Light clusters and pasta phases in warm stellar matter

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Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collision, and astrophysics

ECT*, Trento, September 4, 2019

Acknowledgments:

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

POPH
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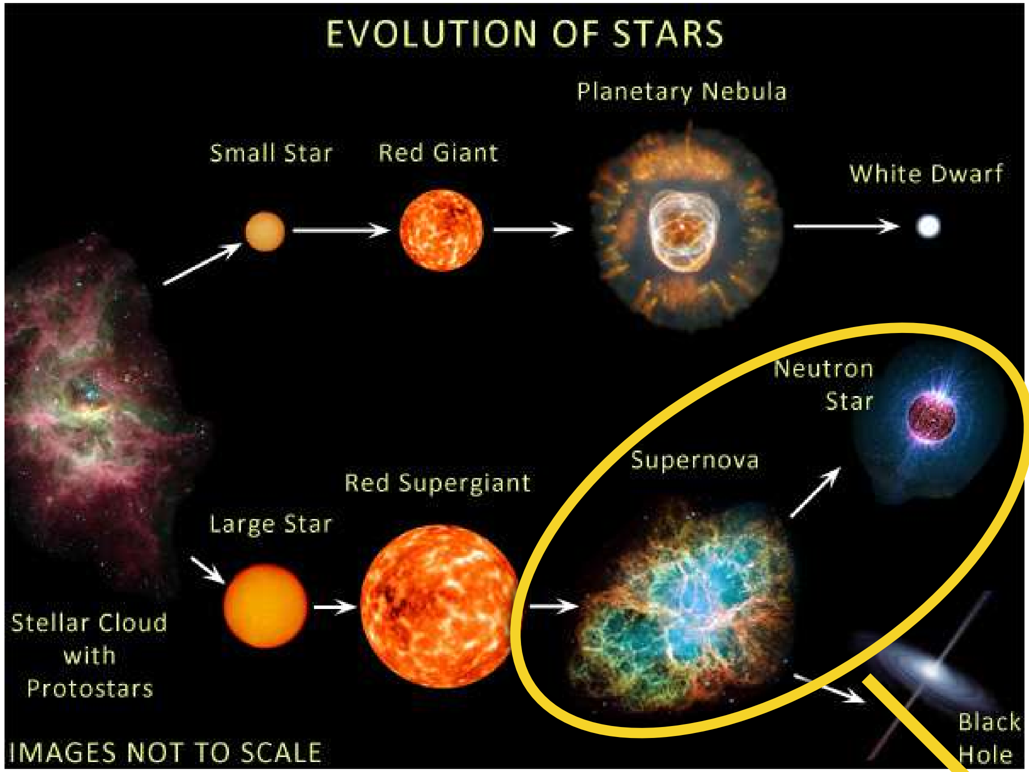
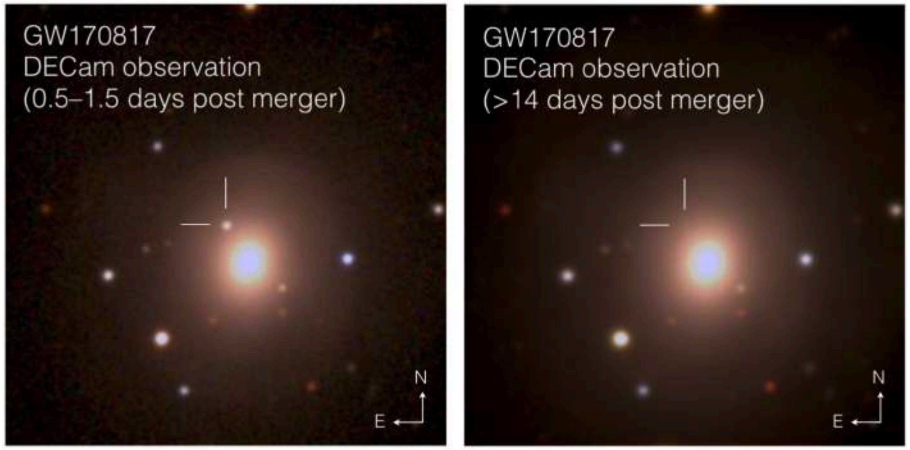
Where do these clusters form?

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 light and heavy clusters are important:
supernovae, NS mergers, (crust of) neutron stars

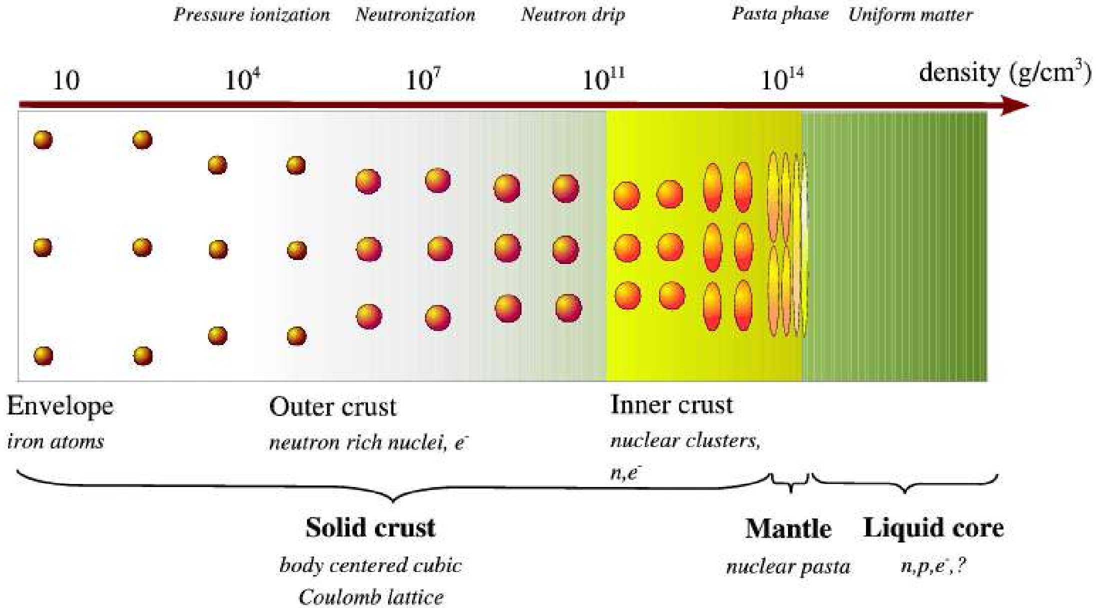
Neutron stars

- Divided in 3 main layers:

1. Outer crust
2. Inner crust
3. Core

- NS: catalized cold stellar matter:

N. Chamel and P. Hansel, Liv. Rev. Rel.11,10, 2008



- Surface: ^{56}Fe, P=0
- Outer crust: Neutron rich nuclei embedded in electron sea
- Inner crust: Above neutron drip density, nucleons form geometrical structures (non-spherical: pasta phases) embedded in neutron and electron background gas.
- Core: Uniform matter, in the centre exotic matter may exist.

How do these clusters affect the star?

- They influence supernova properties: the clusters can modify the neutrino transport, affecting the cooling of the proto-neutron star.
- These clusters may also affect the cooling of binary and accreting systems.

- Magnetars (neutron stars with very strong magnetic fields) may have an inner crust even more complex.

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

electrons

mesons

non-linear mixing coupling

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

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

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

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

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

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

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

Light clusters

- New degrees of freedom of the system.
- Interaction with the medium via the meson couplings.

$$\mathcal{L} = \sum_{j=t,h} \mathcal{L}_j + \mathcal{L}_\alpha + \mathcal{L}_d$$

the vector cluster-meson coupling

$$\boxed{g_{vj} = A_j g_v}$$

with

$$\mathcal{L}_j = \bar{\psi}\left[\gamma_\mu i D_j^\mu - M_j^*\right]\psi, \quad iD_j^\mu = i\partial^\mu - g_{vj}\omega^\mu - \frac{g_\rho}{2}\boldsymbol{\tau}_j \cdot \mathbf{b}^\mu$$

for the fermions tritons and helions,
and for the bosons alphas and deuterons, we have:

$$\mathcal{L}_\alpha = \frac{1}{2}(iD_\alpha^\mu \phi_\alpha)^*(iD_{\mu\alpha}\phi_\alpha) - \frac{1}{2}\phi_\alpha^*\left(M_\alpha^*\right)^2\phi_\alpha,$$

$$\mathcal{L}_d = \frac{1}{4}(iD_d^\mu \phi_d^\nu - iD_d^\nu \phi_d^\mu)^*(iD_{d\mu}\phi_{d\nu} - iD_{d\nu}\phi_{d\mu})$$
$$-\frac{1}{2}\phi_d^{\mu *}\left(M_d^*\right)^2\phi_{d\mu}, \quad iD_j^\mu = i\partial^\mu - g_{vj}\omega^\mu$$

and

$$\boxed{M_j^* = A_j m - g_{sj}\phi_0 - \left(B_j^0 + \delta B_j\right)}$$

with j=t,h,d,4He

In-medium effects - g_{sj}

PRC 97, 045805 2018

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

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

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

the scalar cluster-meson coupling

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

needs to be determined from exp. constraints

In-medium effects - δB_j

PRC 97, 045805 2018

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

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

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

binding energy shift

$$\boxed{\delta B_j = \frac{Z_j}{\rho_0}(\epsilon_p^* - m\rho_p^*) + \frac{N_j}{\rho_0}(\epsilon_n^* - m\rho_n^*)}$$

energetic counterpart of classical ExV mechanism

$$\epsilon_j^* = \frac{1}{\pi^2}\int_0^{p_{F_j}(\mathrm{gas})} p^2 e_j(p)(f_{j+}(p) + f_{j-}(p))dp$$

$$\rho_j^* = \frac{1}{\pi^2}\int_0^{p_{F_j}(\mathrm{gas})} p^2 (f_{j+}(p) + f_{j-}(p))dp\,,$$

the energy states occupied by the gas are excluded: double counting avoided!

associated with the gas lowest energy levels

Supernova EoS with light clusters

- The total baryonic density is defined as:

$$\boxed{\rho = \rho_p + \rho_n + 4\rho_\alpha + 2\rho_d + 3\rho_h + 3\rho_t}$$

- The global proton fraction as

$$\boxed{Y_p = y_p + \frac{1}{2}y_\alpha + \frac{1}{2}y_d + \frac{2}{3}y_h + \frac{1}{3}y_t}$$

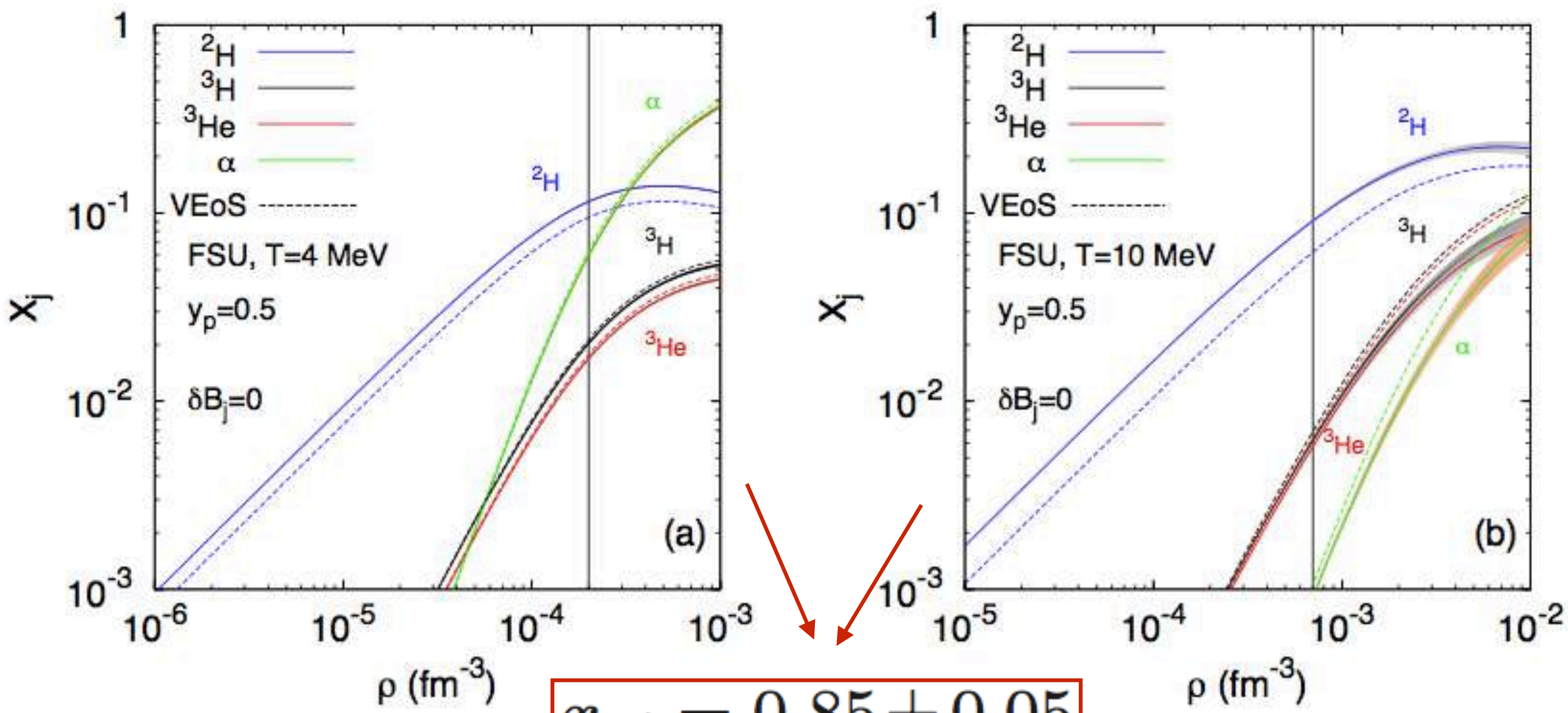
with $y_i = A_i(\rho_i/\rho)$ the mass fraction of cluster i.

- Charge neutrality must be imposed: $\rho_e = Y_p \ \rho$

- The light clusters are in chemical equilibrium, with the chemical potential of each cluster i defined as

$$\boxed{\mu_i = N_i \mu_n + Z_i \mu_p}$$

Determination of x_s: Virial EoS

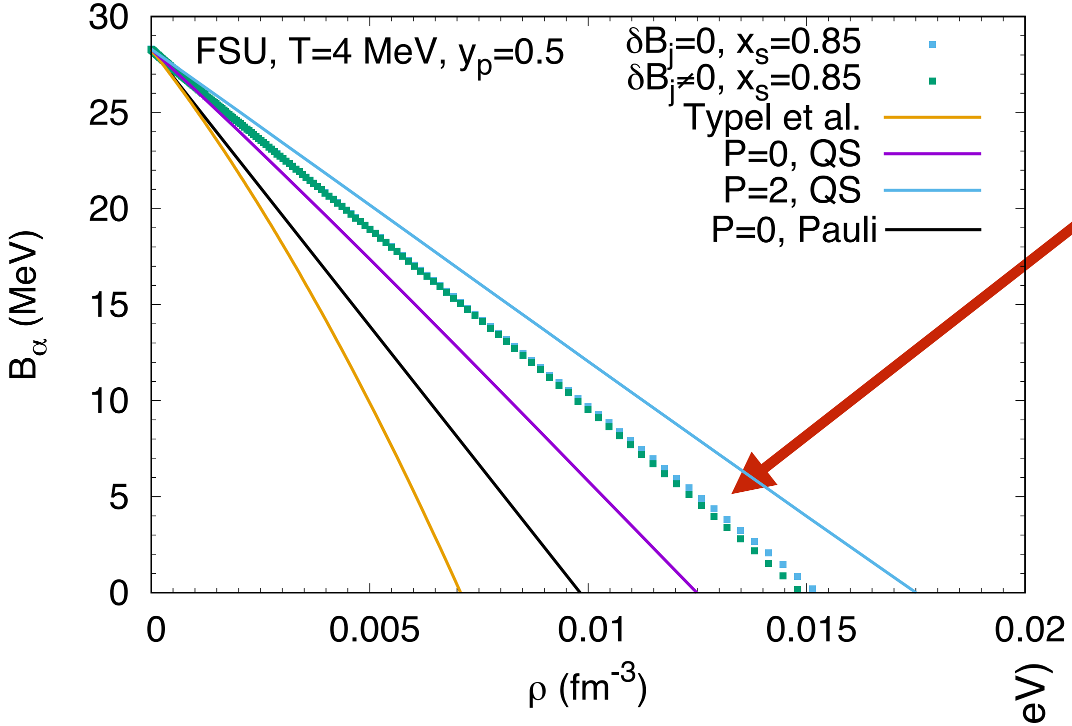


$$\boxed{x_{sj} = 0.85 \pm 0.05}$$

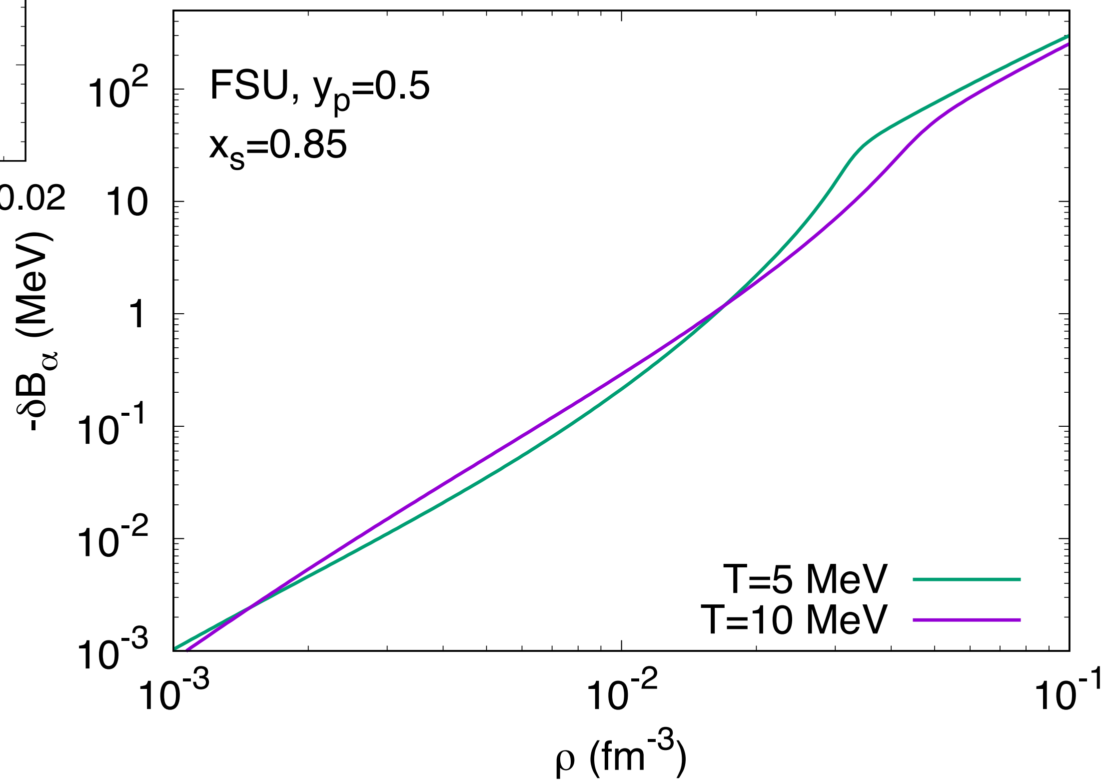
- VEoS: model-independent constraint, only depends on experimentally binding energies and scattering phase shifts.
- Provides correct zero-density limit for finite T EoS.
- Breaks down when interaction with particles becomes stronger:

δB_j takes action!!

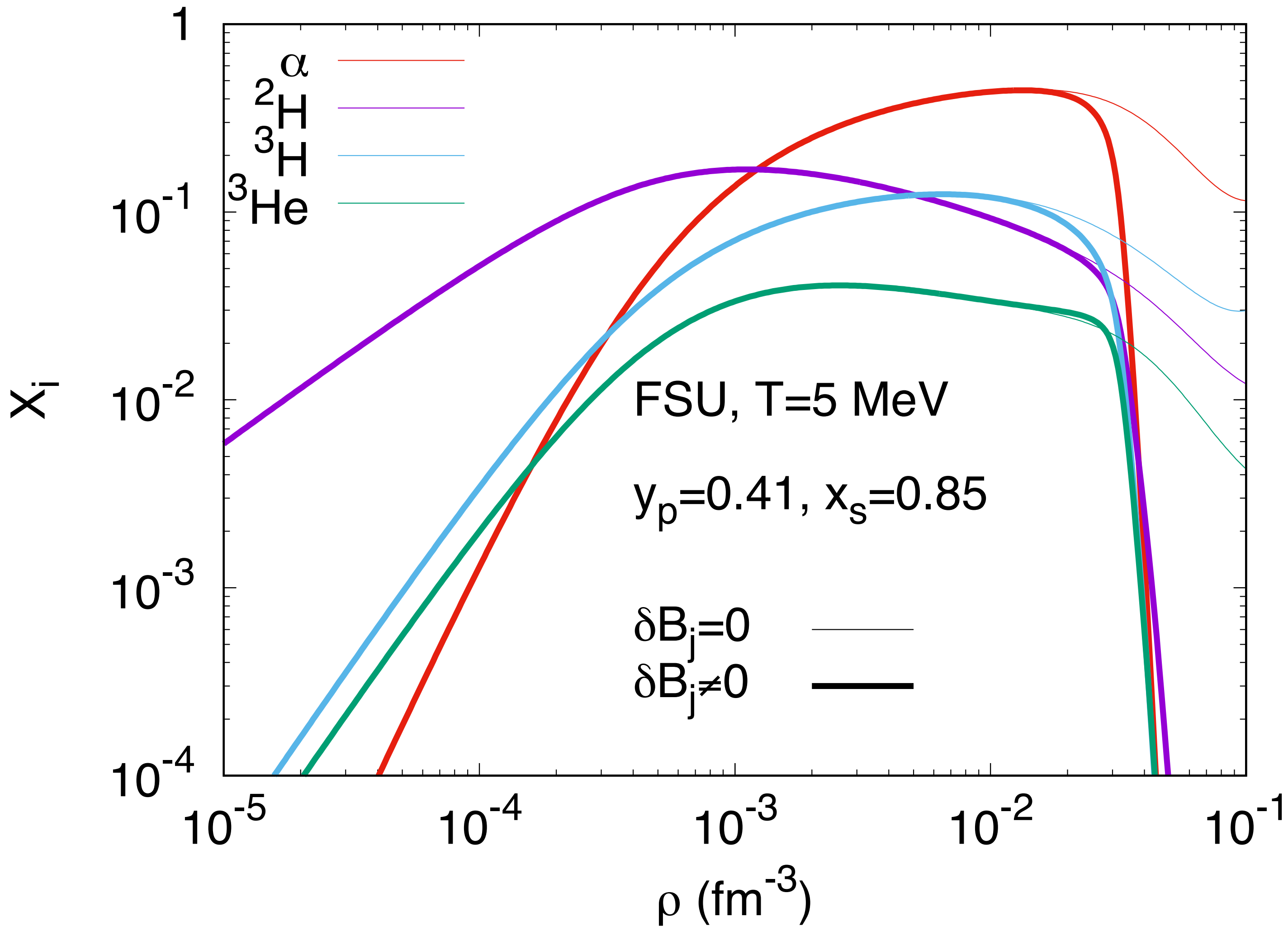
Contribution of δB_j



- δB_j completely negligible in the VEoS range of densities
- but rises fast for larger densities



Cluster fractions - effect of δB_j



δB_j important for dissolution of clusters!

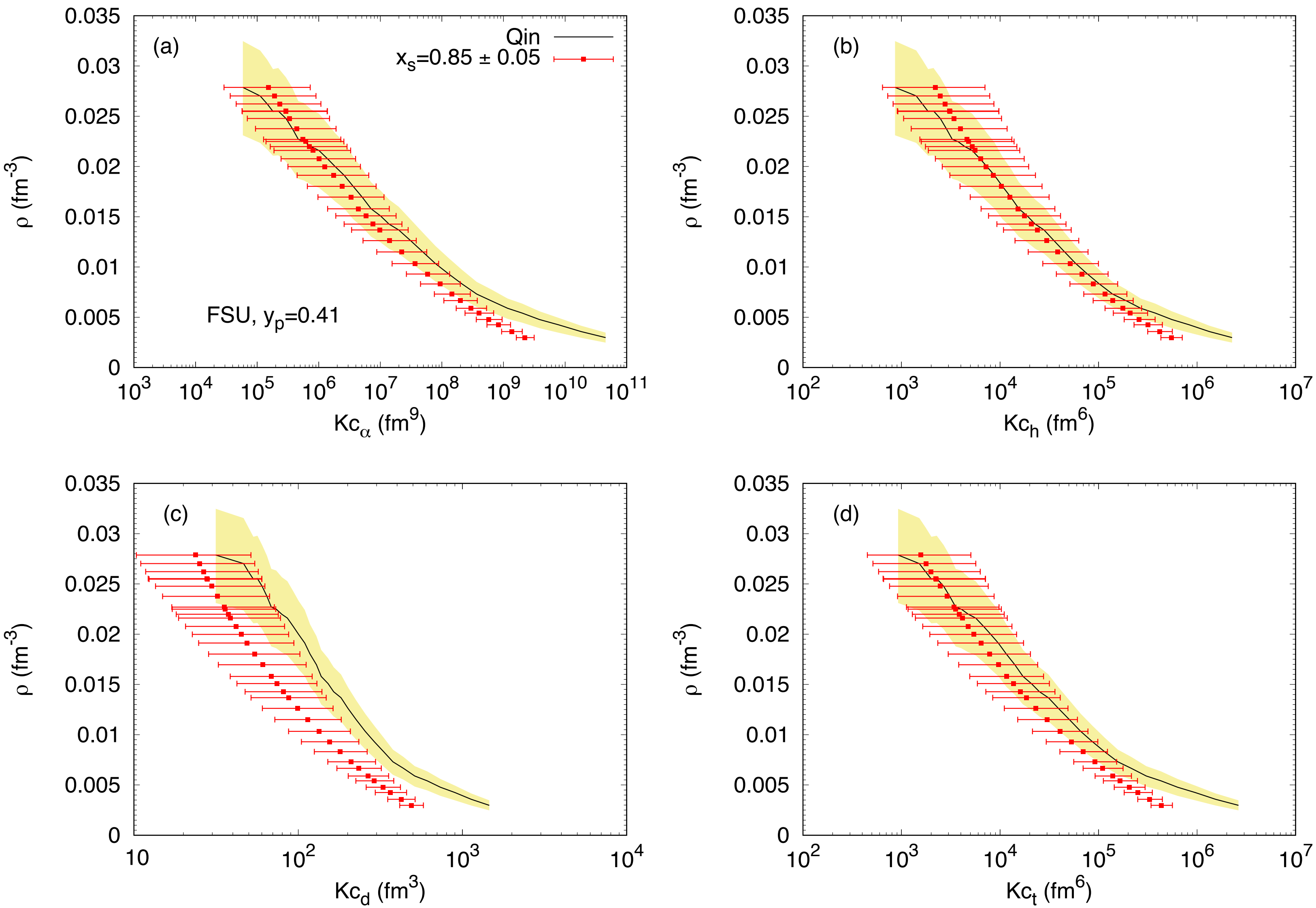
Equilibrium constants

Qin et al, PRL 108, 172701 2012

- Kc calculated with data from HIC:

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

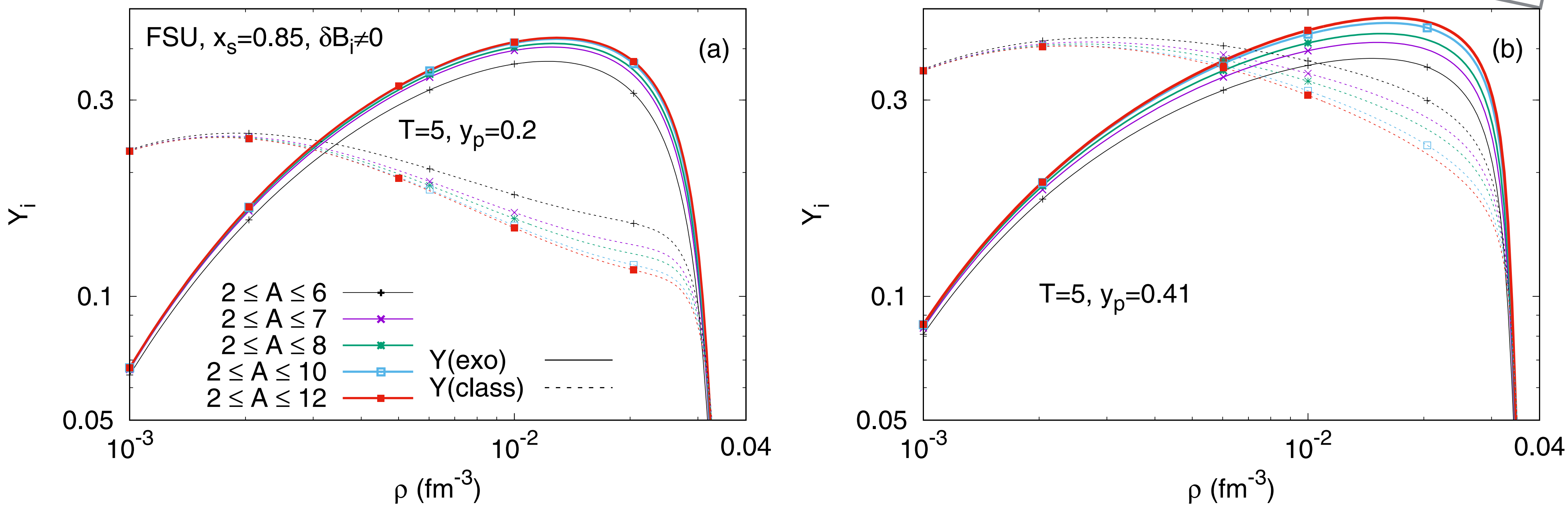
- Unique existing constraint on in-medium modifications of light clusters at finite T



- Our model describes quite well experimental data!

Light clusters: classical + exotic

PRC 99, 055806 2019



$$Y_{\text{light}} = \sum_{i=2}^{A_{\max}} Y_i$$

$$Y_{\text{class}} = Y_d + Y_t + Y_h + Y_\alpha .$$

$$Y_{\text{exo}} = Y_{\text{light}} - Y_{\text{class}}$$

- The largest contribution of the exotic clusters occurs at the maximum of the distribution of the clusters.

Decays and effective densities

PRC 99, 055806 2019

- Decay modes:

$$^{5}\mathrm{He} \longrightarrow {}^{4}\mathrm{He} + \mathrm{n}$$
$$^{4}\mathrm{H} \longrightarrow {}^{3}\mathrm{H} + \mathrm{n}$$
$$^{7}\mathrm{He} \longrightarrow {}^{6}\mathrm{Li} + \mathrm{n}$$
$$^{6}\mathrm{H} \longrightarrow {}^{3}\mathrm{H} + 3\mathrm{n}$$
$$^{5}\mathrm{H} \longrightarrow {}^{3}\mathrm{H} + 2\mathrm{n}$$
$$^{5}\mathrm{Li} \longrightarrow {}^{4}\mathrm{He} + \mathrm{p}$$
$$^{8}\mathrm{Be} \longrightarrow 2({}^{4}\mathrm{He})$$
$$^{7}\mathrm{Be} \longrightarrow {}^{7}\mathrm{Li}$$
$$^{9}\mathrm{He} \longrightarrow 2({}^{4}\mathrm{He}) + \mathrm{n}$$
$$^{7}\mathrm{H} \longrightarrow {}^{3}\mathrm{H} + 4\mathrm{n}$$

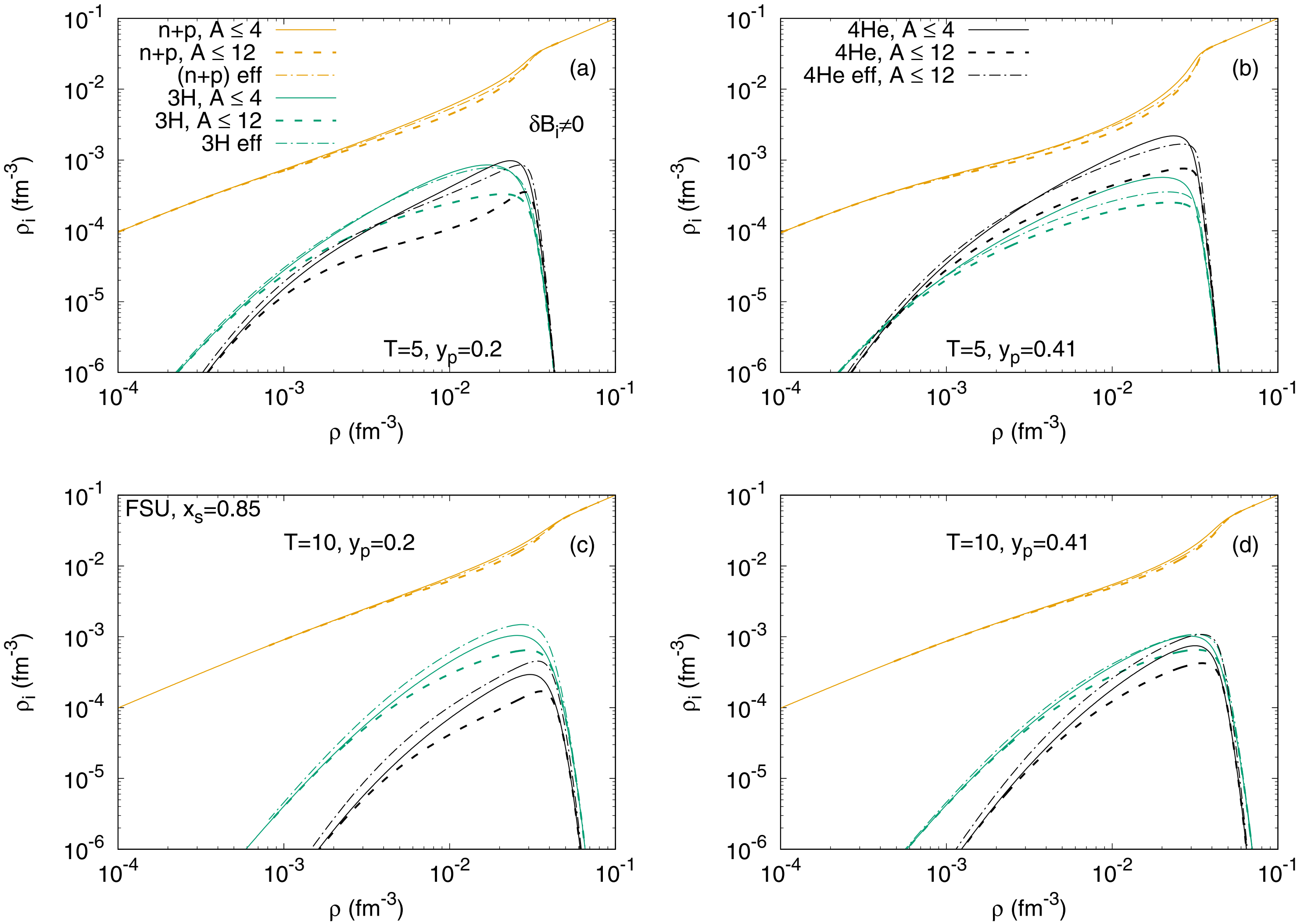
- Effective densities:

$$\begin{aligned}
\widetilde{\rho}_{^4\mathrm{He}} &= \rho_{^4\mathrm{He}} + \rho_{^5\mathrm{He}} + \rho_{^5\mathrm{Li}} + 2\rho_{^8\mathrm{Be}} + 2\rho_{^9\mathrm{He}} \\
\widetilde{\rho}_{^3\mathrm{H}} &= \rho_{^3\mathrm{H}} + \rho_{^4\mathrm{H}} + \rho_{^5\mathrm{H}} + \rho_{^6\mathrm{H}} + \rho_{^7\mathrm{H}} \\
\widetilde{\rho}_{^6\mathrm{Li}} &= \rho_{^6\mathrm{Li}} + \rho_{^7\mathrm{He}} \\
\widetilde{\rho}_{^7\mathrm{Li}} &= \rho_{^7\mathrm{Li}} + \rho_{^7\mathrm{Be}} \\
\widetilde{\rho}_{\mathrm{n}} &= \rho_{\mathrm{n}} + \rho_{^5\mathrm{He}} + \rho_{^4\mathrm{H}} + \rho_{^7\mathrm{He}} + 3\rho_{^6\mathrm{H}} \\
&\quad + 2\rho_{^5\mathrm{H}} + \rho_{^9\mathrm{He}} + 4\rho_{^7\mathrm{H}} \\
\widetilde{\rho}_{\mathrm{p}} &= \rho_{\mathrm{p}} + \rho_{^5\mathrm{Li}}
\end{aligned}$$

Decays and effective densities

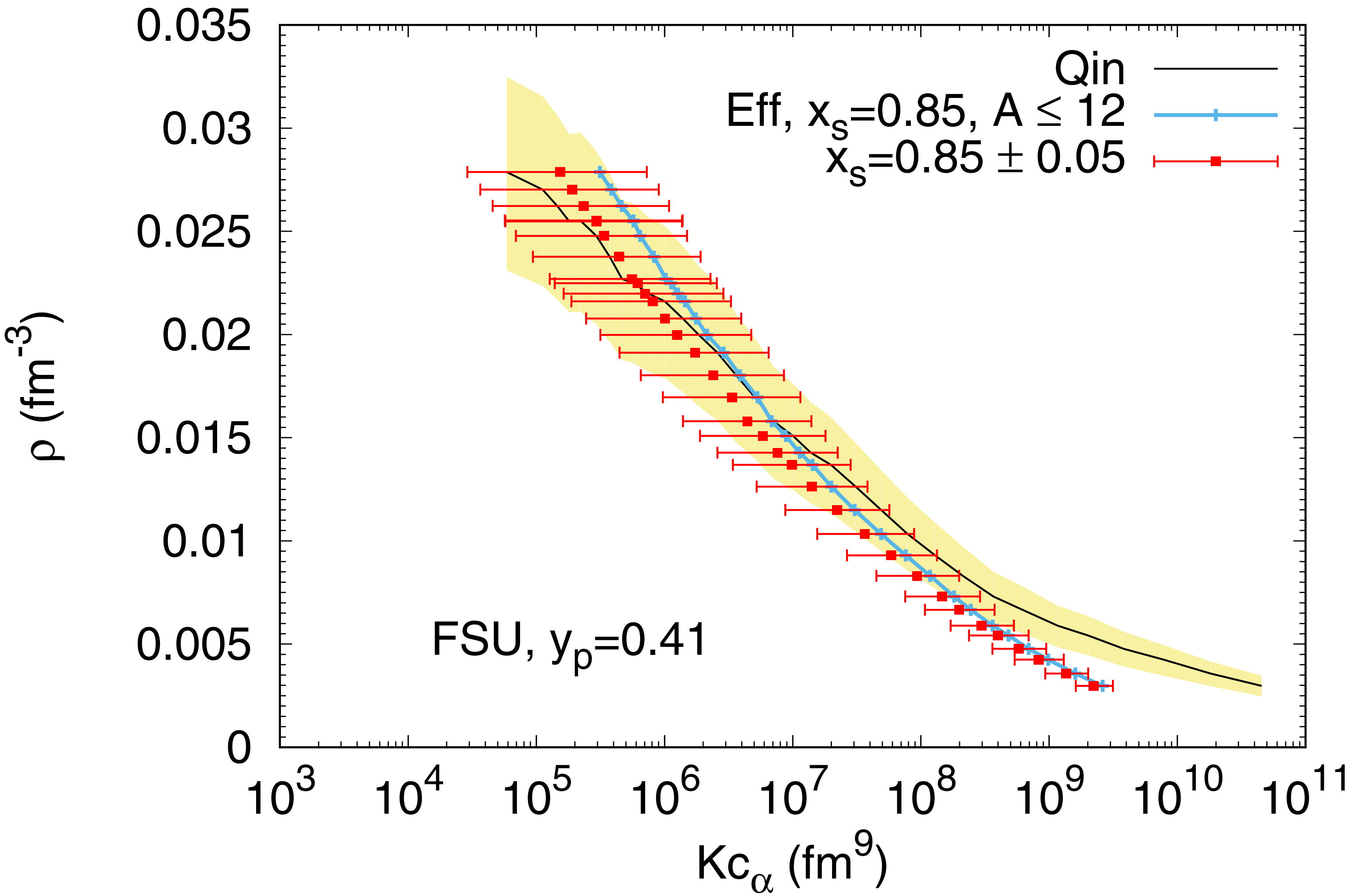
PRC 99, 055806 2019

- Exotic clusters are non-negligible at intermediate densities.
- For low T, at the peak of the distribution: the mass fractions without exotic are more abundant.
- For high T, the opposite happens: there is an increase of the effective.



Equilibrium constants with exotic clusters

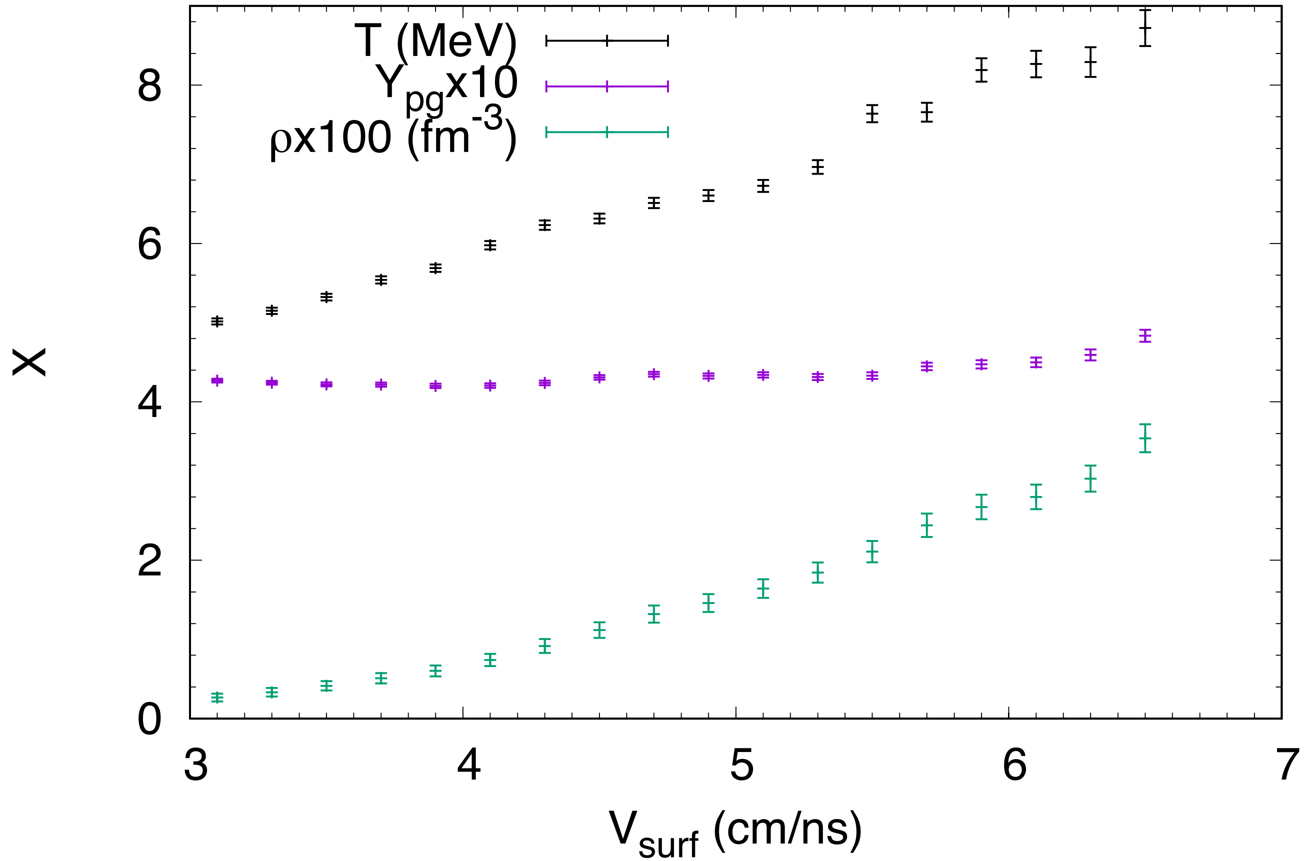
$$K_c[j] = \frac{\rho_j}{\rho_n^{N_j} \rho_p^{Z_j}}$$



- Contribution of exotic clusters are non-negligible at higher densities.

Experimental chemical equilibrium constants with INDRA data

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



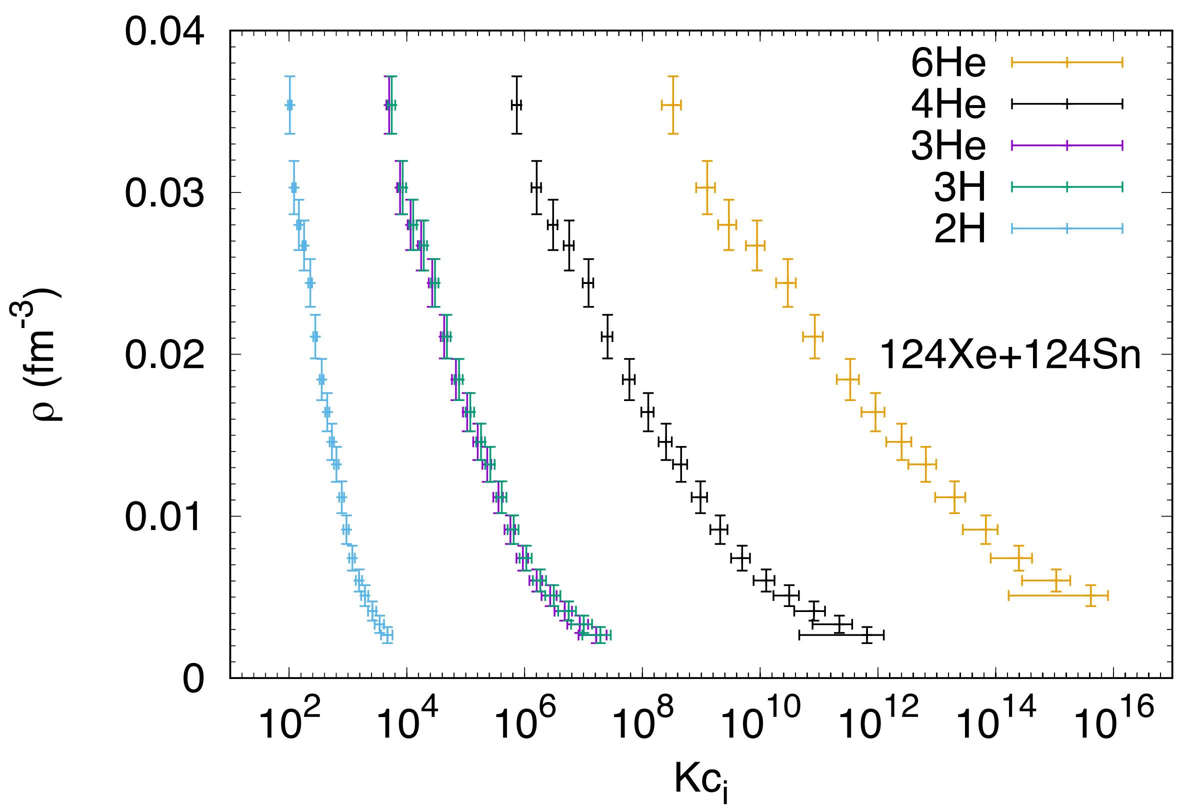
R. Bougault et al, for the INDRA collab, submitted to J. Phys. G (2019)

- Vsurf is the velocity of the emitted particles at the nuclear surface, so fastest particles correspond to earliest emission times.

- The temperature, proton fraction and density as a function of Vsurf, for the intermediate mass system.

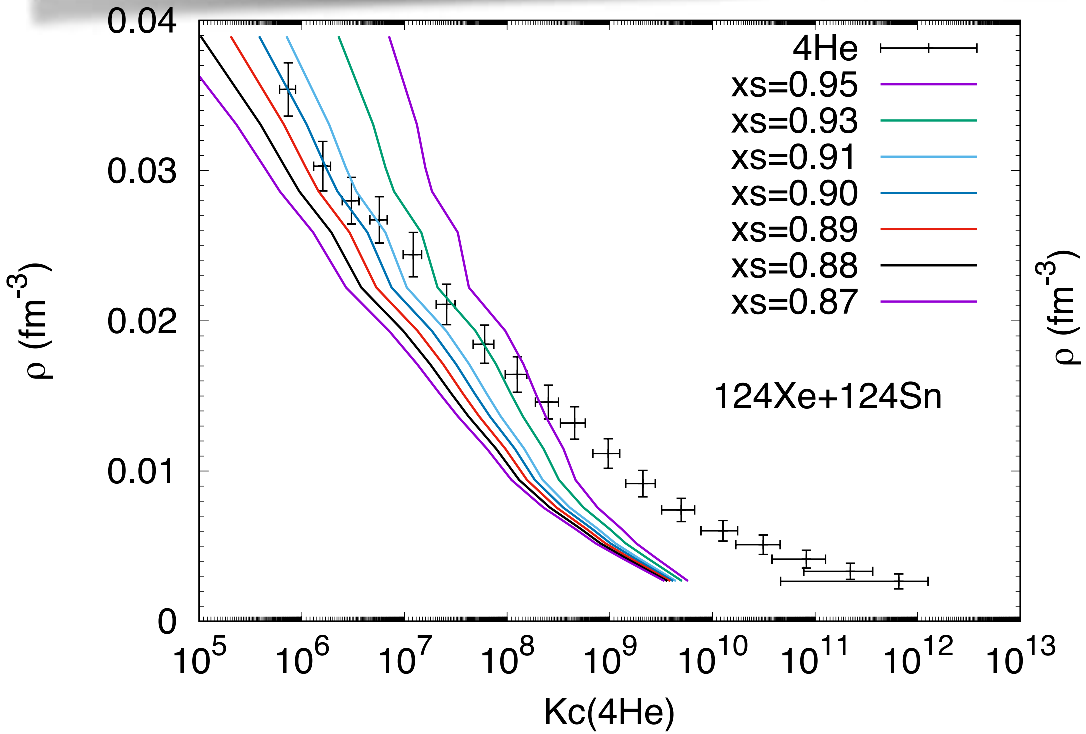
Experimental chemical equilibrium constants with INDRA data

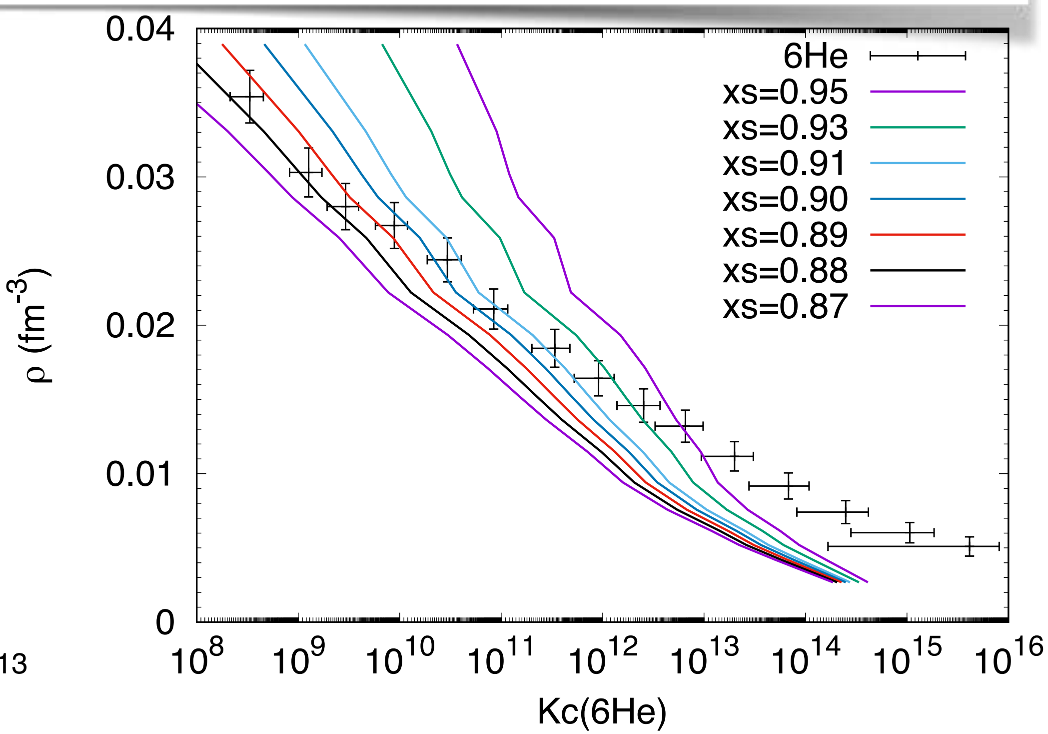
R. Bougault et al, for the INDRA collab, submitted to J. Phys. G (2019)



- Here the chemical equilibrium constants are for the intermediate-mass system, 124Xe+124Sn.

Experimental chemical equilibrium constants with INDRA data



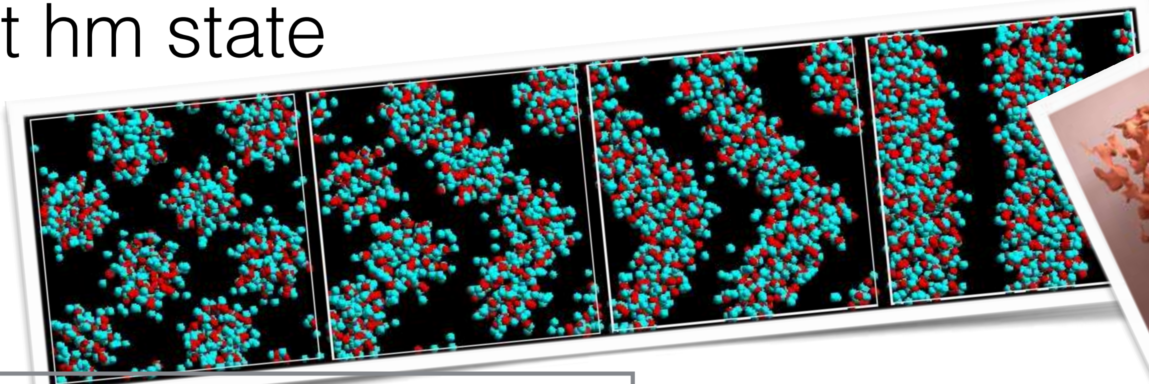


- When we apply our model we need a higher x_s to fit this data, 0.88 (6He)-0.91 (4He), as compared to Qin data, that prefers 0.85.
- The low-density region is very underestimated, and the high-density region is well reproduced.
- The Qin fit is slightly better, but qualitatively it is the same.
  - More work is needed to understand this behaviour.

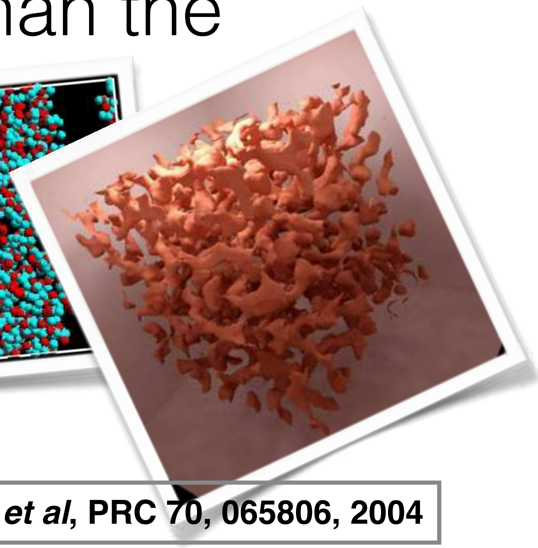
The pasta phases

- Competition between Coulomb and nuclear forces leads to frustrated system
- Geometrical structures, the **pasta phases**, evolve with density until they melt $\longrightarrow$ **crust-core transition**
- Criterium: pasta free energy must be lower than the correspondent hm state

QMD calculations:

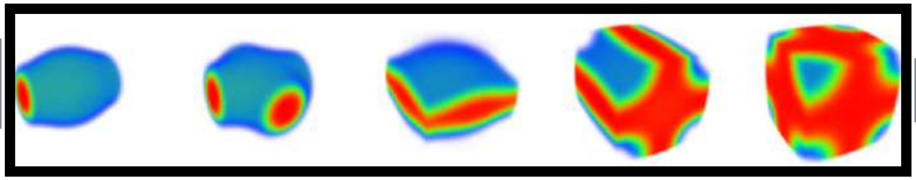


G. Watanabe *et al*, PRL 103, 121101, 2009



C. J. Horowitz *et al*, PRC 70, 065806, 2004

3D-SHF calculation:

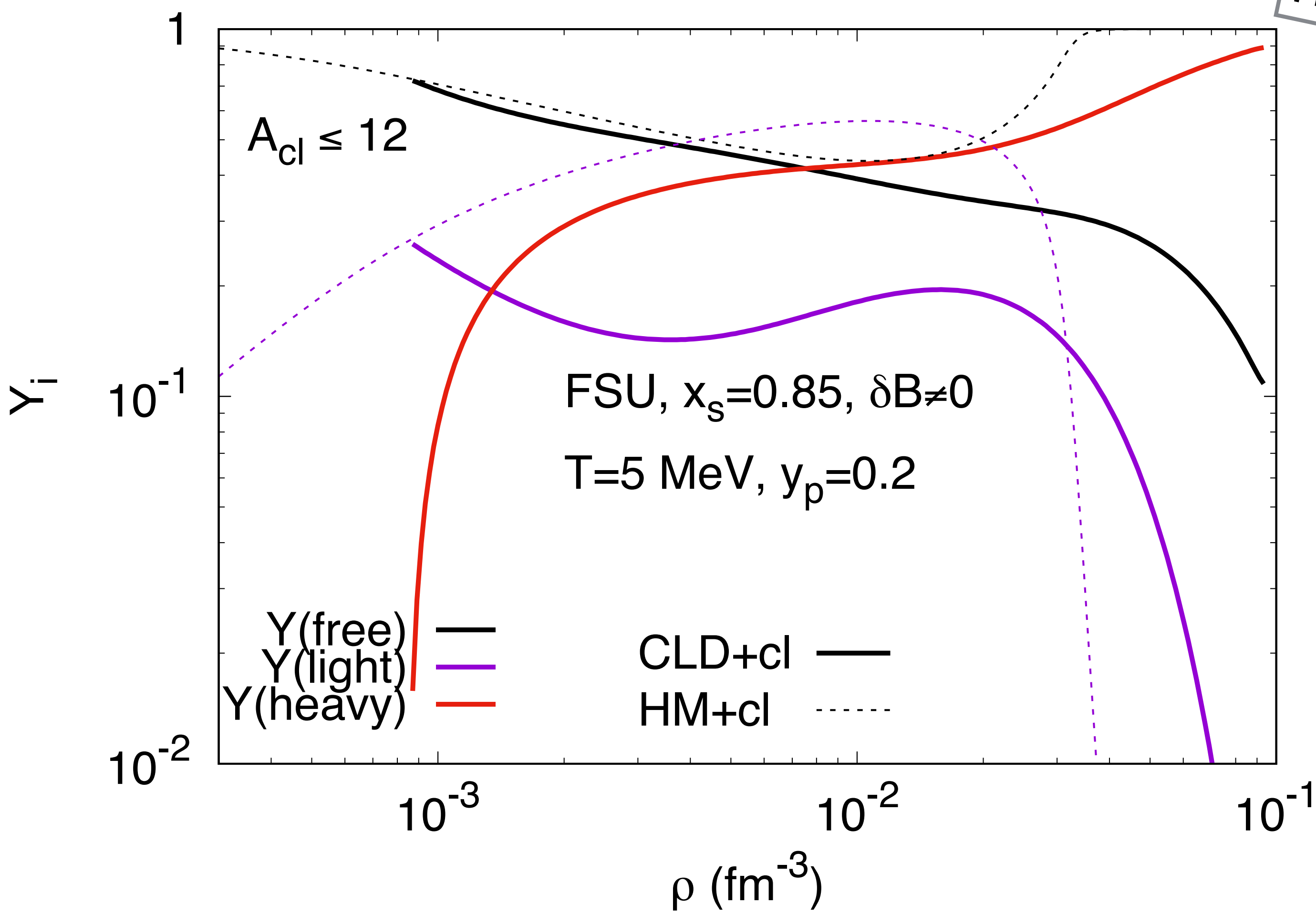


Pais and Stone, PRL 109, 151101, 2012

Cluster fractions - CLD vs HM

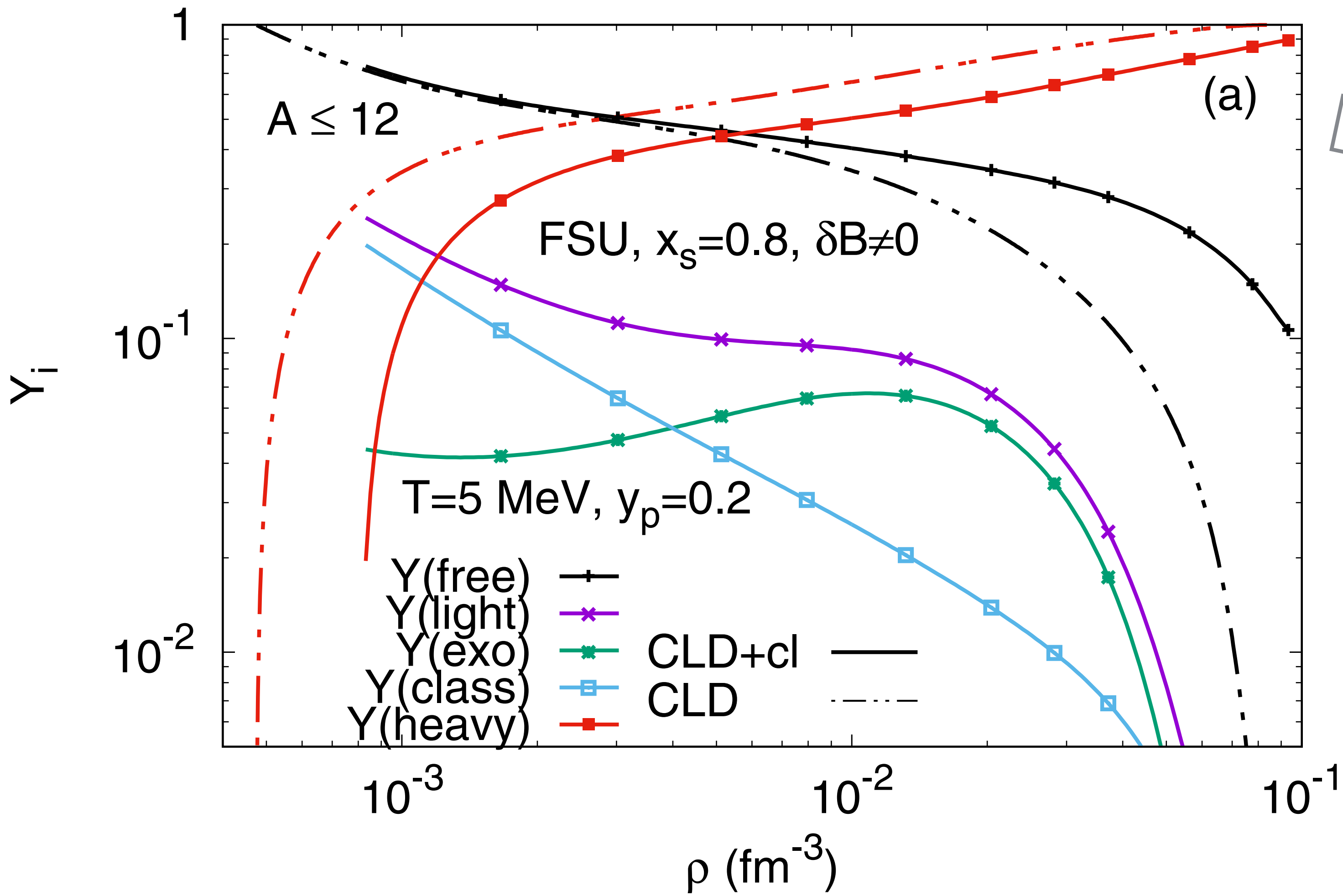
- Heavy cluster with light clusters (CLD+cl) **VS.** homogeneous matter with light clusters (HM+cl).
- Light clusters with $A \leq 12$.

PRC 99, 055806 2019



- The heavy cluster (CLD+cl) calculation: light clusters less abundant but increase their melting density.
- Increasing T: the onset of both heavy and light clusters moves to larger densities.

Pasta versus Cluster fractions with pastas



PRC 99, 055806 2019

The inclusion of light clusters

- moves the onset of the heavy cluster to larger densities
- reduces the mass fraction of the heavy cluster
- increases the fraction of free nucleons in the background

Summary

Thank you!

- A simple parametrisation of in-medium effects acting on light clusters is proposed in a RMF framework.
- Interactions of clusters with medium described by modification of sigma-meson coupling constant.
- Clusters dissolution obtained by the density-dependent extra term on the binding energy.
- $x_{sj} = 0.85 \pm 0.05$ reproduces both virial limit and Kc from Texas HIC data.
- Exotic clusters (4<A<12) have effects on the clusters abundances and equilibrium constants.
- Light clusters and pasta structures are relevant and should be explicitly included in EoS for CCSN simulations and NS mergers.
- The two data sets, Texas and INDRA, are compatible, but one prefers a lower x_s than the other. More work is needed to understand this behaviour.