Heavy-ion collisions and the low-density neutron star equation of state

Helena Pais

CFisUC, University of Coimbra, Portugal

in collaboration with F. Gulminelli (LPC-Caen, France), C. Providência (Univ. Coimbra), and G. Roepke (Univ. Rostock, Germany), and with R. Bougault and the INDRA collaboration (LPC-Caen-France)

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Neutron stars

check eg N. K. Glendenning, Compact Stars: Nuclear Physics, Particle Physics, and General Relativity (Springer, 2000)

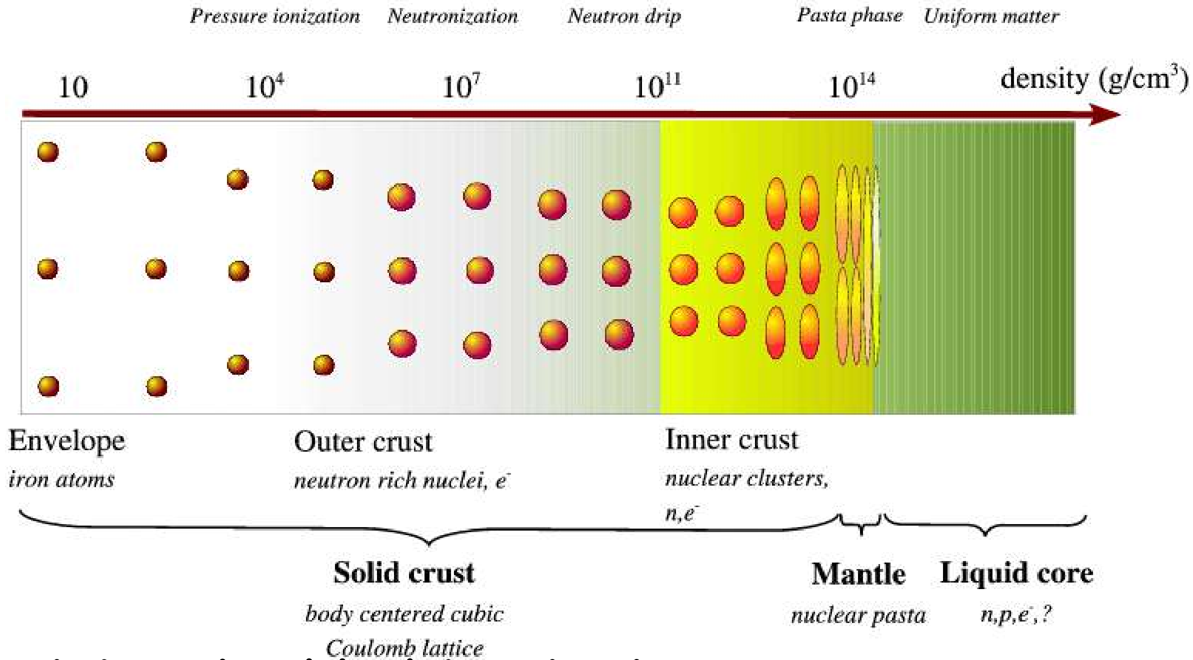
- 3 main layers:

1. Outer crust
2. Inner crust
3. Core

R~10 km; M~1.5 M⊙

- NS: catalized cold stellar matter:

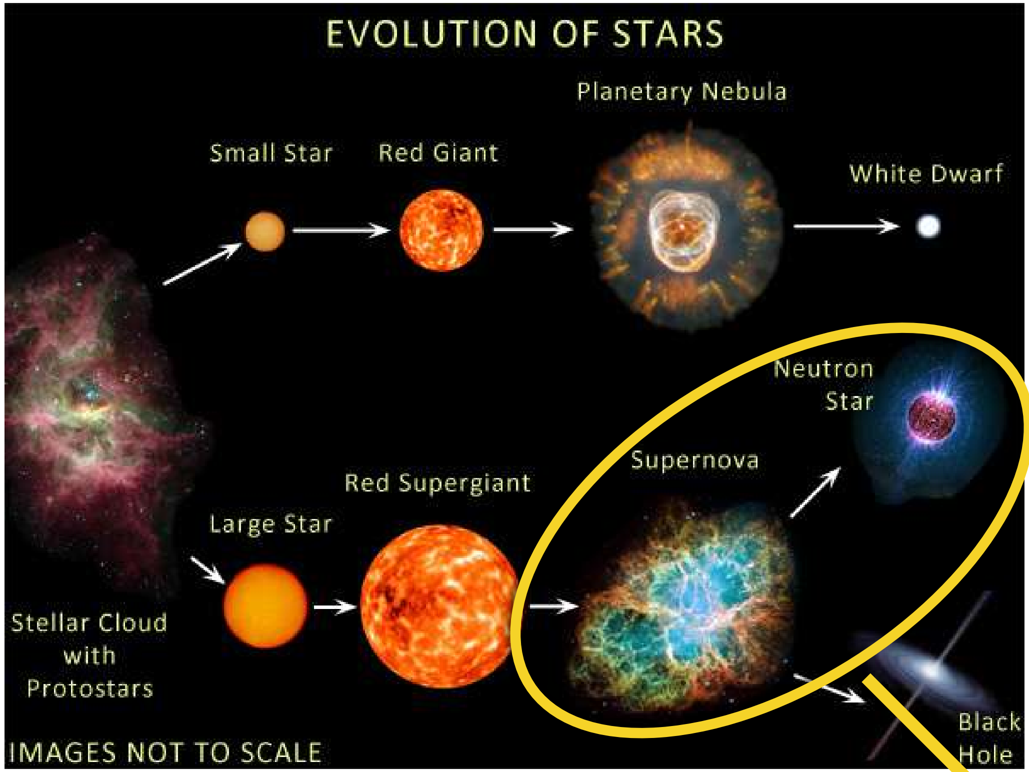
N. Chamel and P. Hansel, Liv. Rev. Rel.11,10, 2008



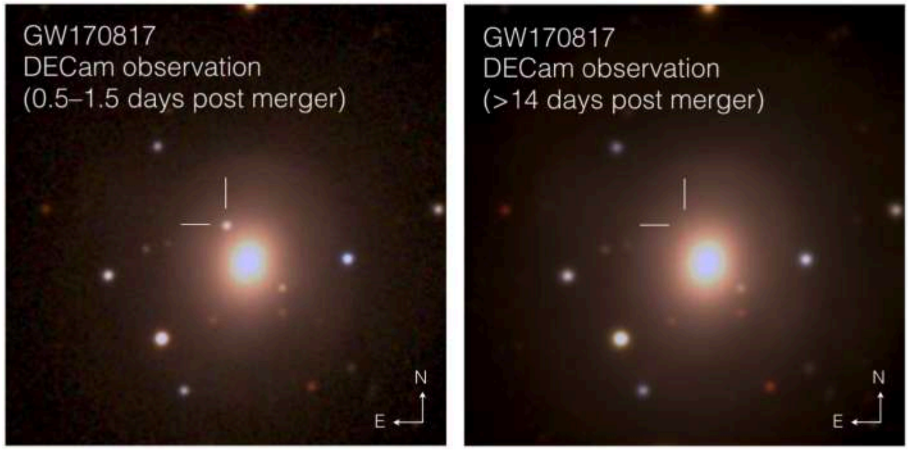
- Surface: ^{56}Fe, P=0
- Outer crust: Neutron rich nuclei embedded in electron sea
- Inner crust: Above neutron drip density, nucleons form geometrical structures (non-spherical: pasta phases) embedded in neutron and electron background gas.
- Core: Uniform matter, in the centre exotic matter may exist.

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

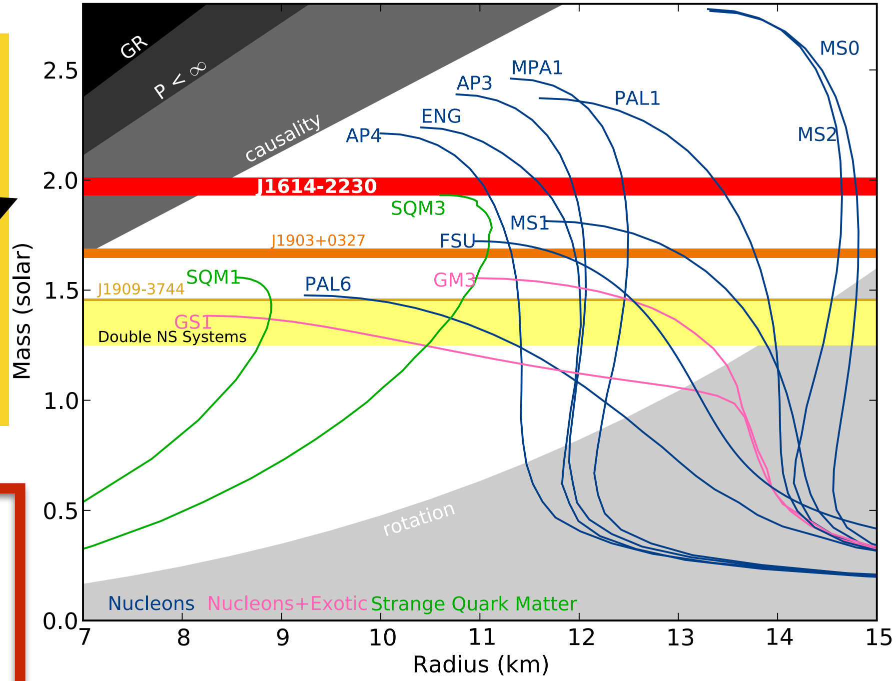
scenarios where light and heavy clusters are important:
supernovae, NS mergers, (crust of) neutron stars

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**…

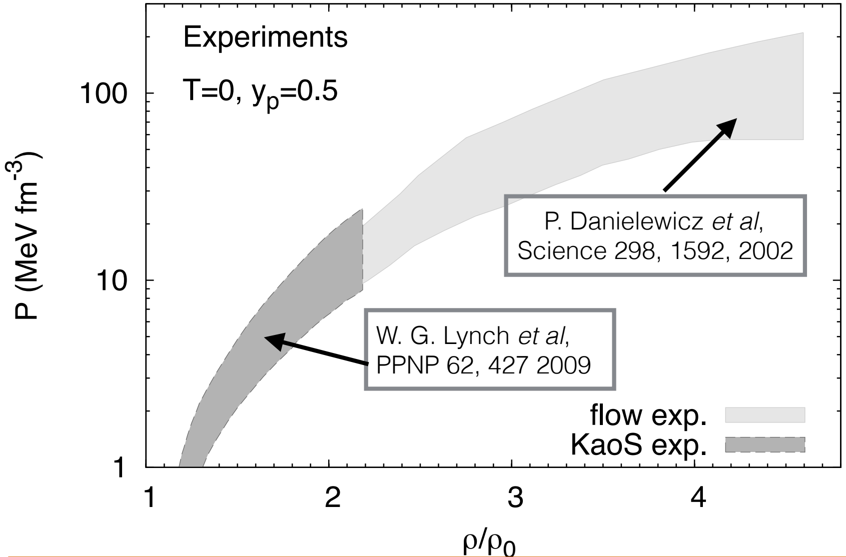
check CompOSE: https://compose.obspm.fr/

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

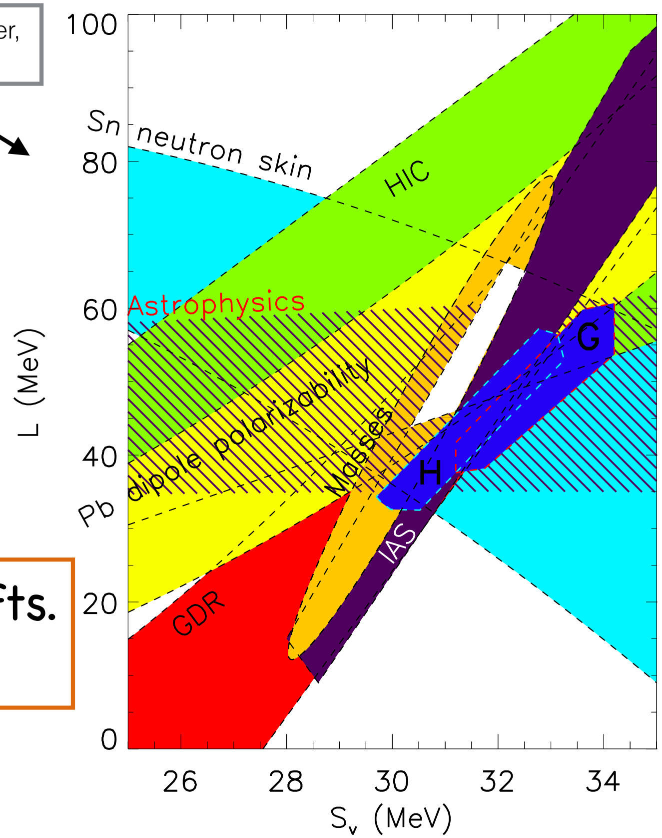
check e.g PRC 85, 035201 (2012), PRC 90, 055203 (2014)

EoS Constraints

- Experiments:



J. M. Lattimer and A. W Steiner, EPJA 50, 40, 2014

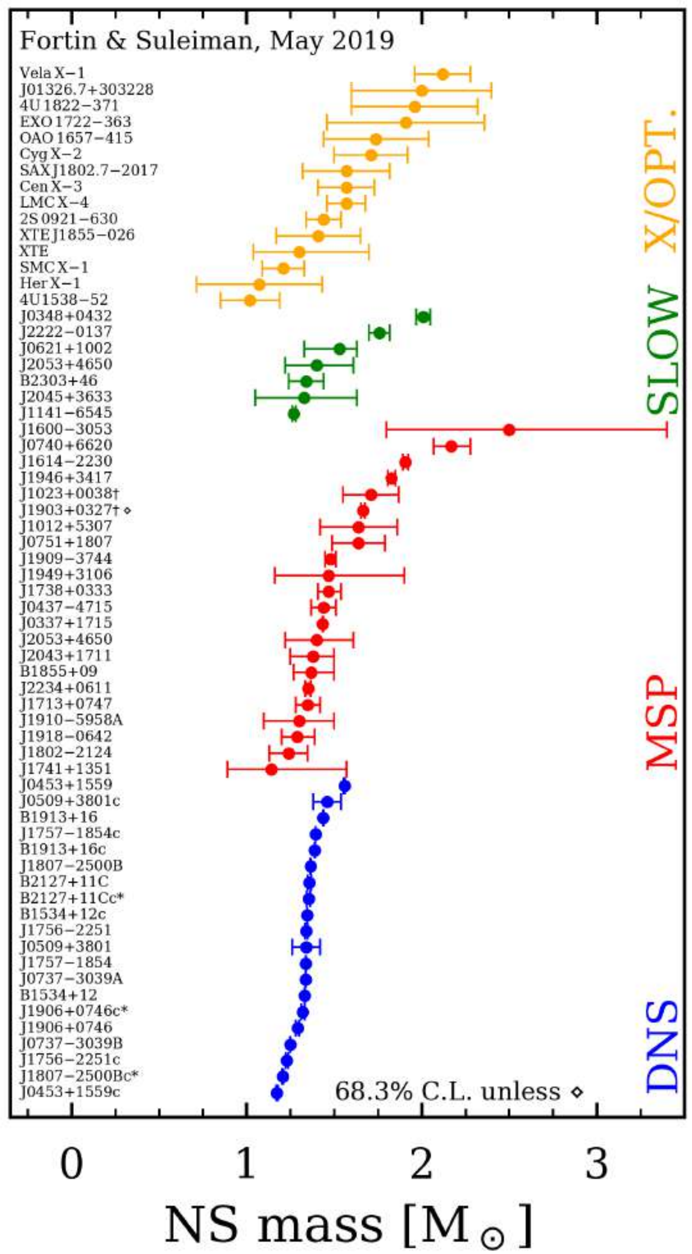


- VEoS: only depends on exp. B and scattering phase shifts. Correct zero-density limit for finite T EoS.

- Kc from HIC: cluster formation observed in HIC.

- PREXII (Adhikari et al, PRL, 126, 172502 (2021): Rn-Rp(208Pb)=0.283 ± 0.071 fm.
-Reed et al, PRL 126, 172503 (2021): L = 106 ± 37 MeV;
-Yue et al, arXiv:2102.05267, L = 85.5 ± 22.2 MeV;
-Essick et al, arXiv:2102.10074, L = 58 ± 19 MeV.
- Spectra of charged pions (Estee et al, PRL 126, 162701 (2021)): 42<L<117MeV.

EoS Constraints



• Observations:

- GW170817 from NS-NS (Abbott et al, PRL 119, 161101 (2017) followed up by GRB170817A and AT2017gfo.

Others followed:

- GW190425 (Abbott et al, ApJL 892, L3 (2020): largest NS binary known to date
- GW190814 (Abbott et al, ApJL 896, L44 (2020): BH+2.5-2.6Msun object (not ruled out yet to be NS).

- NASA's Neutron star Interior Composition Explorer (NICER), a soft X-ray telescope in ISS:
- PSR J0030+0451:

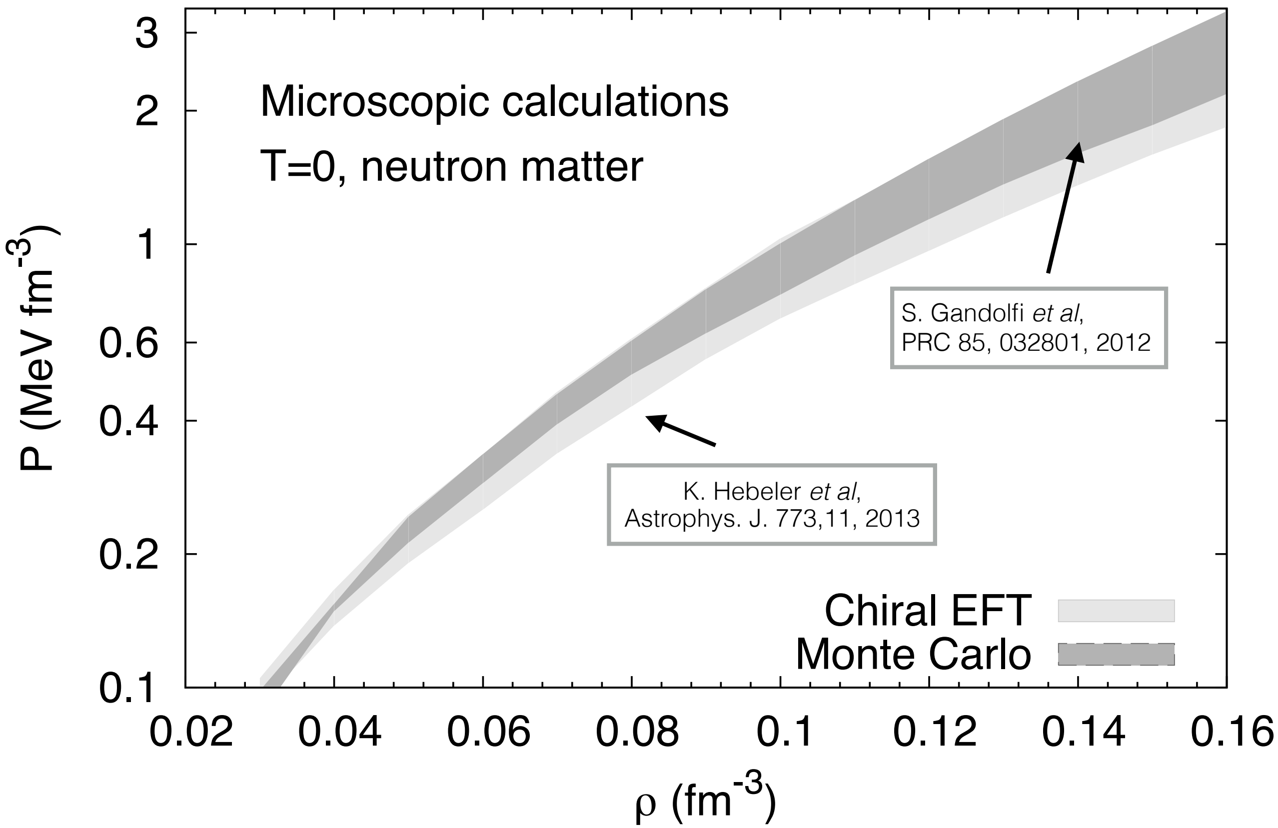
-Riley et al, ApJL 887, L21 (2019):
M=$1.34^{+0.15}_{-0.16}$ $M_\odot$, R=$12.71^{+1.14}_{-1.19}$ km
-Miller et al, ApJL 887, L24 (2019):
M= $1.44^{+0.15}_{-0.14}$ $M_\odot$; R= $13.02^{+1.24}_{-1.06}$ km

- PSR J0740+6620:

-Riley et al, arXiv:2105.06980:
M= $2.072^{+0.067}_{-0.066}$ $M_\odot$; R= $12.39^{+1.30}_{-0.98}$ km

EoS Constraints

- Microscopic calculations



EoS Constraints

In a near future:

- ATHENA, an X-ray high-precision determination observatory for NS mass and radius to be launched in 2028.
- New data on NS systems will heavily increase when SKA, the world's largest radio telescope, will be in full power.
- The radio telescope FAST has started operating, and will give information on the NS mass.
- ...

- On the experimental side, FAIR will put more constraints on the high-density behaviour of nuclear matter, and CREX should release results soon...
- ...

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

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

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

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

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

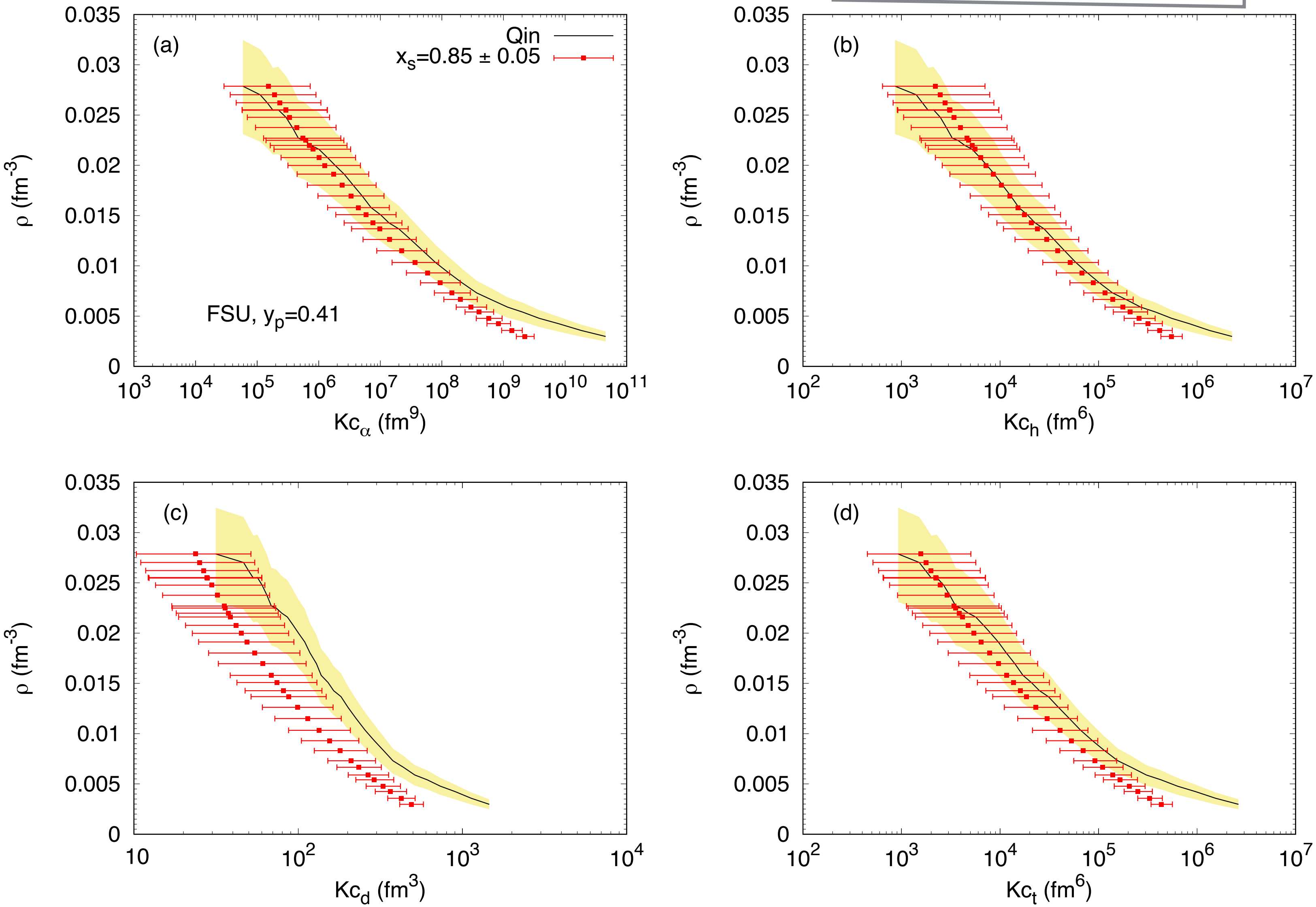
Exp Constraint: Equilibrium constants

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

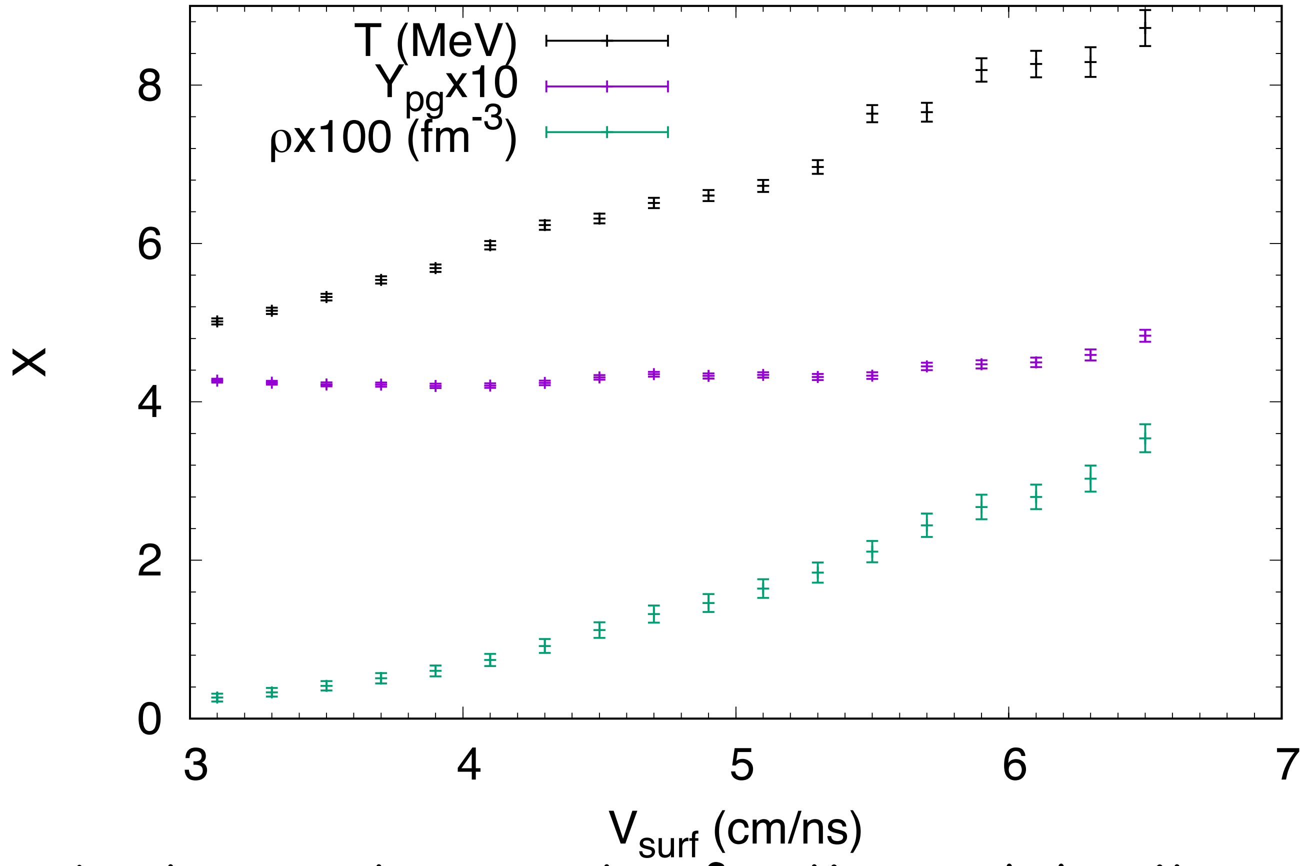


- Our model describes quite well experimental data!

Experimental chemical equilibrium constants with INDRA data

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

- 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, J. Phys. G 47, 025103 (2020)

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

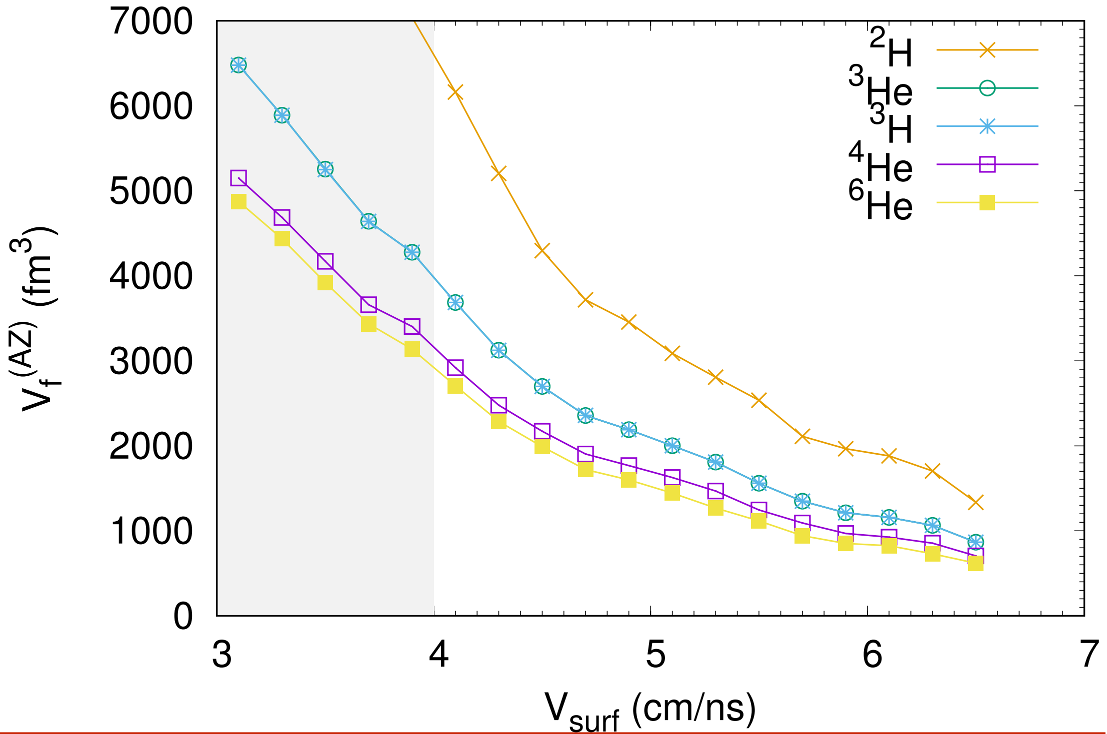
- The temperature, proton fraction and density as a function of Vsurf, for the intermediate mass system.

Experimental determination of chemical equilibrium constants

- Weak point: T and density are NOT directly measured, but deduced from experimental multiplicities, using analytical expressions that assume the physics of an ideal gas...

- Since we are in thermodynamical equilibrium, the free volume calculated for each one of the clusters should be the same!

- But they aren't....



- This is not surprising because we are using an expression for the volume where we consider an ideal gas of classical clusters..

Considering in-medium effects

- How to solve this problem?

- We should take into account the interactions between clusters:

$$V_f = R_{np}^{\frac{A-Z}{A-1}} C_{AZ} \exp\left[\frac{B_{AZ}}{T(A-1)}\right] \left(\frac{g_{AZ}}{2^A} \frac{\tilde{Y}_{11}^{A}(\vec{p})}{\tilde{Y}_{AZ}(A\vec{p})}\right)^{\frac{1}{A-1}}$$

$$C_{AZ} = \exp\left[-\frac{a_1 A^{a_2} + a_3 |I|^{a_4}}{T_{HHe}(A-1)}\right]$$

- C_{AZ} depends on temperature T, number of clusters Ai, and isospin Ii.

Considering in-medium effects

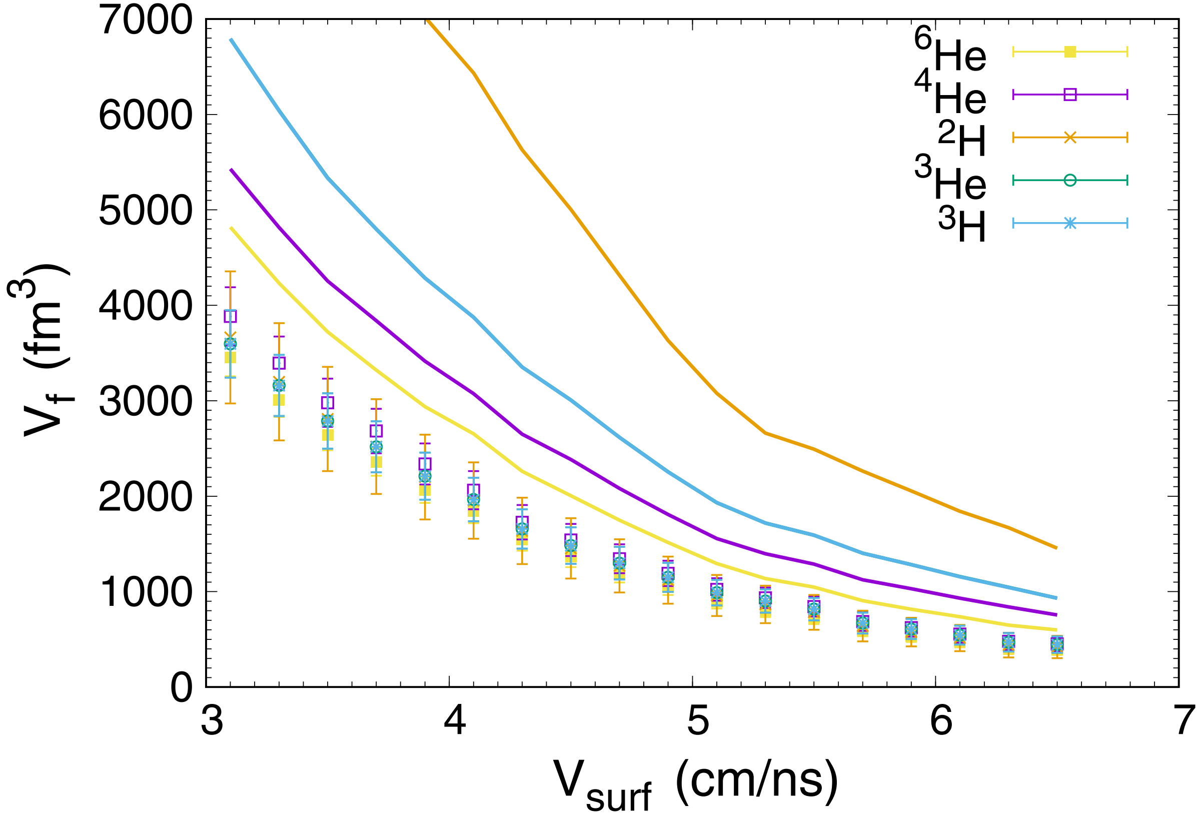
- a1, a2, a3, and a4 are parameters that need to be determined.
- How to do that?

- They are going to be calculated such that the volumes of the clusters are the same, so that the thermodynamical conditions are fulfilled.
- In other words, the variance of the volume of the clusters must be minimum:

$$\sigma = \frac{\sum_i (V_{0_i} - \bar{V_0})^2}{\bar{V}_0^2}$$

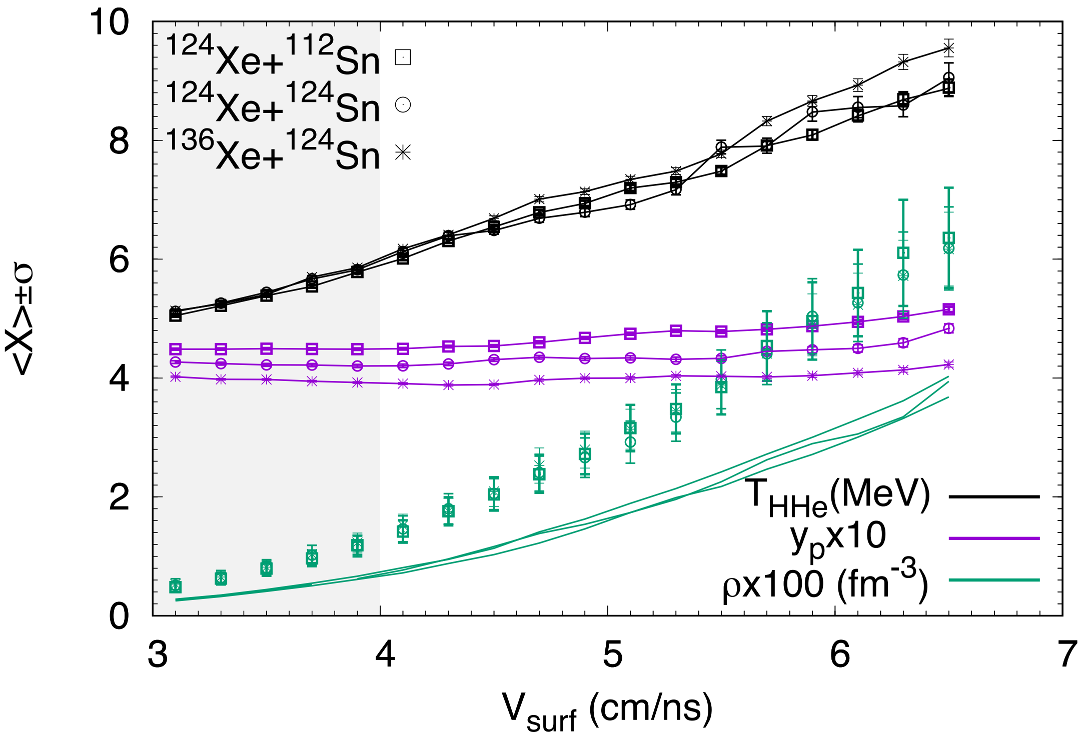
Experimental chemical equilibrium constants with INDRA data

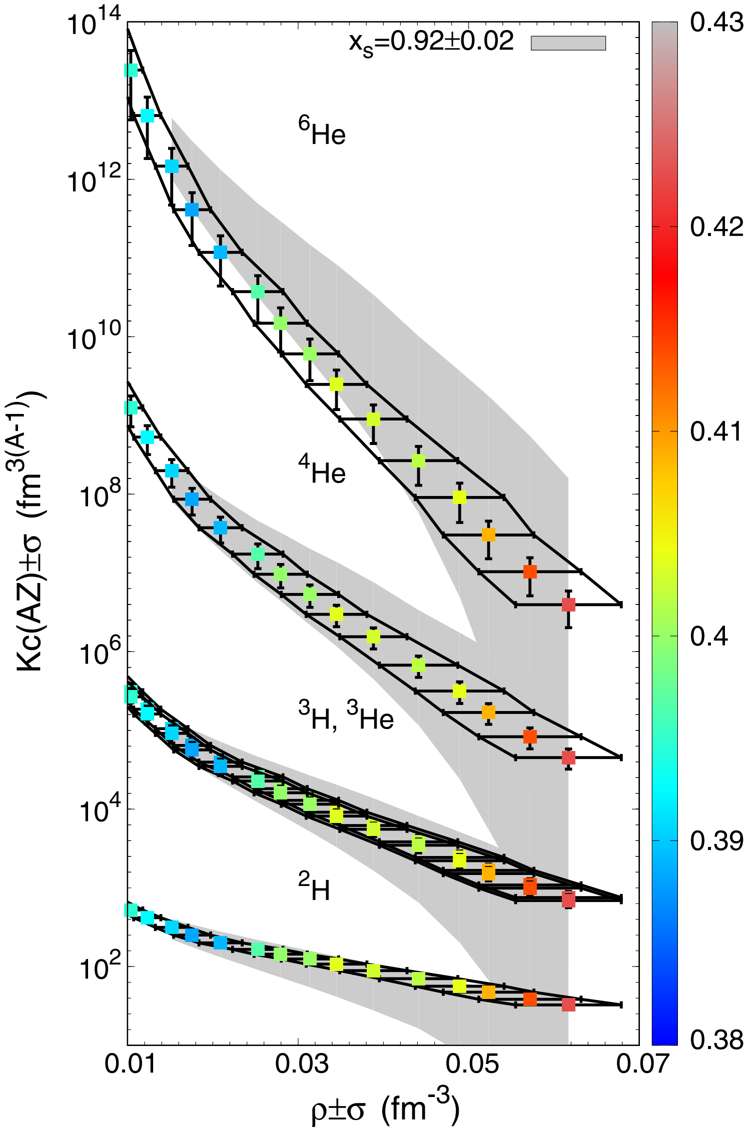
- When we apply the correction, the volumes converge:



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

Equilibrium constants and data from INDRA





- The in-medium effects give rise to larger densities, compared to ideal gas limit.
- The 3 data systems are compatible.

A few take-away messages:

- 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.
- Our model reproduces both virial limit and Kc from HIC data.
- INDRA data was analysed based on a new method, with in-medium effects.
- Comparing to a RMF model, these corrections can be interpreted as a stronger scalar meson coupling of the nucleons bound in clusters, which shifts the dissolution to higher densities.

Thank you!

- Light clusters and pasta structures are relevant and should be explicitly included in EoS for CCSN simulations and NS mergers.