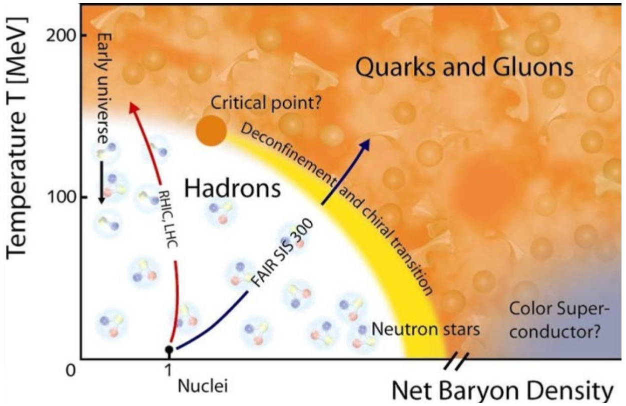


The ASYEOS experiment at GSI and how to proceed towards higher density constraints of the symmetry energy

Y. Leifels

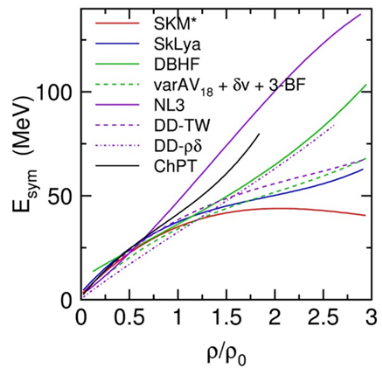
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt

NUSYM2021
online 13.-15.10.2021

FAIR GSI

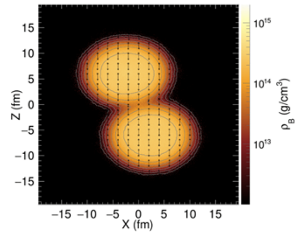
Outline

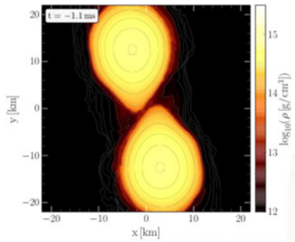
- Short introduction



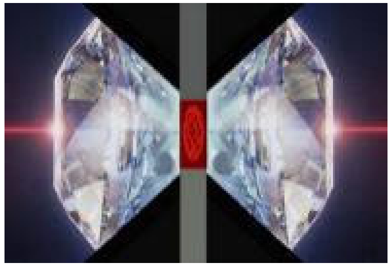
- Experiments at high densities

- Link to astrophysical observations





- Experiments at higher densities



The FOPI collaboration

A. Andronic, R. Averbeck, Z. Basrak, N. Bastid,
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R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I.
Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J.
Frühauf, F. Fu, P. Gasik, O. Hartmann,
N. Herrmann, K.D. Hildenbrand, B. Hong,
T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis,
M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R.
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Korea University, Seoul, Korea, GSI Darmstadt,
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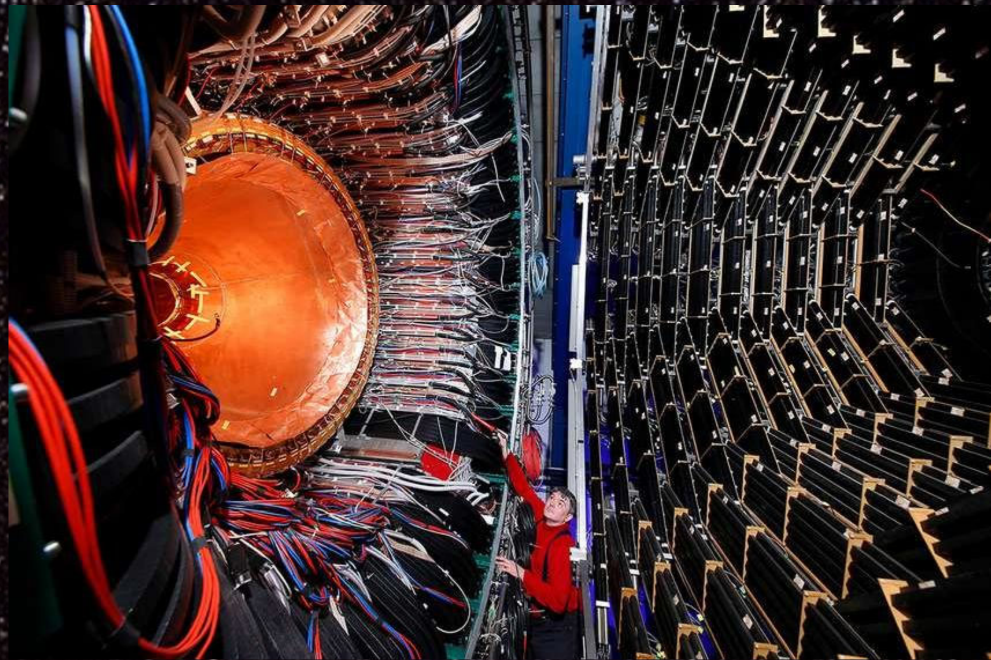
Germany, Univ. of Heidelberg, Germany , Univ. of
Warsaw, Poland, RBI Zagreb, Croatia, IMP Lanzhou,
China, SMI Vienna, Austria, TUM, Munich, Germany,
T.Yamazaki(RIKEN)



The ASY-EOS collaboration

P. Russotto[1], M. Chartier[2], E. De Filippo[1], A. Le Fèvre[3], S. Gannon[2], I. Gašparić[4,5], M. Kiš[3,4], S. Kupny[6], Y. Leifels[3], R.C. Lemmon[7], J. Łukasik[8], P. Marini[9,10], A. Pagano[1], P. Pawłowski[8], S. Santoro[11,12], W. Trautmann[3], M. Veselsky[13], L. Acosta[14], M. Adamczyk[6], A. Al-Ajlan[15], M. Al-Garawi[16], S. Al-Homaidhi[15], F. Amorini[14], L. Auditore[11,12], T. Aumann[5], Y. Ayyad[17], V. Baran[14,18], Z. Basrak[4], J. Benlliure[17], C. Boiano[19], M. Boisjoli[10], K. Boretzky[3], J. Brzychczyk[6], A. Budzanowski[8], G. Cardella[1], P. Cammarata[9], Z. Chajecki[20], A. Chbihi[10], M. Colonna[14], D. Cozma[21], B. Czech[8], M. Di Toro[14,22], M. Famiano[23], E. Geraci[1,22], V. Greco[14,22], L. Grassi[4], C. Guazzoni[19,24], P. Guazzoni[19,25], M. Heil[3], L. Heilborn[9], R. Introzzi[26], T. Isobe[27], K. Kezzar[16], A. Krasznahorkay[28], N. Kurz[3], E. La Guidara[1], G. Lanzalone[14,29], P. Lasko[6], Q. Li[30], I. Lombardo[30,31], W. G. Lynch[20], Z. Matthews[2], L. May[9], T. Minniti[11,12], M. Mostazo[17], M. Papa[1], S. Pirrone[1], G. Politi[1,22], F. Porto[14,22], R. Reifarth[3], W. Reisdorf[3], F. Riccio[19,25], F. Rizzo[14,22], E. Rosato[30,31], D. Rossi[3], H. Simon[3], I. Skwirczynska[8], Z. Sosin[6], L. Stuhl[28], A. Trifirò[11,12], M. Trimarchi[11,12], M. B. Tsang[20], G. Verde[1], M. Vigilante[30,31], A. Wieloch[6], P. Wigg[2], H. H. Wolter[32], P. Wu[2], S. Yennello[9], P. Zambon[19,24], L. Zetta[19,25] and M. Zoric[4]

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[28]Institute of Nuclear Research, Debrecen, Hungary
[29]Università Kore, Enna, Italy
[30]Huzhou Teachers College, China
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Motivation: Equation of state of nuclear matter

EOS in thermodynamics pressure P(ρ,T)

$$P = \rho^2 \left.\frac{\partial\, E/A}{\partial \rho}\right|_{T=const}$$

Nuclear physics EOS

$$\frac{E}{A} = \left. E/A(\rho)\right|_{T=0}$$

Nuclear incompressibility K

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

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

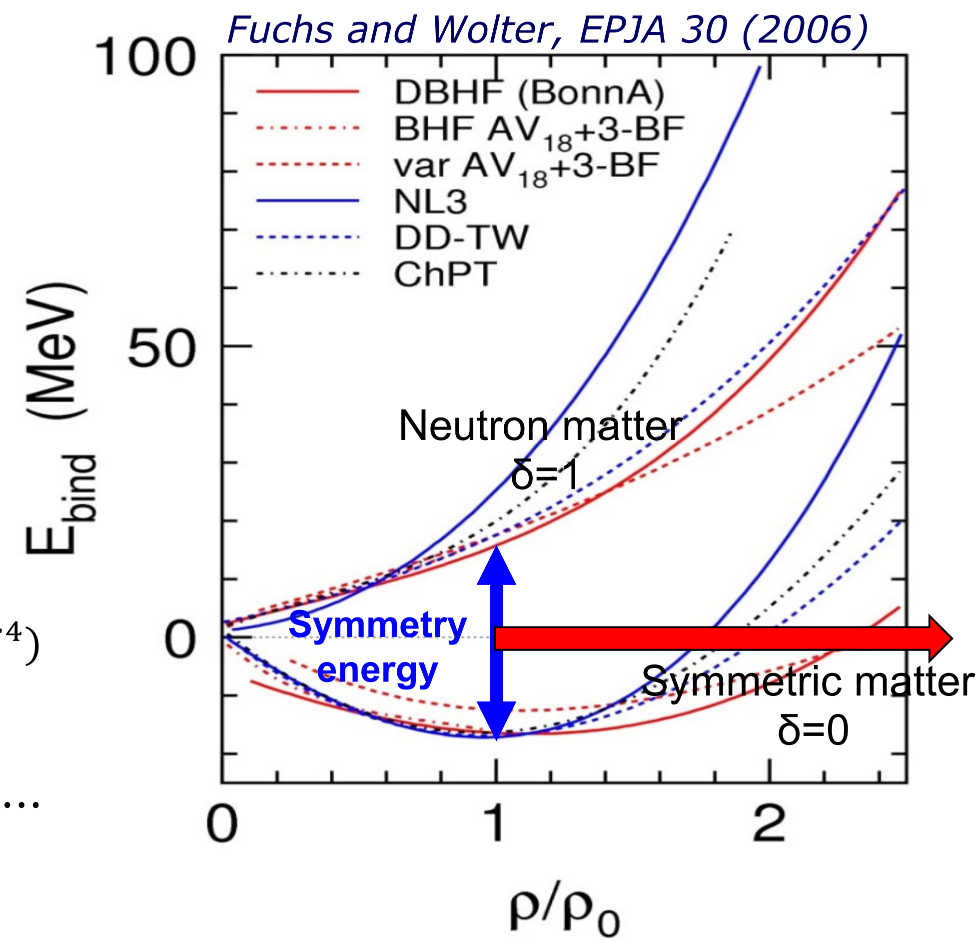
Symmetry energy E_{sym}

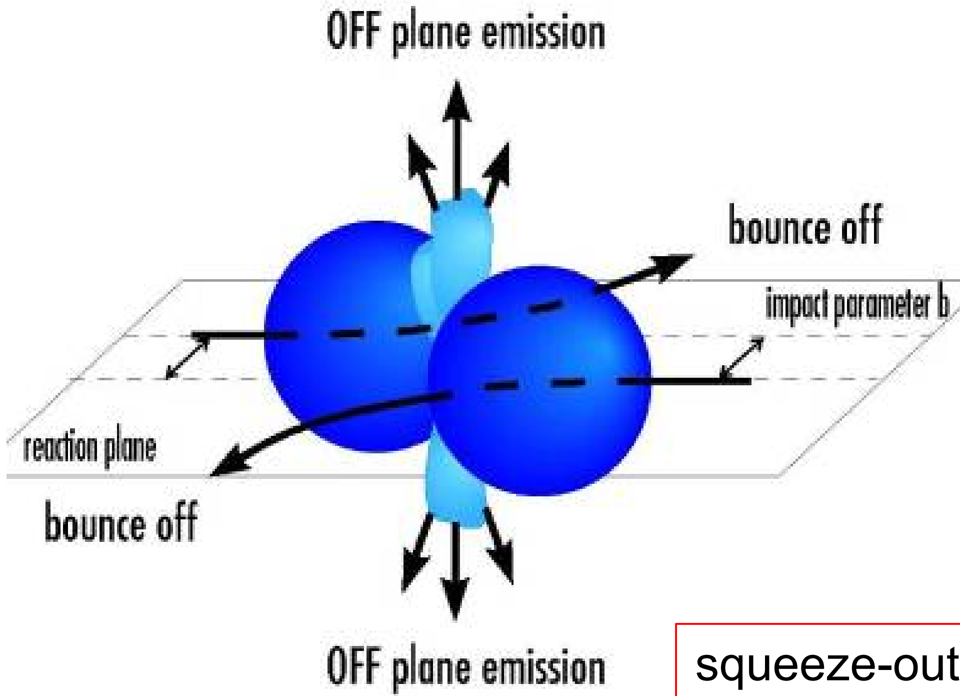
$$E(\rho,\delta) = E_{SNM}(\rho,\delta=0) + \delta^2 E_{sym}(\rho) + O(\delta^4)$$

mit

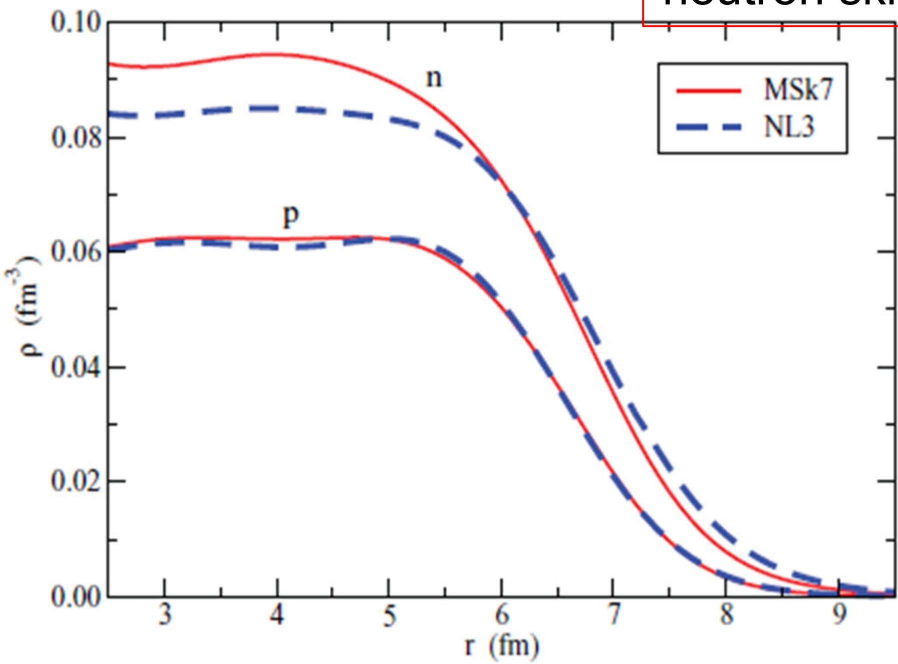
$$E_{sym} = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

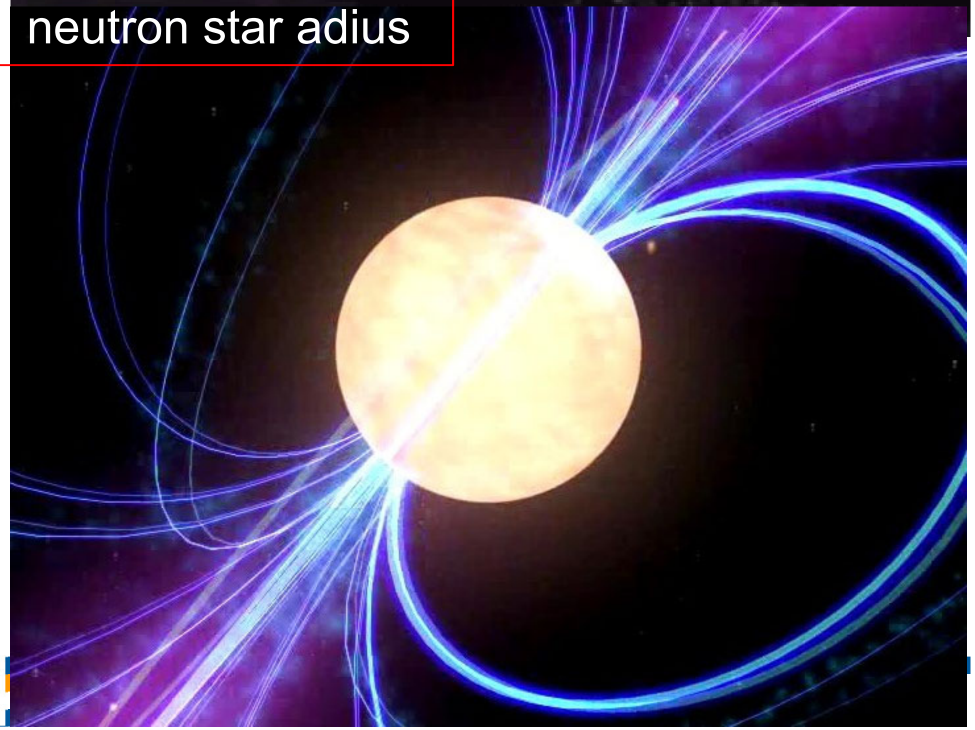
Slope $L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}$





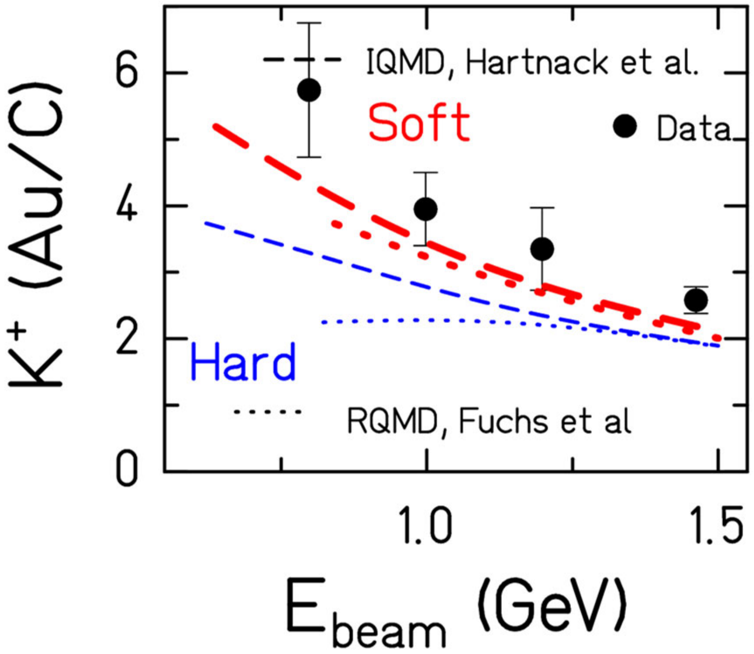
squeeze-out tidal deformation
neutron skin neutron star adius

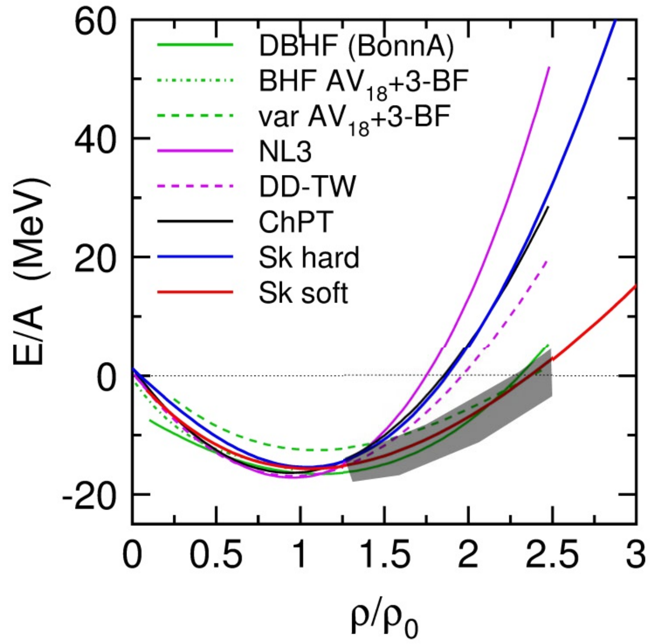




Probing the EOS of symmetric matter with Kaon production

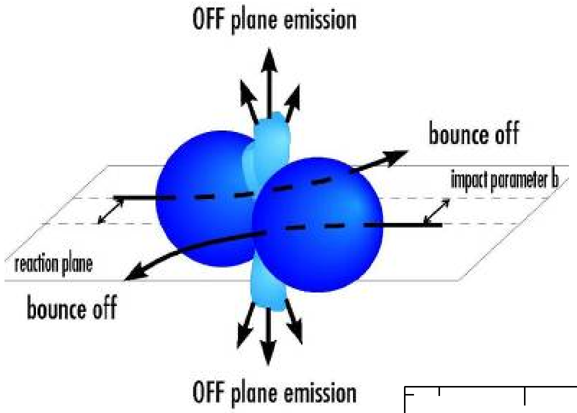
C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 01230
C. Fuchs et al. PRL 86 (2001) 1974

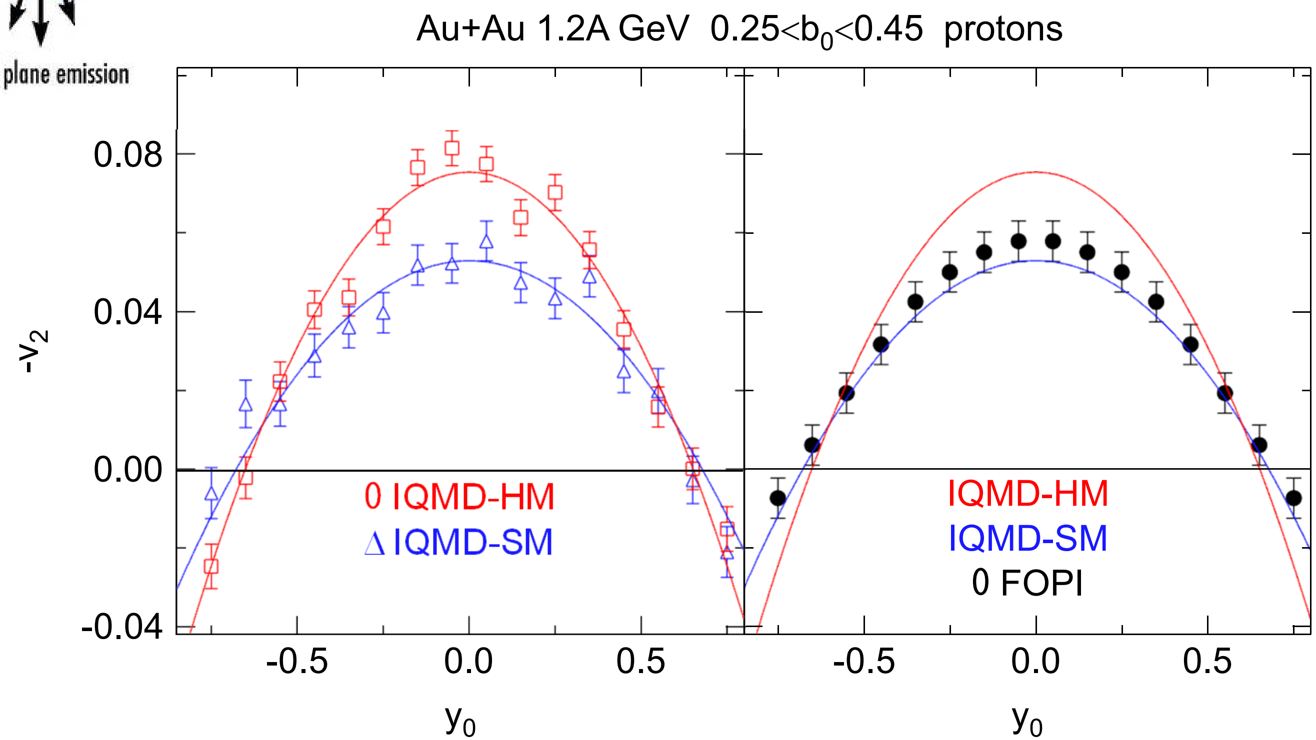




Ratio of yields stable against variation of
K^+ production cross section
Strong sensitivity to EOS due to multistep production (formation of nucleon resonances, e.g. Δ)
-> soft EOS (K=200)
Isospin dependence of EOS [N/Z(Au) = 1.49]

Probing the EOS of symmetric matter with flow



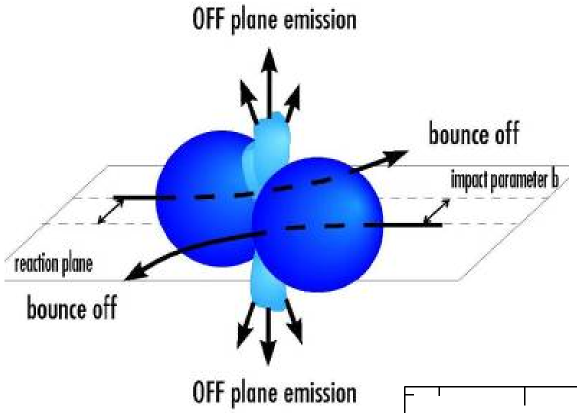


K_0 =
380 MeV ('stiff')
200 MeV ('soft')

With momentum dependent interaction: **compulsory**

A. Le Fèvre et al., NPA 945 (2016) 112–135

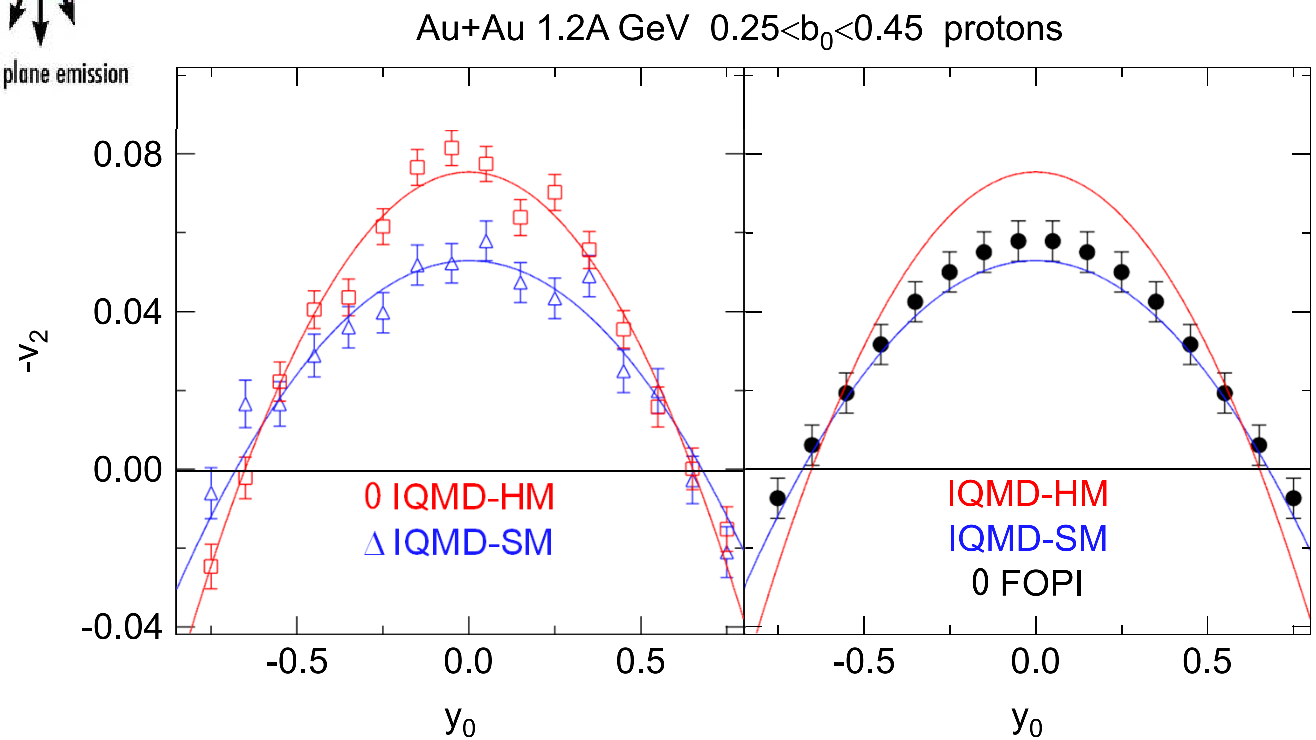
Probing the EOS of symmetric matter with flow



Parametrization of shape:

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

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



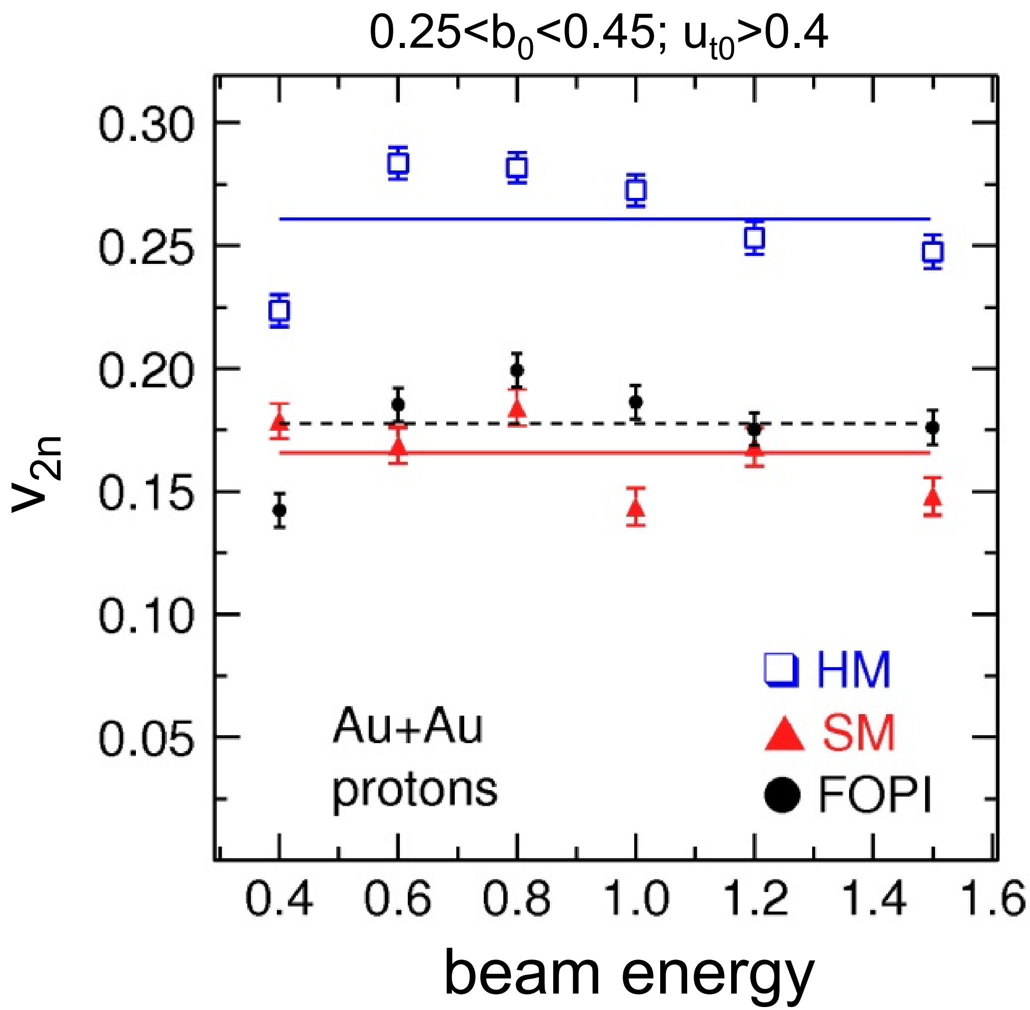
K_0 =
380 MeV ('stiff')
200 MeV ('soft')

With momentum dependent interaction: **compulsory**

A. Le Fèvre et al., NPA 945 (2016) 112–186

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, Nucl. Phys. A 876 (2012) 1

Parametrization of elliptic flow

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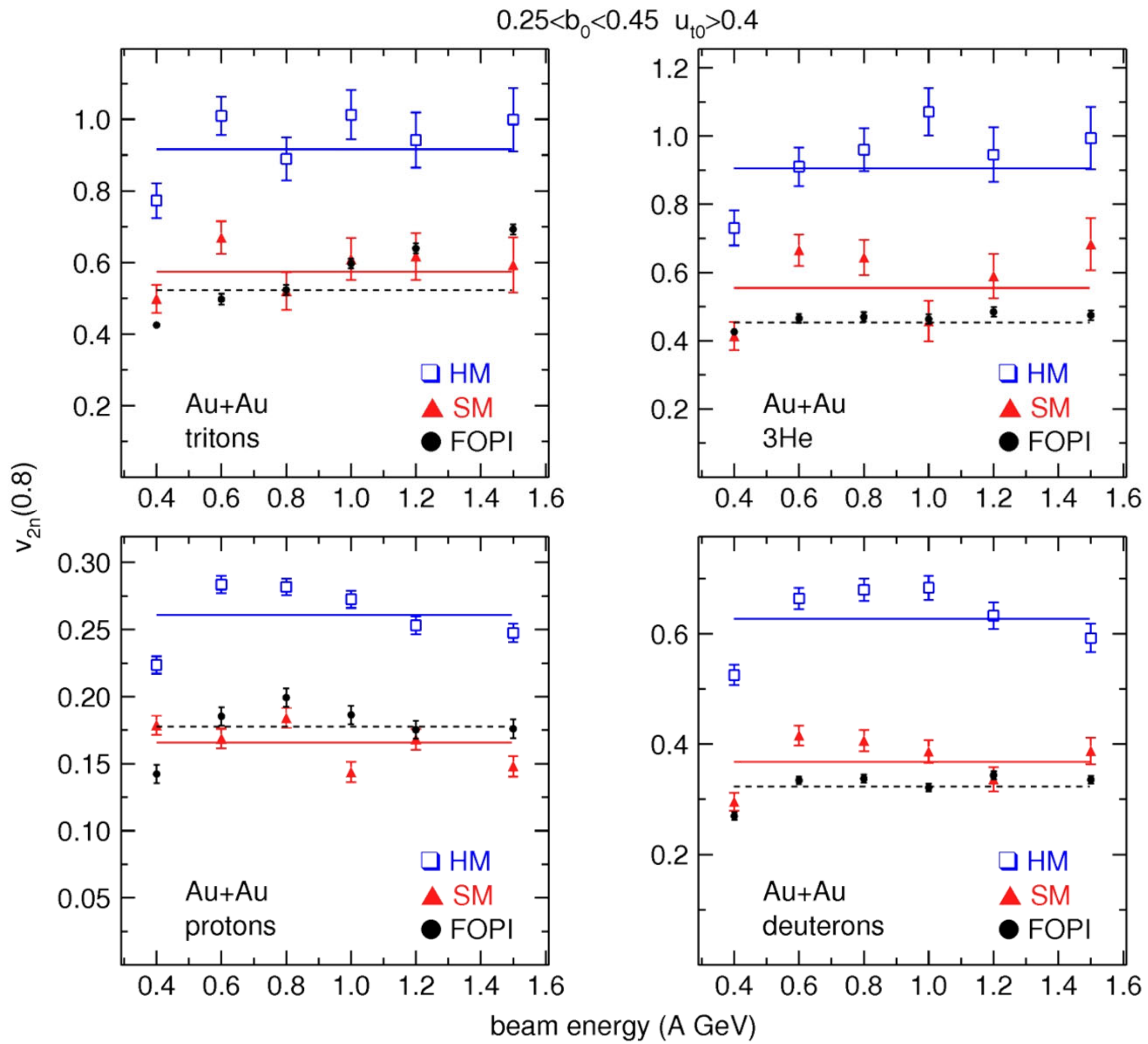
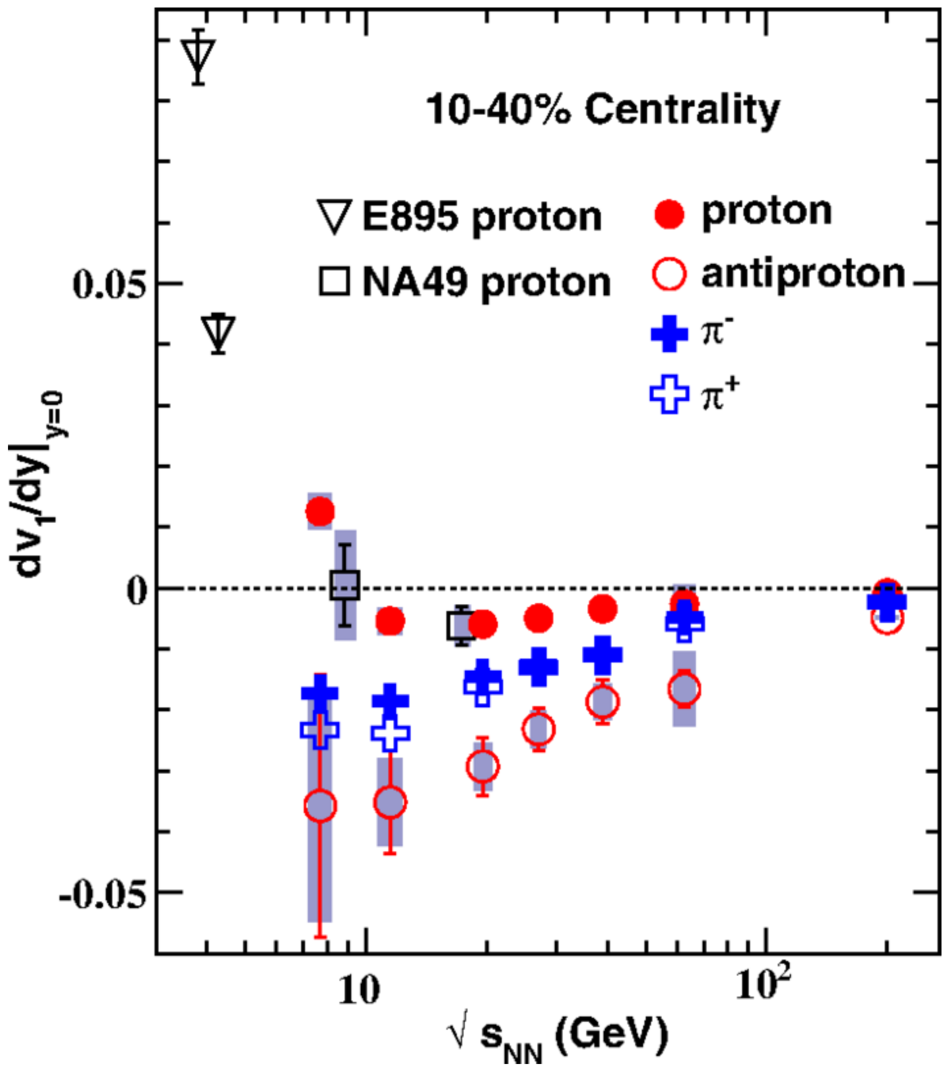


A. LeFevre et al, Nucl. Phys. A 876 (2012) 1

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
- a possible 1. order phase transition would lead to a softening of the EOS and vanishing directed flow: STAR, PRL 112, 162301 (2014), *Y. Nara et al., PLB 769, 543 (2017)*



Constraints for K_0 from elliptic flow

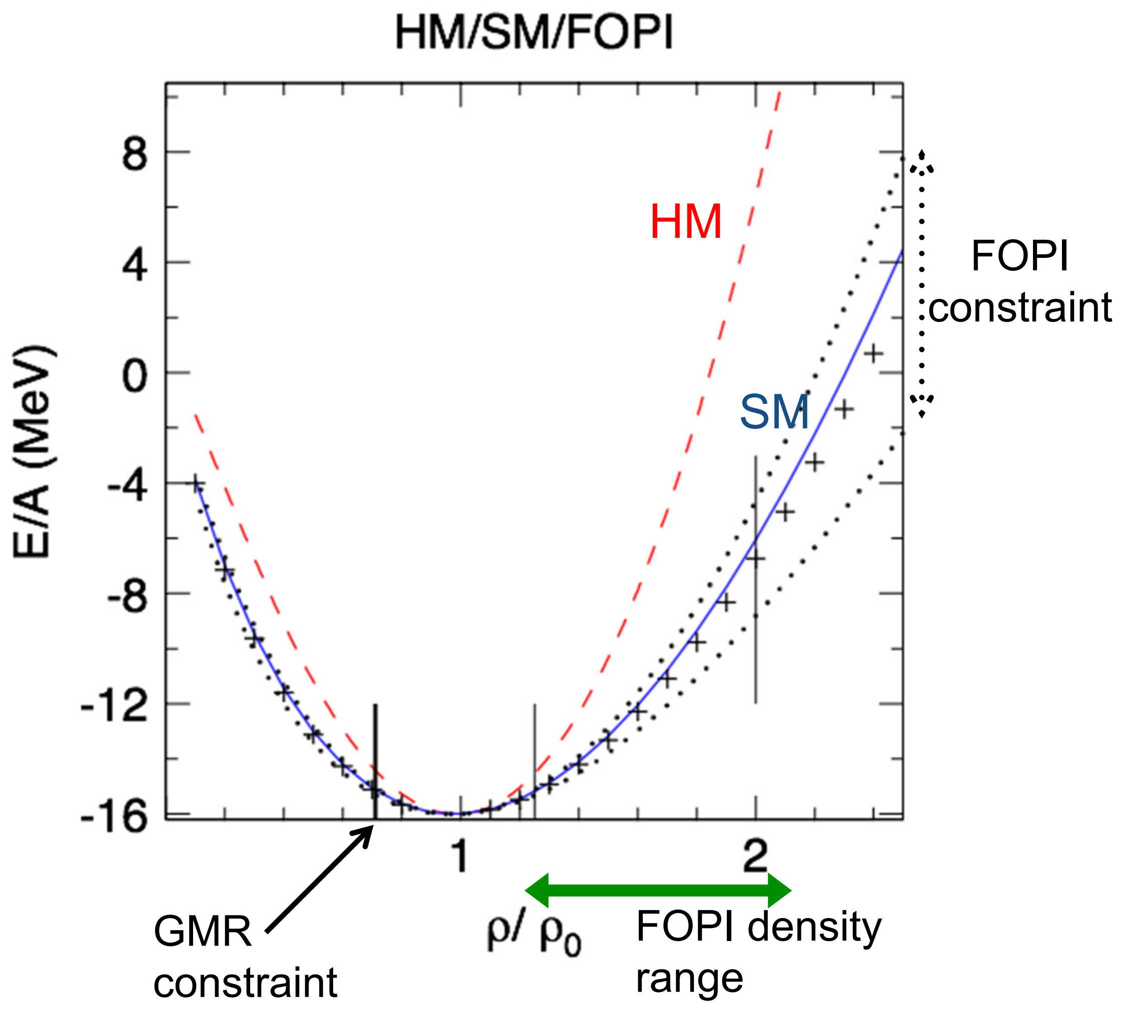
K_0 as from FOPI flow data

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

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

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

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



A. LeFevre et al, Nucl. Phys. A 876 (2012) 1

Symmetry energy at supra-normal densities

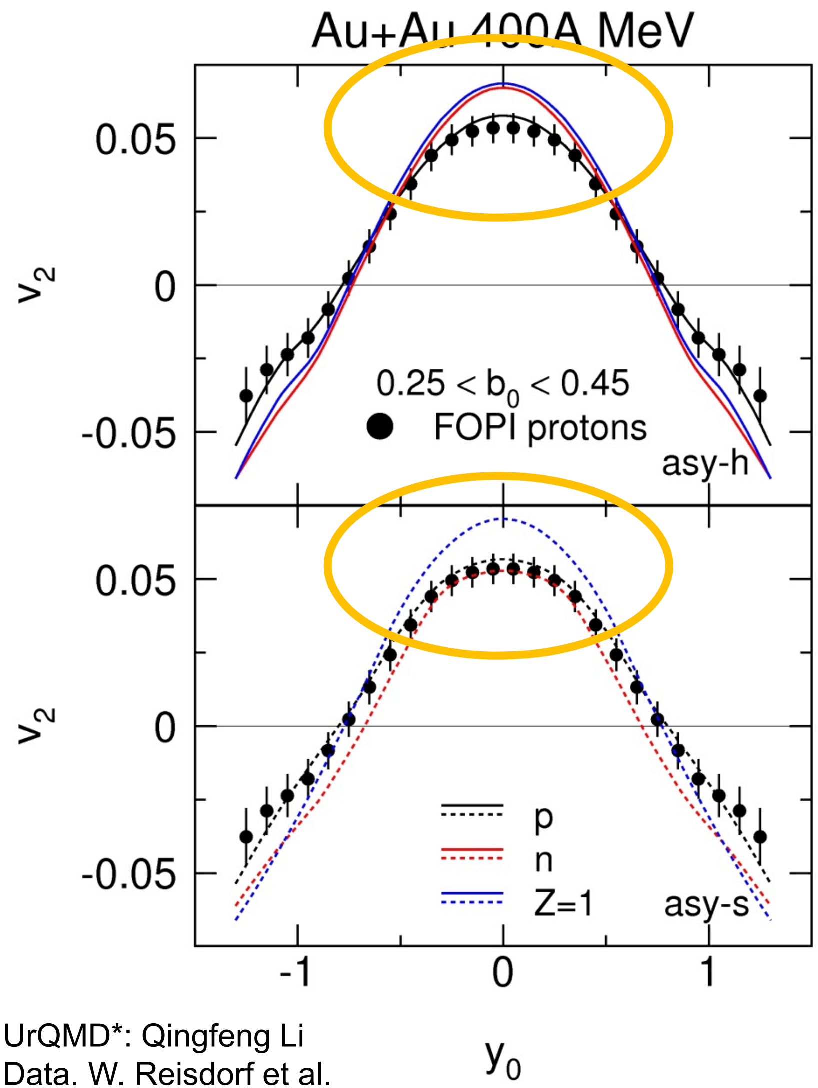
Differential elliptic flow v_2 of n/p
UrQMD* (Q. Li et al.) predicts

"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)



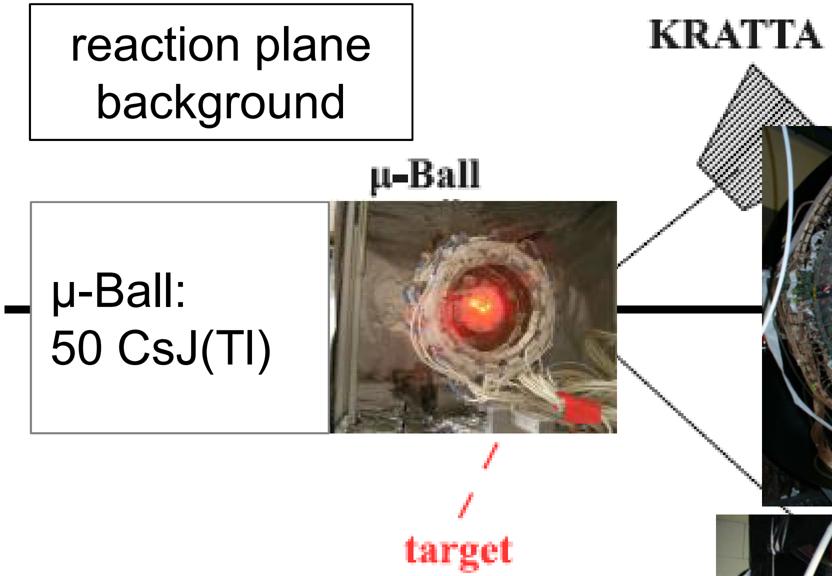
UrQMD*: Qingfeng Li
Data. W. Reisdorf et al.

ASY – EOS Experiment

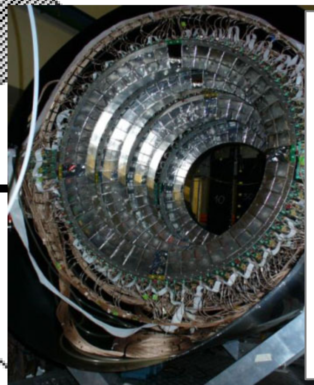
charged particles

reaction plane
background

impact parameter
reaction plane

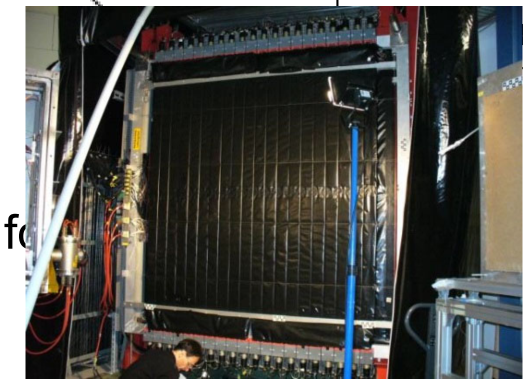


μ-Ball:
50 CsJ(Tl)



CHIMERA:
352CsJ(Tl),
16 silicon
pad
detectors

TOF-Wall:
96 plastic
bars



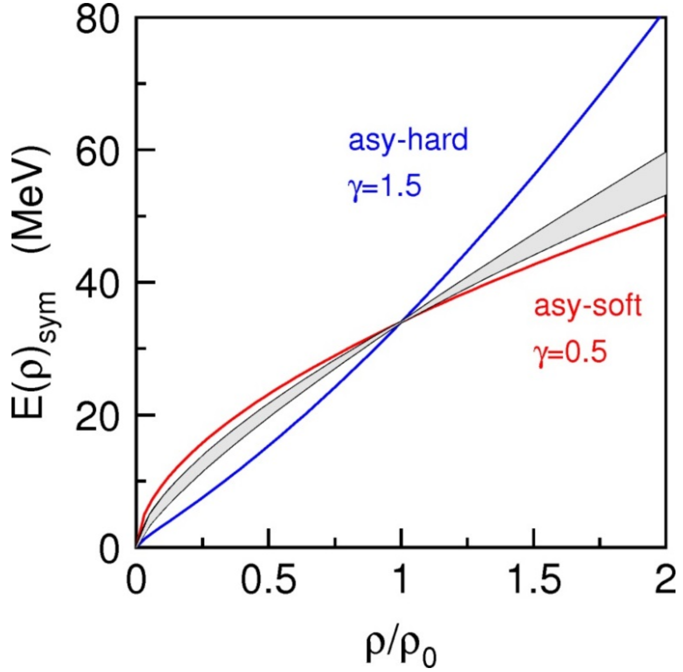
ed particles

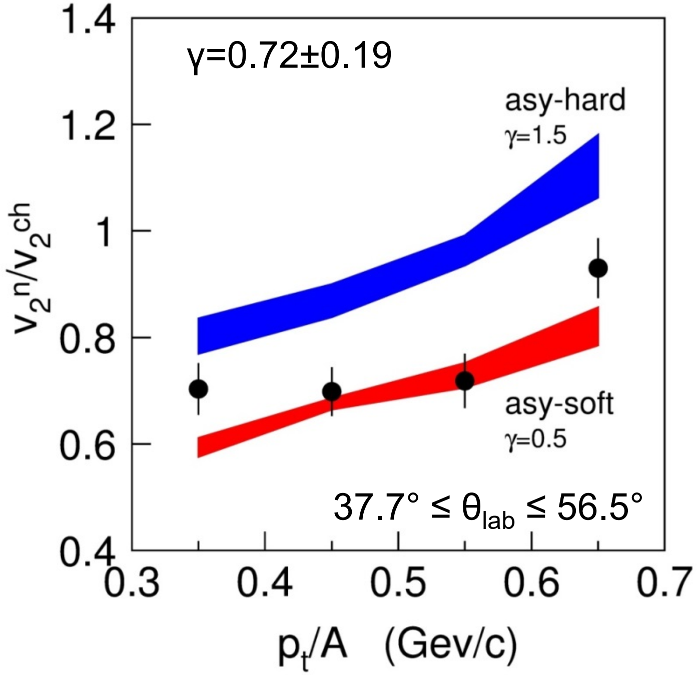
ASY-EOS

- background measurements f[...]
  neutrons (shadow bars)
- 400A MeV Au+Au at GSI

Elliptic flow ratio of neutrons and charged particles

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





Parametrization for SE used in UrQMD* model:

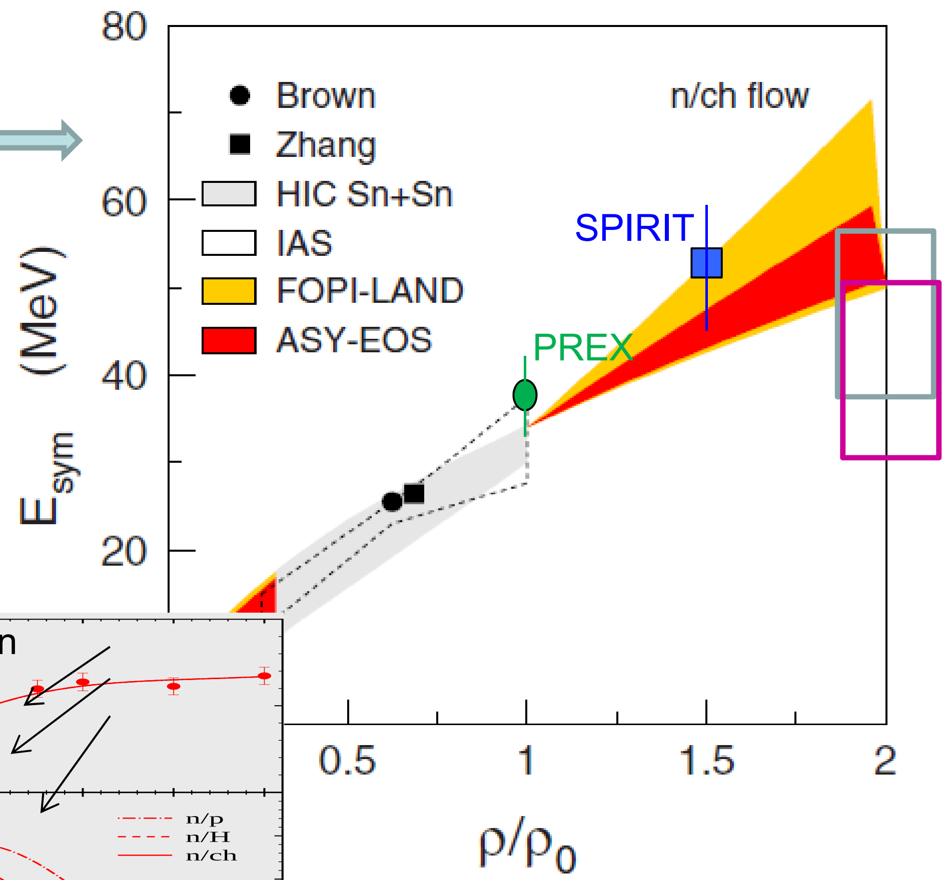
$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\text{MeV}\cdot(\rho/\rho_0)^{\gamma} + 12\text{MeV}\cdot(\rho/\rho_0)^{2/3}$$

Ambiguity in $E_{sym}(\rho_0)$

- slope parameter: L = 72 ± 13 MeV, $E_{sym}(\rho_0)$ = 34 MeV
- slope parameter: L = 63 ± 11 MeV, $E_{sym}(\rho_0)$ = 31 MeV

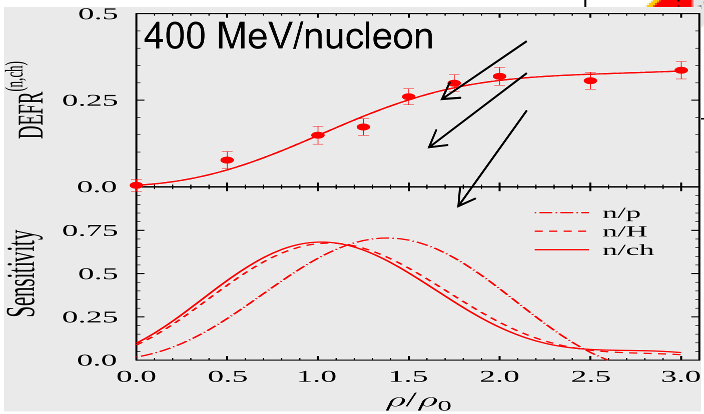
ASY-EOS: constraints on symmetry energy

compiled by
Horowitz et al.,
JPhysG (2014)



neutron star
X-ray observations
Zhang & Li
EPJA 55:39 (2019)
$E_{sym}(2\rho_0)$ =
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



density probed by the elliptic flow ratio
in Au+Au at 400 MeV/nucleon

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

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

PREX, PRL 126, 172502 (2021)

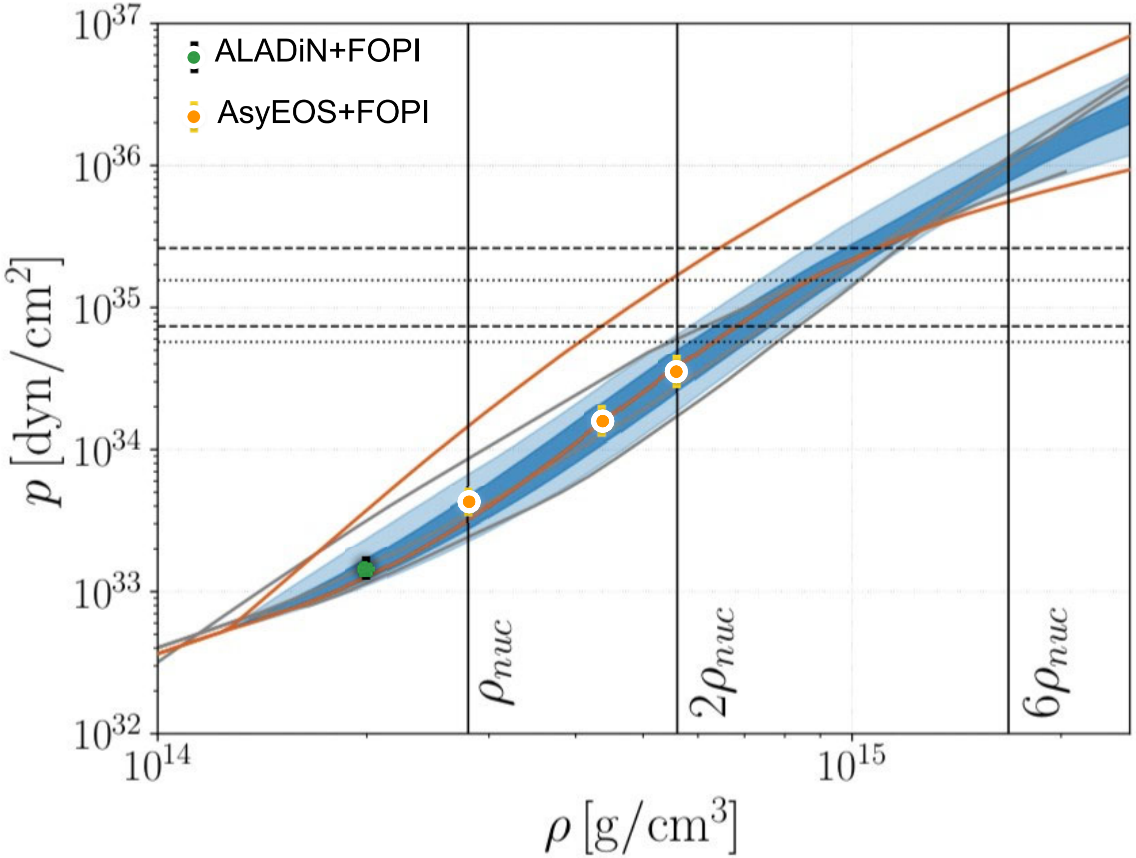
Comparison to results from neutron star merger event GW 170817

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

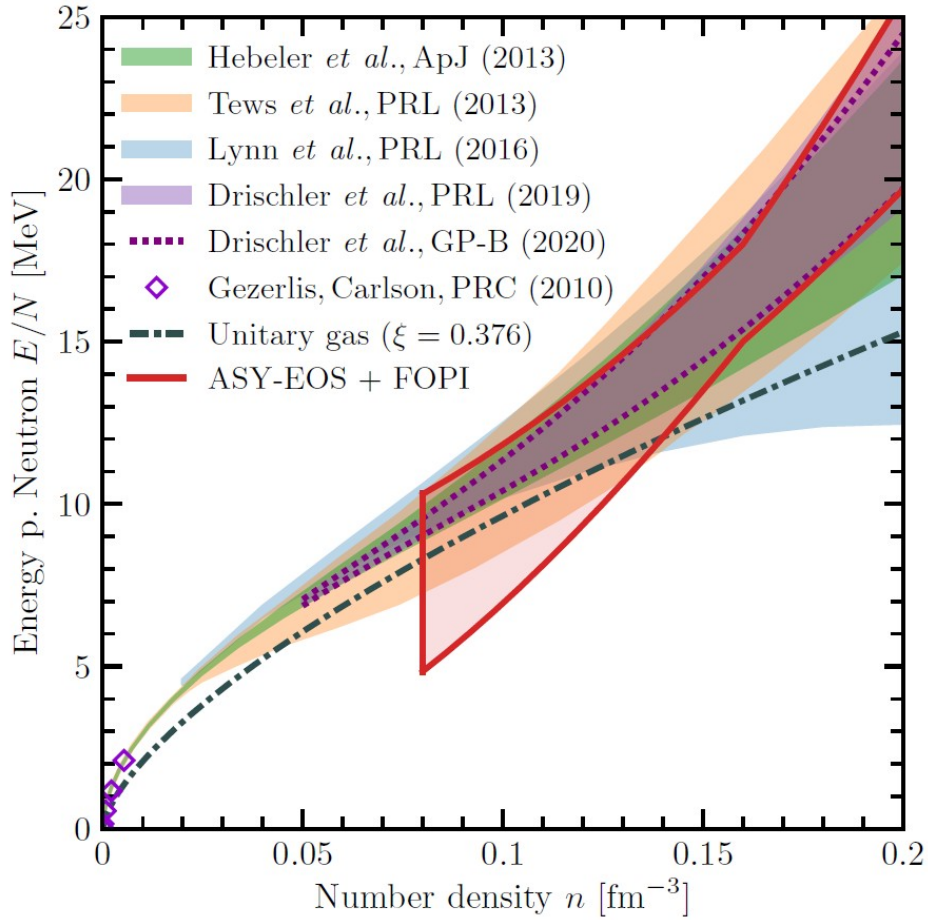
B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration)



Comparison of HIC results to recent astrophysical findings

How can we combine FOPI, AsyEOS 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

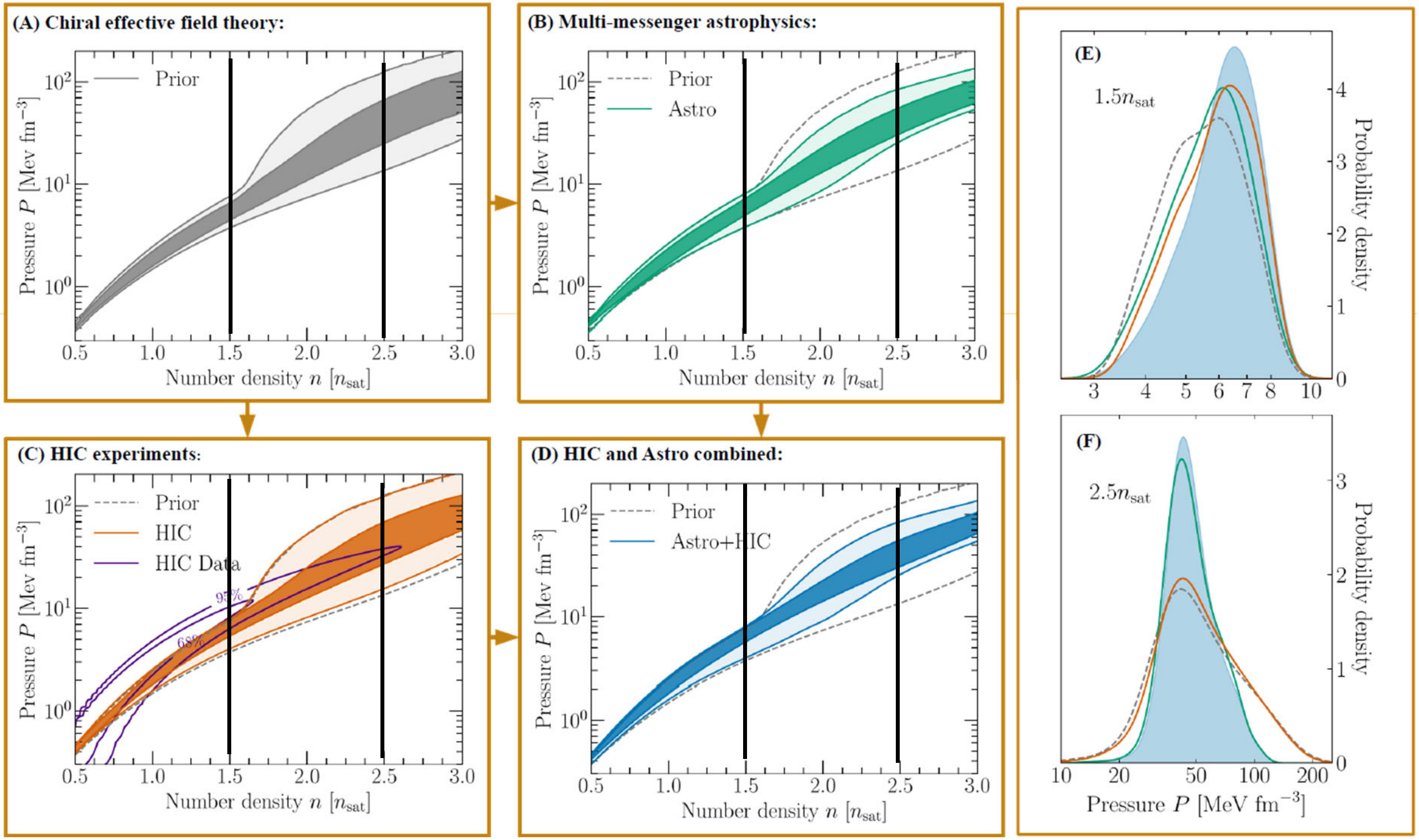


S. Huth, P.T.H. Pang et al., arXiv:2107.06229 (2021)[nucl-th]

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

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

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



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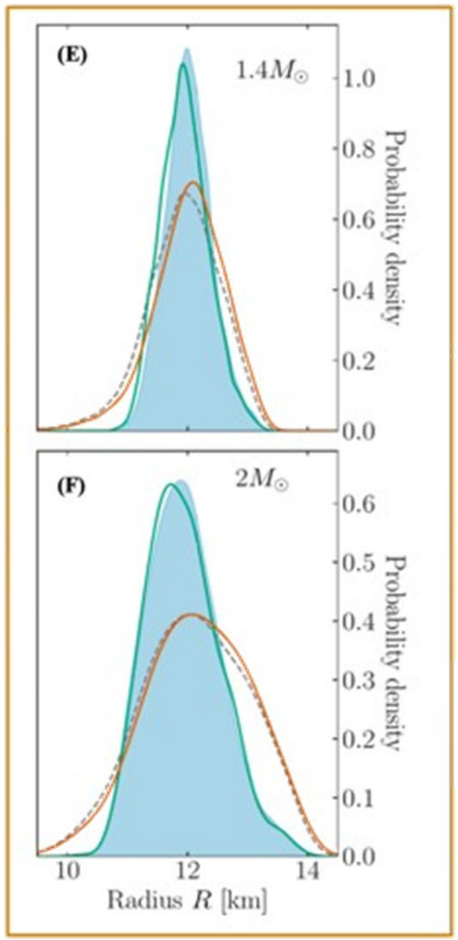
« HIC » = FOPI+ASY-EOS+AGS - « Astro » = GW, NICER (pulsar X-ray hot spots)

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

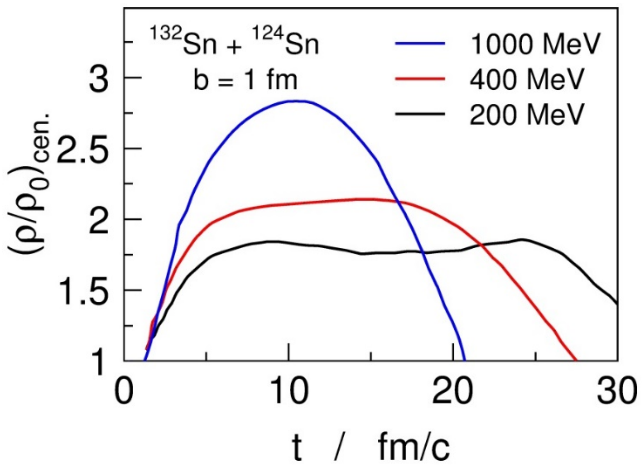
- advancing HIC experiments to higher densities
- investigating transport models



Advancing to higher densities

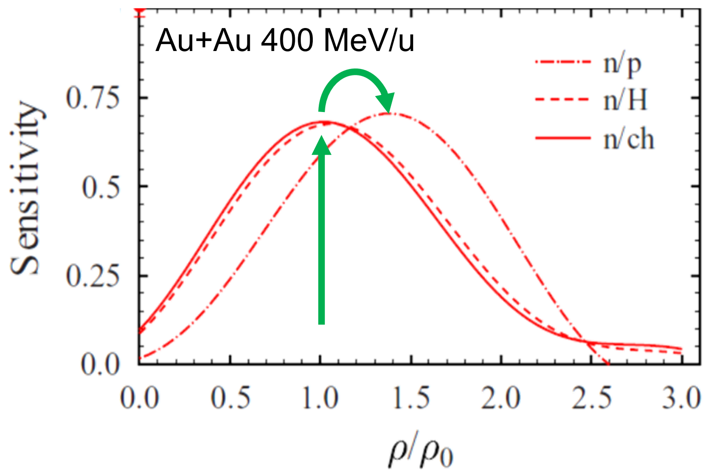
Higher incident energies

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



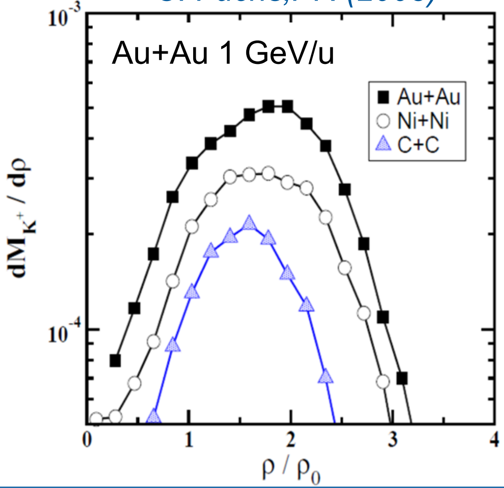
Other observables

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



density probed by the elliptic flow ratio

C. Fuchs,PR (2003)



density probed by kaon production

ASY-EOS II

NEW ASY-EOS proposal:

Study of

Au+Au

250, 400, 600, 1000 MeV/u

measure neutron / proton / hydrogen elliptic flow :

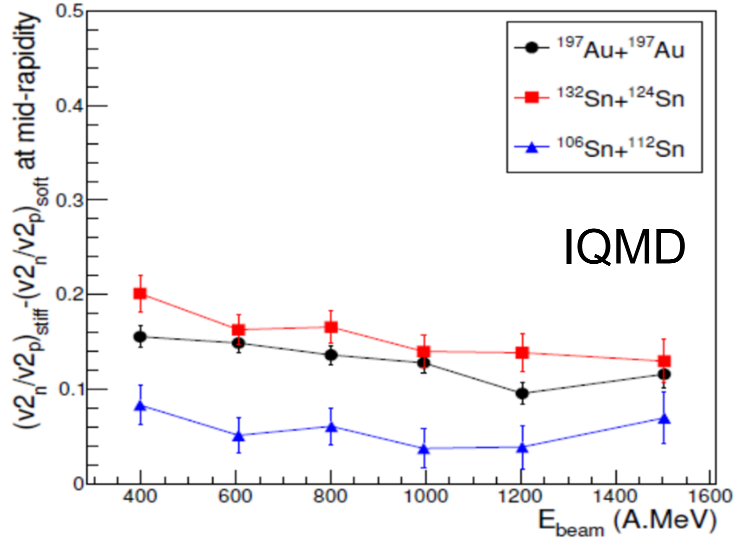
NeuLAND

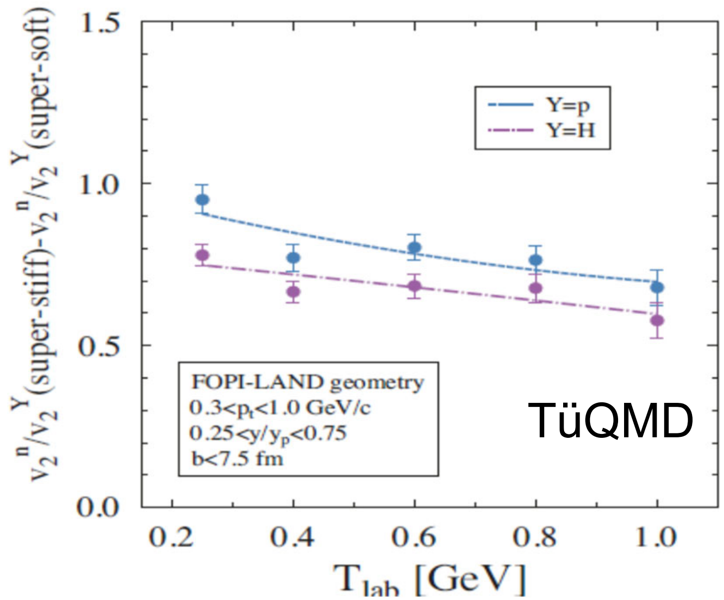
charged particles:

Kratta, Califa

impact parameter vector:

CHIMERA, KRAB

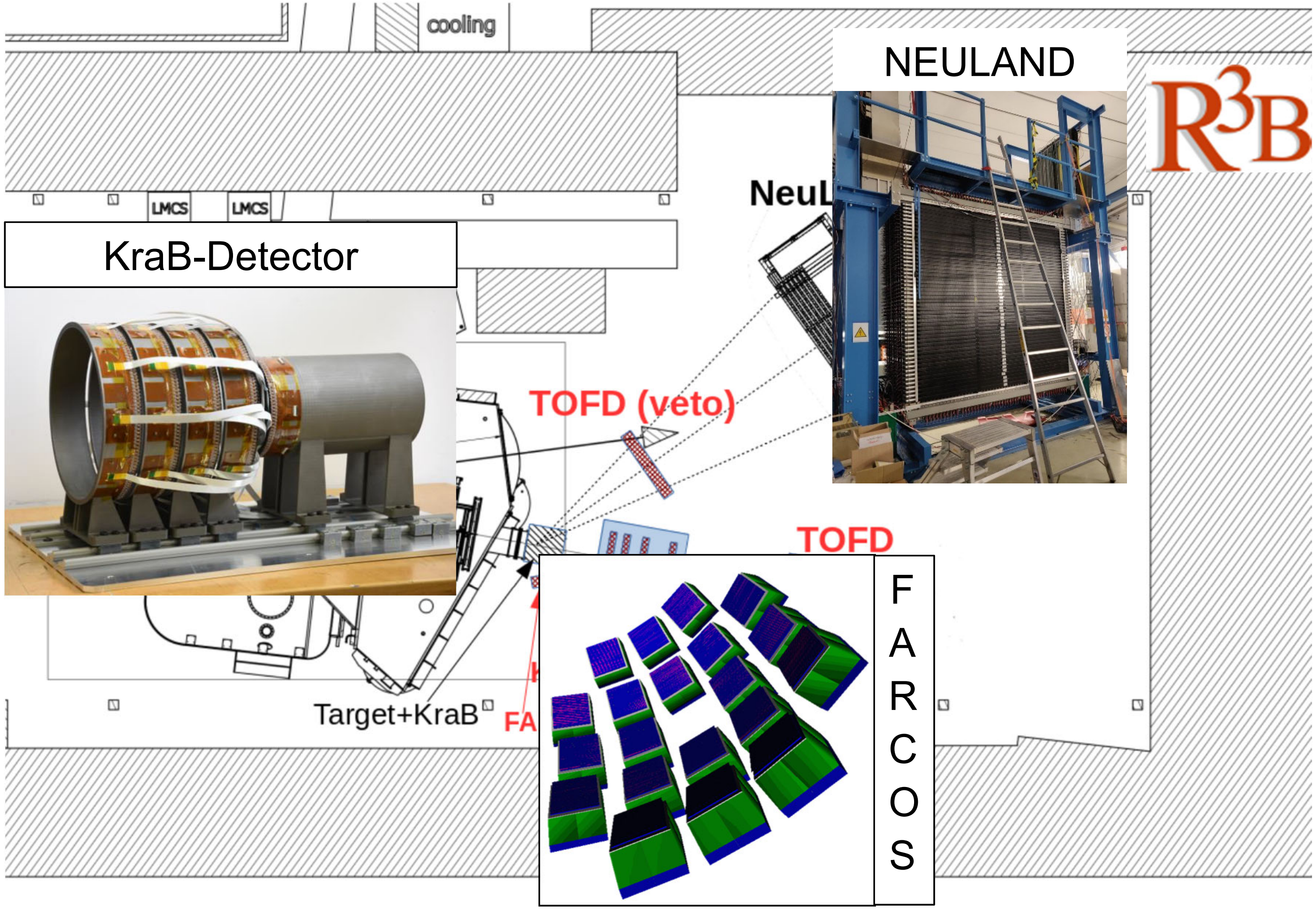




Aim

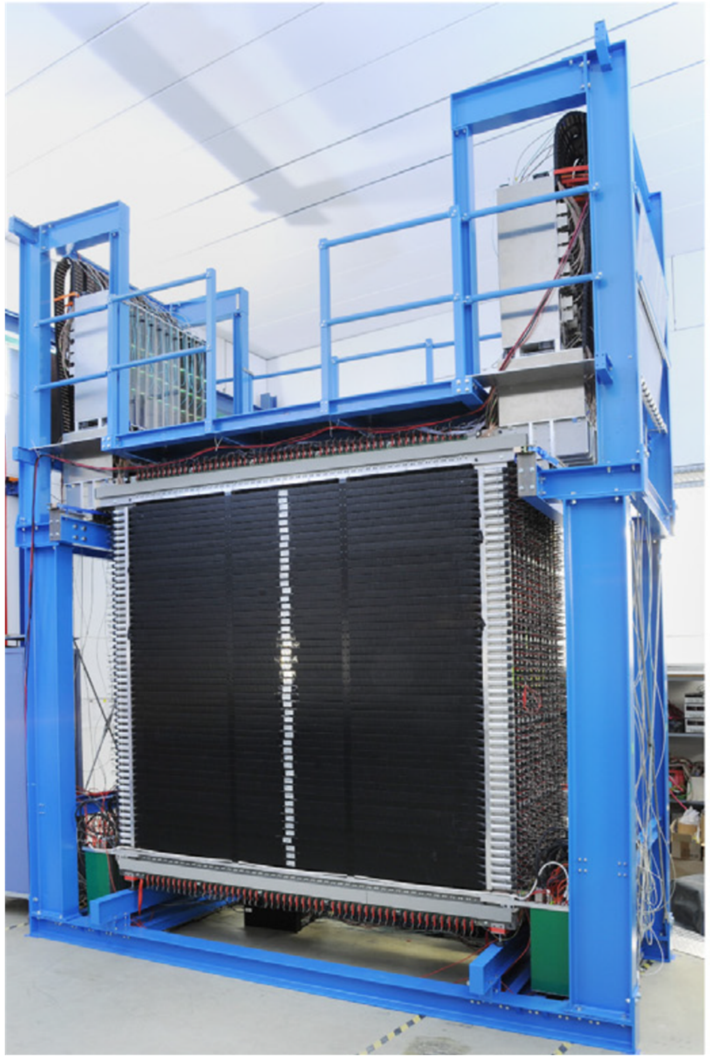
Measure n, p, d, t flow with NeuLAND to access not only slope of symmetry energy but also the ***curvature***

ASY-EOS II in the R3B cave at GSI

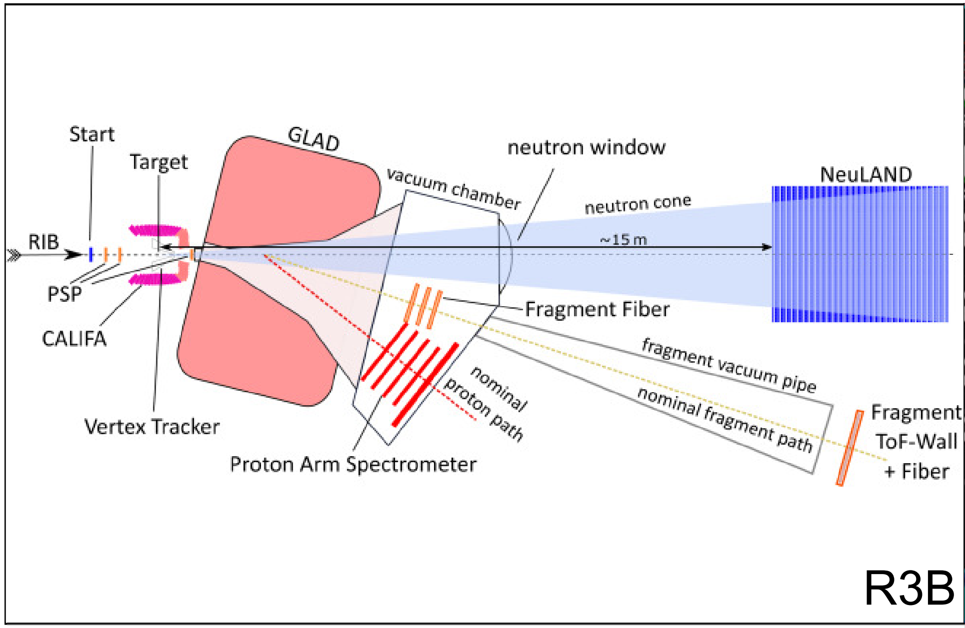


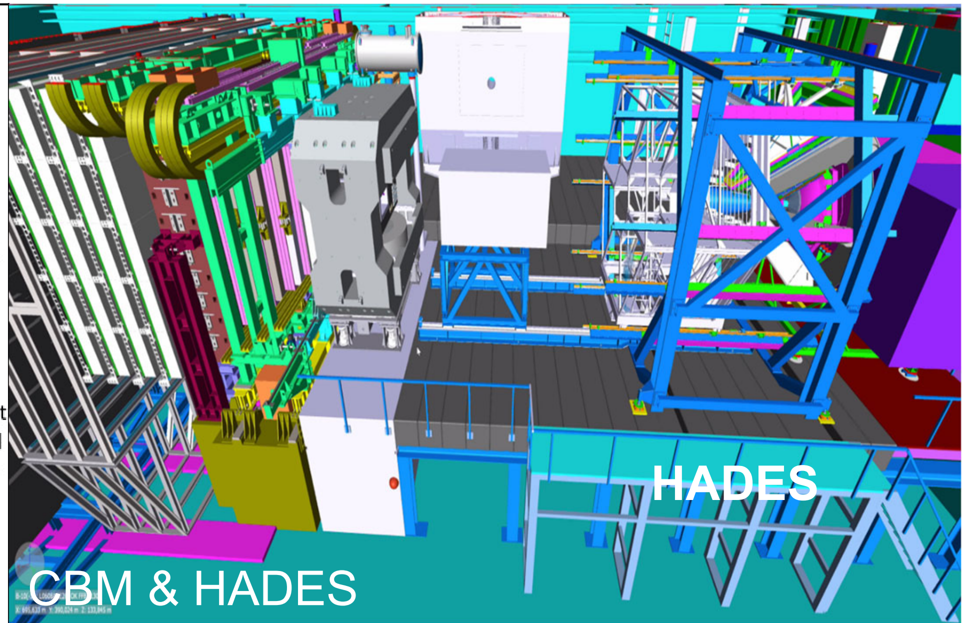
ASY-EOS II next steps

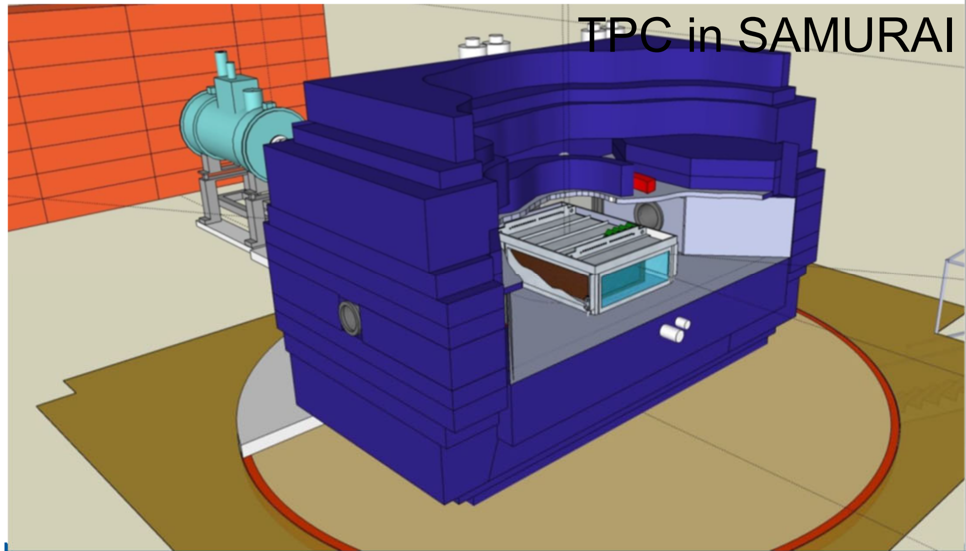
- part of an LOI of the R3B collaboration to the G-PAC of GSI
- participate in the next call for proposals in autumn 2022 for beam times in 2023 and 2024
- tests of the KRAB detector
- preparation for beam time
- working group on transport models together with HADES/CBM

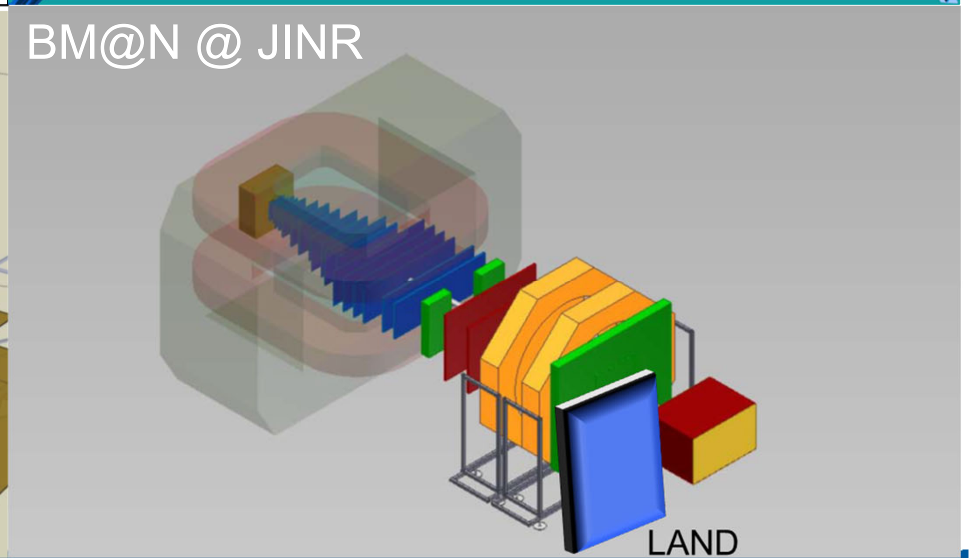


Experiments

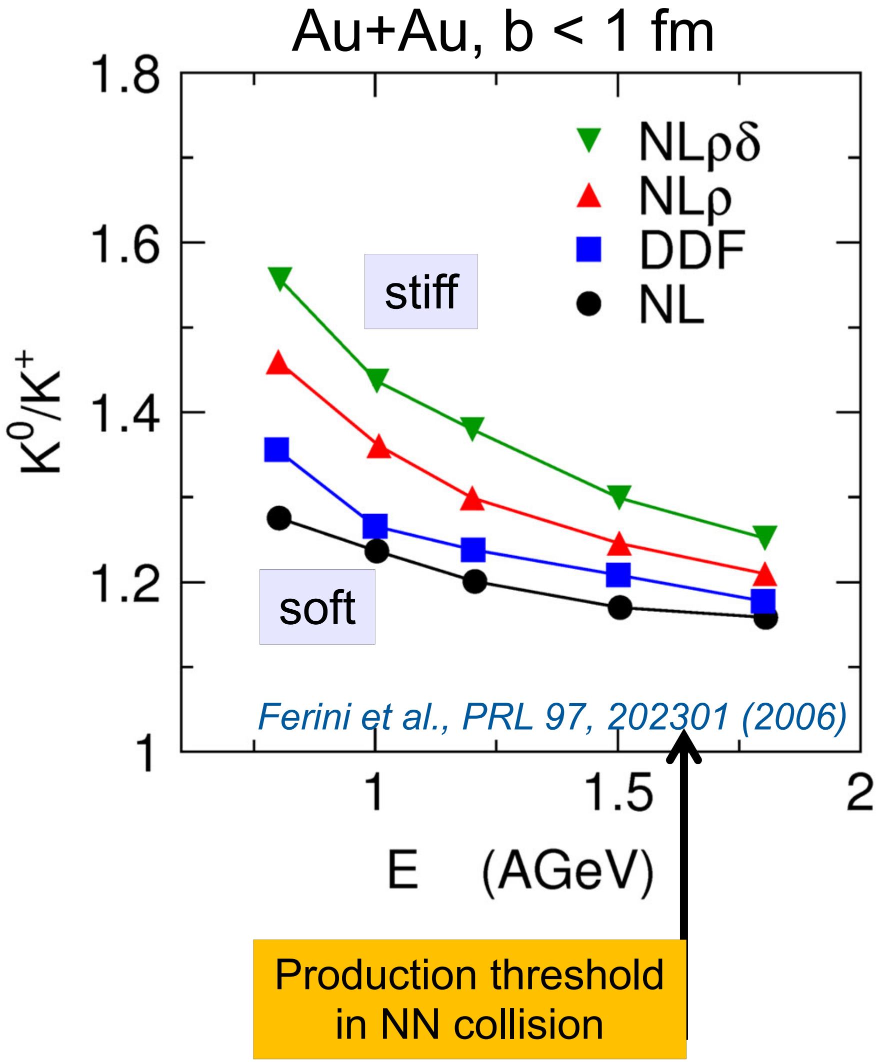


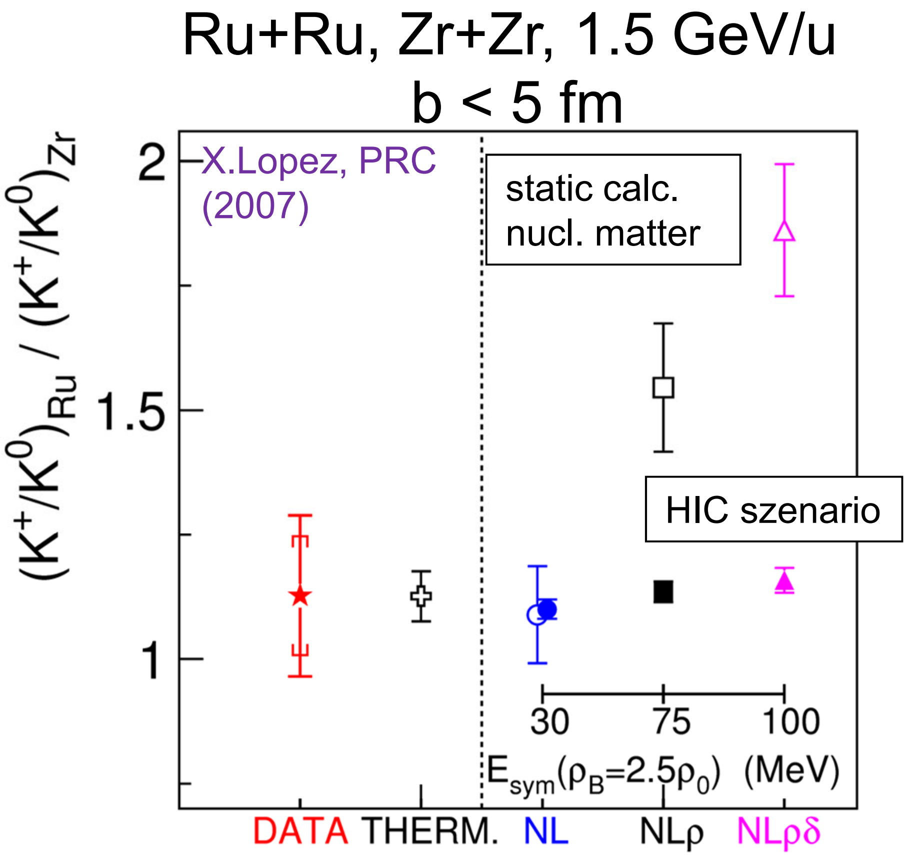






Kaon production probe the symmetry energy





HIC scenario:
- fast neutron emission (mean field)
- NN=>NΔ threshold effects
- nn=>pΔ⁻ **(no chemical equilibrium)**

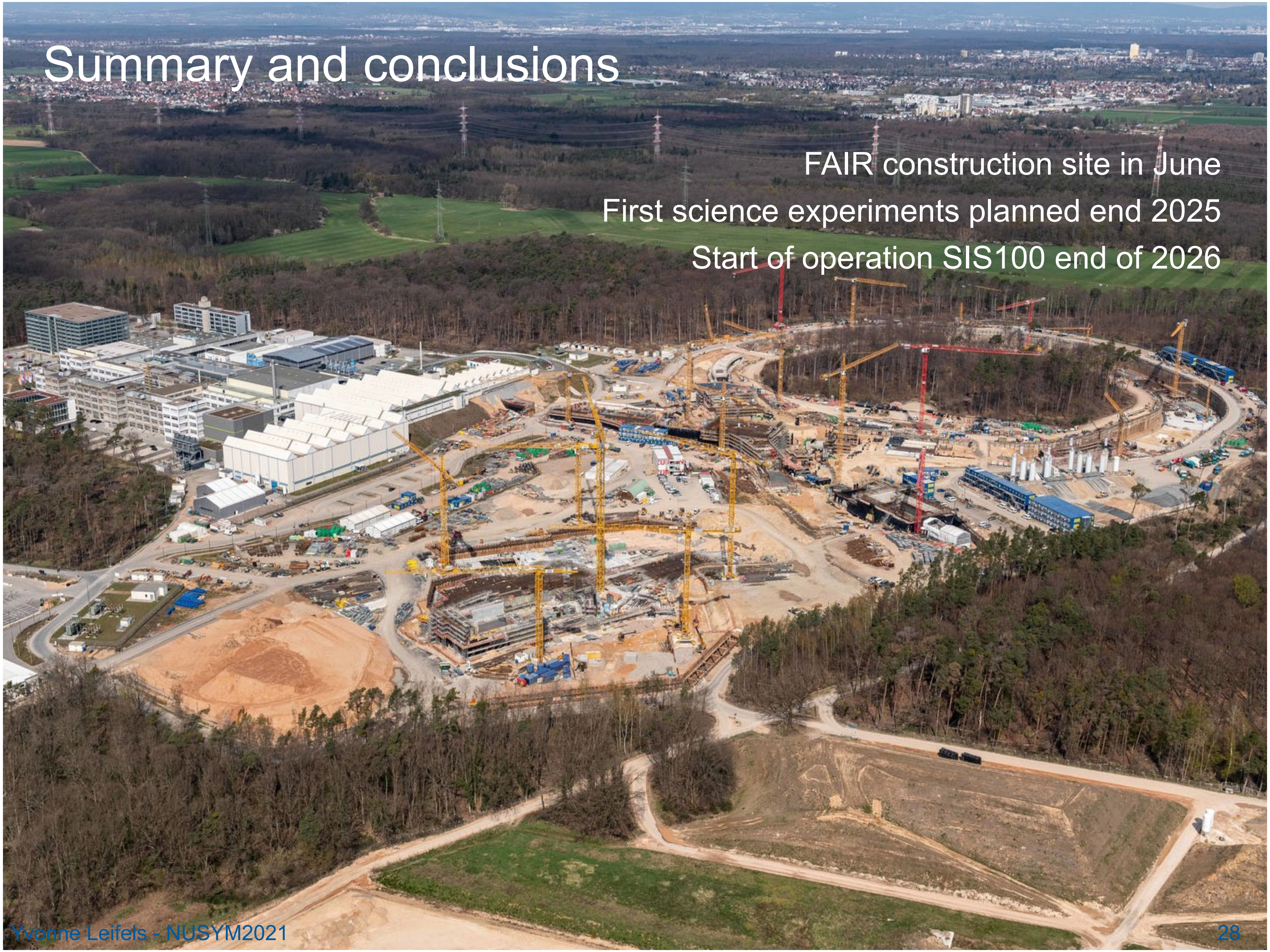
see, e.g., di Toro et al., J.Phys.G (2010)

Summary and conclusions

FAIR construction site in June

First science experiments planned end 2025

Start of operation SIS100 end of 2026



Summary and 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 2 ρ_0, with similar accuracy than astrophysical data
- To access higher densities a new experiment ASY-EOS II is planned at GSI
- Beyond 3 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