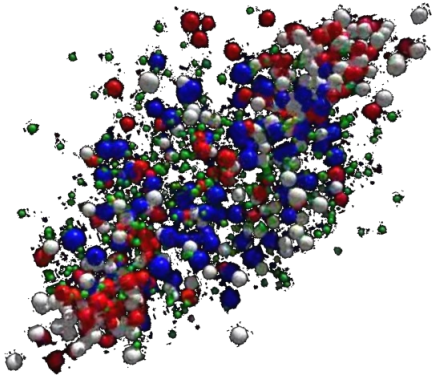
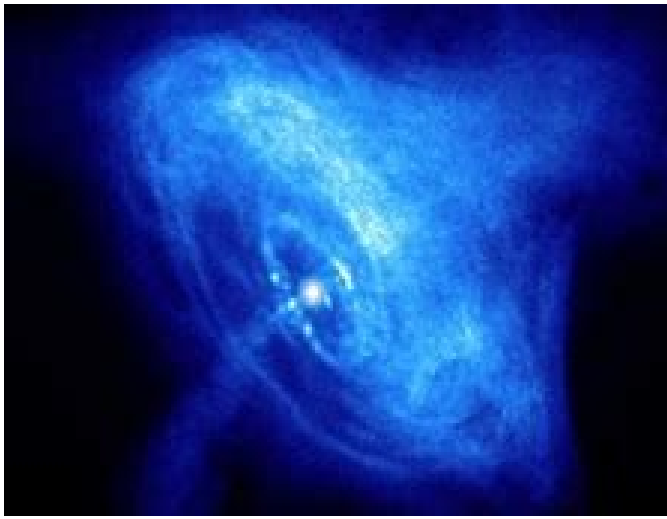
Physics Opportunities at CBM@FAIR



Wolf György@CBM
Wigner RCP, Budapest, Hungary

ExHIC-d workshop on QCD and hadronic dense matter 2025

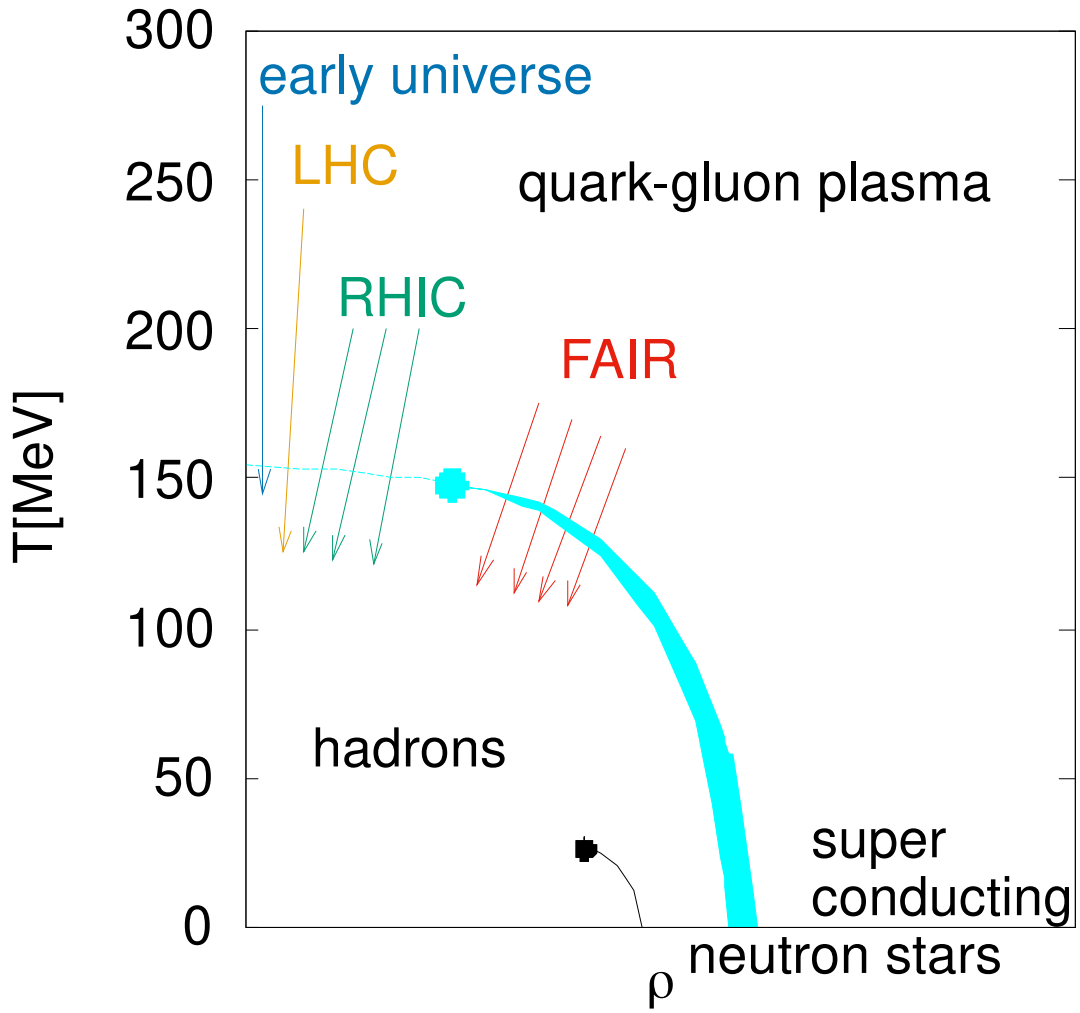
Jeju, 15.11.2025



Outline:

- *Open questions in dense matter*
- *Exploring the high-density EoS in the laboratory*
- *Experimental requirements*
- *Future experiment: CBM at FAIR*

Some of the slides were taken from P. Senger and Tetyana Galatyuk



RHIC, LHC: extreme large T and very low ρ

FAIR: intermediate T (~ 100-150 MeV), ρ~3-8 ρ_0

Neutron stars: low T, ρ~3-8 ρ_0

The main questions of heavy ion physics at high density

Search for landmarks of the QCD matter phase diagram:

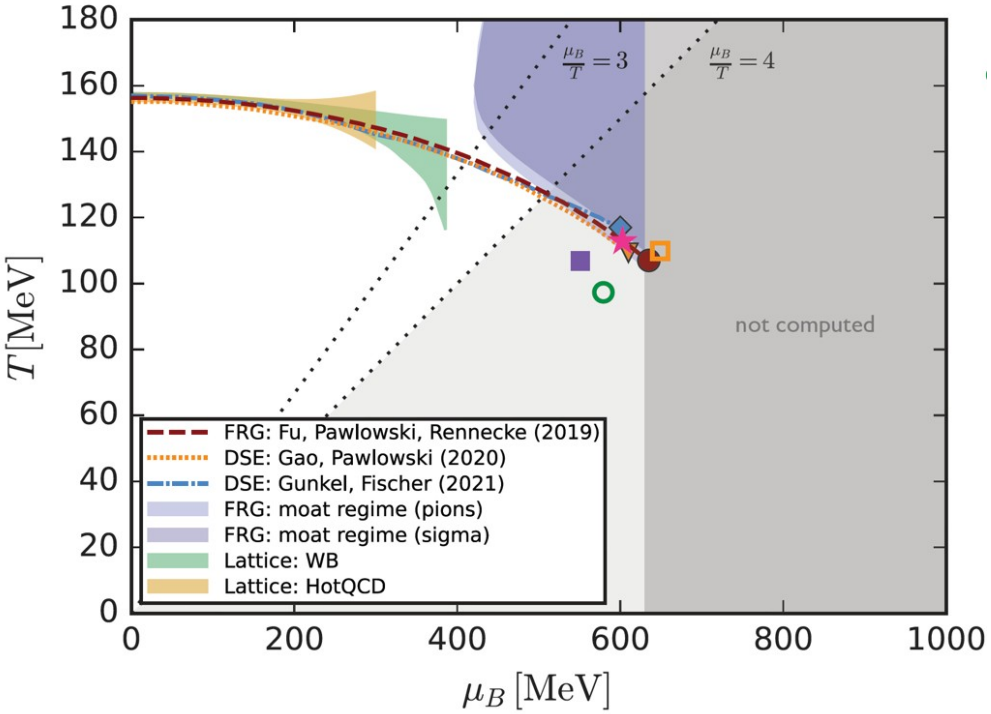
- isolate unambiguous signals of new phases of QCD matter
- order of phase transitions
- conjectured QCD critical point
- establish high net-baryon density EoS
- probe microscopic matter properties

→ **heavy-ion beams**

Study various aspects of meson/baryon physics:

- (*u, d, s, c*) hadron production mechanism
- spectroscopy (|*s*|=*2,3,* |*c*|=*1*), interactions, hadron structure
- electromagnetic transition form-factors

→ **p, d beams**



Many theoretical studies locate the CEP at around $\mu_b \approx 600$ MeV

$\sqrt{s_{NN}} = 3.6 – 4.1$ GeV

in the range of CBM

Observables for dense, strongly interacting matter

1. Nuclear Physics

- $\rho = 0$: NN scattering, YN and YNN interaction from femtoscopy (ALICE), lattice (HALQCD). They are consistent.
- $\rho = \rho_0$: masses of nuclei, hypernuclei, isobar analog states, giant dipole, pigmy resonances, neutron skin thickness

2. Perturbative QCD: $\rho \leq 40\ \rho_0$

N^3LO calculation, hard thermal loops: $\mu = 2.6$ GeV, $p = 3.8$ GeV/fm^3 .

T. Gorda, A. Kurkela, et al., Phys. Rev. Lett. 127 (2021) 162003, arXiv:2103.05658.

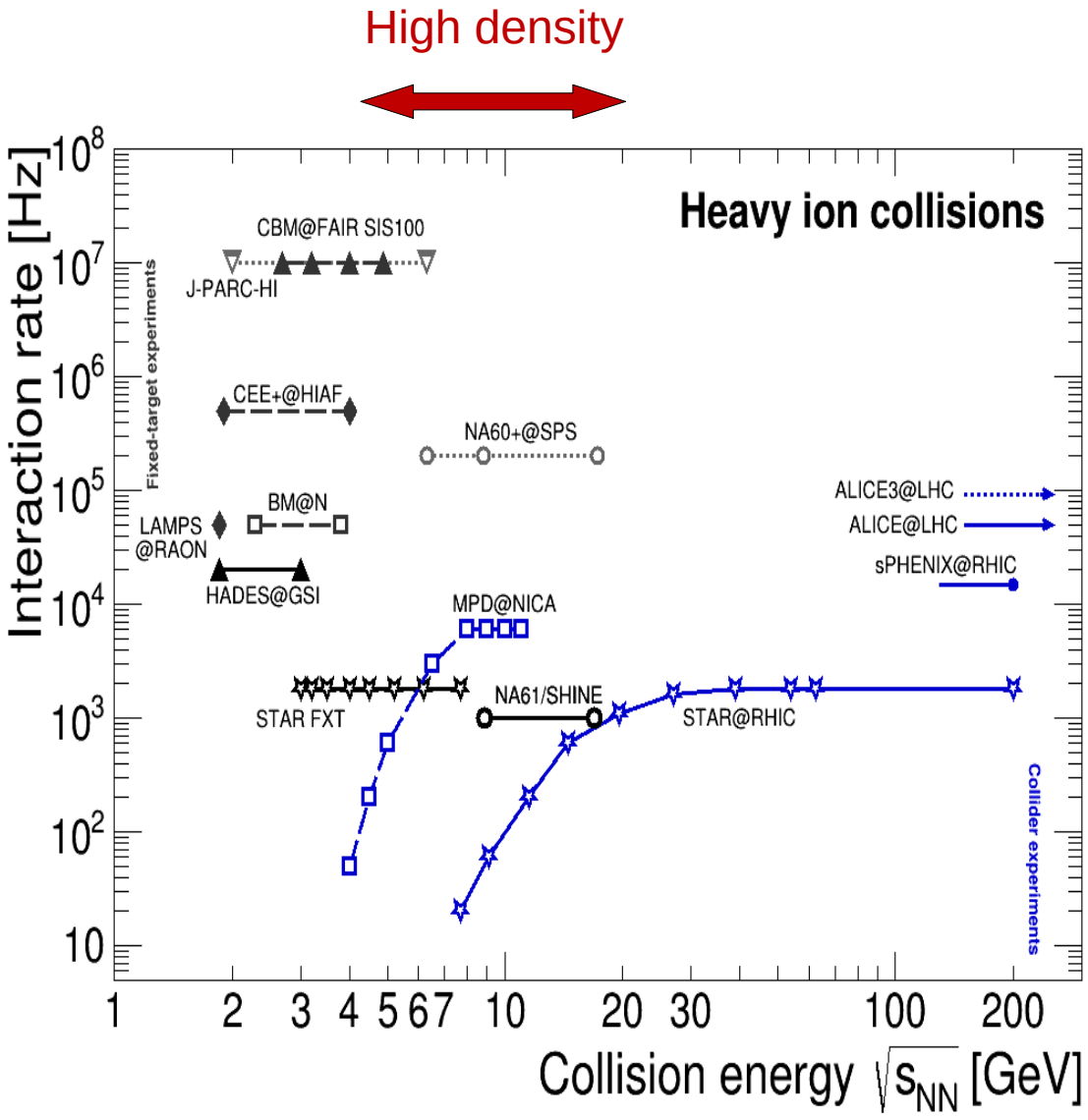
3. Neutron Stars ρ: 1-8 ρ_0

- T=0: M, R, Λ: Quite strong constraints even with no precise data
- T: 1-50 MeV: binary neutron star merger: producing most of the heavy elements, kilonova

4. Heavy ion collisions ρ:1-8ρ_0, T:50–150MeV

Interpretation difficult, many competing effects, equilibrium?

Experiments exploring dense QCD matter



Complementary approaches towards the study of dense baryonic matter, but joint technical developments:

- CBM photon detector used in HADES
- CBM TOF detector and reconstruction software used in STAR
- Foreward calorimeters for CBM and NA61/SHINE

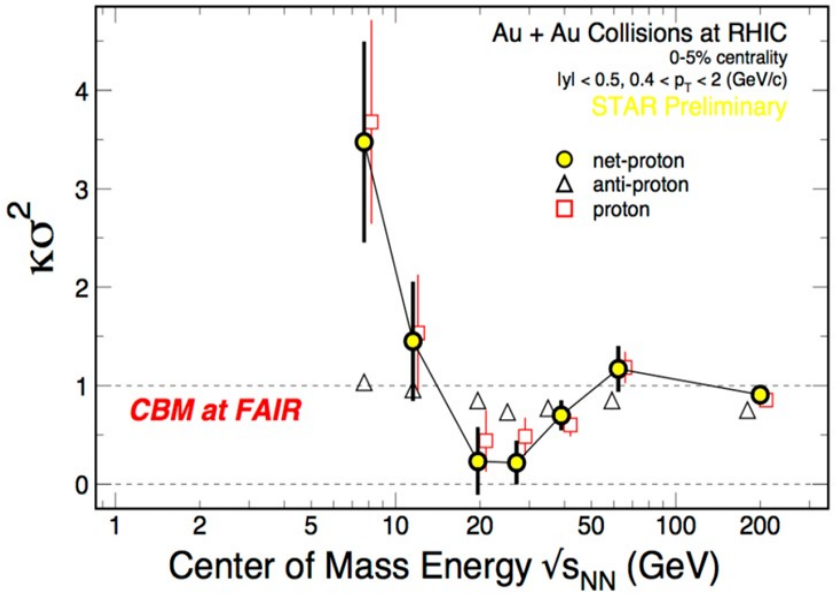
T. Ablyasimov et al., (CBM Collaboration) Eur. Phys. J. A 53 (2017) 60

Critical endpoint of 1st order phase transition

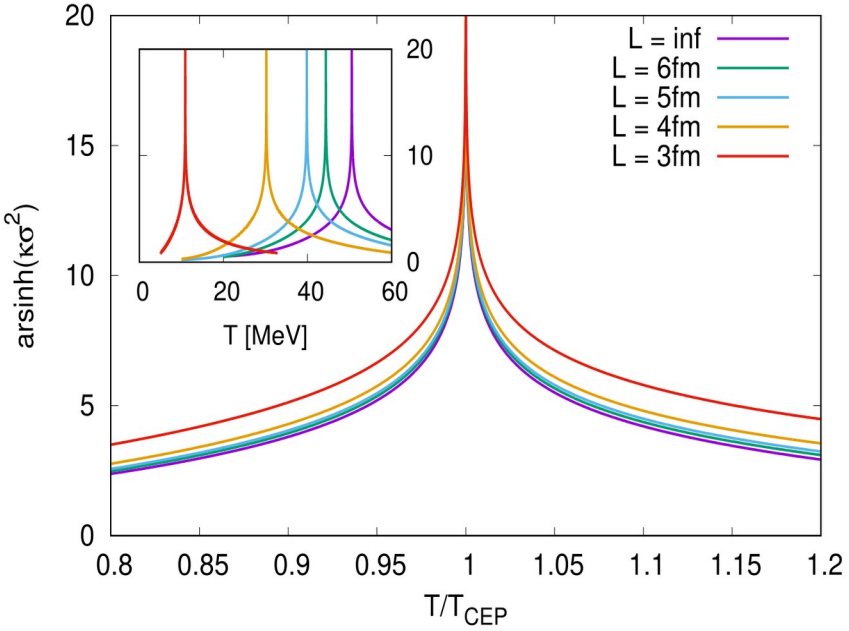
Event-by-event fluctuations of conserved quantities (B,S,Q)

$$\chi_n = \left.\frac{\partial^n p/T^4}{\partial(\mu_q/T)^n}\right|_T \qquad C_n = VT^3\chi_n \qquad \kappa\sigma^2 = \chi_4/\chi_2 \sim \xi^2$$

4th/2nd moment of net-proton multiplicity distribution
STAR beam energy scan



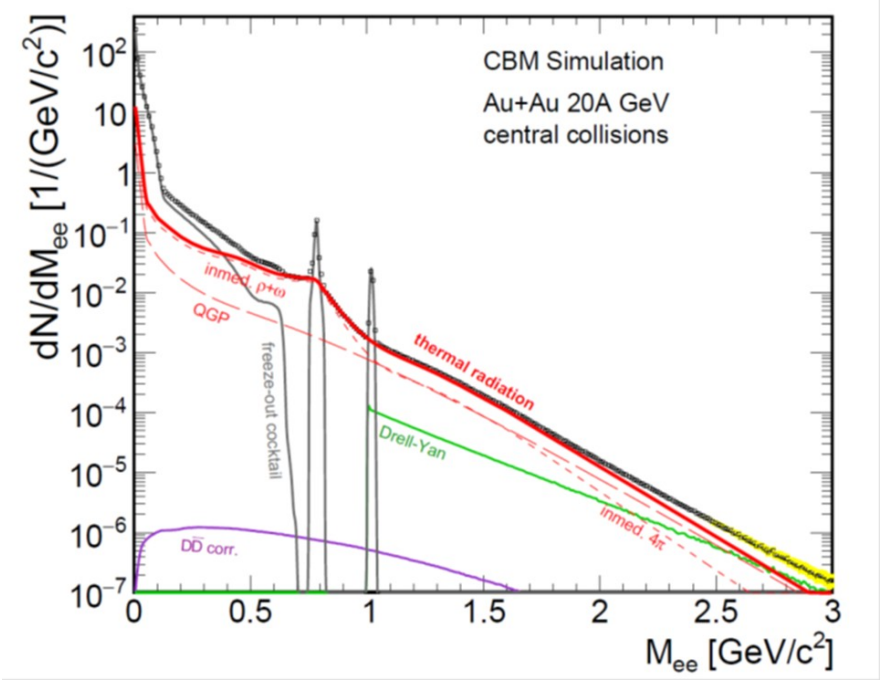
Finite-size effects
Kovács et al., Phys Rev. D108 (2023) 076010.



Experimental indication for a phase transition?

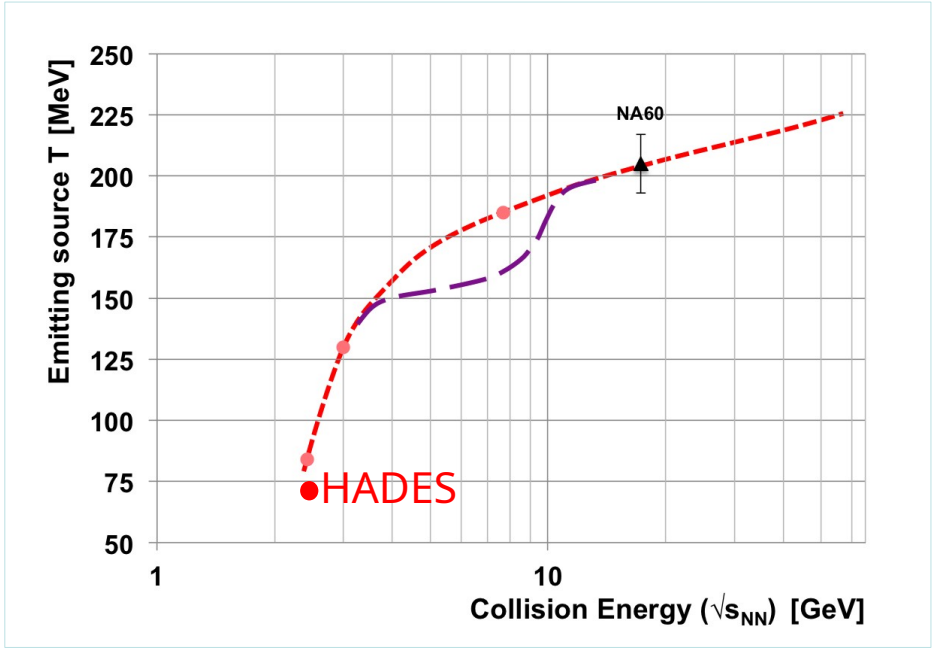
Thermal radiation from fireball → caloric curve (????)

Invariant mass distribution of lepton pairs
Au+Au collisions at 1.25 A GeV: T = 72 MeV
The HADES Collaboration, Nature Physics 2019



Slope of dilepton invariant mass spectrum
1 GeV/c^2 < M$_{inv}$ < 2.5 GeV/c^2

T. Ablyasimov et al., (CBM Collaboration)
Eur. Phys. J. A 53 (2017) 60



Baryon number fluctuation: change pattern

Experimental probes of EOS at CBM

Nuclear Symmetric Matter EOS:

- **Collective flow of Baryons (π, K, p, Λ, Ξ, Ω,...) driven by the fireball's pressure gradient**
- **Sub-Threshold Particle Production of Multi-Strange Hyperons via multi-step processes**

Neutron Matter EOS, Symmetry Energy

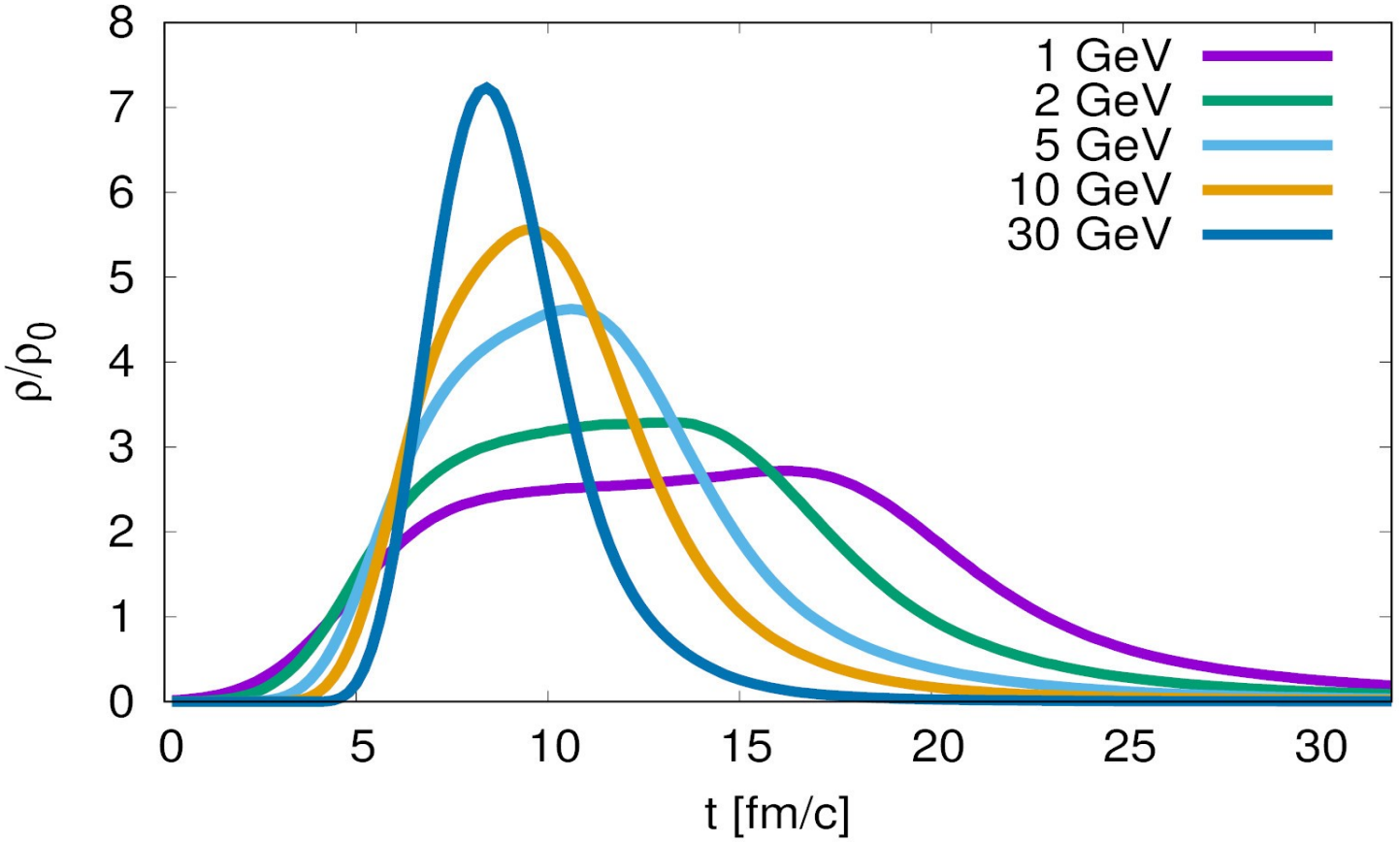
- **Neutron/Proton Elliptic Flow**
- **Sub-Threshold Particle Production of isospin-opposite particles (I_3 = 1) ?**

Hyperon interactions

- **Hypernuclei production and yields**
- **Hypernuclei flow and lifetime**
- **Correlation functions to study interaction cross-sections**

Density evolution in the central cell

Au+Au b=1 fm collisions at different collision energies

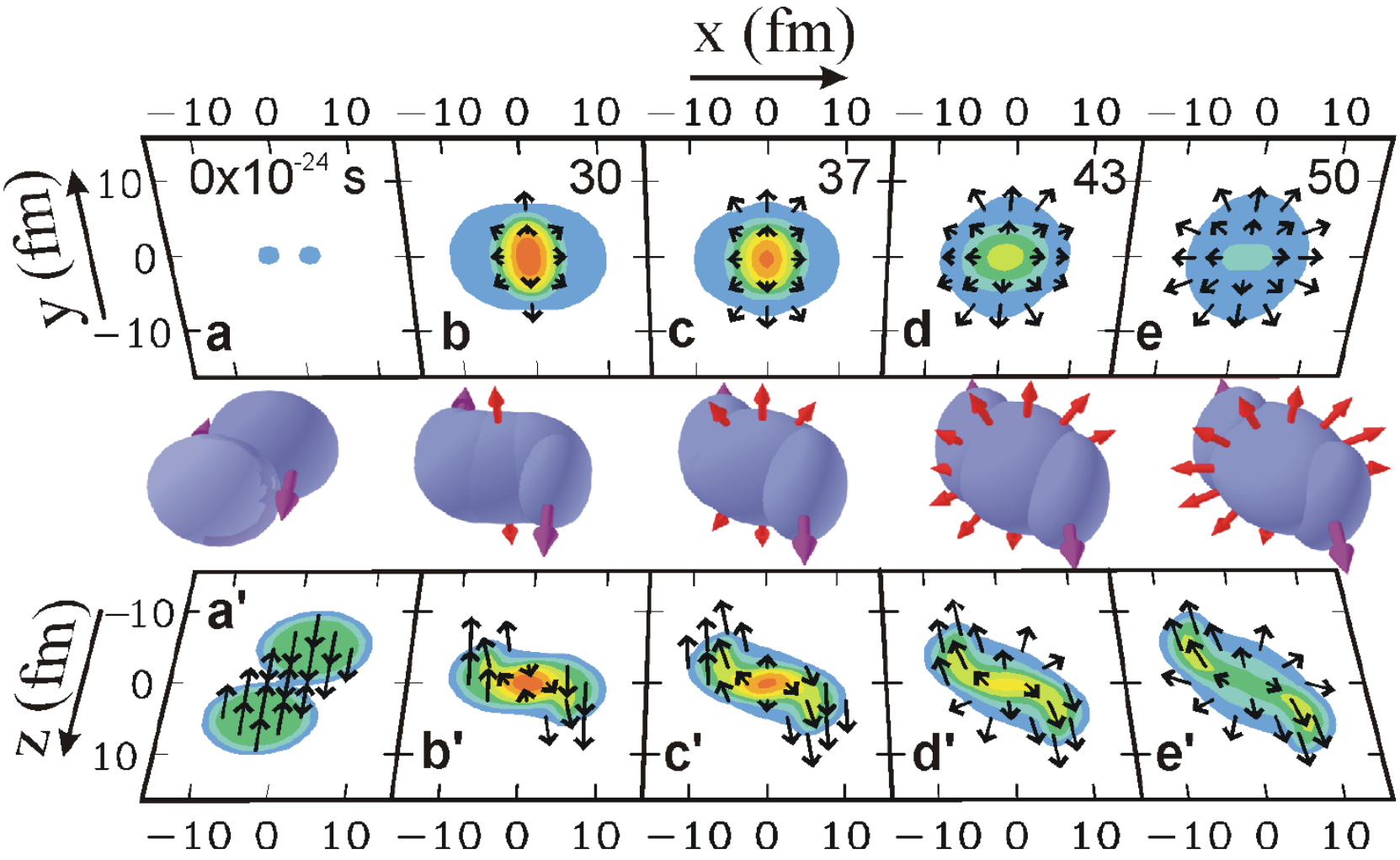


Density evolution as a function of time by BuBUU model

Gy. Wolf, Phys. Lett. B780 (2018) 25.

Collective flow of nucleons

semi-central Au+Au collision at 2 AGeV



Collective flow of nucleons: driven by pressure gradient

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

Collective flow in Au+Au collisions

Beam energy AGeV	central density	flow observable
0.4 – 1.5	$\rho = 1 - 3\ \rho_0$	v_2 of p, d, t, 3He
2 – 10	$\rho = 3 - 5\ \rho_0$	v_1 v_2 of protons
10 – 30	$\rho = 5 - 8\ \rho_0$	v_2 of protons

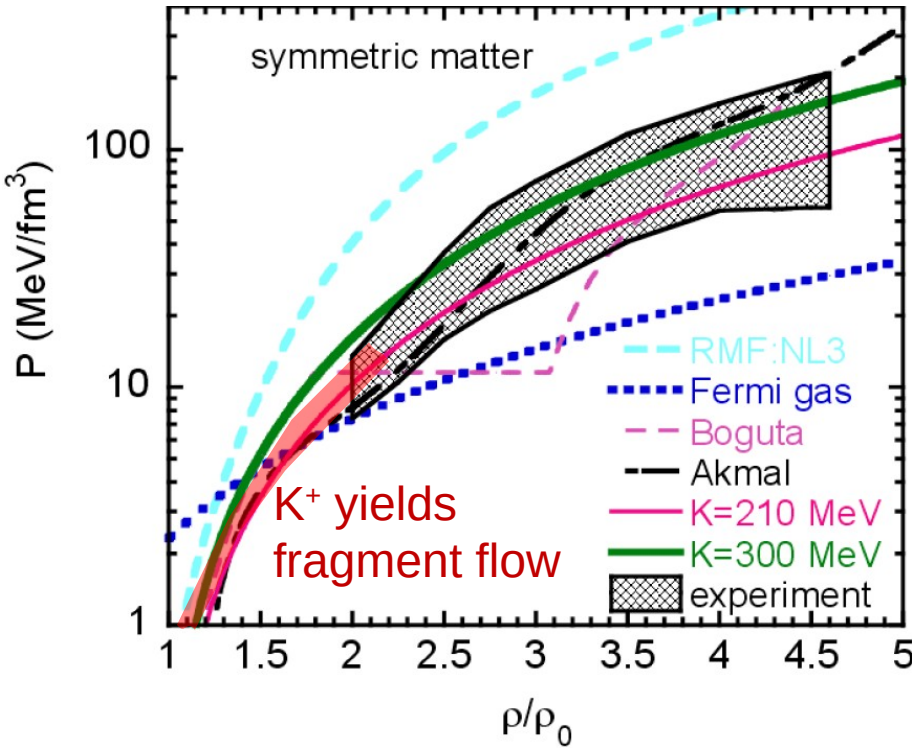
Within microscopic transport models the collective flow (caused by pressure gradient) is sensitive to:

The nuclear matter equation of state (compressibility)

In-medium nucleon-nucleon cross sections

Momentum dependent interactions

Nuclear incompressibility from heavy-ion collisions



hard EoS
soft EoS

EoS at $\rho \geqslant 3\ \rho_0$?

Collective flow of protons:
P. Danielewicz, R. Lacey, W.G. Lynch,
Science 298 (2002) 1592

Collective flow of protons and light fragments
A.Le Fevre et. al., Nucl. Phys. A945 (2016) 112

Kaon yields
C. Sturm et al., (KaoS Collab.) PRL 86 (2001) 39
C. Fuchs PRL 86 (2001) 1974

Symmetry energy

Affects: NS crust thickness, reaction rates involved in the astrophysical r-process, cooling of NS, MR curve

Experimental attemps: nuclear masses, isobaric analog states, neutron skin thicknesses r_{np} =sqrt(<r_n^2>) - sqrt(<r_p^2>), nuclear dipole polarizabilities, giant and pygmy dipole resonance energies, flows in heavy-ion collisions

Recent results from parity-violating electron scattering neutron skin experiments of ^{208}Pb (PREX-I and PREX-II) and ^{48}Ca (they are not very compatible)

The nuclear symmetry energy

$$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2 + \ldots, \quad \delta=(\rho_n-\rho_p)/\rho$$

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

Empirical value $E_{sym}(\rho_0) \approx 30$ MeV

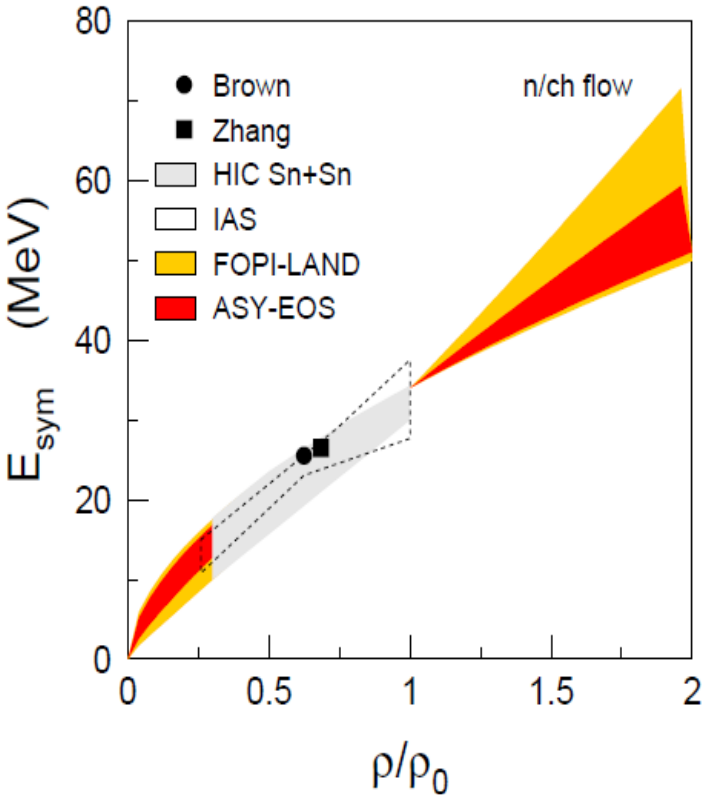
Slope, not very well known: $L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0}$

theoretical value $L(\rho_0) \approx 60$ MeV

B.A. Li and X. Han, Phys. Lett. B 727 (2013) 276

curvature $K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial^2 \rho}\right|_{\rho=\rho_0}$

theoretical value K_{sym} = -700 to 470 MeV

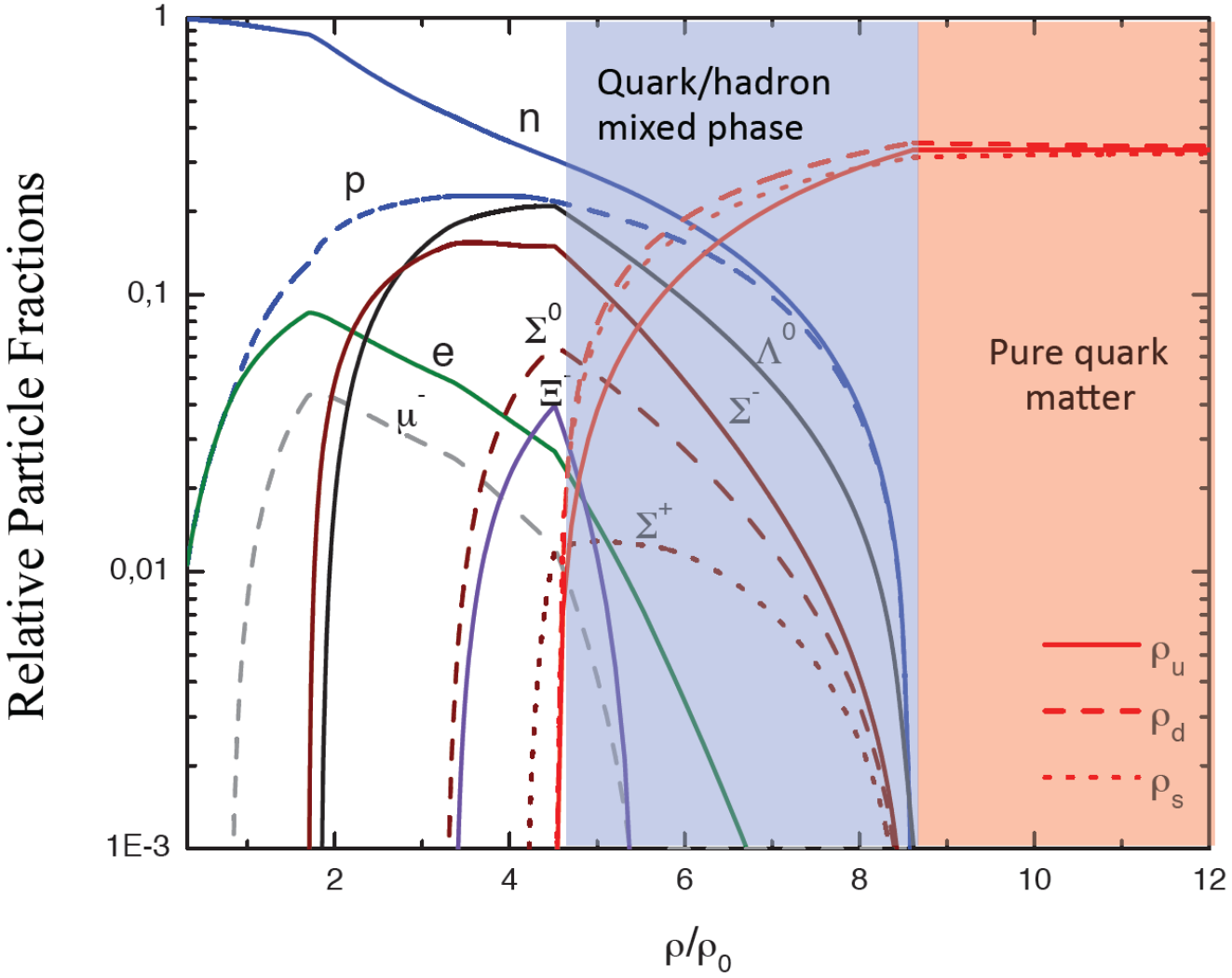


elliptic flow n/ch
Au+Au 400A MeV

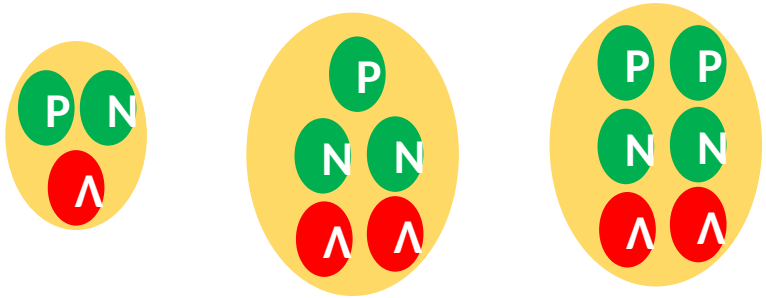
P. Russotto et al., Phys. Rev. C 94, 034608 (2016)

Degrees-of-freedom at neutron star matter

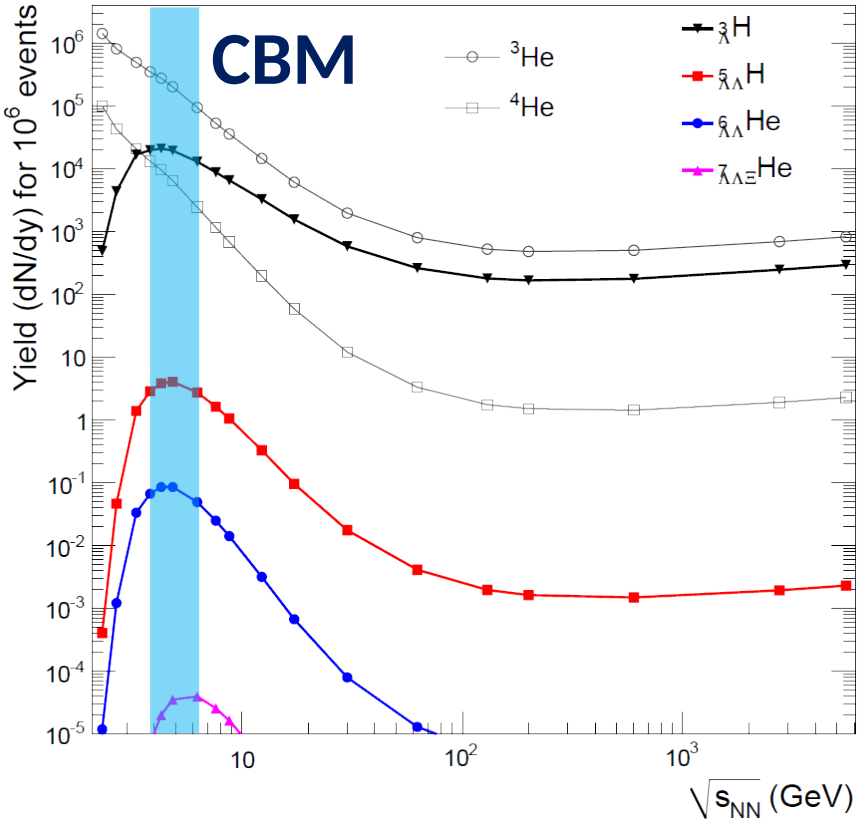
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014 (SU(3)-NJL model calculations)



N-N, Λ-Λ interactions at CBM



<u>Hypernuclei</u> produced in dense matter are excellent particles to study Λ-N, Λ-Λ interactions!



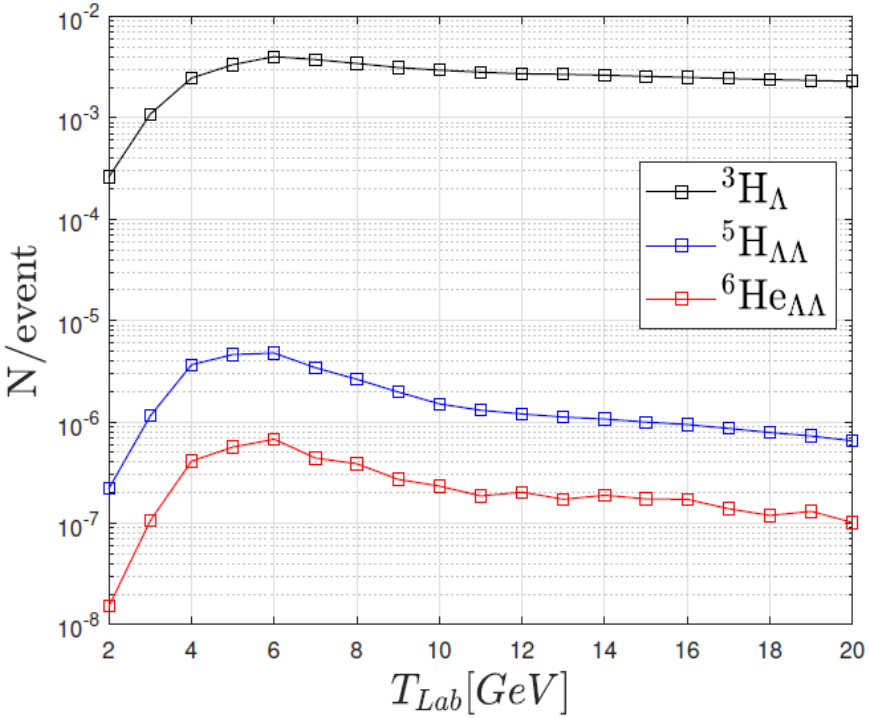
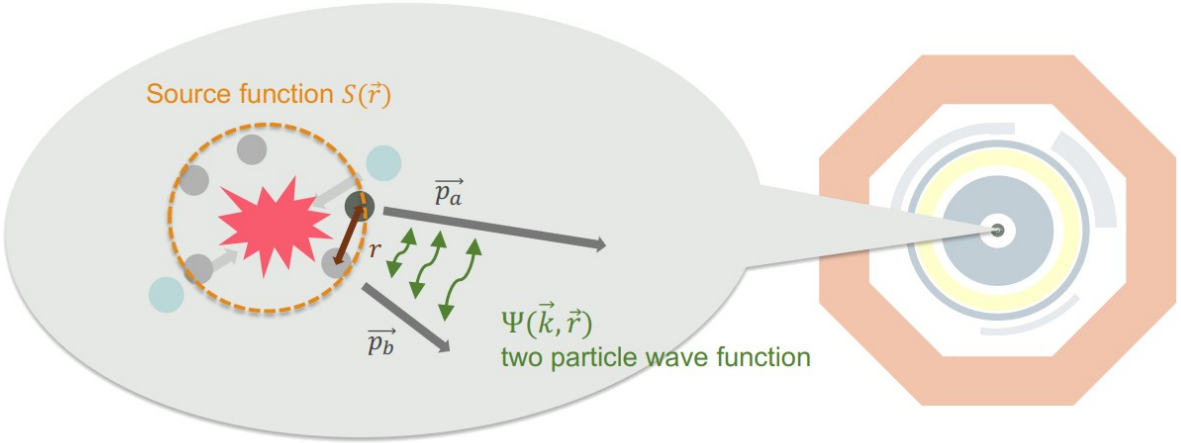


Fig. 2. Hypernuclei production yields in Au+Au collisions at $0-10\%$ centrality, using the assumption of equal $N\Lambda$ and $\Lambda\Lambda$ interaction strengths.

Thermal model:
A. Andronic et al., Phys. Lett. B697 (2011) 203

BuBUU: Balassa, Wolf, Eur. Phys. J. A59 (2023) 89.

NΛ, ΛΛ interactions from femtoscopy



Statistical definition ***Experimental definition*** ***Theoretical definition***

$$C(k) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\text{Same}}(k)}{N_{\text{Mixed}}(k)} = \int S(\vec{r})\left|\Psi(\vec{k},\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k\to\infty} 1$$

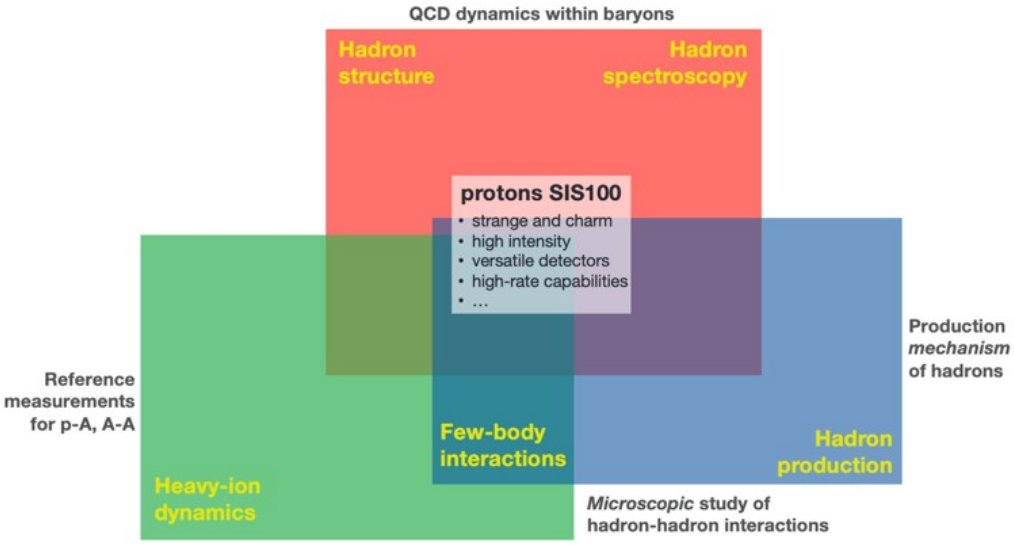
Single-particle momenta

Relative distance / reduced momentum in the rest frame of the pair

Lisa, Pratt, Wiedemann,Solz,
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

C(k) is measurable, S(r) assumed to be known
ψ(k,r) is the solution of the Schrödinger-eq. with a U(r,k) potential

Hadron Physics at GSI and FAIR



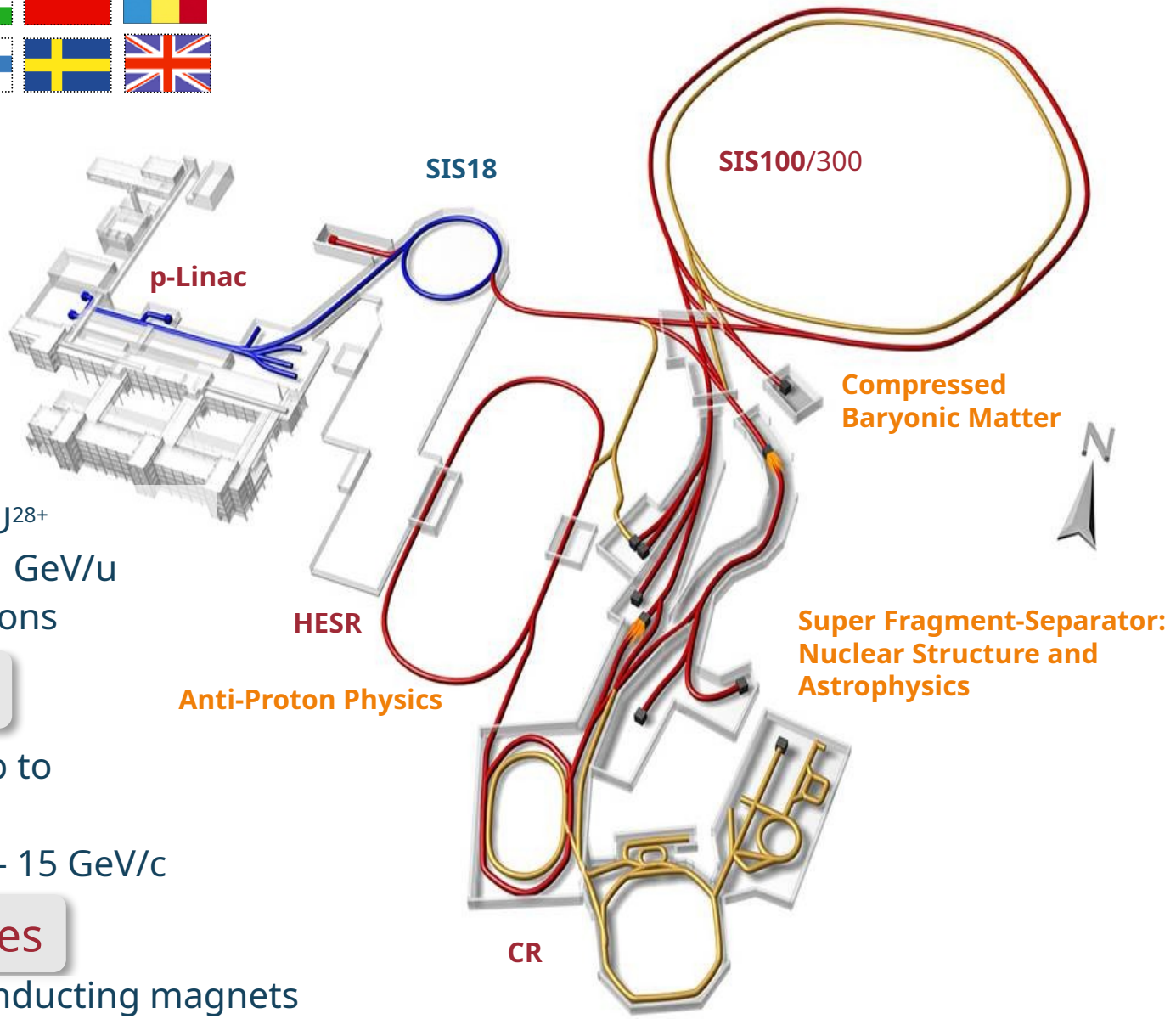
- Initiative (2022) from FAIR-motivated group from within CBM, HADES, PANDA → strengthen CBM science in hadron physics by involving exclusive channels
- High potential for hadron physics with **proton & deuteron beam from SIS100**
- **Substantial extension of QCD program at FAIR** and its impact on increased attractivity/visibility for international community
- **Importance of physics with GSI pion beams + HADES strongly emphasized by the community**

Experimental requirements

- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \sim 50$ μm)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- Triggerless free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

Facility for Antiproton & Ion Research

100 m



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{92+}$ up to 11 GeV/u
- 3x10^{13}/s 29 GeV protons

Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u;
- 10^{11} antiprotons 1.5 - 15 GeV/c

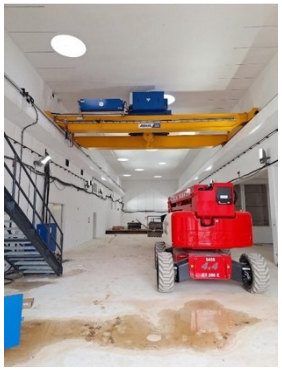
Technical Challenges

- rapid cycling superconducting magnets
- dynamical vacuum

FAIR Project Progress

SIS100 installation

CBM building is accessible by road

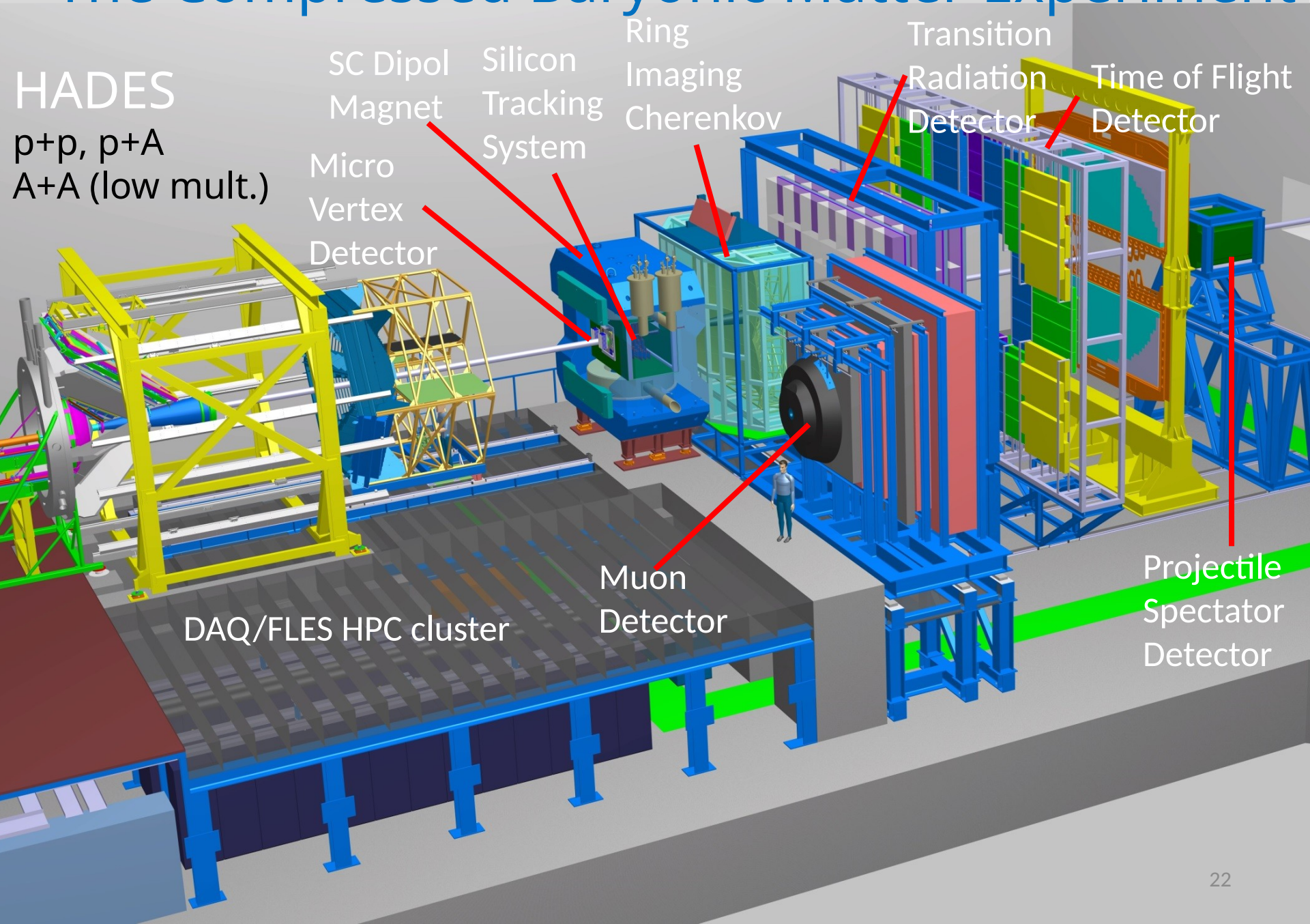


30-ton crane installed and commissioned

Start of commissioning of Cryo plant and Cooling water system

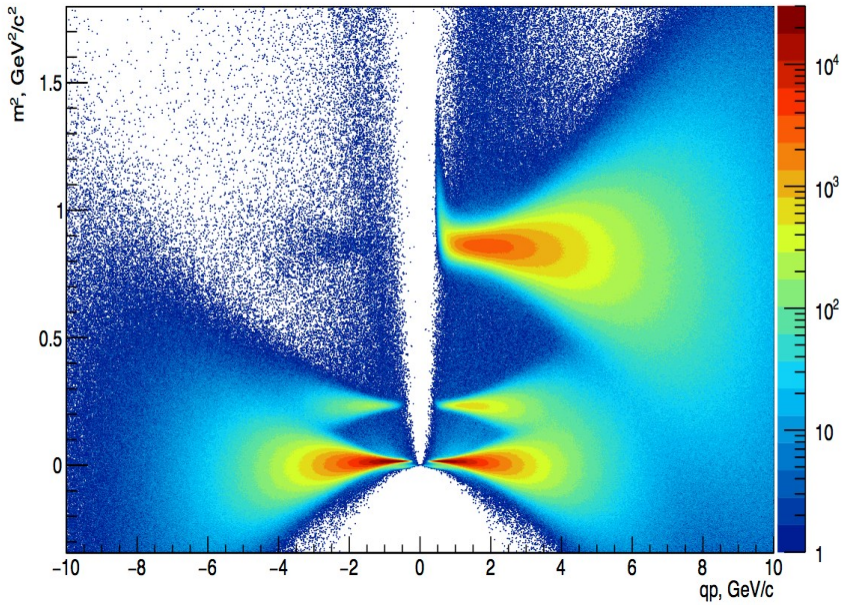
Start of installation of the SIS100 laser cooling system

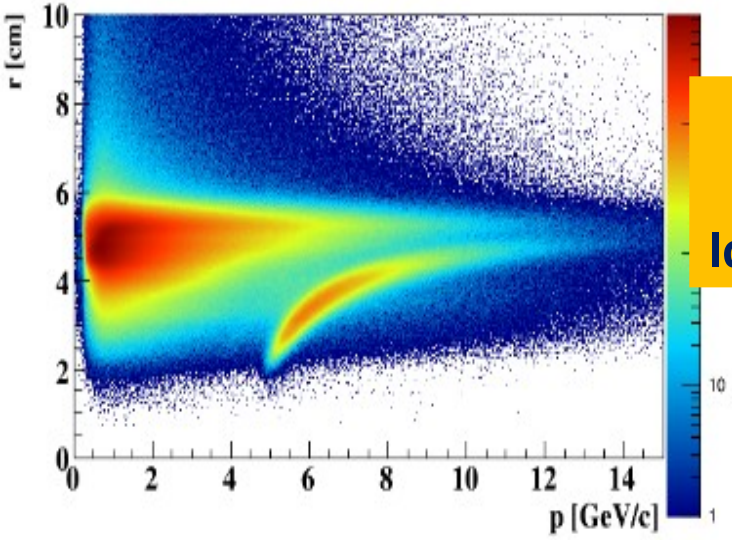
The Compressed Baryonic Matter Experiment



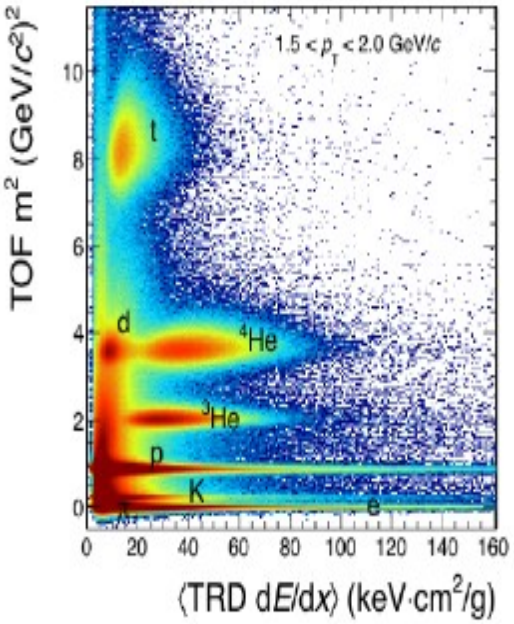
Particle identification

ToF
Hadron Identification





RICH
Electron Identification

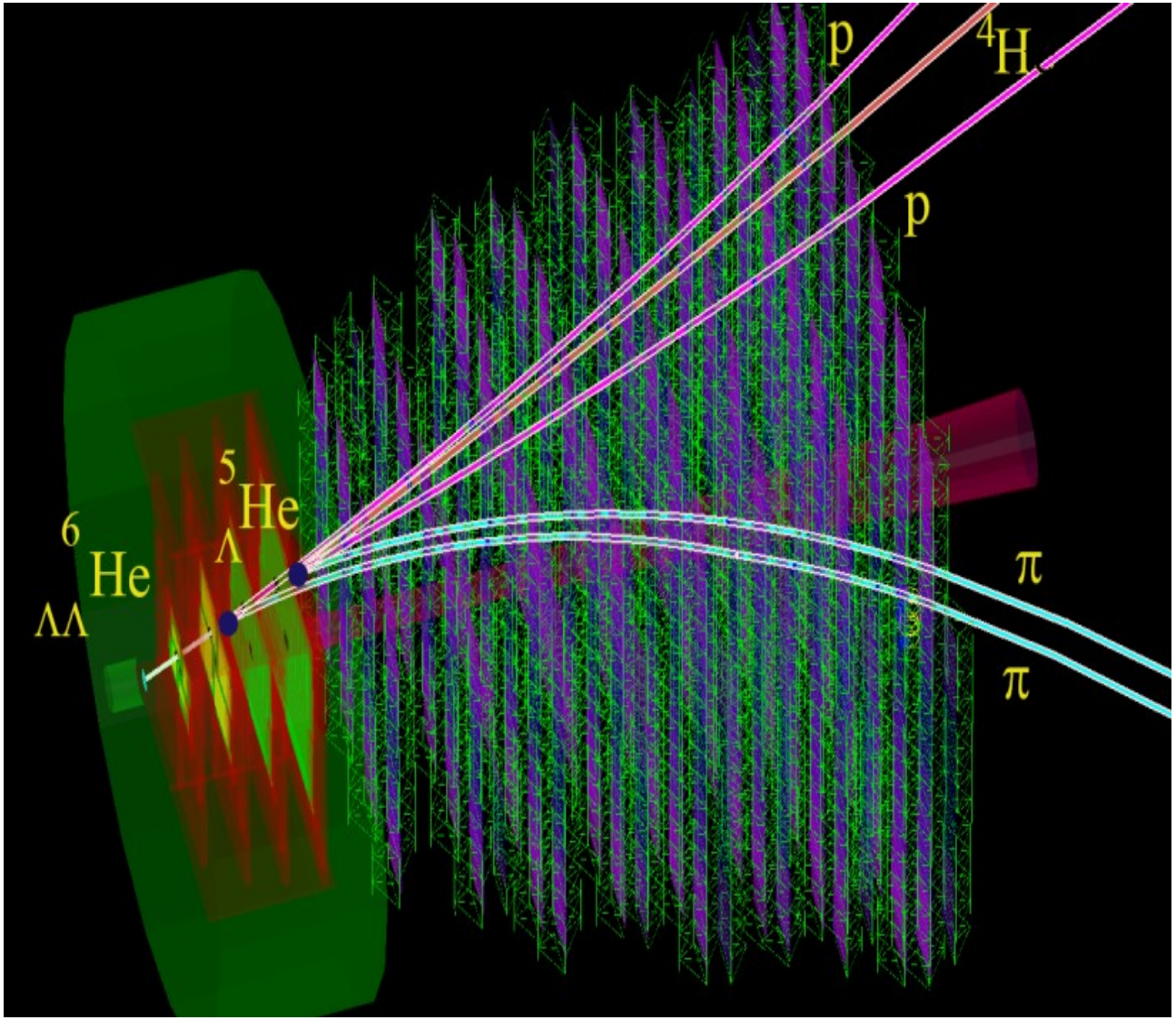


TRD + ToF
Electron, Light Nuclei, Heavy Fragments

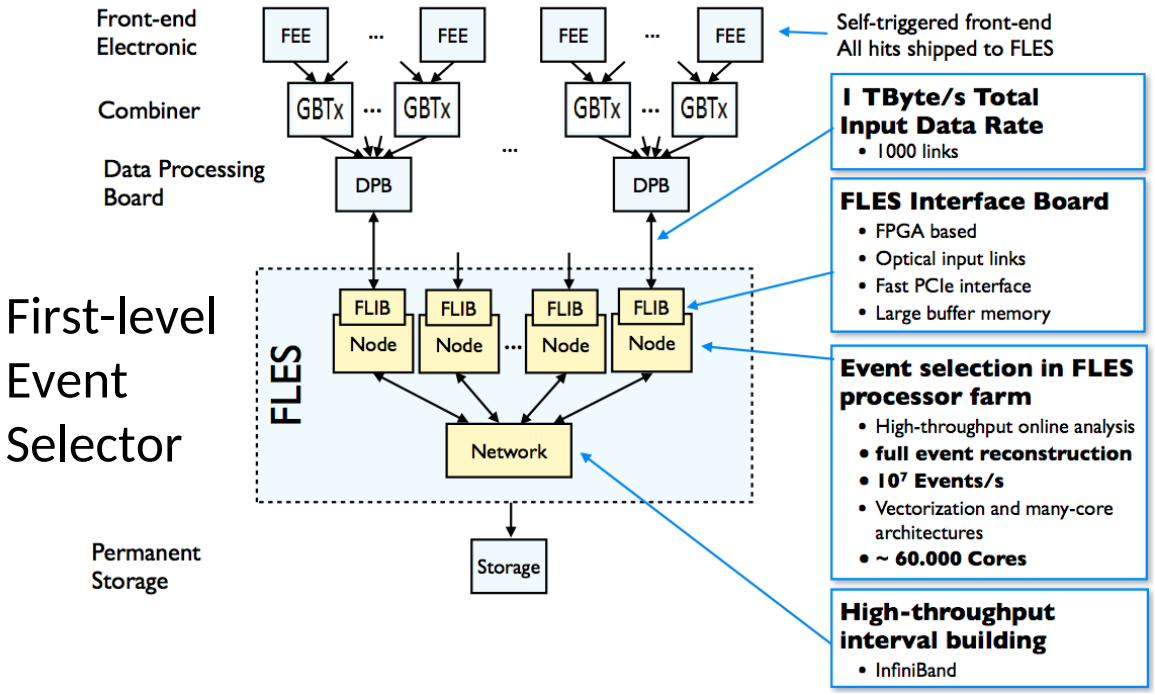
Very precise identification of electrons, charged pions, protons and light nuclei

Reconstruction of decay topology

$^{6}_{\Lambda\Lambda}$He → ^{4}He 2 p 2π



CBM DAQ and online event selection



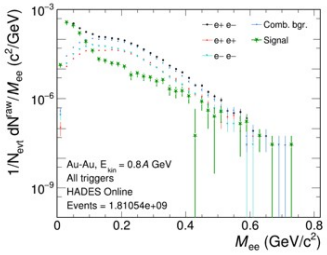
Novel readout and data acquisition system:

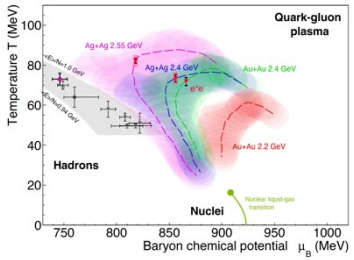
- no hardware trigger on events, free-streaming data read-out
- each detector hit provided with a time stamp
- full online „4-D“ track reconstruction, event definition and data selection by high-speed algorithms running on the GSI GreenIT cube

CBM „phase 0“ experiments: HADES, STAR, E16

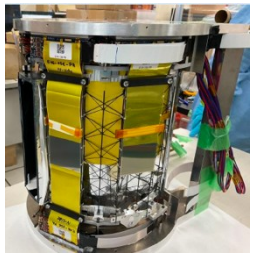
HADES RICH photodetector upgrade employing CBM technology

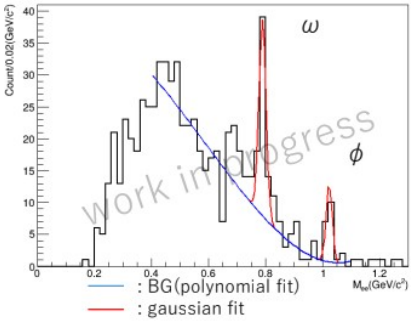
Fast on-line dilpton spectra from 2025 Au+Au, 800 AMeV





N. Schild, S. Kim, QM25

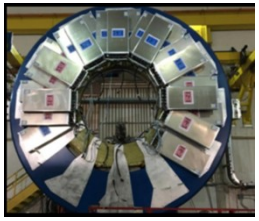


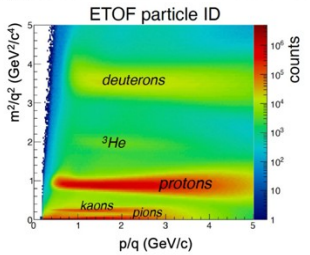


Result of E16 pilot run (p+A collision) ~20h data taking

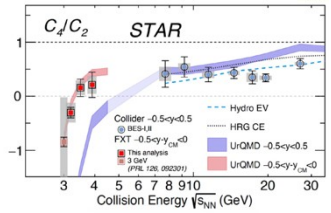
Yuhei Morino, QM25

*10 pre-series STS modules were built, assembled and tested at GSI and are installed as innermost tracking detector of the **E16** experiment at J-PARC*





eTOF provided by CBM-FAIR, crucial for BES-II, especially for the FXT program

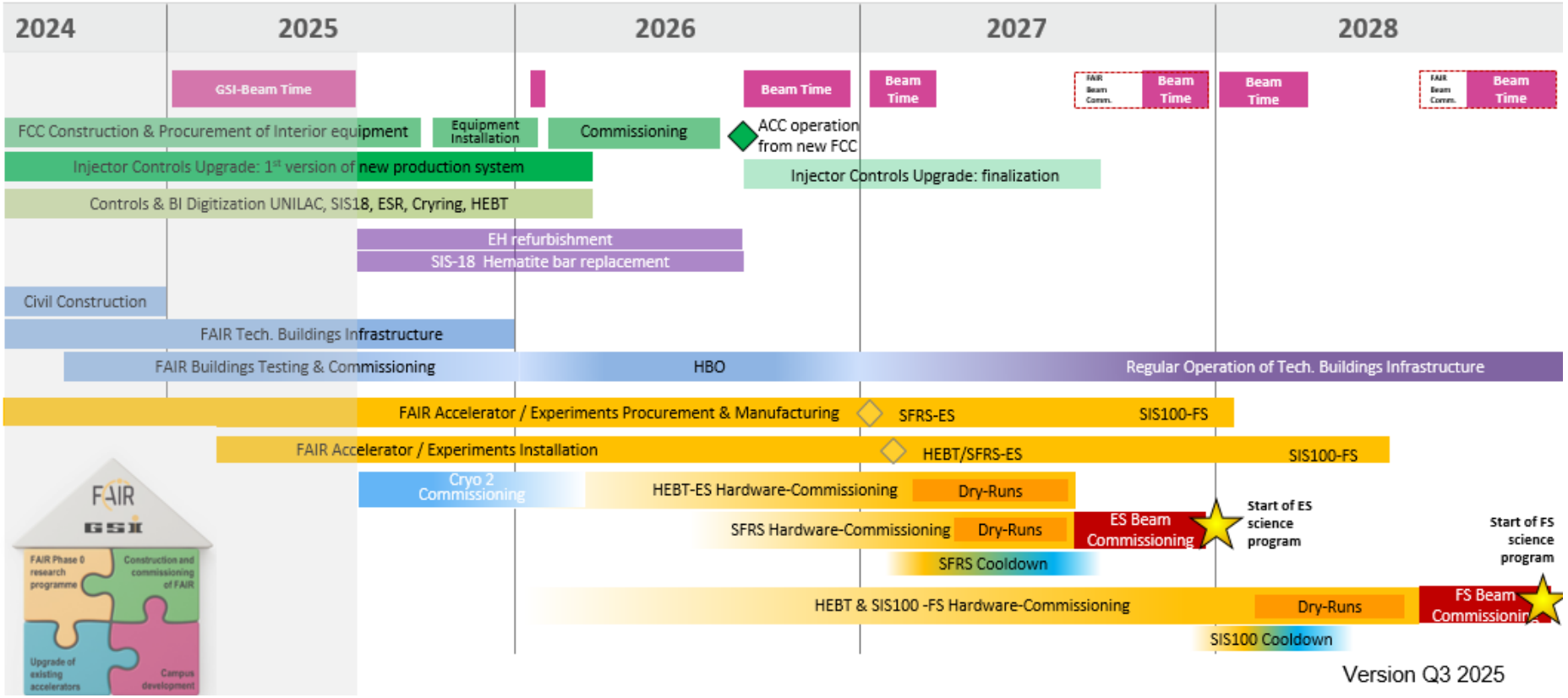


Zachary Sweger, QM25

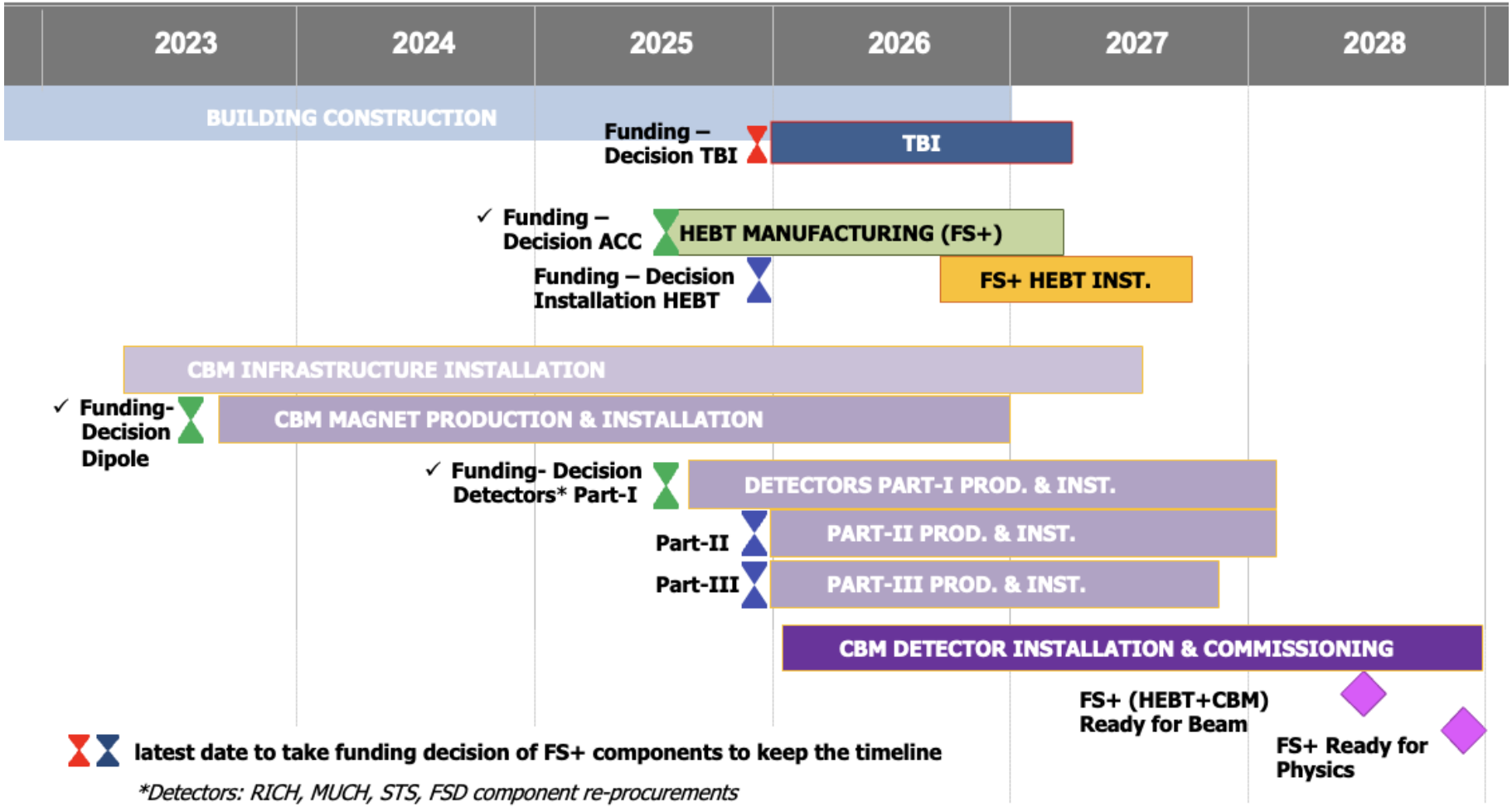
- Demonstrate performance of major components
- Physics results with CBM devices and software packages

The CBM detector will be ready for beam in 2028

FAIR schedule



CBM schedule



Magnet re-procurement *accomplished.*

High Energy Beam Transfer to CBM cave. FAIR Council Jul'25: *"... the procurement of the HEBT beam line to CBM for the value of 1,75 M€@today have been approved"*

Access to the building is available since March '25, crane is installed and commissioned.

Technical Building Infrastructure (**TBI**) of CBM building. *FAIR Council Dec'24 approved the contracting of TBI engineering!*

CBM components: FAIR Council Jul'25: *"Procurement of CBM detector components for the value of 700 k€@today have been approved by Council."*

Summary

The goal of the CBM@FAIR is to explore the fundamental properties of dense strongly interacting matter by measuring multi-differential observables (hadrons and leptons) with unprecedented precision.

Experimental Requirements

- **Unique measurements of bulk & rare probes with CBM**
- **High-rate capability of detectors and triggerless DAQ**
- **Online event reconstruction and selection**

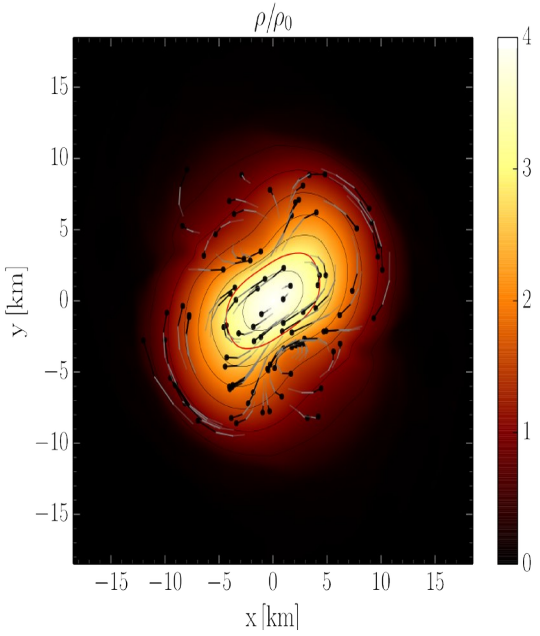
Testing CBM components and analysis methods within FAIR Phase-0 were succesfull

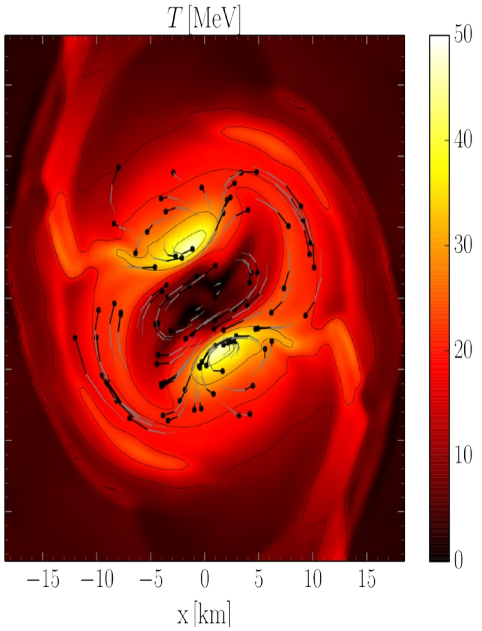
Large discovery potential (Phase transition)

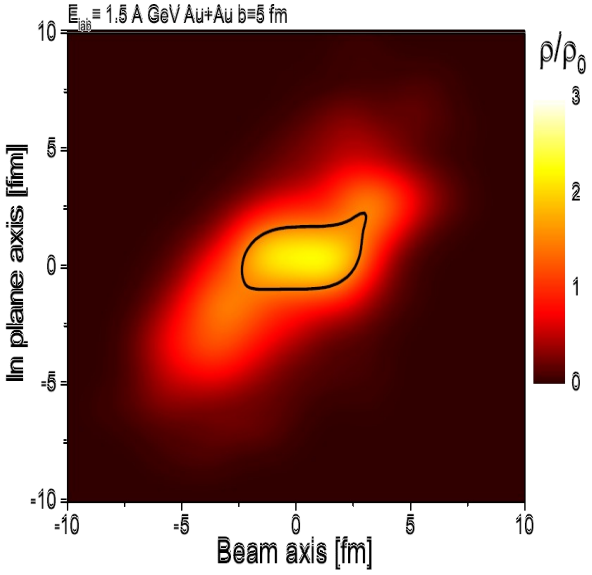
Collaboration Status:

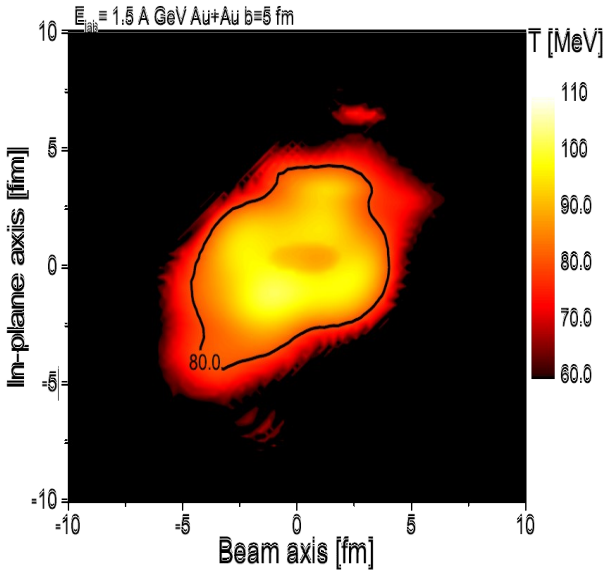
Thanks for your Attention

Dense strongly interacting matter









Neutron star merger

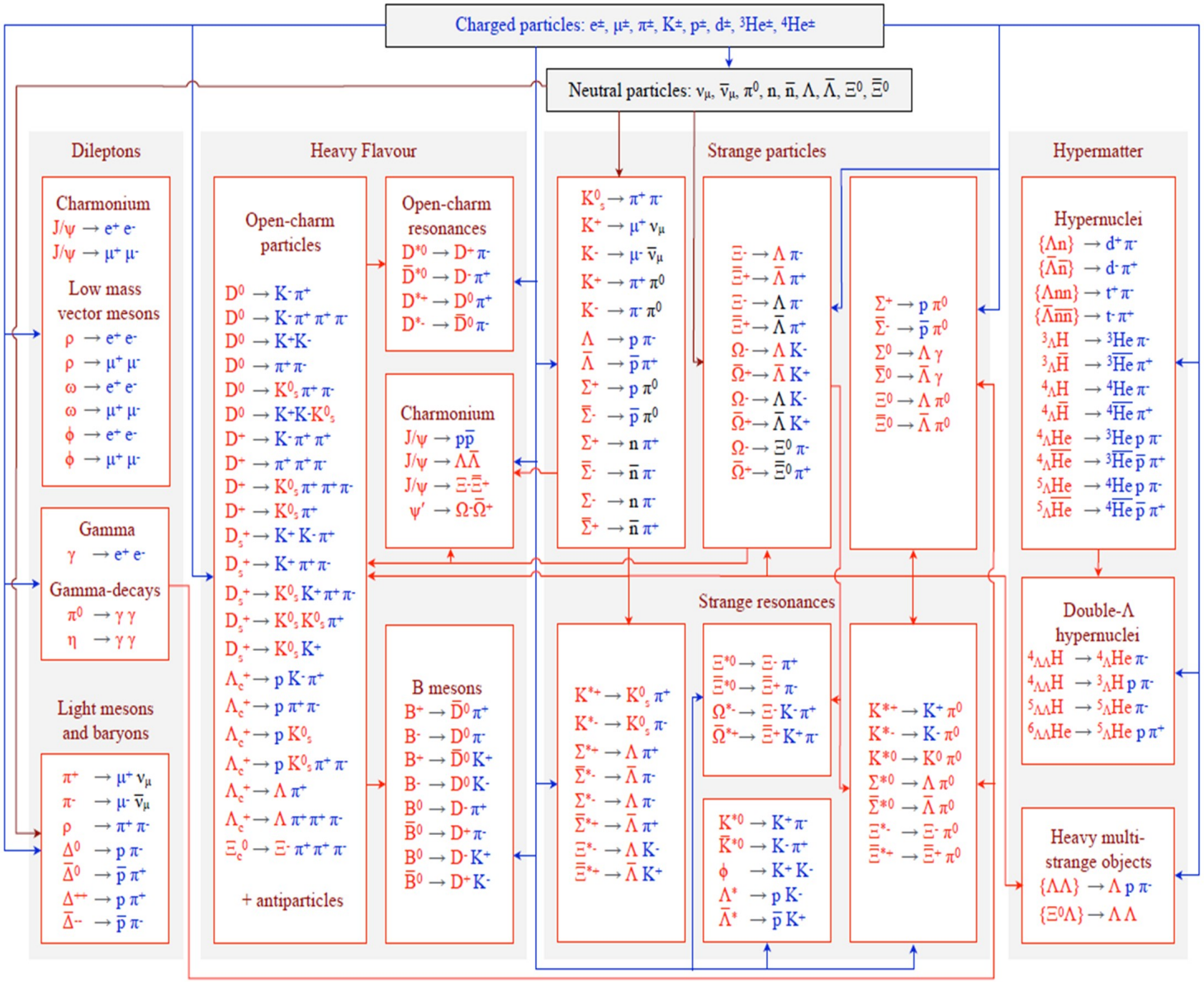
Equation of State (EOS)

$\rho > \rho_0$

Heavy ion collisions

Au+Au 1.5 AGeV b=5fm

Online particle identification in CBM: The Kálmán Filter Particle Finder



Almost 150 decays

All decays are reconstructed online

Kálmán Filter method