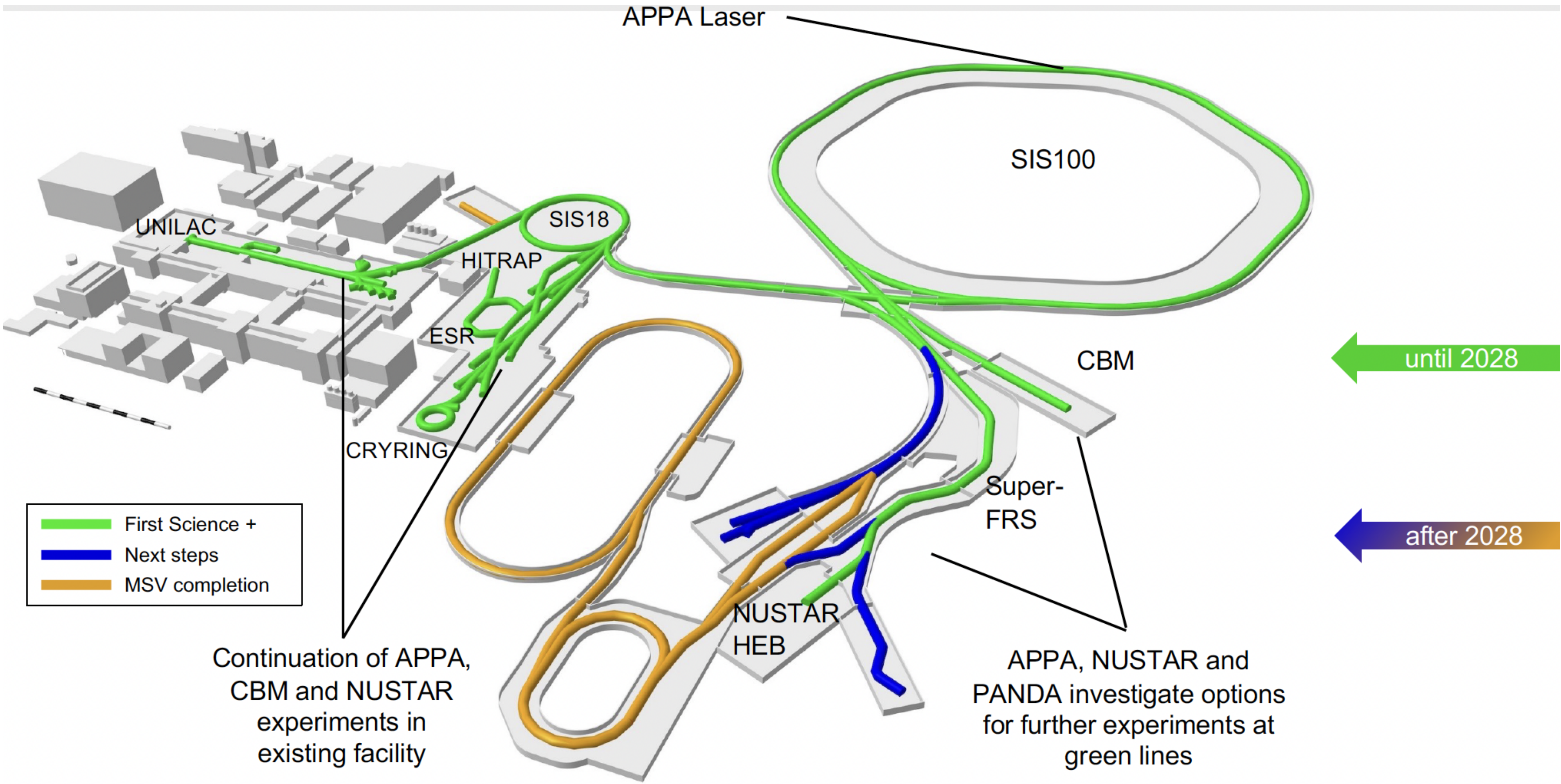
The Compressed Baryonic Matter Experiment

A. Andronic - University of Münster

for the CBM Collaboration

- FAIR
- CBM
  - Detector
  - Physics: motivation, goals, performance
  - Current status
- Summary / Outlook

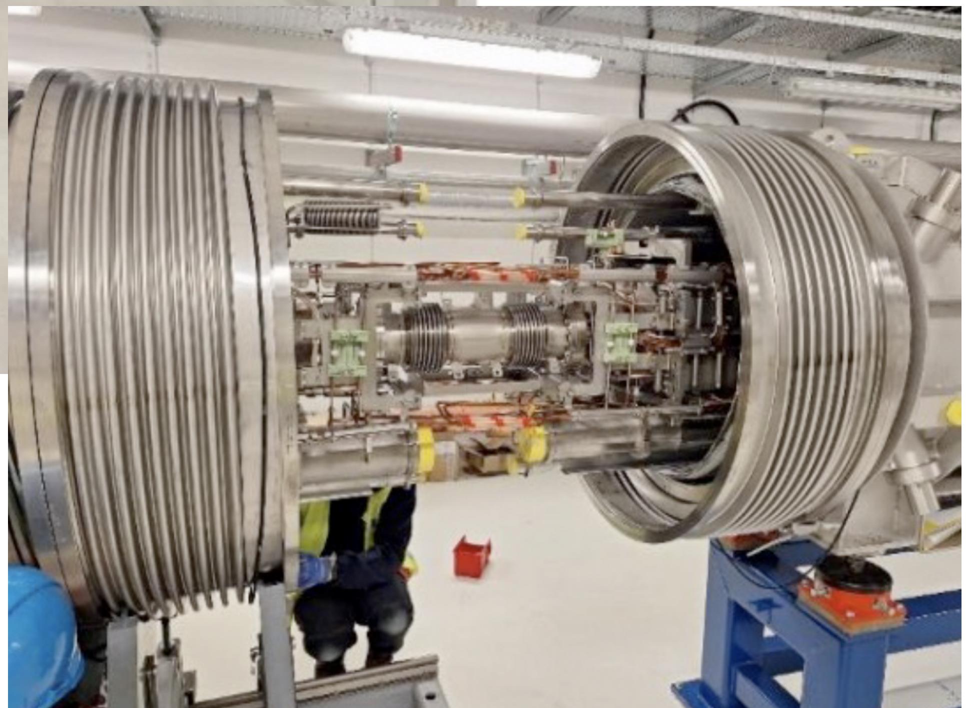
FAIR Complex at GSI Darmstadt




Facility for Antiproton and Ion Research
multi-purpose (strong interaction) facility
FAIR
• Civil construction work completed
• Installation of accelerator components begun
Sep. 2024

FAIR Complex

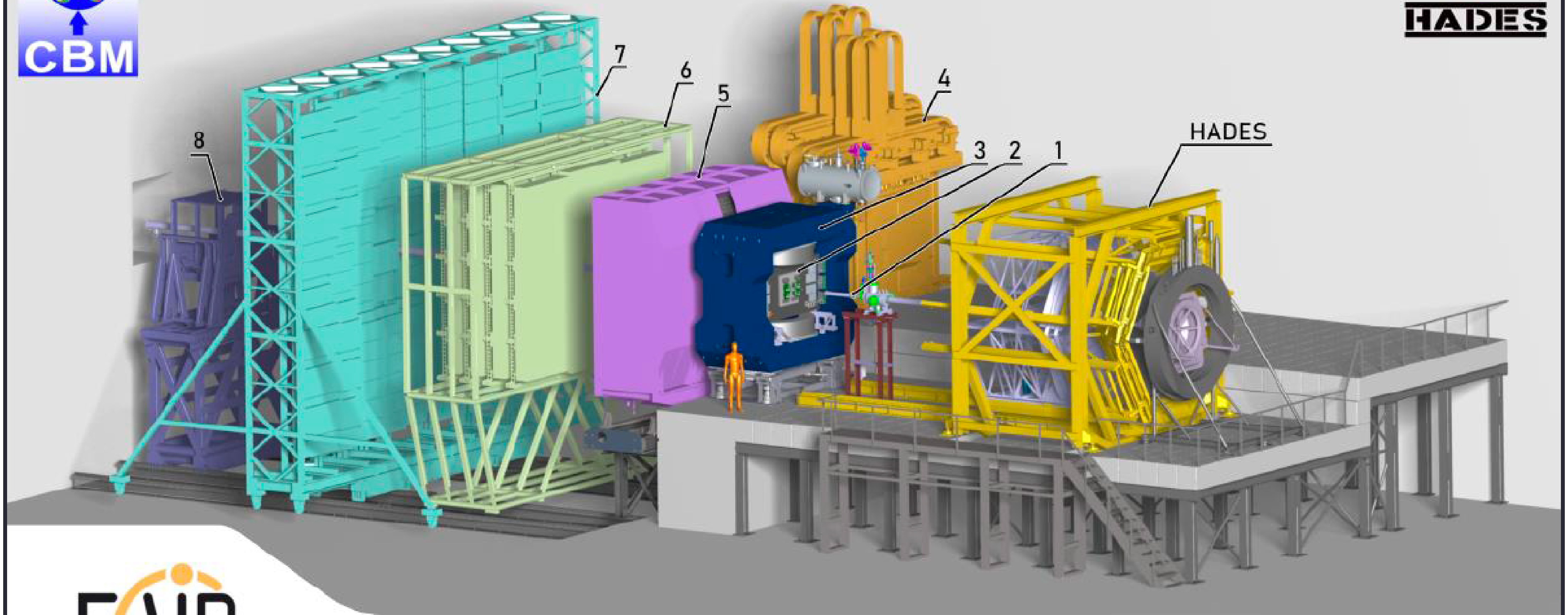
Inside FAIR



see More photos, videos

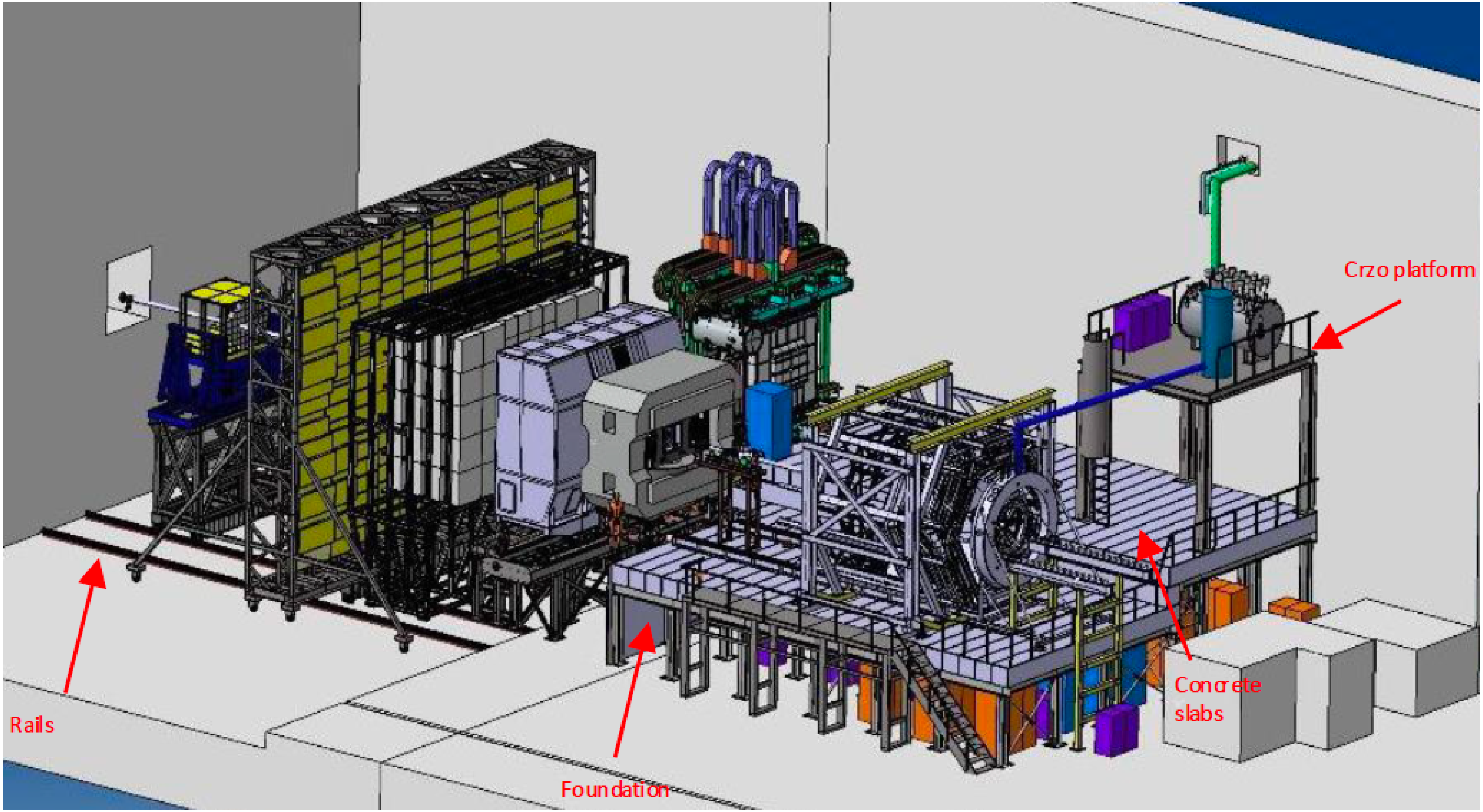
CBM Detector

Compressed Baryonic Matter



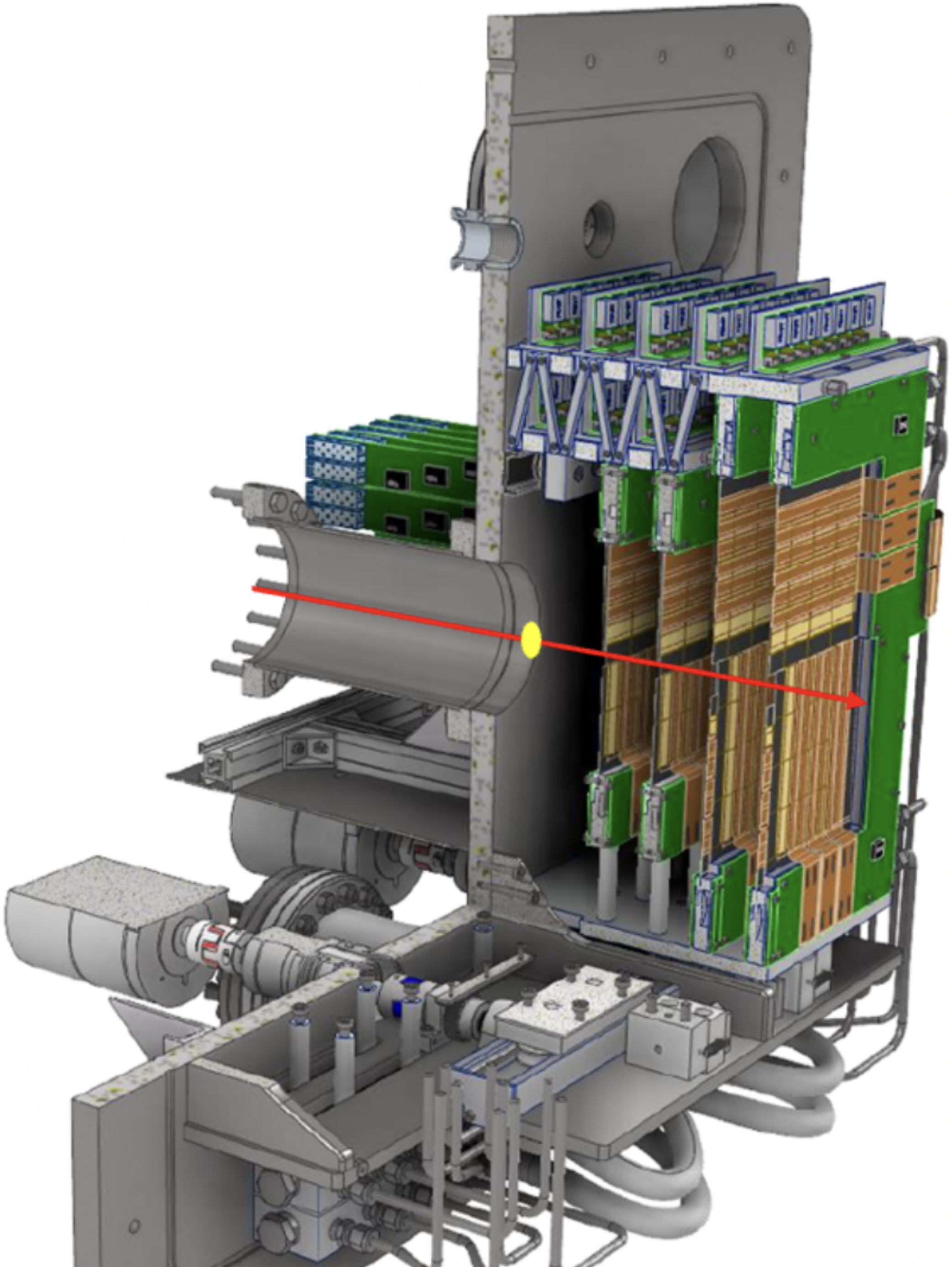
1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

CBM Detector

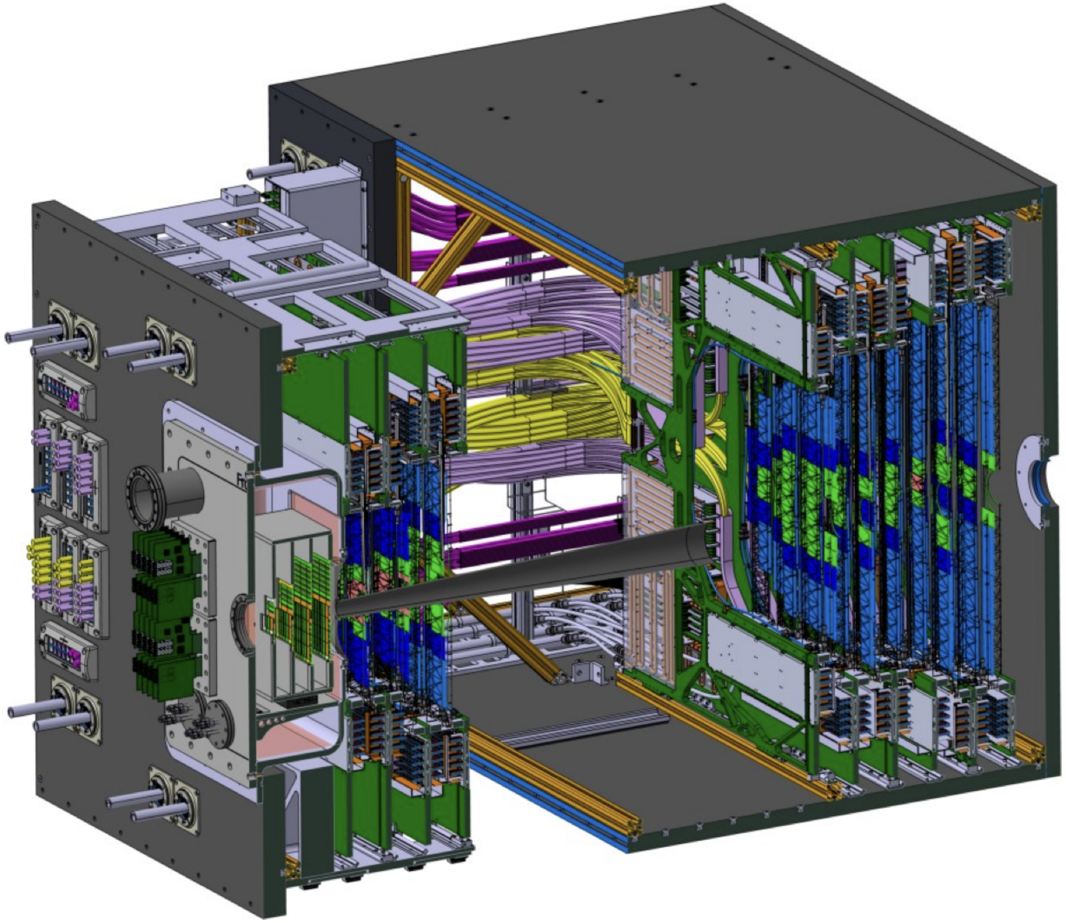


Challenges: huge variation in occupancy (fixed-target); event rates up to 10 MHz

CBM: MVD



- Charmed-hadron reconstruction
- MAPS (180 nm CMOS, Tower; MIMOSIS-3)
- $\sigma_{x,y} = 5\,\mu$m; Power: 100 mW/cm^2
- Radiation:
  5 Mrad & 5$\times 10^{14}\,\mathrm{n_{eq}/cm^2}$
- 4 planes, operated in vacuum

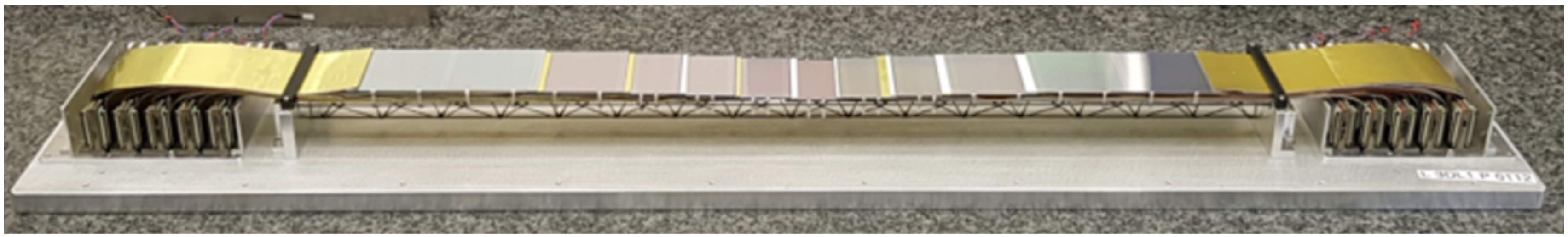


- Tracking and momentum measurement, $\Delta p/p$ =1-2% (B=1 T)
- $\sigma_{x,y} = 30\,\mu$m; $\sigma_t = 5$ ns
- Low material budget (2-8%X_0)
- Double-sided silicon strip det.
- 876 modules, 2x1024 ch. each

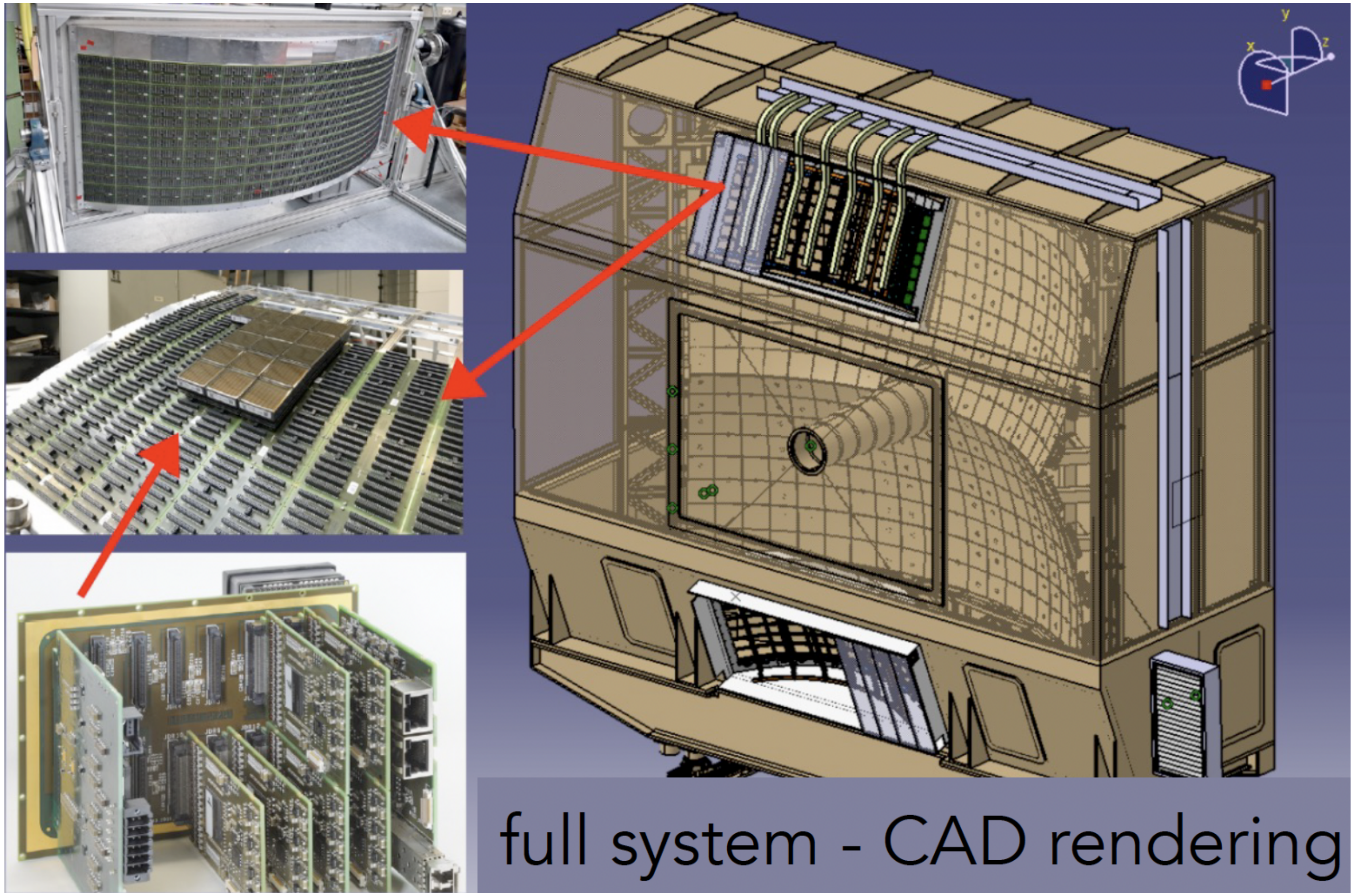
  (62x22, 42, 62, 124 mm^2)

  106 ladders (up to 10 modules)

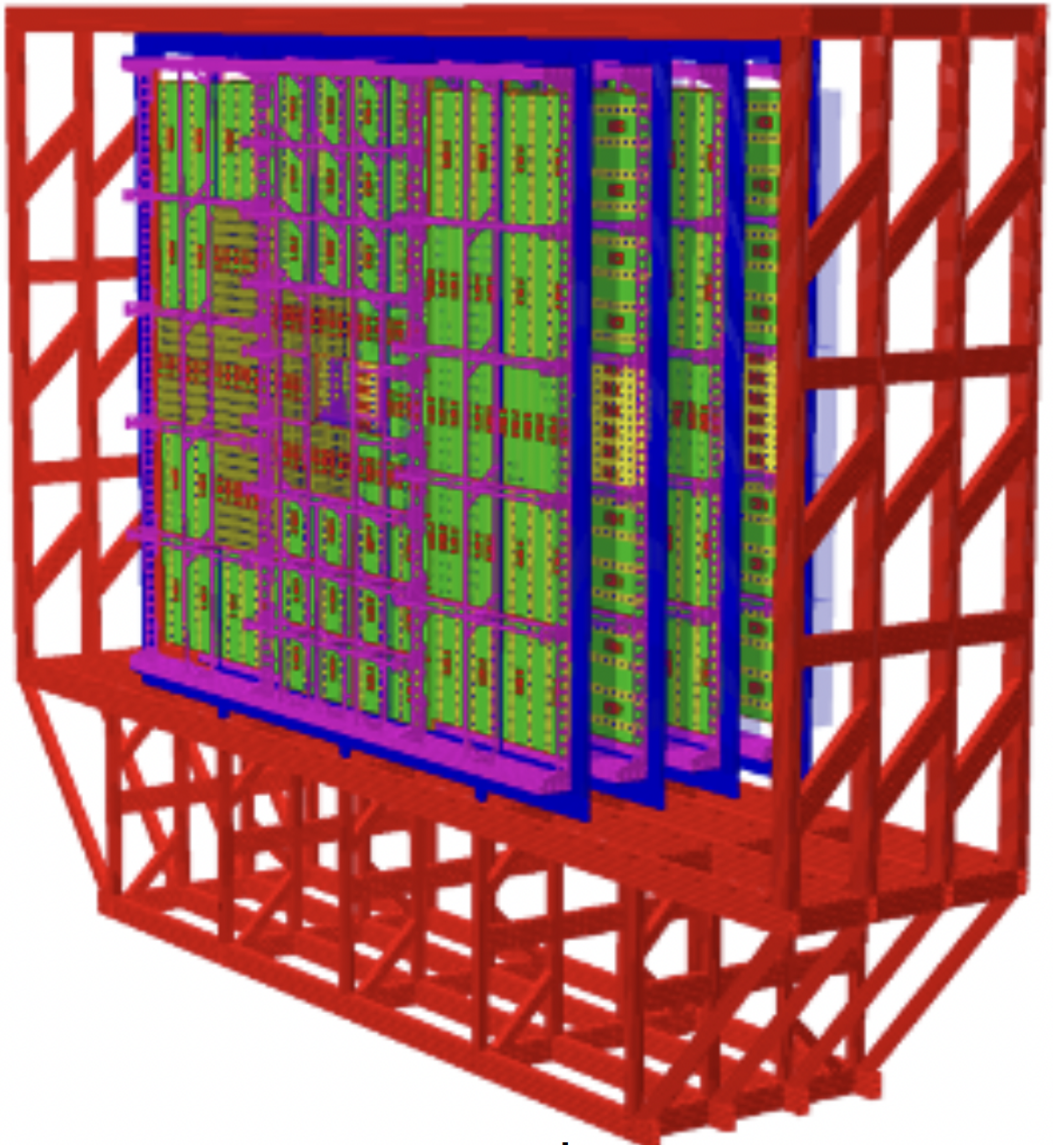
see JINST 9 (2024)



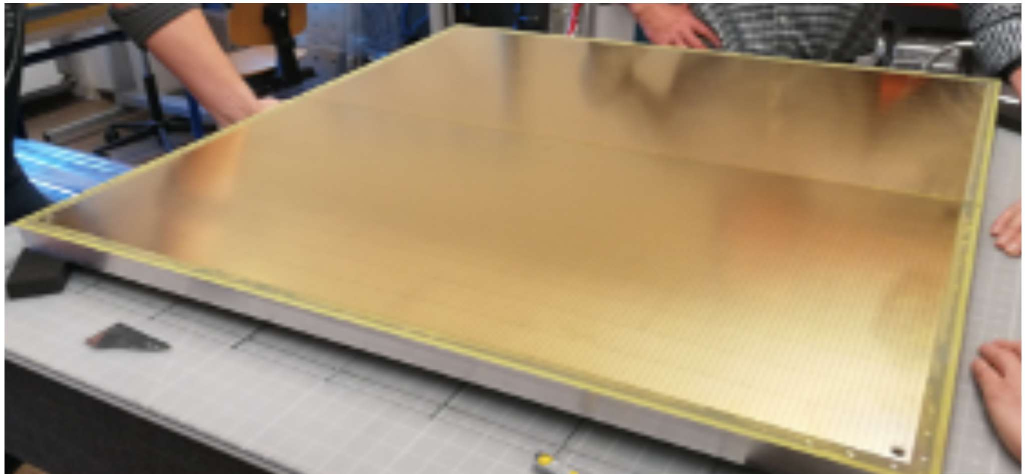
CBM: RICH



- Electron identification
- CO_2 at normal pressure
  n=1.00043, $\gamma_{thr} = 33$
  $p^{\pi}_{thr} \simeq 4.8$ GeV/c
- R^e=4.8 cm
- 2 mirros, focal length 1.5 m
- Multi-anode PMTs (1100)
  70k pixels

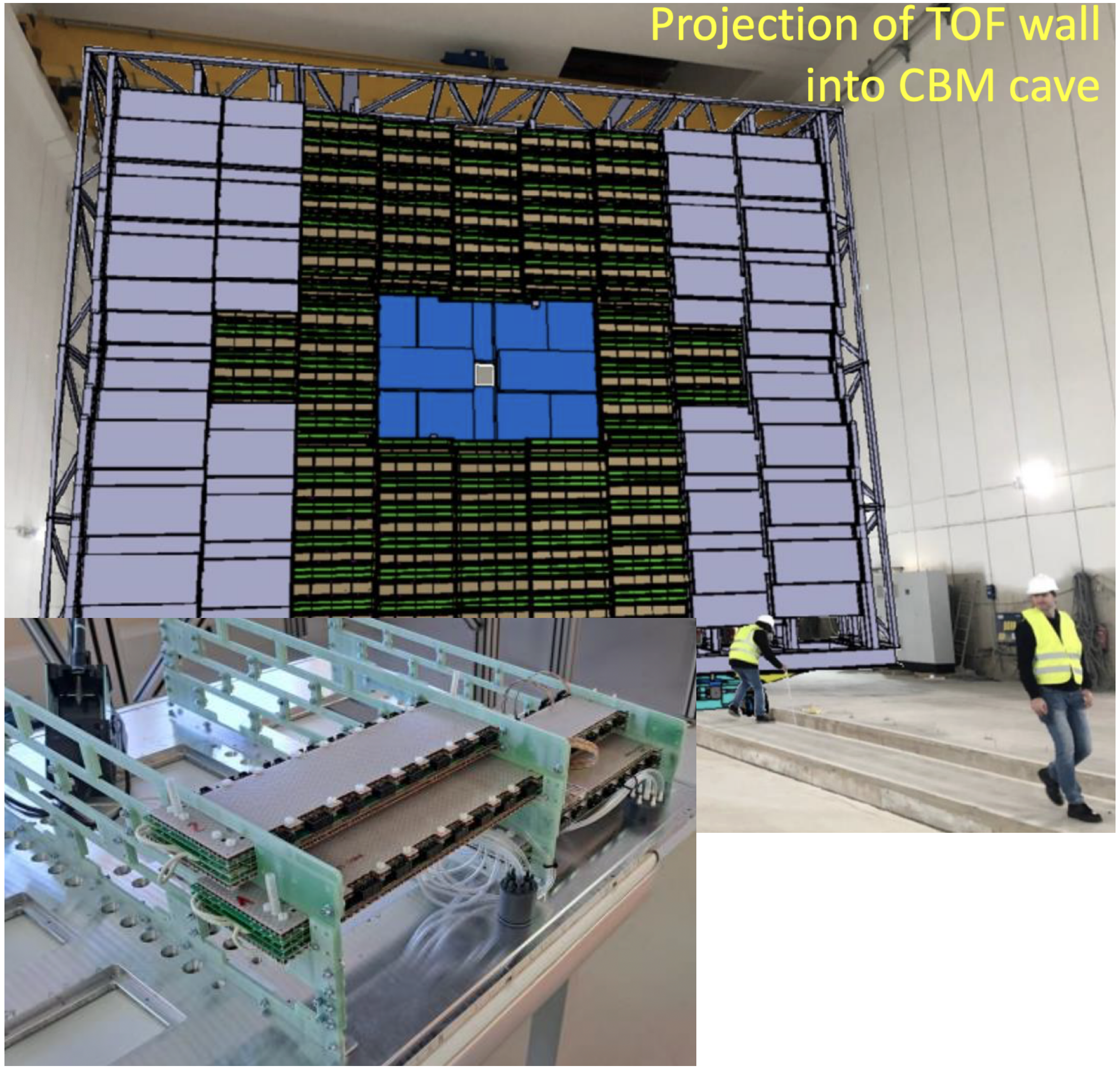


- Electron, light nuclei identification
  Track matching STS-TOF
- $\sigma_{x,y} = 100 - 300\ \mu$m
  (outer, long pads: ~cm)
- Radiator (PE foam), TR: 5-30 keV
  MWPC (1.2 cm, Xe-CO_2)
- Pad readout, FADC; 250k channels

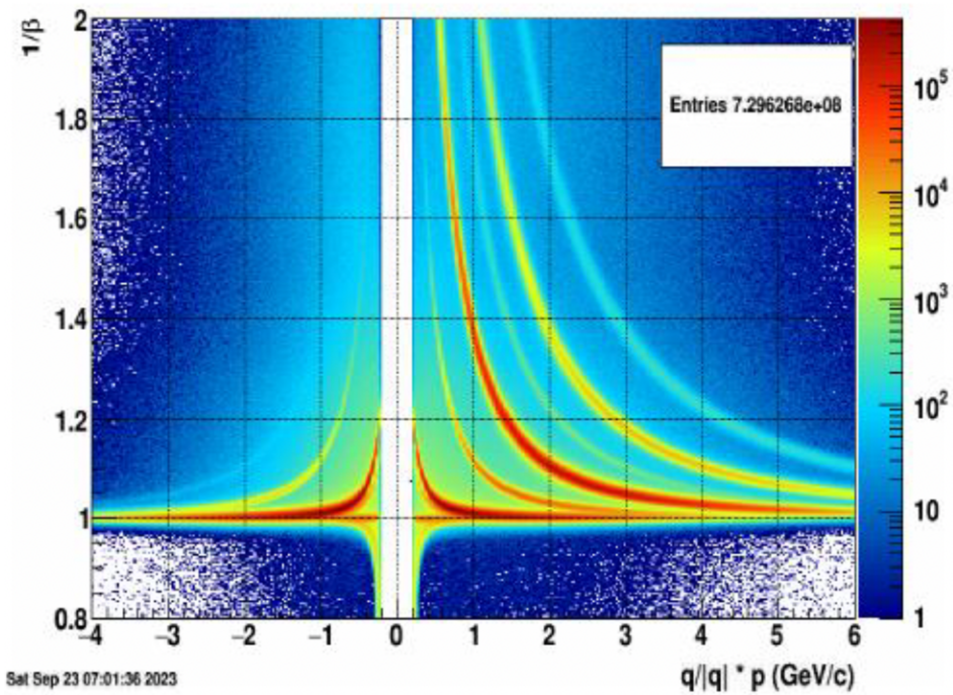


Module production

CBM: TOF

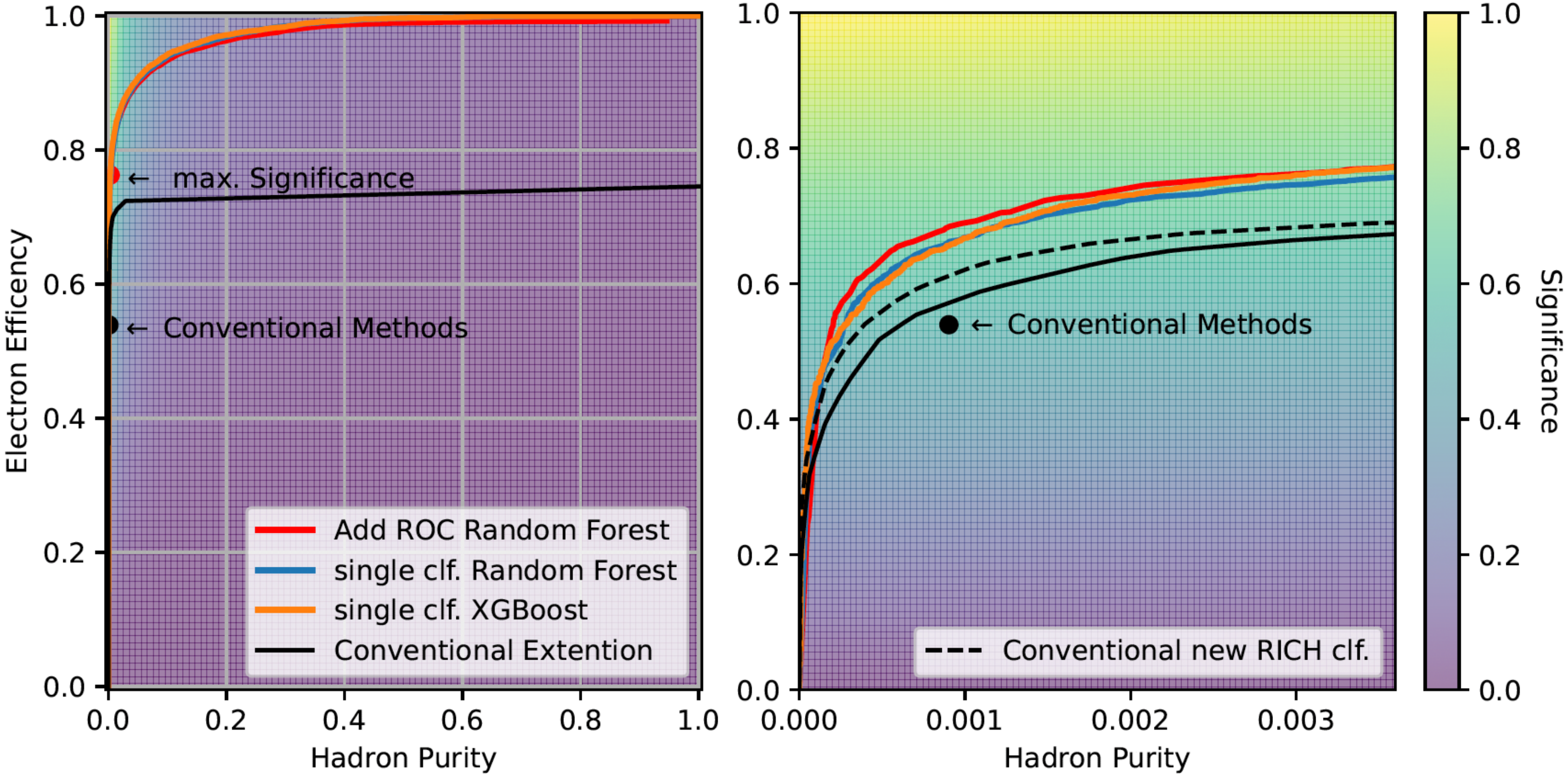


- Hadron identification
- Multi-gap RPCs (glass, strips)
- Resolution: 50-60 ps



Modules installed in STAR, FXT program

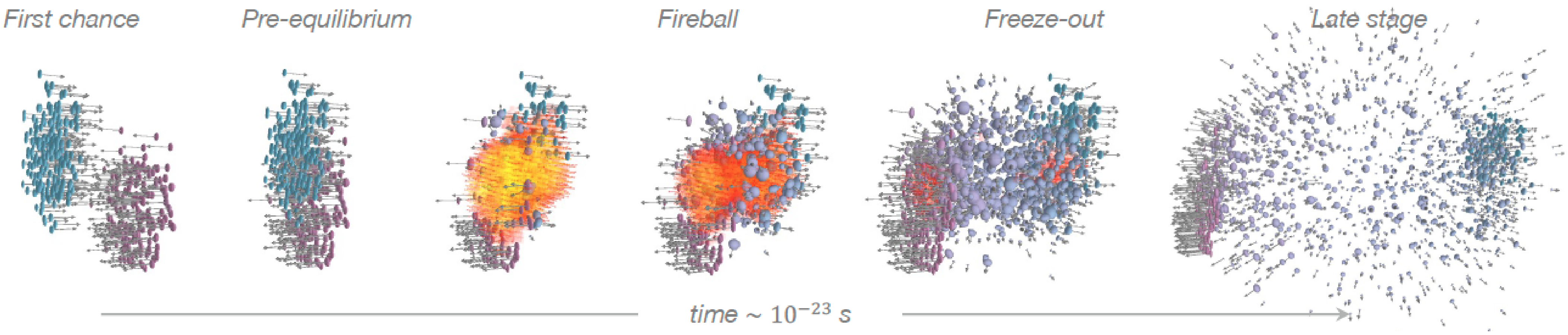
Electron identification performance



Combined RICH-TRD-TOF, ML methods (Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV)

Master Thesis, Hendrik Schiller (Münster, 2022)

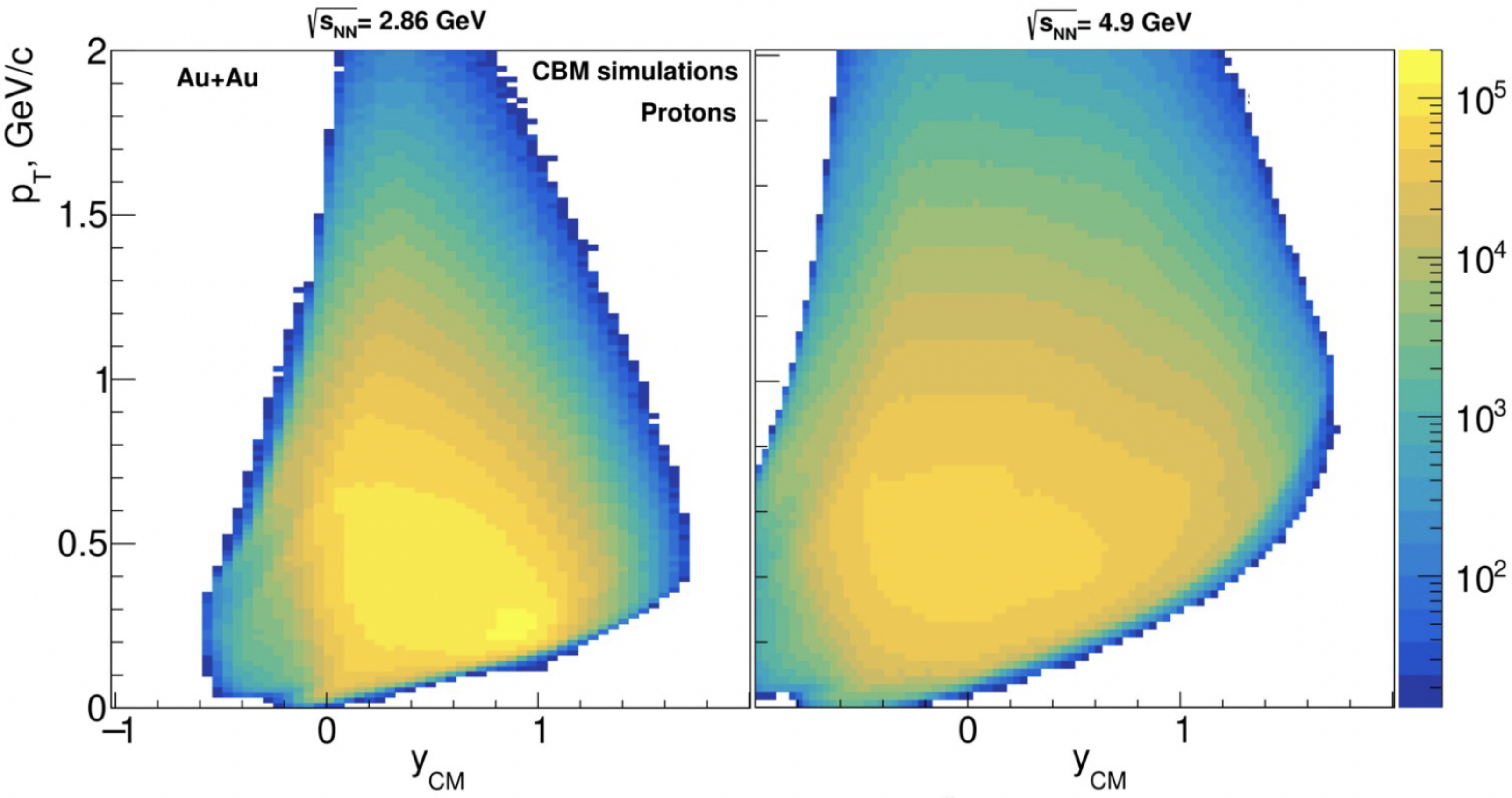
Heavy-ion collisions at FAIR energies



Au-Au collisions, E_{beam} =2-11 GeV/nucleon on fixed target ($\sqrt{s_{NN}} = 2.7 - 4.9$ GeV); centrality selection (FSD)

CBM will measure pA collisions too, rich hadron physics program (proton momentum up to 30 GeV/c)

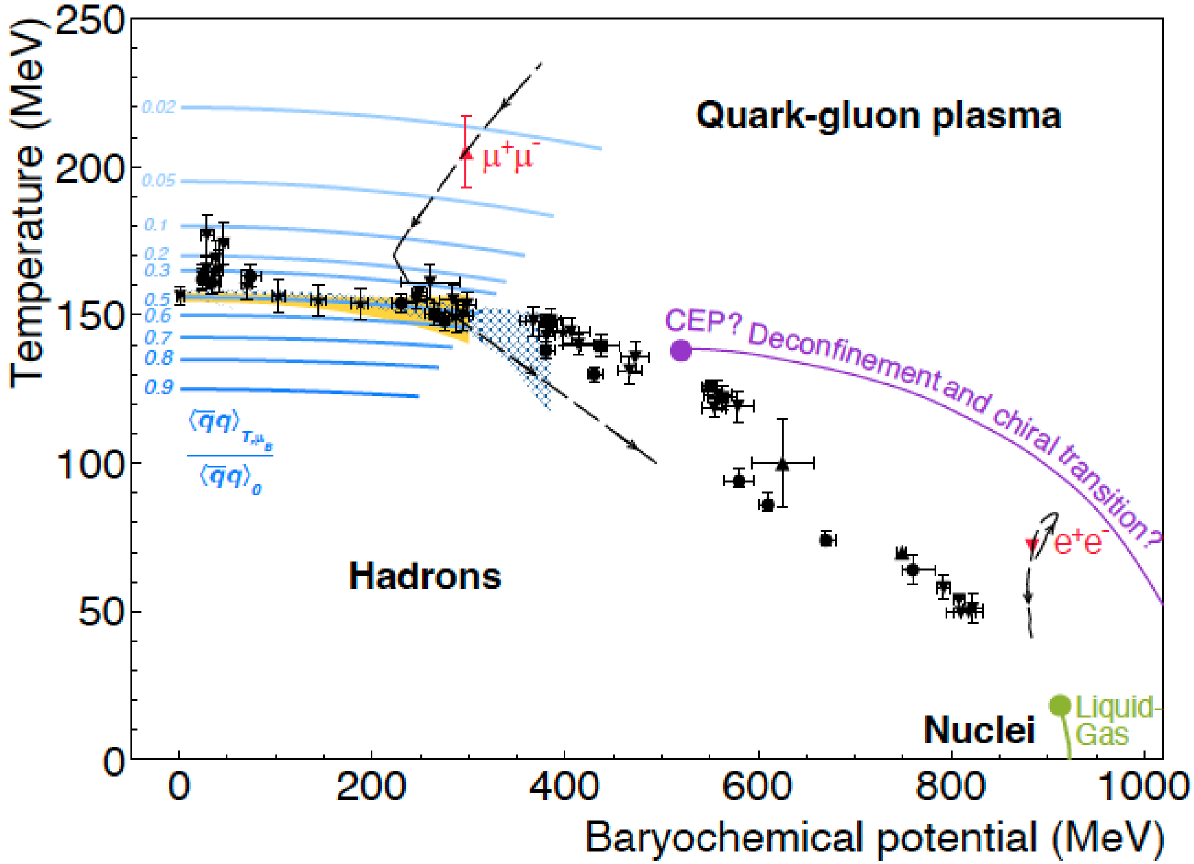
CBM: acceptance



broad phase space coverage, down to low p_T

CBM mission

- characterize hot and dense QCD matter at high μ_B (500-800 MeV), EoS
- establish order of phase transition(s), conjectured QCD critical point



HADES, Nature Phys. 15 (2019) 1040

Andronic et al, Nature 561 (2018) 321

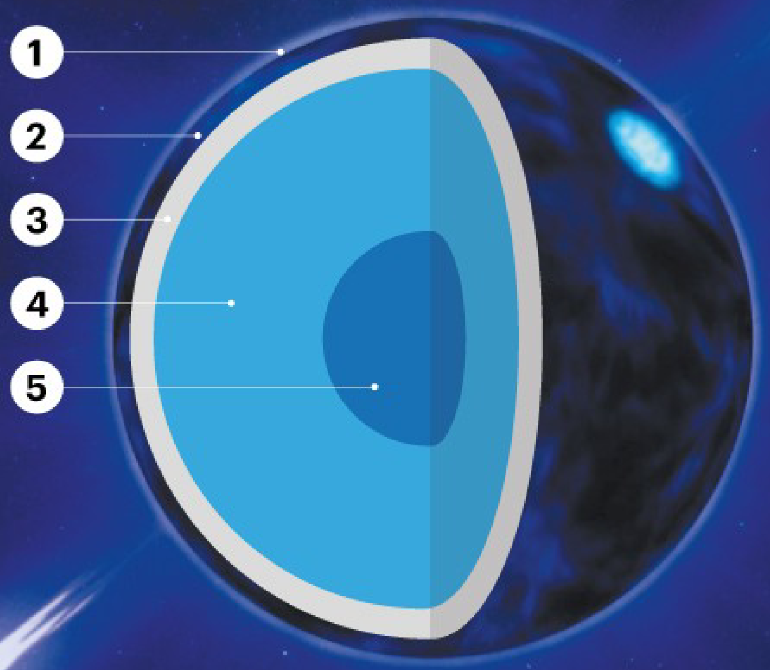
Observables (abundant/rare):

- light flavour hadrons, incl. multi-strange hyperons $\rightarrow$ chemical freeze-out T,μ_B

  flow, vorticity $\rightarrow$ EoS
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction, prod. mechanism)

DENSE MATTER

Neutron stars get denser with depth. Although researchers have a good sense of the composition of the outer layers, the ultra-dense inner core remains a mystery.

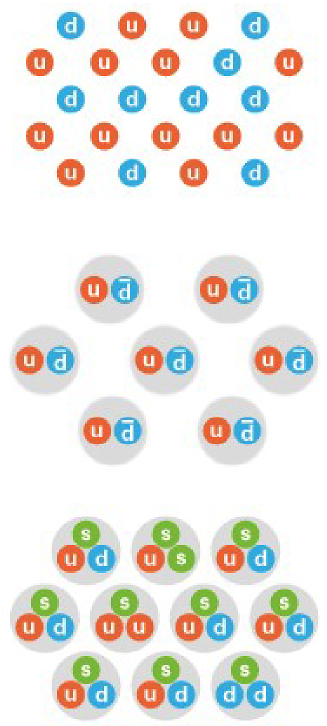


1. Atmosphere	Mostly hydrogen and helium
2. Outer crust	Atomic nuclei and free electrons
3. Inner crust	Free neutrons and electrons, heavier atomic nuclei
4. Outer core	Neutron-rich quantum liquid
5. Inner core	Unknown, ultra-dense matter

Core scenarios

A number of possibilities have been suggested for the inner core, including these three options.

u Up quark s Strange quark
d Down quark d̄ Anti-down quark



Quarks
The constituents of protons and neutrons — up and down quarks — roam freely.

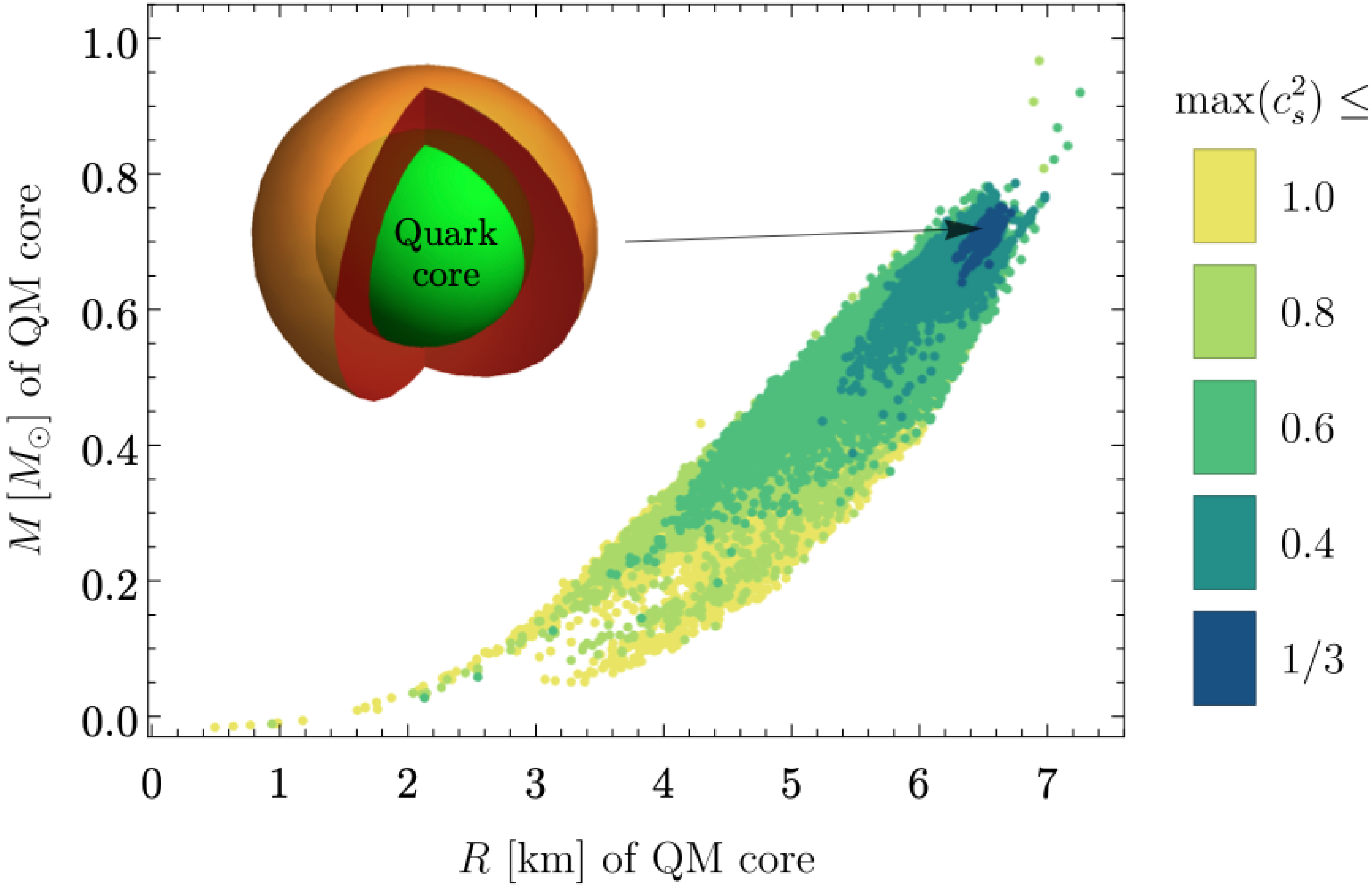
Bose–Einstein condensate
Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.

Hyperons
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

A.Mann, Nature 579 (2020) 20

EoS of crucial relevance

The quark core in a neutron star ($2M_{Sun}$, R=12 km)

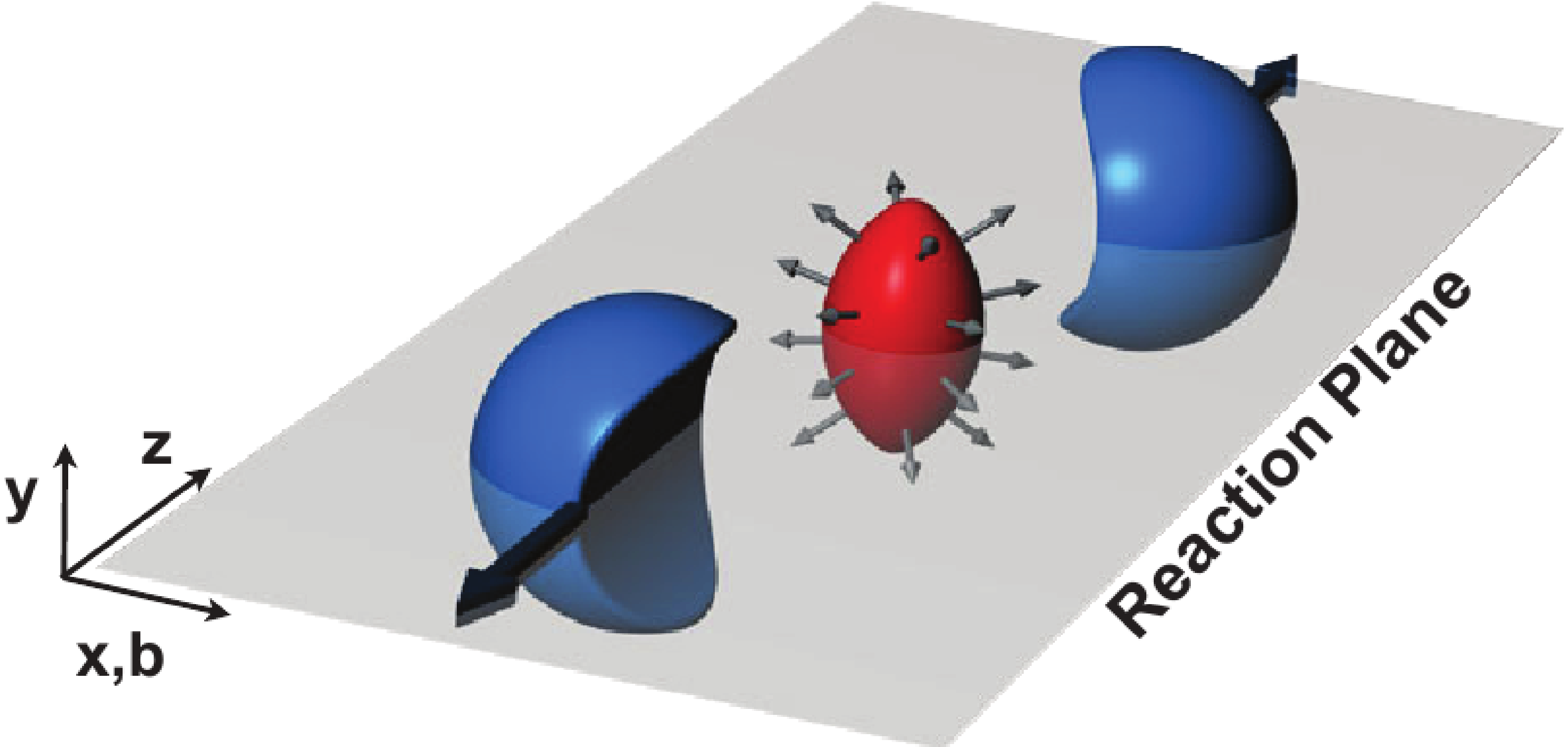


Theoretical calculations, Annala et al, Nature Phys. 16 (2020) 907

the closer to ideal gas ($c_s^2 = 1/3$) quark matter is, the larger/heavier the core

NB: not the quark-gluon matter of LHC ...antiquarks and gluons largely absent here; neutron star quark matter may be produced at FAIR/GSI ...hotter though

Directed and elliptic flow

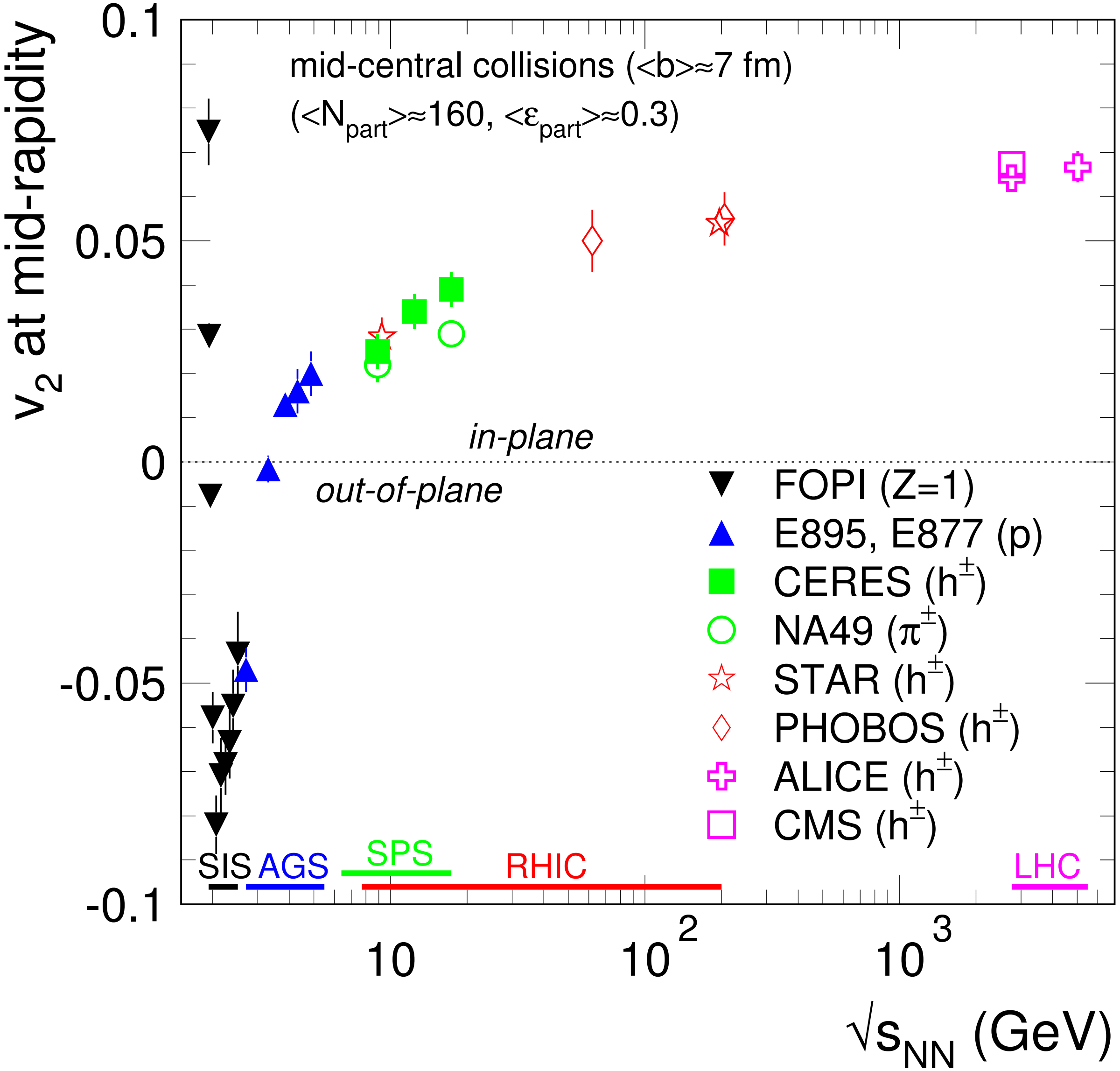


$$\frac{dN}{d\varphi} \sim [1 + 2v_1 \cdot \cos(\varphi) + 2v_2 \cdot \cos(2\varphi) + ...]$$

$\phi =$ azimuthal angle with respect to reaction plane

$v_1 = \langle \cos(\varphi) \rangle$ *directed flow*, $v_2 = \langle \cos(2\varphi) \rangle$ *elliptic flow* (coefficients)

R. Snellings, arXiv:1102.3010



$v_2 = \langle \cos(2\varphi) \rangle$

AGS: CBM regime

3 regimes:

$v_2 > 0$ at low energies: in-plane, rotation-like emission

$v_2 < 0$ onset of expansion, in competition with shadowing by spectators ...which act as a *clock* for the collective expansion:

$t_{coll} = 2R/\gamma_{\rm cm}c$=40-10 fm/$c$

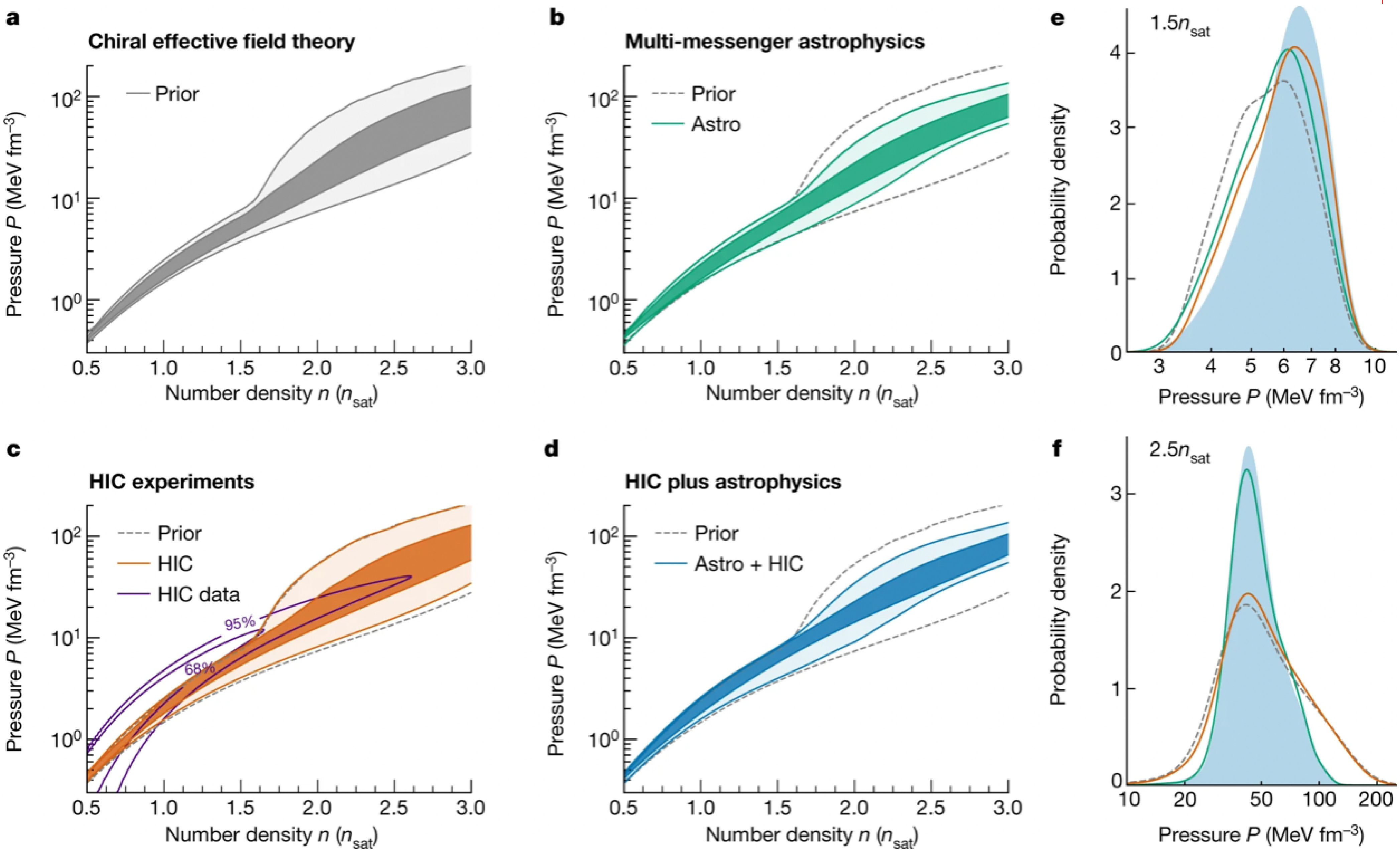
transport models

$v_2 > 0$ at high energies: "free" fireball (almond-shape) expansion

"genuine" elliptic flow

hydrodynamic description

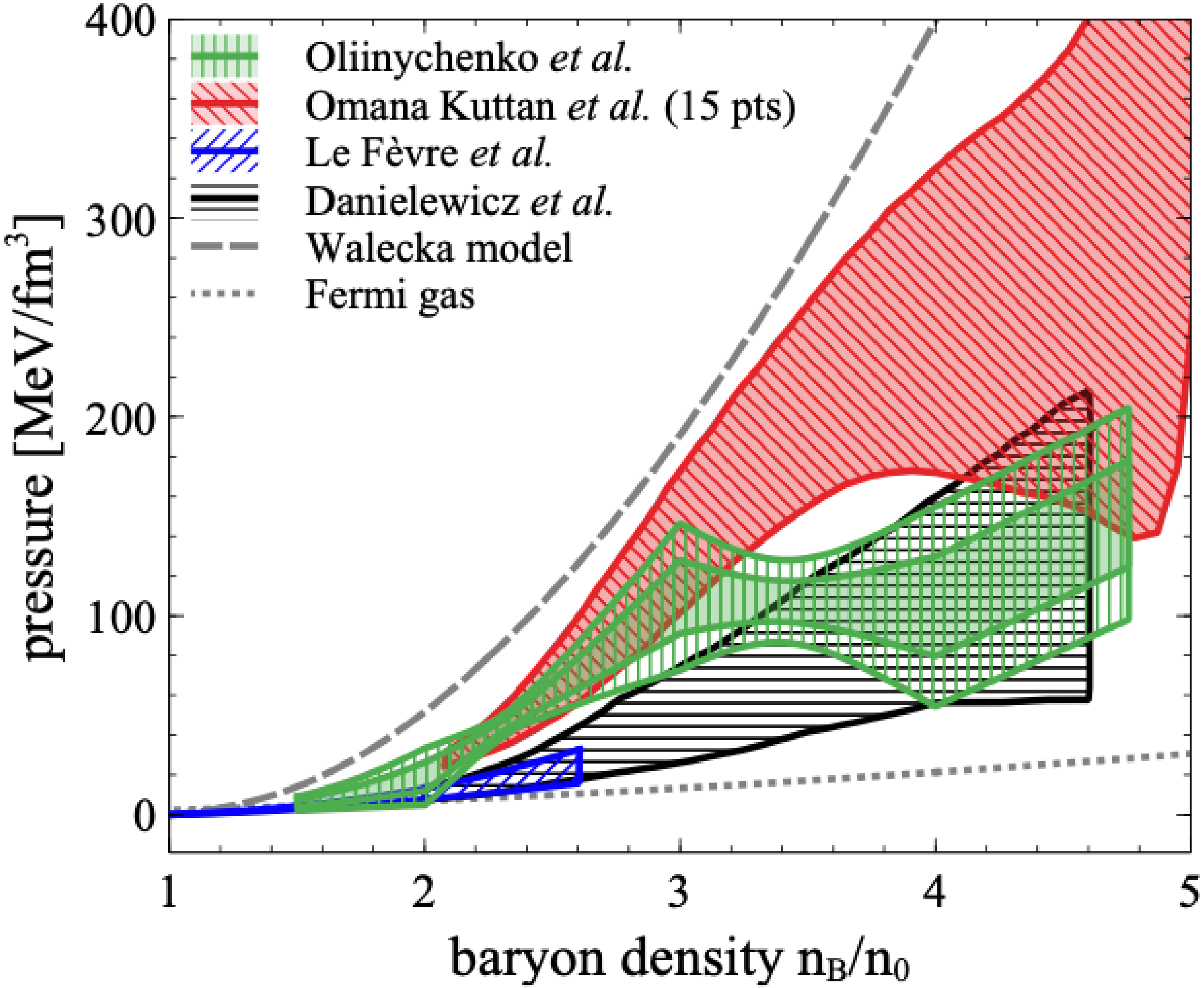
EoS and the stars



Dark: 68%; Light: 95% C.L. (credible intervals)

Huth et al., Nature 606 (2022) 276

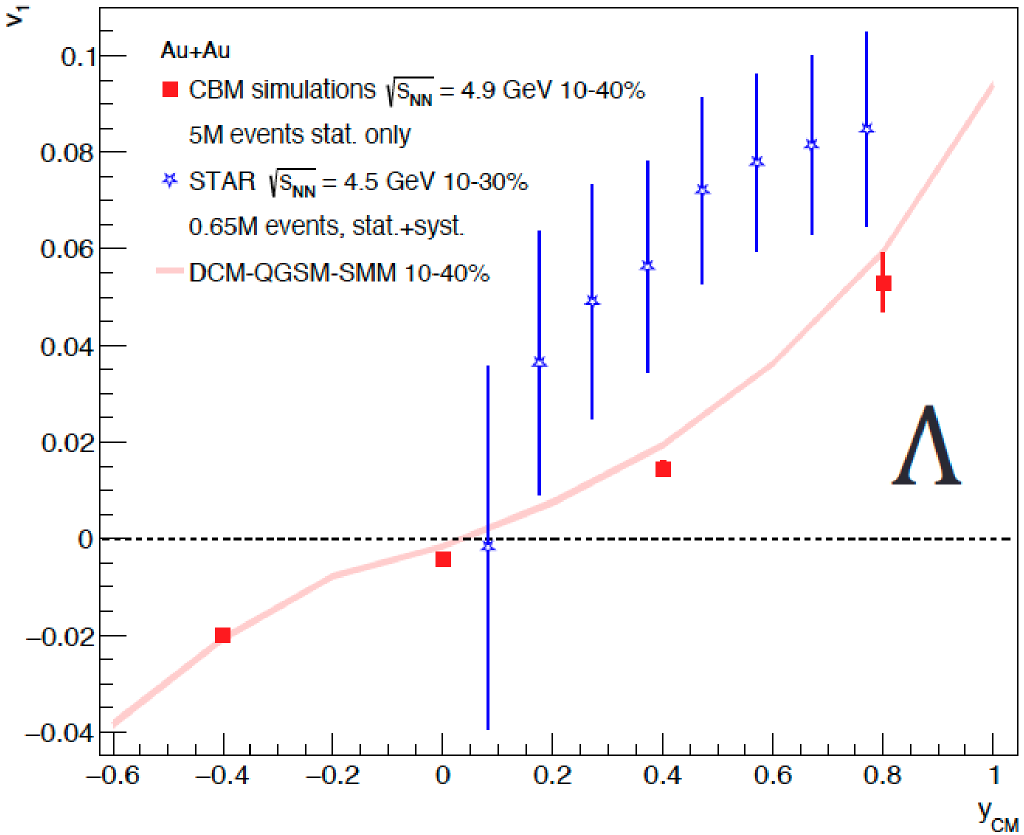
EoS: a complicated business

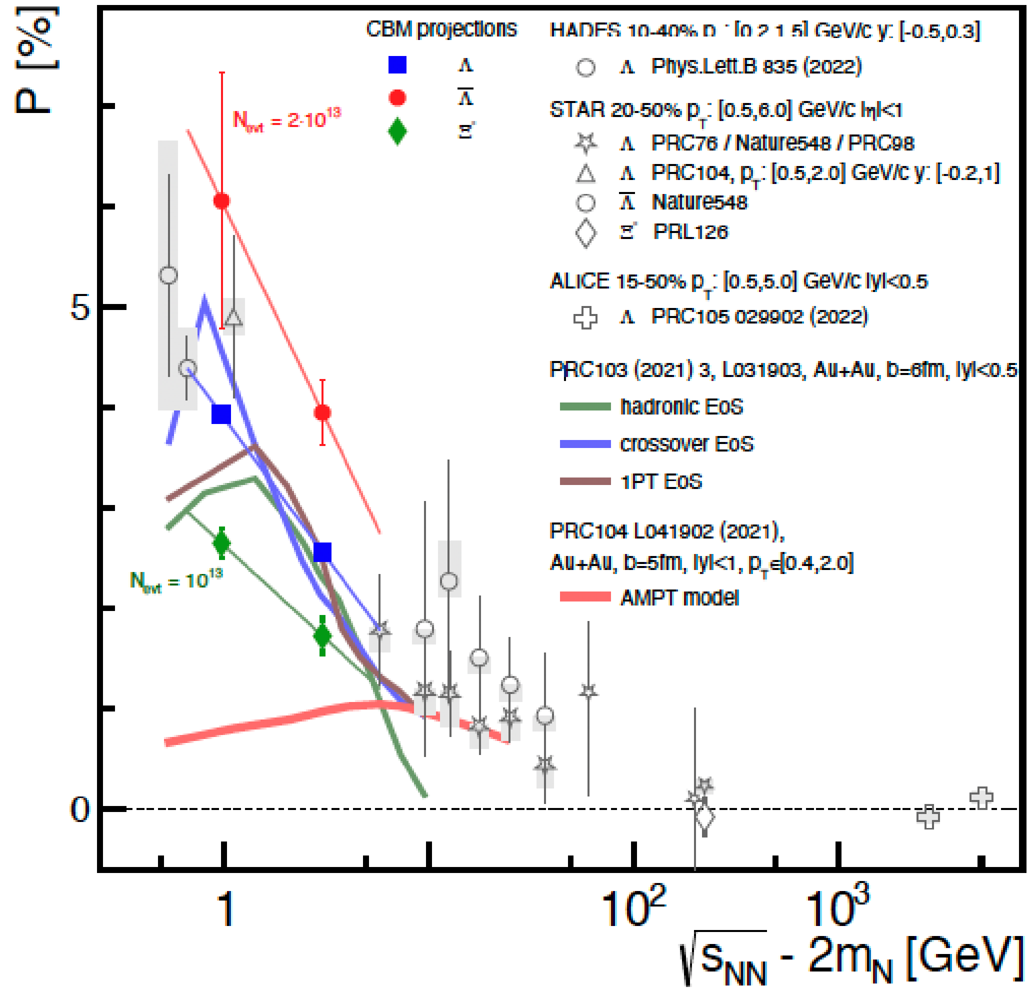


Du, Sorensen, Stephanov, arXiv:2402.10183

Flow data compared to microscopic transport simulations (bands, hadronic)
Momentum-dependent interactions (repulsive at $E_{kin} \gtrsim$200 MeV) are needed
(included only in calc. of black and blue bands in the Fig.)

CBM: Λ flow and polarization





CBM will measure flow in detail and polarization of hyperons (from initial $\vec{L}$)

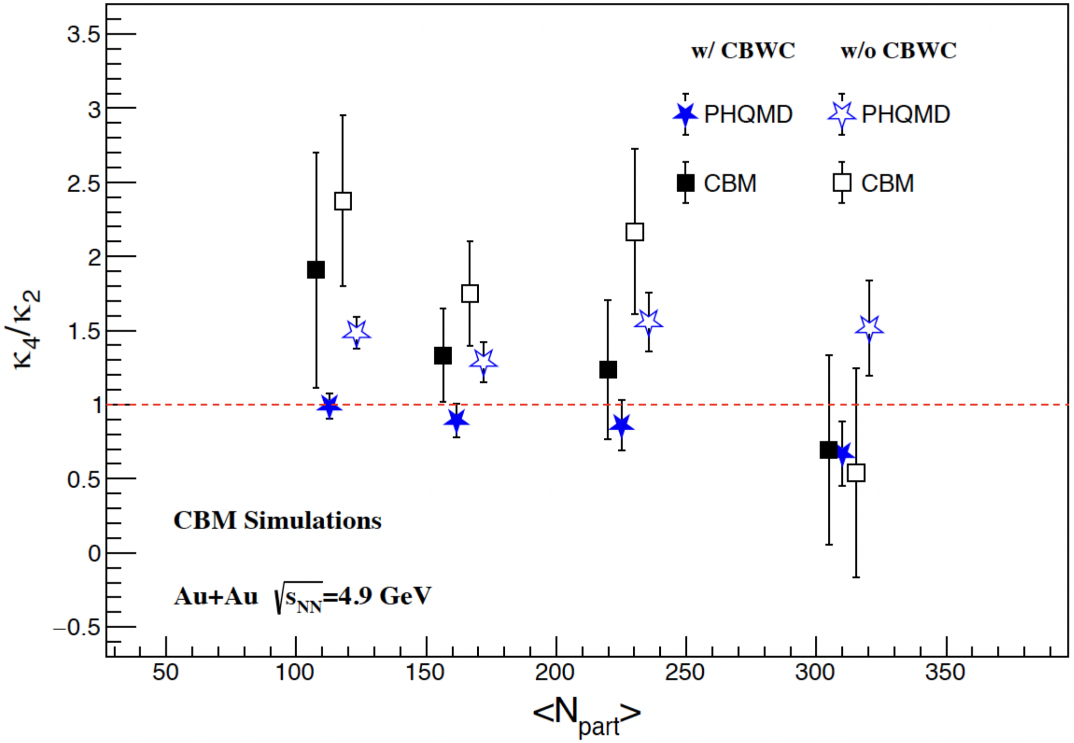
...will constrain EoS in the range 2-5ρ_0

but uncertainties due to transport models need to be reduced too

CBM: net-proton fluctuations

(baryon number conserved)

moments of net-proton $(N_{\rm p} - N_{\bar{\rm p}})$ event-by-event distributions:



σ - variance, S - skewness, κ - kurtosis

$$S\sigma = \frac{T\chi_B^{(3)}}{\chi_B^{(2)}};\ \kappa\sigma^2 = \frac{T^2\chi_B^{(4)}}{\chi_B^{(2)}};\ \frac{\kappa\sigma}{S} = \frac{T\chi_B^{(4)}}{\chi_B^{(3)}}$$

susceptibilities $\chi_B^{(n)}$ calculable in LQCD $(\mu_B = 0)$

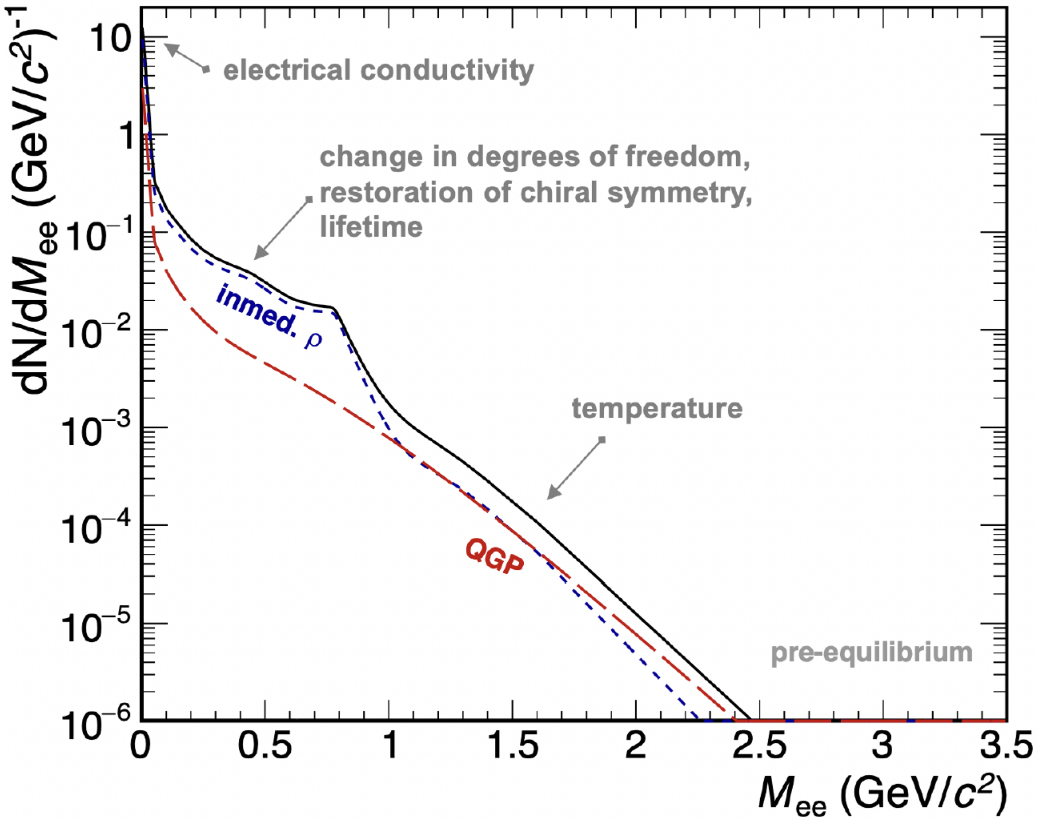
$$\chi_B^{(n)} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$

probe local fluctuations of baryon number

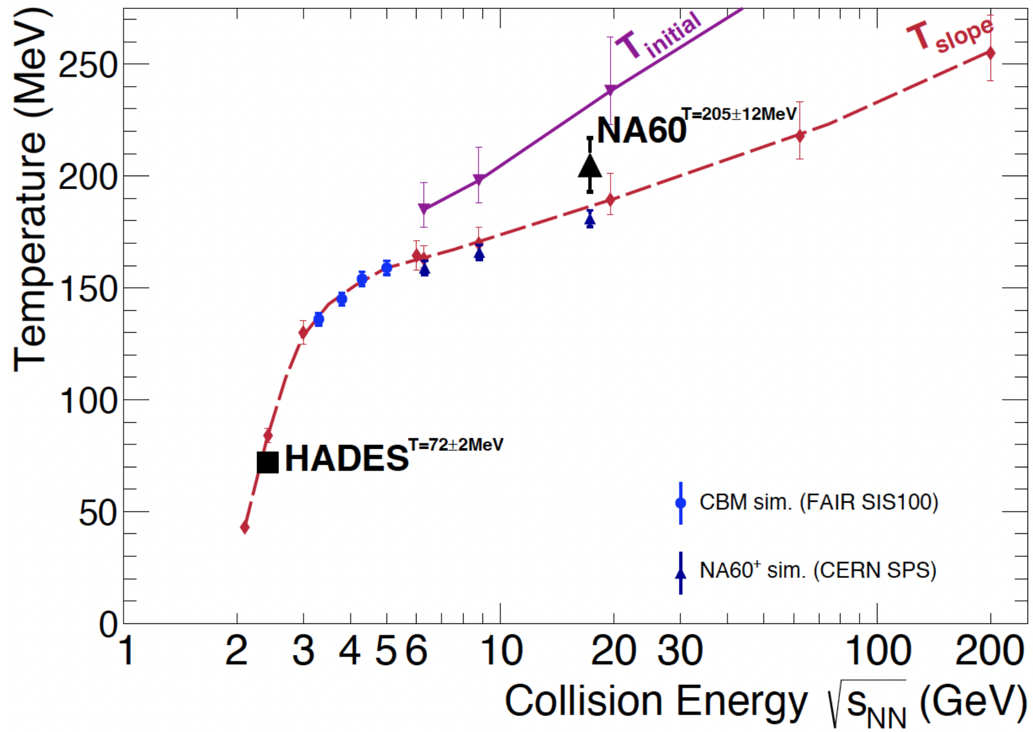
...expected to increase near a critical point

Debated effects: event-by-event volume and detection efficiency fluctuations;
what effect have missed neutrons, hyperons, nuclei?

CBM: dileptons



Rapp, Wambach, Adv. Nucl. Phys. (2000) 25



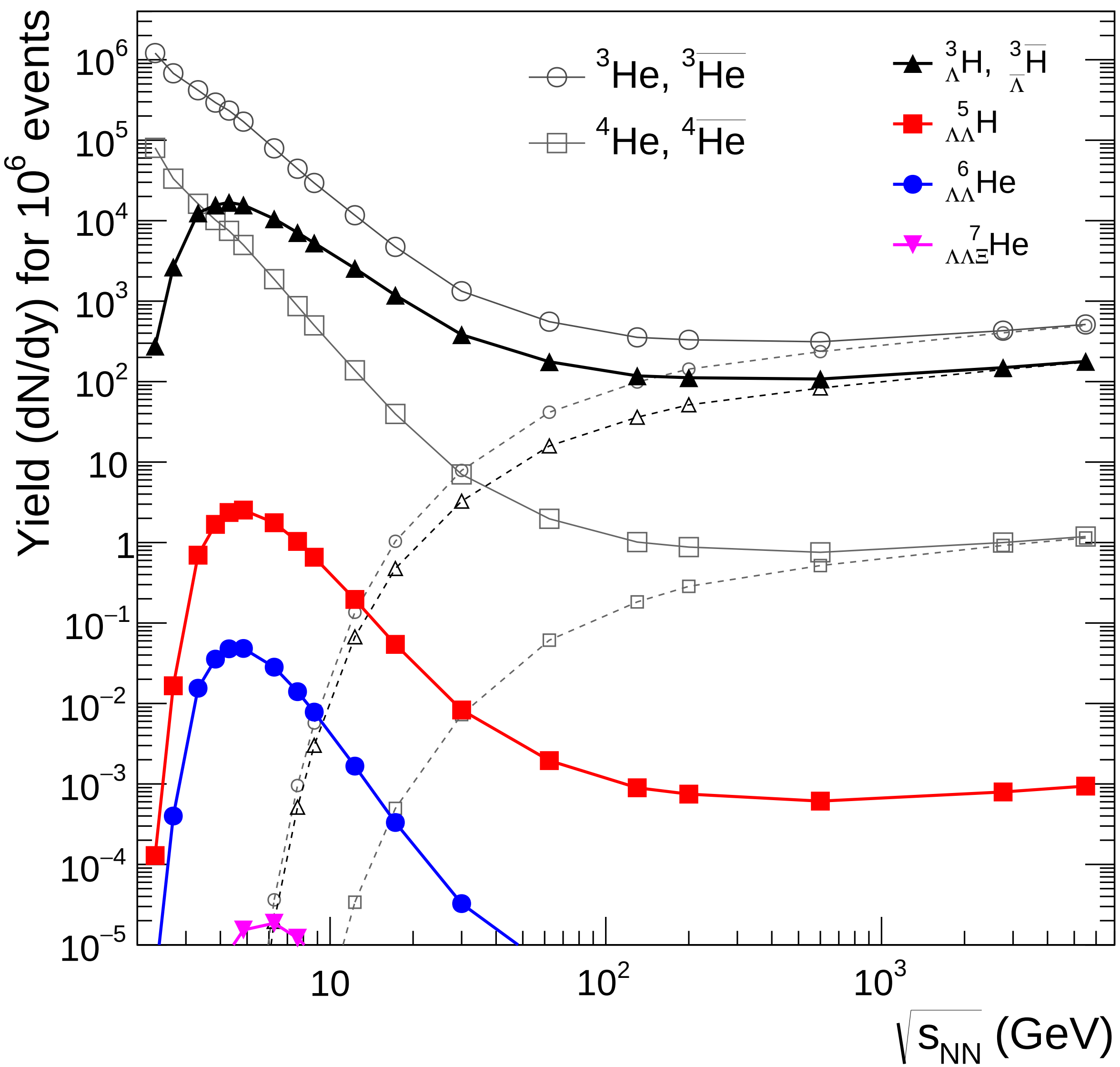
https://github.com/tgalatyuk/QCD_caloric_curve

fit data with: $\mathrm{d}N/\mathrm{d}M \sim M^{3/2}\exp(-M/T)$

Temperature averaged over the lifetime of the fireball (QGP+hadronic phase)

Hypernuclei

...are copiously produced at low (RHIC-BES/FAIR) energies



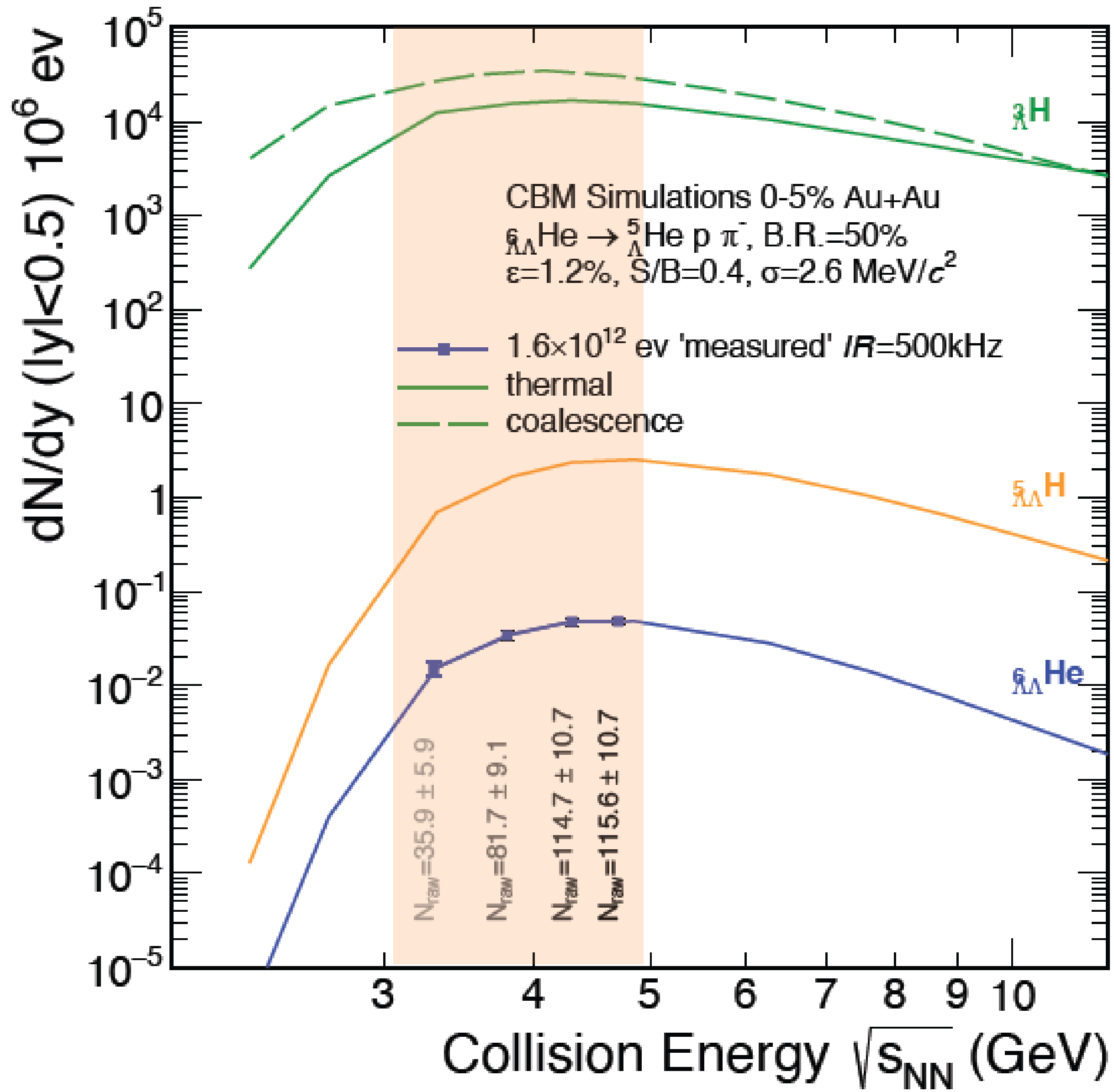
Statistical Hadroniz. Model (thermal)

central AA collisions

maxima: interplay between T and μ_B vs. $\sqrt{s_{NN}}$

AA, PBM, JS, HS, PLB 697 (2011) 203

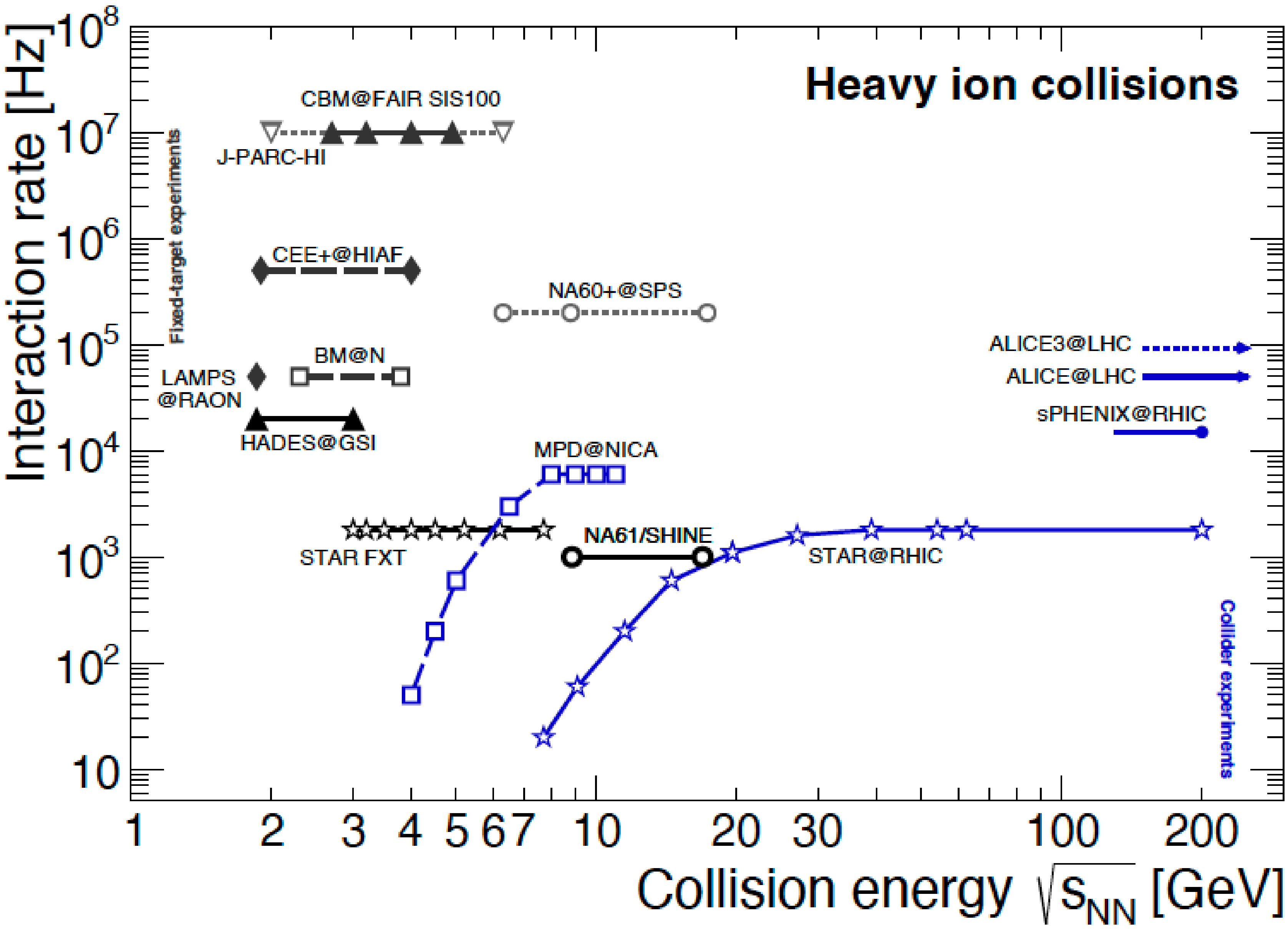
CBM: hypernuclei



CBM will study $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H in detail

and can discover the double-strange hyperons

CBM: the highest-rate experiment

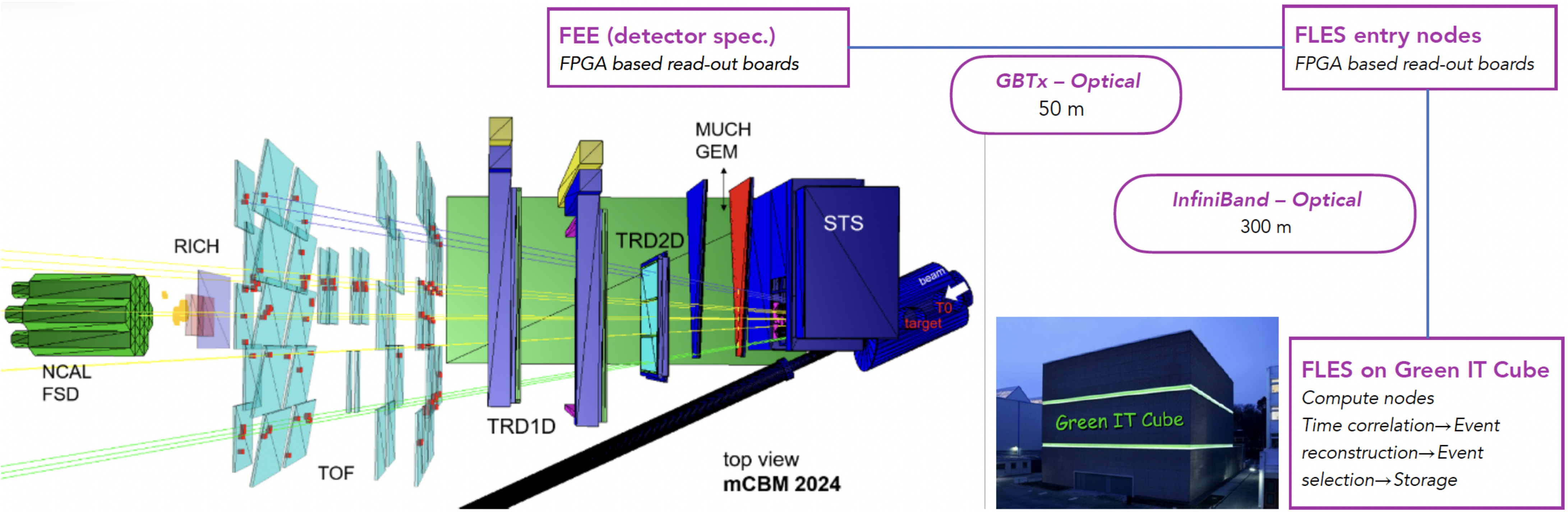


T.Galatyuk, NPA 982 (2019), https://github.com/tgalatyuk/interaction_rate_facilities

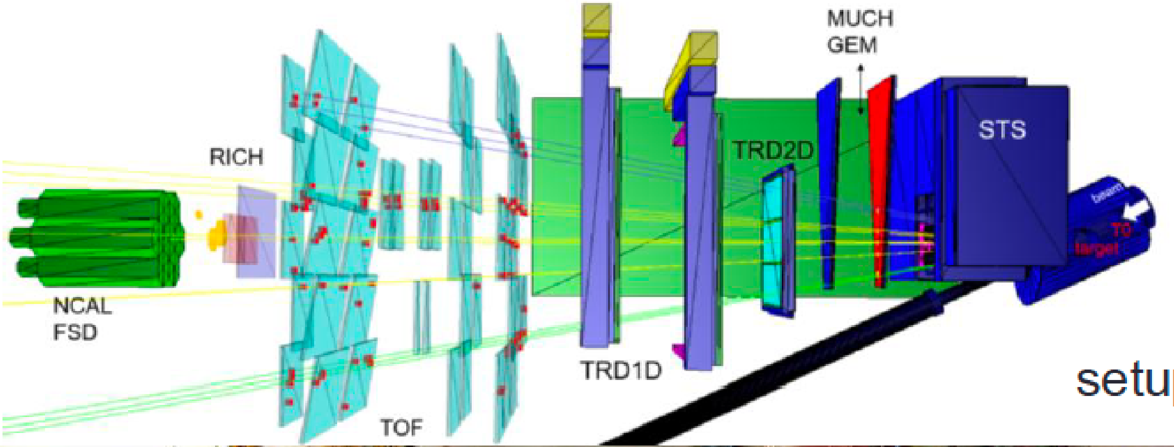
CBM: readout and event selection

Free-streaming readout and First Level Event Selection (FLES)

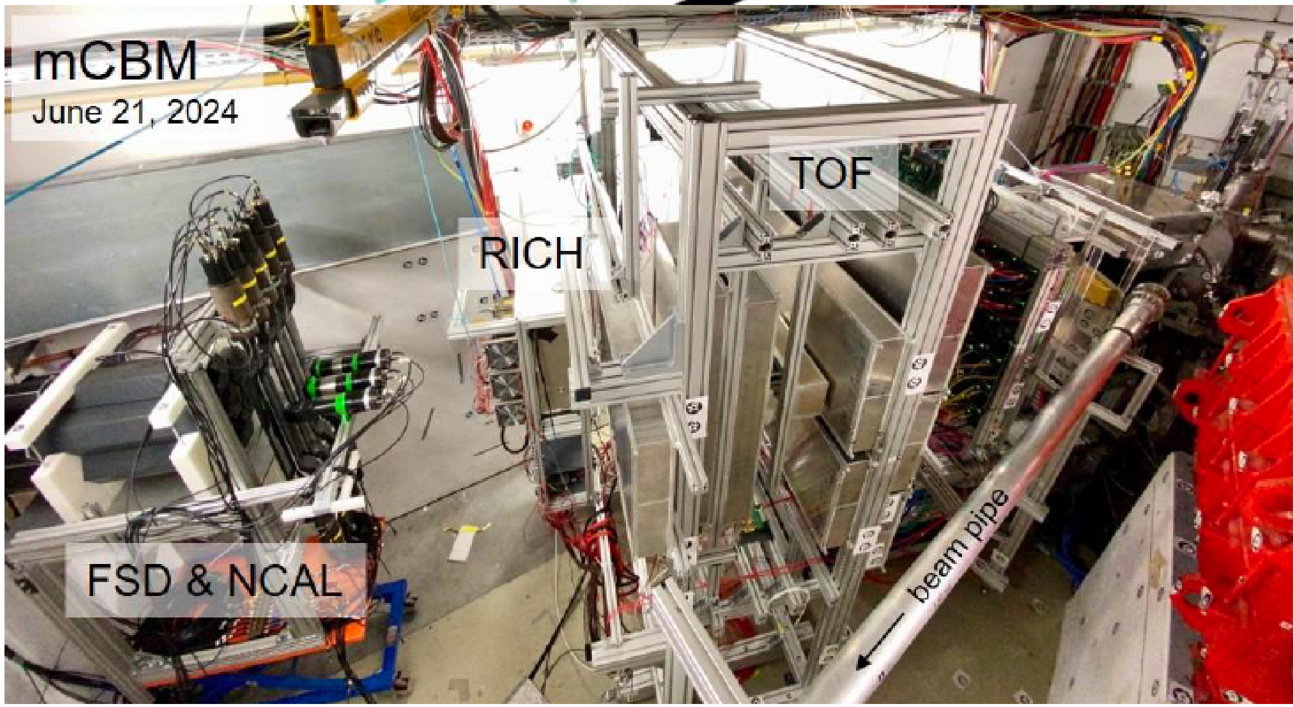
Full readout in mCBM@SIS18, currently commissioning FLES (Λ production)

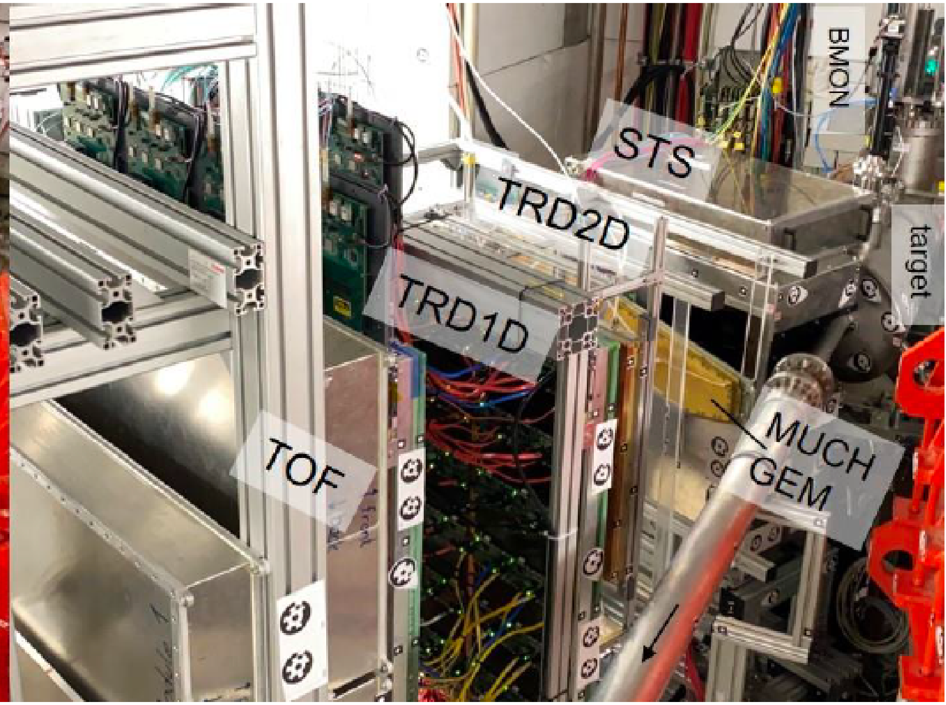


mCBM



setup ‘24

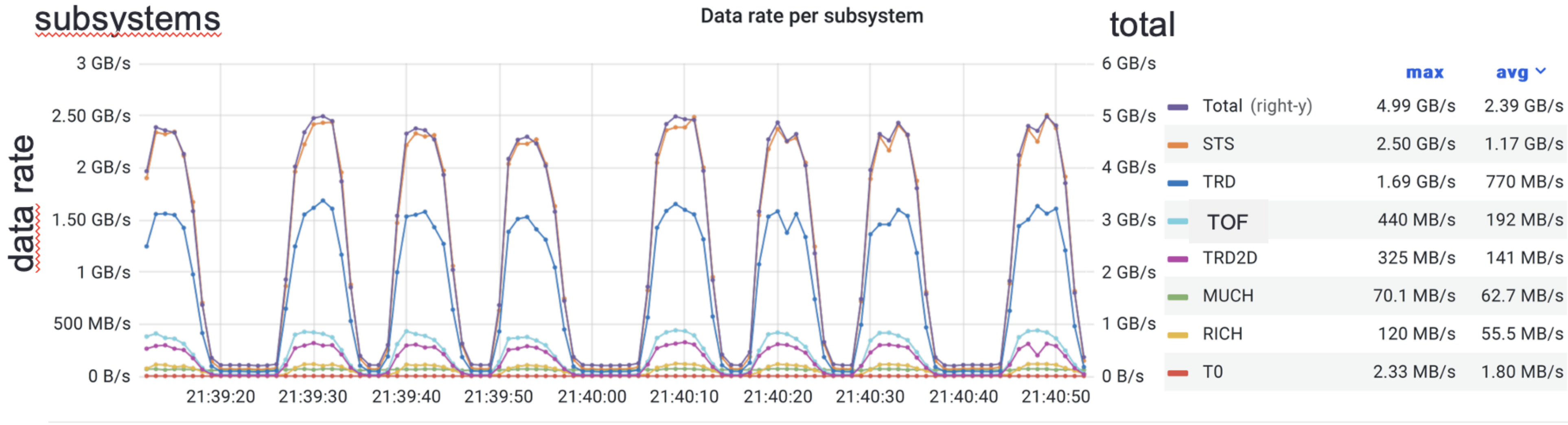




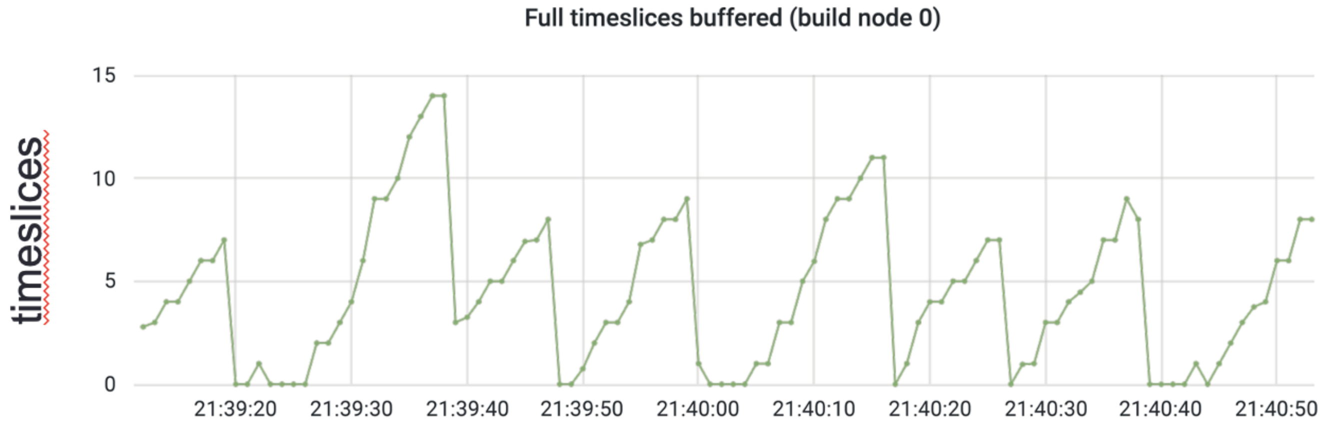
Final prototypes or first-of-series detectors

mCBM: readout

FLES input



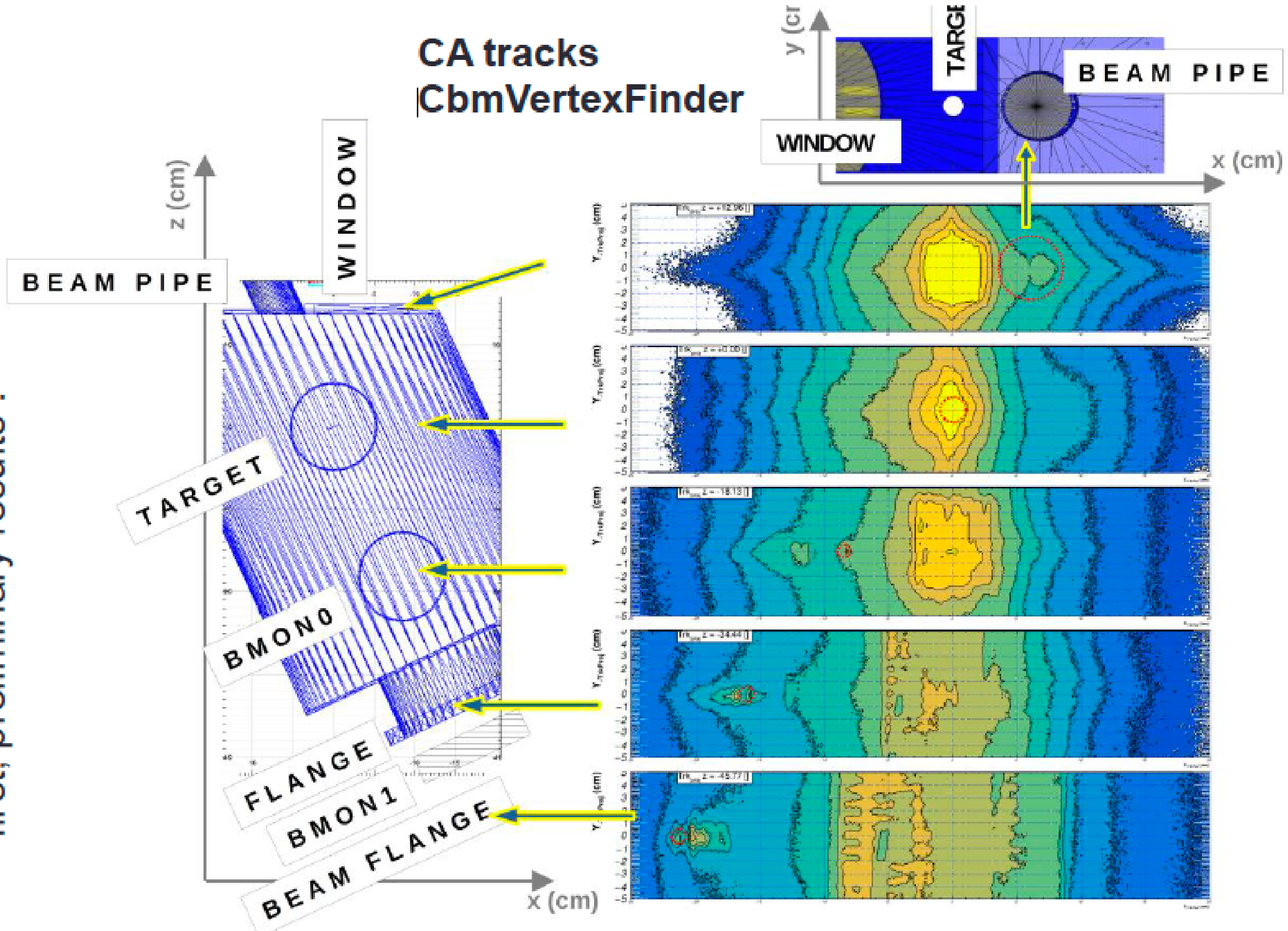
FLES output



mCBM run 2448
June 16, 2022
Au + Au, T = 1.23 AGeV
av. collision rate: 300 - 400kHz
av. data rate 2.4 GB/s to disc

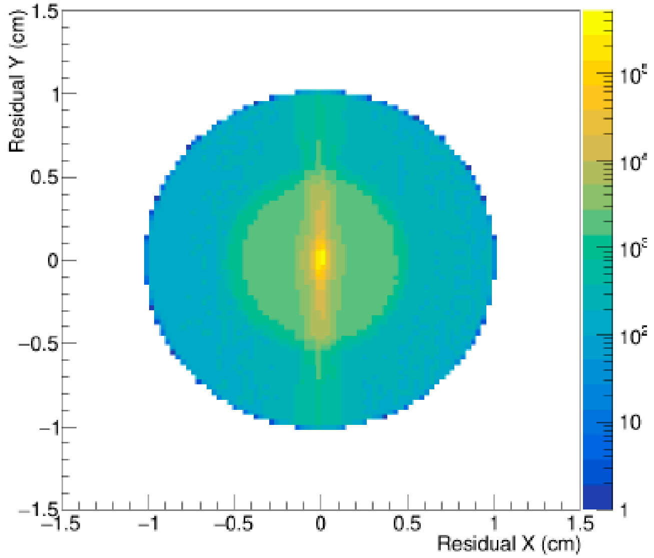
first, preliminary results !

CA tracks
CbmVertexFinder

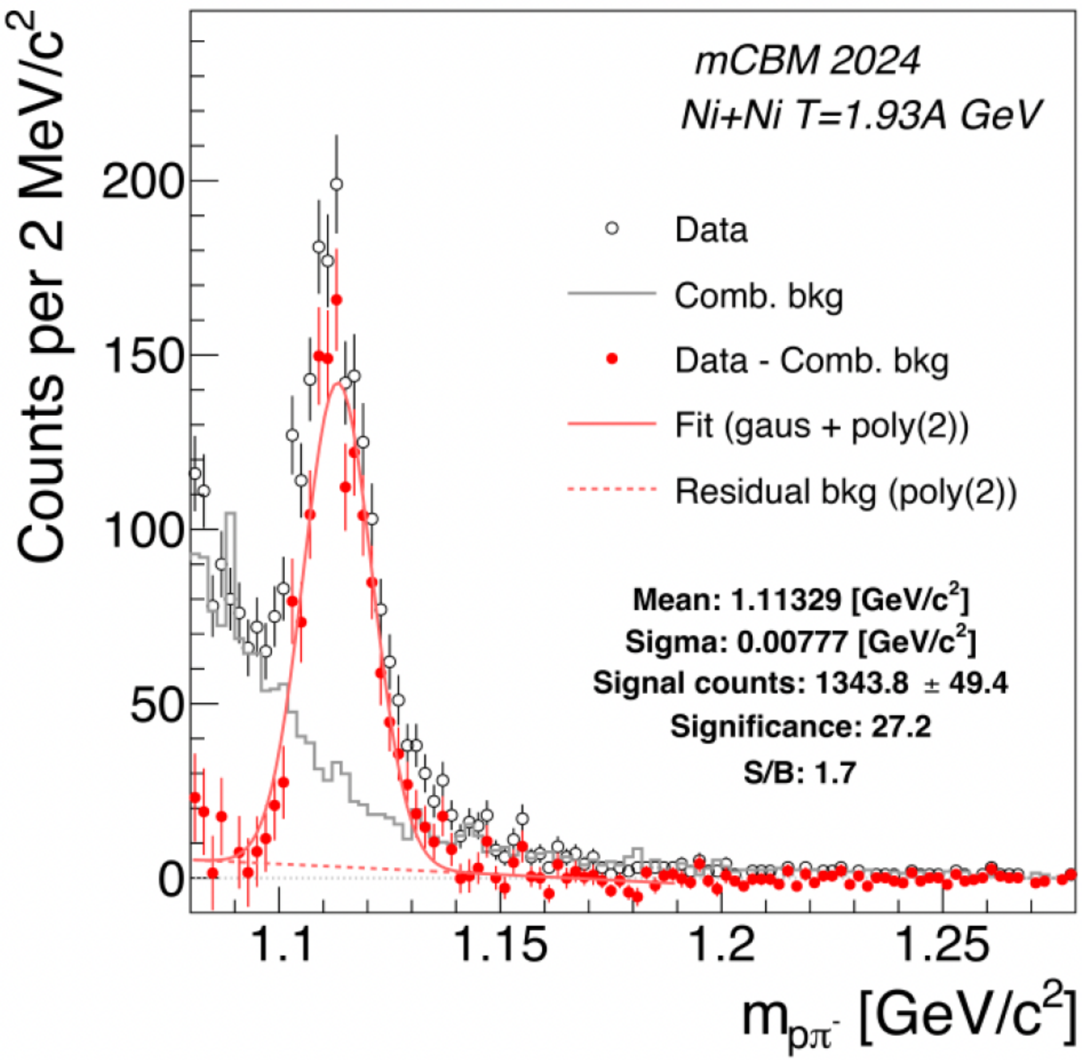


STS tracklets

- STS hits in 3 stations
- extrapolate to primary vertex
- tracklets within:
  - 3σ to the vertex
  - RMS error < 1.5cm



mCBM: Λ reconstruction (benchmark observable)



- CA track reconstruction
- KFParticle package
- Goal: online reconstruction in 2025

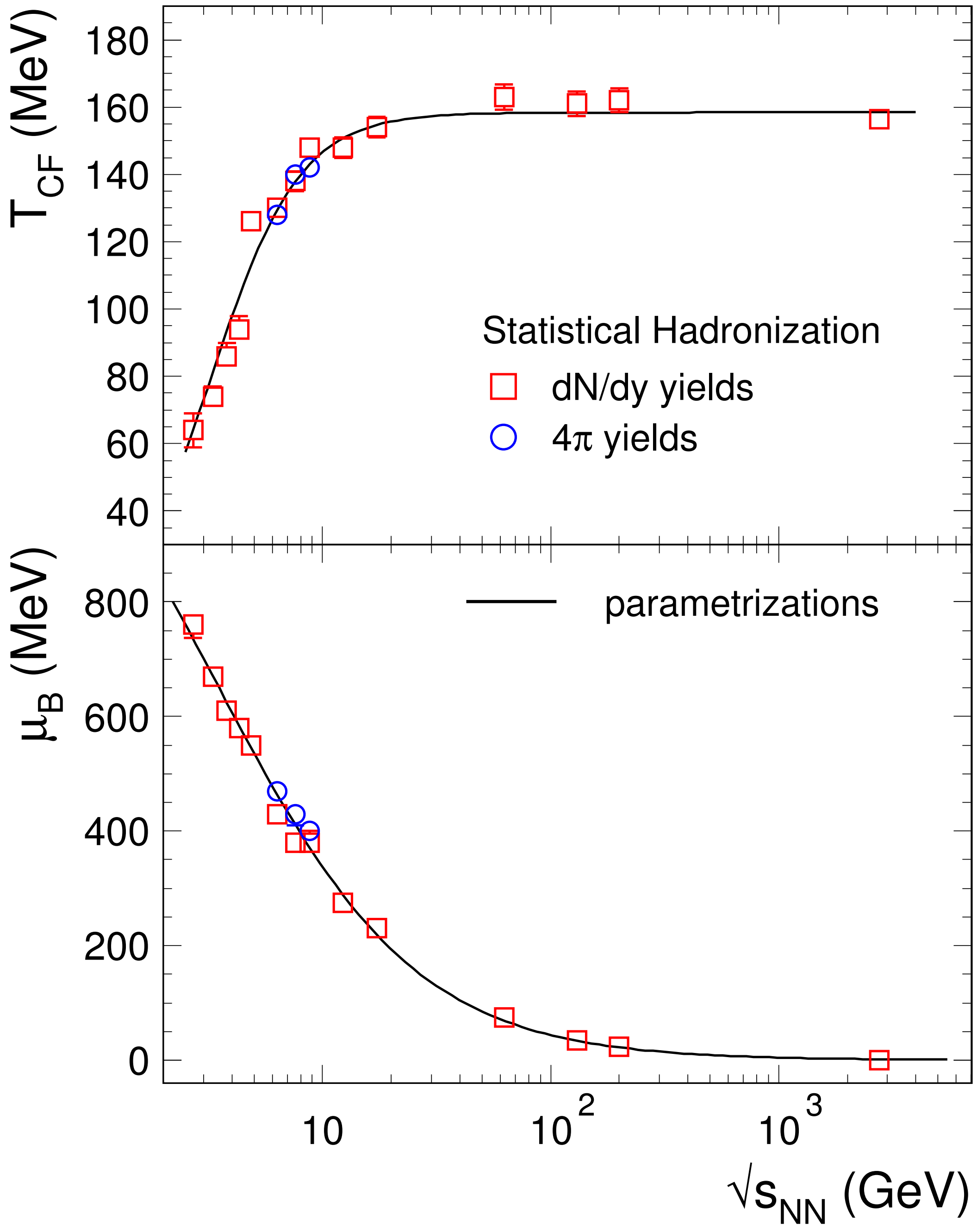
Summary / Outlook

- CBM is progressing well towards the science program with SIS100 beams
- High-rate capabilities (detector, readout) achieved in extensive R&D phase
- Almost all systems in (pre-)series production
- Start of commisioning with SIS100 beam in 2028

Thank you for your attention!

Additional slides

Energy dependence of T, μ_B (central collisions)



thermal fits exhibit a limiting temperature:

$$T_{lim} = 158.4 \pm 1.4 \text{ MeV}$$

$$T_{CF} = T_{lim} \frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}$$

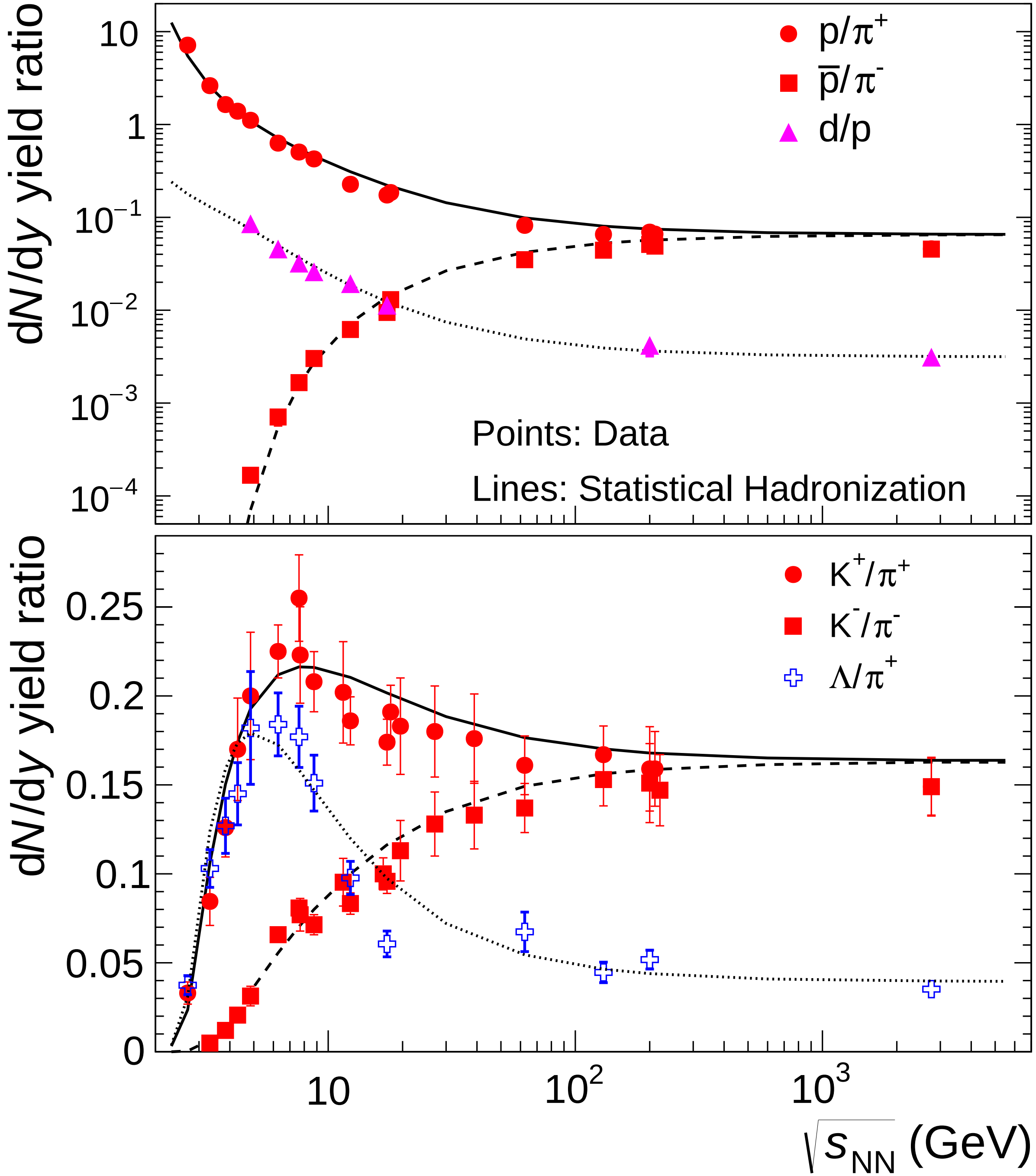
$$\mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

NPA 772 (2006) 167, PLB 673 (2009) 142

μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

determined by the "stopping" of the colliding nuclei

The grand (albeit partial) view



Data:

AGS: E895, E864, E866, E917, E877

SPS: NA49, NA44

RHIC: STAR, BRAHMS

LHC: ALICE

NB: no contribution from weak decays

no S-matrix correction $(\mathrm{p}, \overline{\mathrm{p}})$

d/p ratio is well described for all energies

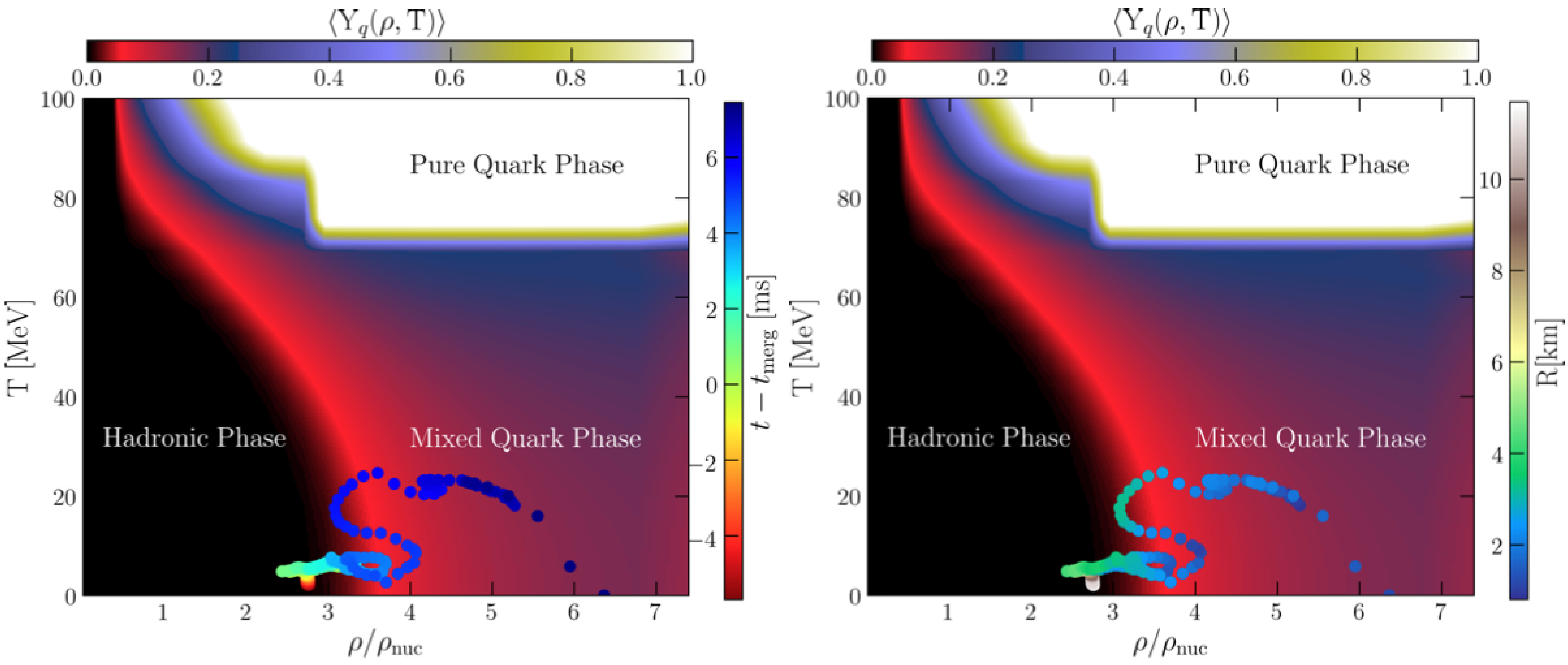
"structures" described by SHM

...determined by strangeness conservation

Λ/π peak reflects increasing T and decreasing μ_B

EoS: a complicated business ...but fundamental

Sampled phase diagram (points) in a merger of 2 neutron stars with 1.33 $M_\odot$



A. Prakash et al., PRD 104 (2021) 083029

EoS with quark degrees of freedom used here; not well constrained for $\rho/\rho_0 \gtrsim 2$

Matter in the NS cores crosses the phase boundary several times post-merger