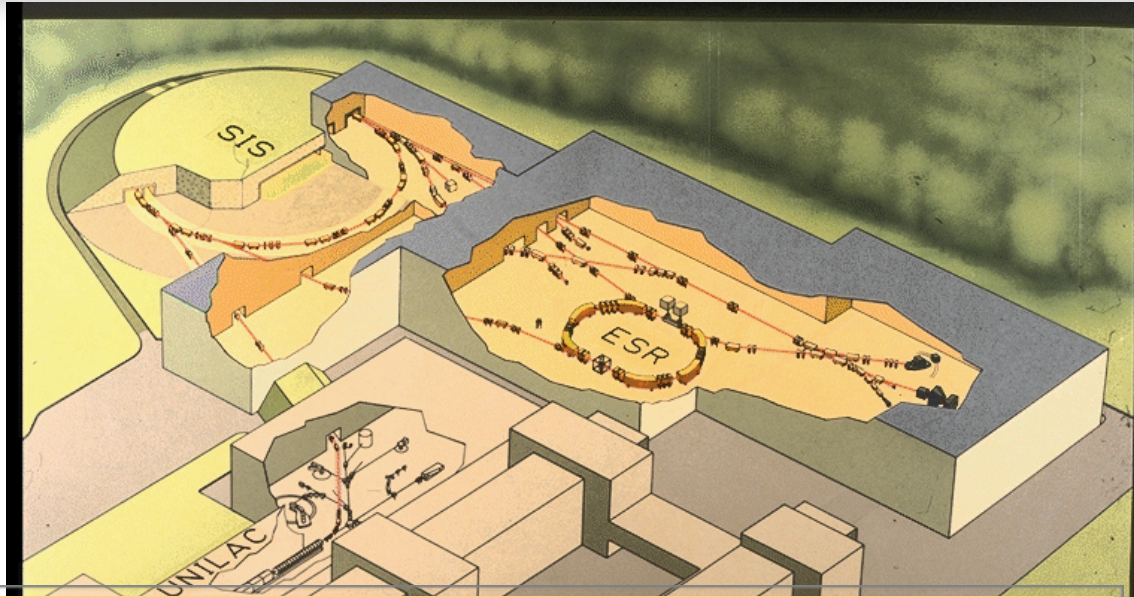


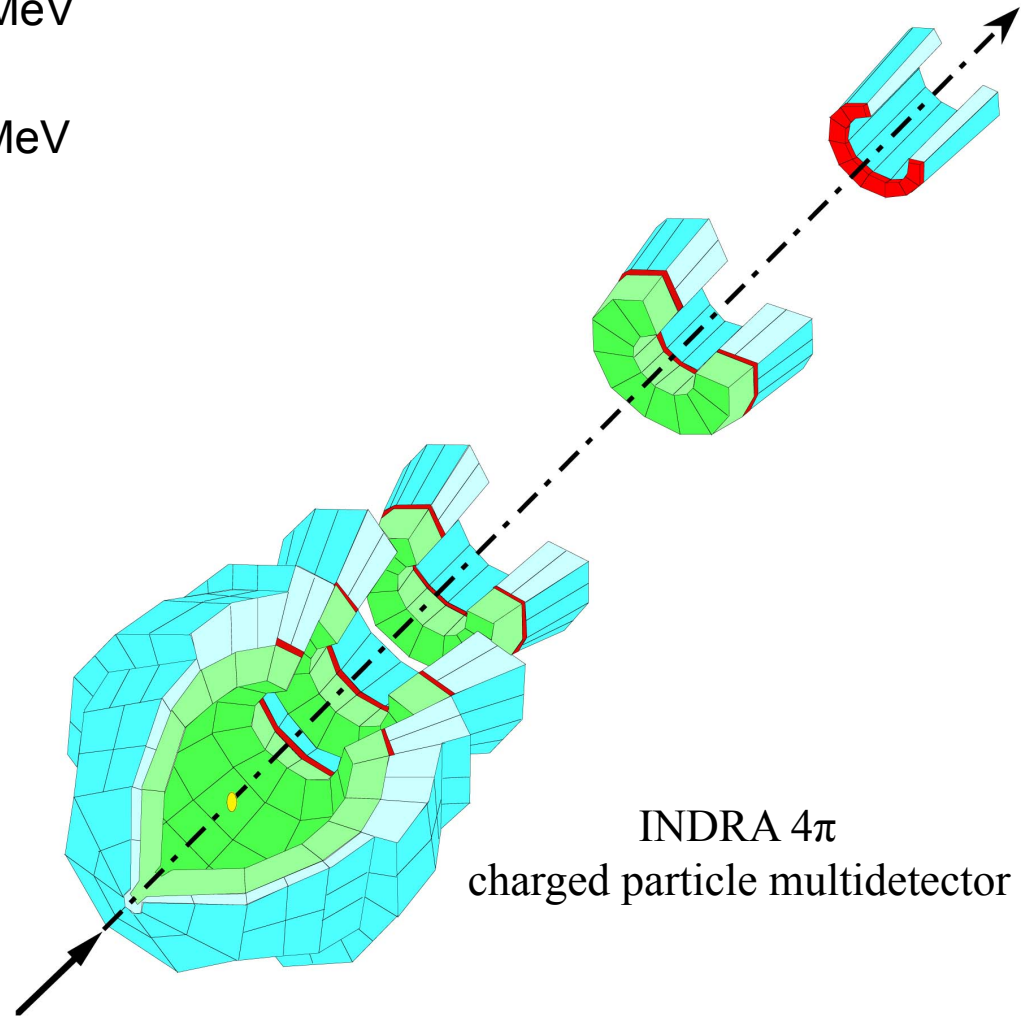
Asymmetry energy and nuclear matter EoS: What have we learnt from experiments at SIS18 ?



- Overview of experiments performed at GSI over 20 years with HICs at relativistic energies.
- From low densities (probed via isotopic yields): INDRA, ALADiN.
- To high densities (probed via elliptic flows of particles, kaon and pion yields): FOPI, KaoS, LAND, AsyEOS.
- A tentative synthesis: how HICs compare with recent astrophysical findings.

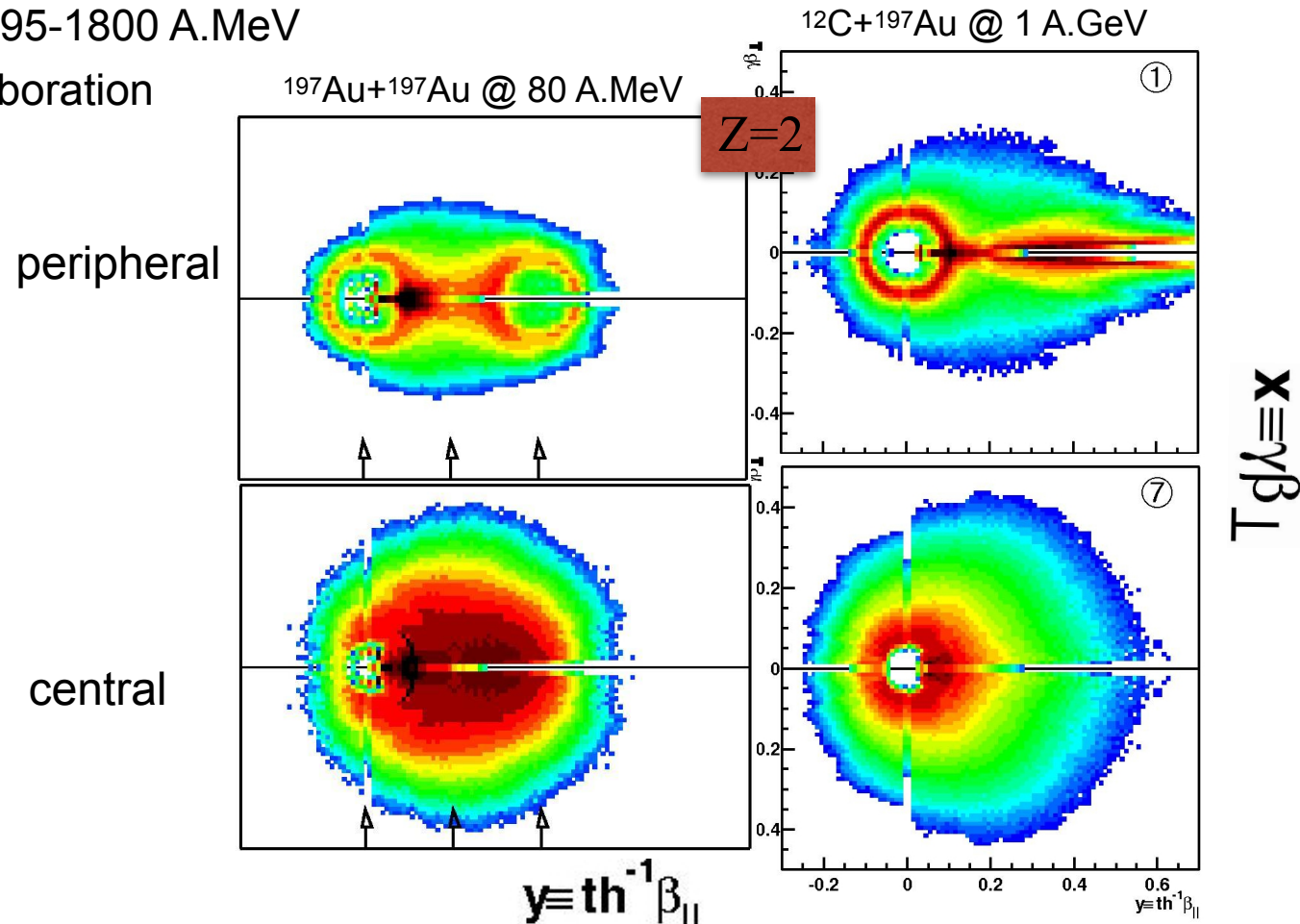
Isotopic method: sub-saturation densities INDRA@GSI

- $^{124,124}\text{Xe} + ^{112,124,\text{nat}}\text{Sn}$ at 50-250 A.MeV
- $^{197}\text{Au} + ^{197}\text{Au}$ at 40-150 A.MeV
- $^{12}\text{C} + ^{197}\text{Au} / ^{112,124}\text{Sn}$ at 95-1800 A.MeV
- INDRA-ALADiN Collaboration
- 1999 campaign.



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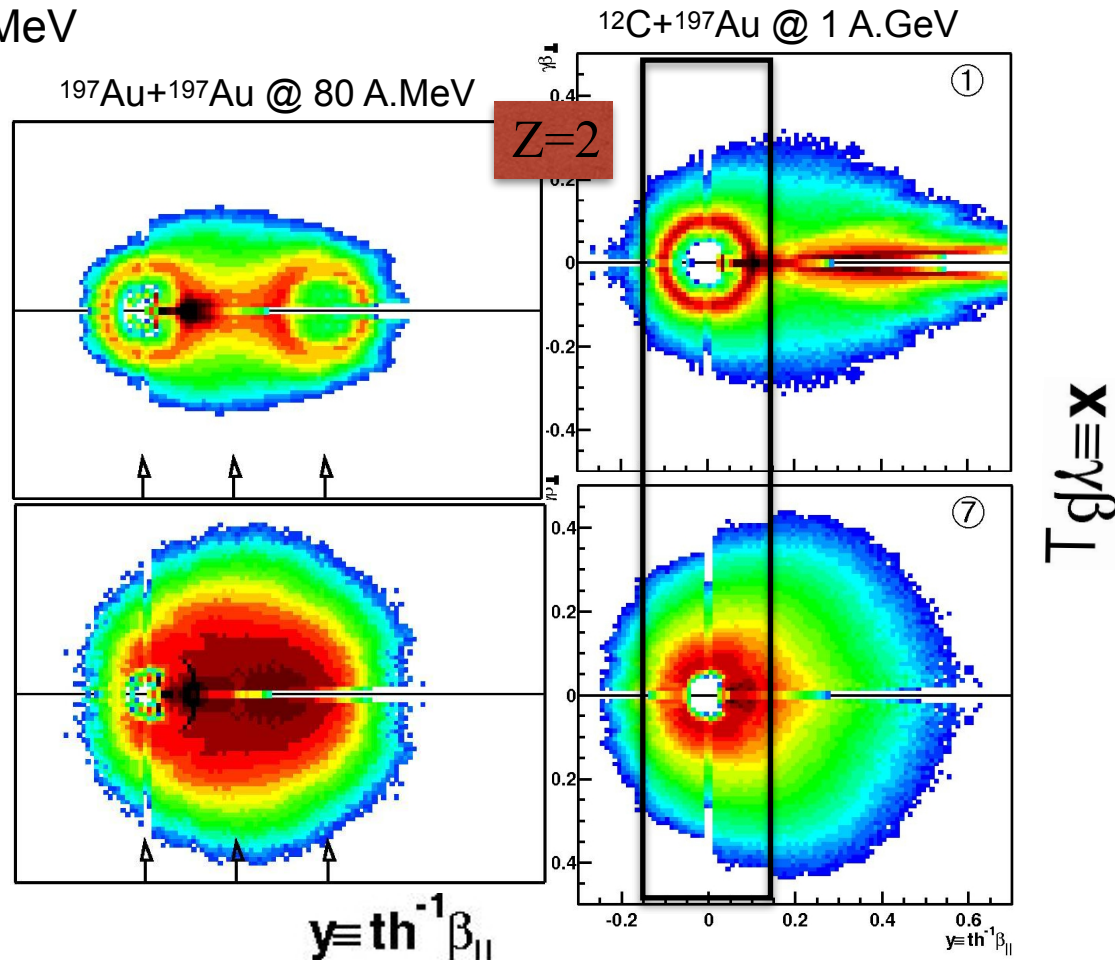
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Focus on target spectator fragmentation of $^{112/124}\text{Sn}$ bombarded with ^{12}C @ 300, 600 A MeV

peripheral

central



Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

► **Isoscaling** = a common phenomenon to many different types of HIC's.

A. Le Fèvre et al., PRL **94**, 162701 (2005)

Isotopic method: sub-saturation densities

INDRA@GSI: 1999 Campaign

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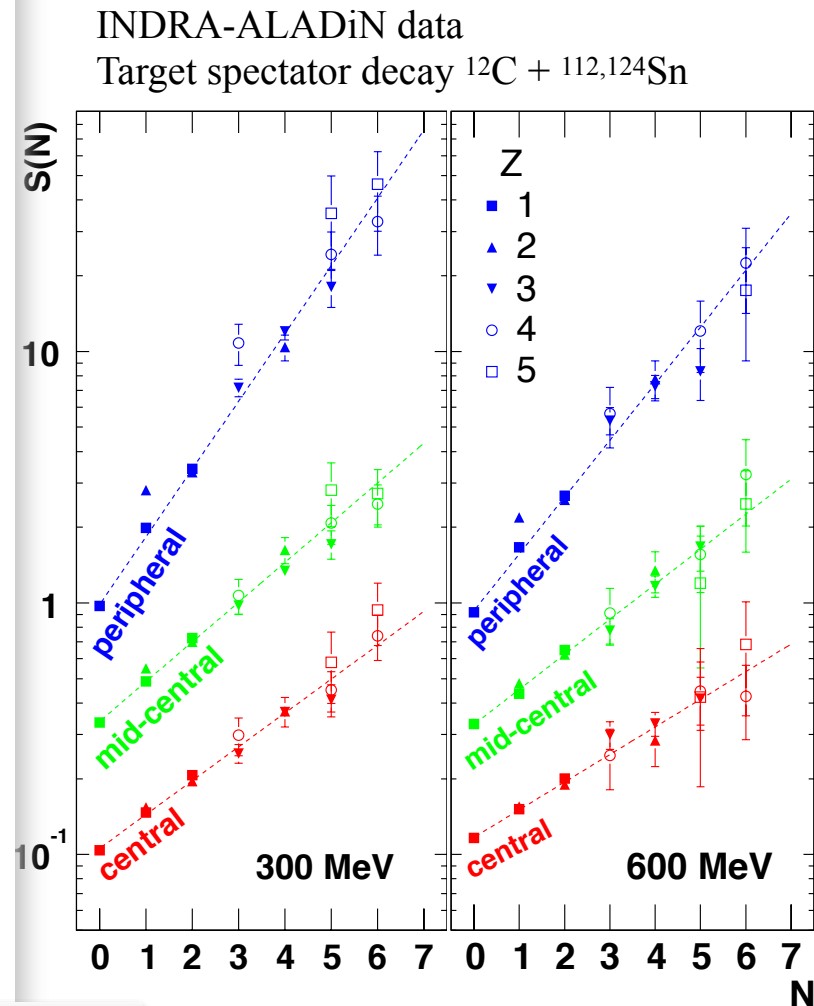
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Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

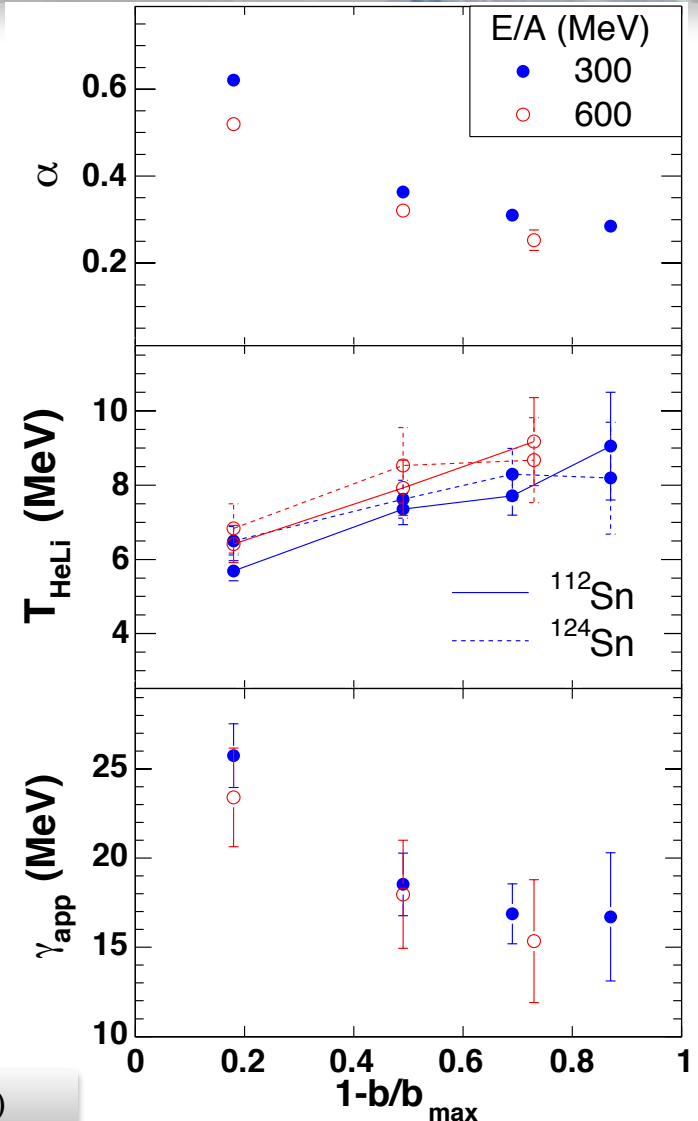
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Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

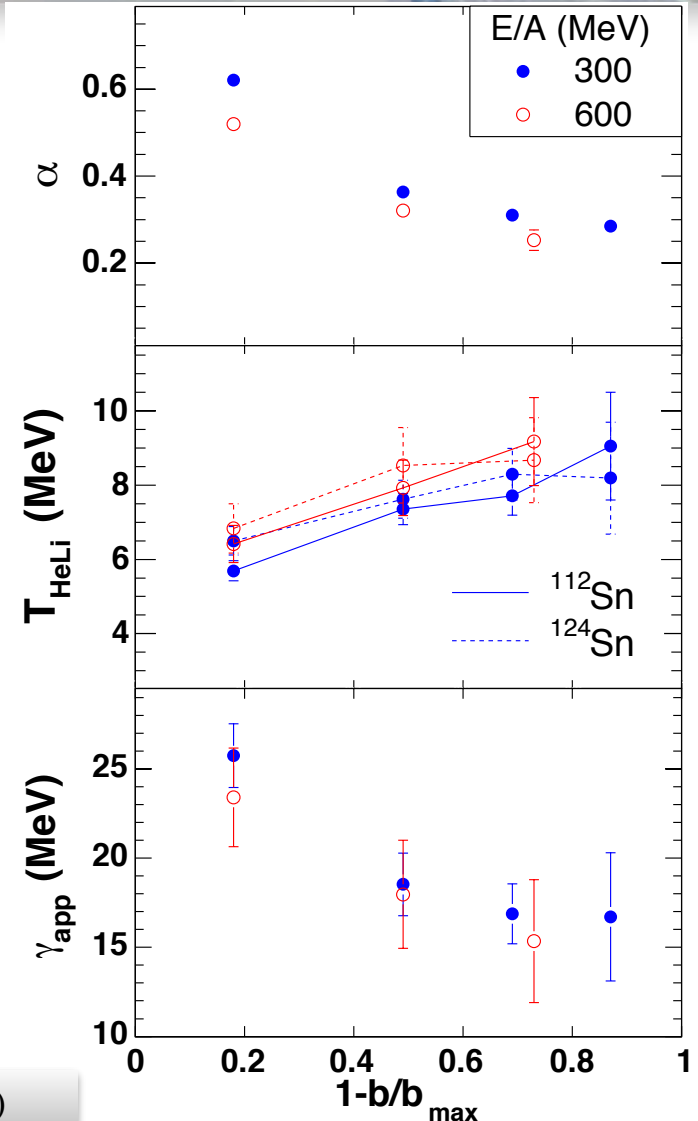
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Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

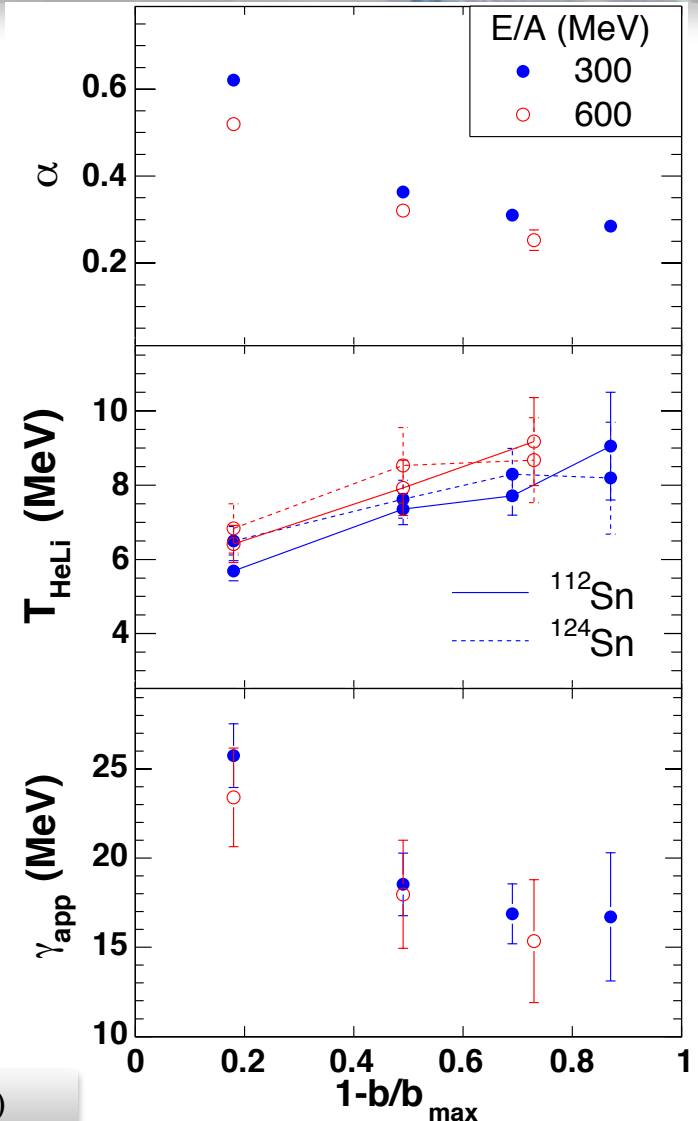
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Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

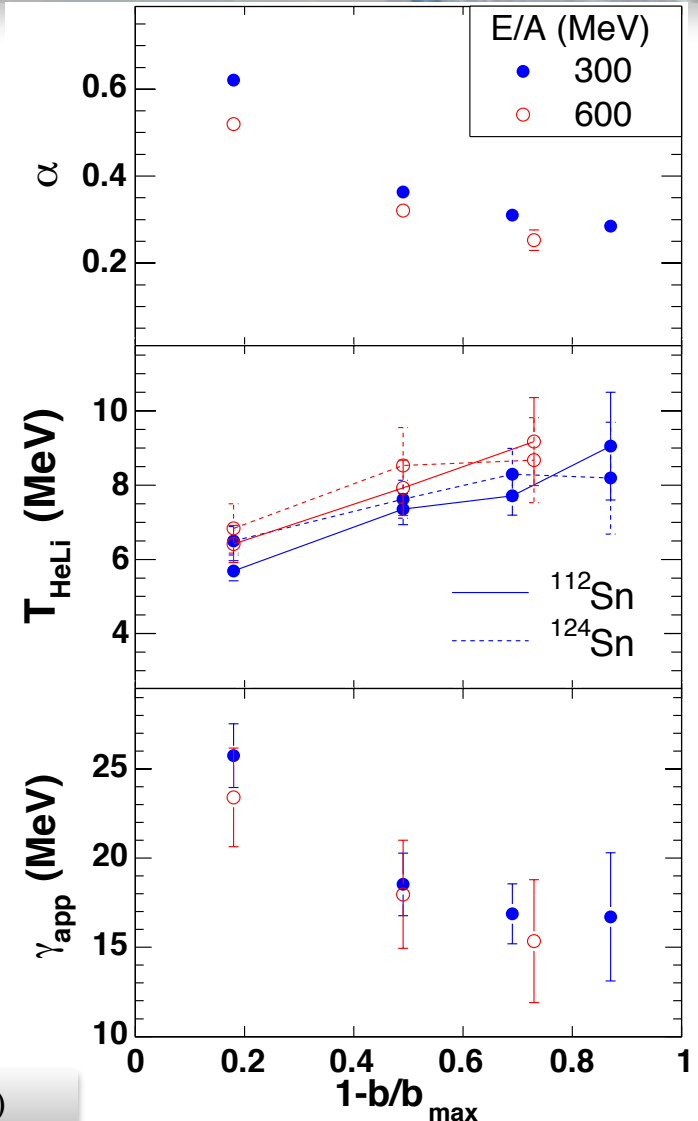
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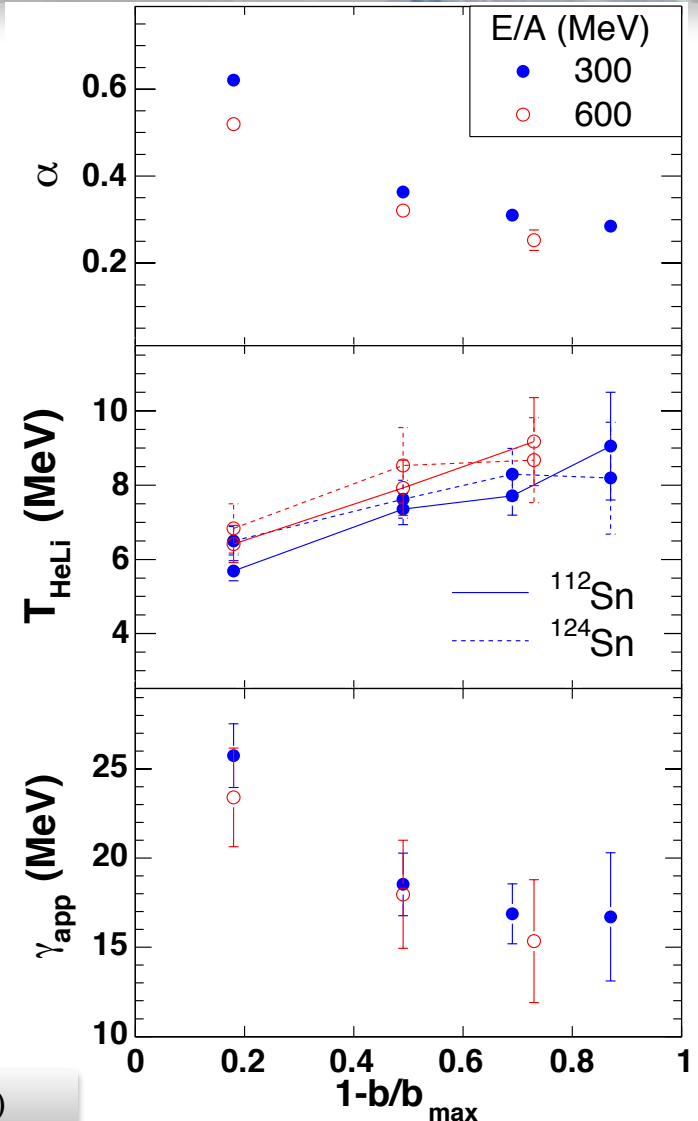
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Isotopic method: sub-saturation densities INDRA@GSI: 1999 Campaign

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 - ▶ $\gamma = 10$ MeV for central events (cluster $\rho \ll \rho_0$?)



A. Le Fèvre et al., PRL 94, 162701 (2005)

Determining the asymmetry part of the EOS: At sub-saturation density.

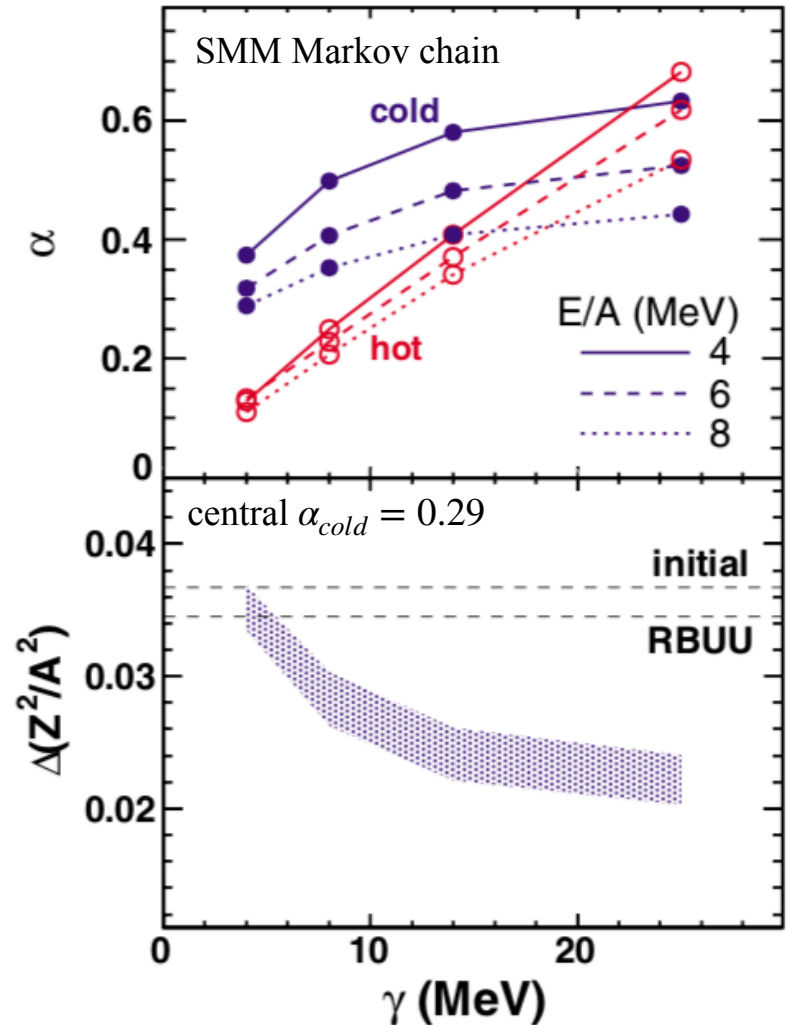
$$\gamma = \alpha \cdot T / [4 \Delta(Z^2/A^2)]$$

In central collisions: corrections to the apparent asymmetry energy

To be taken into account:

effect of secondary decay : model dependent.

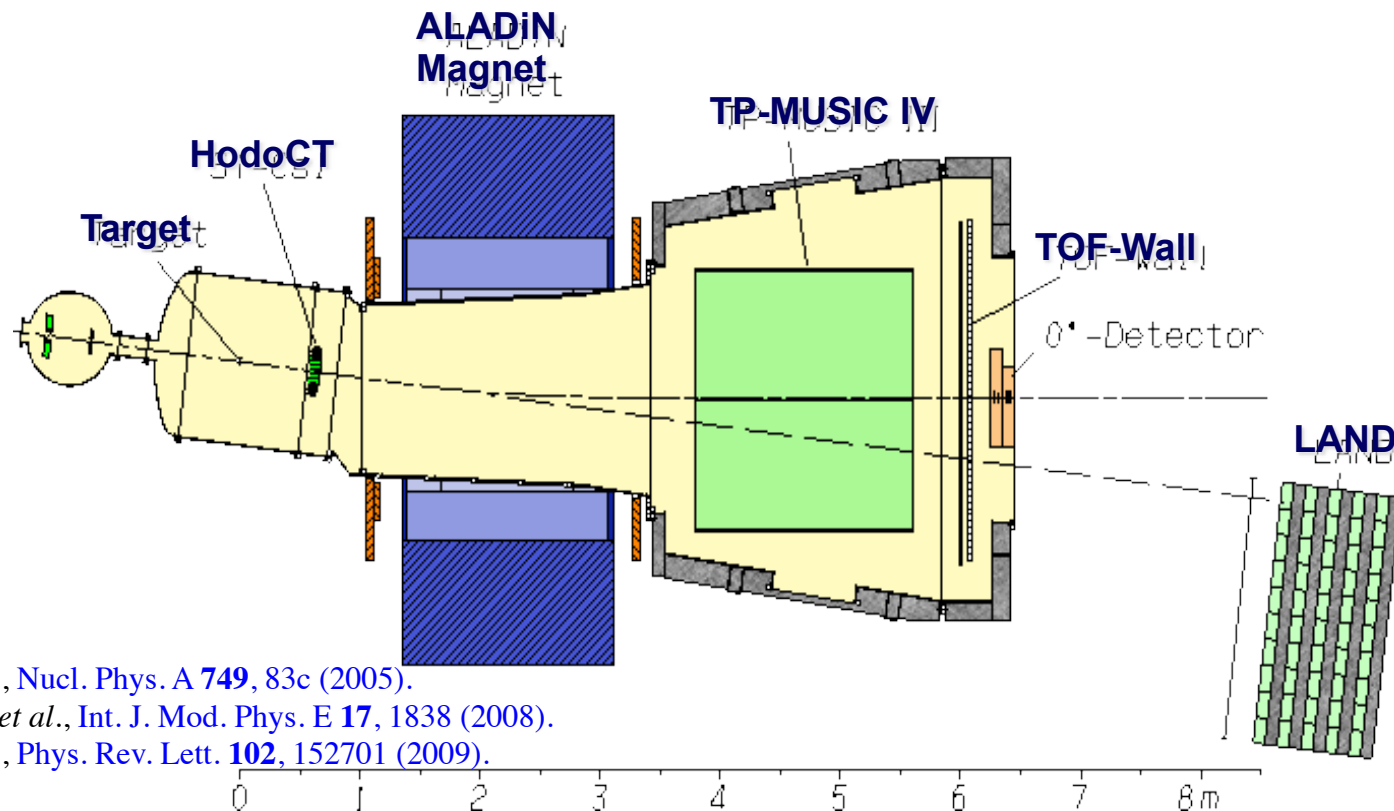
change in $\Delta(Z^2/A^2)$: model dependent.



A. Le Fèvre et al., PRL 94, 162701 (2005)

Isotopic method: sub-saturation densities ALADiN

The S254 experiment (2003)



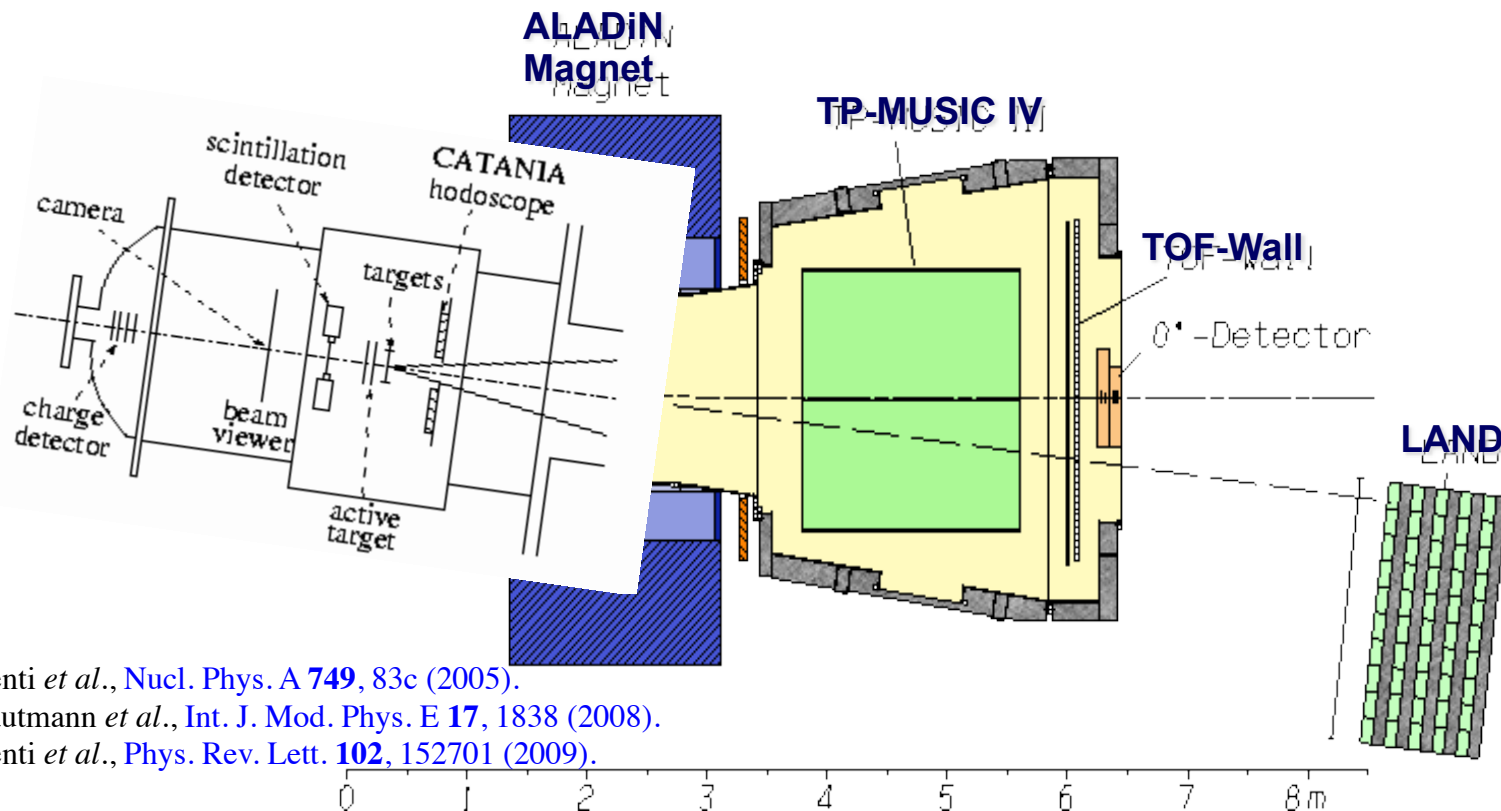
C. Sfienti *et al.*, *Nucl. Phys. A* **749**, 83c (2005).

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Isotopic method: sub-saturation densities ALADiN

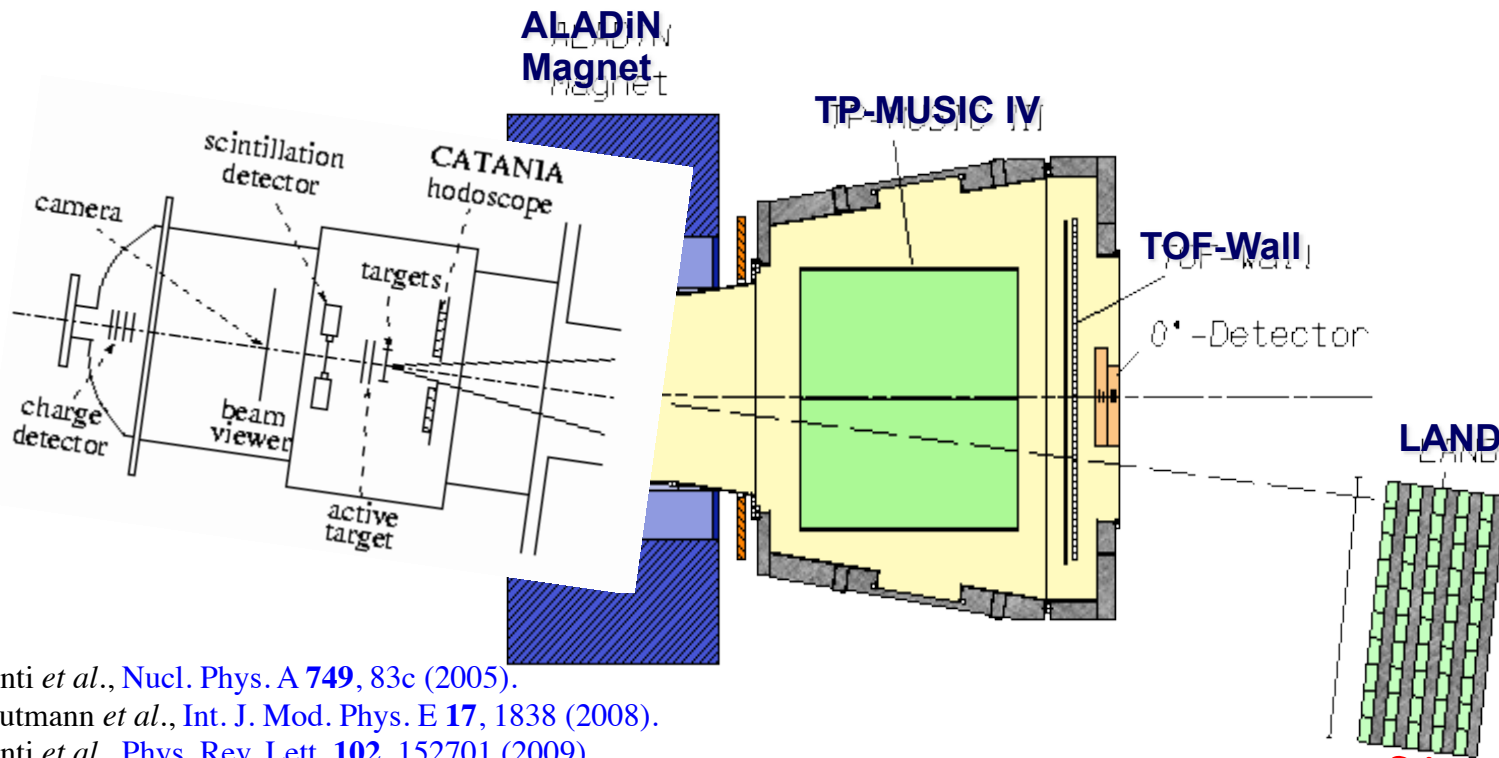
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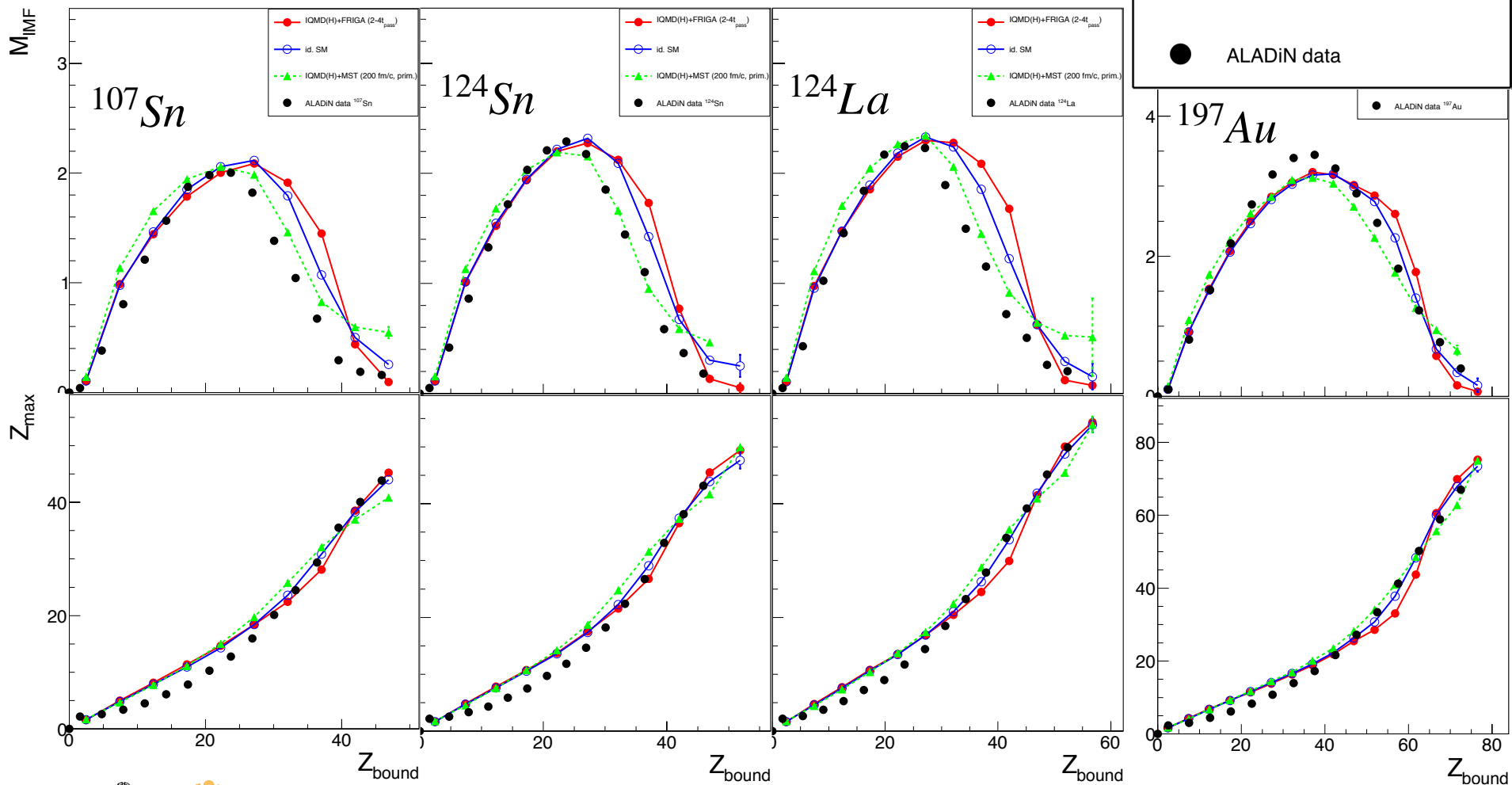
Neutron rich/poor projectiles: ^{197}Au , ^{124}Sn , ^{124}La , ^{107}Sn

**Secondary Beams
(Low Intensities!)**

$$E_{inc} = 600A \text{ MeV} (\approx 1000 \text{ pps})$$

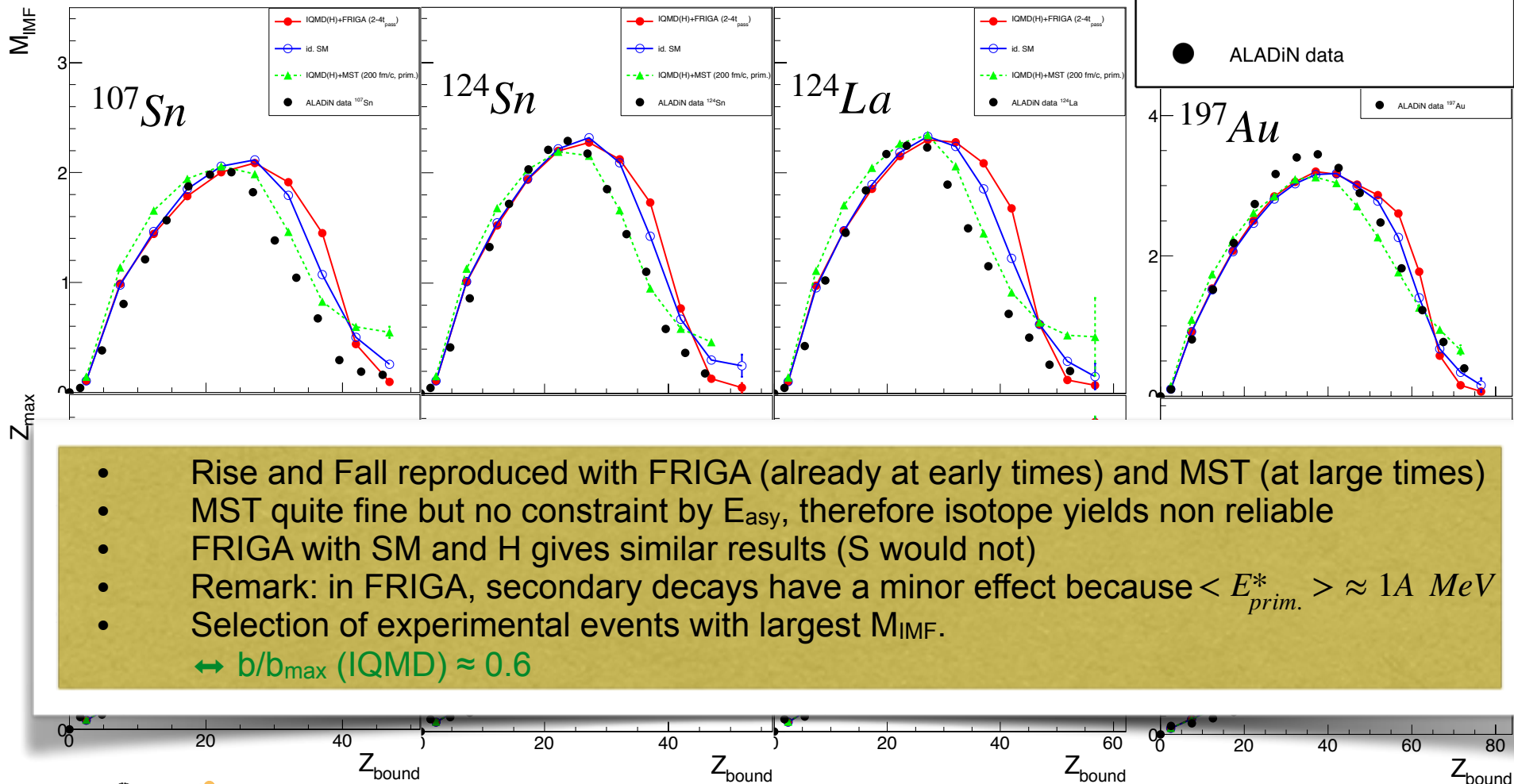
Isotopic method: sub-saturation densities ALADiN - IQMD-FRIGA Model benchmarking

publication on preparation...



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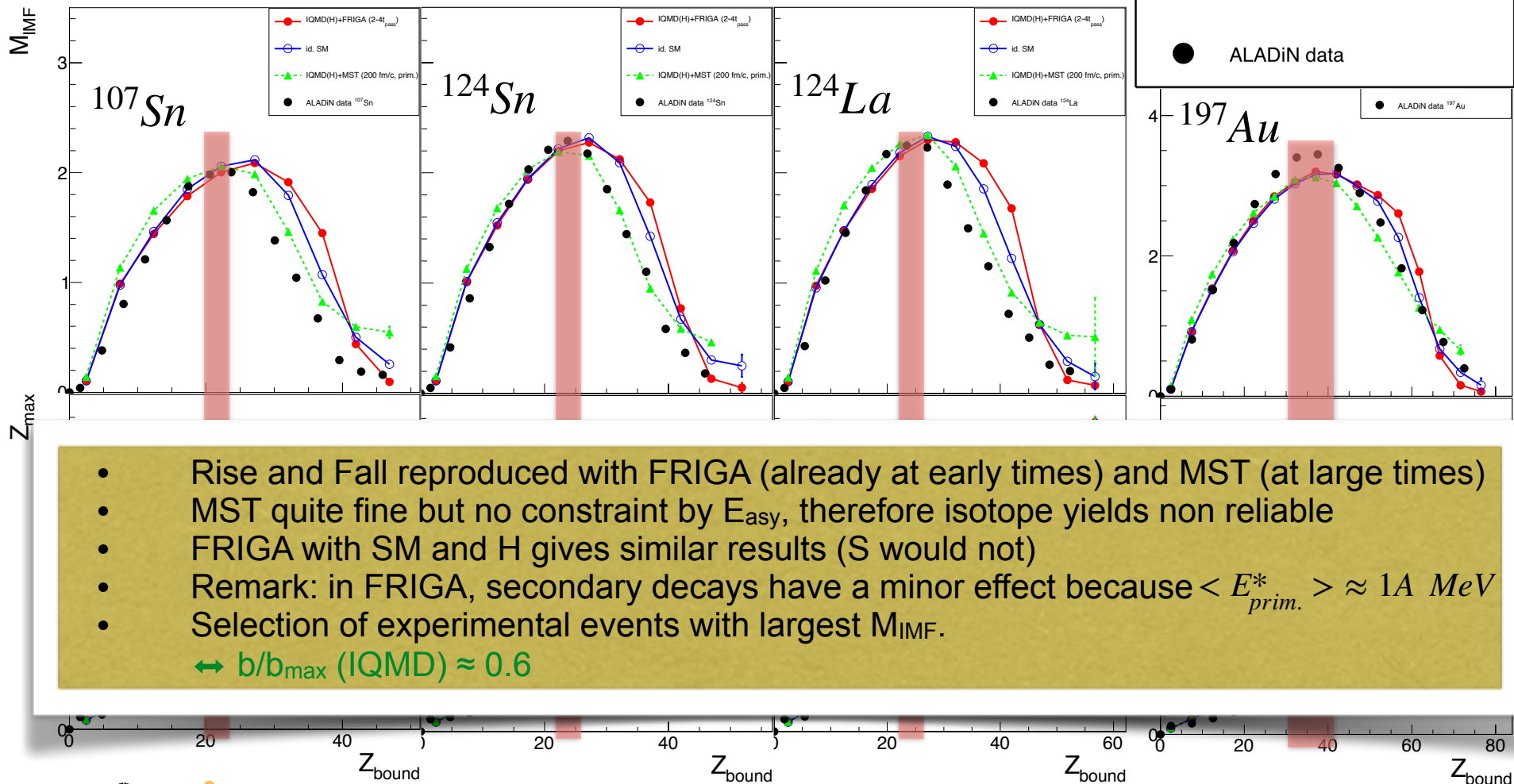
publication on preparation...



- Rise and Fall reproduced with FRIGA (already at early times) and MST (at large times)
 - MST quite fine but no constraint by E_{asy} , therefore isotope yields non reliable
 - FRIGA with SM and H gives similar results (S would not)
 - Remark: in FRIGA, secondary decays have a minor effect because $\langle E_{\text{prim.}}^* \rangle \approx 1A \text{ MeV}$
 - Selection of experimental events with largest M_{IMF} .
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Isotopic method: sub-saturation densities ALADiN - IQMD-FRIGA Model benchmarking

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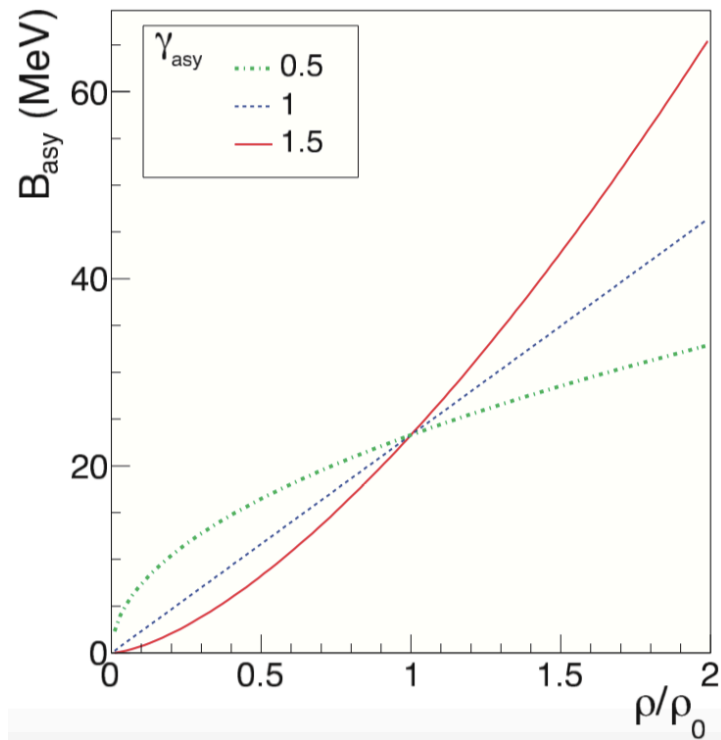


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Isotopic method: sub-saturation densities ALADiN - sensitivity to the asymmetry energy

publication on preparation...

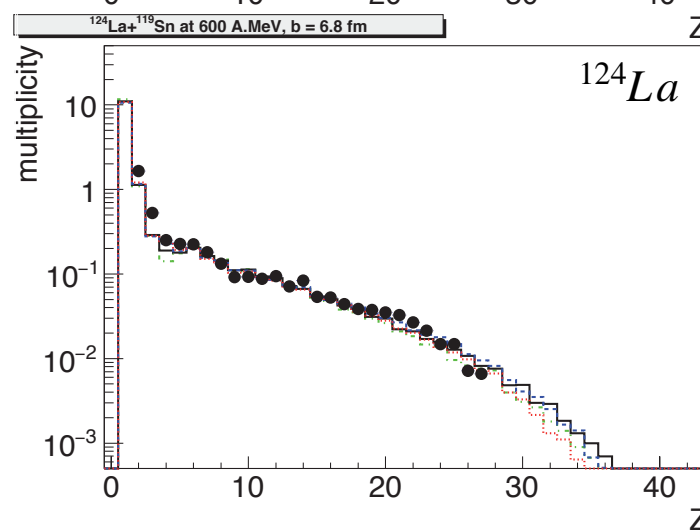
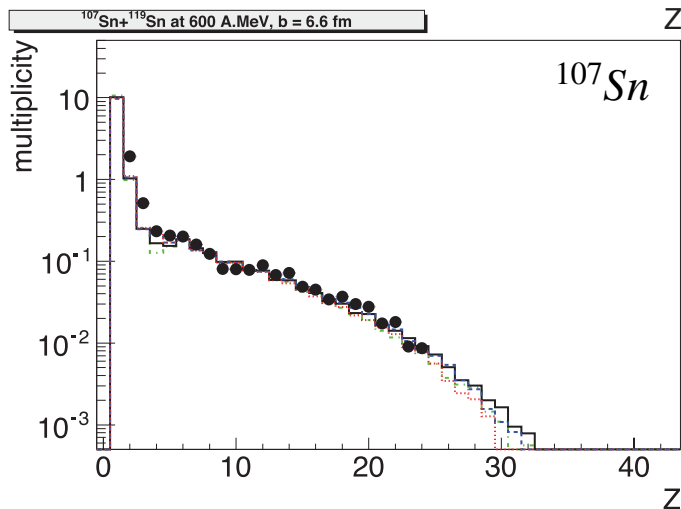
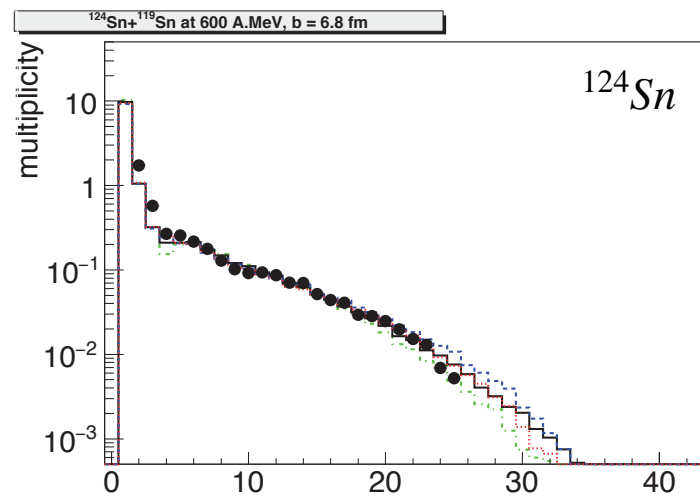
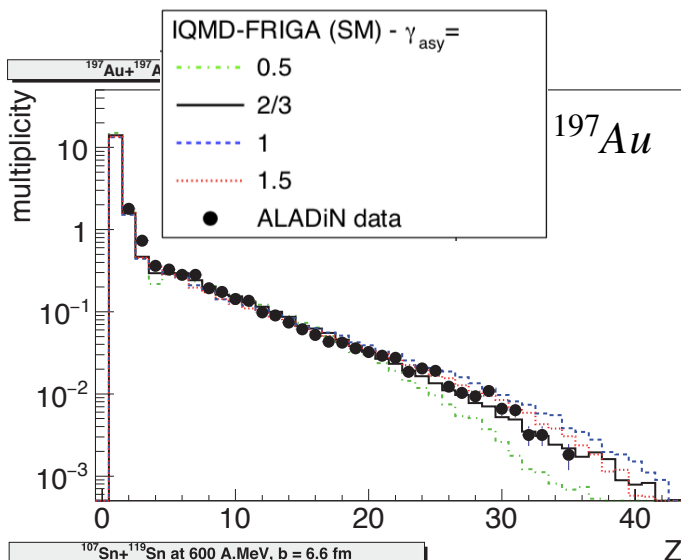
$$\text{IQMD: } E_{asy}\left(\frac{\rho}{\rho_0}\right) = E_{asy}^{pot} + E_{asy}^{kin} = 23.3 \text{ MeV} \left(\frac{\rho}{\rho_0}\right)^\gamma + 9 \text{ MeV} \left(\frac{\rho}{\rho_0}\right)^{2/3}$$



Isotopic method: sub-saturation densities ALADiN - sensitivity to the asymmetry energy

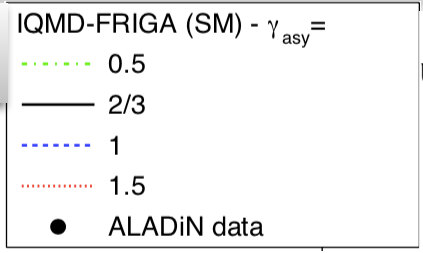
publication on preparation...

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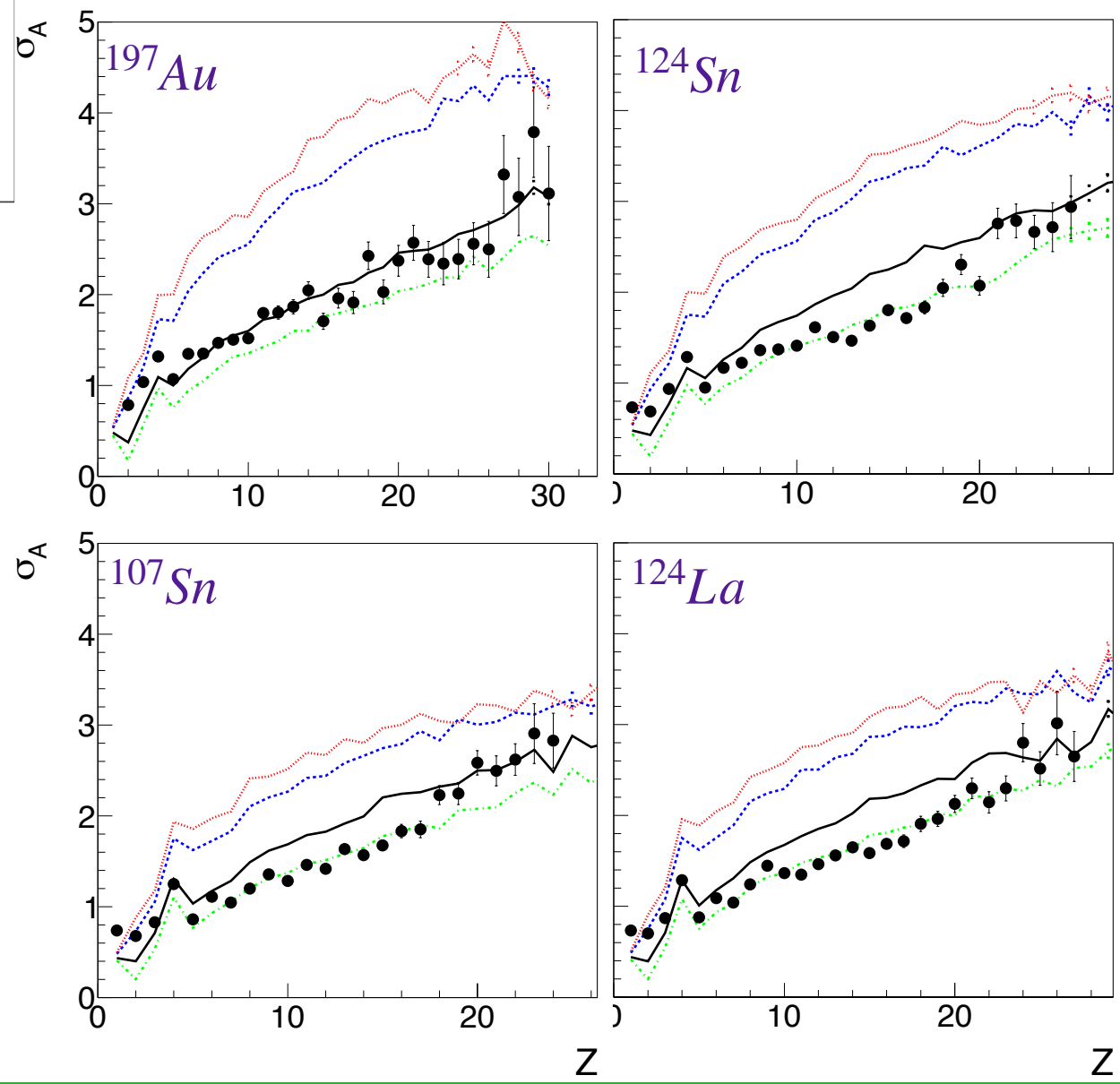


Isotopic method: sub-saturation densities ALADiN - sensitivity to the asymmetry energy

publication on preparation...

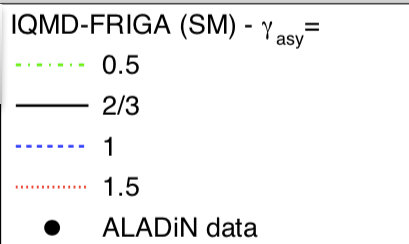


Widths of mass distributions:
even larger sensitivity

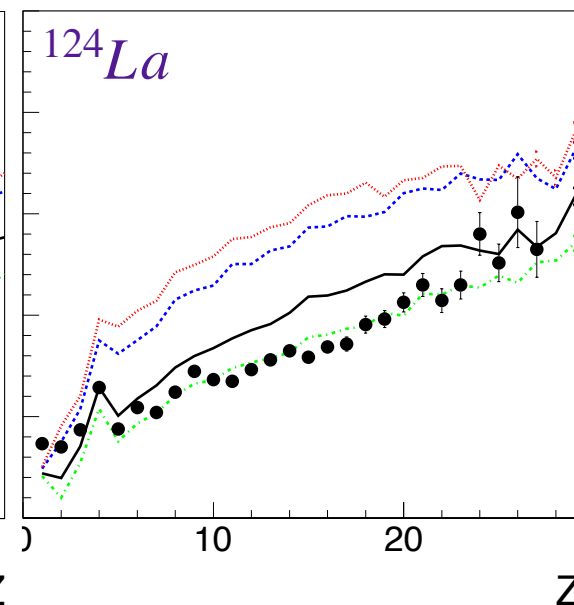
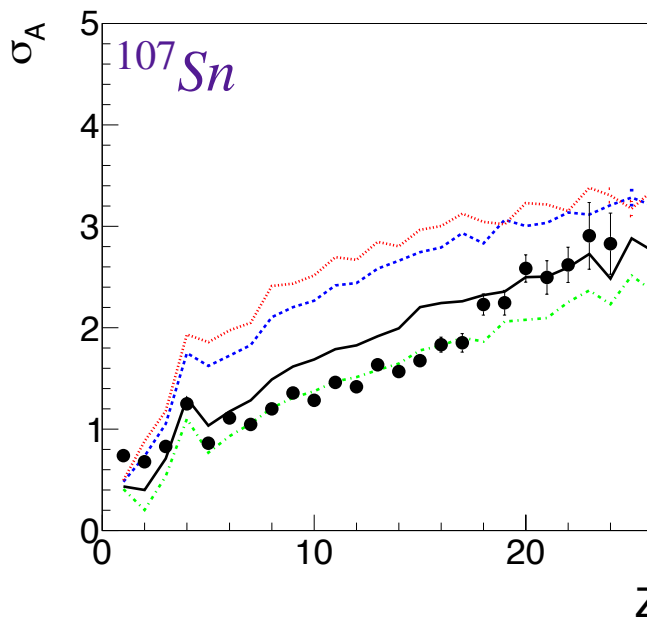
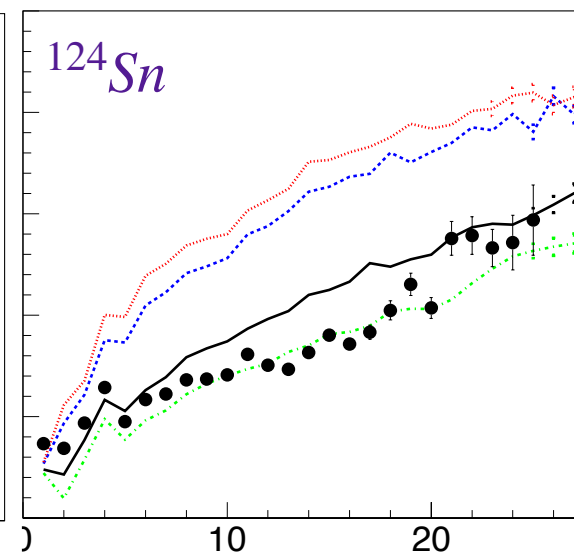
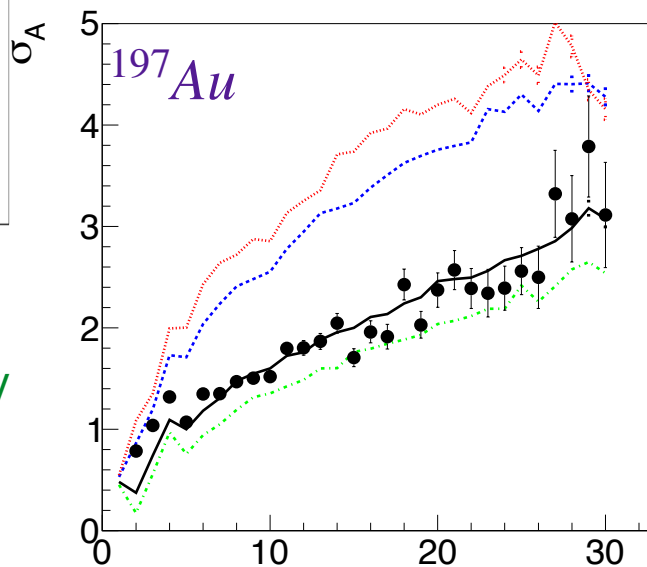
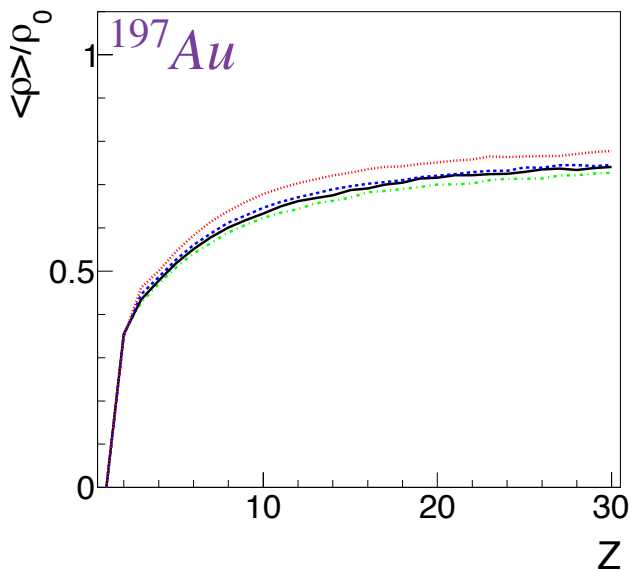


Isotopic method: sub-saturation densities ALADiN - sensitivity to the asymmetry energy

publication on preparation...



Widths of mass distributions:
even larger sensitivity
⚠ probed densities are strongly
related to the cluster size:

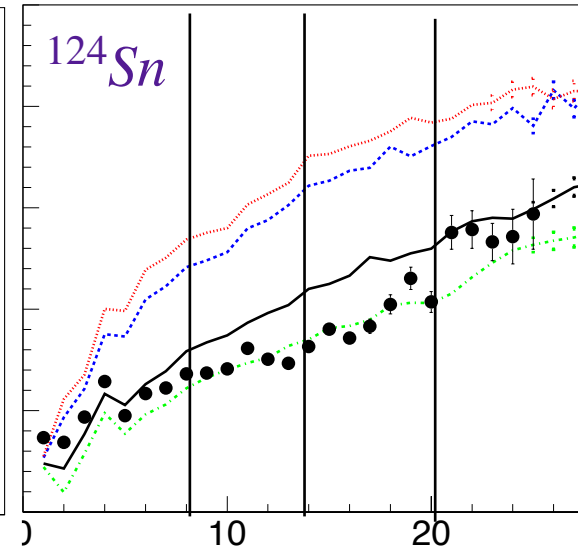
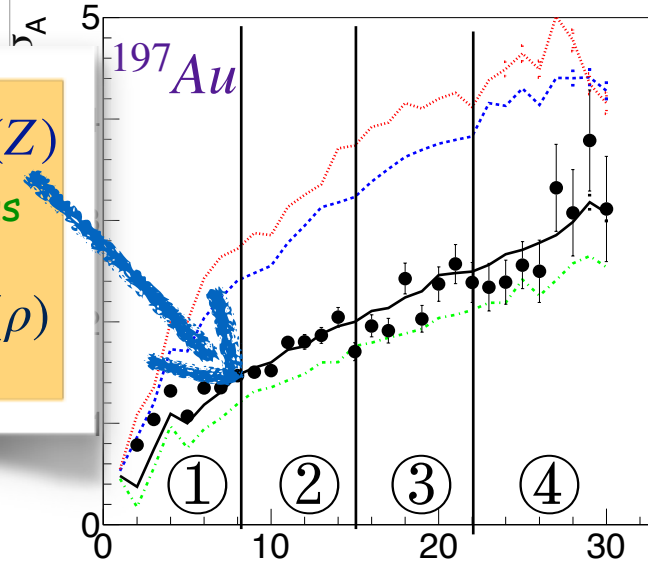


Isotopic method: sub-saturation densities ALADiN - sensitivity to the asymmetry energy

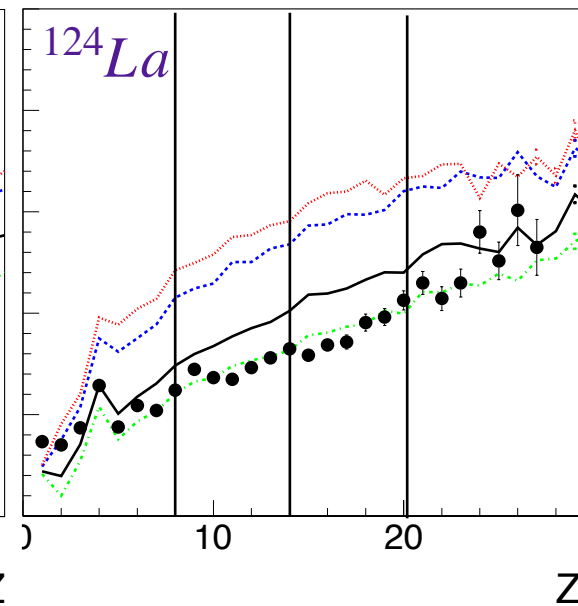
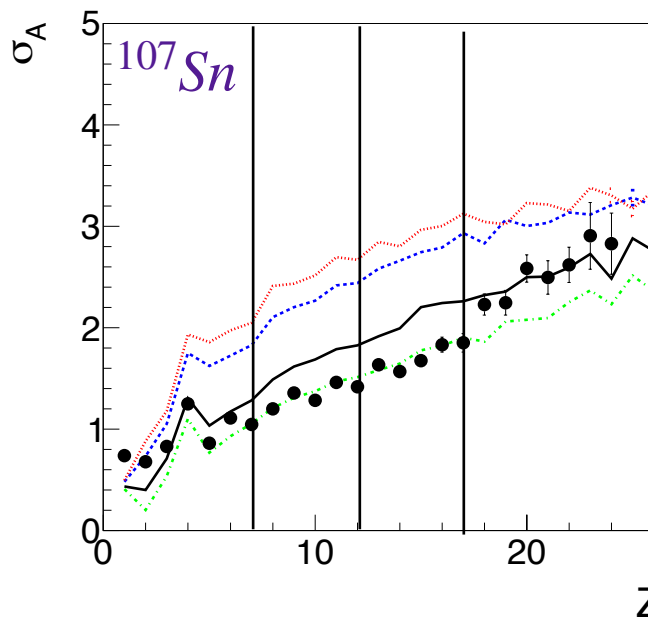
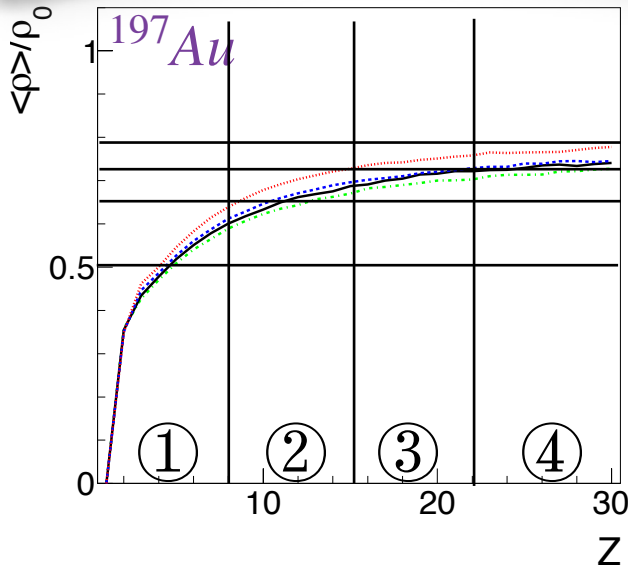
publication on preparation...

IQMD-FRIGA (SM) - $\gamma_{asy} =$
..... 0.5

- ➔ minimisation of $\chi^2(\gamma)$ on $\sigma_A(Z)$ within 4 intervals of $Z \Leftrightarrow$ various density intervals probed
- ➔ highest expectancies of $E_{asy}(\rho)$

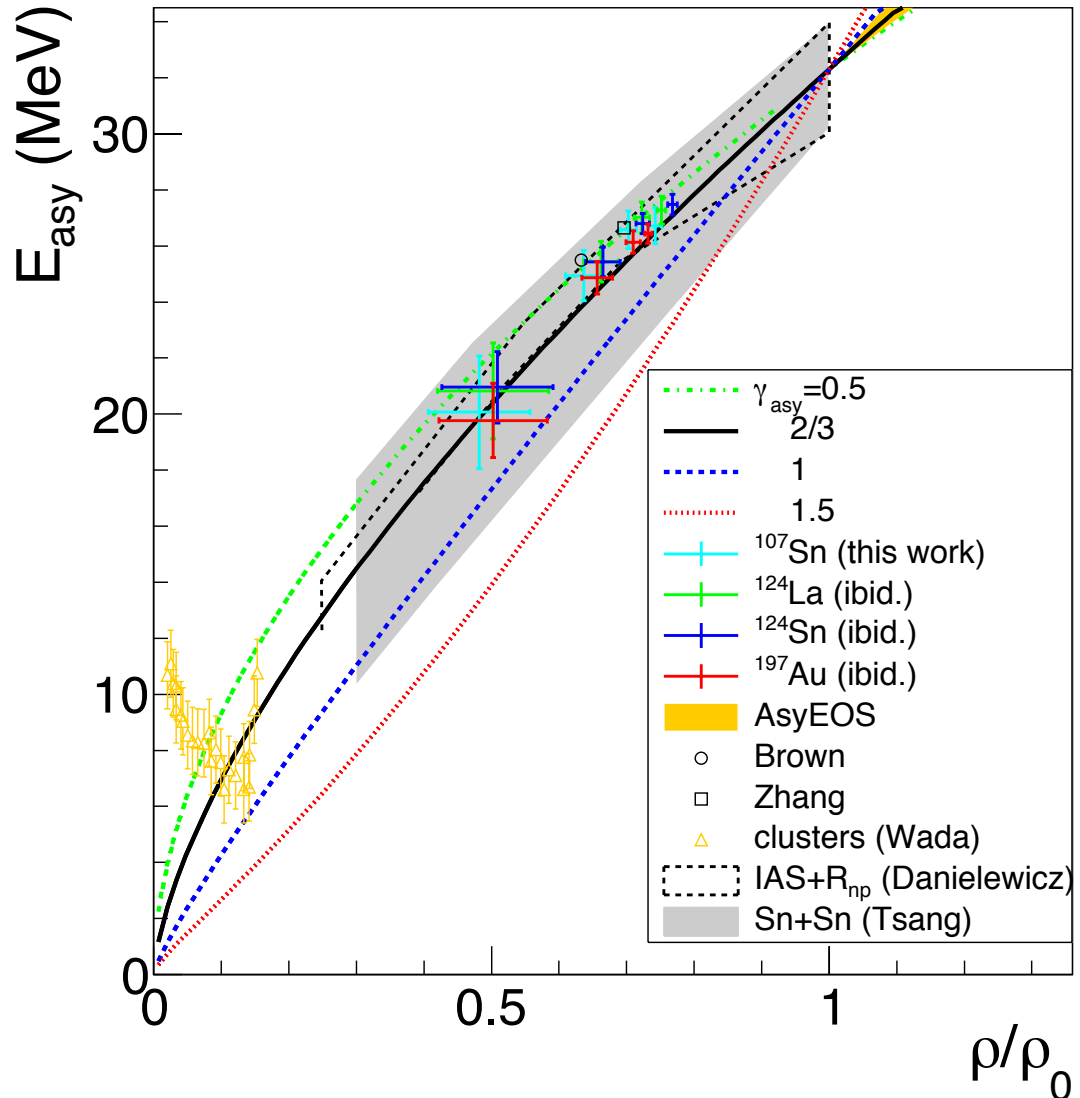


related to the cluster size:



Isotopic method: sub-saturation densities ALADiN - Synthesis over all systems and how its compares with recent findings

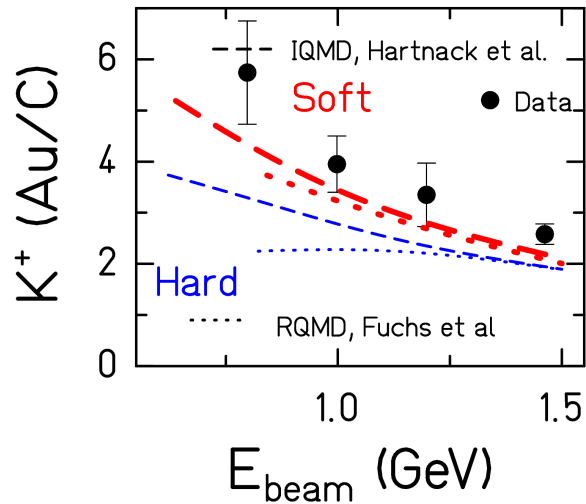
- Neutron rich systems are the most sensitive for this type of analysis
 - ALADiN ($0.6-0.8 \rho_0$)
 - ➔ $L = 60.4 \pm 5.9$ MeV
 - ➔ $\gamma_{asy} = 0,60 \pm 0.06$
- Cross-checking with other models than IQMD needed. All this is preliminary.
Work to be published...





Elliptic flow method: high densities FOPI and the incompressibility K_0

1st results at GSI with KaoS data:



Data: C. Sturm et al., PRL 86 (2001)

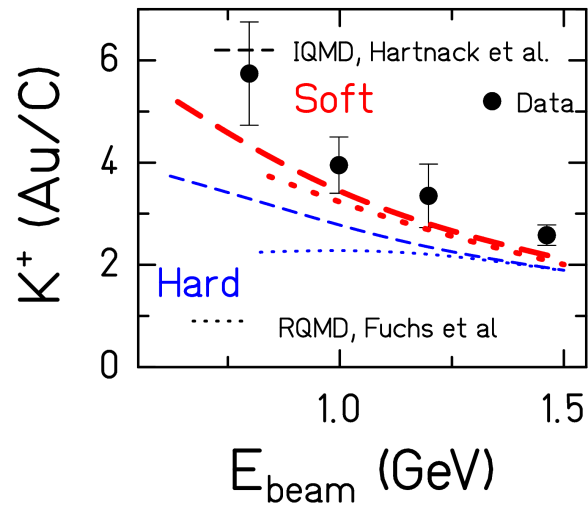
39



Elliptic flow method: high densities FOPI and the incompressibility K_0

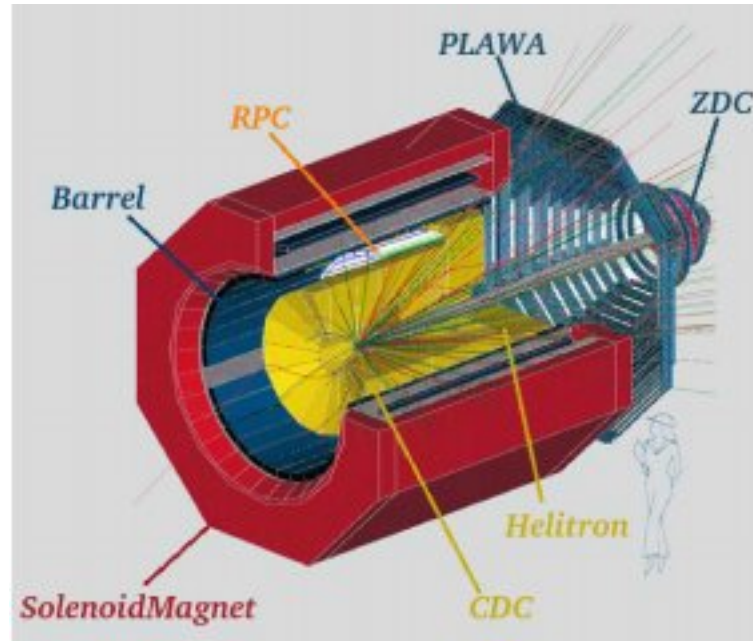
1st results at GSI with KaoS data:

FOPI 1990'-2000' campaigns
Au+Au @ 95 - 1500 A MeV



Data: C. Sturm et al., PRL 86 (2001)

39

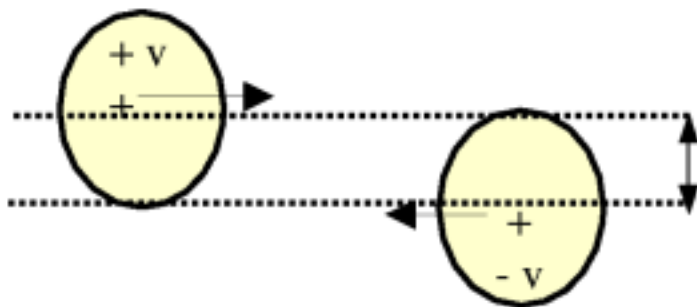




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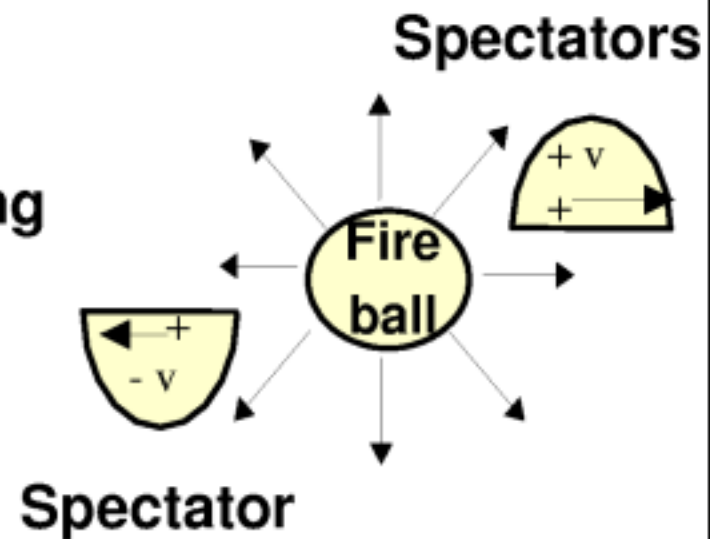
Elliptic flows of particles out of the participant region (« fireball »)

Before the collision



Overlapping
zone

after the collision





Elliptic flow method: high densities FOPI and the incompressibility K_0

Elliptic flows of particles out of the participant region (« fireball »)

Flows at high density in heavy-ion collisions

$$\frac{dN}{d(\phi - \phi_R)}(y, p_t) = \frac{N_0}{2\pi} \left(1 + 2 \sum_{n \geq 1} v_n \cos n(\phi - \phi_R) \right) \frac{1}{\xi}$$

Y = rapidity

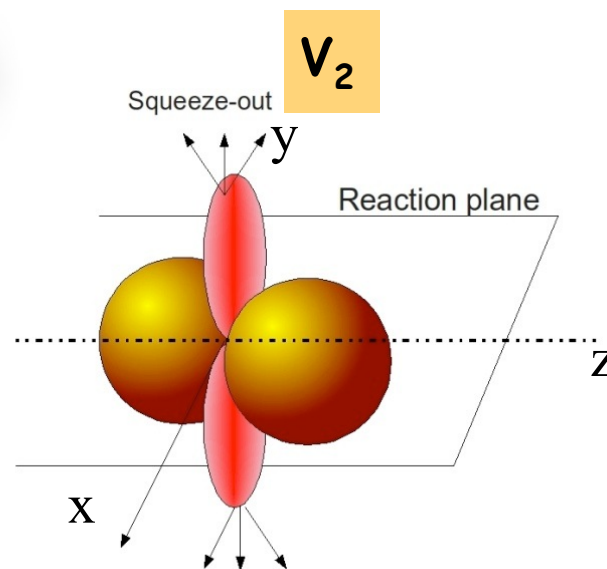
p_t = transverse momentum

Φ_R = reaction plane azimuthal angle

V_1 = 'side/directed flow', $\cos(\Phi - \Phi_R)$ mode

$$V_2(y, p_t) = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

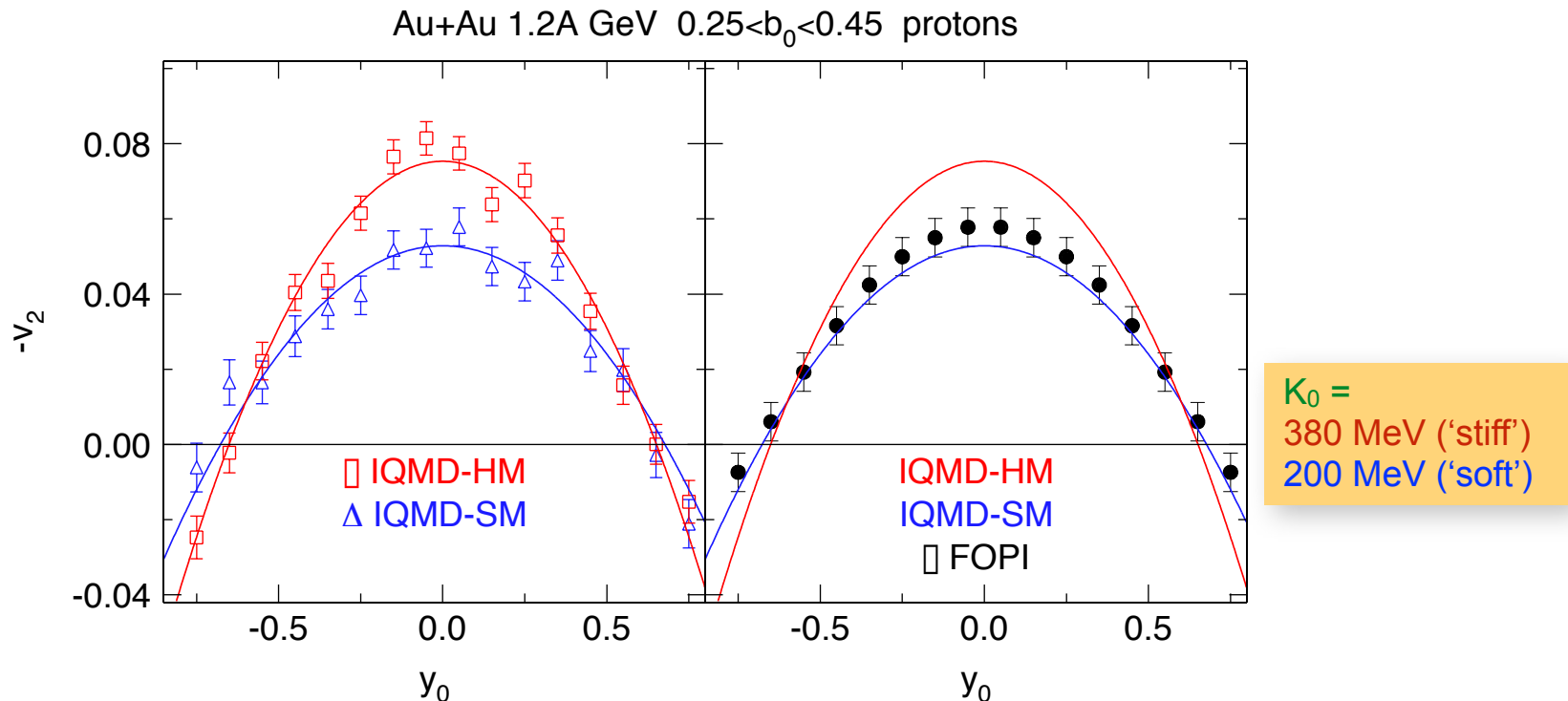
'Elliptic flow': $\cos(2(\Phi - \Phi_R))$ mode, competition between 'in-plane' ($V_2 > 0$) and 'out-of-plane' ejection ($V_2 < 0$).





Elliptic flow method: high densities FOPI and the incompressibility K_0

Elliptic flow



A. Le Fèvre et al., NPA 945 (2016) 112–133



Elliptic flow method: high densities FOPI and the incompressibility K_0

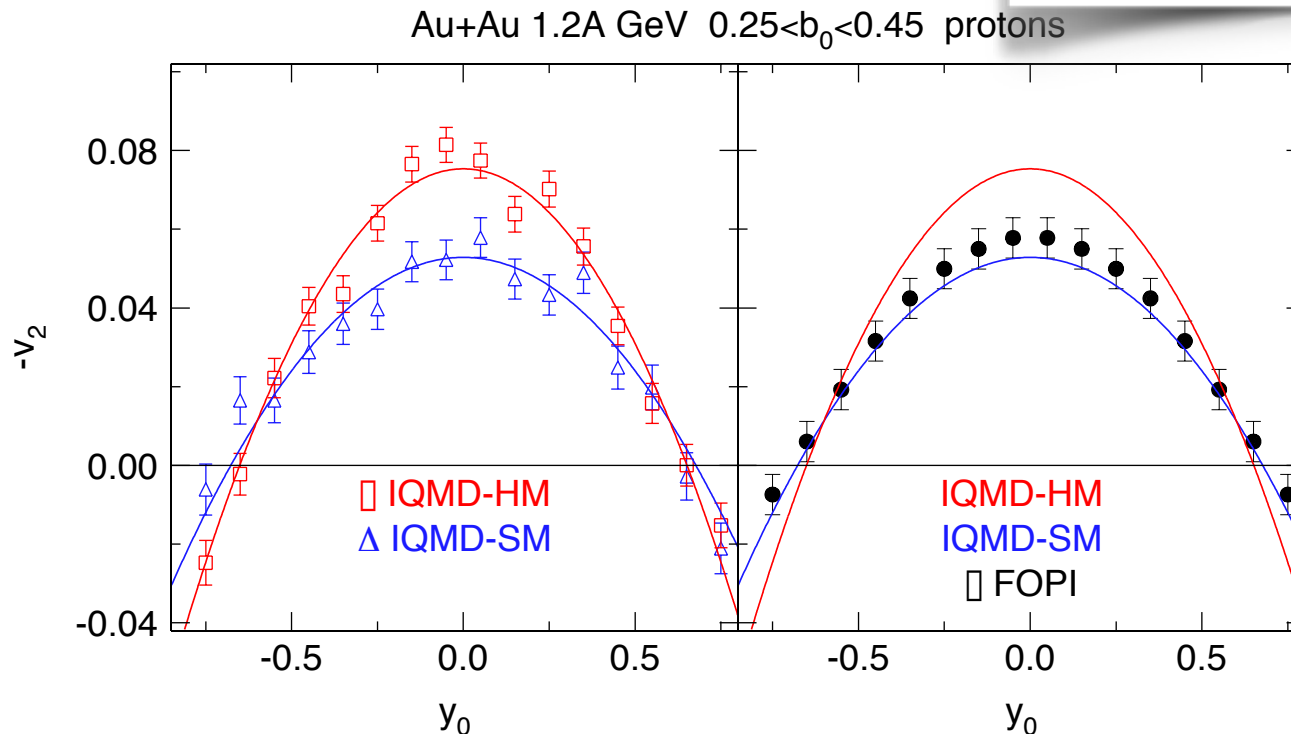
Elliptic flow

Complete shape of $v_2(y_0)$:
a new observable:

$$v_{2n} = |v_{20}| + |v_{22}|,$$

from fit

$$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$$



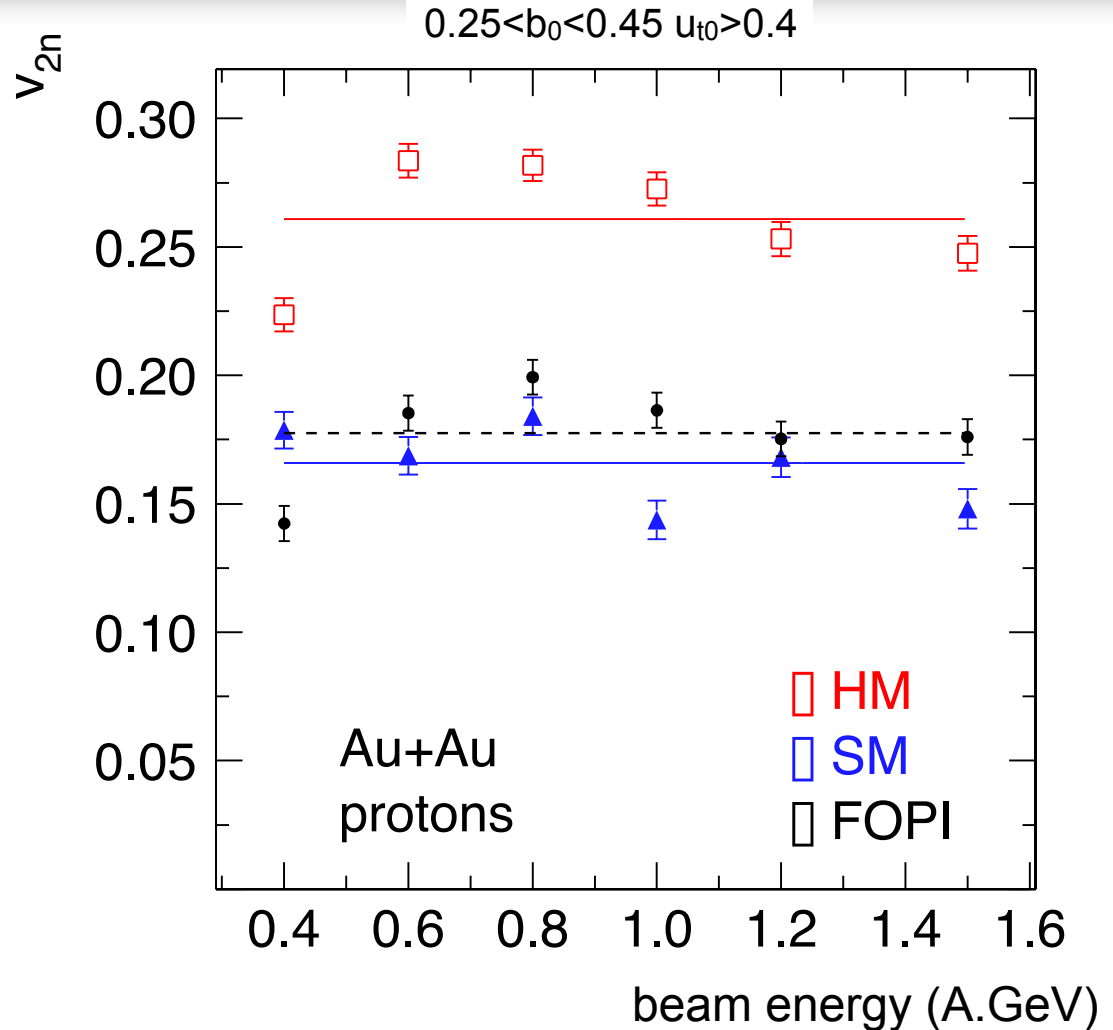
$K_0 =$
380 MeV ('stiff')
200 MeV ('soft')

A. Le Fèvre et al., NPA 945 (2016) 112–133



Elliptic flow method: high densities FOPI and the incompressibility K_0

- $v_{2n}(E_{\text{beam}})$ varies by a factor ≈ 1.6 , \gg measured uncertainty (≈ 1.1)
- clearly favors a 'soft' EOS.

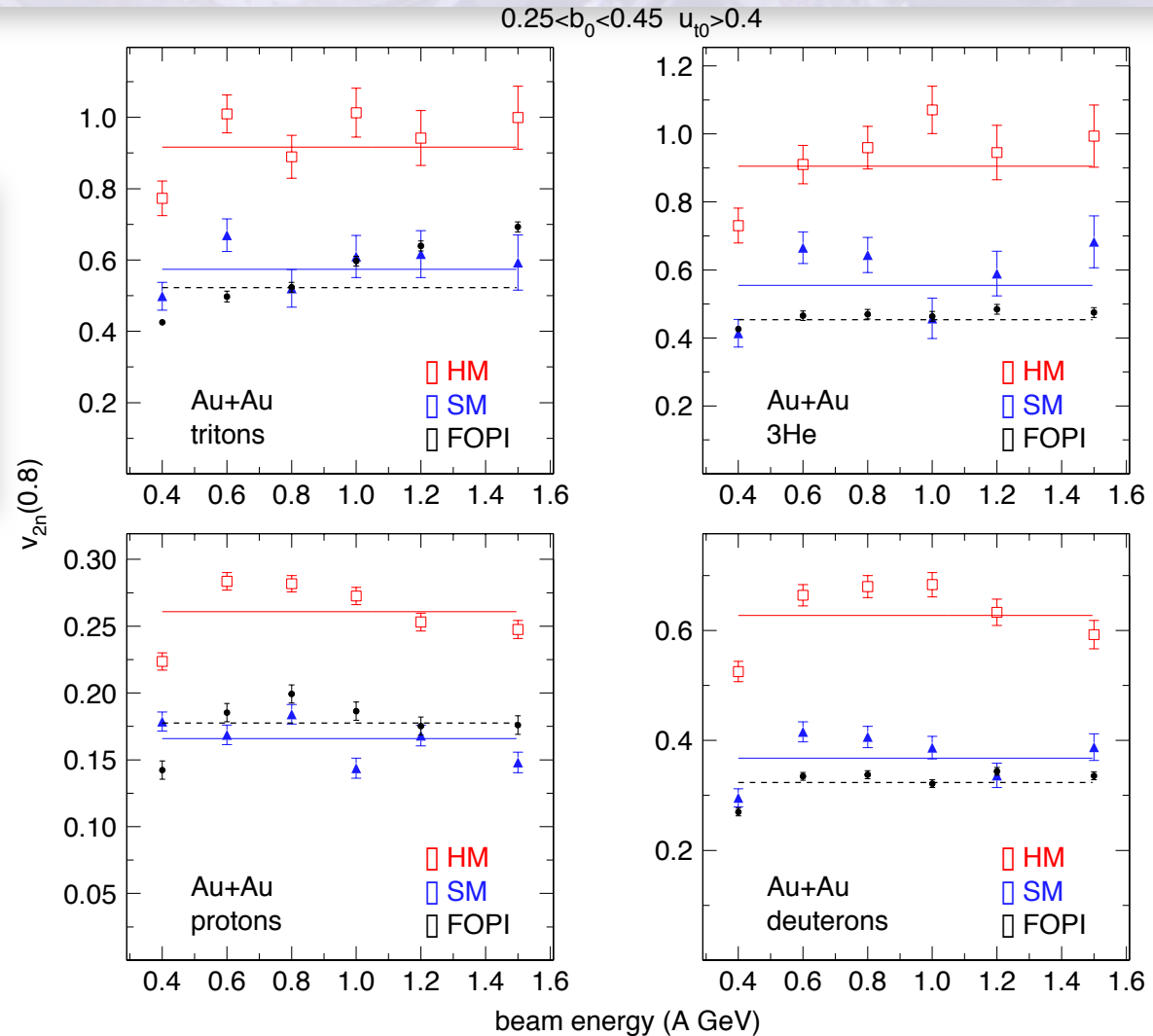


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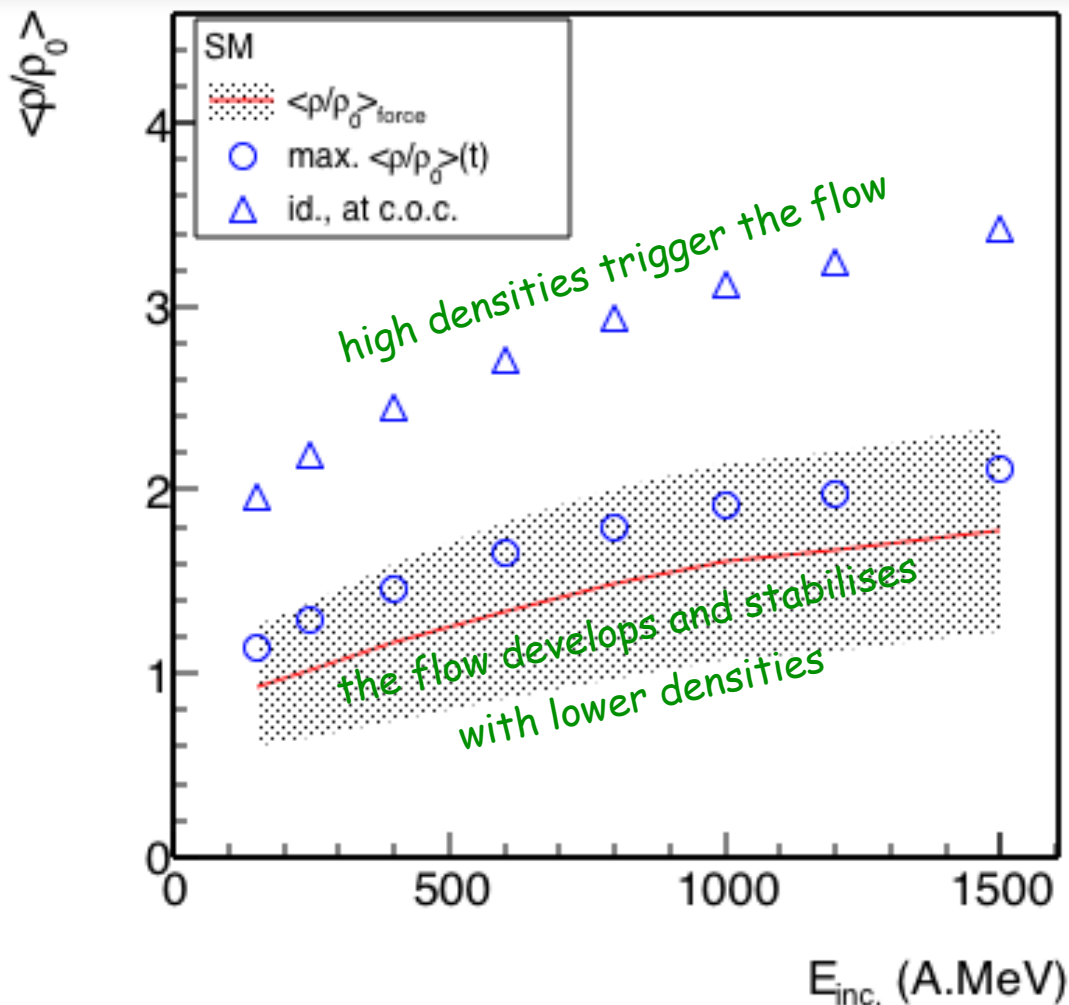
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Elliptic flow method: high densities FOPI and the incompressibility K_0



- ▶ In the QMD model, the EOS must be correct over a **broad range of densities** in order to predict the observed elliptic flow.
- ▶ The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range $\rho \approx (1 - 3) \rho_0$.



Elliptic flow method: high densities FOPI and the incompressibility K_0

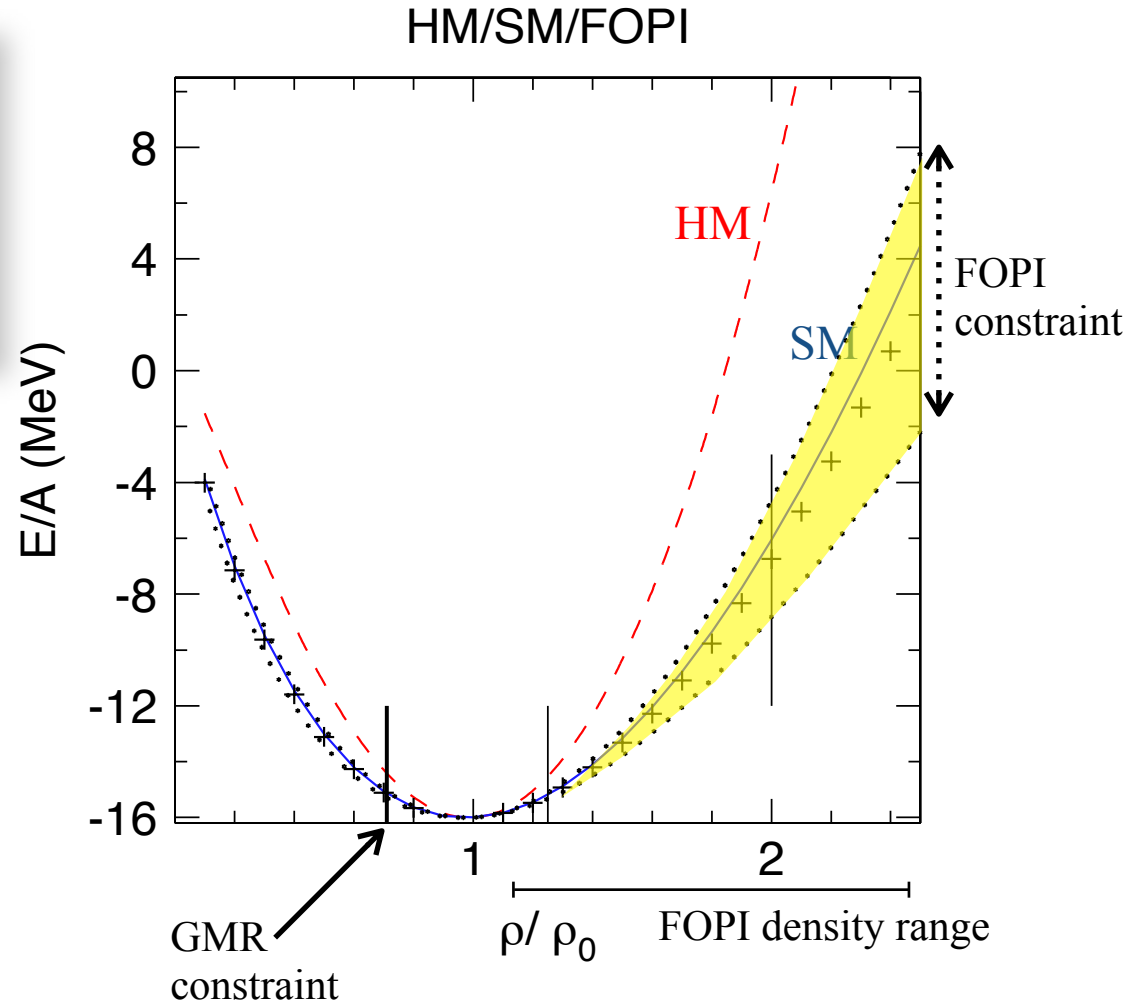
- K_0 as from FOPI flow data

IQMD $\rightarrow K_0 = 190 \pm 30 \text{ MeV}$

[A. Le Fèvre et al., *NPA*945(2016)112-133]

UrQMD $\rightarrow K_0 = 220 \pm 40 \text{ MeV}$

[Y. Wang et al., *PLB*-778(2018)207-212]





Pion yield method: high densities

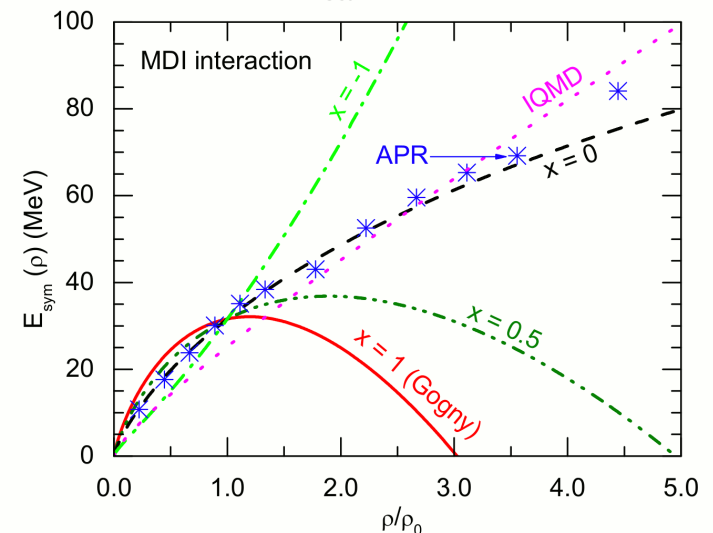
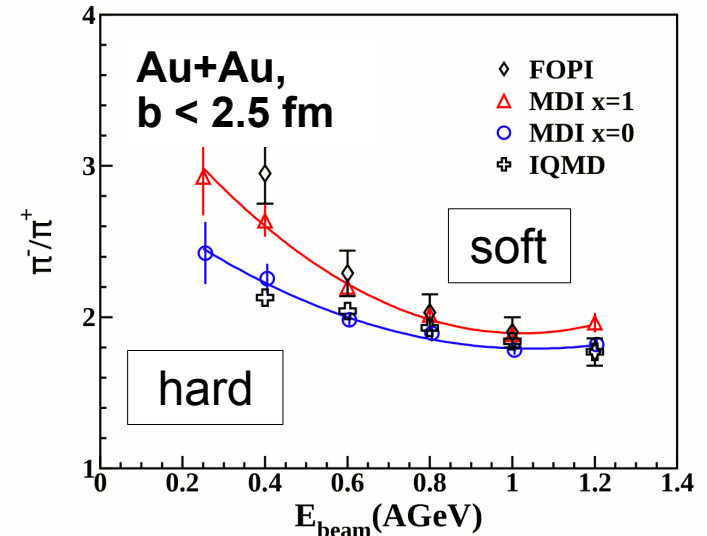
FOPI and the asy-stiffness

- Symmetry energy influences n/p ratio → changes number of nn, np, pp collisions
- Simple ansatz: assume stiff asymmetry energy

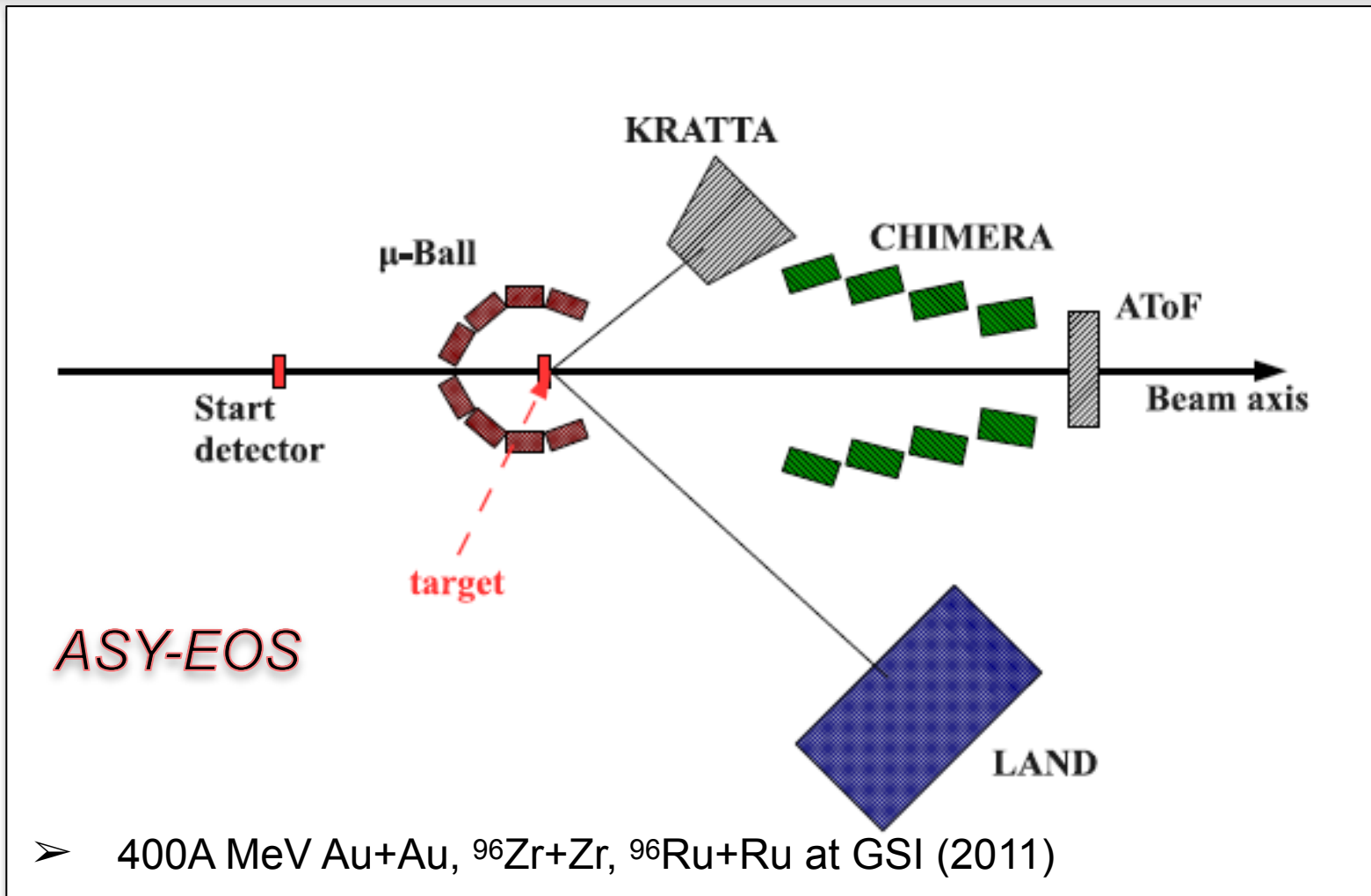
$$\frac{n}{p} \downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})} \downarrow \Rightarrow \frac{\pi^-}{\pi^+} \downarrow$$

- BUT: super-soft E_{asy} from Xiao et al. is inconsistent with results from neutron and proton flow
- Complex medium effects have to be considered
 - pion optical potential, self energies different for π^- and π^+
 - potentials and characteristics of Δ
 - s- vs p-wave production
- Work in progress, no conclusions
 - soft ↔ hard ↔ no dependence on E_{asy}

Data: W. Reisdorf et al., NPA 781 (2007)
 Calculations: Z. Xiao et al, PRL 102. (2009)



Elliptic flow method: high densities Asy-EOS



Elliptic flow method: high densities Asy-EOS

Elliptic flow v_2 of n/p

UrQMD (Q. Li et al.) predicts:

“hard” $E_{\text{sym}}(\rho)$ neutron flow much larger



“soft” $E_{\text{sym}}(\rho)$ neutron, proton flow equal

Towards model invariance:

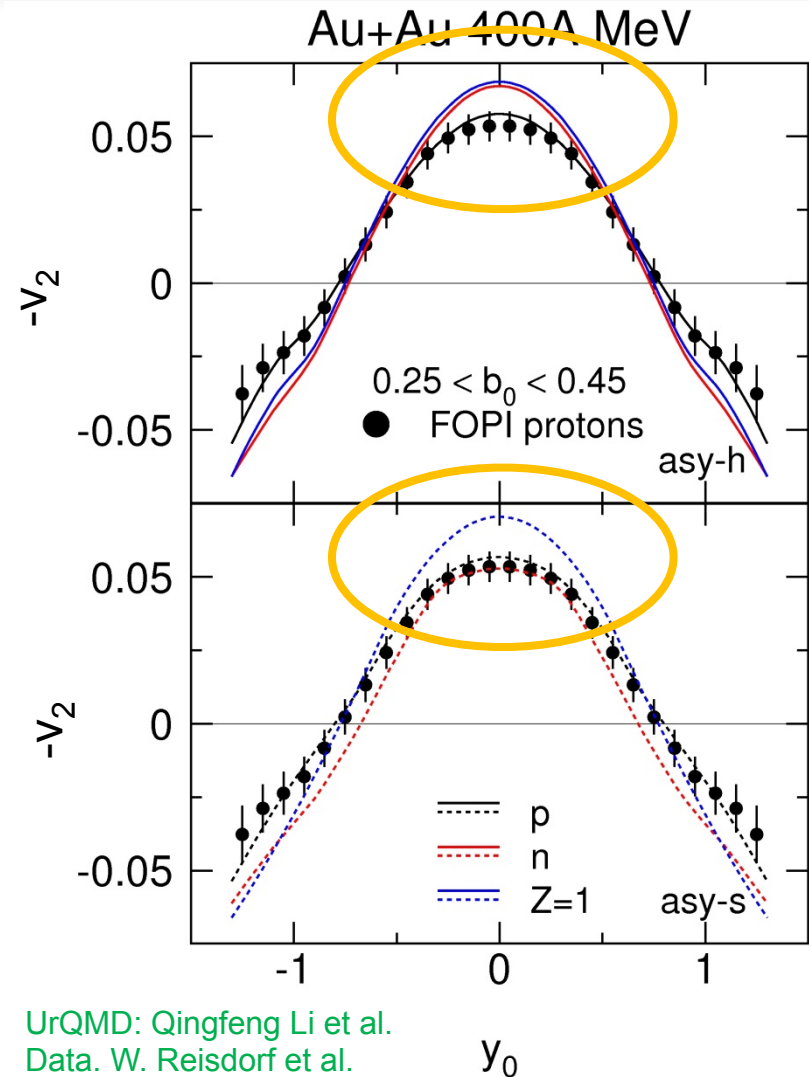
tested stability with different models:

- observation is robust
- various microscopic models tested
- independent on input parameters

M.D. Cozma et al., PRC 88, 044912 (2013)

P. Russotto et al., PLB 267 (2010)

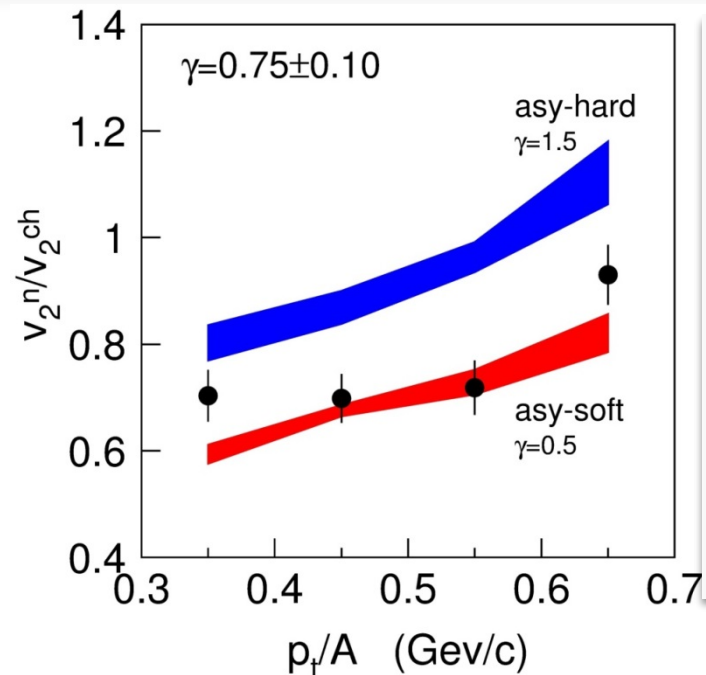
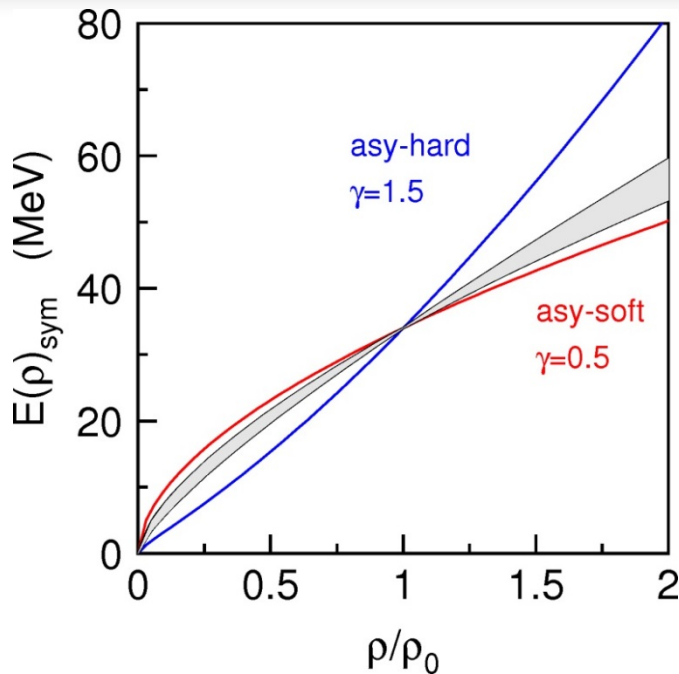
Y. Wang et al., PRC 89, 044603 (2014)



UrQMD: Qingfeng Li et al.
Data: W. Reisdorf et al.

Elliptic flow method: high densities

Asy-EOS



P. Rusotto et al., PRC (2017)

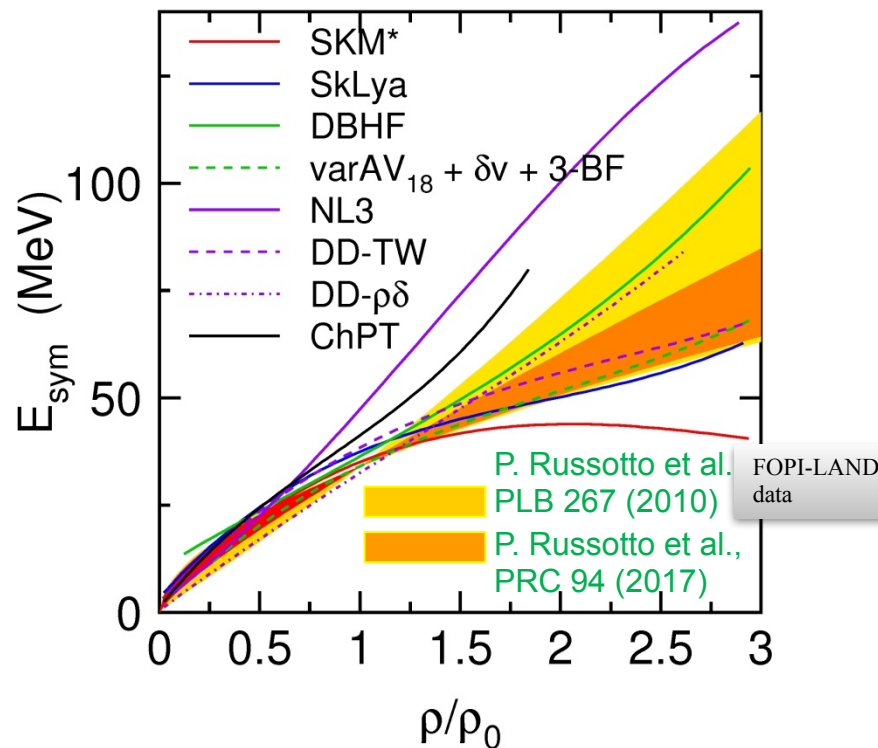
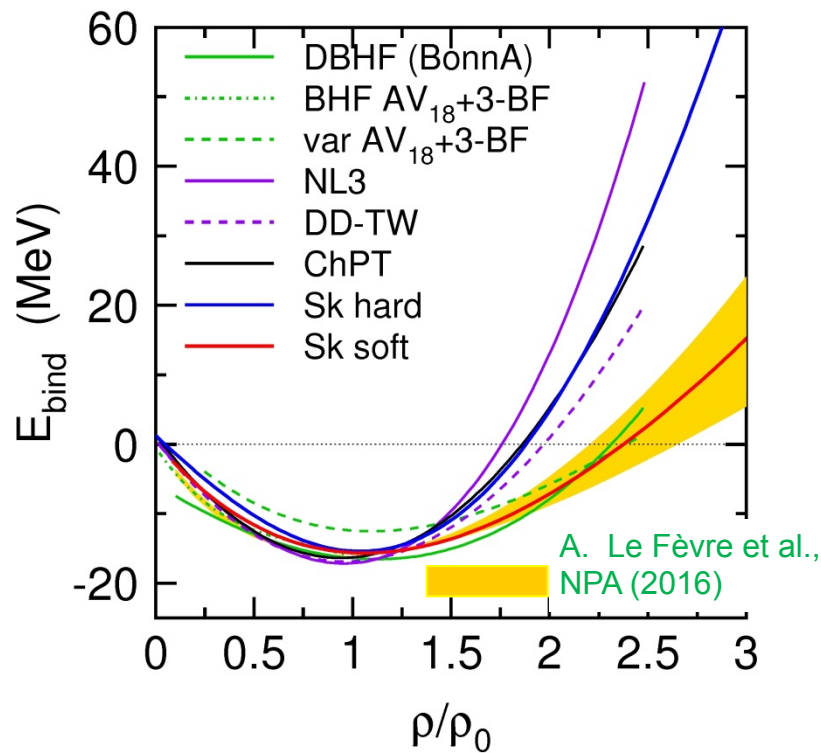
- parametrization for E_{asy} used in the UrQMD model:

$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22 \text{ MeV} \cdot (\rho/\rho_0)^\gamma + 12 \text{ MeV} \cdot (\rho/\rho_0)^{2/3}$$

- systematic errors corrected: $\gamma = 0.72 \pm 0.19$
- slope parameter: $L = 72 \pm 13 \text{ MeV}$, $E_{sym}(\rho_0) = 34 \text{ MeV}$
- slope parameter: $L = 63 \pm 11 \text{ MeV}$, $E_{sym}(\rho_0) = 31 \text{ MeV}$

A tentative synthesis: how HICs at GSI compare with recent astrophysical findings.

Synthesis at high densities

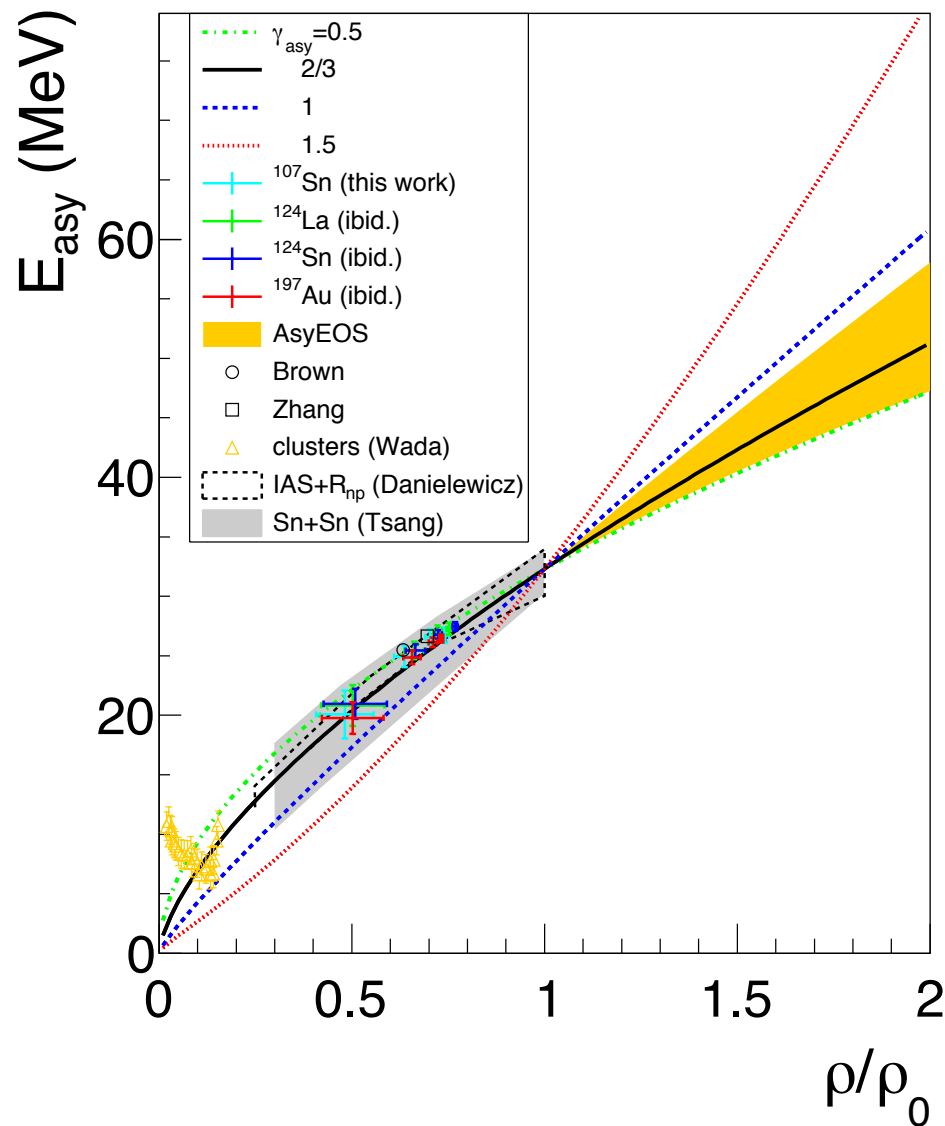


- equation of state of symmetric nuclear matter
- asymmetry energy
 - can be constrained by the systematic study of comparison of the flow of neutrons, protons and charged particles

A tentative synthesis: how HICs at GSI compare with recent astrophysical findings.

Synthesis at low densities

- Neutron rich systems are the most sensitive for this type of analysis
- How it extrapolates and binds to findings at supra-saturation densities :
 - ALADiN ($0.6-0.8 \rho_0$) (preliminary)
 - ➔ $L = 60.4 \pm 5.9$ MeV
 - ➔ $\gamma_{asy} = 0,60 \pm 0.06$
 - AsyEOS ($1-2 \rho_0$)
 - ➔ $L = 63 \pm 11$ MeV
 - ➔ $\gamma_{asy} = 0.68 \pm 0.19$
(for $E_{pot}^{asy}(\rho_0)=19$ MeV)
or $L = 72 \pm 13$ MeV
and $\gamma_{asy} = 0.72 \pm 0.19$
(for $E_{pot}^{asy}(\rho_0)=22$ MeV)



A tentative synthesis: how HICs at GSI compare with recent astrophysical findings.

- How can we combine AsyEOS and ALADiN results to deduce the pressure in a neutron star?

- Have $(P_{NN}^{sym}(K_0) + P_{asy}(L))\delta$

$\delta = 0.9$ (5% protons + degenerate e^-)

- L as from AsyEOS at $1-2\rho_0$

[Russotto et al. PRC94(2016)034608]

- L as from ALADiN at $0.7\rho_0$

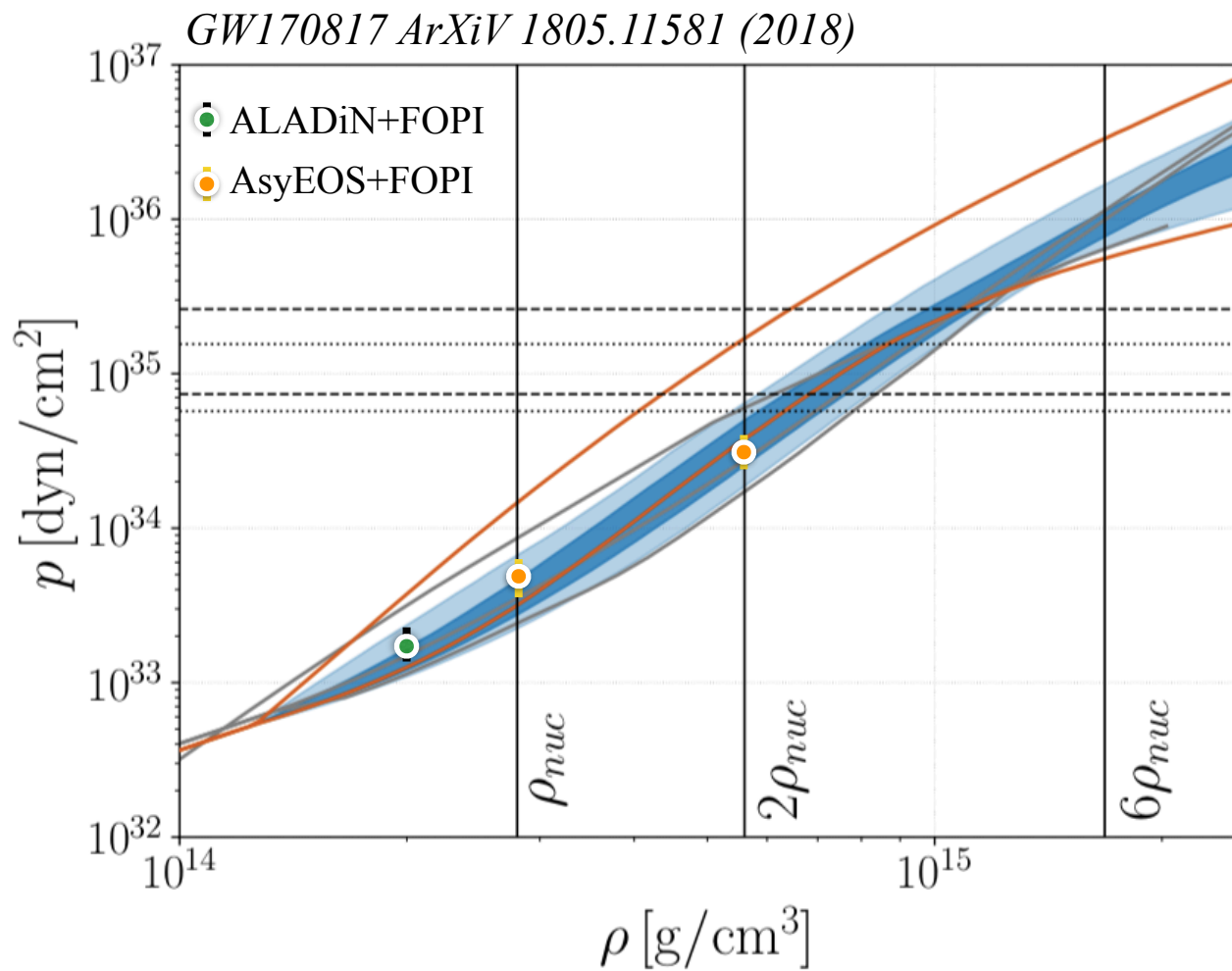
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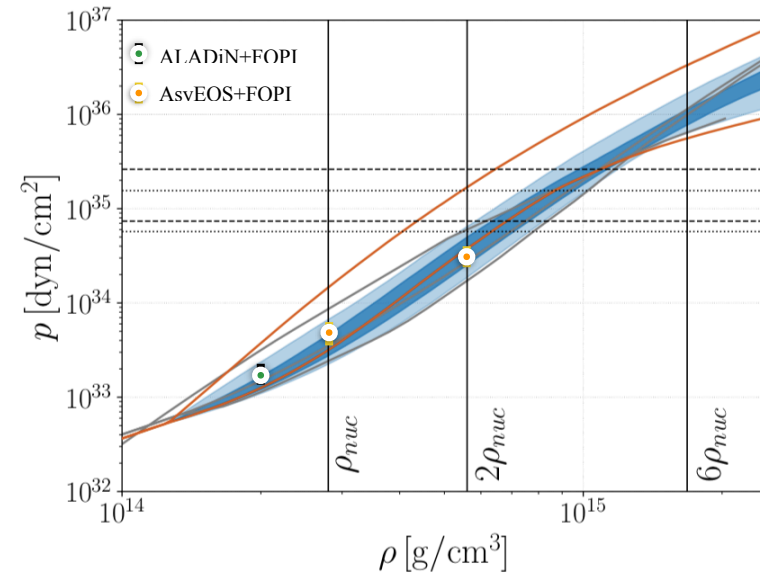
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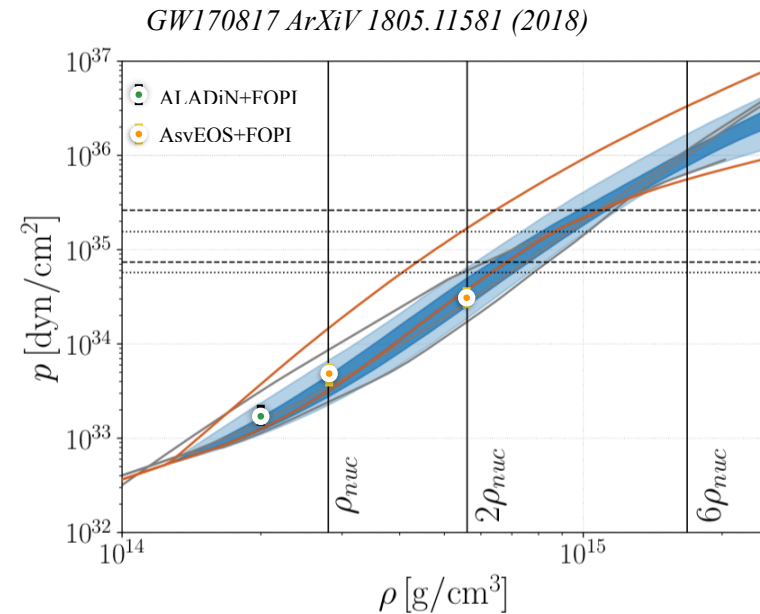
Conclusion and perspectives

GW170817 ArXiv 1805.11581 (2018)



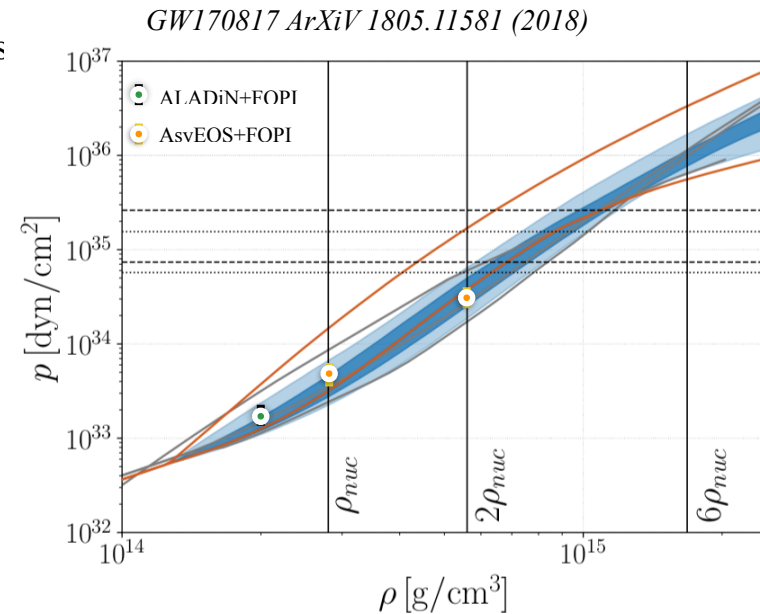
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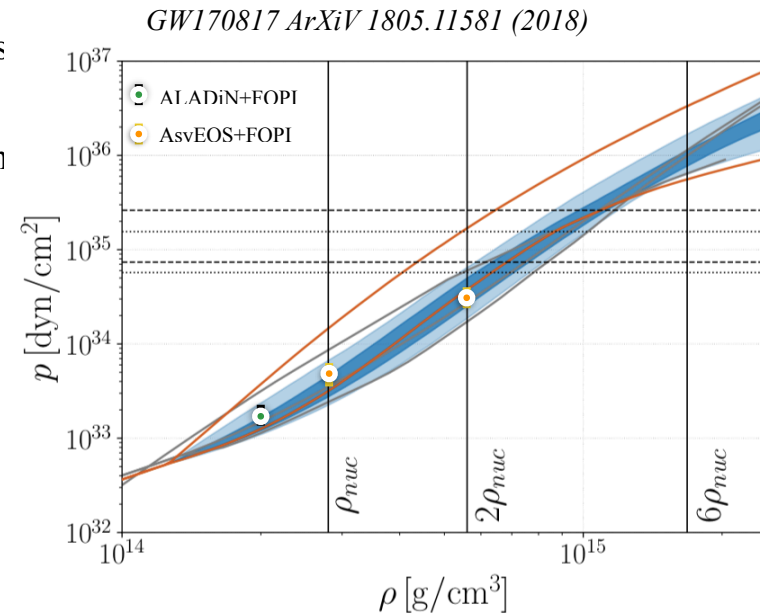
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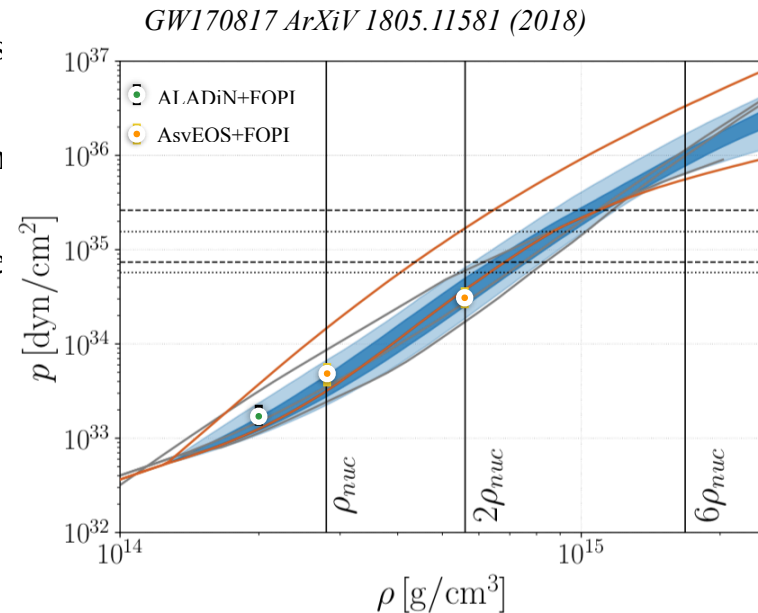
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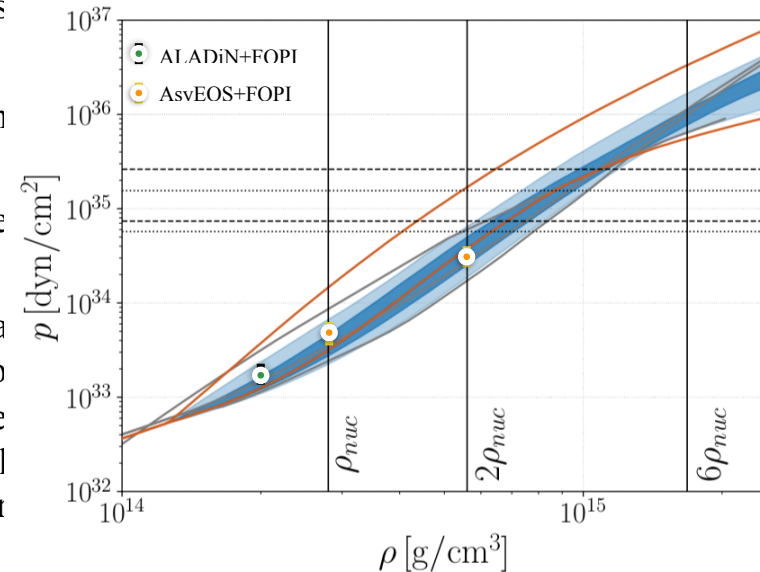
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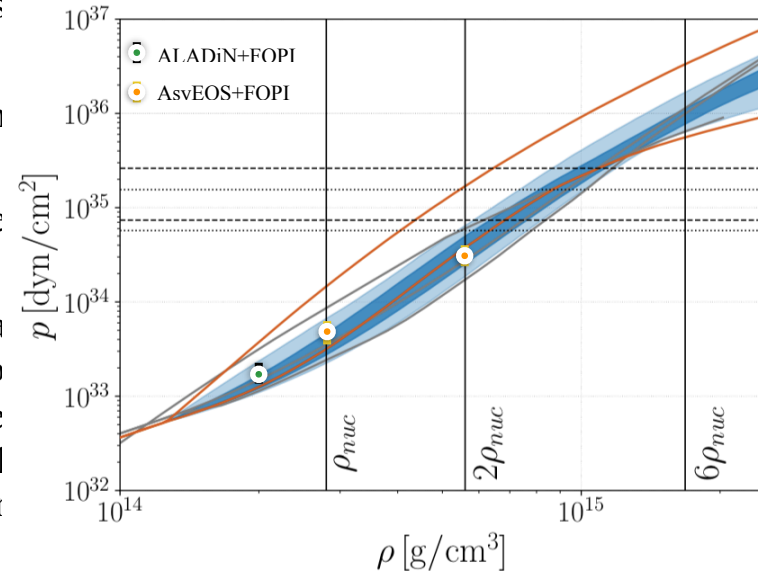
GW170817 ArXiv 1805.11581 (2018)



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- Question our error bars, must be included: reliable model dependencies and corrections due to determinations of K_0 and L at non zero temperature.
- Beyond $3 - 4\rho_0$ (FAIR, NICA), new observables needed to constrain L and K_0 . A new generation of relativistic transport models must arise, benchmarked e.g. with data taken at SIS18 at the highest available beam energies (**FOPI, HADES**).

