Fluid dynamics in the extreme - The Quark-Gluon Plasma

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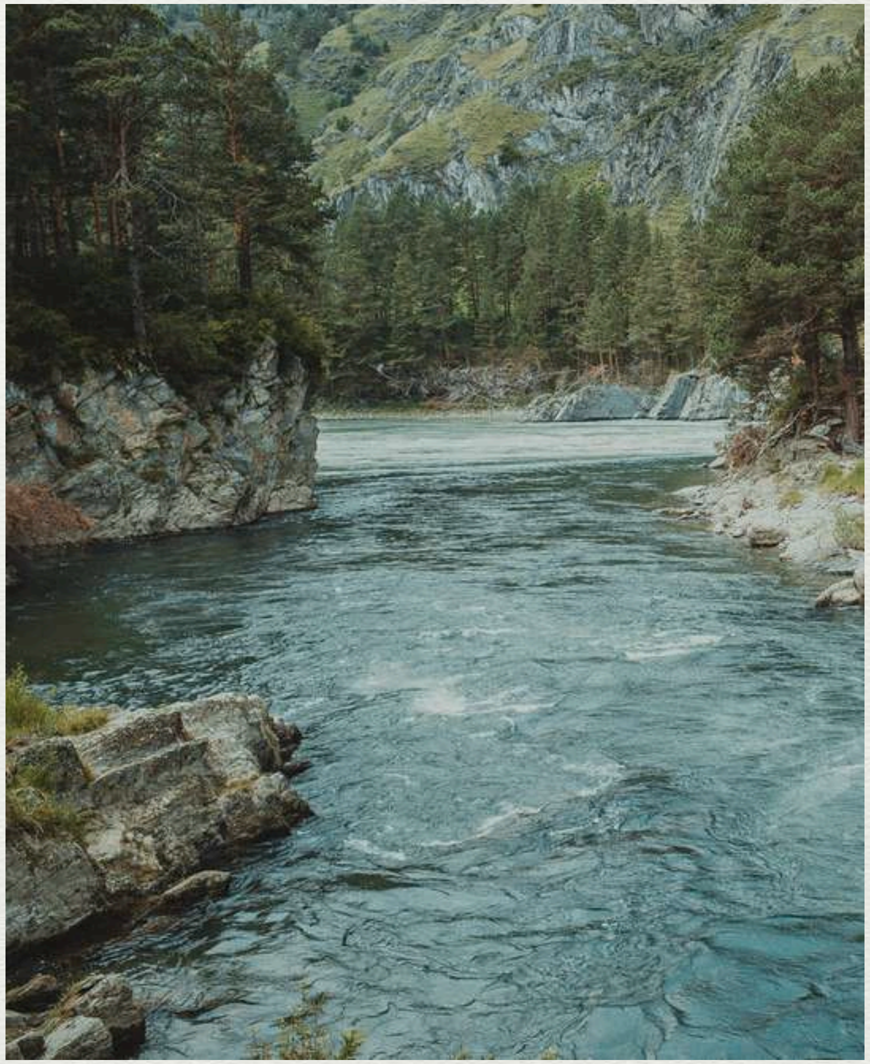
Theoretical Physics Colloquium via Arizona State University

Fluids 101

- It flows (its particles easily move past each other)
- Takes the shape of the container (no permanent shape)
- Cannot resist an outside shearing force
- Variables: $\{\rho, P\}$, not $\{m, F\}$



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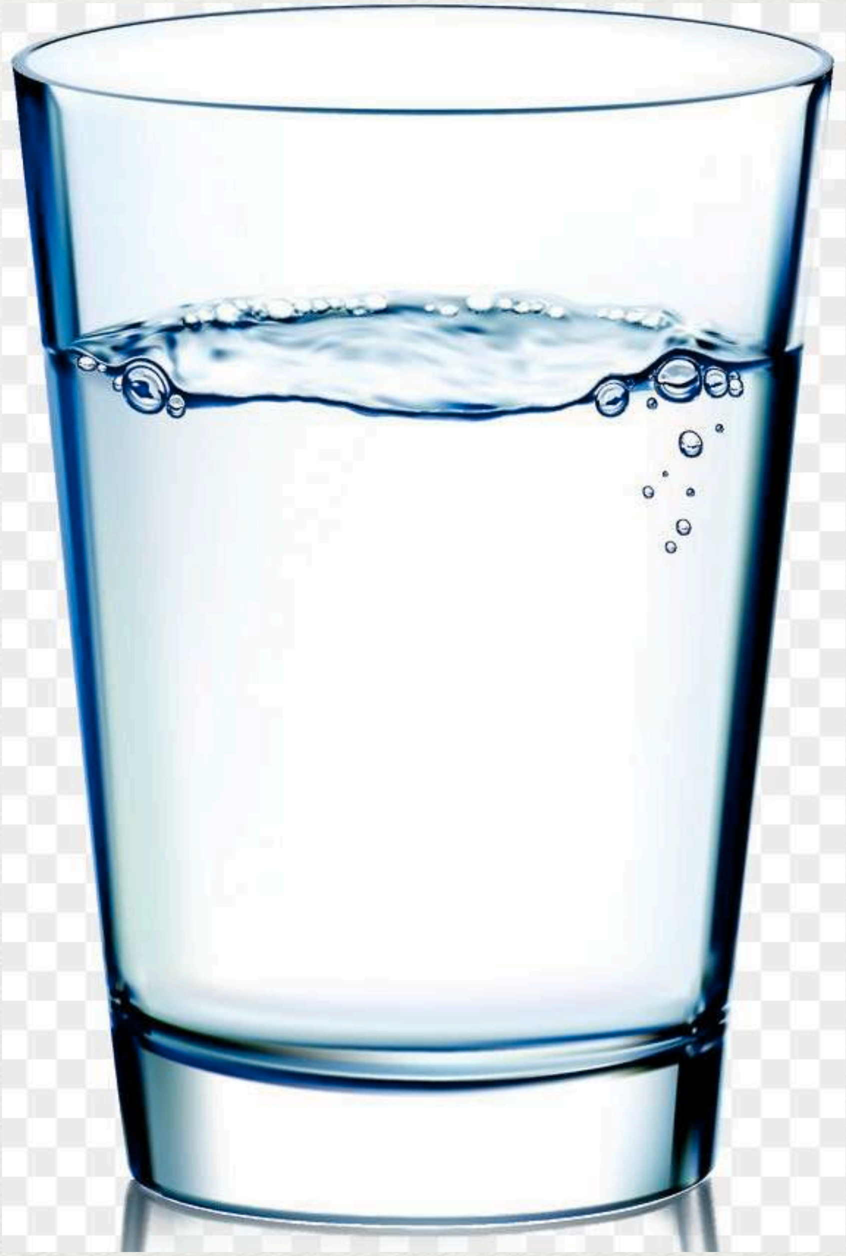

Fluids 101

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When is fluid dynamics applicable?

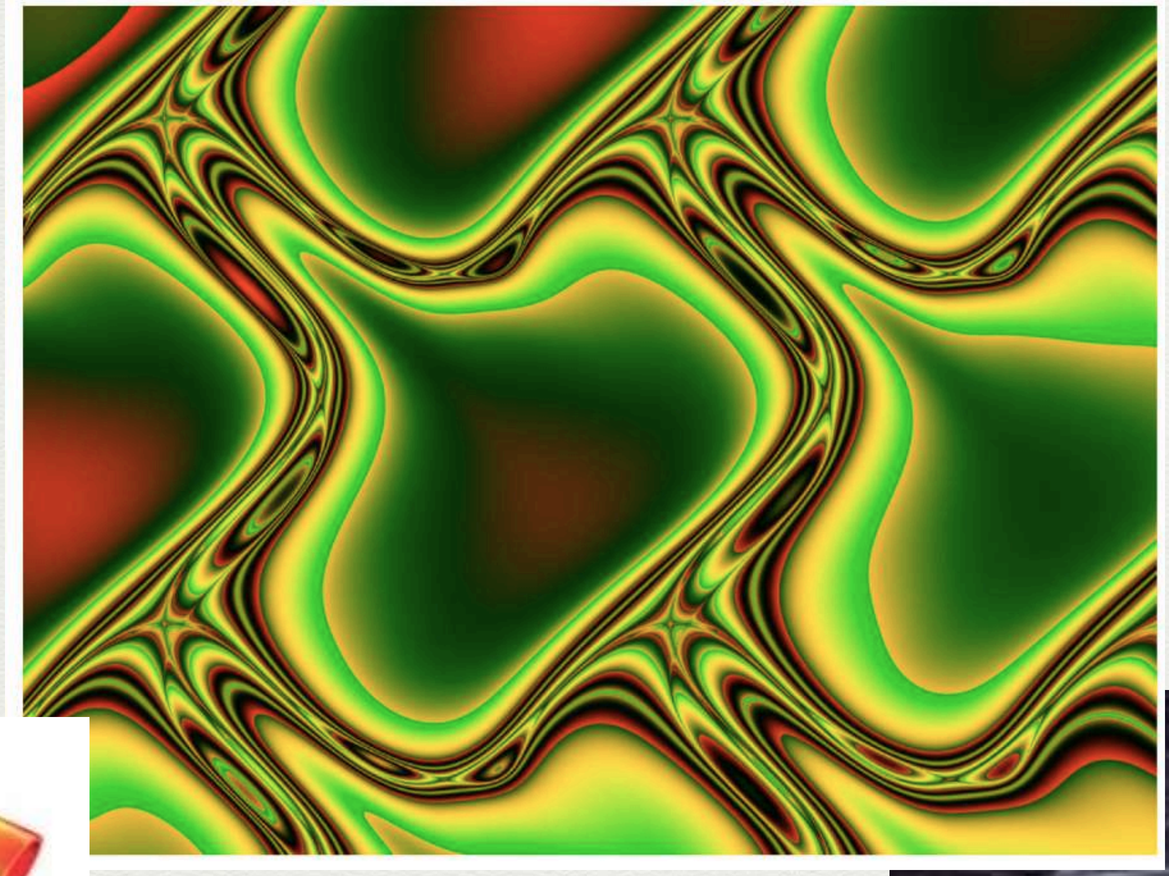
Large separation of scales i.e. small Knudsen (or inverse Reynolds) number

$$Kn \sim \frac{\text{Small scale* } (H_2O \text{ molecule})}{\text{Large scale (size of lake)}}$$

* mean free path i.e. distance before the molecule collides with something else

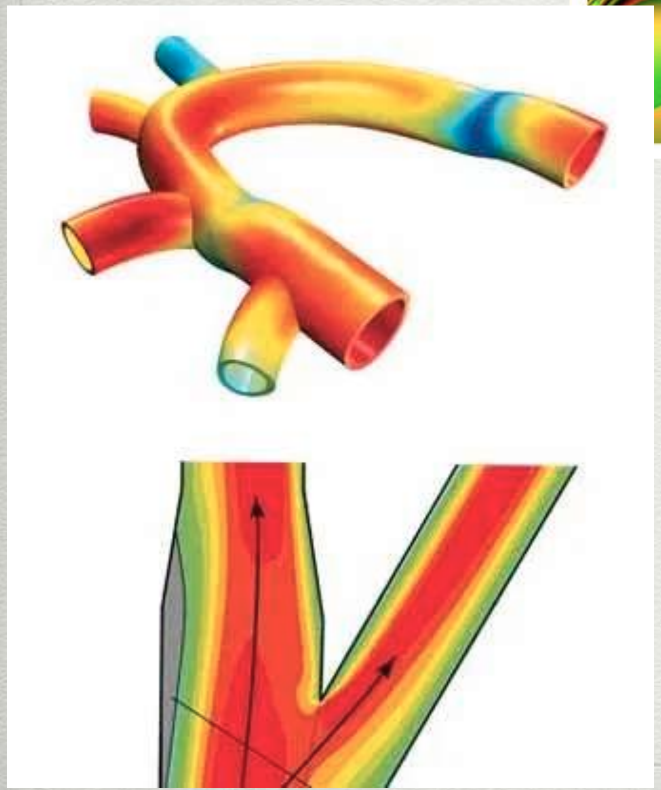
Question: When can you apply fluid dynamics?
Answer: $Kn \ll 1$

Fluids are everywhere



Traffic Jam

Blood flow

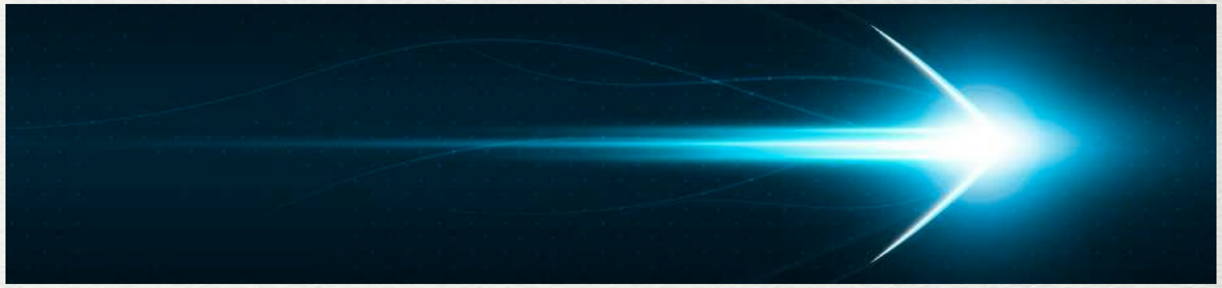


Neutron Star Mergers

Fluids at the **extreme**

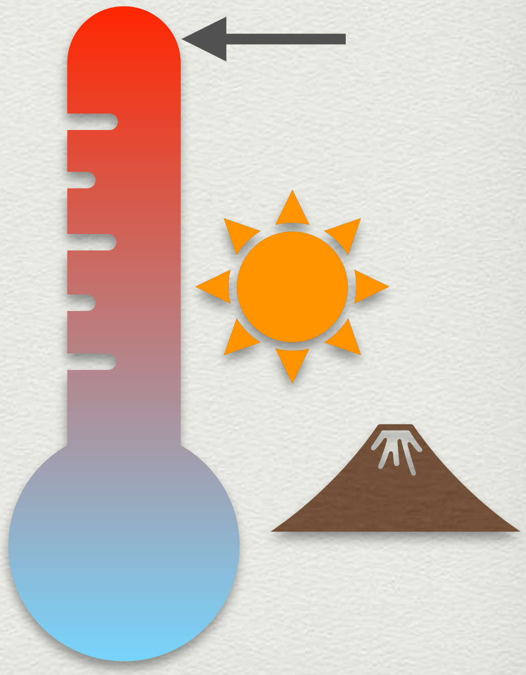
What happens when a fluid moves at the speed of light?

New equations of motion (Israel-Stewart) are needed to preserve casualty and stability



What happens when fluids are heated up to the highest temperatures possible on Earth?

$10^{12}\ K$



The degrees of freedom are deconfined quarks and gluons

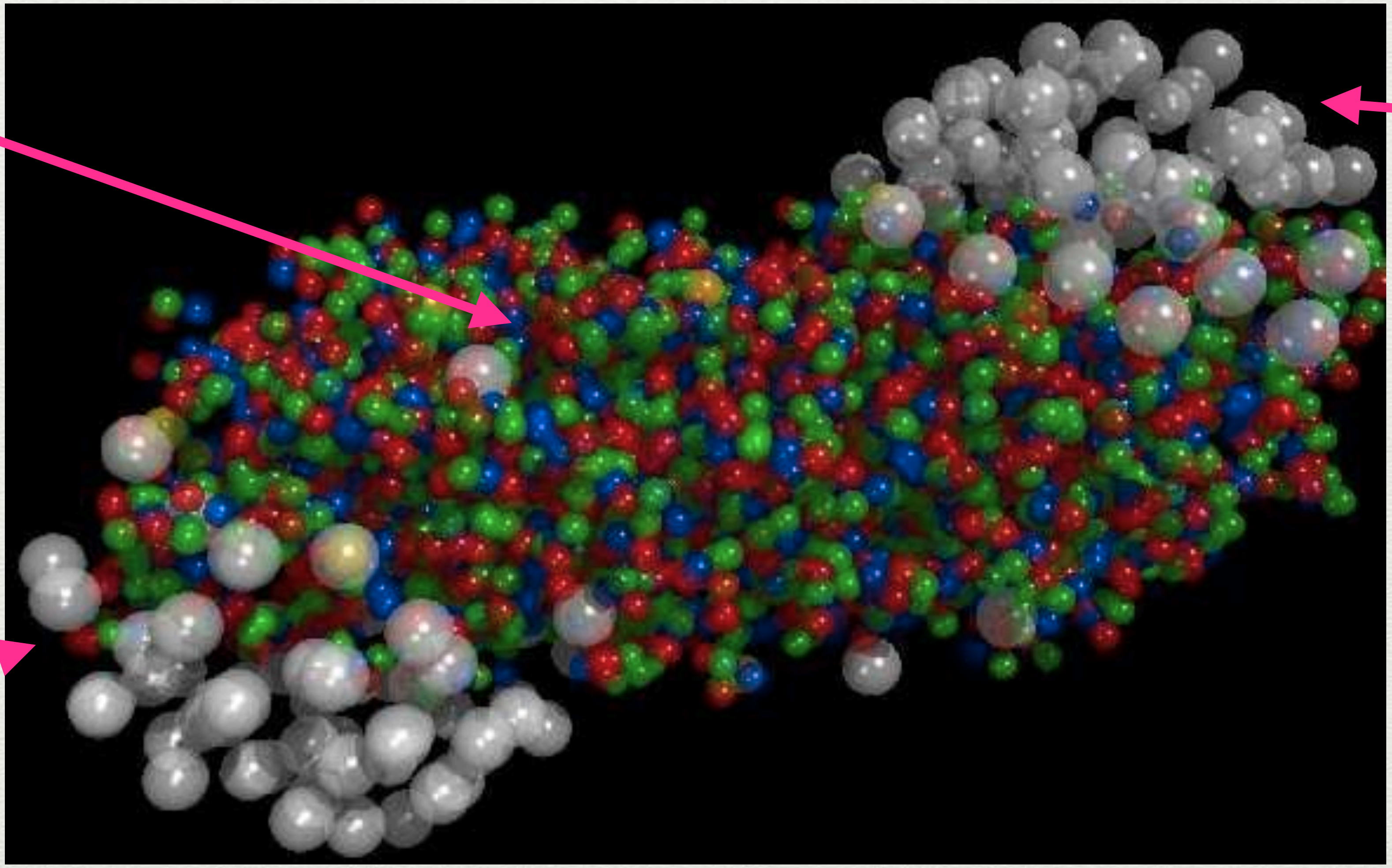
What is the smallest fluid?

We're still figuring that out, but Knudsen numbers get tricky

Why not all three?

The **Quark Gluon Plasma** is created using the highest temperatures on Earth, in the smallest systems possible (colliding nuclei, maybe even colliding protons), and flows at ultra relativistic speeds

Quark Gluon Plasma



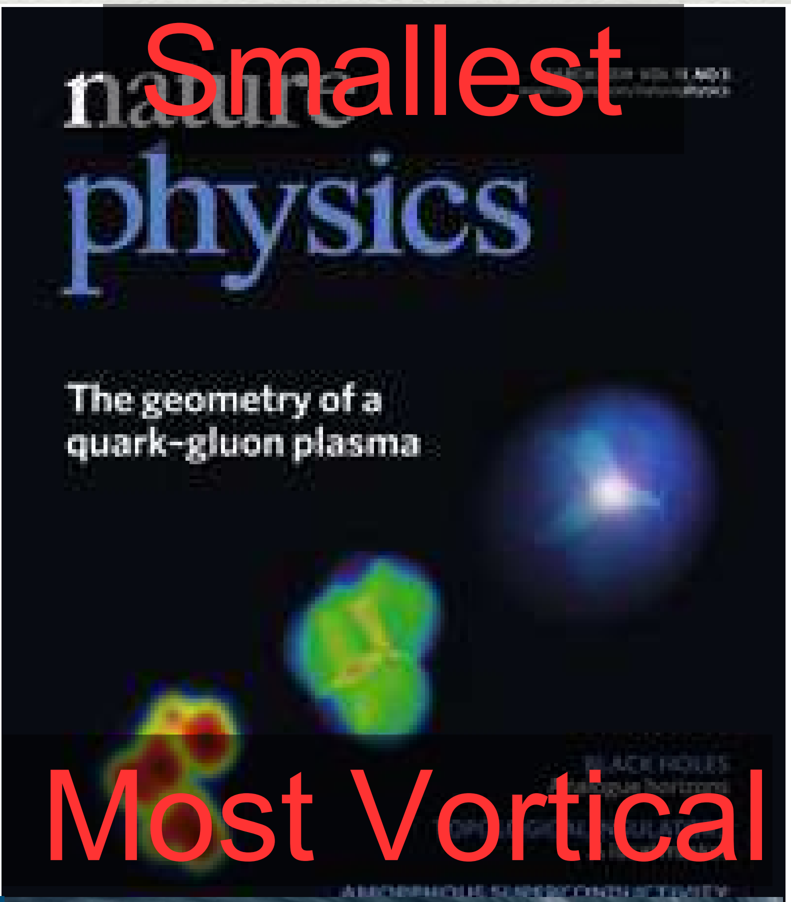
Nucleus

Nucleus

The Quark Gluon Plasma is the ...

Hottest

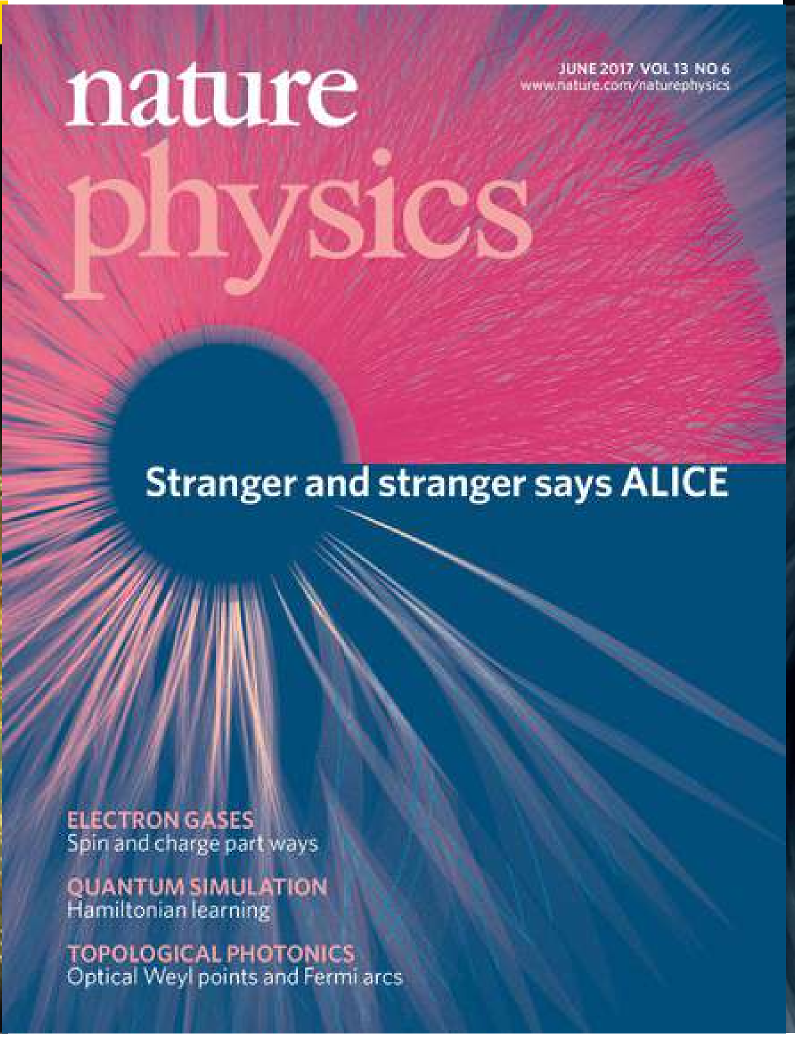
Smallest

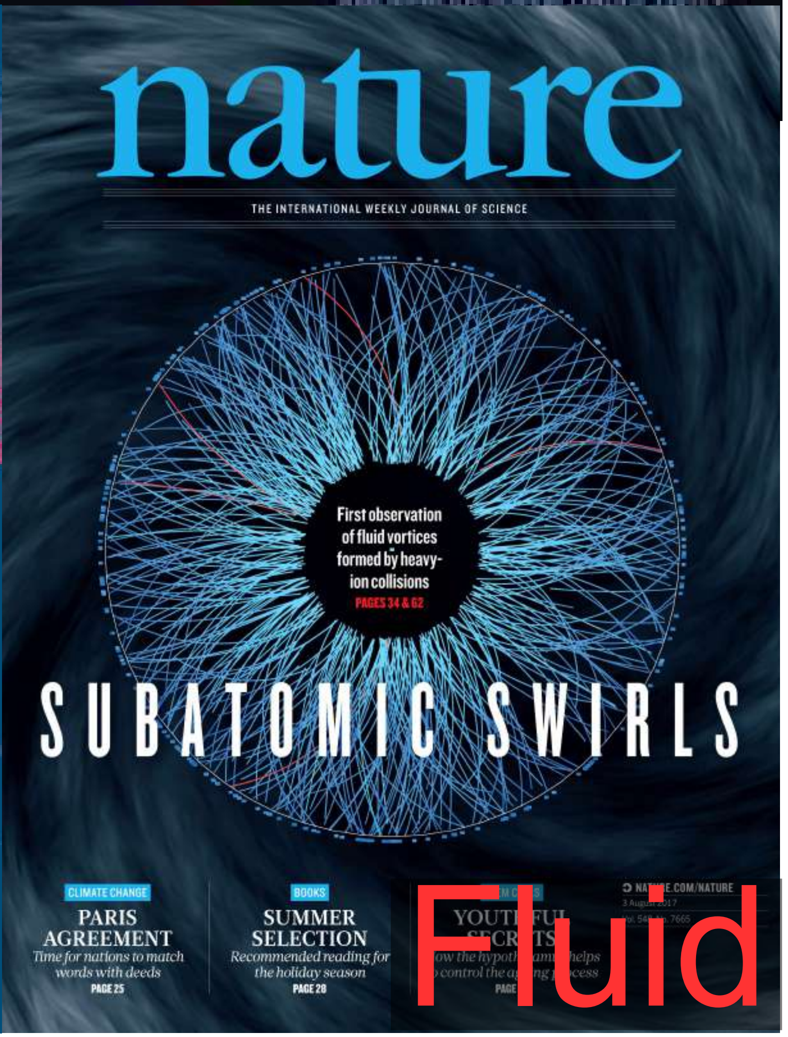


Most Perfect

Strange

Most Vortical

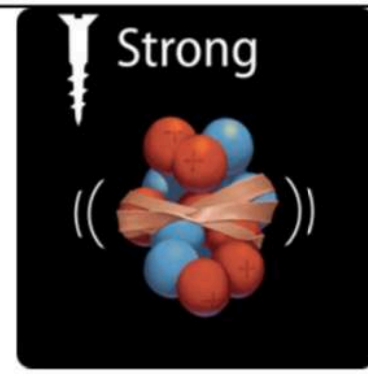
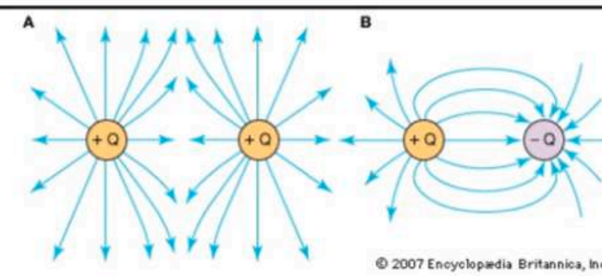
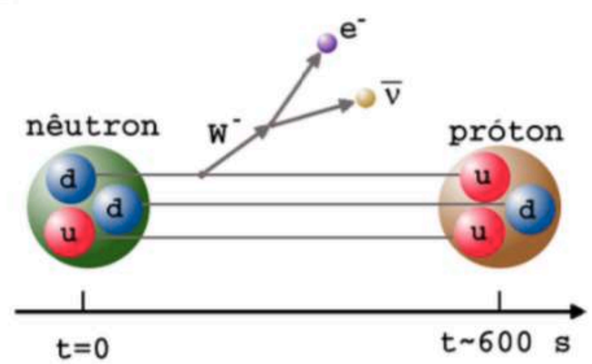
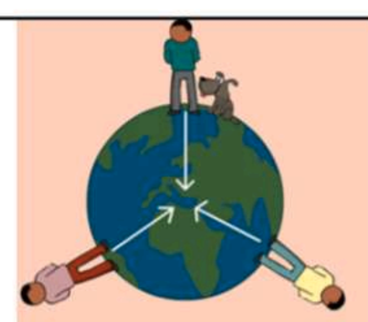




Fluid

To understand the Quark Gluon Plasma, we first need to understand the strong force and Quantum Chromodynamics

Strongest Force

Force		Strength	Range (m)
Strong		1	10^{-15} (size of nucleus)
Electromagnetic		$\frac{1}{137}$	∞
Weak		10^{-6}	10^{-18} (0.1% of the proton)
Gravity		$6 * 10^{-39}$	∞

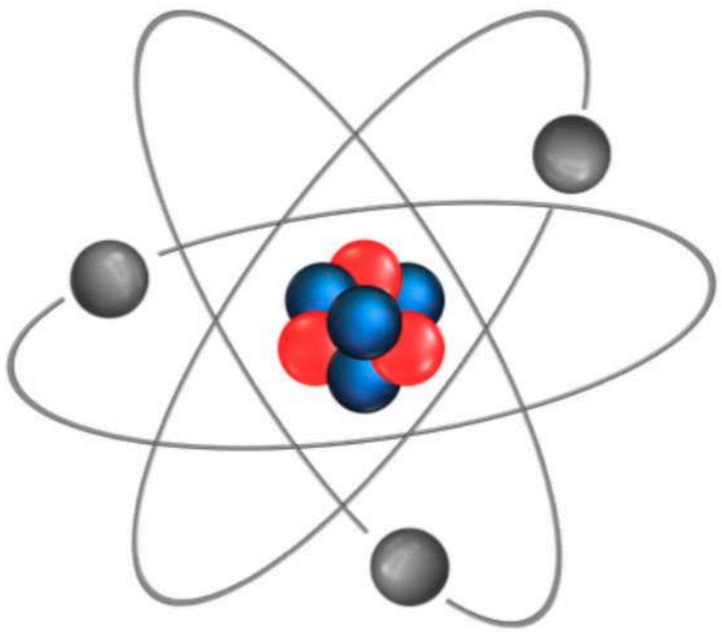
Scales of the universe

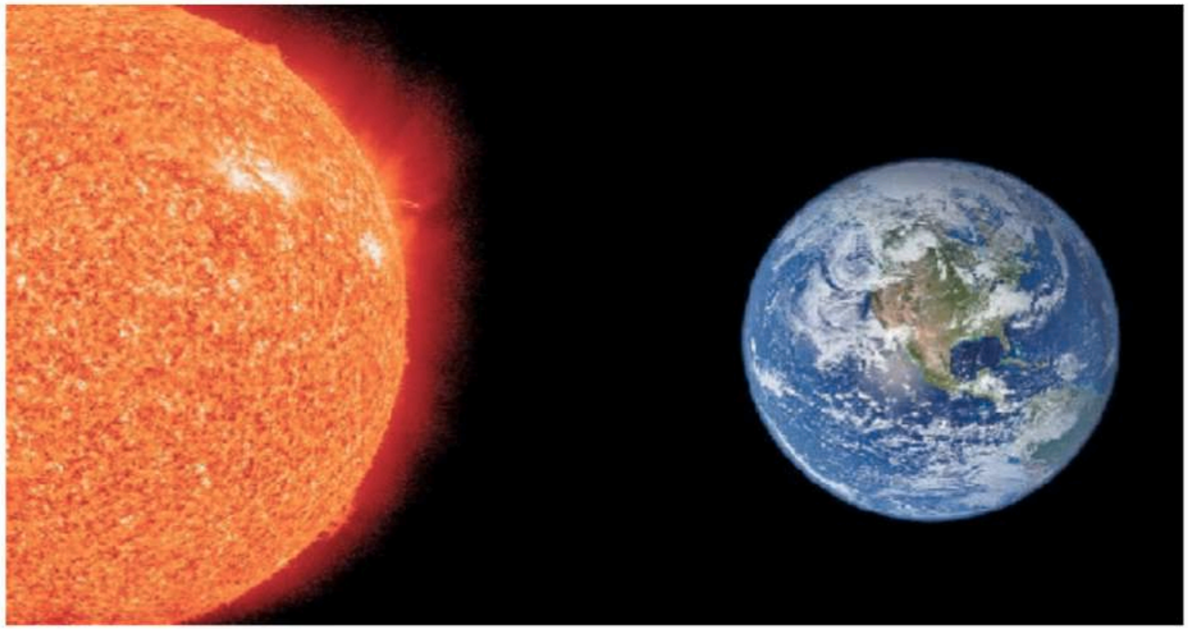
Atom

Scale $\sim 10^{-10}$ meter
Discovered by humans $\sim 1800's$
Experiment Chemistry

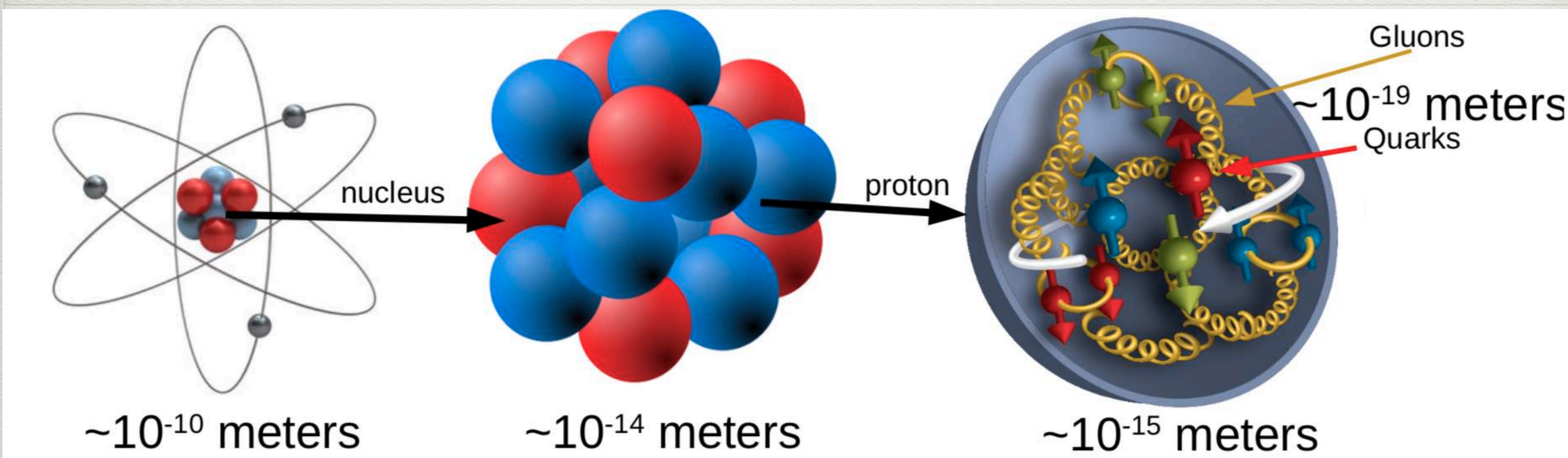
Distance Earth to Sun

Scale $\sim 10^{11}$ meter
Discovered by humans $\sim$ 250 BC
Experiment various





Scales of the strong force



Distance to nearest star (Alpha Centauri system) $\sim 10^{16}\ m$

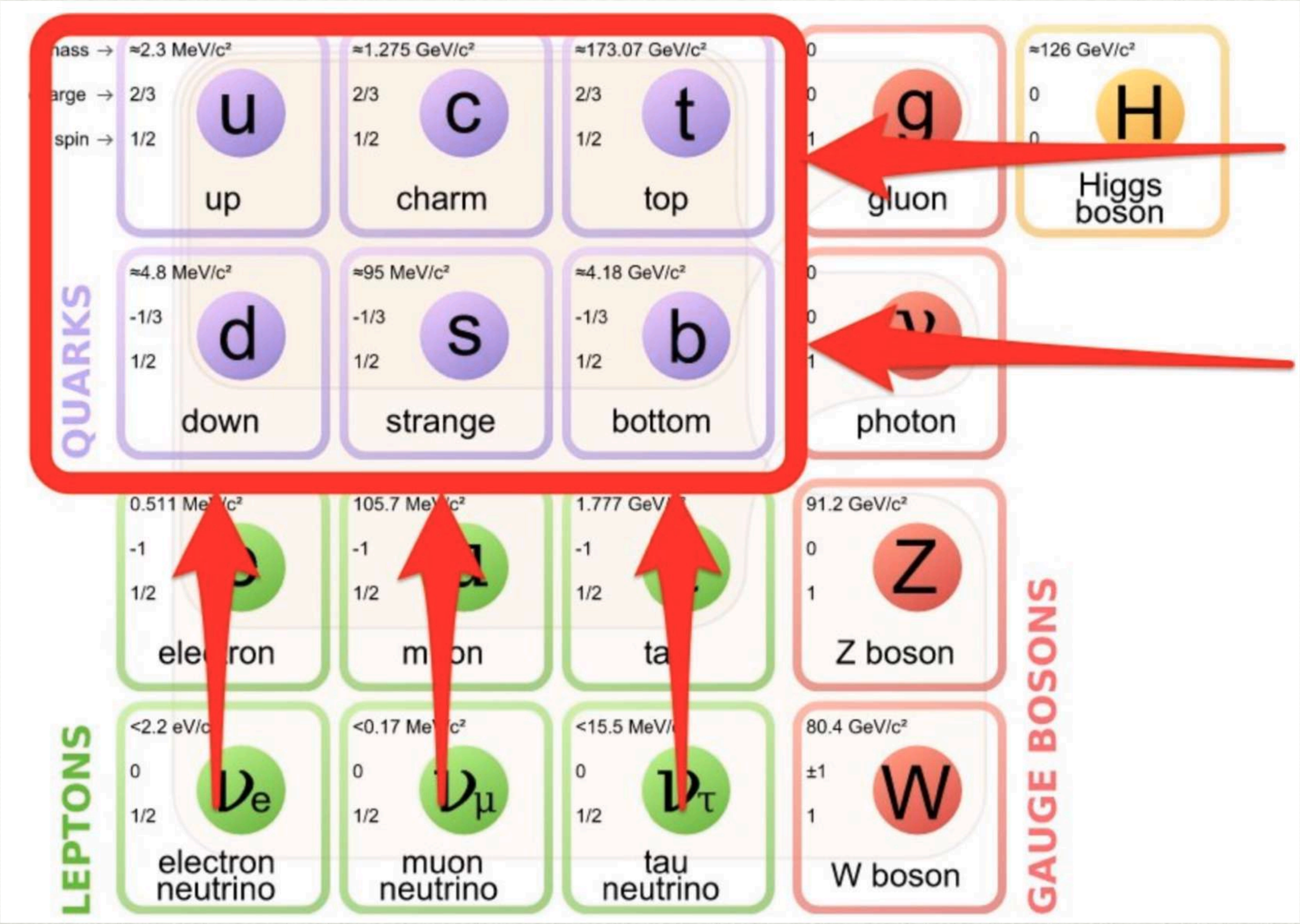
Natural Units: $\hbar = c = 1$ i.e. $E = Mc^2 \rightarrow E = M$

Length 1 Femtometer [fm] = $10^{-}15$ [m]

Temperature 1000 Megaelectron-volt [MeV] = 11 billion [K]

Mass 1 [MeV] = $1.79 * 10^{-30}$ [kg]

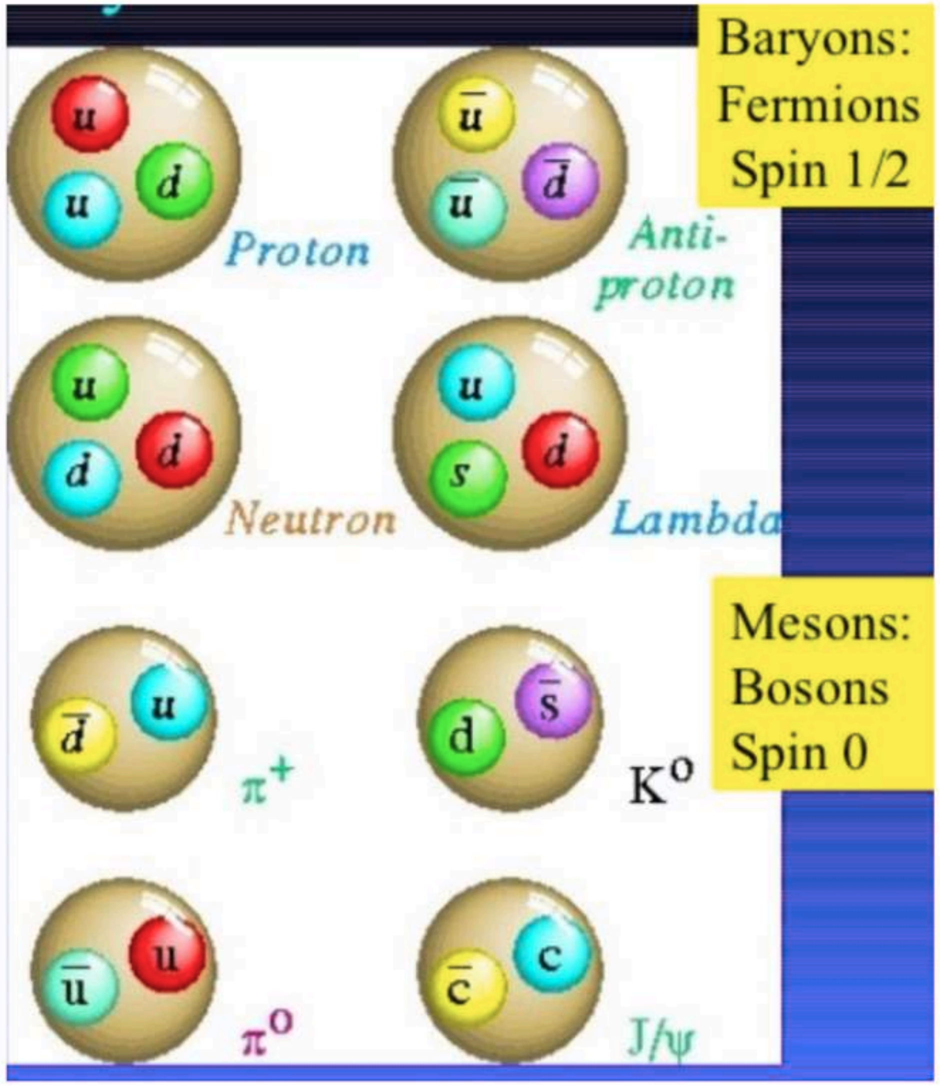
Standard Model



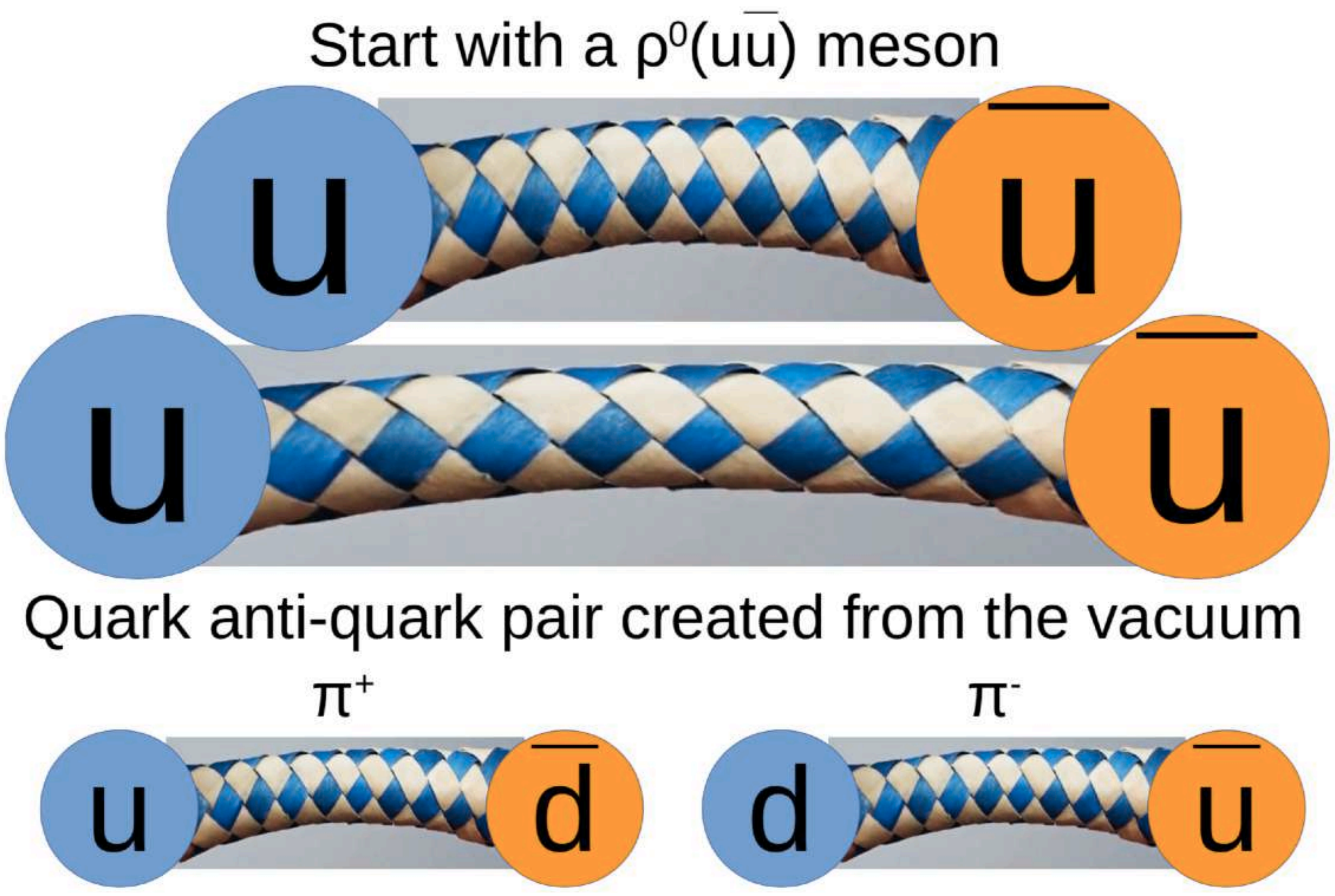
Theory of the strong force: Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD)- David Politzer, Frank Wilczek and David Gross 1973 (2004 Nobel Prize for Physics)

Bound states=Hadrons



Confinement- no free quarks



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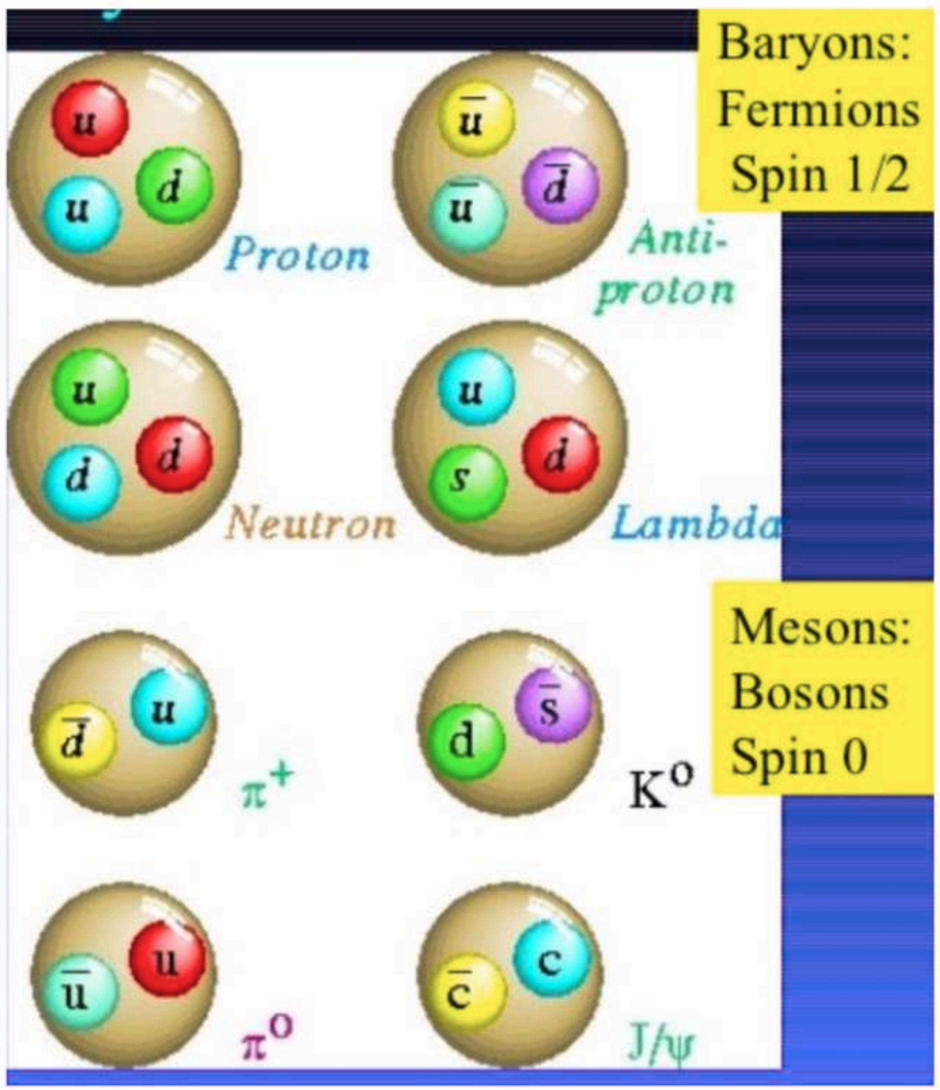

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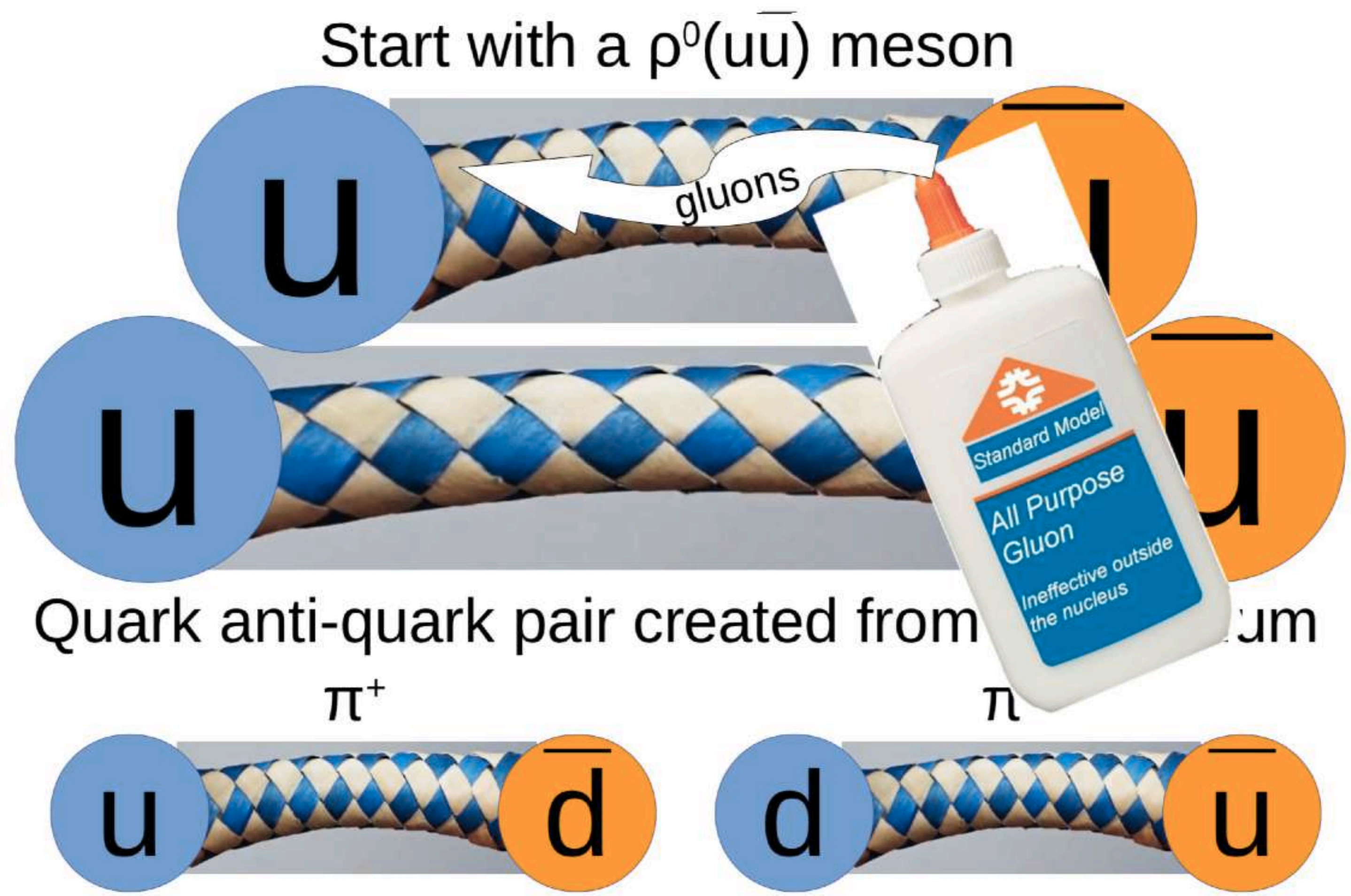
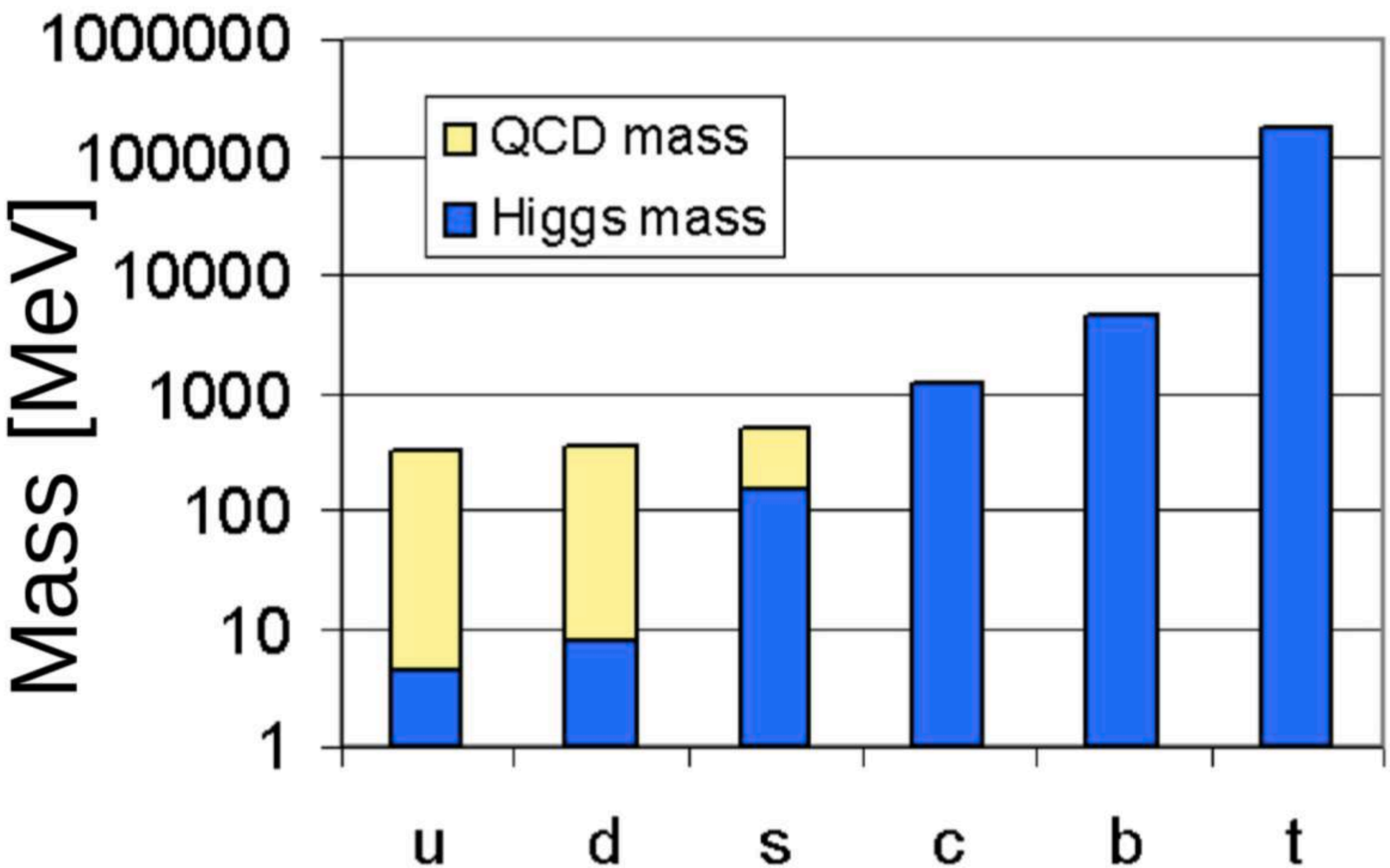
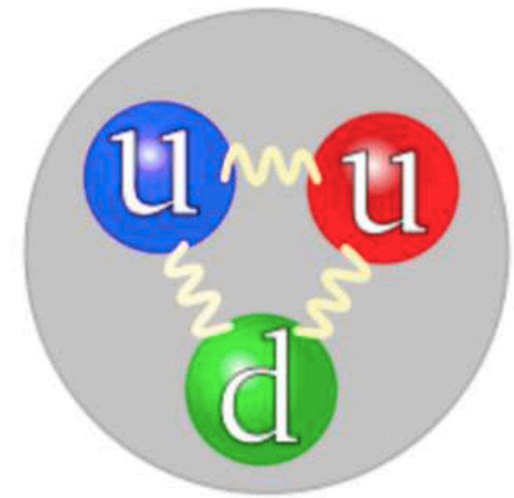


Visible Matter

QCD is ~ 95% of visible (baryonic) matter



Proton



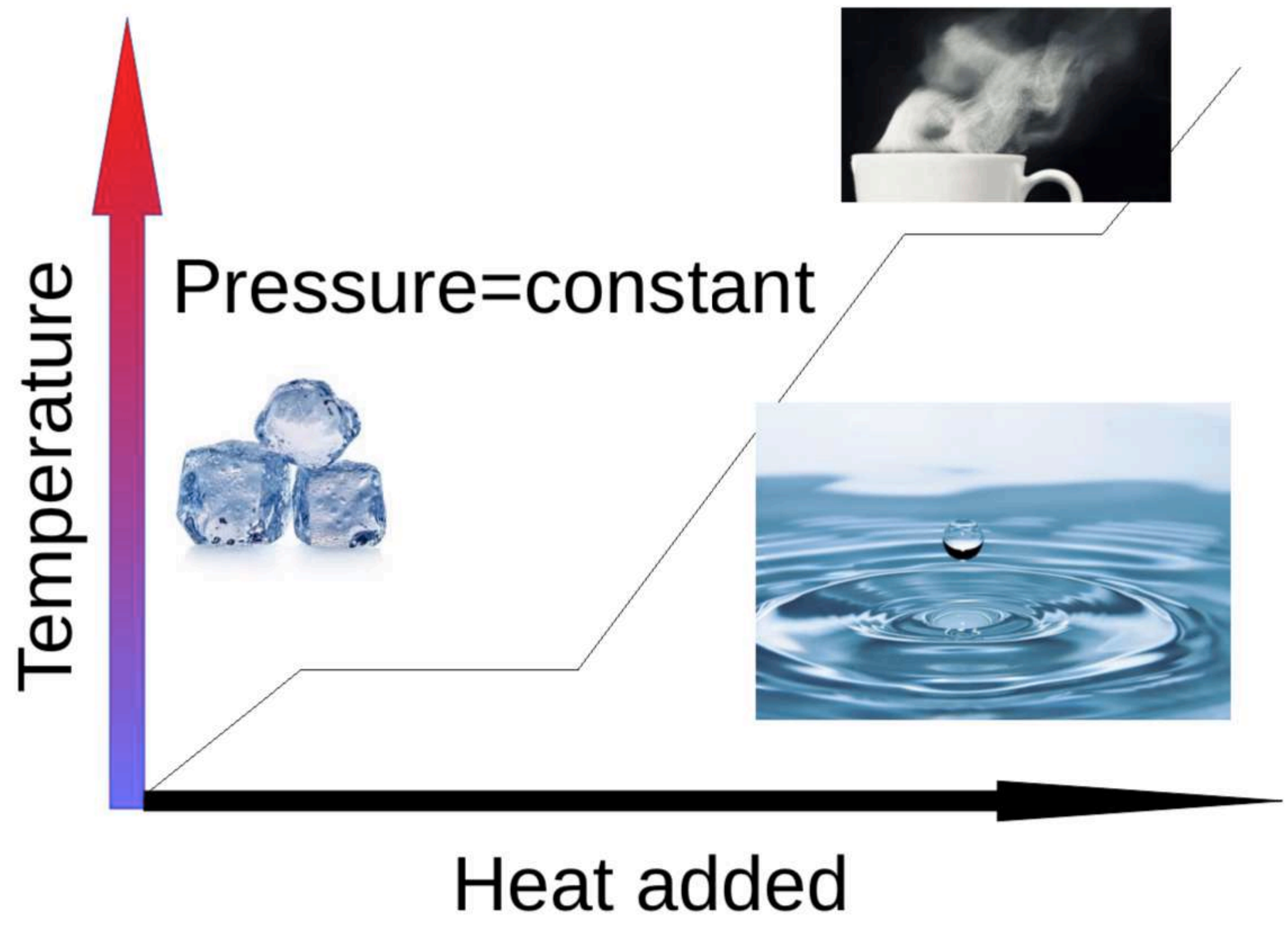
M_{quark}=2*2.3+4.8 [MeV]
=9.4 [MeV]

M_{proton}=938 [MeV]

M_{QCD}=928.6 [MeV]

B. Mueller Nucl.Phys. A750 (2005) 84-97

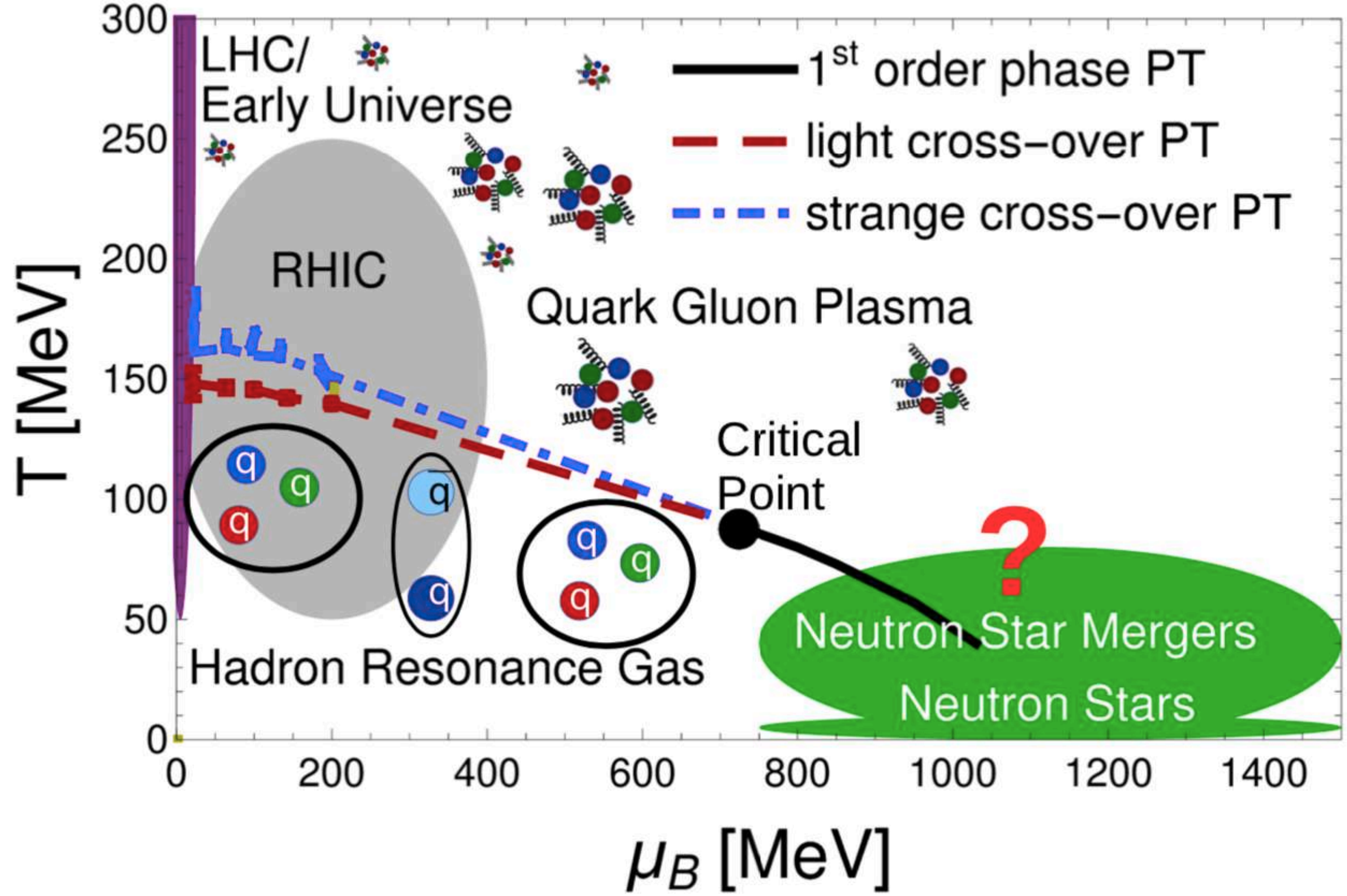
Phase Transitions of Water



Studying strong interactions/Quarks and Gluons

Can we $\Uparrow$ T enough to deconfine Quarks and Gluons?

Current Cartoon of the QCD phase diagram



References

Light transition Phys.Lett. B738 (2014) 305-310; **Strange Transition** JNH and Ratti arvix 1804.10661 ; **Neutron Star (mergers)** V. Dexheimer ariXiv:1708.08342; **Holography** Critelli, JNH et al, Phys.Rev. D96 (2017) no.9, 096026

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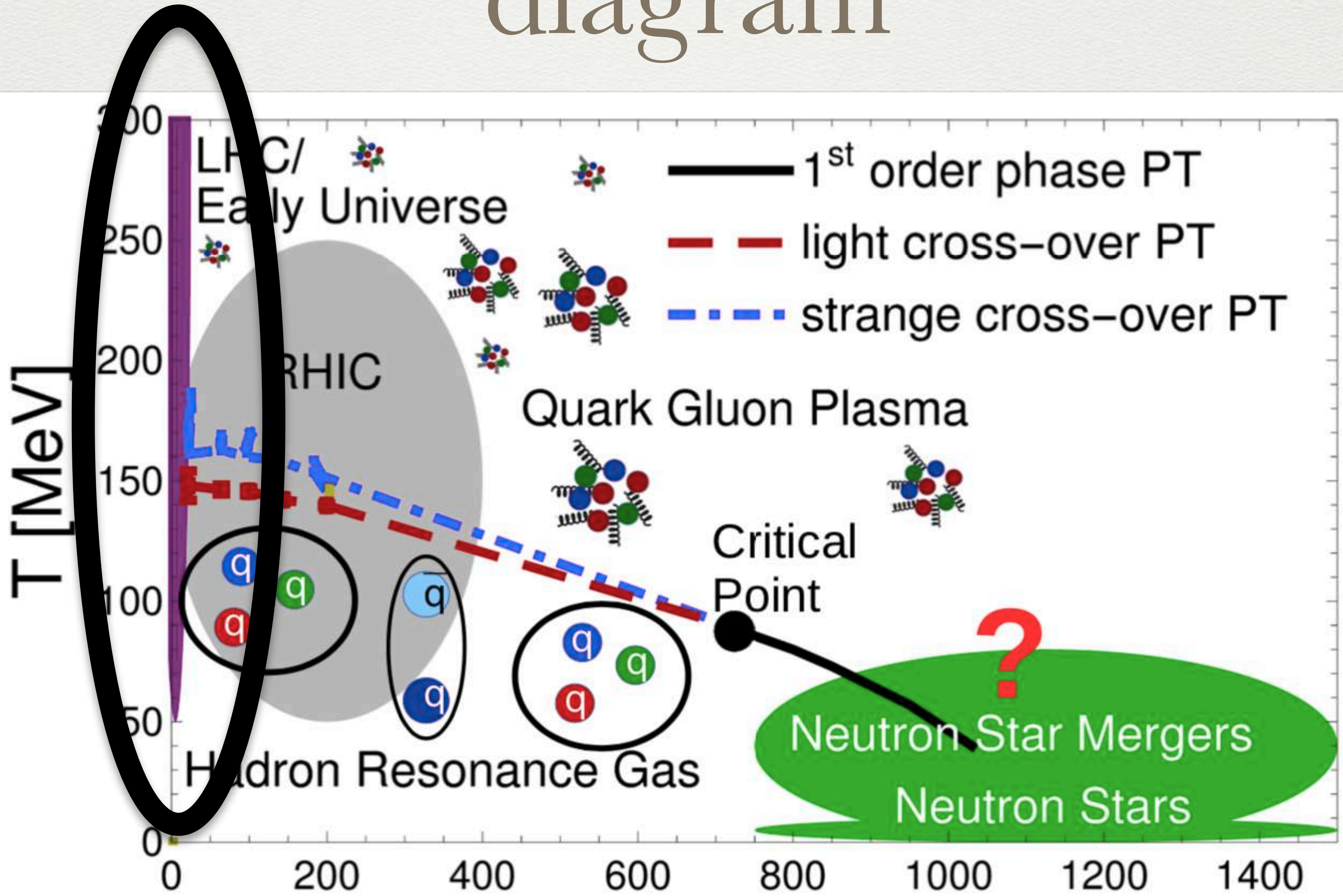

Baryons = anti-baryons

References

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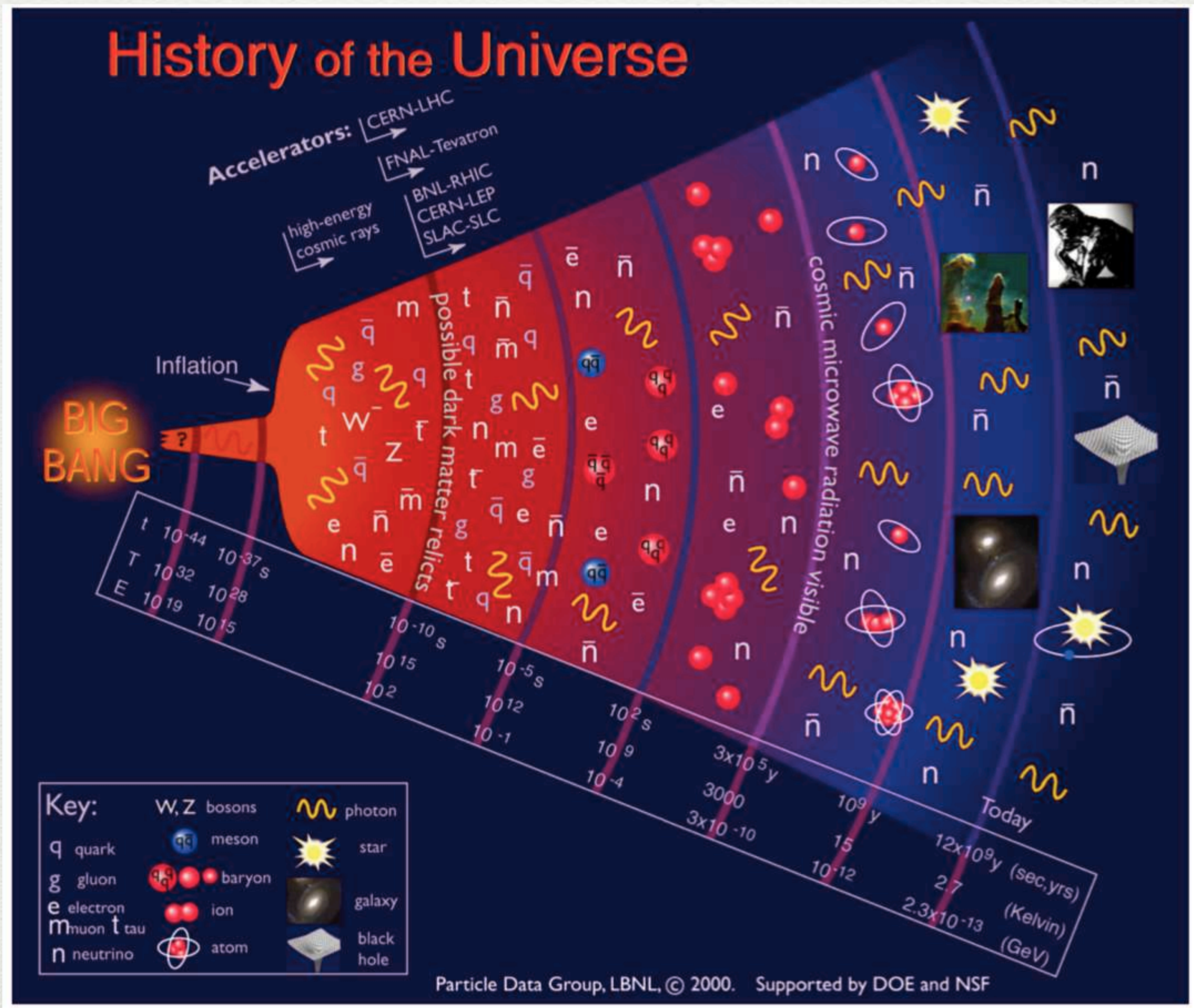
Deconfined Quarks and Gluons in the Early Universe

$\sim 10^{-6}\ s$ after the Big Bang → Quark Gluon Plasma

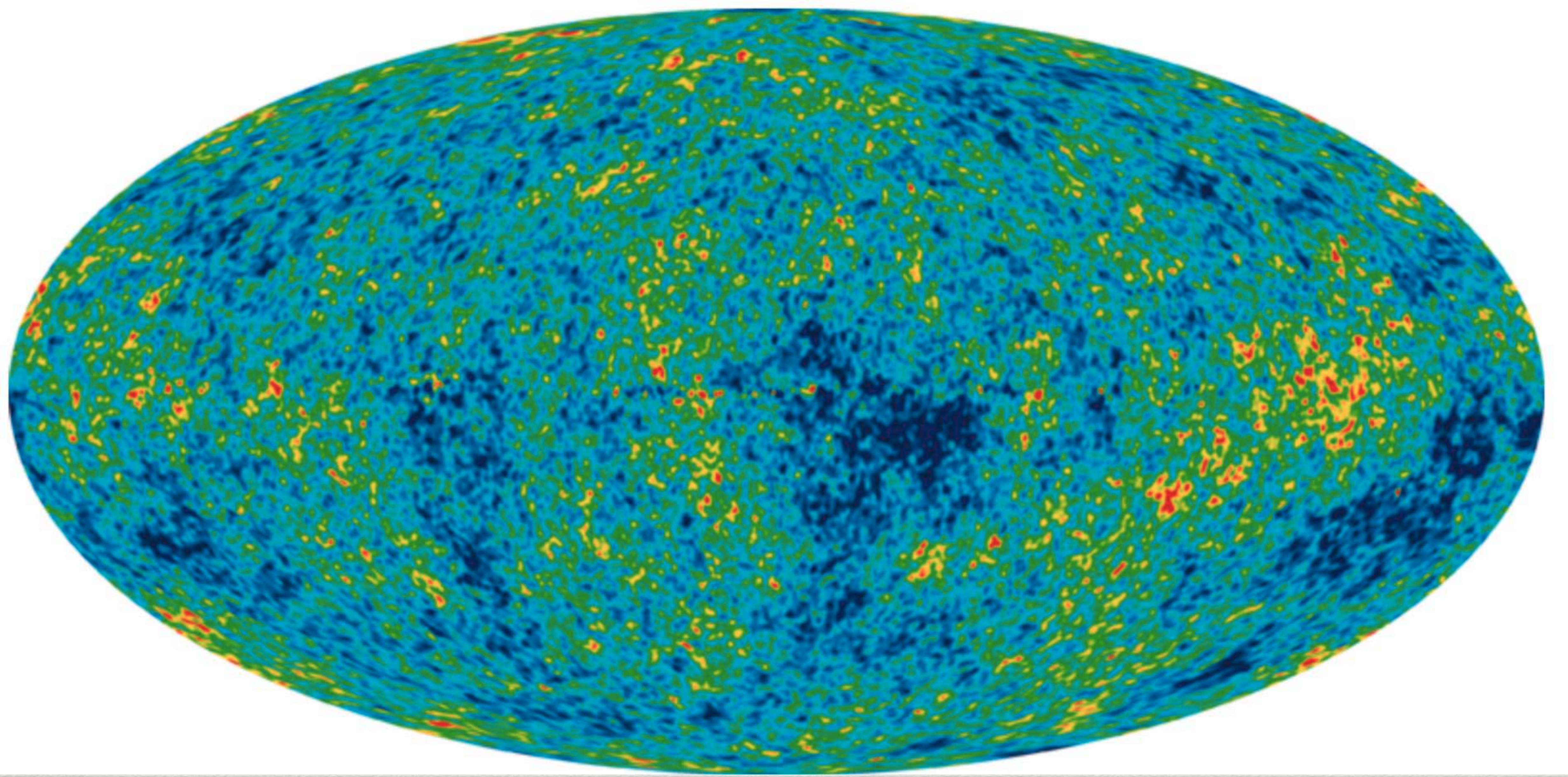
(1975 Collins and Perry)



How far back in time can we see?

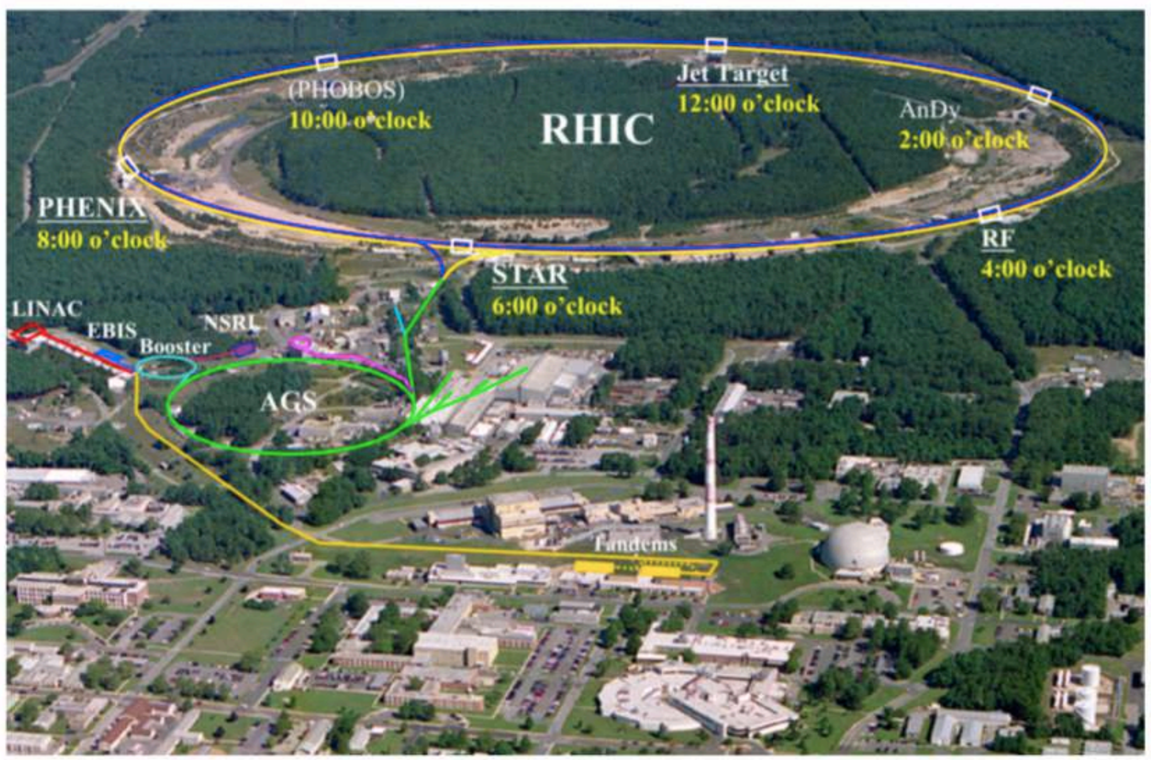
Cosmic Microwave Background ~ 10^5 **years** after Big Bang

Quark Gluon Plasma existed ~ 10^{-6} **seconds**



Little Bangs in the Lab

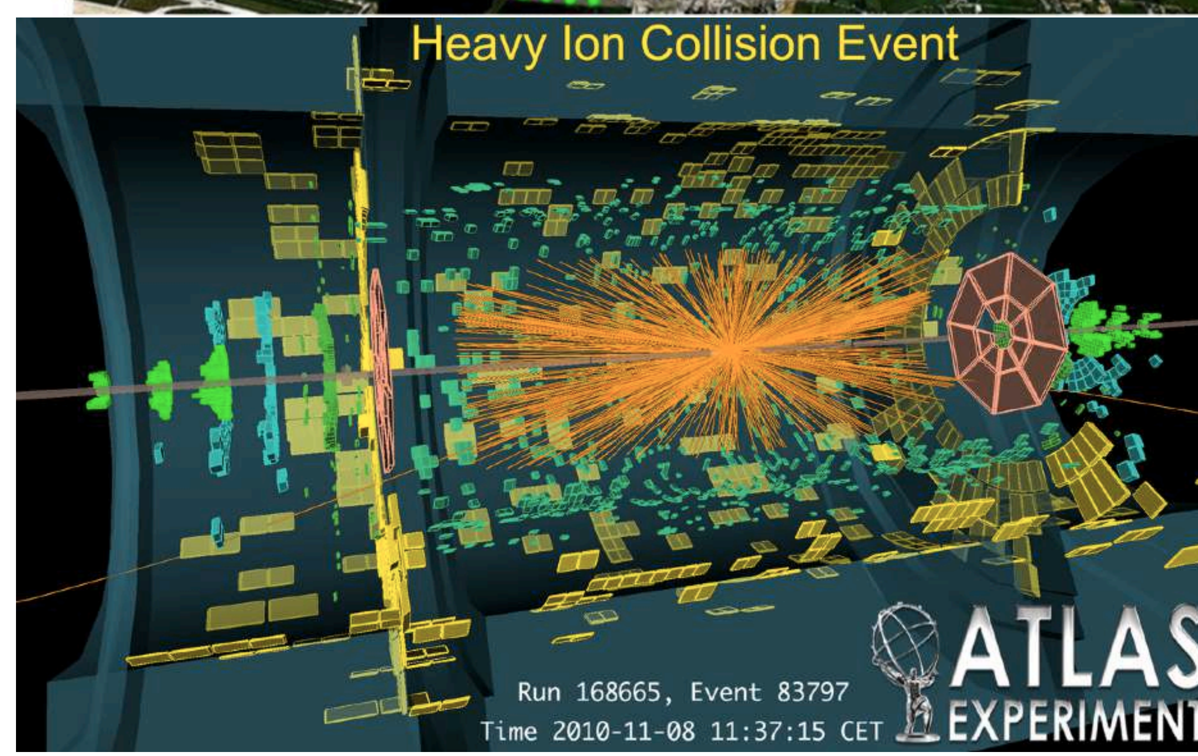
The Large Hadron Collider and RHIC create "little bangs”:
deconfined quarks and gluons in the lab



T=4 trillion degrees Celsius

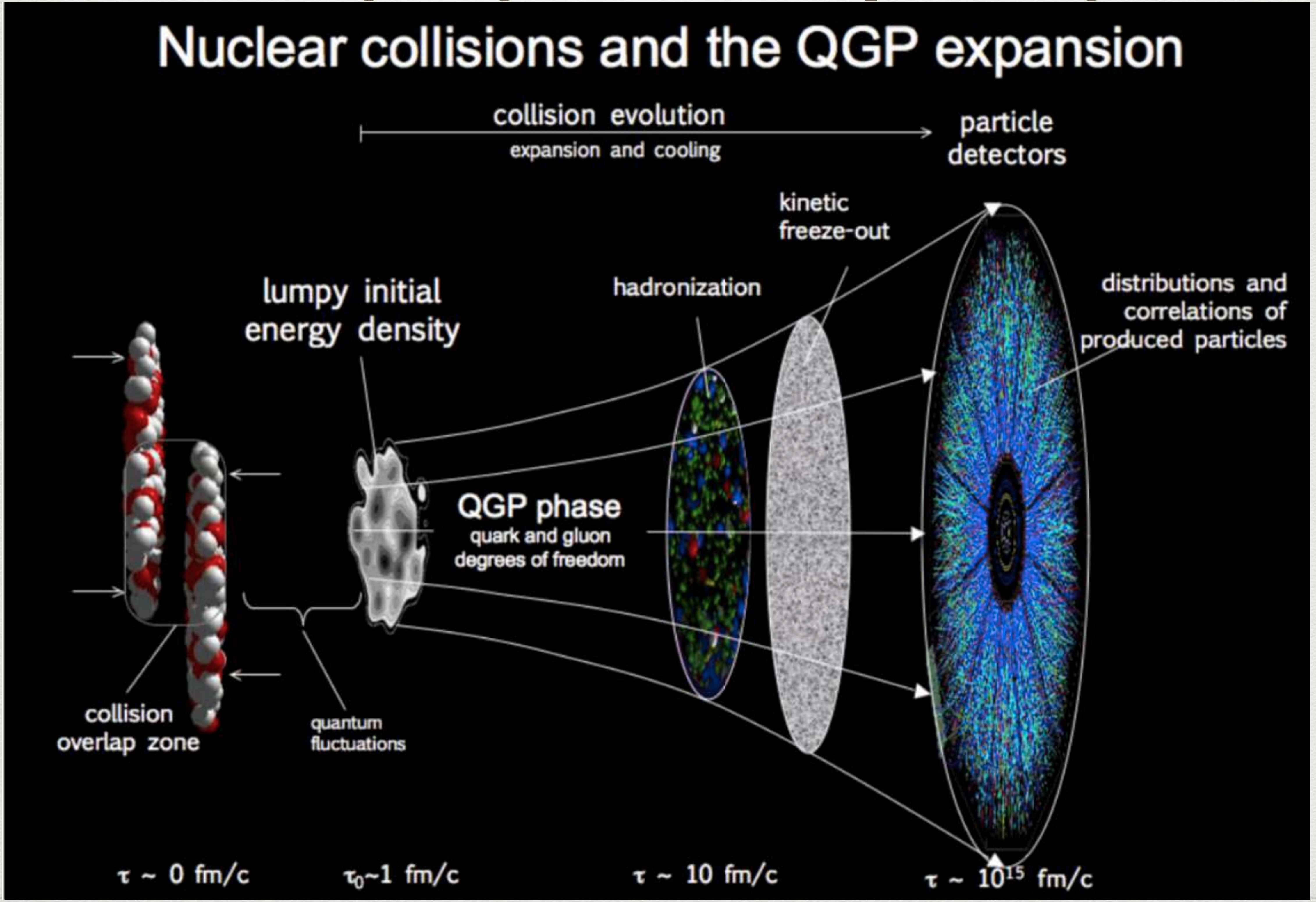
GUINNESS WORLD RECORDS

10^8 times hotter than the sun!



Evolution of a heavy-ion collision

Smashing two gold ions at the speed of light

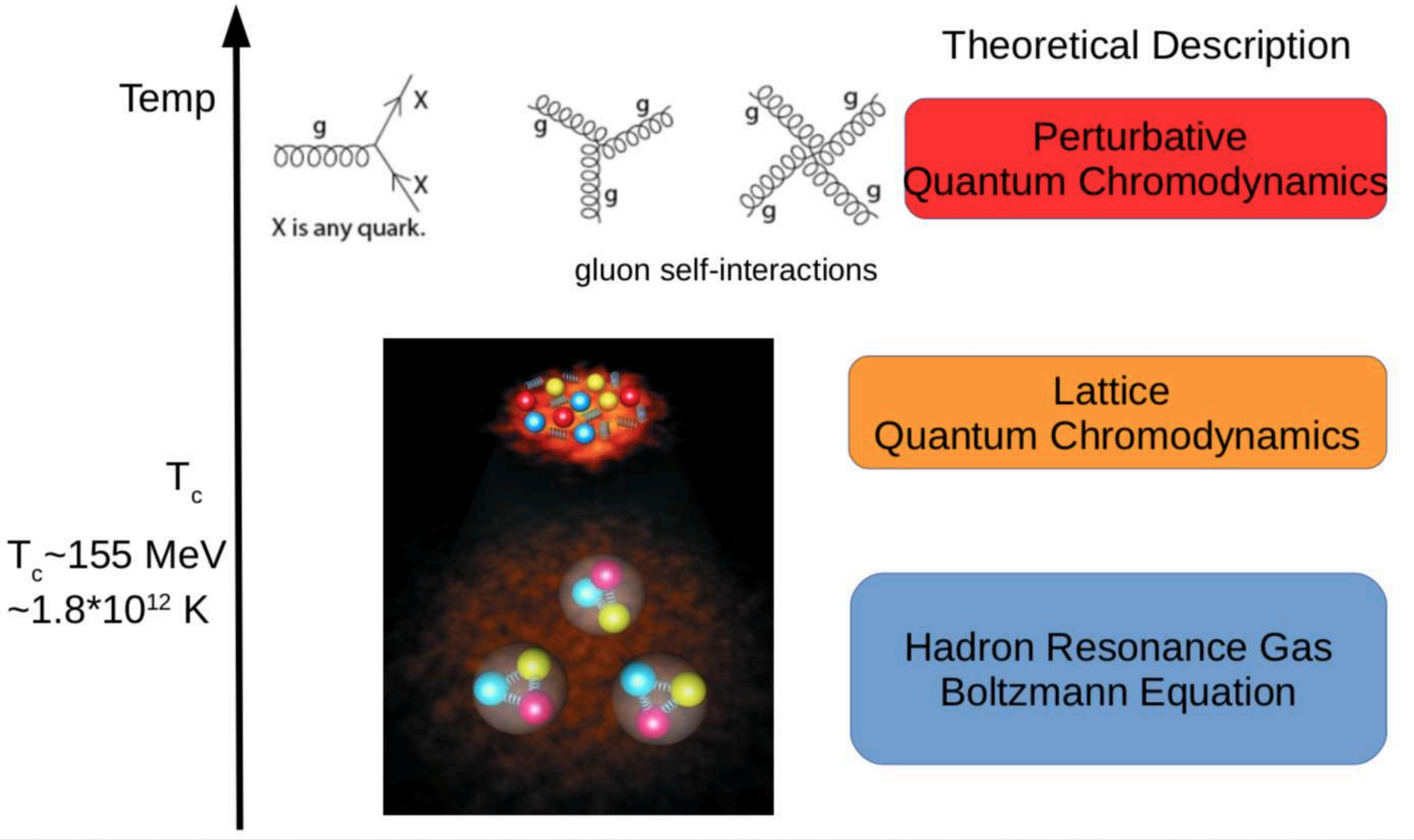


Big Bang vs. Heavy-Ion Collisions

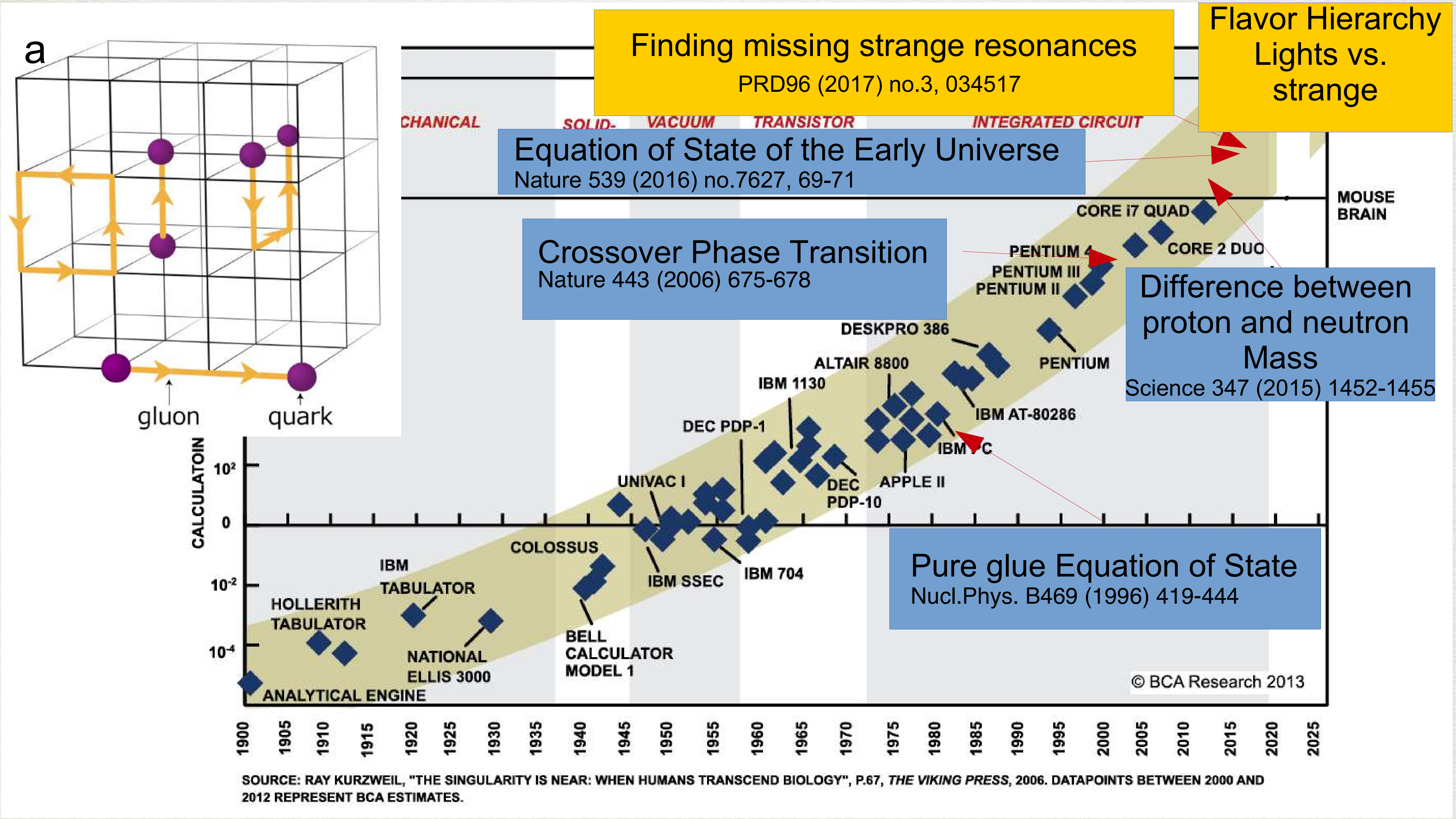
	Quark Epoch	Little Bang
Similarities	Pressure, entropy, energy density	
	Quark/gluons vs. Hadrons	
	Temperature when hadrons are formed	
	Strong Force	
	Nearly perfect fluid	
Differences	**System Size**	
	Entire Universe	10^-14 m
		Finite volume effects
	Equilibrated	**Out-of-Equilibrium**
		Viscosity matters!
		Expansion rate large
	1 data point	**Billions of events**
		Initial Conditions (many different shapes)

Solving Quantum Chromodynamics

$$L_{QCD} = \underbrace{-\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a}_{\text{Gluon Interactions}} + \underbrace{\bar{\psi}^q\left(i\gamma_\mu D^\mu - m_q\right)\psi^q}_{\text{Quark Interactions}} \text{ where } D^\mu = \partial^\mu - ig\underbrace{A^\mu(x)}_{Gluons}$$



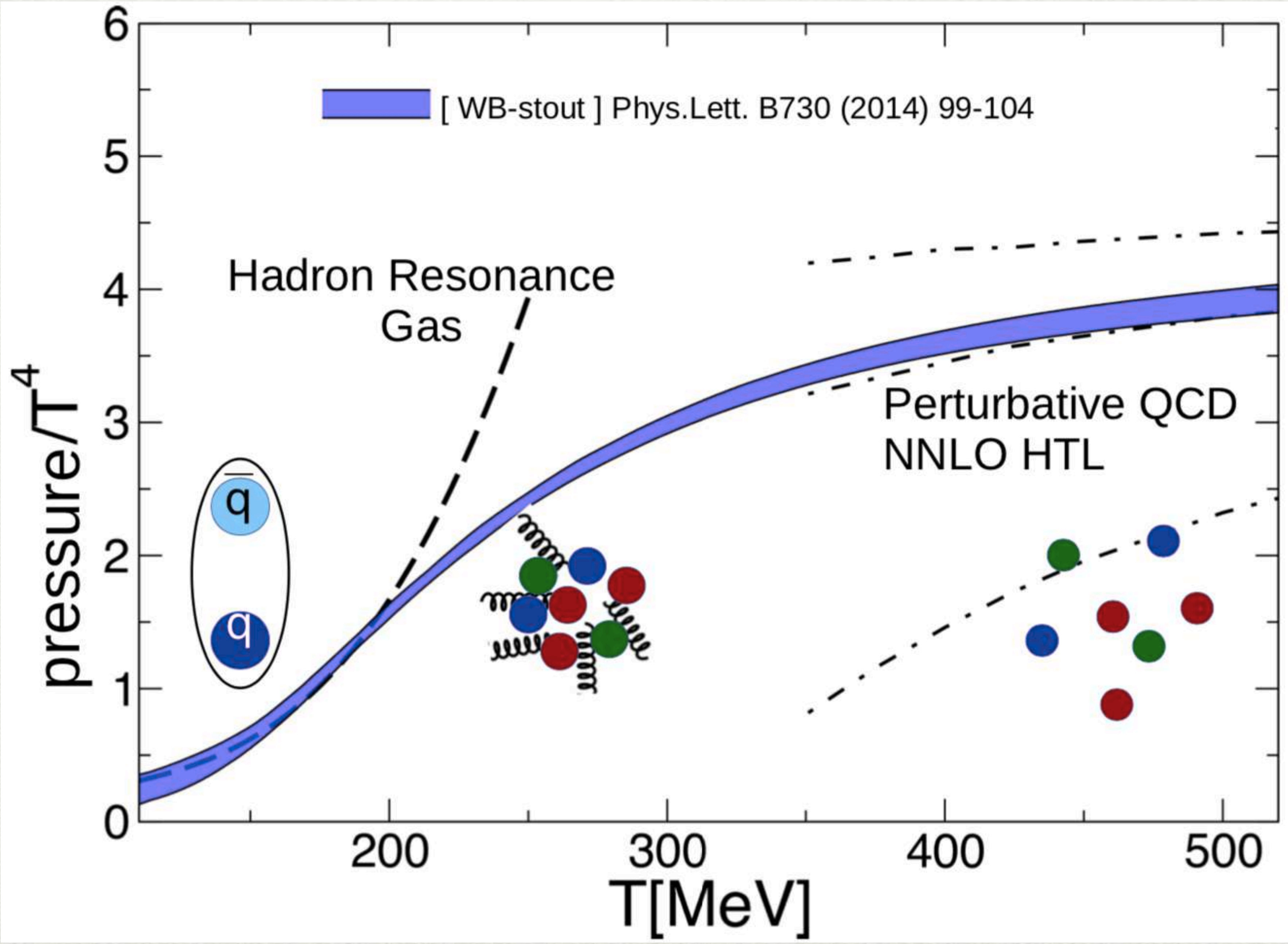
Lattice QCD: Solving Quantum Chromodynamics



Moore's Law: number of transistors per square inch on integrated circuits had doubled every year since their invention

Lattice QCD: Phase Transition

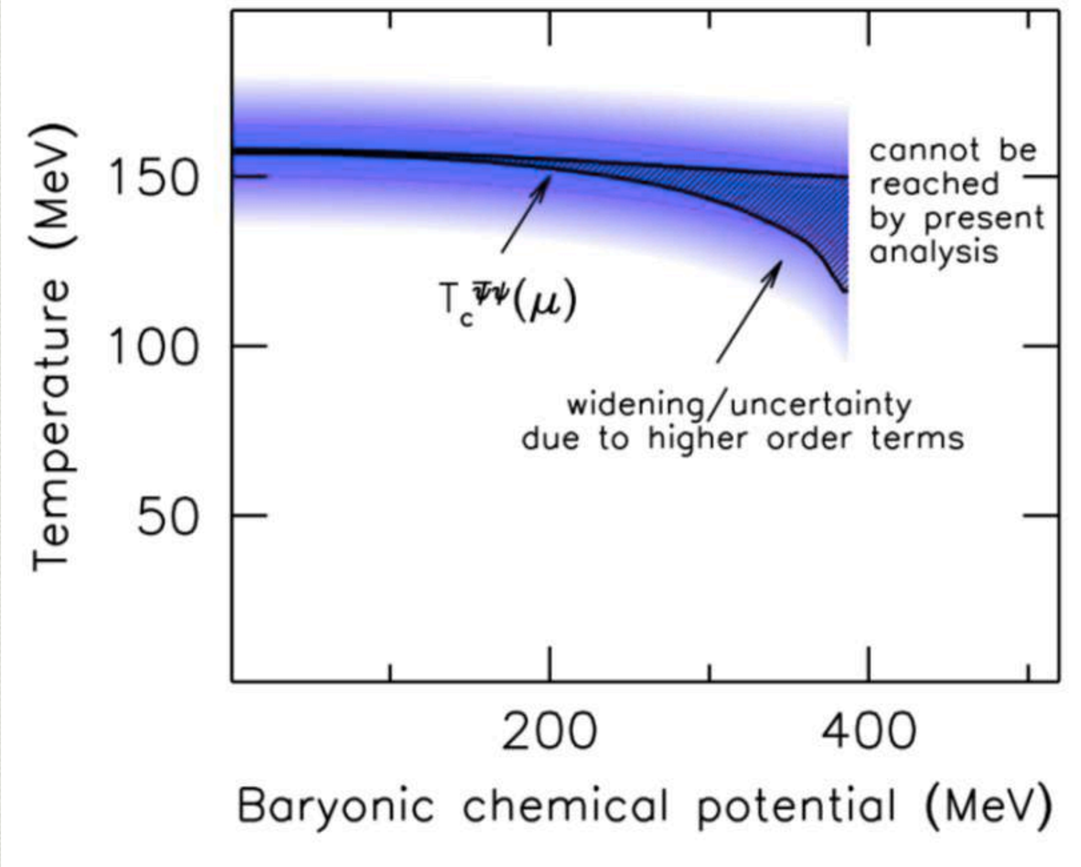
Cross-over phase transition $T \sim 155\ MeV$



Limitations of Lattice QCD

Equilibrium Properties

Fermi Sign Problem
Baryons > # anti-baryons



[WB] R. Bellwied et al., Phys.Lett. B751 (2015) 559-564

Work around - Taylor expansion

Out-of-Equilibrium

- Transport coefficients
- Dynamical description of the Quark Gluon Plasma
- Effective Models:
  The Quark Gluon Plasma can be described by **relativistic viscous hydrodynamics** with a hadronic afterburner

What is a good (or "perfect") fluid?

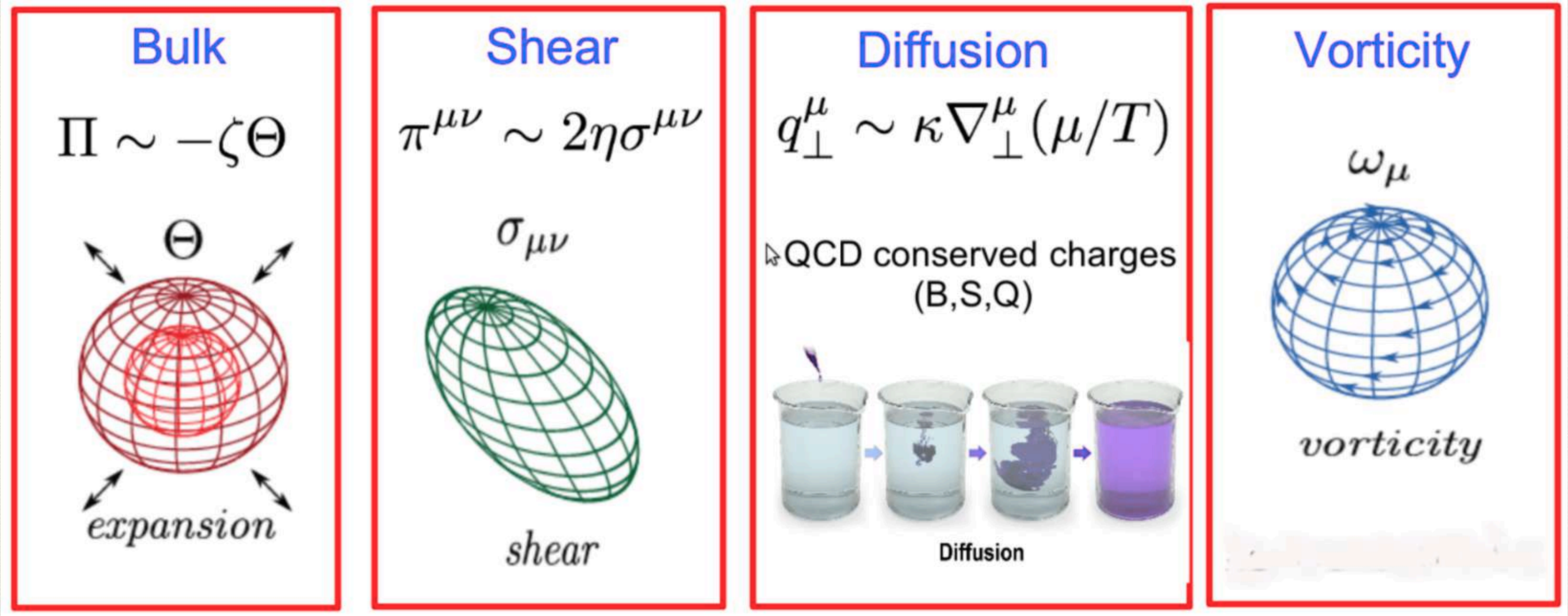
Good fluid

Bad fluid

Best fluids are the closest to an ideal fluid i.e vanishing viscosity

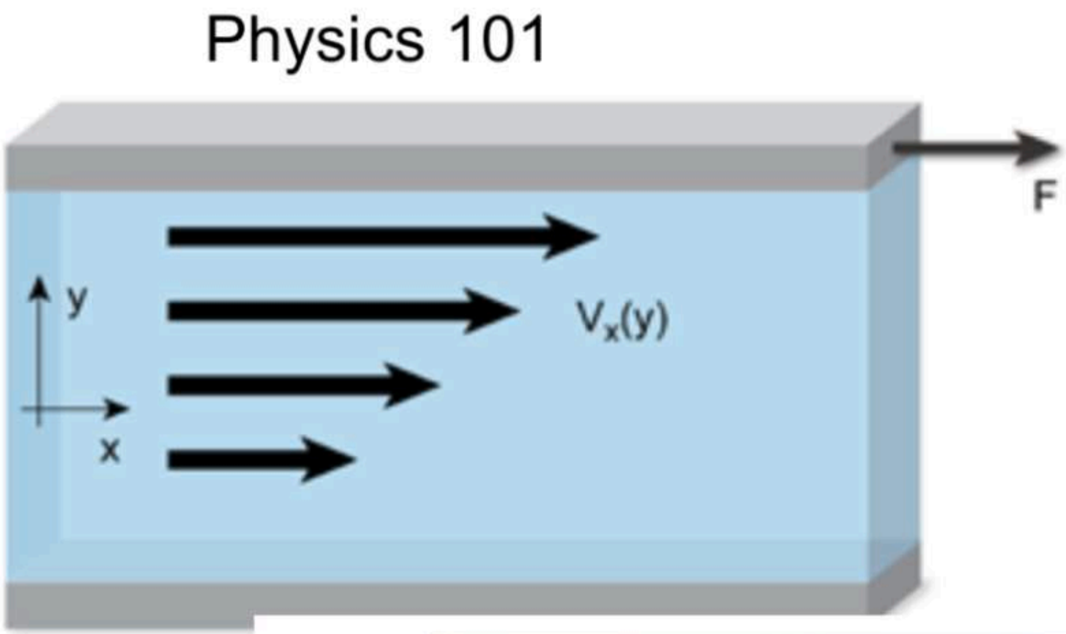
Transport coefficients/viscosities

Transport coefficient: Perturb the fluid from equilibrium- how quickly does it return to equilibrium?



Viscosity - resistance to deformation or "thickness" of liquid

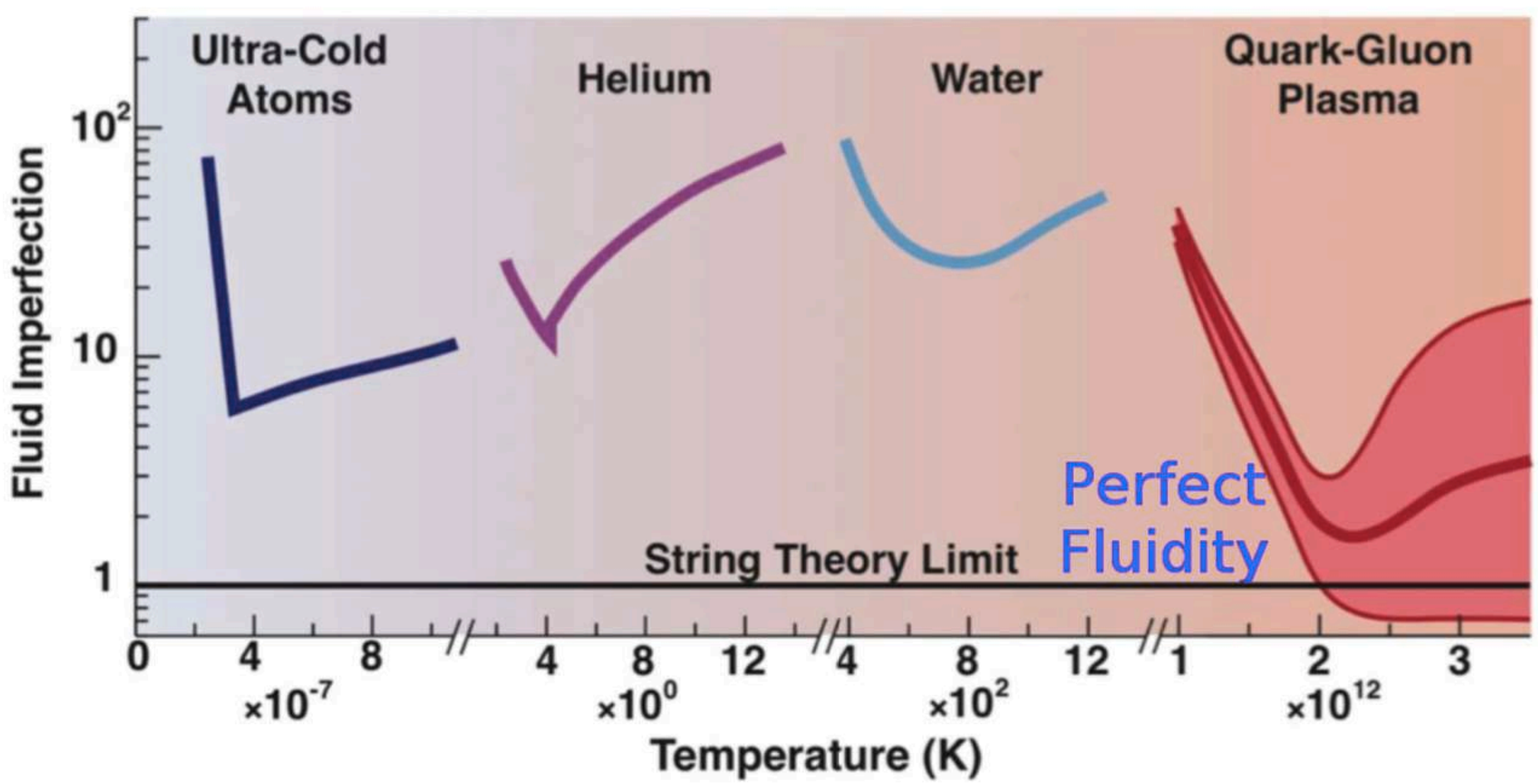
Shear viscosity - η/s



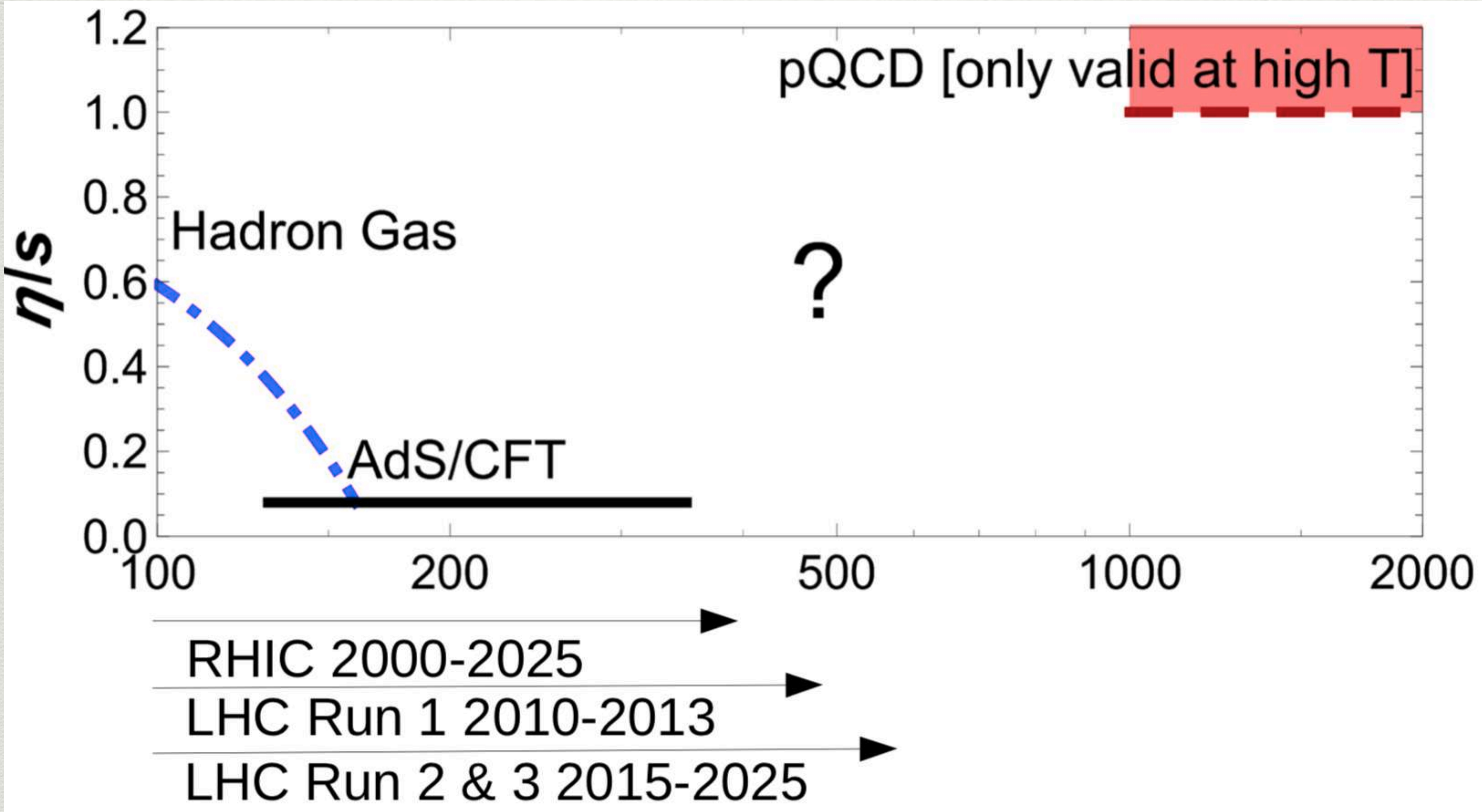
$$\frac{F}{A} = \eta \partial_y V_x(y)$$

For a dilute gas → kinetic theory

$$\eta \sim \frac{1}{3} \sum_i n_i \langle p \rangle_i l_{mfp}$$

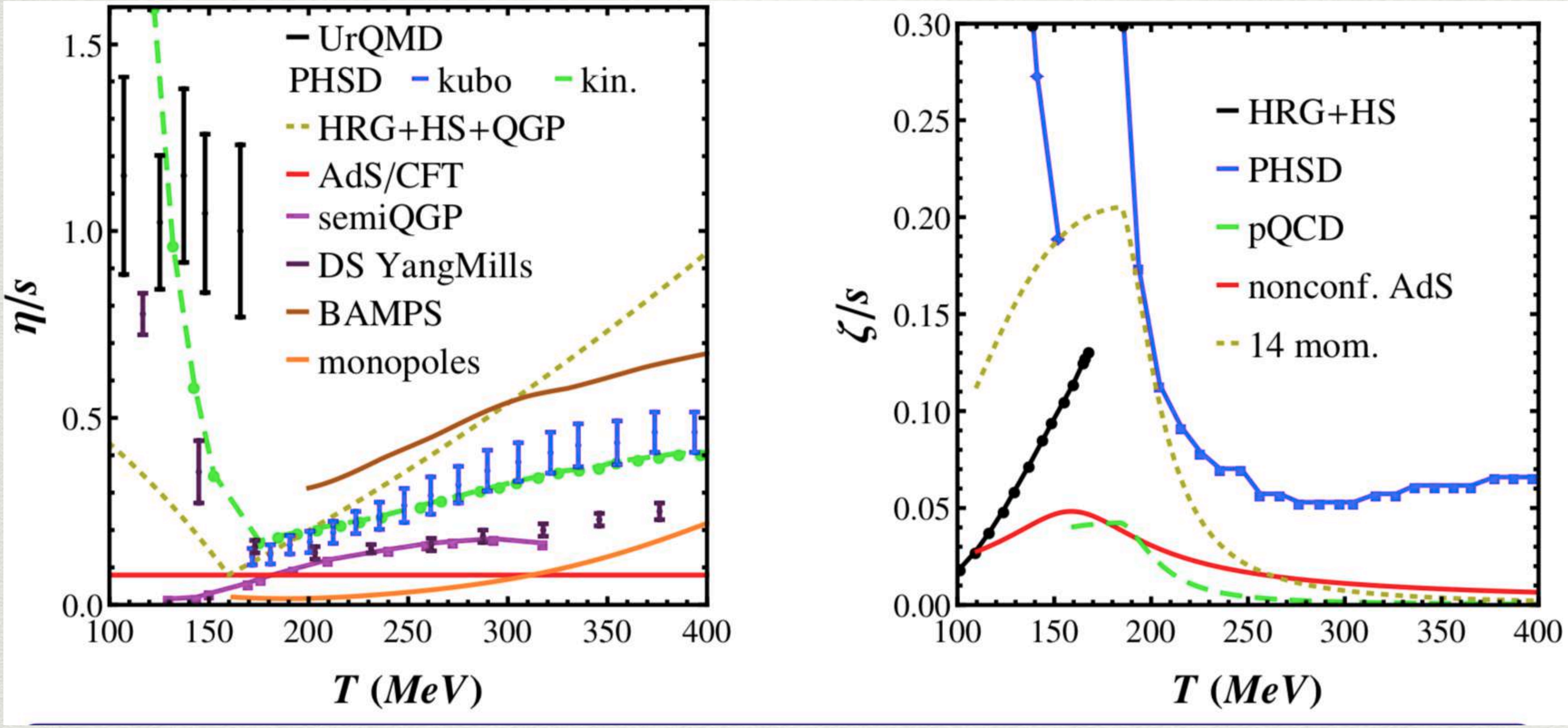


Experimental probes of $\eta/s(T)$



***Hadron Gas**: JNH et al, PRL103(2009)172302; PRC86(2012)024913*
***AdS/CFT:** Kovtun, Son, Starinets PRL94(2005)111601*
***pQCD**: Arnold, Moore, Yaffe JHEP 0011(2000)001 ; JHEP0305(2003)051*

Theoretical calculations of viscosity

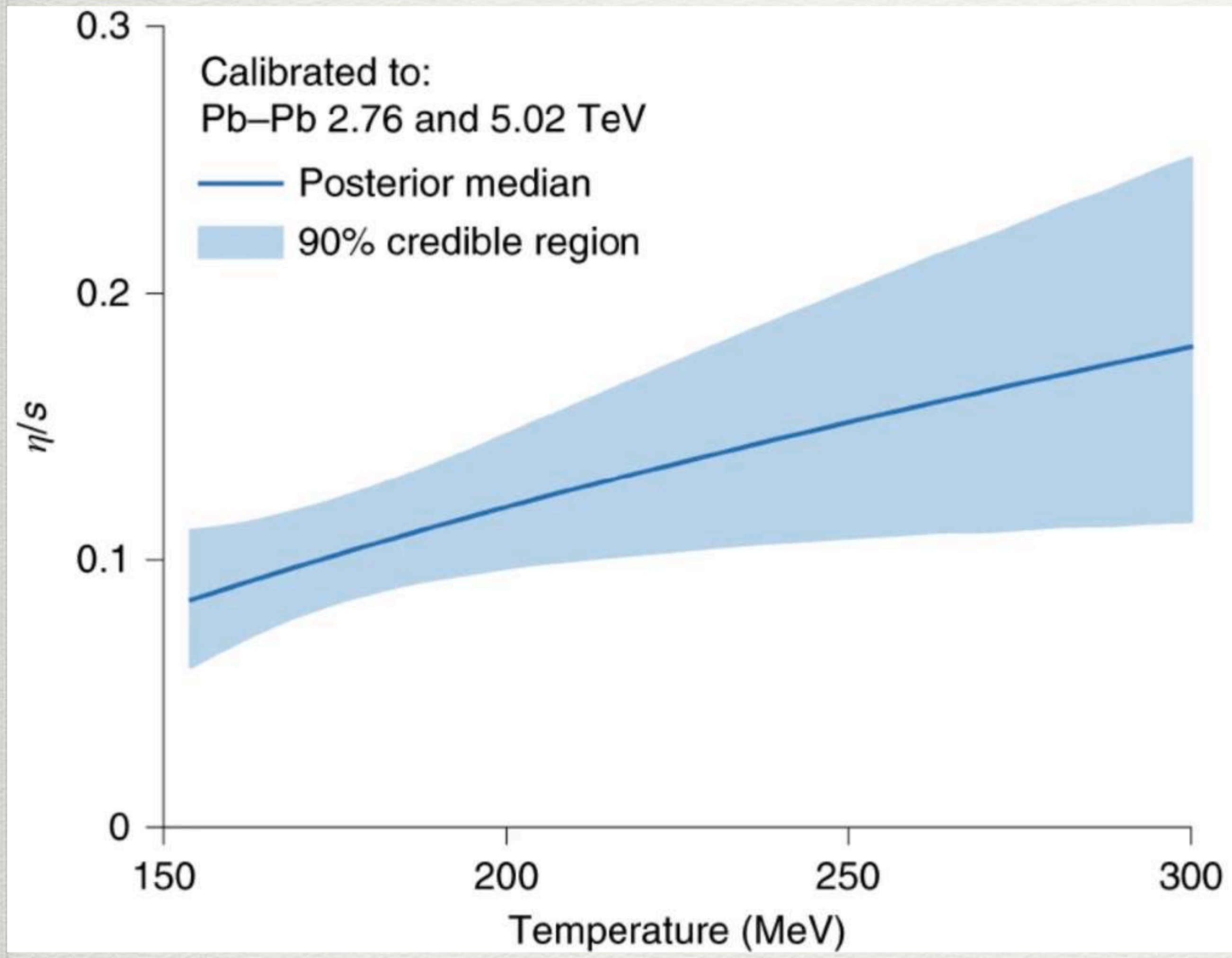


See references in JNH arXiv:1512.06315

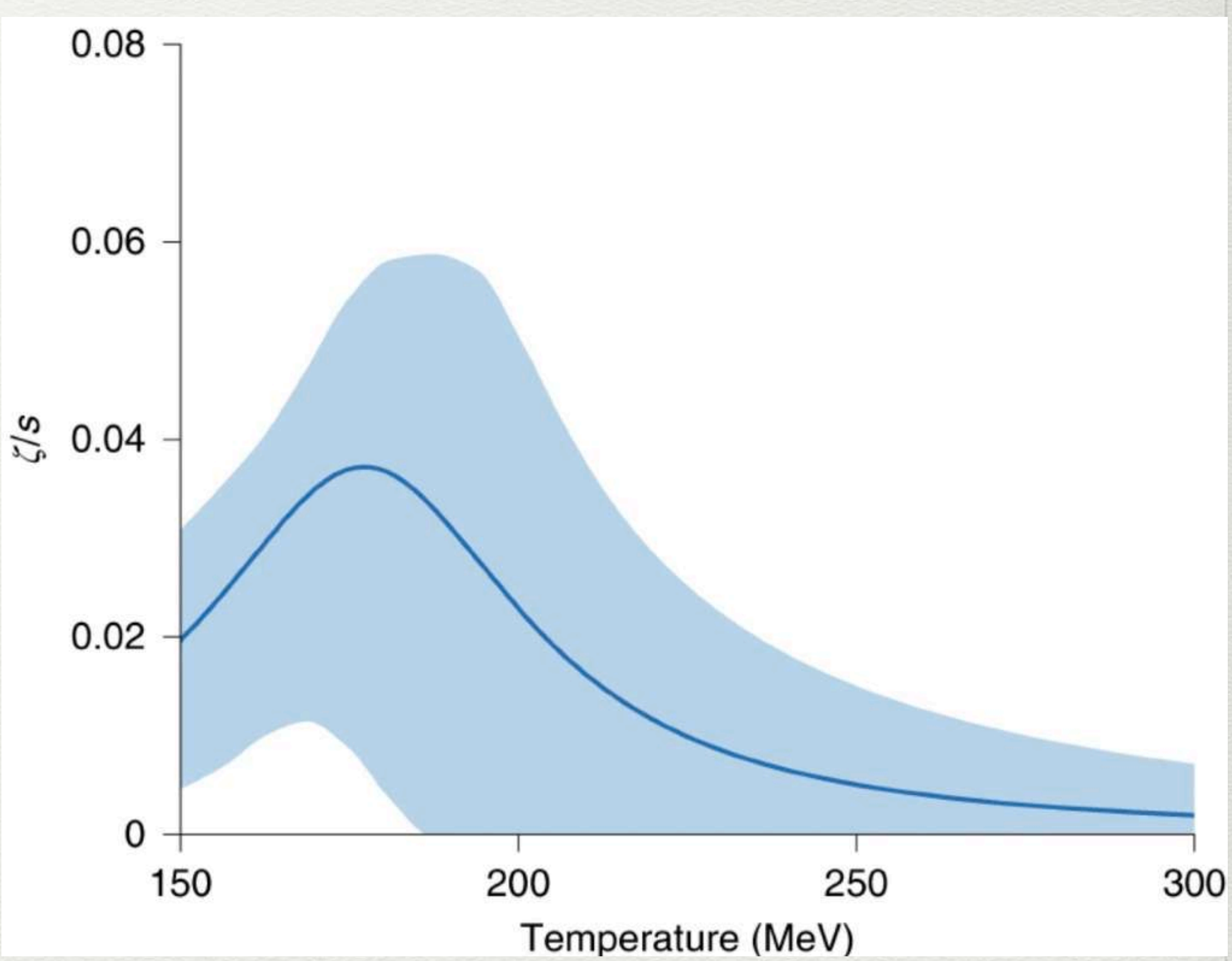
Dip expected: *Phys.Rev.Lett. 97 (2006) 152303, Nucl.Phys. A769 (2006) 71-94, Phys.Rev.Lett. 103 (2009) 172302*

Bayesian analysis (agnostic η/s & ζ/s)

Shear viscosity

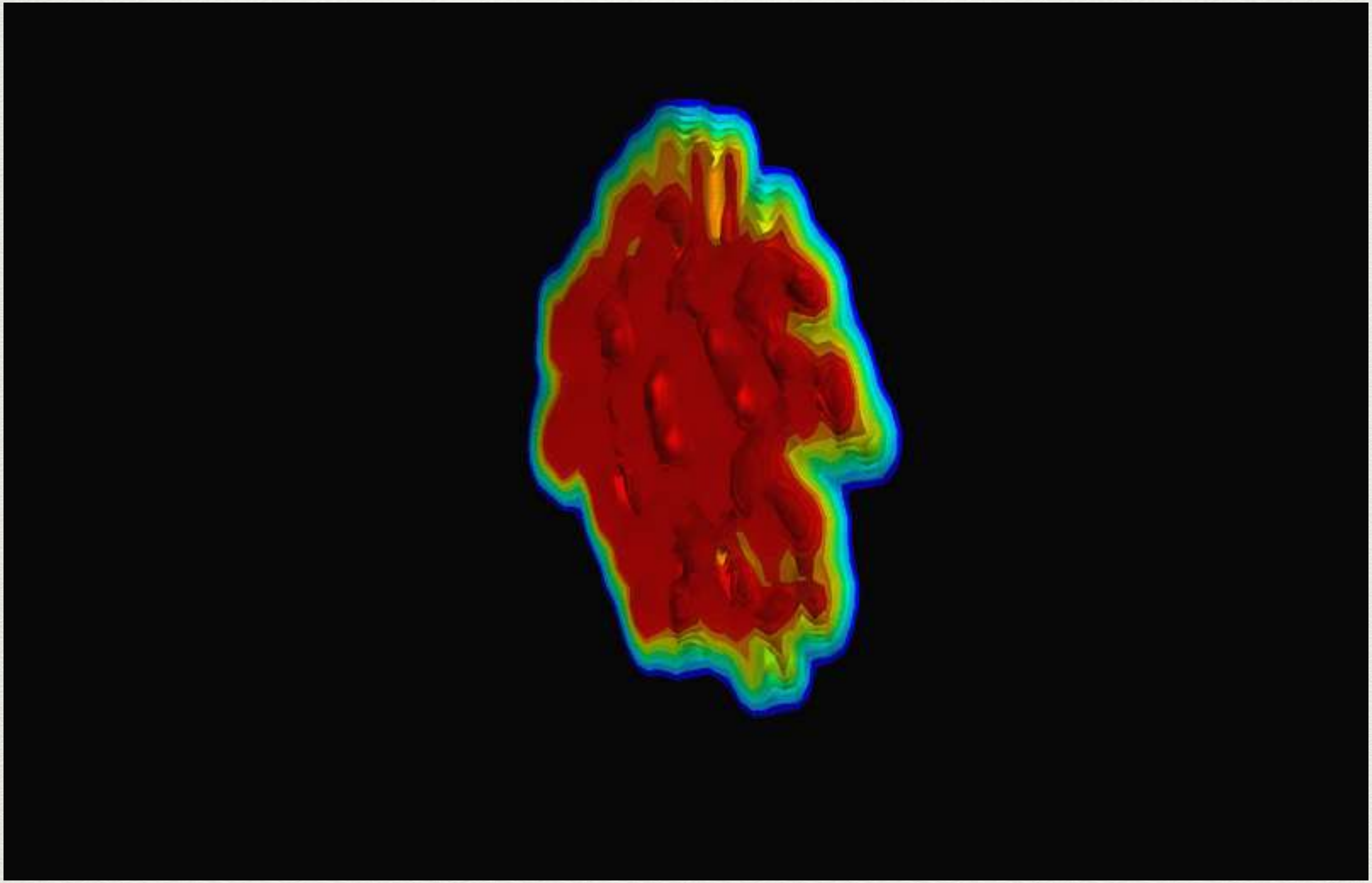


Bulk viscosity



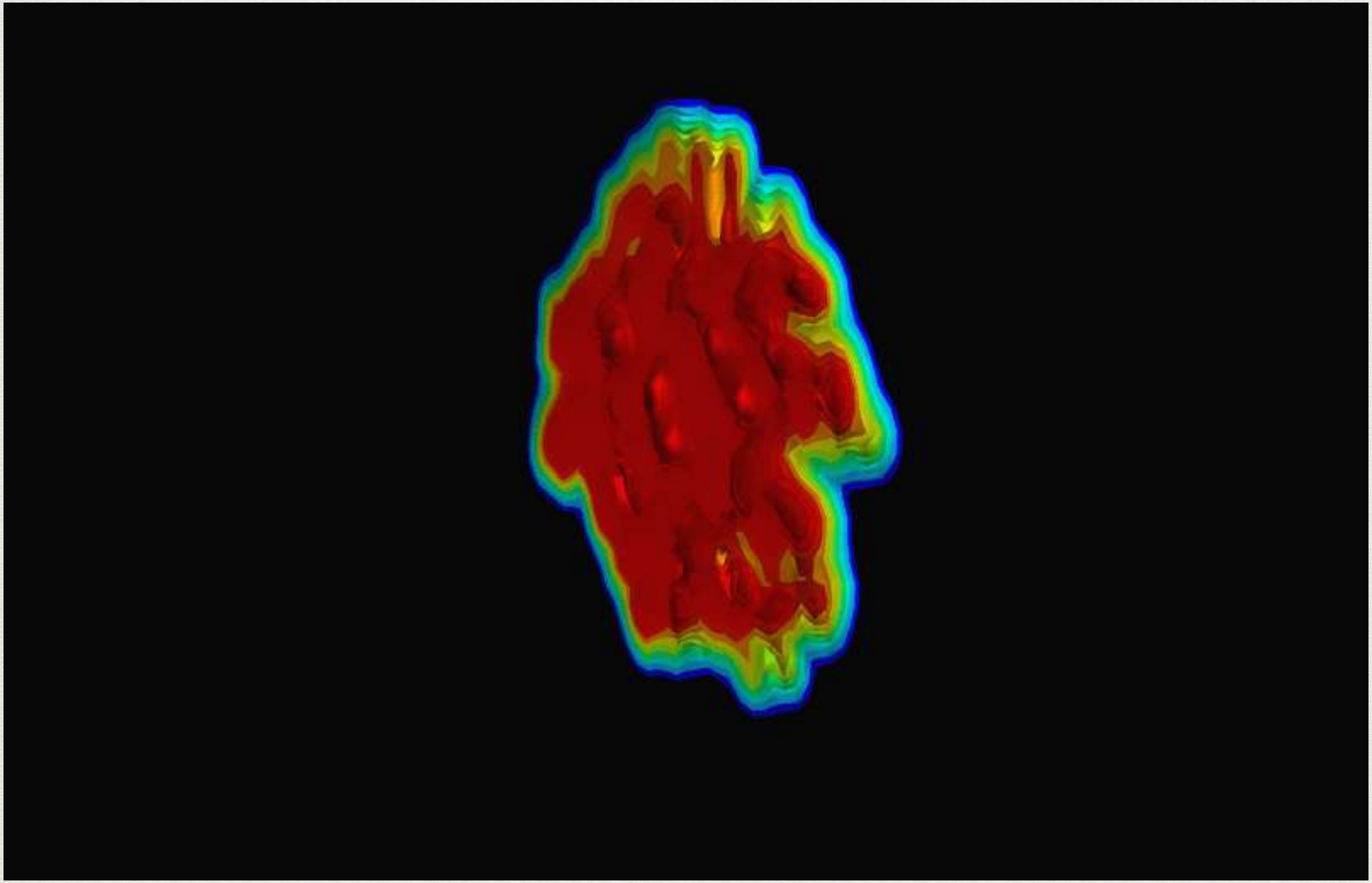
Bernhard, Moreland, Bass Nature Phys. 15 (2019) no.11, 1113-1117

Relativistic fluids



Schenke IP-Glasma+MUSIC

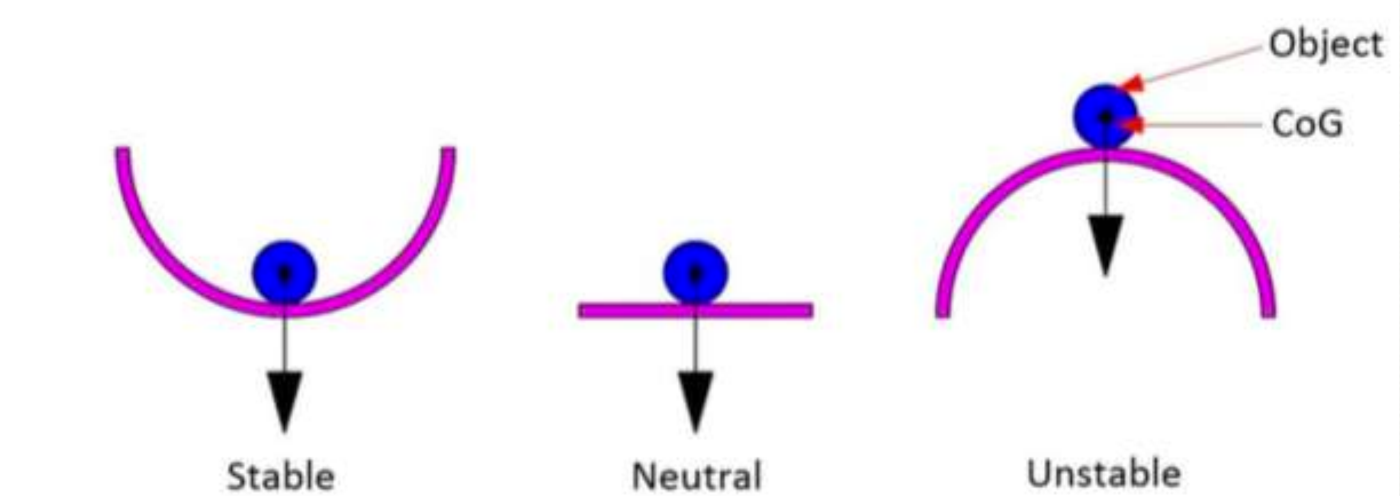
Relativistic fluids



Schenke IP-Glasma+MUSIC

Relativistic viscous fluid dynamics

- Navier stokes equations are used for non-relativistic systems with viscosity
- At relativistic velocities, Navier Stokes equations become **acausal** and **unstable**.



- Israel-Stewart equations incorporate a relaxation time (a finite time for the system to return to equilibrium)

Israel-Stewart Equations of Motion

Annals Phys. 118 (1979) 341-372

Conservation of Energy and Momentum

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

The energy-moment tensor contains a bulk dissipative term Π and the shear stress tensor $\pi^{\mu\nu}$ is

$$T^{\mu\nu} = \varepsilon u^\nu u^\nu - \left(p + \Pi\right) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

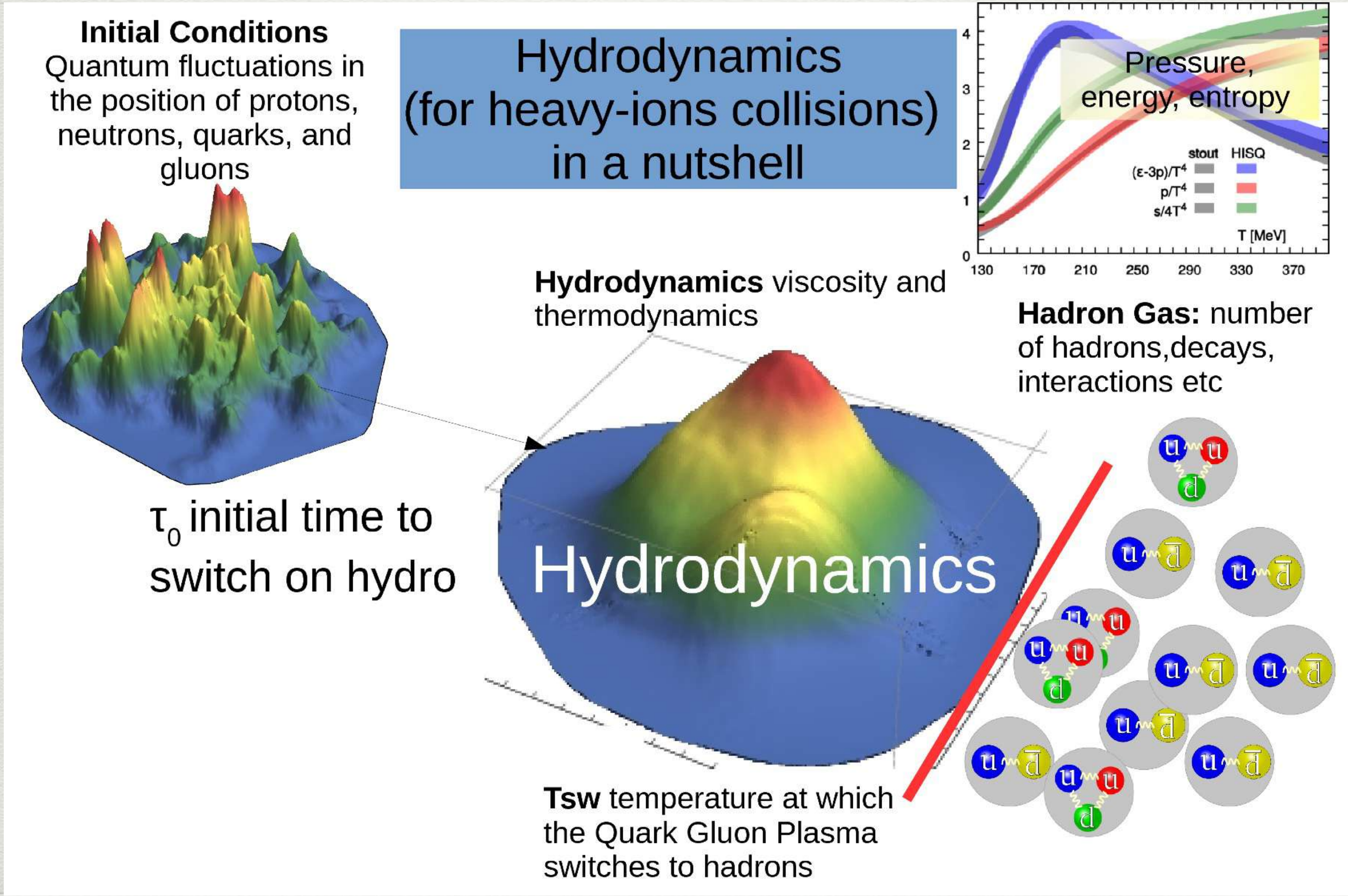
$$\tau_\pi \left(\Delta_{\mu\nu\alpha\beta} D\pi^{\alpha\beta} + \frac{4}{3}\pi_{\mu\nu}\theta \right) = 2\eta\sigma_{\mu\nu} - \pi_{\mu\nu}$$

$$+\Pi, N^\mu \ldots$$

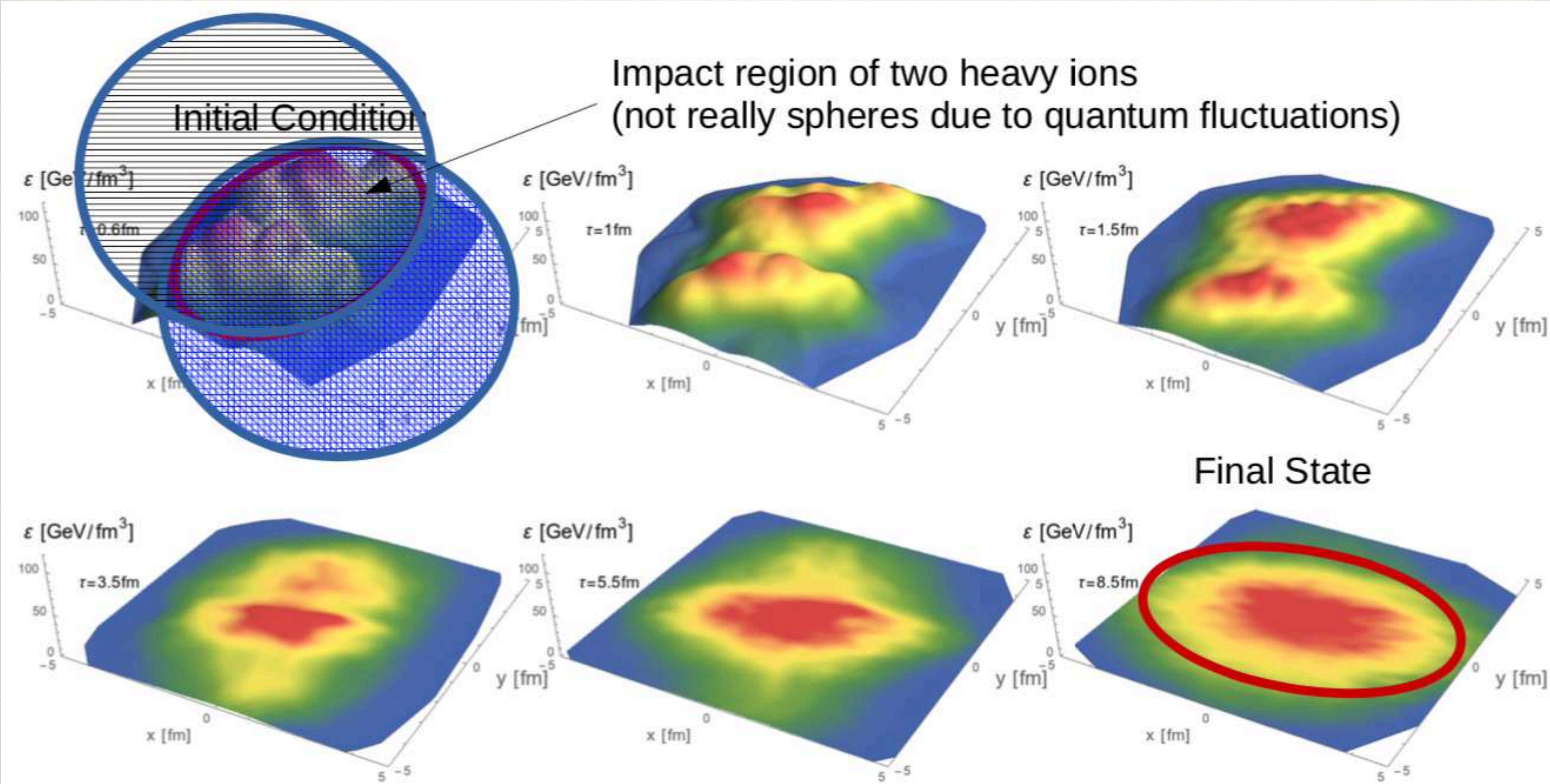
Coordinate System: $x^\mu = \left(\tau, x, y, \eta\right)$ where $\tau = \sqrt{t^2 - z^2}$ and

$$\eta = 0.5 \ln \left(\frac{t + z}{t - z} \right)$$

"Standard Model" of the Quark Gluon Plasma

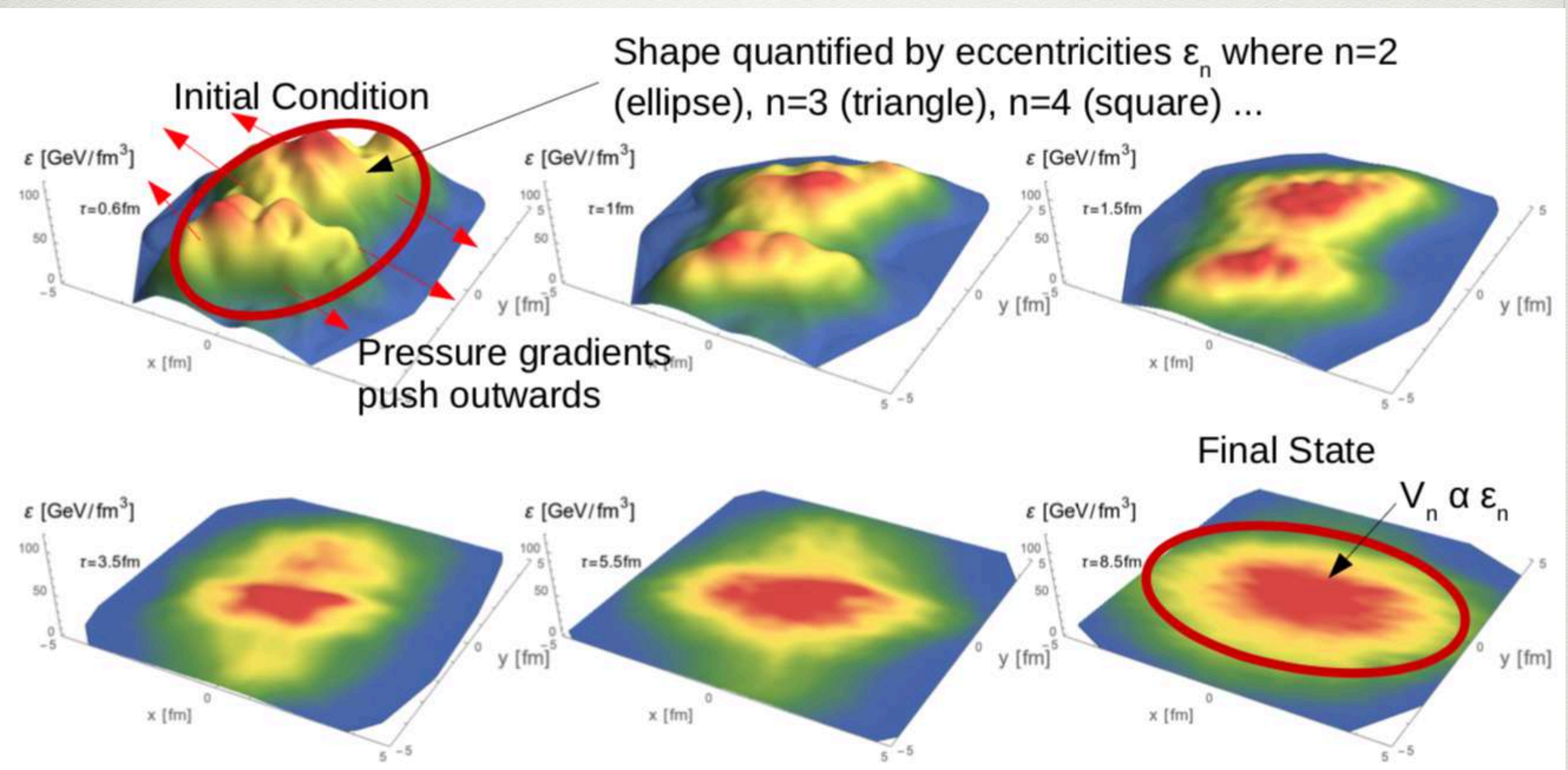


Initial conditions



Eccentricities ε_2's are directly related to the final measured flow observables v_n's

Initial conditions

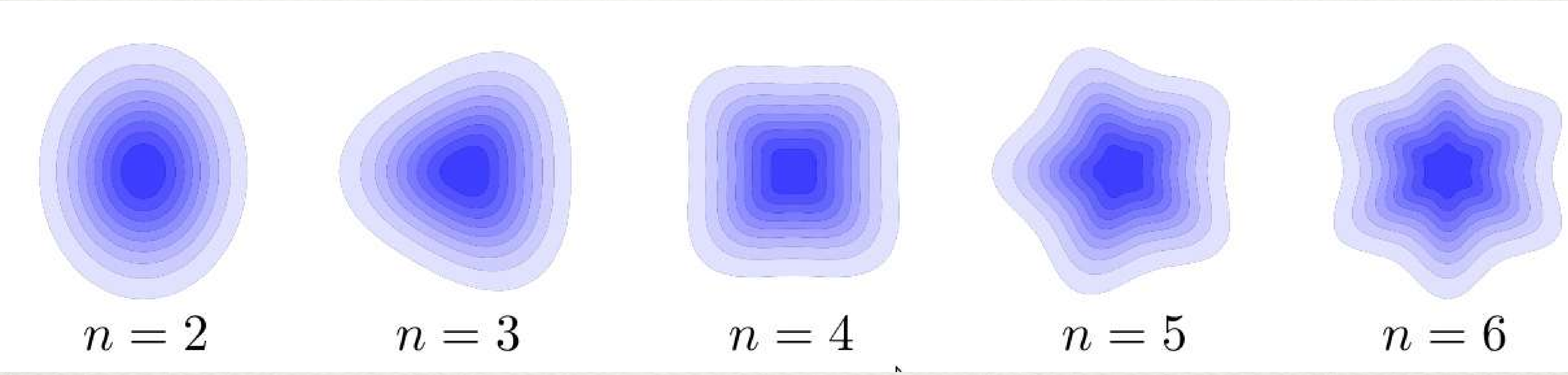


Eccentricities ε_2's are directly related to the final measured flow observables v_n's

Quantifying flow

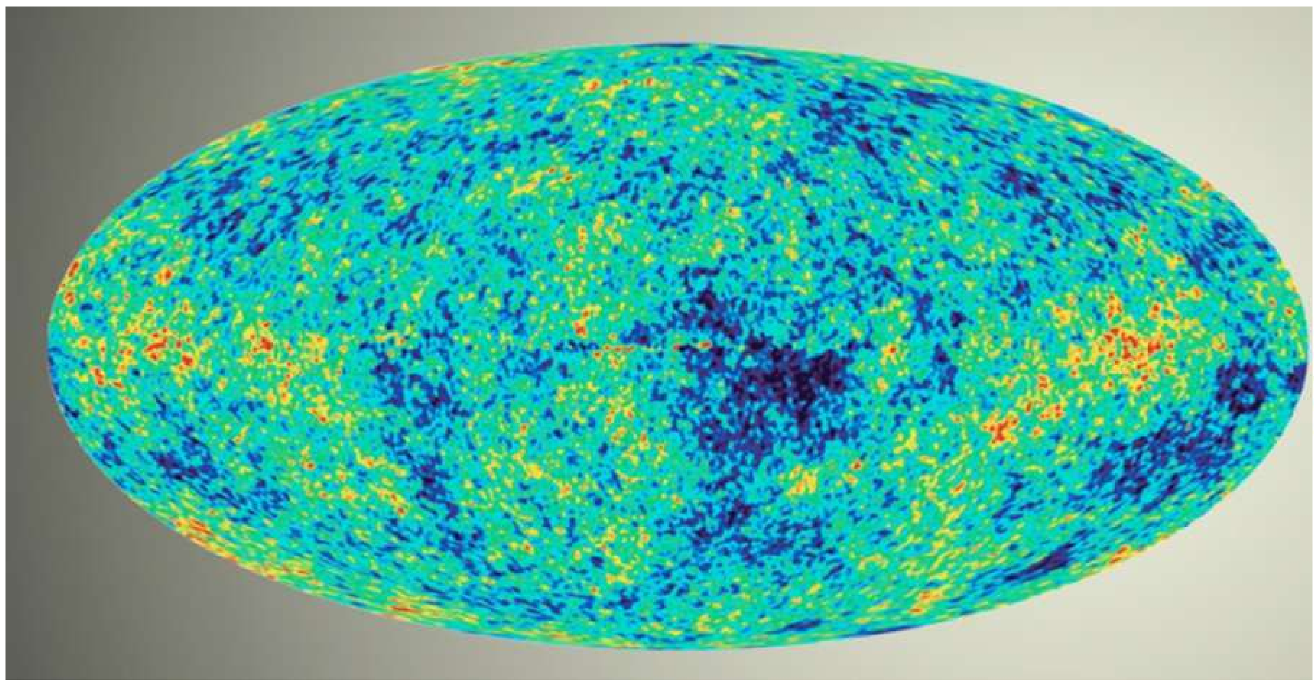
The distribution of particles can be written as a Fourier series

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$

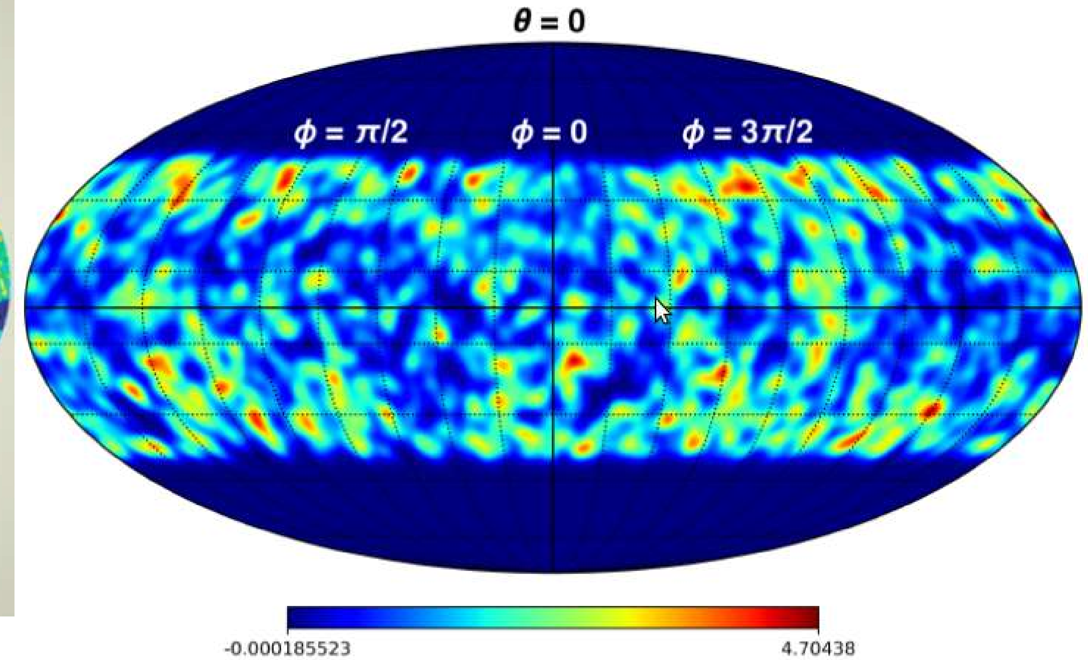


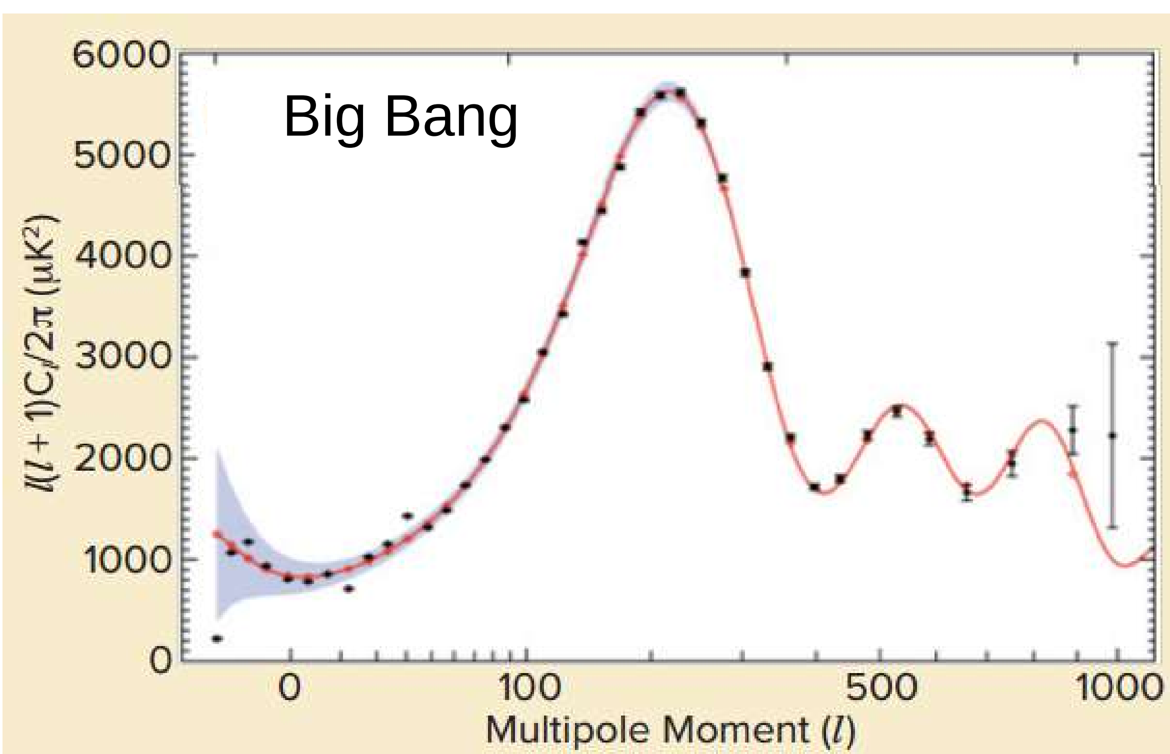
Collective flow: Flow harmonics, $v_n\{m\}$, are calculated by correlating m=2 to 8 particles → collective behavior

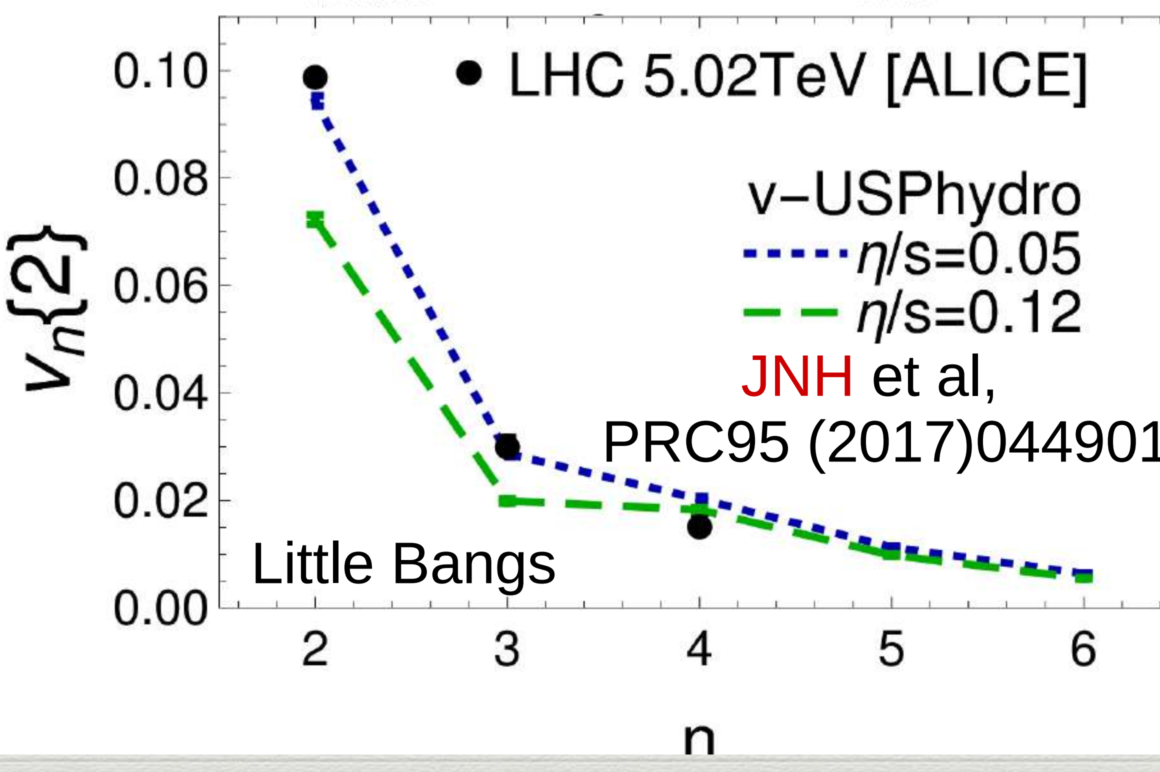
CMB vs. Heavy Ion Collisions



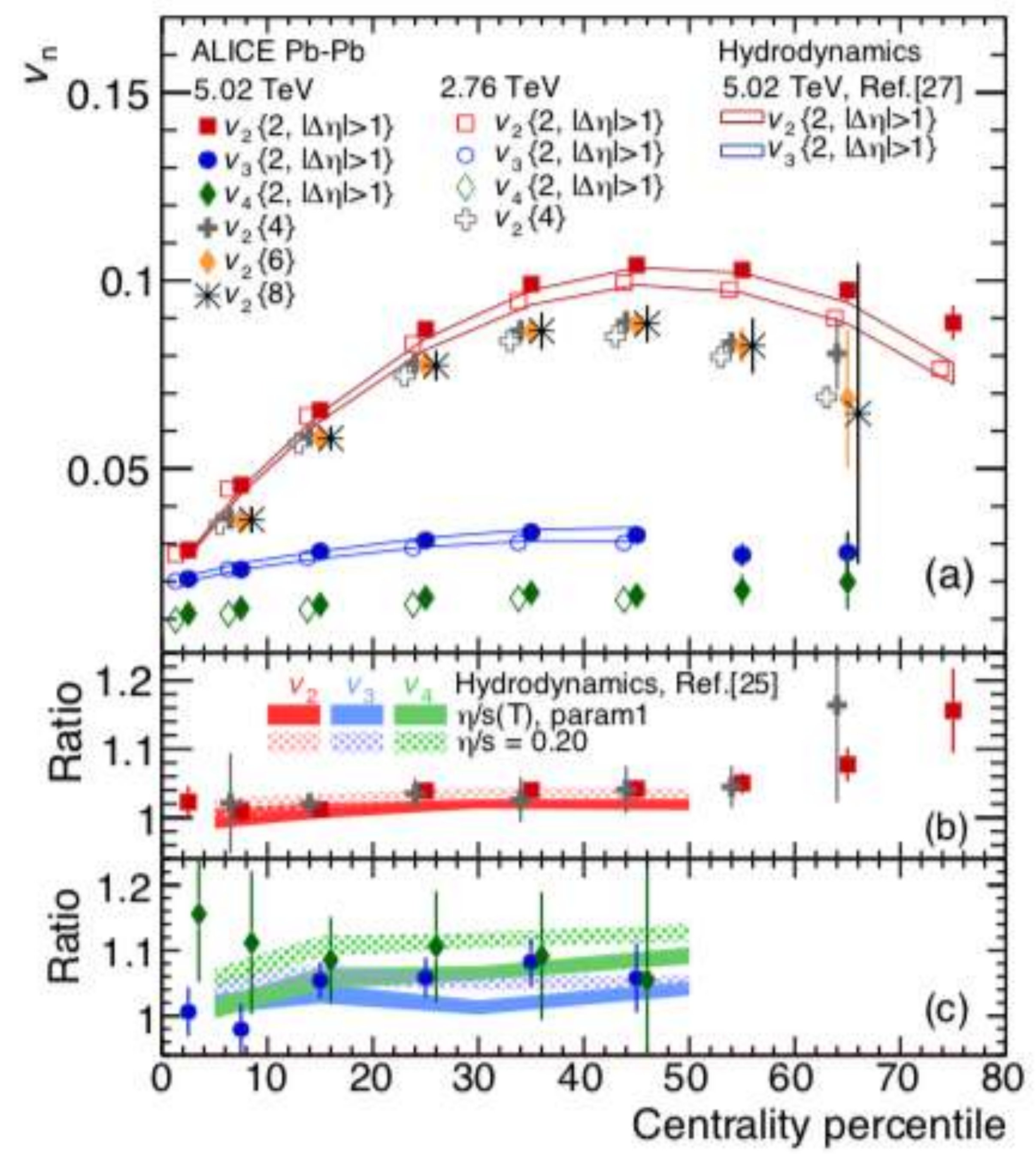
Vieira. Machado et al, Phys.Rev. C99 (2019) no.5, 054910







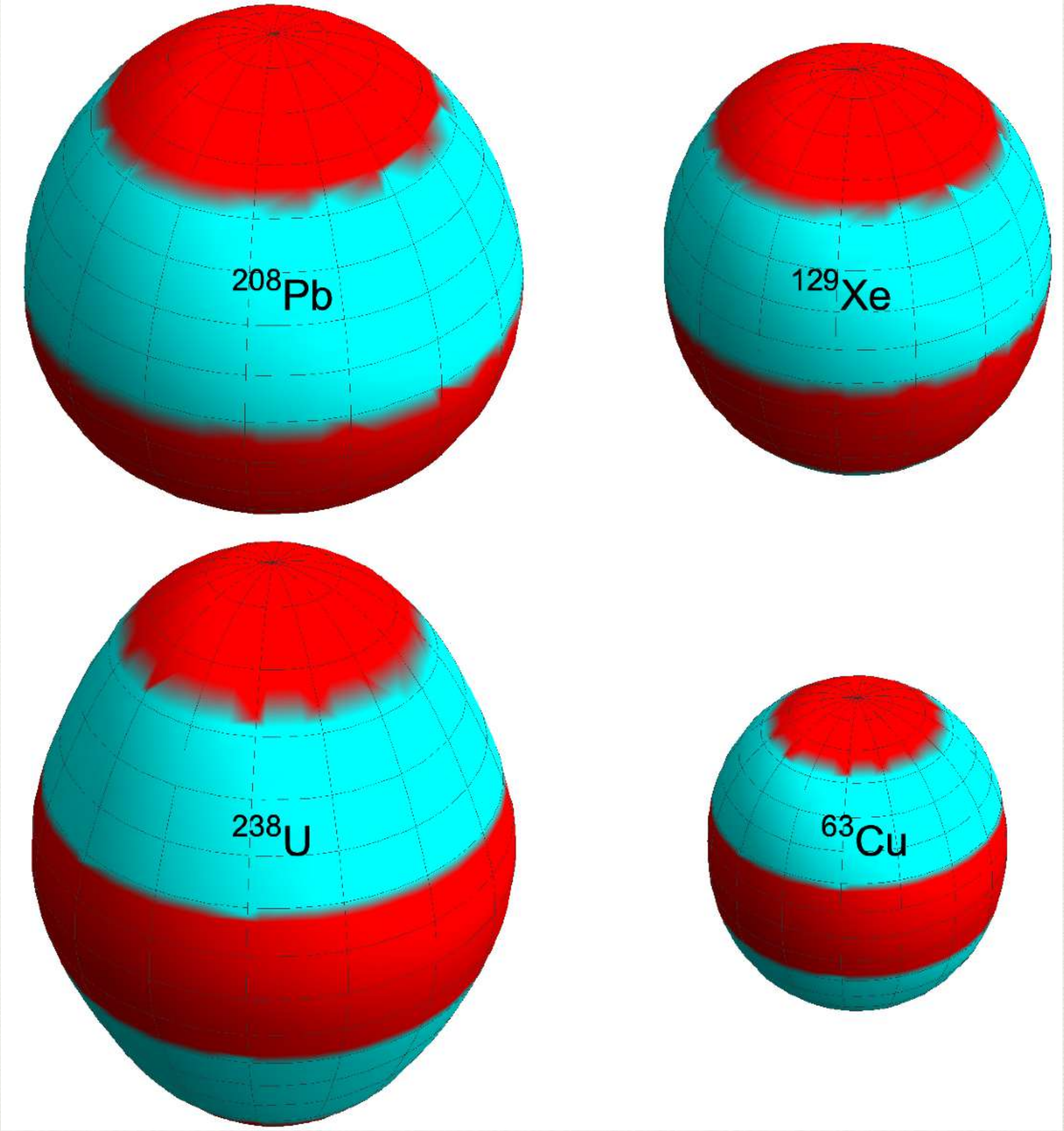
Precise predictions with hydrodynamics



Hydrodynamic models can successfully make predictions at the ~1% level.

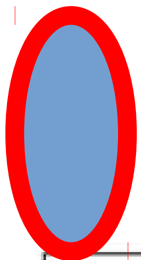
ALICE *Phys.Rev.Lett. 116 (2016) no.13, 132302*
v-USPhydro predictions*: JNH et al, Phys.Rev. C93 (2016) no.3, 034912*
EKRT predictions*: Niemi et al, Phys. Rev. C 93, 014912 (2016)*

Influence of different nuclei

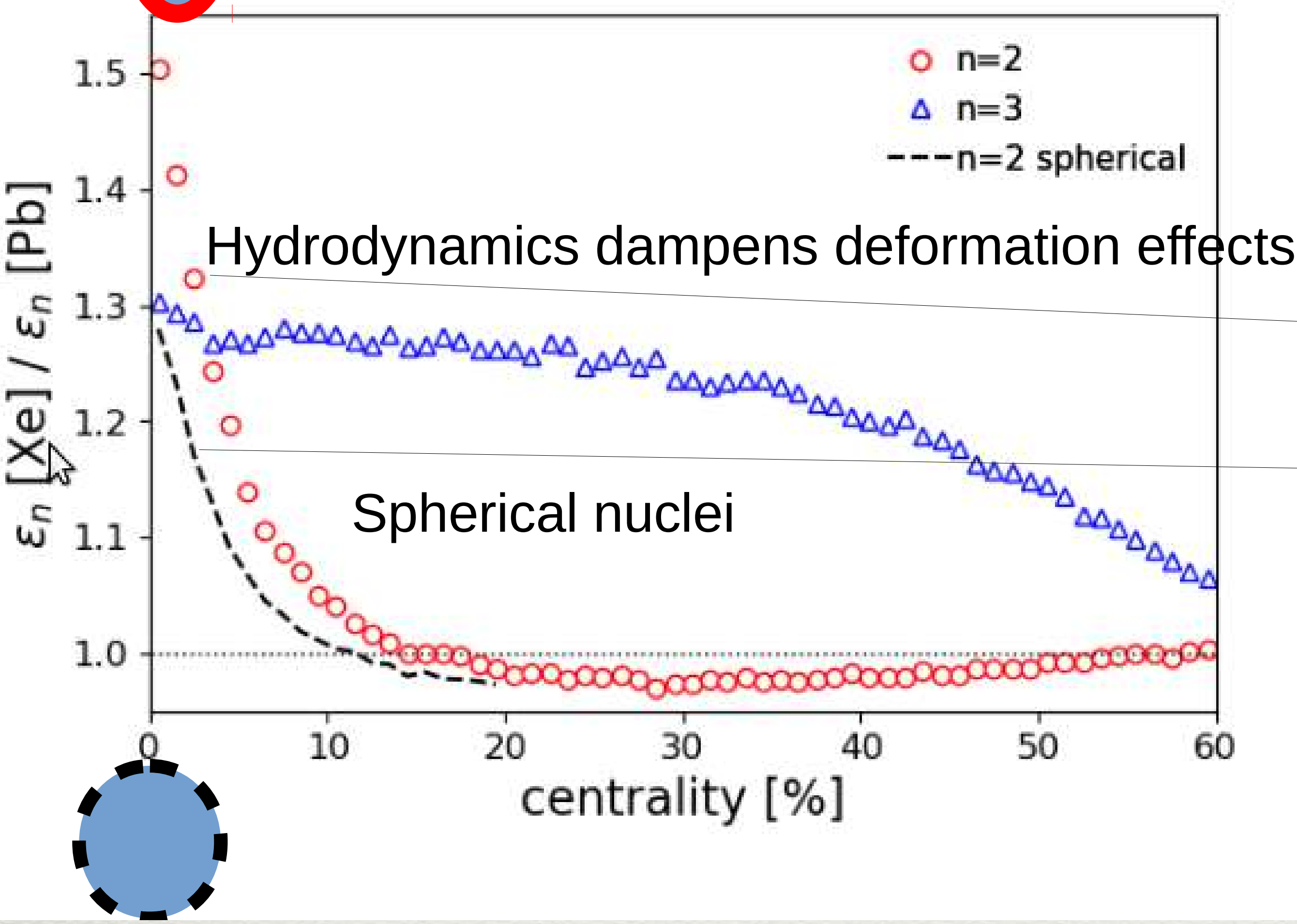


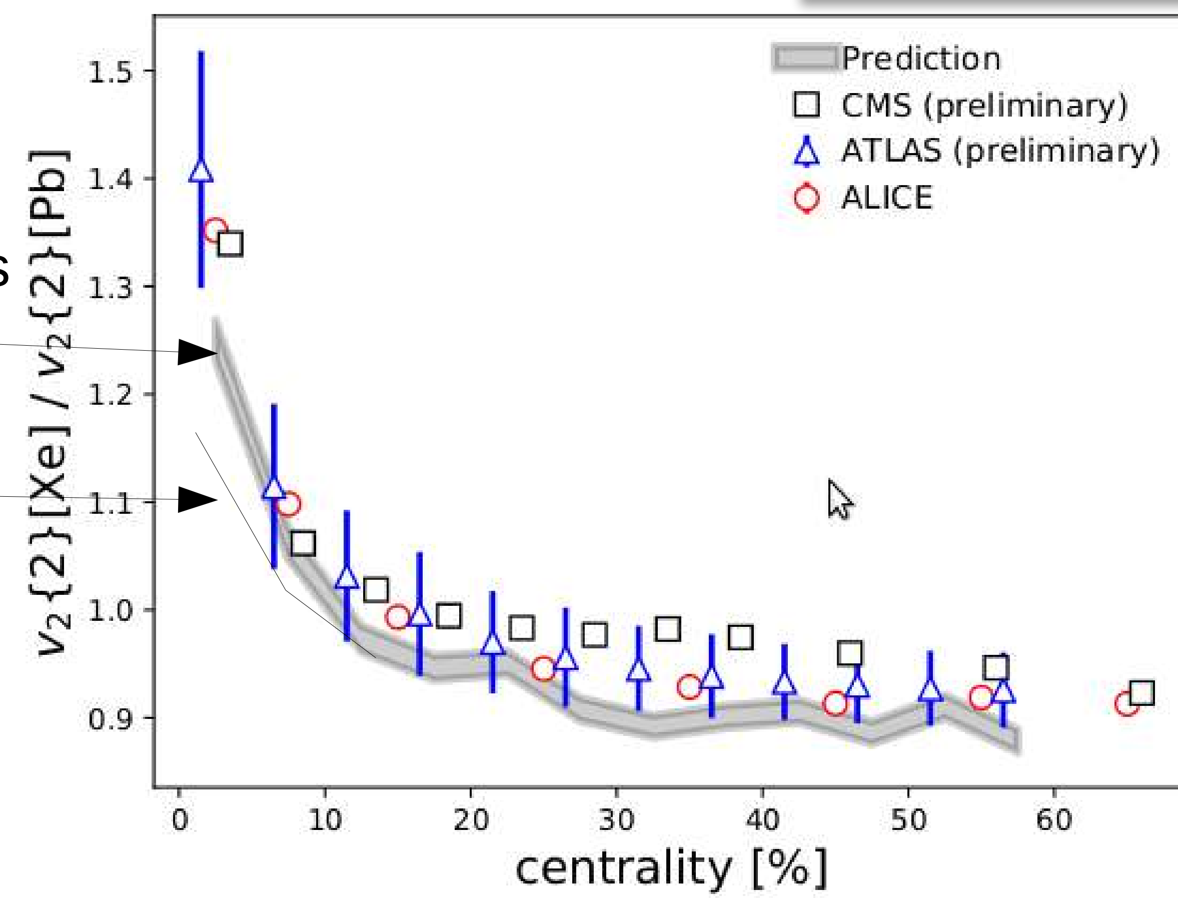
Finding a deformed nucleus in ^{129}Xe

Giuliano Giacalone
PhD Saclay



v-USPhydro sensitive to deformed nucleus
Giacalone, JNH et al. Phys. Rev. C 97,034904 (2018)



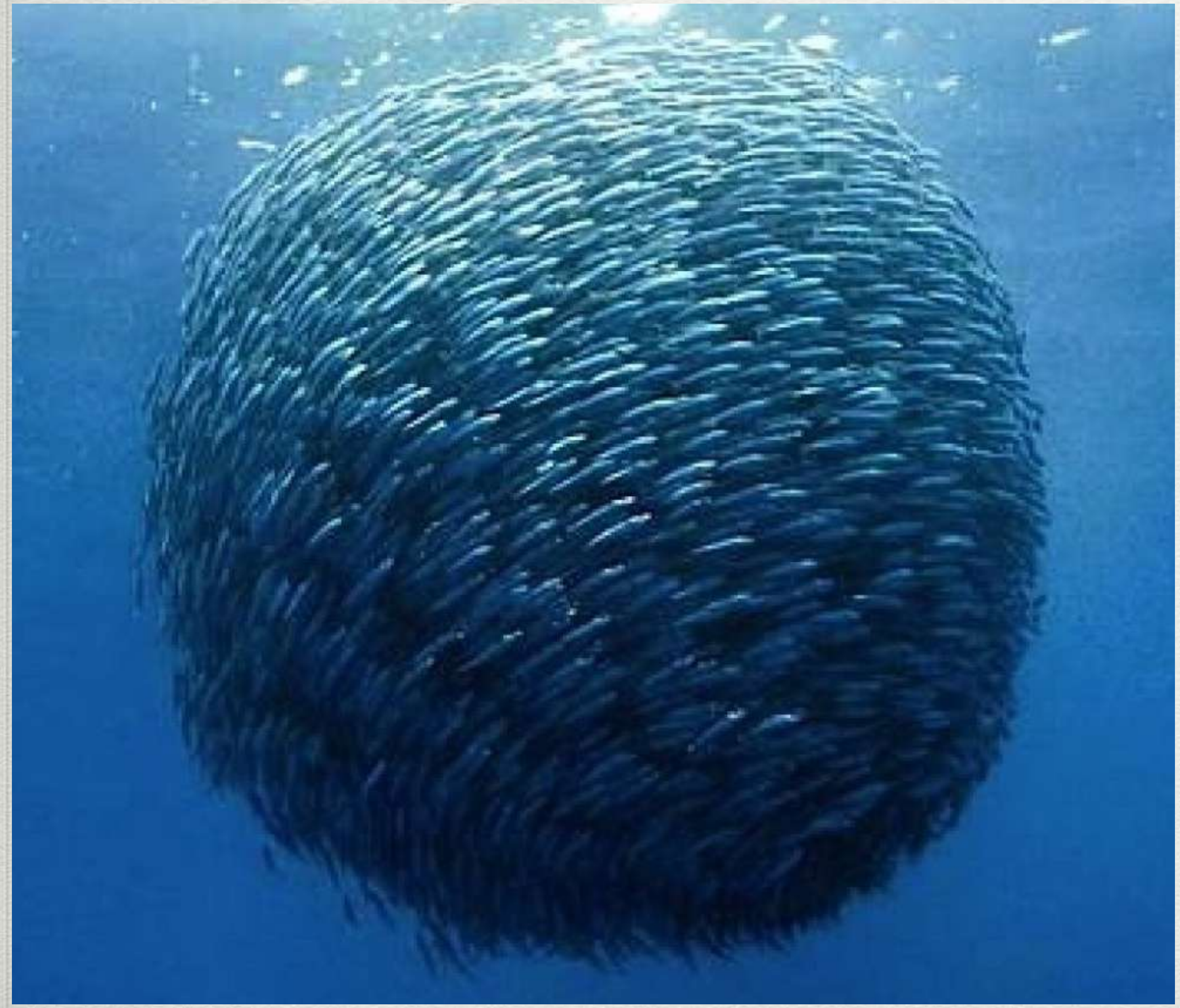


Deviation from experimental data: possible constraints on nuclear structure?

Limits on the smallest fluid

When do you have too few particles to use hydrodynamics?

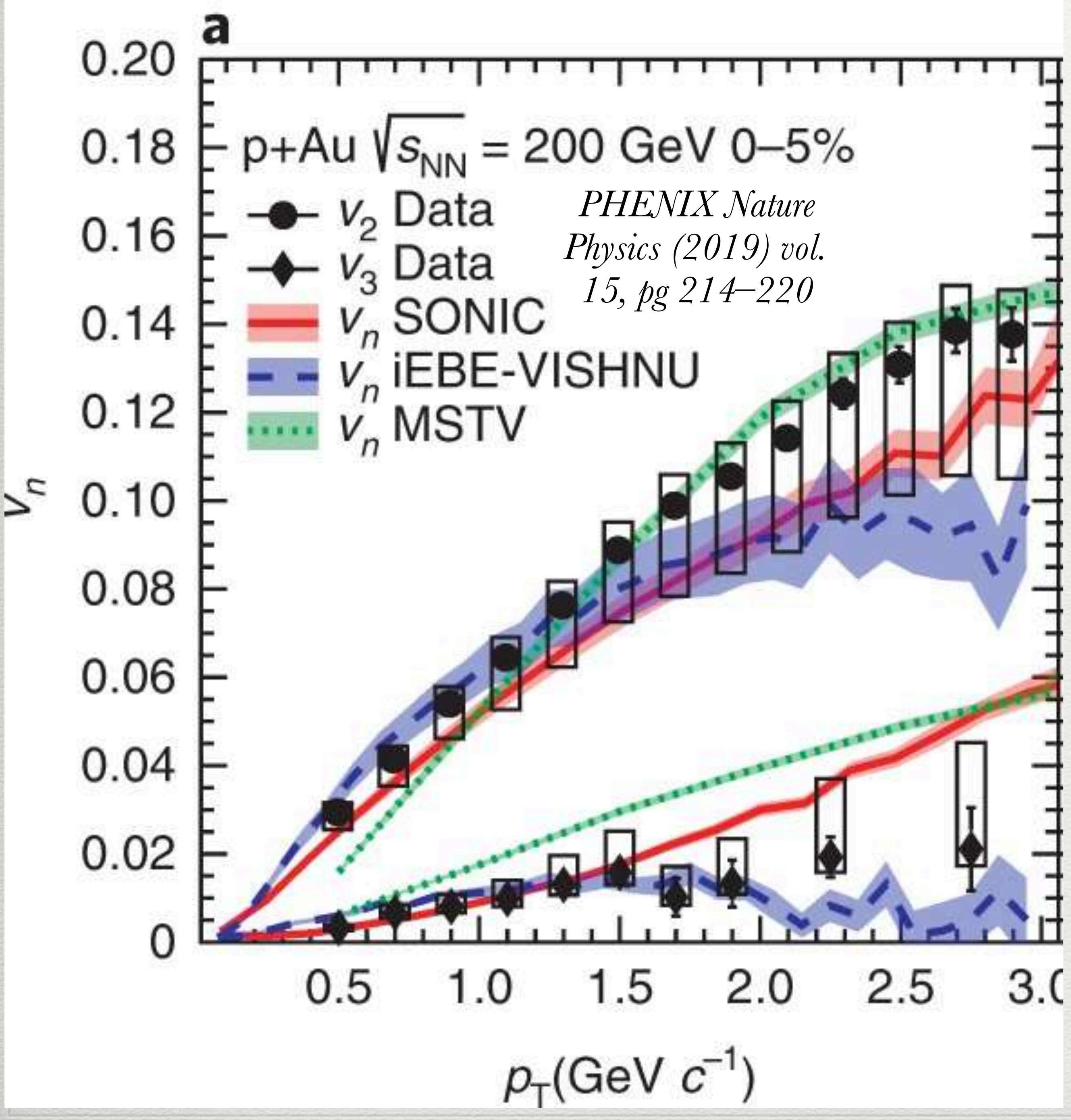
$$Kn \sim \frac{\text{Small scale}}{\text{Large scale}} \sim 1$$



→

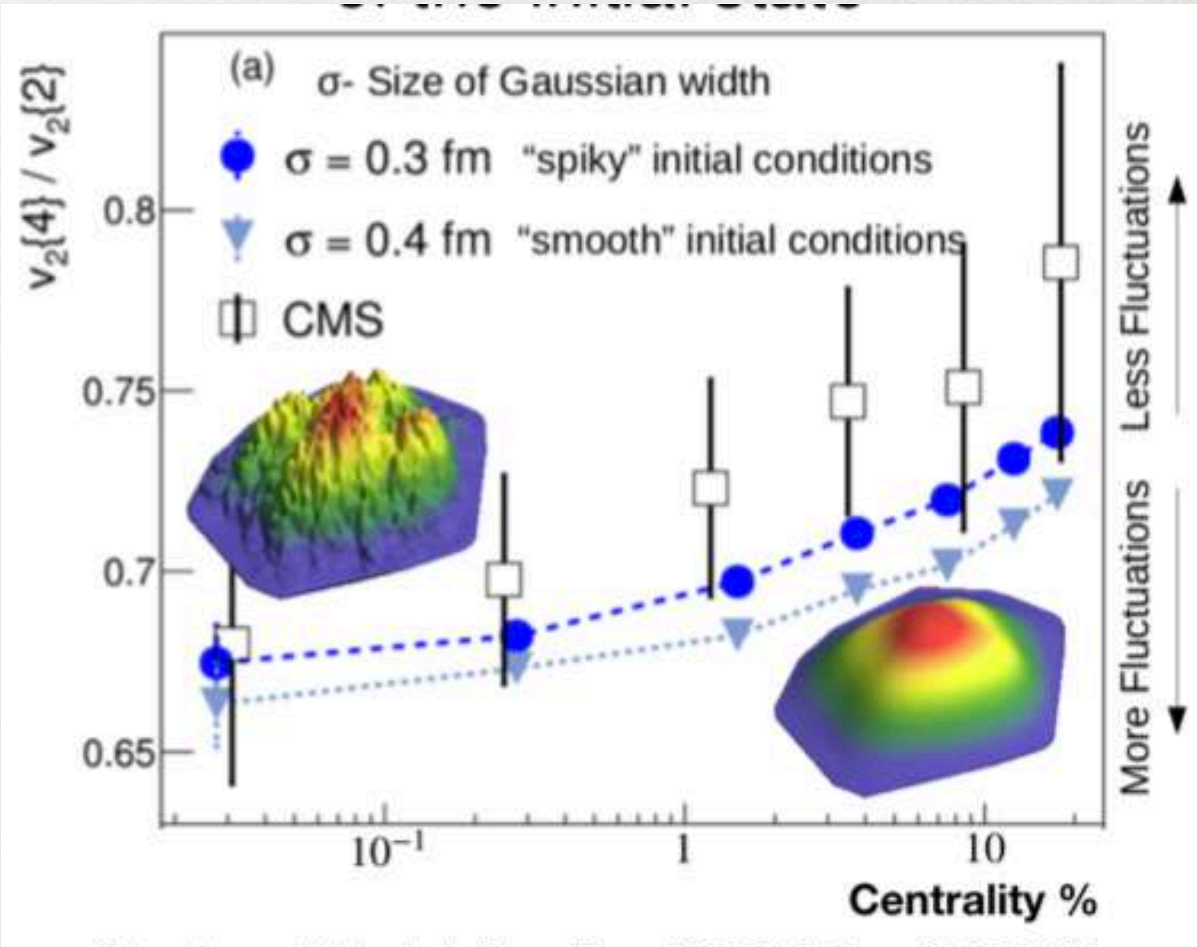
Experiment versus theory in small systems

Hydro matches data well



PHENIX Nature Physics (2019) vol. 15, pg 214–220

Questions remain on the initial conditions, applicability of hydrodynamics, and certain missing signals

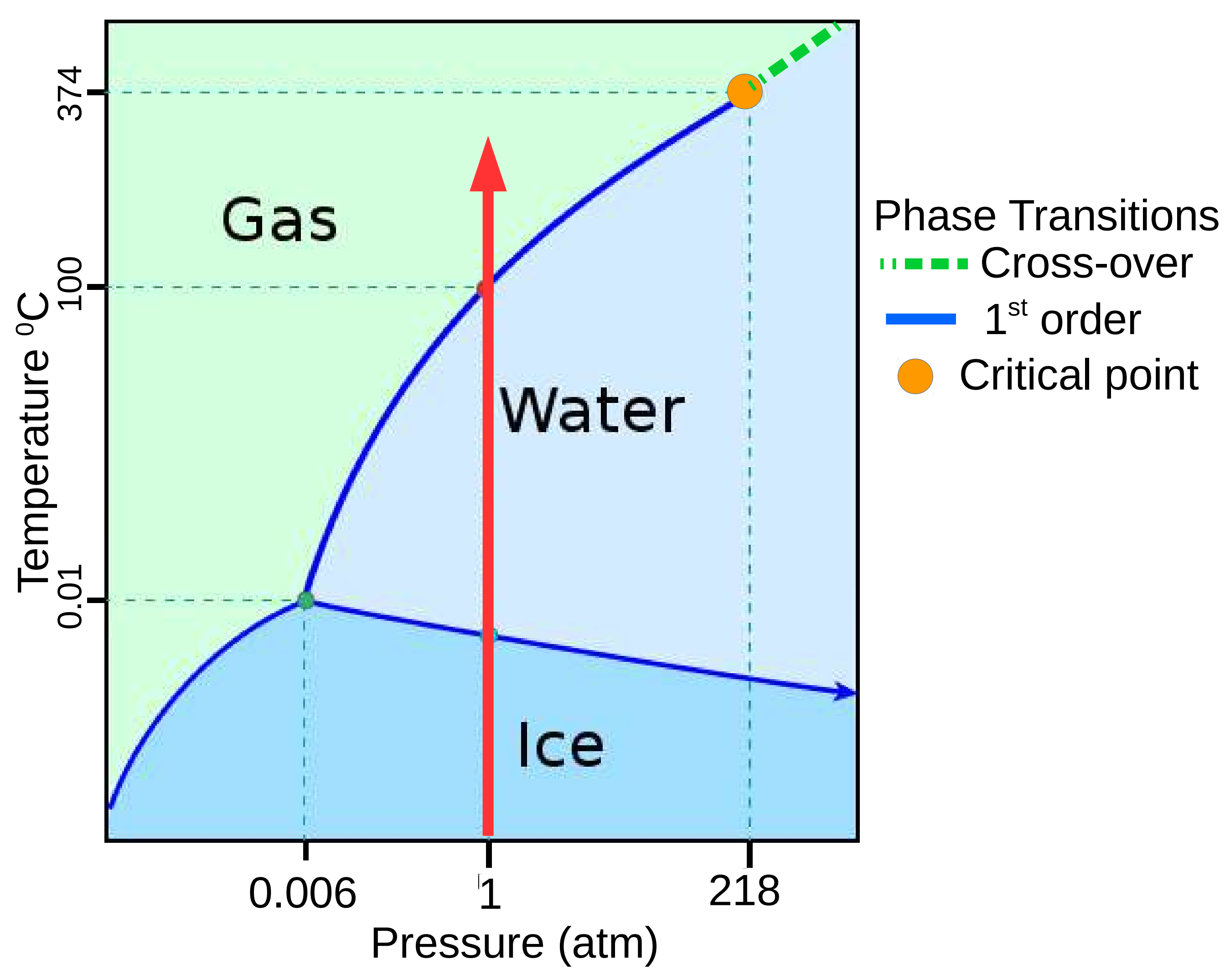


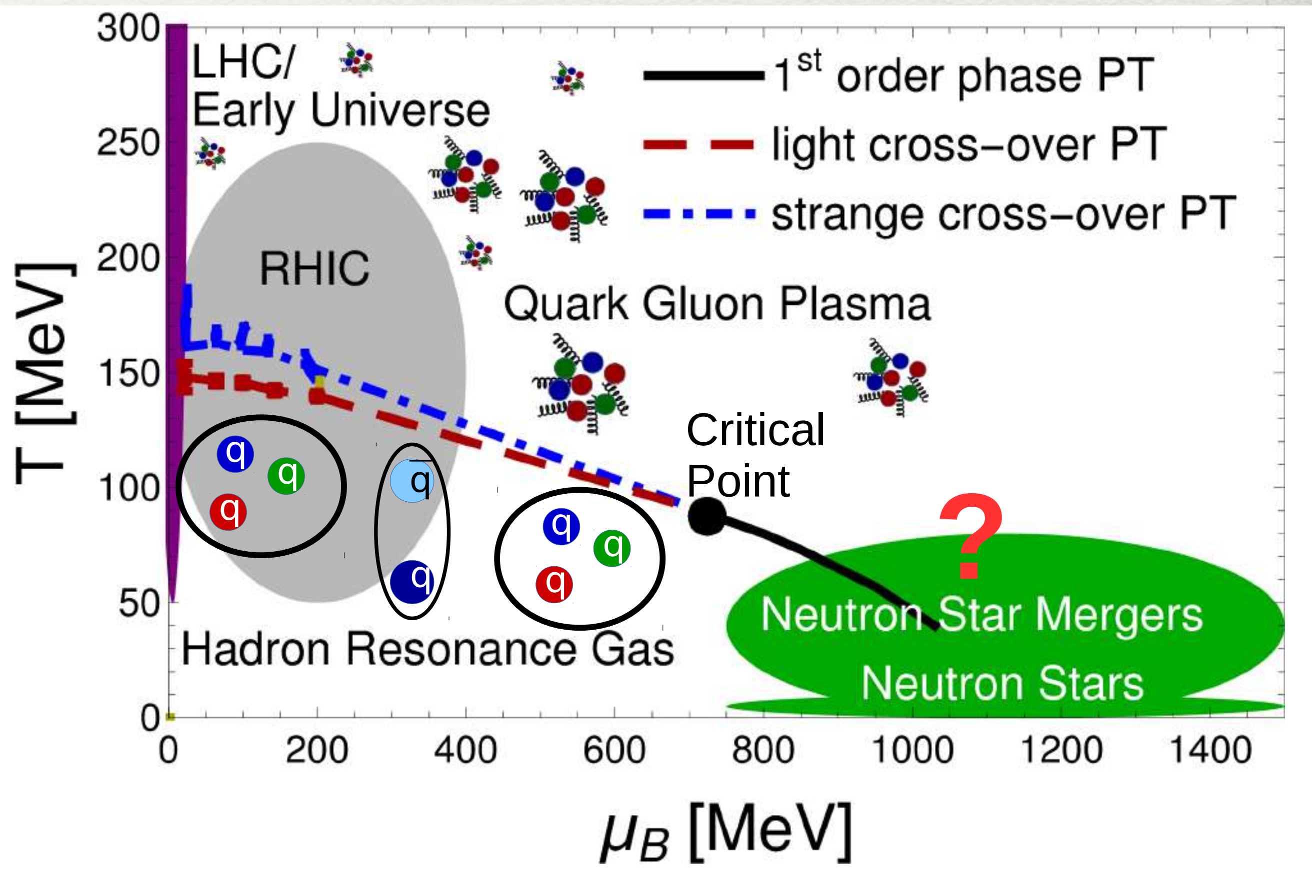
Giacalone, JNH et al, Phys.Rev. C95 (2017) no.5, 054910

Next frontiers of relativistic hydrodynamics

- Magnetohydrodynamics/Chiral Magnetic Effect
- **Conserved charges of QCD- baryon number, strangeness, and electric charge**
  - Each quark carries multiple charges!
- Source term in hydrodynamics for jets
- Critical fluctuations

QCD critical point



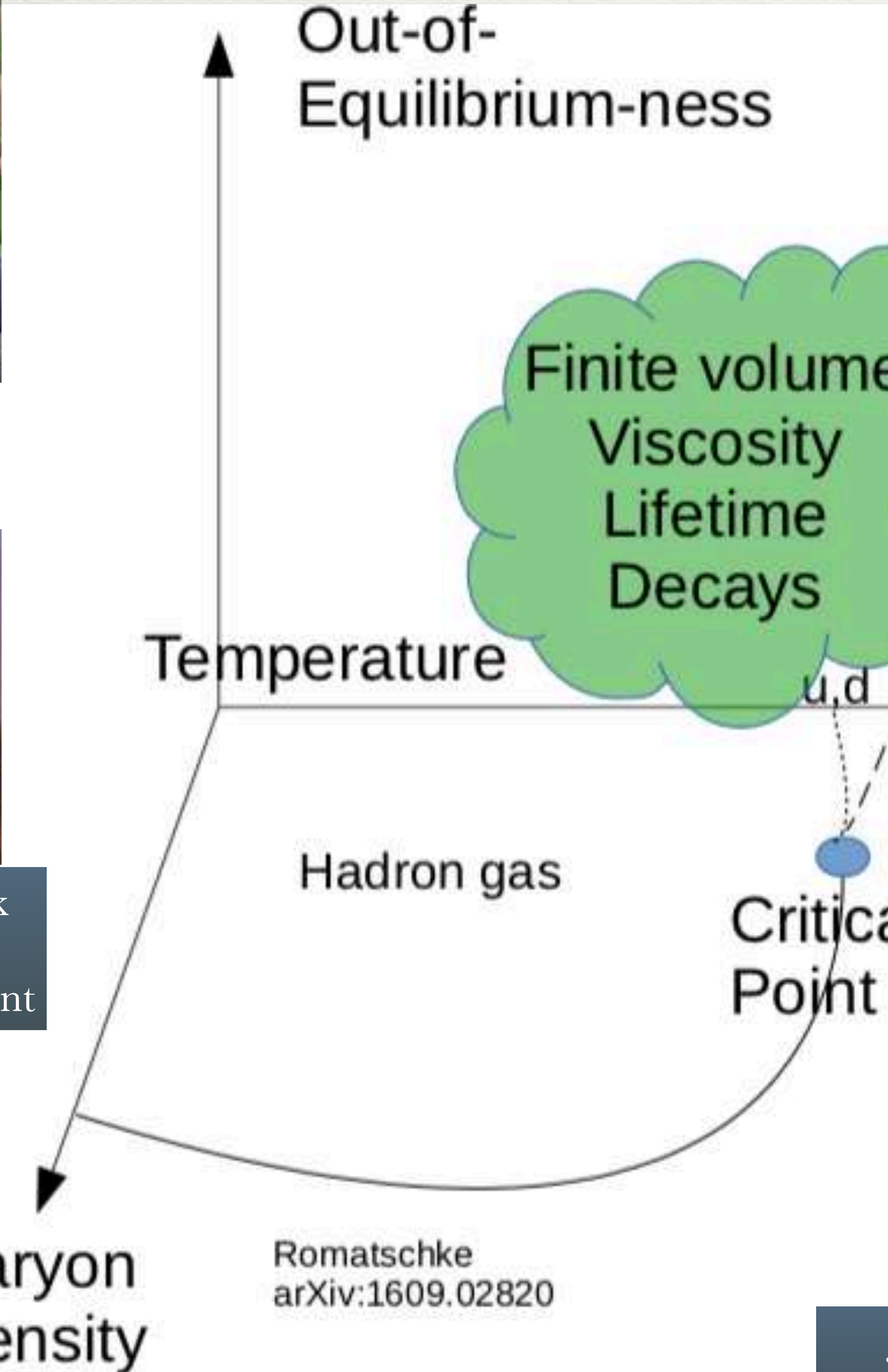


Search underway for the QCD critical point at the Beam Energy Scan II

Out-of-equilibrium search for the CP

Paolo Parotto
PD Wuppertal

Debora Mroczek
REU Houston
UIUC PhD Student



BEST COLLABORATION

Beam Energy Scan Theory Collaboration

- EOS+3D Ising CP

Parotto, JNH, et al, Phys.Rev. C101 (2020) no.3, 034901

- Next, dynamical model with critical fluctuations and out-of-equilibrium effects+Lattice EOS

Jamie Stafford
PhD student Houston

BSQ EOS

Phys.Rev. C100 (2019) no.6, 064910
Phys.Rev. C100 (2019) no.2, 024907

Relativistic hydrodynamics with conserved charges (BSQ)



Matt Sievert
Postdoc UIUC

M. Martinez
PD NCSU

D. Wertepny
PD Ben Gurion

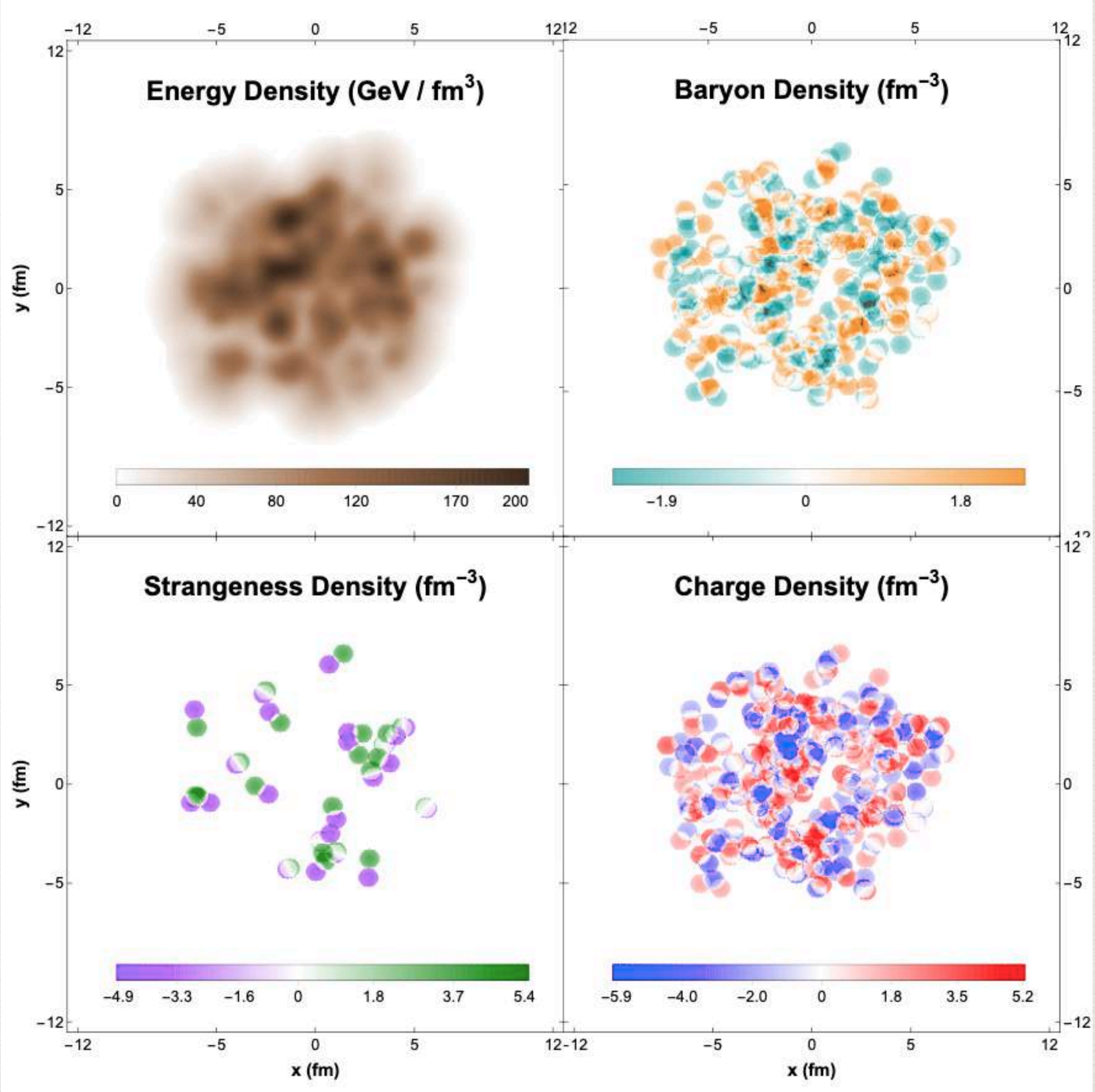
ICCING - Initial conditions with conserved charges (BSQ)

Sievert, Martinez, Wertepny, JNH arXiv:1911.10272; arXiv:1911.12454

Previous initial conditions assumed only gluons → ICCING initializes quarks as well!

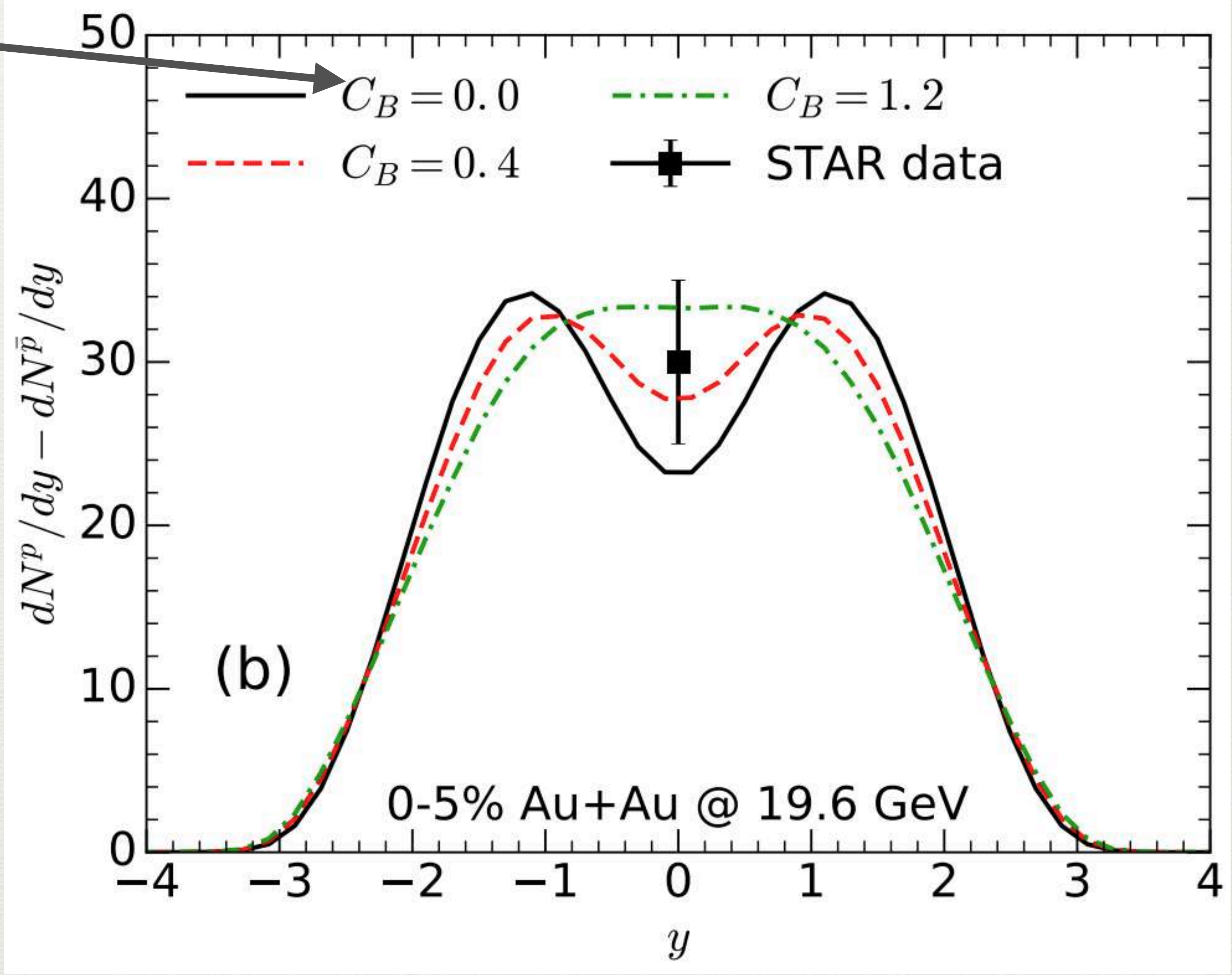
Next, incorporate Parton Distribution Functions (future Electron Icon Collider)

Example Initial Condition



Larger diffusion - net-protons larger in center

Baryon diffusion parameter



Denicol et al, *Phys. Rev. C 98, 034916 (2018)*

BSQ diffusion the next stage

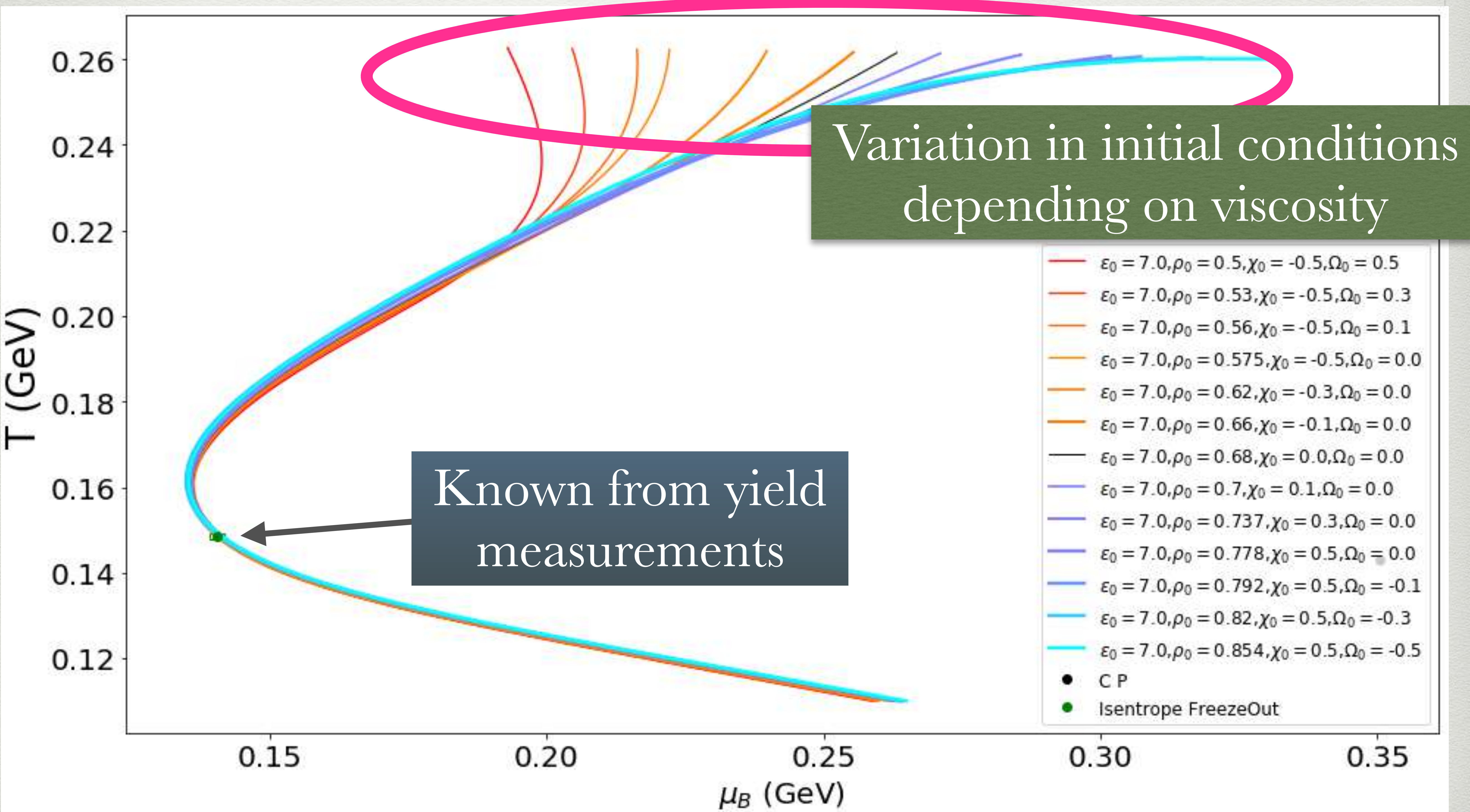
Fotakis et al, arXiv:1912.09103
Rose et al, arXiv:2001.10606

Travis Dore
PhD student

Emma McLaughlin
REU student

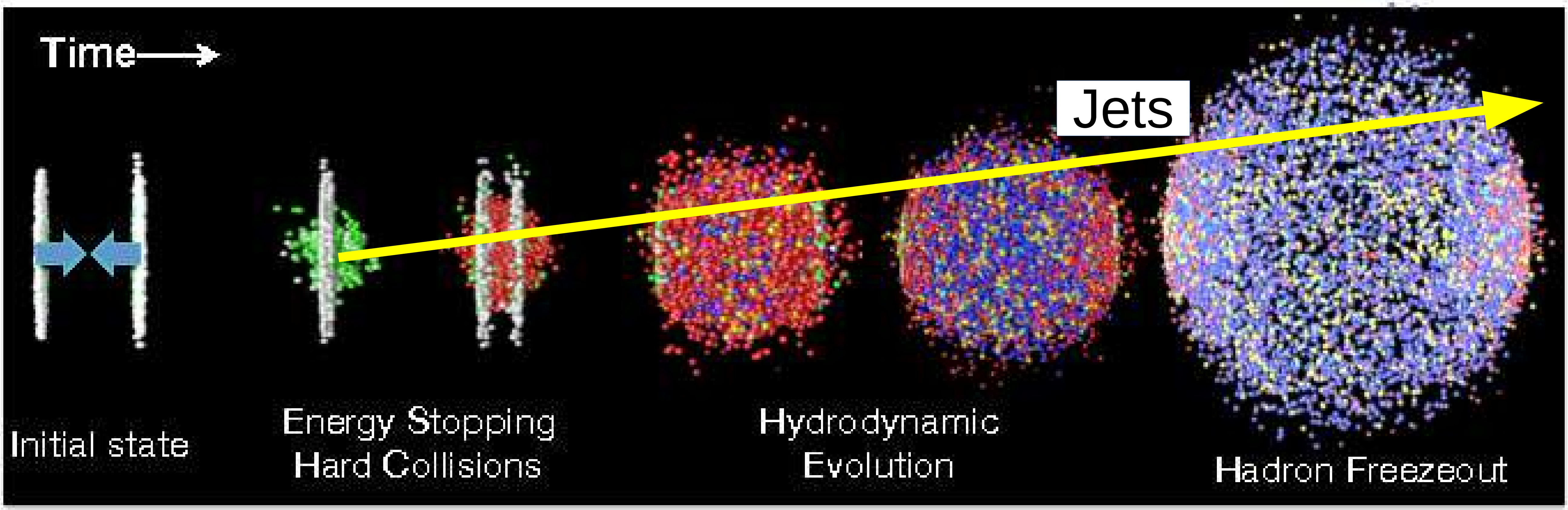
B(SQ) Hydrodynamics

Dore, McLaughlin, JNH, to appear soon




The Future
NEXT EXIT

Future Experiments

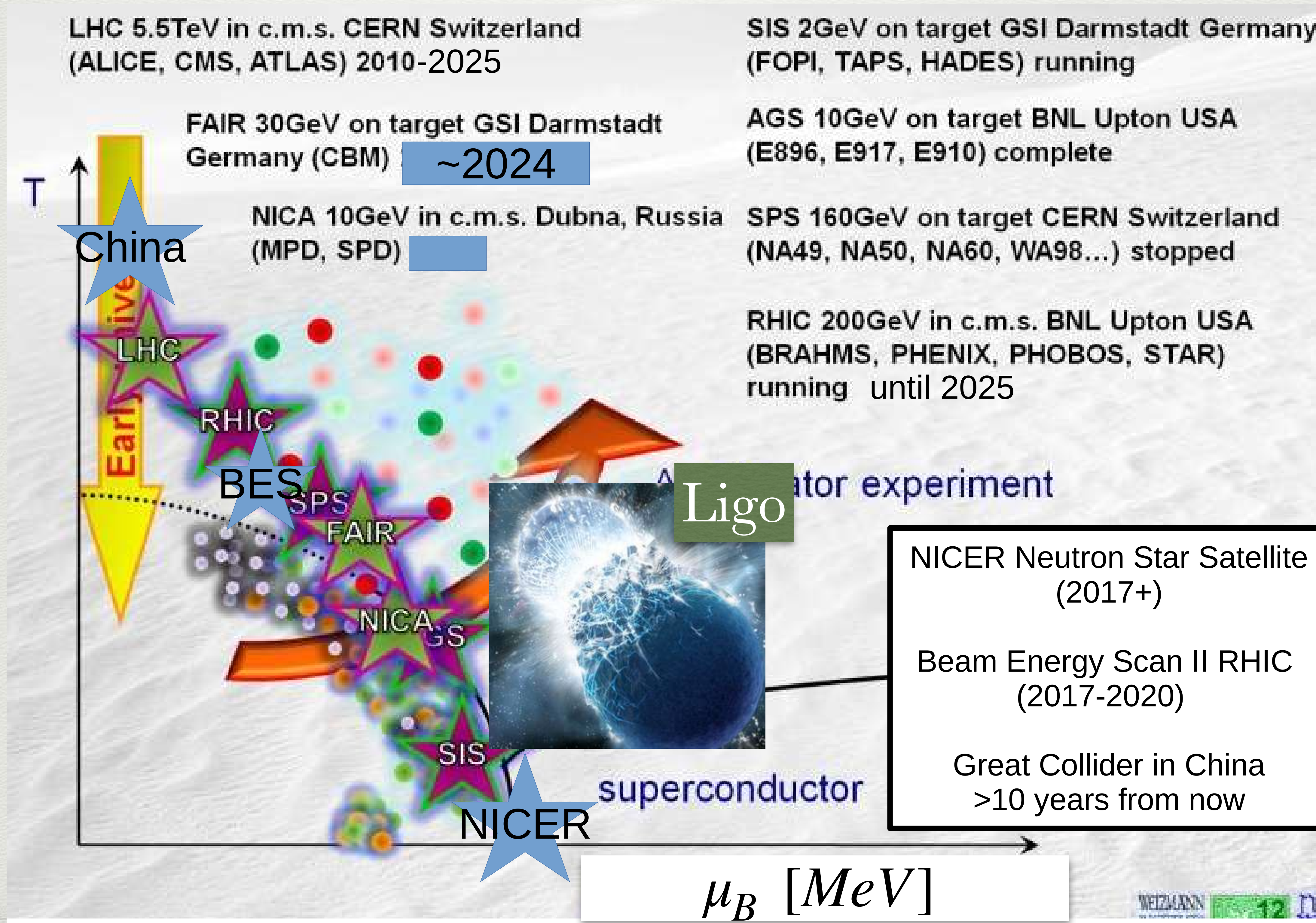


Electron Ion Collider (EIC) - Nucleon/Nuclei Structure affect the initial state (important for small systems) >2025

sPHENIX/LHC -
Jets probe shorter scales i.e. a QGP microscope
2018-2025

Beam Energy Scan (RHIC)/FAIR – High baryon densities, hadron gas phase
2018-2020,>2024

Mapping the QCD phase diagram



Summary

- Relativistic viscous hydrodynamics provides an extremely successful description of the Quark Gluon Plasma
- Much to come in the future on the addition of conserved charges, critical fluctuations, magnetohydrodynamics, jets coupled to hydrodynamics…
- STAR BESII, sPHENIX, EIC, FAIR, LIGO crucial to a further understanding of the Quark Gluon Plasma/ Quantum Chromodynamics