Light and heavy clusters in warm stellar matter

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

POPH
QUALIFICAR É CRESCER.

QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

GOVERNO DA REPÚBLICA PORTUGUESA

UNIÃO EUROPEIA
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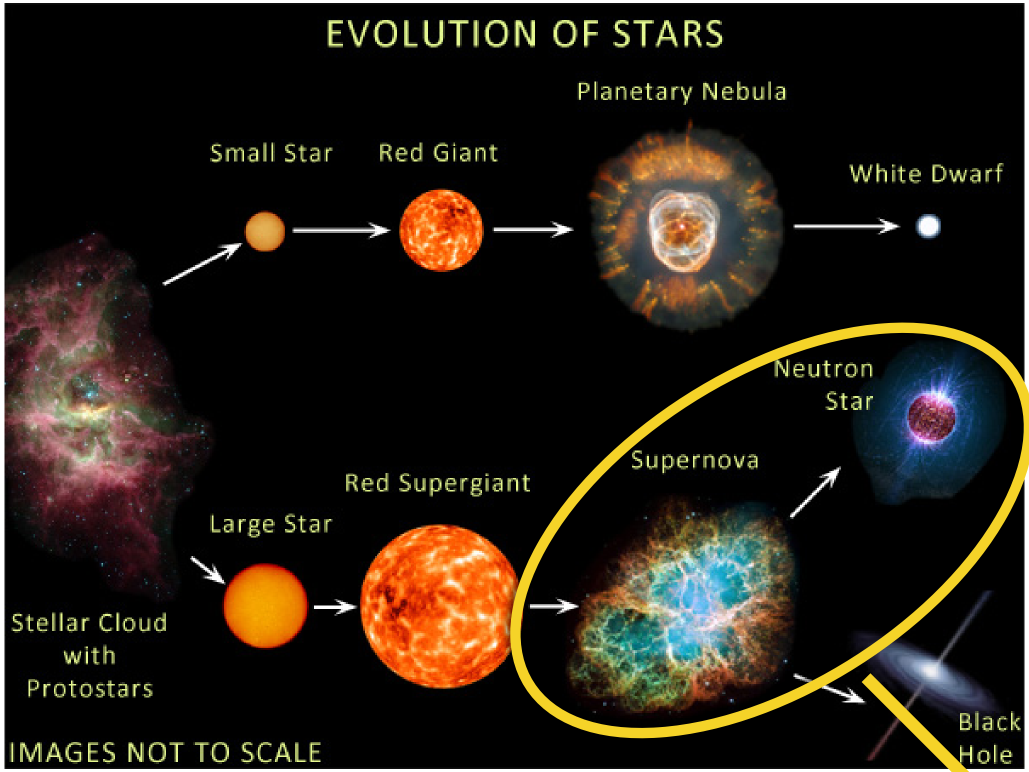
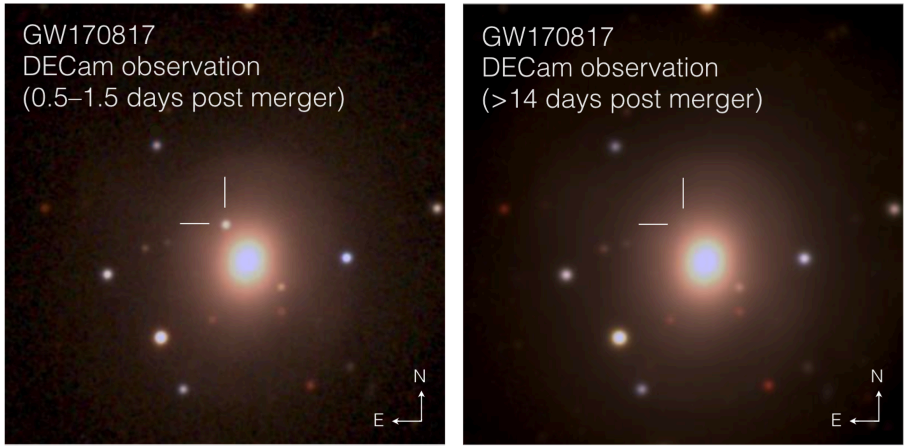
Where do these clusters form?

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

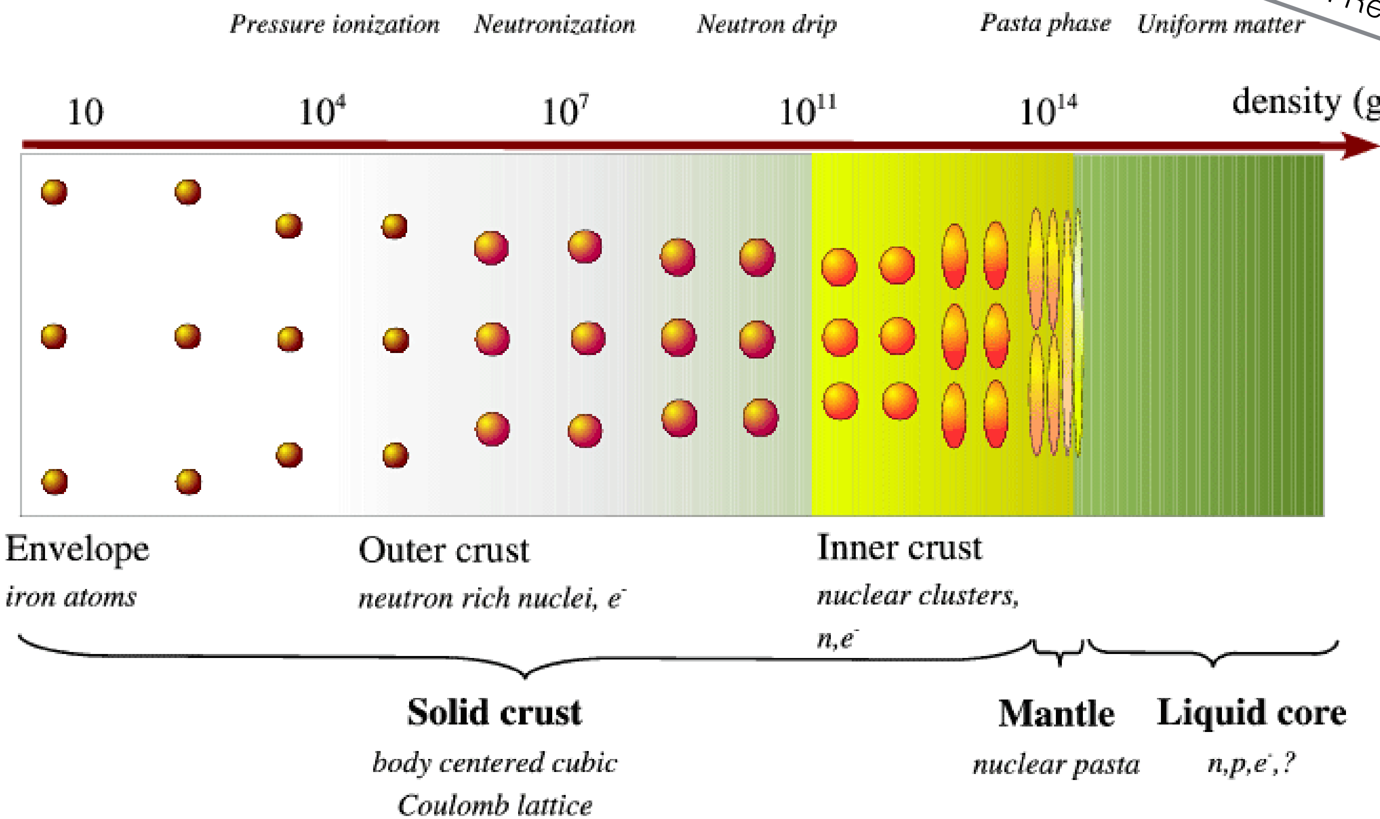
Neutron stars

- 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



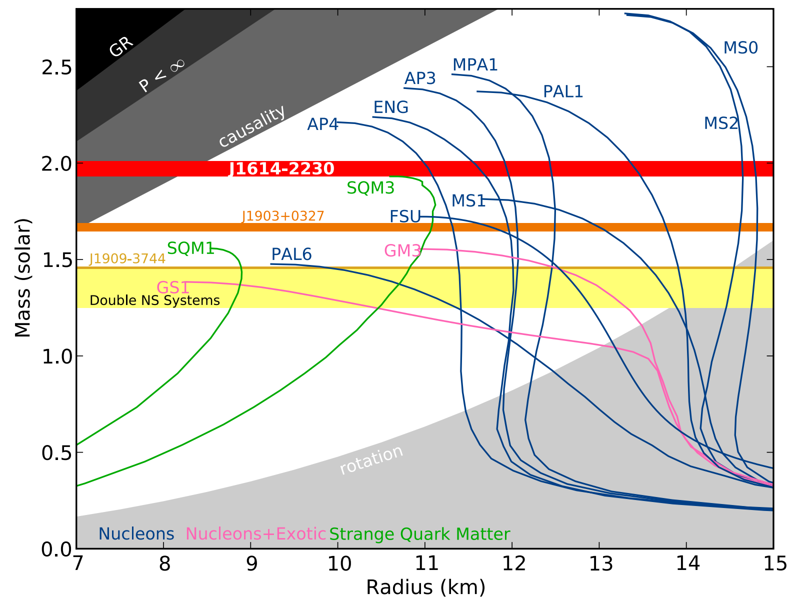
- The clusters, light and heavy, also appear in CCSN (fixed yp and finite T)
- In CCSN, the clusters can modify the neutrino transport, affecting the cooling of the PNS.

Describing neutron stars

P.B. Demorest *et al*, Nature 467, 1081, 2010

Prescription:

1. EoS: $P(E)$ for a system at given ρ and T
2. Compute TOV equations
3. Get star M(R) relation



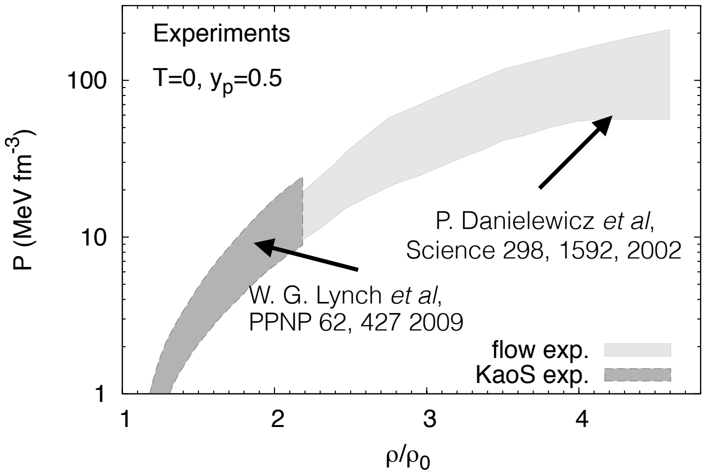
Problem: Which phenomenological EoS to choose?

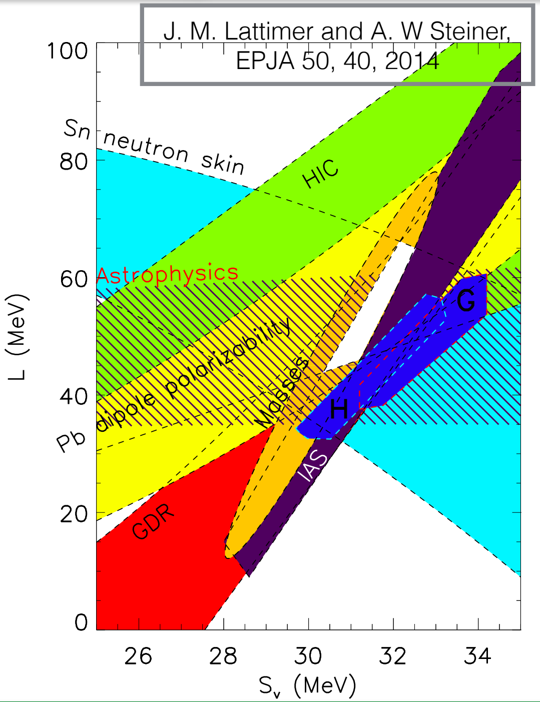
Many EoS models in literature: Phenomenological models (parameters are fitted to nuclei properties): **RMF, Skyrme**…

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

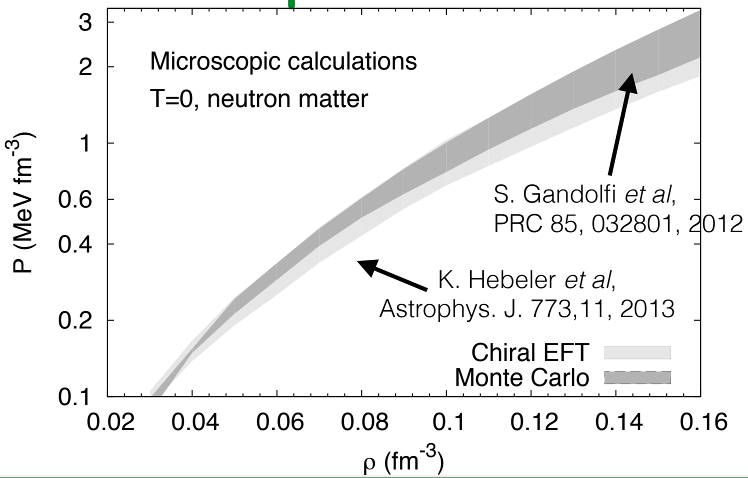
EoS Constraints

•Experiments

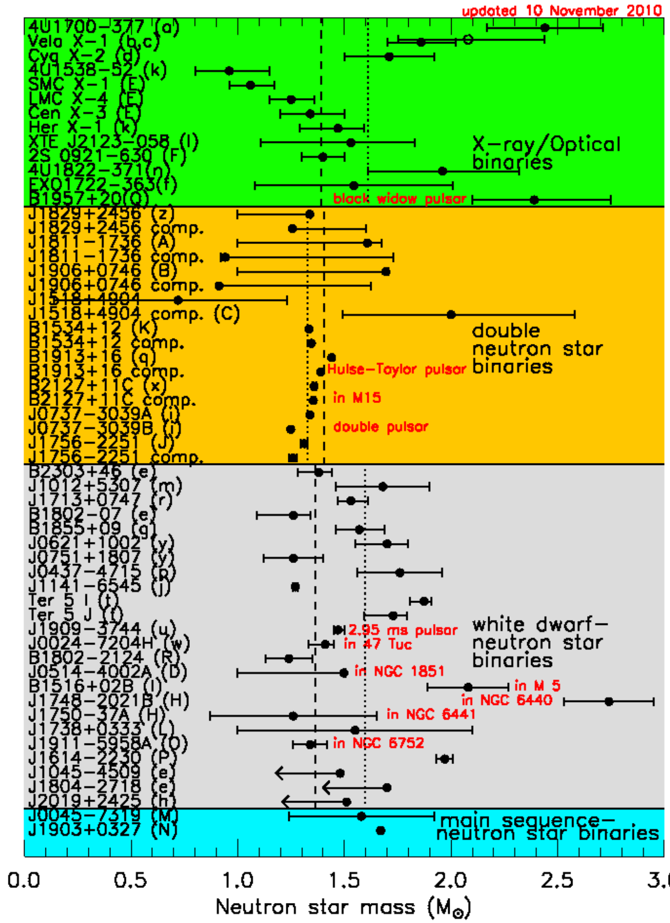




•Microscopic calculations



•Observations



J. M. Lattimer and M. Prakash,
arXiv: 1012.3208 [astro-ph.SR] 2010

Choosing the EoS(s)

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

Solution: Choose 1 EoS for each NS layer:

check e.g. PRC 94, 035804 2016

- 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

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.
- Interact 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

$$g_{vj} = A_j g_v$$

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:

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

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

In-medium effects - g_{sj}

PRC 97, 045805 2018

- 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

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

needs to be determined from exp. constraints

In-medium effects - δB_j

PRC 97, 045805 2018

- 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.

binding energy shift

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

energetic counterpart of classical ExV mechanism

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

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

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

associated with the gas lowest energy levels

EoS for HM with light clusters

- The total baryonic density is defined as:

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

- The global proton fraction as

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

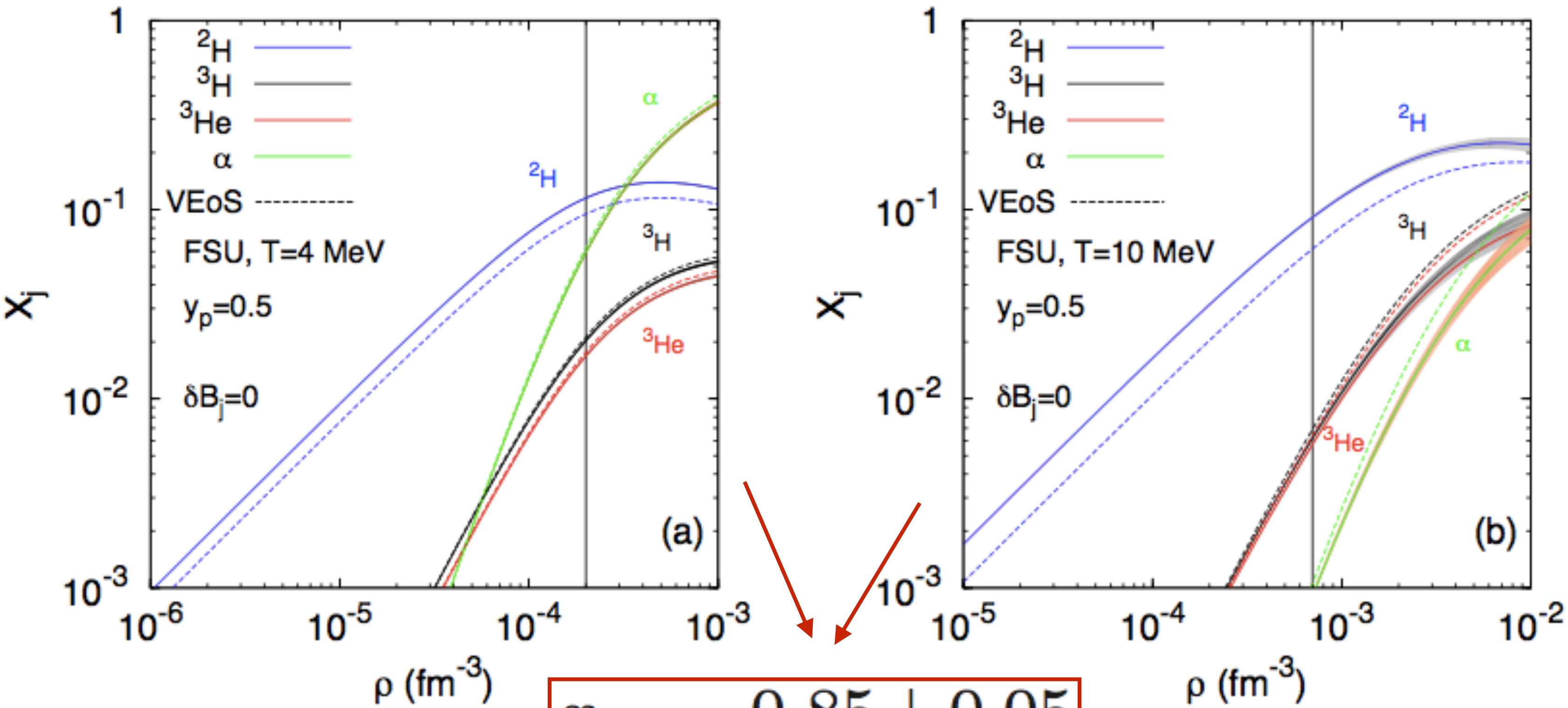
with $y_i = A_i(\rho_i/\rho)$ the mass fraction of cluster i.

- 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

$$\mu_i = N_i\mu_n + Z_i\mu_p$$

Determination of x_s: Virial EoS

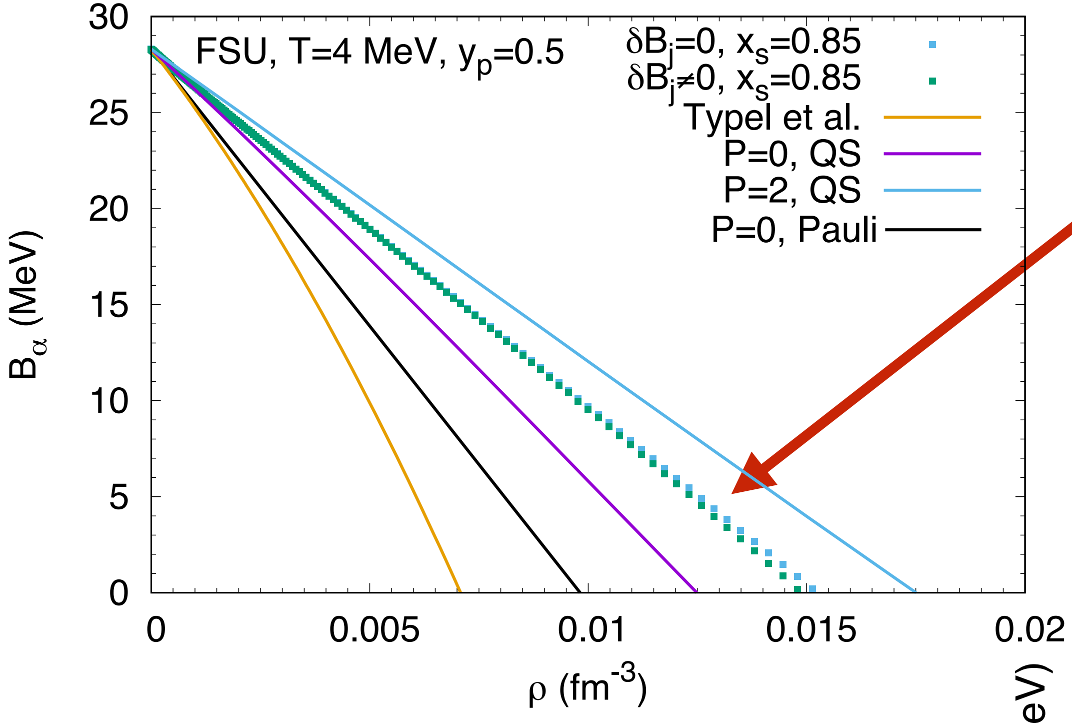


$$x_{sj} = 0.85 \pm 0.05$$

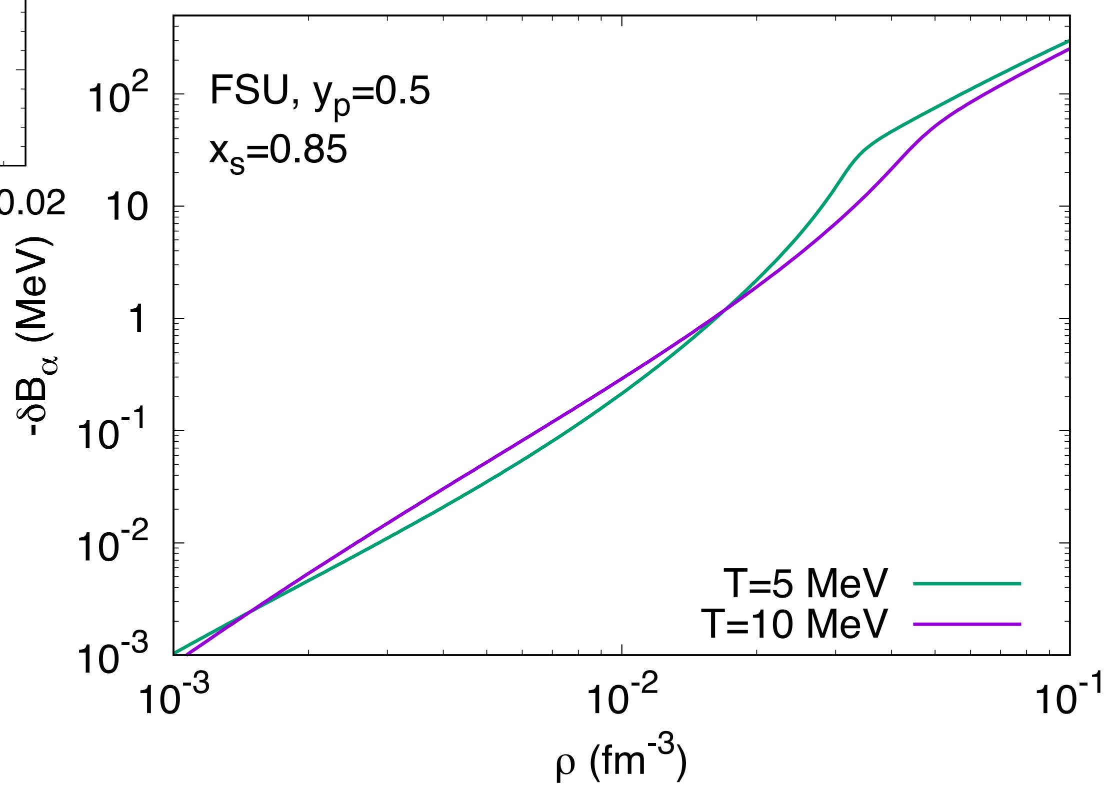
- VEoS: model-independent constraint, only depends on experimentally binding energies and scattering phase shifts.
- Provides correct zero-density limit for finite T EoS.
- Breaks down when interaction with particles becomes stronger:

δB_j takes action!!

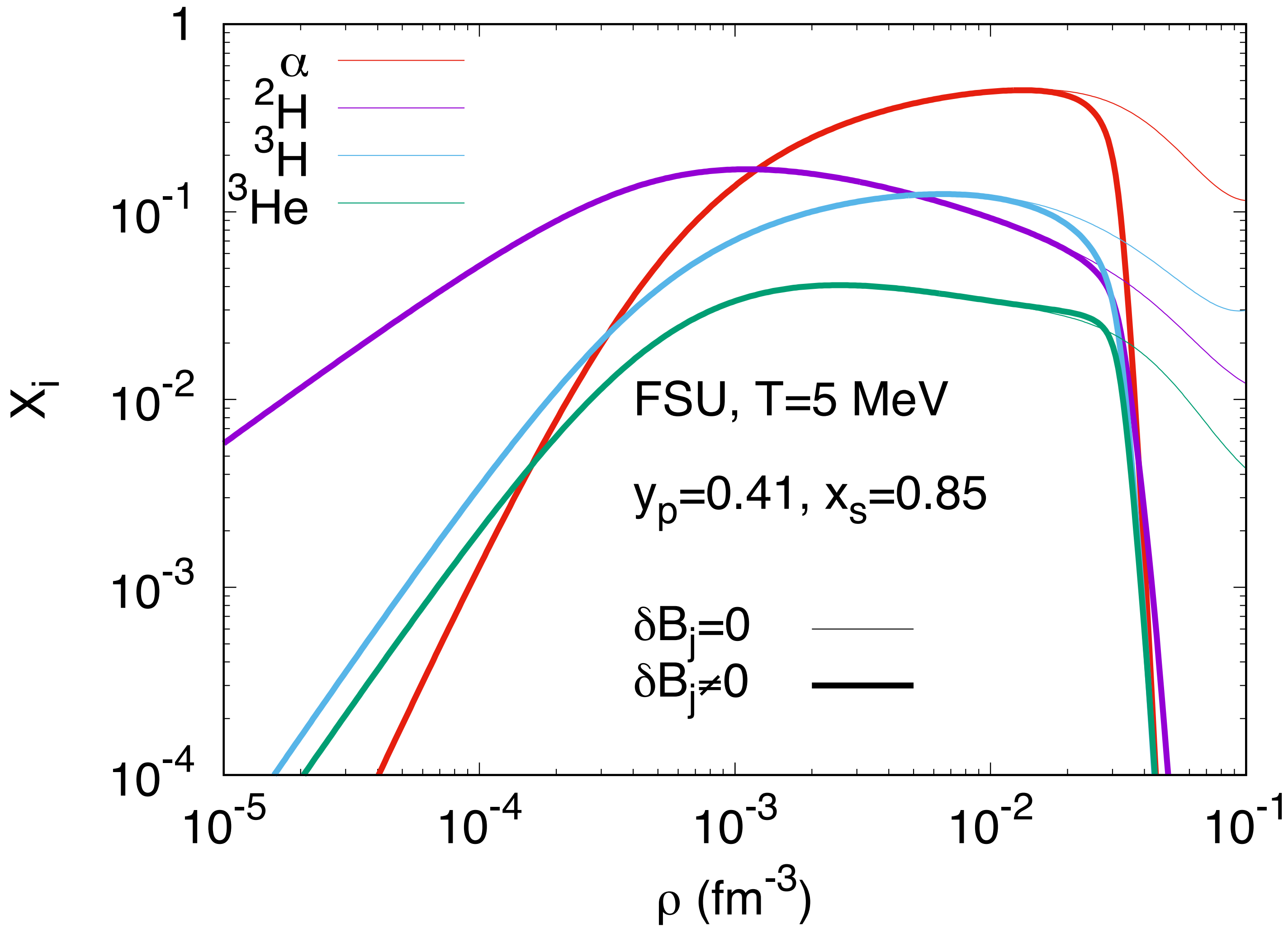
Contribution of δB_j



- 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!

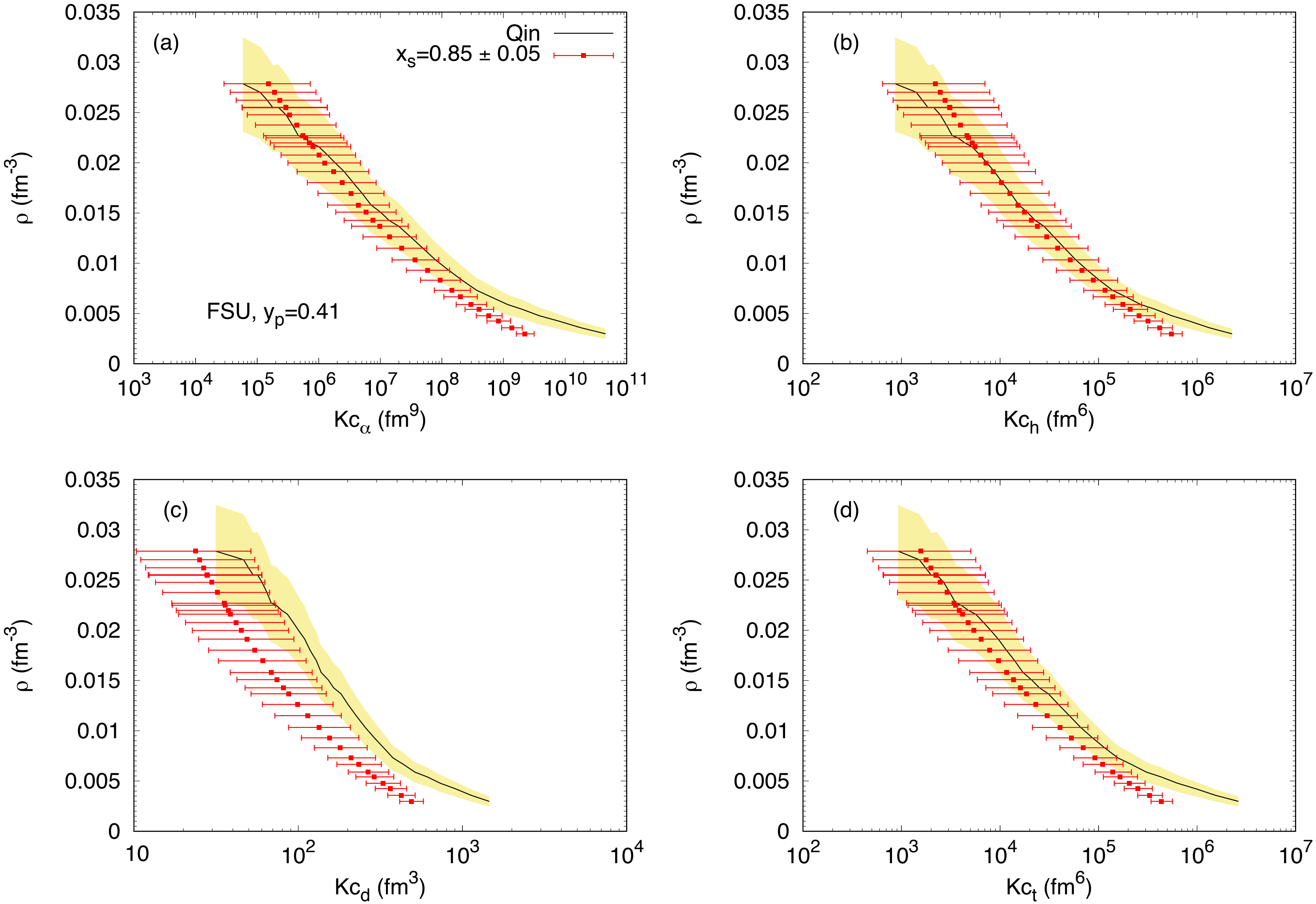
Equilibrium constants

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

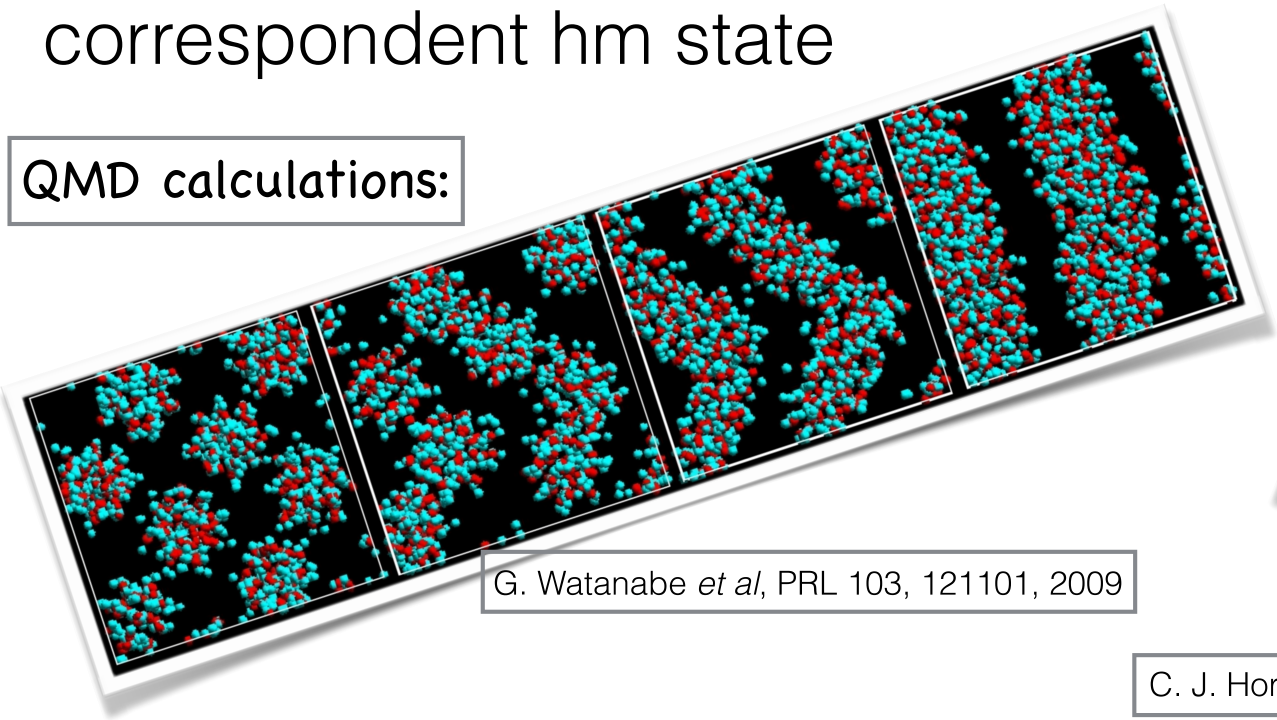


- Our model describes quite well exp data!

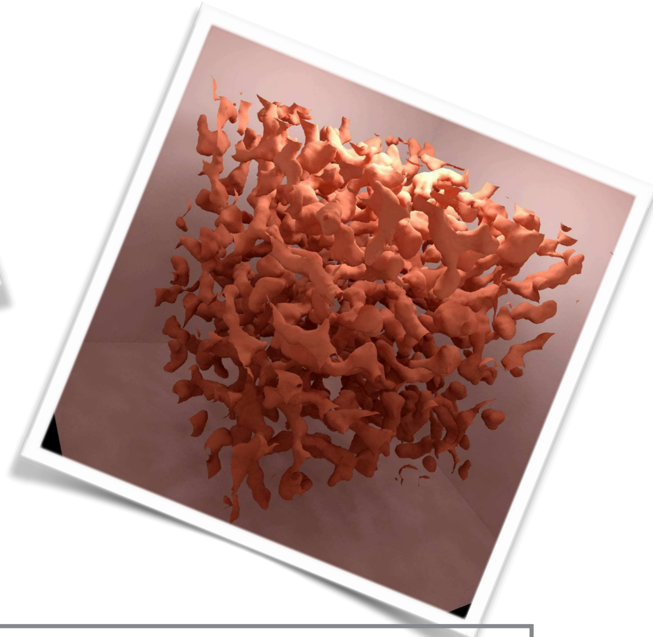
The pasta phases

- Competition between Coulomb and nuclear forces leads to frustrated system
- Geometrical structures, the **pasta phases**, evolve with density until they melt ⟶ **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

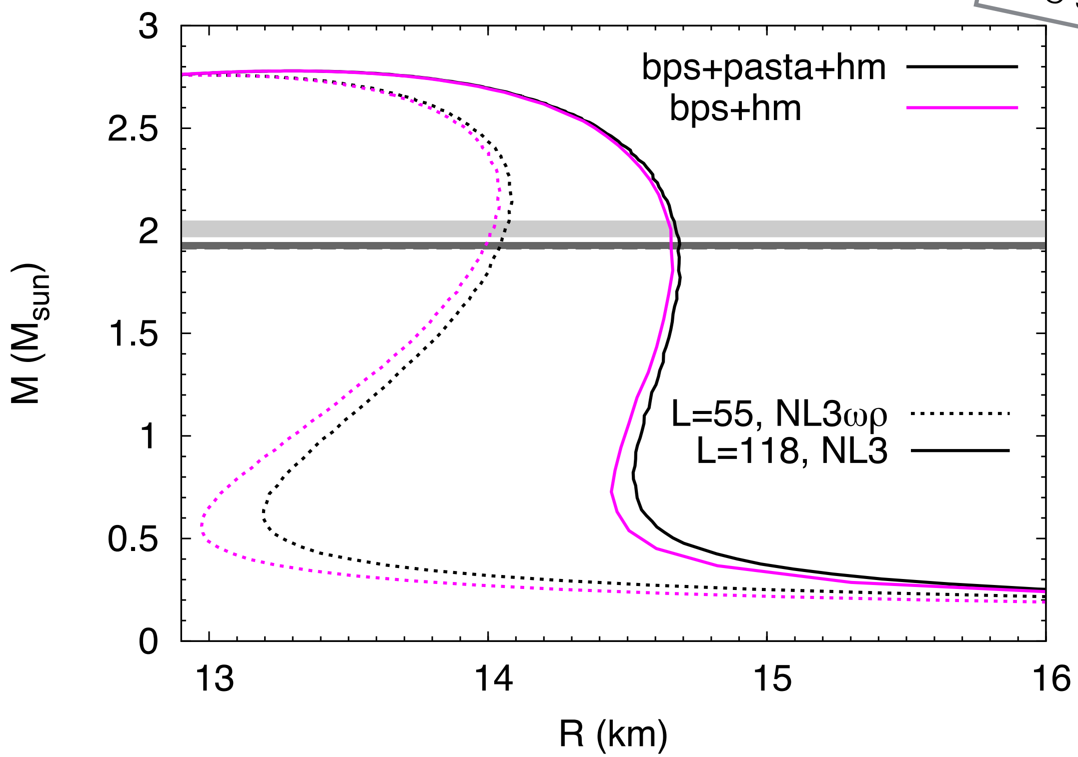


C. J. Horowitz *et al*, PRC 70, 065806, 2004

Why are these phases important?

- They may have an effect in the cooling of the star.
- They do have an effect in the radius of the stars, but not in the maximum mass:

PRC 94, 015808 2016



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

Pasta phases - calculation (I)

check PRC 91, 055801 2015

- Coexistence Phase (CP) approximation:
  - **Separated regions of higher (pasta phases) and lower density (background nucleon gas).**
  - **Gibbs equilibrium conditions: for** $T = T^I = T^{II}$**:**

$$\mu_p^I = \mu_p^{II}$$
$$\mu_n^I = \mu_n^{II}$$
$$P^I = P^{II}$$

  - **Finite size effects are taken into account by a surface and a Coulomb terms in the energy density, after the coexisting phases are achieved.**
  - **Total** $\mathcal{F}$ **and total** ρ_p **of the system:**

$$\mathcal{F} = f\mathcal{F}^I + (1-f)\mathcal{F}^{II} + \mathcal{F}_e + \epsilon_{surf} + \epsilon_{coul}$$

$$\rho_p = \rho_e = y_p\rho = f\rho_p^I + (1-f)\rho_p^{II}$$

and

$$\varepsilon_{\text{surf}} = 2\varepsilon_{\text{Coul}}$$

Pasta phases - calculation (II)

check PRC 91, 055801 2015

- Compressible Liquid Drop (CLD) approximation:

The total free energy density is minimized, including the surface and Coulomb terms.

The Gibbs equilibrium conditions become:

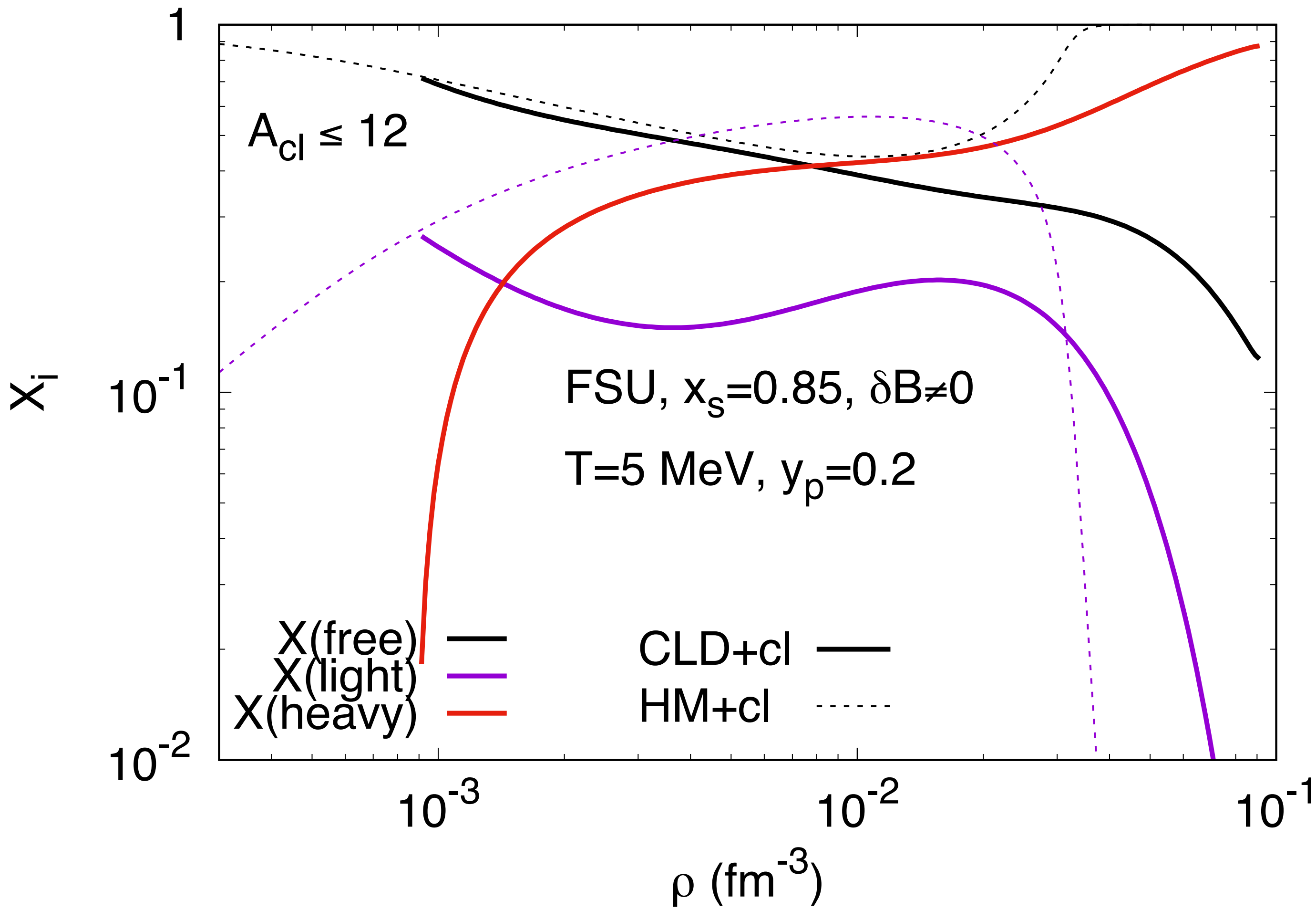
$$\mu_n^I = \mu_n^{II},$$

$$\mu_p^I = \mu_p^{II} - \frac{\epsilon_{surf}}{f(1-f)(\rho_p^I - \rho_p^{II})},$$

$$P^I = P^{II} - \epsilon_{surf}\left(\frac{1}{2\alpha} + \frac{1}{2\phi}\frac{\partial \phi}{\partial f} - \frac{\rho_p^{II}}{f(1-f)(\rho_p^I - \rho_p^{II})}\right)$$

Cluster fractions - CLD vs HM

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



- The heavy cluster makes the light clusters less abundant but increases their melting density, as compared with the HM+cl calculation.
- The background of free nucleons also decreases in the presence of the heavy cluster.

Summary

- 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 HIC.
- Light clusters and pasta structures are relevant and should be explicitly included in EoS for CCSN simulations and NS mergers.
- Extra constraints from experimental data are needed!!

Grazie mille!

Thank you!