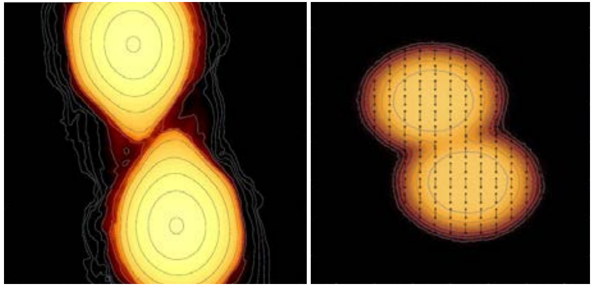
Probing cosmic forms of matter in the laboratory



Pic. TG, Hanauske, Seck

Tetyana Galatyuk, GSI / Technische Universität Darmstadt

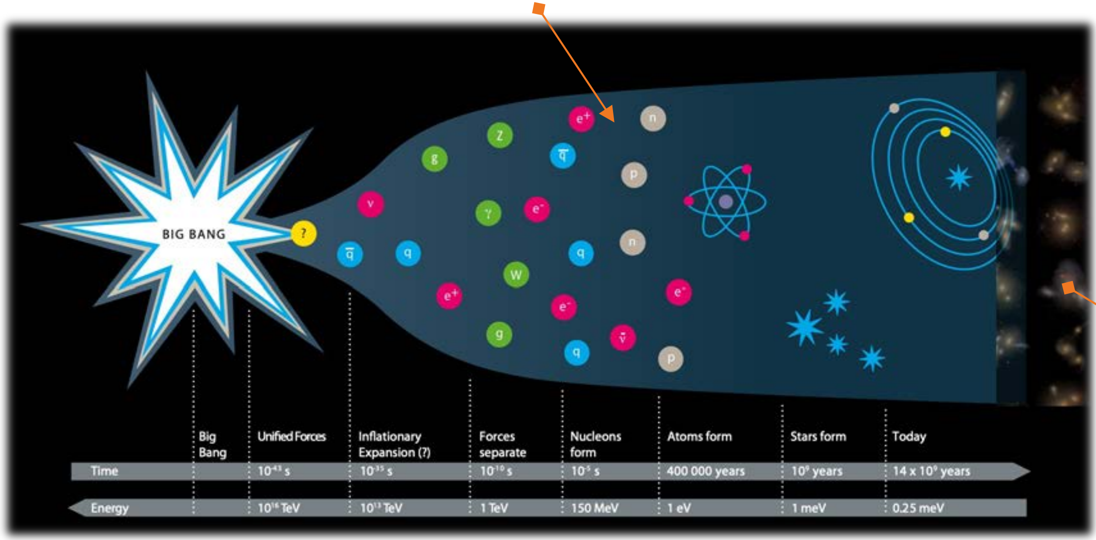
Tsukuba Global Science Week 2024, Sep. 30 – Oct. 4, Online / University of Tsukuba

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

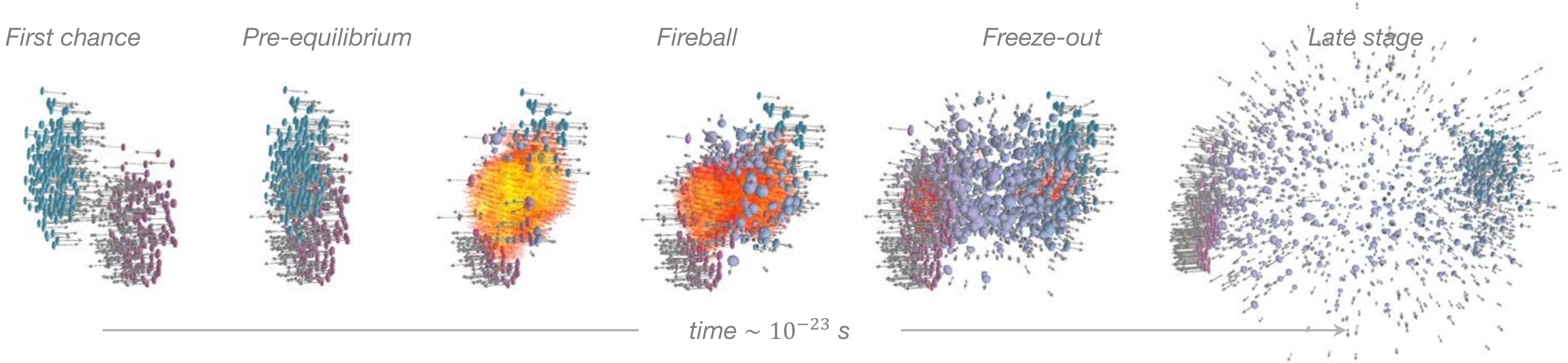
$M \sim 1.4 - 2\ M_\odot$
$R \sim 12$ km
$T \sim$ keV
$n \lesssim 10\ n_{sat}$

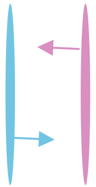
Matter properties in compact stellar objects?

Method

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

Investigate transient states of QCD matter under extreme conditions





LHC energies $\sqrt{s_{NN}} = 2 - 5\,TeV$

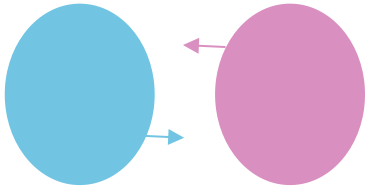
parton parton collisions

$N_{particles} = N_{anti-particles}$

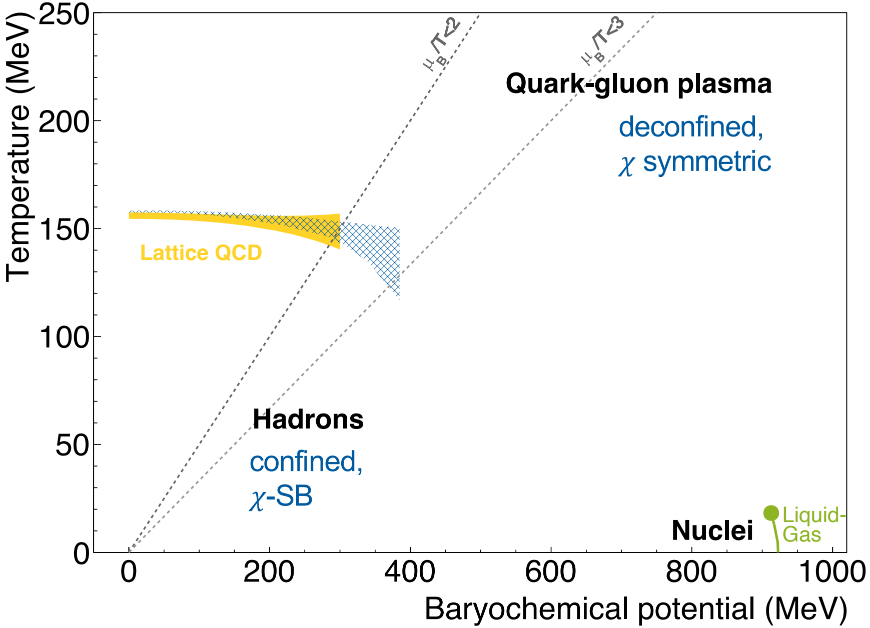
SIS energies $\sqrt{s_{NN}} = 2 - 5\,GeV$

Nuclear stopping

$N_{particles} \gg N_{anti-particles}$



Searching for landmarks of the QCD matter phase diagram



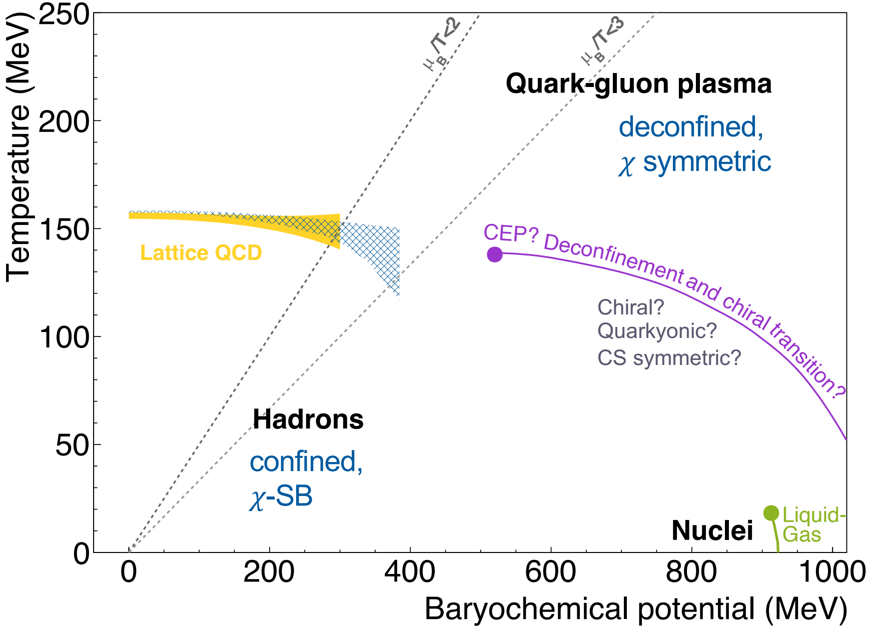
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)
Borsanyi *et al*. [Wuppertal-Budapest], PLB (2014) 730
Borsanyi *et al*. [Wuppertal-Budapest], JHEP 1009 (2010) 073

Vanishing μ_B, high T (lattice QCD):

- **crossover** from hadronic to partonic medium
  - $T_{pc} = 156.5 \pm 1.5$ MeV ($T_c = 132^{+3}_{-6}$ MeV at chiral limit)
  - $T_{pc} = 158.0 \pm 0.6$ MeV
- **no critical point** indicated by lattice QCD at $\mu_B^{CEP}/T_c < 3$

Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Ding *et al.*, [HotQCD], PRL 123 (2019) 6, 062002
Dini *et al.*, PRD 105 (2022) 3, 034510

Searching for landmarks of the QCD matter phase diagram



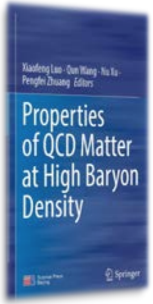
Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
McLerran, Pisarski, NPA 796 (2007) 83
Glozman, Philipsen, Pisarski, EPJA 58 (2022) 12, 247

Large μ_B, moderate T (lQCD inspired effective theories):

- limits of hadronic existence?
- 1st order transition?
- QCD critical point?
- equation-of-state of dense matter?

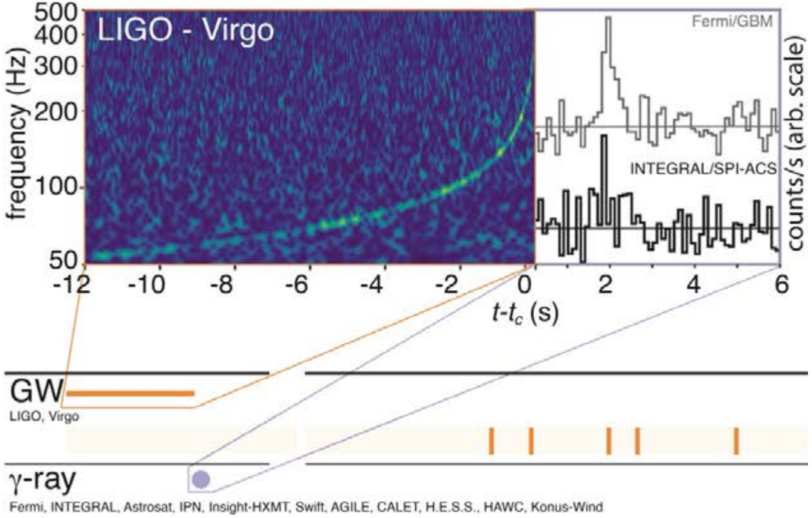
Worldwide experimental and theoretical efforts

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

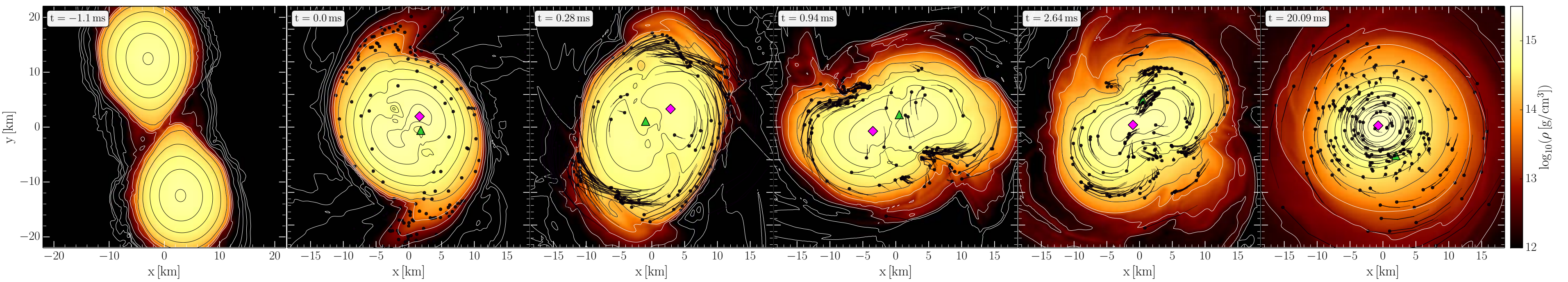
- GRB 170817A ~1,7 s later:
  Observation of the same event through electromagnetic waves (gamma-ray burst)

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

Astrophysical “collider”

LS220-M132 EOS

$1.32{+}1.32 M_\odot$ $\quad \varnothing = 10\,km$ $\quad \tau{\sim}20\,ms$ $\quad n{\sim}(2-3)\,n_{sat}$ $\quad T < 70\,MeV$



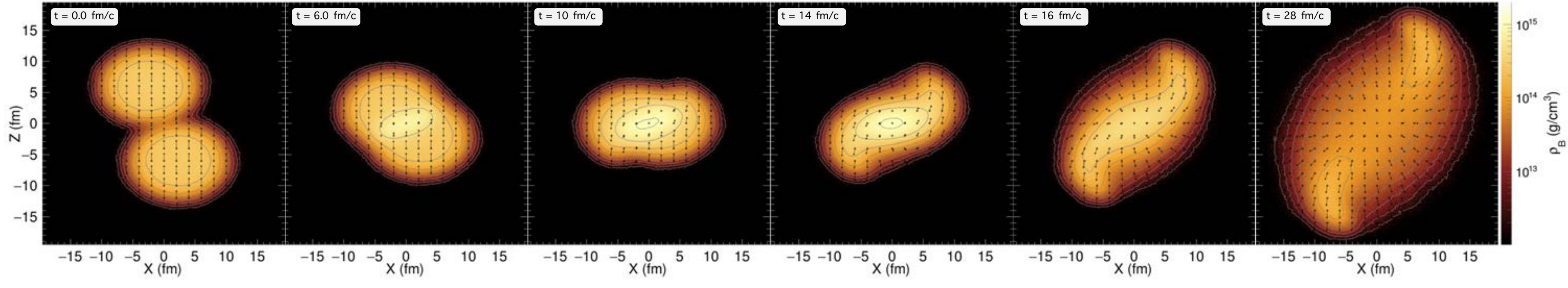
Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

Violent Universe can now be

- “heard” through gravitational waves
- seen through electromagnetic radiation

Laboratory collider

Au+Au $\sqrt{s_{NN}} = 2.4\,GeV$ $\varnothing = 7\,fm$ $\tau \sim 10^{-23}s$ $n \sim (2-3)\,n_{sat}$ $T < 70\,MeV$



Heavy-ion collisions at (ultra-)relativistic energies:

- probe microscopic matter properties
- unique role played by electromagnetic radiation

Laboratory studies of the matter properties in compact stellar objects

nature physics

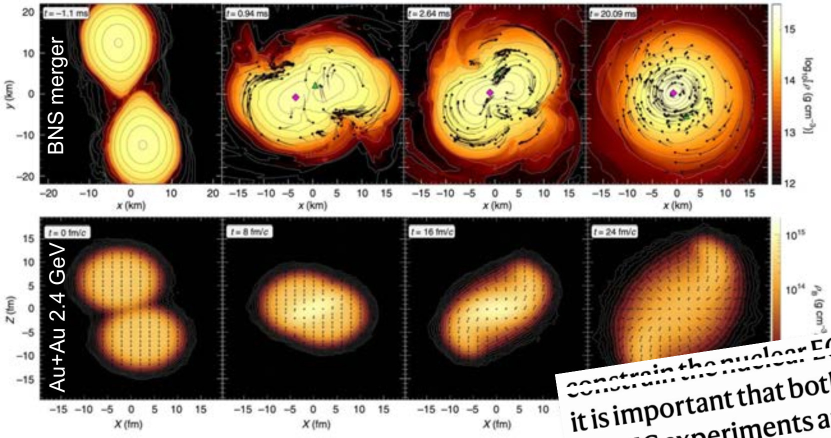
ARTICLES

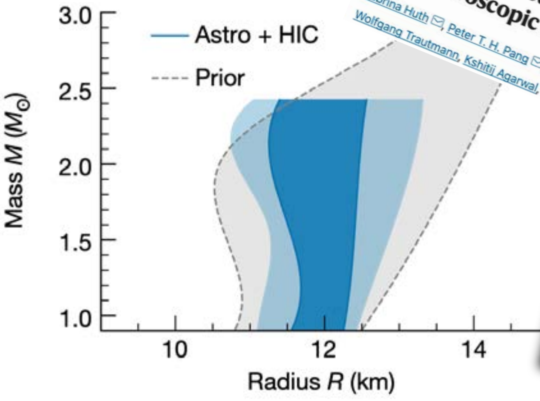
https://doi.org/10.1038/s41567-019-0583-8

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



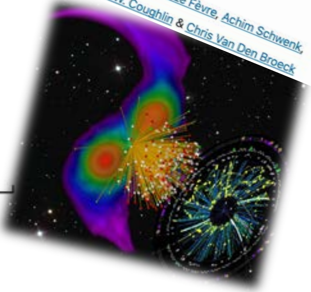


nature

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

constrain the nuclear EOS at supra-saturation densities. Going forward, it is important that both statistic and systematic sources of uncertainty for HIC experiments are further improved. For example, the impact of

and 2), and advancing HIC experiments to probe higher densities, above 2–3n_{sat}, will be key (Extended Data Table 5). Combining the latter

Facility for Antiproton and Ion Research

multi-purpose
(strong interaction)
facility

Under construction, ground breaking: 2017

Existing facility, foundation: 1969

FAIR
- Civil construction work completed
- Installation of accelerator components begun

April 2024, Darmstadt, Germany

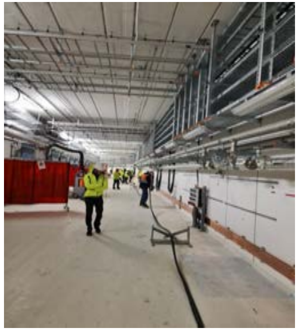
FAIR project status

installation of SIS100 dipoles Apr’24

cryogenic bypass lines SIS100 placed in SIS100 tunnel, Apr‘24

transport of the first quadrupole magnet in tunnel, Mar‘24

start of cable pulling work, Q3/23

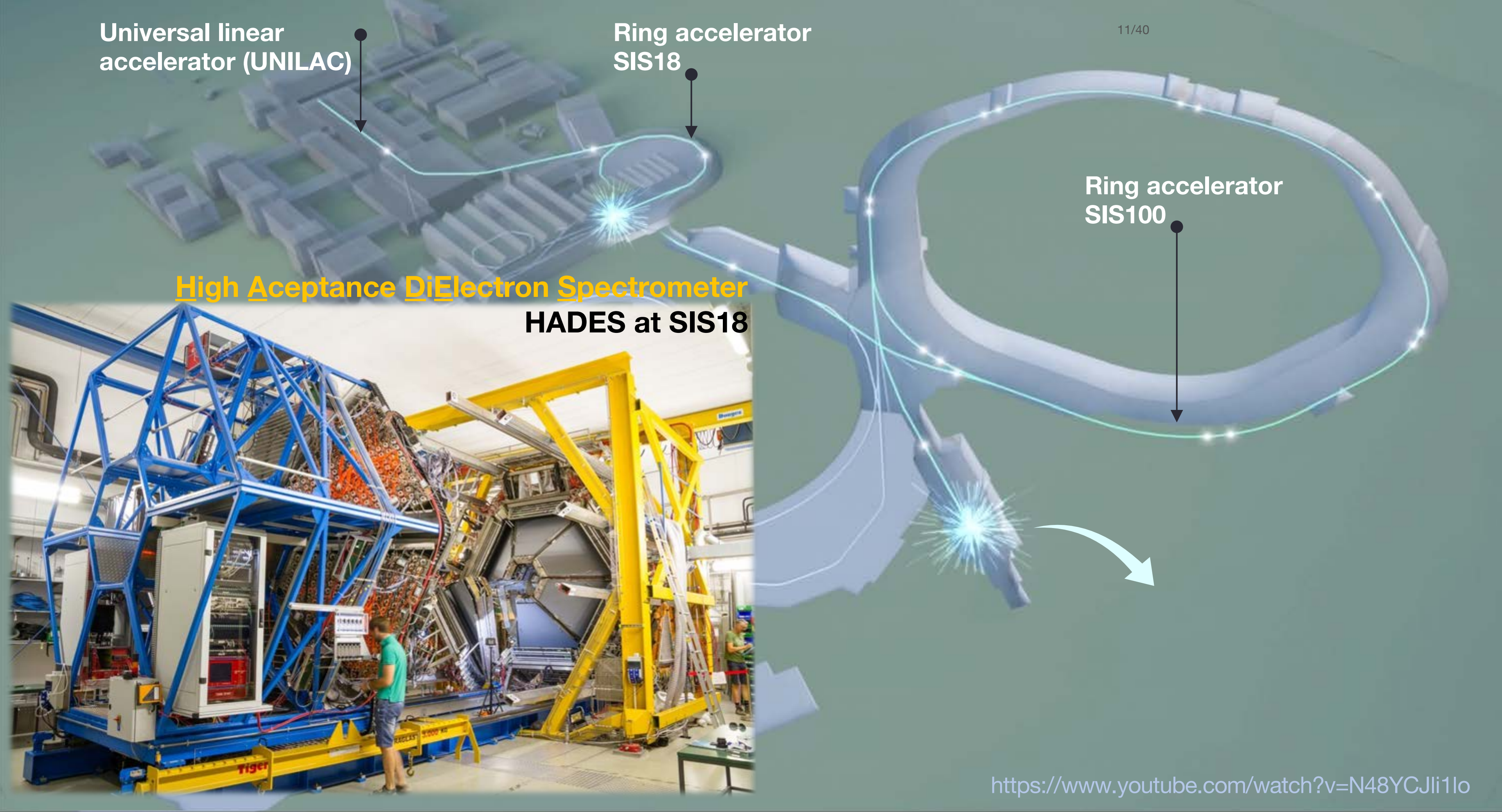


6 He tanks of the cryo facility were installed, Apr’24

installation S-FRS lateral shielding blocks, May’24

construction area south

CBM cave, Jun‘24



Universal linear accelerator (UNILAC)

Ring accelerator SIS18

Ring accelerator SIS100

High Aceptance DiElectron Spectrometer

HADES at SIS18

https://www.youtube.com/watch?v=N48YCJli1Io

Compressed Baryonic Matter experiment at SIS100

© GSI/FAIR, Zeitrausch

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

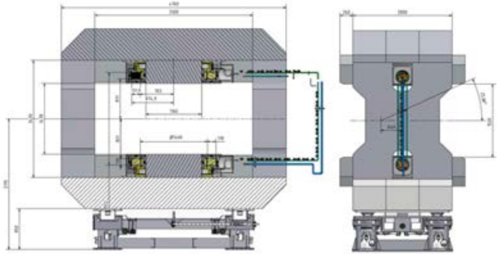
- ***KEK, Tsukuba***
- ***TCHoU University of Tsukuba***
- ***Hiroshima University***

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



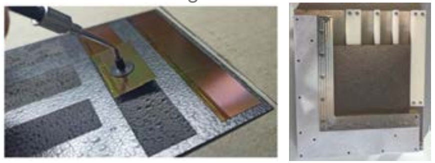
Beam monitoring system

Transition Radiation Detector

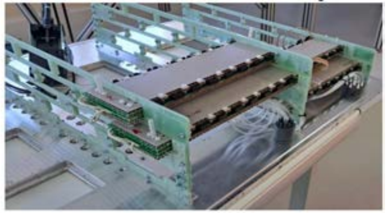
pre-production modules of 1D and 2D options ready

Micro Vertex Detector

sensor/module integration



Time of flight detector



module pre-production concluded

MUon CHamber system

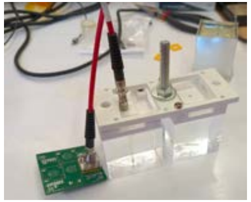
test of full-size GEM and RPC prototypes

Silicon Tracking System

first STS series ladder

> 100 modules assembled

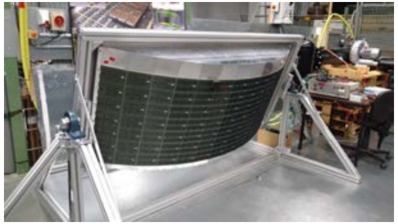
Forward Spectator Detector



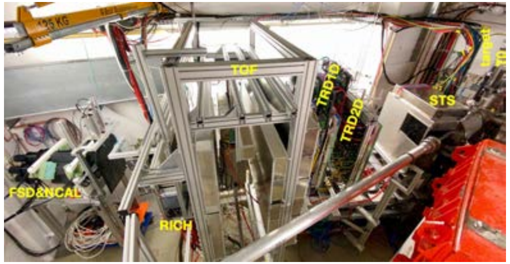
ZnS scintillators and LYSO crystals read-out via SiPM or/and PMT

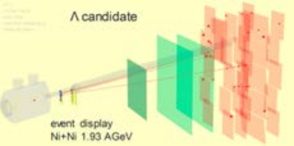
Ring Imaging Cherenkov detector

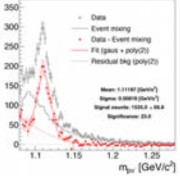
1 of 2 photo cameras ready
50% FEE produced



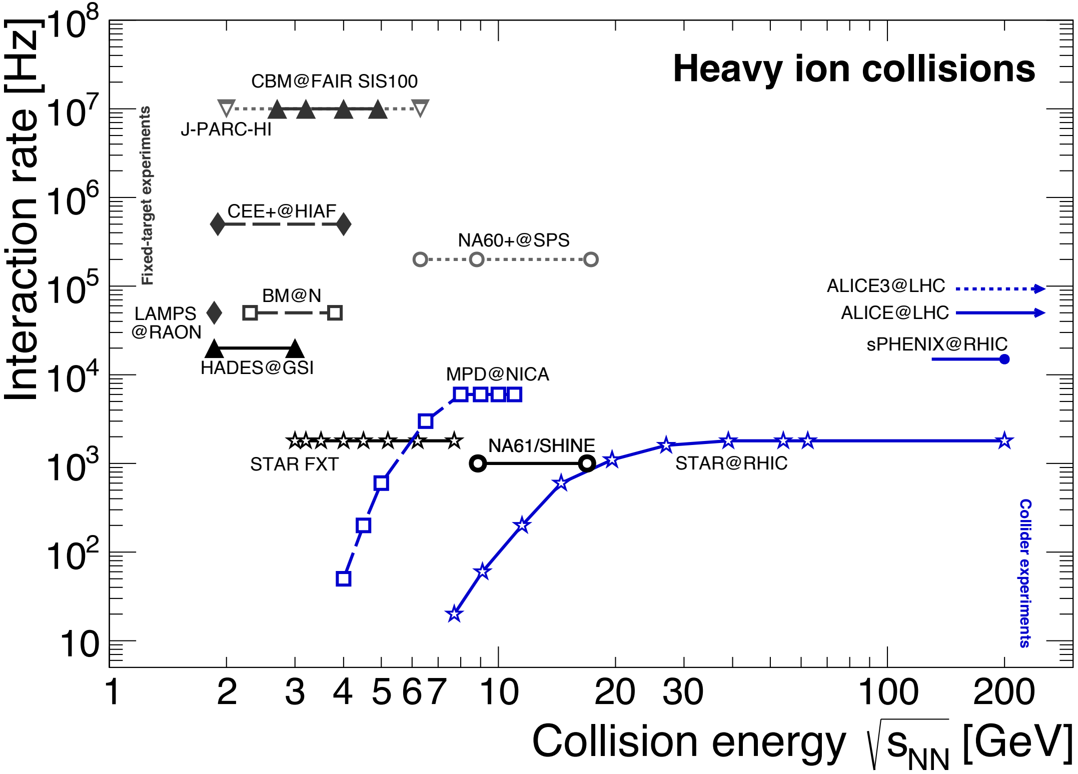
Prototype of CBM online data processing tests with mCBM







Some basic facts on extreme matter facilities

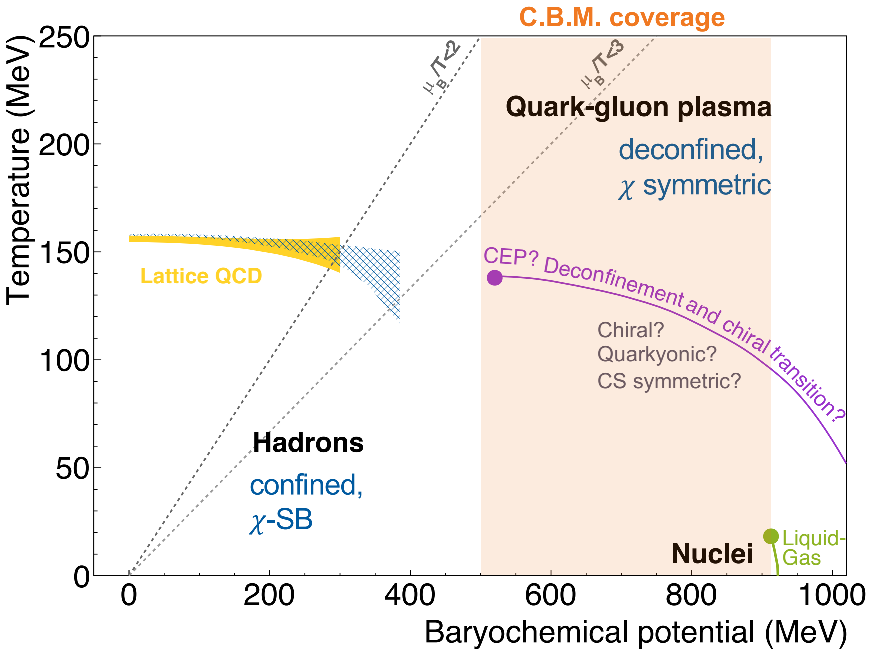


TG, NPA 982 (2019), update 2024 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability
- **HADES**: established thermal radiation at high μ_B, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- Proposals: **CEE+@HIAF, J-PARC-HI, NA60+@SPS**

Program needs ever more precise data and sensitivity for rare signals

Searching for landmarks of the QCD matter phase diagram



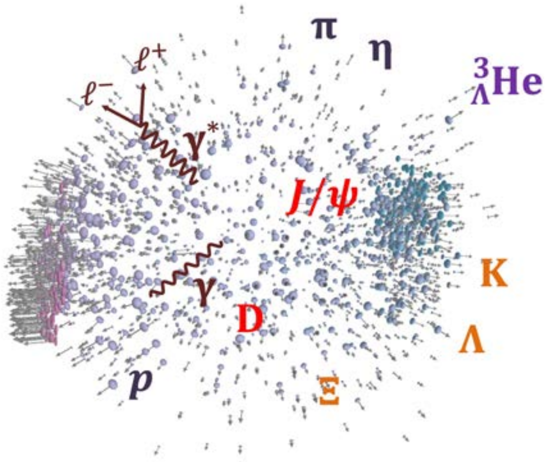
Experimental challenges:

- 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)

Almost unexplored (not accessible) so far in the high μ_B region

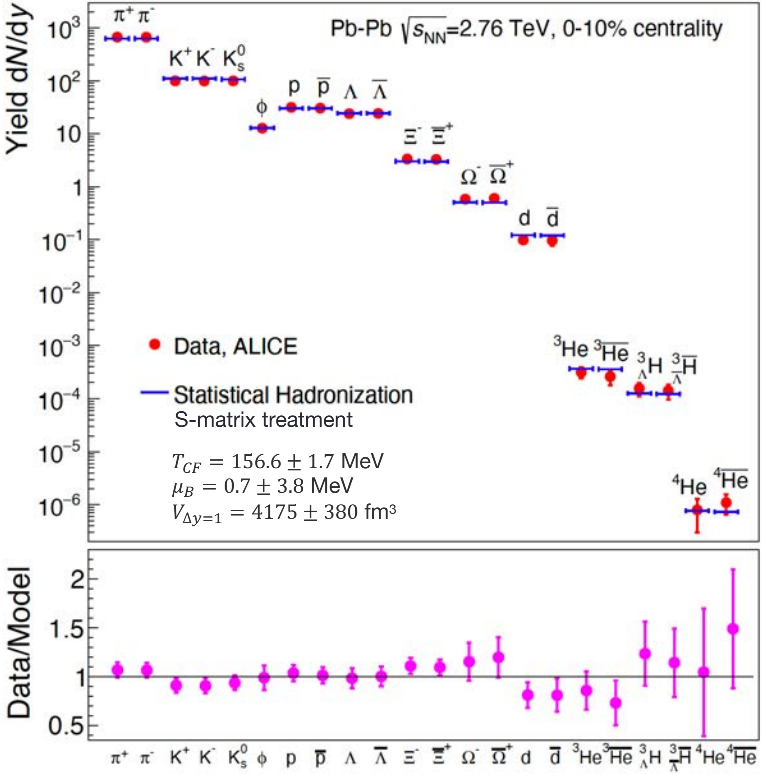


Final state “hadron-chemistry”

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}, μ_B, V

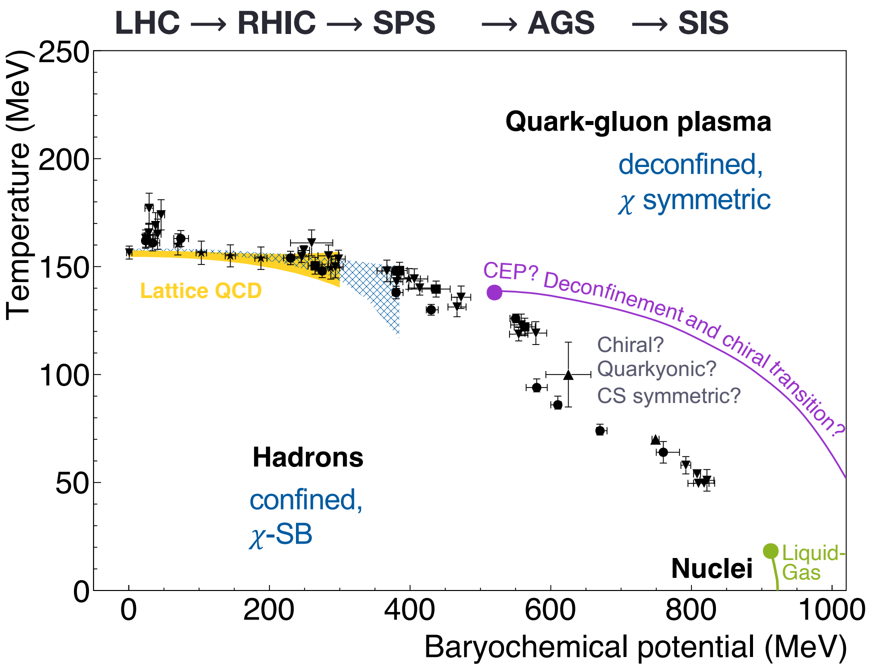
- **ALICE at LHC:**
  - grand canonical partition function
  - essentially 1 free parameter ⇝ temperature T_{CF}

  $\boldsymbol{T_{CF} = 156.5 \pm 1.5 \pm 3}$ **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 μ_B



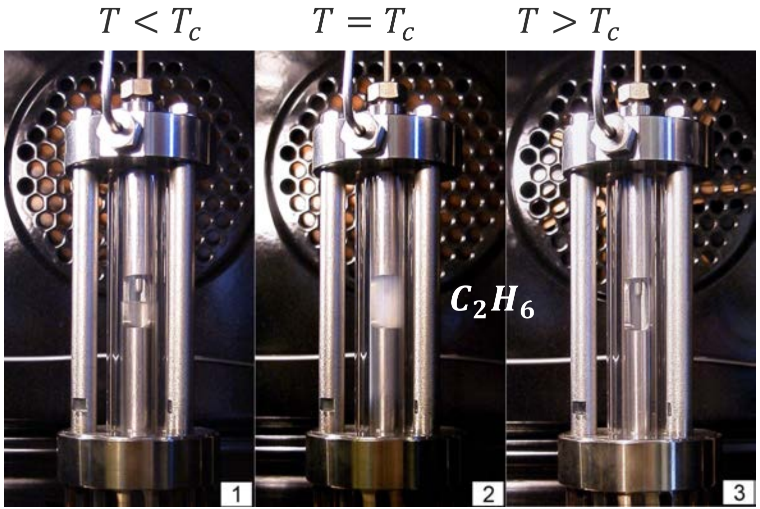
Hadron yields produced in central heavy-ion collisions from LHC down to SIS18 energies well described by statistical ensemble

- 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 μ_B
- QCD critical point is awaiting discovery

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

CRITICALITY

Probing criticality with fluctuations



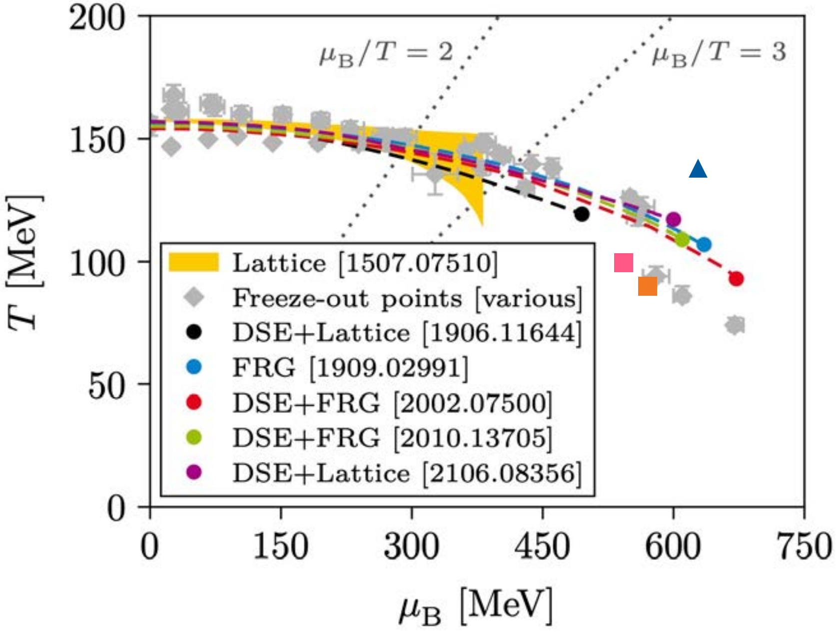
Critical phenomena discovered ~200 years ago by Cagniard de la Tour, using steam digester invented by Denis Papin in 1679

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 χ_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[1-4] 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

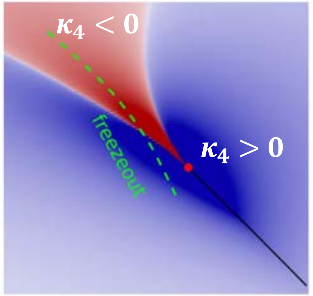
encodes the EoS

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

κ_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

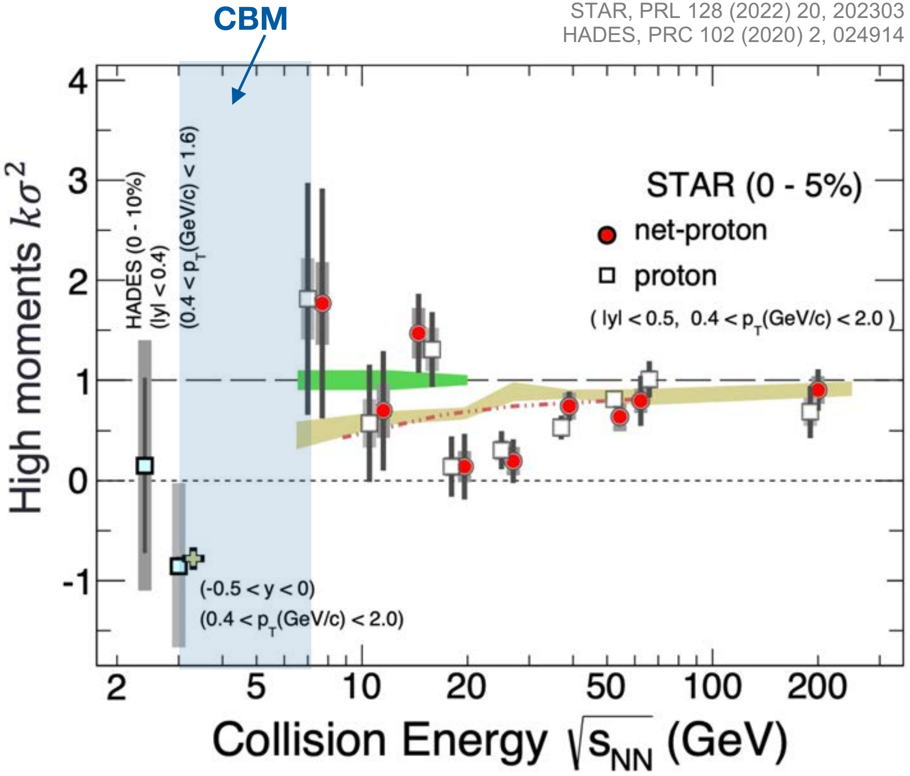
QCD critical point: large correlation length and fluctuations

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

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

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

Critical point search



Non-monotonic trend of the higher moments κ_4/κ_2 of net-proton number distributions, visible in a beam energy scan?

- Current data consistent with non-critical physics?

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

- **Reduced errors from STAR BES-II indicate non-trivial physics!**
- 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

Chemistry, vorticity, flow

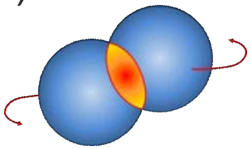
EQUATION OF STATE

Azimuthal anisotropy

with respect to reaction plane (RP)

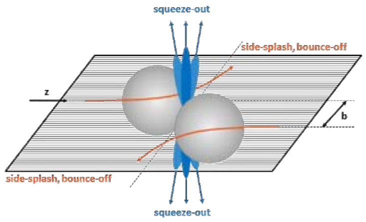
Fourier coefficients of the distribution

$$\frac{dN}{d(\phi-\Psi_{\mathrm{EP}})} \propto 1+2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_{\mathrm{EP}}))$$

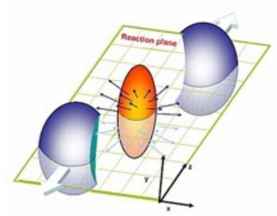


v_1 deflection of matter in the RP (signal of the phase transition?)

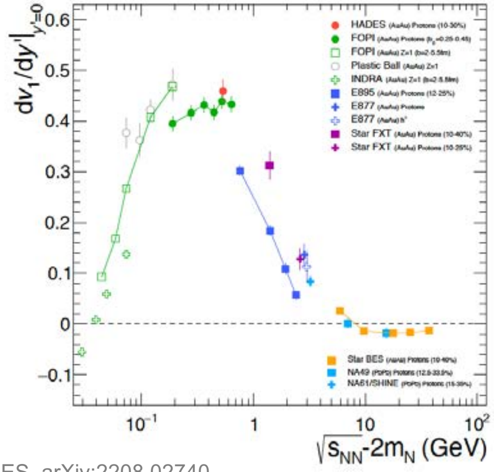
Paech *et al.*, NPA 681 (2001)

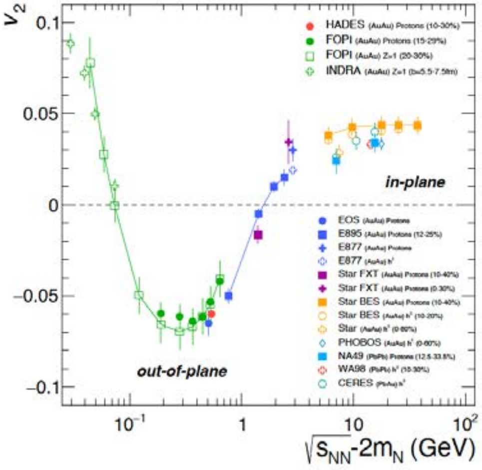


$v_2 < 0$ long spectator passing time $\tau_{passing} \approx \tau_{expansion} \Rightarrow$ “squeeze-out”



$v_2 > 0$ when spectators pass faster than fireball expands



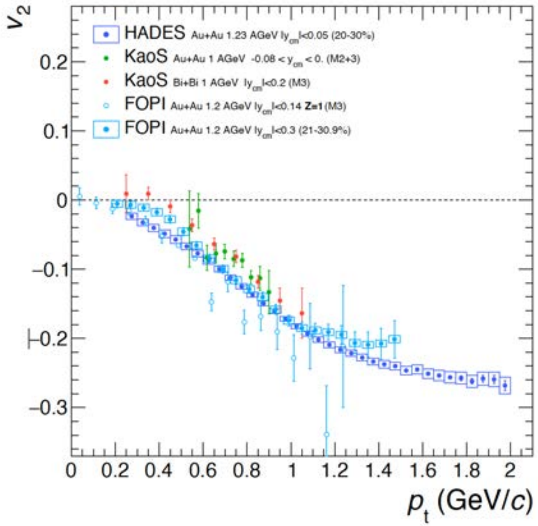


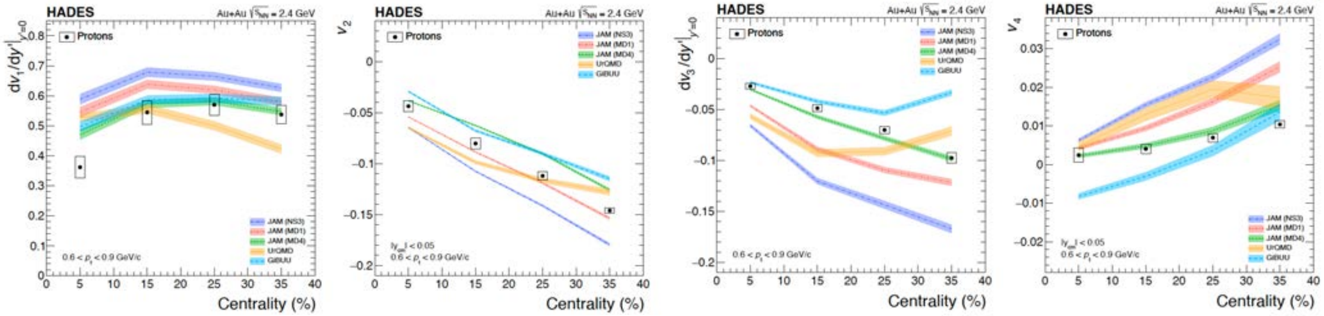
constrain equation-of-state by means of microscopic transport model

HADES, arXiv:2208.02740

Azimuthal anisotropy and EoS

- High precision multi-differential data for protons and light nuclei
- Data compared to QMD and BUU models
  - ➥ higher moments provide more discriminating power
  - ➥ consistent description of all flow harmonics over the whole phase space and at all centralities is missing





JAM (NS3)	hard momentum independent NS3
JAM (MD1)	hard momentum dependent
JAM (MD4)	soft momentum dependent MD4
UrQMD	“hard EoS” (UrQMD 3.4)
GiBUU	“soft EoS” (GiBUU 2019, Skyrme 12)

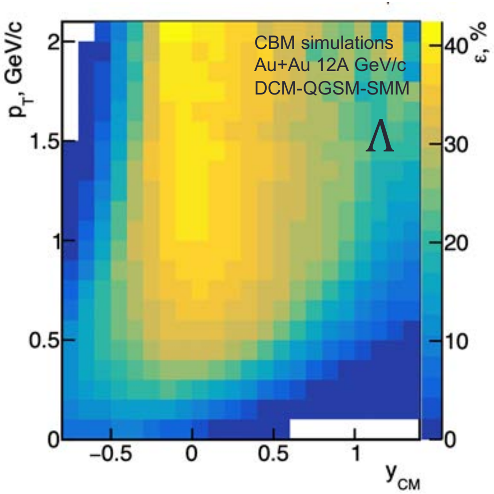
HADES, arXiv:2208.02740

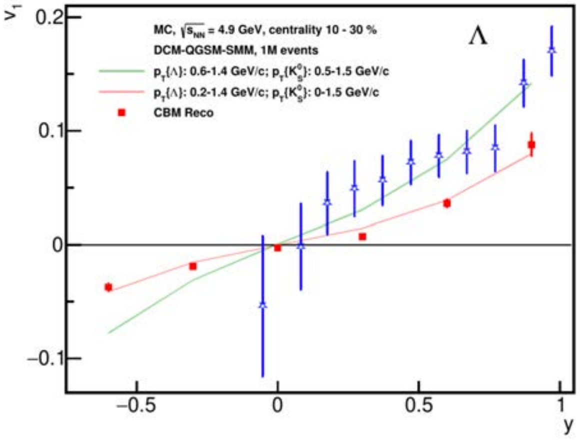
Collective flow and polarization of $\Lambda, \bar{\Lambda}$ and Ξ^- in CBM

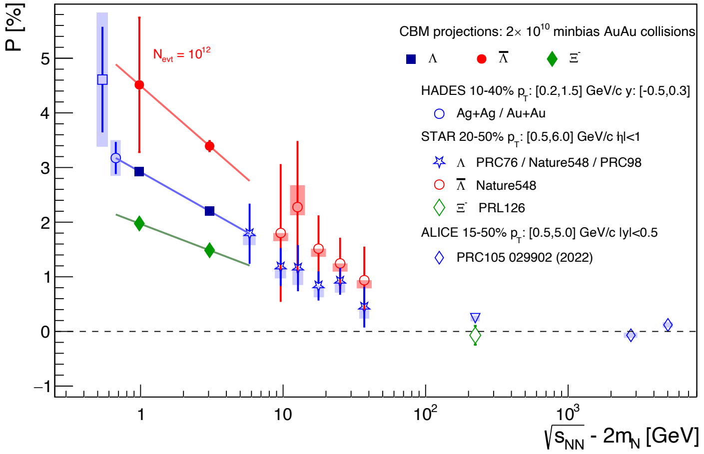
- Excellent phase space coverage (y_{CM} coverage for all $\sqrt{s_{NN}}$)
- Reconstruction efficiency ~30%
- Event plane resolution $\Re 1 \cong 0.8$, $\Re 2 \cong 0.5$

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

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



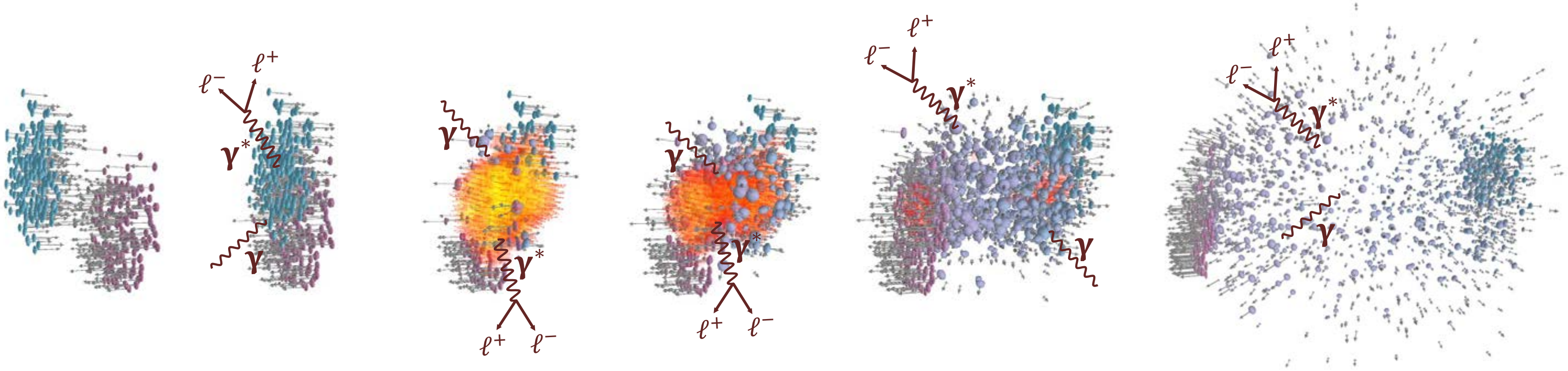


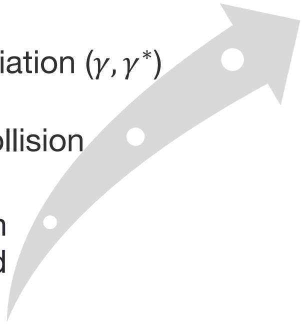


Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation as multi-messenger of fireball





Electromagnetic radiation (γ, γ^*)

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

Electromagnetic radiation as

Spectrometer

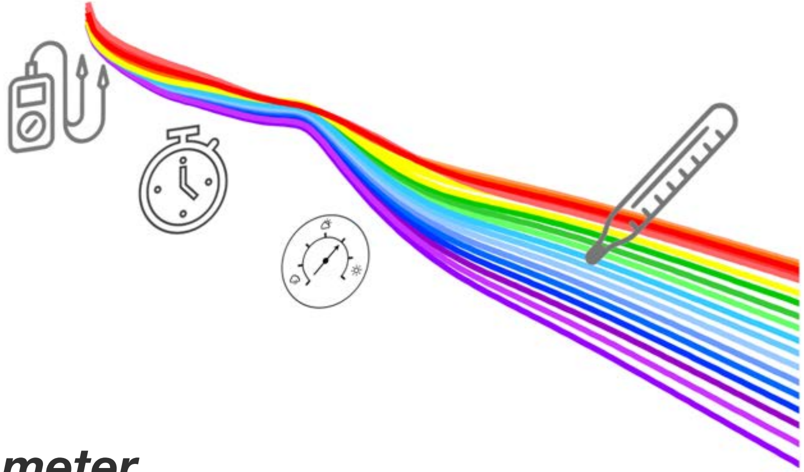
Chronometer

Thermometer

Barometer

Polarimeter

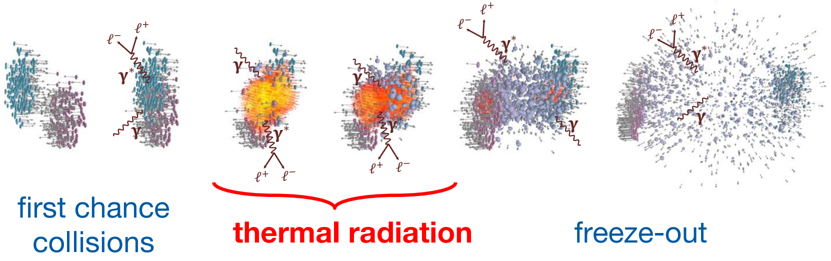
Amperemeter

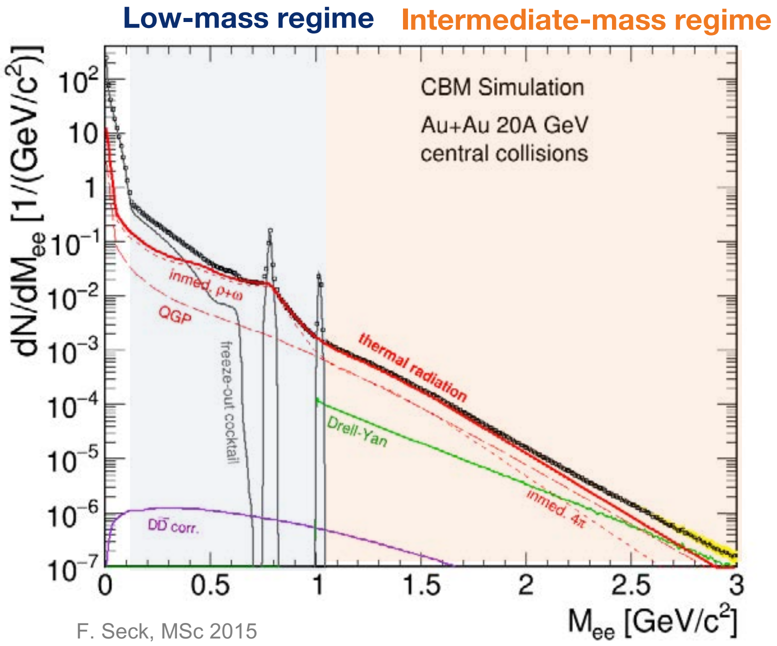


„If you want to detect something new, build a dilepton spectrometer“

Samuel Ting

Thermal dilepton measurements





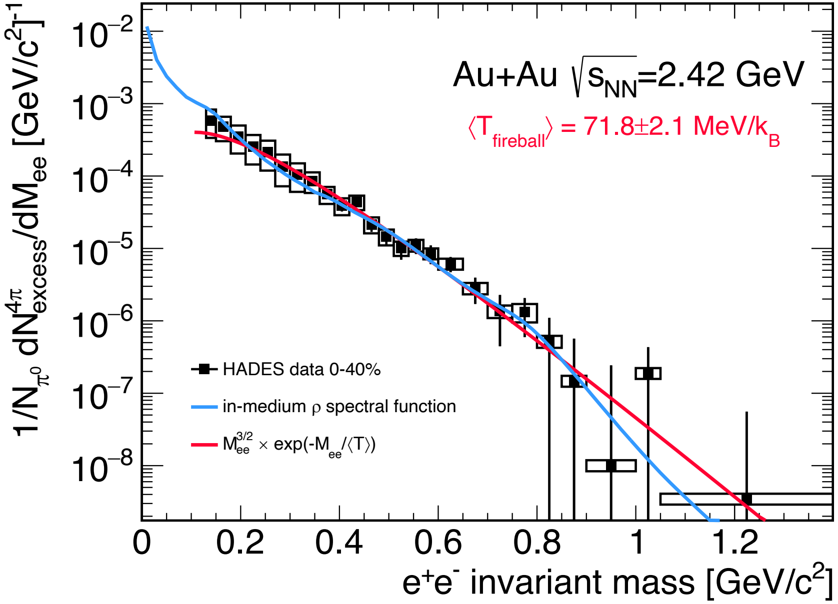
F. Seck, MSc 2015

- 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, $c\bar{c}\ (b\bar{b})$

See review: Salabura and Stroth, PPNP 120 (2021), 103869

Thermal dileptons from baryon rich matter

HADES, Nature Phys. 15 (2019) 1040



'Planck-like'

In-medium spectral function

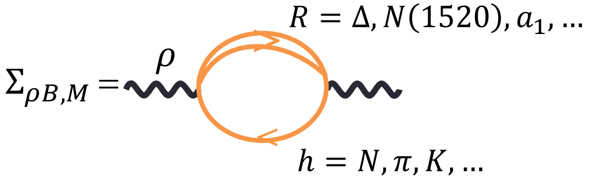
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2}\boxed{f^B(q_0,T)}\boxed{Im\Pi_{em}(M,q,T,\mu_B)}$$

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

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

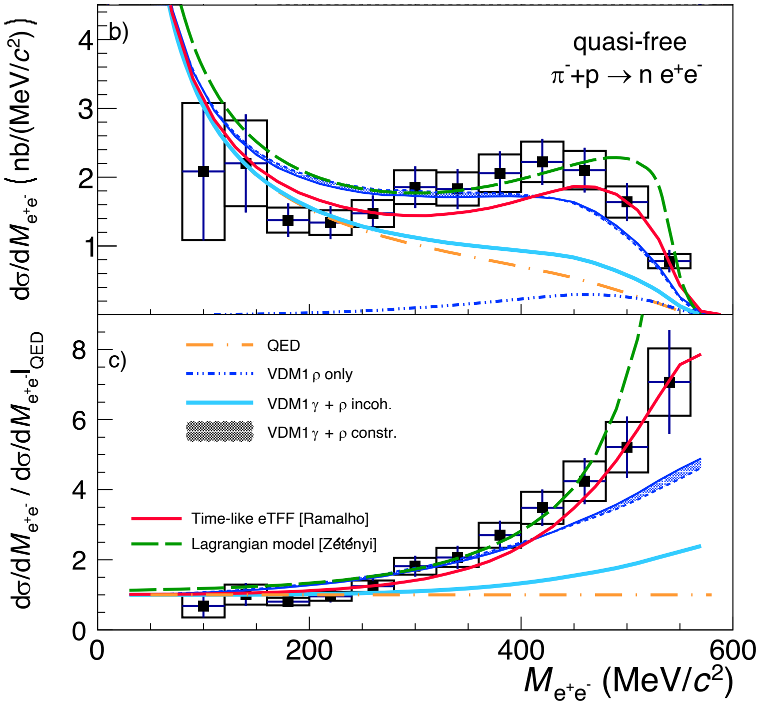
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial

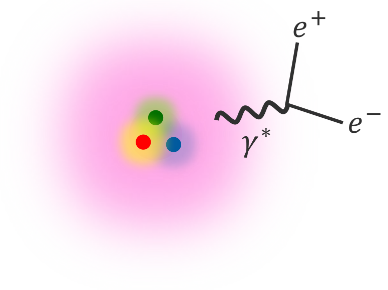


First measurement of massive γ^* emission from N^* baryon resonances (exclusive analysis $\pi^- p \rightarrow e^+ e^- n$)

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

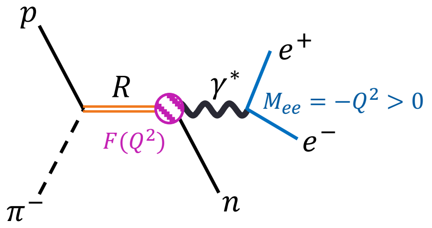


Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282



- 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
  - ρ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**

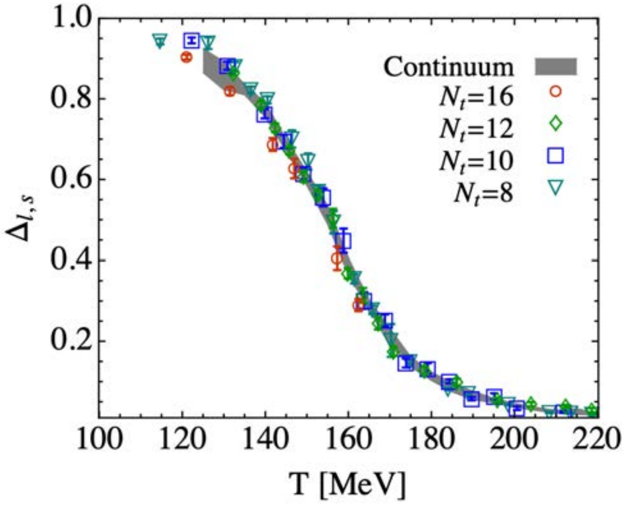


Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum

$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$

Condensates $\langle\bar{q}q\rangle$ calculated by lattice QCD

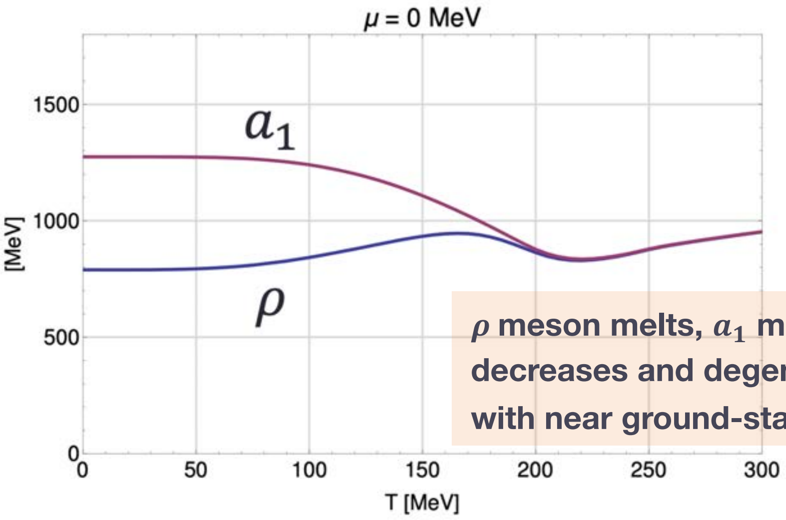


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

Restoration at finite T and μ_B manifests itself through mixing of vector and axial-vector correlators



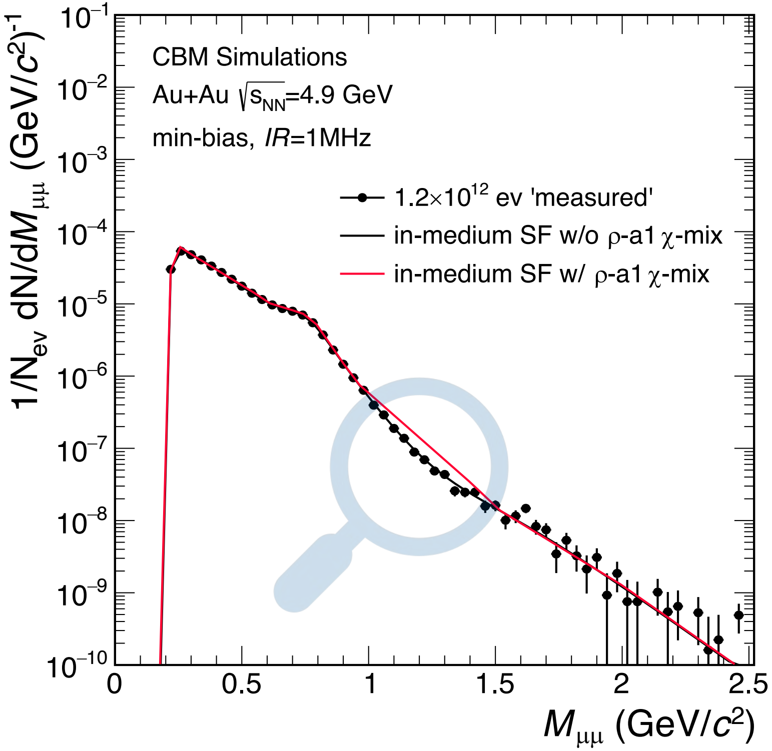
ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)

FRG Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020

Light mesons and baryons from lattice QCD, Aartz, QM2022, April 2022

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



Experimental challenge: physics background ($M_{\ell\ell}$ > 1 GeV)

- correlated charm: excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
- QGP: decrease towards lower energy
- 𝒟rell-𝒴an: pp, pA measurements

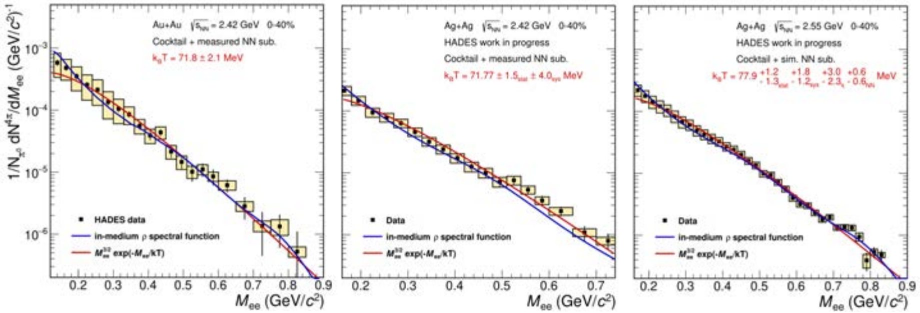
- **20-30% enhancement** w.r.t. no chiral mixing is **predicted** in the region 0.8<M<1.5 MeV/c^2

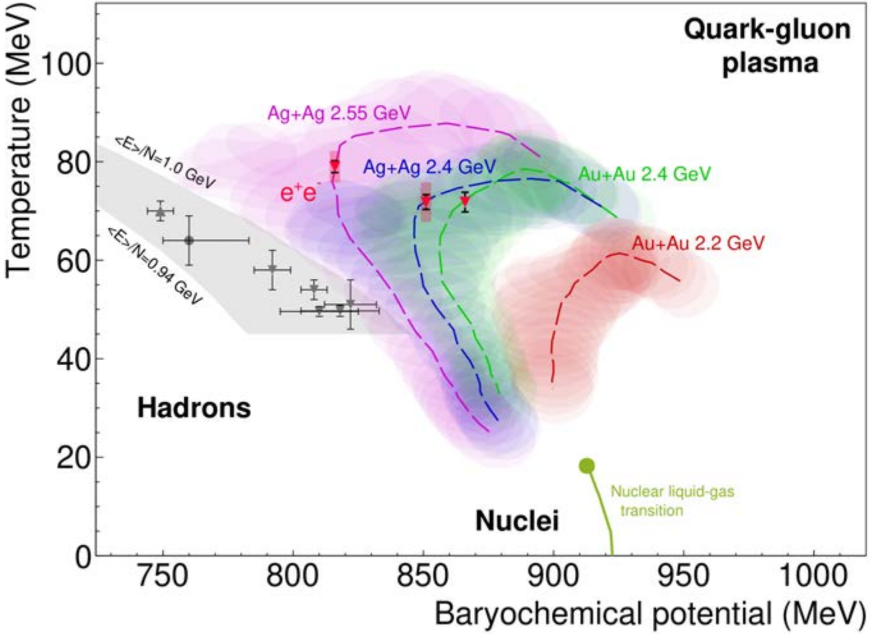
Dey, Eletsky, Ioffe, PLB252 (1990)
Rapp, Wambach, ANP 25 (2000)
Sakai *et al.*, arXiv:2308.03305 [nucl-th]

- **CBM sensitivity** to detect a signal is **demonstrated**

Mapping QCD phase diagram with dileptons

Au+Au $\sqrt{s_{NN}} = 2.42$ **GeV** **Ag+Ag** $\sqrt{s_{NN}} = 2.42$ **GeV** **Ag+Ag** $\sqrt{s_{NN}} = 2.55$ **GeV**





- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region

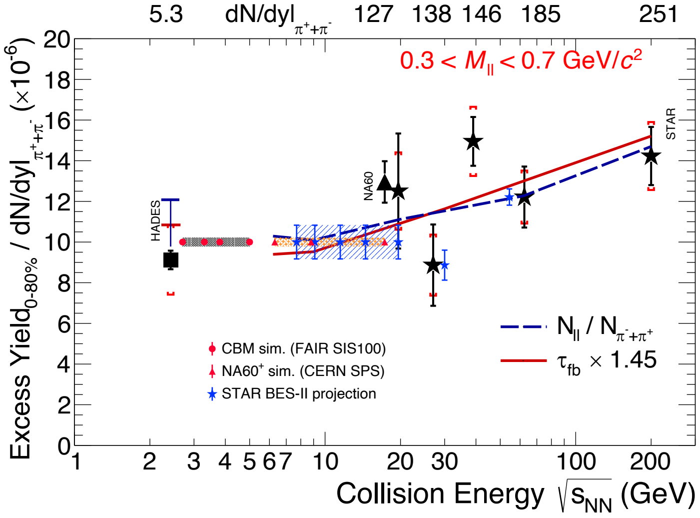
FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: Seck, TG

Thermal dileptons excitation functions

Excess yield in LMR tracks fireball lifetime

- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203

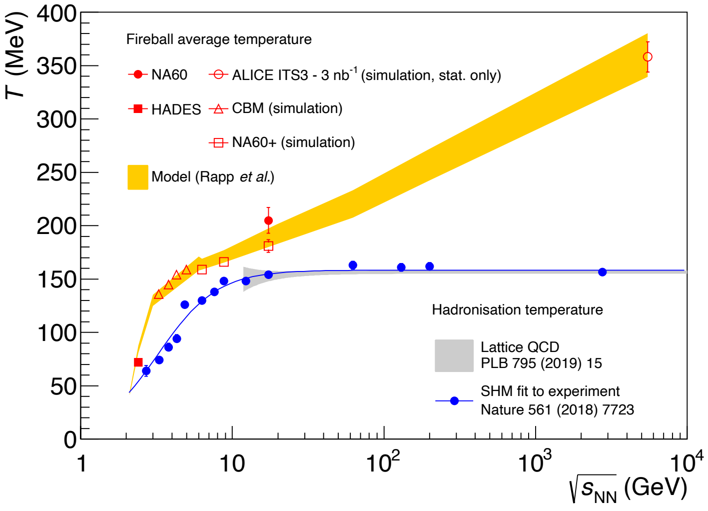


TG, JPS Conf.Proc. 32 (2020) 010079

Invariant mass slope measures radiating source T

- **Flattening** of caloric curve (T vs ε) → evidence for a **phase transition**
- Probe time dependence of fireball temperature: *$M_{\ell\ell}$ versus v_2, photon polarization*

Seck, Friman, TG, van Hees, Speranza, Rapp, Wambach, [arXiv:2309.03189 [nucl-th]]

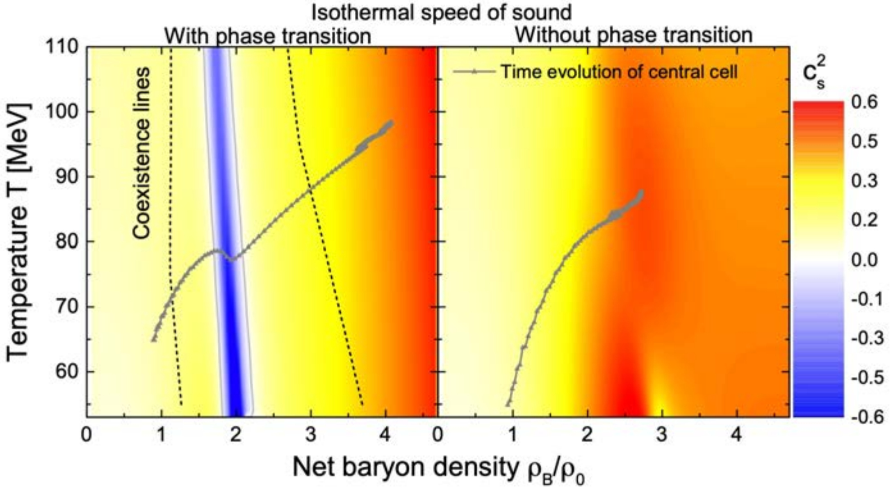


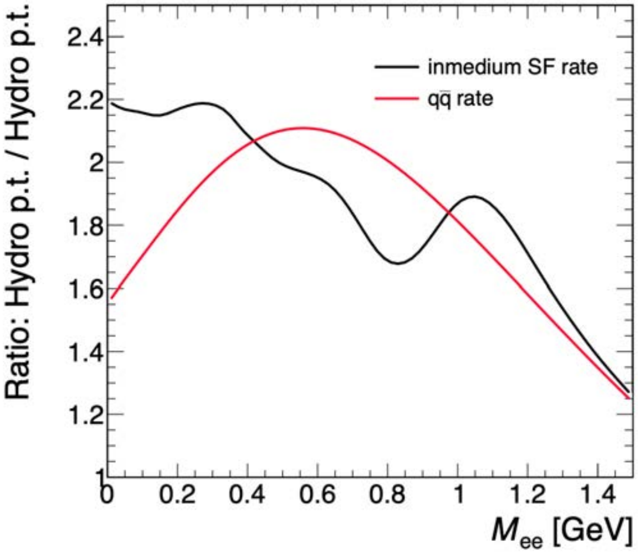
https://github.com/tgalatyuk/QCD_caloric_curve

Dilepton signature of a 1st order phase transition

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904

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





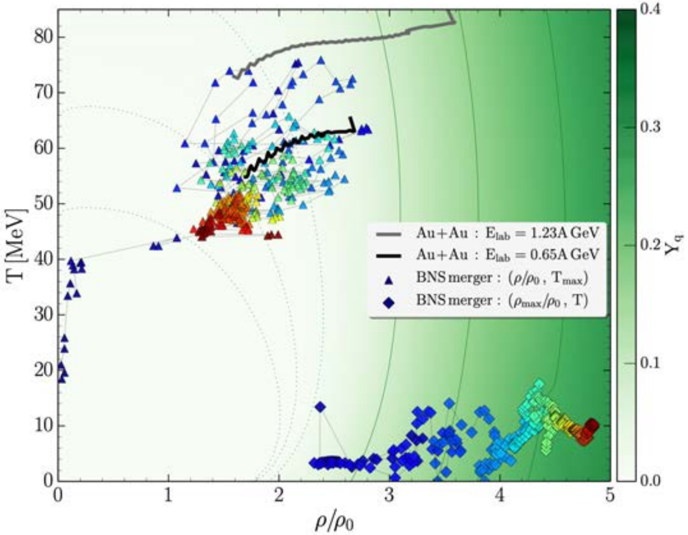
- Ideal hydro simulations with and w/o first order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low μ_B and neutron-star constraints at high density

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

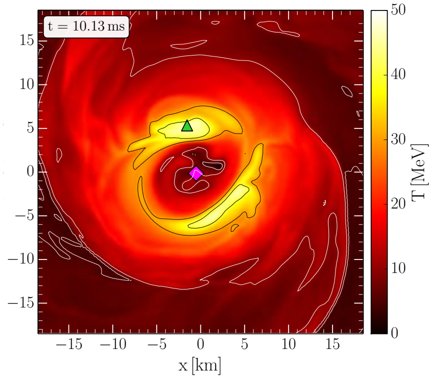
Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended “cooking”

The QCD phase structure at high- and low μ_B

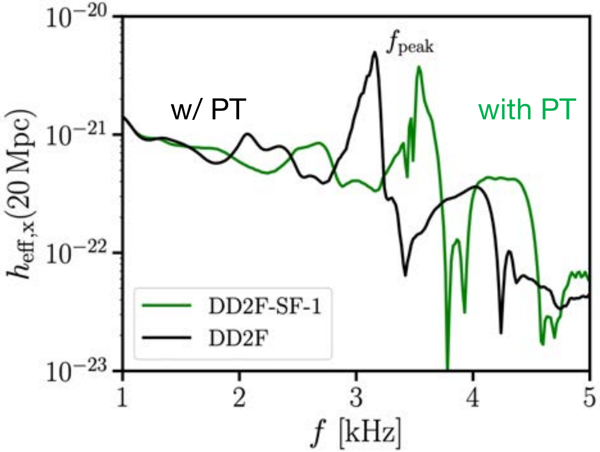
Possible HIC trajectories and NS merger simulations within an effective hadronic model



Hanauske *et al.*, Particles 2 (2019) no.1
Rezzolla *et al.*, PRL 122 (2019) no. 6, 061101



Bauswein *et al.*, PRL 122 (2019) 6, 061102



- NS mergers probe bulk properties of EoS – microphysics only accessible through combined effort
- Consistency between EoS infer from observables from BNS mergers and new high precision HIC

Blacker *et al.*, PRD 109 (2024) 4, 043015
Vijayan *et al.*, PRD 108 (2023) 2, 023020

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

Summary: The future is bright!

Encouraging prospects for studying extreme matter in the laboratory

- **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 quark-gluon plasma and baryon-rich matter**

BONUS SLIDES

The quest to detect the initial electromagnetic field

VORTICITY

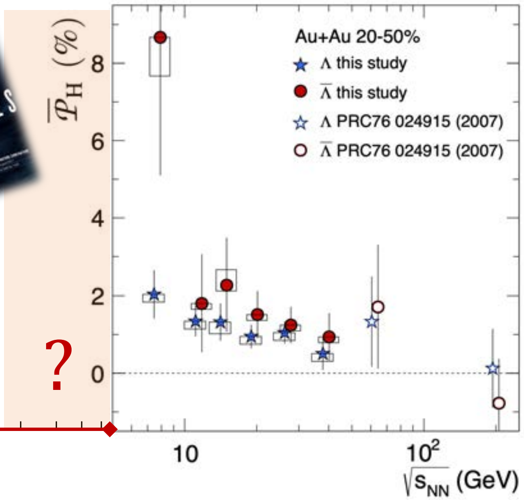
Probing vorticity with spin degres of freedom

$$P(\vec{s}) \propto e^{-\vec{\omega}\vec{s}/k_B T}$$

- Non-central heavy-ion collisions ⇝ large orbital angular momenta ($\sim 1000\hbar$) ⇝ vortical structure of the system?
  - **probed via parity-violating decay of Λ hyperons**
  - estimation of angular momentum direction via spectator deflection

STAR, Nature 548 (2017) 62-65

Global spin polarization of hyperon as a probe of fluid behavior



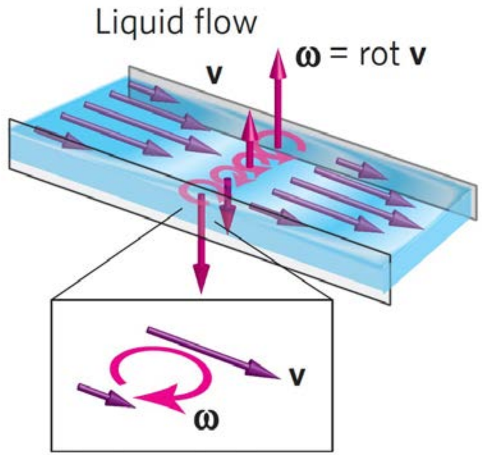
$\omega \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$

evidence for the **most vortical fluid**

and hint for the largest **magnetic field**

$\mathrm{B} = 10^{14}\ \mathrm{T}$

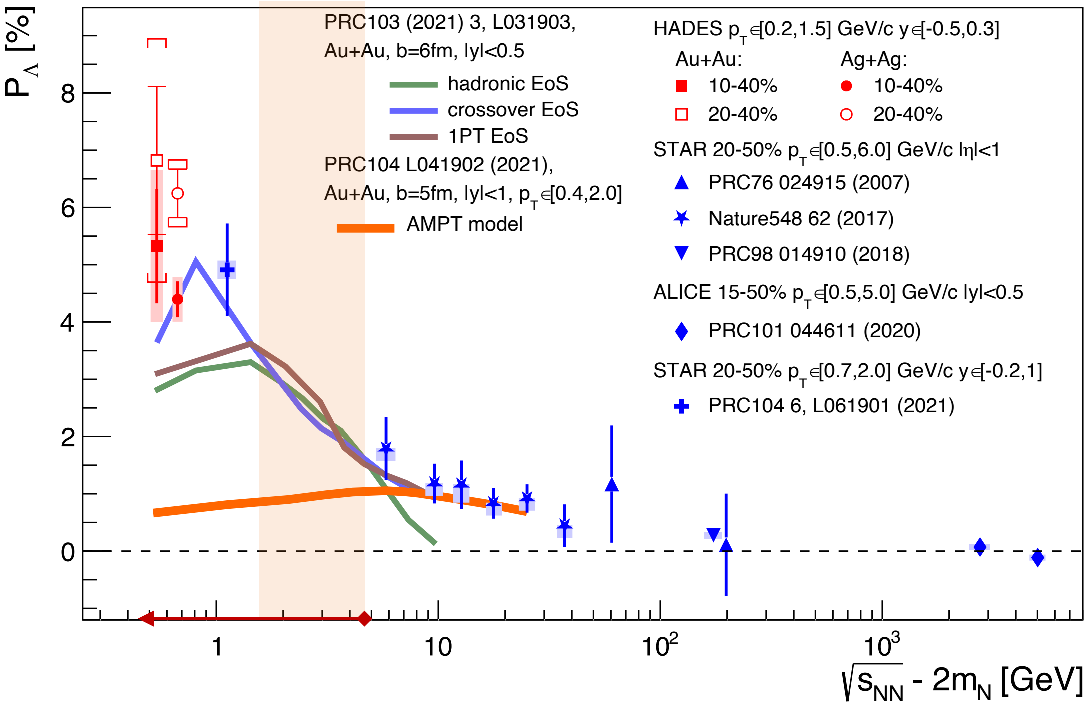
- First observation of fluid vorticity-polarization coupling by Takahashi, *et al*. Nat. Phys. (2016)
  - atomic alignment directly measured
  - direction of angular momentum known



Friction with walls induces vorticity
Vorticity of bulk ⇝ polarization of constituents

Splitting of hyperon polarization

HADES, PLB 835 (2022) 137506



- Strong increase of polarization signal towards few GeV energies
- Highest polarization measured by HADES, SIS18
- Origin of the polarization mechanism? Sensitivity to EoS?
- Mapping of the **excitation function of Λ and $\bar{\Lambda}$** (Ξ^-, Ω) with precision of 5% with CBM

Late stage magnetic field should cause splitting in Λ and $\bar{\Lambda}$ polarization

Performance studies in CBM

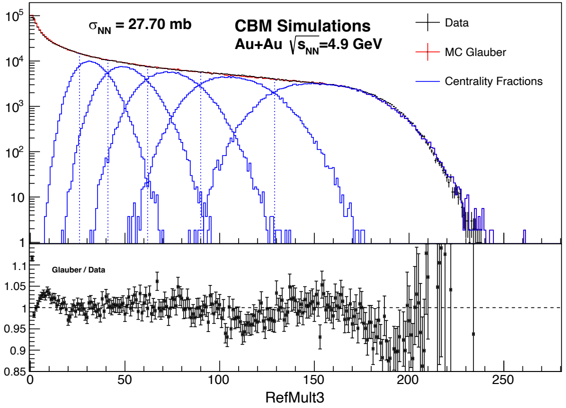
- Corrections for volume fluctuations and conservation laws
- Event-by-event changes of efficiency
- Proper selection of $p_T - y$ bite
- (Net-)baryons vs. protons, neutrons, nuclei

impact of the effects is being scrutinized

CBM after 3 years of running:

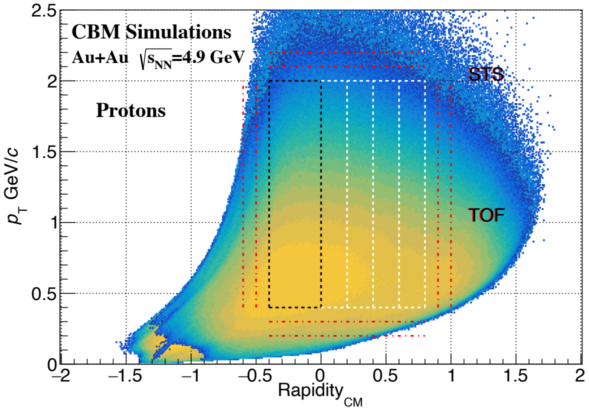
- **completion of the excitation function for $\kappa_4(\mathrm{p})$**
- **first results on $\kappa_6(\mathrm{p})$**
- **extension into strangeness sector $\kappa_4(\Lambda)$**

NA61++: κ_4/κ_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



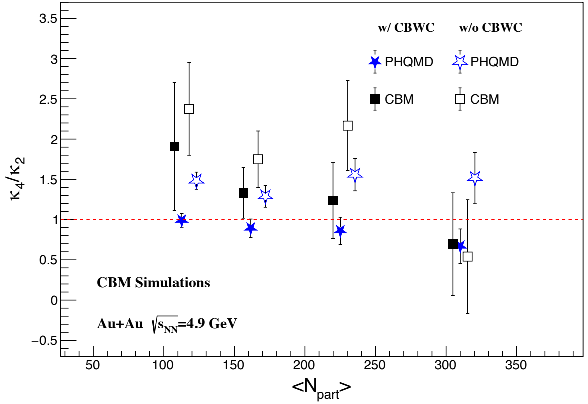
Crucial: centrality determination with independent detector → avoids bias on e-b-e fluctuation observables

Studies employing FSD centrality detector ongoing



Low p_T and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants

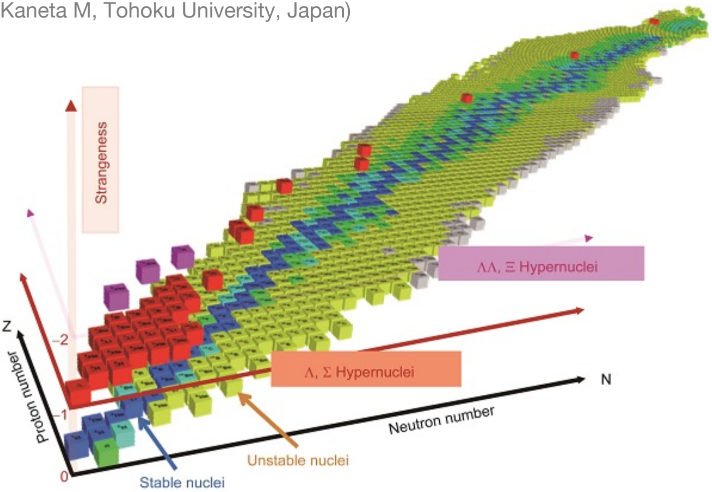


Statistics sufficient to study derivatives of order $> \mathcal{O}(4)$

Nuclei and hyper-nuclei production

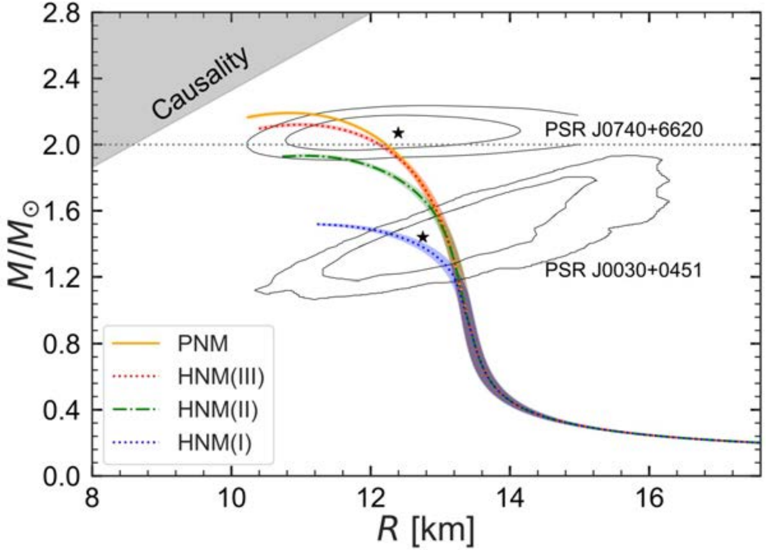
Three-dimensional nuclear chart

(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

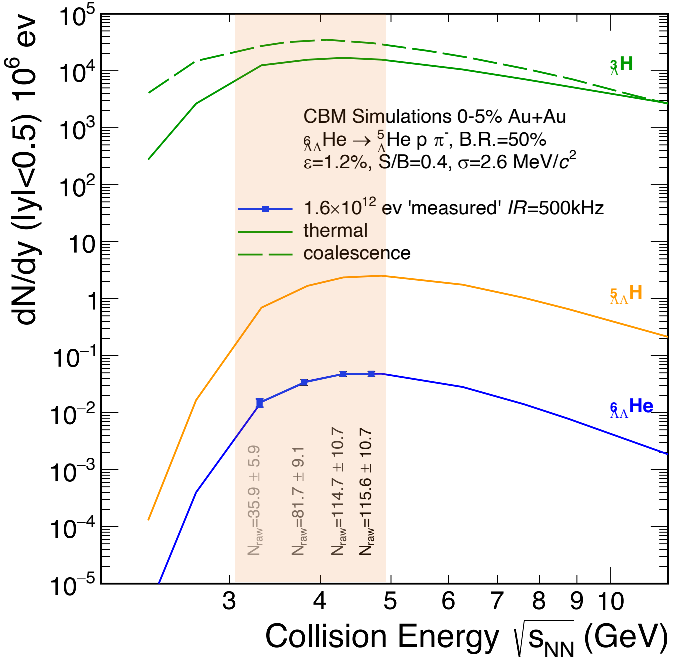
EoS of high density matter

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

CBM performance

CBM collision energies optimal for hypernuclei production

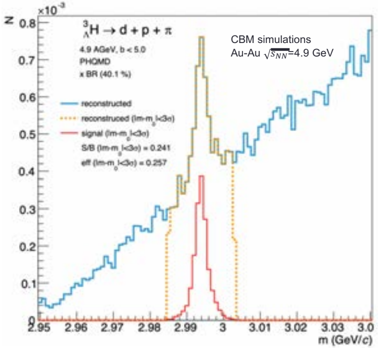
Thermal: Andronic *et al.*, PLB 697 (2011)
Coalescence: Steinheimer *et al.*, PLB 714 (2012)

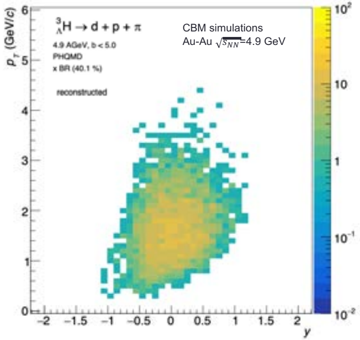


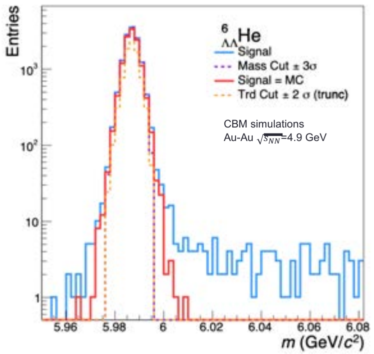
- CBM high interaction rates and clean identification allow precision measurements of single- and double Λ-hypernuclei
  - spectra and flow pattern
  - complex structure via Dalitz plot
  - life-time (particularly sensitive to YN and YY interaction)

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

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



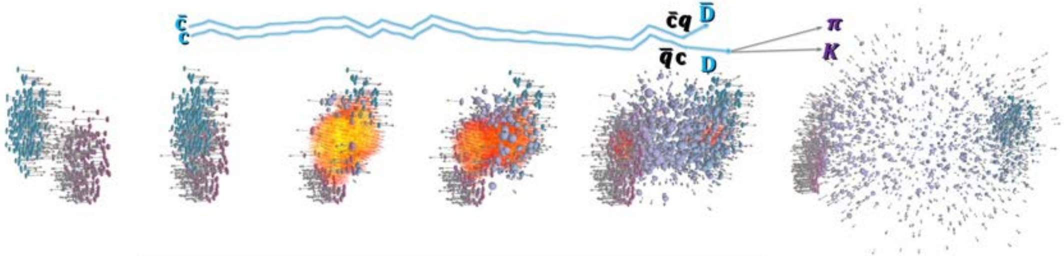




Charm $(c, \bar{c})$ of the baryon-rich matter

IN-MEDIUM QCD FORCE

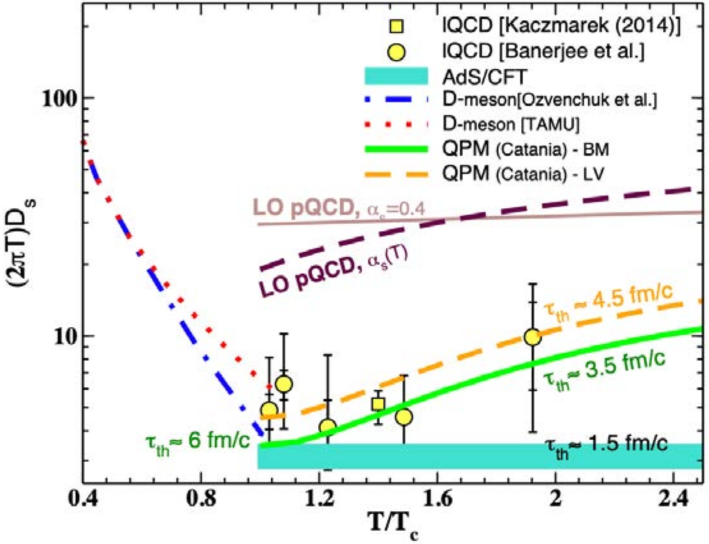
What is so “charming” about charm?



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 (Ψ , Υ 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

Charm performance studies

NA61/SHINE (upgrade of vertex detector)

- measurement of open charm cross section at 150 and 40 *A*GeV Pb-Pb collisions feasible
- study of $c\bar{c}$ correlations could be attempted, might be statistically limited

Larsen *et al.*, NA61/SHINE, EPJ Web Conf. 191 (2018) 05003

NA60++ / CBM (cross-sections unknown!)

Open charm

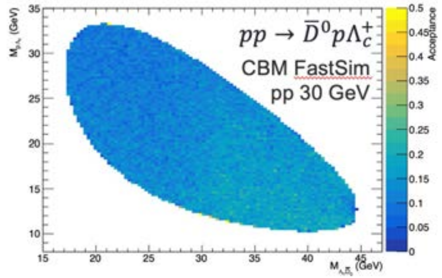
- accessible down at lowest $\sqrt{s_{NN}}$ with 1% statistical precision
  ⤳ R_{AA} and v_2 vs p_T, y and centrality
  → **charm diffusion coefficient and thermalization**
- **D_s** and **Λ_c** yield feasible with statistical precision of few percent
  → **insight on hadronization mechanism**

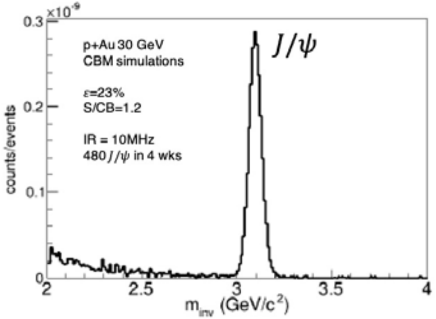
J/ψ

- detection of **onset of anomalous suppression** effects
  down to low SPS energy ($\psi(2S)$ also within reach for E~100 *A*GeV)
- pp/pA collisions to establish cold nuclear matter effects
- study intrinsic charm component of the hadron wave function

Vogt, PRC 106 (2022) 2, 025201
NNPDF, Nature 608 (2022) 7923, 483-487

Charm-N interaction





Tremendous physics potential with proton beam from SIS100

Workshop “physics opportunities with proton beams at SIS100” in Wuppertal, February 2024
https://indico.gsi.de/event/18475/overview