The Compressed Baryonic Matter (CBM) Experiment At FAIR

Kshitij Agarwal

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Eberhard-Karls-Universität Tübingen (DE)

- For the CBM Collaboration -

10th International Conference on New Frontiers in Physics (ICNFP 2021)

Kolymbari, Crete, Greece, August 23 – September 02, 2021

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

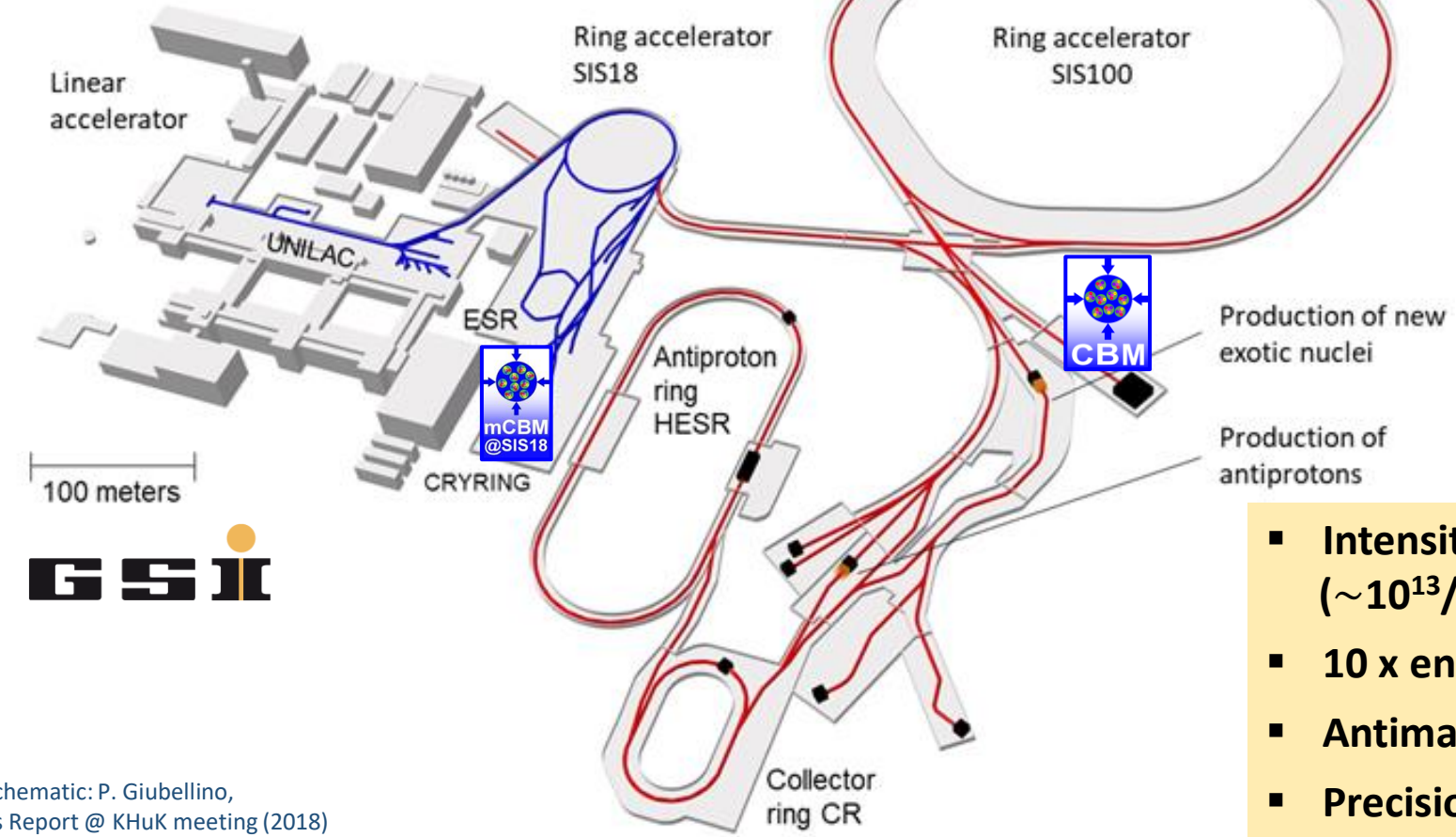
MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

GSI

CBM

FAIR

FACILITY FOR ANTI-PROTON AND ION RESEARCH (FAIR)



SIS-100 Capabilities			
Beam	Z	A	E [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^{13}/s for p; ~10^{10}/s for Au)**
- **10 x energy (compared to SIS-18@GSI)**
- **Antimatter: antiproton beams**
- **Precision: System of storage and cooler rings**

Jens Stadlmann (GSI)

GSI-FAIR Schematic: P. Giubellino, FAIR Status Report @ KHuK meeting (2018)

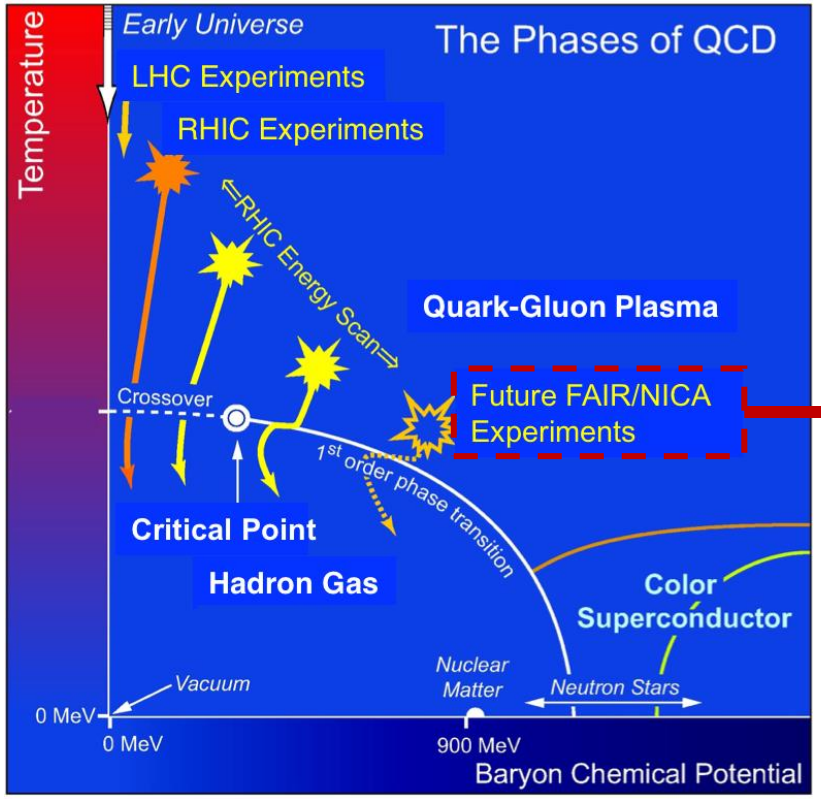
Update On FAIR Construction (June 2021)

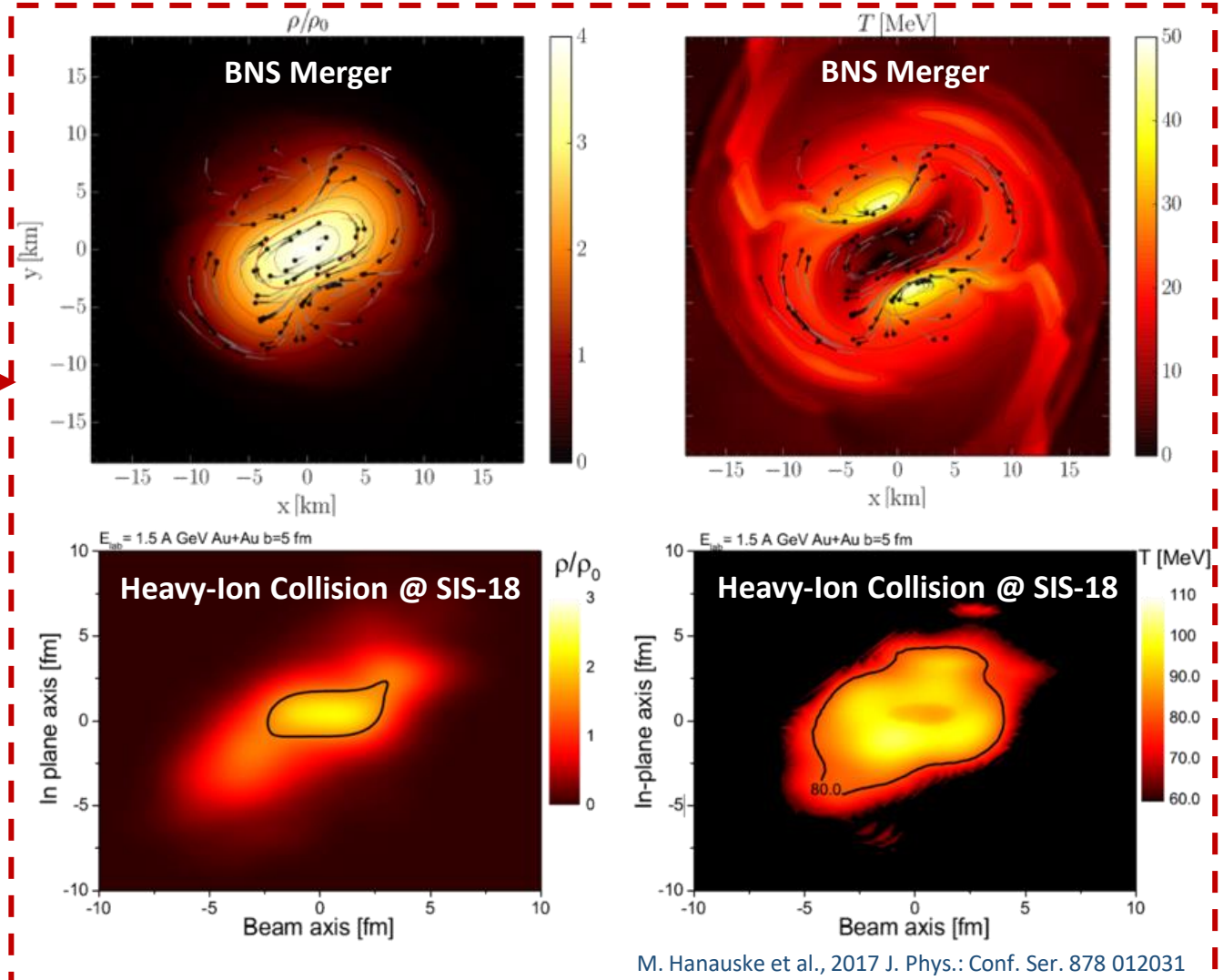
- **FAIR is progressing well towards strategic objectives**
- **CBM Building's construction progressing well on schedule**
- **Ready for 'Heavy Installation' from mid-2022**
- **CBM integration to be completed by 2025**
- **Updates on construction available at: GSI Webpage | YouTube | …**

CBM Physics Case & Observables

CBM Physics Goals

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





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

NuPECC Long Range Plan 2017 Perspectives in Nuclear Physics

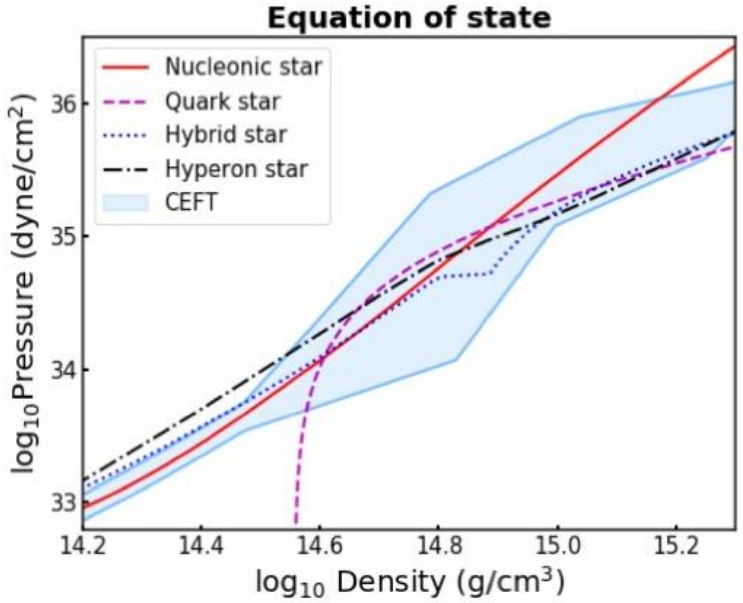
Unanswered fundamental questions for QCD at high densities

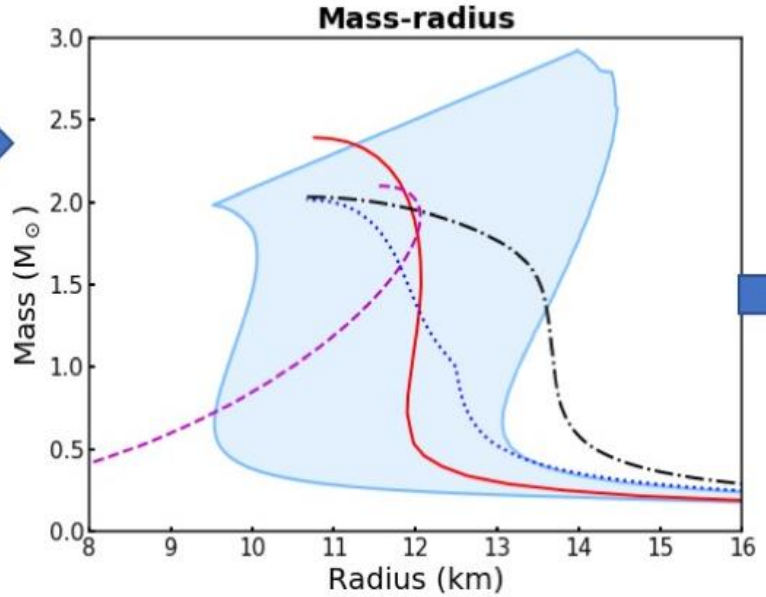
- **Equation of State (EoS) of symmetric nuclear (and asymmetric neutron) matter at neutron star core densities**
- **Phase structure of QCD matter (phase trans.? critical point?)**
- **Chiral symmetry restoration at large μ_B**
- **Bound states with strangeness**
- **Charm in cold and dense matter**

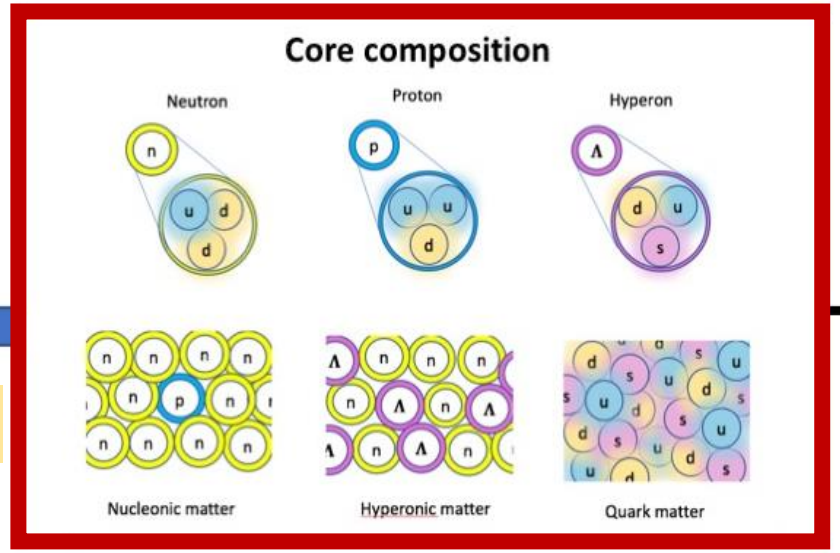
The CBM research program can decipher dense QCD matter properties
Microscopic (CBM) + Macroscopic Collisions (Astro) = True Multi-Messenger Physics

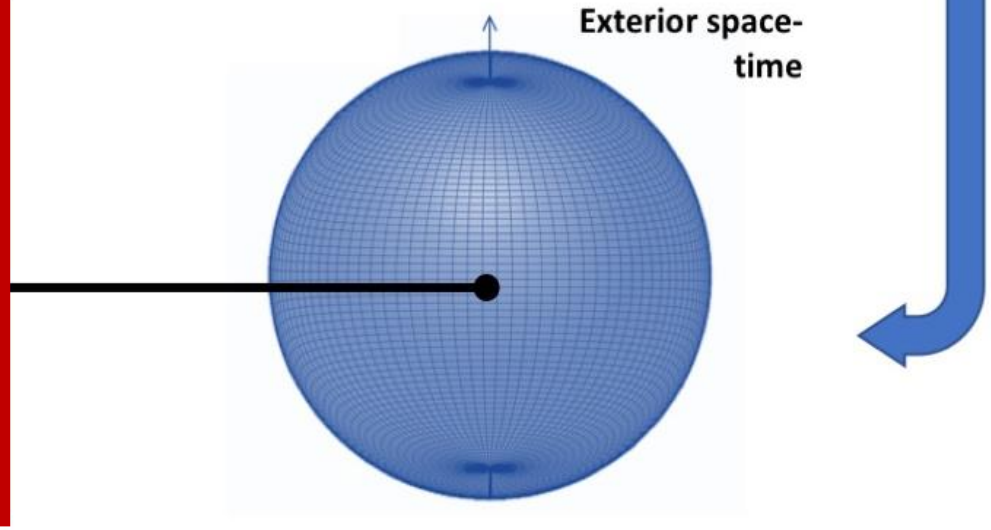
Physics Case 1: Equation Of State And Neutron Star Properties

P. Ray et al., STROBE-X: X-ray Timing and Spectroscopy on Dynamical Timescales from Microseconds to Years, arXiv:1903.03035









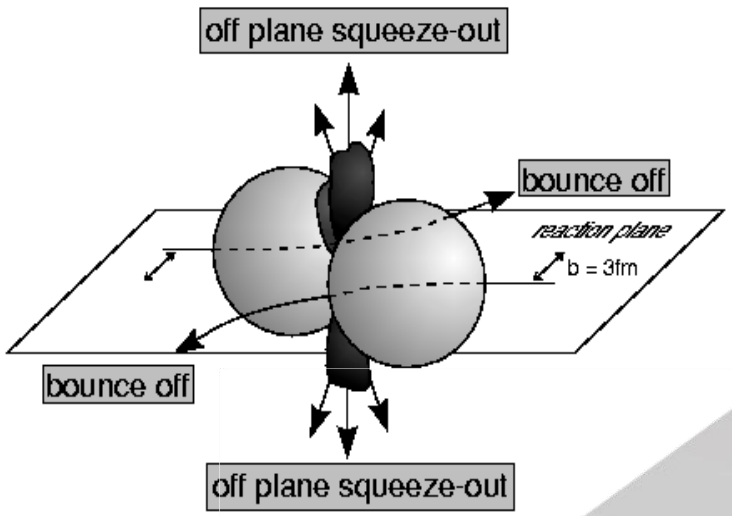
Heavy-Ion Collisions

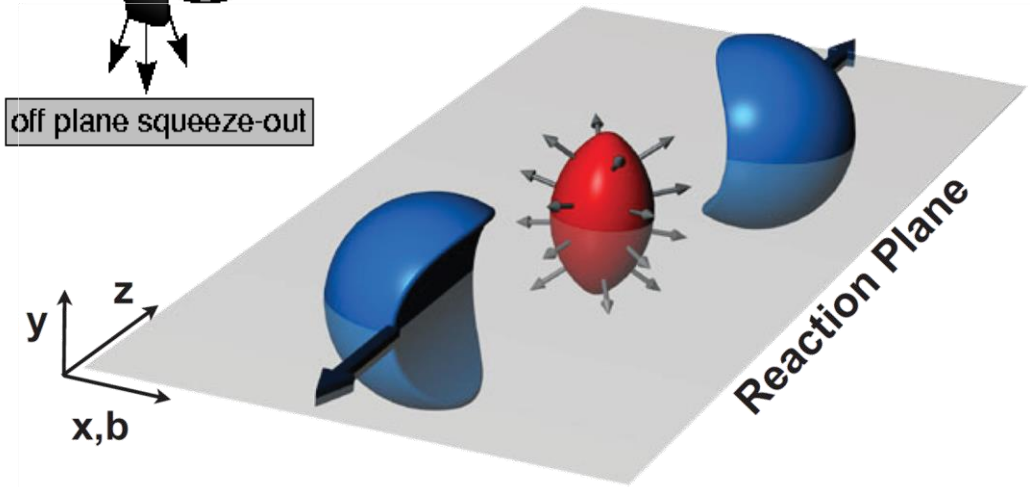
Physics Case 1: Equation Of State And Neutron Star Properties

ANISOTRPIC FLOW

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

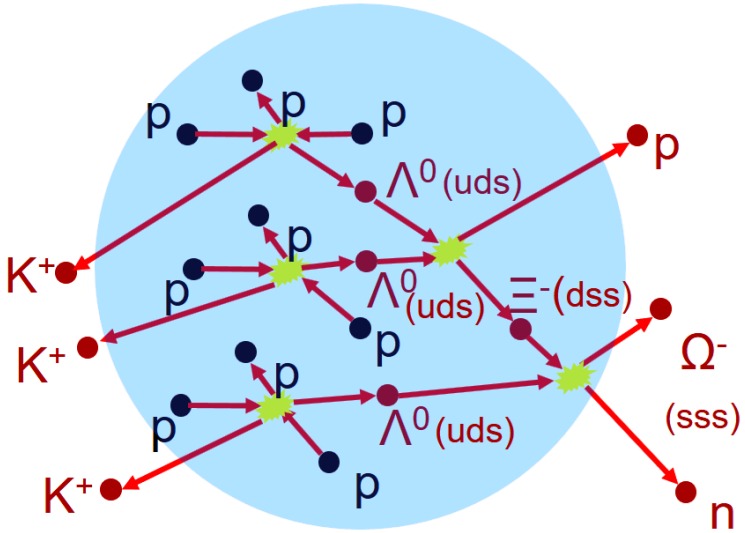
$$\frac{dN}{d\phi} \propto 1 + (2 \cdot v_1 \cdot \cos\phi) + (2 \cdot v_2 \cdot \cos 2\phi) + \cdots$$

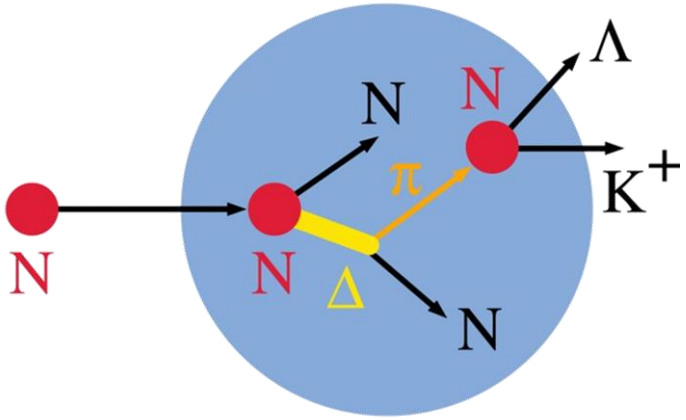


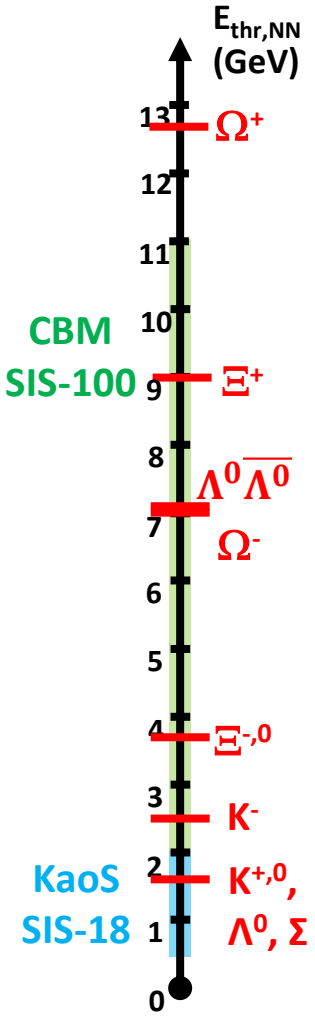


SUB-THRESHOLD STRANGENESS PRODUCTION

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

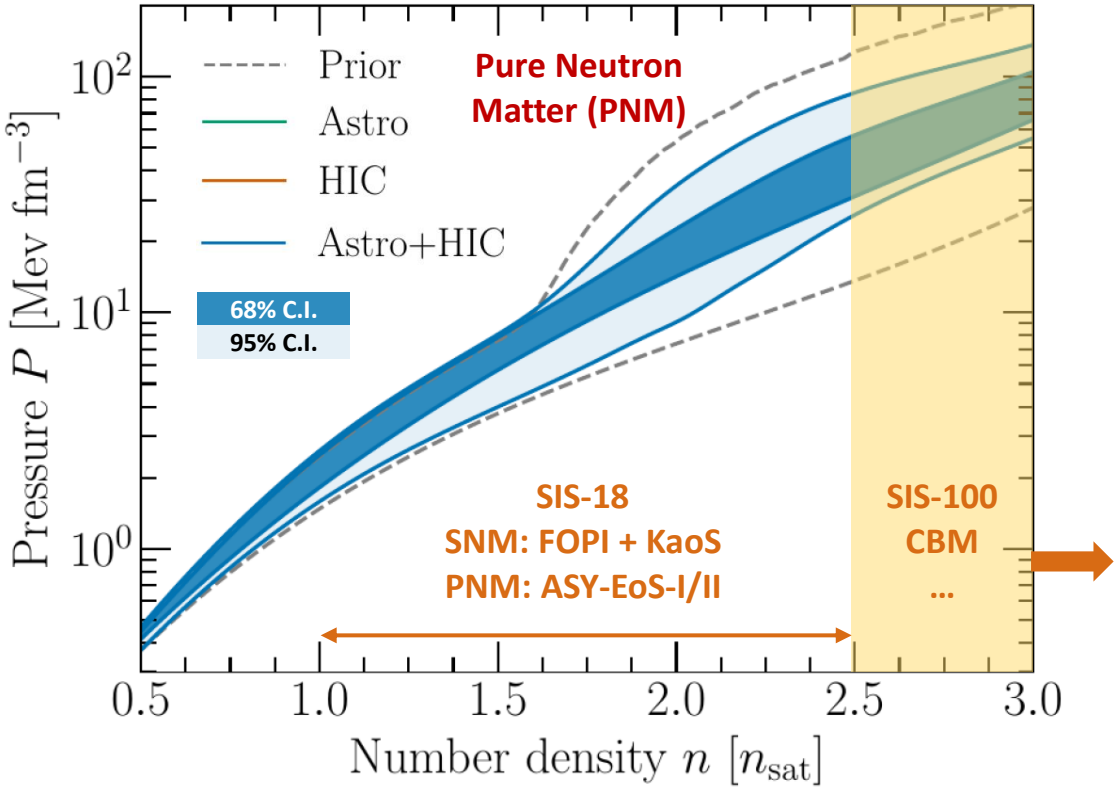


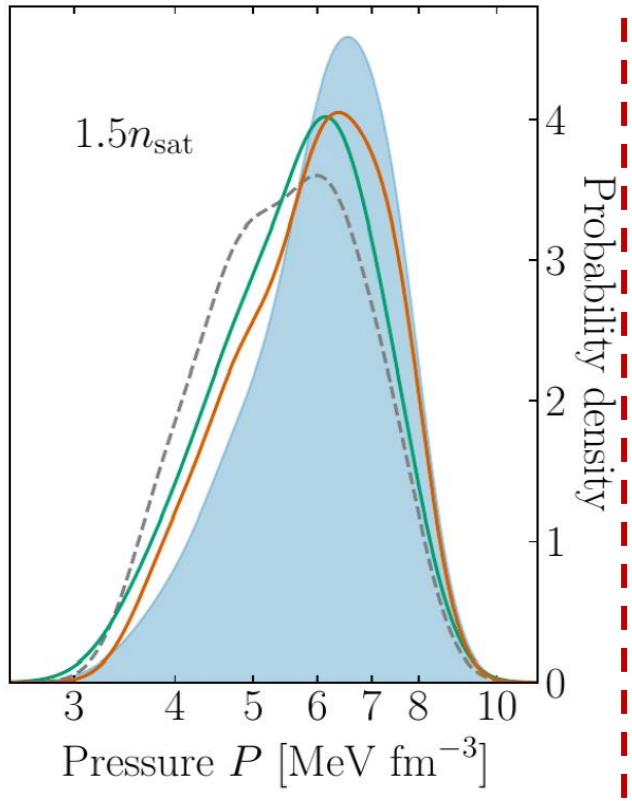


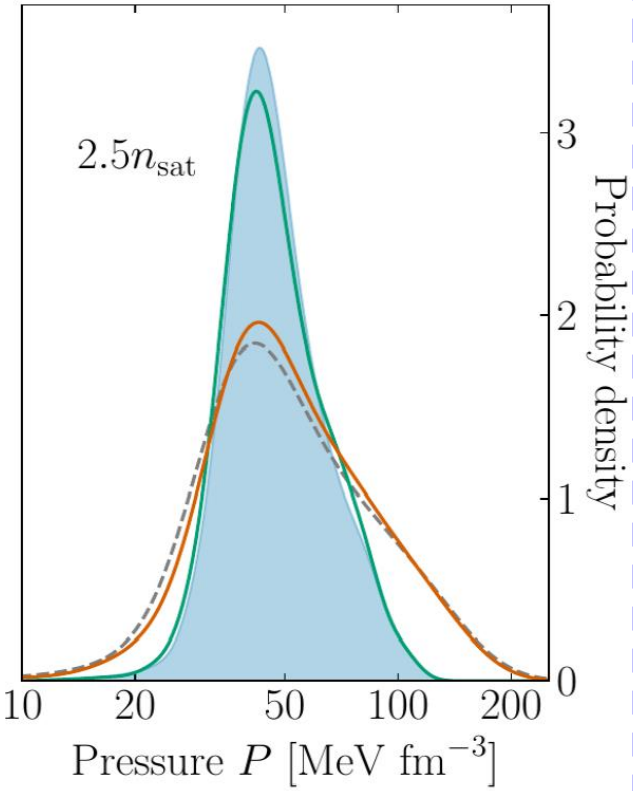


Physics Case 1: Equation Of State And Neutron Star Properties

S. Huth, P.T.H. Pang et al., arXiv:2107.06229 [nucl-th]







FOPI: Nucl. Phys. A 945, 112 (2016)
AGS, BEVALAC: Science 298, 1592 (2002)
KaoS: Phys. Rev. Lett. 86, 39 (2001)
J. Phys. G 28, 1615 (2002)
ASY-EOS-I: Phys. Rev. C 94, 034608 (2016)
SπRIT: Phys. Rev. Lett. 126, 162701 (2021)

CBM, with its capability with observables like particle flow and sub-threshold particle production, is in pole position to push our understanding of SNM and PNM at higher densities, thereby enhancing HIC's compatibility with astrophysical observations

HIC PRESENT (@SIS-18)

- **HIC constraints the EoS only where its sensitivity is highest ($\sim 1.5 n_{sat}$), where it favours stiffer EoS**
- **Constraints are consistent between HIC and astro**

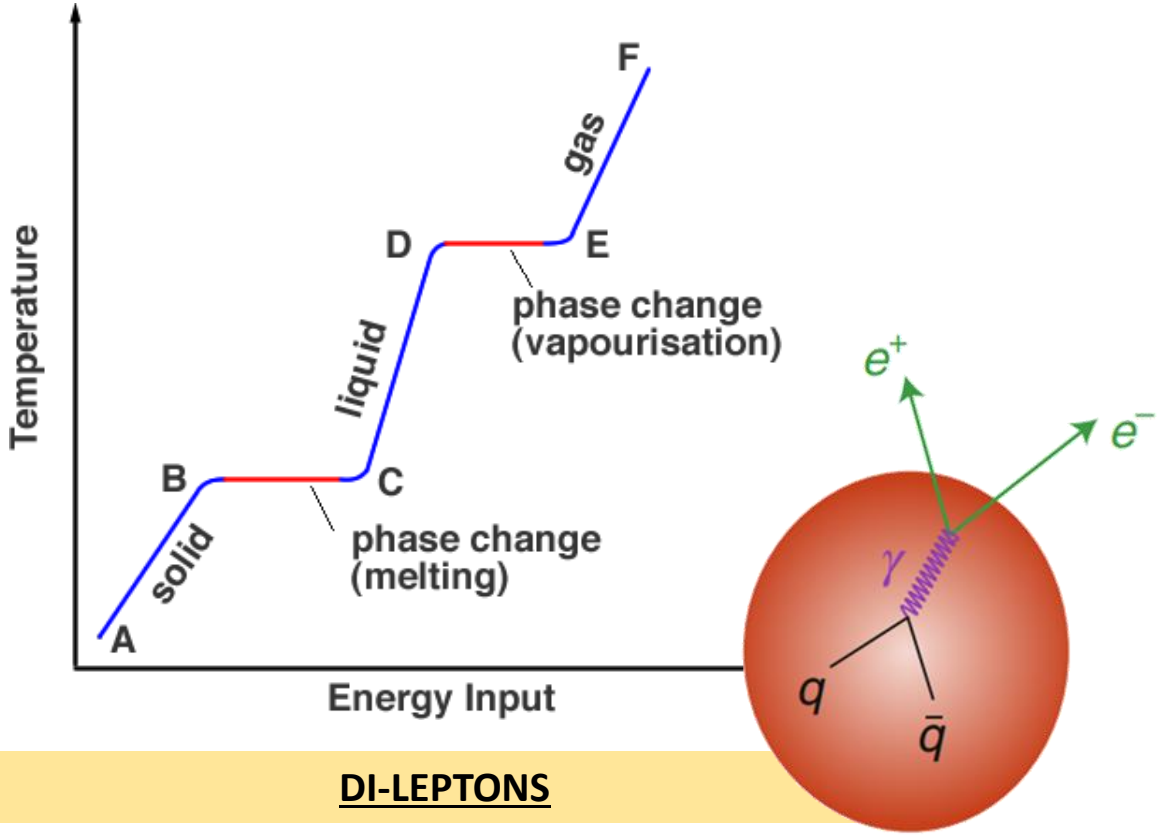
HIC FUTURE (@SIS-18, SIS-100, …)

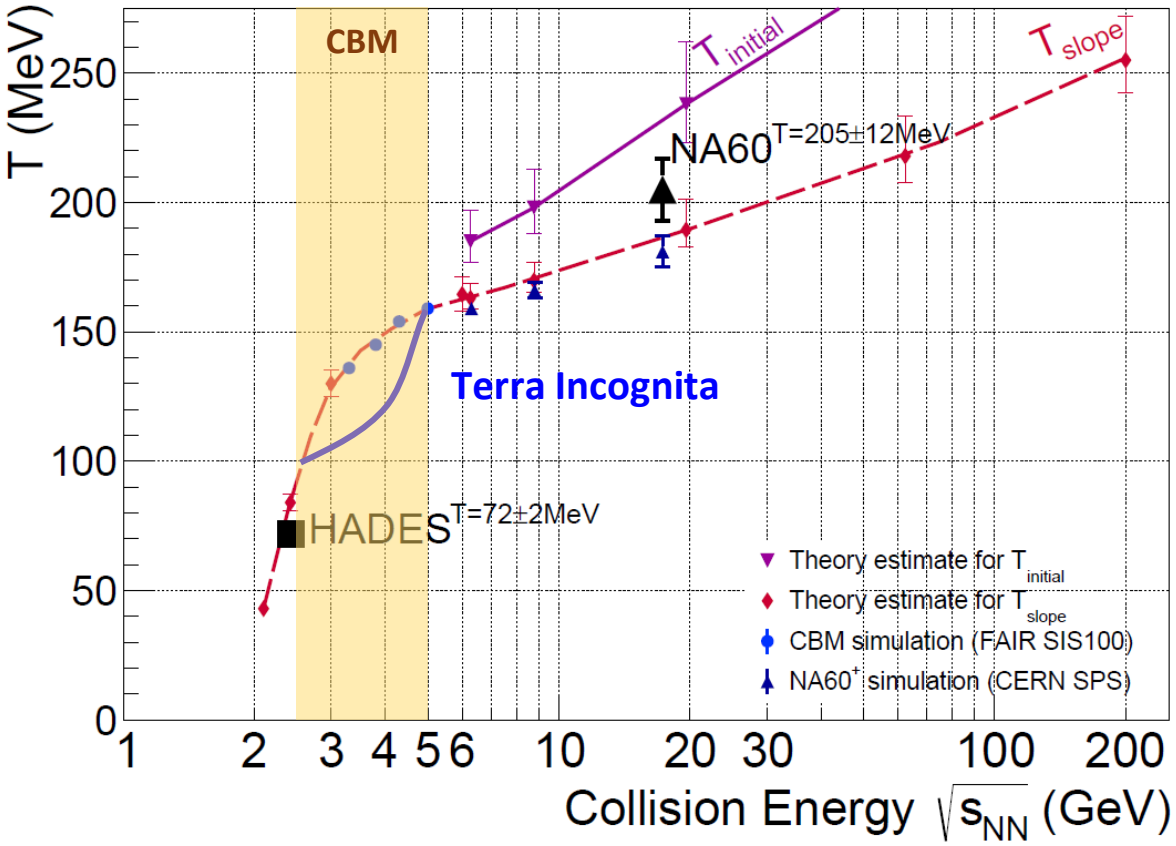
- **Higher density constraints are currently driven by Astro (which are limited in statistics)**
- **HIC has the potential to limit the constraints at higher densities**

Physics Case 2: Caloric Curve And Deconfinement

Image - http://www.splung.com/content/sid/6/page/latentheat
Liquid-Gas Phase Transition - [ALADIN] Phys. Rev. Lett. 75 (1995) 1040

Non-monotonous behaviour of the caloric curve potentially signals phase transition





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

Ralf Rapp, Nature Physics, Volume 15, pg. 990–991 (2019)

DI-LEPTONS

Dileptons, being electromagnetic probes, act as a thermometer of the strong-interacting fireball medium

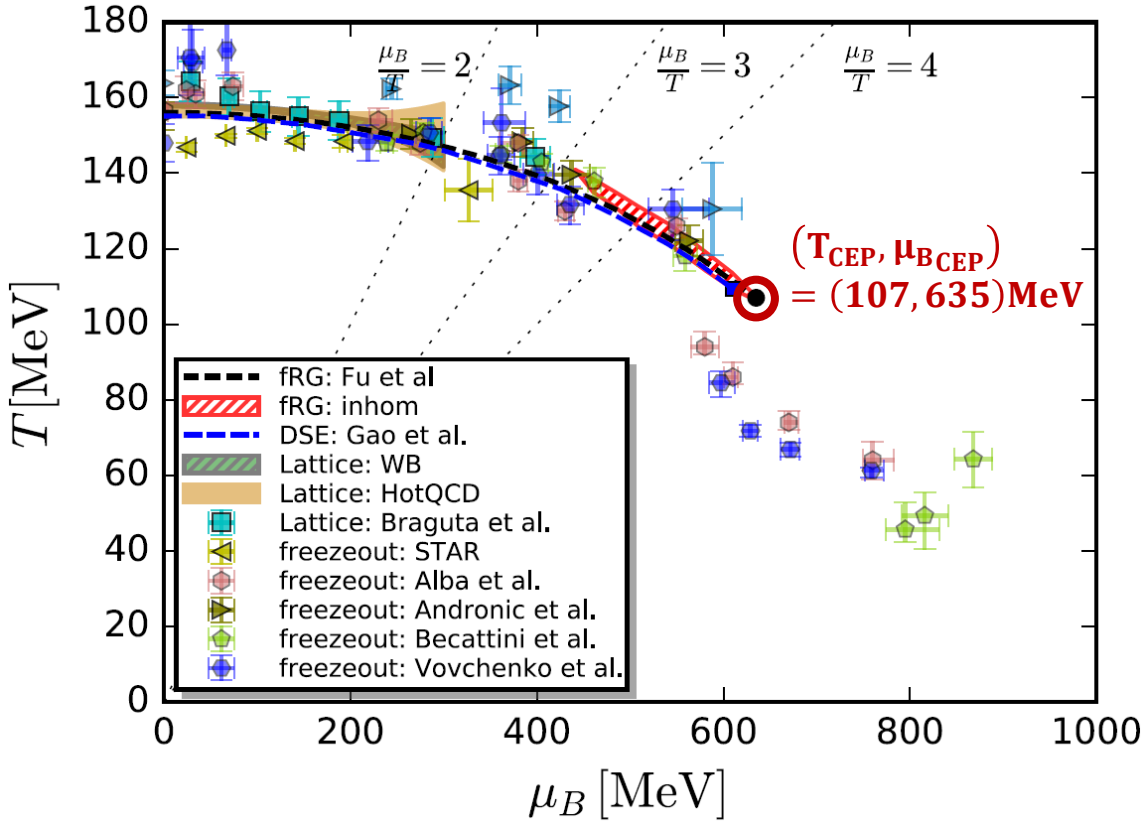
$$\frac{dN}{dM} \sim M^{3/2} \cdot \exp\left(-\frac{M}{T_S}\right)$$

Simplification of McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

CBM will be the first experiment to use di-leptons for systematic measurements in both production channels (e^+e^- and $\mu^+\mu^-$) in the same coverage.

Physics Case 3: QCD Critical End Point

W.J. Fu, J.M. Pawlowski, F. Rennecke, Phys. Rev. D 101, 054032 (2020)

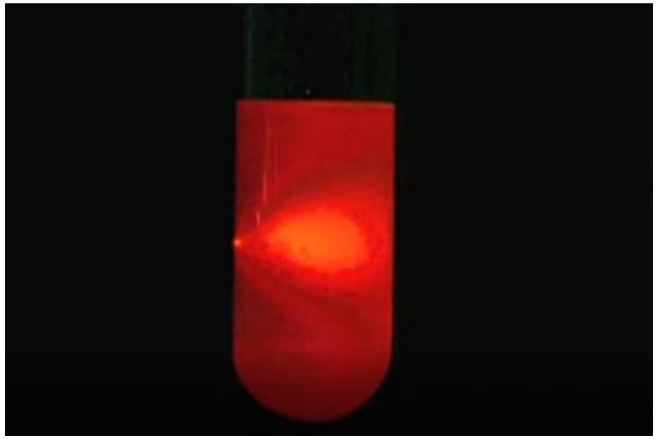


- **Based on the recent fRG and L-QCD results, there are no signs of criticality for $\mu_B/T \lesssim 4$**
- **Most promising range for finding the Critical End Point (CEP): $(135, 450)\text{MeV} \lesssim (T_{CEP}, \mu_{B_{CEP}}) \lesssim (100, 650)\text{MeV}$**

F. Karsch, arXiv:1905.03936
F. Karsch, RHIC Beam Energy Scan and Beyond 2021
A. Lahiri, LATTICE 2021
J.M. Pawlowski, CPOD 2021

EVENT-BY-EVENT FLUCTUATIONS

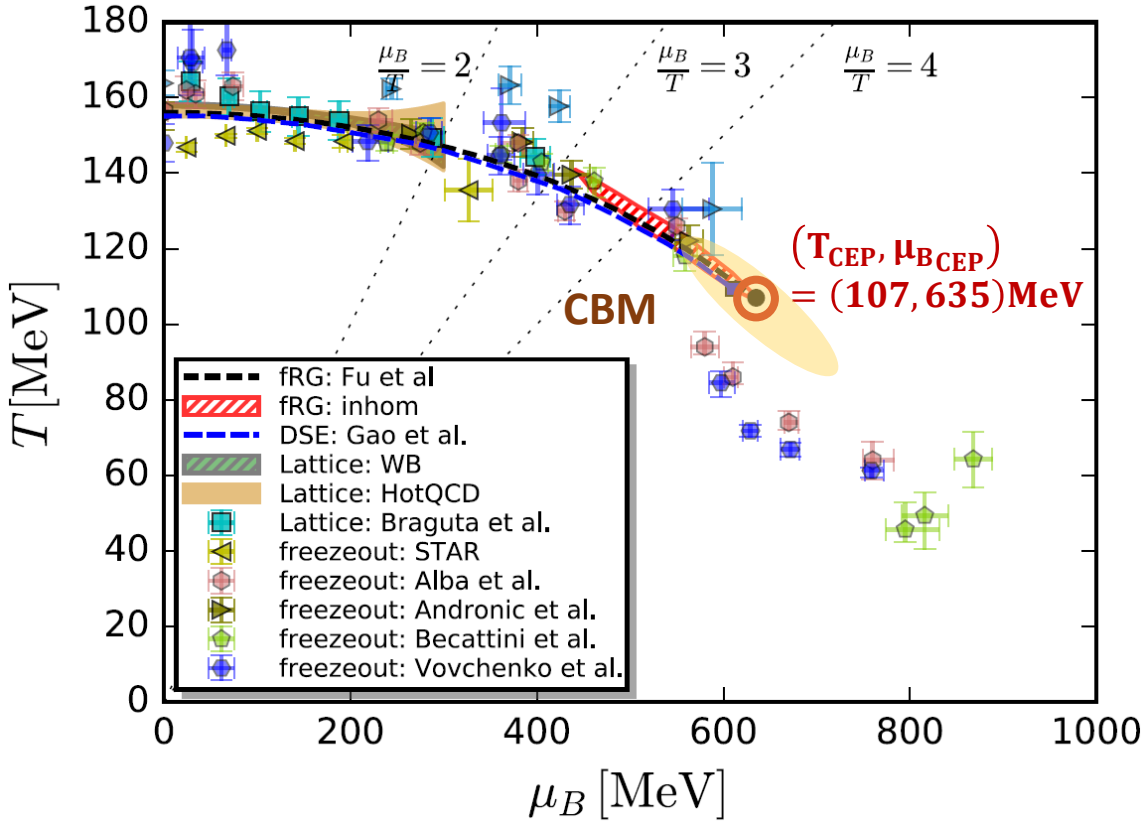
$T \neq T_{CEP}$



$T \approx T_{CEP}$

A vial containing a mixture of cyclohexane and aniline cooling from 35°C, has been filmed perpendicular to the direction of the laser light (left to right) - https://www.doitpoms.ac.uk/vidlib/full_record.php?id=58

Physics Case 3: QCD Critical End Point



W.J. Fu, J.M. Pawlowski, F. Rennecke, Phys. Rev. D 101, 054032 (2020)

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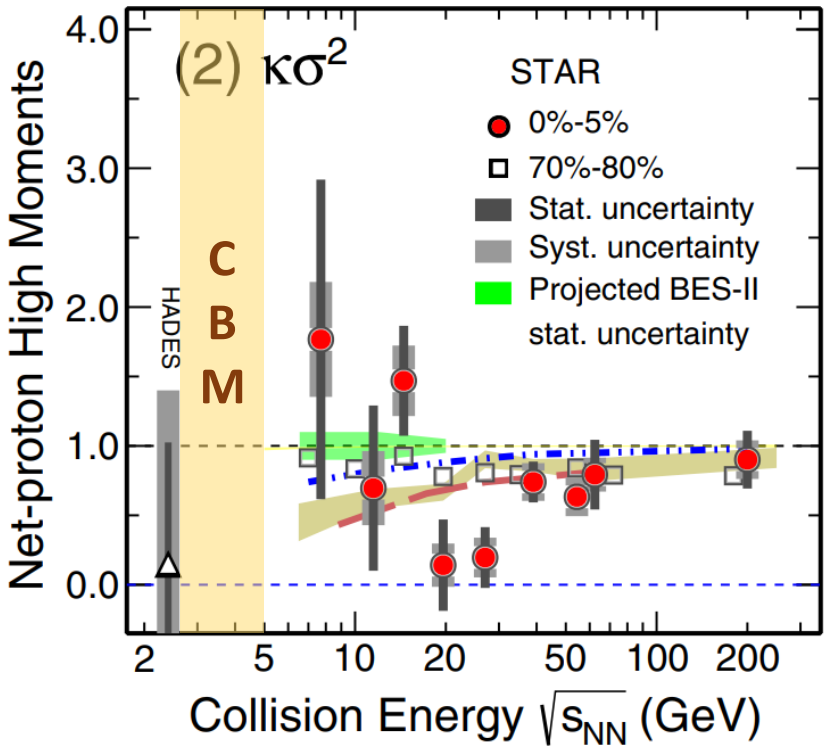
F. Karsch, arXiv:1905.03936
F. Karsch, RHIC Beam Energy Scan and Beyond 2021
A. Lahiri, LATTICE 2021
J.M. Pawlowski, CPOD 2021

EVENT-BY-EVENT FLUCTUATIONS

- **Higher-order cumulants and ratios of conserved quantities (B, Q, S) are sensitive to QCD CEP**

M.A. Stephanov, Phys. Rev. Lett. 102 032301 (2011)
J.W. Chen et al., Phys. Rev. D 95, 014038 (2017)



[STAR] Phys. Rev. Lett. 126, 092 (2021)
[STAR] arXiv:2101.12413 [nucl-ex]
[HADES] Phys. Rev. C 102, 024914 (2020)

CBM can systematically study the higher-order cumulants and ratios to contribute significantly to the search of QCD-CEP

For More Reading...

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

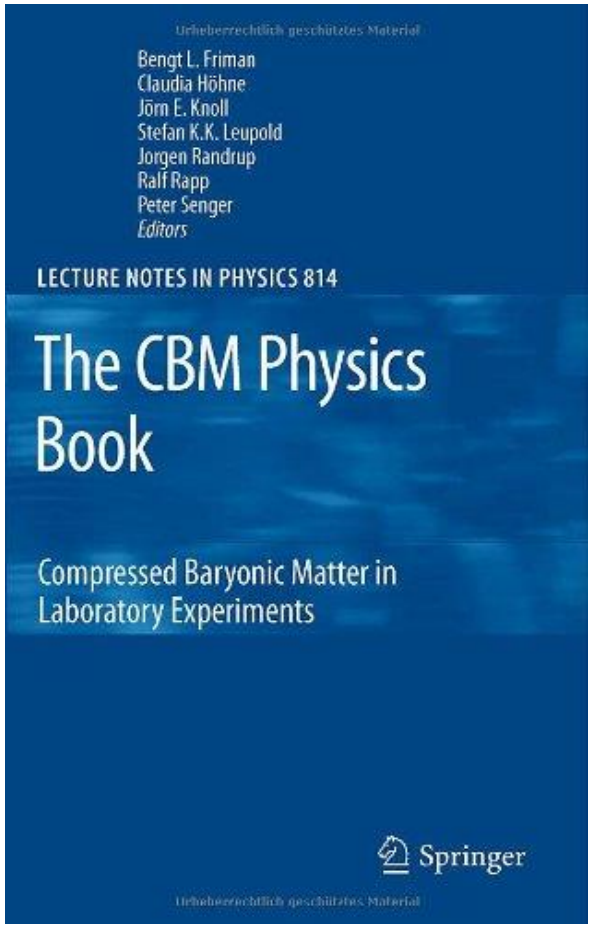
Phase transition
- excitation function of hyperons
- excitation function of LM lepton pairs

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

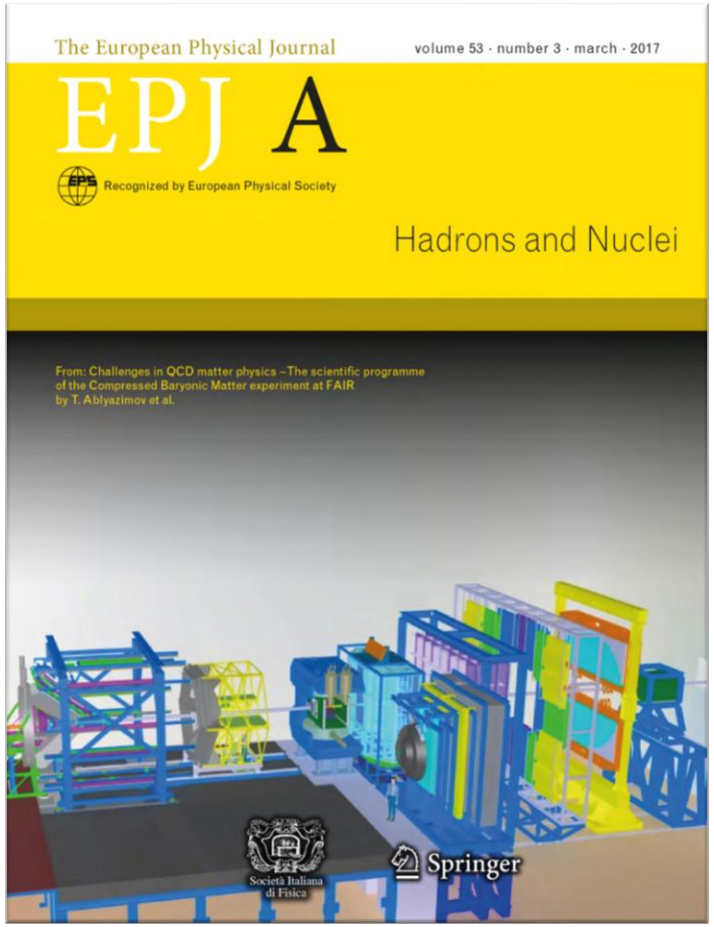
Chiral symmetry restoration at large μ_B
- in-medium modifications of hadrons
- meson-baryon coupling
- dileptons at intermediate invariant masses

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



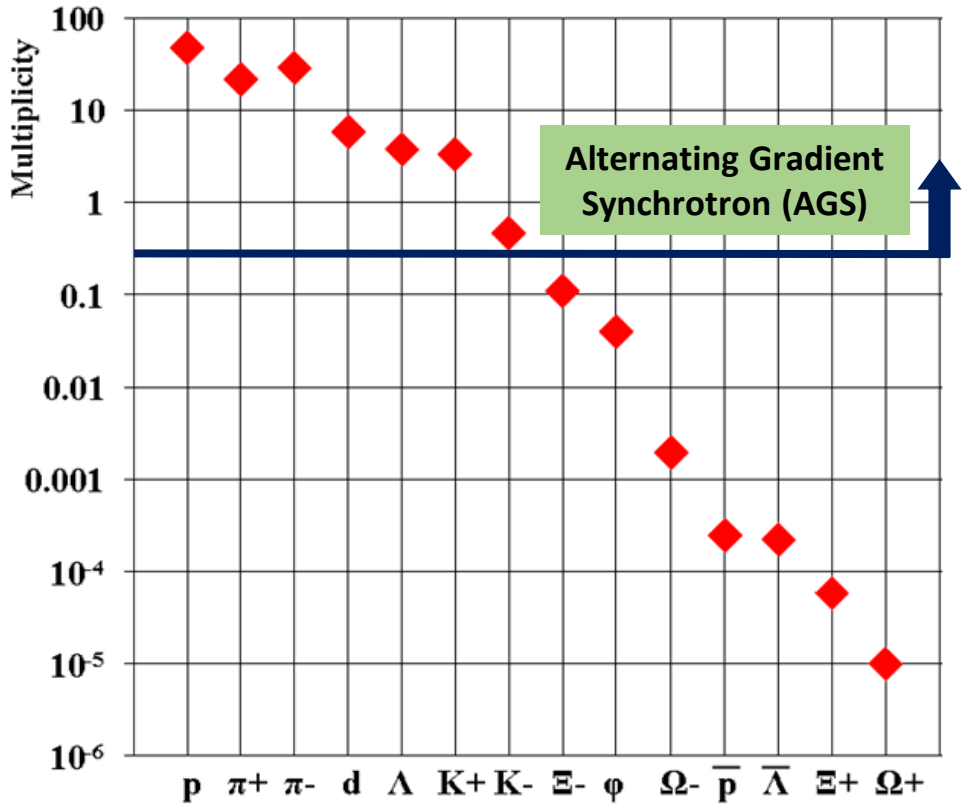
Lect. Notes Phys. 814 (2011) pp.1-980
DOI: 10.1007/978-3-642-13293-3



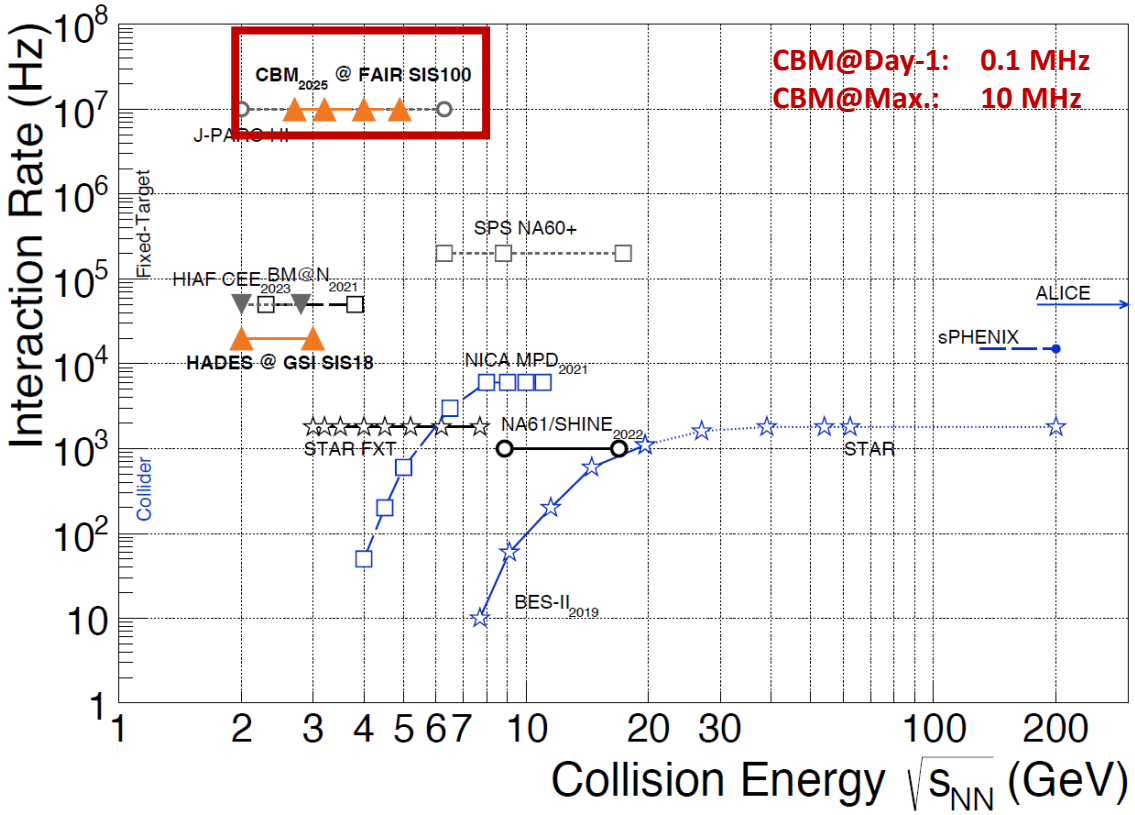
Eur.Phys.J.A 53 (2017) 3, 60
DOI: 10.1140/epja/i2017-12248-y

CBM Simulated Physics Performance

Beam-Target Interaction Rates And Rare Probes' Yields



P. Senger, Phys.Scripta 96 (2021) 5, 054002



[CBM], Eur.Phys.J.A 53 (2017) 3, 60
T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169, update (2021)

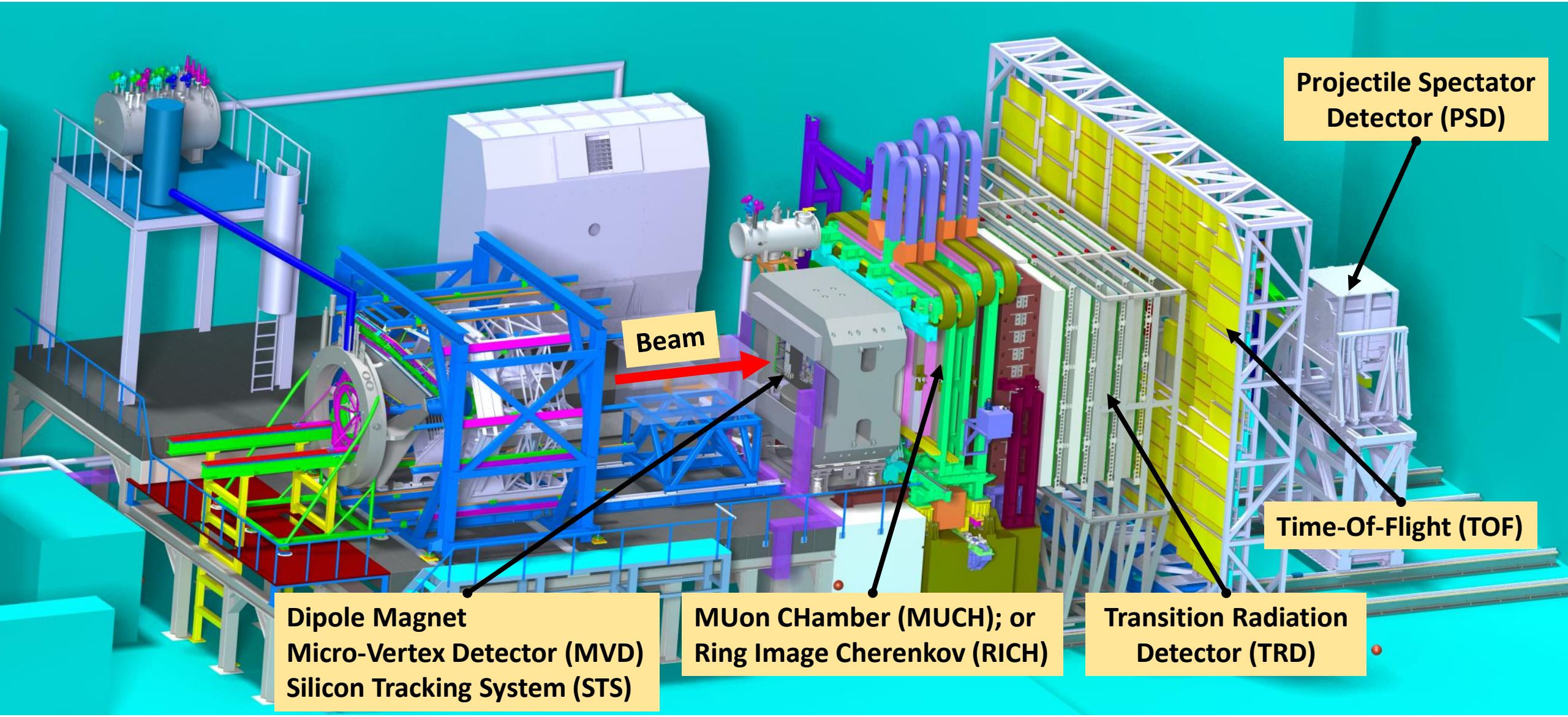
The CBM research program comprises a comprehensive scan of observables, beam energies and collision systems at up to 10 MHz beam-target interaction rates giving an unprecedent access to the 'rare probes'

Yield at 0.1 MHz I.R. (Day-1) in 90 days		
Particle (mass MeV/c²)	6 AGeV	10 AGeV
$\bar{\Lambda}$ (1115)	1.2×10^8	1.0×10^9
Ξ^- (1321)	2.0×10^9	7.0×10^9
Ξ^+ (1321)	3.0×10^7	2.5×10^8
Ω^- (1672)	4.0×10^6	2.6×10^7

Yield at 0.1 MHz I.R. (Day-1) in 90 days		
Particle (mass MeV/c²)	6 AGeV	10 AGeV
Ω^+ (1672)	7.0×10^4	1.4×10^7
${}^3_\Lambda$H (2993)	2.7×10^8	2.5×10^8
${}^3_\Lambda$He (3930)	1.7×10^7	1.4×10^7
${}^4_{\Lambda\Lambda}$He (5047)	15	250

Y. Vassiliev (GSI)

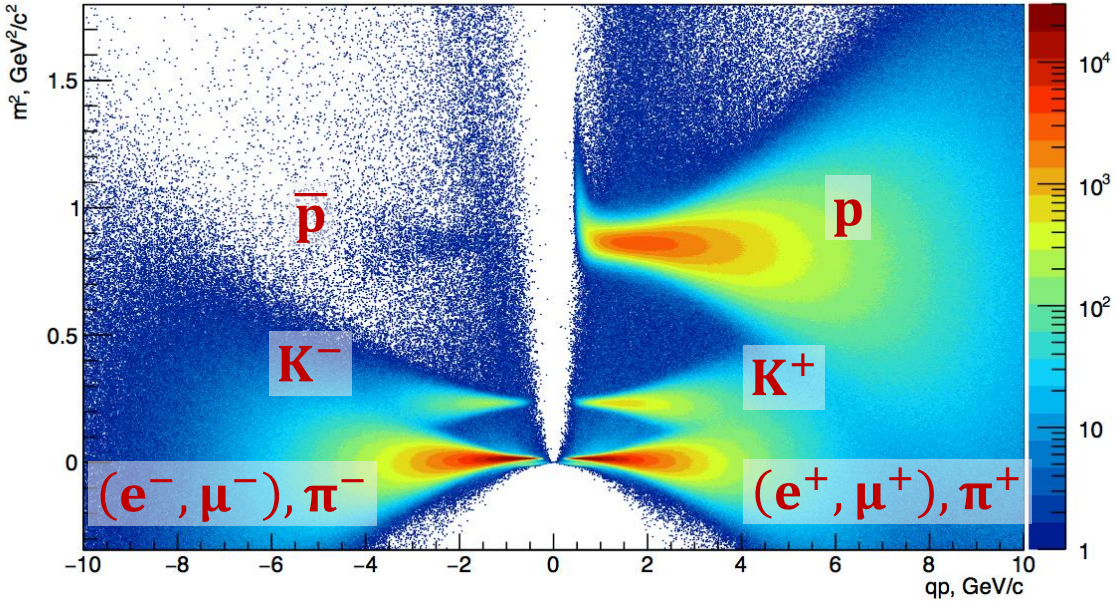
CBM Experimental Setup (Day-1)



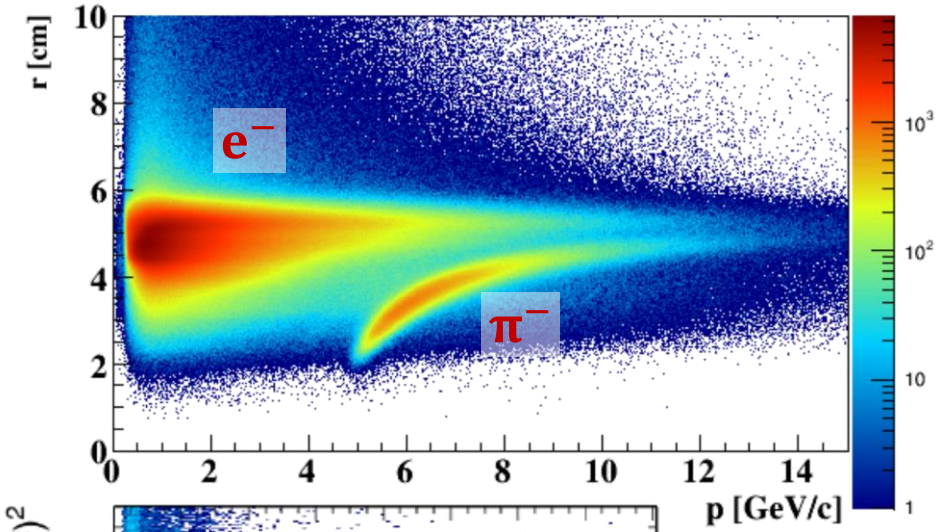
Particle Identification With CBM

CBM Simulations, central Au-Au@10AGeV

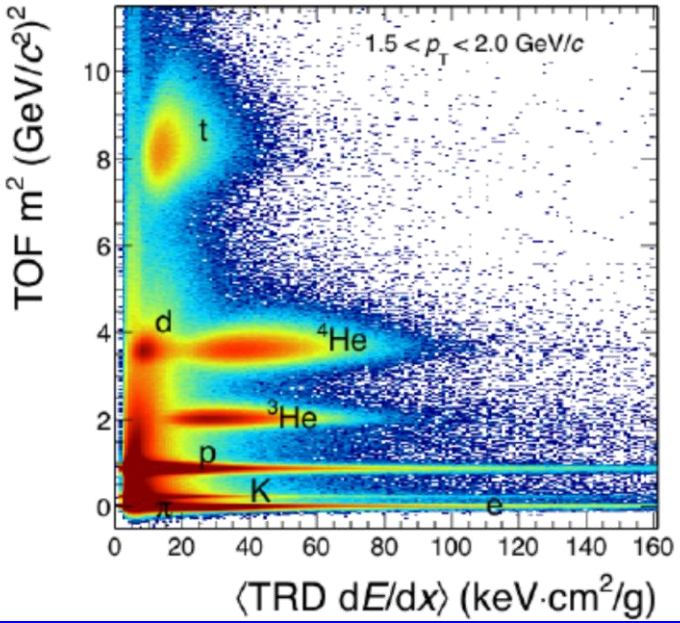
ToF - Hadron Identification



Clear separation between charged protons, pions and kaons



RICH - Electron ID

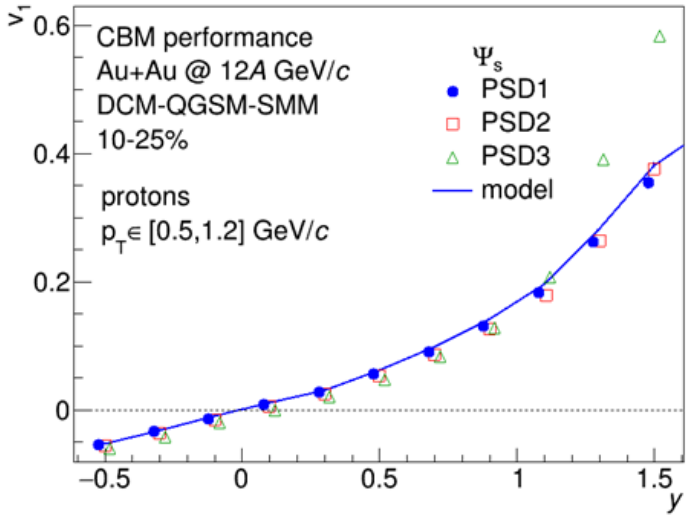


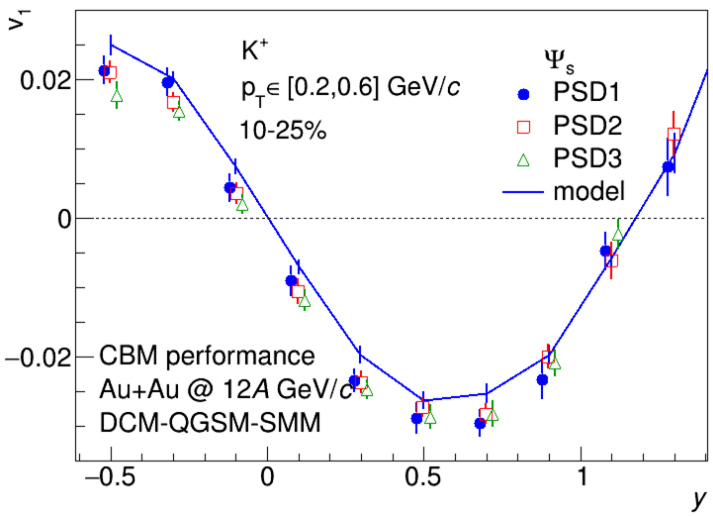
TRD + ToF - Electron, Light Nuclei, Heavy Fragments

Clear separation between pions and electrons, and light nuclei

Physics Performance – [I]

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

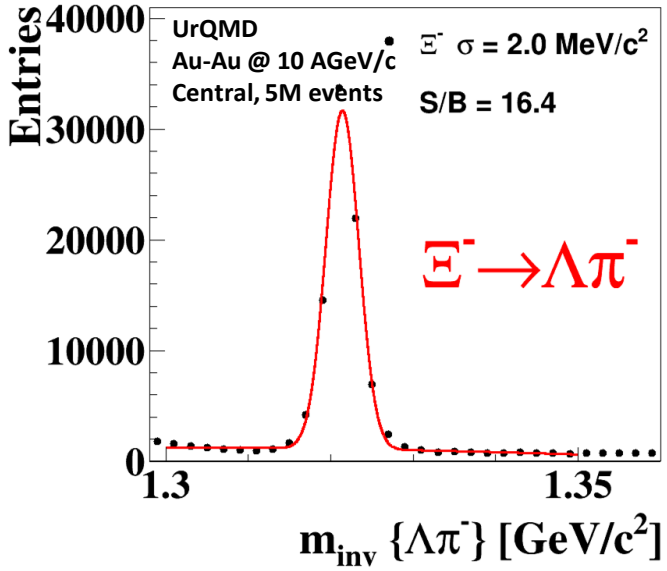


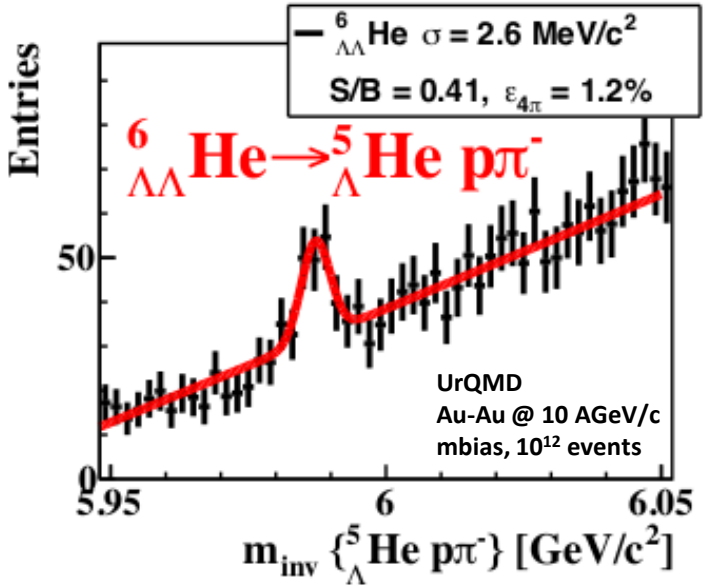


Anisotropic Flow

- Input model v_1 is recovered using data-driven methods with projectile spectators
- Procedures for centrality determination, particle identification and corrections for effects of detector's azimuthal non-uniformity are applied
- Results for v_1 of π^+, Λ also available

  O. Lubynets et al., Particles 2021, 4(2), 288-295
  O. Golosov, CPOD 2021
- Ongoing – Higher harmonics (v_2, …)

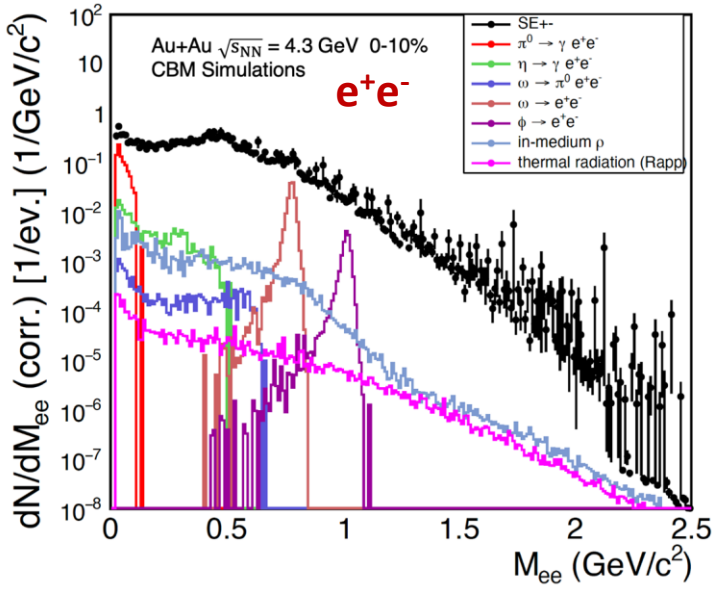


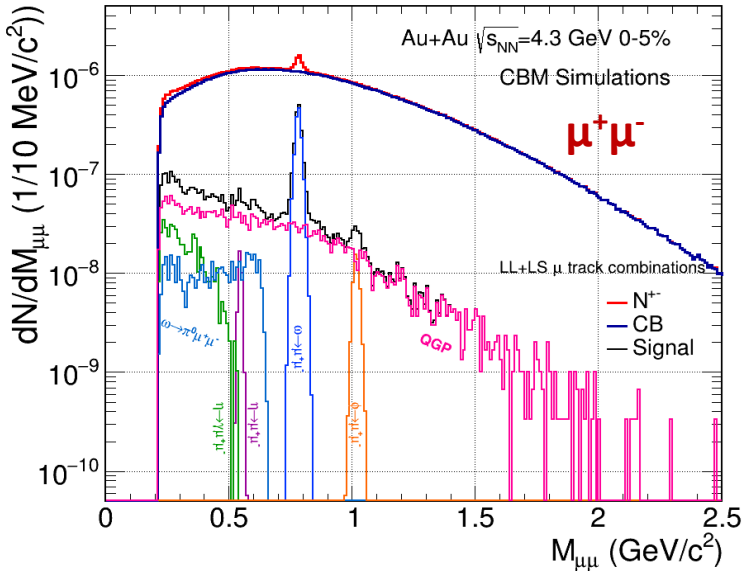


(Multi-) Strangeness Production

- Tools for the multi-differential physics analysis are prepared for strange hadrons
- Reconstruction is based on the dedicated KFParticleFinder package
- Magnetic field scaling and multi-strange hyperon reconstruction performance also studied at lowest SIS-100 energies I. Vassiliev et al., CBM Progress Report 2020
- Possible improvements by using Machine Learning are ongoing S. Khan, SQM 2021

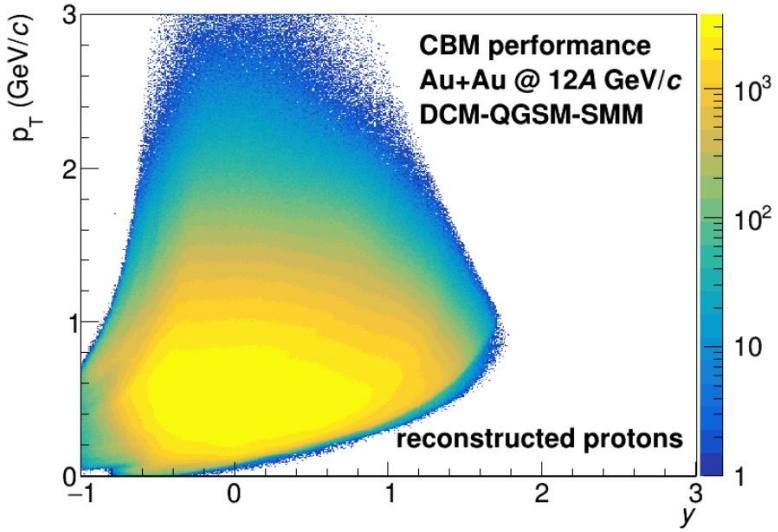
Physics Performance – [II]

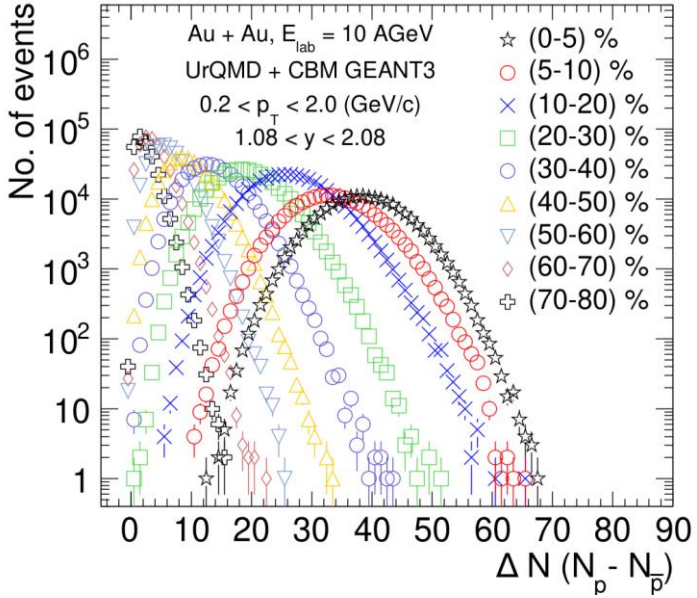




Di-lepton Distribution

- Clear peaks for the low mass vector mesons in both production channels, with 5M Au-Au collisions
- Negligible contribution from Drell-Yan and open charm decay
- Access to thermal signal is feasible with good background description
- Statistical accuracy for T_{slope} of 10% requires ~ 10^{11} events, ~ 20 days of beamtime @ 0.1 MHz I.R.





Net-Proton Multiplicities and Cumulants

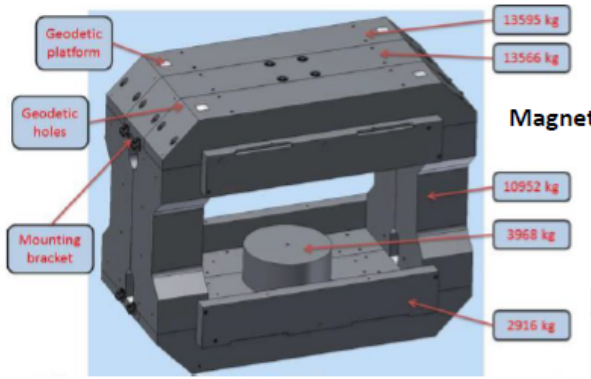
- The centrality dependence of cumulants of net-proton up to order four is under investigation
- Plans to analyze cumulants up to order six with large statistics and other SIS-100 energies
- Analysis ongoing for the net-charge and net-kaon

Experimental Challenges

Recent Achievements In Detector Projects – [I]

Magnet (GSI, BINP Novosibirsk, JINR Dubna)

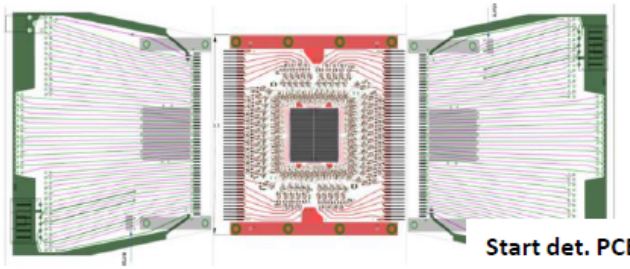
- Progress in design of coils, branch box, transfer line, cryostat.
- Successful Yoke and Power Supply Production Readiness Review in February 2021
- Hall at BINP prepared for Factory Acceptance Tests



Magnet yoke

Beam monitor and start detectors (TU Darmstadt, GSI)

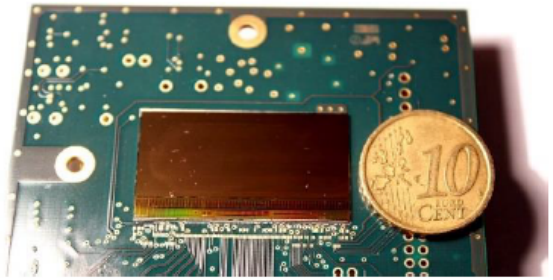
- Endorsed as an independent project
- Start detector Concept for Day-1 based on pcCVD high purity diamond sensors
- A concept of the beam abort system being worked out



Start det. PCB

MVD (U Frankfurt, GSI, IKF Frankfurt, IPHC Strasbourg, Pusan Nat'l Univ.)

- MIMOSIS-1: first full size sensor prototype available! First tests successful, systematic studies ongoing
- TDR submitted to ECE/ECSG in May 2021
- MIMOSIS-2 submission in H2.2021



MIMOSIS-1 (evaluation PCB)

STS (GSI Darmstadt, JINR Dubna, KIT Karlsruhe, JU Crakow, AGH Crakov, KINR Kiev, Univ. Tübingen, Warsaw UT)

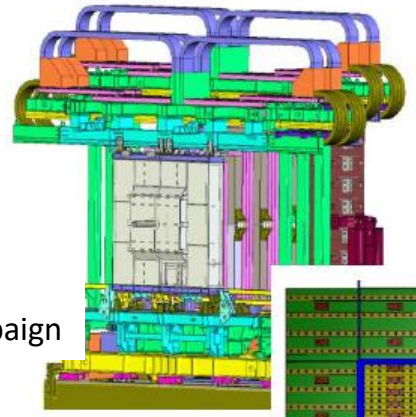
- All sensors delivered, QA done
- Successful Module and Ladder assembly EDR in Dec. 2020
- New ASICS available (STS-XYter2.2)
- Preproduction in Q2/Q3.2021

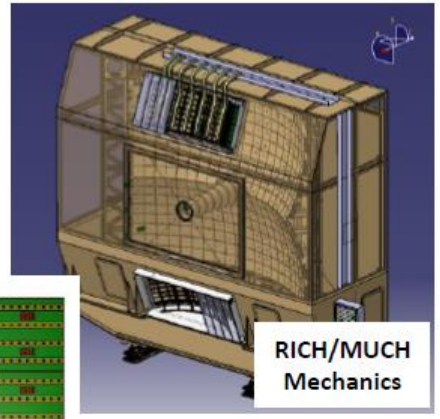
Assembled STS module

Recent Achievements In Detector Projects – [II]

MUCH (Aligarh Muslim Univ., Bose Inst. Kolkata, Panjab Univ., Univ. of Jammu. , Univ. of Kashmir, Univ. of Calcutta, B.H. Univ. Varanasi, VECC Kolkata, IOP Bhubaneswar, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Gauhati Univ., PNPI Gatchina)

- CDRs accepted for LV, GEM, Mechanics and Gas systems
- 2nd GEM station assembled and tested with cosmic rays using MUCH/STS-XYTER
- mCBM with mMUCH couldn't be attended due to covid, planning for the next campaign

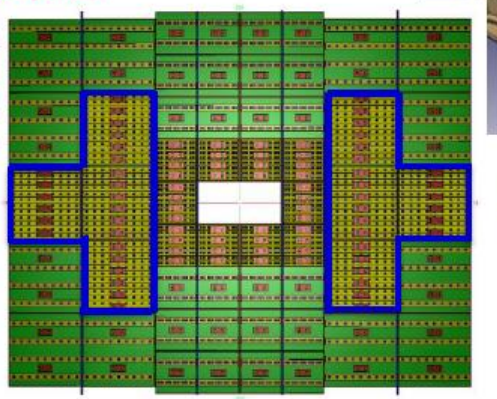




RICH/MUCH Mechanics

RICH (Univ. Giessen, Univ. Wuppertal, PNPI Gatchina, GSI Darmstadt)

- Mechanics CDR accepted, EDR in 09.2021
- Camera design EDR completed; pre-production (demonstrator incl. cooling) launch in 2021
- Mirrors EDR/PRR in Q1.2021 followed by start of mirror production



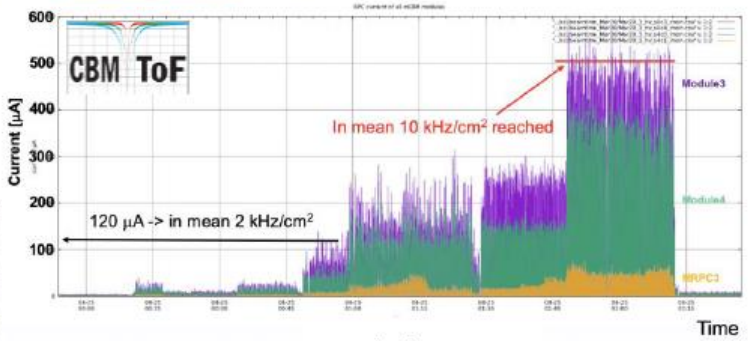
TRD wall layout
Module type "5"

TRD (NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, IRI Frankfurt)

- Outer modules PRR completed, first of series production (5 modules) in H1.2021
- Inner modules TDR Addendum submitted to ECE/ECSG in 05.2021
- SPADIC 2.3 ASIC test submission in Dec. 2020

TOF (THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan)

- New ASIC PADI XI successfully tested – PRR in 06.2021
- Particle fluxes > 10 kHz/cm^2 reached
- Ageing studies ongoing in Bucharest (ISRAM facility);



TOF high-rate test

PSD (INR Moscow, TU Darmstadt, CTU Prague, NPI Rez)

- All modules produced, Upper support structure arrived at FAIR in 09.2020

PSD support SAT

FAIR Phase 0 – Avoiding Risks And Spectacular Failures…

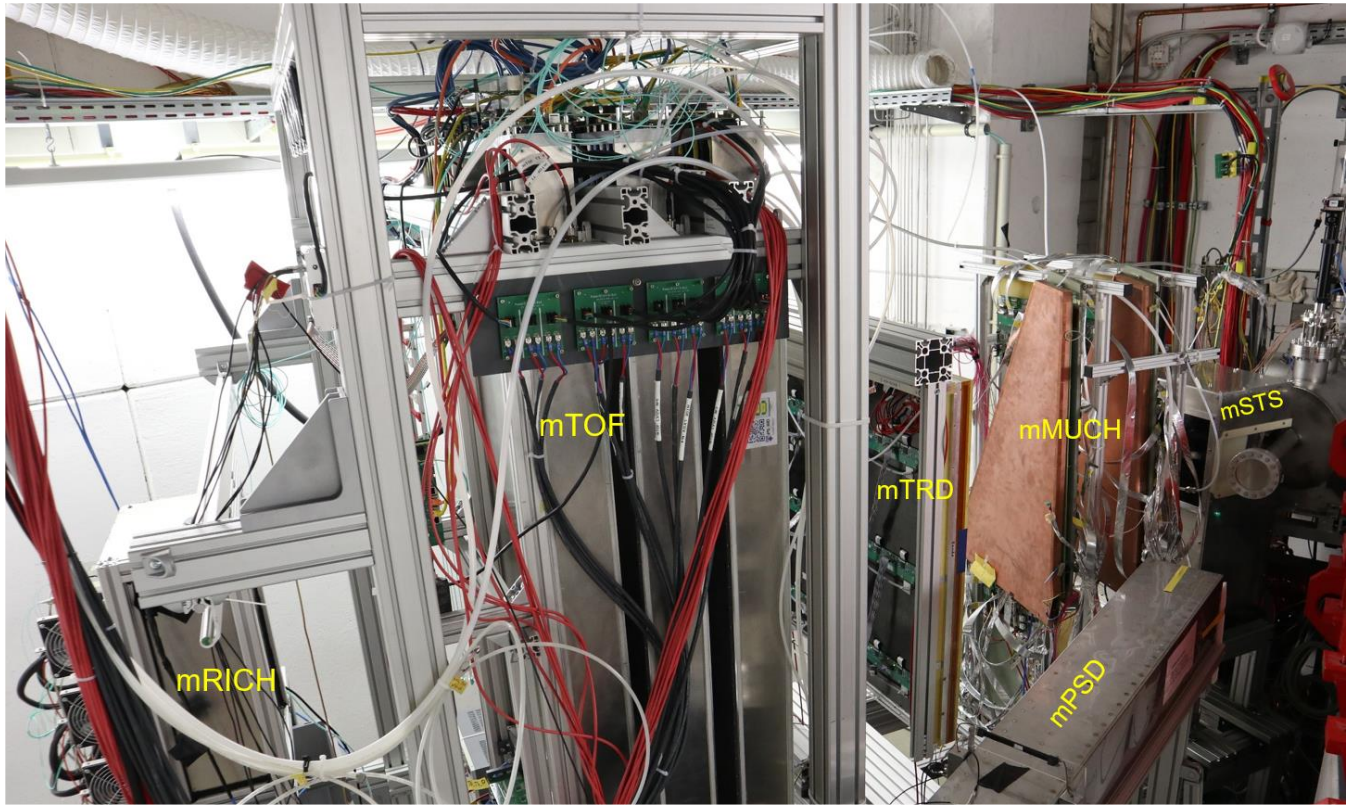
However, we can save 700 lira and two months by not taking soil tests.

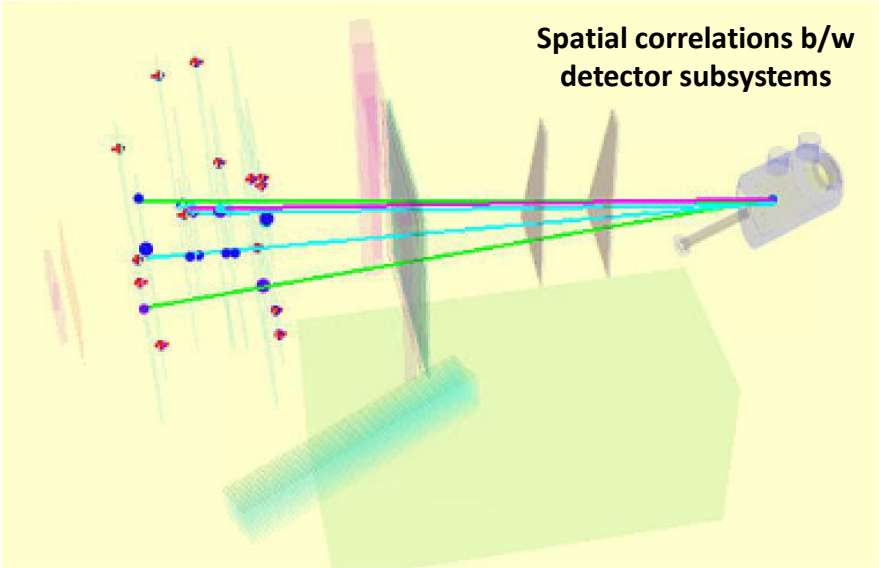
L.E. Wiele and M.E. Messner, Essential Elements of a Successful Engineering and Construction Project, JOM 36, 41–45 (1984)

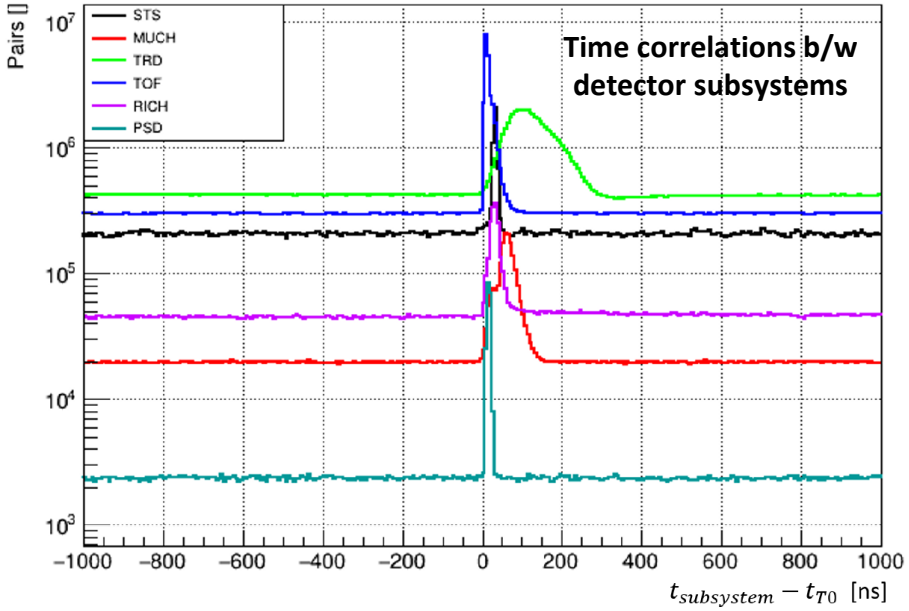
FAIR Phase 0 Research Program

mCBM @ SIS-18

C. Sturm, N. Herrmann, CBM Progress Report 2020
N. Herrmann, S-QM 2021





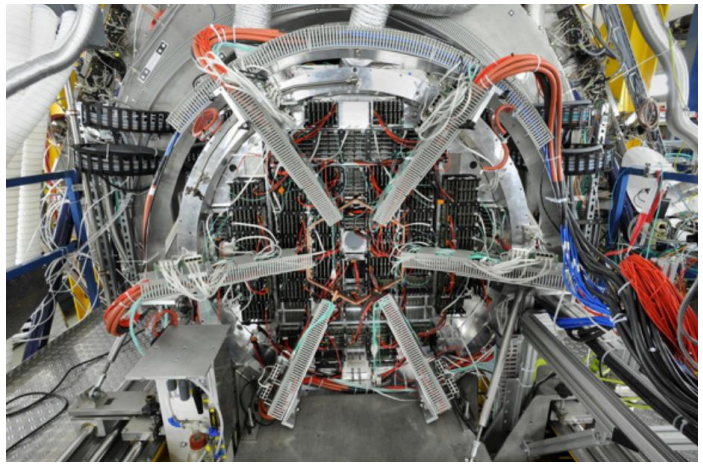


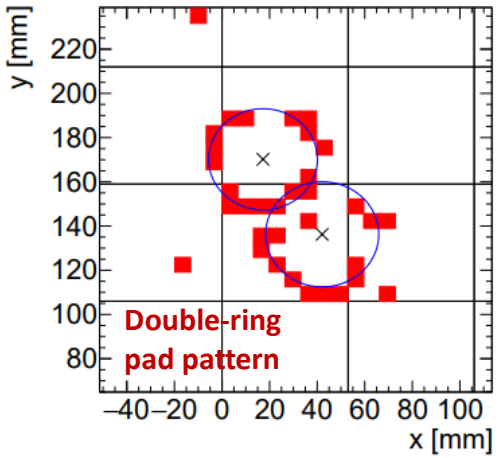
- **mCBM - Pre-series and prototype detectors under realistic conditions with SIS18 beams**
- **First results show time and spatial correlations between the synchronized data streams of the detector subsystems demonstrating for the first time a conceptual verification of the triggerless-streaming read-out and data transport of CBM**
- **Charged particle fluxes up to 20 kHz/cm² at 3m from the target → Detailed high-rate tests for TOF and MVD, LGADs, SMX FEB, STS LV with Pb and Xe beams → validated radiation tolerance**

CBM Contribution To FAIR Phase 0

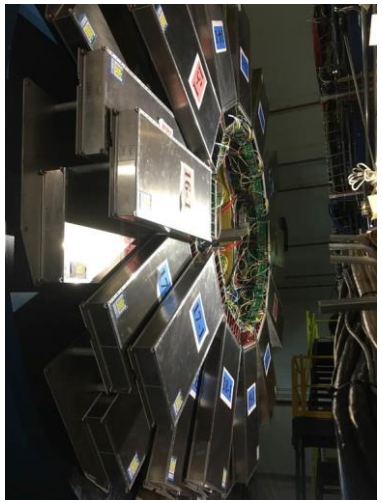
HADES-RICH: Already 1/2 (430 MAPMTs + FEE) of CBM-RICH

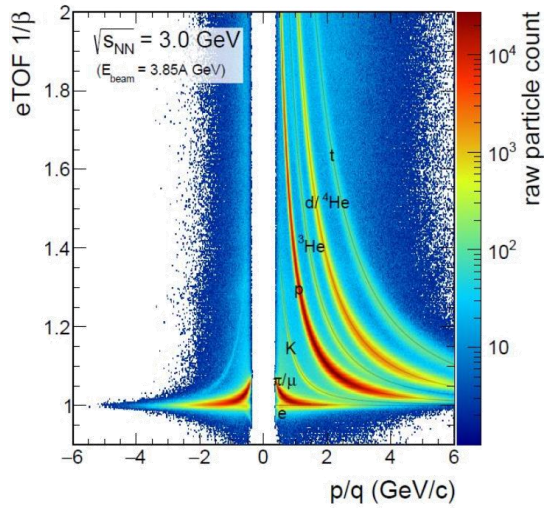
J. A-Musch et al., CBM Progress Report 2020





STAR-eTOF: 10% (108 MRPCs) of CBM-TOF

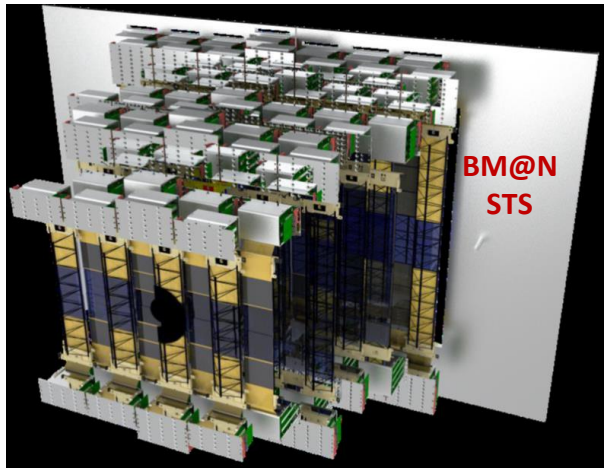


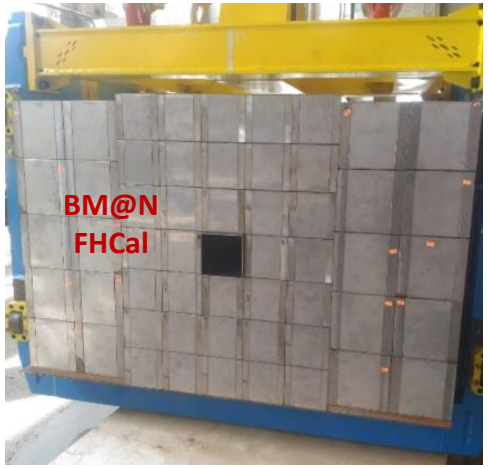


I. Deppner et al., CBM Progress Report 2019
P. Weidenkaff et al., CBM Progress Report 2019

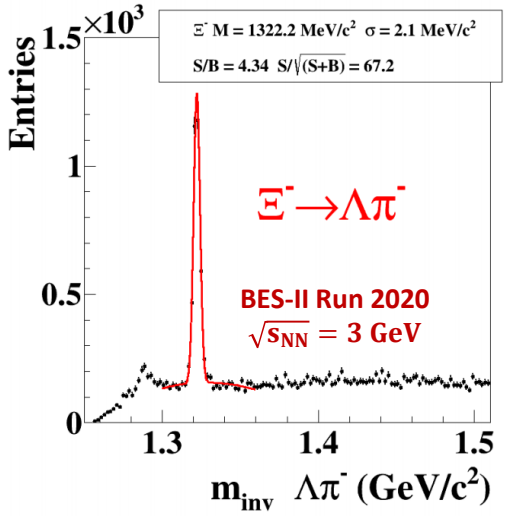
BM@N-STS: 1/3 (300 Si-sensors; 4 tracking layers) of CBM-STS
BM@N-FHCal & NA61-PSD: 20 and 13 modules, respectively, of CBM-PSD

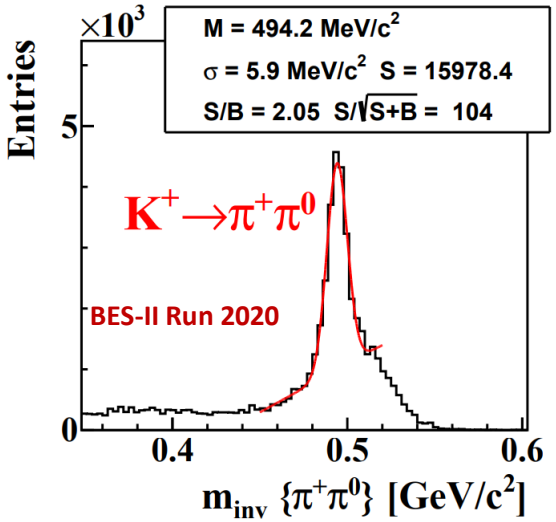
A. Sheremetev et al., CBM Progress Report 2020
S. Morozov et al., CBM Progress Report 2020





CBM Online Reconstruction Software for STAR-BES





I. Vassiliev et al., CBM Progress Report 2020
Y. Fisyak et al., CBM Progress Report 2020

SUMMARY

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

FAIR (Intermediate Objective) is secured and on track

- **to start operation in 2026+**

employ high statistics capability

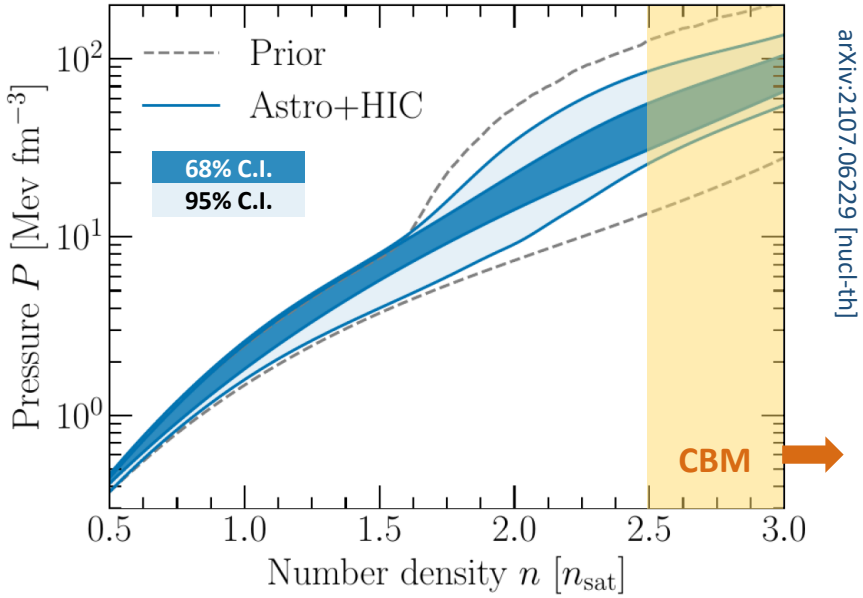
- **to achieve high precision of multi differential observables**
- **to enable rare processes as sensitive probes**

CBM day-1 setup already has significant discovery potential

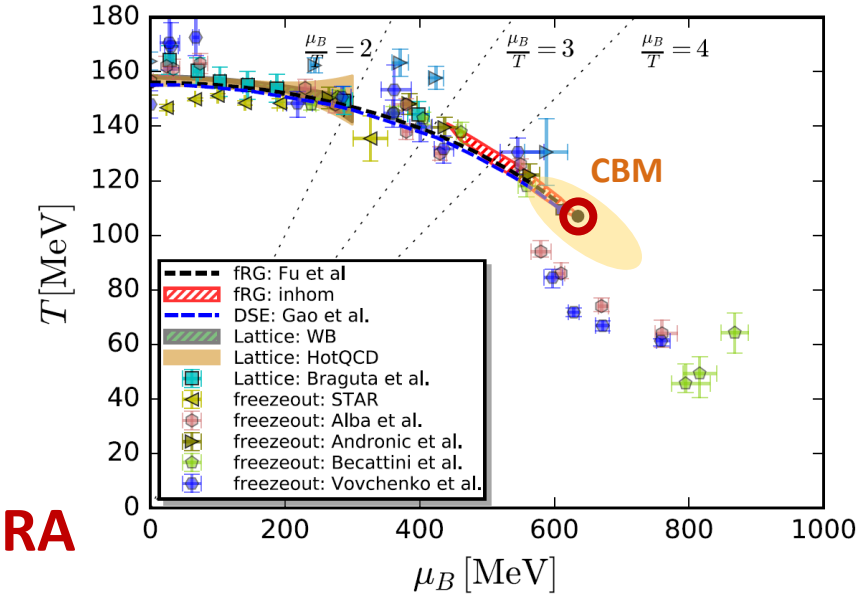
- **excitation function of hyperon production**
- **excitation function of di lepton production**
- **study of light hyper-nuclei**

CBM Phase 0 activities (HADES, STAR, BM@N, NA61, mCBM)

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



S. Huth, P.T.H. Pang et al., arXiv:2107.06229 [nucl-th]

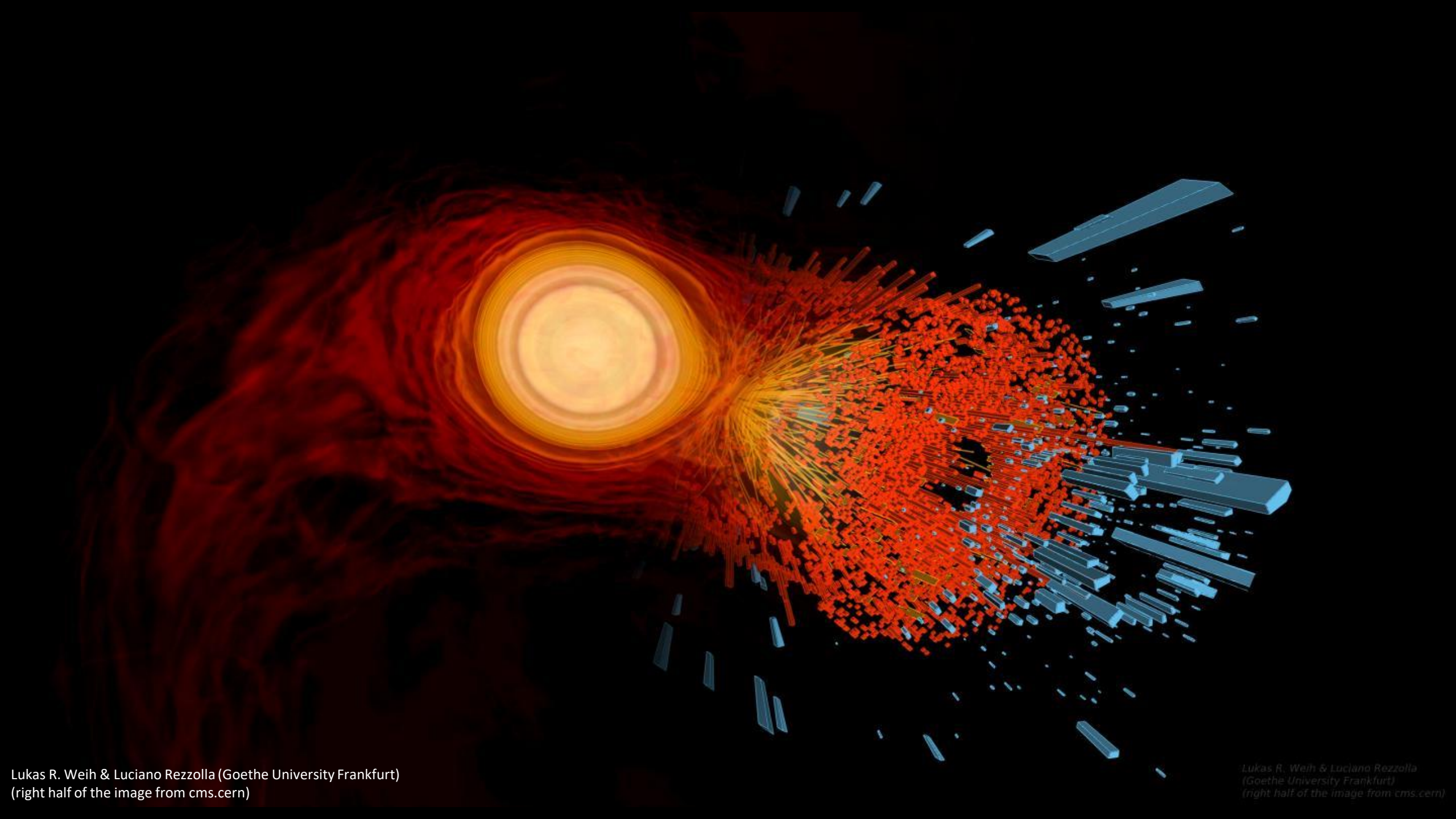


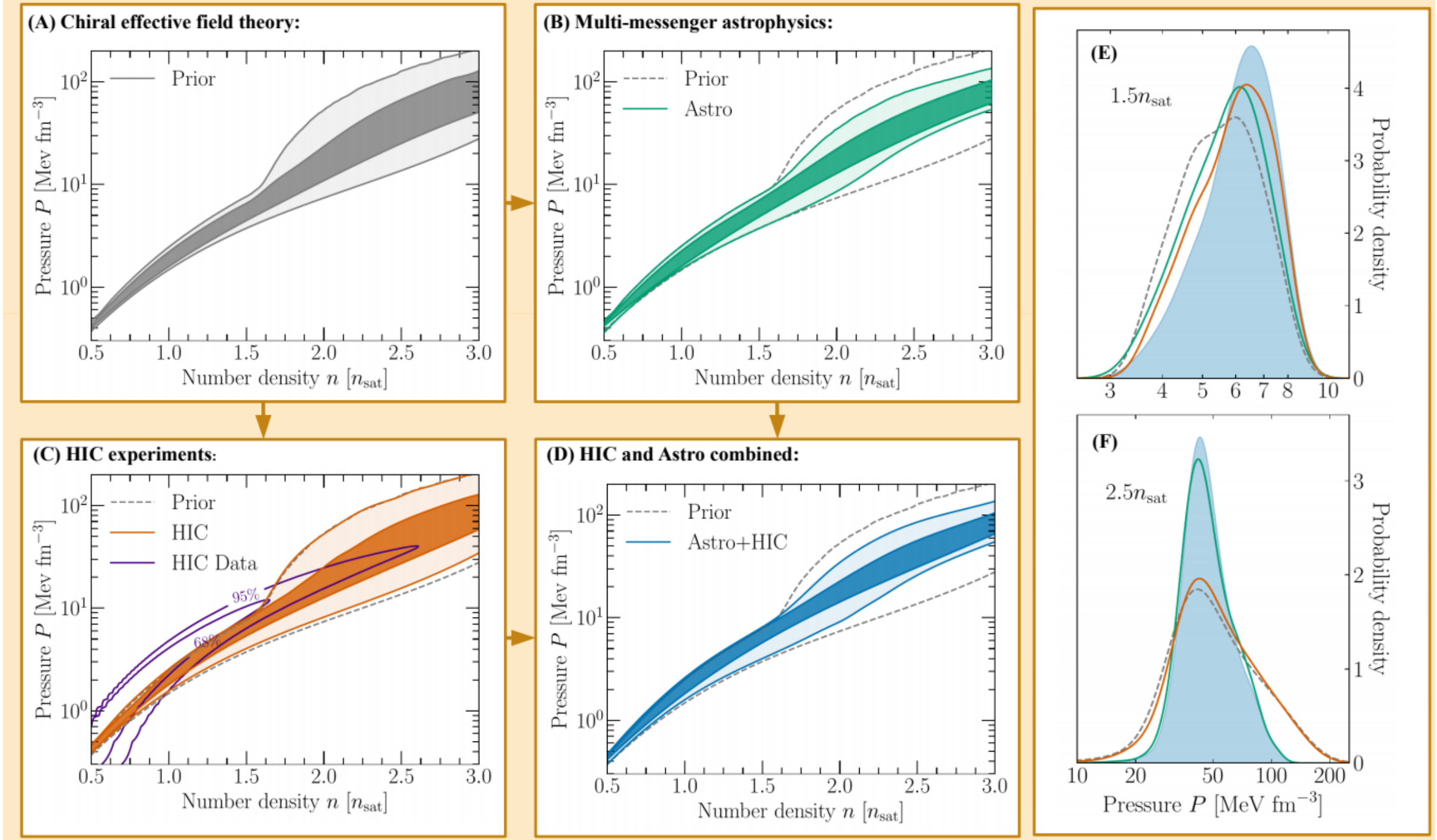
W.J. Fu, J.M. Pawlowski, F. Rennecke, Phys. Rev. D 101, 054032 (2020)

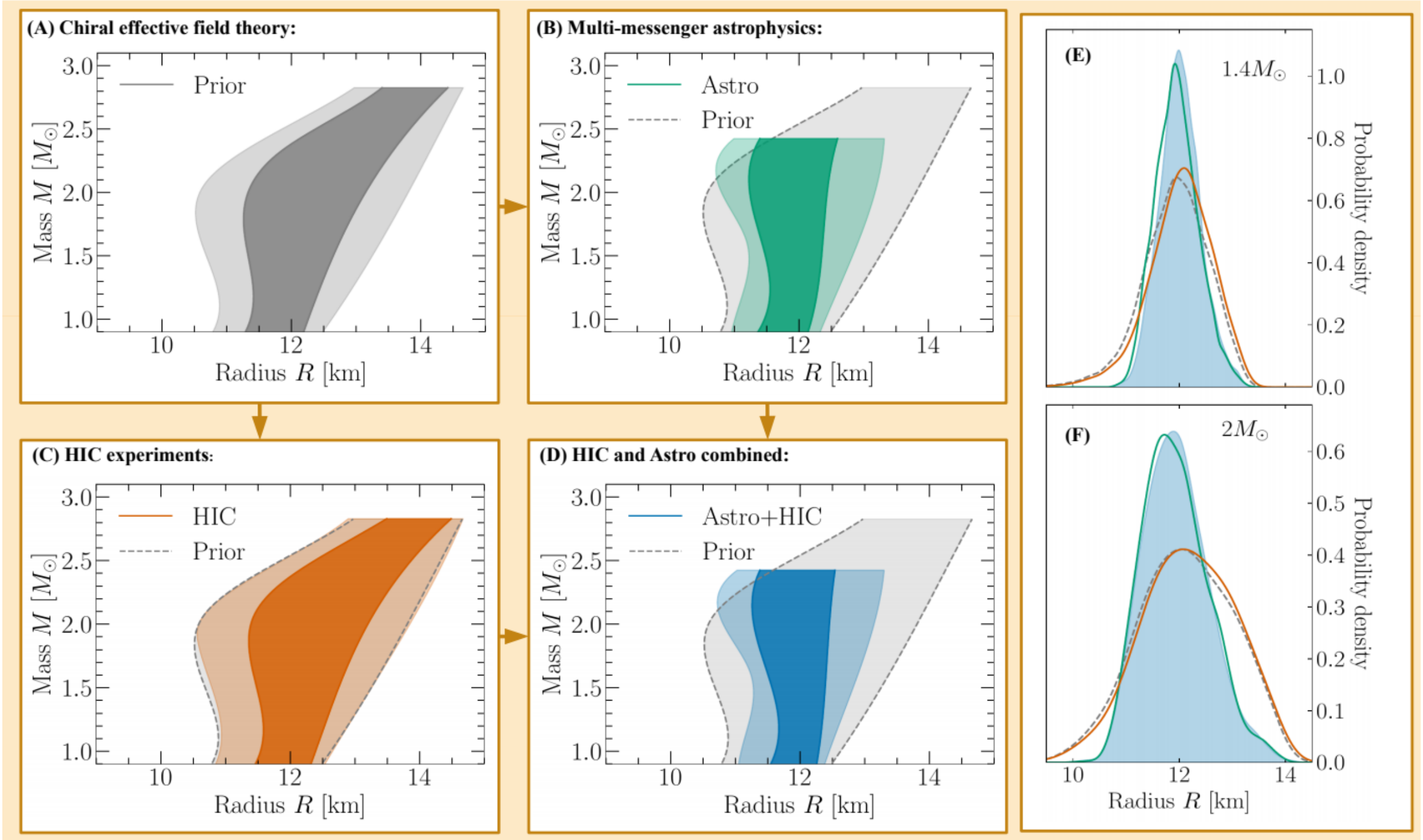
MOVING TOWARDS A TRULY MULTI-MESSENGER PHYSICS ERA

THANK YOU

HELMHOLTZ GEMEINSCHAFT · GSI · FAIR · HFHF Helmholtz Forschungsakademie Hessen für FAIR · ESCAPE · STRONG 2020 · CREMLIN PLUS · Bundesministerium für Bildung und Forschung · MINISTRY OF EDUCATION YOUTH AND SPORTS · भारत सरकार GOVERNMENT OF INDIA · विज्ञान और प्रौद्योगिकी मंत्रालय MINISTRY OF SCIENCE AND TECHNOLOGY · Ministry of Science and Higher Education Republic of Poland · JOINT INSTITUTE FOR NUCLEAR RESEARCH SCIENCE BRINGS NATIONS TOGETHER 1956 · NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE" · MINISTERUL EDUCAȚIEI · ROSATOM · DST@ 1971-2021 DEPARTMENT OF SCIENCE & TECHNOLOGY


Lukas R. Weih & Luciano Rezzolla (Goethe University Frankfurt)
(right half of the image from cms.cern)


(A) Chiral effective field theory:
Prior
Pressure P [Mev fm^{-3}]
Number density n [$n_{\rm sat}$]
(B) Multi-messenger astrophysics:
Prior
Astro
Pressure P [Mev fm^{-3}]
Number density n [$n_{\rm sat}$]
(C) HIC experiments:
Prior
HIC
HIC Data
95%
68%
Pressure P [Mev fm^{-3}]
Number density n [$n_{\rm sat}$]
(D) HIC and Astro combined:
Prior
Astro+HIC
Pressure P [Mev fm^{-3}]
Number density n [$n_{\rm sat}$]
(E)
$1.5n_{\rm sat}$
Probability density
(F)
$2.5n_{\rm sat}$
Probability density
Pressure P [MeV fm^{-3}]


(A) Chiral effective field theory:
Prior
Mass M [$M_\odot$]
Radius R [km]
(B) Multi-messenger astrophysics:
Astro
Prior
Mass M [$M_\odot$]
Radius R [km]
(C) HIC experiments:
HIC
Prior
Mass M [$M_\odot$]
Radius R [km]
(D) HIC and Astro combined:
Astro+HIC
Prior
Mass M [$M_\odot$]
Radius R [km]
(E)
$1.4M_\odot$
Probability density
(F)
$2M_\odot$
Probability density
Radius R [km]