Hot-dense Lattice QCD:
Supercomputing Extreme Quark-Gluon Matter

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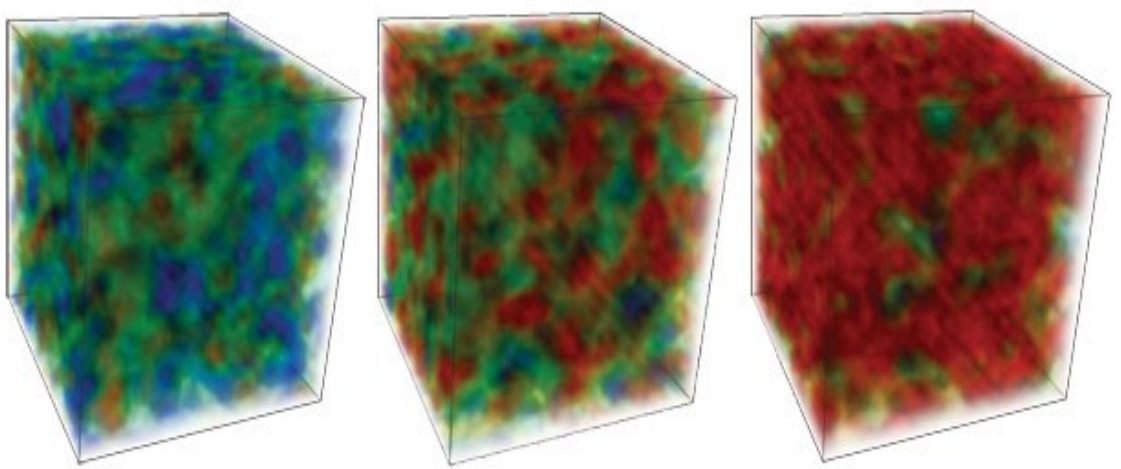
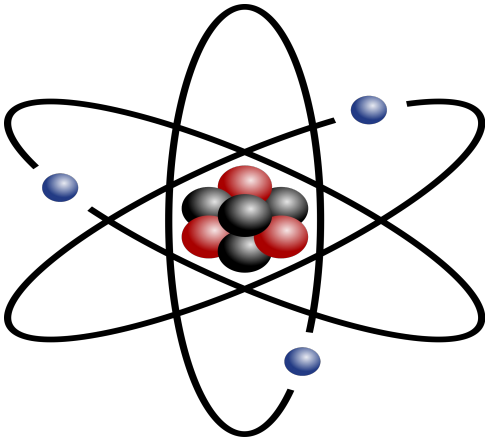
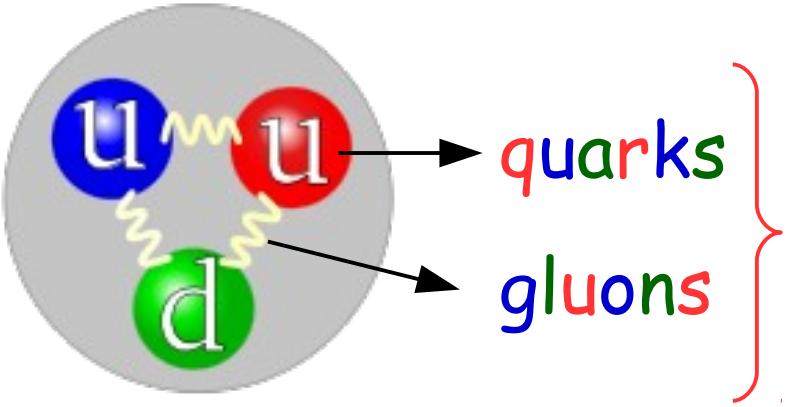


March 2016, BNL

quarks, gluons & QCD





proton

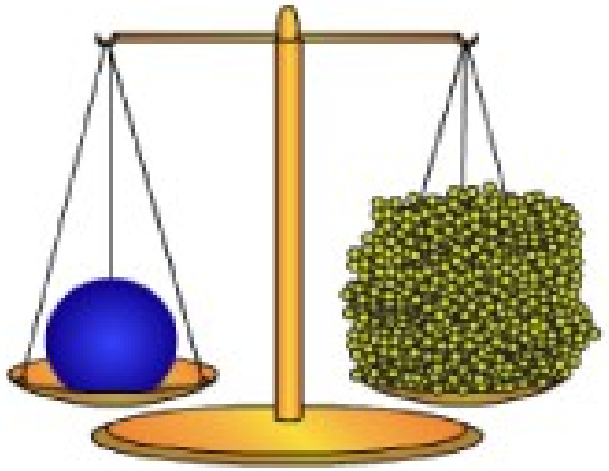
strong force

Quantum ChromoDynamics

(QCD)

strong force

mass of
1 proton



~ mass of
300 quarks

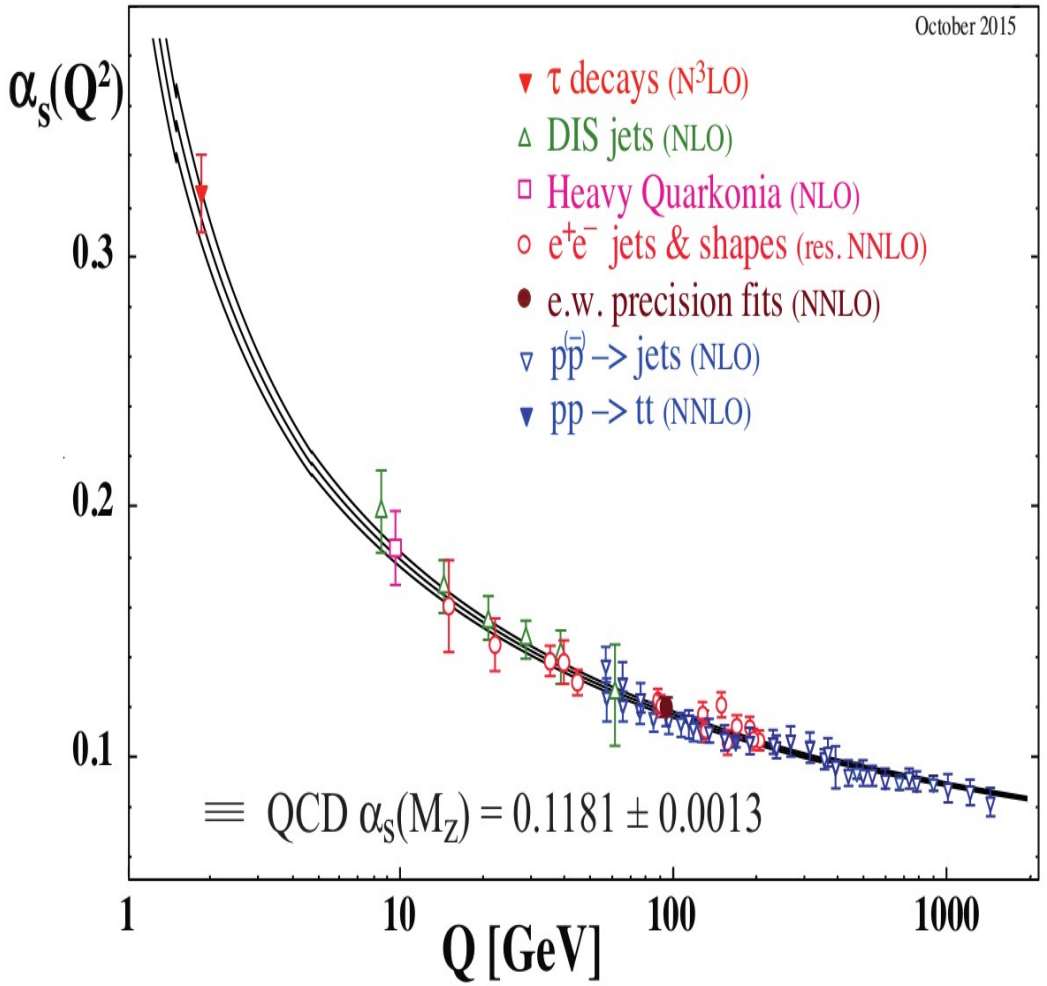
$\sim 10^5$ N

responsible for the mass of
almost entire visible universe

strong force

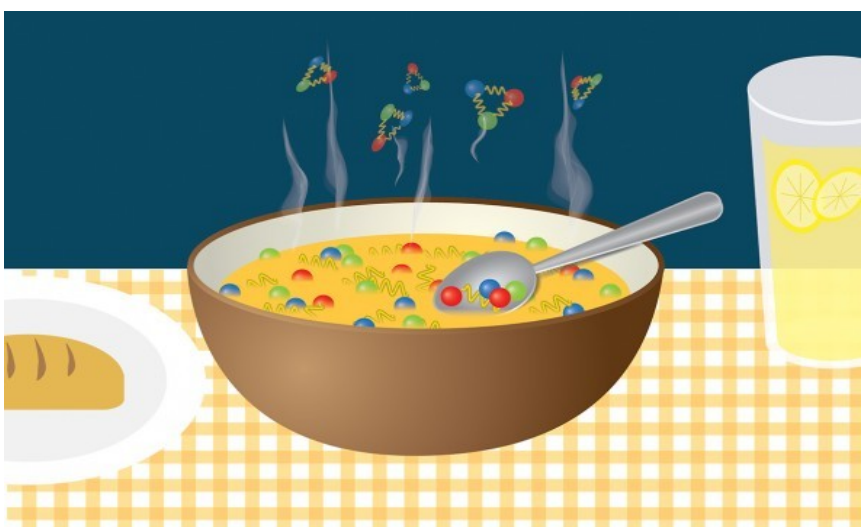
asymptotically free

coupling strength decrease with increasing energy



heat up ordinary nuclear matter up to:

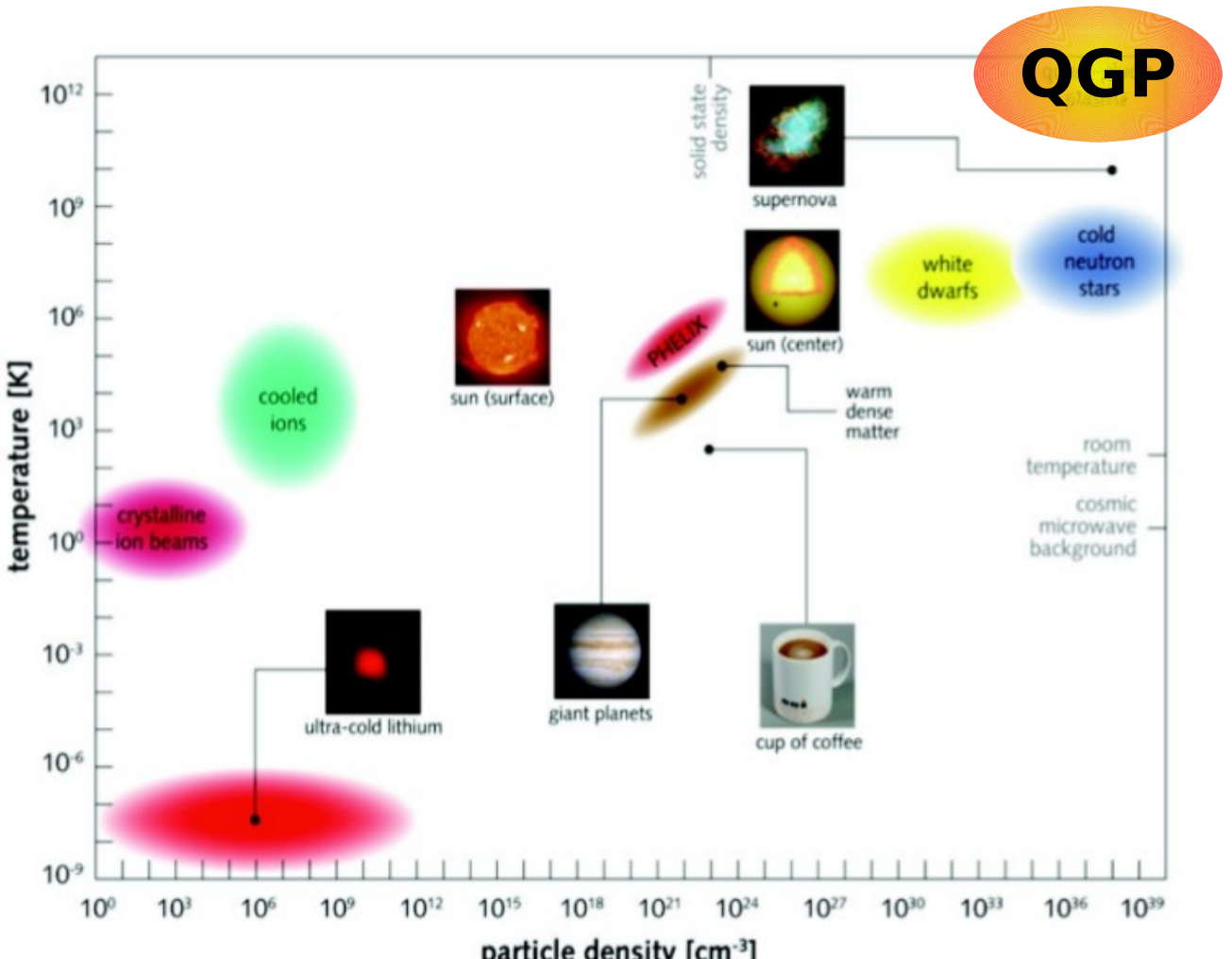
temperature ~ 10^{12} C



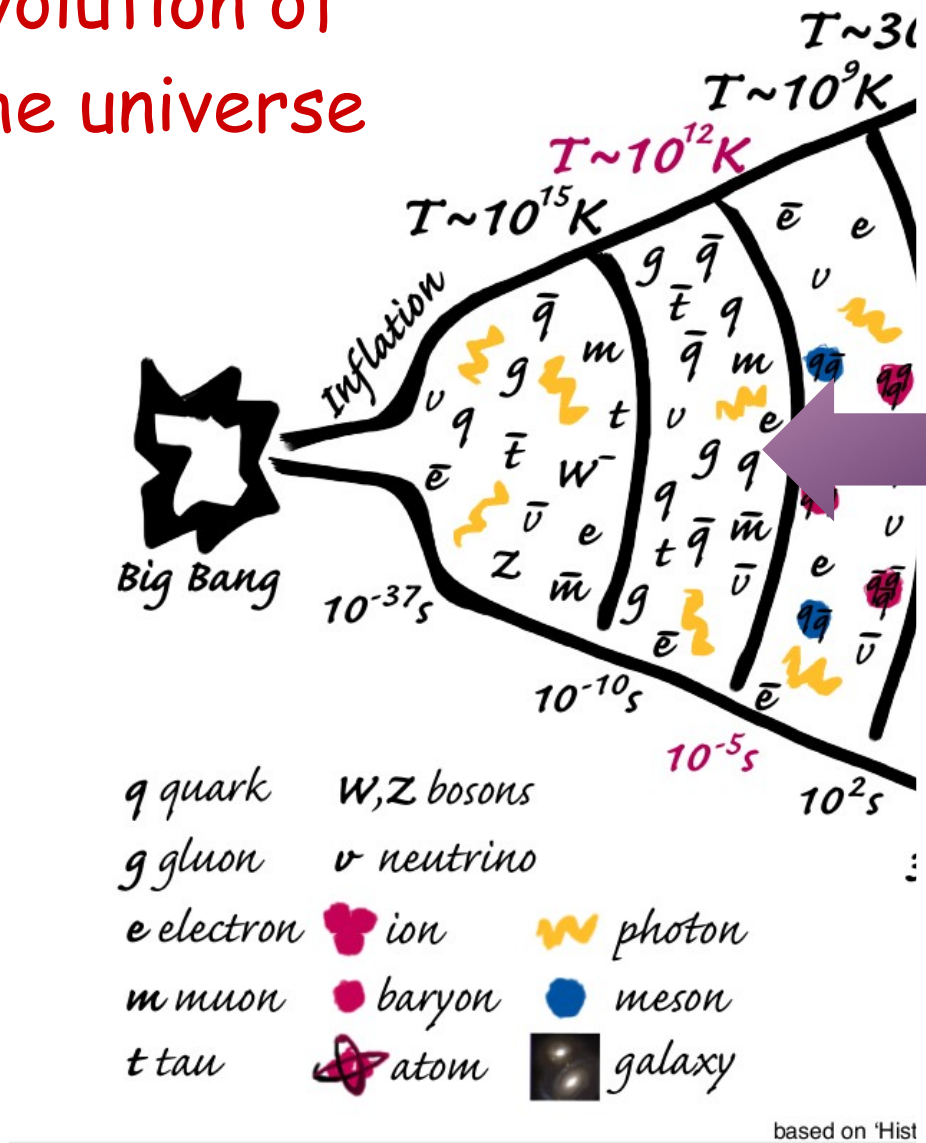
quarks and gluons not confined within nucleons

Quark Gluon Plasma (QGP)

QGP: extreme matter



evolution of the universe

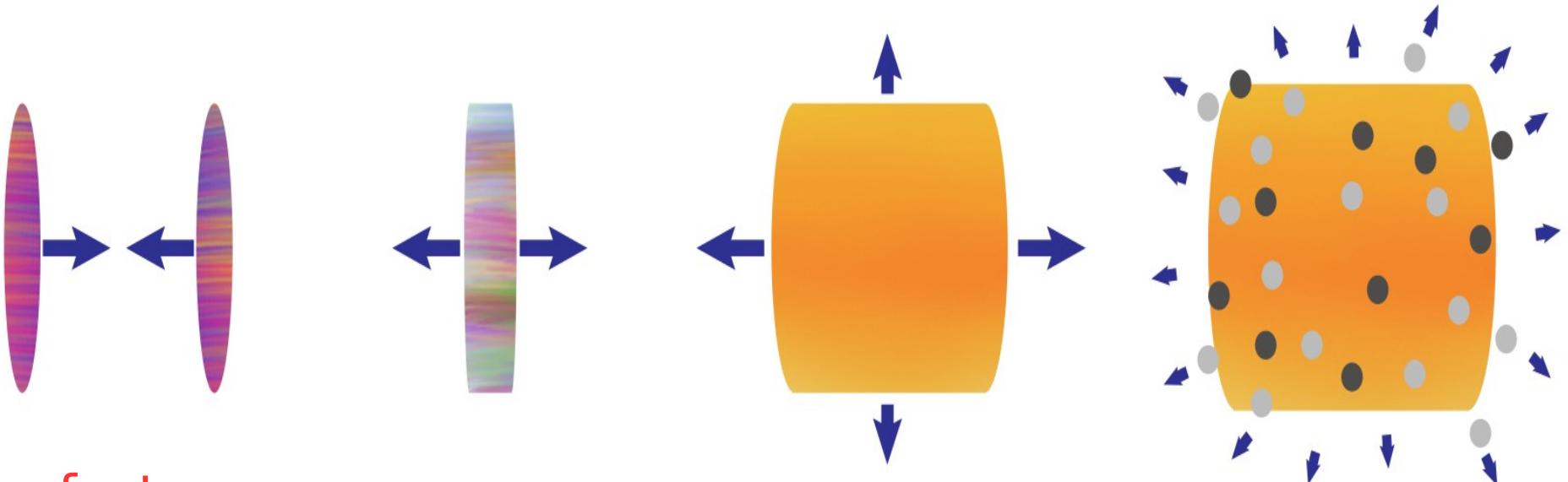


$\sim 10^{-6}$ s after Big Bang

temperature ~ 10^{12}C

~ 70000 x hotter than the center of the sun

recreating QGP on earth: little bangs



fast moving nuclei

nuclei collide

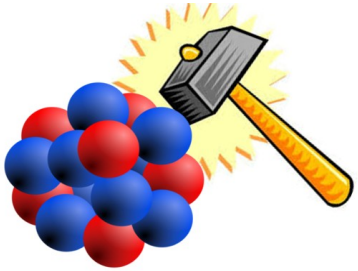
expanding & cooling QGP

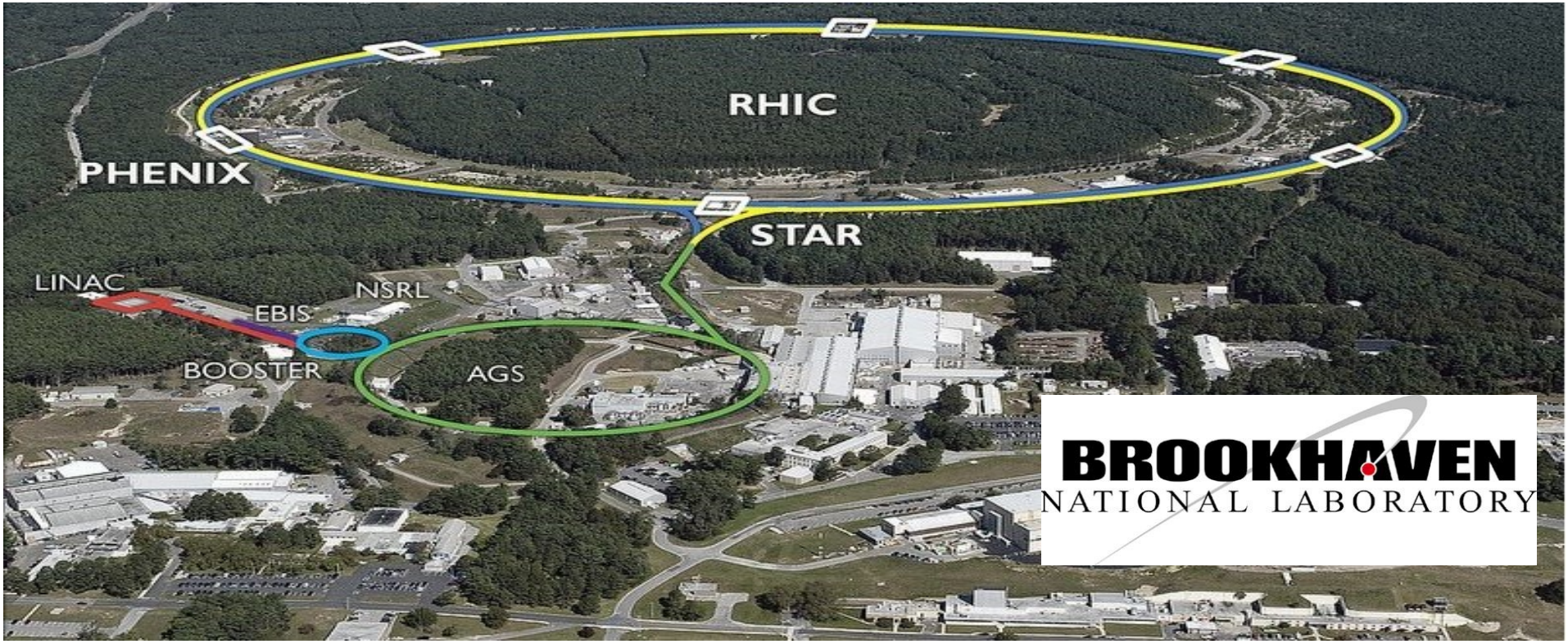
hadrons reformed

observed in experiments

freeze-out

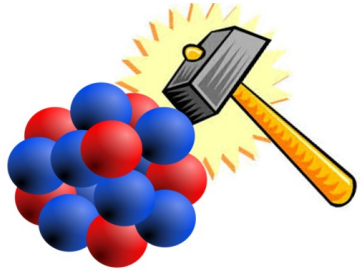
recreating QGP on earth: atom smashers





Relativistic Heavy-Ion Collider (RHIC)

recreating QGP on earth: atom smashers



Large Hadron Collider (LHC)

temperatures reached ...

RHIC: $T_{avg} \approx 220$ MeV $(4 \times 10^{12}$ C$)$

~ 270000 x hotter than the center of the sun

PHENIX: Phys. Rev. Lett. 104, 132301 (2010)

LHC: $T_{avg} \approx 304$ MeV $(5.5 \times 10^{12}$ C$)$

~ 370000 x hotter than the center of the sun

ALICE: Nucl. Phys. A904, 573c (2013)

high enough to recreate the primordial quark-gluon soup ??

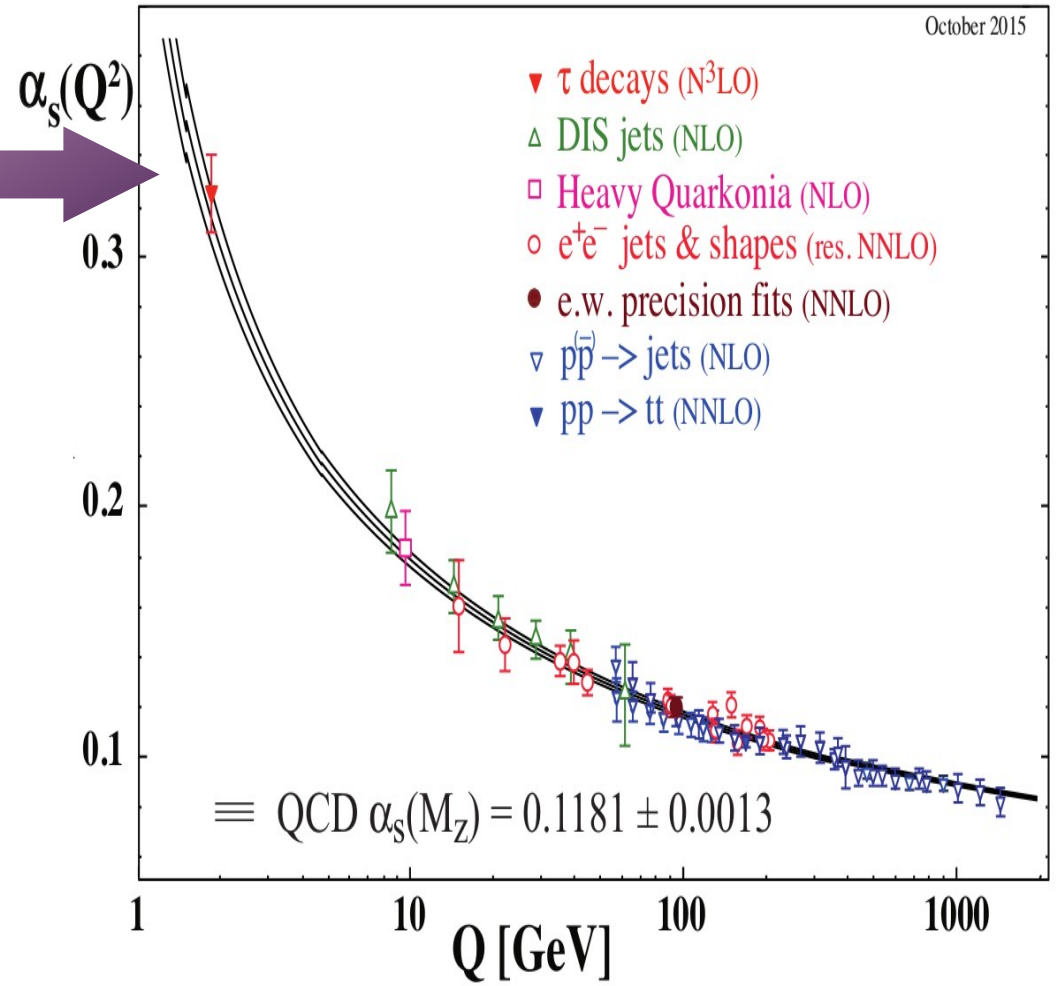
strong force

large coupling constant

$\alpha_{QED} \approx 0.007$

expansion in coupling, i.e. perturbation technique unreliable

require non-perturbative technique

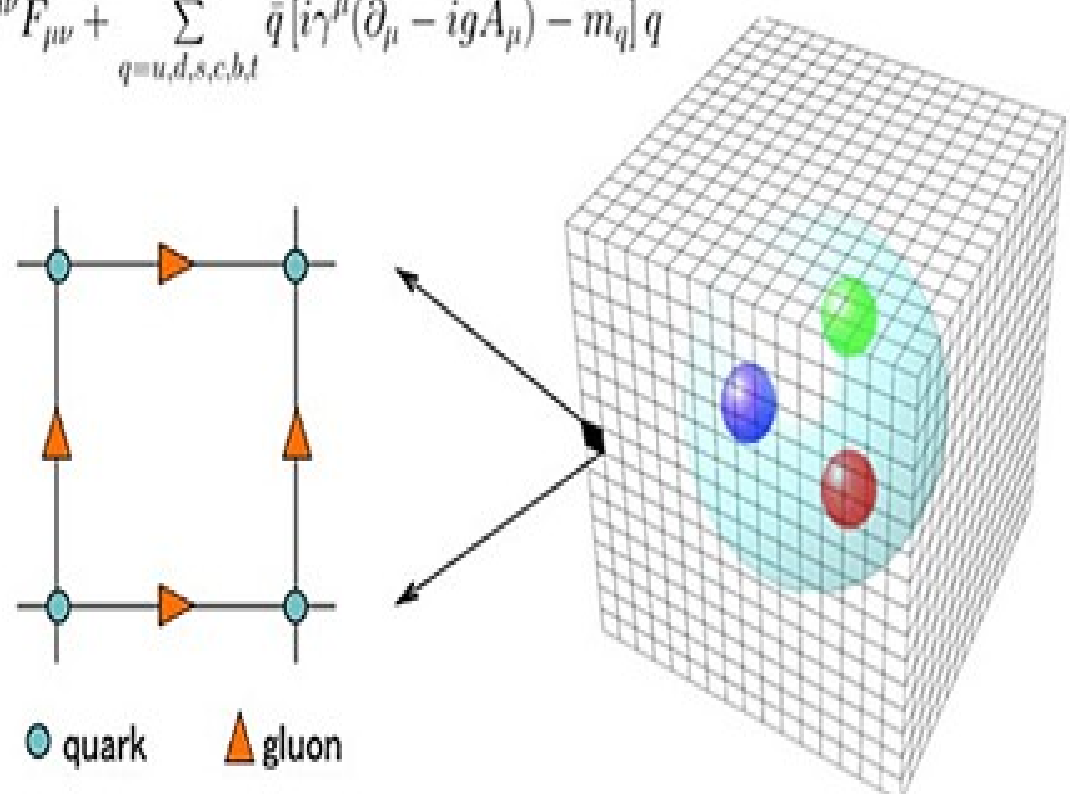


QGP from QCD: hot-dense Lattice QCD

no approximation
no free parameter

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right]q$$



QCD on discretized space-time grid

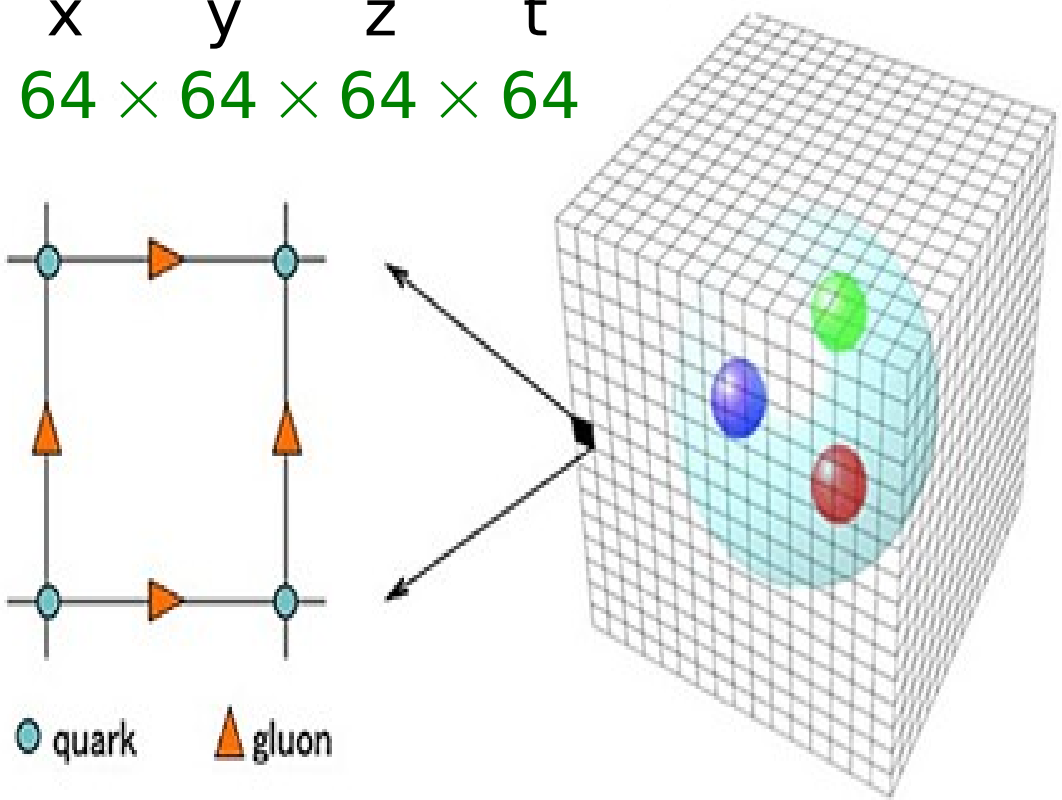
time: Euclidean

QGP from QCD: hot-dense Lattice QCD

grid points

x y z t

$64 \times 64 \times 64 \times 64$



~billion variables

supercomputers

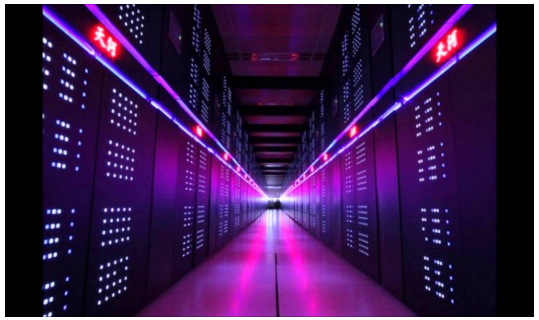
Titan

Oak Ridge National Laboratory

~ million x

… and very high performance codes

TOP500 rank: 1



Tianhe-2, China

TOP500 rank: 2

Titan, USA

TOP500 rank: 3

Sequoia, USA

TOP500 rank: 5

Mira, USA

TOP500 rank: 8

Juqueen, Germany

TOP500 rank: 9

Vulcan, USA

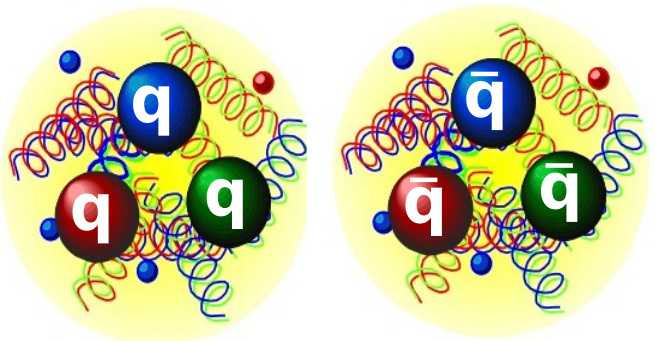
temperature needed to create QGP

baryon number → B

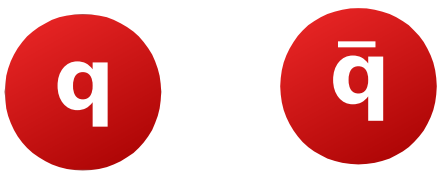
fluctuation → B^2

bound states of quarks: $B^2 = 1$

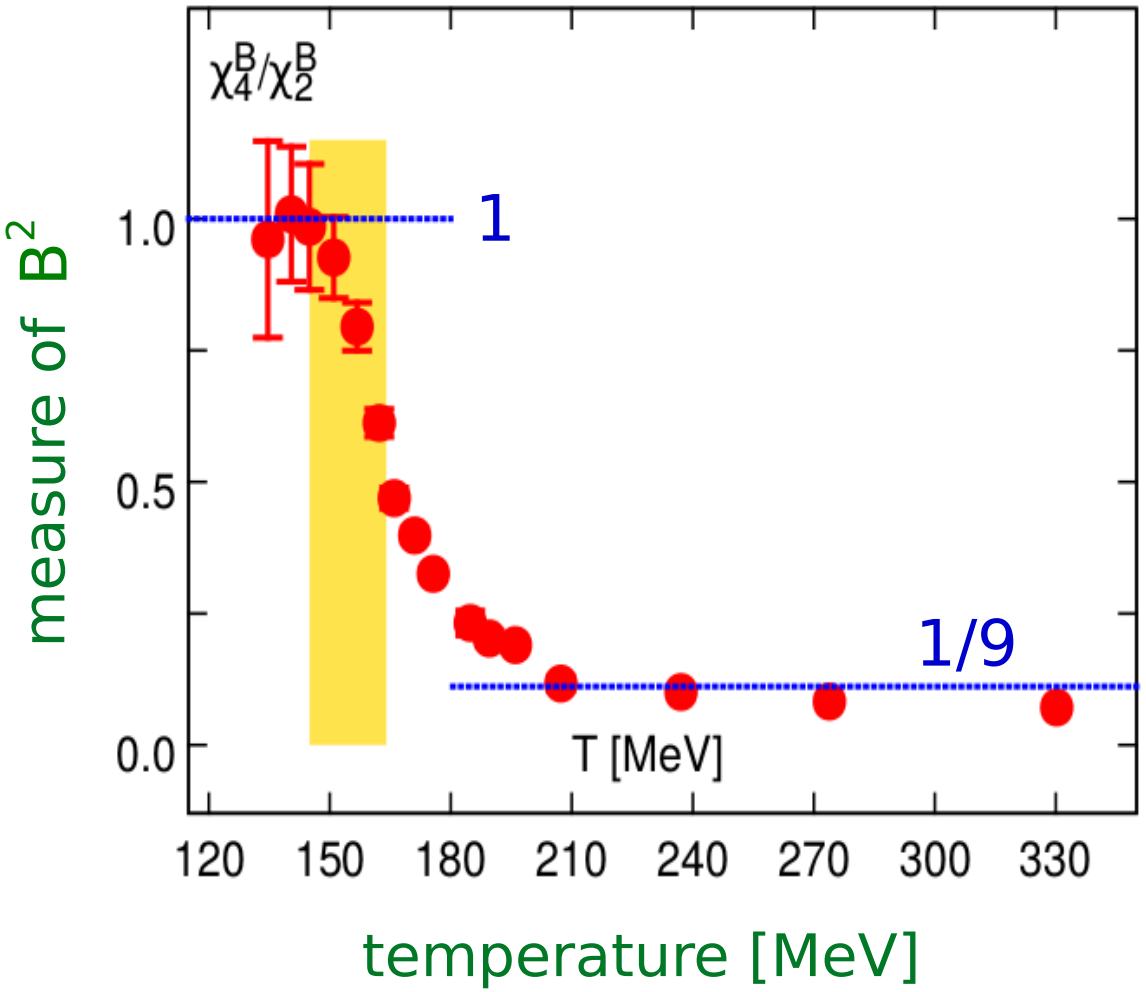
quarks: $B^2 = \frac{1}{9}$



$B = 1, -1$

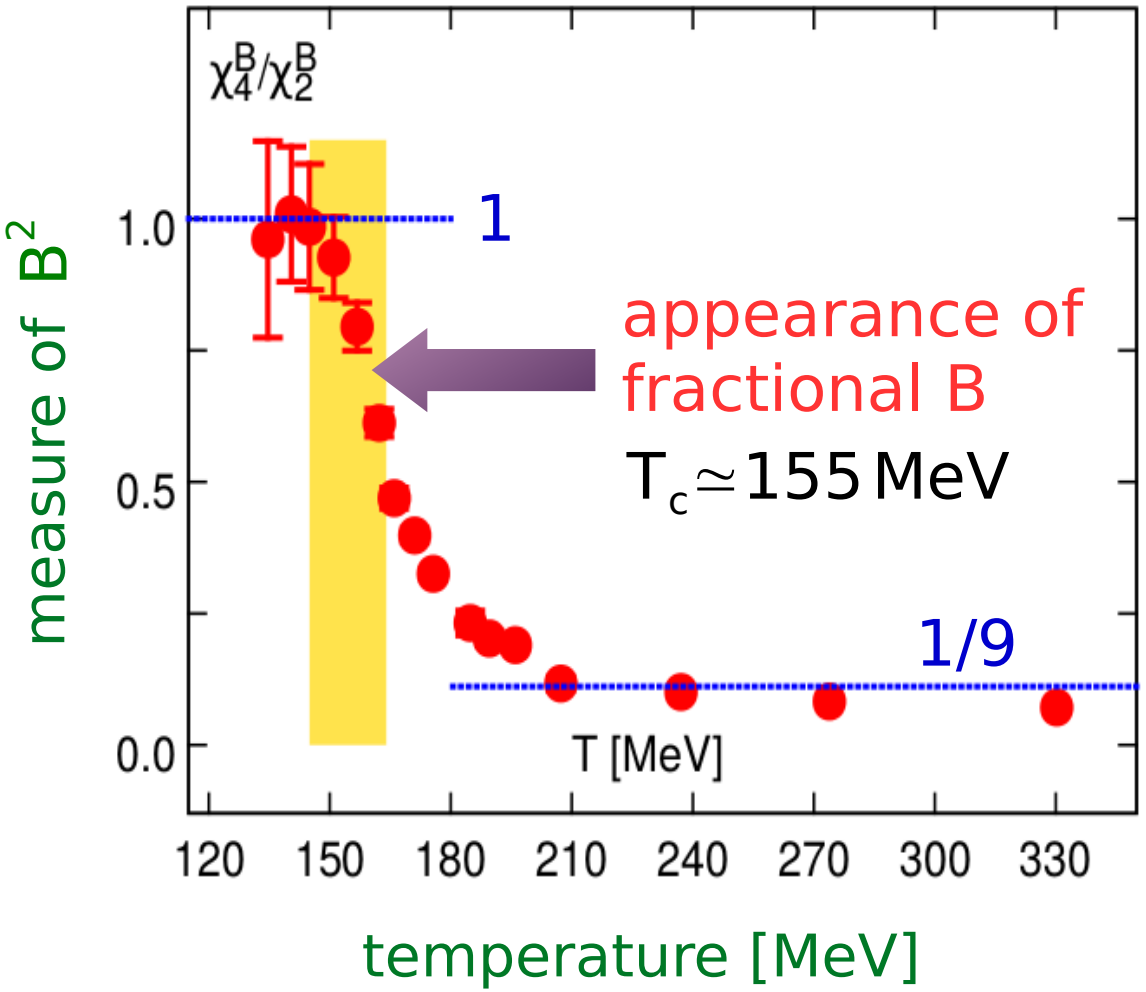


$B = \frac{1}{3}, -\frac{1}{3}$

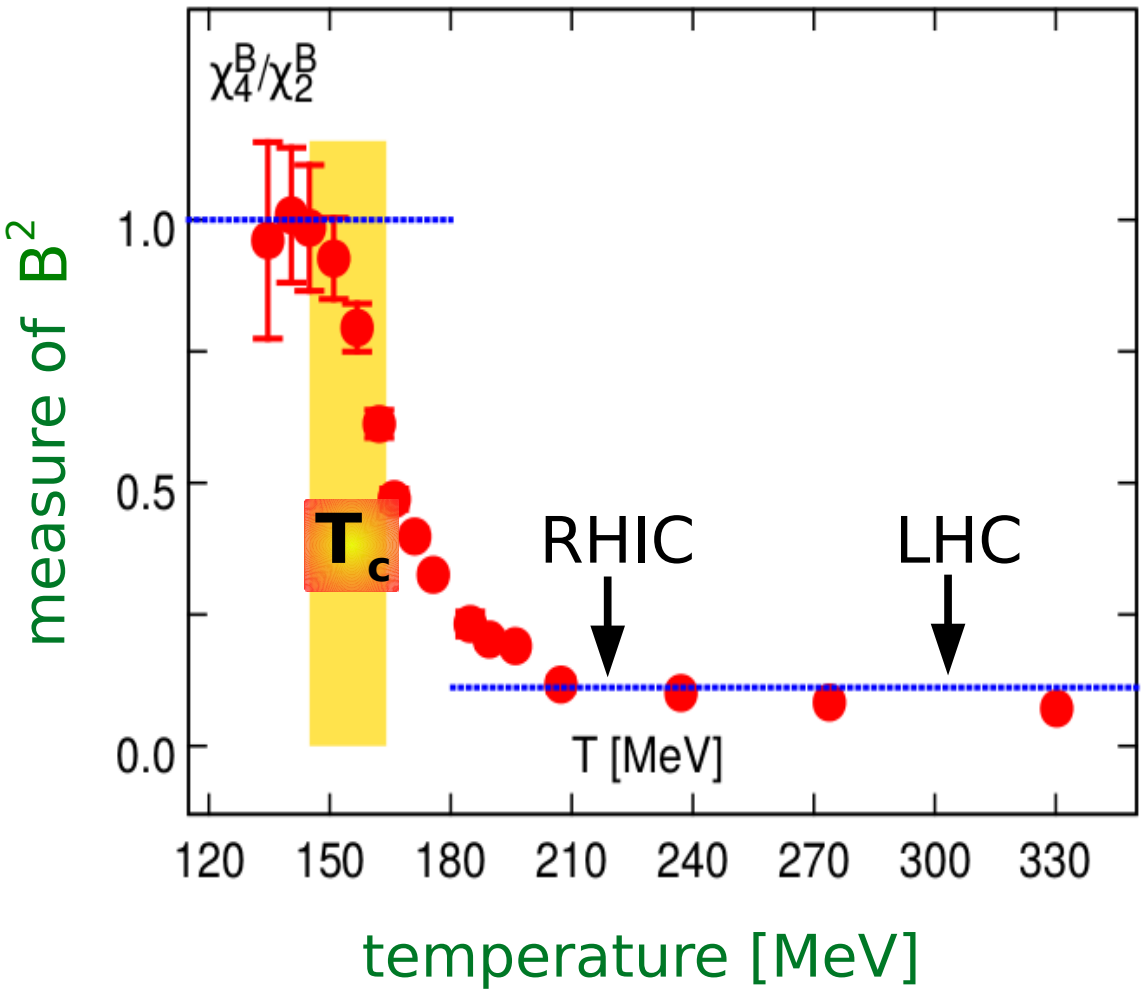


B: baryon number

BNL-Bielefeld-CCNU:
Phys. Rev. Lett. 111, 082301 (2013)
Phys. Lett. B737, 210 (2014)



BNL-Bielefeld-CCNU:
Phys. Rev. Lett. 111, 082301 (2013)
Phys. Lett. B737, 210 (2014)



$T_c = 2.8 \times 10^{12}$ C

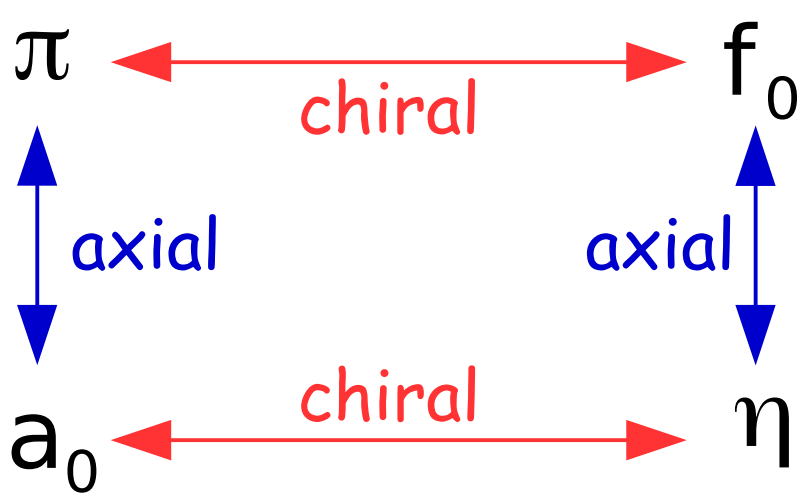
~ 190000 x hotter than the center of the sun

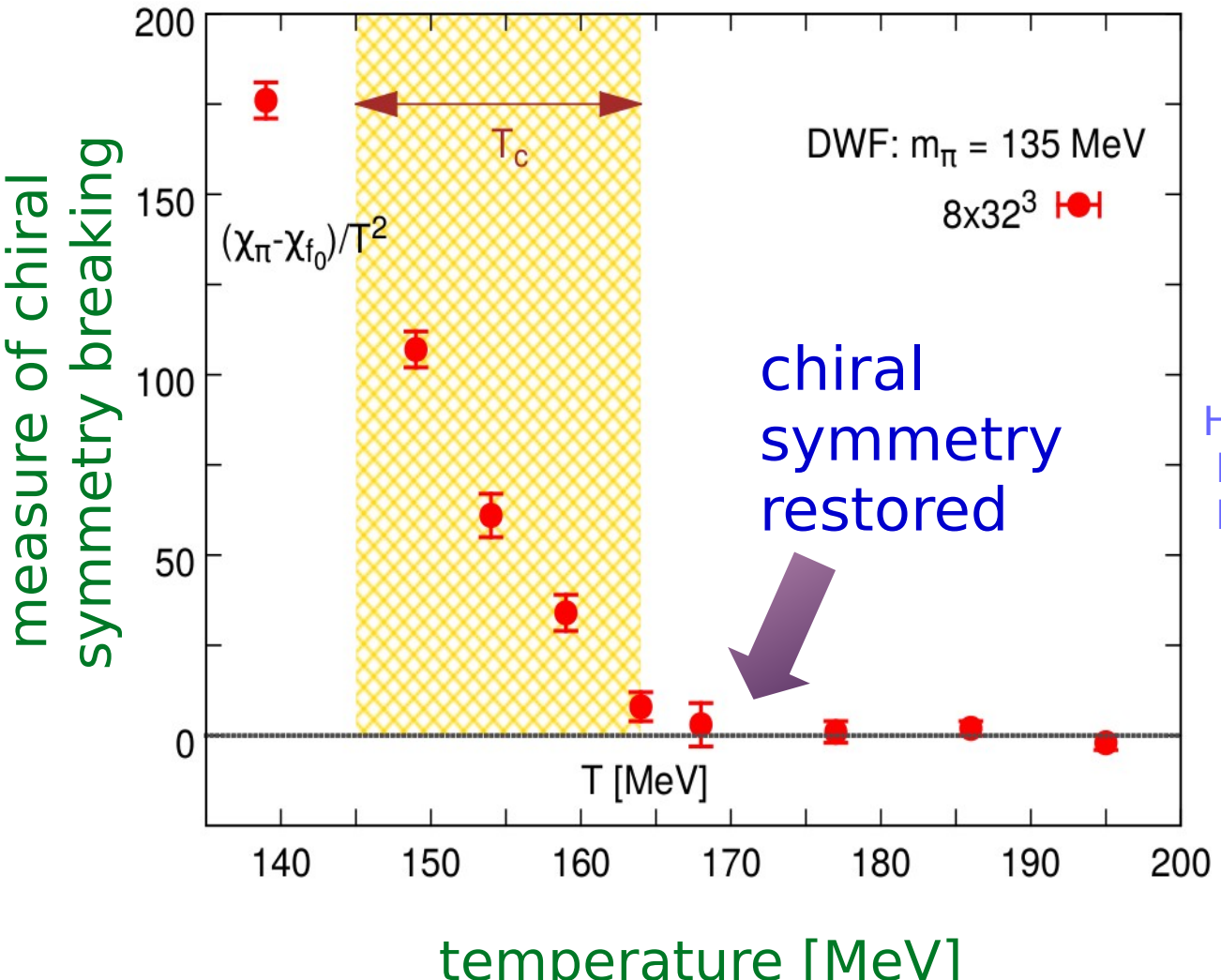
hadrons to quarks: fate of global symmetries

QCD in the limit of massless quarks:

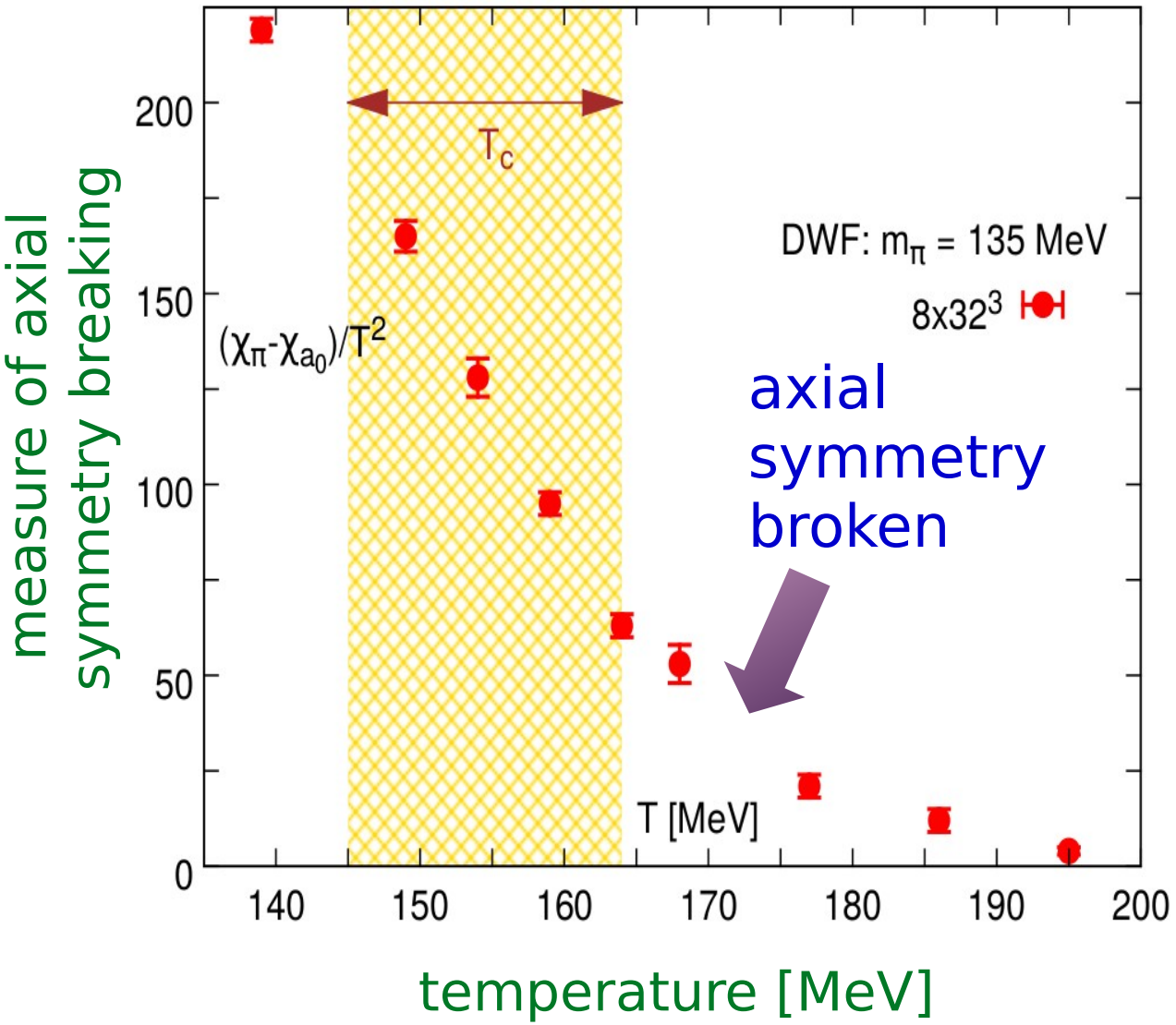
chiral symmetry → spontaneously broken in vacuum

axial symmetry → broken through quantum fluctuations

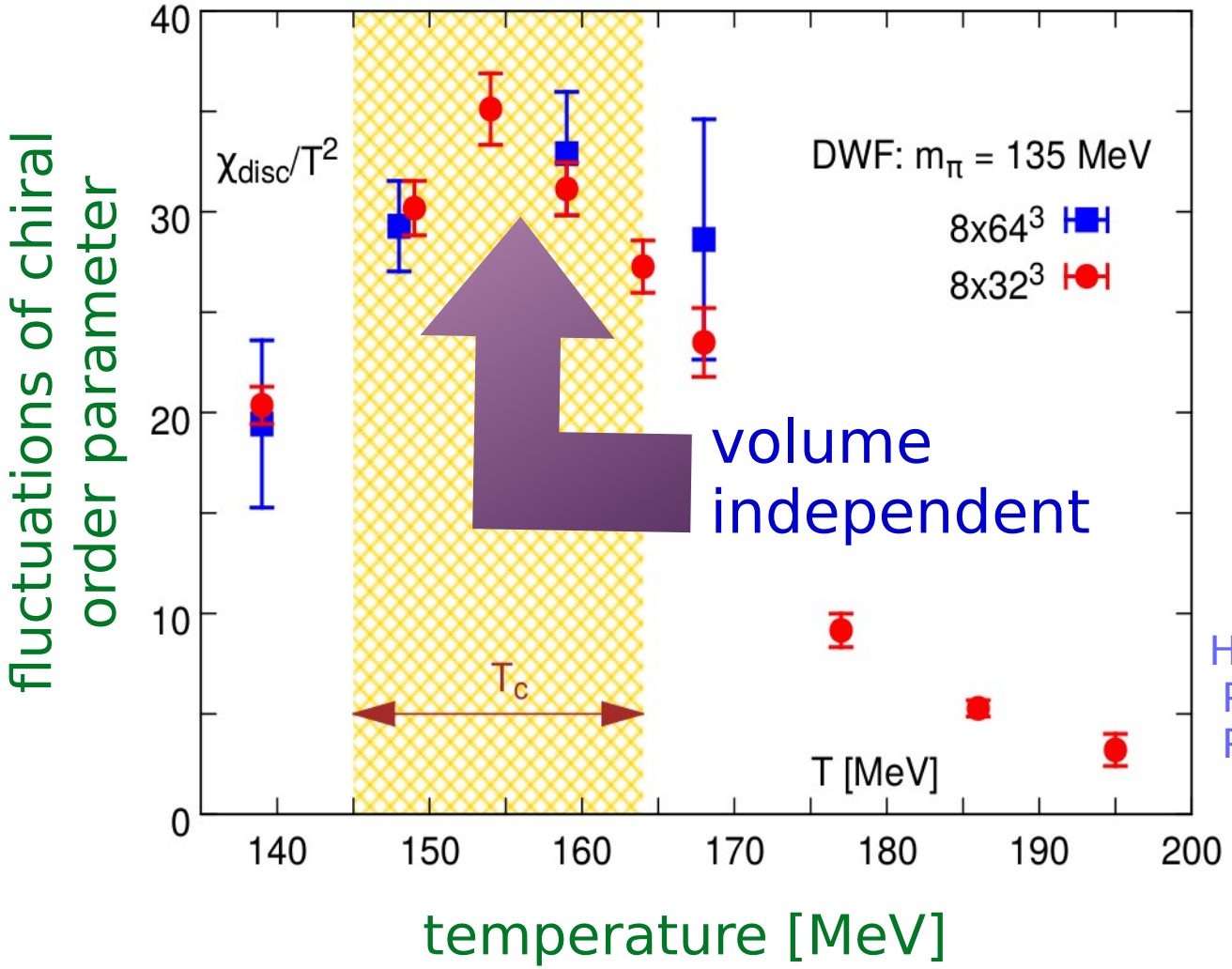




HotQCD:
Phys. Rev. Lett. 113, 082001 (2014)
Phys. Rev. D85, 054503 (2012)



HotQCD:
Phys. Rev. Lett. 113, 082001 (2014)
Phys. Rev. D85, 054503 (2012)

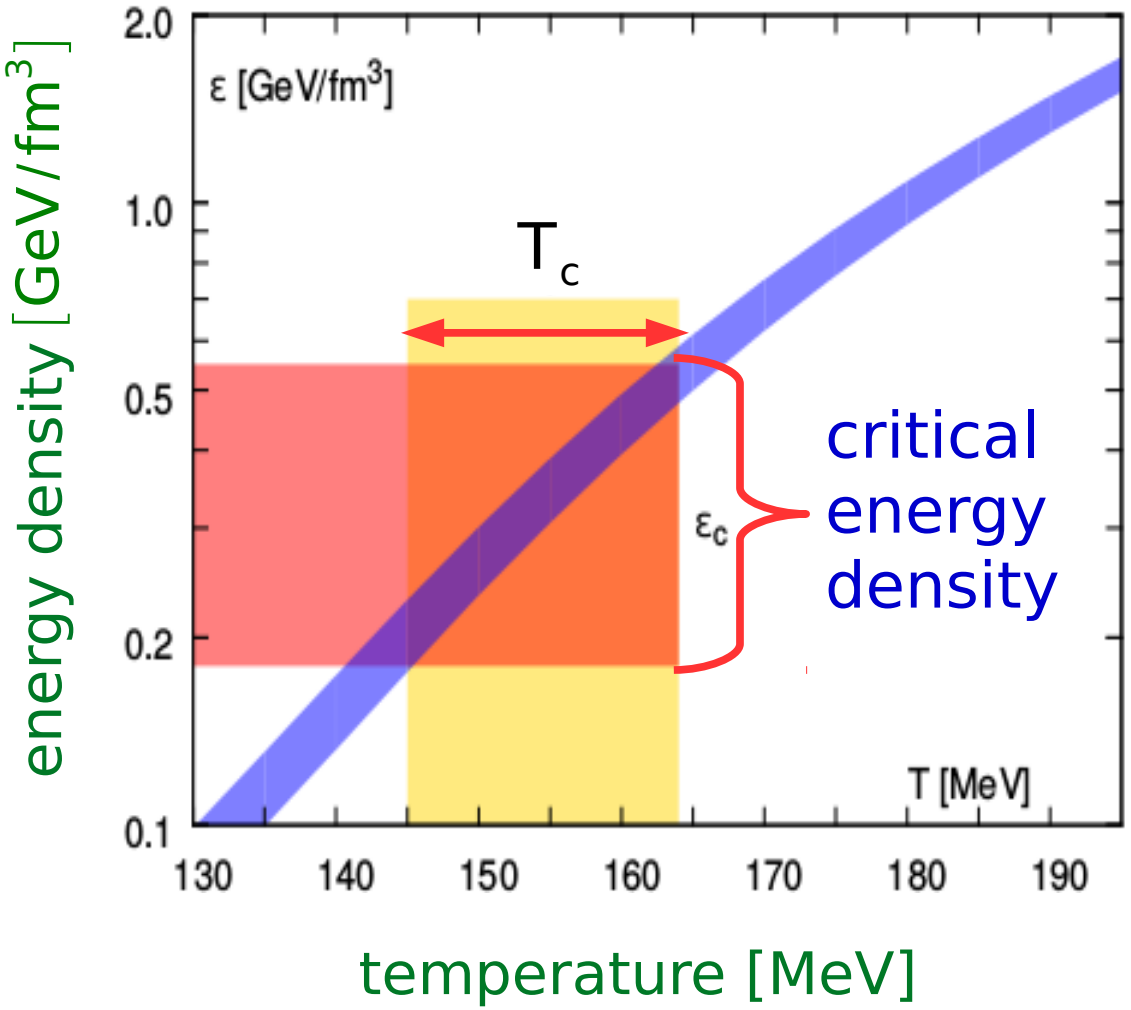


crossover transition

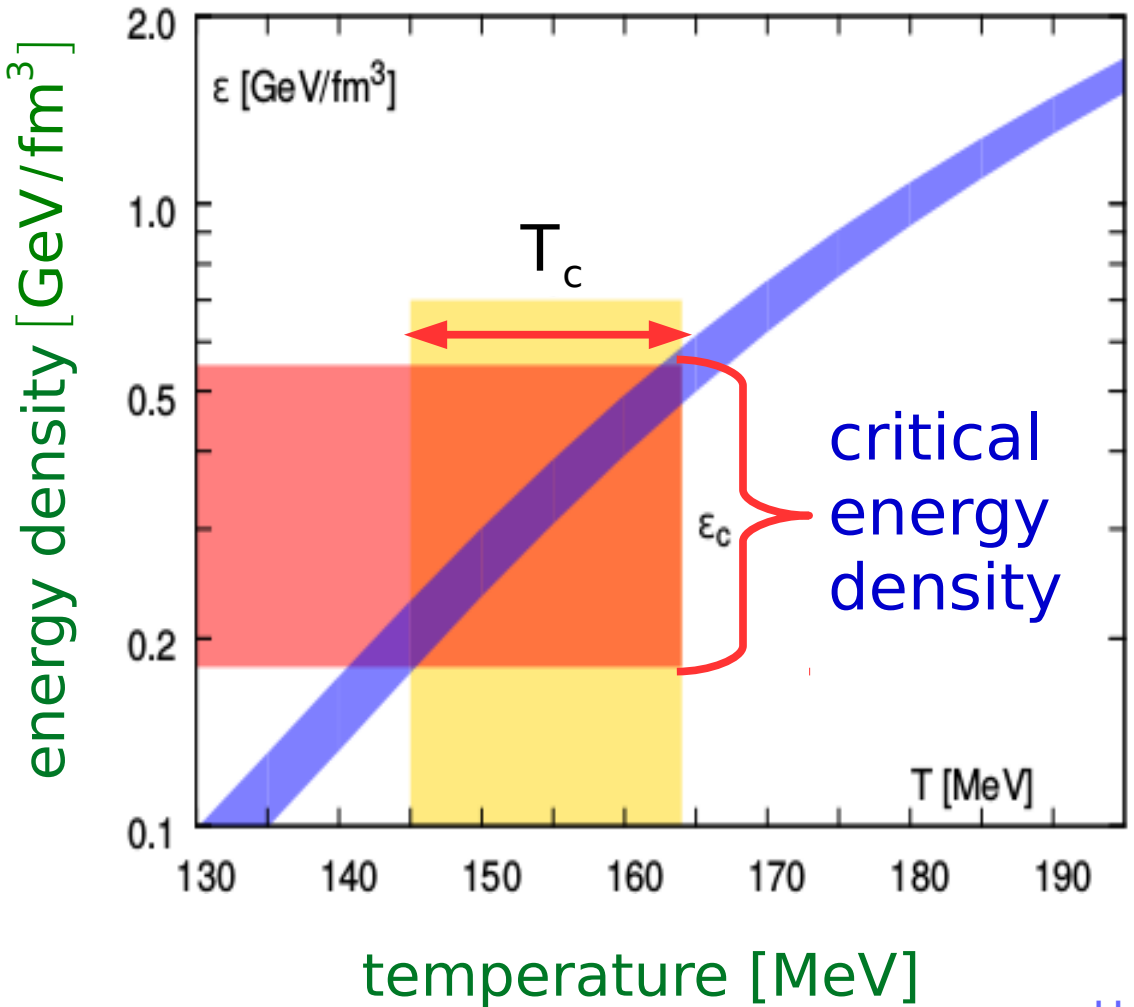
remnant of a 2nd order transition in massless limit

HotQCD:
Phys. Rev. Lett. 113, 082001 (2014)
Phys. Rev. D85, 054503 (2012)

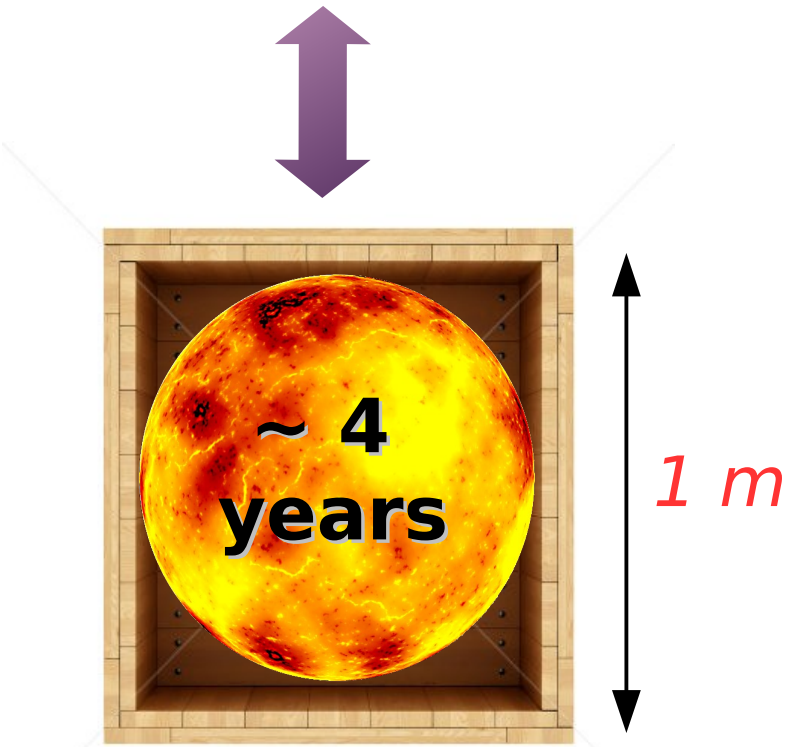
energy needed to create QGP



HotQCD:
Phys. Rev. D90, 094503 (2014)



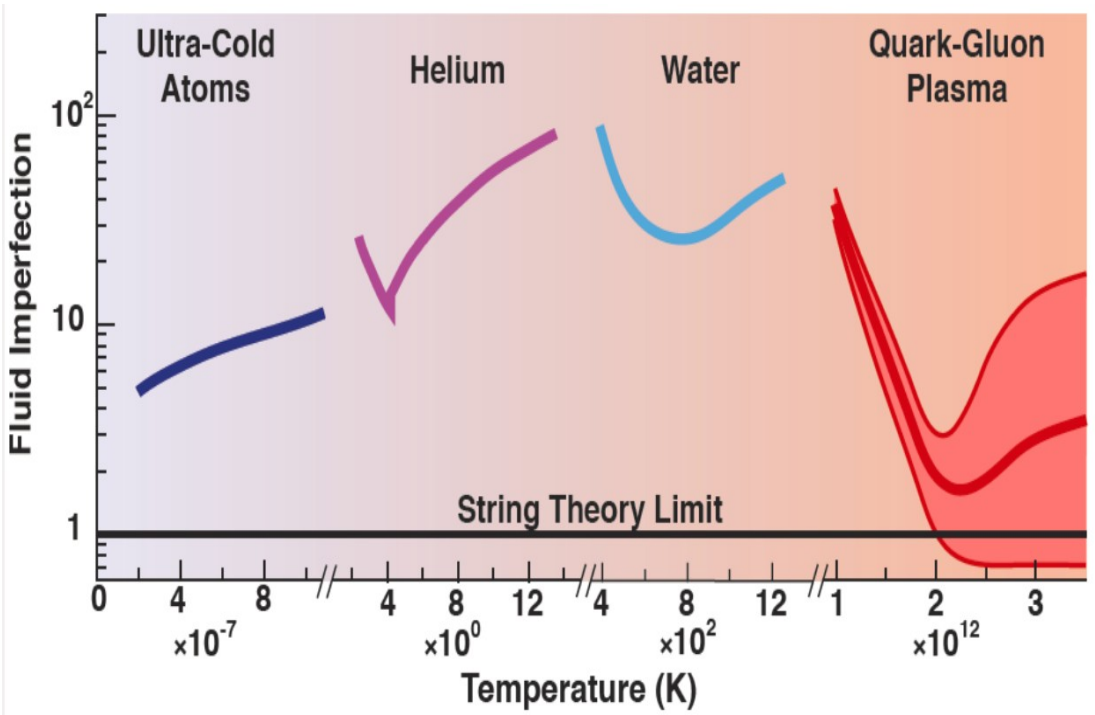
$\epsilon_c \simeq 5\times10^{34}$ J/m^3



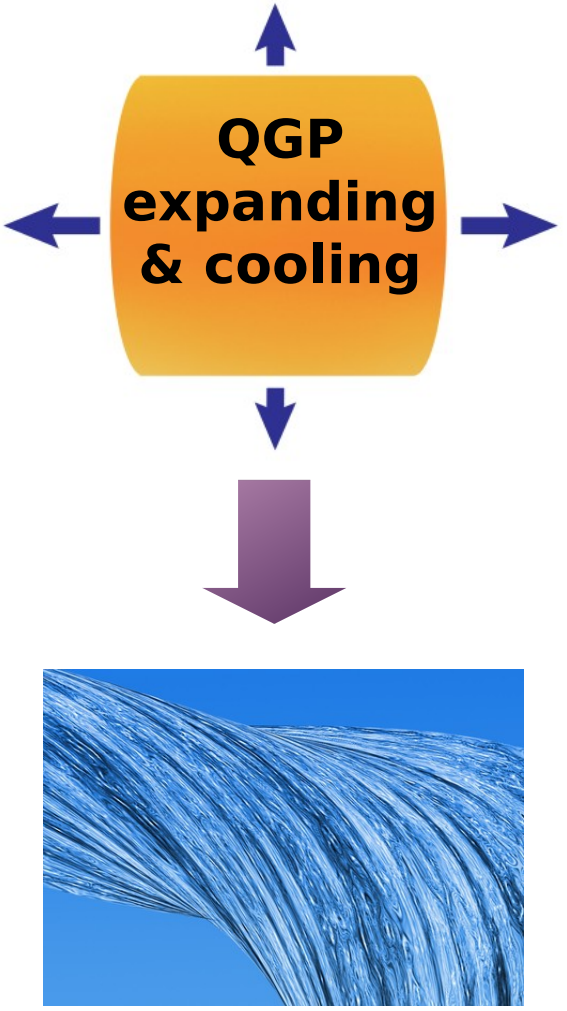
HotQCD:
Phys. Rev. D90, 094503 (2014)

flowing QGP: a nearly perfect liquid ...

$$\frac{4\pi T \eta}{\epsilon + p}$$



temperature [K]



η: shear viscosity ϵ: energy density

T: temperature p: pressure

lattice QCD: microscopic properties of QGP

$\epsilon(T)$, $p(T)$

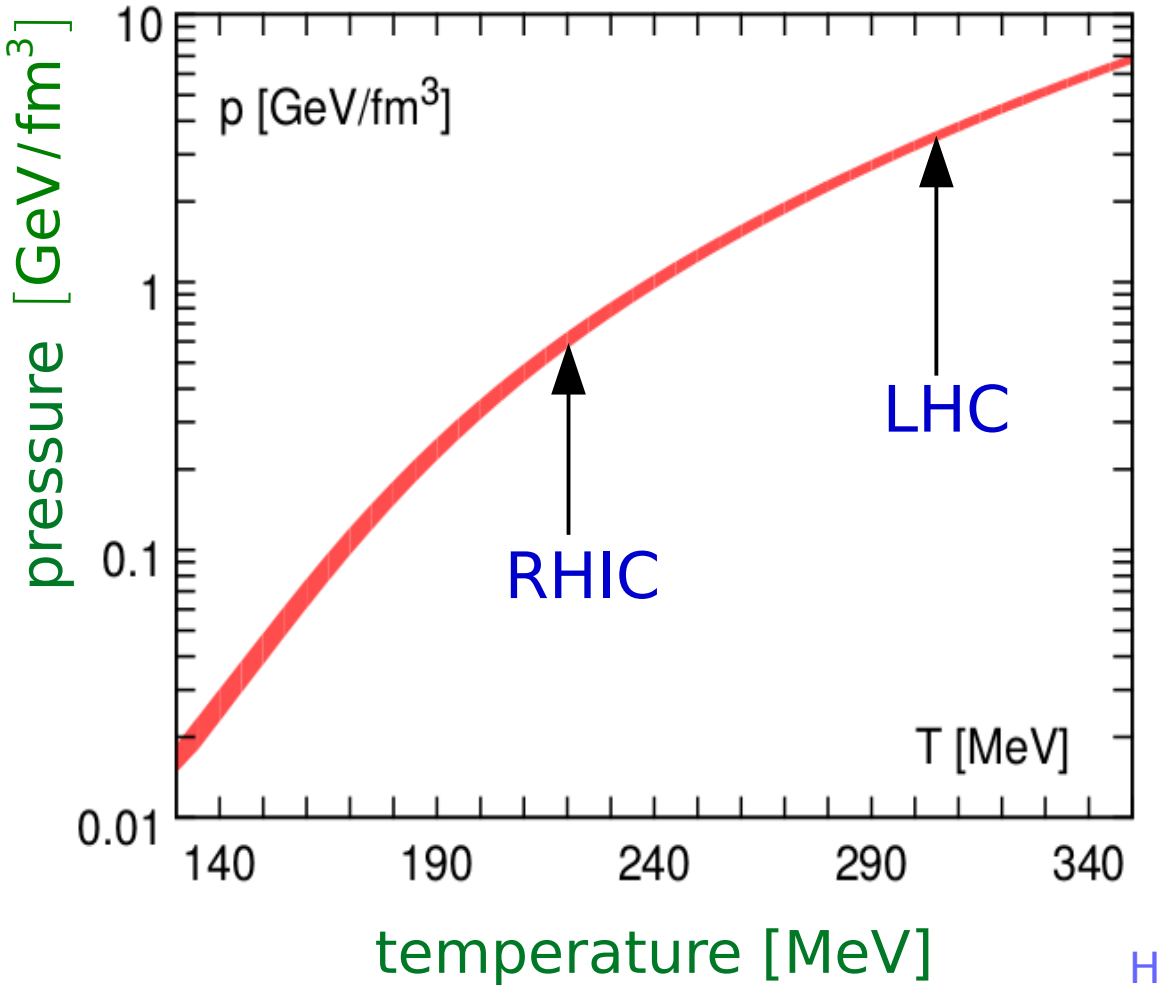
hydrodynamic modeling

$$\frac{4\pi T \eta}{\epsilon + p}$$

experimental measurements

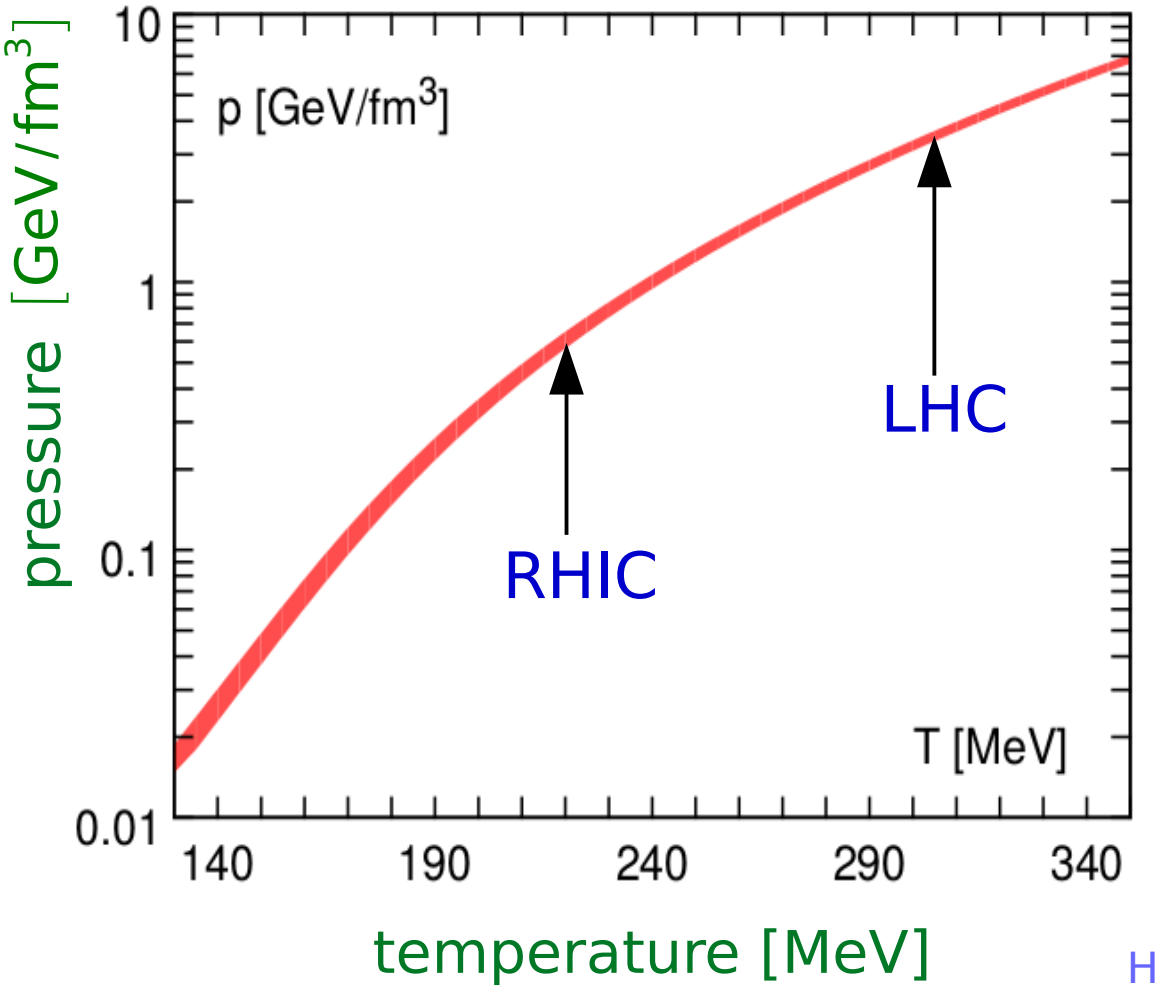
energy-momentum conservation

pressure inside QGP

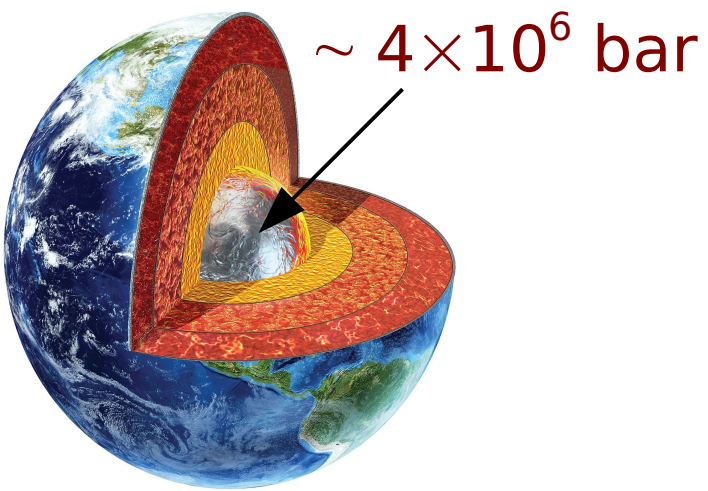


RHIC: $p \simeq 10^{30}$ bar

HotQCD:
Phys. Rev. D90, 094503 (2014)



RHIC: $p \simeq 10^{30}$ bar



HotQCD:
Phys. Rev. D90, 094503 (2014)

extreme hadronic matter: uncharted strange baryons

hadronic pressure = $\sum p_h$

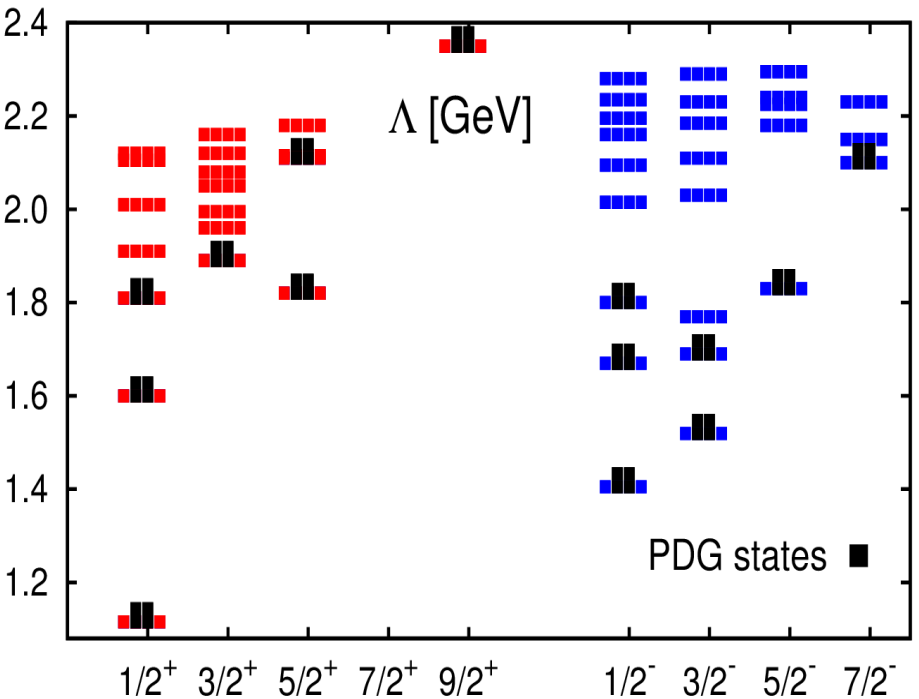
expt. observed hadrons

+
unobserved hadrons

contributions increase
with increasing temperature

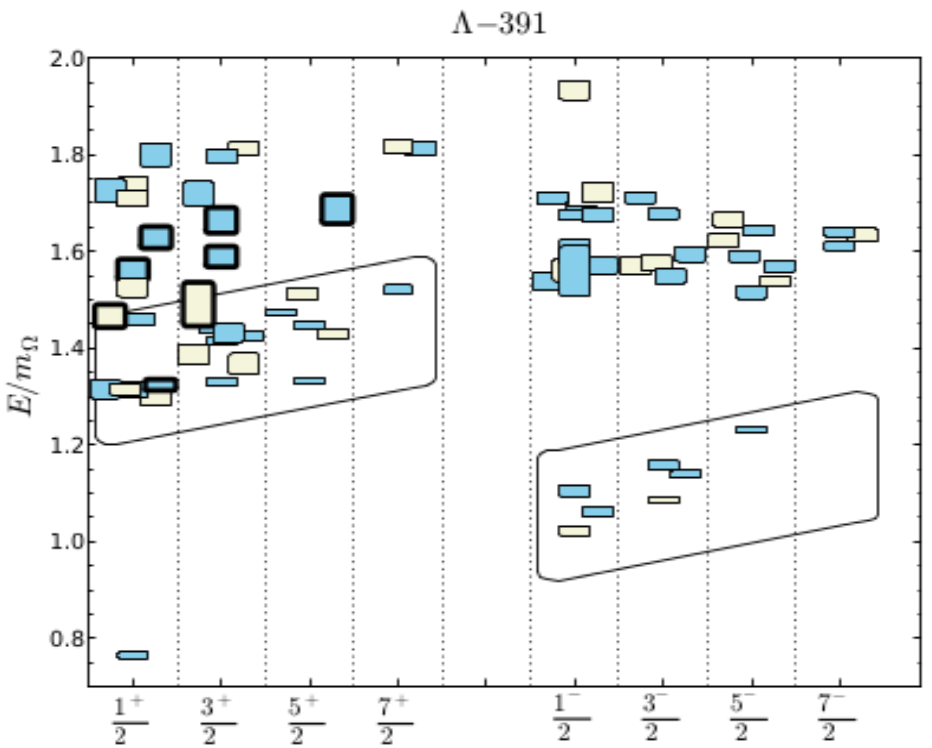
uncharted strange baryons

Quark Model

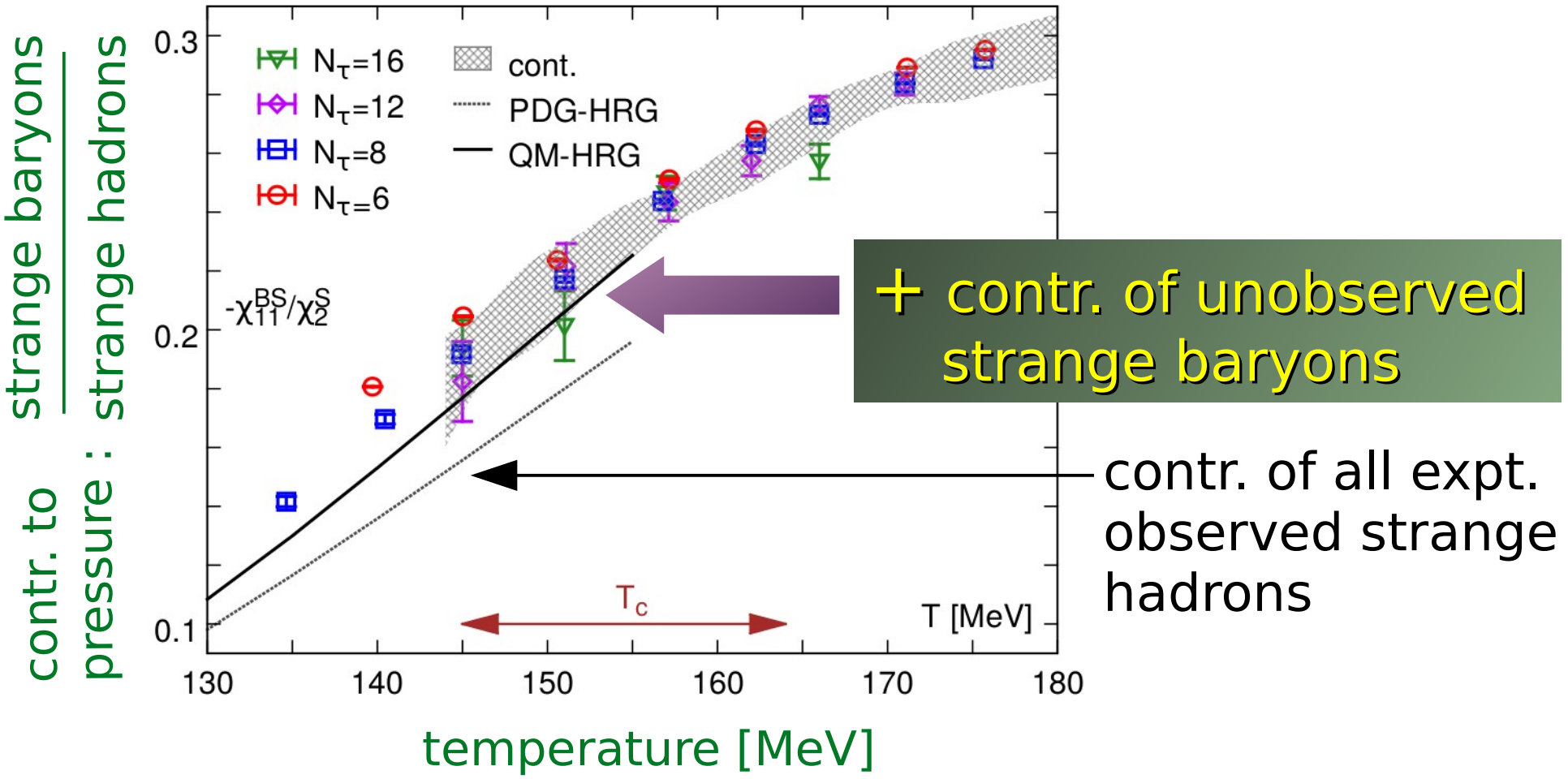


Capstick-Isgur:
Phys. Rev. D34, 2809 (1986)

lattice QCD: T=0



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



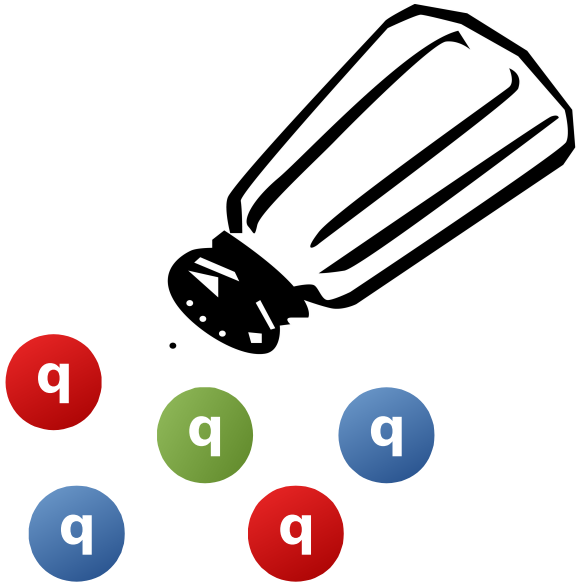
indirect signatures in heavy-ion experiments

BNL-Bielefeld-CCNU: Phys. Rev. Lett. 113, 072001 (2014)

baryon-rich QGP

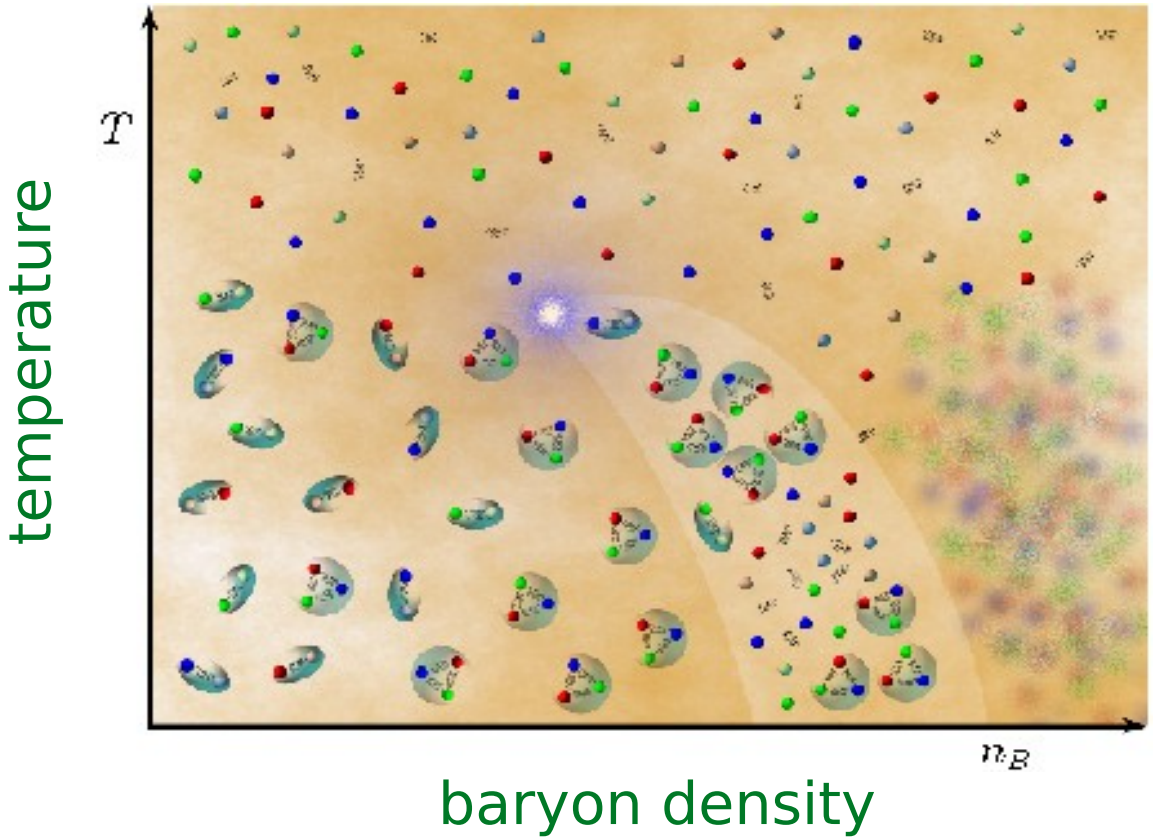
baryon density

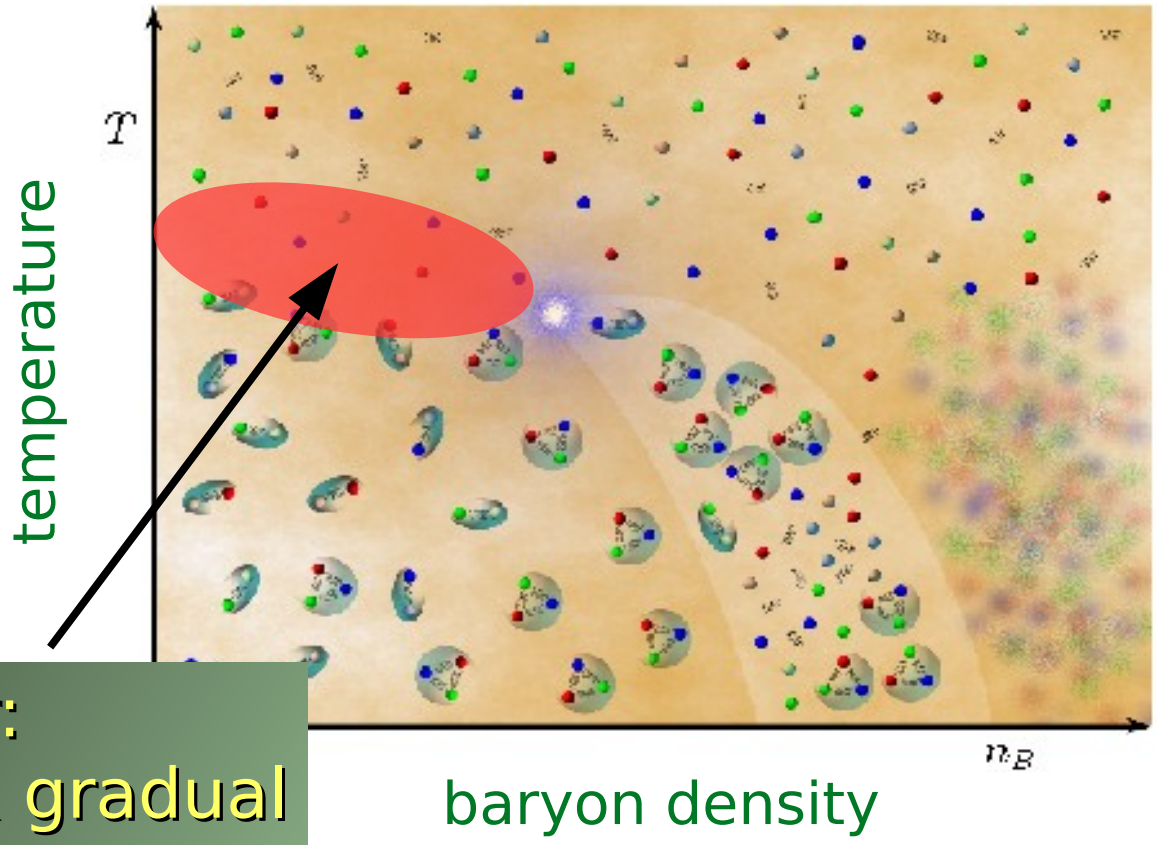
$n_B > 0$



more quarks
than anti-quarks

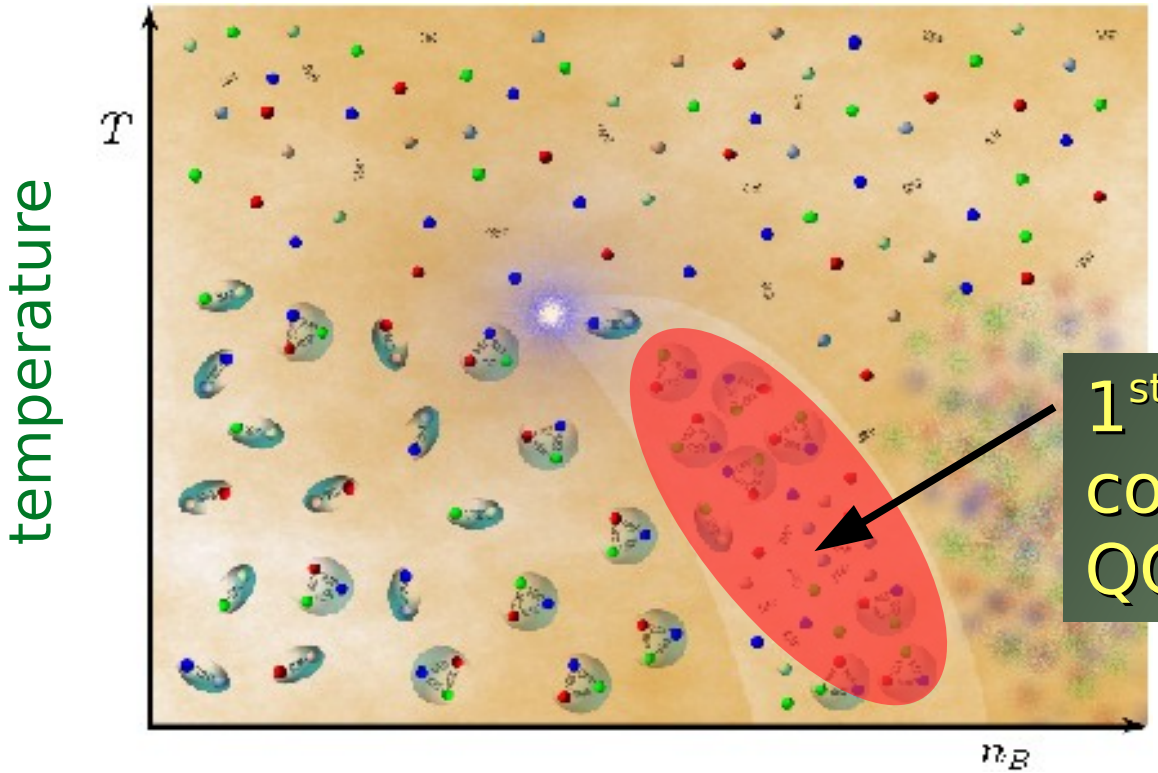
phase diagram of quark-gluon matter





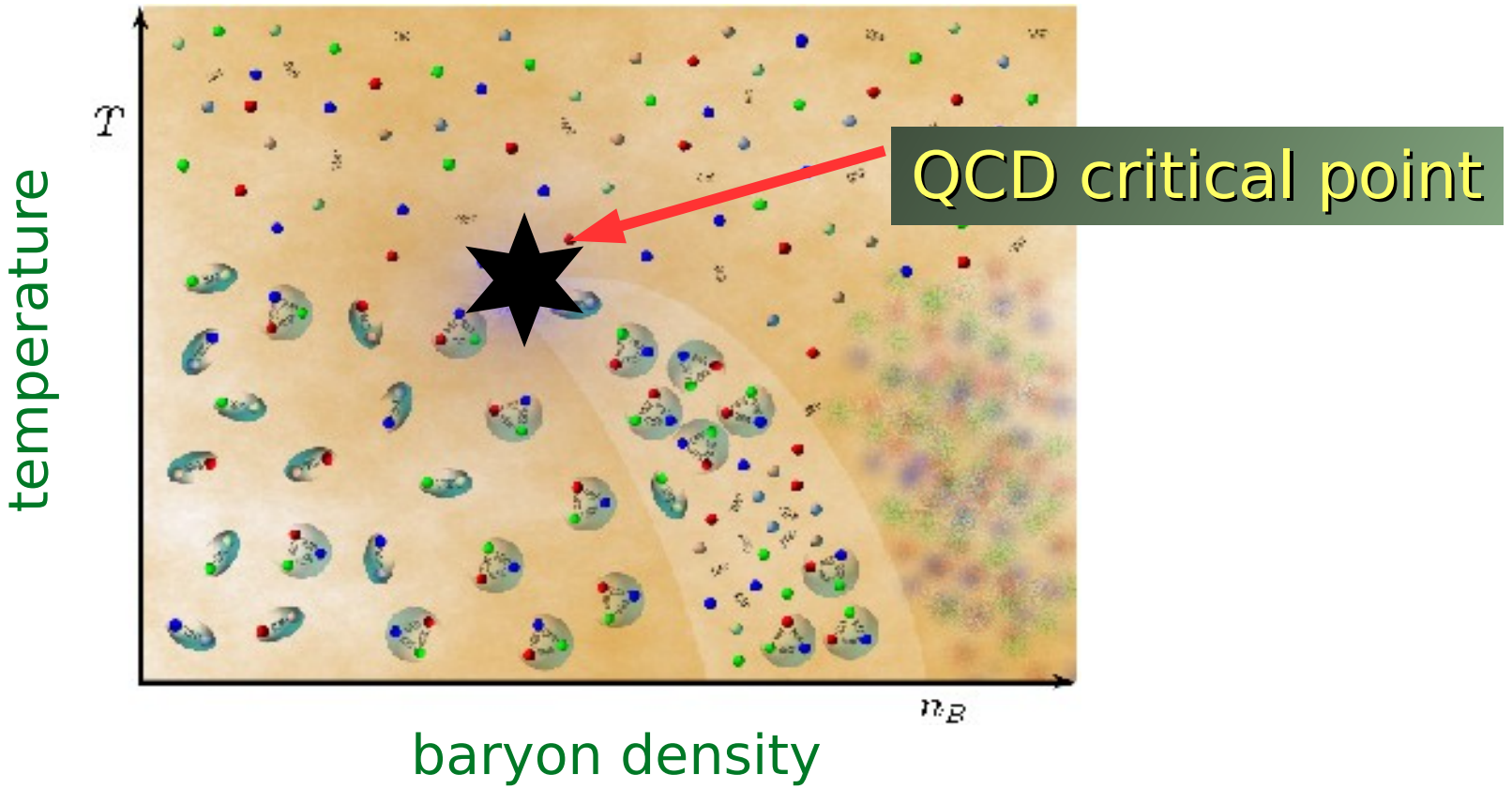
crossover:
smooth & gradual

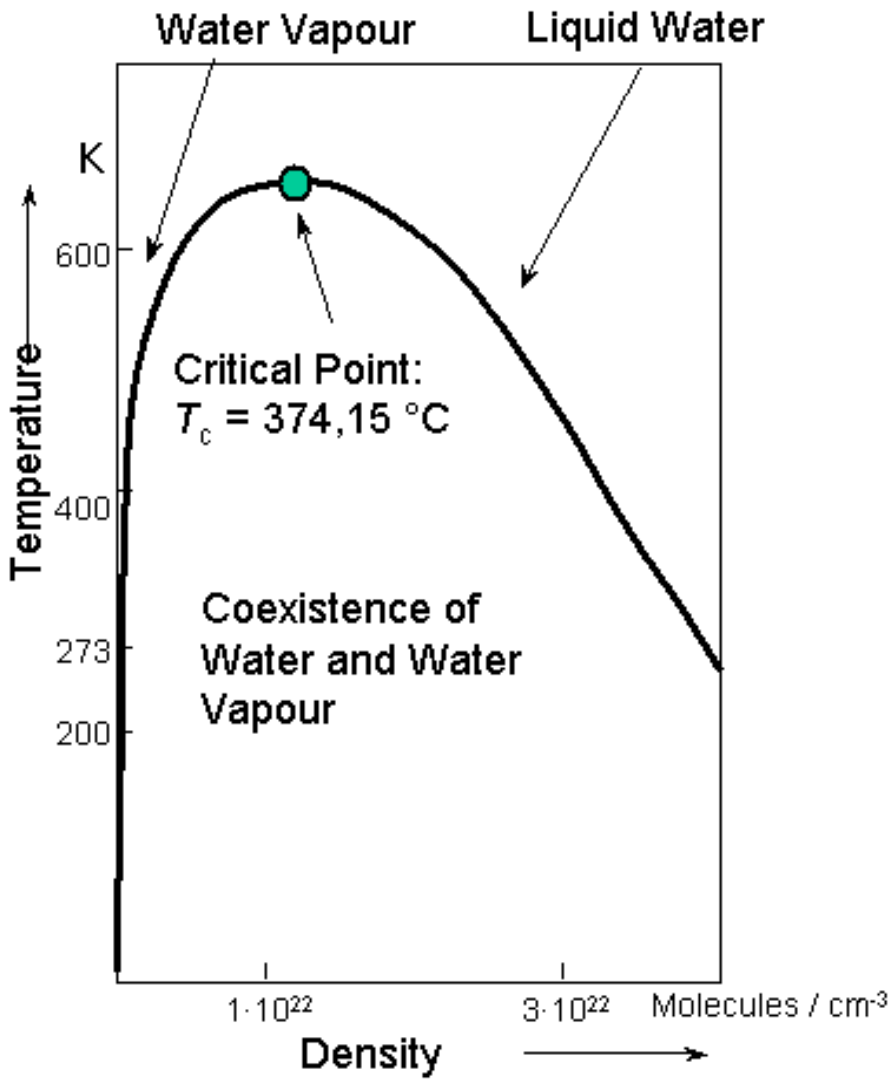
established from
lattice QCD calculations

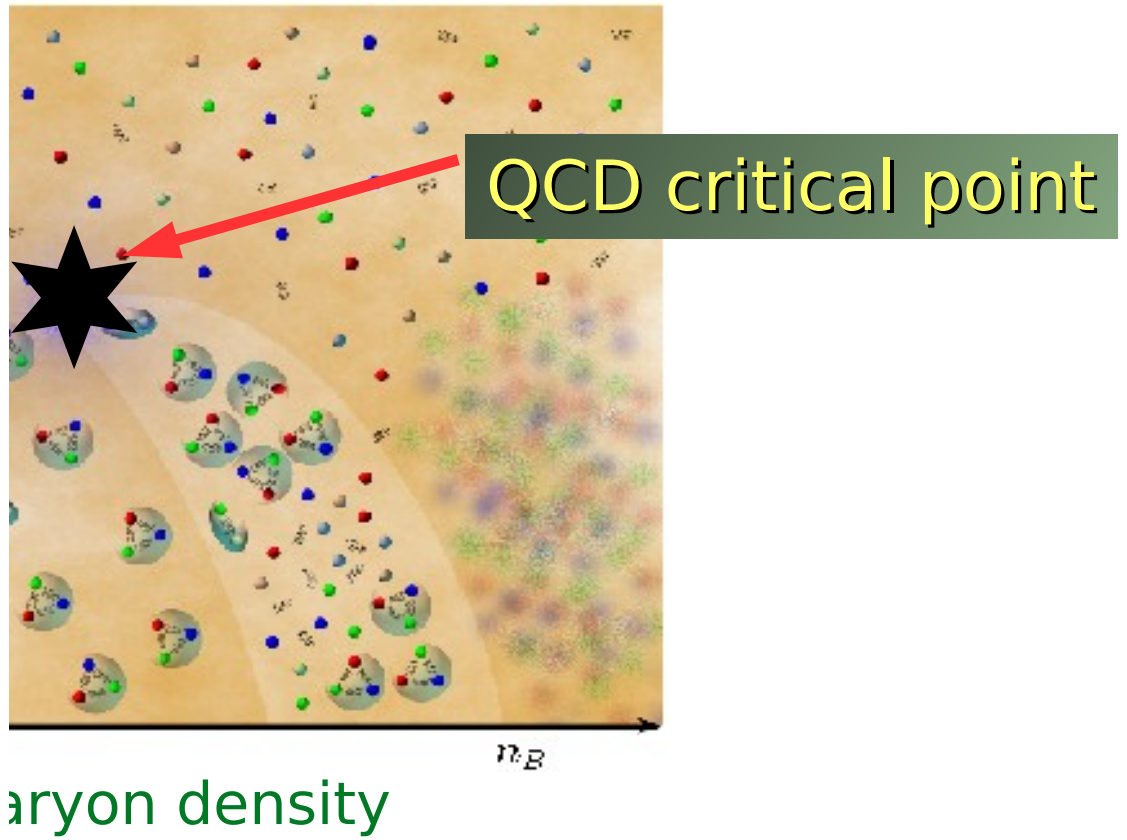


1st order: coexistence of QGP & hadrons

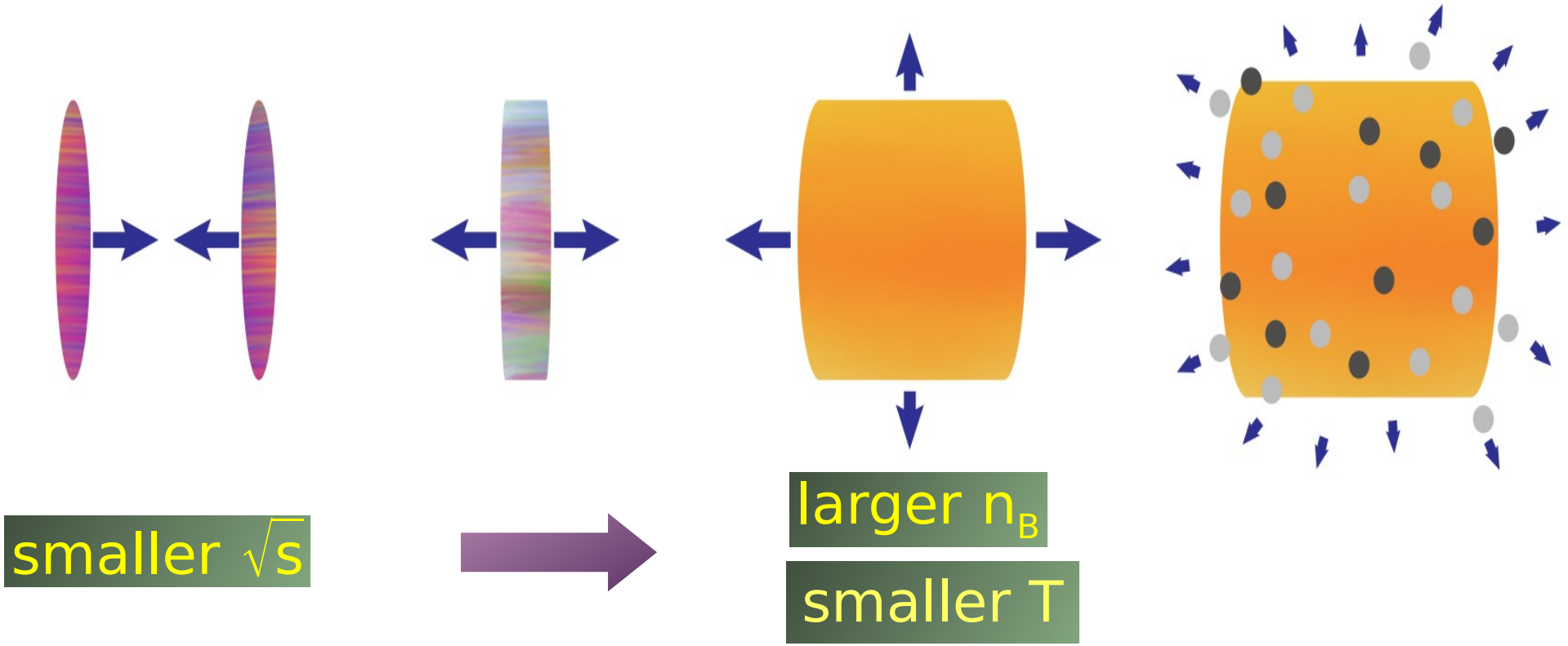
expectation, model-based


QCD critical point
temperature
T
n_B
baryon density


Water Vapour
Liquid Water
K
600
400
273
200
Temperature
Critical Point:
T_c = 374,15 °C
Coexistence of
Water and Water
Vapour
1·10²²
3·10²²
Molecules / cm⁻³
Density


QCD critical point
n_B
aryon density

baryon-rich QGP at RHIC: Beam Energy Scan (BES)



$\sqrt{s}$: collision energy

n_B : baryon density

T : temperature

$\sqrt{s} \rightarrow (T, n_B)$: charting phase diagram

easier if:

n_B → μ_B : baryon chemical potential

energy needed to add an additional baryon to the system

$$\sqrt{s} \rightarrow (T, \mu_B)$$

$\sqrt{s} \rightarrow (T, \mu_B)$: charting phase diagram

choose two appropriate quantities ...

compare

experiments

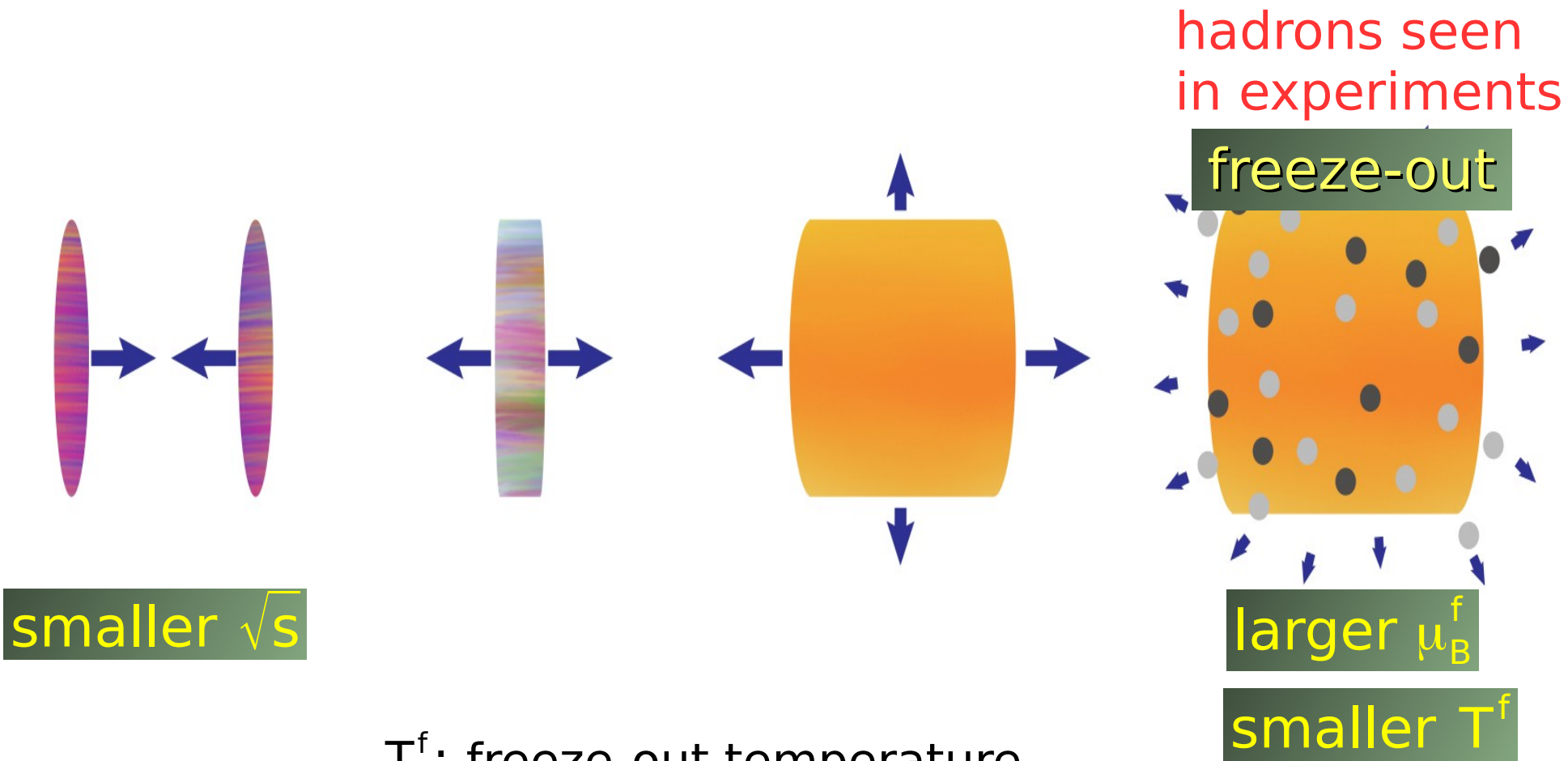
measure
at each $\sqrt{s}$

(lattice) QCD

calculate
for (T, μ_B)

$\sqrt{s} \rightarrow (T, \mu_B)$

$\sqrt{s} \rightarrow (T^f, \mu_B^f)$: charting phase diagram



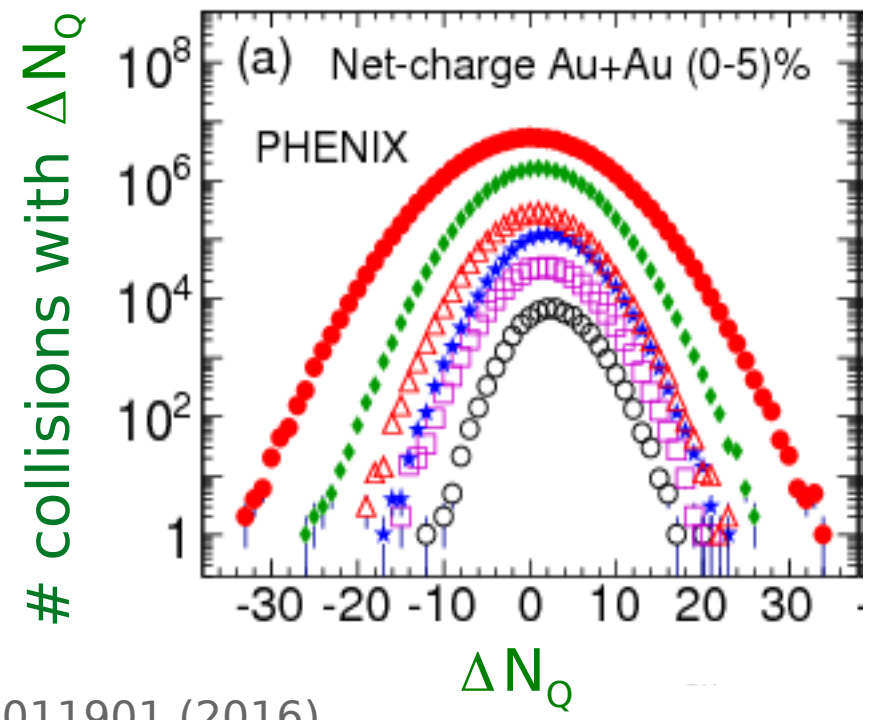
T^f: freeze-out temperature

μ_B^f : freeze-out baryon chemical potential

cumulants of net-charge fluctuations

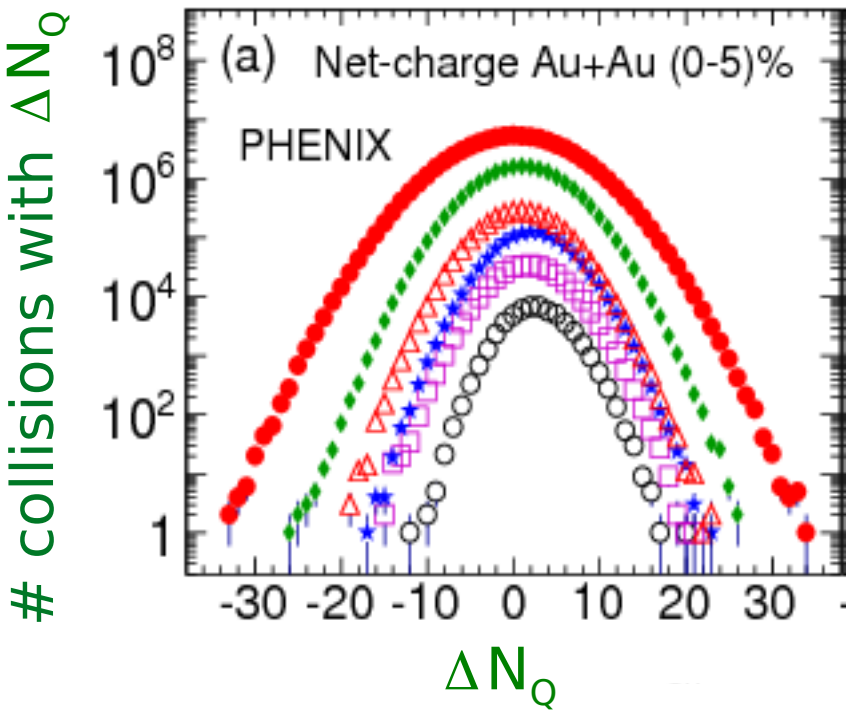
measure net-charge ΔN_Q in each collision

ΔN_Q = (# + charges – # - charges)



PHENIX:
Phys. Rev. C93, no. 1, 011901 (2016)

characterize the distribution



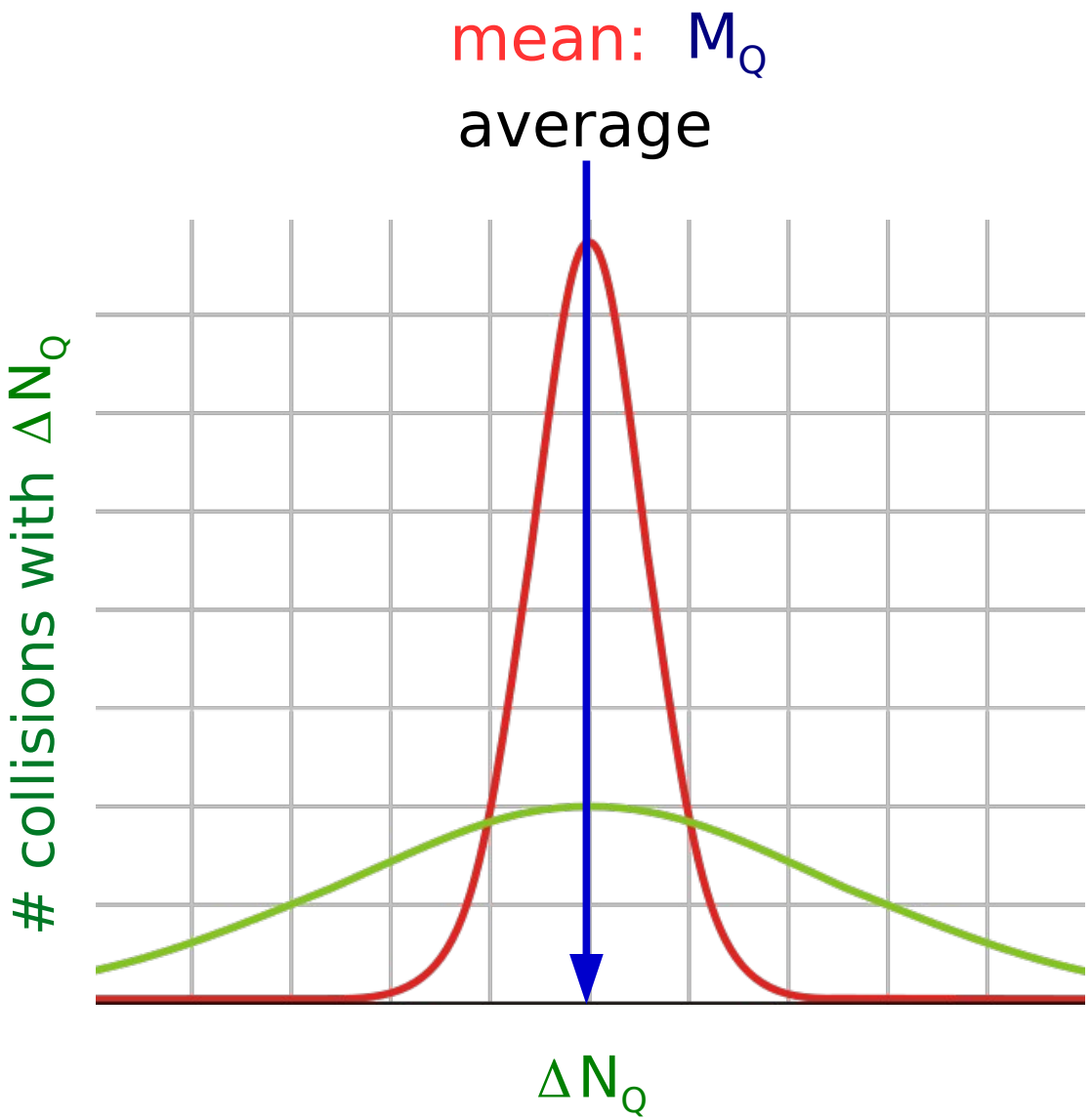
cumulants:

mean: M_Q

variance: σ_Q

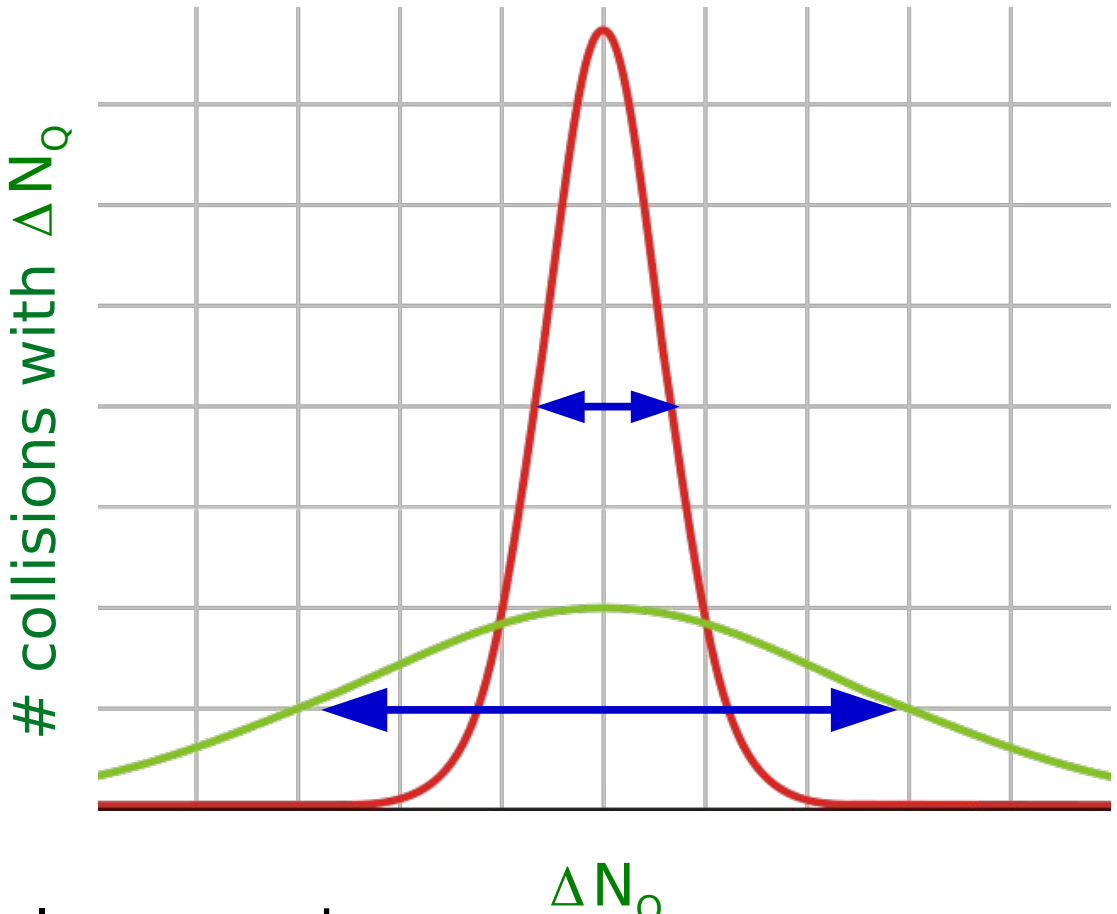
skewness: S_Q

PHENIX:
Phys. Rev. C93, no. 1, 011901 (2016)


mean: M_Q
average
collisions with ΔN_Q
ΔN_Q

variance: σ_Q

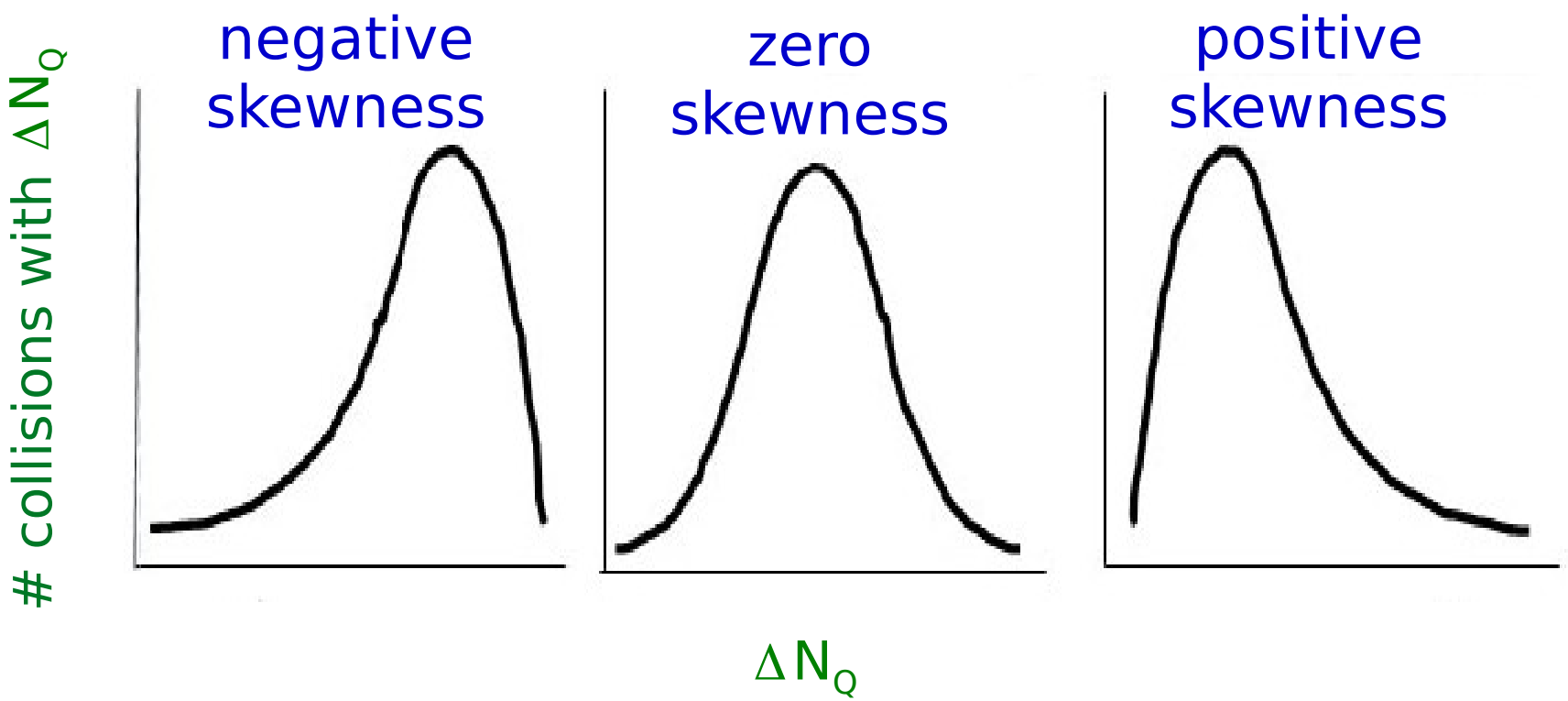
width



larger width → larger variance

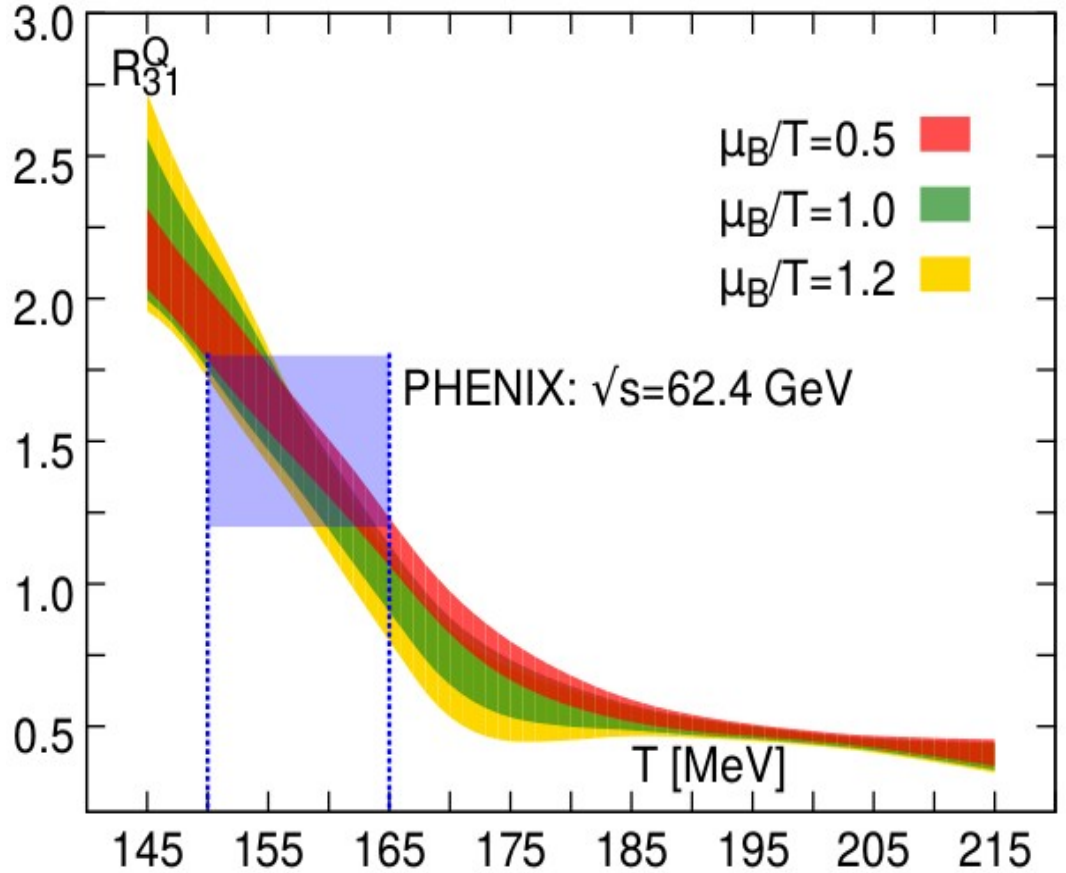
skewness: S_Q

asymmetry



'thermometer'

$$\frac{S_Q \sigma_Q^3}{M_Q}$$



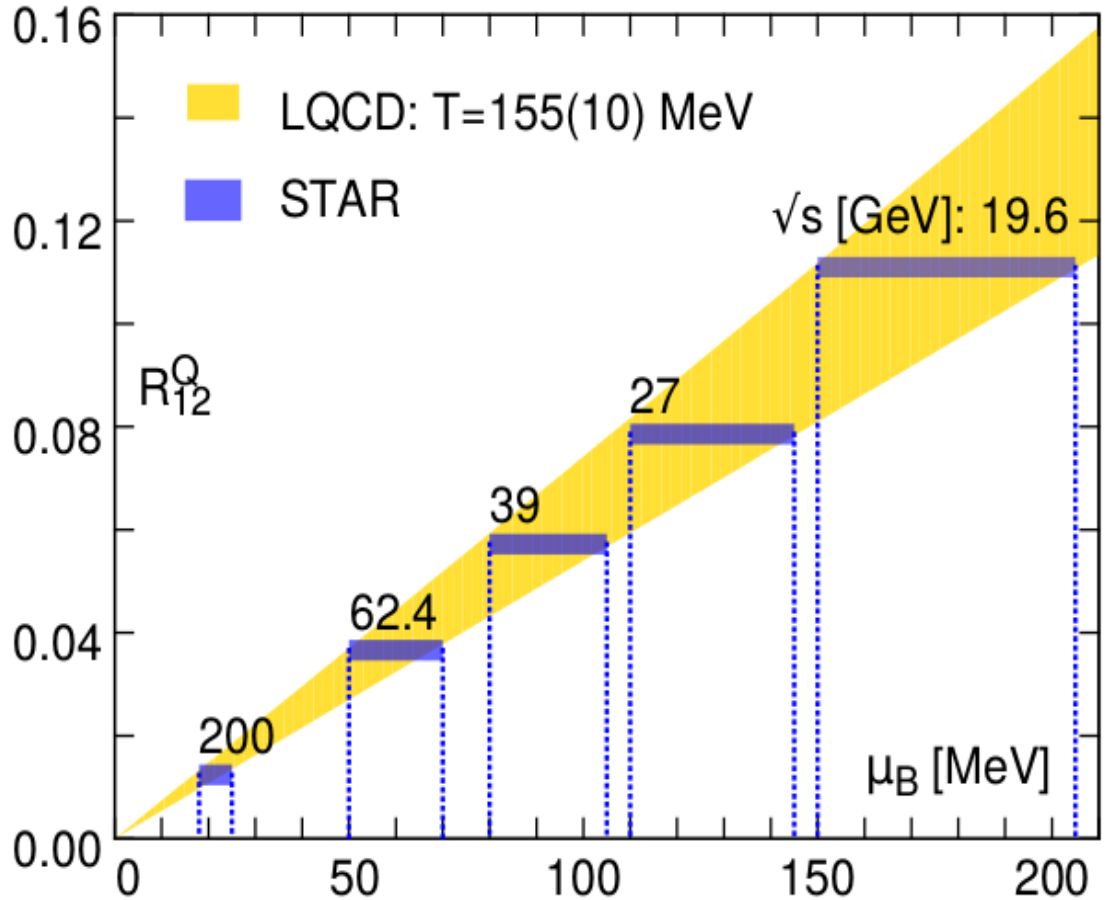
temperature [MeV]

PHENIX:
Phys. Rev. C93, no. 1, 011901 (2016)

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

'baryometer'

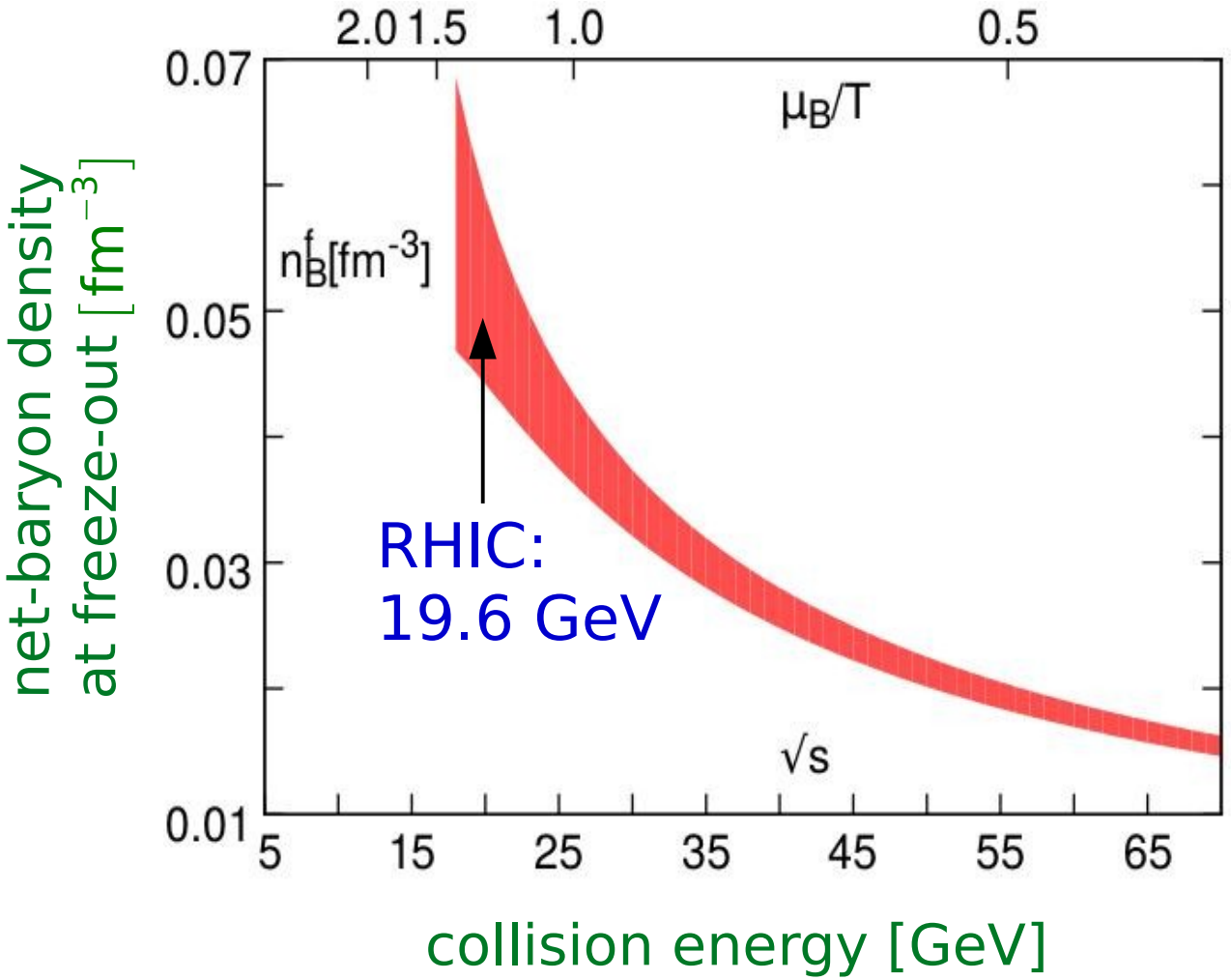
$$\frac{M_Q}{\sigma_Q^2}$$



baryon chemical potential [MeV]

STAR:
Phys. Rev. Lett. 113, 092301 (2014)

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



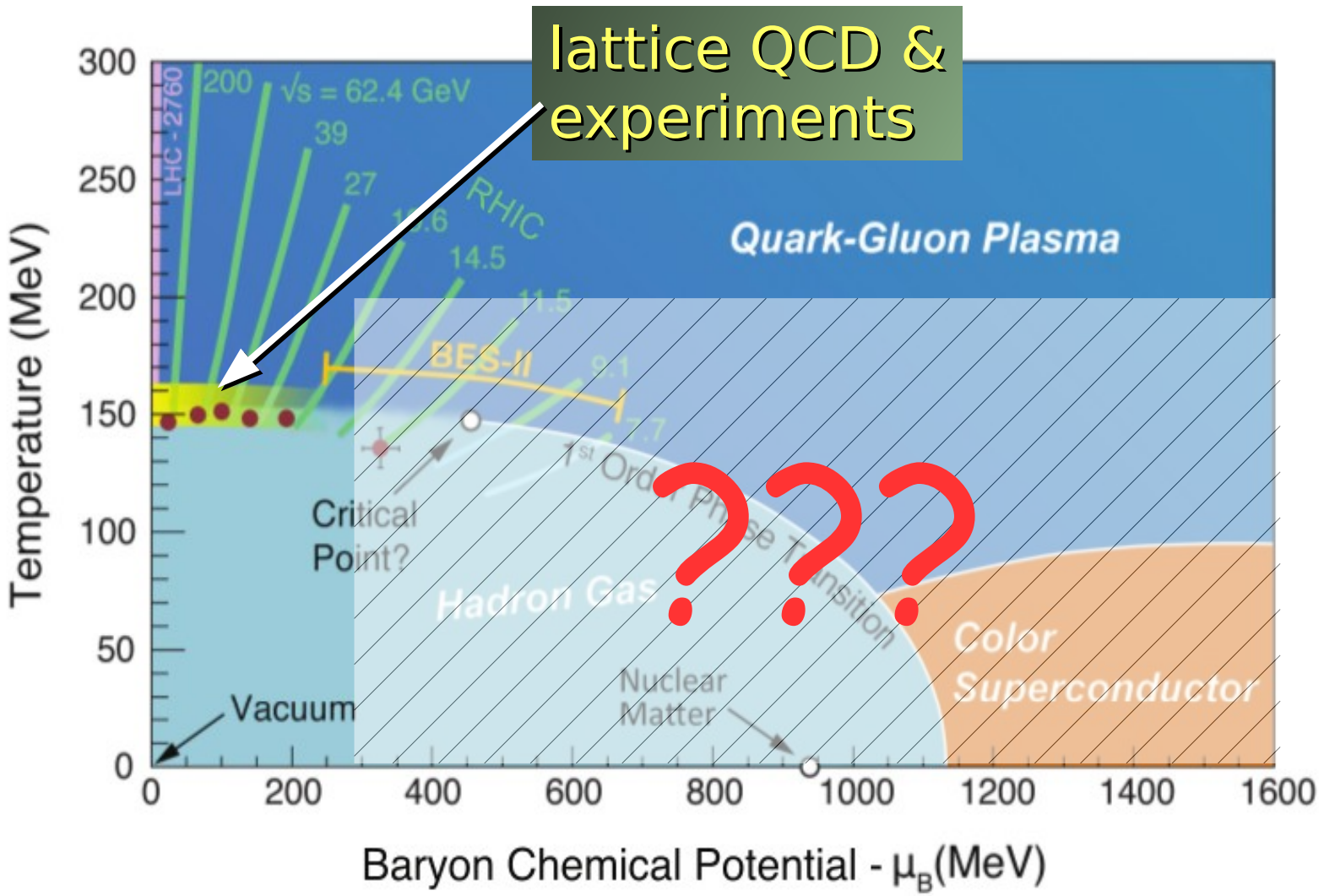
net-baryon density

$n_B^f \simeq 5\times10^{43}\ /m^3$

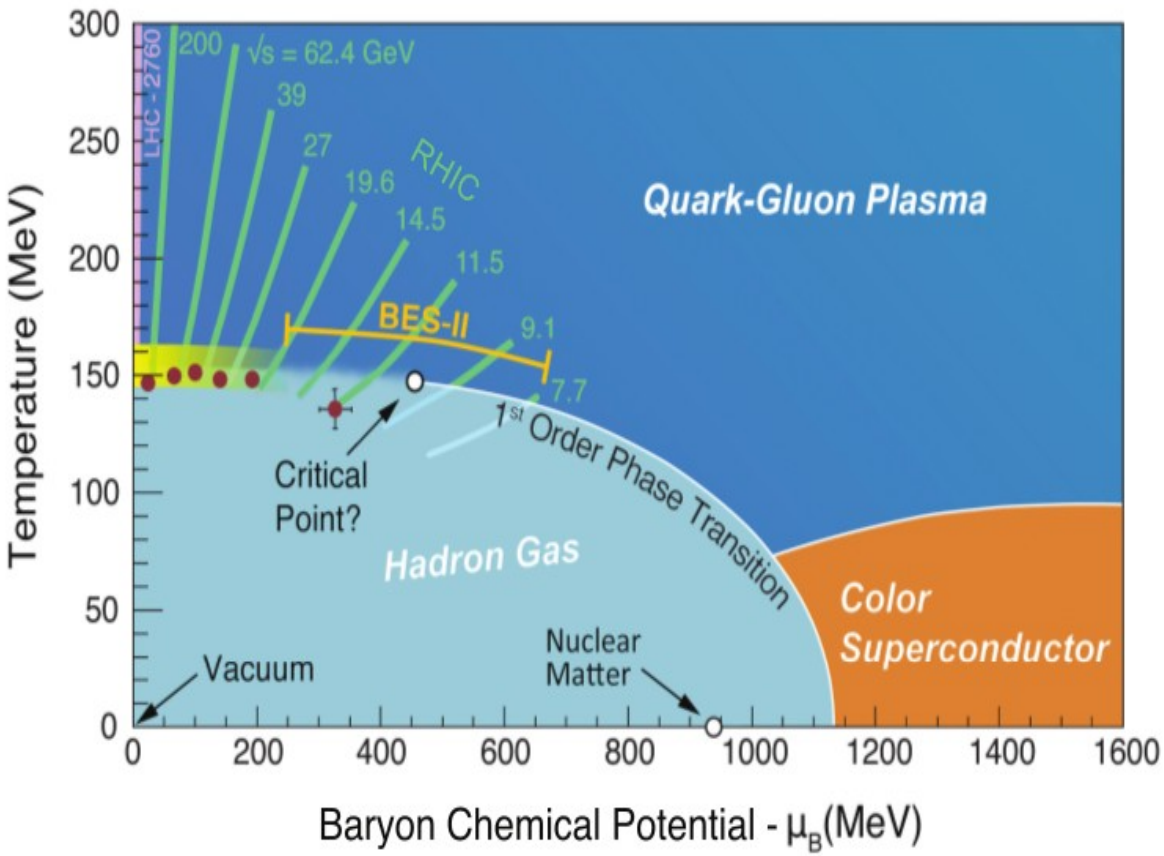
molecular number density

$\sim 1.8\times10^{29}$

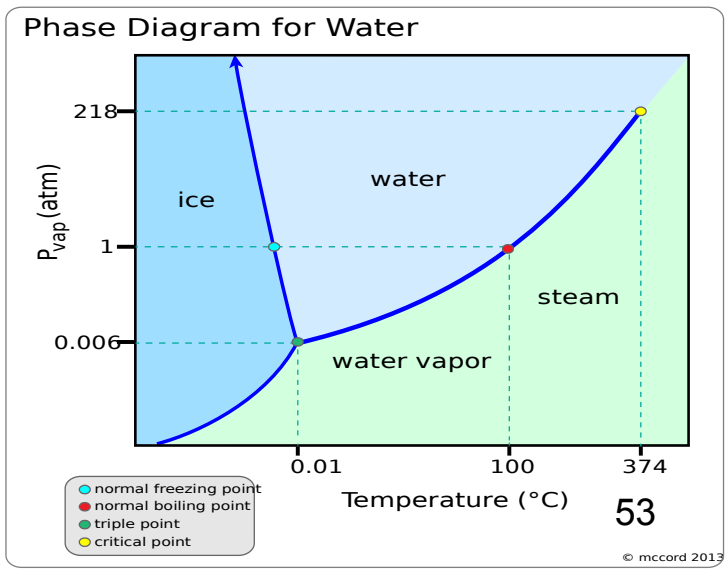
map of QCD phase diagram



outlook

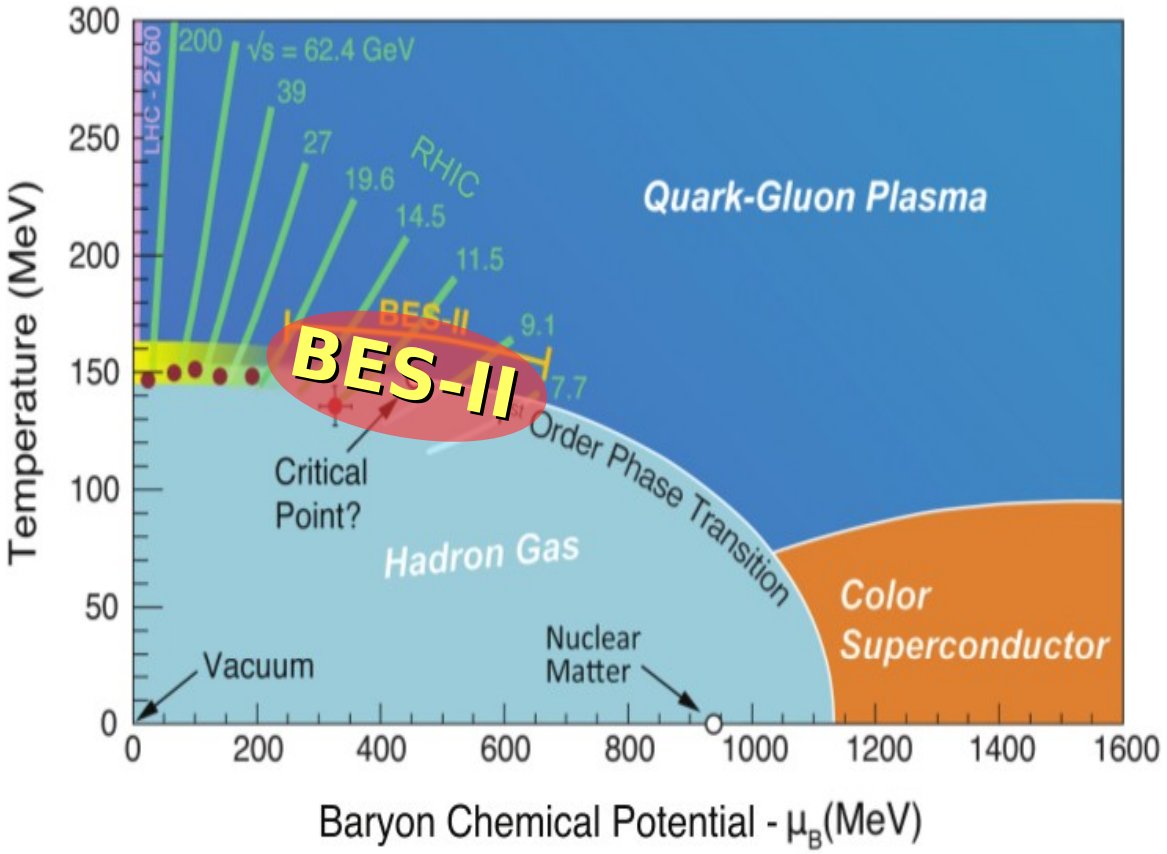


characterization of phases of the liquid made of fundamental objects: quarks & gluons



outlook: RHIC Beam Energy Scan, phase II (BES-II)

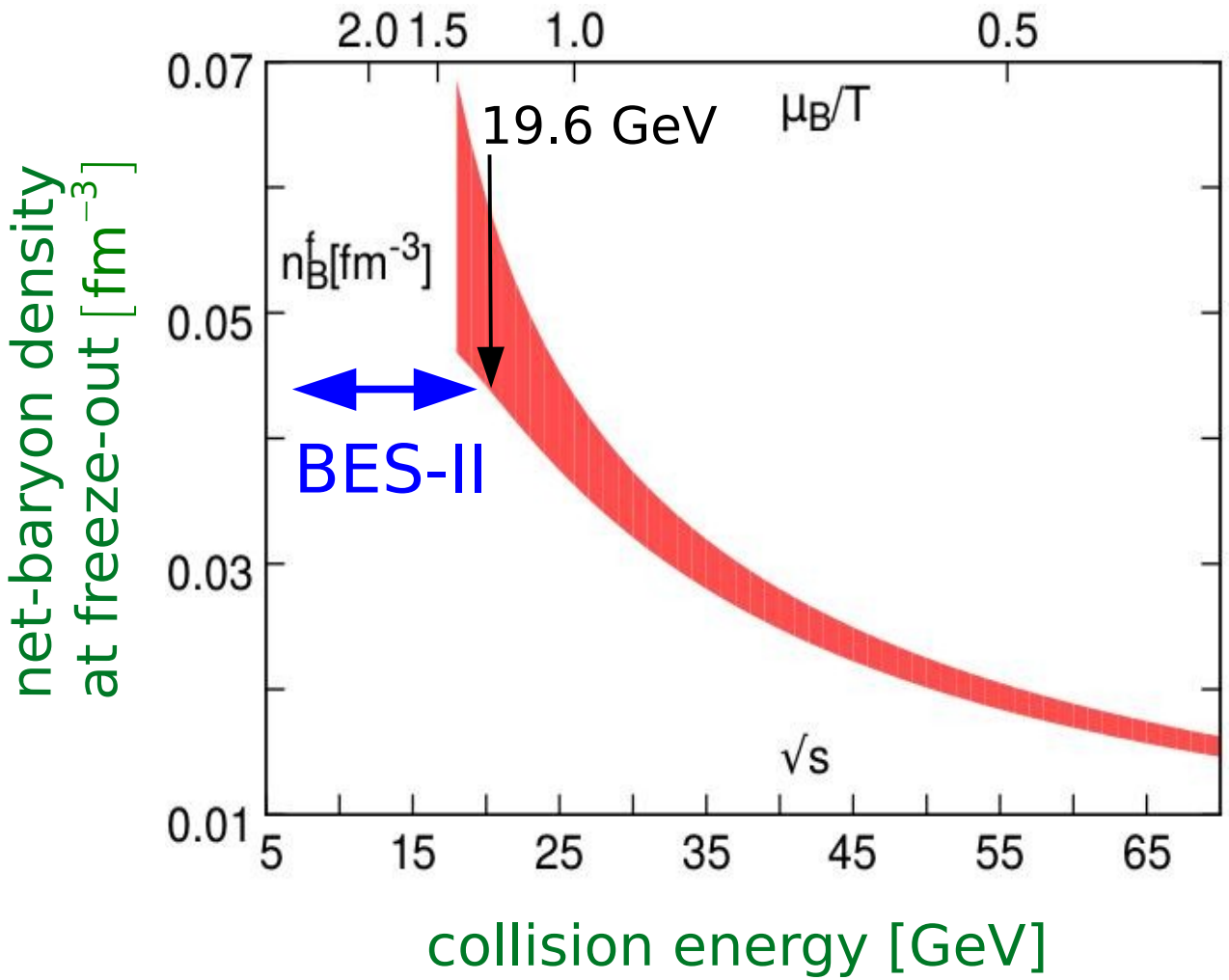
2019-2020



QCD critical point & properties of baryon-rich QGP

following up on tantalizing hints from BES-I

outlook: BES-II & hot-dense lattice QCD



extend the reach of hot-dense lattice QCD calculations to BES-II regime

outlook: hot-dense lattice QCD ...

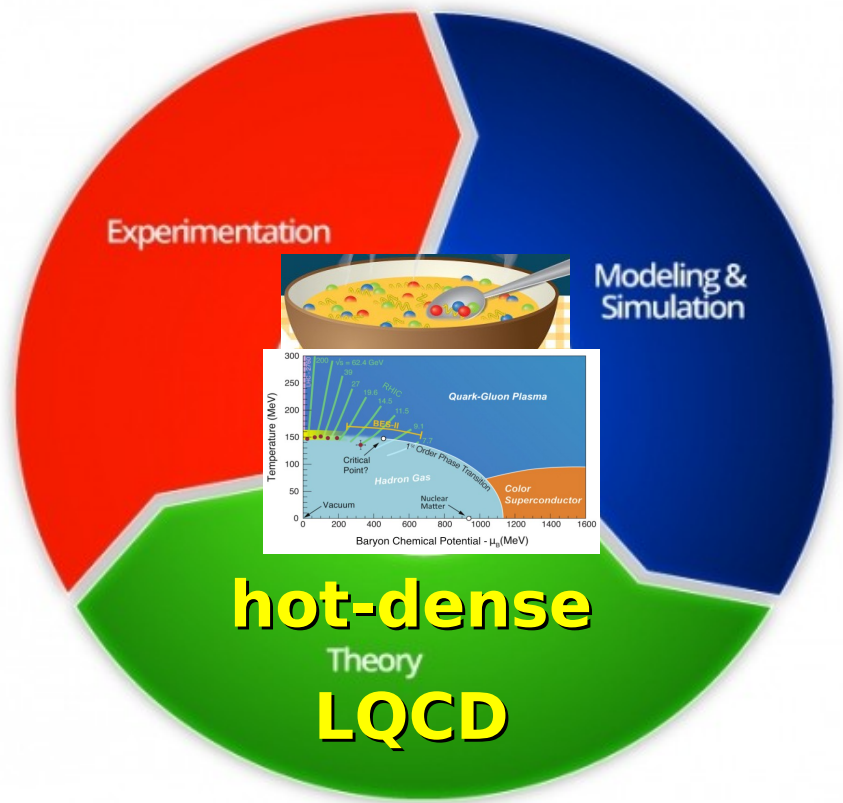
other issues: near-equilibrium physics

- electrical conductivity & charge diffusion
- thermal di-lepton & photon emission
- fate of heavy quark anti-quark bound states
- energy loss of heavy quarks in QGP
- viscosities of QGP

summary

hot-dense lattice QCD:
an essential component

in our quest for understanding the phases & properties of extreme quark-gluon matter

extracting physics from heavy-ion experiments need theory inputs based on hot-dense lattice QCD

hot-dense lattice QCD has made a big leap forward: more direct connections with experiment