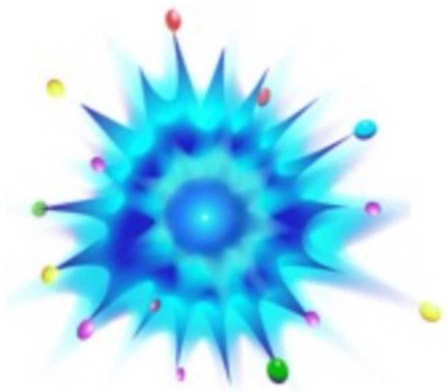


Probing the Nature's Primordial Fluid

Volodymyr Vovchenko (University of Houston)

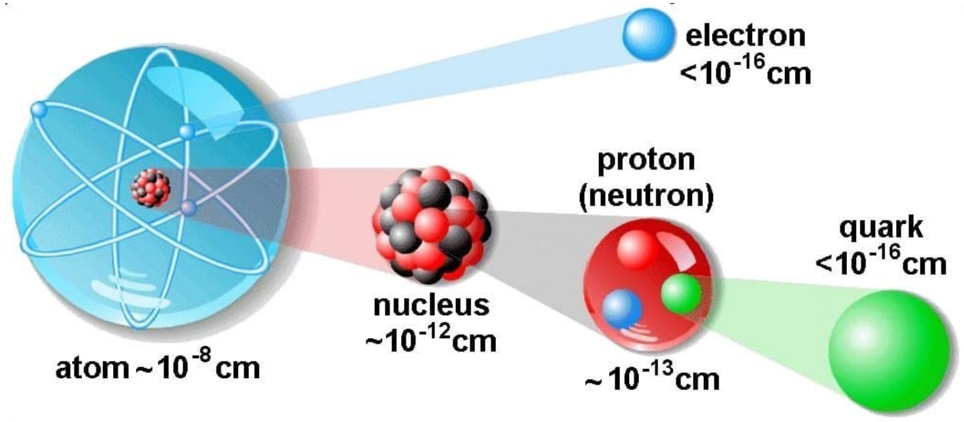
vvovchen@central.uh.edu – https://vovchenko.net

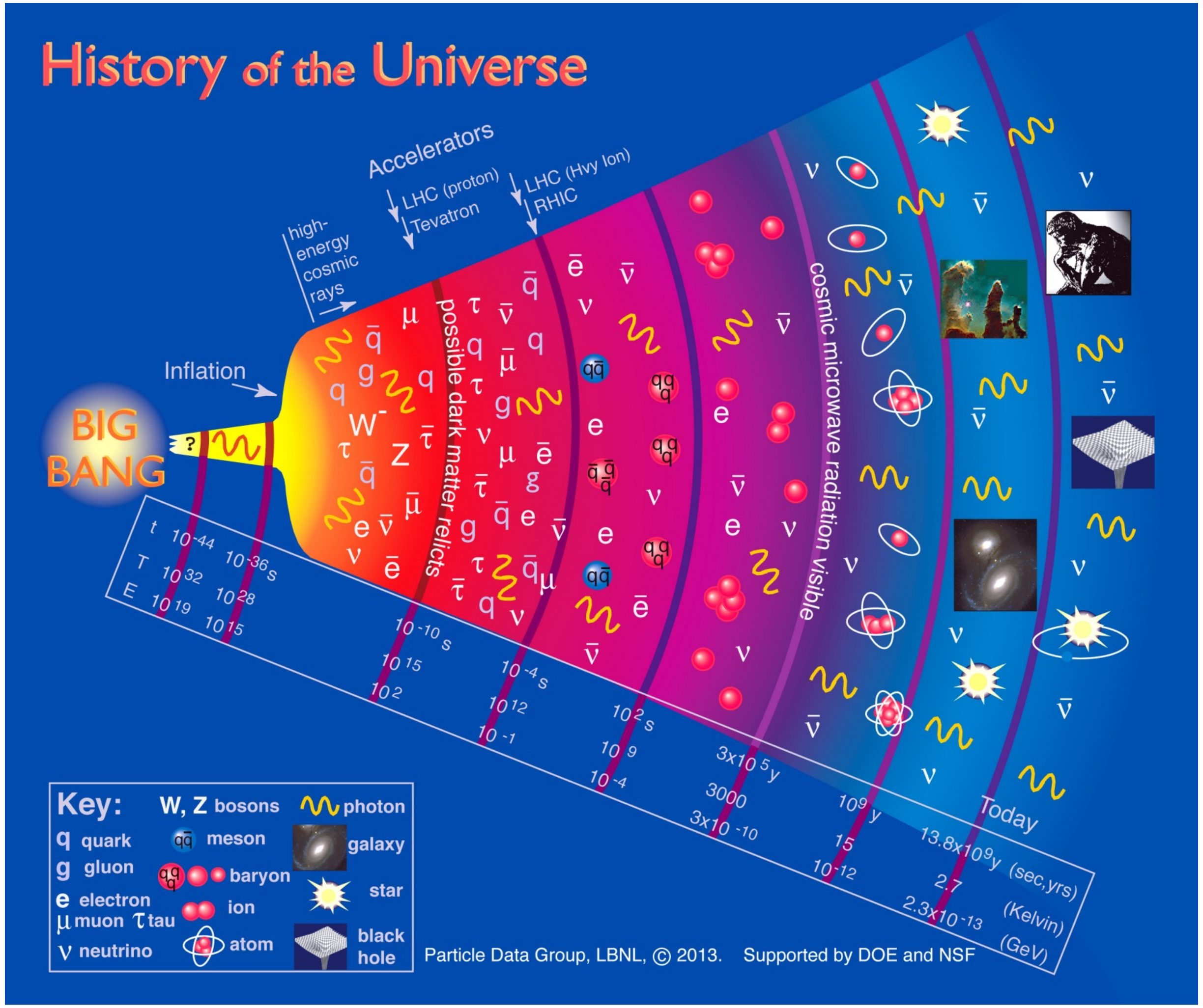
QuarkNet Summer Workshop 2025 – Rice University

June 10, 2025

UNIVERSITY OF HOUSTON

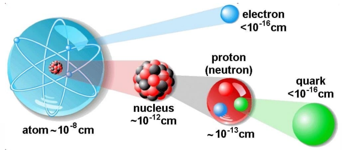
Structure of matter

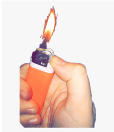




Extreme states of matter

Fermi 1953

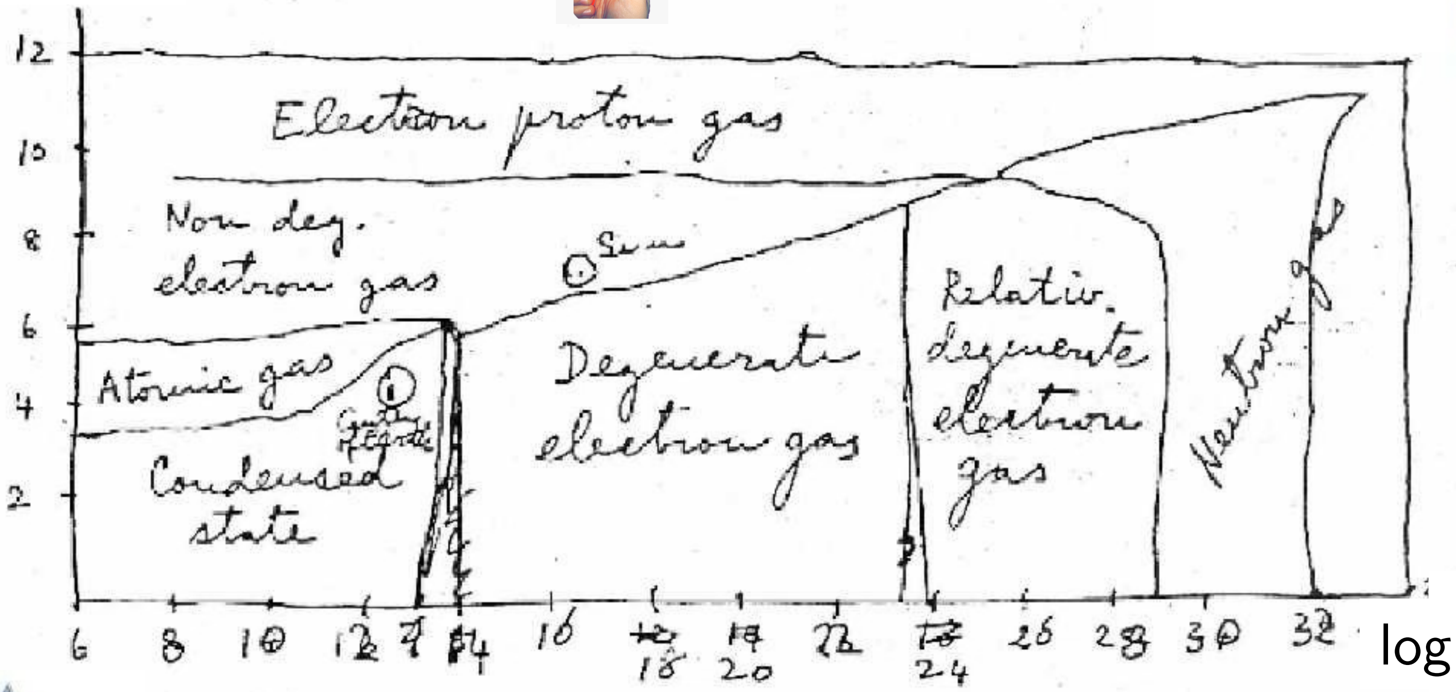




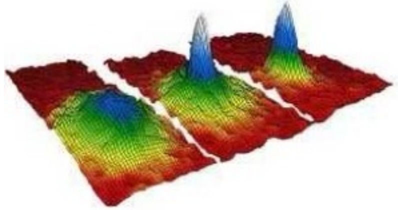
log T

tera Kelvin

1 MeV ~ 10^{10} K

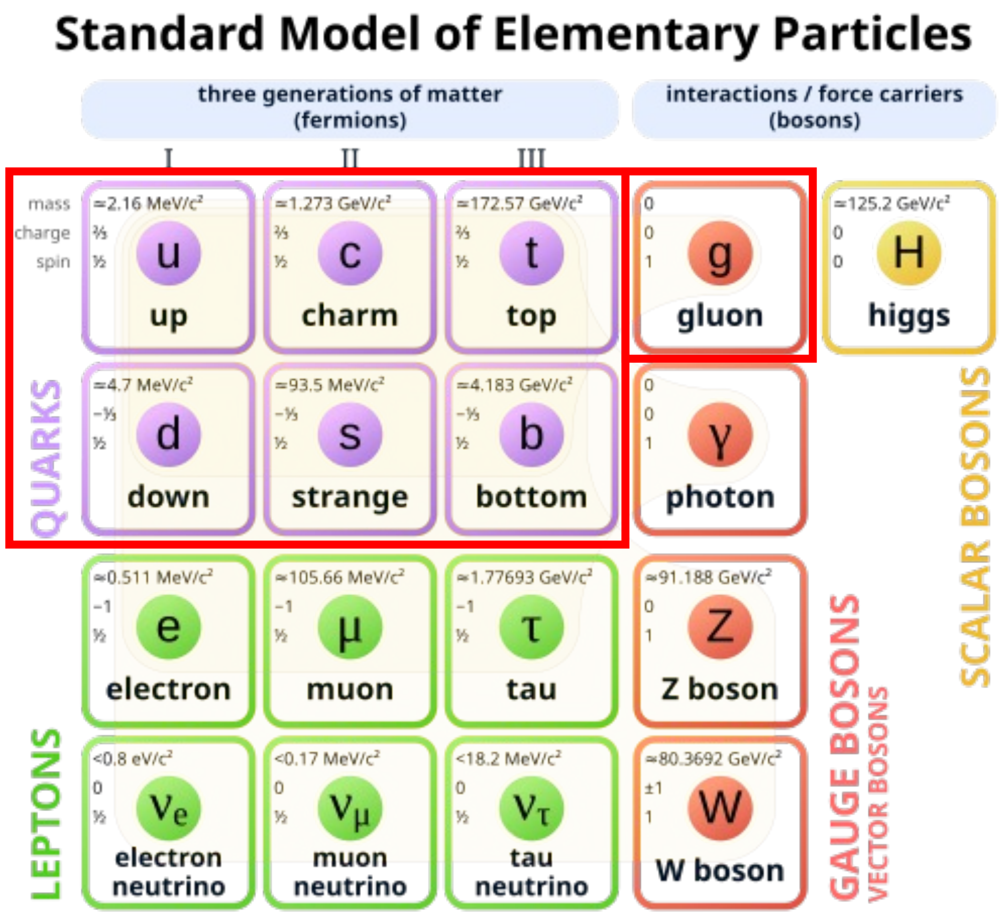


log p



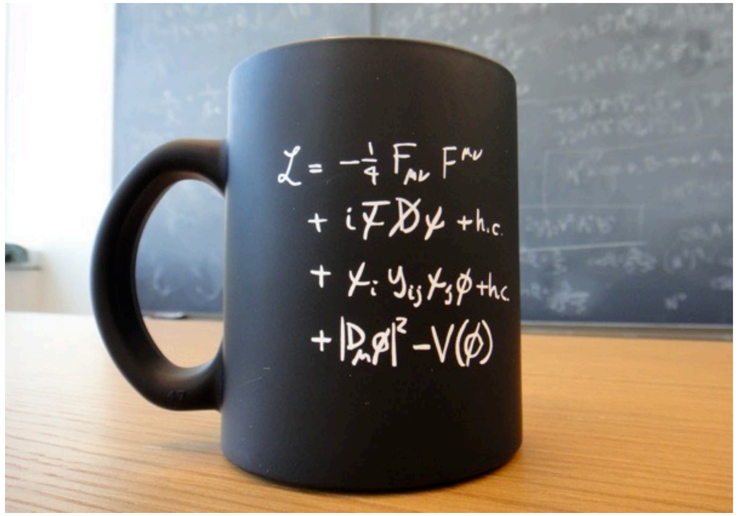
Matter in unusual conditions

Standard model



mid-1970s

Predicted the top quark (disc. 1995), the tau neutrino (disc. 2000), and the Higgs boson (disc. 2012)

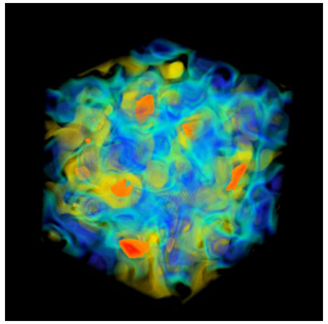


- Strong (nuclear) force
  - Quarks and gluons, short-range
- Electromagnetic force
  - Charged particles (Coulomb), long-range
- Weak force
  - Fermions (incl. neutrinos)

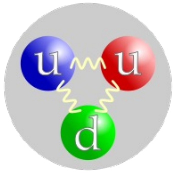
Strongly interacting matter

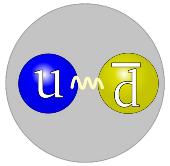
- Theory of strong interactions: *Quantum Chromodynamics* (QCD)

$$\mathcal{L} = \sum_{q=u,d,s,\dots} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA^{a}_{\mu}\lambda_{a}) - m_{q}\right] q - \frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$



- Basic degrees of freedom: quarks and gluons that carry color charge
- At smaller energies confined into baryons (qqq) and mesons $(q\bar{q})$



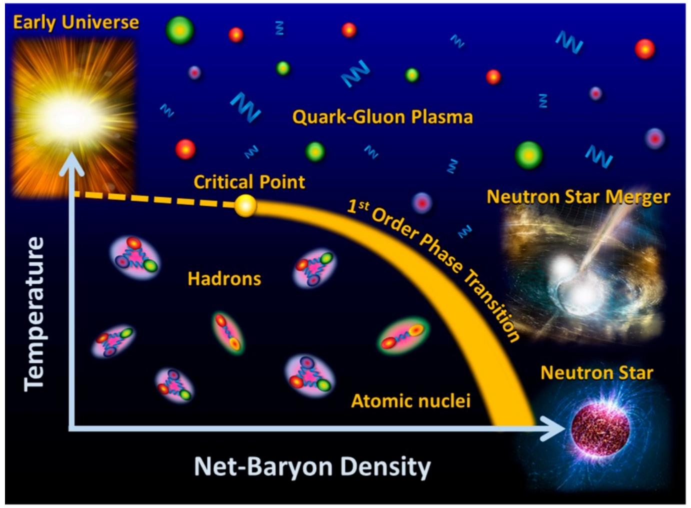


Scales

- Length: 1 femtometer $= 10^{-15}$ m
- Temperature: 100 MeV$/k_B = 10^{12}$ K

Where is it relevant?

- Early Universe
- Astrophysics: Neutron star (mergers)

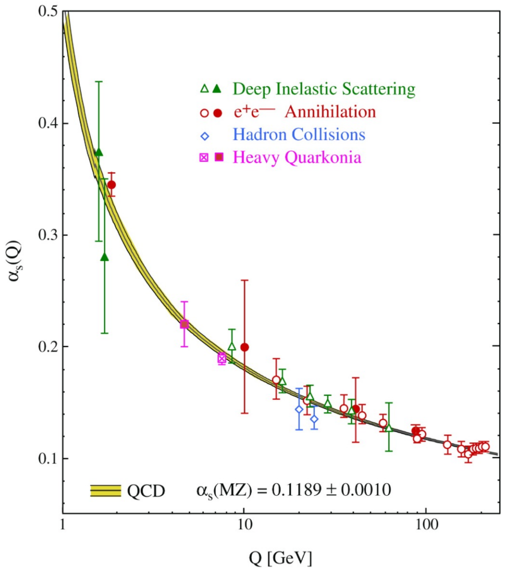


Studied in **laboratory** with heavy-ion collisions

QCD features and emergent phenomena

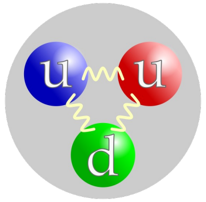
- Asymptotic freedom Gross, Politzer, Wilczek (1973)
  - Interaction becomes *weaker* at high energies/small distances
  - Theory is in perturbative regime at small distances

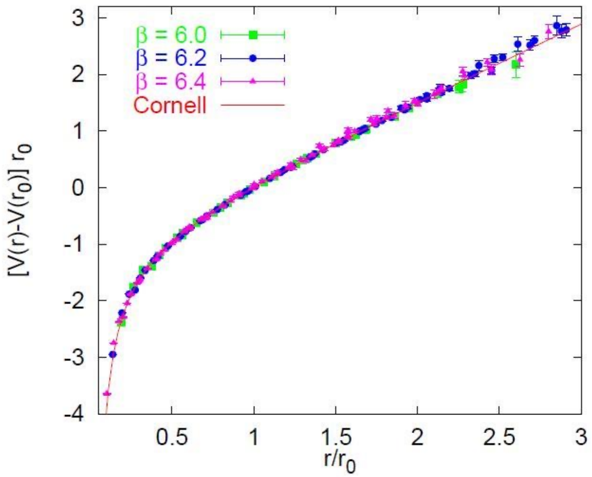
2004



S. Bethke

- Hadrons (confinement)
  - No free quarks or gluons ever observed
  - They must form composite, color-neutral objects – the hadrons
    - Proton (uud) and neutron (udd)
  - No small parameter makes the theory virtually untractable ☹



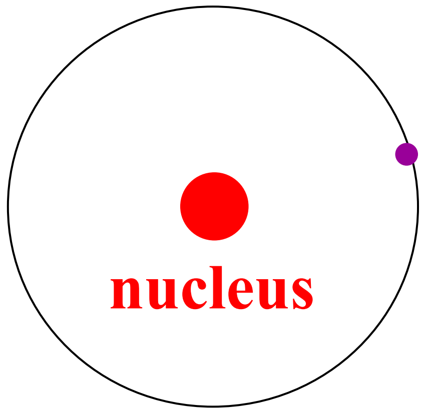


G. Bali

- Dynamical mass generation
  - Proton (uud) mass is $m_p = 938$ MeV/c^2 but $m_u + m_u + m_d \sim 15$ MeV/c^2
  - >95% of proton's mass from QCD, only <5% is from Higgs

Confinement

- Forces usually get weaker with distance



can easily separate constituents

$$F \sim 1/r^2$$

neutral atom

Confinement

- Forces usually get weaker with distance

electron

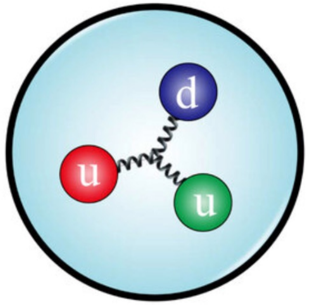
can easily separate constituents

$$F \sim 1/r^2$$

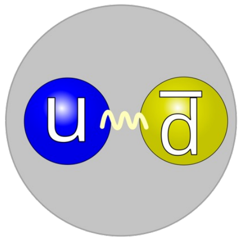
charged nucleus

- Quarks in QCD are confined

- Try to separate quarks

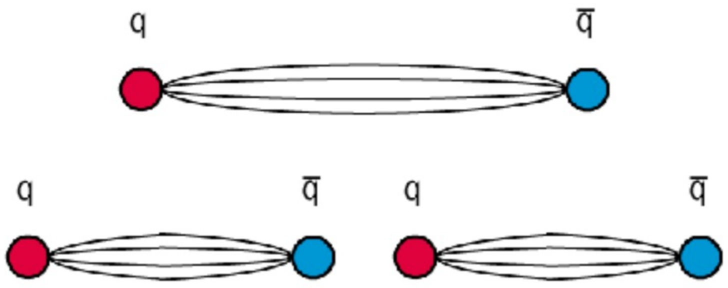


“white” proton
(confined quarks)



“white” pion
(confined $q\bar{q}$)

$$F \sim r$$

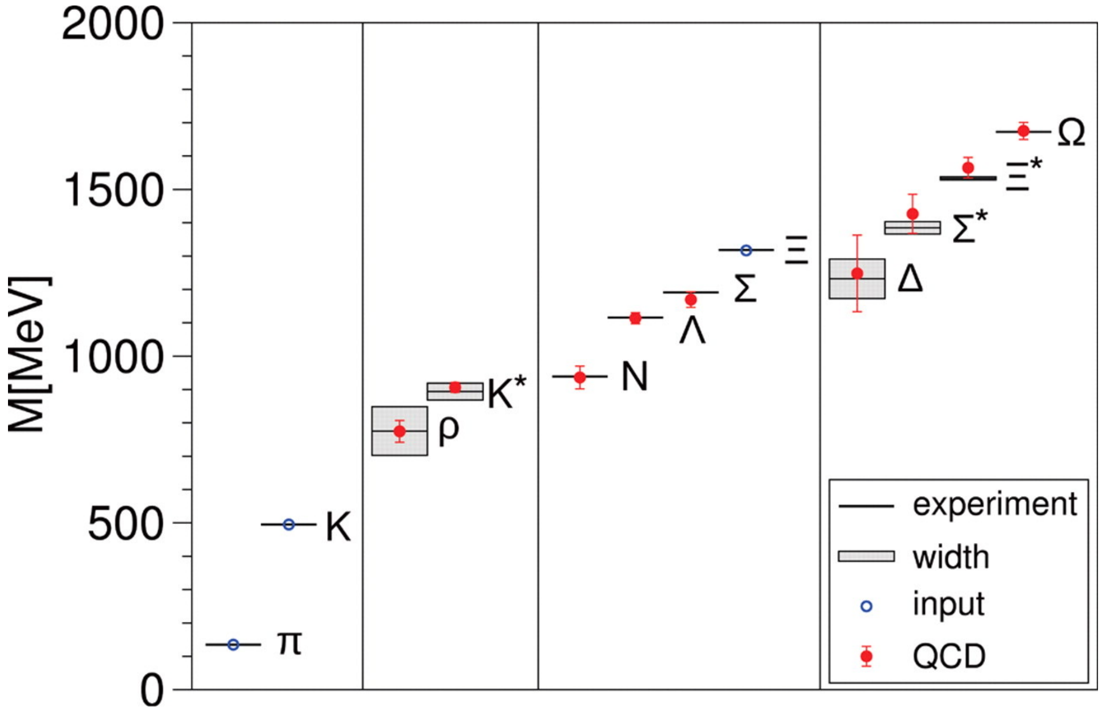


quark-antiquark pair
created from vacuum

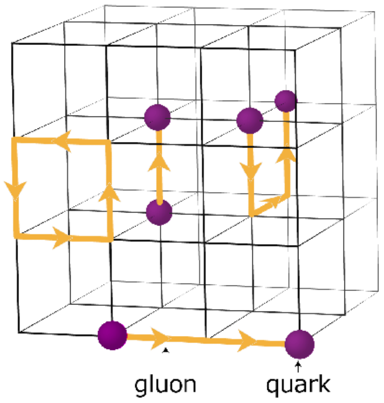
Non-perturbative methods

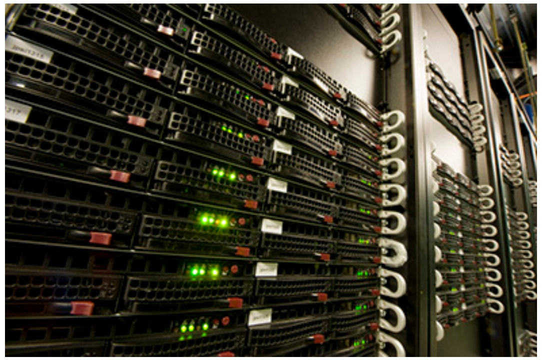
First-principle tool: **Lattice QCD** – a brute force Monte Carlo solution on a discretized space-time grid

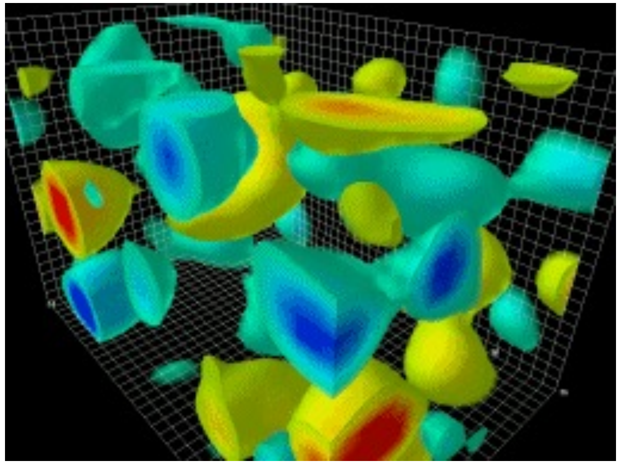
Ab-initio calculation of hadron masses



BMW Collaboration, Science 322, 1224 (2008)







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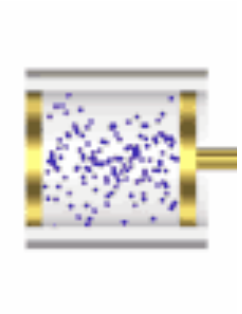
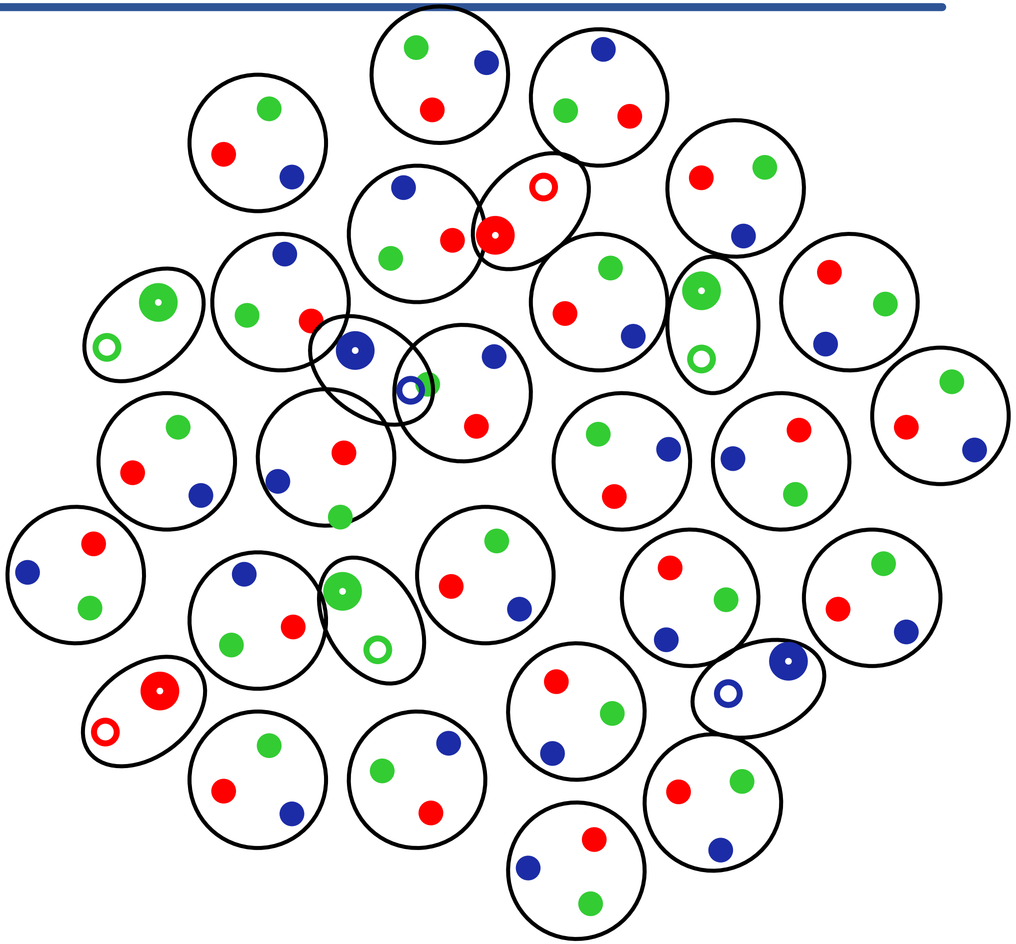
Remarkable agreement of QCD with the experiment

From confinement to deconfinement

1. heating 

2. compression 

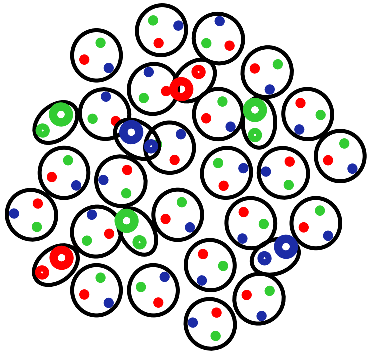
→ *deconfined color matter (quark-gluon plasma)*



Quark Gluon Plasma
deconfined!

Deconfinement transition from lattice QCD

$$\frac{\varepsilon}{T^4} \sim \#\,\text{of d.o.f.}$$



confined: few d.o.f.

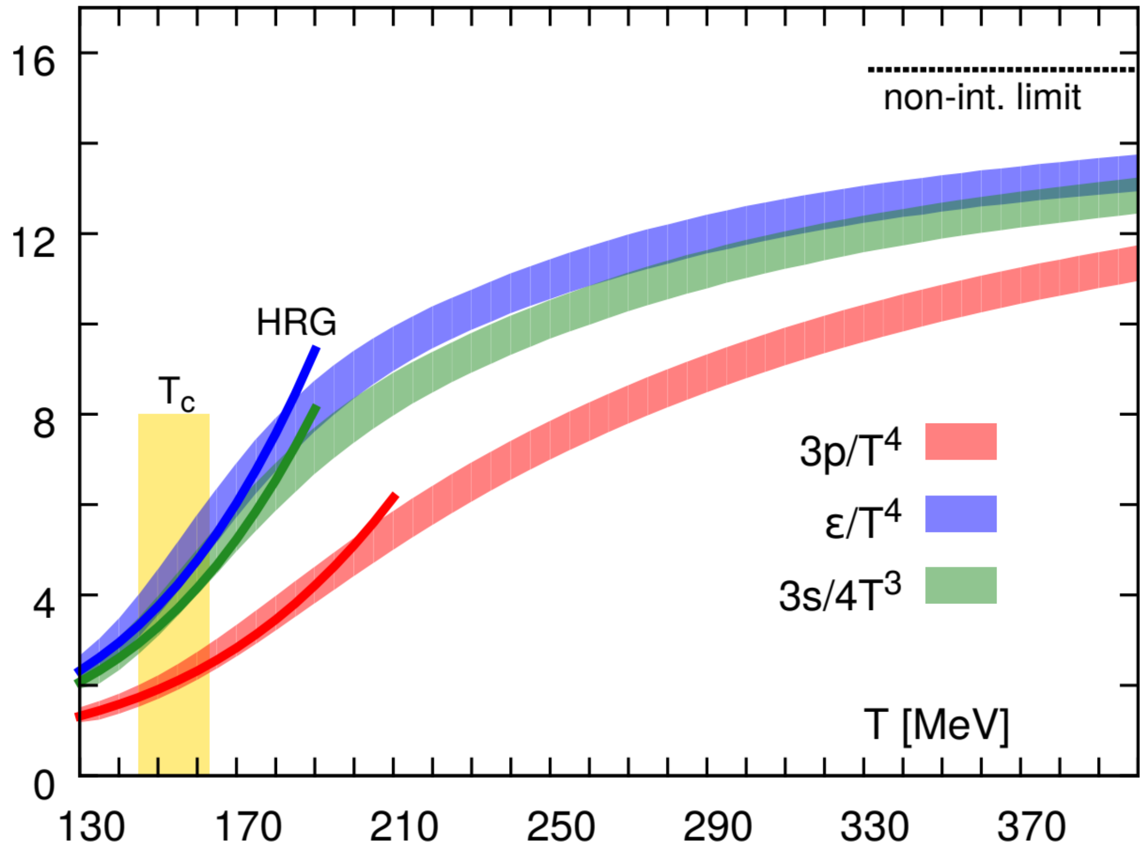
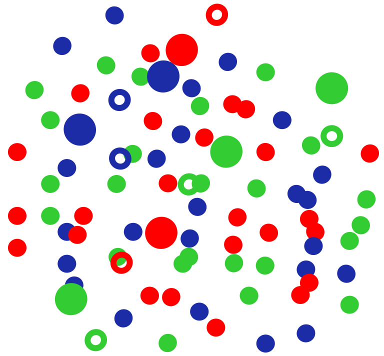


Figure from HotQCD coll., PRD '14

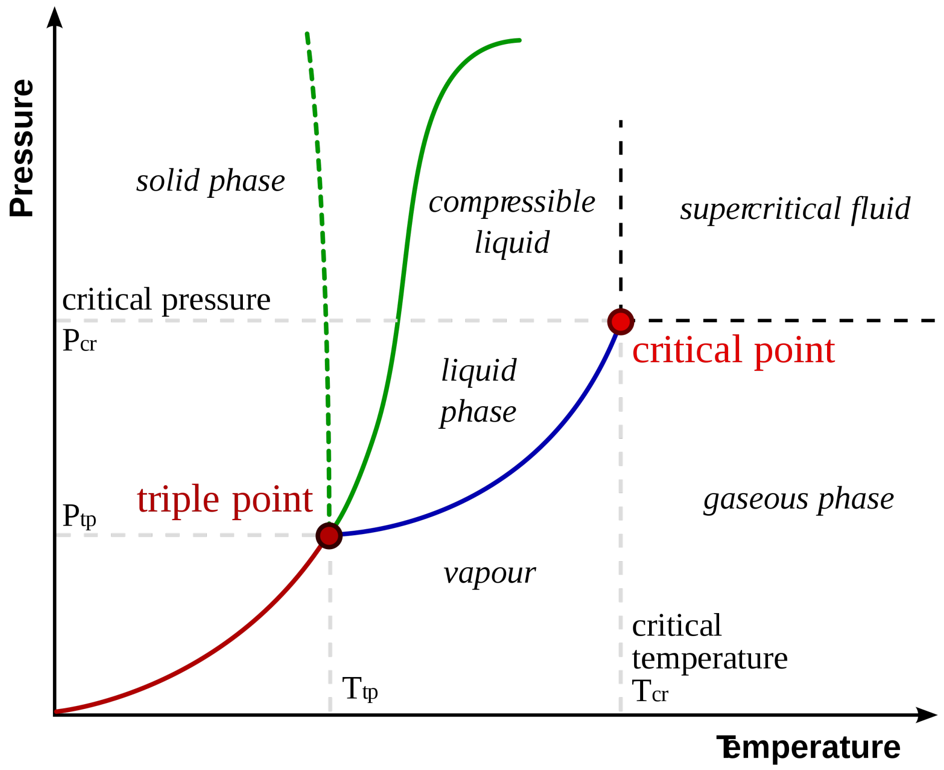


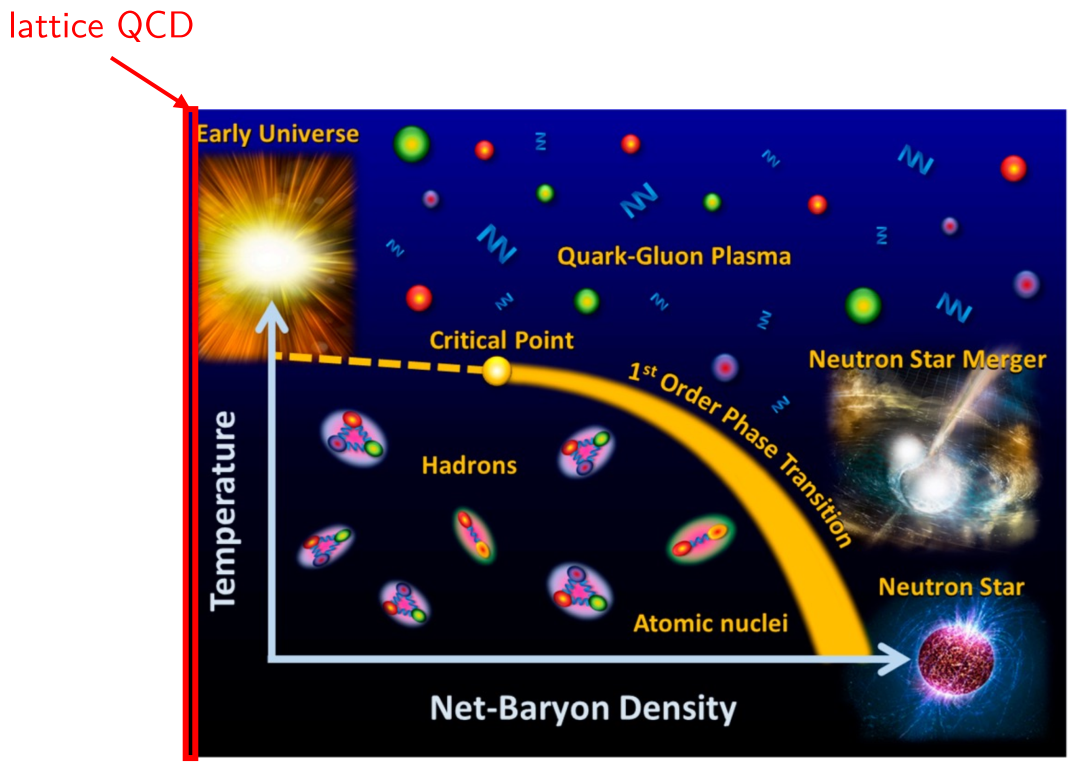
deconfined: many d.o.f

Crossover transition at $T_C \approx 155$ MeV $\approx 2{\cdot}10^{12}$ K $\approx 130{,}000{\cdot}$T [Sun's core]

[Y. Aoki et al., Nature 443, 675 (2006)]

QCD phase diagram

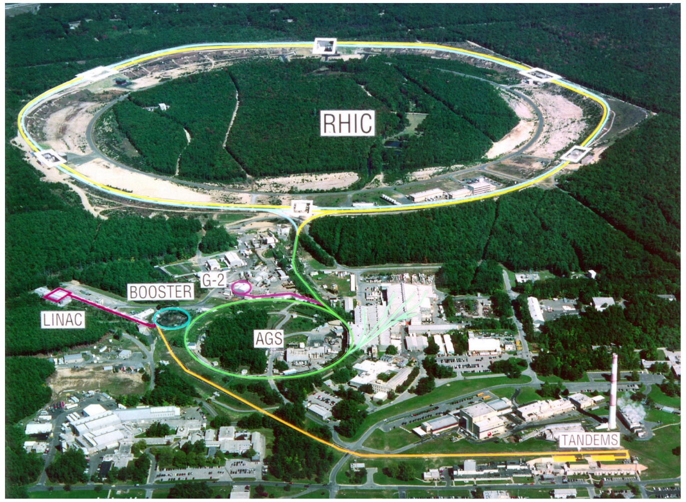




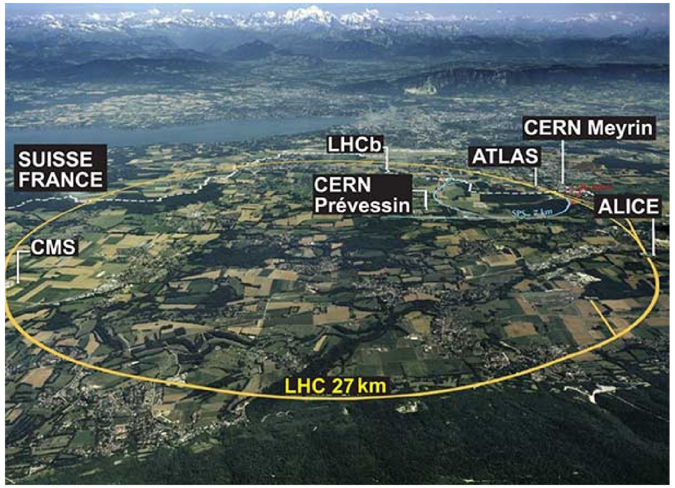
Excess of particles over antiparticles

- Finite baryon densities inaccessible due to the sign problem
- Possible existence of a phase transition is a conjecture
- Laboratory: **heavy-ion collisions** – test of QCD and a tool unveil its many properties

QCD laboratories (∼1980-...)



RHIC@BNL (2000-), 200 GeV, 99.995% speed of light



LHC@CERN (2010-), 5020 GeV, 99.9999991% speed of light

FAIR@GSI [2026(?)-], 5 GeV (less is more)


ALICE detector

Relativistic Heavy Ion Collider (RHIC)

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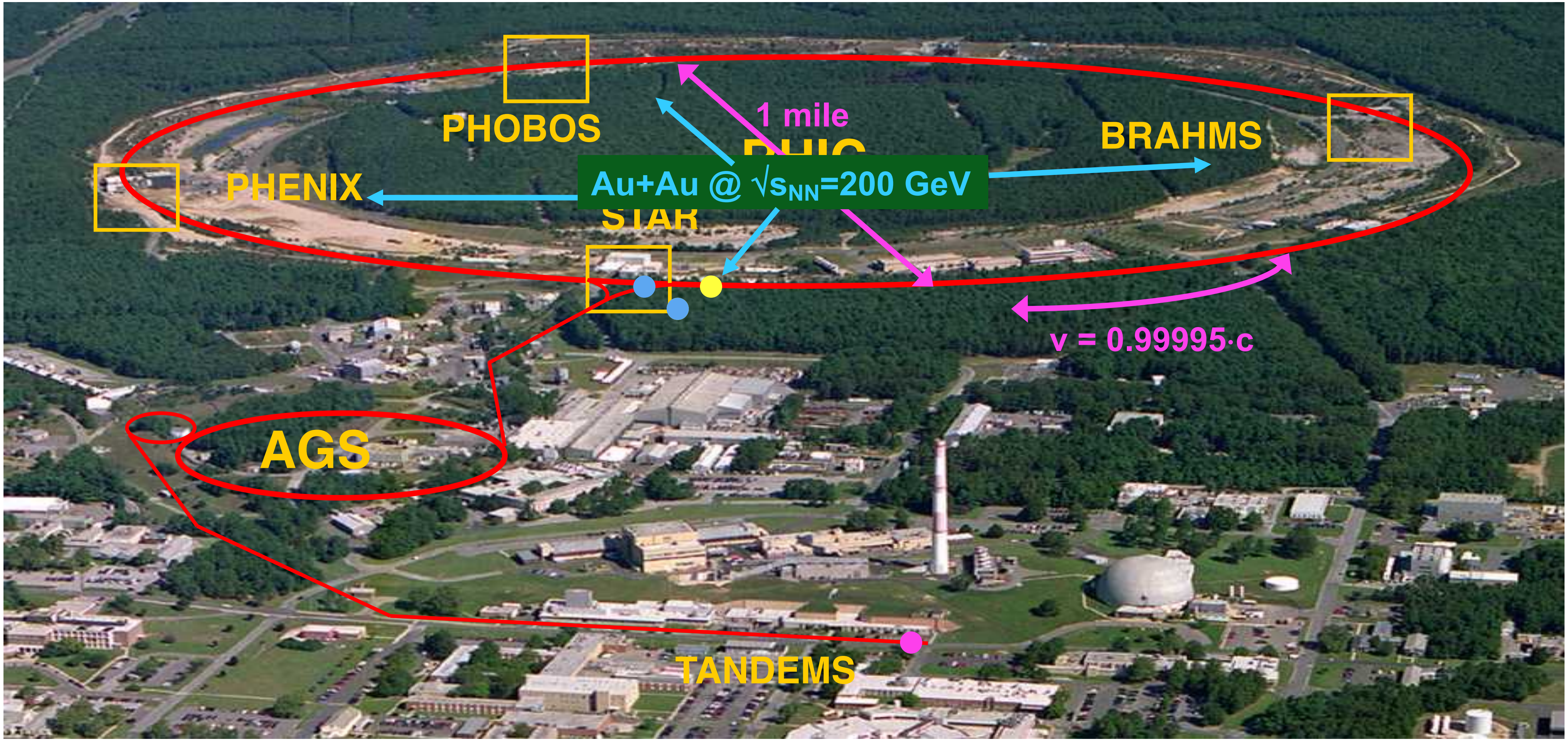
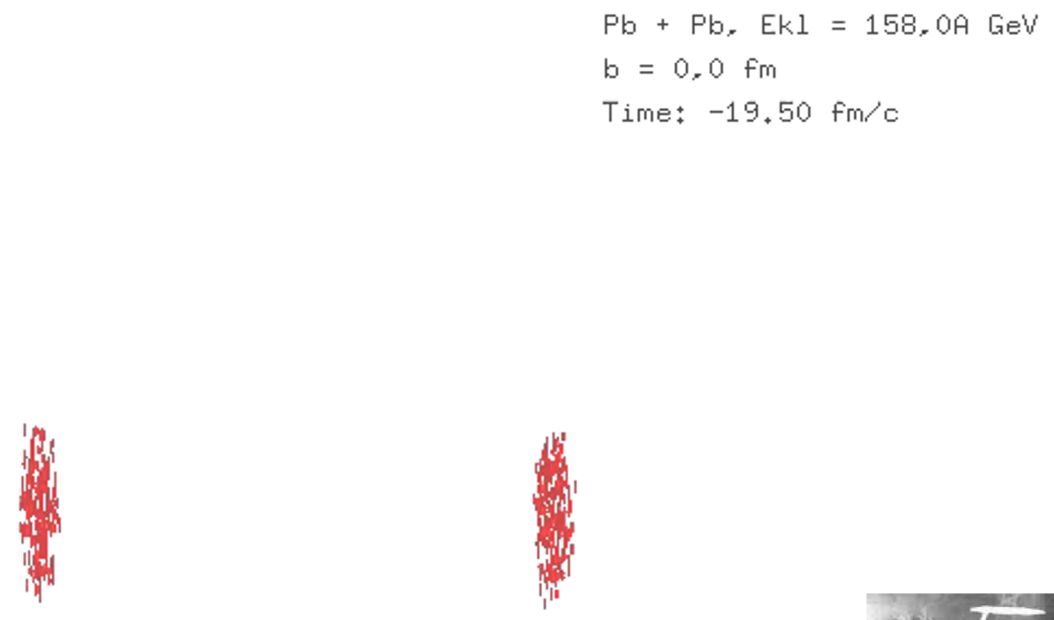
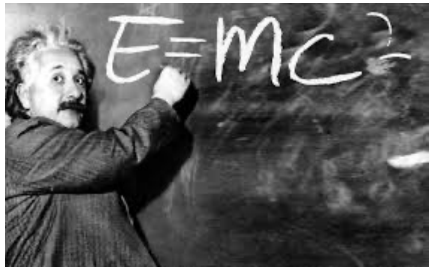


Relativistic heavy-ion collisions



UrQMD model simulation



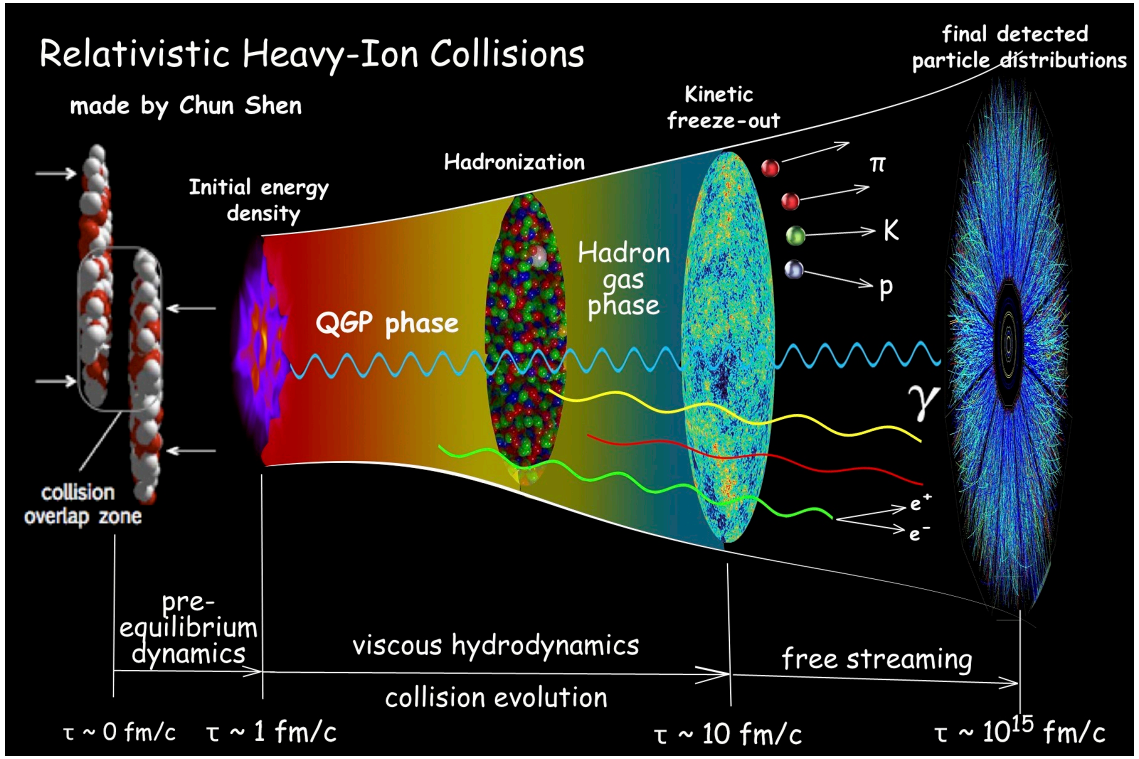
Relativistic collision energy leads to particle production

Length: 10^{-15} m

Time: 10^{-22} s

Temperature: 10^{12} K

Relativistic heavy-ion collisions – "Little Bangs"



Control parameters

- Collision energy $\sqrt{s_{NN}} = 2.4 - 5020$ GeV
- Size of the collision region

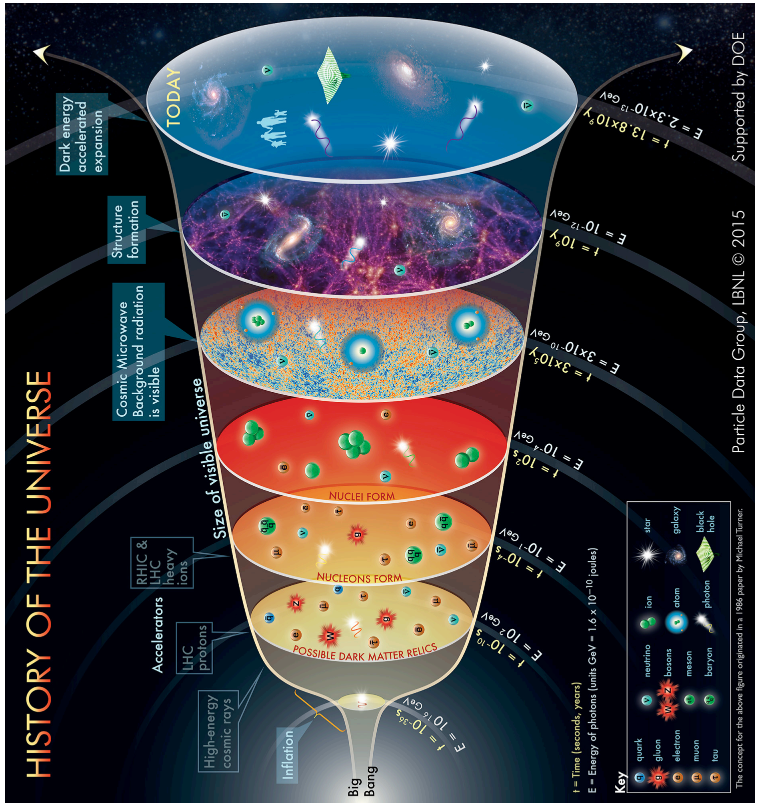
Measurements

- Final hadron abundances and momentum distributions

Big Bang vs Little Bang

Time

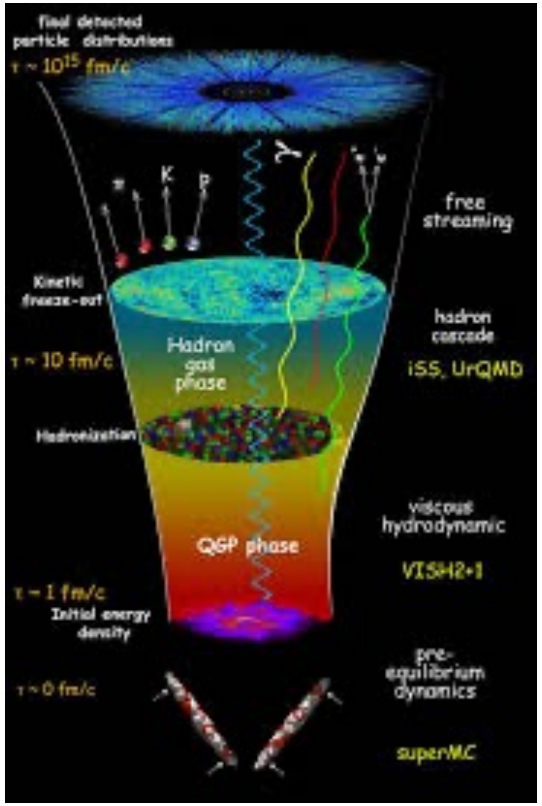
Big Bang



1 event

Slow expansion, long-lived

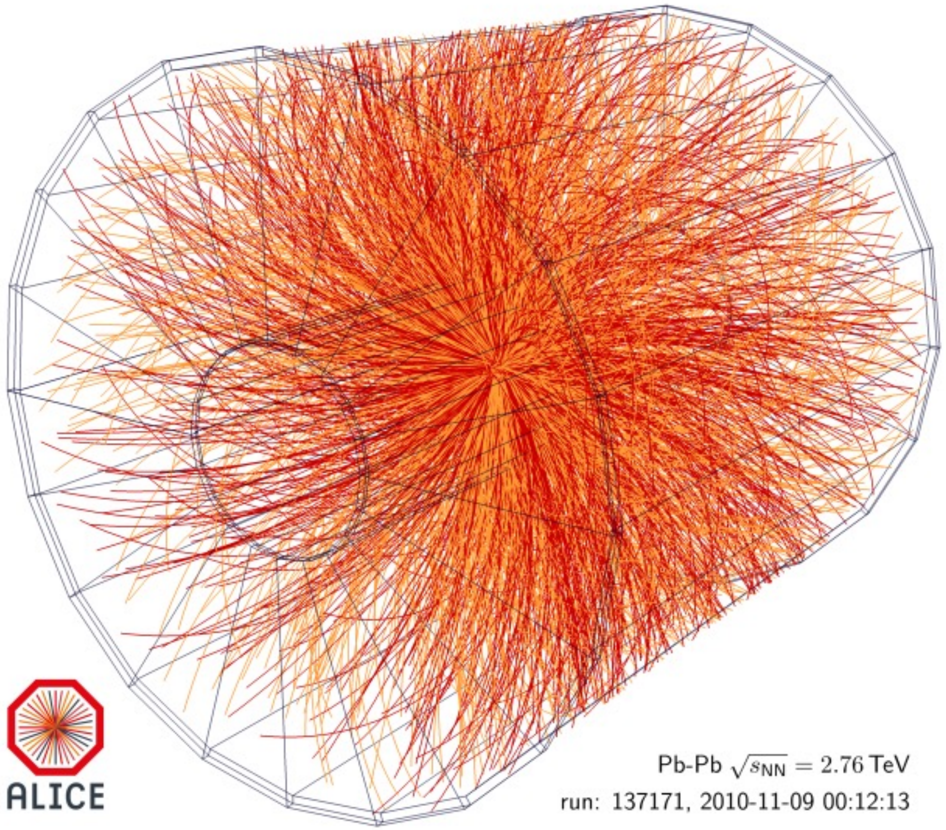
Heavy-Ion Collision



Millions of events

Rapid expansion, short-lived

Fireball in heavy-ion collisions



Event display of a Pb-Pb collision in ALICE at the LHC

Thousands of particles created in relativistic heavy-ion collisions

⬇

Apply concepts of statistical mechanics

Particle production in heavy-ion collisions

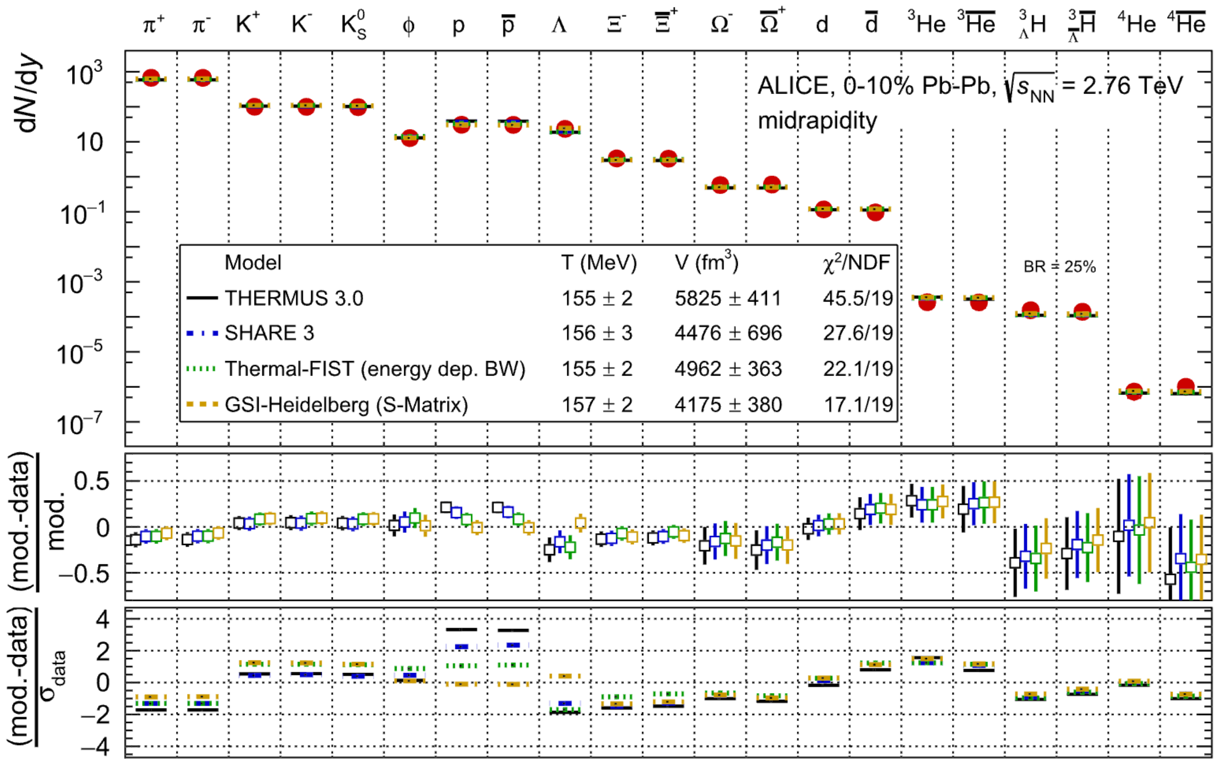
Ideal gas law (E. Clapeyron, 1834)

$$P_i V = N_i k_B T \quad (+\text{ feeddown})$$

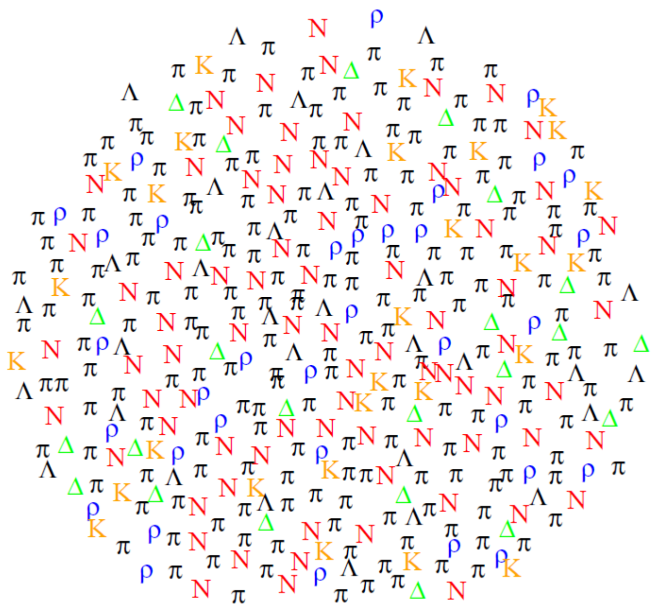
is the simplest model of particle production

$$N_i = \frac{d_i V}{2\pi^2} \int dk\, k^2 \left[1 \pm \exp\left(\frac{\sqrt{k^2 + m_i^2} - \mu_i}{T}\right)\right]^{-1}$$

Bose-Einstein & Fermi-Dirac, 1924-1926



ALICE Collaboration, EPJC 84, 813 (2024)



© J. Cleymans

Mapping heavy-ion collisions onto the QCD phase diagram

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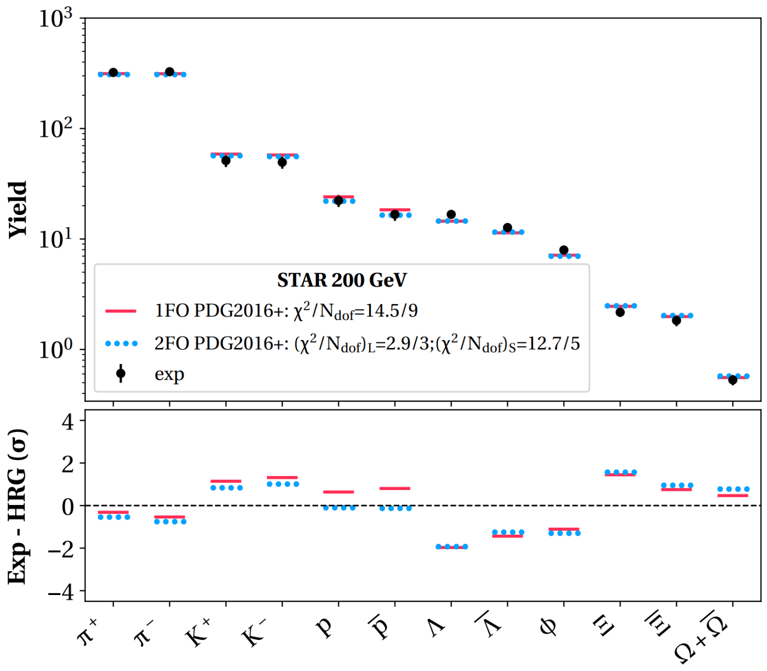
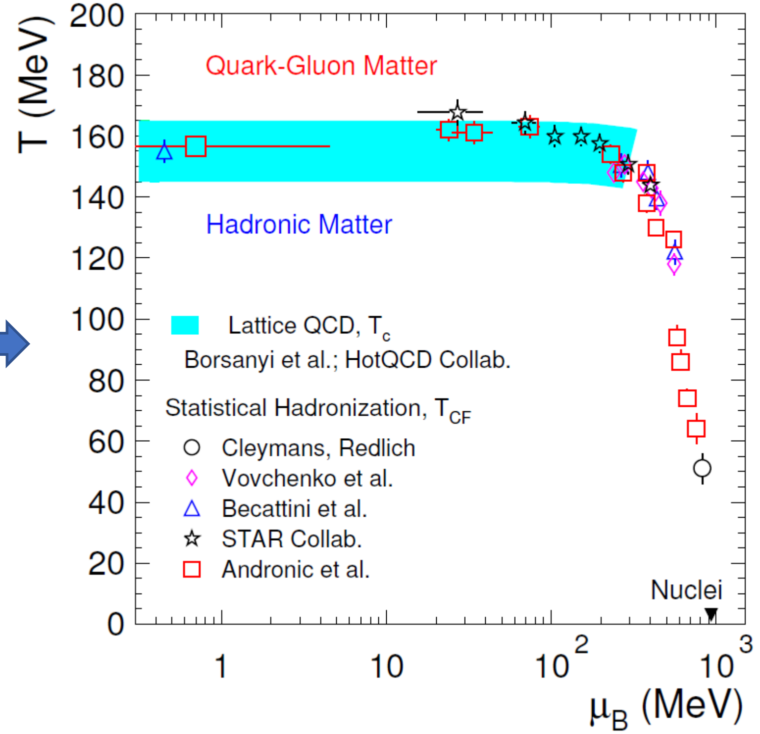
Fit hadron yields with the HRG model



P. Alba et al. (UH group), Phys. Rev. C 101, 054905 (2020)

$$T(\sqrt{s_{NN}})$$
$$\mu_B(\sqrt{s_{NN}})$$



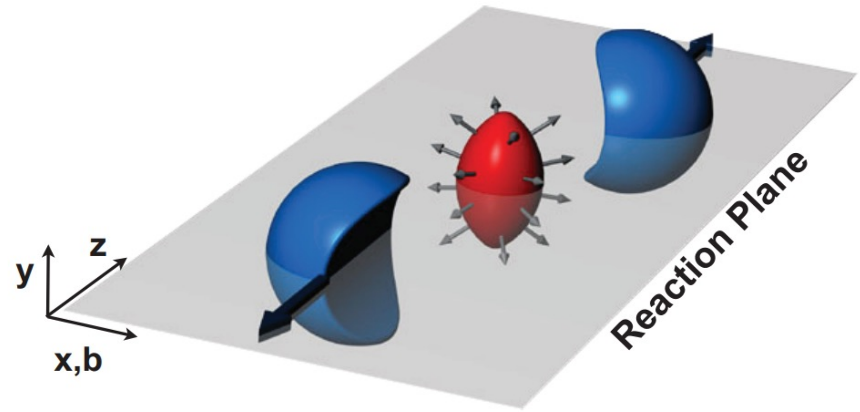
A. Andronic et al., Nature 561, 321 (2018)

$\sqrt{s_{NN}} \searrow$ $\longrightarrow$ $\mu_B \nearrow$

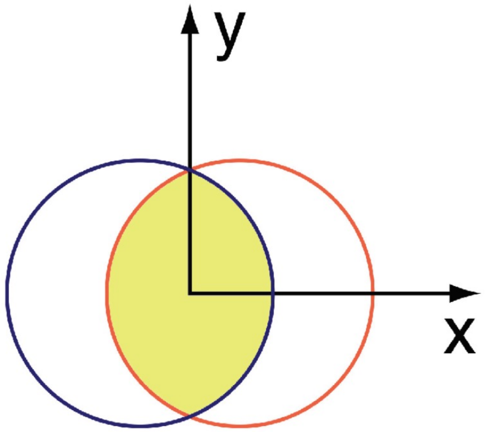
Heavy-ion freeze-out probes the QCD transition at zero and non-zero baryon density

Flow and hydrodynamics

$$\frac{dN}{d\Phi dp_t} = \frac{dN}{dp_t}\left(1 + v_1(p_t)\cos(\Phi) + 2v_2(p_t)\cos(2\Phi) + \ldots\right)$$



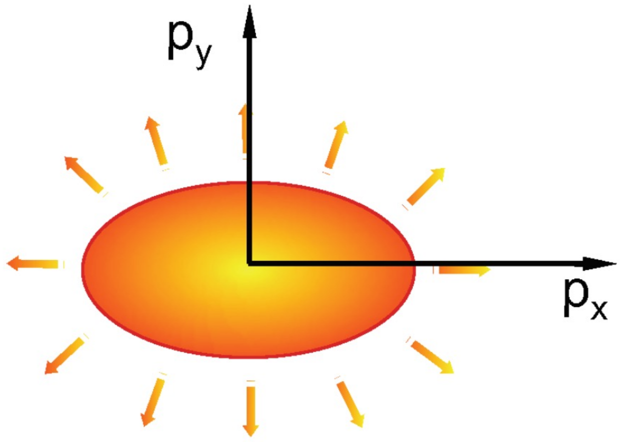
coordinate-space anisotropy



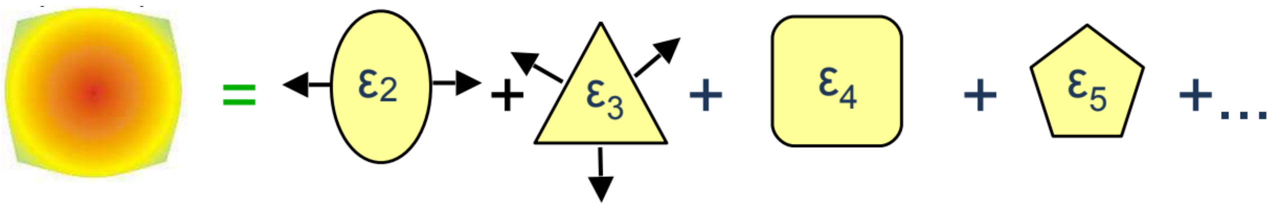
$\partial_\mu T^{\mu\nu} = 0$

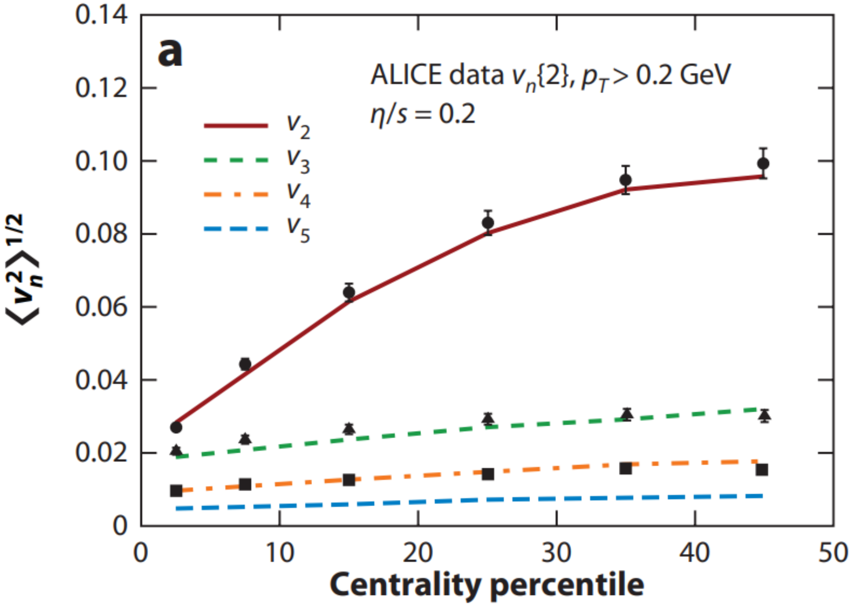
(relativistic) hydrodynamics

momentum-space anisotropy

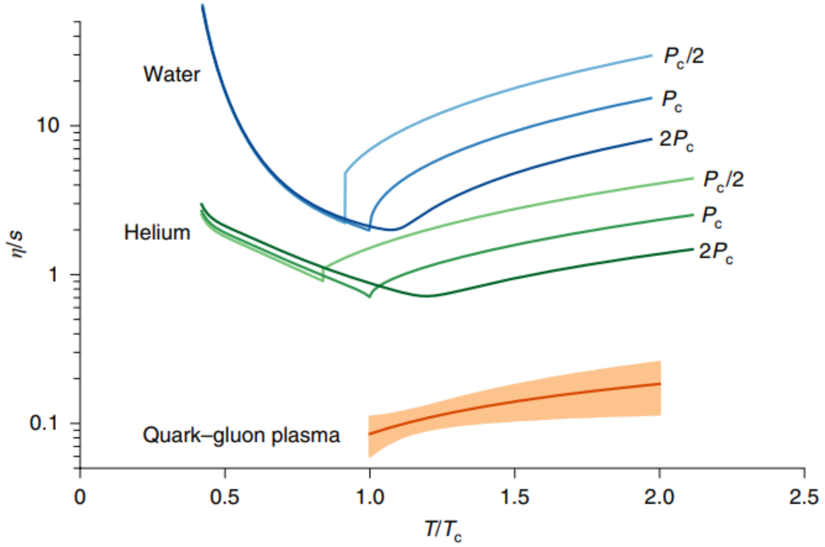


QGP is a fluid!

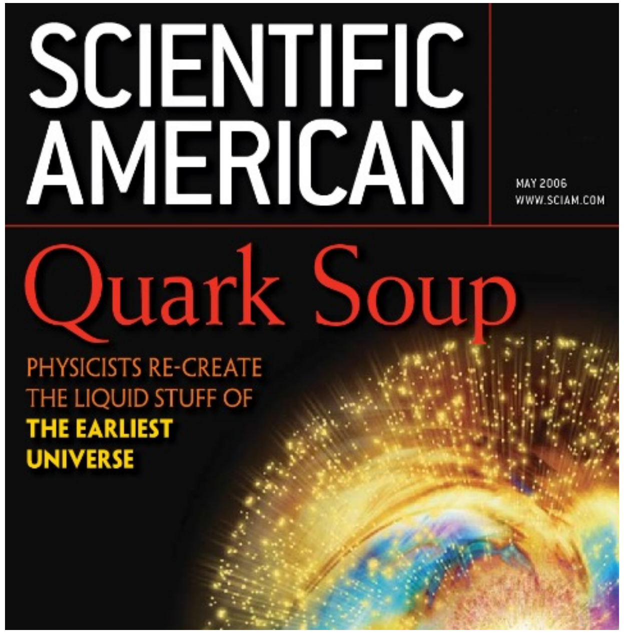




From ALICE Collaboration, Phys. Rev. Lett. 107, 032301 (2011)



From Bernhard, Moreland, Bass, Nature Physics 15, 1113 (2019)



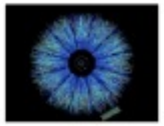
Shear viscosity over entropy of QGP: $\eta/s \leq 0.25$ – a near 'perfect' fluid

The early universe behaves like a perfect liquid rather than a gas or plasma

QGP is the hottest and most vortical fluid created on Earth

	The Earths magnetic field	0.6 Gauss
	A common, hand-held magnet	100 Gauss
	The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
	The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
	Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
	Surface field of Magnetars	10^{15} Gauss

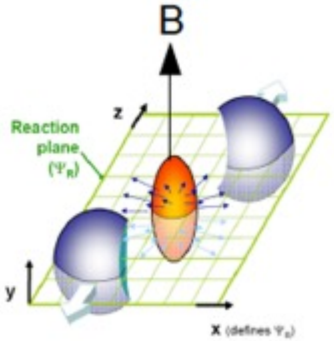
http://solomon.as.utexas.edu/~duncan/magnetar.html

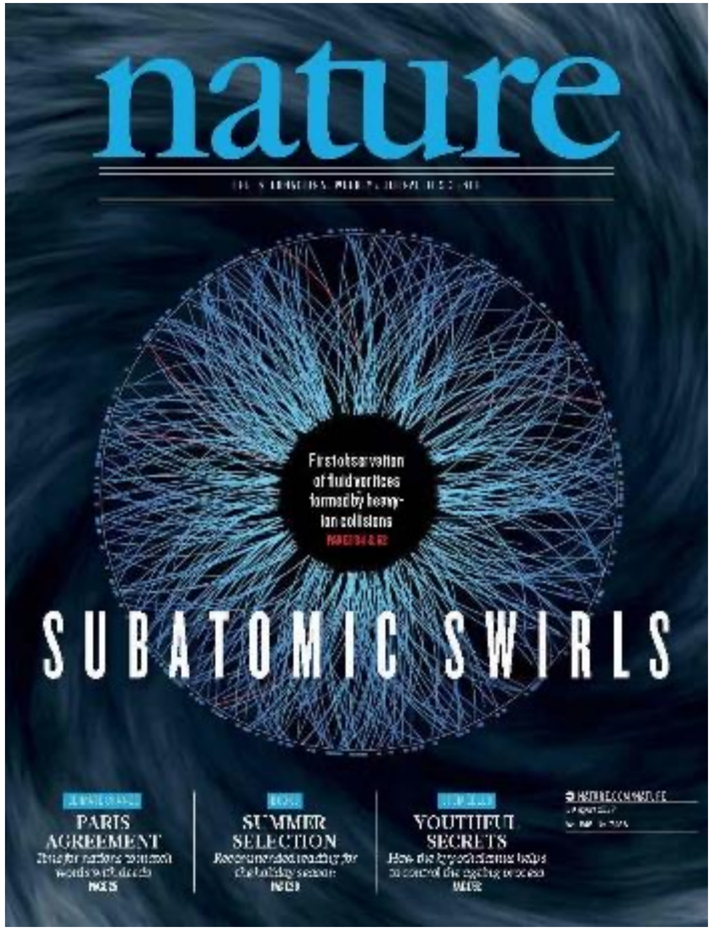


Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$eB(\tau=0) \sim 10^{19}$ Gauss



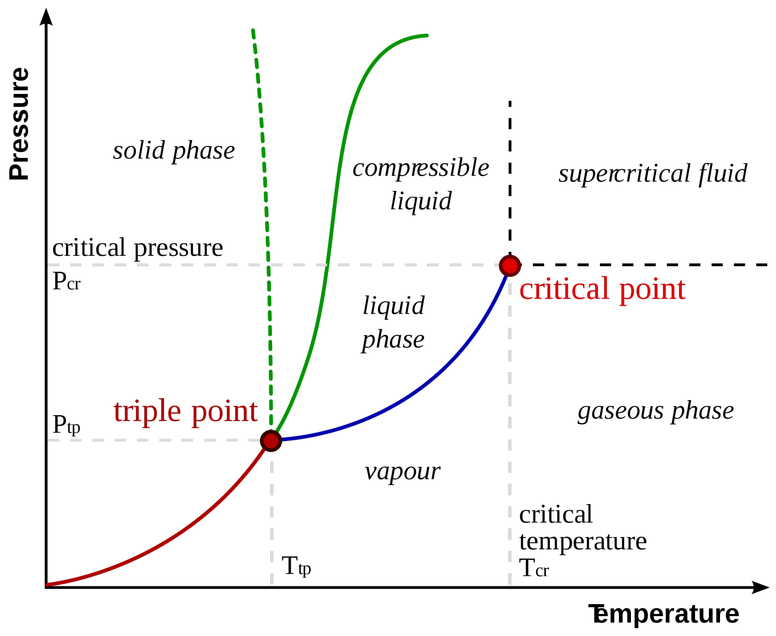


The challenge of discovering the QCD critical point

Disclaimer: This is my area of active research

QCD critical point

Ordinary fluid (e.g. water)



QCD

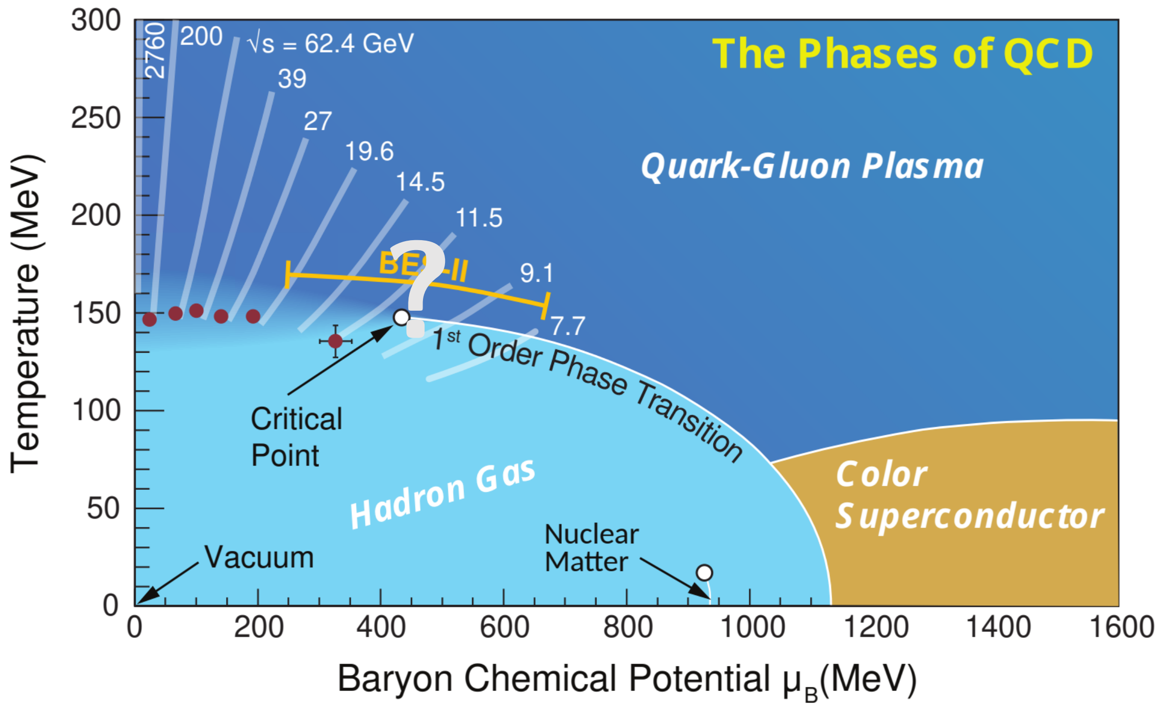


Figure from Bzdak et al., Phys. Rept. '20 and 2015 Nuclear Long Range Plan

What is the nature of the quark-hadron transition at finite baryon density?

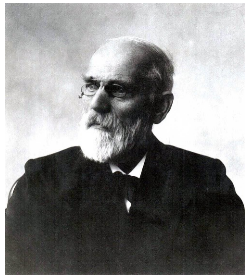
Is there a QCD phase transition and ***critical point****? Where?*

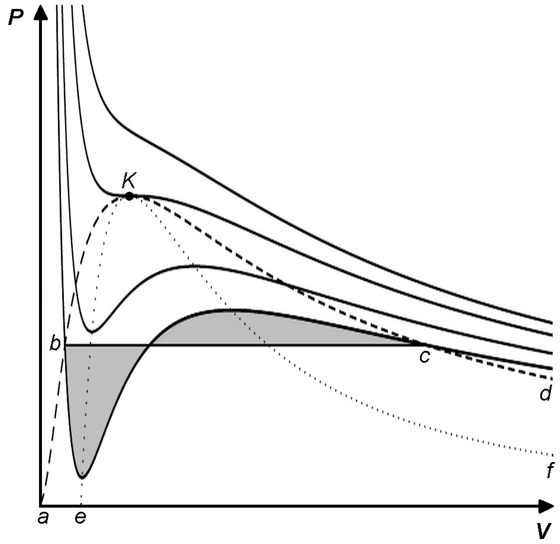
Lattice QCD: sign problem prevents simulations at non-zero baryon density

Heavy-ion collisions: access finite density but might be too short-lived to observe a signal

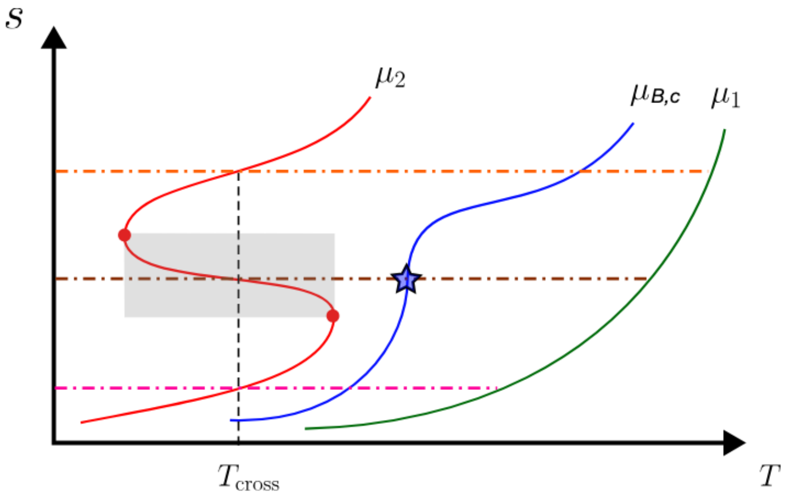
Extrapolating critical point from lattice

van der Waals (1873)





change the variables



Critical Point:

$$\left(\frac{\partial P}{\partial \rho_B}\right)_T = 0, \qquad \left(\frac{\partial^2 P}{\partial \rho_B^2}\right)_T = 0.$$

$$\left(\frac{\partial T}{\partial s}\right)_{\mu_B} = 0, \qquad \left(\frac{\partial^2 T}{\partial s^2}\right)_{\mu_B} = 0.$$

Extrapolate from $\mu_B = 0$!

Looking for entropy crossings

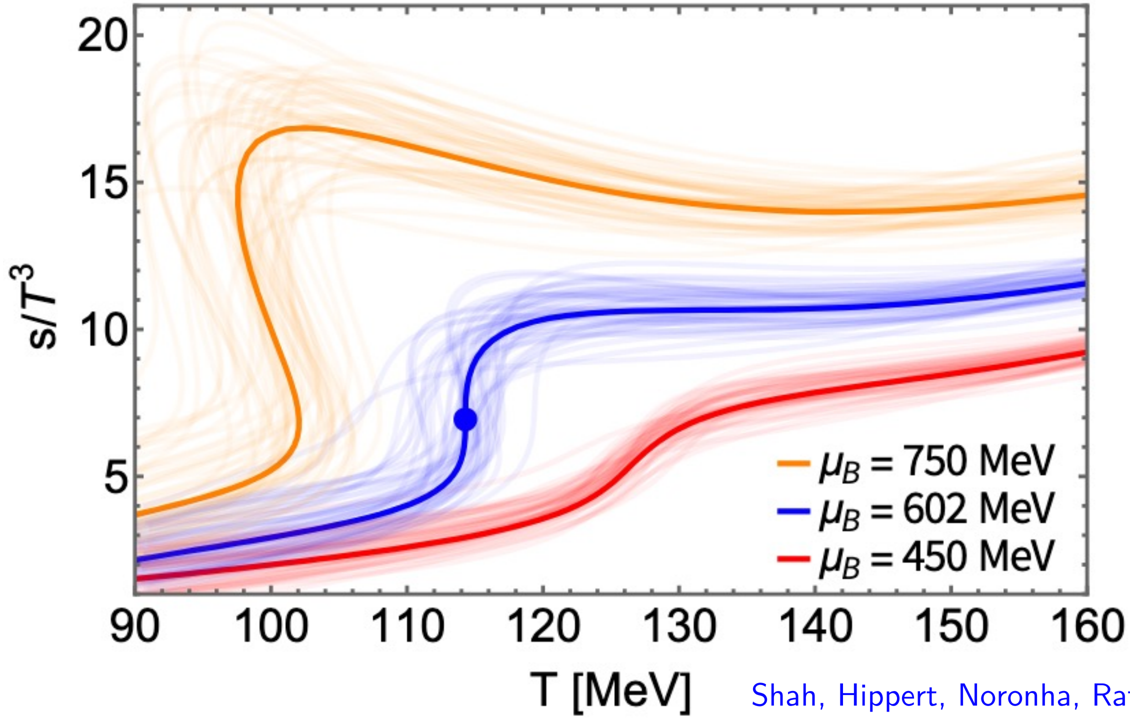
- Critical point ruled out (2σ level) at $\mu_B <$ 400 MeV

Borsanyi et al., arXiv:2502.10267

- Try going further

Expansion around $\mu_B = 0$

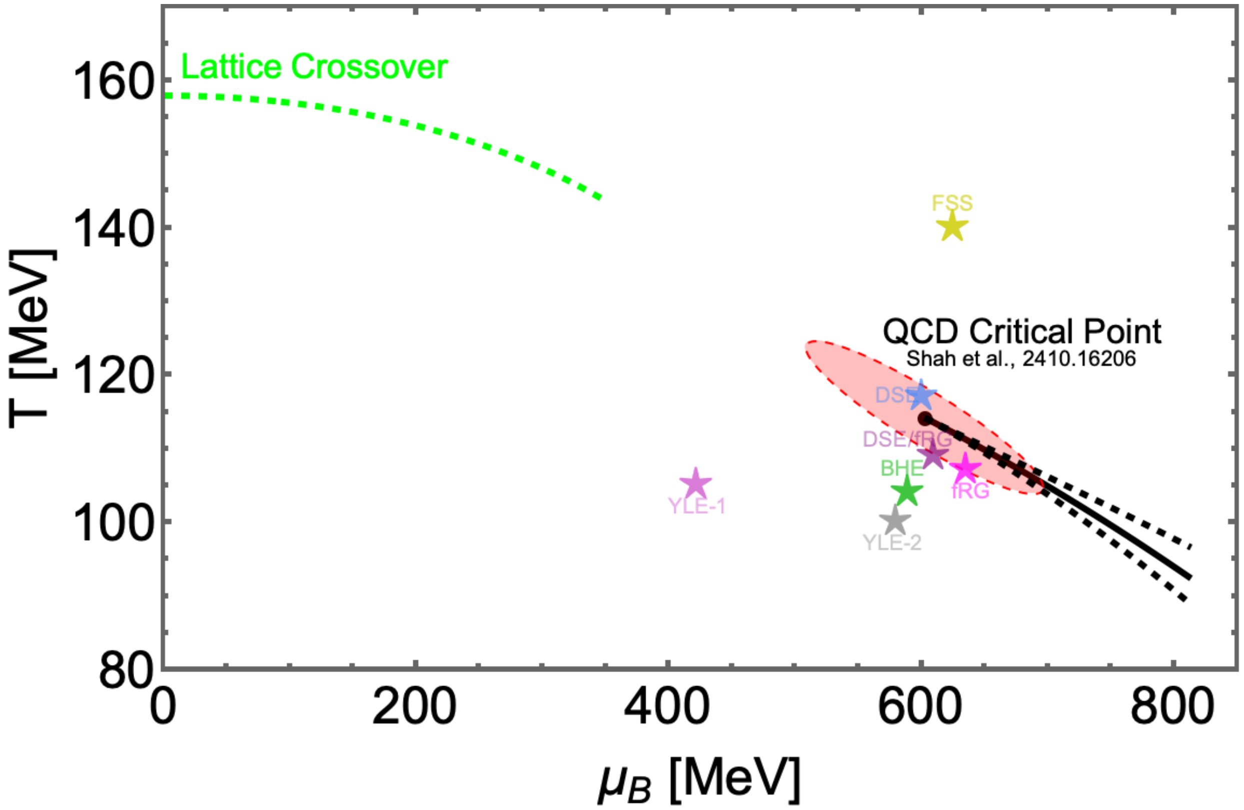
$$T_s(\mu_B; T_0) = T_0 + \alpha_2(T_0)\frac{\mu_B^2}{2}$$



Shah, Hippert, Noronha, Ratti, VV, arXiv:2410.16026

- First-order phase transition emerges at $\mu_B >$ 600 MeV

QCD critical point estimates



Critical point estimate at $O(\mu_B^2)$:

$T_c = 114 \pm 7$ MeV, $\mu_B = 602 \pm 62$ MeV

Estimates from recent literature:

YLE-1: D.A. Clarke et al. (Bielefeld-Parma), arXiv:2405.10196

YLE-2: G. Basar, PRC 110, 015203 (2024)

BHE: M. Hippert et al., arXiv:2309.00579

fRG: W-J. Fu et al., PRD 101, 054032 (2020)

DSE/fRG: Gao, Pawlowski., PLB 820, 136584 (2021)

DSE: P.J. Gunkel et al., PRD 104, 052022 (2021)

FSS: A. Sorensen et al., arXiv:2405.10278

Optimist's view: Different estimates converge onto the same region because QCD CP is likely there

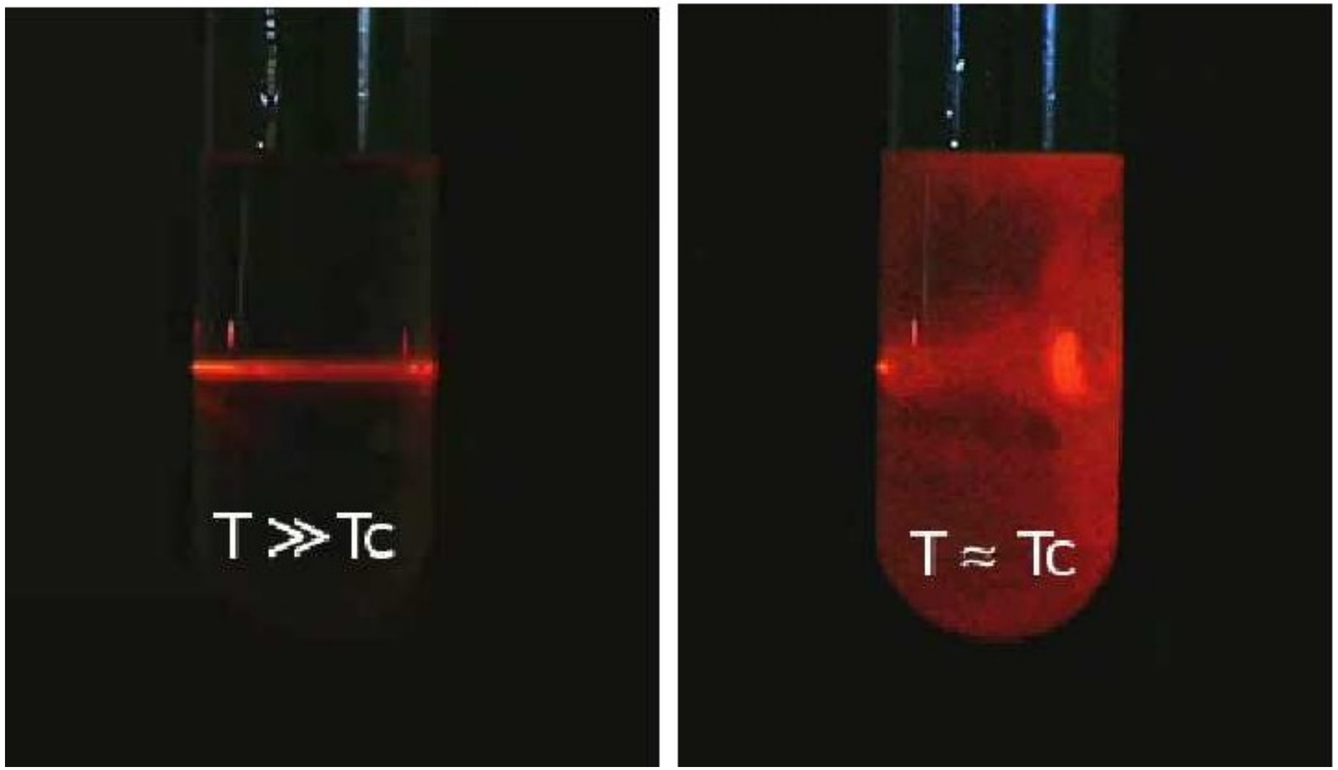
Pessimist's view: Different estimates converge onto the same region because it's the closest not yet ruled out by LQCD

Can be tested in laboratory with **heavy-ion collisions**

Critical point and fluctuations

Density fluctuations at macroscopic length scales

Critical opalescence



Unfortunately, we cannot do this in heavy-ion collisions

Event-by-event fluctuations and statistical mechanics

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Consider a fluctuating number N

Cumulants: $G_N(t) = \ln\langle e^{tN}\rangle = \sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!}$

variance $\kappa_2 = \langle(\Delta N)^2\rangle = \sigma^2$  width

skewness $\kappa_3 = \langle(\Delta N)^3\rangle$  asymmetry

kurtosis $\kappa_4 = \langle(\Delta N)^4\rangle - 3\langle(\Delta N^2)\rangle^2$  peak shape

Experiment:

$$P(N) \sim \frac{N_{events}(N)}{N_{events}^{total}}$$

Statistical mechanics:

Grand partition function

$$\ln Z^{\text{gce}}(T, V, \mu) = \ln\left[\sum_N e^{\mu N} Z^{\text{ce}}(T, V, N)\right],$$

$$\boxed{\kappa_n \propto \frac{\partial^n(\ln Z^{\text{gce}})}{\partial(\mu_N)^n}}$$

Cumulants measure chemical potential derivatives of the (QCD) equation of state

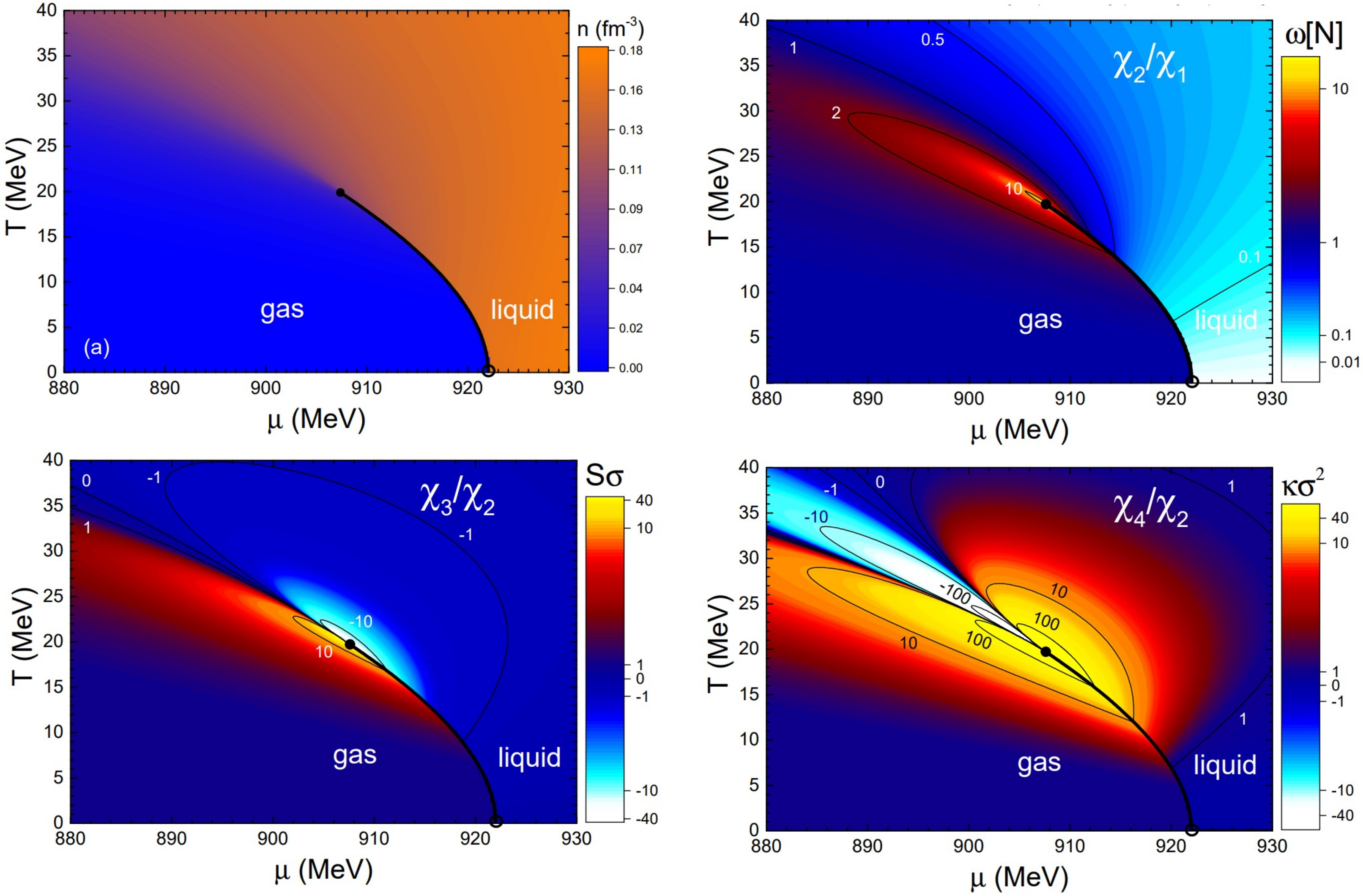
Example: (Nuclear) Liquid-gas transition

- **(QCD) critical point:** large correlation length and fluctuations

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

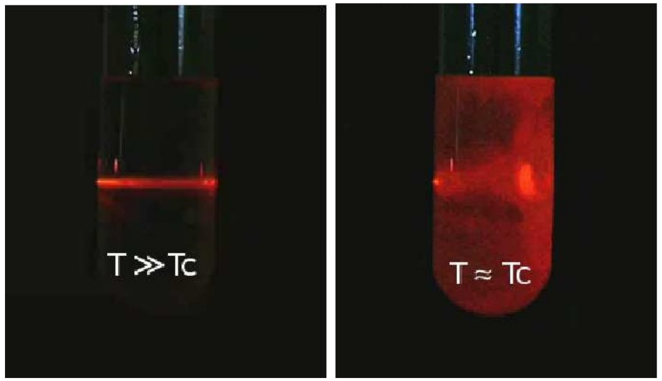
$$\xi \to \infty$$

M. Stephanov, PRL '09, '11



VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

Critical opalescence



$$\langle N^2 \rangle - \langle N \rangle^2 \sim \langle N \rangle \sim 10^{23}$$

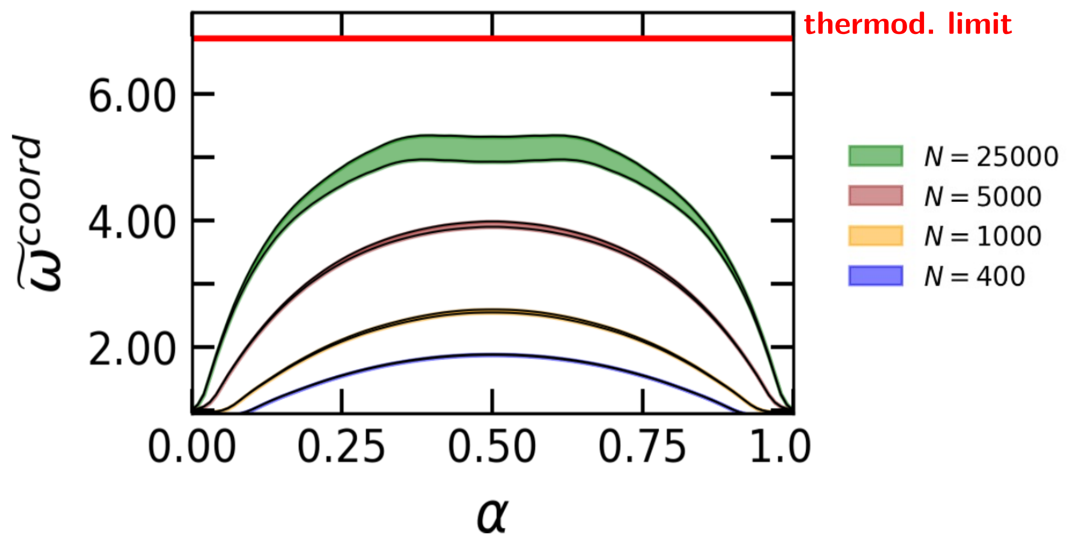
in equilibrium

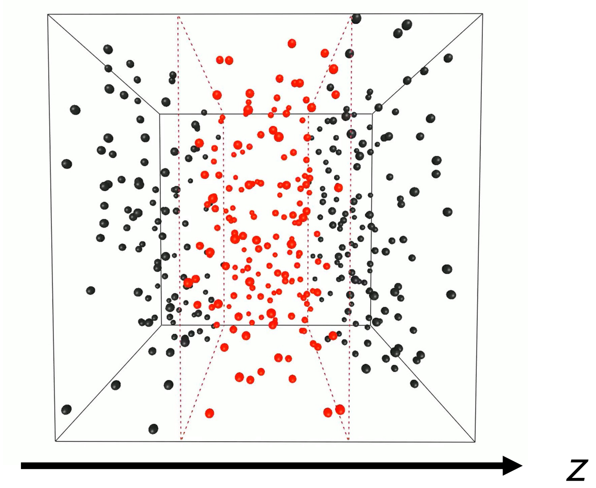
Example: Critical fluctuations in microscopic simulation

V. Kuznietsov (grad student UH) et al., Phys. Rev. C 105, 044903 (2022)

Instead of observing system macroscopically, track each single particle

Classical molecular dynamics simulations of the **Lennard-Jones fluid** near critical point ($T \approx 1.06 T_c$, $n \approx n_c$) of the liquid-gas transition

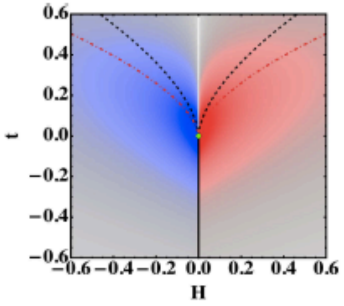


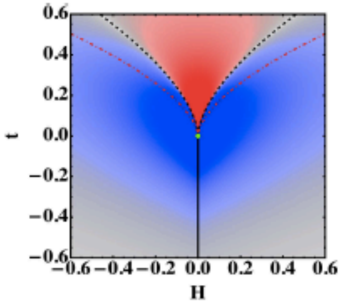


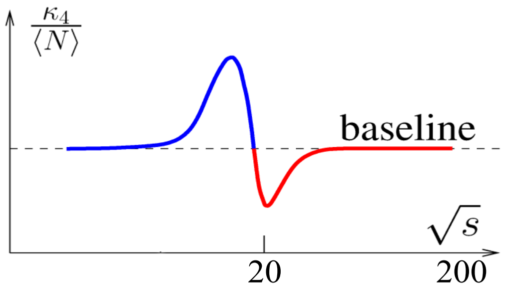
Large fluctuations survive despite strong finite-size effects and are large as advertised near the critical point

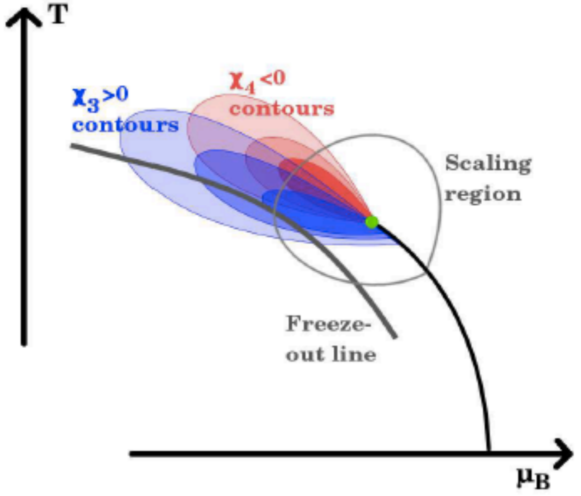
Equilibrium Expectations and Beam Energy Scan

Expectation from Calculations







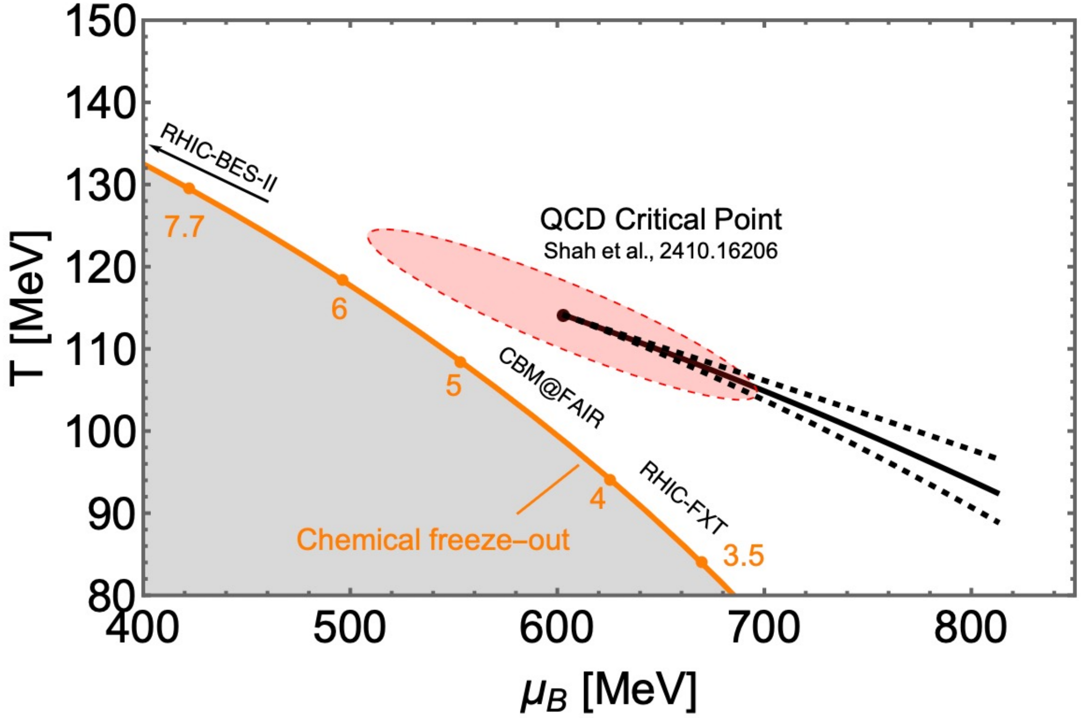


N. Xu, CPOD 2016

Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

Compare recent CP estimates and the freeze-out curve



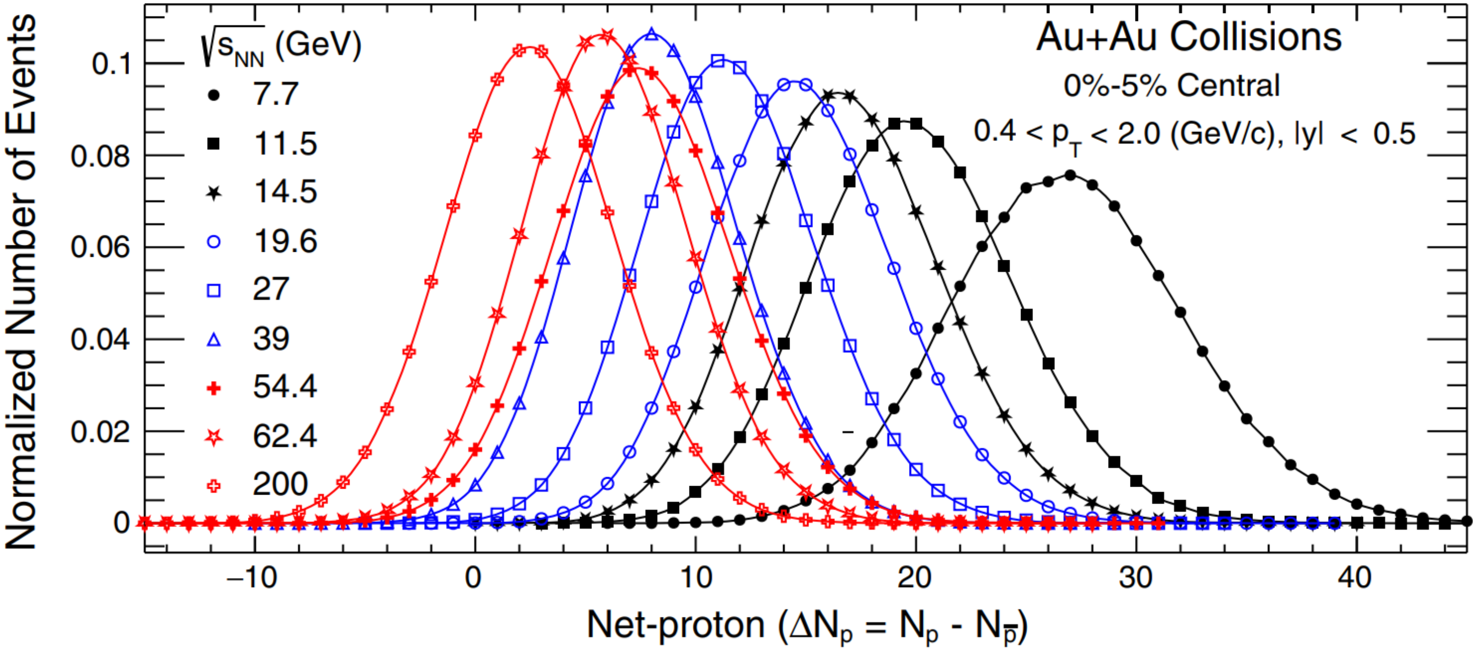
One of primary motivations for beam energy scan (BES) programs at RHIC BES-I (7.7-200 GeV) and BES-II (3-4.5 & 7.7-39 GeV)

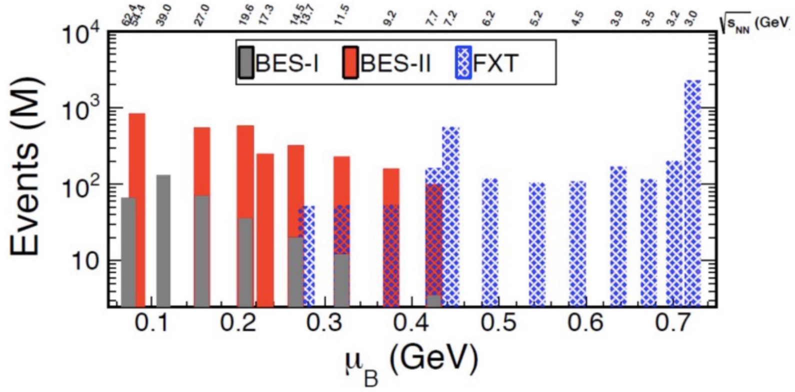
Measuring cumulants in heavy-ion collisions

Count the number of events with given number of e.g. (net) protons

$$P(\Delta N_p) \sim \frac{N_{\text{events}}(\Delta N_p)}{N^{total}_{events}}$$

STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)





Statistics-hungry observables

Cumulants are extensive, $\kappa_n \sim V$, use ratios to cancel out the volume

$$\frac{\kappa_2}{\langle N \rangle}, \qquad \frac{\kappa_3}{\kappa_2}, \qquad \frac{\kappa_4}{\kappa_2}$$

Look for subtle critical point signals

Theory vs experiment

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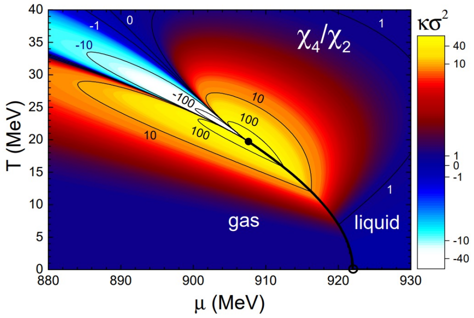
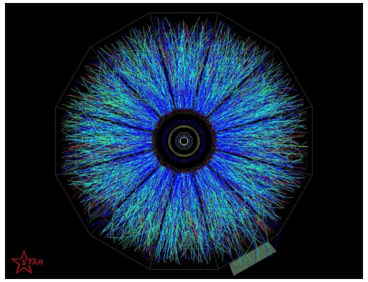
guidance from theory



experiment (the real thing)



Comparing theory and experiment should be done very carefully

Some effects that are unrelated to the CP may masquerade the signal

On the other hand, due to rapid expansion of the fireball the actual critical point signal may be very subtle

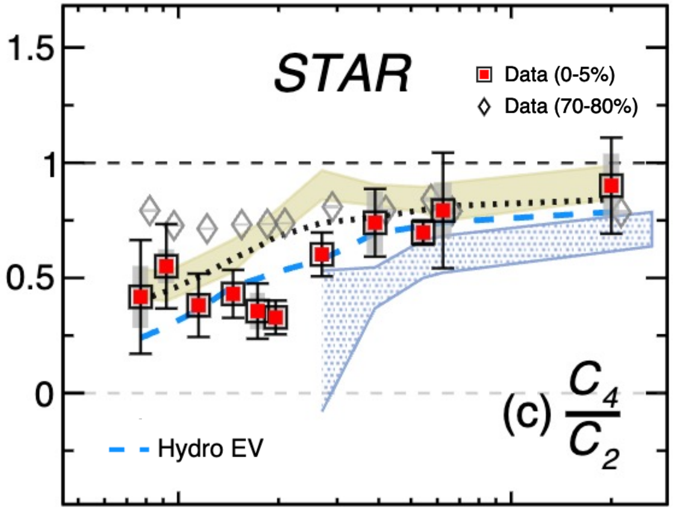
hydro simulation

critical slowing down

canonical effects

kinematic cuts

hadronic phase



track reconstruction

event selection

efficiency correction

CBWC

purity

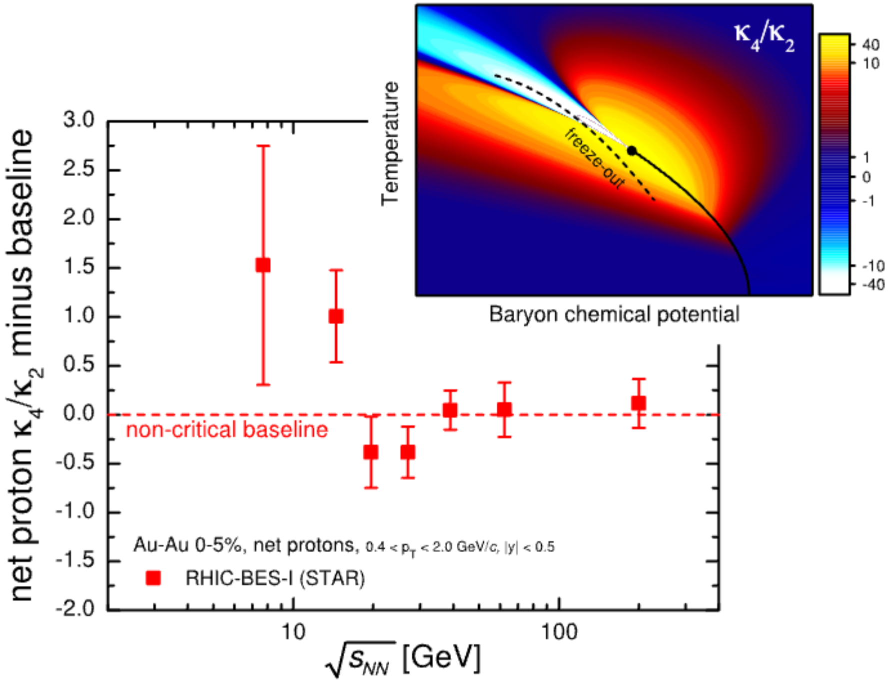
Hints from RHIC-BES-I

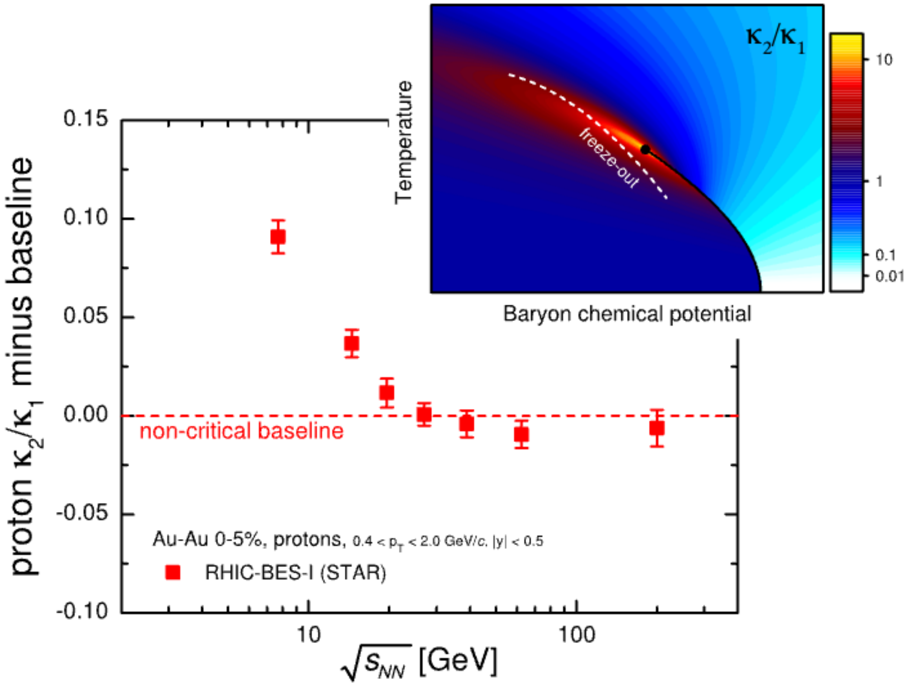
Quantitative calculations of critical fluctuations are still not available

State-of-the-art non-critical baseline computed using hydrodynamics

VV, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)

Subtract it from the data and look for a possible signal of CP

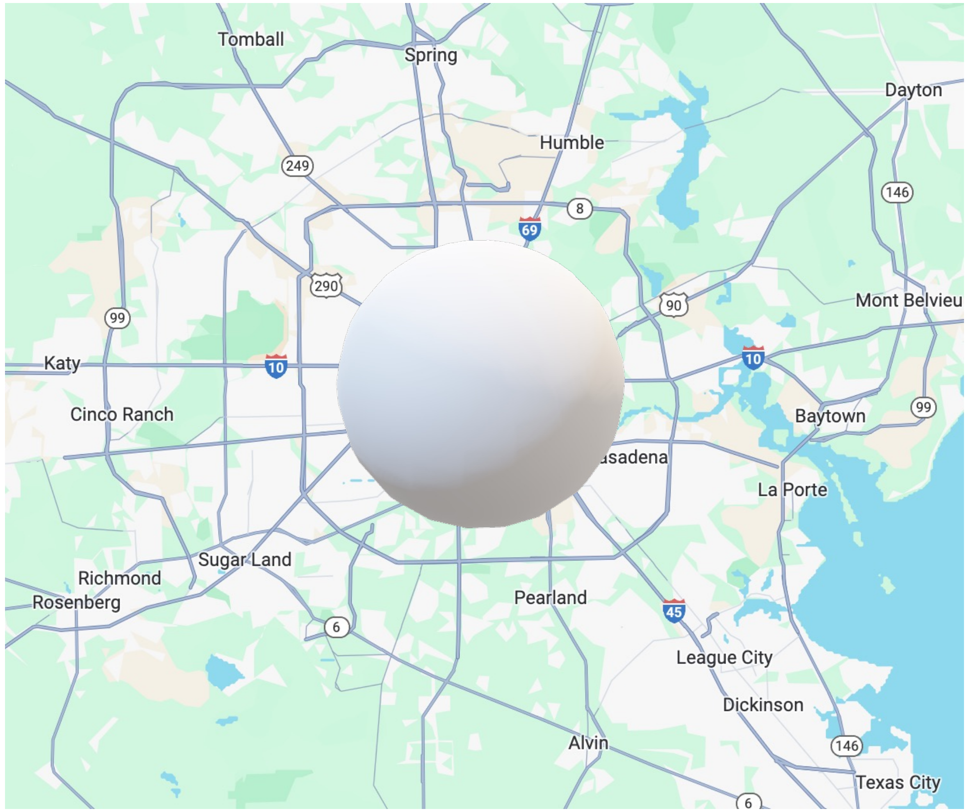


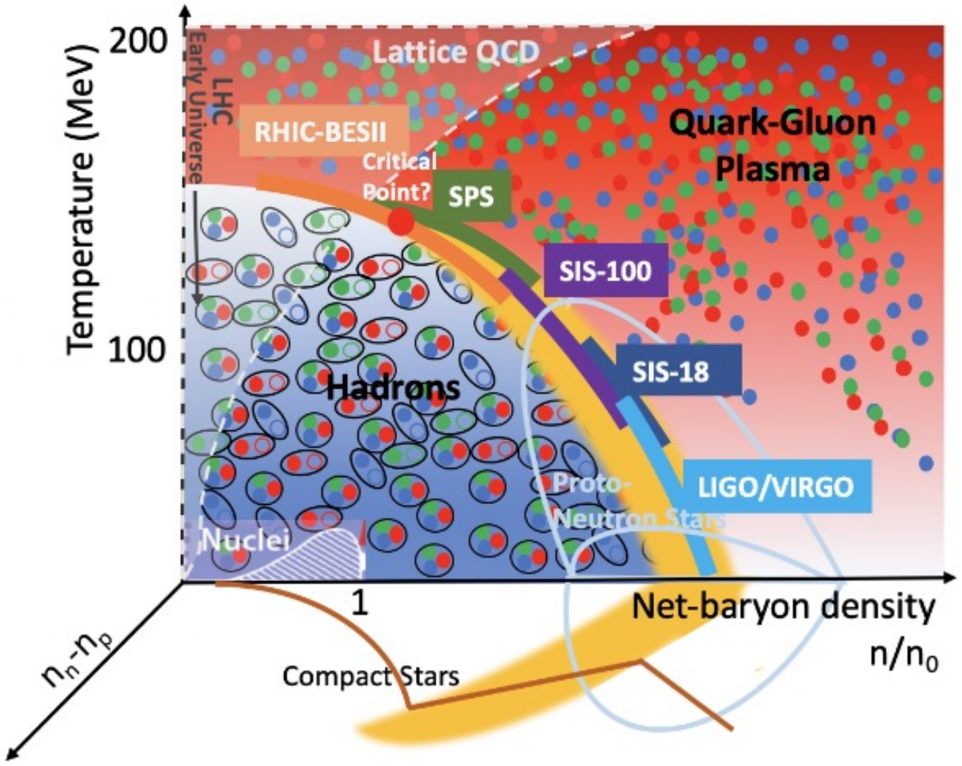


Analysis of RHIC-BES-II data in progress

QCD in astrophysics

Neutron stars are extremely compact objects (1-2 solar masses confined to an 8-mile sphere)

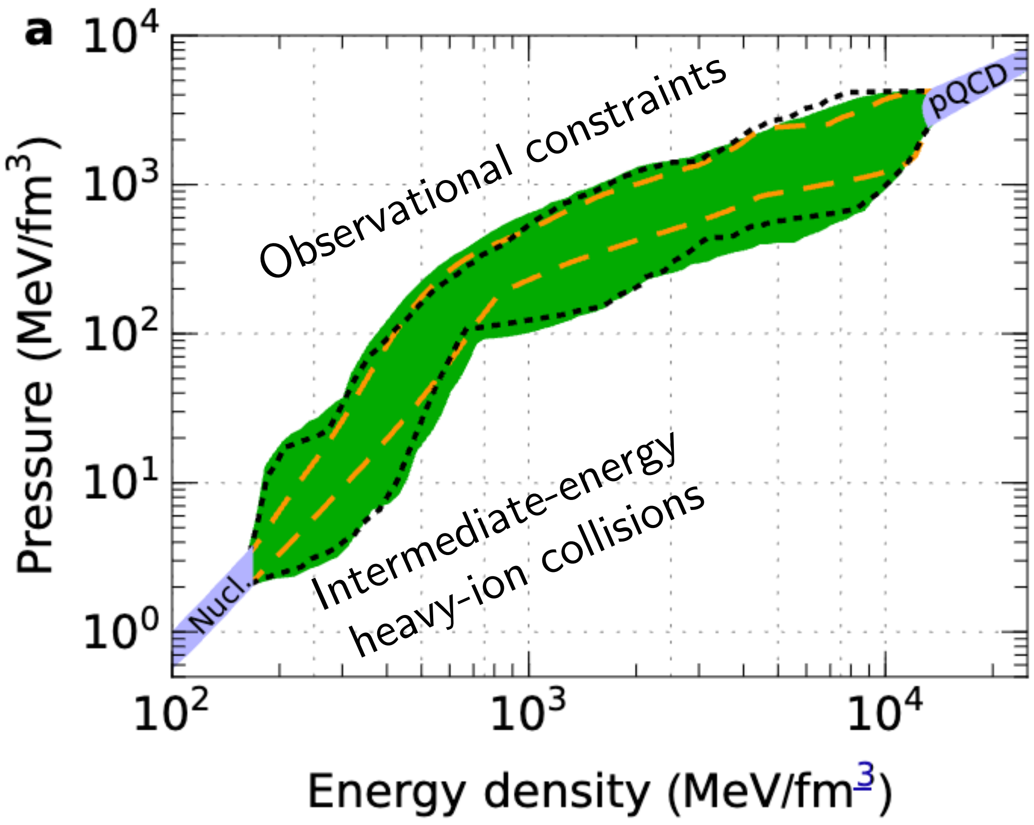


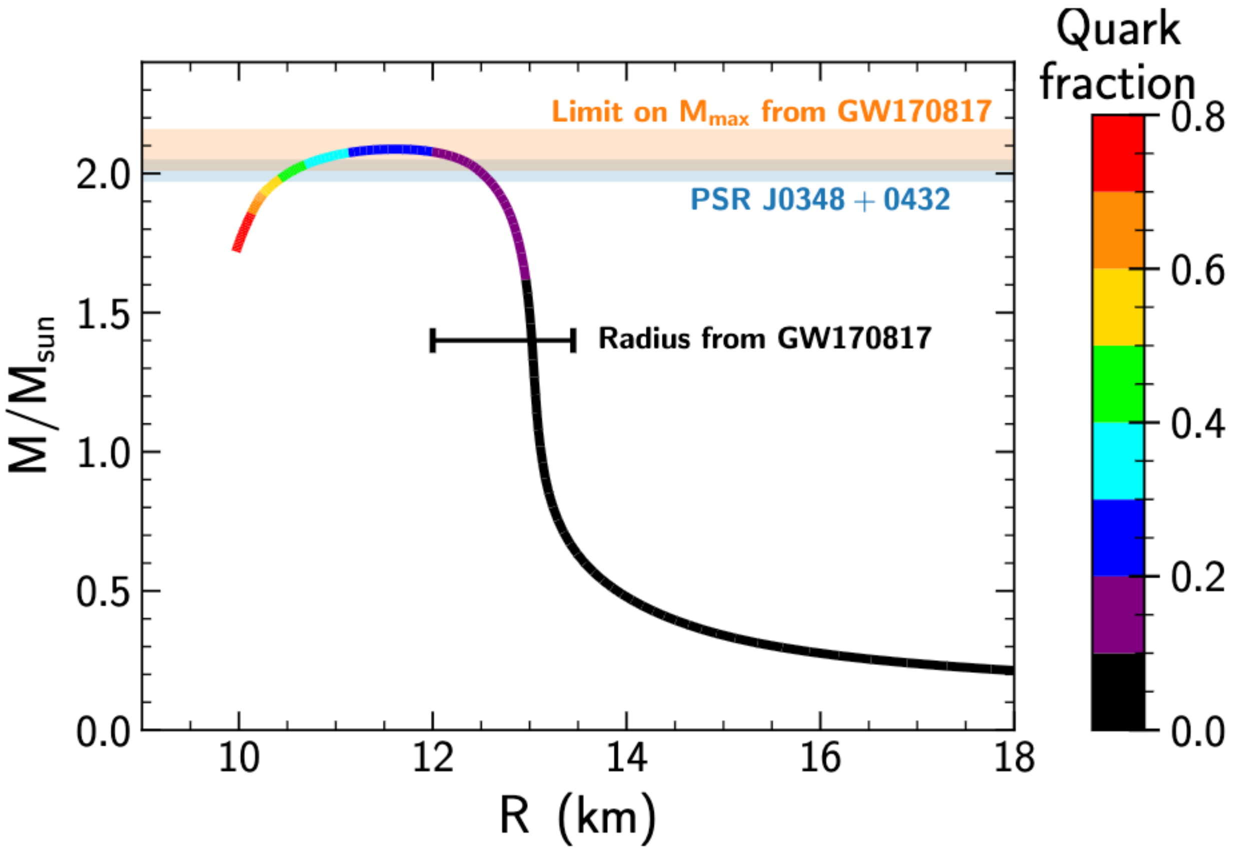


Pressure of dense nuclear matter balances the gravitational pull

QCD in astrophysics

Properties of dense nuclear matter define how heavy neutron stars can be and how large they are





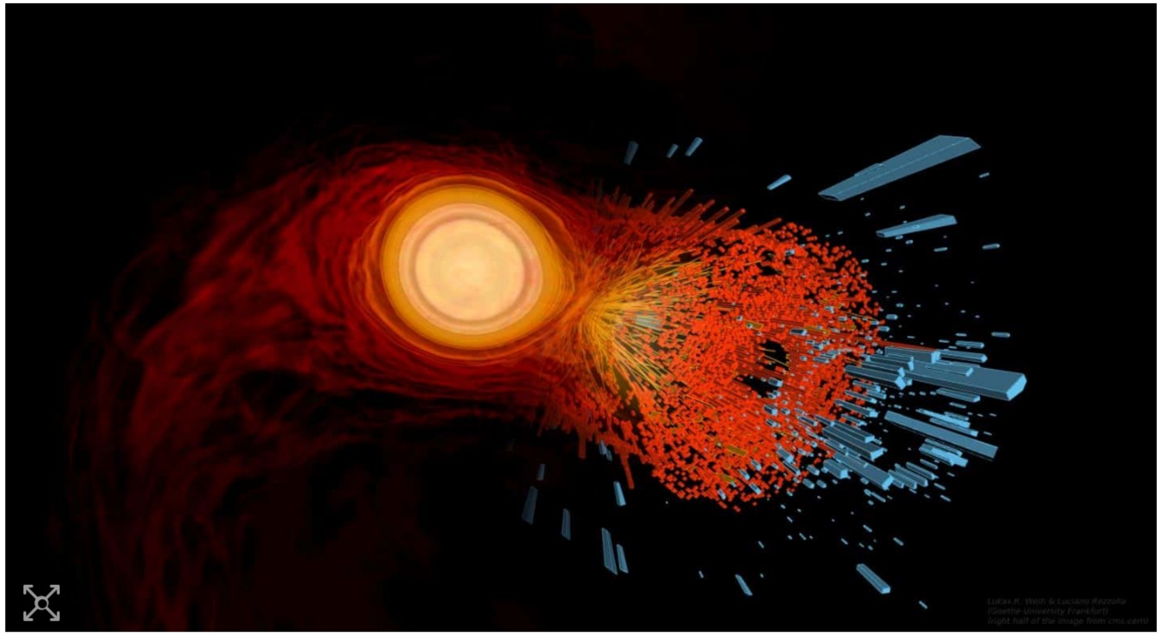
Intermediate energy heavy-ion collisions probe same dense nuclear matter

The ultimate “heavy-ion” collision

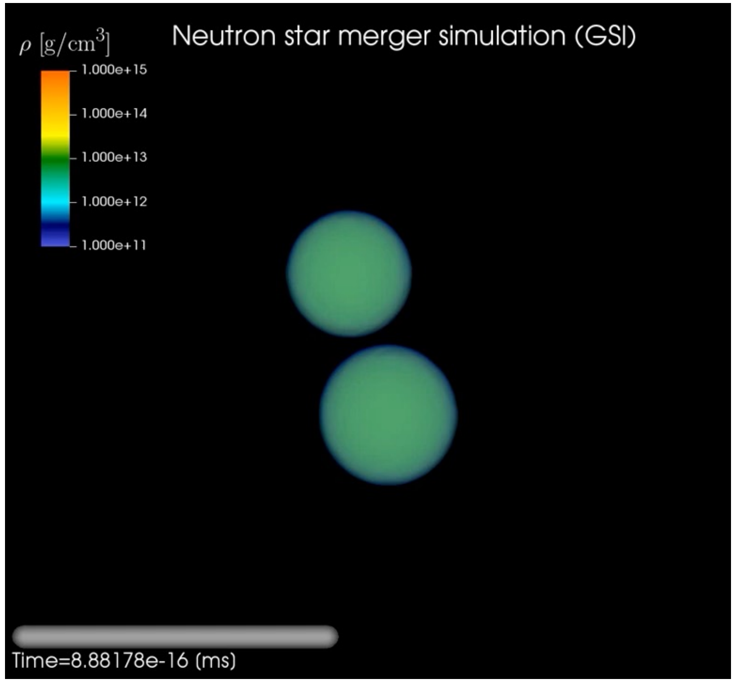
COSMOLOGY | RESEARCH UPDATE

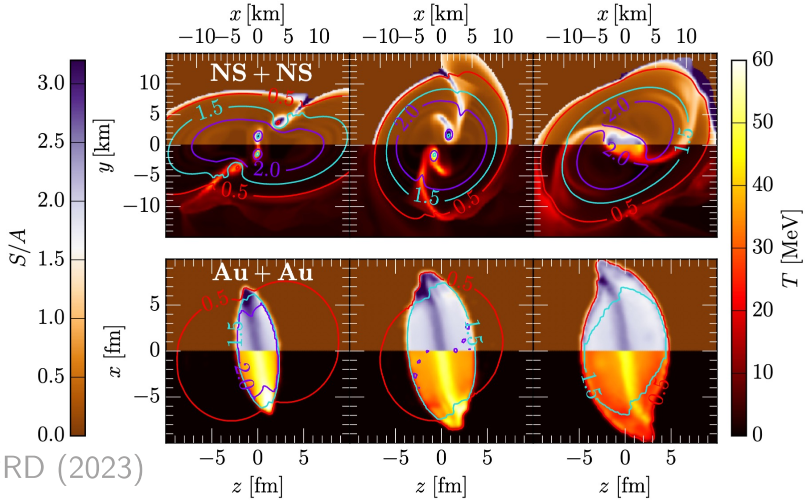
Gravitational waves from neutron-star mergers could reveal quark-gluon plasma

15 May 2020



Dark star crashes: the computer simulation of two merging neutron stars (left) blended with an image of heavy-ion collisions at CERN to highlight the connection of astrophysics with nuclear physics. Courtesy: Lukas R Weih and Luciano Rezzolla/Goethe University Frankfurt and CMS/CERN)





Most et al., PRD (2023)