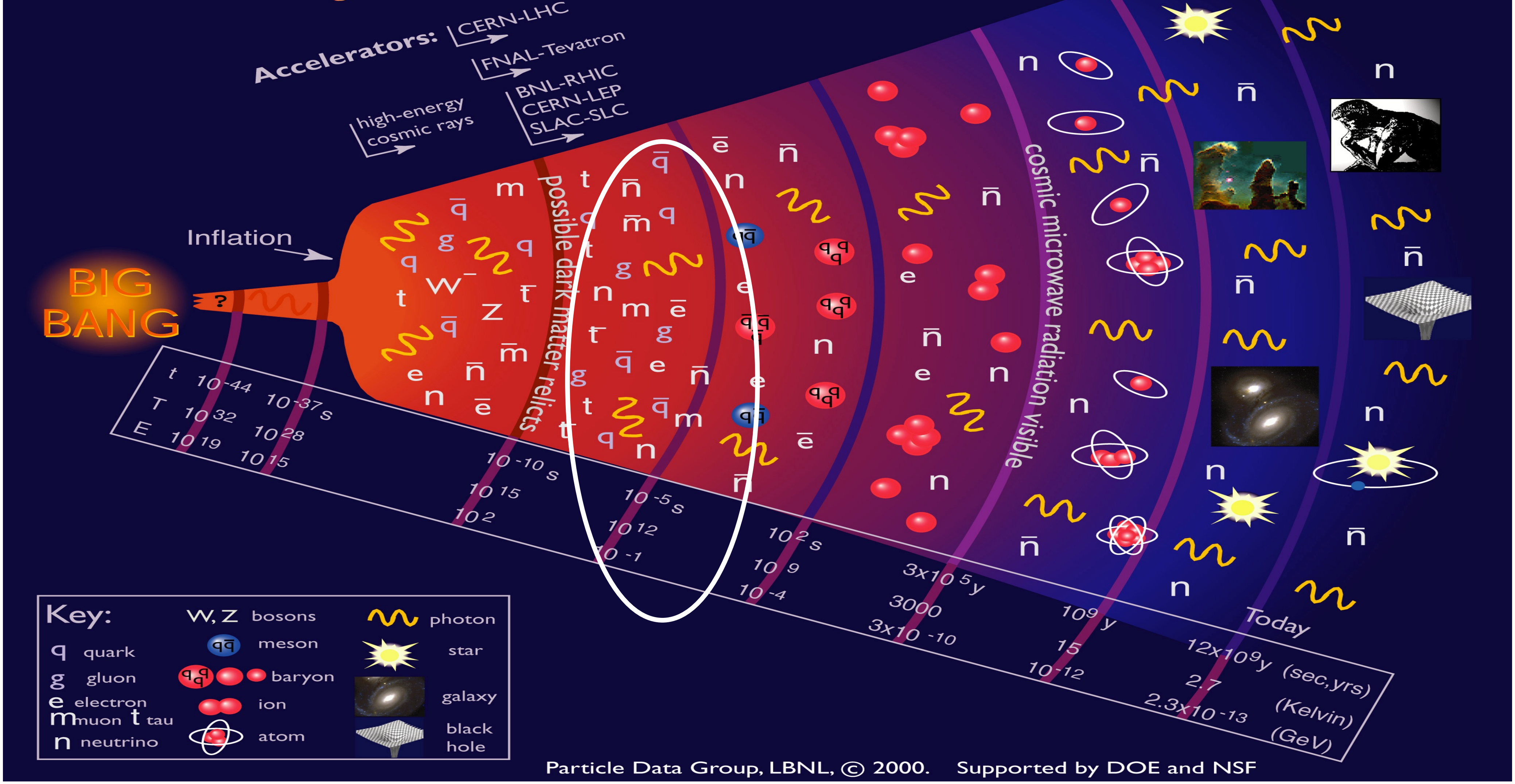
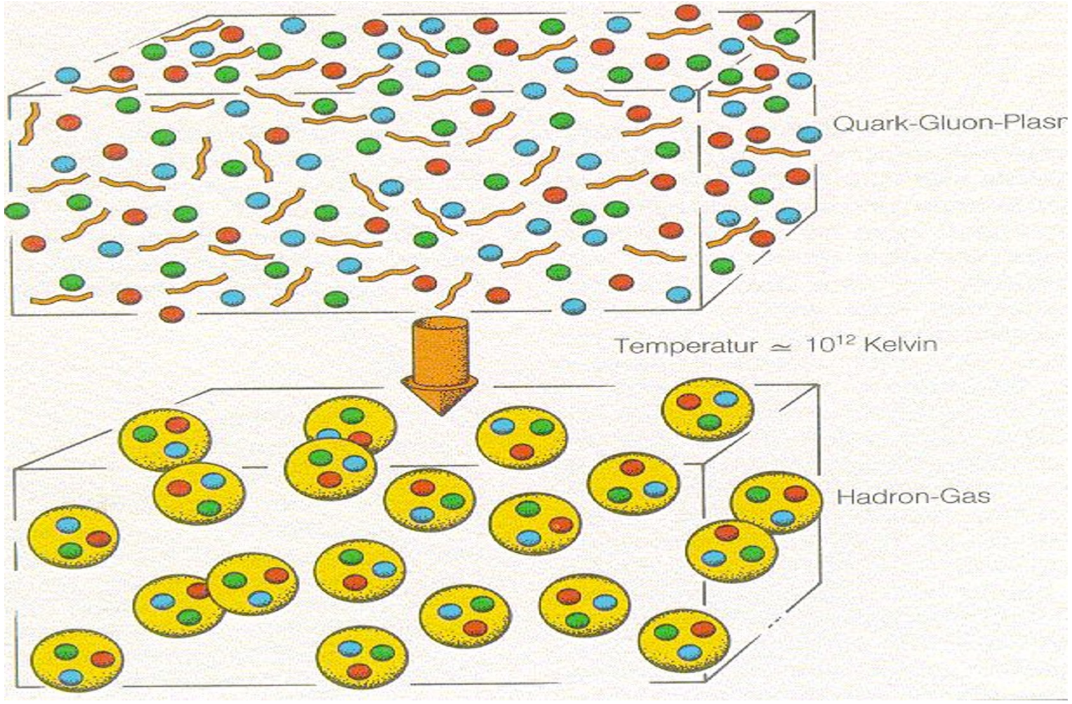
Quark-Gluon Plasma: Recreating matter of the early universe on earth

History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Universe evolved from a Quark-Gluon Plasma to a Hadron Gas



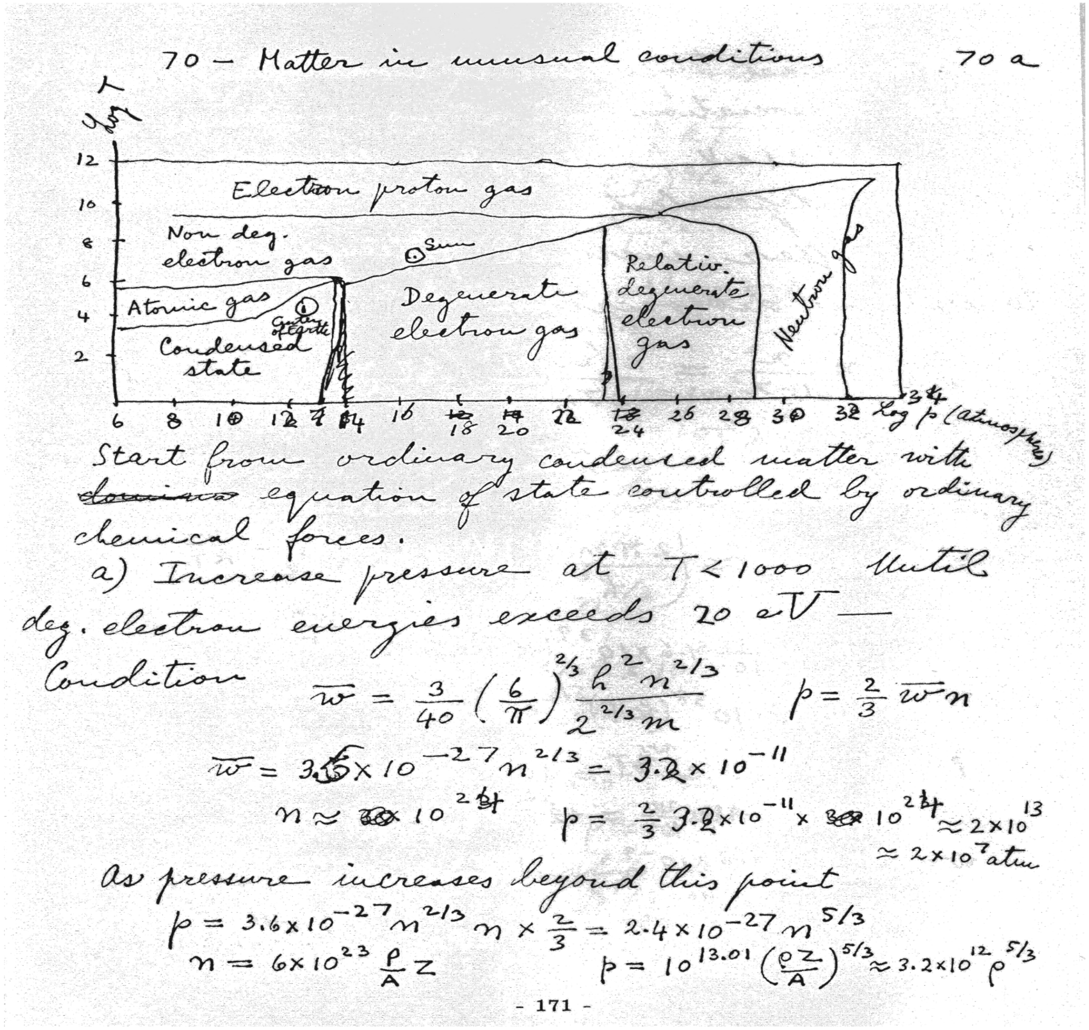
How did this happen ?

Is there a phase transition (a la vapor to liquid) transition ?

What are the properties of this matter ?

An old quest: Strongly interacting matter in unusual conditions

E. Fermi: Notes on Thermodynamics
and Statistics " (1953)


70 – Matter in unusual conditions 70 a

Start from ordinary condensed matter with ~~[illegible]~~ equation of state controlled by ordinary chemical forces.

a) Increase pressure at $T < 1000$ until deg. electron energies exceeds 20 eV —

Condition $\overline{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3} \frac{h^2 n^{2/3}}{2^{2/3} m}$ $p = \frac{2}{3}\overline{w} n$

$$\overline{w} = 3.5 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$$

$$n \approx \cancel{30} \times 10^{24} \qquad p = \frac{2}{3} 3.2 \times 10^{-11} \times \cancel{30}\, 10^{24} \approx 2 \times 10^{13}$$

$$\approx 2 \times 10^{7} \text{atm}$$

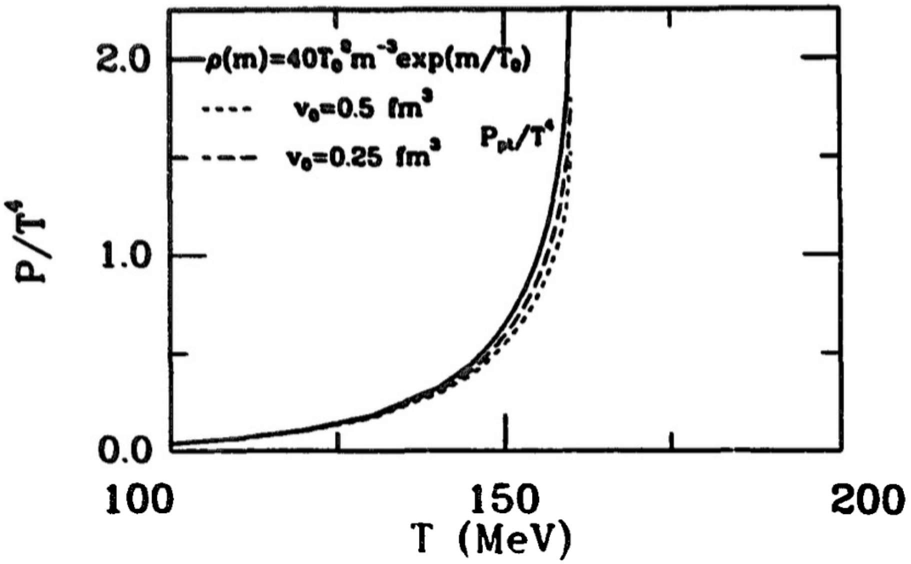
As pressure increases beyond this point

$$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$$

$$n = 6 \times 10^{23} \frac{\rho}{A} Z \qquad p = 10^{13.01} \left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$$

- 171 -

Hagedorn catastrophe: A limiting temperature for the early universe?



Particle accelerators in the 50s-60s discovered a “hadron” zoo:
mesons (pions,kaons,rho,eta,…): $q\bar{q}$
baryons (Delta,Lambda,Sigma,Omega,…): qqq

Apparent exponential increase in the density of hadron states suggested the pressure of strongly interacting matter diverged at a limiting temperature

Hagedorn (1965)

K.Huang, S. Weinberg, PRL25 (1970)
“Ultimate temperature and history of the universe”

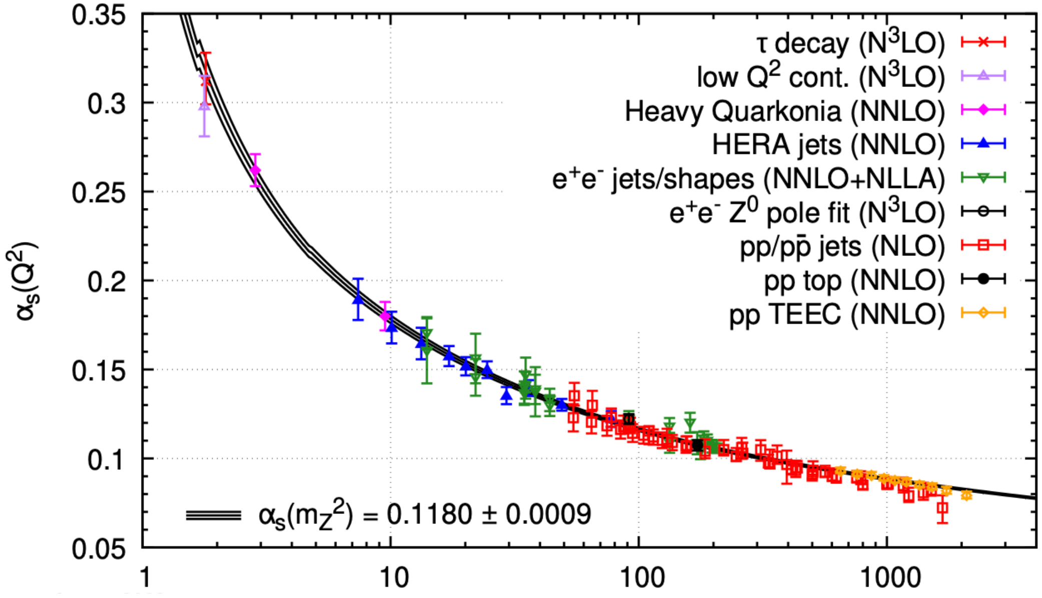
Hagedorn catastrophe: A limiting temperature for the early universe?

> *Thus, our ignorance of microscopic physics stands as a veil,*
> *obscuring our view of the very beginning*

Steven Weinberg, The First Three Minutes (1973)

QCD lifts the veil – allowing us to peer back in time

Key features of QCD: 1) Asymptotic freedom



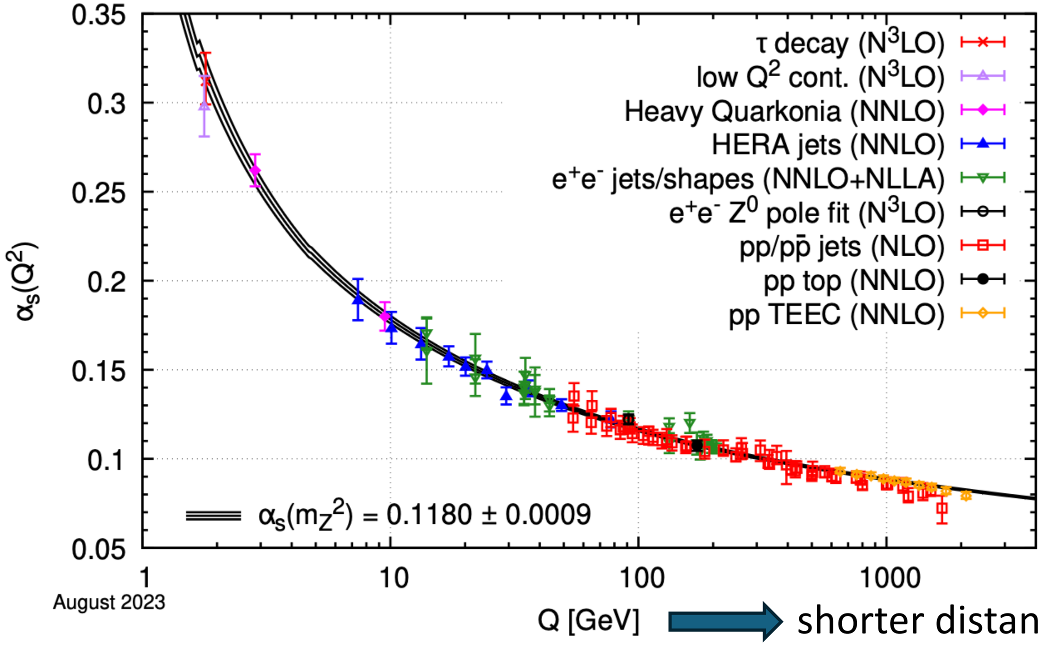
Particle Data Group (2024)

Q [GeV] → shorter distances → Higher Temperatures / Matter Densities

Quarks and gluons are increasingly weakly coupled (”asymptotically free”) at shorter distances due to the *self-interactions of gluons* - force carriers of color charge

Gross, Wilczek, Politzer (2004)

Key features of QCD: 1) Asymptotic freedom



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Gross, Wilczek, Politzer (2004)

→ shorter distances → Higher Temperatures / Matter Densities

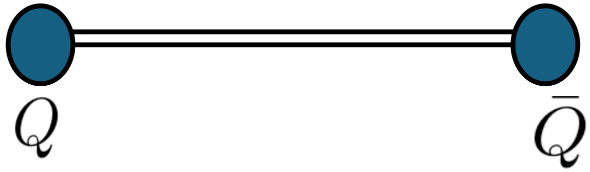
Major consequence: phase change of super-dense and super-hot QCD matter to a *weakly coupled gas of quarks and gluons* -- thus lifting the putative veil on the early universe

Cabibbo, Parisi (1975)

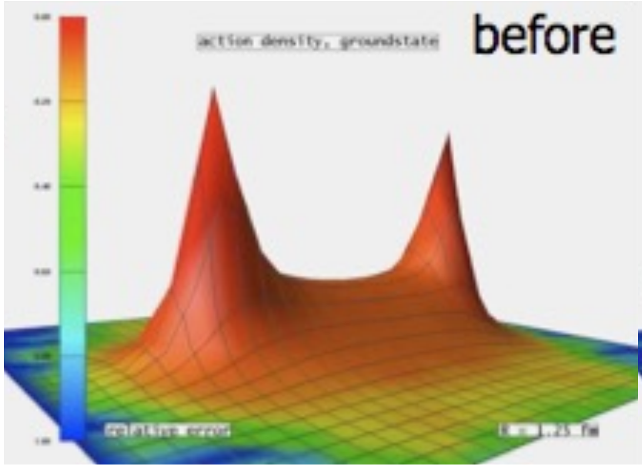
Quark matter at the core of neutron stars?

Collins, Perry (1975)

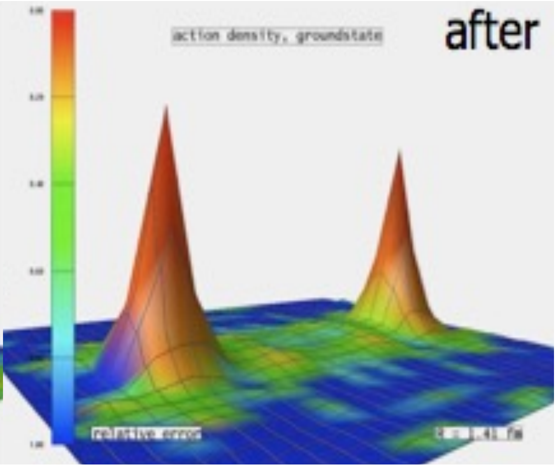
Key features of QCD: II) Quark (and gluon) confinement



Potential between static quark-anti-quark pair grows linearly at large distances -
intuitive picture of confinement of color charge

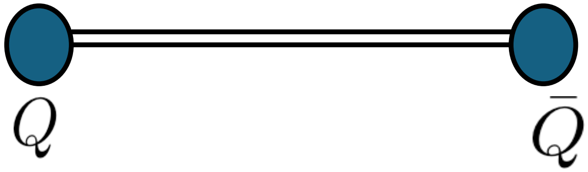


Chromoelectric flux between quark-antiquark pair

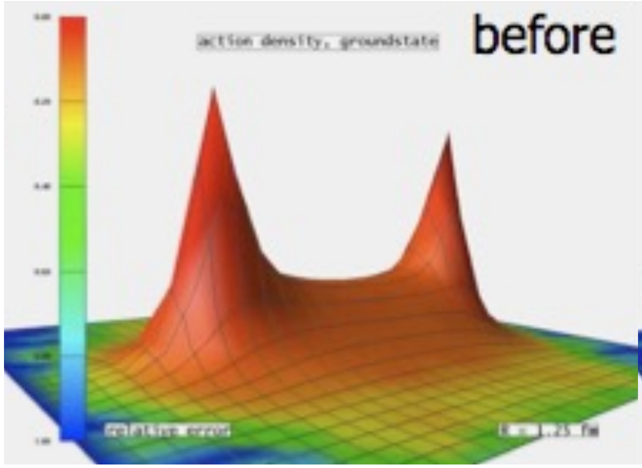


Flux tube ”snaps” at larger distances creating color-less mesons

Key features of QCD: II) Quark (and gluon) confinement



Potential between static quark-anti-quark pair grows linearly at large distances - intuitive picture of confinement of color charge



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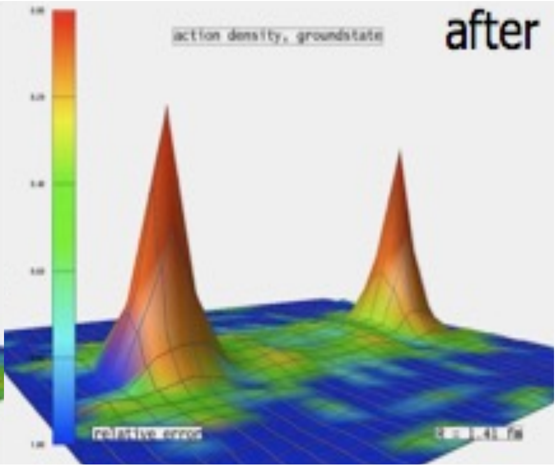


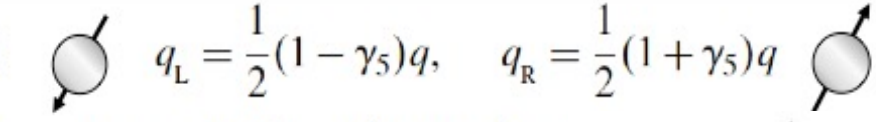
Flux tube "snaps" at larger distances creating color-less mesons

QCD matter at low temperatures and densities is an interacting meson/baryon gas

Tremendous progress in lattice QCD simulations at finite Temp. and Baryon chemical potential

Wilson (1982)

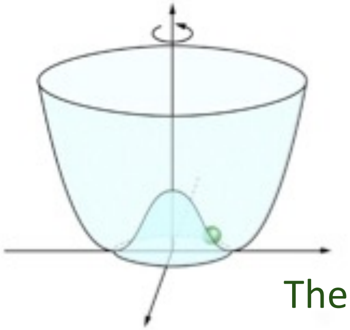
Key features of QCD: III) Chiral symmetry breaking



$$q_L = \frac{1}{2}(1-\gamma_5)q, \quad q_R = \frac{1}{2}(1+\gamma_5)q$$

QCD equations of motion (if quarks are massless) separately describe motions of ”left” and “right” -handed quarks

Quantum QCD vacuum spontaneously breaks this chiral symmetry:

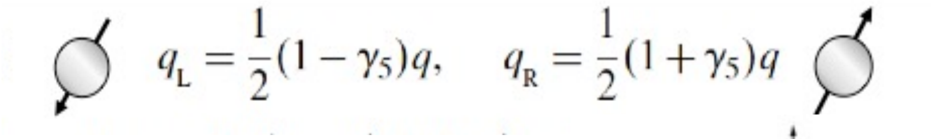


$$\Rightarrow \quad \langle \bar{q}_R q_L \rangle \neq 0$$

The vacuum forces left & right-handed quarks to march lockstep

Nambu (2008)

Key features of QCD: III) Chiral symmetry breaking



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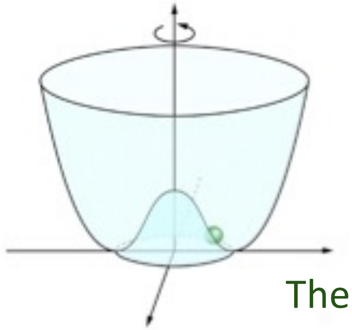

$$\longrightarrow \quad \langle \bar{q}_R q_L \rangle \neq 0$$

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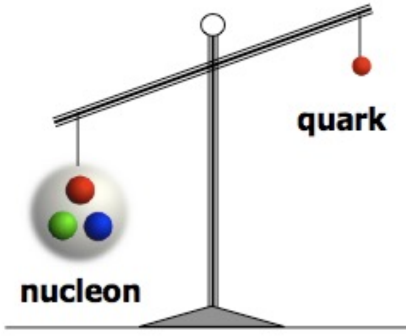


m_N / m_q ~ 100

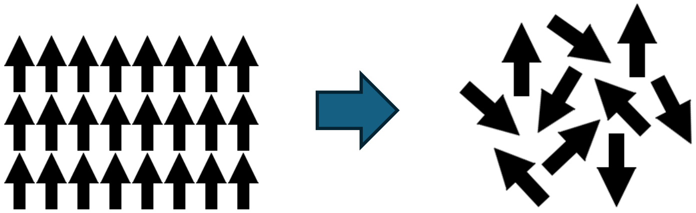
The existence of 99% of visible matter in the universe is due to the spontaneous breaking of chiral symmetry

…with a little assist from Prof. Higgs

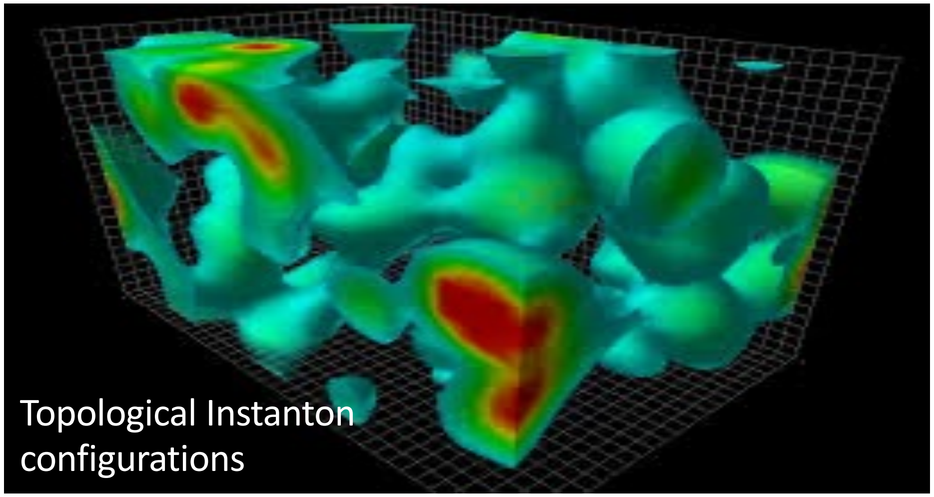
Key features of QCD: III) Chiral symmetry breaking

Chiral condensate melts at high temperature restoring chiral symmetry $\langle \bar{q}q \rangle \longrightarrow 0$
"Order parameter" characterizing phase transitions
- sensitive to # of quark species ("flavors"), colors, and masses

Analogous to the destruction of magnetization due to thermal fluctuations above the Curie temperature

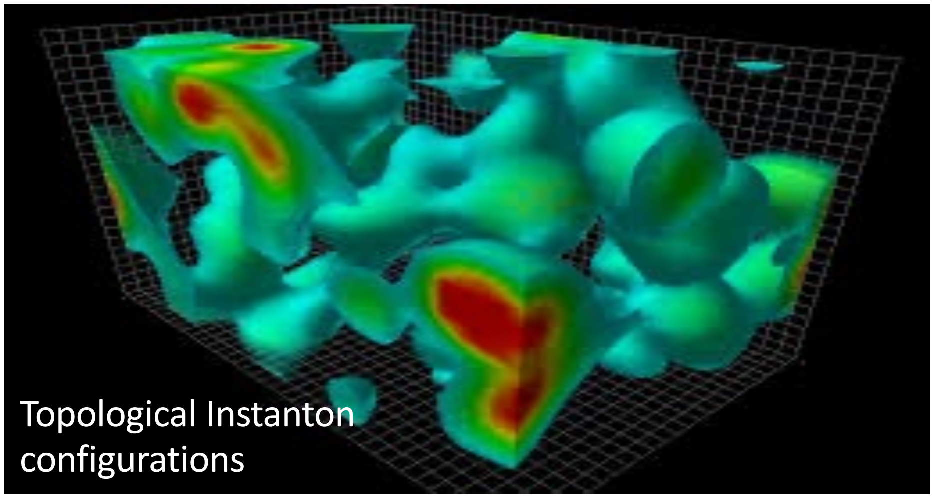


Key features of QCD: IV) QCD vacuum exhibits non-trivial topology



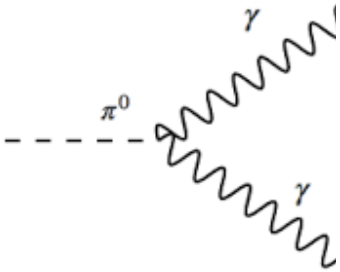
Lattice Gauge simulation
Derek Leinweber

Key features of QCD: IV) QCD vacuum exhibits non-trivial topology


Topological Instanton configurations

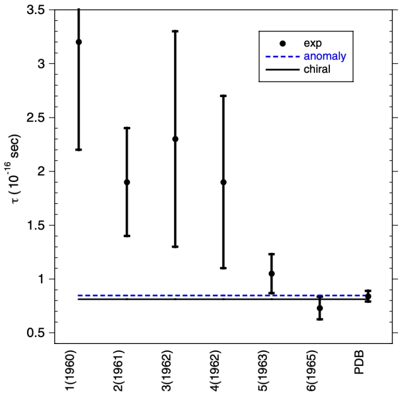
Lattice Gauge simulation
Derek Leinweber

Real-world manifestations:



The decay of $\pi^0 \rightarrow 2\gamma$

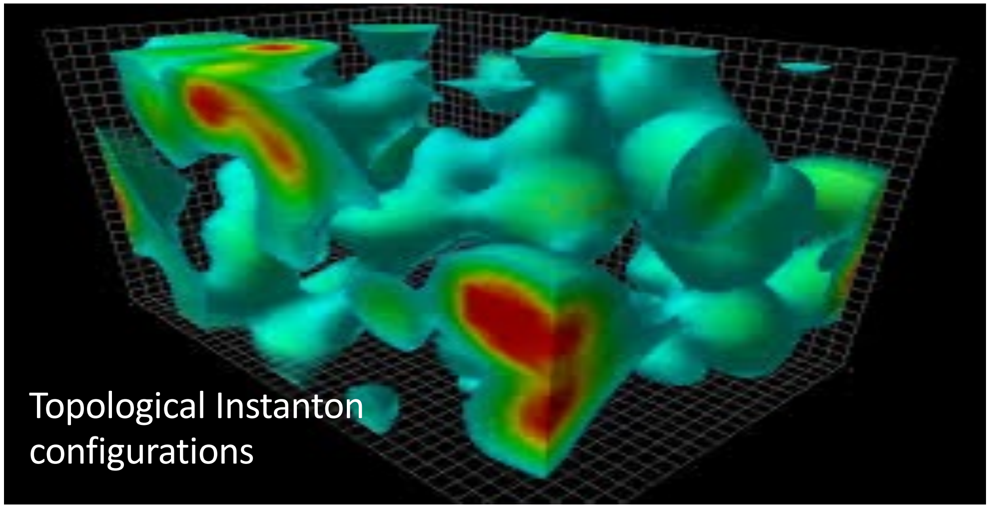
Adler; Bell-Jackiw (1969)



The mass of the η' meson (> the proton)
Is almost entirely generated by topology

t’Hooft (1976))
Witten; Veneziano (1979)

Key features of QCD: IV) QCD vacuum exhibits non-trivial topology

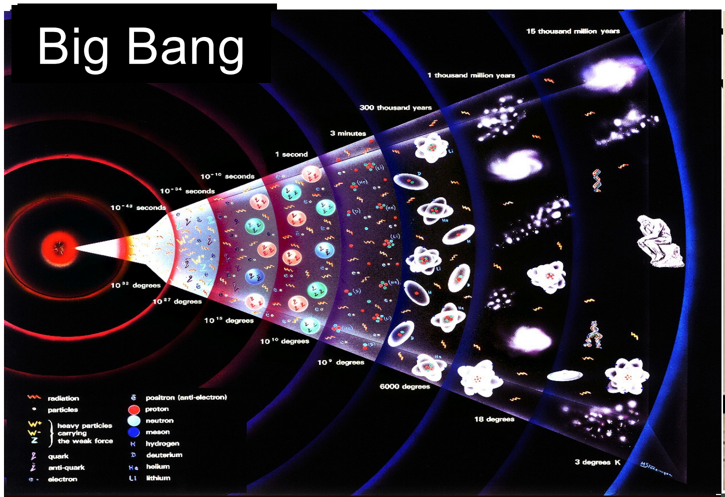


Lattice Gauge simulation
Derek Leinweber

Quantum violation of an "axial" symmetry due to topology of the QCD vacuum is also restored at high temperatures

Callan, Dashen, Gross (1978)
Gross, Pisarski, Yaffe (1981)
Pisarski,Wilczek (1984)

How can we study QCD matter ?


Big Bang


Lattice QCD


Who wants to wait?…

Neutron stars

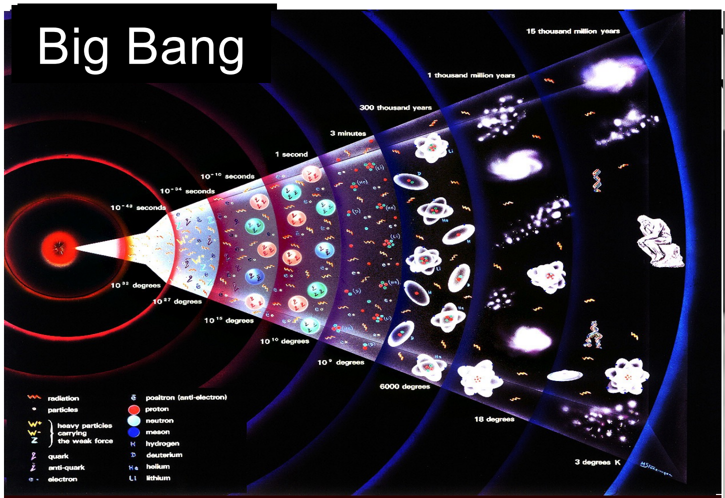

200 GeV/nucleon heavy-ion collisions

RHIC

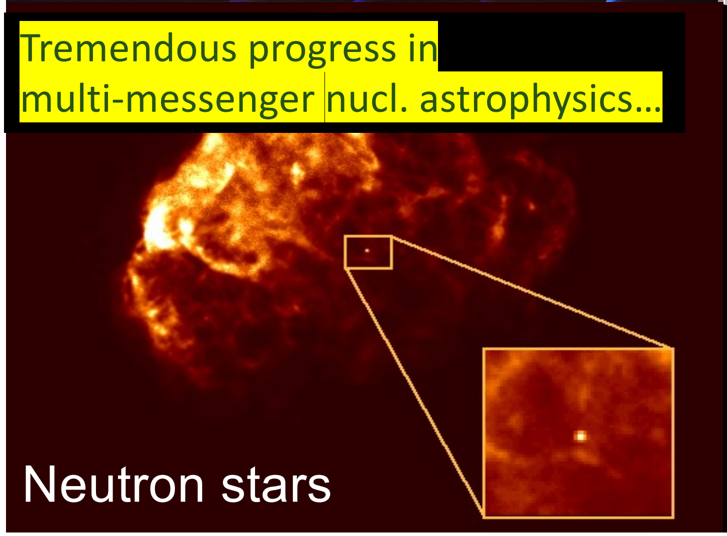
Its long run ended February 2026

Peter Steinberg
(circa 2008)

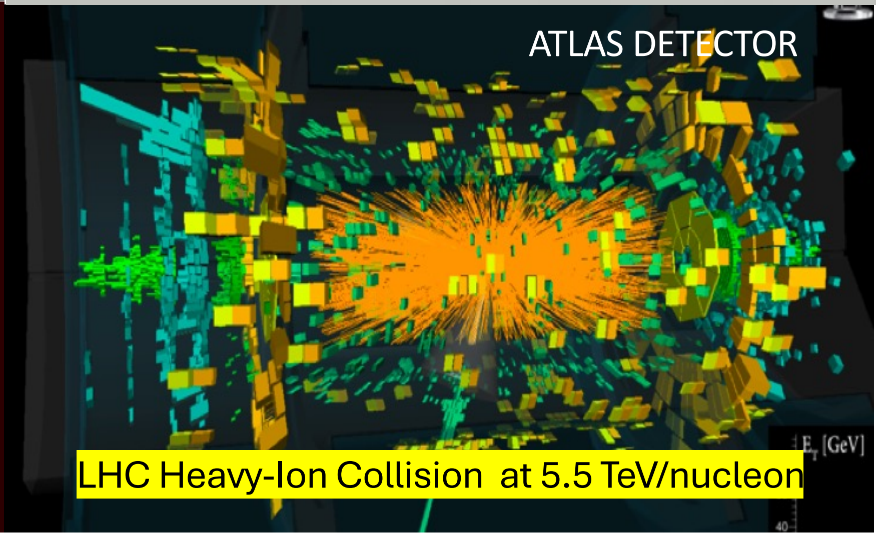
How can we study QCD matter ?


Big Bang


Exascale Era of High Performance Computing

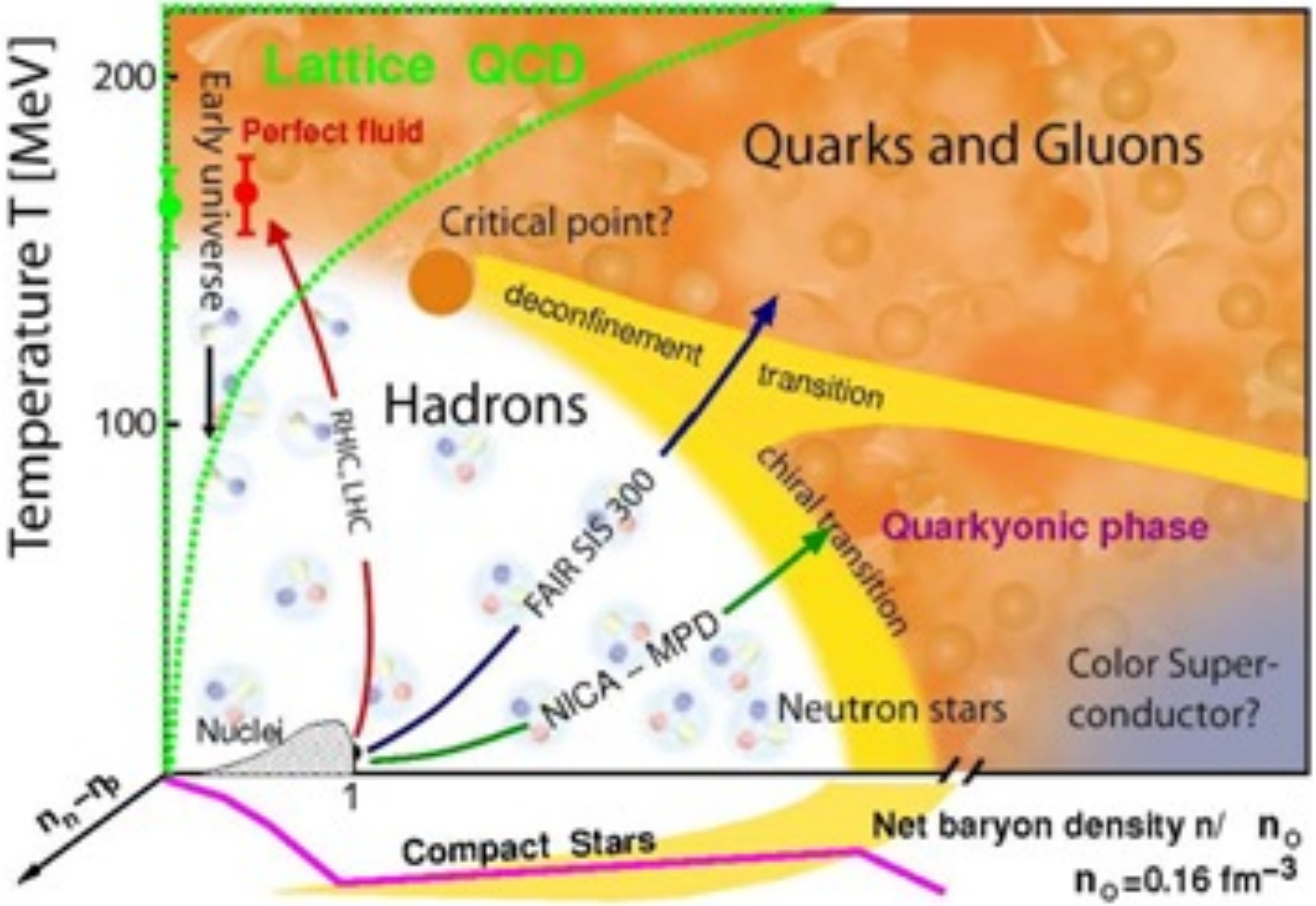

Tremendous progress in
multi-messenger nucl. astrophysics…

Neutron stars


ATLAS DETECTOR

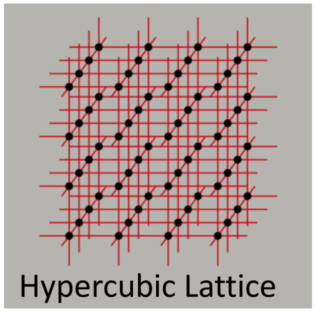
LHC Heavy-Ion Collision at 5.5 TeV/nucleon

Conjectured QCD phase diagram



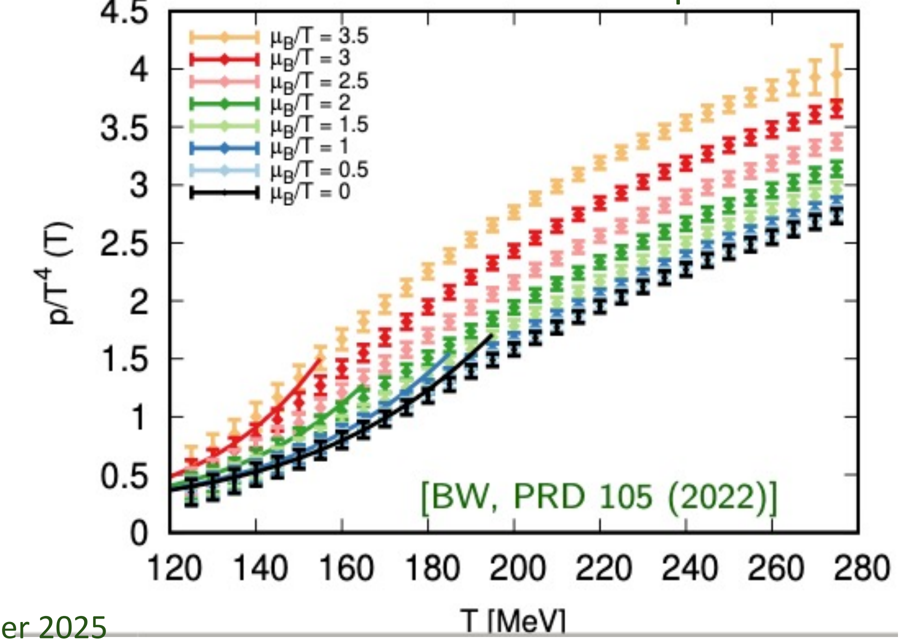
K. Fukushima

First principles Lattice QCD results



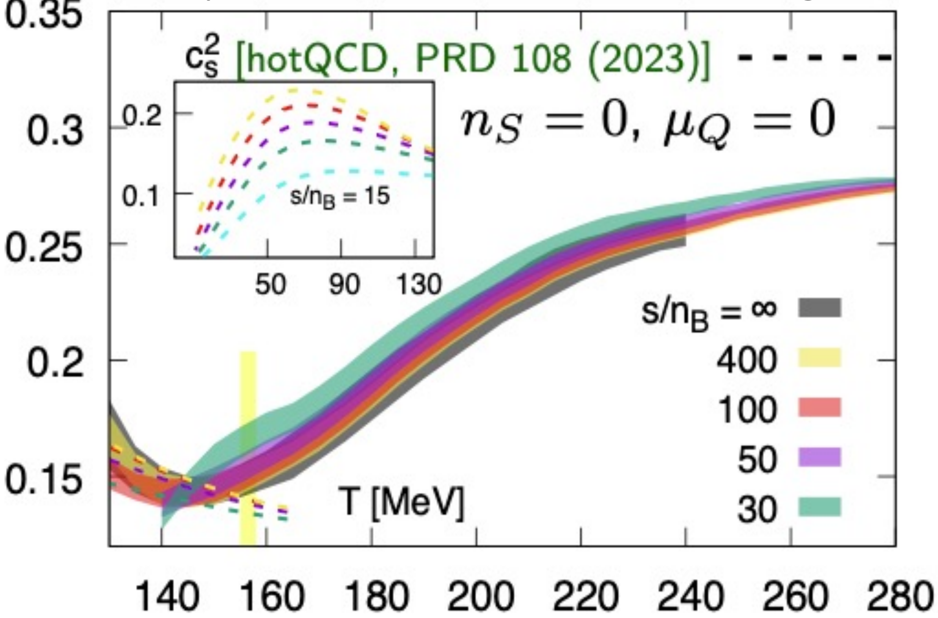
The pressure and the speed of sound in a Quark-Gluon Plasma as a function of Temperature (150 MeV ~ 1.75 Trillion Kelvin !)

Pressure normalized to temperature

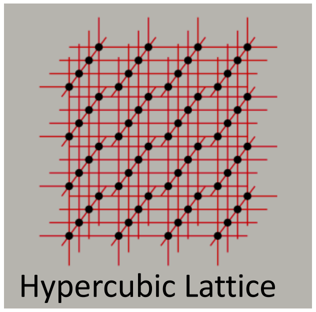


B. Brandt,
Quark Matter 2025

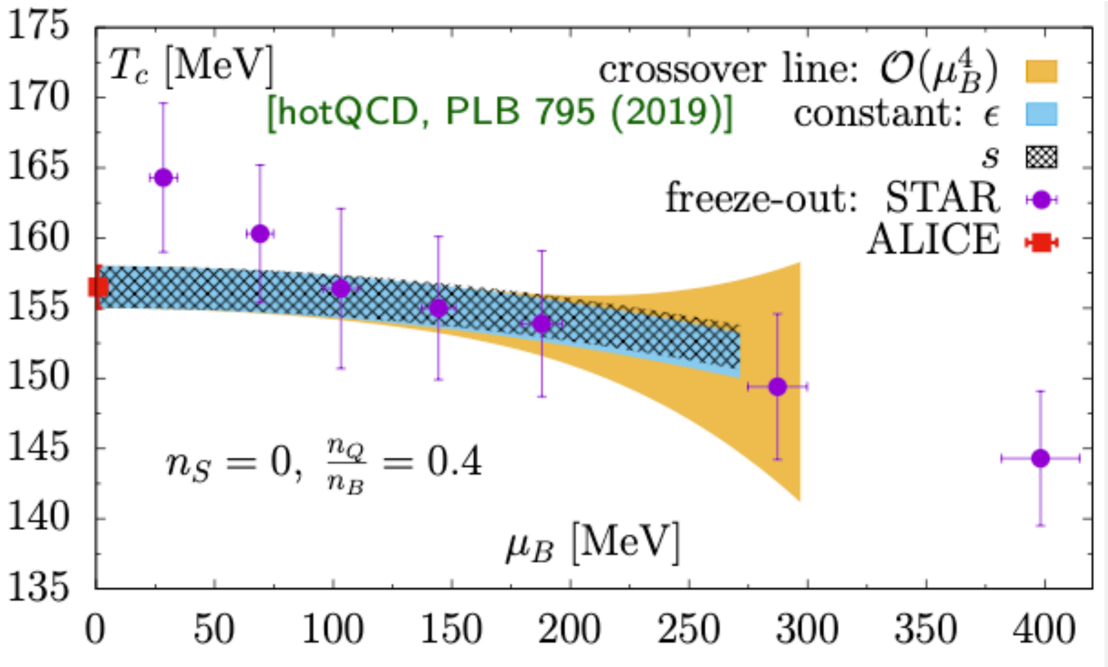
QGP speed of sound relative to that of light



First principles Lattice QCD results



Critical (cross-over) Temperature from LQCD
compared to Heavy-Ion collision results

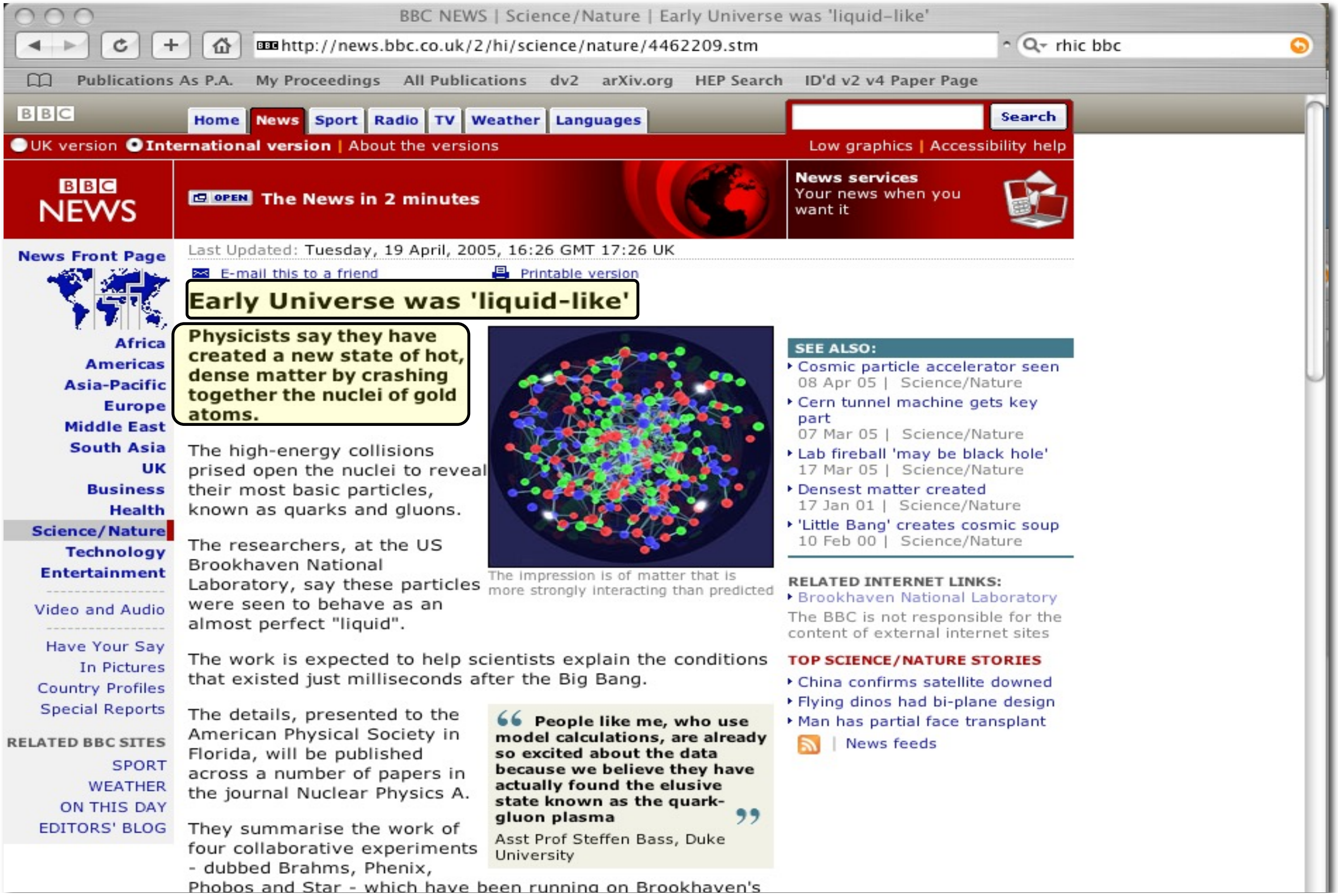


Increasing baryon density/
Decreasing collision energy

Heavy-Ion collisions create the hottest/densest matter on earth in excess of 5.5 trillion Kelvin

Guinness Book of World Records

The QGP is a nearly perfect fluid



Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

> **"People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma"**
>
> Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's

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News feeds

Perfect fluidity at RHIC and the LHC

Change in QGP energy density ε due to gradients in the pressure P and the fluid velocity ($\propto$ viscosity η)

"Bjorken" relativistic hydrodynamics

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

Viscous term smaller than ideal term for

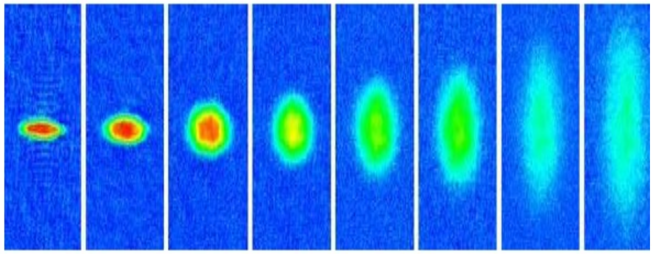
$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} \equiv \boxed{\frac{\eta}{s}}\frac{1}{\tau T} << 1$$

From kinetic theory

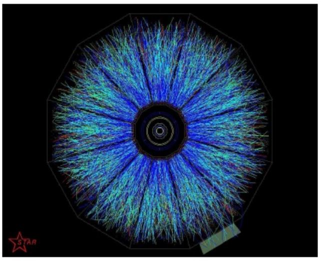
$$\boxed{\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{\tau_{\text{relax.}}}{\tau_{\text{quant.}}}}$$

H_2O

^{4}He



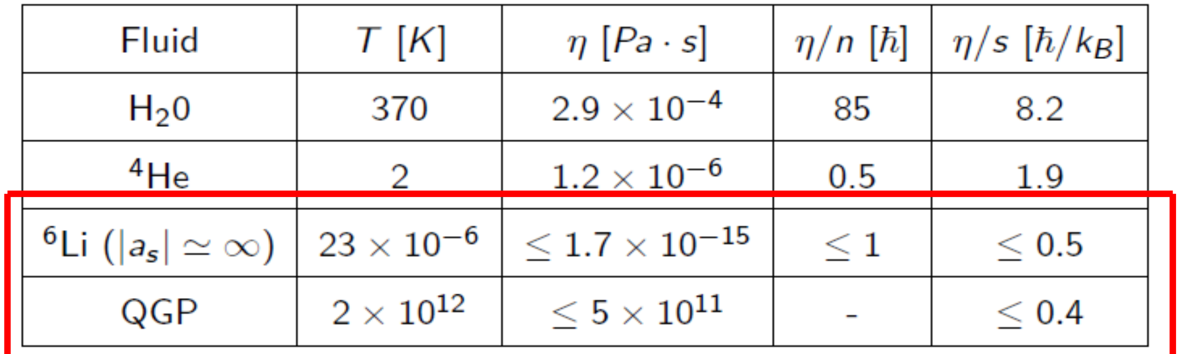
^{6}Li



sQGP

Perfect fluidity at RHIC and the LHC

$$\boxed{\frac{\eta}{s} \sim \frac{\hbar}{k_B} \frac{\tau_{\text{relax.}}}{\tau_{\text{quant.}}}}$$



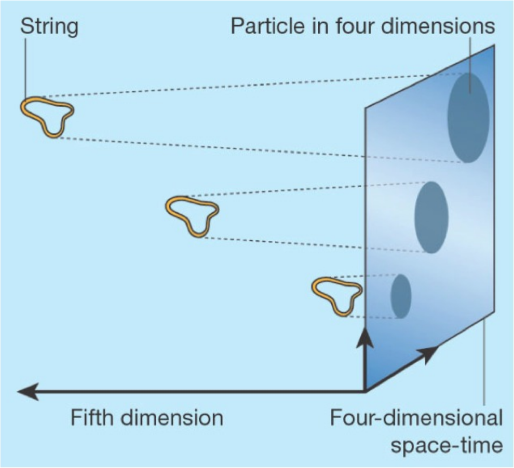
Fluid	T $[K]$	η $[Pa \cdot s]$	η/n $[\hbar]$	η/s $[\hbar/k_B]$
H_20	370	2.9×10^{-4}	85	8.2
^{4}He	2	1.2×10^{-6}	0.5	1.9
^{6}Li $(\lvert a_s \rvert \simeq \infty)$	23×10^{-6}	$\leq 1.7 \times 10^{-15}$	≤ 1	≤ 0.5
QGP	2×10^{12}	$\leq 5 \times 10^{11}$	-	≤ 0.4

Ultra-cold matter

Ultra-hot matter

Teaney, Schafer (2009)

Perfect fluidity at RHIC and the LHC



J.Maldacena, Nature 2003

Absorption cross-section of a graviton on a black brane $\sigma(\omega) = \frac{8\pi G}{\omega} \int dt d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t,\mathbf{x}), T_{xy}(0,0)] \rangle$

From Kubo, $\eta = \frac{\sigma(0)}{16\pi G}$ From Bekenstein & Hawking, $s = \frac{a}{4G}$ Theorem: $\sigma(0) = a$

Putting these together, $\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$ Conjectured universal lower bound

Kovtun, Son, Starinets (2005)

Perfect fluidity at RHIC and the LHC

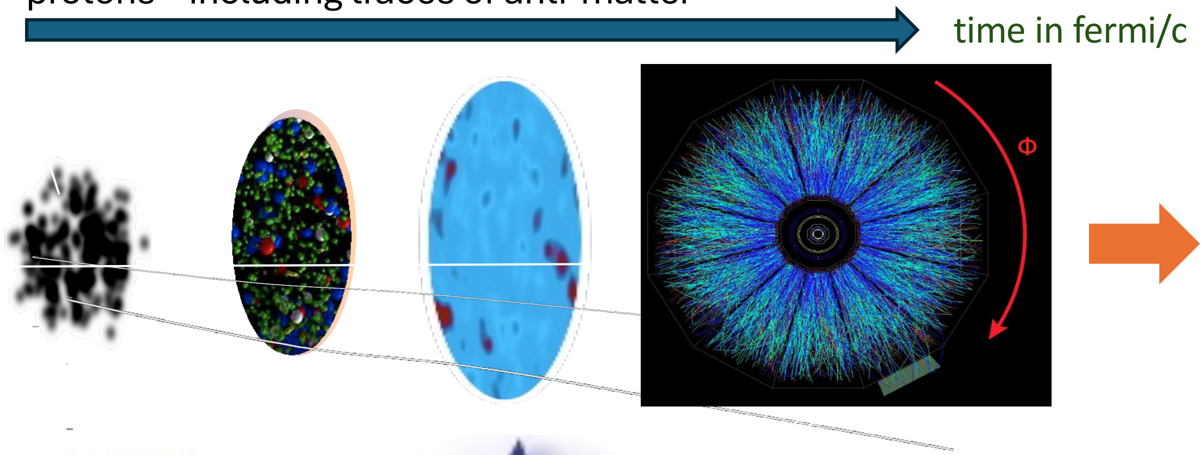
$$\boxed{\frac{\eta}{s} \sim \frac{\hbar}{k_B} \frac{\tau_{\mathrm{relax.}}}{\tau_{\mathrm{quant.}}}}$$

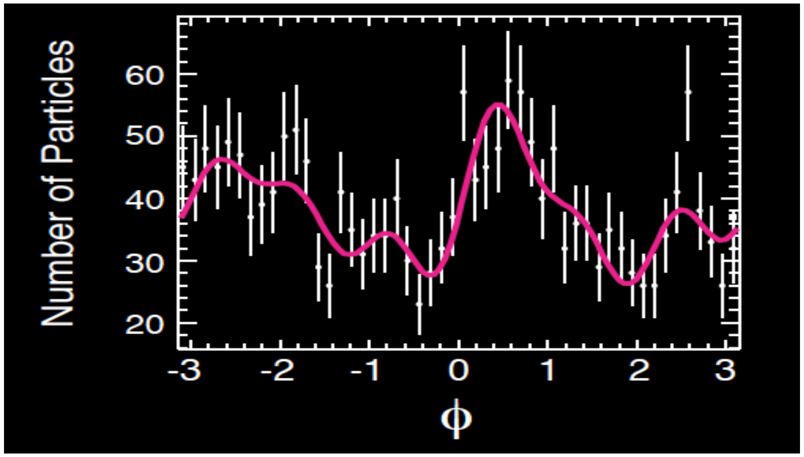
Pitch drop experiment (1927-)
-world's longest running lab
experiment

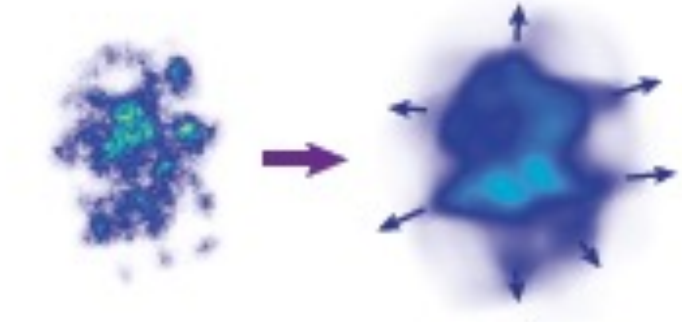
QGP is 10,000 times more viscous than tar but…has nearly perfect response to external forces (pressure gradients)

The unreasonable effectiveness of hydrodynamics in the little Bang

From lumpy glue (and quarks) to shower of pions, kaons, protons – including traces of anti-matter



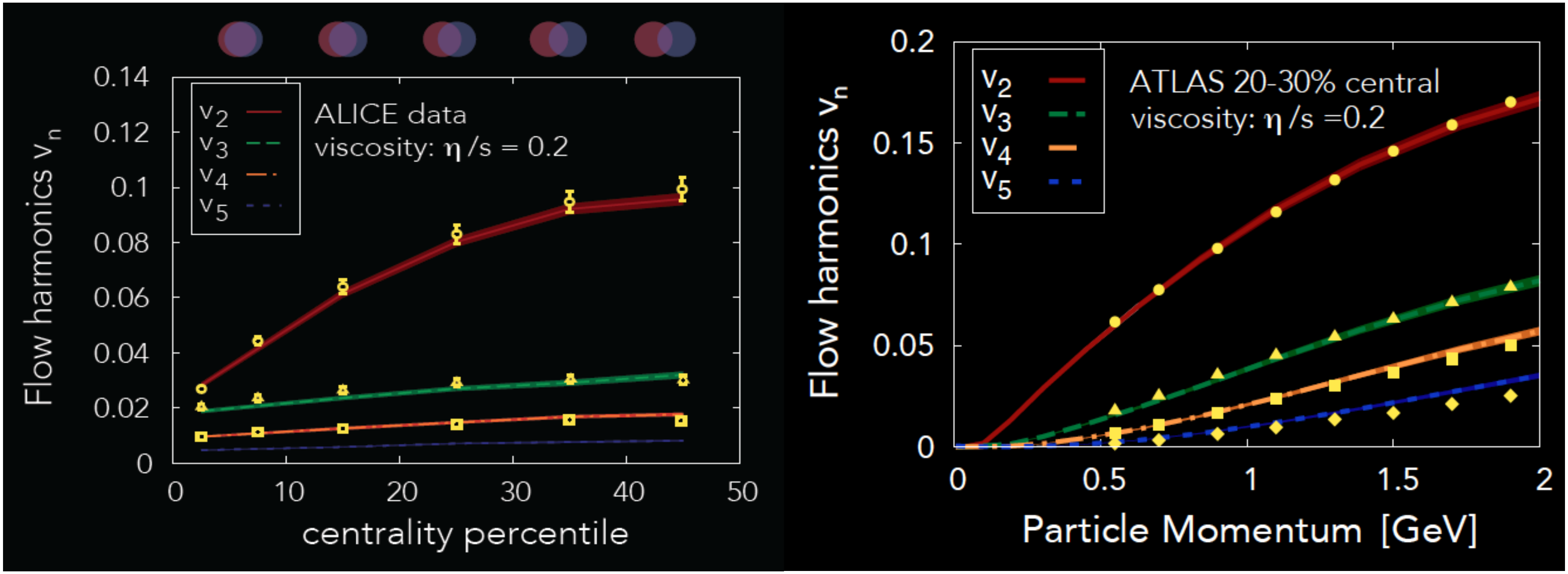




$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\left(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots\right)\right)$$

Efficient transfer of spatial anisotropy to momentum anisotropy:
Characterized by flow moments – v_2,v_3,…v_8,…

The unreasonable effectiveness of hydrodynamics



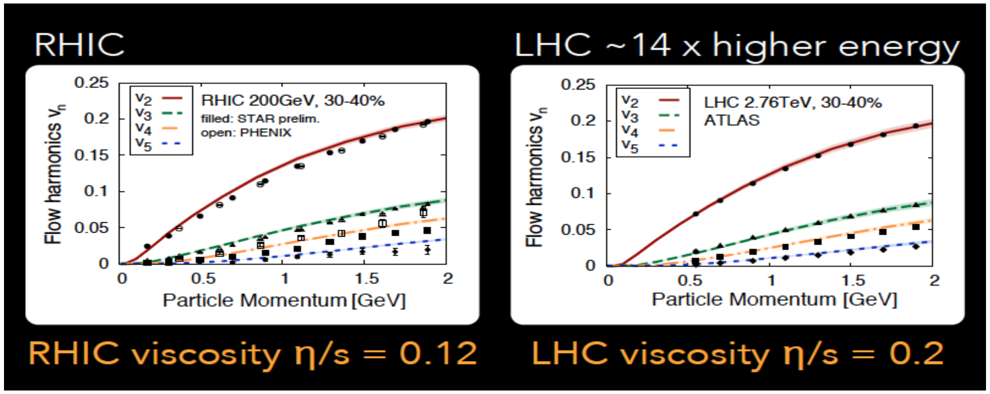
Theory curves: 3+1-D relativistic viscous hydrodynamics simulations: “IP-Glasma model”

Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL 110, 012302 (2013)

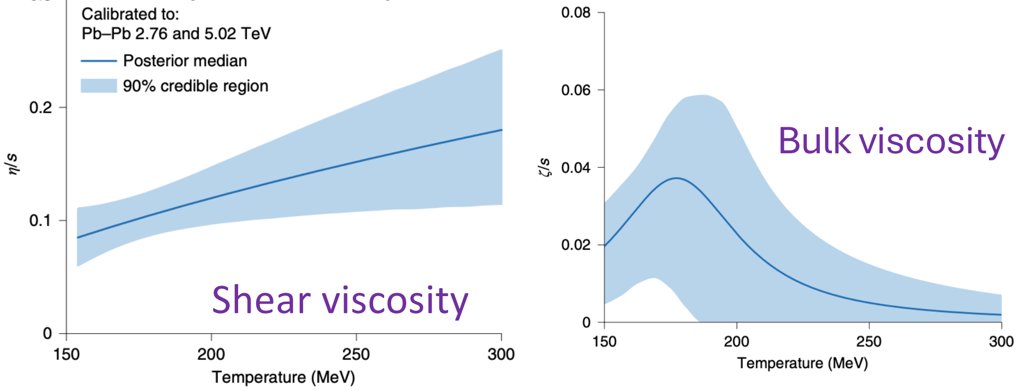
Experimental data: ALICE & ATLAS Coll.

PRL 107, 012301 (2011) & Phys. Rev. C86, 014907 (2012)

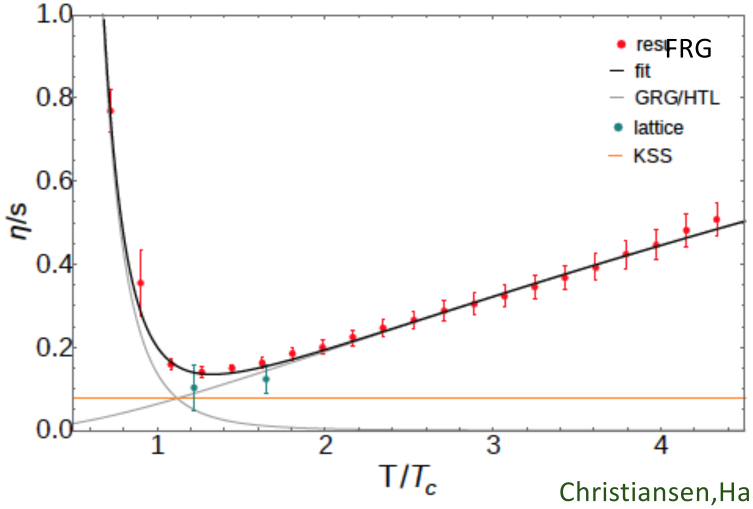
Temperature dependence of QGP transport coefficients



Bayesian analysis of combined RHIC & LHC data



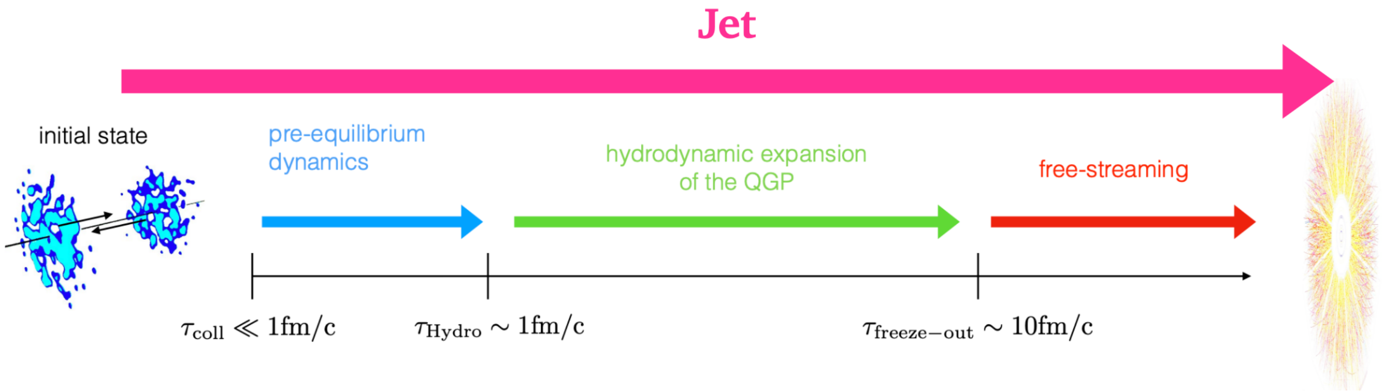
Bernhard,Moreland,Bass, Nature Physics Letters (2019)



Christiansen,Haas,Pawlowski,Strodthoff,PRL115 (2015)112002

Theory approaches to transport properties of the QGP: Functional renormalization group , Lattice QCD, Hard Thermal loop perturbation theory,…

Hard probes of the QGP: many-body structure at fine resolution



Jet

initial state

pre-equilibrium dynamics

hydrodynamic expansion of the QGP

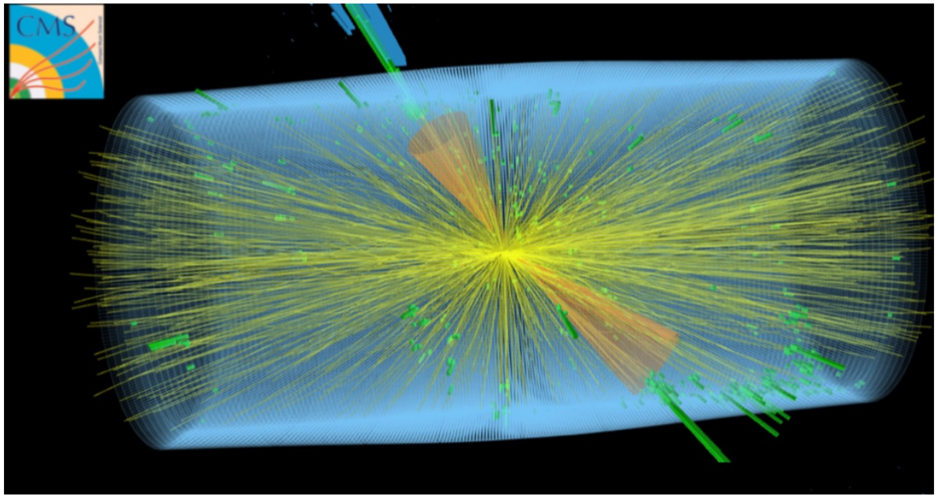
free-streaming

$\tau_{\rm coll} \ll 1{\rm fm/c}$

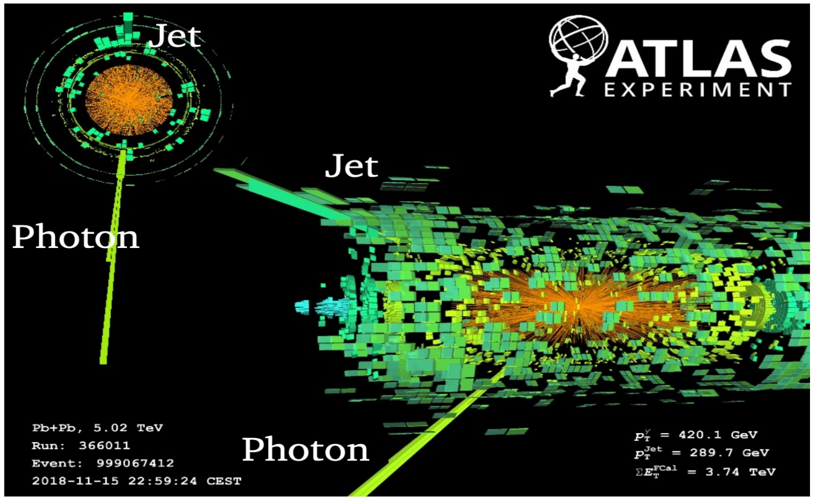
$\tau_{\rm Hydro} \sim 1{\rm fm/c}$

$\tau_{\rm freeze-out} \sim 10{\rm fm/c}$

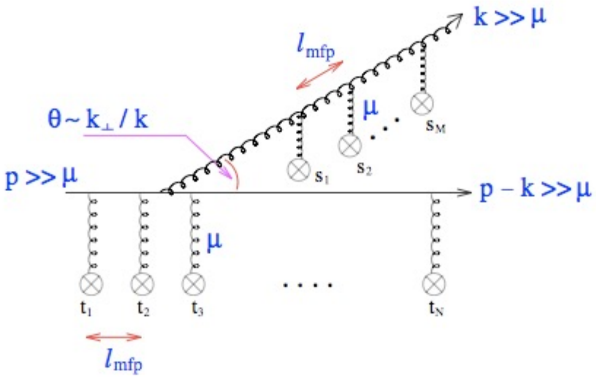
Di-jets in Lead-Lead (Pb+Pb) collisions at the LHC



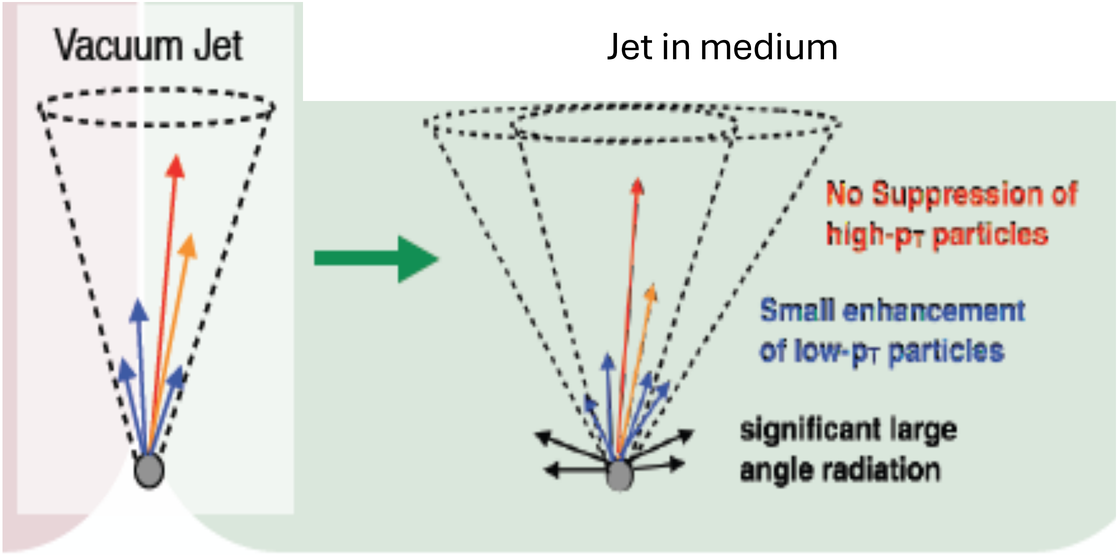
Photon+jet event in Pb+Pb collisions at the LHC



Hard probes of the QGP: many-body structure at fine resolution

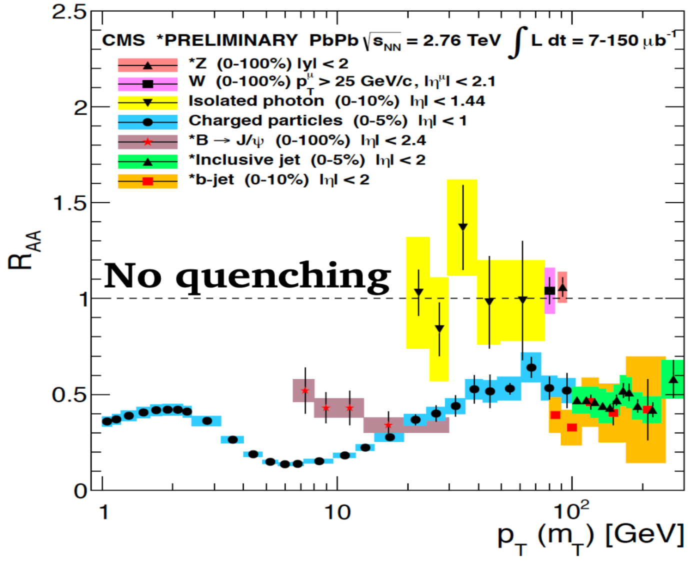


Radiative and collisional energy loss of quark/gluon jets as they traverse the expanding QGP



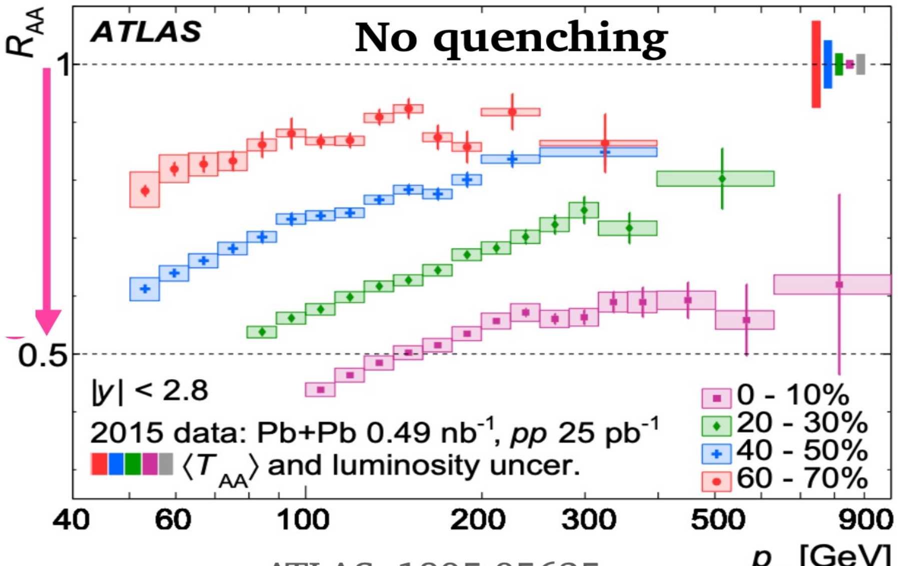
Hard probes of the QGP: many-body structure at fine resolution

Energy loss in Pb+Pb / p+p
versus momentum

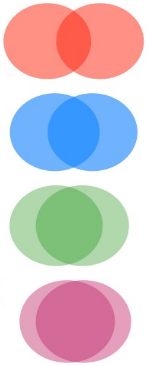


Quenched jets

Energy loss in Pb+Pb / p+p versus QGP fireball size

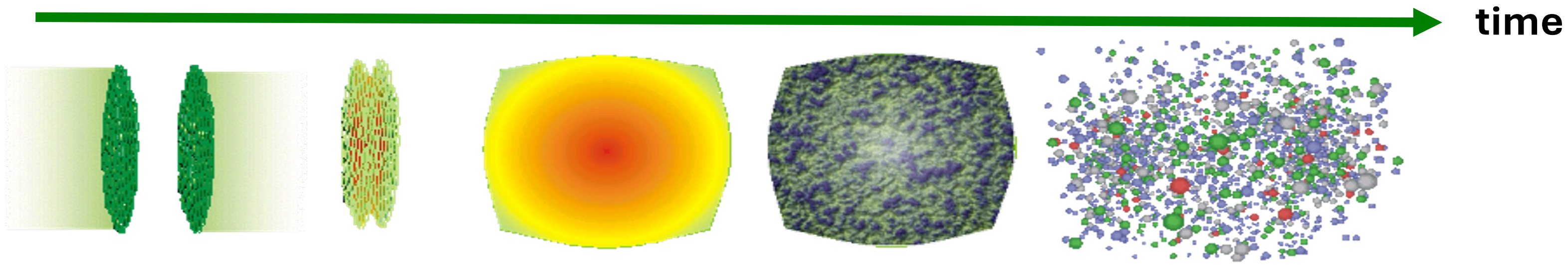


ATLAS, 1805.05635



Other probes: Heavy Quarks, Hard Photons, Z-bosons, Z+Jet, even Top Quarks!

How does the QGP thermalize?



Relevant d.o.f
in wave-fn.?

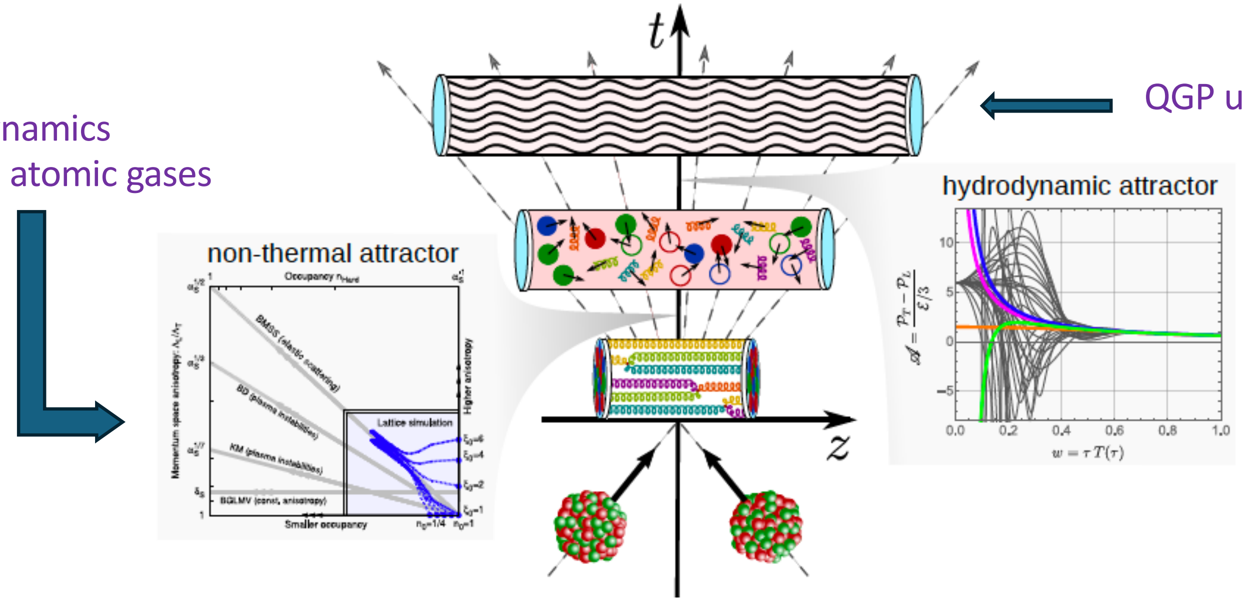
How is entropy
generated?

Universal non-equil.
dynamics?

Transport in the
sQGP perfect fluid

Hadron Gas

How does the QGP thermalize?

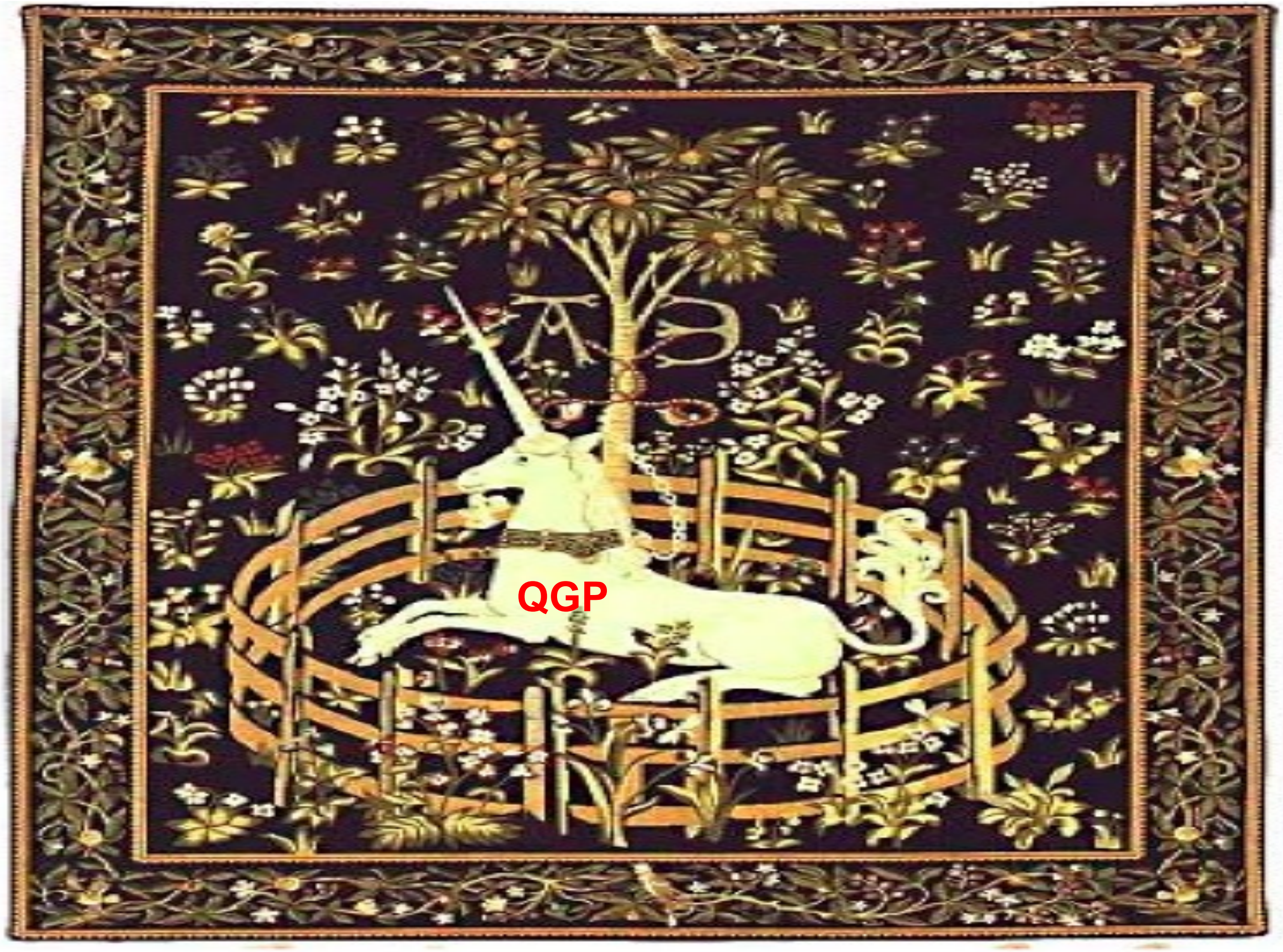


Universal dynamics
to ultra-cold atomic gases

QGP undergoing hydrodynamic expansion

Colliding Color Glass Condensate shockwaves

QCD thermalization: Ab initio approaches
and interdisciplinary connections
Jürgen Berges, Michal P. Heller, Aleksas Mazeliauskas, and R. V.
Rev. Mod. Phys. **93**, 035003 (2021)



Asymtotic Freedom led to the recreation of a novel form of matter:
Much remains to understand it fully