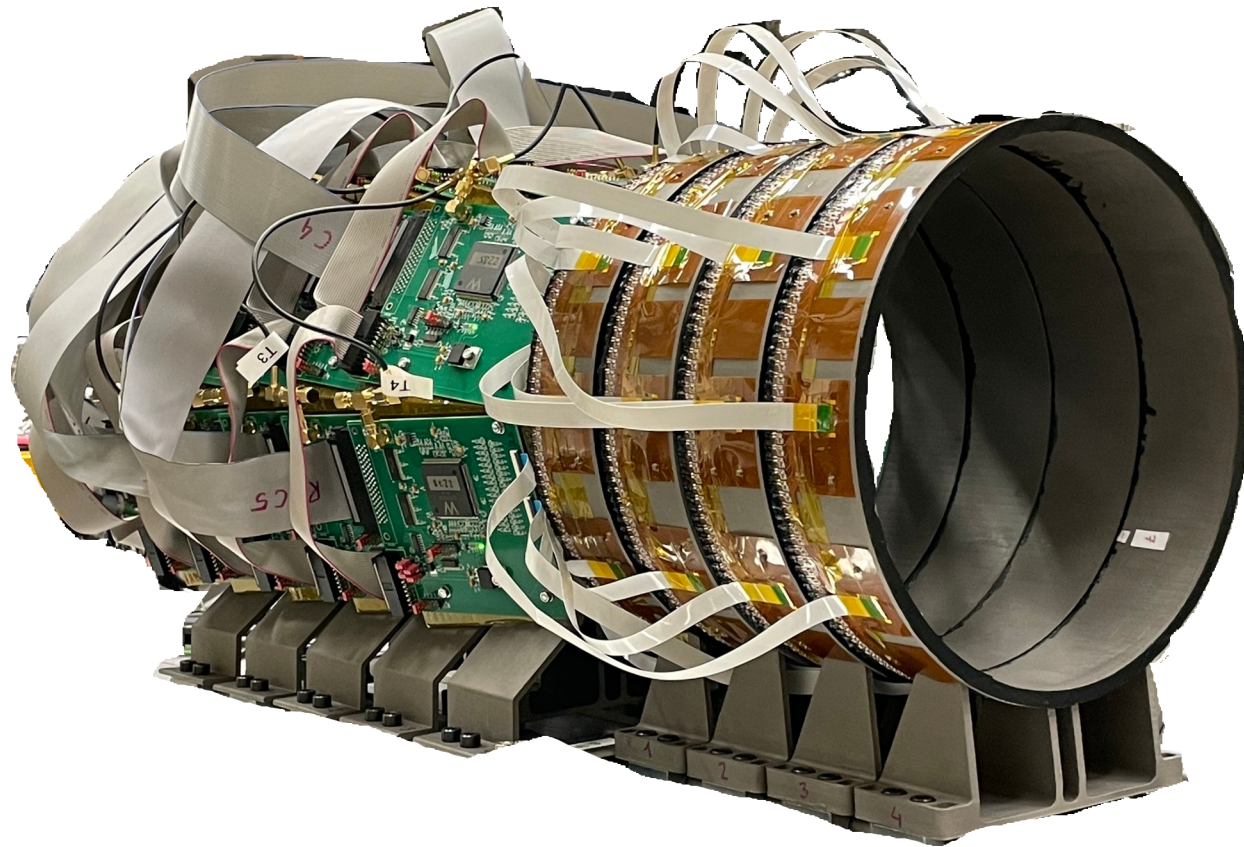


# Symmetry Energy at High Densities from Heavy Ion Collisions

## ASY-EOS II experiment using KRAB detector and the R3B infrastructure

J. Łukasik

IFJ PAN

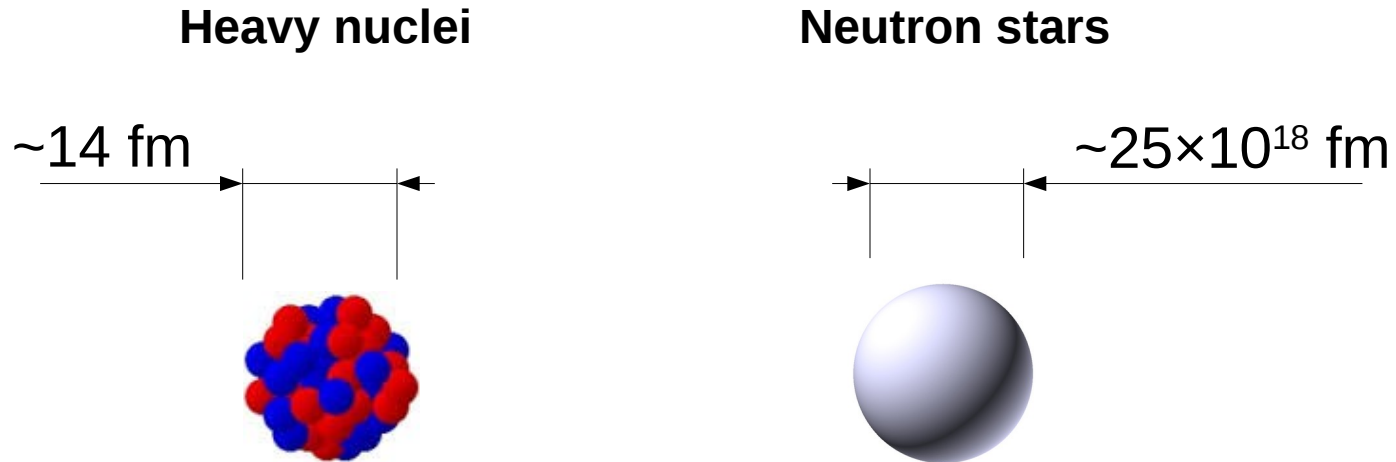


FAIR Seminar, 7.06.2024

# Outline

- Symmetry Energy – why so interesting, important and difficult?
- Current constraints from astrophysics, GW and heavy ions
- ASY-EOS II experiment
- **KRAB (KRAków B**arrel) detector
  - requirements
  - construction
  - CCB and GSI beam test results

# Nuclear matter



The properties of **asymmetric nuclear matter** can be obtained from the observables related to the **nuclear structure**, from the density and asymmetry dependent processes in **heavy ion collisions**, from **astrophysical** observations and from **gravitational waves** accompanying collisions of neutron stars.

The nuclear and astrophysical sources are expected to provide coherent results despite their 18 orders of magnitude difference in scale. After all, they are driven by the same nuclear interactions. But, how is it in reality?

# Symmetry Energy

Energy per nucleon in a nucleus:

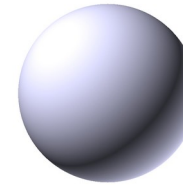
$$\frac{E_B}{A} = \underbrace{-a_V}_{Volume} + \underbrace{a_S \frac{1}{A^{1/3}}}_{Surface} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{Coulomb} + \underbrace{+a_A \left( \frac{N-Z}{A} \right)^2}_{Symmetry} \pm \underbrace{a_P \frac{1}{A^{3/2}}}_{Pairing}$$

$$\begin{aligned} A &\rightarrow \infty \\ V &\rightarrow \infty \\ \rho &< \infty \\ a_c &= 0 \\ K &> 0 \end{aligned}$$



Energy per nucleon in nuclear matter (EoS):

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



$\rho_n, \rho_p \rightarrow$  neutron, proton densities

$\rho = \rho_n + \rho_p \rightarrow$  nucleon density

$\delta = \frac{\rho_n - \rho_p}{\rho} \rightarrow$  isospin asymmetry

# Symmetry Energy

Energy per nucleon in a nucleus:

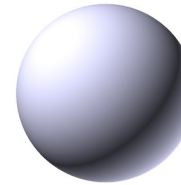
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$A \rightarrow \infty$   
 $V \rightarrow \infty$   
 $\rho < \infty$   
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 $K > 0$



Energy per nucleon in nuclear matter (EoS):

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



neutron - symmetric

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

$\rho_n, \rho_p \rightarrow$  neutron, proton densities

$\rho = \rho_n + \rho_p \rightarrow$  nucleon density

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Energy per nucleon in nuclear matter (EoS):

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

dominant symmetric matter (N=Z) term (isoscalar):

$$E(\rho, 0) \approx -a_V + \frac{K}{18} \left( \frac{\rho - \rho_0}{\rho_0} \right)^2 + \dots$$

symmetry term (isovector):

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

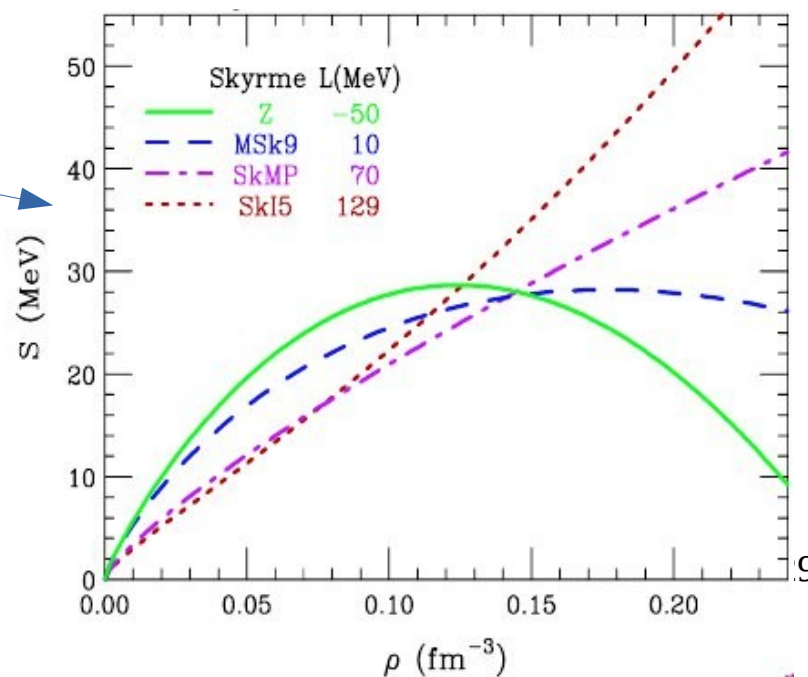
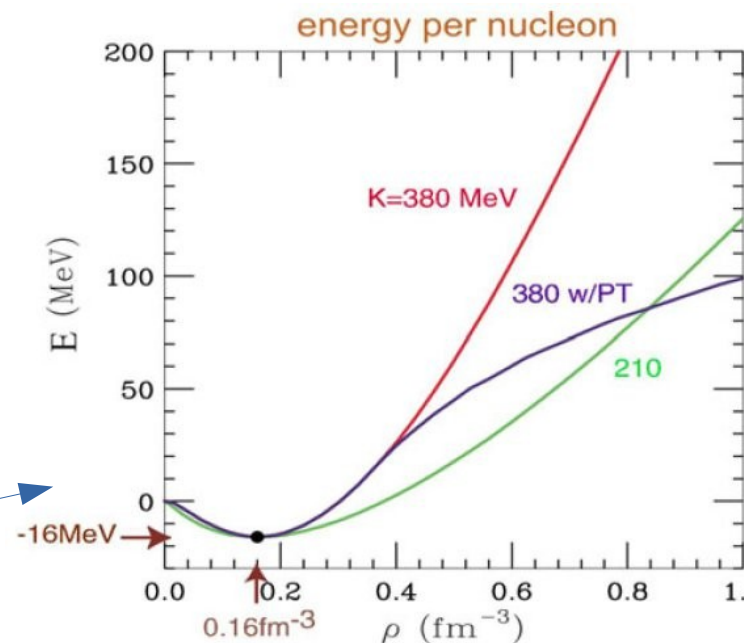
$\rho_n, \rho_p \rightarrow$  neutron, proton densities

$\rho = \rho_n + \rho_p \rightarrow$  nucleon density

$\delta = \frac{\rho_n - \rho_p}{\rho} \rightarrow$  isospin asymmetry

$L = 3 \rho_0 \left. \frac{\partial E_{\text{sym}}}{\partial \rho} \right|_{\rho=\rho_0} \rightarrow \sim$  symmetry pressure

$K = 9 \rho_0^2 \left. \frac{\partial^2 E}{\partial \rho^2} \right|_{\rho=\rho_0} \rightarrow$  compressibility



# Symmetry Energy

Energy per nucleon in a nucleus:

$$\frac{E_B}{A} = \underbrace{-a_V}_{\text{Volume}} + \underbrace{a_S \frac{1}{A^{1/3}}}_{\text{Surface}} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{\text{Coulomb}} + \underbrace{a_A \left( \frac{N-Z}{A} \right)^2}_{\text{Symmetry}} \pm \underbrace{a_P \frac{1}{A^{3/2}}}_{\text{Pairing}}$$

$A \rightarrow \infty$   
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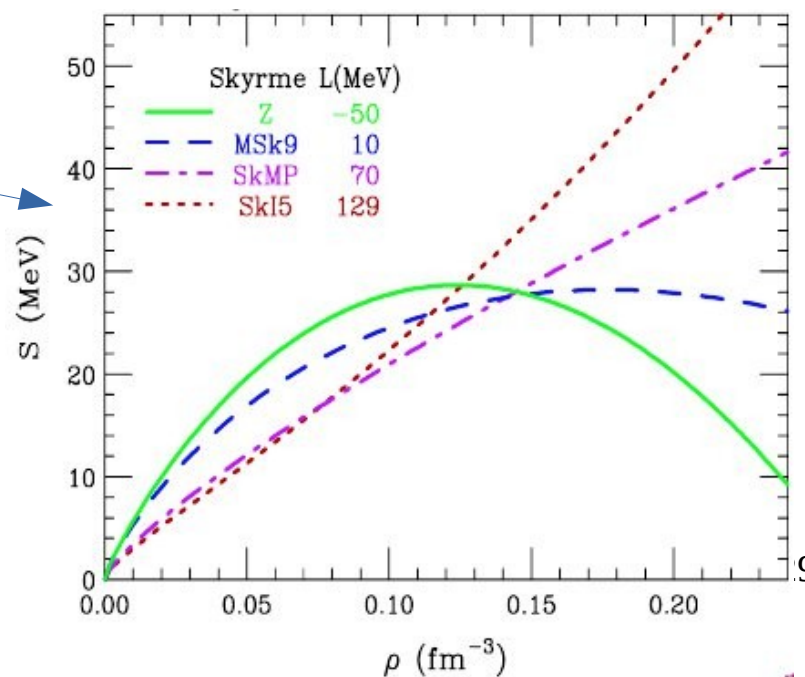
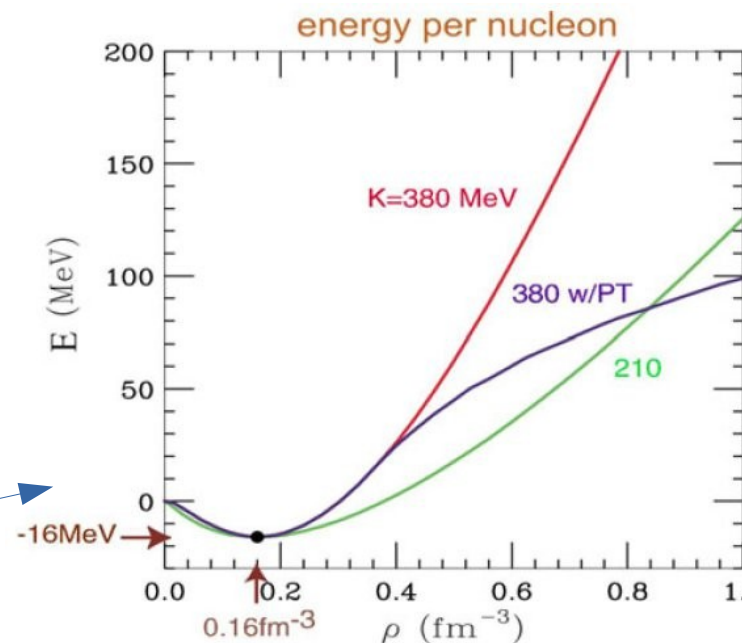
$\rho_n, \rho_p \rightarrow$  neutron, proton densities

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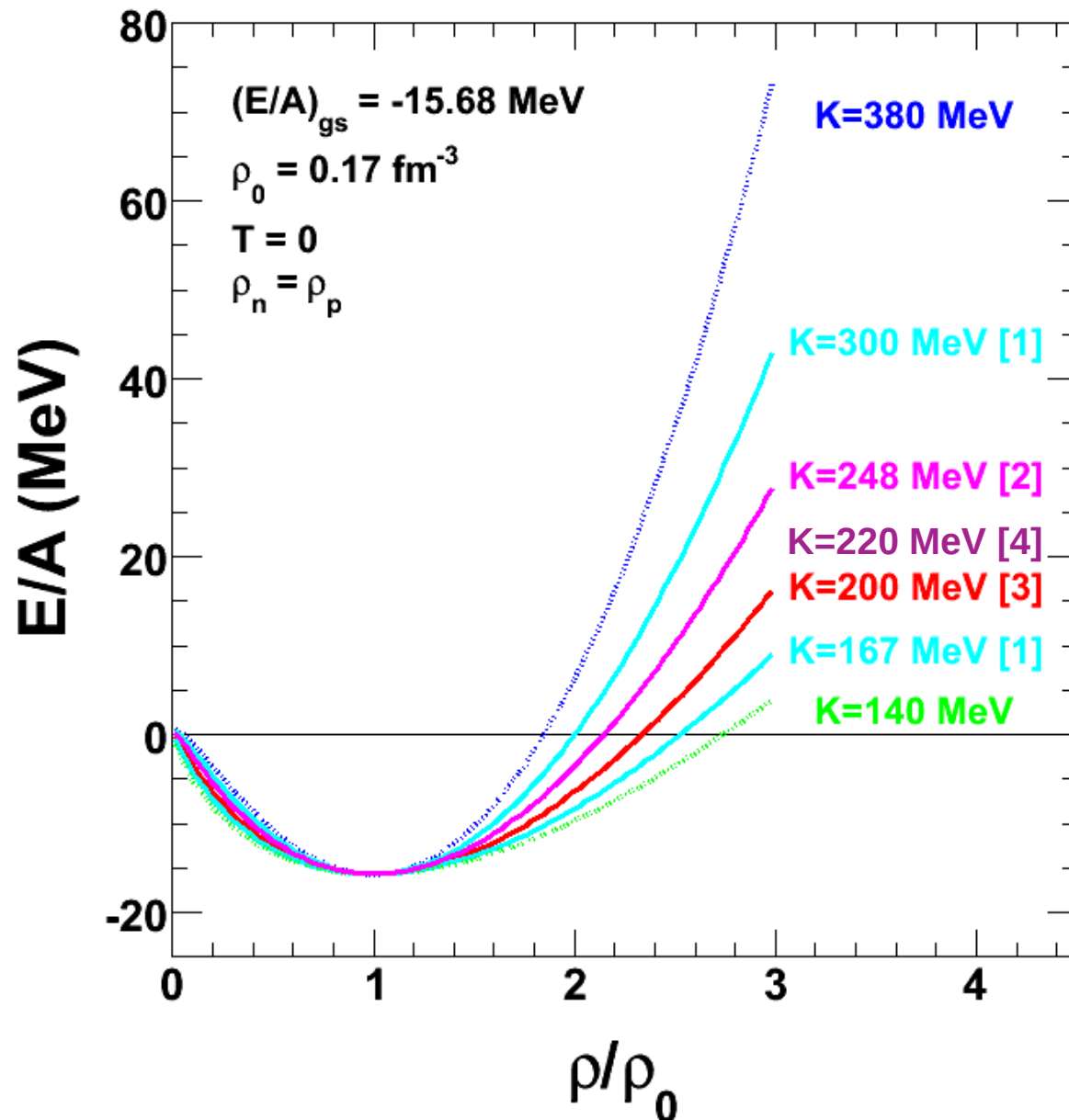
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$K = 9 \rho_0^2 \left. \frac{\partial^2 E}{\partial \rho^2} \right|_{\rho=\rho_0} \rightarrow$  compressibility



# K for symmetric matter ( $\delta=0$ )



[1] Flow:

P. Danielewicz et al., Science 298 (02) 1592  
 BME:  $K = 167\text{-}300 \text{ MeV}$

[2] ISGMR:

J. Piekarewicz, PRC 69 (04) 041301

RMF:  $K=248 \text{ MeV}$

G. Colò et al., PRC 70 (04) 024307

Skyrme HF:  $K=230 \text{ MeV}$

S. Shlomo, et al. Eur. Phys. J. A 30, 23 (2006)

$K = 240 \pm 20 \text{ MeV}$

[3] Subthreshold  $K^+$ :

C. Sturm et al., PRL 86 (01) 39

Ch. Hartnack et al., PRL 96 (06) 012302

Flow:

W. Reisdorf (FOPI) arXiv:1307.4210 [nucl-ex]

IQMD:  $K=200 \text{ MeV}$

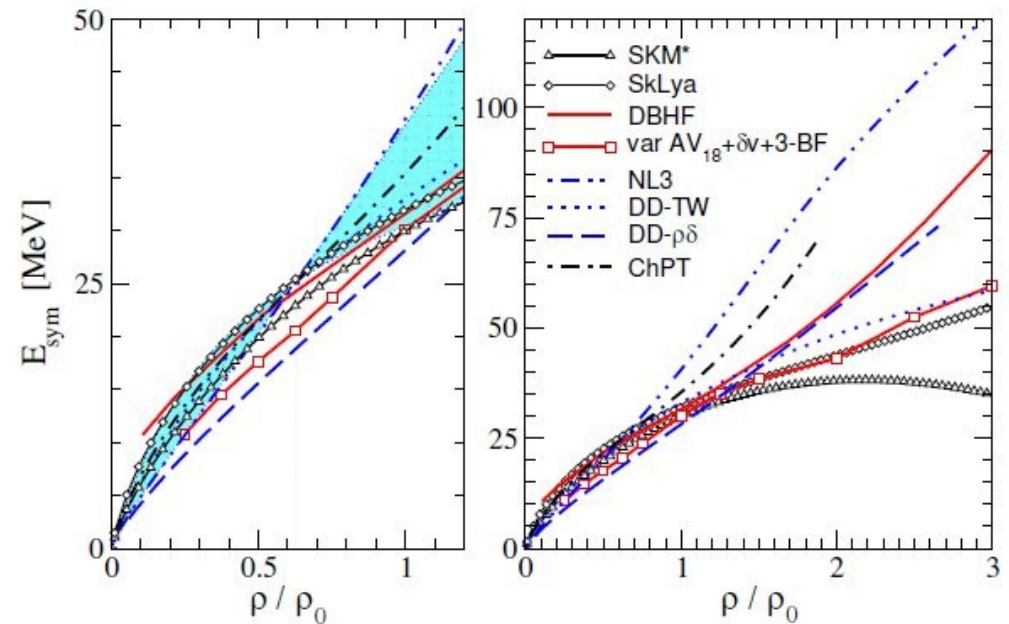
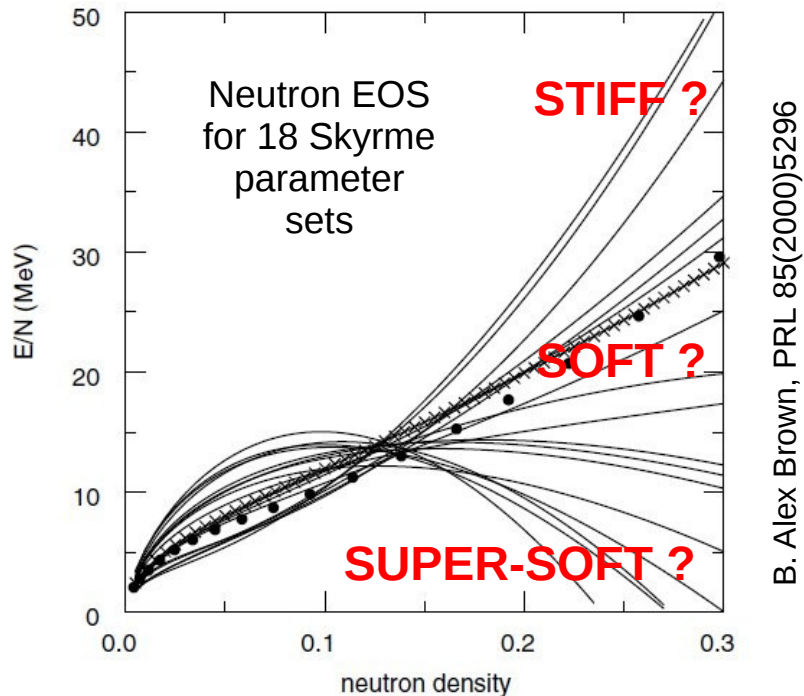
[4] Y. Wang et al., PLB 778 (2018) 207

UrQMD + FOPI:  $K = 220 \pm 40 \text{ MeV}$

“Generally accepted” value of  
 $K = 240 \pm 20 \text{ MeV}$

# Symmetry term. Why so uncertain? (theory)

Symmetry energy uncertain at high density and modified by clustering at low density. It accounts for a difference of energy per nucleon in a pure neutron matter w.r.t. a symmetric one.



C. Fuchs and H.H. Wolter, EPJA 30(2006)5

## Phenomenological forces and effective field theories

with parameters constrained around saturation (masses, radii) and for nearly isospin-symmetric matter. Poor knowledge of effective forces in neutron-rich matter. Uncertainties in the nature of the three-neutron force. Uncertain extrapolations above the saturation density.

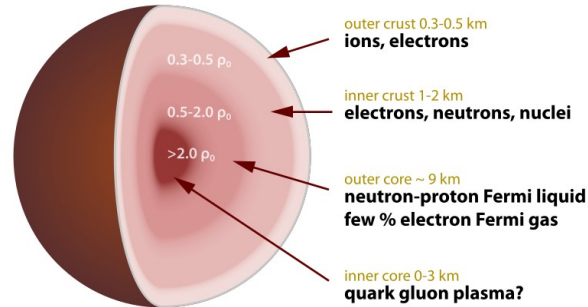
## “Ab-initio” approaches

in principle without free parameters, based on two and three-body “realistic” forces tuned to reproduce the nucleon-nucleon scattering data and deuteron properties. Heavier mesons, such as  $\rho$ ,  $\omega$  and  $\sigma$  included in the construction of NN potentials. Three- and more nucleon forces important at high densities.

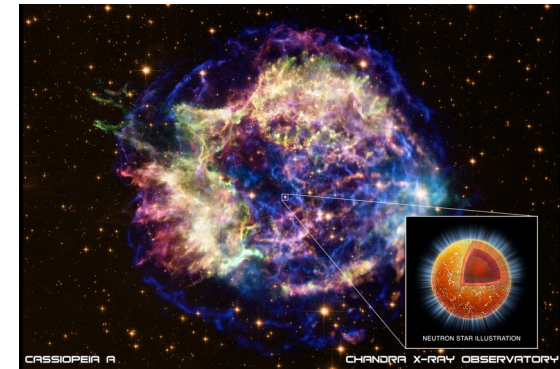
# Why so important?

## ASTROPHYSICS

- Neutron star structure, composition, size, mass and cooling rate, crust-core transition density
- Pulsars, masses, spin rates
- Supernova explosions
- Stellar nucleosynthesis, r-process



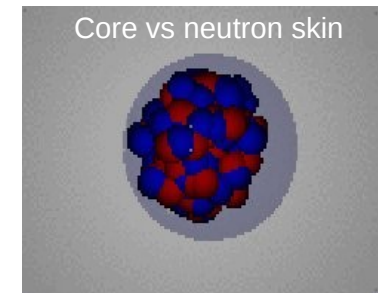
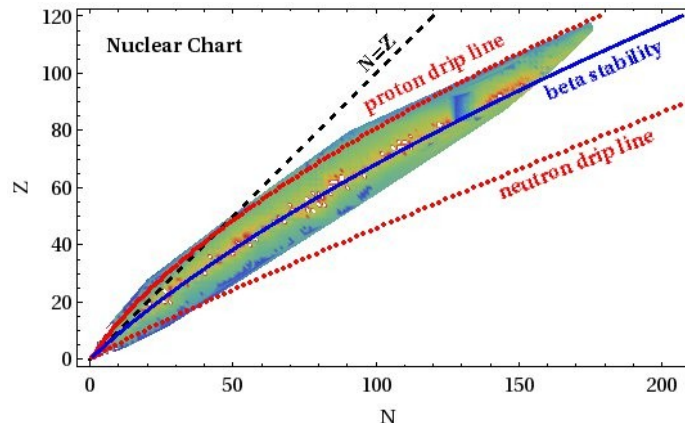
Robert Schulze (Wikipedia)



Cassiopeia A Supernova Remnant  
(<http://chandra.harvard.edu/photo/printgallery/2004/>)

## STRUCTURE

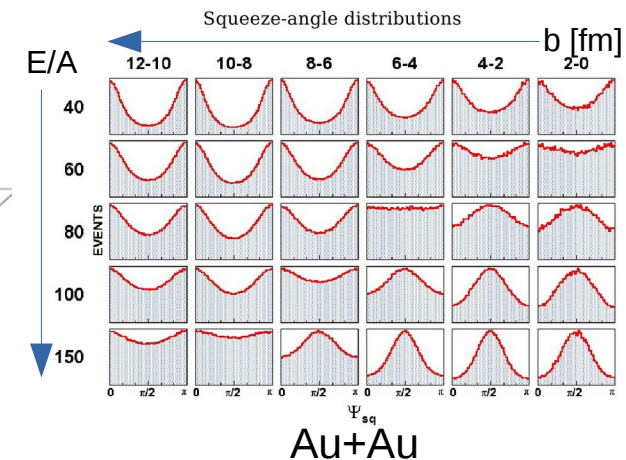
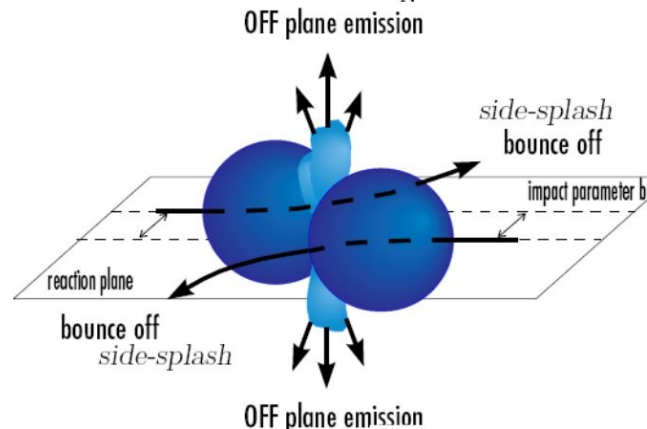
- Structure of exotic nuclei (masses, drip lines → limits of stability)
- Neutron skin thickness
- IvGDR
- Pygmy resonances
- Isobaric Analog States (IAS)



PDR

## REACTIONS

- Flow patterns in HIC
- Multifragmentation, isoscaling, isospin diffusion
- $n/p$ ,  $t/^3\text{He}$ ,  $\pi^-/\pi^+$ ,  $K^+/K^0$  ratios in HIC



GSI/FAIR

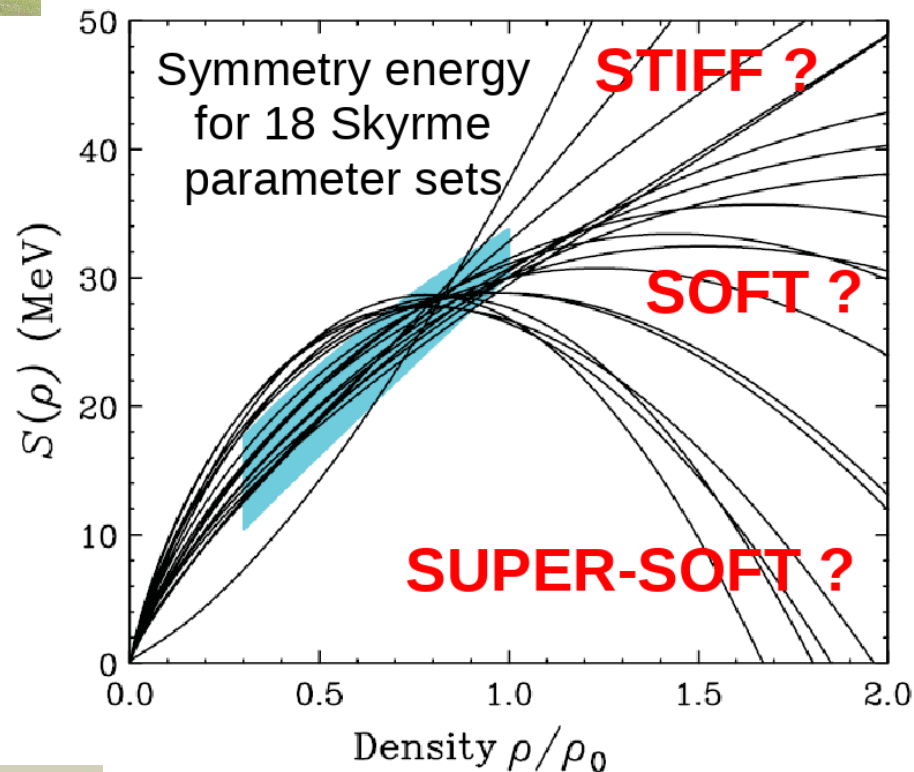


**Symmetry Energy** accounts for the difference in binding of nucleons in a pure neutron matter w.r.t. a symmetric one  
(it is the cost of converting all protons in a symmetric matter into neutrons)

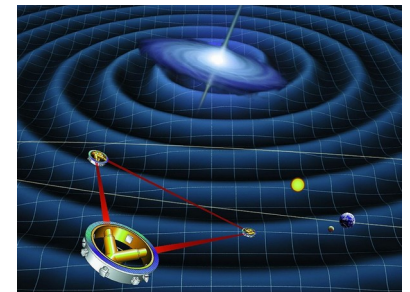
LIGO/VIRGO



NICER@ISS



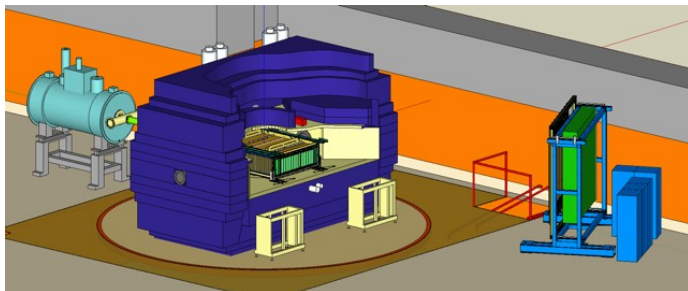
LISA



JLab



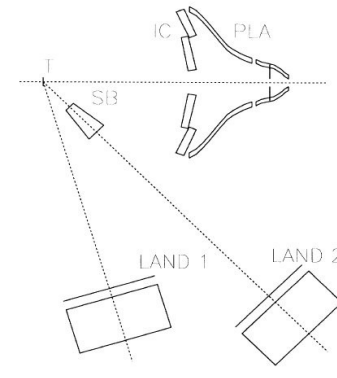
RIKEN



**How stiff or soft is the Symmetry Energy at high densities (up to  $\sim 2 \rho_0$ )?**

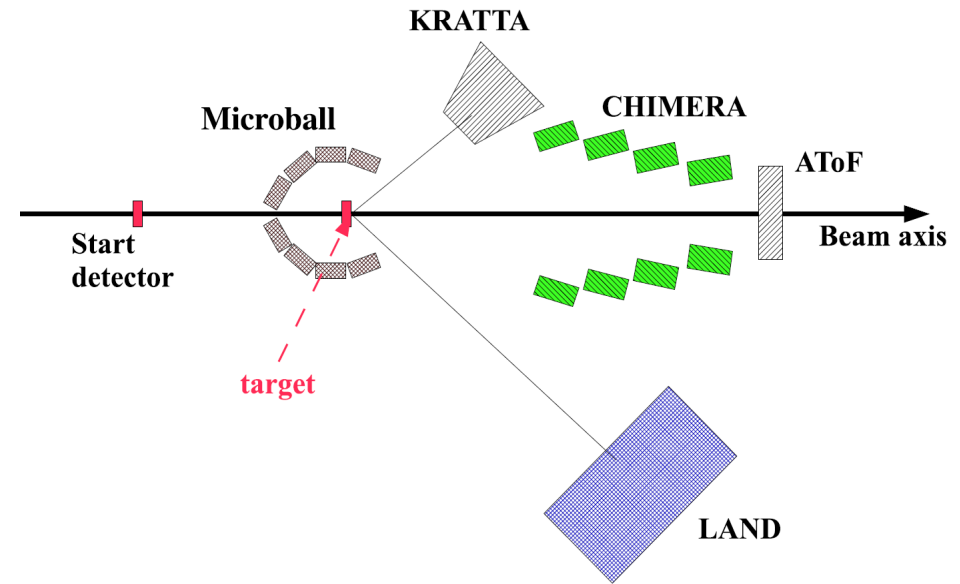
# High energy (density) experiments

(1) FOPI/LAND data (GSI 1993/2011)



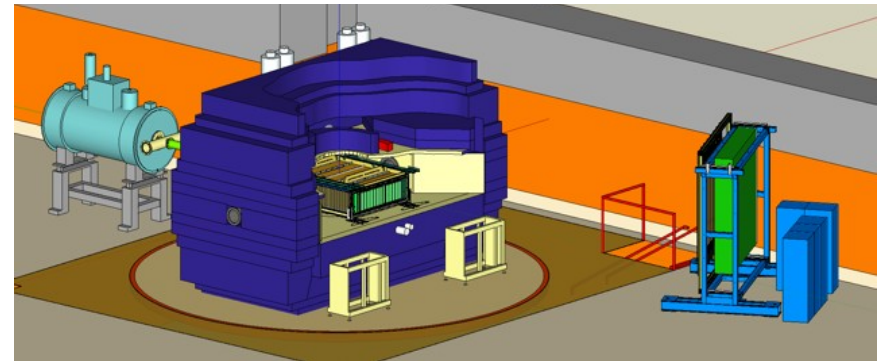
(2) ASY-EOS experiment (GSI 2011)

**KRATTA** → IFJ PAN + IF UJ



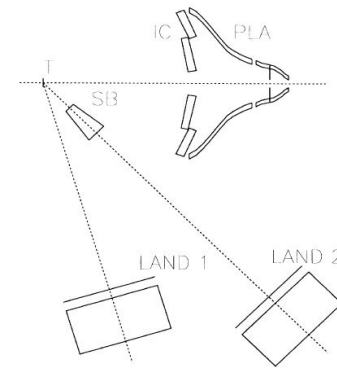
(3) SPiRIT experiment (RIKEN 2016)

**KATANA** → IFJ PAN + IF UJ



# High energy (density) experiments

(1) FOPI/LAND data (GSI 1993/2011)

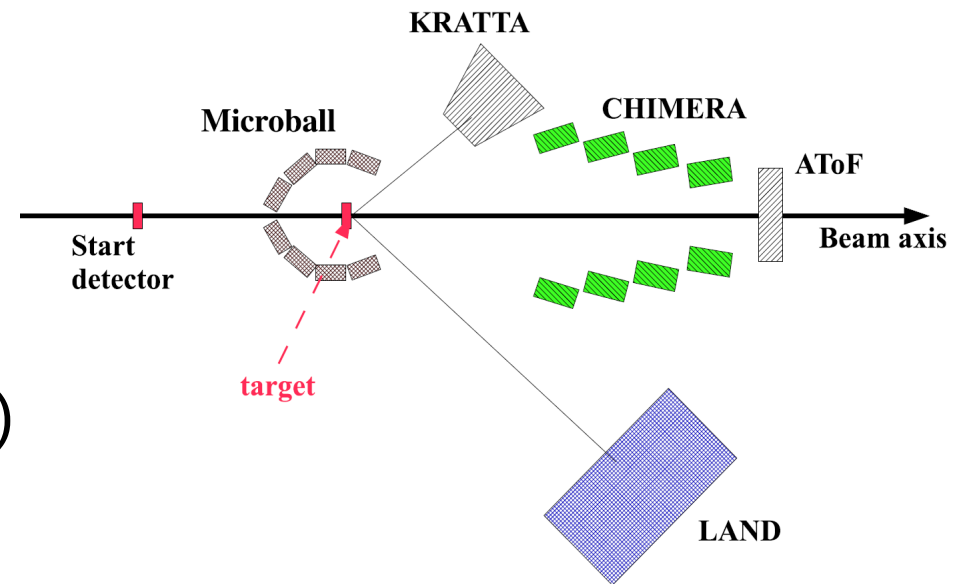


(2) ASY-EOS experiment (GSI 2011)

**KRATTA** → IFJ PAN + IF UJ

(5) ASY-EOS II experiment (GSI 2025)

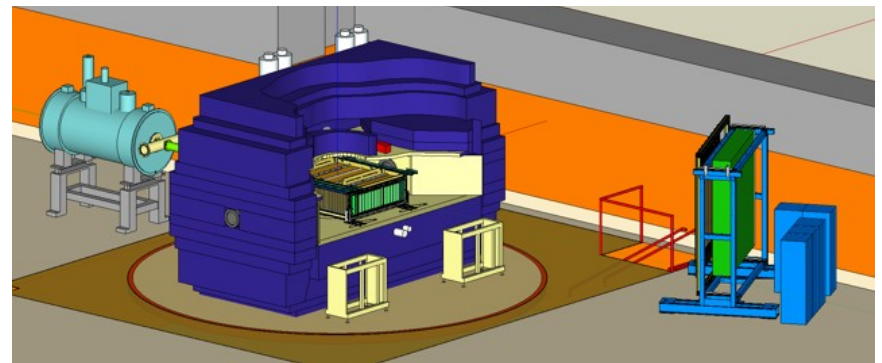
**KRAB + KRATTA** → IFJ PAN + IF UJ



(3) SPiRIT experiment (RIKEN 2016)

**KATANA** → IFJ PAN + IF UJ

(4) SPiRIT II experiment (RIKEN 2024)

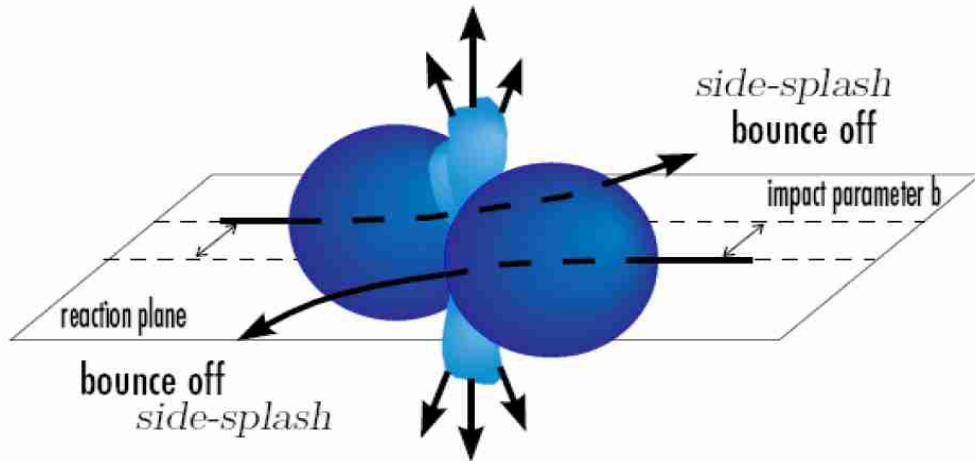


# Flow analysis ( $v_1, v_2$ )

Squeezing the Symmetry Energy out of Heavy Ion Collisions

**elliptic flow**

OFF plane emission



**directed flow**

OFF plane emission

Fourier decomposition of **azimuthal distributions** with respect to the **reaction plane** ( $\phi_R$ ):

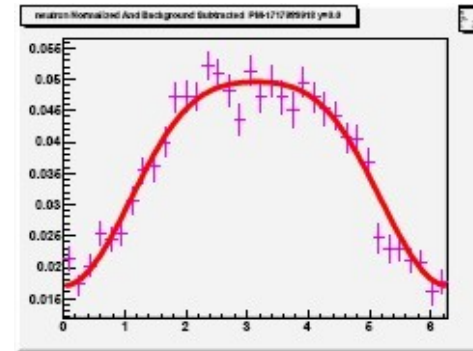
$$\frac{dN}{d(\phi - \phi_R)} = \frac{N_0}{2\pi} \left( 1 + 2 \sum_{n \geq 1} v_n \cos n(\phi - \phi_R) \right)$$

**directed flow:**  $v_1 \equiv \langle \cos(\phi - \phi_R) \rangle$

**elliptic flow:**  $v_2 \equiv \langle \cos 2(\phi - \phi_R) \rangle$

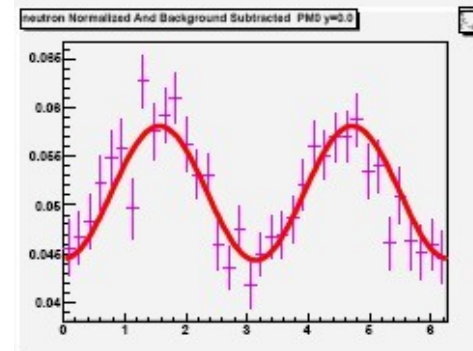
$$v_n = v_n(b, Z, A, y, p^T)$$

W. Trautmann et al., 2011

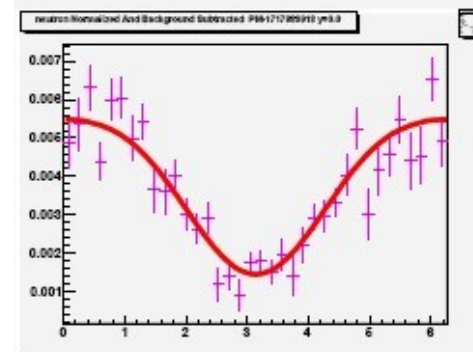


Au+Au @ 400 AMeV

Target rapidity  
(strong directed flow)



Mid-rapidity  
(strong elliptic flow-squeeze-out)



Projectile rapidity  
(strong directed flow)

0  $\Delta\phi$   $2\pi$

# ASY-EOS

Symmetry Energy from elliptic flows of neutrons and hydrogens

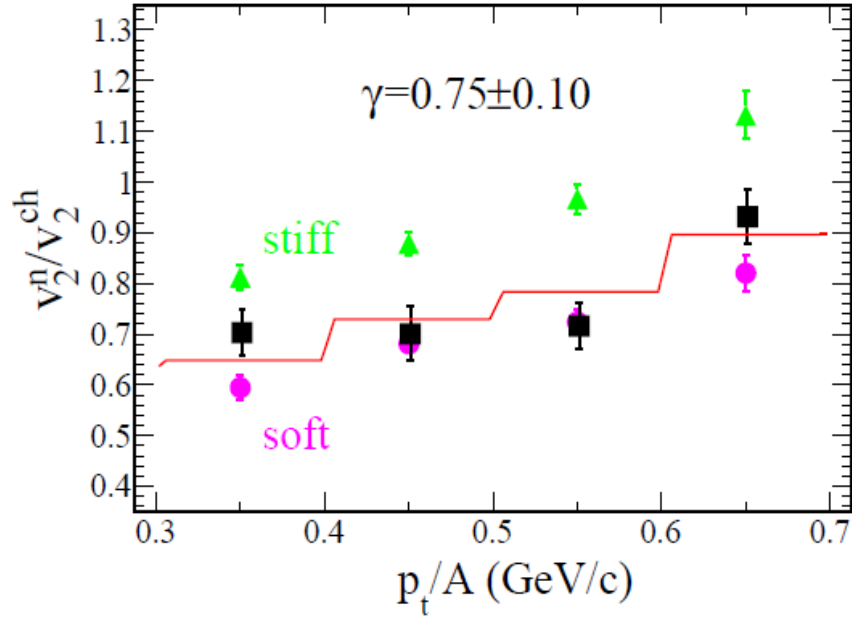


FIG. 15: (Color online) Elliptic flow ratio of neutrons and charged particles for moderately central ( $b < 7.5$  fm) collisions of  $^{197}\text{Au}+^{197}\text{Au}$  at 400 MeV/nucleon as a function of the transverse momentum per nucleon  $p_t/A$ , evaluated with a fraction of 80% for the second step of timing corrections (see Sec. IV A). The full squares represent the experimental data, the triangles and dots represent the UrQMD predictions for stiff ( $\gamma = 1.5$ ) and soft ( $\gamma = 0.5$ ) power-law exponents of the potential term. The full line is the result of a linear interpolation between the predictions, leading to the indicated  $\gamma = 0.75 \pm 0.10$ .

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

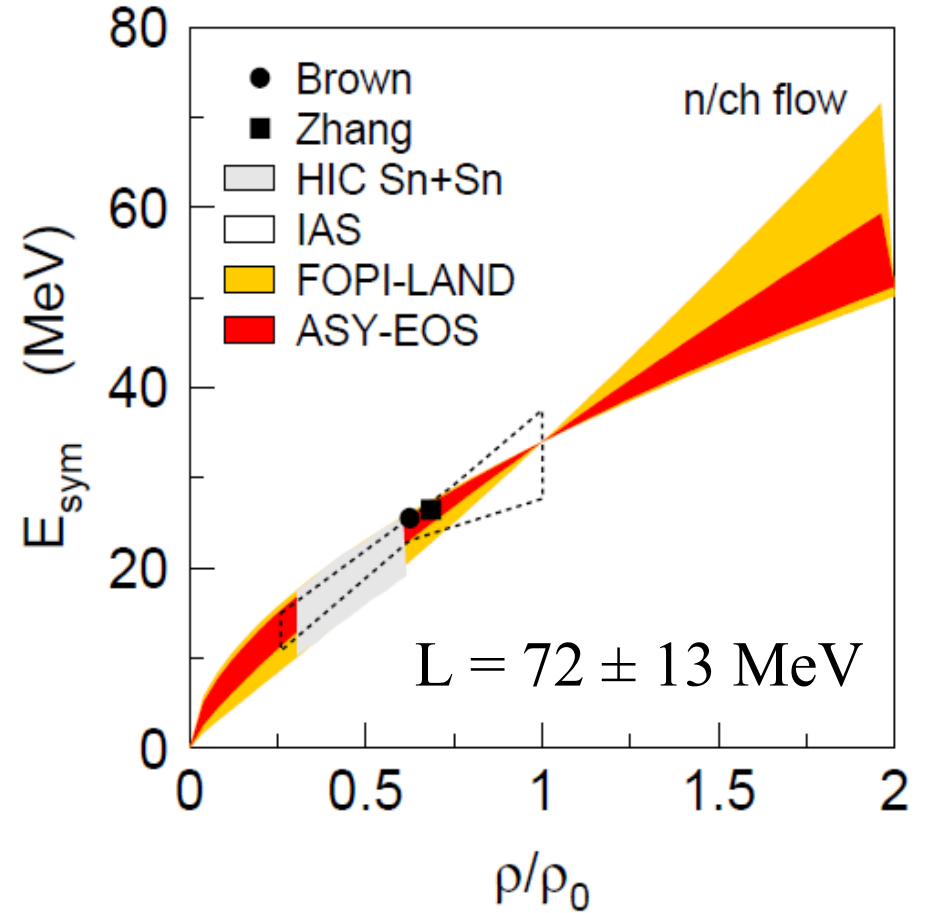
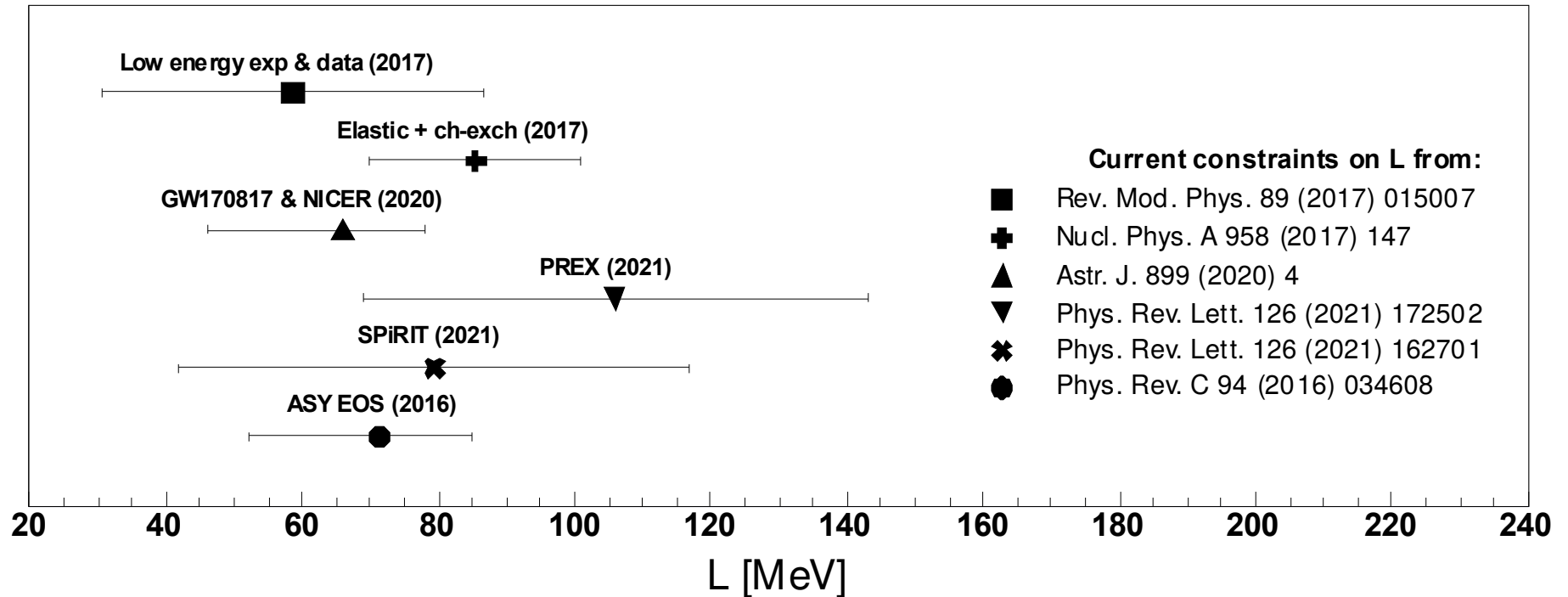


FIG. 19: (Color online) Constraints deduced for the density dependence of the symmetry energy from the present data in comparison with the FOPI-LAND result of Ref. [5] as a function of the reduced density  $\rho/\rho_0$ . For reference, the low-density results of Refs. [66–69] as presented in Ref. [70] are included.

# Slope of the Symmetry Energy

## some experimental constraints



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

# The EoS and the Neutron Stars

In the first approximation NS can be described using spherical Newtonian structure equations for a stellar object in a hydrostatic equilibrium:

$$\left\{ \begin{array}{l} \frac{dP}{dr} = - \frac{G m \rho}{r^2} \\ \frac{dm}{dr} = 4 \pi \rho r^2 \end{array} \right. \xrightarrow[\text{TOV}]{\text{GR}} \left\{ \begin{array}{l} \frac{dP}{dr} = - \frac{G(m + 4 \pi r^3 P)(\rho + P)}{r(r - 2 G m)} \\ \frac{dm}{dr} = 4 \pi \rho r^2 \end{array} \right.$$

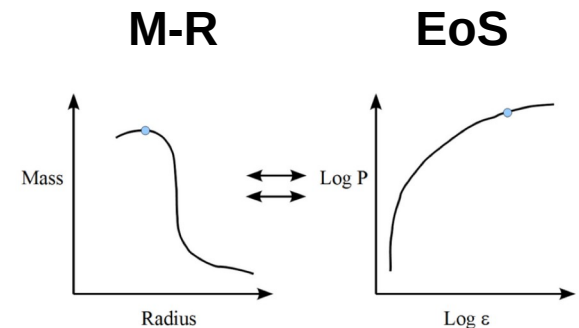
they provide a dependence of the gradients of the pressure,  $P$ , and of the enclosed mass,  $m$ , on the (mass-energy) density,  $\rho$ , thus two equations and three unknowns, all depending on the radius,  $r$ . A third equation, **the EoS, relating pressure and density** is needed to solve the problem:

$$P = P(\rho) = \rho^2 \frac{\partial E/A}{\partial \rho}$$

Thus, the EoS of neutron rich matter becomes indispensable for realistic NS simulations.

For compact stars, like NS, Tolman-Oppenheimer-Volkoff (TOV) equation resulting from general relativity (GR) has to be used.

The structure equations + EoS provide a **unique** correspondence between the **EoS** and the **Mass-Radius** relation.



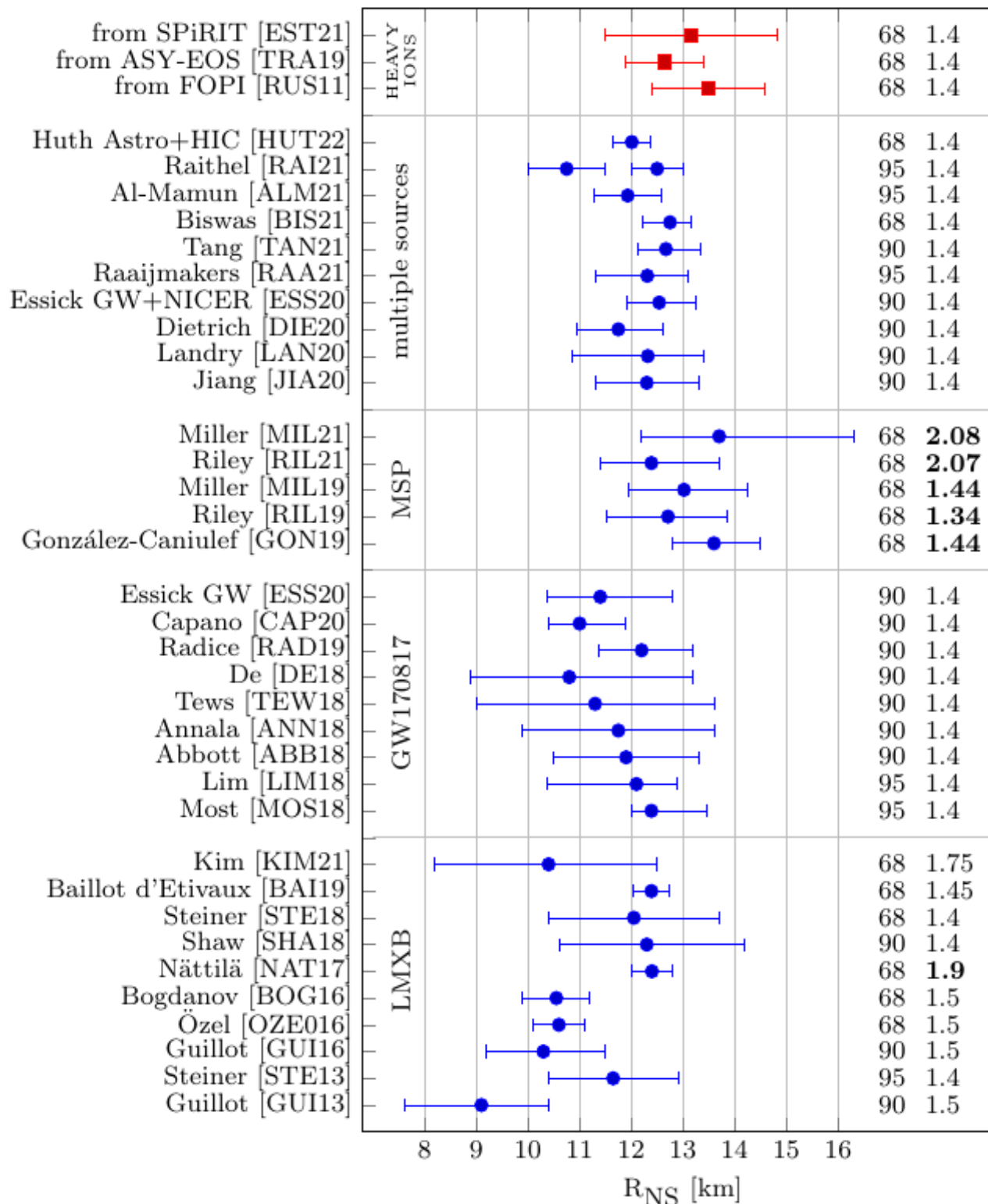


## NS radii from different analyses

Neutron star radii ( $R_{\text{NS}}$ ) from different analyses of Low Mass X-ray Binaries, LMXB, from GW170817 event, from the millisecond pulsars, MSP, from mixed sources of information and from the interpretation of the results of the three heavy ion experiments, from bottom to top. The numbers to the right of the symbols denote the confidence levels (in %) for the radii and the masses of the NS in solar mass units. The masses emphasized in boldface are the inferred/measured ones. The remaining masses are the assumed or averaged ones.

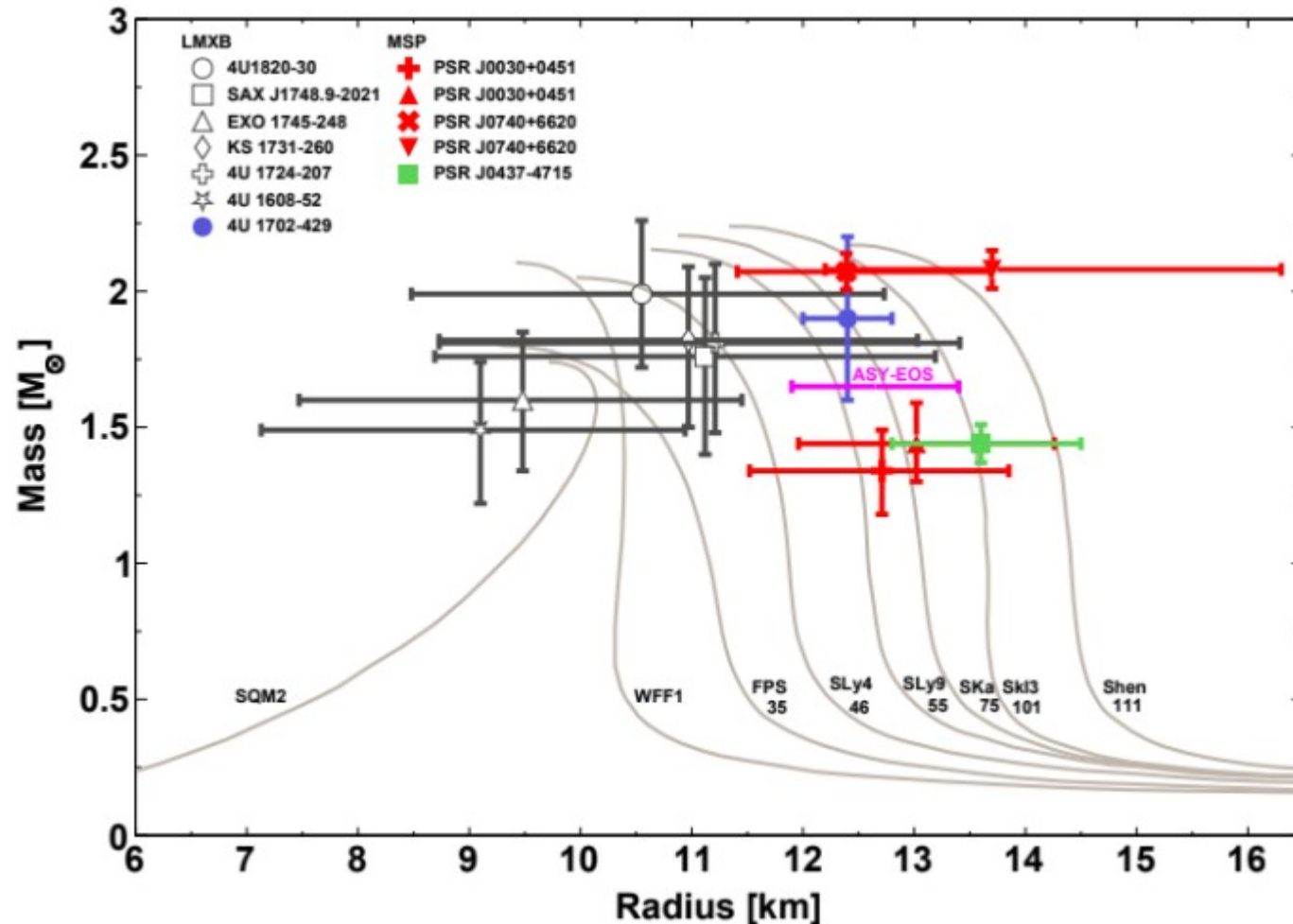
$$L \propto R^4 \text{ and thus } \Delta L/L = 4\Delta R/R$$

[J.M. Lattimer, M. Prakash, Phys. Rep. 621, 127 (2016)]



# Masses and Radii for selected NS

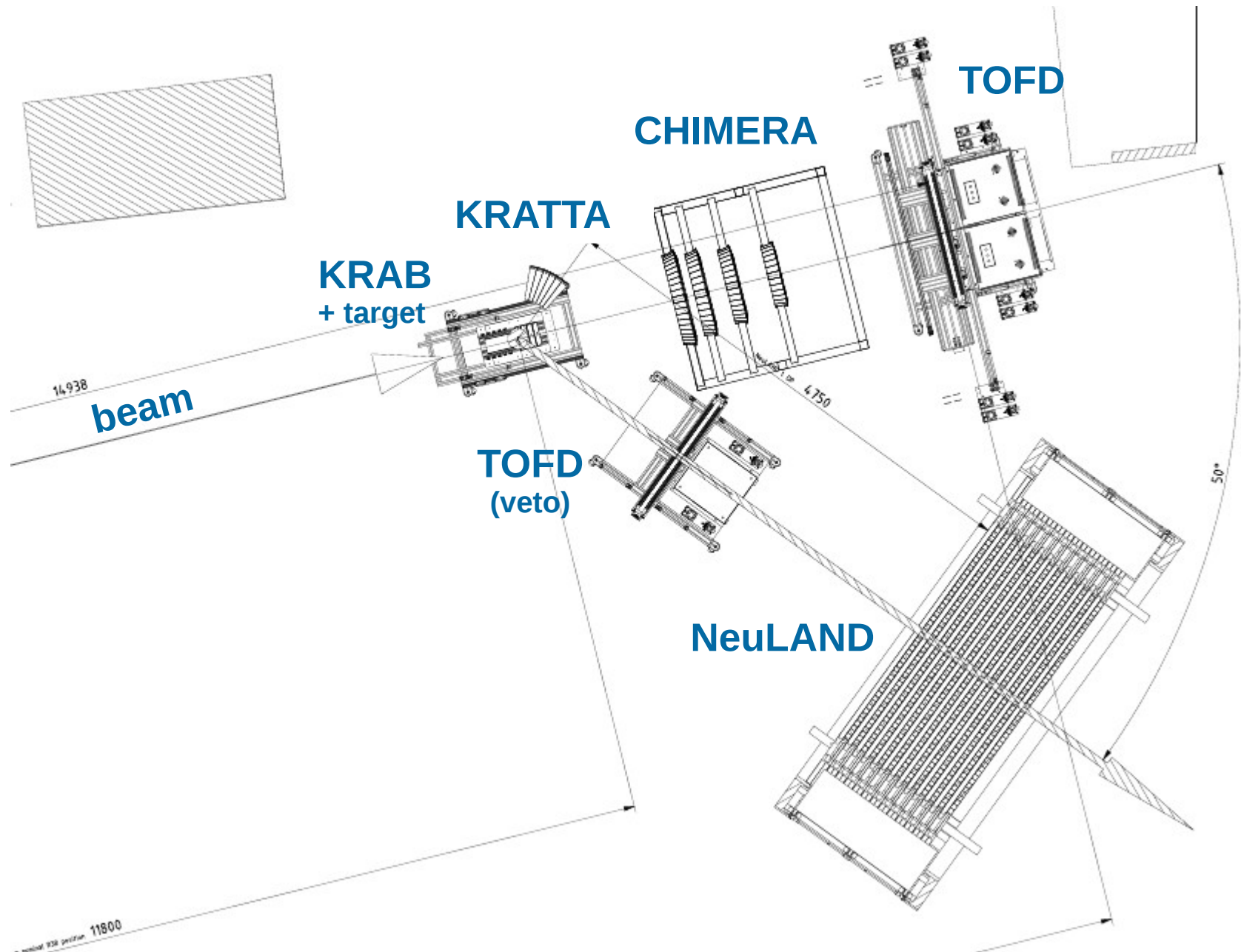
”reverse engineering” approach to pick the right EoS



The data for LMXB were taken from [Kim21] (open symbols) and from [Nättilä17] (filled blue circle). The data for millisecond pulsars measured by NICER (red symbols) were taken from [Riley19] and [Riley21] for J0030 and J0740 (filled crosses) and from [Miller19] and [Miller21] (filled triangles) for the same pulsars, respectively). The data point for J0437 MSP measured by HST+ROSAT (green filled square) was taken from [González-Caniulef19]. The radius range labeled as ASY-EOS was obtained by translating the symmetry energy slope parameter range obtained from the ASY-EOS heavy-ion experiment [Russotto16] to the NS radius range [Trautmann19]. It corresponds to a NS mass of 1.4 M but has been displaced arbitrarily in vertical direction for clarity. The labeled gray lines represent the M-R relations for selected EoSs. The lines for SQM2 and WFF1 were taken from [Degenaar18]. The line for FPS was taken from [Sotani22] and the remaining lines were taken from [Sotani22] (see these references for description of the lines). The numbers below the acronyms of the EoSs (where available) denote the corresponding values of the symmetry energy L parameter in MeV

# S122: ASY-EOS II @ GSI (March 2025)

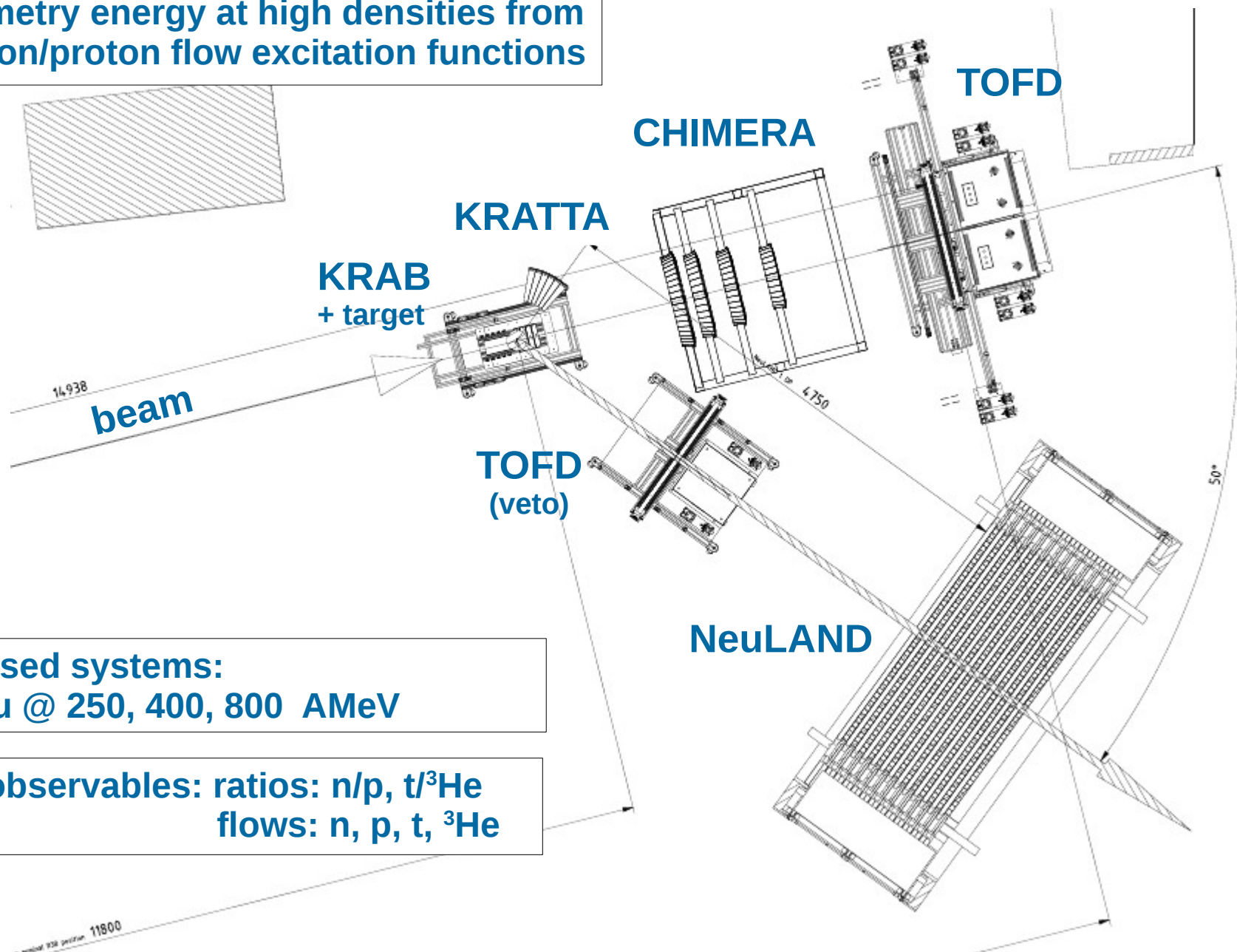
Proposed setup in CAVE C



# S122: ASY-EOS II @ GSI (March 2025)

Proposed setup in CAVE C

Symmetry energy at high densities from  
neutron/proton flow excitation functions



Proposed systems:  
Au+Au @ 250, 400, 800 AMeV

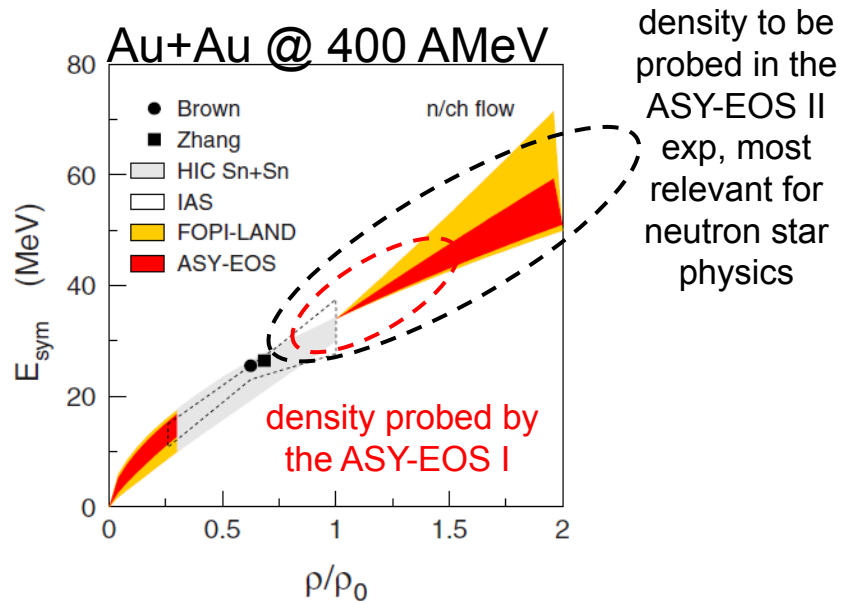
Main observables: ratios:  $n/p$ ,  $t/{}^3\text{He}$   
flows:  $n$ ,  $p$ ,  $t$ ,  ${}^3\text{He}$

# Beam time schedule

## as of 07.06.2024

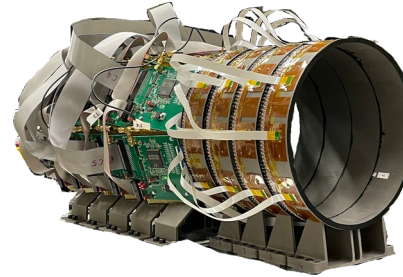
| MAR     | Sat              | Sun | Mon                | Tue              | Wed | Thu | Fri              | Sat | Sun | Mon | Tue              | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon              | Tue | Wed | Thu    | Fri | Sat | Sun | Mon |
|---------|------------------|-----|--------------------|------------------|-----|-----|------------------|-----|-----|-----|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------------------|-----|-----|--------|-----|-----|-----|-----|
| 2025 v5 | 1                | 2   | 3                  | 4                | 5   | 6   | 7                | 8   | 9   | 10  | 11               | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24               | 25  | 26  | 27     | 28  | 29  | 30  | 31  |
| IS N    | 107-Ag           |     | 197-Au             |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     | 208-Pb |     |     |     |     |
| IS S    |                  |     | 197-Au (25 Hz)     |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| ECR     |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| MAZ     | X                |     | X                  |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     | X      |     |     |     |     |
| UNILAC  |                  |     | UMAT, X0, 197-Au   |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| UNILAC  |                  |     | UMAT, M1-3, 197-Au |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| UNILAC  |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| UNILAC  |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| SIS     | 101, HFS, 107-Ag |     |                    | 022, HAD, 197-Au |     |     |                  |     |     |     | 122, HTC, 197-Au |     |     |     |     |     |     |     |     |     |     |     |     | 150, HFS, 208-Pb |     |     |        |     |     |     |     |
| SIS     |                  |     |                    |                  |     |     | 101, HTC, 107-Ag |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| SIS     |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| ESR     |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |
| CRY     |                  |     |                    |                  |     |     |                  |     |     |     |                  |     |     |     |     |     |     |     |     |     |     |     |     |                  |     |     |        |     |     |     |     |

# S122: ASY-EOS II @ GSI (March 2025)

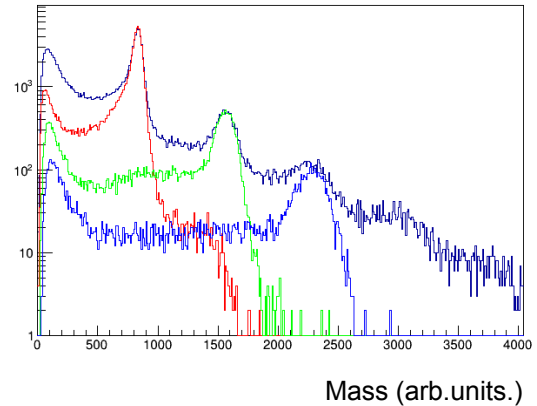


[P. Russotto et al., PRC 94, 034608 (2016)]

improved resolution and higher densities probed

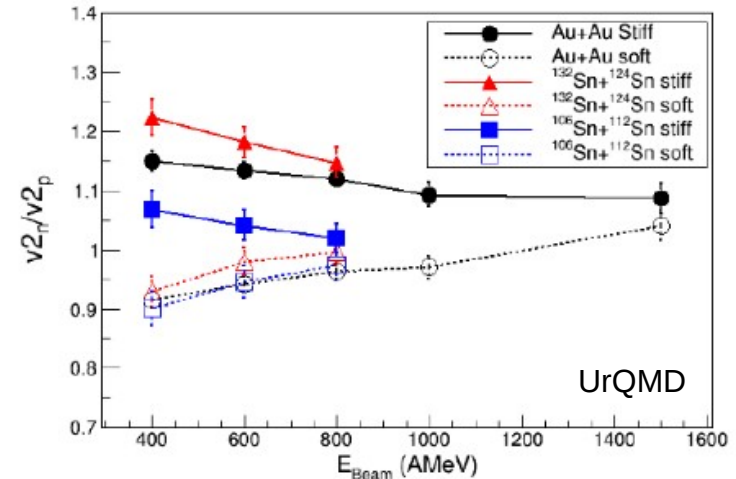


**KRAB:** new detector for reaction plane determination and on-beam centrality selection



**NeuLAND:** capability to resolve **p, d, t**

| Beam                              | Energy [AMeV] | Justification                                                  |
|-----------------------------------|---------------|----------------------------------------------------------------|
| $^{197}\text{Au}+^{197}\text{Au}$ | 250           | highest sensitivity on $K_{\text{sym}}$                        |
| $^{197}\text{Au}+^{197}\text{Au}$ | 400           | reference to ASY-EOS I, n/p tests higher densities than before |
| $^{197}\text{Au}+^{197}\text{Au}$ | 800           | highest sensitivity on L, high-density tested                  |



possible discrimination of the stiffness of  $E_{\text{sym}}$  also through trends of excitation function of elliptic flow ratios of n and p

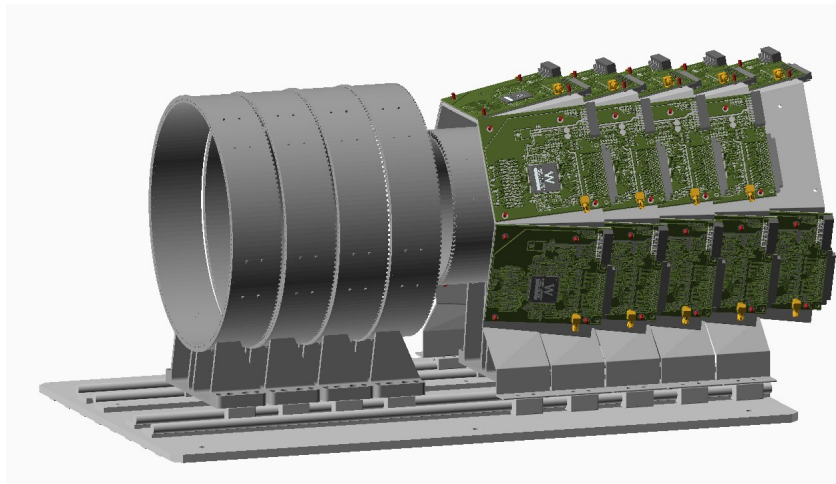
## ...a lesson learned with $\mu$ Ball

- higher segmentation would do better
- faster scintillators would do better
- better  $\delta$ -electron shielding is needed

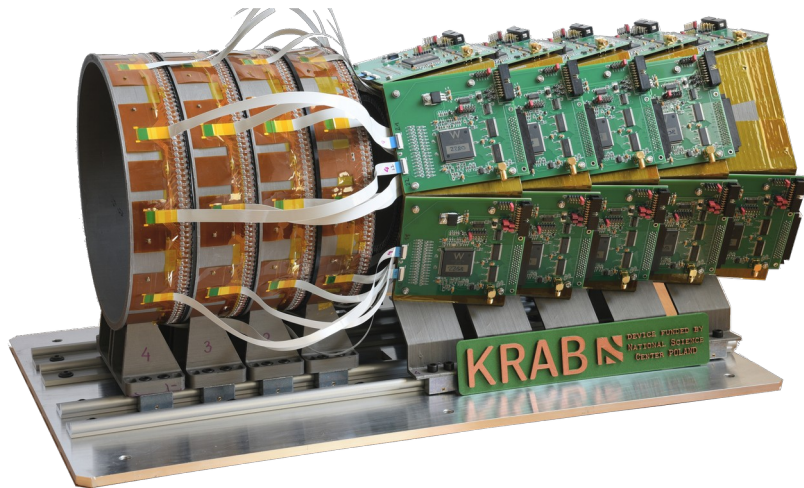
### **a new detector around the target should:**

- provide fast multiplicity trigger
- provide reasonable centrality estimates
- allow sharp estimates of the reaction plane
- provide discrimination for upstream reactions in air/windows/helium
- be as much as possible insensitive to  $\delta$ -electrons
- be compact and as much as possible neutron blind

# KRAB multiplicity trigger | reaction plane | centrality detector



design



actual view

## Main characteristics:

- 3D printed mechanical structure (ABS)
- 5 rings of  $4 \times 4 \text{ mm}^2$  fast scintillating fibers (BCF-10)
- read out by  $3 \times 3 \text{ mm}^2$  SiPMs (SensL MicroFJ-30035)
- $4 \times 160$  segments in forward rings and 96 in backward ring
- 736 channels
- 32 ch CITIROC 1A ASICs used for signal processing
- compact A7585D SiPM power modules
- broad coverage from  $30^\circ$  to  $165^\circ$
- high geometrical efficiency  $\sim 87\%$  (within covered angles)
- $\sim 5\%$  multihit probability (for 1 AGeV Au+Au reaction)
- sufficiently large for radioactive beams
- sufficiently small and lightweight not to disturb neutrons
- min radius - 7 cm, max radius - 12 cm
- length  $\sim 43 \text{ cm}$  (size of a  $\sim 24''$  monitor)
- He sleeve to suppress the  $\delta$ -electrons background
- remotely controlled target wheel with 4 slots
- ZnS target + camera
- ControlBox to control and setup CITIROCs
- TriggerBox to produce trigger, bit pattern and for
- slow control monitoring (scalars)
- multiplicity based trigger produced after 50 ns
- bit pattern of fired segments sent to V2495 logic module
- RIO4 + MBS based data acquisition
- GUI based remote control software

# KRAB multiplicity trigger | reaction plane | centrality detector

## ControlBox

- 5 boards, 1 per ring
- sets LV for CITIROCS and HV for SiPMs,
- uses A7585D SiPM power modules
- used for setting and control of CITIROC parameters: biases, gains, thresholds,
- allows control of analog signal probe

## TriggerBox



- 6 boards,
- 5 FPGA per board
- generates multiplicity based trigger
- allows setting and control of trigger: threshold, gates
- provides slow control scalars independent of DAQ,
- produces the fired module bit pattern for V2495

## Helium sleeve



- fits inside KRAB
- ~13 l volume
- contains target wheel

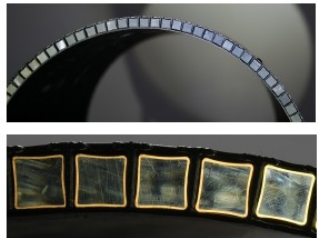


## Target wheel

- remotely controlled
- stepper motor driven,
- fits inside sleeve,
- 4 target slots,
- with inductive sensors for position verification
- possible camera preview

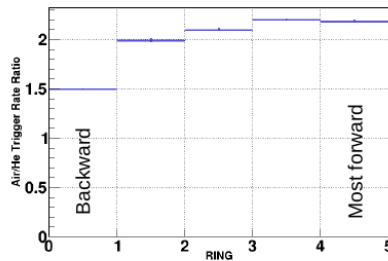
## Mechanics

Ring frames and supports were 3D printed with ABS. Below: backward ring filled with SciFi segments



## Helium effect

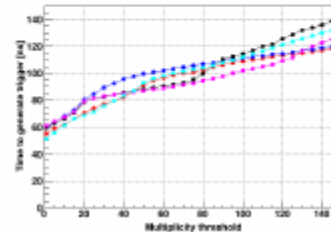
Trigger rate ratio for measurement in air and in helium without the target on proton beam at 80 MeV.



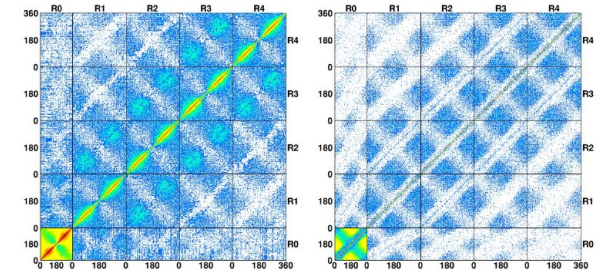
The count rate drops in He by a factor of 2 in forward rings. Multiplicity threshold was set to 1.

## Trigger timing

Time to generate trigger in the TriggerBox varies from about 50 to about 140 ns, depending on the threshold setting. Different curves correspond to electromagnetic excitation of different sections of rings.

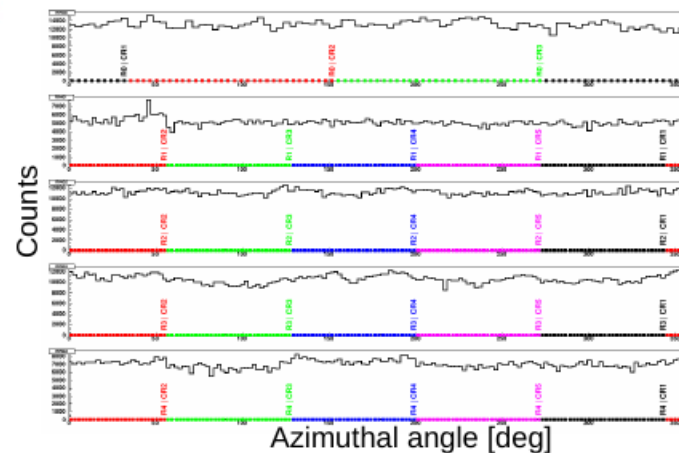
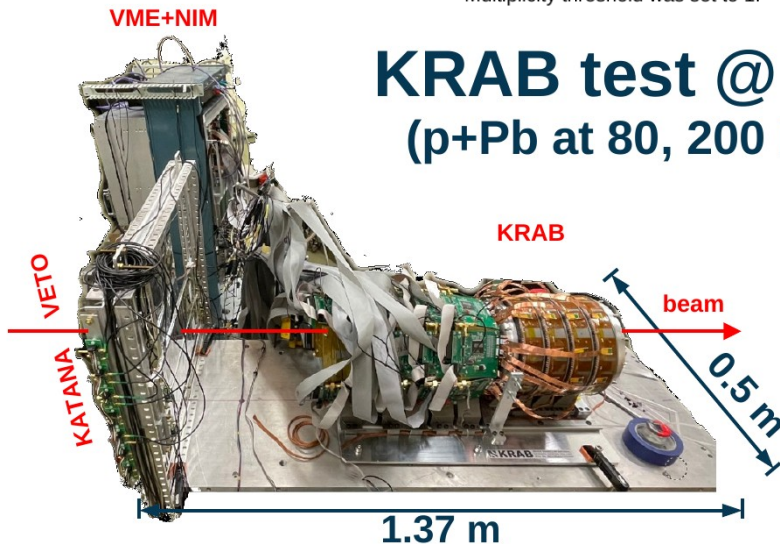


## Cosmics



Cosmic rays are emitted mostly vertically as seen from the correlation on the left for  $MULT \geq 2$  condition. Right plot shows correlation for  $MULT == 2$  condition.

## KRAB test @ CCB (p+Pb at 80, 200 MeV)



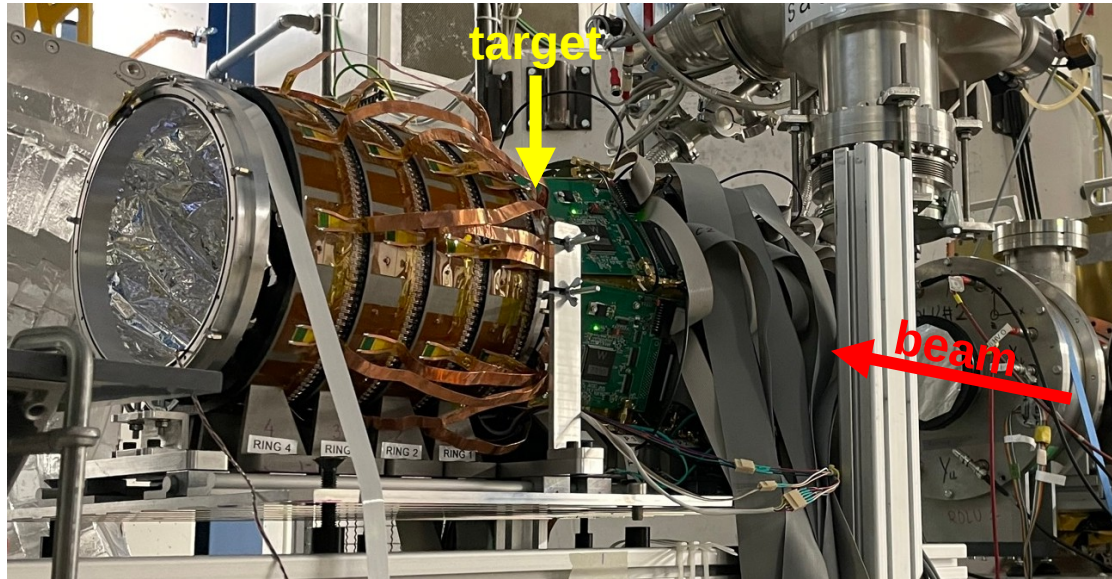
## Azimuthal angles

Azimuthal distributions for p+Pb @ 200 MeV for RINGS 0-4 from top to bottom. Channels covered by different CITIROCS are marked with different colors.

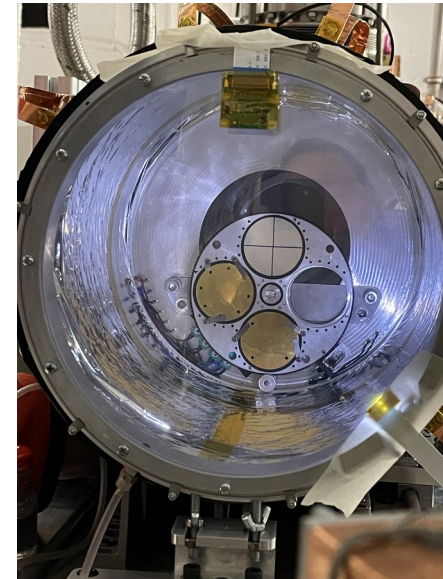
# KRAB beam test at GSI (March 2024)

Au @ 400 & 800 AMeV

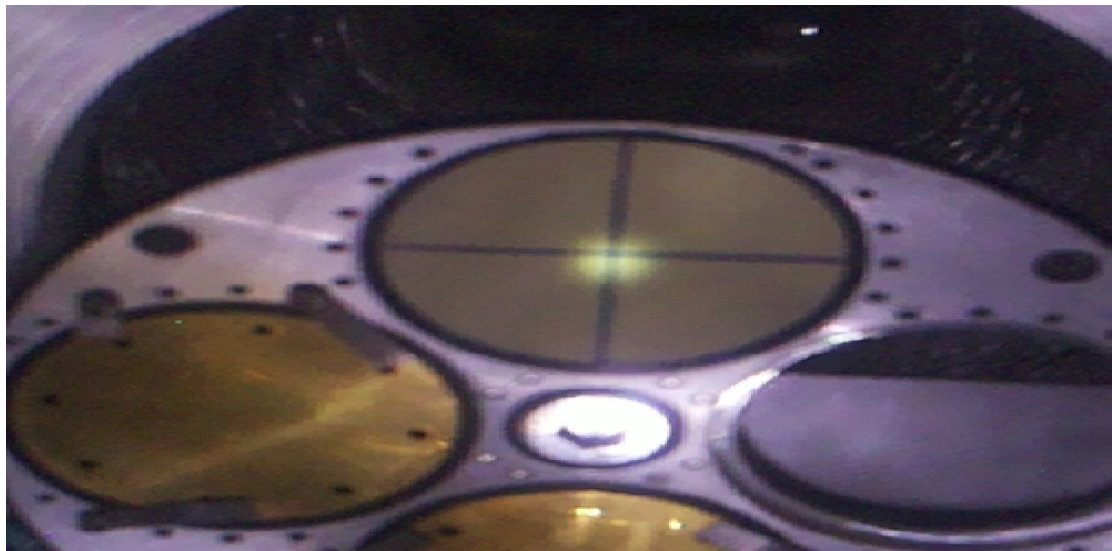
KRAB in CAVE C



filled with He

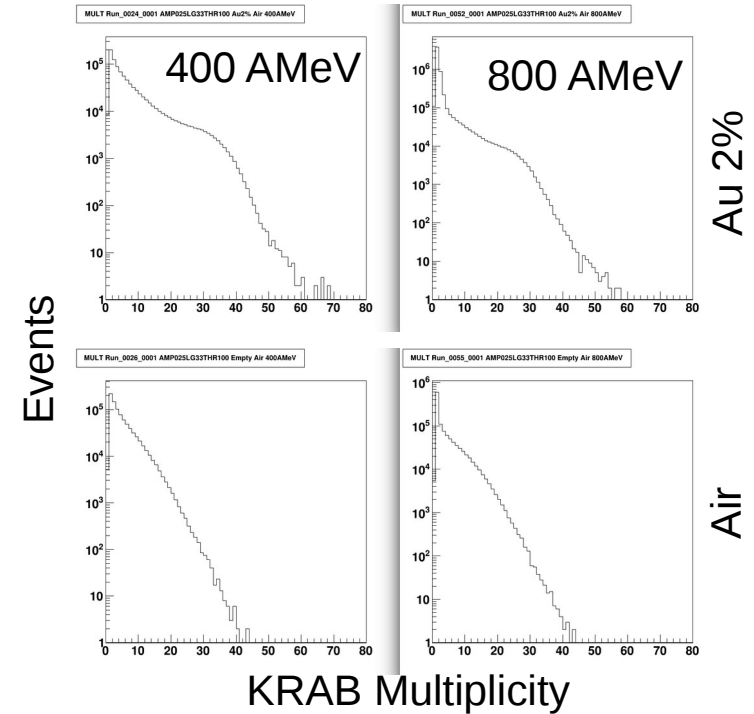
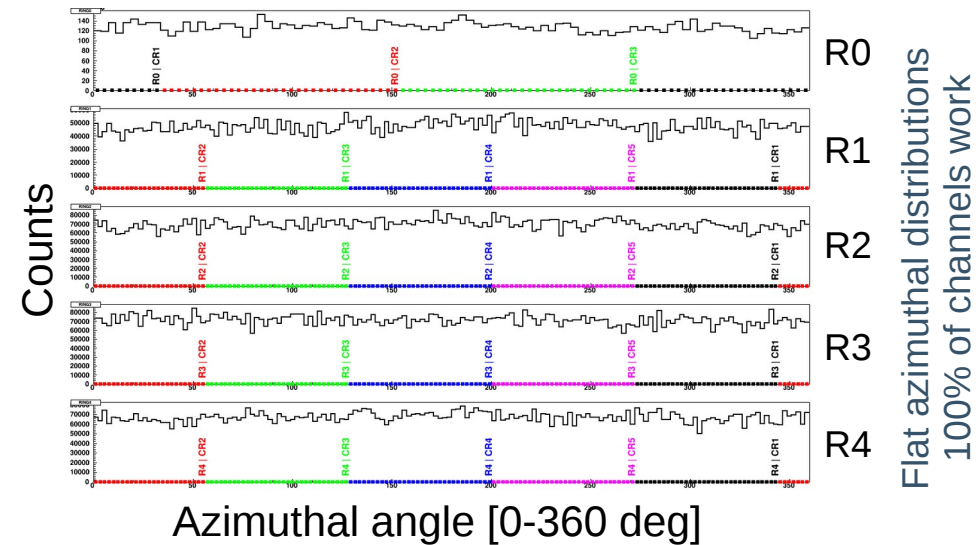


Au @ 400 AMeV beam spot on the ZnS target

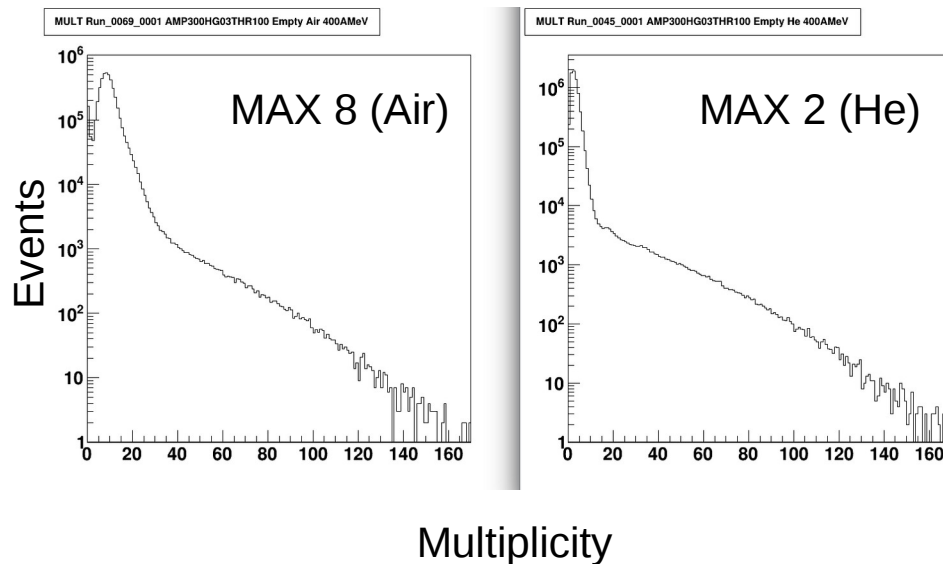


# KRAB beam test at GSI (March 2024)

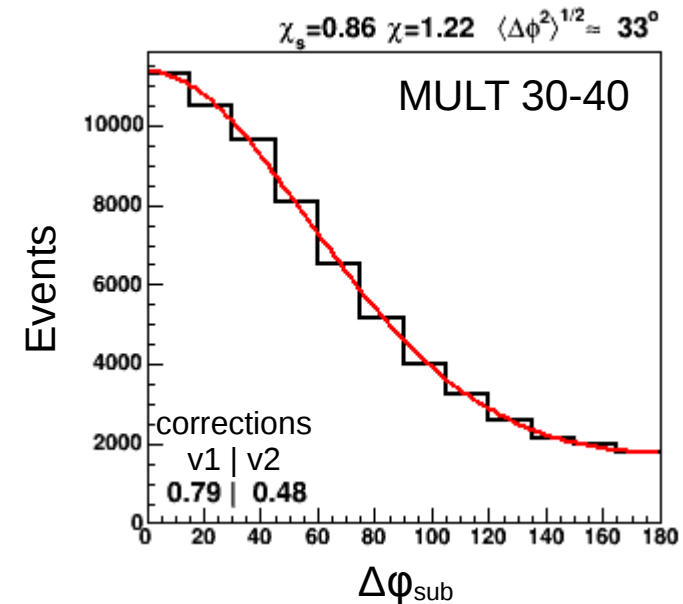
## Au @ 400 & 800 AMeV



Reasonable multiplicity distributions  
for “low-gain high-thresholds” setting



Multiplicity of hits on  $\delta$ -electrons  
reduced by a factor of 4 in He  
for “high gain” setting



Reasonable reaction plane  
resolution

# Summary & Conclusions

- The first ASY-EOS measurement yielded a moderately soft to linear density dependence of the symmetry energy with  $L = 72 \pm 13$  MeV. It appears close to the upper limit of the LMXB inferences, of the LIGO/VIRGO constraints and of the low energy results, but is well compatible with the NICER results.
- Precise measurements are needed up to  $\sim 1$  AGeV to explore the Symmetry Energy at densities up to  $\sim 2 \rho_0$ . ASY-EOS II measurement is scheduled for March 2025 at GSI within R3B infrastructure. NeuLAND, KRAB and TOFDs assure improved resolutions.
- KRAB detector will play a crucial role in the ASY-EOS II experiment, it will:
  - provide fast multiplicity trigger
  - provide reasonable centrality estimates
  - provide estimates of the reaction plane
  - provide discrimination for upstream reactions in air/windows/helium
  - be as much as possible insensitive to  $\delta$ -electrons
  - be compact and neutron blind

# ASY-EOS II + R3B Collaboration/Proposal

## SYMMETRY ENERGY AT HIGH DENSITIES FROM NEUTRON/PROTON FLOW EXCITATION FUNCTIONS

### R3B Collaboration and

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**PRINCIPAL INVESTIGATORS:** M.D. Cozma<sup>4</sup>, E. De Filippo<sup>5</sup>, I. Gašparić<sup>6</sup>, A. Le Fèvre<sup>2</sup>, Y. Leifels<sup>2</sup>, J. Łukasik<sup>3</sup>, S. Pirrone<sup>5</sup>, G. Politi<sup>5,7</sup>, P. Russotto<sup>1</sup>

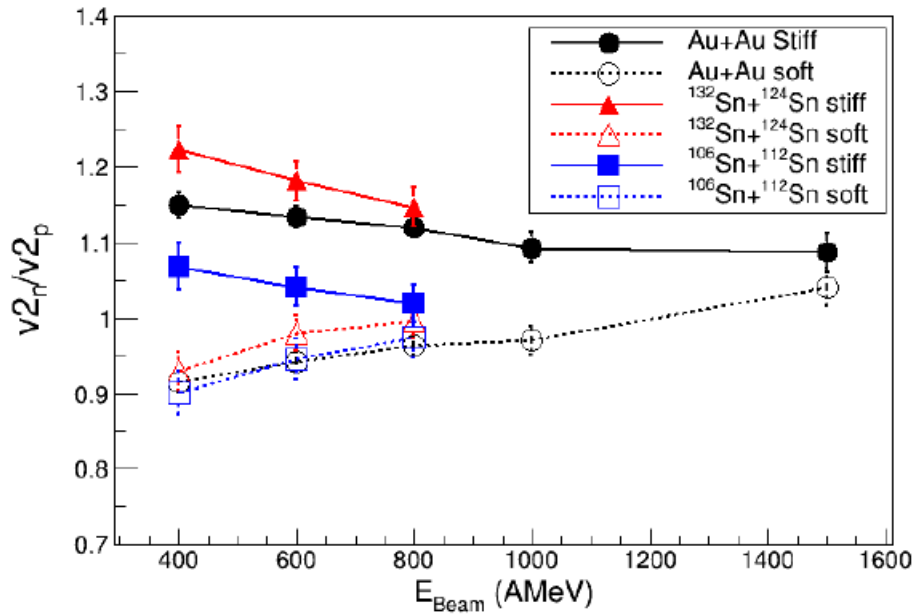
**PARTICIPANTS:** L. Acosta<sup>8</sup>, K. Agarwal<sup>9</sup>, T. Aumann<sup>2,10</sup>, E. Bonnet<sup>11</sup>, K. Boretzky<sup>2</sup>, J. Brzychczyk<sup>12</sup>, Ch. Caesar<sup>2</sup>, G. Cardella<sup>5</sup>, A. Chbihi<sup>13</sup>, A. Corsi<sup>14</sup>, J.E. Ducret<sup>13</sup>, M. Famiano<sup>15</sup>, F. Favela<sup>16</sup>, J. Gauthier<sup>17</sup>, E. Geraci<sup>5,7</sup>, B. Gnoffo<sup>5,7</sup>, K. Göbel<sup>18</sup>, C. Guazzoni<sup>19</sup>, K. Hagel<sup>17</sup>, T. Isobe<sup>20</sup>, D. Jelavić Malenica<sup>10</sup>, A. Krasznahorkay<sup>21</sup>, K. Krawczyk<sup>12</sup>, P. Lasko<sup>3</sup>, I. Lihtar<sup>22</sup>, K. Łojek<sup>12</sup>, W.G. Lynch<sup>23</sup>, P. Marini<sup>24</sup>, D.J. Marín-Lámbarri<sup>8</sup>, N.S. Martorana<sup>1,7</sup>, A.B. McIntosh<sup>17</sup>, L. McIntosh<sup>17</sup>, E.V. Pagano<sup>1</sup>, P. Pawłowski<sup>3</sup>, F. Rizzo<sup>1,7</sup>, P. Senger<sup>25</sup>, V.R. Sharma<sup>8</sup>, H. Simon<sup>2</sup>, B. Sowicki<sup>3</sup>, W. Trautmann<sup>2</sup>, A. Trifirò<sup>26</sup>, M. Trimarchi<sup>26</sup>, M.B. Tsang<sup>23</sup>, G. Verde<sup>5</sup>, A. Wieloch<sup>12</sup> and S.J. Yennello<sup>17</sup> K. Szczepaniec<sup>12</sup>

**THEORY SUPPORT:** J. Aichelin<sup>11</sup>, M. Colonna<sup>1</sup>, M.D. Cozma<sup>4</sup>, P. Danielewicz<sup>23</sup>, Ch. Hartnack<sup>11</sup>, A. Le Fèvre<sup>2</sup>, Q.F. Li<sup>27</sup>, Y. Wang<sup>27</sup> and H.H. Wolter<sup>28</sup>

**INSTITUTIONS:** <sup>1</sup>INFN-LNS, Catania, Italy; <sup>2</sup>GSI, Darmstadt, Germany; <sup>3</sup>IFJ PAN, Kraków, Poland; <sup>4</sup>IFIN-HH, Bucharest, Romania; <sup>5</sup>INFN-Sezione di Catania, Italy; <sup>6</sup>RBI, Zagreb, Croatia; <sup>7</sup>Università di Catania, Italy; <sup>8</sup>IF-UNAM, México; <sup>9</sup>Univ of Tübingen, Germany; <sup>10</sup>Technische Univ. Darmstadt, Germany; <sup>11</sup>SUBATECH-CNRS, Nantes, France; <sup>12</sup>Jagiellonian University, Kraków, Poland; <sup>13</sup>GANIL, Caen, France; <sup>14</sup>CEA-IRFU, Saclay, France; <sup>15</sup>Western Michigan University, Kalamazoo, MI, USA; <sup>16</sup>ICN-UNAM, México; <sup>17</sup>Texas A&M Univ., College Station, USA; <sup>18</sup>Goethe-Univ., Frankfurt, Germany; <sup>19</sup>Politecnico di Milano and INFN-Milano, Italy; <sup>20</sup>RIKEN, Wako-shi, Japan; <sup>21</sup>Institute for Nuclear Research, Debrecen, Hungary; <sup>22</sup>Univ. of Zagreb, Croatia; <sup>23</sup>NSCL/MSU, East Lansing, USA; <sup>24</sup>CENBG, Bordeaux Gradignan, France; <sup>25</sup>FAIR, Darmstadt, Germany; <sup>26</sup>Dipartimento di Scienze MIFT, Univ. di Messina, Italy. <sup>27</sup>School of Science, Huzhou University, P.R. China; <sup>28</sup>Univ of München, Germany;

# UrQMD predictions

flow ratios



sensitivity

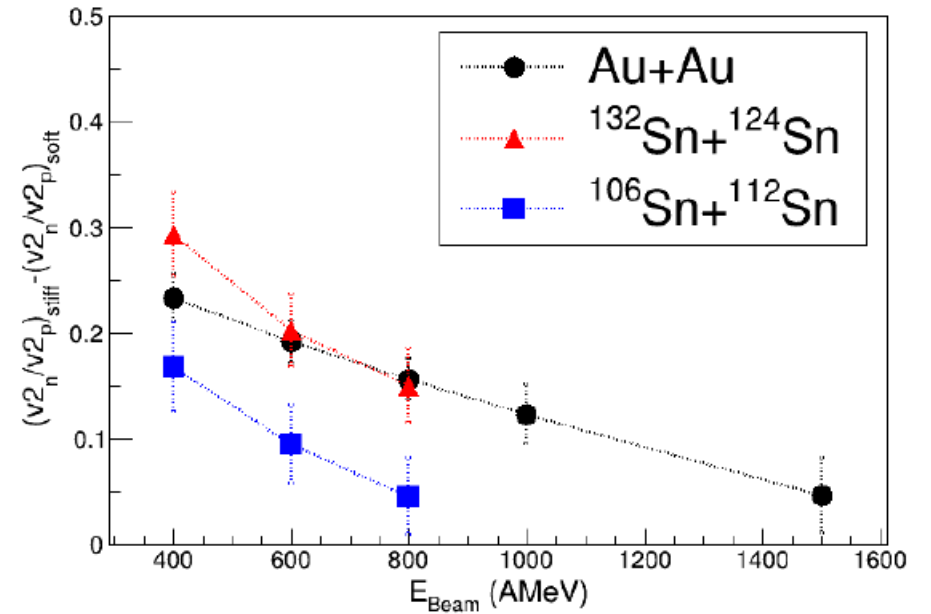


Figure 4: Left panel: Excitation functions of neutron-to-proton elliptic flow ratios,  $v2_n/v2_p$ , at mid-rapidity for semi-central Au+Au,  $^{132}\text{Sn}+^{124}\text{Sn}$ , and  $^{106}\text{Sn}+^{112}\text{Sn}$  collisions, as predicted by the UrQMD model for stiff and soft  $E_{\text{sym}}(\rho)$ . Right panel: differences between the stiff and soft results.

# Justification of the beam time request

Proposed systems:  $^{197}\text{Au} + ^{197}\text{Au}$  @ 250, 400, 600, 1000 AMeV

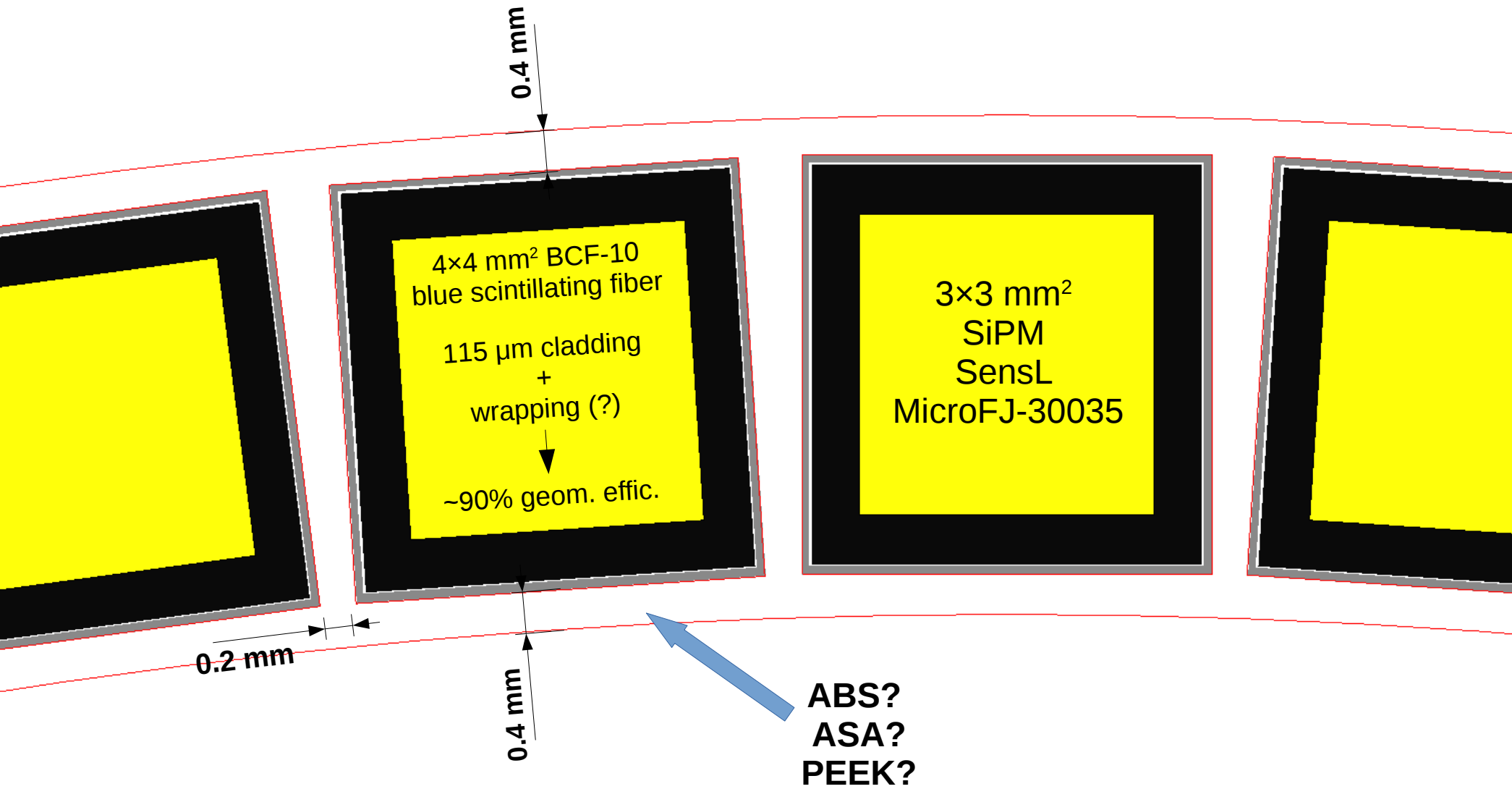
**250 AMeV** → according to TüQMD, results at this energy show the highest sensitivity on  $K_{\text{sym}}$ . This energy corresponds also to the dynamic range of KRATTA assuring clean p, d, t identification without punch-through segments.

**400 AMeV** → is the energy measured in the first ASY-EOS experiment and is necessary as a reference point for unveiling the systematic differences between the new and old measurements. This is the energy of the maximum squeeze-out, it also assures no punch-through segments in NeuLAND identification maps.

**600 AMeV** → according to TüQMD simulations this energy shows the highest sensitivity on  $L$ .

**1000 AMeV** → allows to explore the highest densities where the neutron/proton elliptic flow observable keeps a significant sensitivity ( $\sim 15\%$ ) to symmetry energy parametrization, according to the UrQMD calculations of Fig. 4;

# ring segments



schematic diagram of the  
signal/power/information flow

CITIROC 1A ASIC (?)  
32×(preamp+discr.)

SiPM

flexi band



32 pin connector

20+3 × rectangular boards  
(5 or 3 per ring)

EXP

Trigger  
box

to VME

V2495  
Programmable  
Logic Unit

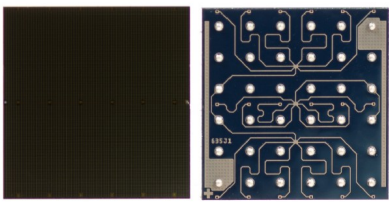
ACQ

HV+LV

Mult. Thr.  
Remote  
Setting

Discr. Thr.  
Multiplex.  
Remote  
Control

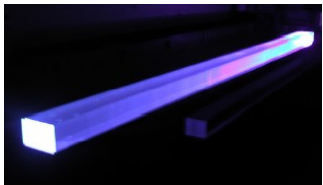




3×3 mm<sup>2</sup>

## SiPM+Plastic

| <b>MicroFJ-300xx-TSV SiPM</b>    |            |       | 20μm   35μm                                             |       |                     |
|----------------------------------|------------|-------|---------------------------------------------------------|-------|---------------------|
| Parameter                        | $\Delta V$ | min   | typical                                                 | max   | units               |
| Breakdown Voltage (Vbr)          |            | 24.25 | 24.50                                                   | 24.75 | V                   |
| Overvoltage ( $\Delta V$ )       |            | 1     |                                                         | 6     | V                   |
| Spectral Range                   |            | 200   | 420 (peak)                                              | 900   | nm                  |
| Photon detection efficiency @    | Vbr +2.5 V |       | 31   <b>38</b>                                          |       | %                   |
| Photon detection efficiency @    | Vbr +6.0 V |       | 42   <b>51</b>                                          |       | %                   |
| Dark Count Rate @                | Vbr +2.5 V |       | 45                                                      | 75    | kHz/mm <sup>2</sup> |
| Dark Count Rate @                | Vbr +5.0 V |       | 80                                                      | 157   | kHz/mm <sup>2</sup> |
| Gain @                           | Vbr +2.5 V |       | $9.1 \times 10^5$   <b><math>2.8 \times 10^6</math></b> |       |                     |
| Gain @                           | Vbr +5.0 V |       | $1.7 \times 10^6$   <b><math>5.3 \times 10^6</math></b> |       |                     |
| Dark Current @                   | Vbr +2.5 V |       | 0.2                                                     | 0.3   | μA                  |
| Dark Current @                   | Vbr +5.0 V |       | 1.1                                                     | 1.6   | μA                  |
| Rise time                        |            |       | 100                                                     |       | ps                  |
| Microcell recharge time constant |            |       | <b>12</b>   37                                          |       | ns                  |
| Microcell fill factor            |            |       | 62   <b>75</b>                                          |       | %                   |
| No. of microcells                |            |       | <b>14850</b>   5676                                     |       |                     |
| Cover refractive Index           |            |       | 1.53 @ 436nm                                            |       |                     |

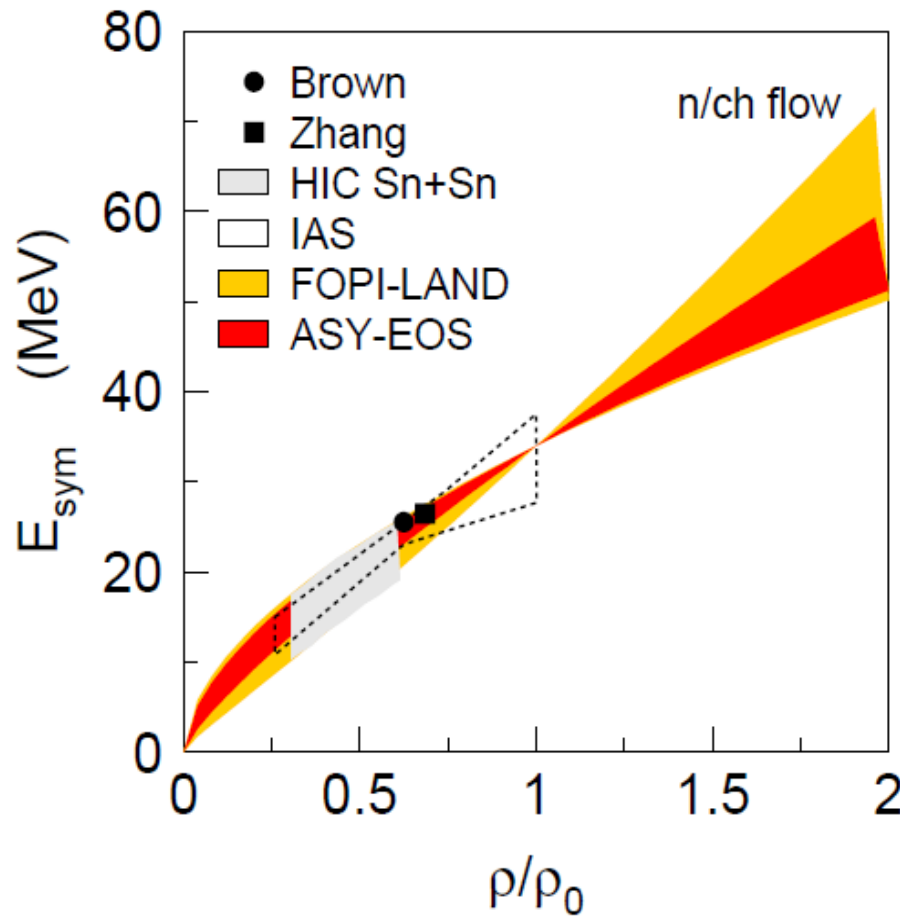


| <b>Plastic Scintillator</b> | Emission | Peak   | Decay Time | Refr. Ind. | Density                 |
|-----------------------------|----------|--------|------------|------------|-------------------------|
| BCF-10 fiber                | blue     | 432 nm | 2.7 ns     | 1.60       | 1.050 g/cm <sup>3</sup> |
| BC-490 casting resin        | blue     | 425 nm | 2.3 ns     | 1.58       | 1.032 g/cm <sup>3</sup> |

size comparable to that of a 24" monitor



# LAND@ASY-EOS

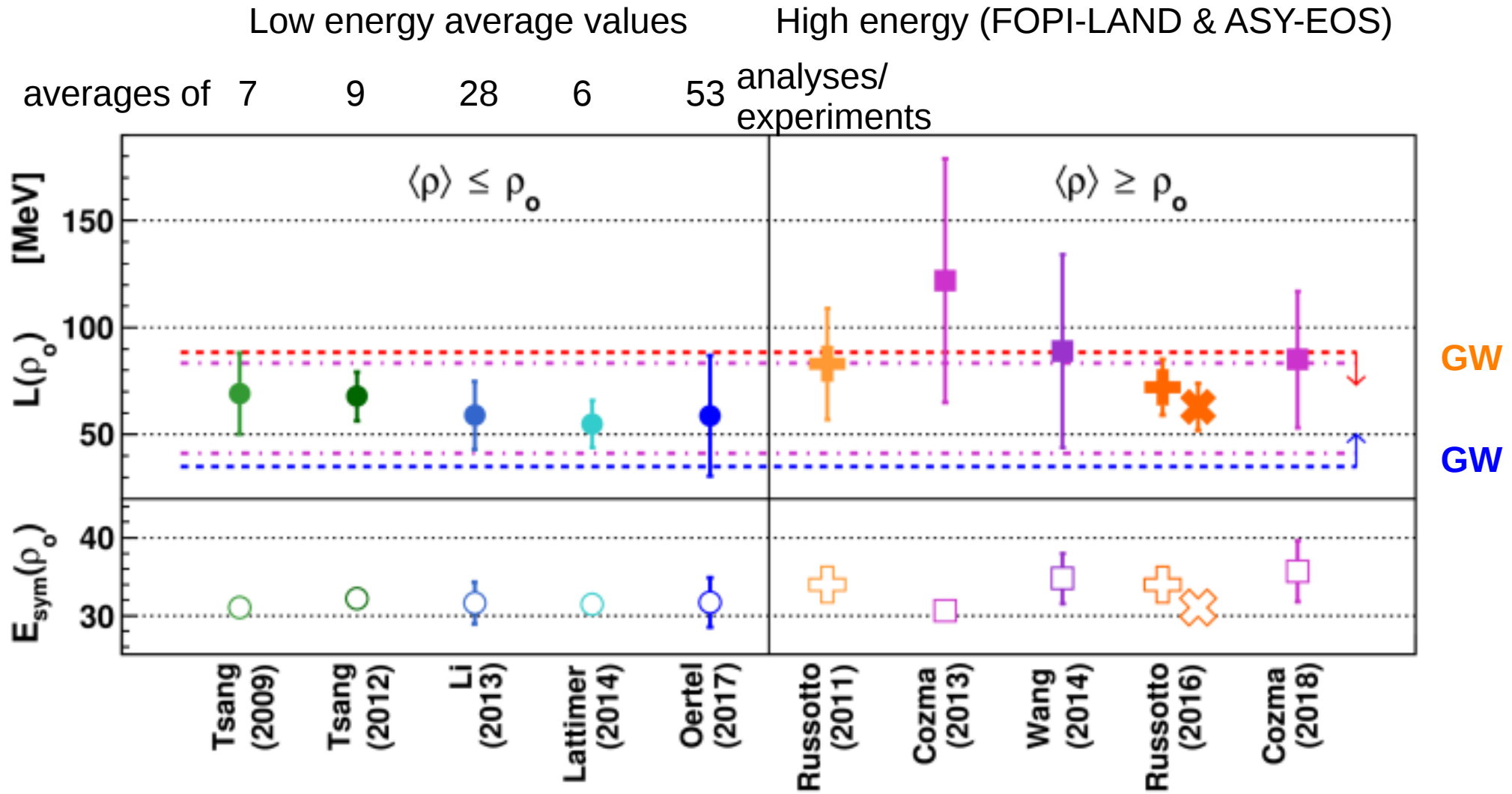


$$\gamma = 0.72 \pm 0.19$$

$$L = 72 \pm 13 \text{ MeV}$$

FIG. 19: (Color online) Constraints deduced for the density dependence of the symmetry energy from the present data in comparison with the FOPI-LAND result of Ref. [5] as a function of the reduced density  $\rho/\rho_0$ . For reference, the low-density results of Refs. [66–69] as presented in Ref. [70] are included.

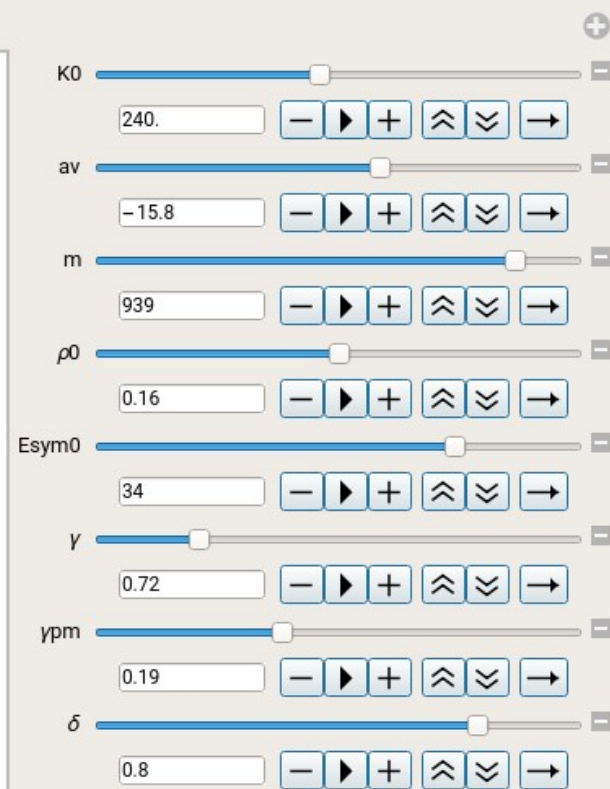
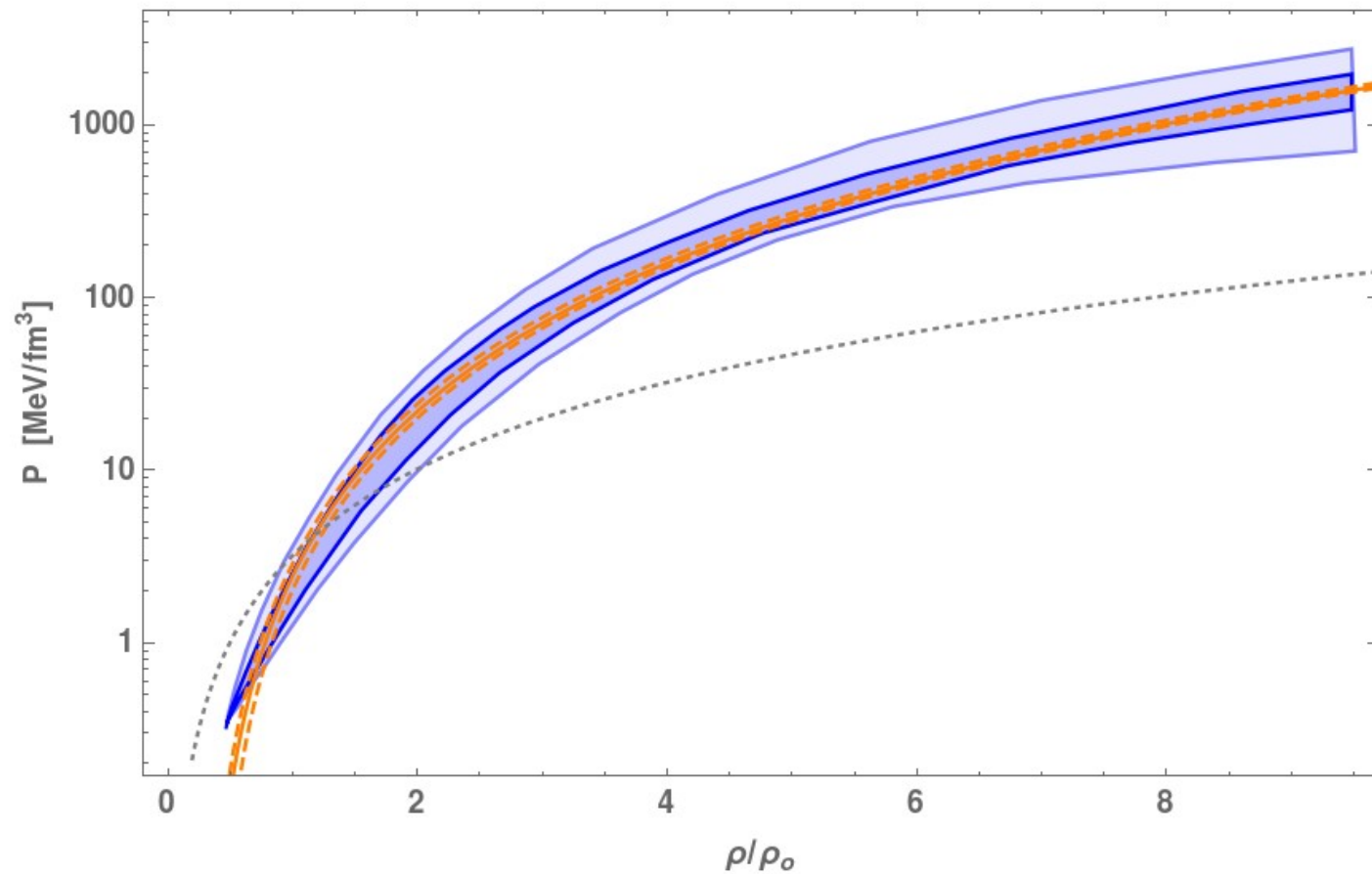
# Current Symmetry Energy constraints



GW170817  
Abbott PRL 2018

ASY-EOS + Skyrme

Fermi Gas



# densities probed in HIC

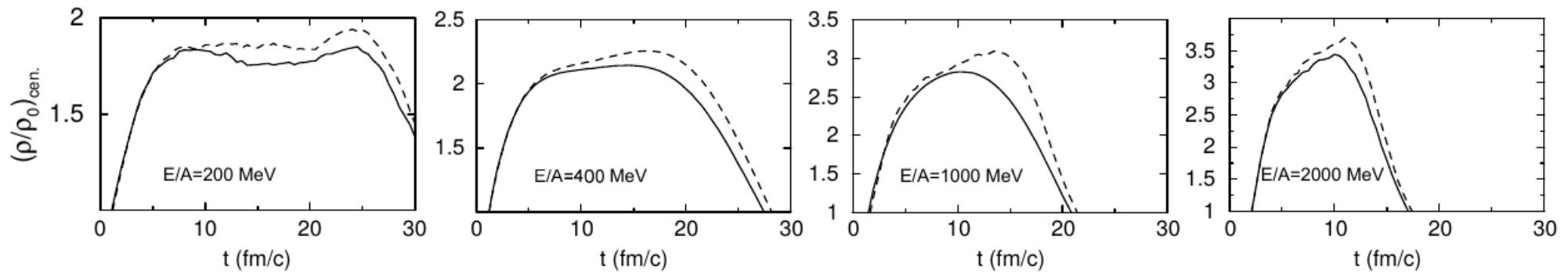


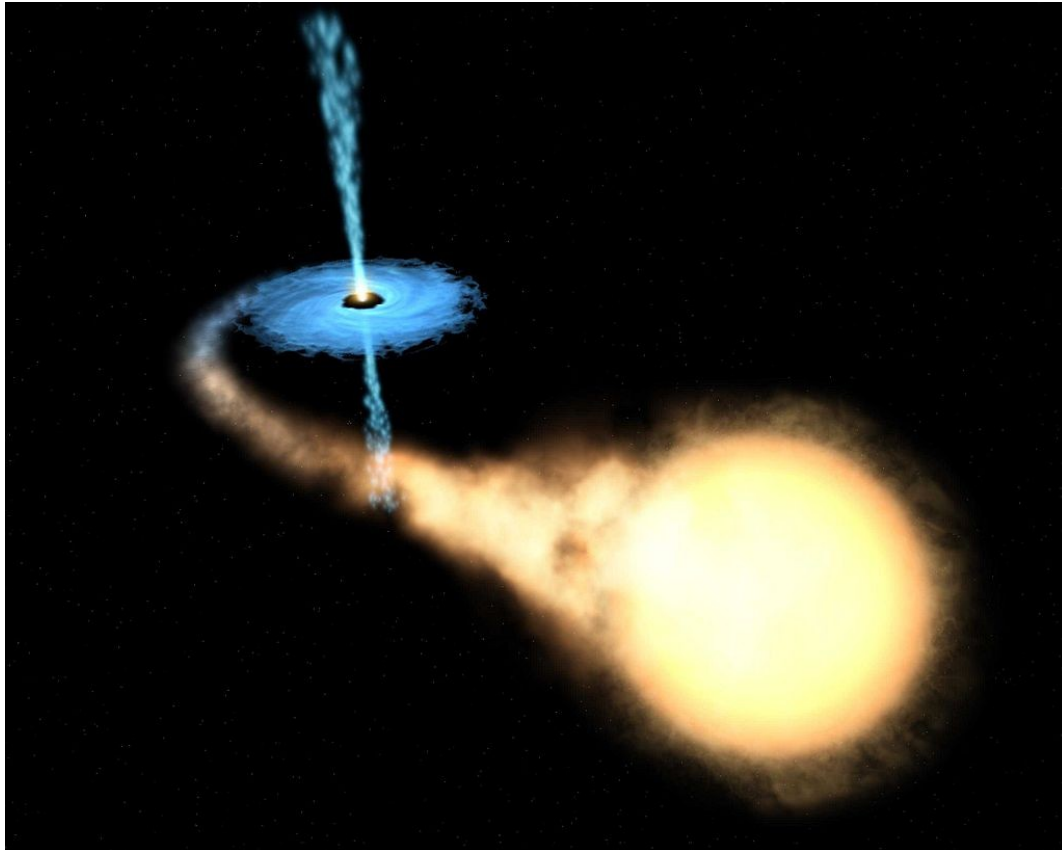
Figure 3: Evolution of the central baryon density in  $^{132}\text{Sn} + ^{124}\text{Sn}$  collisions at beam energies from 200 to 2000 MeV/nucleon for  $b = 1$  fm, as predicted by the hadronic transport model of [31].

adapted from B.-A. Li, Nucl. Phys. A 708 (2002) 365.

# The Mass & Radius of Neutron Stars

from LMXB

A “nuclear diesel”



The measurement of flux  $F_{\infty} \propto \left( \frac{R_{\infty}}{D} \right)^2 \sigma T_{eff}^4$   
and temperature (black b.)  $T_c \propto \lambda_{max}^{-1}$

yields an apparent angular size:

$$\frac{R_{\infty}}{D} = \frac{R}{D} \frac{1}{\sqrt{1 - \frac{2GM}{c^2 R}}}$$

uncertainties:

- distance  $D$ ,
- interstellar absorption  $N_H$
- atmospheric composition