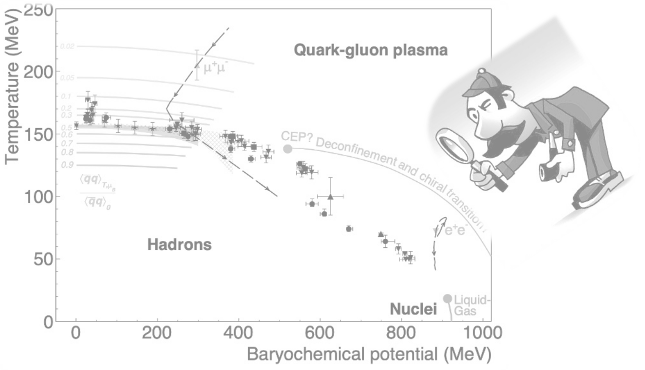
# Unravelling the phase structure of strong-interaction matter with CBM



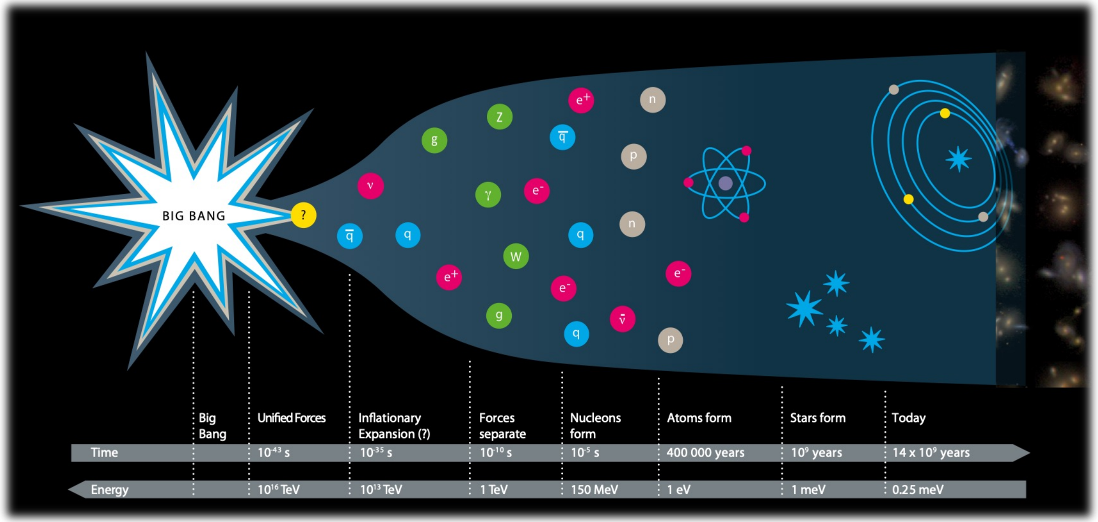

**Tetyana Galatyuk,**
**GSI / Technische Universität Darmstadt**

R3B Collaboration Meeting
July 11, 2024
GSI, Darmstadt

# Objective

**Decode the phases of nuclear matter in the non-perturbative regime of QCD**

**Unravel the role of the strong interaction in the evolution of our universe**

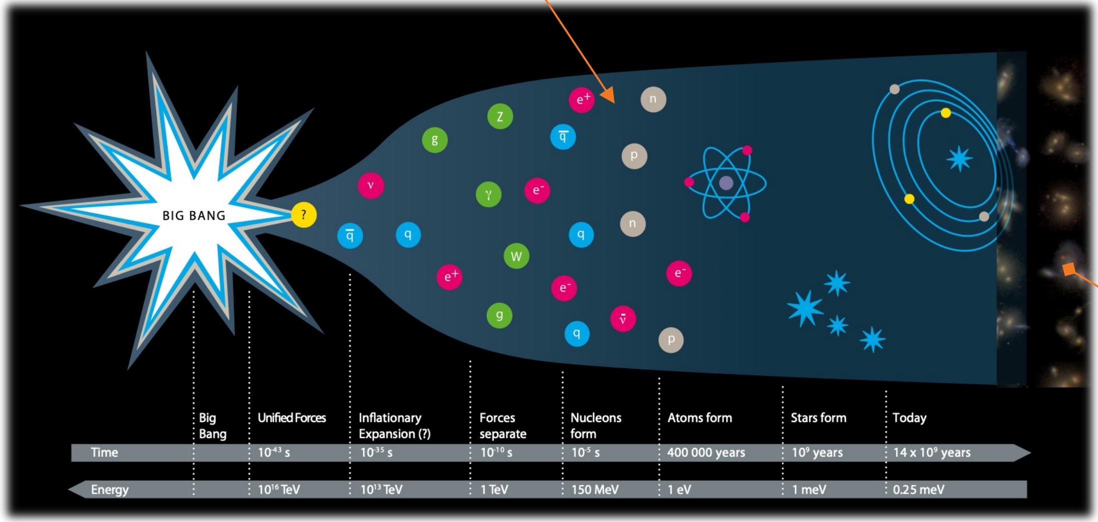


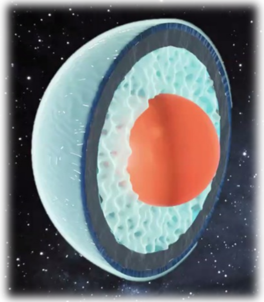
# Objective

**Decode the phases of nuclear matter in the non-perturbative regime of QCD**

**Unravel the role of the strong interaction in the evolution of our universe**

**Nature of phase transitions in strong-interaction matter?**



**Neutron star**

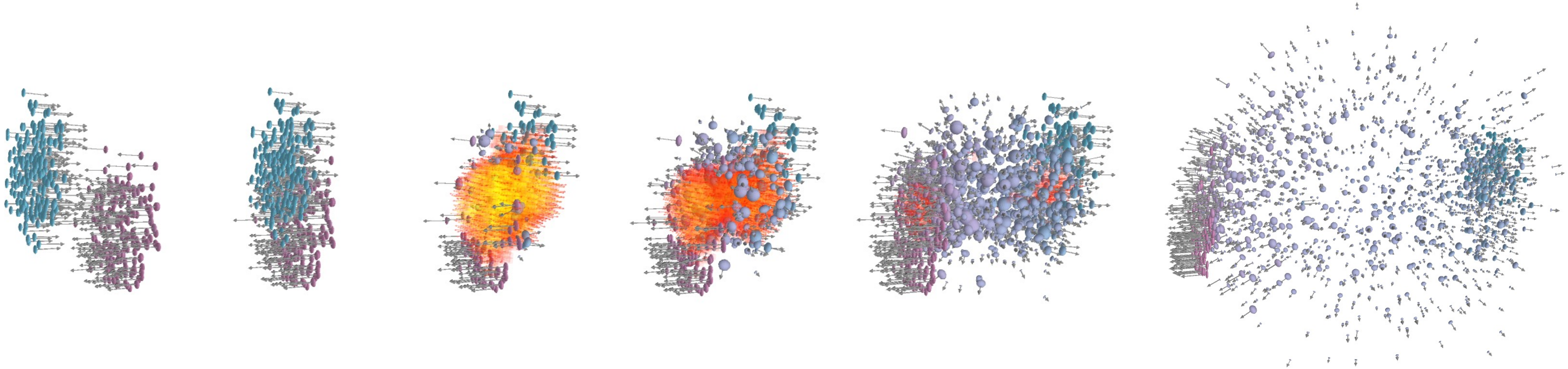
$M \sim 1.4 - 2\, M_{\odot}$
$R \sim 12$ km
$T \sim$ keV
$n \lesssim 10\, n_{sat}$

**Matter properties in compact stellar objects?**

# Method

**Recreate various forms of cosmic matter in laboratory → high-energy heavy-ion collisions**

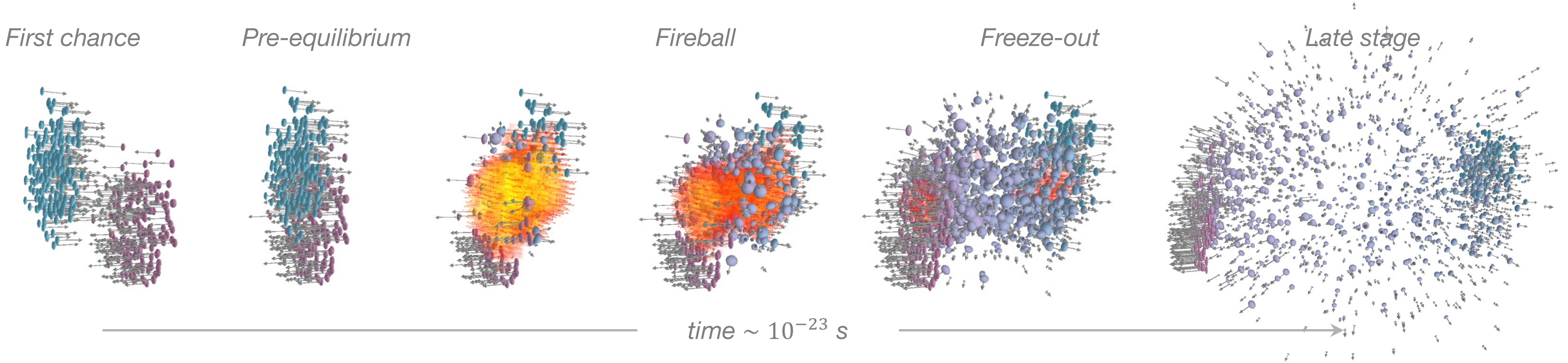
**Investigate transient states of QCD matter under extreme conditions**

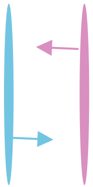


# Method

**Recreate various forms of cosmic matter in laboratory → high-energy heavy-ion collisions**

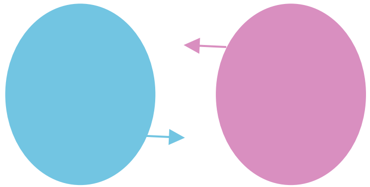
**Investigate transient states of QCD matter under extreme conditions**



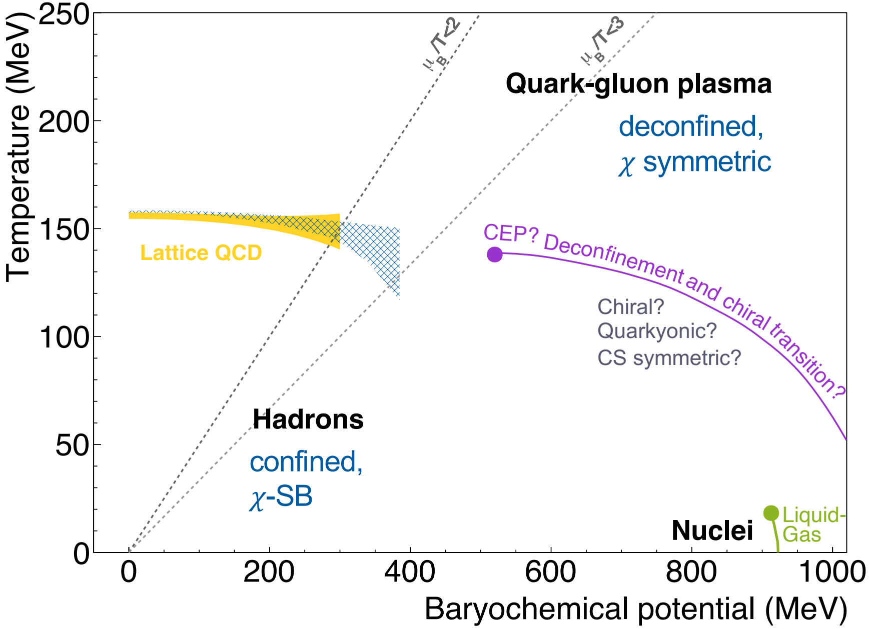



LHC energies $\sqrt{s_{NN}} = 2 - 5\ TeV$
parton parton collisions
$N_{particles} = N_{anti-particles}$

SIS energies $\sqrt{s_{NN}} = 2 - 5\ GeV$
Nuclear stopping
$N_{particles} \gg N_{anti-particles}$



# Searching for landmarks of the QCD matter phase diagram



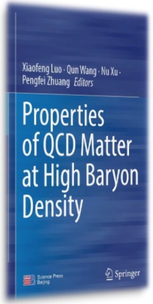

**Experimental challenges:**

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

**Measure with utmost precision:**

- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction)

**Worldwide experimental and theoretical efforts**
**Relevance for astrophysics**




Chen, Dong, Fukushima, Galatyuk, *et al.*, doi:10.1007/978-981-19-4441-3_4 (2022)

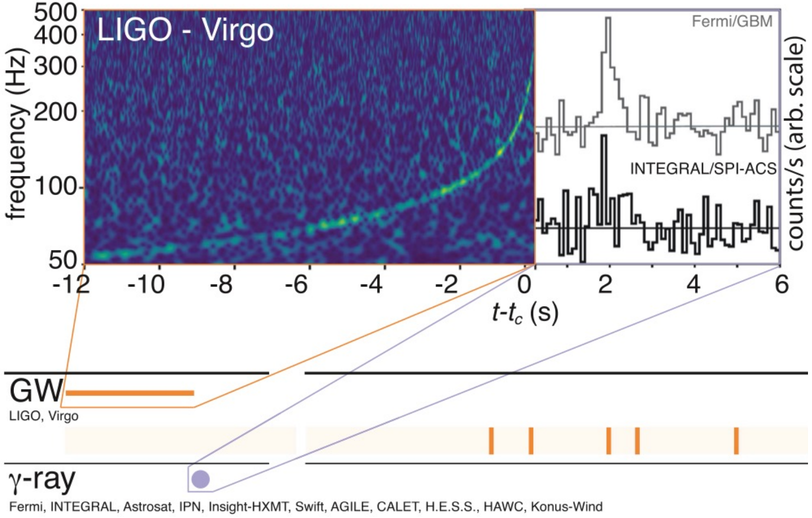
# Multi-messenger signals from neutron star merger


- GW170817 17 Aug 2017 12:41:04 UTC
  First detection of a binary neutron star merger through gravitational waves

  LIGO + VIRGO, PRL 119 (2017) 1611001

- GRB 170817A ~1,7 s later:
  Observation of the same event through electromagnetic waves (gamma-ray burst)

  Fermi GBM + INTEGRAL + LIGO + Virgo, Astrophys.J.Lett. 848 (2017)




⋮

# Laboratory studies of the matter properties in compact stellar objects


nature physics

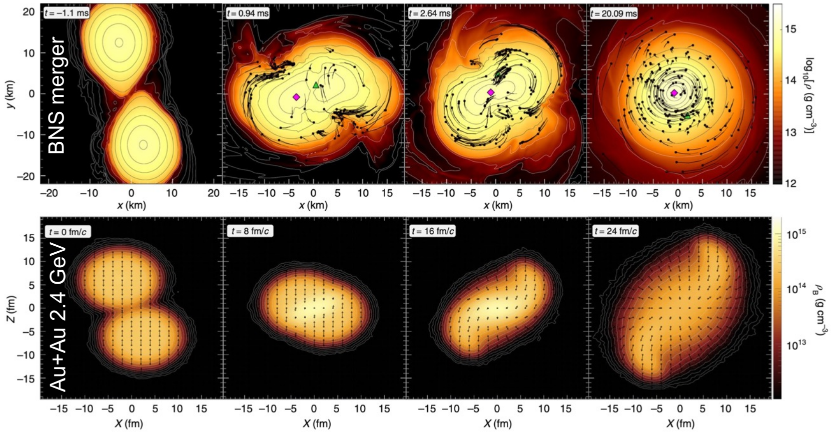
ARTICLES

https://doi.org/10.1038/s41567-019-0583-8

Probing dense baryon-rich matter with virtual photons

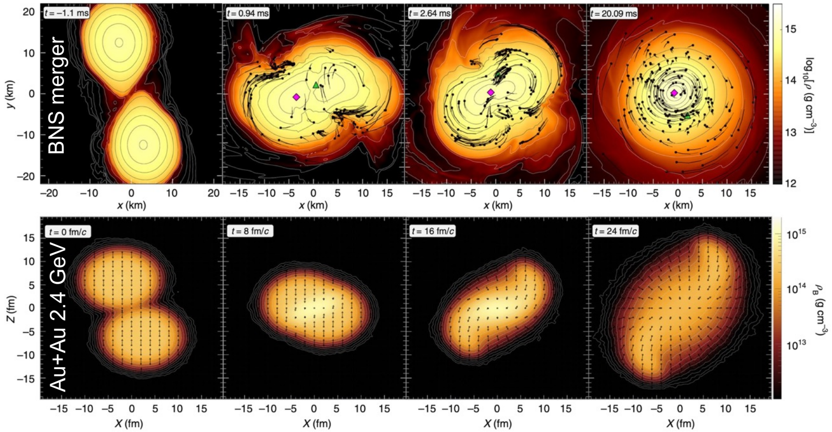
The HADES Collaboration*

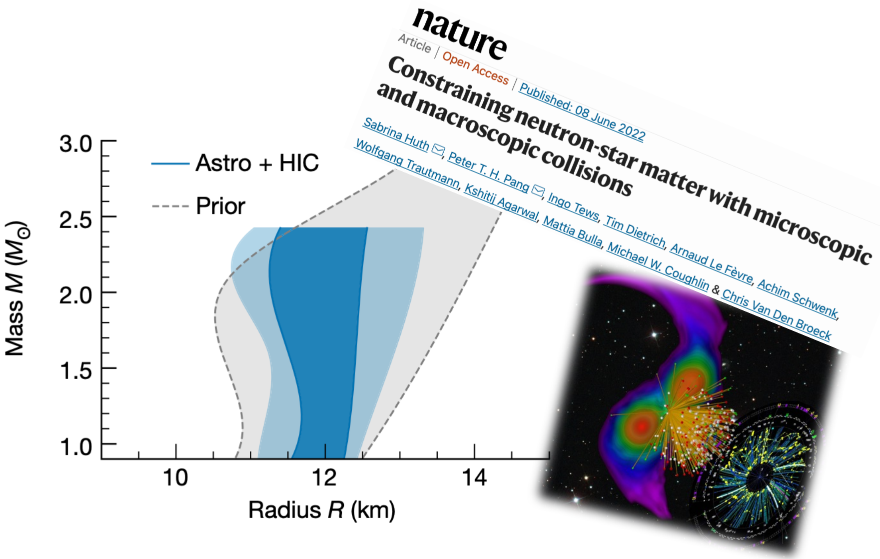
**18 orders of magnitude in scales**
**still similar T < 70 MeV, $\rho < 3\rho_0$ for both**



# Laboratory studies of the matter properties in compact stellar objects


**18 orders of magnitude in scales**
**still similar T < 70 MeV, ρ < 3ρ$_0$ for both**




**Remarkable consistency between multi-messenger observations and constraints from heavy-ion data**

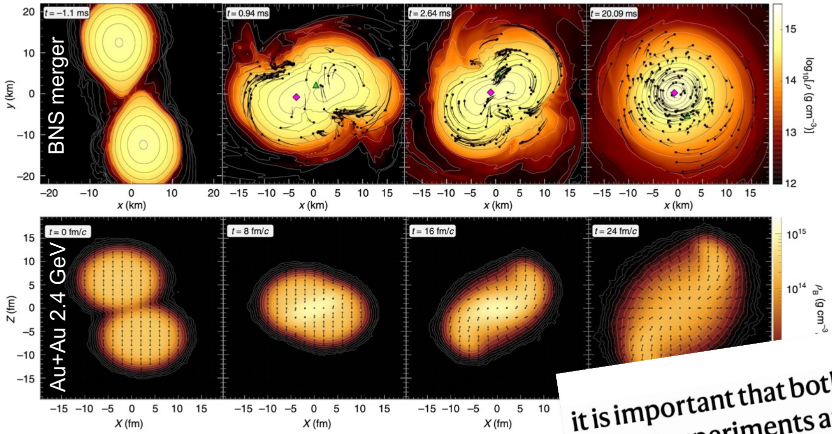
# Laboratory studies of the matter properties in compact stellar objects

nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0583-8

**Probing dense baryon-rich matter with virtual photons**

The HADES Collaboration*

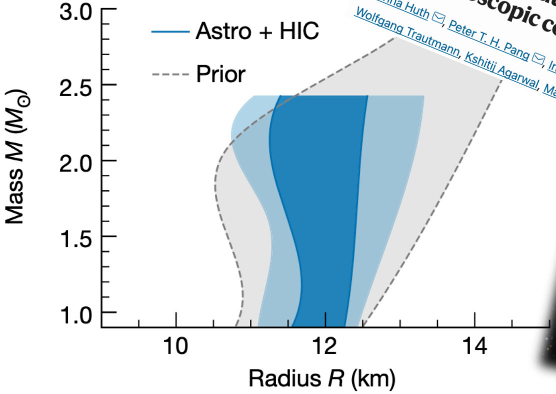
**18 orders of magnitude in scales**
**still similar T < 70 MeV, $\rho < 3\rho_0$ for both**

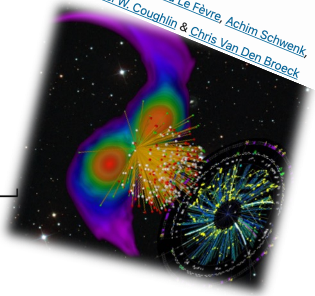



nature
Article | Open Access | Published: 08 June 2022

**Constraining neutron-star matter with microscopic and macroscopic collisions**

Sabrina Huth, Peter T. H. Pang, Ingo Tews, Tim Dietrich, Arnaud Le Fèvre, Achim Schwenk, Wolfgang Trautmann, Kshitij Agarwal, Mattia Bulla, Michael W. Coughlin & Chris Van Den Broeck



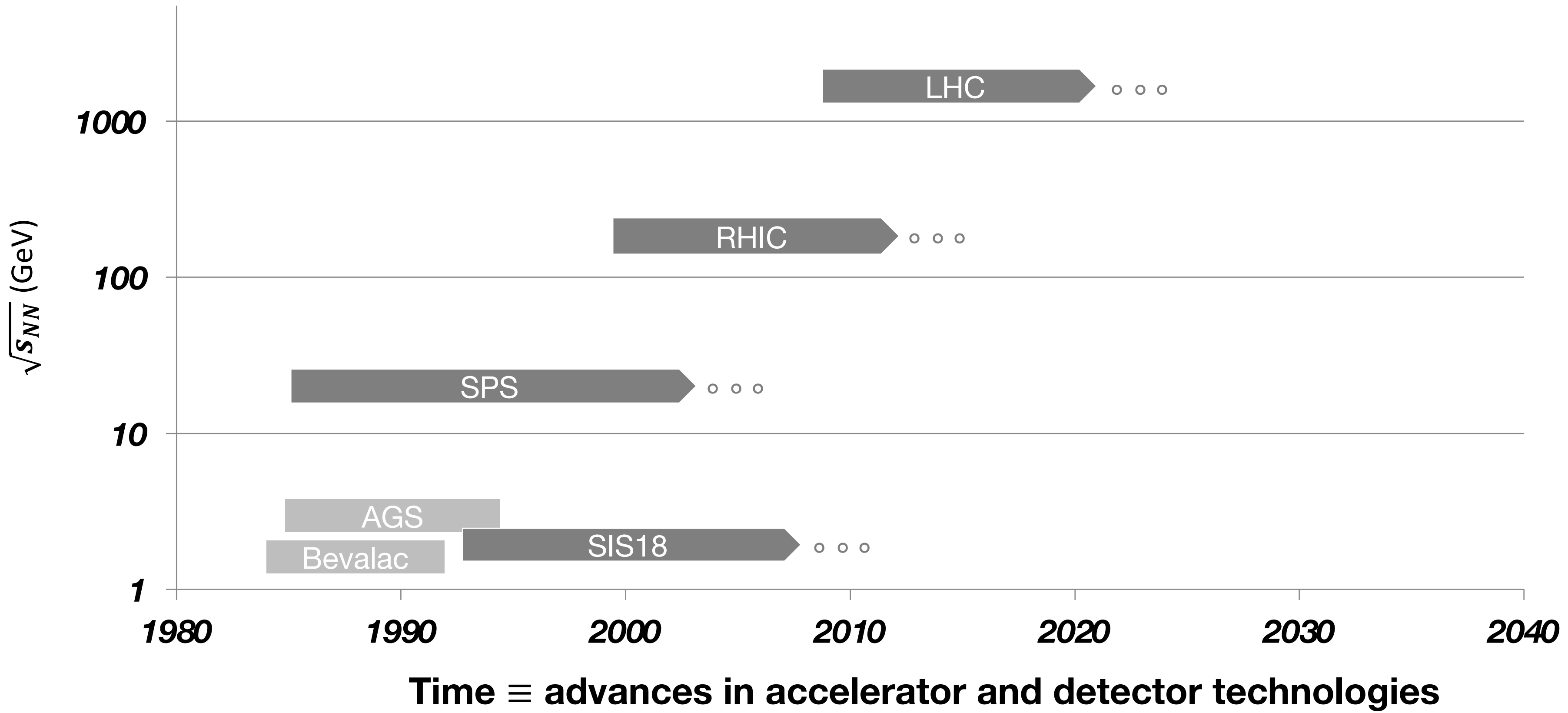



**Remarkable consistency between multi-messenger observations and constraints from heavy-ion data**

Going forward, it is important that both statistic and systematic sources of uncertainty for HIC experiments are further improved.

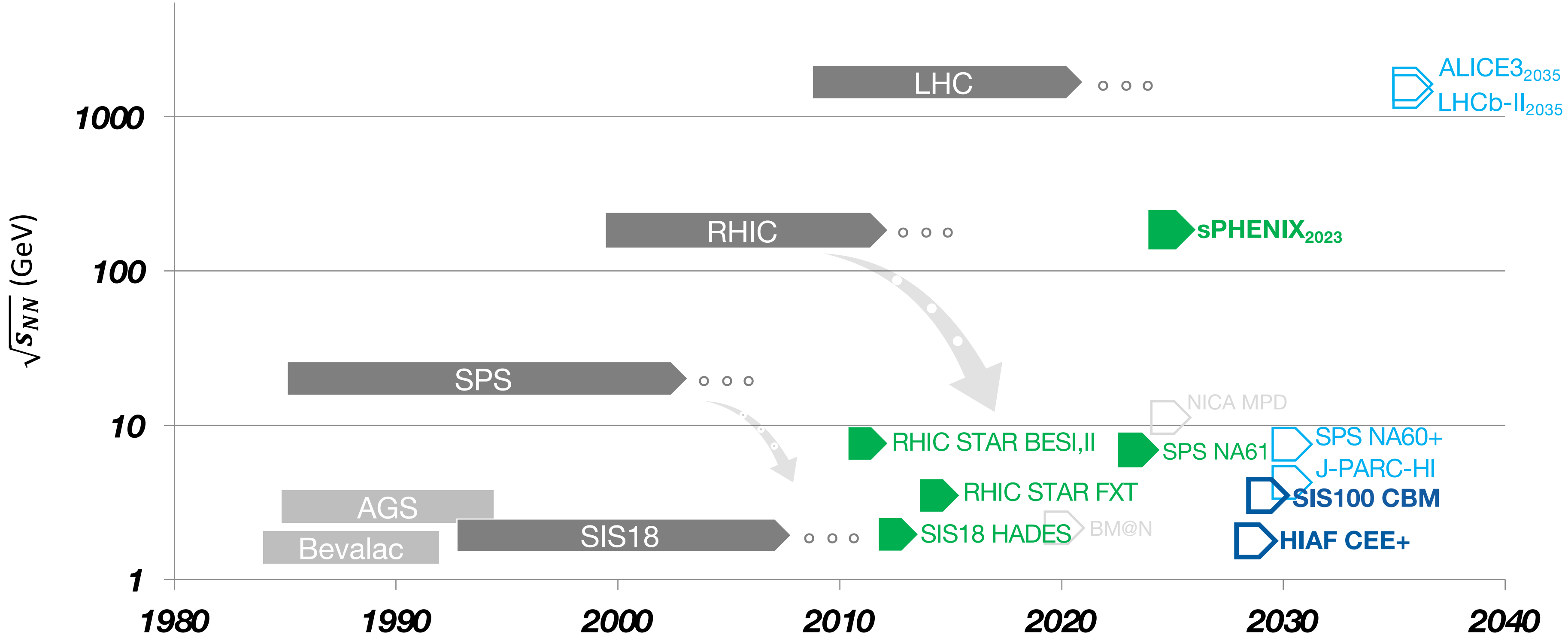
advancing HIC experiments to probe higher densities, above 2–3$n_{sat}$, will be key

# The quest for highest energy



# The quest for utmost precision and sensitivity for rare signals

~25 years progress in technology since AGS (begin of high $\mu_B$ explorations)

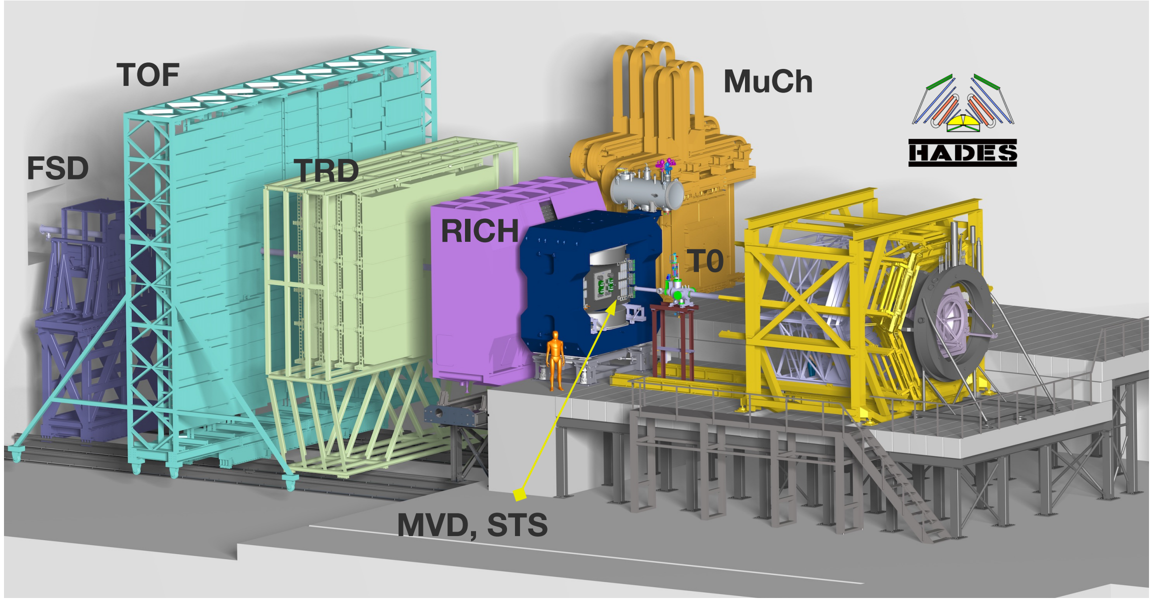



Time ≡ advances in accelerator and detector technologies

# Compressed Baryonic Matter experiment

*315 full members from 10 countries*
*47 full member institutions*
*10 associated member institutions*

- Fixed target experiment
  → obtain highest luminosities
- Versatile detector systems
  → optimal setup for given observable
- Tracking based entirely on silicon
  → fast and precise track reconstruction
- Free-streaming FEE
  → nearly dead-time free data taking
- On-line event selection
  → highly selective data reduction



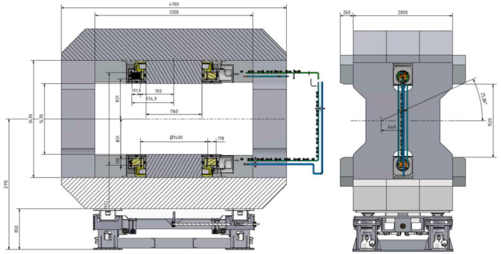

*Q4 2027 – installation and commissioning w/o beam*
*Q4 2028 – commissioning with SIS100 beam*

# CBM subsystems are on the verge of series production

## ➡ pre-production is ongoing in all systems

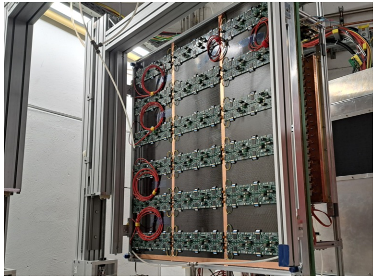
### Superconducting dipole magnet

*award of contract to Bilfinger Noell GmbH 20.12.2023*



### Beam monitoring system

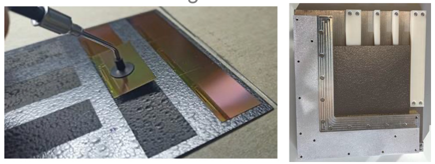
### Transition Radiation Detector



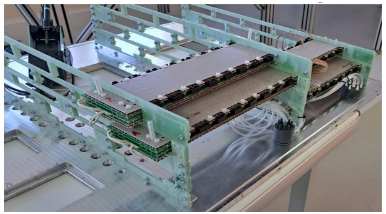
*pre-production modules of 1D and 2D options ready*

### Micro Vertex Detector

*sensor/module integration*



### Time of flight detector

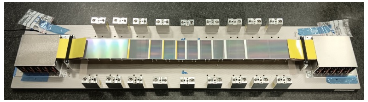


*module pre-production concluded*

### MUon CHamber system

*test of full-size GEM and RPC prototypes*

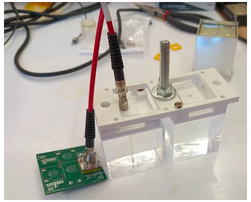
### Silicon Tracking System



*first STS series ladder*

*> 100 modules assembled*

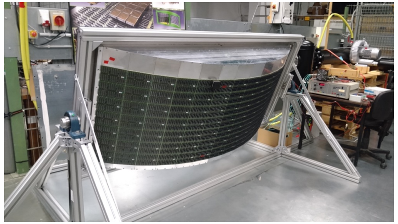
### Forward Spectator Detector



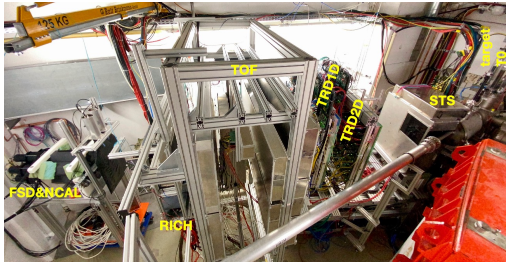
*ZnS scintillators and LYSO crystals read-out via SiPM or/and PMT*

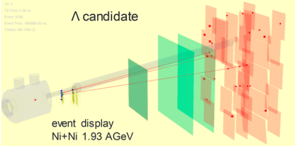
### Ring Imaging Cherenkov detector

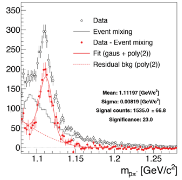
*1 of 2 photo cameras ready*
*50% FEE produced*



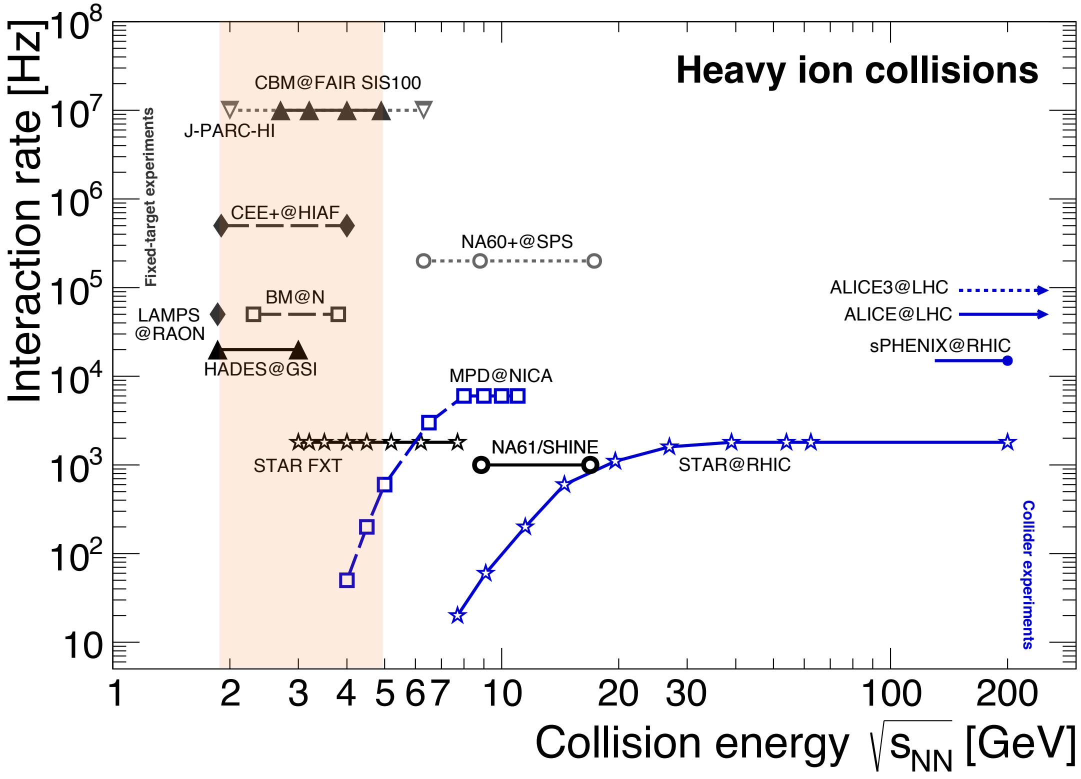
### Prototype of CBM online data processing tests with mCBM



# Some basic facts on extreme matter facilities

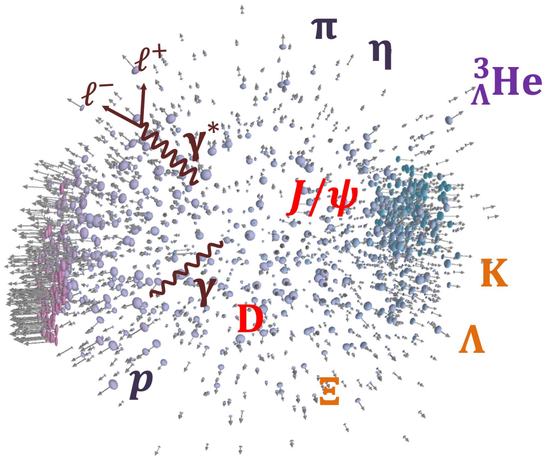



- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high $\mu_B$ with rare and electromagnetic probes: high rate capability, **energy range 3** $< \sqrt{s_{NN}} <$ **5 GeV**
- **HADES:** established thermal radiation at high $\mu_B$, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV

- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **CEE+@HIAF construction**: multipurpose detector based on TPC, anticipated rate capability 500 kHz, anticipated start 2025
- **Proposals: NA60+ at SPS, J-PARC-HI**

**Program needs ever more precise data and sensitivity for rare signals**

TG, NPA 982 (2019), update 2021 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

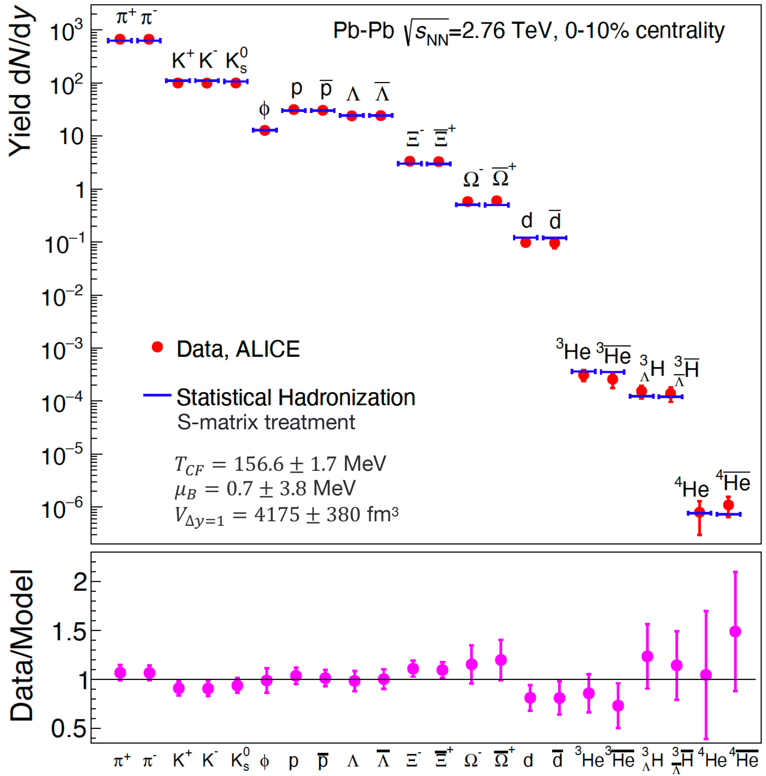



Final state “hadron-chemistry”

# HADRON PRODUCTION

# Hadronization of the fireball

Andronic, Braun-Munzinger, Redlich, Stachel,
Nature 561 (2018) no.7723




- Analysis of hadron yields within the statistical (thermal) model
- Test hypothesis of hadron abundancies in equilibrium ⇝ $T_{CF}, \mu_B, V$

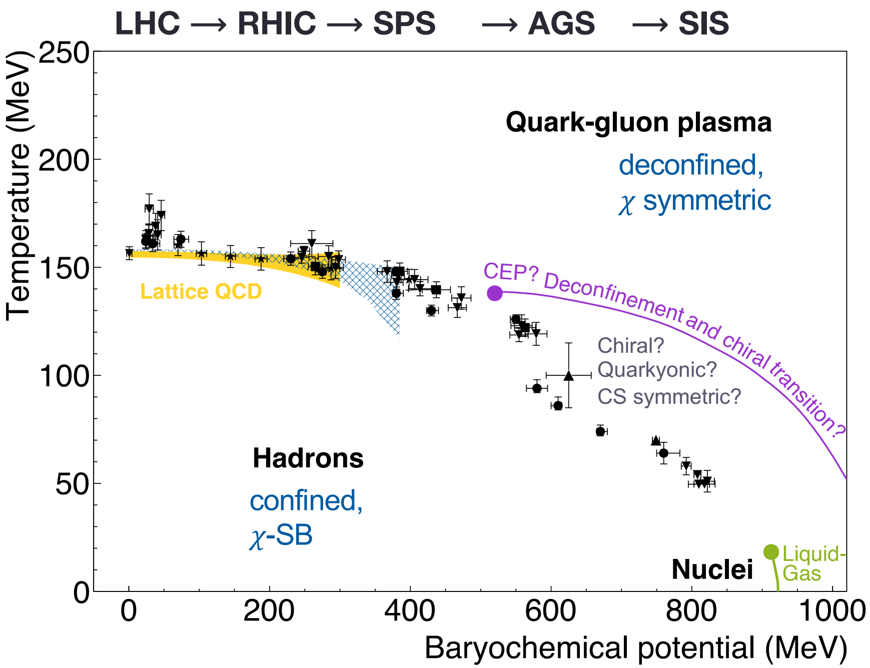
- **ALICE at LHC:**
  - grand canonical partition function
  - essentially 1 free parameter ⇝ temperature $T_{CF}$

  $\boldsymbol{T_{CF} = 156.5 \pm 1.5 \pm 3}$ **MeV** (sys)

**Agreement over 9 orders of magnitude with QCD statistical operator prediction!**

- matter and antimatter are formed in equal portions
- noticeably, loosely-bound objects follow the same systematics

# Energy dependence of T and $\mu_B$




**Hadron yields produced in central heavy-ion collisions from LHC down to SIS18 energies well described by statistical ensemble**

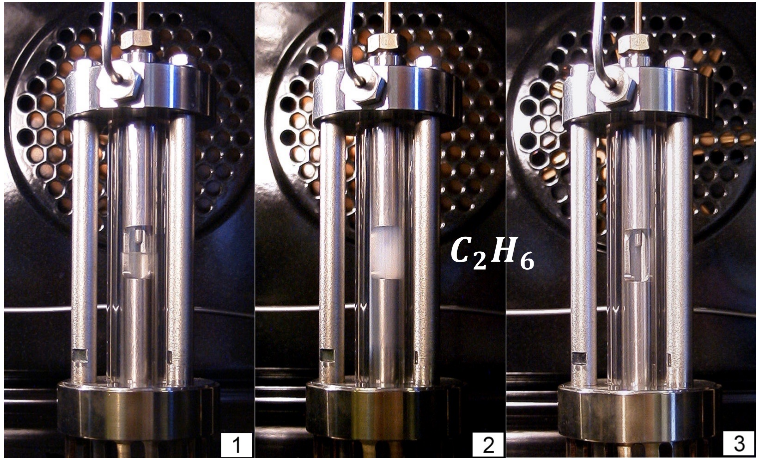
- Factor 1000 in beam energy ↔ factor ~2 in temperature
- Thermal fits exhibit a limiting temperature ($\sqrt{s_{NN}} \geq 12$ GeV):
  $T_{lim} = 158.4 \pm 1.4$ MeV Andronic, Braun-Munzinger, Stachel, PLB 673 (2009) 142
- ALICE result is in remarkable agreement with the pseudo-critical temperature from lattice QCD
  $T_{pc} = 156.5 \pm 1.5$ MeV Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
  $T_{pc} = 158.0 \pm 0.6$ MeV Borsanyi *et al.* [Wuppertal-Budapest], PRL 125 (2020)
- Chiral crossover at $\mu_B = 0$ may turn into a first-order phase transition at finite $\mu_B$
- QCD critical point is awaiting discovery

Quest for critical phenomenon connected to the 1st order phase transition

# CRITICALITY

# Probing criticality with fluctuations

$T < T_c$ $T = T_c$ $T > T_c$



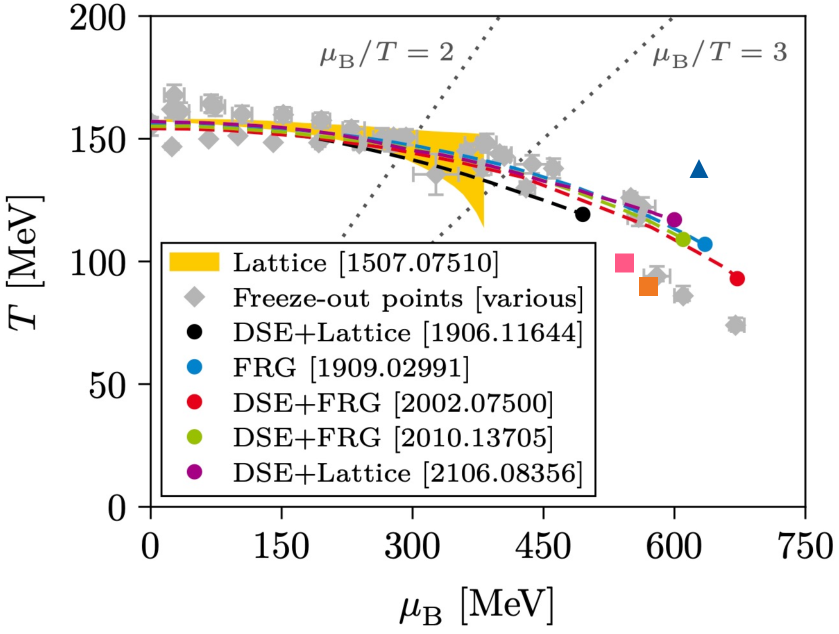

Critical phenomena discovered ~200 years ago by Cagniard de la Tour, using steam digester invented by Denis Papin in 1679

Ann. Chim. Phys., 21 (1822) 127-132

$$\frac{\langle\rho^2\rangle - \langle\rho\rangle^2}{\langle\rho\rangle^2} = \frac{T\chi_T}{V} \qquad \chi_T = -\frac{1}{V\left(\frac{\partial P}{\partial V}\right)_T}$$

- Increase in density fluctuations near $T_c$
- At $T_c$ thermal susceptibility $\chi_T$ diverges

# Critical point predictions from theory




Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)

- Lattice QCD disfavours QCD critical point at $\mu_B/T < 3$
- Effective QCD theories[1-3] and lattice-Pade[5,6] predict QCD critical point in a similar ballpark $\boldsymbol{T \sim 90 - 120\ \mathrm{MeV}, \mu_B \sim 500 - 650\ \mathrm{MeV}}$
- If true, reachable in heavy-ion collisions at $\sqrt{s_{NN}} \boldsymbol{\sim 3 - 5\ \mathrm{GeV}}$
- Including possibility that the QCD critical point does not exist

Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
Vovchenko *et al.*, PRD 97, 114030 (2018)

[1]DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)
[2]FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)
[3]BHE: Hippert et al., arXiv:2309.00579
▲ [4]FSS: Sorensen and Sorensen, arXiv:2405.10278 [nucl-th]
■ [5]lQCD-Pade: Basar, arXiv:2312.06952
■ [6]lQCD-Pade: Clarke *et al.*, PoS LATTICE2023 (2024), 168

# Event-by-event fluctuations and statistical mechanics

- In strong interactions, baryons, electrical charges and strangeness are conserved ($q \in \{B, Q, S\}$)
- Event-by-event fluctuations of $q$ predicted within grand canonical ensemble

cf. Friman *et al.*, EPJC 71 (2011) 1694
Stephanov, RPL 107 (2011) 052301

**encodes the EoS**

$$\frac{\kappa_n(N_q)}{VT^3} = \frac{1}{VT^3}\frac{\partial^n lnZ(V,T,\vec{\mu})}{\partial(\mu_q/T)^n} = \frac{\partial^n \hat{P}}{\partial \hat{\mu}_q^n} \equiv \hat{\chi}_n^q$$

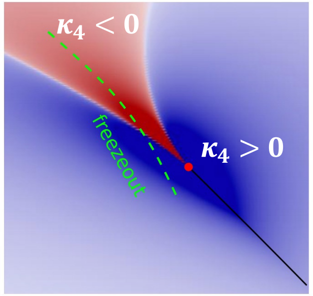
$\kappa_n$ - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

Higher order cumulants describe the shape of measured distributions and quantify fluctuations

*Variance* $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$

*Skewness* $\kappa_3 = \langle(\delta N)^3\rangle$

*Kurtosis* $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$




Stephanov, RPL 107 (2011) 052301

**QCD critical point:** large correlation length and fluctuations

$\kappa_2 \sim \xi^2,\ \kappa_3 \sim \xi^{4.5},\ \kappa_4 \sim \xi^7$

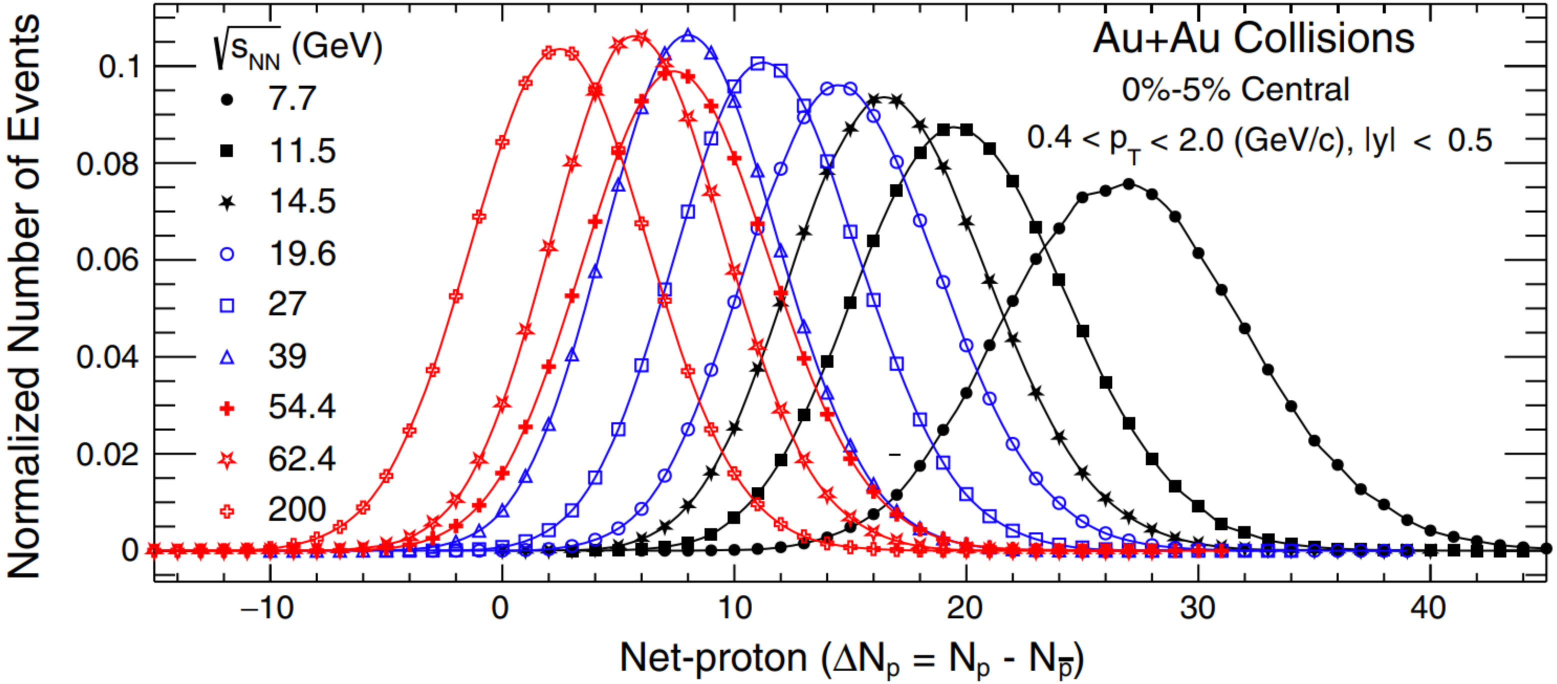
$\xi \rightarrow \infty$ **diverges at critical point**

➡ Look for **enhanced fluctuations** and **non-monotonicity**

# Measuring cumulants in heavy-ion collisions

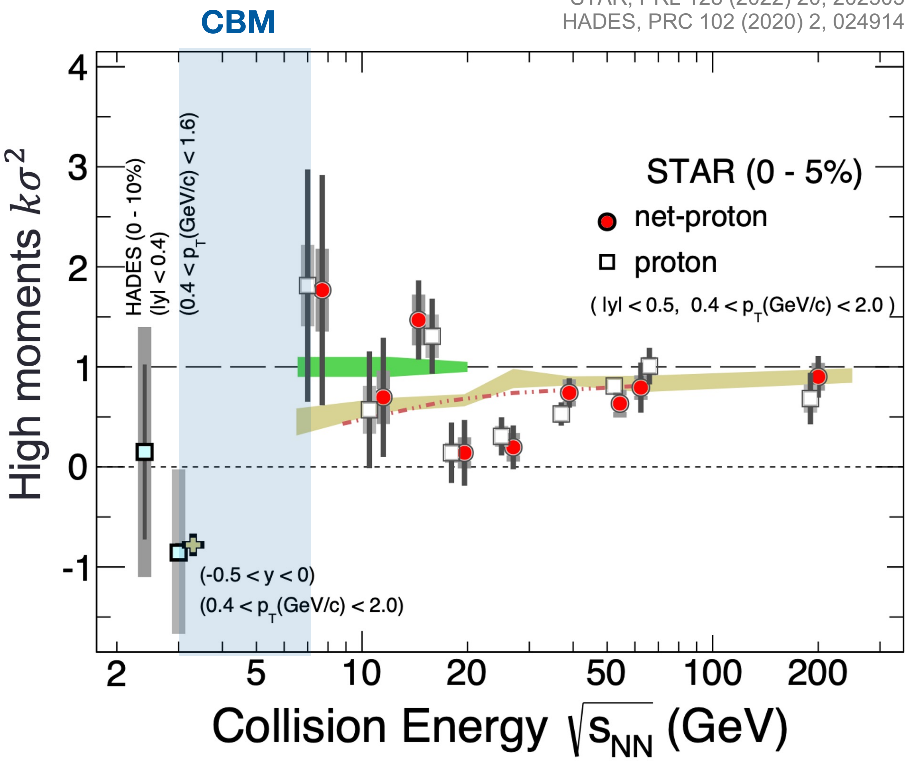
- Count the number of events with given number of e.g. net-protons
- Look for subtle critical point signals → **critical signal is in these distributions**

STAR, PRL 126, 092301 (2021)



# Critical point search

STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914




**Non-monotonic trend of the higher moments $\kappa_4/\kappa_2$ of net-proton number distributions, visible in a beam energy scan?**

Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008 (2021) 122141

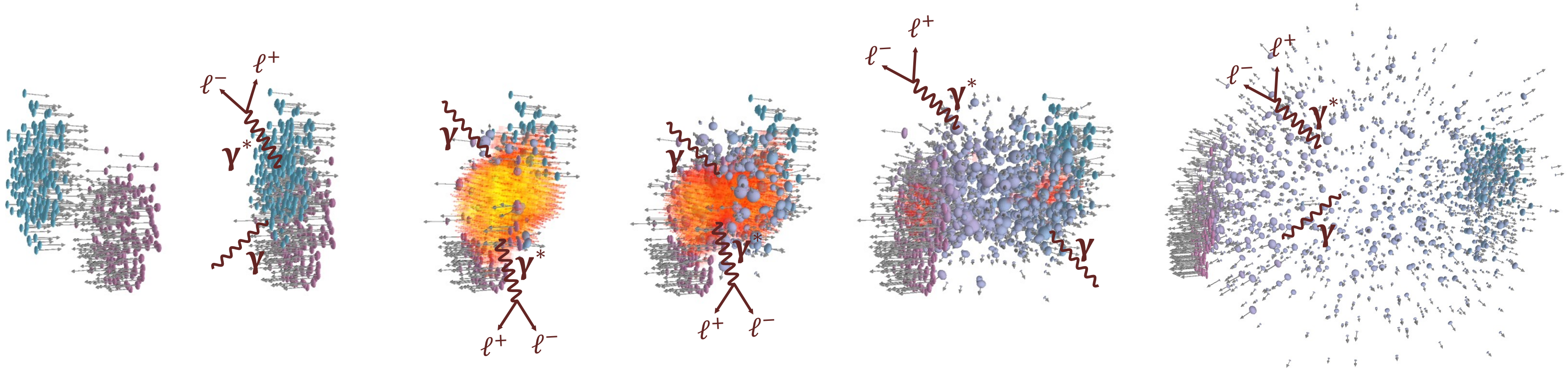
- Current data consistent with non-critical physics?
  → reduced errors from STAR BES-II
- Sensitivity to features of the QCD phase diagram grows with the order of the moment
- **Higher order moments probe the tails – statistics/artefacts!**
- Detailed **systematic** studies of experimental effects **is curtail**

Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598 [nucl-th]
Kitazawa'2012, Skokov'2013, Bzdak '2016, Kitazawa'2016, Braun-Munzinger'2017

## Electromagnetic radiation

# EMISSIVITY

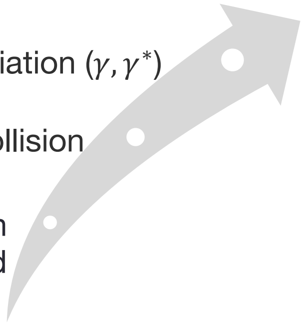
# Electromagnetic radiation as multi-messenger of fireball




Electromagnetic radiation $(\gamma, \gamma^*)$

Reflect the whole history of a collision

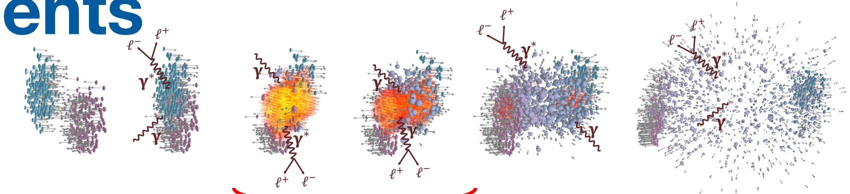
No strong final state interaction
⇝ leave reaction volume undisturbed

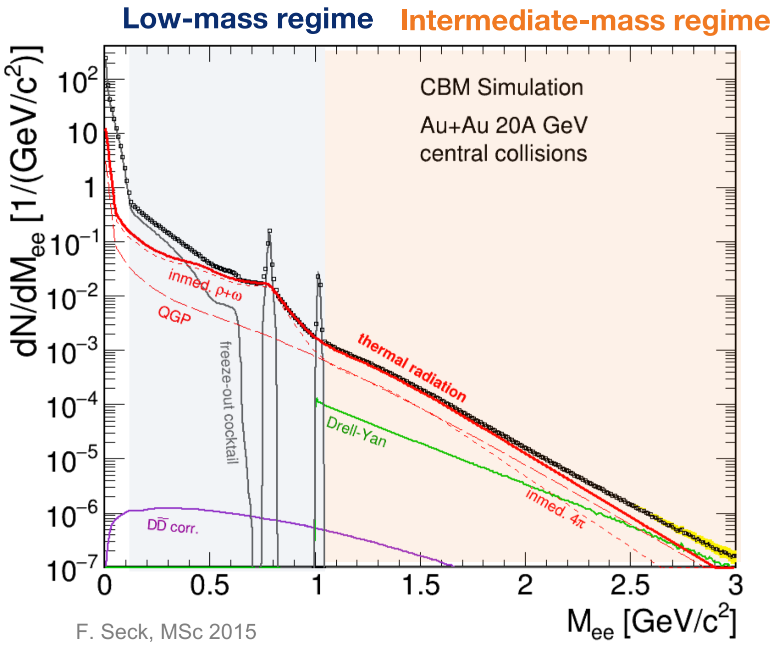


Encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

# Thermal dilepton measurements



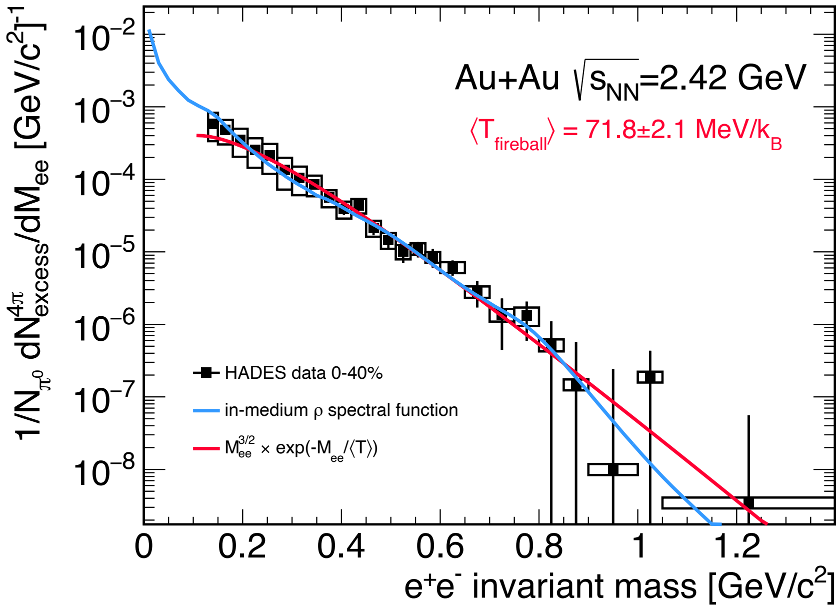



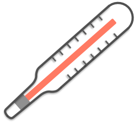

F. Seck, MSc 2015

- Dileptons are rare probes!
- Decisive parameters for data quality:
  interaction rates $(IR)$ and signal-to-combinatorial background ratio $(S/CB)$: effective signal size: $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low-$M_{\ell\ell}$, and low-$p$
- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$

# Thermal dileptons from baryon rich matter

HADES, Nature Phys. 15 (2019) 1040



'Planck-like'

In-medium spectral function

$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2}\, f^B(q_0,T)\, Im\Pi_{em}(M,q,T,\mu_B)$$

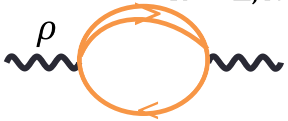
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - $\rho$-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial

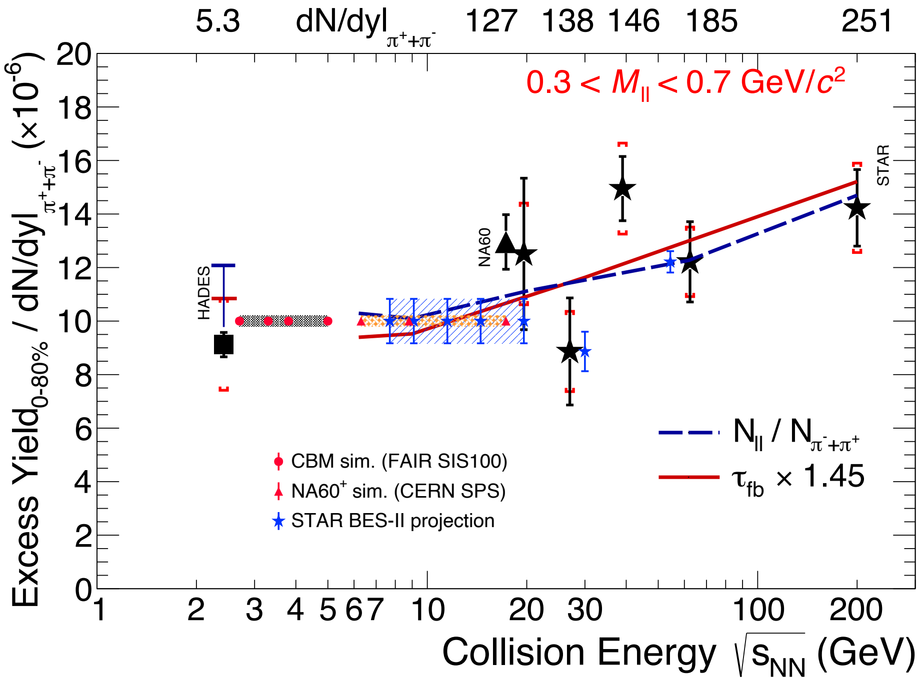
$\Sigma_{\rho B,M} =$




$R = \Delta, N(1520), a_1, \ldots$

$h = N, \pi, K, \ldots$

# Lifetime of the interacting medium




TG, JPS Conf.Proc. 32 (2020) 010079

- Integrated low-mass **excess yield** radiation $0.3 < M < 0.7$ GeV/$c^2$ tracks the fireball **lifetime**

Heinz and Lee, PLB 259, 162 (1991)
Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
Rapp, van Hees, PLB 753, 586 (2016)

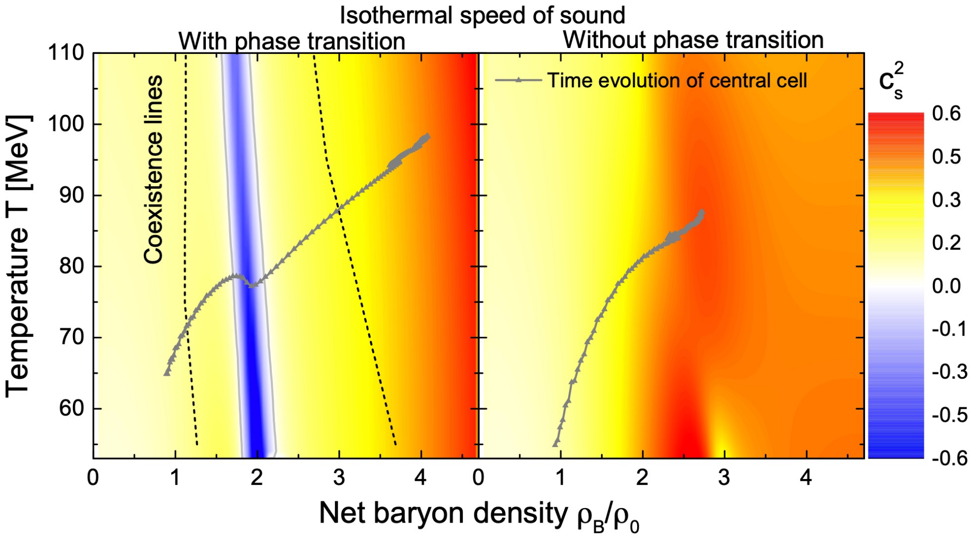
- CBM, NA60+ performance studies with realistic detector geometries, material budget, response, S/B and statistics ⇝ precision 1.5 – 4.5%

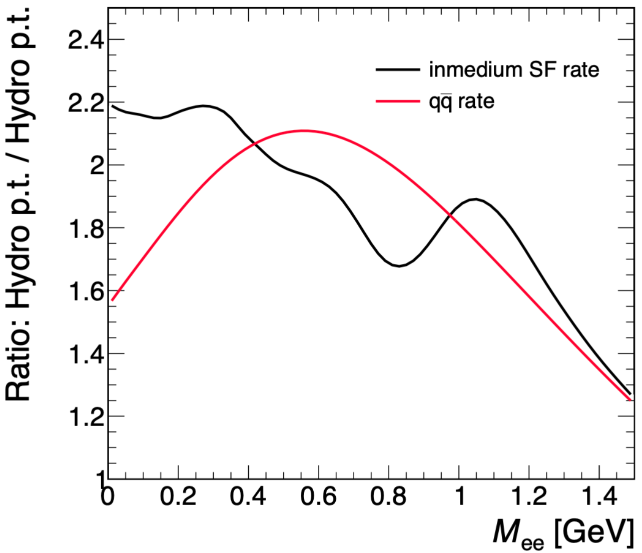
- Search for emerging signatures indicative of a 1st order **phase transition** (and critical point?):
  - prolonged lifetime of the system due to latent heat → "**excess excess-radiation**"?

# Dilepton signature of a 1st order phase transition

Seck, TG, Mukherjee, Rapp, Steinheimer, Stroth, Wiest, PRC 106 (2022) 1, 014904

See also
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Li and Ko, PRC 95 (2017) no.5, 055203
Tripolt *et al.*, NPA 982 (2019) 775



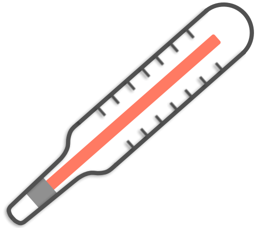



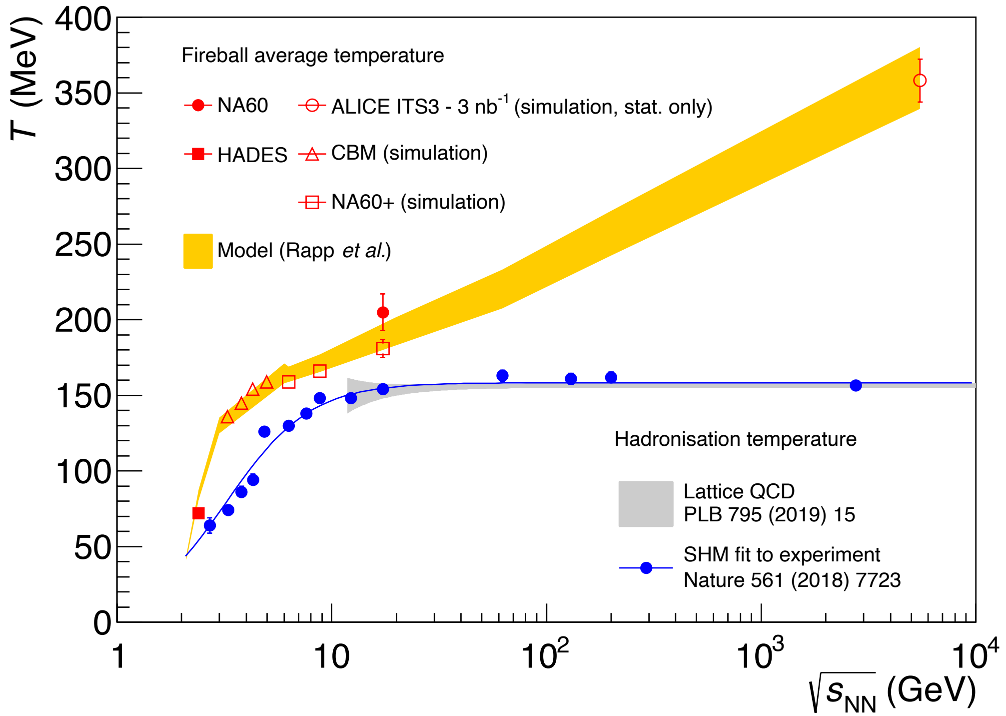

- Ideal hydro simulations with and w/o 1st order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low $\mu_B$ and neutron-star constraints at high density

Most *et al.*, PRD 107 (2023) 4, 043034

**Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended “cooking”**

# Mapping the QCD “caloric curve” (T vs ε)





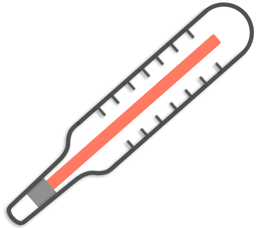

https://github.com/tgalatyuk/QCD_caloric_curve

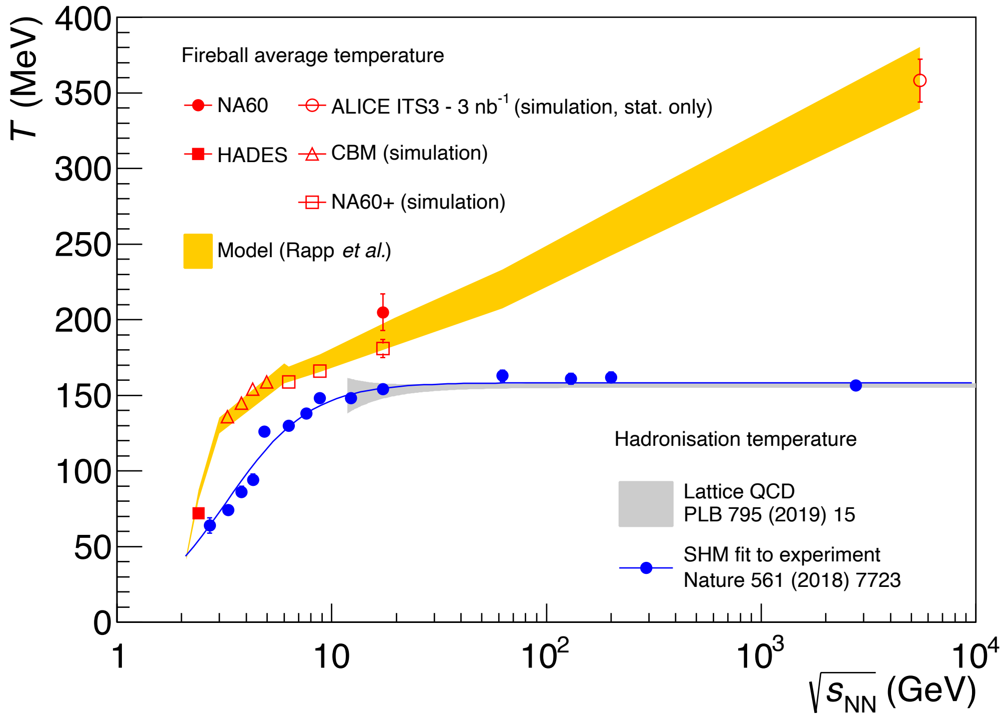
**Invariant mass slope measures true (no blue shift!) radiating source temperature:**

$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$$

- Search for **flattening** of caloric curve ($T$ vs $\varepsilon$) → evidence for a **phase transition**

# Mapping the QCD "caloric curve" (T vs ε)






https://github.com/tgalatyuk/QCD_caloric_curve

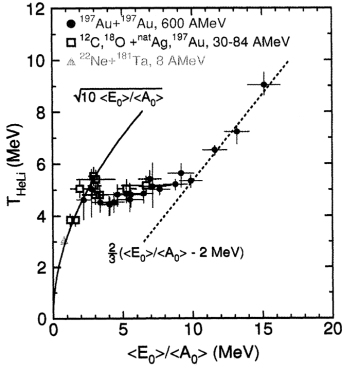
**Invariant mass slope measures true (no blue shift!) radiating source temperature:**

$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$$

- Search for **flattening** of caloric curve ($T$ vs $\varepsilon$) → evidence for a **phase transition**

**Nuclear liquid-gas phase transition**

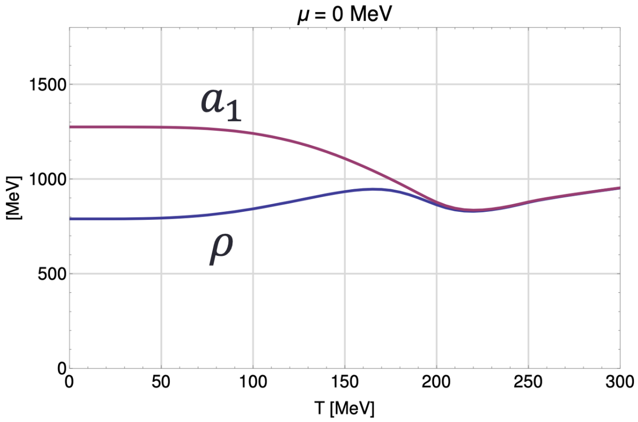
Pochodzalla *et al.*,
PRL 75 (1995) 1040-1043



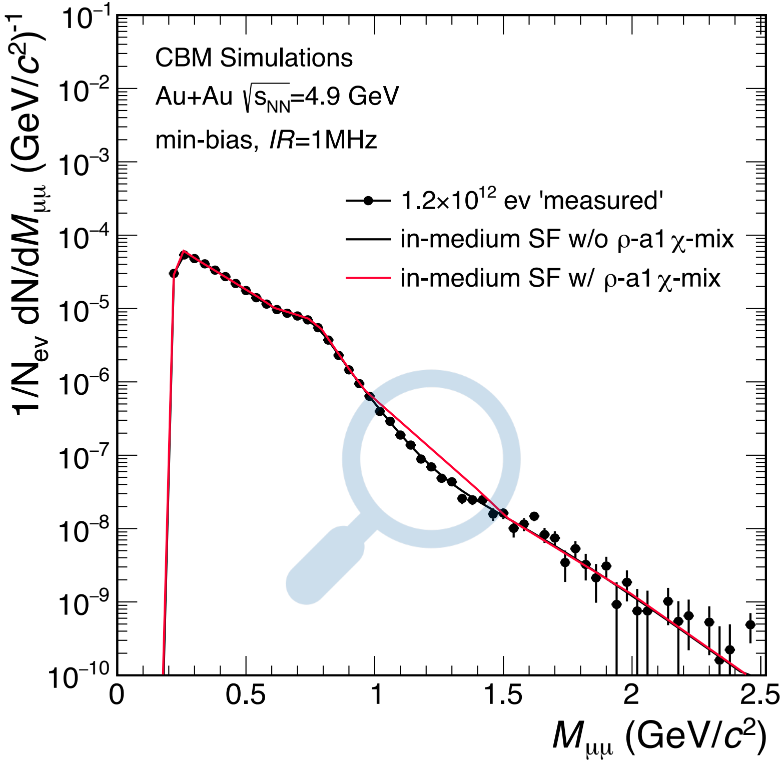
# Signature for chiral symmetry restoration: $\rho - a_1$ chiral mixing

**Spontaneously broken** in the vacuum

**Restoration** at finite $T$ and $\mu_B$ manifests itself through mixing of vector and axial-vector correlators




**$\rho$ meson melts, $a_1$ mass decreases and degenerates with near ground-state mass**




**Hadronic many-body theory** Hohler and Rapp, PLB 731 (2014)
**Functional Renormalization Group** Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
**Light mesons and baryons: lattice QCD results,** Aartz, QM2022, April 2022

**CBM energies:** negligible correlated charm contribution, decrease of QGP, Drell-Yan contribution?

# Summary: The future is bright!

## Encouraging prospects for studying extreme matter at high $\mu_B$ with CBM

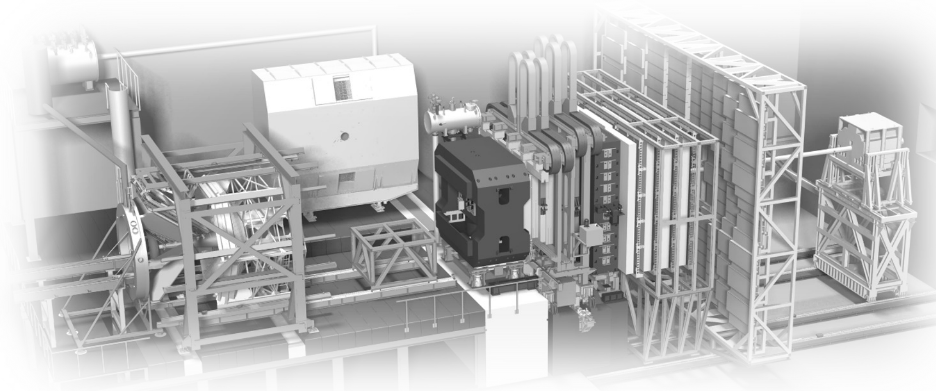
- **Challenges**
  - rare and statistics „hungry“ observables, systematic effects
  - many aspects – nature of transitions between the various phases, relevant EoS, spectral properties of hadrons in the medium, collective and transport properties of the medium, ... – await a better understanding
- **Opportunities**
  - discoveries, EoS of dense matter and connection to violent stellar processes
  - development of forefront detector technologies
- **Success through perfect teamwork** of experts in many fields (accelerators, detectors, high-performance computing, data analysis and interpretation)

➥ **Understand quantitatively the microscopic properties of baryon-rich matter**

➥ **Complementary program on exclusive measurements in $\pi$, p induced reactions with HADES and CBM**

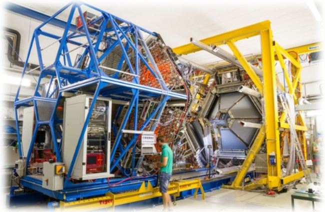

Thank you
for your attention!

# Bonus slides



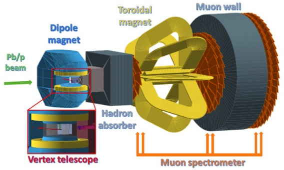
# High $\mu_B$ instruments

HADES at SIS18 (running)

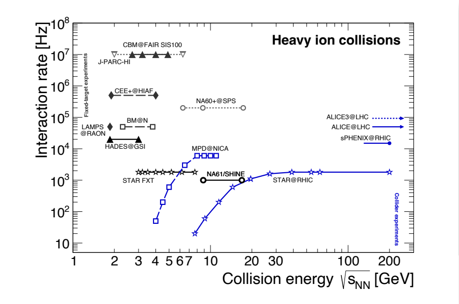


NA61/SHINE at SPS (running)

NA60+ at SPS (>2030, after LHC LS3)

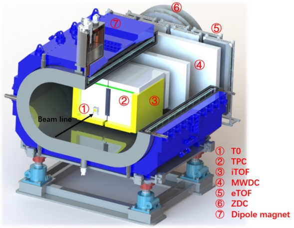



CBM/HADES at SIS100 (2028)

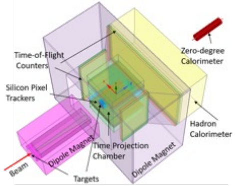




STAR at RHIC (completed)

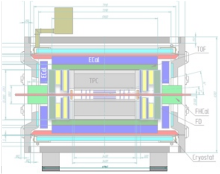

CEE+ at HIAF (2027)



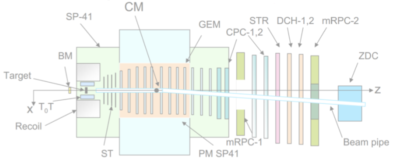

J-PARC-HI




MPD at NICA

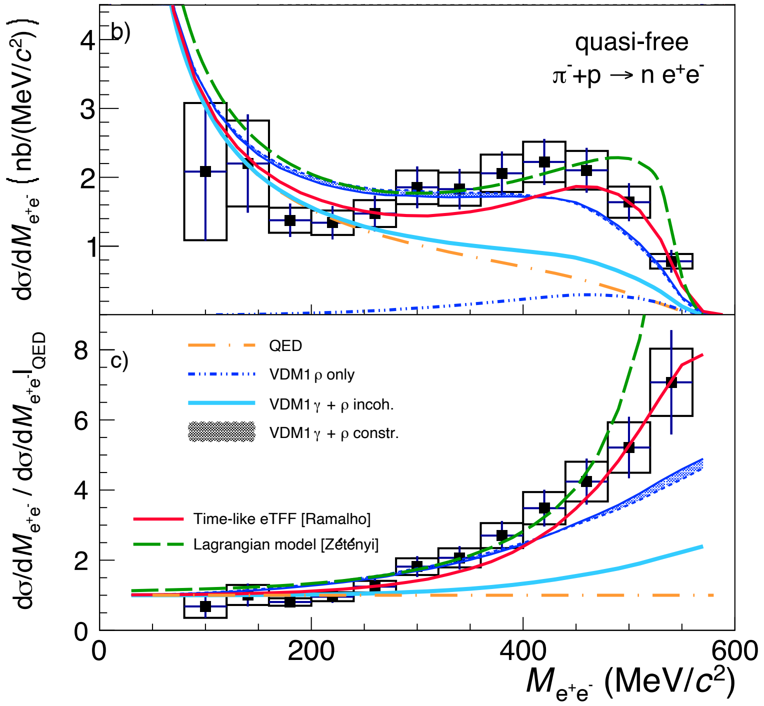


BM@N

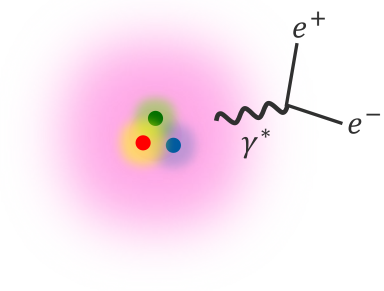


# First measurement of massive $\gamma^*$ emission from $N^*$ baryon resonances (exclusive analysis $\pi^- p \rightarrow e^+ e^- n$)

HADES, arXiv:2205.15914 [nucl-ex], with PRL
HADES, arXiv:2309.13357 [nucl-ex], with PRC

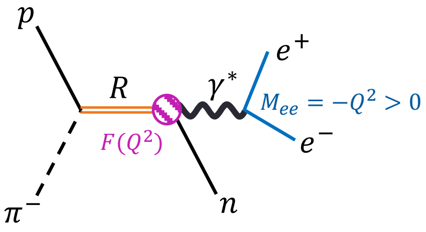



Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282




- Study the structure of the nucleon as an extended object (quark core and meson cloud)

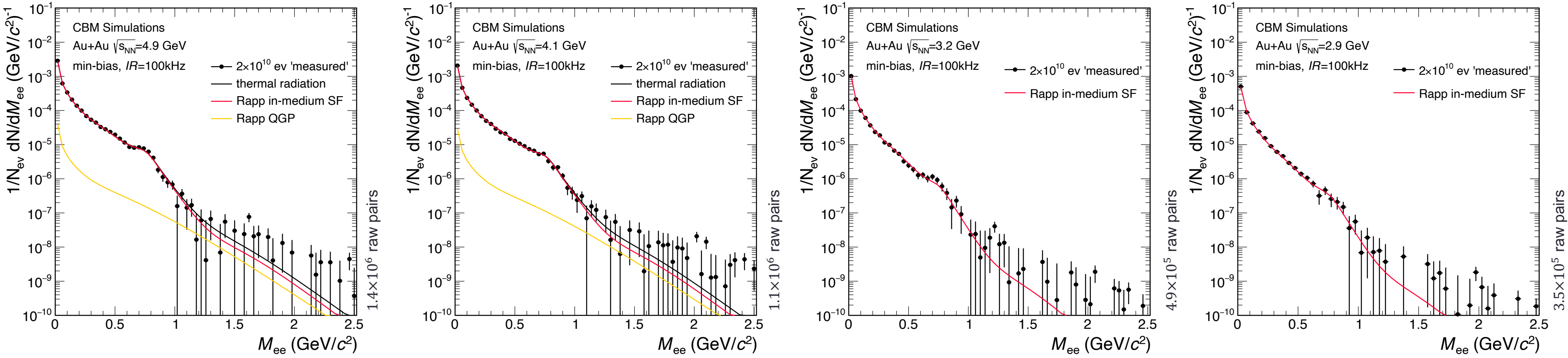
- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - $\rho$ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**



# CBM dielectron performance (first year, 5 days / energy)

Isolated dielectron thermal radiation yield, corrected for acceptance x efficiency:

- Dominated by $\rho$ contribution at low mass ($M_{\ell\ell}$ <1GeV/$c^2$); can be reconstructed with precision of 1.5 – 4.5%
  - allows fireball lifetime measurement
  - transport properties – electrical conductivity? $\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$
- Intermediate mass range ($M_{\ell\ell}$>1GeV/$c^2$) accessible, statistics will not (yet) be sufficient to extract physics

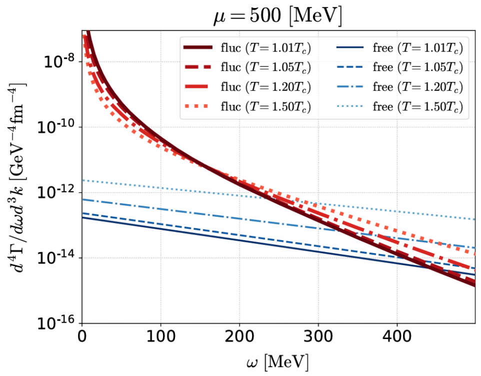



$T$ vs. baryon density effects
from partonic to hadronic fireballs

# Low-mass low-momentum dileptons

- Color superconductivity could manifest itself in an enhanced yield of low-energy dileptons

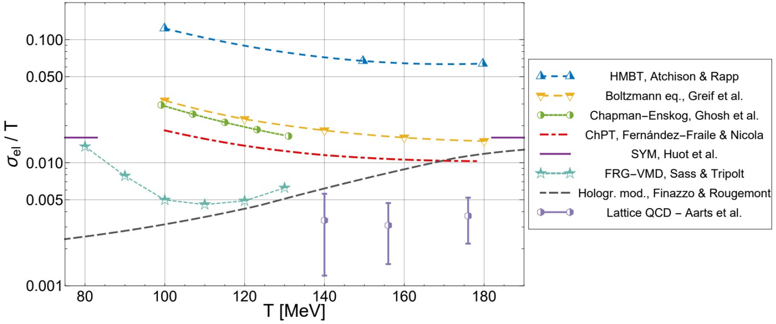
Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02




- Transport properties of the medium - electrical conductivity - can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586
Moore, Robert, arXiv:hep-ph/0607172 (2006)
Atchison, Rapp, NPA 1037 (2023) 122704
Flörchinger *et al.*, PLB 837 (2023) 137647
Nishimura, Kitazawa, Kunihiro, arXiv:2312.09483 [hep-ph]




Geurts, Tripolt, PPNP 128 (2023) 104004

**Non-monotonic trend of $\sigma_{el}$ as the phase transition occurs? visible in a beam energy scan?**

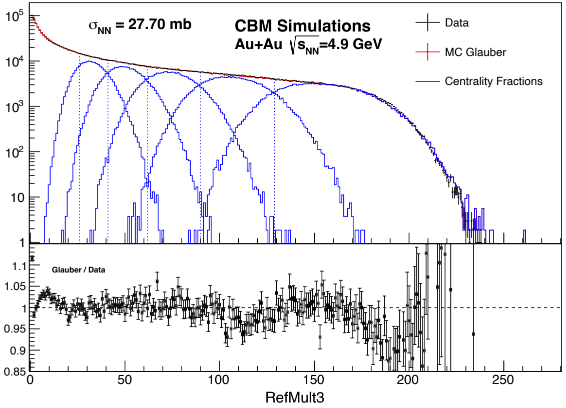
# Performance studies in CBM

- Corrections for volume fluctuations and conservation laws
- Event-by-event changes of efficiency
- Proper selection of $p_T - y$ bite
- (Net-)baryons vs. protons, neutrons, nuclei

} impact of the effects is being scrutinized

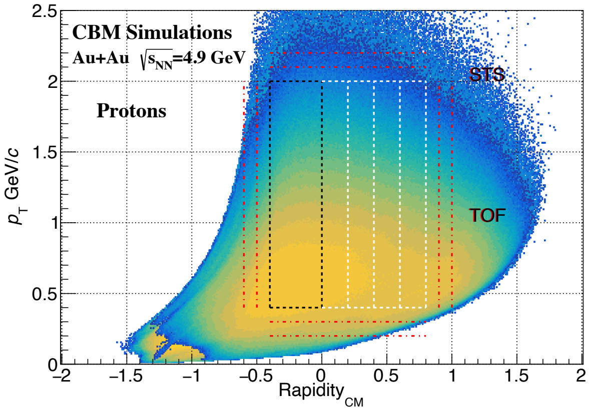
**CBM after 3 years of running:**
- **completion of the excitation function for $\kappa_4(\mathrm{p})$**
- **first results on $\kappa_6(\mathrm{p})$**
- **extension into strangeness sector $\kappa_4(\Lambda)$**

**NA61++: $\boldsymbol{\kappa_4/\kappa_2}$** is universally negative when the critical point is approached on the crossover side ⇝ Pb-Pb data crucial to establish/verify the non-monotonic trend



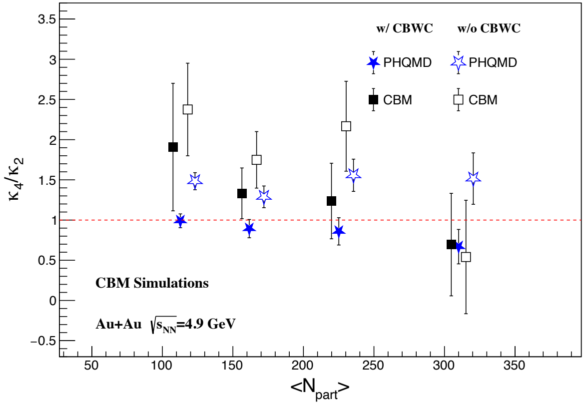

Crucial: centrality determination with independent detector → avoids bias on e-b-e fluctuation observables

Studies employing FSD centrality detector ongoing




Low $p_T$ and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants

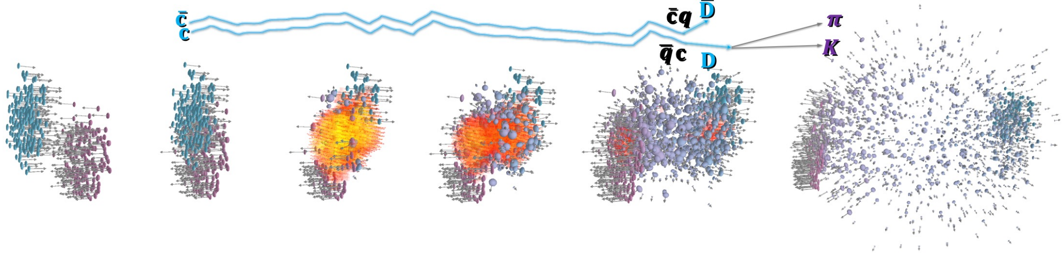



Statistics sufficient to study derivatives of order $> \mathcal{O}(4)$

Charm $(c, \bar{c})$ of the baryon-rich matter

# IN-MEDIUM QCD FORCE

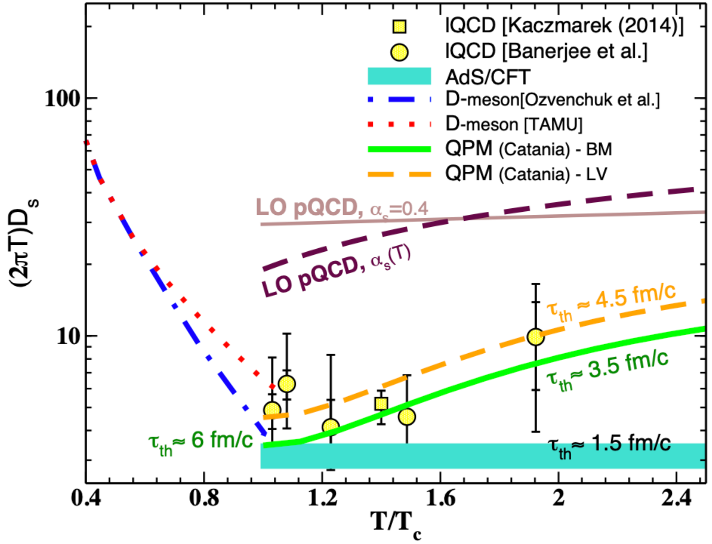
# What is so "charming" about charm?




**Heavy quarks**

- produced in initial hard scattering processes
- experience the full evolution of the QCD medium

**→ probe in-medium QCD force!**




Scardina *et al.*, PRC96, 044905 (2017)
HotQCD, PRL 132 (2024) 5, 051902

- heavy-quark potential accurately known in the vacuum ($\Psi$ , $\Upsilon$ spectroscopy)
- $\mu_B = 0$, finite T – heavy-quark potential is modified (screened), guidance from LQCD

**How is the fundamental QCD force screened at $\mu_B > 0$?**

**Consequences for heavy-quark transport**

**$\sqrt{s_{NN}}$~6 GeV (and below) increased sensitivity to hadronic medium effects – important input for precision measurements at LHC**

Chemistry, vorticity, flow

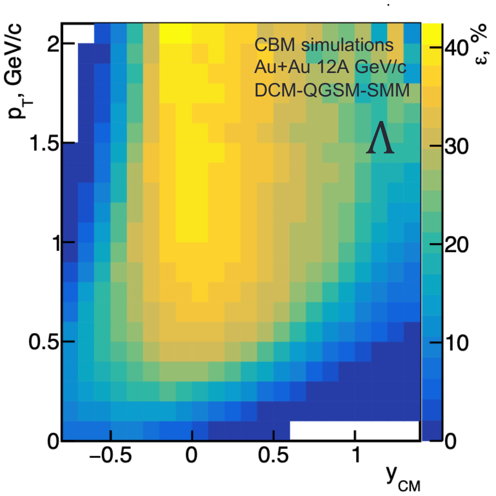
# EQUATION OF STATE

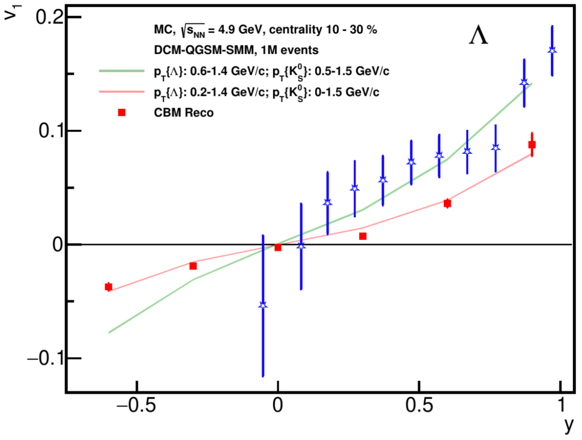
# Collective flow and polarization of $\Lambda, \bar{\Lambda}$ and $\Xi^-$ in CBM

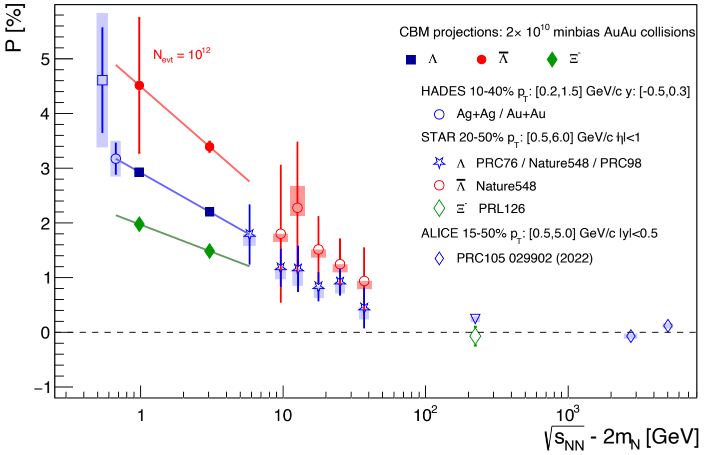
- Excellent phase space coverage ($y_{CM}$ coverage for all $\sqrt{s_{NN}}$)
- Reconstruction efficiency ~30%
- Event plane resolution $\Re 1 \cong 0.8$, $\Re 2 \cong 0.5$

- Precision measurement of spectra and flow pattern (no data for $\Xi, \Omega$ available below AGS energies)
- Superior CBM performance to the STAR-FXT flow measurements

- Measurement of polarization of $\Lambda$ and $\Xi^-$ with precision of 5%
- Mapping of the excitation function for $\bar{\Lambda}$ requires $\geq 10^{13}$



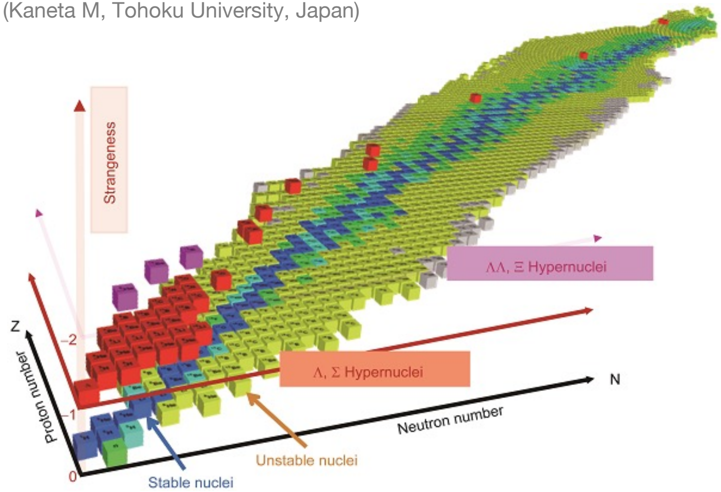



# Nuclei and hyper-nuclei production

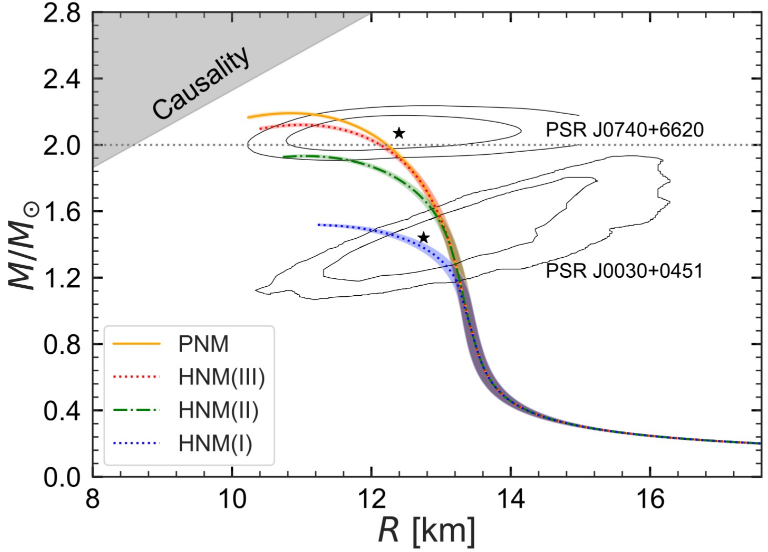
Three-dimensional nuclear chart

(Kaneta M, Tohoku University, Japan)




*Ab initio* calculation of hyper-neutron matter

Tong, Elhatisari, Meißner, [arXiv:2405.01887 [nucl-th]]




- How do nuclei and hyper-nuclei form?
- What are their properties?
- How do $YN$ and $YY$ interact?

**Crucial for neutron star physics**

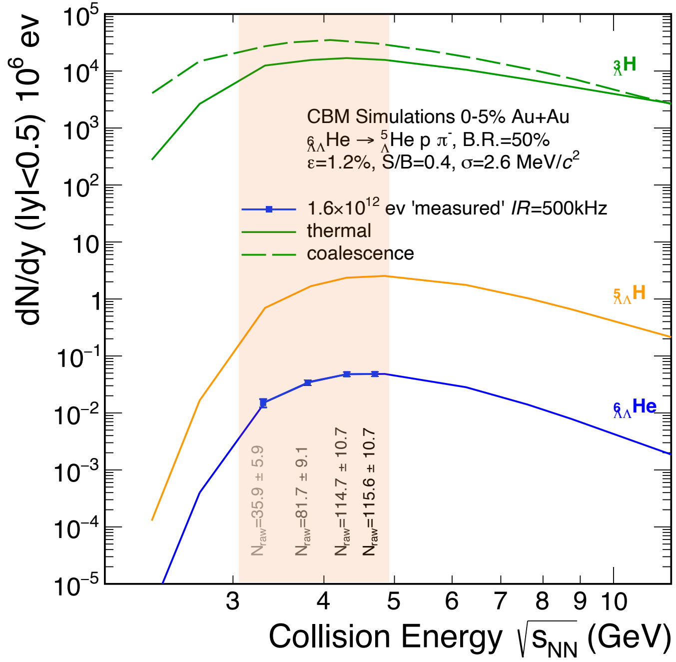
**EoS of high density matter**

three-body hyperon-nucleon interaction plays a fundamental role in the softening of the EoS

# CBM performance

CBM collision energies optimal for hypernuclei production

Thermal: Andronic *et al.*, PLB 697 (2011)
Coalescence: Steinheimer *et al.*, PLB 714 (2012)




- CBM high interaction rates and clean identification allow precision measurements of single- and double $\Lambda$-hypernuclei
  - spectra and flow pattern
  - complex structure via Dalitz plot
  - life-time (particularly sensitive to $YN$ and $YY$ interaction)

- Search for the new hyper-nucleus or charmed nucleus ${}^{4}_{D}He$

Dover, Kahana, PRL 39, 1506, 1977
Xu, Lin, Yang in preparation