EoS and Symmetry Energy experimental studies at GSI/FAIR energies

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on behalf of the ASY-EOS collaboration

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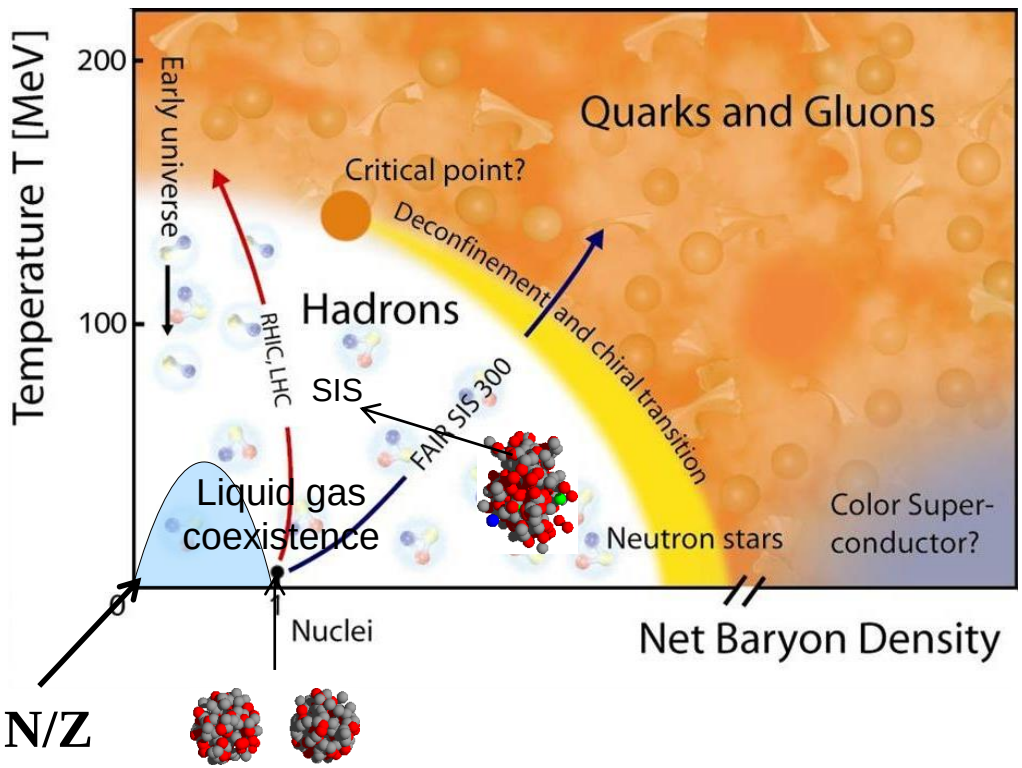
EOS for nuclear matter

The nuclear EOS describes the relation between energy, pressure, density, temperature and isospin asymmetry. It is an essential ingredient in nuclear physics and astrophysics.

Question: how E/A depends on the density ϱ and isospin asymmetry $\delta=\frac{\varrho_n-\varrho_p}{\varrho_n+\varrho_p}$

$E/A(\varrho, \delta)$=????

Nuclear matter phase diagram (schematic)



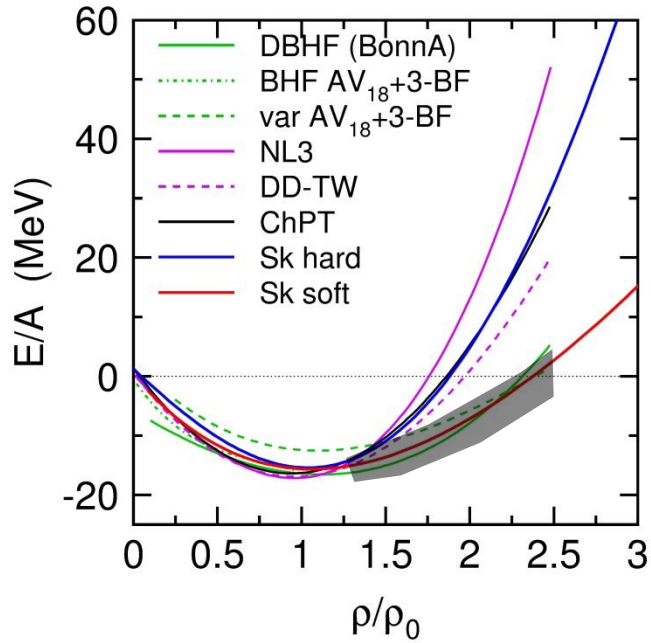
In this talk we will review some observable used with Heavy Ions reactions in order to obtain information on the EOS above the nuclear saturation density ϱ_0

Probing the EOS of symmetric matter with Kaon production

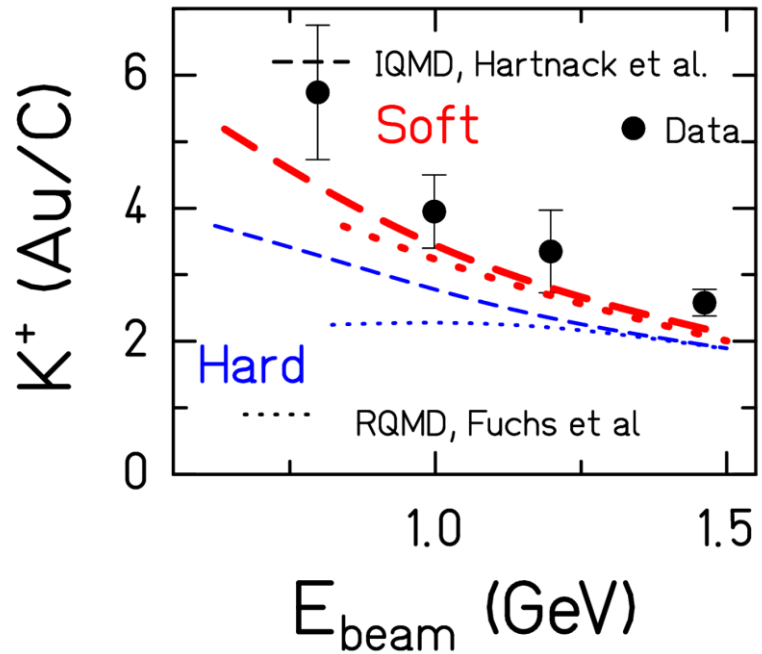
Energy per nucleon (E/A)

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \ldots$$

$$E(\rho,\delta=0) = E(\rho_0) + \frac{K}{18}\frac{(\rho-\rho_0)^2}{\rho_0}$$



C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 01230
C. Fuchs et al. PRL 86 (2001) 1974



Ratio of yields stable against variation of K^+ production cross section

Strong sensitivity to EOS due to multistep production (formation of nucleon resonances, e.g. Δ)

-> soft EOS (K=200 MeV)

Isospin dependence of EOS [N/Z(Au) = 1.49]

Flows

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

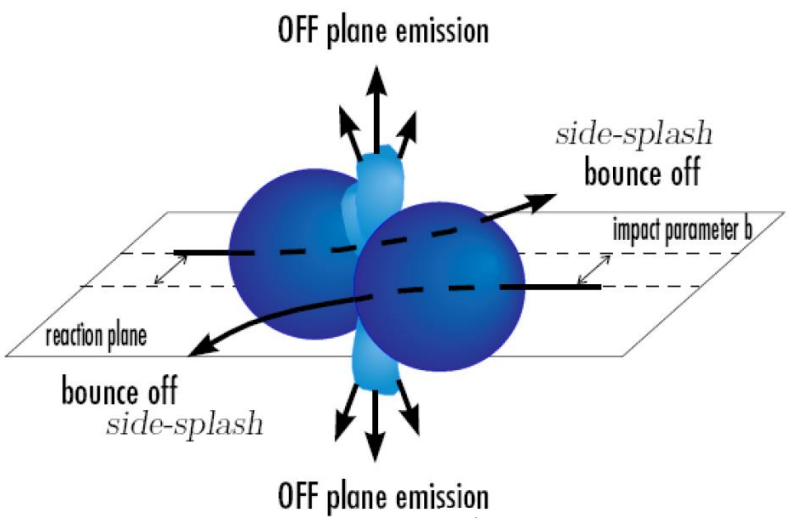
y = rapidity
p_t = transverse momentum

$$v_1(y,p_t)=\left\langle\frac{p_x}{p_t}\right\rangle$$

Transverse flow: it provides information on the angular distribution in the reaction plane

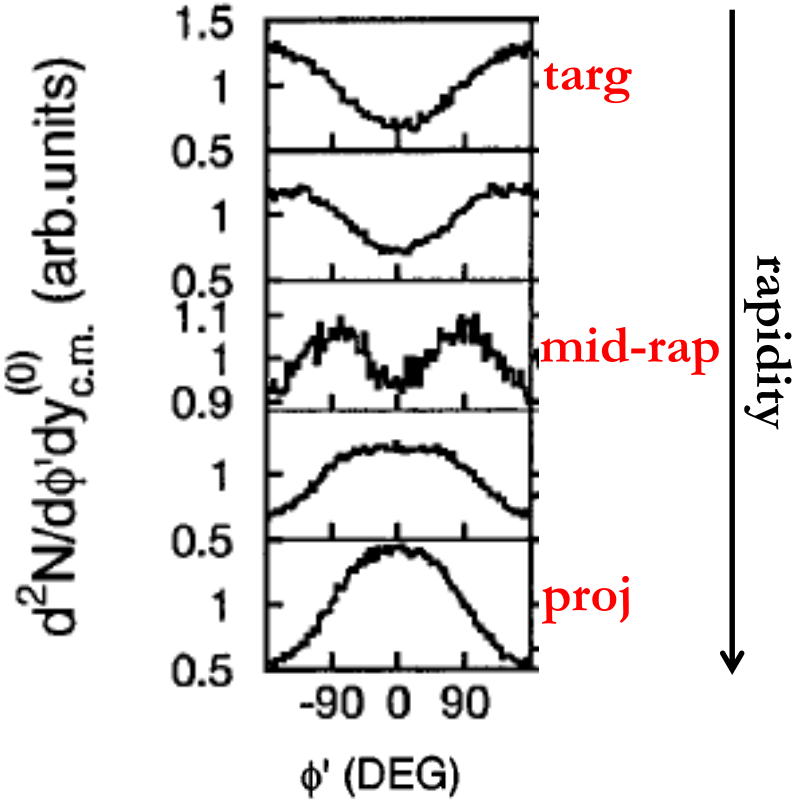
$$v_2(y,p_t)=\left\langle\frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

Elliptic flow: competition between in plane ($v_2>0$) and out-of-plane ejection ($v_2<0$)

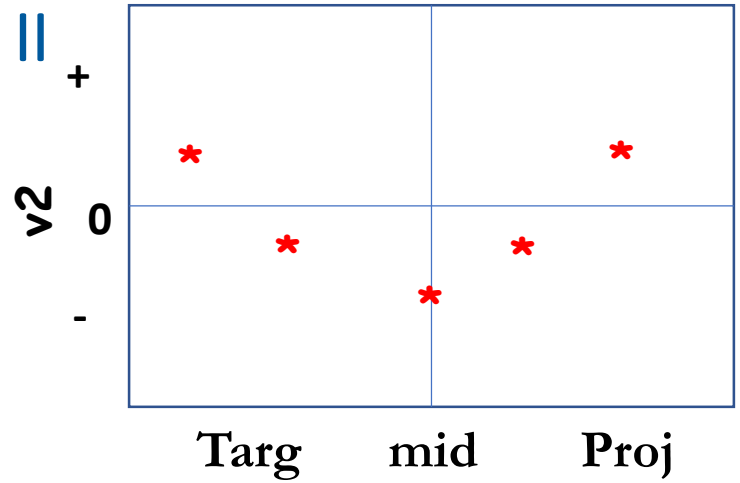


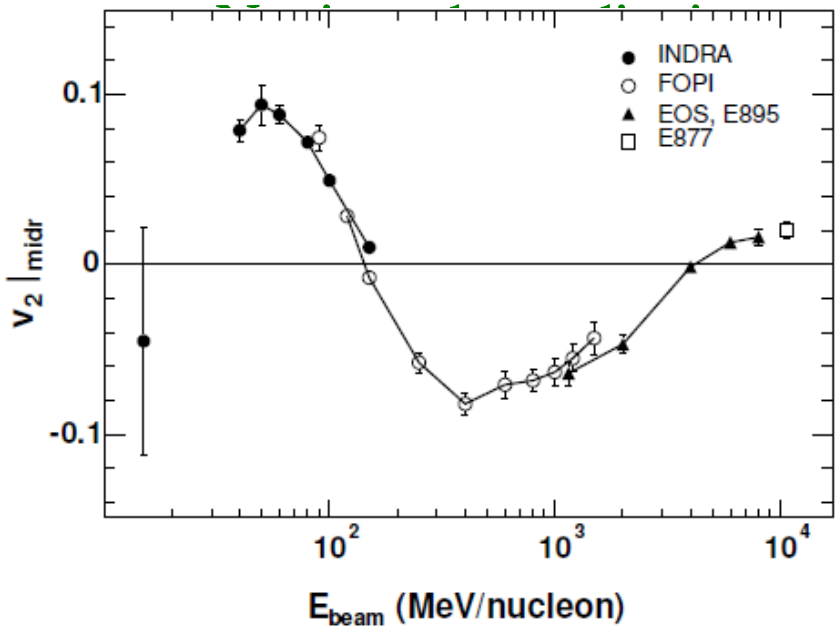
Flows II

Au+Au @ 2 AGeV



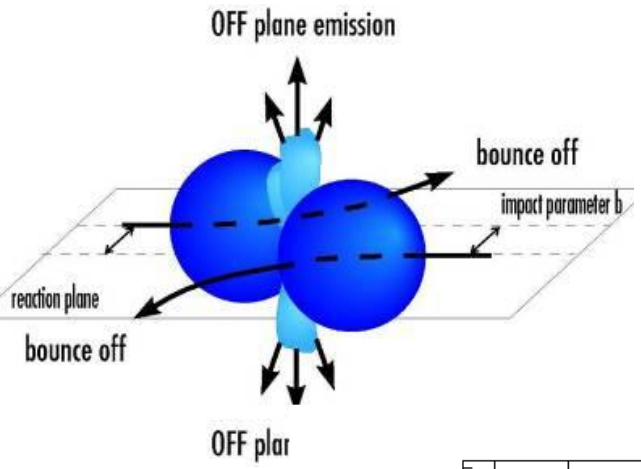
C.Pinkenburg et al., PRL 83 (1999) 1295
nucl-ex/9903010





Au+Au data from INDRA, FOPI, AGS exps
A.Andronic et al., EPJA 30(2006)

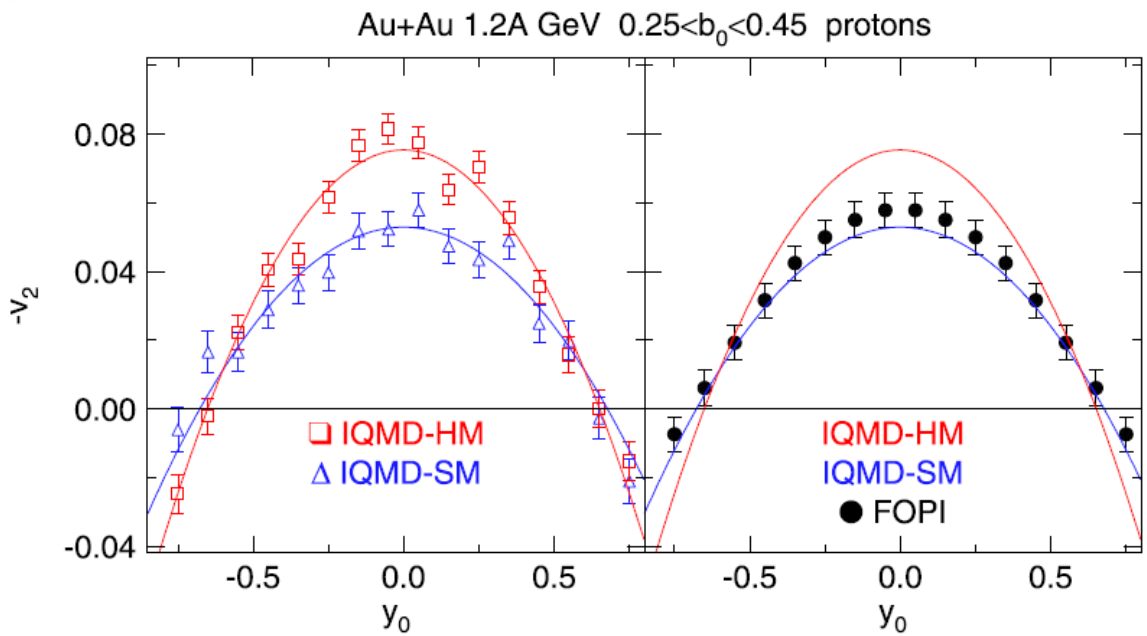
Probing the EOS of symmetric matter with flow



Parametrization of shape:

$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

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



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

With momentum dependent interaction: **compulsory**

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

$y_0 = y/y_{proj}$ in c.m.r.s. (scaled rapidity)
$b_0 = b/b_{max}$ (scaled impact parameter)

Parametrization of elliptic flow

- sensitive to EOS over a large energy range
- relevant density range ρ ≃ (1 – 3) ρ_0

K_0 as from FOPI flow data

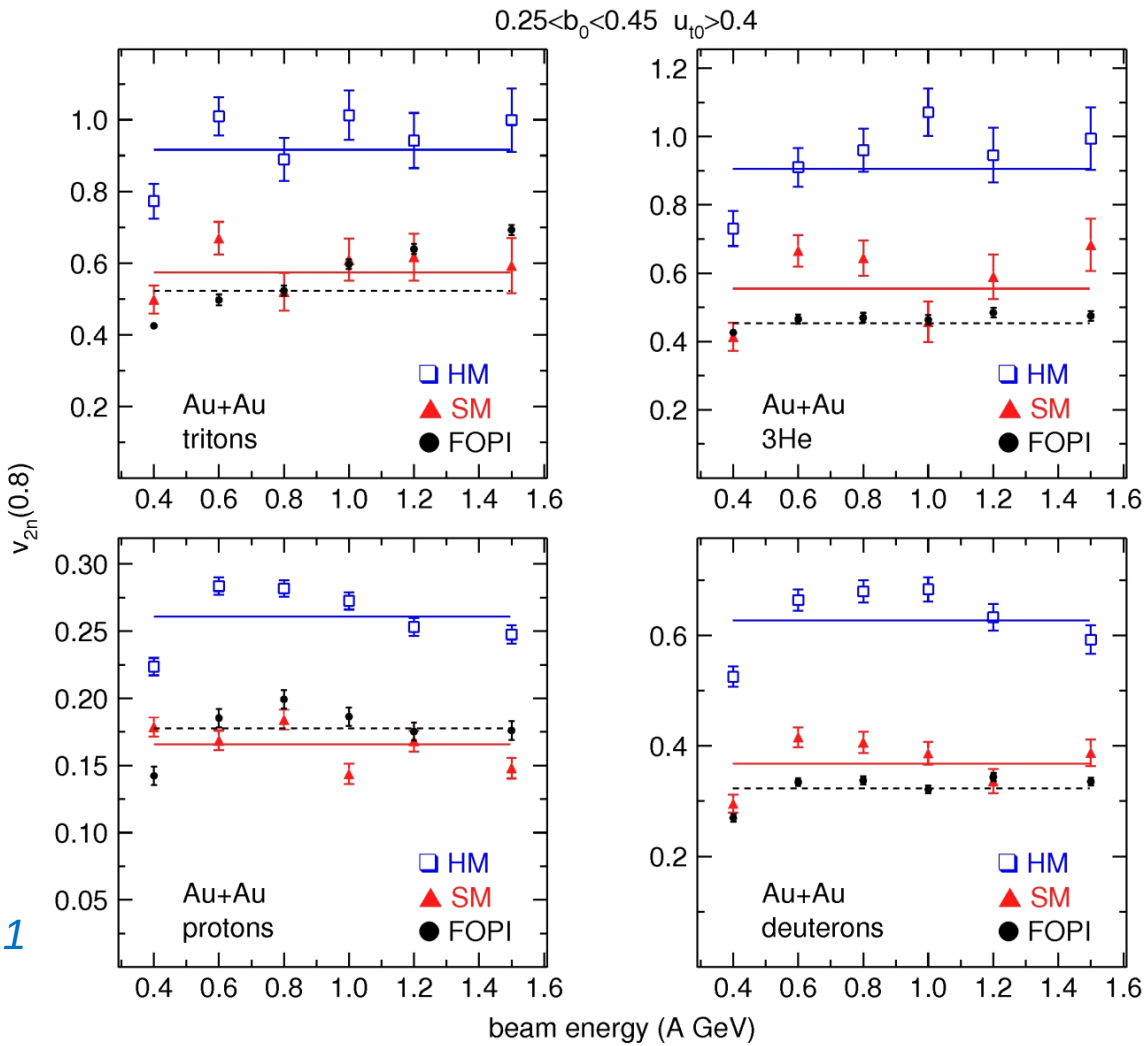
IQMD –> K_0 = 190 ± 30 MeV

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

UrQMD –> K_0 = 220 ± 40 MeV

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

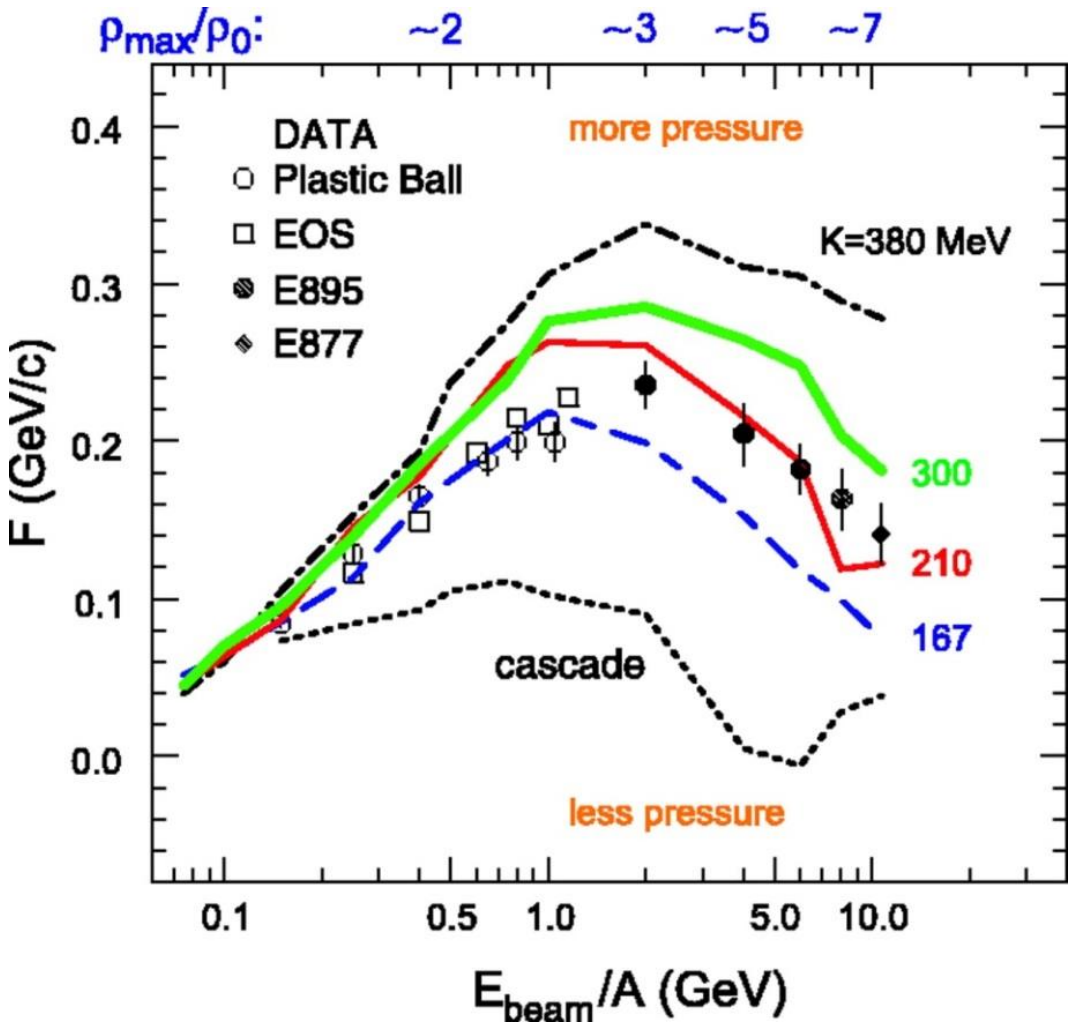
A. LeFevre et al, NPA 876 (2012) 1



$u_{t0} = u_t/u_p$ with $u_p = \beta_p \gamma_p$ in c.m.r.s. (scaled transverse momentum)

Some comparisons

- consistent to former results *P. Danielewicz et al. Science 298, 1592 (2002)*
- elliptic flow is less sensitive to stiffness of EOS at higher energies



Symmetry energy

Asymmetry parameter $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$

$$E(\rho,\delta) = E_{SNM}(\rho,\delta=0) + E_{sym}(\rho)\,\delta^2 + O(\delta^4)$$

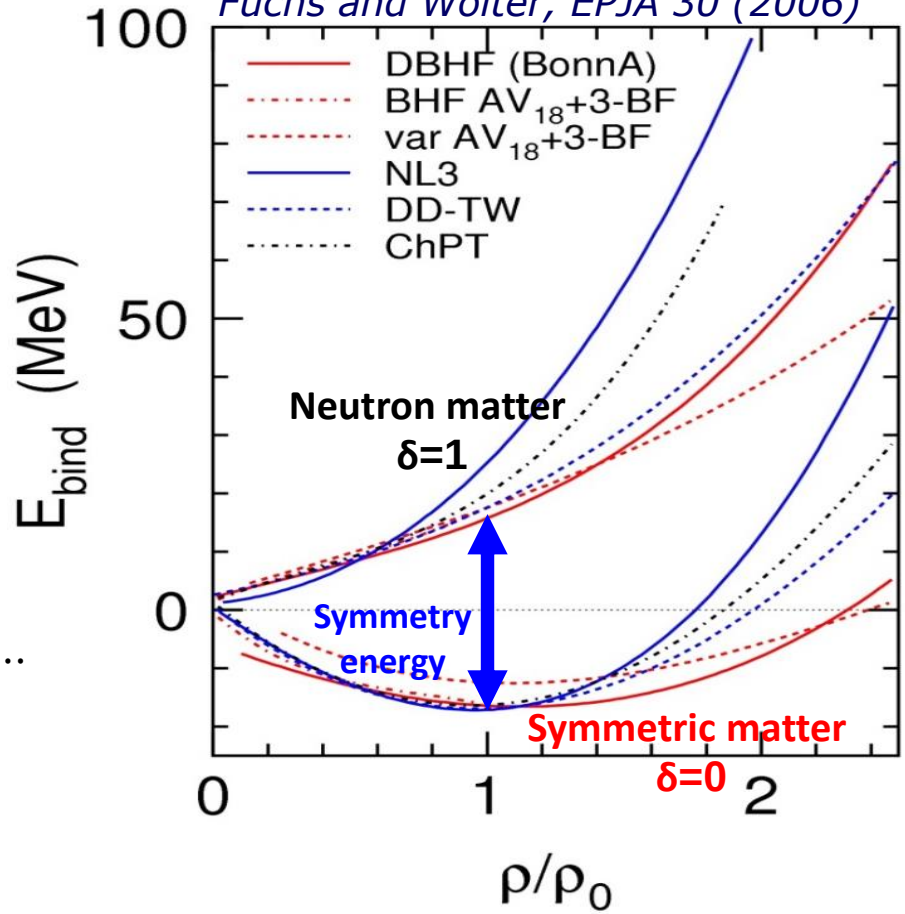
with

Symmetry energy E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

Slope $L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}$

Fuchs and Wolter, EPJA 30 (2006)



$$E_{sym}(\rho) = E(\rho,\delta=1) - E(\rho,\delta=0)$$

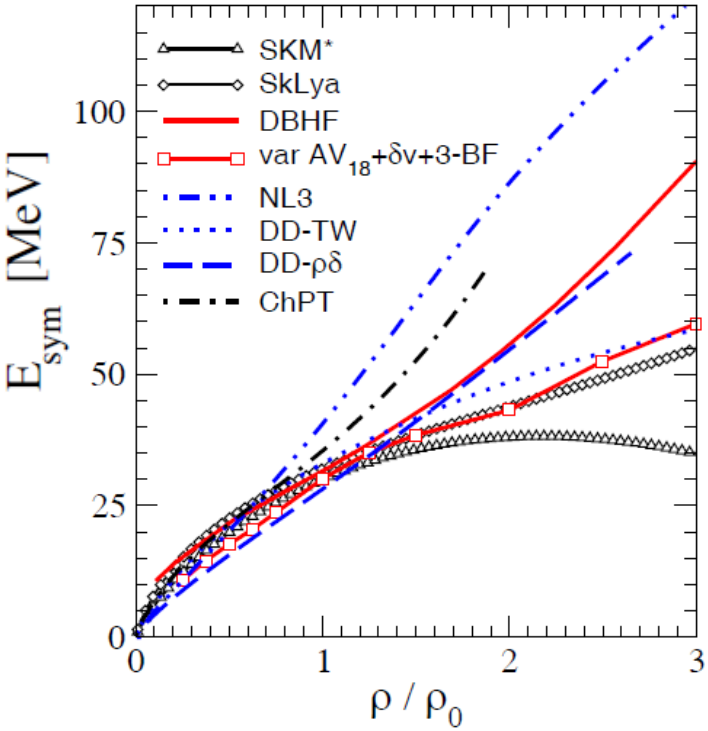
Symmetry energy above ρ_0

Fuchs and Wolter, EPJA 30 (2006)

GSI/FAIR

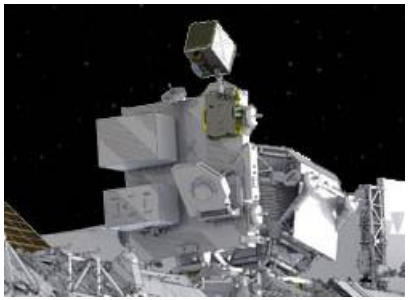
RIKEN

JLab

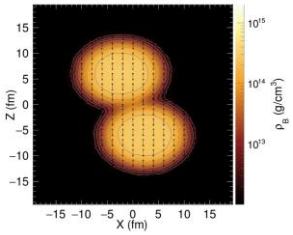


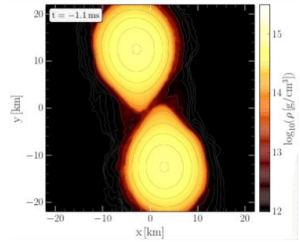
LIGO/VIRGO

NICER@ISS



Several constraints quite consistent among them below (or toward) ϱ_0 but few constraints above ϱ_0!





NS mass/Shapiro Delay

Symmetry energy at supra-normal densities

Differential elliptic flow v_2 of n/p

UrQMD* (Q. Li et al.) predicts

"hard" E_{sym} → "soft" E_{sym}

protons unchanged

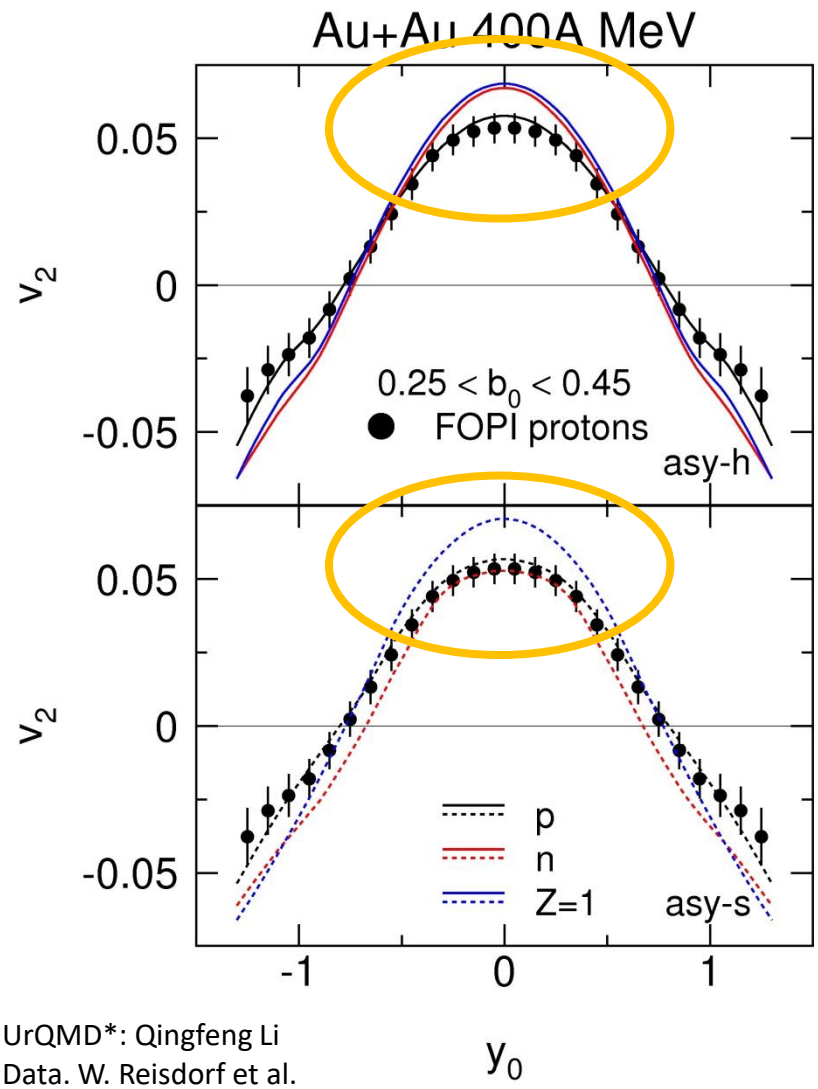
neutron and proton flow inverted

Towards model invariance:

tested stability with different models:

- soft vs. hard EOS **190<K<280 MeV**
- density dependence of $\sigma_{NN,elastic}$
- asymmetry dependence of $\sigma_{NN,elastic}$
- optical potential
- momentum dependence of isovector potential

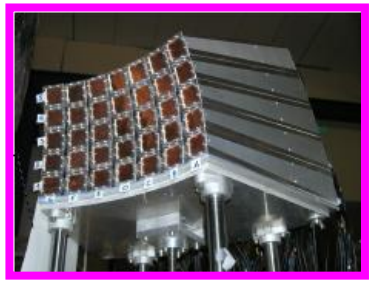
M.D. Cozma et al., arXiv:1305.5417
P. Russotto et al., PLB 267 (2010)
Y. Wang et al.,PRC 89, 044603 (2014)



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

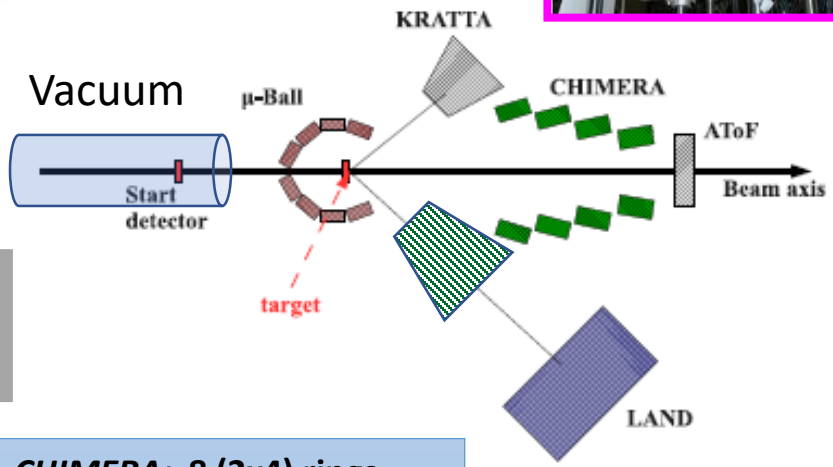
ASY-EOS S394 experiment @ GSI Darmstadt (May 2011)

µBall: 4 rings 50 CsI(Tl), Θ>60°. Discriminate target vs. reactions with air. Multiplicity and reaction plane measurements.

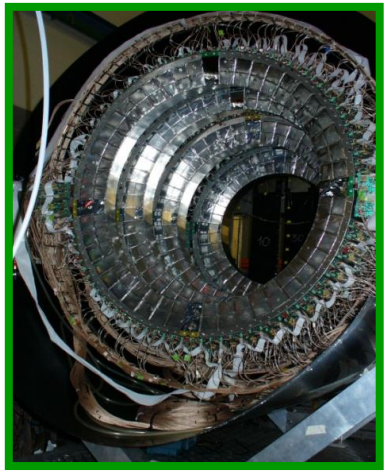


KraTTA: 35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . Light particles and IMFs emitted at midrapidity

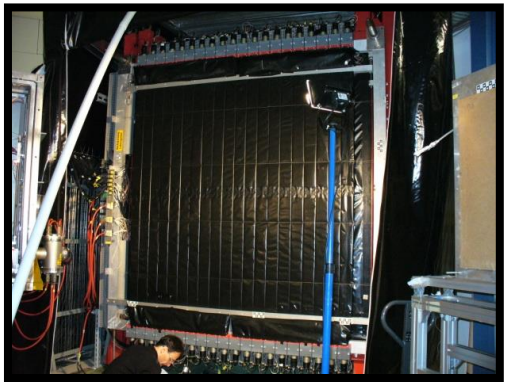
Shadow bar: evaluation of background neutrons in LAND



TOFWALL: 96 plastic bars; ToF, ΔE, X-Y position. Trigger, impact parameter and reaction plane determination



CHIMERA: 8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy: impact parameter and reaction plane determination



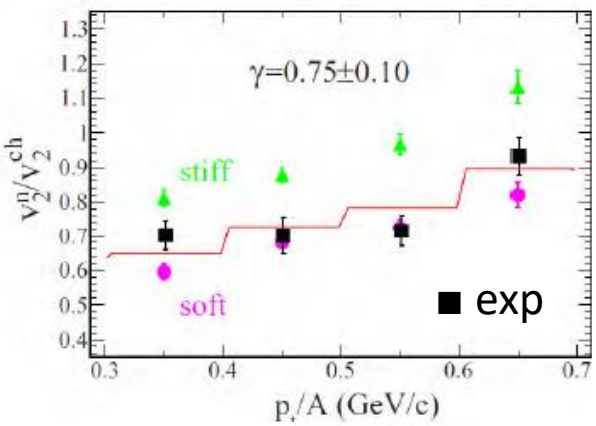
LAND: Large Area Neutron Detector . Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. Neutrons and Hydrogen detection. Flow measurements

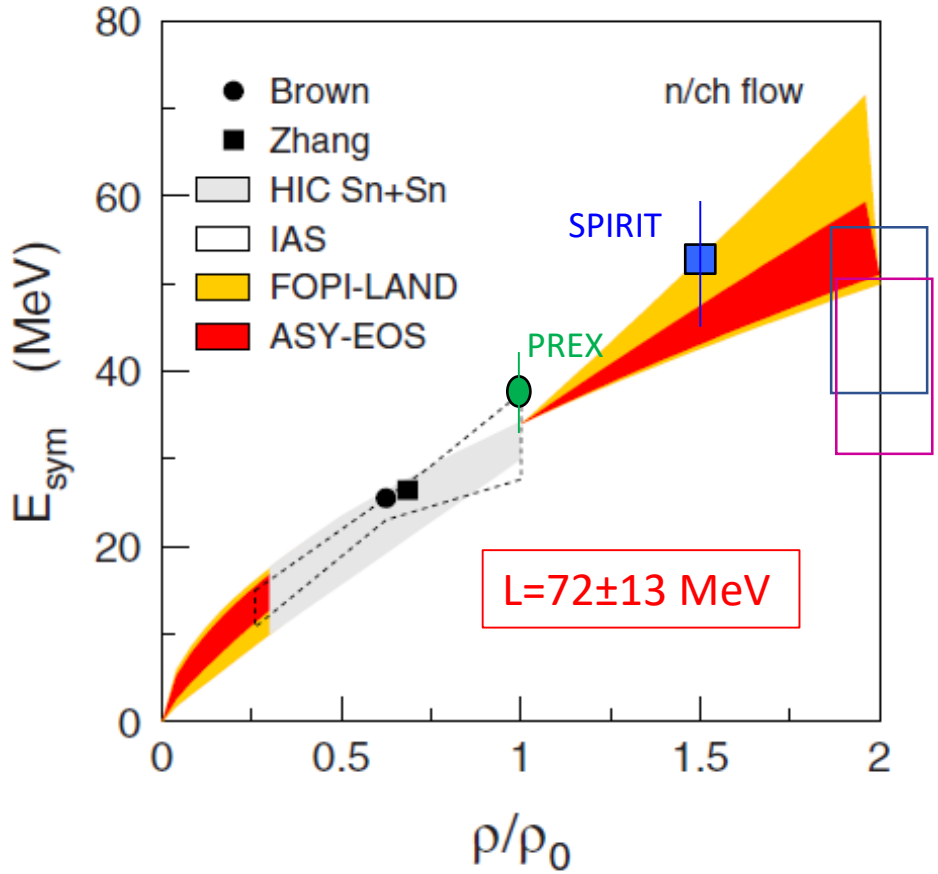
P.Russotto et al., PRC 034608 (2016)

ASY-EOS S394 experiment results

Au+Au @ 400 AMeV

Main observable neutron-proton (charged particles) elliptic flow ratio: robust and effective in exploring high density behaviour of Esym





neutron star
X-ray observations
Zhang & Li
EPJA 55:39 (2019)
Esym (2ρ0) =
47 ± 10 MeV

Bayesian analysis
GW170817 and
radii of QLMXB
Xie & Li
arXiv:1907.10741
R = 10.8 – 11.9 km
E_{sym} $(2\rho_0)$ =
39+12−8 MeV

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

stiff γ=1.5, soft γ=0.5

P. Russotto et al., PRC 94, 034608 (2016)

W.G. Lynch, M.B. Zhang, arXIv:2106.10119

PREX, PRL 126, 172502 (2021)

Comparison to results from neutron star merger event GW 170817

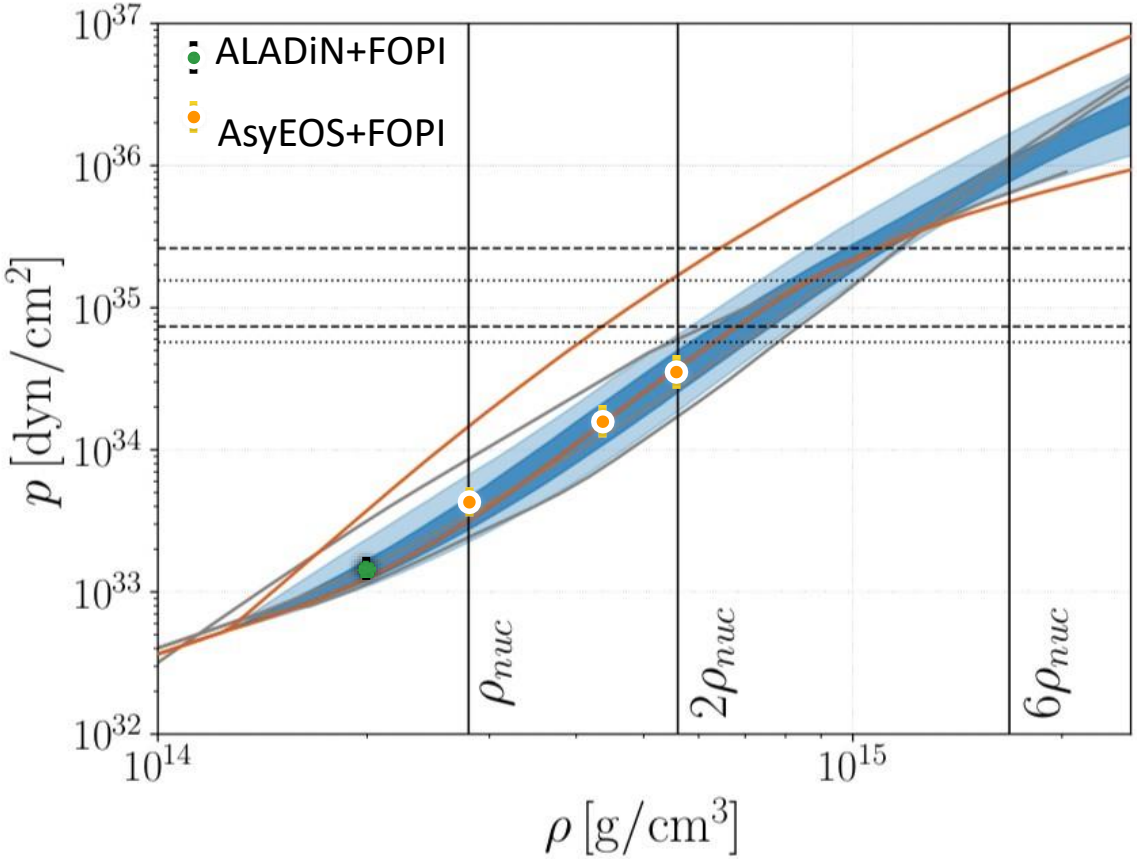
How can we combine FOPI, AsyEOS and ALADiN results to deduce the pressure in a neutron star?

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

  $\delta = 0.9(5\%protons + degenerate\ e^-)$
- L as from AsyEOS at 1-2ρ_0
- K_0 as from FOPI flow data

Gravitational Wave 170817

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



Combining HIC and astrophysical results in the same Bayesian analysis to constrain neutron matter EOS

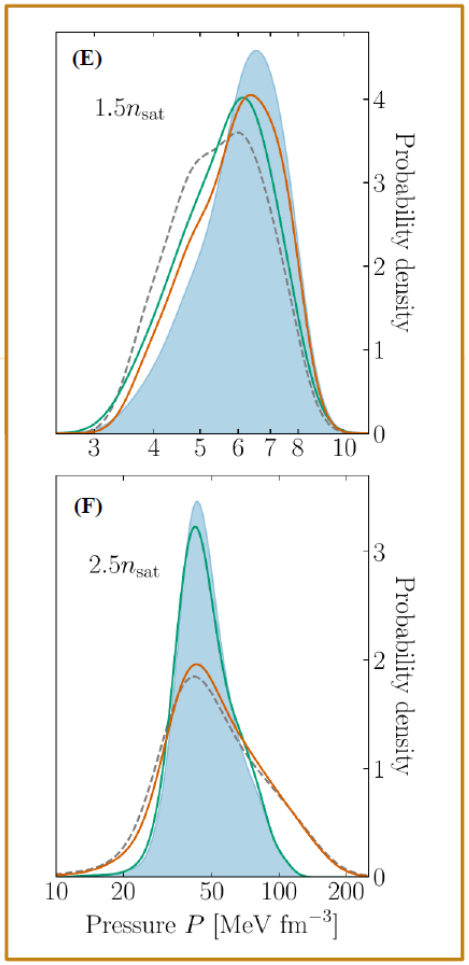
« **HIC** » = FOPI+ASY-EOS+AGS - « **Astro** » = GW, NICER (pulsar X-ray hot spots)

Combining information from HICs and astrophysical informations

- HIC data favors larger pressures at 1-1.5 ρ_0 , where sensitivity is highest
- similar observations with NICER data
- low densities, HICs have clear impact on total posteriors
- EOS at higher densities (>2ρ_0) mostly determined by astrophysical observations

Conclusion

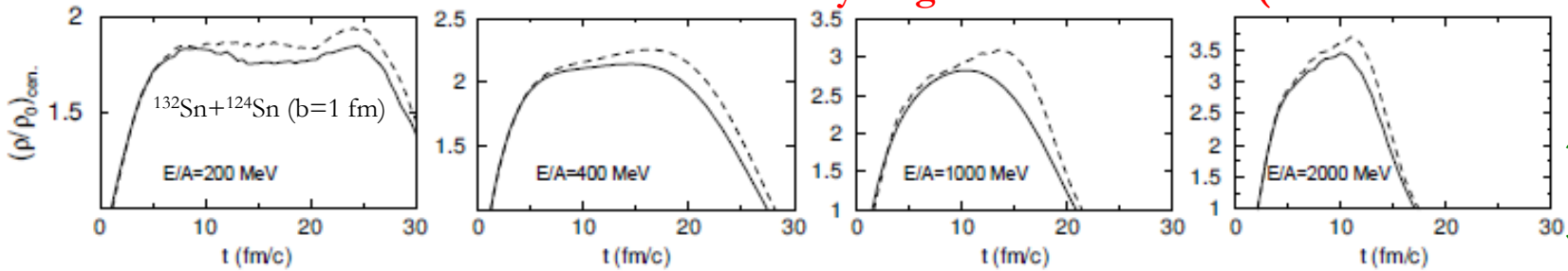
- advancing HIC experiments to higher densities
- investigating transport models



Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions, S. Huth et al., **arXiv:2107.06229 (2021)[nucl-th]**

Symmetry energy (L & Ksym) @ higher density

Which densities can be reached in the early stage of the reaction ? (BUU calculations)

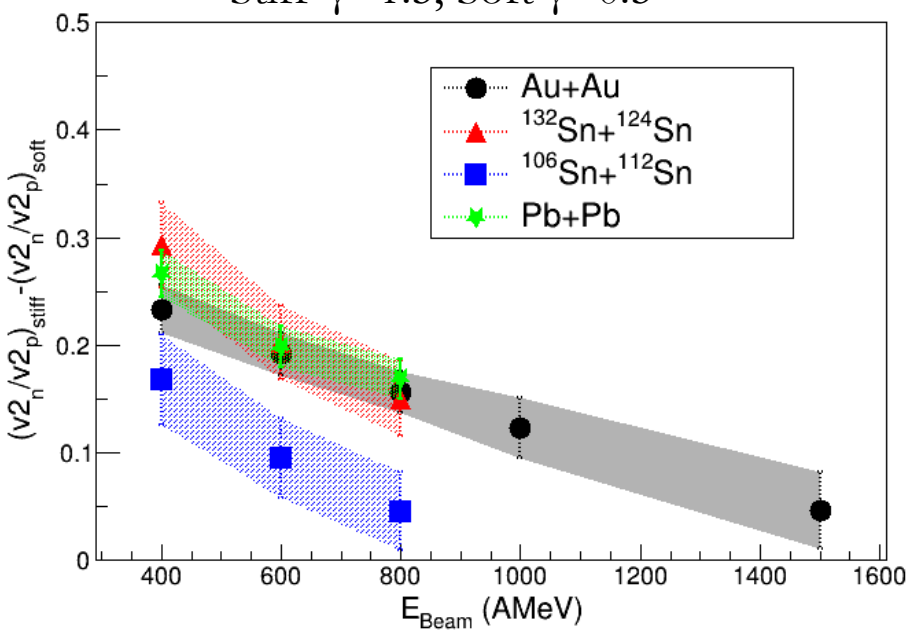


Bao-An Li, NPA 708 (2002)

UrQMD predictions

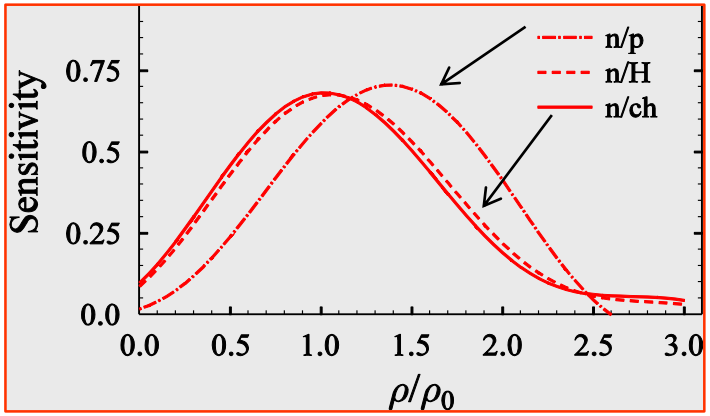
$$E_{sym} = 22\,\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\,\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

Stiff γ=1.5, Soft γ=0.5



Sensitivity of Elliptic Flow Ratio to density

Au+Au @ 400AMeV (b<7.5



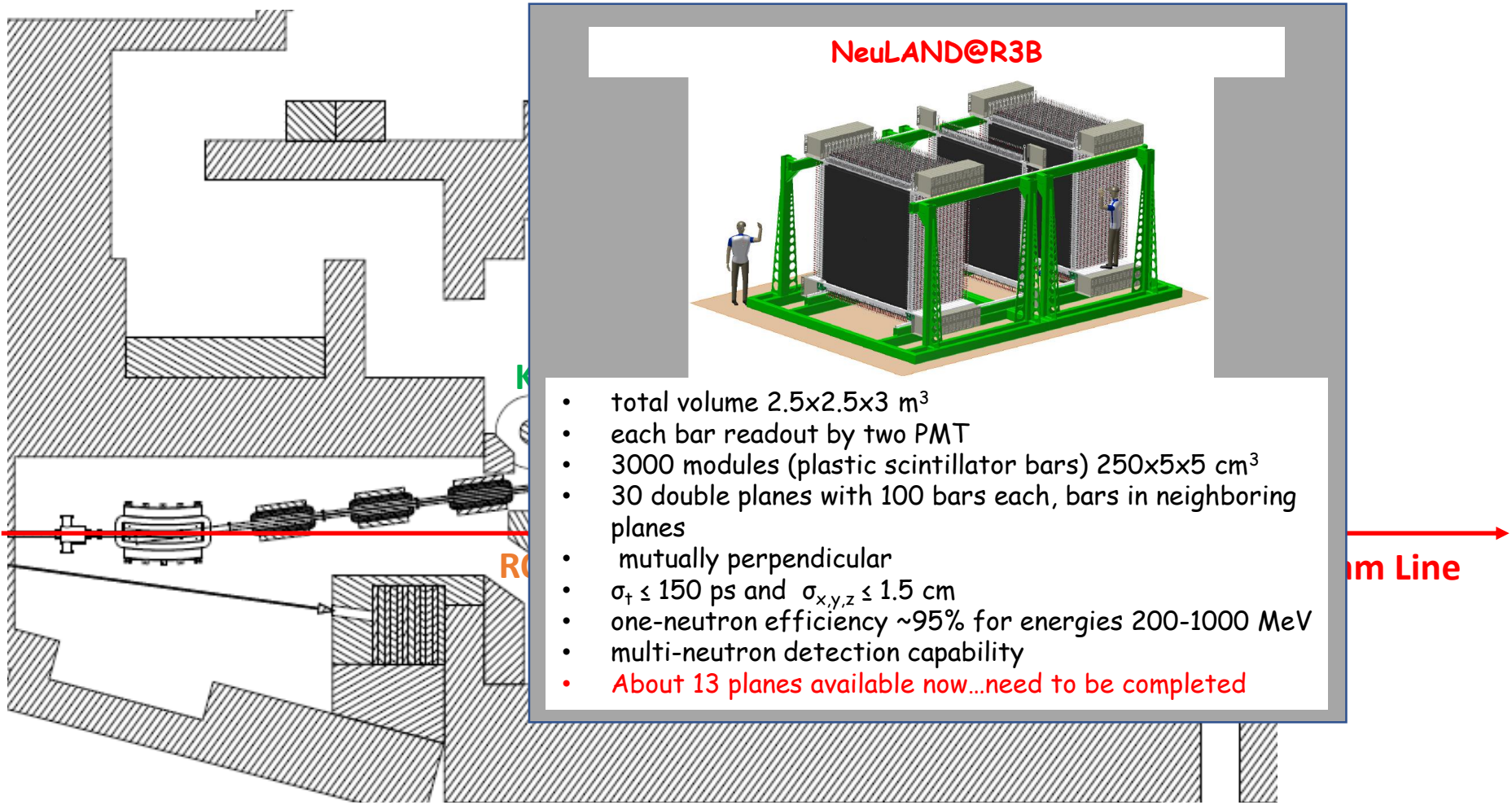
P. Russotto et al.,PRC 94, (2016)
M.D. Cozma TuQMD calculations

To explore higher densities:

- **raise the beam energy**
- **use n-p observable**

ASY-EOS II

proposed reactions: Au+Au @ 250,400,600, 1000 AMeV



- total volume 2.5x2.5x3 m^3
- each bar readout by two PMT
- 3000 modules (plastic scintillator bars) 250x5x5 cm^3
- 30 double planes with 100 bars each, bars in neighboring planes
- mutually perpendicular
- $\sigma_t \leq 150$ ps and $\sigma_{x,y,z} \leq 1.5$ cm
- one-neutron efficiency ~95% for energies 200-1000 MeV
- multi-neutron detection capability
- About 13 planes available now…need to be completed

Conclusions

- Heavy ion collisions are a powerful tool to constrain the nuclear matter EOS
  - Studied a wide range of energies and systems at SIS18
- Combination of FOPI and ASY-EOS results allows to predict a density dependence of the pressure in a neutron star between 0.5 to about 1.5 ρ_0, with similar accuracy than astrophysical data
- To (better) access higher densities a new experiment ASY-EOS II is planned at GSI
- If interested take a look at recent pion results (Sπirit) at RIKEN
- Beyond about 2.5 to 4 ρ_0 new observables are needed to constraint NS EOS
- Beam energy scan BES at RHIC and new experimental set-ups will be available at Nuclotron at JINR and at FAIR
- Benchmarking transport models for the energy regime between 1 – 5 GeV/u

Thanks

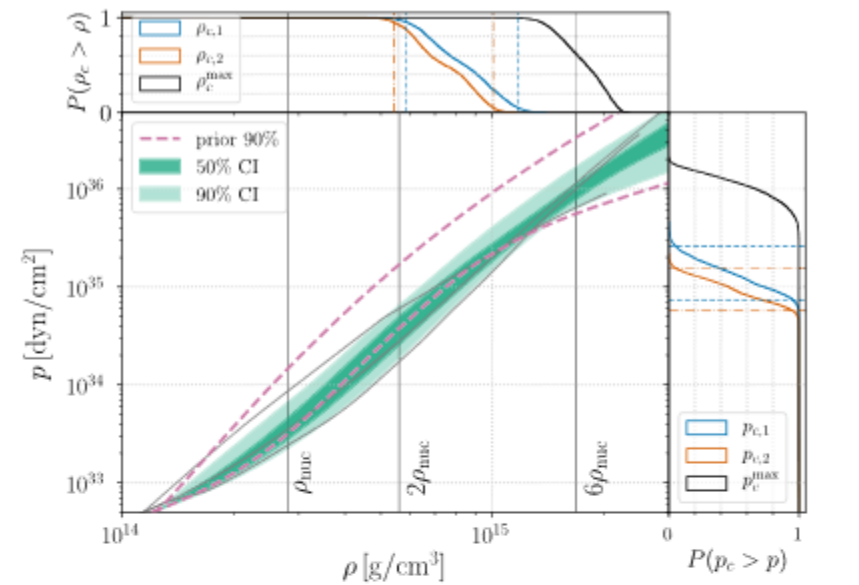
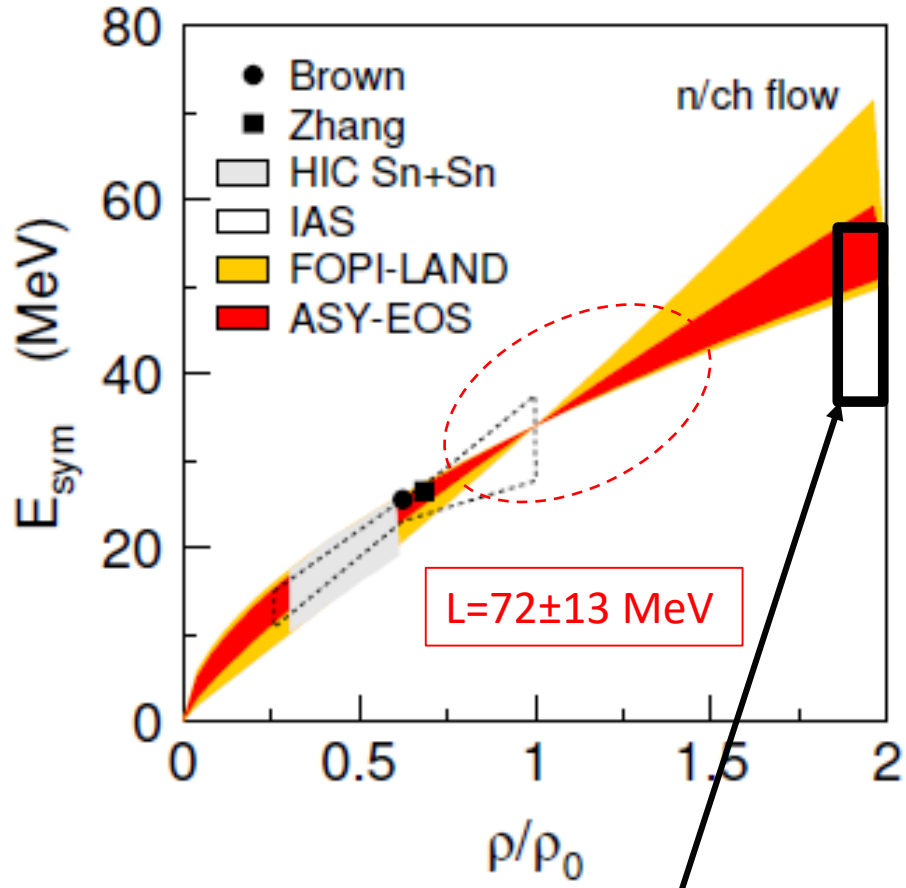


FIG. 2. Marginalized posterior (green bands) and prior (purple dashed) for the pressure p as a function of the rest-mass density ρ of the NS interior using the spectral EOS parametrization and imposing a lower limit on the maximum NS mass supported by the EOS of 1.97 $M_\odot$. The dark (light) shaded region corresponds to the 50% (90%) posterior credible level and the purple dashed lines show the 90% prior credible interval. Vertical lines correspond to once, twice, and six times the nuclear saturation density. Overplotted in gray are representative EOS models [121,122,124], using data taken from [19]; from top to bottom at $2\rho_{nuc}$ we show H4, APR4, and WFF1. The corner plots show cumulative posteriors of central densities ρ_c (top) and central pressures p_c (right) for the two NSs (blue and orange), as well as for the heaviest NS that the EOS supports (black). The 90% credible intervals for ρ_c and p_c are denoted by vertical and horizontal lines respectively for the heavier (blue dashed) and lighter (orange dot-dashed) NS.

ASY-EOS S394 experiment results

Au+Au @ 400 AMeV

Main observable neutron-proton (charged particles) elliptic flow ratio: robust and effective in exploring high density behaviour of E_{sym}



Zhang & Li, $E_{sym}(2\rho_0)$=47±10 MeV NS radius, max. mass, tidal polarizabilty EPJA 55 39 (2019)

$R_{1.4}$= 12.6±0.7 km (ASY-EOS)
$R_{1.4}$= 12.7±1,1 km (NICER)

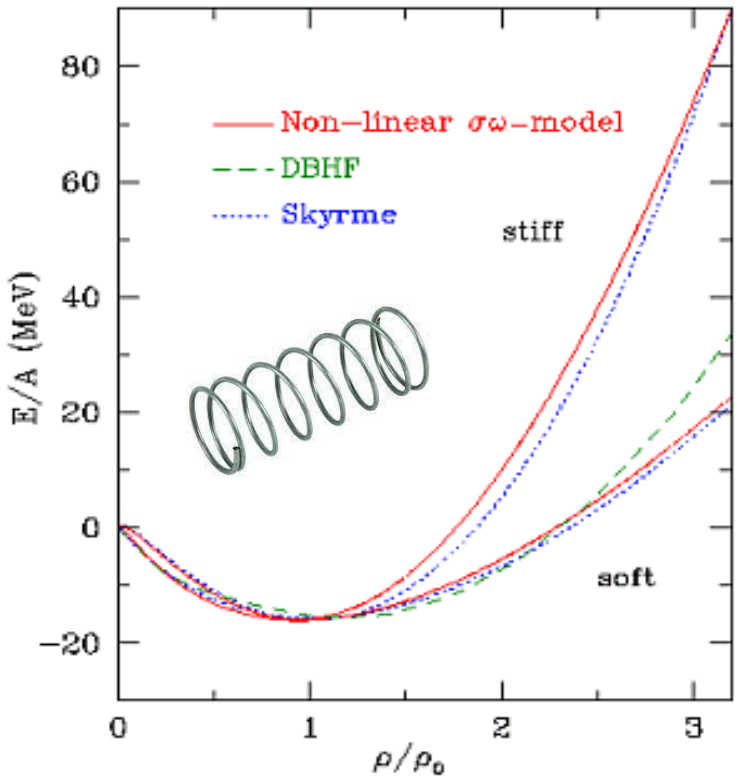
P.Russotto et al., PRC 034608 (2016)

EOS of symmetric nuclear matter

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{N - Z}{A}$$

$$E(\rho,\delta=0)=E(\rho_0)+\frac{K}{18}\frac{(\rho-\rho_0)^2}{\rho_0}$$

$$K = 9\,\rho^2 \left.\frac{\partial^2 E/A}{\partial^2 \rho}\right|_{\rho=\rho_0}$$

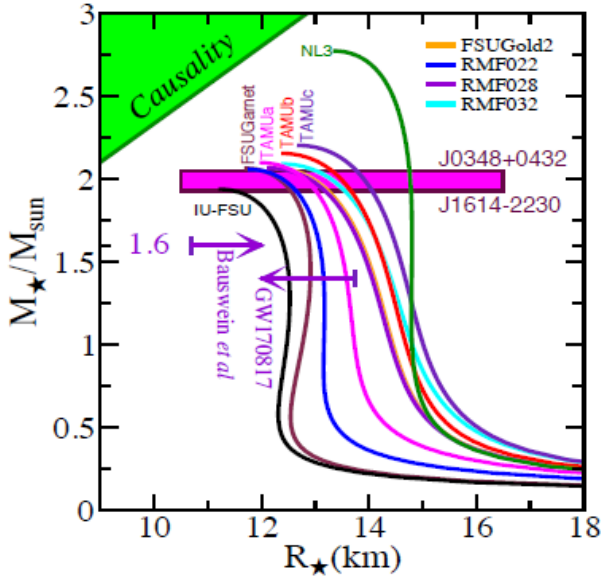


key question:

"How much energy is needed to compress hadronic matter?"

Symmetry energy and neutron stars

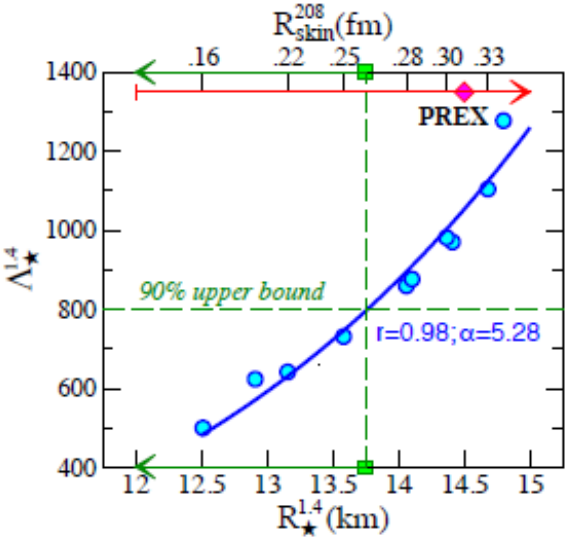
Neutron Stars & Symmetry Energy



Fattoyev, Piekarewicz, Horowitz

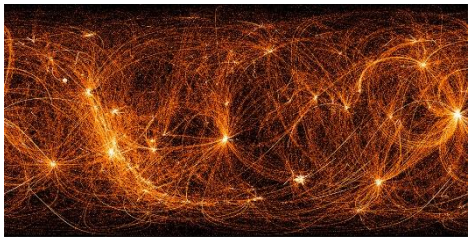
arXiv:1711.06615v2 [nucl-th]

GW from the BNS merger GW170817 from LIGO: Multi-messenger astronomy



$$\Lambda = \frac{2}{3}k_2\left(\frac{c^2R}{GM}\right)^5 = \frac{64}{3}k_2\left(\frac{R}{R_s}\right)^5$$

NASA's Neutron star Interior Composition Explorer NICER on the ISS from June 2017



NP needs to explore high density behaviuor:

- Huge divergences in models
- "Direct" astrophysical interest
- Compare with astrophysical observation

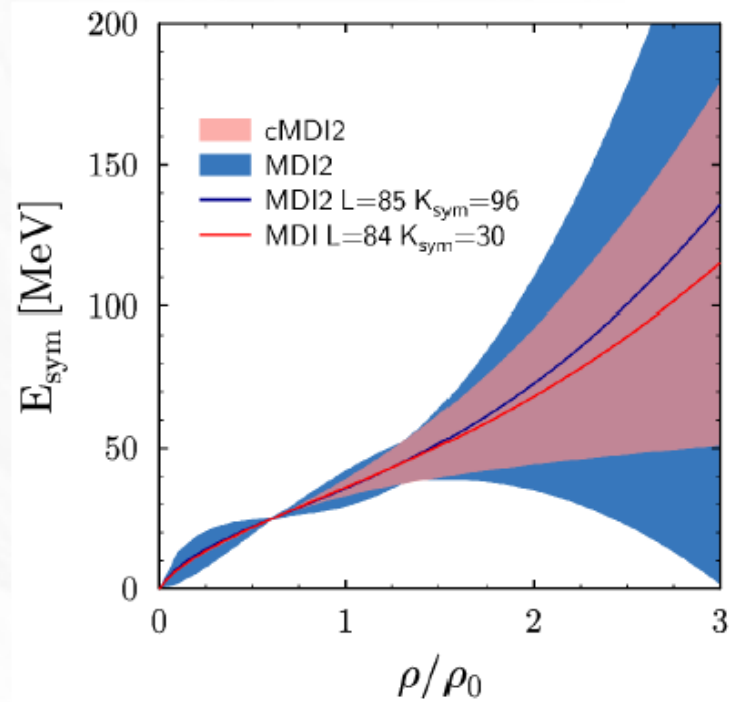
Constraints for L and K_{sym}

- Free of systematical uncertainties (cMDI2)
  neutron-proton v_2^n/v_2^p

$$L = 84 \pm 30(\text{exp}) \pm 18(\text{th}) \text{ MeV}$$
$$K_{sym} = 30 \pm 142(\text{exp}) \pm 85(\text{th}) \text{ MeV}.$$

- Full MDI2 freedom
  neutron-proton v_2^n/v_2^p +neutron-charged part. v_2^n/v_2^{ch}

$$L = 85 \pm 22(\text{exp}) \pm 20(\text{th}) \pm 12(\text{sys}) \text{ MeV}$$
$$K_{sym} = 96 \pm 315(\text{exp}) \pm 170(\text{th}) \pm 166(\text{sys}) \text{ MeV}$$



- Isovector compressibility: $K_\tau = K_{sym} - 6L - \frac{J_0}{K_0} L$

$$K_\tau = -354 \pm 228 \text{ MeV(cMDI2)}$$
$$K_\tau = -290 \pm 421 \text{ MeV(MDI2)}.$$

Literature:
ISGMR: -500±100 MeV
Gogny interaction: -370±100 MeV

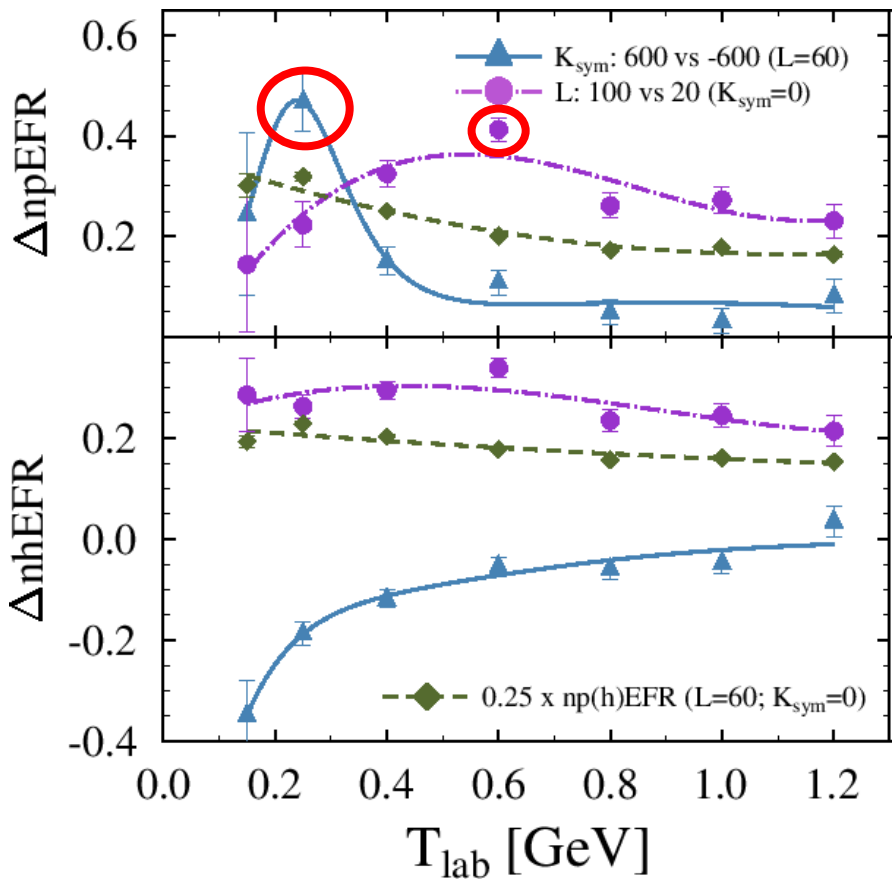
arXiv:1706.01300 [nucl-th]

ASY-EOS: TuQMD predictions

L and KSym sensitivities

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho - \rho_o}{\rho_o}\right) + \frac{K_{\mathrm{sym}}}{18}\left(\frac{\rho - \rho_o}{\rho_o}\right)^2 + \ldots,$$

$$\Delta np(h)EFR = \left[\frac{v_2^n}{v_2^{p(h)}}\right]_{(a)} - \left[\frac{v_2^n}{v_2^{p(h)}}\right]_{(b)}$$

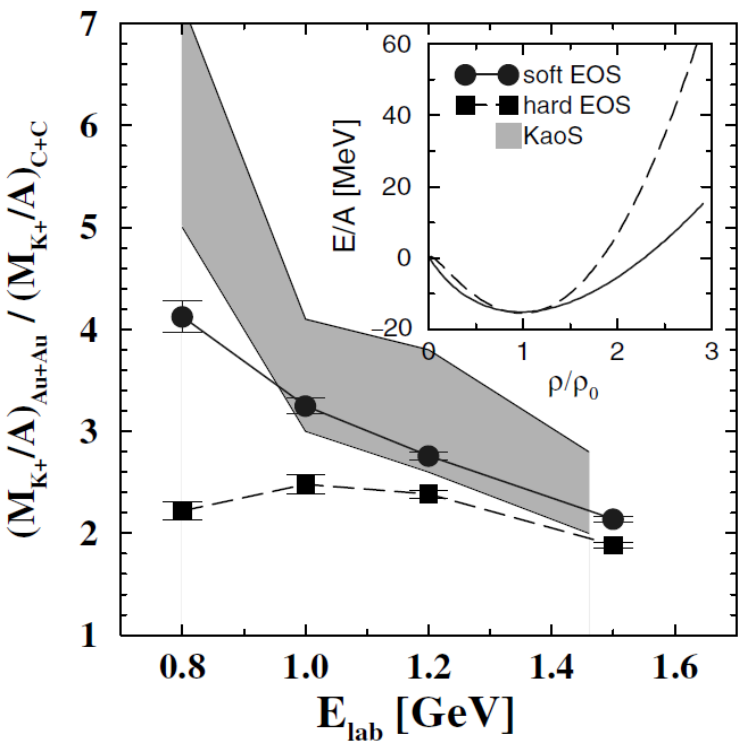


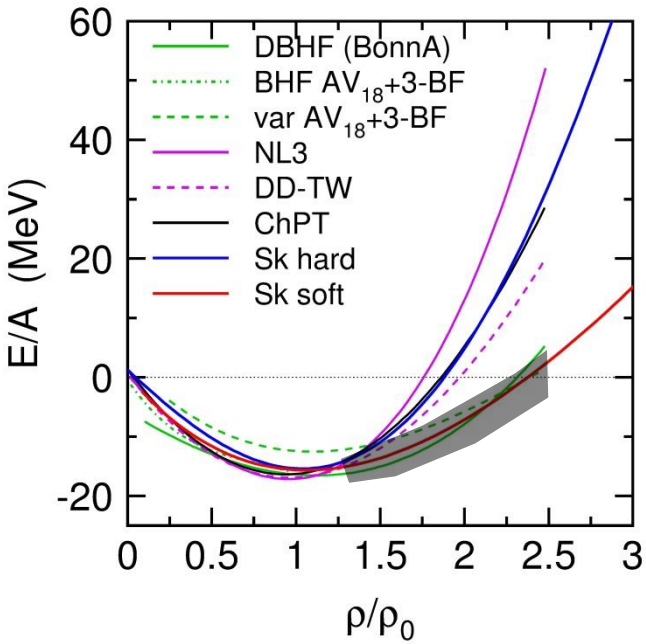
M.D Cozma, EPJA
arXiv:1706.01300

Au+Au b<7.5 fm

Probing the EOS of symmetric matter with Kaon production

C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 01230
C. Fuchs et al. PRL 86 (2001) 1974





Ratio of yields stable against variation of K^+ production cross section

Strong sensitivity to EOS due to multistep production (formation of nucleon resonances, e.g. Δ)

-> soft EOS (K=200)

Isospin dependence of EOS [N/Z(Au) = 1.49]

Constraints for K0 from elliptic flow

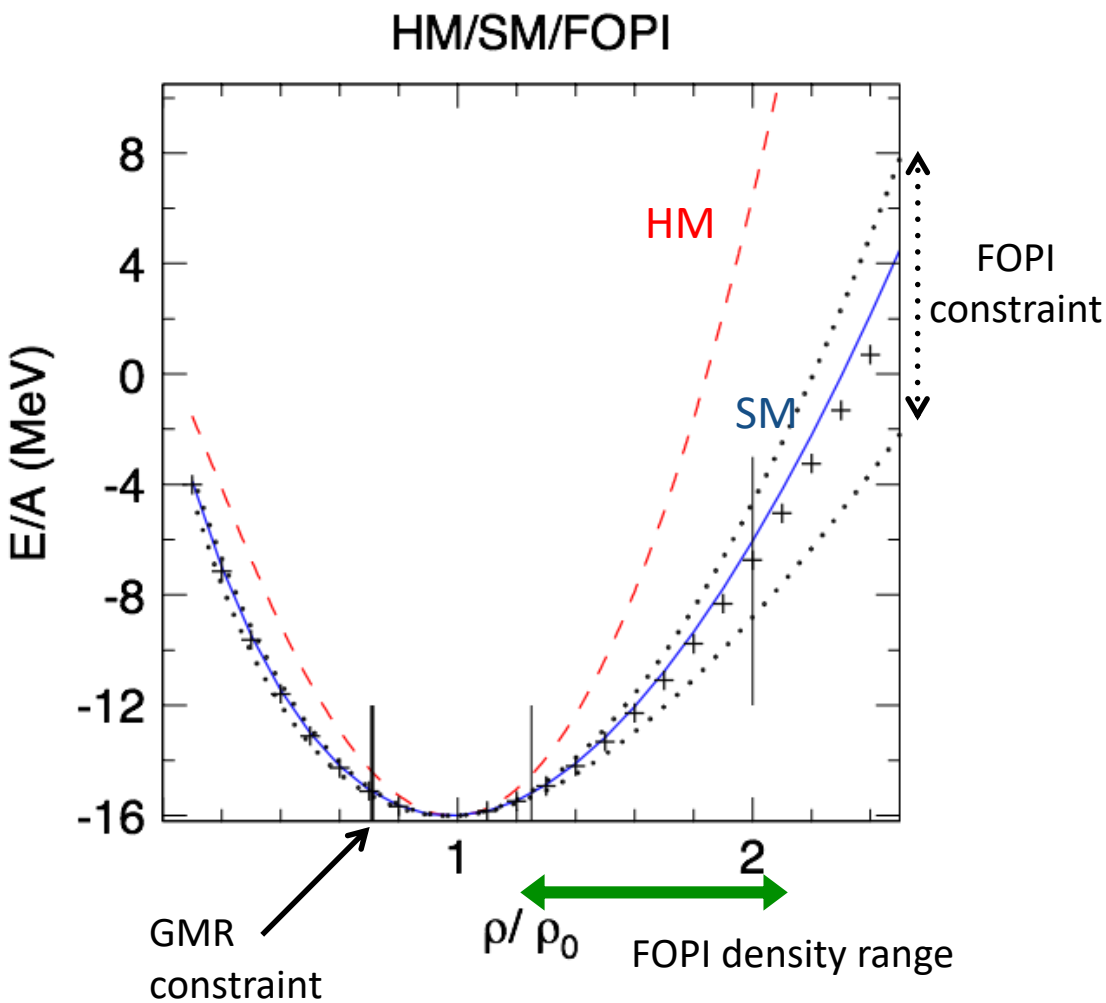
K_0 as from FOPI flow data

$IQMD \rightarrow K_0 = 190 \pm 30\ MeV$

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

$UrQMD \rightarrow K_0 = 220 \pm 40\ MeV$

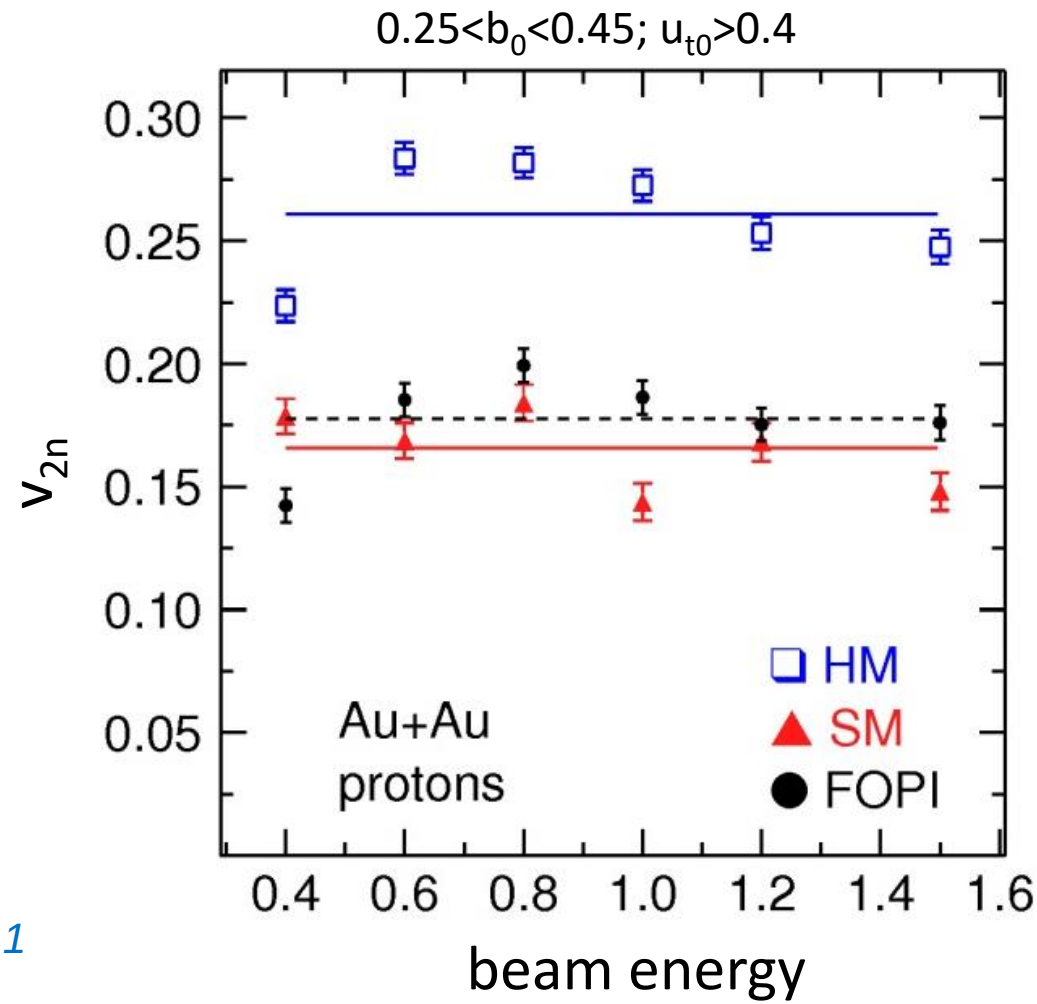
[Y. Wang et al., PLB-778(2018)207-212]



A. LeFevre et al, NPA 876 (2012) 1

Parametrization of elliptic flow

- sensitive to EOS over a large energy range
- $v_{2n}(E_{beam})$ varies by a factor ≈1.6, > measured uncertainty (≈1.1)
- relevant density range $\rho \simeq (1-3)\,\rho_0$

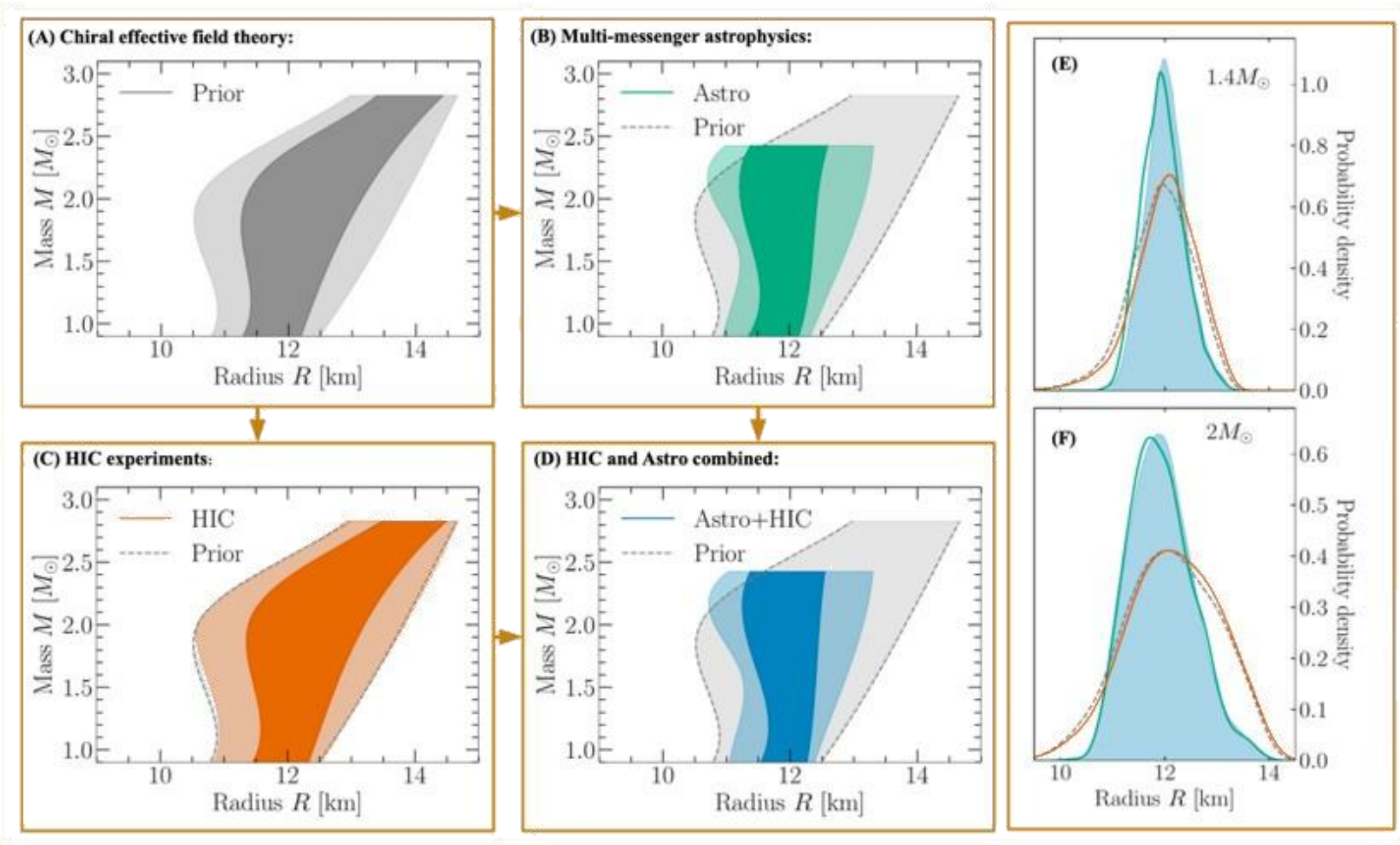


A. LeFevre et al, NPA 876 (2012) 1

$u_{t0} = y/y_{proj}$ (scaled transverse momentum)

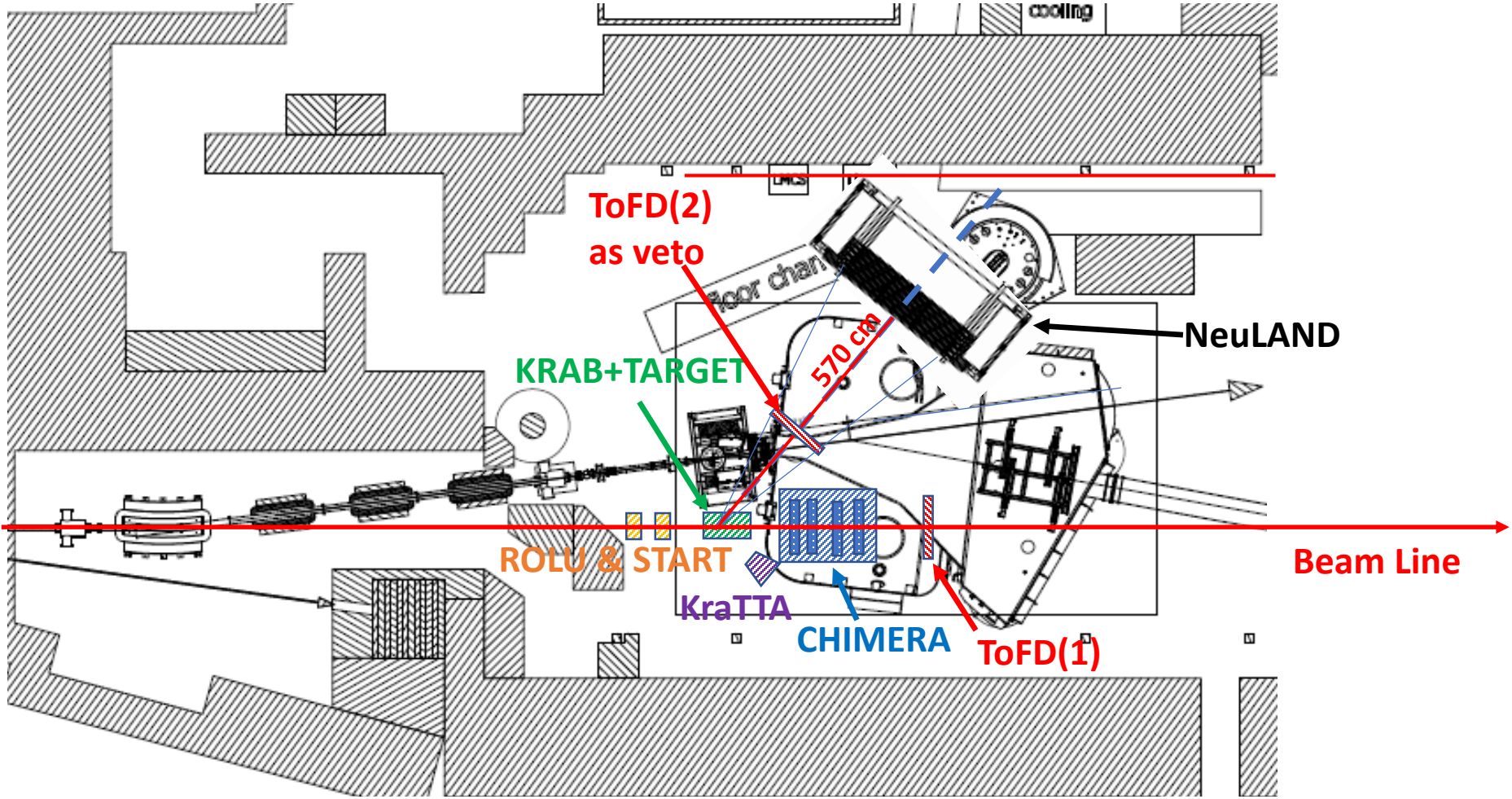
Combining HIC and astrophysical results in the same Bayesian analysis to constrain neutron matter EOS

« **HIC** » = FOPI+ASY-EOS+AGS - « **Astro** » = GW, NICER (pulsar X-ray hot spots)

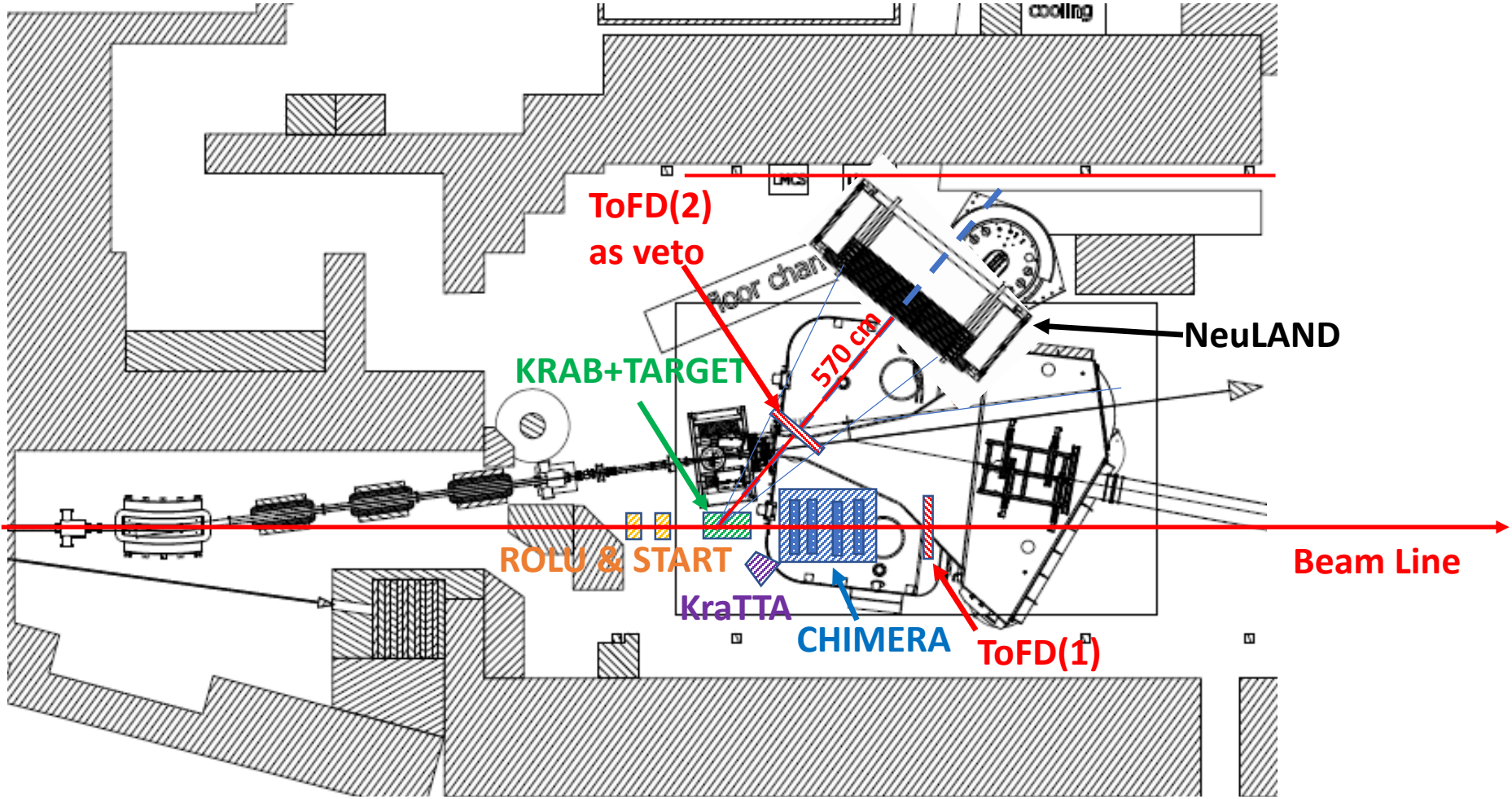


Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions, S. Huth et al., **arXiv:2107.06229 (2021)[nucl-th]**

EoS and symmetry energy experimental studies at GSI/FAIR energies



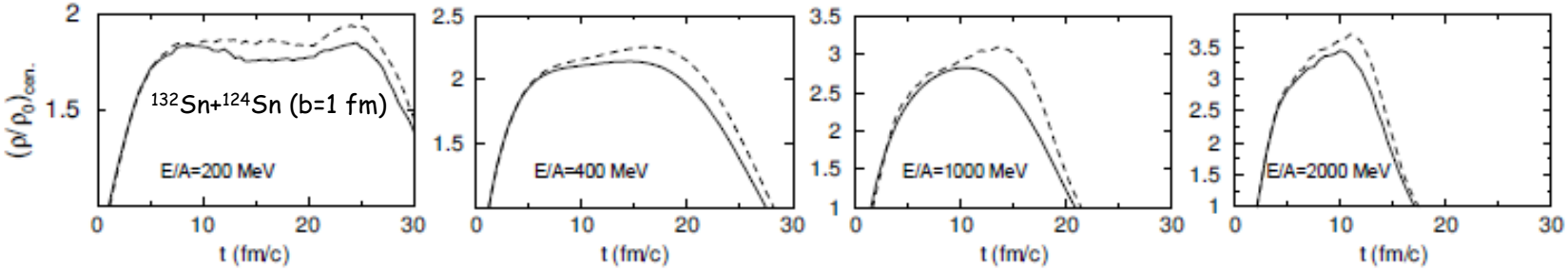
ASY-EOS II proposed reactions: Au+Au @ 250,400,600, 1000 AMeV and setu-up



ASY-EOS II LoI (2017)

Symmetry energy (L & K_{sym}) @ higher density

Which densities can be reached in the early stage of the reaction ? (BUU calculations)



Bao-An Li, NPA 708 (2002)

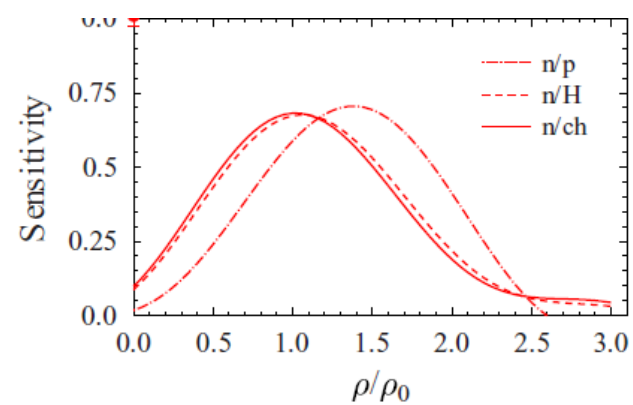
UrQMD predictions

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

Stiff γ=1.5, Soft γ=0.5

Sensitivity of Elliptic Flow Ratio to density

Au+Au @ 400AMeV (b<7.5 fm)



P. Russotto et al.,PRC 94, (2016)
M.D. Cozma TuQMD calculations

To explore higher densities:
- raise the beam energy
- use n-p observable

EoS and symmetry energy experimental studies at GSI/FAIR energies

Beam	Energy [AMeV]	Shifts	Days	Justification
^{197}Au	250	10	3.33	highest sensitivity on K_{sym}
^{197}Au	400	10	3.33	maximum squeeze-out, reference to ASY-EOS I
^{197}Au	600	10	3.33	highest sensitivity on L
^{197}Au	1000	10	3.33	highest densities probed with still significant sensitivity (~15%)
heavy	~400	5	1.66	commissioning of KRAB, FARCOS of the setup and DAQ, can be parasitic
		40+5	**15**	**Measurement of all energies will allow to discriminate between the soft and stiff assumptions from the observed trends (see left panel)**

Flows I

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

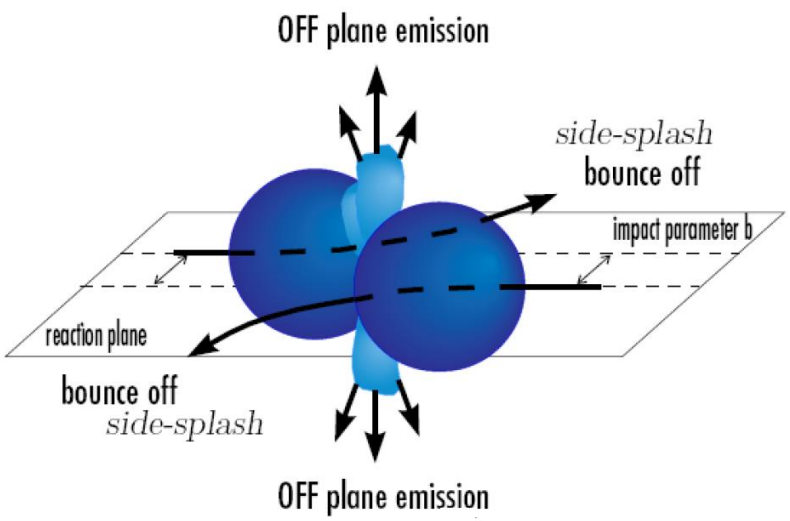
Y = rapidity
p_t = transverse momentum

$$V_1(y,p_t)=\left\langle\frac{p_x}{p_t}\right\rangle$$

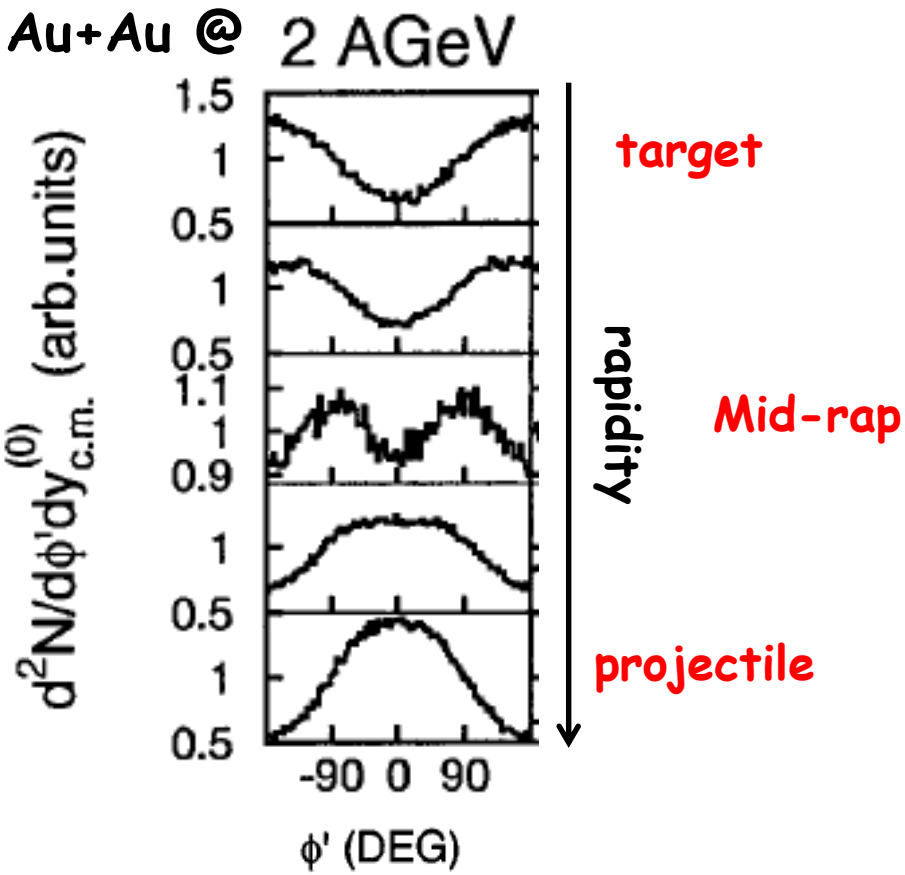
Transverse flow: it provides information on the angular distribution in the reaction plane

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

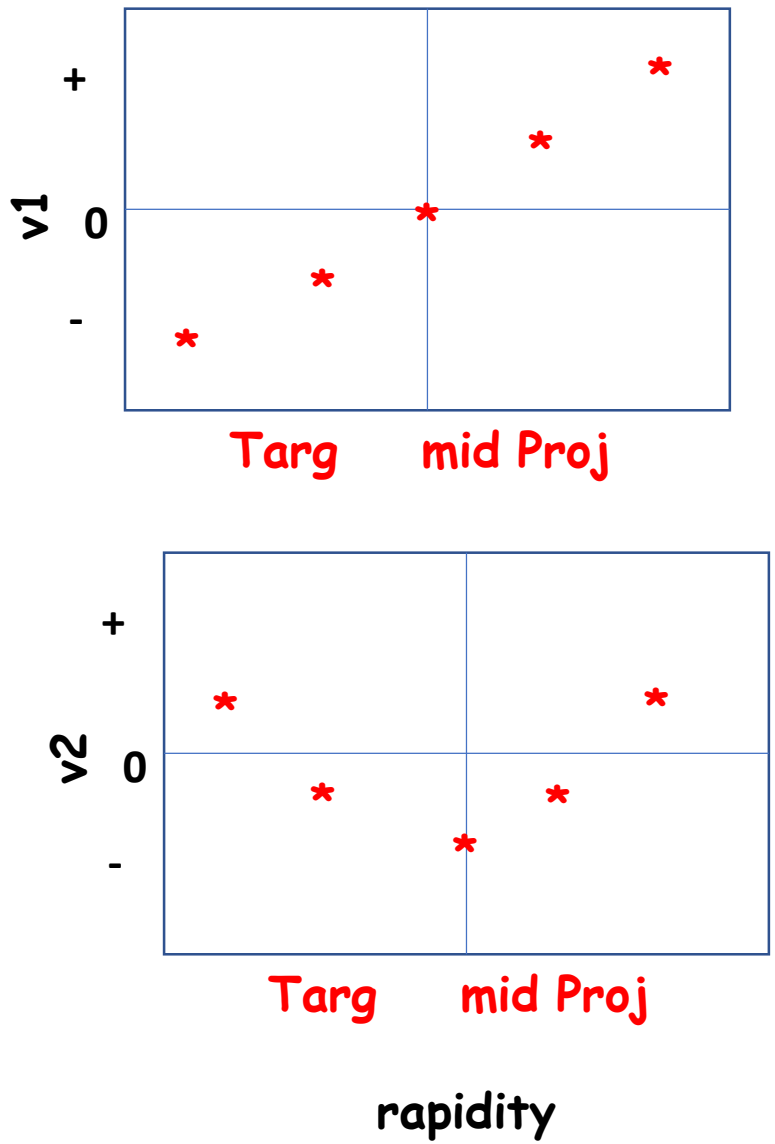
Elliptic flow: competition between in plane (V_2>0) and out-of-plane ejection (V_2<0)



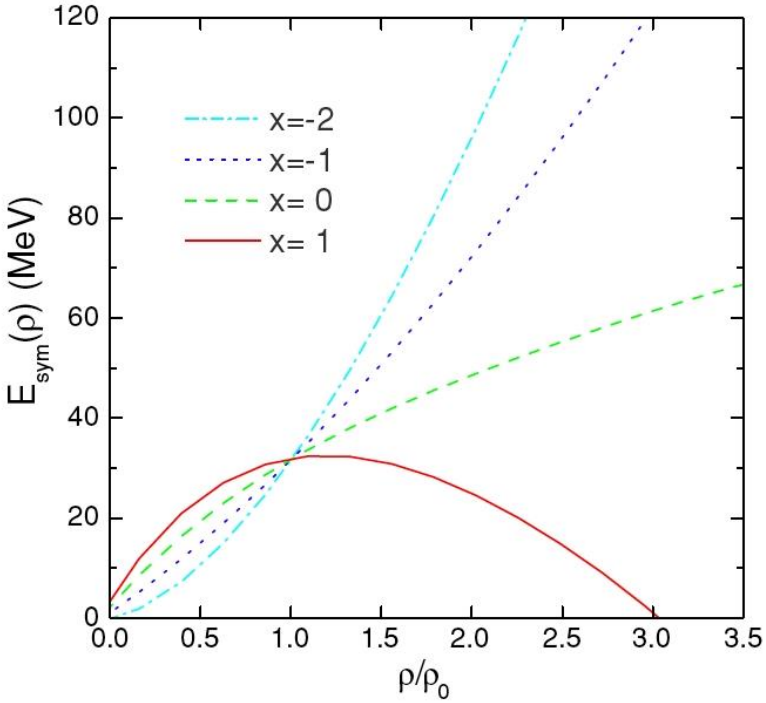
Flows II



C.Pinkenburg et al., (E895),
Phys.Rev.Lett. 83 (1999) 1295
nucl-ex/9903010



Not in scale: qualitative



Neutron/hydrogen

FP1: $\gamma = 1.01 \pm 0.21$

FP2: $\gamma = 0.98 \pm 0.35$

neutron/proton

FP1: $\gamma = 0.99 \pm 0.28$

FP2: $\gamma = 0.85 \pm 0.47$

adopted:

$L_{Sym} = 106 \pm 46$

High densities observable: flows

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

y = rapidity, pt = transverse momentum

ϕ_R = reaction plane orientation

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

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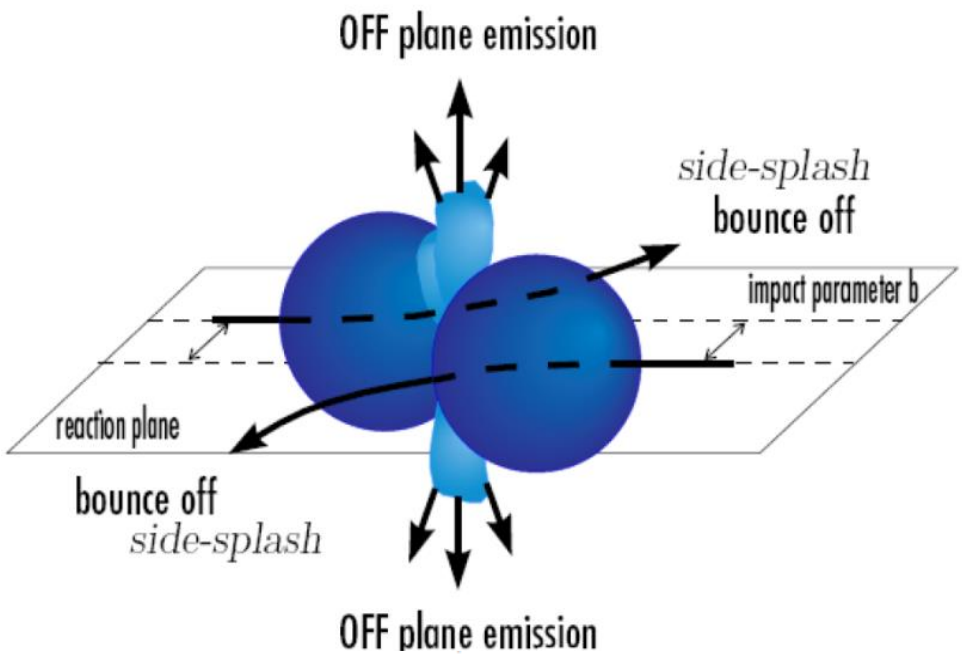
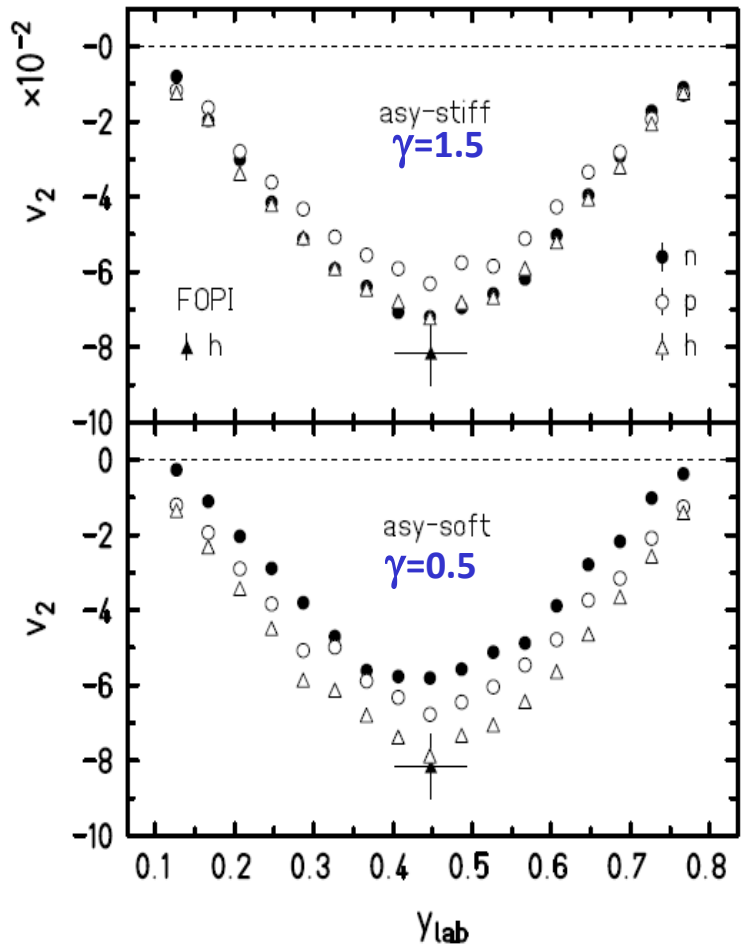


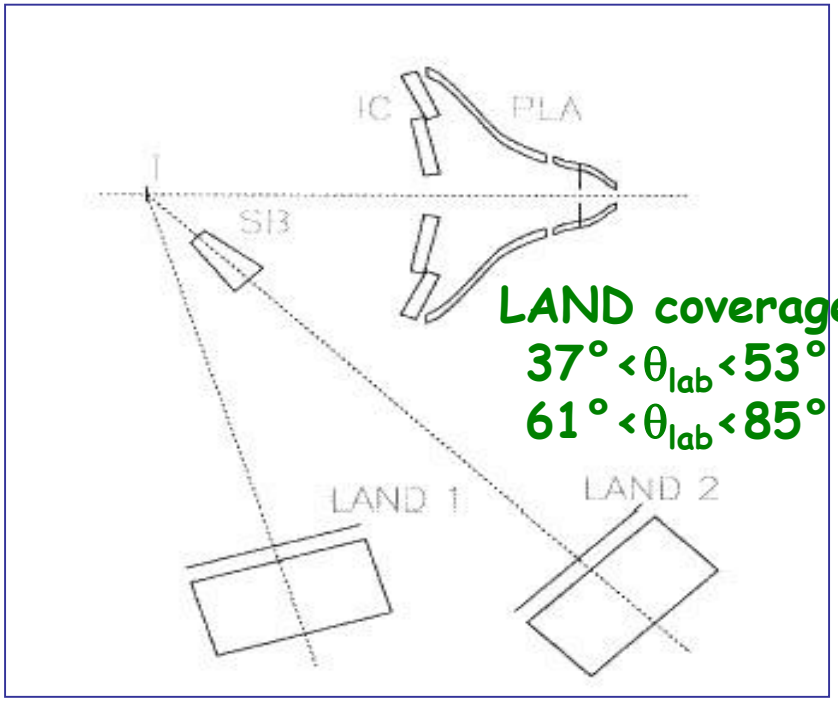
UrQMD :Au+Au @ 400 AMeV
5.5<b<7.5 fm

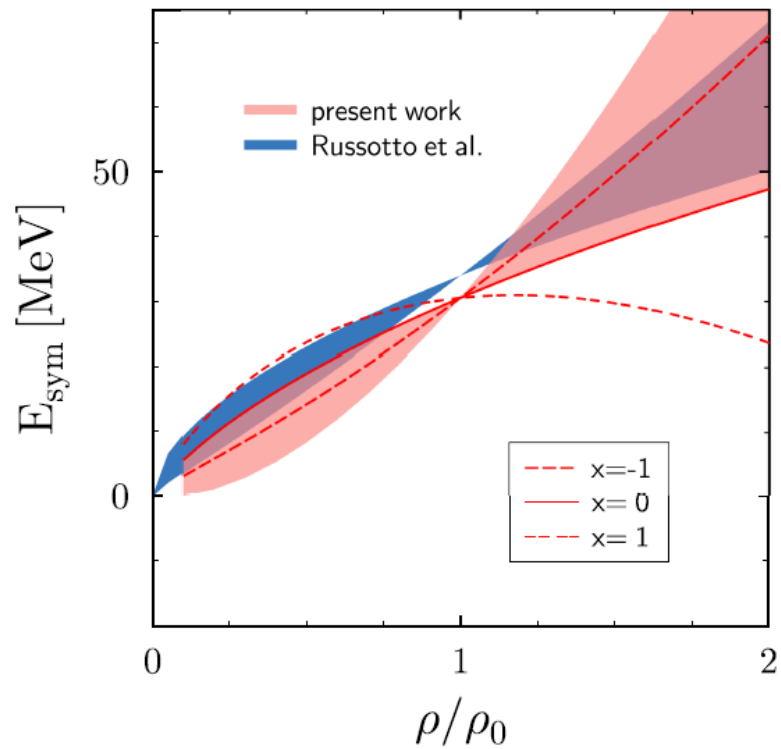


$$E_{sym}=E_{sym}^{pot}+E_{sym}^{kin}$$
$$=22\,\text{MeV}\cdot(\rho/\rho_0)^{\gamma}+12\,\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

Qingfeng Li, J. Phys. G31 1359-1374 (2005)
P.Russotto et al., Phys. Lett. B 697 (2011)

FOPI/LAND experiment on neutron squeeze out (1991)





UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law parameterization of the symmetry energy
γ = 0.9 ± 0.4, L=83±26

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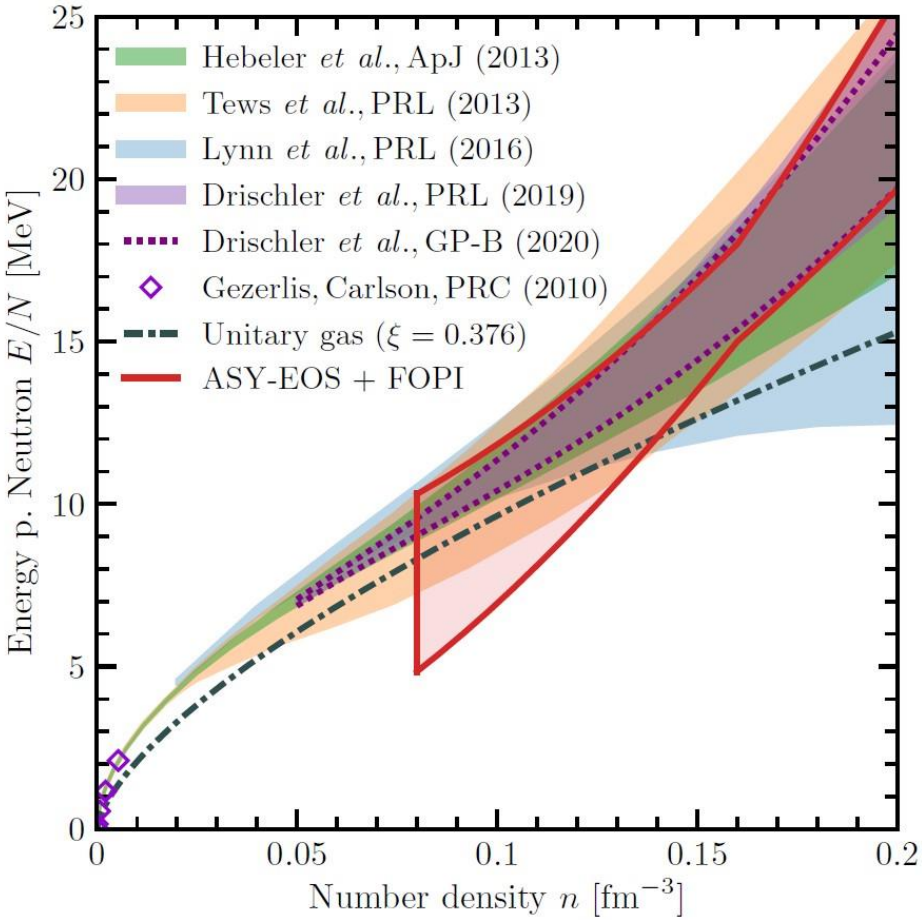
Y. Leifels et al., PRL 71, 963 (1993)
P.Russotto et al., PLB 697 (2011)

Comparison of HIC results to 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 1-2ρ_0
- K_0 as from FOPI flow data



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

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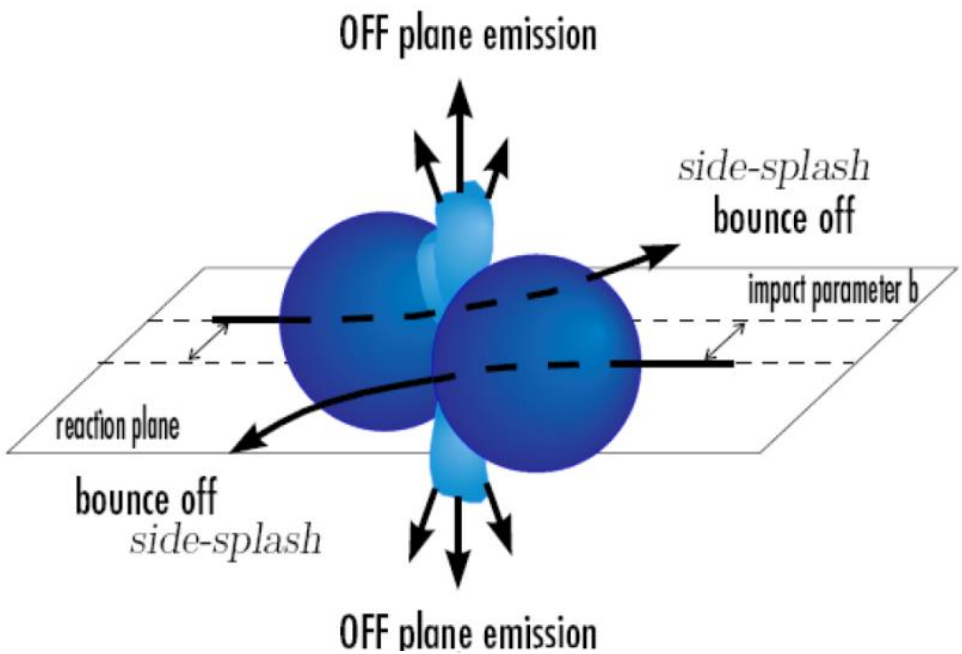

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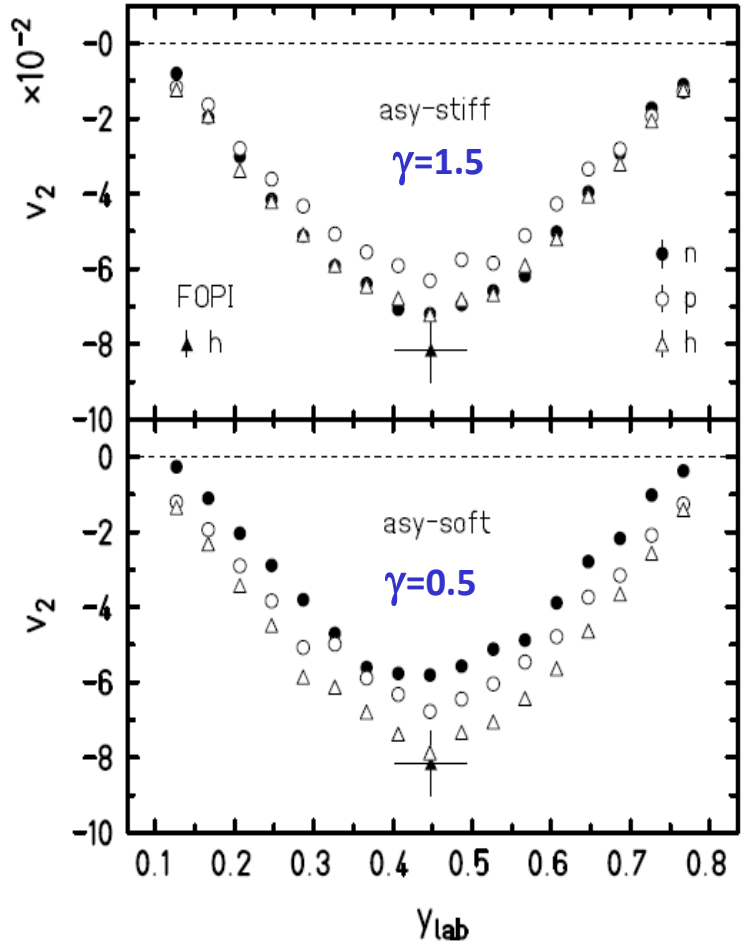

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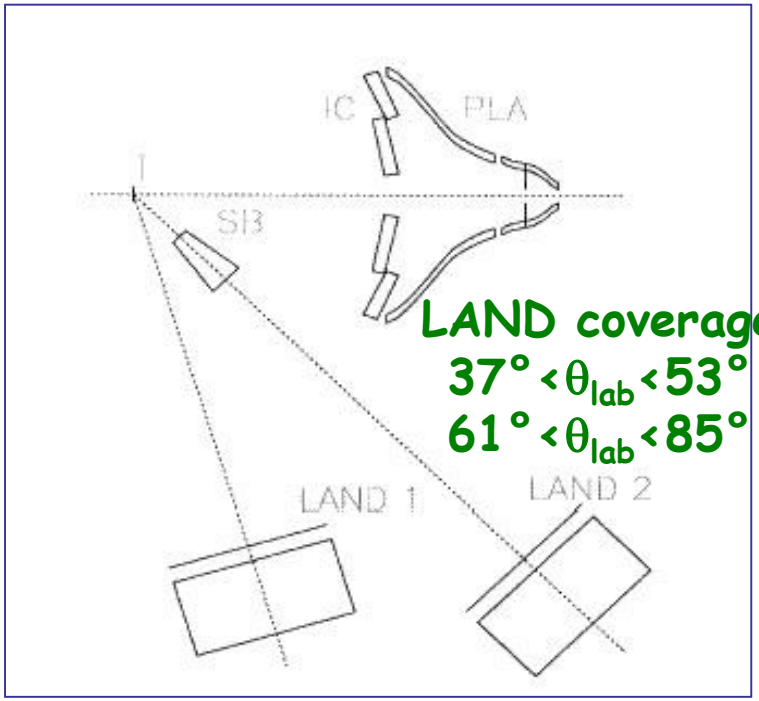

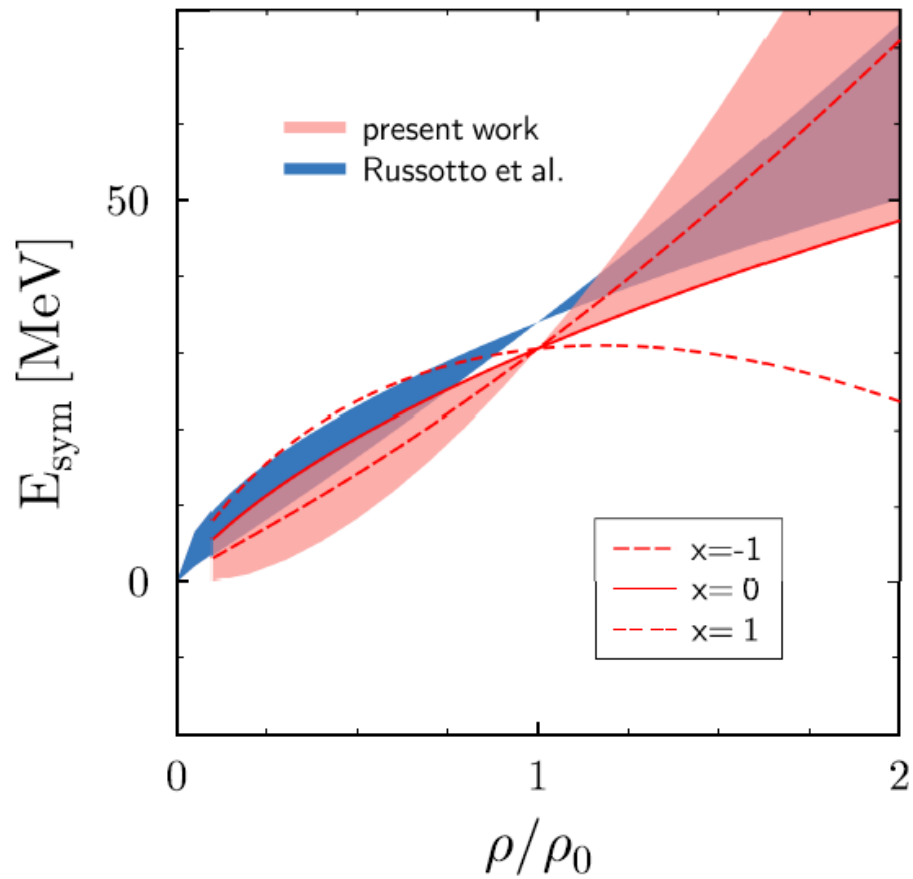

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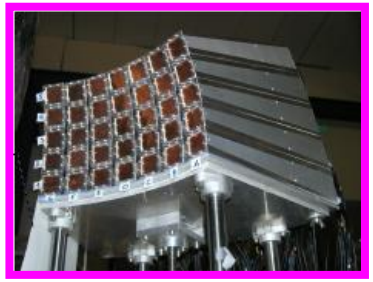
P.Russotto et al., PLB 697 (2011)

ASY-EOS S394 experiment @ GSI Darmstadt (May 2011)

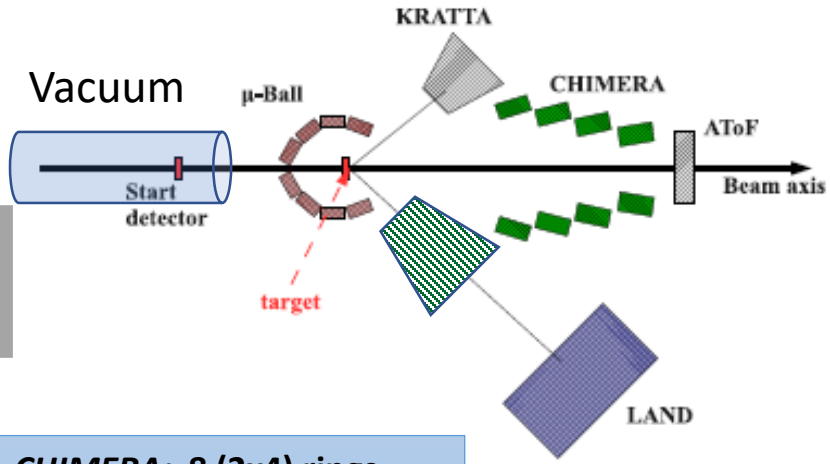
After re-analysis of Au+Au FOPI-LAND data (1991) P.Russotto et al., PLB 697 (2011)

µBall: 4 rings 50 CsI(Tl), Θ>60°. Discriminate target vs. reactions with air. Multiplicity and reaction plane measurements.

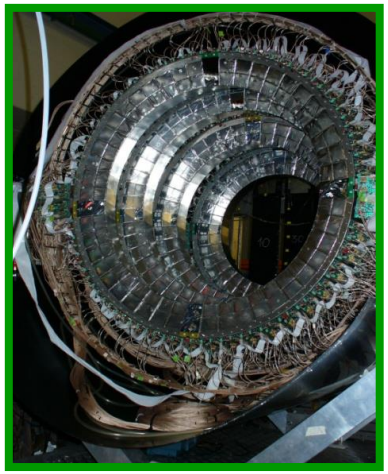


KraTTA: 35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . Light particles and IMFs emitted at midrapidity

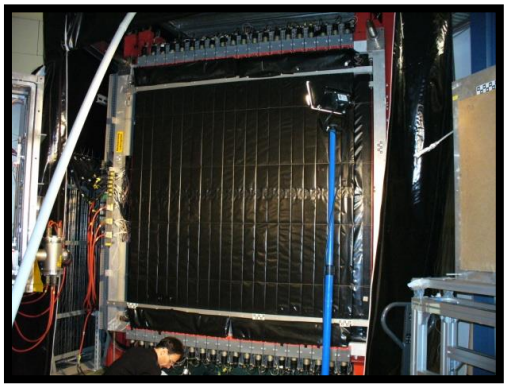
Shadow bar: evaluation of background neutrons in LAND



TOFWALL: 96 plastic bars; ToF, ΔE, X-Y position. Trigger, impact parameter and reaction plane determination



CHIMERA: 8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy: impact parameter and reaction plane determination



LAND: Large Area Neutron Detector . Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. Neutrons and Hydrogen detection. Flow measurements