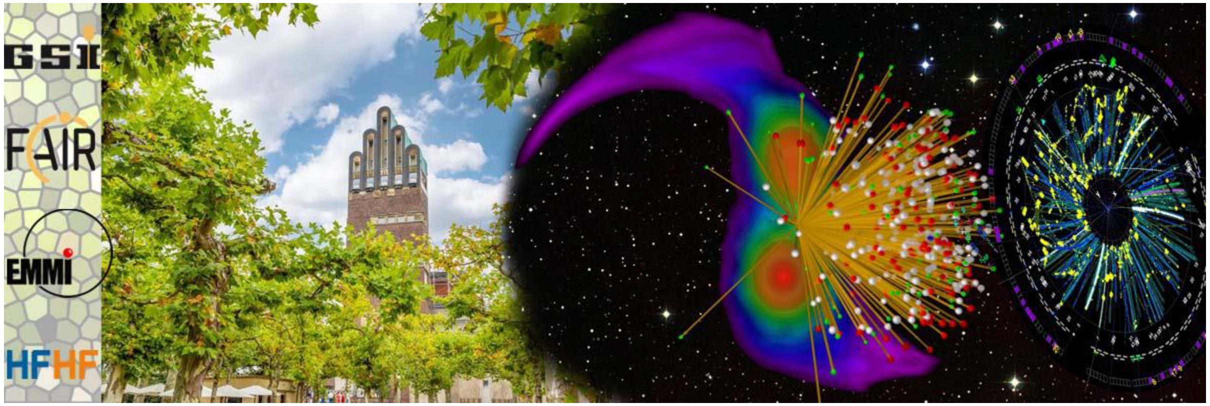
NuSym23, 11th International Symposium on Nuclear Symmetry Energy

Darmstadt (Germany), September 18-22, 2023



P. Russotto[1] , A. Le Fèvre[2], J. Łukasik[3]
on behalf of R3B Collaboration

ASY-EOS II – observables and expectations

[1]INFN-Laboratori Nazionali del Sud, Catania, Italy
[2]GSI, Darmstadt, Germany
[3]IFJ PAN, Kraków, Poland

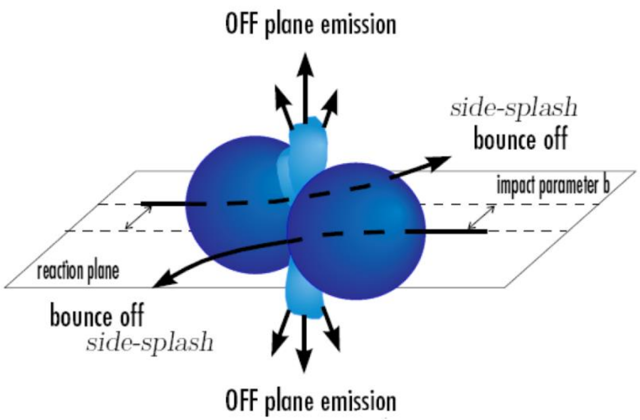
Elliptic flow as a probe of high-density symmetry energy

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

y = rapidity
p_t = transverse momentum

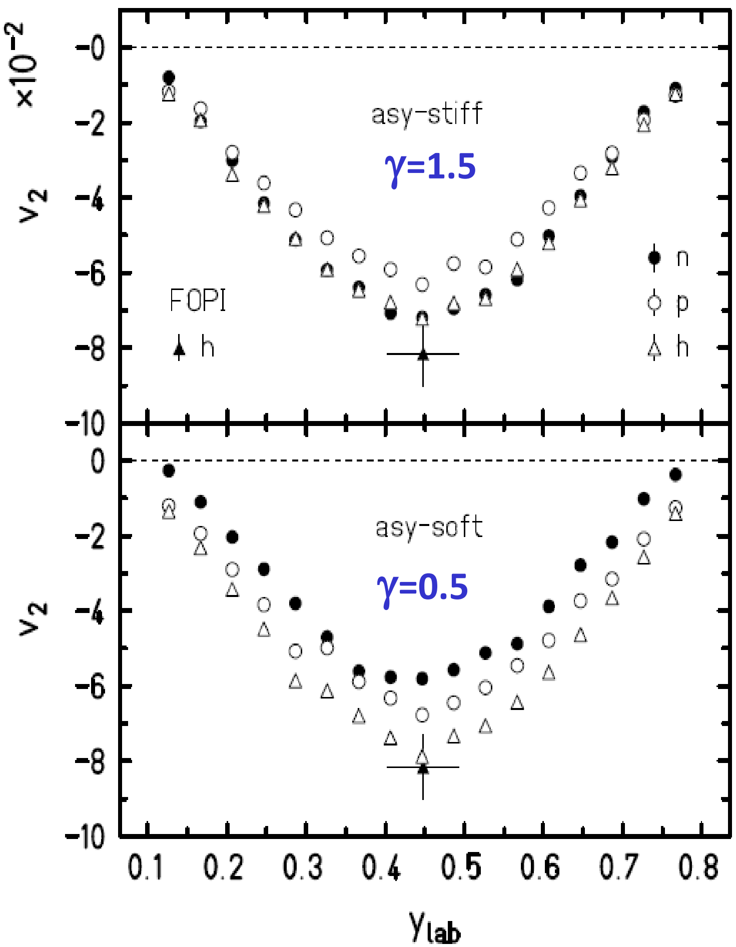
$$V_2(y,p_t)=\left\langle \frac{p_x^2-p_y^2}{p_t^2}\right\rangle$$

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



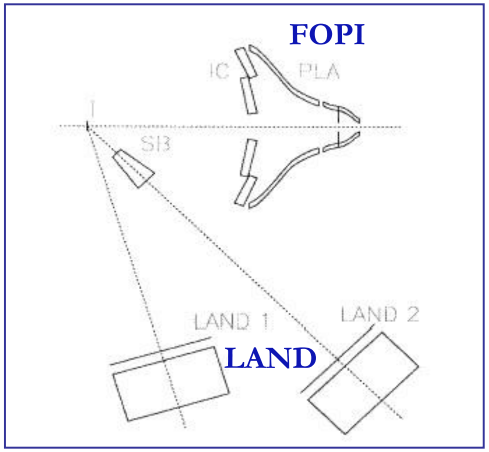
$$E_{\text{sym}}=E_{\text{sym}}^{\text{pot}}+E_{\text{sym}}^{\text{kin}}$$
$$=22\text{ MeV}\cdot(\rho/\rho_0)^{\gamma}+12\text{ MeV}\cdot(\rho/\rho_0)^{2/3}$$

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



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

Results from FOPI-LAND data re-analysis



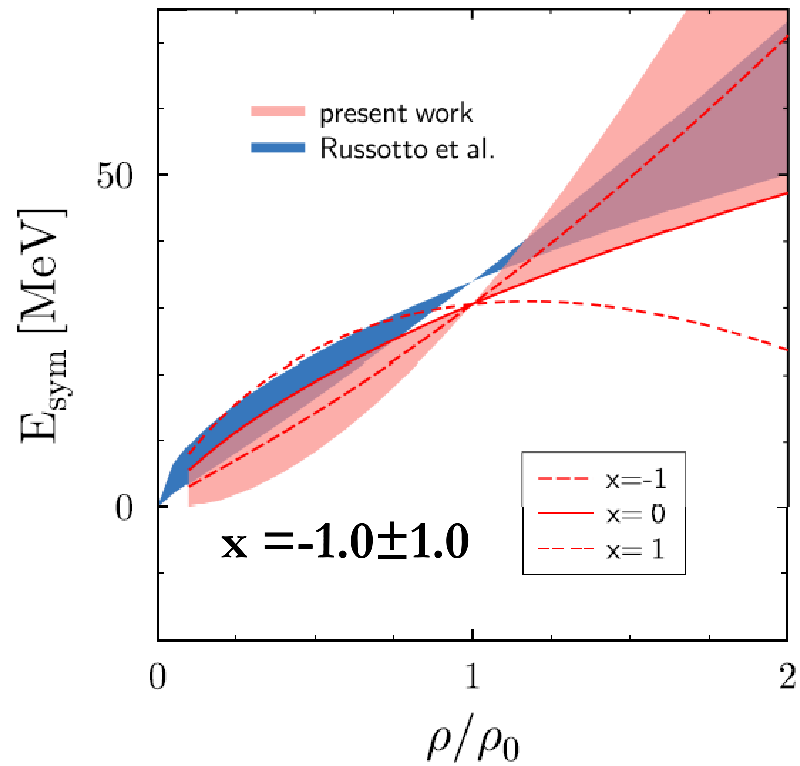
Y.Leifels et al., PRL71 963 (1993)

v_2^n/v_2^H and
v_2^n/v_2^p but
poor statistics

UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS
momentum independent power-law parameterization of the symmetry energy
P.Russotto et al., Phys. Lett. B 697 (2011)

Tübingen-QMD:
density dep. of NNECS
soft vs. hard symmetric-matter EoS
width of wave packets
momentum dependent (Gogny inspired) parameterization of the symmetry energy
M.D. Cozma, PLB 700, 139 (2011)

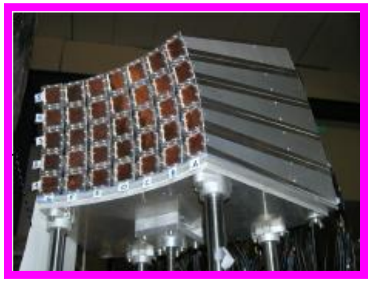
Au+Au 400 AMeV b< 7.5 fm



M.D. Cozma et al., Towards a model-independent constraint of the high-density dependence of the symmetry energy, PRC88 044912 (2013)

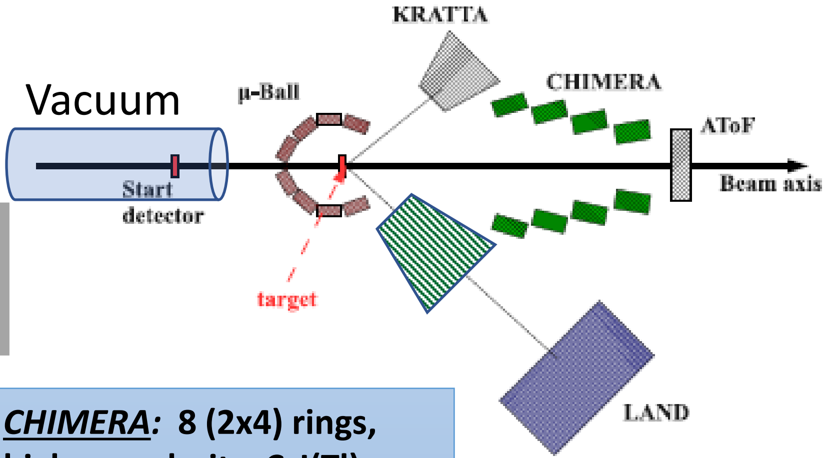
ASY-EOS (S394) experiment at GSI Darmstadt (May 2011)
Au+Au @ 400 AMev

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

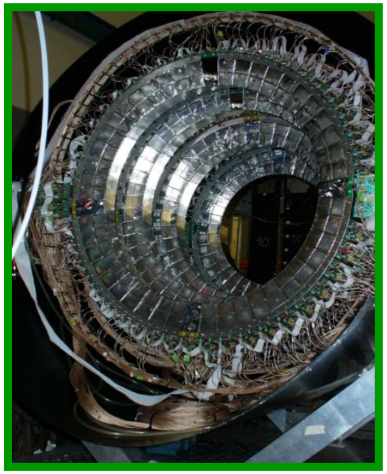


***KraTTA*:** 35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . **Light particles and IMFs emitted at midrapidity**

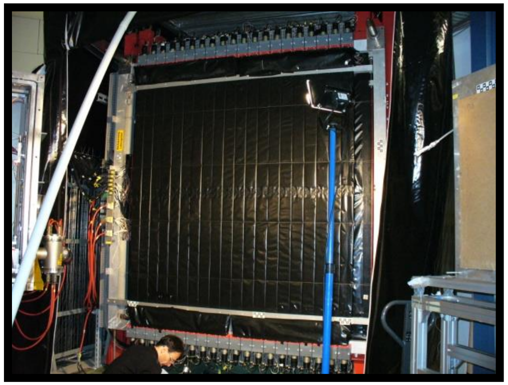
Shadow bar: evaluation of neutron background in LAND



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

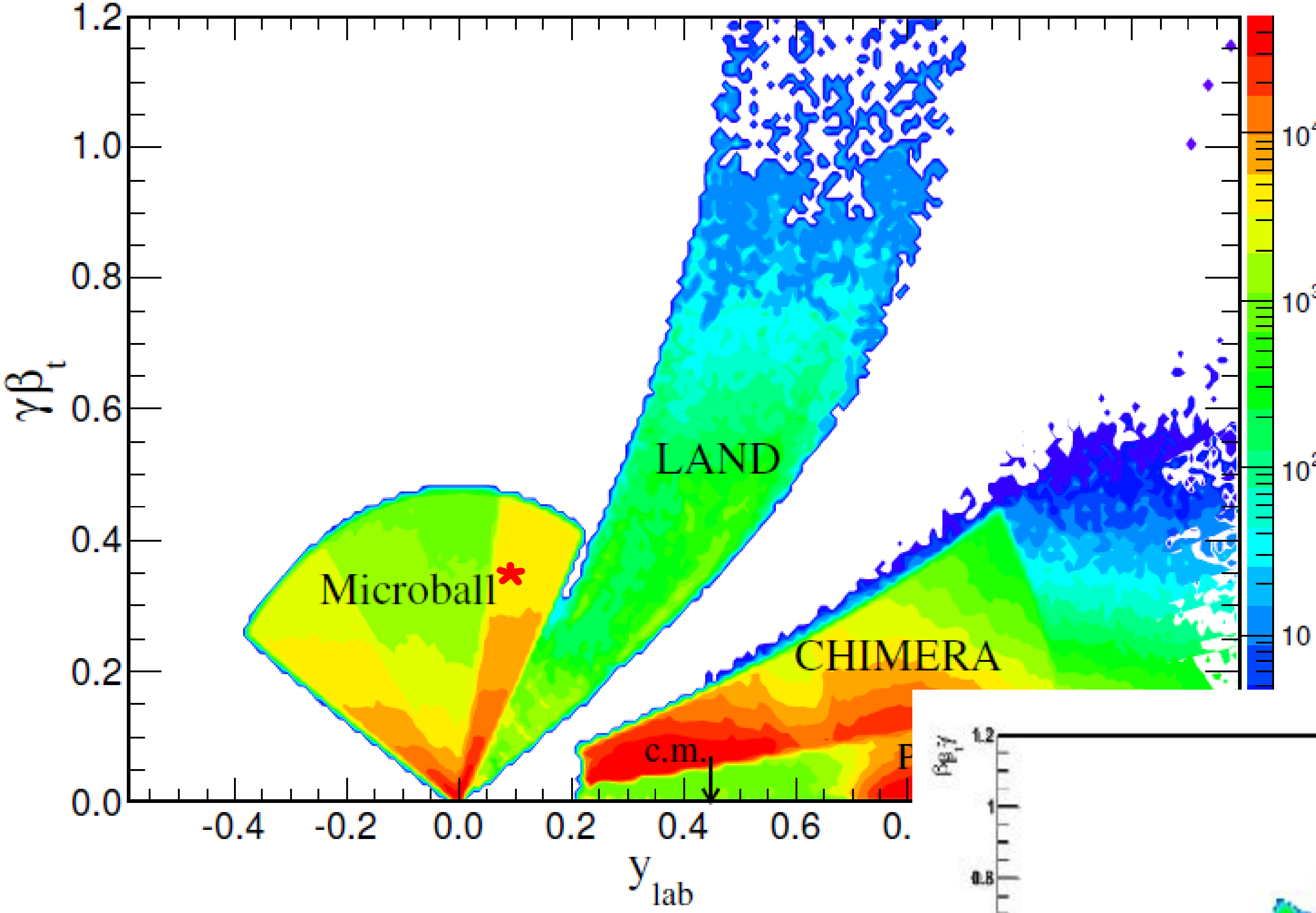


***CHIMERA*:** 8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. **Multiplicity, Z, A, Energy: impact parameter and reaction plane determination**

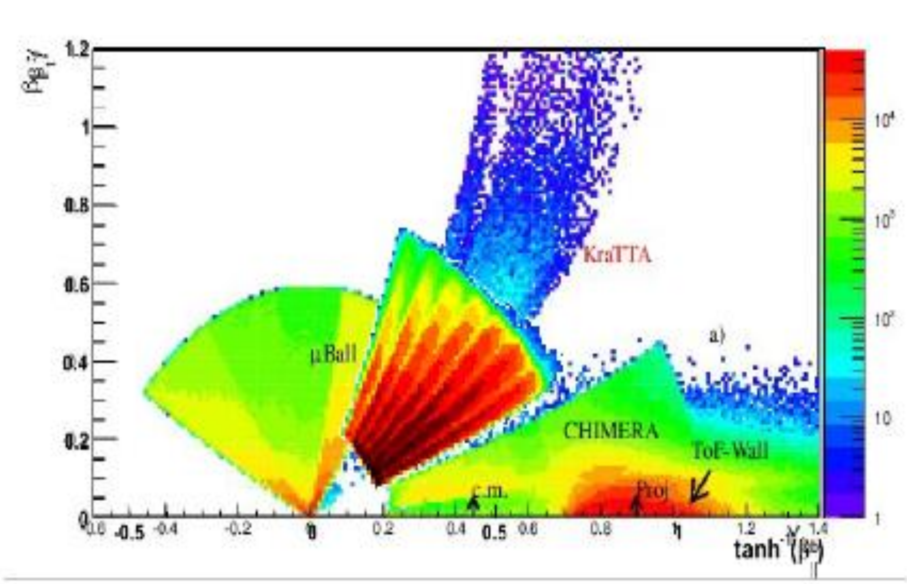


***LAND*:** Large Area Neutron Detector+Veto. Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. **Neutrons and Hydrogen detection. Flow measurements**

Au+Au @ 400 A.MeV: Some kinematics



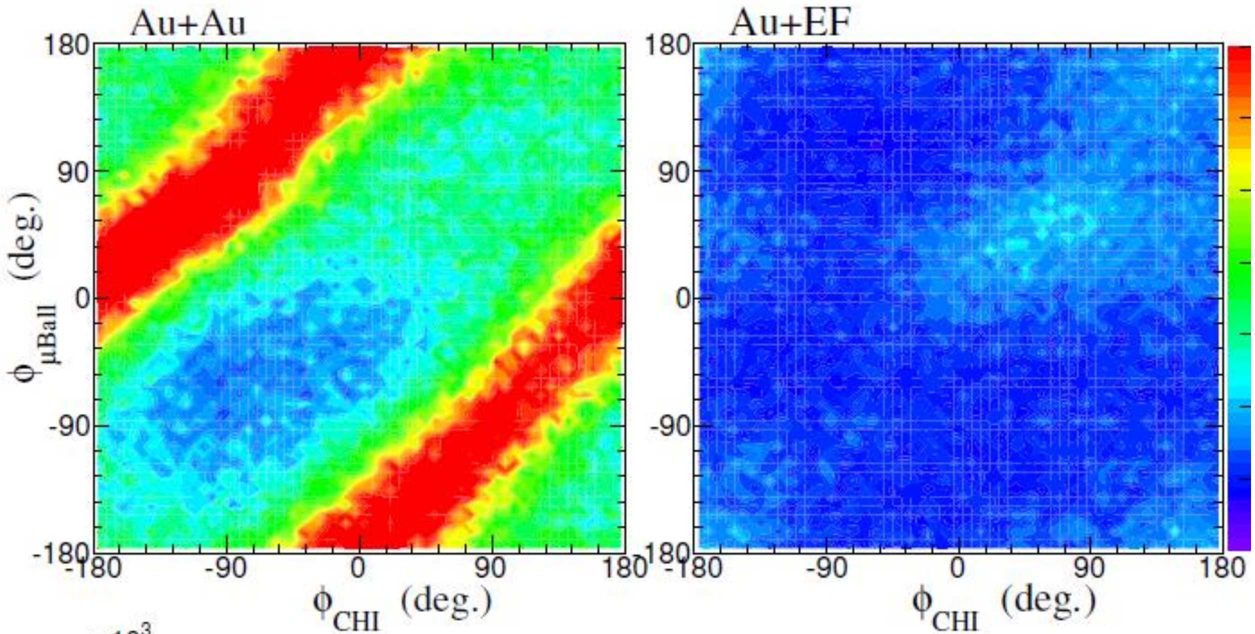
KRATTA:
J. Lukasik et al., Nucl. Instr. Meth. 709 (2013) 120128

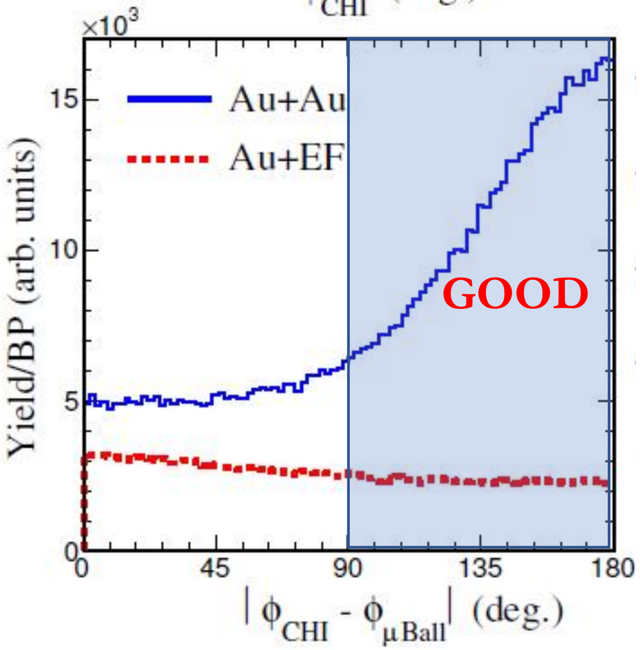


*** Uniform distribution with E_{Kin}<100 Mev**

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

Au+Au @ 400 AMeV: Background rejection





CHIMERA *mult(y_{cm}>0.1) ≥ 4*

$$\vec{Q} = \sum_{i=1}^{M} w_i Z_i \gamma \vec{\beta}_t^{\,i} \qquad w_i = \begin{cases} 1 & \text{for } Y_{cm} > 0.1 \\ 0 & \text{for } Y_{cm} < 0.1 \end{cases}$$

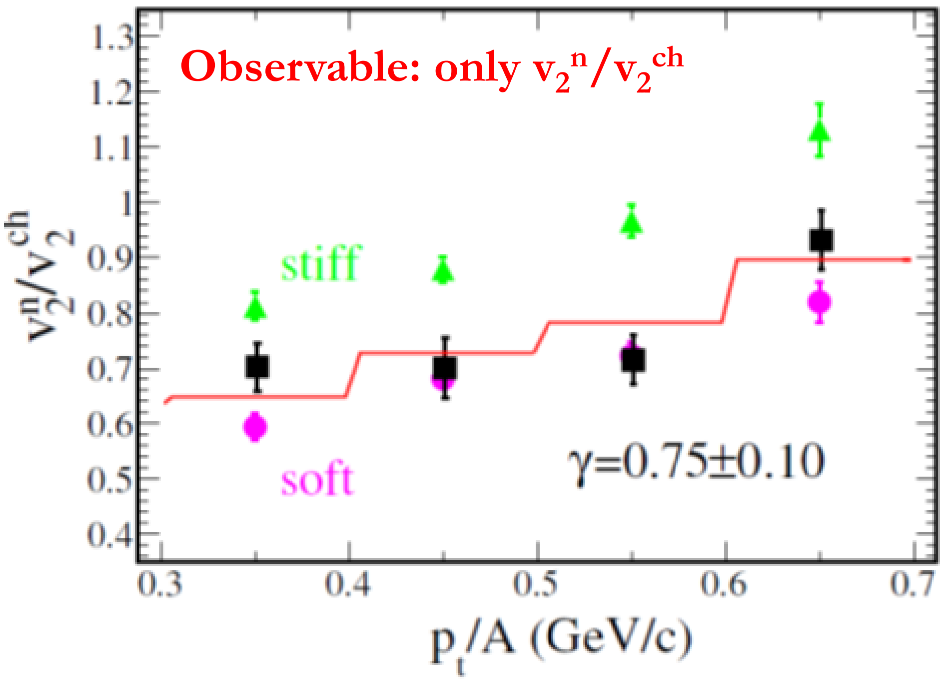
μBall *mult ≥ 2*

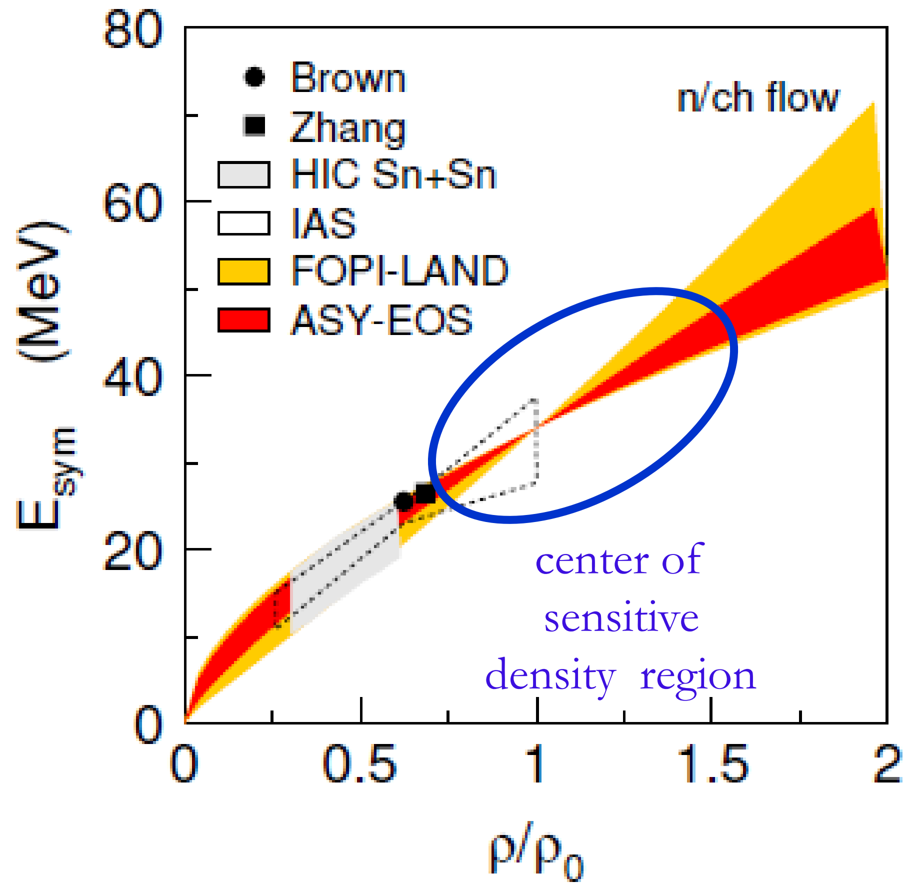
$$\vec{Q} = \sum_{i=1}^{M} \hat{r}_t^{\,i}$$

ad. from P. Danielewicz et al., PLB 1985

ASY-EOS results with UrQMD

Au+Au @ 400 AMeV b<7.5 fm





ASY-EOS DATA: P. Russotto et al., PRC 94, 034608 (2016)

γ = 0.72± 0.19 ; L=72±13 MeV

FOPI-LAND DATA : P. Russotto et al., Phys. Lett. B 697 (2011)

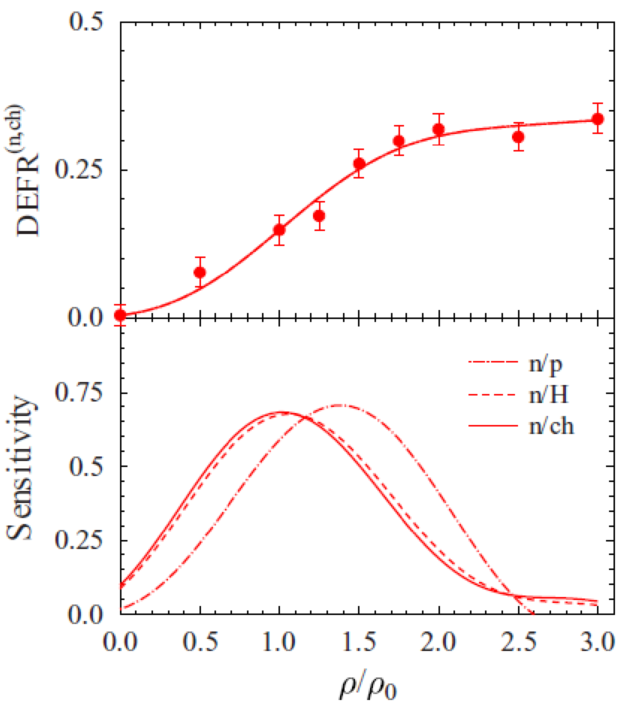
γ = 0.9 ± 0.4 ; L=83±26 MeV

HIC (isospin diffusion) M.B. Tsang et al., PRC 86, 015803 (2012)
Isobaric **A**nalog **S**tates P. Danielewicz & J. Lee, NPA922 (2014).
Double magic nuclei, neutron skin, binding energies: Brown, PRL 111, 232502 (2013); Zhang & Chen, Phys. Lett. B 726 (2013),

ASY-EOS results with TuQMD

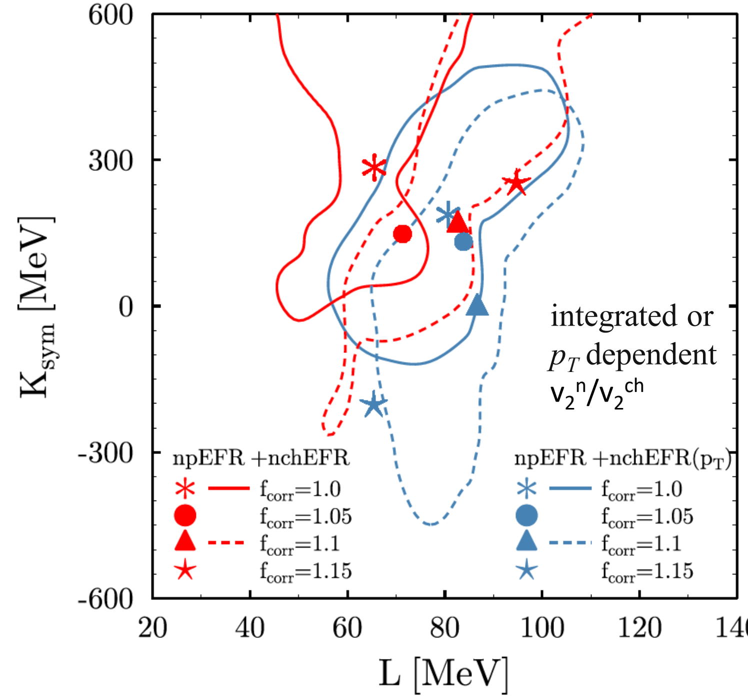
$$\mathrm{DEFR}^{(n,Y)}(\rho) = \frac{v_2^n}{v_2^Y}(x=-1,\rho) - \frac{v_2^n}{v_2^Y}(x=1,\rho)$$

$$V_{\mathrm{sym}}(x,\tilde{\rho}) = \begin{cases} V_{\mathrm{sym}}^{\mathrm{Gogny}}(x,\tilde{\rho}) & \tilde{\rho} \leqslant \rho, \\ V_{\mathrm{sym}}^{\mathrm{Gogny}}(0,\tilde{\rho}) & \tilde{\rho} > \rho, \end{cases}$$



TuQMD calculations by M.D. Cozma
P. Russotto et al., PRC 94, 034608 (2016)

TuQMD MDI2 interaction:
independent variations of L and K_{sym}

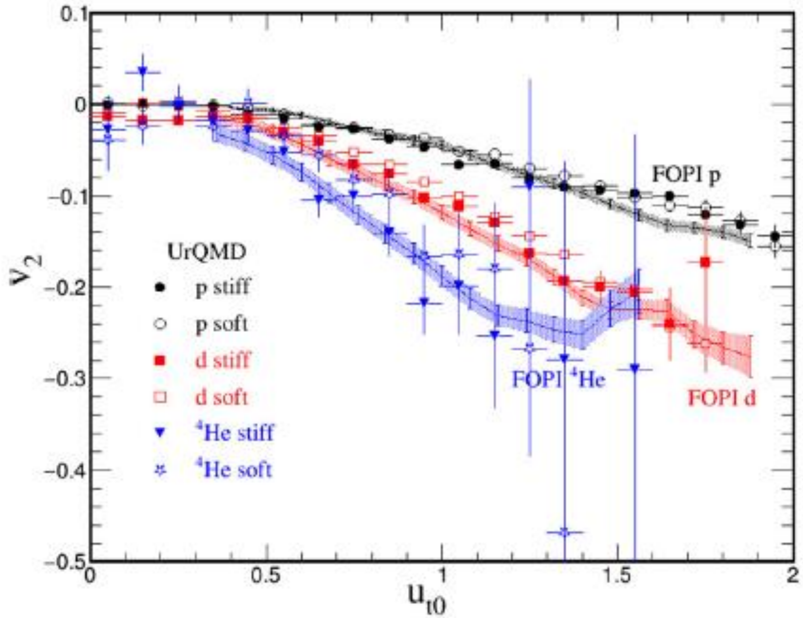


MDI2:
$$L = 85 \pm 22(\mathrm{exp}) \pm 20(\mathrm{th}) \pm 12(\mathrm{sys})\ \mathrm{MeV}$$
$$K_{sym} = 96 \pm 315(\mathrm{exp}) \pm 170(\mathrm{th}) \pm 166(\mathrm{sys})\ \mathrm{MeV}.$$

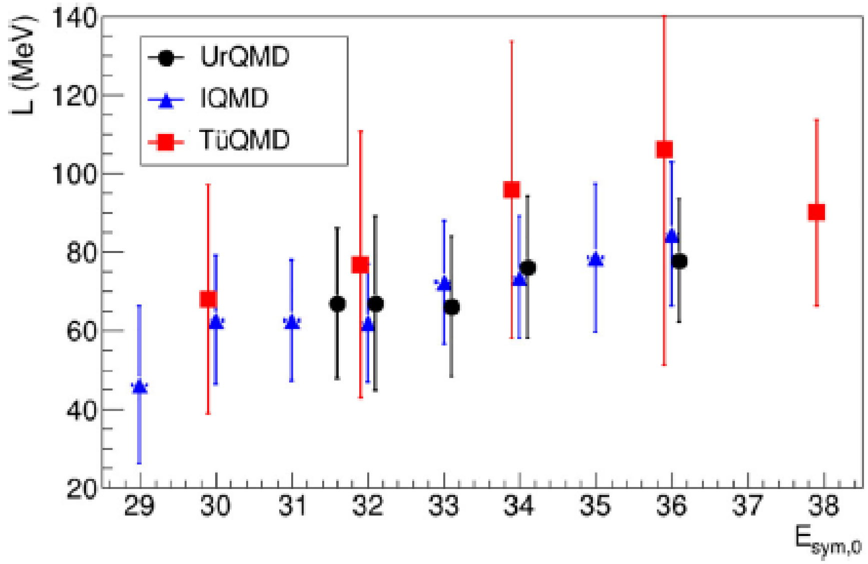
cMDI2: $L = 84 \pm 30(\mathrm{exp}) \pm 19(\mathrm{theor})\ \mathrm{MeV}$
(only FOPI-LAND v_2^n/v_2^p):

M.D. Cozma, Feasibility of constraining the curvature parameter of the symmetry energy using elliptic flow data. EPJA 54(3), 40 (2018).

ASY-EOS results: comparison among models



Newer UrQMD version as of Y. Liu et al. PRC103 014616 (2021) compared to FOPI data



UrQMD, TuQMD and IQMD used with same prescriptions:

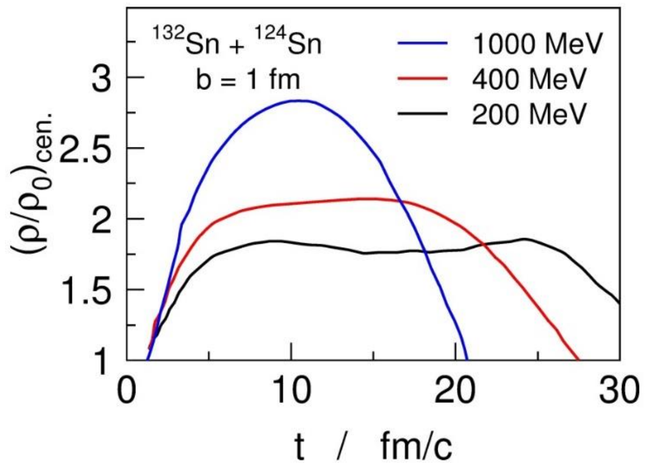
- clusterization algorithm tuned to FOPI charge distribution
- FOPI flow reproduction (to the best)
- re-weighting isotope contribution to v_2^{ch}

P. Russotto et al., Riv. Nuovo Cimento 46, 1 (2023)

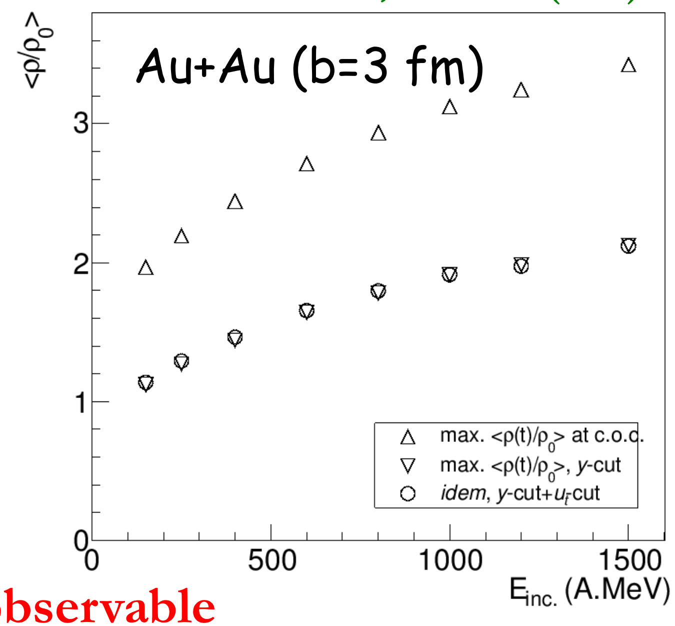
Advancing to:

♦ higher energies ≈ higher densities

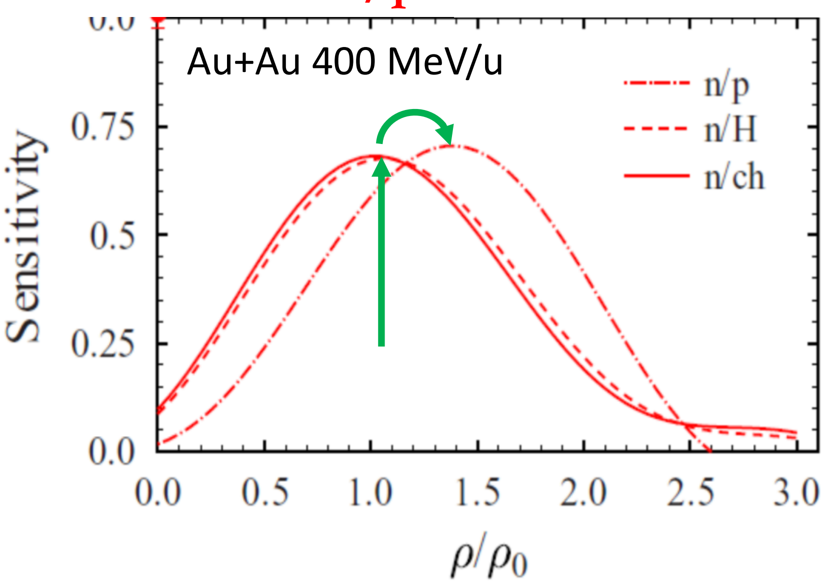
Li, Bao-An, NPA 708, 365 (2002)



A. Le Fèvre et al., NPA 945 (2016)



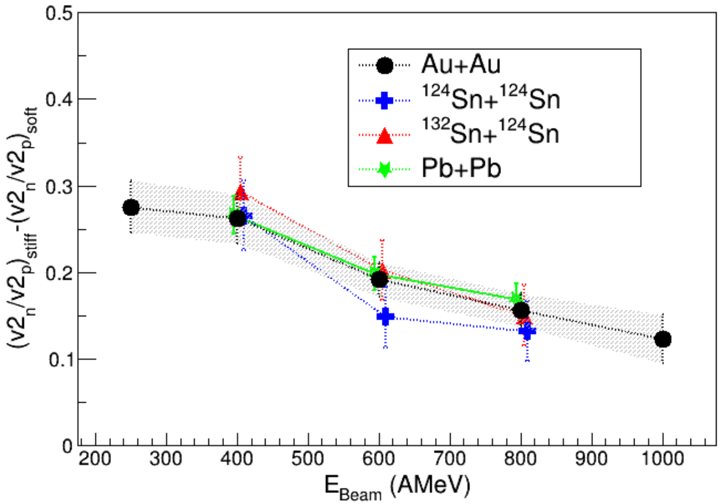
♦ the n/p observable



Advancing to higher densities with:

♦ sufficient sensitivity

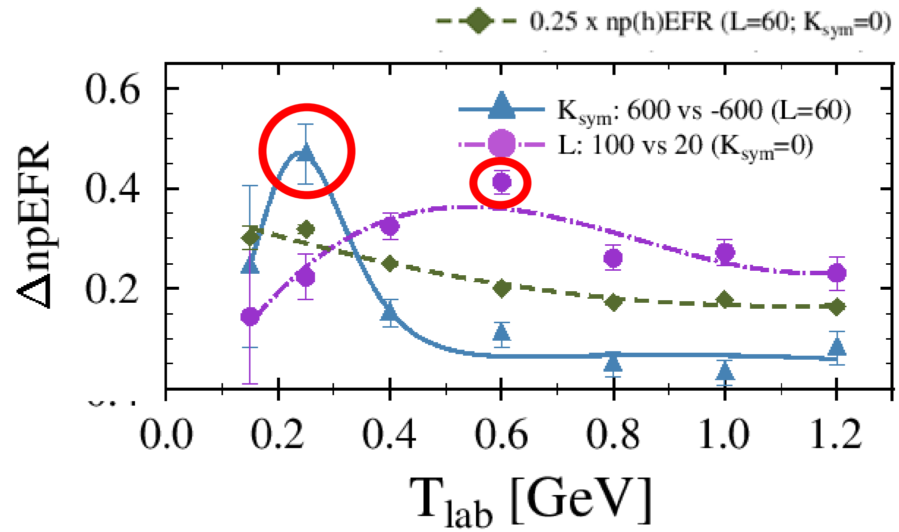
UrQMD predictions



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

Stiff γ=1.5, Soft γ=0.5

TuQMD predictions



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

M.D. Cozma, EPJA 54 (2018) 40

♦ and extract both L and K_{sym}

Combining HIC and astrophysical results to constrain neutron matter EOS

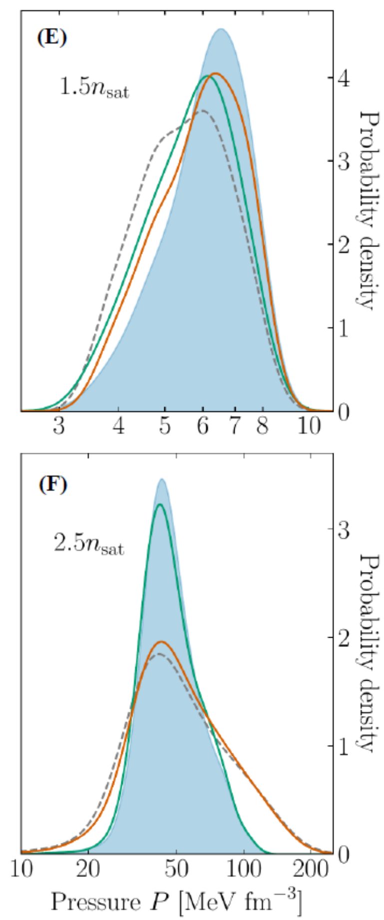
« HIC » = FOPI+ASY-EOS+AGS - « Astro » = GW, NICER (pulsar X-ray hot spots)

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 ($>2\rho_0$) 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., ***Nature volume 606, pages 276–280 (2022)***

See Peter T.H. Pang talk on Thursday

Last G-PAC (Sep 2022) : proposed set-up and beam requests

- We asked to run in cave C in 2024 once GLAD and other dets will be moved out

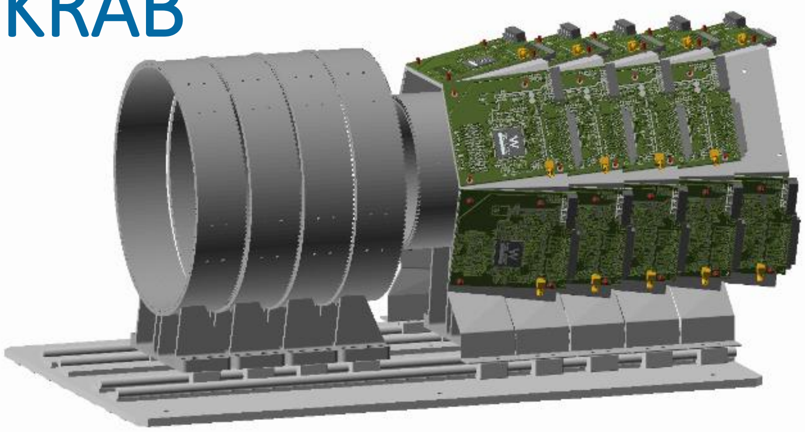
• **confirm the ASY-EOS result and improve the precision**: given the highest-sensitivity of the n-p ratio and the expected better detector response, we expect to be able to reduce the total uncertainty on L by, at least, a factor 2, i.e. at the level of ~ 7 MeV;
• **extend the knowledge of the symmetry energy to higher densities** with respect to those tested in the ASY-EOS experiment; for that we plan to use a multi-parametric description of the Esym, and fit the v_2^n/v_2^p and v_2^n/v_2^H at different beam energies, corresponding to different density regions tested, simultaneously. We aim to reach a similar, as in the previous item, precision on L and an error on Ksym ~ 50 – 75 MeV ;
• **confirm/improve the model invariance of the obtained results**: ASY-EOS data analyses based on UrQMD, TüQMD and IQMD have shown a substantial agreement of results, at the level of 5-10%. Assessing residual model dependences through extended comparison of the results obtained from the new data is an important objective.

Beam	Energy	Time		Purpose	Note
^{197}Au	250 AMeV	11 shifts	= 3.66 days	setting-up(1 shift)+data taking	
^{197}Au	400 AMeV	11 shifts	= 3.66 days	setting-up(1 shift)+data taking	
^{197}Au	600 AMeV	11 shifts	= 3.66 days	setting-up(1 shift)+data taking	
^{197}Au	1000 AMeV	11 shifts	= 3.66 days	setting-up(1 shift)+data taking	
^{197}Au or similar	400 AMeV	4 shifts	= 1.33 days	commissioning and debugging	also parasitic
	Total	44+4 shifts	= 16 days		

Advancing to higher densities with:

♦ improved resolution

KRAB



design

multiplicity trigger, reaction plane and centrality detector for the ASYEOS II experiment at GSI/FAIR

Main characteristics:

- 5 rings of 4×4 mm^2 segments of fast scintillating fibers
- (BCF-10)
- read out by 3×3 mm^2 SiPMs (SensL MicroFJ-30035)
- high resolution 3D printed mechanical structure
- (ABS, 0.2 mm nozzle, 10 μm accuracy)
- ASICs used for signal processing (32 ch CITIROC 1A)
- assure compactness of the electronics and wiring

See J. Łukasik mini-talk and poster for more details

- …overed angles)
- …u reaction)
- it will be sufficiently large for radioactive beams
- and sufficiently small and lightweight not to disturb neutrons
- min radius - 7 cm
- max radius - 12 cm
- length ~43 cm (size of a ~24" monitor)
- 4×160 segments in forward rings
- 96 segments in backward ring
- 736 channels
- He sleeve to suppress the δ-electron background

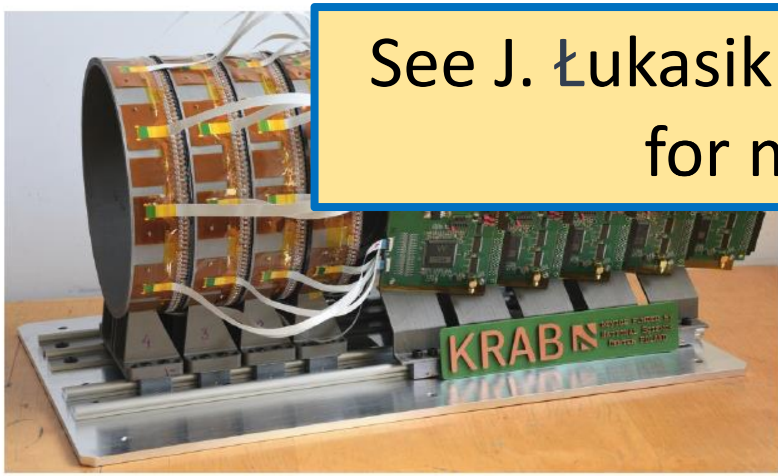


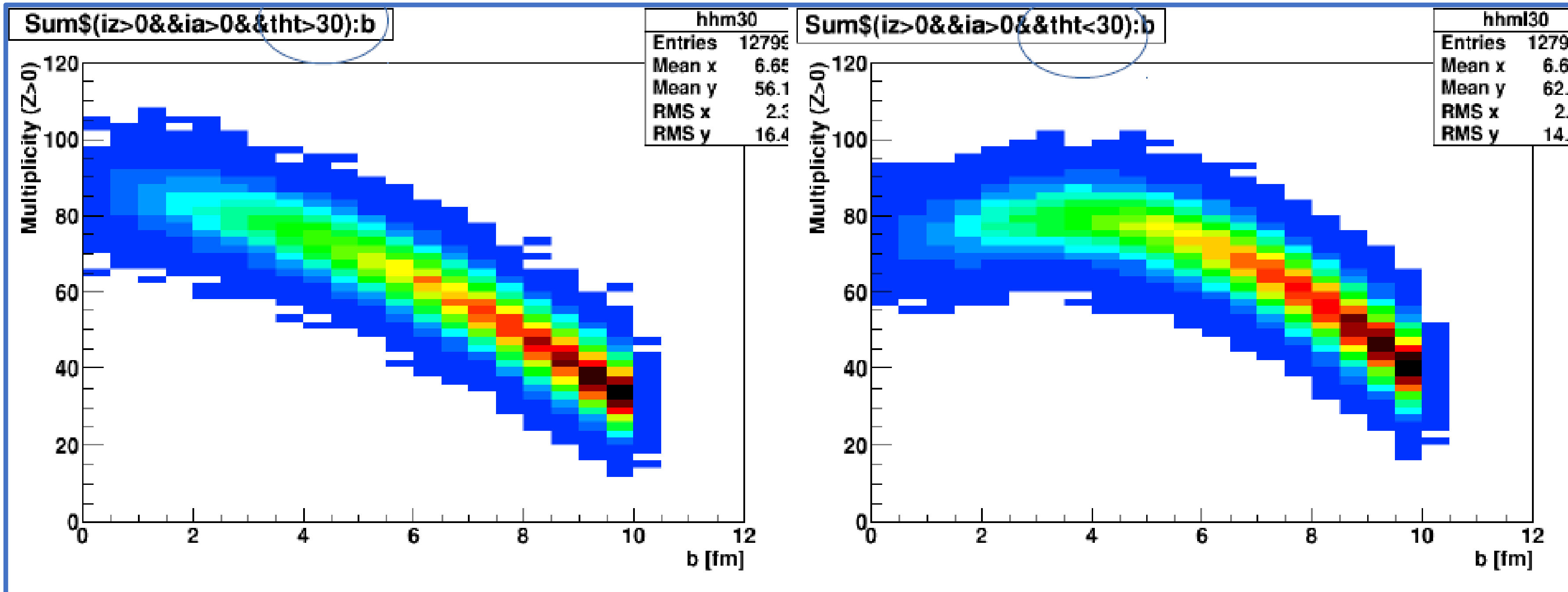
Figure 2: KRAB detector with the CITIROC boards. March 2022.

♦ improved resolution

KRAB

multiplicity trigger, reaction plane and centrality detector
for the ASYEOS II experiment at GSI/FAIR

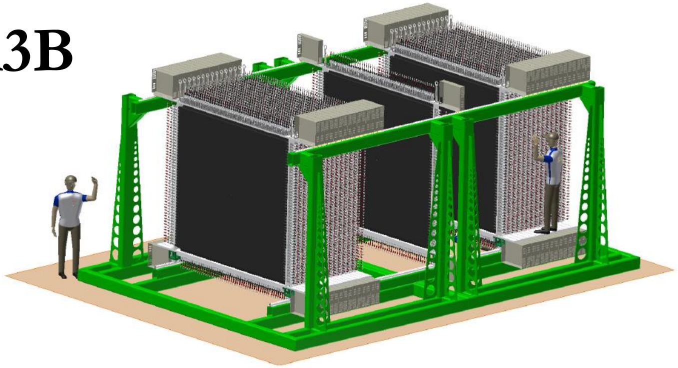
UrQMD + clustering: Au+Au 1000 AMeV, 0-10 fm, 200 fm/c



Better trigger, increased resolution (736 instead of 50 channels) w.r.t. to ASY-EOS I

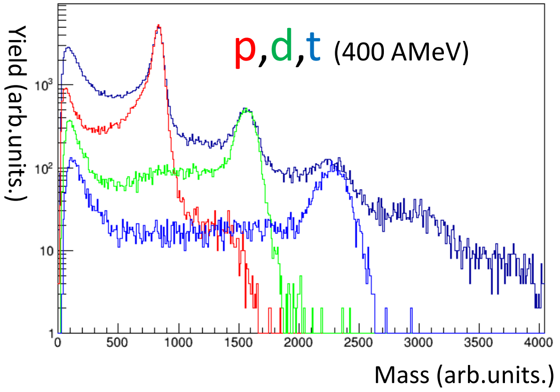
♦ improved resolution

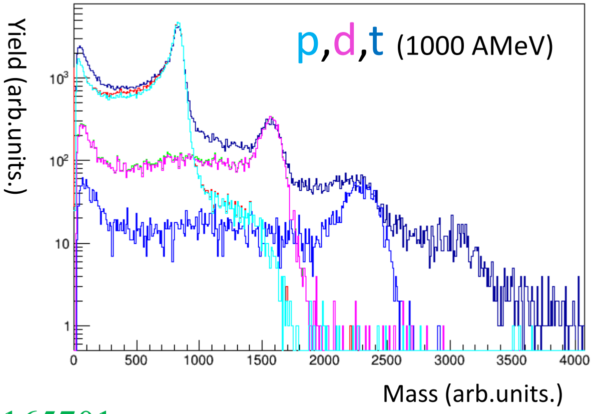
NeuLAND@R3B



- 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…but new planes are going to be built

Simulated NeuLAND capability to resolve p,d,t @ 400 and 1000 AMeV





K. Boretzky et al. (R3B coll) NIM A (2021) 165701

ToFD@R3B

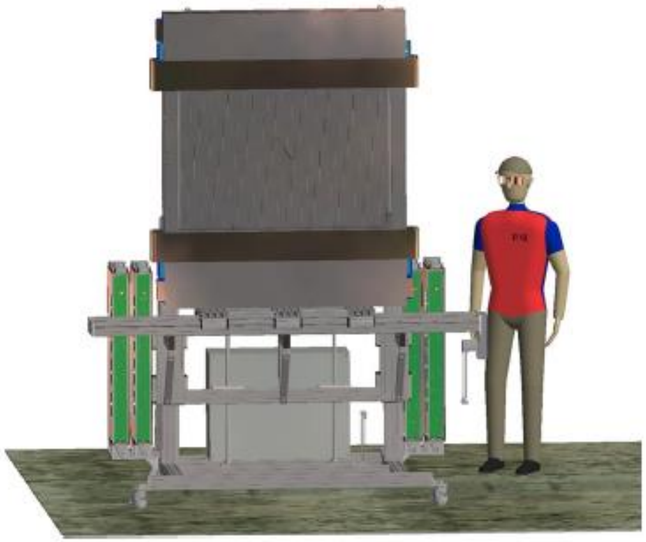


Fig. 13 Mechanical design of ToFD: The detector is mounted on an

- 2 frames (one as forward detector, one as NeuLAND veto)
- each frame containing 2 layers of scintillator bars
- each plane contains 44 vertical scintillator bars with the dimensions 1000×27×5 mm^3
- The bars of 2 successive planes are shifted by half a bar width

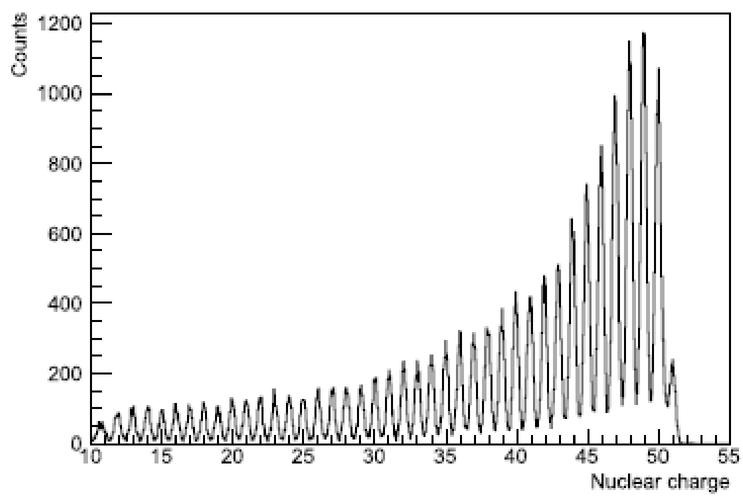


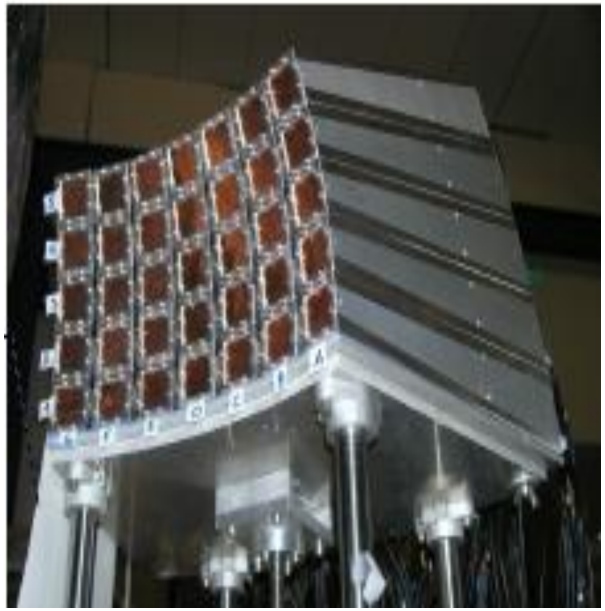
Fig. 15 Nuclear charge of the reactions products from the reactions of ^{120}Sn beam at 800 MeV/nucleon with a carbon target and measured with the new ToFD detector

M. Heil et al. (R3B coll) Eur. Phys. J. A (2022) 58:248

CHIMERA-KRATTA

CHIMERA

KraTTA



Both detectors were used in ASY-EOS I and will be used in the same way.

- CHIMERA is a slow and old detector but it has the 2π symmetry desirable for reaction plane determination

- KraTTA will measure LCPs flow and yield in the same angular region covered by NeuLAND

G-PAC outcome

"The G-PAC recognizes the scientific importance of the proposal aiming to determine the symmetry energy in the density region of twice the normal nuclear matter density via measurements of the ratio of elliptic flow (v2) of neutrons and protons predicted to be sensitive to the stiffness of the symmetry energy vs nuclear matter density. The results will provide complementary information to measurements of ground and satellite based X-ray telescopes and with GW interferometers.

The SIS18/FAIR-Phase-0 provides a unique place to study Au+Au collisions in the desired energy range together with unique NeuLAND PID capabilities to resolve p and n necessary to perform the measurements planned. Due to high overbooking of shifts, the G-PAC recommends the proposal **to be graded as A-** with a partial reduction of shifts from 44 to **33 main shifts (plus 4 setup with beam)** with Au (or similar) beam at 250 AMeV, 400 AMeV and one higher energy in the range between 600-1000 AMeV (the exact value t.b.d. by the proponents) which should not compromise the physics goals originally planned. In addition, **4 secondary shifts (A-) for commissioning** are granted as well. The G-PAC notes that the schedule of the experiment is restricted to the end of 2024 when most of the devices in Cave C will be moved out. "

The technical part G-22-00122-1.1-S has been ranked category A-.

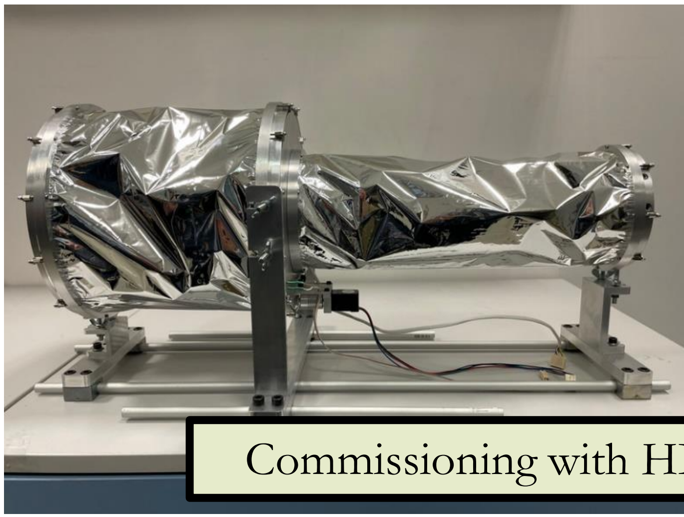
*** If it has been ranked ranked category A- (reserve list), and **in case it becomes possible to run the experiment** (if more beamtime becomes available) up to the amount of shifts recommended by the committee may be used for this experiment.

A final scheduling is not possible yet but we are working on being ready at the earliest possible date.

KRAB status

KRAB 1.1 has 100% channels working (736), a remotely controlled target wheel for 4 targets, better helium sleeve, better shielding, better firmware and a very nice software for online steering and control.

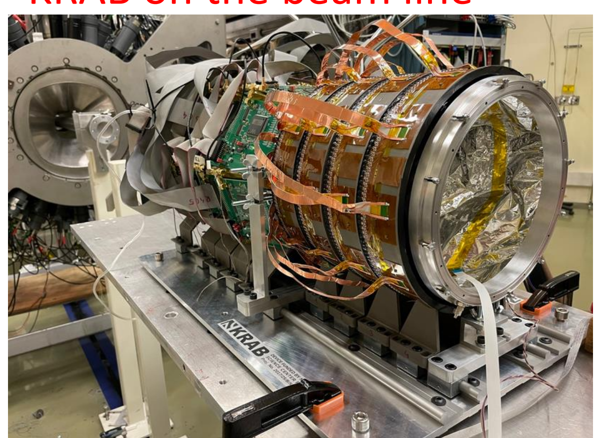
Helium sleeve



Motor driven target wheel inside sleeve

Commissioning with HI beams at GSI scheduled on March 2024.

KRAB on the beam line



DAQ

DAQ: Syncronization and TimeStamp VME – GET and VME - White-Rabbit

Phase 1: «portable» DAQ simulating complete DAQ Chimera : ok

Phase 2 : Syncro GET-Mutant-Beast-VME : ok (note 100 MHz GET timestamp is not compatible with WR)

Phase 3 : VETAR2 + WR on VME : ok

Phase 4 : Test coupling WR VME + Febex with **Pexaria5**: not yet done

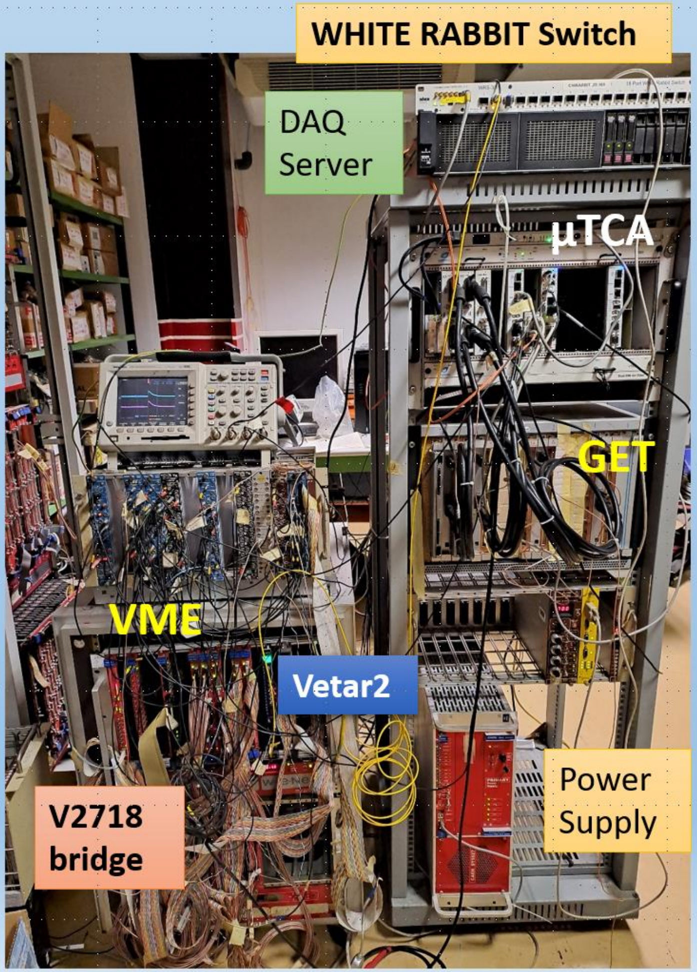
Vetar2: 125 MHz 48/64 bit White Rabbit VME timing receiver/sender

C++ class for fully handling VETAR2 inside the KaliMera VME DAQ library without the need of a «GSI» kernel module

Thanks to Joern Adamczensky-Musch for giving me a template with fully description of VETAR2 registers and addresses

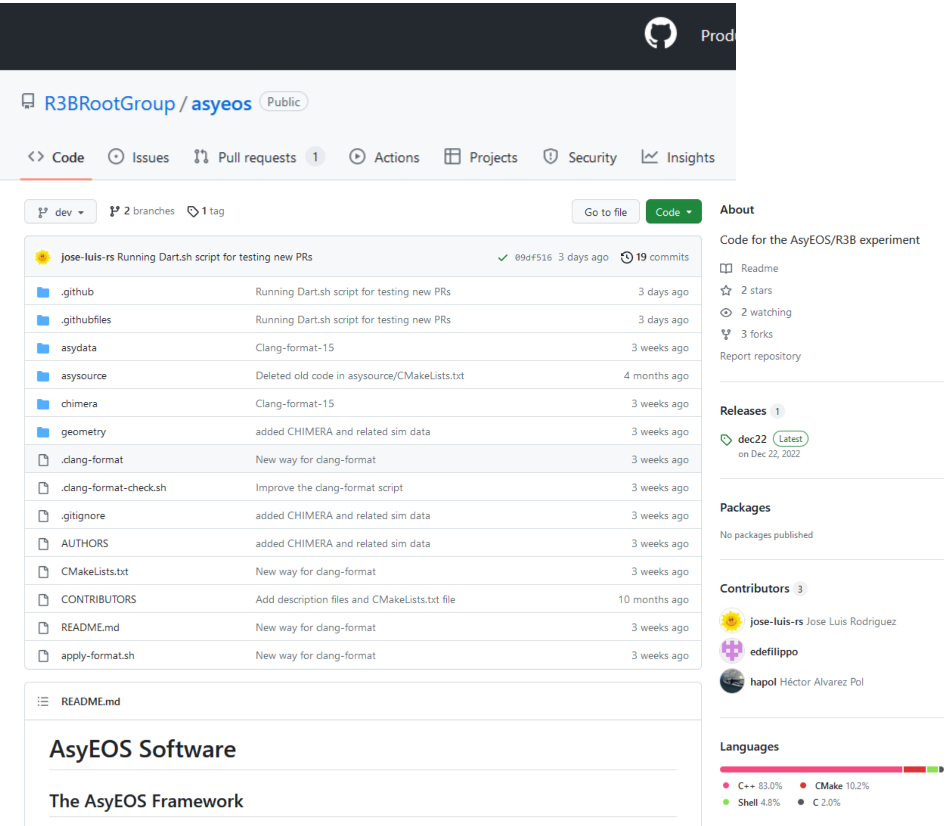
SFP to WR switch

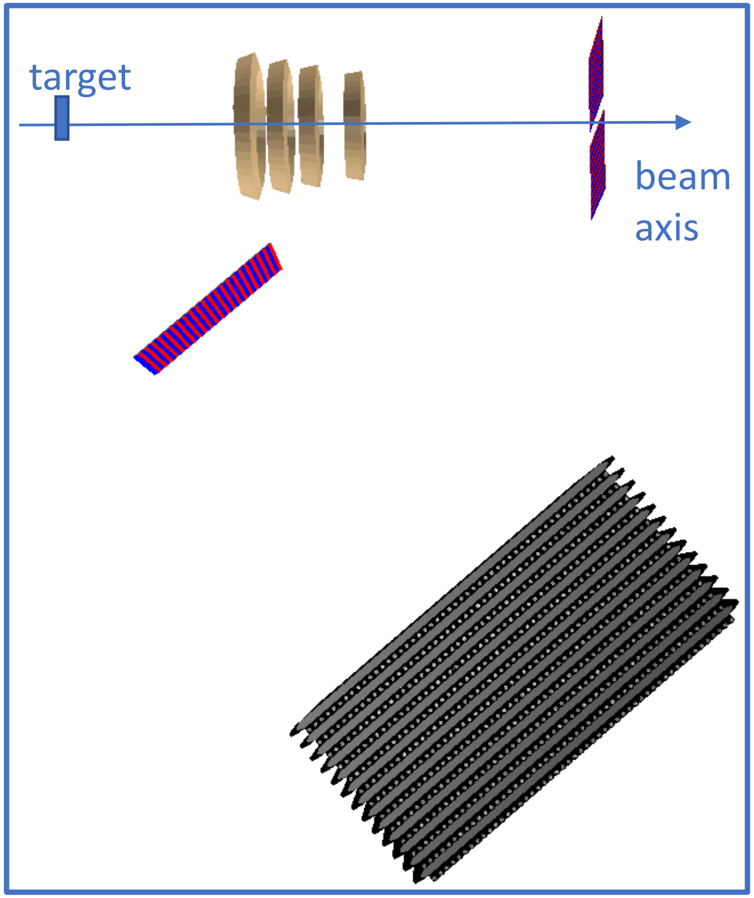
Trigger input



From E. De Filippo mini-talk at past R3B coll meeting

SOFTWARE





R3BRoot framework is going to be used for simulations, on-line monitoring, data analysis
https://github.com/R3BRootGroup/asyeos

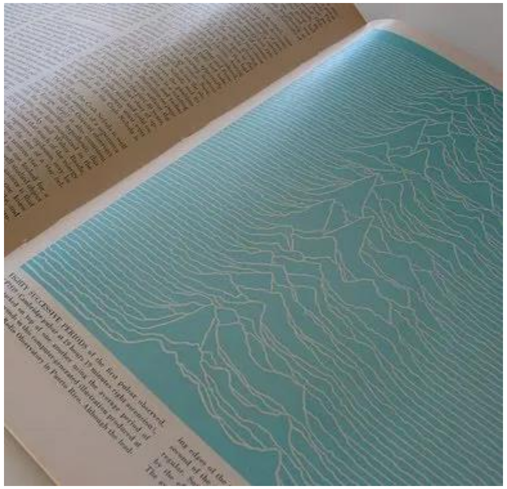
Conclusion messages

- n-p elliptic flow ratio has proven to be effective in constraining high-density symmetry energy; model dependency, as for other observable, is an important issue. Some work on comparison among UrQMD, dcQMD and IQMD has been done but only at 400 MeV/nucleon. A TMEP-like initiative would be desirable, especially if new data will be produced.

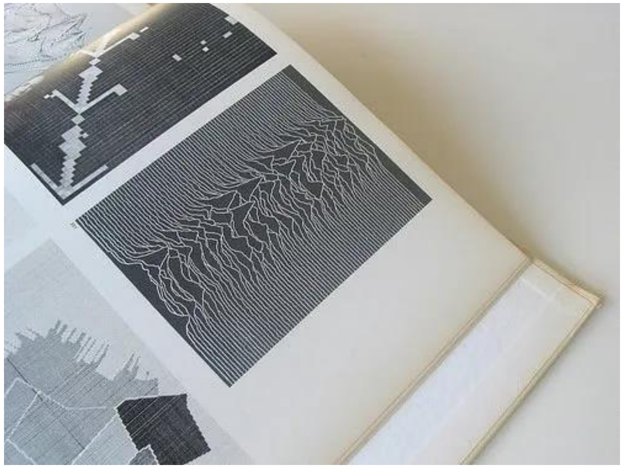
- Our knowledge on high-density symmetry energy has made relevant progress w.r.t. ten years ago. Multi-messenger astronomy has been an enormous novelty. But there is still need of nuclear physics results. And joining efforts and experience (RIKEN+MSU+GSI) is needed.

- A program to investigate how and where study EoS beyond 2-3 ρ_0 should be started by the above-mentioned communities…now.

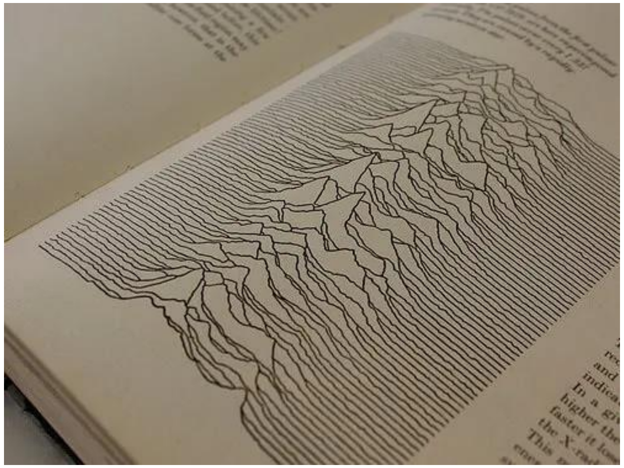
pulses from the first pulsar discovered by Jocelyn Bell Burnell, PSR B1919+21



Jerry Ostriker, January 1971 issue of Scientific American



Graphis Diagrams in 1974



Cambridge Encyclopedia of Astronomy in 1977

Unknown pleasures by Joy Divisions, 1979 debut album…one of the most iconic cover of the history of music