Studying The Neutron Star Equation Of State With The Compressed Baryonic Matter (CBM) At FAIR

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– For the CBM Collaboration –

Online Conference on Gravitational Physics and Astronomy (GPA-2022)

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EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

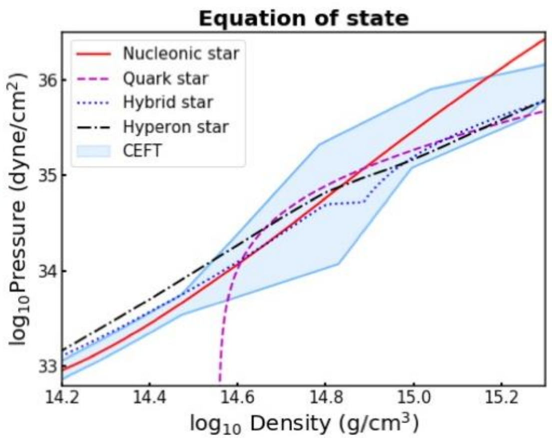
Sources To Study Neutron Star EOS

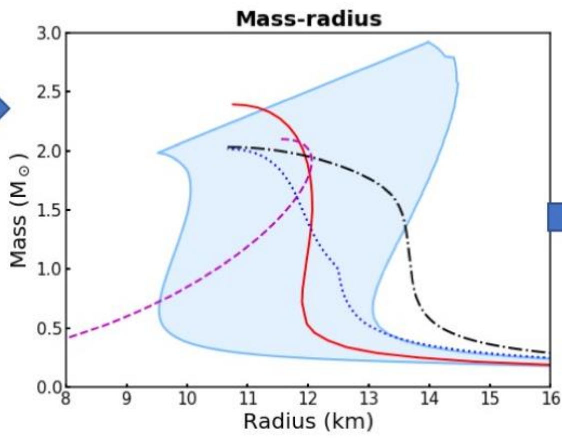
Microscopic composition (E/N vs n, P vs n, …) in the interior of a neutron star determines its macroscopic properties (Mass vs Radius) and vice versa → Linked to Equation of State (EOS)

$$P = n^2 \frac{\mathrm{d}\, E/N}{\mathrm{d}n}$$

$$c_s^{\ 2} = \frac{\partial P}{\partial \varepsilon}$$

$$\varepsilon = n\left(E/N + m_n\right)$$

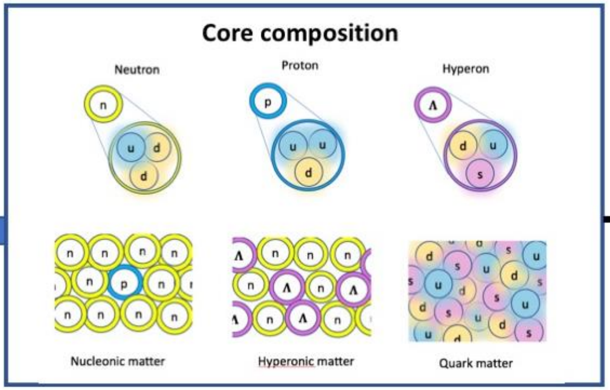


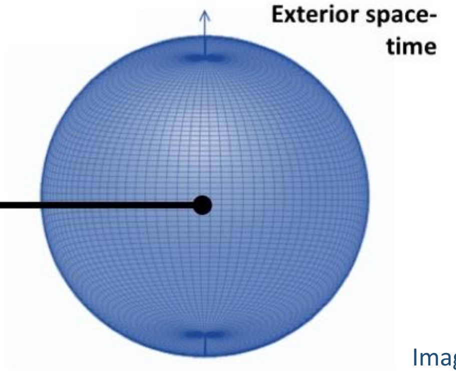


Astrophysical Events (Gravitational Waves, X-Ray Observations)

Tolman – Oppenheimer – Volkoff (TOV) Eq.

$$\frac{dP}{dr} = -\frac{GM}{R^2}\rho \frac{\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{Mc^2}\right)}{\left(1-\frac{2GM}{Rc^2}\right)}$$





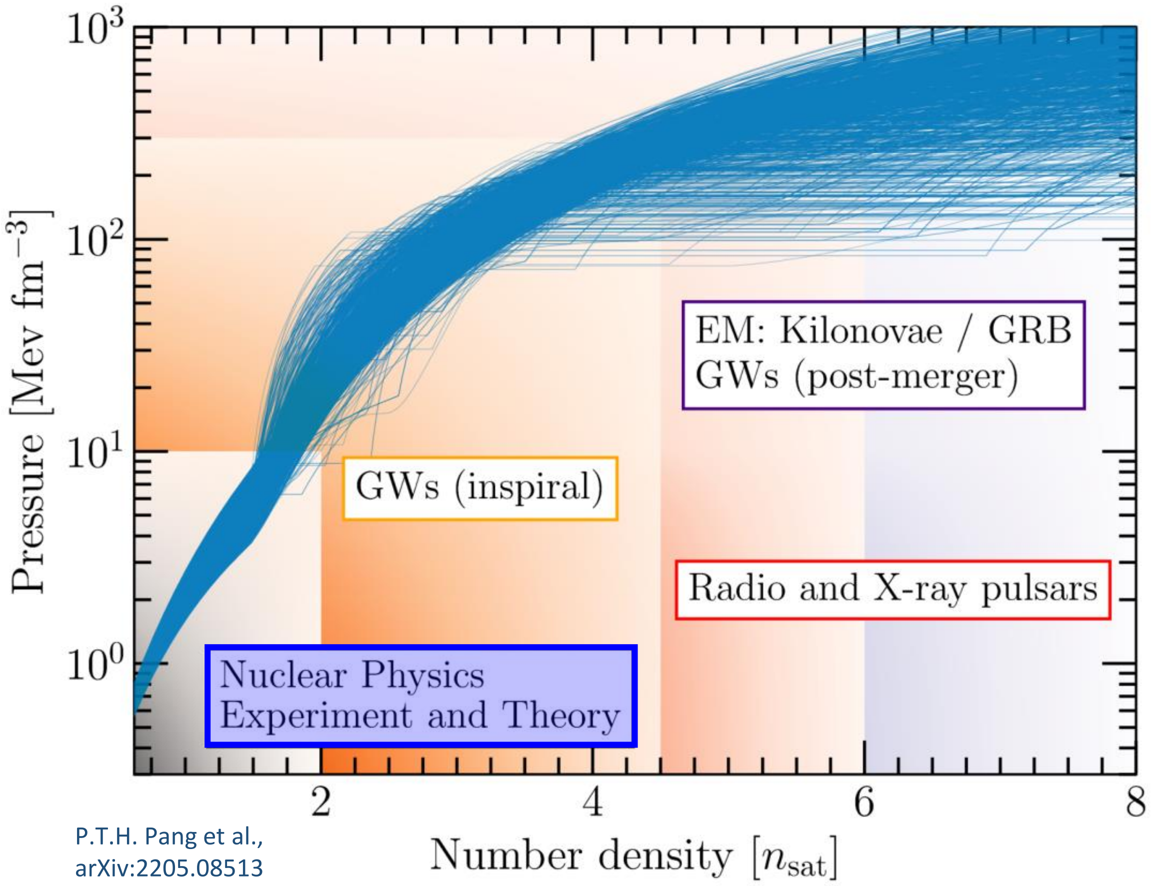
Nuclear Theory and Heavy Ion Collisions

Image Credits: P. Ray et al., arXiv:1903.03035

Motivation: Is there a way to connect these seemingly disjointed sets of measurements and observations to filter out the underlying Equation of State (EOS)? What is the role of heavy-ions collisions in this whole process?

Nuclear Theory & Astrophysical Observations

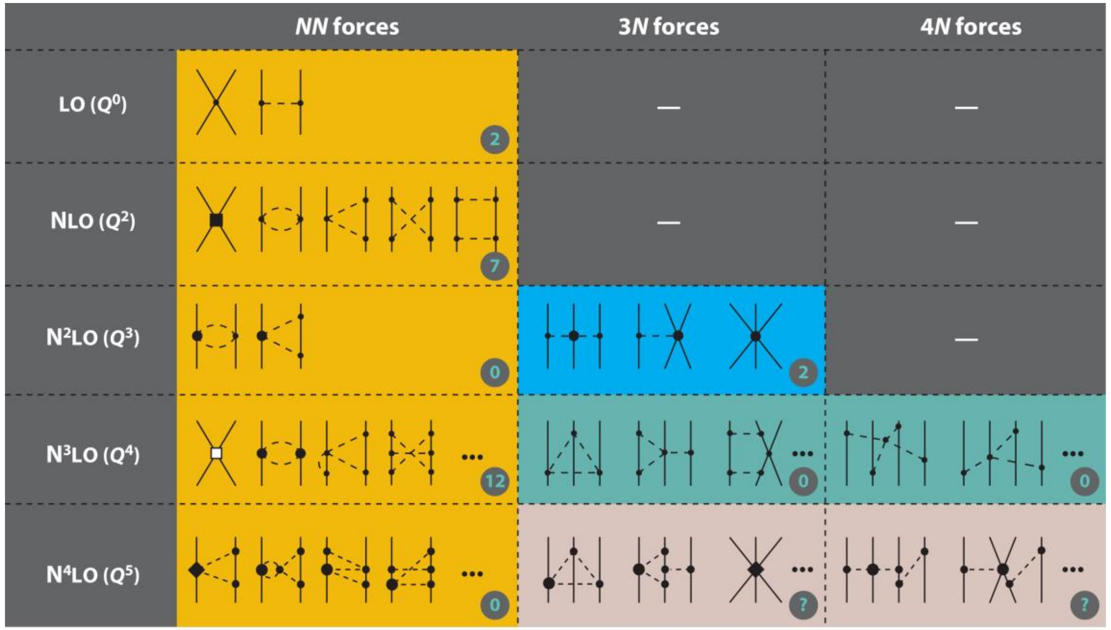
Neutron Stars And Chiral Effective Field Theory (χEFT)



P.T.H. Pang et al., arXiv:2205.08513

In essence, the core composition of a neutron star is a strongly-interacting system, therefore it could be explained by QCD

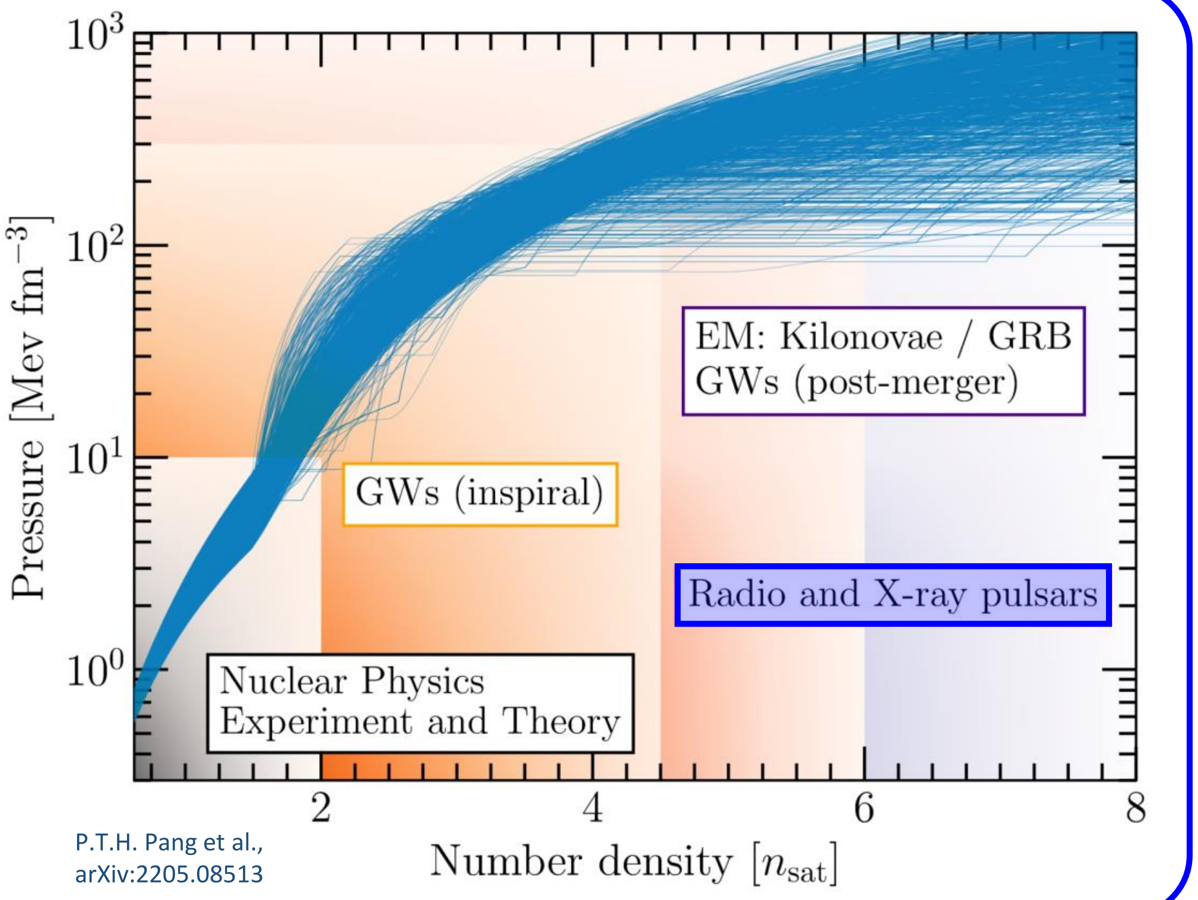
- χEFT is an effective theory of QCD that describes strong interactions at lower energy scales ($Q \sim 200$ MeV) or distances (~ 1 fm)
- χEFT order-by-order expansion in terms of nucleon and pion degrees of freedom using a systematic momentum expansion enables estimates of theoretical uncertainties



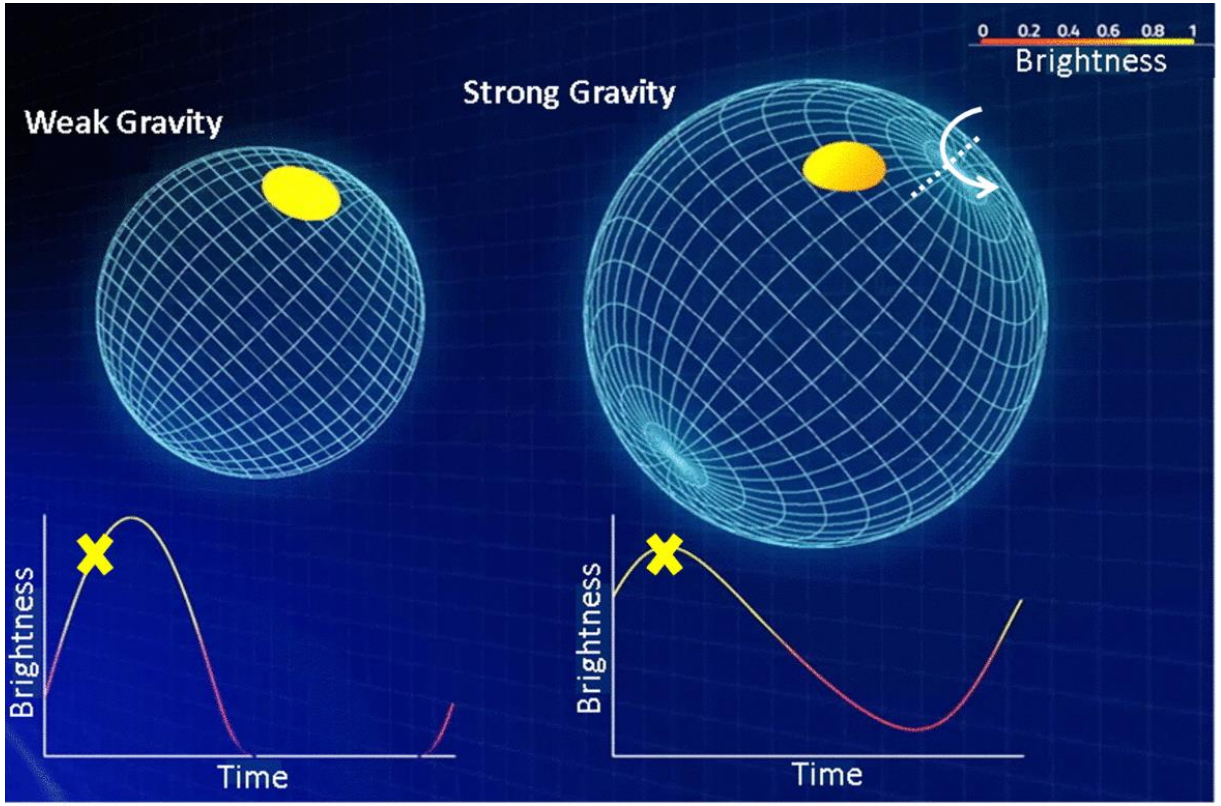
C. Drischler et al., Annu. Rev. Nucl. Part. Sci. 71, 403-432 (2021)

- The inherent breakdown scale of χEFT makes it unsuitable at higher momentum scales (~ 500 MeV/c) or densities ($\gtrsim 2\ n_{sat}$)

NICER – X-Ray Pulse Profile Modelling



P.T.H. Pang et al., arXiv:2205.08513

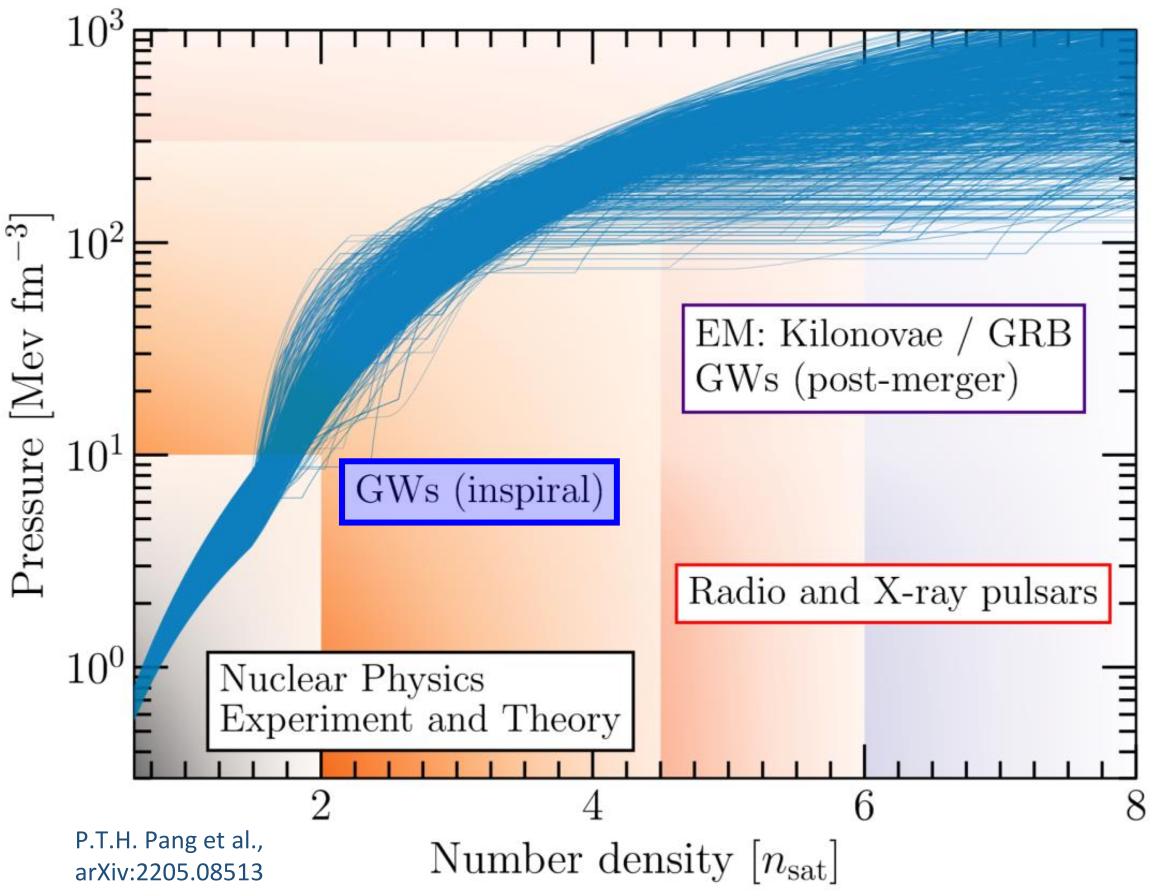


P. Ray et al., arXiv:1903.03035

The pulsed X-ray emission caused by hot spots on a rotating neutron star's surface can help measure the neutron star compactness ($\xi \sim M/R$)

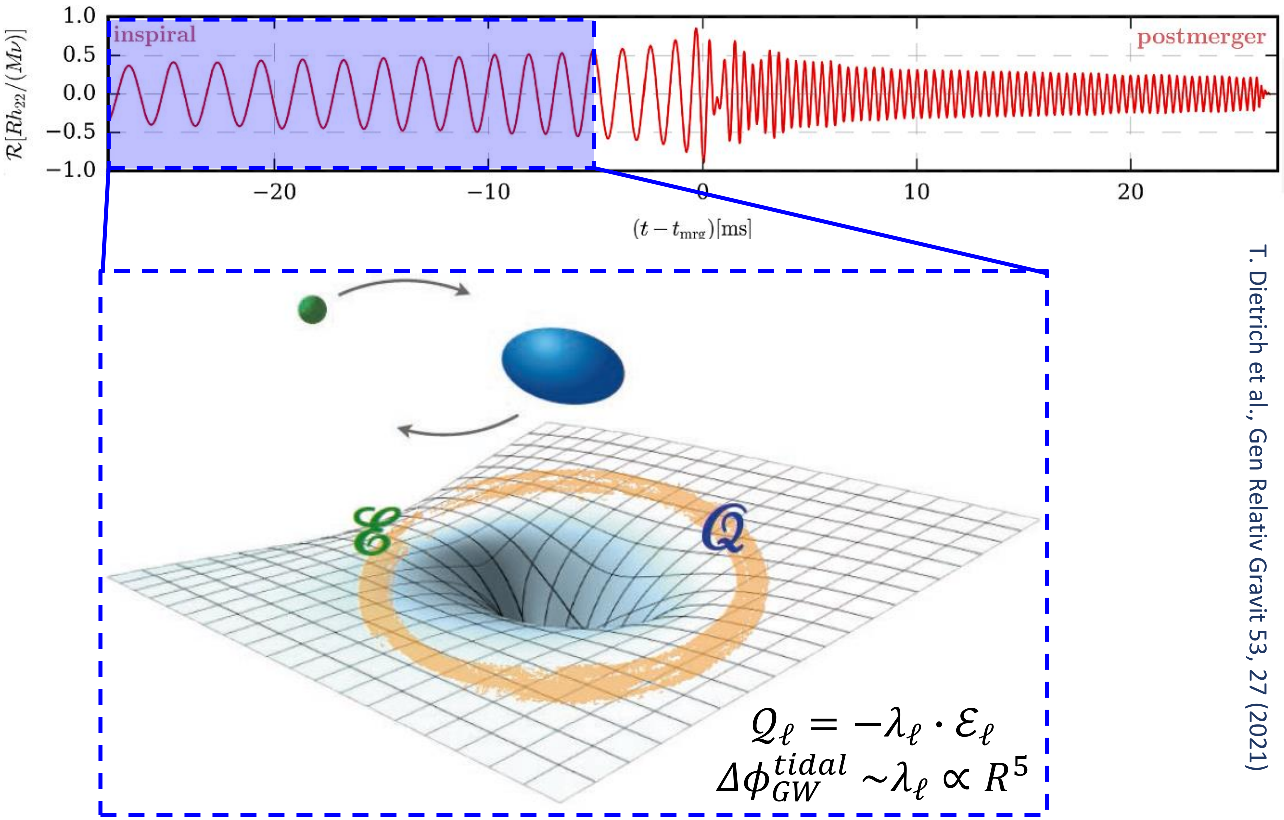
- Neutron Star Interior Composition Explorer (NICER) on board of the International Space Station (ISS) since 2017
- Obtained precise (±10%, 1 sigma) mass and radius measurements for PSR J0030+0451 and PSR J0740+6620

M.C. Miller et al., Astrophys. J. Lett. 887, L24 (2019)
T.E. Riley et al., Astrophys. J. Lett. 887, L21 (2019)
M.C. Miller et al., Astrophys. J. Lett. 918, L28 (2021)
T.E. Riley et al., Astrophys. J. Lett. 918, L27 (2021)



P.T.H. Pang et al., arXiv:2205.08513

The Inspiral Phase of a binary neutron star merger allows to infer the mass and radius of the binaries

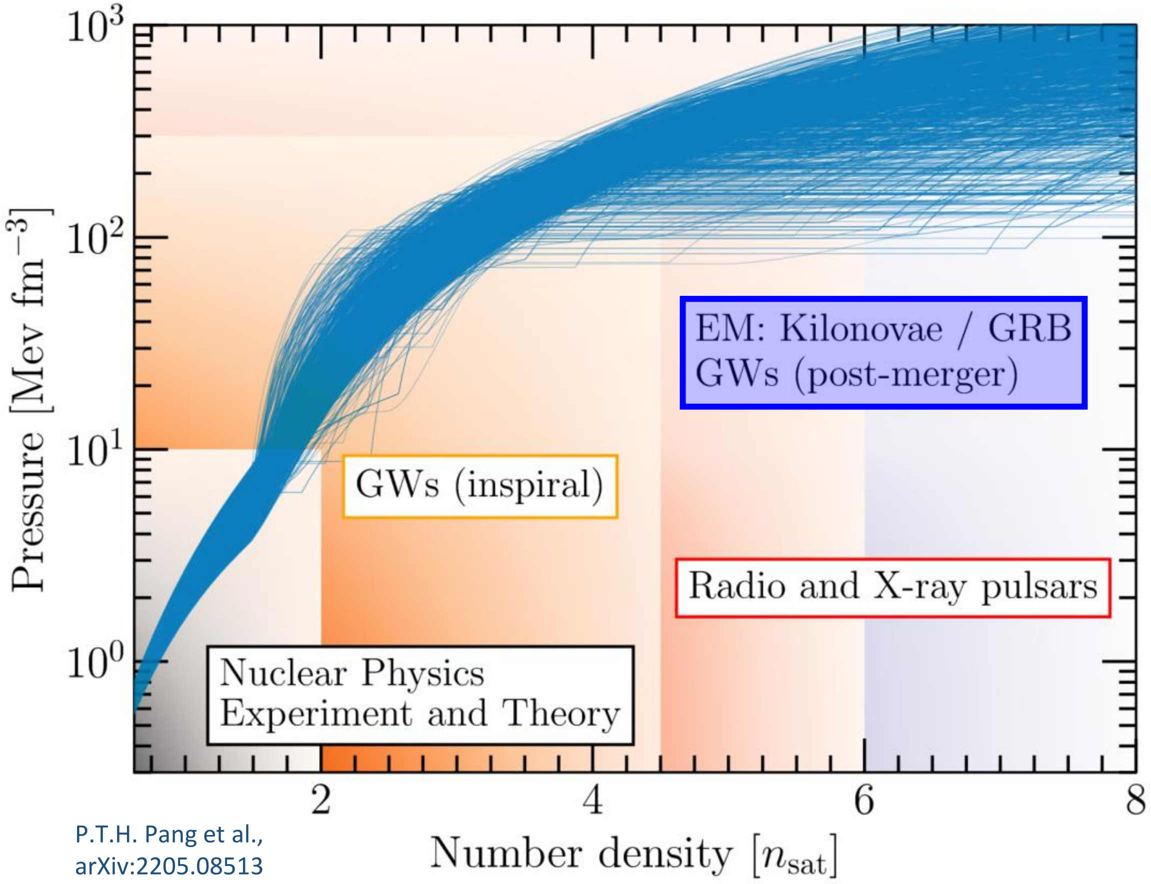


T. Dietrich et al., Gen Relativ Gravit 53, 27 (2021)

- During the inspiral phase of the BNS merger, the neutron stars deform under strong gravitational field of partner
- This deformation known as the “tidal polarizability” is dependent on the nature of the underlying EoS, and is sensitive to radius

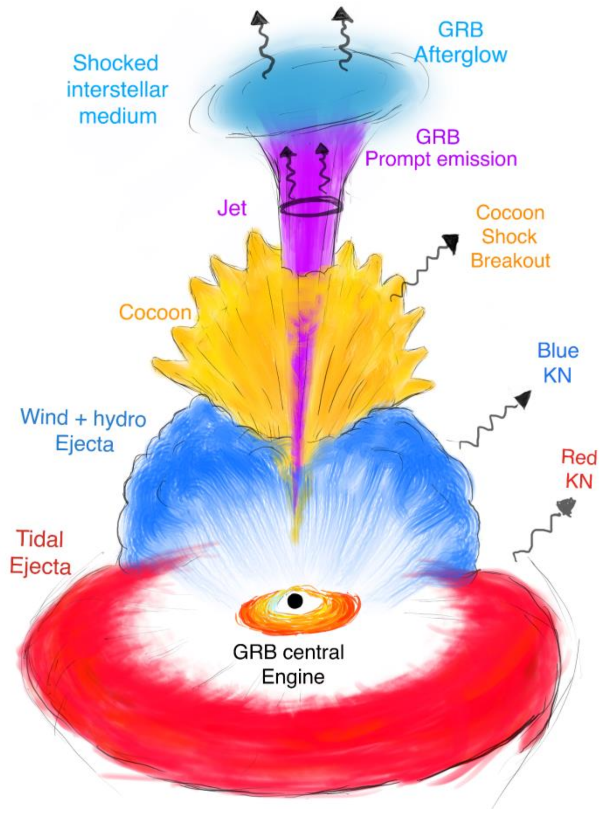
LIGO-VIRGO, Phys. Rev. Lett. 119, 161101 (2017)
LIGO-VIRGO, Astrophys. J. Lett. 892, L3 (2020)

KILONOVA (AT2017gfo) FROM BNS MERGER (GW170817)

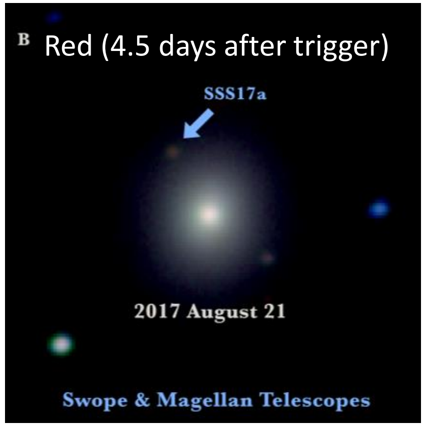


P.T.H. Pang et al., arXiv:2205.08513

The existence of a postmerger remnant and the nature of Kilonova puts stringent limits on the total mass and radii of the colliding binaries, which are determined by the EOS



S. Ascenzi, J. Plasma Phys. 87 (2021) 845870102

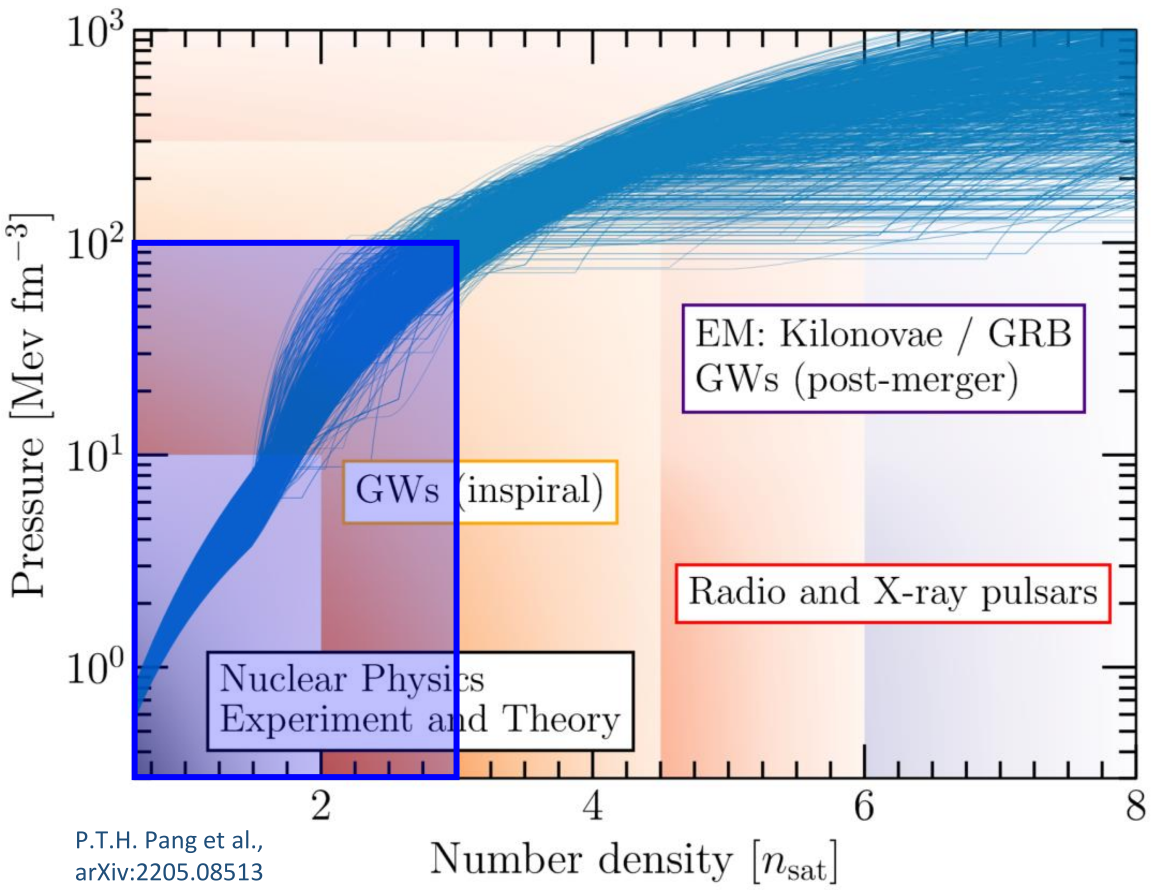


M.R. Drout, Science 358, 1570-1574 (2017)

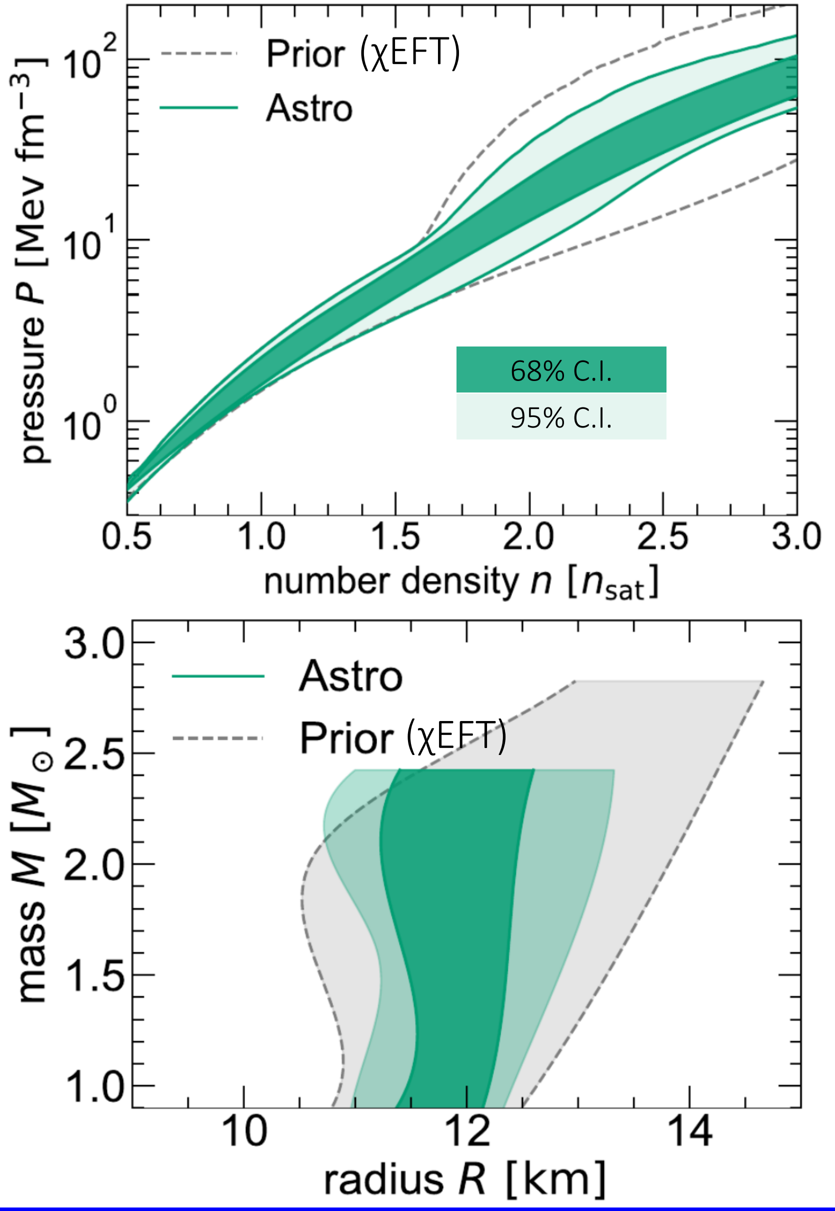
- Analysis of the post-merger remnant's light curves dependent on the ejecta properties ($M_{\rm dyn}$, $\langle v_{\rm ej}\rangle$, $\langle Y_{\rm e}\rangle$) gives an insight on the kilonova properties and the underlying EOS

M.W. Coughlin et al., Astrophys. J. 849, 12 (2017)
M.W. Coughlin et al., Mon. Not. R. Astron. Soc. 480 (2018)
M.W. Coughlin et al., Mon. Not. R. Astron. Soc. 489 (2019)

Current Status With Nuclear Theory & Astrophysics



P.T.H. Pang et al., arXiv:2205.08513

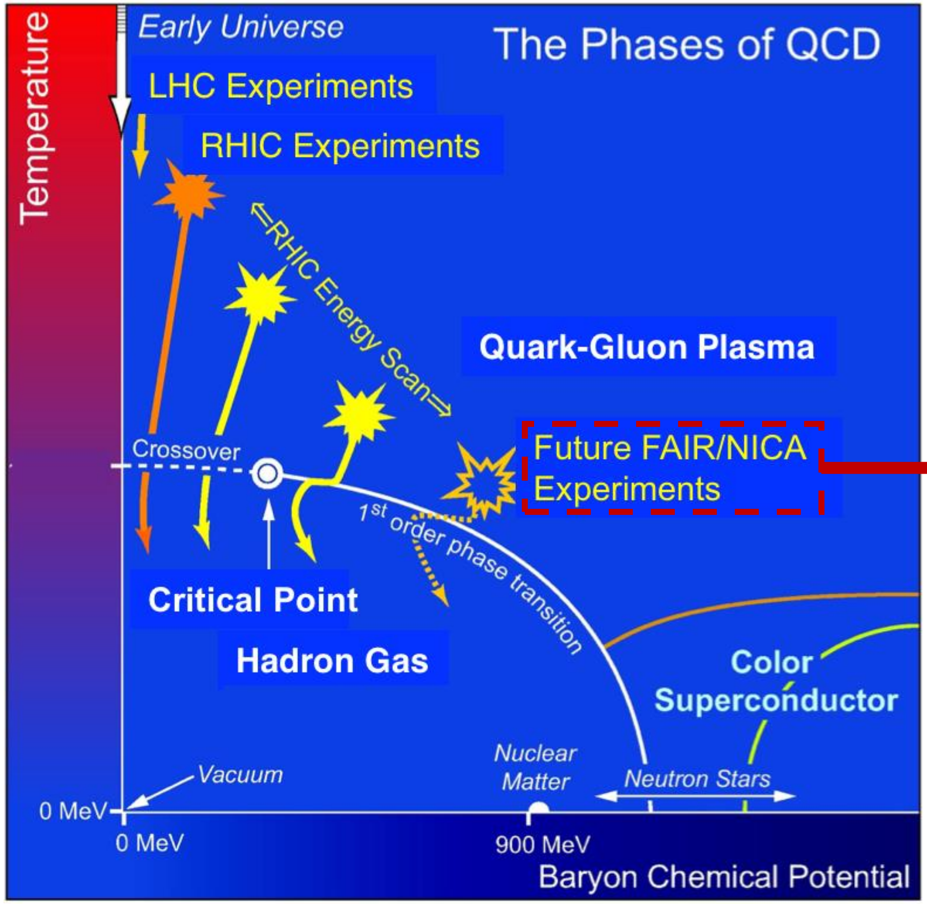


T. Dietrich et al., Science 370, 1450-1453 (2020)
S. Huth, P.T.H. Pang et al., Nature 606, 276-280 (2022)

Constraints strongest above 1.5n_{sat} and high-mass region, thereby exclude the stiffest EOSs (i.e., largest radii)

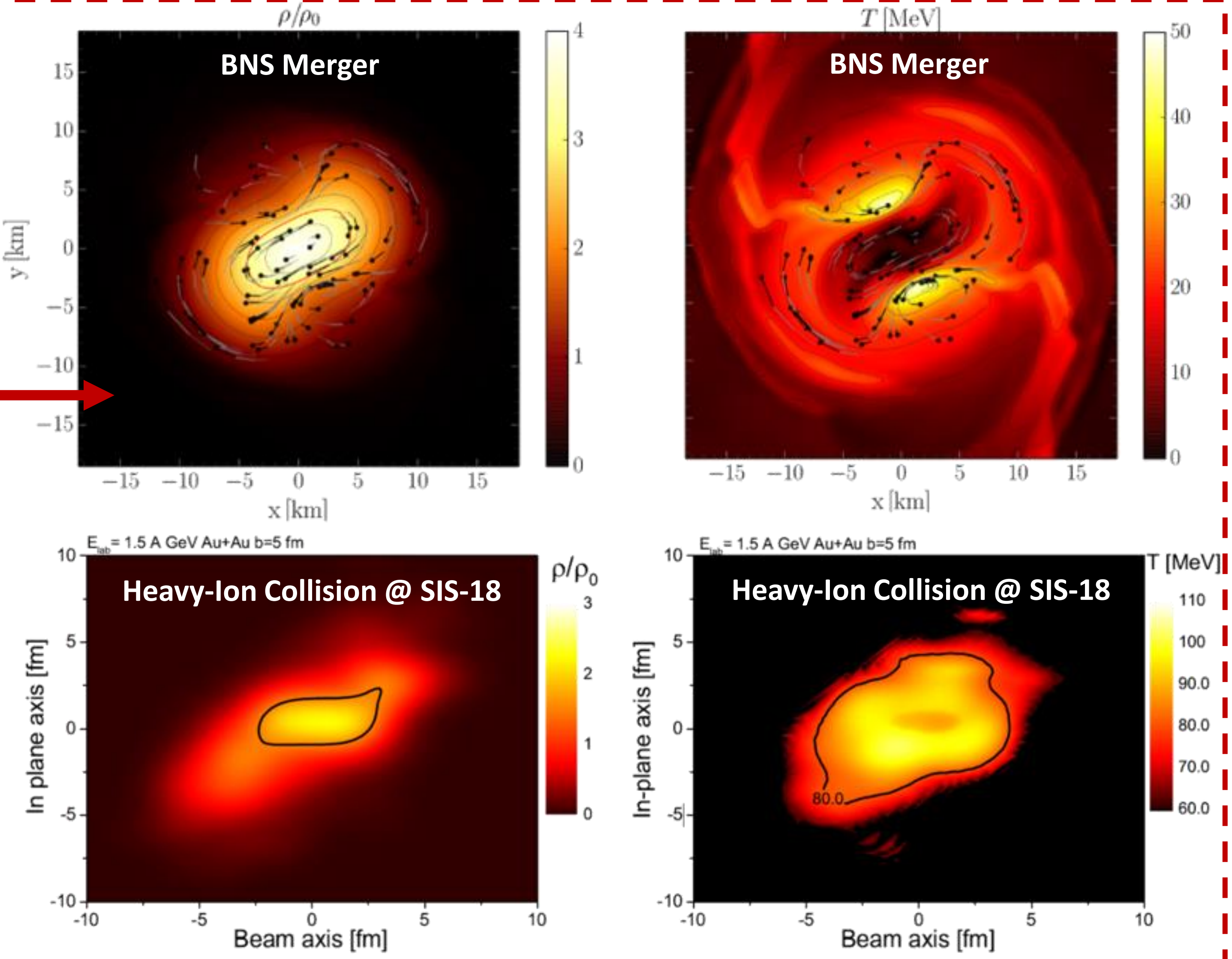
Existing Role Of Heavy-Ion Collisions In Deducing Nuclear Matter EoS At $\gtrsim \rho_0$

Micro- & Macroscopic Collisions



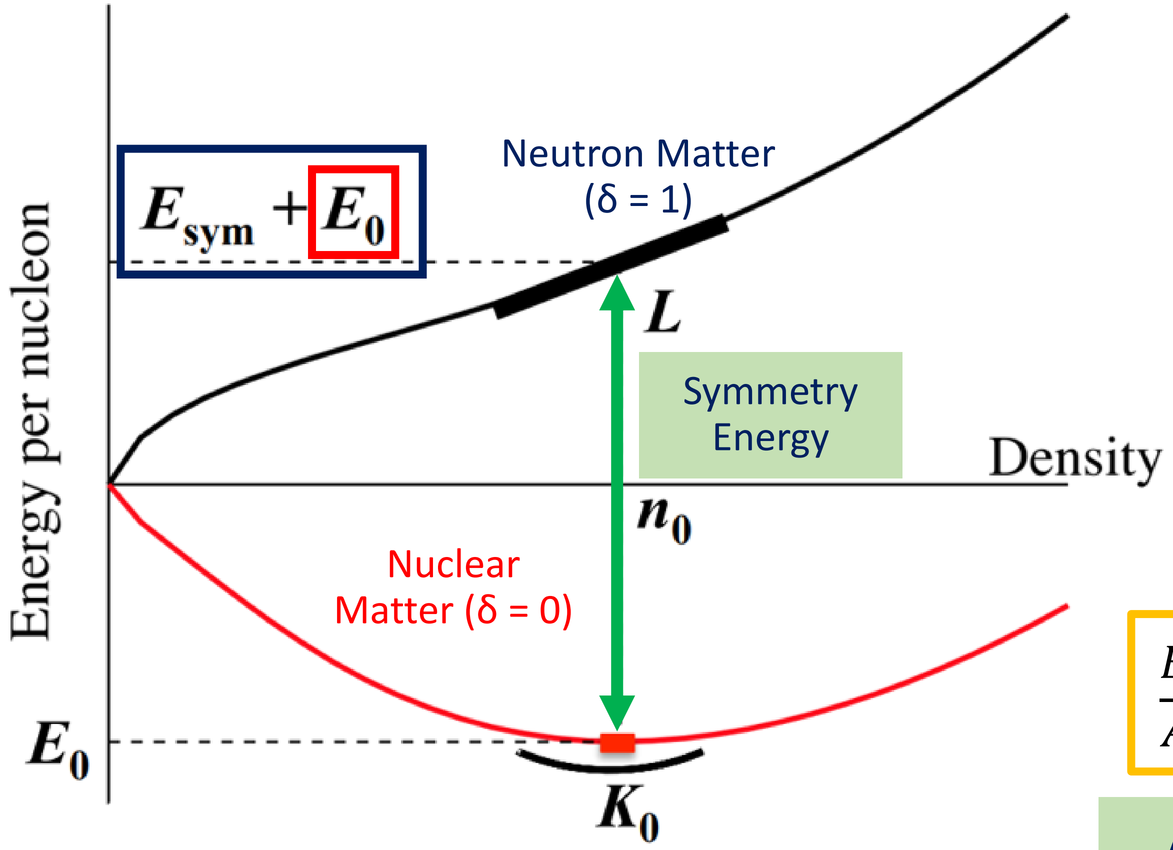
[STAR], Studying the Phase Diagram of QCD Matter at RHIC, STAR Note 598 (2014)

Temperature and density created in the HIC fireball at intermediate energies ($E_{kin} = 2.5 - 11\ A\ \text{GeV}$) mimic the conditions created in binary neutron star mergers, therefore can probe the PNM-EOS in the laboratory.



M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

EOS Ingredients For HIC Perspective



Hajime Togashi, New perspectives on Neutron Star Interiors - ECT* (2017)

Heavy Ion Collisions aims to probe to the Symmetric Nuclear Matter and Symmetry Energy, thereby the Asymmetric Nuclear Matter

$$\frac{E}{A}(\delta) = \left[-a_{vol} + \frac{a_{surf}}{A^{1/3}} + a_c\frac{Z^2}{A^{4/3}} + \frac{E_{pair}}{A}\right] + \left[a_{sym}\left(\frac{N-Z}{A}\right)^2\right]$$

Symmetry Term
protons = # neutrons

Asymmetry Term
protons ≠ # neutrons

$$\frac{E}{A}(\rho,\delta) = \left[\frac{E}{A}(\rho,0)\right] + \left[E_{sym}(\rho)\times\delta^2\right]$$

Asymmetric Matter EOS	Nuclear/Symmetric Matter EOS	Symmetry Energy

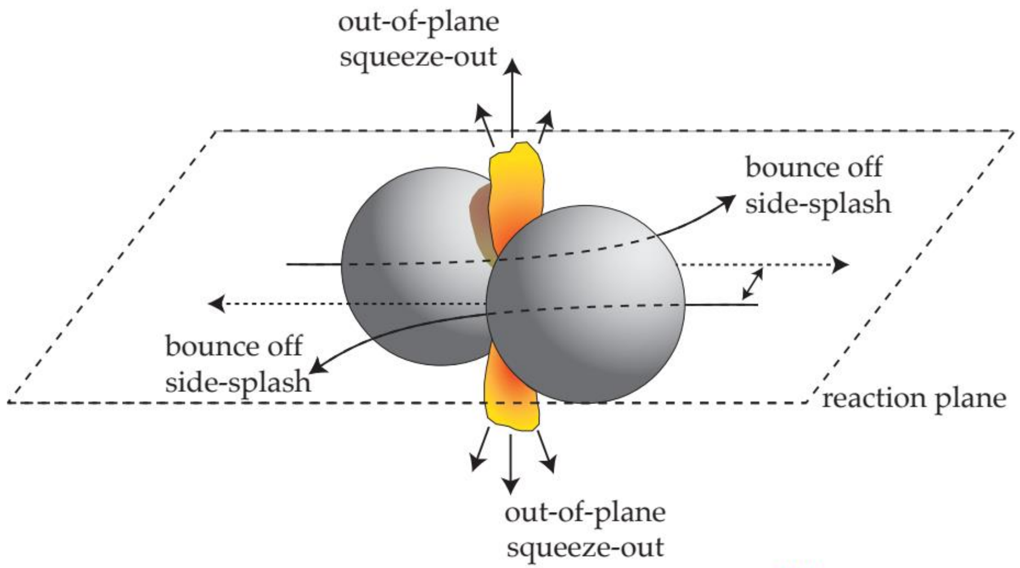
where, $\delta = \frac{\rho_N - \rho_P}{\rho_N + \rho_P}$

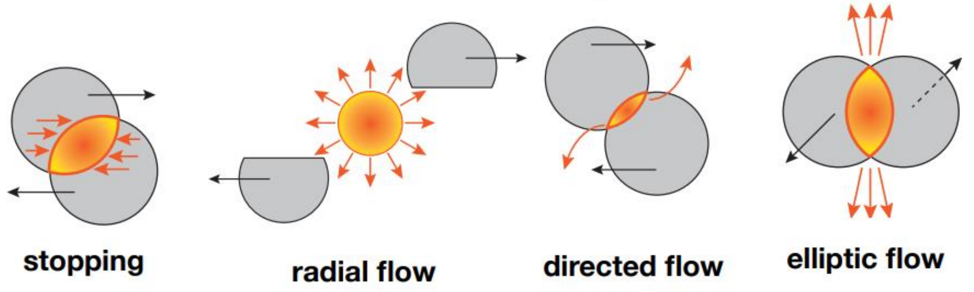
Experimental Observables

ANISOTRPIC FLOW

Nucelar EoS ∝ ‘(In)Compressibility’ of the nuclei ∝ ‘Flow’ direction of participants and spectators

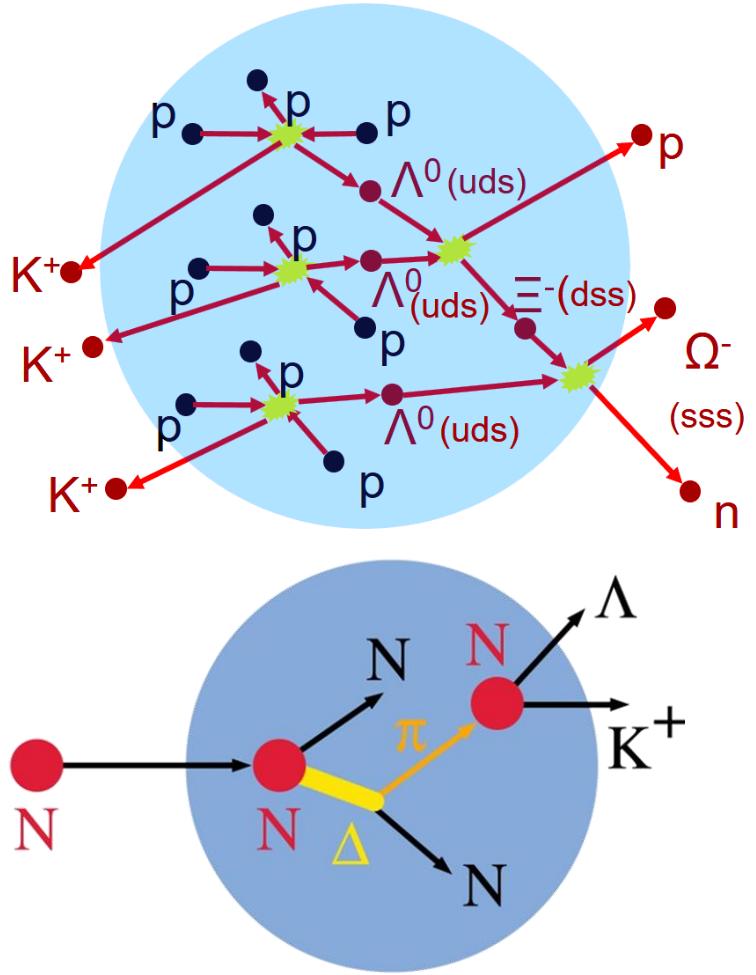
$$\frac{dN}{d\phi} \propto 1 + (2 \cdot v_1 \cdot \cos\phi) + (2 \cdot v_2 \cdot \cos 2\phi) + \cdots$$

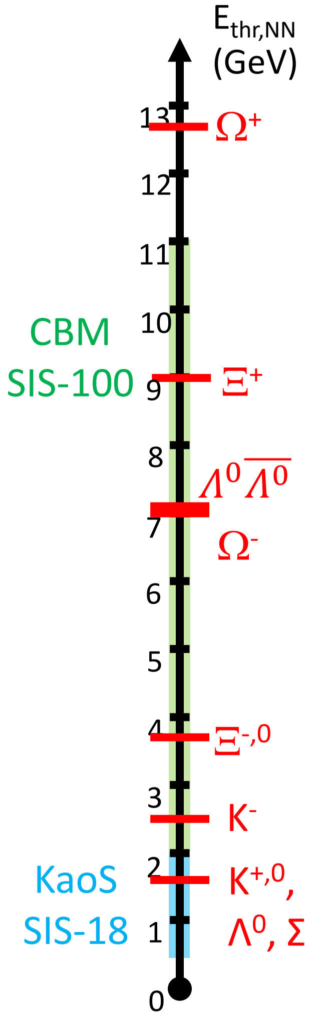




SUB-THRESHOLD STRANGENESS PRODUCTION

Nucelar EoS ∝ ‘(In)Compressibility’ of the nuclei ∝ Density ∝ Strangeness Yield

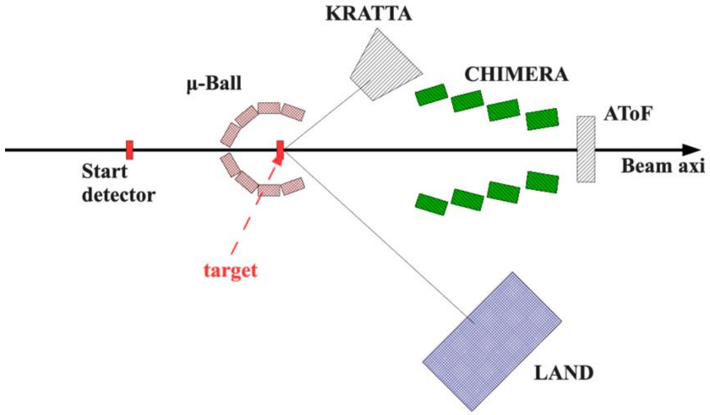




Experimental History Contributing To Nuclear EOS

Plastic Ball @ Bevelac

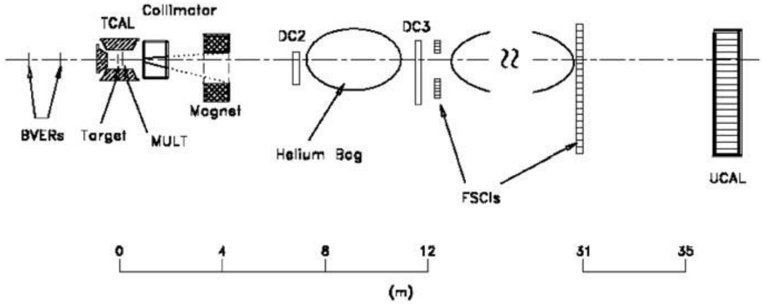
KaoS @ SIS-18

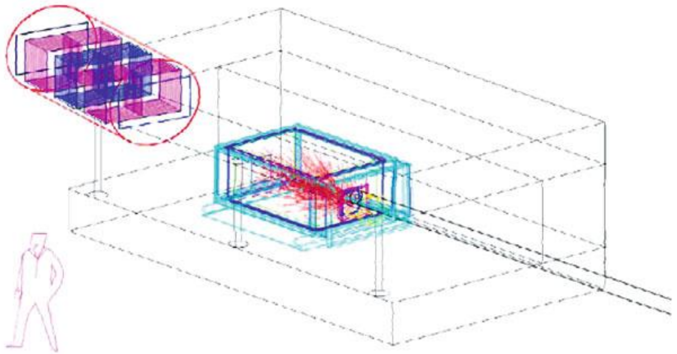


ASY-EOS @ SIS-18

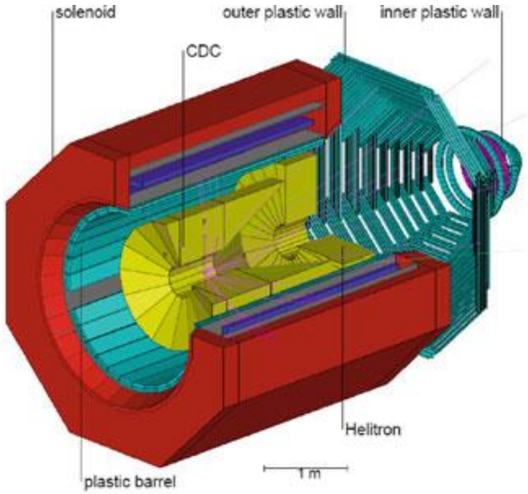
AGS Experiments

(E814-E877, E895, ...)



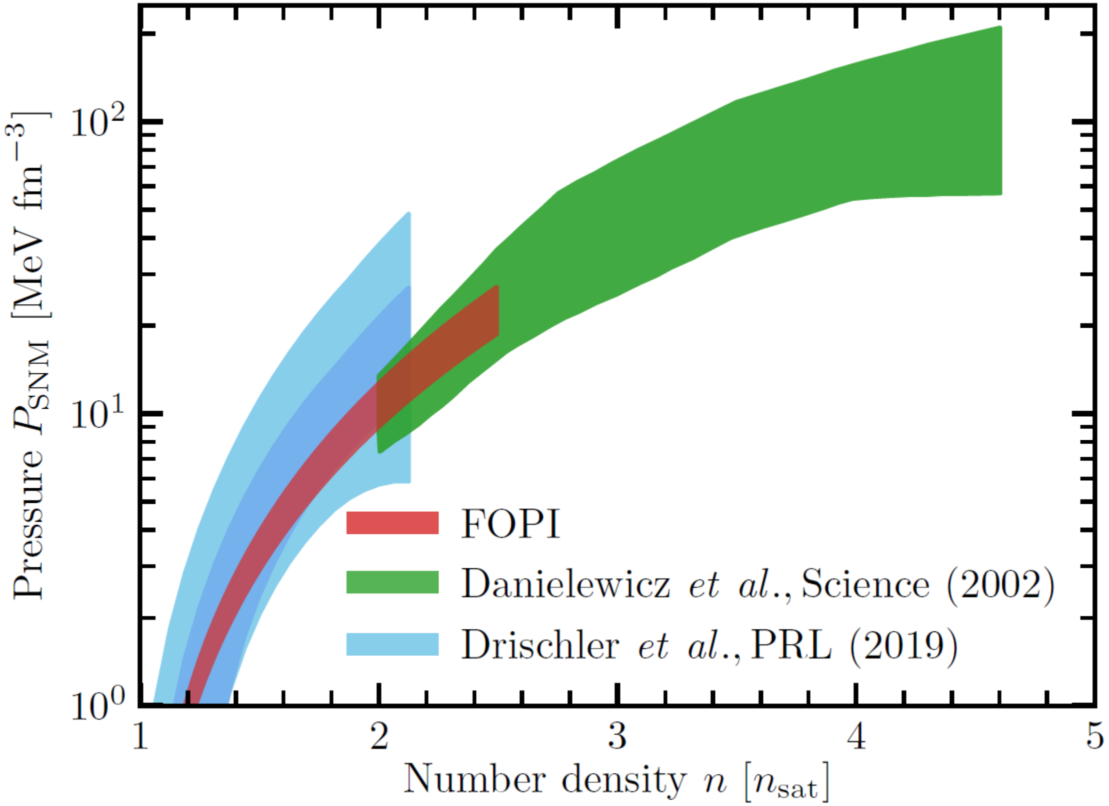


FOPI @ SIS-18



Current HIC EoS Data At $\gtrsim \rho_0$

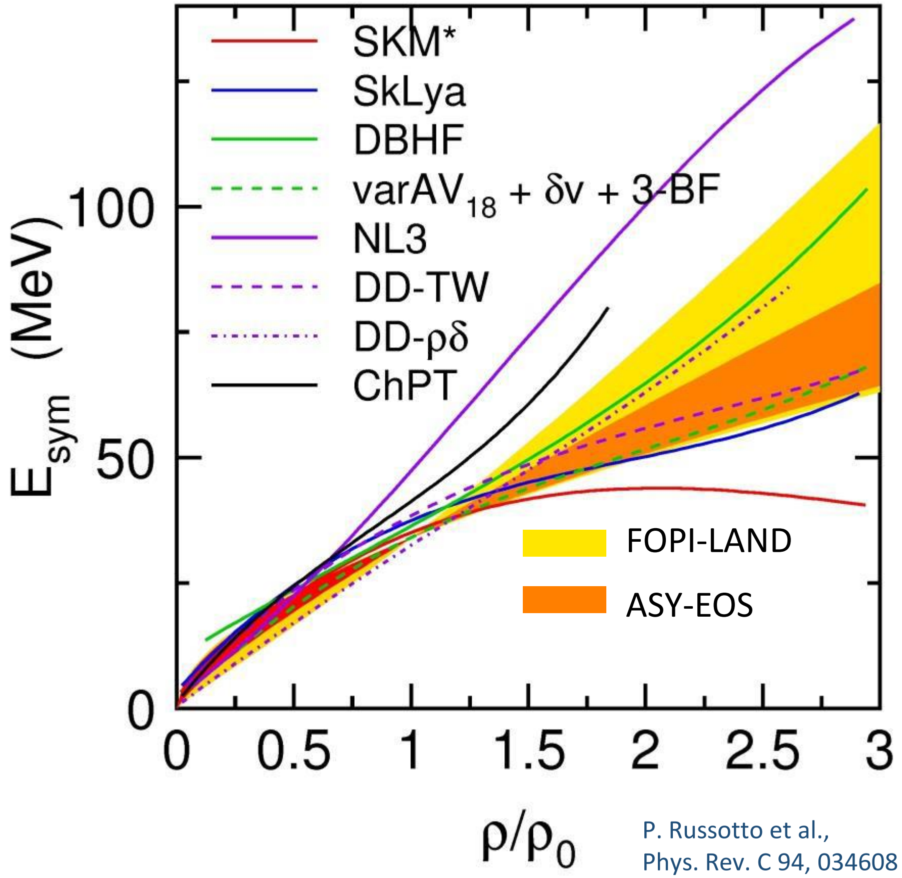
Symmetric Nuclear Matter



S. Huth, P.T.H. Pang et al., Nature 606, 276-280 (2022)

Symmetric Nuclear Matter is still loosely constrained above $2.5\rho_0$ (2 AGeV Au+Au)

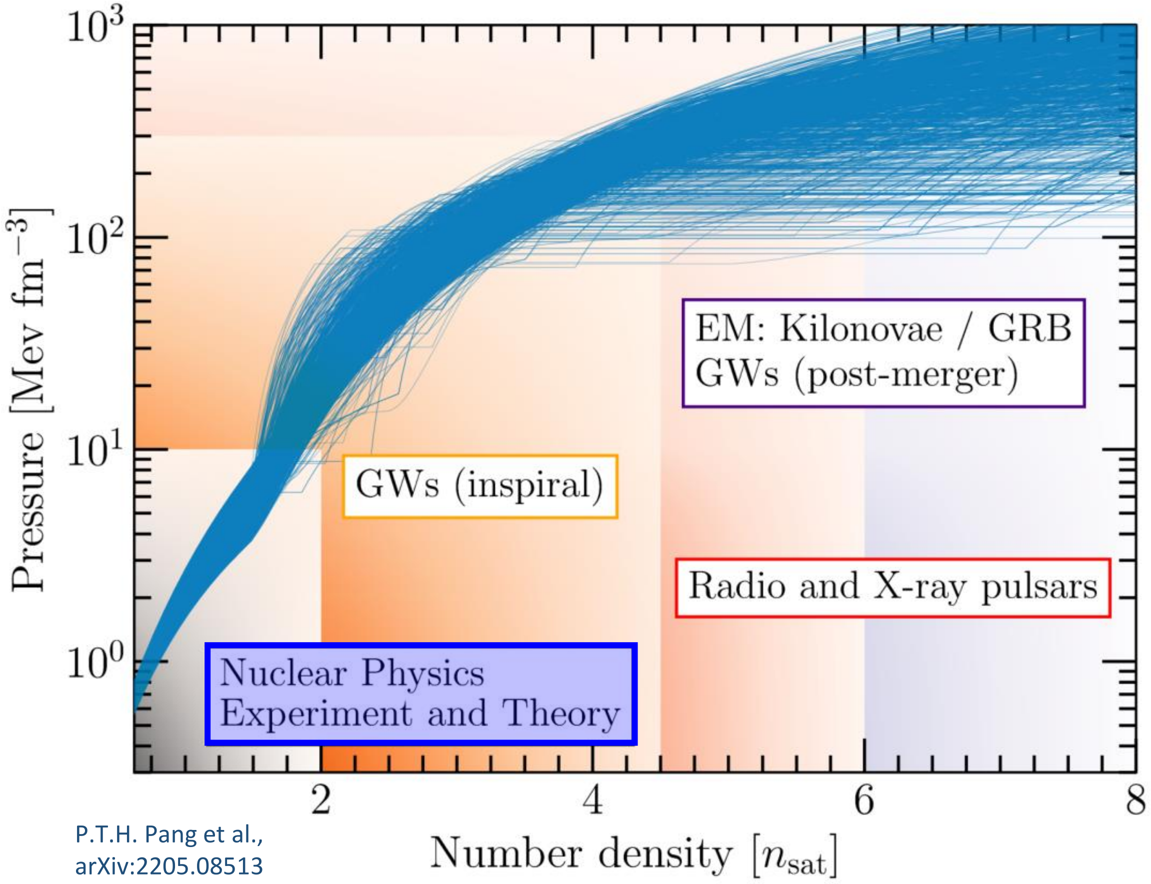
Symmetry Energy



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

Symmetry Energy has no data above $2\rho_0$ (0.4 AGeV Au+Au)

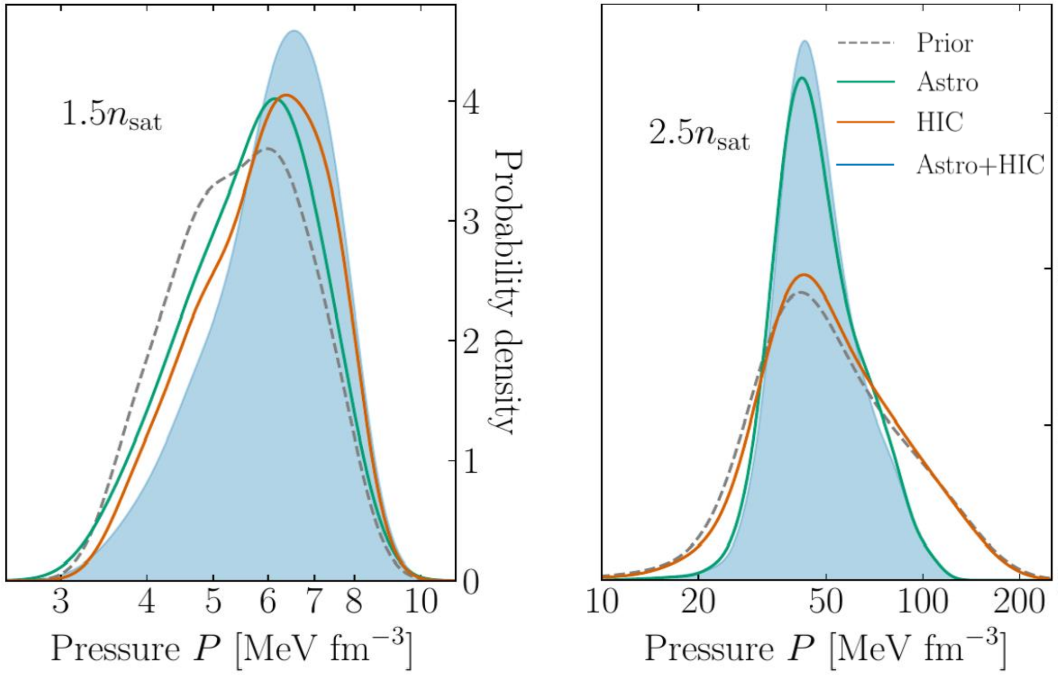
Combining Heavy-Ion Collisions And Astrophysics



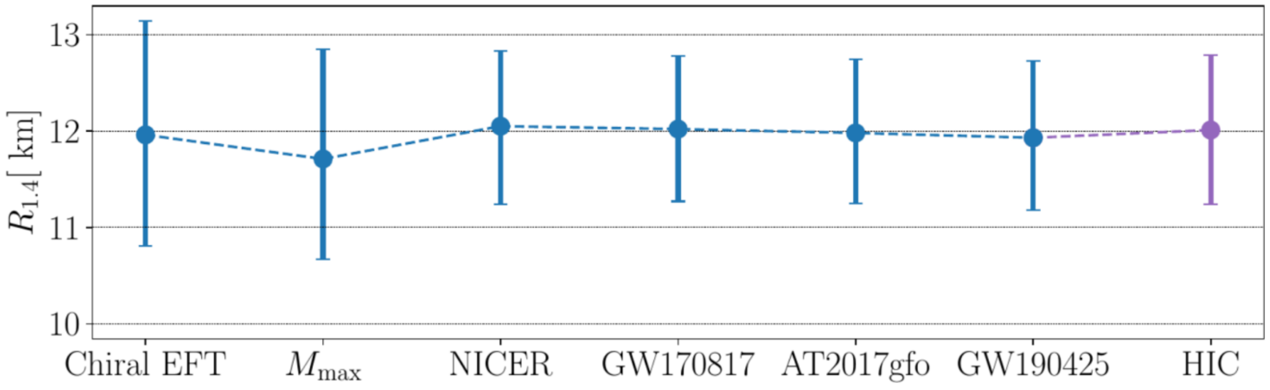
P.T.H. Pang et al., arXiv:2205.08513

Existing HIC Experiments

Motivation for higher densities



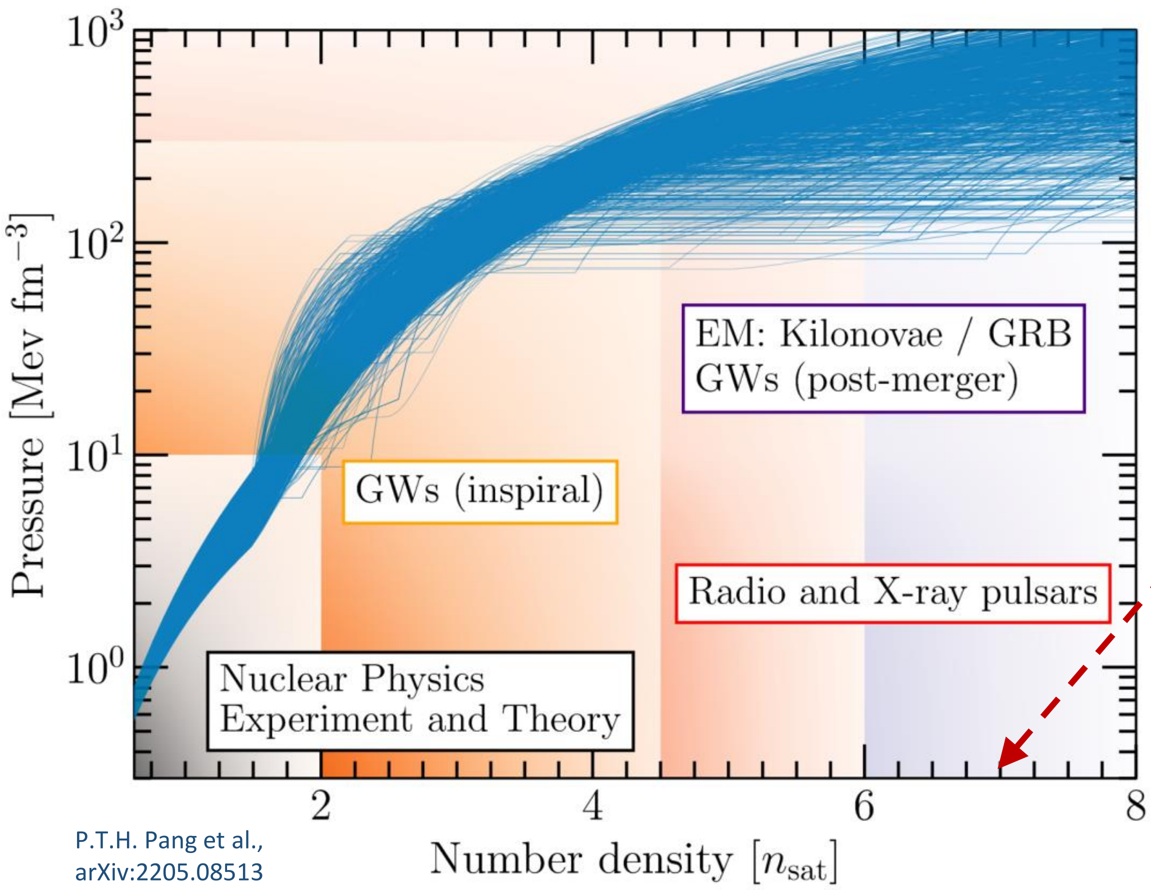
S. Huth, P.T.H. Pang et al., Nature 606, 276-280 (2022)



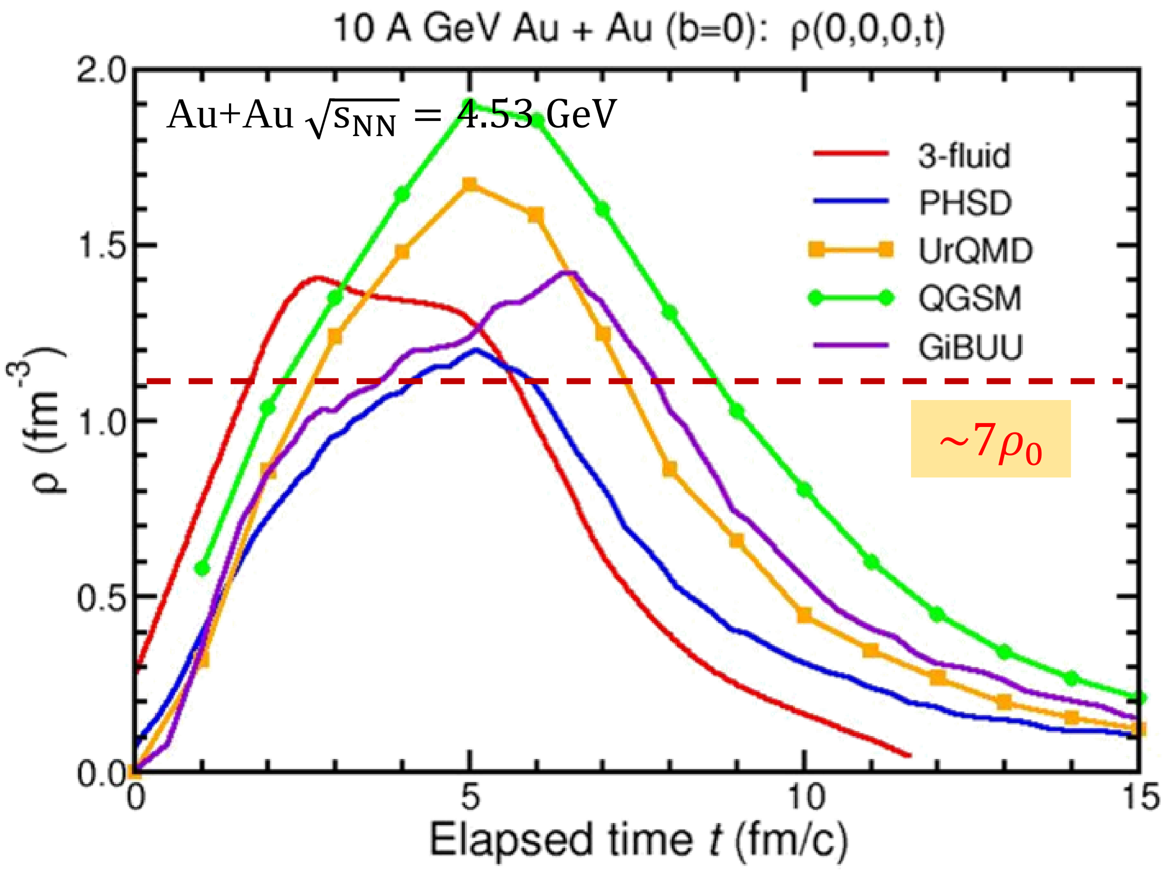
Bayesian interference to show that constraints on Pure Neutron Matter (PNM) EoS obtained by heavy-ion collisions (HIC) are consistent with multi-messenger astrophysics at lower densities

ROLE OF CBM-FAIR

Landscape Of Nuclear Matter EoS At $\gtrsim \rho_0$



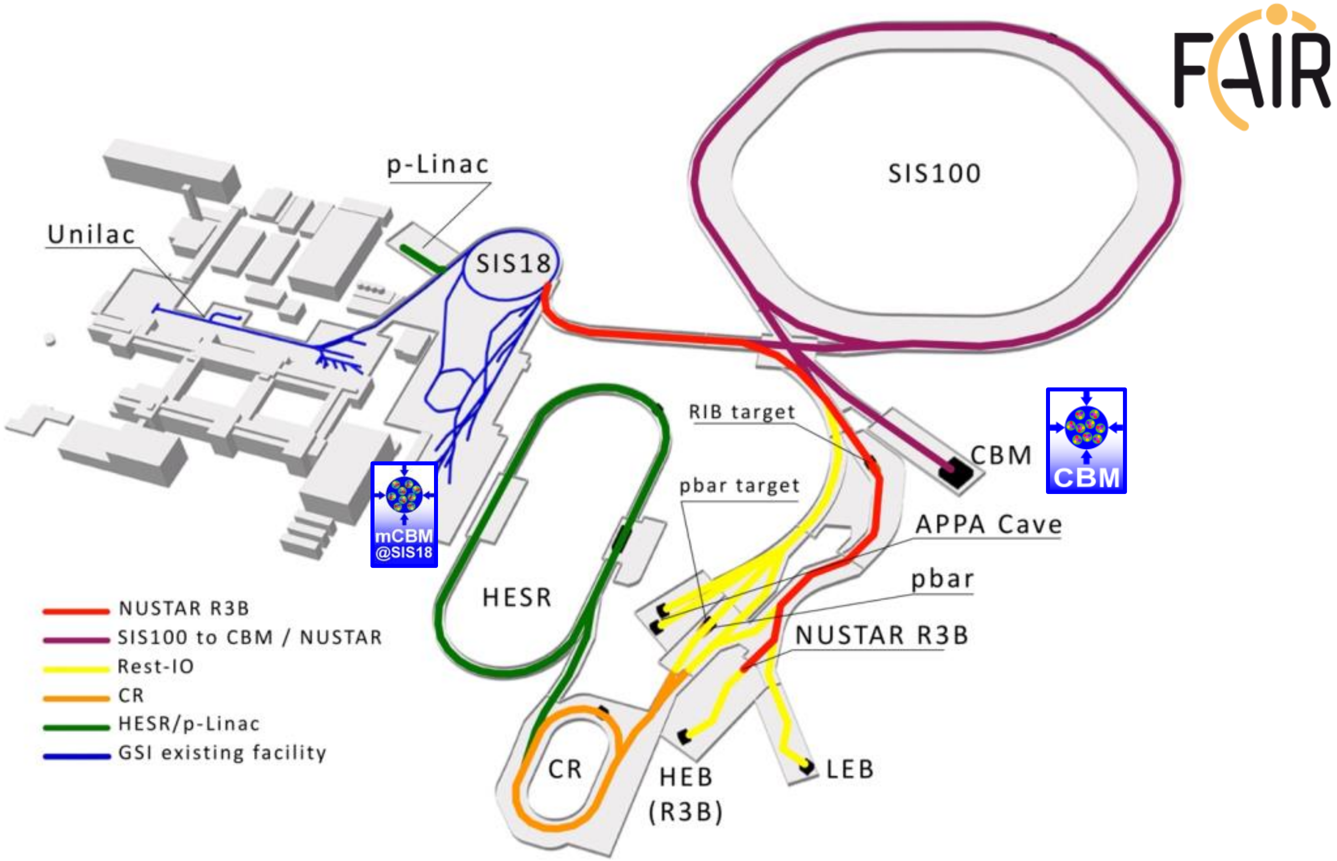
P.T.H. Pang et al., arXiv:2205.08513



I.C. Arsene et al., Phys.Rev.C 75 (2007) 034902

Heavy-Ion Collisions at relatively higher energies (Au+Au > 3A GeV) will give us a possibility to explore EoS where currently, the only reliable info comes from MMA

Facility For Anti-Proton And Ion Research (FAIR)



SIS-100 Capabilities			
Beam	Z	A	E_{max} [AGeV]
p	1	1	29
d	1	2	14
Ca	20	40	14
…			
Au	79	197	11
U	92	238	10.7

C. Höhne et al. (2011) CBM Experiment. In: B. Friman (eds) The CBM Physics Book. Lecture Notes in Physics, vol 814. Springer

M. Durante et al., Phys. Scr. 2019, 94, 033001

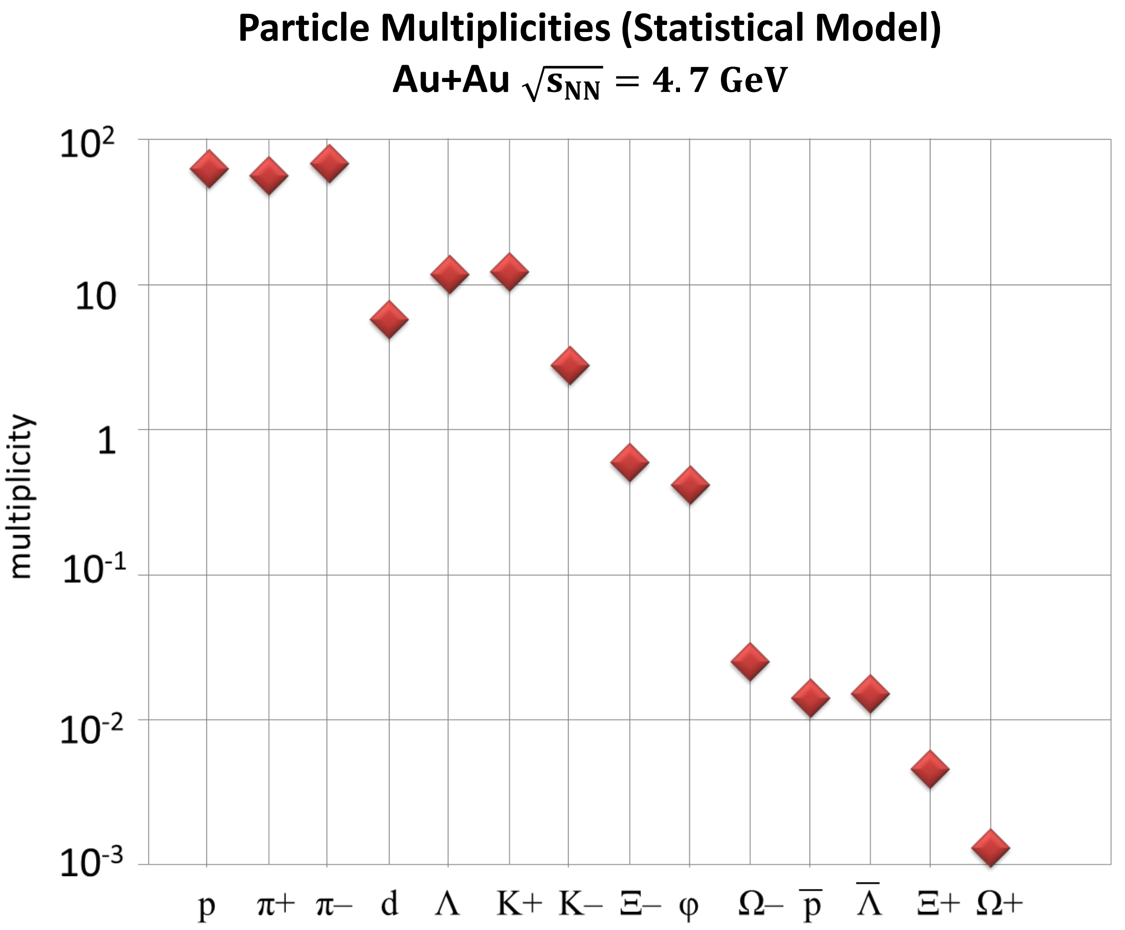
- Intensity gain: x 100 – 1000 (~10^{10}/s for Au)
- Energy gain: 10 x energy (compared to SIS-18@GSI)
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings
- see “FAIR Operation Modes” for more details

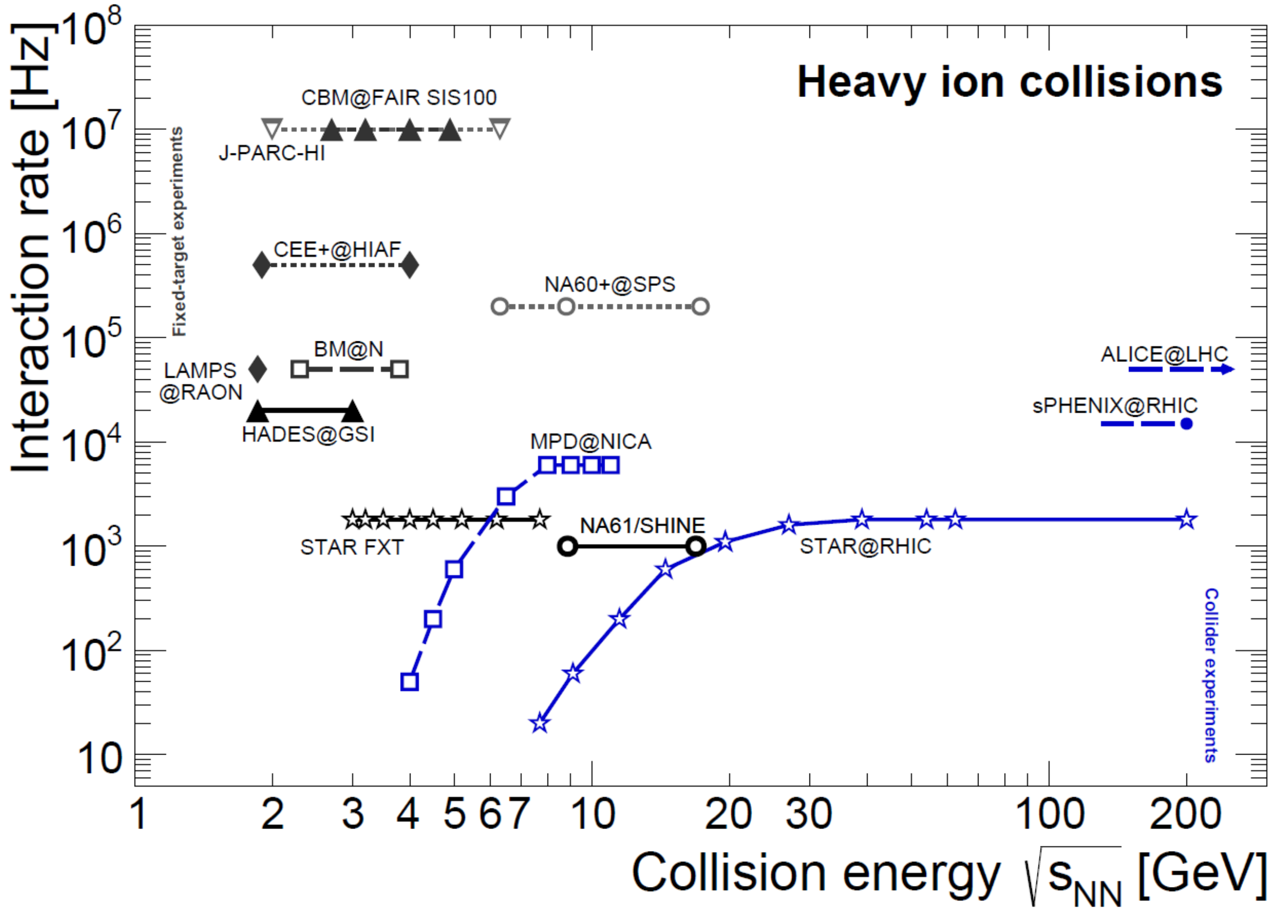
- Current estimate: SIS100 commissioning with beams starts in 2028-29
- Recommendation: downscale FAIR project (SIS100 & SFRS/R3B & CBM); Decision by FAIR council expected in Feb. 2023

Update On FAIR Construction (October 2022)

- Interior work on SIS-100 tunnel ongoing - SIS100 ready for commissioning w/ beams 2028
- CBM Building's construction is on schedule and is ready for 'heavy installation' from 2022-23
- CBM ready for beam in 2027-28, ~12 months contingency for CBM global commissioning
- Updates on construction available at: GSI Webpage | YouTube | …

BEAM-TARGET INTERACTION RATES AND RARE PROBES' YIELDS

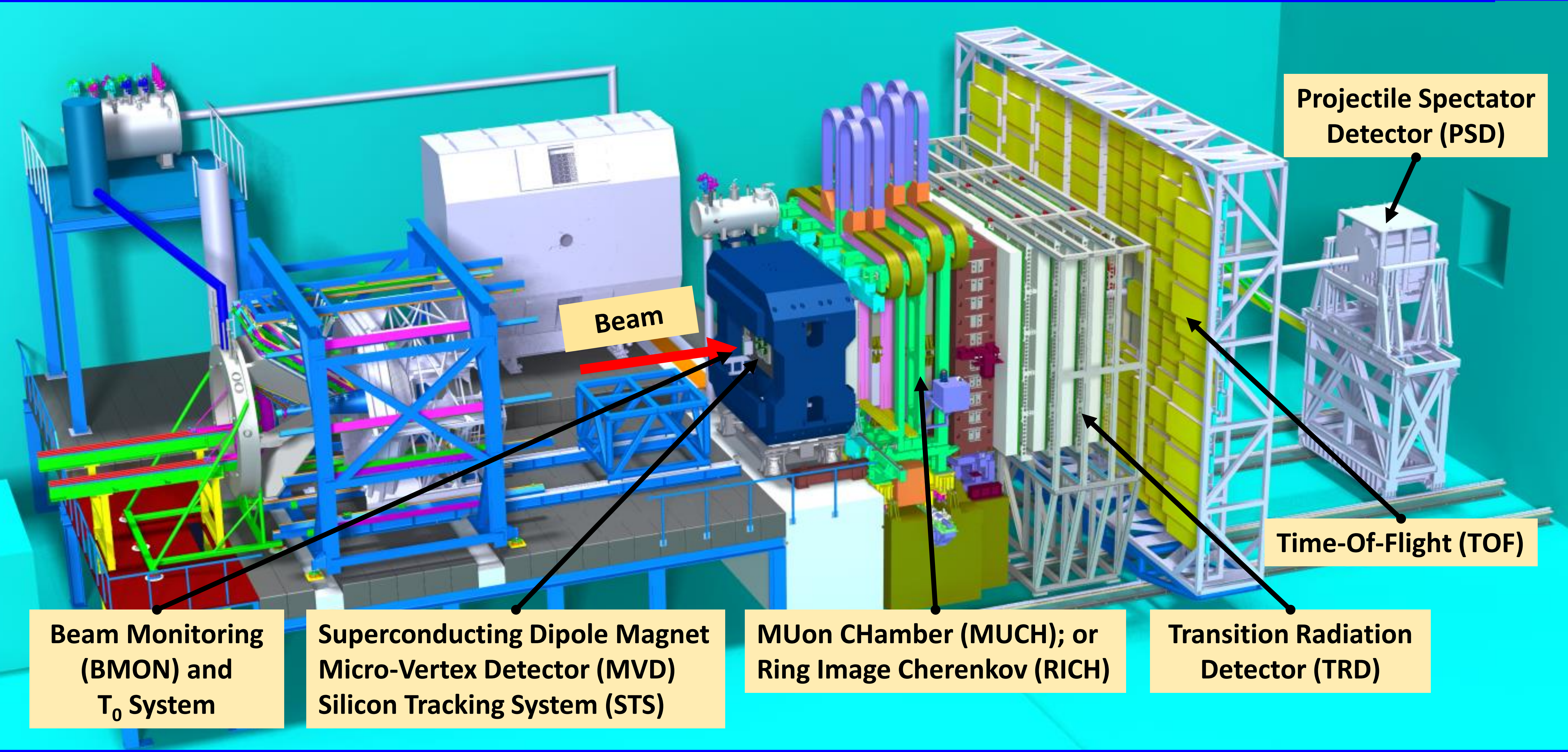




[CBM], Eur.Phys.J.A 53 (2017) 3, 60
T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169, update (06/2022)

CBM is designed to conduct its research program at up to 10 MHz beam-target interaction rates giving an unprecedent access to the 'rare probes'

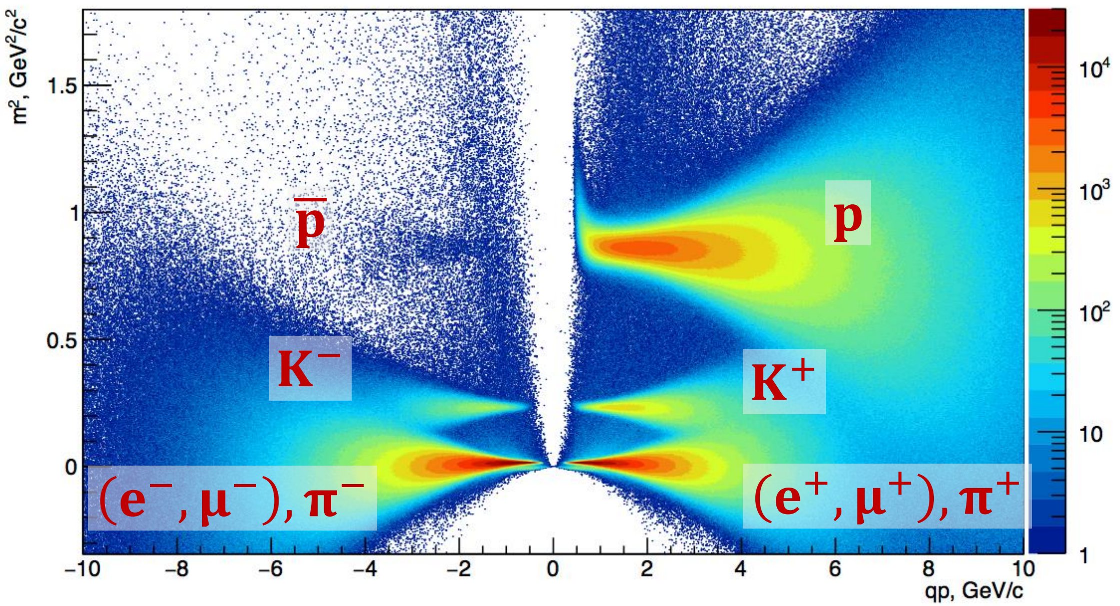
CBM EXPERIMENTAL SETUP @SIS-100



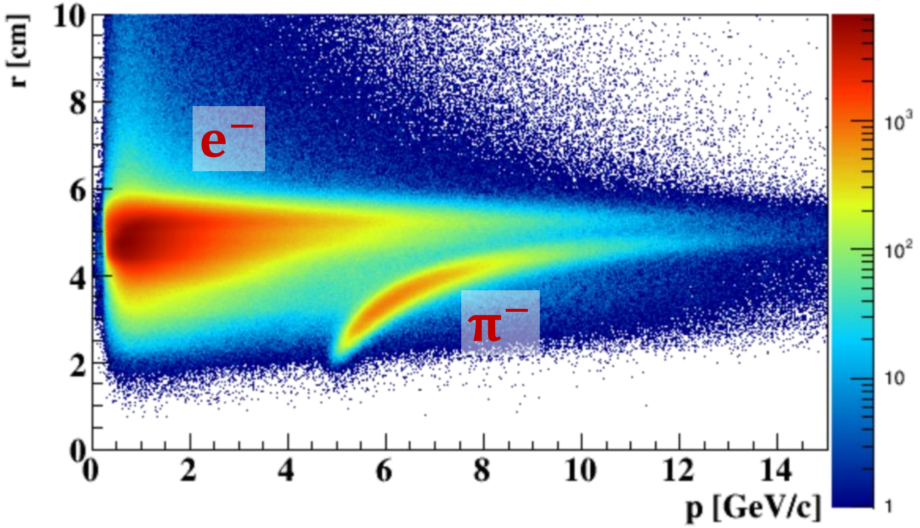
Particle Identification With CBM

CBM Simulations, central Au-Au@10AGeV

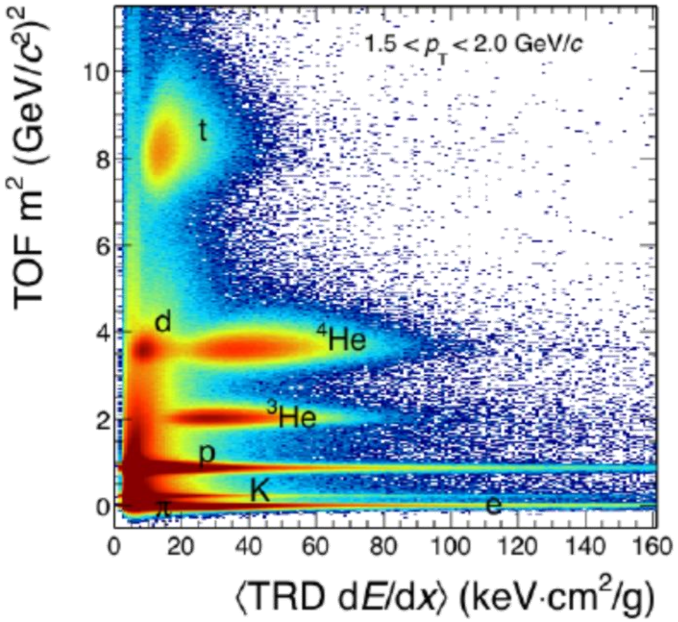
ToF - Hadron Identification



Clear separation between charged protons, pions and kaons



RICH - Electron ID

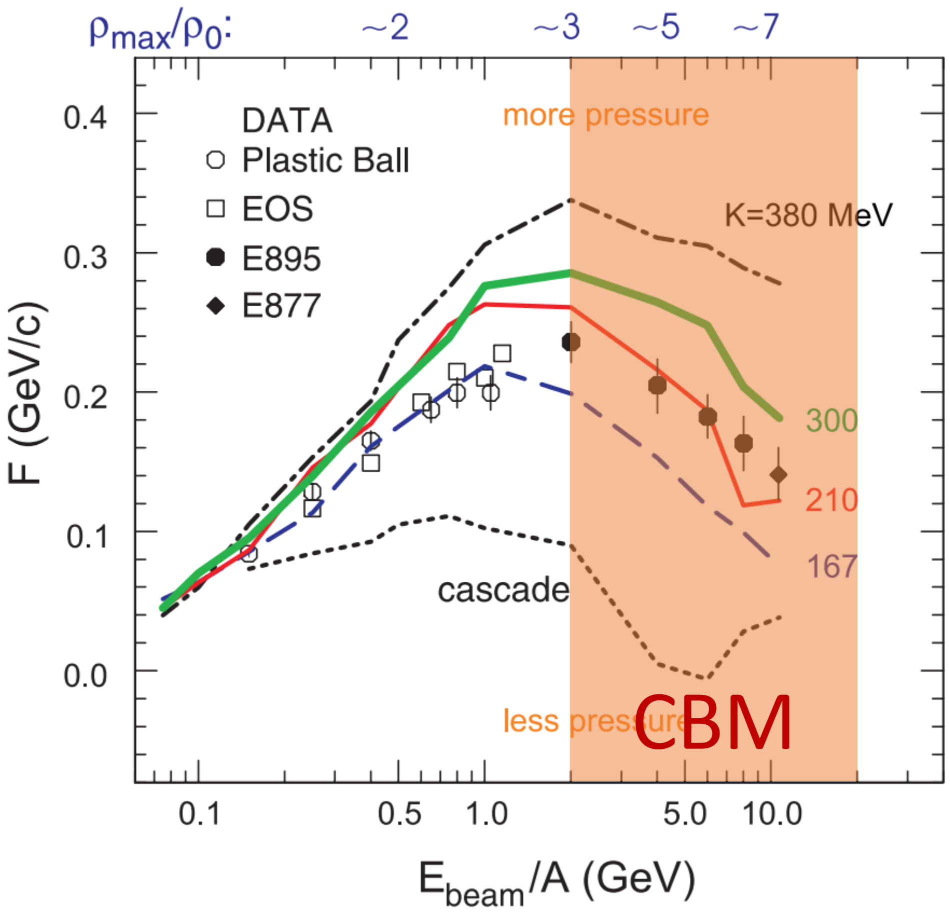


TRD + ToF - Electron, Light Nuclei, Heavy Fragments

Clear separation between pions and electrons, and light nuclei

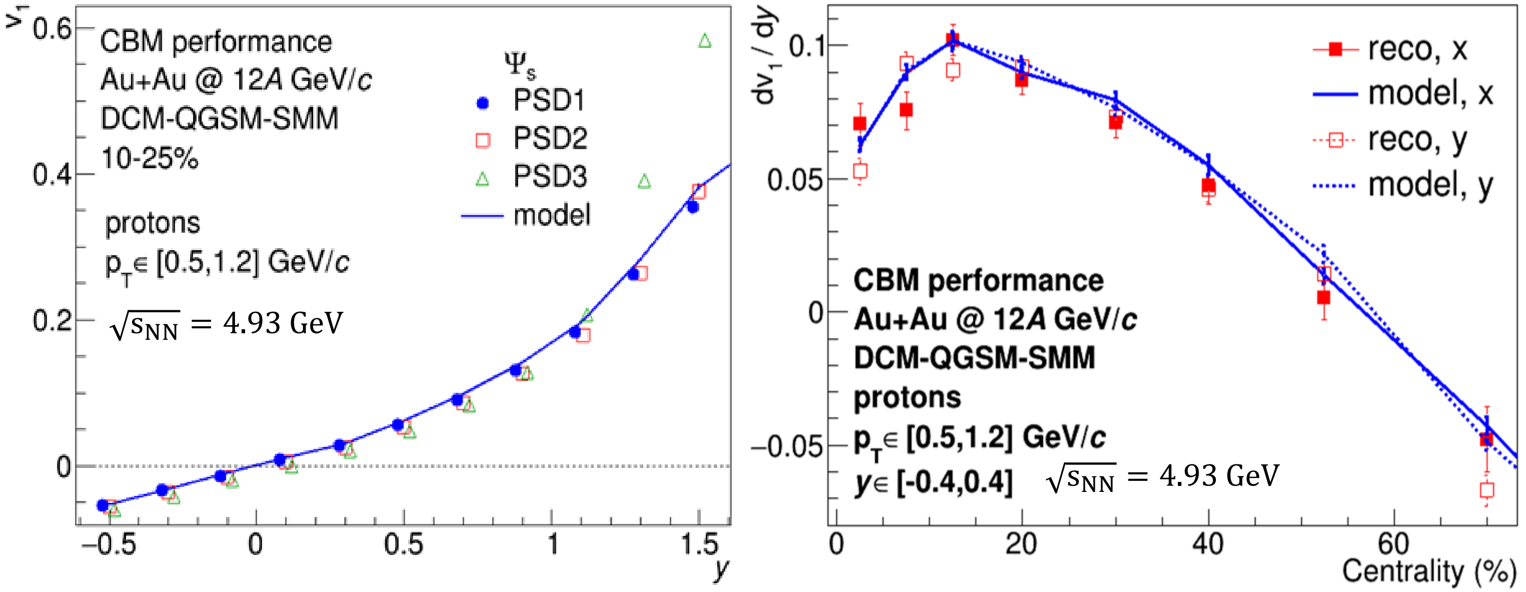
CBM'S EXPERIMENTAL OBSERVABLES AND EXPECTED PHYSICS PERFORMANCE

Observable #1: Collective Flow (v_1)



P. Danielewicz, Science 298 (2002) 1592-1596

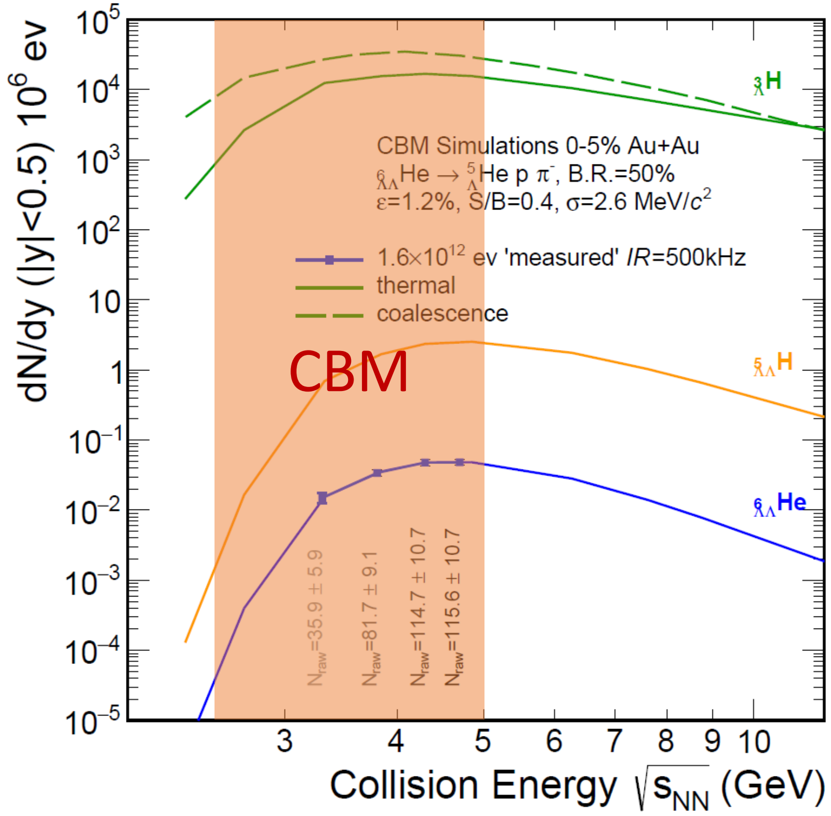
Collective flow driven by the pressure gradient in the fireball and thus carry the information about the underlying EOS



O. Golosov et al., CBM Progess Report 2020
O. Golosov et al., J.Phys.Conf.Ser. 1690 (2020) 1, 012104

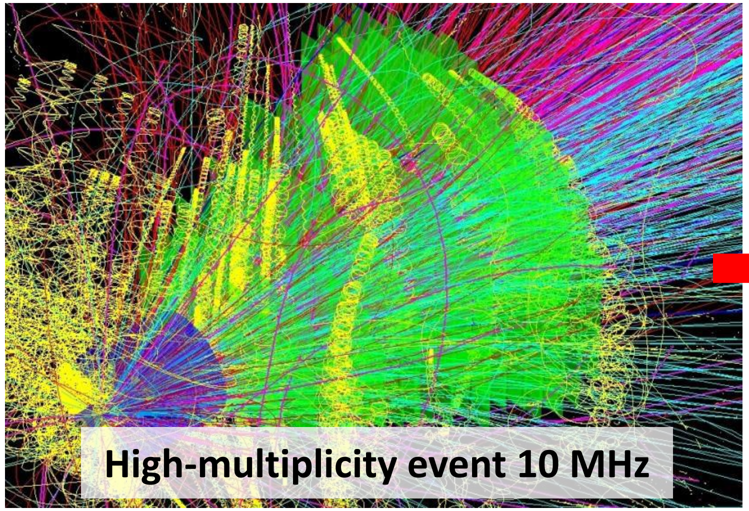
- Data-driven methods to perform extensive multi-differential v_1 flow analysis for protons have been developed
- Procedures for centrality determination, particle identification and corrections for effects of detector's azimuthal non-uniformity are applied
- Input model v_1 from DCM-QGSM-SMM is recovered using data-driven methods with projectile spectators
- Ongoing – Higher harmonics (v_2, …), other particle spieces and energy scan

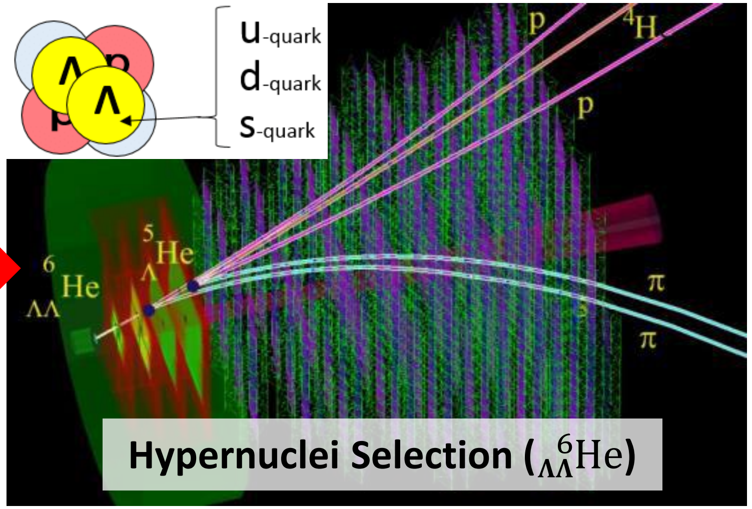
OBSERVABLE #2: HYPERNUCLEI



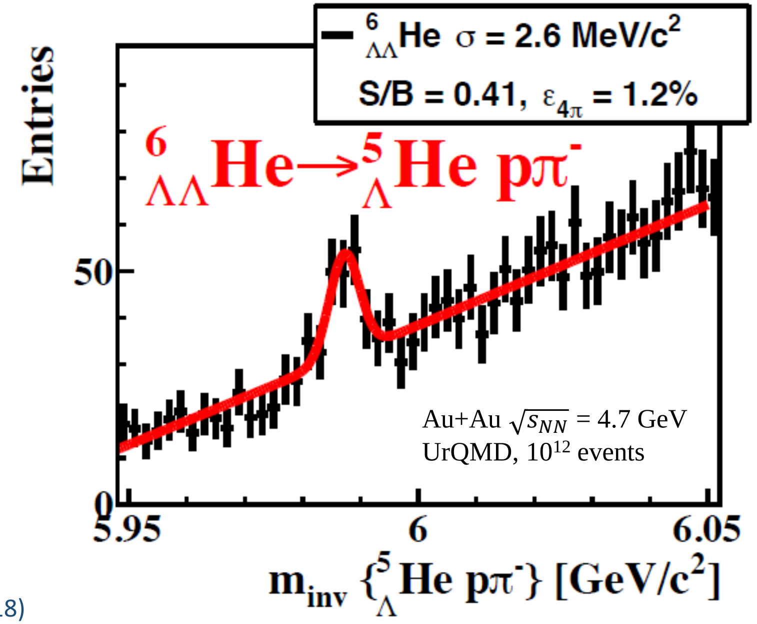
Thermal: A. Andronic et al., Phys.Lett.B 697 (2011) 203-207
Coalescence: J. Steinheimer et al., Phys.Lett.B 714 (2012) 85-91

Hypernuclei carry essential information to study 2- and 3-body YN interactions and solve the 'Hyperon Puzzle'→
Yields maximum at CBM@SIS-100 regime!





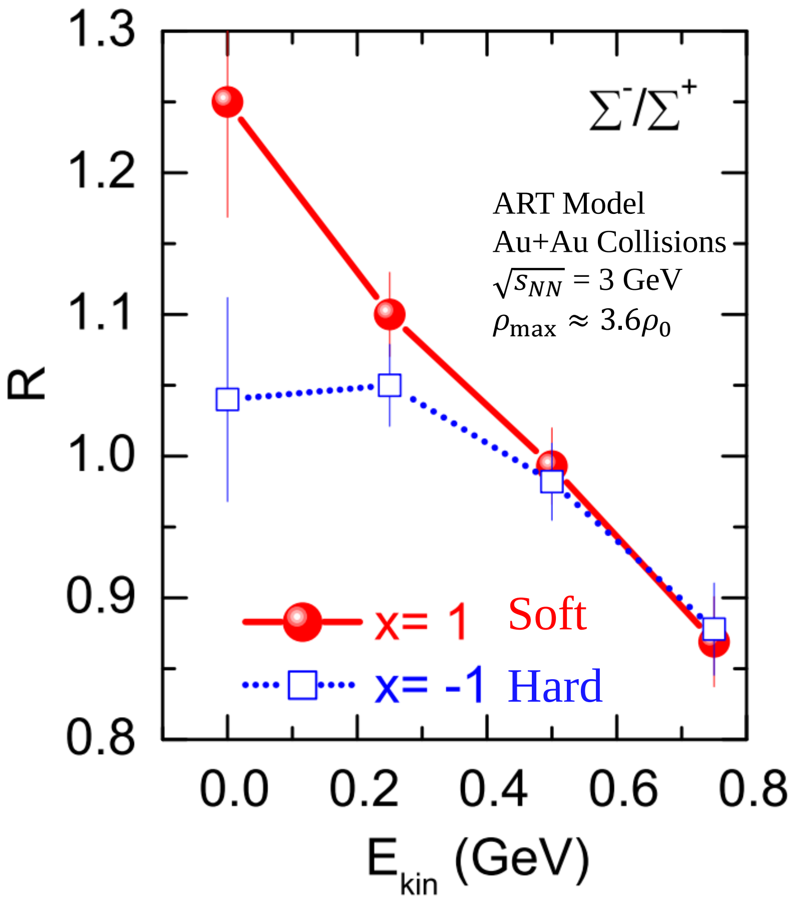
- Tools in place for the multi-differential physics analysis of strange hadrons and hypernuclei
- Reconstruction based on the dedicated KFParticleFinder package (efficiency and cuts optimization are ongoing)
- Expected collection rate: ∼ 60 $^{6}_{\Lambda\Lambda}He$ in 1 week at 10MHz IR



I. Vassiliev, Quark Matter 2022
I. Kisel, J.Phys.Conf.Ser. 1070, 012015 (2018)

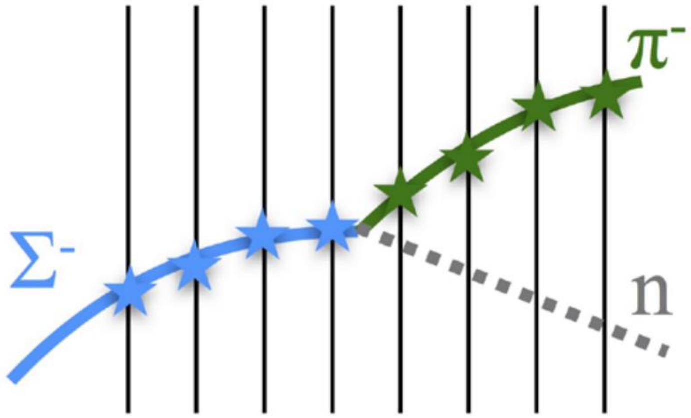
Observable #3: $(n/p)_{\text{like}}$ Particle Ratios

G-C. Yong et al., Phys. Rev. C 106, 024902 (2022)



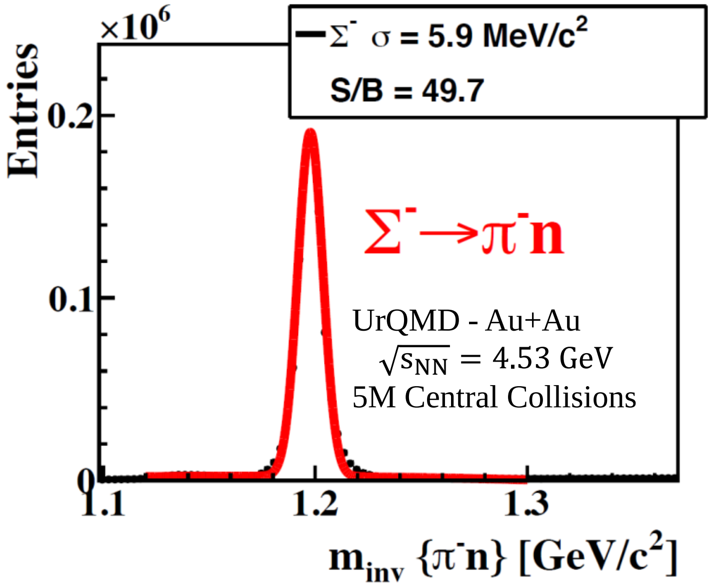
Σ^-/Σ^+ ratio is expected to carry the $E_{sym}(\rho)$ information since its production is dominated by primordial pions $(\pi + N \rightarrow \Sigma)$

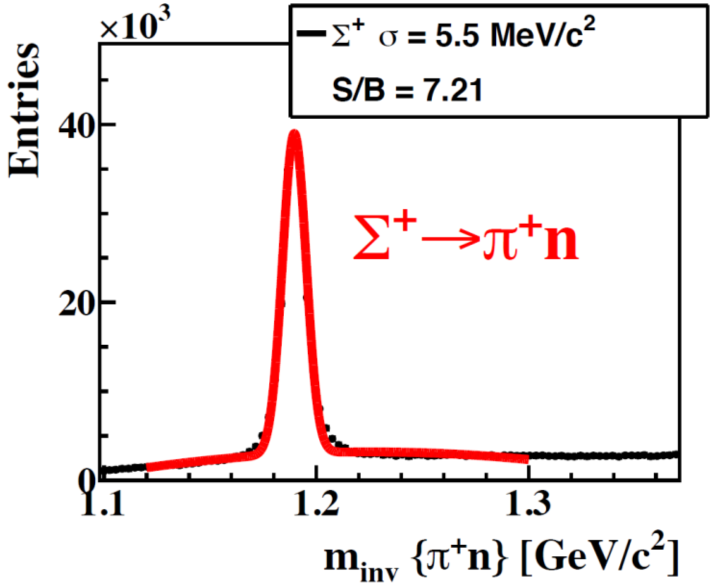
Q. Li et al., Phys. Rev. C 71, 054907 (2005)



P. Kisel et al., EPJ Web Conf. 173 (2018) 04009

- Experimentally, Σ baryons are difficult to identify as they are short-lived ($c\tau_{\Sigma^+}$ = 2.4 cm and $c\tau_{\Sigma^-}$ = 4.4 cm) and decay with at least one neutral daughter particle
- Tracking-Vertexing detectors located close to the target, in combination with the Missing Mass Method of particle reconstruction allows to achieve clean identification of Σ





Broader CBM Physics Goals And Observables

Comprehensive roster of physics goals and observables

QCD equation-of-state and symmetry energy
- collective flow of identified particles
- particle production at threshold energies

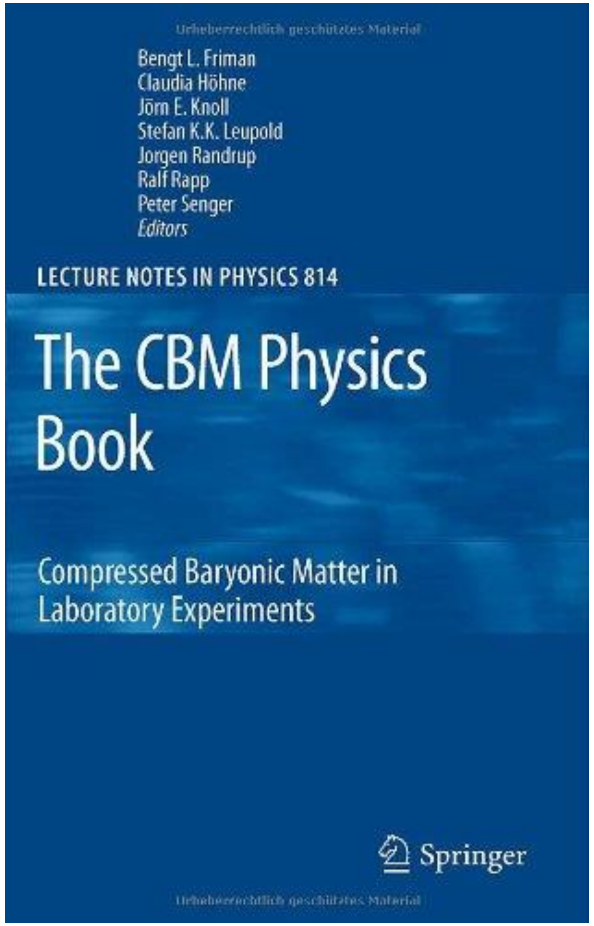
Phase transition
- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point
- event-by-event fluctuations of conserved quantities

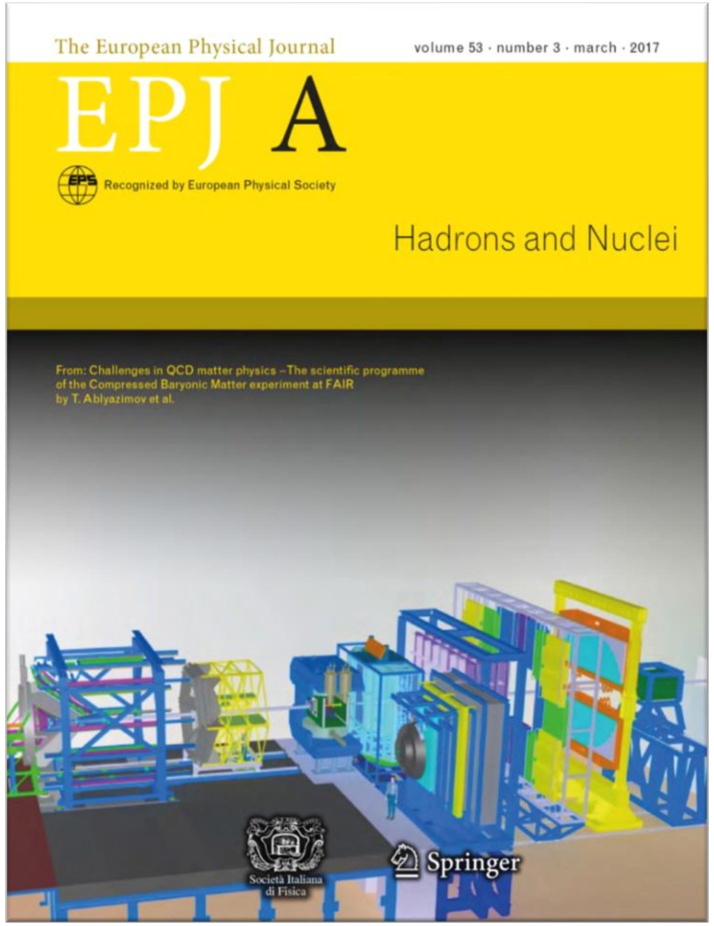
Chiral symmetry restoration at large μ_B
- in-medium modifications of hadrons
- meson-baryon coupling
- dileptons at intermediate invariant masses

Strange matter
- (double-) lambda hyper-nuclei
- search for meta-stable objects (e.g., strange dibaryons)

Heavy flavor in cold and dense matter
- excitation function of charm production



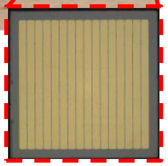
Lect. Notes Phys. 814 (2011) pp.1-980
DOI: 10.1007/978-3-642-13293-3



Eur.Phys.J.A 53 (2017) 3, 60
DOI: 10.1140/epja/i2017-12248-y

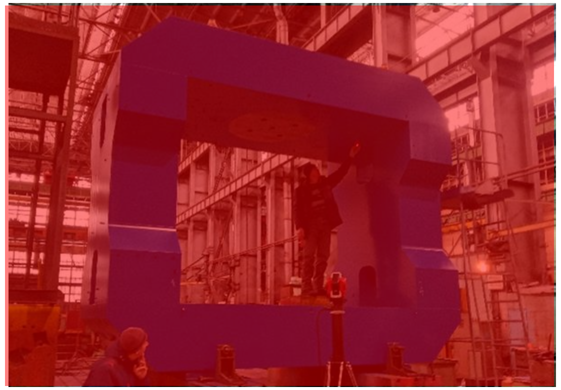
Recent (& Brief) Achievements In Detector Projects

Beam Monitoring (BMON) Detector

pcCVD diamond sensor (16-ch)
for high-intensity tests

Superconducting Dipole Magnet



Magnet Yolk housed in BINP (Russia).
Tendering for replacement started.

Micro-Vertex Detector (MVD)

MVD's TDR accepted.
Improved MIMOSIS-2 being submitted.

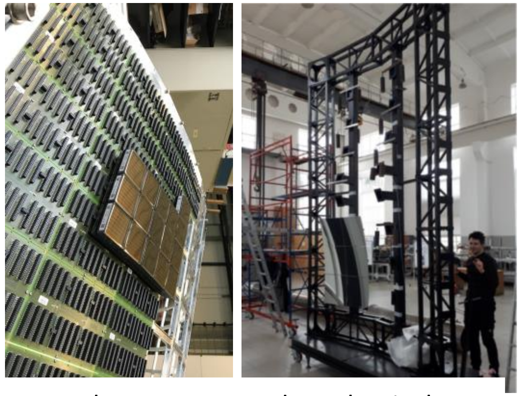
Silicon Tracking System (STS)

Pre-series STS module production for E16 (J-PARC) exp.

Muon Chambers (MUCH)

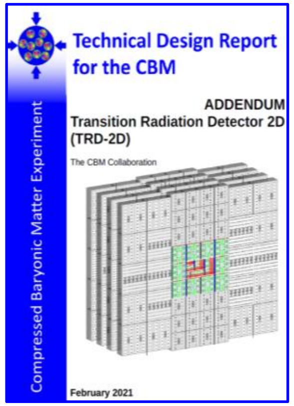
RPCs at tested at nominal
rates at GIF++ (Nov.21)

Ring Imaging Cherenkov (RICH) Detector



Photocamera and Mechanical
Prototypes (Mirror Wall)

Transition Radiation Detector (TRD)



TRD-2D-addendum submitted.
TRD-1D pre-production by Q1-2023.

Time-of-Flight (ToF) Wall

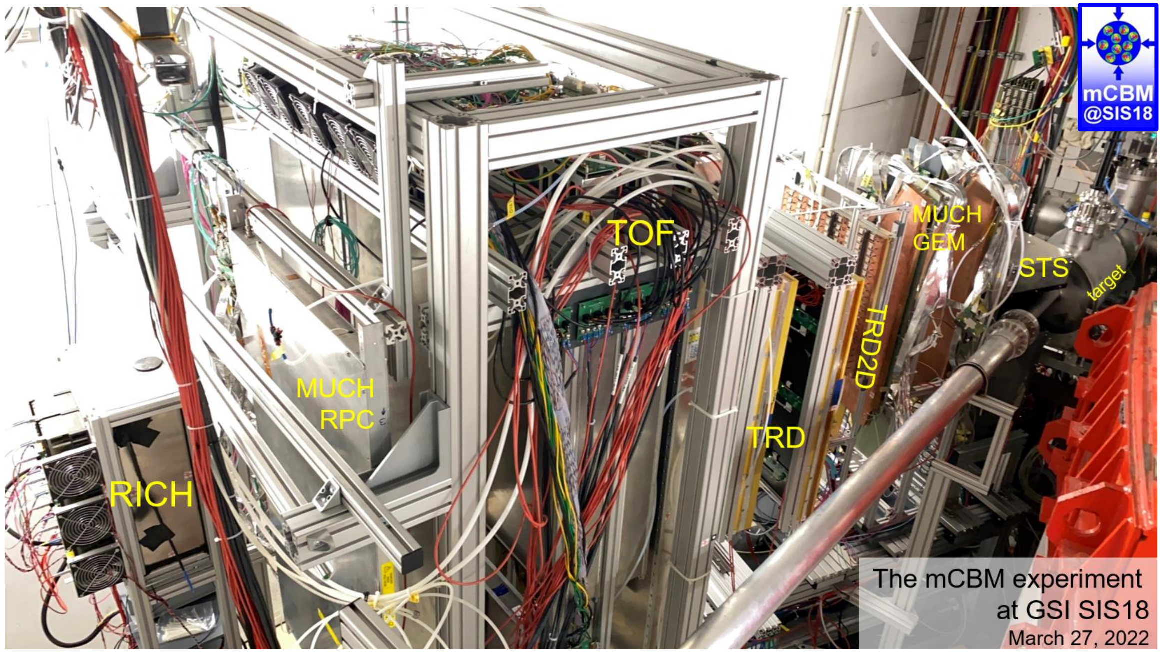
Full-size counters (all types) built and tested
for high-rate and longer-term tests

Projectile Spectator Detector (PSD)

Efforts to replace PSD with
HADES-like FWALL. Still open issue.

CBM Contribution To FAIR Phase 0

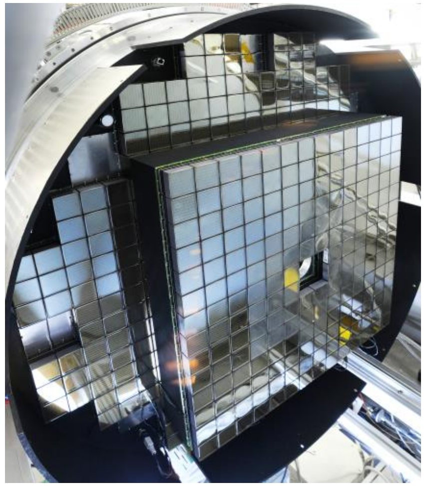
mCBM@SIS-18: Pre-production components of CBM's detector sub-systems tested to test the triggerless-streaming readout and data transport of CBM $\mathcal{O}$ (1 MHz) interaction rates

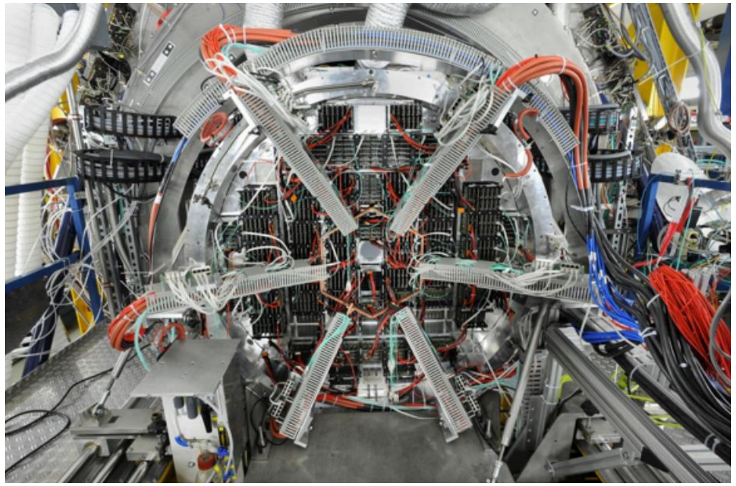


The mCBM experiment at GSI SIS18
March 27, 2022

- Major effort put towards mimicking the final DAQ/data transport system by integrating all subsystems to the Common Readout Interface (CRI)
- Systematic high-rate studies performed for various detector subsystems and underlying components with up to 10 MHz collision rates during 2021-22 campaigns

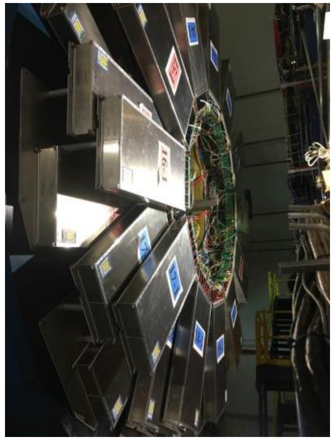
HADES-RICH: Already 1/2 (430 MAPMTs + FEE) of CBM-RICH

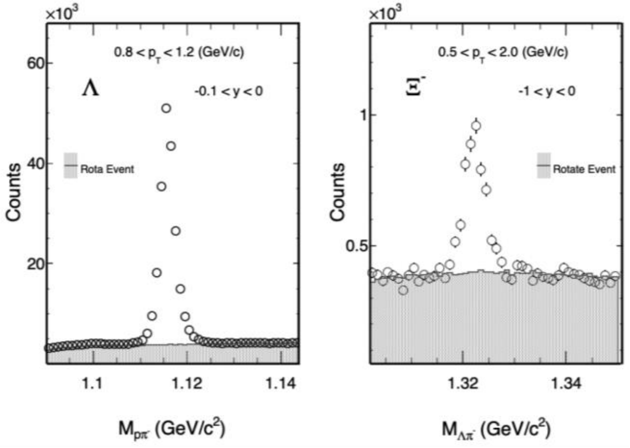




J. A-Musch et al., CBM Progress Report 2020

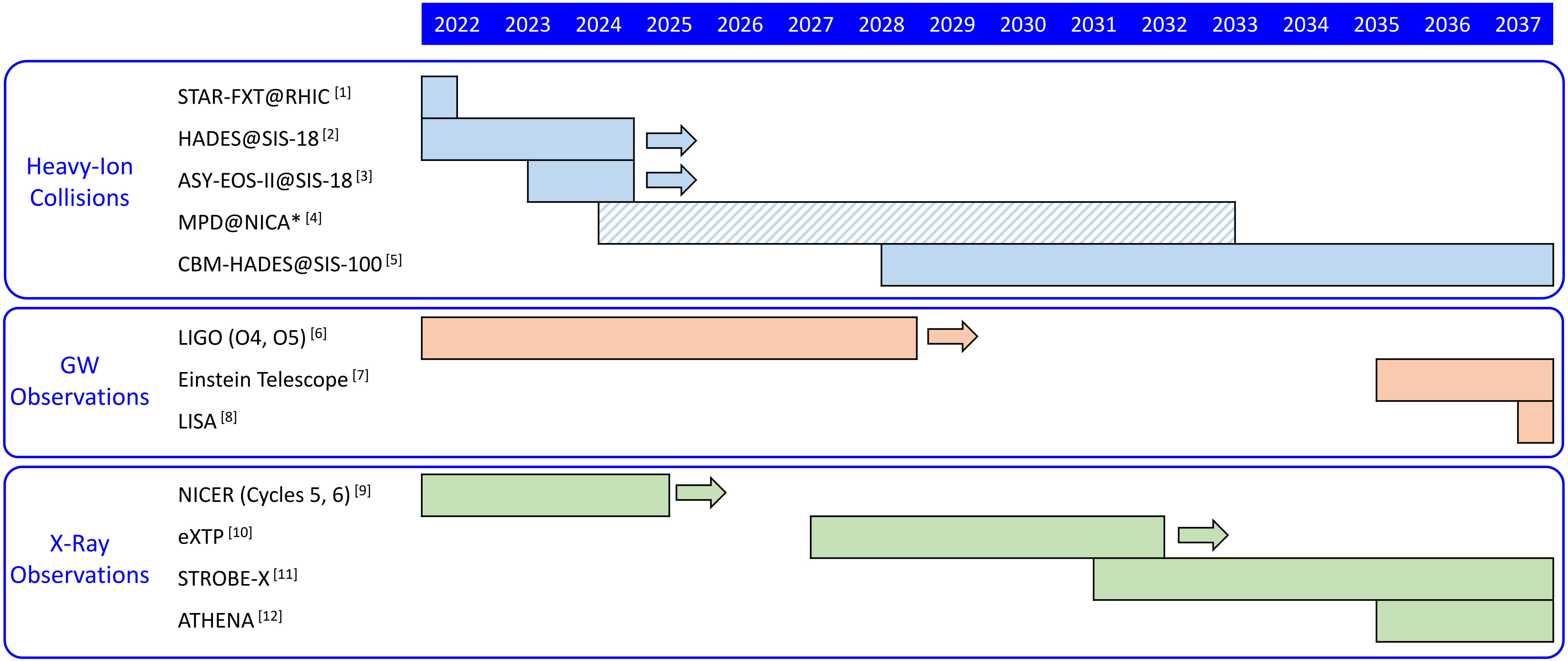
STAR-eTOF: 10% (108 MRPCs) of CBM-TOF
CBM Online Reconstruction Software for STAR-BES





Guannan Xie, Strangeness in Quark Matter (2021)

Growing Multi-Messenger Era (At Suprasaturation Densities)



[1] D. Morrison, Quark Matter 2022 | Link
[2] Proposal for Beamtime in 2023-24, GSI G-PAC (2022)
[3] Proposal for Beamtime in 2023-24, GSI G-PAC (2022)
[4] I. Maldonado, A. Ayala, EuNPC 2022 | Link
[5] First-Science and Staging Review of the FAIR Project (2022) | Link
[6] LIGO-Virgo-KAGRA Observing Run Plan | Link
[7] Einstein Telescope Homepage | Link
[8] LISA ESA Factsheet | Link
[9] NICER Proposals Guide – Cycle 5 | Link
[10] eXTP Homepage | Link
[11] STROBE-X White Paper for the Astro 2020 Decadal Survey | Link
[12] ATHENA ESA Factsheet | Link

Summary And Outlook

CBM@SIS-100 has significant discovery potential

- excitation function of hyperon production
- excitation function of di lepton production
- study of light hyper-nuclei

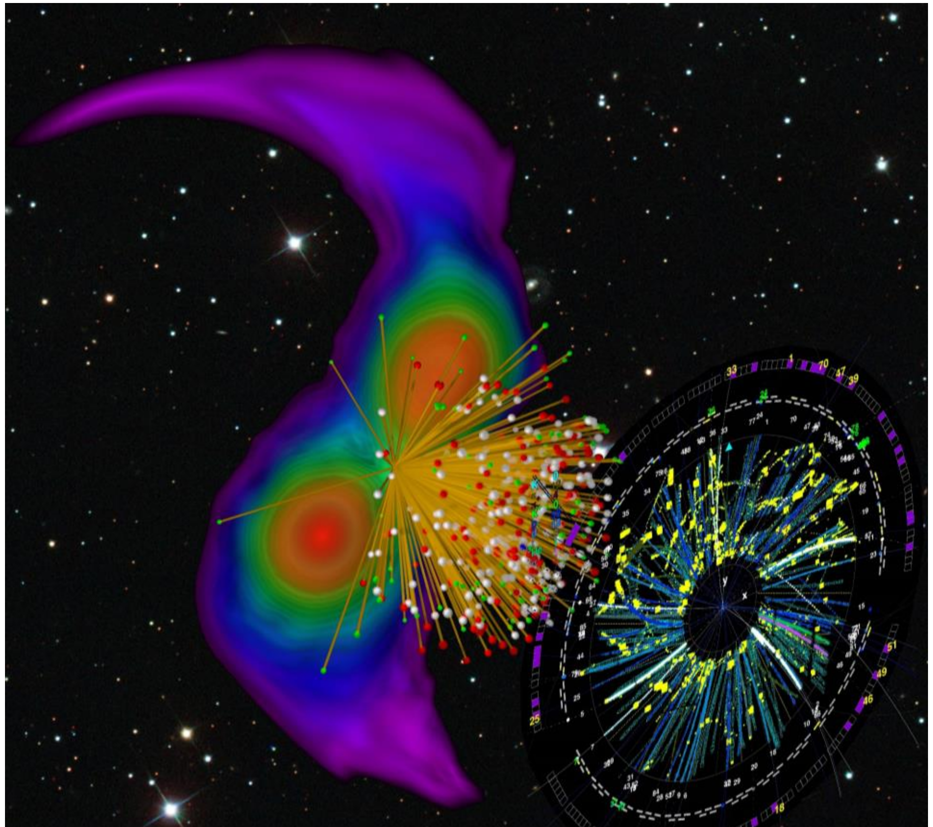
Pushing the high-rate capability frontier

- to achieve high precision of multi differential observables
- to enable rare processes as sensitive probes

CBM Phase 0 activities (HADES, STAR, mCBM)

- understanding of major components
- production of physics results with CBM devices

Efforts are ongoing to compensate for the loss of Russian in-kind contributions to CBM due the war in Ukraine and sanctions imposed on Russia.



Tim Dietrich, Arnaud Le Fevre, Kees Huyser; Background: ESA/Hubble, Sloan Digital Sky Survey

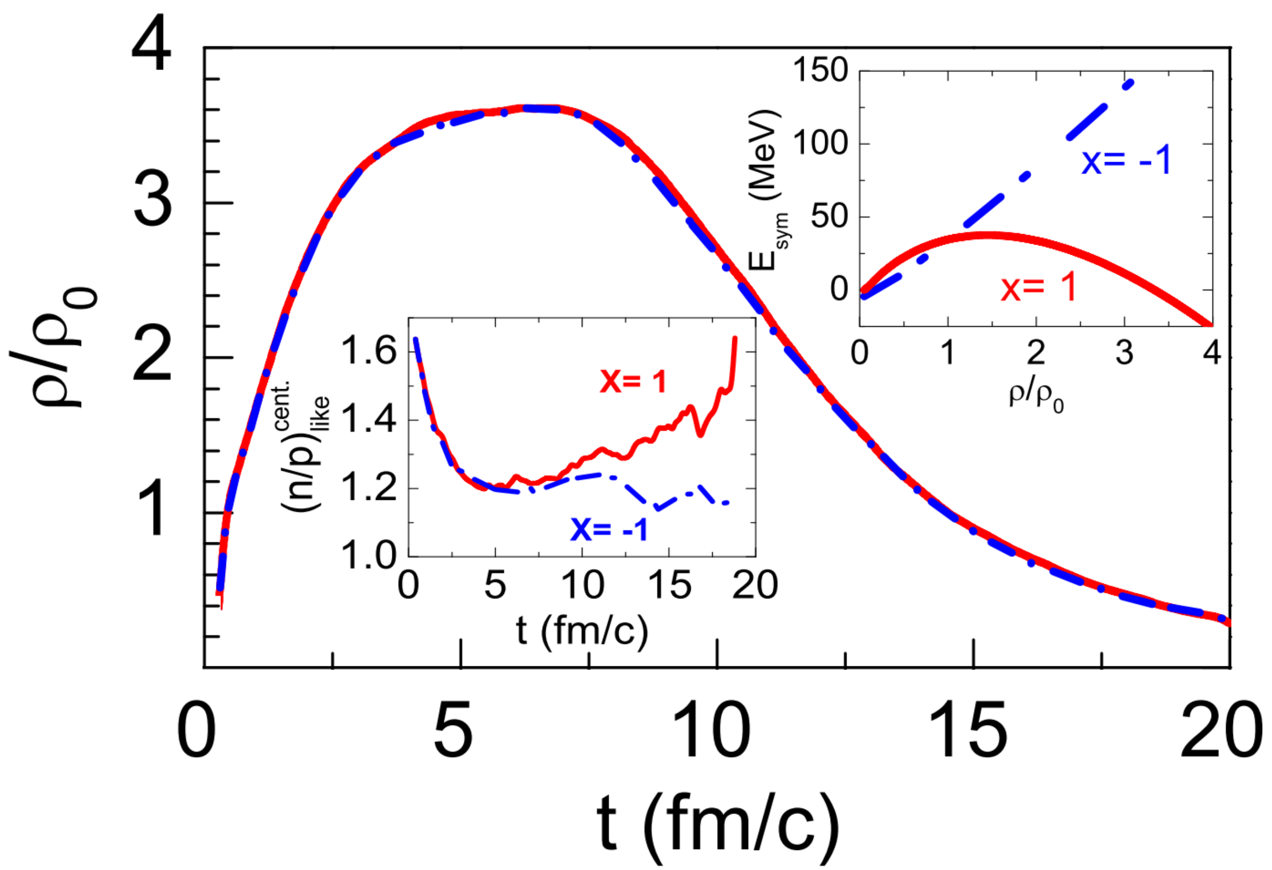
CBM@SIS-100 (2 – 11 AGeV Au-Au) provides unique conditions in lab to probe QCD matter properties at neutron star core densities, including the high-density EOS, and the search for new phases at higher densities

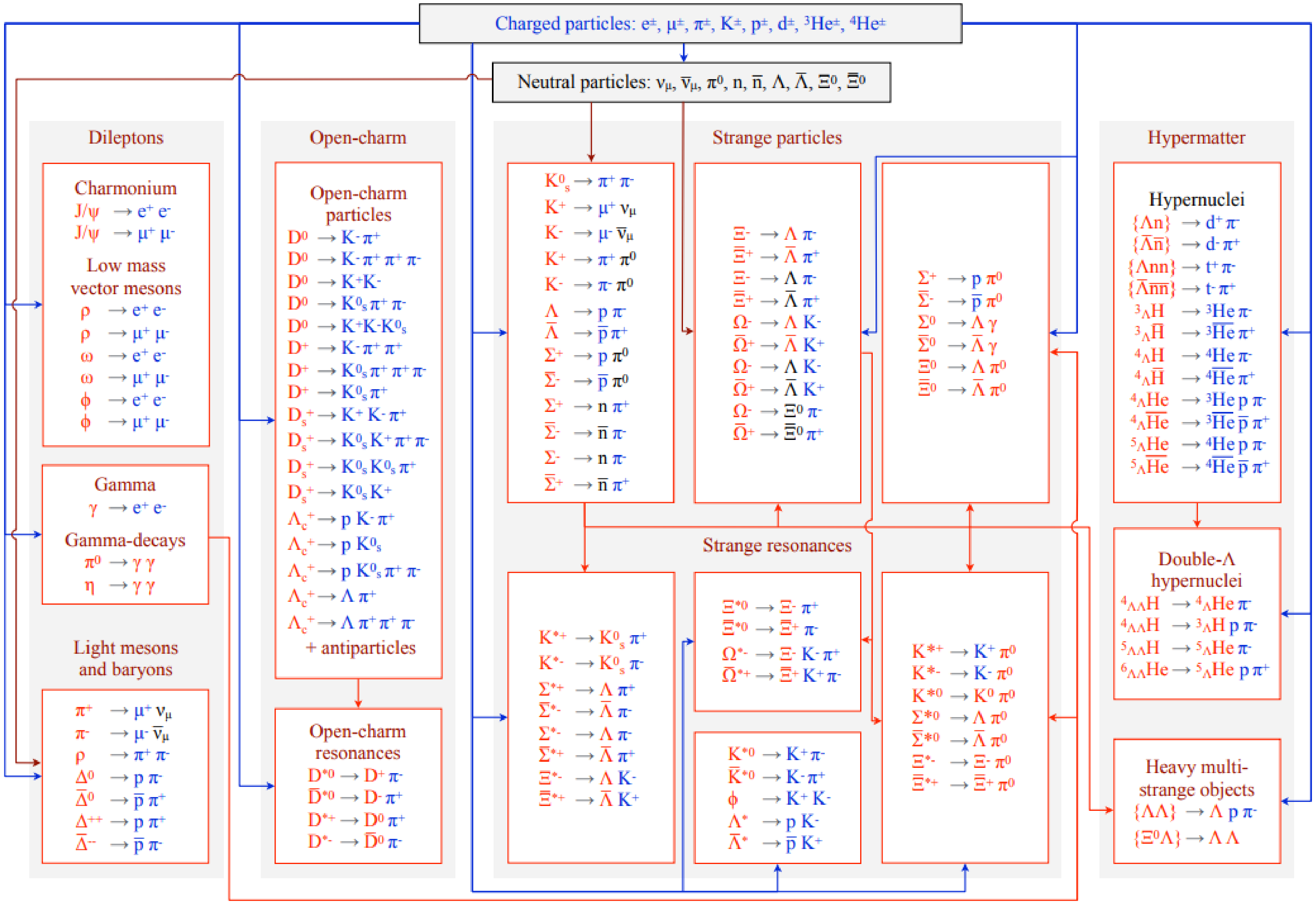
MOVING TOWARDS A NEW MULTI-MESSENGER PHYSICS ERA

THANK YOU

40th CBM Collaboration Meeting, Oct. 2022, WUT, Warsaw

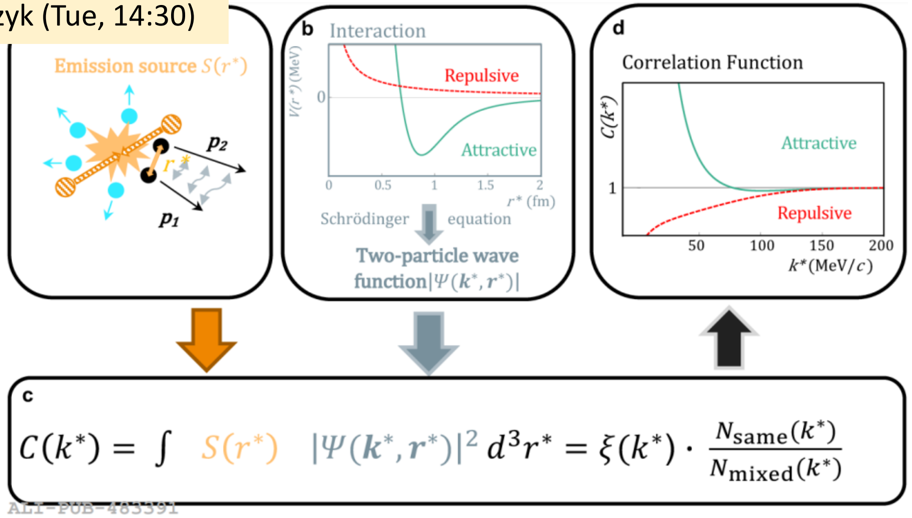
HELMHOLTZ GEMEINSCHAFT · GSI · FAIR · HFHF · ESCAPE · STRONG 2020 · Bundesministerium für Bildung und Forschung · Ministry of Science and Higher Education Republic of Poland · MŠMT · MINISTRY OF EDUCATION YOUTH AND SPORTS · MINISTERUL EDUCAȚIEI · GOVERNMENT OF INDIA MINISTRY OF SCIENCE AND TECHNOLOGY · DEPARTMENT OF SCIENCE & TECHNOLOGY


4
3
2
1
ρ/ρ0
0
5
10
15
20
t (fm/c)
150
100
50
0
Esym (MeV)
x= -1
x= 1
0
1
2
3
4
ρ/ρ0
1.6
1.4
1.2
1.0
(n/p)cent. like
x= 1
x= -1
0
5
10
15
20
t (fm/c)


Charged particles: $e^\pm, \mu^\pm, \pi^\pm, K^\pm, p^\pm, d^\pm, {}^3He^\pm, {}^4He^\pm$
Neutral particles: $\nu_\mu, \bar{\nu}_\mu, \pi^0, n, \bar{n}, \Lambda, \bar{\Lambda}, \Xi^0, \bar{\Xi}^0$
Dileptons
Charmonium
$J/\psi \to e^+ e^-$
$J/\psi \to \mu^+ \mu^-$
Low mass vector mesons
$\rho \to e^+ e^-$
$\rho \to \mu^+ \mu^-$
$\omega \to e^+ e^-$
$\omega \to \mu^+ \mu^-$
$\phi \to e^+ e^-$
$\phi \to \mu^+ \mu^-$
Gamma
$\gamma \to e^+ e^-$
Gamma-decays
$\pi^0 \to \gamma\gamma$
$\eta \to \gamma\gamma$
Light mesons and baryons
$\pi^+ \to \mu^+ \nu_\mu$
$\pi^- \to \mu^- \bar{\nu}_\mu$
$\rho \to \pi^+ \pi^-$
$\Delta^0 \to p \pi^-$
$\bar{\Delta}^0 \to \bar{p} \pi^+$
$\Delta^{++} \to p \pi^+$
$\bar{\Delta}^{--} \to \bar{p} \pi^-$
Open-charm
Open-charm particles
$D^0 \to K^- \pi^+$
$D^0 \to K^- \pi^+ \pi^+ \pi^-$
$D^0 \to K^+ K^-$
$D^0 \to K^0_s \pi^+ \pi^-$
$D^0 \to K^+ K^- K^0_s$
$D^+ \to K^- \pi^+ \pi^+$
$D^+ \to K^0_s \pi^+ \pi^+ \pi^-$
$D^+ \to K^0_s \pi^+$
$D_s^+ \to K^+ K^- \pi^+$
$D_s^+ \to K^0_s K^+ \pi^+ \pi^-$
$D_s^+ \to K^0_s K^0_s \pi^+$
$D_s^+ \to K^0_s K^+$
$\Lambda_c^+ \to p K^- \pi^+$
$\Lambda_c^+ \to p K^0_s$
$\Lambda_c^+ \to p K^0_s \pi^+ \pi^-$
$\Lambda_c^+ \to \Lambda \pi^+$
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$
+ antiparticles
Open-charm resonances
$D^{*0} \to D^+ \pi^-$
$\bar{D}^{*0} \to D^- \pi^+$
$D^{*+} \to D^0 \pi^+$
$D^{*-} \to \bar{D}^0 \pi^-$
Strange particles
$K^0_s \to \pi^+ \pi^-$
$K^+ \to \mu^+ \nu_\mu$
$K^- \to \mu^- \bar{\nu}_\mu$
$K^+ \to \pi^+ \pi^0$
$K^- \to \pi^- \pi^0$
$\Lambda \to p \pi^-$
$\bar{\Lambda} \to \bar{p} \pi^+$
$\Sigma^+ \to p \pi^0$
$\bar{\Sigma}^- \to \bar{p} \pi^0$
$\Sigma^+ \to n \pi^+$
$\bar{\Sigma}^- \to \bar{n} \pi^-$
$\Sigma^- \to n \pi^-$
$\bar{\Sigma}^+ \to \bar{n} \pi^+$
$\Xi^- \to \Lambda \pi^-$
$\bar{\Xi}^+ \to \bar{\Lambda} \pi^+$
$\Xi^- \to \Lambda \pi^-$
$\bar{\Xi}^+ \to \bar{\Lambda} \pi^+$
$\Omega^- \to \Lambda K^-$
$\bar{\Omega}^+ \to \bar{\Lambda} K^+$
$\Omega^- \to \Lambda K^-$
$\bar{\Omega}^+ \to \bar{\Lambda} K^+$
$\Omega^- \to \Xi^0 \pi^-$
$\bar{\Omega}^+ \to \bar{\Xi}^0 \pi^+$
$\Sigma^+ \to p \pi^0$
$\bar{\Sigma}^- \to \bar{p} \pi^0$
$\Sigma^0 \to \Lambda \gamma$
$\bar{\Sigma}^0 \to \bar{\Lambda} \gamma$
$\Xi^0 \to \Lambda \pi^0$
$\bar{\Xi}^0 \to \bar{\Lambda} \pi^0$
Strange resonances
$K^{*+} \to K^0_s \pi^+$
$K^{*-} \to K^0_s \pi^-$
$\Sigma^{*+} \to \Lambda \pi^+$
$\bar{\Sigma}^{*-} \to \bar{\Lambda} \pi^-$
$\Sigma^{*-} \to \Lambda \pi^-$
$\bar{\Sigma}^{*+} \to \bar{\Lambda} \pi^+$
$\Xi^{*-} \to \Lambda K^-$
$\bar{\Xi}^{*+} \to \bar{\Lambda} K^+$
$\Xi^{*0} \to \Xi^- \pi^+$
$\bar{\Xi}^{*0} \to \bar{\Xi}^+ \pi^-$
$\Omega^{*-} \to \Xi^- K^- \pi^+$
$\bar{\Omega}^{*+} \to \bar{\Xi}^+ K^+ \pi^-$
$K^{*0} \to K^+ \pi^-$
$\bar{K}^{*0} \to K^- \pi^+$
$\phi \to K^+ K^-$
$\Lambda^* \to p K^-$
$\bar{\Lambda}^* \to \bar{p} K^+$
$K^{*+} \to K^+ \pi^0$
$K^{*-} \to K^- \pi^0$
$K^{*0} \to K^0 \pi^0$
$\Sigma^{*0} \to \Lambda \pi^0$
$\bar{\Sigma}^{*0} \to \bar{\Lambda} \pi^0$
$\Xi^{*-} \to \Xi^- \pi^0$
$\bar{\Xi}^{*+} \to \bar{\Xi}^+ \pi^0$
Hypermatter
Hypernuclei
$\{\Lambda n\} \to d^+ \pi^-$
$\{\bar{\Lambda}\bar{n}\} \to d^- \pi^+$
$\{\Lambda nn\} \to t^+ \pi^-$
$\{\bar{\Lambda}\bar{n}\bar{n}\} \to t^- \pi^+$
${}^3_\Lambda H \to {}^3He\, \pi^-$
${}^3_\Lambda \bar{H} \to {}^3\bar{He}\, \pi^+$
${}^4_\Lambda H \to {}^4He\, \pi^-$
${}^4_\Lambda \bar{H} \to {}^4\bar{He}\, \pi^+$
${}^4_\Lambda He \to {}^3He\, p\, \pi^-$
${}^4_\Lambda \bar{He} \to {}^3\bar{He}\, \bar{p}\, \pi^+$
${}^5_\Lambda He \to {}^4He\, p\, \pi^-$
${}^5_\Lambda \bar{He} \to {}^4\bar{He}\, \bar{p}\, \pi^+$
Double-Λ hypernuclei
${}^4_{\Lambda\Lambda} H \to {}^4_\Lambda He\, \pi^-$
${}^4_{\Lambda\Lambda} H \to {}^3_\Lambda H\, p\, \pi^-$
${}^5_{\Lambda\Lambda} H \to {}^5_\Lambda He\, \pi^-$
${}^6_{\Lambda\Lambda} He \to {}^5_\Lambda He\, p\, \pi^+$
Heavy multi-strange objects
$\{\Lambda\Lambda\} \to \Lambda p \pi^-$
$\{\Xi^0 \Lambda\} \to \Lambda \Lambda$

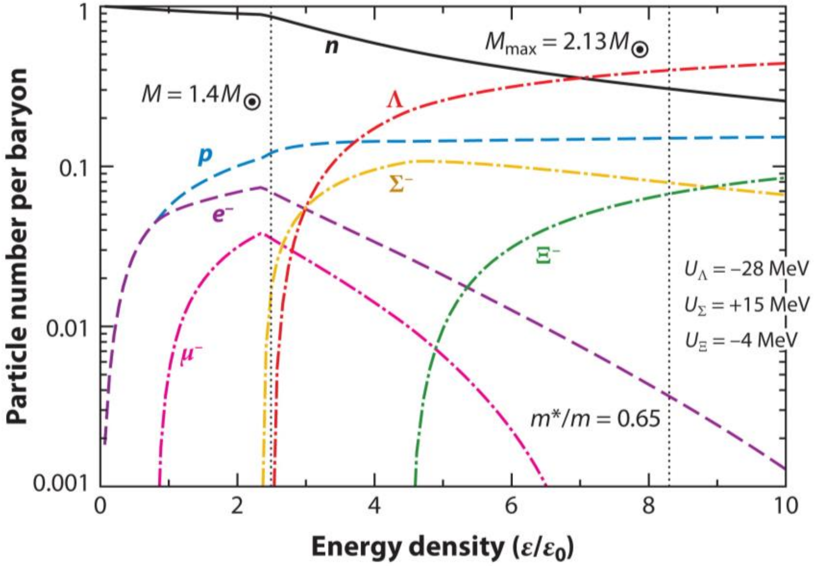
OBSERVABLE #4: FEMTOSCOPIC CORRELATIONS & YN INTERACTIONS

H. Zbroszczyk (Tue, 14:30)

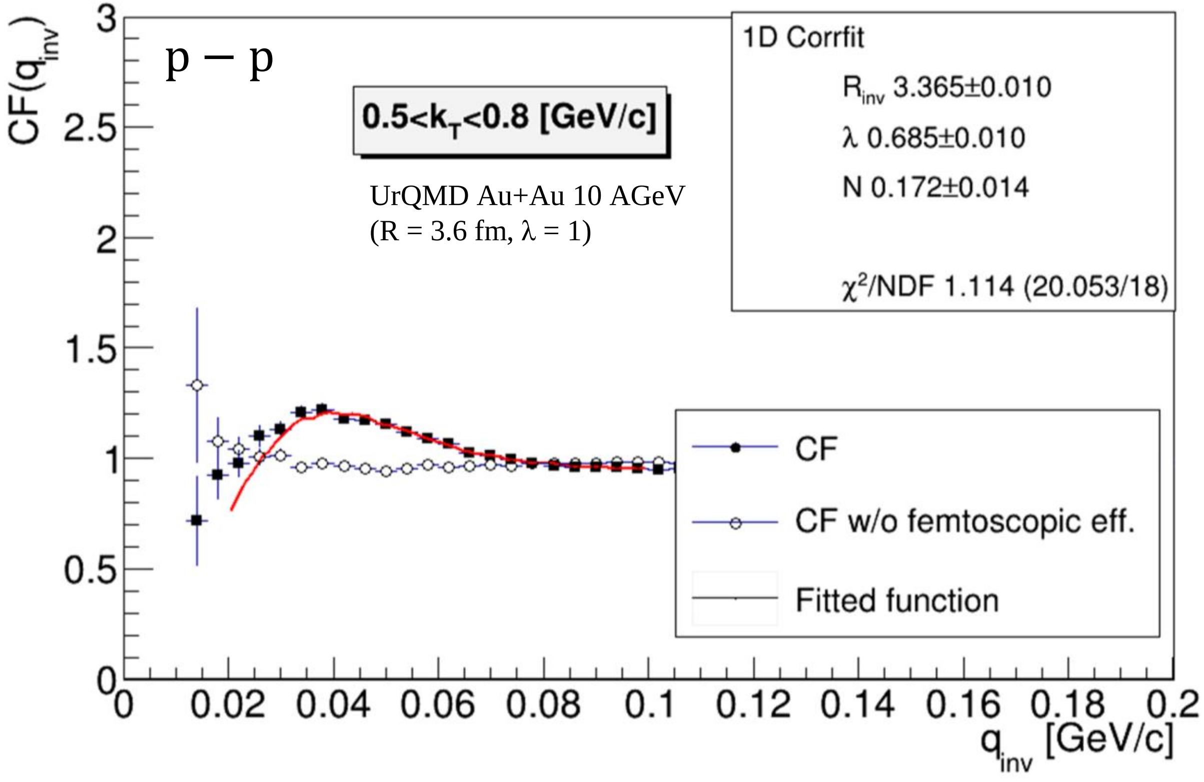


[ALICE], Nature 588, 7837 (2020)

Mean-Field Calculations +
ALICE-LHC Measurements



L. Fabbietti et al., Ann.Rev.Nucl.Part.Sci. 71 (2021)
MF Calculations: D. Chatterjee, S. Gosh, J. Schaffner-Bielich
ALICE Data: Phys. Rev. Lett. 123:112002 (2019)



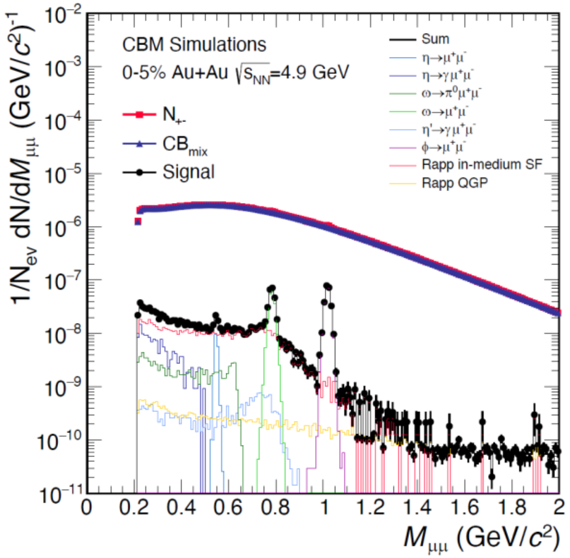
- Feasibility studies carried out to conduct measurements of proton-proton and pion-pion correlations

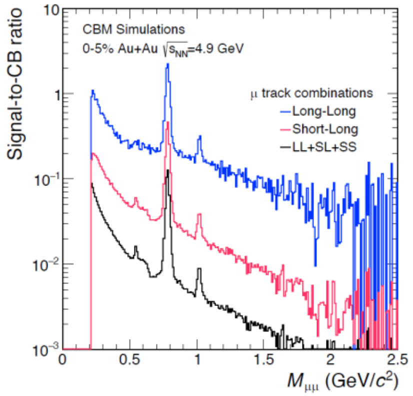
D. Wielanek, Proc.SPIE Int.Soc.Opt.Eng. 11581 (2020) 115811E
D. Wielanek, Quark Matter 2022

- Further analysis with higher statistics and improved cuts ongoing for precise reconstruction of source properties

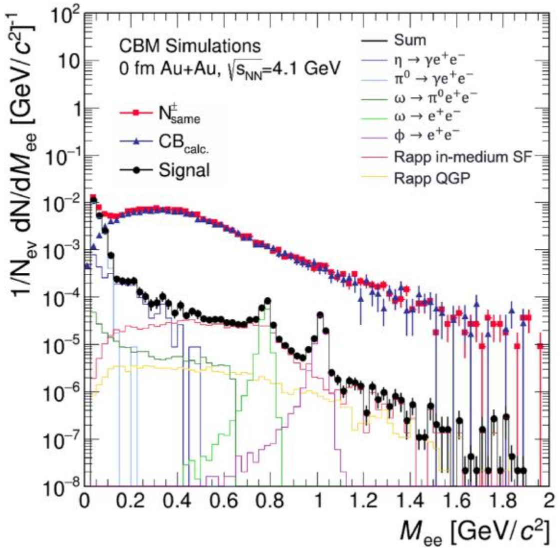
Observable #3: Caloric Curve Via Dileptons

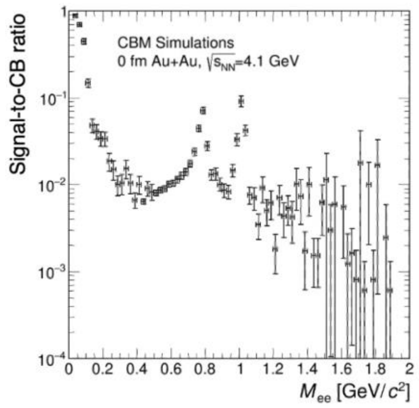
Muon Setup ($\mu^+\mu^-$)
$R_{int} = \mathcal{O}$ (1 MHz)

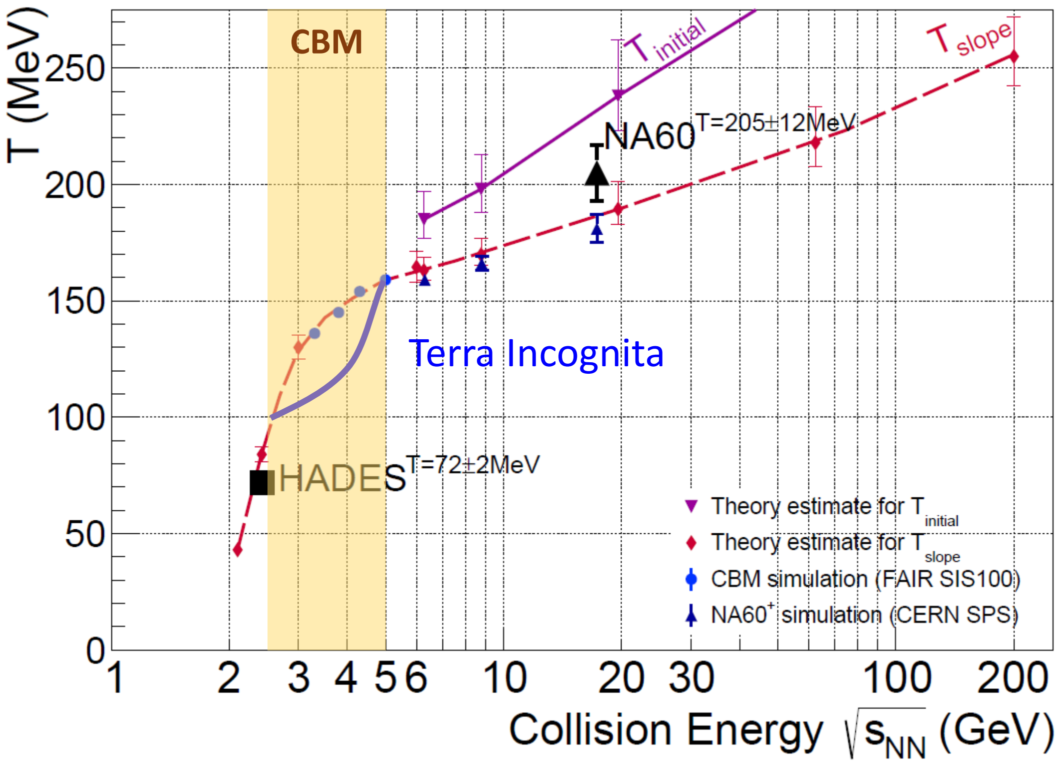




Electron Setup ($\mu^+\mu^-$)
$R_{int} = \mathcal{O}$ (0.1 MHz)







Nucl.Phys.A 1005 (2021) 121755
[NA60]: Eur. Phys. J. C 59 (2009) 607
[HADES]: Nature Physics 15 (2019) 1040

Theory: $\sqrt{s_{NN}} > 6$GeV - Phys. Lett. B 753 (2016) 586
$\sqrt{s_{NN}} < 6$GeV - Eur. Phys. J. A 52 (2016) 131

- Performance studies with realistic detector geometries, material budget, and response
- Access to thermal signal is feasible with good background description; Mass Resolution $\sigma_{M_{ll}}(\omega)$ = 14 MeV/c²