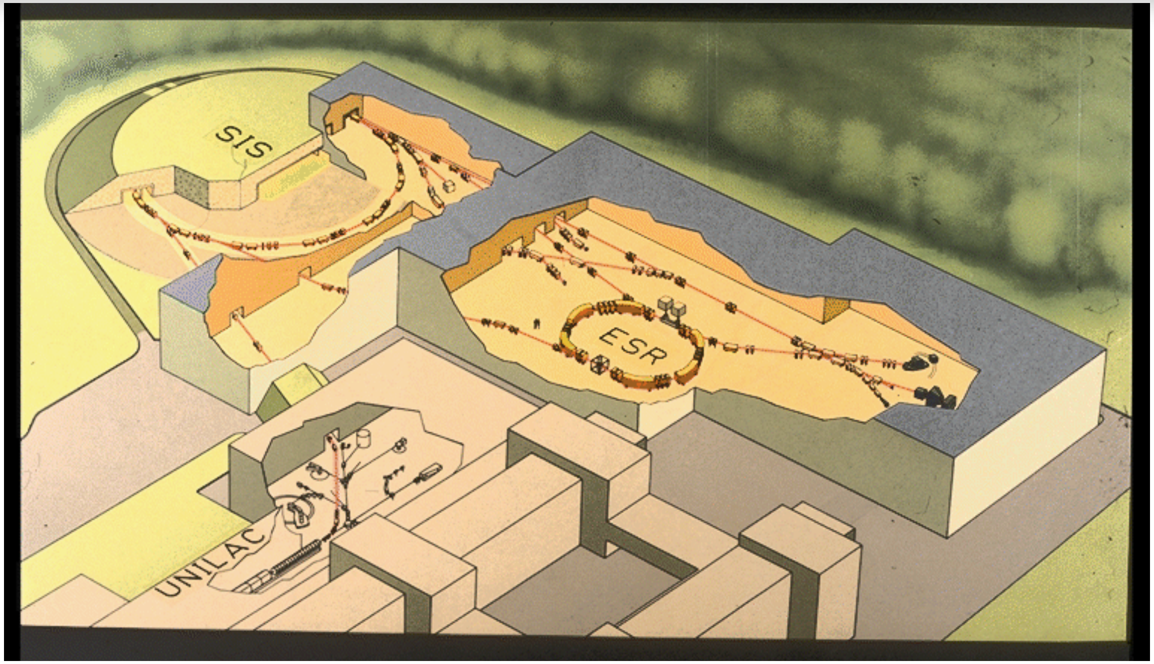
Asymmetry energy and nuclear matter EoS: What have we learnt from experiments at SIS18 ?



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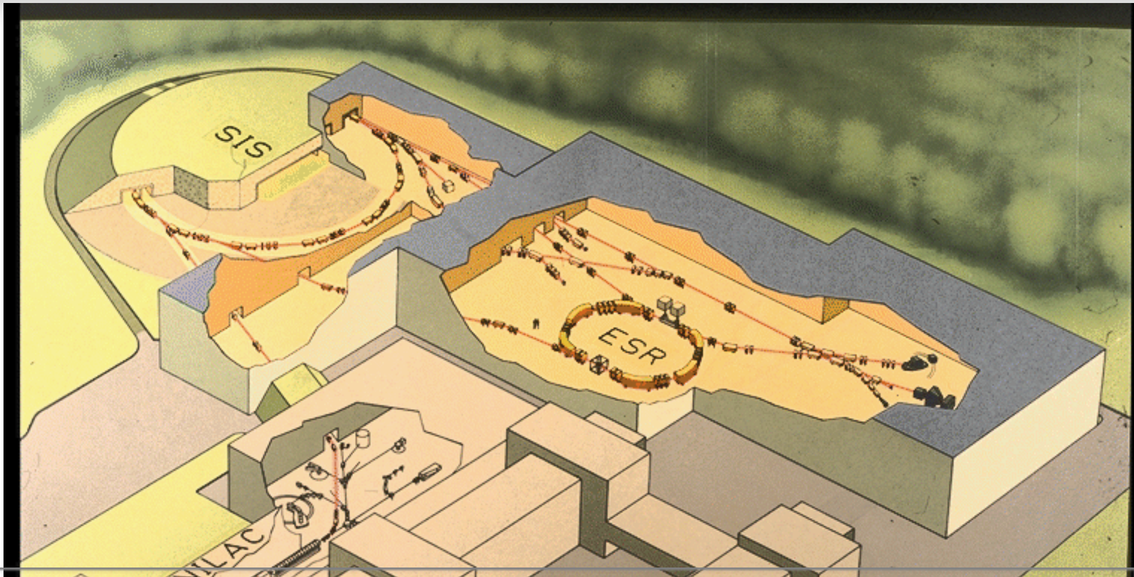
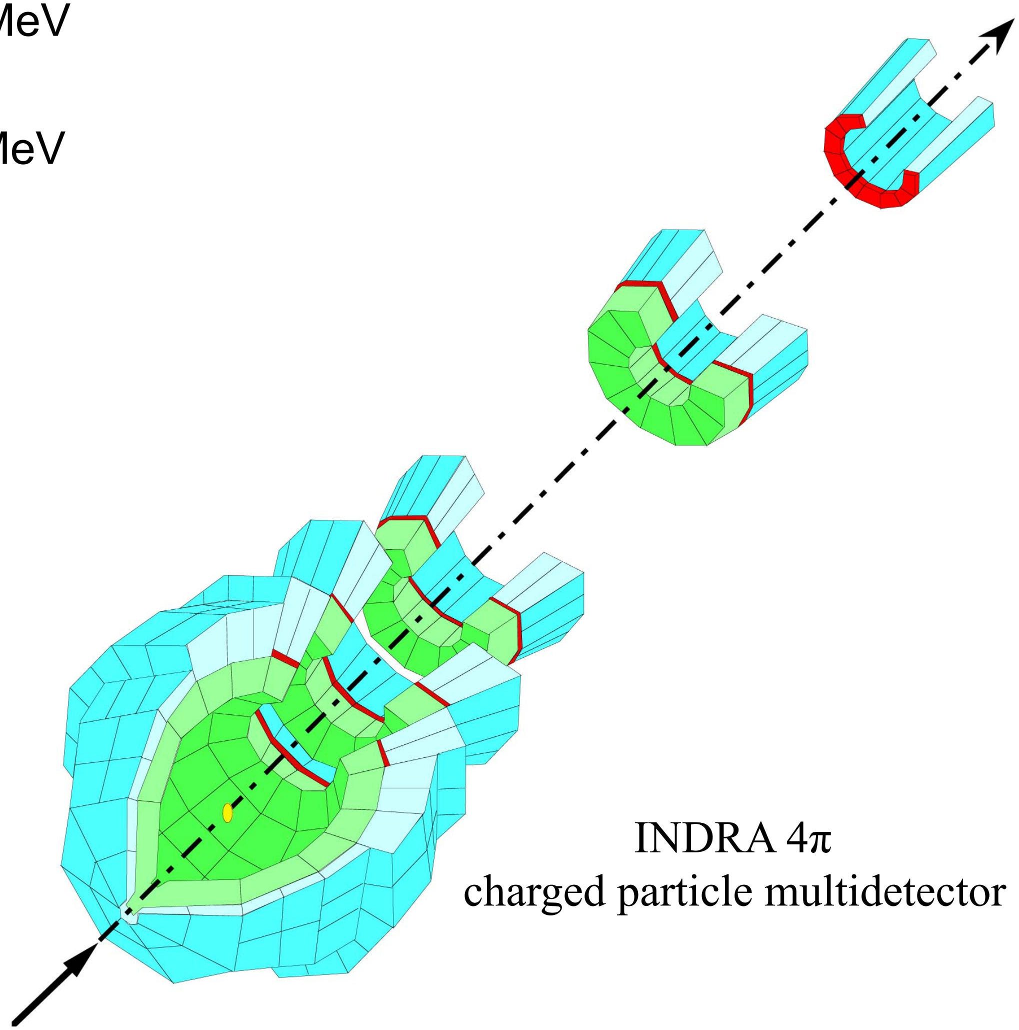


- Overview of experiments performed at GSI over 20 years with HICs at relativistic energies.
- From low densities (probed via isotopic yields): INDRA, ALADiN.
- To high densities (probed via elliptic flows of particles, kaon and pion yields): FOPI, KaoS, LAND, AsyEOS.
- A tentative synthesis: how HICs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

Isotopic method: sub-saturation densities INDRA@GSI

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



INDRA 4π
charged particle multidetector

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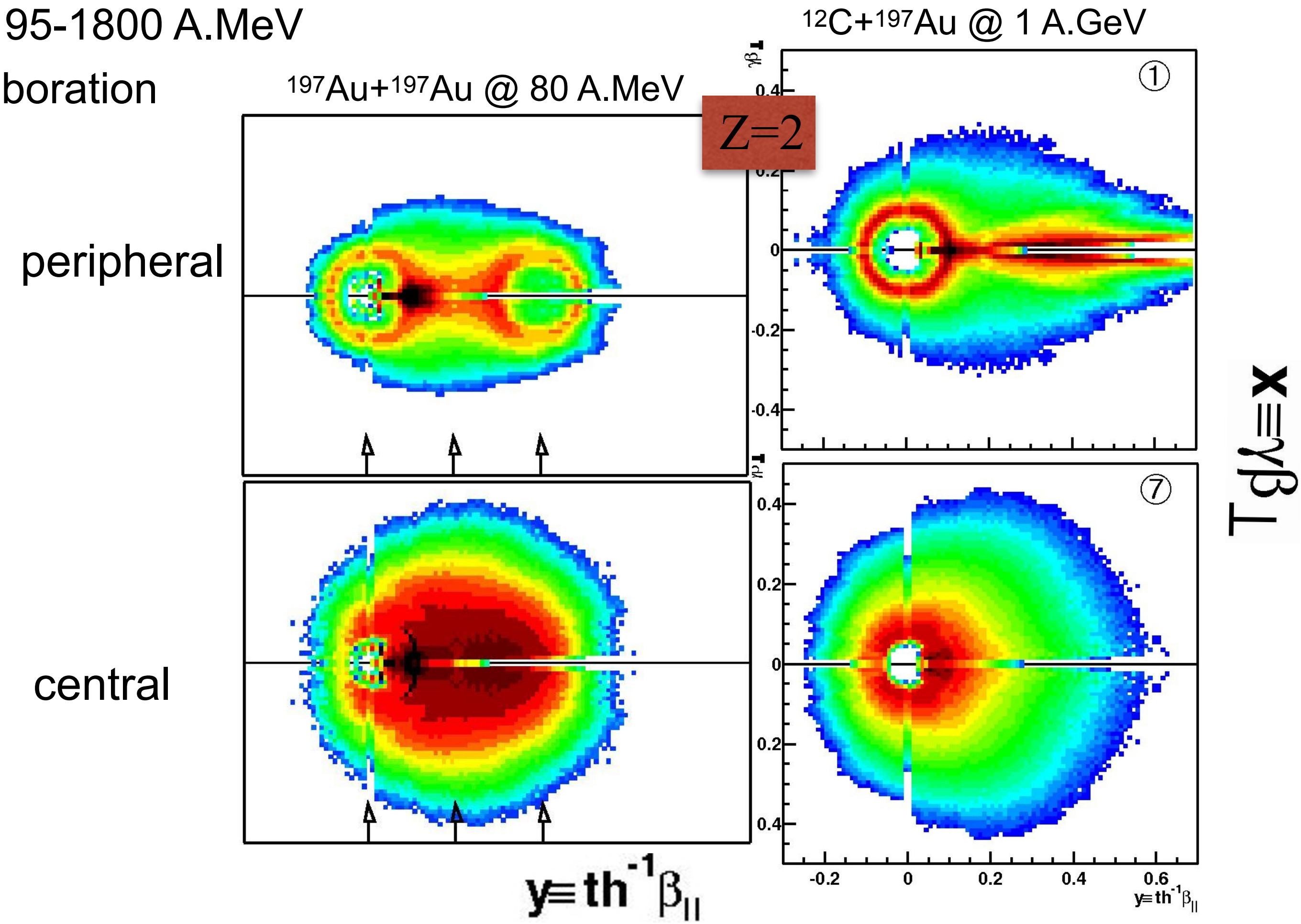

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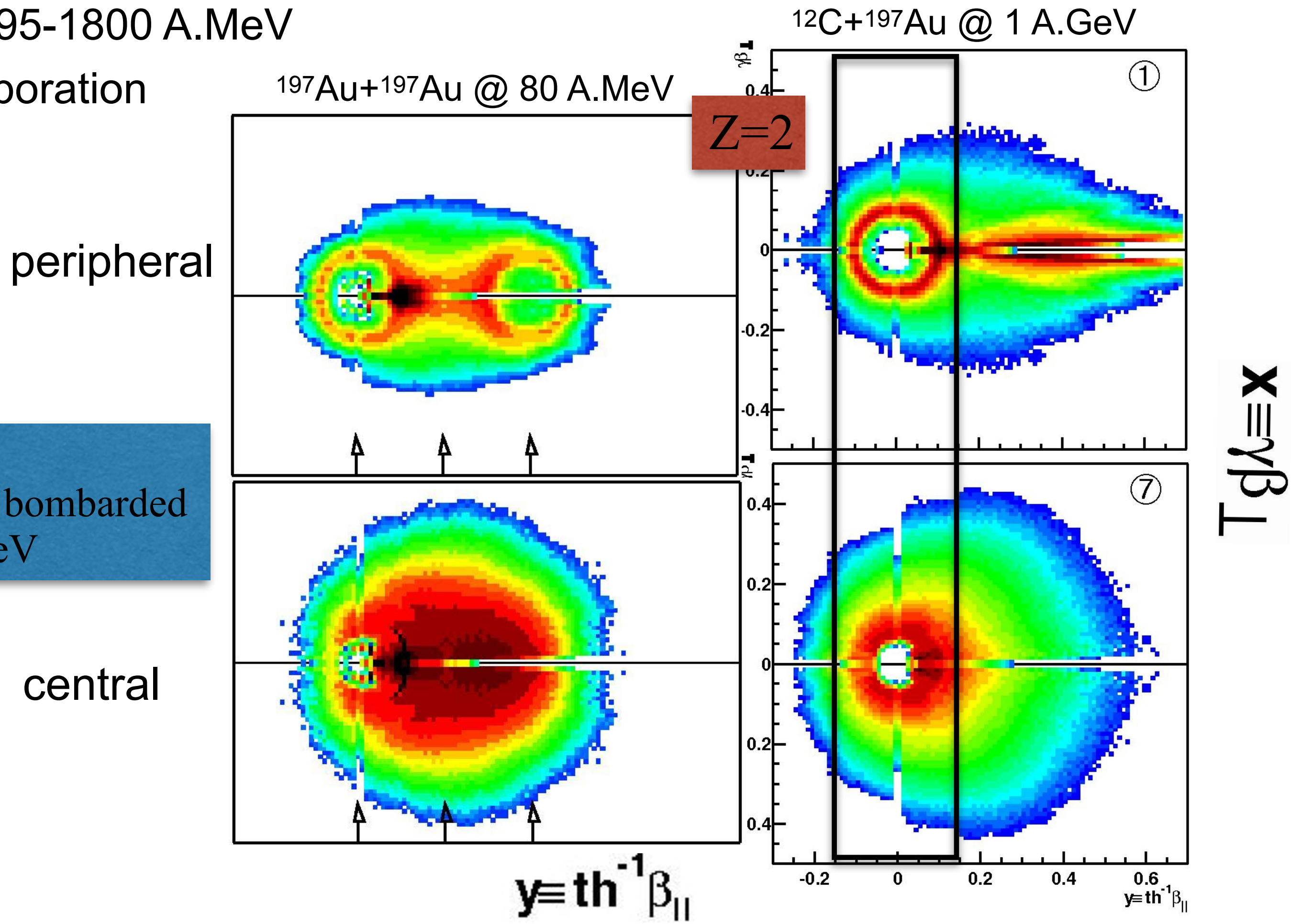
Focus on target spectator fragmentation of $^{112/124}Sn$ bombarded with ^{12}C @ 300, 600A MeV



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

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

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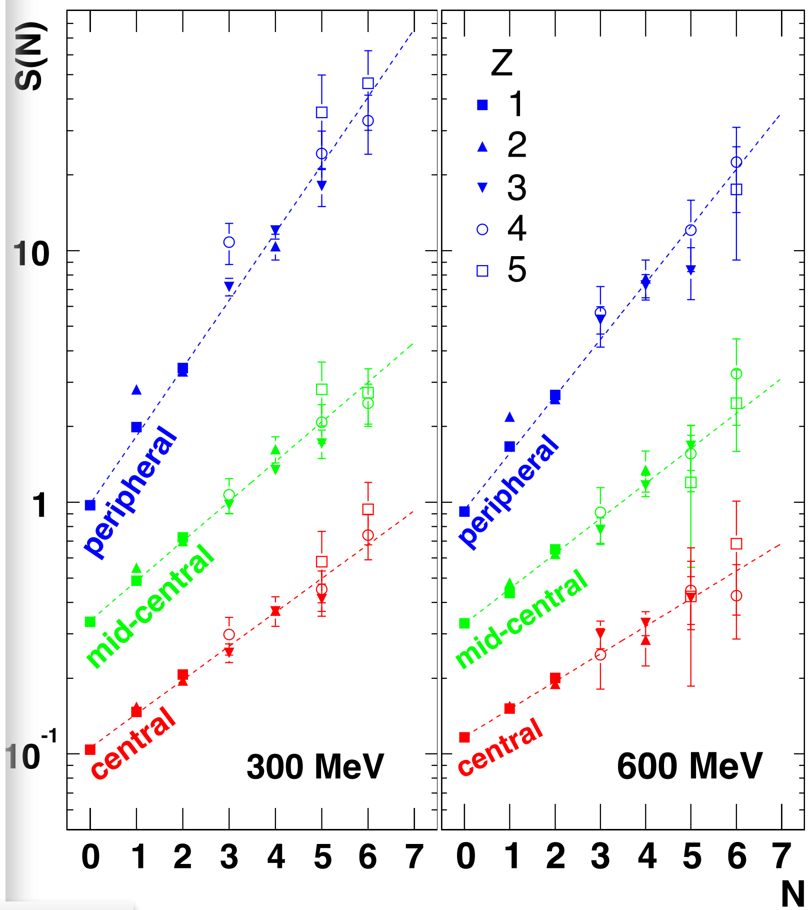
INDRA-ALADiN data
Target spectator decay $^{12}C + ^{112,124}Sn$



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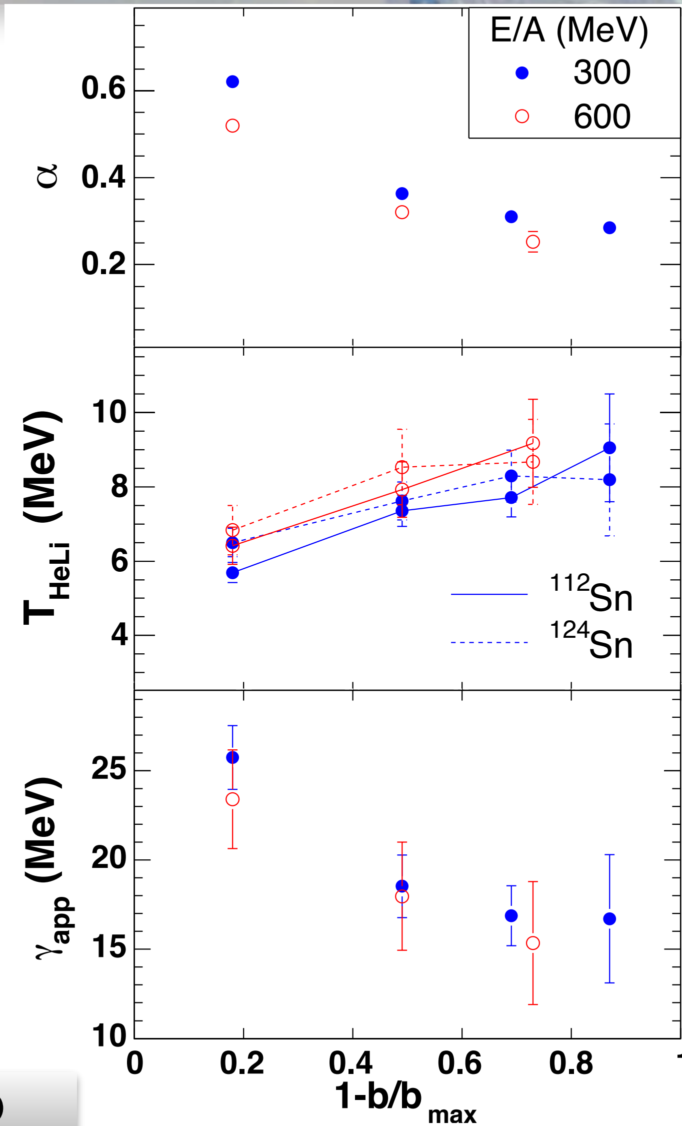

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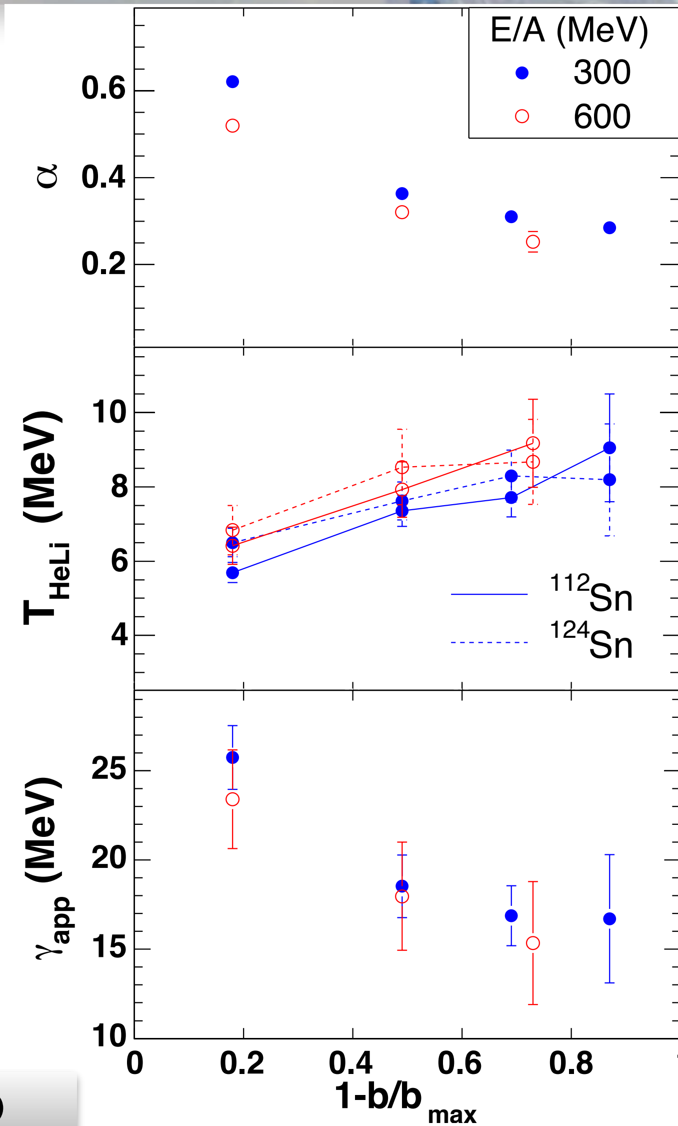

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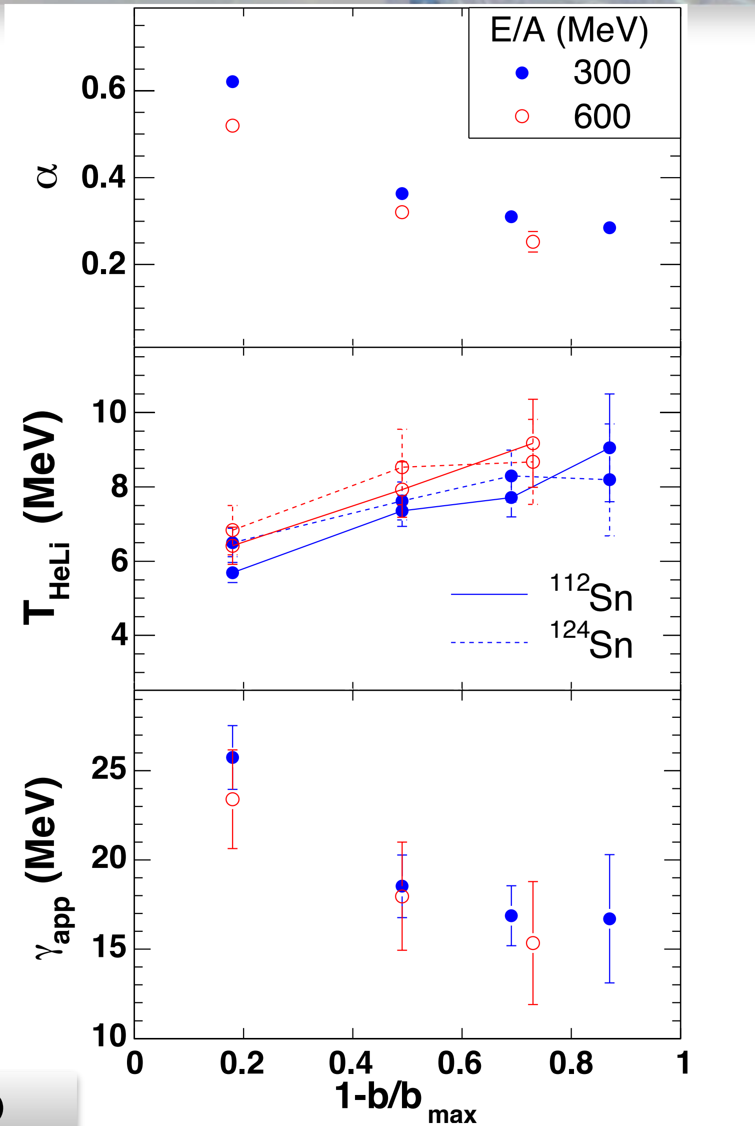

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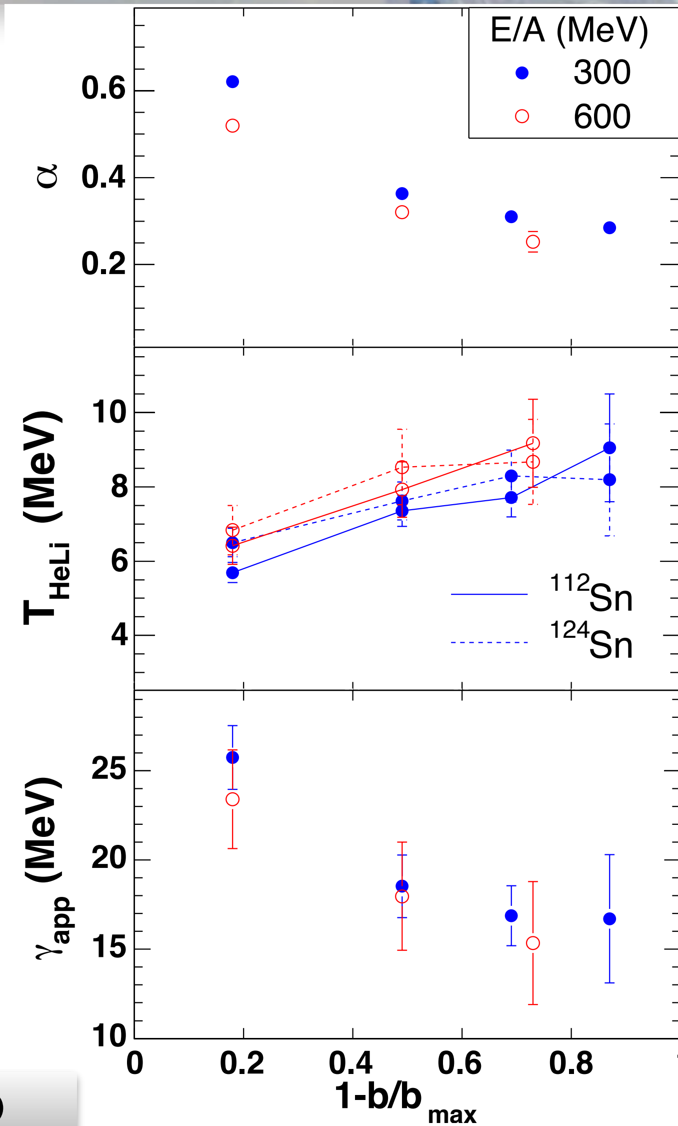
  - γ = 25 MeV for peripheral events (liquid-drop model standard at ρ_0)



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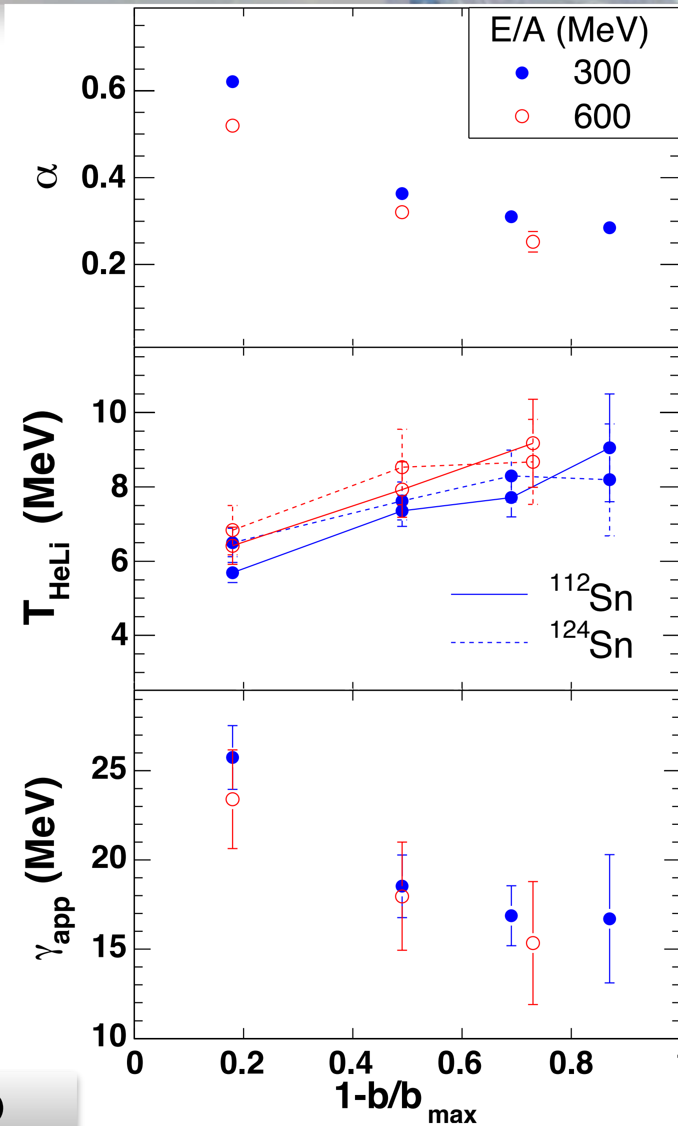
- Experimental results:
  - γ = 25 MeV for peripheral events (liquid-drop model standard at ρ_0)
  - γ = 10 MeV for central events (cluster $\rho << \rho_0$?)



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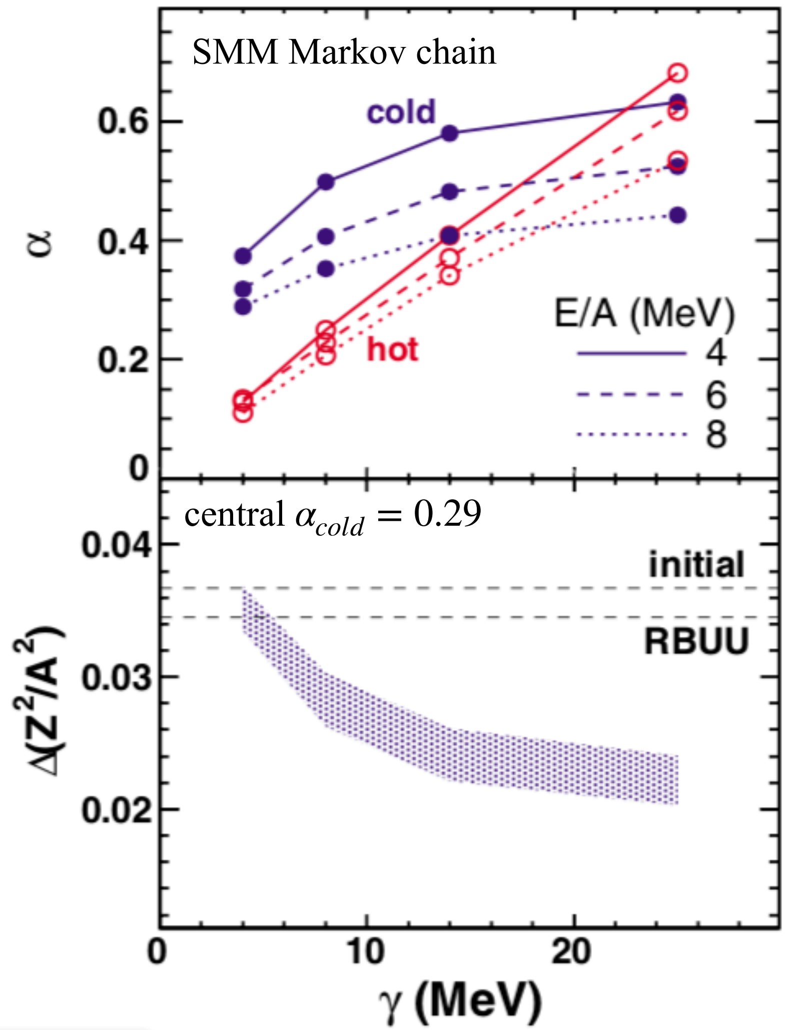
GSI FAIR HELMHOLTZ ASSOCIATION

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

$$\gamma = \frac{\alpha T}{4\Delta(\frac{Z}{A})^2}$$

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.



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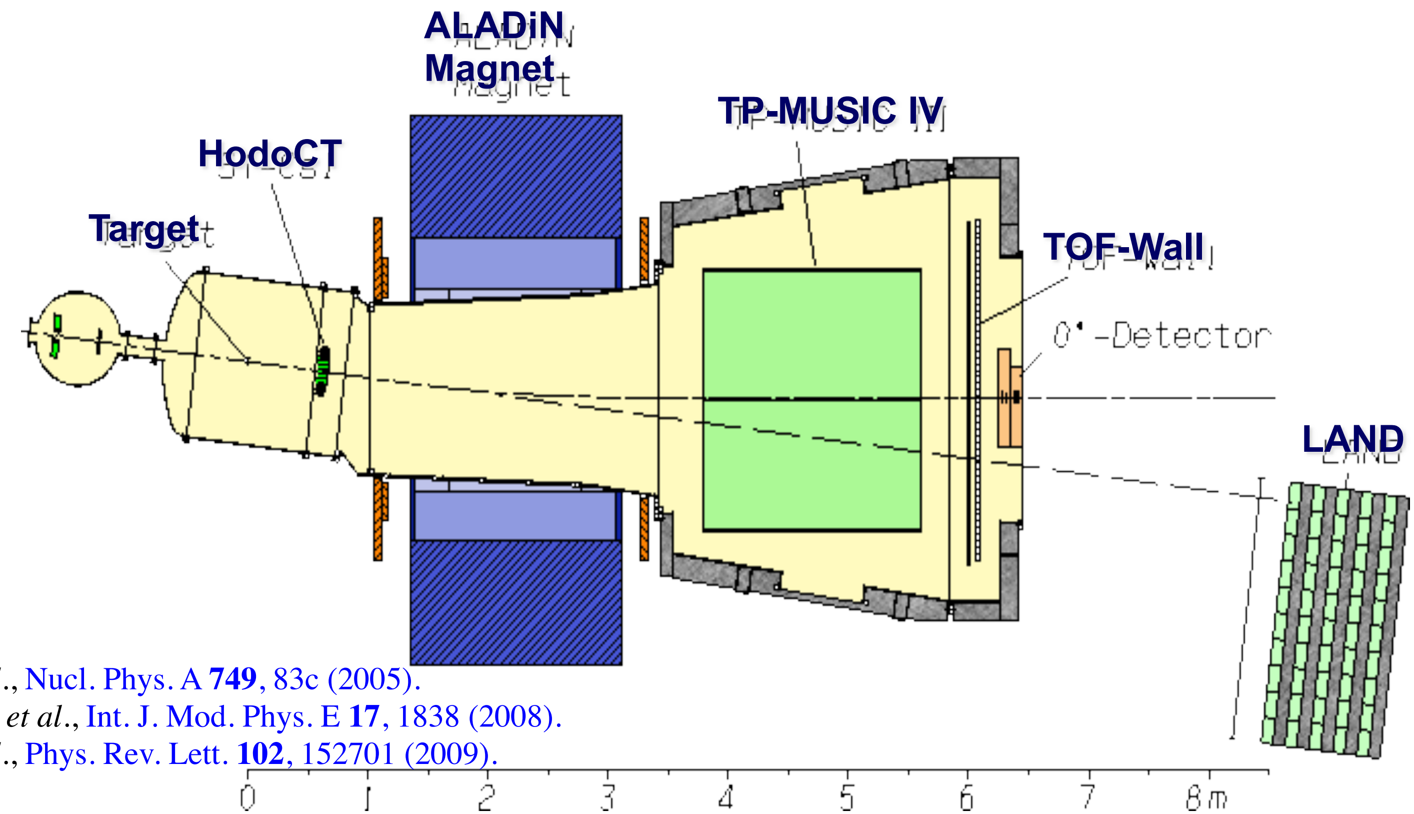
Isotopic method: sub-saturation densities ALADiN

The S254 experiment (2003)



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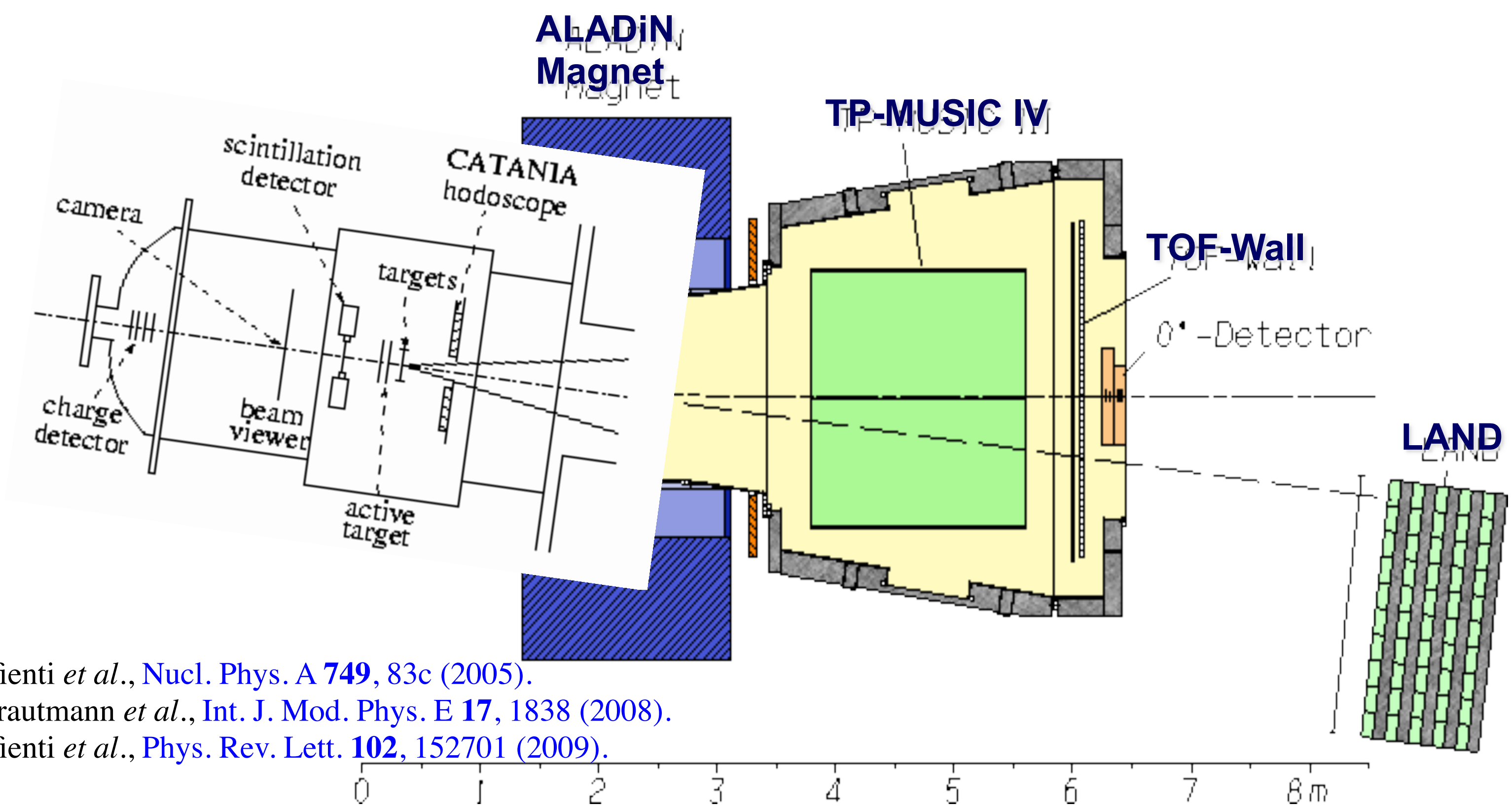

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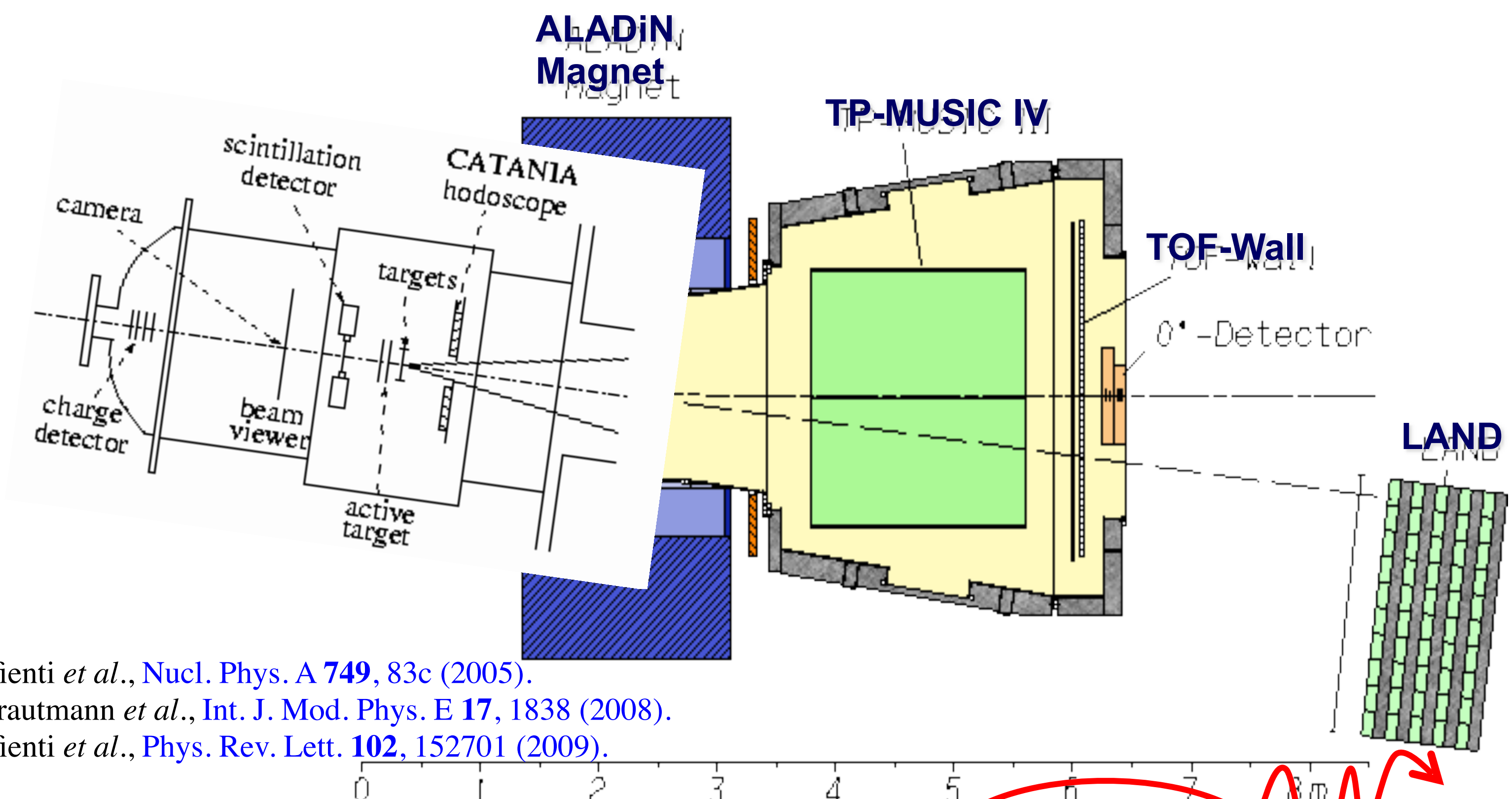

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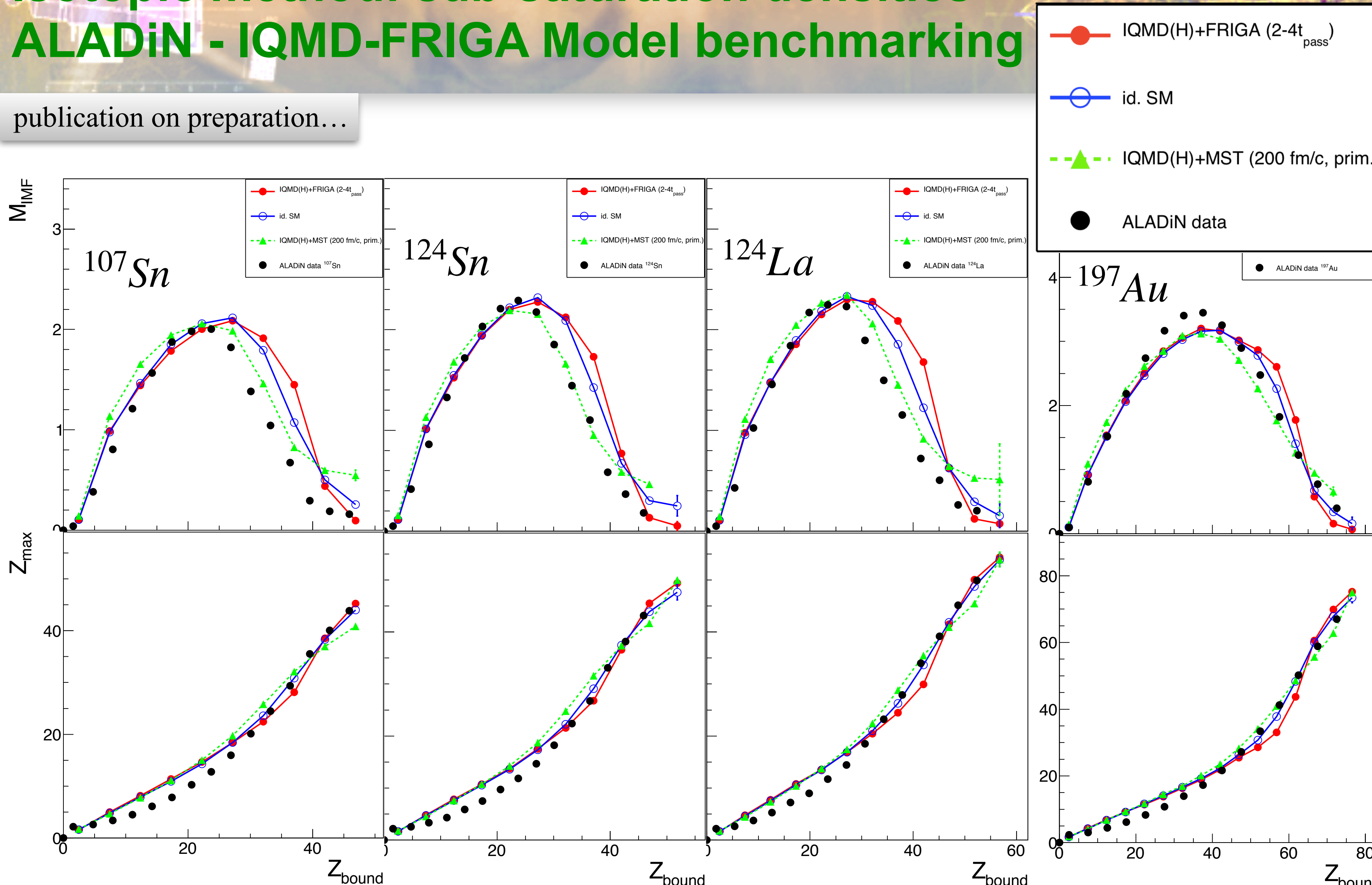
Neutron rich/poor projectiles: $^{197}Au, ^{124}Sn, ^{124}La, ^{107}Sn$

Secondary Beams (Low Intensities!)

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

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

publication on preparation…



FRIGA: A. Le Fèvre et al., PRC100 (2019) 034904 - IQMD: Hartnack et al.

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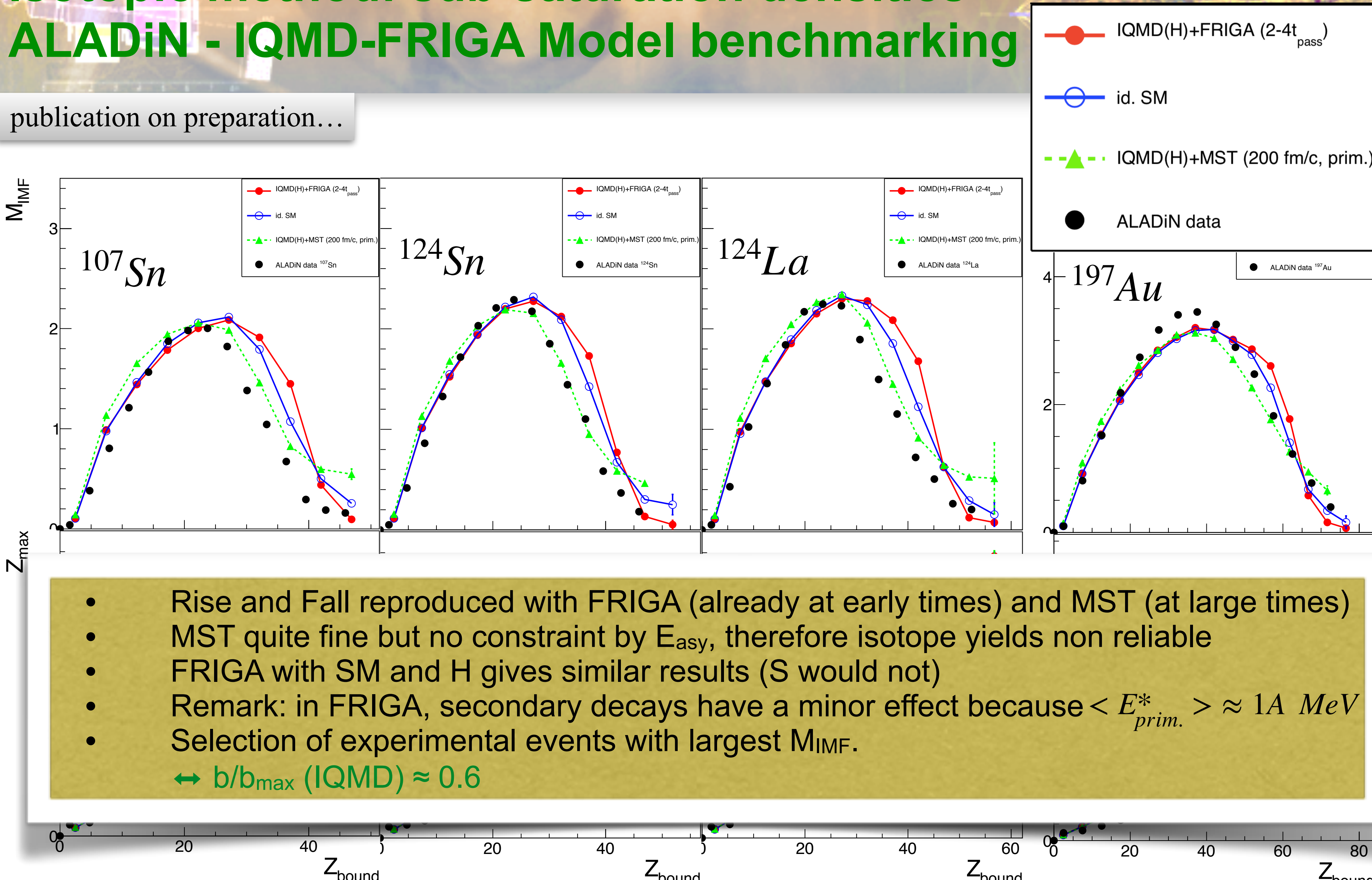

- Rise and Fall reproduced with FRIGA (already at early times) and MST (at large times)
- MST quite fine but no constraint by E_{asy}, therefore isotope yields non reliable
- FRIGA with SM and H gives similar results (S would not)
- Remark: in FRIGA, secondary decays have a minor effect because $< E^*_{prim.}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

↔ b/b_{max} (IQMD) ≈ 0.6

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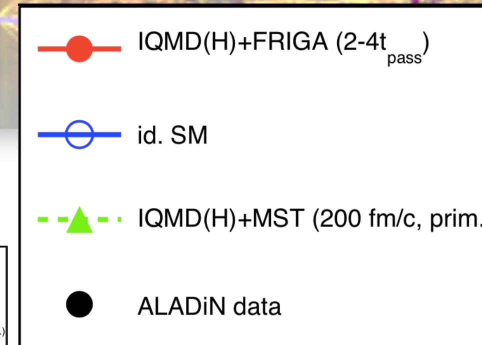

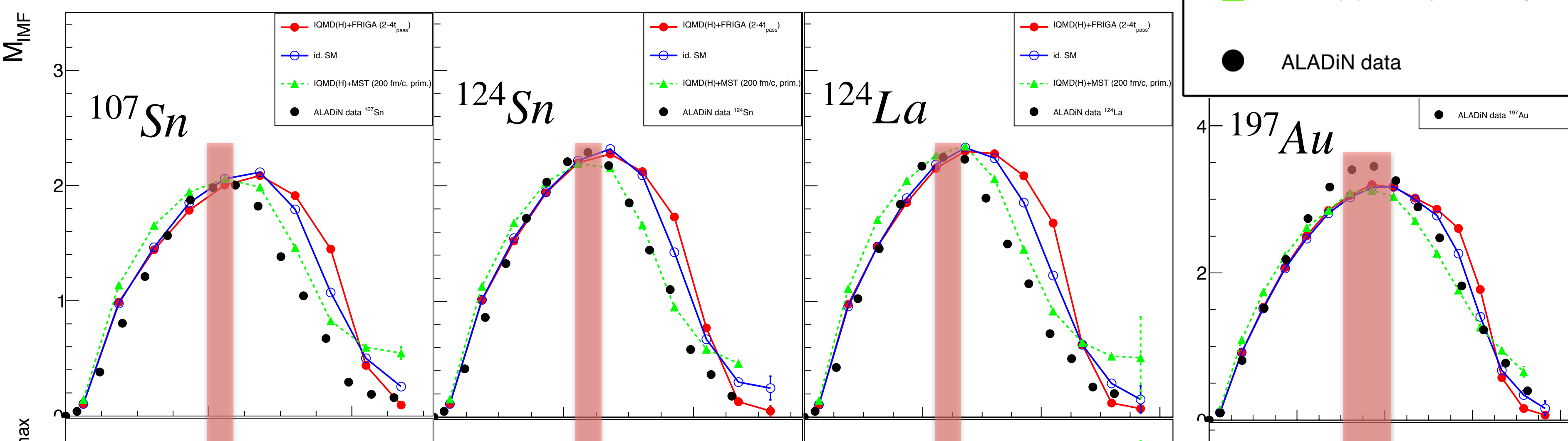

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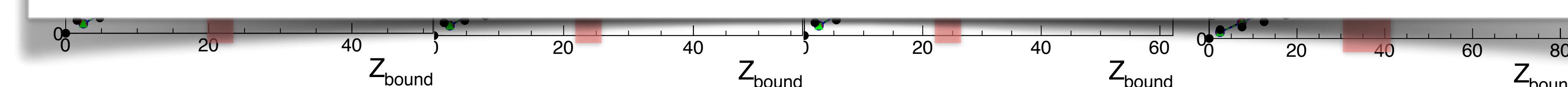

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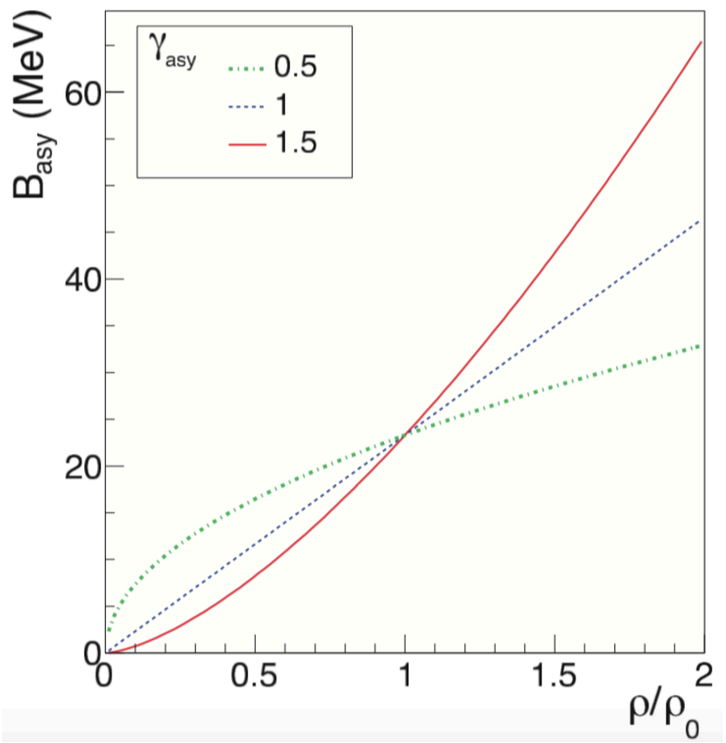
Isotopic method: sub-saturation densities
ALADiN - sensitivity to the asymmetry energy

publication on preparation…

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



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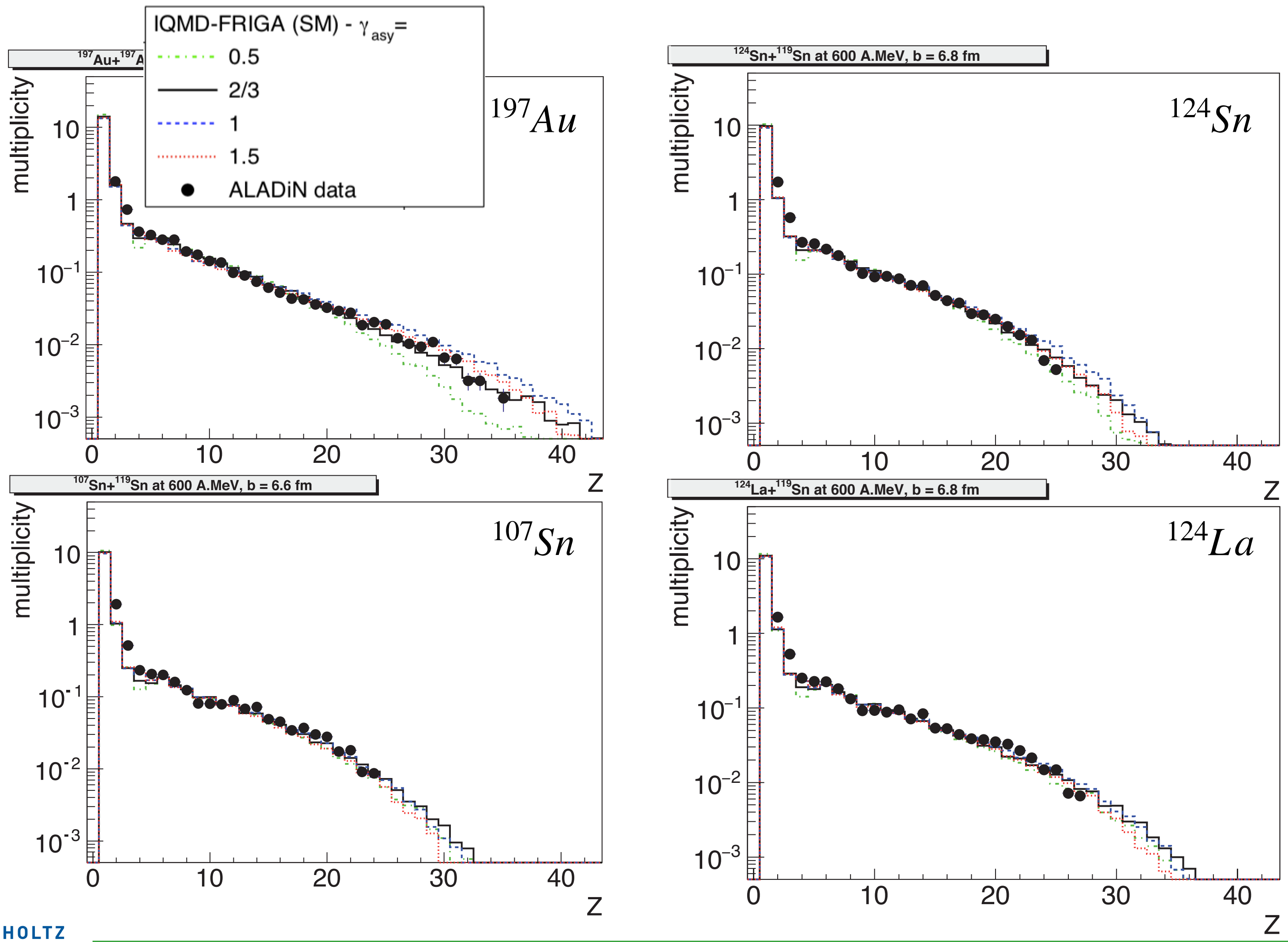

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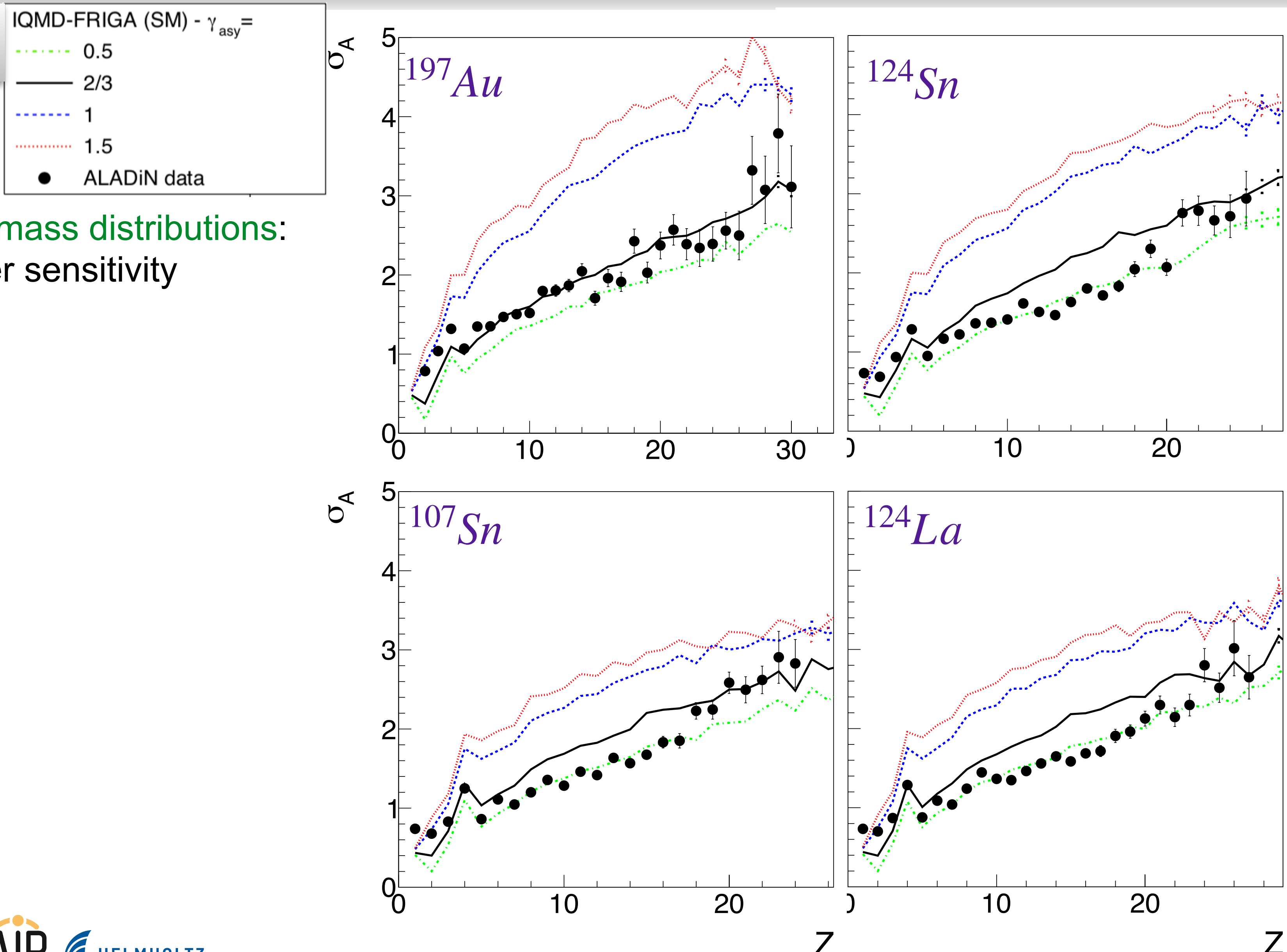


Widths of mass distributions: even larger sensitivity

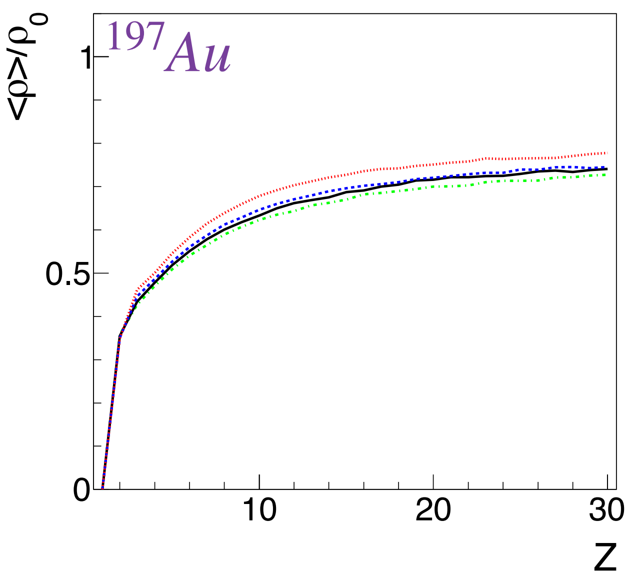
Isotopic method: sub-saturation densities
ALADiN - sensitivity to the asymmetry energy

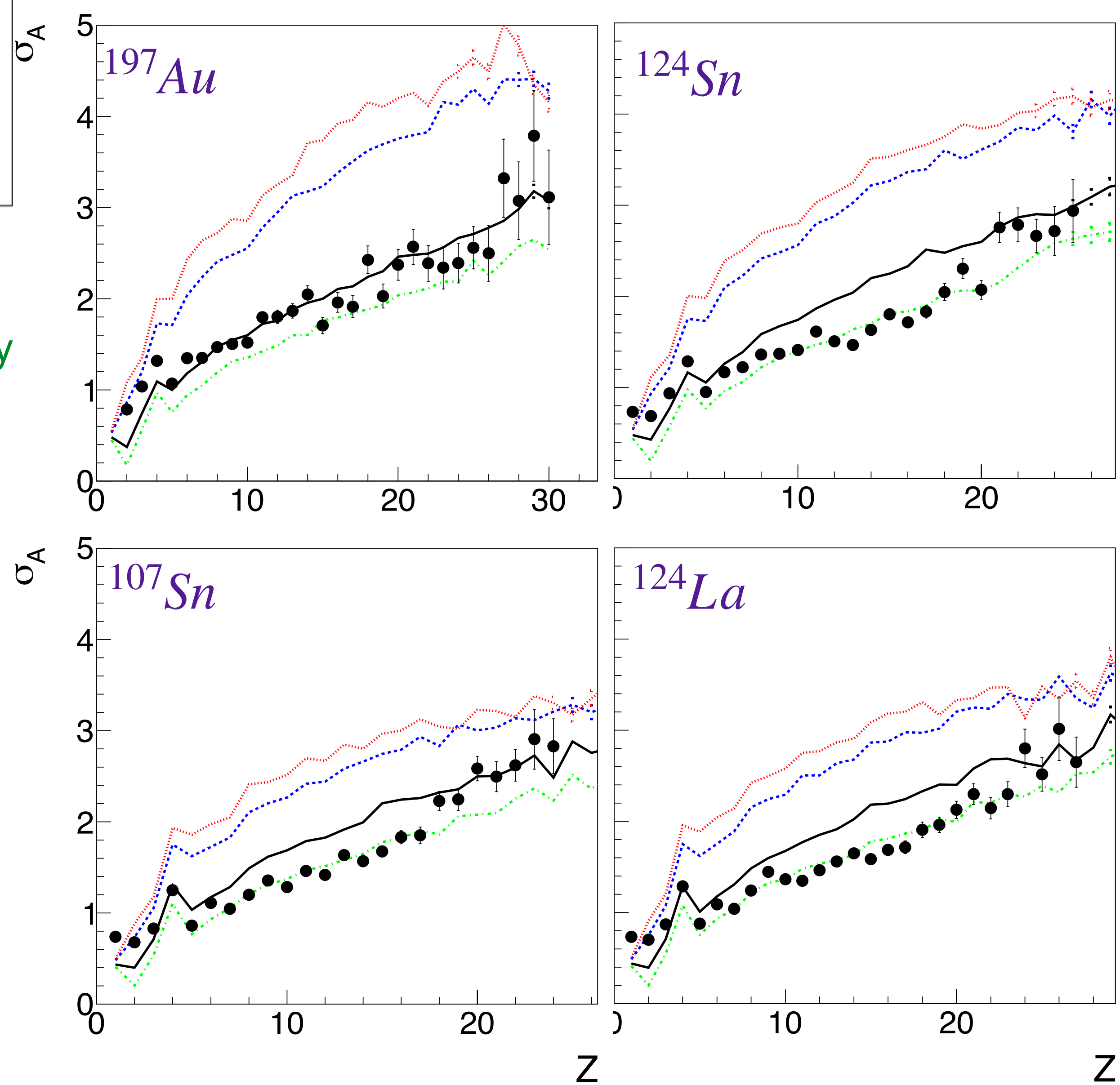
publication on preparation…

IQMD-FRIGA (SM) - γ_{asy}=
- 0.5
- 2/3
- 1
- 1.5
- ALADiN data

Widths of mass distributions: even larger sensitivity

⚠ probed densities are strongly related to the cluster size:





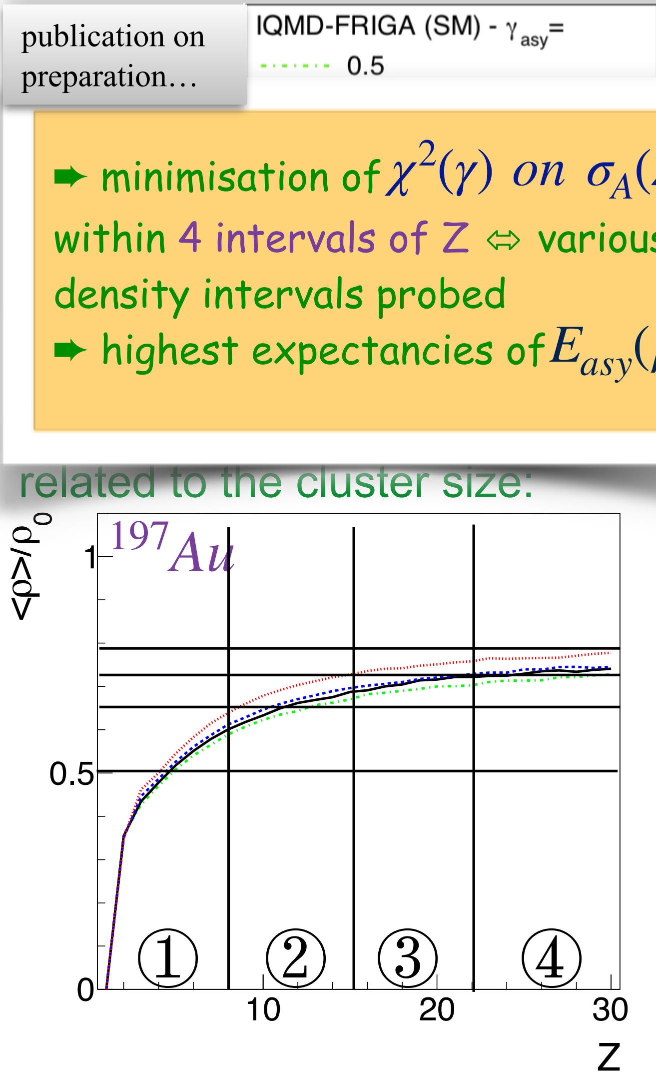
Isotopic method: sub-saturation densities
ALADiN - sensitivity to the asymmetry energy

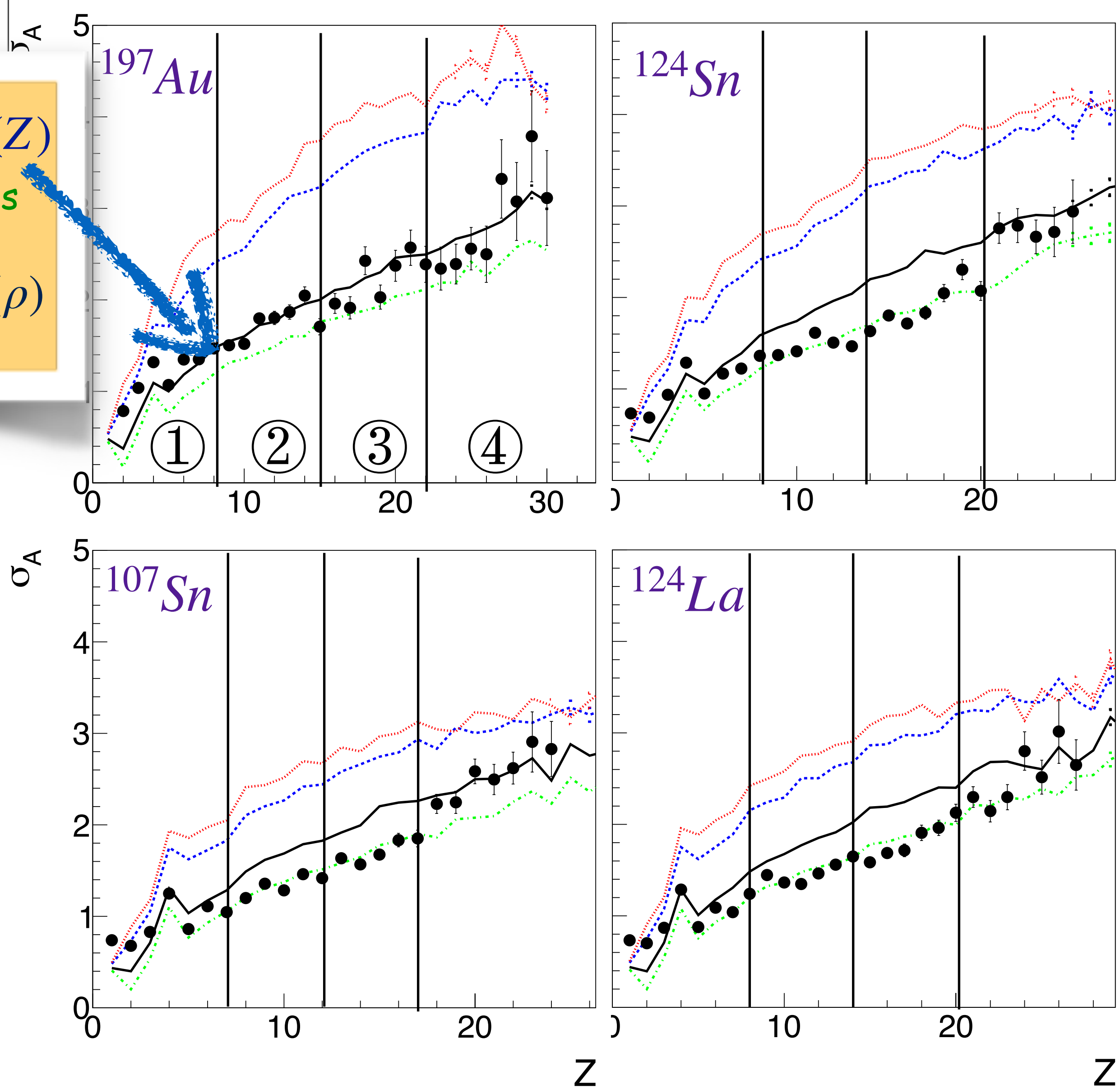
publication on preparation…

➨ minimisation of $\chi^2(\gamma)$ on $\sigma_A(Z)$ within 4 intervals of Z ⇔ various density intervals probed

➨ highest expectancies of $E_{asy}(\rho)$

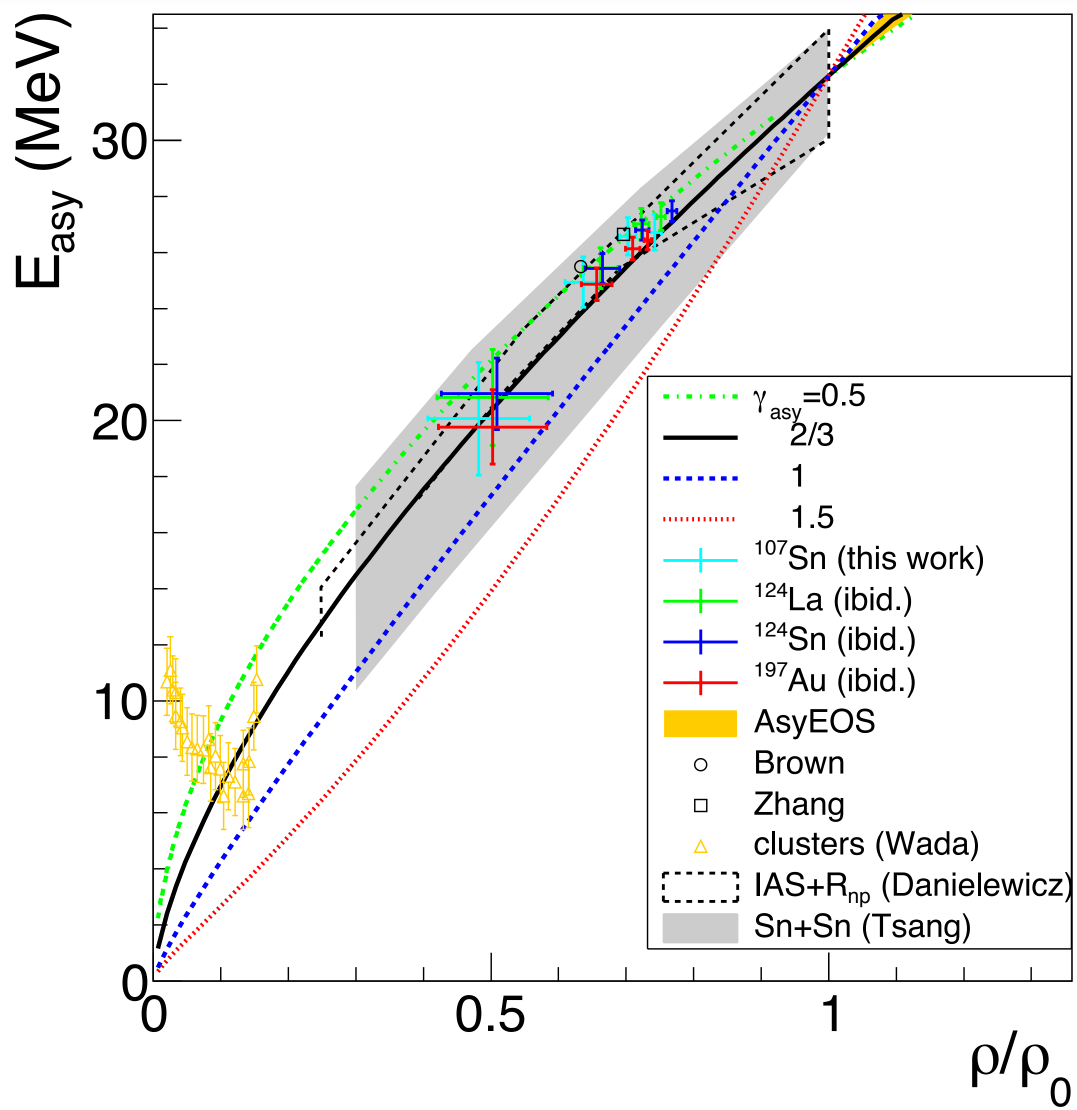
related to the cluster size:





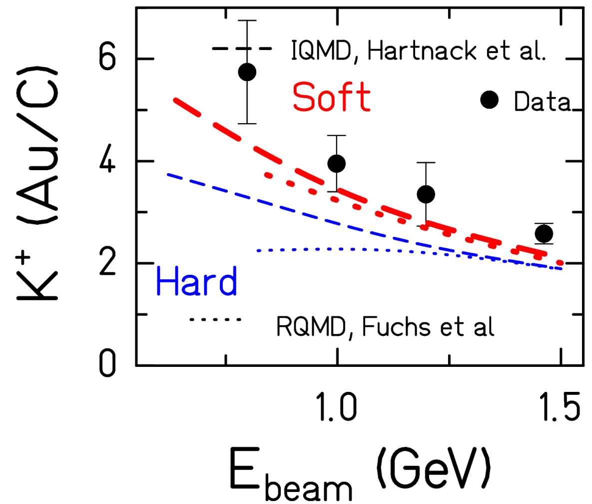
Isotopic method: sub-saturation densities ALADiN - Synthesis over all systems and how its compares with recent findings

- Neutron rich systems are the most sensitive for this type of analysis
  - ALADiN (0.6-0.8 ρ_0)
    - ➽ **L = 60.4 ± 5.9 MeV**
    - ➽ $\boldsymbol{\gamma_{asy} = 0{,}60 \pm 0.06}$
- **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

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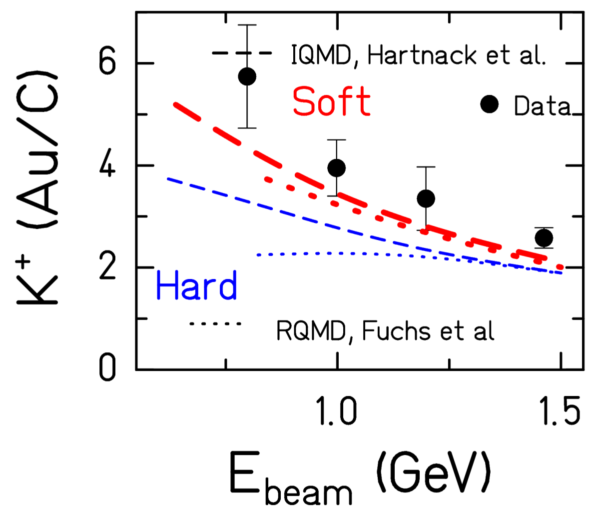

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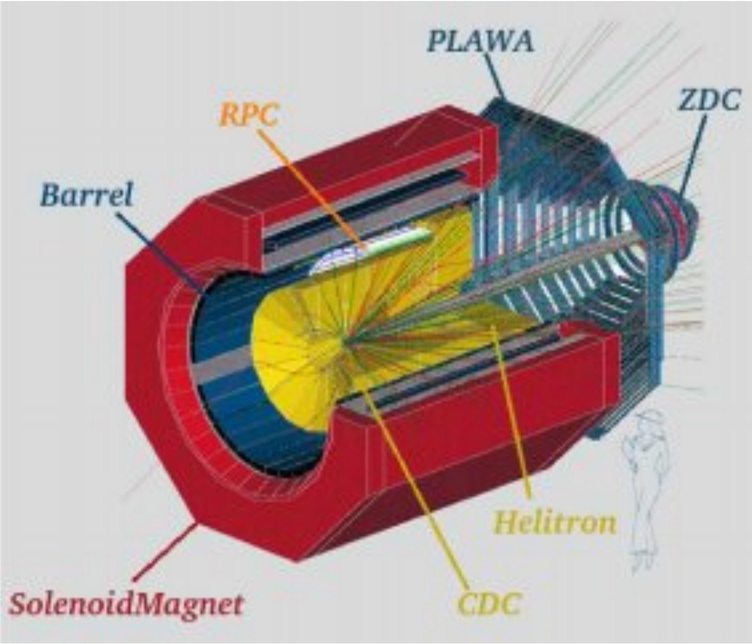
FOPI 1990'-2000' campaigns
Au+Au @ 95 - 1500 A MeV



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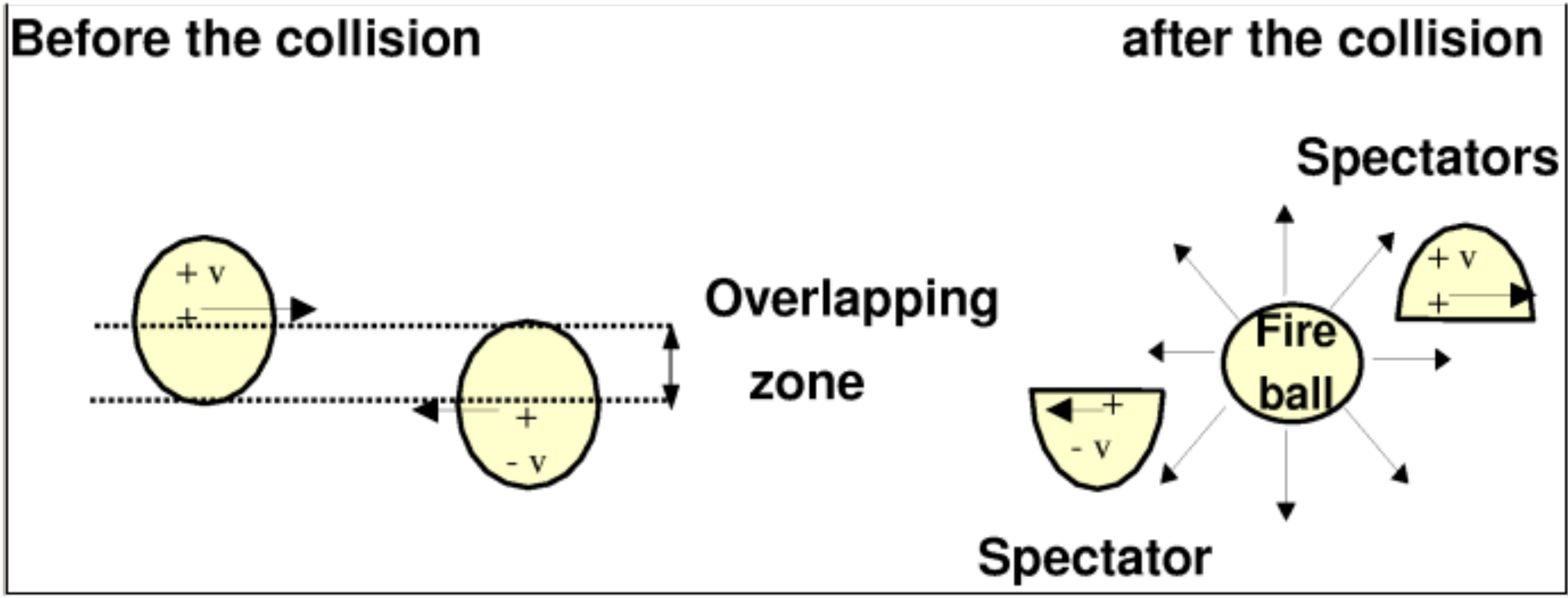
Elliptic flows of particles out of the participant region (« fireball »)



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

Flows at high density in heavy-ion collisions

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

Y = rapidity

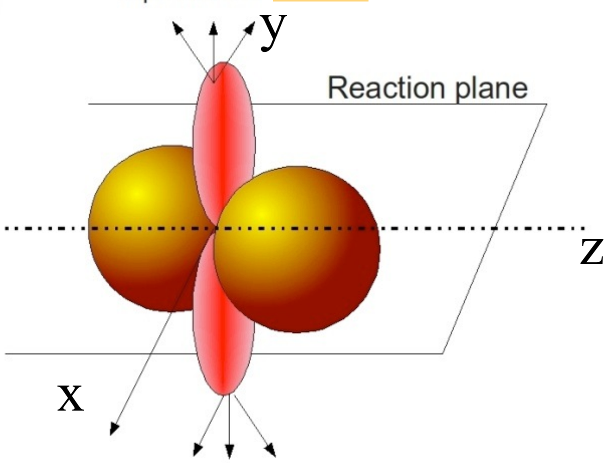
p_t = transverse momentum

Φ_R = reaction plane azimuthal angle

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

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

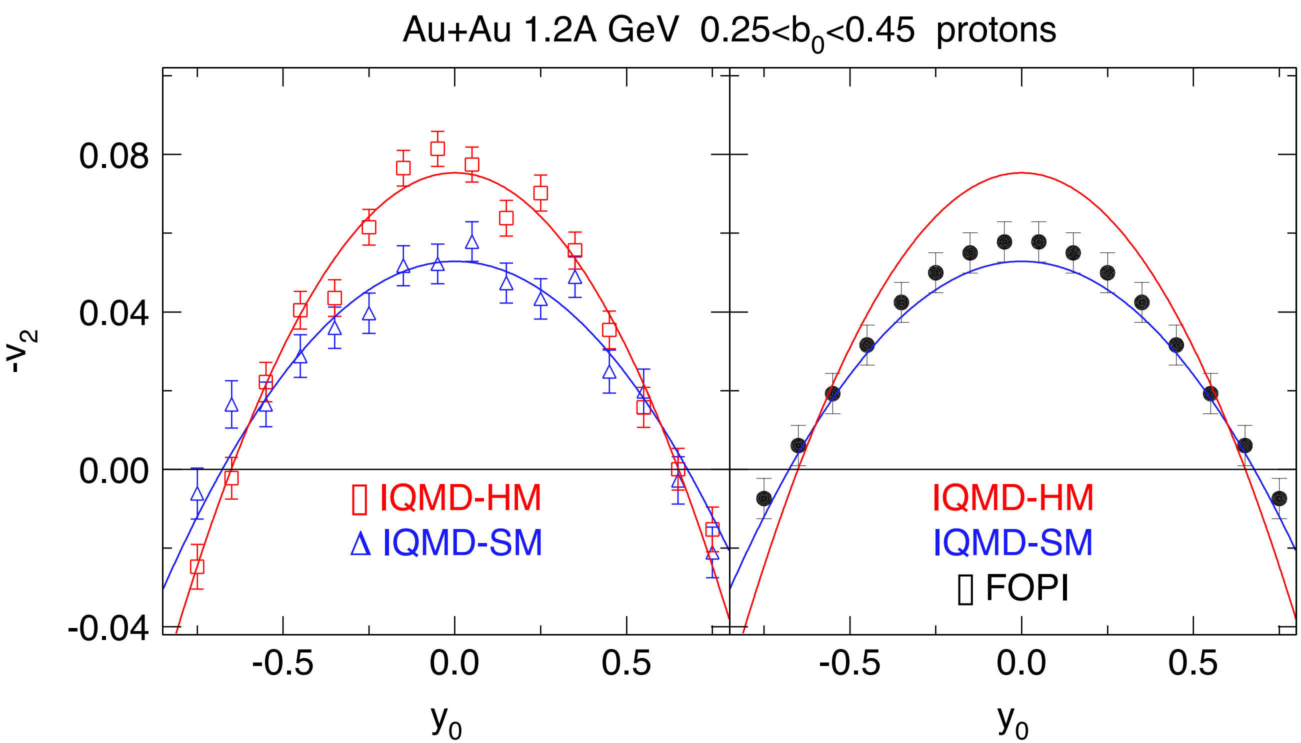
V_2



'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



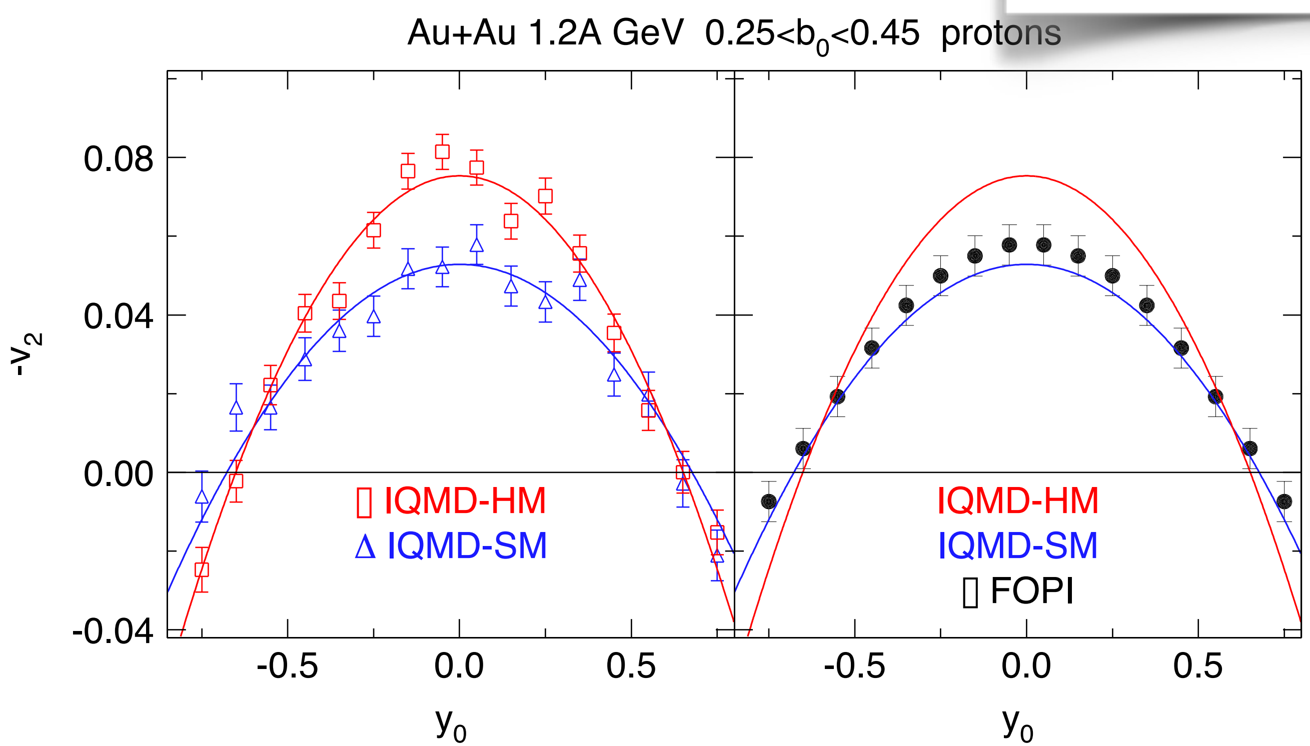
K_0 =
380 MeV (‘stiff’)
200 MeV (‘soft’)

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

Elliptic flow method: high densities FOPI and the incompressibility K_0

Complete shape of $v_2(y_0)$: a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$

Elliptic flow



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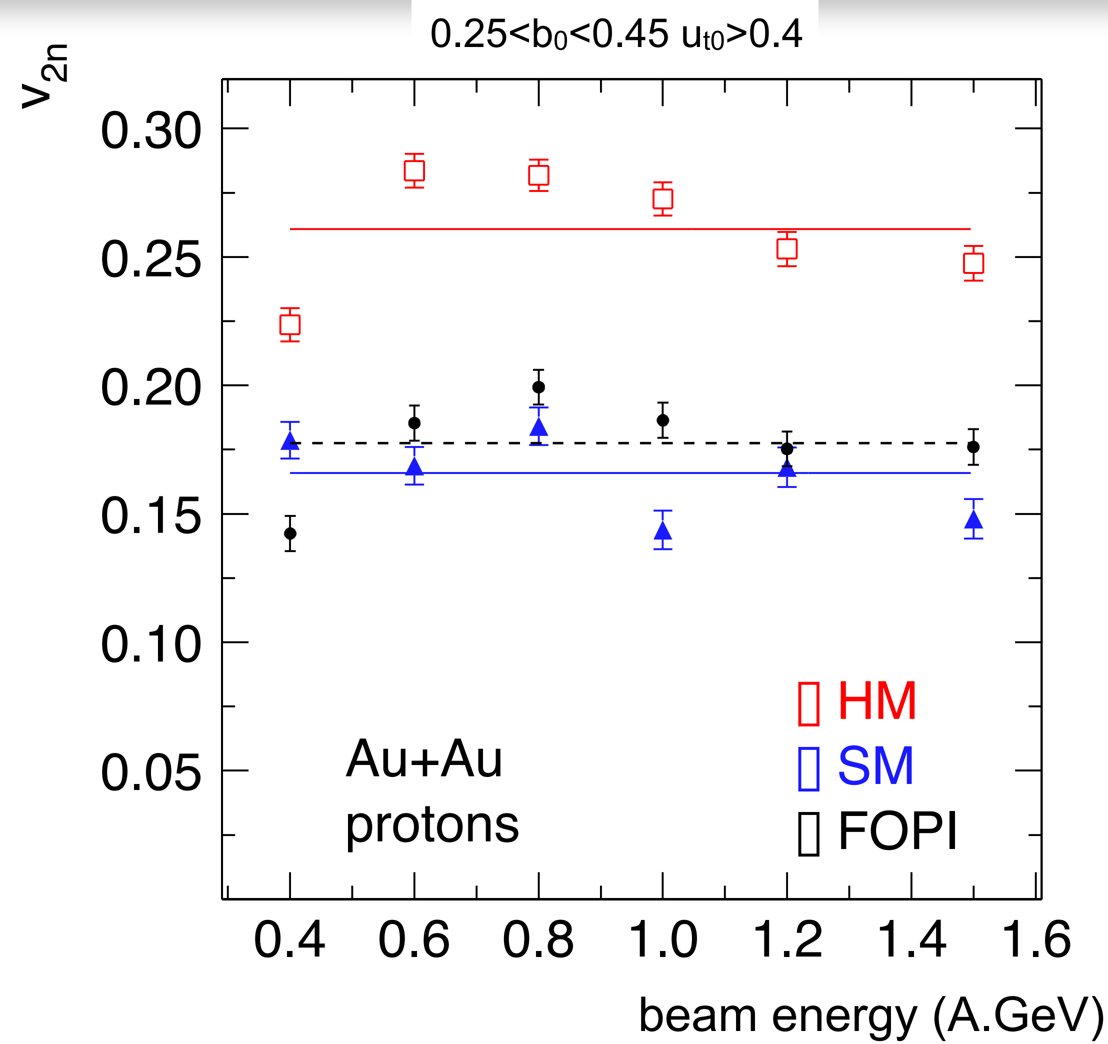
A. Le Fèvre et al., NPA 945 (2016) 112–133

Elliptic flow method: high densities FOPI and the incompressibility K_0

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



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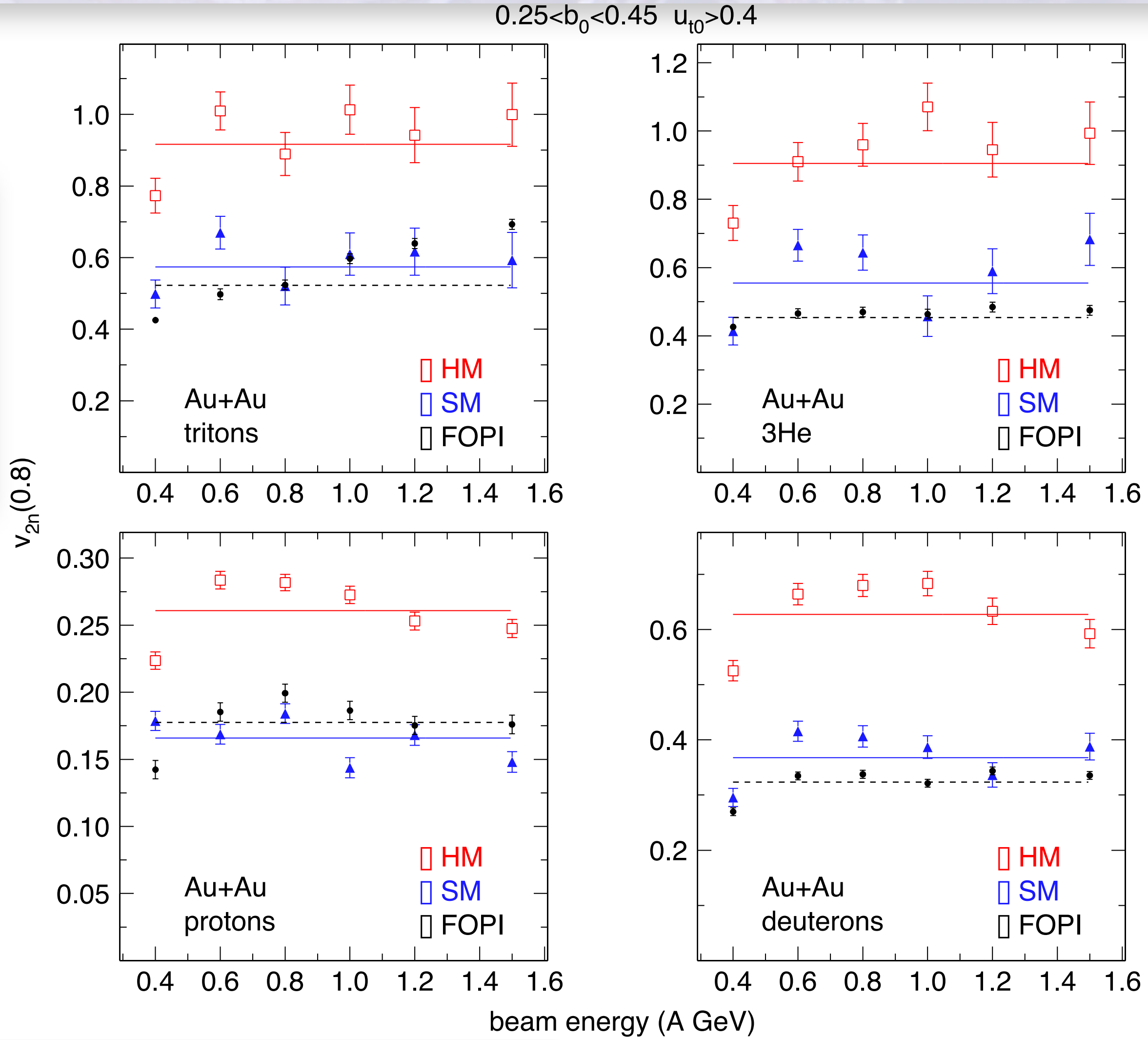

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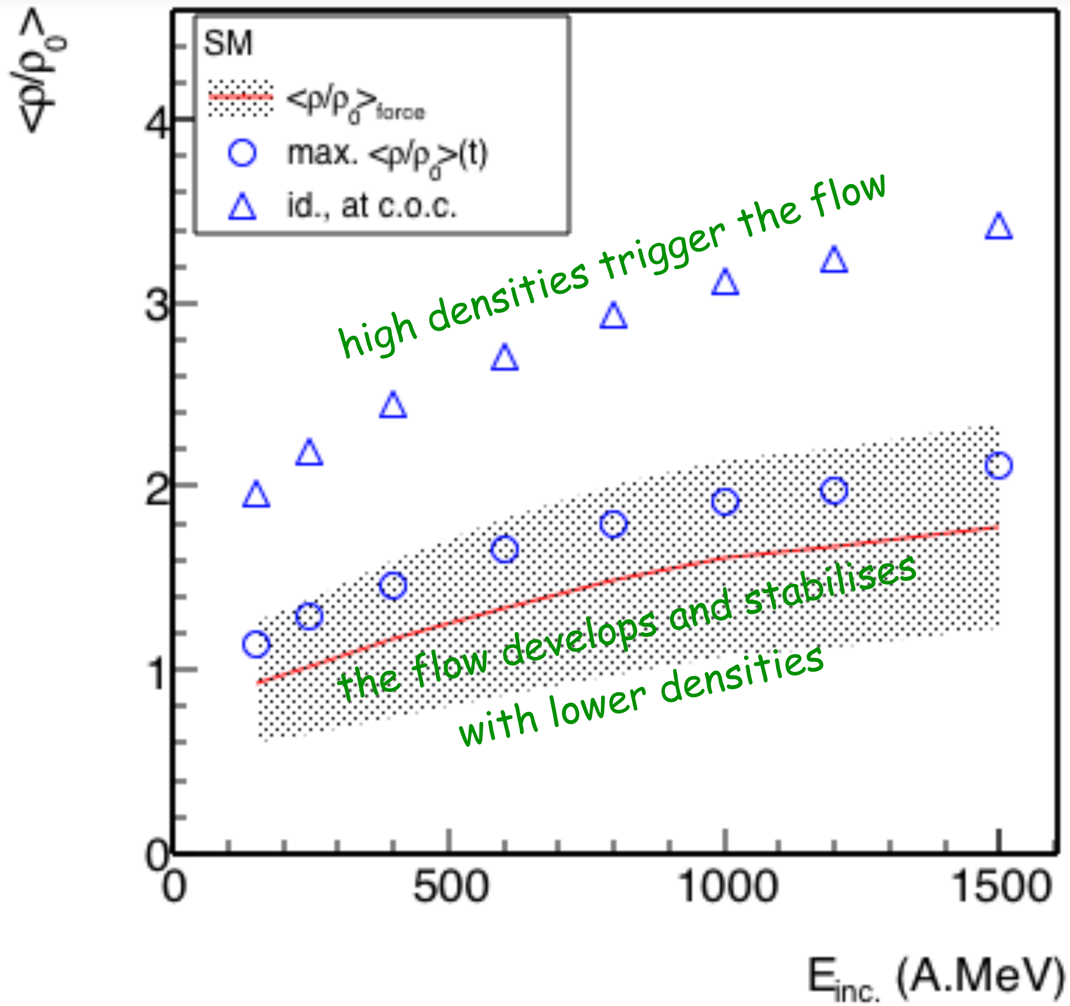

- In the QMD model, the EOS must be correct over a broad range of densities in order to predict the observed elliptic flow.
- The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range $\rho \simeq (1 - 3)\,\rho_0$.

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

Elliptic flow method: high densities FOPI and the incompressibility K_0

- K_0 as from FOPI flow data

$$IQMD -> K_0 = 190 \pm 30\ MeV$$

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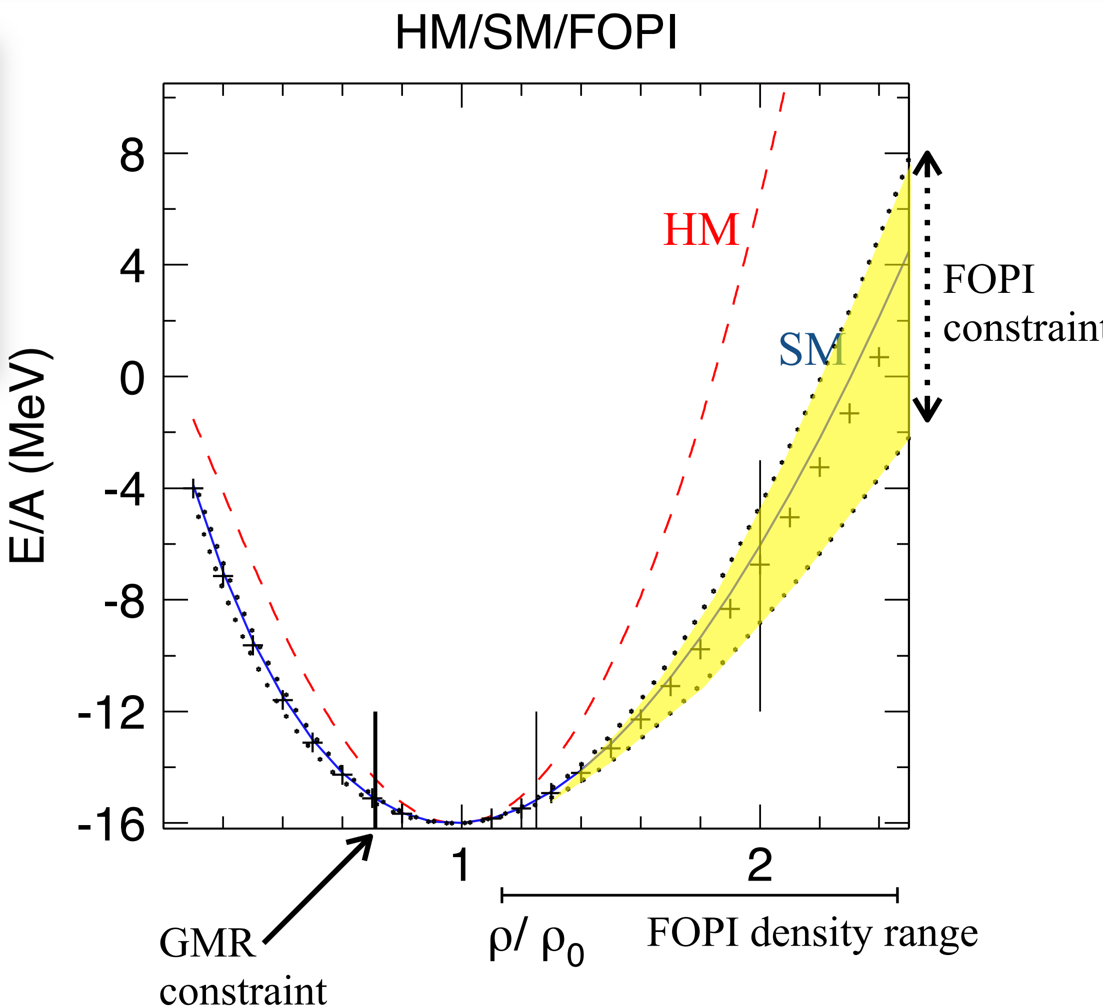
[Y. Wang et al., PLB-778(2018)207-212]



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

Pion yield method: high densities FOPI and the asy-stiffness

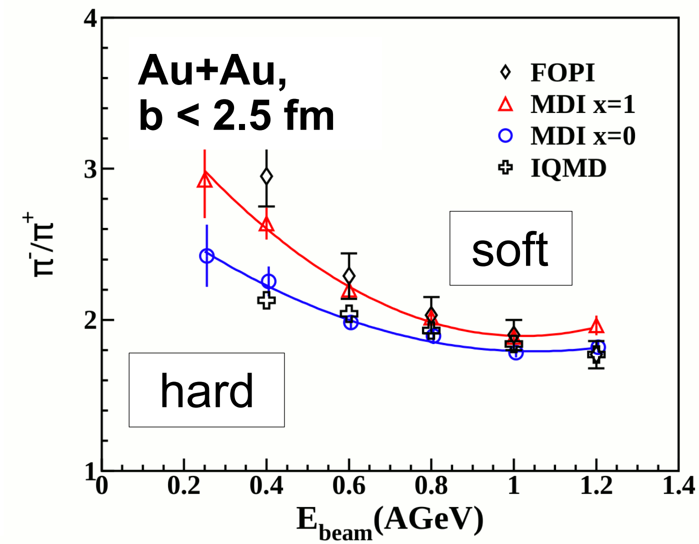
Data: W. Reisdorf et al., NPA 781 (2007)
Calculations: Z. Xiao et al, PRL 102, (2009)

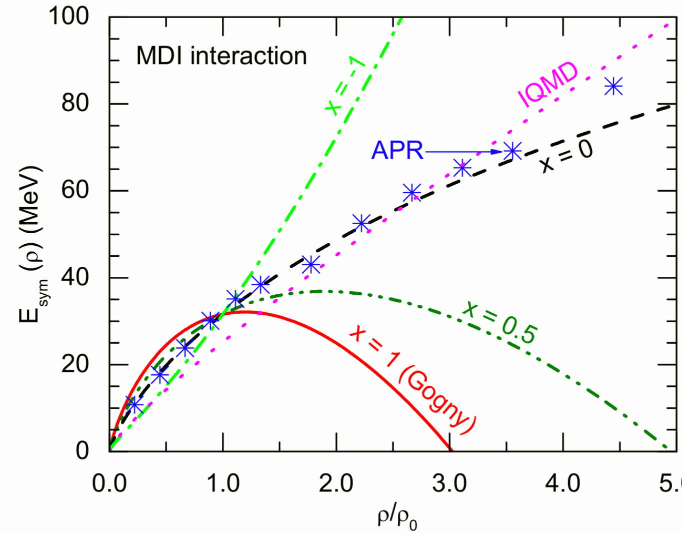
- Symmetry energy influences n/p ratio → changes number of nn, np, pp collisions
- Simple ansatz: assume stiff asymmetry energy

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

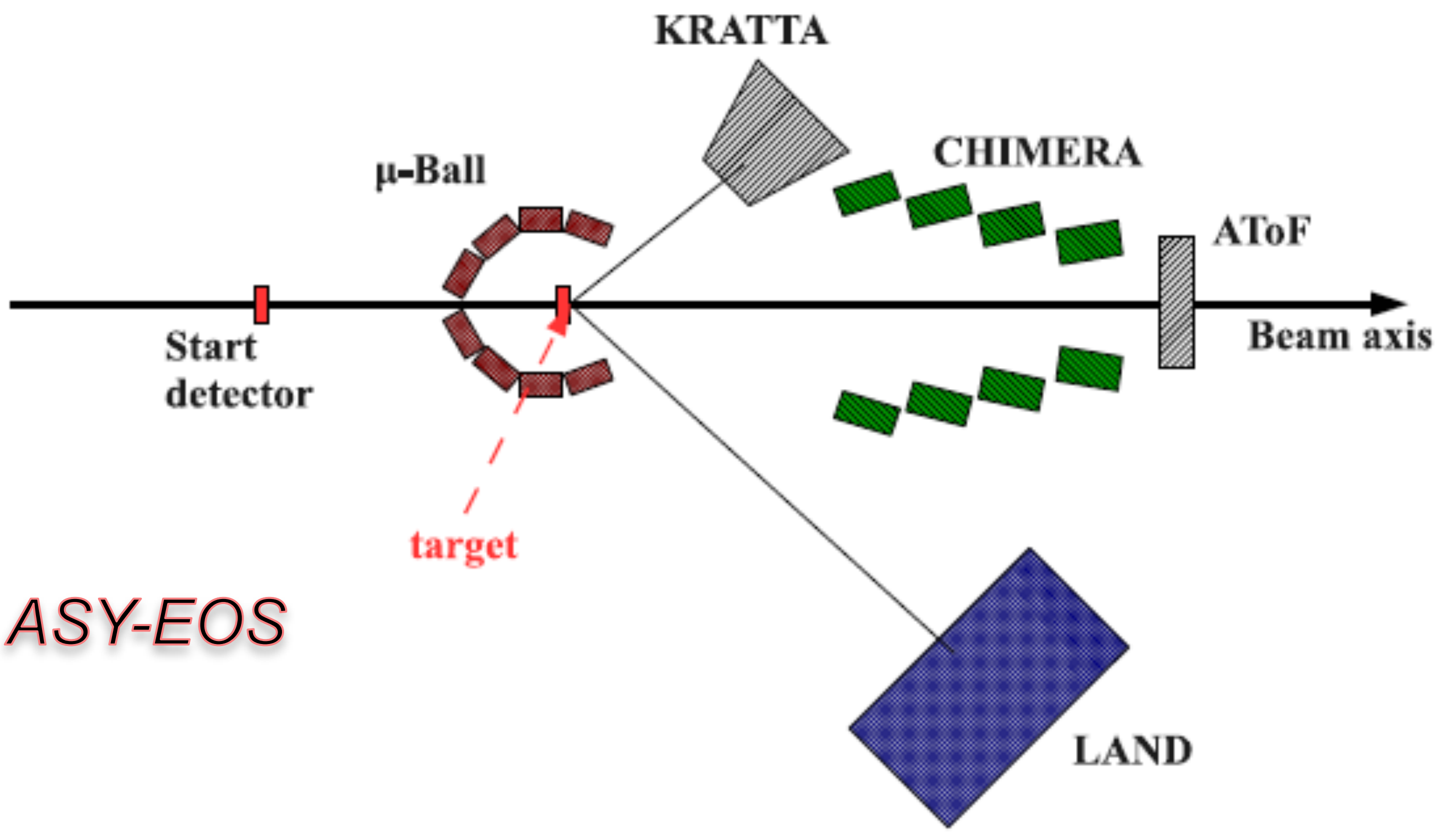
- BUT: super-soft E_{asy} from Xiao et al. is inconsistent with results from neutron and proton flow
- Complex medium effects have to be considered
  - pion optical potential, self energies different for π^- and π^+
  - potentials and characteristics of Δ
  - s- vs p-wave production
- Work in progress,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

  soft ↔ hard ↔ no dependence on E_{asy}





Elliptic flow method: high densities
Asy-EOS



➢ 400A MeV Au+Au, ^{96}Zr+Zr, ^{96}Ru+Ru at GSI (2011)

Elliptic flow method: high densities Asy-EOS

Elliptic flow v_2 of n/p

UrQMD (Q. Li et al.) predicts:

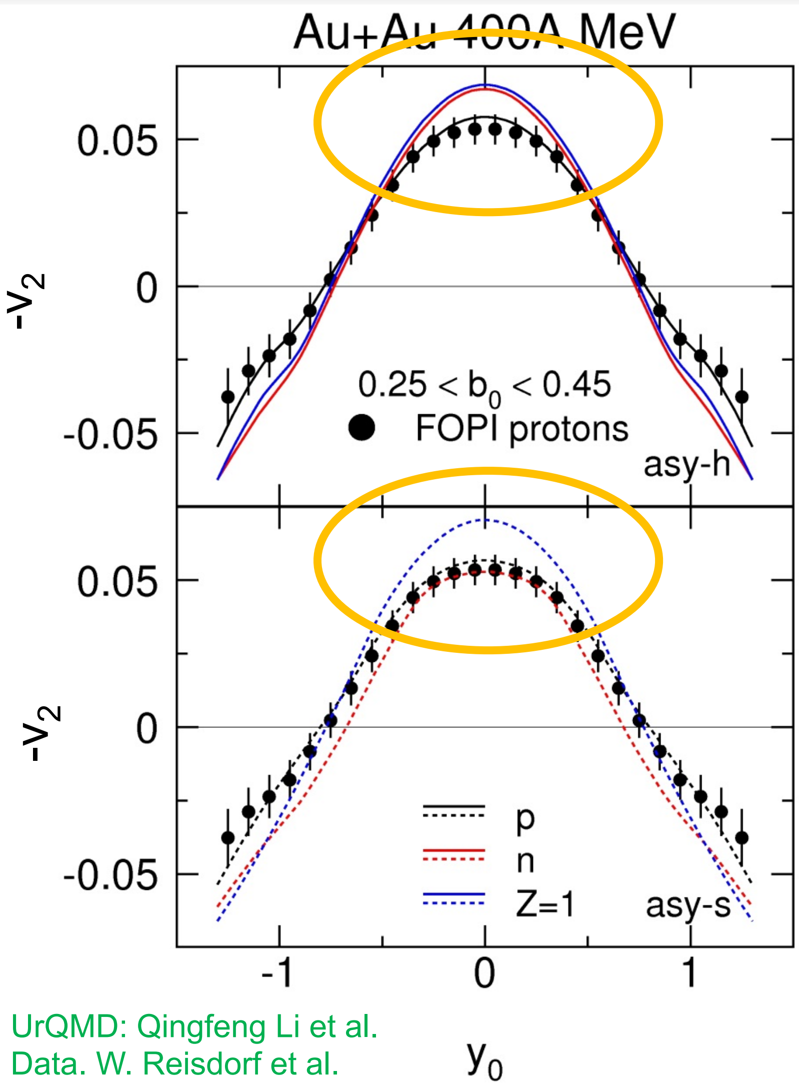
"hard" $E_{sym}(\rho)$ → neutron flow much larger

"soft" $E_{sym}(\rho)$ neutron, proton flow equal

Towards model invariance:

tested stability with different models:

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



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

M.D. Cozma et al.,PRC 88, 044912 (2013)
P. Russotto et al., PLB 267 (2010)
Y. Wang et al.,PRC 89, 044603 (2014)

Elliptic flow method: high densities
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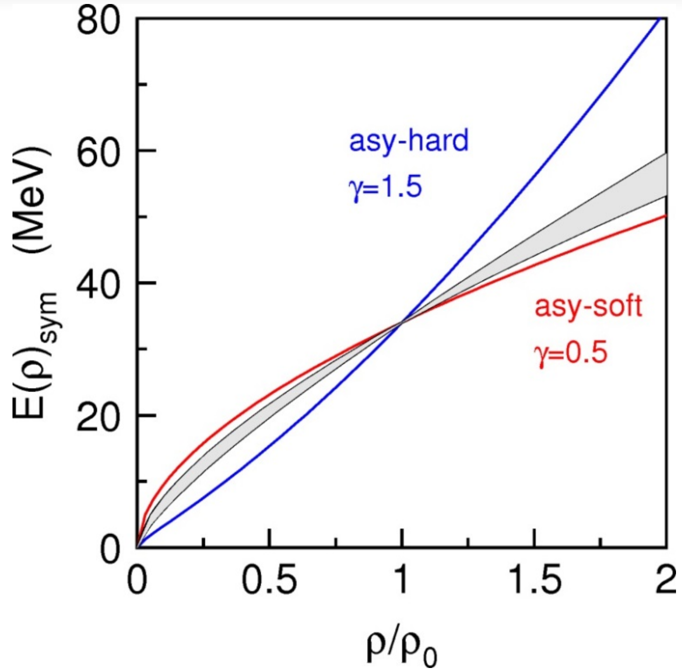
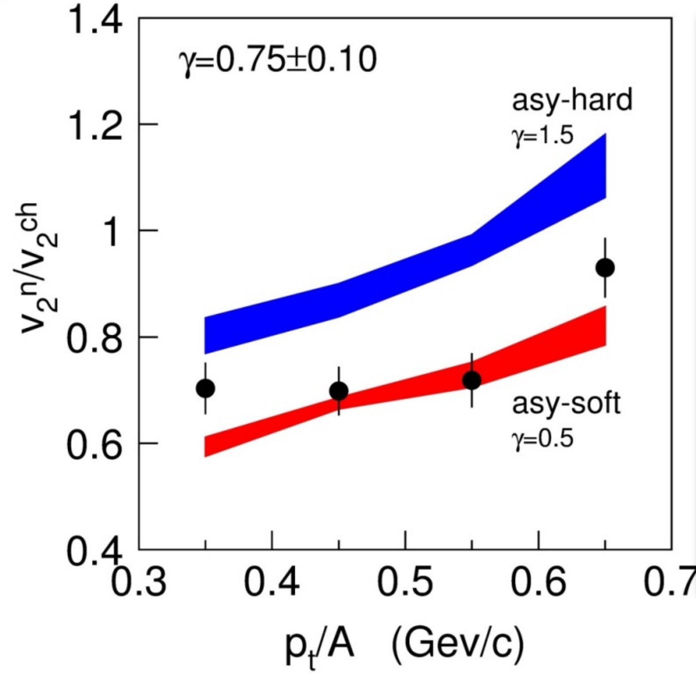




P. Russotto et al., PRC (2017)

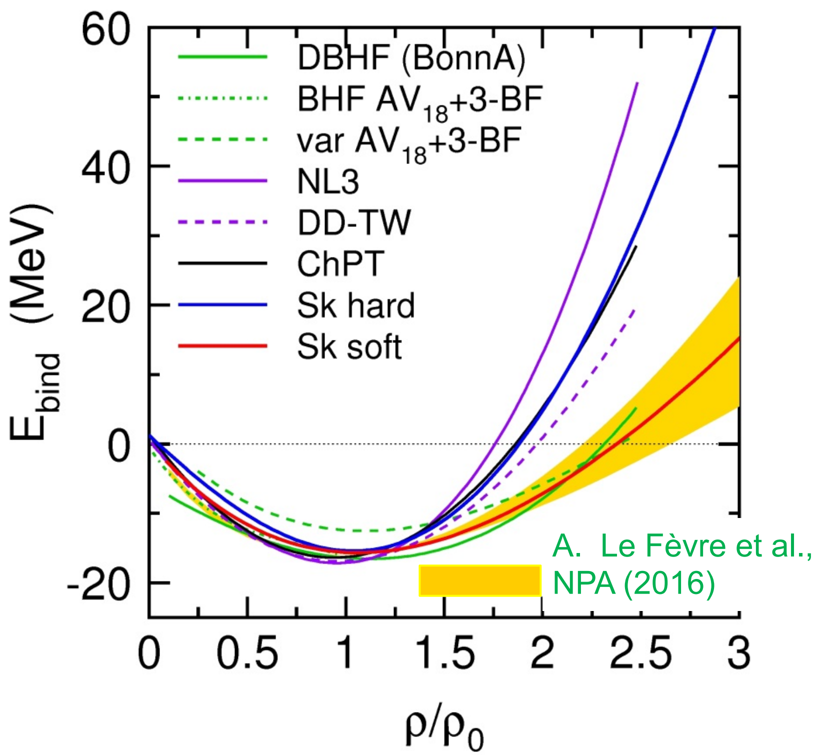
- parametrization for E_{asy} used in the UrQMD model:

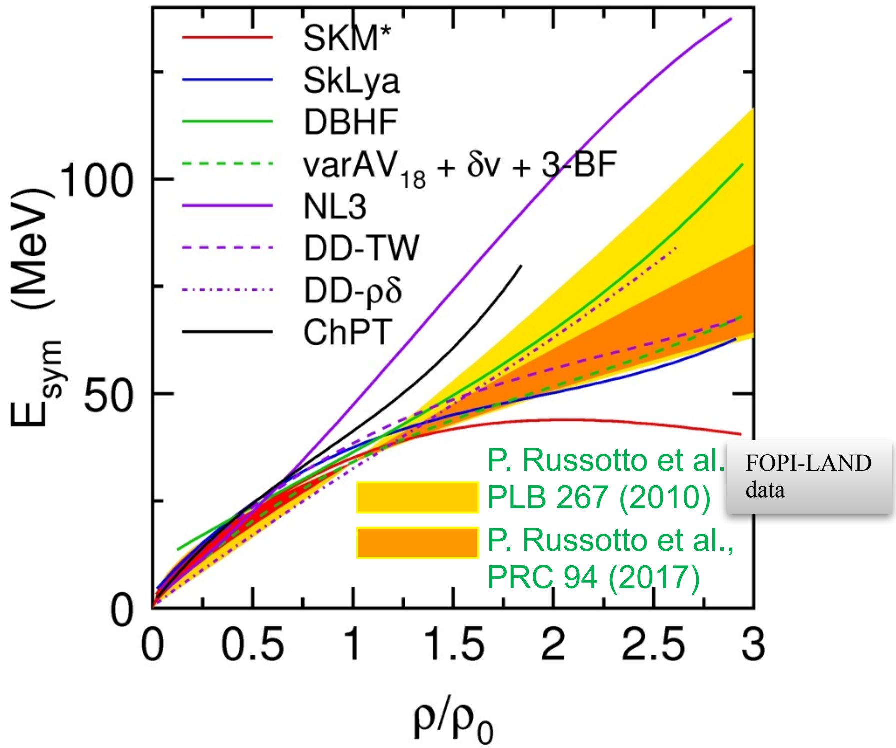
  $$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\ \text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\ \text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

- systematic errors corrected: $\gamma = 0.72 \pm 0.19$
- slope parameter: $L = 72 \pm 13$ MeV, $E_{sym}(\rho_0) = 34$ MeV
- slope parameter: $L = 63 \pm 11$ MeV, $E_{sym}(\rho_0) = 31$ 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 ρ_0) (preliminary)
    ➼ L = 60.4 ± 5.9 MeV
    ➼ γ_{asy} = 0,60 ± 0.06
  - AsyEOS (1-2 ρ_0)
    ➼ L = 63 ± 11 MeV
    ➼ γ_{asy} = 0.68 ± 0.19
    (for $E_{pot}^{asy}(\rho_0)$=19 MeV)
    or L = 72 ± 13 MeV
    and γ_{asy} = 0.72 ± 0.19
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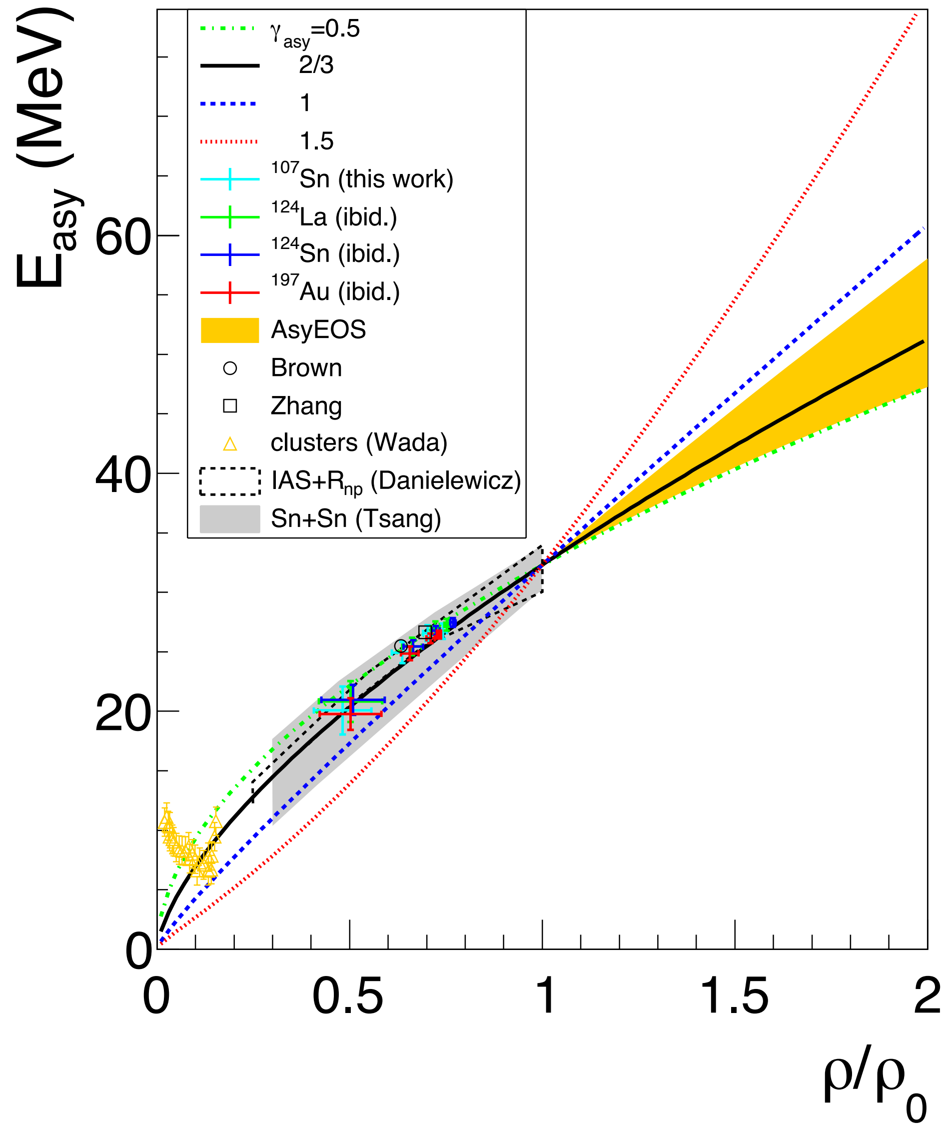
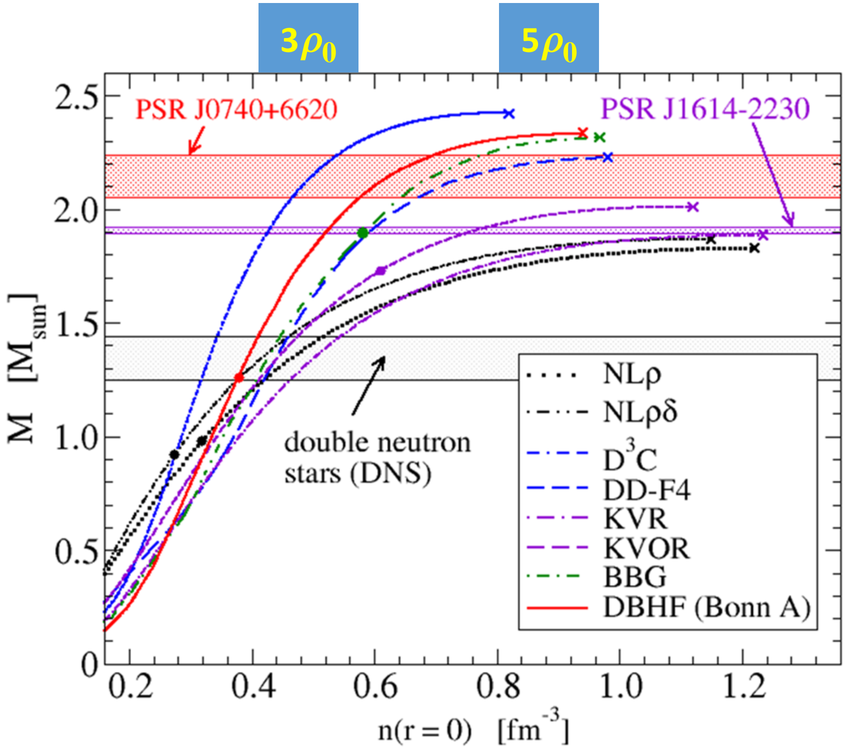


A tentative synthesis: how HICs at GSI compare with recent astrophysical findings.

- Neutrons stars probe the nuclear EoS: produced in core collapse supernova
- Extremely compact, massive objects $R \approx 10km$, mass $1 - 2M_{\odot}$
- Extreme densities, core density: 5-10 times nuclear density, average mass density ≈3.5 times nuclear density



T. Klaehn et al., Phys. Rev. C74: 035802, 2006

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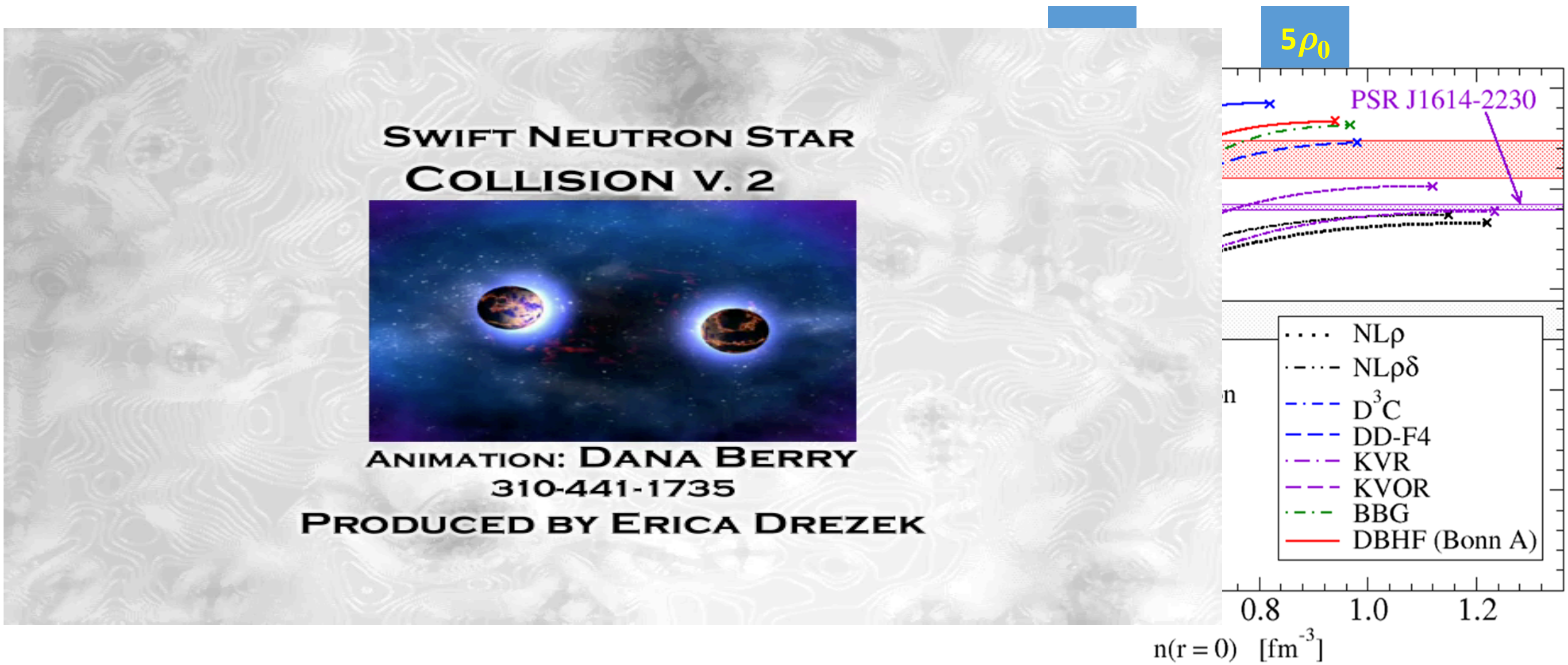
- Gravitational waves generated by neutron star mergers (2 NS spiralling inward):



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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 1-2ρ_0

[Russotto et al. PRC94(2016)034608]

- L as from ALADiN at 0.7ρ_0

- K_0 as from FOPI flow data

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[A. Le Fèvre et al., NPA945(2016)112-133]

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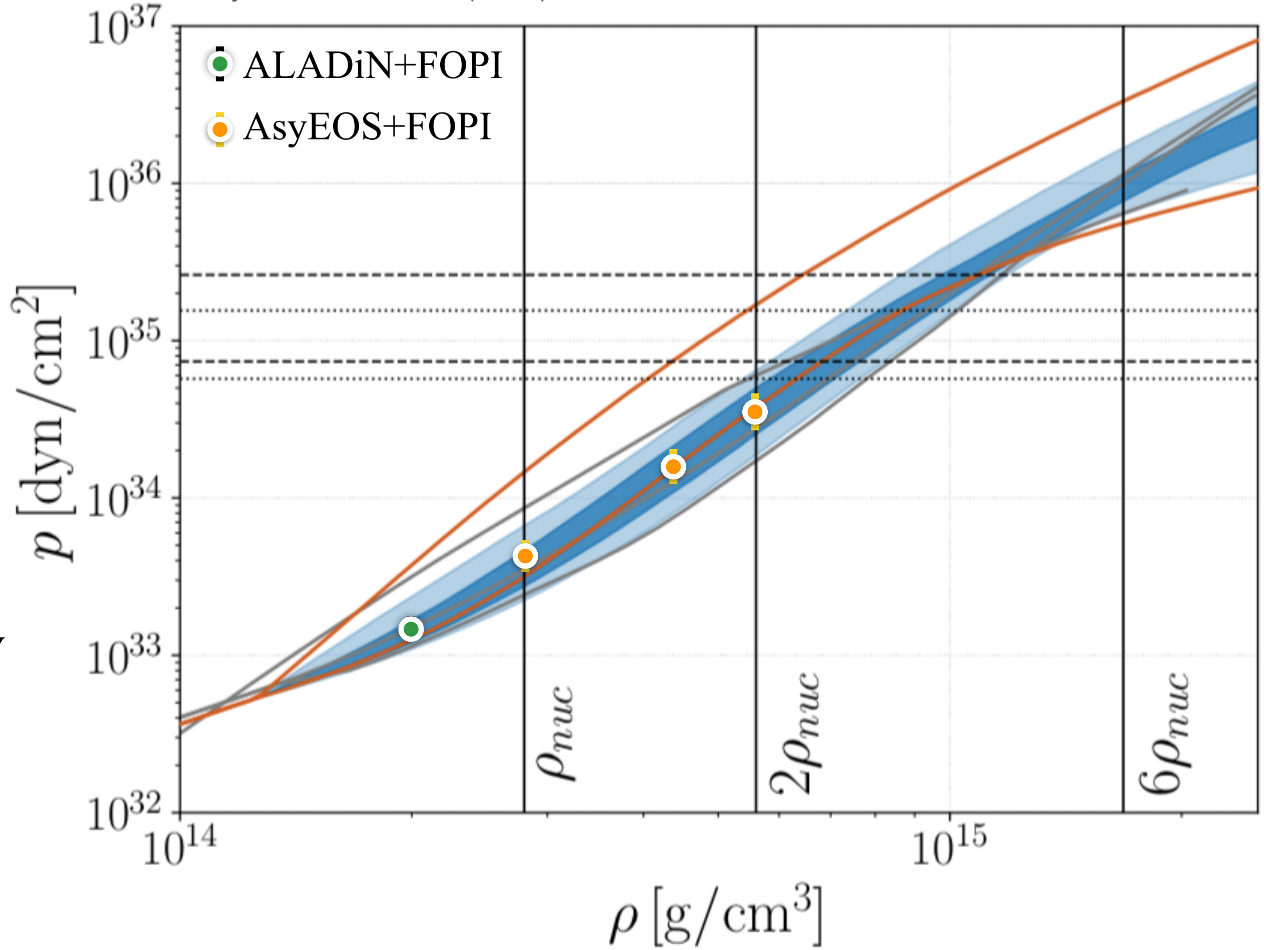
Gravitational Wave 170817

B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration)
Phys. Rev. Lett. **121** (2018), 161101



Conclusion and perspectives

GW170817
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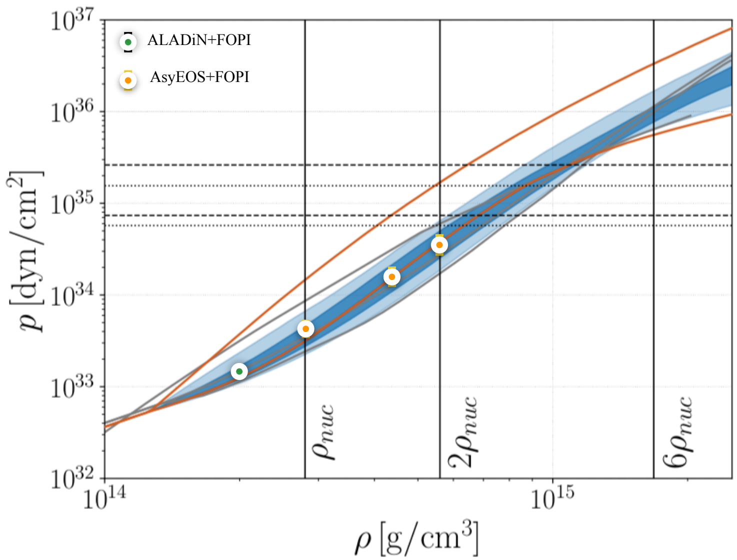

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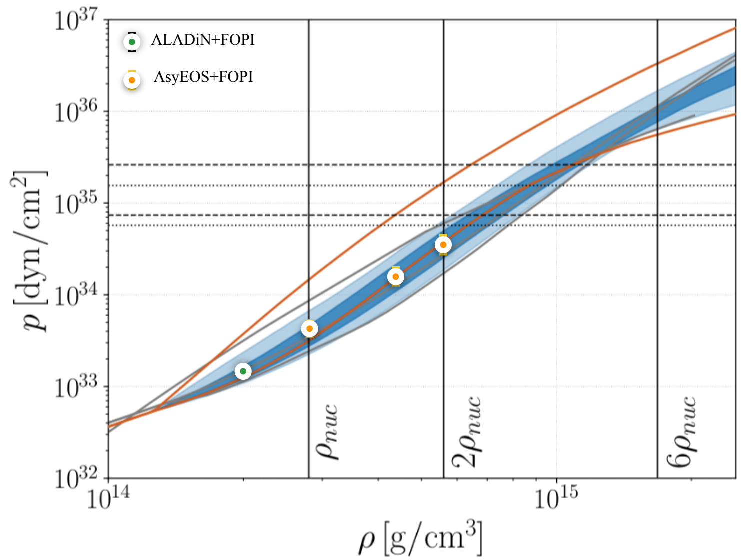

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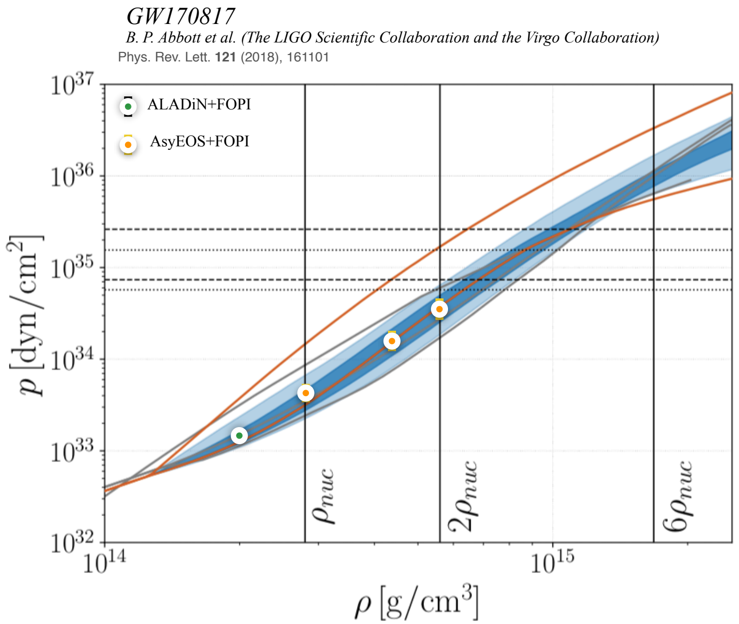

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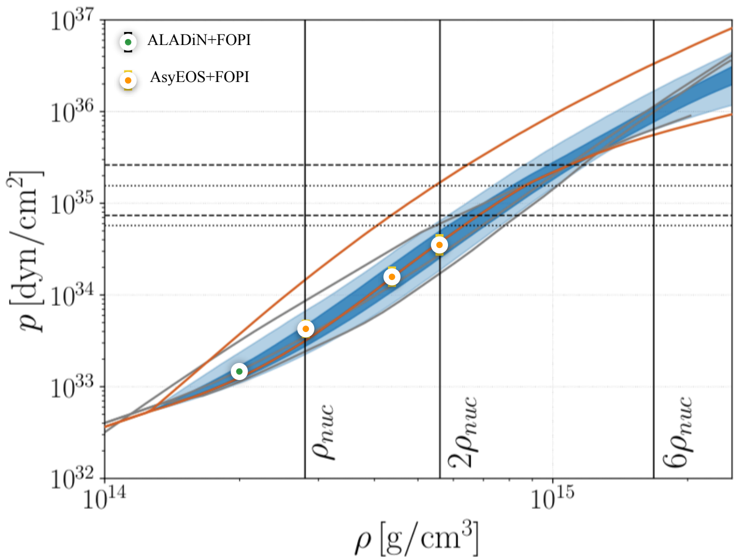

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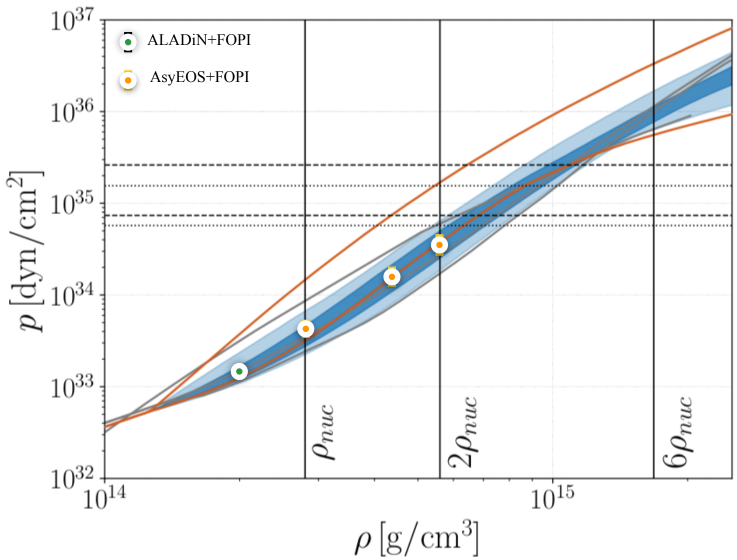

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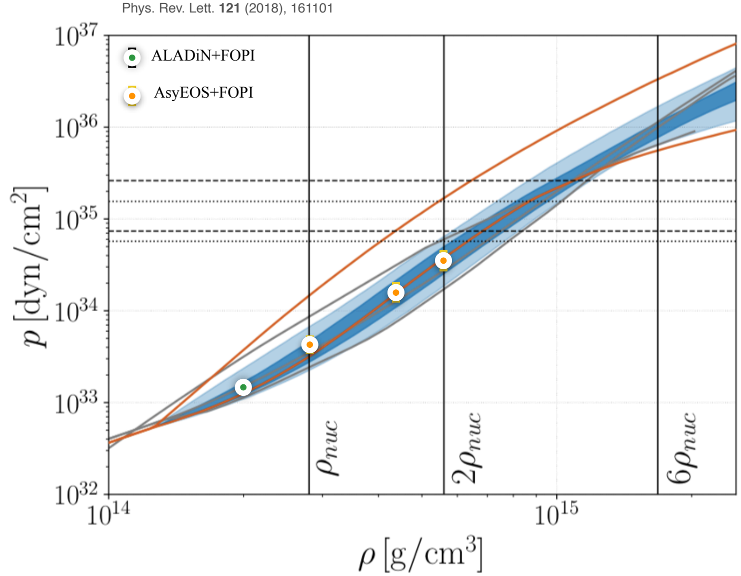

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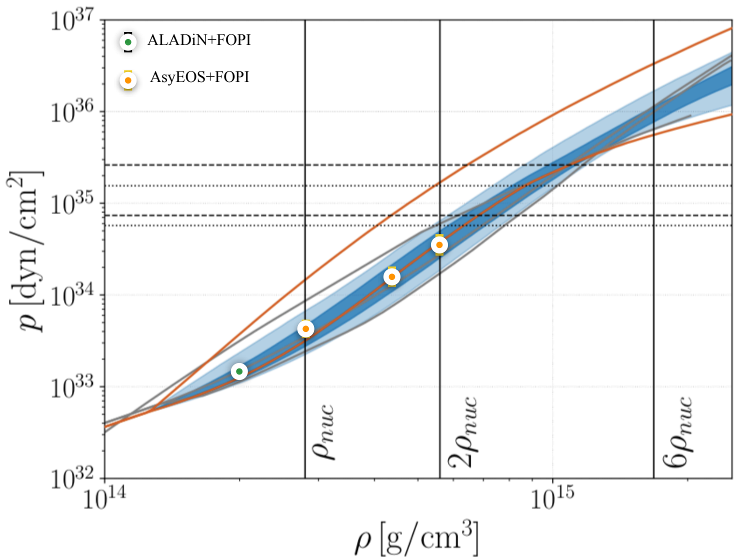

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- Beyond $3 - 4\rho_0$ (FAIR, NICA), new observables needed to constrain L and K_0. A new generation of relativistic transport models must arise, benchmarked e.g. with data taken at SIS18 at the highest available beam energies (FOPI, HADES).

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