Light clusters in hot nuclear matter: calibrating the interaction with heavy-ion collisions

(arXiv:2407.02307 [nucl-th])

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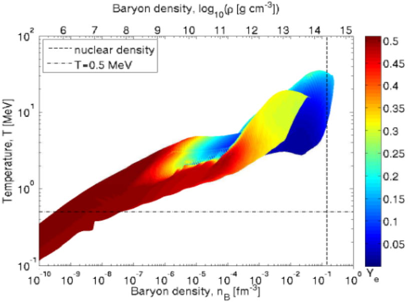
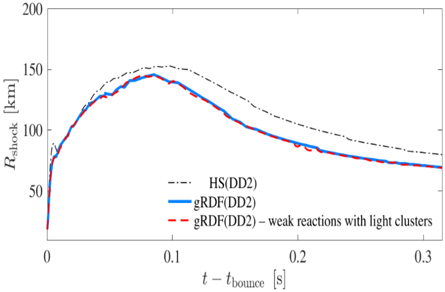
Motivation

- Light nuclei might be present in both Core-Collapse Supernova and Binary Neutron Star Mergers
- Their presence influences the dynamics of these astrophysical events
- Accounting for in-medium modifications to the light clusters is essential to determine their correct abundances



[Fischer et al. (2014)]



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- In Relativistic Mean-Field Theory, the interactions are mediated via the exchange of virtual mesons:

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- The Lagrangian density for matter made of protons, neutrons and light clusters is:

$$\mathcal{L} = \sum_{b=n,p} \mathcal{L}_b + \sum_{m=\sigma,\omega,\rho} \mathcal{L}_m + \sum_{\substack{i={}^2\mathrm{H},{}^3\mathrm{H},\\ {}^3\mathrm{He},{}^4\mathrm{He}}} \mathcal{L}_i \tag{2}$$

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- The Lagrangian density for the **nucleons** is:

$$\mathcal{L}_b = \bar{\Psi}_b(x) \left[i\gamma_\mu D_b^\mu - m_b^* \right] \Psi_b(x) \; , \tag{3}$$

$$iD_b^\mu = i\partial^\mu - g_{\omega b}\omega^\mu - g_{\rho b}\vec{I}_b \cdot \vec{\rho^\mu} \tag{4}$$

$$m_b^* = m_b - g_{\sigma b}\sigma \tag{5}$$

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- Calibrated to experimental nuclear parameters (e.g. FSU)

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• Light clusters can be included as point-like independent quasi-particles, in the same way as nucleons, taking into account their corresponding spins

$$\mathcal{L}_i = \bar{\Psi}_i \left[\gamma_\mu i D_i^\mu - M_i^*\right] \Psi_i, \; i = {}^3\mathrm{H}, {}^3\mathrm{He} \tag{6}$$

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$$\begin{aligned}\mathcal{L}_i = {}& \frac{1}{4}\left(iD_i^\mu \Psi_i^\nu - iD_i^\nu \Psi_i^\mu\right)^* \left(iD_{\mu i}\Psi_{\nu i} - iD_{\nu i}\Psi_{\mu i}\right) \\ & -\frac{1}{2}\Psi_i^{\mu *}(M_i^*)^2\Psi_{\mu i}, \quad i = {}^2\mathrm{H}\end{aligned} \tag{8}$$

Relativistic Nuclear Field Theory

- Light clusters ($i = {}^2\mathrm{H}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}$) will have their own cluster-meson couplings:

$$g_{\sigma i} = x_s A_i g_{\sigma N} \tag{9}$$

$$g_{\omega i} = A_i g_{\omega N} \tag{10}$$

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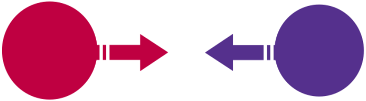
• $x_s(\rho, T)$ is a way of accounting for in-medium modification of the clusters self-energies

INDRA Heavy-Ion Collisions

$$\boxed{{}^{136,124}\mathrm{Xe}+{}^{124,112}\mathrm{Sn}\ (32\mathrm{MeV/nucleon})}$$

- Only **central collisions** selected (most violent)

Projectile-target central collision



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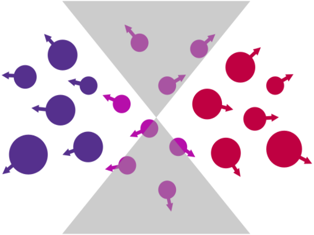

Angular selection : mid-velocity products

Credits: Alex Rebillard-Soulié

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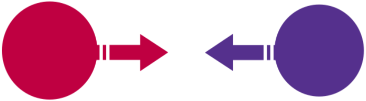

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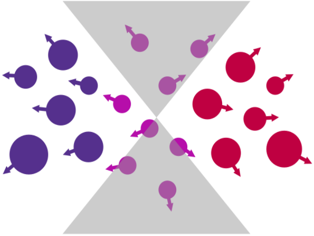

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- **Angular selection** to reduce secondary decays from other sources

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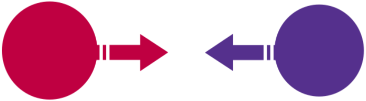

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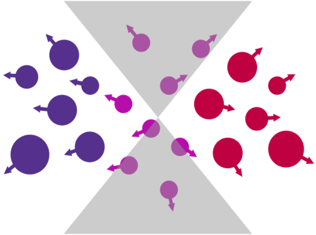

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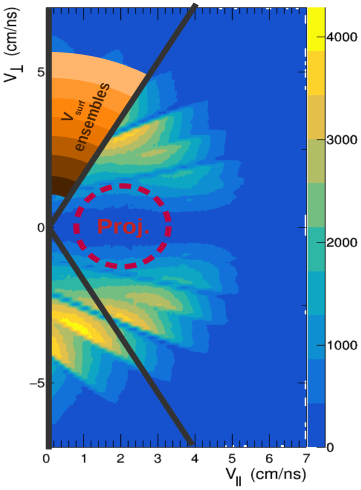
- Data sorted in bins of the average Coulomb-corrected particle velocities v_{surf}



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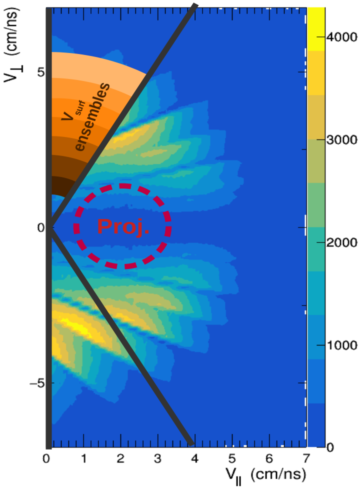

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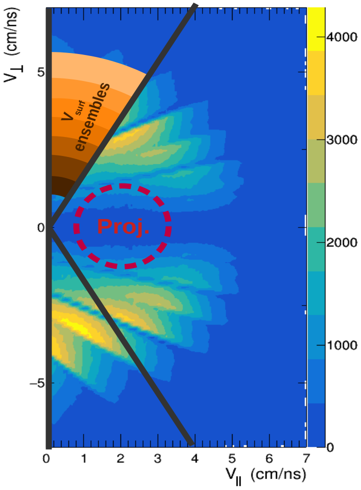

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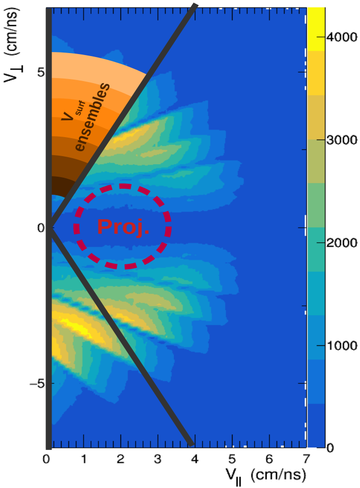
- Associate a statistical ensemble to each v_{surf} with corresponding particle mass fractions (nucleons and light clusters)



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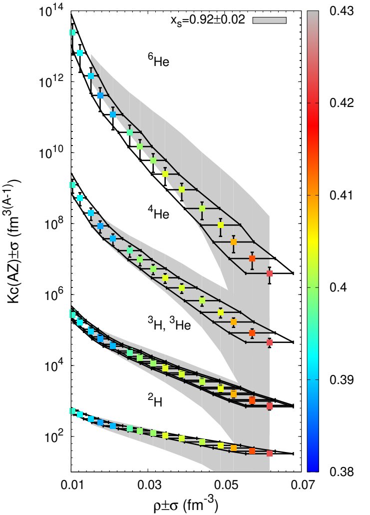
Calibration of x_s with Kc from HIC

- T and ρ estimated considering an ideal gas of clusters in the grand canonical ensemble
[Bougault et al. (2020)]



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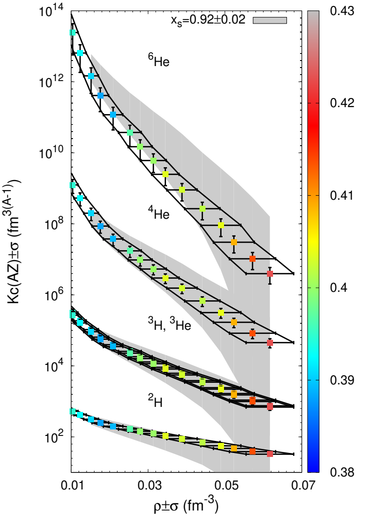

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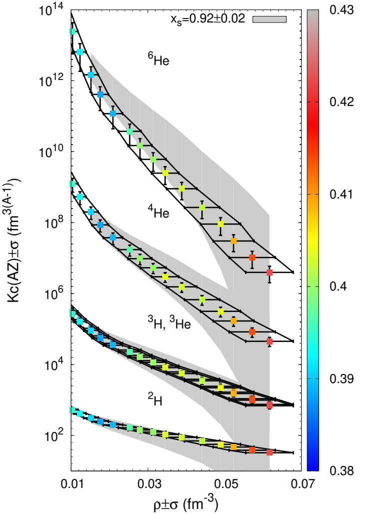

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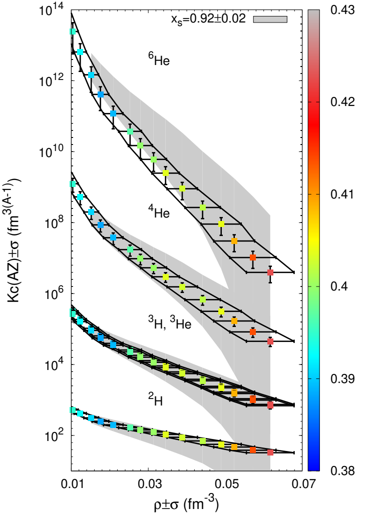
- x_s has been calibrated by roughly considering the values that best fit the data visually



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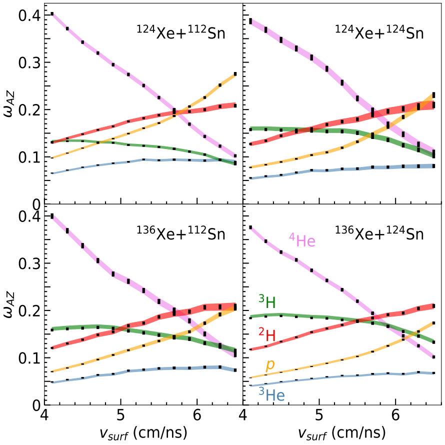
• For each system and v_{surf} bin, we carry out an independent Bayesian inference on the measured mass fractions ($4N_v = 52$)

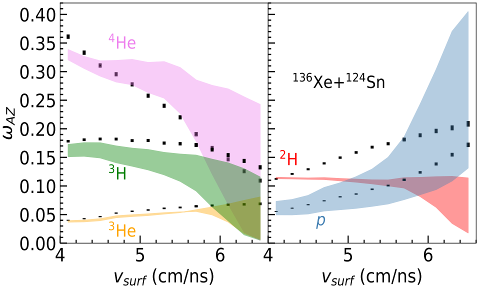
$$p_i\left(\theta|\{\omega_{AZ}\}\right) = \frac{p_\theta}{\mathcal{Z}} \mathcal{L}_{\mathrm{g}}\left(\{\omega_{AZ}\}_i|\theta\right), \quad \theta = \{T, \rho, x_s(\rho, T)\} \qquad (12)$$

Mass Fractions

Present Study

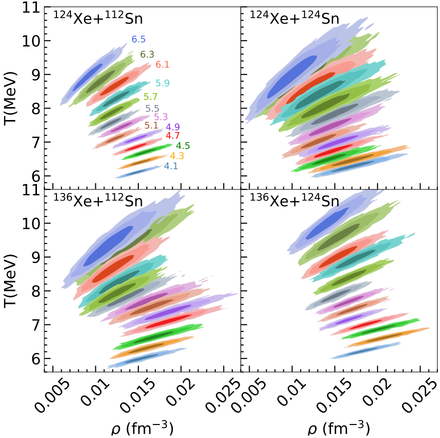


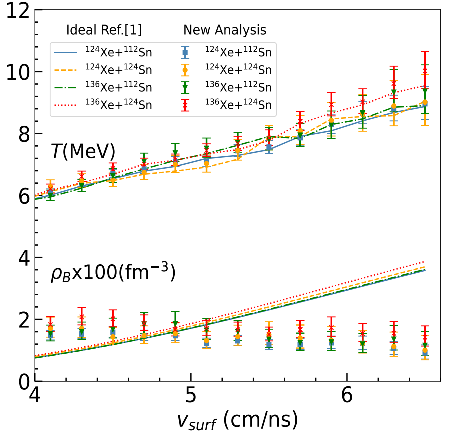
Modified Ideal Gas



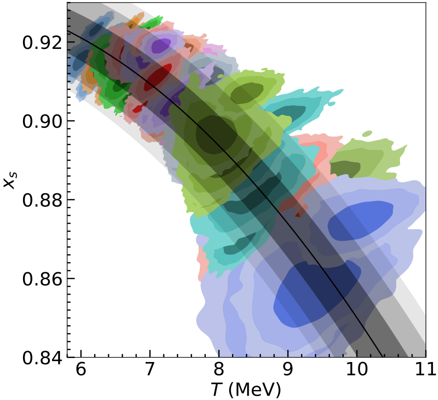
Calibrated Temperatures and Densities

- Temperature evolution similar to the ideal gas estimation
- Results compatible with a single density $\sim$0.015 fm^{-3}: chemical freeze-out density at the surface of the emitting source (?)





Calibrated $x_s(T)$

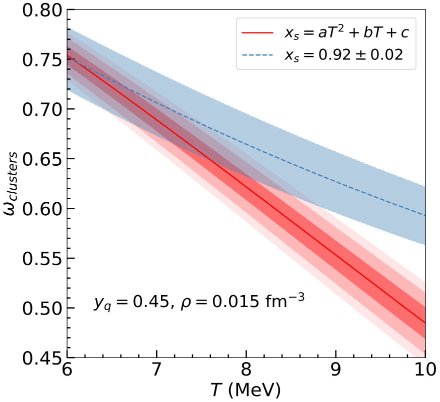


- x_s is temperature dependent
- Interaction weakens with T
- $x_s(T)$ compatible for all four entrance channels
- Limited ρ range cannot provide information on possible x_s dependence on ρ

Parameter	Unit	Median	1σ	2σ
a	MeV^{-2}	-0.00203	± 0.00003	± 0.00006
b	MeV^{-1}	0.01477	± 0.00047	± 0.00093
c		0.90560	± 0.0018	± 0.00355

Table: Parameter estimates a, b, c with 1, 2σ uncertainties for the quadratic fit $x_s = aT^2 + bT + c$

Consequences of $x_s(T)$ for light cluster abundances



- Above $T \sim 8$ MeV abundances are systematically lower than the predictions of modified ideal gas
- Smaller x_s corresponds to weaker cluster-σ coupling, resulting in less bound clusters and, consequently, smaller abundances

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- T shows same increasing behaviour as before but the density turned out to be constant: chemical freeze-out (?)
- x_s shows a dependence on T, weakening the clusters binding and abundances

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