Equation-Of-State (EOS) Of Dense Nuclear Matter With CBM-FAIR And STAR-RHIC

Kshitij Agarwal

/ʂɪ.t̪ɪd͡ʒ əg.ɾᵊ.vɑːl/

Eberhard-Karls-Universität Tübingen (DE)

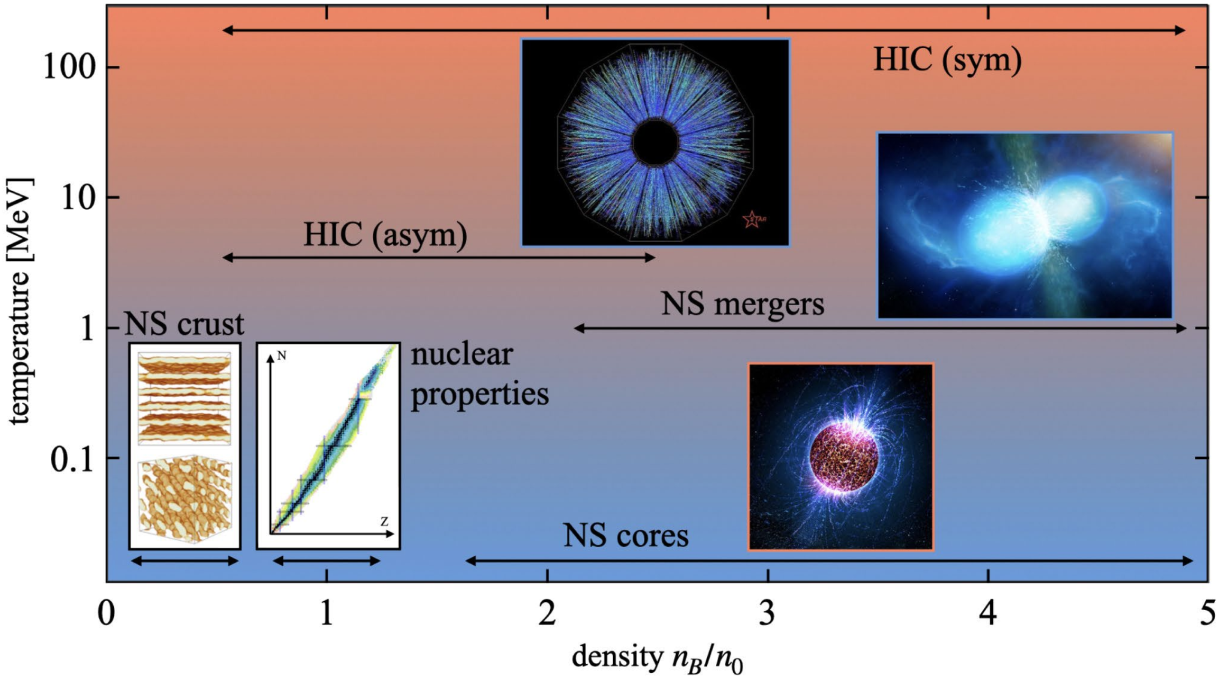
17th Workshop on Particle Correlations and Femtoscopy (WPCF 2024)

Laboratoire des 2 Infinis - Toulouse (L2IT), November 04 – 08, 2024

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

Success Story: EOS From Nuclear Exp. W/ Astro

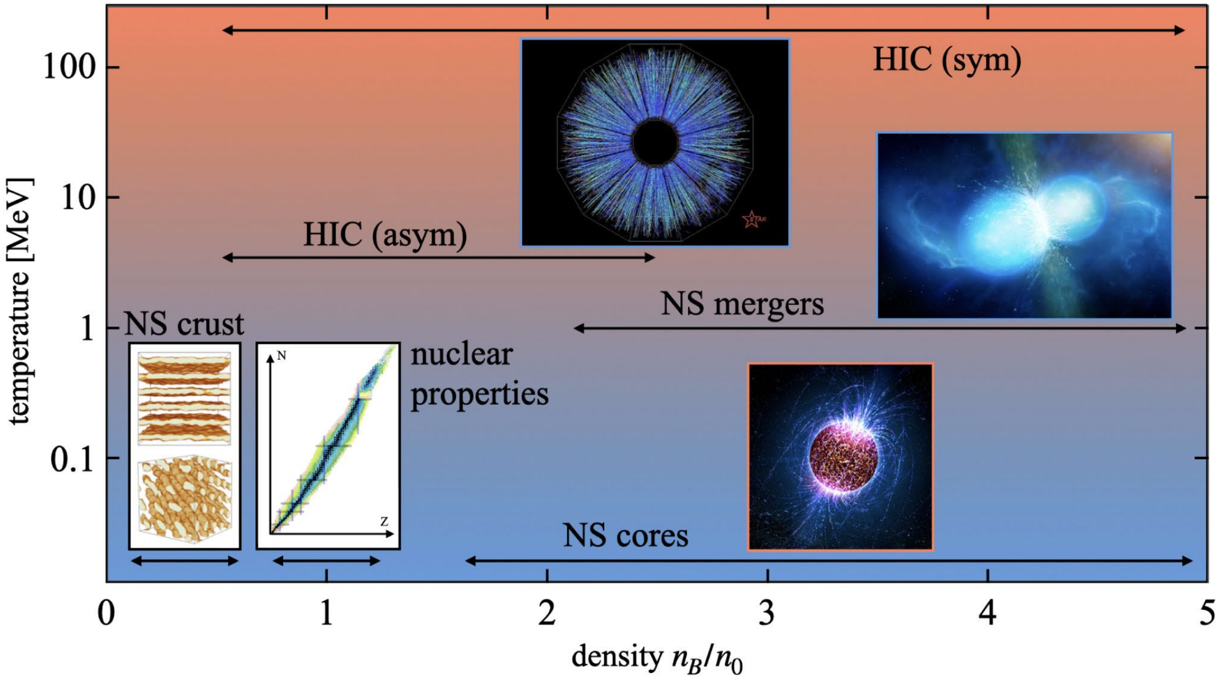


A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

The study of equation of state (EOS) of dense nuclear matter is now a truly multi-messenger endeavour

- Heavy-ion collisions
- Neutron-skin thicknesses of Sn isotopes
- Giant dipole resonances
- Dipole polarizability of ^{208}Pb
- Nuclear masses
- Isovector skins
- Ab initio calculations
- Gravitational waves (inspiral, post-merger)
- Radio and X-ray pulsars
- Kilonovae
- ...

Success Story: EOS From Nuclear Exp. W/ Astro

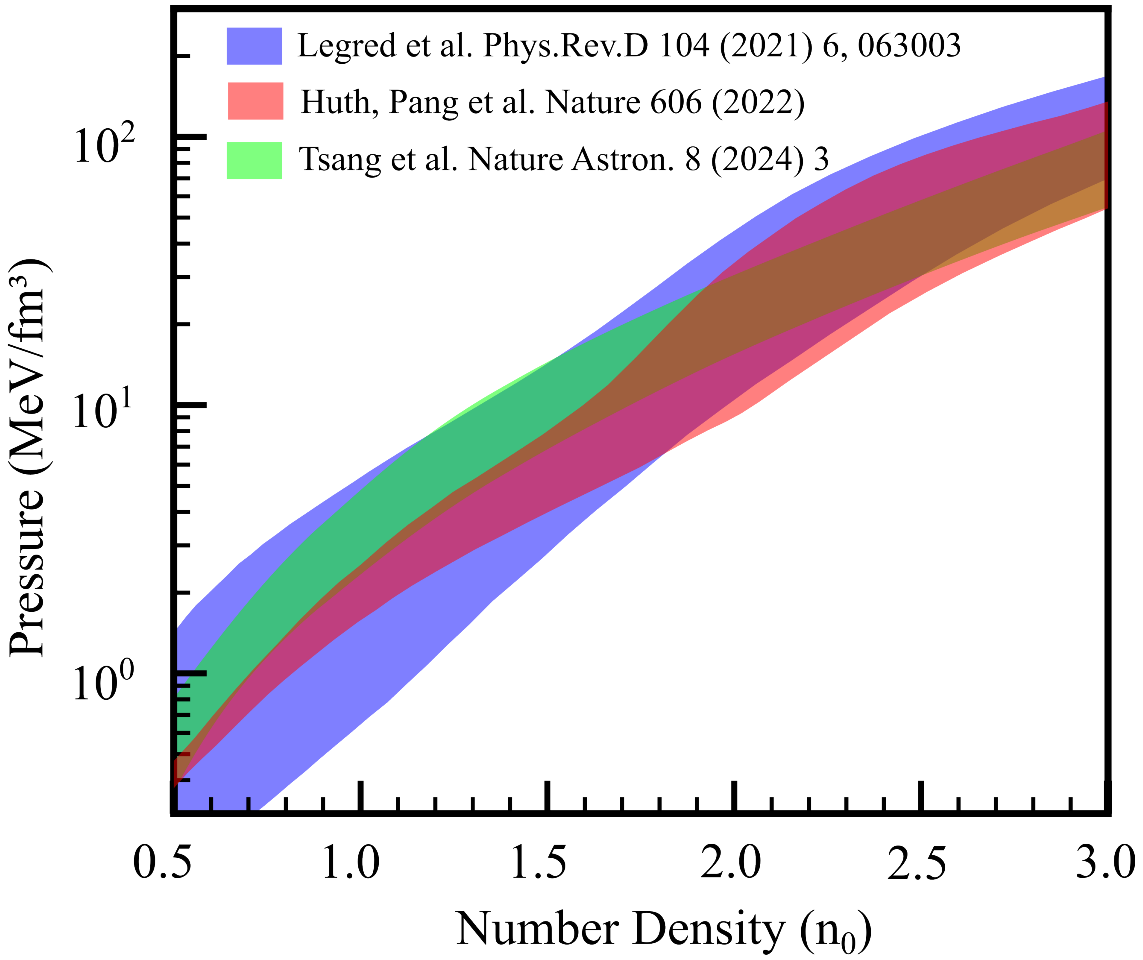


A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

The study of equation of state (EOS) of dense nuclear matter is now a truly multi-messenger endeavour

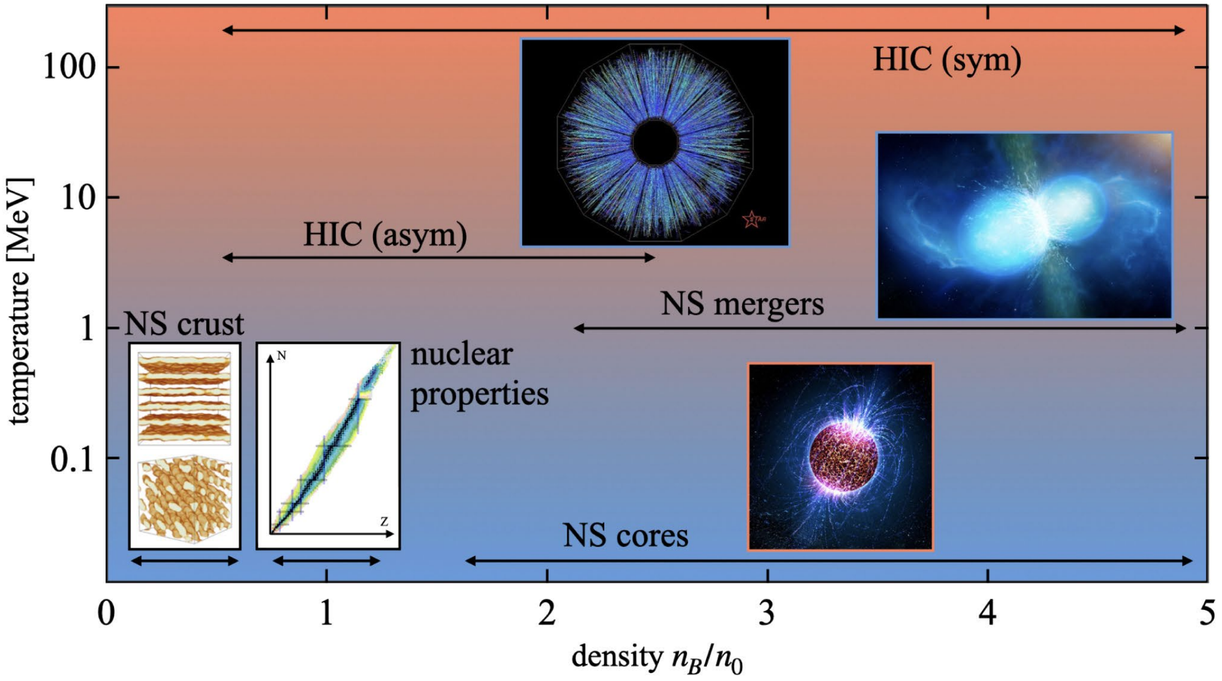
- Heavy-ion collisions
- Neutron-skin thicknesses of Sn isotopes
- Giant dipole resonances
- Dipole polarizability of ^{208}Pb
- Nuclear masses
- Isovector skins
- Ab initio calculations
- Gravitational waves (inspiral, post-merger)
- Radio and X-ray pulsars
- Kilonovae
- …

A remarkable compatibility has been established between different information sources, including heavy-ion collisions, till 1.5ρ_0 (further improvements expected from GSI-SIS-18 and FRIB experiments, and transport codes)



Adapted from: C.Y. Tsang et al., Nature Astron. 8 (2024) 3, 328-336

Success Story: EOS From Nuclear Exp. w/ Astro

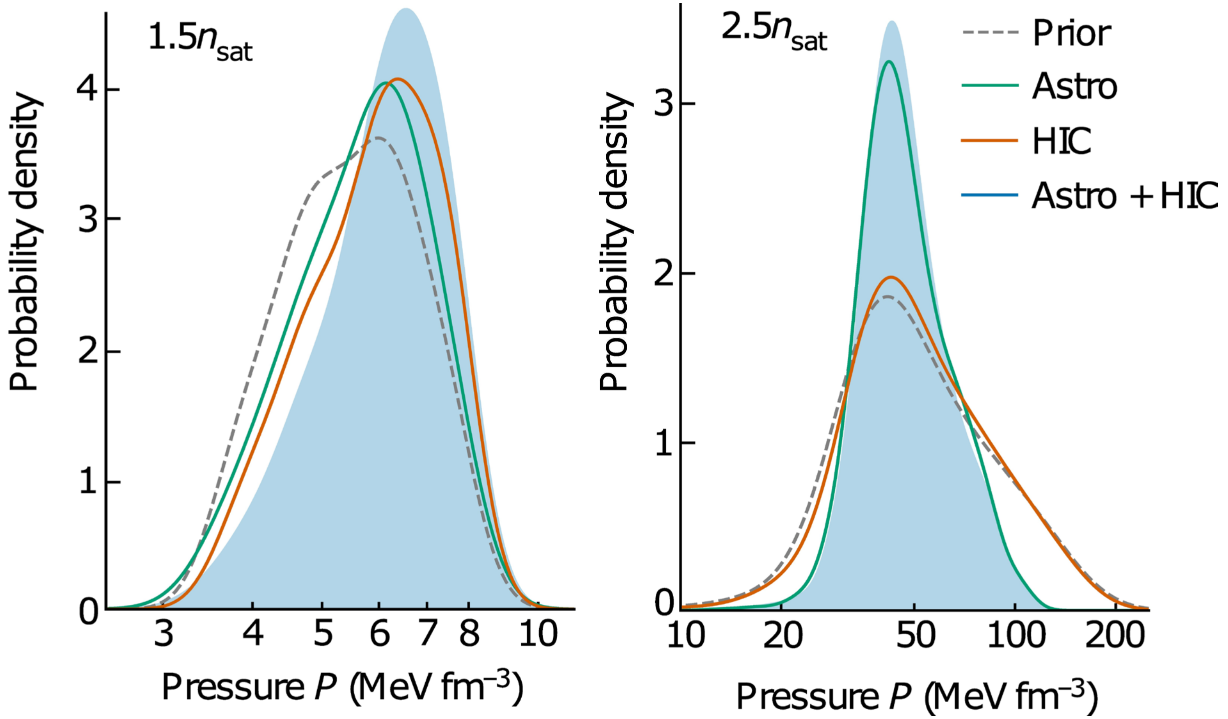


A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

The study of equation of state (EOS) of dense nuclear matter is now a truly multi-messenger endeavour

- Heavy-ion collisions
- Neutron-skin thicknesses of Sn isotopes
- Giant dipole resonances
- Dipole polarizability of ^{208}Pb
- Nuclear masses
- Isovector skins
- Ab initio calculations
- Gravitational waves (inspiral, post-merger)
- Radio and X-ray pulsars
- Kilonovae
- ...

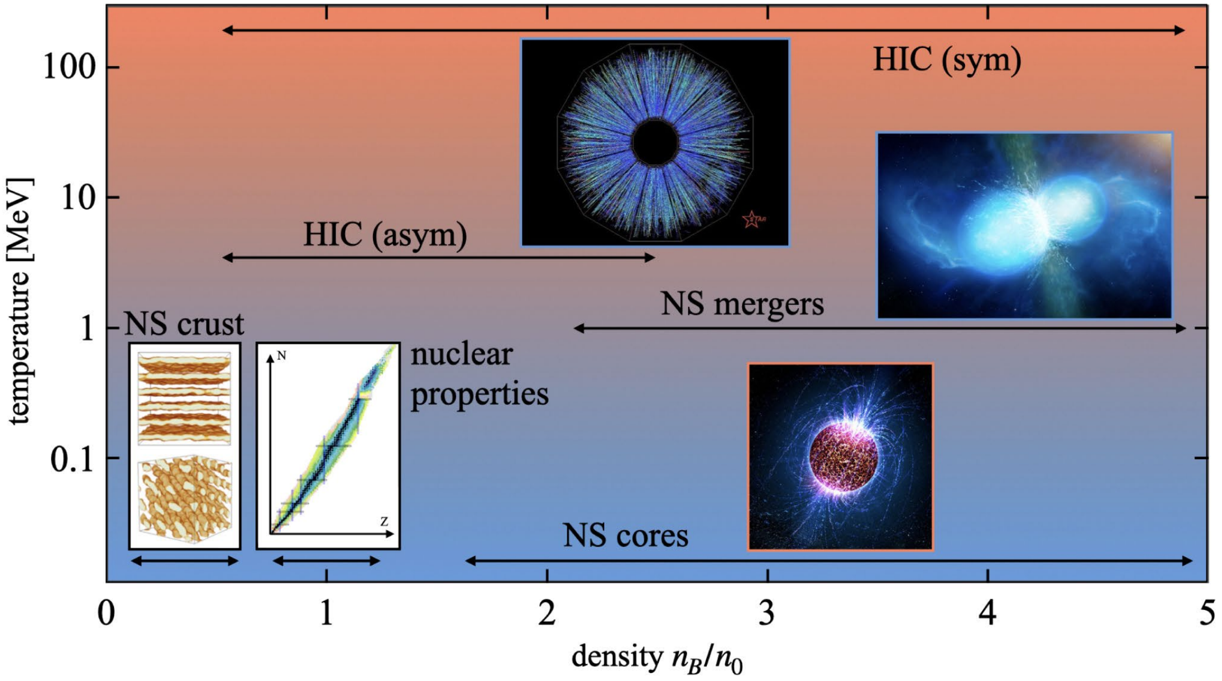
A remarkable compatibility has been established between different information sources, including heavy-ion collisions, till 1.5ρ_0 (further improvements expected from GSI-SIS-18 and FRIB experiments, and transport codes)



Improvement at: FAZIA@FRIB, L. Baldesi (07.11)

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

Success Story: EOS From Nuclear Exp. W/ Astro

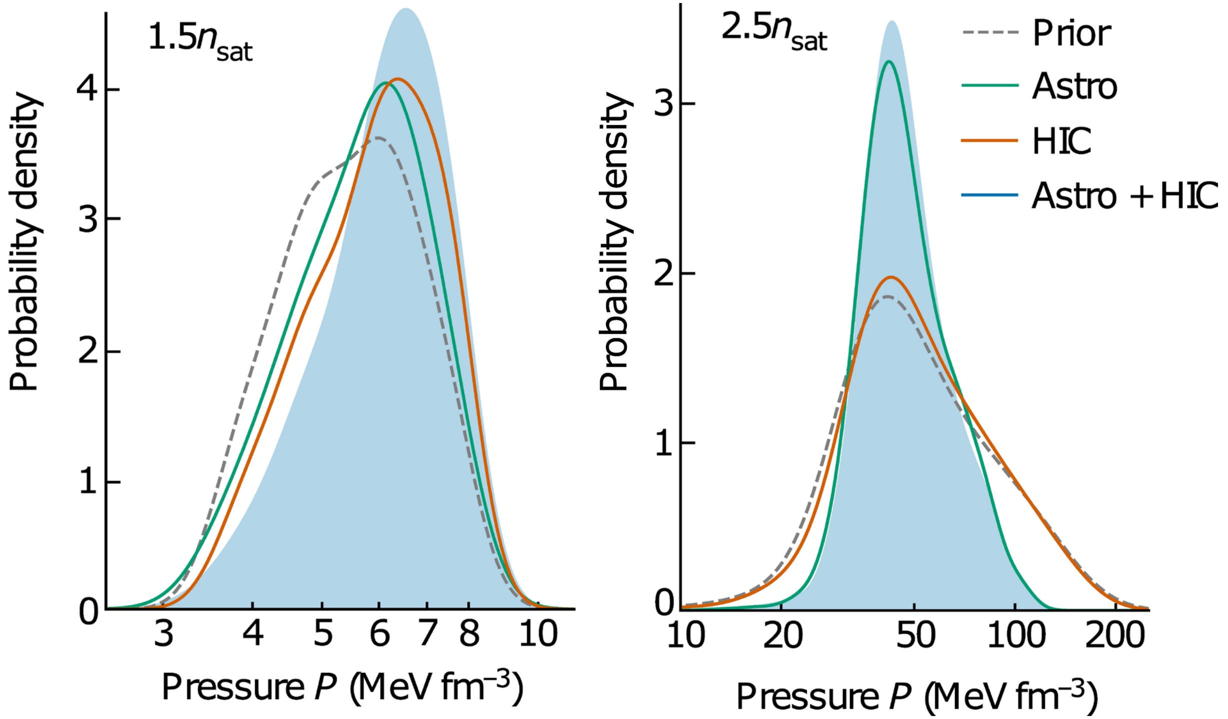


A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

The study of equation of state (EOS) of dense nuclear matter is now a truly multi-messenger endeavour

- Heavy-ion collisions
- Neutron-skin thicknesses of Sn isotopes
- Giant dipole resonances
- Dipole polarizability of ^{208}Pb
- Nuclear masses
- Isovector skins
- Ab initio calculations
- Gravitational waves (inspiral, post-merger)
- Radio and X-ray pulsars
- Kilonovae
- …

A remarkable compatibility has been established between different information sources, including heavy-ion collisions, till $1.5\rho_0$ (further improvements expected from GSI-SIS-18 and FRIB experiments, and transport codes)



Improvement at: FAZIA@FRIB, L. Baldesi (07.11)

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

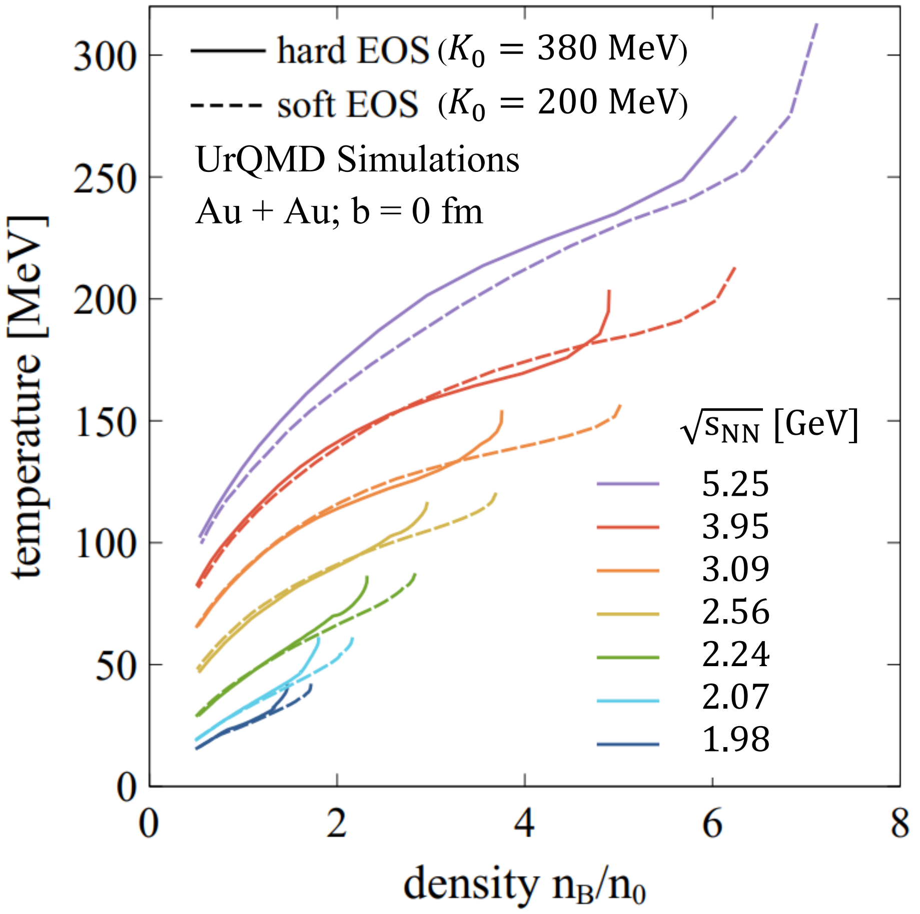
But dense matter EOS at neutron star core densities is driven by astrophysical sources, so the terra incognita for heavy-ion collisions lies beyond $\sim 2\rho_0$, where current data hints at some softening and potential transition to partons

E. Annala et al., Nature Commun. 14 (2023) 1, 841; D. Oliinychenko et al., Phys.Rev.C 108 (2023) 3, 034908

Ingredients To Access The Terra Incognita

INGREDIENTS TO ACCESS THE TERRA INCOGNITA

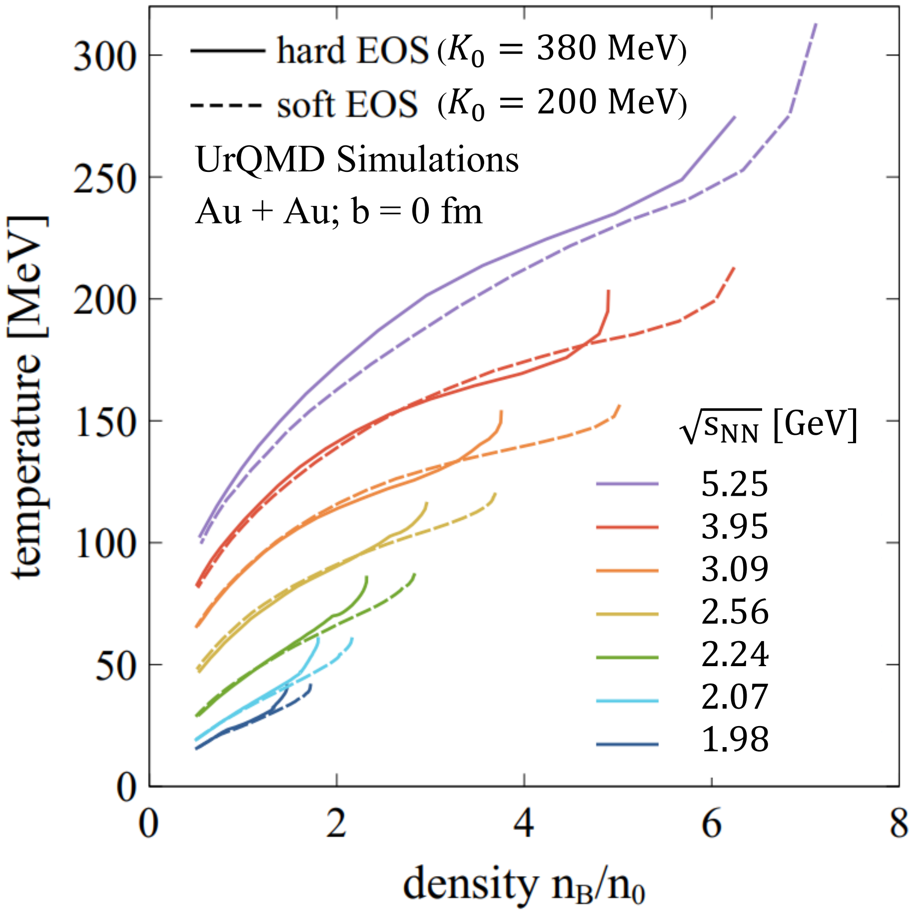
INGREDIENT #1: Heavy-ion high-intensity beams



A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

Ingredients To Access The Terra Incognita

INGREDIENT #1: Heavy-ion high-intensity beams



A. Sorensen et al., Prog.Part.Nucl.Phys. 134 (2024) 104080

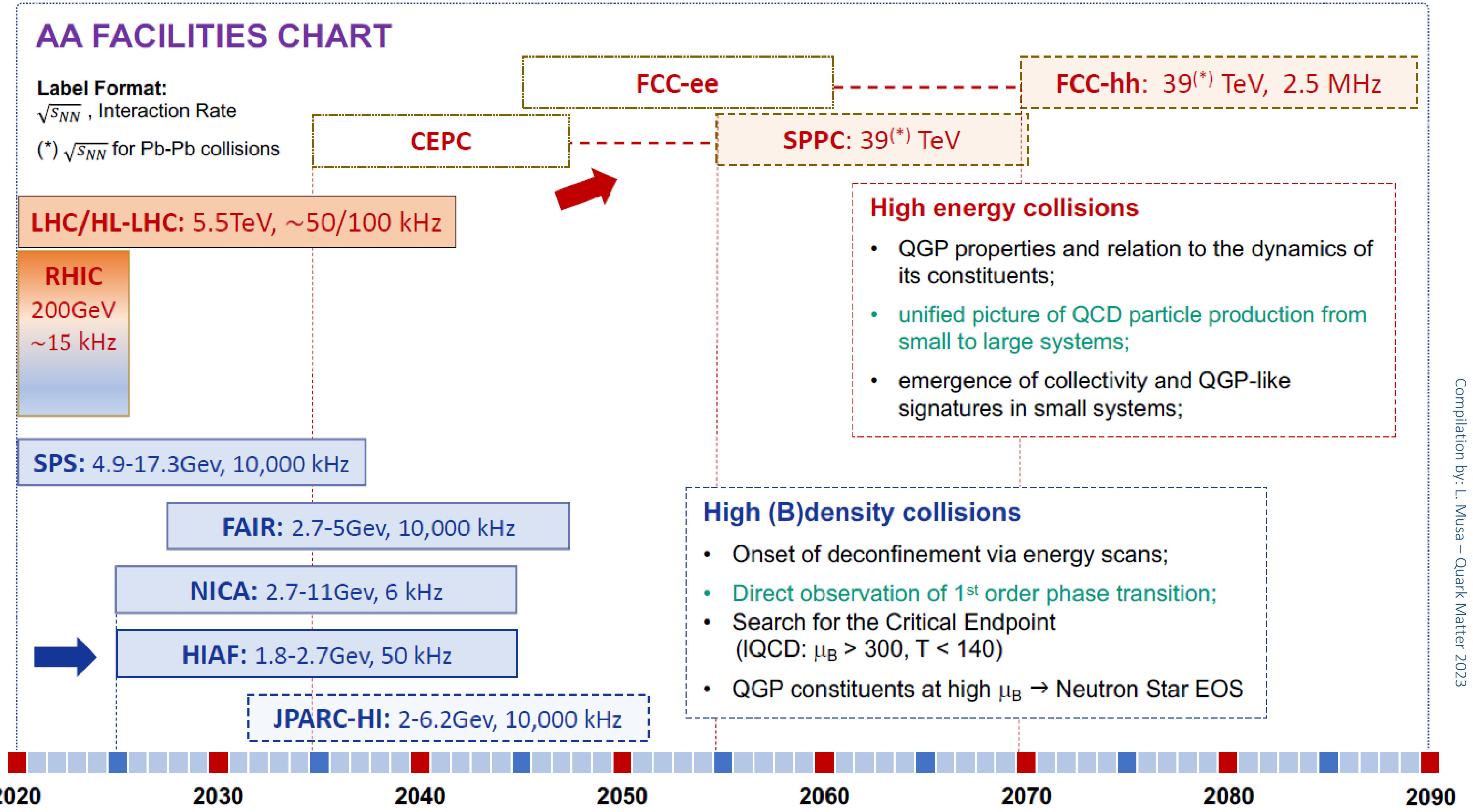
INGREDIENT #2: Experiment capable of measuring candidate observables

High Density Nuclear EOS Observables

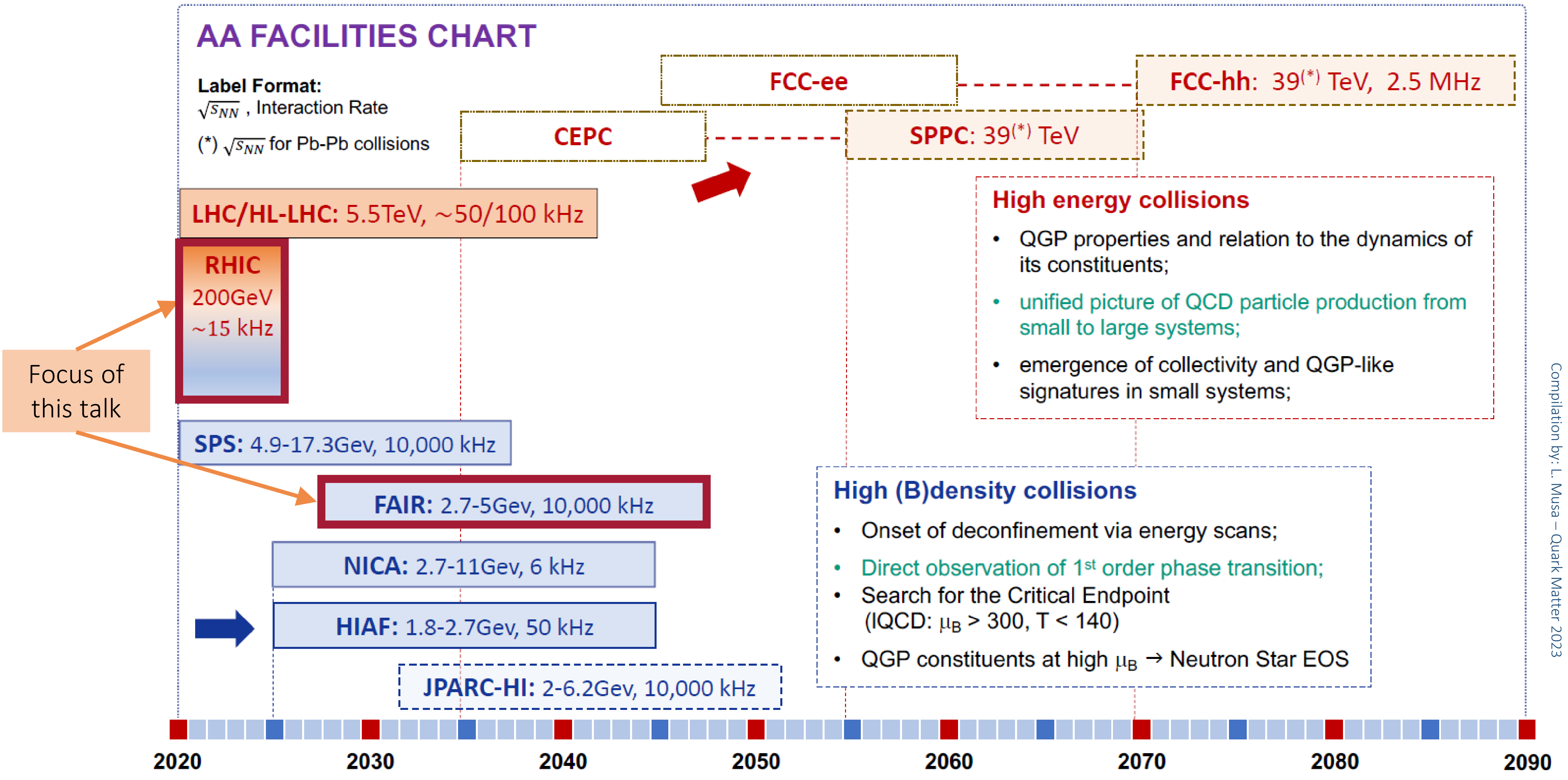
(Incomplete list)

- Sub-threshold Strangeness Production (KaoS@SIS-18)
- Neutron-to-proton (like) yields and flow (SπRIT@RIKEN, ASY-EOS & FOPI-LAND@SIS-18)
- Collective Flow (Bevalac, FOPI & HADES @SIS-18, AGS exp., STAR@RHIC)
- Dileptons Yields, Flow and Temperature (HADES@SIS-18)
- 2- and 3-Particle Correlations (STAR@RHIC, ALICE@LHC)
- Hypernuclei Properties (STAR@RHIC, ALICE@LHC)

Global A+A Collision Facilities (2020 – ...)



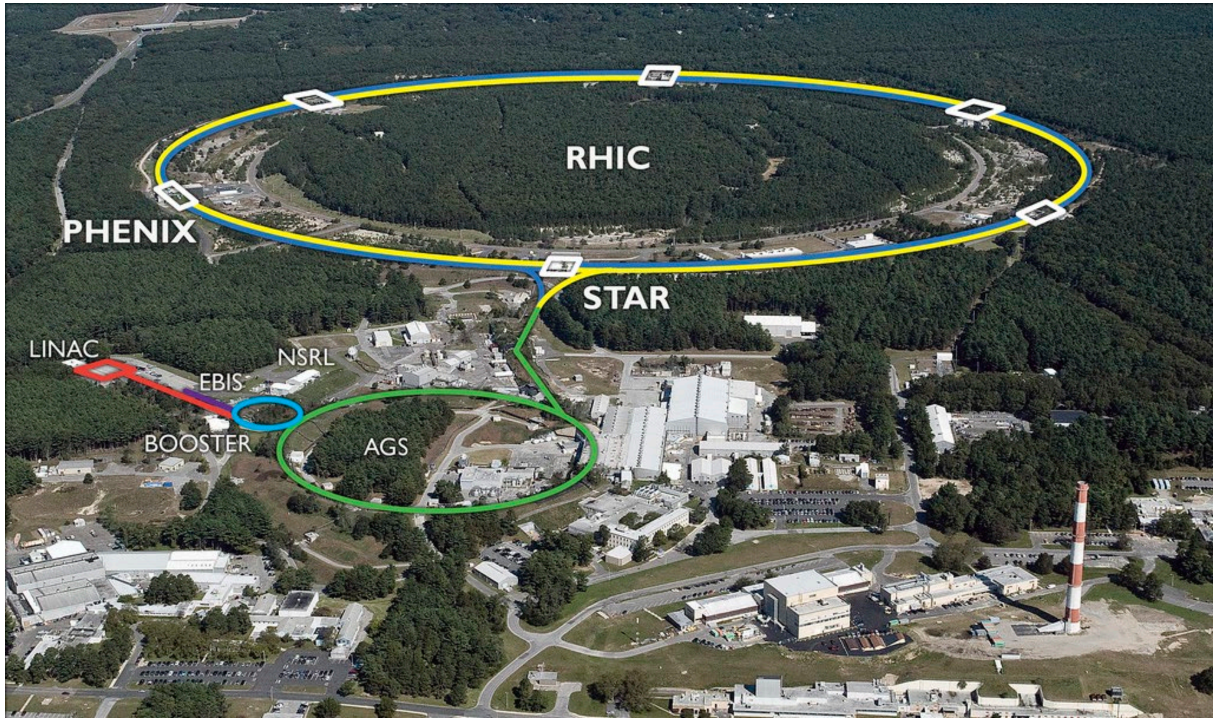
Global A+A Collision Facilities (2020 – ...)



A+A Collision Facilities In Focus

A+A Collision Facilities In Focus

Relativistic Heavy Ion Collider (RHIC; 2000 – …)



Top collision energies

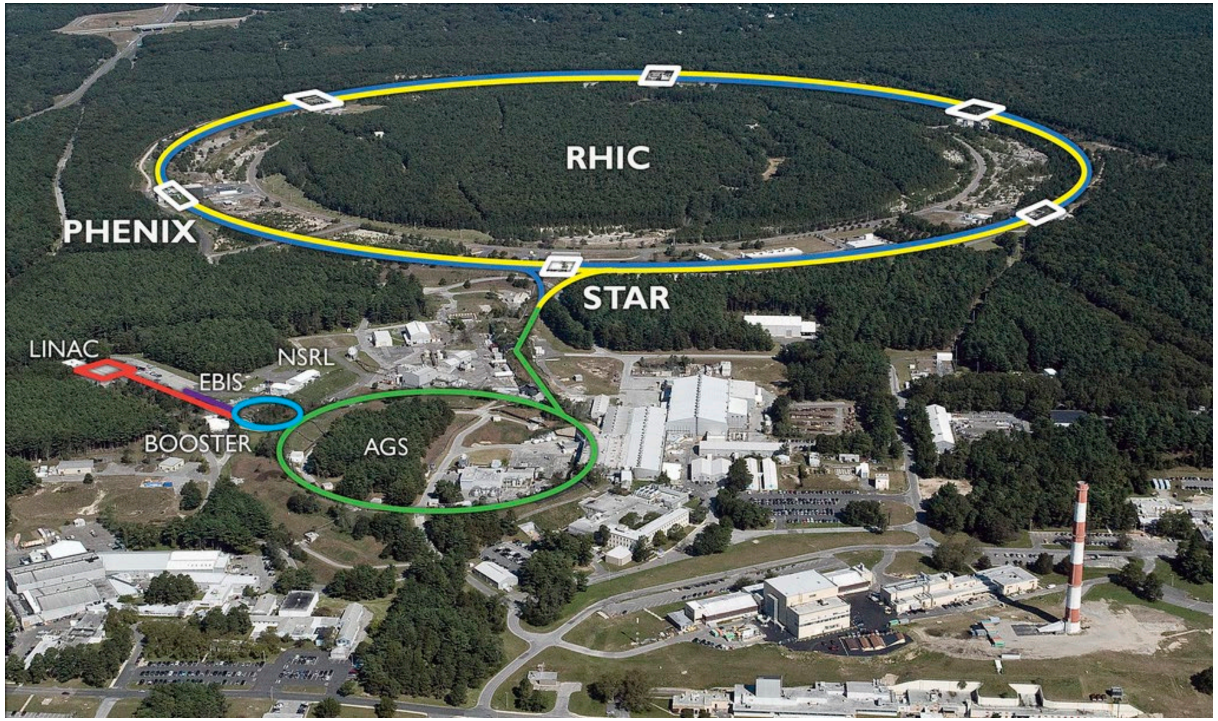
- $\sqrt{s_{NN}} = 200$ GeV U + U / Au + Au / Zr + Zr / Ru + Ru / O+O
- $\sqrt{s} = 510$ GeV p + p

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)

A+A Collision Facilities In Focus

Relativistic Heavy Ion Collider (RHIC; 2000 – …)



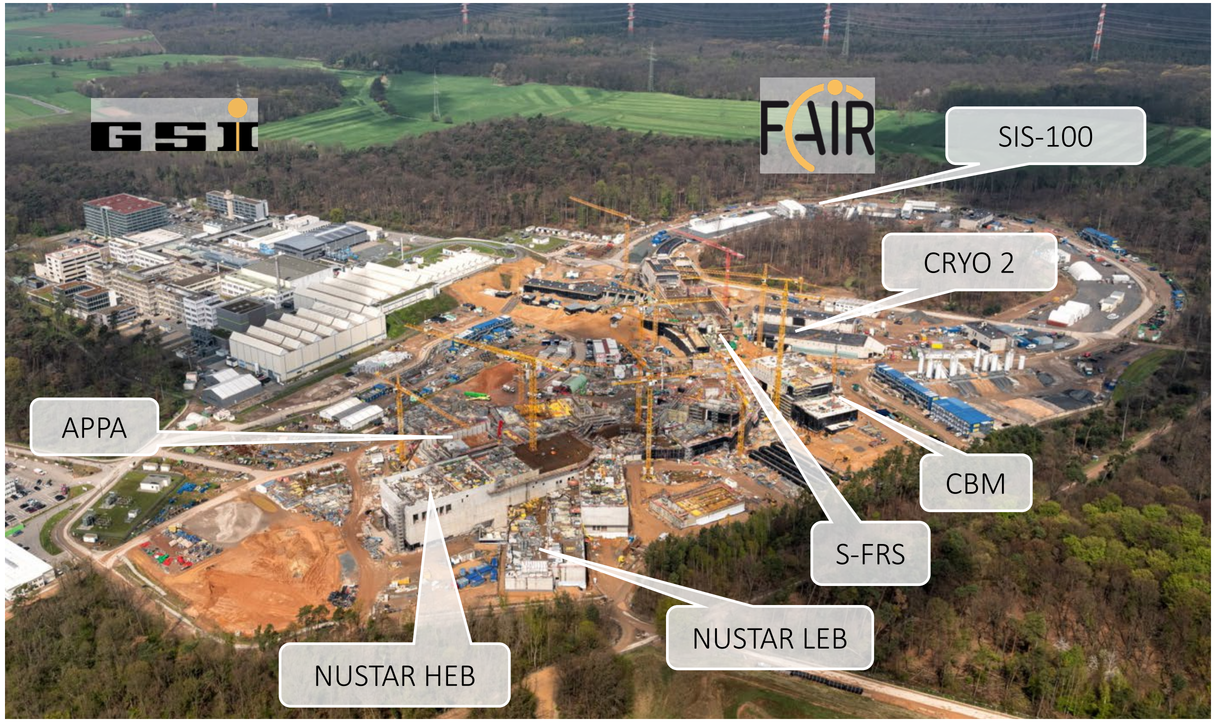
Top collision energies

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

Beam Energy Scan (BES)

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

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

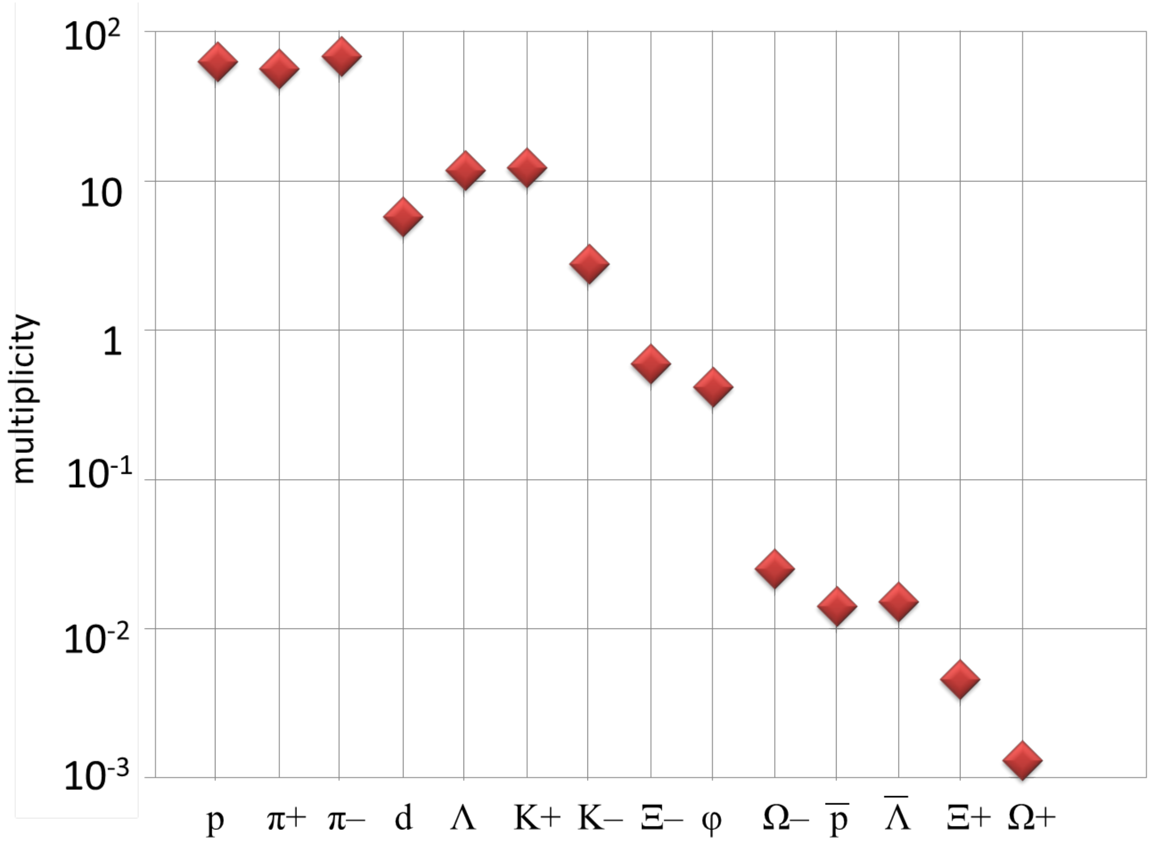


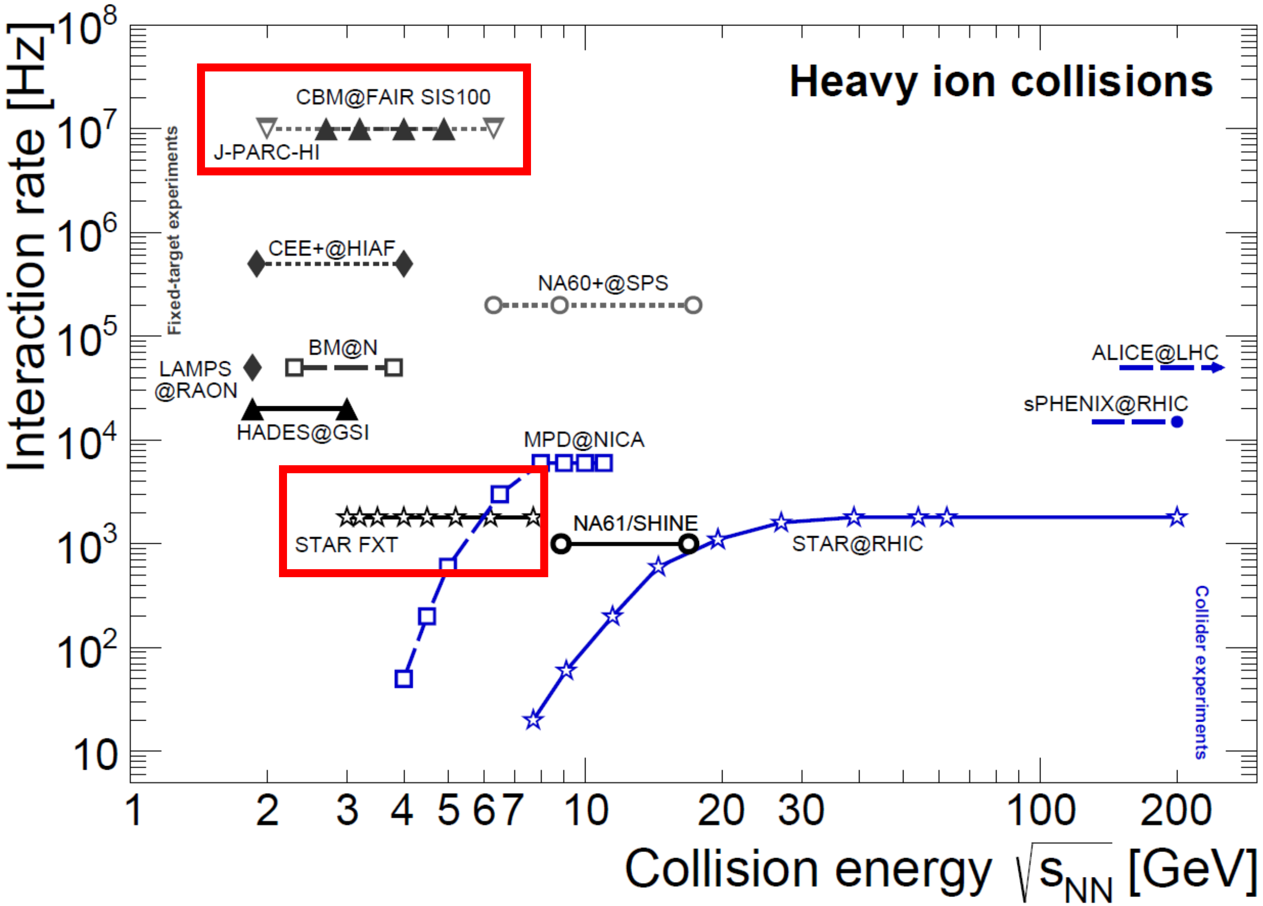
- Intensity gain w.r.t. SIS-18@GSI: x 100 – 1000 (~10^9/s for Au)
- Energy gain w.r.t. SIS-18@GSI : x 10
- Ion beams up to 11 A GeV energy → $\sqrt{s_{NN}} = 2.9 \;...\; 4.9$ GeV (Au + Au)
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings
- Current estimate: SIS-100 commissioning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

Beam-Target Interaction Rates & Rare Probes' Yields

Particle Multiplicities (Statistical Hadronisation Model)

Au+Au $\sqrt{s_{NN}} = 4.7$ GeV



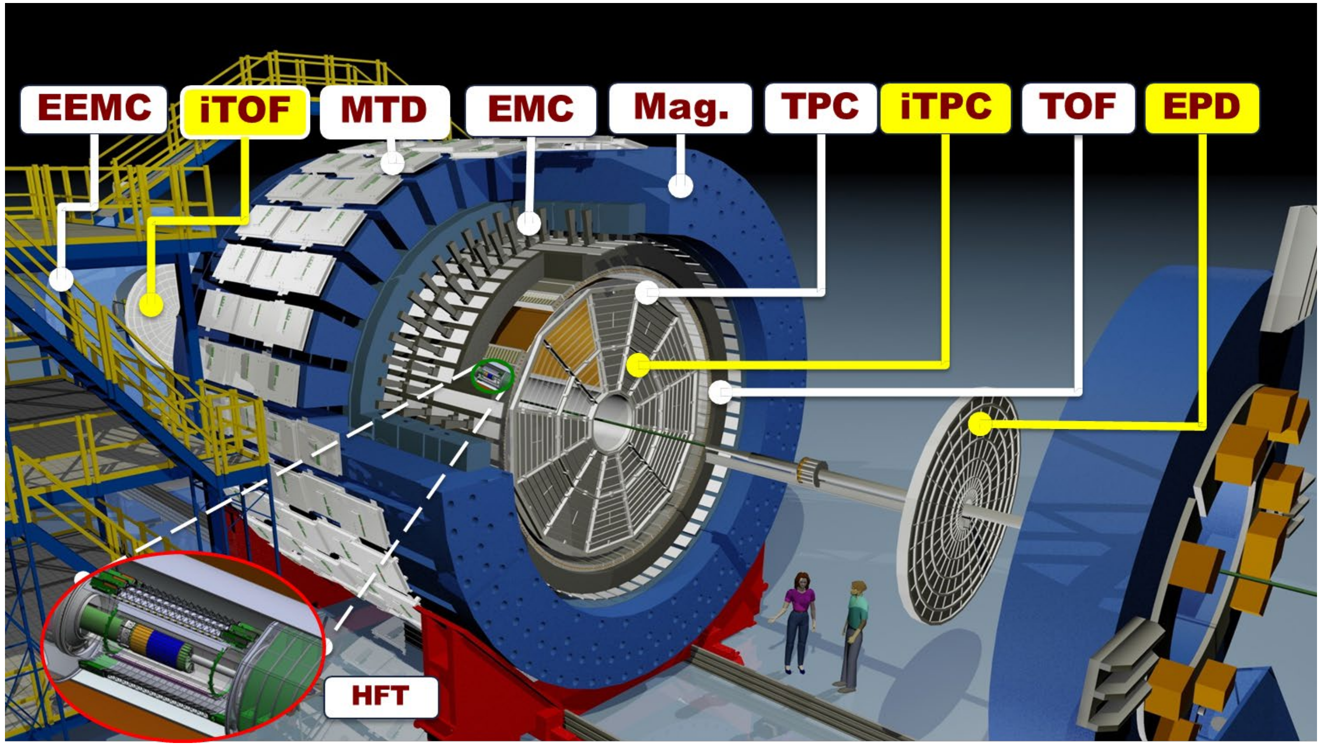


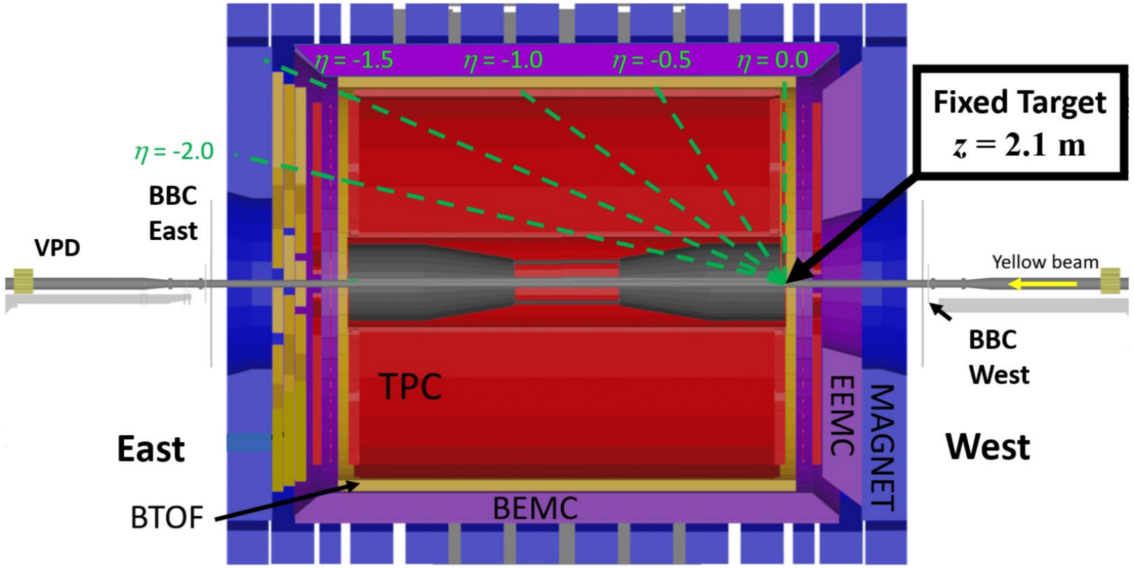
[CBM], Eur.Phys.J.A 53 (2017) 3, 60

T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169, update (06/2022)

Great complementarity between the CBM and STAR, both in terms of physics programmes and timelines, allowing CBM to build on the learnings from STAR-FXT

STAR Experimental Setup (Fixed-Target Mode; FXT)



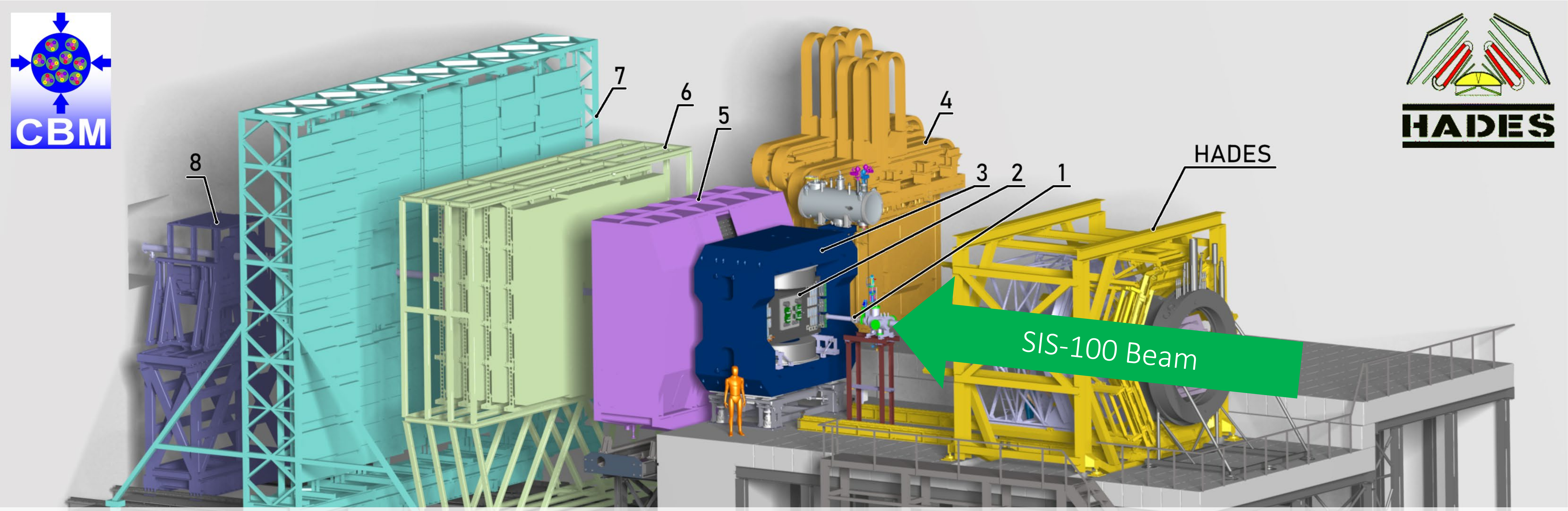


Au + Au Collisions at STAR (2018-21; Fixed-Target Mode)			
$\sqrt{s_{NN}}$ (GeV)	Events ($\times 10^6$)	$\sqrt{s_{NN}}$ (GeV)	Events ($\times 10^6$)
13.7	50	5.2	100
11.5	50	4.5	110
9.2	50	3.9	120
7.7	260	3.5	120
7.2	470	3.2	200
6.2	120	3.0	260 + 2000

N. Xu, EMMI Physics Day 2023

- STAR-RHIC operational since 2000 in collider mode (QGP-runs at $\sqrt{s_{NN}} = 200$ GeV)
- Fixed target setup allows to probe lower energies ($\sqrt{s_{NN}} = 13.7\ \dots\ 3$ GeV), i.e., higher baryonic densities ($\mu_B = 721\ \dots 276$ MeV)
- At $\sqrt{s_{NN}} = 3$ 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)

CBM Experimental Setup @ SIS-100

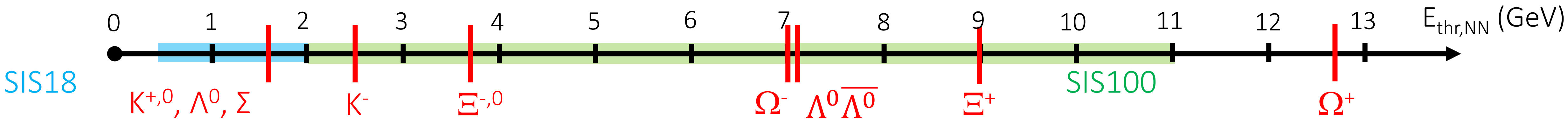


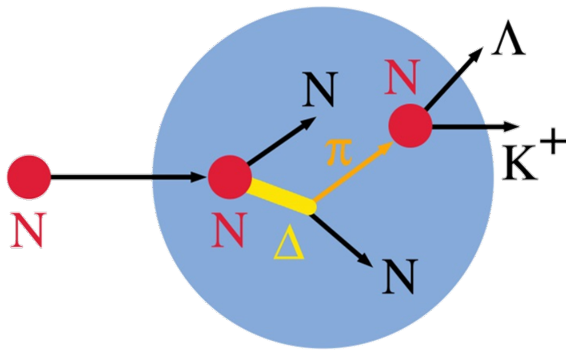
1. Time-Zero Detector and Beam Diagnostics
2. Silicon Tracking System and Micro Vertex Detector
3. Superconducting Dipole Magnet
4. Muon Chambers
5. Ring Imaging Cherenkov Detector
6. Transition Radiation Detector
7. Time of Flight Detector
8. Forward Spectator Detector

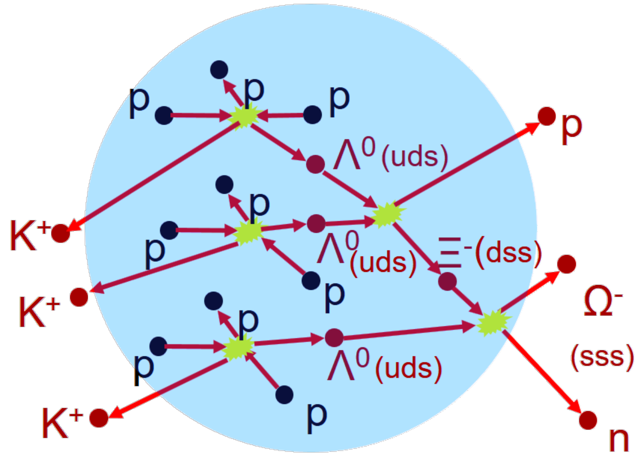
- Determination of vertices ($\sigma \approx 50\ \mu$m)
- Identification of leptons and hadrons
- Di-electron and muon setup
- Fast and radiation hard detectors
- Trigger-less free-streaming readout
- Online event selection
- 4-D event reconstruction
- Operation with beam from 2028-29

H. Zbroszczyk (08.11)

Observable #1: Sub-Threshold Strangeness Production

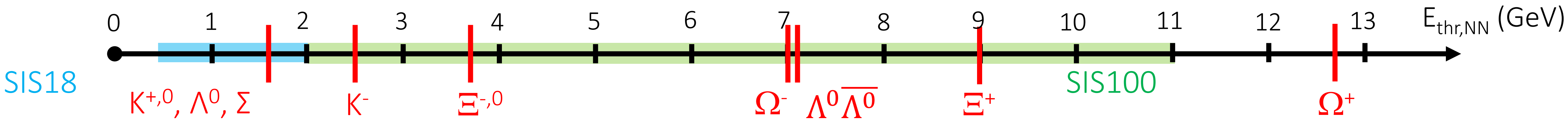


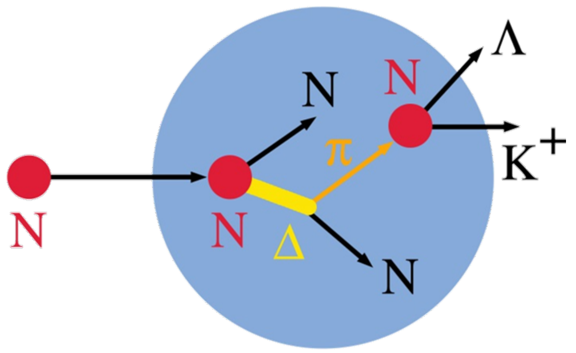


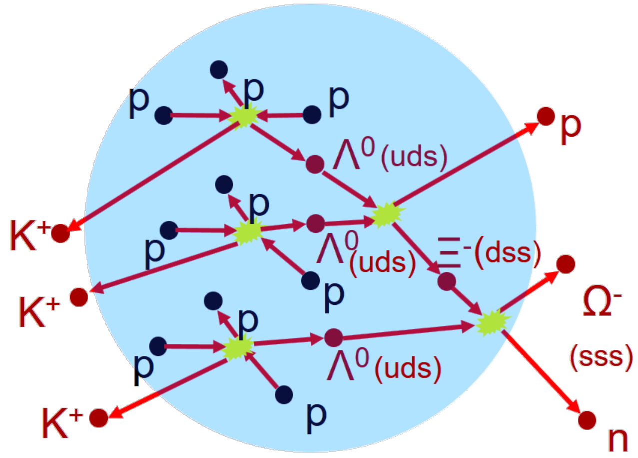


- Sub-threshold production of (multi-)strange hadrons can be achieved from the multiple collisions of nucleons, produced particles, and short-lived resonances → sensitivity of EOS

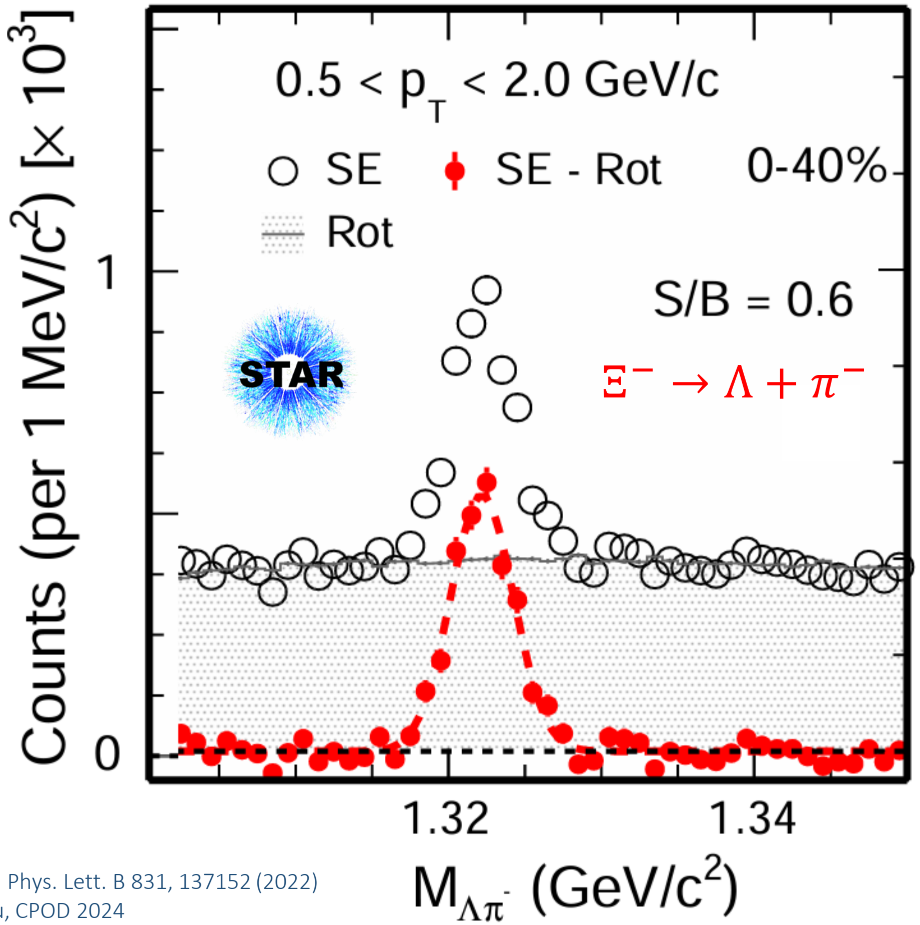
Observable #1: Sub-Threshold Strangeness Production





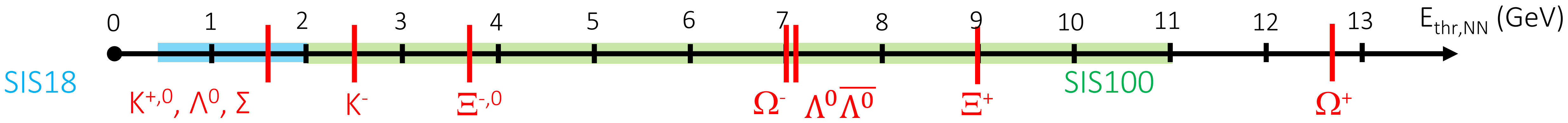


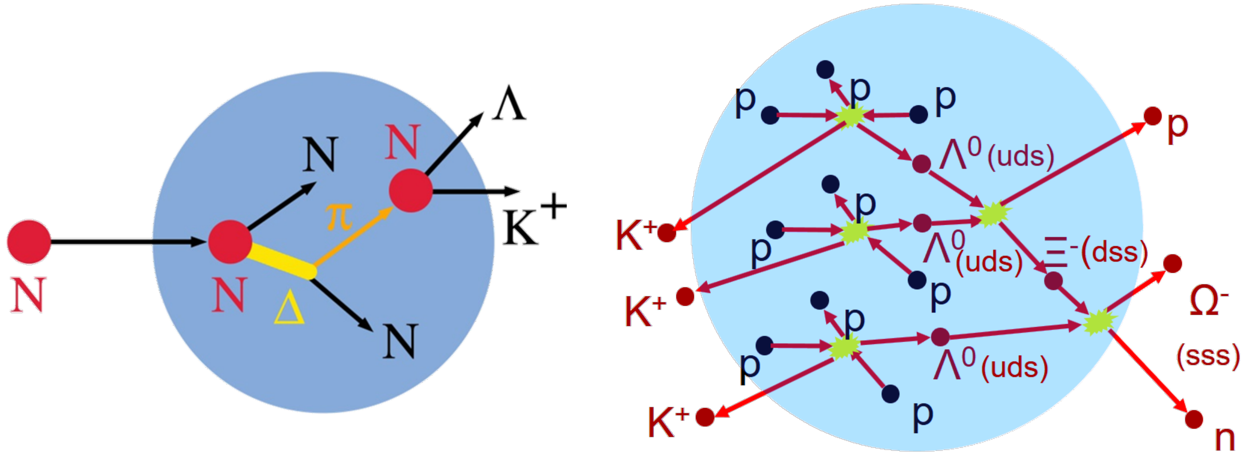
- Sub-threshold production of (multi-)strange hadrons can be achieved from the multiple collisions of nucleons, produced particles, and short-lived resonances → sensitivity of EOS
- STAR-FXT performed first measurements of sub-threshold Ξ^- production at $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions

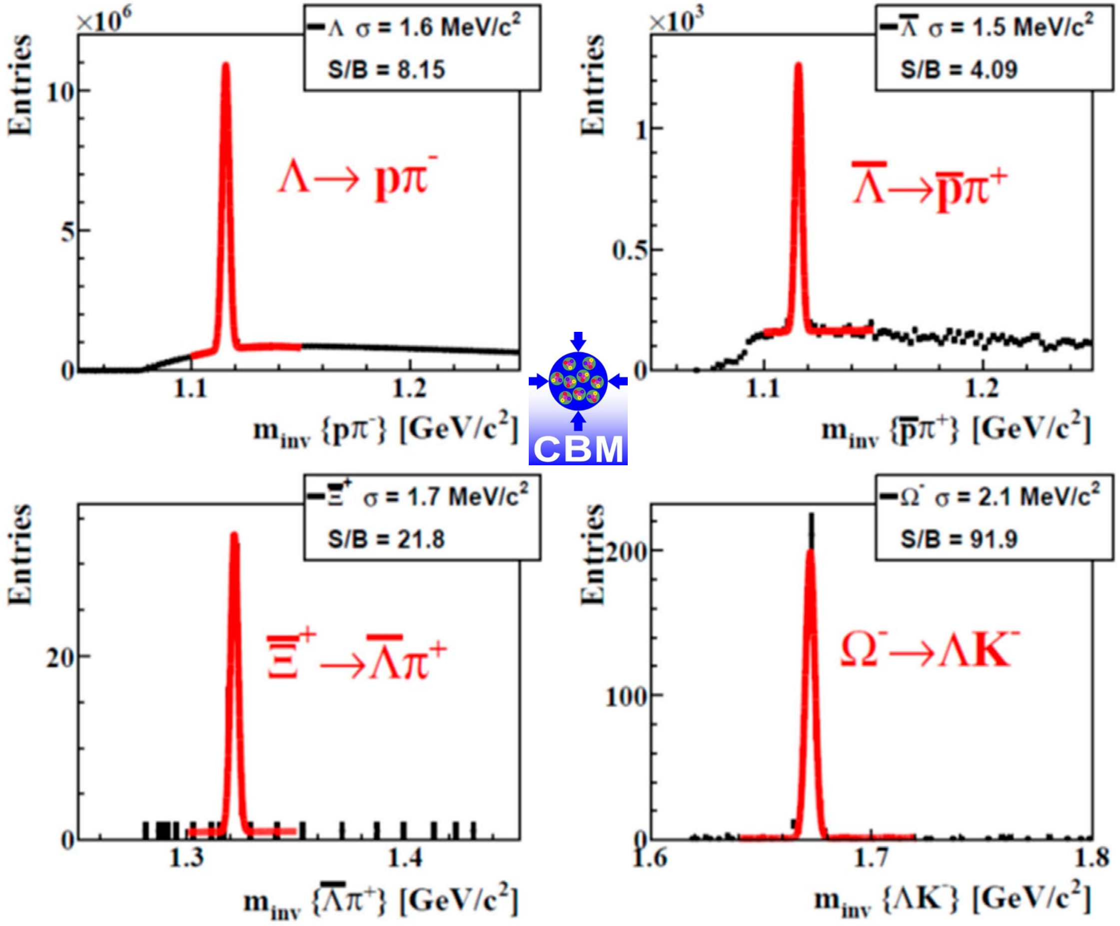


[STAR], Phys. Lett. B 831, 137152 (2022)
Y. Zhou, CPOD 2024

Observable #1: Sub-Threshold Strangeness Production



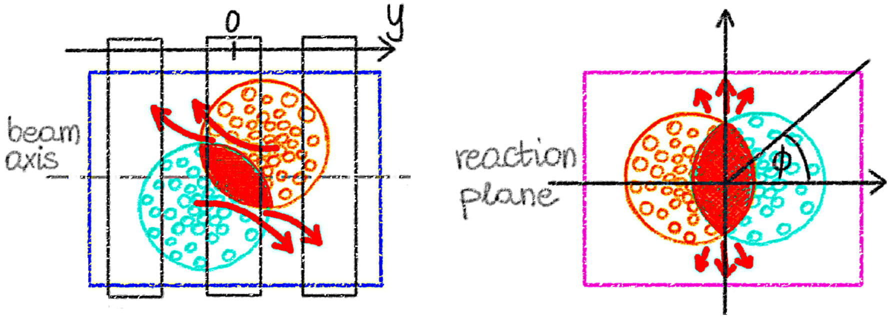




- Sub-threshold production of (multi-)strange hadrons can be achieved from the multiple collisions of nucleons, produced particles, and short-lived resonances → sensitivity of EOS
- STAR-FXT performed first measurements of sub-threshold Ξ^- production at $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions
- High-rate capabilities of CBM allows it to access other multi-strange particles with lower production multiplicities
- Reconstruction based on the dedicated KFParticleFinder package, same for both experiments

I. Vassiliev et al., CBM Progress Report 2019 (2020)

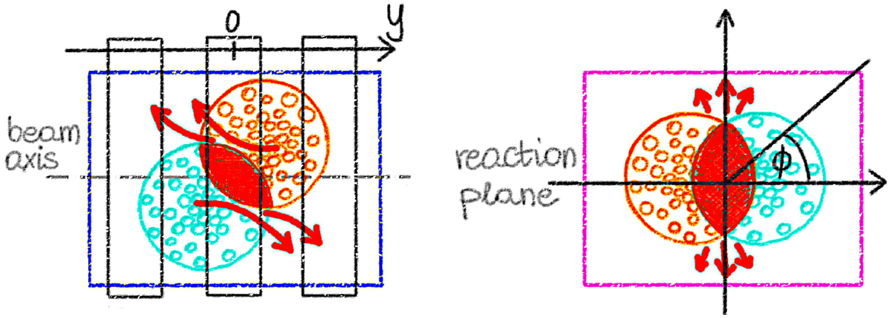
Observable #2: Collective Flow (v_1, v_2)



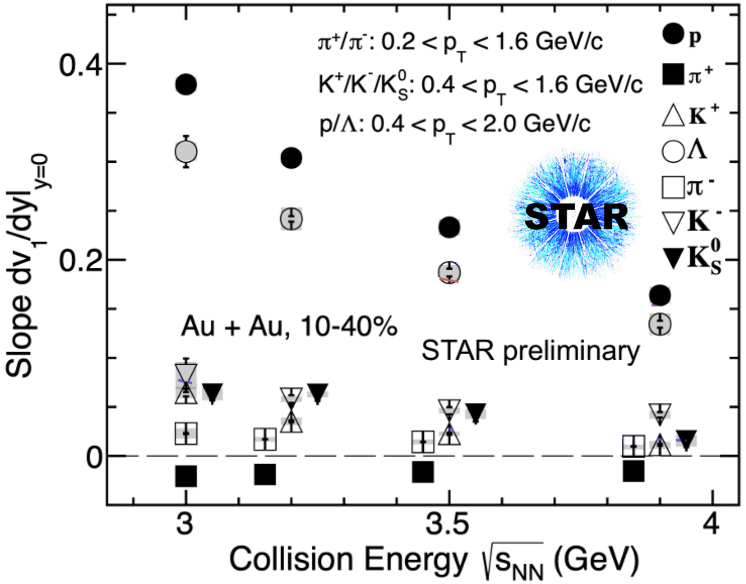
L. Du et al., Int.J.Mod.Phys.E 33 (2024) 07, 2430008

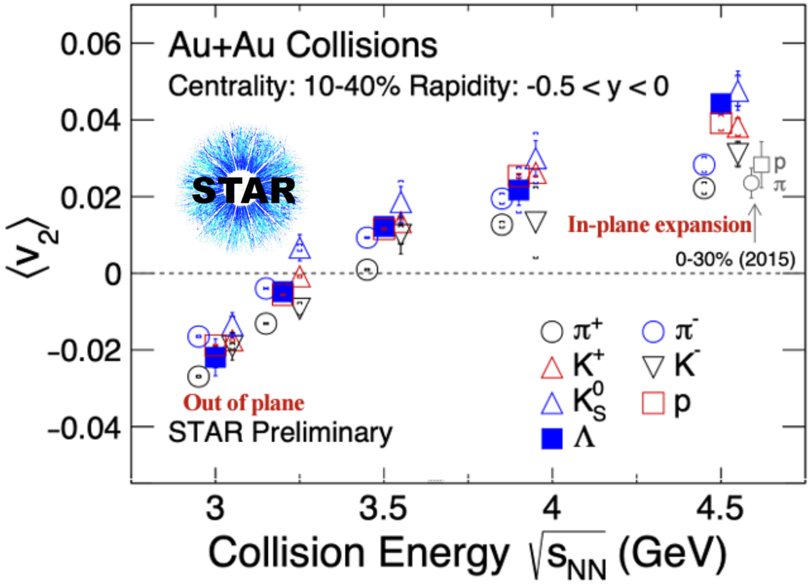
- Collective flow driven by the pressure gradient in the fireball and thus carry the information about the underlying EOS

Observable #2: Collective Flow (v_1, v_2)



L. Du et al., Int.J.Mod.Phys.E 33 (2024) 07, 2430008

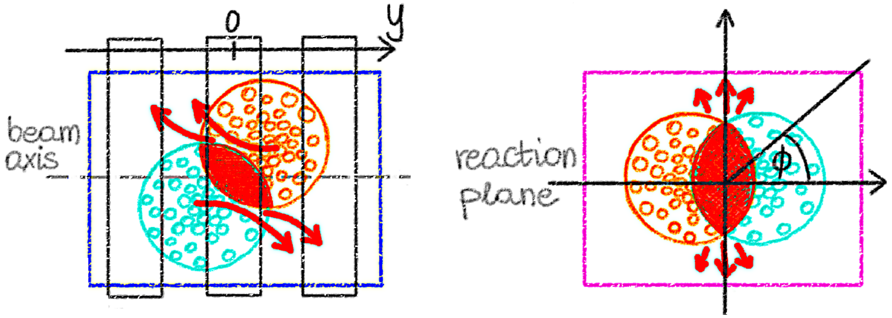




[STAR], SQM and CPOD 2024

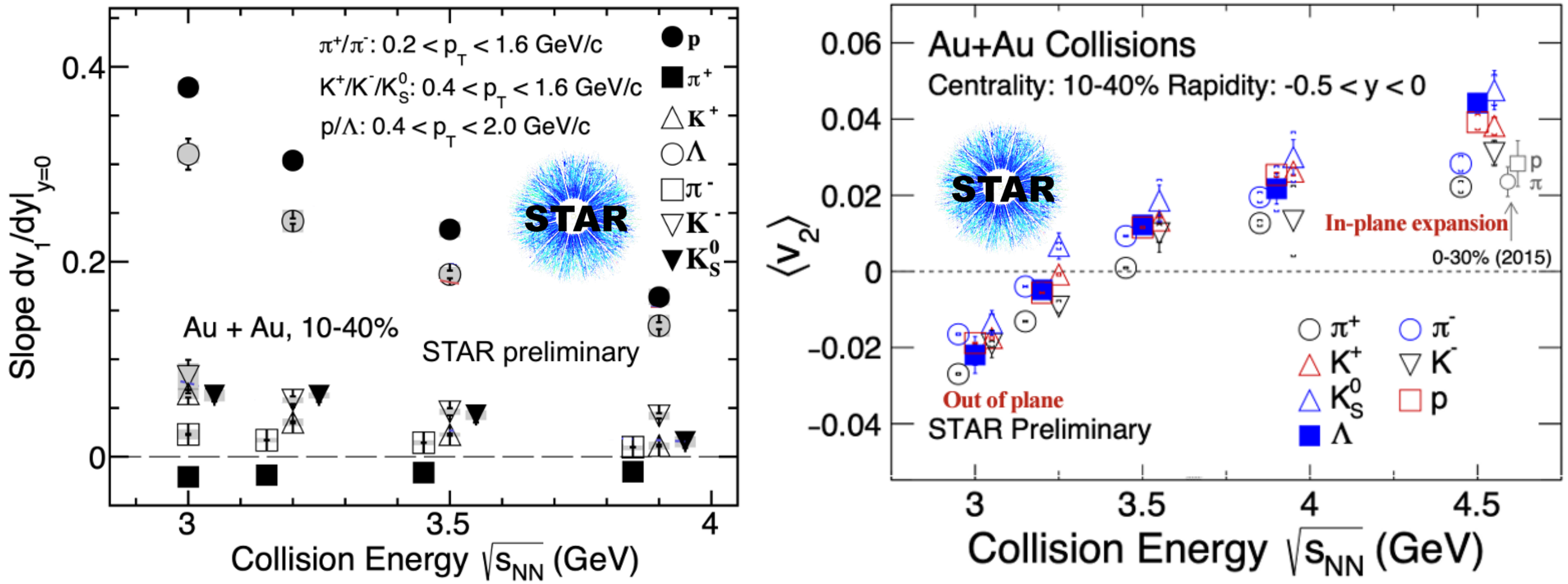
- Collective flow driven by the pressure gradient in the fireball and thus carry the information about the underlying EOS
- STAR-FXT has preliminarily done collective flow analysis for commonly produced mesons (π^+, π^-, K_S^0) and Lambda (Λ) at the high-baryon density region ($\sqrt{s_{NN}} = 3.0 \ldots 3.9$ GeV). Further extensive multi-differential analyses are ongoing
- NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.9 to 4.5 GeV

Observable #2: Collective Flow (v_1, v_2)

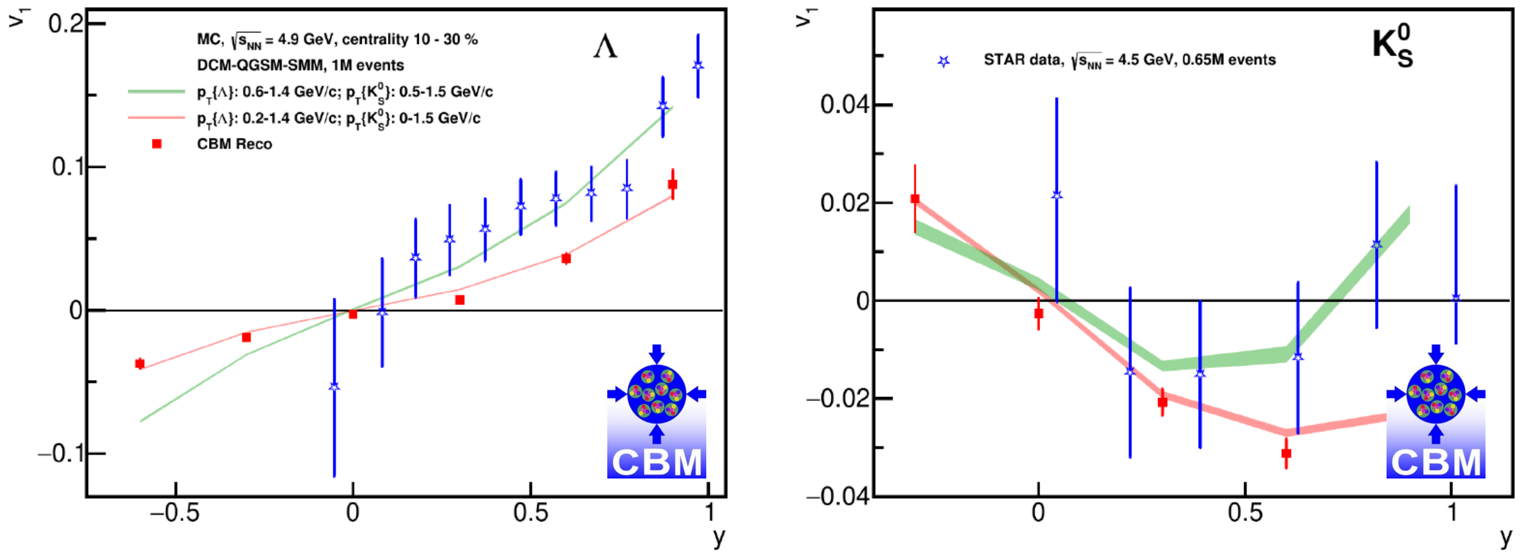


L. Du et al., Int.J.Mod.Phys.E 33 (2024) 07, 2430008

- Collective flow driven by the pressure gradient in the fireball and thus carry the information about the underlying EOS
- 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
- NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.9 to 4.5 GeV
- High-rate capability of CBM can enable a precise multi-differential flow analyses of not only protons, but of strange hadrons too. v_1 analyses tools have been developed and for high-harmonics are under development.



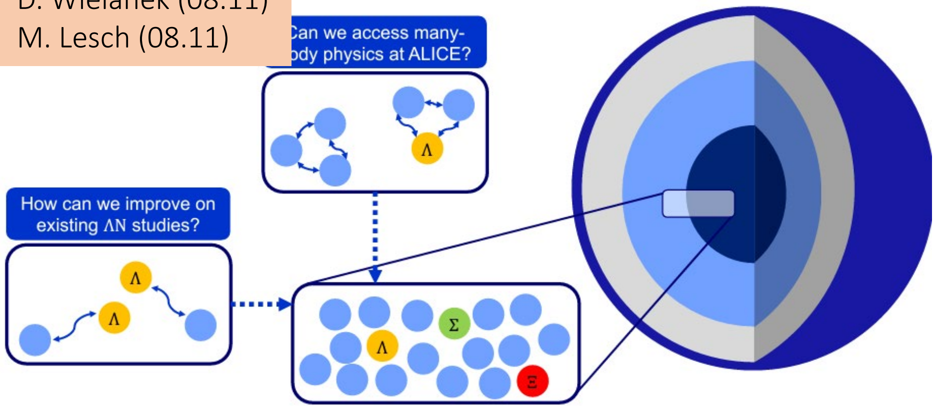
[STAR], SQM and CPOD 2024

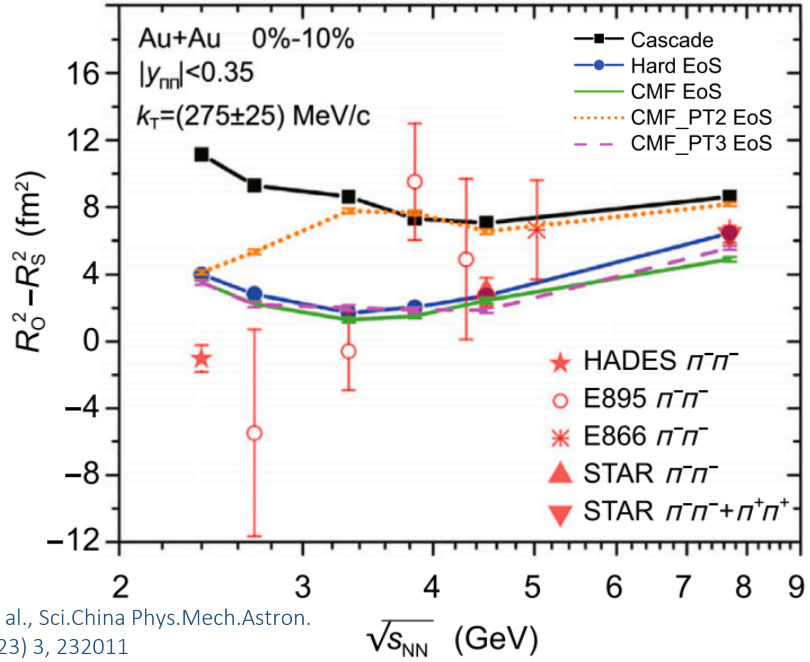


O. Lubynets, FAIRNESS 2022
[STAR], Phys. Rev. C 103, 034908 (2021)

OBSERVABLE #3: FEMTPSCOPY & PARTICLE CORRELATIONS

D. Wielanek (08.11)
M. Lesch (08.11)



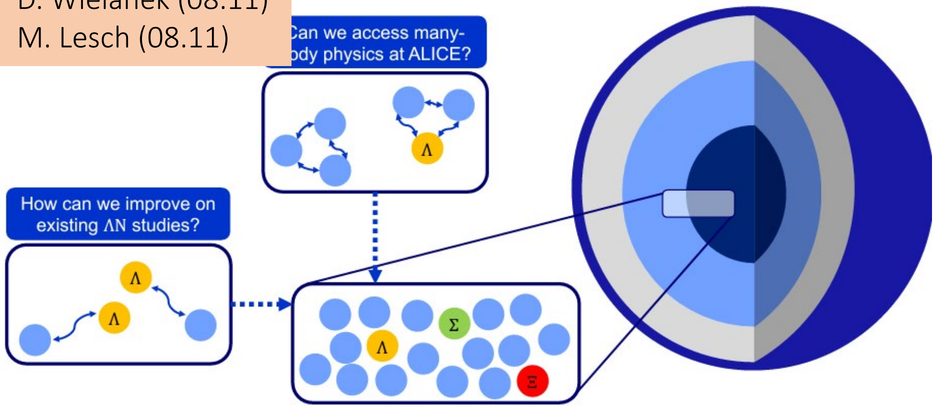


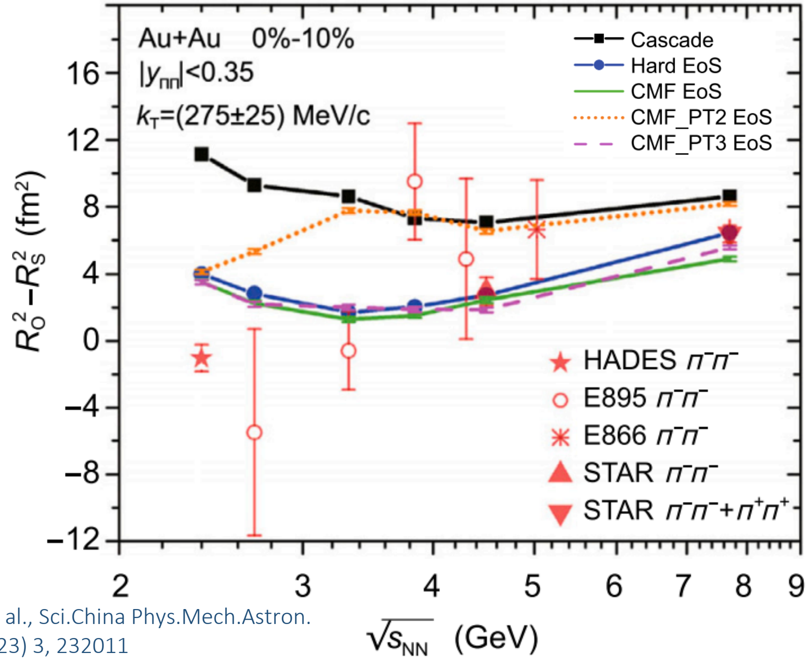
P. Li et al., Sci.China Phys.Mech.Astron. 66 (2023) 3, 232011

- Femtoscopy gives us access to (a) 2- and 3- body YN interactions are key to understand the nuclear structure neutron stars, (b) space-time extent of the produced fireball in HIC

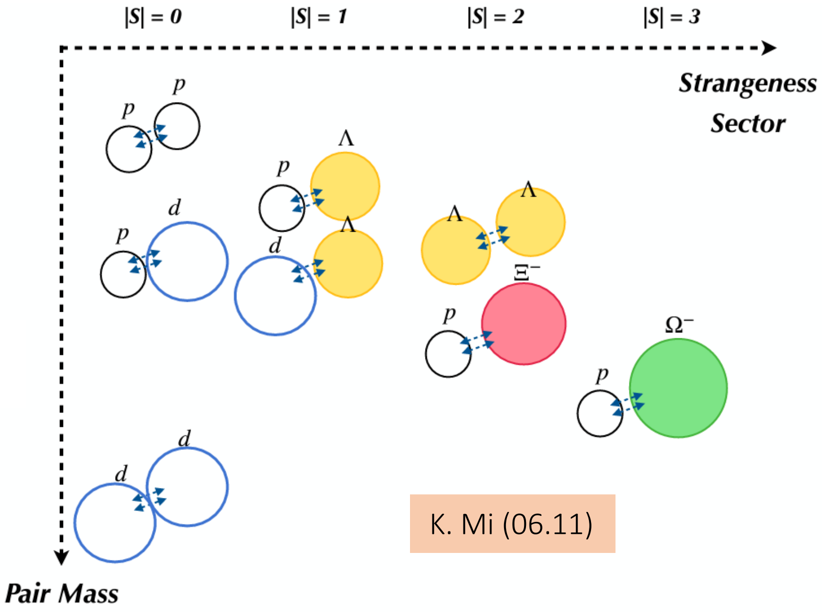
OBSERVABLE #3: FEMTPSCOPY & PARTICLE CORRELATIONS

D. Wielanek (08.11)
M. Lesch (08.11)

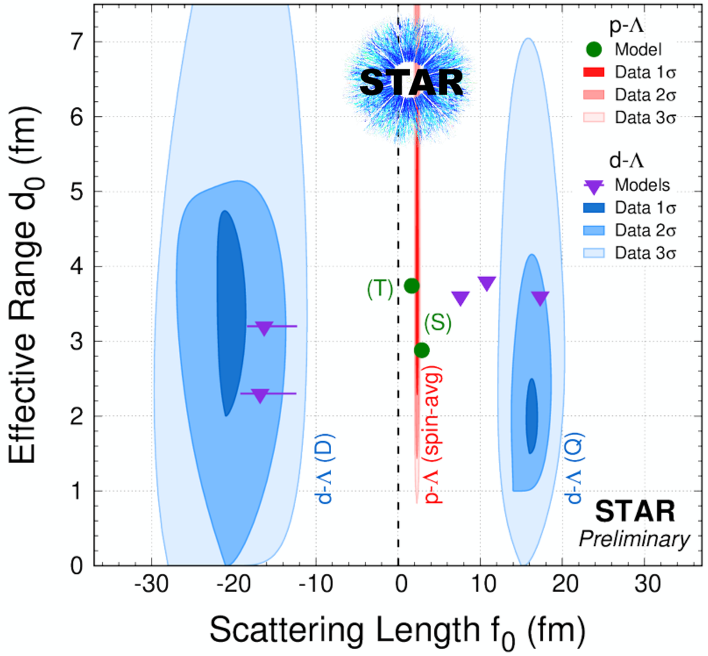




P. Li et al., Sci.China Phys.Mech.Astron. 66 (2023) 3, 232011



K. Mi (06.11)

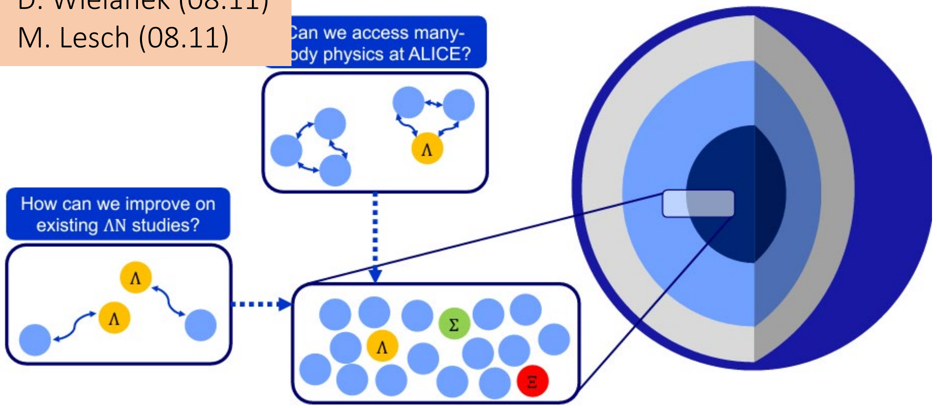


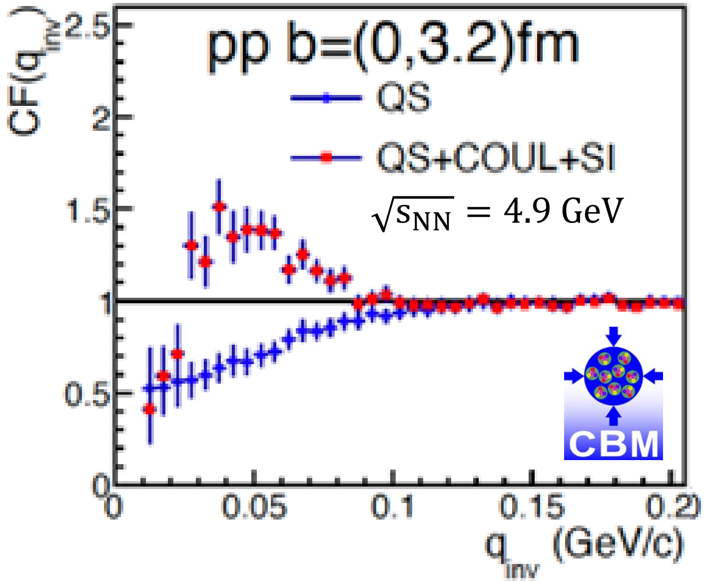
- Femtoscopy gives us access to (a) 2- and 3- body YN interactions are key to understand the nuclear structure neutron stars, (b) space-time extent of the produced fireball in HIC
- STAR has analysed the nature of several 2-body YY and YN interactions during BES-I
- More statistics during BES-II will enable correlation measurements with different species and getting an azimuthal picture of the emission source

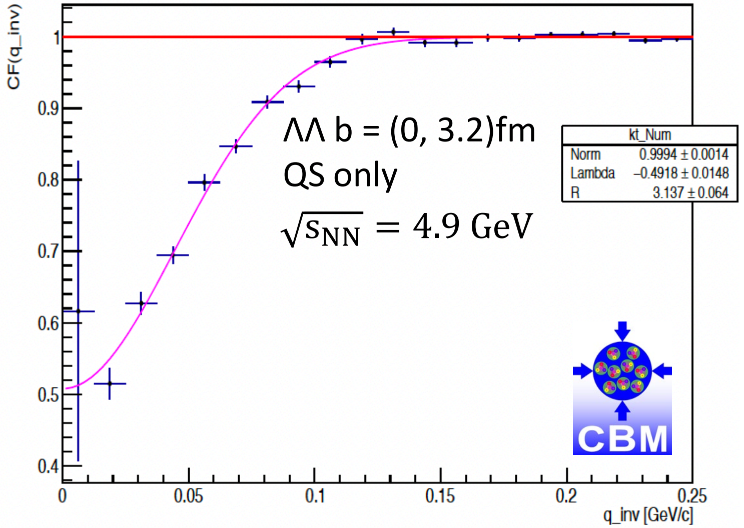
Y. Khyzhniak (04.11)

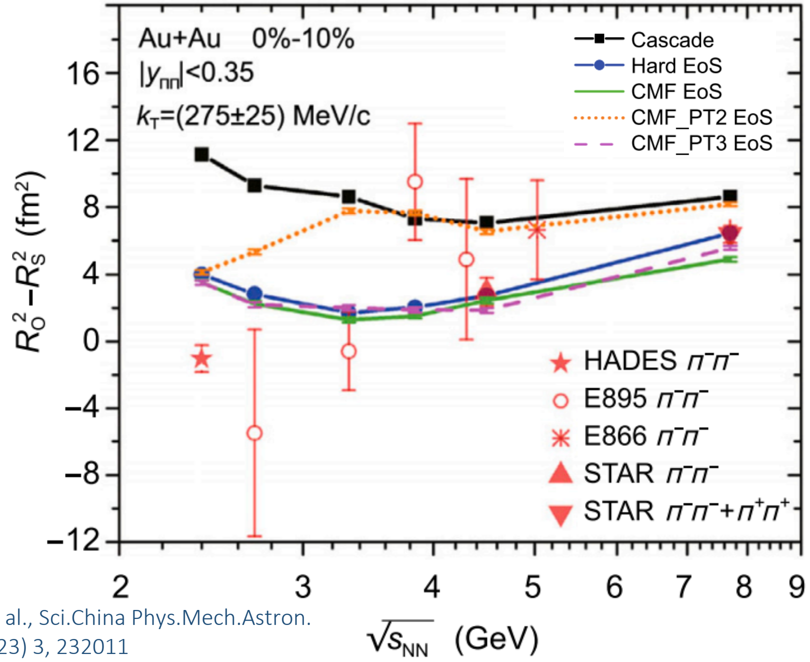
Observable #3: Femtpscopy & Particle Correlations

D. Wielanek (08.11)
M. Lesch (08.11)









P. Li et al., Sci.China Phys.Mech.Astron. 66 (2023) 3, 232011

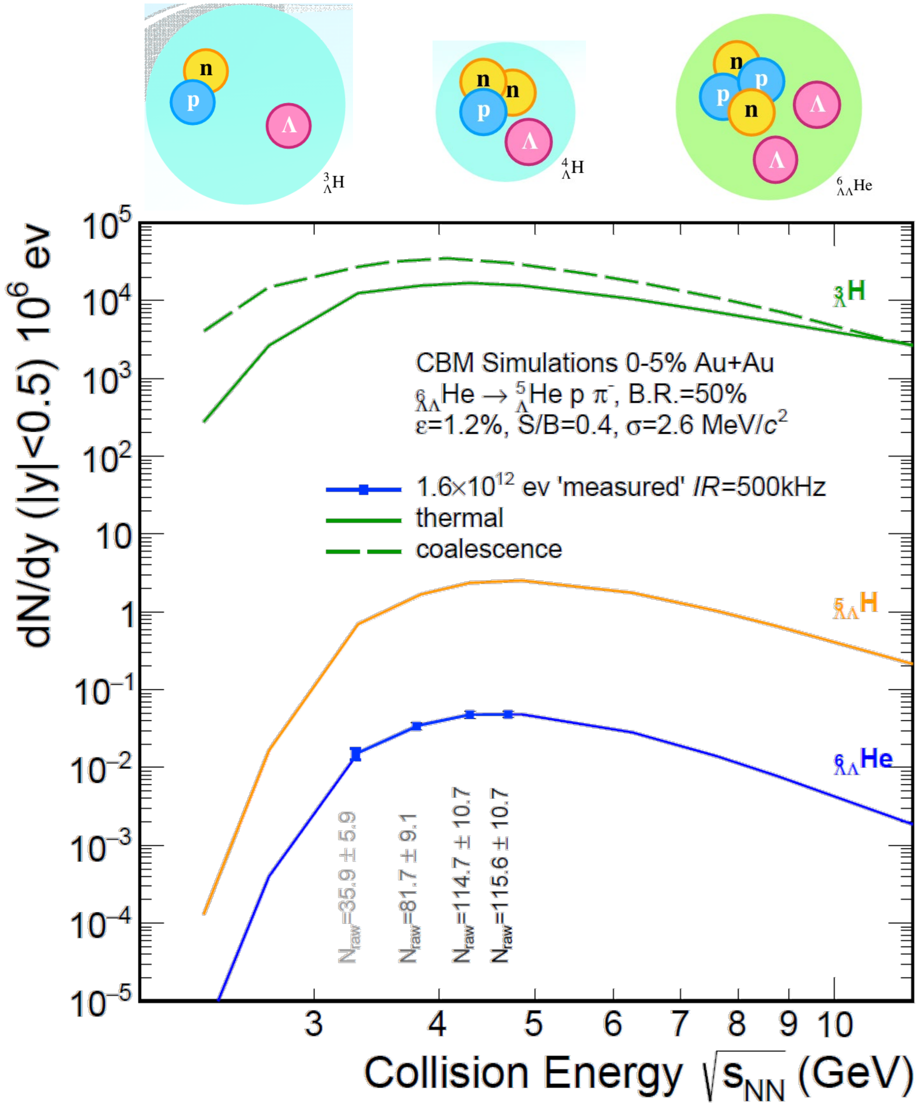
- Femtoscopy gives us access to (a) 2- and 3- body YN interactions are key to understand the nuclear structure neutron stars, (b) space-time extent of the produced fireball in HIC
- STAR has analysed the nature of several 2-body YY and YN interactions during BES-I
- More statistics during BES-II will enable correlation measurements with different species and getting an azimuthal picture of the emission source

Y. Khyzhniak (04.11)

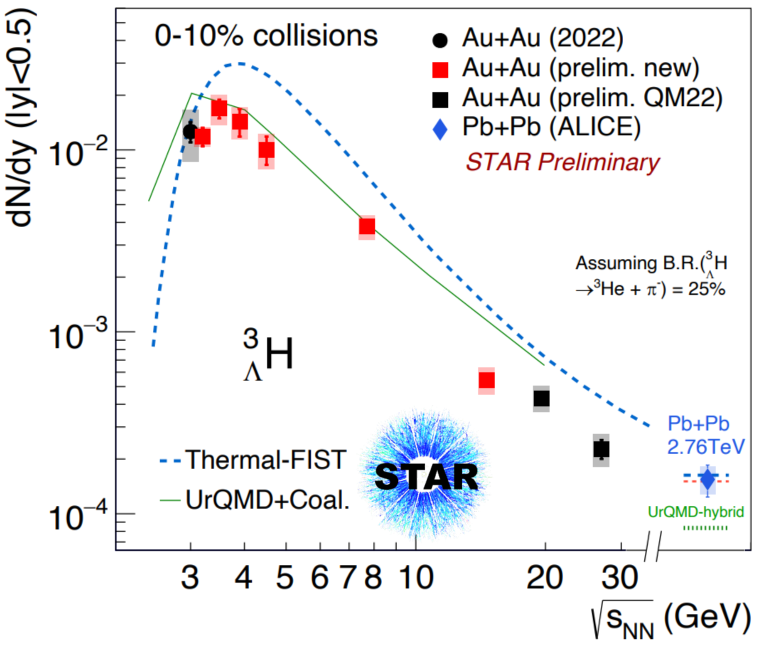
- The currently large experimental uncertainties on emission source represent an opportunity for CBM to explore azimuthally dependent femtoscopy

Chi Kin Tam (06.11)
P. Nzabahimana (06.11)

Observable #4: Hypernuclei Properties



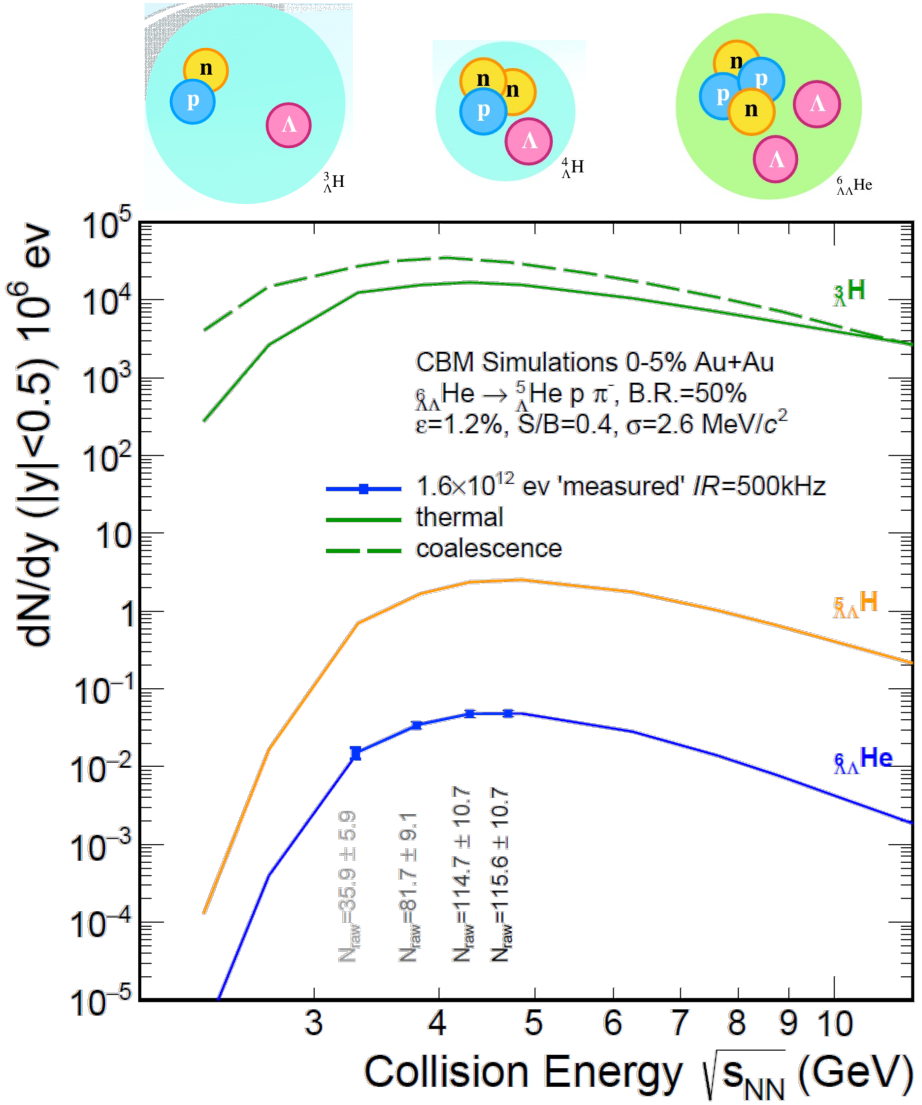
Thermal: A. Andronic et al., Phys.Lett.B 697 (2011) 203-207
Coalescence: J. Steinheimer et al., Phys.Lett.B 714 (2012) 85-91



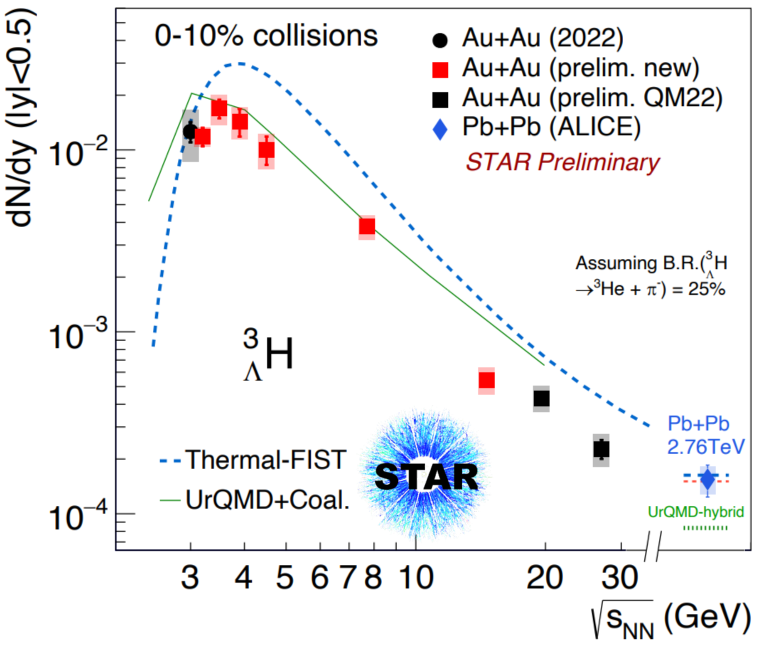
[STAR] Phys.Rev.Lett. 128 (2022) 20, 202301
Yue Hang Leung, CPOD 2024

- STAR-FXT at BES-I has shown its capabilities to do differential yield measurements and flow analyses for $^{3}_{\Lambda}$H hypernuclei for a range of energies. Studies for heavier hypernuclei ongoing at BES-II ($^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He, $^{6}_{\Lambda}$H).
- Production mechanism? Probed densities?

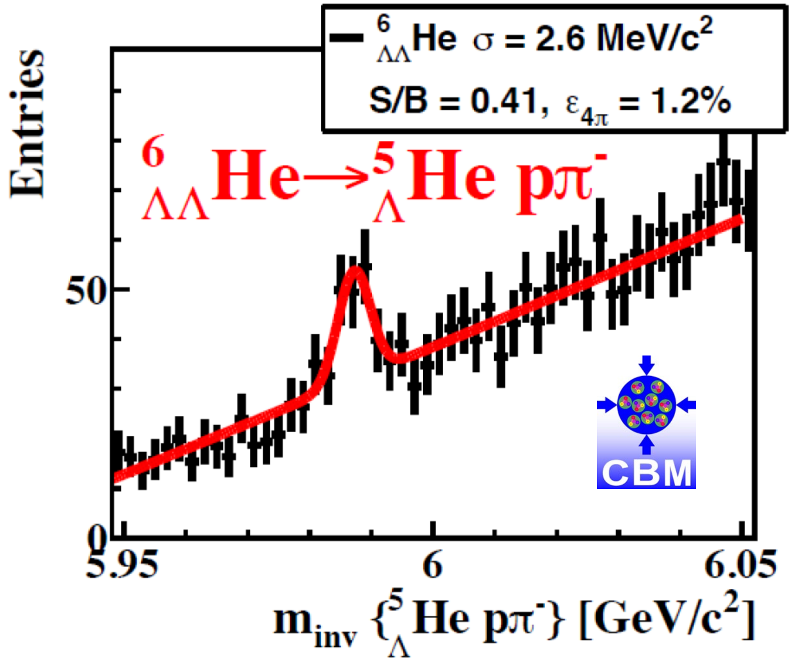
Observable #4: Hypernuclei Properties



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



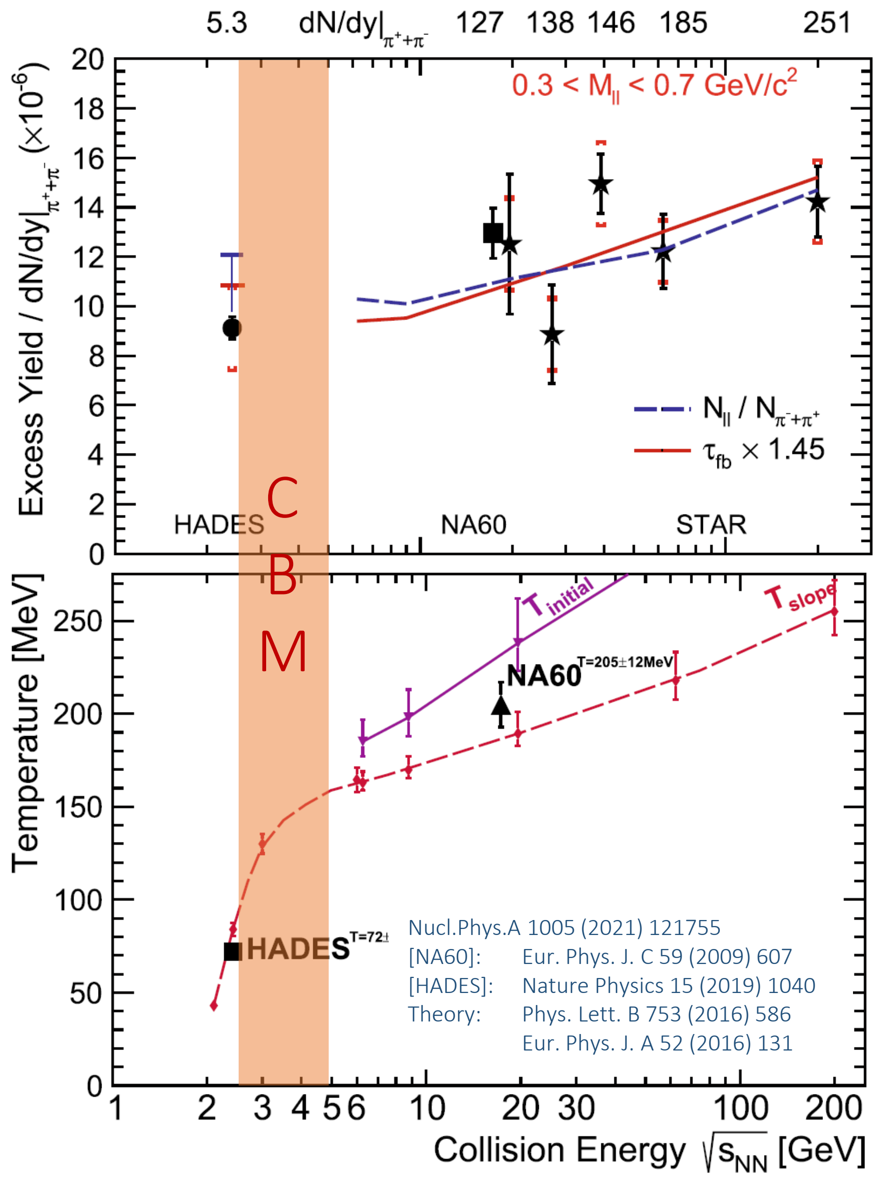
[STAR] Phys.Rev.Lett. 128 (2022) 20, 202301
Yue Hang Leung, CPOD 2024



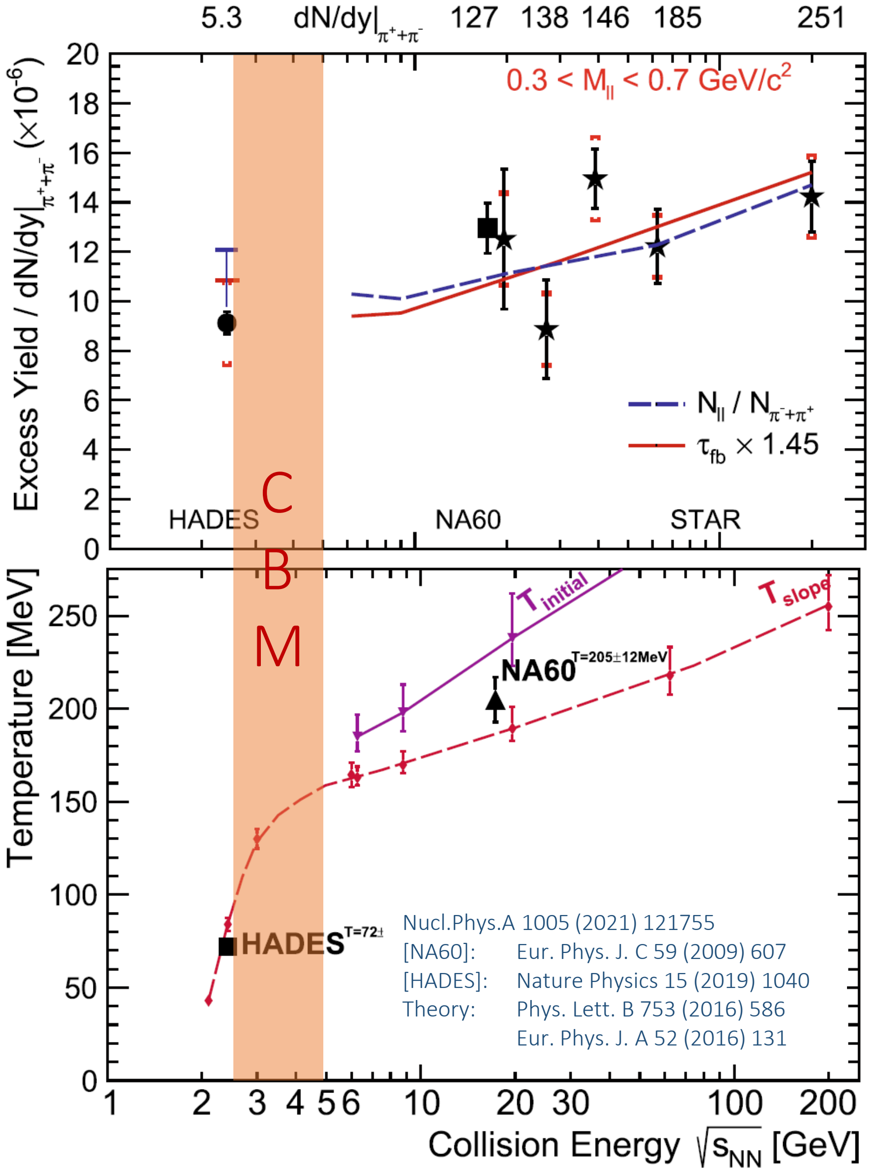
S. Glässel [CBM], Quark Matter 2023
I. Vassiliev [CBM], Strangeness in Quark Matter 2024

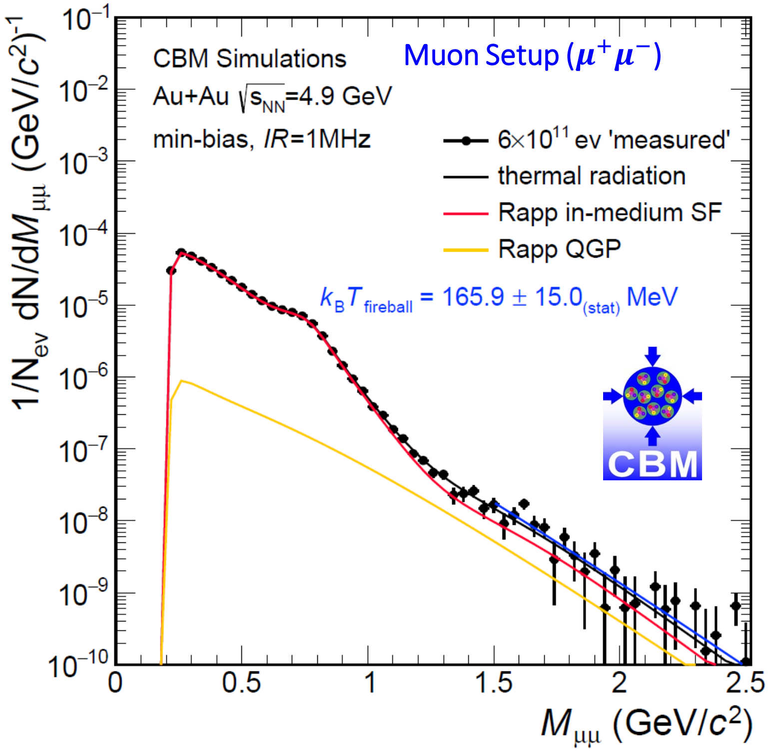
- STAR-FXT at BES-I has shown its capabilities to do differential yield measurements and flow analyses for $^{3}_{\Lambda}H$ hypernuclei for a range of energies. Studies for heavier hypernuclei ongoing at BES-II ($^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$, $^{6}_{\Lambda}H$).
- Production mechanism? Probed densities?
- Approx. 100 $^{6}_{\Lambda\Lambda}He$ signal counts at 0.5 MHz interaction rate for 90 days of CBM running
- Reconstruction based on the dedicated KFParticleFinder package, same for both experiments. Therefore, tools in place to conduct multi-differential analysis to probe hypernuclei production

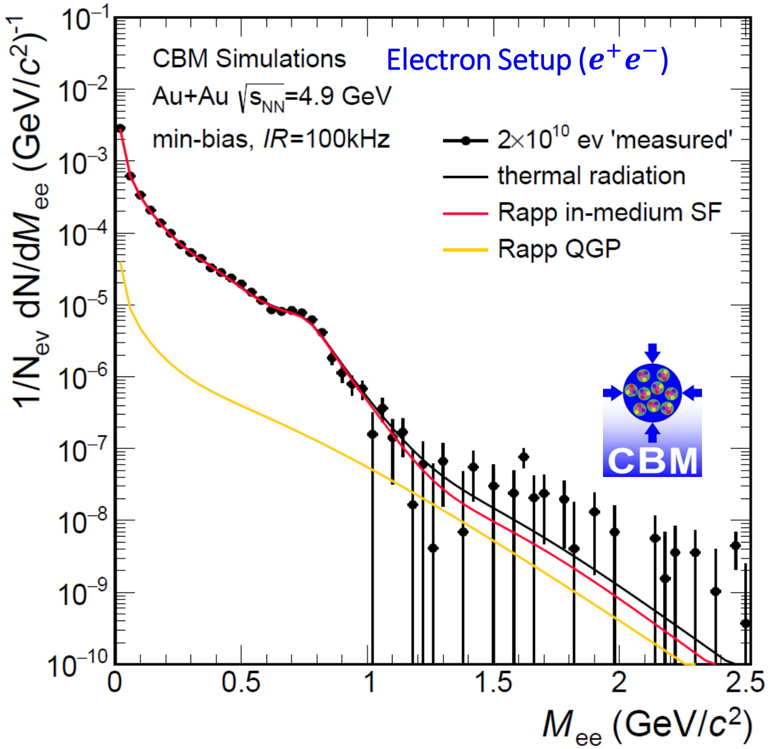
OBSERVABLE #5: FIREBALL LIFETIME & TEMPERATURE



Observable #5: Fireball Lifetime & Temperature



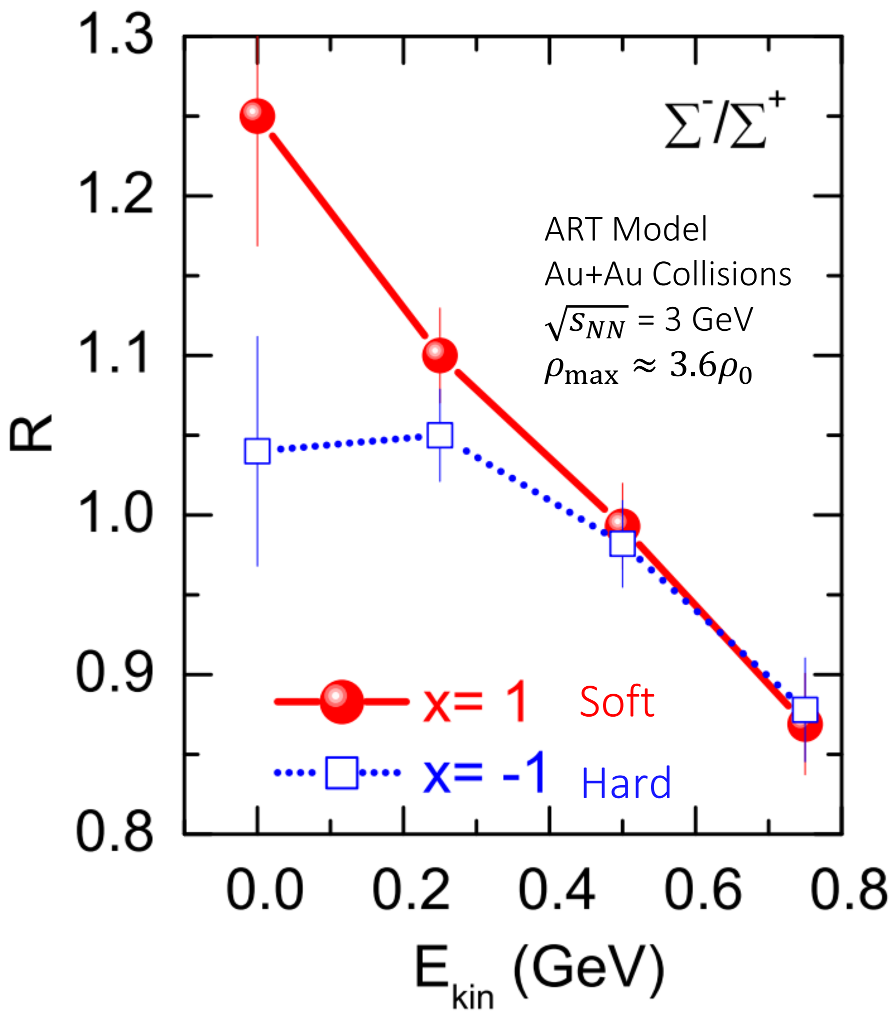




- Performance studies with realistic detector geometries, material budget, and response for both, muon ($\mu^+\mu^-$) and electron setup (e^+e^-)
- Access to thermal signal is feasible with good background description; Mass Resolution $\sigma_{M_{ll}}(\omega)$ = 14 MeV/c²

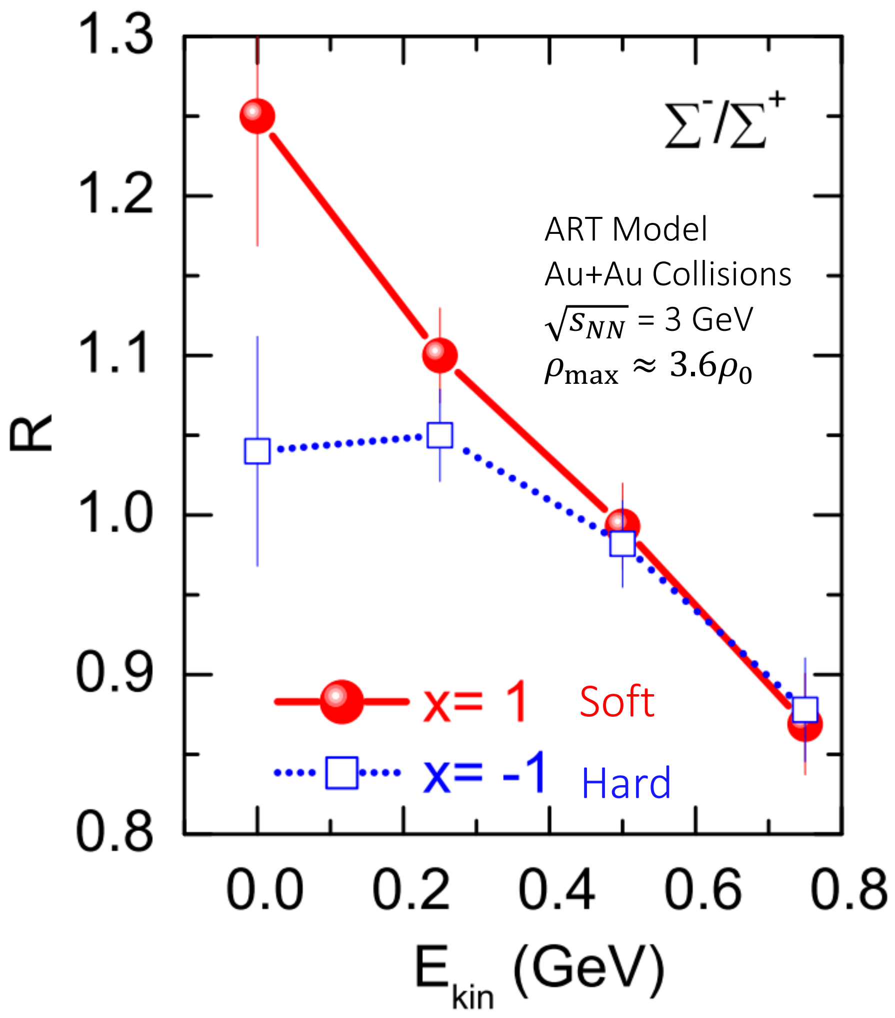
CBM, operable in muon- and electron-setup, can efficiently detect dileptons to scan the energy dependence of fireball properties (lifetime, temperature, lifetime, …) to detect potential phase transition signatures

Observable #6: $(n/p)_{\text{like}}$ Particle Ratios



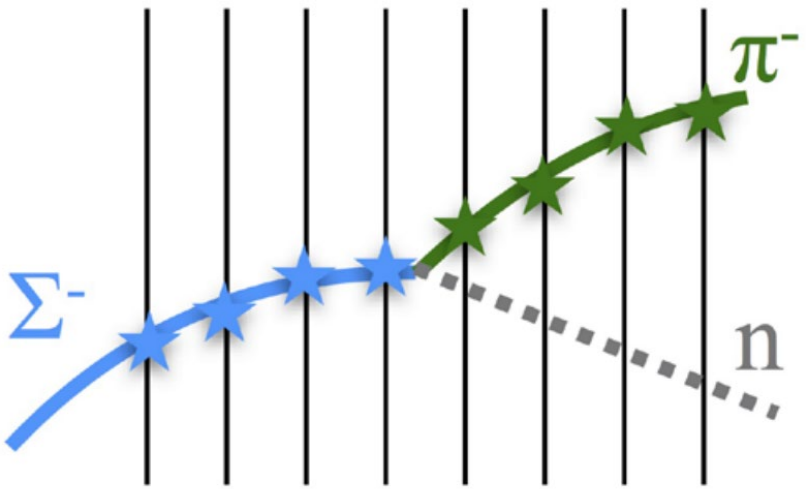
G-C. Yong et al., Phys. Rev. C 106, 024902 (2022)

OBSERVABLE #6: $(n/p)_{\text{like}}$ PARTICLE RATIOS

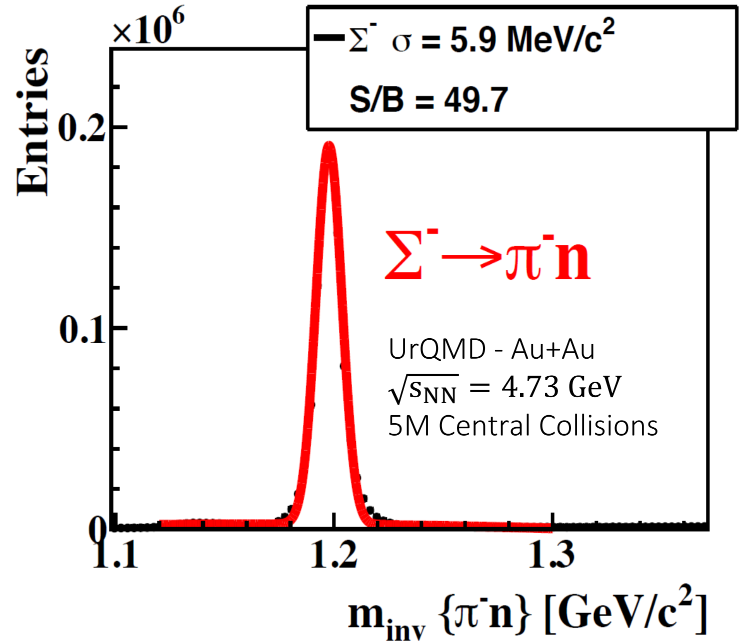


G-C. Yong et al., Phys. Rev. C 106, 024902 (2022)

- 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

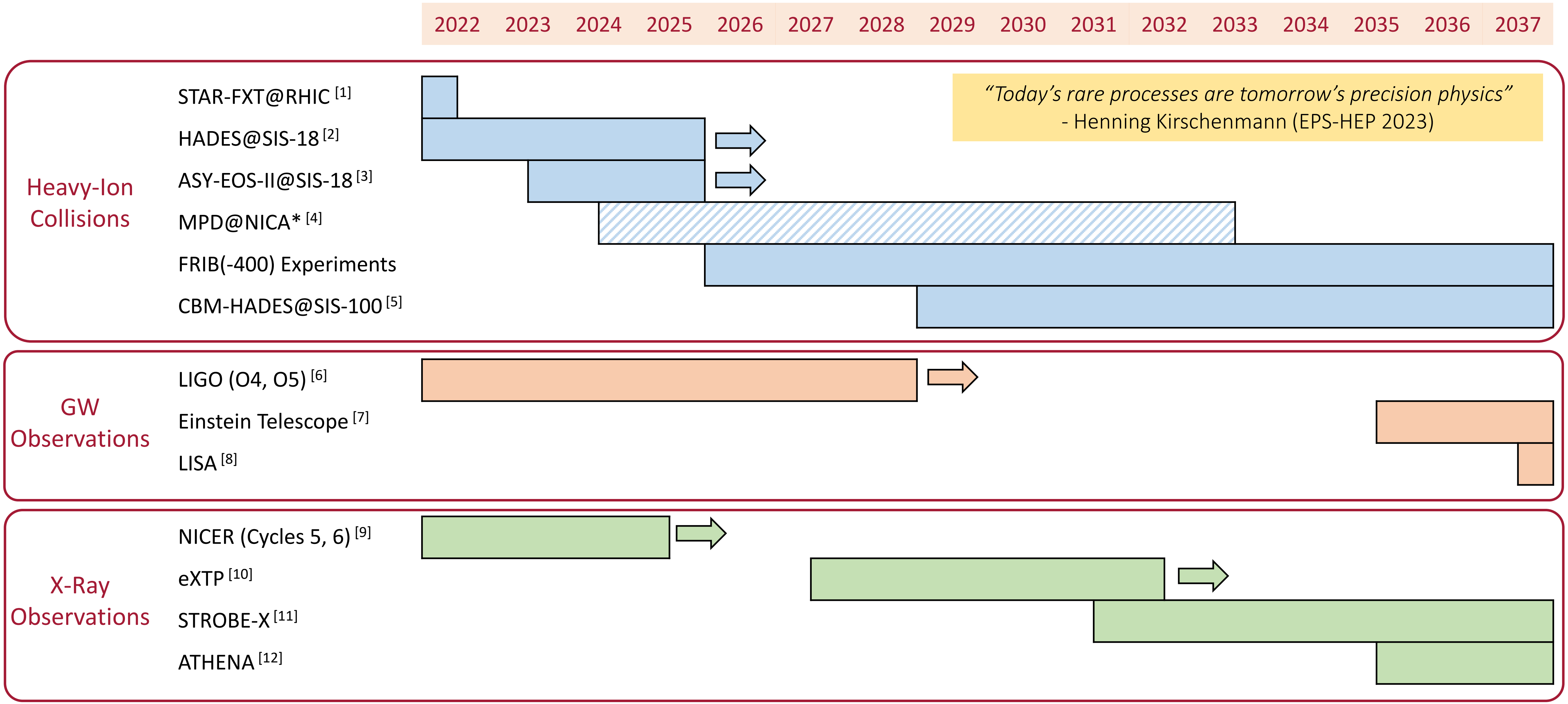


P. Kisel et al., EPJ Web Conf. 173 (2018) 04009



The vertexing and tracking detectors of CBM 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

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



[1] D. Morrison, Quark Matter 2022 | Link
[2] Proposal for Beamtime in 2023-24, GSI G-PAC
[3] Proposal for Beamtime in 2023-24, GSI G-PAC
[4] I. Maldonado, A. Ayala, EuNPC 2022 | Link
[5] 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 | Link
[12] ATHENA ESA Factsheet | Link

A Potential Path Ahead

Dense Nuclear Matter Equation of State from Theory and Experiments

28 October 2024 to 1 November 2024
IRL-NPA FRIB
US/Eastern timezone

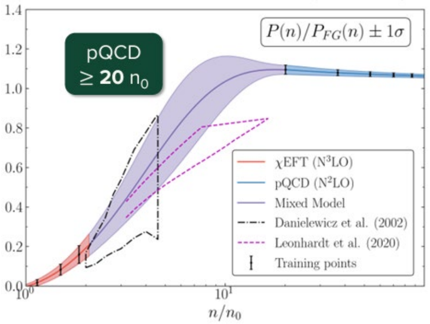
FRIB · IRL NPA CNRS-MSU

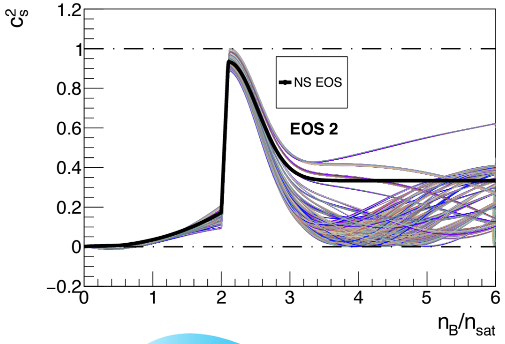
https://indico.in2p3.fr/event/33316/overview

Need for collaboration, common standards & methods, open data, better models & flexible tools

ELSEVIER
Progress in Particle and Nuclear Physics
Available online 19 September 2023, 104080
In Press, Journal Pre-proof ⓘ What's this?

Review
Dense nuclear matter equation of state from heavy-ion collisions





Dimensionality Reduction in Nuclear Physics – Presented by ASCSN

BAND – Bayesian Analysis of Nuclear Dynamics

NMMA

muses

and several other frameworks discussed at other forums …
Hopefully, some convergence at some point in time!

SUMMARY AND OUTLOOK (KEY QUESTIONS)

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

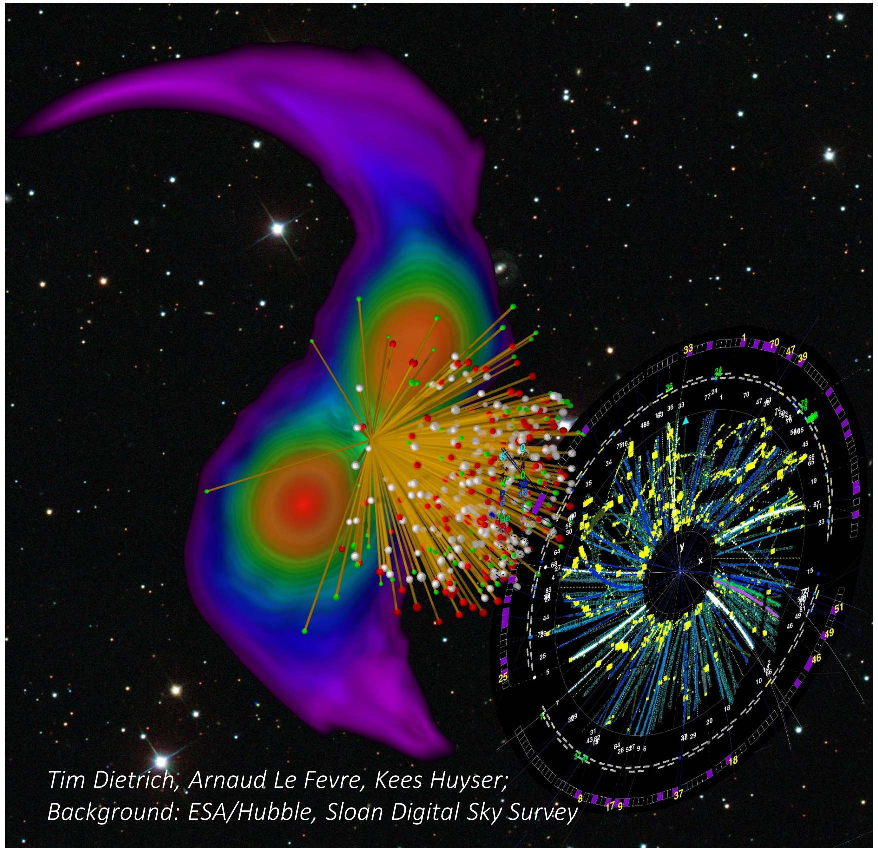
STAR-FXT@RHIC ($\sqrt{s_{NN}} = 13.7 \ldots 3$ GeV) and CBM@SIS-100 ($\sqrt{s_{NN}} = 2.9 \ldots 4.9$ GeV) are crucial to constraint high-density EOS, where the only reliable info comes from MMA

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

- Collective Flow excitations functions analysed ($\pi^+, \pi^-, K^0_S, \Lambda$)
- 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…*



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

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, where there are some community-wide developments…

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

THANK YOU ☺

And to the following for providing the necessary insights for this review:

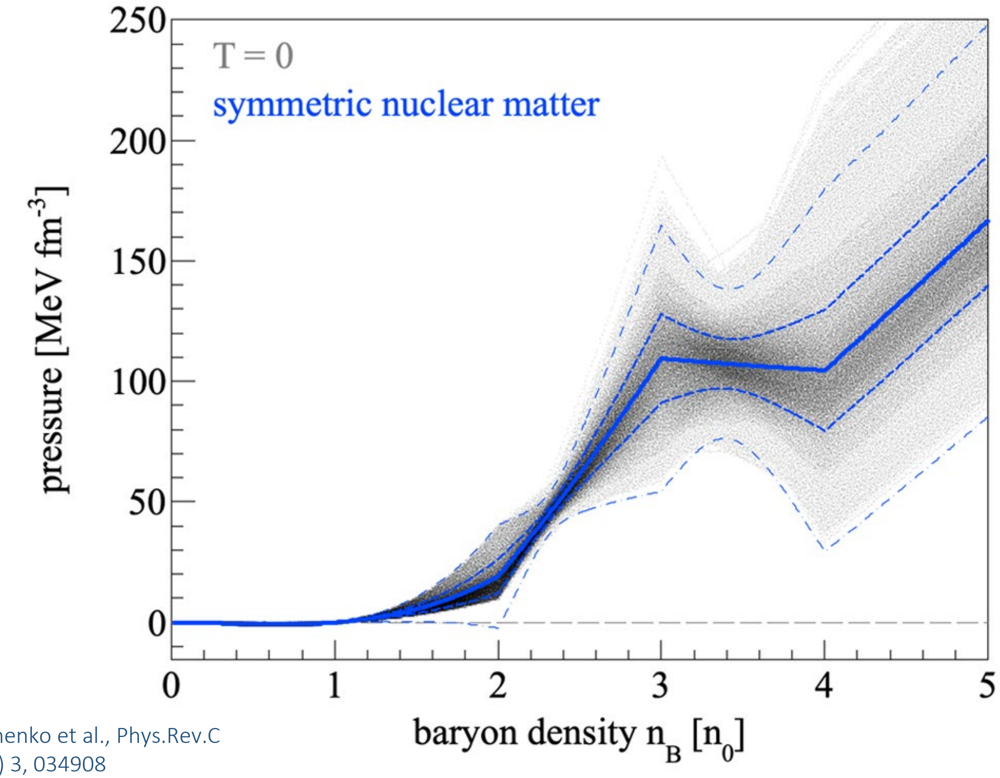
T. Galatyuk, A. Le Fevre, H.R. Schmidt, I. Selyuzhenkov, P. Senger, A. Sorensen, C. Sturm, W. Trautmann, I. Vassiliev, N. Xu, H. Zbroszczyk.

Hints Of Interesting Phenomena Emerging At $\gtrsim 2\rho_0$

Current data and observations hint that the nuclear matter at neutron-star core densities, both symmetric and neutron-rich, exhibit some softening and potential transition from hadronic to partonic degrees-of-freedom

Symmetric Nuclear Matter

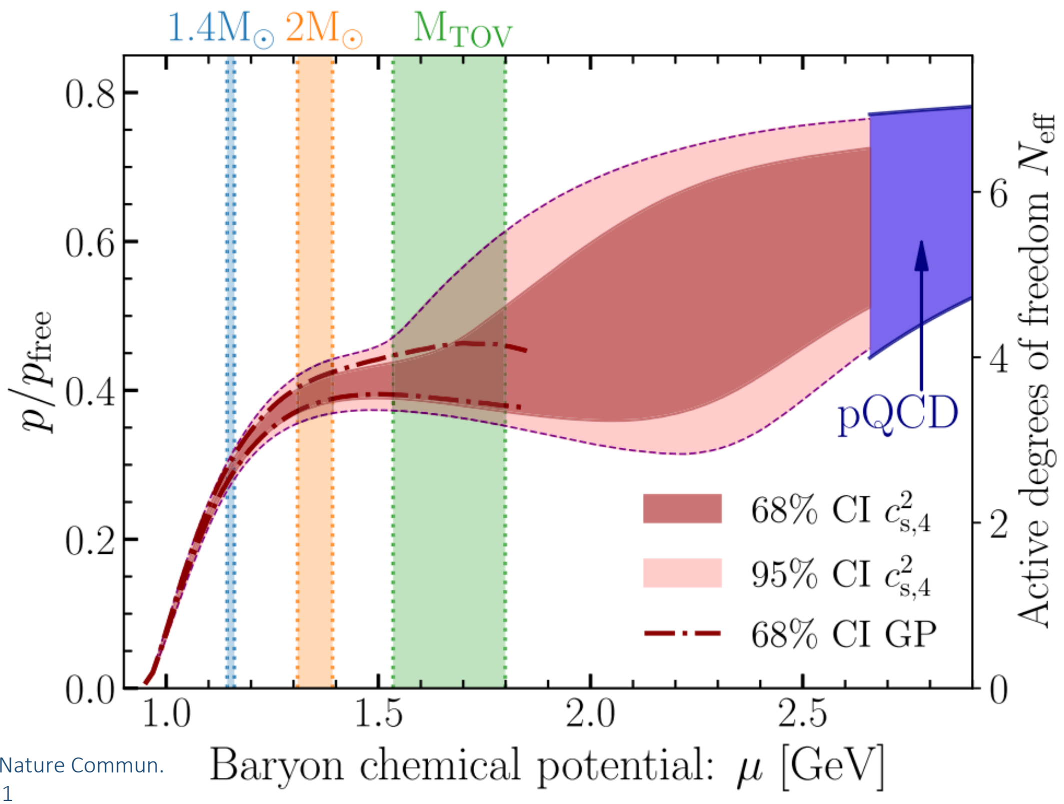
Heavy-Ion Collisions
STAR Flow Data (v_1 and v_2) at $\sqrt{s_{NN}}$ = 3 and 4.5 GeV (Au + Au)
SMASH Transport Code (w/o p-dependence)



D. Oliinychenko et al., Phys.Rev.C 108 (2023) 3, 034908

Neutron Star Matter

ChEFT constraints till 1.2 n_{sat} and pQCD constraints from 40 n_{sat}
Parametric ($c_s{}^2, \gamma$) and non-parametric (GP) interpolation at int. densities
Astrophysical observations (X-ray, GW)



E. Annala et al., Nature Commun. 14 (2023) 1, 8451