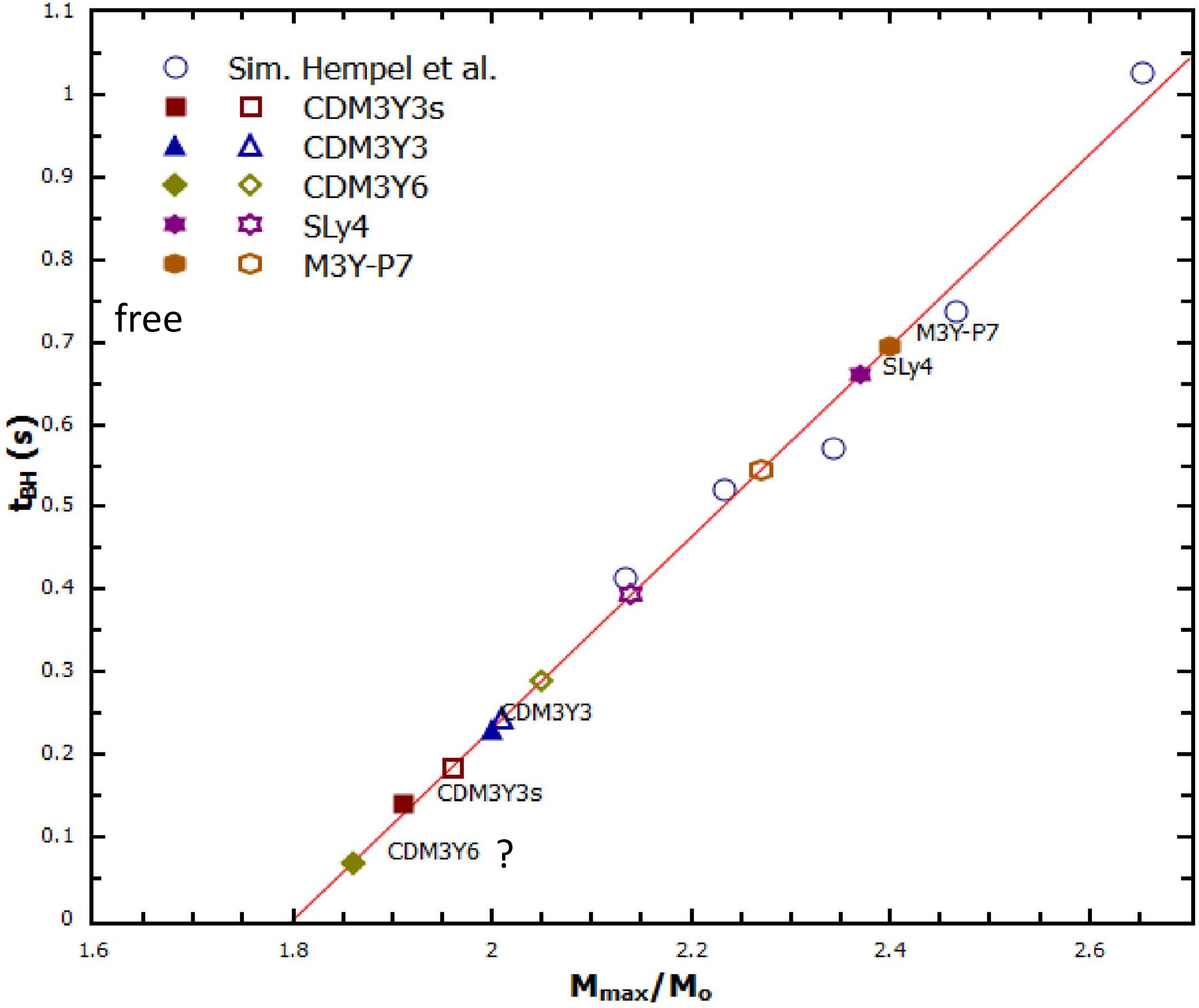


Phenomenon is more pronounced in ν-free case:

→ The hotter PNS, the larger Maximum mass.

→ As ν escapes>> less mass gain gravitational >>form BH

Properties of isentropic PNS matter



Summary, conclusion and outlook

- Both the EOS of neutrino-free and neutrino-trapped baryonic matters in β-equilibrium and static properties of PNS have been investigated at different temperatures and entropy per baryon s= 1, 2 and 4.
- Question about correlation between stiff-soft and maximum mass
- t_{BH} may related to the symmetry energy but others parameters should be considered
- ν mean free path.

Thank you for your attention!