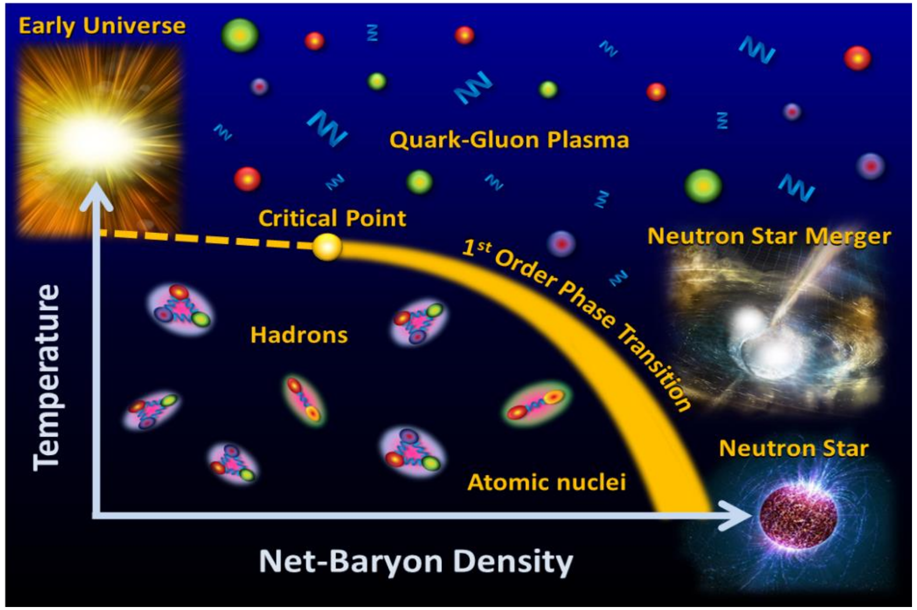
# Full-scale simulation of the MPD-NICA experimental setup and data analysis techniques


**Arkadiy Taranenko on behalf of the MPD Collaboration**

11th International Conference "Distributed Computing and Grid Technologies in Science and Education" (GRID'2025), 08/07/2025

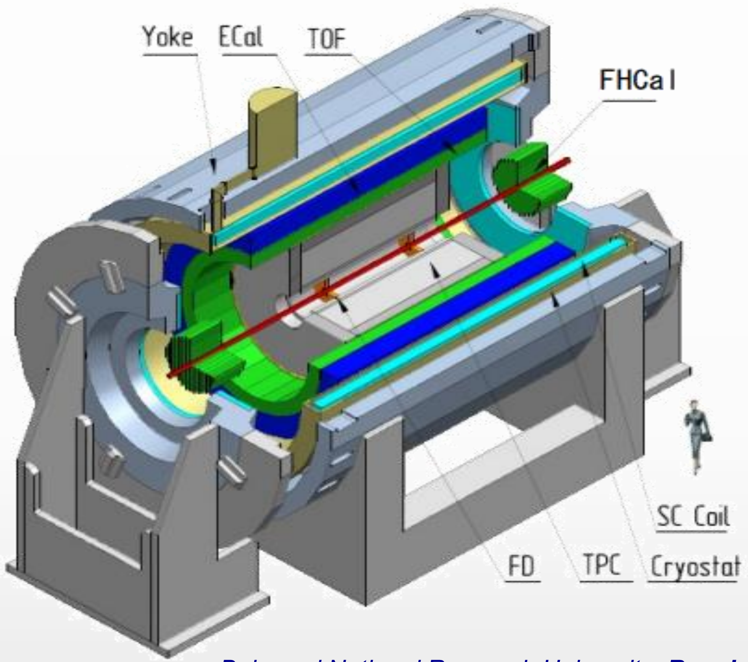
# Multi-Purpose Detector (MPD) Collaboration

*MPD International Collaboration was established in 2018 to construct, commission and operate the detector*

*12 Countries, >500 participants, 38 Institutions and JINR*

## Organization

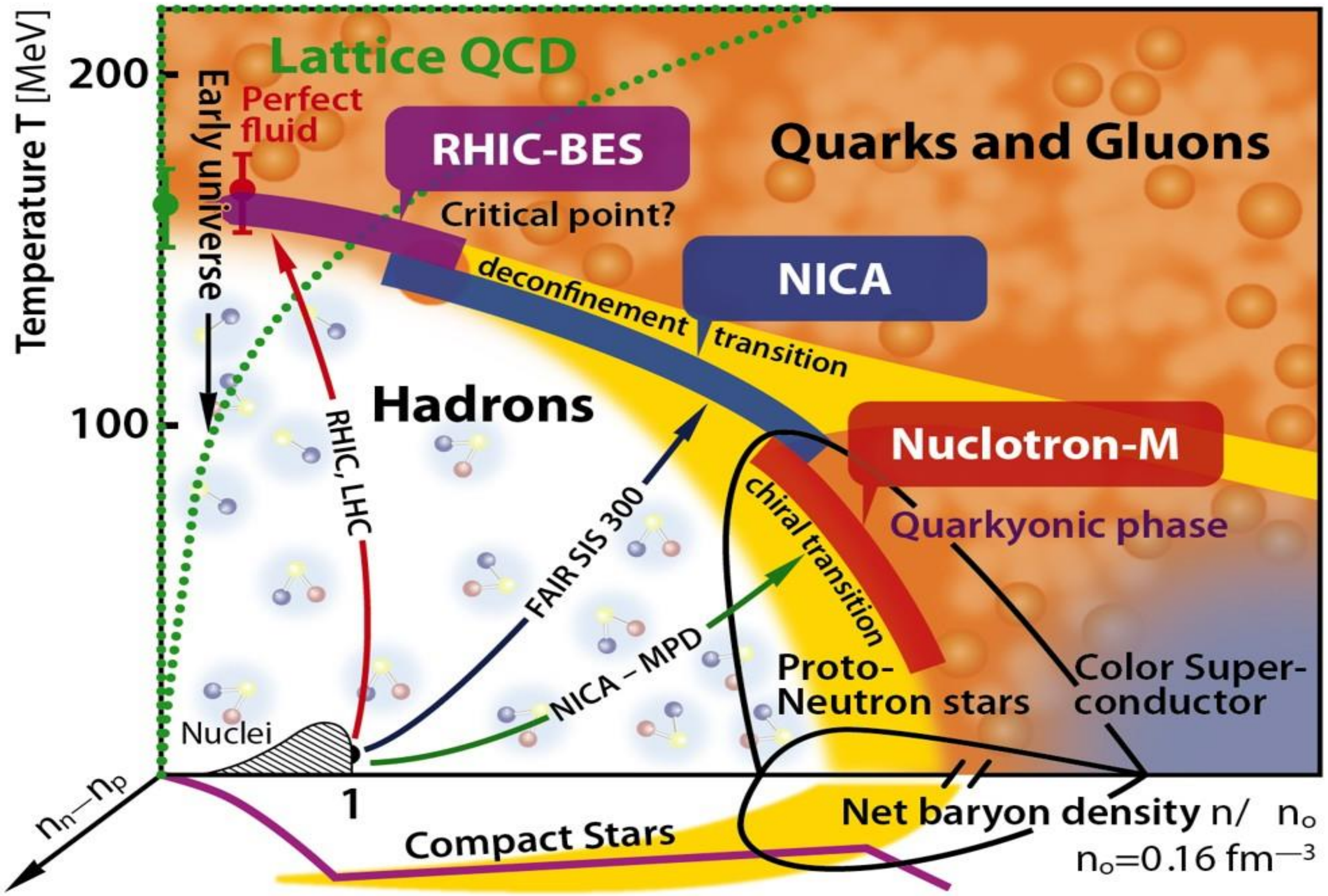
| | |
|---|---|
| *Acting Spokesperson:* | ***Victor Riabov*** |
| *Deputy Spokespersons:* | ***Zebo Tang, Arkadiy Taranenko*** |
| *Institutional Board Chair:* | ***Alejandro Ayala*** |
| *Project Manager:* | ***Slava Golovatyuk*** |

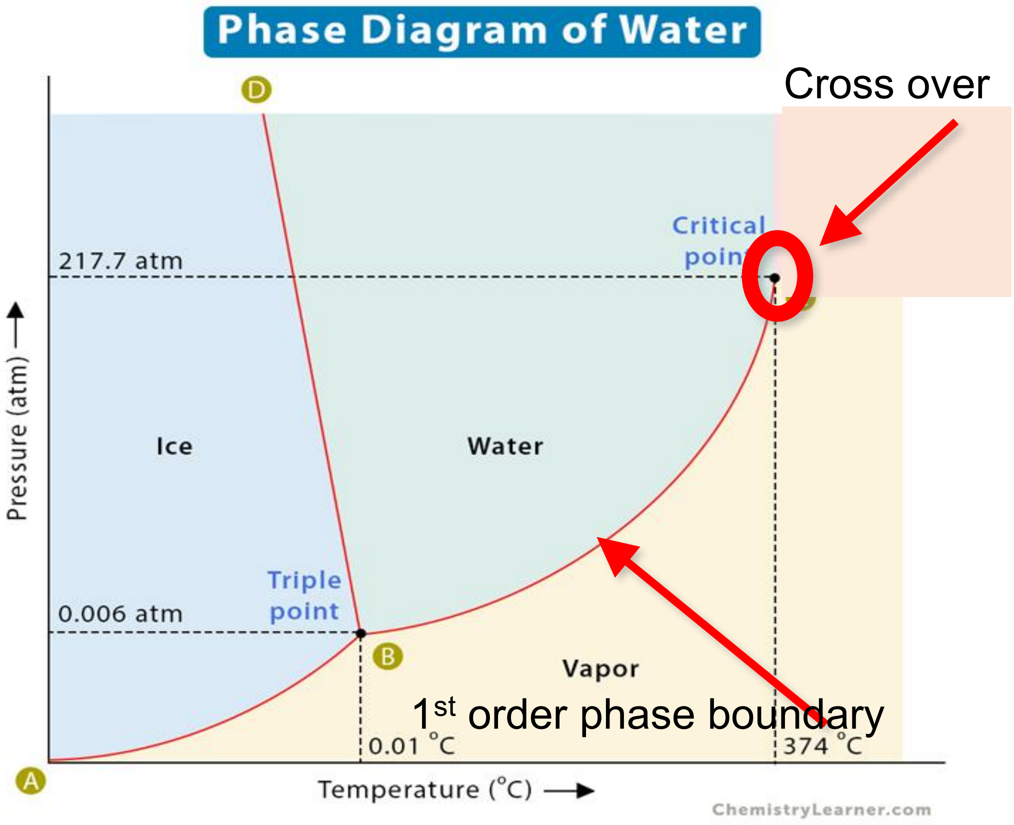



*Joint Institute for Nuclear Research;*
*A.Alikhanyan National Lab of Armenia, Yerevan, **Armenia;***
*Institute for Nuclear Problems of Belarusian State University, **Belarus**;*
*Institute of Power Engineering of the National Academy of Sciences of Belarus, **Belarus**;*
*University of Plovdiv, **Bulgaria;***
*Tsinghua University, Beijing, **China**;*
*University of Science and Technology of China, Hefei, **China**;*
*Huzhou University, Huizhou, **China**;*
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China**;*
*Central China Normal University, **China**;*
*Shandong University, Shandong, **China**;*
*University of Chinese Academy of Sciences, Beijing, **China**;*
*University of South China, **China**;*
*Three Gorges University, **China**;*
*Institute of Modern Physics of CAS, Lanzhou, **China**;*
*Egyptian Center for Theoretical Physics, **Egypt**;*
*Tbilisi State University, Tbilisi, **Georgia**;*
*Institute of Physics and Technology, Almaty, **Kazakhstan**;*
*Instituto de Ciencias Nucleares, UNAM, **Mexico**;*
*Universidad Autónoma de Sinaloa, **Mexico**;*
*Universidad Autónoma Metropolitana, **Mexico**;*
*Universidad de Colima, **Mexico**;*
*Universidad Michoacana de San Nicolás de Hidalgo, **Mexico**;*
*Institute of Physics and Technology, **Mongolia**;*

*Belgorod National Research University, **Russia**;*
*High School of Economics University, Moscow, **Russia;***
*Institute for Nuclear Research of the RAS, Moscow, **Russia**;*
*National Research Nuclear University MEPhI , Moscow, **Russia**;*
*Moscow Institute of Science and Technology, **Russia**;*
*North Ossetian State University, **Russia**;*
*National Research Center "Kurchatov Institute", **Russia**;*
*National Research Tomsk Polytechnic University, **Russia**;*
*Peter the Great St. Petersburg Polytechnic University Saint Petersburg, **Russia**;*
*Plekhanov Russian University of Economics, Moscow, **Russia**;*
*St.Petersburg State University, **Russia**;*
*Skobeltsyn Institute of Nuclear Physics, Moscow, **Russia**;*
*Petersburg Nuclear Physics Institute, Gatchina**, Russia**;*
*Vinča Institute of Nuclear Sciences**, Serbia**;*
*Pavol Jozef Šafárik University, Košice, **Slovakia***

# Relativistic Heavy-Ion Collisions and QCD Phase Diagram




| Method | $\mu_c$ (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** |

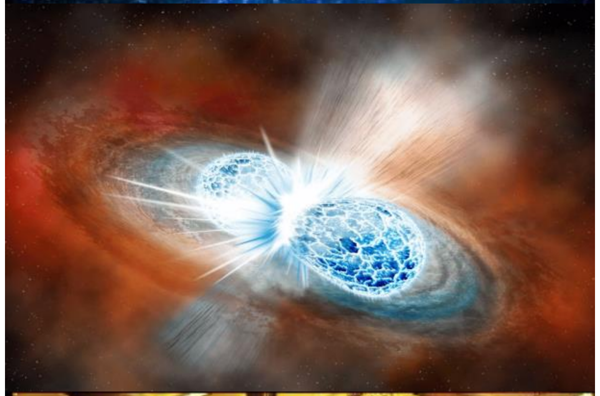
$(\mu_c, T_c)$ = (495 - 654, 100 - 119) MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

- ❖ What is the structure of the QCD phase diagram in the high baryon density region?
- ❖ How the dominant degrees of freedom in HIC change with the beam energy?
- ❖ Can the onset of the 1st order phase transition and QCD CEP be detected?

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

# Neutron Stars and Big Questions

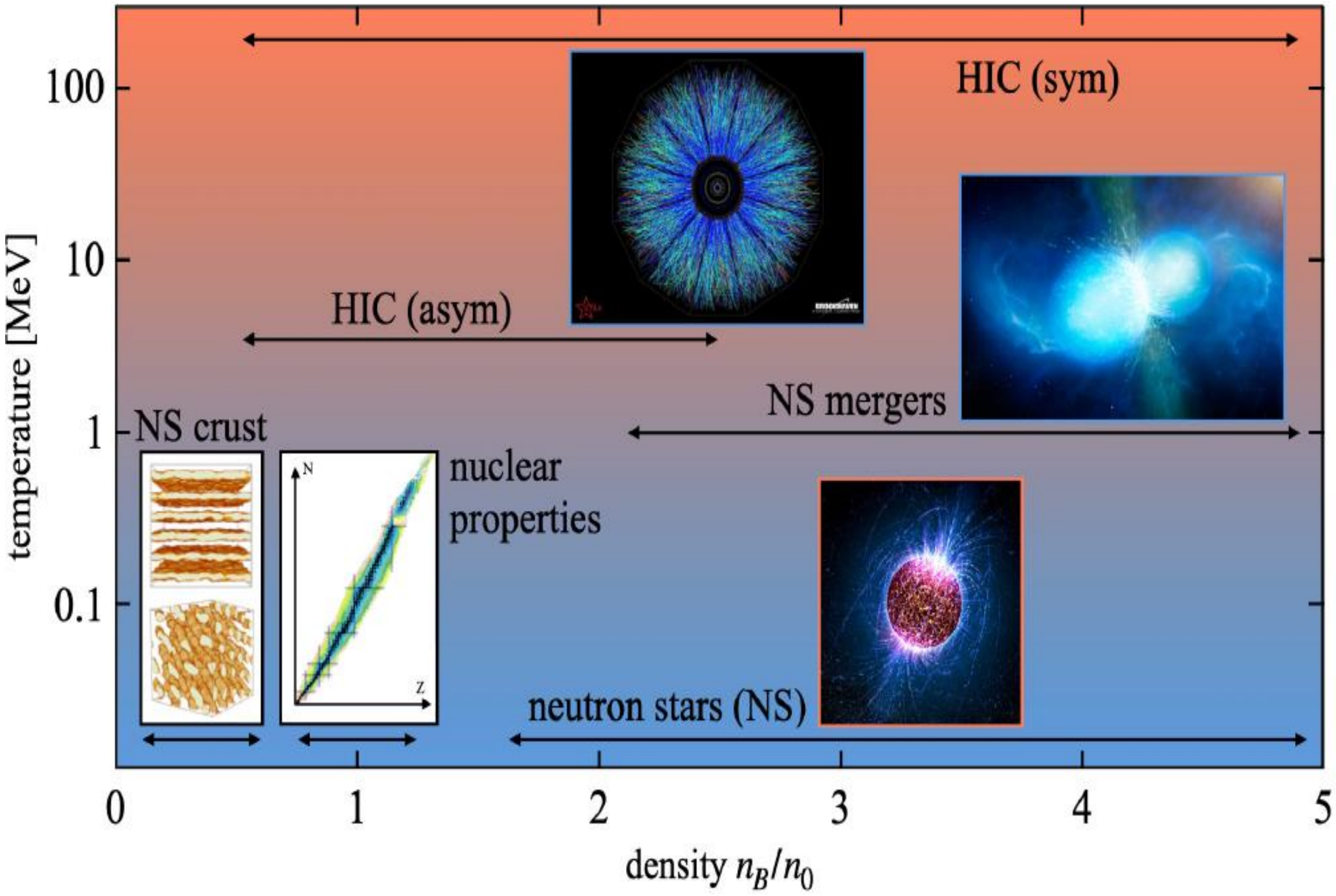
**Nature of matter at extreme density?**



**Origin of cosmic explosions?**

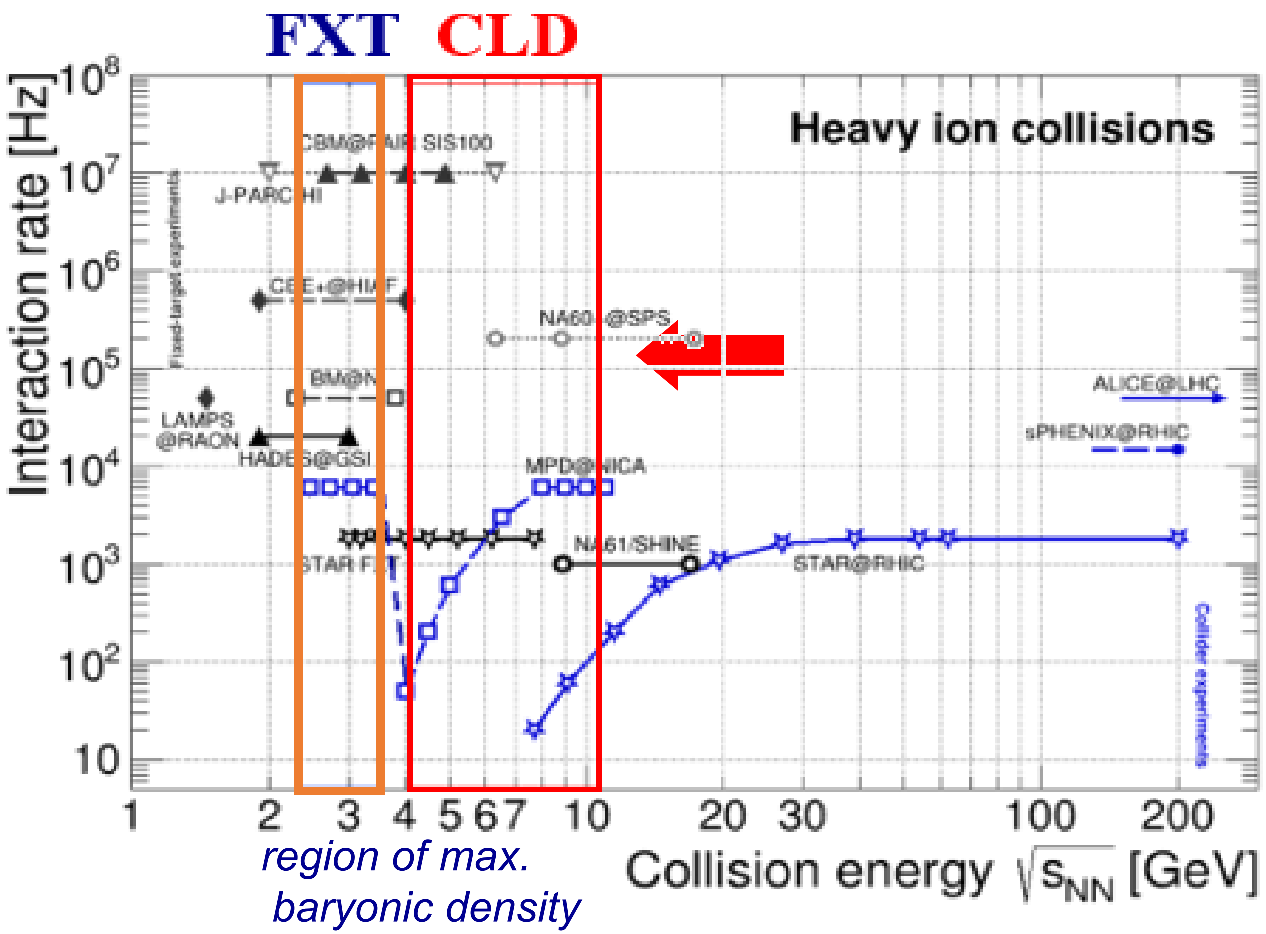
**Synthesis of heavy elements?**

# Dense Nuclear Matter




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

# Relativistic Heavy Ion Collision Experiments




MPD competitors:

<u>Present:</u>

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

<u>Future:</u>

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-?)

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

❖ **MPD-CLD and MPD-FXT from start-up (2026-):**

- ✓ Collider mode: Xe+Xe (Bi+Bi) at $\sqrt{s_{NN}} \sim 7$ GeV
- ✓ Fixed-target mode: Xe (Bi) beam + W/Au target (~ 50-100 μm wire) at $\sqrt{s_{NN}} \sim 3$ GeV :
  - extends energy range to those of (HADES, BM@N, CBM); high event rate even with low-intensity beam

# Full-scale simulation of the MPD (NICA): collider mode

Nuclear Physics Revista Mexicana de Física **71** 041201 1–45 JULY-AUGUST 2025

**MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV**

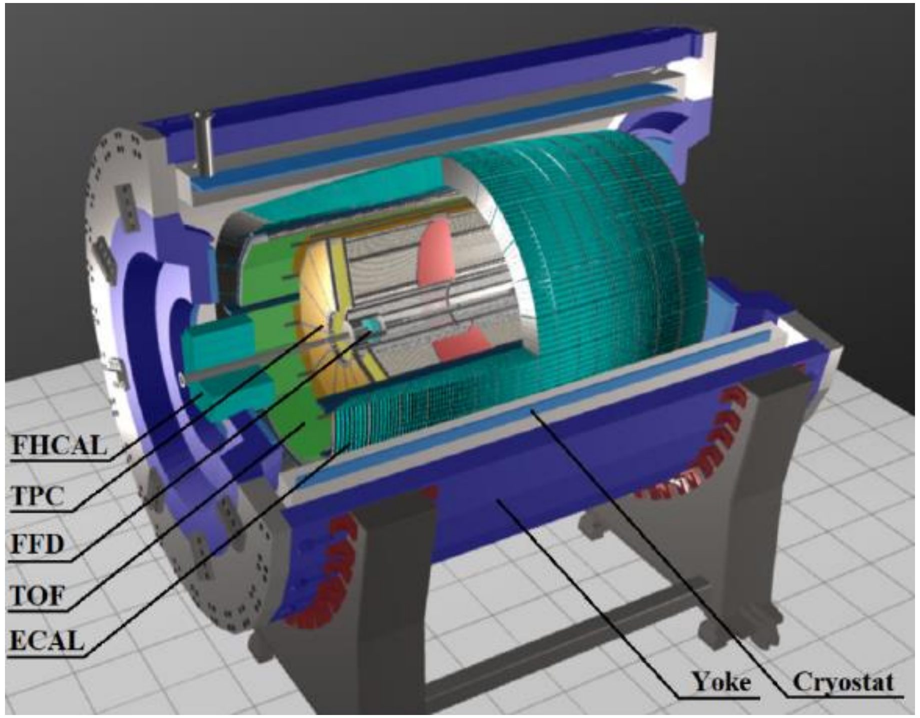
R. Abdulin[20], V. Abgaryan[1], R. Adhikary[16], K.G. Afanaciev[16,13], S.V. Afanaciev[16], G. Agakishiev[16], E.I. Alexandrov[16], I.N. Alexandrov[16], M. Alvarado-Hernández[14], D.I. Andreev[16], S.V. Andreeva[16], T.V. Andreeva[16], E.V. Andronov[28], N.V. Anfimov[16], A. Anikeev[21], A.V. Anufriev[28], A.A. Aparin[16], R. Arteche-Diaz[16], V.I. Astakhov[16], T. Aushev[23], S.P. Avdeev[16], G.S. Averichev[16], A.V. Averyanov[16],A. Ayala[14], V.N. Azorskiy[16], L. Bavichev[32], V.A. Babkin[16], P. Bakhtin[19], A.I. Balandin[16], N.A. Balashov[16], A. Baranov[10], D.A. Baranov[16], N.V. Baranova[31], R.V. Baratov[16], N. Barbashina[21], V. Barbasová[23], V.M. Baryshnikov[16], K.D. Basharina[16], A.E. Baskakov[16], V.G. Bayev[13], A.G. Bazhazhin[16], S.N. Bazylev[16], P. Beletsky[25], S.V. Belokurova[28], A.V. Belyaev[16], E.V. Belyaeva[16], D.V. Belyakov[16], Y. Berdnikov[24], F. Berezov[22], M. Bhattacharjee[16], W. Bietenholz[14], D. Blau[19], G.A Bogdanova[31], D.N. Bogoslovsky[16], I.V. Boguslavski[16], E.A. Bondar[12], E.E. Boos[31], A. Botvina[10], A. Brandin[21], S.A. Bulychjov[19], V. Burdelnaya[25], N. Burmasov[20], M.G. Buryakov[16], J. Busa Jr.[16], A.V. Butenko[16], S.G. Buzin[16], A.V. Bychkov[16], Z. Cao[35], C. Ceballos-Sánchez[16], V.V. Chalyshev[16], V.F. Chepurnov[16], Vl.V. Chepurnov[16], G.A. Cheremukhina[16], A.S. Chernyshov[31],

https://doi.org/10.31349/RevMexFis.71.041201

**( 40+ pages, 445 auhors)**

TABLE I. The list of centralized MC productions for physics feasibility studies.

| No. | Generator | Events | Purpose |
|---|---|---|---|
| 1 | UrQMD | 50 M | General purpose |
| 2 | DCM-QGSM-SMM | 1 M | Trigger |
| 3 | PHQMD | 20 M | (Hyper)nuclei |
| 4 | PHSD | 15 M | Global polarization |
| 5 | vHLLE+UrQMD | 15 M | Flow, correlations |

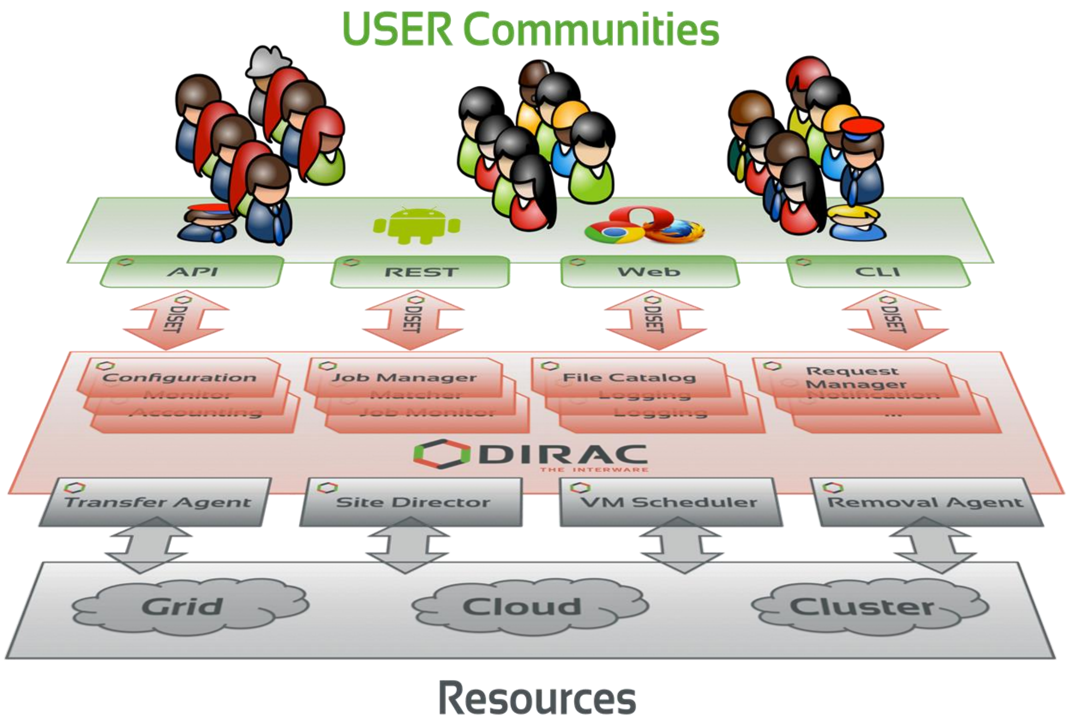



**TPC**: $|\Delta\varphi| < 2\pi$, $|\eta| \le 1.6$; **TOF, EMC**: $|\Delta\varphi| < 2\pi$, $|\eta| \le 1.4$
**FFD**: $|\Delta\varphi| < 2\pi$, $2.9 < |\eta| < 3.3$; **FHCAL**: $|\Delta\varphi| < 2\pi$, $2 < |\eta| < 5$

UrQMD → GEANT4 → Reconstruction → Flow analysis

Славомир Гнатич (JINR), July 10, 2025
Software development for MPD experiment
*https://indico.jinr.ru/event/5170/contributions/32048/*

**DIRAC** provides all the necessary components to build ad-hoc grid infrastructures **interconnecting** computing resources of different types, allowing **interoperability** and simplifying **interfaces**. This allows to speak about the DIRAC *interware*.



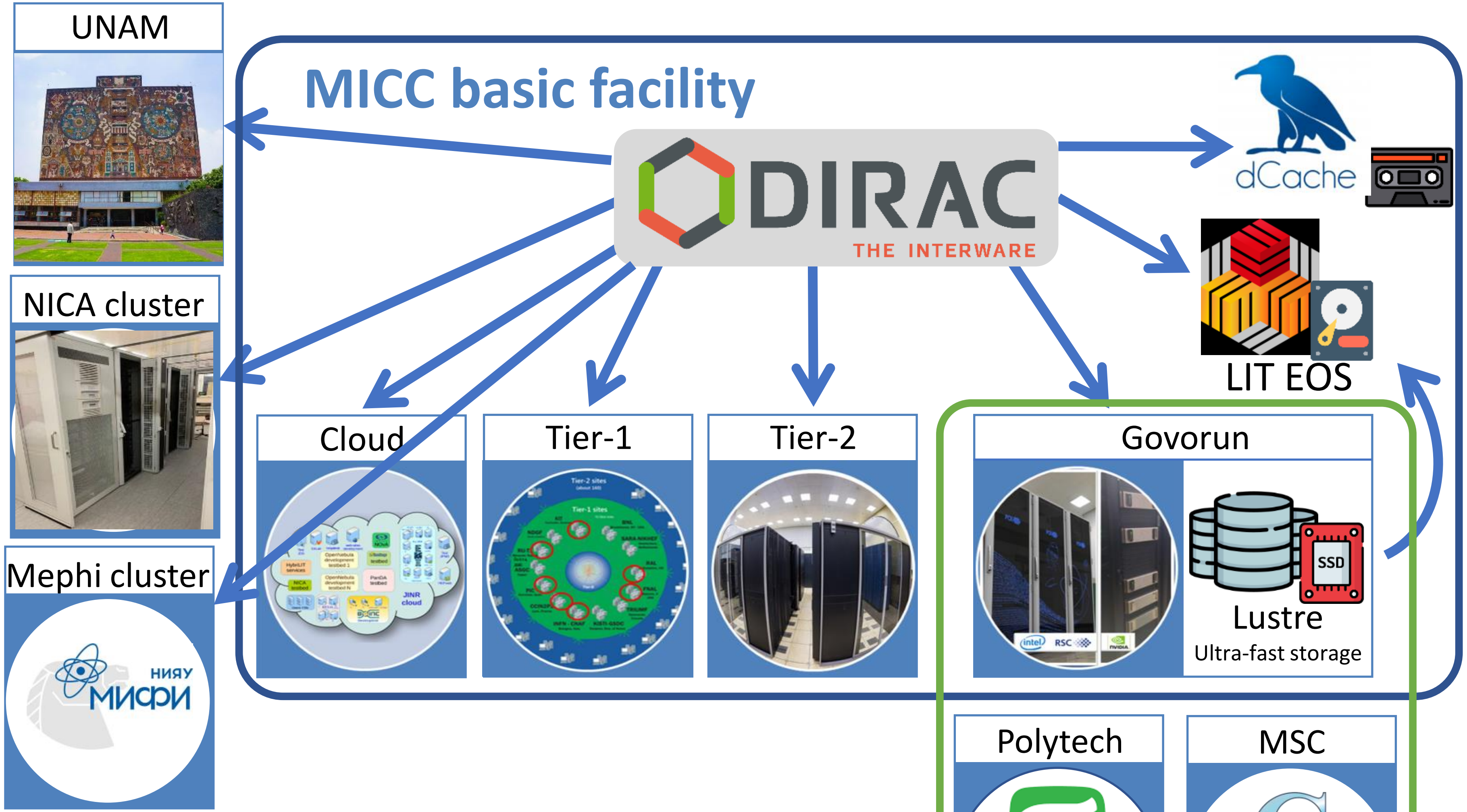

Web

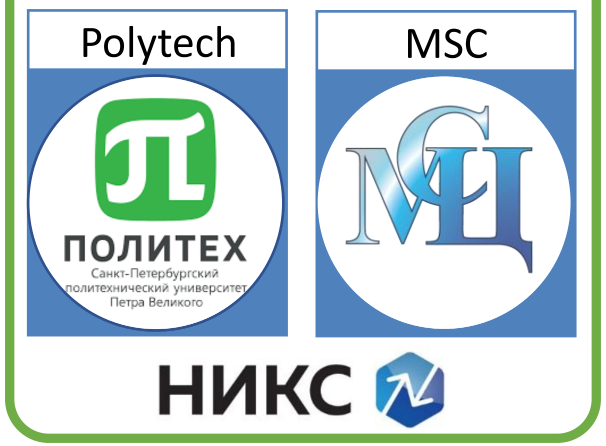
CLI

API

REST

Igor Pelevanyuk , 08/07/2025 17-00
https://indico.jinr.ru/event/5170/contributions/31763/

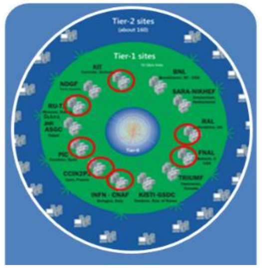



- NICA offline cluster 1000 cores(limit for users)
- GOVORUN up to 3260 cores in last production
- Tier1 1500 cores
- Tier2 1000 cores
- Clouds(JINR and JINR Member States) 70 cores
- UNAM(Mexico University) 100 cores
- National Research Computer Network of Russia (now resources from SPBTU and JSCC) 672 cores

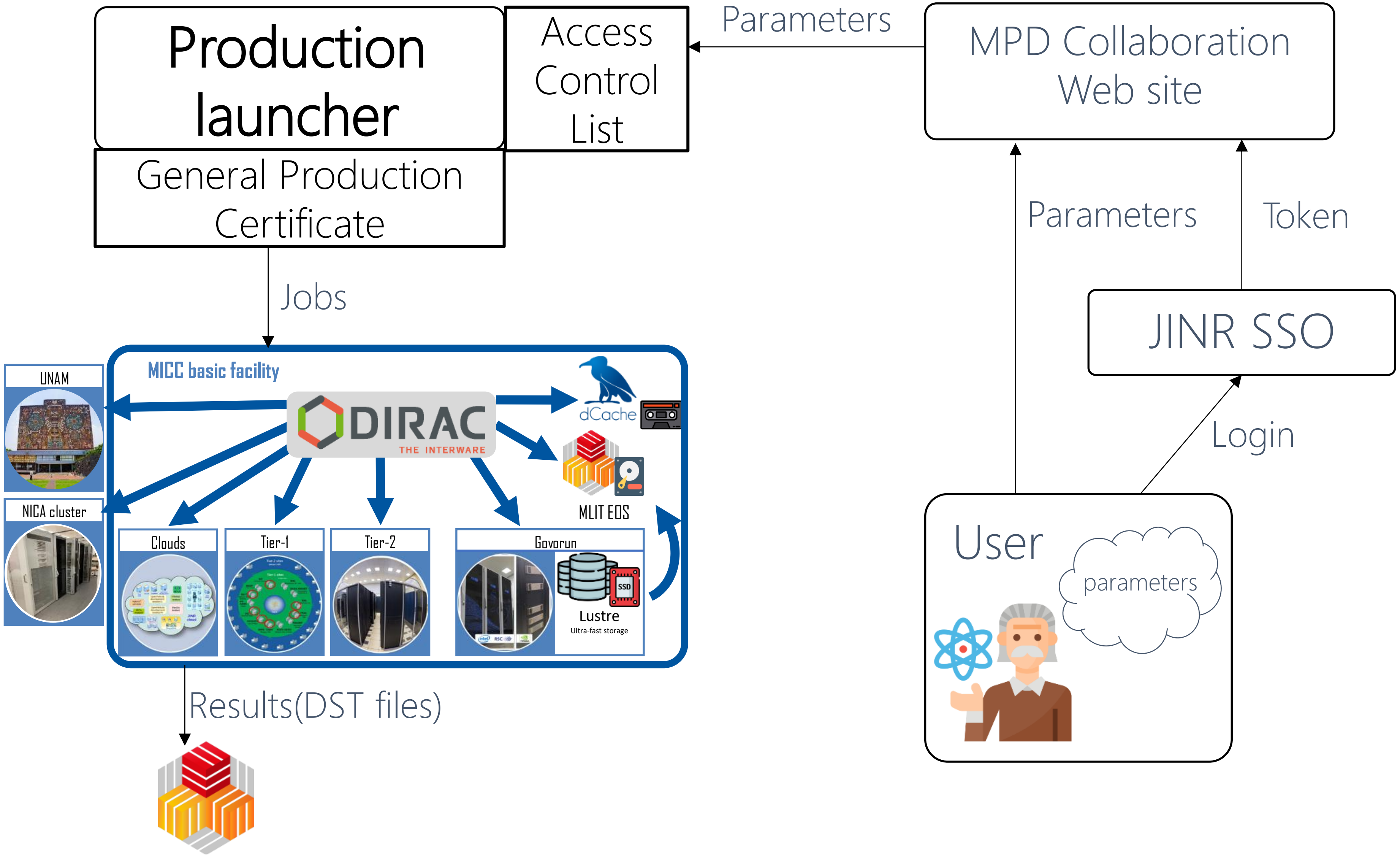
**Mass production storages integrated in Dirac File Catalog have size 9,2 PB.**

# MICC Resources

| | | | | |
|---|---|---|---|---|
| Storage | EOS | dCache Disk, Tape | ceph | lustre |
| Protocol | local, root | GridFTP, root | local | local |
| Auth Storage | Kerb. , x509 | x509 | ceph key | *HybriLIT* |
| Auth Jobs | x509 | x509 | SSO | *HybriLIT* |
| Job Submit. | Grid | Grid | OpenNebula | Slurm |
| Component |  |  |  |  |
| | **Tier-2/CICC** | **Tier-1** | **Cloud** | **Govorun/HybriLIT** |

Mescheryakov Laboratory of Information Technologies take active participation in MPD collaboration works. We are grateful for providing computing resources, development and support of IT services.

# MPD mass production launcher



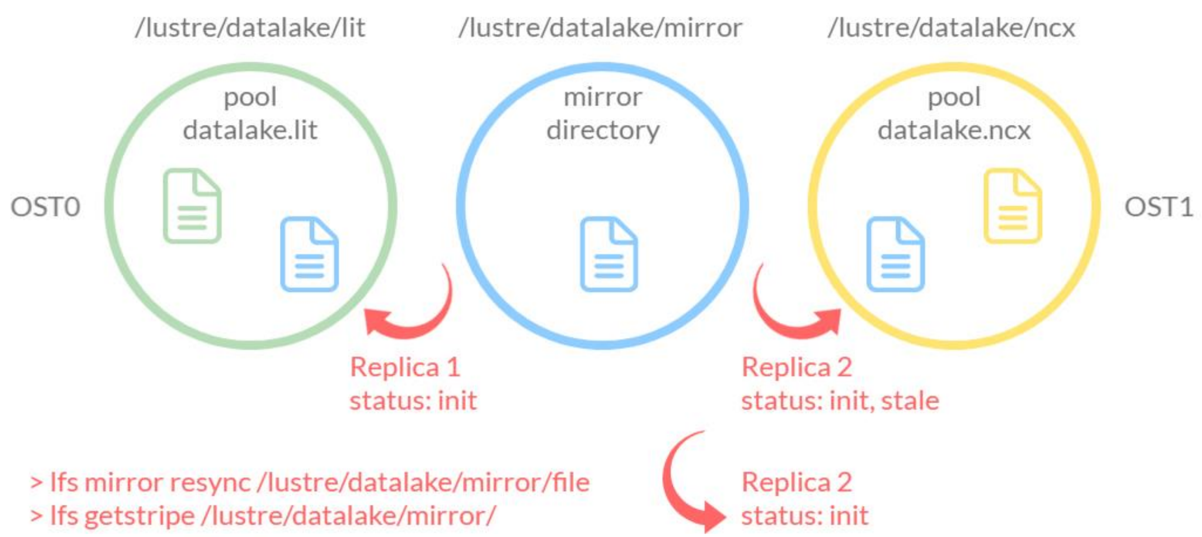

Igor Pelevanyuk (LIT)

EOS

# Distributed system for processing and data storage for experiments at the Complex NICA

**MLIT Team**

Belyakov D.V.,
Dolbilov A.G.,
Kokorev A.A.,
Lyubimova M.A.,
Pelevanuk I.S.,
Podgainy D.V.




**LHEP Team**

Moshkin A.A.,
Rogachevsky O.V.,
Slepov I.P.

MLIT servers

2x
Dell PowerEdge R730xd

2x 160 TB, SAS

| | |
|---|---|
| Motherboard | PowerEdge R730/R730xd System Board |
| Processor | 2x Intel Xeon E5-2660 v4 @ 2.00 GHz |
| Memory | 8x Micron DDR4 2400 MHz, 16 GB (128 GB) |
| RAID | Dell PERC H730P |
| Disk | 2x Dell MFC6G (Samsung) SSD SAS, 400 GB (2x 400 GB) |
| | 16x HGST UltraStar HE10 SAS, 10TB (160 TB) |
| Network | Dell 99GTM (Intel X540-T2 2x 10 Gb/s + Intel I350 Dual Port 2x 1 Gb/s) |
| Power | 2x 750W Redundant Power Supply |

**Data flow rates**
**100 Gbps**

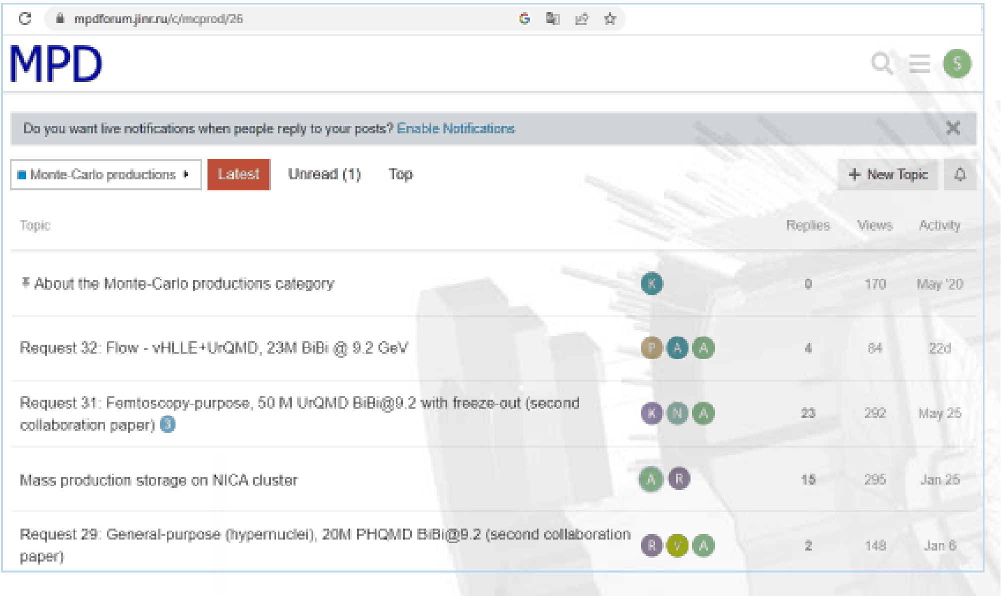
LHEP servers

2x
Supermicro SSG 1029P-NEL32R

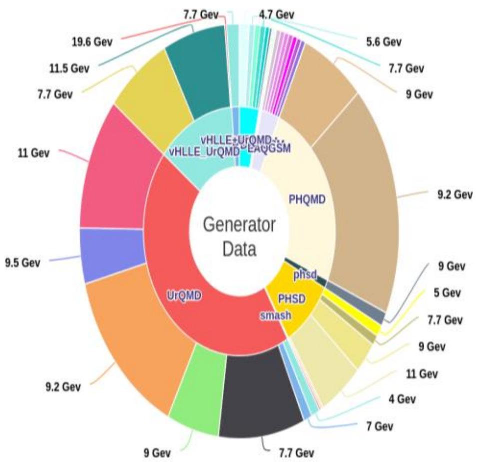
2x 244.8 TB, NVMe (Rulers)

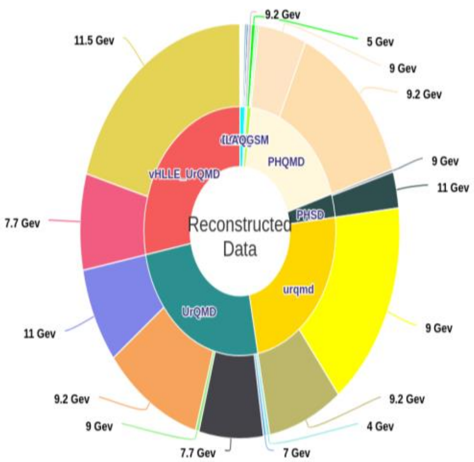
| | |
|---|---|
| Motherboard | Supermicro X11DPS-RE |
| Processor | 2x Intel Xeon Gold 6230R @ 2.10 GHz |
| Memory | 12x Samsung DDR4 2993 MHz, 64 GB (768 GB) |
| Disk | 2x Apacer SSD NVME m.2 , 512 GB (2x 512 GB) |
| | 16x Intel DC P4510 SSD NVME (Ruler), 15.3TB (244.8 TB) |
| Network | Intel X550-T Dual Port 2x |
| | NVidia (Mellanox MT27800) ConnectX-5 Dual Port 2x 100 Gb/s Ethernet |
| Power | 2x 1600W Redundant Power Supply |

Distributed high-speed buffers (about 200 megabits per second) for the data transfer between two sites of LIT and LHEP, on the NICA cluster and the Govorun supercomputer  have been created ( based on the lustre file system) , after fine-tuning for the user it will look like a single buffer with high access speed, and a single mounting path on all JINR clusters, which will be convenient for processing data from MPD on different JINR clusters as on one cluster.




http://db-nica.jinr.ru/mpdmc/stat.php




| Generator | PWG | Coll. | $\sqrt{s}$ | # of events( $10^6$ ) | Reco |
|---|---|---|---|---|---|
| UrQMD | PWG4 | AuAu | 11 | 15 | + |
| | | BiBi | 9 | 10 | + |
| | | | 9.46 | 10 | + |
| | | | 9.2 | 135 | + |
| | PWG2 | AuAu | 11 | 10 | + |
| | PWG3 | AuAu | 7.7 | 10 | + |
| | | BiBi | 7.7 | 10 | + |
| | | | 9 | 15 | + |
| | | pp | 9 | 10 | + |
| | | BiBi fix target | 2.5 | 12 | + |
| | | BiBi fix target | 3.0 | 12 | + |
| | | BiBi fix target | 3.5 | 12 | + |
| | | XeW fix target | 2.5 | 15 | + |
| | | XeXe fix target | 2.5 | 15 | + |
| | PWG1 | BiBi | 9.2 | 76 | + |
| DCM-SMM | PWG1 | BiBi | 9.2 | 2 | + |
| PHQMD | PWG2 | BiBi | 8.8 | 15 | + |
| | | | 9.2 | 61 | + |
| | | | 2.4/3.0/4.5 | 10/10/2 | - |
| vHLLE-UrQMD | PWG3 | BiBi | 11.5 | 15 | + |
| | | AuAu | 11.5 | 15 | + |
| | | AuAu | 7.7 | 20 | + |
| | | BiBi | 9.2 | 48 | + |
| Smash | PWG1 | BiBi | 9.46 | 10 | + |
| | | ArAr | 4/7/9/11 | 20/20/20/20 | - |
| | | AuAu | 4/7/9/11 | 20/20/20/22 | - |
| | | XeXe | 4/7/9/11 | 20/20/20/20 | - |
| | | CC | 4/7/9/11 | 20/20/20/20 | - |
| | | pp | 4/7/9/11 | 50/50/50/50 | - |
| JAM | PWG3 | AuAu | 3/3.3/3.5/3.8/4.0/4.2/4.5/5 | 40/40/40/40/40/40/40 | |
| DCM-QGSM-SMM | PWG3 | AuAu | 4/9.2 | 5/5 | + |
| | | AgAg | 4/9.2 | 5/5 | + |
| | | BiBi | 4/9.2 | 5/6 | + |
| PHSD | | BiBi | 9/9.2 | 25 | + |
| Total | | | | 1453 | 609 |

Total amount of generated data is around 1.8 PB, 39 mass productions have been done.

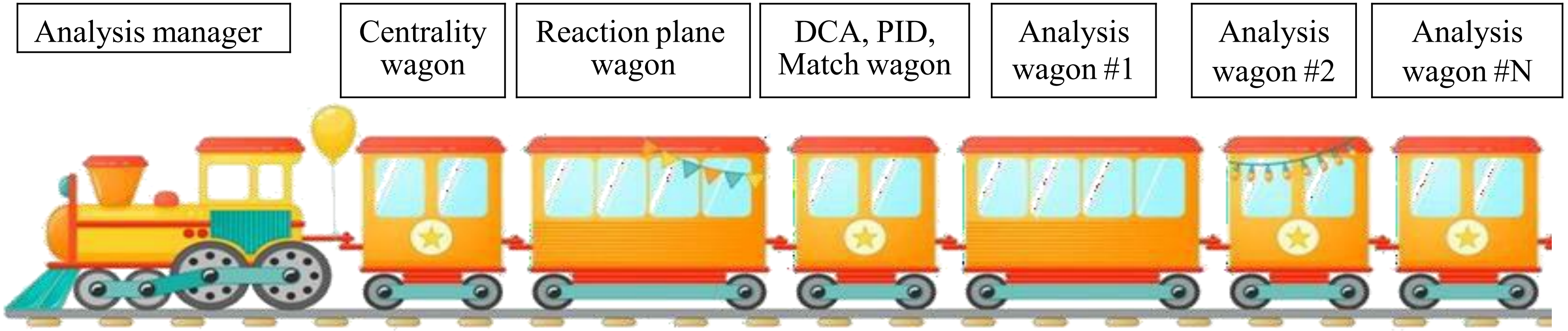
# Handling the big data sets

❖ Centralized Analysis Framework for access and analysis of data:

✓ consistent approaches and results across collaboration, easier storage and sharing of codes and methods

✓ reduced number of input/output operations for disks and databases, easier data storage on tapes

❖ Analysis manager reads event into memory and calls wagons one-by-one to modify and/or analyze data:




❖ 12 productions of physical analysis of simulated data already done.

- Example:
- Wagon #1 – event selector – selects events to be analyzed
- Wagon #2 – centrality analyzer – returns values of centrality for all other wagons in the train
- Wagon #3 – recalibrator – redefines some DST variables that need recalibration after production
- ………………………
- Wagon #4, 5, … – physics analysis 1, 2, …

# MPD physics program

G. Feofilov, P. Parfenov

**Global observables**

- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section measurement
- Event plane measurement at all rapidities
- Spectator measurement

V. Kireev, Xianglei Zhu

**Spectra of light flavor and hypernuclei**

- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diag.

K. Mikhailov, A. Taranenko

**Correlations and Fluctuations**

- Collective flow for hadrons
- Vorticity, $\Lambda$ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward corr.
- Jet-like correlations

D. Peresunko, Chi Yang

**Electromagnetic probes**

- Electromagnetic calorimeter meas.
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

Wangmei Zha, A. Zinchenko

**Heavy flavor**

- Study of open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

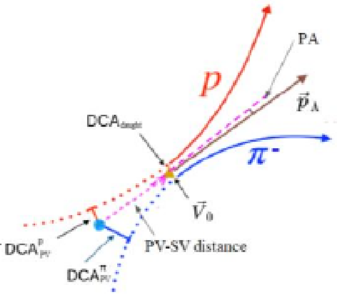
❖ Cross-PWG format of meetings for discussion of results and analysis techniques



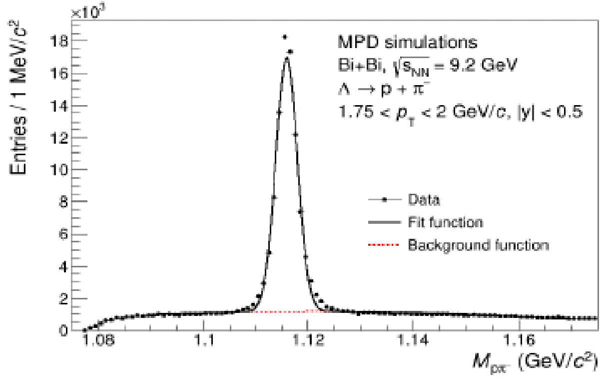
14

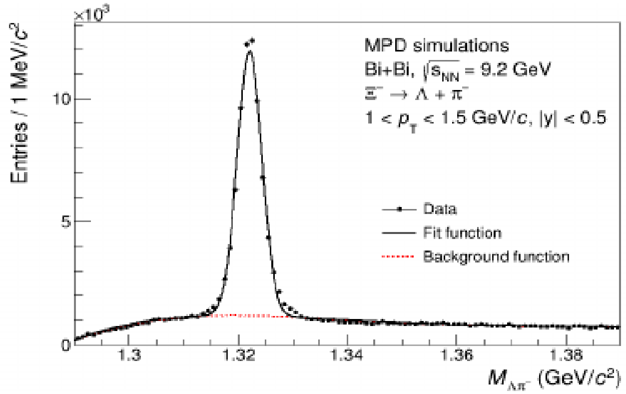
# MPD feasibility study: (multi)strange baryons

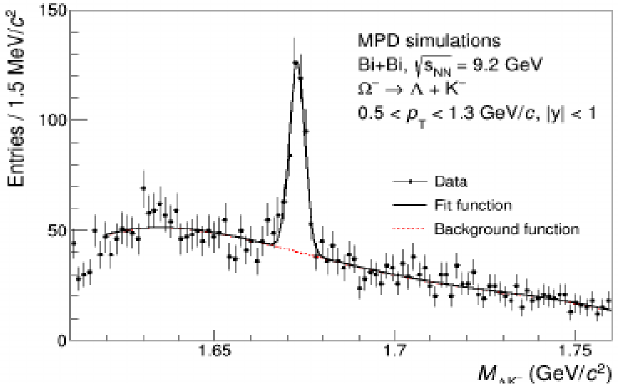
- Secondary vertex reconstruction (topology selections) in the TPC and PID for daughters

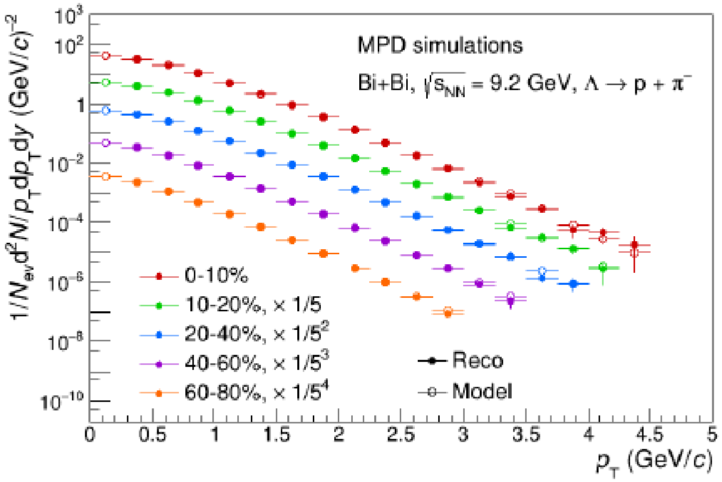


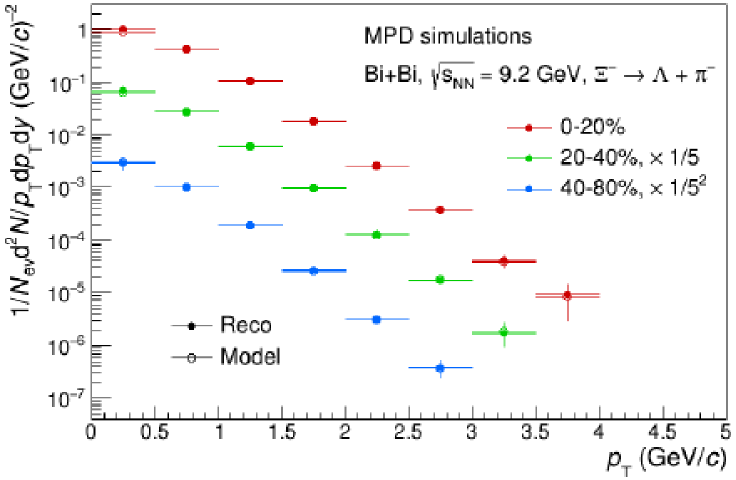

Rev. Mex. Fís., vol. 71, no. 4, pp.1–45,2025.

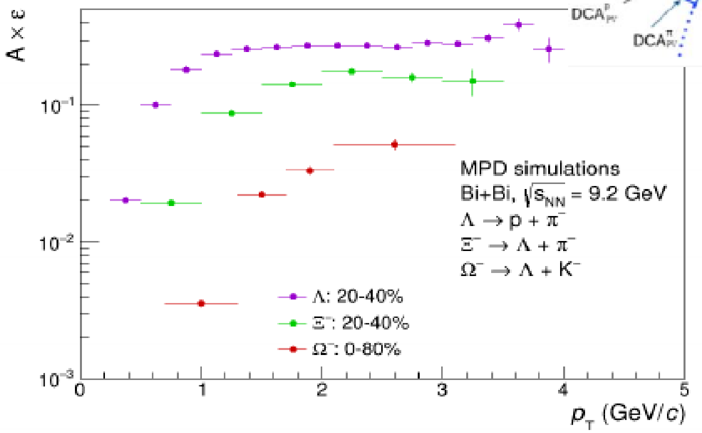


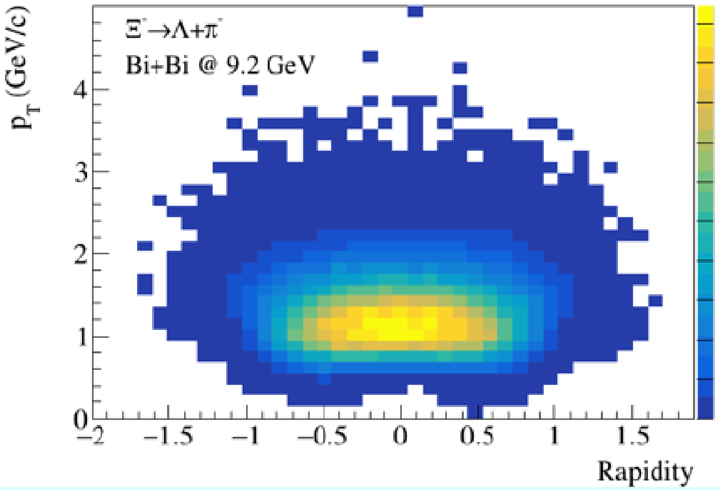



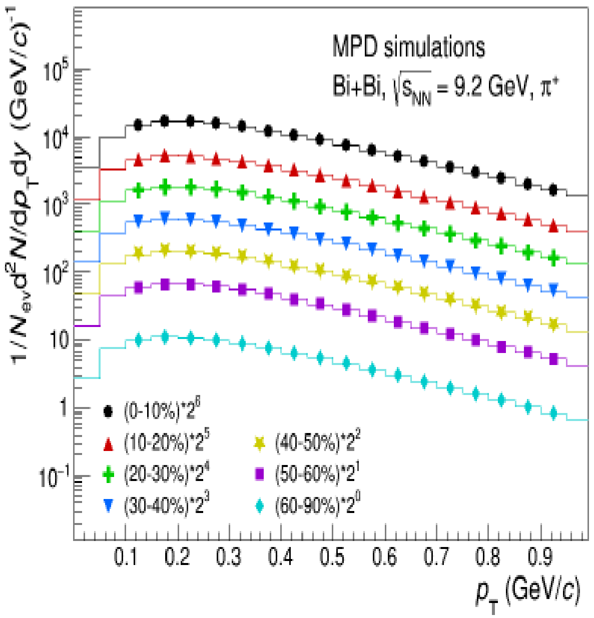



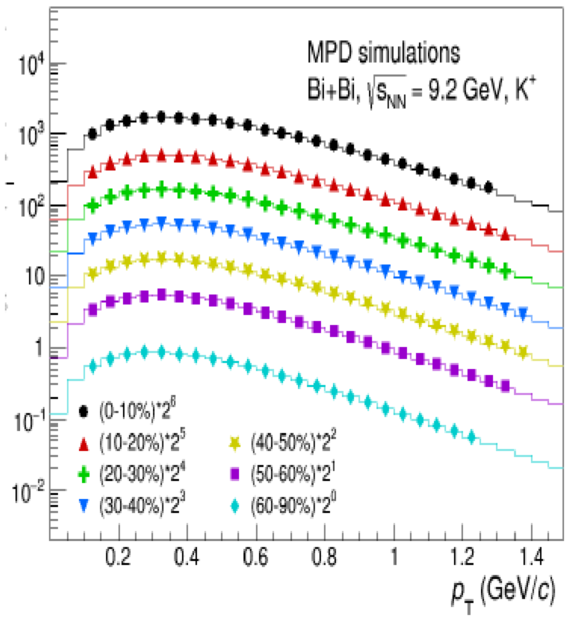



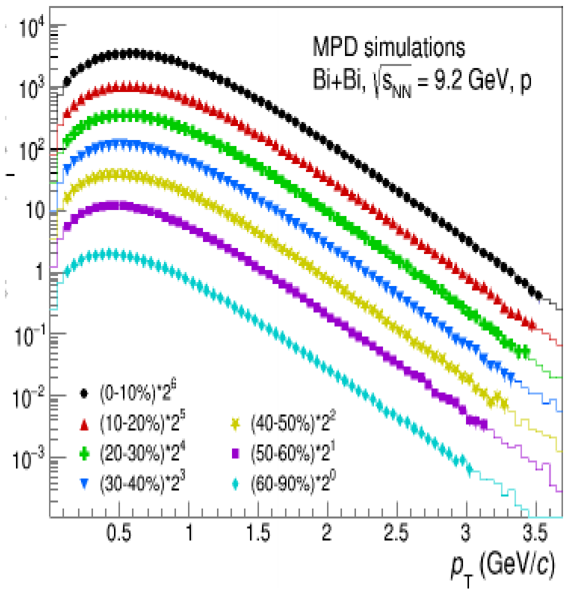

MPD setup performance for hyperons:

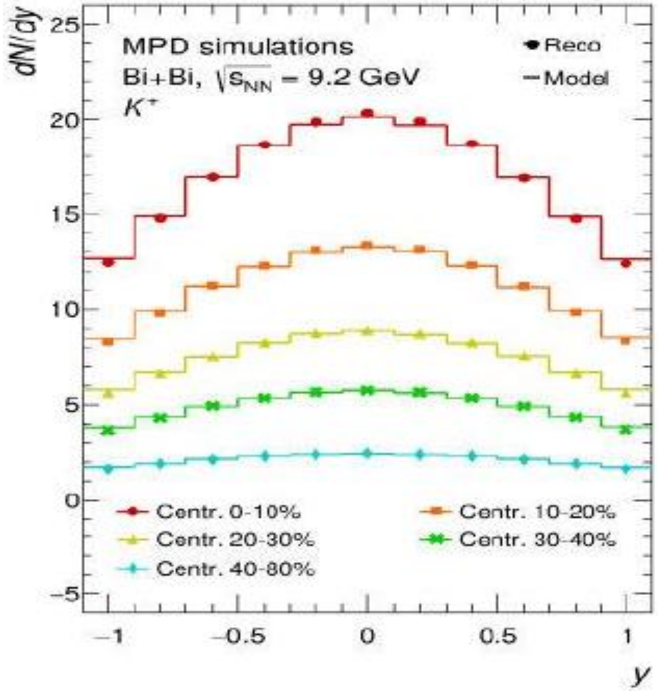
- large signal-to-background ratios
- good phase-space coverage

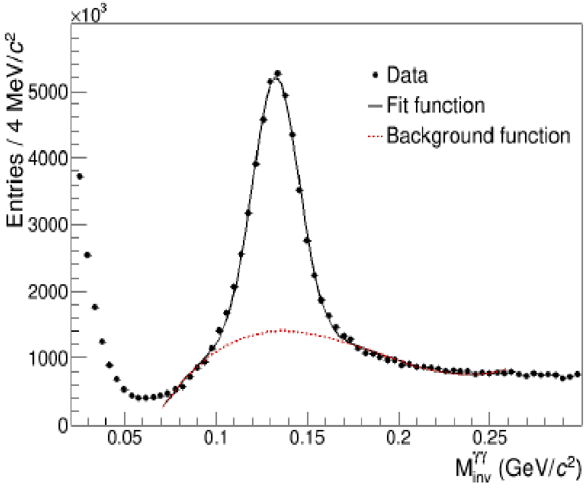
# MPD feasibility study: light identified hadrons

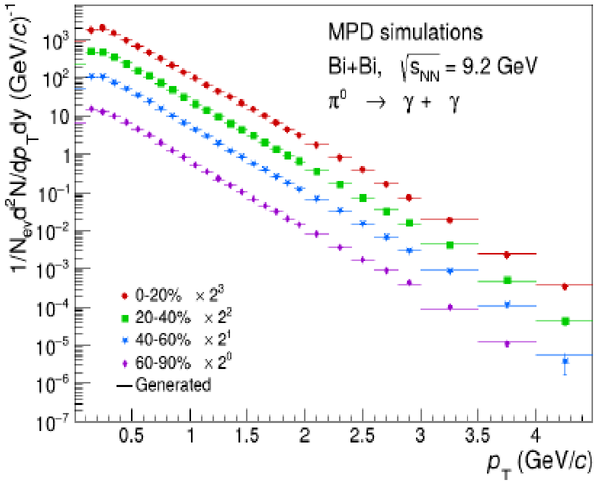


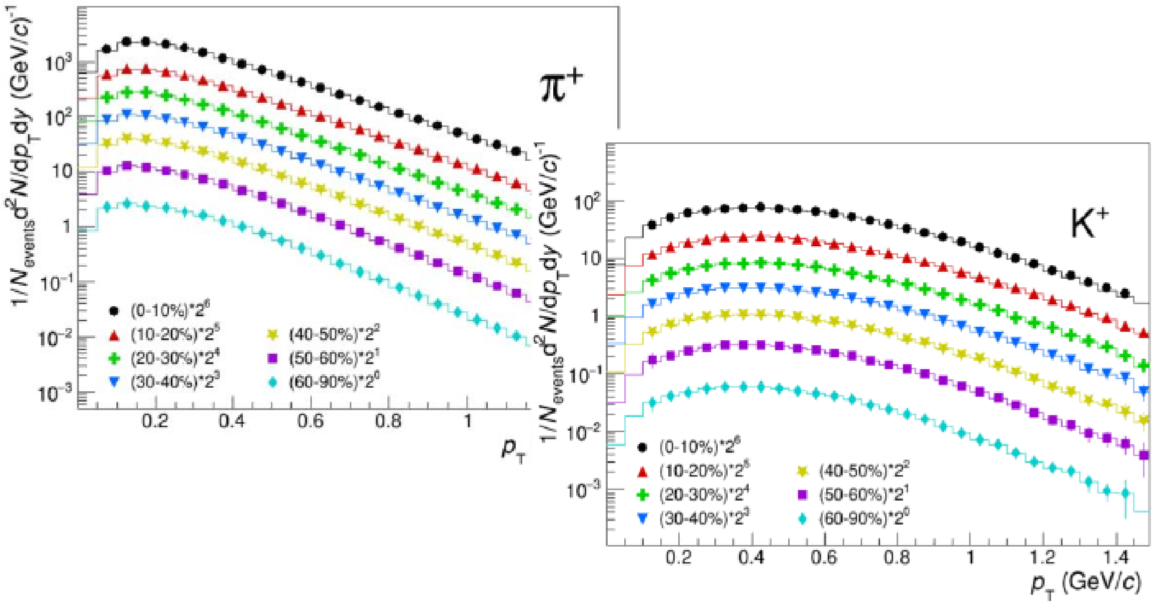



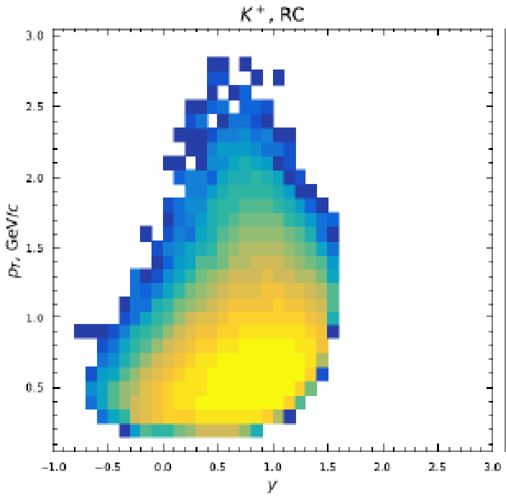



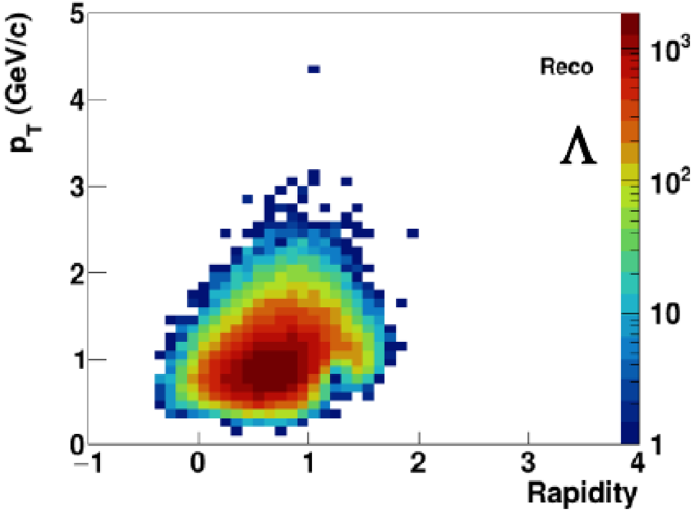

- Charged hadrons: excellent PID and good phase-space coverage ( ~ 70% of the π/K/p)
- Neutral mesons ($\pi^0$, η, $K_S$, ω, η'): ECAL reconstruction + photon conversion method (PCM) allow to extend $p_T$ ranges of charged particle measurements and provide different systematics

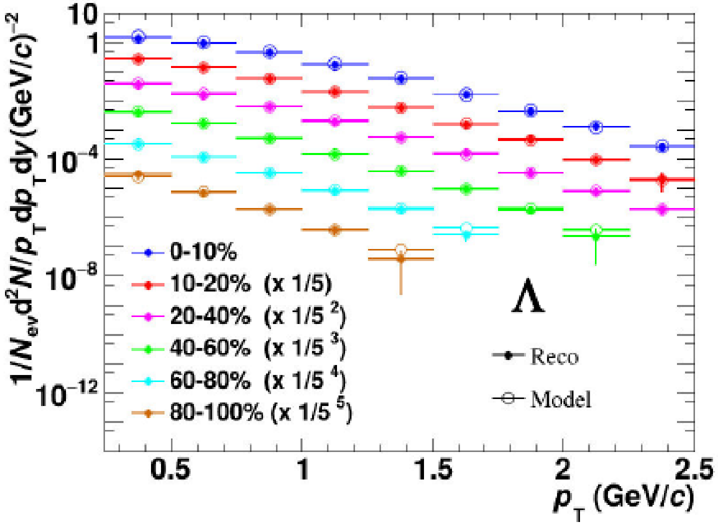
# MPD feasibility study for the Fixed-Target Mode

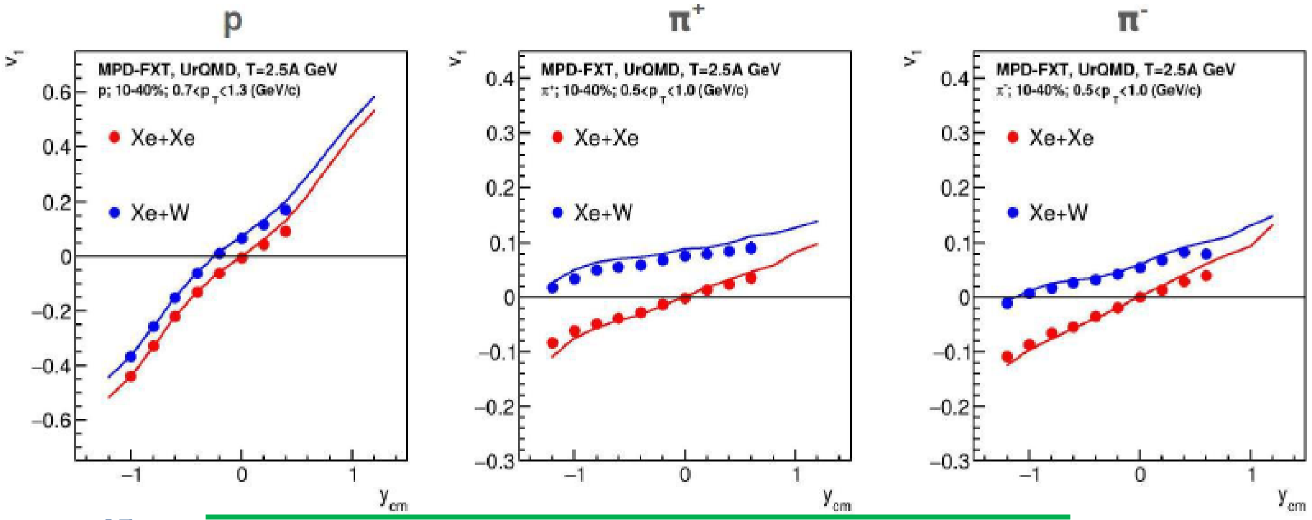
- MPD feasibility studies using large-scale Monte Carlo productions for Xe+W at T=2.5A GeV



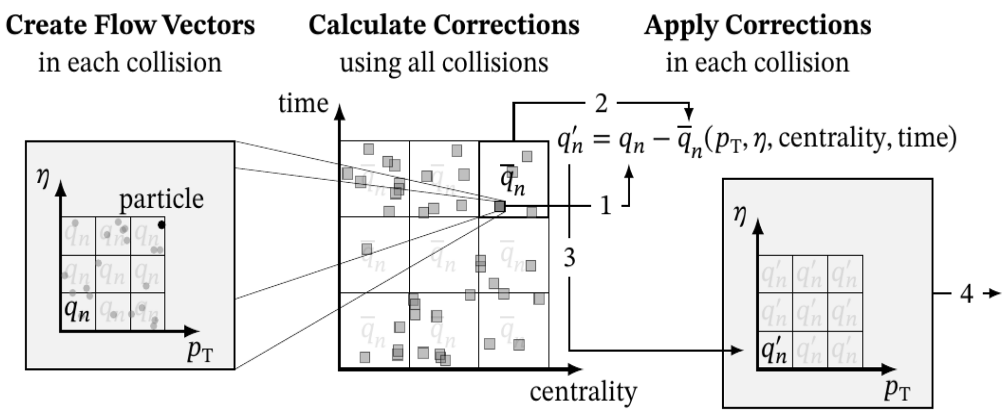



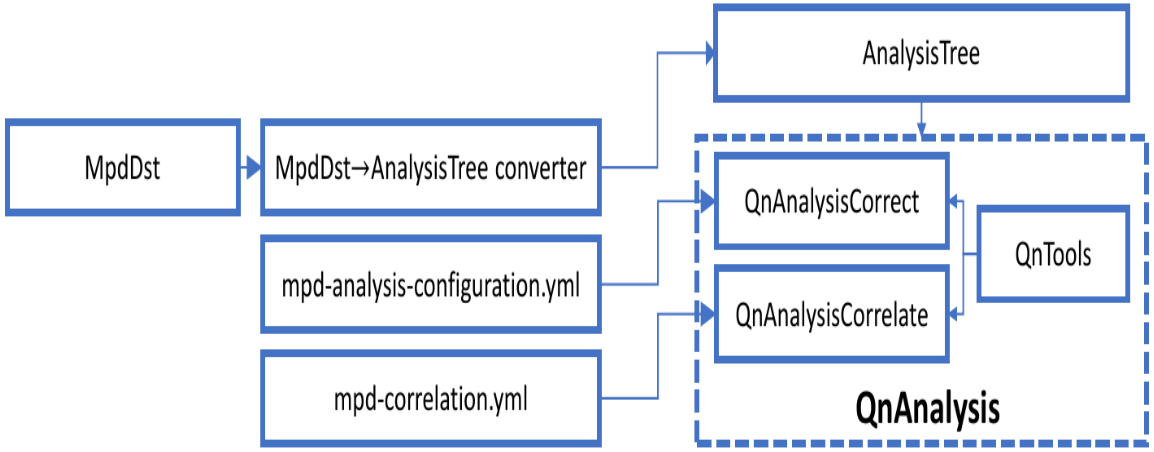



# QnTools: universal framework for analysis of anisotropic flow




Heavy-ion experiments have very different environment, but may use similar analysis techniques:
**QnTools** – have the potential to be a unified platform for anisotropic flow analysis in all experiments

- Iterative correction procedure
- Data-driven correction extraction
- Experiment-independent formalisms
- Configurable multidimensional corrections for each detector subsystem or kinematic window of a particle

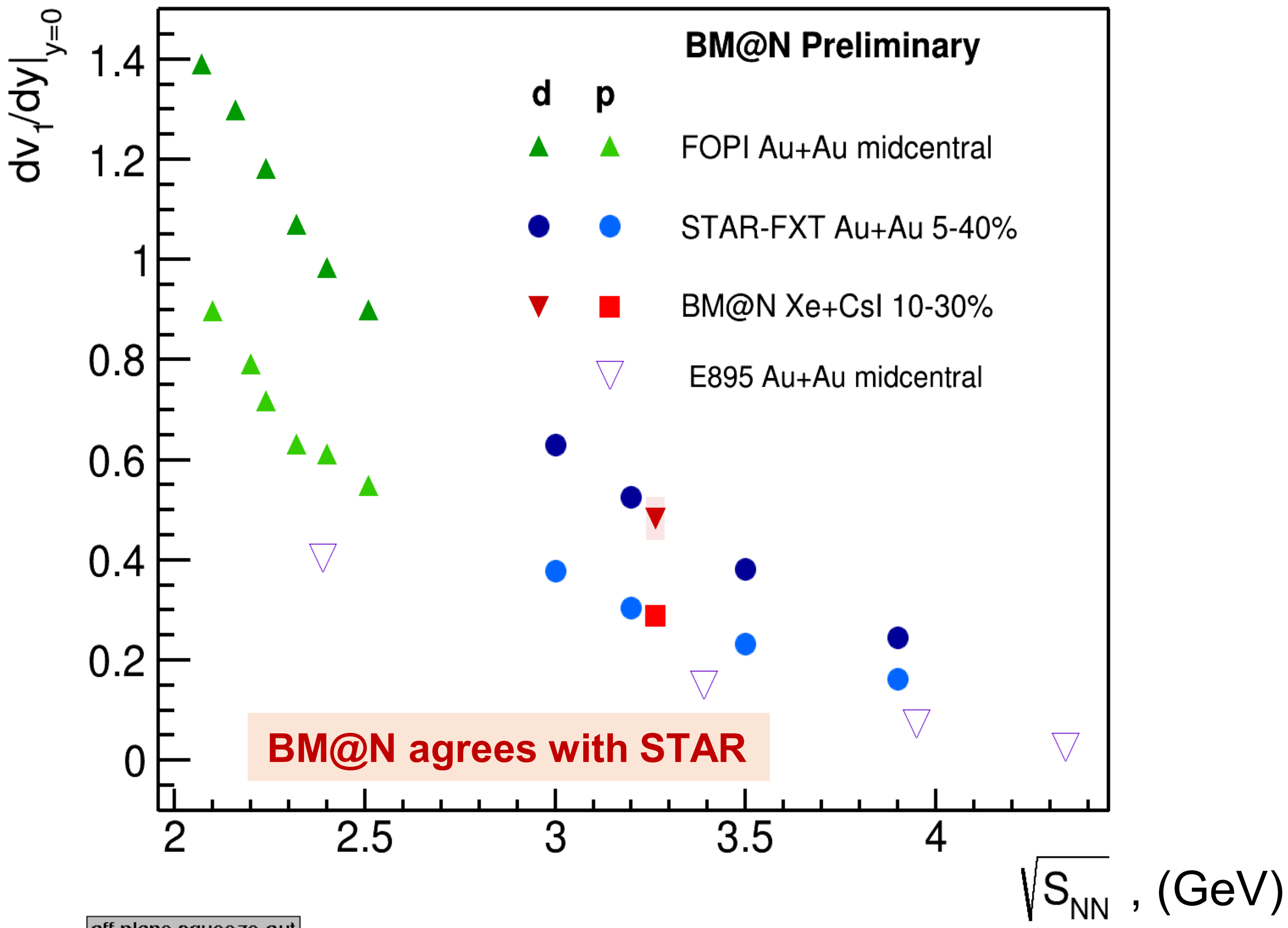
Multidimensional correlations

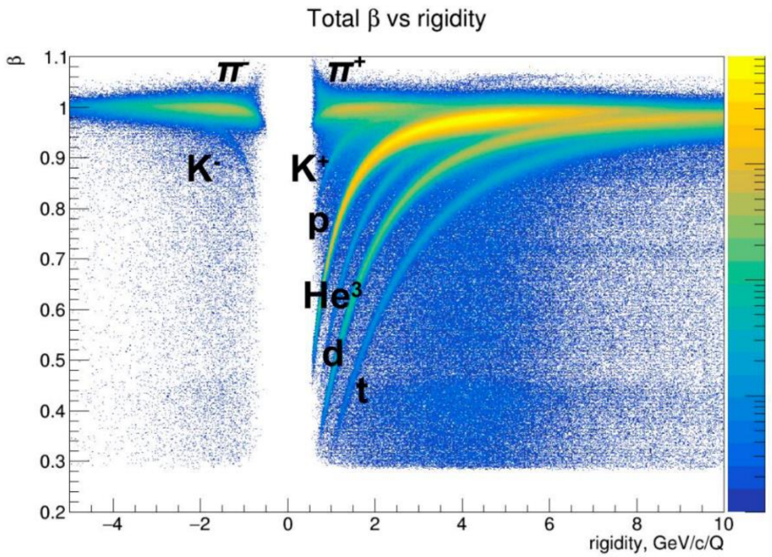
- Easily extendable with new observables
- Bootstrapping uncertainty calculated
- Uses ROOT RDataFrame for a high-level interface

*https://github.com/HeavyIonAnalysis/QnTools*

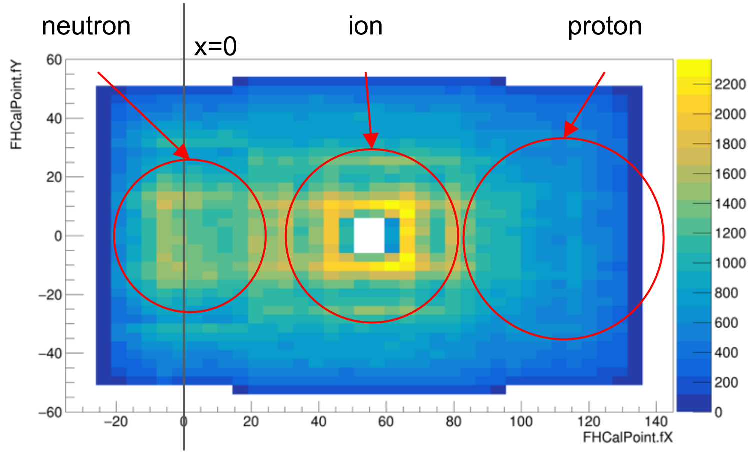
Talk by Mihail Mamaev: "Implementing the universal framework for analysis of anisotropic flow for MPD and BM@N", 08/07/2025, 14:15. *https://indico.jinr.ru/event/5170/contributions/31781/*

# QnTools: Directed flow of protons and deuterons (BM@N run8 data)

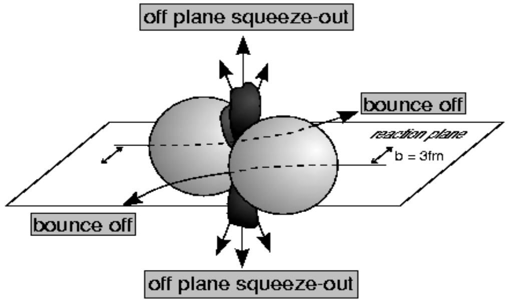



TOF

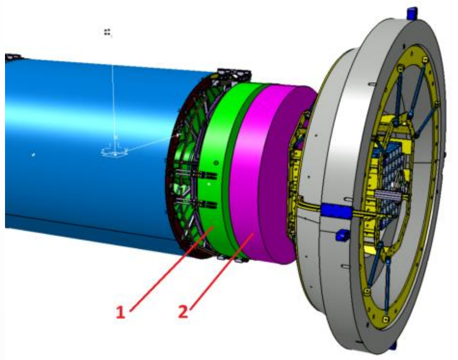



FHCaL



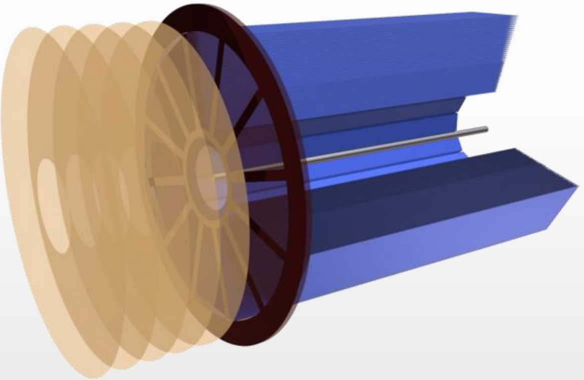

Talk by Mihail Mamaev: "Implementing the universal framework for analysis of anisotropic flow for MPD and BM@N", 08/07/2025, 14:15.
*https://indico.jinr.ru/event/5170/contributions/31781/*

# Development of the Forward Spectrometers for MPD

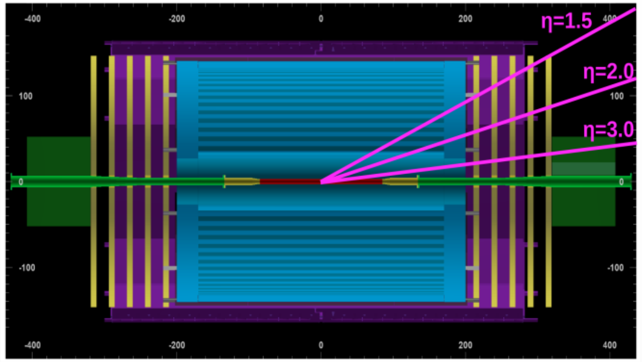



Two volumes available for the installation of forward tracker stations

**Conception of the Forward Tracker (FTD)**

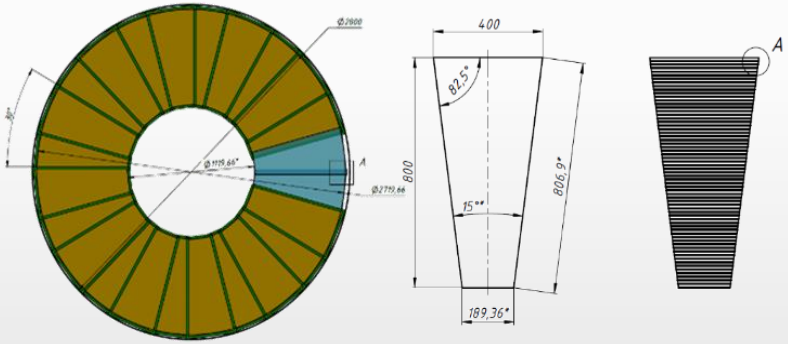


- ✓ five tracking layers within z = 210–300 cm,
- ✓ 1% $X_0$, ~ 80 μm spatial resolution




Pseudorapidity coverage of the forward spectrometer

**Conception of the end-cup TOF detector**




- ✓ a layer of MRPC-based TOF detectors, δτ ~ 50-70 ps

❖ Talk : "Implementation of ACTS (A Common Tracking Software project) -based track reconstruction for the forward detector in the MPD experiment at NICA" by Evgeny Kryshen (JINR, PNPI), 8/07/ 2025, 14:30 *https://indico.jinr.ru/event/5170/contributions/31783/*

# Summary


❖ MPD commissioning in the end of 2025-2026 remains the main priority

❖ Extensive program of physics feasibility studies for MPD-CLD and MPD-FXT

❖ Prepare software and analysis infrastructure for real data analysis

# Equation of state (EoS) for high baryon density matter

*pressure*   *energy per nucleon*

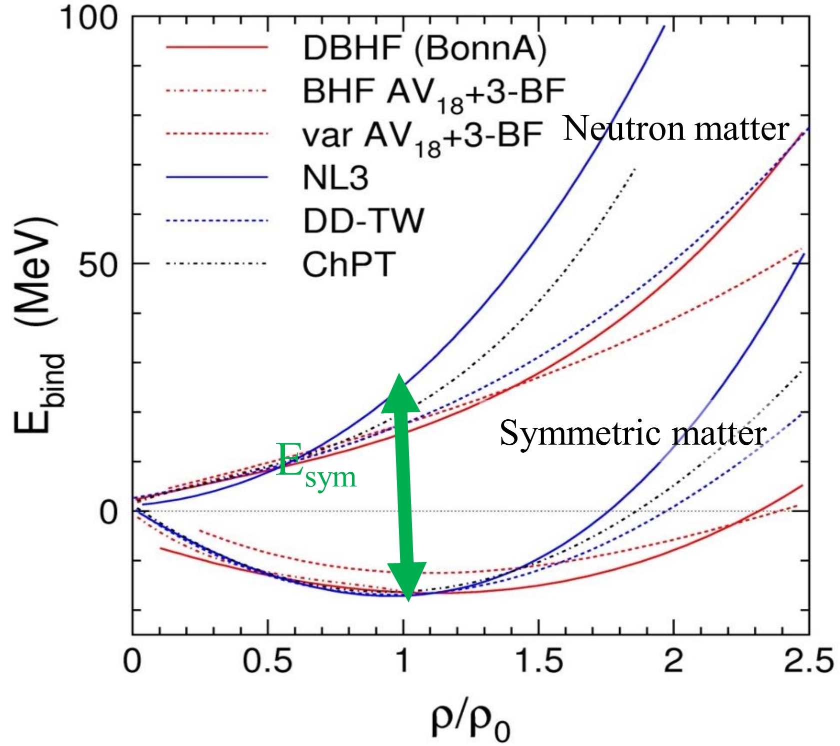
$$\frac{E}{A} = m_N + E_A(n_B) + E_{\rm sym}(n_B)\frac{(n_p - n_n)^2}{n_B^2}$$

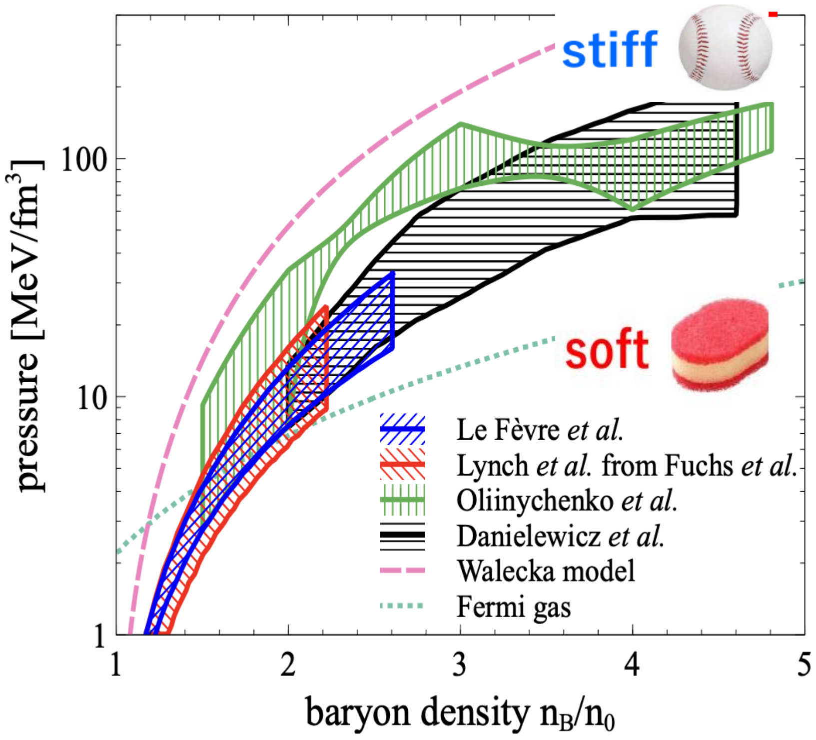
isospin asymmetry

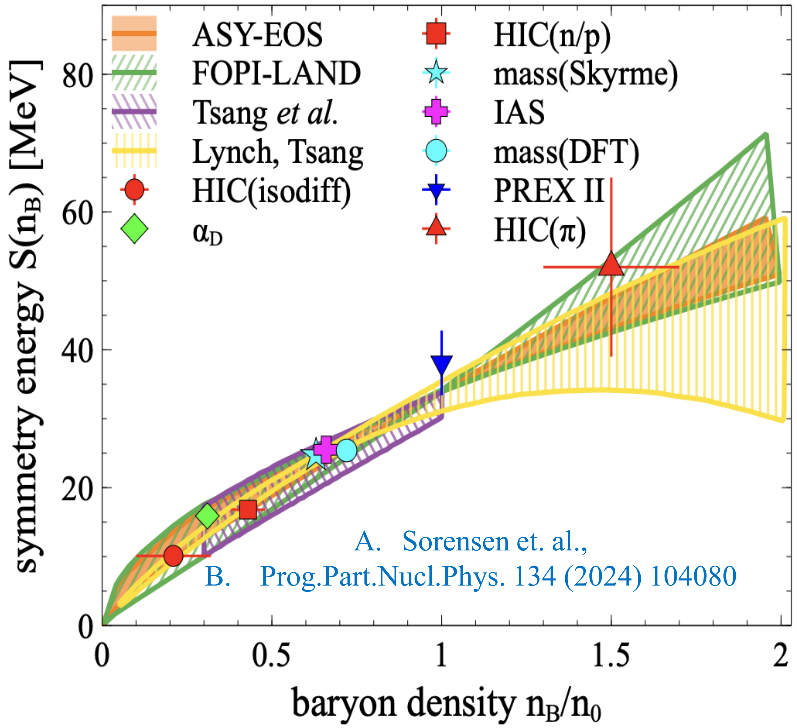
$$P = n^2 \frac{d(E/A)}{dn_b}$$

$$n_B = n_p + n_n$$

**Symmetric matter**   **Symmetry energy**



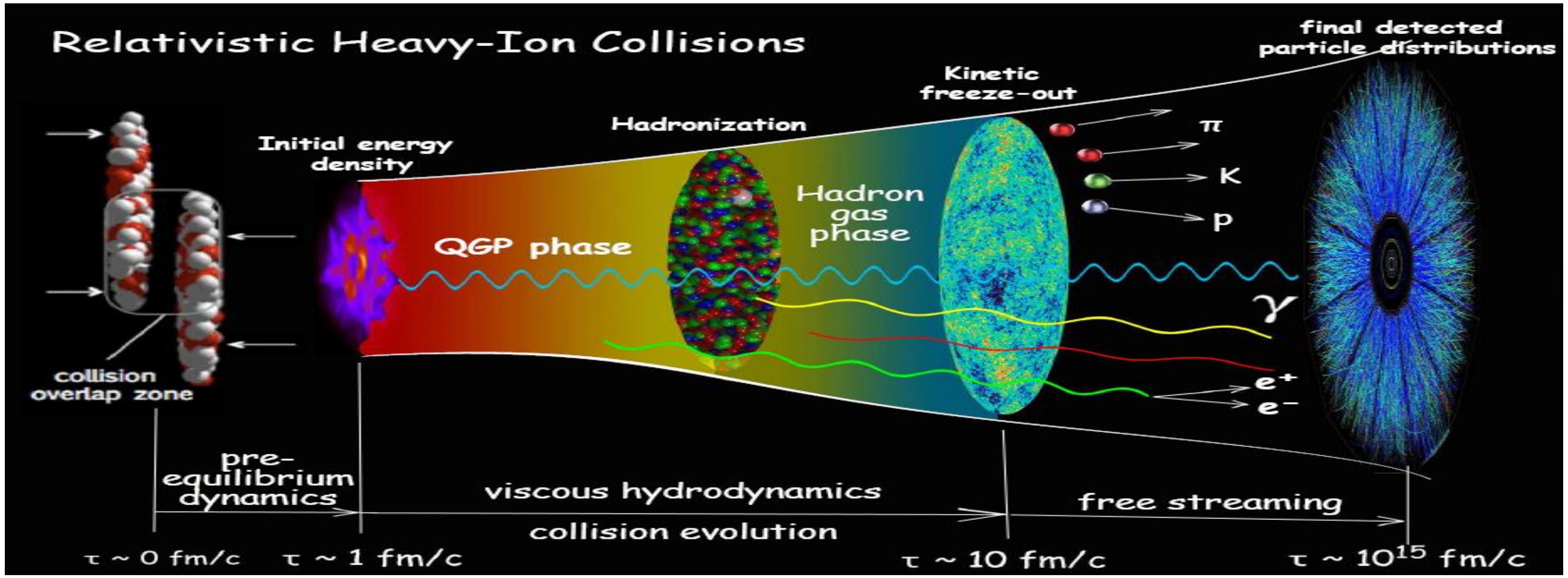



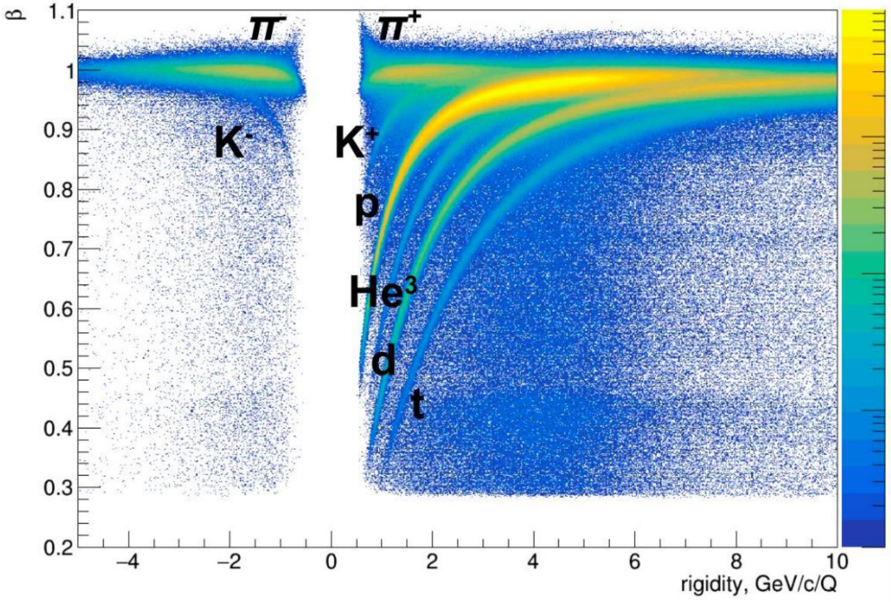




EOS describes the relation between density ($n_B$), pressure (P), temperature (T), energy (E), and isospin asymmetry $(n_p\text{-}n_n)/n_B$

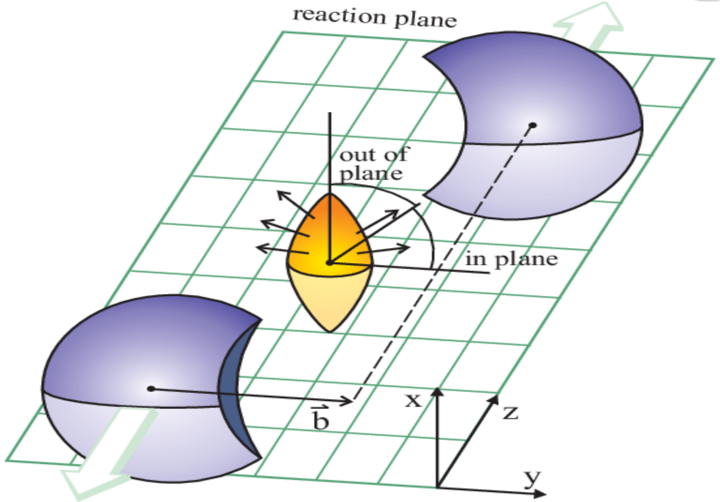
**HADRON** → **QGP**

| ~1980 | ~1990 | ~2000 | ~2005 | ~2010 |
|---|---|---|---|---|
| **Bevalac** | **AGS** | **SPS** | **RHIC** | **LHC** |
| ~1 GeV | ~5 GeV | ~20 GeV | ~100 GeV | ~5000 GeV |




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




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

# Equation of state (EoS) for high baryon density matter

*pressure*

$$P = n^2 \frac{\mathrm{d}(E/A)}{\mathrm{d}n_b}$$

*energy per nucleon*

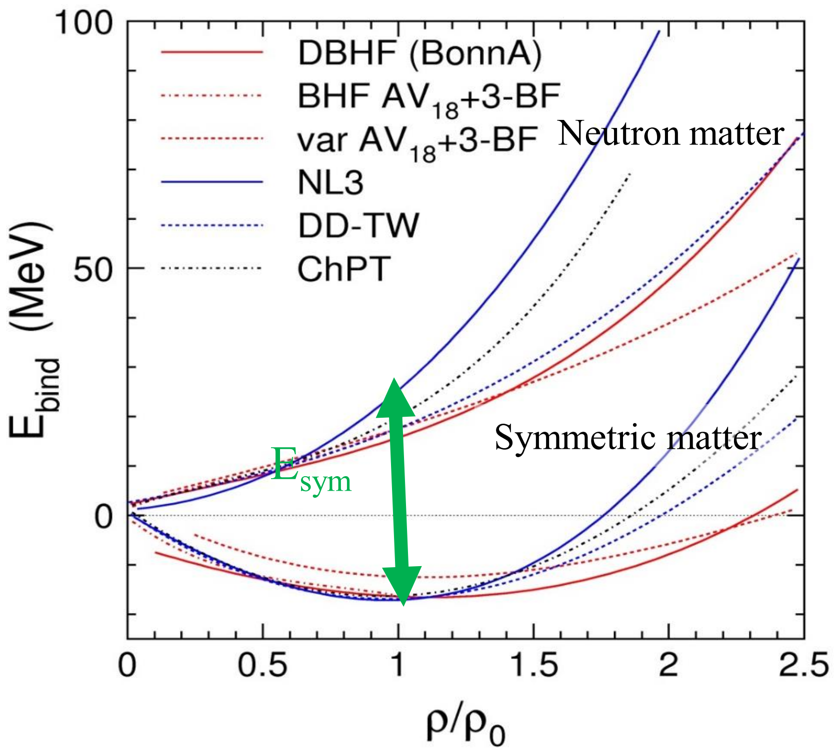
$$\frac{E}{A} = m_N + E_A(n_\mathrm{B}) + E_\mathrm{sym}(n_\mathrm{B}) \frac{(n_p - n_n)^2}{n_\mathrm{B}^2}$$

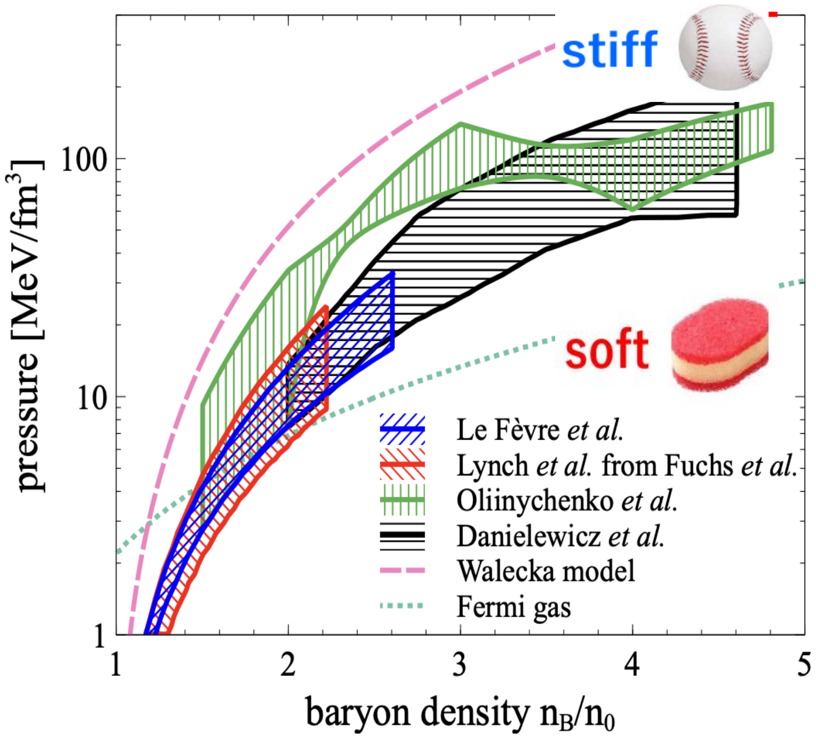
isospin asymmetry

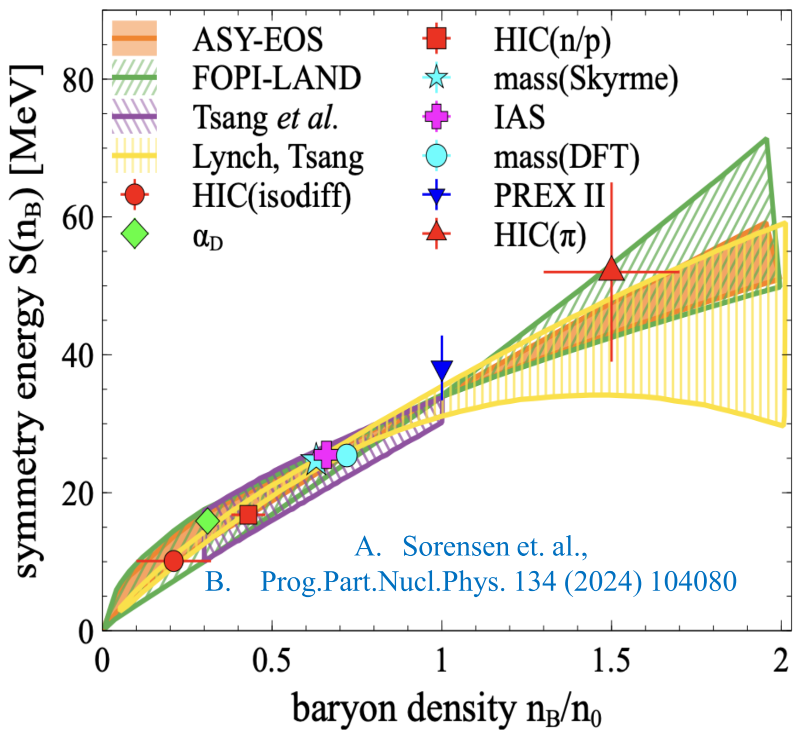
$$n_\mathrm{B} = n_p + n_n$$

**Symmetric matter**

**Symmetry energy**

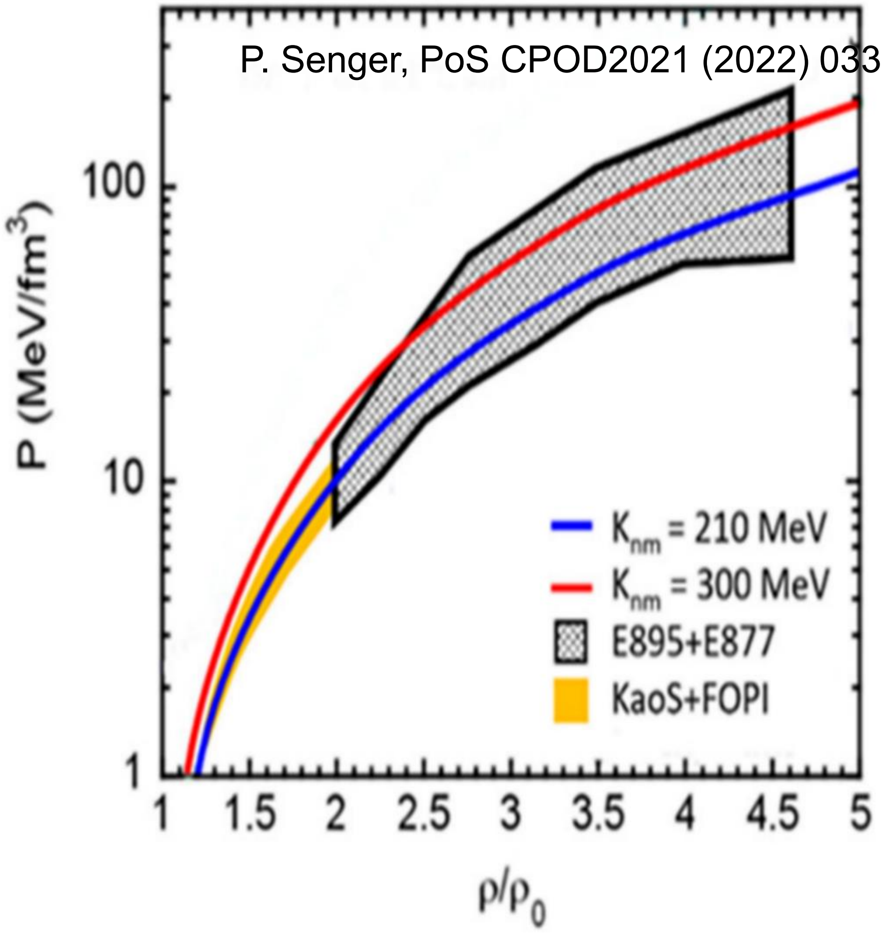


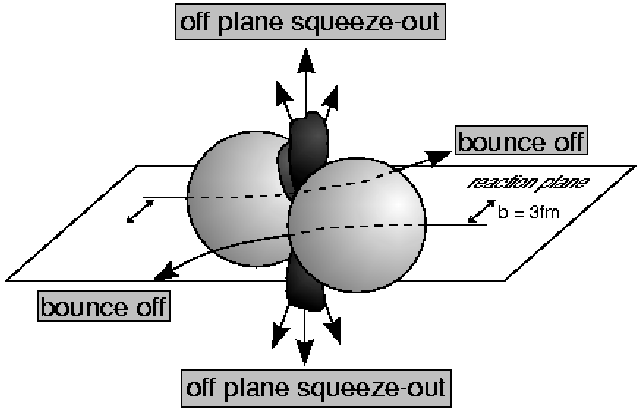



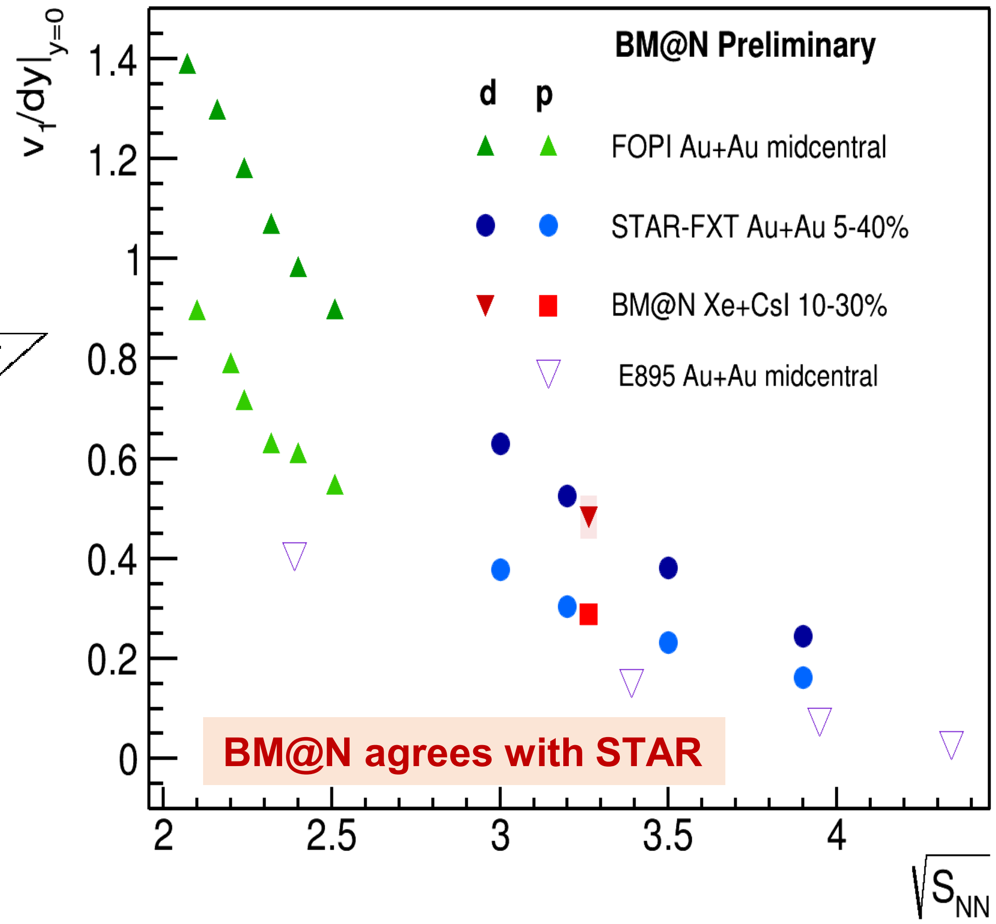

EOS describes the relation between density ($n_B$), pressure (P), temperature (T), energy (E), and isospin asymmetry $(n_p - n_n)/n_B$

# Directed flow of protons and EOS of symmetric matter



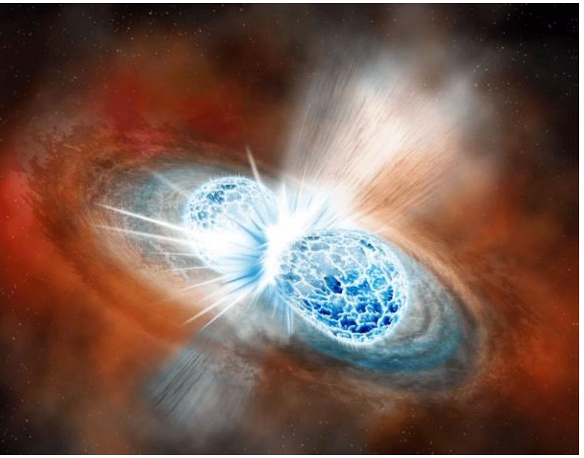

Nuclear incompressibility from collective proton flow
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

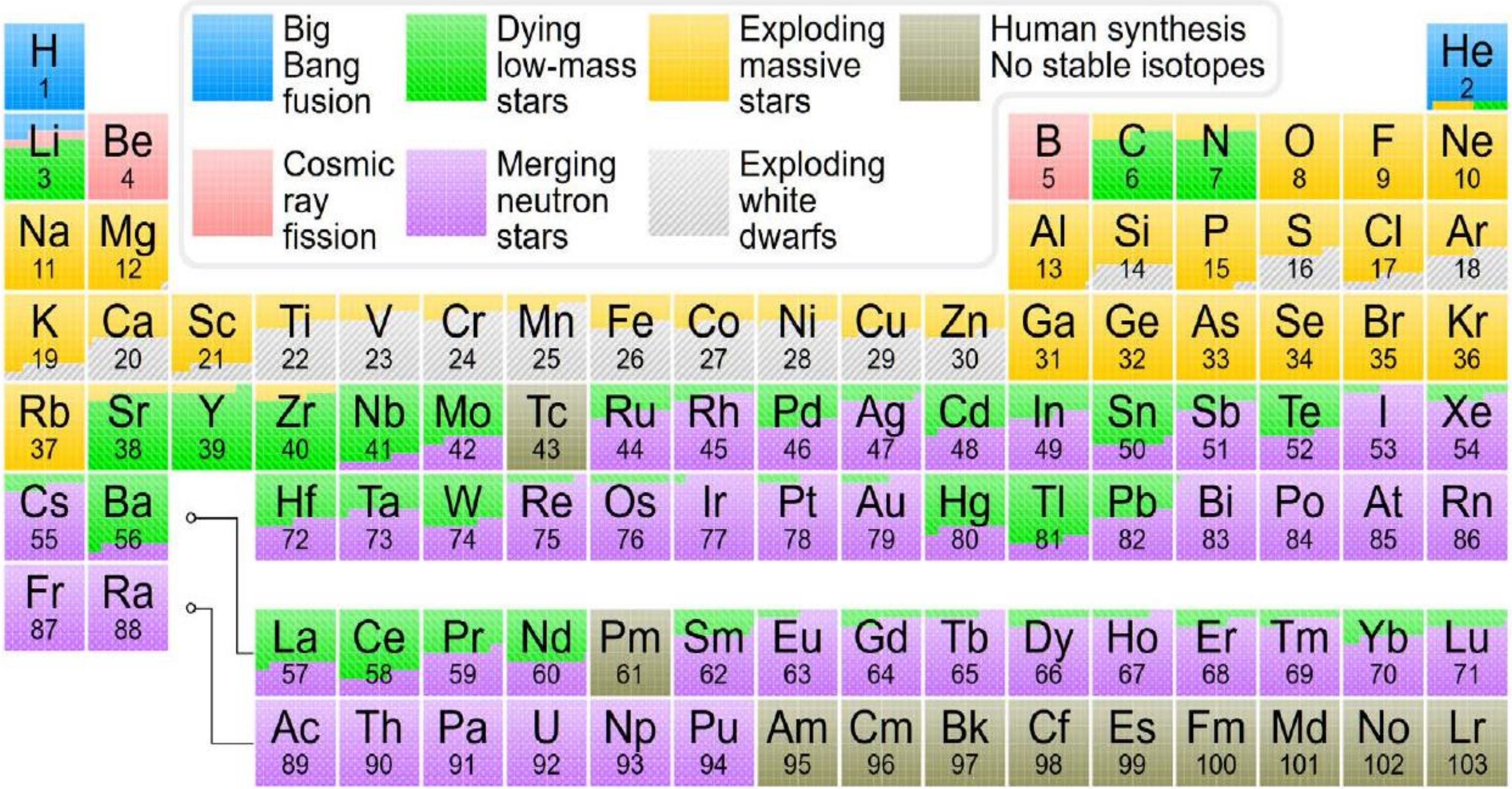



**Both STAR and BM@N results for directed flow prefer stiff EOS**

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

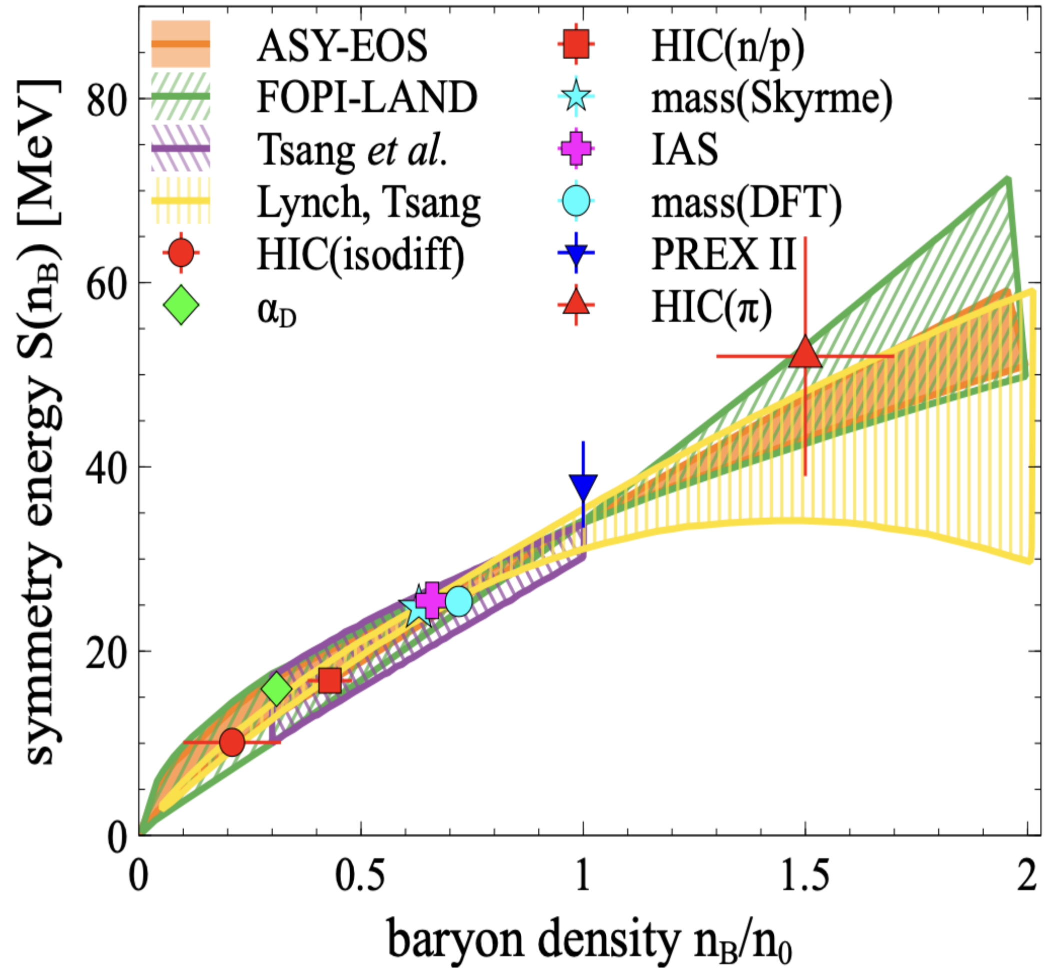





**r-process - source of heavy elements including gold, platinum, and uranium.**

# Observables to study symmetry energy (EoS)

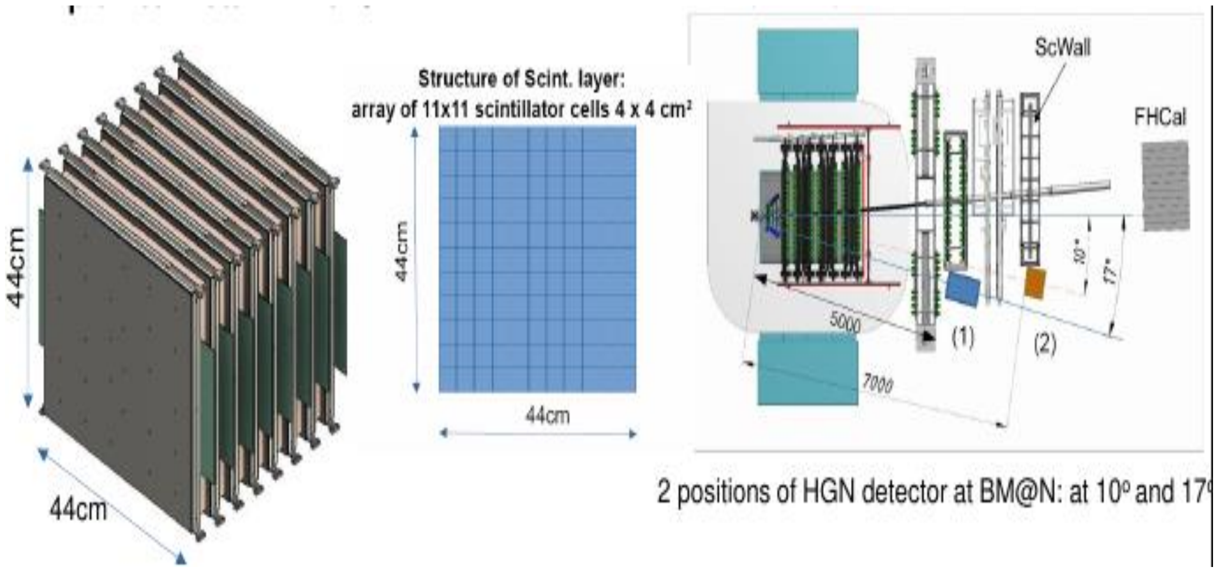
A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080




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

**Symmetry energy $E_{sym}$ has strong density dependence**

BM@N Neutron Detector (2026-)

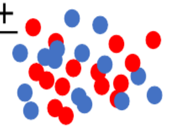



The Highly-Granular time-of-flight Neutron Detector for the BM@N experiment, Nucl. Instrum. Meth. A 1072 (2025) 170152

**Stiff symmetry energy (large L)**

→ lower $\rho_n/\rho_p$ in higher dense region

→ lower n/p, lower $\pi$-/$\pi$+



**Soft symmetry energy (small L)**

→ larger $\rho_n/\rho_p$ in higher dense region

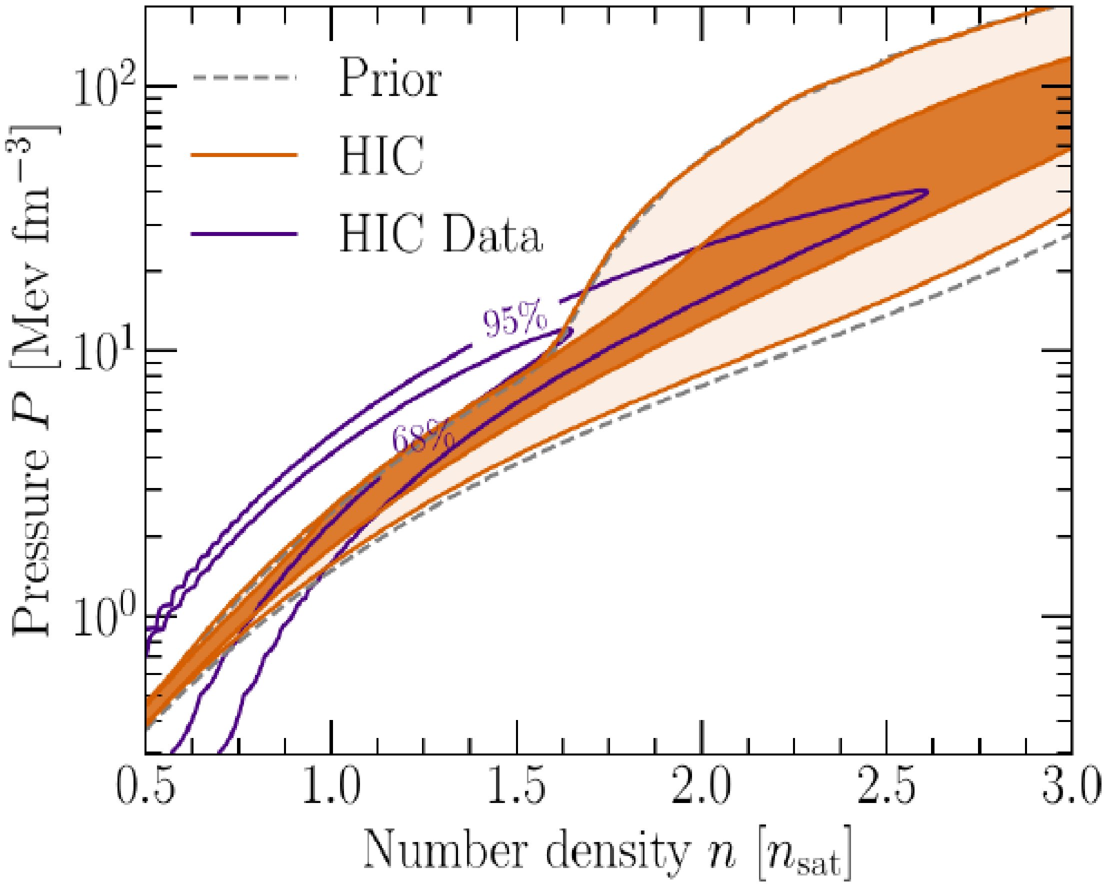
→ larger n/p, higher $\pi$-/$\pi$+

# Constraining neutron-star matter with microscopic and macroscopic collisions

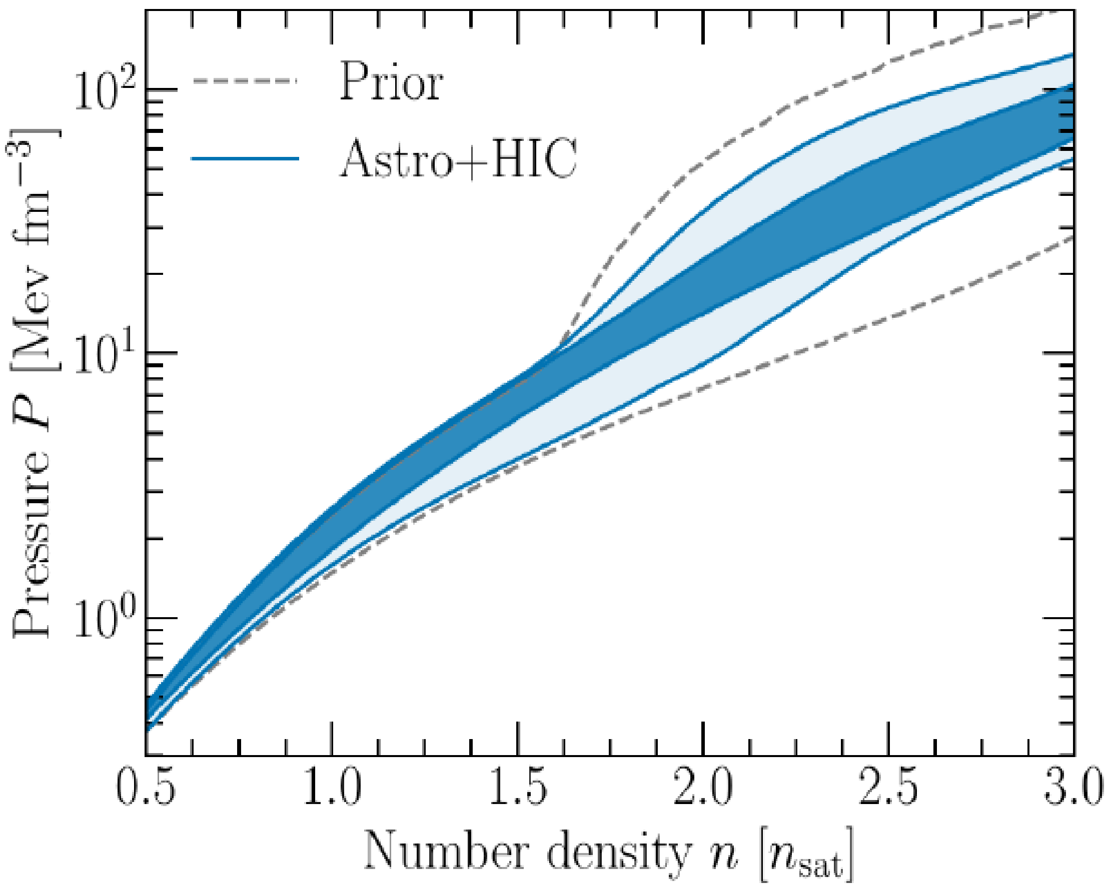
*Huth, Pang et al. Nature 606(22)276*

**HIC experiments:**

Bayesian combinations




**HIC and Astro combined:**




Astrophysical observations narrow constraints above 2 $n_{sat}$

# 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.

Twelve young scientists and Ph.D. students from JINR member states are doing physics analyses at BM@N preparing their theses.

# Backup slides

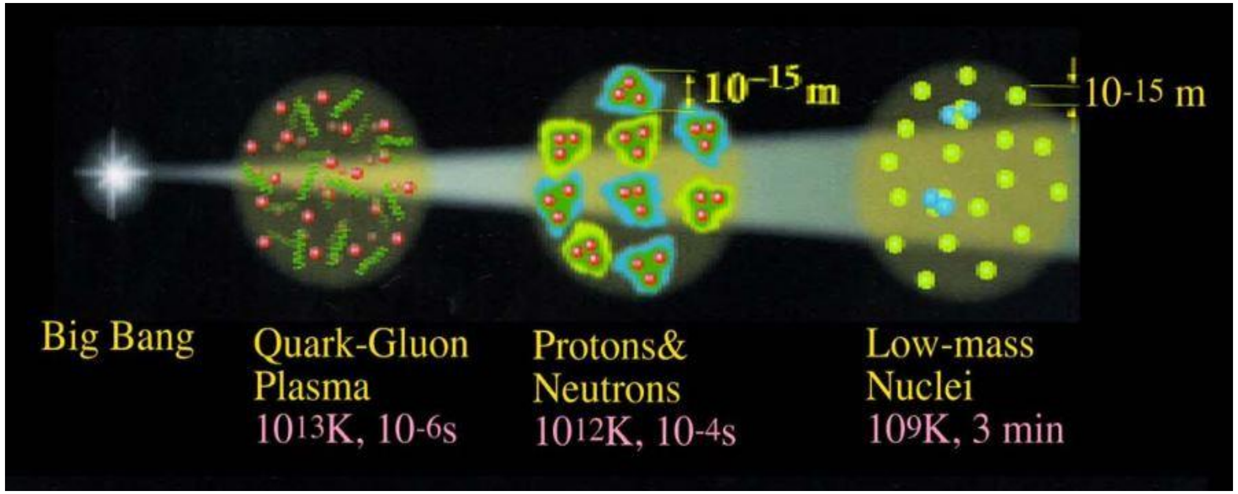
# *Relativistic Heavy-Ion Collisions and Quark Gluon Plasma (QGP)*

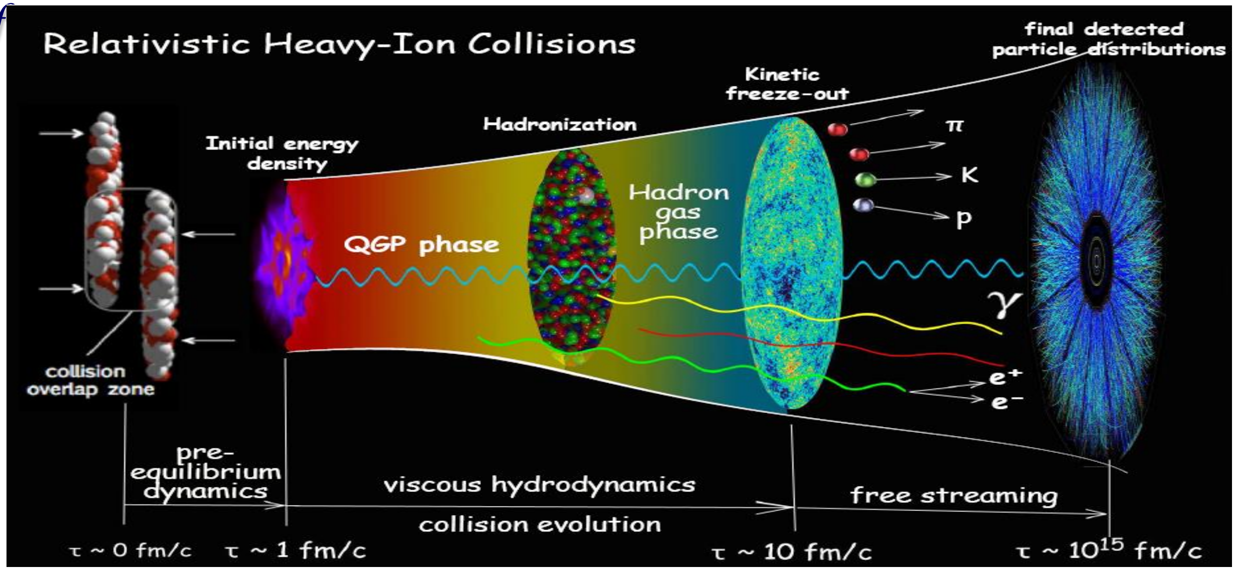
1


2. *It was present during the first few microseconds of the Big Bang.*

3. *It provides an example of phase transitions which may occur at a variety of higher temperature scales in the early universe.*

4. *It can provide important insights on the origin of mass for matter, and how quarks are confined into hadrons.*

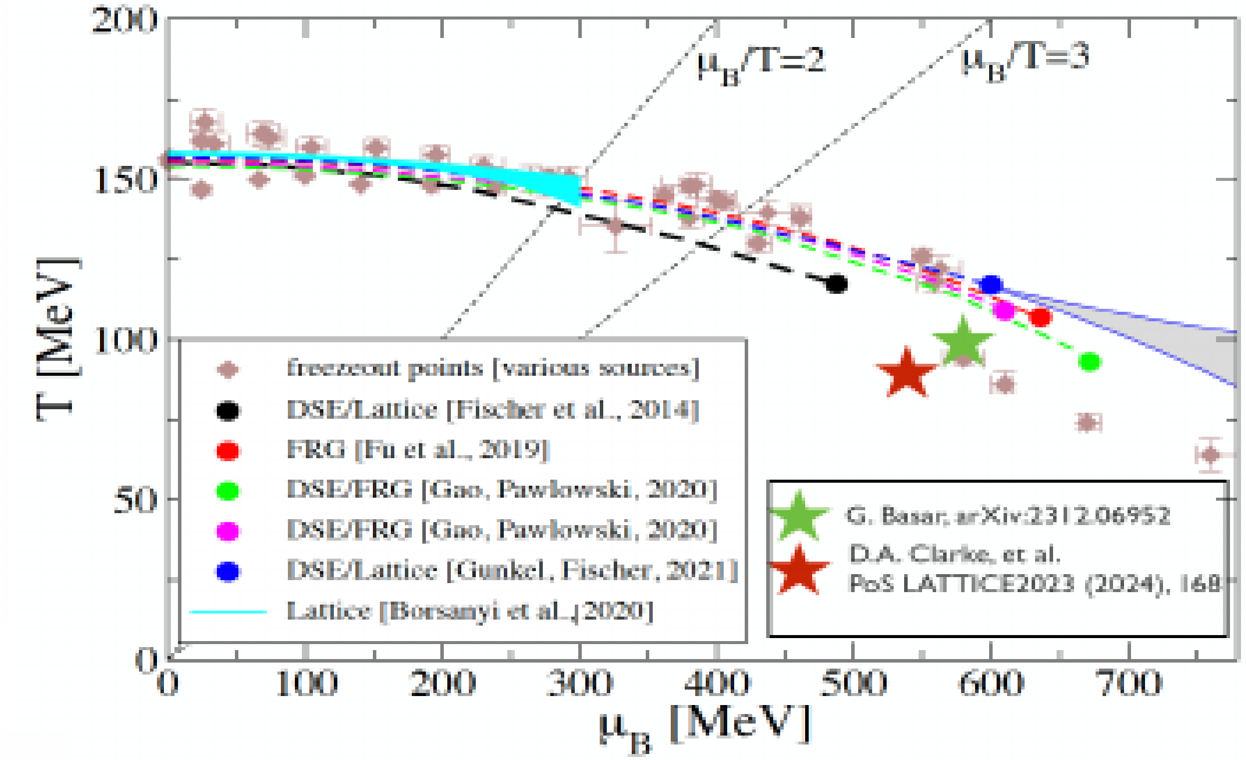


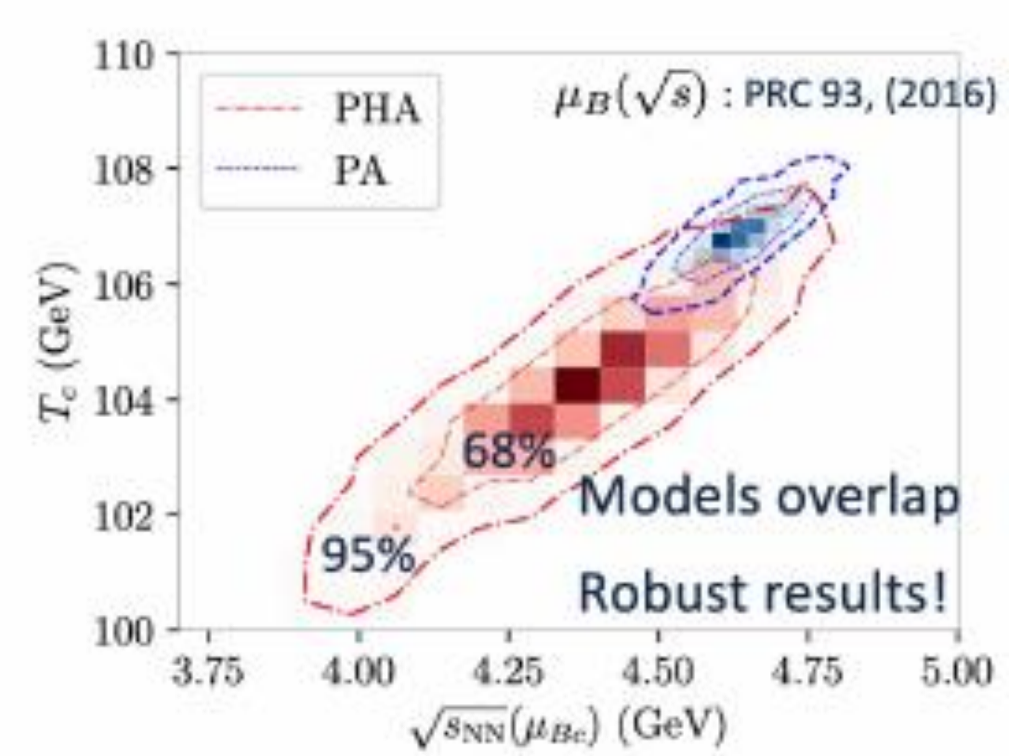

*M. Gyulassy, Nucl. Phys. A750, 30-63, 2005*

Temperature ~150-170 MeV ($2*10^{13}$ K)
and density ~1 GeV/fm$^3$ ($10^{15}$ g/cm$^3$)

# Location of the QCD Critical Point: Theoretical Estimation/Prediction




M. Hippert et al., Phys. Rev. D 110, 094006 (2024)



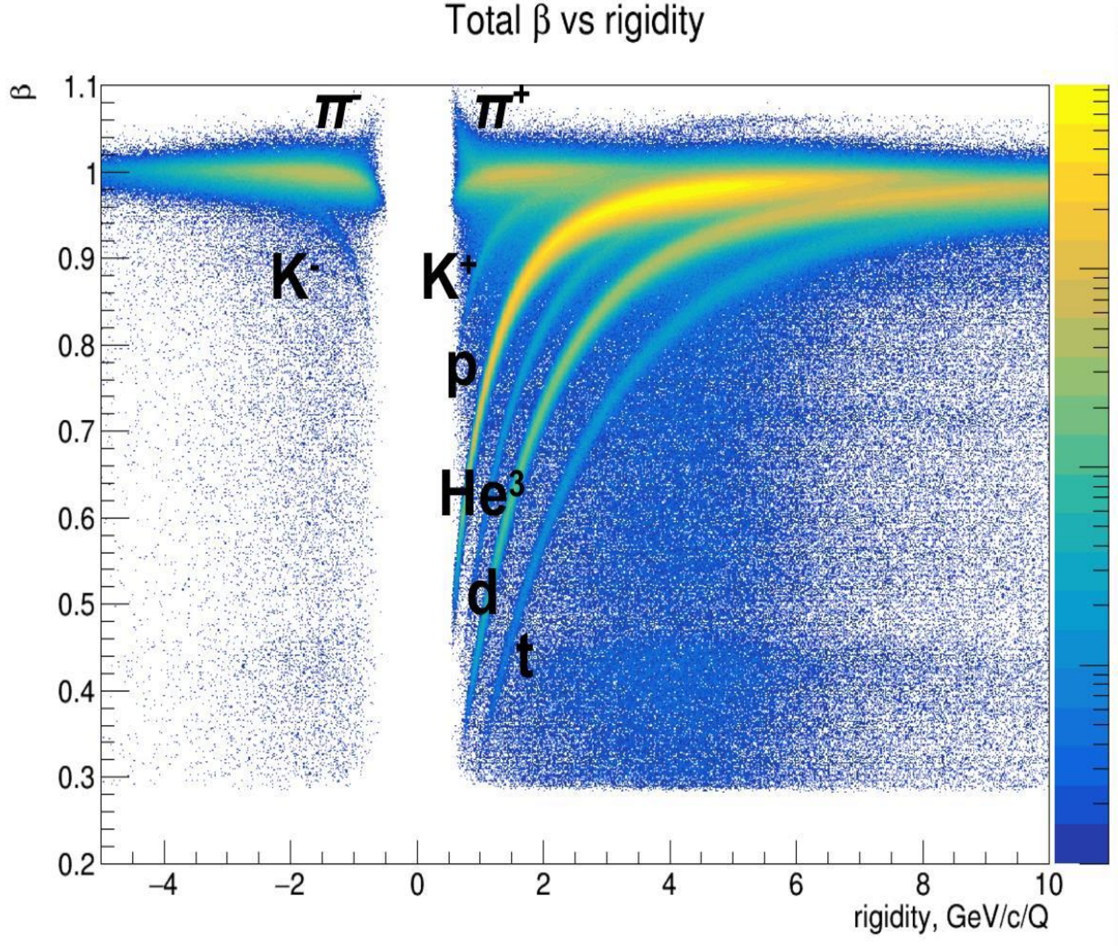

| Method | $\mu_c$ (MeV) | $T_c$ (MeV) |
|---|---|---|
| Holography + Bayesian | 560 - 625 | 101 - 108 |
| FRG/DSE | 495 - 654 | 108 - 119 |
| Lee-Yang edge singularities | 500 - 600 | 100 - 105 |
| Lattice QCD | $\mu_c/T_c > 3$ | F. Karsch et al. |
| **Summary** | **495 - 654** | **100 - 119** |

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

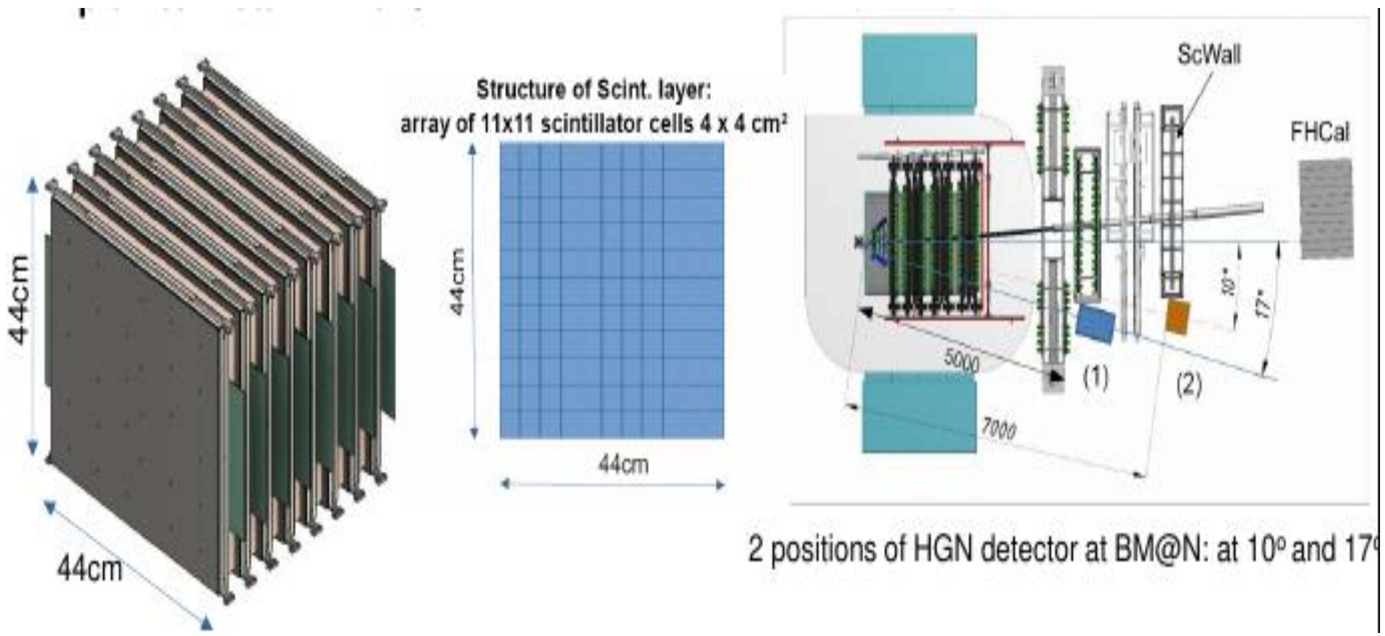
**BM@N and MPD are both in the collision energy range of the predicted CEP location.**

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

# BM@N: Observables to study symmetry energy




BM@N Neutron Detector




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

# Nuclear Matter Equation of State

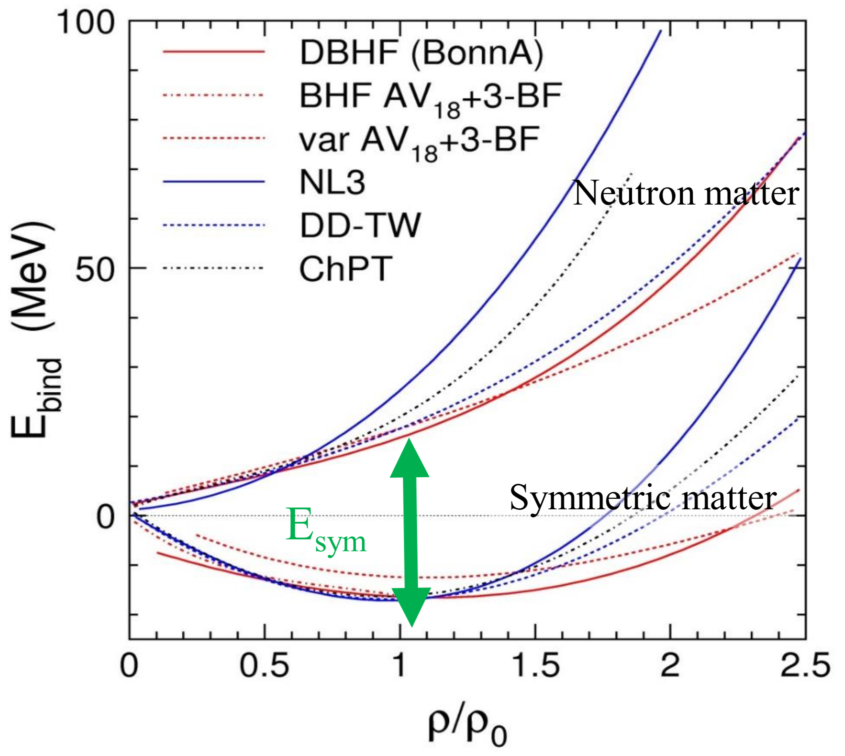
$E(N_p,N_n)$ Energy of the system of A nucleons ($N_p$, $N_n=A-N_p$)     $\mathcal{E}$ - energy density

The binding energy per nucleon: $$E_{\mathrm{bind}}(n_p,n_n) = \frac{E}{A} - m_N = \frac{\mathcal{E}}{n} - m_N = E_A(n_b) + E_{\mathrm{sym}}(n_b)\frac{(n_p-n_n)^2}{n_b^2}$$

isospin asymmetry

symmetric matter

symmetry energy




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

- Being extensively studied nowadays using observables (flow, meson yields, etc.) to explore compressibility
- $$K_0 = 9n_0^2 \frac{\mathrm{d}^2 E_A}{\mathrm{d}n^2}\bigg|_{n_0}$$
- One of the main sources of uncertainty: discrepancy between experimental data

- One of the main parameters to study is the $E_{sym}$ slope

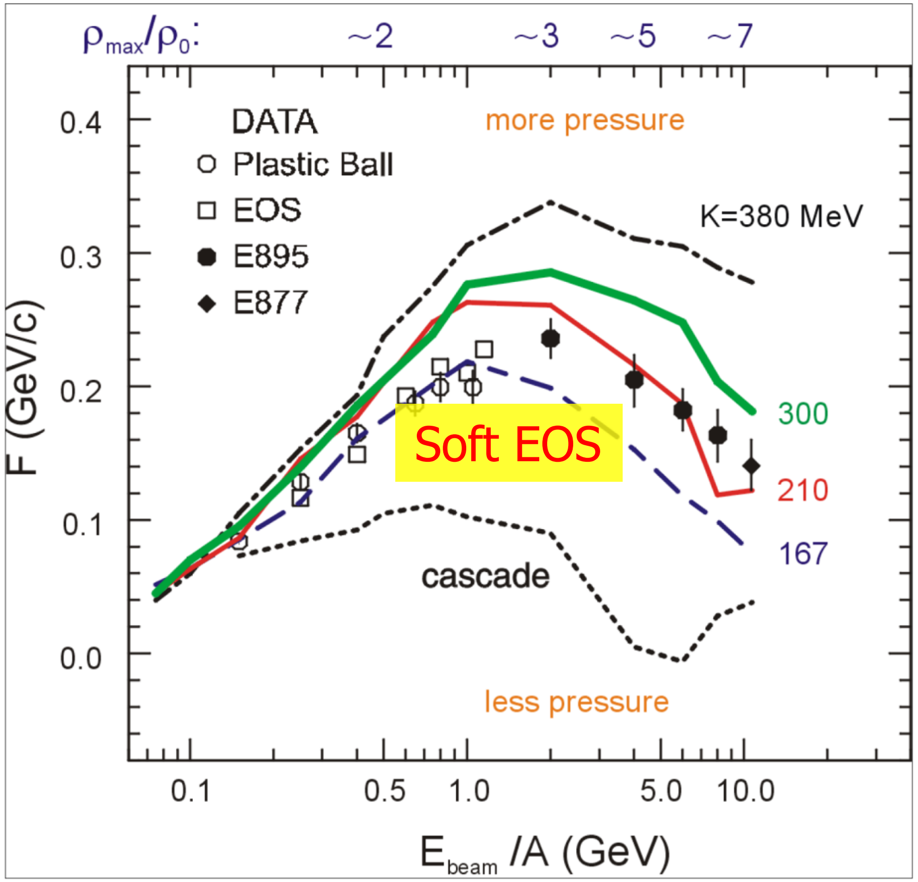
$$L = 3n_0 \frac{\mathrm{d}E_{\mathrm{sym}}}{\mathrm{d}n}\bigg|_{n_0}$$

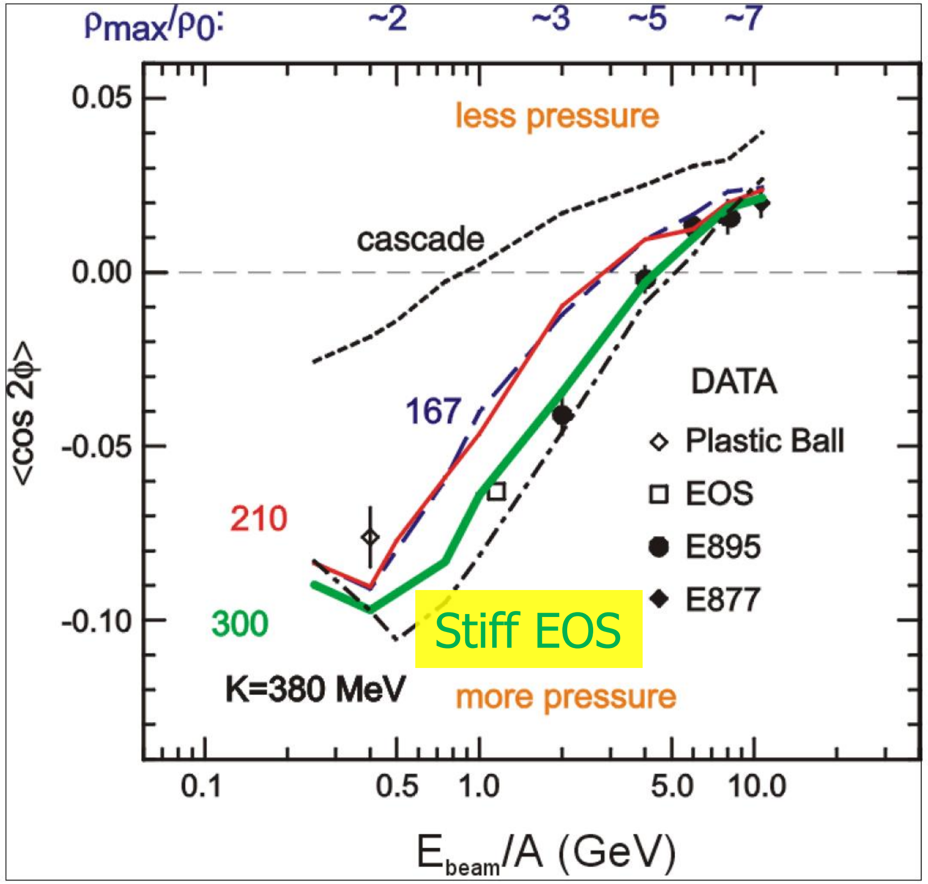
- No experimental data for beam energies $E_{kin} > 0.4$ GeV
- One needs to establish observables sensitive to ***L*** and obtain new experimental data

New data is needed to further constrain transport models with hadronic d.o.f.

# Nuclear incompressibility from collective proton flow

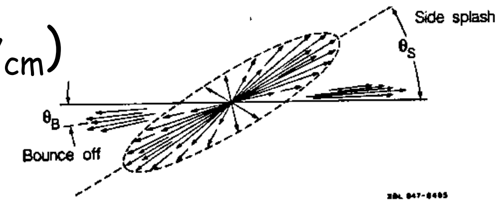
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



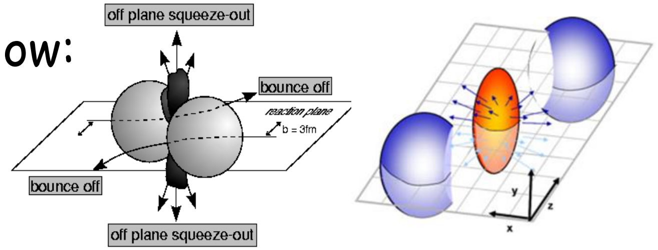




Transverse in-plane flow:

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



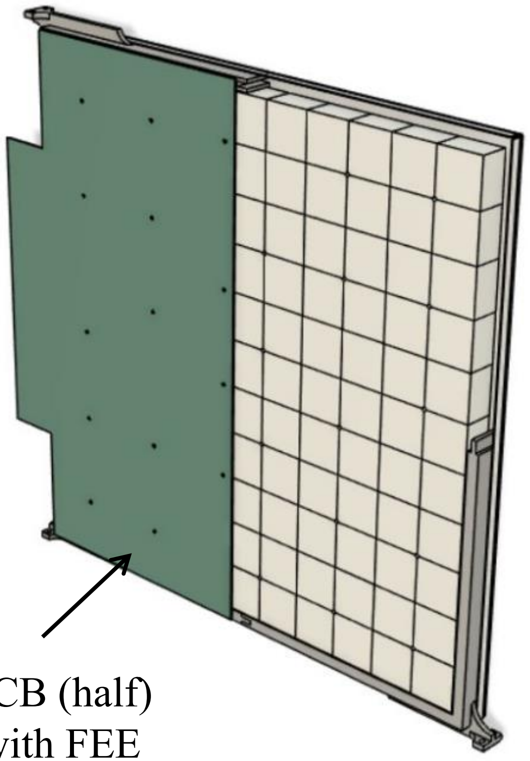

Elliptic flow:




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

F. Guber, et al., Instrum. Exp. Tech. №3 (2024)

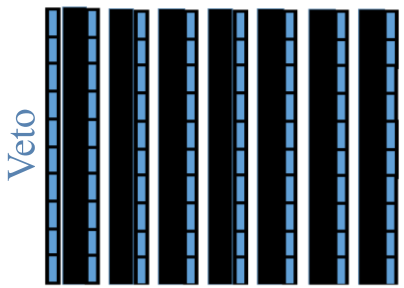
# Mechanical design

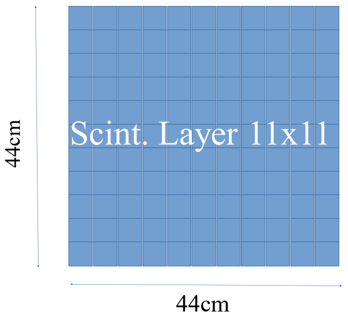


PCB (half)
with FEE

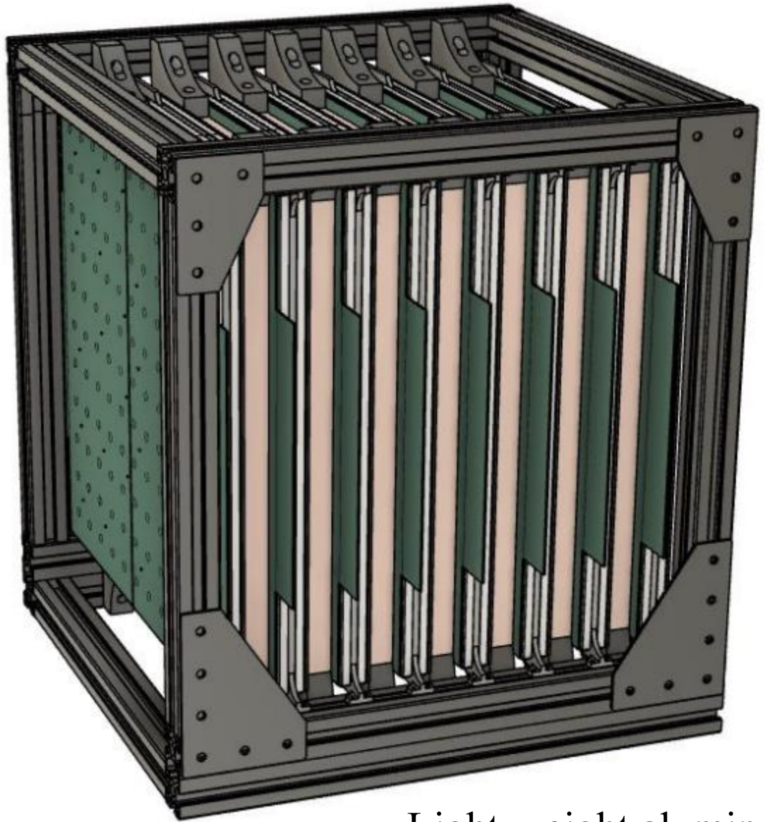
Light-tight and air-cooled assembly
- 1 veto-layer
- 7 Cu absorber layers (3 cm thick)
- 7 sensitive layers:
    - 11x11 matrix of scintillator detectors 4x4x2.5 $cm^3$
    - surrounded from both sides by PCBs
        - upstream board: LEDs for time calibration
        - downstream board: SiPMs and FEE

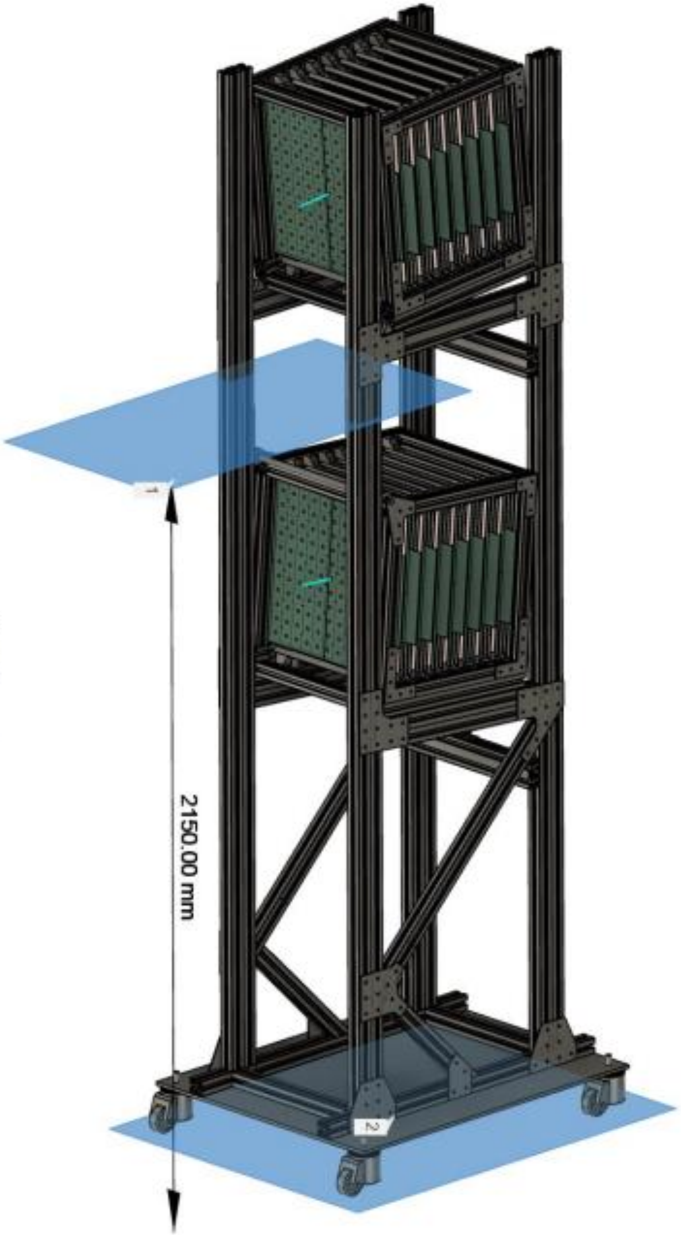
7 layers (Cu/Scint)




total length ~ 48cm (1.5 $\lambda_{in}$)






Light-weight aluminum frame

# EOS for high baryon density matter

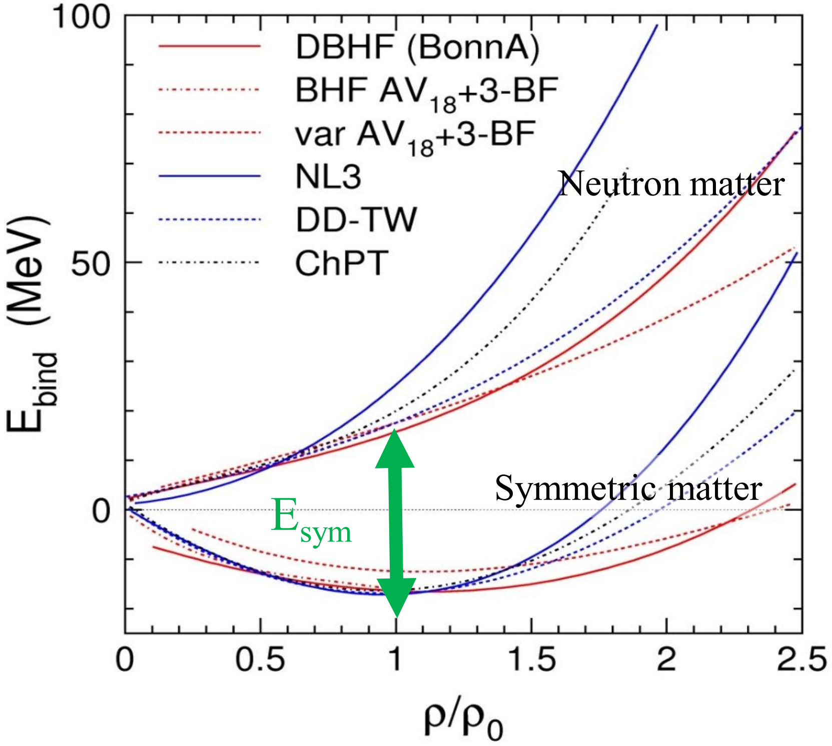
The binding energy per nucleon: $E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$

Isospin asymmetry:

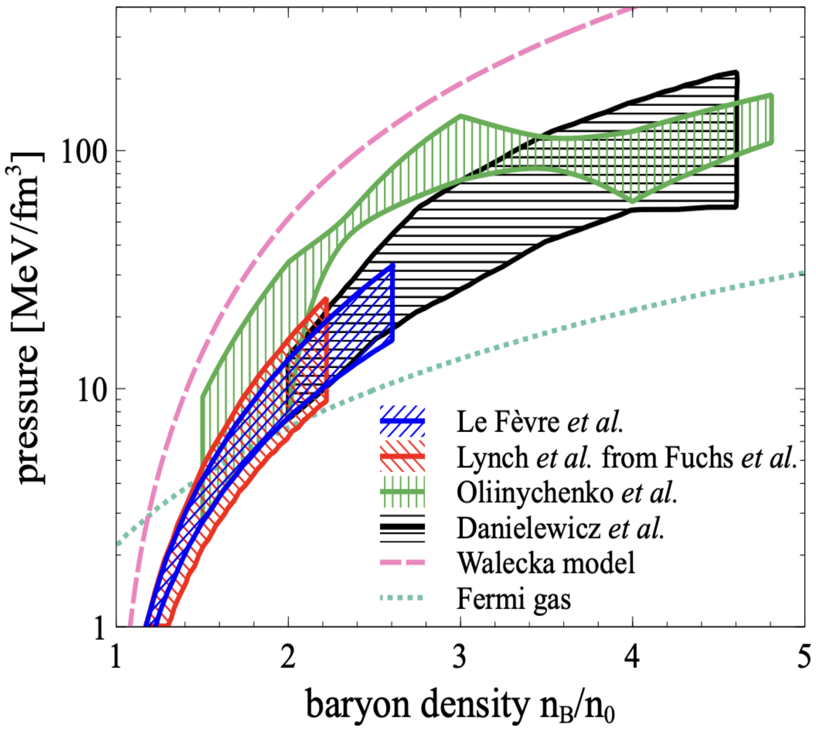
$\delta = (\rho_n - \rho_p)/\rho$

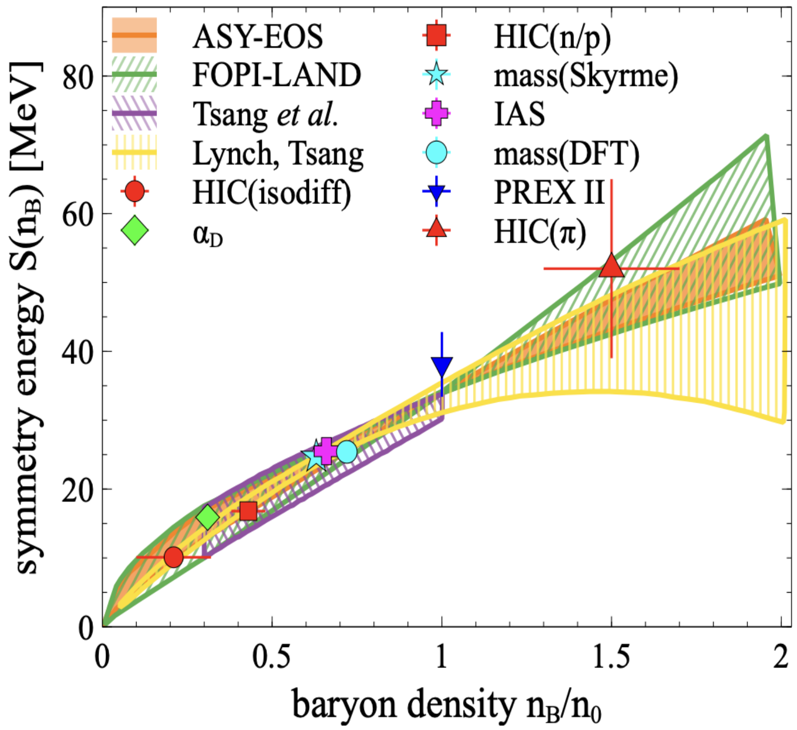
Symmetric matter

Symmetry energy




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




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