ASTROPHYSICS IN LABORATORY: THE COMPRESSED BARYONIC MATTER (CBM) EXPERIMENT

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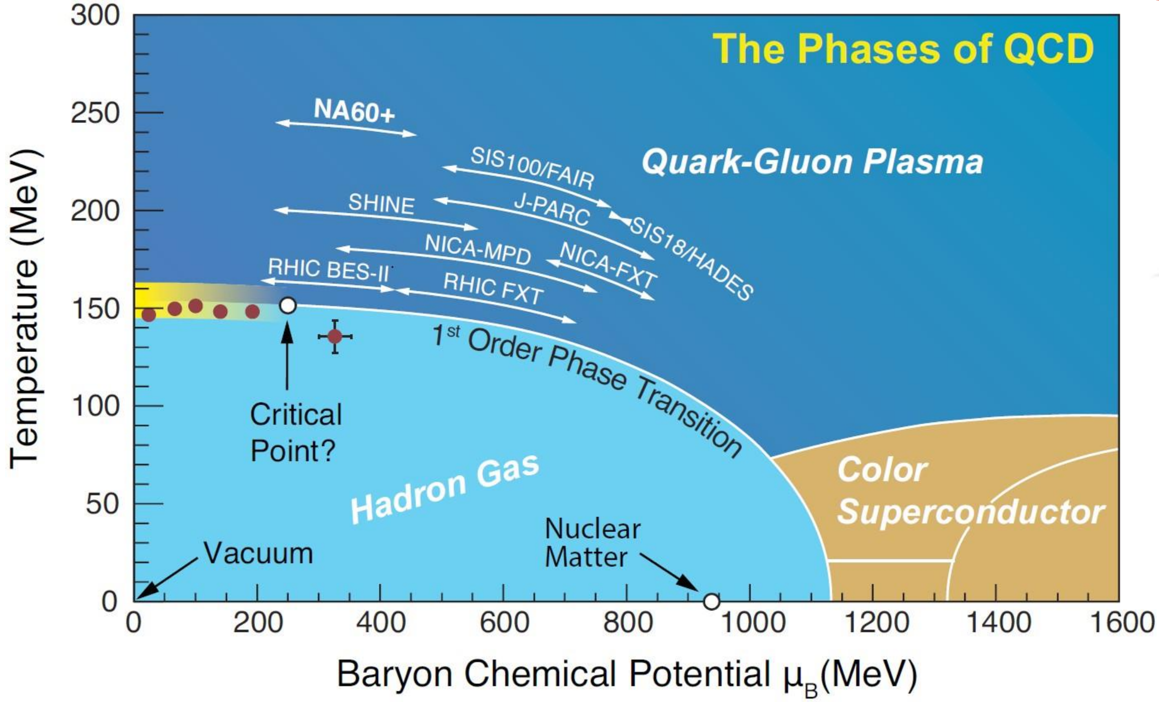
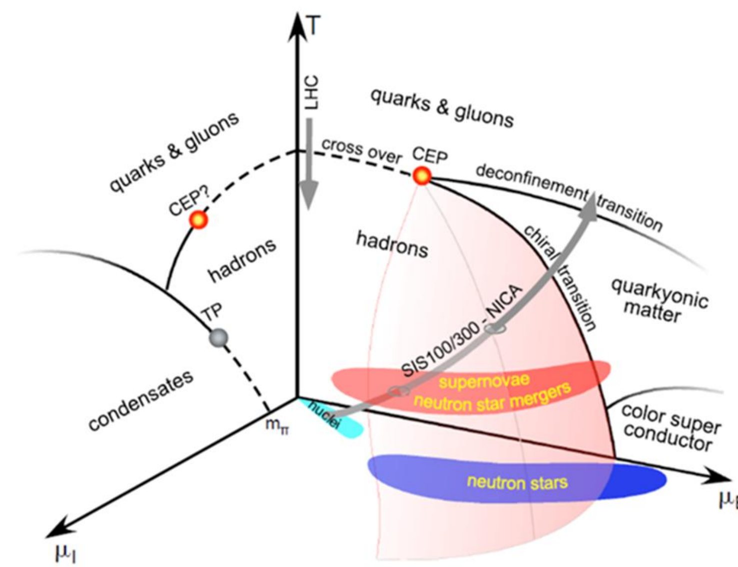
विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF SCIENCE & TECHNOLOGY

FAIR

CBM

Quark-Hadron Phase Diagram





Low μ_B, High T:

- Cross-over transition
- No critical point for $\mu_B/T < 3$

High μ_B, Low T:

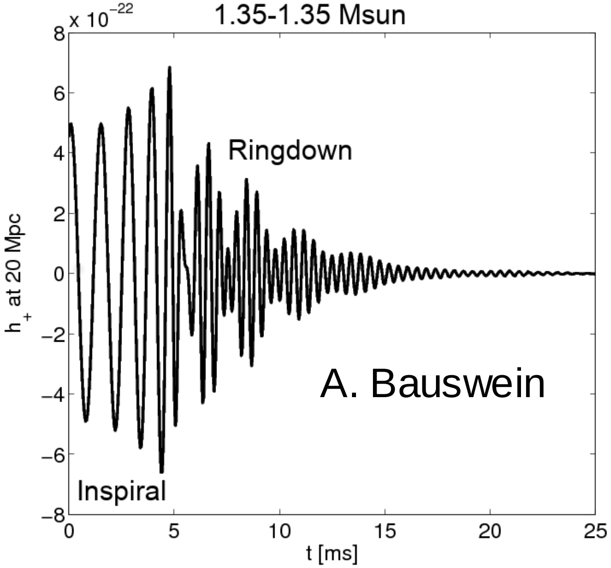
- Unknown phase structure
- Equation of state
- Neutron star core

STAR BES I: 2010-2017
7.7 GeV – 200 GeV

STAR BES II: 2019 – 2021
Collider: 7.7 GeV – 27 GeV
Fixed Target: 3 GeV – 13.7 GeV

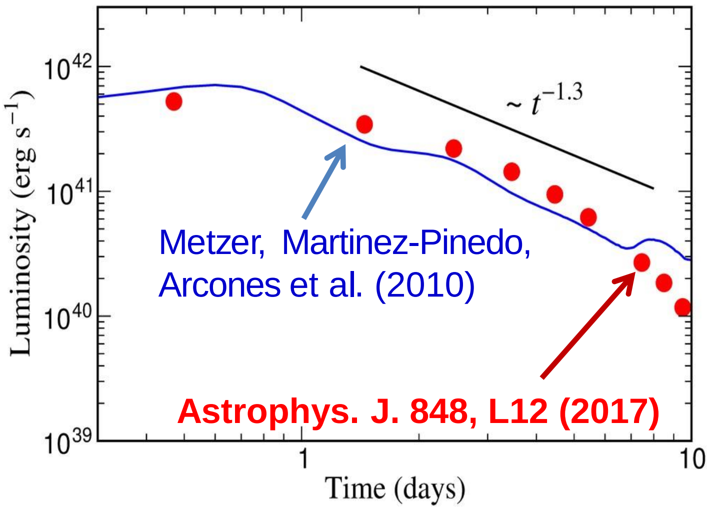
CBM: 2028 –
2.7 GeV – 4.9 GeV (μ_B : 800 – 500 MeV)

A renewed interest!



Gravitational Wave Signal

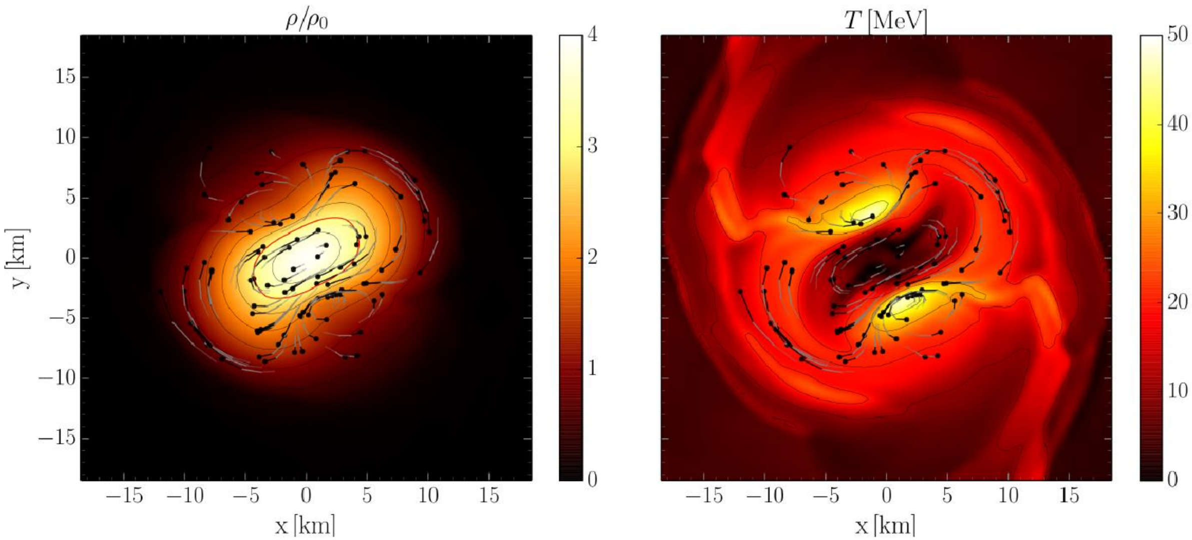
Copyright: Dana Berry, SkyWorks Digital, Inc

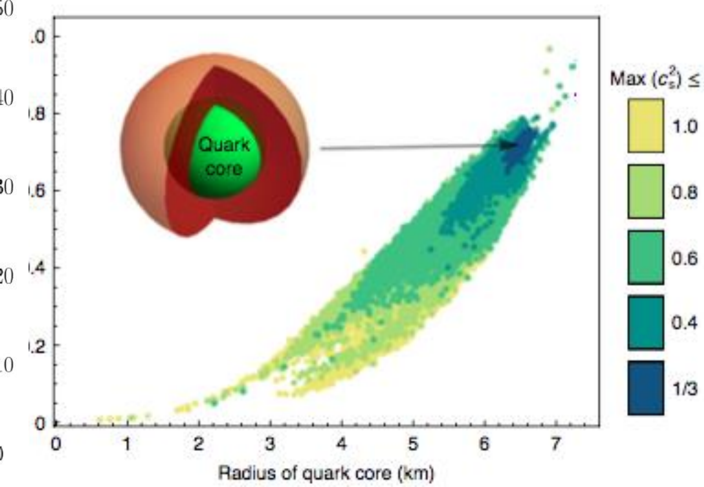


Electromagnetic "Kilonova" Signal

- Electromagnetic "Kilonova" signal due to "r process" in neutron star merger theoretically predicted in 2010.
- Confirmation by recent astronomical observations after gravitational wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum and uranium.

Recent results from neutron stars and others





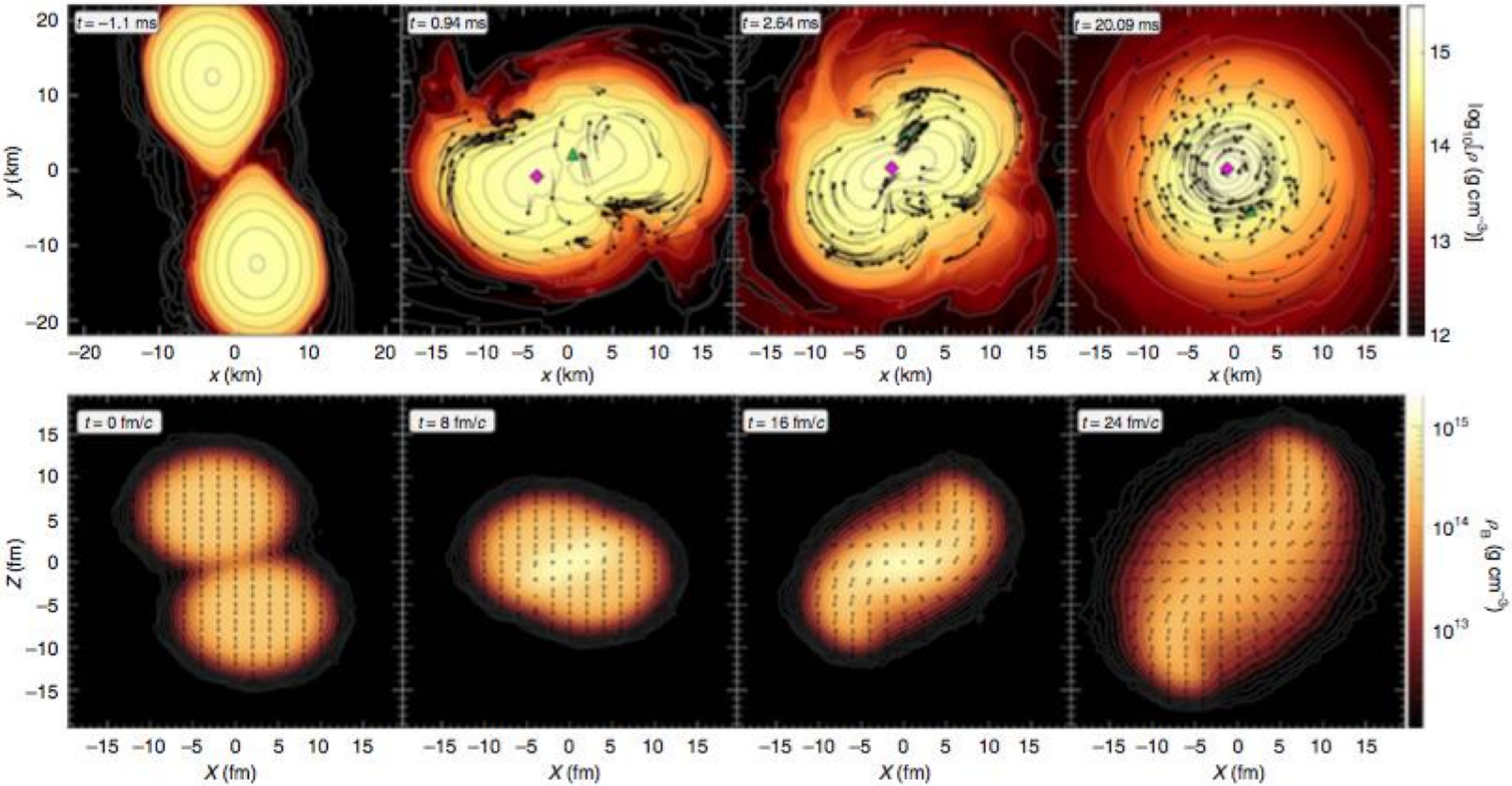
M. Hanauske et al. J Phys. Conf. Ser. 878 (2016) 012031

Nature Physics Letters 16 (2020) 907

In this conference

- Recent theoretical advancements on studying dense QCD phase transition
  Srimoyee Sen
- Overview of Neutron stars and their connection to QCD Phase Transitions
  Rana Nandi
- Observational constraints on the properties of the Neutron STAR Matter
  Tuhin Malik
- Neutron Star Physics in the Multi-messenger Era
  Ritam Mallick

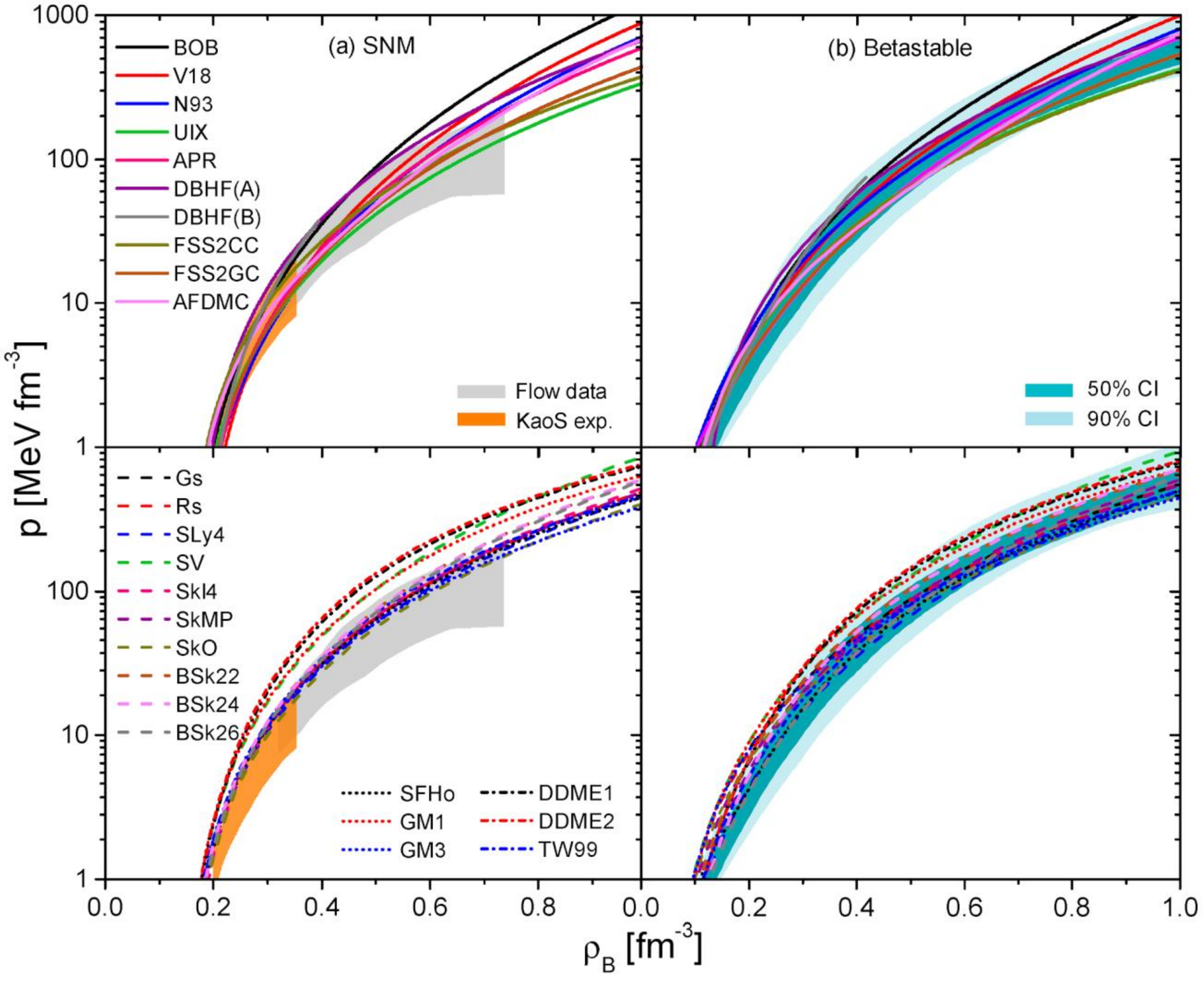
In the meantime from Heavy-ion physicists



Top panel: Binary neutron star encounter of two neutron stars of similar masses (1.35 solar mass)
Bottom panel: Time evolution of energy density achieved in non-central Au+Au @ 2.42 GeV

UrQMD simulation ; **Nature Physics 15 (2019) 10, 1040**

Constraints on EoS

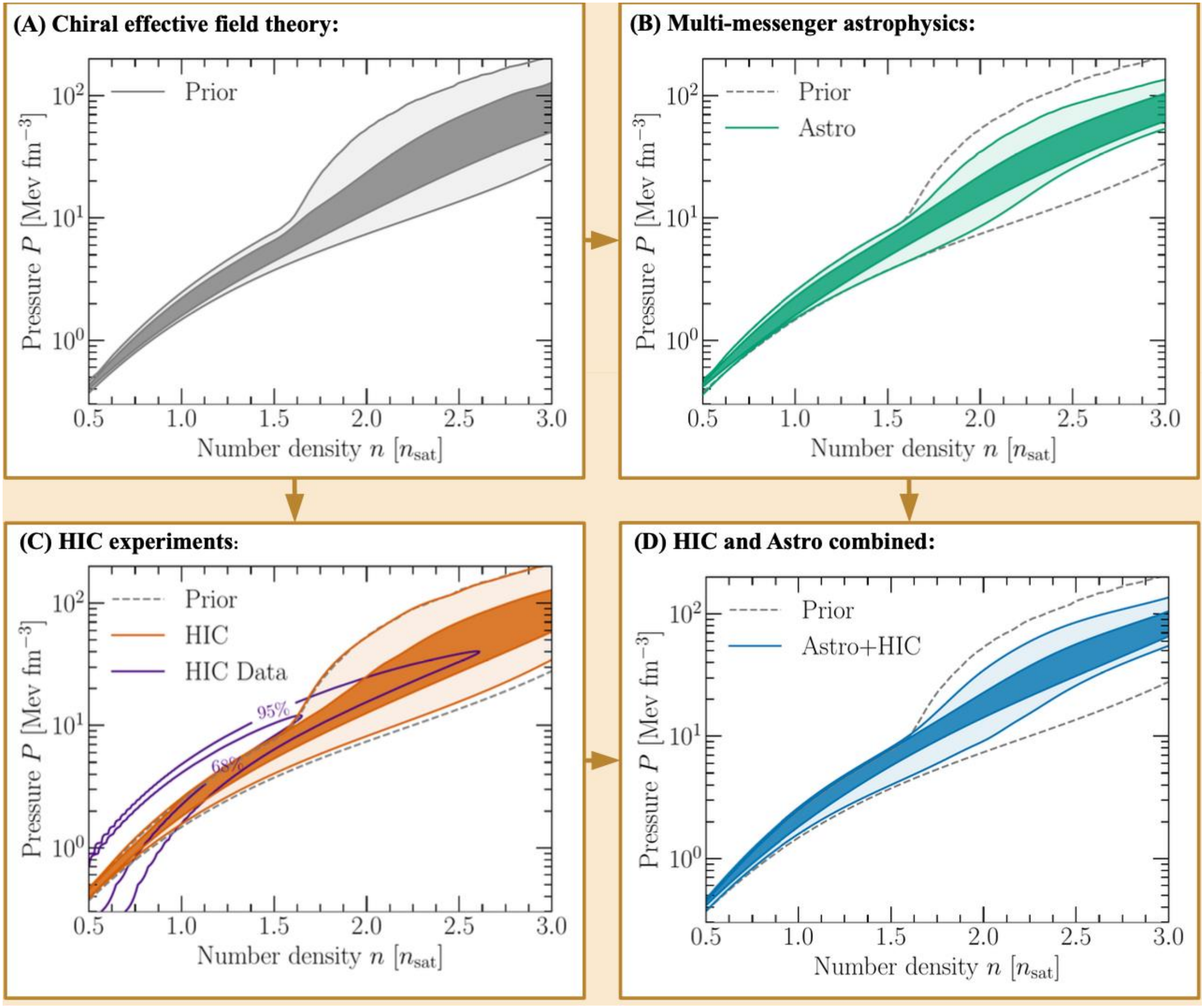


Measurements of anisotropic flow constrain the transport coefficients and equation of state (EoS) of the. matter created in heavy ion collisions

orange KaoS experiment
grey Flow data (FOPI-LAND)
blue GW170817 limits

G. F. Burgio et al. Symmetry 13 (2021) 400

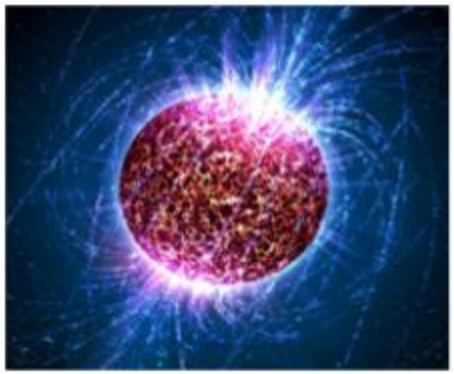
EoS: HIC and multi-messenger astronomy



S. Huth et al. Nature 606 (2022) 276

What do we expect to see?

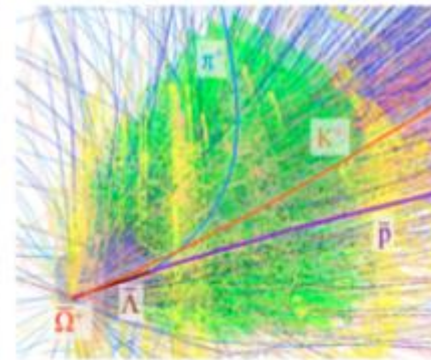
Neutron stars



Neutron star merger

GW170817

Heavy-ion collisions



SIS100 energies

Temperature (T)	< 10 MeV	~10-100 MeV	< 120 MeV
Density (ρ)	$< 10\ \rho_0$	$< 2\text{-}6\ \rho_0$	$< 5\text{-}15\ \rho_0$
Lifetime / Reaction time (t)	∞	~10 ms	$\sim 10^{-23}$ s

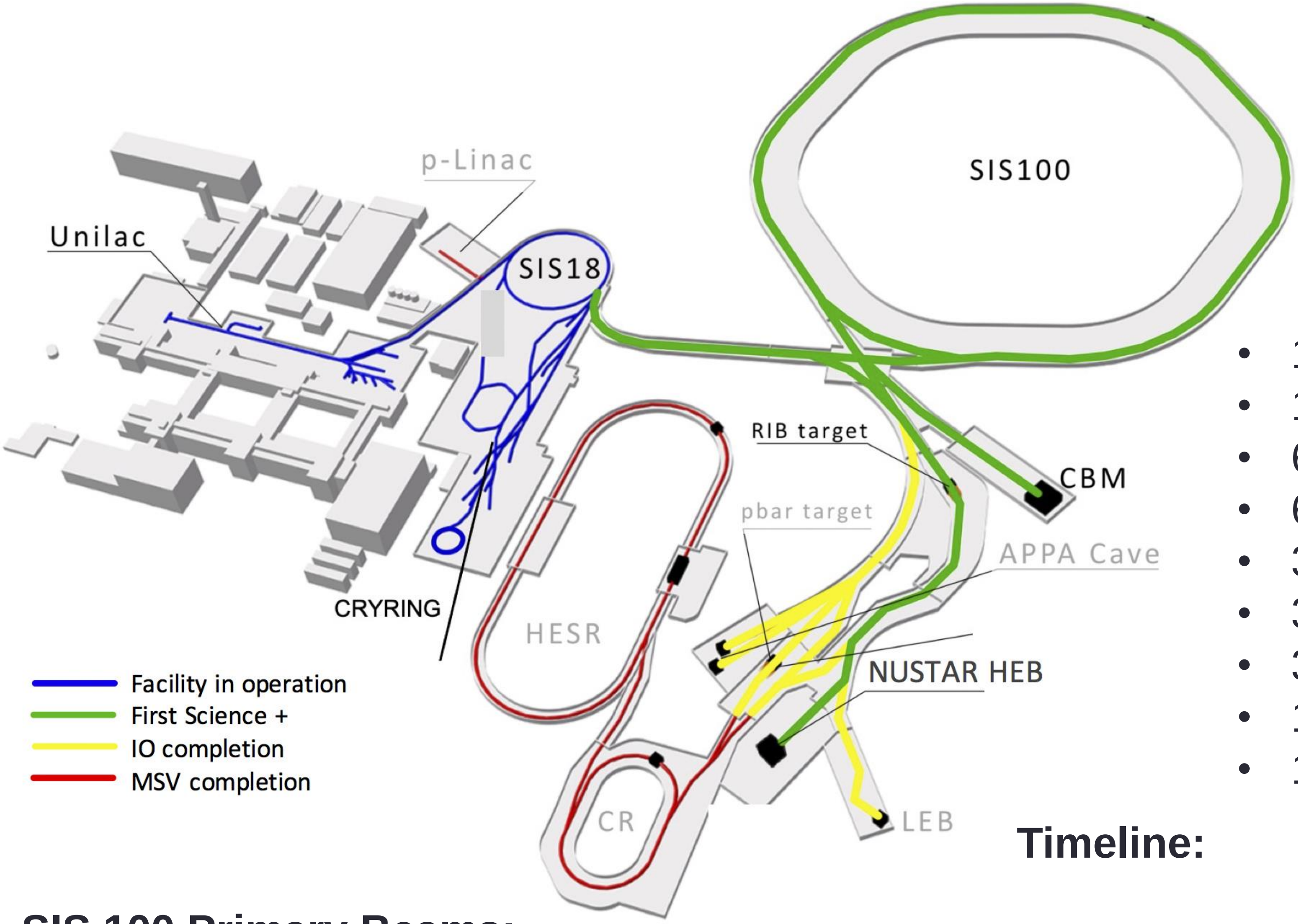
Coming up : Compressed Baryonic Matter (CBM) experiment at FAIR, Darmstadt (2028 -)

QGP is there, it is strongly interacting system, but

- What is the equation of state at high baryon densities ?
- Order of phase transition at high baryon densities ?
- Where is the critical end point ?

- Multipurpose facility
- Nuclear, Atomic, Particle physics experiments
- Very high intensity beams

India is a shareholder



- 1.1 km circumference
- 17 m underground
- 600k m^3 concrete
- 65 kt steel
- 3.3 billion Euro
- 3000 researchers
- 300k processors
- 100 PB storage
- 1TB/s transmission

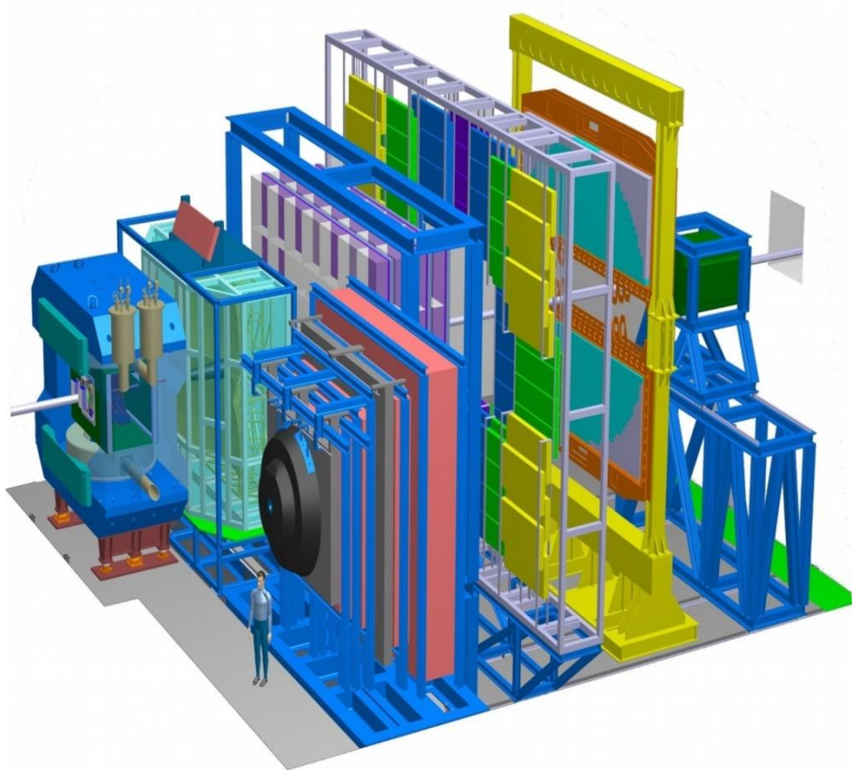
Timeline:

- July 2017 : Start of excavation
- July 2018 : Start of civil construction
- 2023 : Buildings completed; Installation of infrastructural equipment started
- 2028 : Beams expected

SIS 100 Primary Beams:

- 10^9/s Au up to 11 GeV/u (\sqrt{s} =4.9 GeV)
- 10^9/s C, Ca up to 14 GeV/u
- 10^{11}/s p up to 29 GeV (\sqrt{s} = 7.5 GeV)

The CBM experimental set up



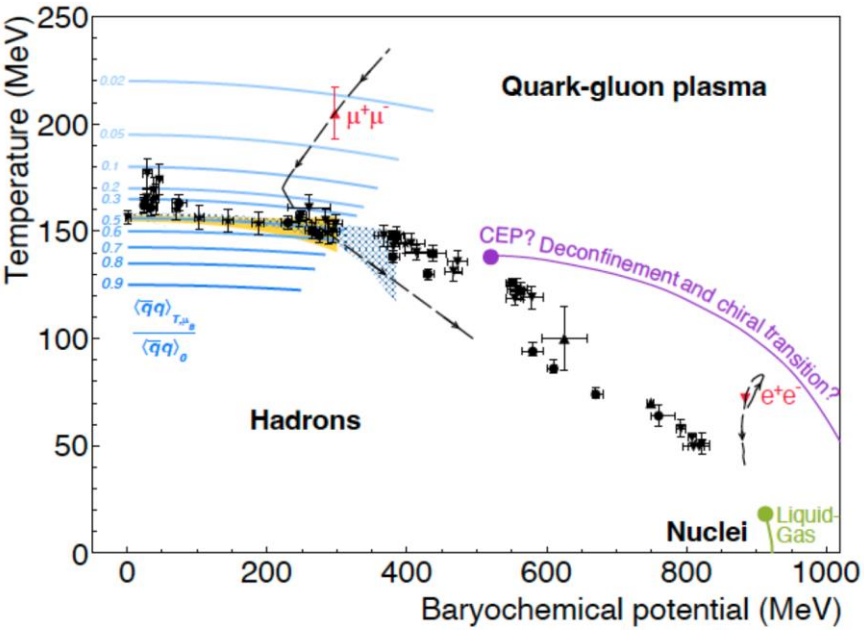
- Tracking acceptance: $2.5^o < \theta_{Lab} < 25^o$
- Peak R_{int} is 10 MHz for Au+Au (300 kHz for MVD)
- Fast & radiation hard detectors
- Free-streaming DAQ
- 4D tracking (space, time)
- Online event reconstruction and selection
- Data rate: 1 TB/sec

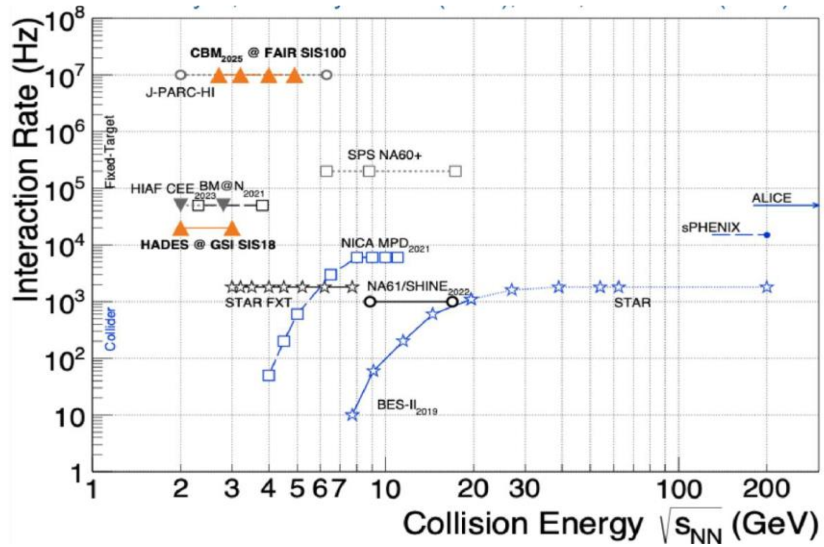
MVD: Micro Vertex Detector
STS: Silicon Tracking System
MuCH or RICH: Muon Chamber System /Ring Imaging Cherenkov Detector

TRD: Transition Radiation Detector
TOF: Time-of-Flight Detector
PSD: Projectile Spectator Detector

GSI GreenITCube
High performance computing farm for data processing

CBM Mission





NuPECC Long Range Plan 2024

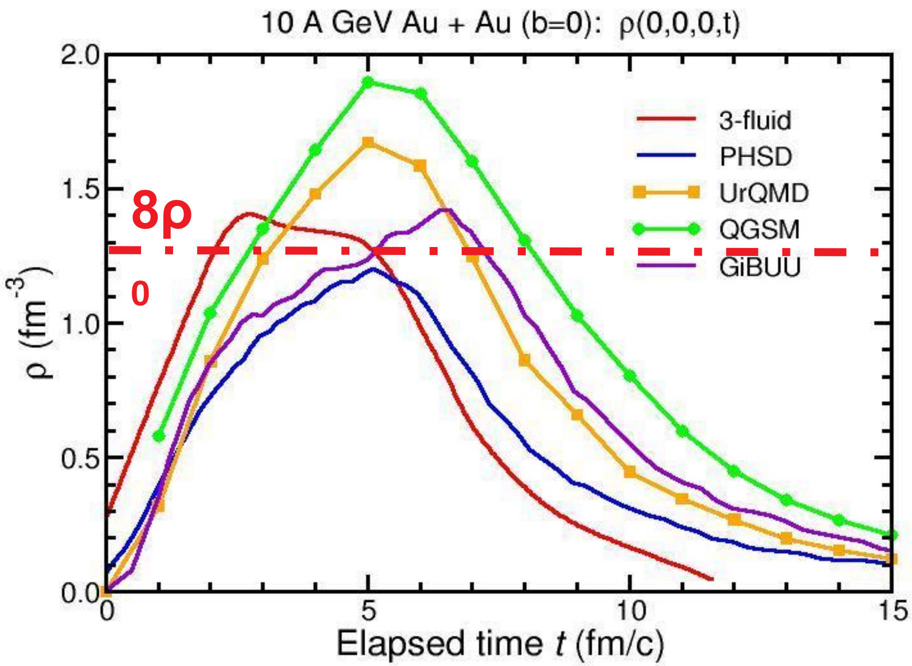
- ✓ Characterize hot and dense QCD matter at high μ_B (500 – 800 MeV)
- ✓ Find QCD critical point, order of phase transition

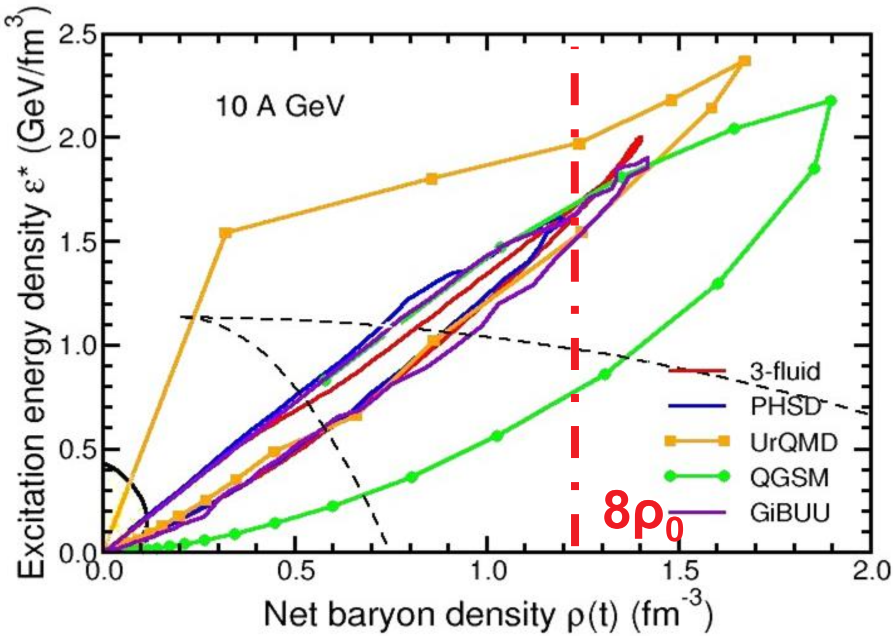
Observables

- Light flavor hadrons (including multi-strange hadrons): chemical freezeout T, μ_B, flow, vorticity, EoS
- Event by Event fluctuations (criticality)
- Dileptons (emissivity)
- Charmoniums (transport properties)
- Hypernuclei (interactions / production mechanism)

High statistics needs high reaction rates: 10^5 - 10^7 Au+Au collisions/sec!

Net baryon densities at SIS100 energies



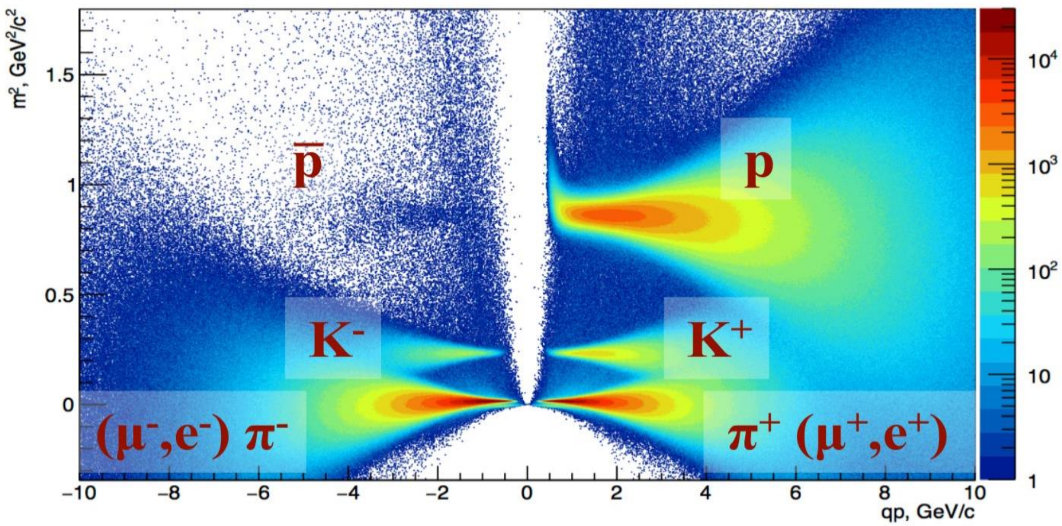


I. Arsene et al. PRC75 034902 (2007)

High baryon densities during system evolution!

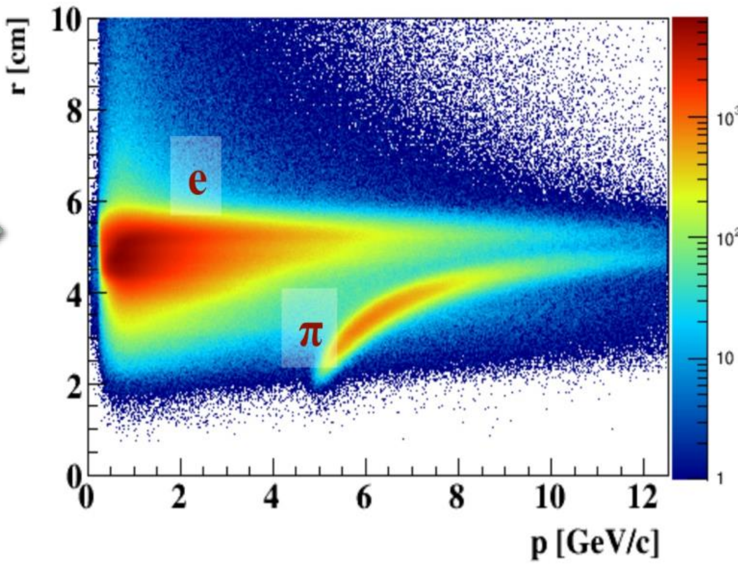
Particle identification at CBM

CBM simulation central Au+Au collisions @ 10*A* GeV/*c*

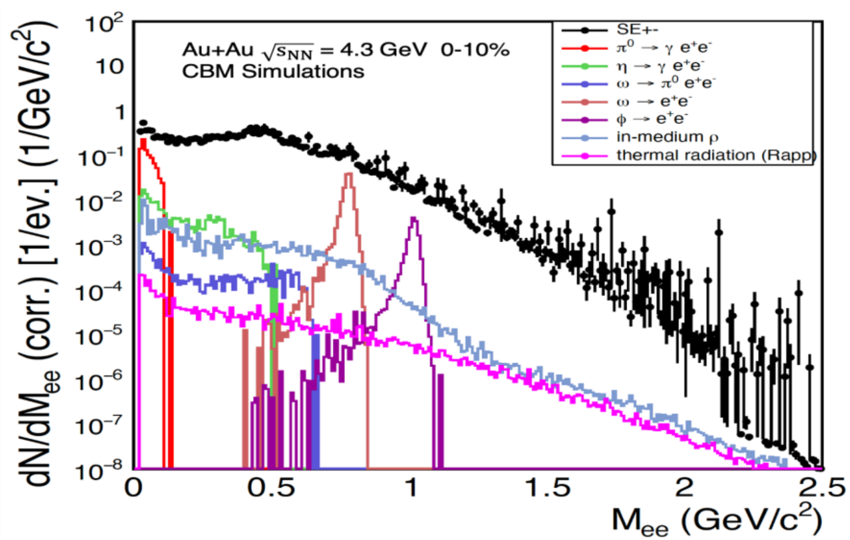


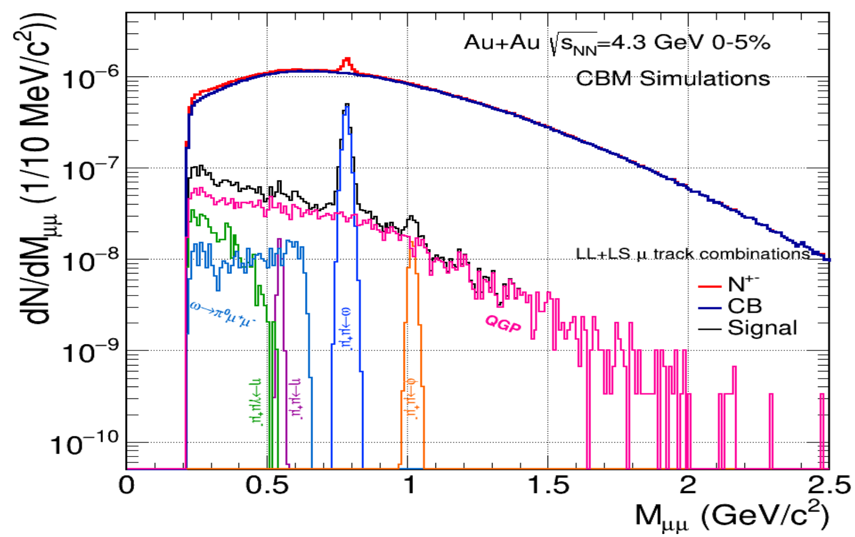
Performance of TOF

Performance of RICH



Dileptons: di-electrons and di-muons

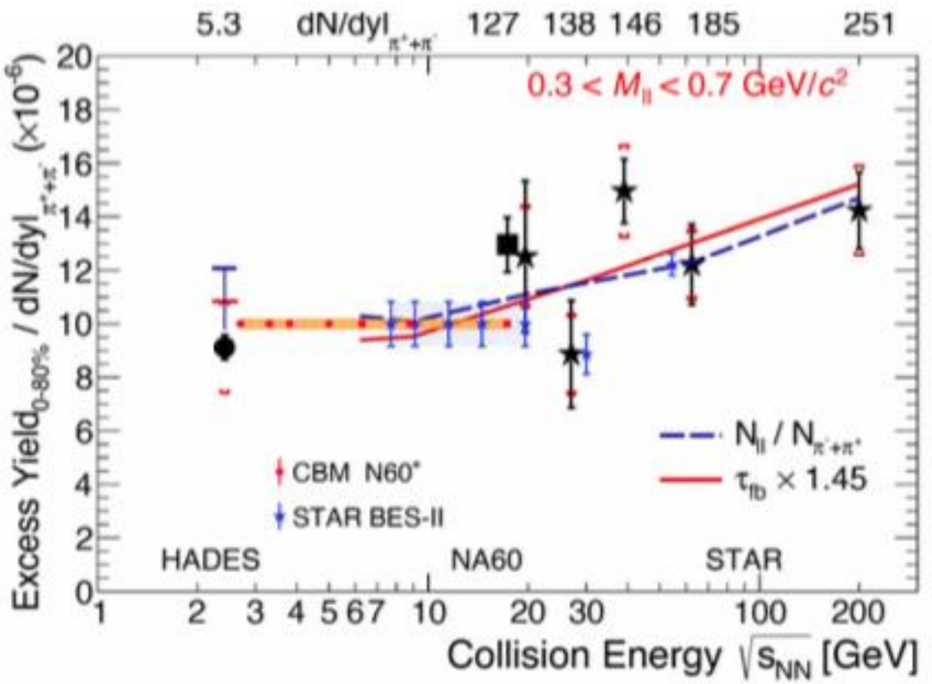


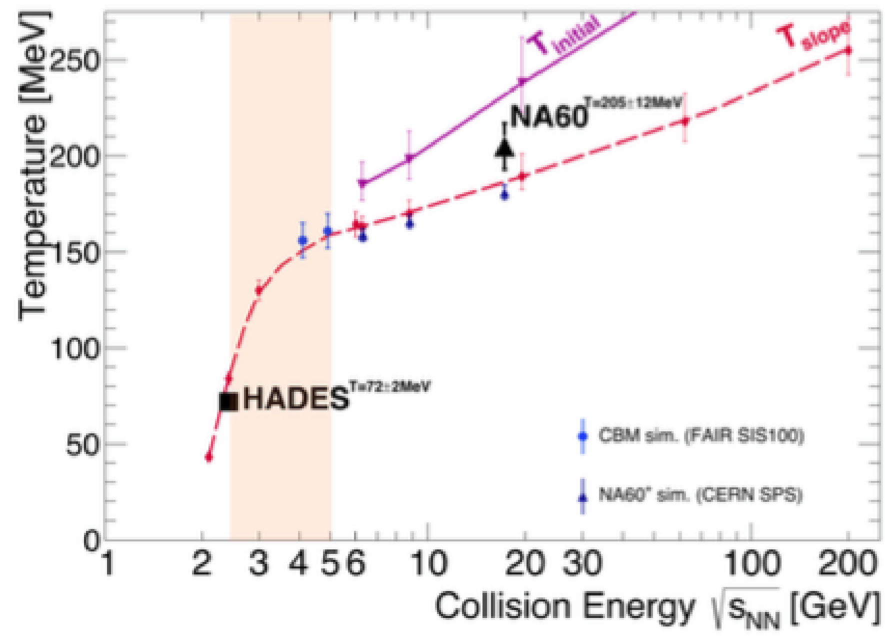


- Carry information about the early phases of the fireball
- Dileptons are considered as thermometer, chronometer and barometer of the emitting source

- Clear signal peaks for the low mass vector mesons with 5M Au+Au collisions
- Negligible contribution from Drell-Yan and open charm decay
- Access to thermal signal with good background description
- Excitation function measurable with 10^5 collisions/sec

Temperature/lifetime (or emissivity)

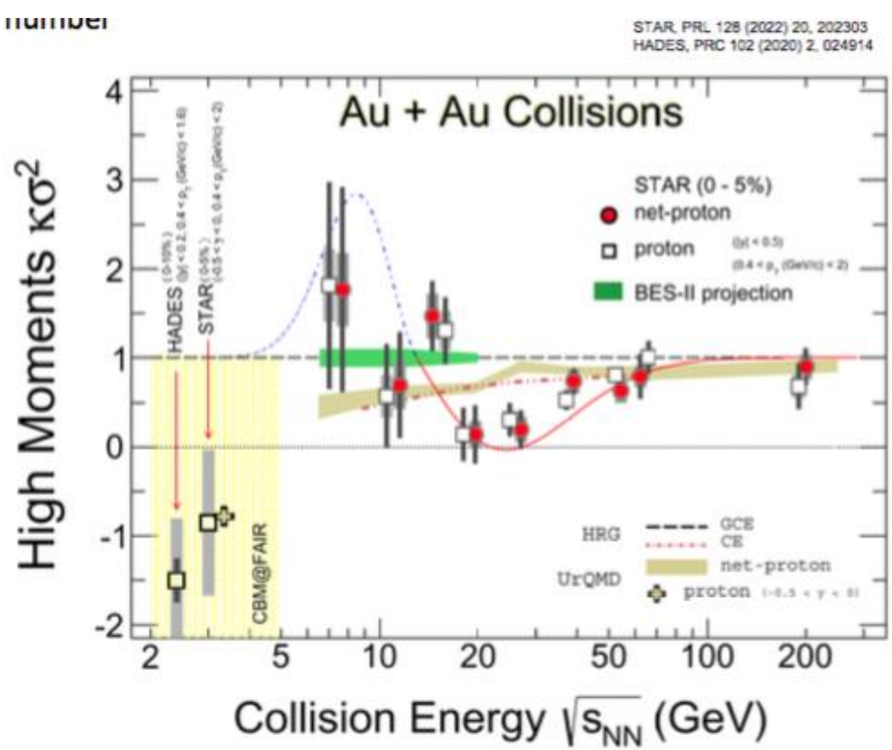


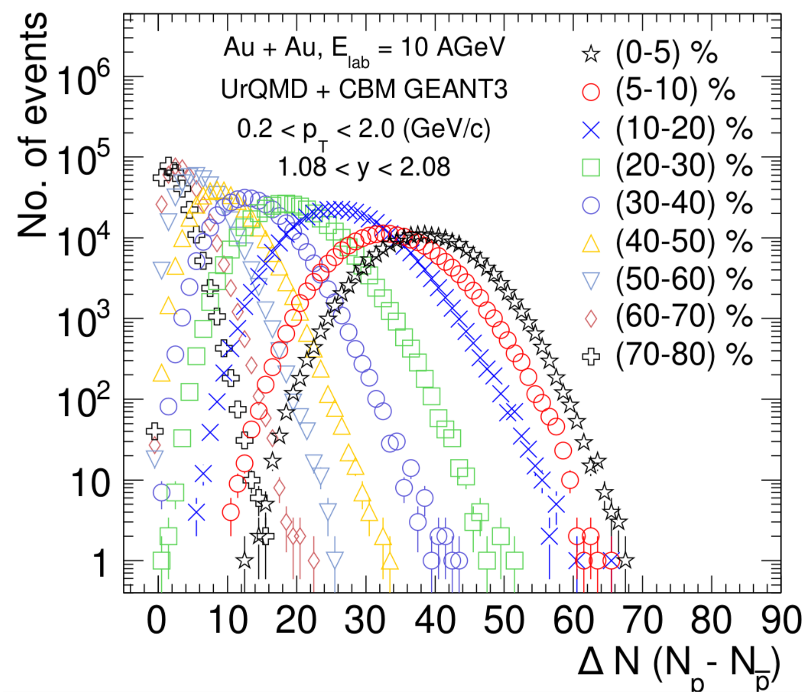


- ✓ Excess yield in Low Mass Region provides lifetime
- ✓ Excess radiation indicates latent heat at phase transition

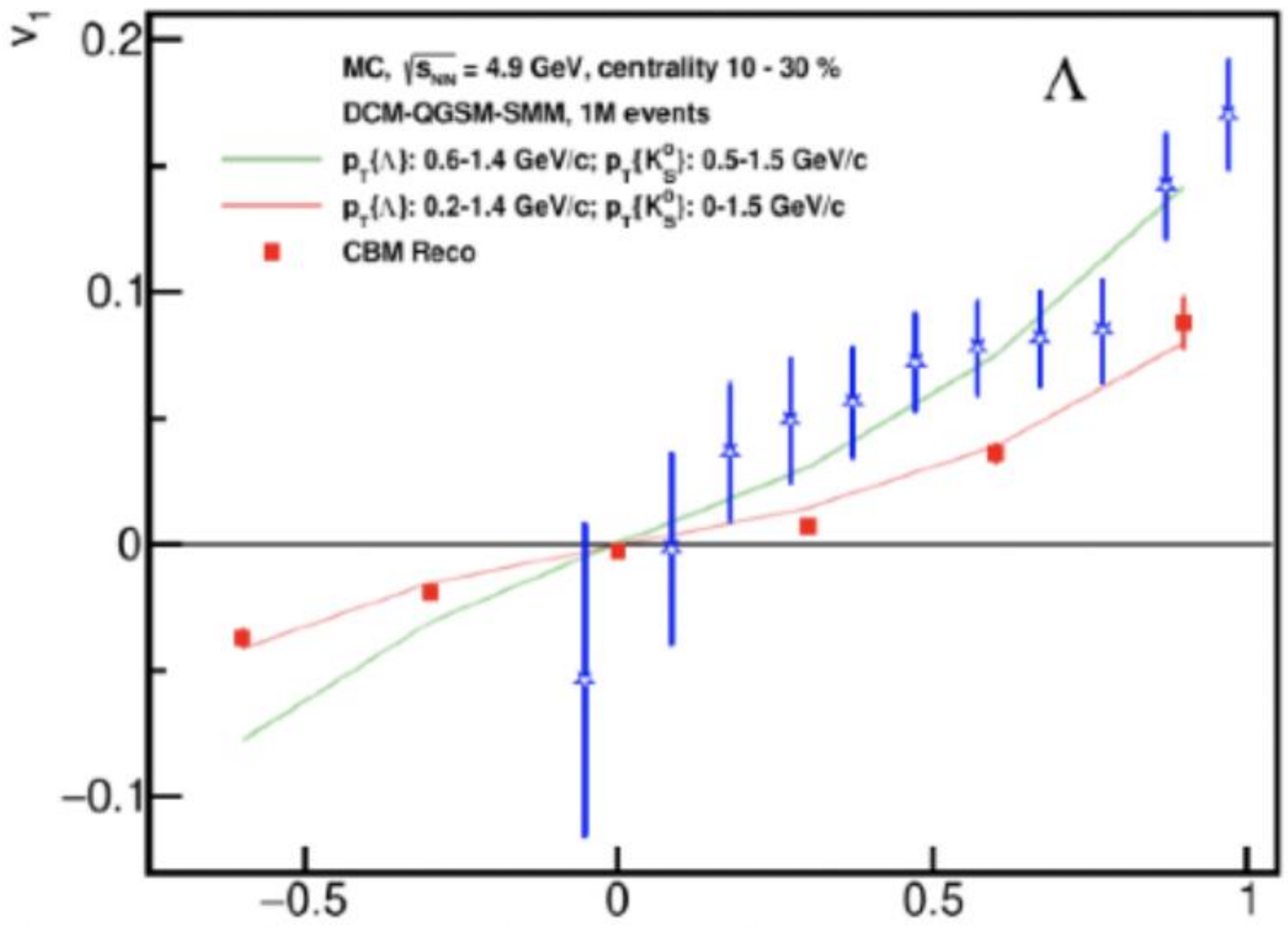
- ✓ Slope of invariant mass spectra in Intermediate Mass Region provides temperature
- ✓ Flattening of the curve (T vs. E) indicates phase transition

Fluctuations (or criticality)



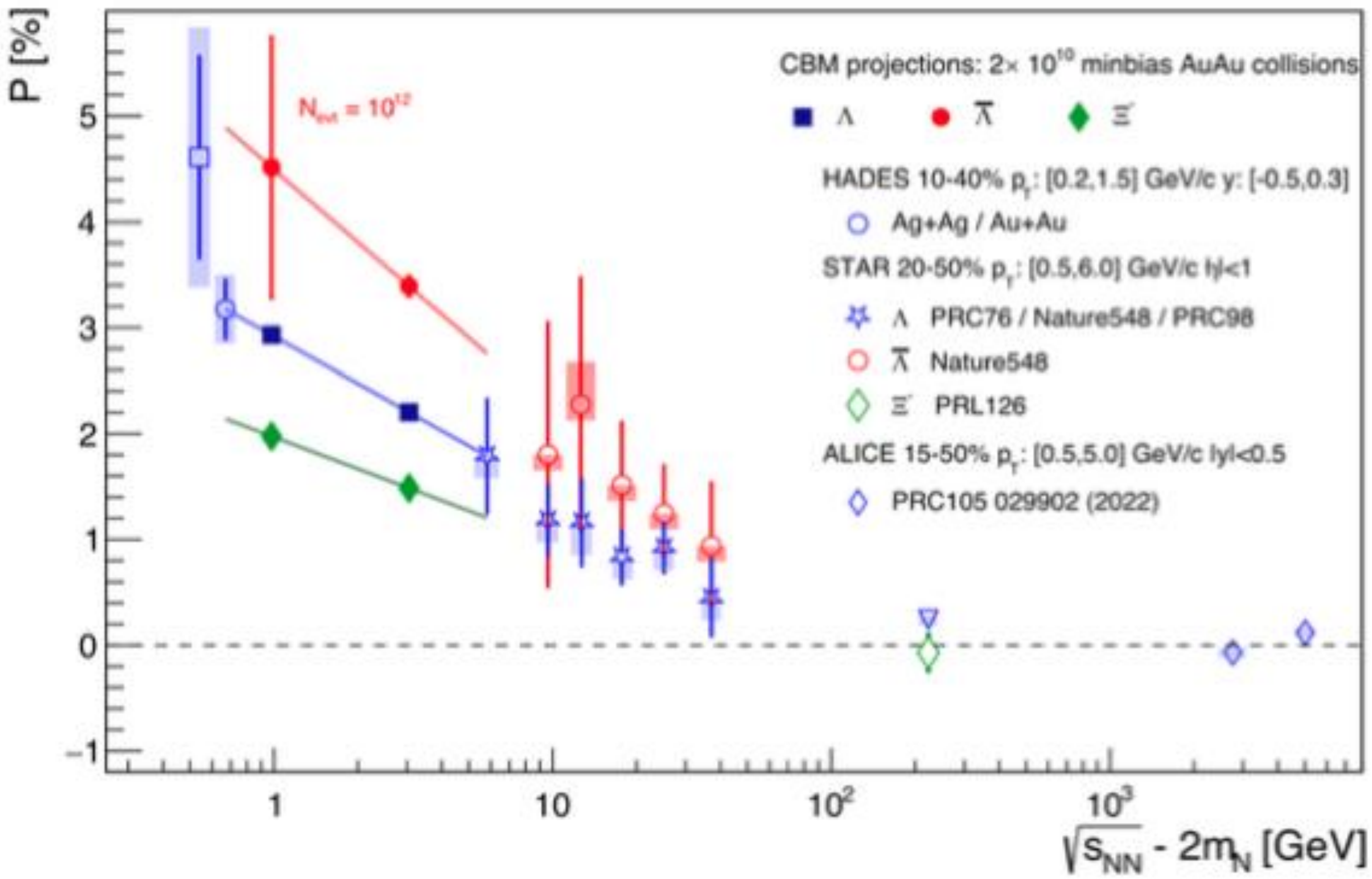


Flow /EoS



v1
0.2
0.1
0
−0.1
−0.5
0
0.5
1
MC, √sNN = 4.9 GeV, centrality 10 - 30 %
DCM-QGSM-SMM, 1M events
pT{Λ}: 0.6-1.4 GeV/c; pT{K0S}: 0.5-1.5 GeV/c
pT{Λ}: 0.2-1.4 GeV/c; pT{K0S}: 0-1.5 GeV/c
CBM Reco
Λ

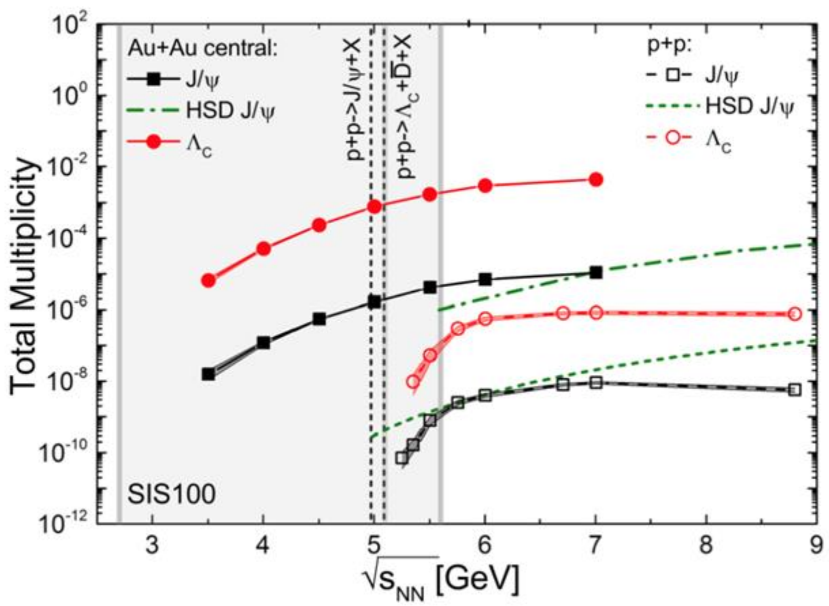
Polarization of hadrons (or vorticity)



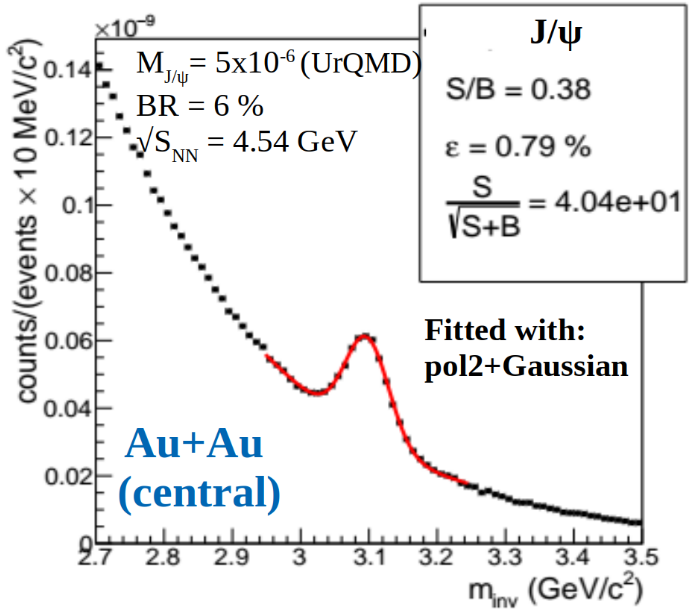
- Measurement of Λ and Ξ polarization with 5% precision is possible
- (anti)Λ excitation function requires more than 10^{13} events

Charmonium at SIS100 in Au+Au Collisions

J. Steinheimer et al., PRC 95 (2017) 1, 014911



10 A GeV/c central Au+Au collisions



J/ψ production is rare but measurement is feasible

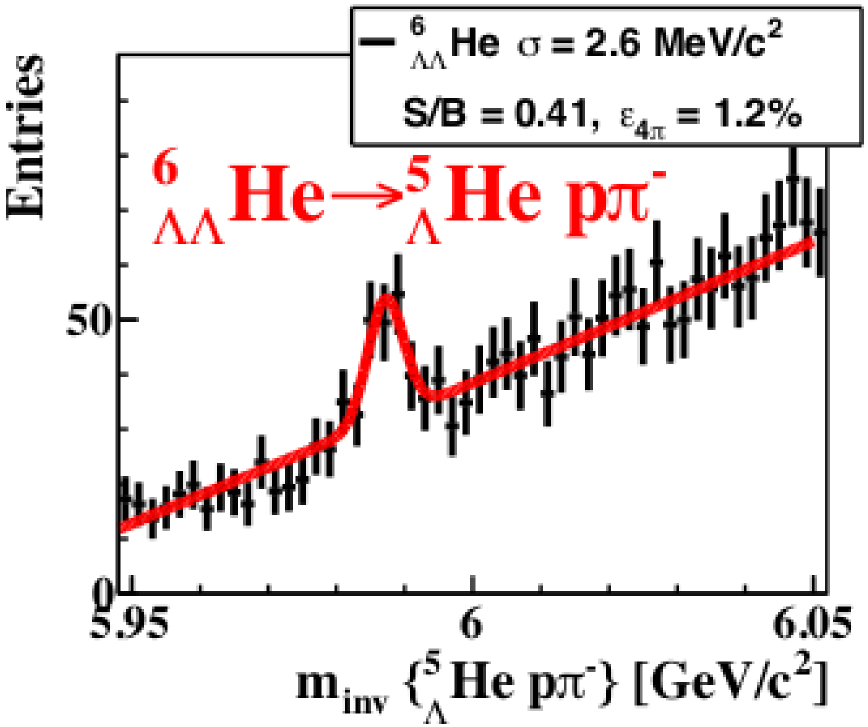
- Production below kinematic threshold
- Production via multiple collision process
- No data below collision energy 158*A* GeV

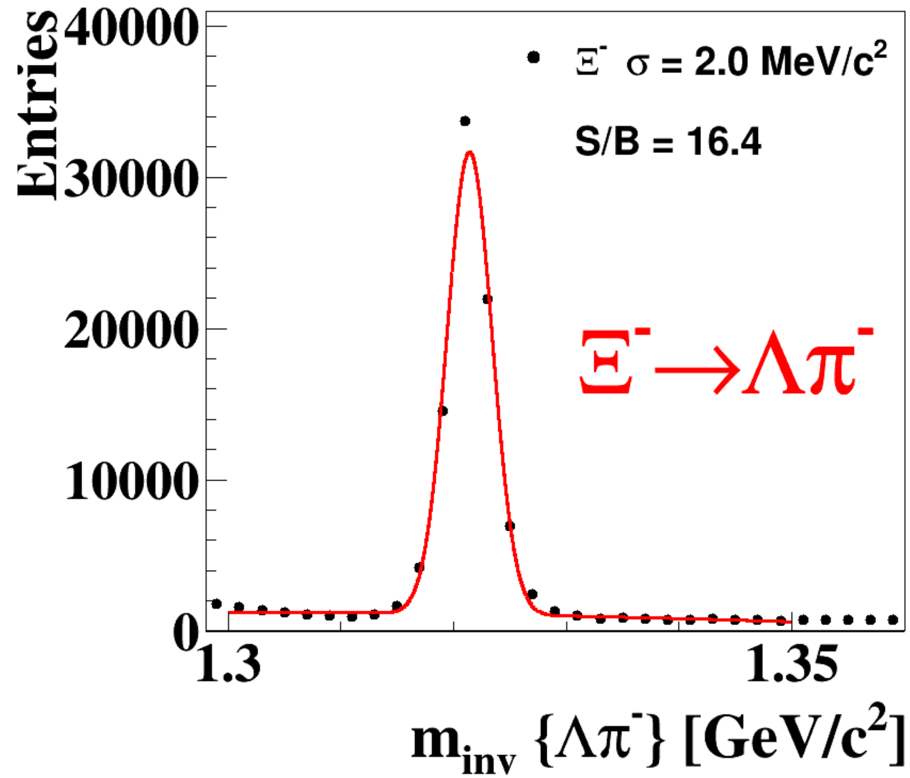
Reconstruction via $\mu^+\mu^-$ decay channel

- Clear signal peak -> feasible detection
- Detectors: STS+MuCh+TRD
- Expected yield:

~ 30K J/ψ in 4 weeks @R_{int} = 10 MHz

Hypernuclei and multi-strange hadrons

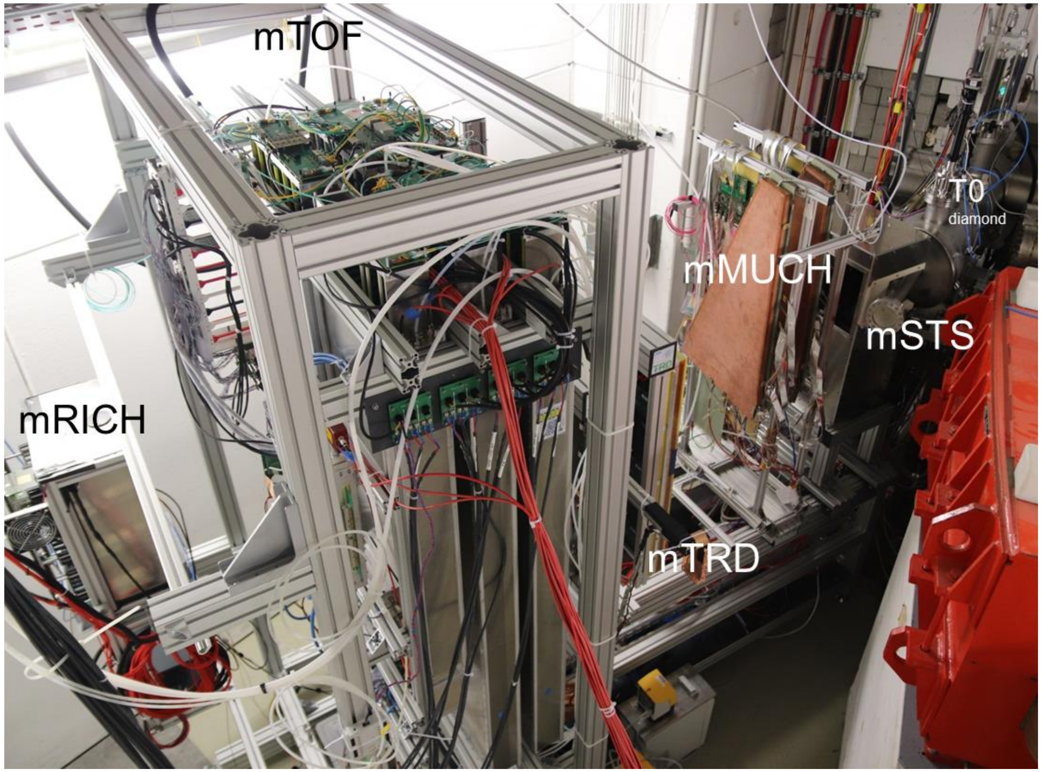




CBM simulation (UrQMD)
Au+Au @10*A* GeV/*c* mbias, 10^{12} events

CBM simulation (UrQMD)
Au+Au @ 10*A* GeV/*c* central, 5M events

mCBM @ GSI/SIS18



Data analysis ongoing:

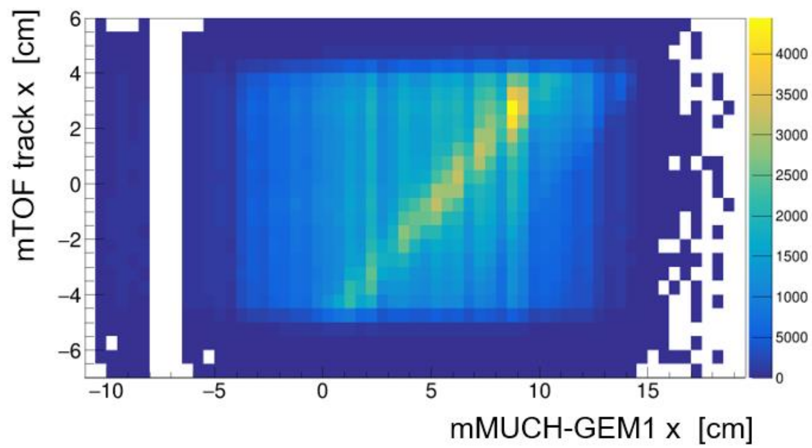
Data transport of all subsystems in a common,
synchronized data stream

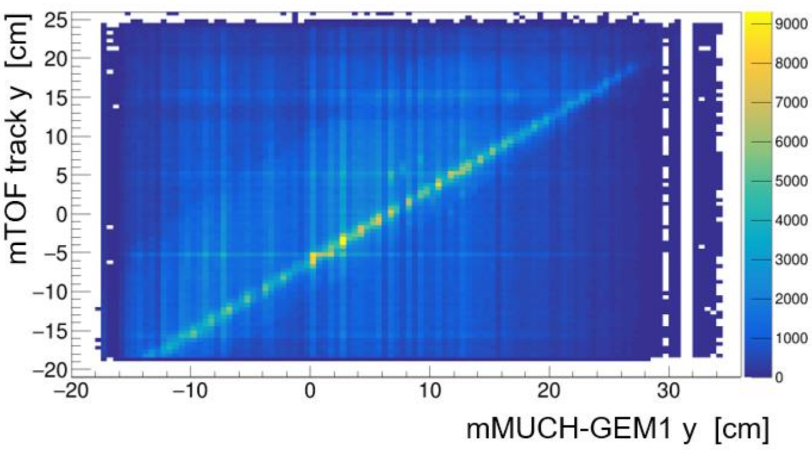
Collision rate up to 10 MHz for Ag+Ag collisions
(1 MHz for Pb+Pb) -> CBM conditions reached!

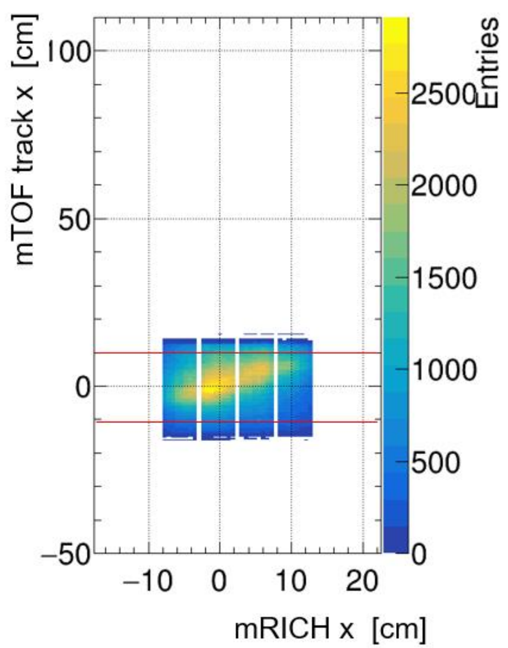
Observed time and spatial correlations between detector subsystems:

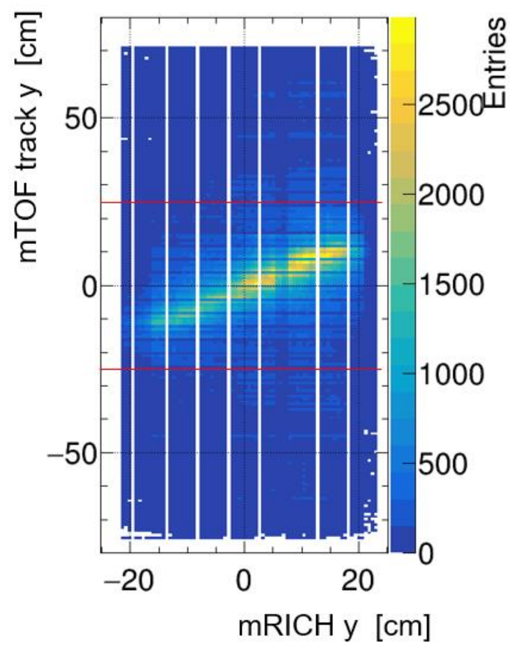
First steps towards verification of the triggerless-streaming DAQ system of CBM

mCBM: Preliminary results

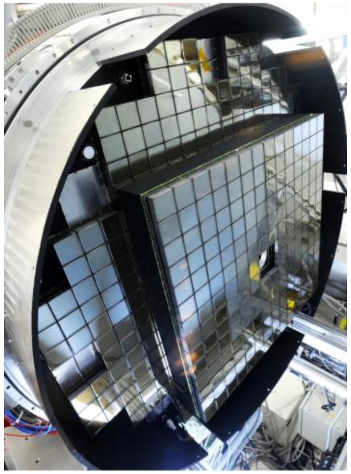






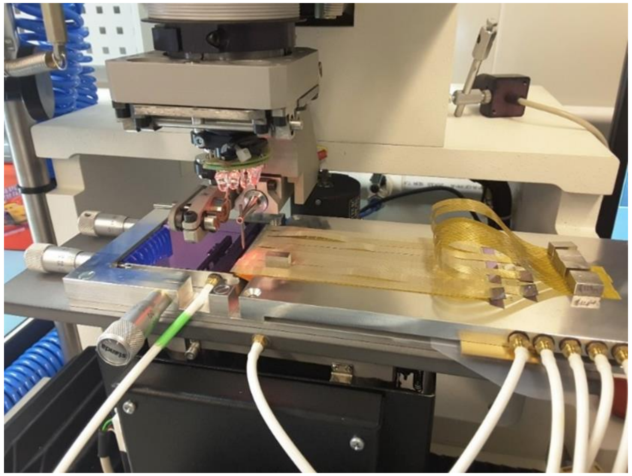


Gearing up for beam on target

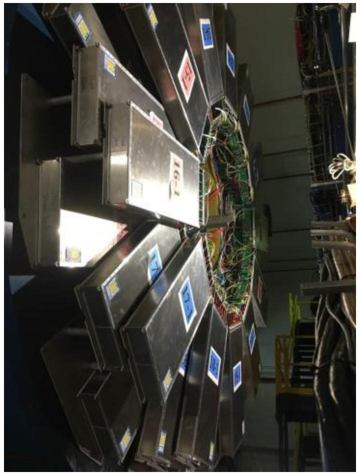


RICH @ HADES

PSD @ NA61/SHINE

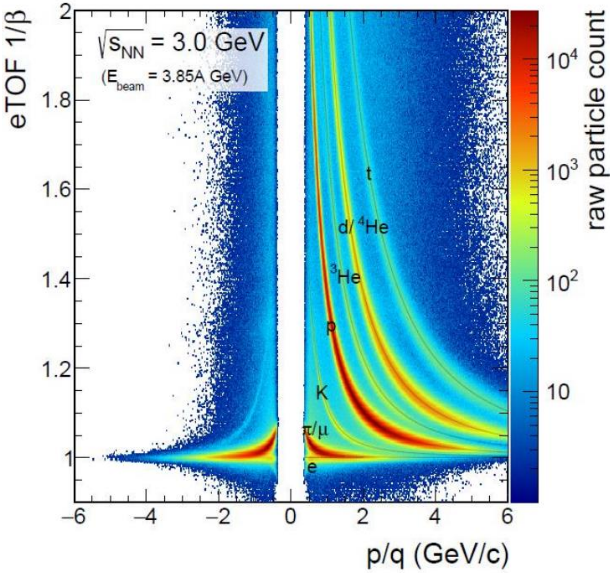


STS @ BM@N



eTOF @ STAR

3 layers
12 sectors
36 modules
108 MRPCs
6912 channels



Summary and outlook

- ✓ Core of the neutron stars have high enough baryon density to create deconfined state of matter.
- ✓ Recorded neutron star merger events and further observed astrophysical events have generated renewed interest in the field.
- ✓ Matter existing in the core of a neutron star could be accessed through ultra-relativistic heavy-ion collisions.
- ✓ With unprecedented interaction rates CBM@FAIR has unique opportunity to study this with high precision.
- ✓ CBM is set to shed more lights onto the QCD phase diagram e.g. location of critical point and order of phase transition.
- ✓ Almost all key probes such as EoS, temperature, in-medium modification of hadron mass, criticality, vorticity, production of charmonium are part of CBM physics program.
- ✓ Promising p+A programs at CBM using SIS100

So, stay tuned!

My talk is a work of many …