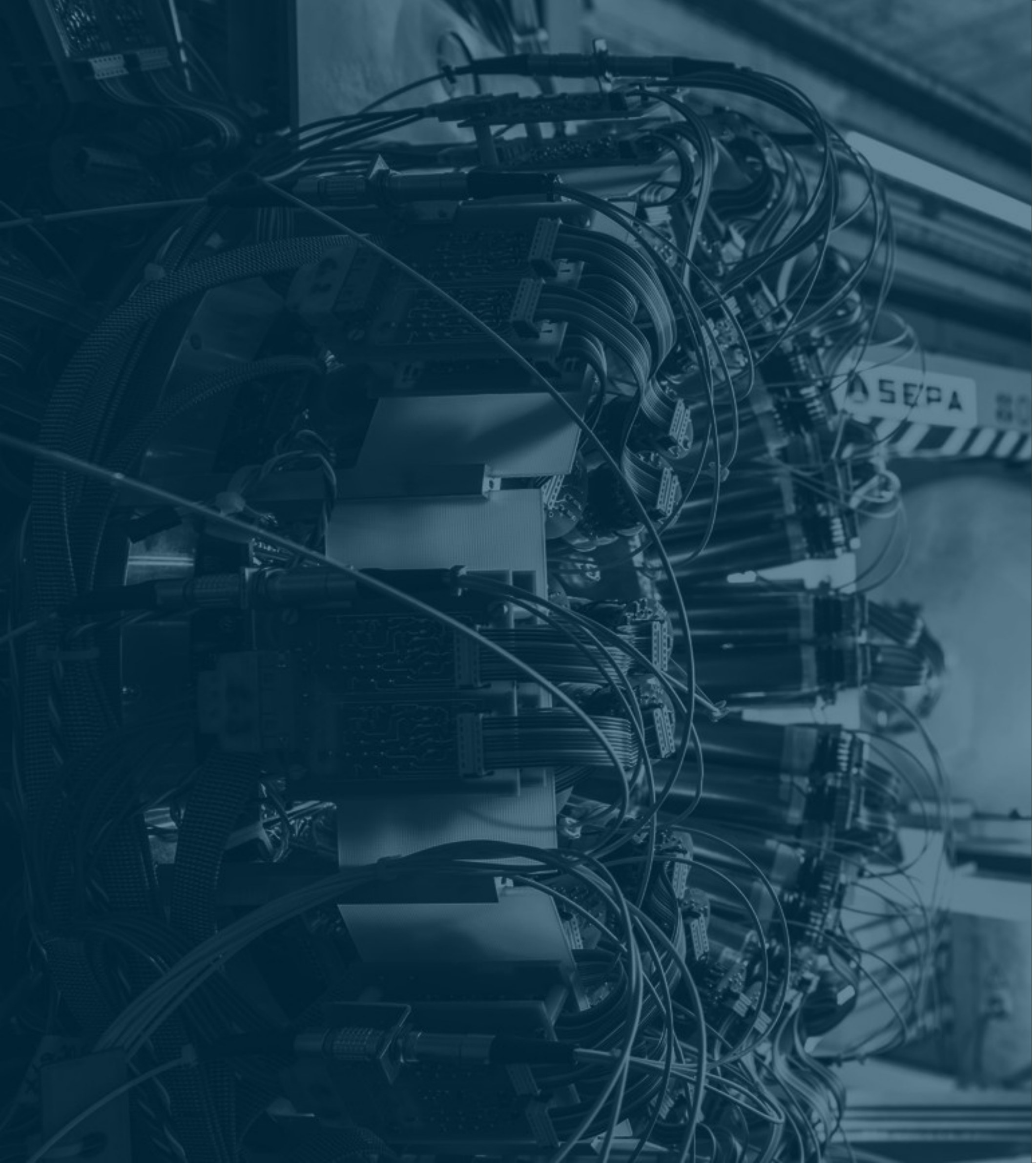


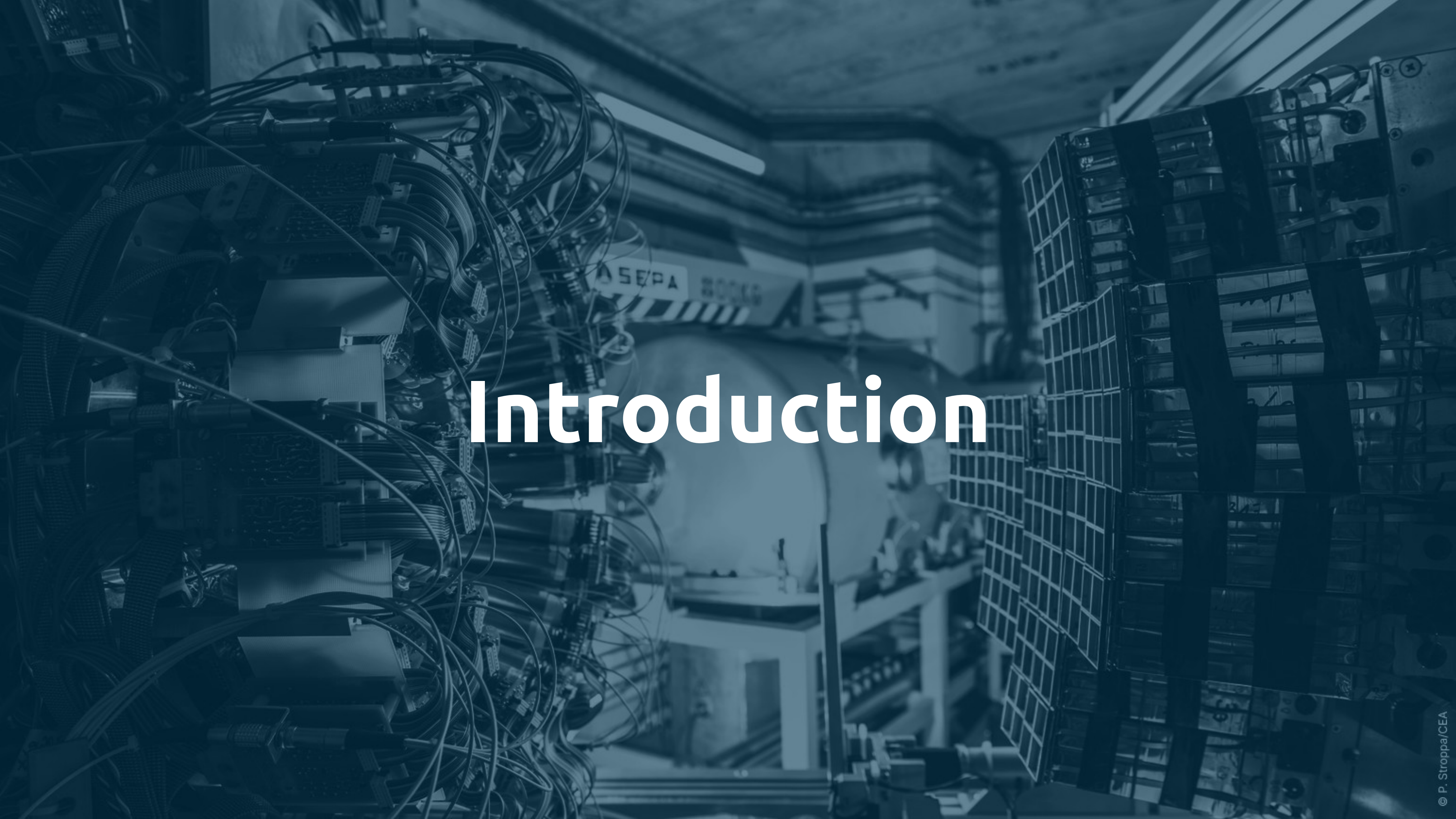
Bayesian calibration of the in-medium modification of light cluster binding energies

Tiago Custodio[1], **Alex Rebillard-Soulié**[2], Rémi Bougault[2], <u>Diego Gruyer</u>[2], Francesca Gulminelli[2], Tuhin Malik[1], Helena Pais[1], Constança Providencia[1]

[1] CFisUC , University of Coimbra, Portugal
[2] LPC, Caen, France

→ PESSOA France-Portugal agreement

Introduction

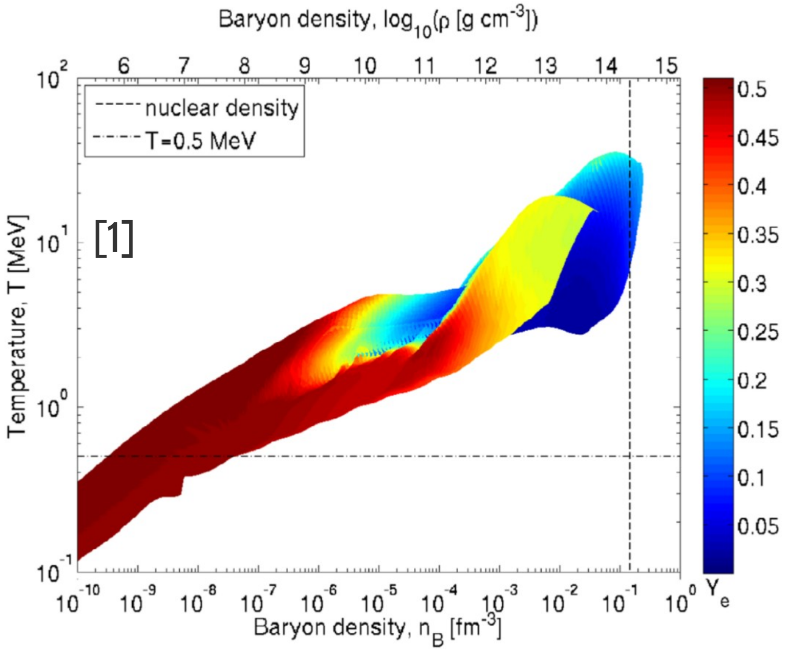


Astro-motivations

During core-collapse supernovae, nuclear matter explores a wide range of temperatures and densities

Dense matter composition

At low density and finite temperature, correlations between nucleons increases and light clusters appear
Cluster can affect the neutrino transport and the shock wave proparation



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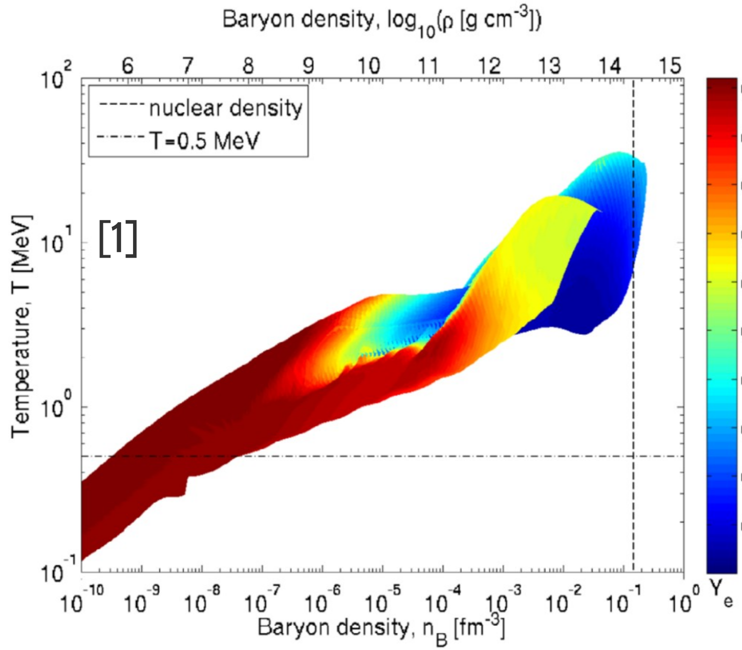
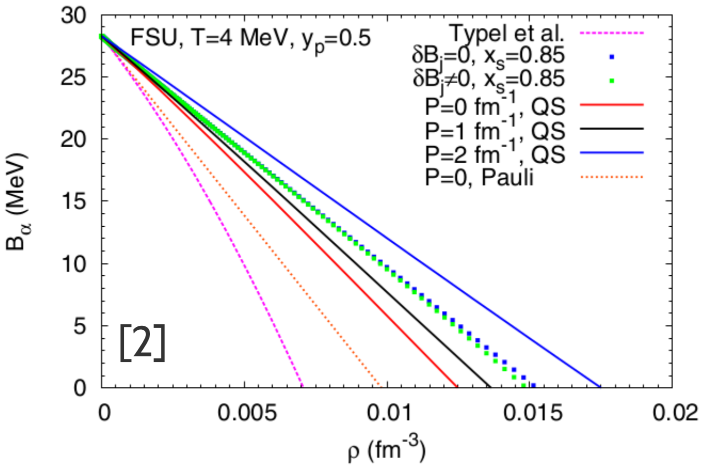
Clusters are not in vacuum, they interact with the surrounding medium wich can affect their properties
→ Binding energies depend on temperature and density





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→ These ingredients need to be calibrated on data !

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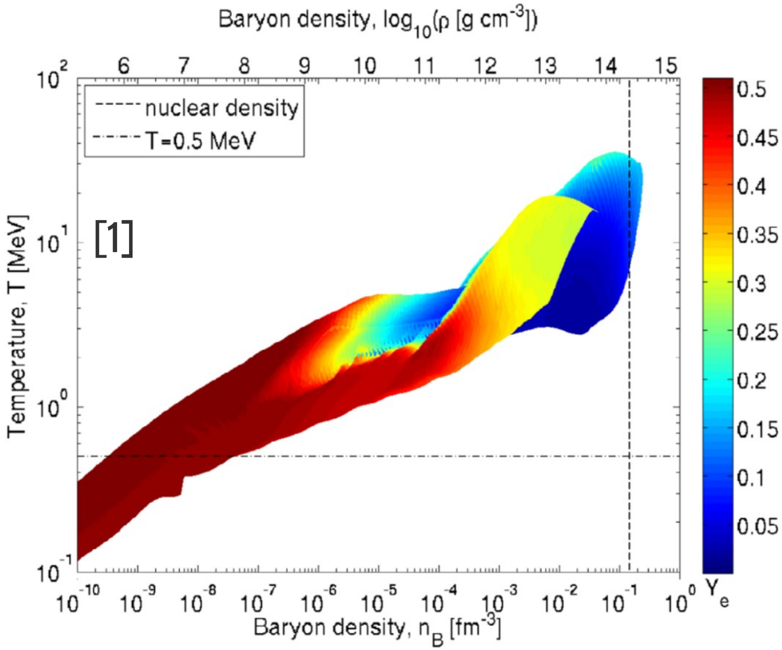

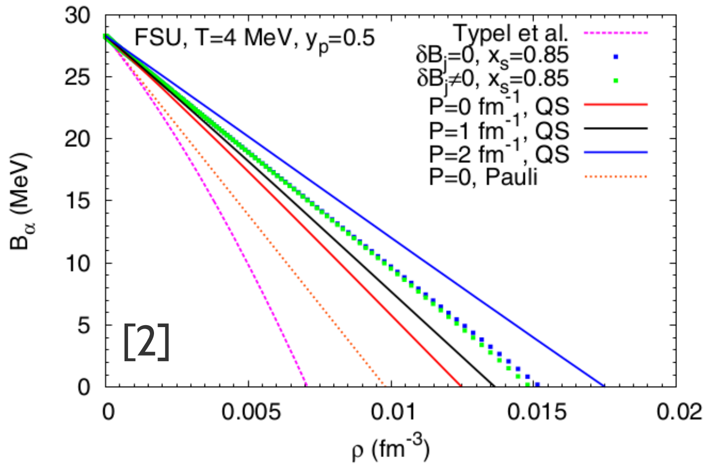

Texas A&M idea

Highly energetic particles produced by participant zone in central heavy-ion collisions : gas of nucleons and clusters (^{2}H, ^{3}H, ^{3}He and ^{4}He) at different thermodynamic conditions

L. Qin et al. PRL108 (2012) 172701

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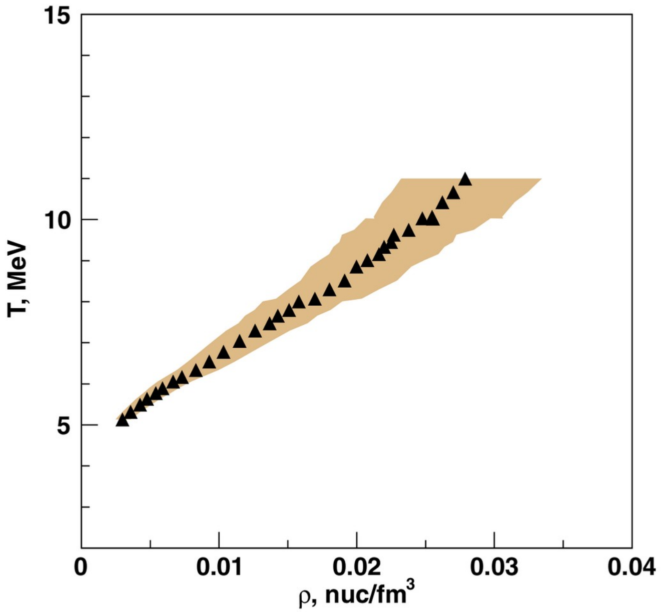
Grand canonical equilibrium model (ideal gas hypothesis) :

- Temperature (T) from H and He yields
- Density (ρ) from momentum space density

→ Low density ~$\rho_0/10$ and temperature ~5-10 MeV



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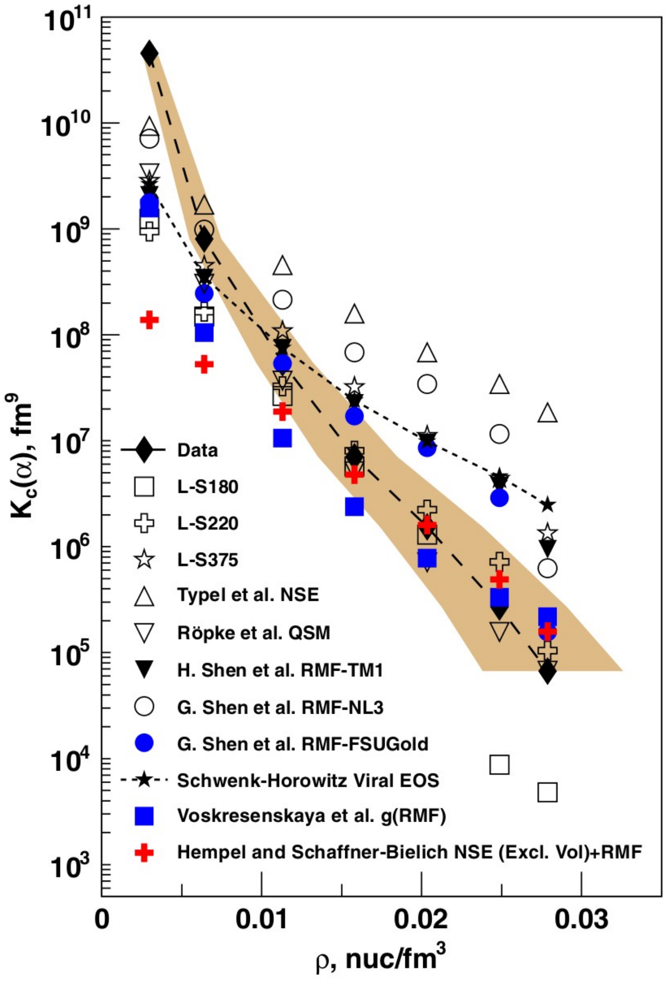
Equilibrium constants (K_c) from mass fractions and density compared with nuclear matter calculations

→ Properties of nucleons and clusters in nuclear medium do not correspond to their vacuum properties



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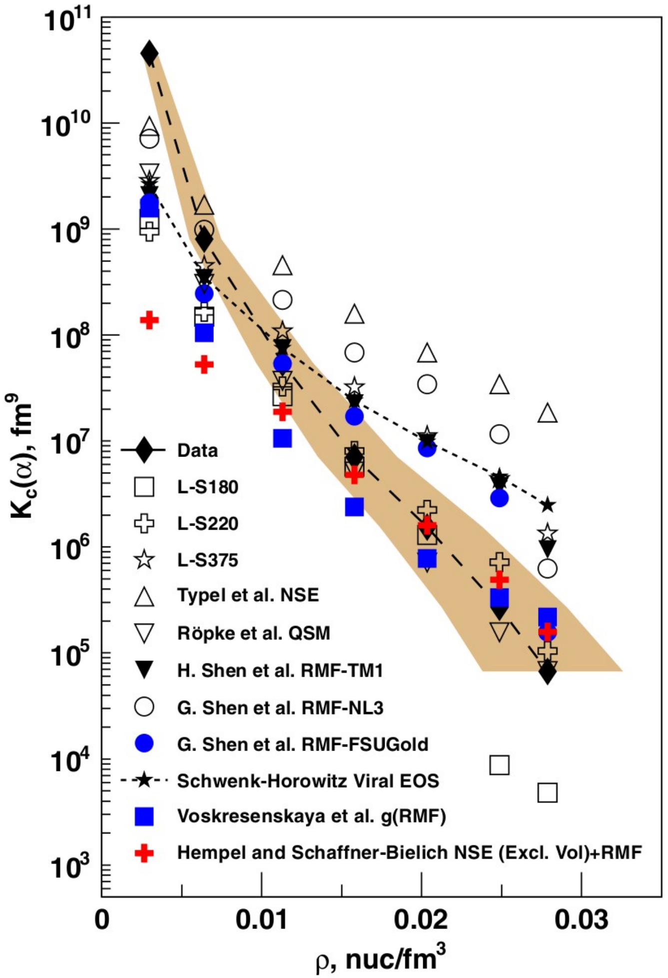
→ We can provide experimental constraints on in-medium cluster properties using heavy-ion collisions !



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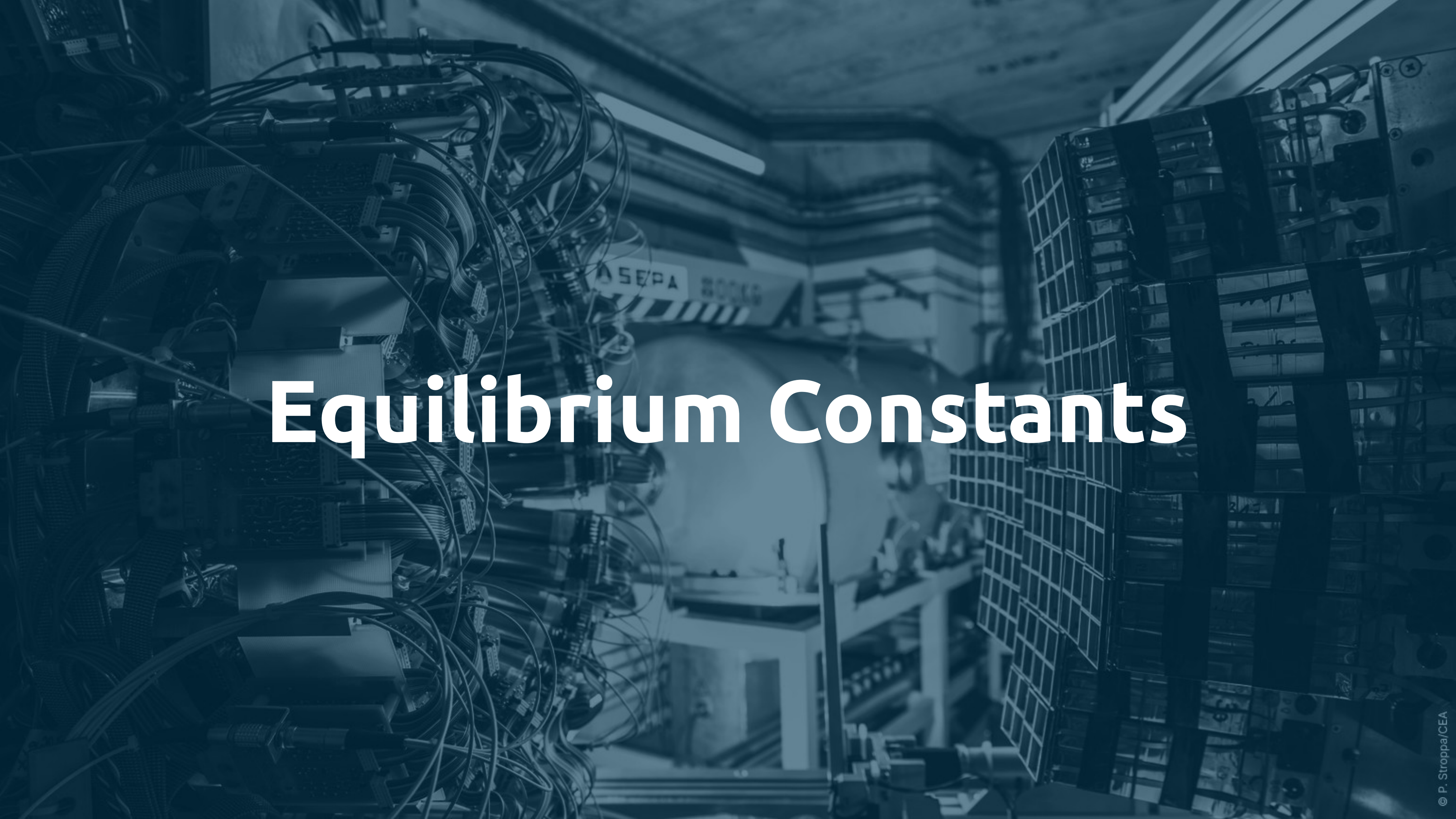
Equilibrium Constants

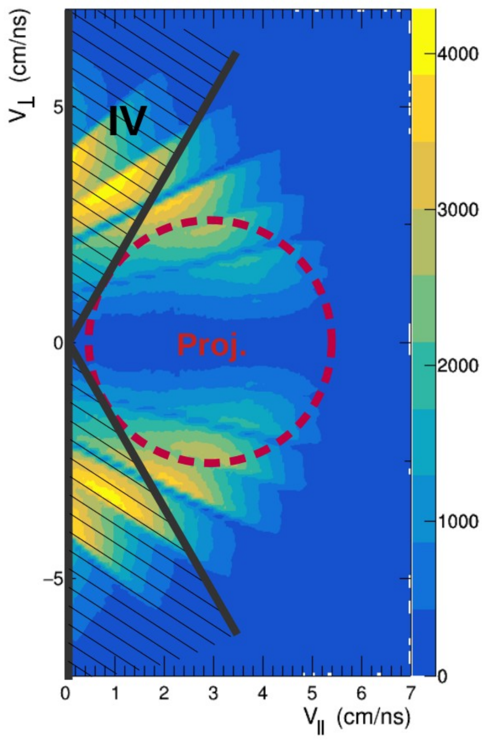


Experimental data

- $^{136,124}Xe + ^{124,112}Sn$ at 32 MeV/nuc. reactions at GANIL
- Charged reaction products measured with the INDRA 4π multidetector (no neutron detection)

Data selection

- Central collisions (cut on light particle transverse energy)
- Mid-velocity cut to select particles originating from the participant zone, excluding contribution from projectile



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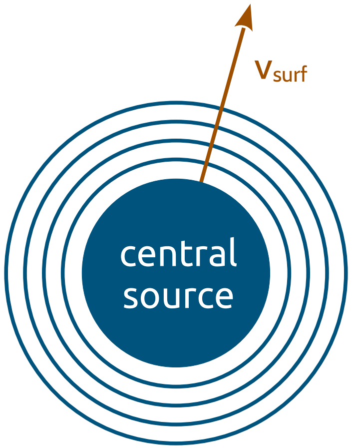
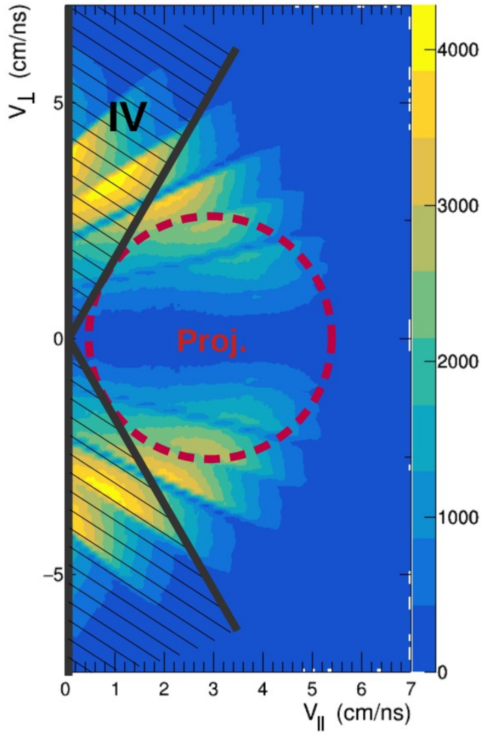
Evolution intervals

Surface velocity (v_{surf}) : particle velocity corrected from Coulomb repulsion of the « central » source :

$$v_{surf} = c \times \sqrt{1 - \left(\frac{mc^2}{E_k - Z \times E_C + mc^2}\right)^2}$$

→ v_{surf} bins correspond to different ensembles with different temperature and density





Temperature

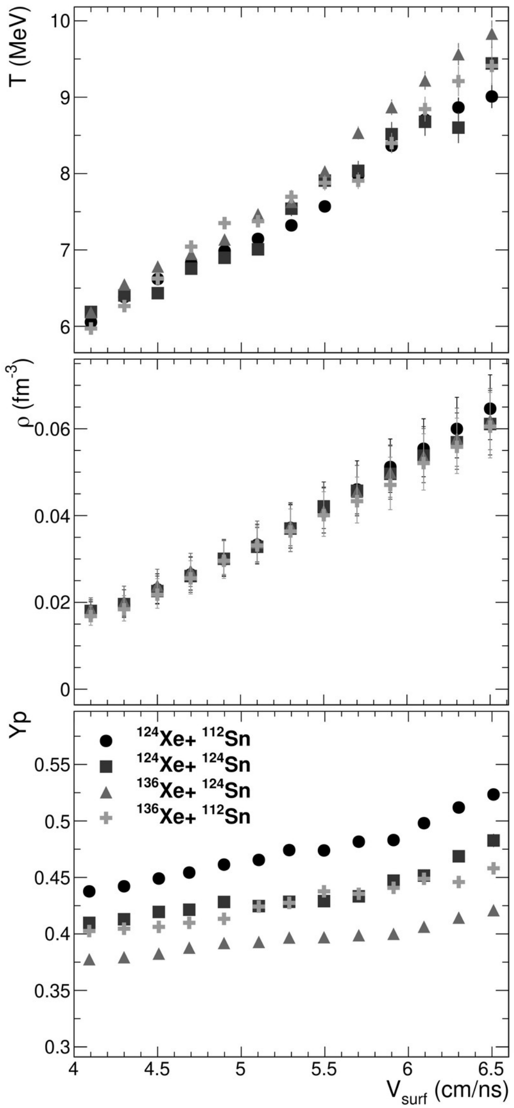
Albergo thermometer from ^{2}H, ^{3}H, ^{3}He and ^{4}He yields and vacuum binding energies

Density

Ratio of the total mass of the source and the free volume computed from momentum space density power law

Proton fraction

Neutron and proton content of measured clusters, free protons and free neutron (from ^{3}H and ^{3}He yields)



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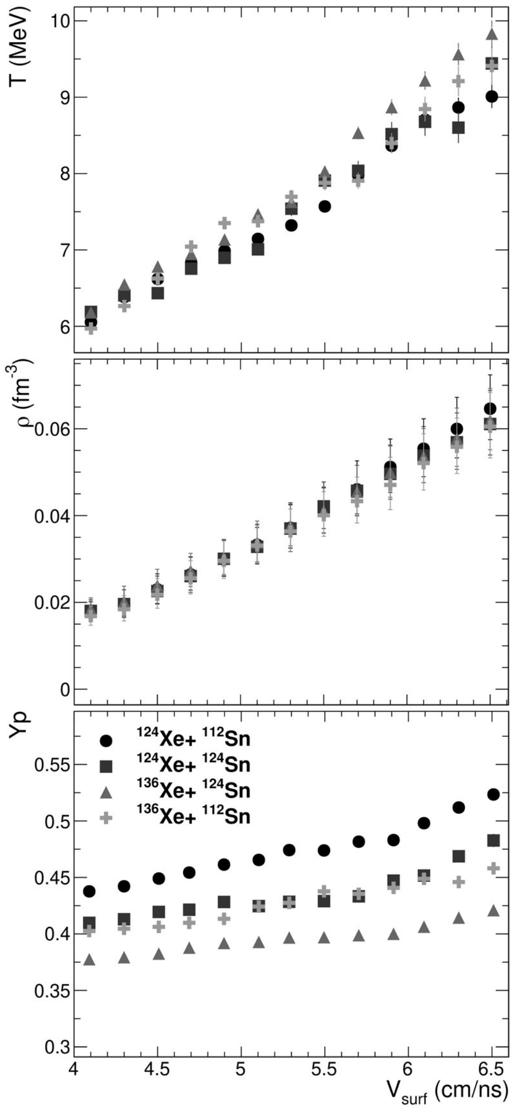
Proton fraction

Neutron and proton content of measured clusters, free protons and free neutron (from ^{3}H and ^{3}He yields)

→ Temperature, density and proton fraction increases with v_{surf}, coherent with an expanding source picture
→ Absolute values similar to NIMROD data
→ Proton fraction depends on the N/Z of the system

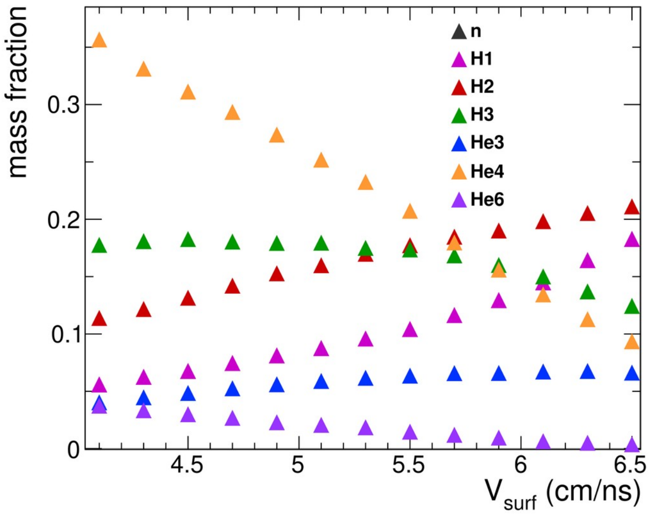


Mass fractions

Cluster and free nucleons mass fraction computed from measured cluster yields in each v_{surf} bin. Neutron yields estimated from ^3H and ^3He yields.

$$w_j = \frac{M_j \times A_j}{\sum_{i=1}^{M_{tot}} A_j}$$

→ Mostly ^4He at low density and temperature
→ ^4He decreases while other cluster increases with increasing desity and temperature



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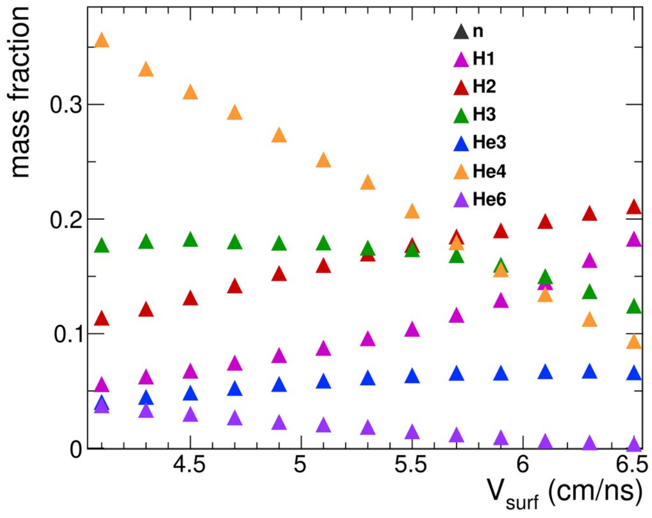
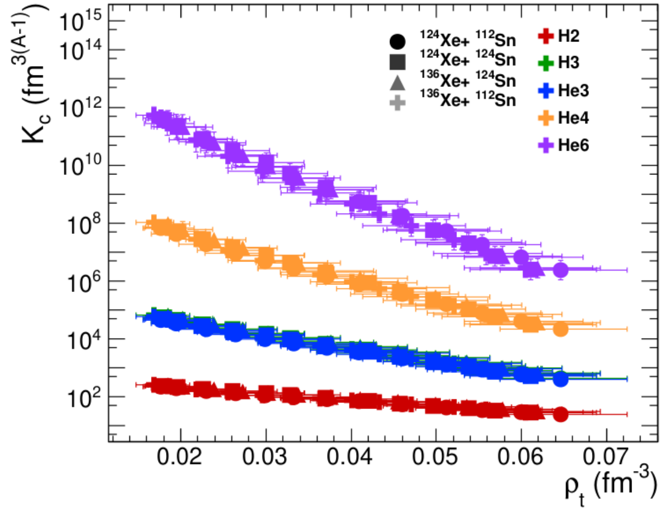


Equilibrium constants

Equilibrium constants (K_c) from mass fractions and density :

$$K_c(A, Z) = \frac{\rho(A, Z)}{\rho_p^Z \rho_n^{(A-Z)}} = \frac{\omega_{AZ}}{A\omega_{11}^Z \omega_{10}^{A-Z}} \left(\frac{V_T}{A_T}\right)^{A-1}$$

→ K_cs decrease with increasing density and temperature



RMF formalism

Nucleons and clusters treated as independent quasi-particles
Interactions are mediated by virtual mesons exchange

$$\mathcal{L} = \sum_{\substack{j=n,p,\\ ^2\mathrm{H},^3\mathrm{H},\\ ^3\mathrm{He},^4\mathrm{He}}} \mathcal{L}_j + \sum_{m=\sigma,\omega,\rho} \mathcal{L}_m + \mathcal{L}_{\omega\rho}$$

In-medium effects

- Binding energy shift (δB) due to Pauli blocking (theory)
- Quenching of the cluster-σ coupling x_s to be calibrated

$$M_j^* = A_j m - g_{\sigma j}\sigma - (B_j^0 + \delta B_j)$$
$$g_{\sigma j} = x_s A_j g_\sigma$$

→ H. Pais et al. PRC97, 045805 (2018)
→ H. Pais et al. PRC99, 055806 (2019)

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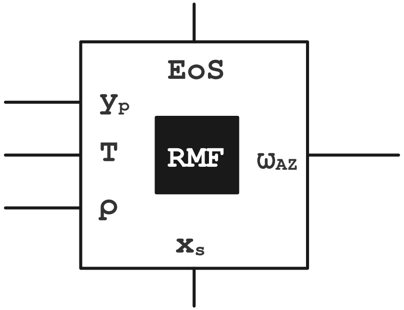

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RMF for experimentalists

- Input : proton fraction (y_p), density (ρ) and temperature (T)
- Output : nucleons and cluster mass fractions (ω_{AZ})
- Parameter : cluster coupling (x_s) and EoS

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Phase diagram exploration

- Fraction of clusters depends on ρ and T
- Individual mass fraction (ω_{AZ}) depend on ρ and T
- Clusters disolution density depends on x_s

→ H. Pais et al. PRC97, 045805 (2018)
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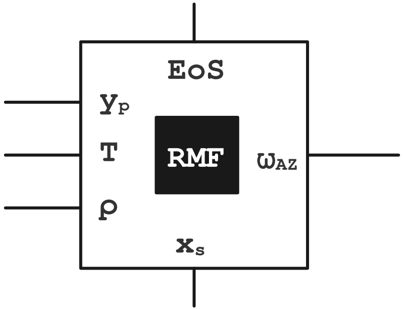
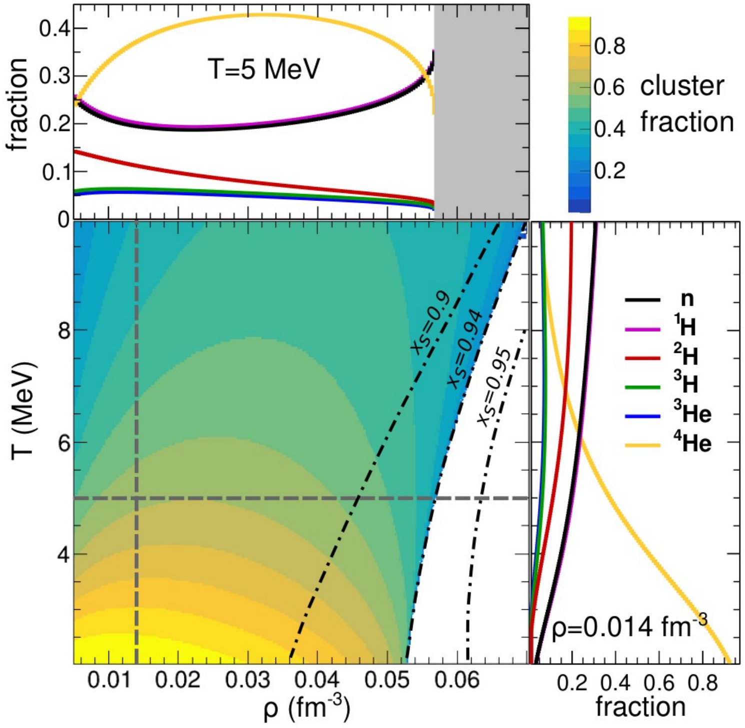


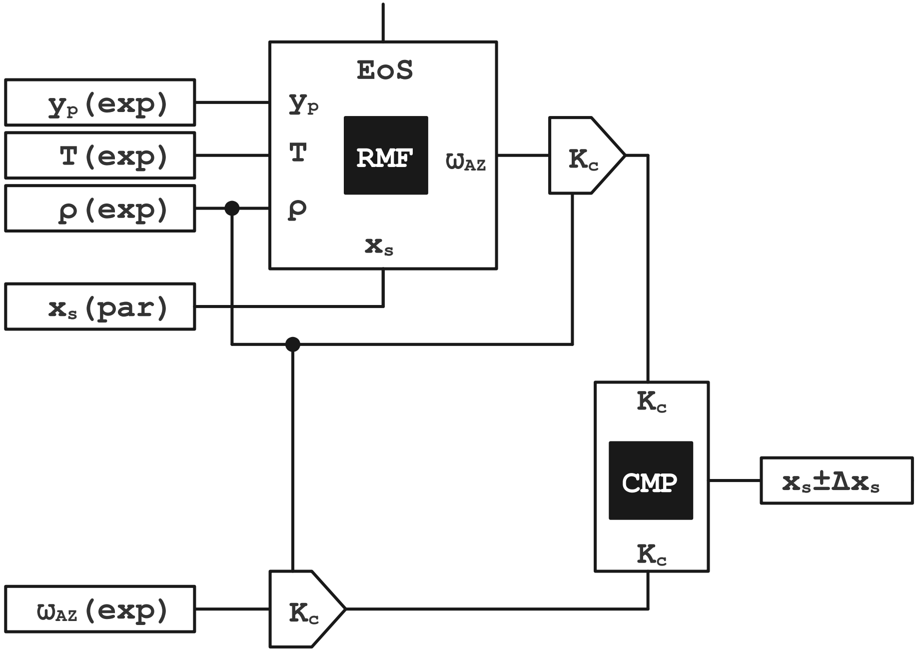


Inputs

- « Experimental » proton fraction (y_p)
- « Experimental » temperature (T)
- « Experimental » density (ρ)
- x_s parameter

Matching criteria

- Simple comparison of experimetal and simulated equilibrium constants for all clusters



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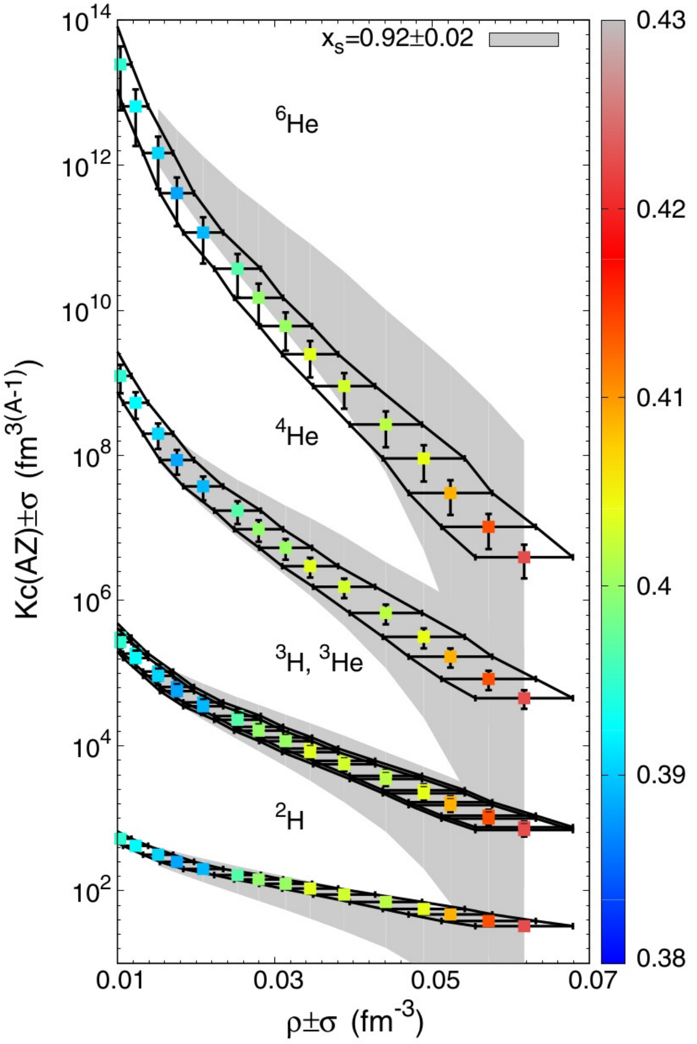
Result

Equilibrium constants of all clusters can be reproduced by RMF with a single value of **x_s = 0.92 ± 0.02**

→ H. Pais et al. J. Phys. G 47 (2020) 105204
→ H. Pais et al. PRL 125 (2020) 012701



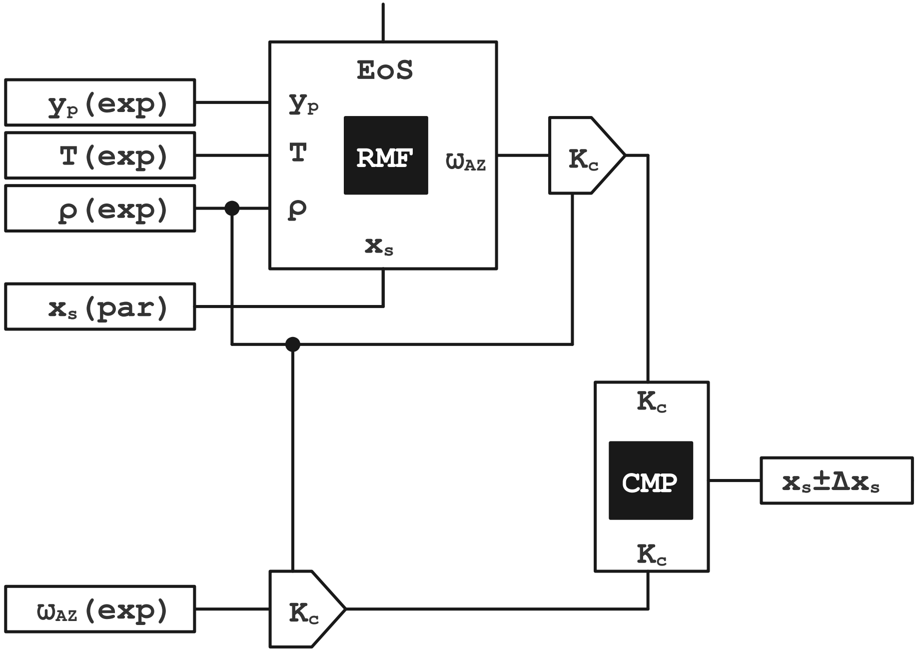
Contradiction

Experimental density and temperature rely on ideal gas hypothesis using vacuum binding energies

→ Binding energy modified, not an ideal gas !

Ubiquitous density

- Density as input of RMF calculation
- Density to compute RMF K_c from ω_{AZ}
- Density to compute experimental K_c from ω_{AZ}



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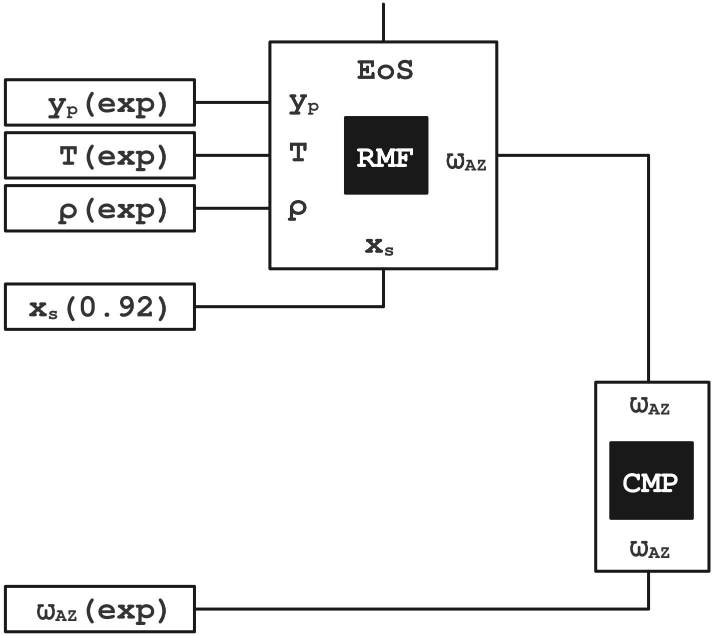
Temporary fix

Remove part of the densities comparing ω_{AZ}
Compute RMF mass fractions with the value of x_s extracted from K_c



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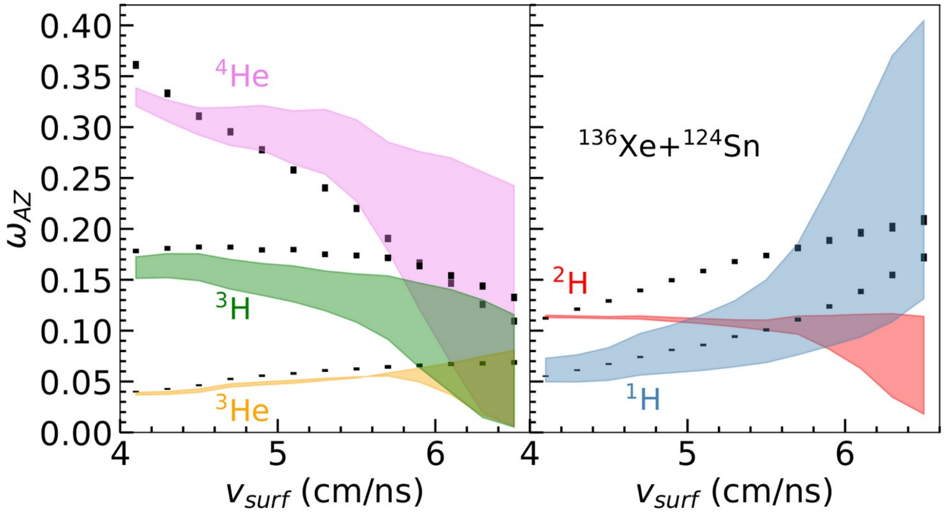
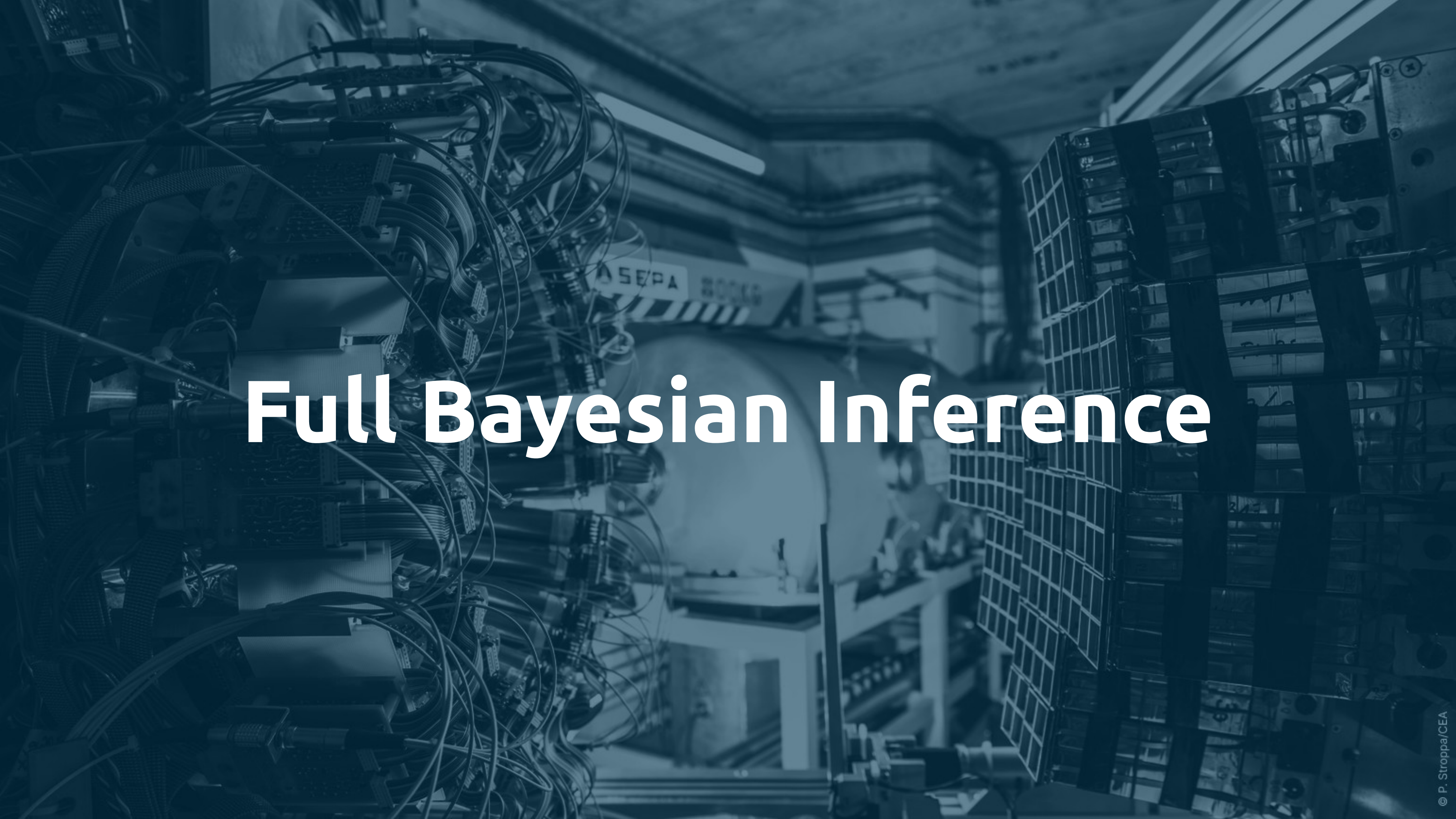
Disappointment

- Poor reproduction of ^3H and ^3He
- Terrible reproction of ^2H (not even the trend)



Full Bayesian Inference

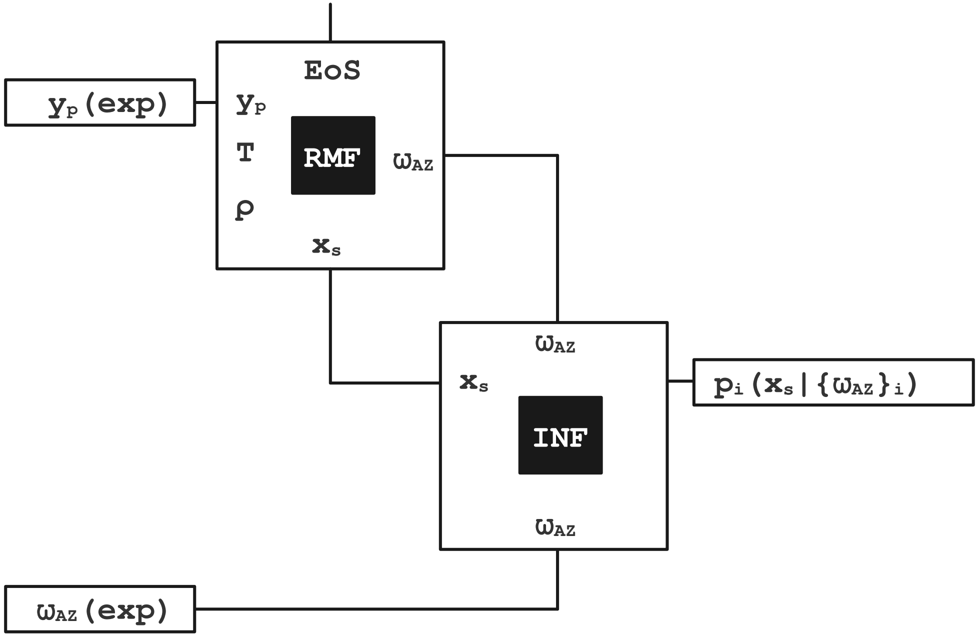


Guidelines

Replace the simple comparison procedure with a proper bayesian inference

Emancipate from ideal gas hypothesis :

- Use only direct observables as RMF input
- Compare experimental and RMF mass fractions



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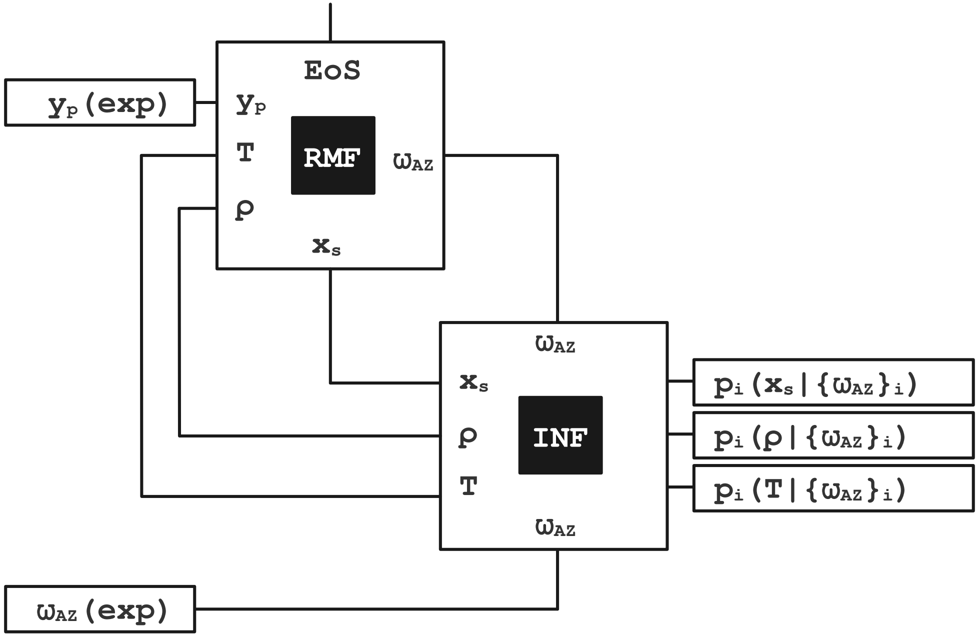

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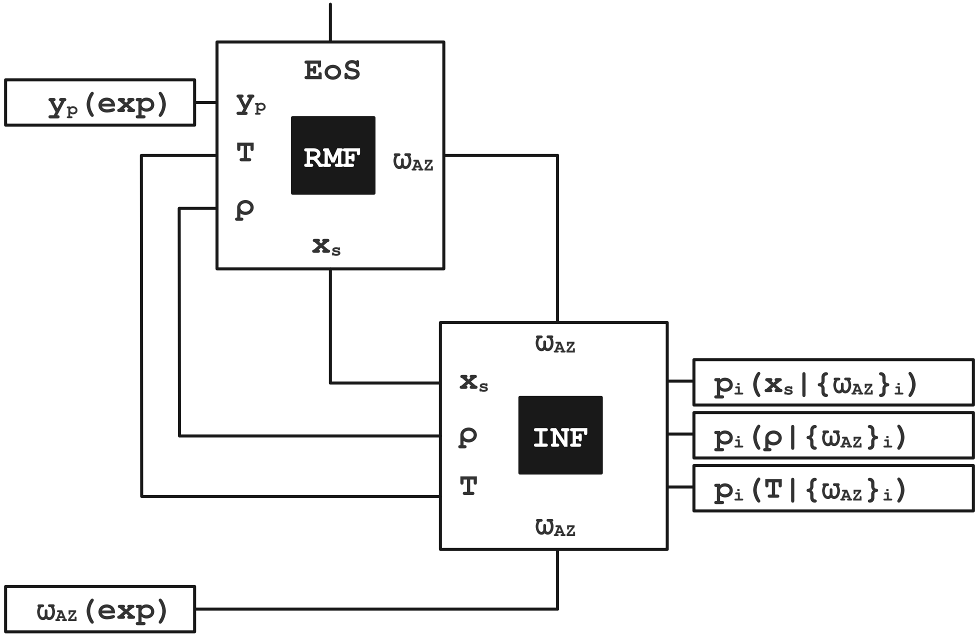
Inputs

- Experimental proton fraction (y_p)
- Experimental mass fractions (ω_{AZ})

Output

Posterior distributions of x_s, ρ, and T for each v_{surf} bin and each reaction system using flat priors and gaussian likelihood



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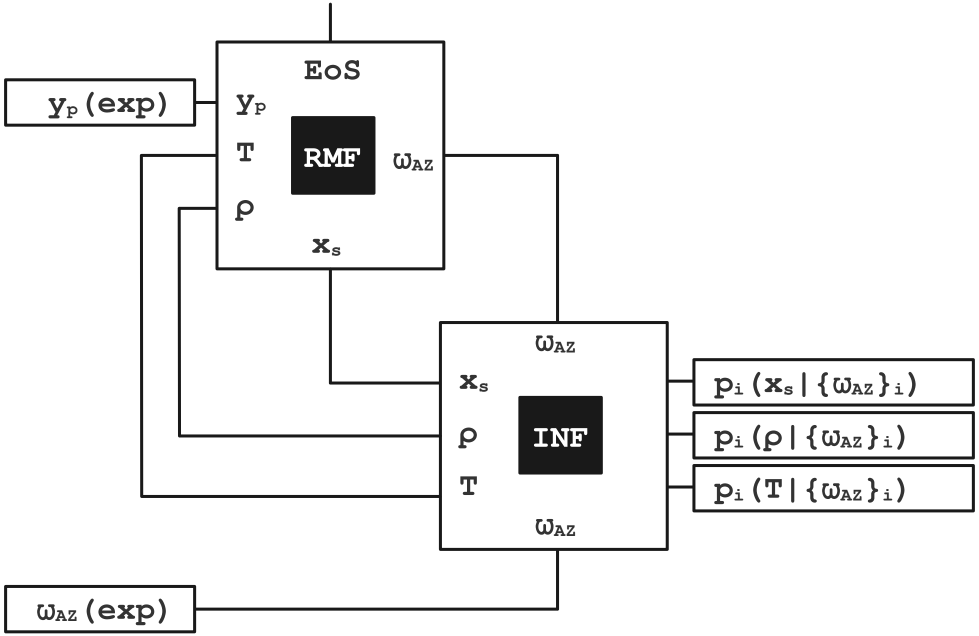
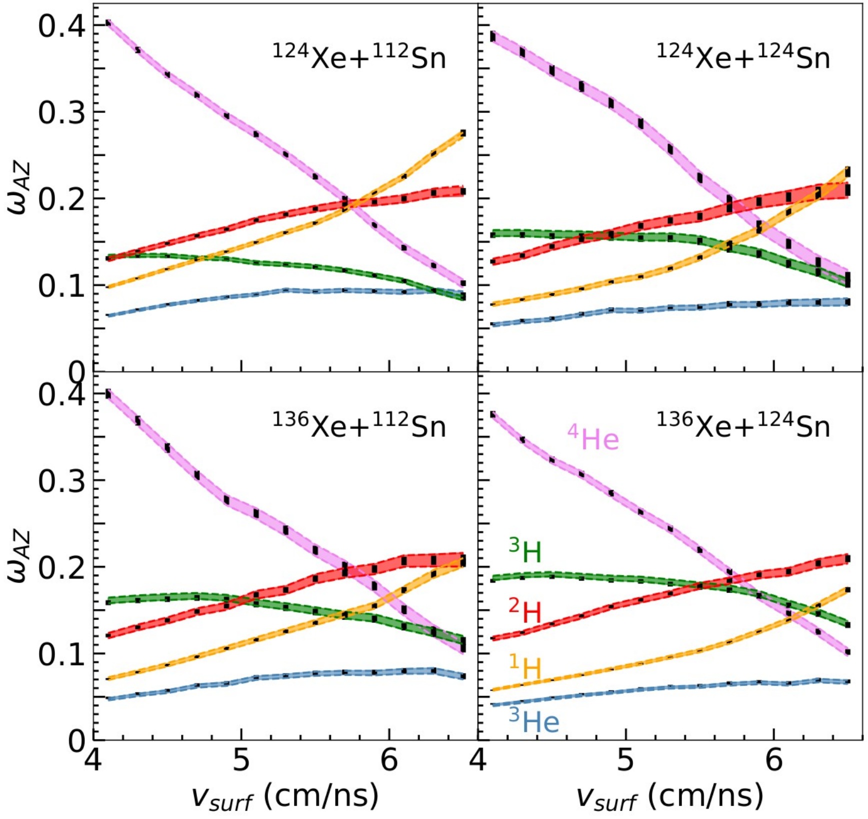
Implementation

Inference performed using **`PyMultiNest`** sampler and verified with julia wrapper



Model calibration

RMF mass fractions using marginalised posterior distributions (2σ) compared to INDRA data
→ Excellent reproduction of the mass fractions for all v_{surf} bins and for all systems



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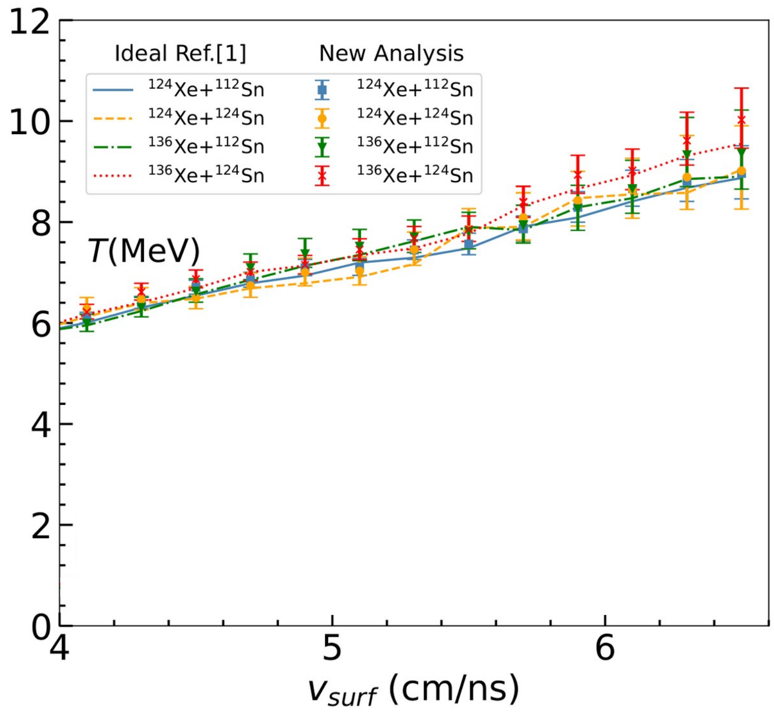
Temperature

Temperature still increases with increasing v_{surf}

Compatible with previous ideal gas estimate

$$T = \frac{B(^4He) + B(^2H) - B(^3He) - B(^3H)}{\ln\left(\sqrt{9/8} \times 1.59 \frac{M(^2H)M(^4He)}{M(^3H)M(^3He)}\right)}$$



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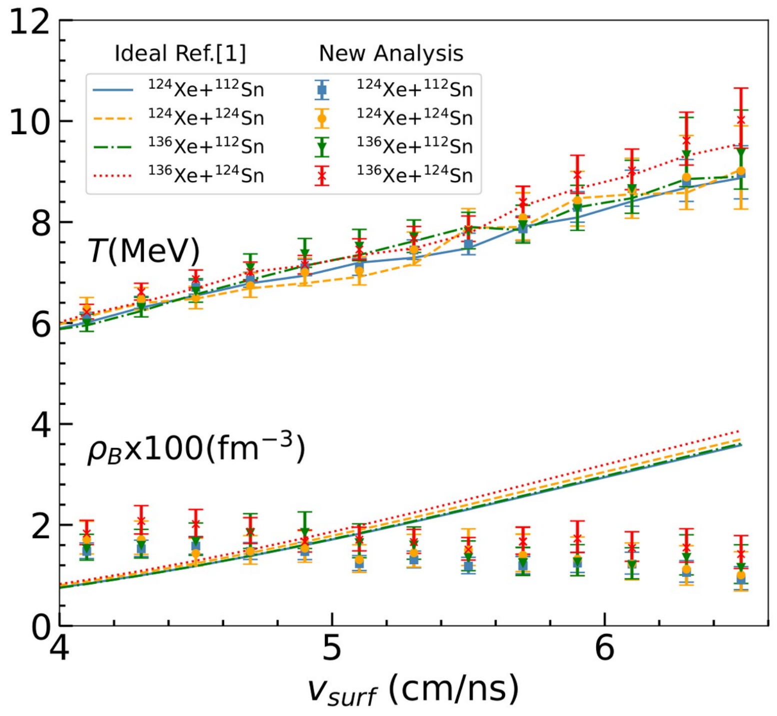
Density

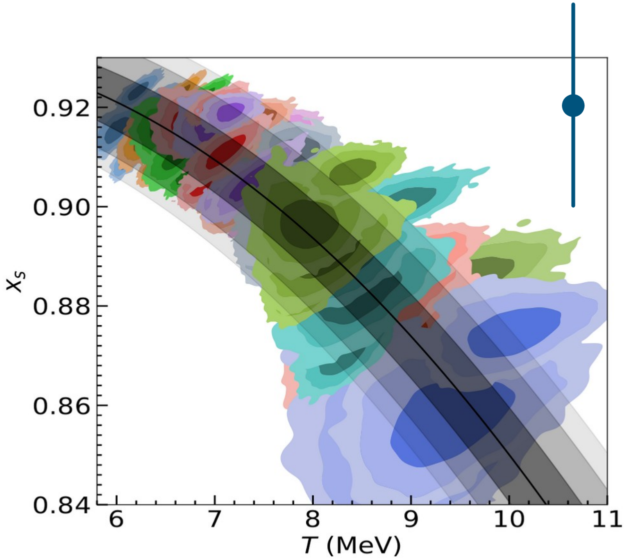
Almost same density for all v_{surf} bins
Very different with respect to ideal gas estimate
→ Compatible with a fixed density freeze-out picture

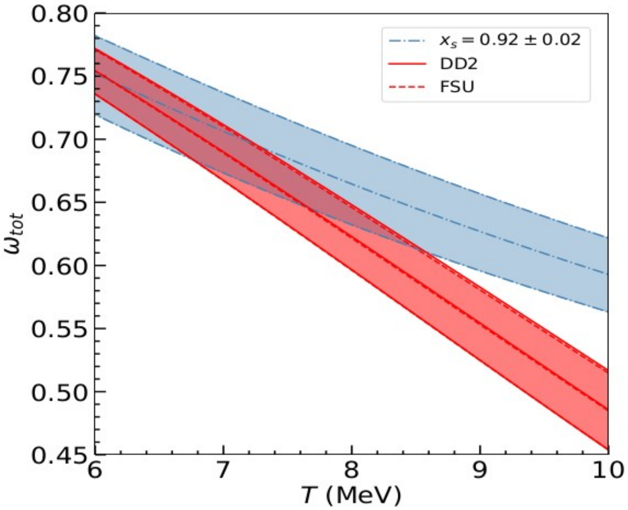


Cluster coupling

- Similar value as previous analysis at low temperature
- x_s decreases with increasing temperature
- We could not extract any density dependance because the inference pointed to a unique density

$$M_j^* = A_j m - g_{\sigma j}\sigma - (B_j^0 + \delta B_j)$$
$$g_{\sigma j} = x_s A_j g_\sigma$$





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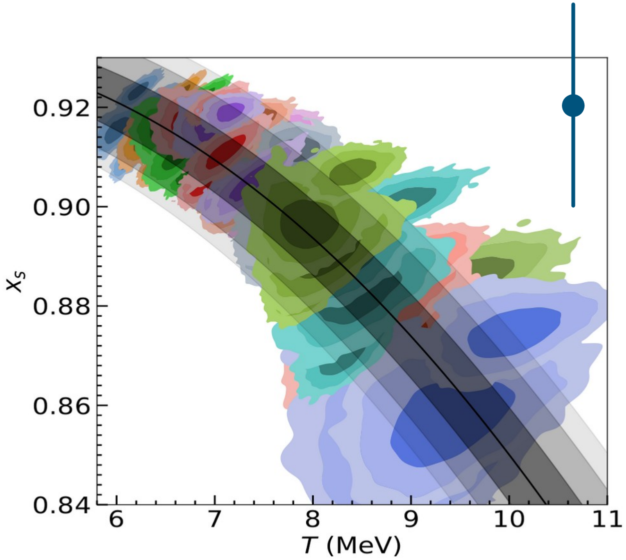
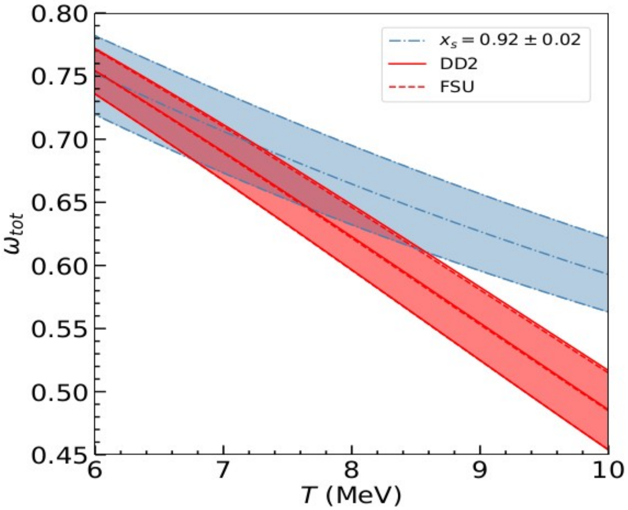
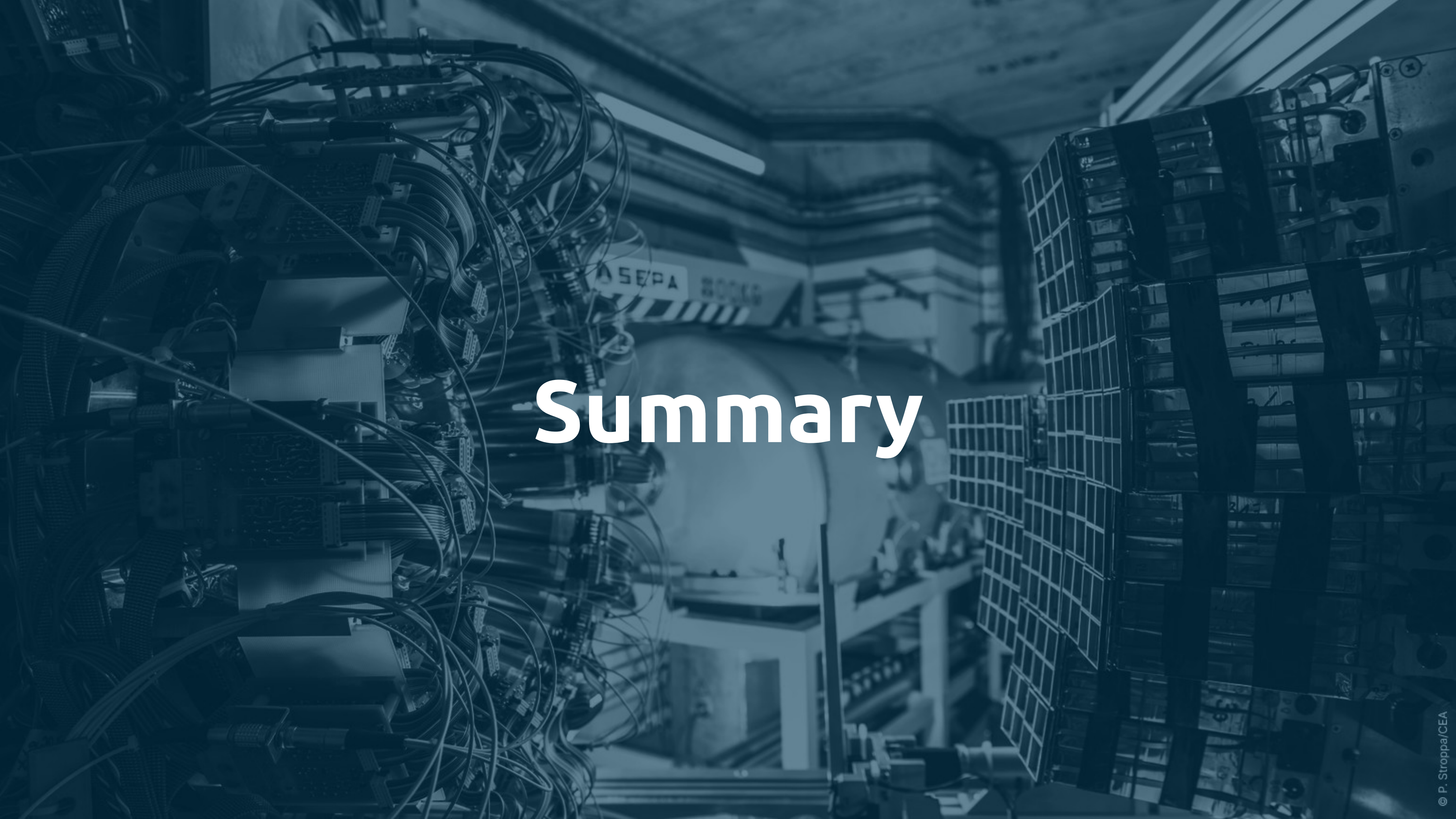
$$g_{\sigma j} = x_s A_j g_\sigma$$

Cluster fraction

Same total cluster fraction at low temperature (same x_s)
→ Cluster fraction decreases faster with increasing temperature







Summary

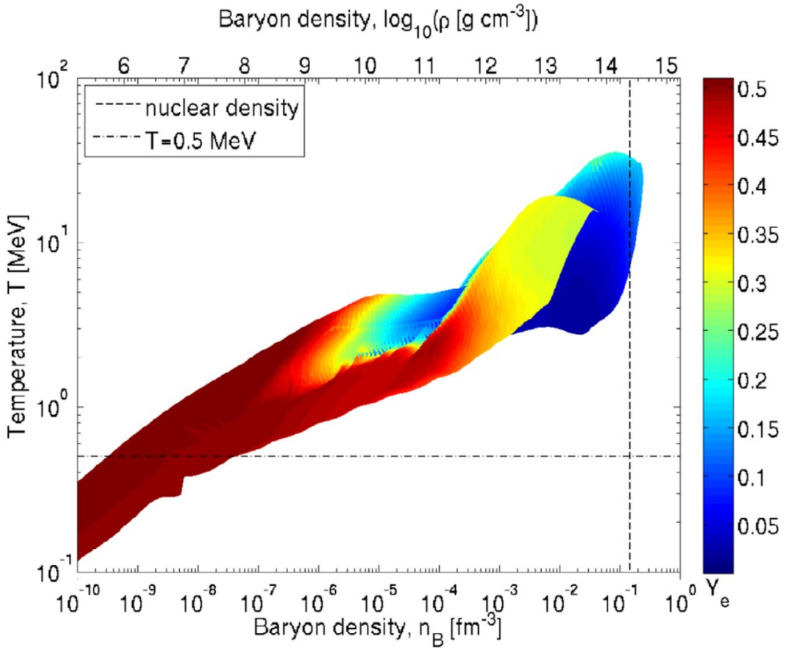
Motivations

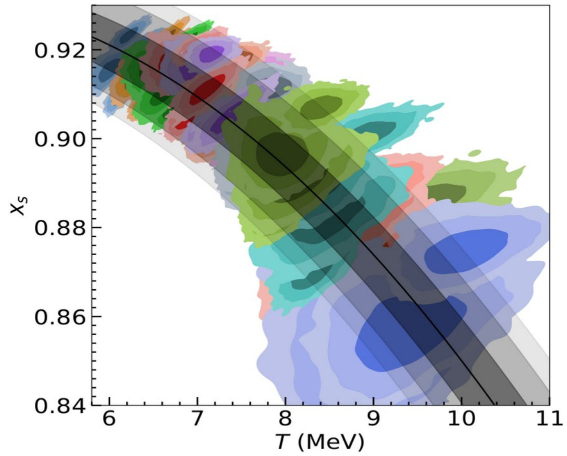
Modeling low density nuclear matter with clusters needs experimental input to calibrate in-medium cluster properties

Bayesian calibration

Cluster mass fractions measured with INDRA were compared to RMF calculations :

- Temperature posterior similar to ideal gas hypothesis
- Density posterior compatible with single density
- σ-meson-cluster coupling (x_s) posterior distribution





Motivations

Modeling low density nuclear matter with clusters needs experimental input to calibrate in-medium cluster properties

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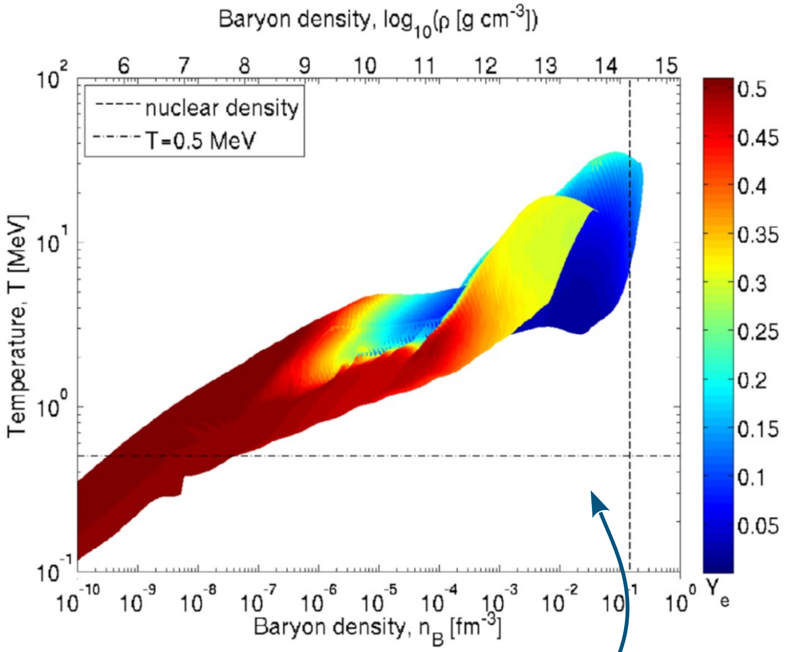
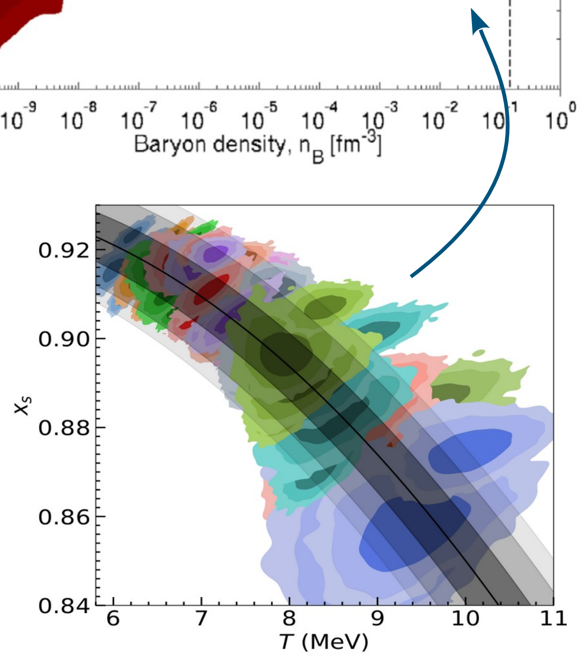
And then ?

Use this posterior to feed astrophysic simulations



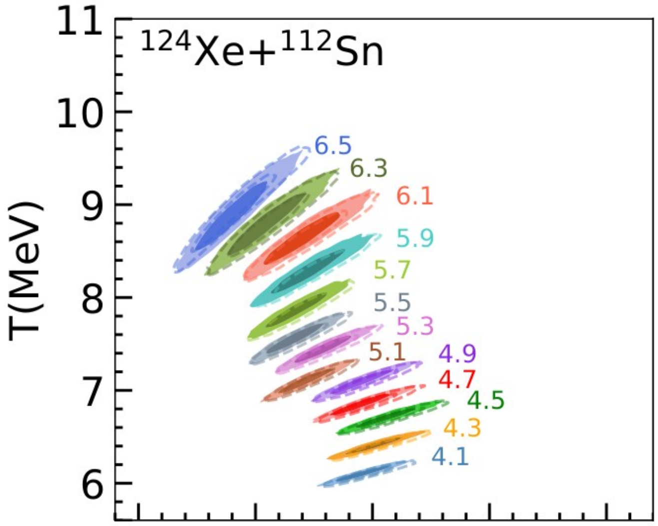


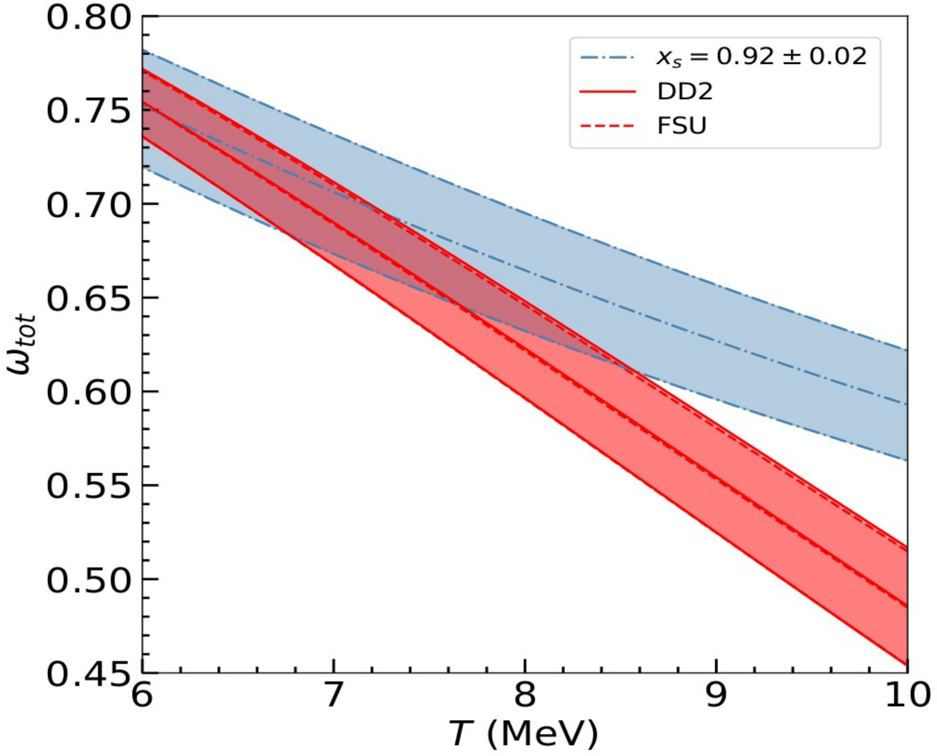
And the EoS ?

- Full analysis done with two EoS (FSU and DD2)

→ No effect on temperature and density posterior

→ No effect on x_s posterior and cluster fractions





Vaporisation source

- Check the analysis and interpretation with particles from quasi-projectile vaporisation source
- Explore different thermodynamics conditions
- Extend to higher mass clusters (Li, Be…)

New experiment

- Ar + Ni and Ni + Ni at 74 MeV/nuc.
- INDRA-FAZIA coupling at GANIL

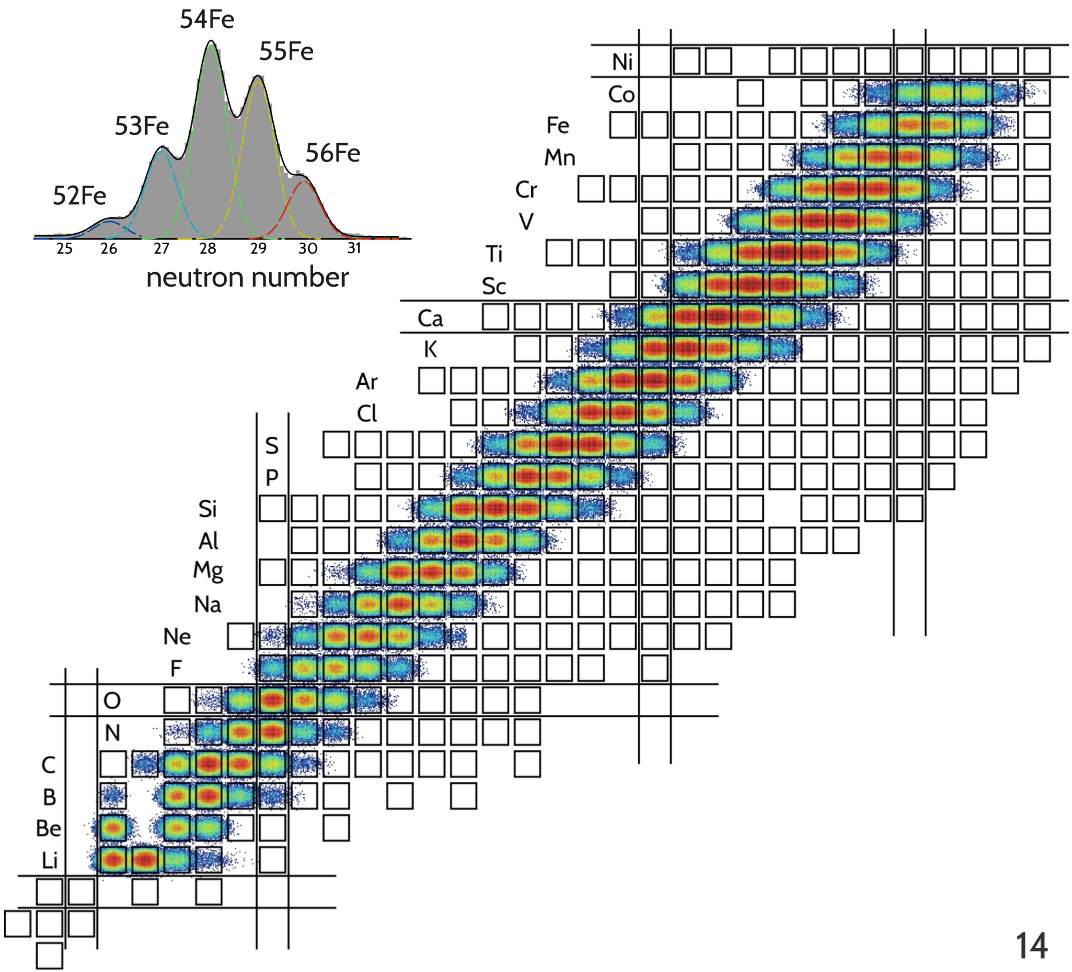
→ Allows for a good reconstruction of the collision geometry and isotopic identification of all forward emitted particles

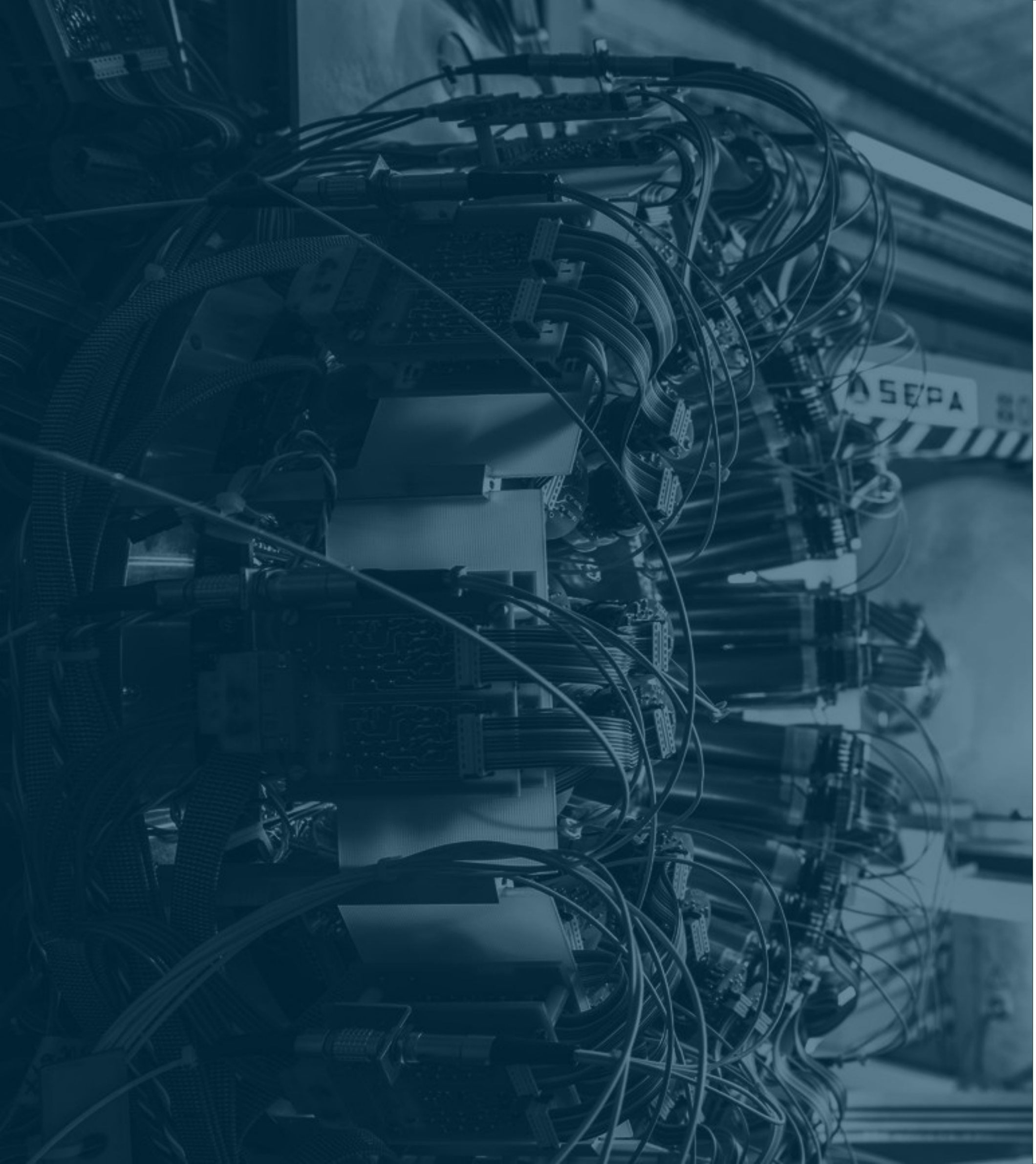
Analysis

- Experiment performed in 2022
- Data reduction finished (Alex)

→ Results available soon !

→ Compare with transport models ?





Many thanks to :

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[1] CFisUC , University of Coimbra, Portugal
[2] LPC, Caen, France

Support :
PESSOA agreement

IRL NPA CNRS - MSU

Many thanks to the organizers !

Thank you