Equation-Of-State Studies With CBM (Perspectives) And RHIC Data

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Eberhard Karls Universität Tübingen

Mathematisch-Naturwissenschaftliche Fakultät

Physikalisches Institut

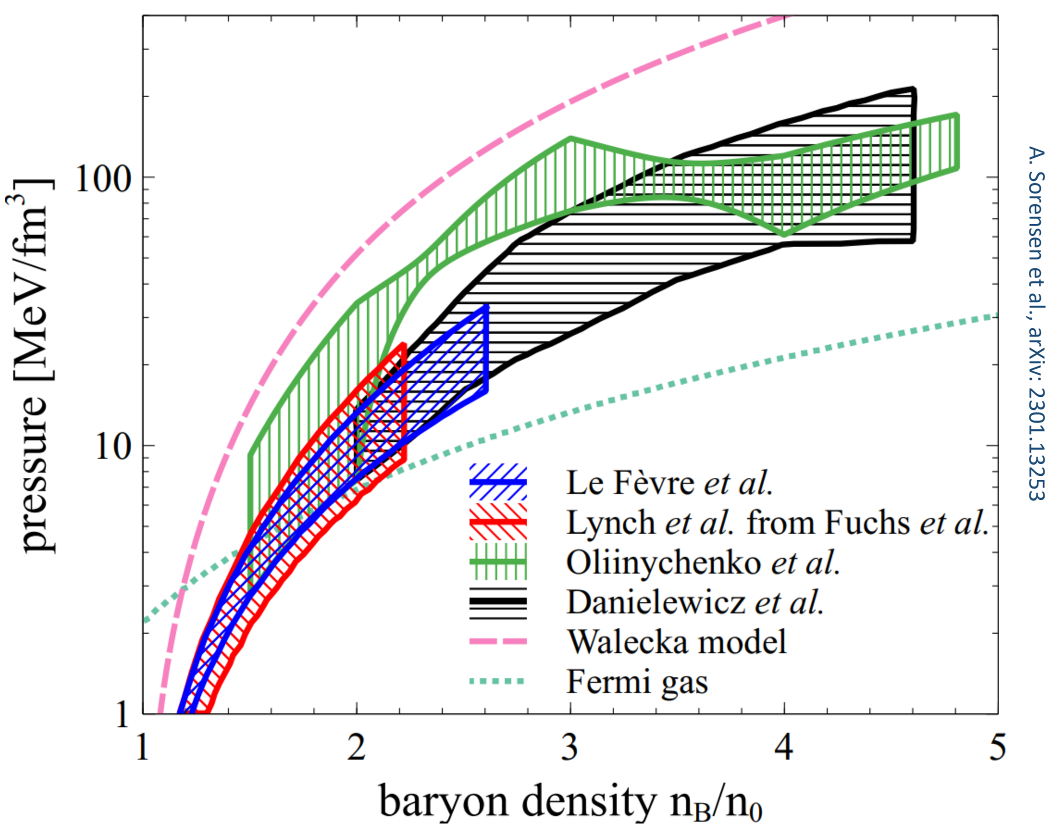
Current Landscape Of Nuclear Matter EoS At $\gtrsim \rho_0$

HIC Nuclear Matter EoS At $\gtrsim \rho_0$

W. Lynch (18.09)
A. Sorensen (18.09)

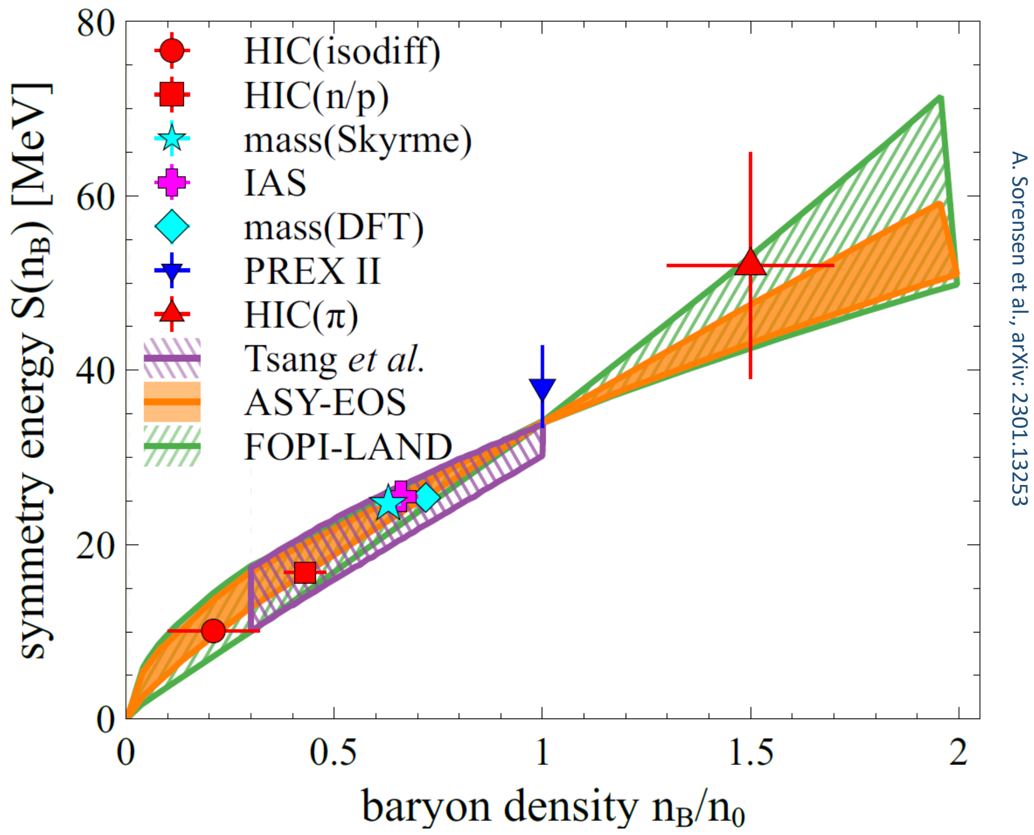
Symmetric Nuclear Matter

Still loosely constrained above $2.5\rho_0$ (2 AGeV Au+Au)



Symmetry Energy

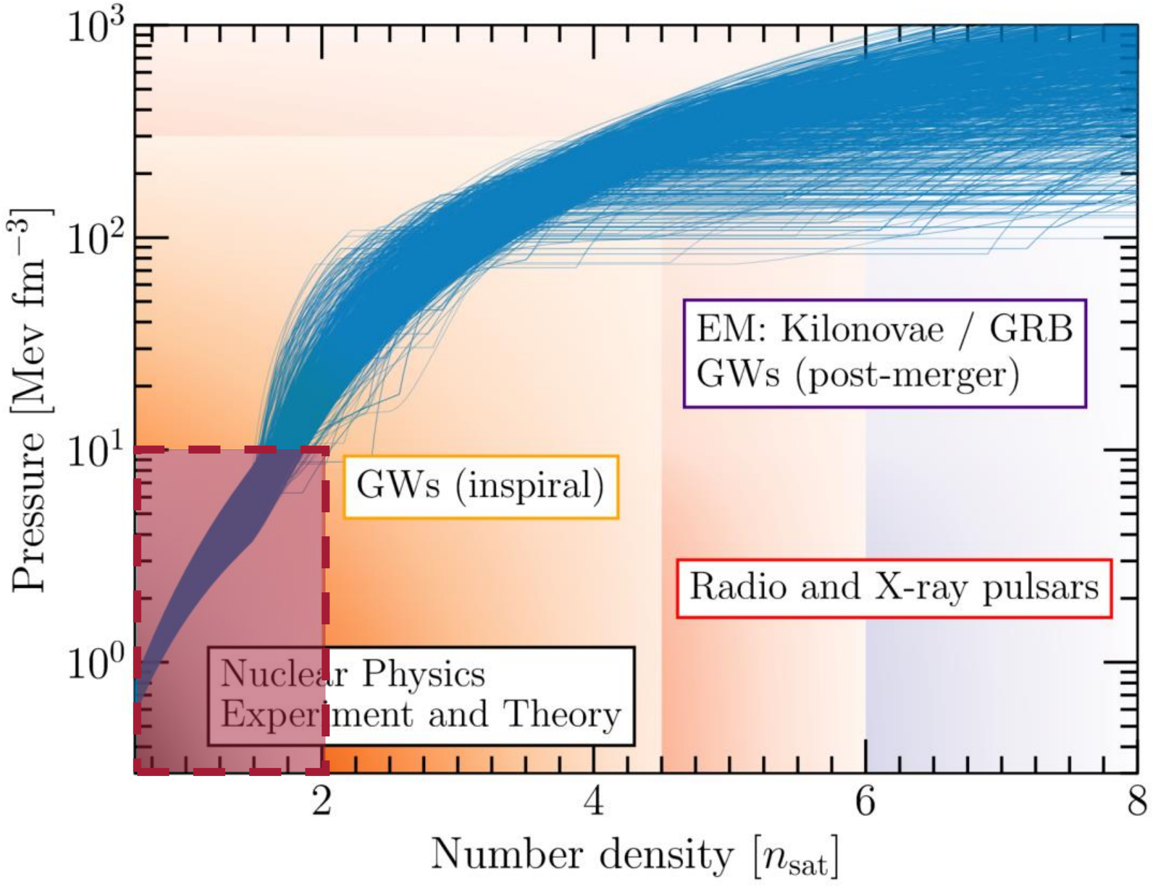
No data above $2\rho_0$ (0.4 AGeV Au+Au)



The terra incognita for heavy-ion collisions lies beyond $\sim 2\rho_0$

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

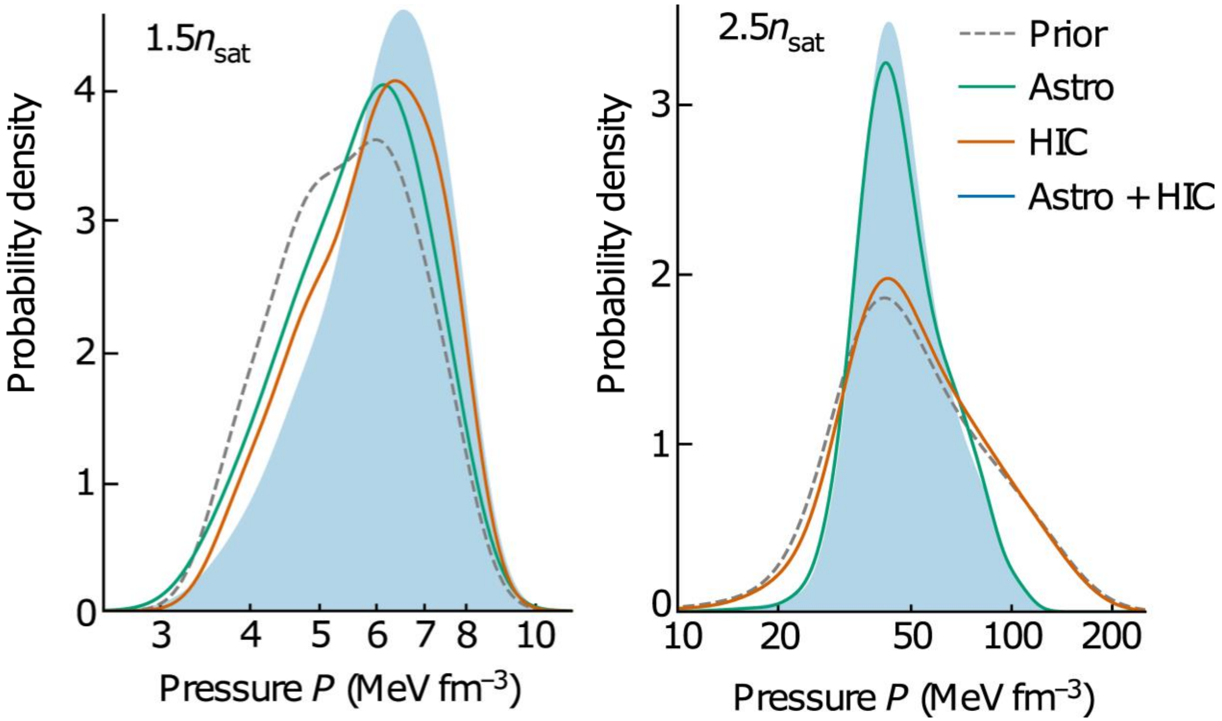
Neutron Star EOS



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

Bayesian Inference used to combine the information from nuclear theory (χEFT), astrophysical observations and heavy-ion collision experiments

W. Lynch (18.09), T. Dietrich (21.09), P.T.H. Pang (21.09), B. Tsang (21.09)



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

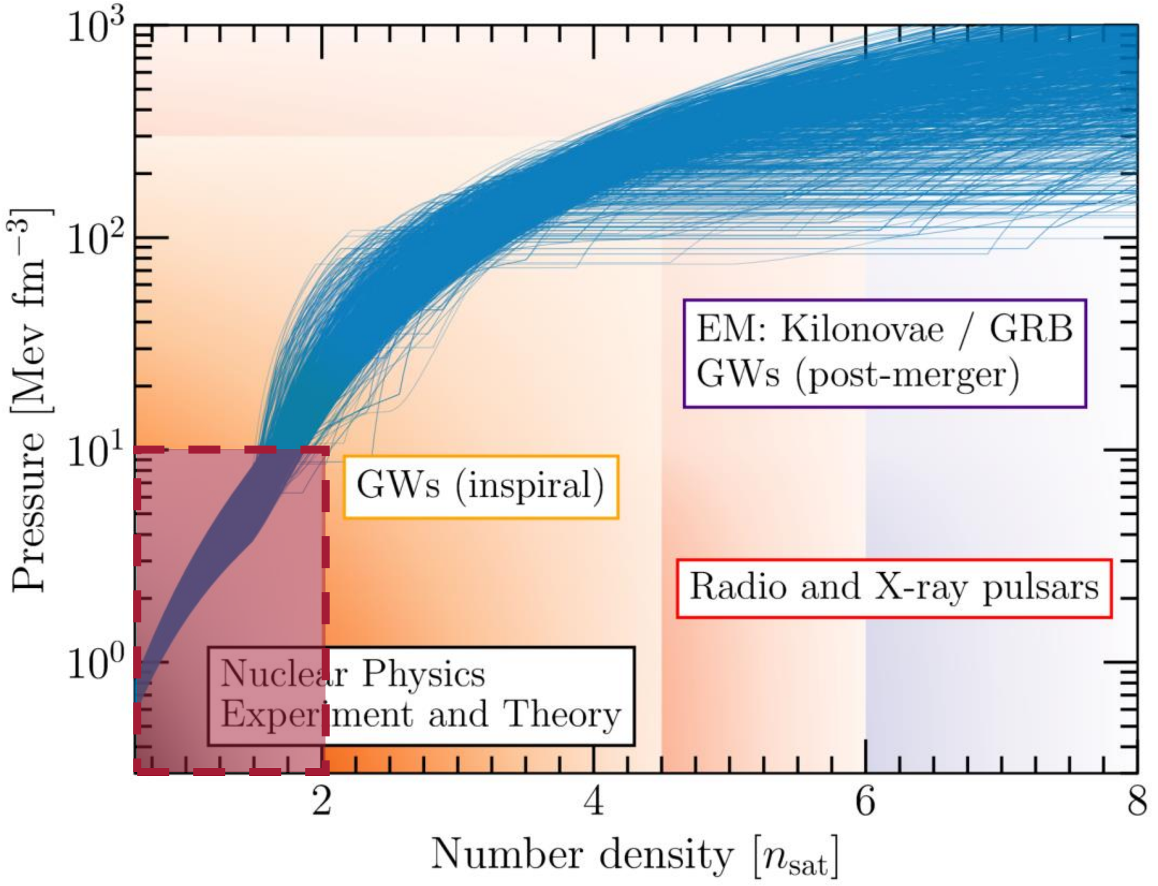
Neutron Star EOS info from Heavy-Ion Collisions has shown remarkable compatibility at 1.5ρ_0, but this compatibility loosens at higher densities (~2.5ρ_0) → Missing high statistics data and reliable transport models

Role of ASY-EOS II
P. Russotto (18.09)

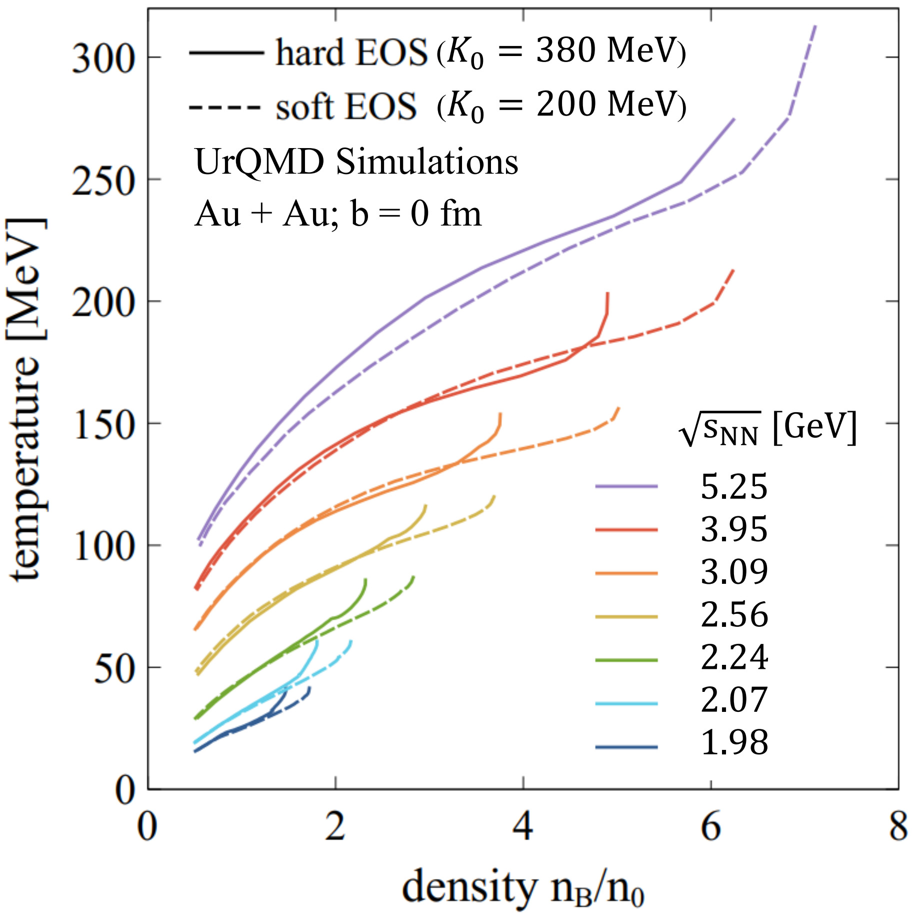
HIC Experimental Requirements To Probe $\gtrsim 3\rho_0$

Landscape Of Nuclear Matter EoS At $\gtrsim 3\rho_0$

Neutron Star EOS



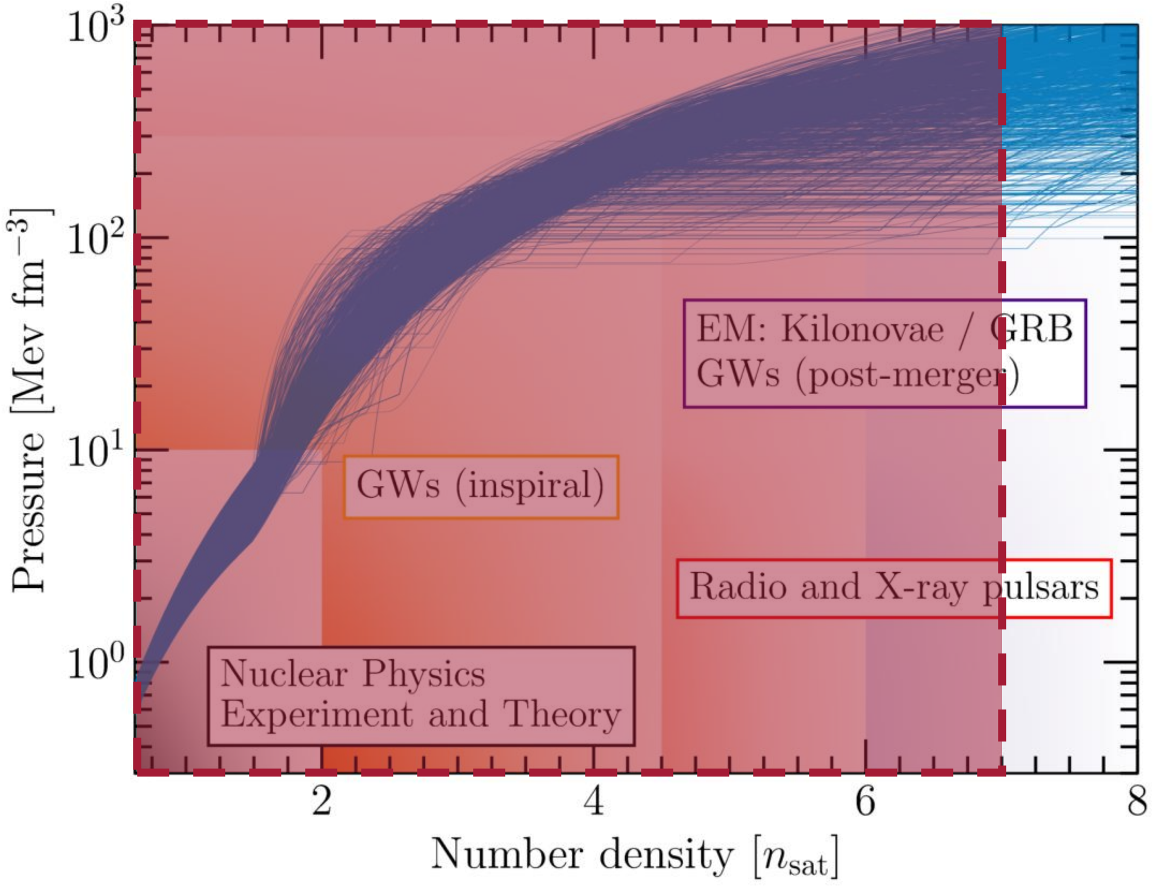
P.T.H. Pang et al., arXiv:2205.08513



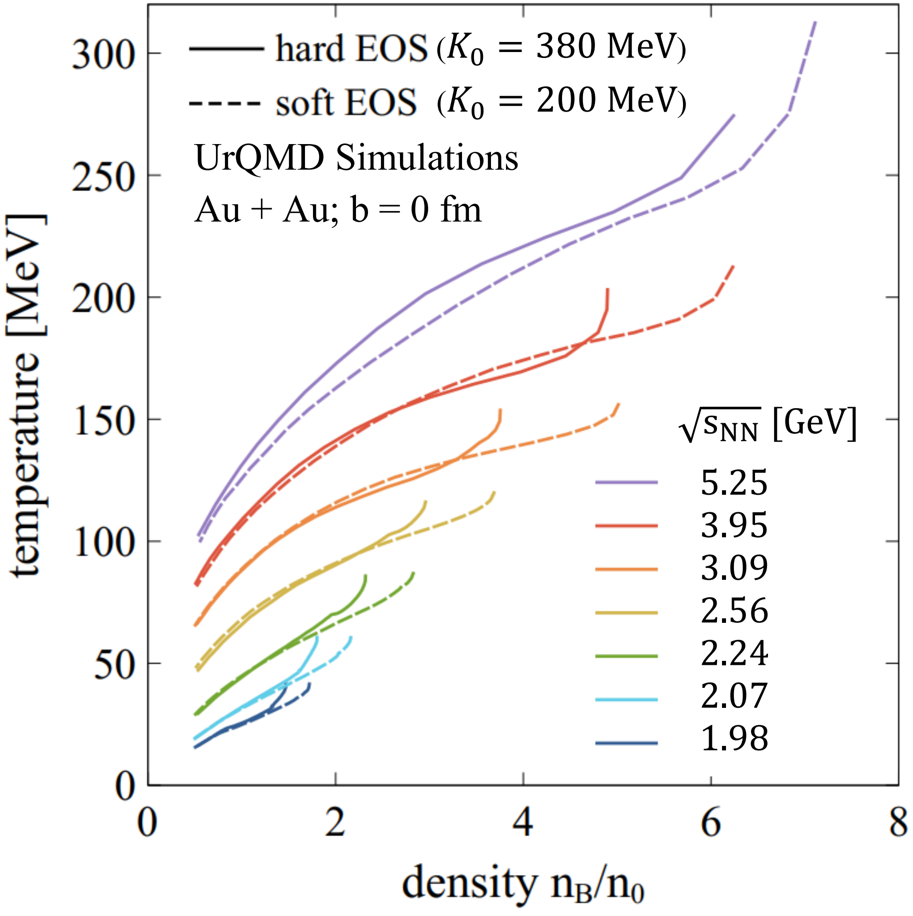
A. Sorensen et al., arXiv: 2301.13253

Landscape Of Nuclear Matter EoS At $\gtrsim 3\rho_0$

Neutron Star EOS



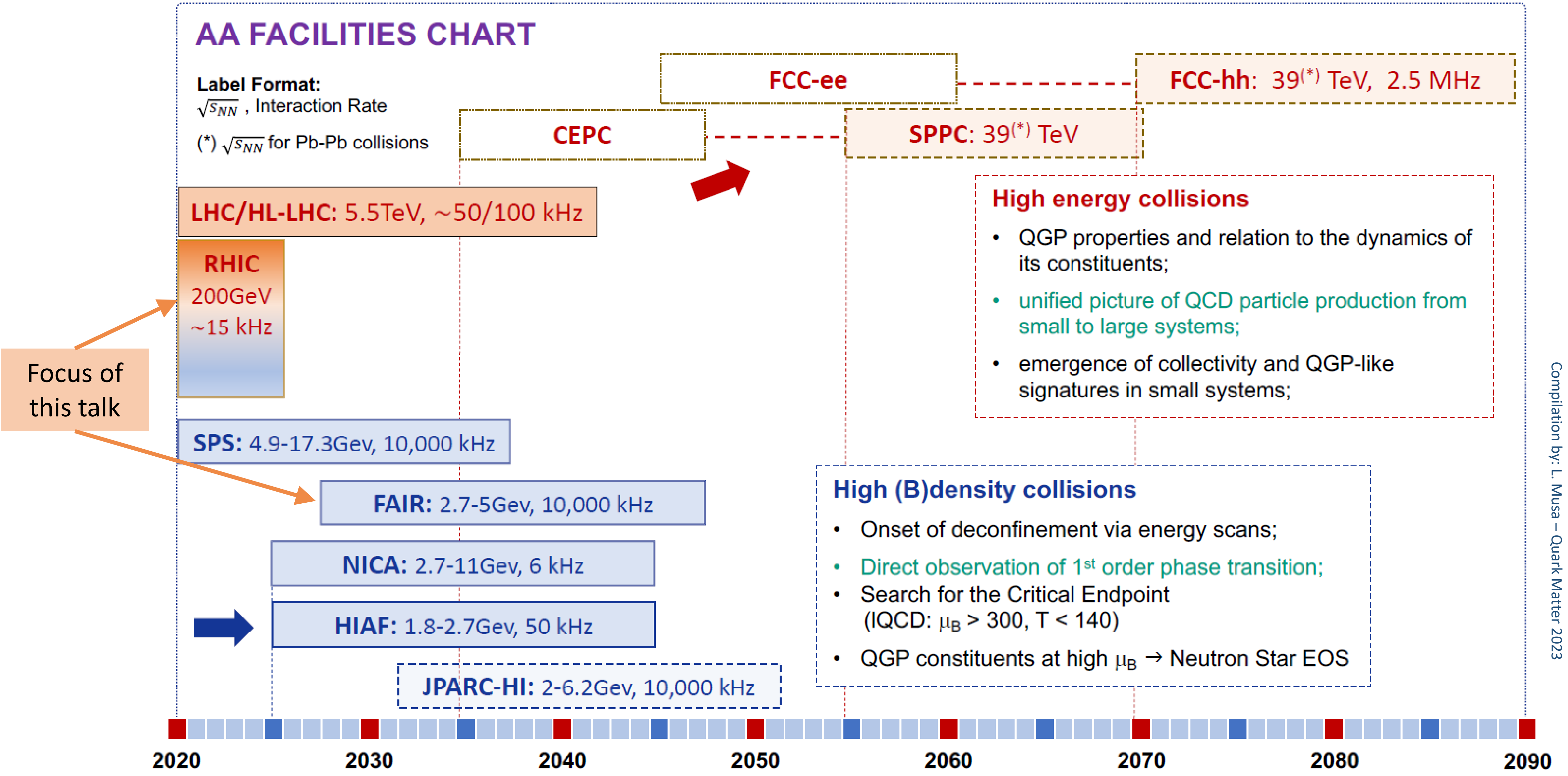
P.T.H. Pang et al., arXiv:2205.08513



A. Sorensen et al., arXiv: 2301.13253

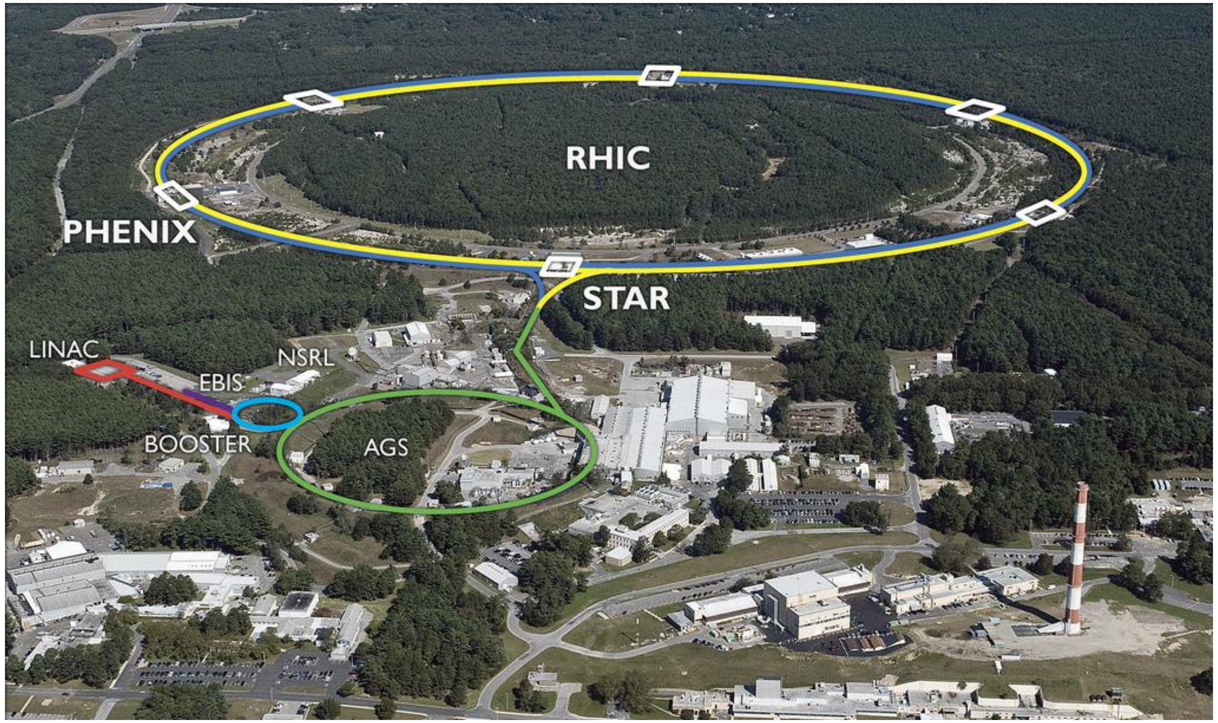
Heavy-Ion Collisions at relatively higher energies (Au+Au $\sqrt{s_{NN}}$ > 3 GeV) will give us a possibility to explore EoS where currently, the only reliable info comes from MMA

GLOBAL A+A COLLISION FACILITIES (2020 – ...)



A+A Collision Facilities In Focus

Relativistic Heavy Ion Collider (RHIC; 2000 – …)



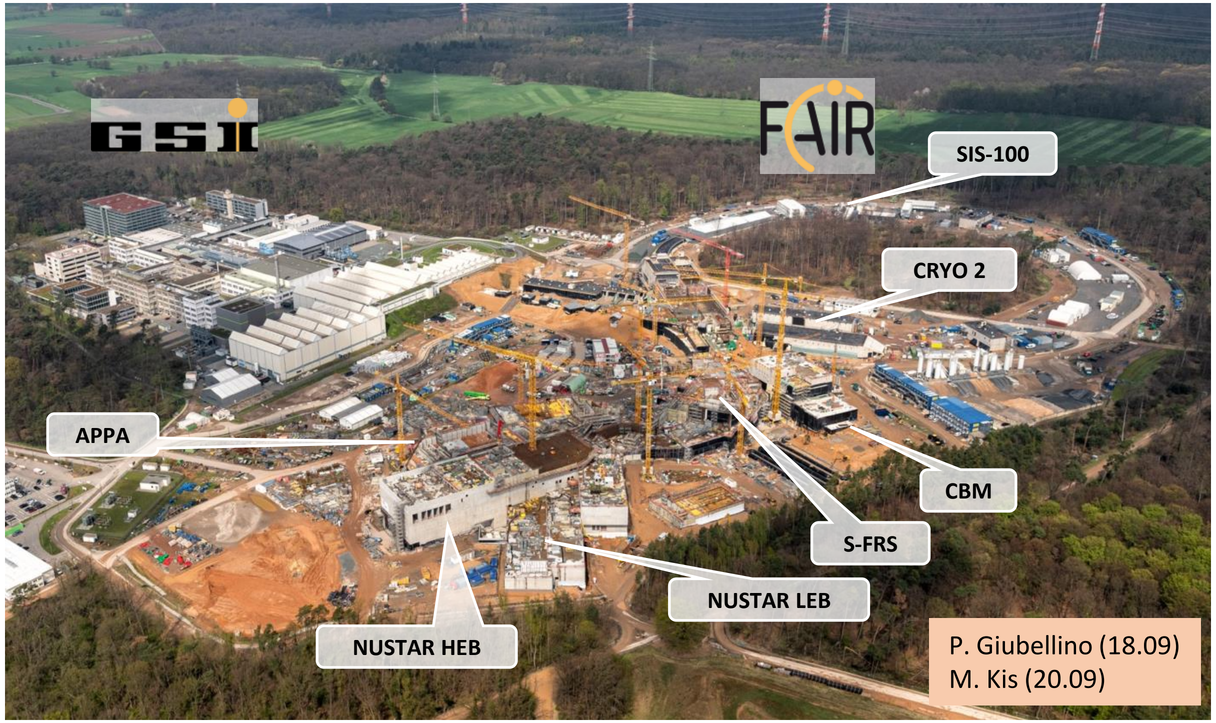
Top collision energies

- $\sqrt{s_{NN}} = 200$ GeV U + U / Au + Au / Zr + Zr / Ru + Ru / O+O
- $\sqrt{s} = 510$ GeV p + p

Beam Energy Scan (BES)

- $\sqrt{s_{NN}} = 200\ \ldots\ 7.7$ GeV (collider mode)
- $\sqrt{s_{NN}} = 13.7\ \ldots\ 3$ GeV (fixed-target mode)

Facility for Antiproton and Ion Research (FAIR; 2028 – …)

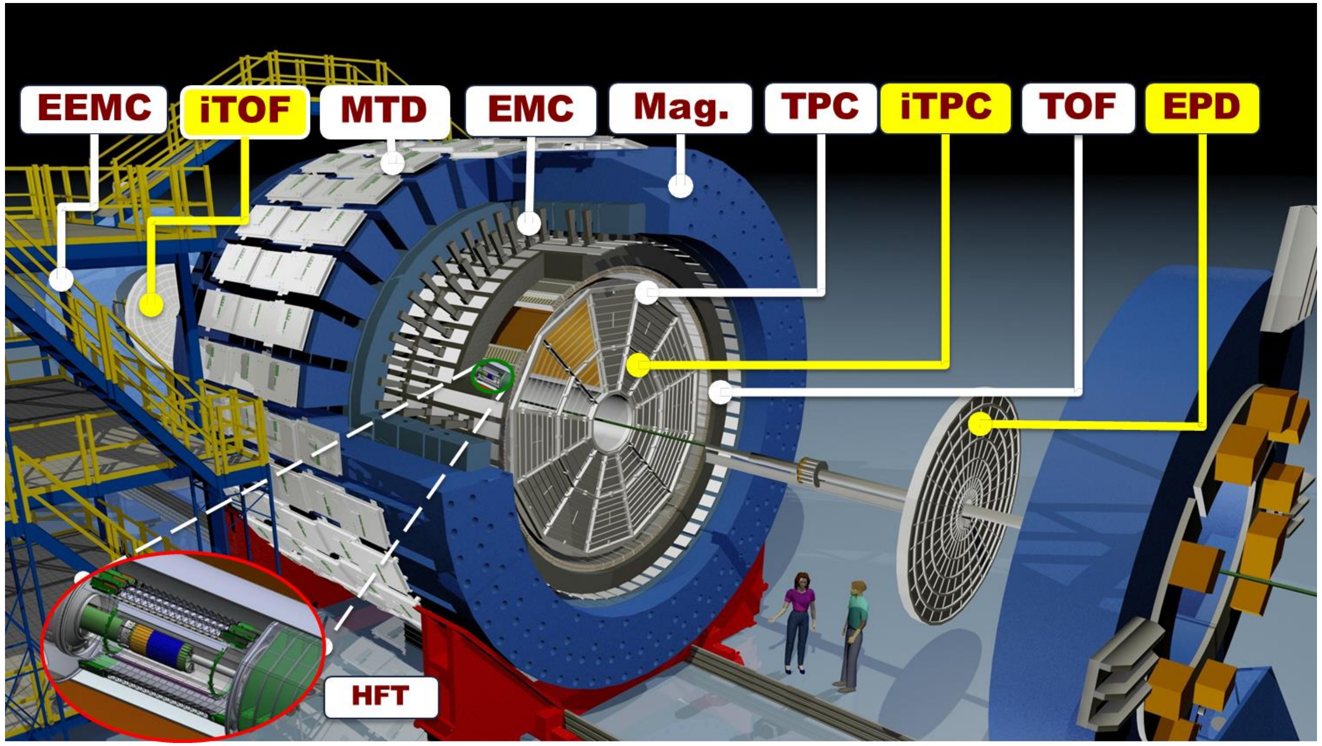


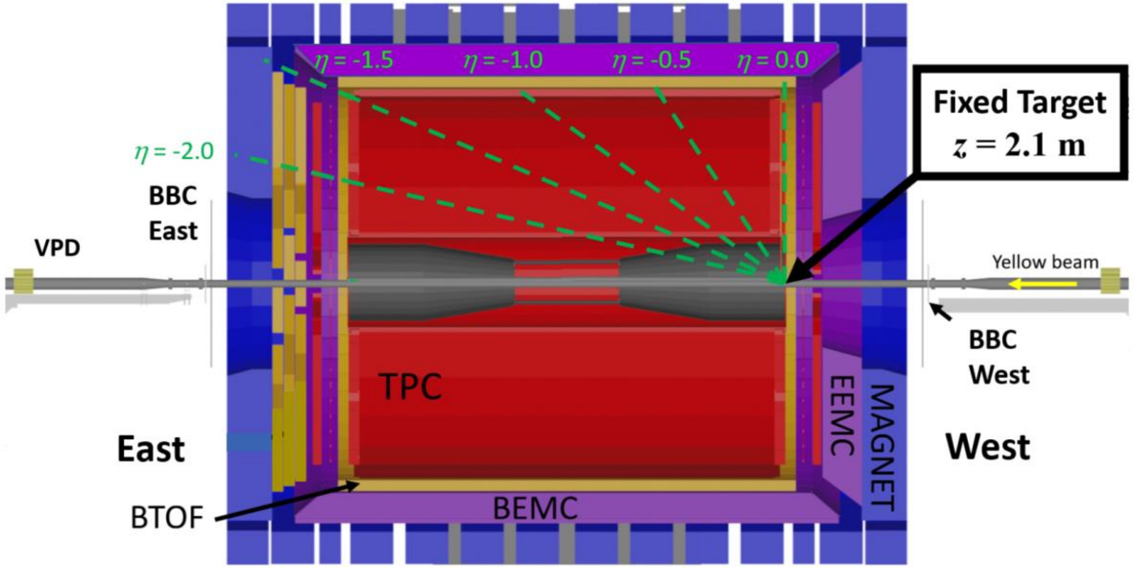
P. Giubellino (18.09)
M. Kis (20.09)

- Intensity gain w.r.t. SIS-18@GSI: x 100 – 1000 ($\sim 10^9$/s for Au)
- Energy gain w.r.t. SIS-18@GSI : x 10
- Ion beams up to 11 A GeV energy → $\sqrt{s_{NN}} = 2.9\ \ldots\ 4.9$ GeV (Au + Au)
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings
- Current estimate: SIS-100 commissioning with beams starts in 2028-29

Solenoidal Tracker At RHIC (STAR)

STAR Experimental Setup (Fixed-Target Mode; FXT)





Au + Au Collisions at STAR (2018-21; Fixed-Target Mode)			
$\sqrt{s_{\mathrm{NN}}}$ (GeV)	Events ($\times 10^6$)	$\sqrt{s_{\mathrm{NN}}}$ (GeV)	Events ($\times 10^6$)
13.7	50	5.2	100
11.5	50	4.5	110
9.2	50	3.9	120
7.7	260	3.5	120
7.2	470	3.2	200
6.2	120	3.0	260 + 2000

N. Xu, EMMI Physics Day 2023

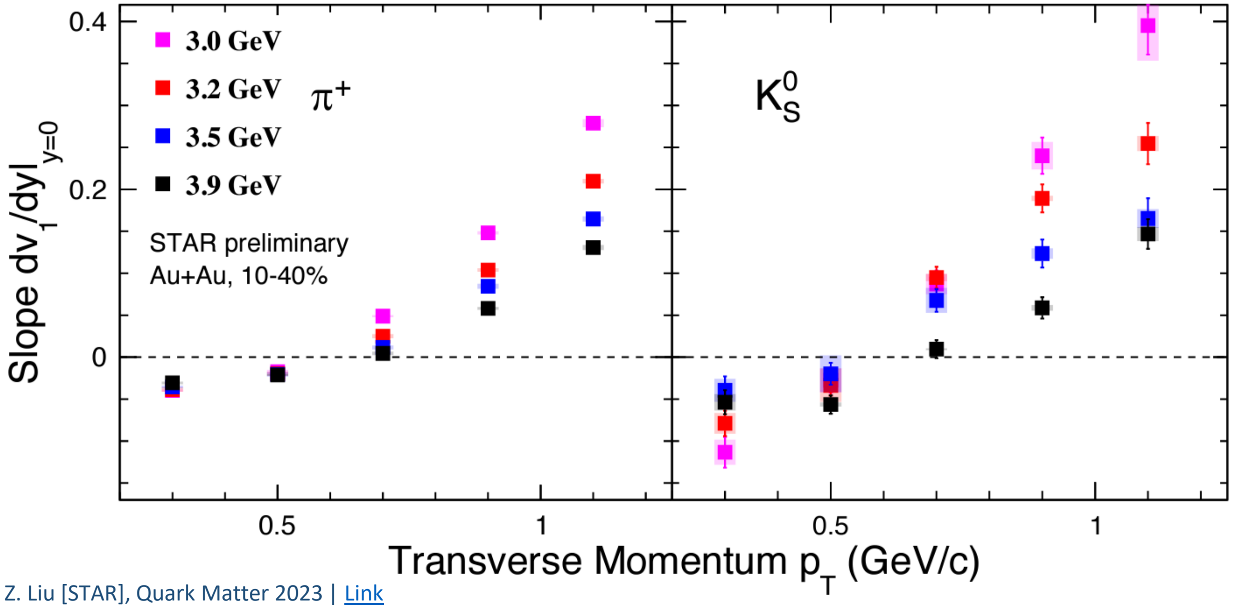
- STAR-RHIC operational since 2000 in collider mode (QGP-runs at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV)
- Fixed target setup allows to probe lower energies ($\sqrt{s_{\mathrm{NN}}} = 13.7\ \dots\ 3$ GeV), i.e., higher baryonic densities ($\mu_{\mathrm{B}} = 721\ \dots 276$ MeV)
- At $\sqrt{s_{\mathrm{NN}}} = 3$ GeV, STAR has a full mid-rapidity coverage for protons ($|y_p| < 0.5$ and $0.4 < p_T < 2$ GeV/c) and unprecedently high statistics (2.26×10^9 events)
- Recent detector upgrades allow extended coverage and enhanced PID (iTPC, eTOF, EPD)

Observable #1: Collective Flow (v_1, v_2)

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

Directed Flow Slope ($dv_1/dy_{y=0}$)

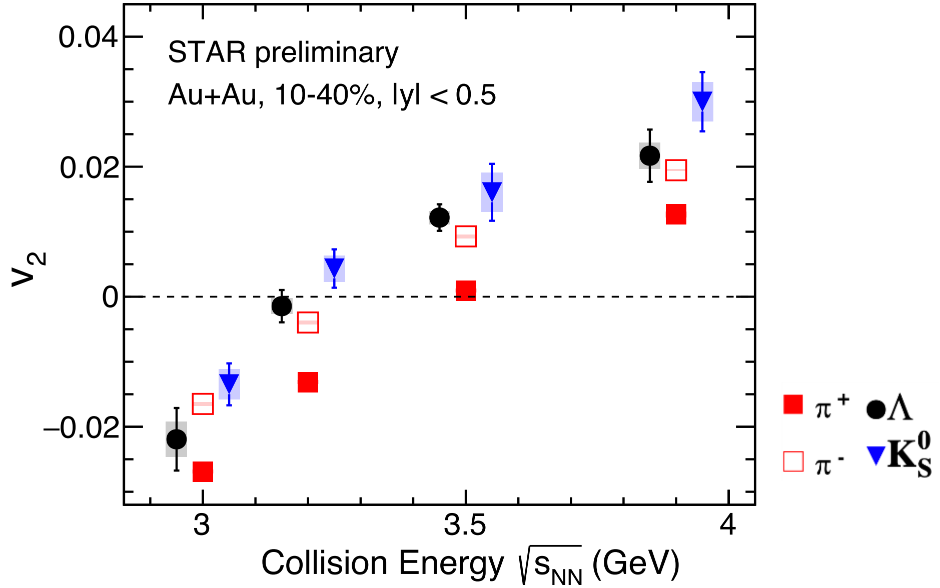
- Energy dependence of $dv_1/dy_{y=0}$ analysed from $\sqrt{s_{NN}} = 3.0 \ldots 3.9$ GeV
- Anti-flow observed for π^+, K_S^0 at low p_T, which could be explained by shadowing from the passing spectators could explain this effect



Z. Liu [STAR], Quark Matter 2023 | Link
X. Wu [STAR], Quark Matter 2023 | Link
G. Wang [STAR], Quark Matter 2023 | Link

Elliptic Flow (v_2) and Number-of-Constituent-Quark (NCQ) Scaling

- Out-of-plane to in-plane emission observed for π^+, π^-, K_S^0, Λ
- NCQ scaling breaks between $\sqrt{s_{NN}} = 3.2 \ldots 14.6$ GeV, indicating a medium dominated by hadronic interactions. Finer studies ongoing.



[STAR] Phys.Lett.B 827 (2022) 137003
Z. Liu [STAR], Quark Matter 2023 | Link
X. Wu [STAR], Quark Matter 2023 | Link

STAR-FXT has preliminarily done collective flow analysis for commonly produced mesons (π^+, π^-, K_S^0) and Lambda (Λ) at the high-baryon density region ($\sqrt{s_{NN}} = 3.0 \ldots 3.9$ GeV). Further extensive multi-differential analyses are ongoing.

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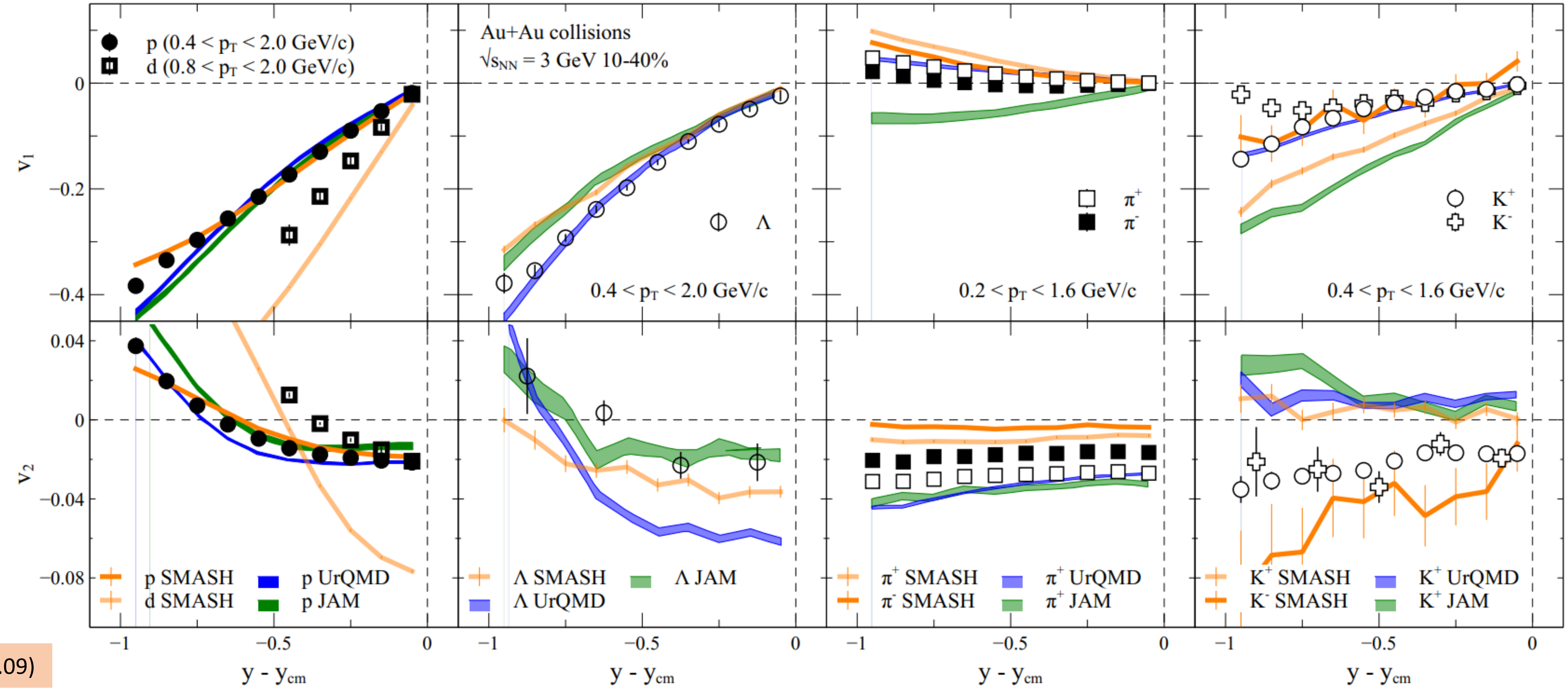
Observable #1: Collective Flow ($v_1, v_2, \ldots$)

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



[STAR] Phys.Lett.B 827 (2022) 137003
D. Oliinychenko et al., arXiv:2208.1196
A. Sorensen et al, arXiv:2301.13253

A. Sorensen (18.09)

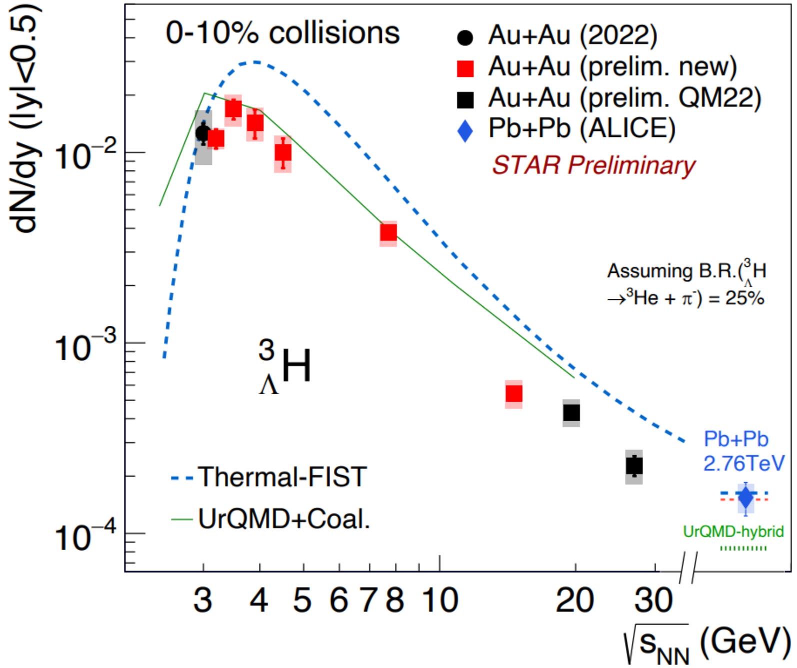
Successful inference of the nuclear matter EOS from STAR-FXT data requires transport codes to not only describe proton v_1, v_2 (where momentum-dependent interactions are anyhow missing), but also the flow of Lambda baryons and mesons

Observable #2: Hypernuclei

Hypernuclei carry essential information to study 2- and 3-body Y-N interactions and solve the 'Hyperon Puzzle'

Energy Dependence of ${}^{3}_{\Lambda}H$ Yields

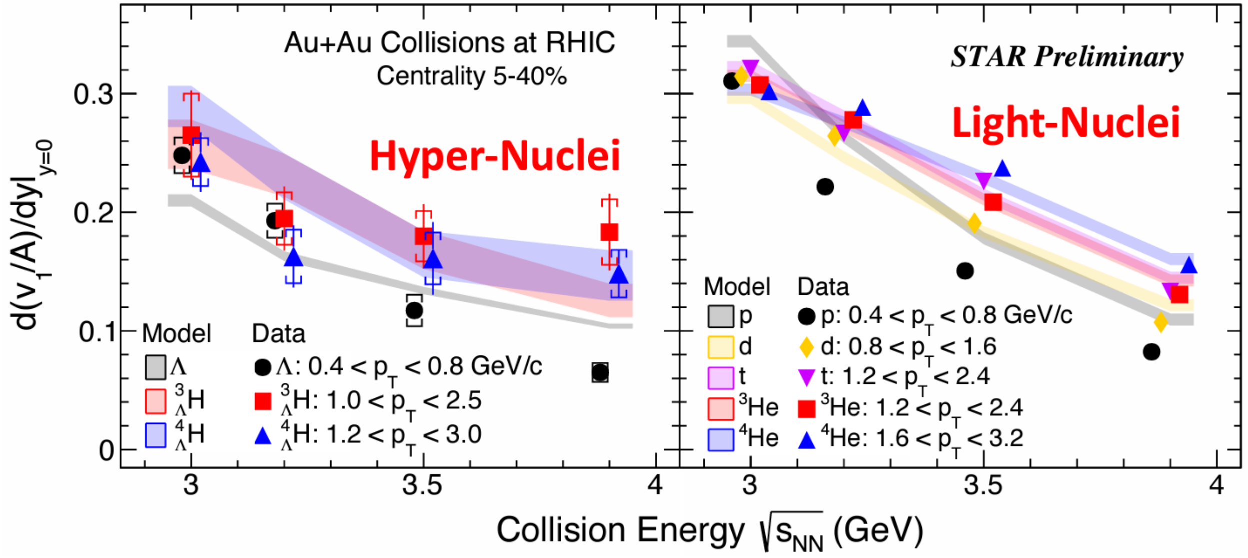
- Abundant hyper-nuclei at the high baryon density region
- Multi-differential measurements in p_T and y for various centralities
- Similar analyses for A ≥ 4 nuclei (${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$, …) are ongoing



[STAR] Phys.Rev.Lett. 128 (2022) 20, 202301
Y. Ji [STAR], Quark Matter 2023 | Link
X. Li [STAR], Quark Matter 2023 | Link

Energy Dependence of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Directed Flow Slope

- Hypernuclei collectivity provides a new insight into Y-N and Y-Y interactions under finite pressure gradient
- Follows similar mass scaling as light nuclei (p, d, t, ${}^{3}He$, ${}^{4}He$)



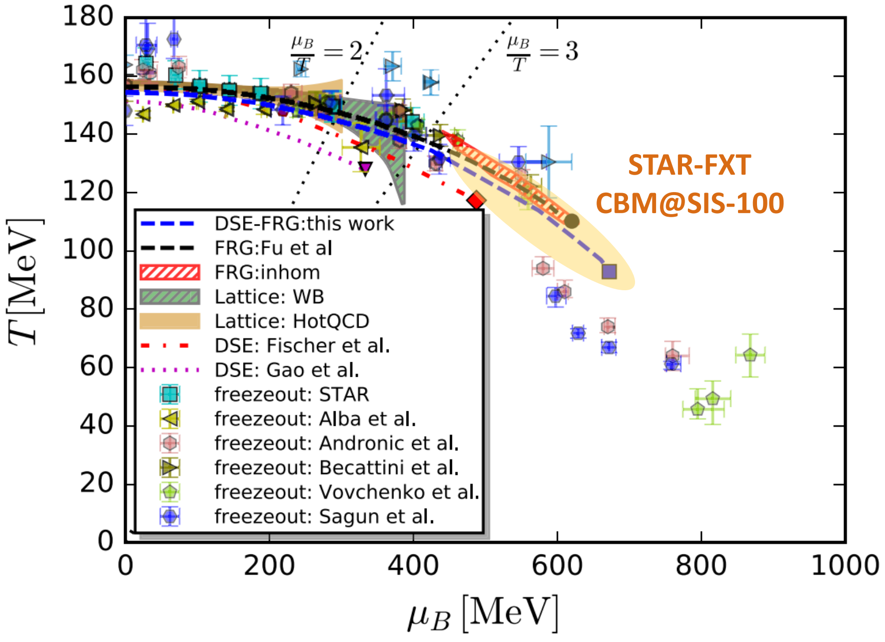
[STAR] Phys.Rev.Lett. 130 (2023) 21, 212301
J. Han [STAR], Quark Matter 2023 | Link

STAR-FXT has shown its capabilities to do differential yield measurements and flow analyses for hypernuclei for a range of energies. Transport codes + coalescence afterburner seem to (qualitatively) reproduce the data. Production mechanism? Probed densities?

Observable #3: Cumulant Ratios

Higher-order cumulants and ratios of conserved quantities (B, Q, S) are sensitive to QCD Critical End Point (CEP), i.e., phase change

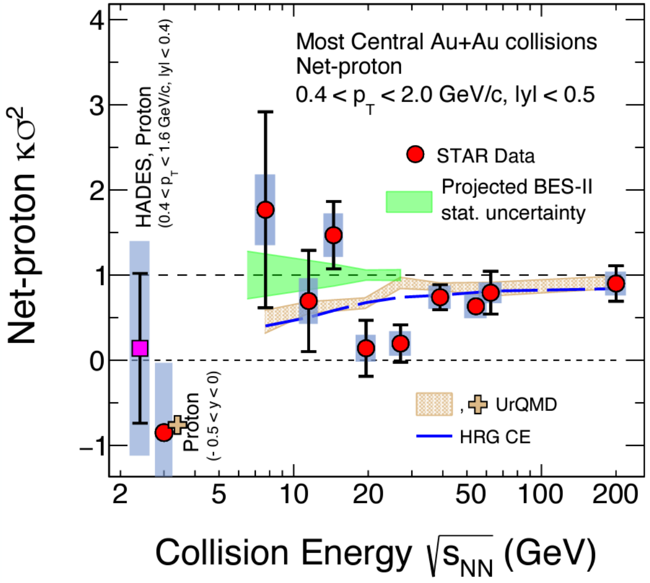
Most promising range to find the Critical End Point (CEP):
$(135{,}450)\text{MeV} \lesssim (\mathrm{T}, \mu_B)_{CEP} \lesssim (100{,}650)\text{MeV}$
$\sqrt{s_{NN}} \approx 3.0 \ldots 5.0$ GeV

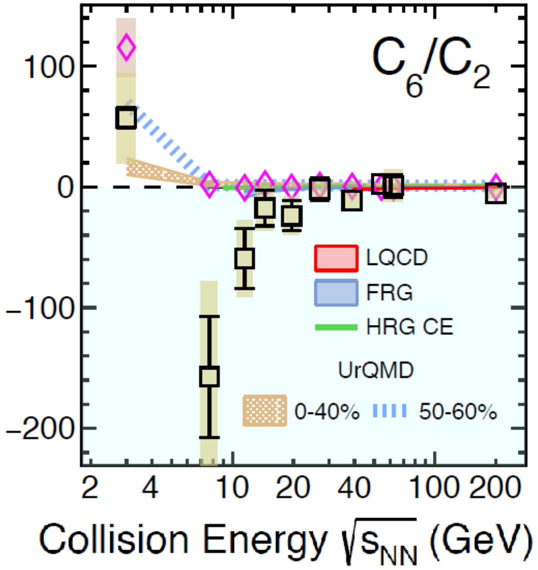


F. Gao, J.M. Pawlowski, Phys.Rev.D 102 (2020) 3, 034027

fRG: W.J. Fu et al., Phys.Rev.D 101 (2020) 5, 054032, W.J. Fu et al., arXiv: 2308.15508 [hep-ph]
DSE: F. Gao et al., Phys.Lett.B 820 (2021), 136584, P.J. Gunkel et al., Phys.Rev.D 104 (2021) 5, 054022
LQCD: F. Karsch, PoS CORFU2018 (2019) 163, S. Borsányi et al., Phys.Rev.Lett. 126 (2021) 23, 232001
BH Eng.: M. Hippert et al., arXiv: 2309.00579 [nucl-th]

- Increasing non-Gaussian behaviour of event-by-event proton multiplicity distribution (C_4/C_2, C_5/C_1, C_6/C_2) have been extensively studied by STAR-BES@RHIC to map out the QCD phase diagram ($\sqrt{s_{NN}} = 3.0 \ldots 200.0$ GeV)
- Data (qualitatively) compatible with LQCD for $\sqrt{s_{NN}} = 7.7 \ldots 200.0$ GeV
- Hints of non-monotonous behaviour seen at high-baryonic density region, including change of cumulant ratios ordering → QCD CEP?



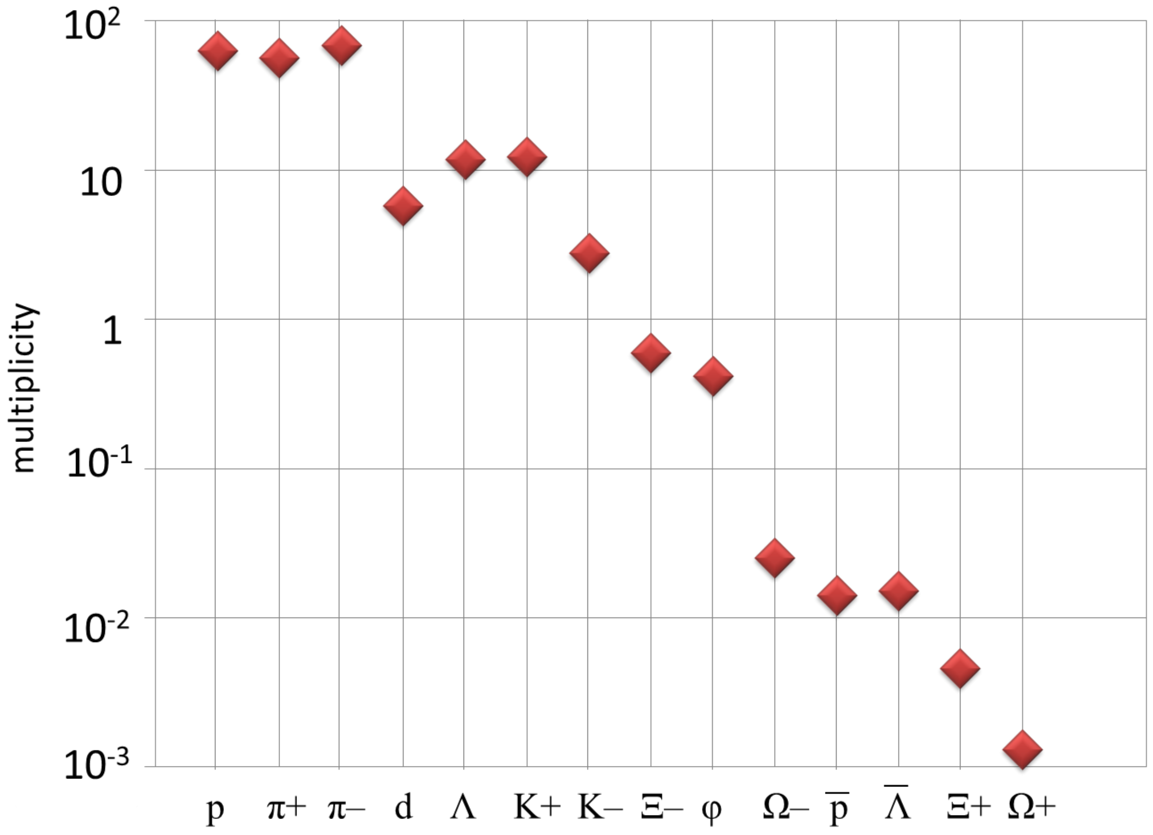


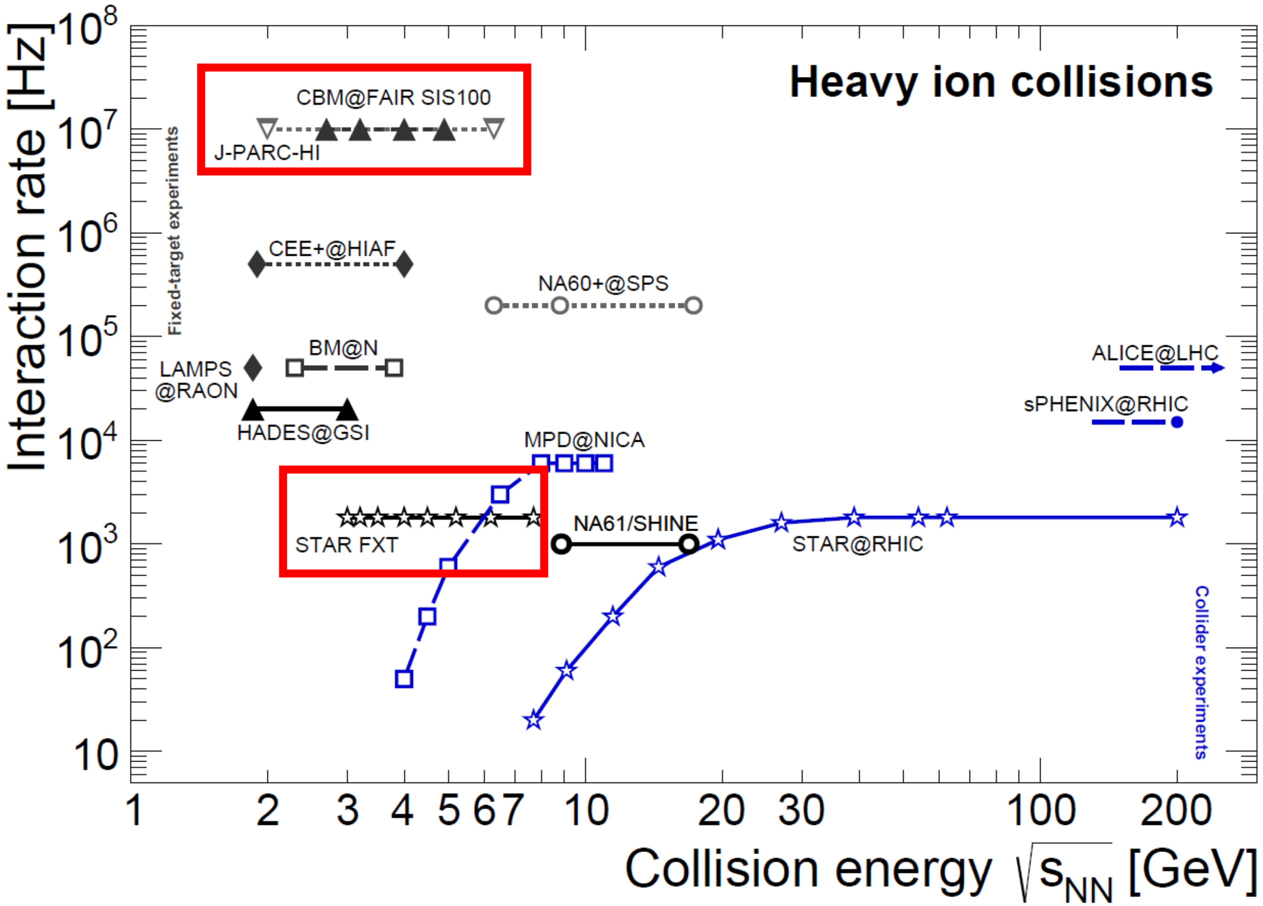
STAR-BES has observed a non-monotonic energy dependence for net-proton (C_4/C_2) at $\sqrt{s_{NN}} = 7.7 \ldots 27.0$ GeV with 3.1σ, and has shown hints of CEP. Further measurements with STAR-FXT ongoing to bridge the gap in data ($\sqrt{s_{NN}} = 3.0 \ldots 7.7$ GeV).

Compressed Baryonic Matter (CBM) Experiment At FAIR

Beam-Target Interaction Rates & Rare Probes' Yields

Particle Multiplicities (Statistical Hadronisation Model)
Au+Au $\sqrt{s_{NN}} = 4.7$ GeV

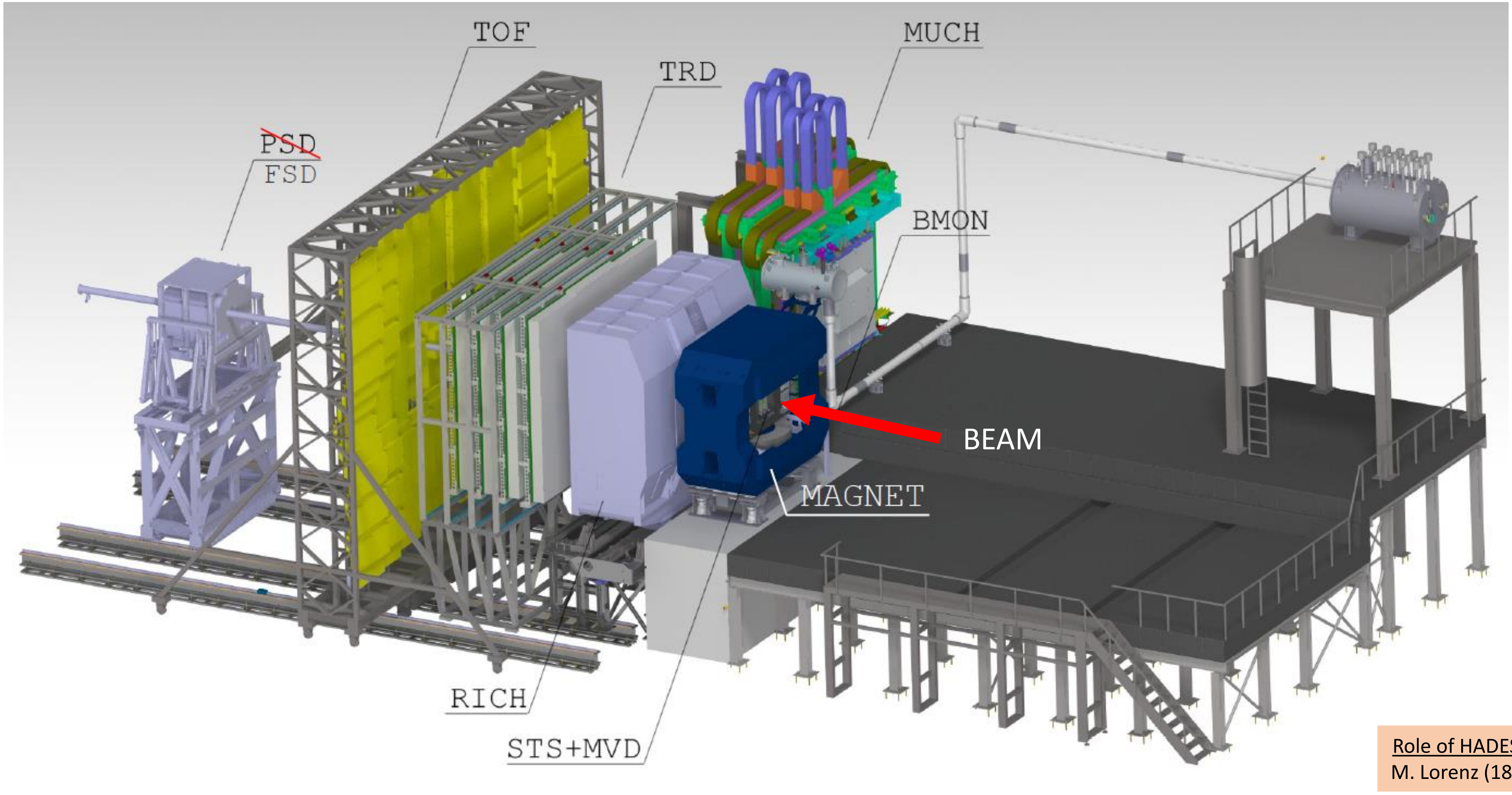




[CBM], Eur.Phys.J.A 53 (2017) 3, 60
T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169, update (06/2022)

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'

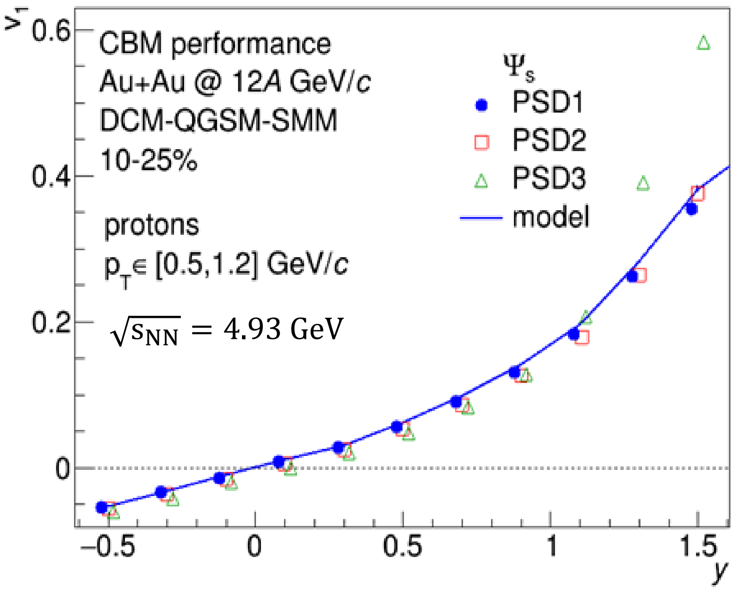
CBM Experimental Setup @SIS-100



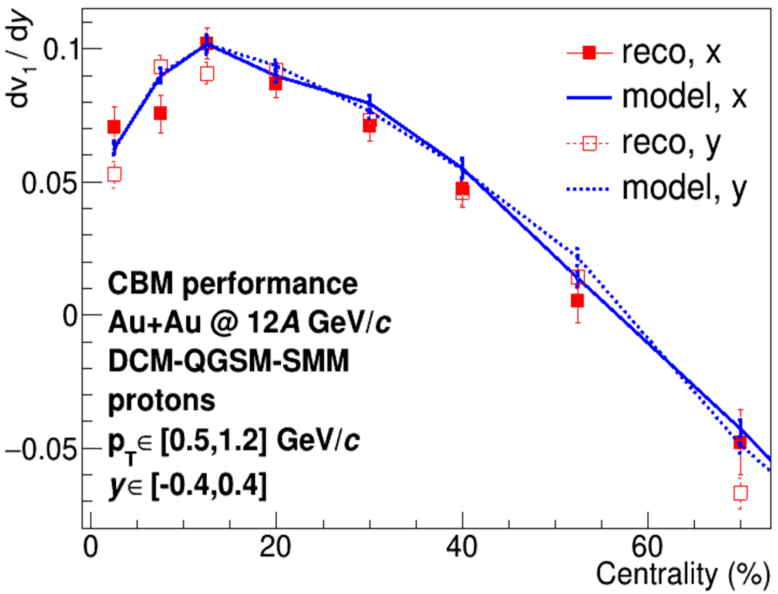
Role of HADES@SIS-100
M. Lorenz (18.09)

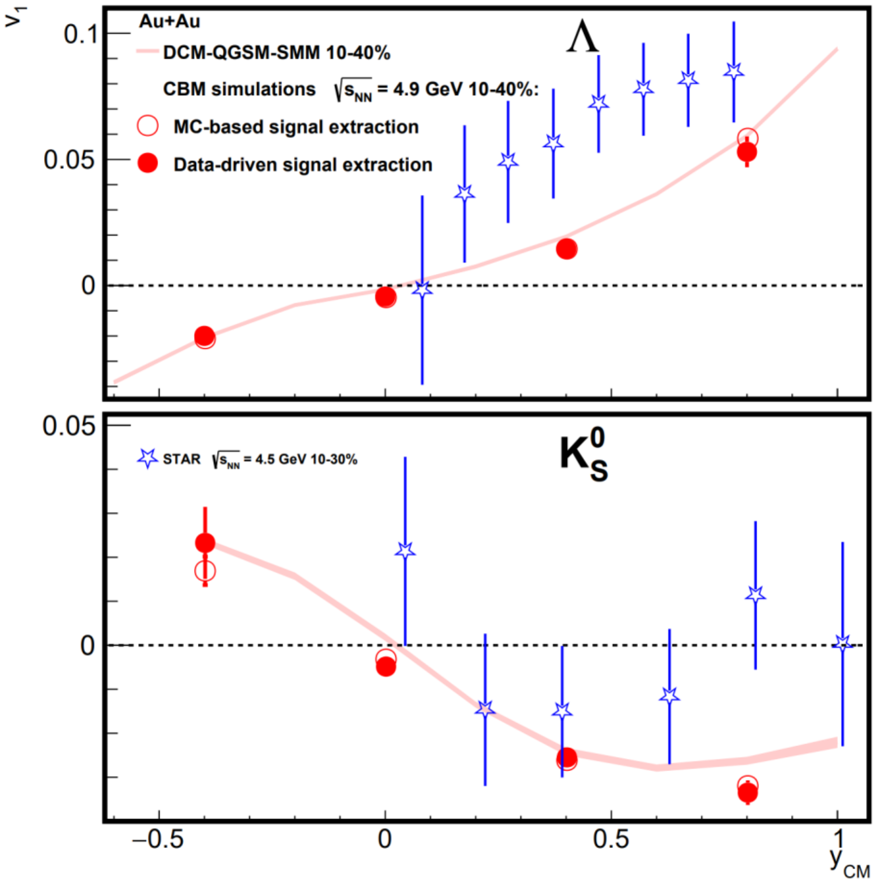
Observable #1: Collective Flow (v_1, …)

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





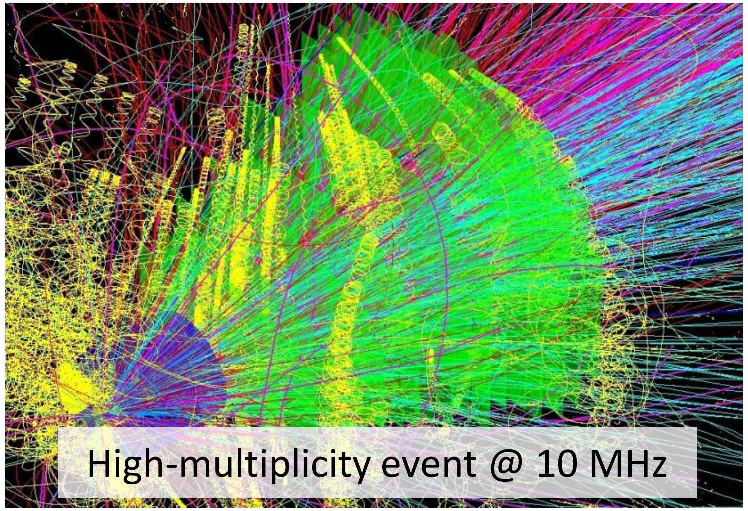
O. Lubynets, FAIRNESS 2022
[STAR], Phys. Rev. C 103, 034908 (2021)

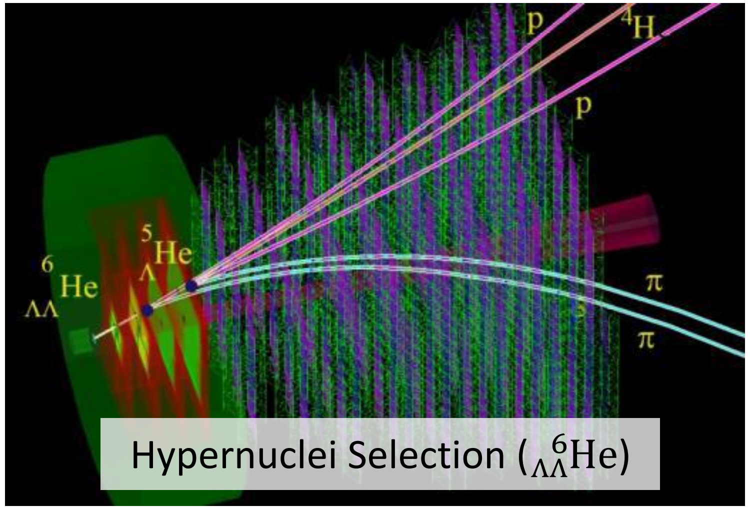
- Data-driven methods to perform extensive multi-differential v_1 flow analysis for protons and strange hadrons (Λ, K^0_S) have been developed
- Ongoing – Higher harmonics (v_2, …) and energy scan throughout SIS-100 range
- Comparable v_1 predicted by DCM-QGSM-SMM for STAR-FXT at $\sqrt{s_{NN}}$ = 4.5 GeV

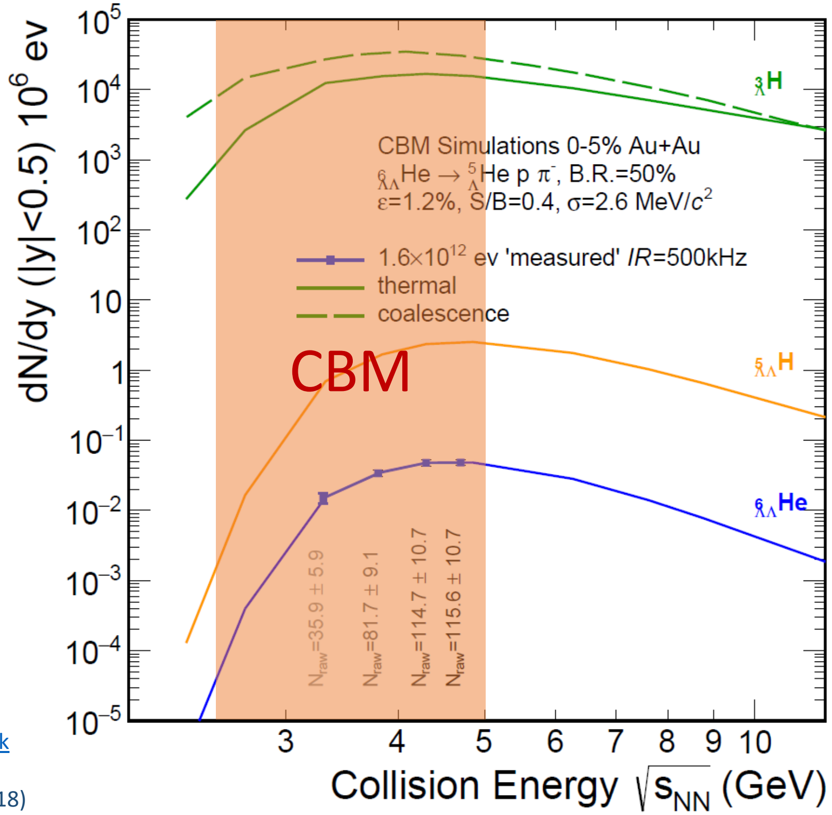
High-rate capability of CBM-FAIR can enable a precise multi-differential analyses flow analysis of not only protons, but of strange hadrons too. v_1 analyses tools have been developed and for high-harmonics are under development.

Observable #2: Hypernuclei

Hypernuclei carry essential information to study 2- and 3-body Y-N interactions and solve the ‘Hyperon Puzzle’







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

- Tools in place for the multi-differential physics analysis of strange hadrons and hypernuclei
- Reconstruction based on the dedicated KFParticleFinder package, with reconstruction routines tested with STAR FXT data (efficiency and cuts optimization are ongoing with ML approach)
- Production estimate for $^{6}_{\Lambda\Lambda}$He at 0.5 MHz interaction rate for 90 days:

$\Rightarrow \mathrm{IR} \times f_{av} \times \varepsilon_{duty} \times P_{prod} \times f_{mb/cen} \times \mathrm{BR} \times \varepsilon_{rec} \times \Delta t$

$\approx (0.5 \times 10^6) \times 0.5 \times 0.7 \times (0.5 \times 10^{-7}) \times 0.25 \times 0.5 \times 0.012 \times (7.6 \times 10^6)$

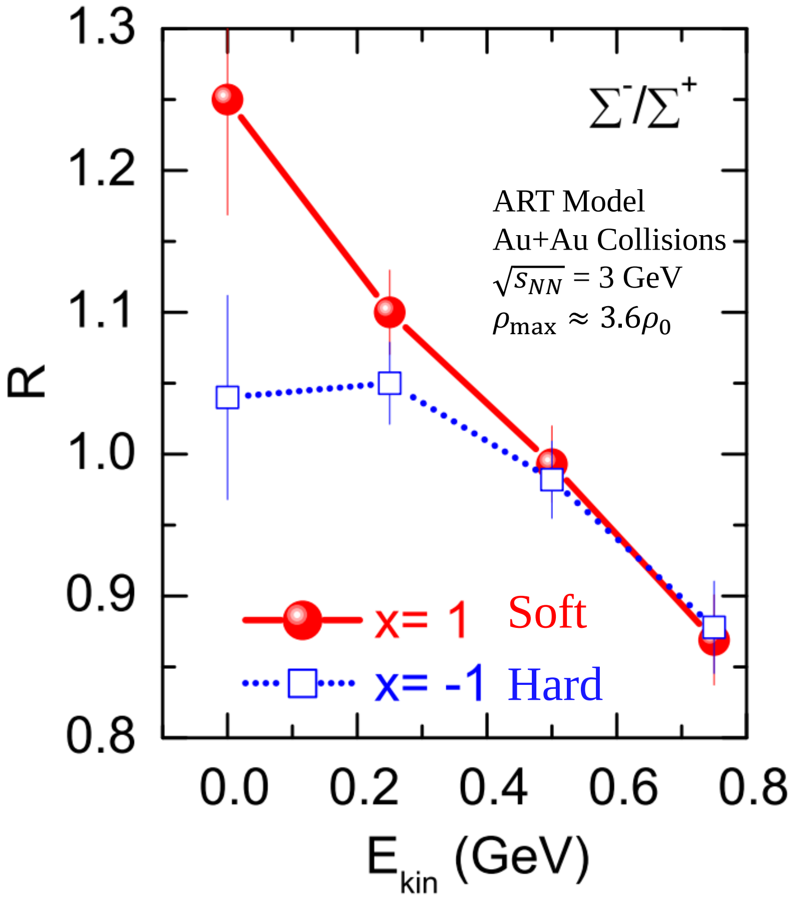
$=$ 100 signal counts (currently, only 3 observations reported)

S. Glässel [CBM], Quark Matter 2023 | Link
I. Vassiliev [CBM], Quark Matter 2022
I. Kisel, J.Phys.Conf.Ser. 1070, 012015 (2018)

The high-interaction rate at CBM-FAIR will give a better handle on Y-Y interactions by studying elusive hypernuclei such as $^{6}_{\Lambda\Lambda}$He

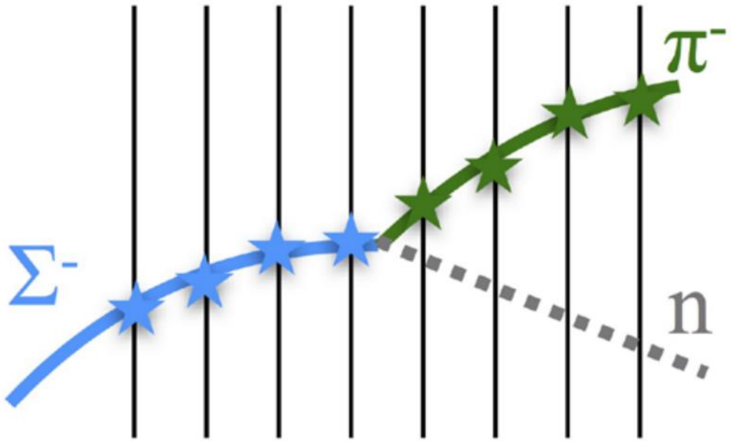
OBSERVABLE #3: $(n/p)_{like}$ PARTICLE RATIOS

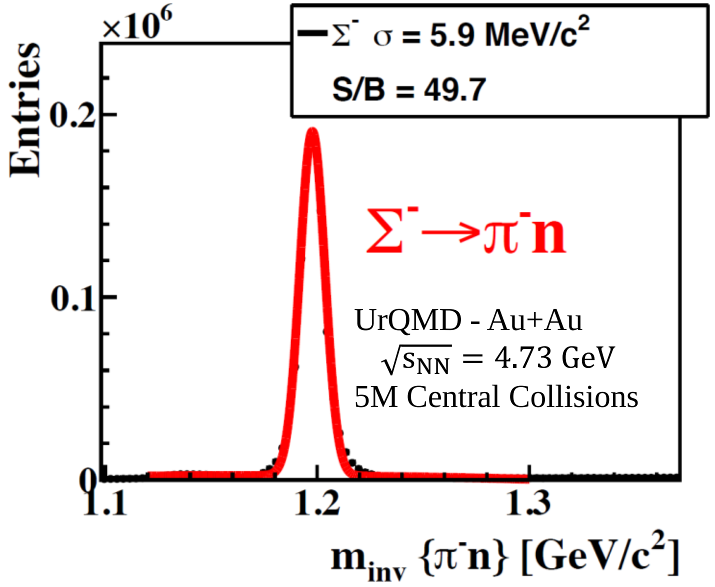
Σ^-/Σ^+ ratio is expected to carry the $E_{sym}(\rho)$ information since its production is dominated by primordial pions ($\pi + N \to \Sigma$)



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

- Experimentally, Σ baryons are difficult to identify
  → Short-lived ($c\tau_{\Sigma^+}$ = 2.4 cm and $c\tau_{\Sigma^-}$ = 4.4 cm)
  → Decay with at least one neutral daughter particle ($\Sigma^- \to n\pi^-, \Sigma^+ \to n\pi^+, \Sigma^+ \to p\pi^0$)
- 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



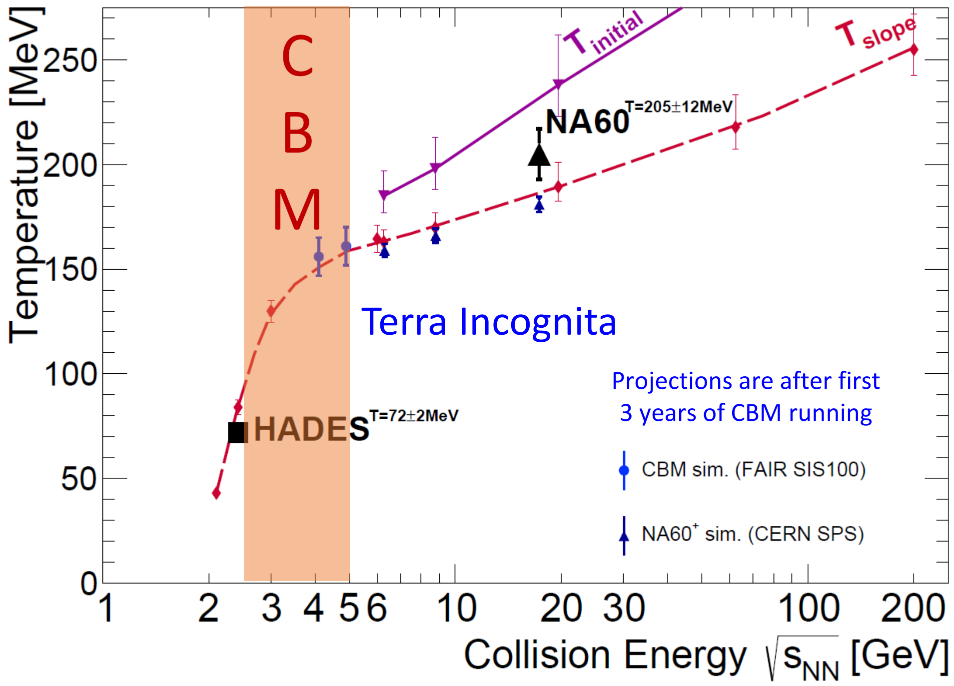


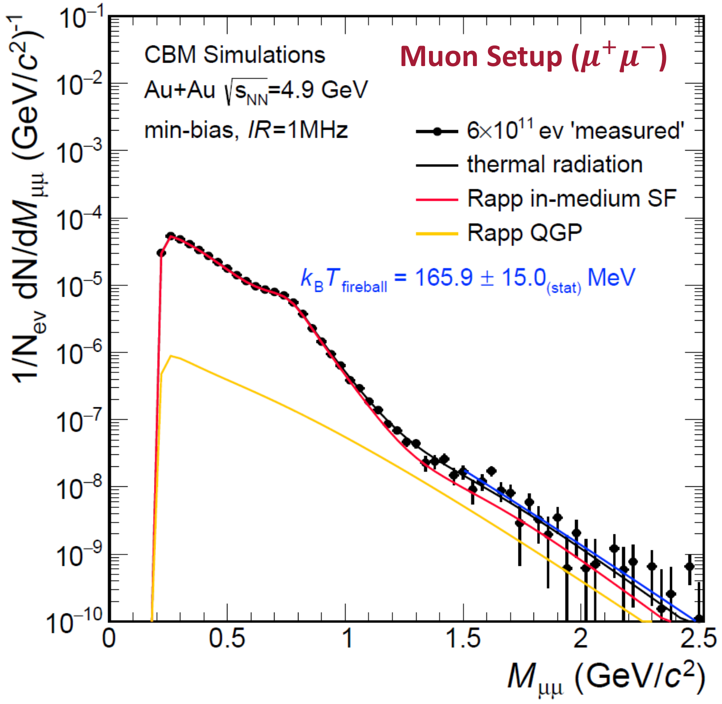
P. Kisel et al., EPJ Web Conf. 173 (2018) 04009

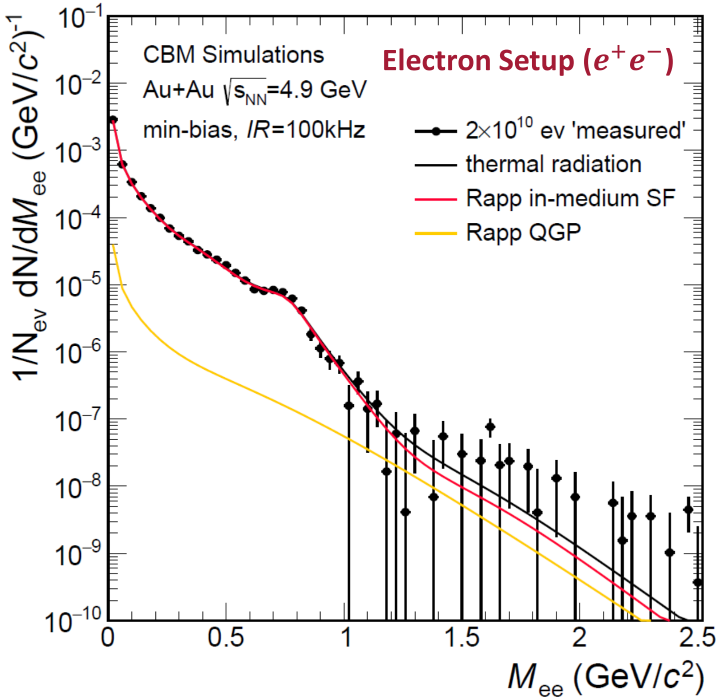
The vertexing and tracking detectors of CBM-FAIR are located close to the interaction point, in conjunctions with novel track reconstruction methods enable high-statistics measurement of Σ hyperons to systematically study the isospin effects

Observable #4: Fireball Caloric Curve Via Dileptons

Any non-monotonous behaviour of fireball temperature would hint a change of the degrees of freedom (hadronic to partonic)







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

Dileptons at HADES@SIS-18
M. Lorenz (18.09)

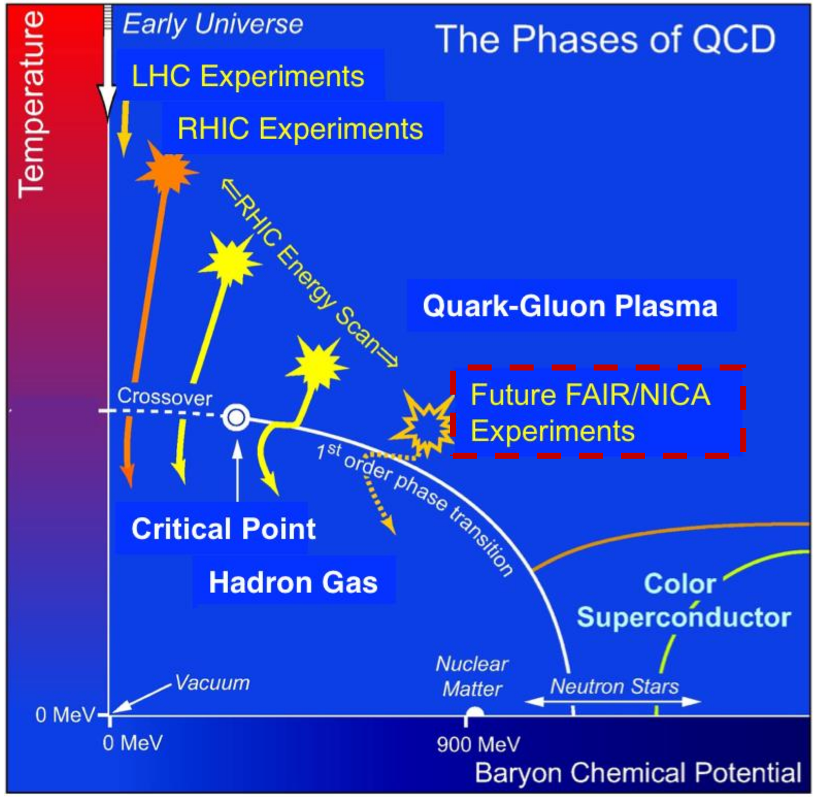
Theory: $\sqrt{s_{NN}} > 6$GeV - Phys. Lett. B 753 (2016) 586
$\sqrt{s_{NN}} < 6$GeV - Eur. Phys. J. A 52 (2016) 131

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

CBM-FAIR, operable in muon- and electron-setup, can efficiently detect dileptons to scan the energy dependence of fireball properties (temperature, lifetime, density, …) to detect potential phase transition signatures

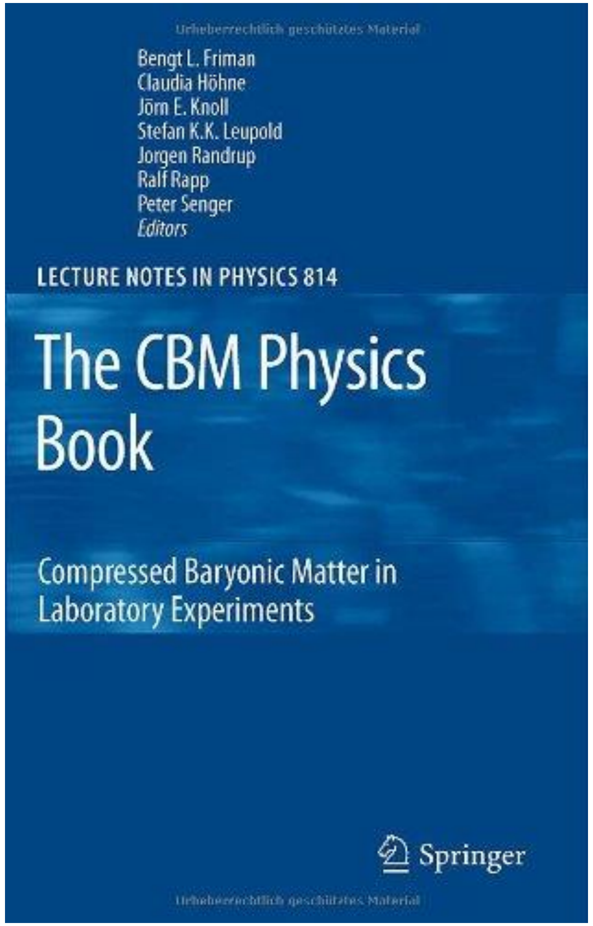
CBM@SIS-100: Much More Than EOS Physics

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

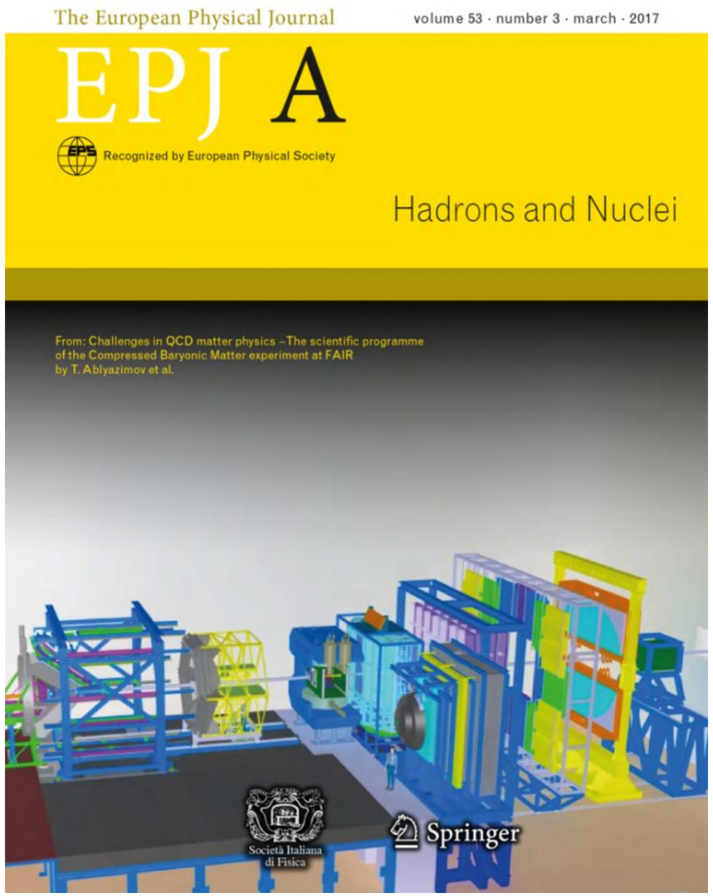


Unanswered fundamental questions for QCD at high densities

- Equation of State (EoS) of symmetric nuclear (and asymmetric neutron) matter at neutron star core densities
- Phase structure of QCD matter (1st-order phase trans.? critical point?)
- Chiral symmetry restoration at large μ_B
- Bound states with strangeness
- Charm in cold and dense matter



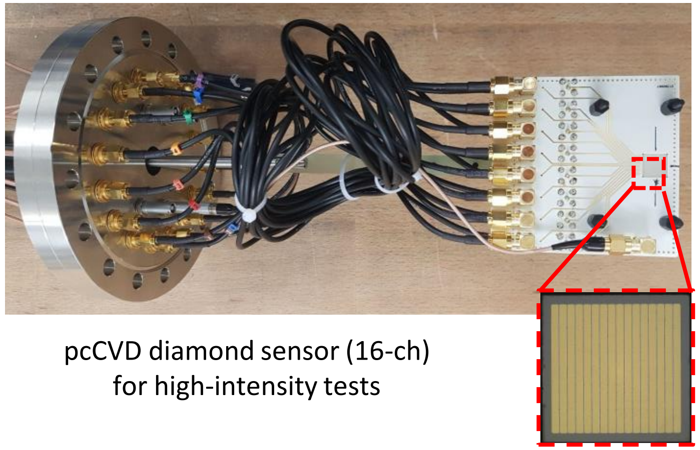
Lect. Notes Phys. 814 (2011) pp.1-980
DOI: 10.1007/978-3-642-13293-3



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

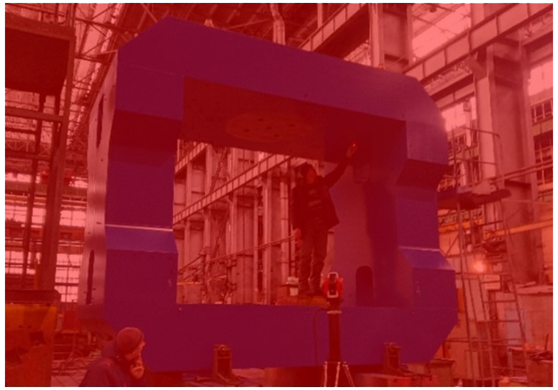
Recent (& Brief) Achievements In Detector Projects

Beam Monitoring (BMON) Detector



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

Superconducting Dipole Magnet



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

Micro-Vertex Detector (MVD)


Technical Design Report for the CBM
Micro Vertex Detector (MVD)
The CBM Collaboration
GSI Report : in preparation
Compressed Baryonic Matter Experiment

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

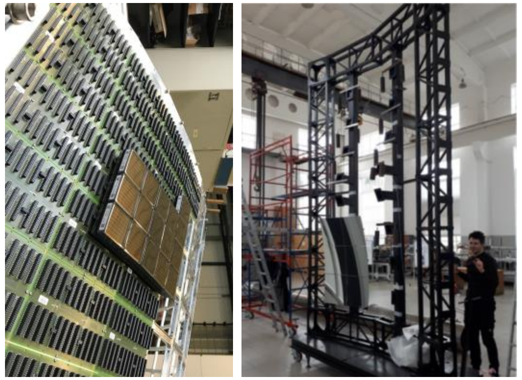
Silicon Tracking System (STS)

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

Muon Chambers (MUCH)

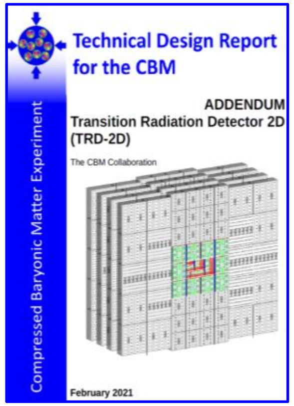
RPCs at tested at nominal
rates at GIF++ (Nov.21)

Ring Imaging Cherenkov (RICH) Detector



Photocamera and Mechanical
Prototypes (Mirror Wall)

Transition Radiation Detector (TRD)


Technical Design Report for the CBM
ADDENDUM
Transition Radiation Detector 2D (TRD-2D)
The CBM Collaboration
February 2021
Compressed Baryonic Matter Experiment

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

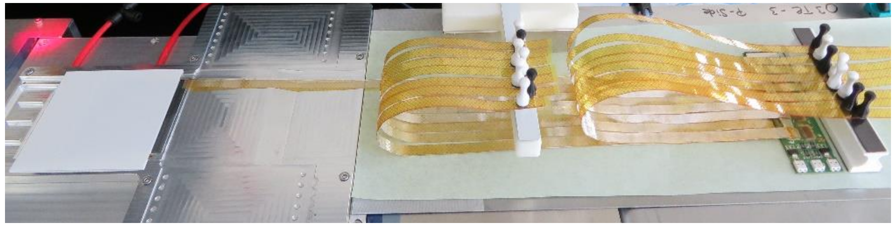
Projectile Spectator Detector (PSD)

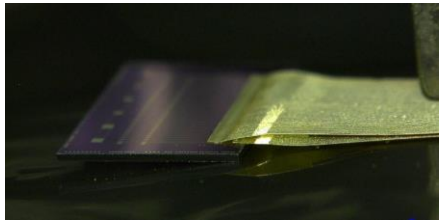
Efforts to replace PSD with
HADES-like FWALL. Still open issue.

CBM Related Developments At GSI-FAIR

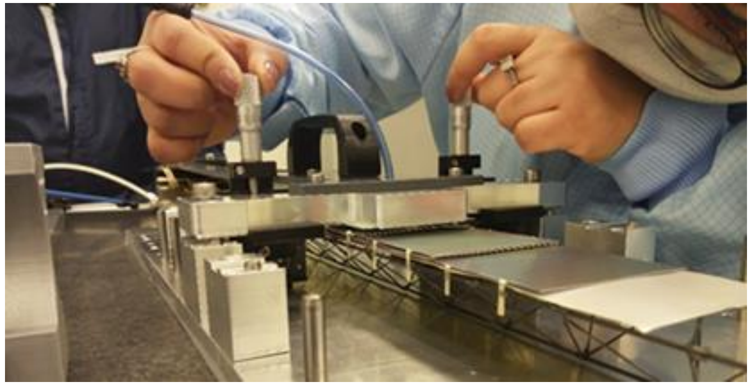
CBM Cave at FAIR
Upstream Platform: First user installation at FAIR

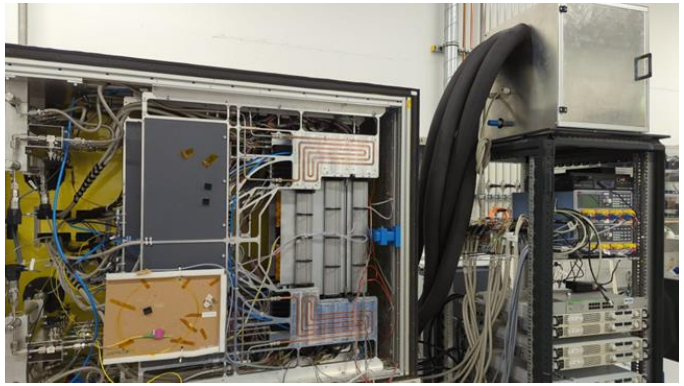
Assembly of STS-Module
Silicon Sensors, Shielded Thin Microcables, FEE-Boards



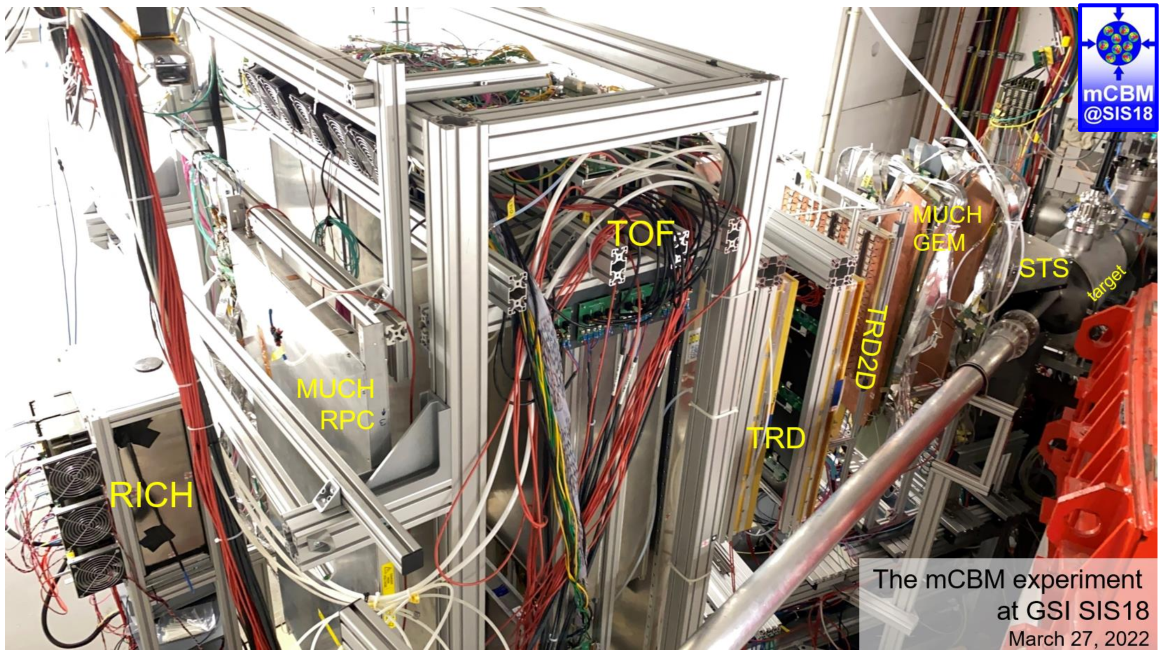


Integration and Testing of Lightweight Largescale Structures
STS-Module Integration of CF Support + STS Thermal Demonstrator + CF Beampipe

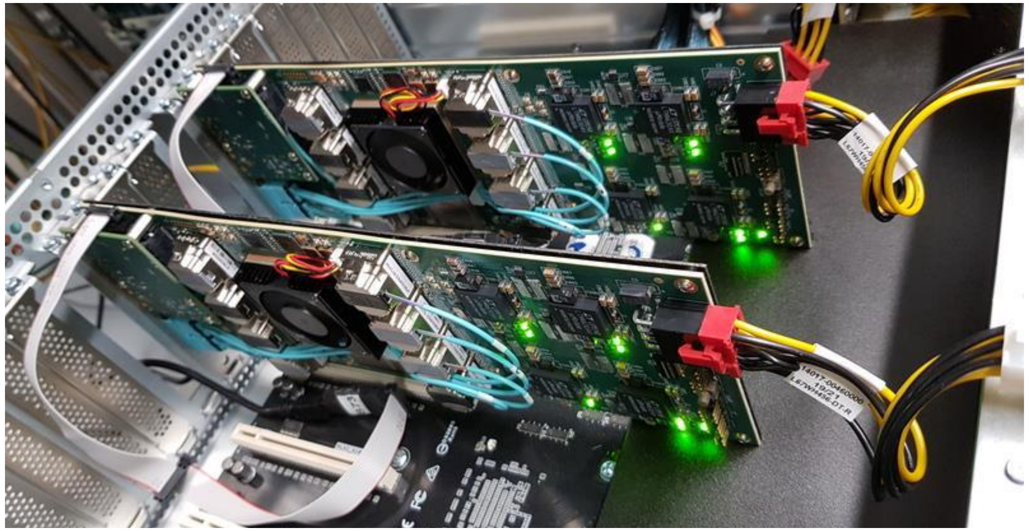




mCBM @ SIS-18



The mCBM experiment at GSI SIS18 March 27, 2022



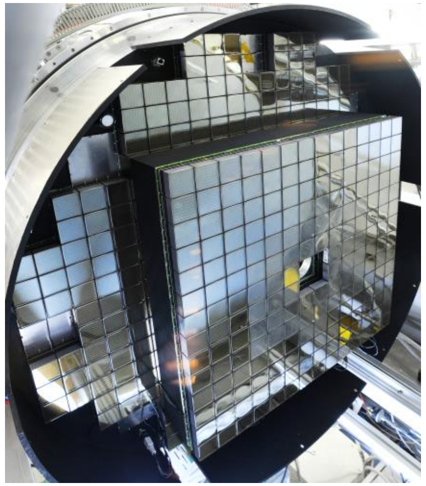
New mCBM DAQ with CRIs (prototype for CBM) in an entry node

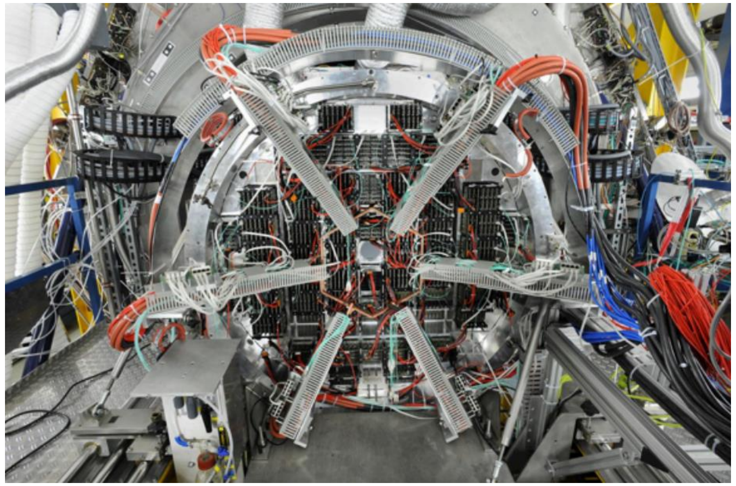
mCBM data sent forward, backward and forward to bridge a similar distance as later with CBM

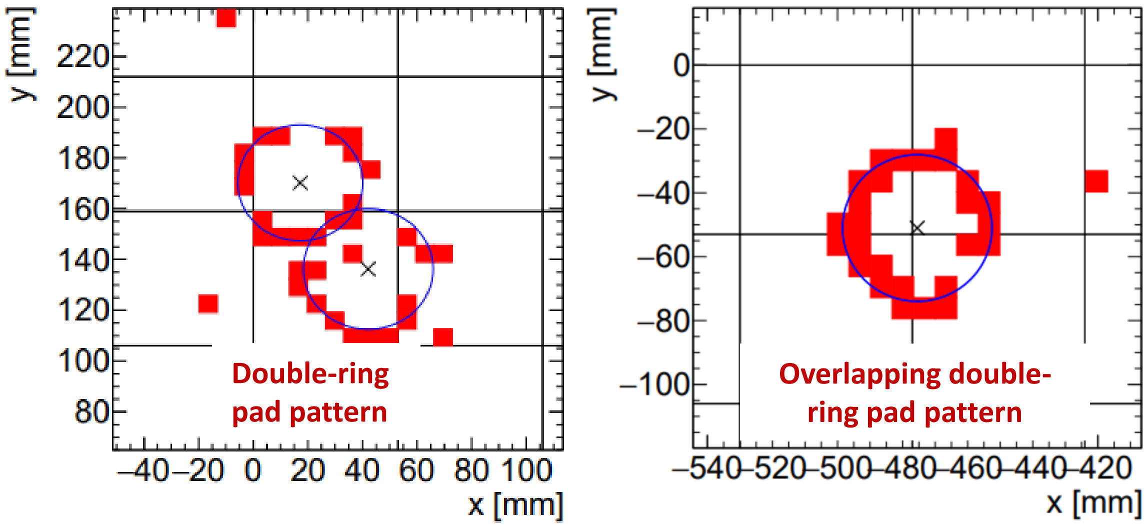
- Conceptual verification of the triggerless-streaming read-out and data transport of CBM at $\mathcal{O}$ (1 MHz) interaction rates
- Major effort put towards mimicking the final DAQ/data transport system by integrating all subsystems to the Common Readout Interface (CRI)
- Systematic high-rate studies performed for various detector subsystems and underlying components with up to 10 MHz collision rates during 2021-22 campaigns

CBM Contribution To FAIR Phase 0

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

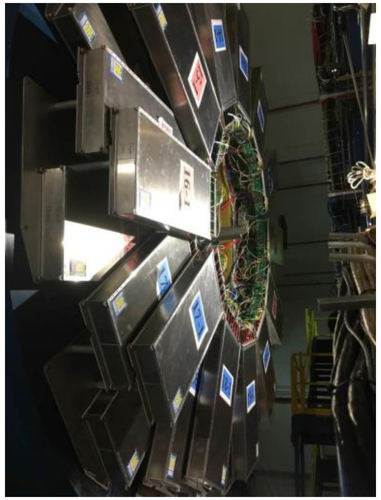


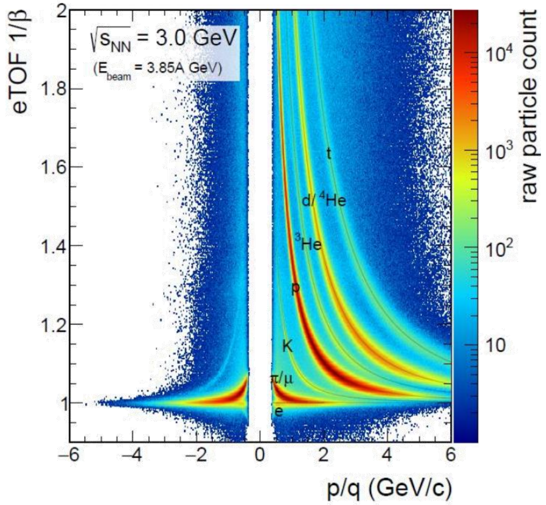




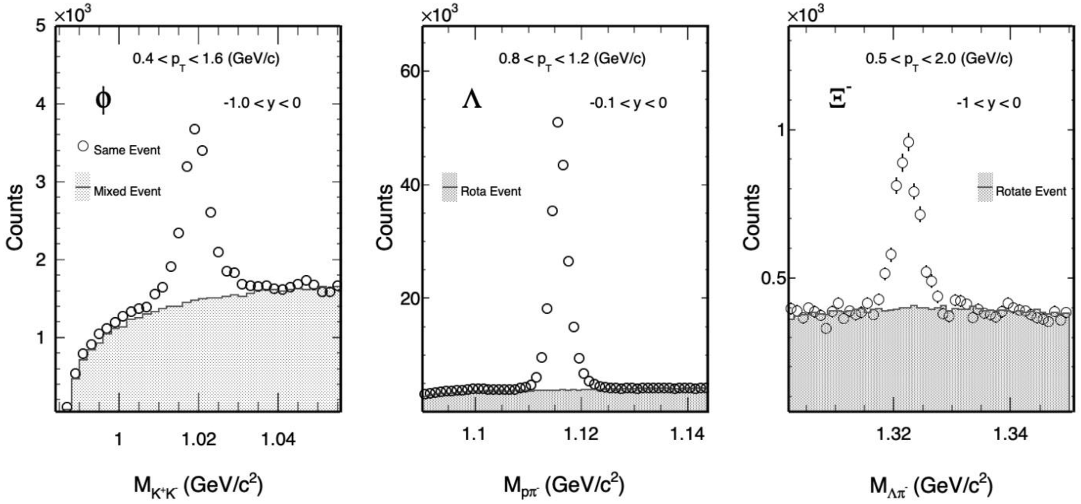
J. A-Musch et al., CBM Progress Report 2020

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





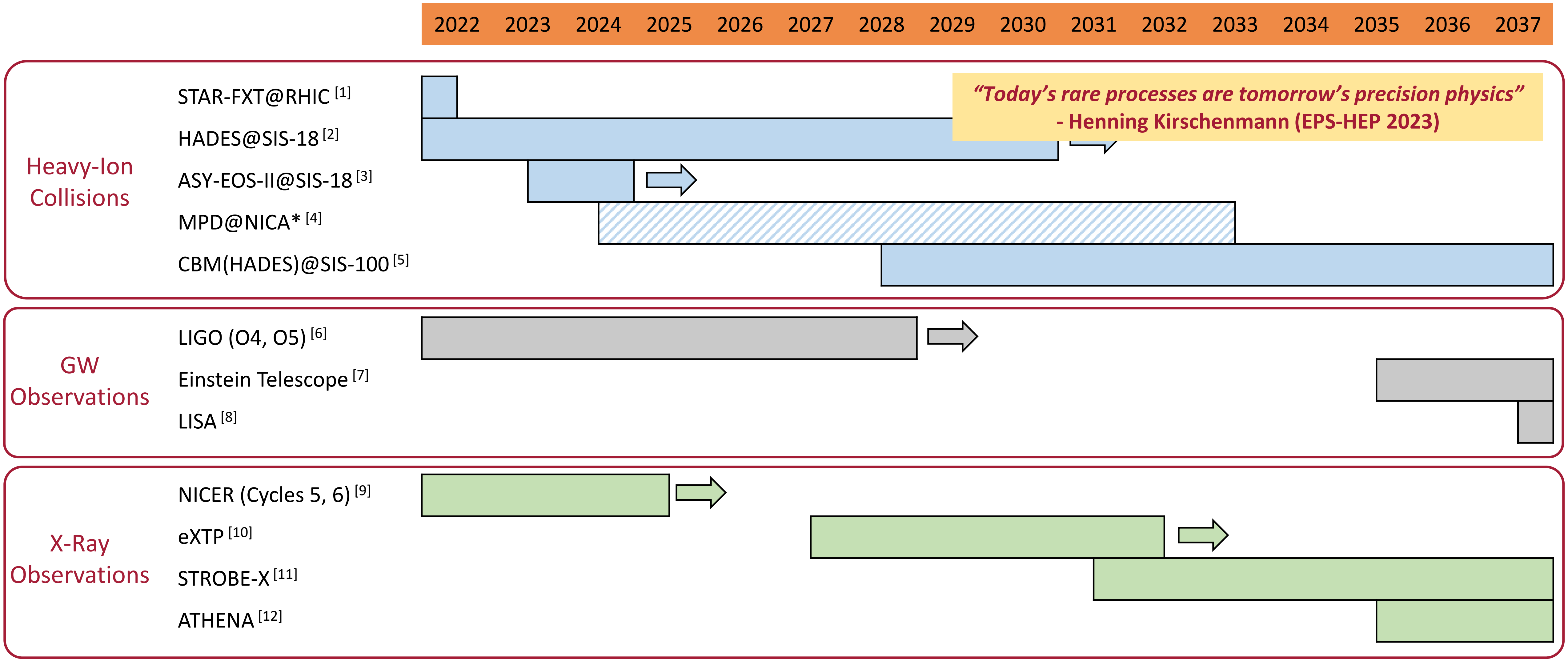
STAR Preliminary Au+Au $\sqrt{s_{NN}} = 3$ GeV



Guannan Xie, Strangeness in Quark Matter (2021)

A Look Into The Future
(Atleast Into One Of The Scenarios)

Growing Multi-Messenger Era (At Densities $\gtrsim \rho_0$)



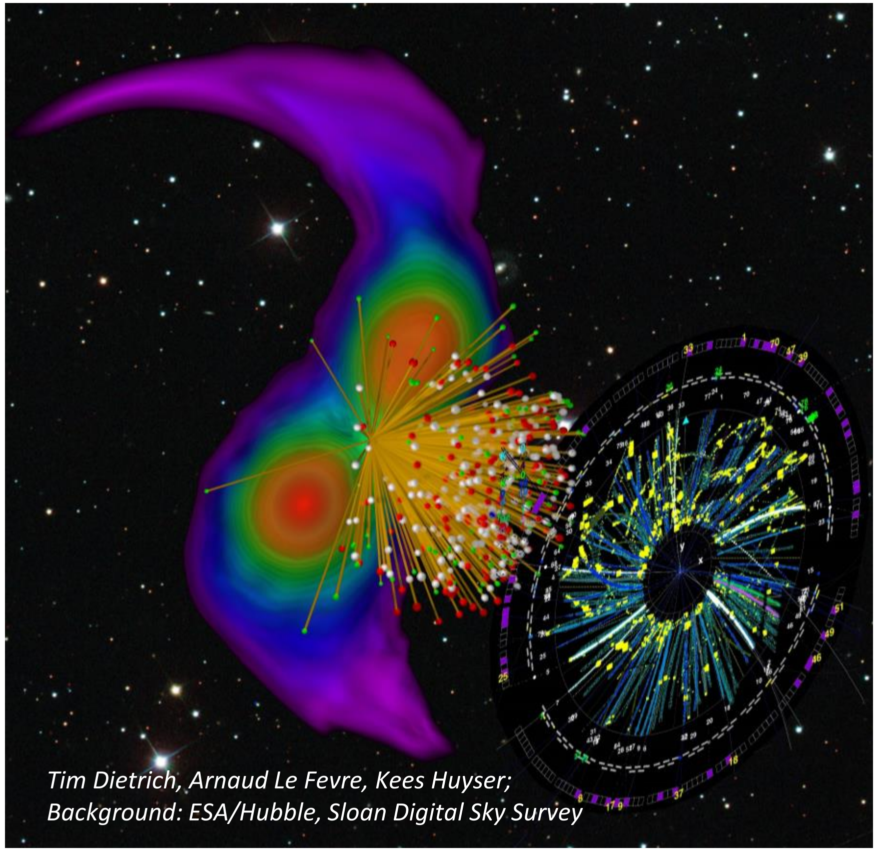
[1] D. Morrison, Quark Matter 2022 | Link
[2] Proposal for Beamtime in 2023-24, GSI G-PAC (2022)
[3] Proposal for Beamtime in 2023-24, GSI G-PAC (2022)
[4] I. Maldonado, A. Ayala, EuNPC 2022 | Link
[5] First-Science and Staging Review of the FAIR Project (2022) | Link
[6] LIGO-Virgo-KAGRA Observing Run 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

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

SUMMARY AND OUTLOOK (KEY QUESTIONS)

Heavy-ions collisions have been cemented as a reliable source to infer neutron star properties at ~$1.5\rho_0$ but their role at higher densities is still underwhelming

STAR-FXT@RHIC ($\sqrt{s_{NN}} = 13.7 \dots\ 3$ GeV) and CBM@SIS-100 ($\sqrt{s_{NN}} = 2.9\ \dots\ 4.9$ GeV) are crucial to constraint high-density EOS, where the only reliable info comes from MMA


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

STAR-FXT@RHIC CBM@SIS-100 has significant discovery potential

- Collective Flow excitations functions analysed (π^+, π^-, K^0_S, Λ)
- Transport model description is still underwhelming
- Energy Dependence of ${}^3_\Lambda H$ and ${}^4_\Lambda H$ yields and directed flow → Coalescence?
- Charm in cold and dense matter

CBM@SIS-100 pushes the high-rate frontier (10 MHz interaction rate)

- Track reconstruction, particle identification and event characterisation tools developed and tested to achieve high precision of multi differential observables
- CBM Phase 0 activities (HADES, STAR, mCBM) to test and optimize major components → production of physics results with CBM devices
- *Preparing to go online 2028…*

STAR-FXT@RHIC and CBM@SIS-100 (HADES@SIS-18/100) provide unique conditions in lab to probe QCD matter properties at neutron star core densities, and the search for new phases at higher densities.

BUT theoretical description to extract the underlying physics is gravely needed. Future is now…

MOVING TOWARDS A NEW MULTI-MESSENGER PHYSICS ERA WITH HEAVY ION COLLISIONS AT RHIC & FAIR

SUMMARY AND OUTLOOK (KEY QUESTIONS)

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THANK YOU ☺

And to the following for great discussions:

T. Galatyuk, A. Le Fevre, H.R. Schmidt, I. Selyuzhenkov, P. Senger, A. Sorensen, C. Sturm, W. Trautmann, I. Vassiliev, N. Xu.

(and coauthors from Huth, Pang et al., DOE/NSF NSAC LRP EOS White Paper, and many more …)

Vote Of Confidence For CBM-FAIR

Report

from the Committee for

First-Science and Staging Review of the FAIR Project

Submitted to FAIR Council, October 2022

GSI Press Release – Link
Report PDF – Link

The committee came unanimously to the following recommendations in order to advance FAIR to science beyond Phase-0:

- First priority should be the completion of the S-FRS into the HEB cave for NUSTAR to carry out the Early Science program.
- Completion of SIS100 needs to have the next highest priority.
- If resources are tightly constrained, completing SIS100 with beams into the S-FRS and HEB cave, plus setting up and commissioning the CBM experiment offers an intermediate solution for developing world-class science at FAIR.
- Completing the infrastructure and instrumenting the APPA cave should have priority over instrumenting the additional area in LEB for NUSTAR.
- Tendering for civil construction of the West lot should be postponed, but a plan is needed for the time frame to implement PANDA.
- The orderly set of steps towards the IO, presented in this document, represents the most cost-effective plan for moving FAIR forward. In order to accomplish this, a yearly budget

- The Heuer-Tribble Committee suggests a stepwise approach for the realization of FAIR
- Completion of SIS-100 was noted to be “existential” to FAIR
- Further endorsement obtained that bringing CBM to life will extend FAIR’s first science programme at a “minimal cost”

Accelerator Parameters And Comparisions

Table 4.1 Main parameters of accelerators around the world. Taken from [370]. In case of RAON linear accelerator, the length from the superconducting electron cyclotron resonance ion sources to the LAMPS experimental setup is given

	SIS18	SIS100	Nuclotron	NICA	HIAF	RAON	J-PARC
Circumference/length, m	216.72	1083	251.5	503.04	569.1	687	1567.5
Rigidity, Tm	18	100	25 – 43.25	45	36		160
Repetition rate, Hz	0.3 – 1	0.7			0.09		
Cycle duration, s		1.5	5		3 – 10		5.52
B-field ramp, T/s	10	4	1		4		
Accelerated ion	U^{73+}	Au^{79+}	Au^{79+}	Au^{79+}	U^{34+}	U^{79+}	U^{92+}
Extraction E ion, GeV	1	12	4.5	4.5	0.2 - 0.8	0.2	11.2 (19.5)
Extraction E proton, GeV	4.5	29	12.6	12.6		0.6	30 (50)
Intensity ion, ions/cycle	4×10^9	5×10^{10}	1×10^9	1×10^9	10^{11}	8.3 pμA	4×10^{11}
Intensity proton, p/cycle	10^{11}	2×10^{13}	1×10^{11}	1×10^{11}		660 μA	2×10^{14}
Extraction scheme	Fast, slow	Fast, slow	Single-turn, slow		Slow		Slow
Emittance, mm mrad		12/5			18/9		
Number of bunches/cycle				22			
β function, m				0.35		0.51 (SSR2)	
Rms bunch length, m				0.6			

Xiaofeng Luo, Qun Wang, Nu Xu, Pengfei Zhuang (Eds.), Properties of QCD Matter at High Baryon Density, Springer Singapore, eBook ISBN - 978-981-19-4441-3

Detector Parameters And Comparisions

Table 4.2 Running and planned high μ_B facilities. The facility and experiment, the anticipated year for data tacking, the range in μ_B and $\sqrt{s_{NN}}$ as well as capabilities of measuring hadrons, dileptons, and charm are listed. Taken from [370]

Facility	Experiment	Start	$\sqrt{s_{NN}}$, GeV	μ_B, GeV	Hadrons	Dileptons	Charm
RAON	LAMPS	>2027	≤1.46	$\gtrsim$ 880	+		
HIAF	CEE+	2023	1.9 – 4	880 – 760	+		
Nuclotron	BM@N	2022 (Au)	2 – 3.5	880 – 670	+		
J-PARC-HI	DHS, D2S	>2025	2 – 6.2	880 – 430	+	+	(+)
SIS100	CBM / HADES	2025	2.7 – 5	760 – 500	+	+	(+)
NICA	MPD	2023	4 – 11	580 – 300	+	+	+
SPS	NA60+	> 2025	4.9 – 17.3	560 – 230	(+)	+	+
SIS18	HADES/mCBM	running	1.9 – 2.6	880 – 670	+	+	
RHIC	STAR	running	3 – 19.6	720 – 210	+	+	+
SPS	NA61	running	4.9 – 17.3	520 – 230	+		+

Xiaofeng Luo, Qun Wang, Nu Xu, Pengfei Zhuang (Eds.), Properties of QCD Matter at High Baryon Density, Springer Singapore, eBook ISBN - 978-981-19-4441-3

PLANNED mCBM-SIS18 RUNS

2022	Projectile	T_{proj}	Beam intensity per spill (10s)	Av. collision rate	Objective
March 29 - April 1	^{238}U(73+)	1.00 AGeV	10^7 - 10^9	100 kHz - 10 MHz	high-rate studies TOF & MUCH
May 26	^{58}Ni(28+)	1.93 AGeV	$4{\cdot}10^7$	400 kHz	benchmark run I
June 16 - 18	^{197}Au(69+)	1.23 AGeV	$2 - 3{\cdot}10^7$	200 - 300 kHz	benchmark run II
June 19 - 20	^{197}Au(67+)	1.13 AGeV	$1{\cdot}10^7 - 4{\cdot}10^8$	100 kHz - 4 MHz	high-rate studies TOF & MUCH

Table 2.0.1: mCBM data taking in 2022.

Collision system	M_Λ, reconstr.	Av. collision rate	Beam intensity per spill (10s)	N_Λ reconstr. per 8h-shift
Ni + Ni 1.93 AGeV	$2.3{\cdot}10^{-5}$	400 kHz	$4{\cdot}10^7$	90k
Au + Au 1.24 AGeV	$2.2{\cdot}10^{-6}$	200 kHz	$2{\cdot}10^7$	4.4k
Ag + Ag 1.58 AGeV	$5{\cdot}10^{-6}$	300 kHz	$3{\cdot}10^7$	15k

Table 3.1.1: Rate estimate for Λ reconstruction with mCBM: the Λ yields for Ni + Ni collisions at 1.93 AGeV and for Au + Au at 1.24 AGeV are taken from simulations depicted in Fig. 3.1.1. Yields for Ag + Ag collisions at 1.58 AGeV were interpolated from above listed Ni and Au simulations (median in mass number and kinetic projectile energy). With a spill length of 10 s, 4 spills per minute and a duty cycle of about 0.5, approx. 1000 spills are taken per 8h-shift. The benchmark runs will be measured at moderate beam intensities resulting to 200 - 400 kHz averaged collision rate while using 10 % interaction probability targets.

	Year	Objective	Projectile	Intensity per spill	Extraction	User type	Shifts
(1)	2023	high-rate detector studies	ions 1 - 2 AGeV, preferably: Au, Pb, U	10^7 - 10^9	slow, 10 s	secondary	6
(2)	2023	commissioning for benchmark run	ions 1 - 2 AGeV, preferably: Ni 1.93 AGeV	10^7 - 10^8	slow, 10 s	secondary	3
(3)	2023	benchmark runs, Λ production excitation function	Ni 1.93, 1.58, 1.23, 1.0 AGeV	10^8	slow, 10 s	main	18
(4)	2024	high-rate detector studies	ions 1 - 2 AGeV, preferably: Au, Pb, U	10^7 - 10^9	slow, 10 s	secondary	6
(5)	2024	commissioning for benchmark run	ions 1 - 2 AGeV, preferably: Ag 1.58 AGeV	10^7 - 10^8	slow, 10 s	secondary	3
(6)	2024	benchmark runs, Λ production excitation function	Ag 1.58, 1.23, 1.0 AGeV	10^8	slow, 10 s	main	18

Table 3.1.2: Beam time application for the years 2023 and 2024 on SIS18 beam time for mCBM.

G-PAC Proposal for mCBM@SIS-18 (2023/24):

- https://indico.gsi.de/event/15266/contributions/64063/attachments/40205/55084/mcbm-proposal-23-24-final.pdf
- https://indico.gsi.de/event/15901/#38-mcbm-presentation-at-the-g

KF-Particle Finder