Results of the ALADiN experiment at GSI: The asymmetry energy at sub-saturation density

by A. Le Fèvre[1] , Y. Leifels[1] , W. Trautmann[1]
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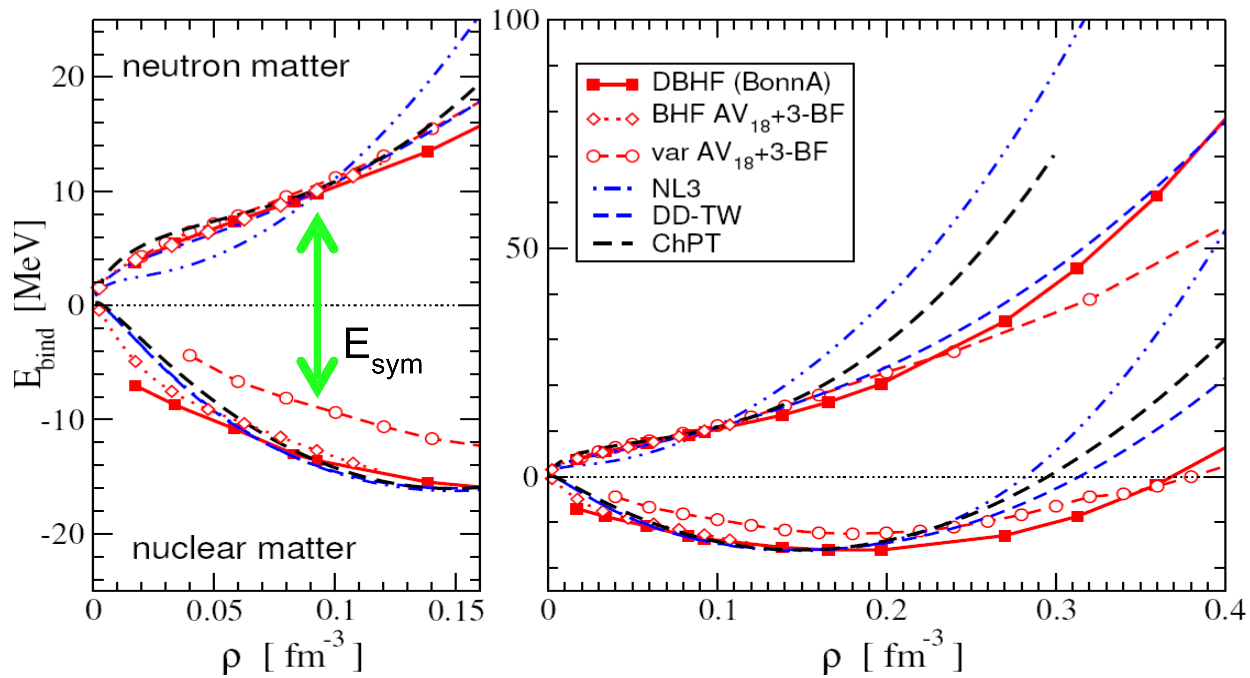
- Physics motivation
- The ALADiN experiment
- Data quality
- Transport and clustering models, benchmarking the fragment production in spectator decay
- Asymmetry energy and density out of isotope yields
- Comparison with past findings.

Introduction

$$E_{asy}(\rho) = E(\rho, I = 1) - E(\rho, I = 0)$$

$$I = \frac{N - Z}{N + Z}$$



Introduction

- Constraining further the density dependance of the asymmetry energy via the **cluster production in HIC** is believed to probe sub-saturation densities.
- Ab initio calculations (red) compared to phenomenological approaches ⇨ relatively large deviations at high densities, which prolongate at sub-saturation densities.
- Using **isotope yields** from exclusive selection of **spectator decay** (dissipation under control) and relate to a possible **sensitivity to the asymmetry energy** in the process of **cluster formation in the framework of a transport model.**

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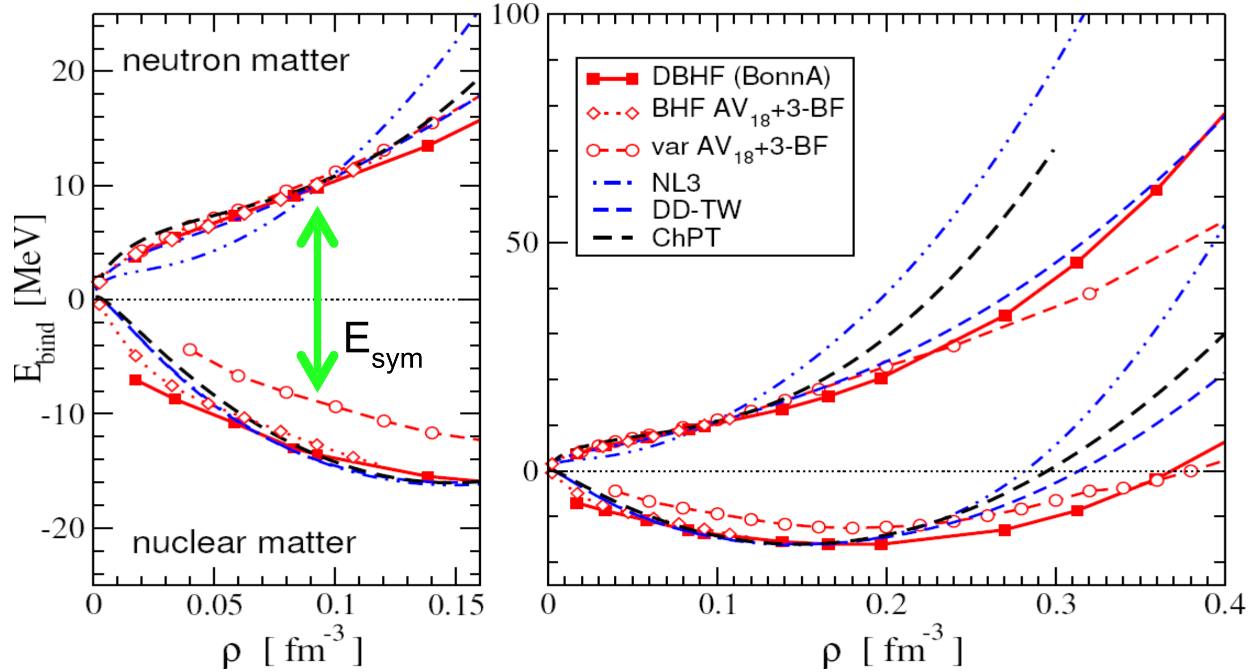

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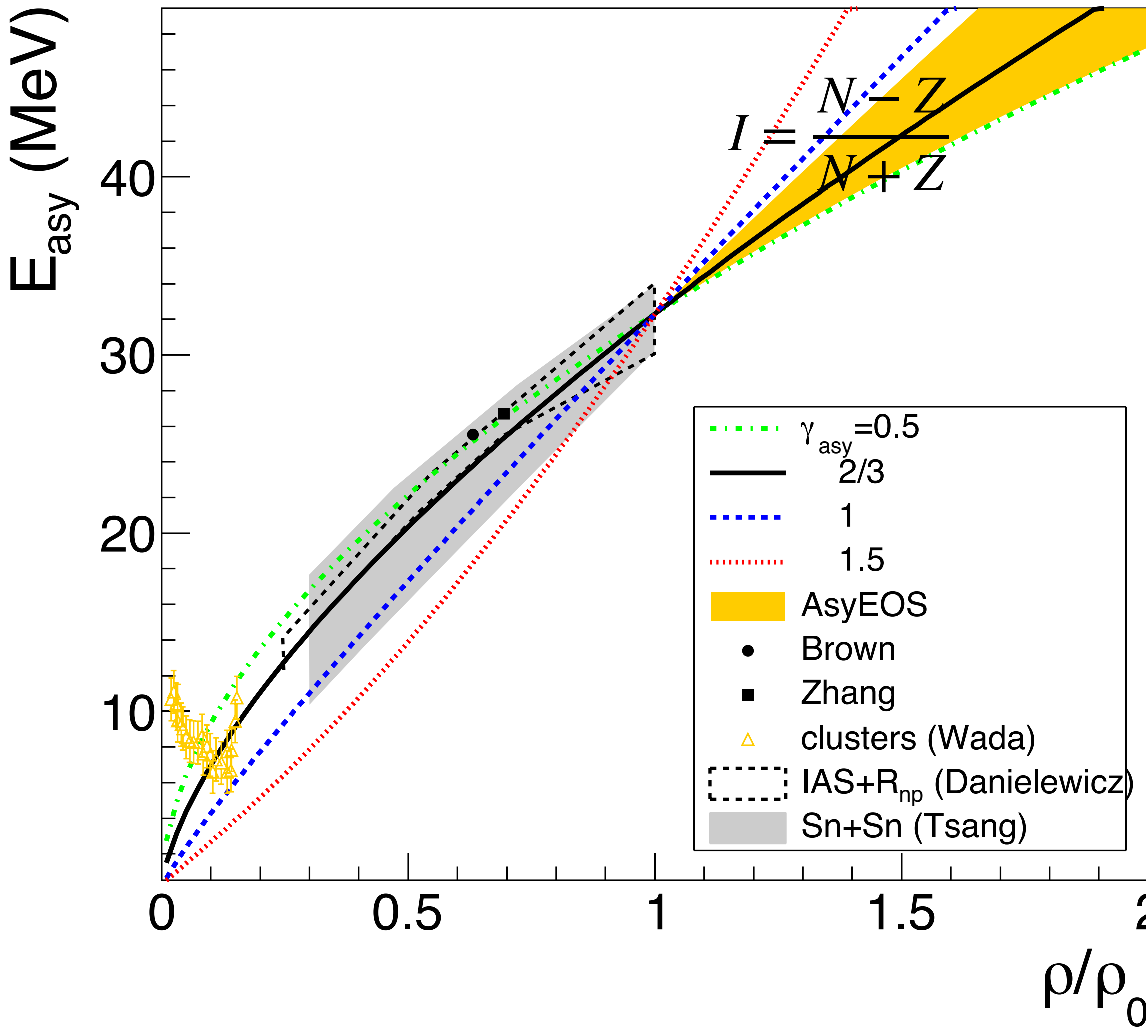
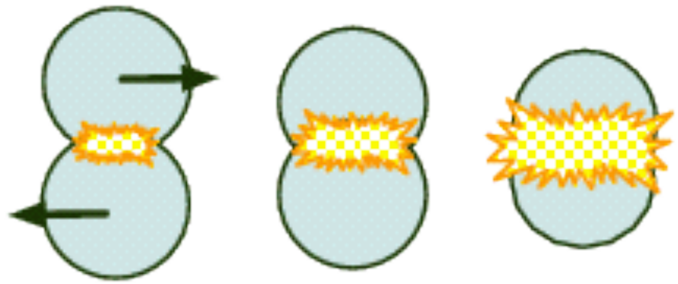


ALADiN set-up and experiment

Heating of spectator at relativistic bombarding energies



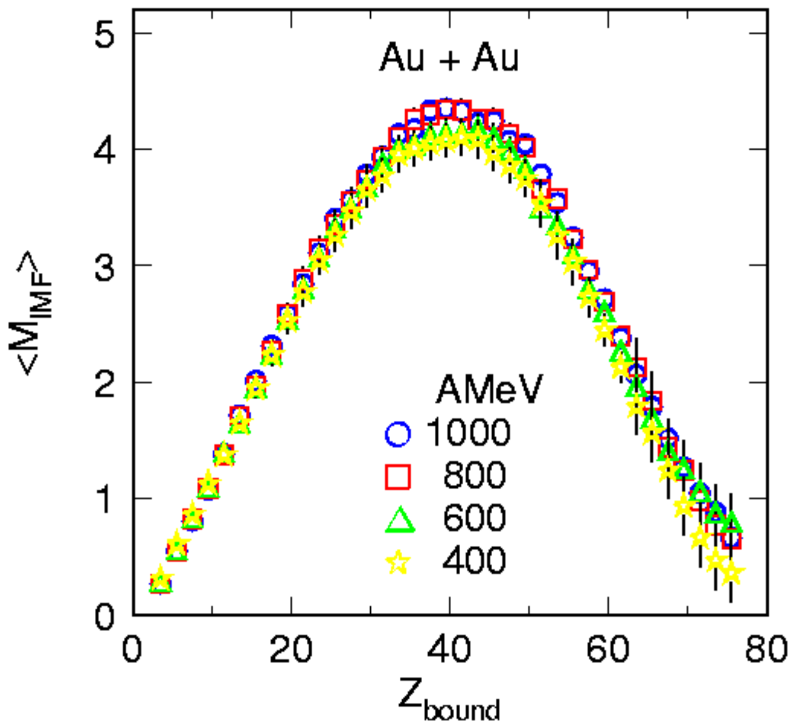
increasing centrality →

- Typical Incident Energy ≈ 1 AGeV
- Spectator:
  - (*almost*) no flow
  - Source well localized in rapidity
  - Mostly equilibrated system
  - Easy 4π coverage for fragments

ALADiN set-up and experiment

UNIVERSALITY of spectator fragmentation

$$Z_{bound} = \sum_{Z_i > 1} Z_i \qquad M_{IMF} : 2 < Z \leq 30$$



Schüttauf et al., NPA607 (1996) 457-486

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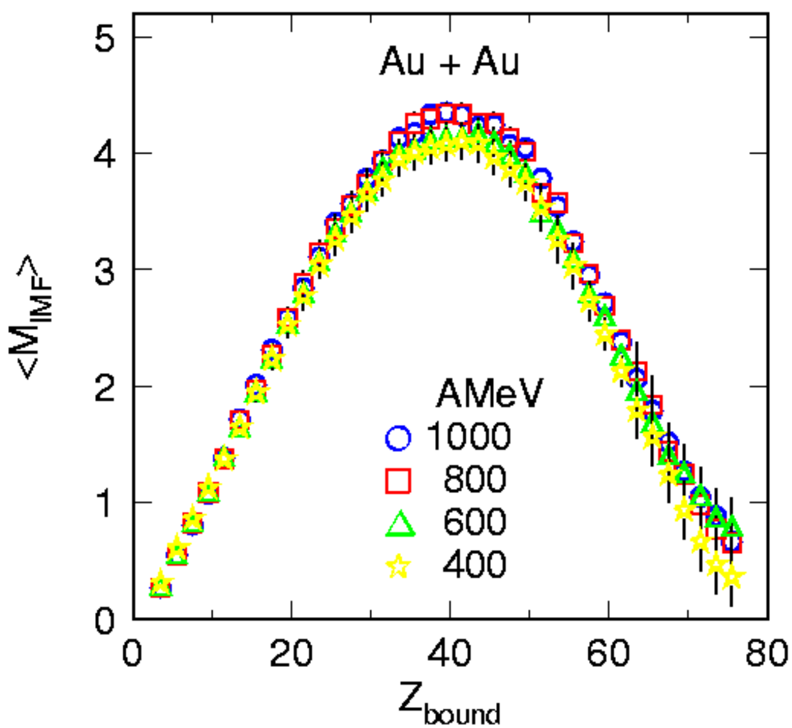

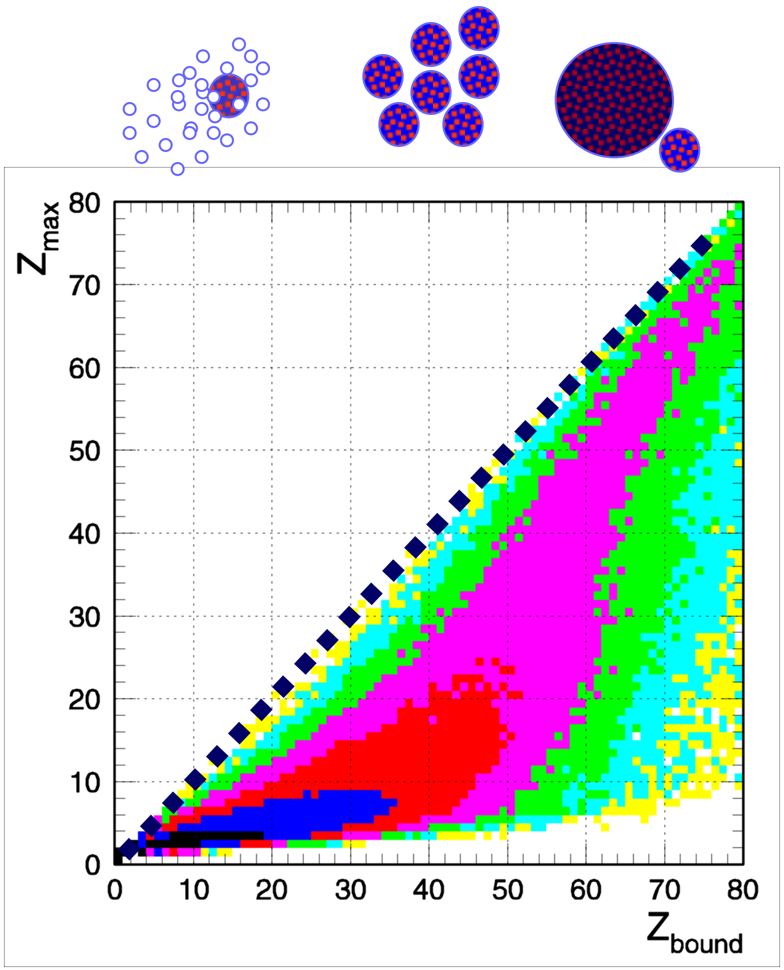

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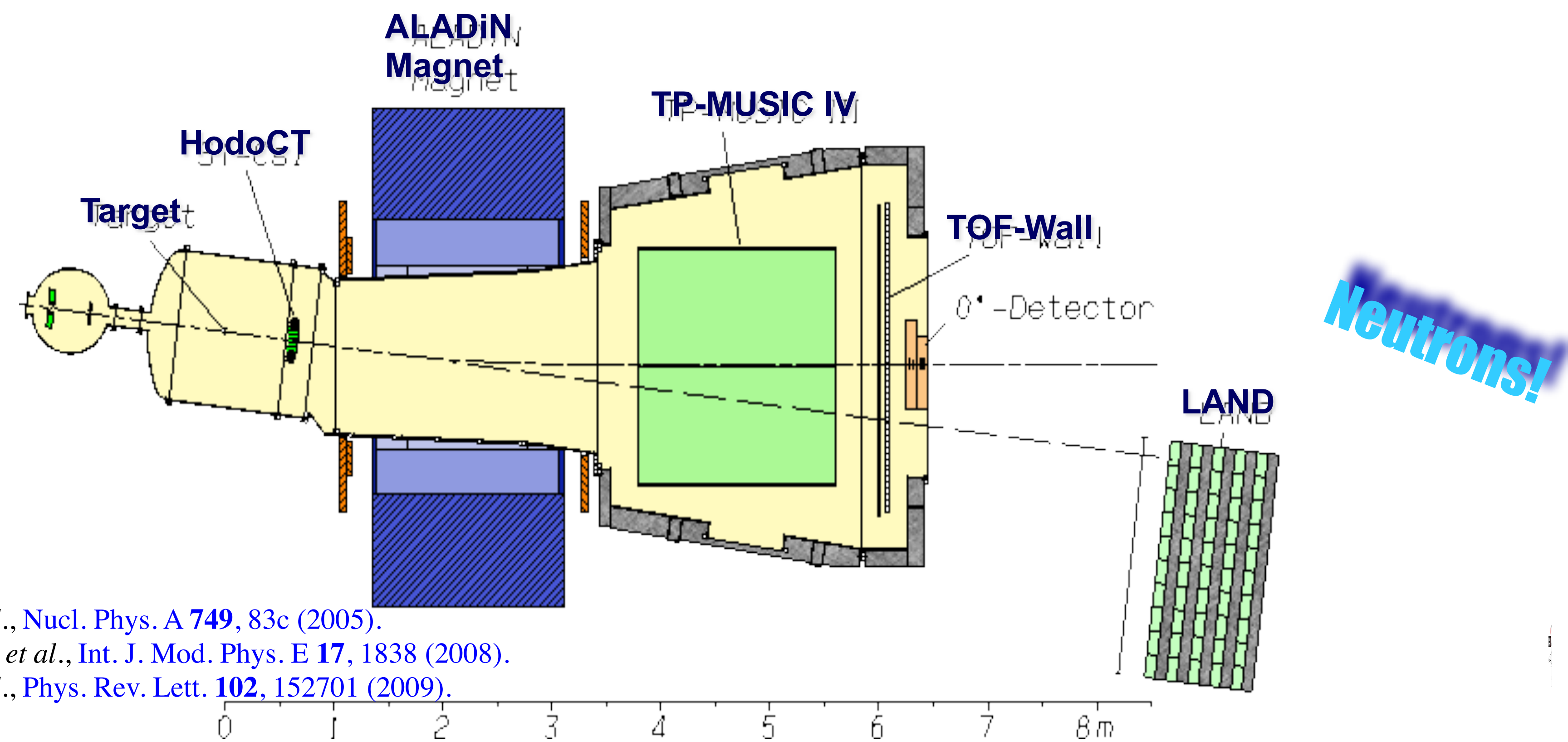
ALADiN set-up and experiment

The S254 experiment (2003)



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ALADiN set-up and experiment

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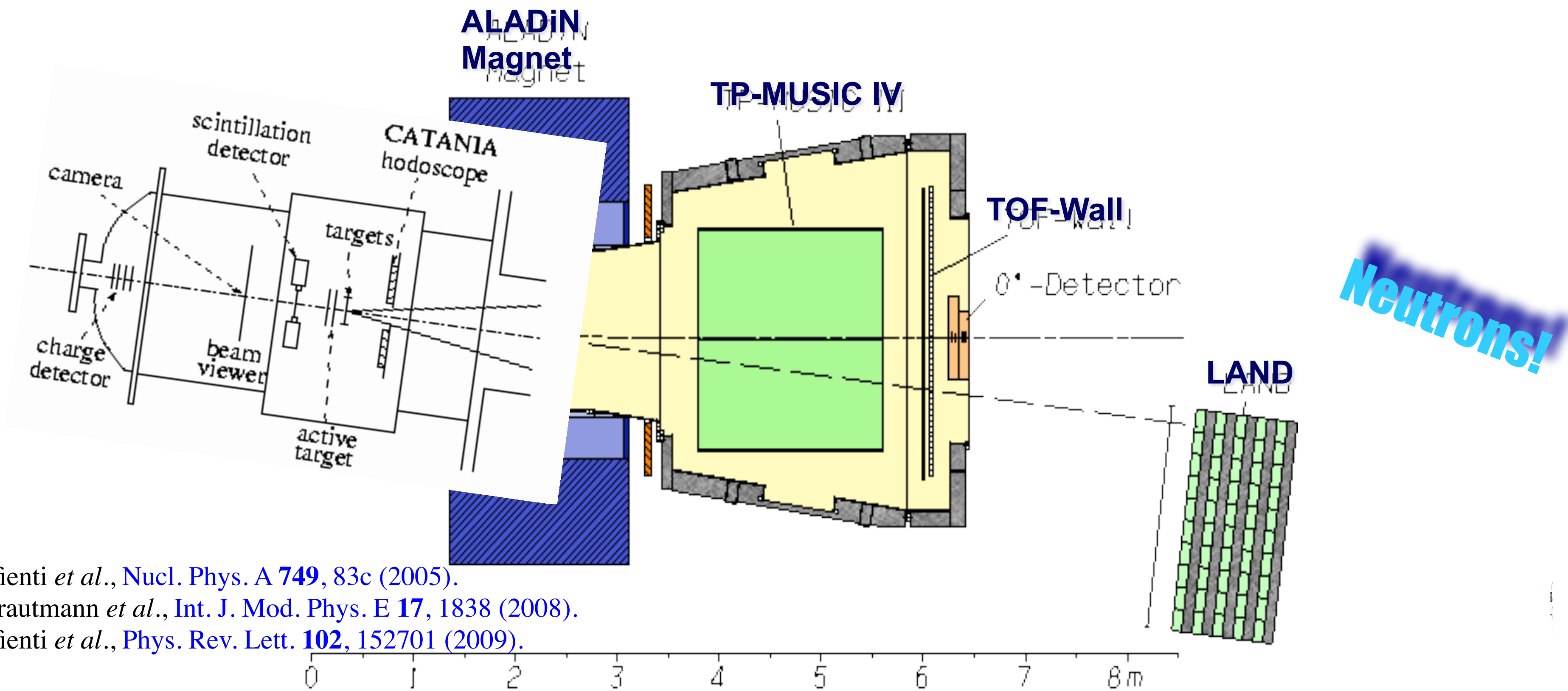

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ALADiN set-up and experiment

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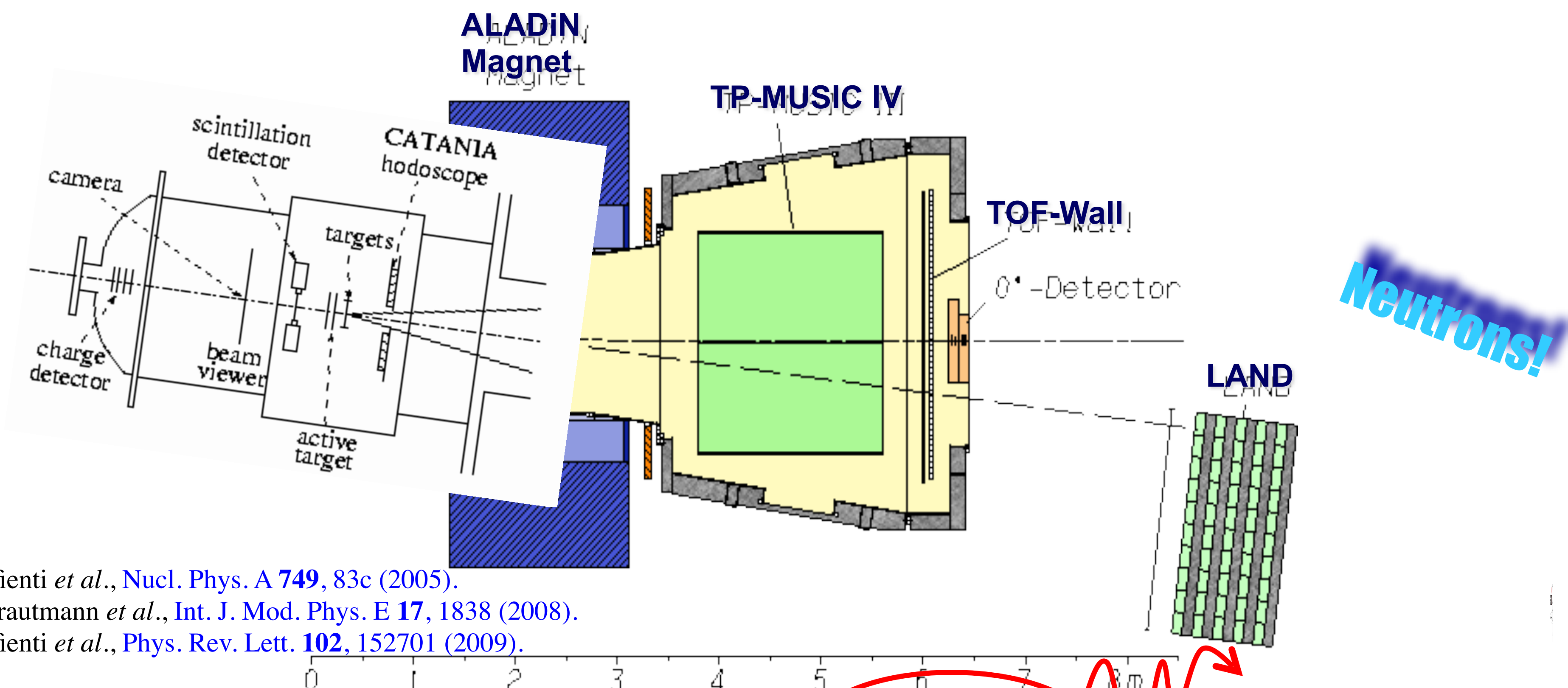

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Neutron rich/poor projectiles: $^{197}Au, ^{124}Sn, ^{124}La, ^{107}Sn$

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

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ALADiN set-up and experiment

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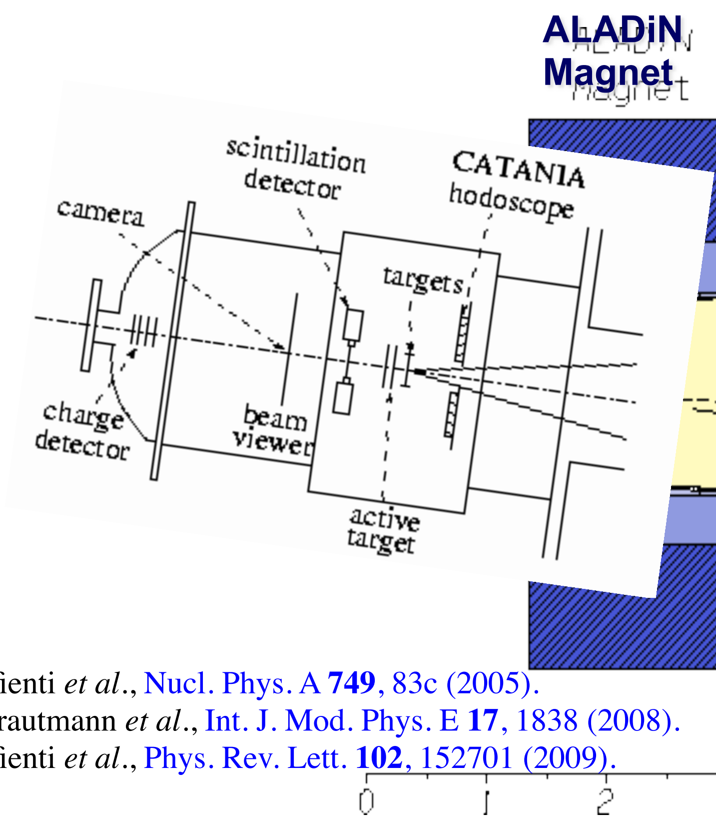

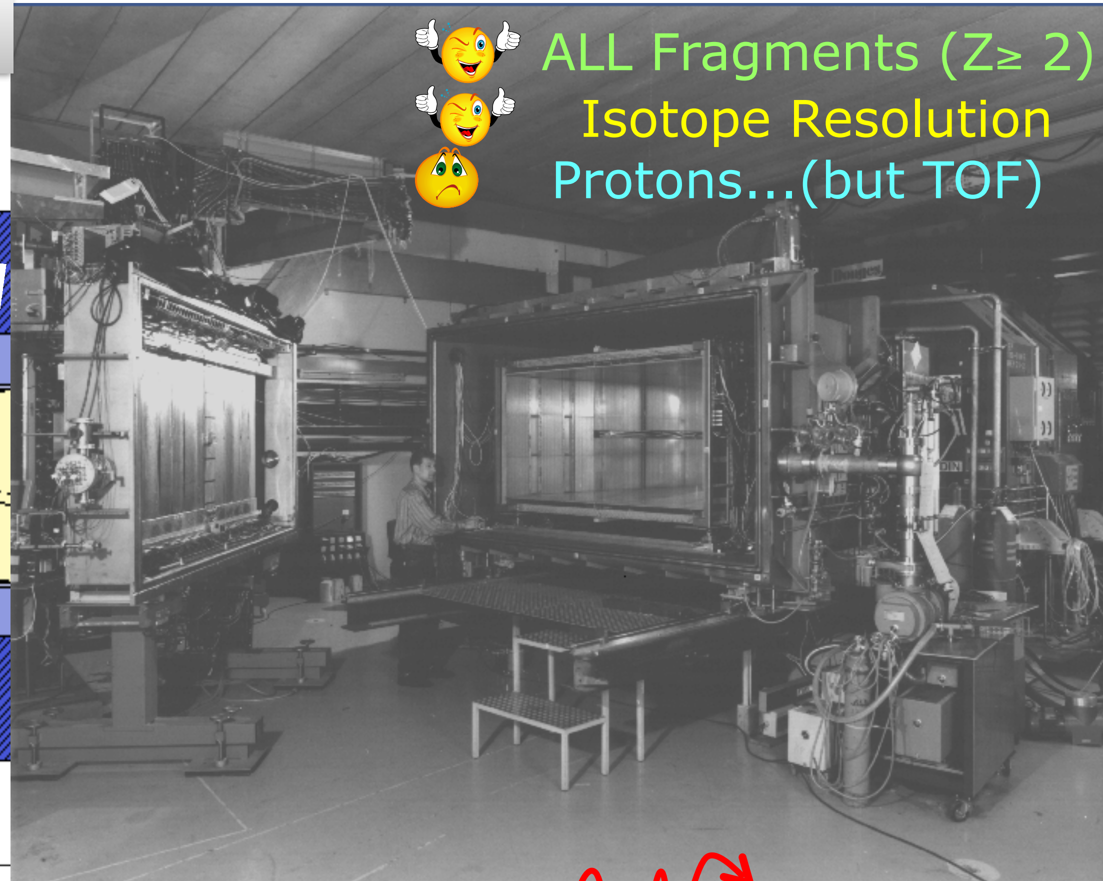

ALL Fragments (Z≥ 2)
Isotope Resolution
Protons...(but TOF)

C. Sfienti *et al*., Nucl. Phys. A **749**, 83c (2005).
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Secondary Beams (Low Intensities!)

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

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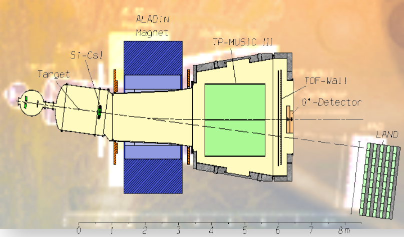
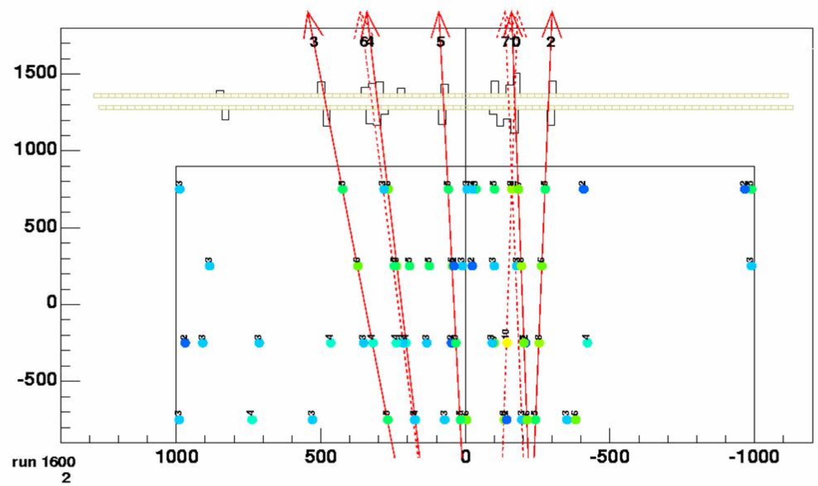


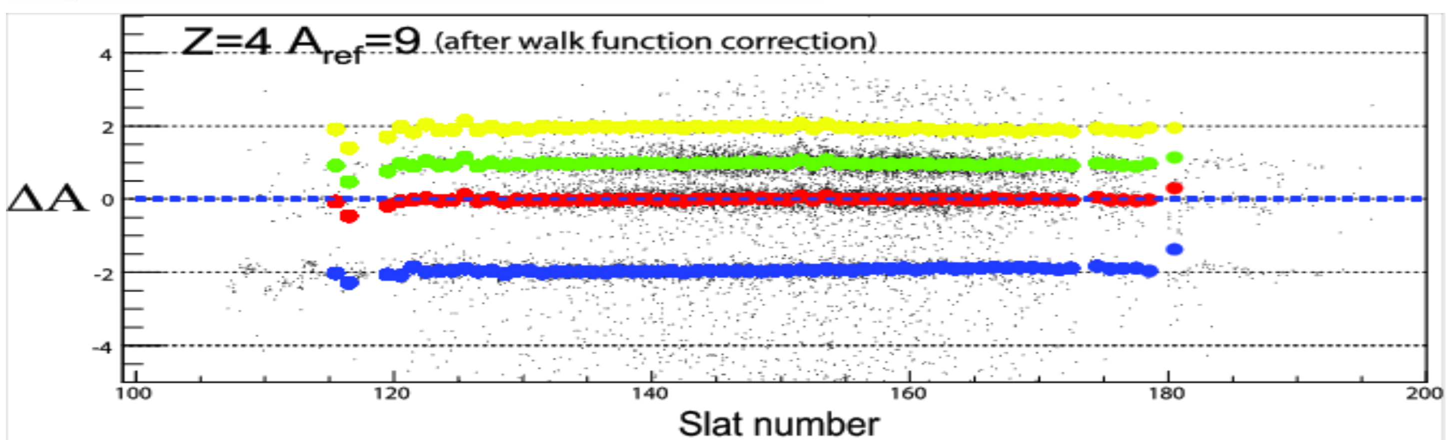
ALADiN set-up and experiment

MUSIC IV upgrade with new proportional counters

➡ improvement of the tracking for light charged particles

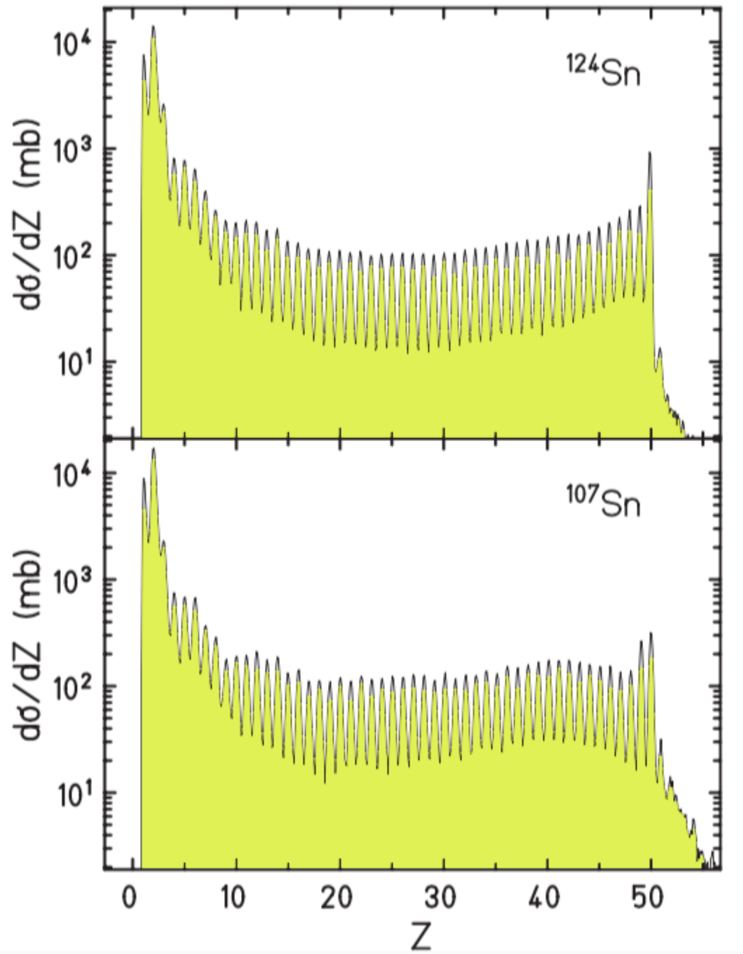


$$A = \frac{0.3\left|\vec{R}\right|Z\sqrt{1-\beta^{2}}}{m_0\beta}$$

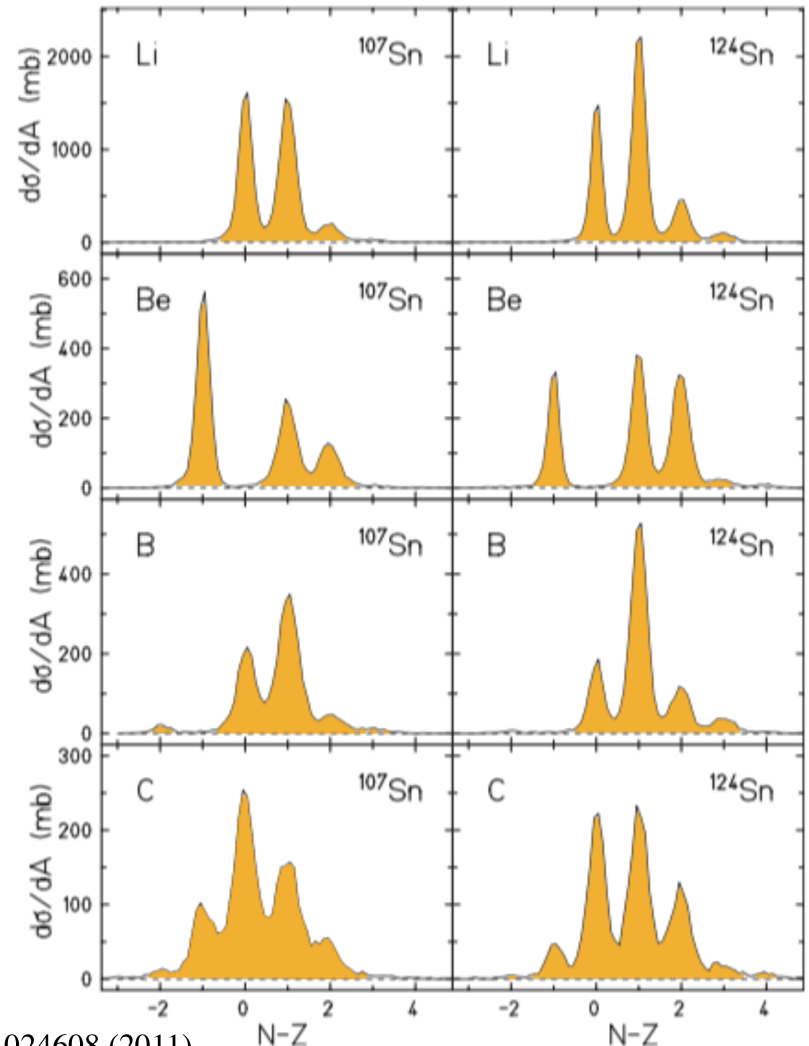


Data quality

TP-MUSIC IV

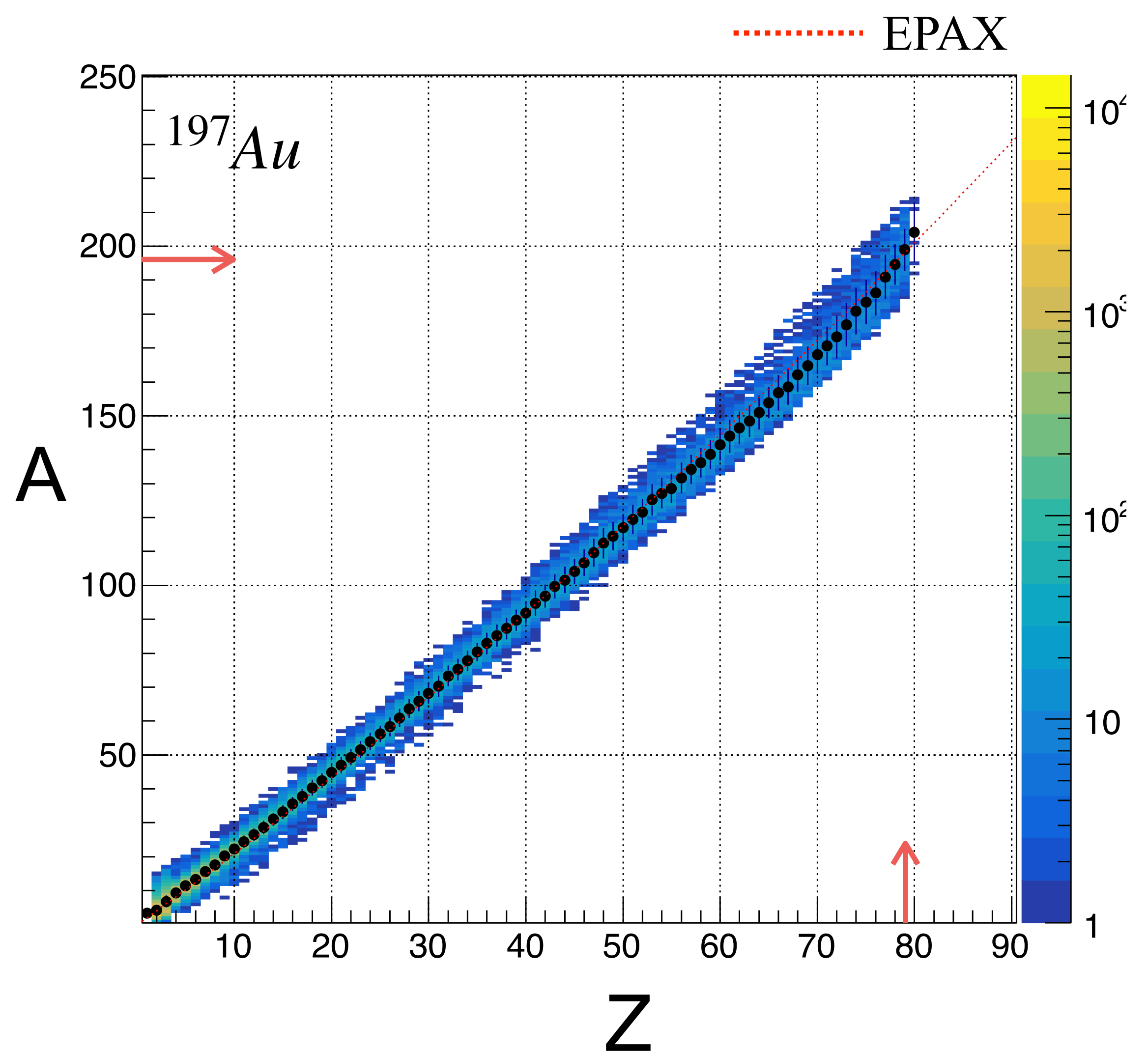


MUSIC + ToF-Wall



R. OGUL *et al*. PHYSICAL REVIEW C **83**, 024608 (2011)

Data quality



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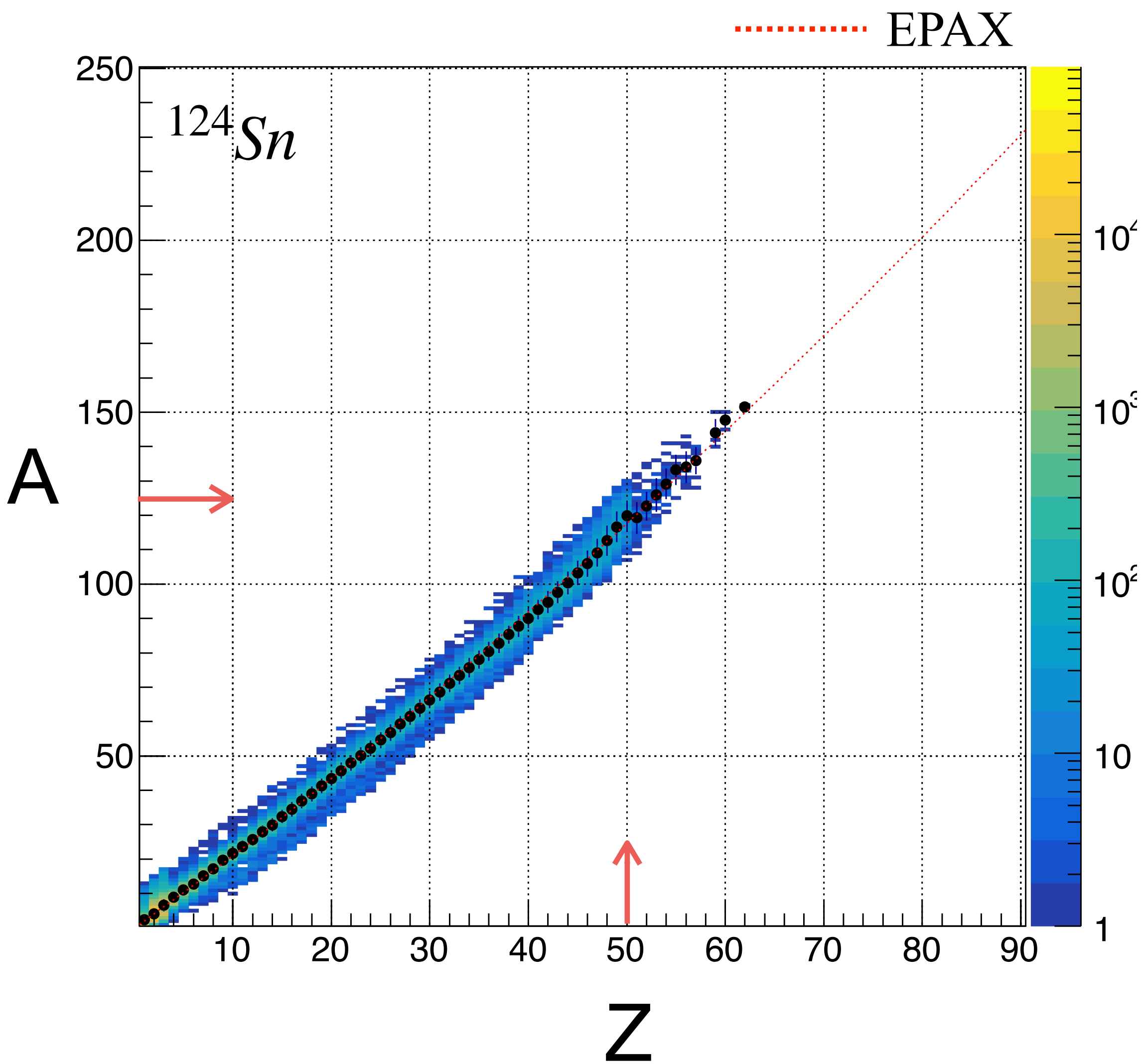

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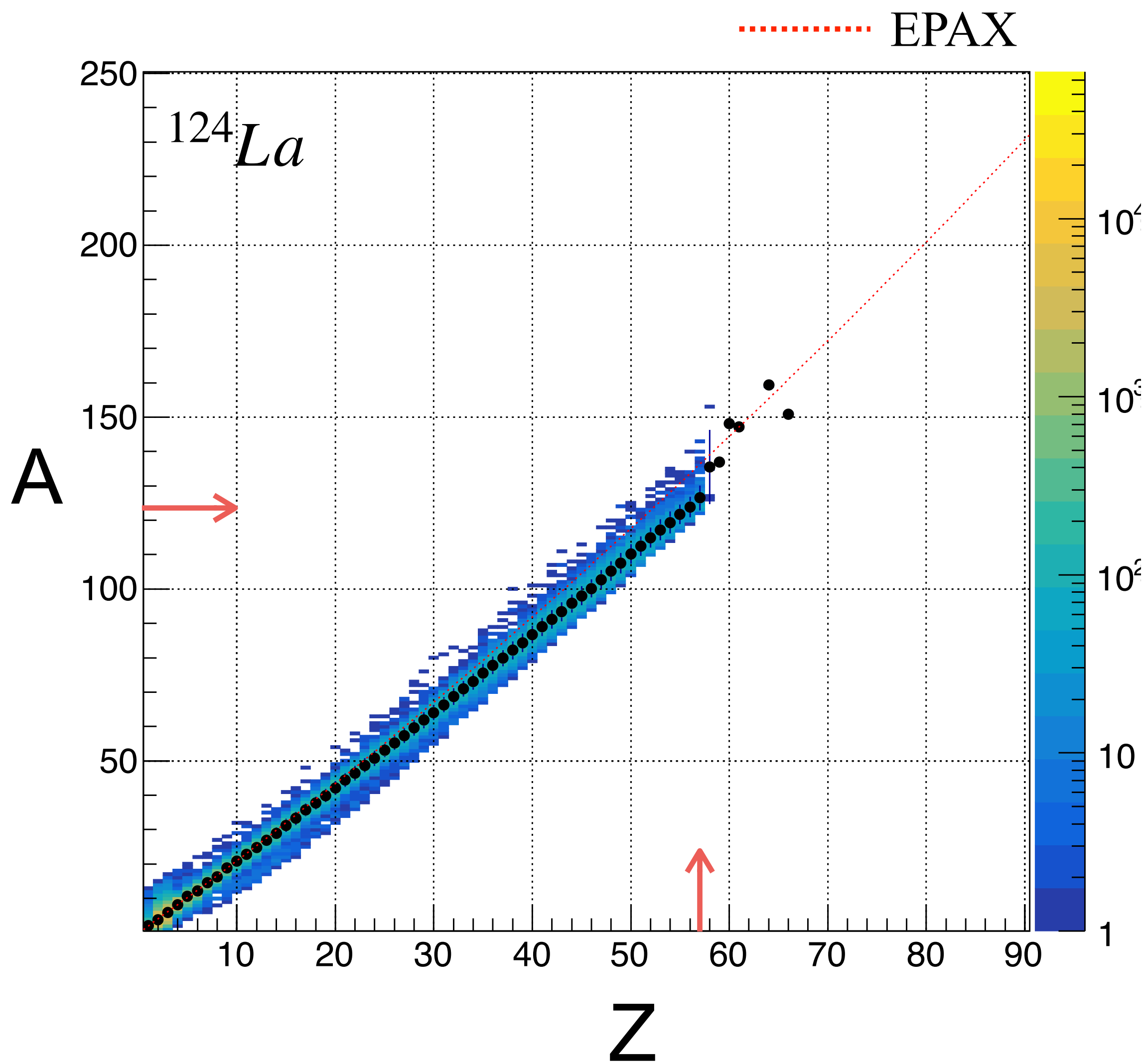

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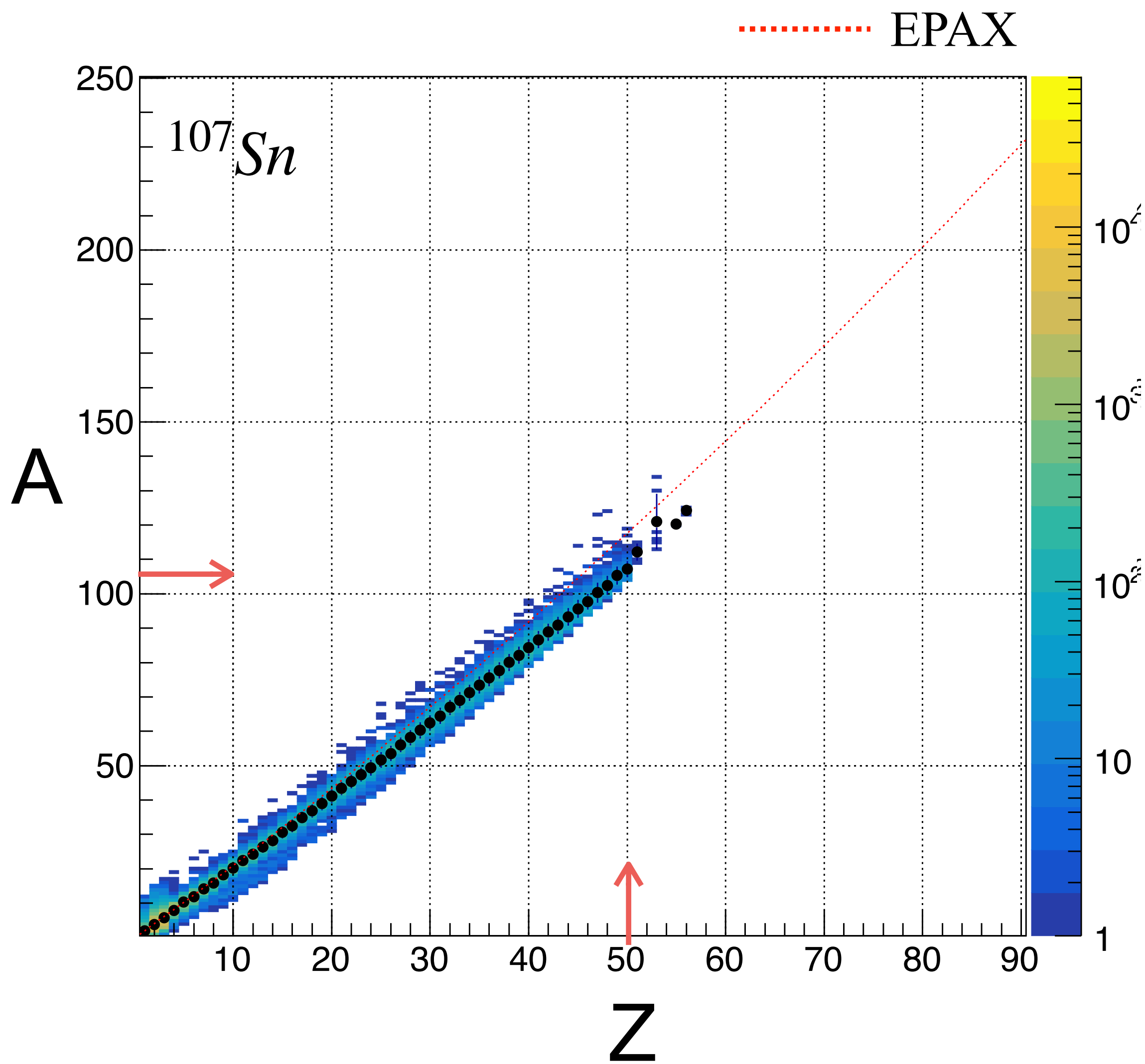


Model used

- Transport : **IQMD** *(C. Hartnack et al., Eur. Phys. J. A 1 (1998) 151)*
  - adapted to the energy regime
  - benchmarked mean-field
    W. Reisdorf et al. [FOPI Collaboration], Nucl. Phys. A 876 (2012) 1
    A. Le Fèvre et al., Nucl. Phys. A 945 (2016) 112
  - asymmetry energy included:

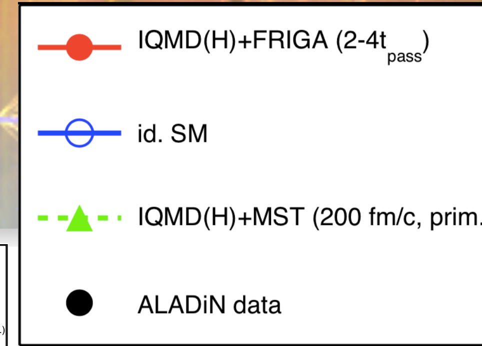
$$E_{asy}(\frac{\rho}{\rho_0}) = E_{asy}^{pot} + E_{asy}^{kin} = 23.3MeV(\frac{\rho}{\rho_0})^{\gamma} + 9MeV(\frac{\rho}{\rho_0})^{2/3}$$

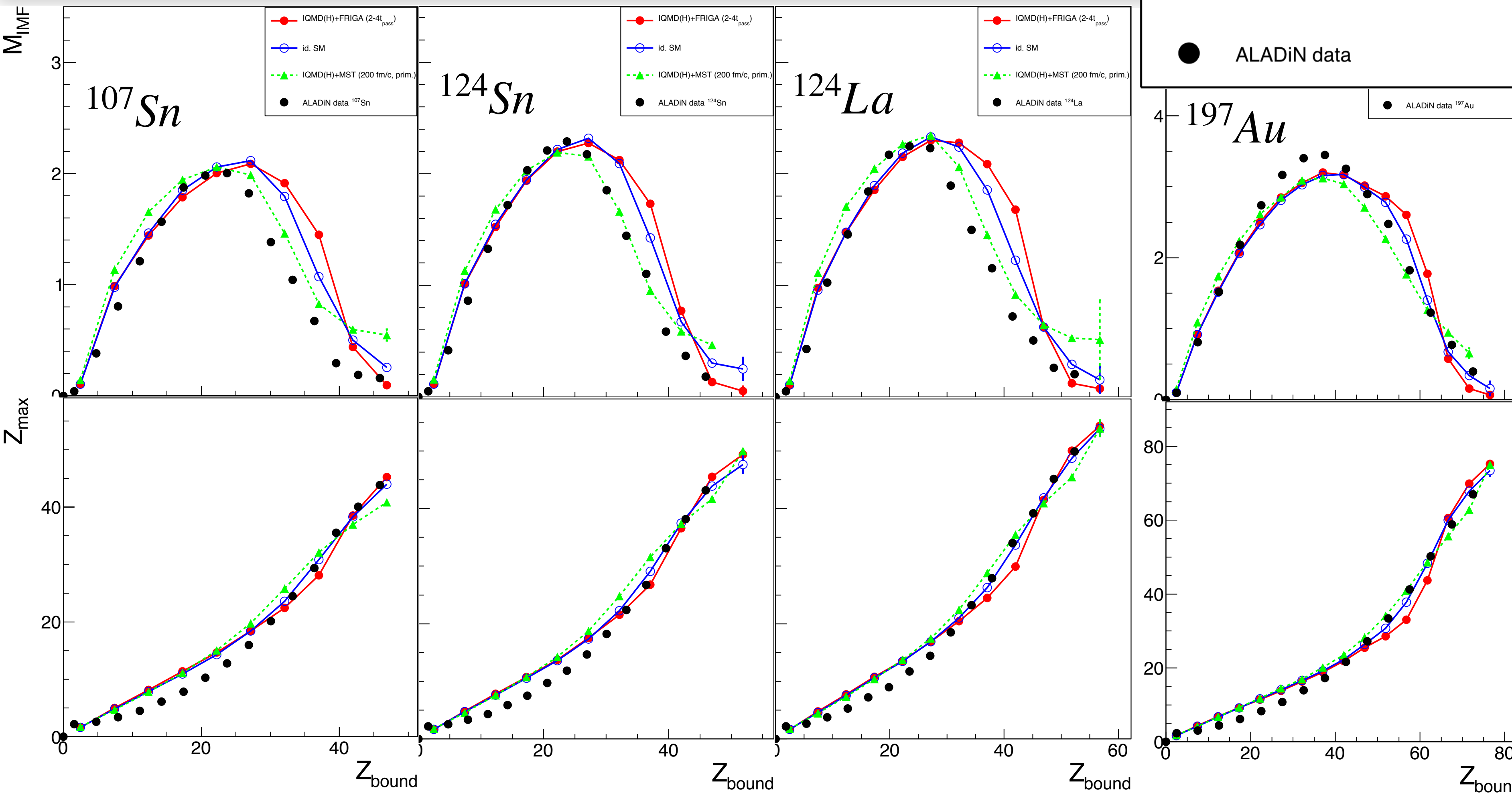
- + Clustering algorithm: **FRIGA** *(A. Le Fèvre et al, 2016 J. Phys.: Conf. Ser. 668 012021)*
  - simulated annealing with Minimum Spanning Tree coalescence as 1st step
    + overall cluster binding energy minimisation:

$$E_{bind} = E_{kin} + E_{Coul} + E_{m.f.} + E_{Yuk.}^{surf.} + E_{asy}^{pot}$$

  - veto of unstable isotopes
  - secondary decay of excited primary clusters (GEMINI);
- Model predictions are corrected from the ALADiN spectrometer acceptance.

Model benchmarking





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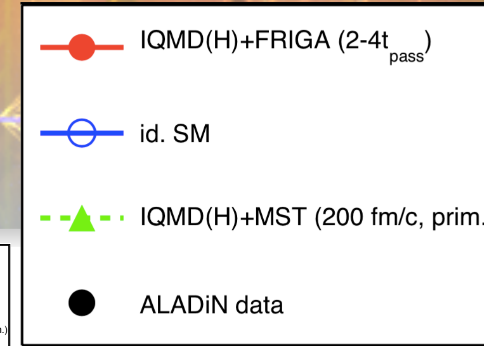
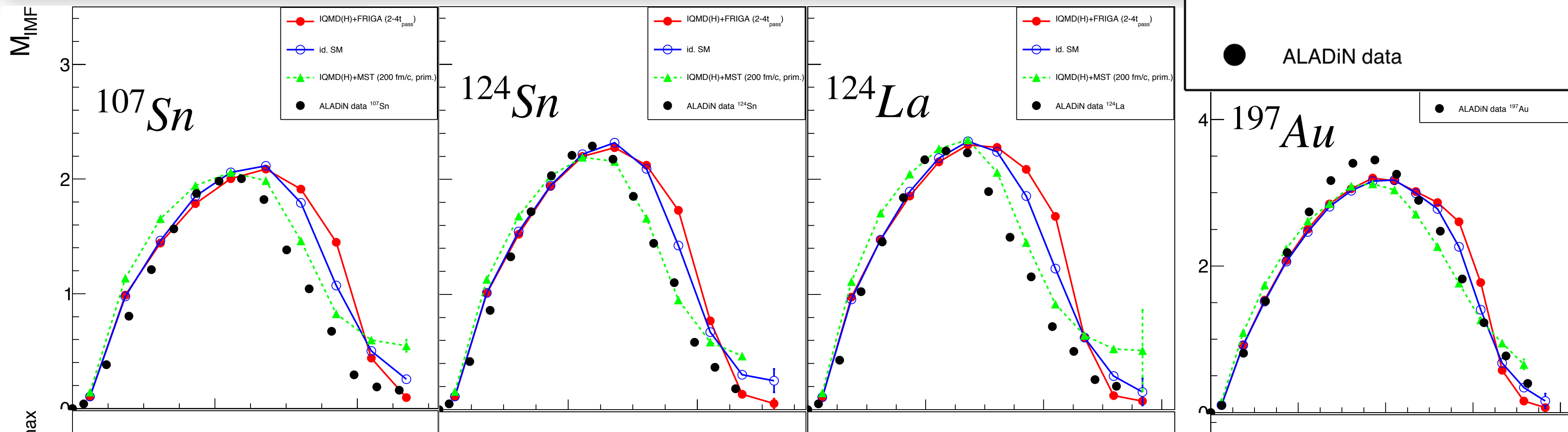
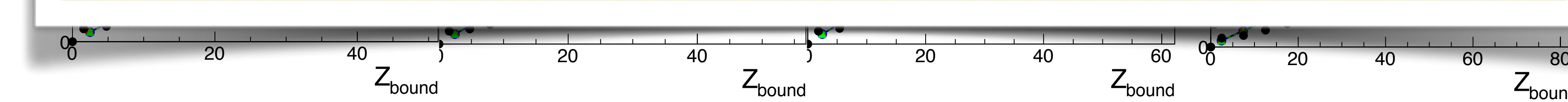




- Rise and Fall reproduced with FRIGA (already at early times) and MST (at large times)
- MST quite fine but no constraint by E_{asy}, therefore isotope yields non reliable
- FRIGA with SM and H gives similar results (S would not)
- Remark: secondary decays have a minor effect because $< E^{*}_{prim.}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

↔ b/b_{max} (IQMD) ≈ 0.6



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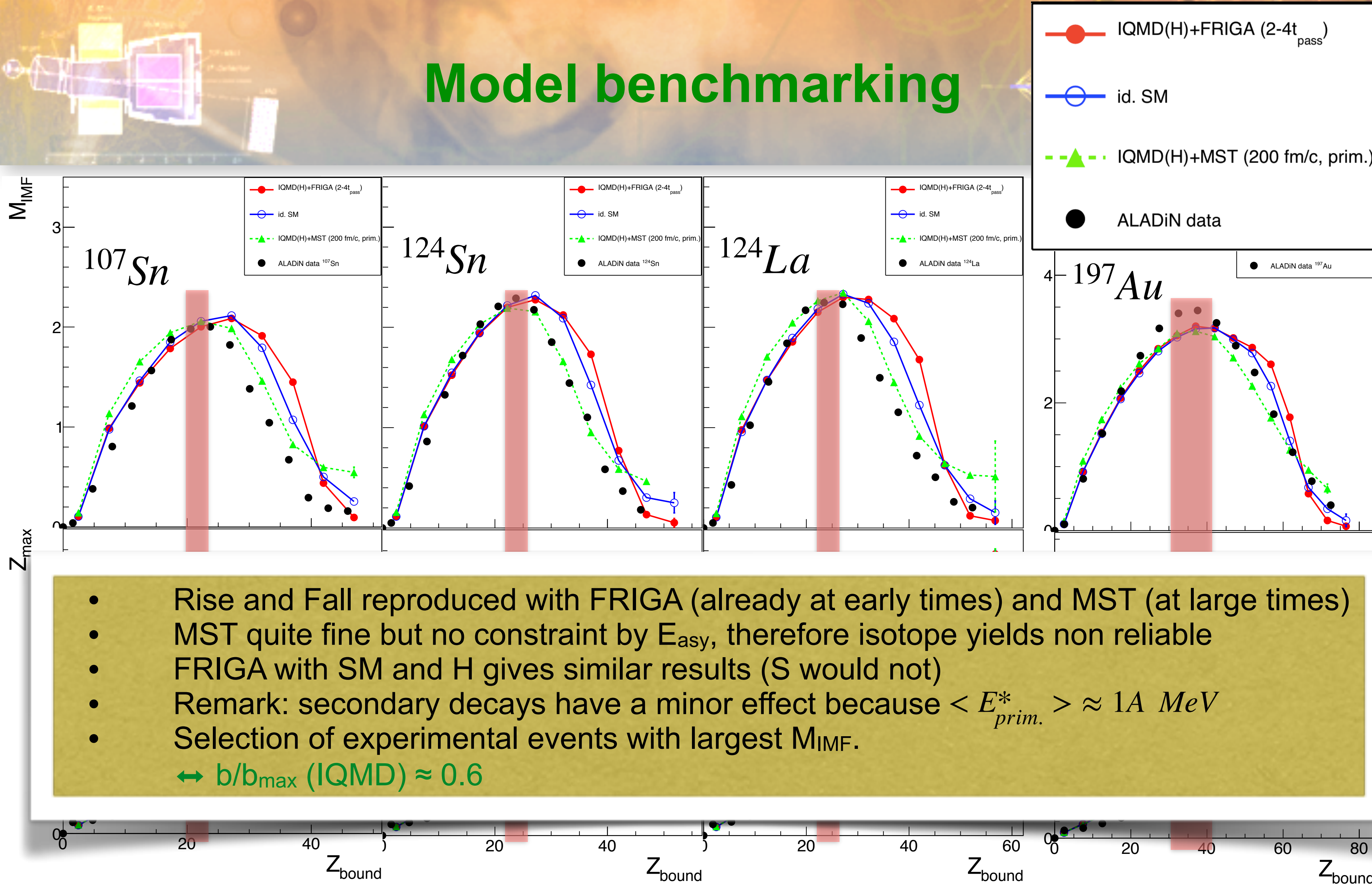

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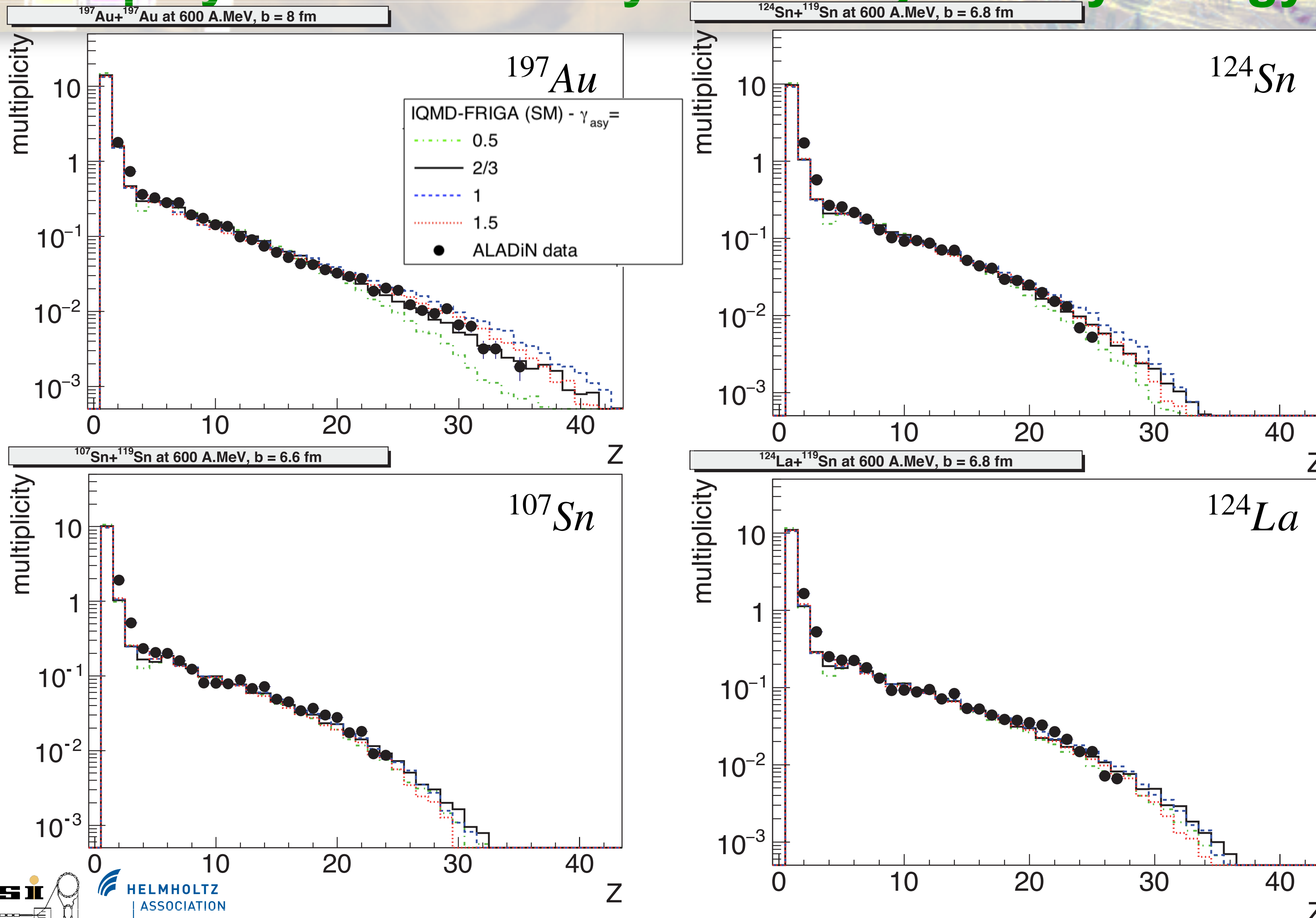
Isotope yields: sensitivity to the asymmetry energy



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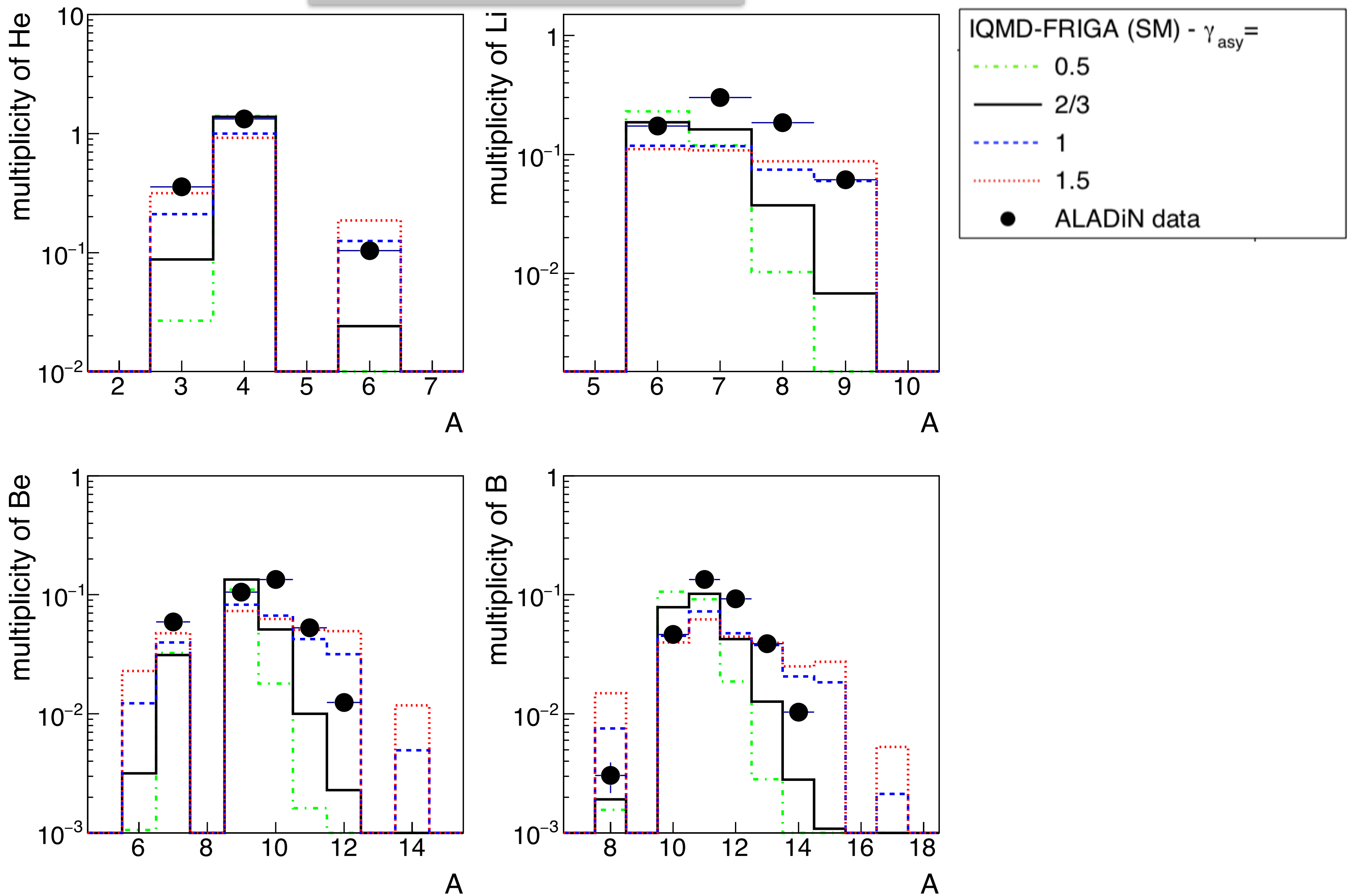
Isotope yields: sensitivity to the asymmetry energy

Light isotope yields

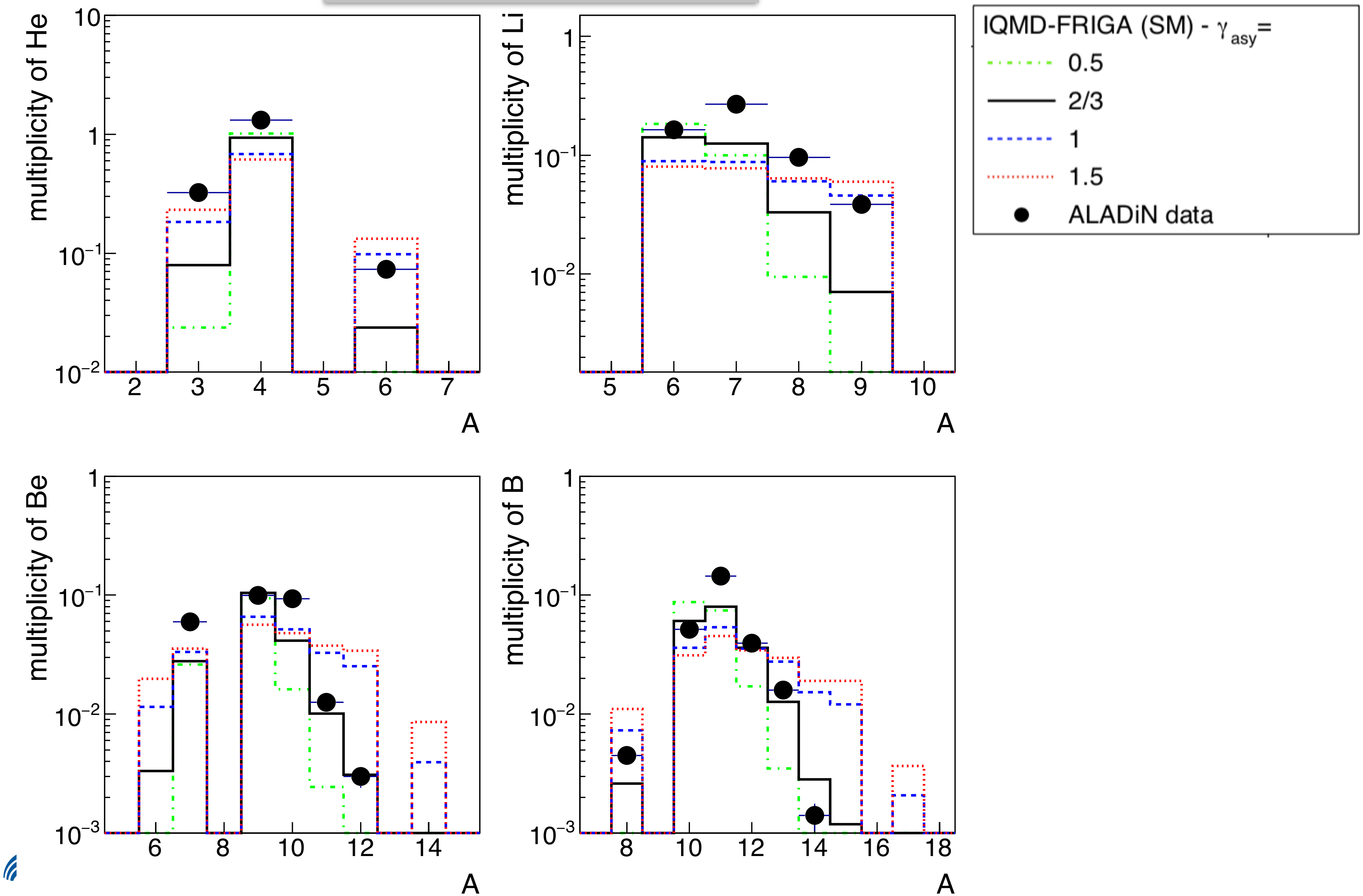
^{197}Au



Isotope yields: sensitivity to the asymmetry energy

^{124}Sn

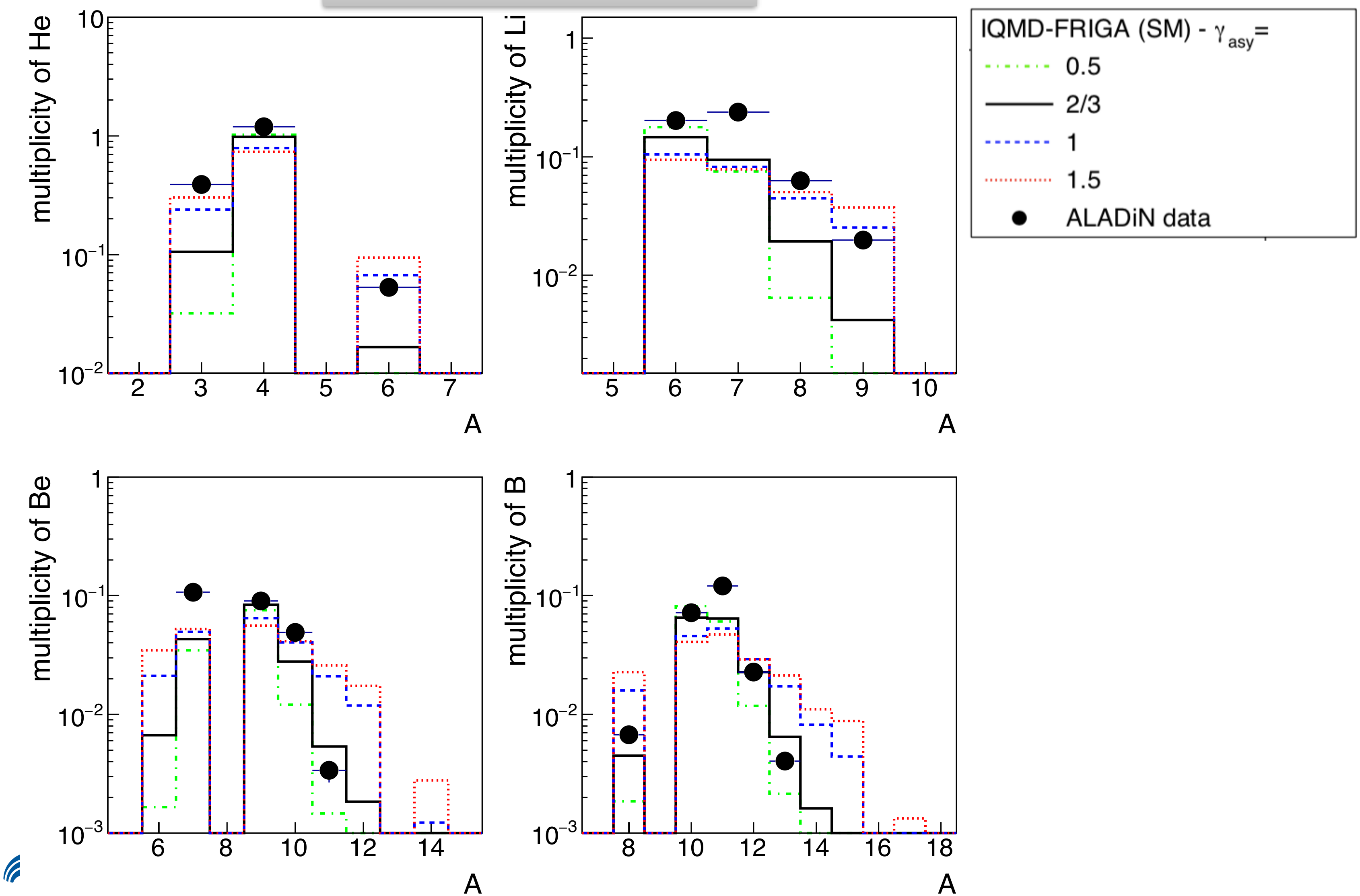
Light isotope yields



Isotope yields: sensitivity to the asymmetry energy

Light isotope yields

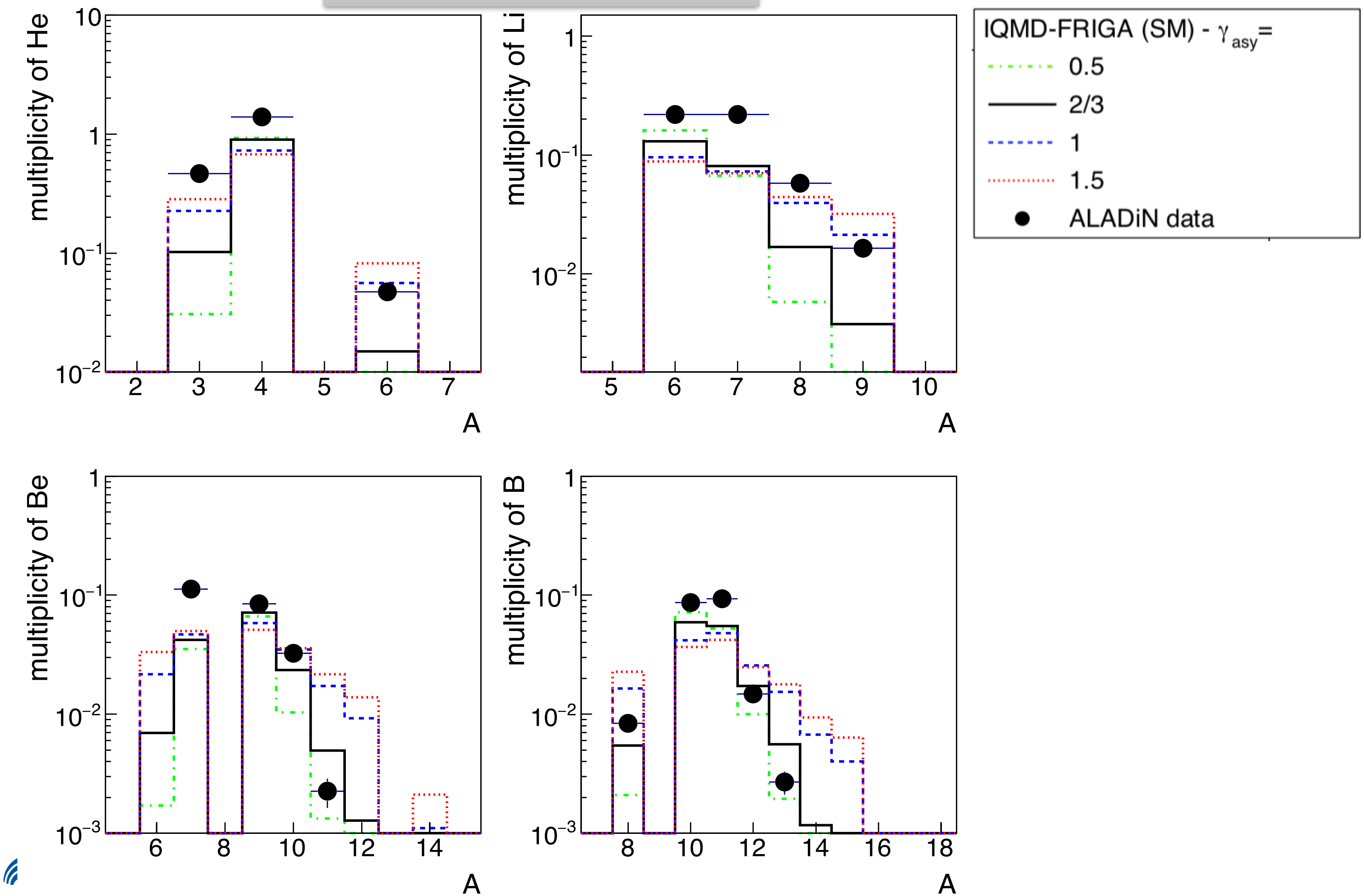
^{124}La



Isotope yields: sensitivity to the asymmetry energy

Light isotope yields

^{107}Sn



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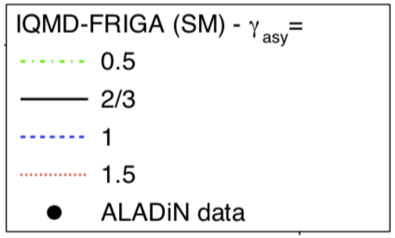
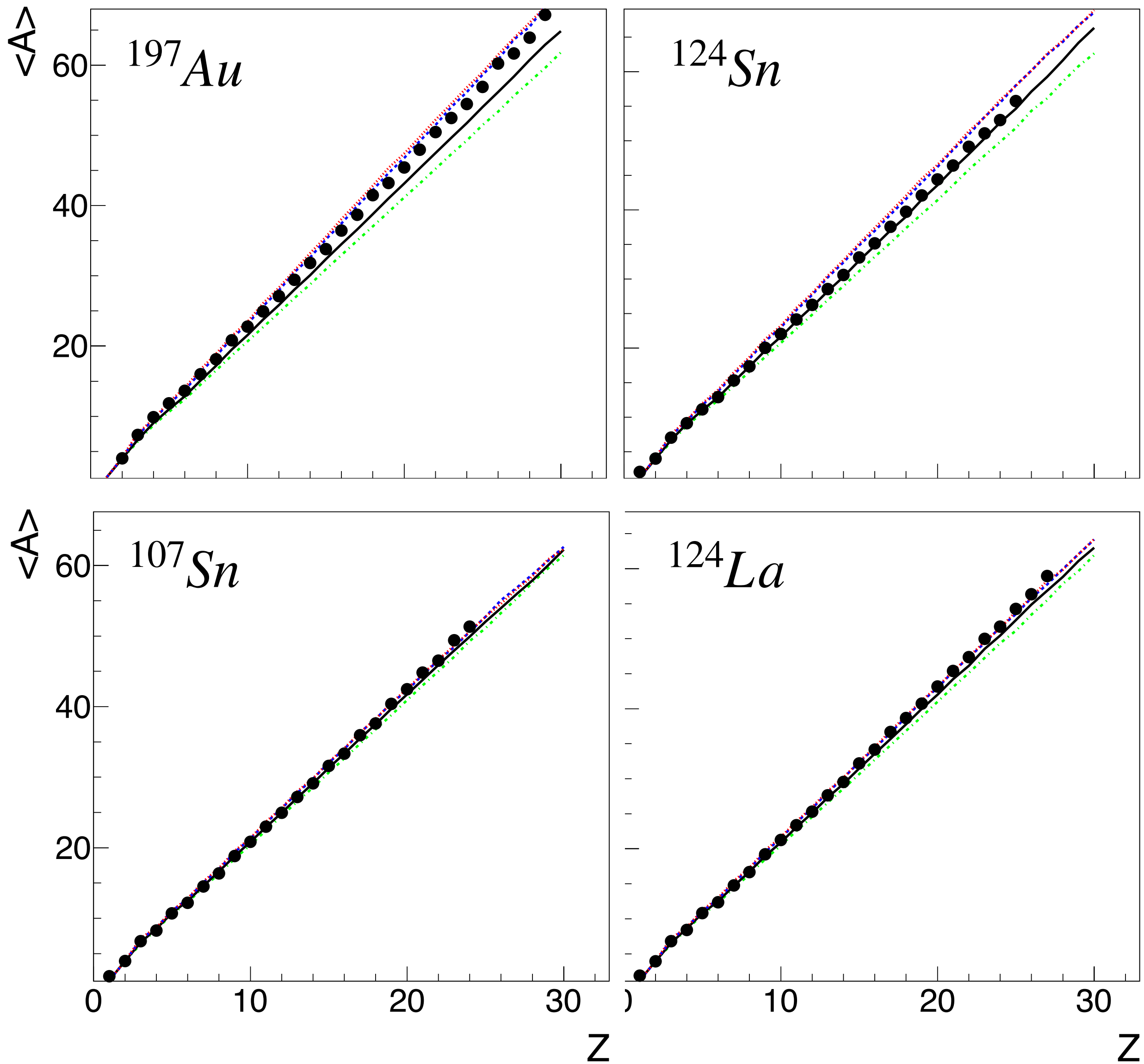
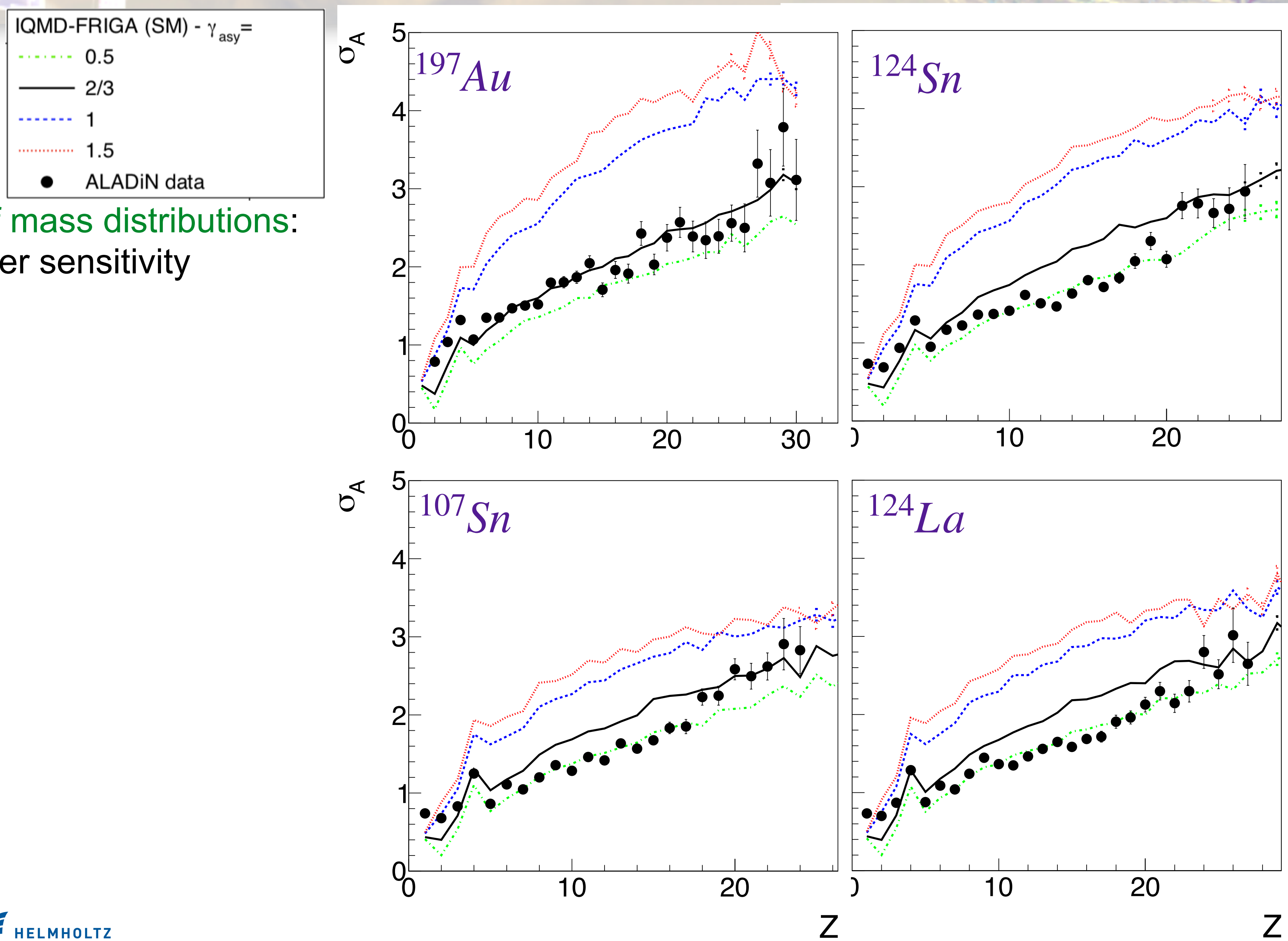




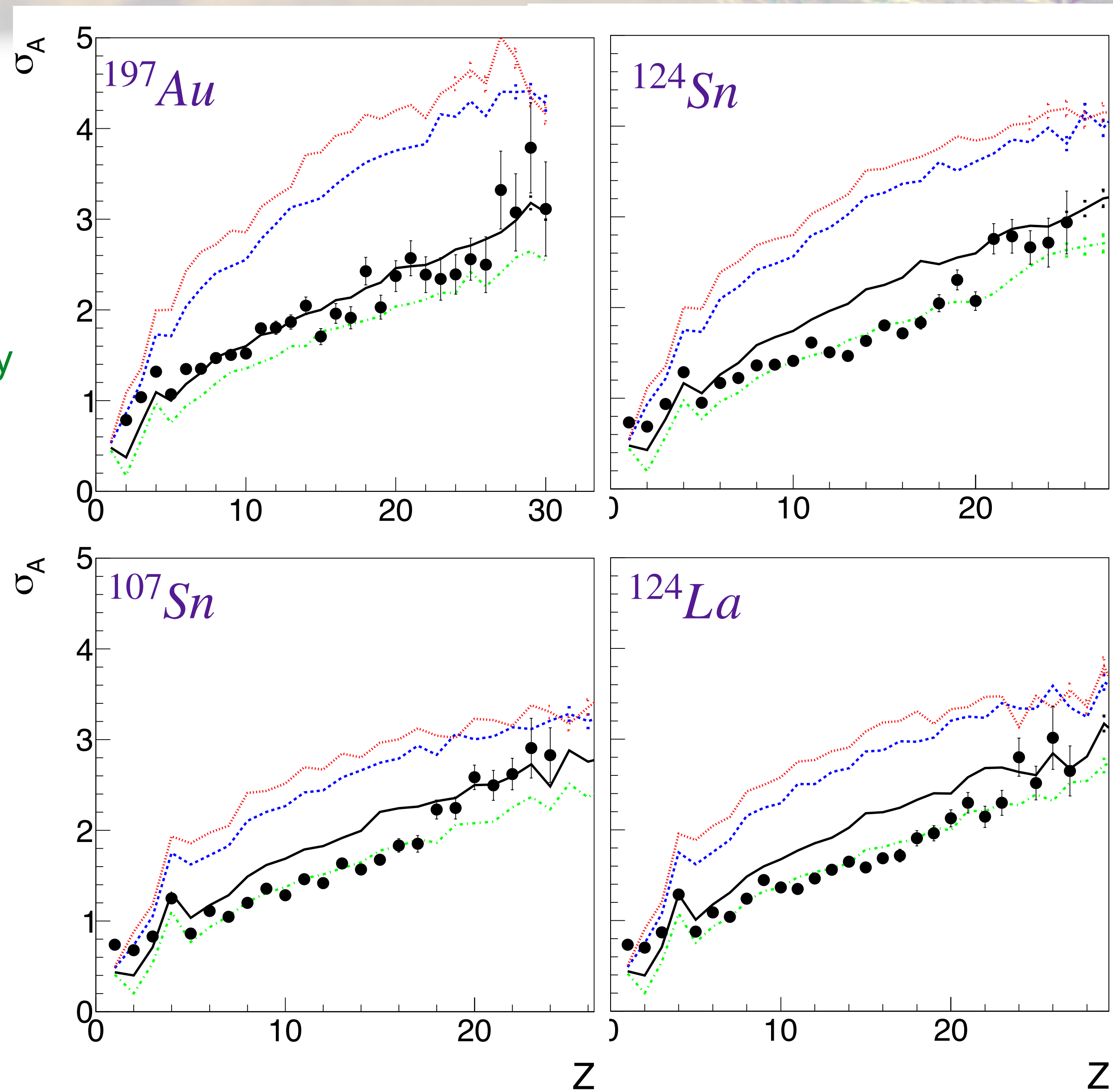
Average masses: largest sensitivity for the neutron rich systems

Isotope yields: sensitivity to the asymmetry energy



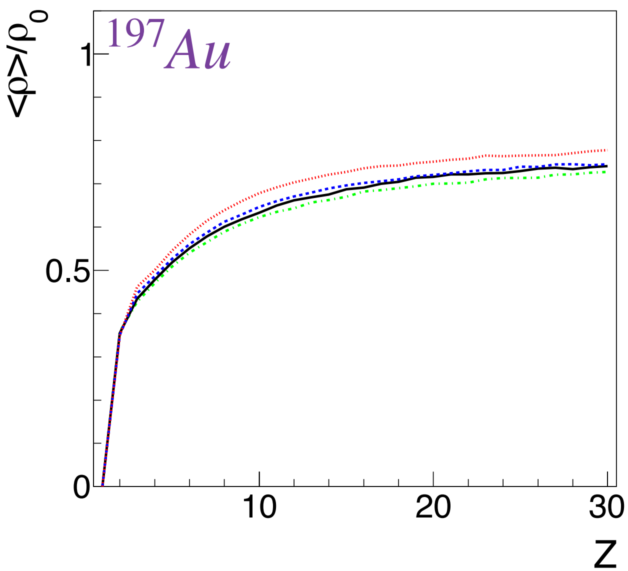
Widths of mass distributions:
even larger sensitivity

Isotope yields: sensitivity to the asymmetry energy



Widths of mass distributions:
even larger sensitivity

⚠ probed densities are strongly related to the cluster size:

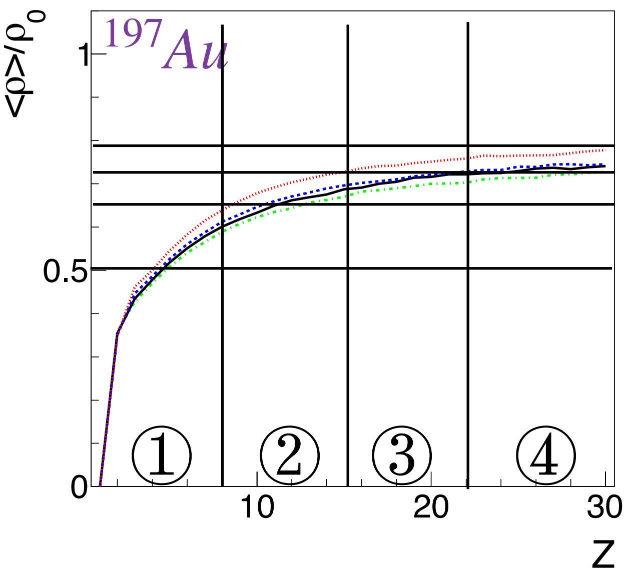


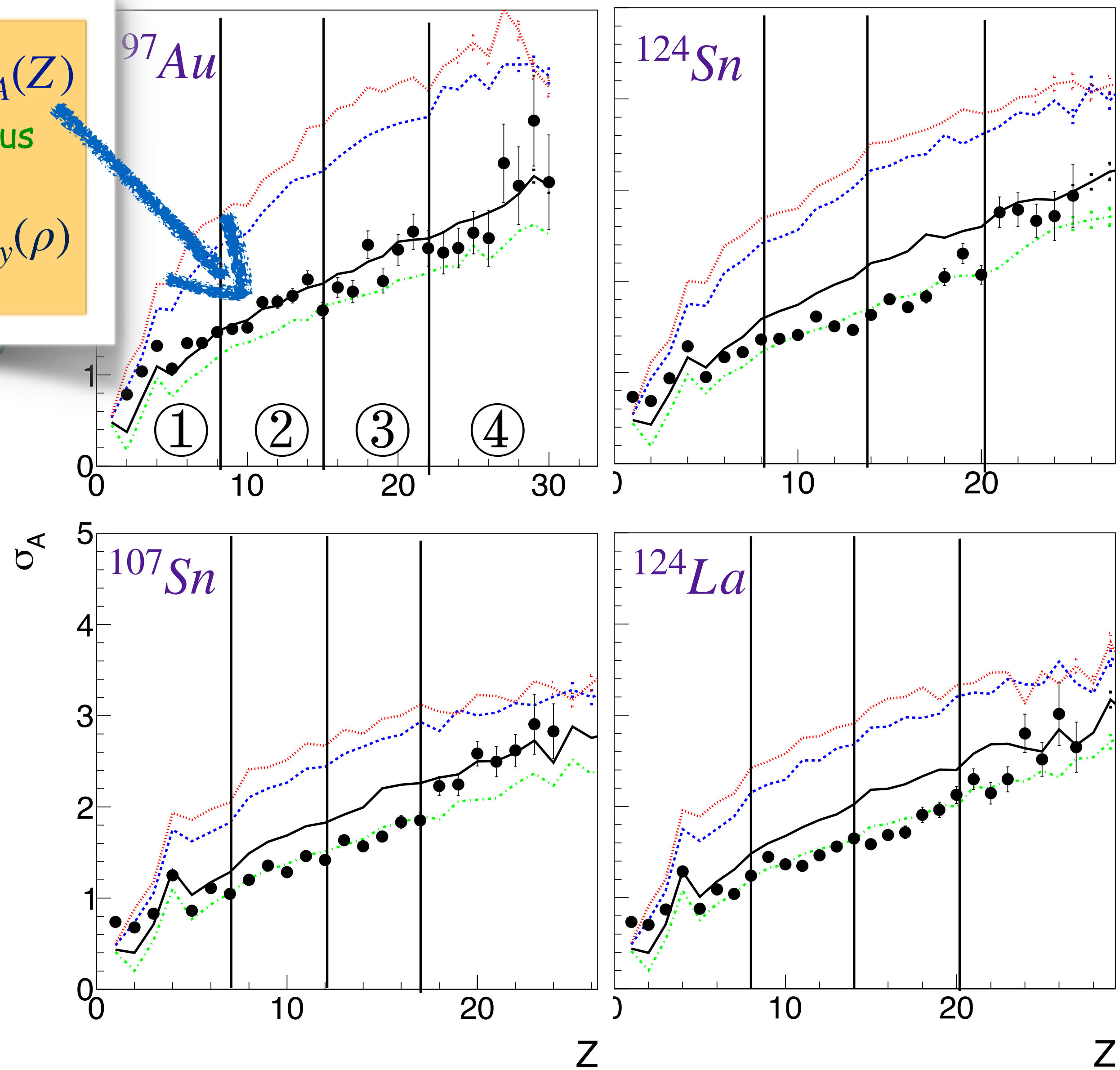
Isotope yields: sensitivity to the asymmetry energy

➡ 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:

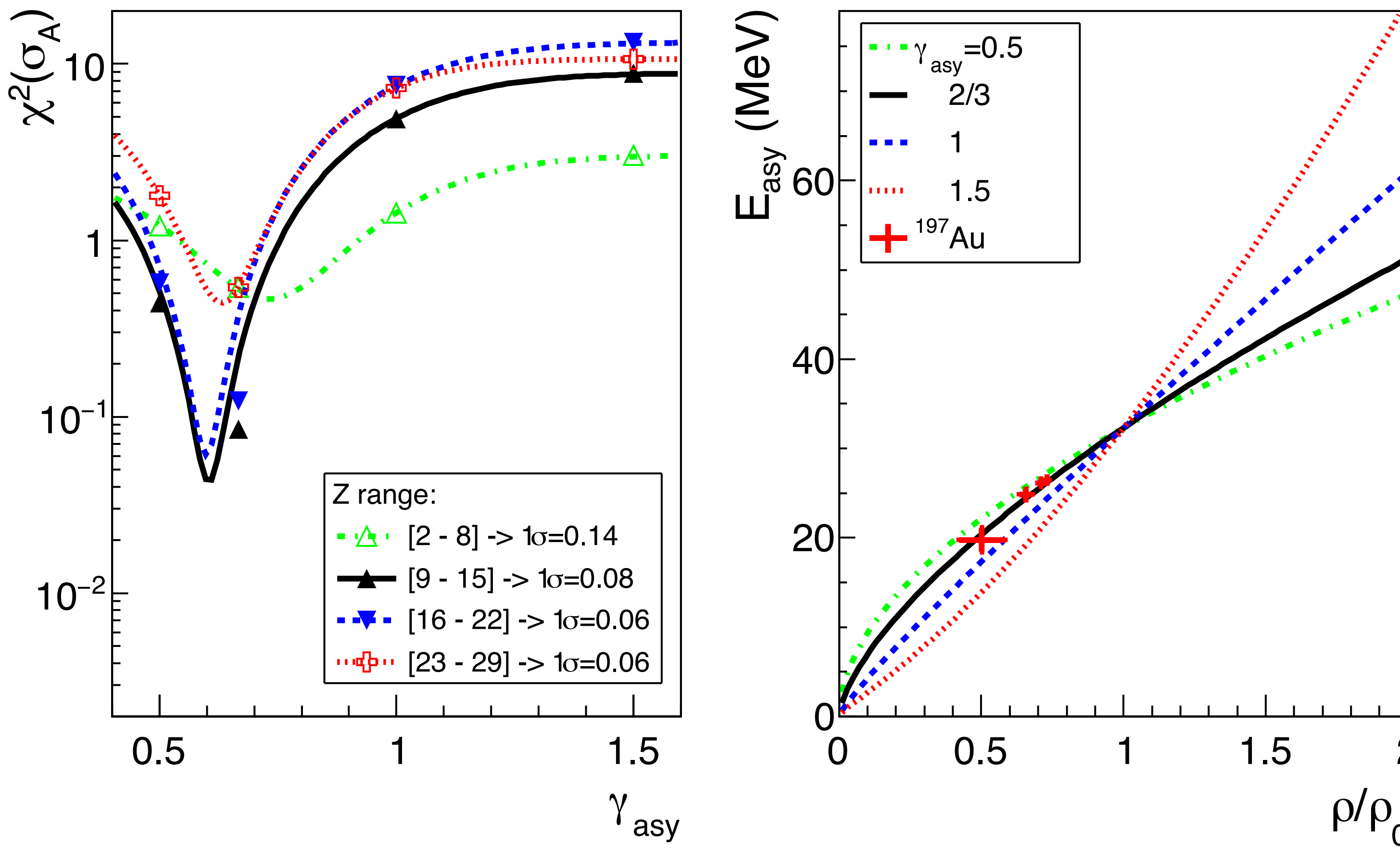




χ^2 minimisation on $\sigma_A(Z)$

^{197}Au

Highest $E_{asy}(\rho)$ expectancies



χ^2 minimisation on $\sigma_A(Z)$

^{124}Sn

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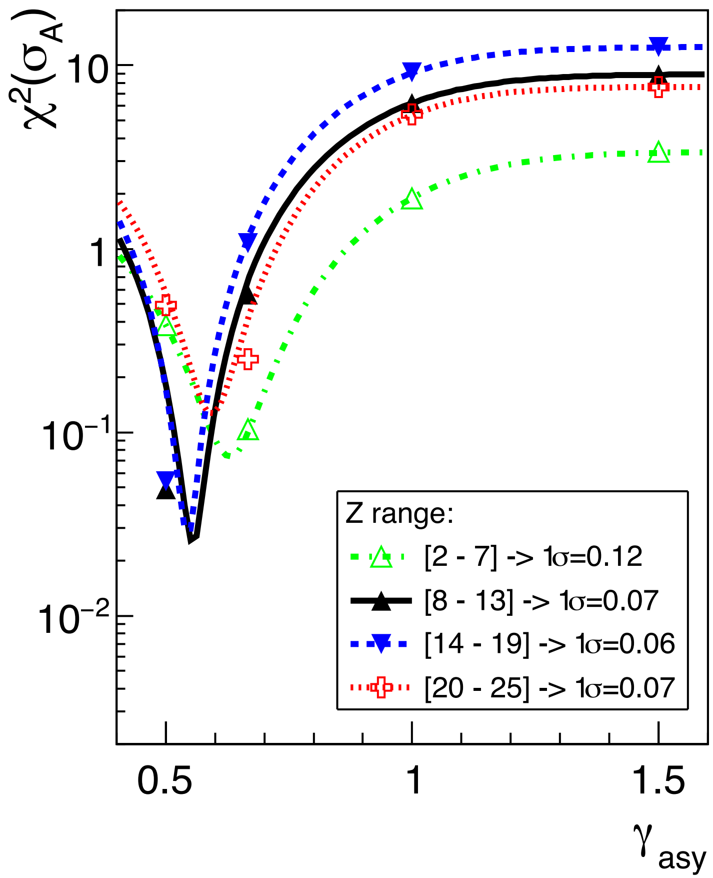
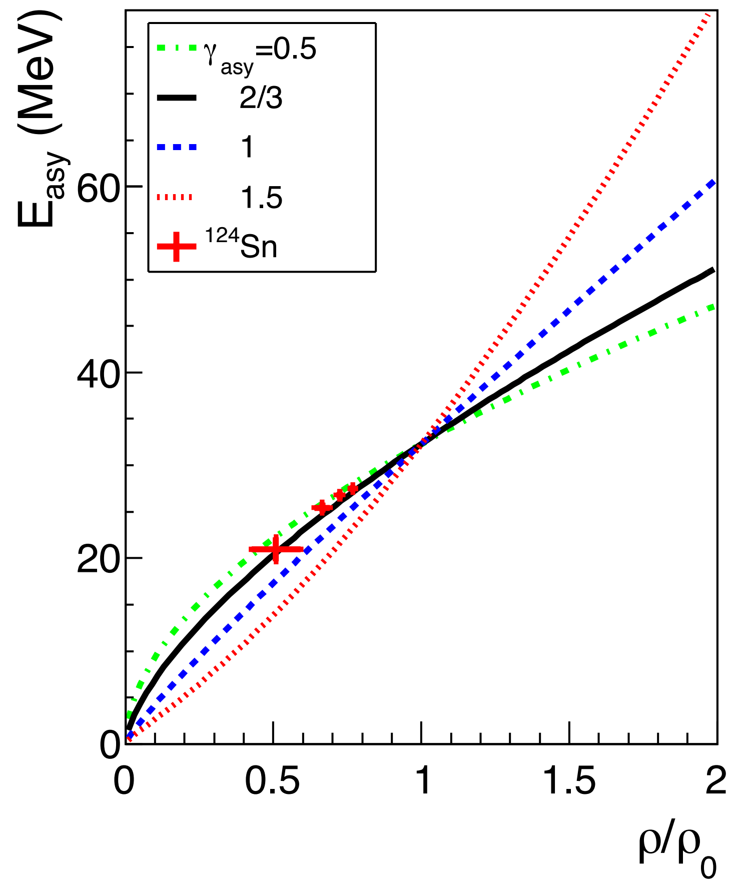
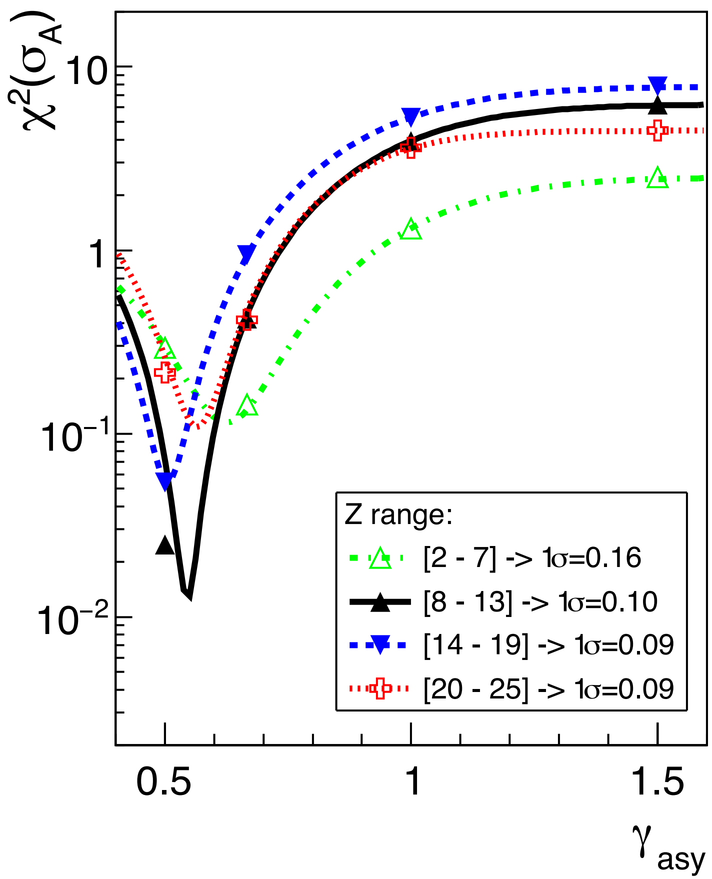


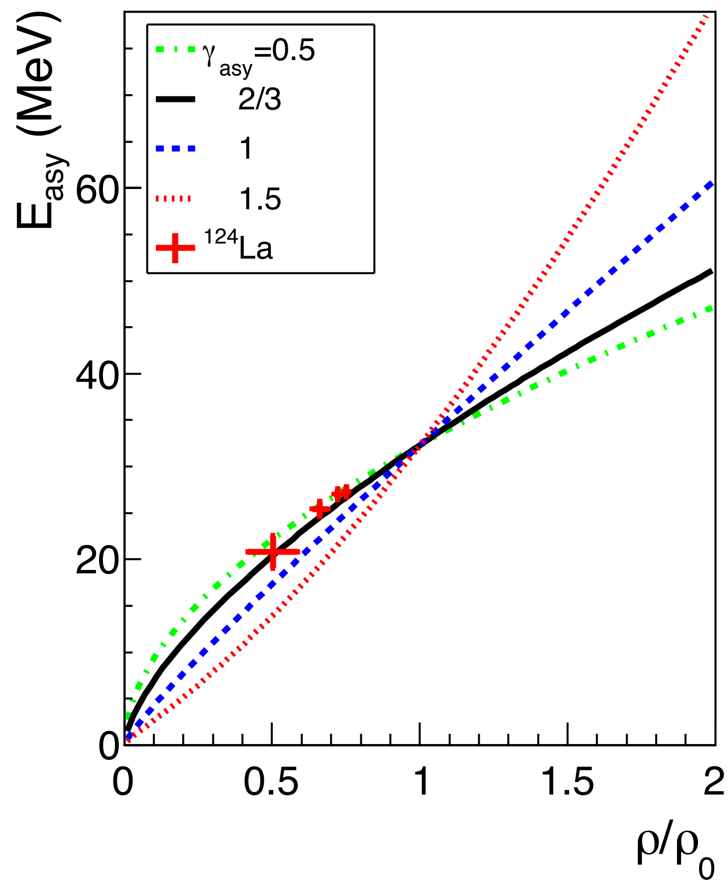


χ^2 minimisation on $\sigma_A(Z)$

^{124}La

Highest $E_{asy}(\rho)$ expectancies

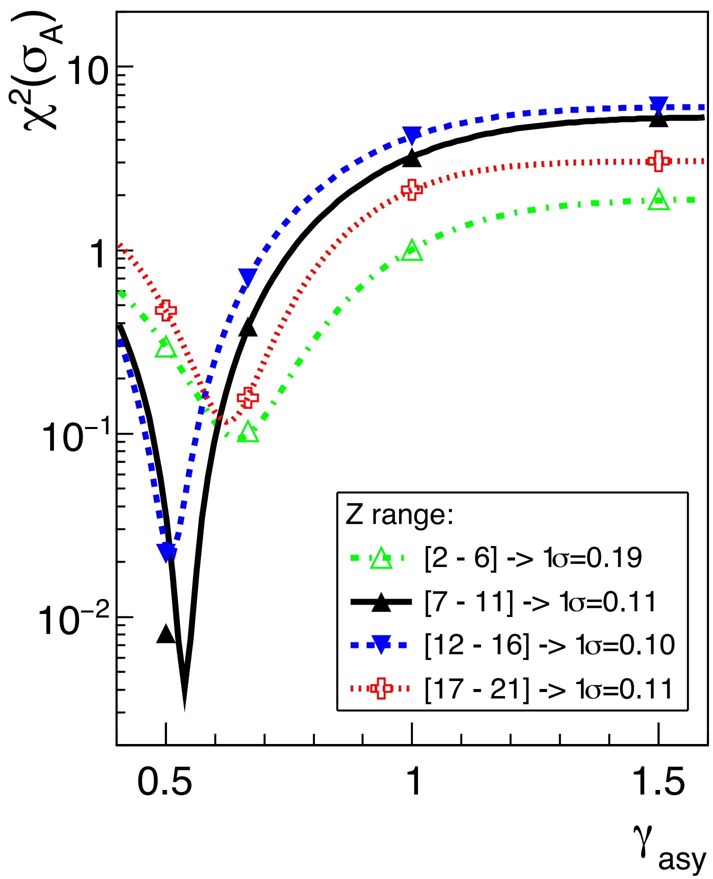


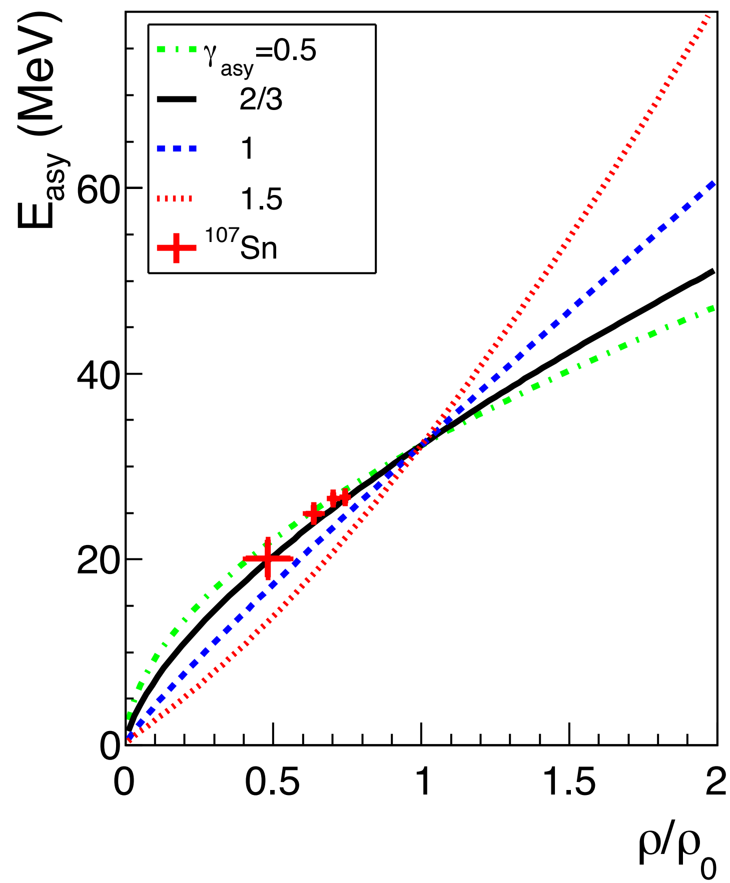


χ^2 minimisation on $\sigma_A(Z)$

^{107}Sn

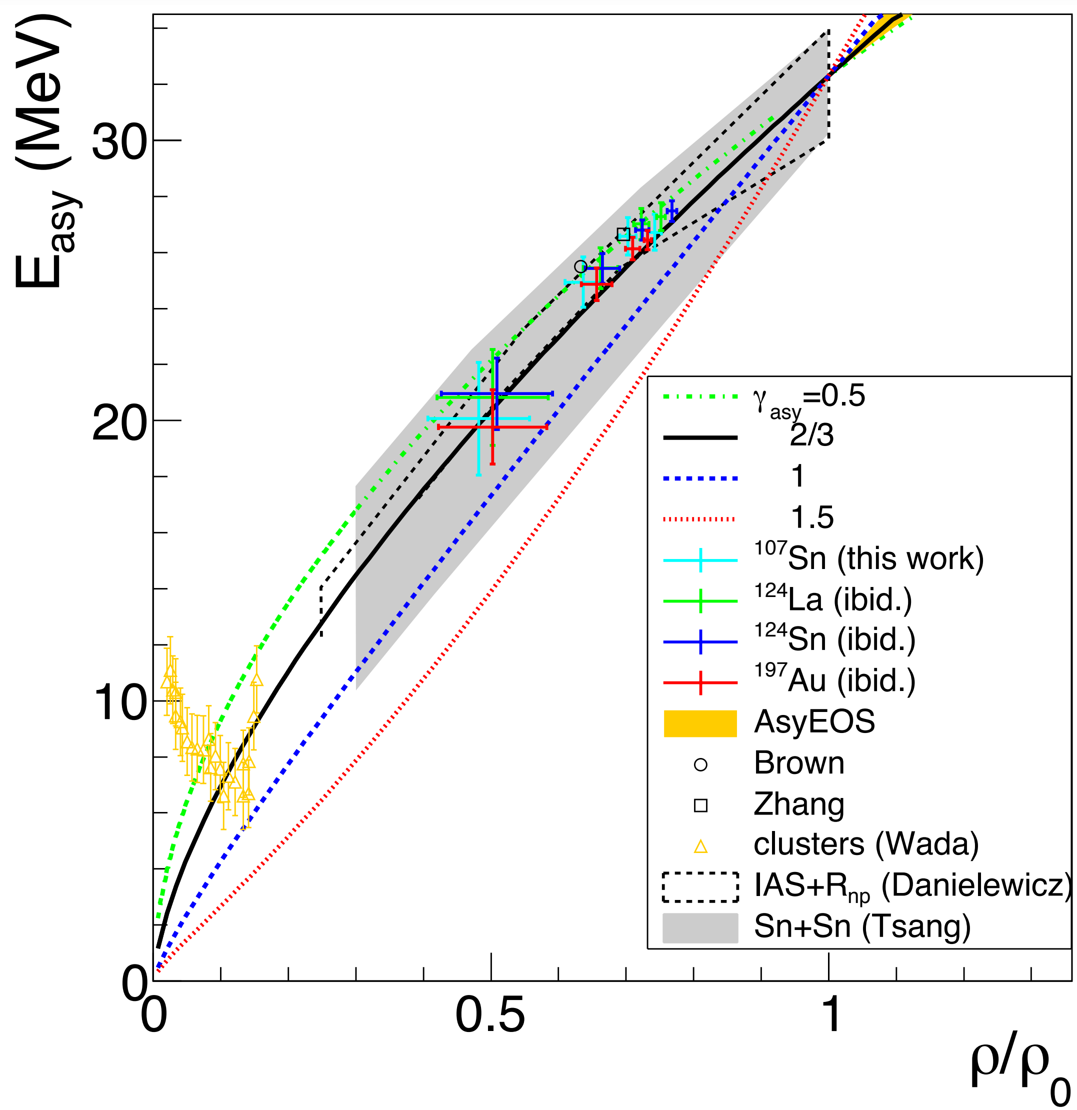
Highest $E_{asy}(\rho)$ expectancies





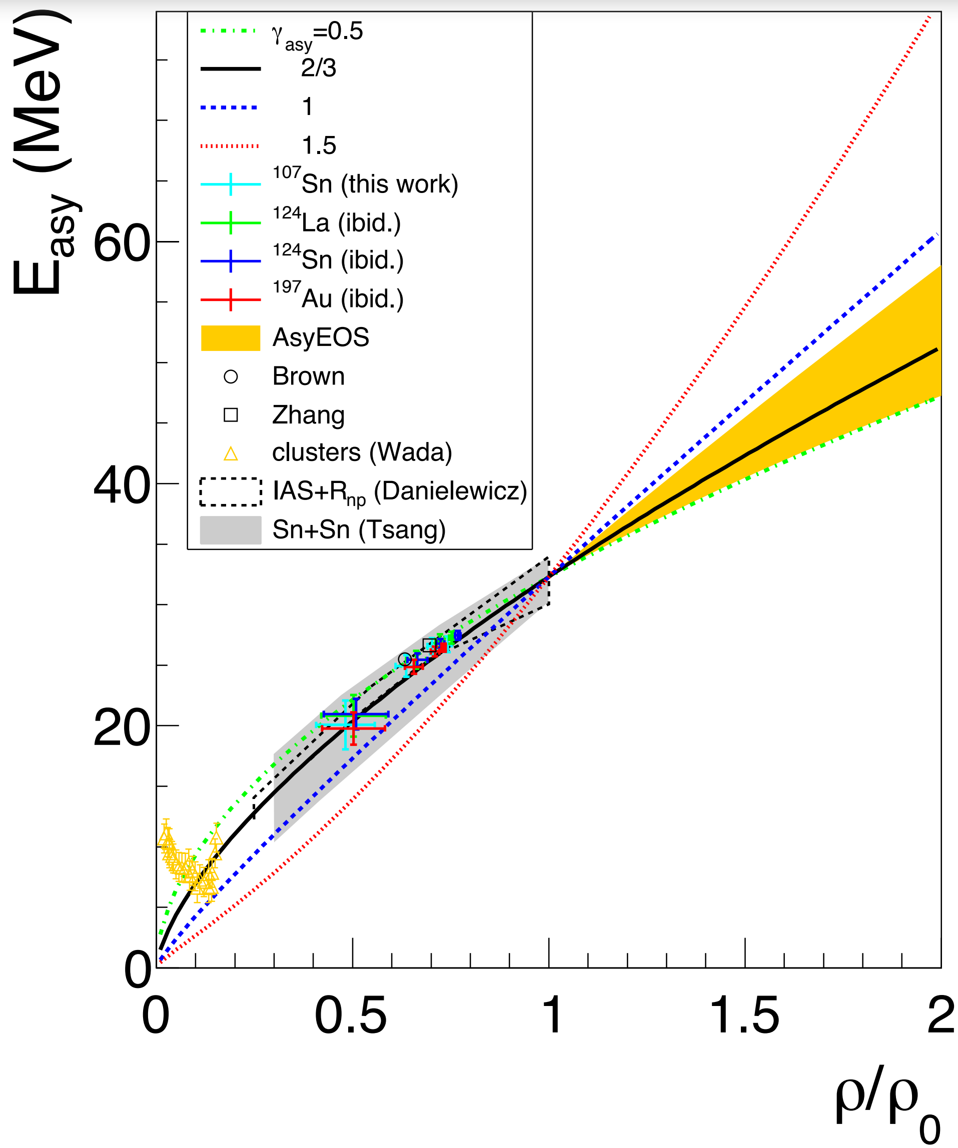
Synthesis over all systems and how its compares with recent findings

- Neutron rich systems are the most sensitive for this type of analysis



Synthesis over all systems and how its compares with recent findings

- 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)
    ➺ **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 (for $E_{pot}^{asy}(\rho_0)$=22 MeV)
- All this is preliminary.
  Work to be published…



Synthesis over all systems and how its compares with recent 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

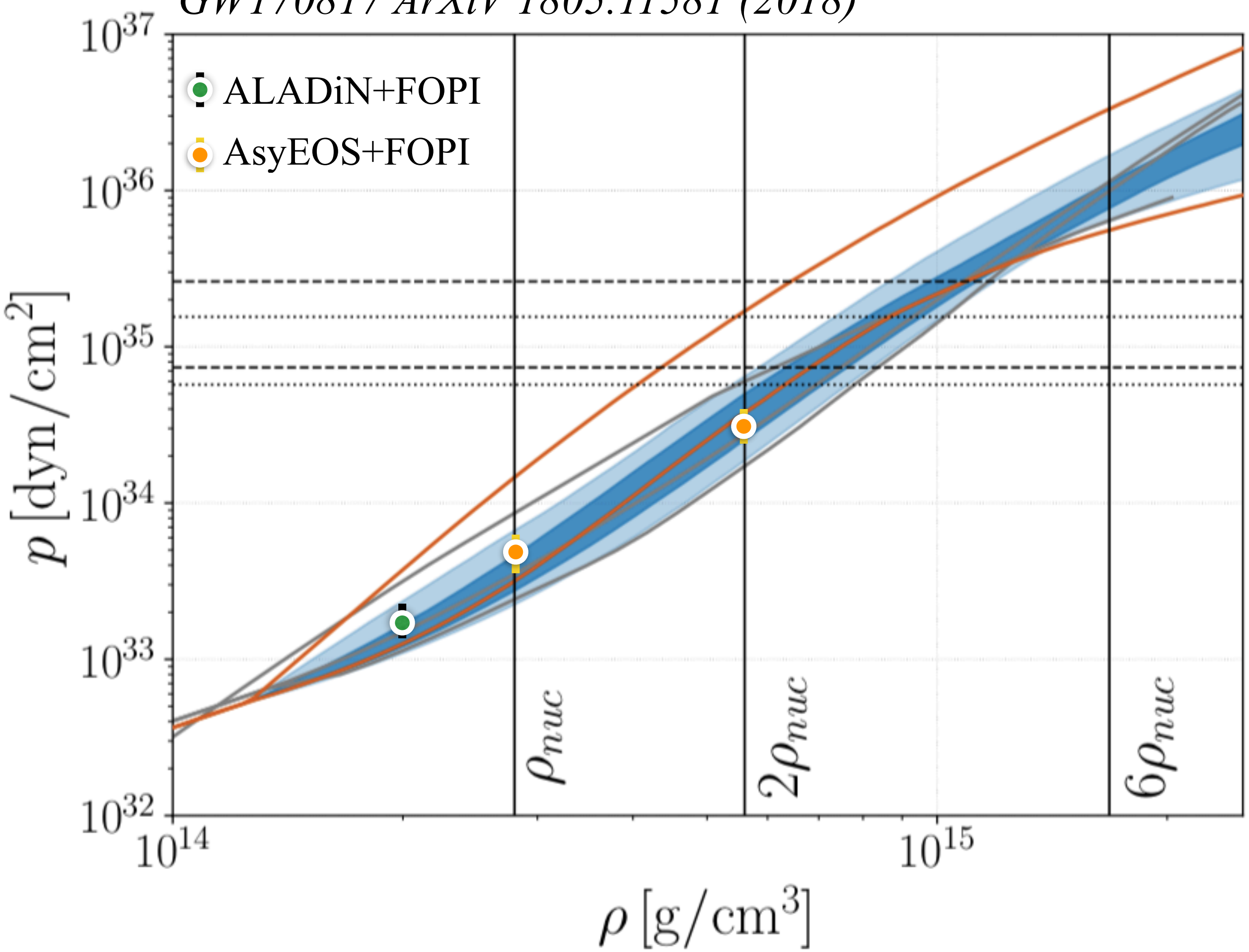
$$IQMD -> K_0 = 190 \pm 30\ MeV$$

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

$$UrQMD -> K_0 = 220 \pm 40\ MeV$$

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

GW170817 ArXiV 1805.11581 (2018)



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