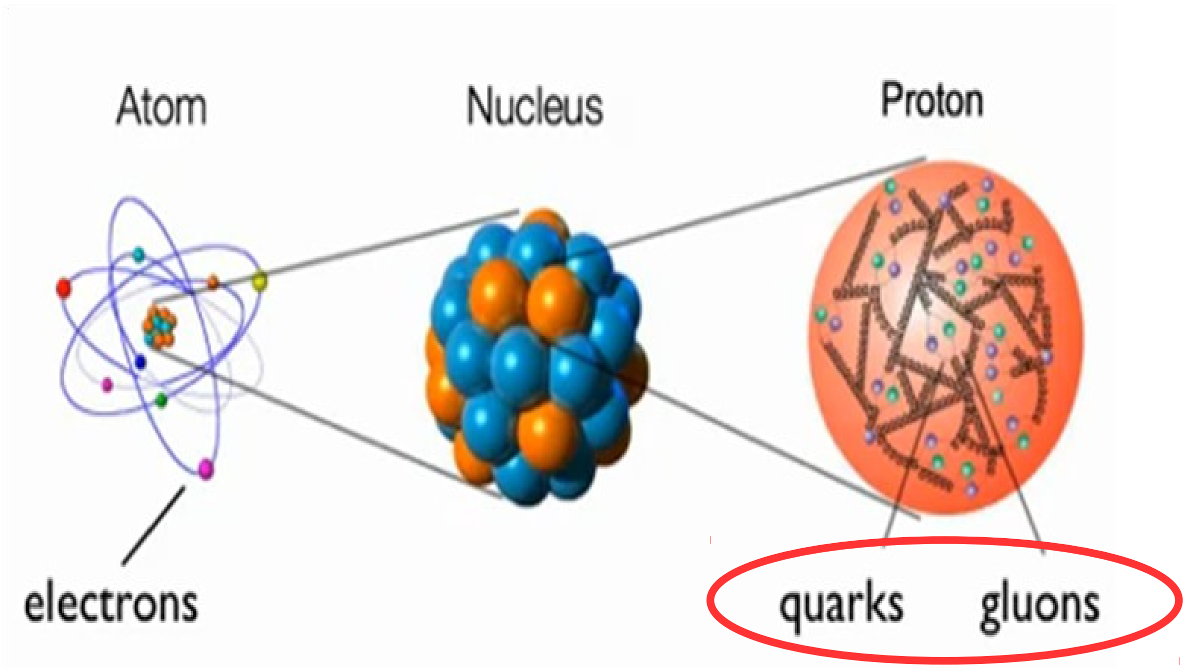
Supercomputing Extreme Matter

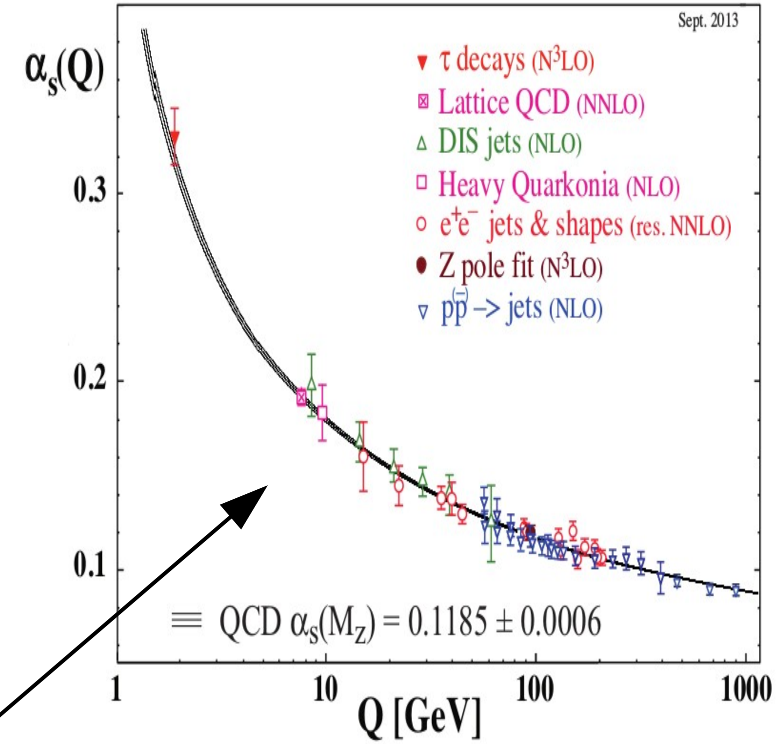
Swagato Mukherjee

BROOKHAVEN NATIONAL LABORATORY

July 2014, Washington DC

Quarks, Gluons and QCD





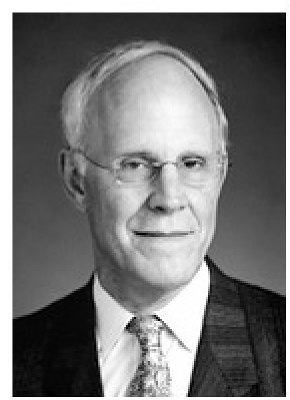
strong interaction

Quantum Chromo Dynamics

asymptotically free

coupling strength decrease with increasing energy

Nobel Prize 2004

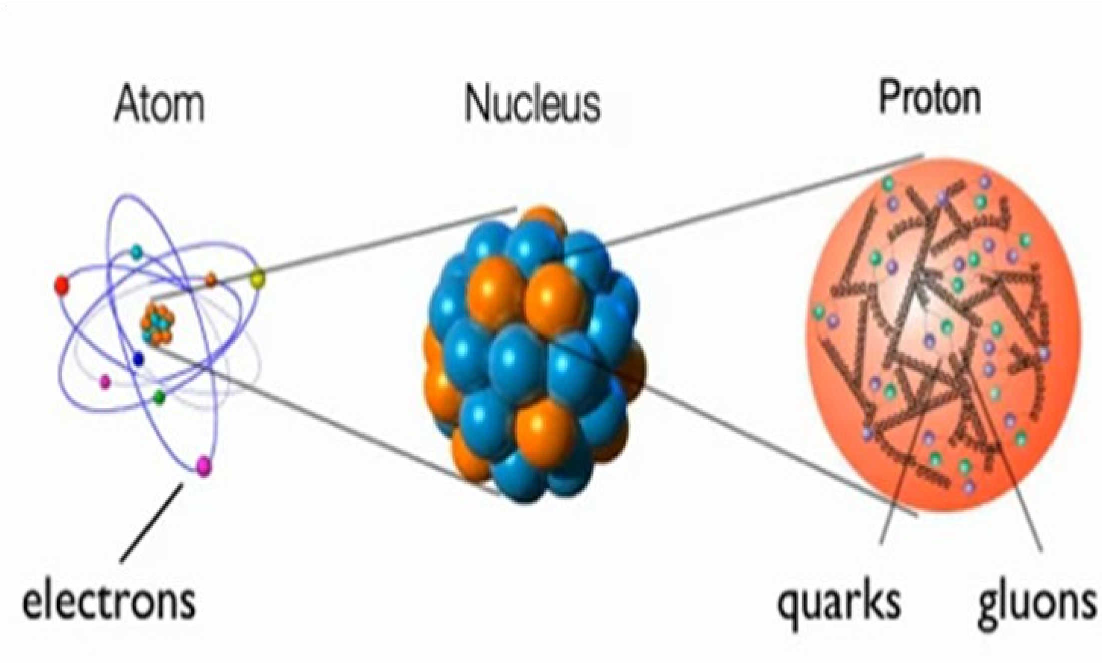


David J. Gross

H. David Politzer

Frank Wilczek

QGP: a new state of matter



density $\sim 10^{18}$ kg/m^3

temperature $\sim 10^{12}$ °C

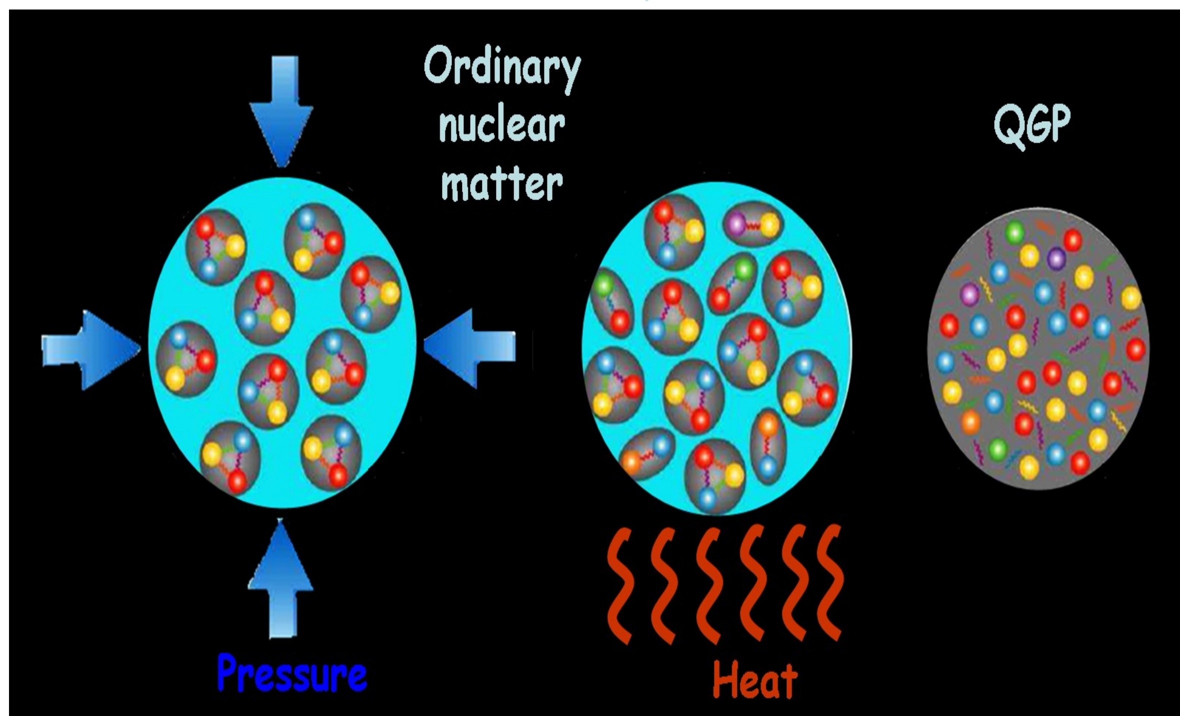
100,000 times hotter than the core of the sun

$T \gg \mu_B \gg \lambda_{QCD}$

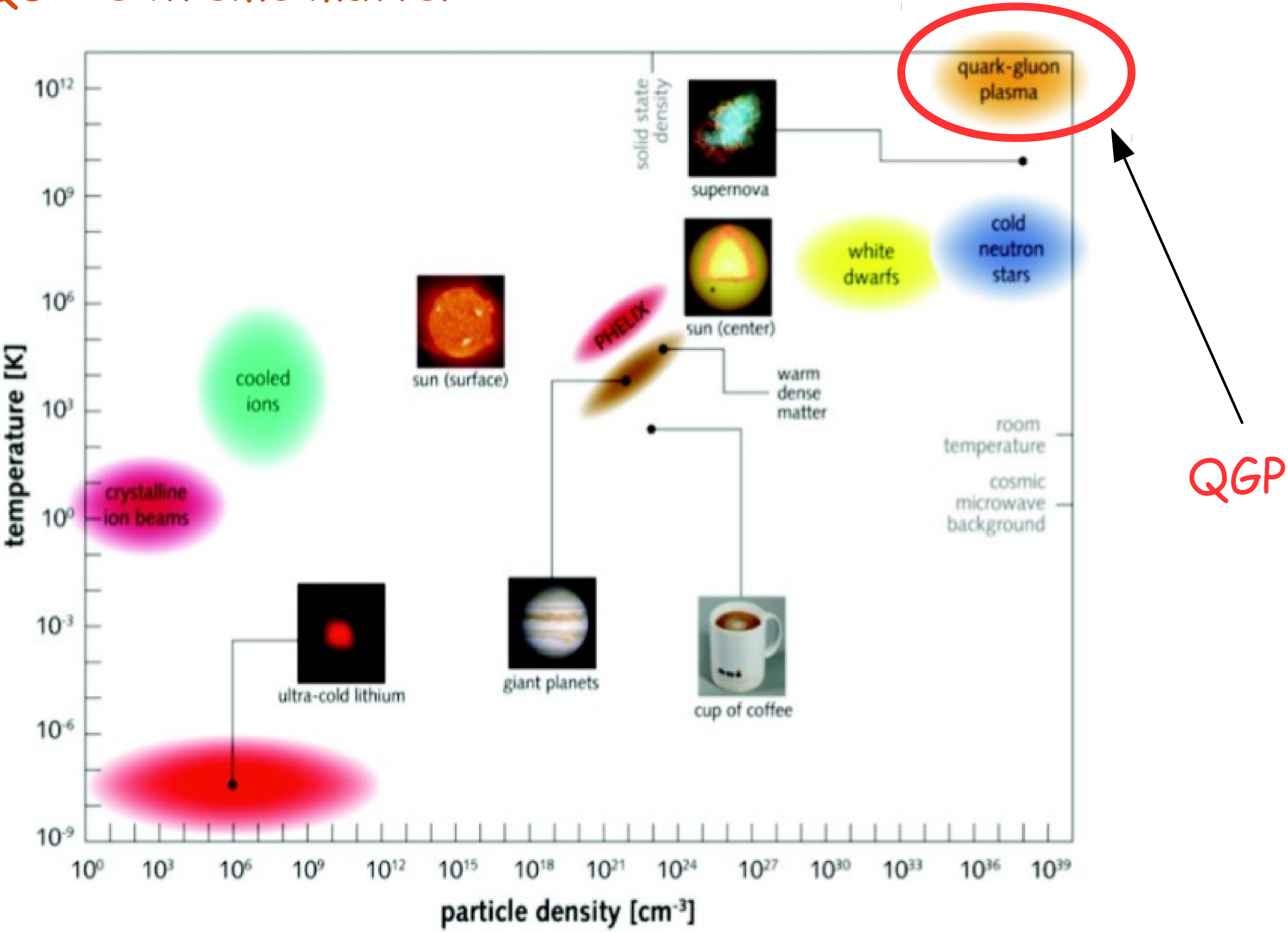
quarks & gluons get liberated from nucleons

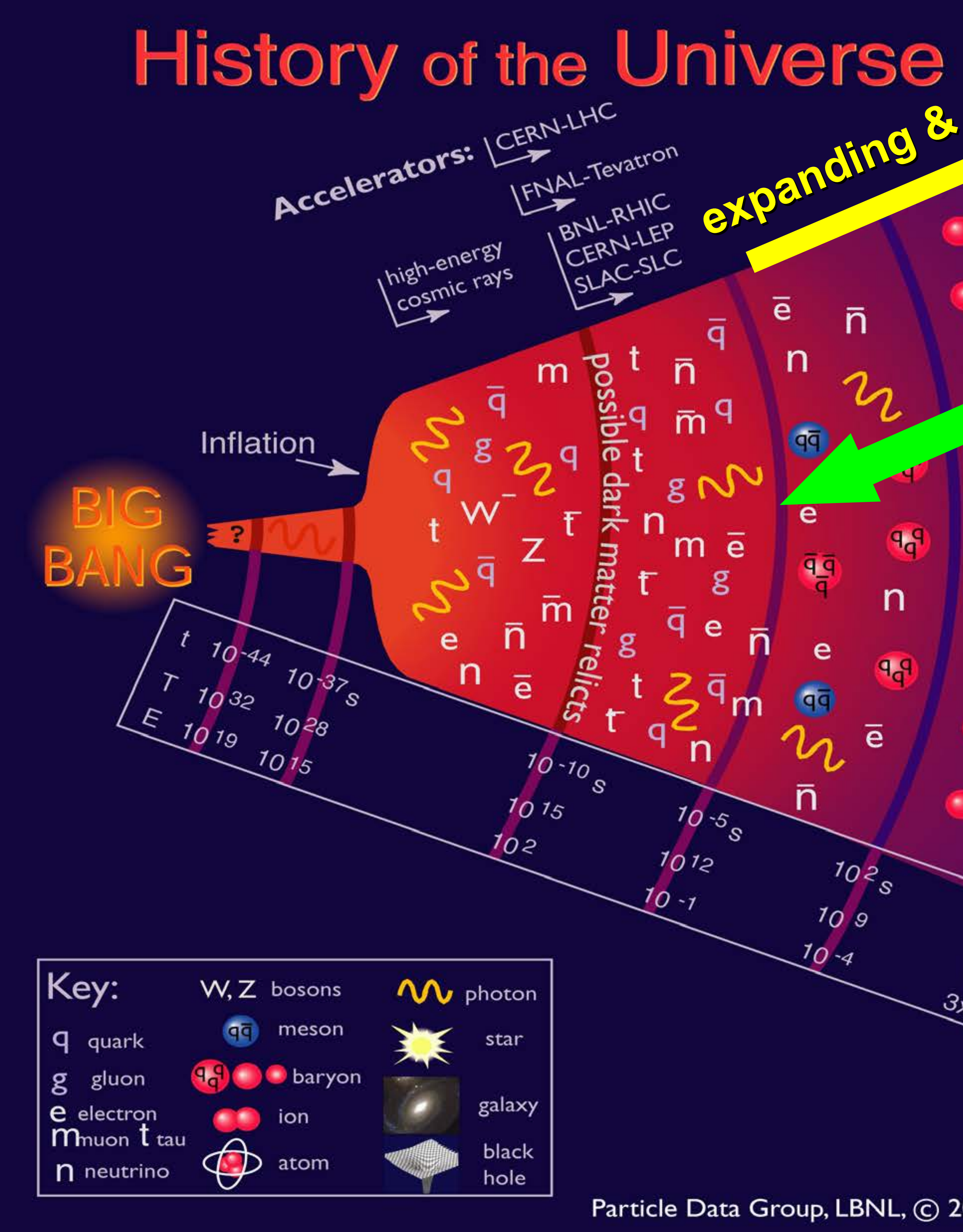
a new state of matter

Quark Gluon Plasma (QGP)



QGP: extreme matter





$\sim 10^{-5}$ sec

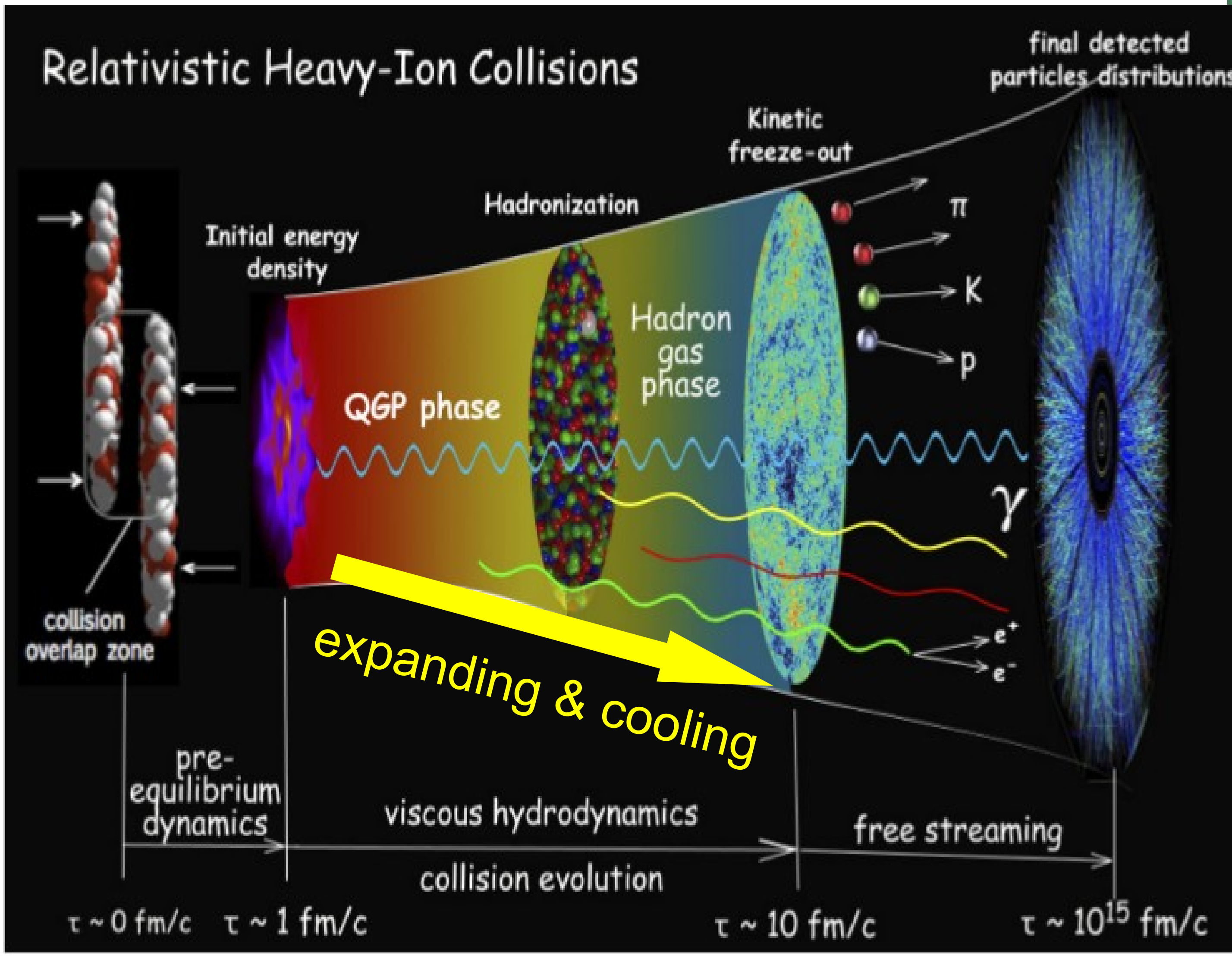
after the Big Bang

temperature $\sim 10^{12}$ °C

transition from
Quark Gluon Plasma
hadronic matter

quarks & gluons
recombine to form
hadronic matter
that we see today

Recreating QGP on earth with Little Bang



RHIC (BNL, NY)

LHC (CERN, Geneva)

HIGHEST MAN-MADE TEMPERATURE

Tweet 0 g+1 0 Like Send Be the first of your friends to like this.

FOR THE RECORD

WHO:
BROOKHAVEN NATIONAL LABORATORY'S RELATIVISTIC HEAVY ION COLLIDER

WHAT:
HIGHEST MAN-MADE TEMPERATURE

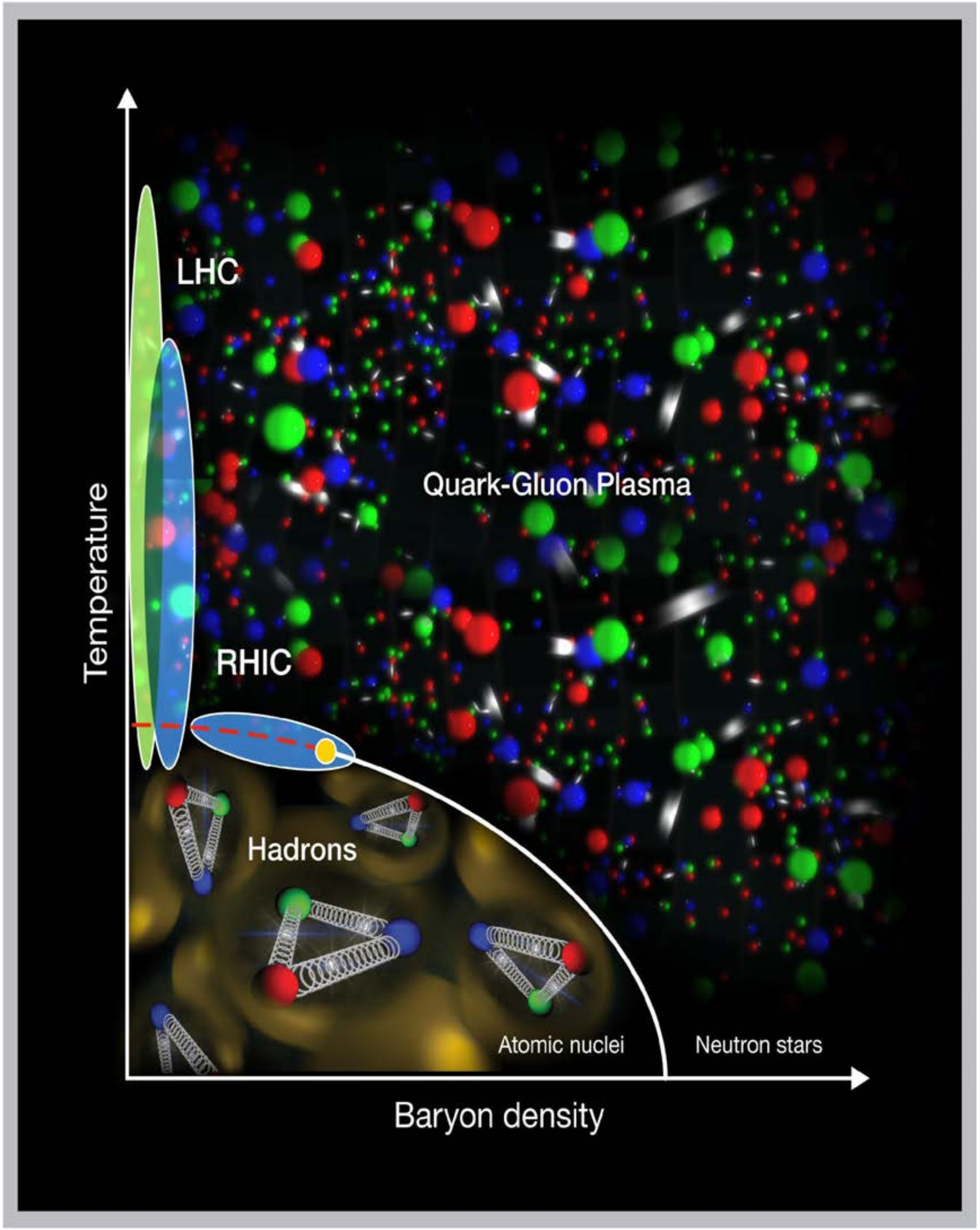
WHERE:
UNITED STATES

In February 2010, scientists at Brookhaven National Laboratory's Relativistic Heavy Ion Collider on Long Island, New York, USA, announced that they had smashed together gold ions at nearly the speed of light, briefly forming an exotic state of matter known as a quark-gluon plasma. This substance is believed to have filled the universe just a few microseconds after the Big Bang. During the experiments – which began in July 2001 and have taken a decade to authenticate – the plasma reached temperatures of around 4 trillion°C, some 250,000 times hotter than the centre of the Sun.

$$4 \cdot 10^{12}\ {}^oC \ \simeq \ \mathbf{220\ MeV}$$

250.000 times hotter than the center of the sun

From here to QGP and back



what are the various phases of the strongly interacting matter ?

at what temperature/density transition from ordinary matter to QGP takes place ?

what are the properties of QGP ?

how and when do we get back ordinary matter from QGP ?

how does ordinary matter behave just after QGP ceases to exist ?

how do we answer these questions from the fundamental theory, QCD ?

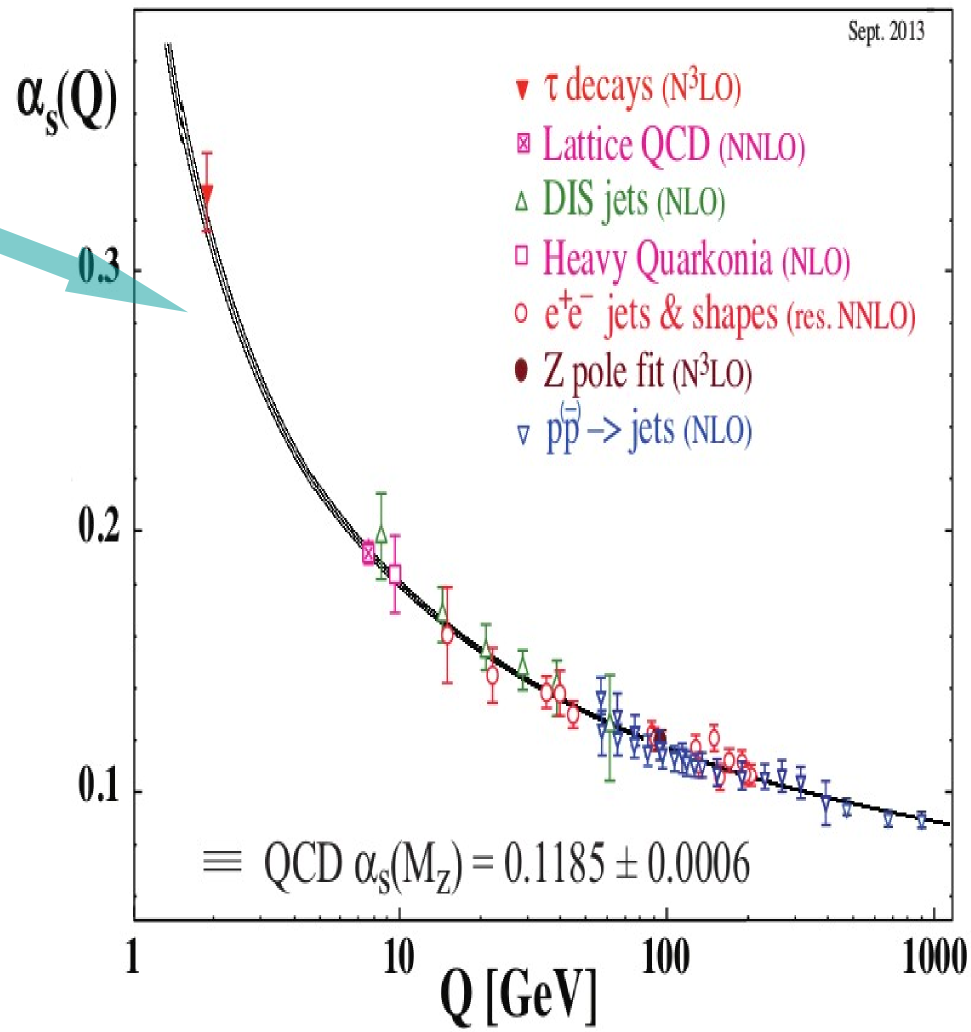
QGP from first principle QCD

$\alpha_s(\lambda_{QCD})$ is not small

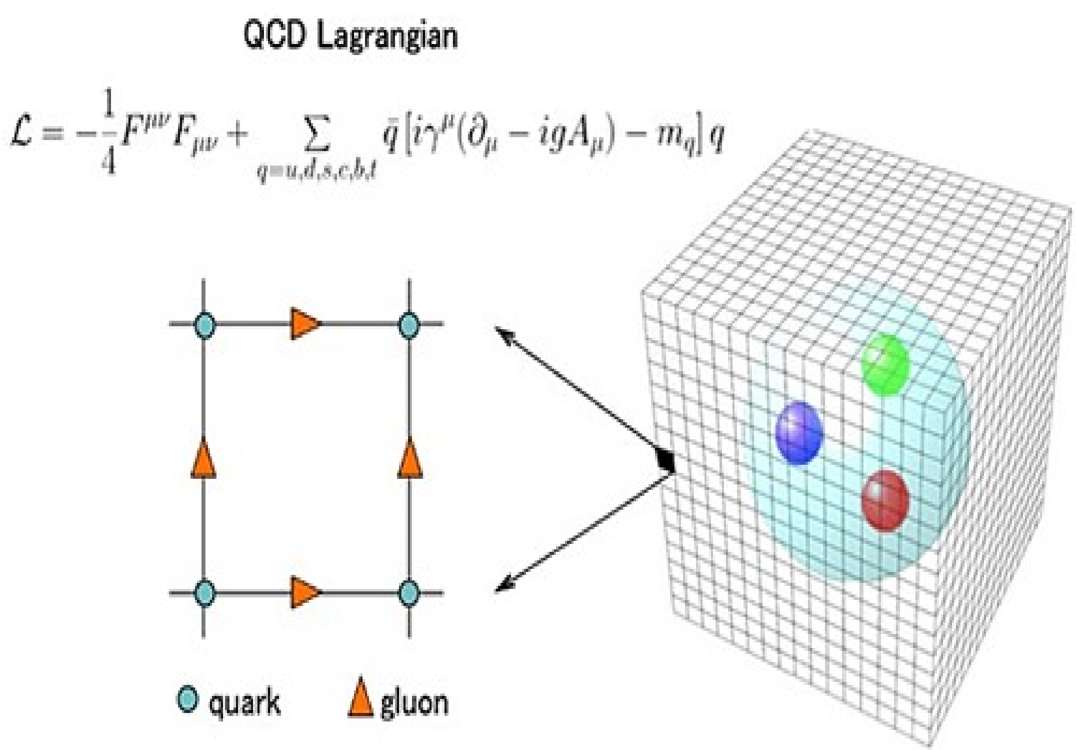
expansion in powers of the coupling fails, *i.e.* perturbation theory not reliable

need non-perturbative technique, analytic calculations difficult

hot-dense Lattice QCD



Hot-dense Lattice QCD



QCD on a discretized (Euclidean) space-time lattice

non-perturbative technique

equilibrium & near-equilibrium properties of QCD

temperature: space =/= time
(breaking Lorentz symmetry)

density: chemical potential
coupled to conserved current in QCD Lagrangian

no free parameter
bare parameters of QCD Lagrangian fixed by reproducing physics at T=0

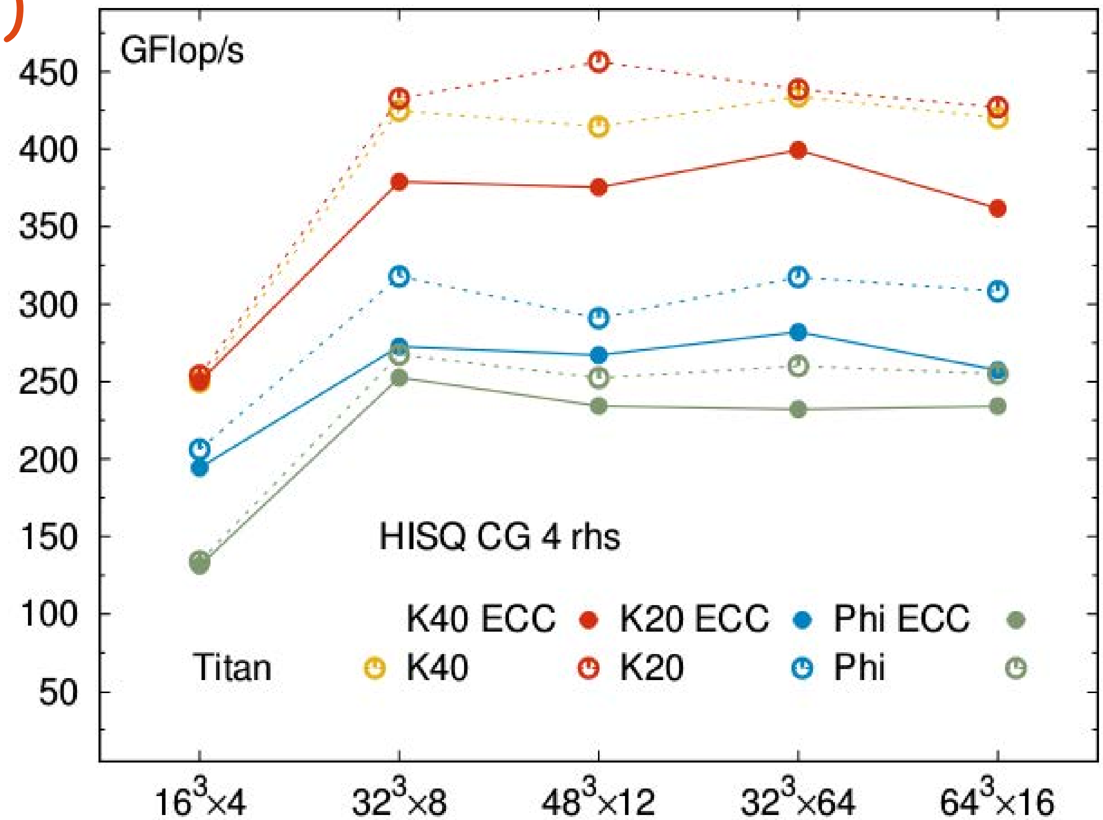
perform path integral numerically using Monte-Carlo technique
~ 130M dimensional integral for a modest 16×64^3 lattice

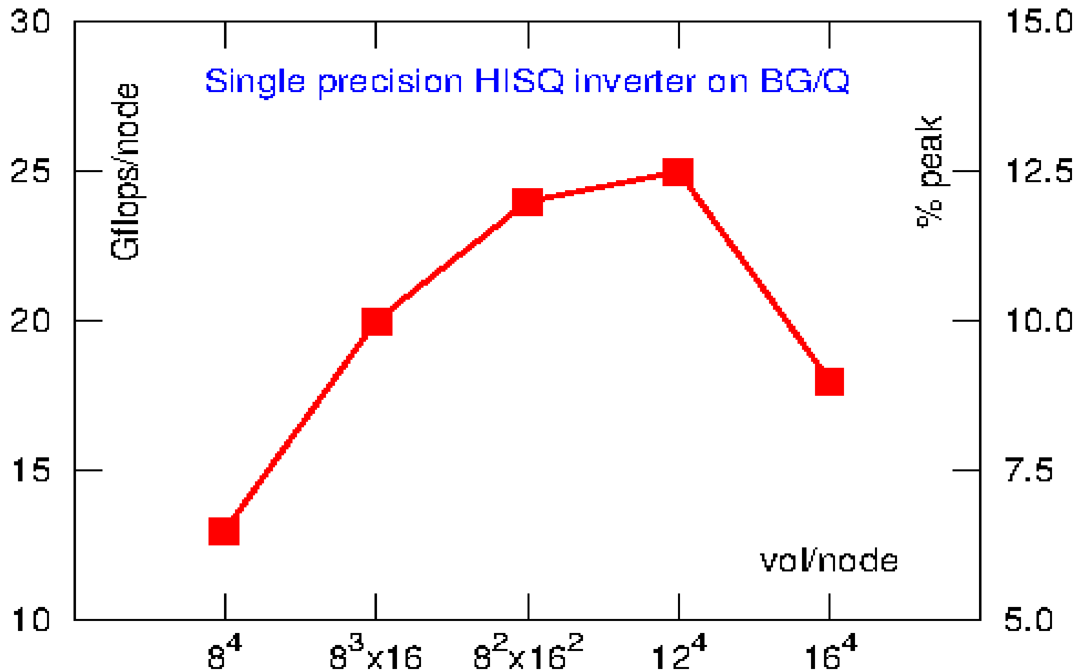
leadership class supercomputing is essential

cost dominated by numerous inversions of very large, sparse fermion matrices

Inverter performance (HISQ)

Titan @ ORNL, USA

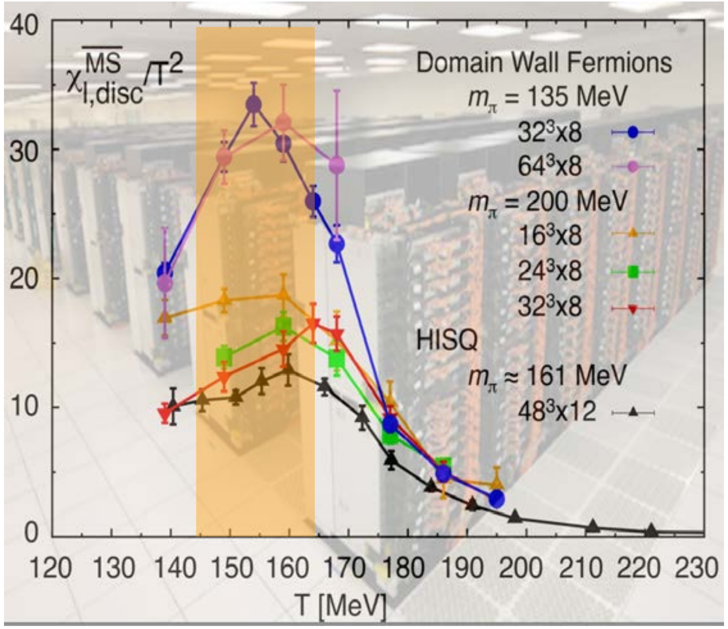




Mira @ ANL, USA

Temperature required to form QGP

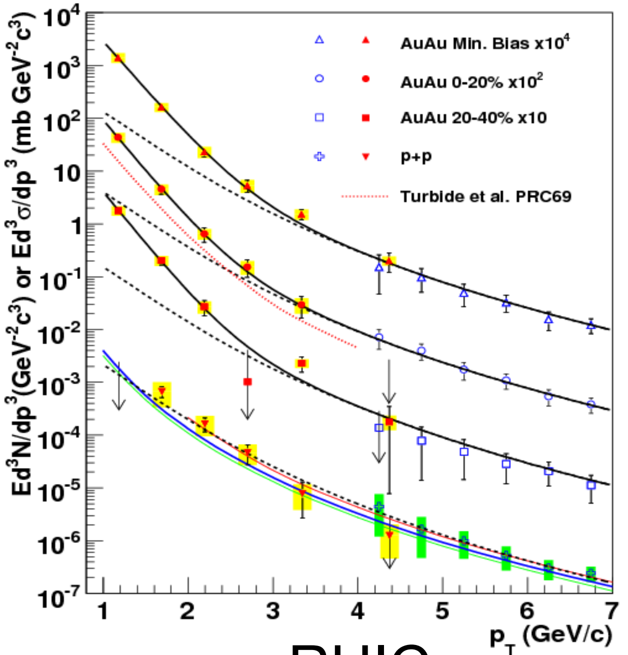
from hadrons to QGP: $T_c = 154(9)$ MeV



chiral crossover

calculations with
3 physical pions

HotQCD: arXiv:1402.5175
to appear in Phys. Rev. Lett.
(editor's suggestion)



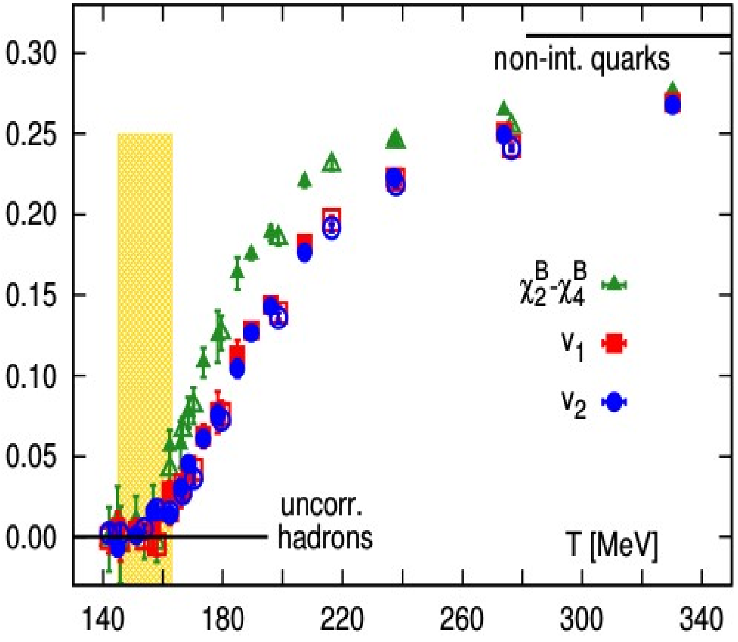
RHIC

photon emission spectra

$T_{avg} = 221 \pm 19 \pm 19$ MeV

PHENIX: PRL 104, 132301 (2010)

is this T high enough
to form QGP ?



deconfinement
crossover

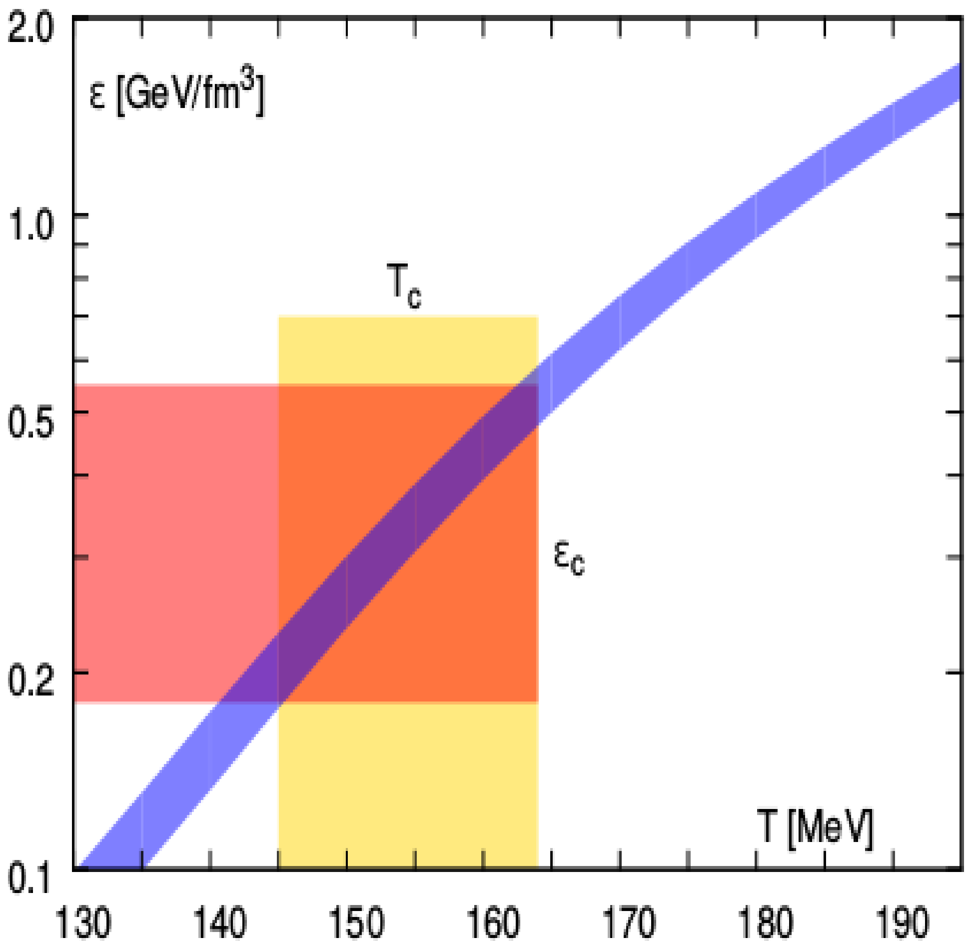
BNL-Bi:
Phys. Rev. Lett., 111, 082301 (2013)

Energy density required to form QGP

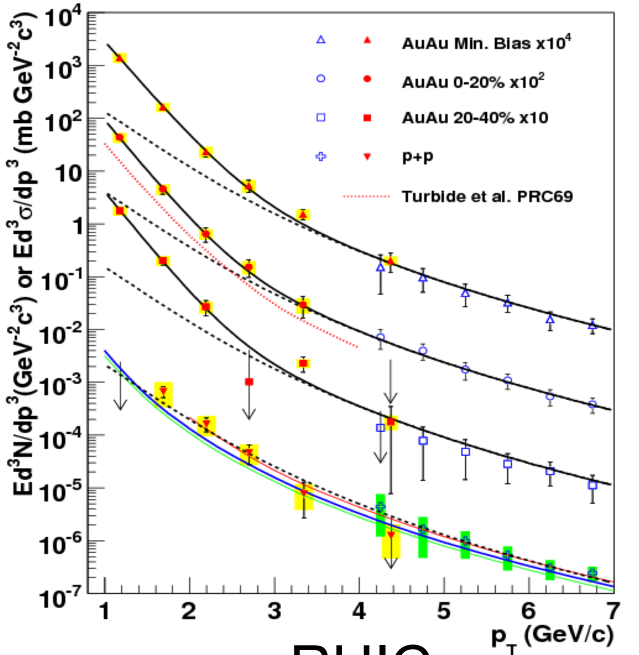
from hadrons to QGP:

$$\epsilon_c = 0.18 - 0.55\ \mathrm{GeV/fm^3}$$

$$\epsilon_c = (1.2 - 3.5)\,\epsilon_{nuclear}$$



HotQCD: arXiv:1407.6387



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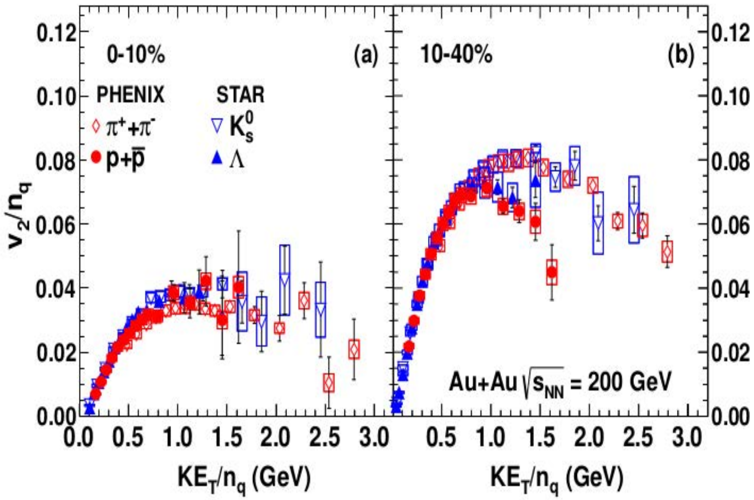
PHENIX: PRL 104, 132301 (2010)

is this T high enough to form QGP ?

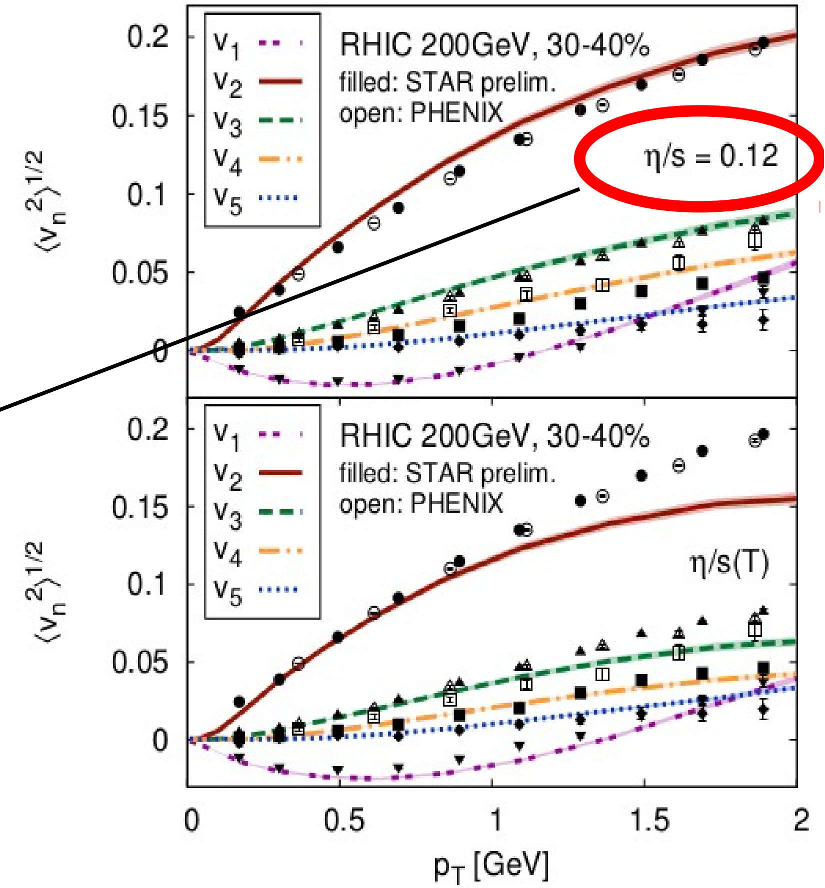
Flowing QGP: a nearly perfect fluid

Gale et al, PRL 110, 012302 (2012)

PHENIX: PRC 85, 064914 (2012)



collective flow seen at HIC is hydrodynamic, at the partonic level



shear viscosity to entropy density ratio:

$$\eta/s \approx 0.12$$

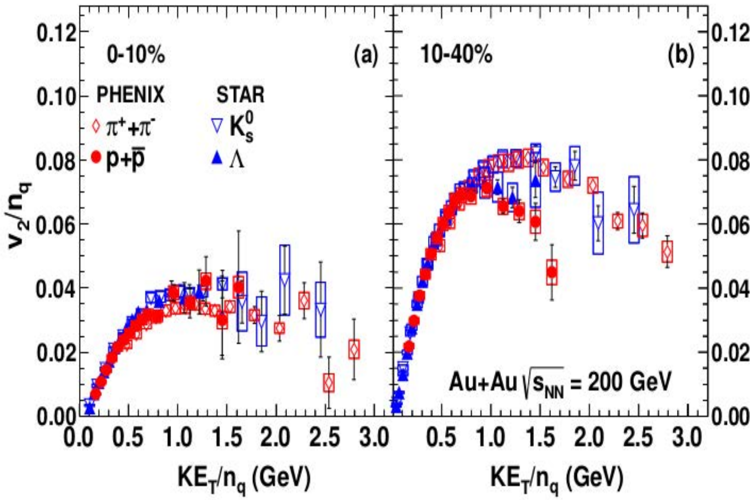
quantum lowest bound:

$$\eta/s \geqslant 1/4\pi = 0.08$$

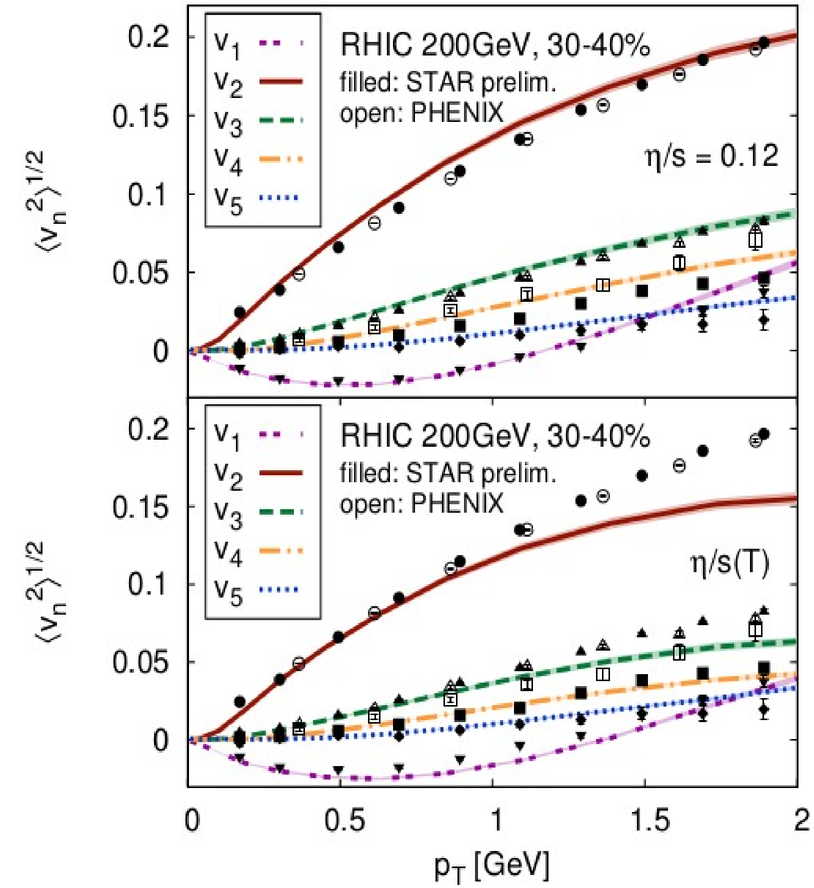
Policastro, Son, Starinets:
PRL 87, 081601 (2001)

Flowing QGP

PHENIX: PRC 85, 064914 (2012)

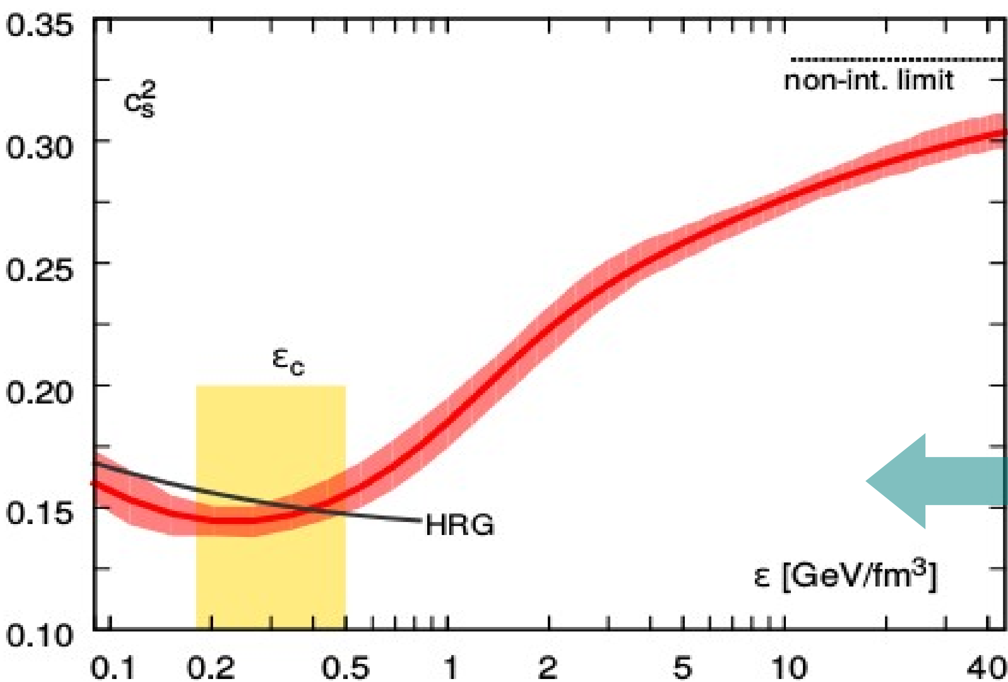


Gale et al, PRL 110, 012302 (2012)



collective flow seen at HIC is hydrodynamic, at the partonic level

LQCD: speed of sound of QCD



HotQCD: arXiv:1407.6387

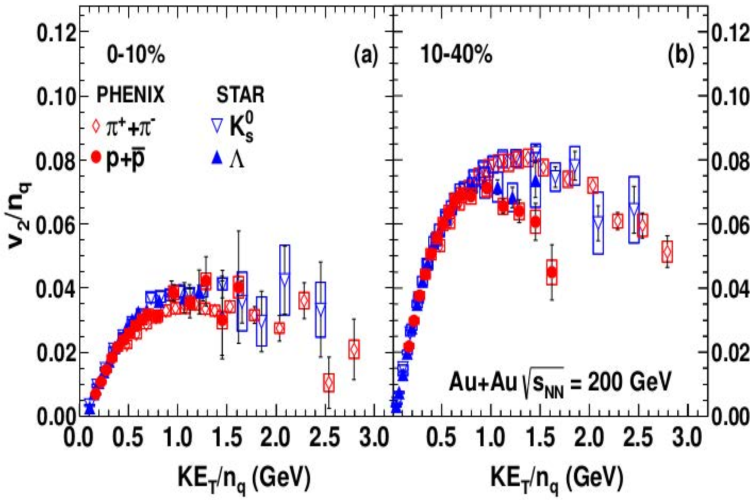
hydrodynamics == conservation laws

information of QCD enters only through the Equation of State of the medium calculated using Lattice QCD

Flowing QGP: a nearly perfect fluid

Gale et al, PRL 110, 012302 (2012)

PHENIX: PRC 85, 064914 (2012)



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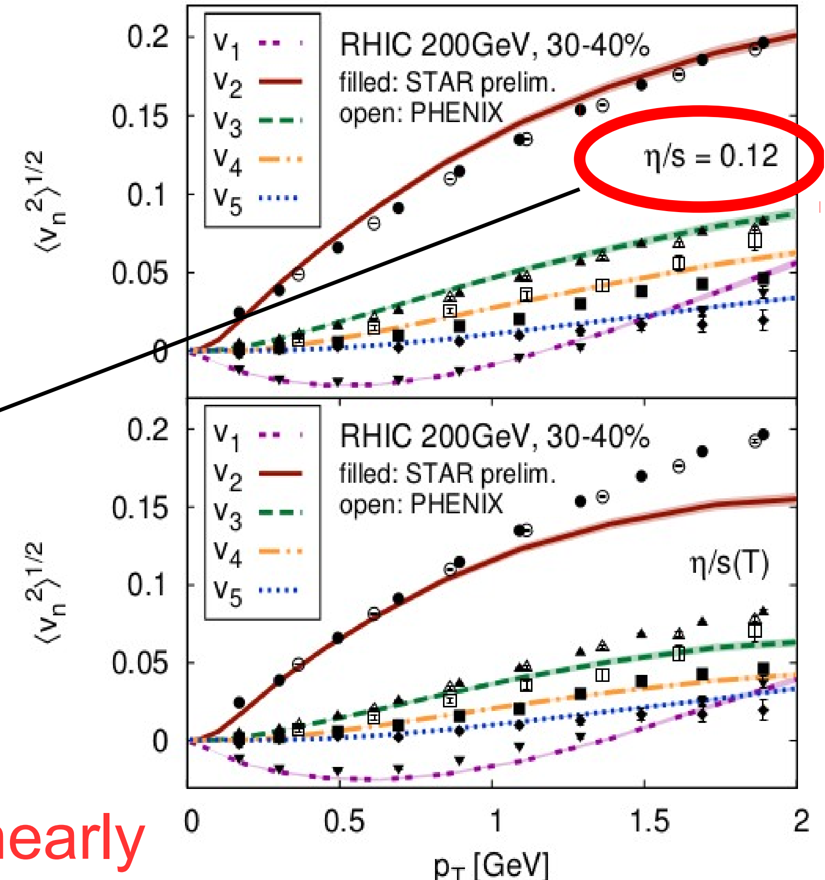

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$$\eta/s \approx 0.12$$

quantum lowest bound:

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Policastro, Son, Starinets: PRL 87, 081601 (2001)

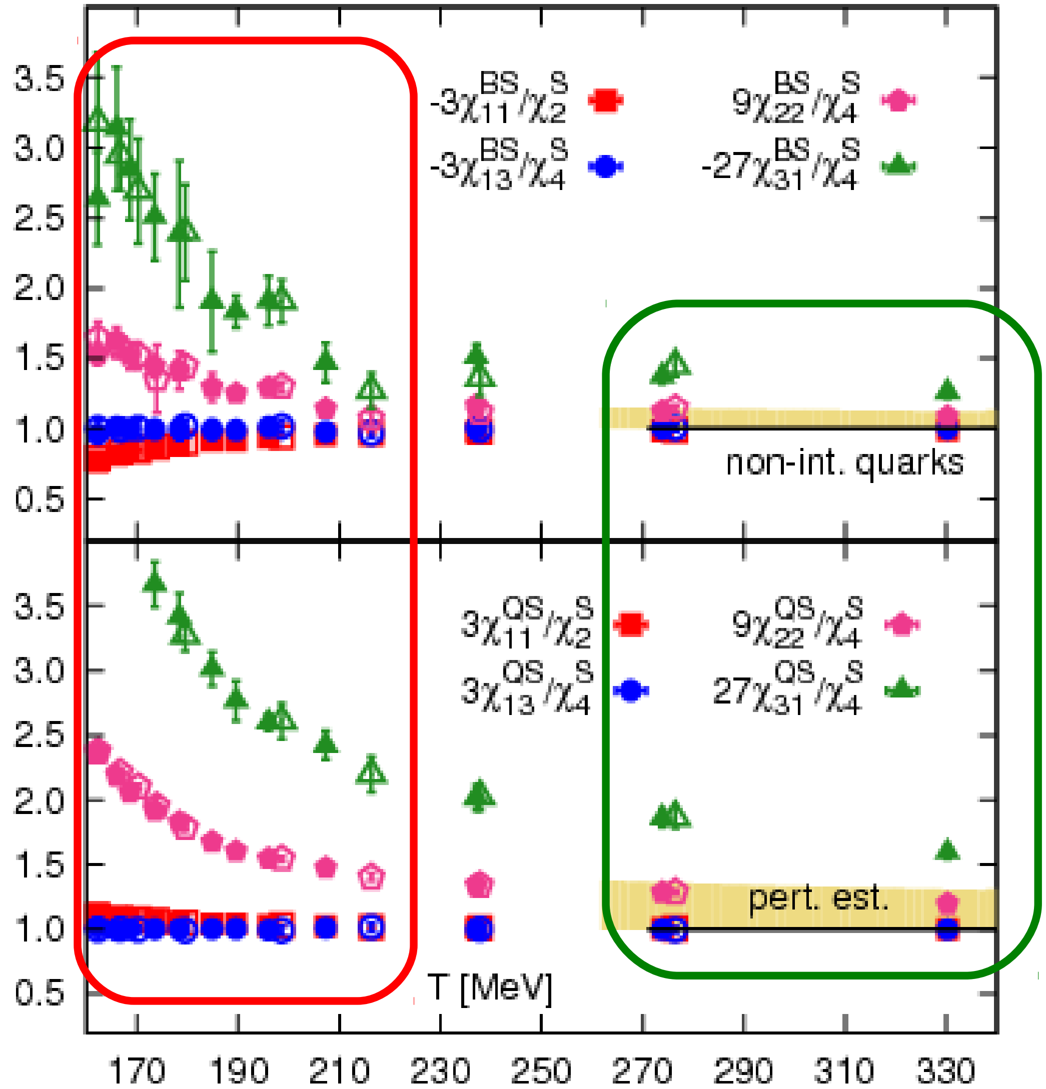
QGP is nearly perfect fluid

very short mean free path

quarks and gluons are strongly interacting inside QGP

theoretical evidence for strongly interacting QGP ?
when does it become weakly interacting ?

LQCD: evidence of strongly interacting QGP and transition to weakly interacting plasma



weakly/non-interacting quasi-quarks

$S=-1,\ B=1/3,\ Q=-1/3$

baryon–strangeness correlation

$$\chi_{mn}^{BS}/\chi_n^S = B^m S^n = (-1)^n/3^m$$

charge–strangeness correlation

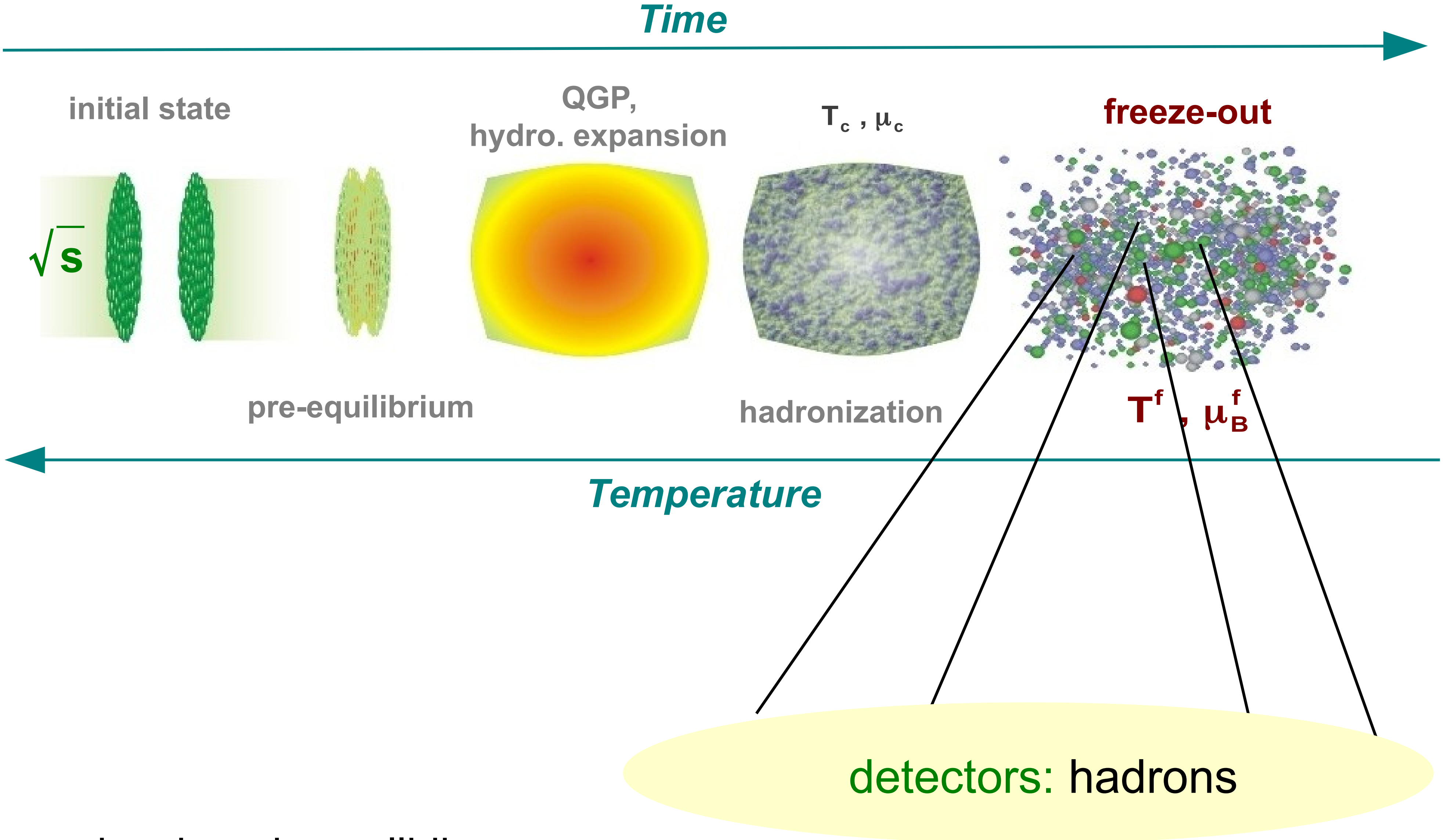
$$\chi_{mn}^{QS}/\chi_n^S = Q^m S^n = (-1)^{m+n}/3^m$$

weakly interacting strange quasi-quarks for $T \gtrsim 2T_C$

strongly interacting sDoF for $T_c \lesssim T \lesssim 2T_C$

BNL-Bi: Phys. Rev. Lett. 111, 082301 (2013)

Heavy ion collisions: a sketch



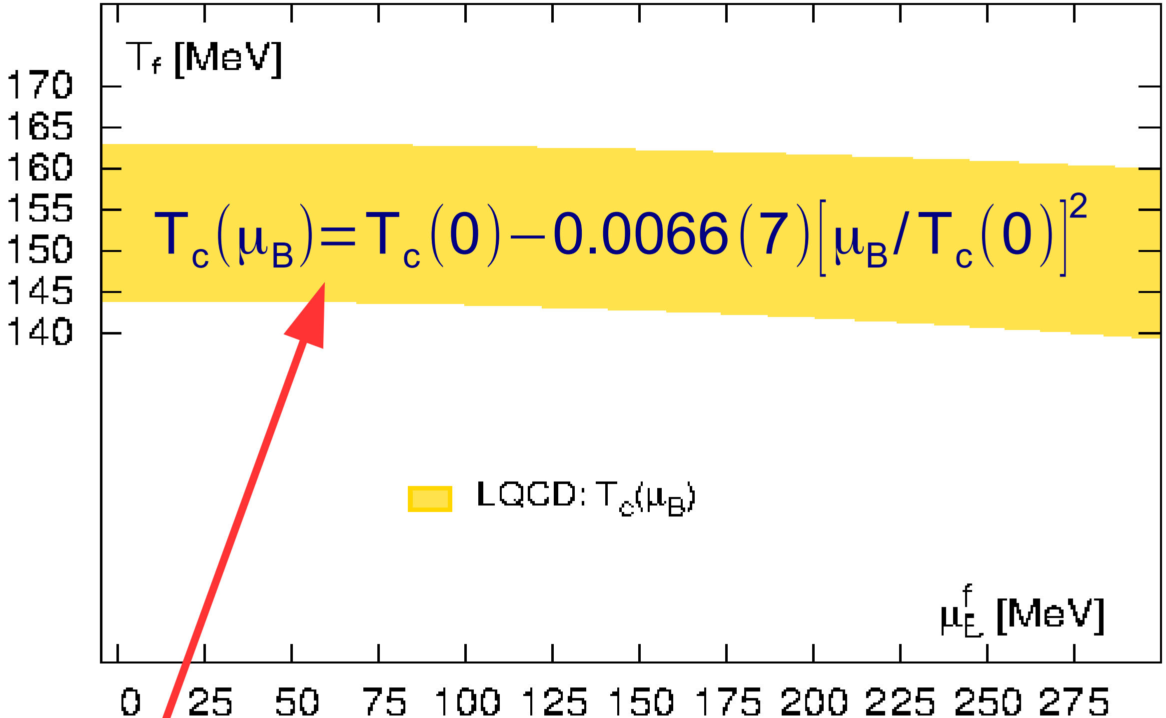
scan by changing colliding energies and species to come closer to the phase boundary

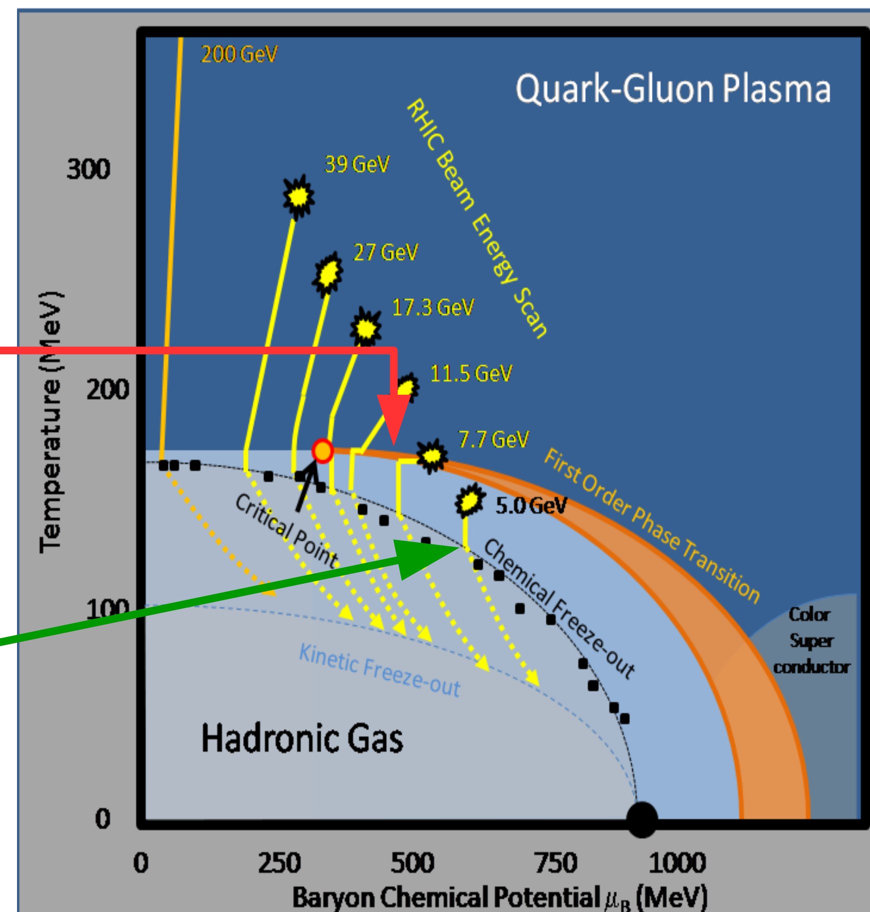
→ freeze-out stage "observed" in HIC

Transition to dense QGP

RHIC Beam Energy Scan
probing QCD phase diagram

the phase boundary and the freeze-out line must be close enough to probe the QCD phase diagram in HIC





phase boundary in T, μ_B plane

BNL-Bi: Phys. Rev. D83, 014504 (2011)

freeze-out

T^f, μ_B^f

"observed" in HIC

Freeze-out in HIC from LQCD

$\left(T^{f,ch}, \mu_B^{f,ch}\right)$: by comparing experimentally measured higher order cumulants of electric charge fluctuations

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\langle N_Q \rangle}{\langle (\delta N_Q)^2 \rangle} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)} = R_{12}^Q(T,\mu_B)$$

$$\frac{S_Q(\sqrt{s})\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\langle (\delta N_Q)^3 \rangle}{\langle N_Q \rangle} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)} = R_{31}^Q(T,\mu_B)$$

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

HIC

mean: M_Q

variance: σ_Q^2

skewness: S_Q

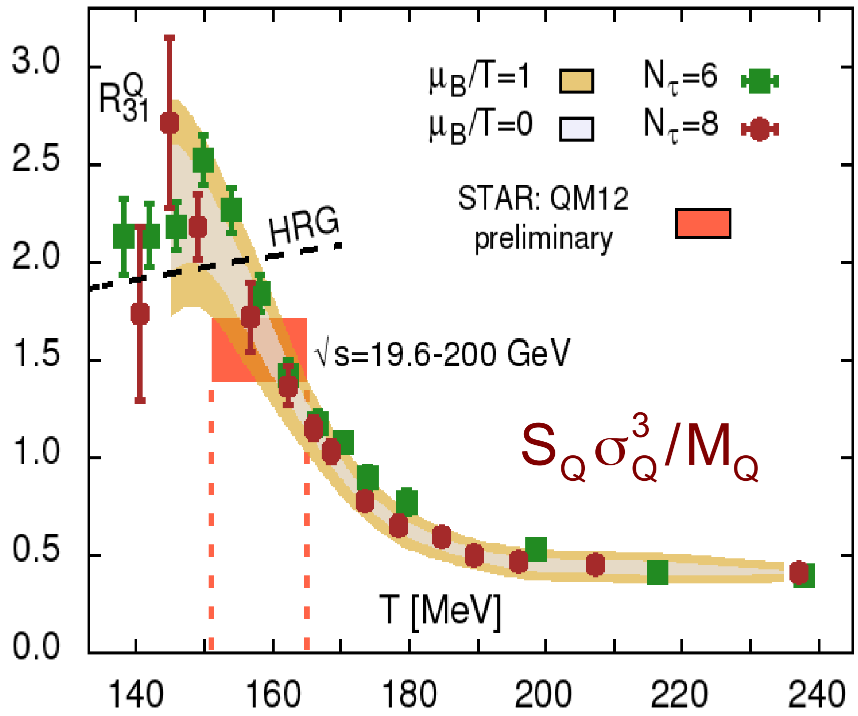
$\delta N_Q = N_Q - \langle N_Q \rangle$

LQCD

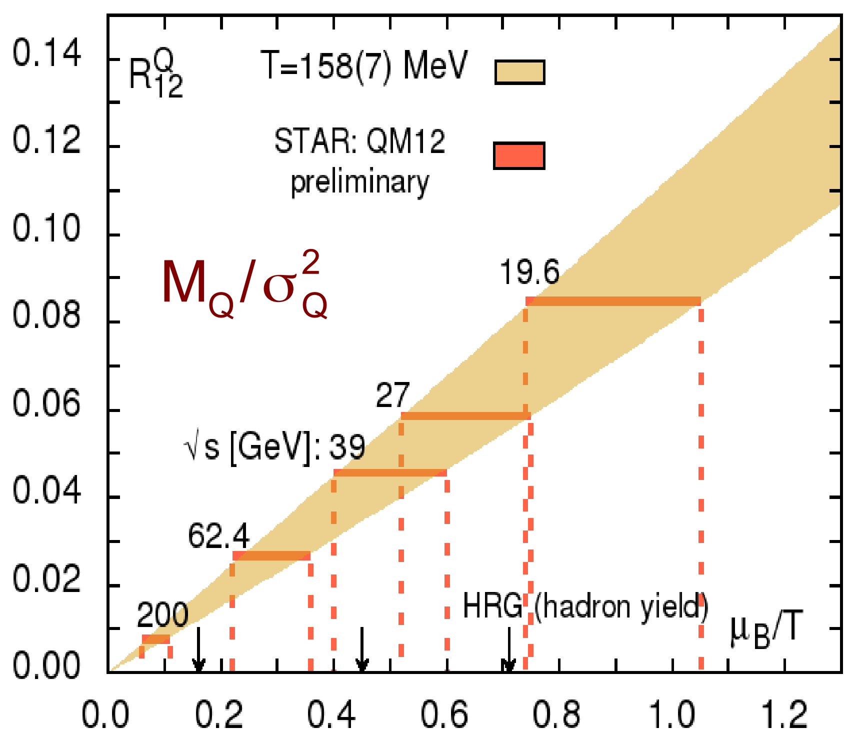
generalized charge susceptibilities:

$$\chi_n^Q(T,\vec{\mu}) = \frac{1}{VT^3} \frac{\partial^n \ln \mathbb{Z}(T,\vec{\mu})}{\partial(\mu_Q/T)^n}$$

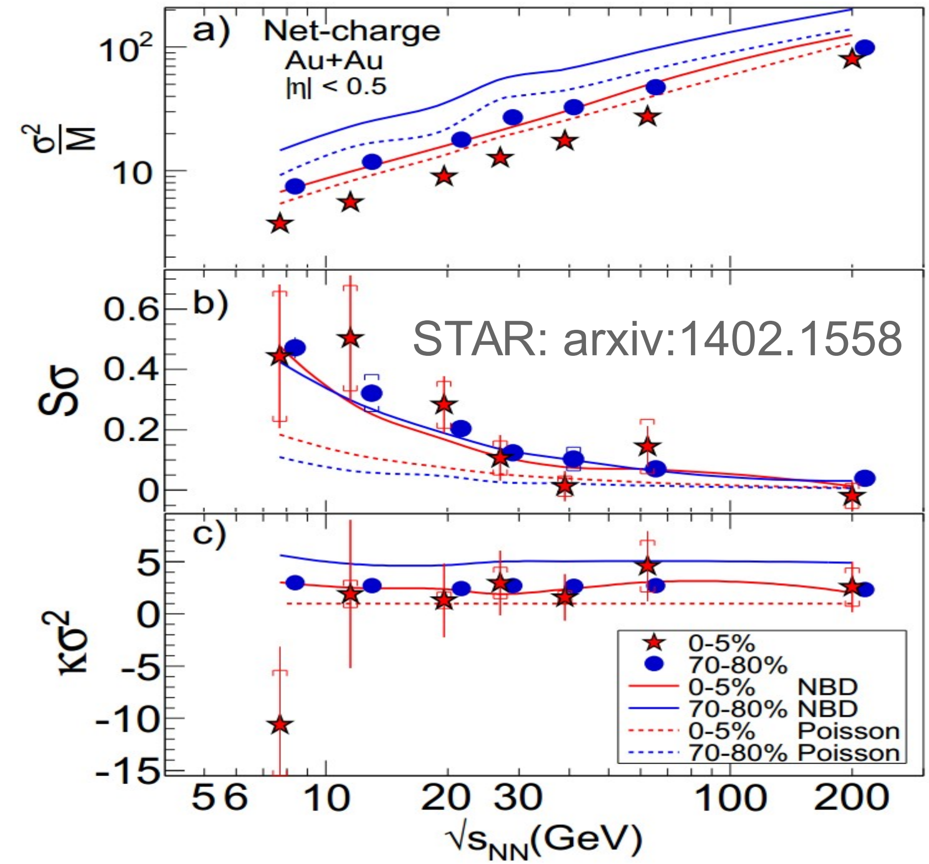
Freeze-out temperature and chemical potential "seen" at RHIC



thermometer : T^f



baryometer : μ_B^f

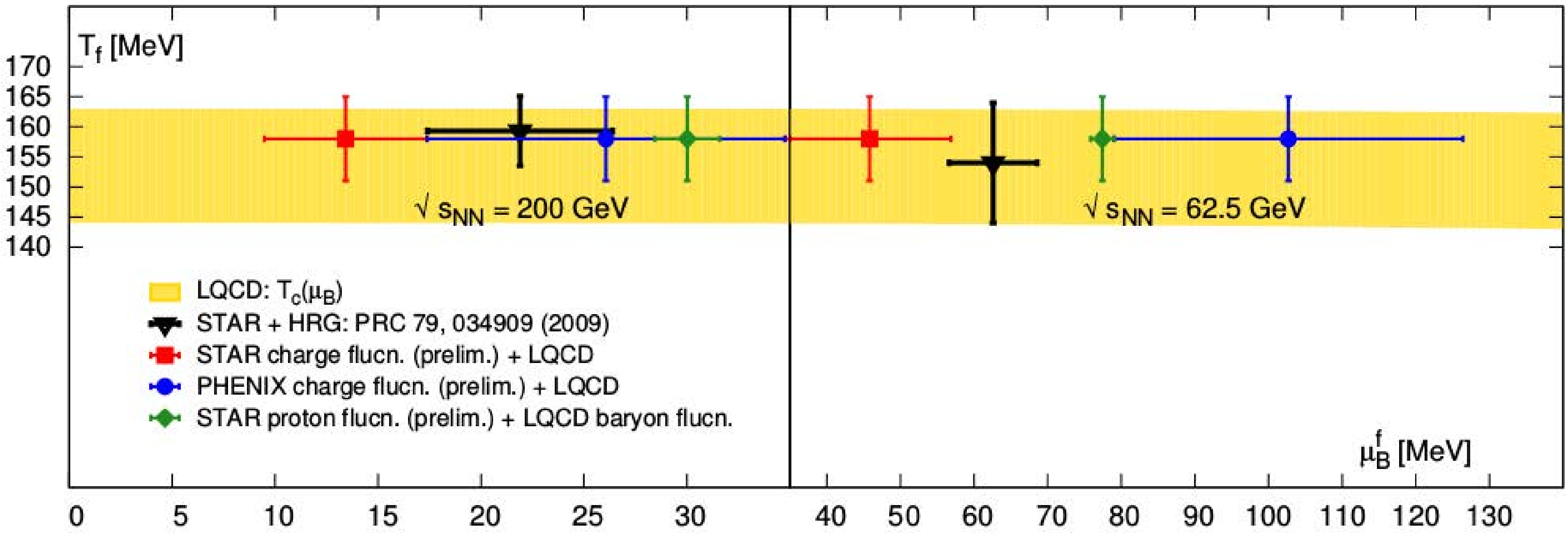


direct comparisons between LQCD calculations and experimentally measured higher order cumulants of electric charge fluctuations

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

SM: PoS CPOD2013, 039 (2013)

Freeze-out temperature and chemical potential "seen" at RHIC



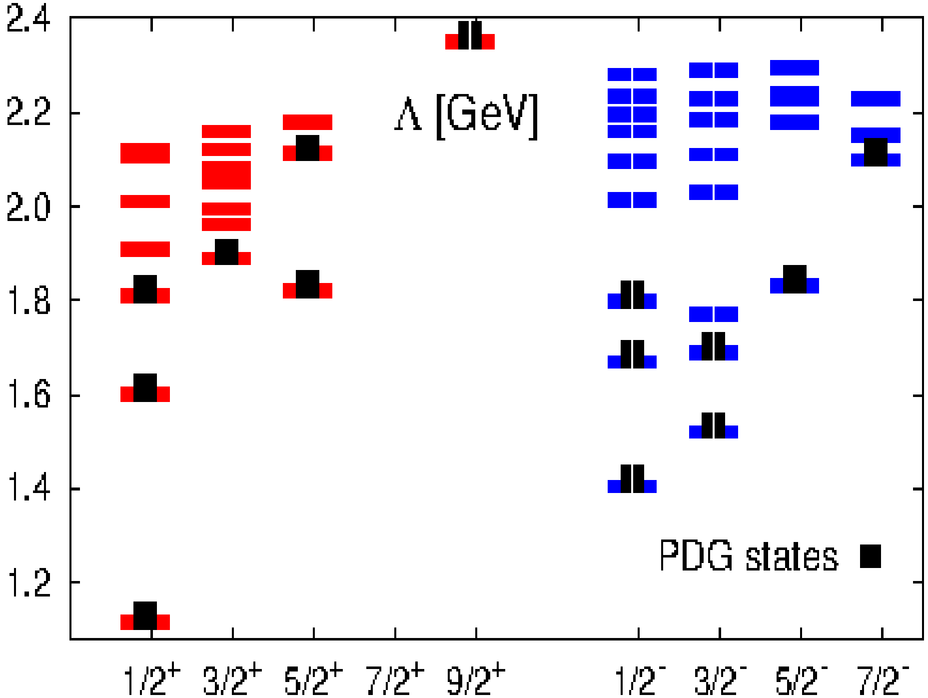
freeze-out in RHIC takes place close to the phase boundary

SM: PoS CPOD2013, 039 (2013)

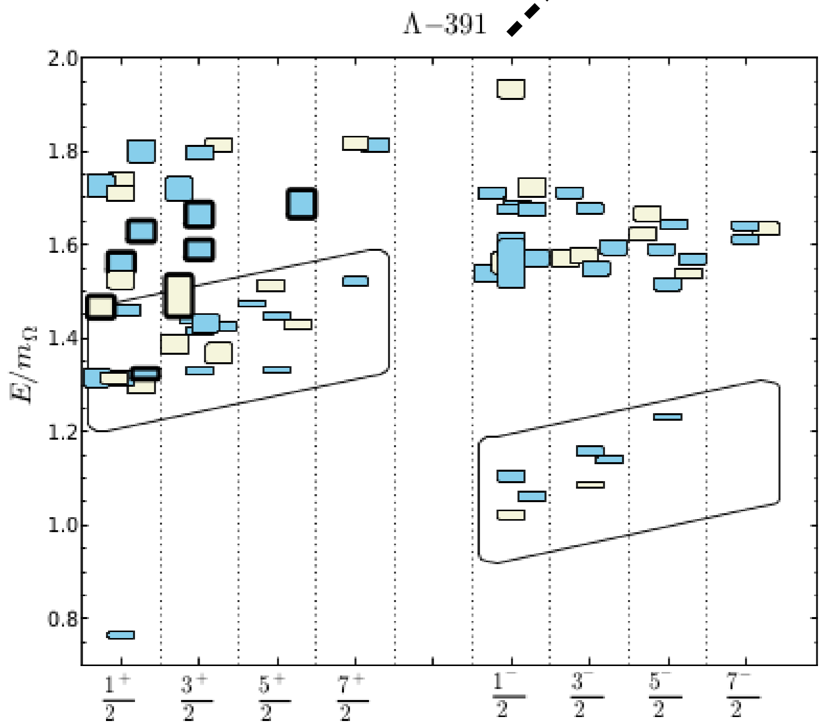
Matter at the edge of QGP:
signatures of undiscovered strange baryons

hadronic pressure: $P_{hadron} = \sum_{h \in \text{all hadrons}} P_h$

all expt. seen hadrons
+ undiscovered ones



quark model
Capstick-Isgur: Phys. Rev. D34, 2809 (1986)

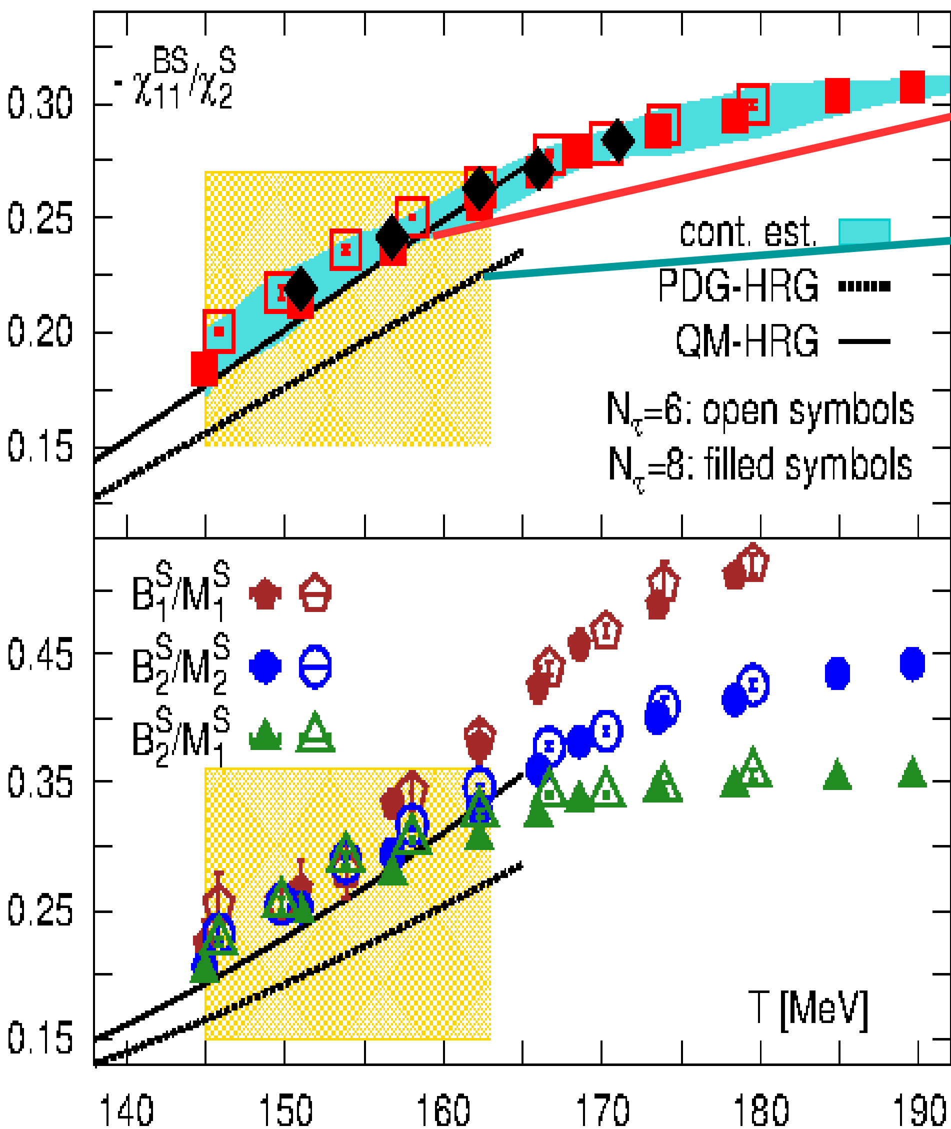


LQCD
JLab: Phys. Rev. D87, 054506 (2013)

Matter at the edge of QGP:
signatures of undiscovered strange baryons

relative thermodynamic contributions of strange baryons to strange mesons

BNL-Bi: arXiv:1404.6511
to appear in Phys. Rev. Lett.
(editor's suggestion)



+ undiscovered strange baryons

contributions of all expt. observed strange hadrons

contributions of undiscovered strange baryons are required to reproduce the hot-dens (L)QCD calculation

thermodynamic signatures of additional, undiscovered strange baryons

can we see imprint of these undiscovered states in Little Bangs of HIC ?

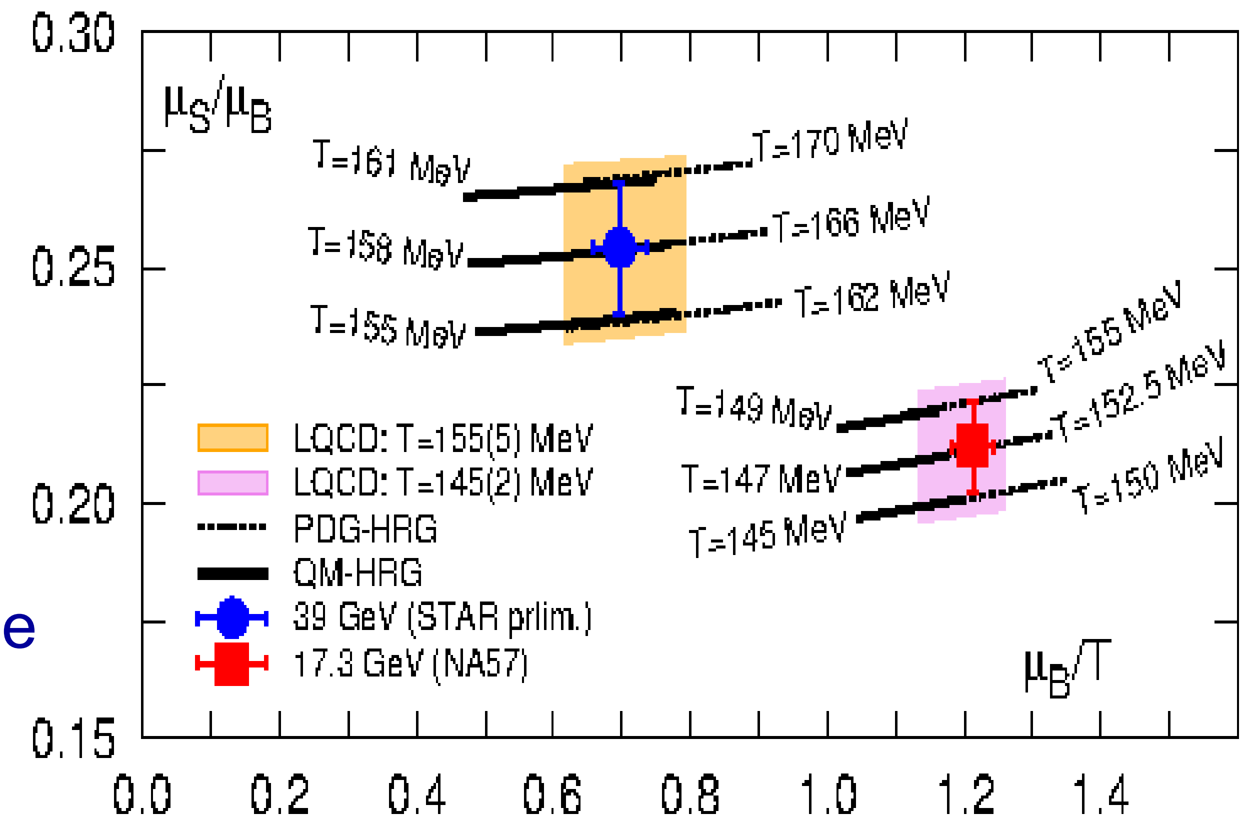
Matter at the edge of QGP:
signatures of undiscovered strange baryons

BNL-Bi: arXiv:1404.6511
to appear in Phys. Rev. Lett.
(editor's suggestion)

strangeness neutrality of the "observed" hadronic medium in HIC

$$n_S = 0 \;\Rightarrow\; \frac{\mu_S}{\mu_B} \simeq \frac{\chi_{11}^{BS}}{\chi_2^S} + O(\mu_B^2)$$

determined by the relative thermodynamic contributions of strange baryons to meson



presence of the additional, undiscovered strange hadrons get imprinted in the yields of ground state strange hadrons

reduction in the "observed" (freeze-out) temperature in the Little Bangs of HIC

Summary: hot-dense lattice QCD

the only viable parameter-free, non-perturbative theoretical technique to study the extreme matter recreated during Little Bangs of heavy-ion collisions at RHIC & LHC starting from the QCD Lagrangian

demands leadership class supercomputing: huge progress over the last years driven by significant algorithmic and specific architecture targeted software developments

no longer a simulation of QCD: actual QCD calculations with physical quark masses and continuum extrapolated results

many important scientific achievements: crossover temperature, equation of state, evidence for strongly interacting QGP, freeze-out parameters, signature of undiscovered hadrons ...

essential partner in the explorations of the extreme matter at RHIC and LHC by providing necessary guidance & interpretations

ultimate goal:

solve the puzzle of QCD phase diagram ...