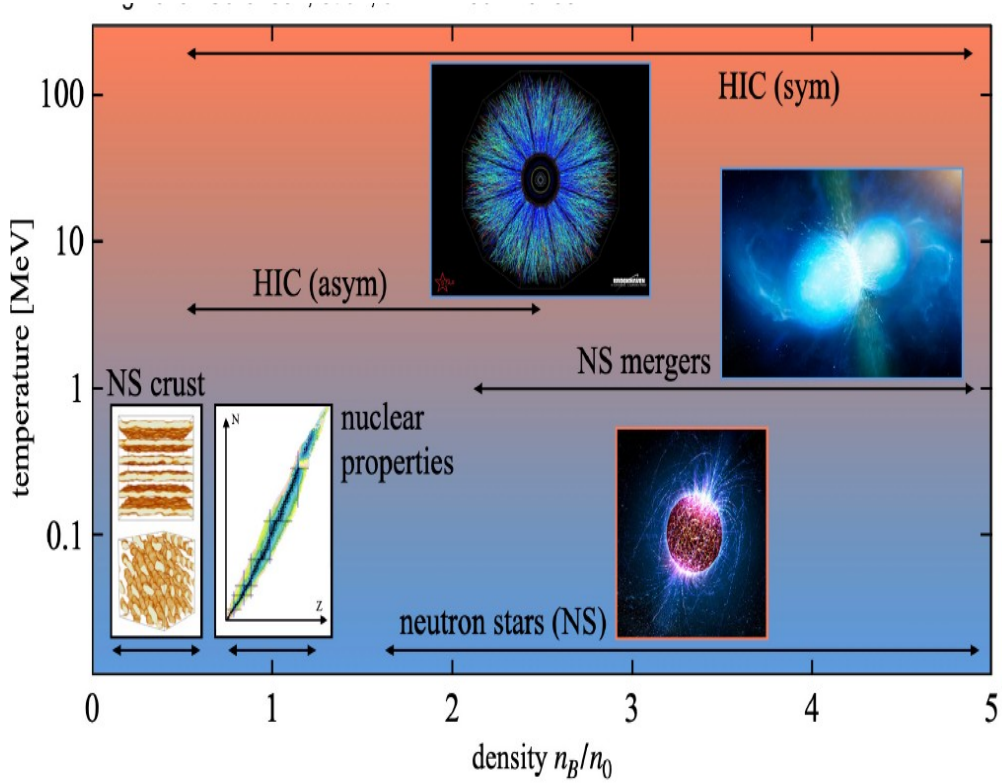
Relativistic Heavy-ion Collisions and Nuclear Equation of State





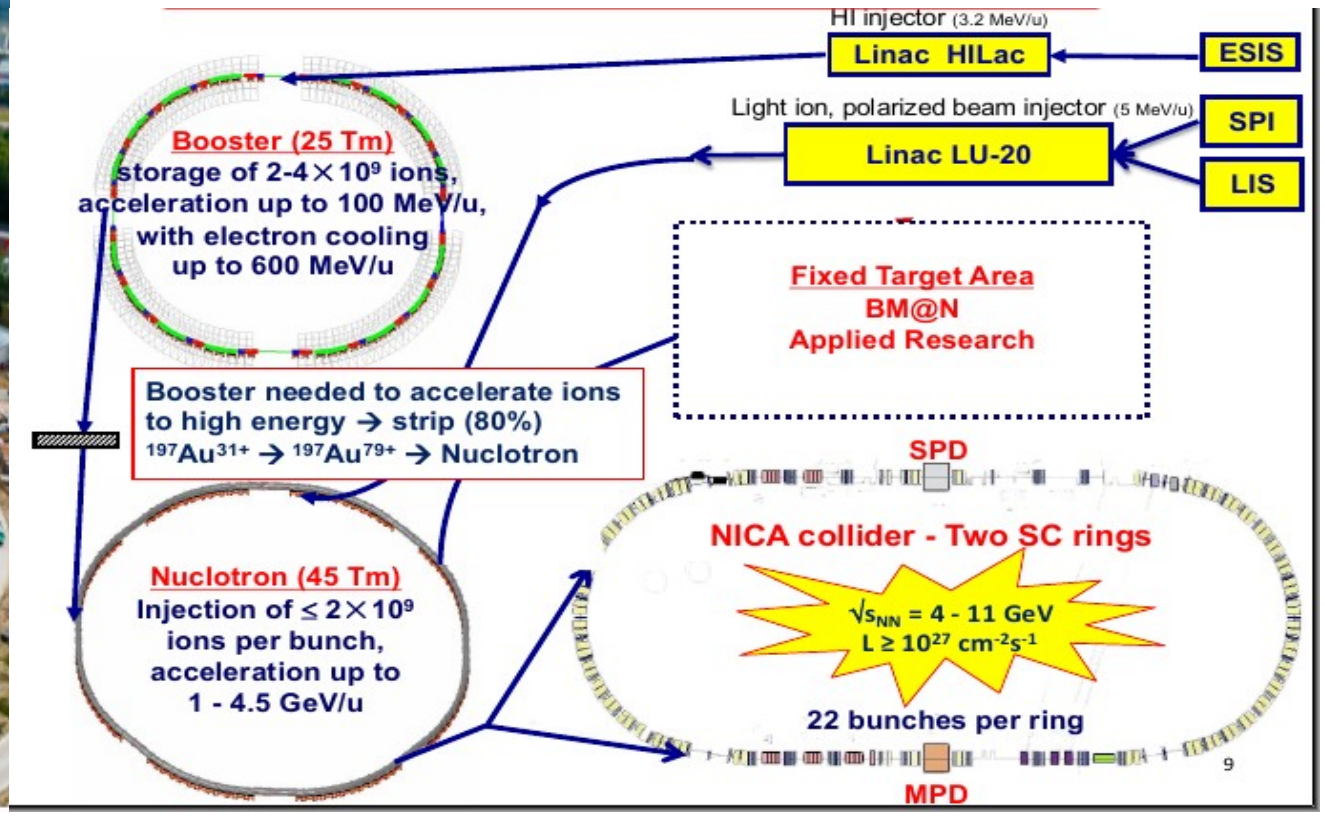
Arkadiy Taranenko (ataranenko@jinr.ru)

JINR-CUBA SCHOOL: "HADRON STRUCTURE AND HADRONIC MATTER PHYSICS"

December 1-5, 2025, La Habana, Cuba

Relativistic Heavy-ion Collisions at NICA



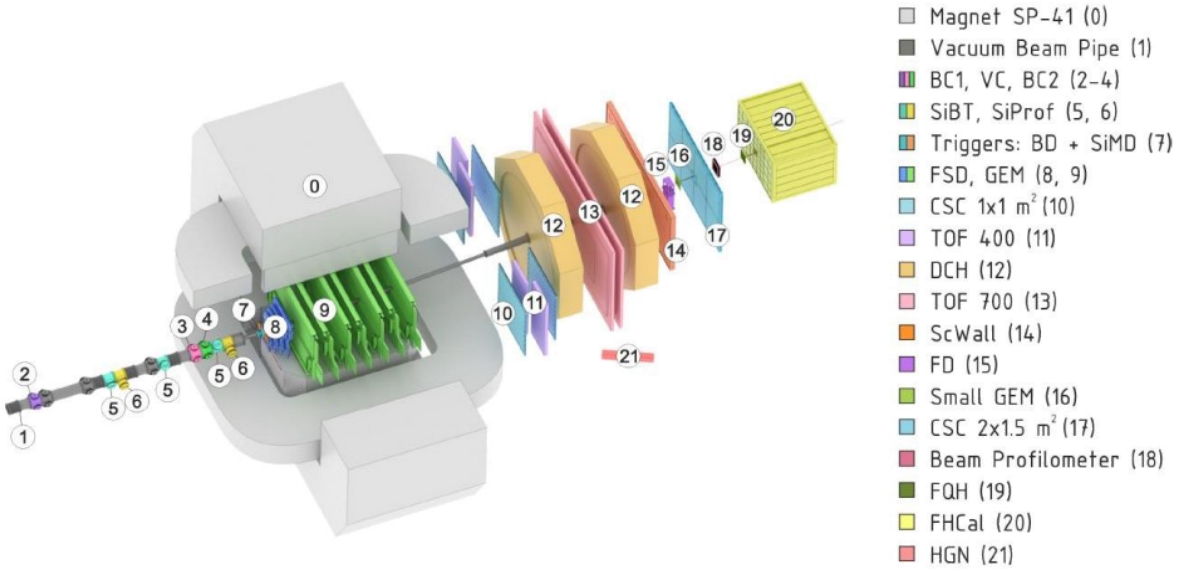


NICA (Nuclotron based Ion Collider fAcility) - a superconducting collider of protons and heavy ions, being built at the Laboratory of High Energy Physics (LHEP, JINR), first beams: 2026

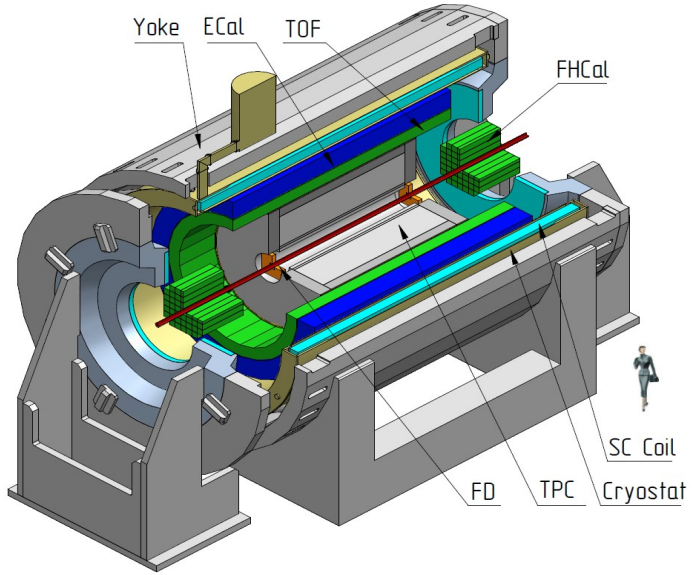
- BM@N ("**Baryonic Matter at Nuclotron**") – fixed-target experiment, first physics run Xe+CsI at 3.0 and 3.8 A GeV, 2022-2023
- MPD ("**Multi-Purpose Detector**") - collider+fixed target experiment, NICA, 2026

NICA: BM@N and MPD Collaborations

The BM@N spectrometer at the NICA accelerator complex
Nucl.Instrum.Meth.A 1965 (2024) 169352



Status and initial physics performance studies of the MPD experiment at NICA , Eur.Phys.J.A 58 (2022) 7, 140



BM@N: ~214 participants - 13 institutes, 5 countries



MPD: ~500 participants - 38 institutes, 12 countries



Nuclear Matter and QGP

- **Normal nuclear matter density:**

  $\rho = A / V_N \quad V_N = 4/3\ \pi R^3 \quad R = r_0 A^{1/3} \quad r_0 \sim 1.15$ fm

  $= 0.16$ nucleon/fm^3

  Normal nuclear matter energy density:

  $\varepsilon = A m_n / V_N \quad m_n = 0.94$ GeV

  $= 0.15$ GeV/fm^3

- **What does this mean in terms of compactness of the nucleus?**
- Fraction of the nuclear volume occupied by nucleons:

  $f = A v_n / V_N \quad v_n = 4/3\ \pi r_n^3$

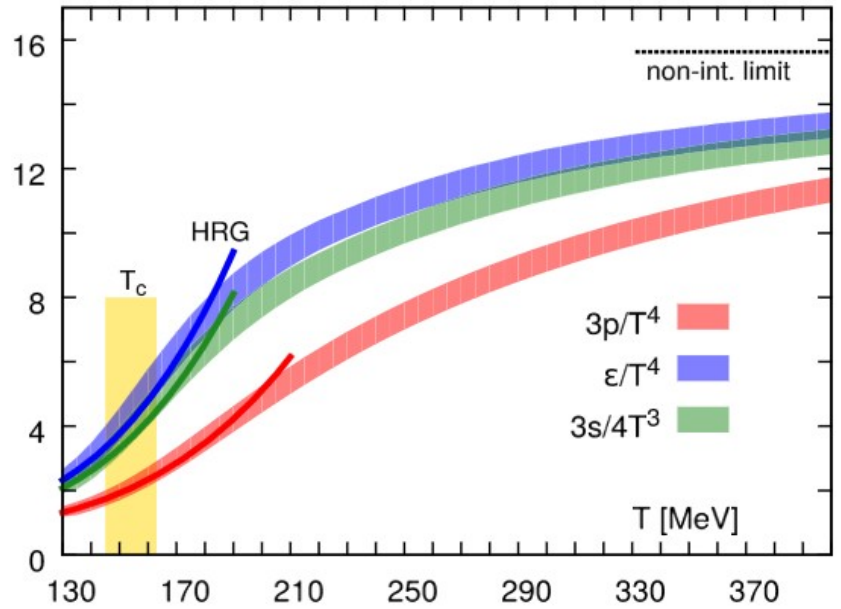
  $r_n \sim 0.84$ fm (charge radius of the proton)

  ~ 0.38

  → **~60% of the nuclear volume is empty!**
- **QGP expected at a density ~10 times larger than the normal nuclear matter energy density:** $\varepsilon \sim 2$ GeV/fm^3



Energy density ε
Pressure p
Entropy density s



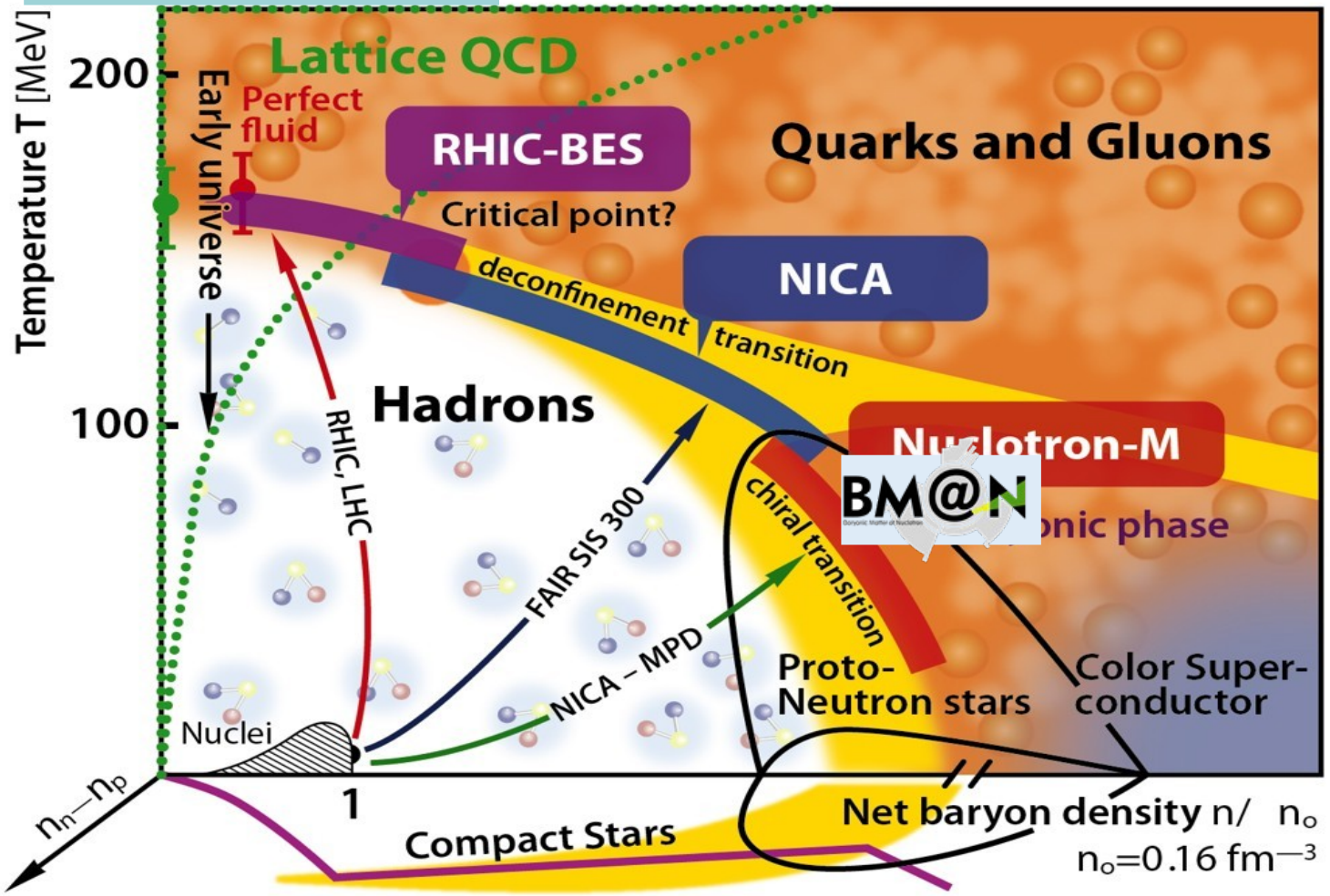
Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

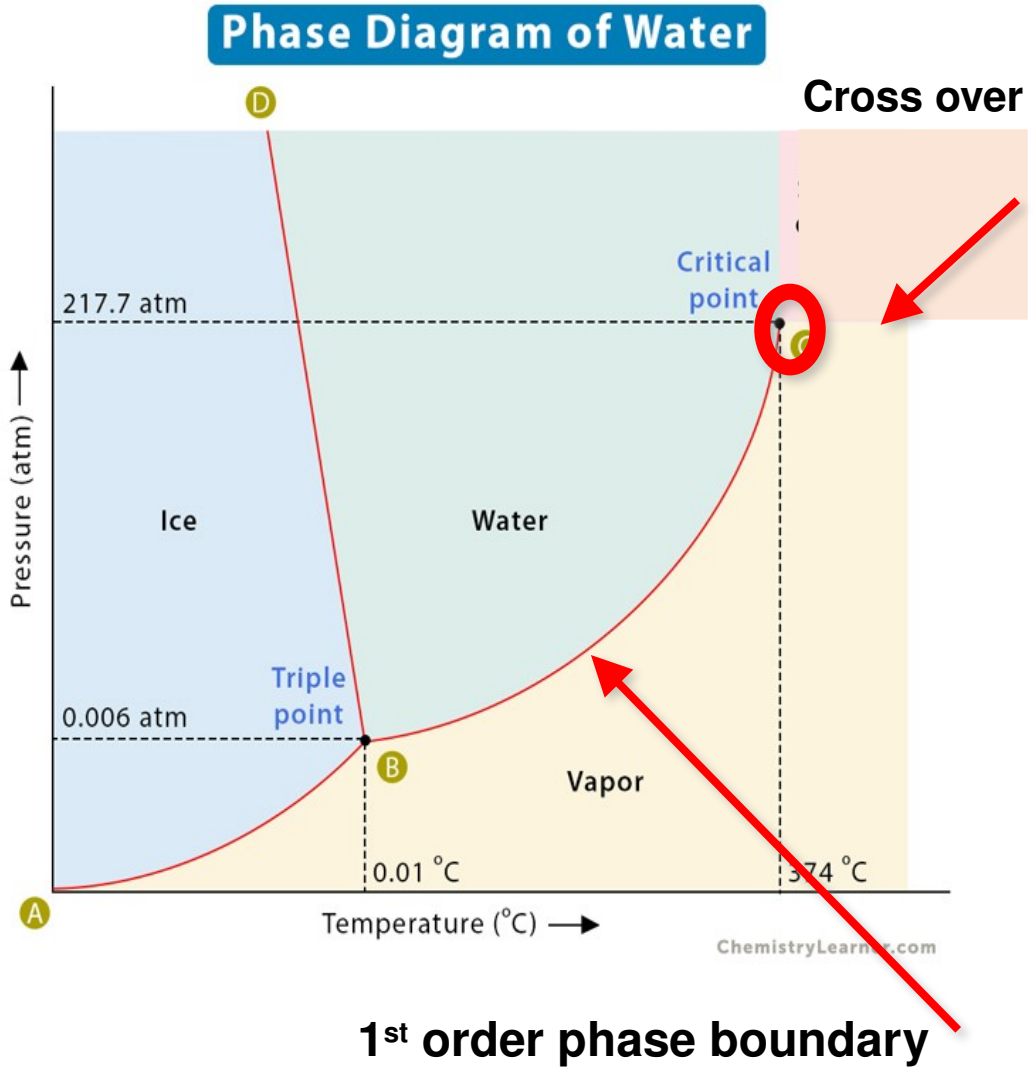
Crossover transition at $T_c \approx 156 \pm$ MeV $\approx 2 \cdot 10^{12}$ K $\approx 130{,}000 \cdot T$ [Sun's core]

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

Critical Temperature
$T_c \approx 156$ +/- 9 MeV

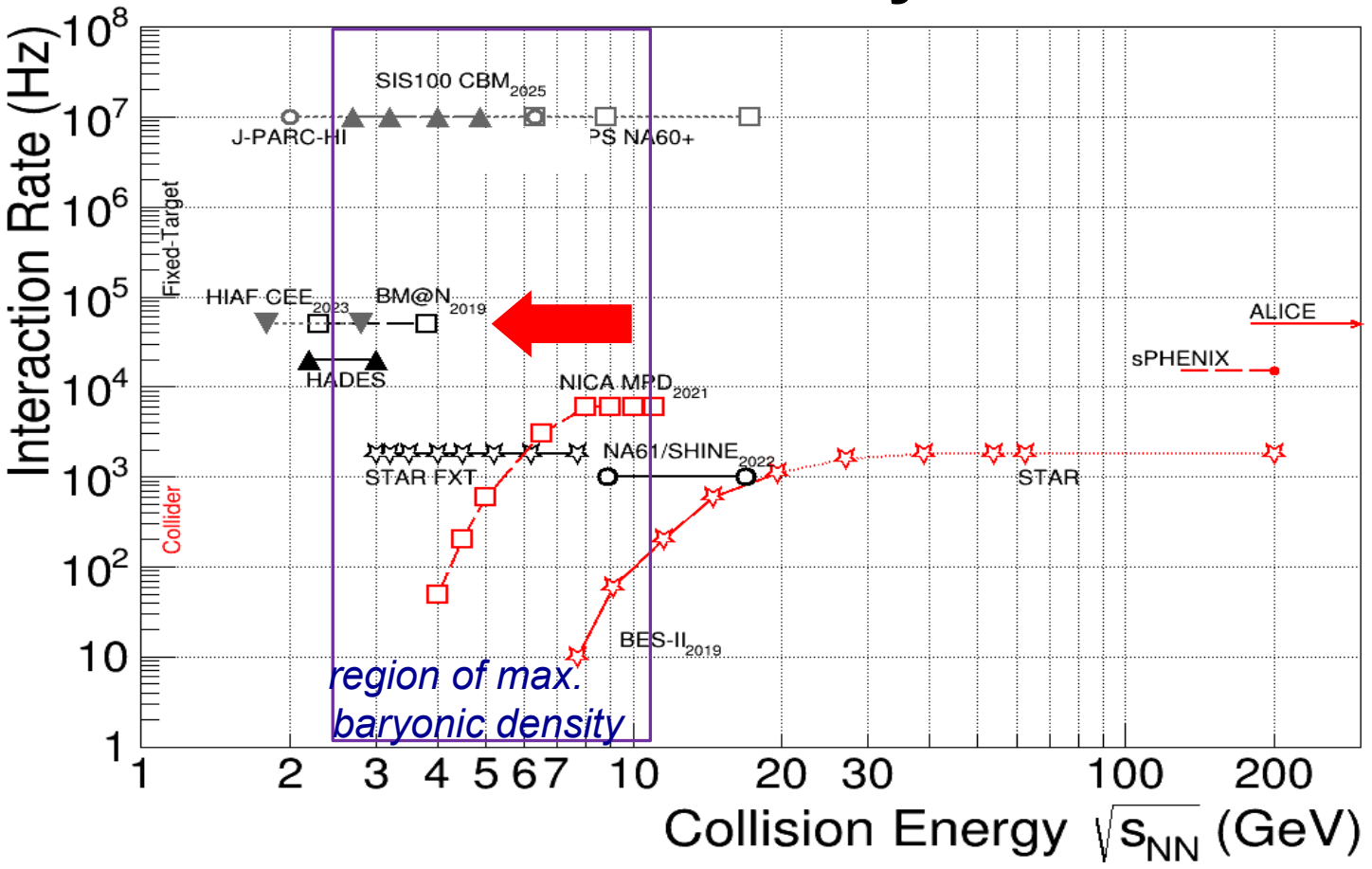
[PRD 90 094503 (2014)]





Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

Relativistic Heavy Ion Collision Experiments



MPD, BM@N competitors:

Present:

RHIC/STAR (USA) 3-200 GeV
NA61/SHINE (CERN): 5.1-17.3 GeV
SIS18/HADES (Germany) 2.4-2.55 GeV

Future:

HIAF/CEE (China) 2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany) 2.4-4.9 GeV (2029-?)
JPARC-HI (Japan) 2-5 GeV (2030-?)
NA60+(CERN) 6.1-16.4 GeV (2029-?)

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

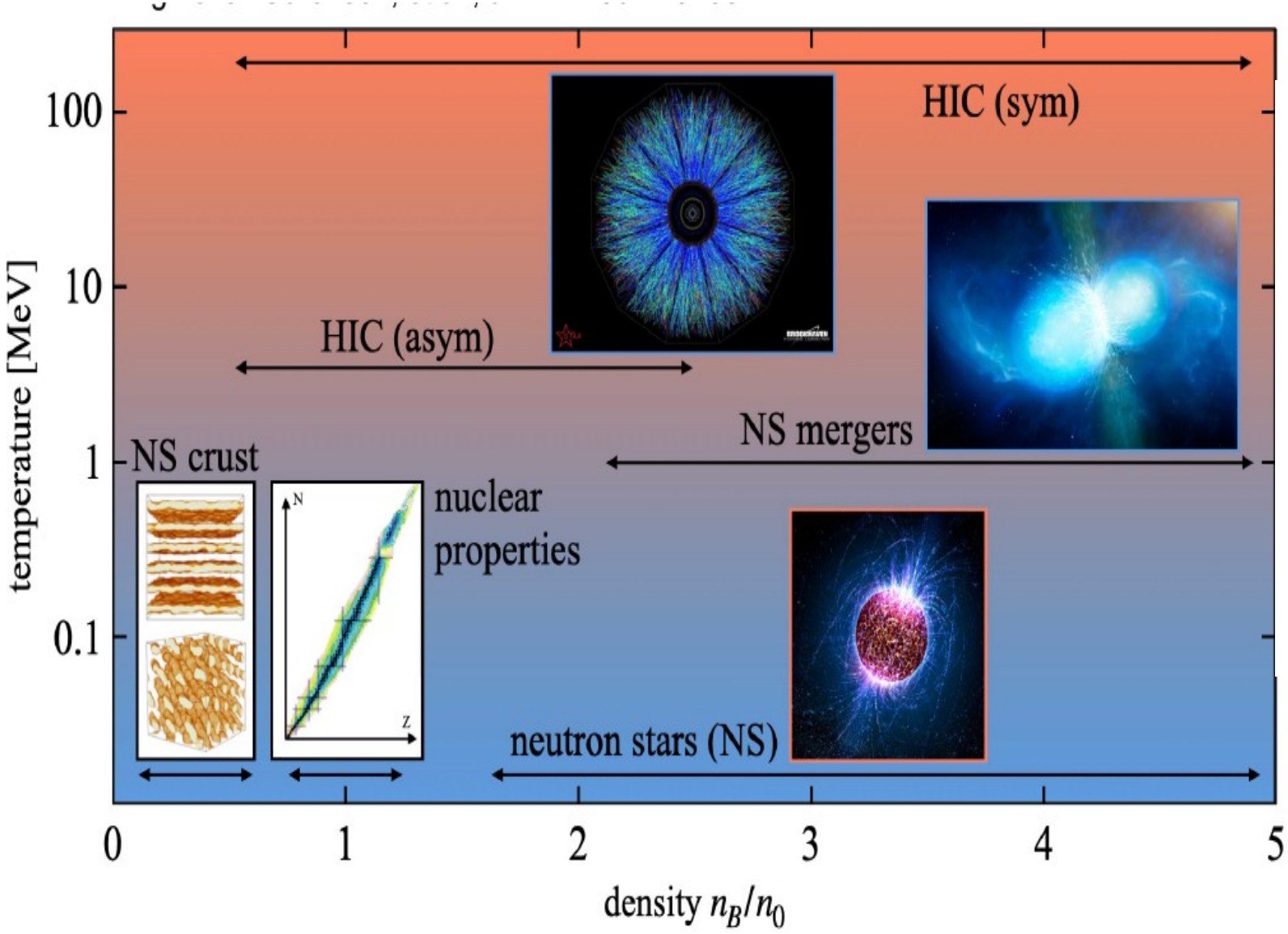
$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

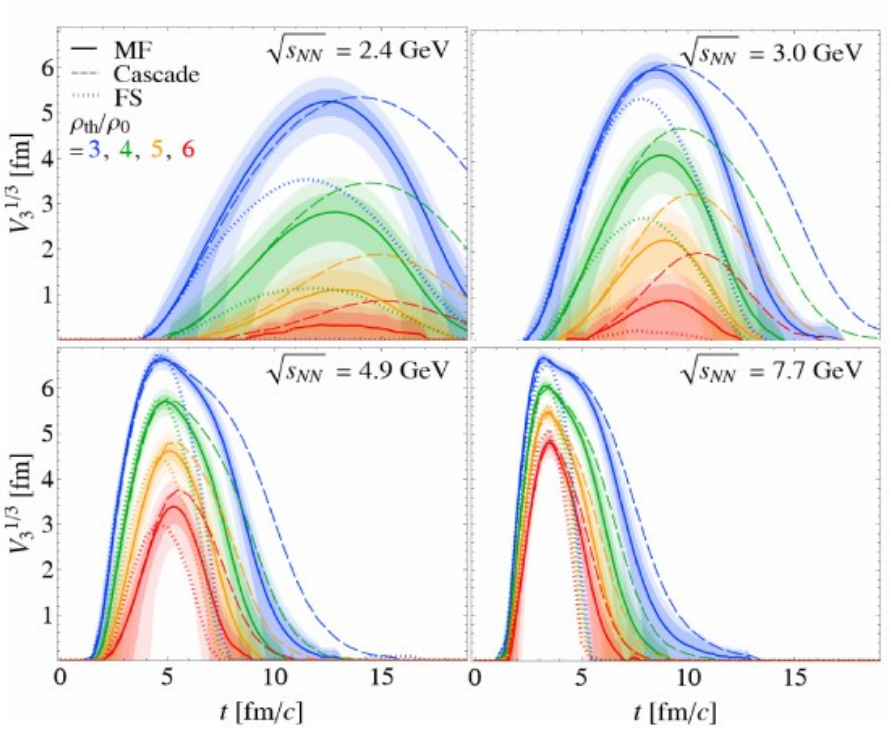
BM@N: $\sqrt{s_{NN}}$ = 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$ = 4 - 11 GeV

BM@N and MPD are both in the collision energy range of the predicted CEP location.

Dense Nuclear Matter

J.Subatomic Part.Cosmol. 3 (2025) 100015





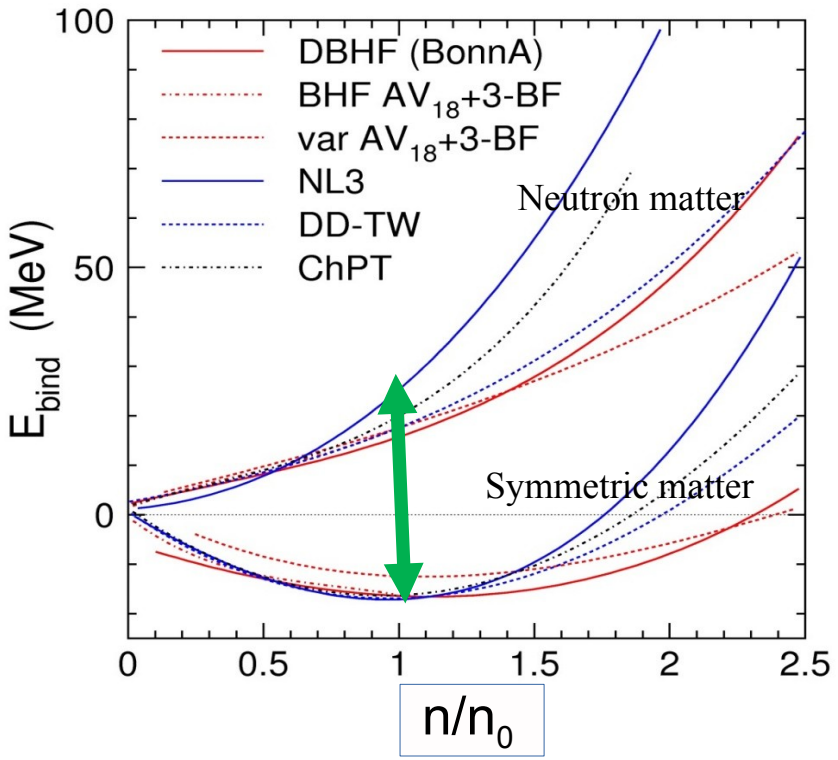
Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

The Nuclear Equation of State (EOS)

$$E/A(n,\delta) = E/A(n,0) + S(n)\delta^2 + ... \quad \text{with}$$

baryon density

isospin asymmetry $\delta=(n_p-n_n)/n$



energy of symmetric nuclear matter

$$E/A(n,0) = E_0/A + \frac{1}{18}K_0\ \varepsilon^2 + ...$$

$$\varepsilon = \frac{n-n_0}{n_0}$$

symmetry energy

$$S(n) = S_0 + \frac{1}{3}L\varepsilon + \frac{1}{18}K_{sym}\ \varepsilon^2 + ...$$

$n_0 = 0.16 \pm 0.01\ \text{fm}^{-3}$

$E_0/A = -16 \pm 1.0\ \text{MeV}$

binding energy per nucleon at saturation density n_0

$$S_0 \equiv \frac{1}{2}\left(\frac{\partial^2(E/A)(n,\delta)}{\partial\delta^2}\right)_{n=n_0,\delta=0}$$

symmetry energy at n_0

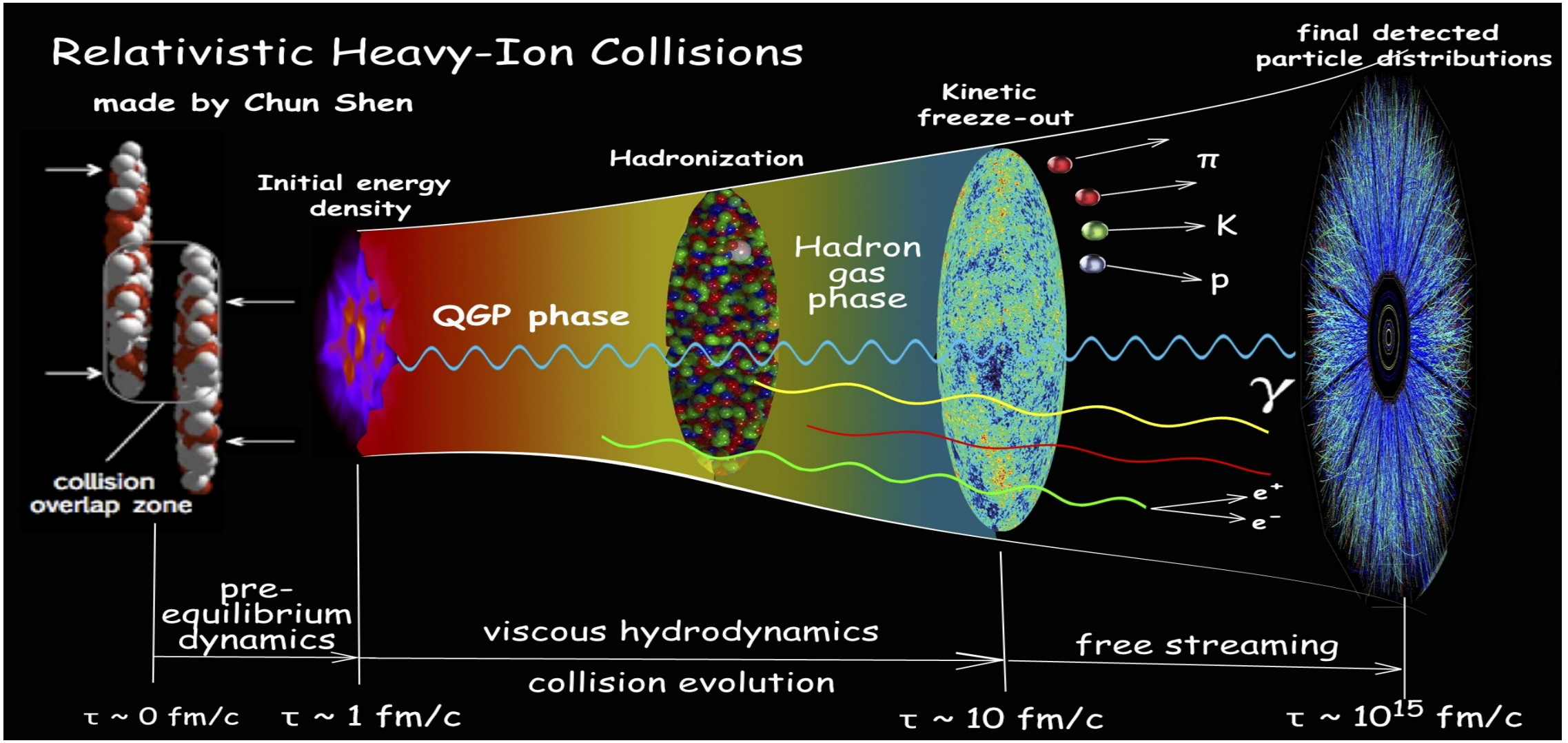
$$L \equiv 3n_0\left(\frac{\partial S(n)}{\partial n}\right)_{n=n_0}$$

$$K_0 \equiv 9n_0^2\left(\frac{\partial^2(E/A)(n,\delta)}{\partial n^2}\right)_{n=n_0,\delta=0}$$

incompressibility at n_0

$$K_{sym} \equiv 9n_0^2\left(\frac{\partial^2 S(n)}{\partial n^2}\right)_{n=n_0}$$

EOS describes the relation between density (n), pressure (P), temperature (T), energy (E), and isospin asymmetry $\delta=(n_p-n_n)/n$



~200+200 nucleons in 10^{-22} seconds = 1000-30000 hadrons

Understanding RHIC physics is hard. Many-body physics across many scales; strongly interacting, relativistic, and very, very small

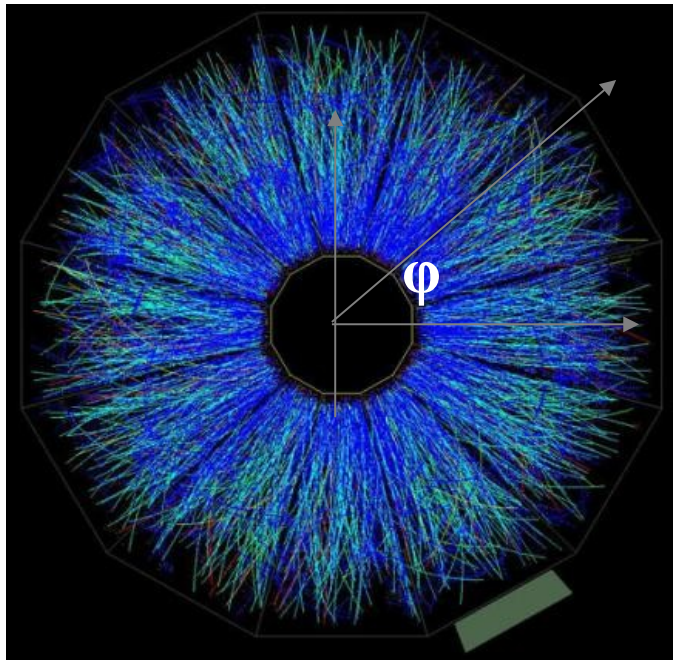
RHIC : Kinematic variables

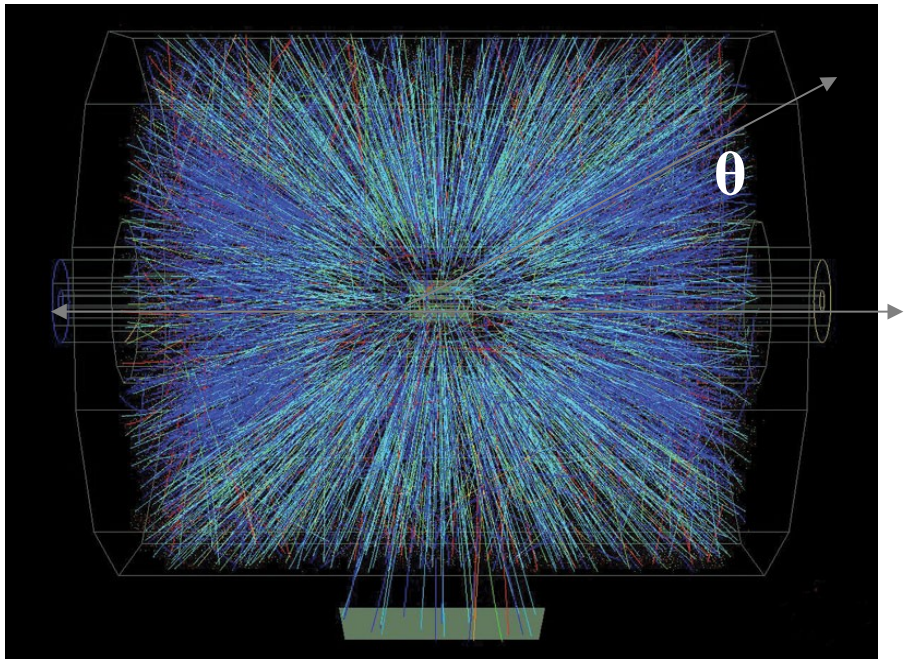
кинематические распределения образовавшихся частиц обычно выражаются как функции
y – rapidity of the particle and p_T – transverse momentum

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) \qquad p_T = \sqrt{p_x^2 + p_y^2} \qquad m_T = \sqrt{m^2 + p_T^2}$$

- p_T: Lorentz-invariant with respect to acceleration in the beam direction and generated during a collision (p_z = present «before collision»)

- y: not a Lorentz invariant, but an additive transformation law → y'=y-ycm (ycm – rapidity of the ref system)





$$\eta = \frac{1}{2}\log\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

y~η for relativistic particles

MPD experiment at NICA

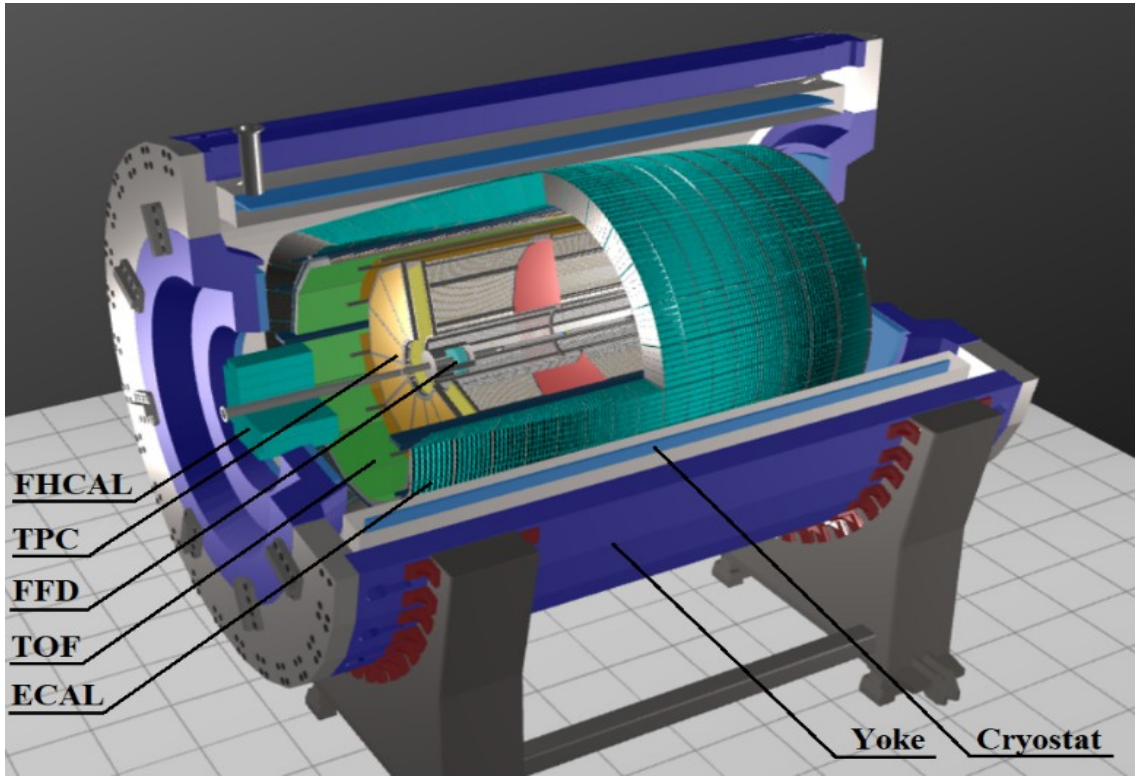
Main subsystems at Stage-I:

TPC ($|\eta| \leq 1.6$): charged particle tracking + momentum reconstruction + dE/dx identification

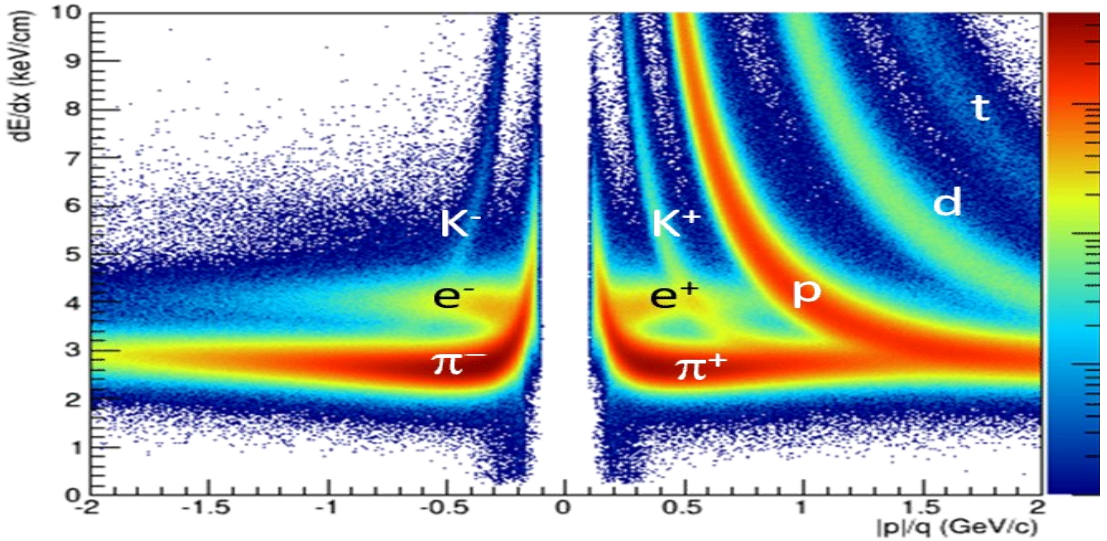
TOF ($|\eta| \leq 1.4$): charged particle identification

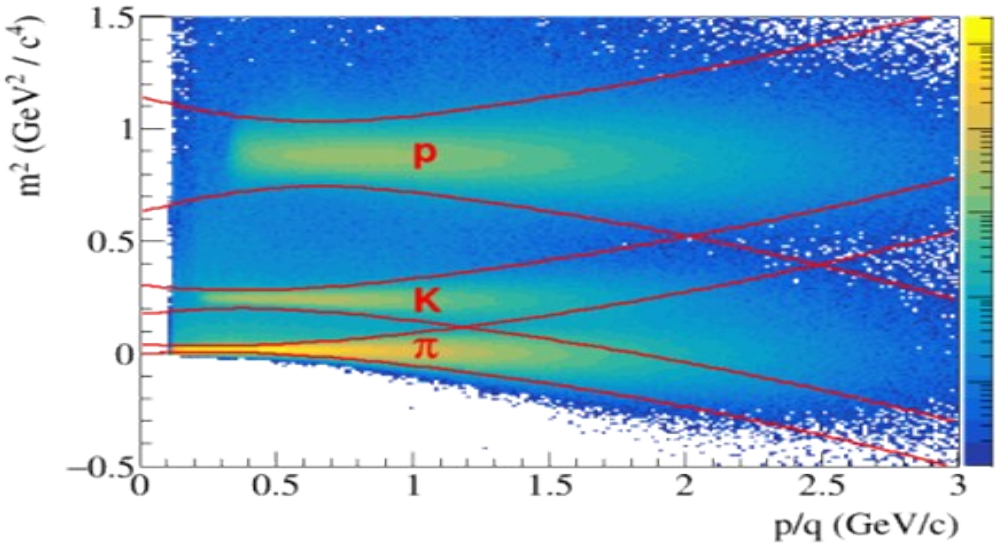
ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

FHCal ($2 < |\eta| < 5$) and **FFD** ($2.9 < |\eta| < 3.3$): event triggering + event geometry

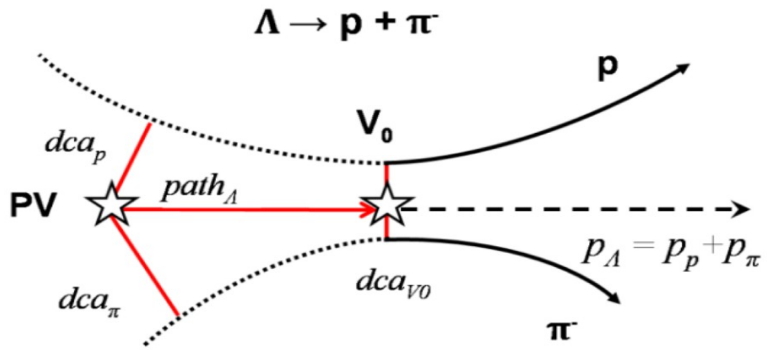


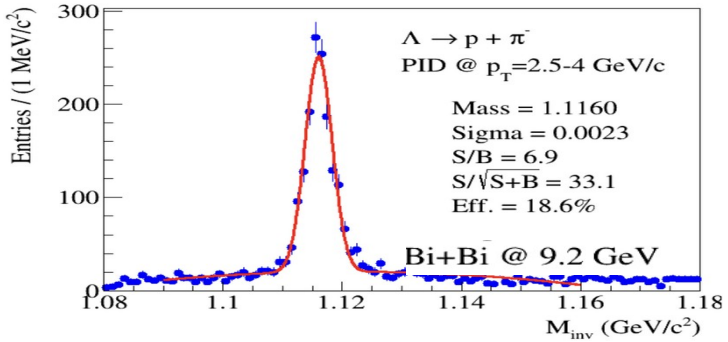
γ, e, μ, π, K, p, n

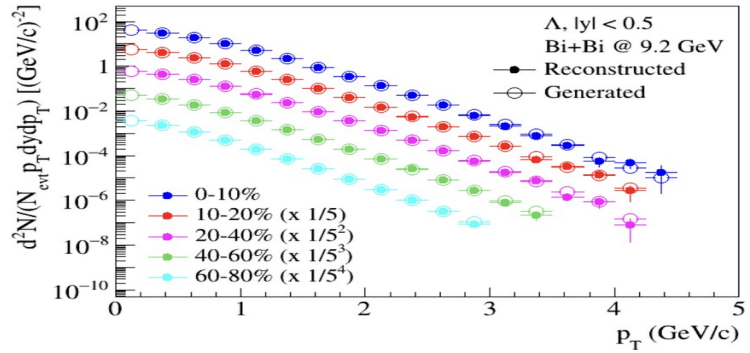


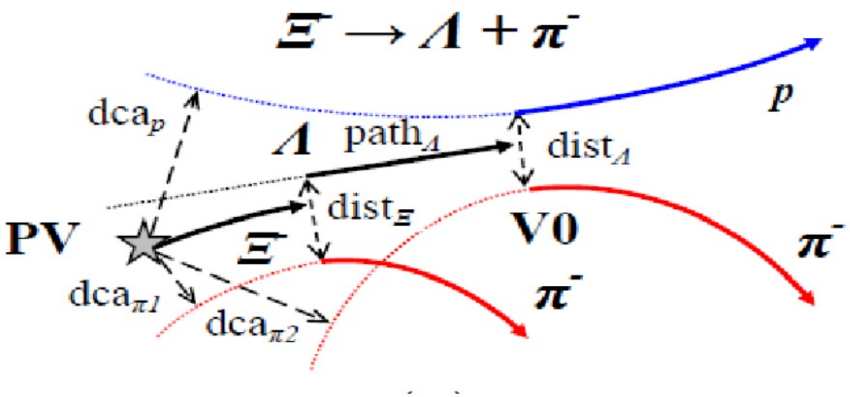


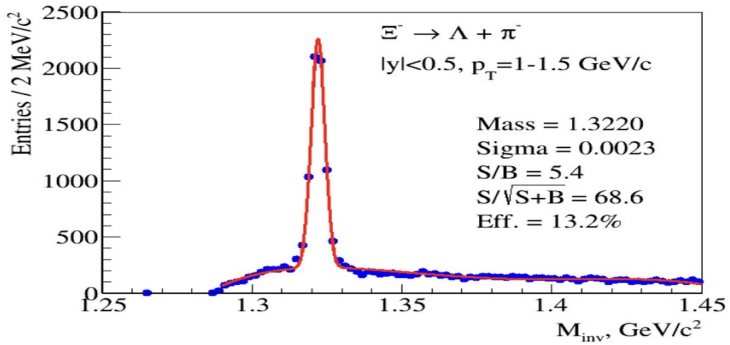
PID via Topology and Invariant Mass

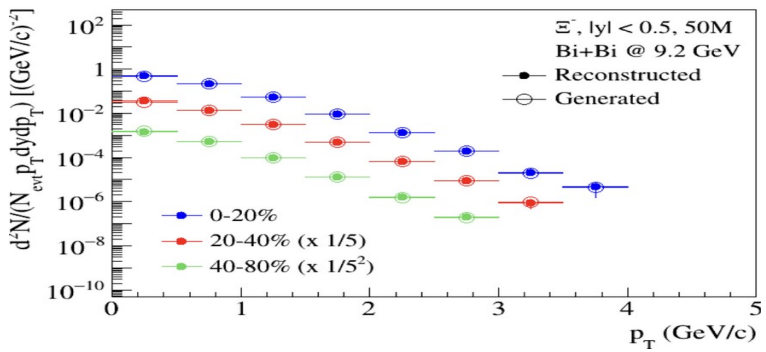






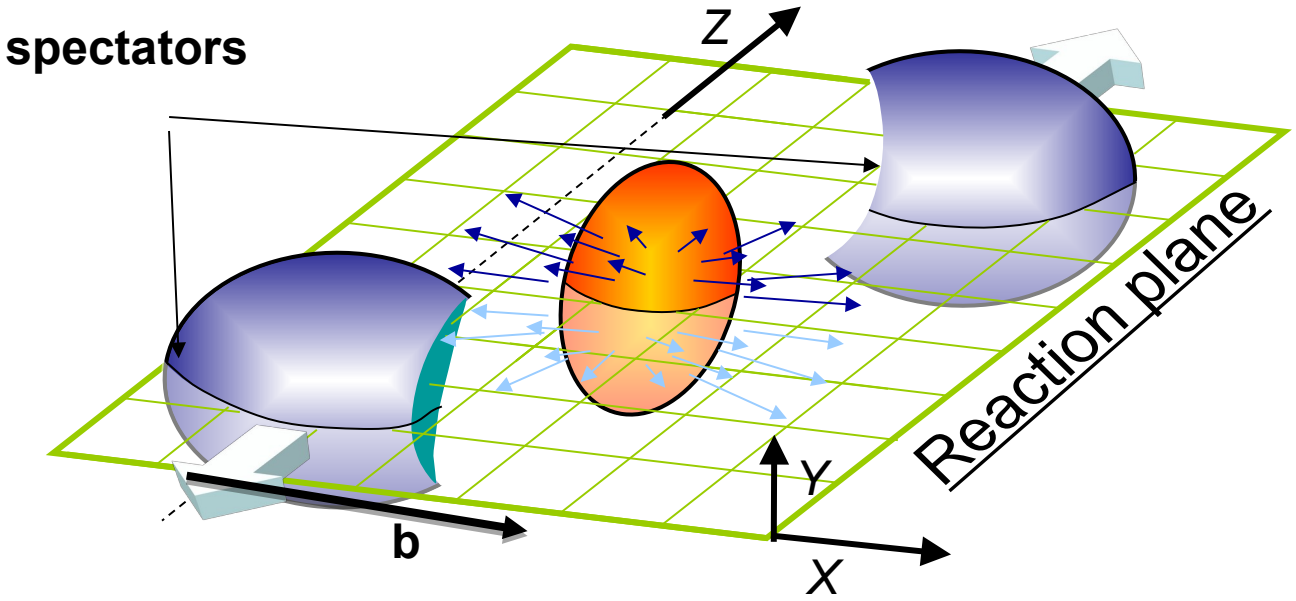


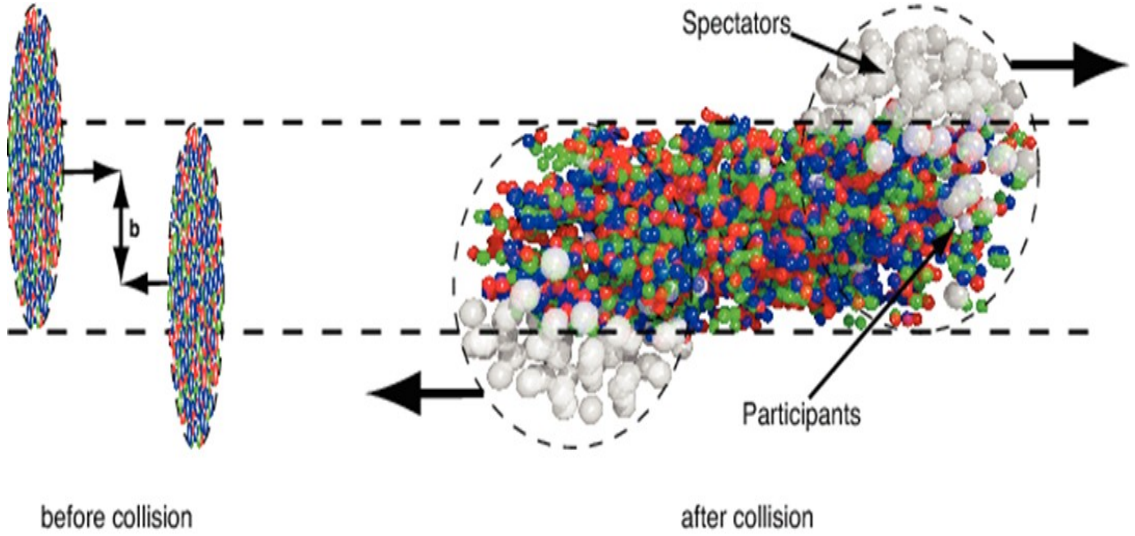




$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$

HIC: Impact parameter & Reaction plane



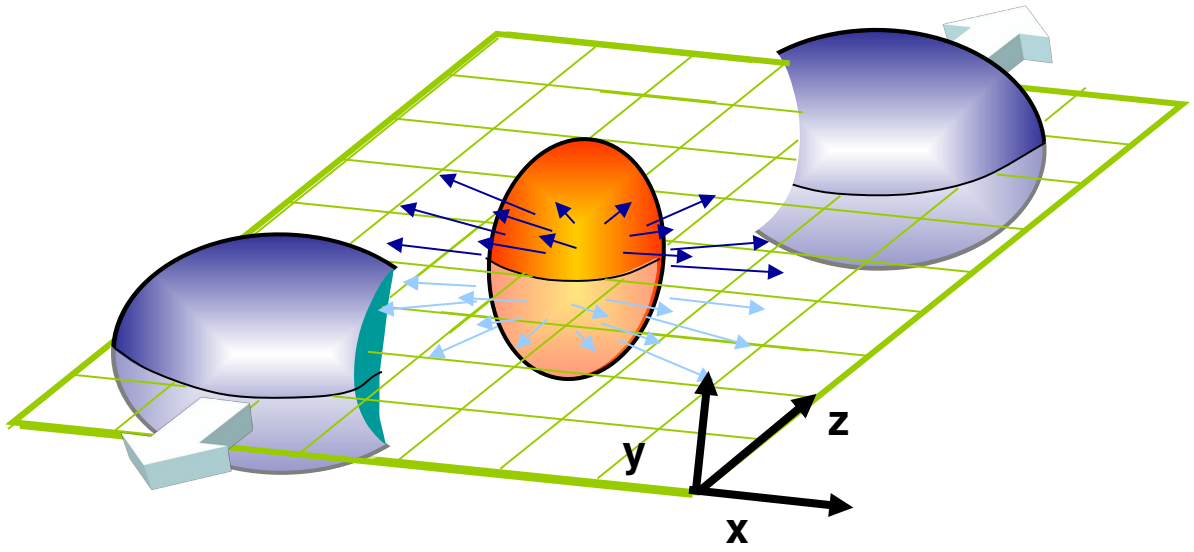


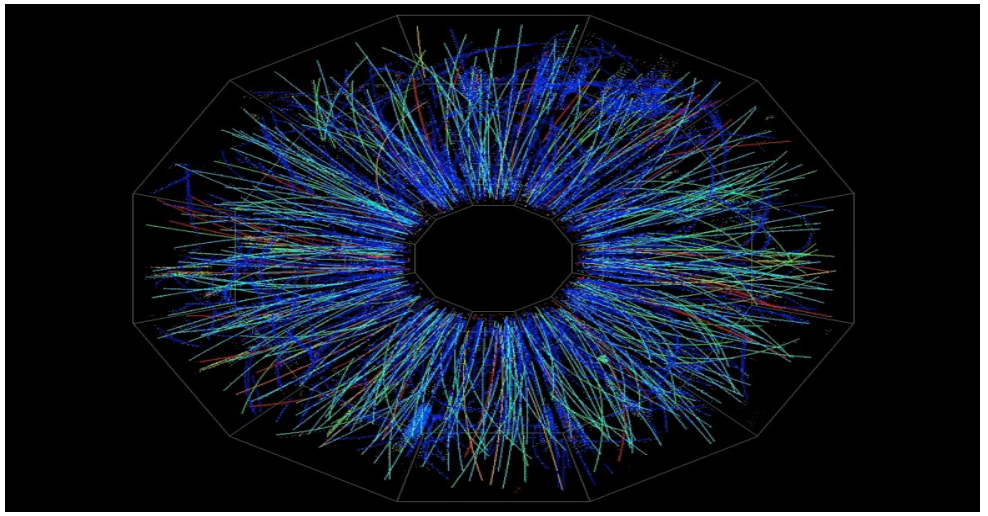
- **Impact parameter b:**
  ⊥ to the beam direction (**z**) ,
  connects centers of colliding nuclei

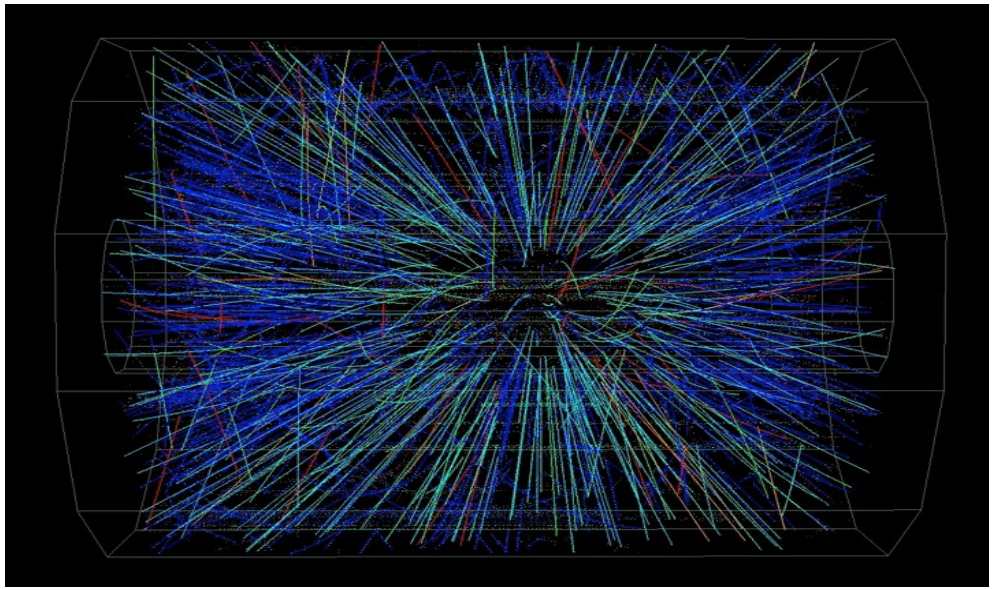
- **Reaction plane:** spanned by beam direction (**z**) and impact parameter (**b**)

- **"Passage time":** $2R/\gamma c$ ~ 1-10 fm/c (BM@N-MPD)

HIC: Peripheral Collision

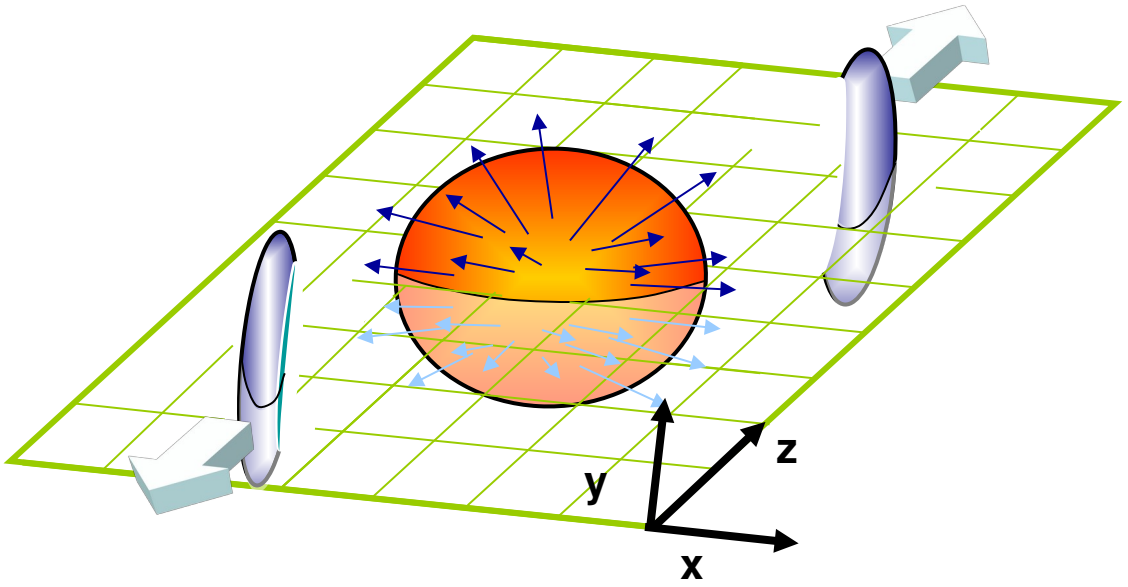


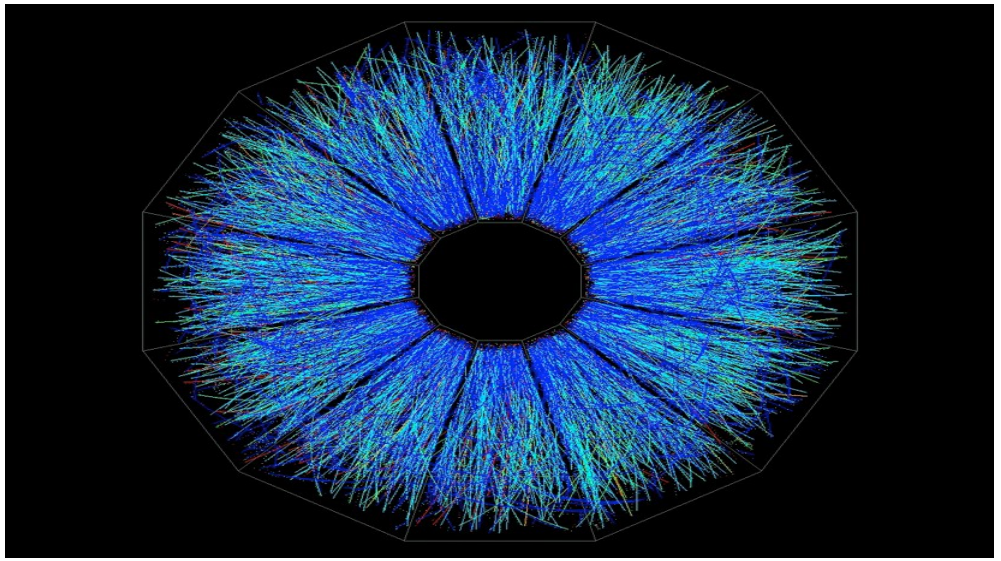


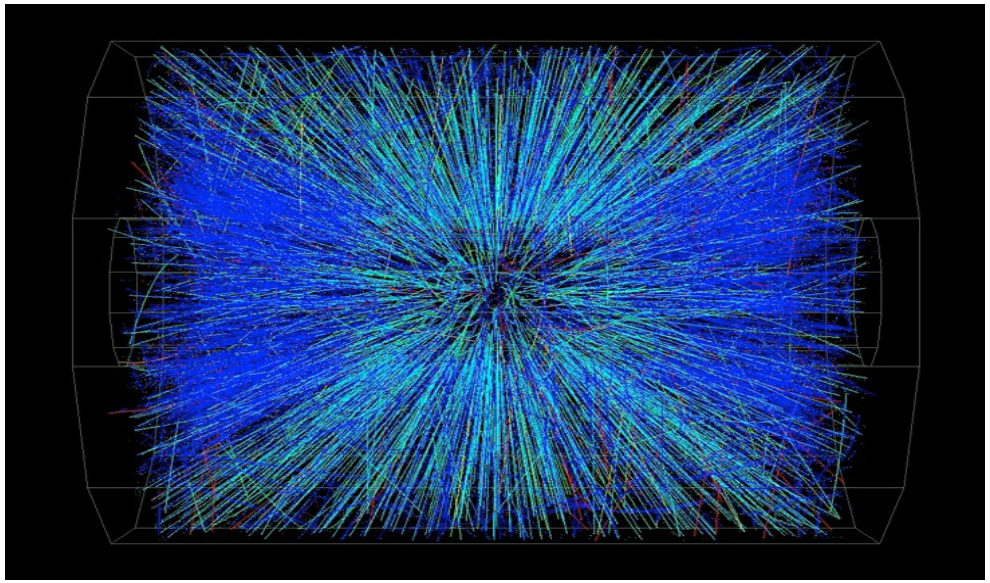


- Large impact parameter **b**
- Overlap region is strongly asymmetric in the x-y plane
- Many spectators
- Few produced particles

HIC: Central Collision

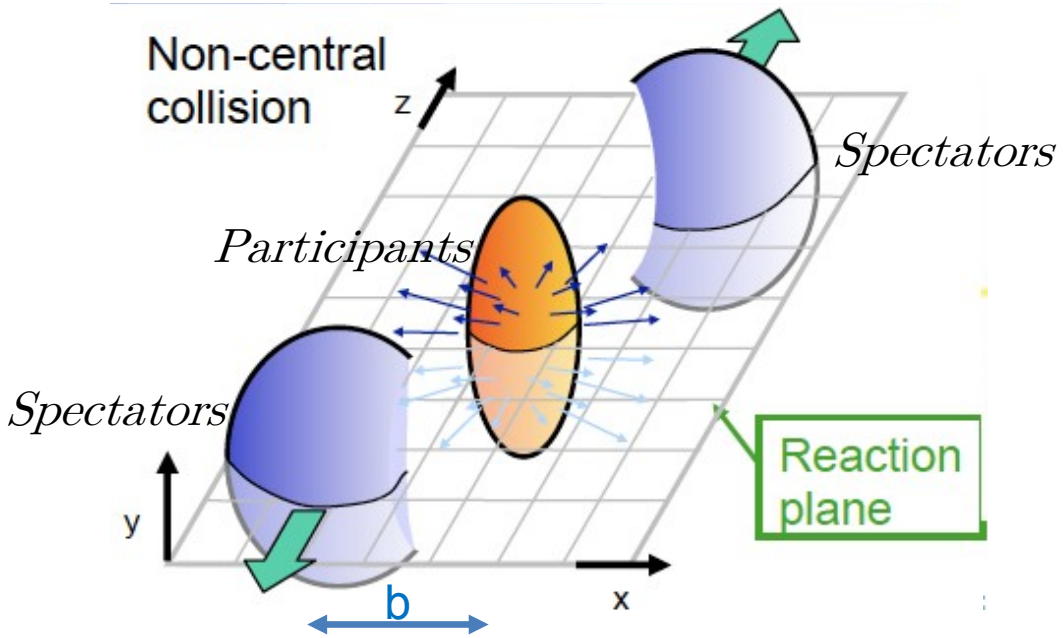


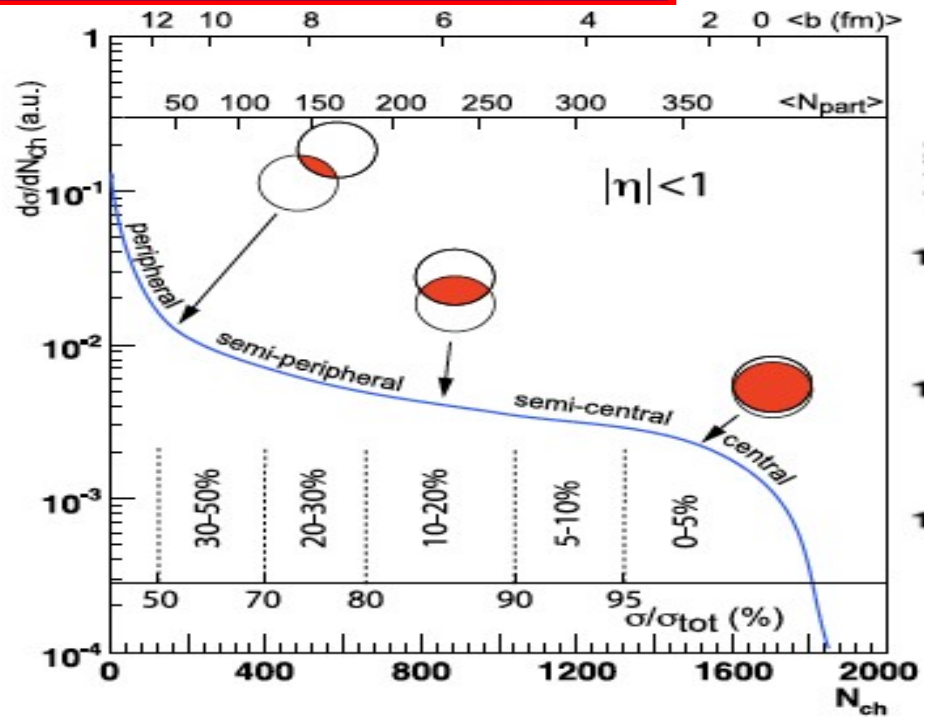




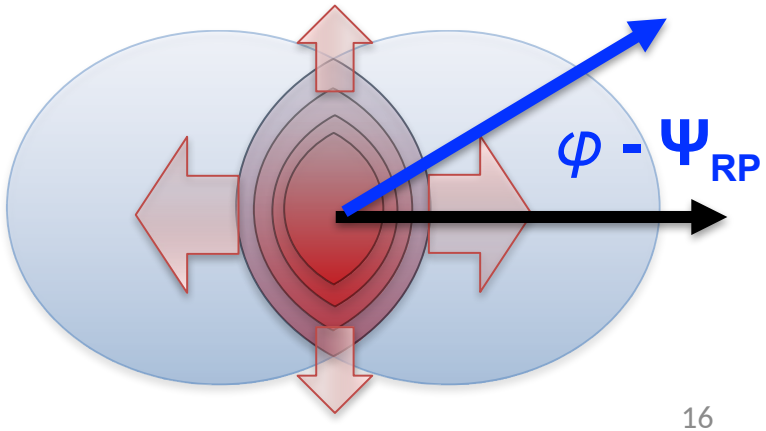
- Small impact parameter **b**
- Overlap region is close to be symmetric in the x-y plane
- Few spectators
- Many produced particles

Geometry of Heavy-Ion Collisions

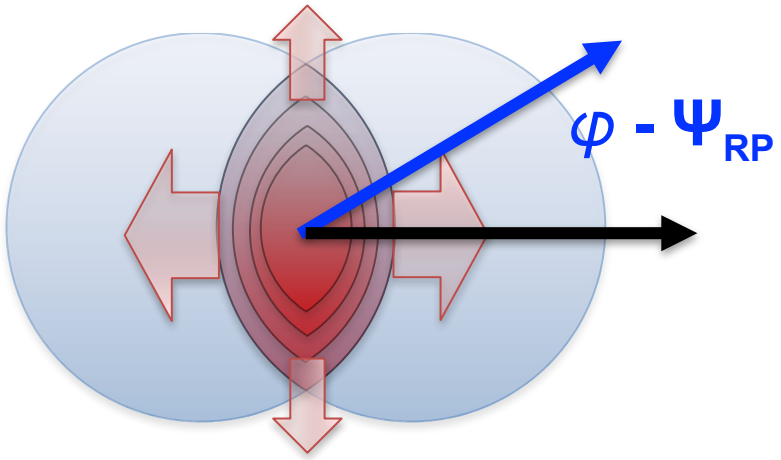




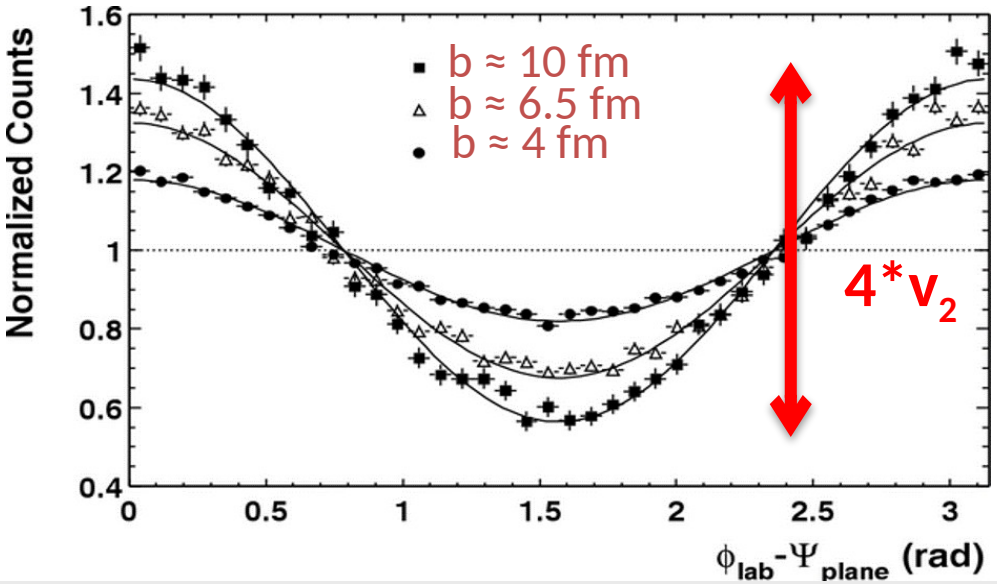
- $N_{participants}$: number of nucleons in the overlap region
- $N_{collisions}$: number of inelastic nucleon-nucleon collisions
- Reaction plane: defined by beam axis and impact parameter
- Centrality: percentile of the total cross section



Anisotropic flow of particles at HIC



STAR, PRL**90** 032301 (2003)



Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

$$\frac{dN}{d(\varphi - \Psi_{RP})} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos(2(\varphi - \Psi_{RP})) + \ldots\right)$$

- The sinus terms are skipped by symmetry arguments
- From the properties of Fourier's series one has

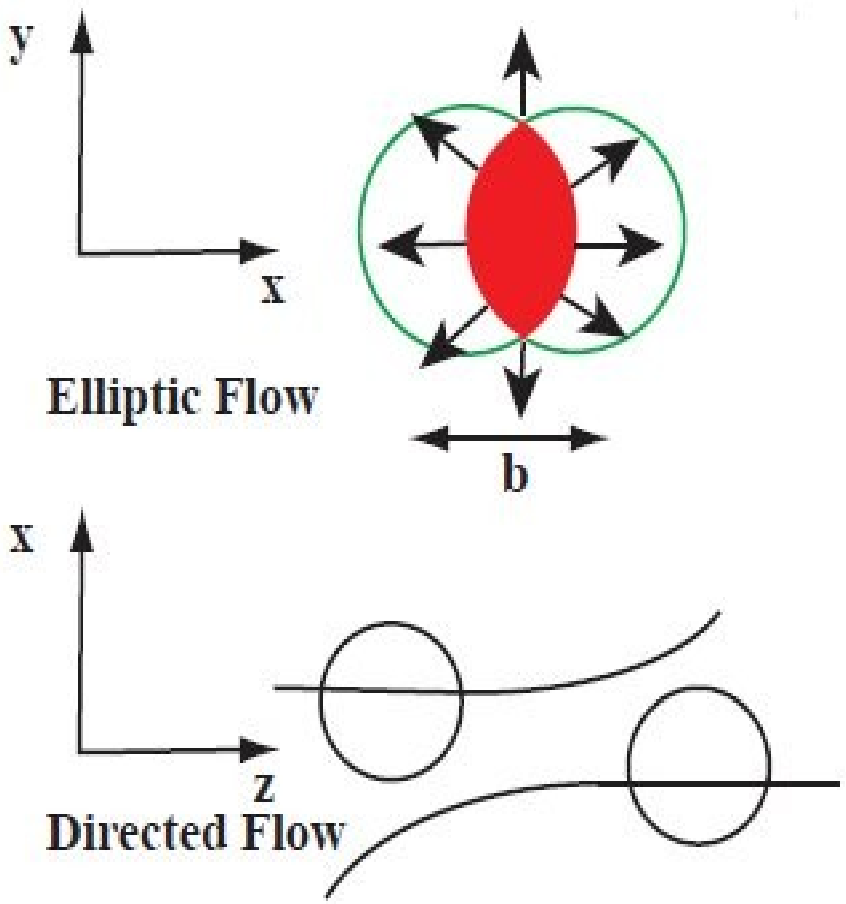
$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

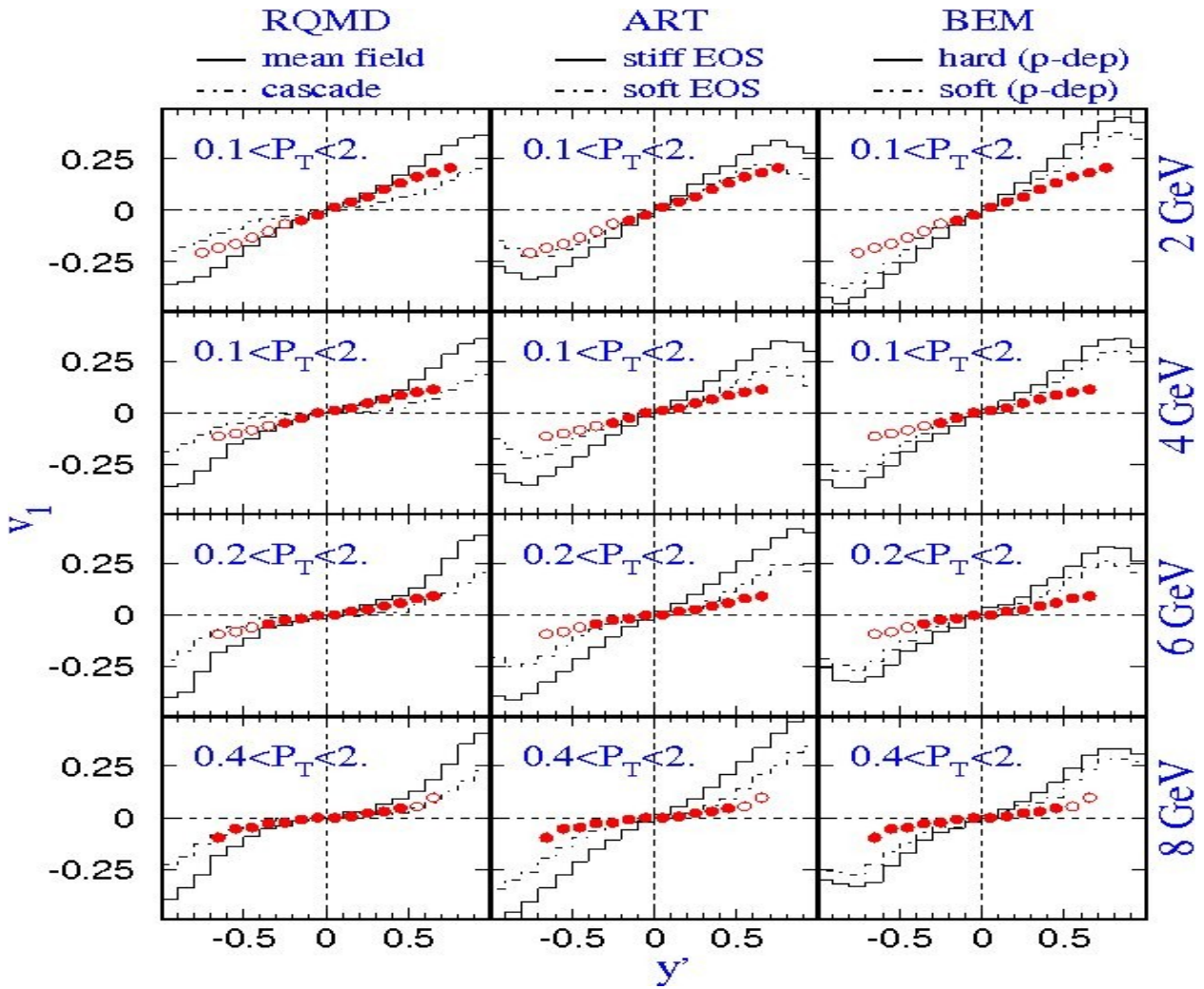
- Fourier coefficients $\mathbf{V_n}$ quantify anisotropic flow:

v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior of particles in event or multiparticle azimuthal correlation

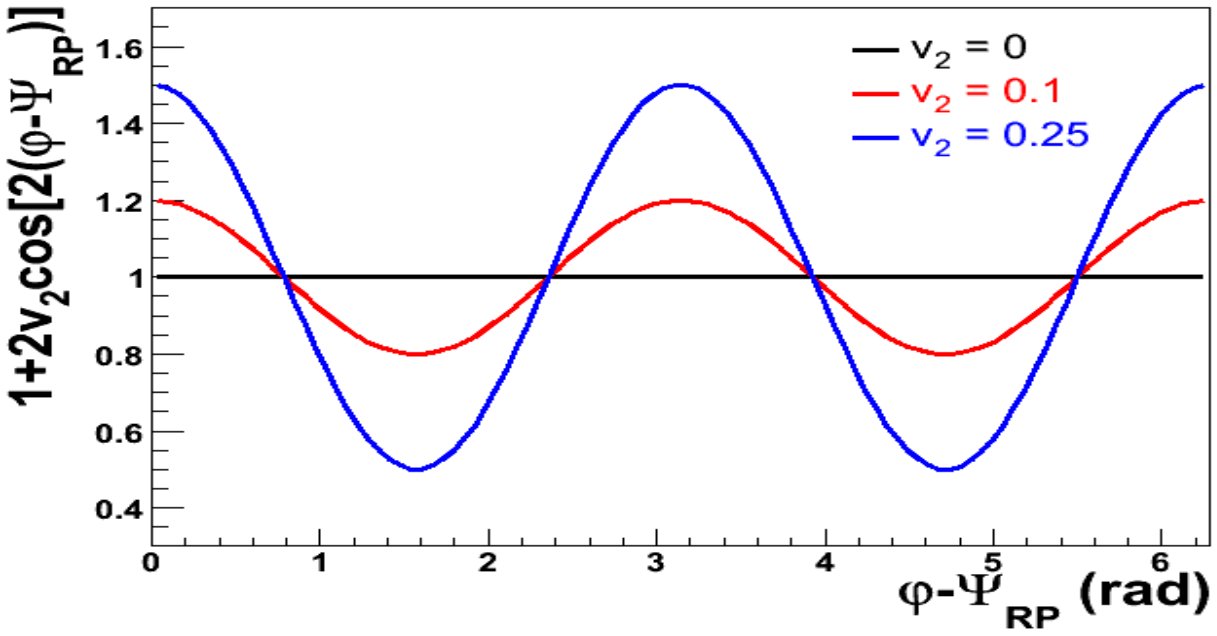
Directed Flow in HIC





Elliptic Flow V_2

$$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$

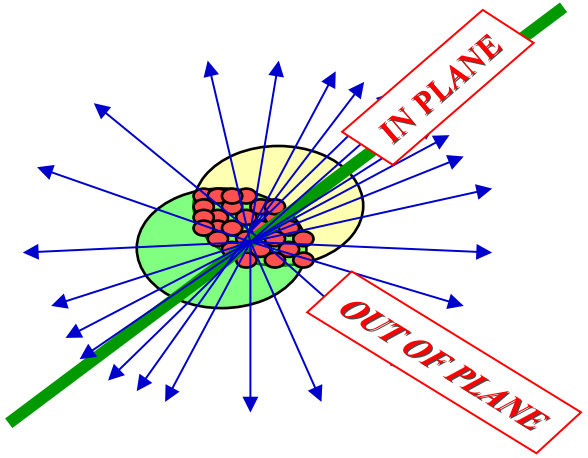


$v_2 > 0$ → in-plane flow,
$v_2 < 0$ out-of-plane flow

- **$v_2 \neq 0$** - difference between the (||) **[N(0⁰) + N(180⁰)]** and (⊥) **[N(90⁰) + N(270⁰)]** to the impact parameter (**b**)

- **$V_2 = 0.25 \rightarrow R_{in/out} = 3$** (3 times more particles emitted in-plane than out-of- the plane)

$$R_{in/out} = \frac{N(0^0) + N(180^0)}{N(90^0) + N(270^0)} \sim \frac{1 + 2V_2}{1 - 2V_2}$$



Relativistic Heavy-Ion Collisions: Constraints on Nuclear Equation of State

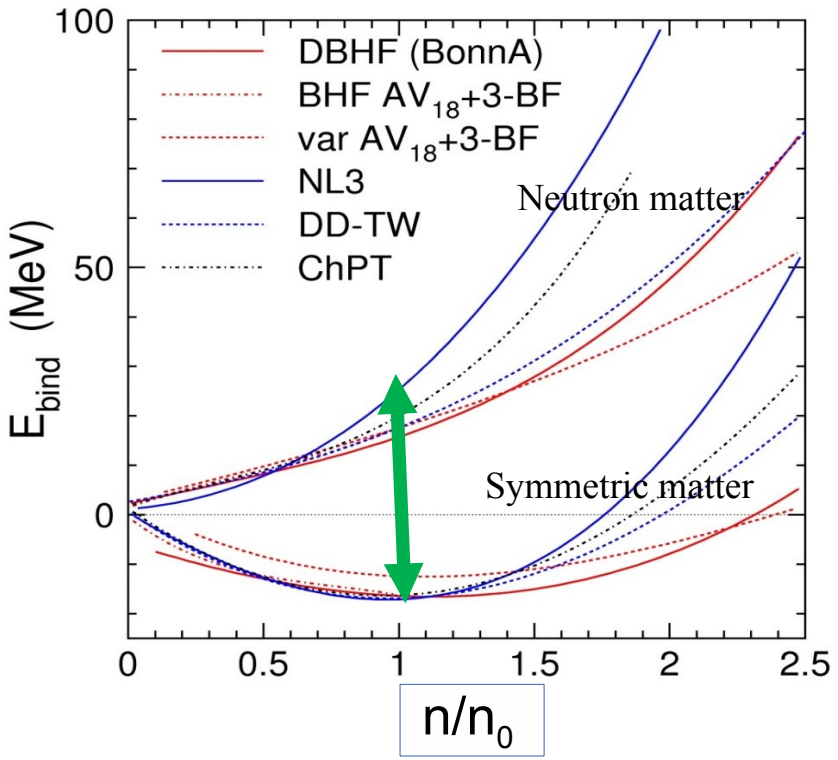
$$E/A(n,\delta) = E/A(n,0) + S(n)\delta^2 + ... \quad \text{with}$$

baryon density

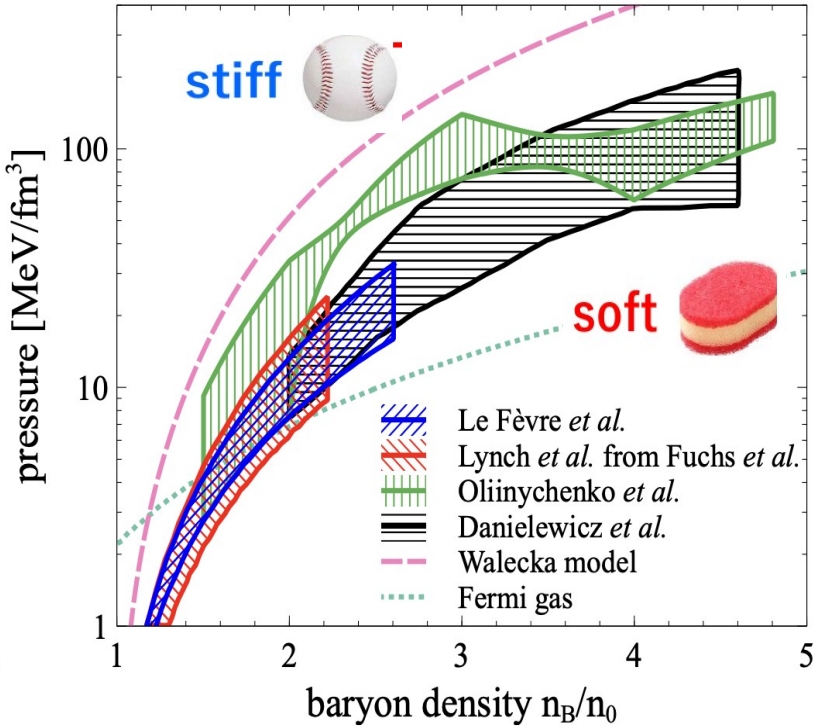
isospin asymmetry $\delta=(n_p-n_n)/n$

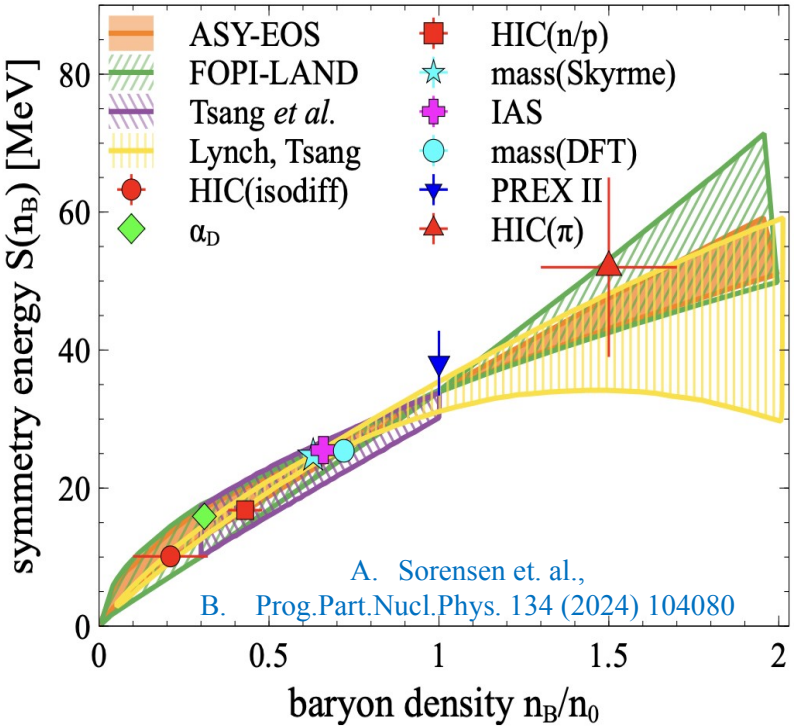
Symmetric nuclear matter

Symmetry energy



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

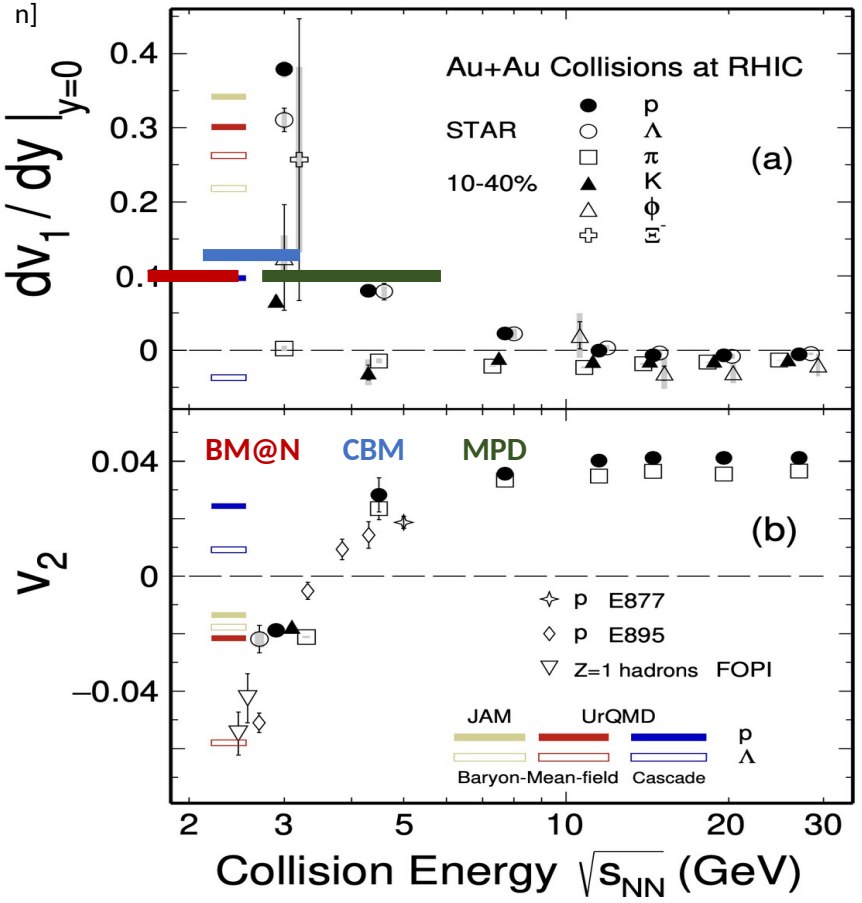


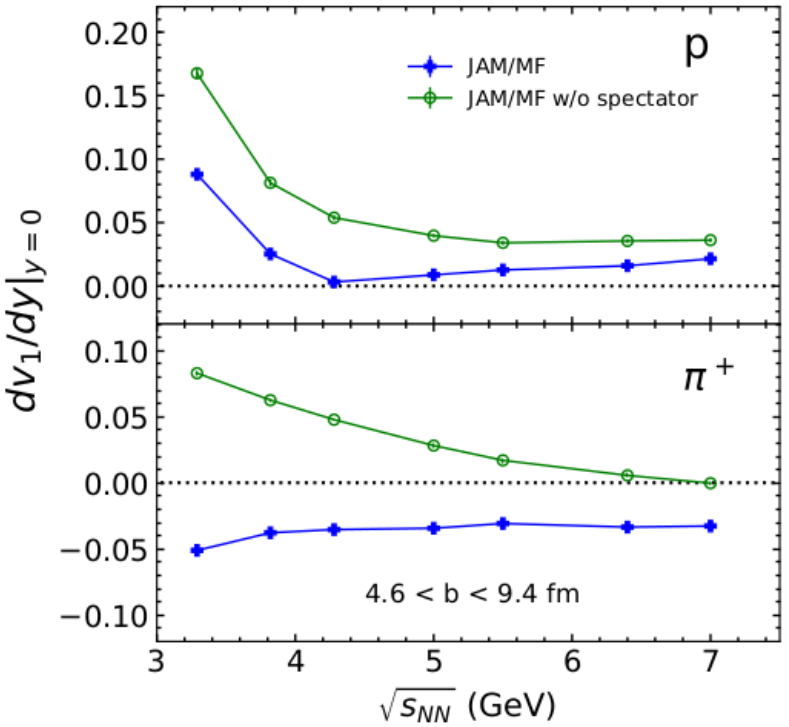


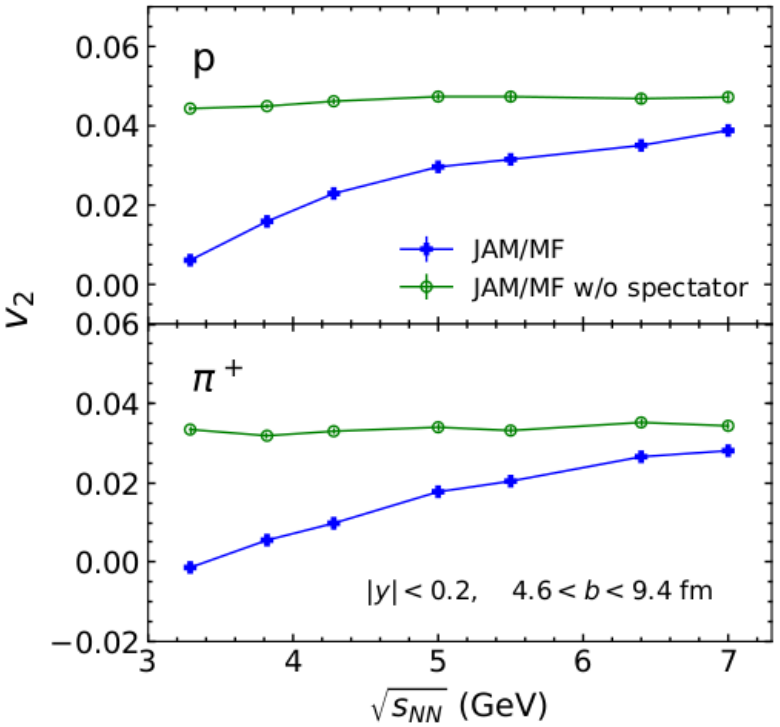
EOS describes the relation between density (n), pressure (P), temperature (T), energy (E), and isospin asymmetry $\delta=(n_p-n_n)/n$

Anisotropic flow in heavy-ion collisions at high baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)
n]







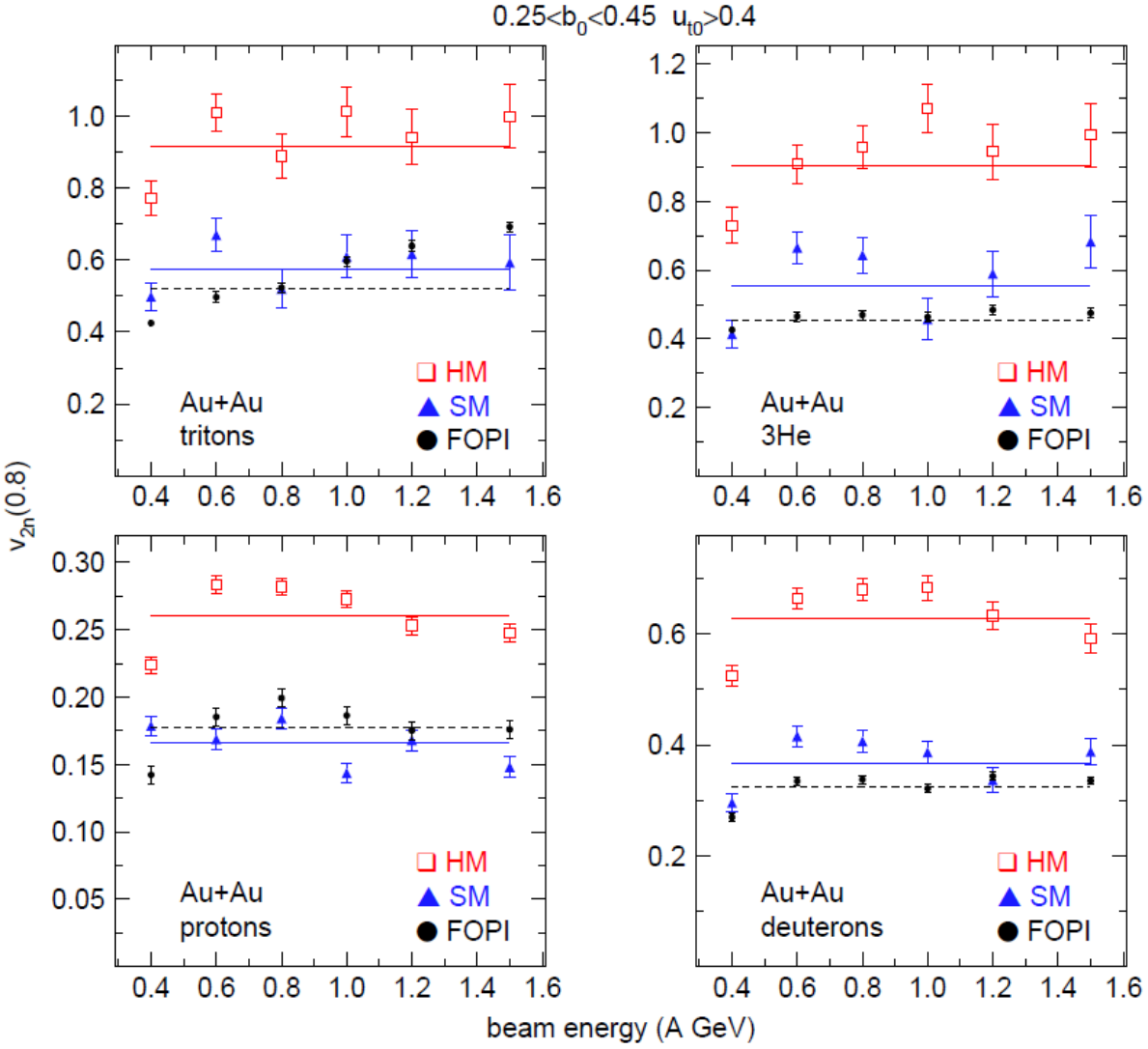
Phys. Rev. C 97, 064913 (2018)

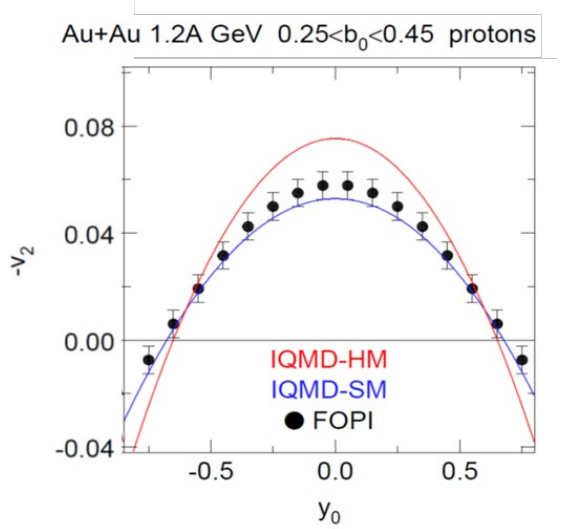
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

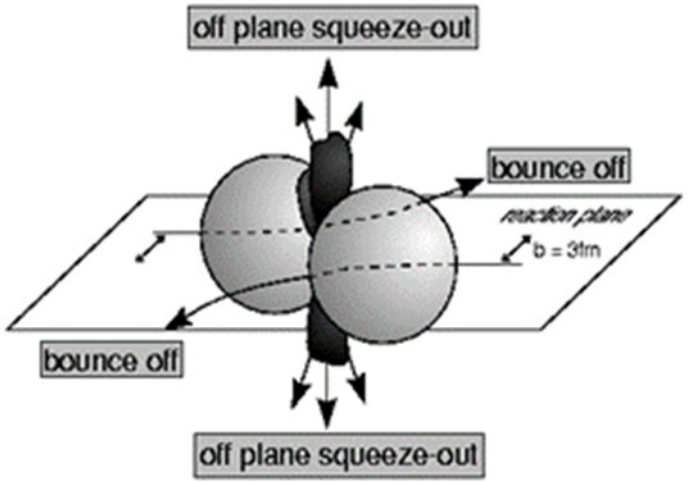
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$) and

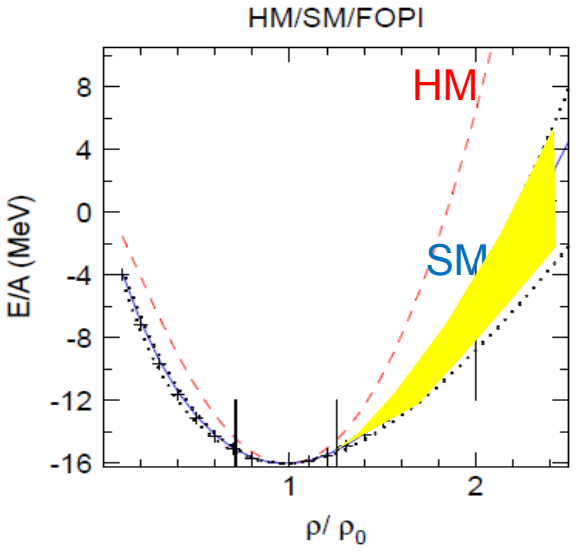
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

FOPI at GSI: EOS from the elliptic flow of fragments in Au+Au collisions at SIS18 energies ($\rho \approx 2.5\rho_0$)









Hard Momentum-dependent
HM: K_{nm} = 380 MeV

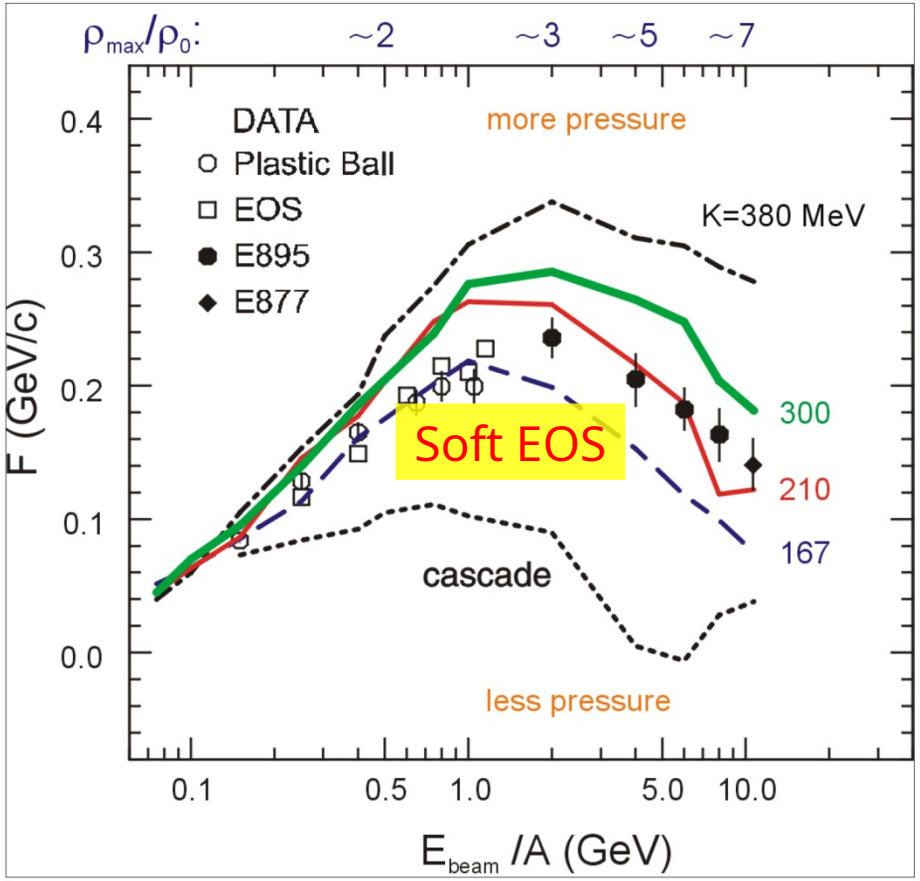
Soft Momentum dependent
SM: K_{nm} = 200 MeV

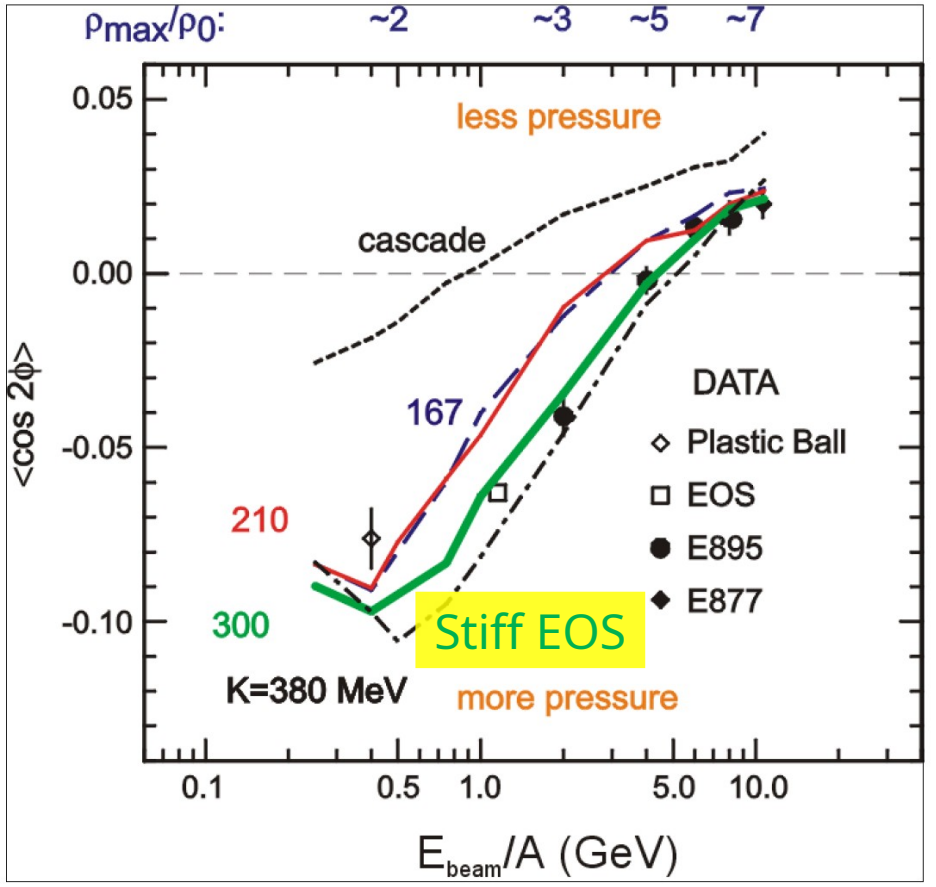
Nuclear incompressibility
K_{nm}=190 ±30 MeV

A. Le Fevre , Y Leifels, W. Reisdorf, J. Aichelin, Ch. Hartnack, Nucl. Phys. A945 (2016) 112

Nuclear incompressibility from collective proton flow

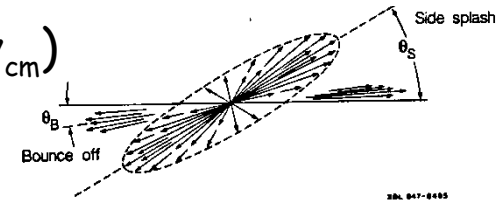
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



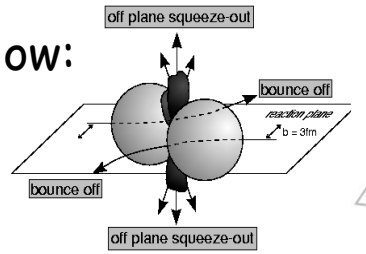


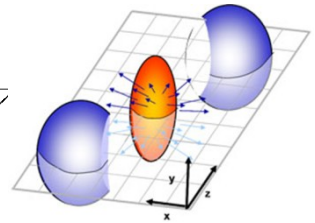
Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



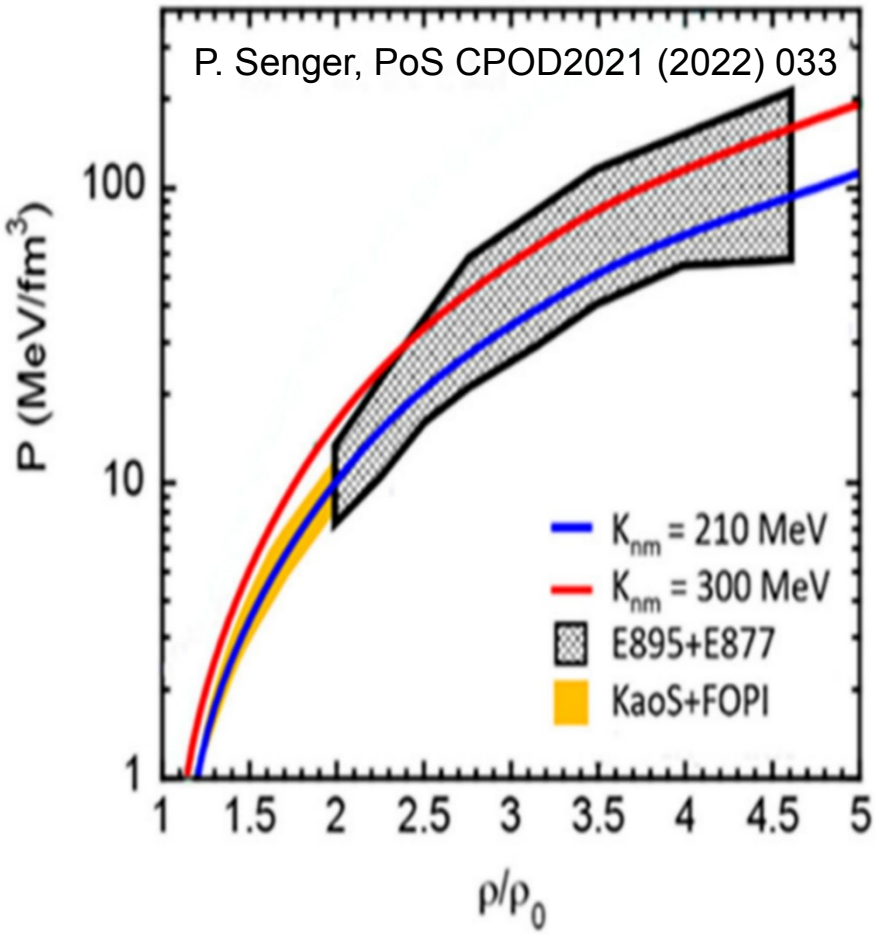
Elliptic flow:

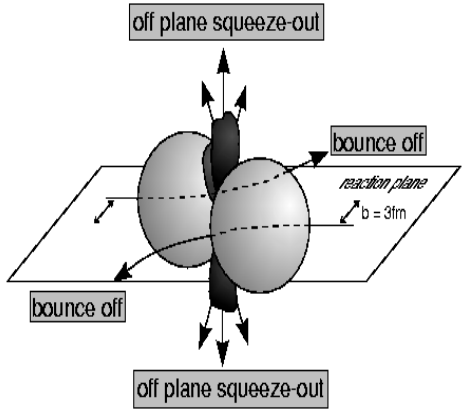


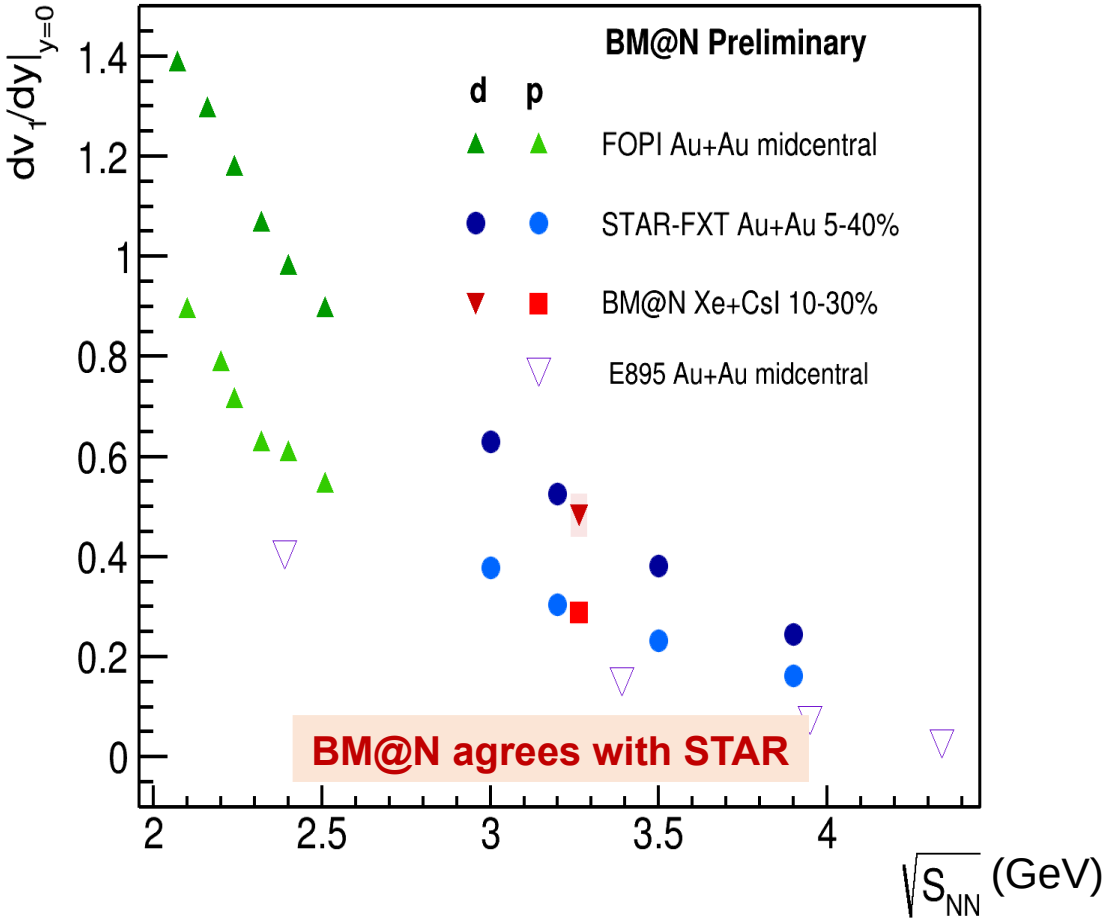


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Directed flow of protons and EOS of symmetric matter





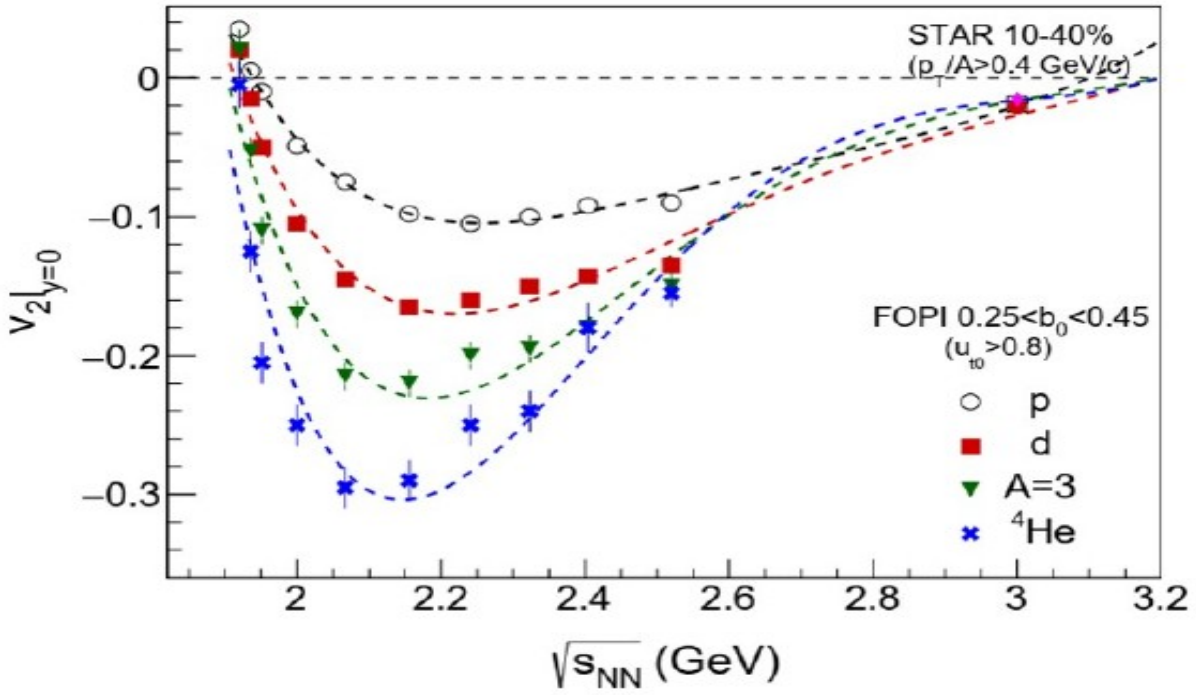


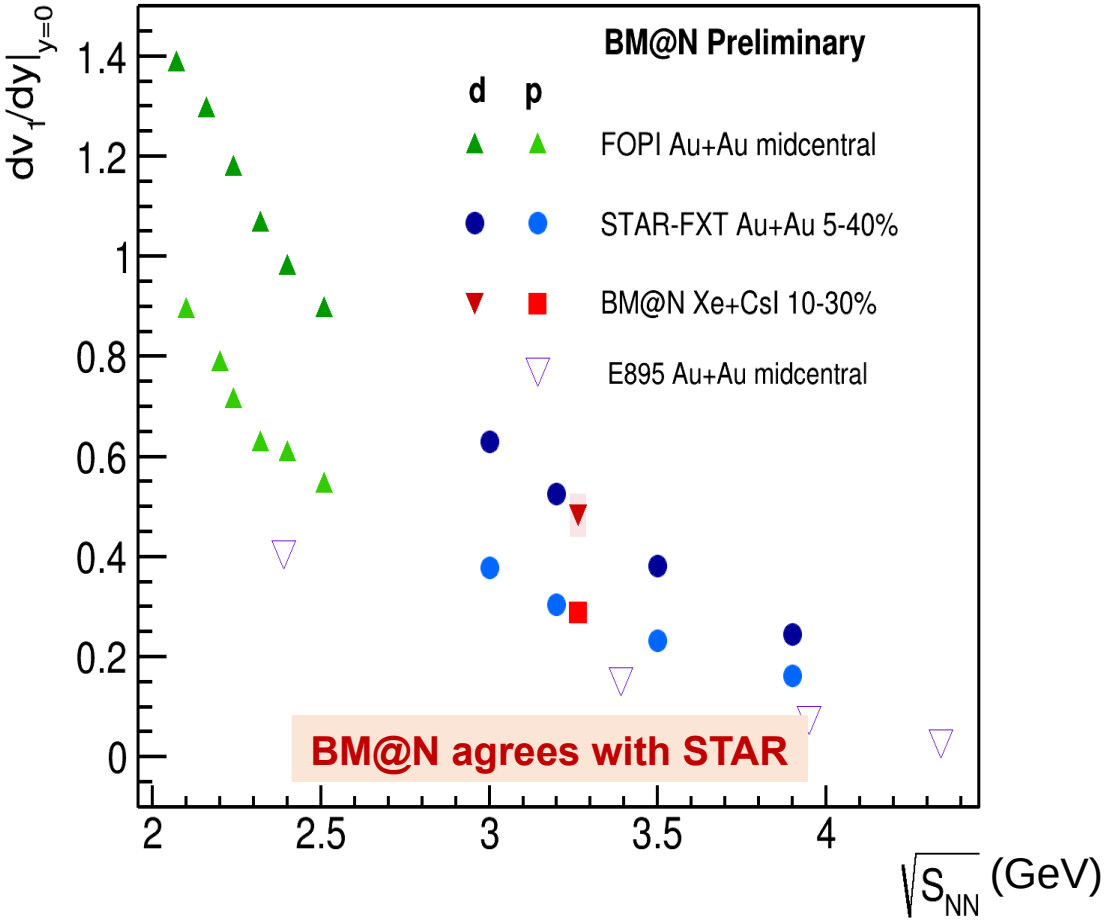
Nuclear incompressibility from collective proton flow

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Both STAR and BM@N results for directed flow prefer stiff EOS

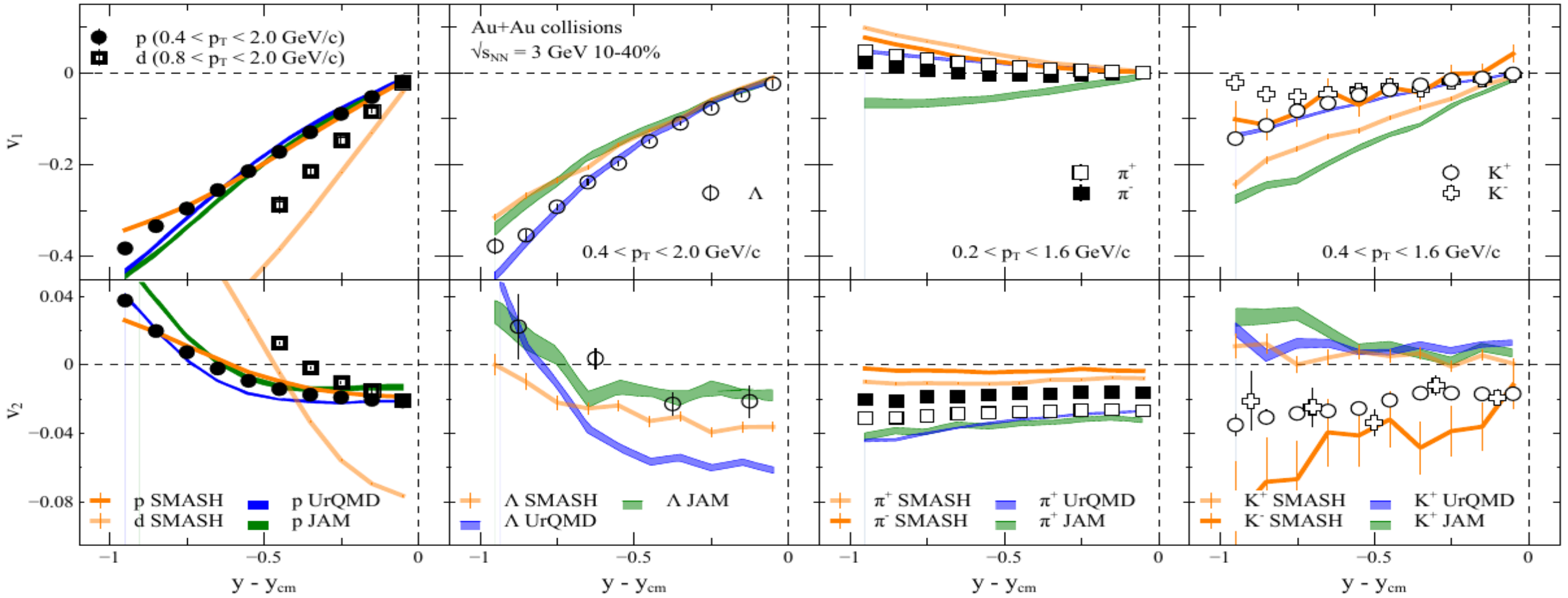
Directed and elliptic flow and EOS of symmetric matter





Describing proton flow is not enough

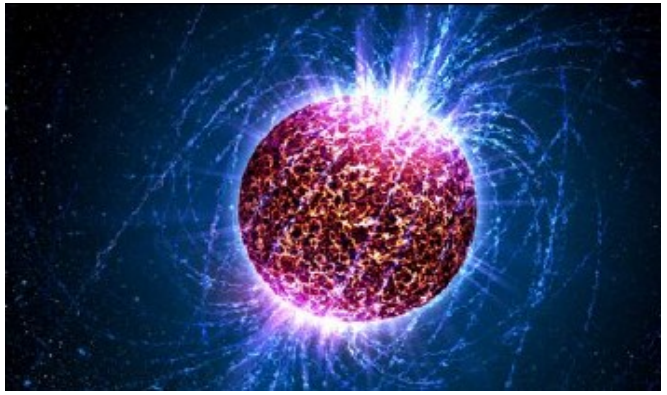
Prog.Part.Nucl.Phys. 134 (2024) 104080



Strange baryons are not well described
— the results may depend on:
• nucleon-hyperon and hyperon-hyperon interactions
• in-medium modifications of interactions

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

Neutron Stars and Big Questions



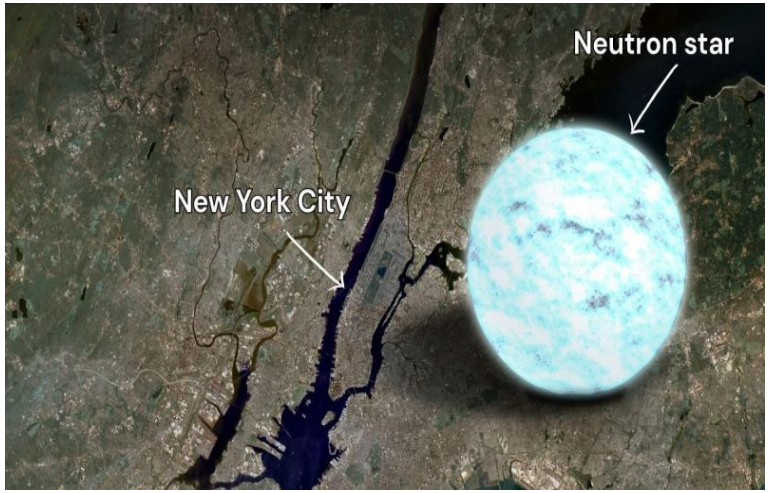
Nature of matter at extreme density?



Origin of cosmic explosions?

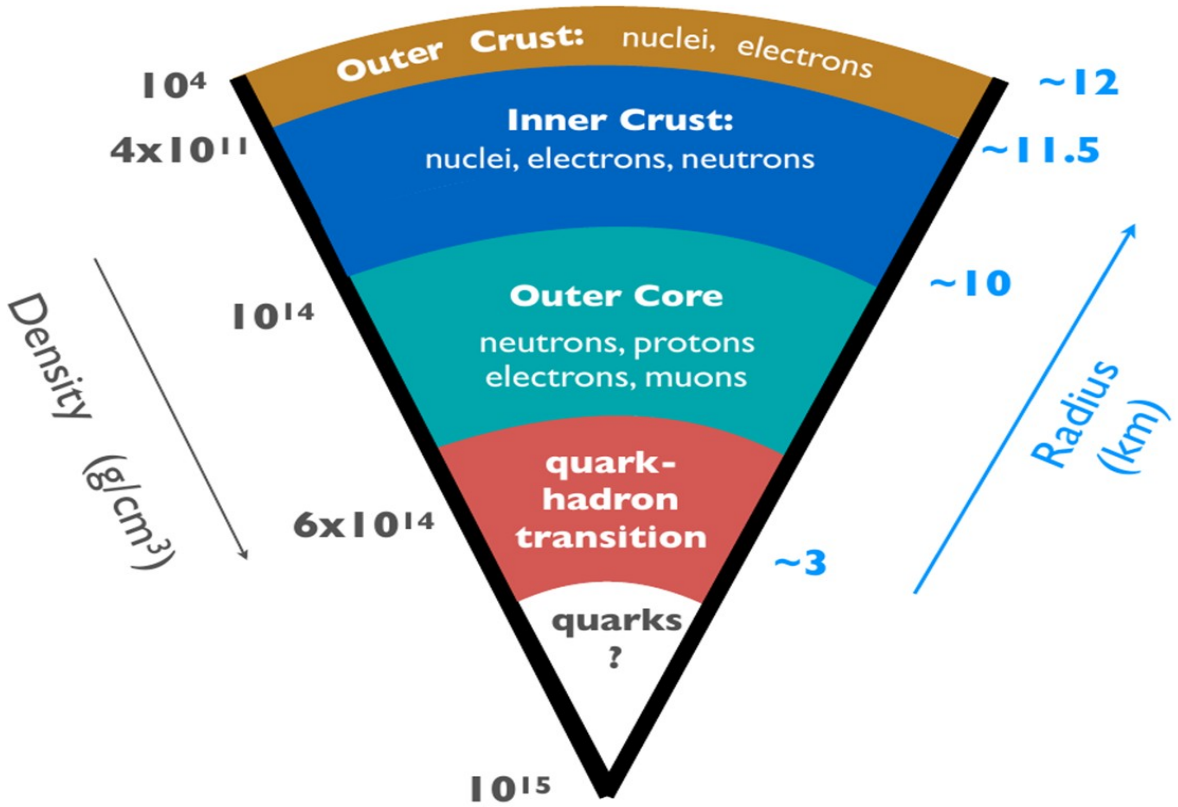


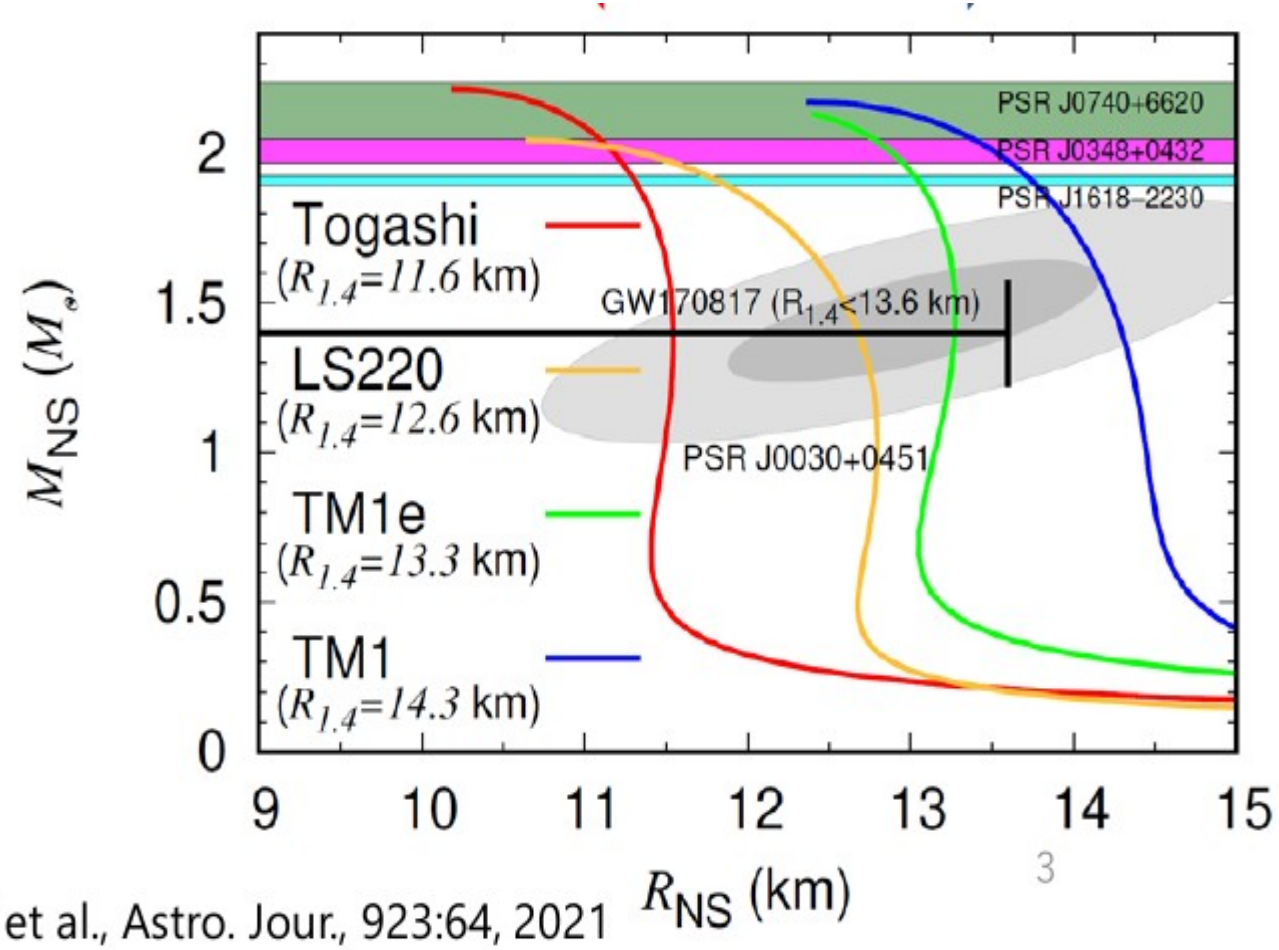
Synthesis of heavy elements?



- usually refer to compact objects with $M \approx 1\text{-}2\ M_{\odot}$ and $R \approx 10\text{-}12$ Km
- produced in core collapse supernova explosions, usually observed as pulsars
- extreme densities up to $5\text{-}10\ \rho_0$ ($n_0 = 0.16$ fm^{-3} => $\rho_0 = 3 \cdot 10^{14}$ g/cm^3)

Neutron Stars (NS): Mass and Radius



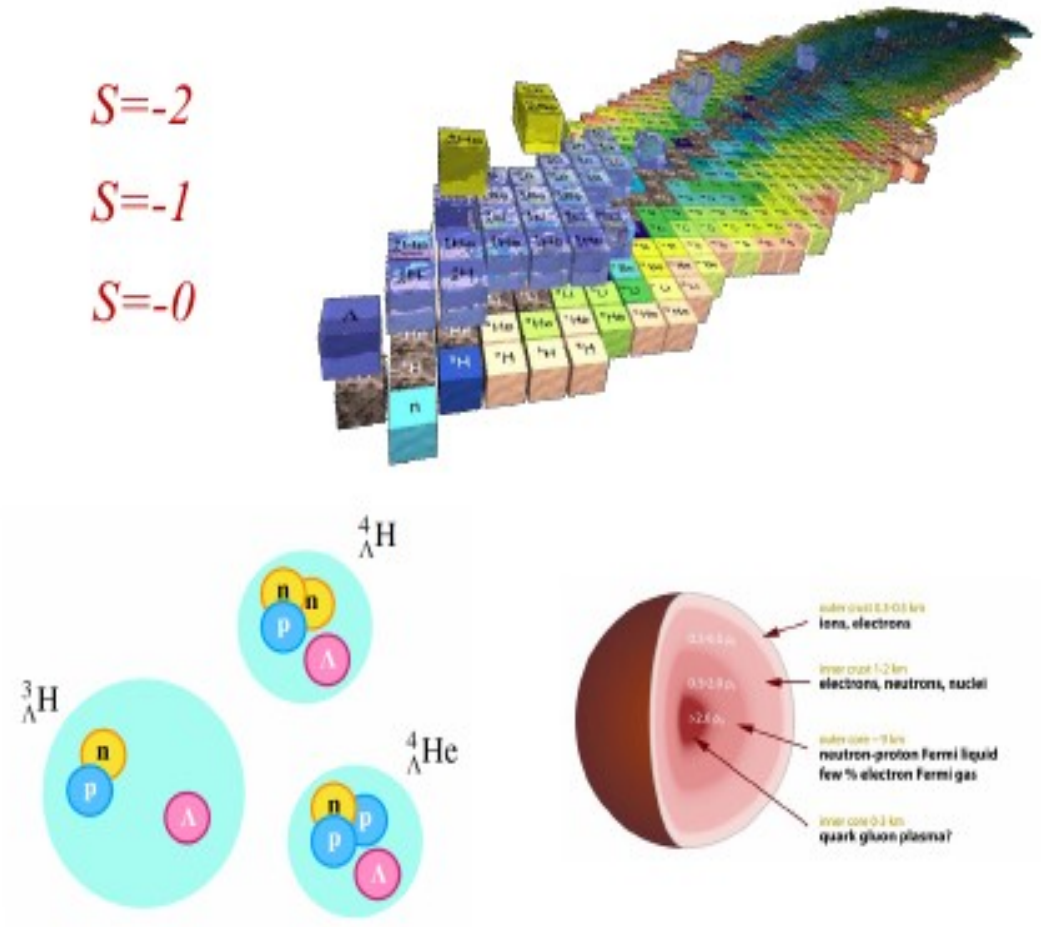


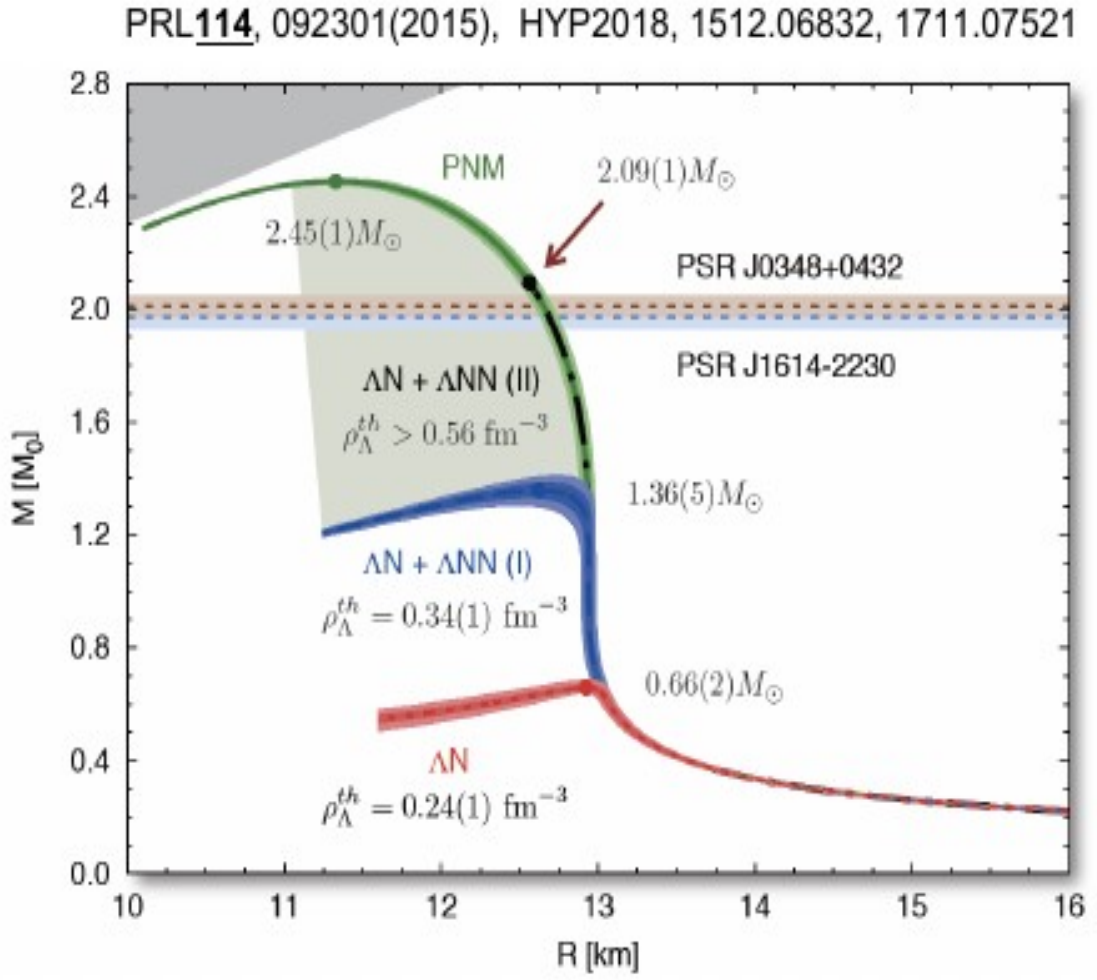
Dohi et al., Astro. Jour., 923:64, 2021

Mass-Radius relation is "unique" to the underlying EoS

- Soft EoS: low maximum mass and small radii
- Stiff EoS: high maximum mass and large radii

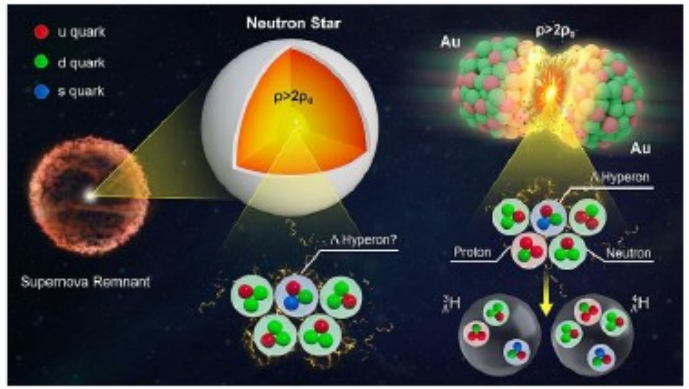
Hyperon and Hyper-Nuclei Production in Heavy-Ion Collisions and Neutron Stars





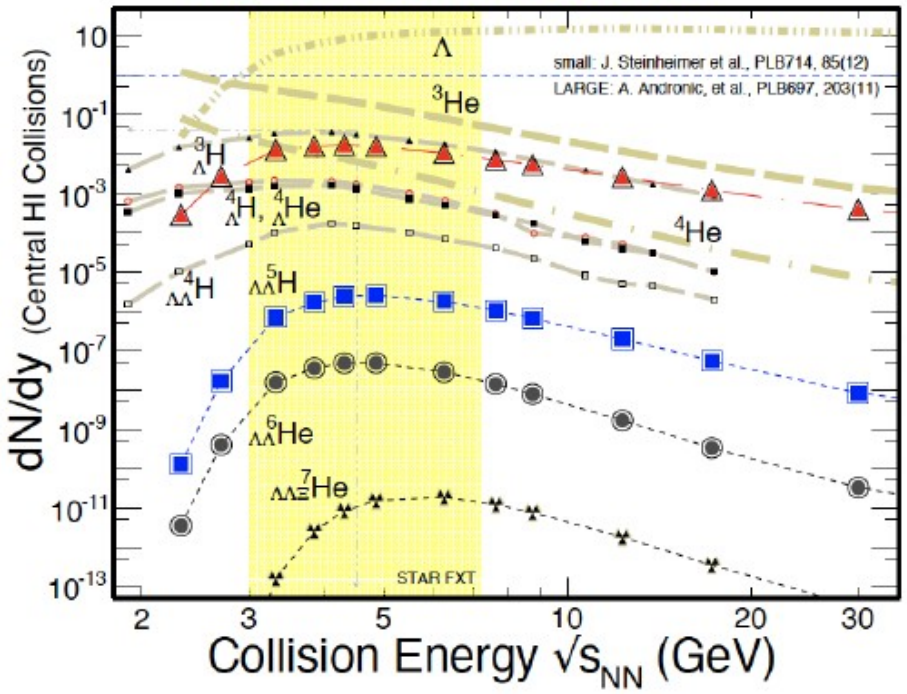
Hyperon and Hyper-Nuclei production provide access to the hyperon–nucleon interactions: NY, YNN, : key to understand the EoS at high baryon density and inner structure of neutron star.

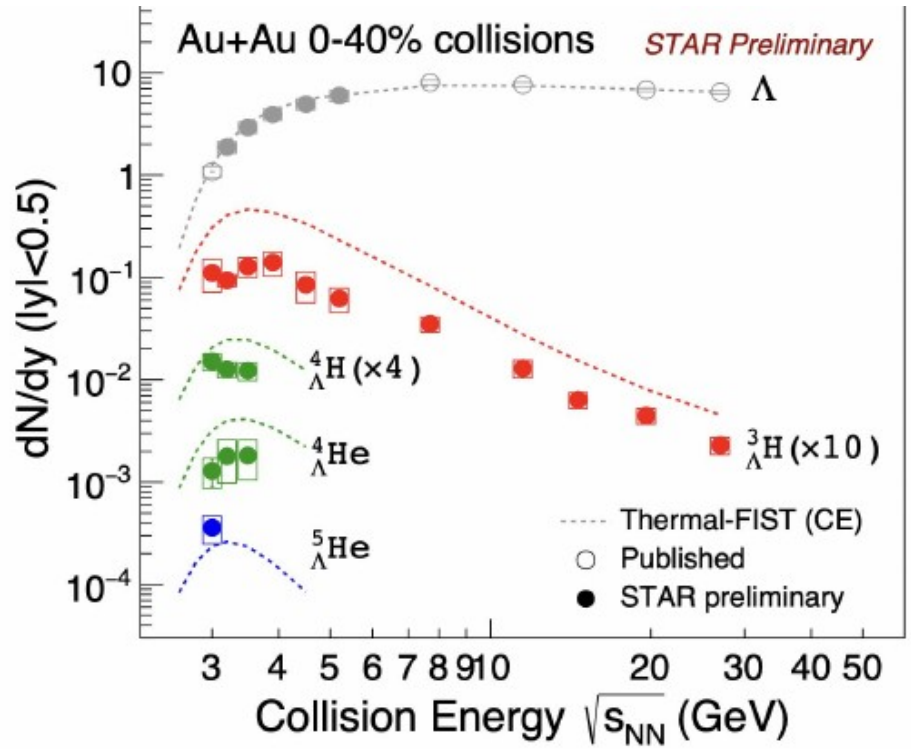
Bonus: hypernuclei production

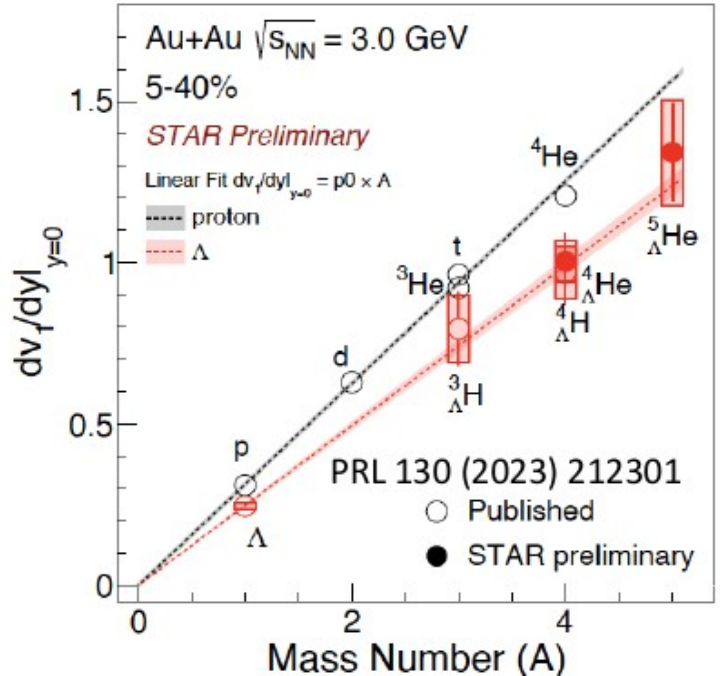


Picture credit:
BNL news article
https://www.bnl.gov/newsroom/news.php?a=121192

Hypernuclei Production





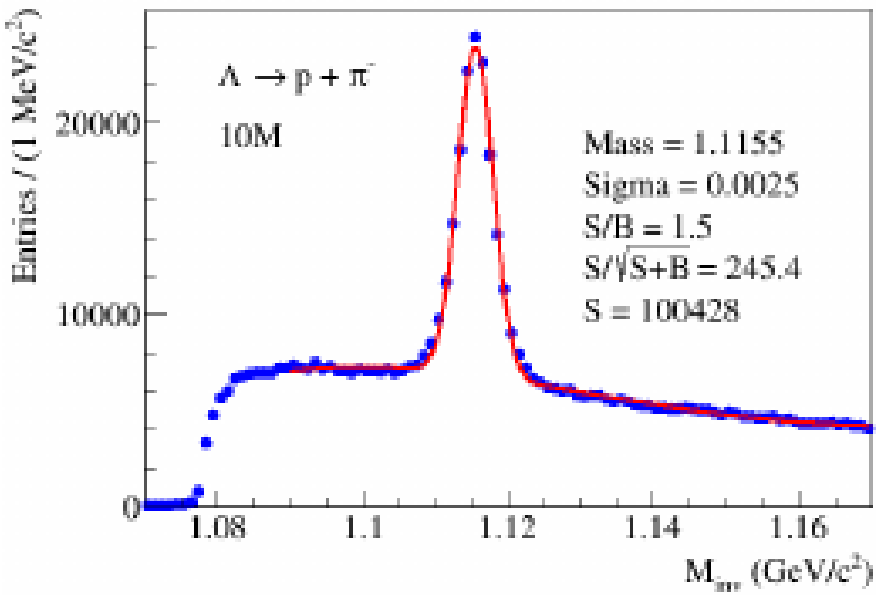


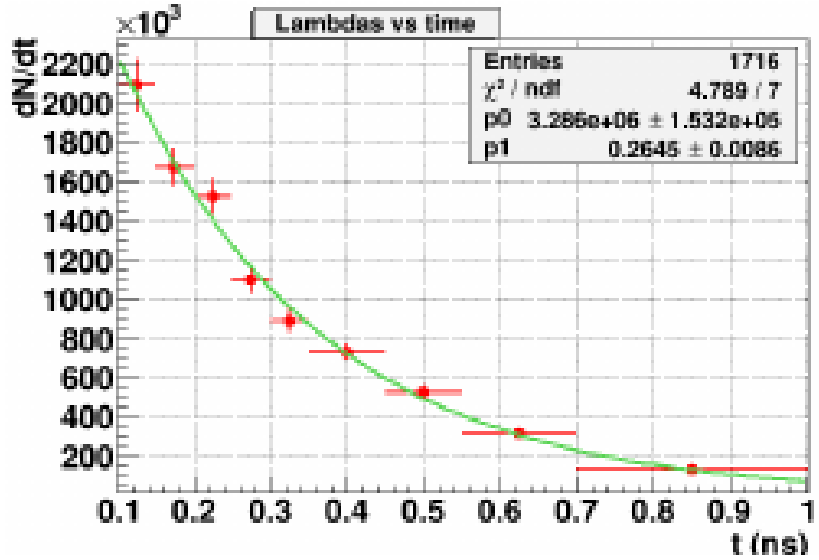
Midrapidity v_1 slopes follow baryon number scaling, implying that coalescence is the dominant production mechanism

Constrain hyperon – nucleon and hyperon-hyperon interaction

Connection to neutron stars

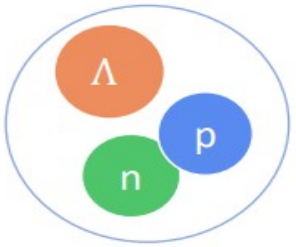
Hyperons and Hyper-Nuclei Production in Xe+Cs(I) at 3.8 AGeV (BM@N)



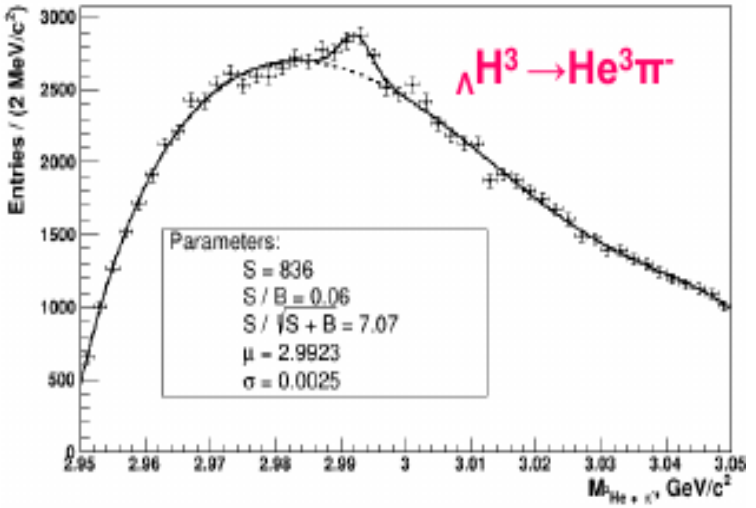




Λ

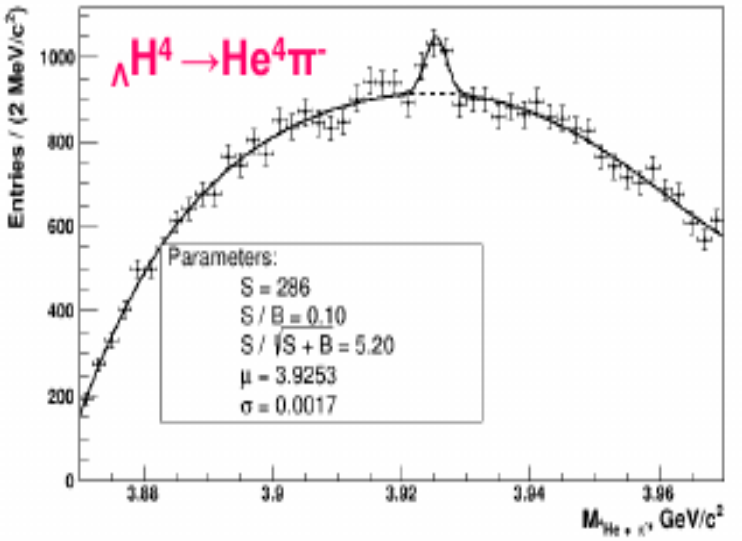


$^{3}_{\Lambda}H$



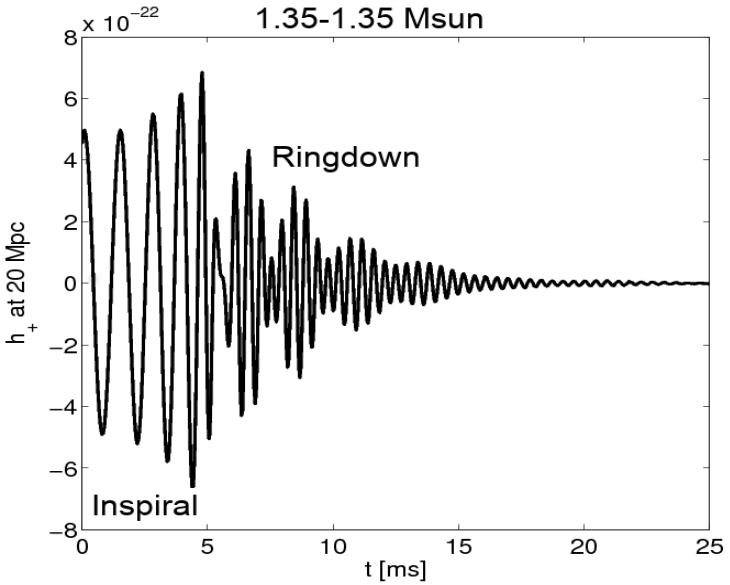


$^{4}_{\Lambda}H$



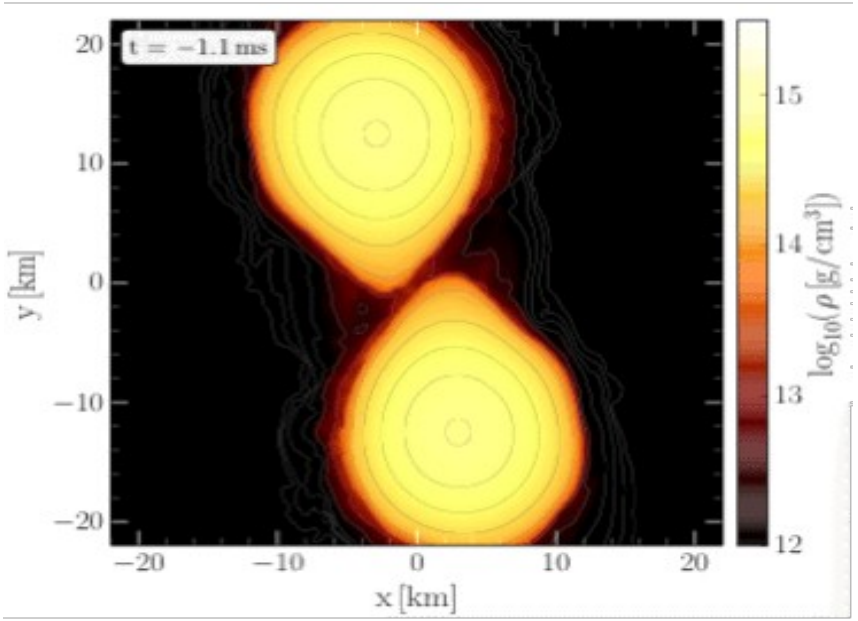
Neutron star mergers and heavy-ion collisions

Nature Phys. 15 (2019) 10, 1040-1045

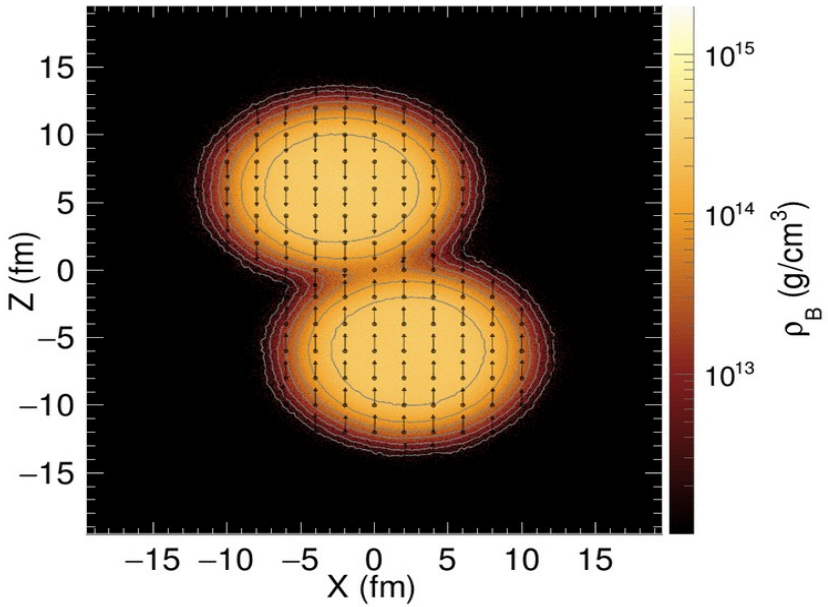


Gravitational Wave Signal

LIGO and Virgo Collaborations, Phys. Rev. Lett. 119 (2017) 16, 161101



NS mergers

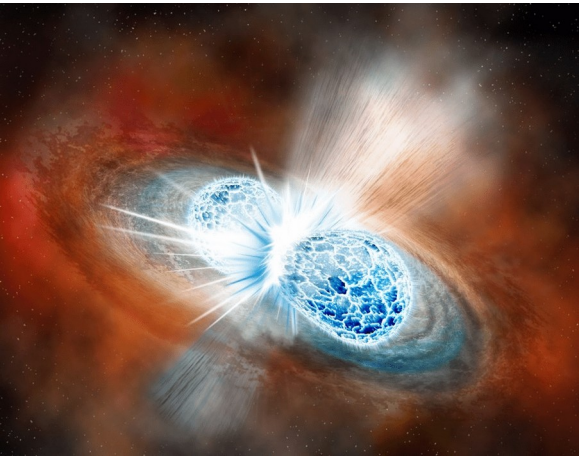


Au+Au 1.25A GeV

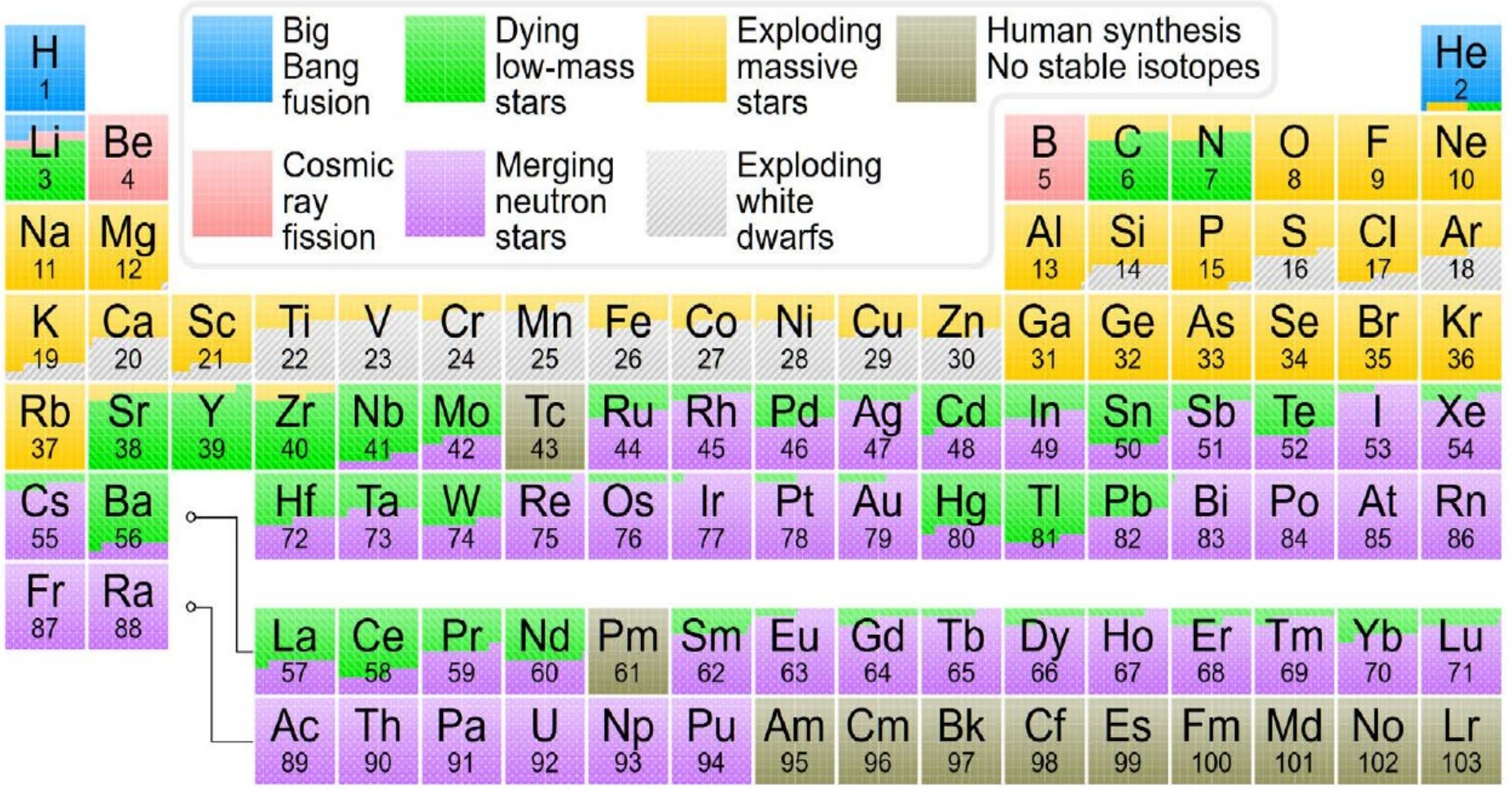
- T<70 MeV, $\rho \cong 3\rho_0$ for both
- Probe NS merger matter in the laboratory

- Confirmation by astronomical observations after gravitational wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum, and uranium.

Nuclear EoS is important also for the r-process nuclear synthesis in neutron star merger







r-process - source of heavy elements including gold, platinum, and uranium.

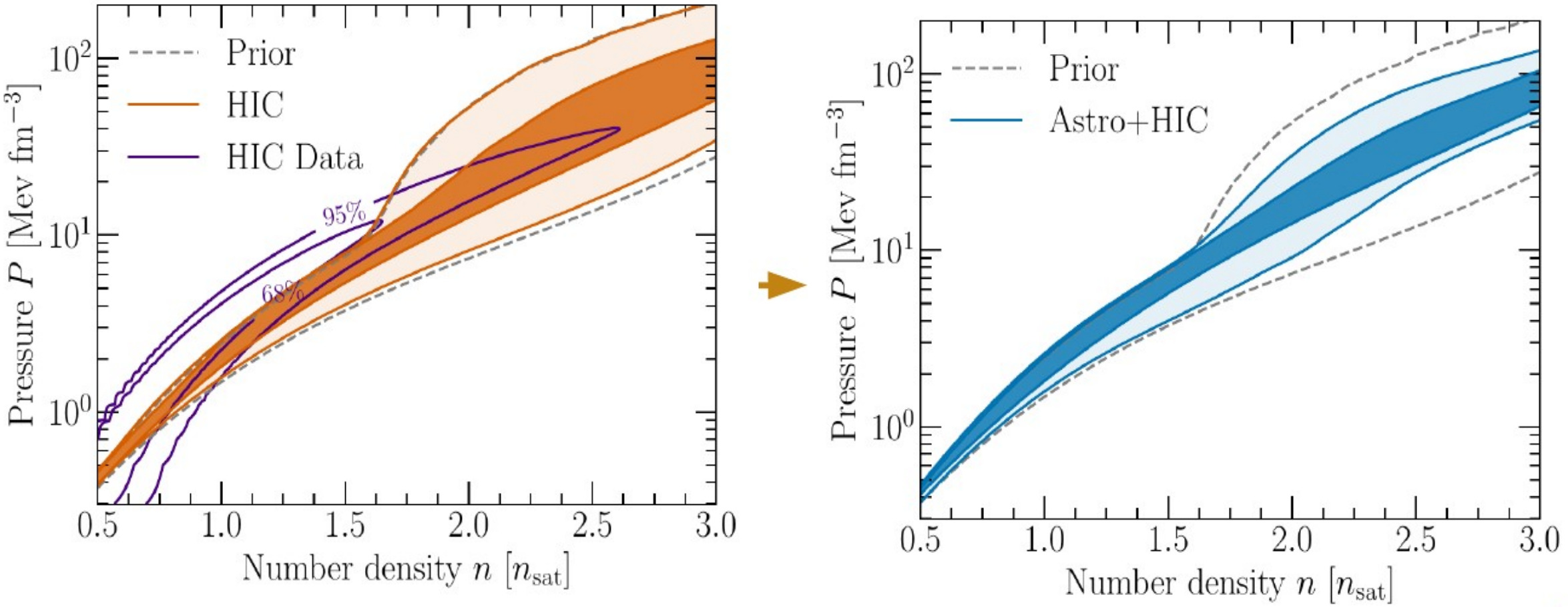
Constraining neutron-star matter with microscopic and macroscopic collisions

Huth, Pang et al. Nature 606(22)276

HIC experiments:

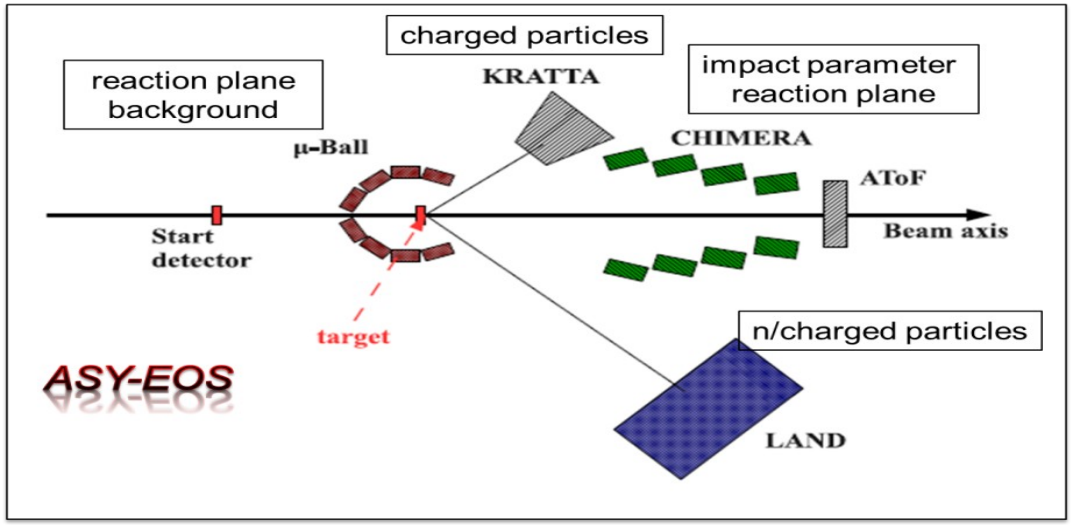
Bayesian combinations

HIC and Astro combined:



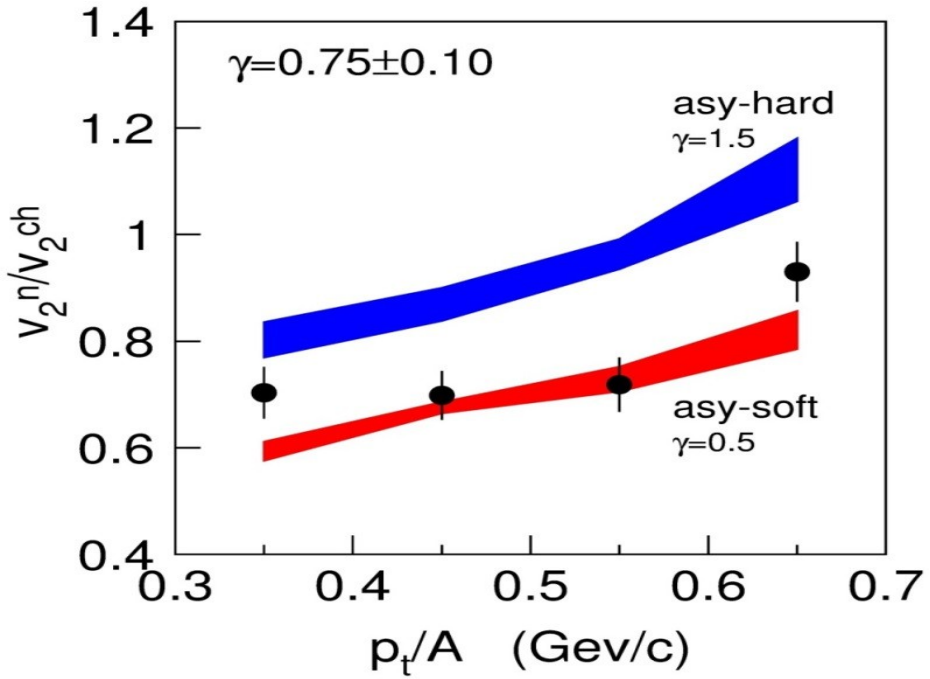
Astrophysical observations narrow constraints above 2 n_{sat}

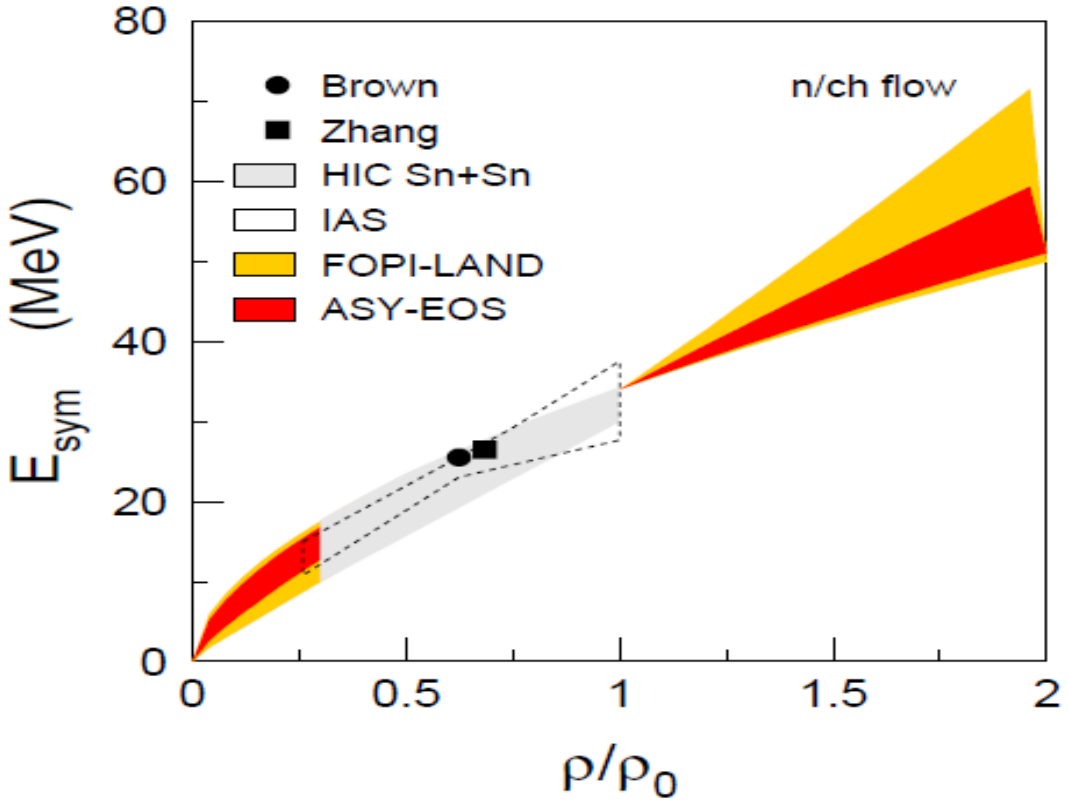
The ASY-EOS experiment at GSI:
The symmetry energy up to densities of $2\rho_0$



P. Russotto et al.,
Phys. Rev. C 94, 034608 (2016)

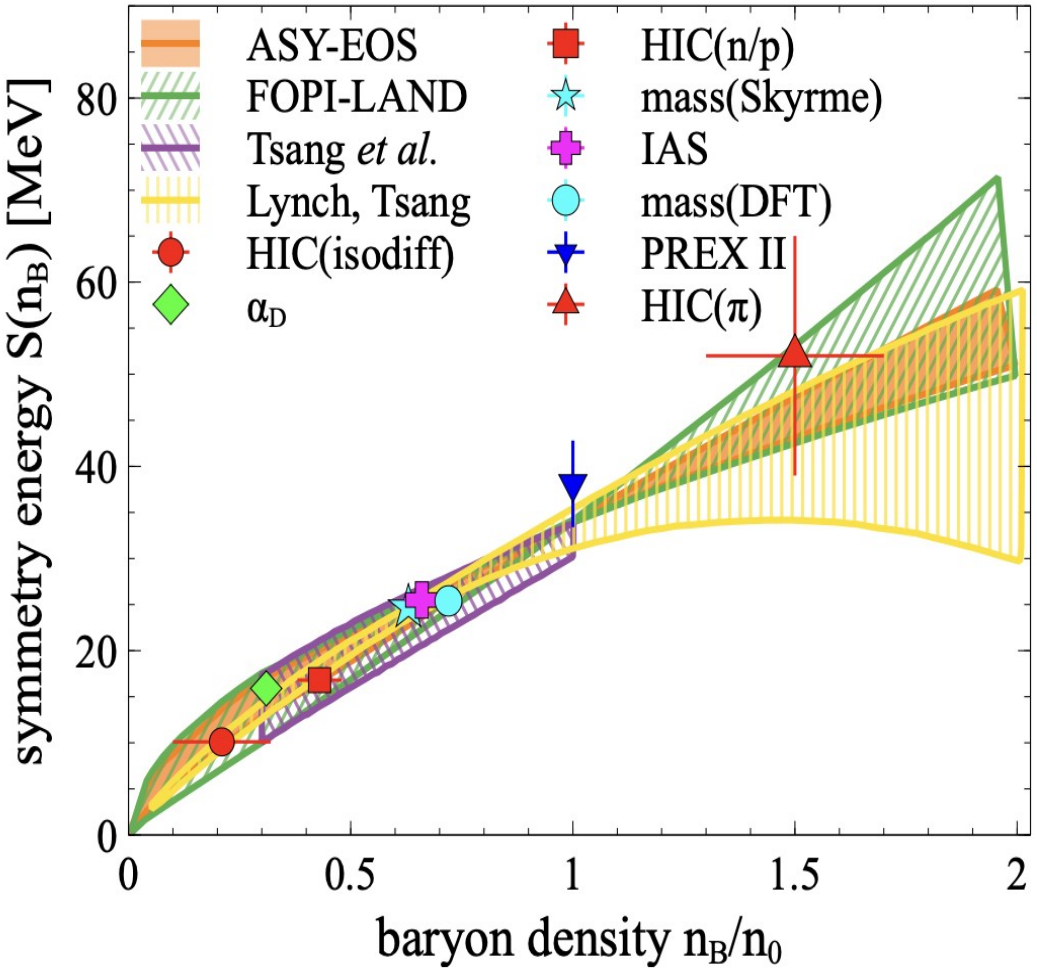
Measuring the elliptic flow of charged particles and neutrons in Au+Au collisions at 400A MeV



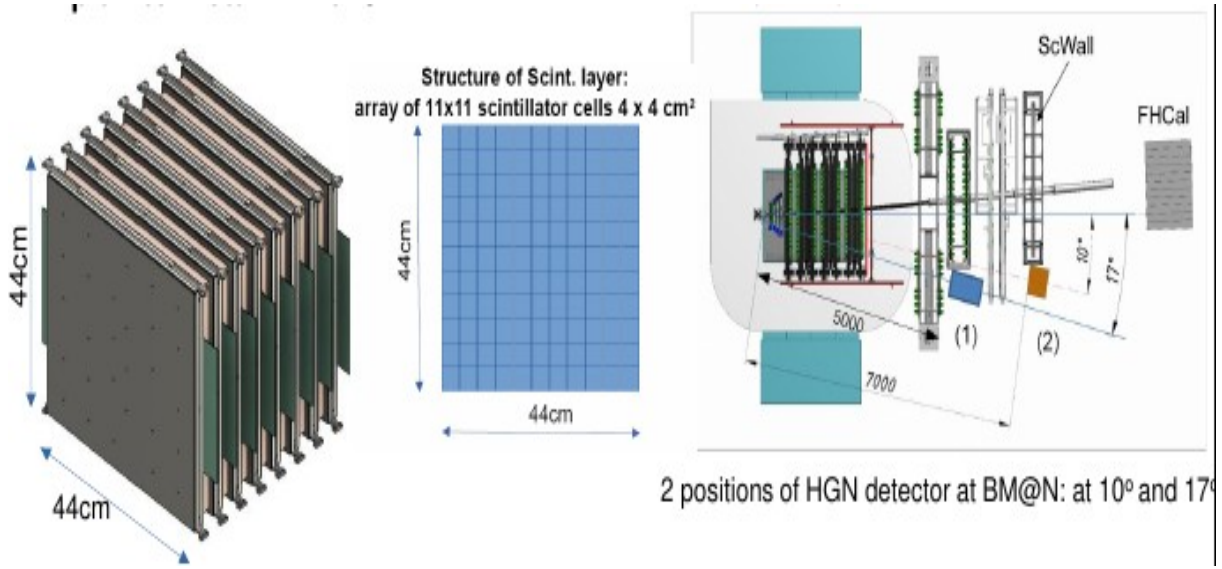


Observables to study symmetry energy (EoS)

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



BM@N Neutron Detector (2027-)

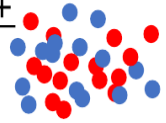


The Highly-Granular time-of-flight Neutron Detector for the BM@N experiment, Nucl. Instrum. Meth. A 1072 (2025) 170152

Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

→ lower n/p, lower π^-/π^+



Soft symmetry energy (small L)

→ larger ρ_n/ρ_p in higher dense region

→ larger n/p, higher π^-/π^+



Nuclotron-NICA density region: $2 < n_B/n_0 < 8$

Symmetry energy E_{sym} has strong density dependence

Conclusion and outlook:

Relativistic Heavy-ion collisions at Nuclotron-NICA provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

Physics at High Baryon Density

Critical point and phase boundary;
Nuclear matter EOS at high baryon density;
Y-N interactions, inner structure of compact stars.

BM@N: ~214 participants - 13 institutes, 5 countries



MPD: ~500 participants - 38 institutes, 12 countries

