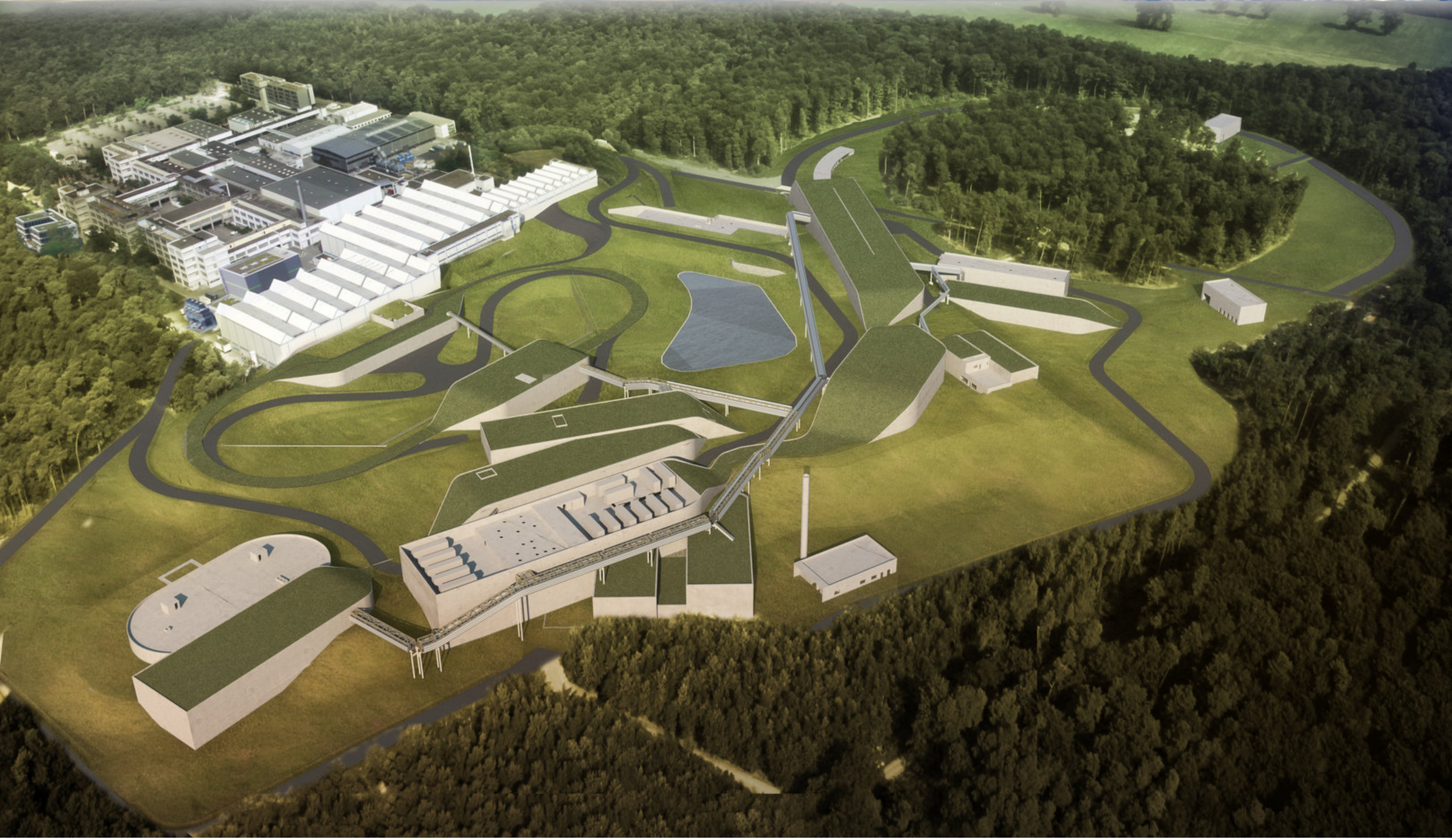
# Asymmetry energy and nuclear matter equation of state: What have we learnt from experiments at GSI ?



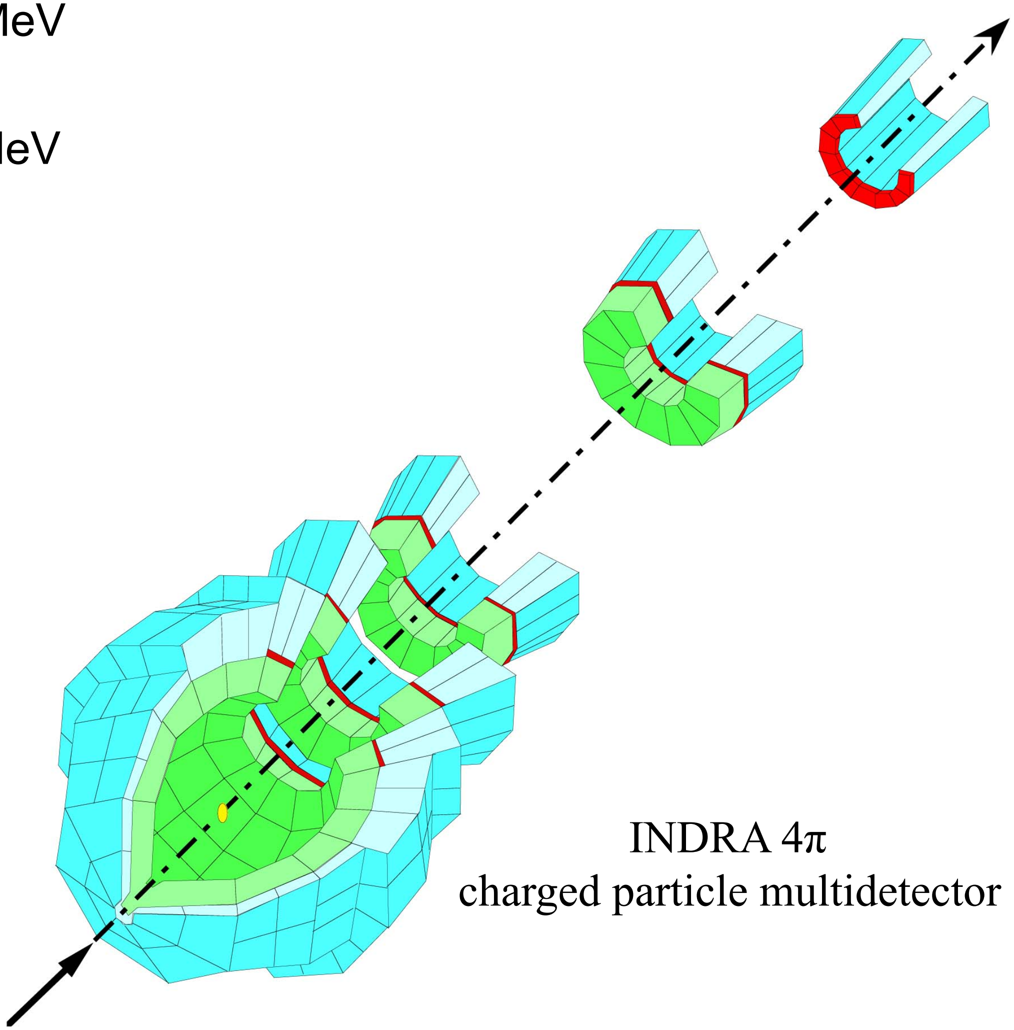
Arnaud Le Fèvre - Colloque GANIL 2021

# Asymmetry energy and nuclear matter equation of state: What have we learnt from experiments at GSI ?

- 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, meson yields): FOPI, KaoS, LAND, AsyEOS.
- How HICs compare with recent astrophysical findings.
- Perspectives: Towards larger densities…

# 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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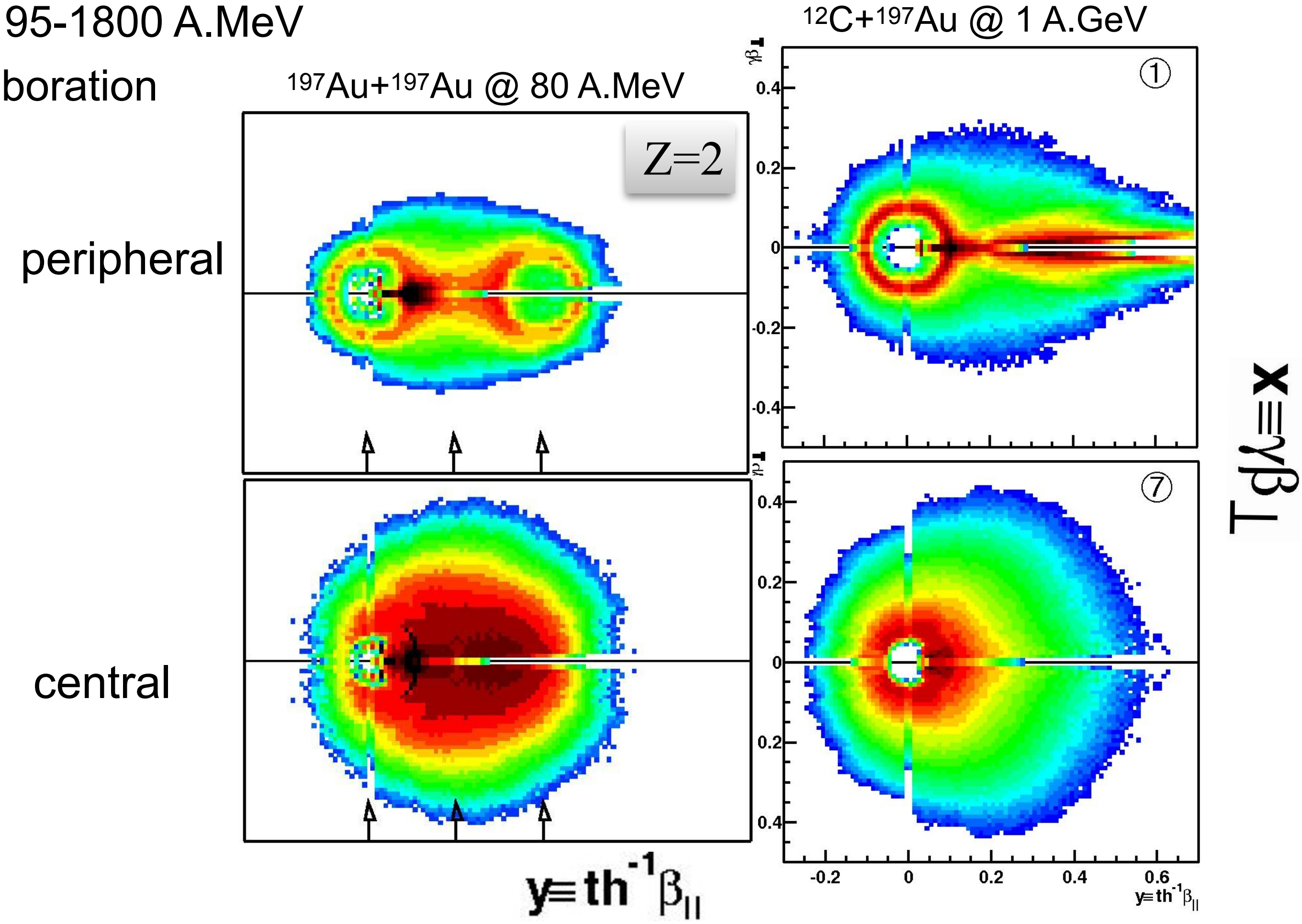

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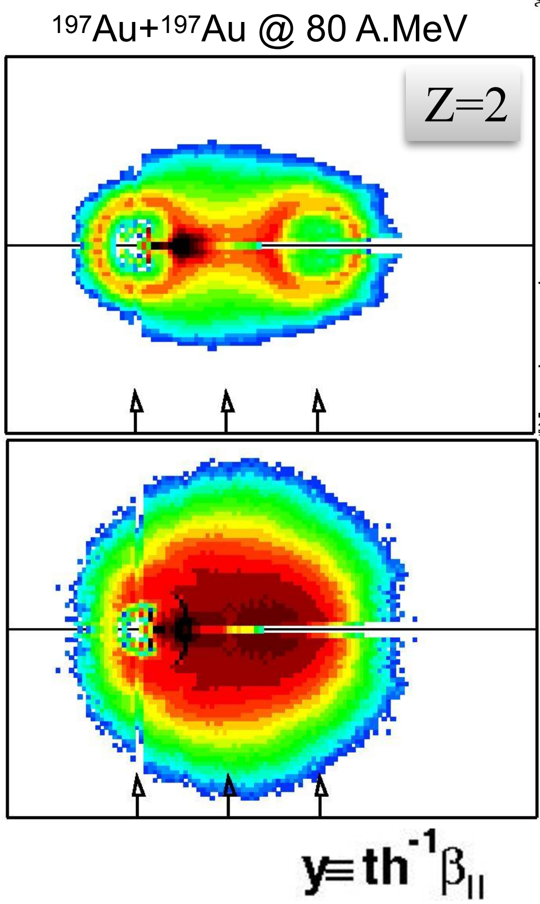
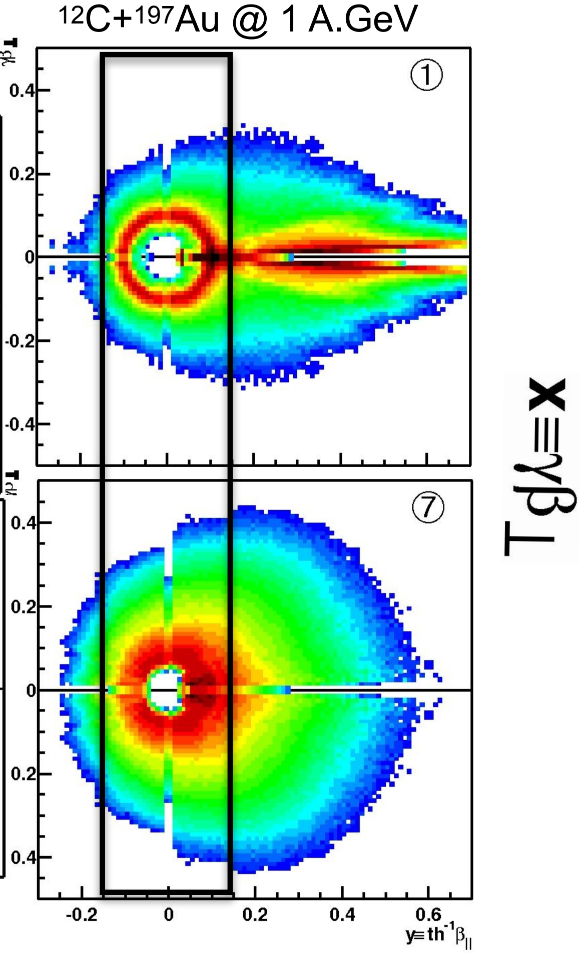
Focus on target spectator fragmentation of $^{112/124}$Sn bombarded with $^{12}$C @ 300, 600A MeV





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

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- 2 different projectile and/or target isotopes: (1) = $^{112}$Sn, (2) = $^{124}$Sn different targets.

➠ yield ratios scaling like (macrocanonical assumption)

$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C.\exp(\alpha N + \beta Z)$

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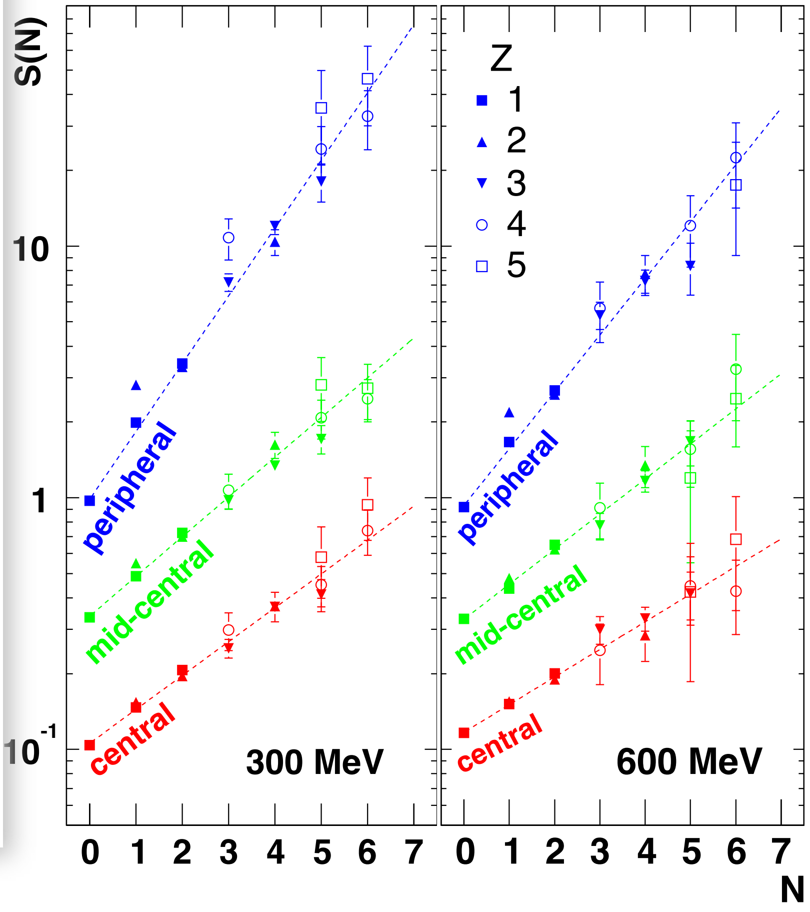
INDRA-ALADiN data
Target spectator decay $^{12}$C + $^{112,124}$Sn



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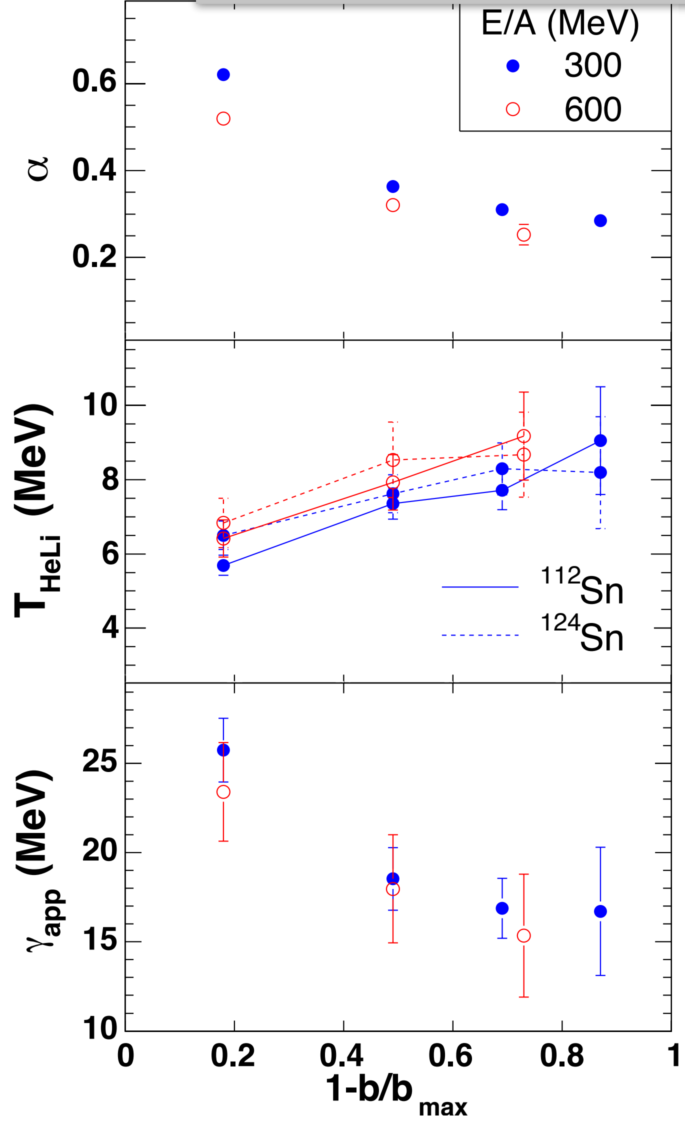

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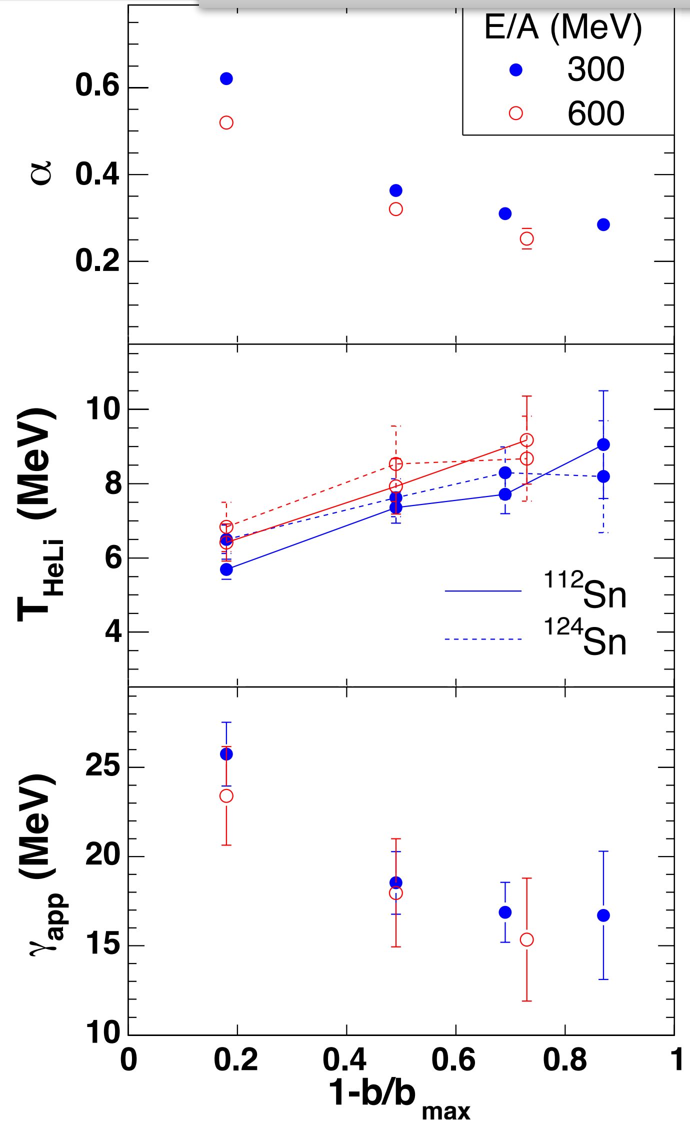

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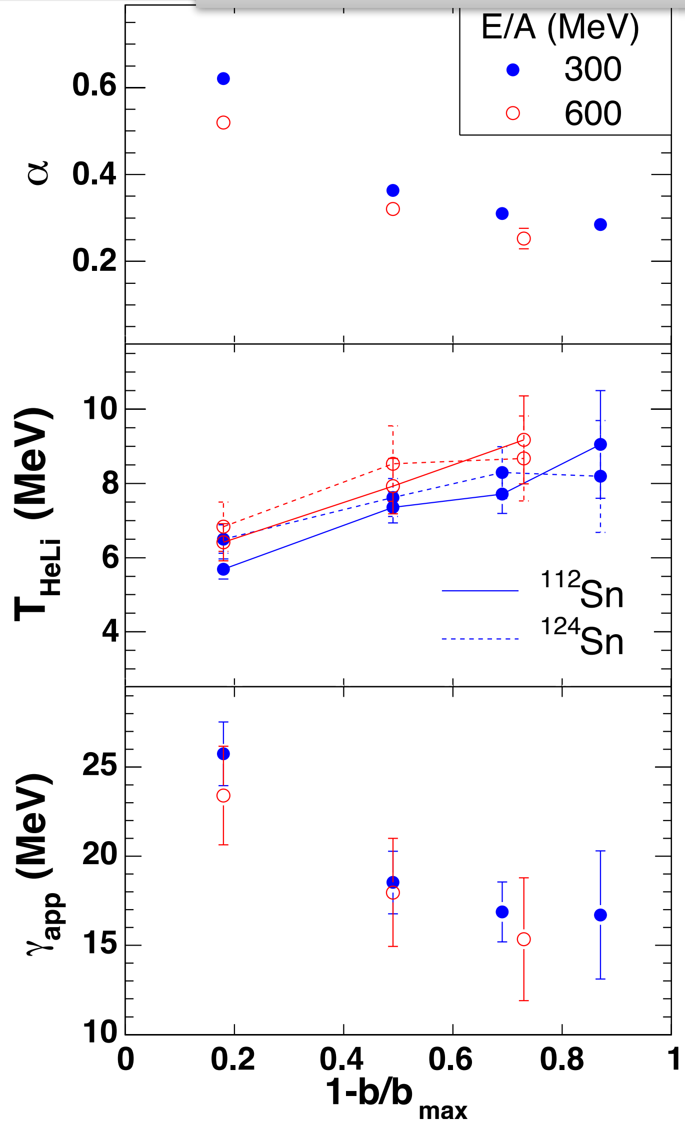

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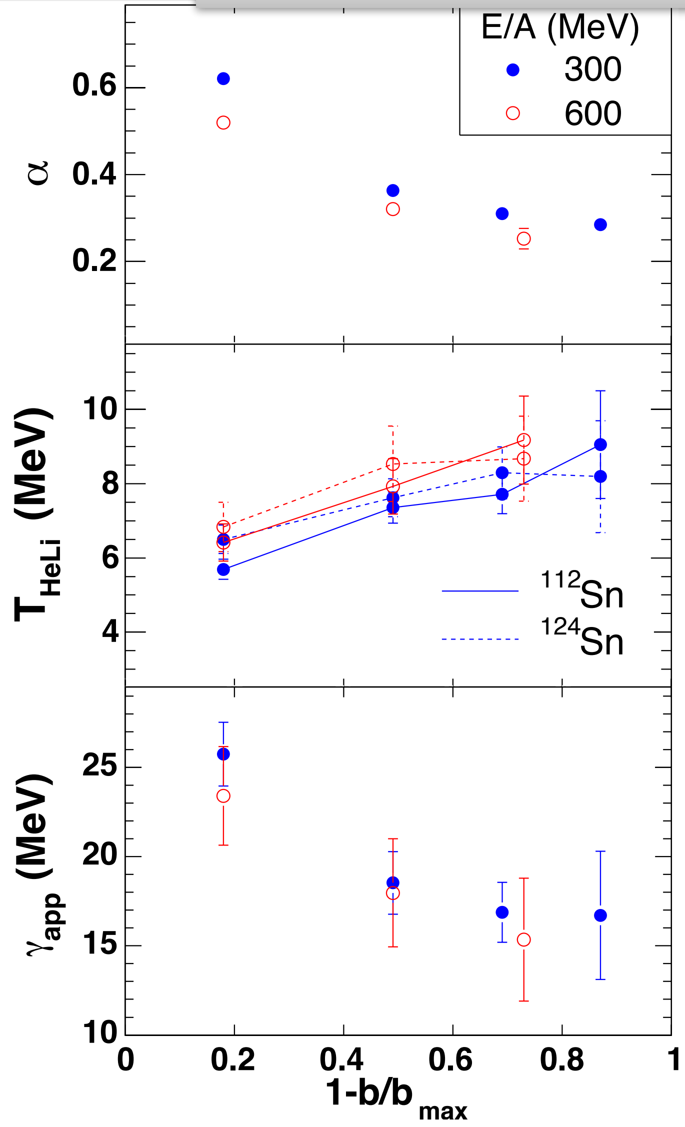

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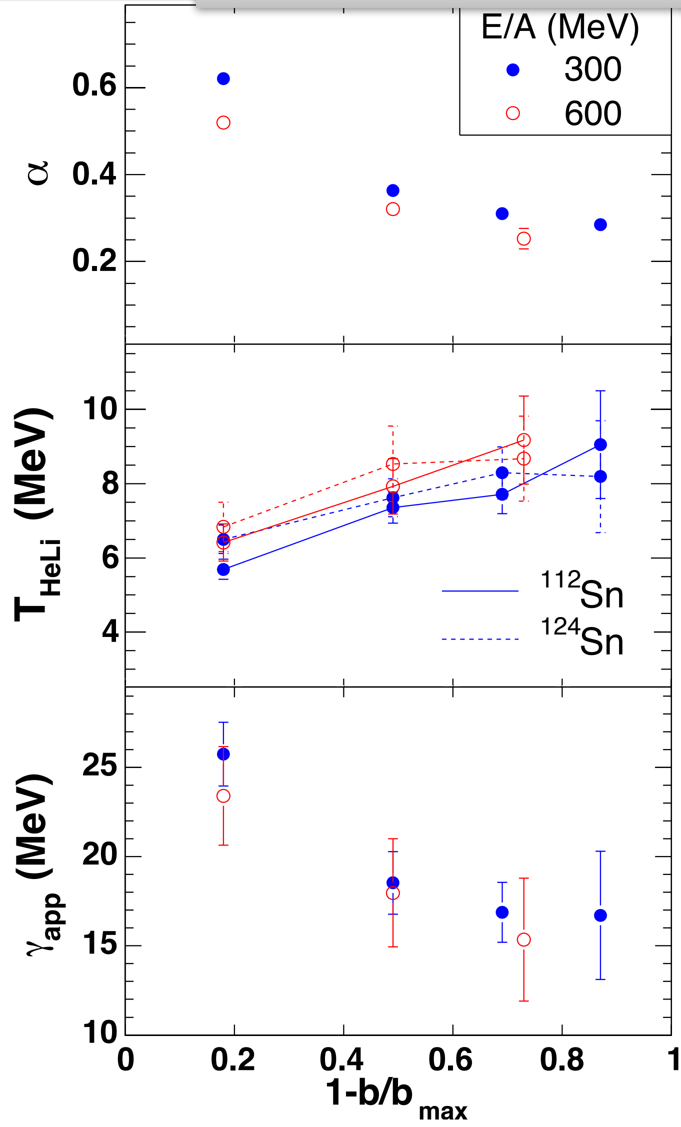
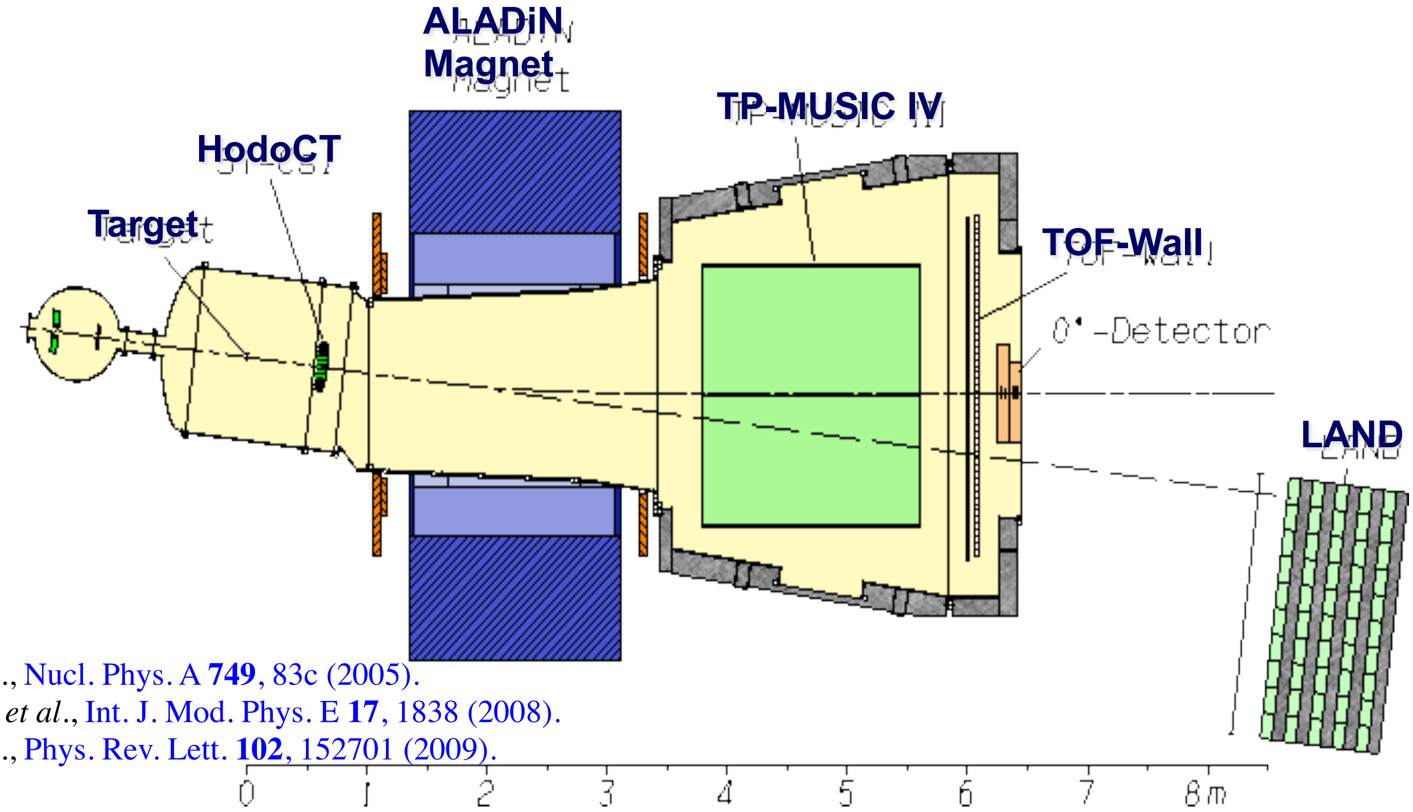


See Quentin Fable's poster

# Isotopic method: sub-saturation densities ALADiN

## The S254 experiment (2003)



C. Sfienti *et al.*, Nucl. Phys. A **749**, 83c (2005).
W. Trautmann *et al.*, Int. J. Mod. Phys. E **17**, 1838 (2008).
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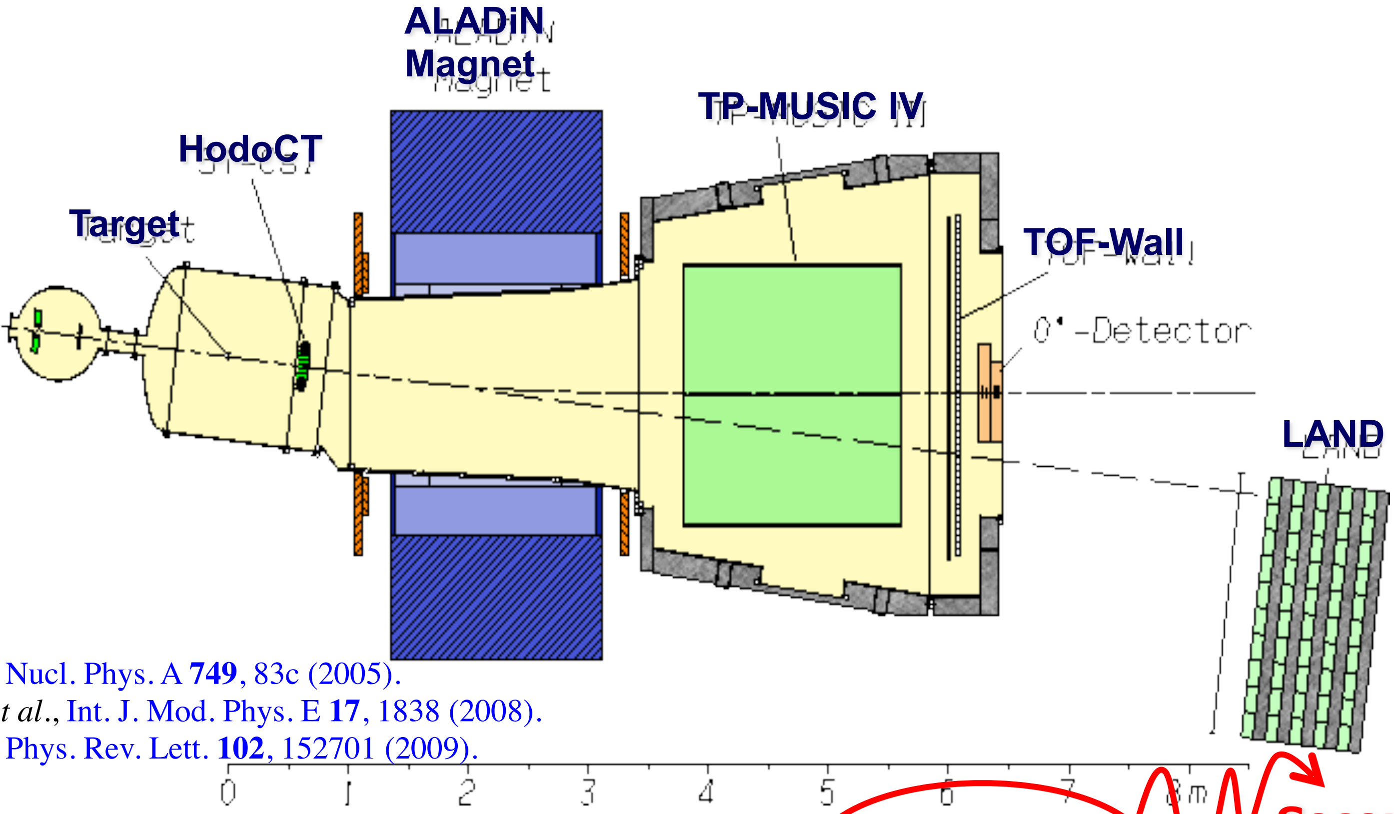

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Neutron rich/poor projectiles: $^{197}Au, ^{124}Sn, ^{124}La, ^{107}Sn$

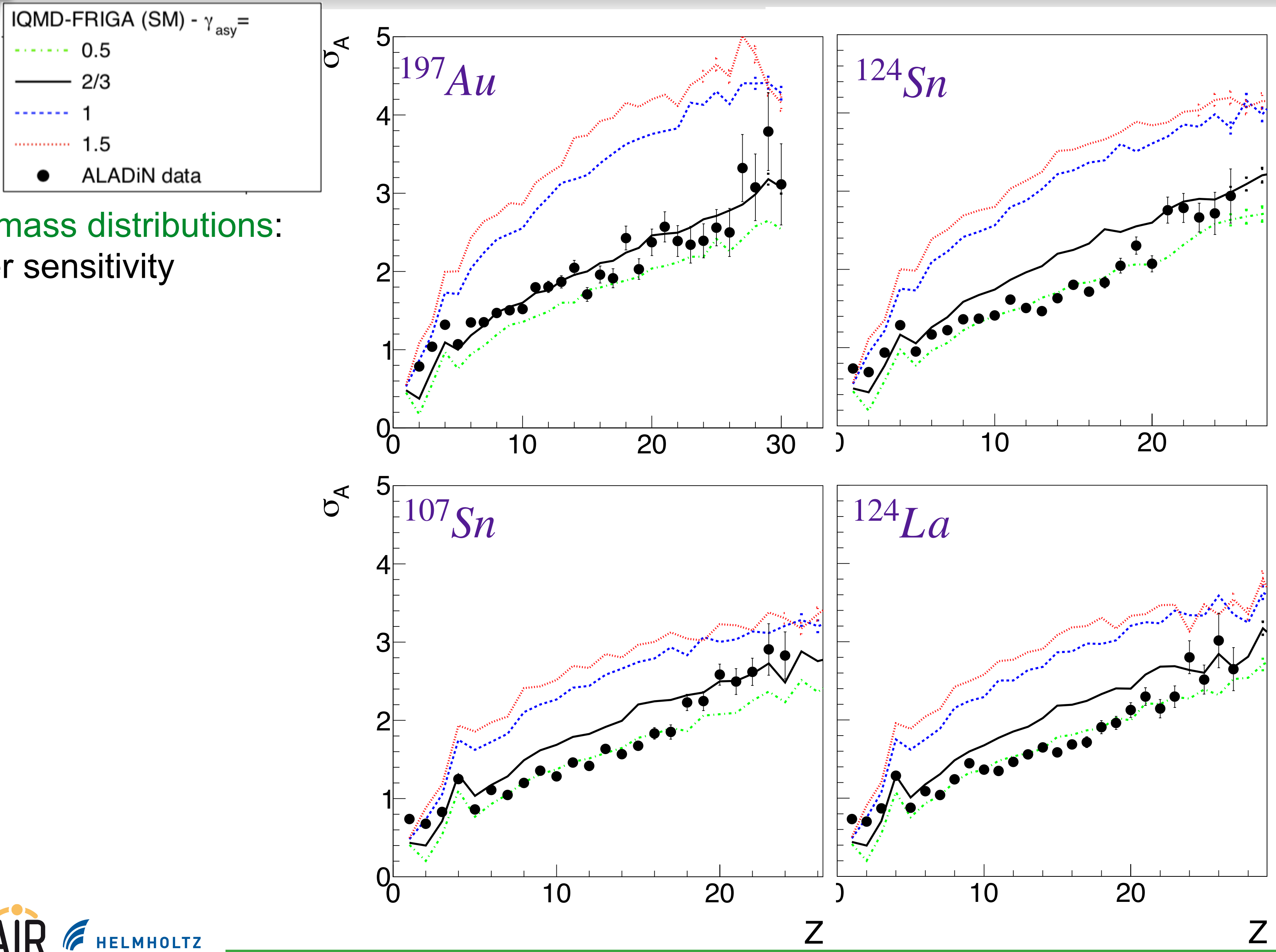
**Secondary Beams (Low Intensities!)**

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

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

Under submission

Widths of mass distributions:
even larger sensitivity



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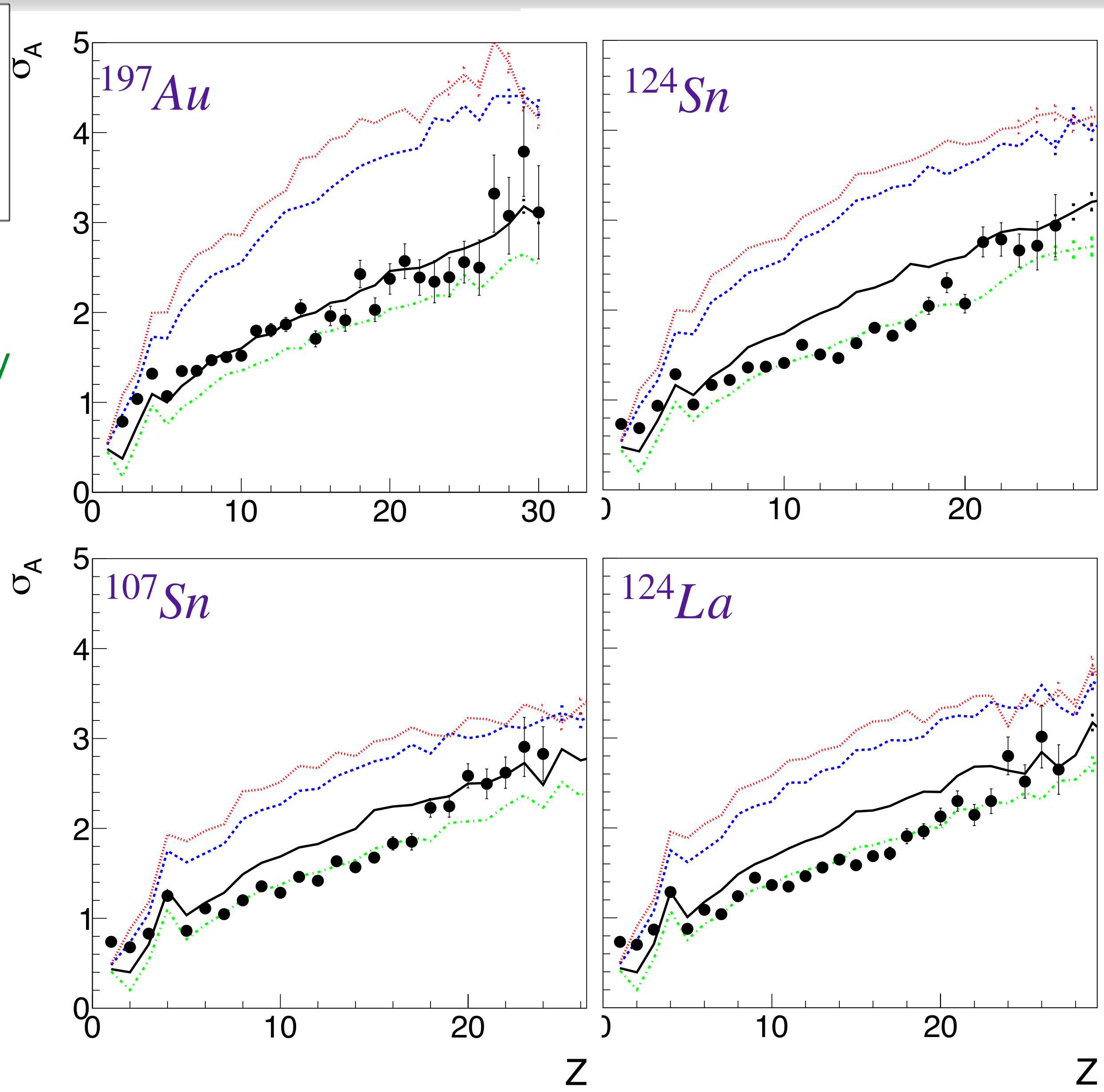
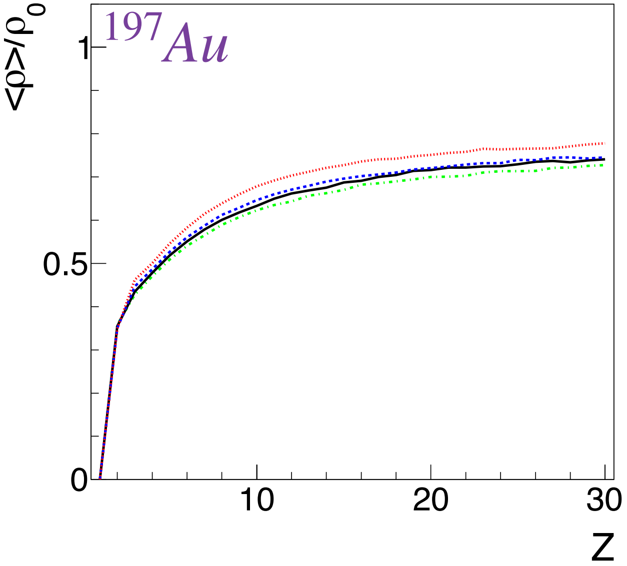


Widths of mass distributions: even larger sensitivity

⚠ probed densities are strongly related to the cluster size:



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

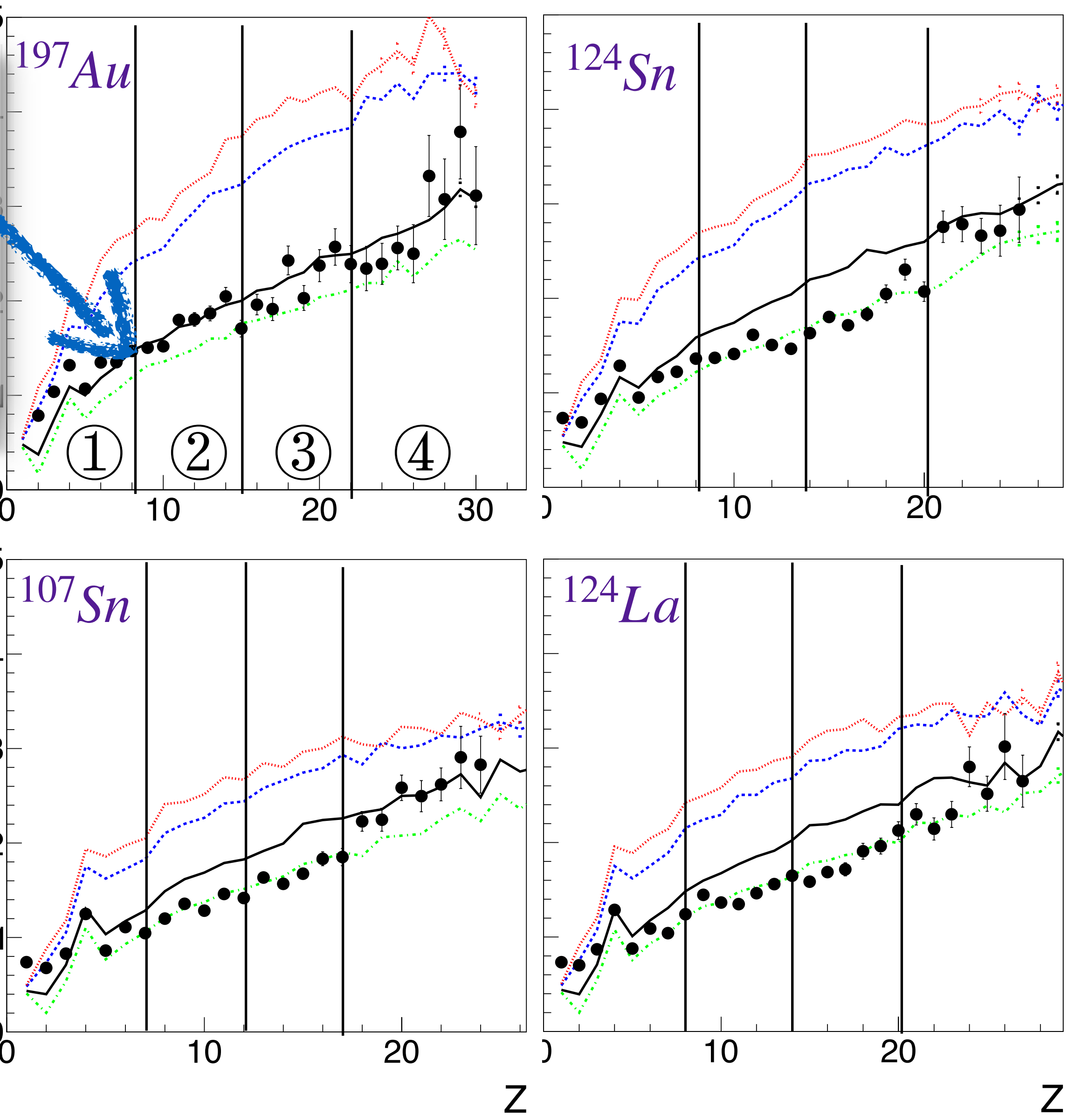
Under submission

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

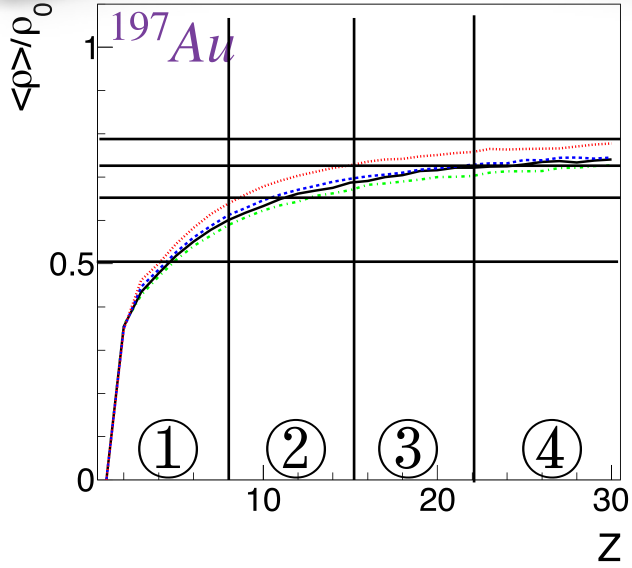
0.5

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

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



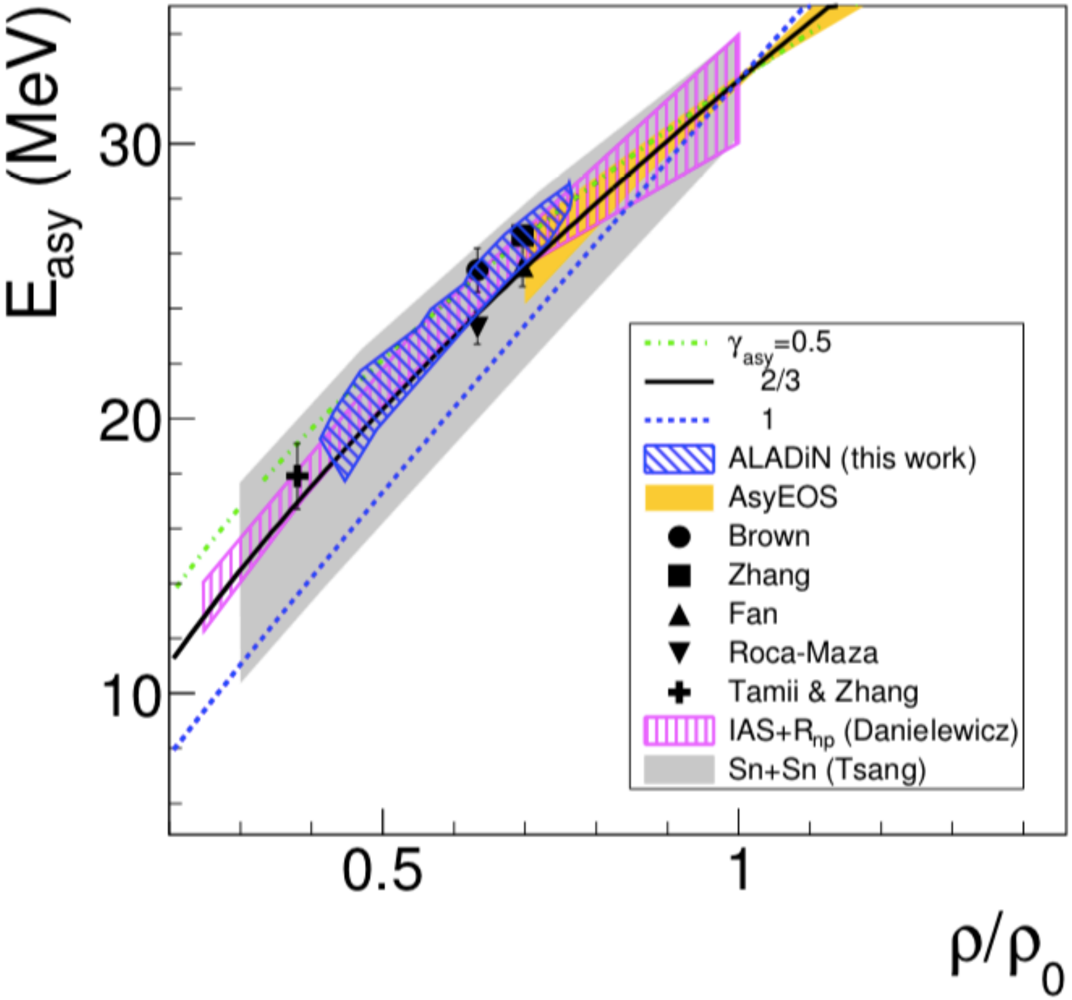
related to the cluster size:



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

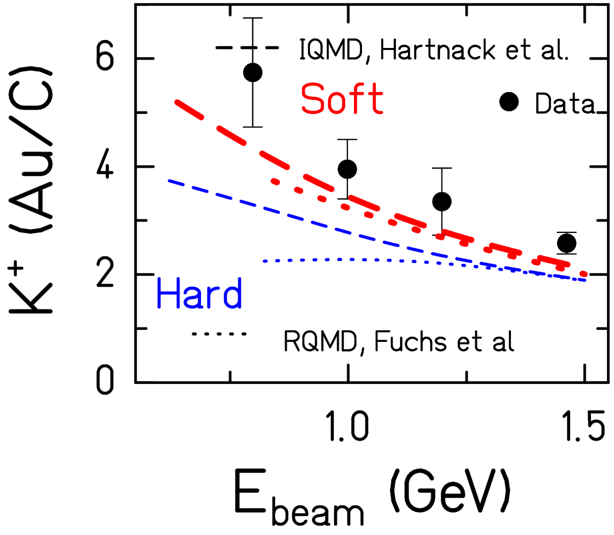
Under submission

- Neutron rich systems are the most sensitive for this type of analysis
  - ALADiN (0.4-0.8 $\rho_0$)
    ➽ $L = 54.2 \pm 4.2$ MeV
    ➽ $\gamma_{asy} = 0.52 \pm 0.06$
- Results are compatible with the most precise nuclear structure findings, with a similar accuracy.



# 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
IQMD: C. Hartnack et al.,
PRL96:012302,2006

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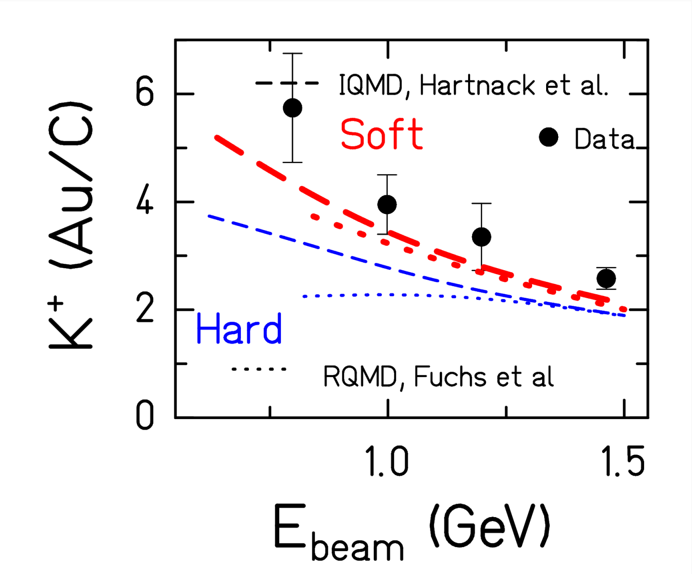

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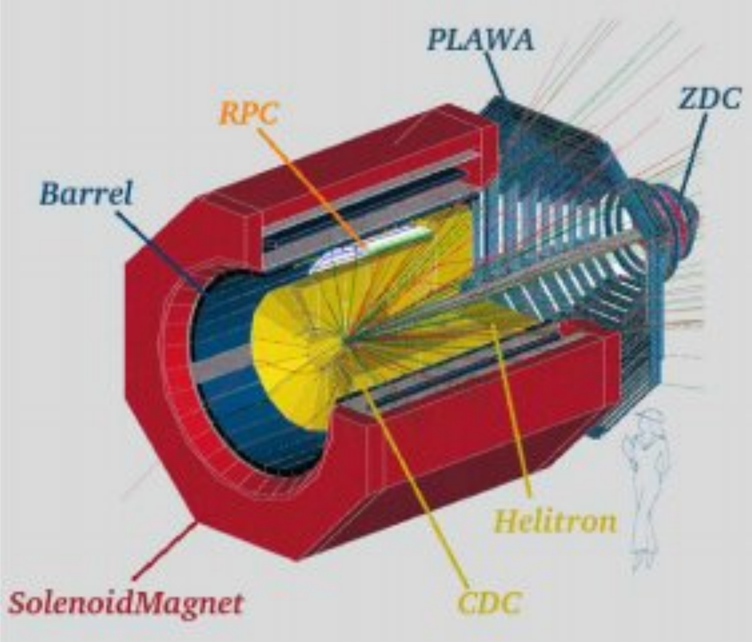
FOPI 1990'-2000' campaigns
Au+Au @ 95 - 1500 A MeV



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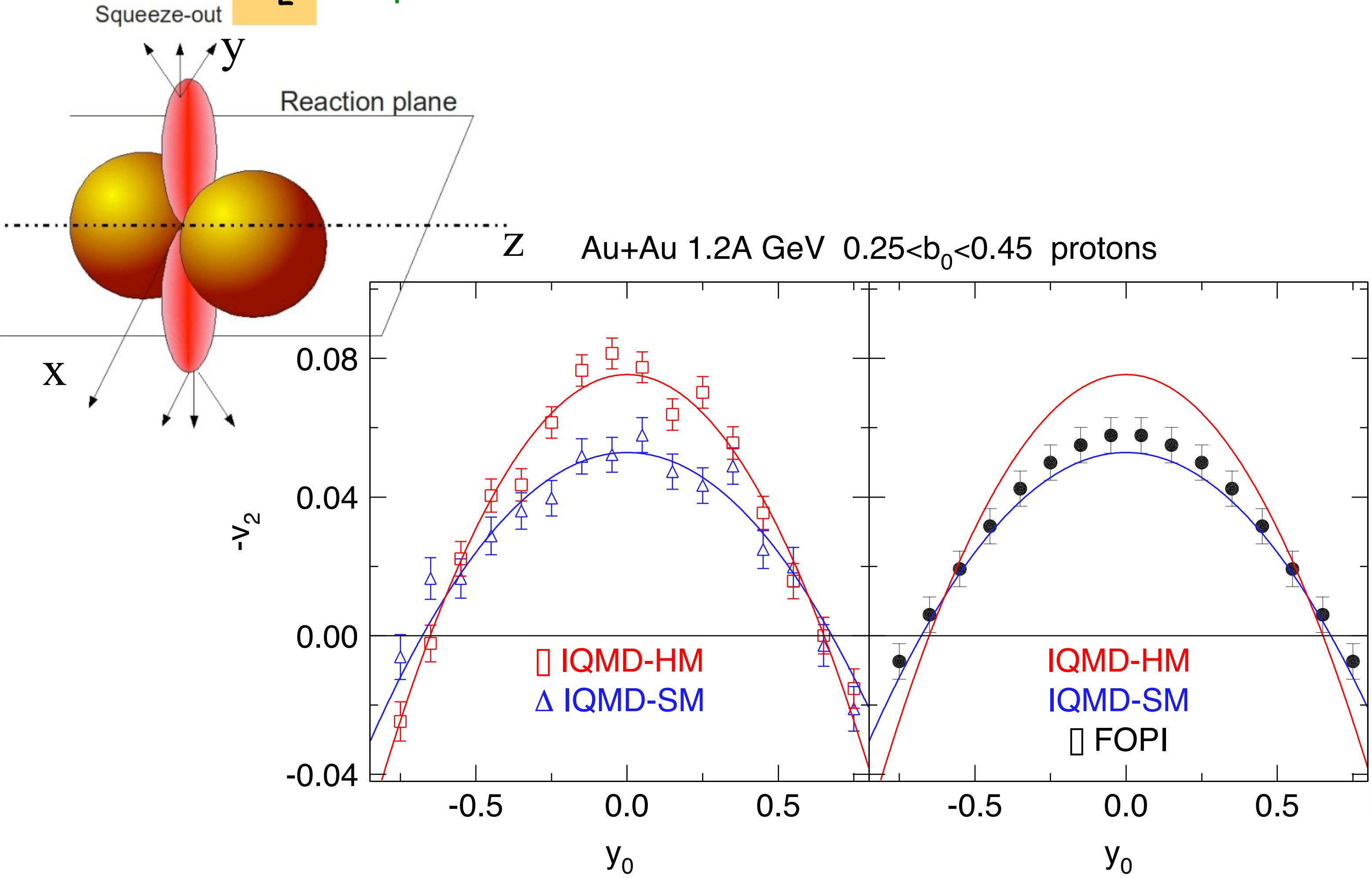
**$V_2$** Elliptic flow



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

With momentum dependant interaction: **compulsory**

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

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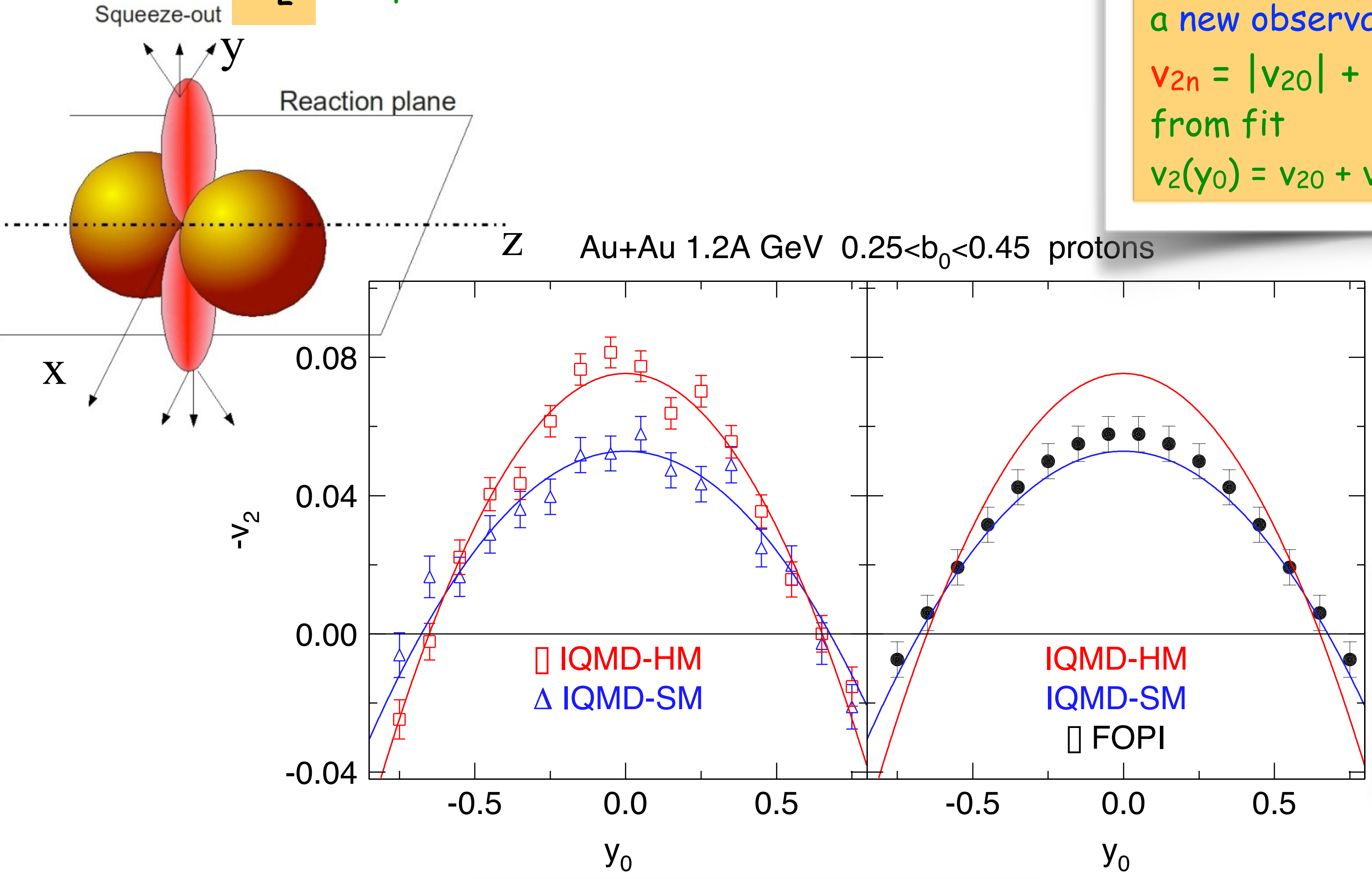

Complete shape of $v_2(y_0)$:
a new observable:
$v_{2n} = |v_{20}| + |v_{22}|$,
from fit
$v_2(y_0) = v_{20} + v_{22} \cdot y_0^2$

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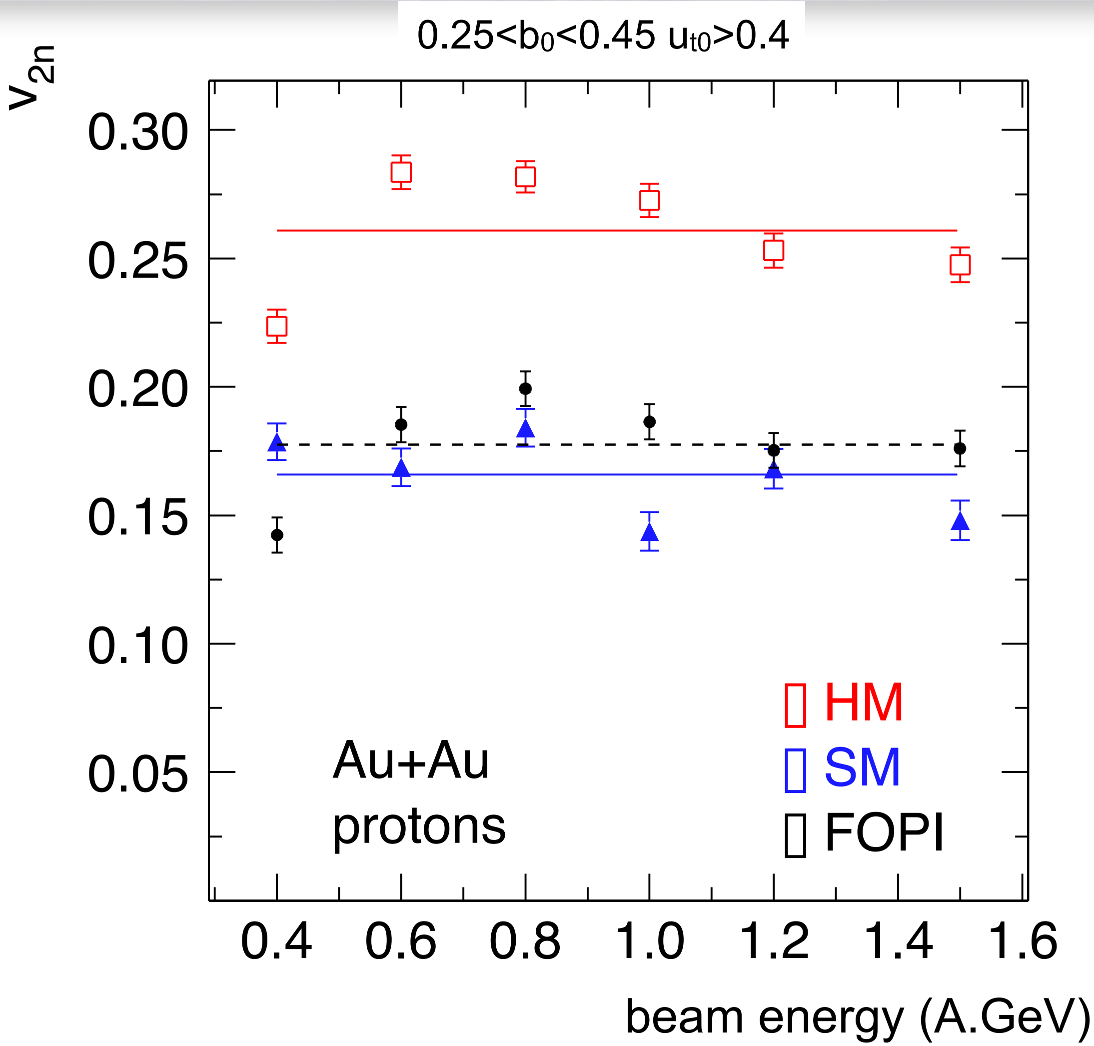
# Elliptic flow method: high densities FOPI and the incompressibility $K_0$

→ $v_{2n}(E_{beam})$ varies by a factor ≈1.6, » measured uncertainty (≈1.1)

→ clearly favors a 'soft' EOS.



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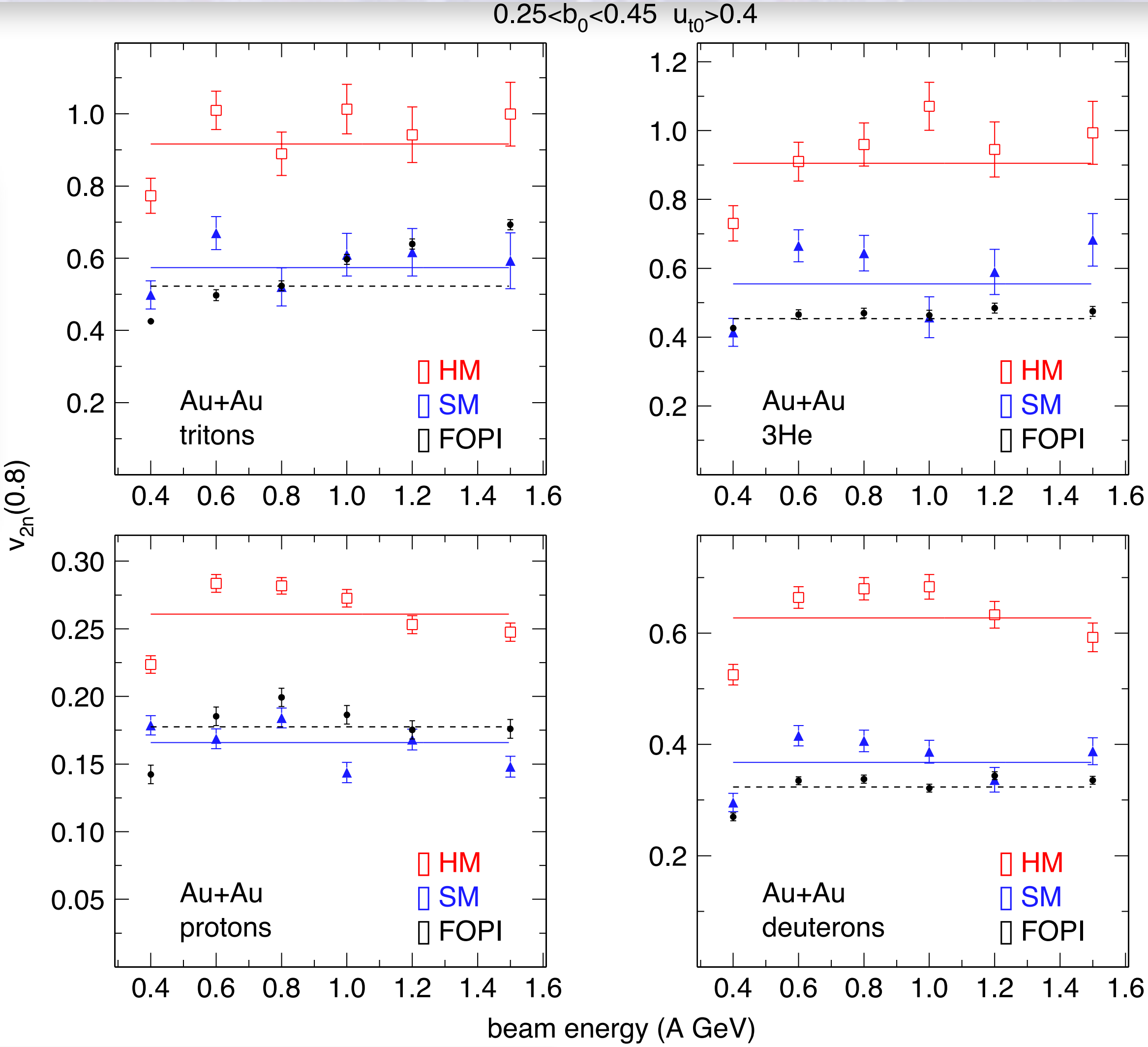

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# Elliptic flow method: high densities FOPI and the incompressibility $K_0$

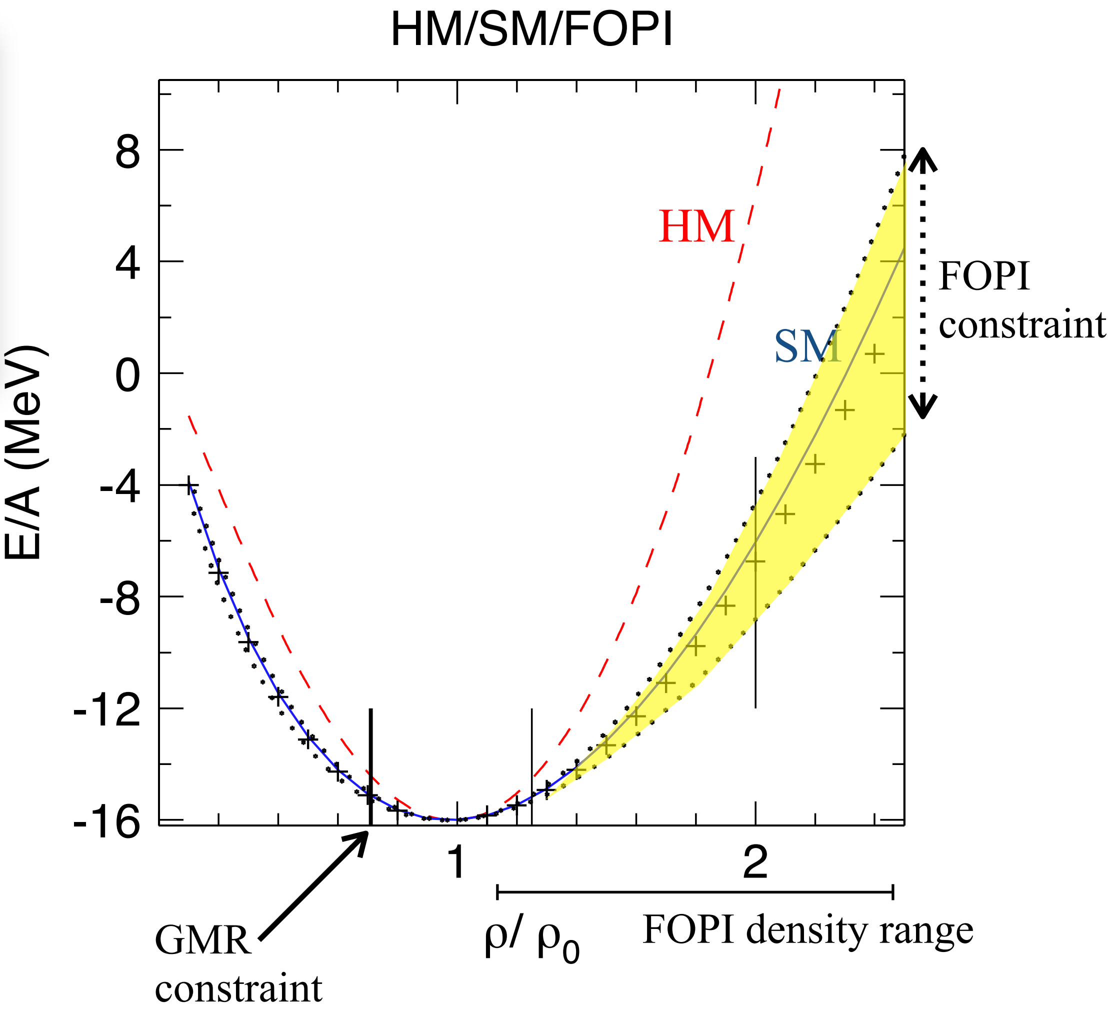
- $K_0$ as from FOPI flow data

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

*[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]*



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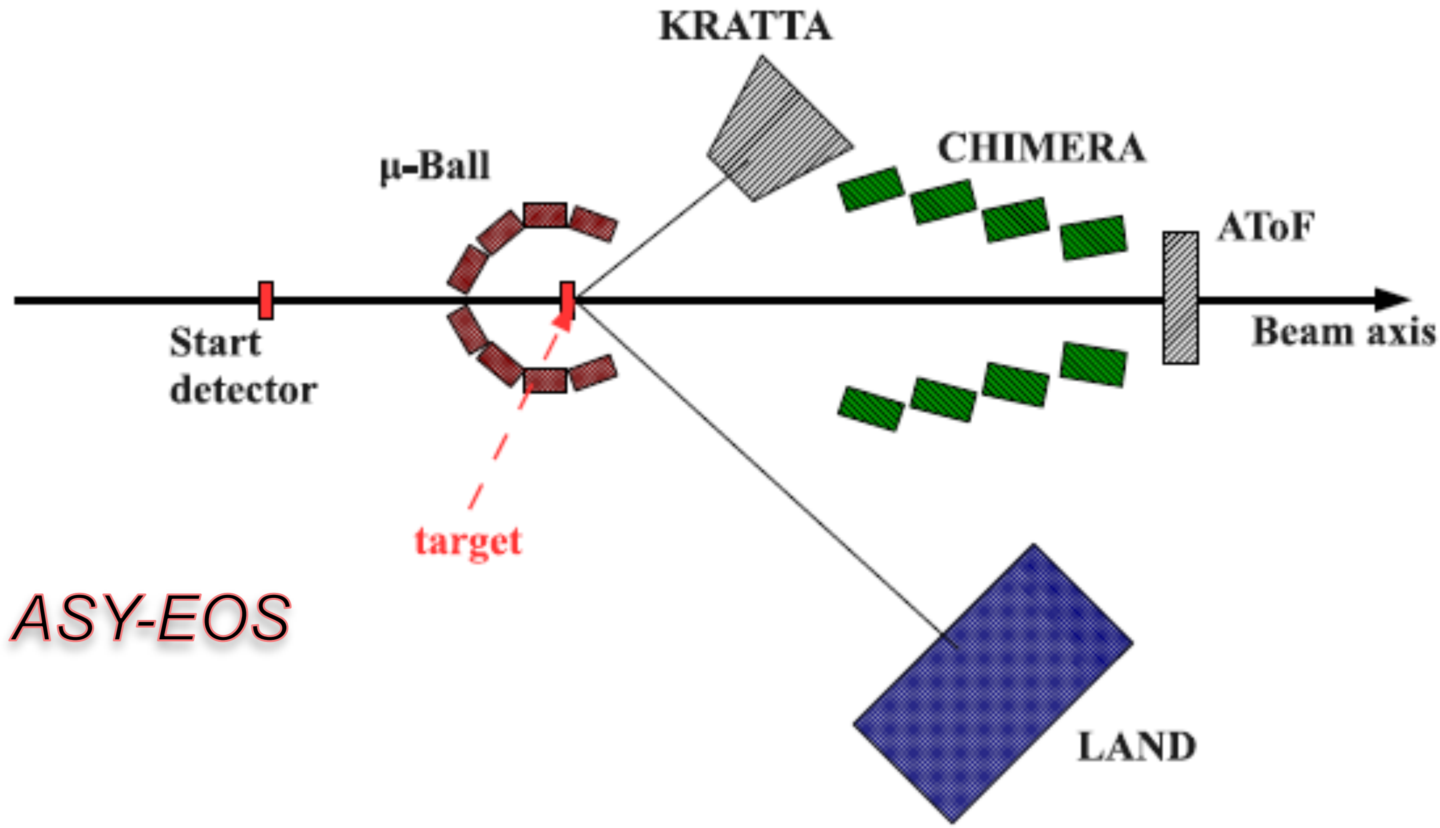
# Elliptic flow method: high densities
# Asy-EOS



*ASY-EOS*

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

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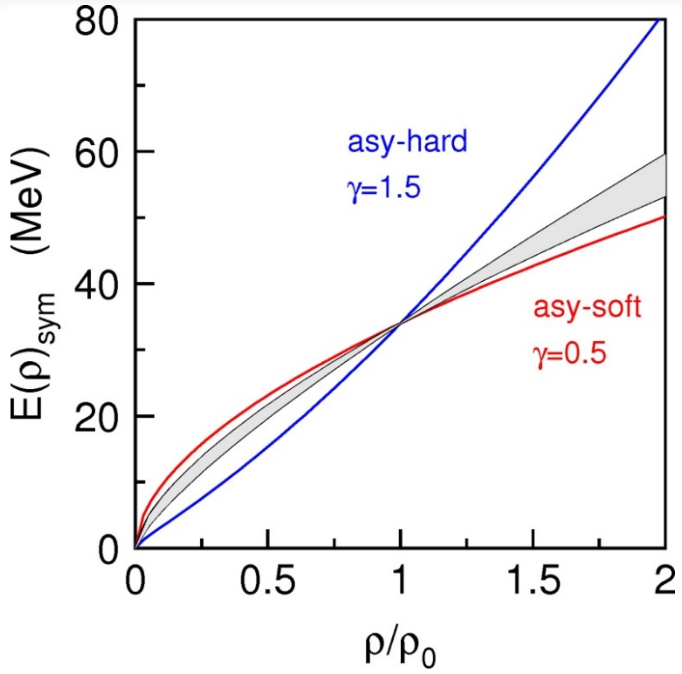
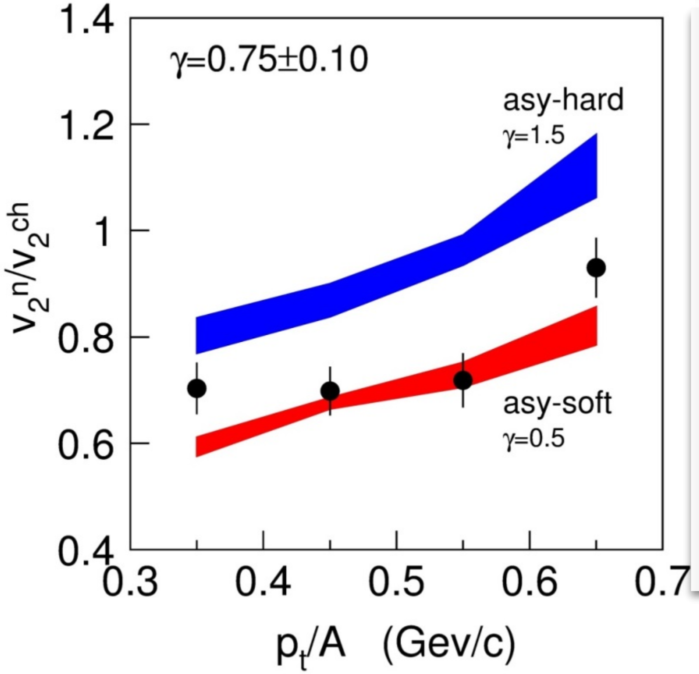




P. Russotto et al., PRC (2017)

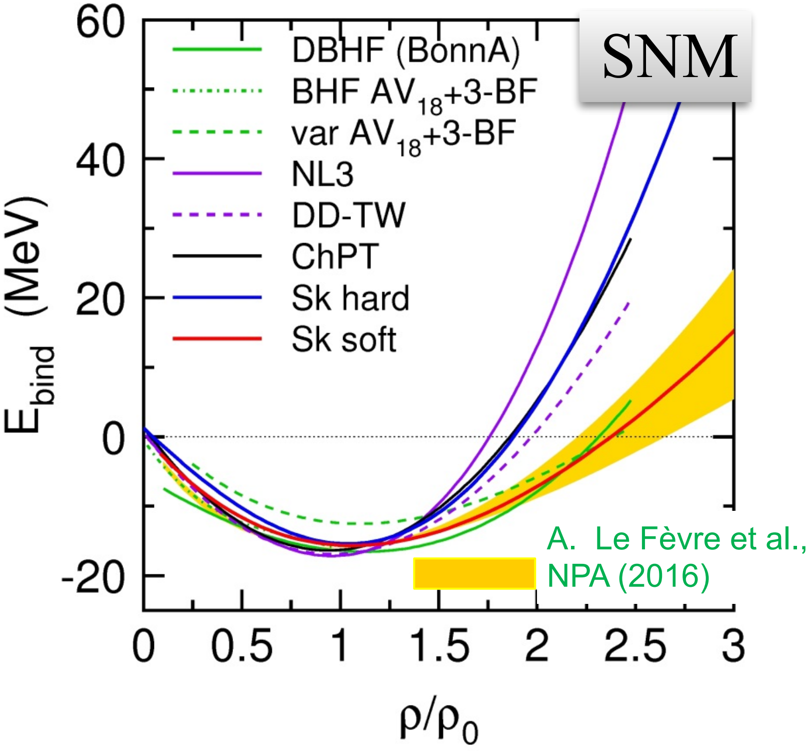
- parametrisation for $E_{asy}$ used in the UrQMD model:

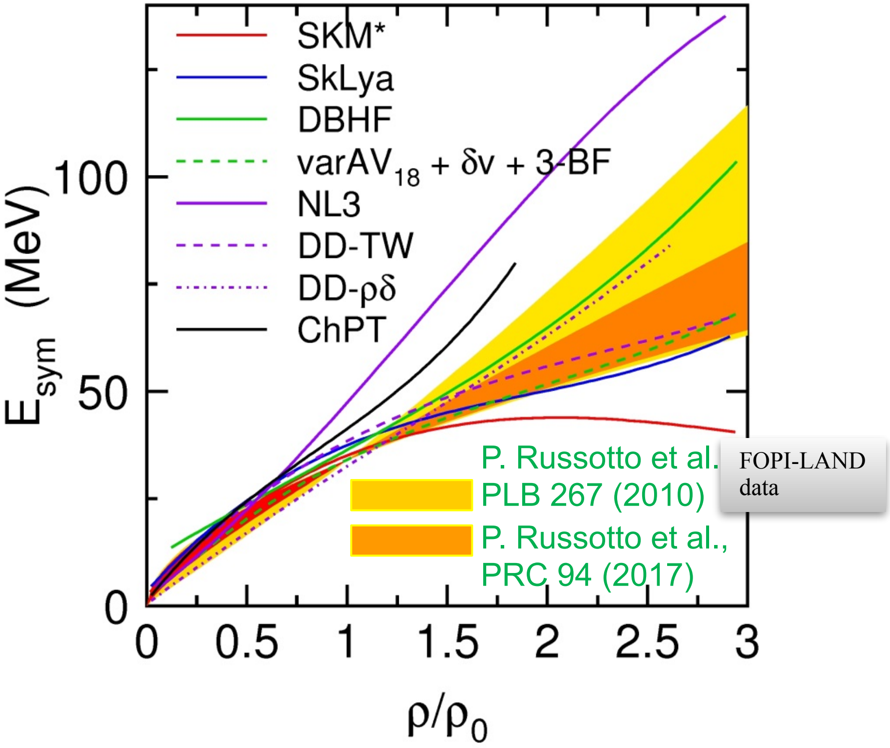
$$E_{asy} = E_{asy}^{pot} + E_{asy}^{kin} = 22MeV\left(\frac{\rho}{\rho_0}\right)^{\gamma} + 12MeV\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

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

# How HICs at GSI compare with recent astrophysical findings.

## Synthesis at high densities



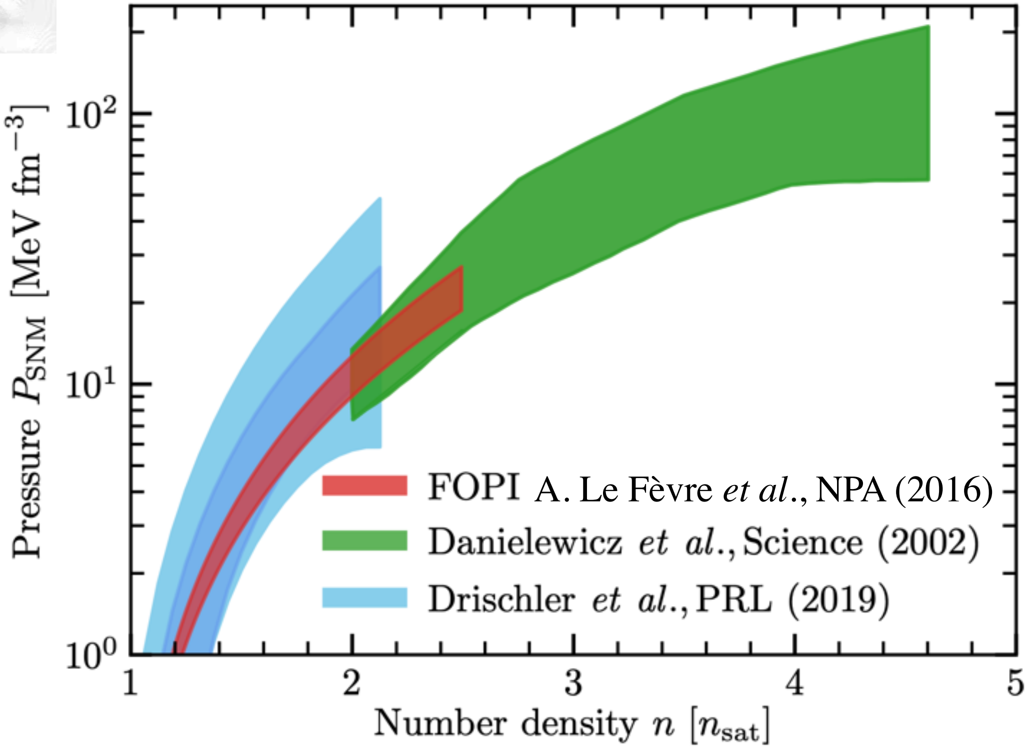


- equation of state of symmetric nuclear matter (SNM)
- asymmetry energy
  - can be constrained by the systematic study of comparison of the flow of neutrons, protons and charged particles

# How HICs at GSI compare with recent astrophysical findings.

How can we combine FOPI, 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$\rho_0$
- L as from ALADiN at 0.7$\rho_0$
- $K_0$ as from FOPI flow data



S. Huth, P.T.H. Pang et al., arXiv:2107.06229 (2021)[nucl-th]

# How HICs at GSI compare with recent astrophysical findings.

SWIFT NEUTRON STAR
COLLISION V. 2

ANIMATION: DANA BERRY
310-441-1735
PRODUCED BY ERICA DREZEK

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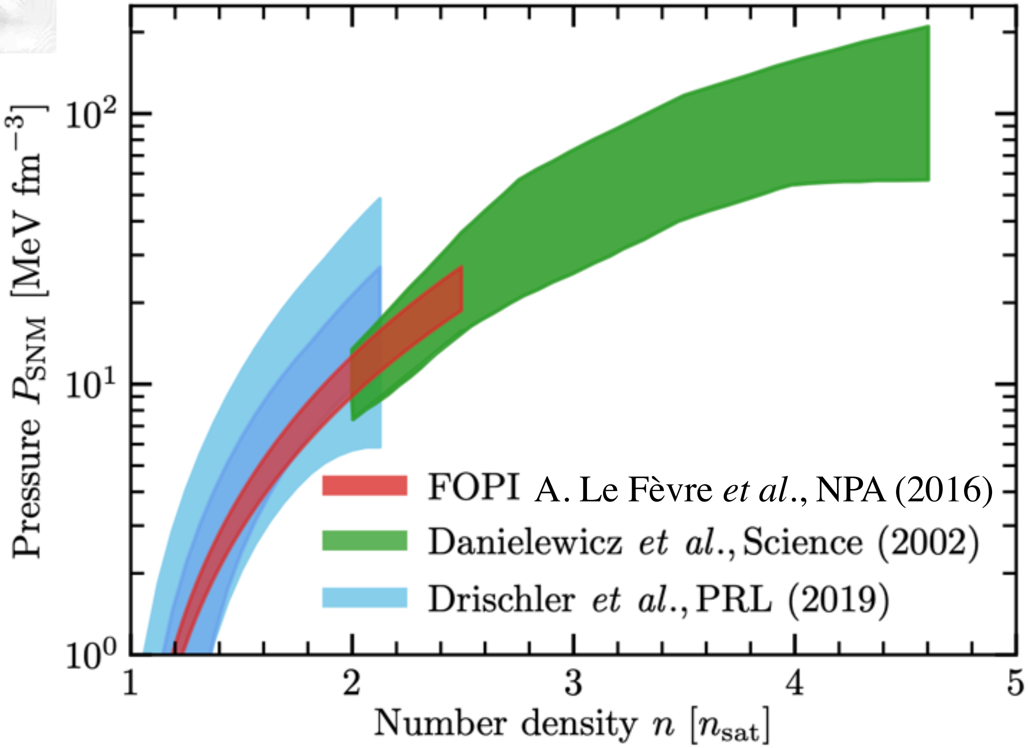

S. Huth, P.T.H. Pang et al., arXiv:2107.06229 (2021)[nucl-th]

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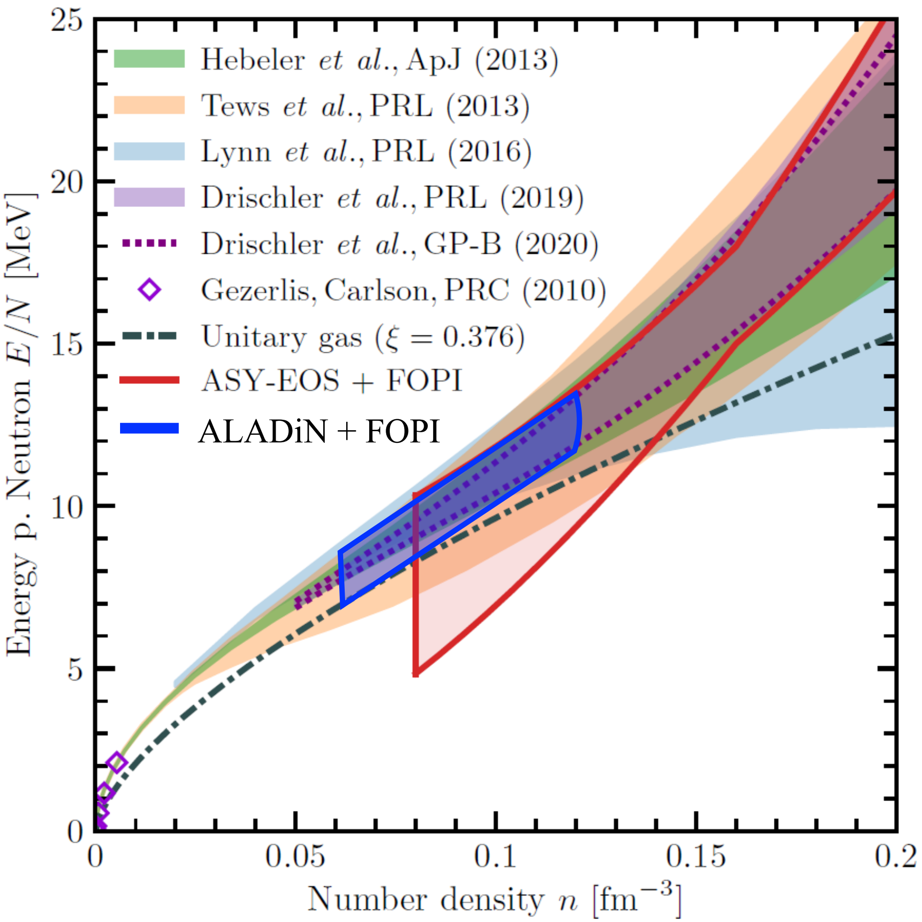

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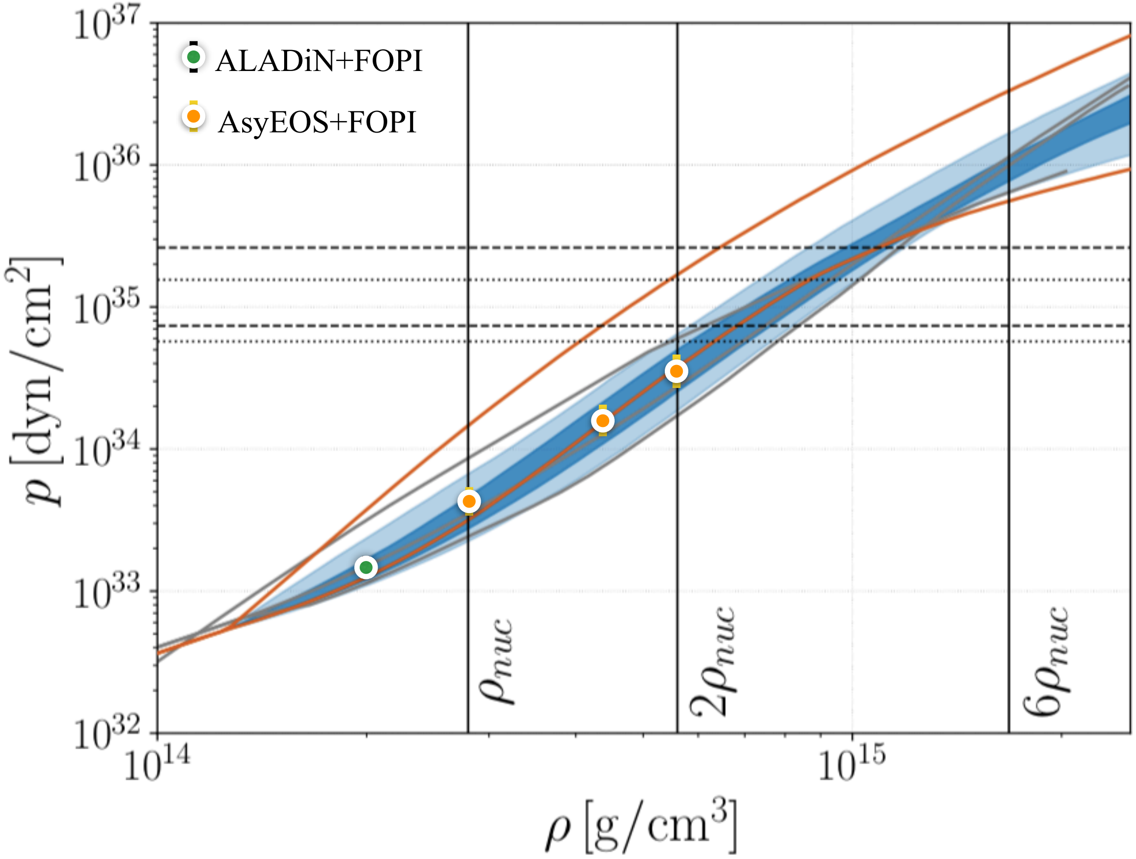
*Gravitational Wave 170817*

*B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration)*



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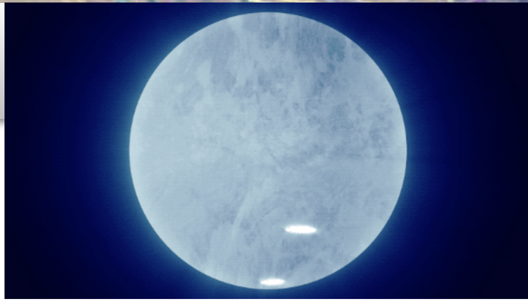

*Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions*

Sabrina Huth, Peter T. H. Pang, Ingo Tews, Tim Dietrich, Arnaud Le Fèvre, Achim Schwenk, Wolfgang Trautmann, Kshitij Agarwal, Mattia Bulla, Michael W. Coughlin, and Chris Van Den Broeck - **arXiv:2107.06229 (2021)[nucl-th]**

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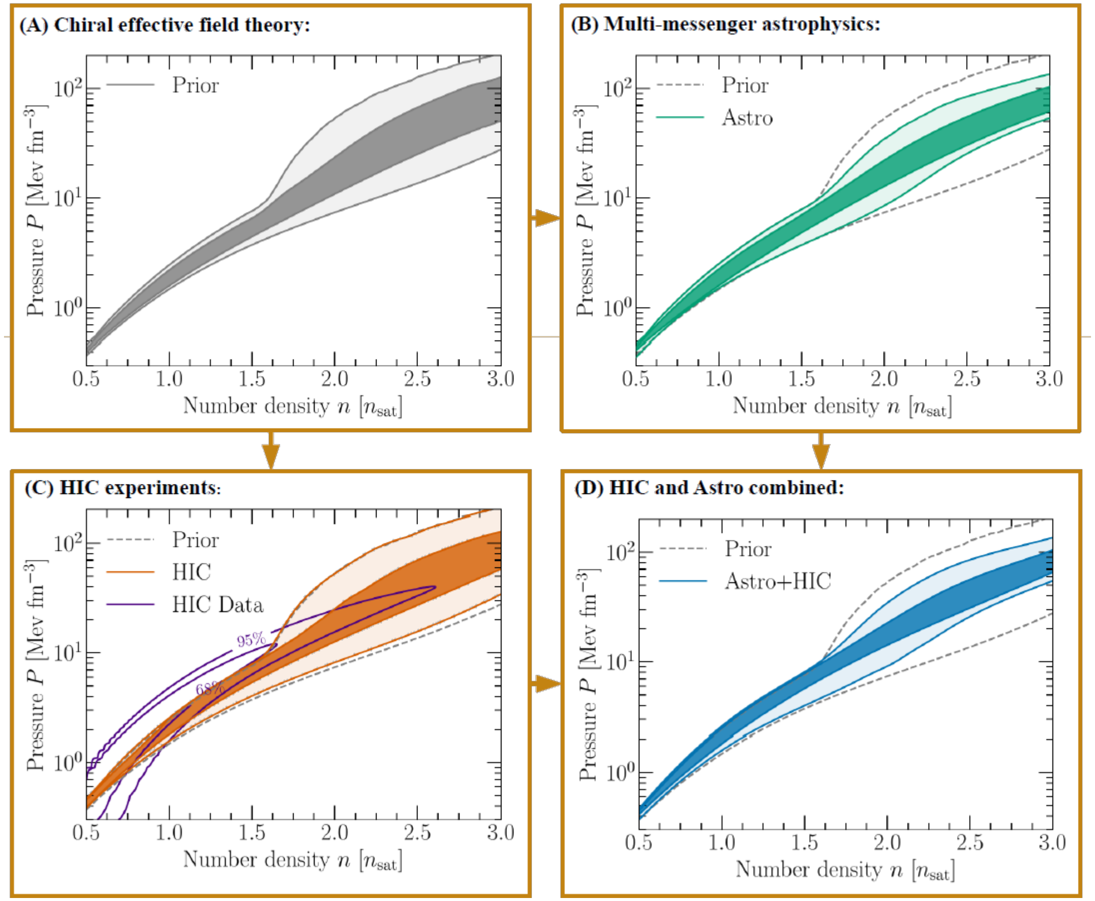

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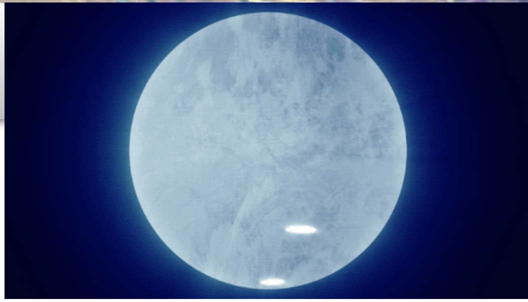

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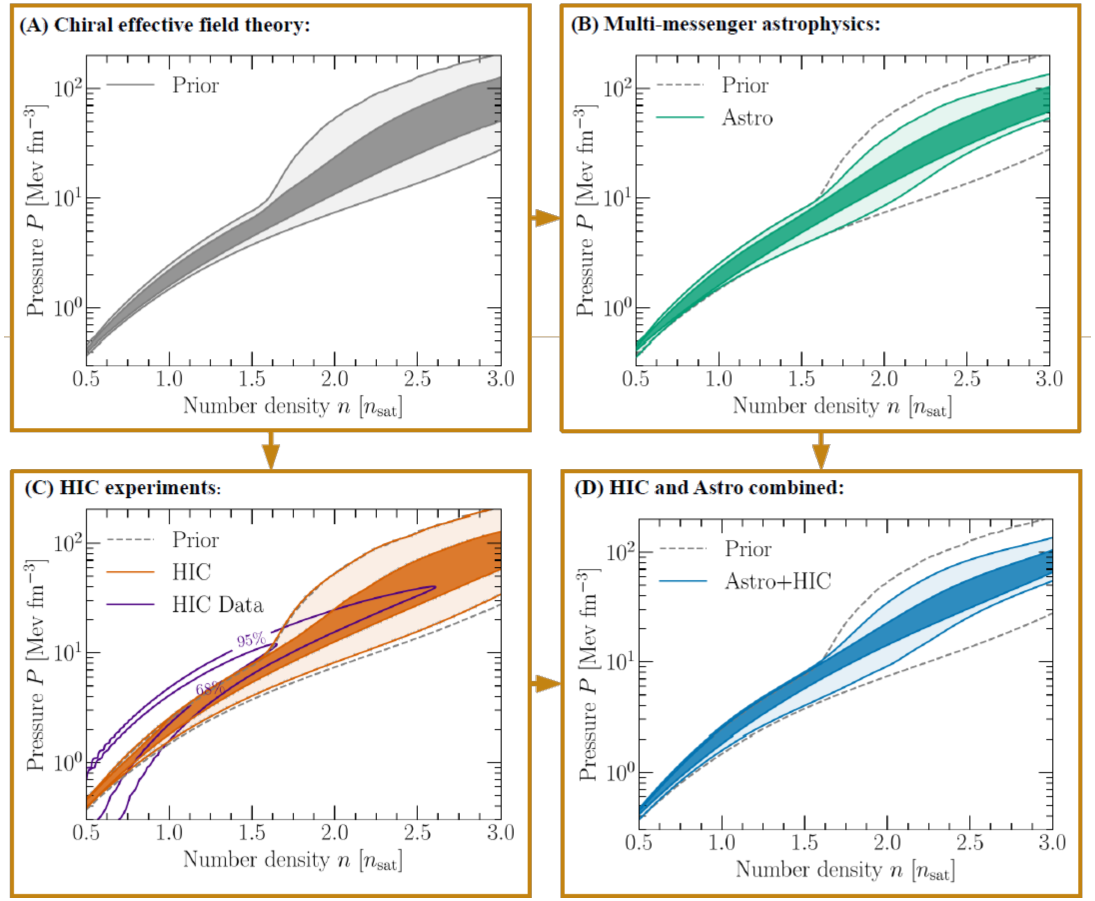

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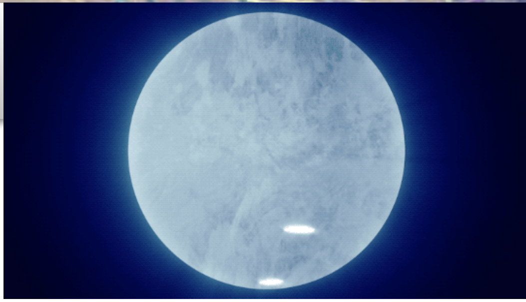

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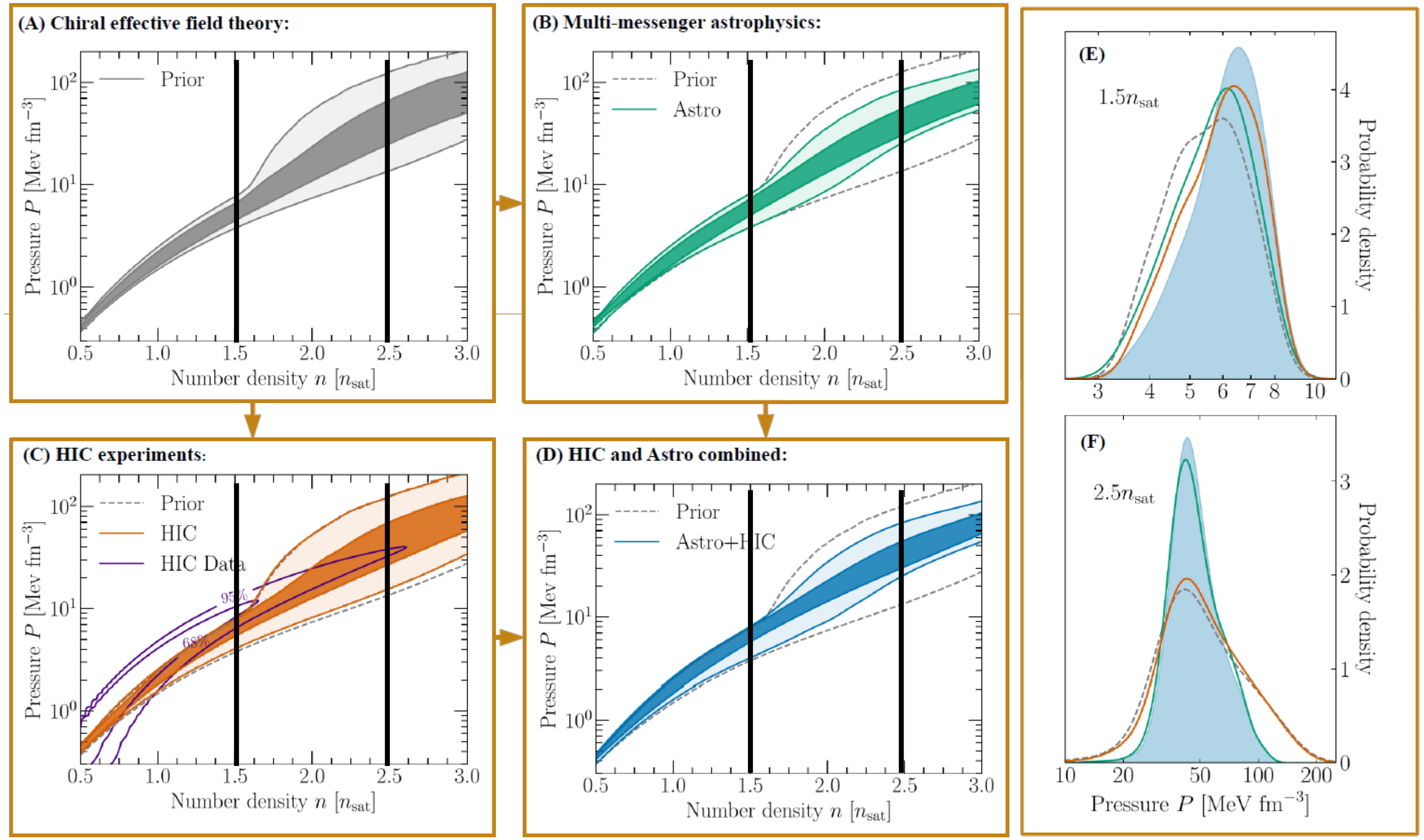

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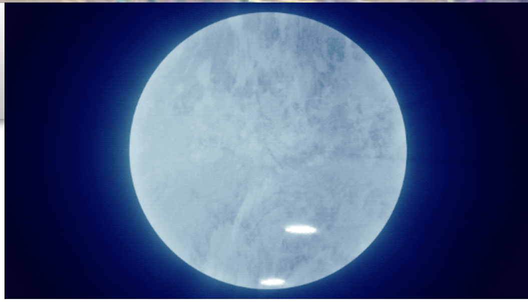

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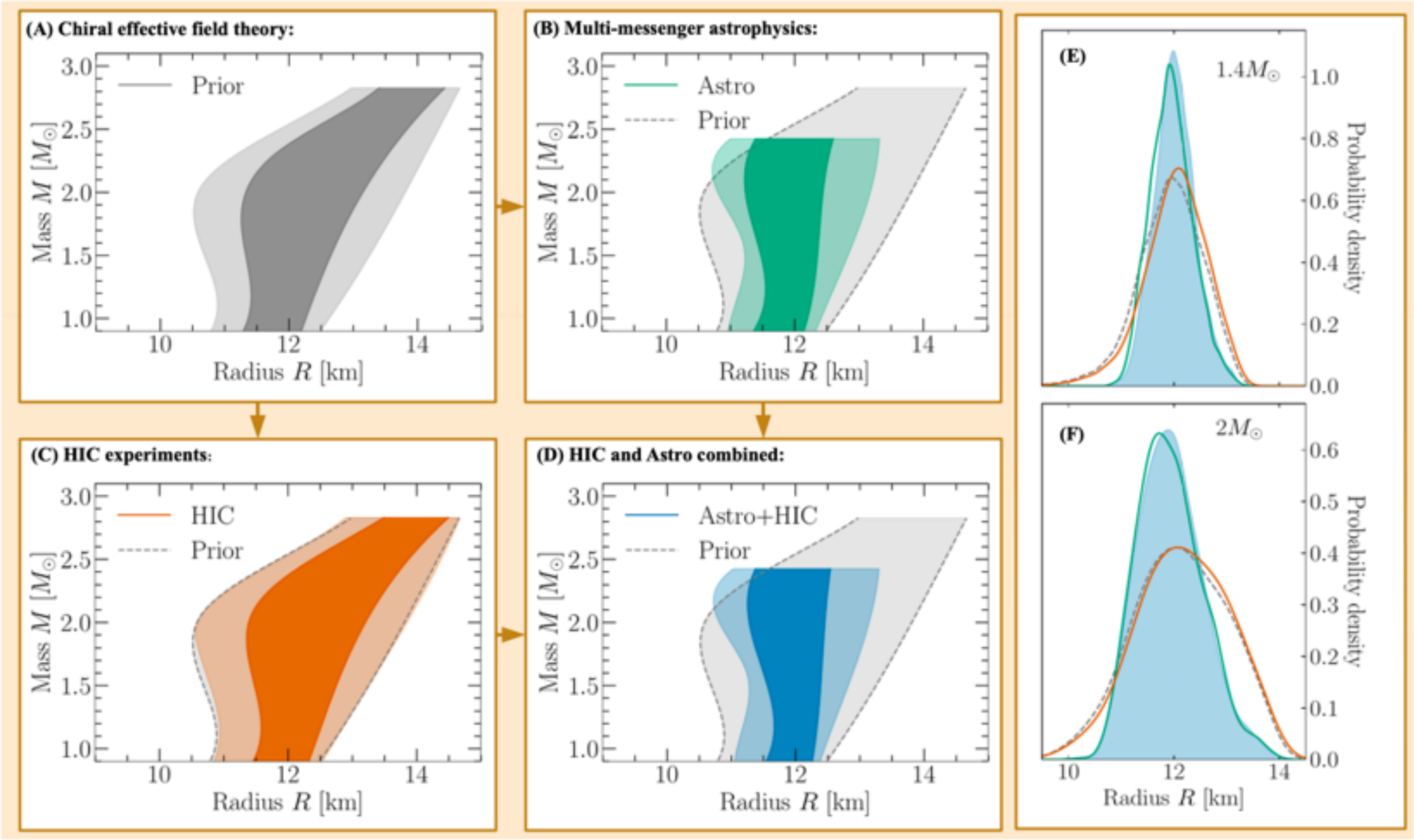

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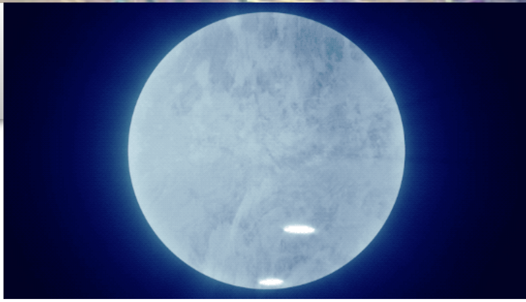

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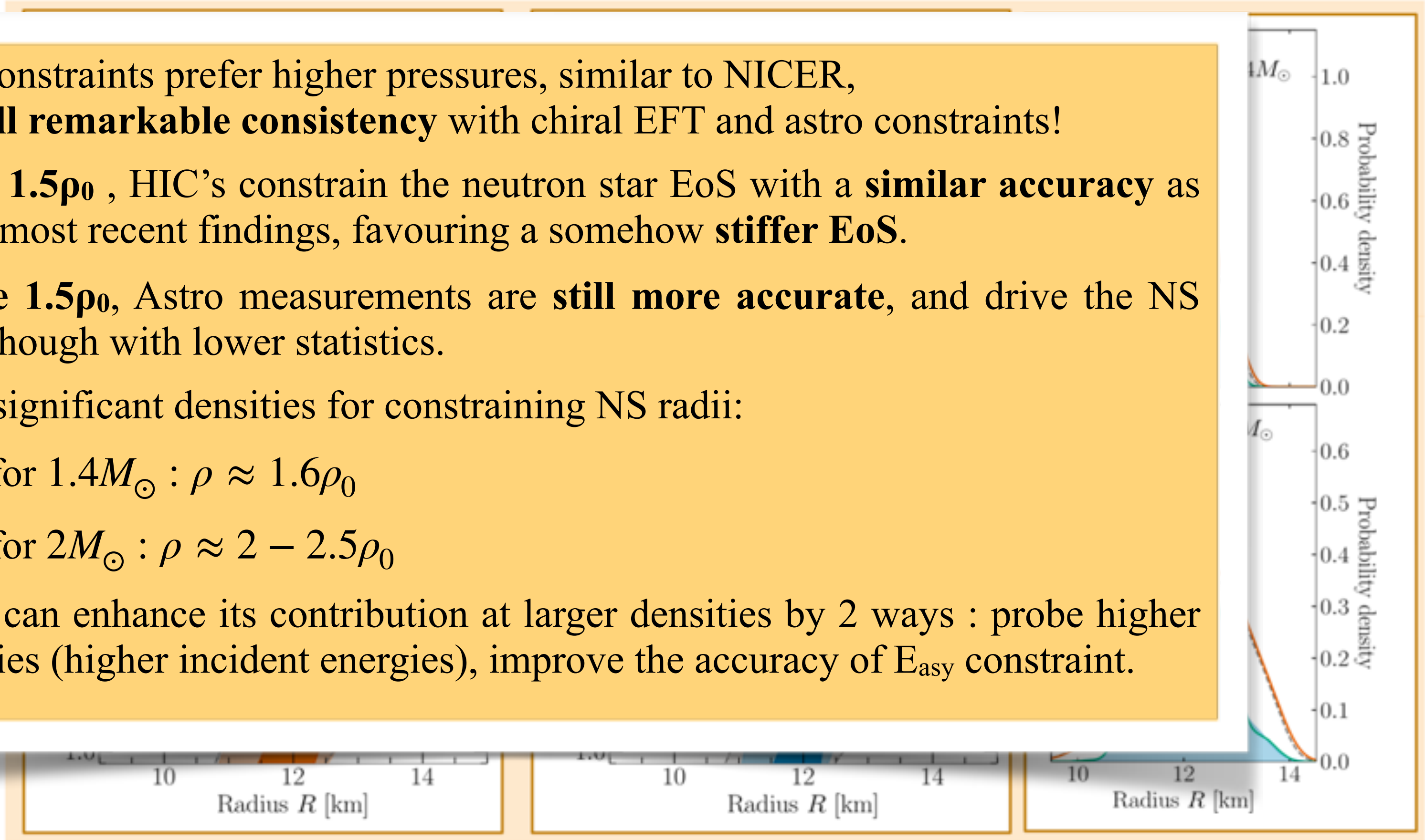
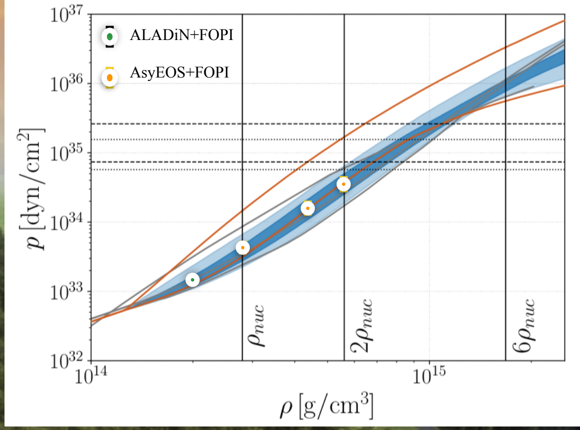
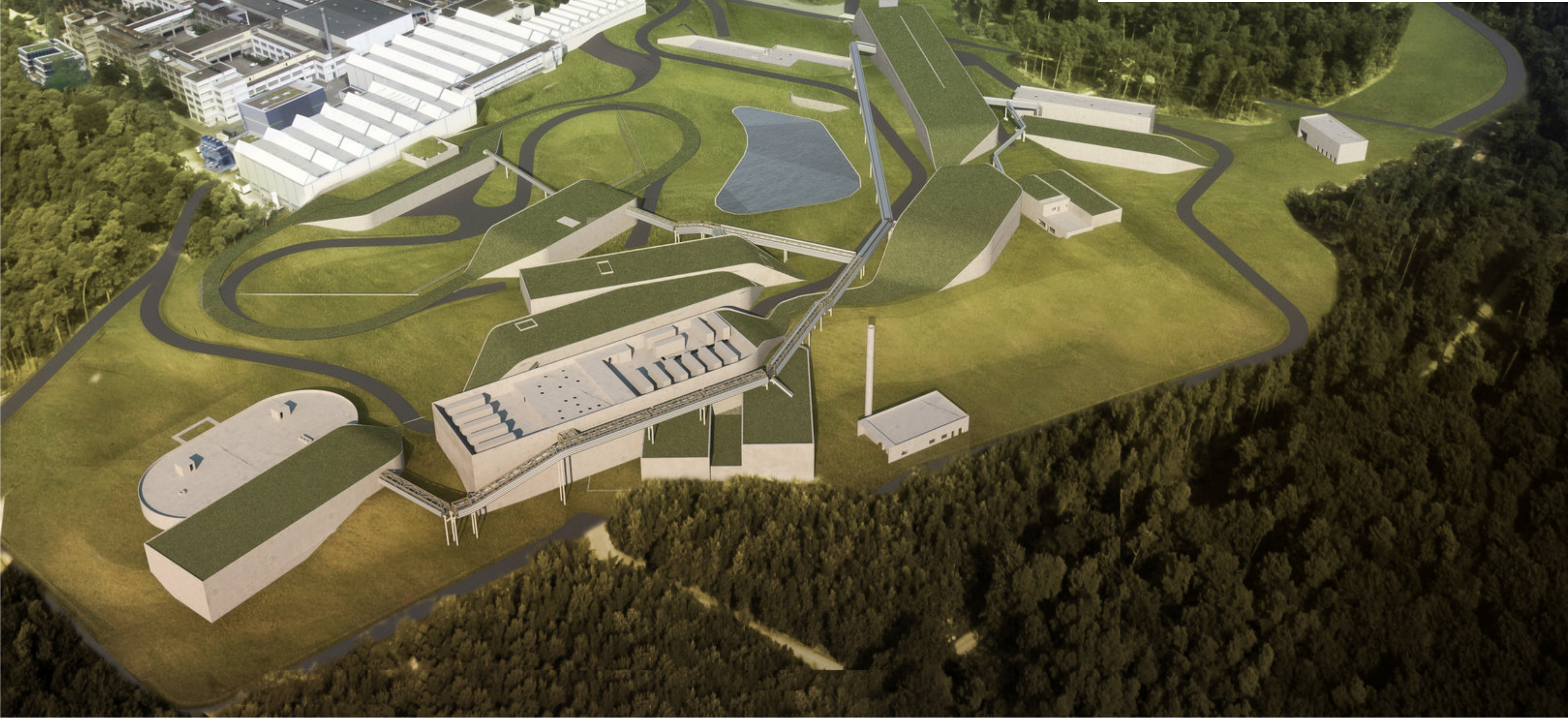


- HIC constraints prefer higher pressures, similar to NICER, **overall remarkable consistency** with chiral EFT and astro constraints!
- **Up to $1.5\rho_0$** , HIC's constrain the neutron star EoS with a **similar accuracy** as Astro most recent findings, favouring a somehow **stiffer EoS**.
- **Above $1.5\rho_0$**, Astro measurements are **still more accurate**, and drive the NS EoS, though with lower statistics.
- Most significant densities for constraining NS radii:
  - for $1.4M_\odot : \rho \approx 1.6\rho_0$
  - for $2M_\odot : \rho \approx 2 - 2.5\rho_0$
- HIC's can enhance its contribution at larger densities by 2 ways : probe higher densities (higher incident energies), improve the accuracy of $E_{asy}$ constraint.

# Conclusion and perspectives





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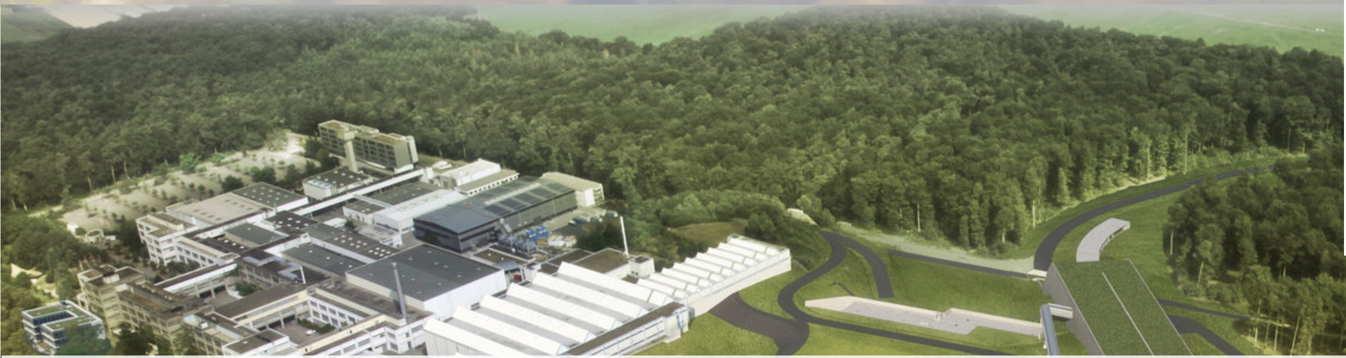

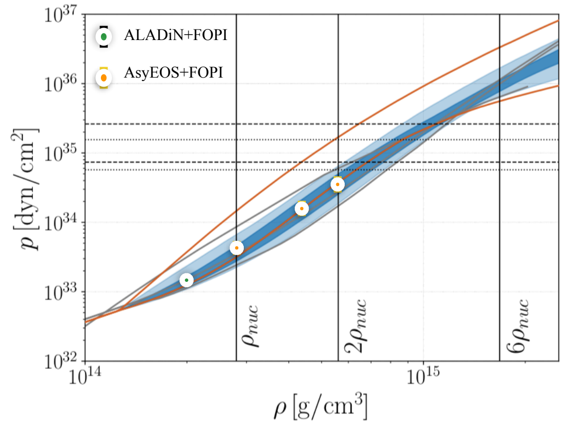

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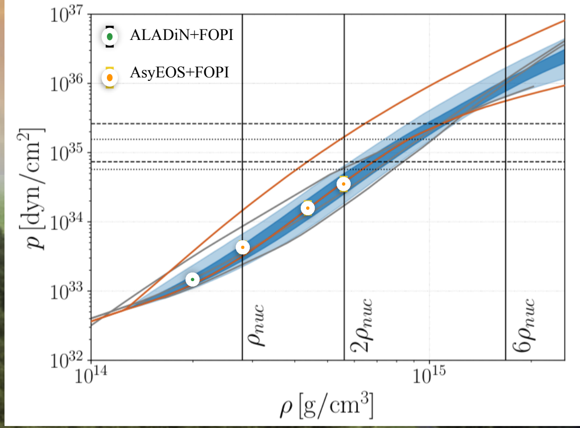

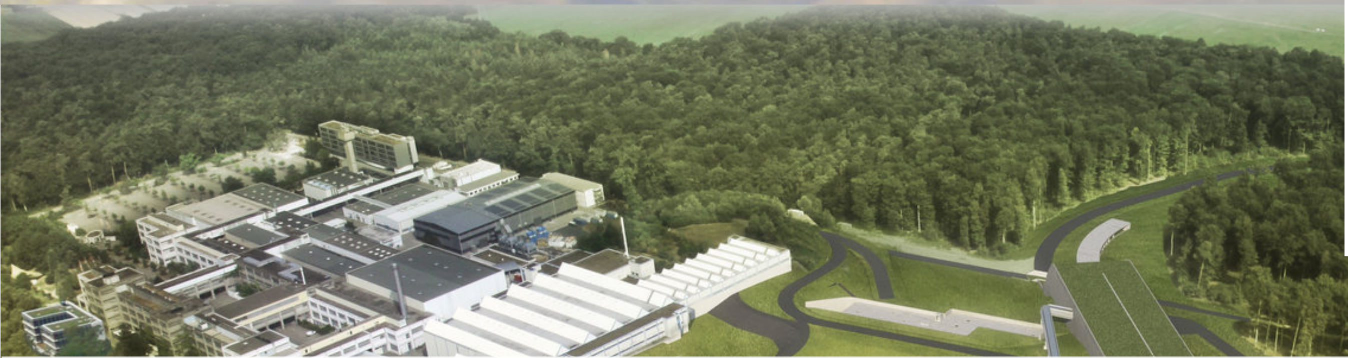

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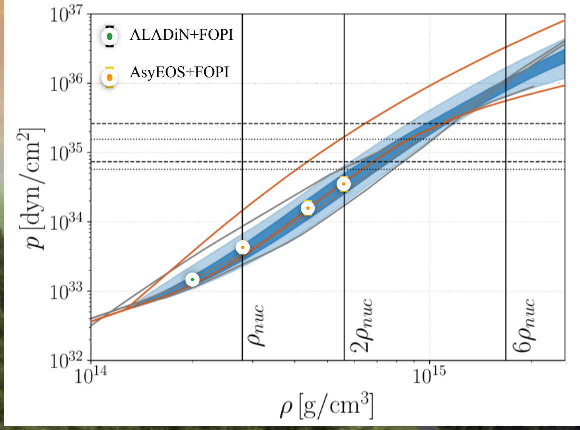

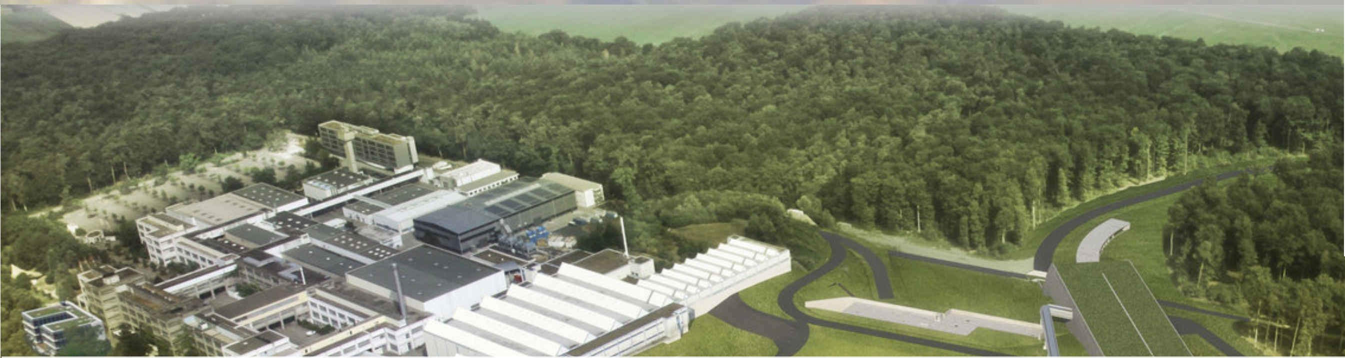

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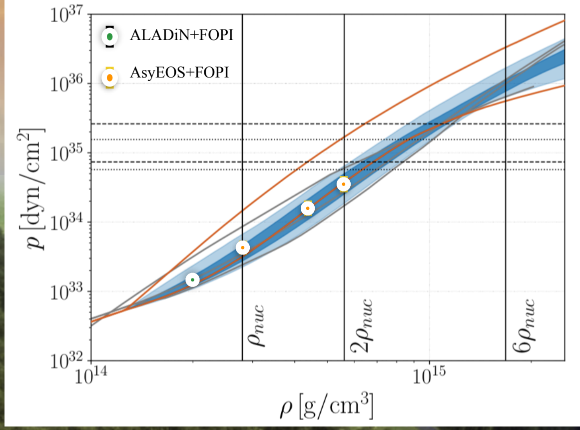

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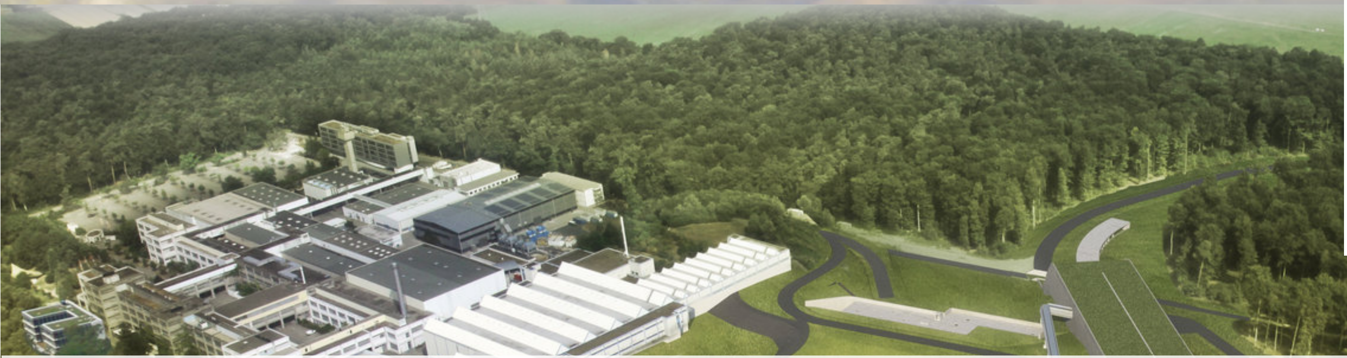

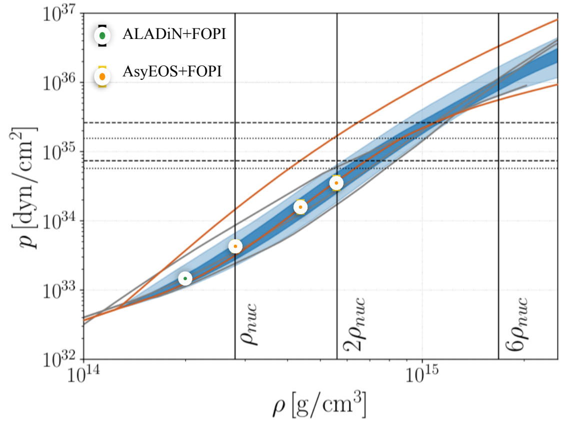

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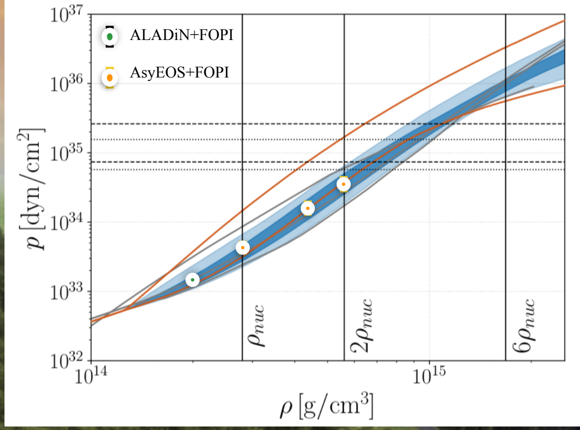

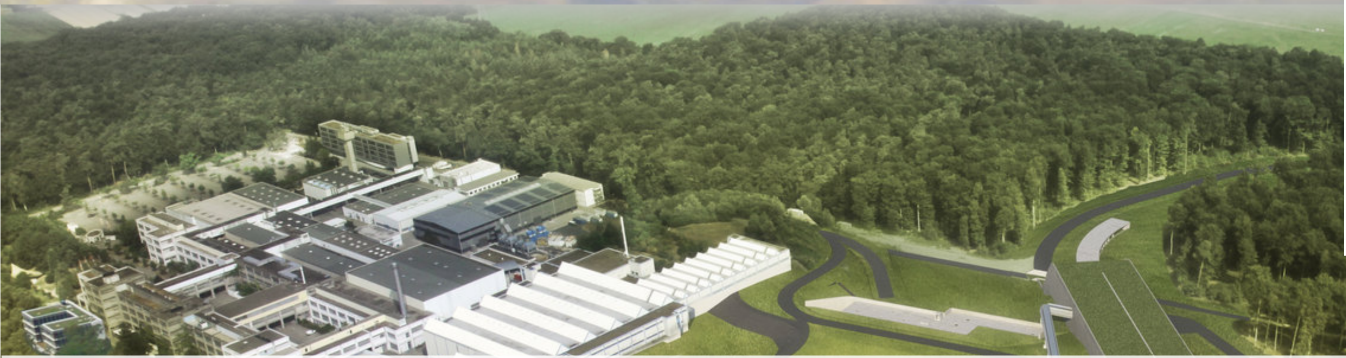

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- Beyond $3 - 4\rho_0$ (FAIR, NICA), new observables needed to constrain SNM and NS EoS. A new generation of relativistic transport models must arise, benchmarked e.g. with data taken at SIS18 at the highest available beam energies (FOPI, HADES).

Thank you for your attention!