The low-density EoS under core-collapse supernova and heavy-ion collision conditions

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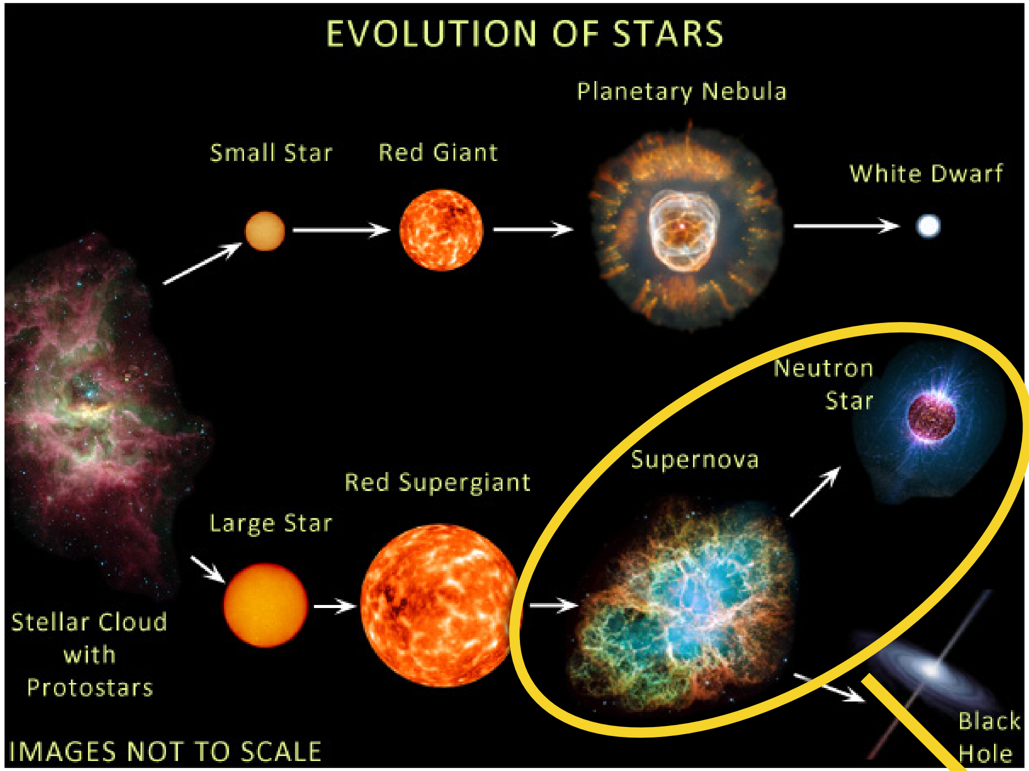
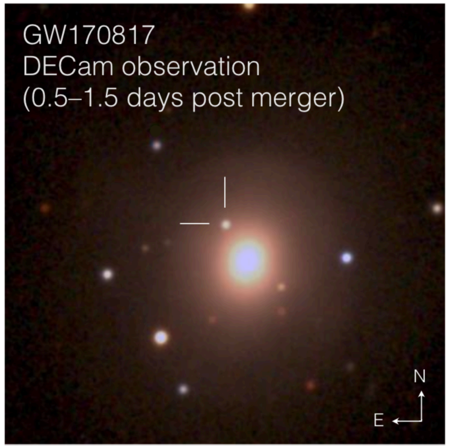
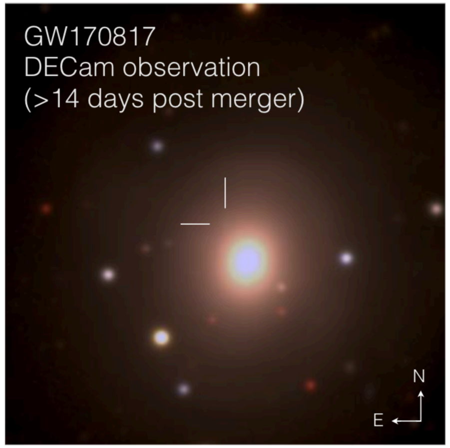
Where do these clusters form?

in http://essayweb.net/astronomy/blackhole.shtml



in https://www.ligo.org/detections/GW170817.php
Credit: Soares-Santos et al. and DES Collab





NS mergers

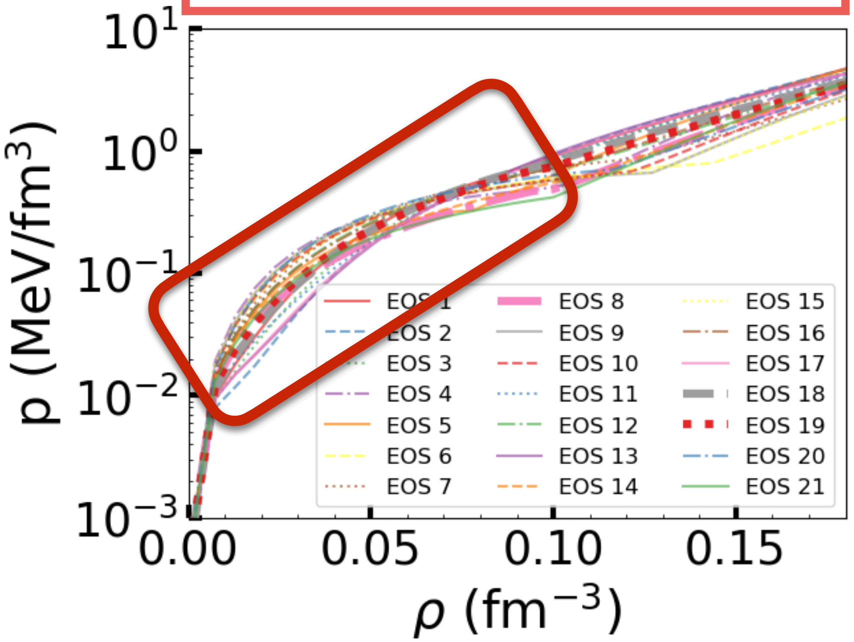
scenarios where these clusters are important:
supernovae, NS mergers, (crust of) neutron stars

Why are these clusters important?

- They influence supernova properties: the clusters can modify the neutrino transport, affecting the cooling of the proto-neutron star and/or binary and accreting systems.
- Transport coefficients are determined by the collision rates of electrons and/or neutrinos with clusters, which depend on the cluster abundances and sizes.
- In binary mergers, the recombination of free nucleons into alpha particles can generate enough energy to induce mass outflows.

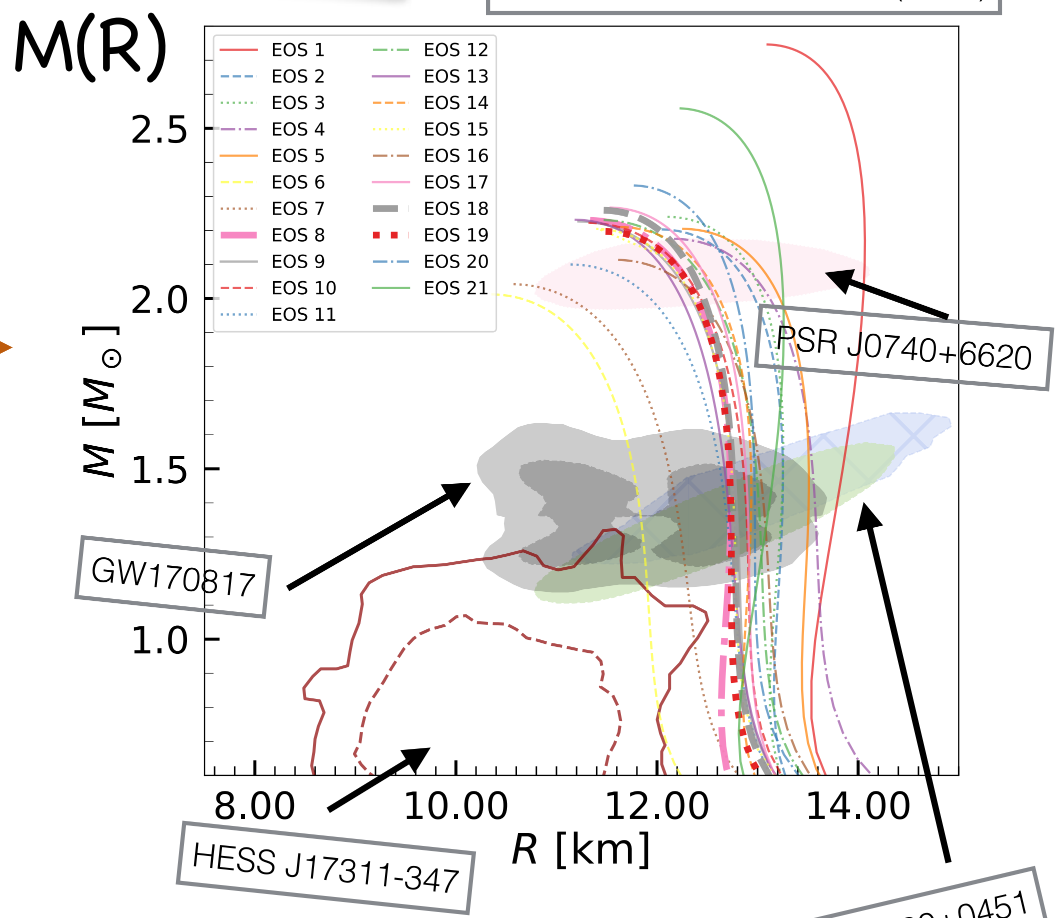
Describing neutron stars

EoS, i.e. P(E) for a given density and temperature:



TOV

Malik et al, A&A 689 A242 (2024)



Many EoS models in literature, like e.g. phenomenological models, whose parameters are fitted to nuclei properties, such as **RMF**, or **Skyrme.**

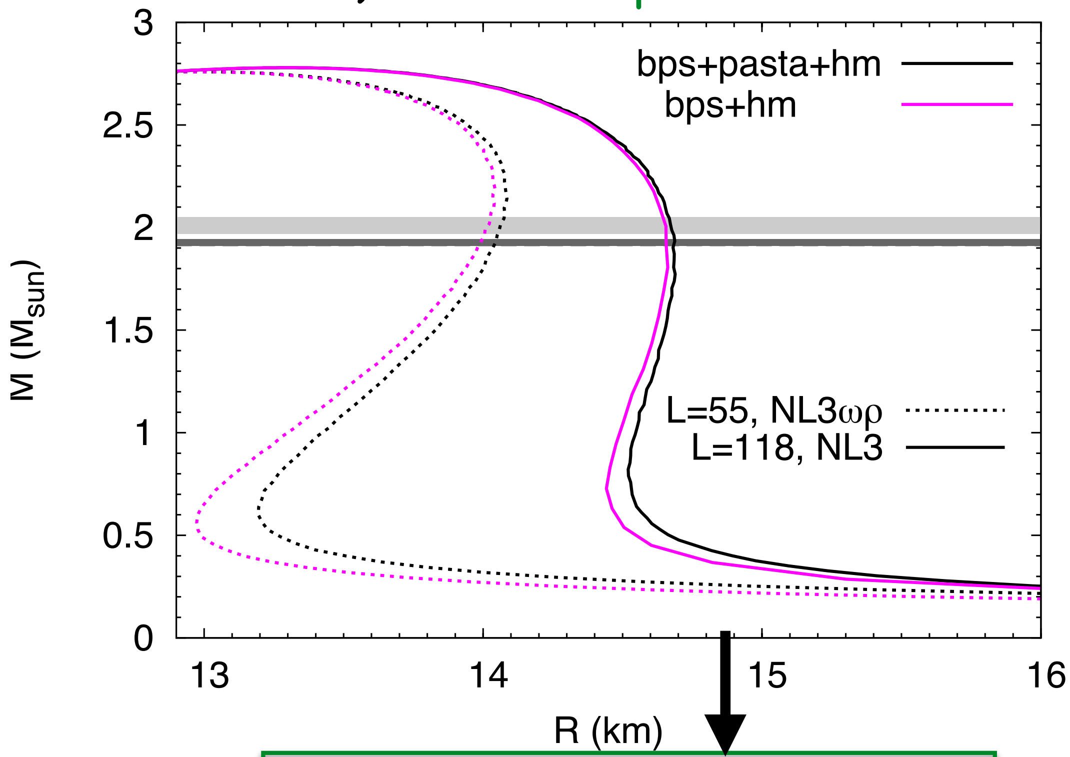
check **CompOSE**:
https://compose.obspm.fr/

Solution: Need Constraints (Experiments, Observations, Microscopic calculations)

Why are these phases important?

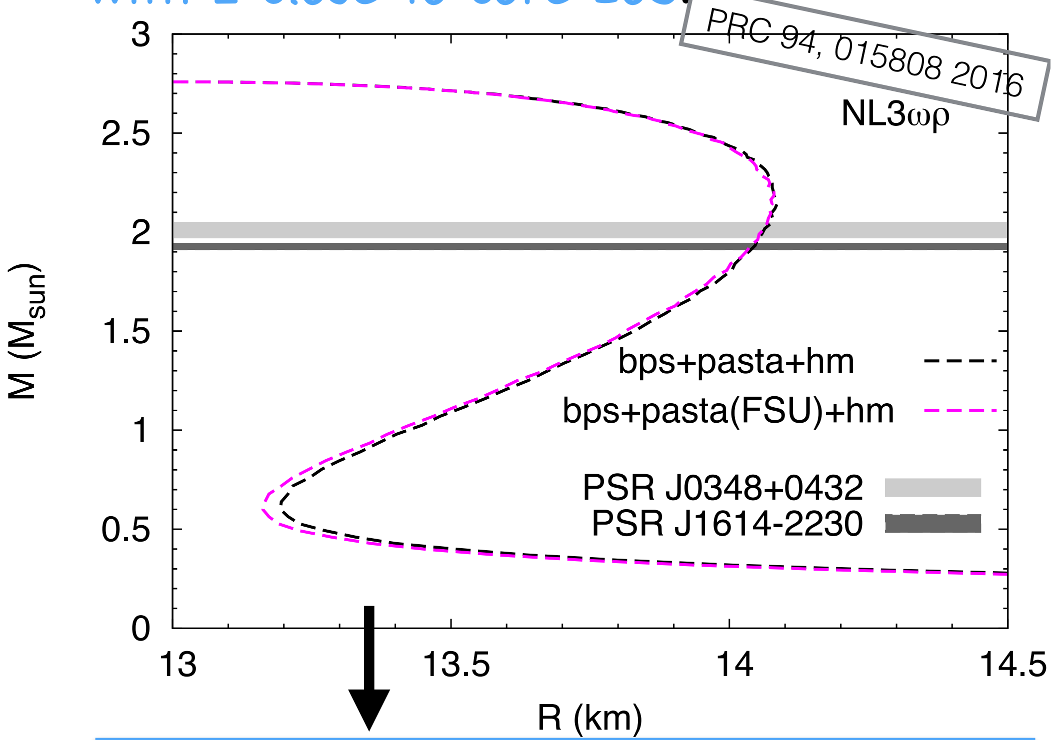
- They are present in the NS inner crust, and they do have an effect in the NS radius, but not in the NS maximum mass:

a) effect of pasta:



No effect on Mmax, but effect on the radius!

b) effect of different inner crust EoS with L close to core EoS:



The error on the determination of the radius is negligible for all masses.

For **1.4M⊙ stars**, the RMF models that passed the **experimental and observational constrains** predict **R=13.6 ± 0.3 km,** with a crust thickness of **ΔR=1.36 ± 0.06km**.

Choosing the EoS(s)

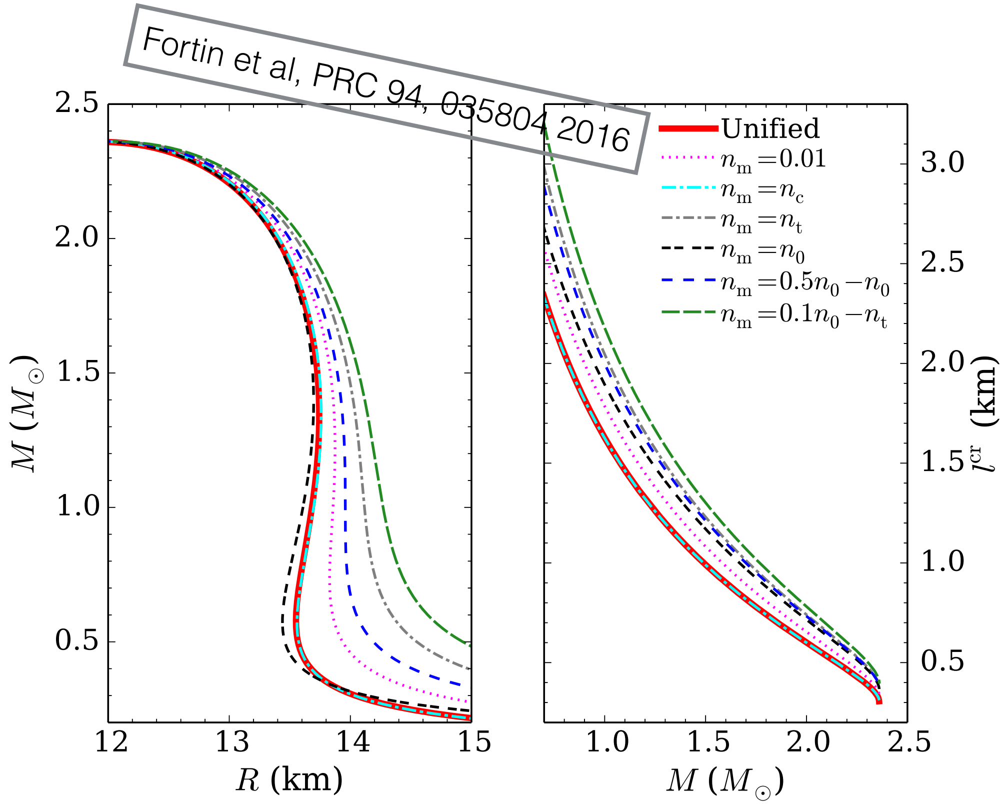
Problem: How to build the EoS for different star regions, Ts?

Solution: Choose 1 EoS for each NS layer:

- Outer crust EoS (BPS, HP, or RHS, …) ⟶ M(R) not affected
- *Inner crust EoS* ⟶ *pasta phases ? unified core EoS ?*
- Core EoS ⟶ homogeneous matter

and then

- Match OC EoS at the neutron drip with IC EoS
- Match IC EoS at *crust-core transition* with Core EoS



Supernova EoS with light clusters

- The SN EoS should incorporate: all relevant clusters, (mean-field) interaction between nucleons and clusters, and a suppression mechanism of clusters at high densities.

- Different methods: nuclear statistical equilibrium, quantum statistical approach, and

- RMF approach: clusters as new degrees of freedom, with effective mass dependent on density.
- In-medium effects: cluster interaction with medium described via the meson couplings, or effective mass shifts, or both
- Constrains are needed to fix the couplings:
  low densities: Virial EoS
  high densities: cluster formation has been measured in HIC

Non-linear Walecka Model

mesons: mediation of nuclear force

$$\mathcal{L} = \sum_{i=p,n} \mathcal{L}_i + \mathcal{L}_e + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\omega\rho}$$

nucleons — $\mathcal{L}_i$; electrons — $\mathcal{L}_e$; mesons — $\mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho$; non-linear mixing coupling — $\mathcal{L}_{\omega\rho}$

$$\mathcal{L}_i = \bar{\psi}_i \left[\gamma_\mu i D^\mu - M^*\right] \psi_i$$

$$\mathcal{L}_e = \bar{\psi}_e \left[\gamma_\mu \left(i\partial^\mu + eA^\mu\right) - m_e\right] \psi_e$$

$$\mathcal{L}_\sigma = \frac{1}{2}\left(\partial_\mu \phi \partial^\mu \phi - m_s^2 \phi^2 - \frac{1}{3}\kappa\phi^3 - \frac{1}{12}\lambda\phi^4\right)$$

$$\mathcal{L}_\omega = -\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu + \frac{1}{4!}\xi g_v^4 (V_\mu V^\mu)^2$$

$$\mathcal{L}_\rho = -\frac{1}{4}\mathbf{B}_{\mu\nu} \cdot \mathbf{B}^{\mu\nu} + \frac{1}{2}m_\rho^2 \boldsymbol{b}_\mu \cdot \boldsymbol{b}^\mu$$

non-linear mixing coupling term:
responsible for density dependence of Esym

$$\mathcal{L}_{\omega\rho} = g_{\omega\rho} g_\rho^2 g_v^2 V_\mu V^\mu \mathbf{b}_\nu \cdot \mathbf{b}^\nu$$

In-medium effects

- Binding energy of each cluster: $B_j = A_j m^* - M_j^*\,, \quad j = d, t, h, \alpha\,,$

with $m^* = m - g_s\phi_0$ the nucleon effective mass and

$$M_j^* = A_j m - g_{sj}\phi_0 - (B_j^0 + \delta B_j)$$ the cluster effective mass.

the scalar cluster-meson coupling

$$g_{sj} = x_{sj} A_j g_s$$

binding energy shift

Pauli blocking effect

In-medium effects - g_{sj} and δB_j

- The Binding energy of each cluster then becomes:

$$B_j = A_j g_s \phi_0 (x_{sj} - 1) + B_j^0 + \delta B_j \,.$$

- x_{sj} can vary from 0 to 1 so for the two extreme cases, we have:

$$B_j = B_j^0 + \delta B_j \,, \text{if}\, x_{sj} = 1 \,,$$
$$B_j = B_j^0 + \delta B_j - A_j g_s \phi_0 \,, \text{if}\, x_{sj} = 0 \,.$$

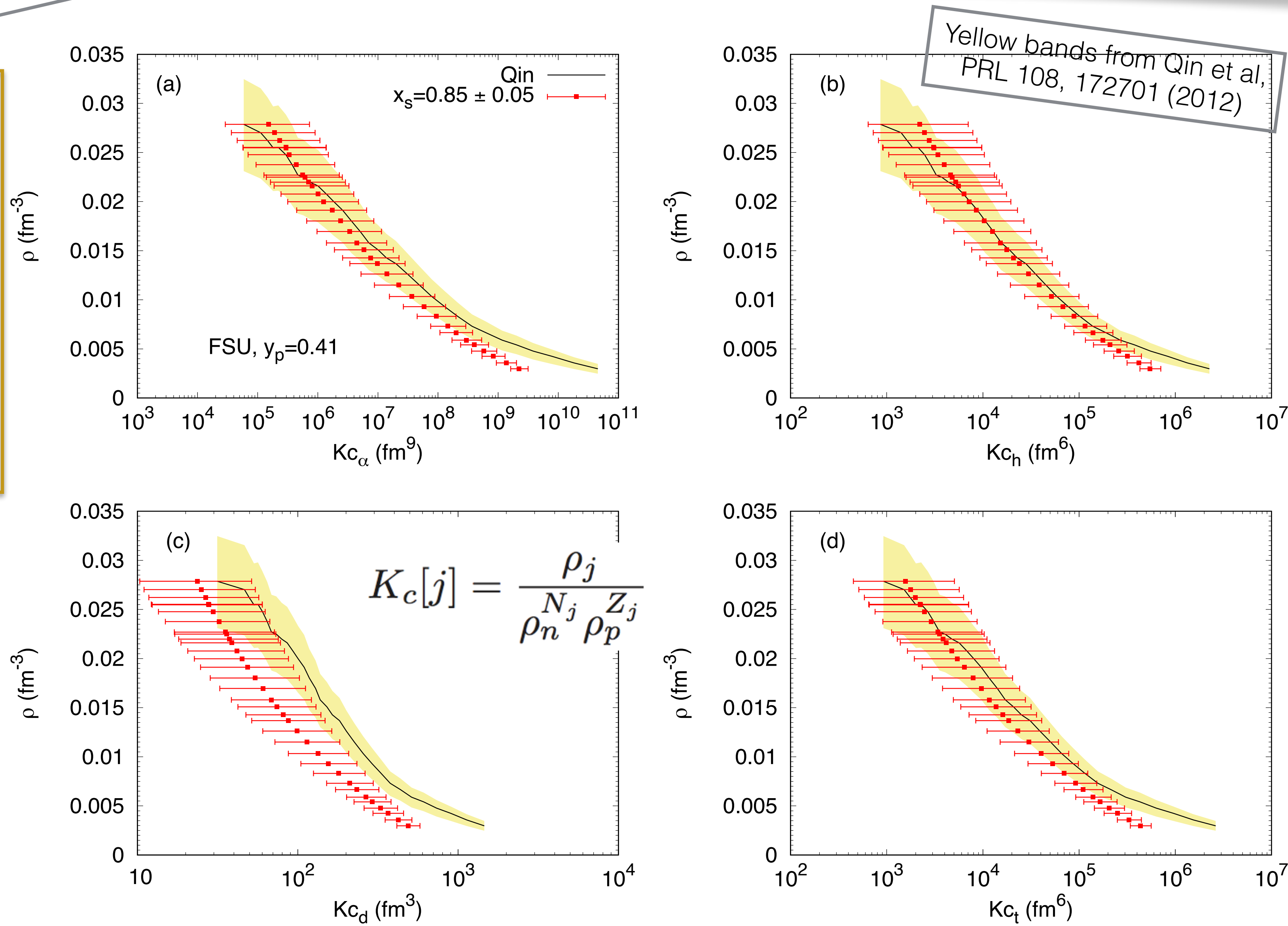
- This implies that a larger x_{sj} corresponds to a larger B_j, and that the cluster dissolution density will occur at larger densities.

x_{sj} needs to be determined from **exp. constraints**

Exp Constraint: Equilibrium constants

PRC 97, 045805 2018

- Yellow bands: exp data from Qin et al
- Red points: RMF model calculated at (T,rho,yp) of exp data with $x_s = 0.85 \pm 0.05$



$$K_c[j] = \frac{\rho_j}{\rho_n^{N_j} \rho_p^{Z_j}}$$

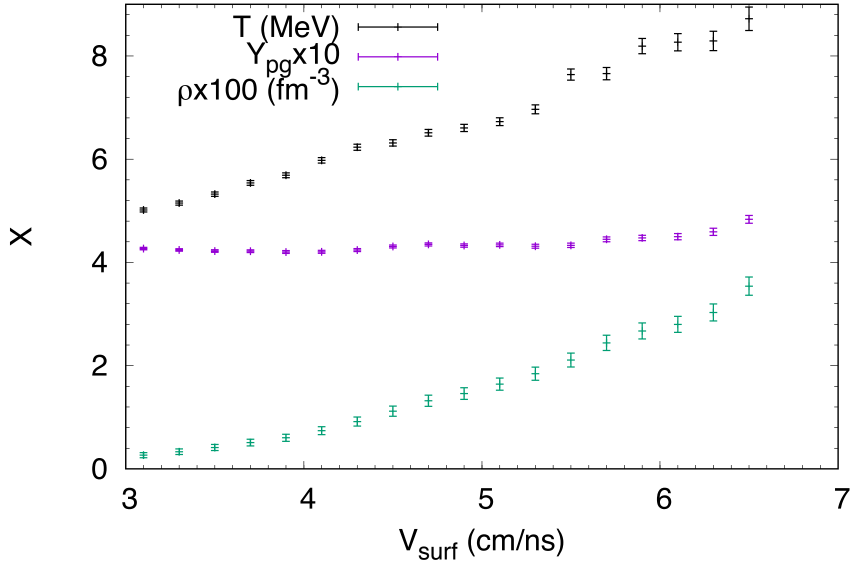
- x_s first fitted to the Virial EoS, model-ind constraint, only depends on exp B and scattering phase shifts. Provides correct zero-density limit for finite-T EoS.

- Our theoretical model describes quite well experimental data, except for deuteron

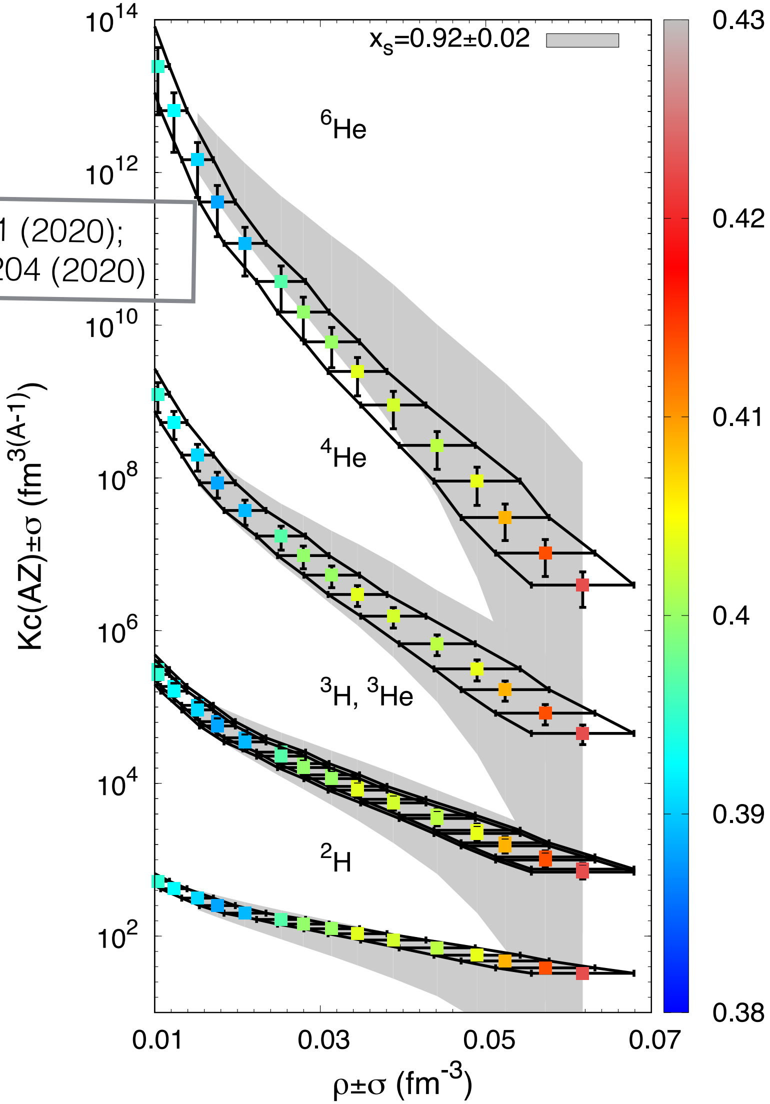
Equilibrium constants and data from INDRA

R. Bougault et al, for the INDRA collab, J. Phys. G 47, 025103 (2020)

- Experimental data includes 4He, 3He, 3H, 2H, and 6He.
- 3 experimental systems: 136Xe+124Sn, 124Xe+124Sn, and 124Xe+112Sn at 32MeV/nucleon.



PRL 125, 012701 (2020); J.Phys.G 47, 105204 (2020)

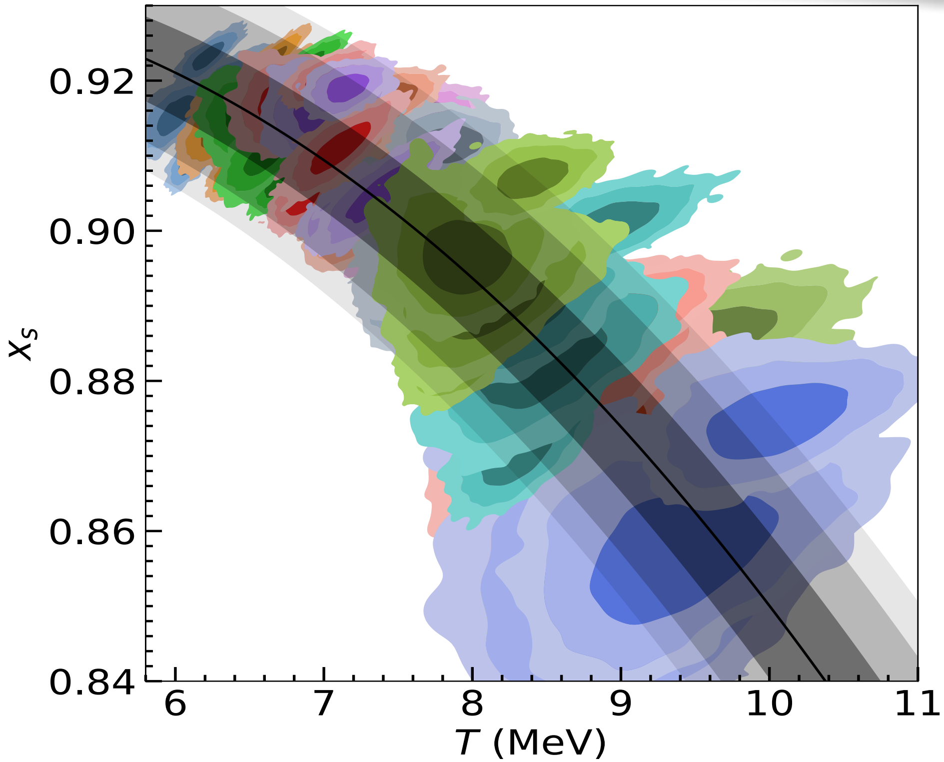


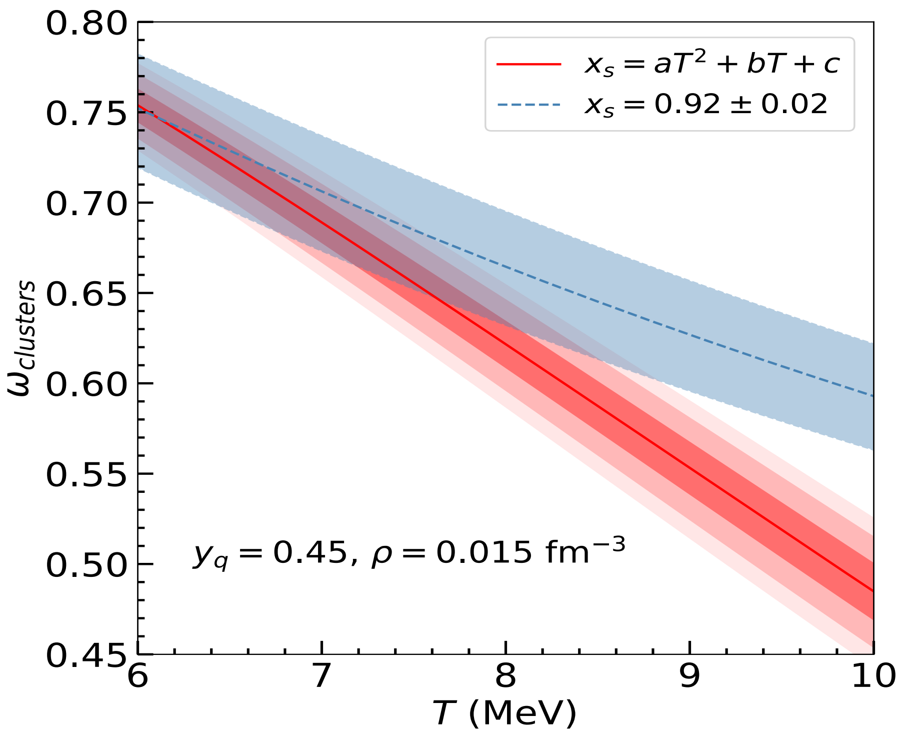
- In an analysis where we considered in-medium effects:
- We obtain a higher x_s as compared to the previous fit of Qin et al data:
- The higher the x_s, the bigger the binding energies (and the smaller effect of the medium), and the higher the dissolution densities of the clusters.

Analysing mass fractions from INDRA data

T. Custódio et al, arXiv: 2407.02307

- More recently, a new analysis has been performed, without any a-priori assumptions on T and n_B, and considering data from 4 colliding systems.
- We obtained a x_s dependent on the temperature.





- This smaller x_s that is obtained with increasing T means less bound clusters, resulting in cluster dissolution at lower temperatures.

Inclusion of 4n

Duer et al, Nature 606, 678 (2022)

- Experiment at RIKEN with SAMURAI detector, using high-energy beam of 8He on p target:

- Duer et al reported production of a resonant state of four neutrons with energy: $E_{4n} = 2.37 \pm 0.38(\text{stat}) \pm 0.44(\text{sys})\,\text{MeV}$ and width of

$$\Gamma = 1.75 \pm 0.22(\text{stat}) \pm 0.30(\text{sys})\,\text{MeV}$$

- Considerably higher value in E (and lower width) than previous result, Kisamori et al. 2016.

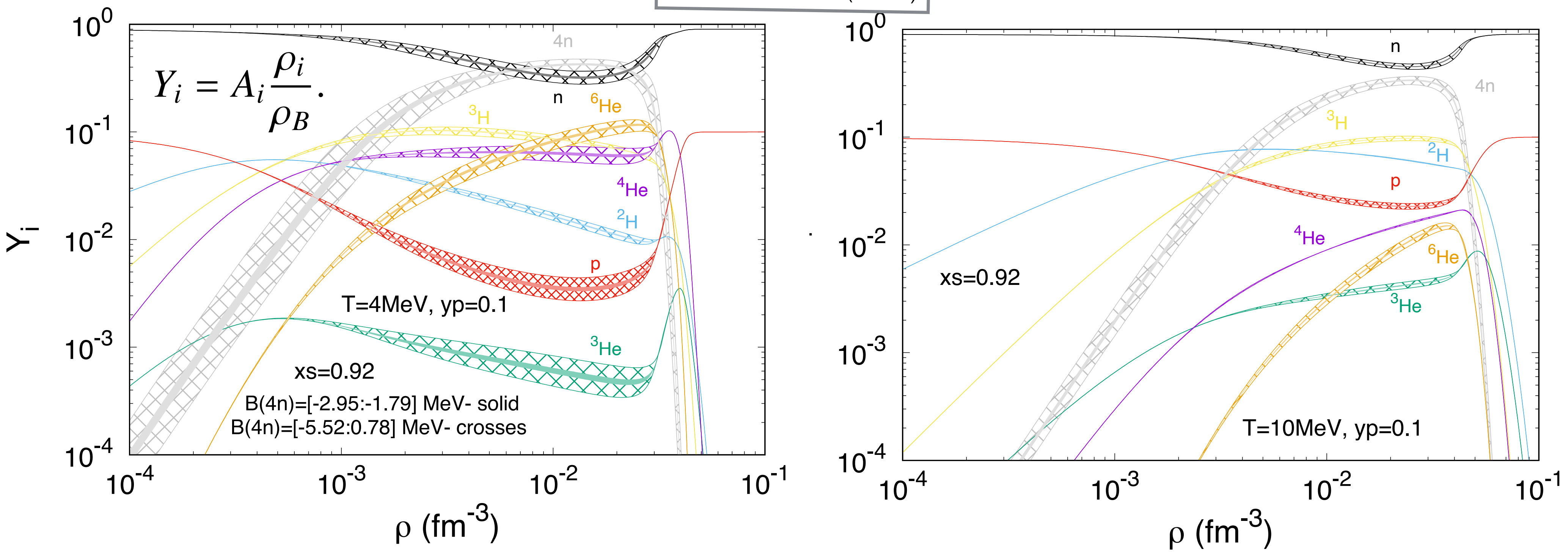
- Here, we consider 4n energy given by two bands:

$$B^0_{4n} = -2.37 \pm \sqrt{0.38^2 + 0.44^2} = [-2.95 : -1.79],$$

$$B^0_{4n} = -2.37 \pm 1.8\Gamma = [-5.52 : 0.78],$$

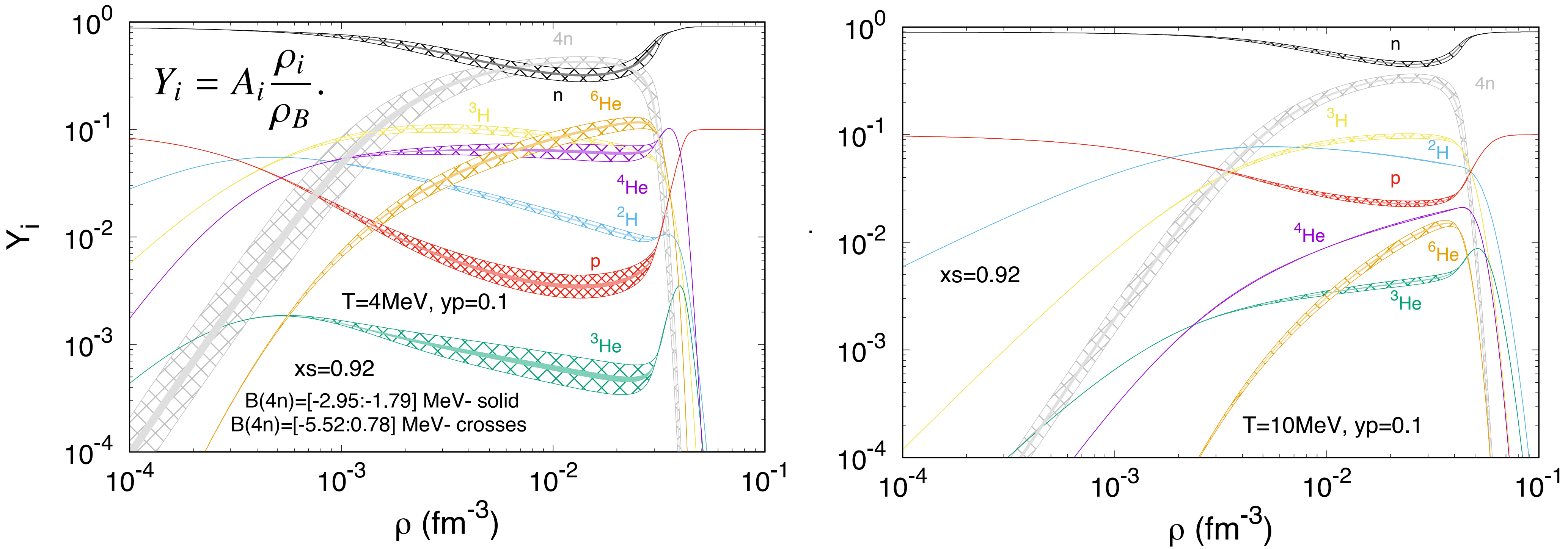
Inclusion of 4n - effect of binding energy

A&A 679, A113 (2023)



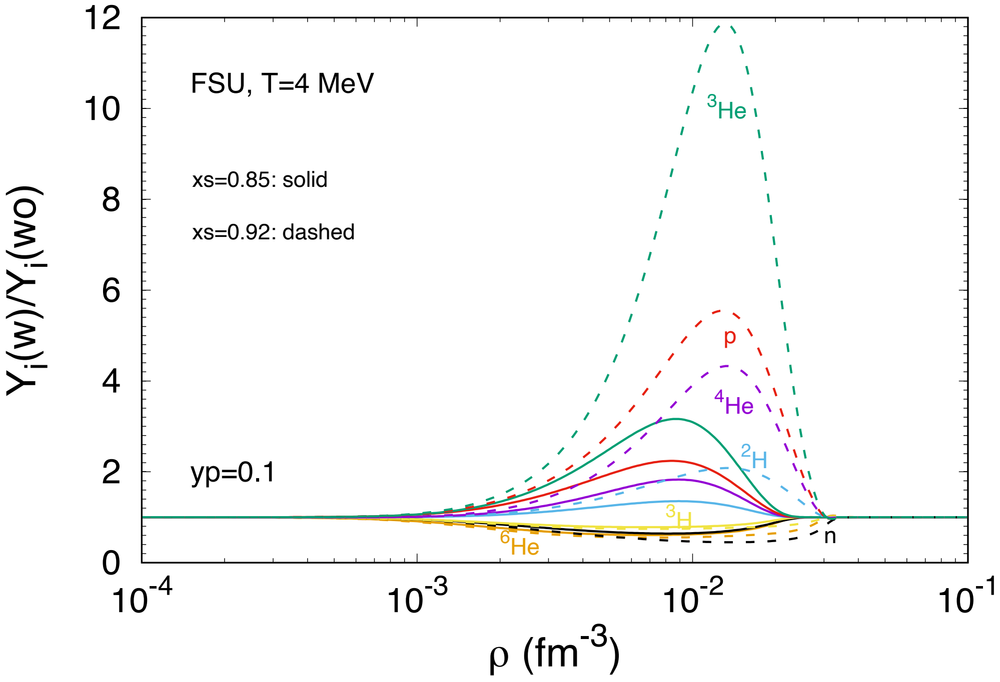
- The crossed bands give slightly wider regions but the same overall behaviour is obtained as for the solid bands.
- The difference in the abundances of the other clusters with respect to B(4n) is not significant.
- This difference is only non-negligible at the maximum of Y(4n).

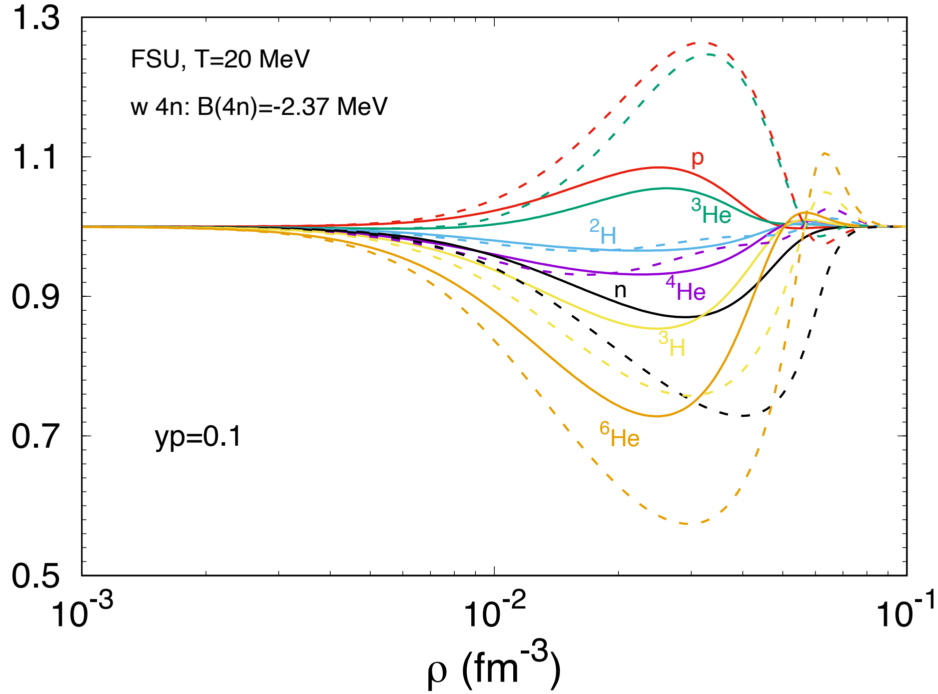
Inclusion of 4n - effect of temperature



- The Y(4n) is the largest among the clusters;
- The largest the temperature, the smaller the effect of the binding energy:
- At T=4 MeV, 6He and 4He have larger abundances as the B plays a bigger role.
- At T=10 MeV, it is the neutron content and the magnitude of the mass that define the abundances: at 0.02 fm-3, 4n are still the most abundant due to n content; then we have 3H (next cluster in mass with largest n content) and 2H (the lightest cluster).

Inclusion of 4n - effect of including 4n on Yi





- All clusters dissolve below 0.1 fm-3;
- The fraction maxima goes from ~0.01 at T=4MeV to ~0.03fm-3 at T=20MeV;
- The p-rich and symmetric clusters increase abundance with 4n; the n-rich decrease as n are being consumed by 4n.
- The higher the T, the weaker this effect is. At T=20MeV, p-rich are not as abundant, and 4He even decreases.
- The scalar cluster-meson coupling gives strong effect! -> Calibrating EoS very important!

Some conclusions

Thank you!

- Our model reproduces both the virial limit and Kc from HIC data (NIMROD and INDRA) with success.
- INDRA data was reanalysed based on a new method, with in-medium effects.
- Fitting our theoretical RMF model to the new data: a larger scalar coupling (more attractive interaction) is obtained than the one found NOT including in-medium effects in the data analysis.
- This implies bigger binding energies => larger melting densities => MORE clusters in CCSN matter!!
- More recently, a weaker attractive interaction at higher T was found and, as a consequence, a dissolution of the clusters at lower T is obtained.
- The effect of 4n is stronger in very n-rich matter and for very low T.
- 4n increases the abundances of free protons and 4He, while decreasing the abundance of free neutrons —> transport properties can be affected.