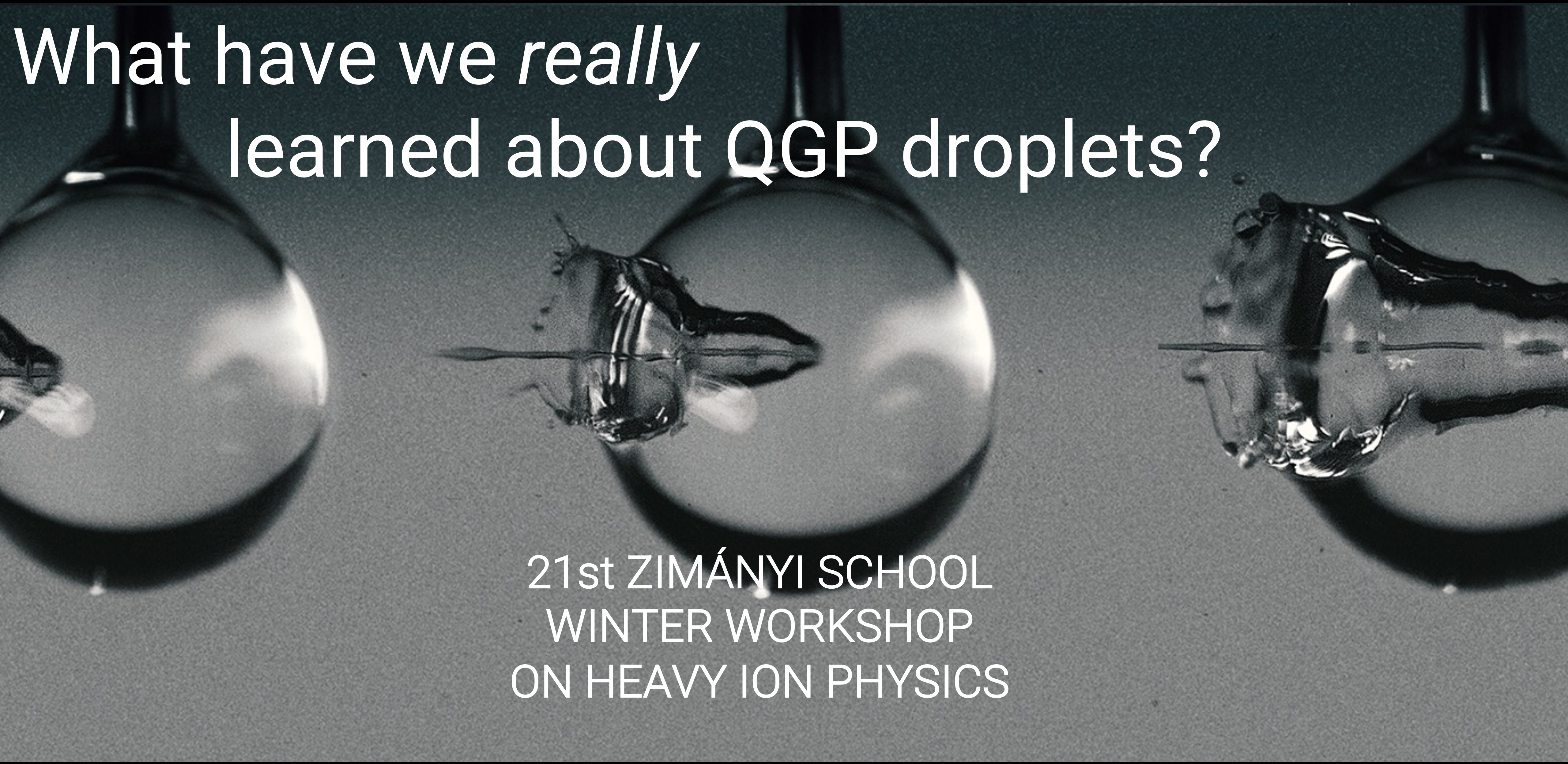


What have we *really* learned about QGP droplets?

21st ZIMÁNYI SCHOOL
WINTER WORKSHOP
ON HEAVY ION PHYSICS

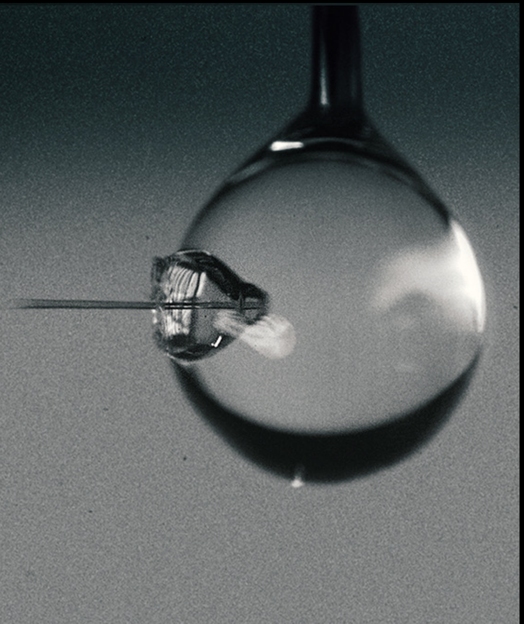
Jamie Nagle
University of Colorado Boulder

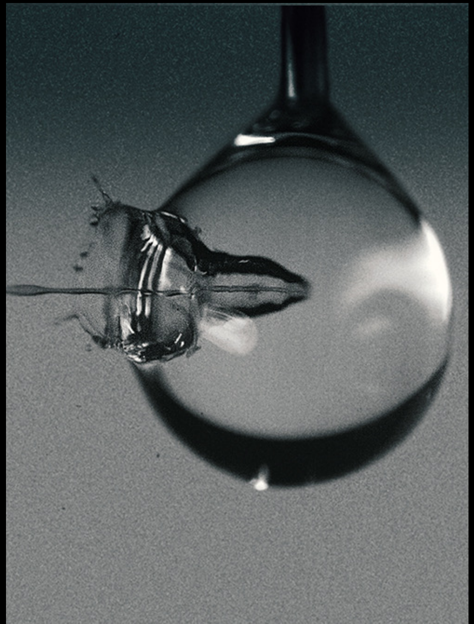
December 09, 2021

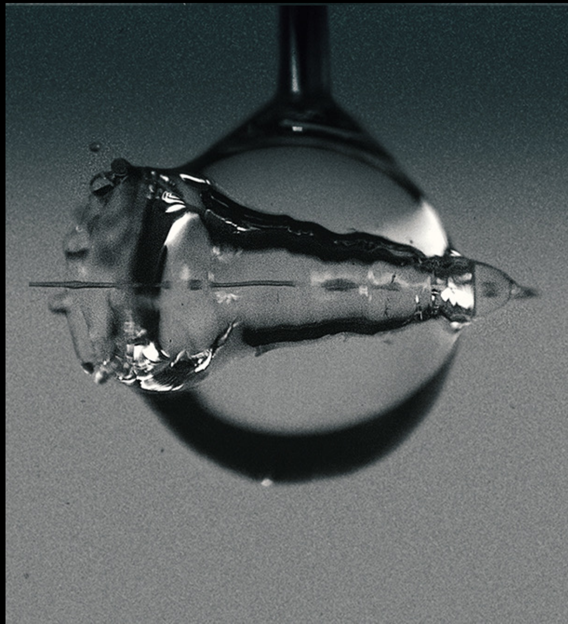
RHIC Heavy Ion Program will be ending in the next 5 years *or so* to make way for the Electron Ion Collider…

sPHENIX and **STAR** (with forward upgrades) still ahead and longer term LHC Heavy Ion program into 2030s

Good to take stock of what we have learned and what we have not learned…







Physics goals of RHIC

• Achieve highest energy densities in extended matter for relatively long times

•Learn the dynamics of high density matter:
energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout

•Search for collective effects beyond individual pp scattering, or pA scattering

•Study role of new degrees of freedom

•Produce and study quark-gluon plasma with large A at E above a few GeV/fm^3

•Extract nuclear equation of state, application to astrophysics

G. Baym, 1/95

What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales (ρ_0=0.16/fm^3, E_0=0.15GeV/fm^3) to orders of magnitude beyond?

•What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.

•What are the states of matter?
Recognizable quark-gluon plasma? Strangelets? ...?

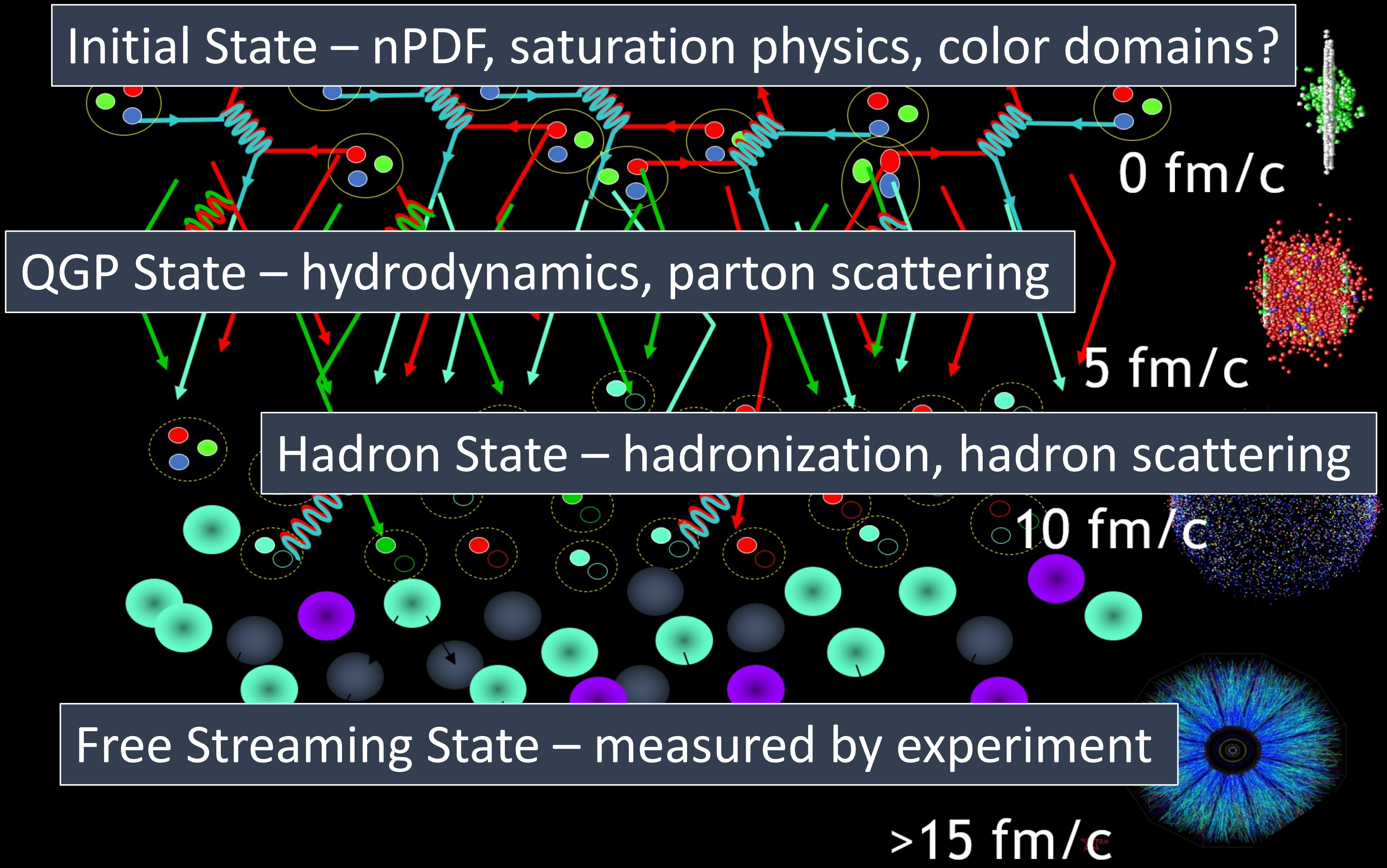
•What is the structure of qcd on large distance scales? Phase transitions? Monopoles?

•Surprises!

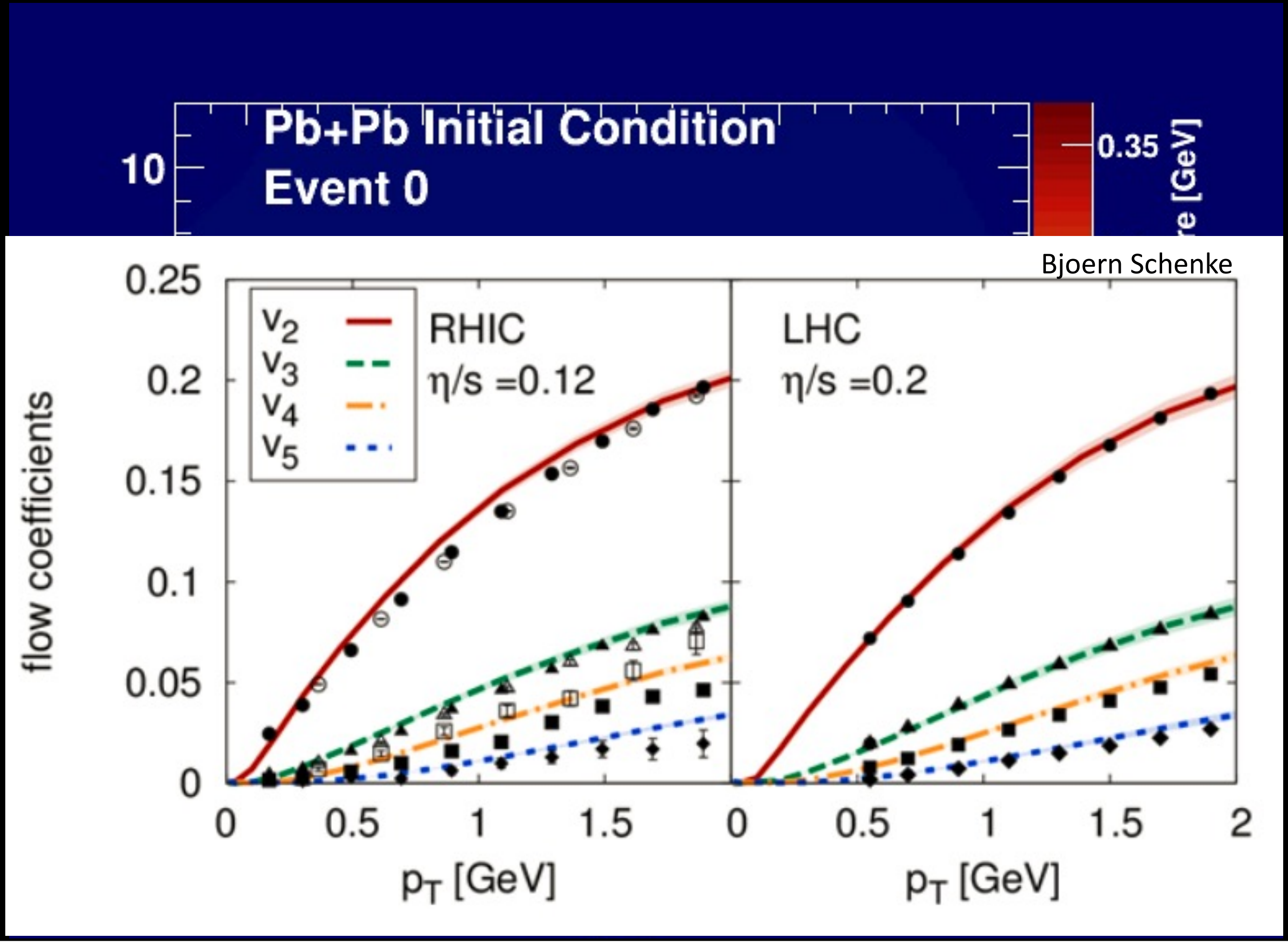
Terra incognita

G. Baym, 1/95

Standard Time Evolution Model of Heavy Ion Collisions



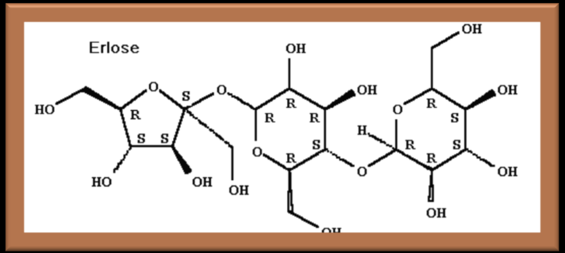
Standard Time Evolution Model of Heavy Ion Collisions



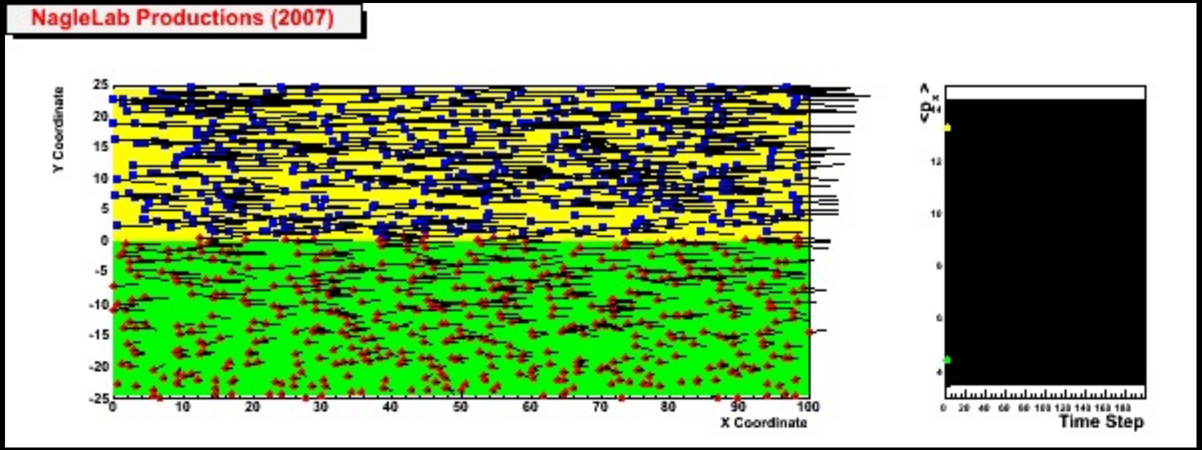
$$\frac{dN}{d\phi} = 1 + 2v_2\cos[2(\phi-\Psi_2)] + 2v_3\cos[3(\phi-\Psi_3)] + 2v_4\cos[4(\phi-\Psi_4)] + 2v_5\cos[5(\phi-\Psi_5)] + \ldots$$

Shear Viscosity and Strong Coupling

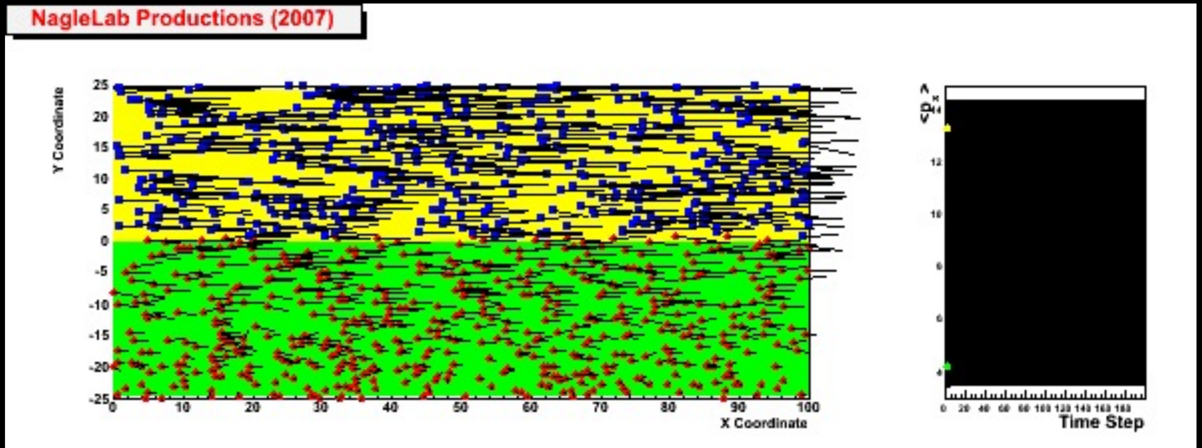
Honey – viscosity decreases at higher temperatures
viscosity increases with stronger coupling



Weak coupling (σ=0)



Strong coupling (σ ↑)



Inhibited diffusion

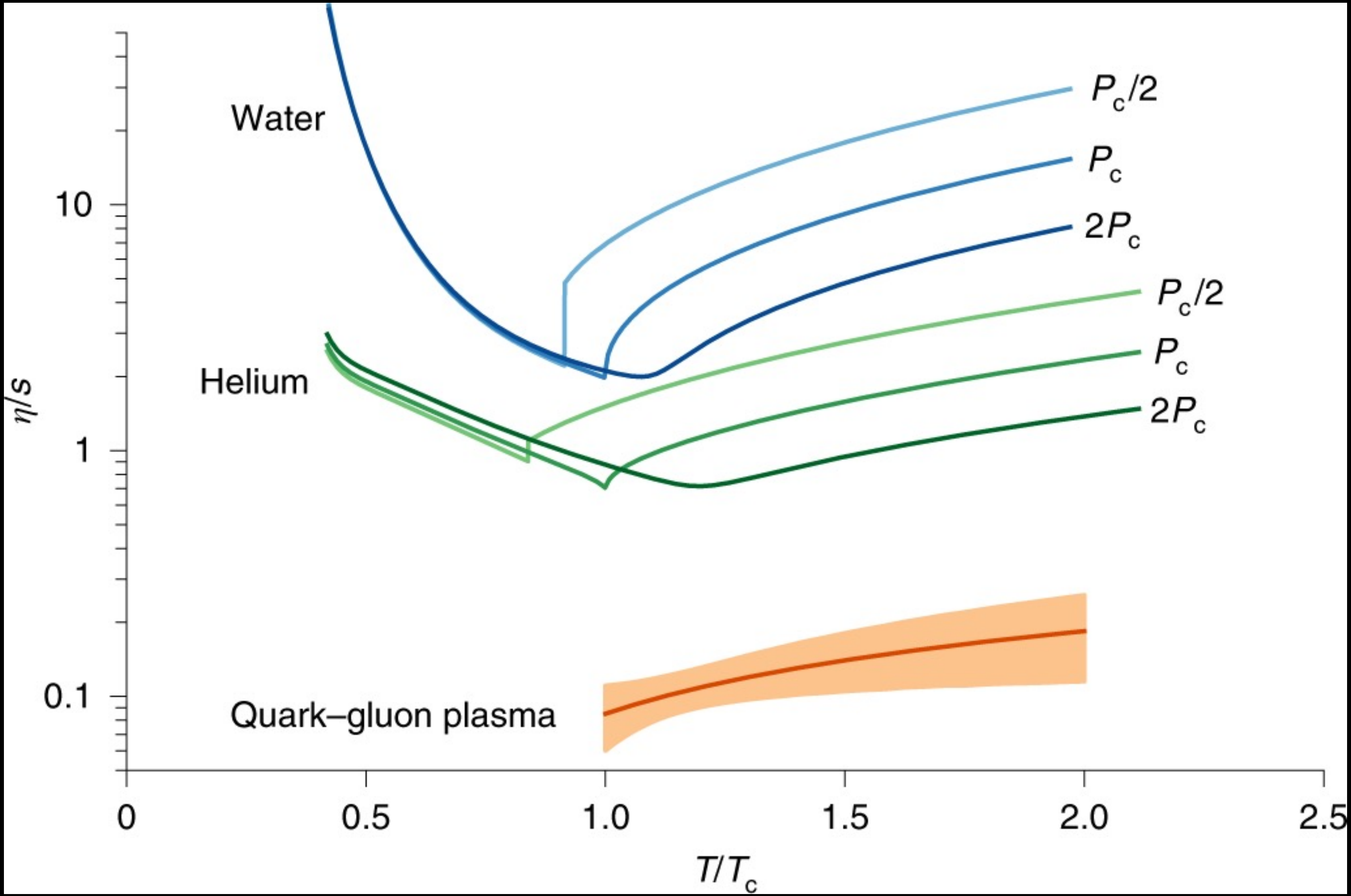
↓

Small viscosity

↓

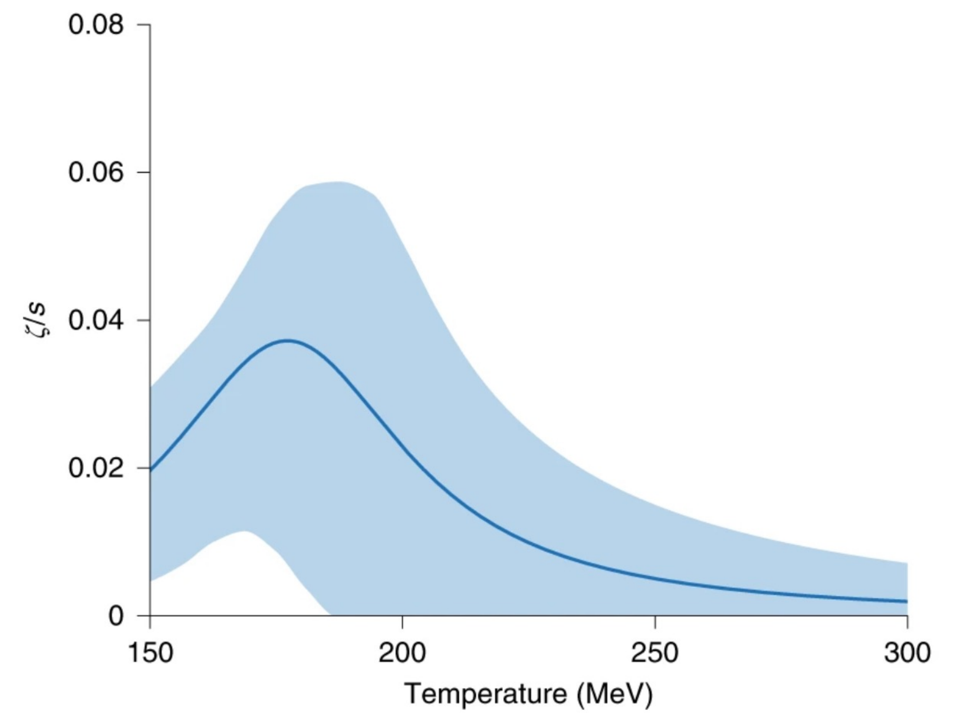
Perfect fluid

Quantitative Assessment of Most Perfect Fluid



https://www.nature.com/articles/s41567-019-0611-8?proof=t

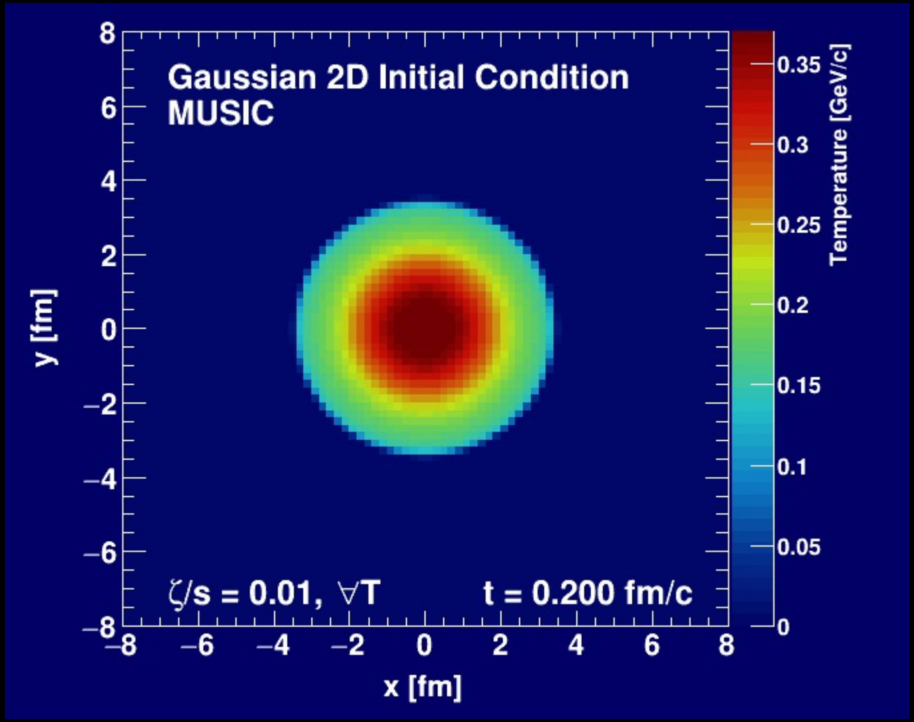
Quantitative Assessment of Bulk Viscosity?



https://www.nature.com/articles/s41567-019-0611-8?proof=t

Early pre-hydrodynamic expansion is critical here

Bayesian analyses only consider free streaming case and not weak versus strong coupling case, and thus the constraint is misleading…

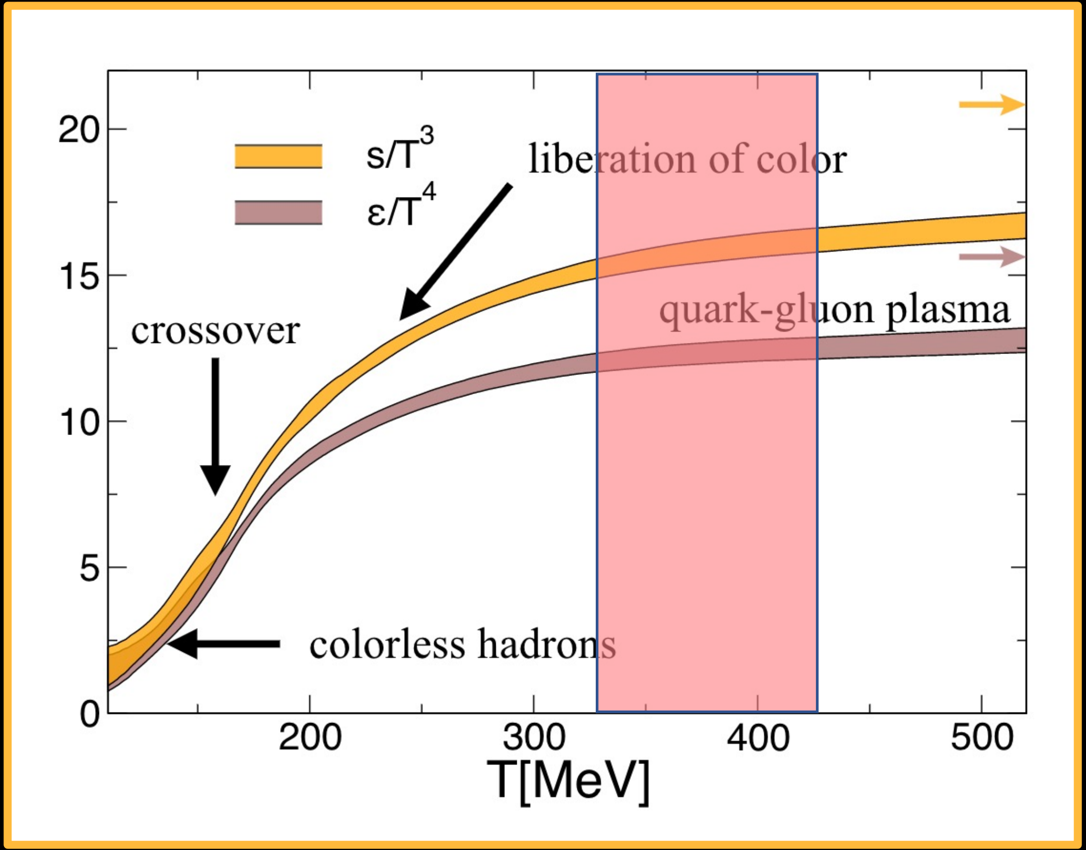


M. Byres, https://arxiv.org/abs/1910.12930

Nearly perfect fluid – yes!

Most perfect fluid measured to date – yes!

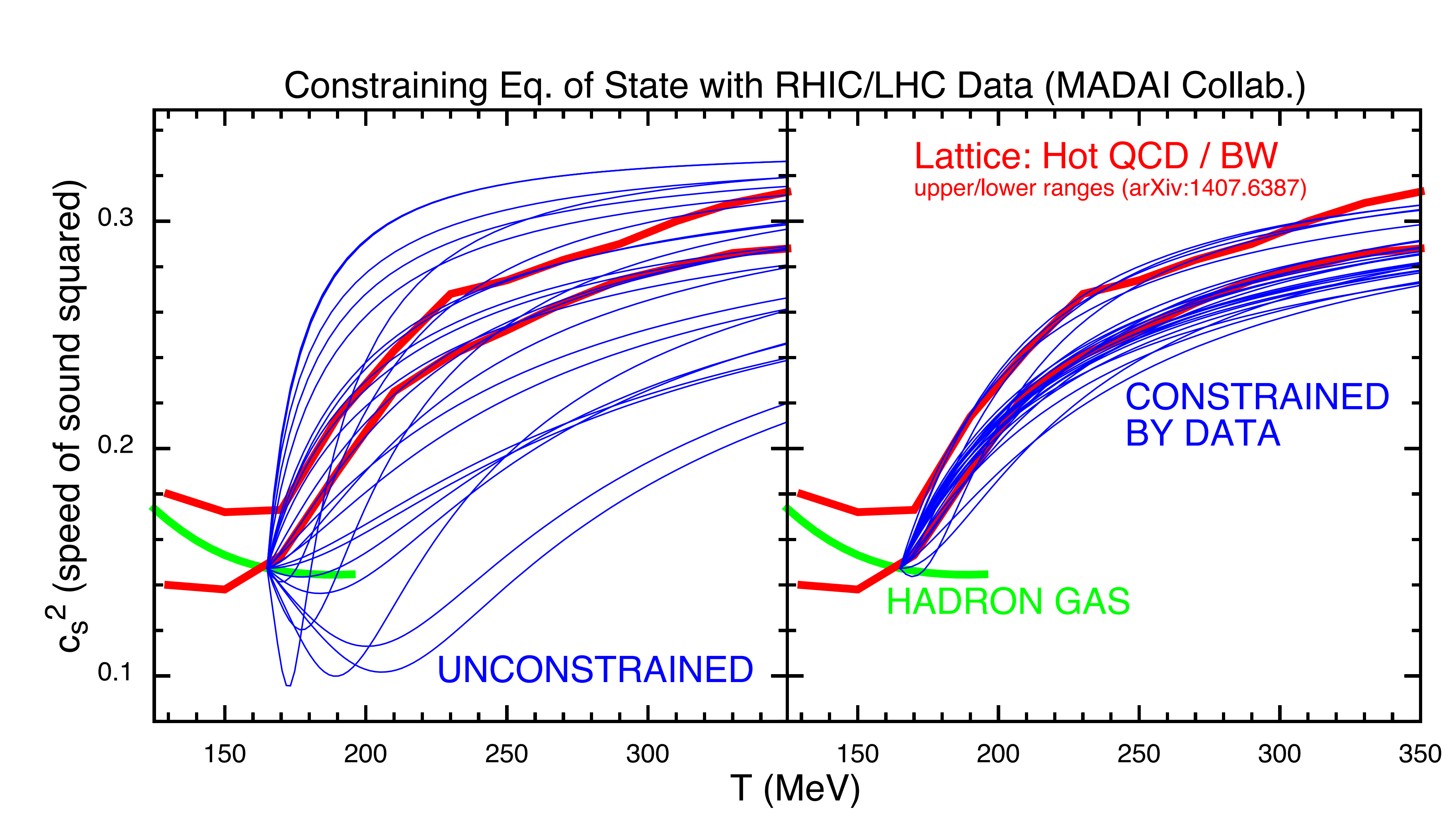
Quark-gluon plasma?



Hydrodynamic calculations typically start with T = 340 (420) MeV at RHIC (LHC), which is well above T = 155 MeV transition temperature.

Temperature alone does not tell you directly the degrees of freedom.

Equation of State Constrained by Data



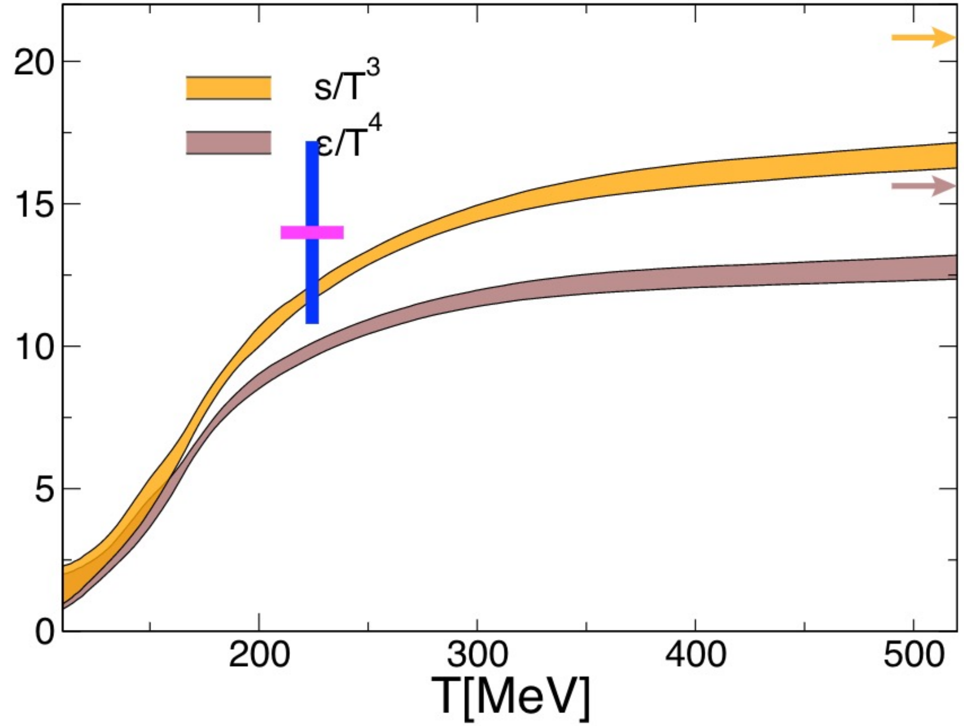
With beam energy scan data, can we constrain equation of state to see μ_B dependence?
See comment soon regarding lack of full equilibration…

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

$$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$$

$$\varepsilon = 37\cdot\frac{\pi^2}{30}T^4$$

Slide from J.Y. Ollitrault



T_{eff}=222 ± 9 MeV

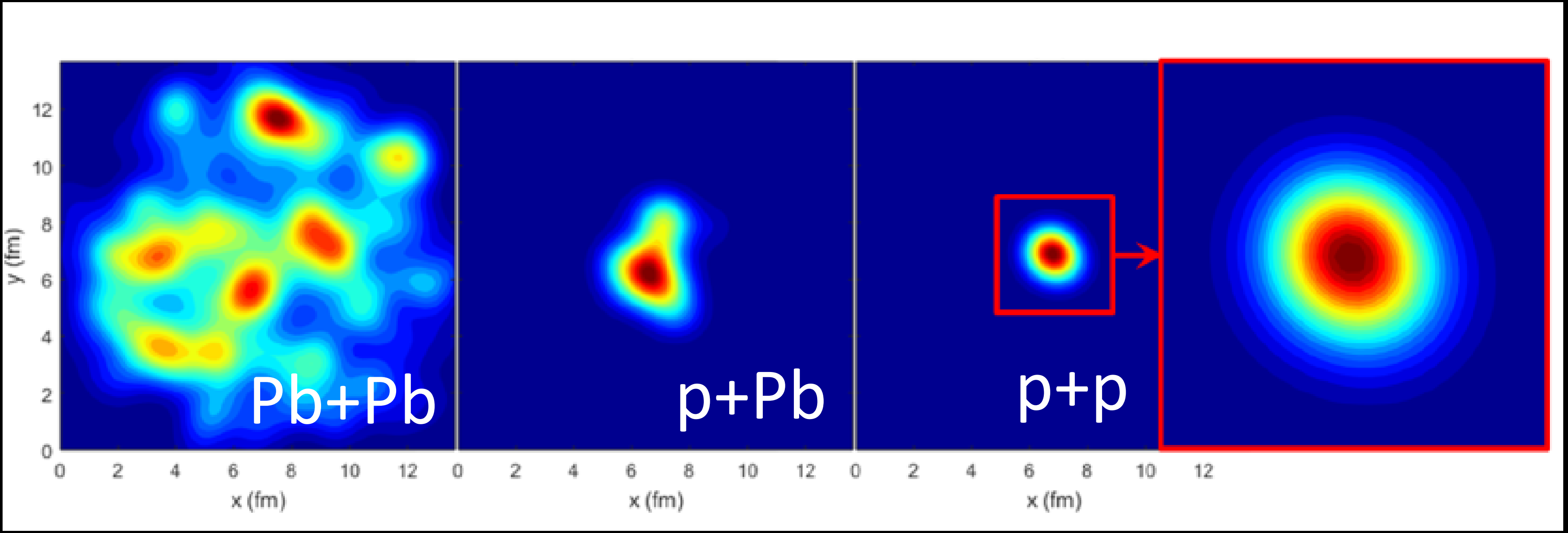
$s(T_{eff})/T_{eff}^3 = 14 \pm 3.5$

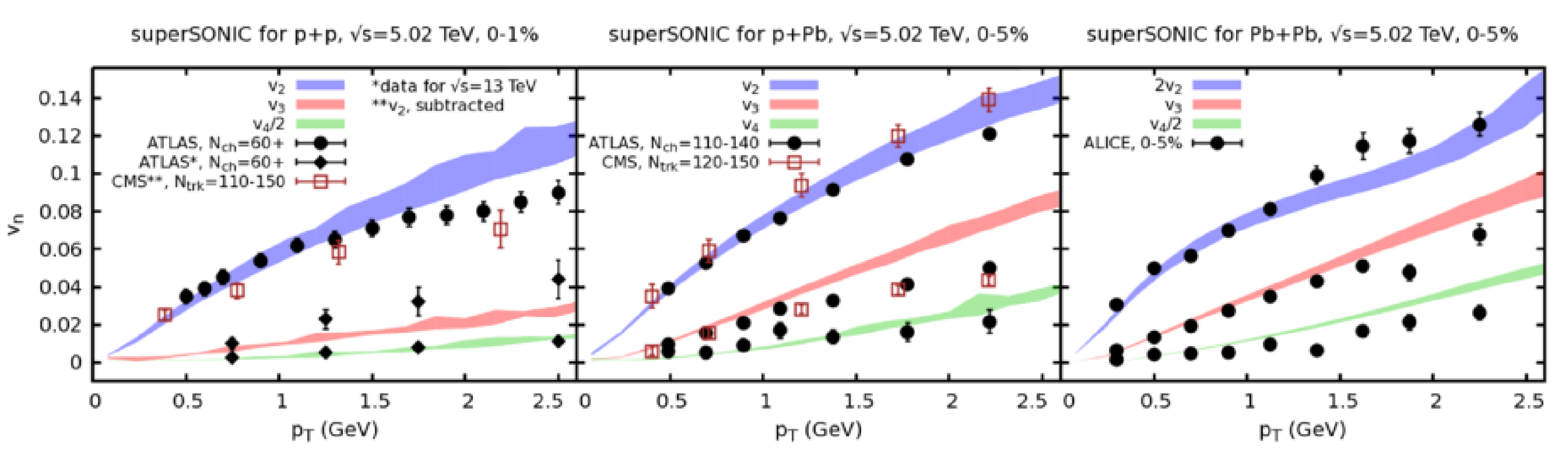
compatible with lattice.

Confirms large number of degrees of freedom, implying that color is liberated: ***deconfinement observed!***

Nature Phys. 16 (2020) 6, 615-619

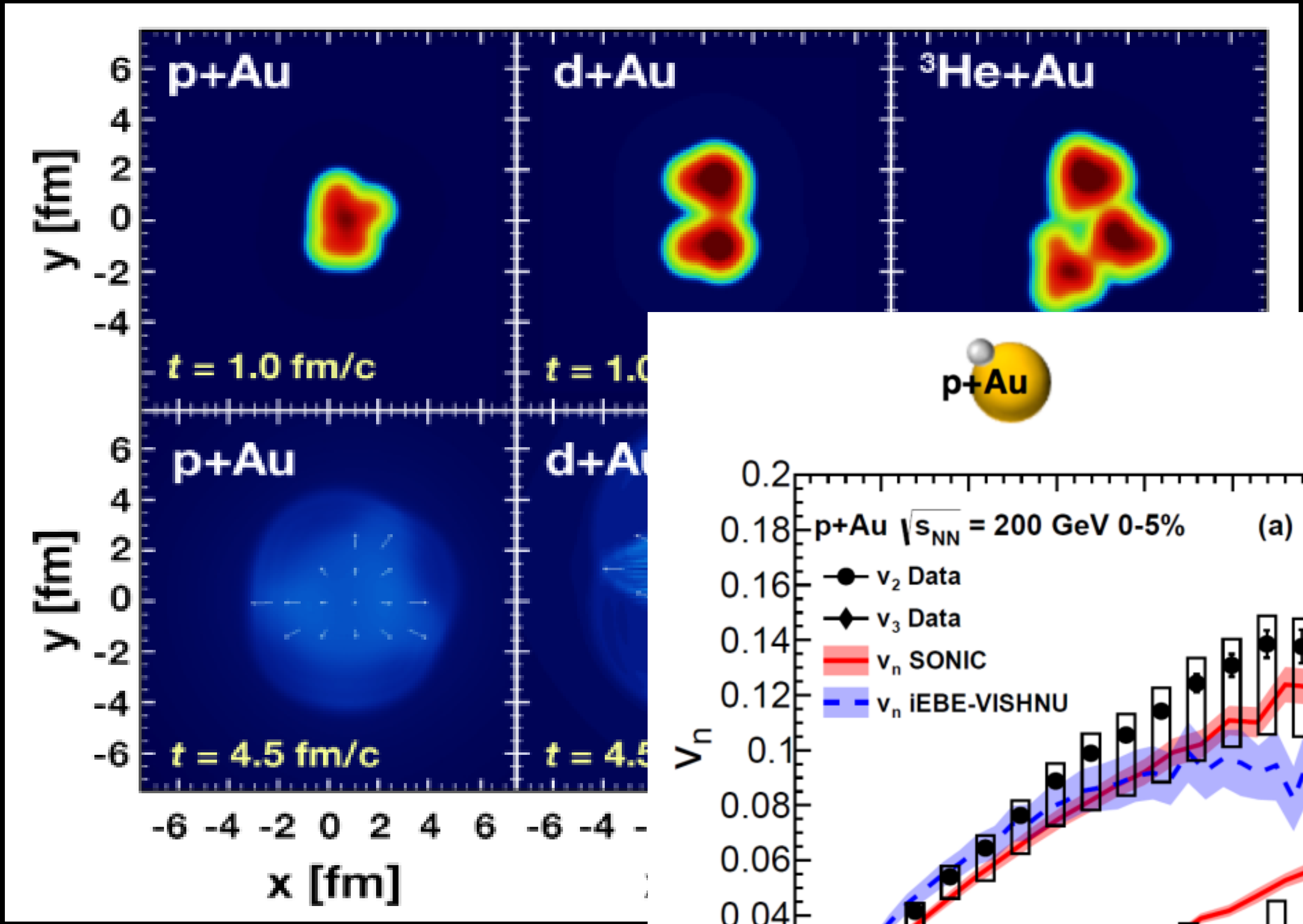
What about smaller droplets?

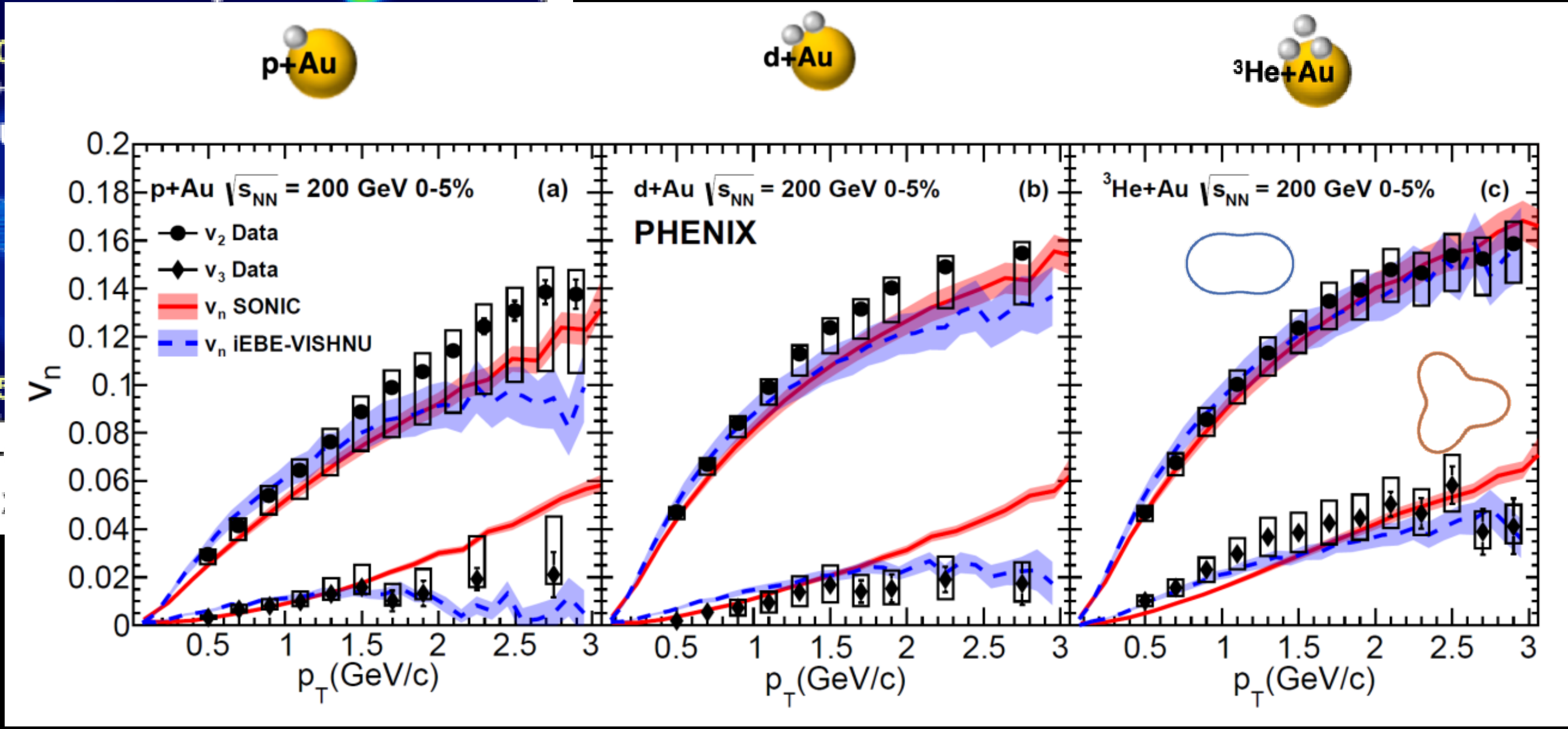




Weller and Romatschke, https://arxiv.org/abs/1701.07145

One, Two, Three Droplets of QGP





PHENIX, **Nature Phys. 15 (2019) no.3, 214-220**

What does it all mean?

I thought hydrodynamics only applies if
(1) system is near equilibrium
(2) system has a size scale L >> mean free path

How can these be true in p+p, p+Au, d+Au, ^{3}He+Au, etc.?

Maybe they are NOT!

String Theory Dual (completely solvable at strong coupling)
Systems very far from equilibrium still described by hydrodynamics as long as non-hydrodynamic modes are damped → hydrodynamic attractor.

Major re-thinking well beyond field of heavy ion physics

Nuclear Theory

Relativistic Fluid Dynamics In and Out of Equilibrium -- Ten Years of Progress in Theory and Numerical Simulations of Nuclear Collisions

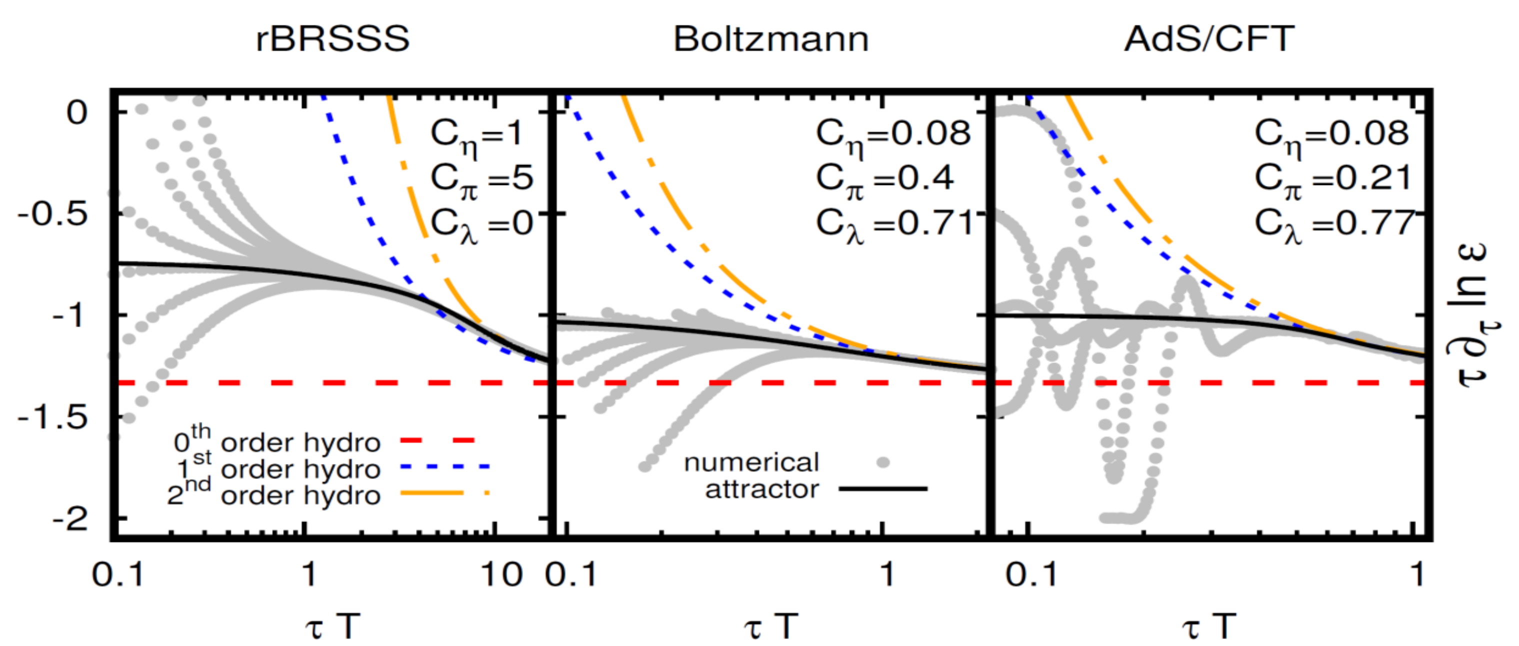
Paul Romatschke, Ulrike Romatschke

(Submitted on 15 Dec 2017 (v1), last revised 2 Mar 2018 (this version, v2))

Ten years ago, relativistic viscous fluid dynamics was formulated from first principles in an effective field theory framework, based entirely on the knowledge of symmetries and long-lived degrees of freedom. In the same year, numerical simulations for the matter created in relativistic heavy-ion collision experiments became first available, providing constraints on the shear viscosity in QCD. The field has come a long way since then. We present the current status of the theory of non-equilibrium fluid dynamics in 2017, including the divergence of the fluid dynamic gradient expansion, resurgence, non-equilibrium attractor solutions, the inclusion of thermal fluctuations as well as their relation to microscopic theories. Furthermore, we review the theory basis for numerical fluid dynamics simulations of relativistic nuclear collisions, and comparison of modern simulations to experimental data for nucleus-nucleus, nucleus-proton and proton-proton collisions.

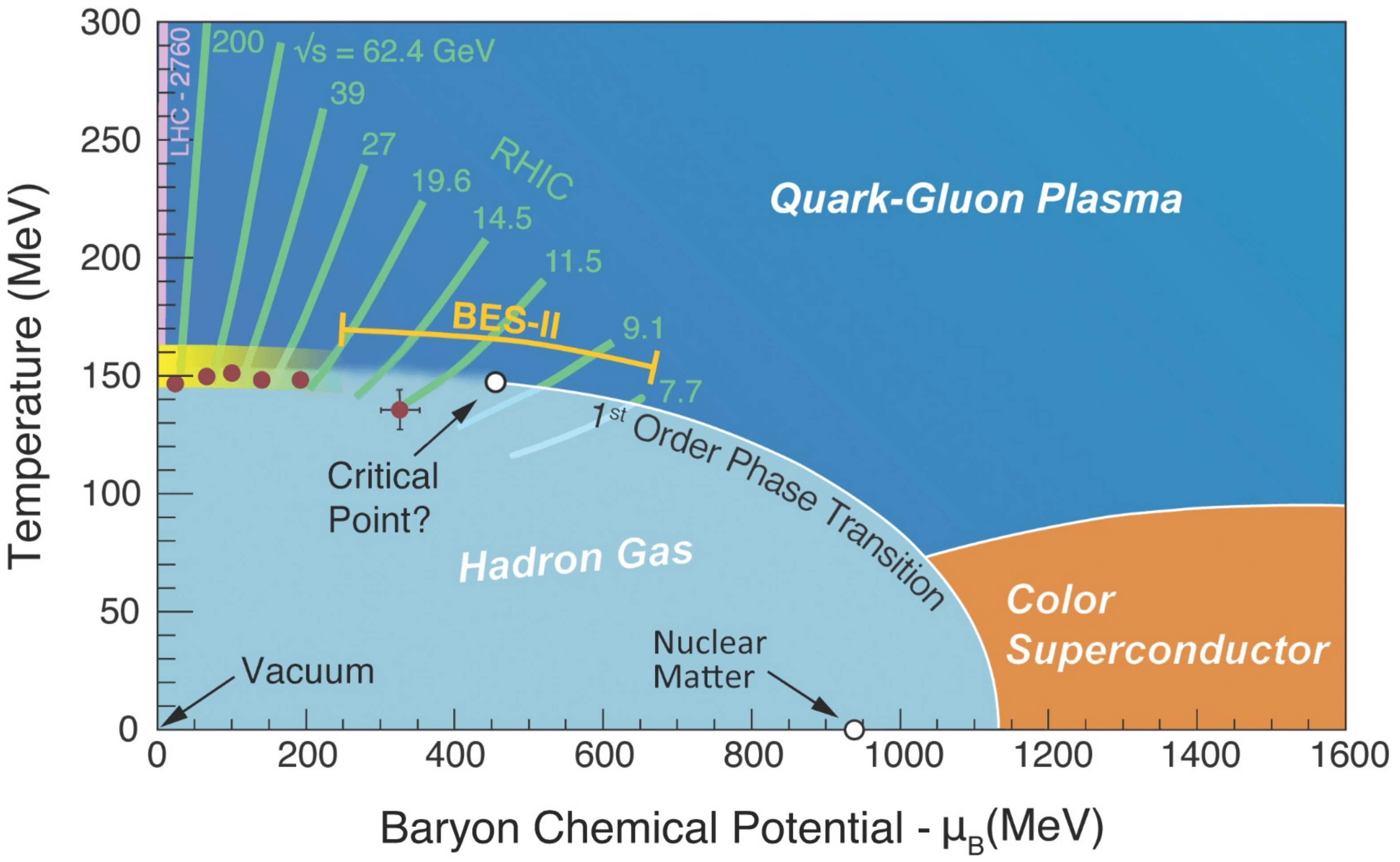
Comments: 196 pages, 35 figures; uninvited review; v2: typos fixed, references added; comments, criticism, citation requests and publisher recommendations still welcome

https://arxiv.org/abs/1712.05815



Not equilibrated …

What does that mean?

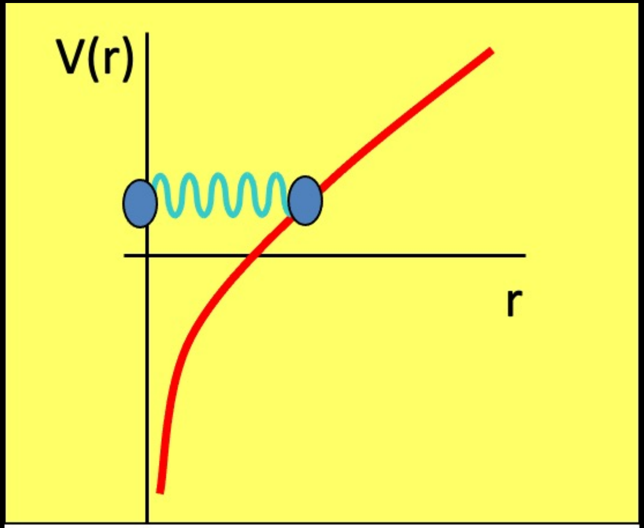


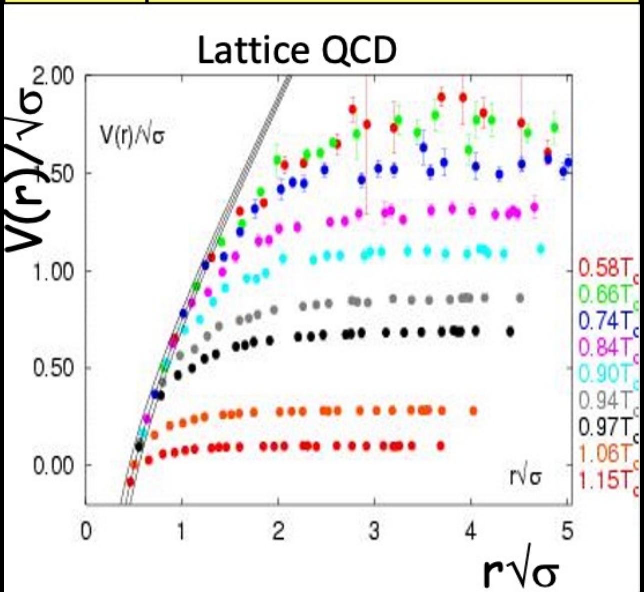
Not really on this QGP phase diagram

Extracted parameters like η/s and susceptibilities might not be the equilibrium values

What else did we want to learn?

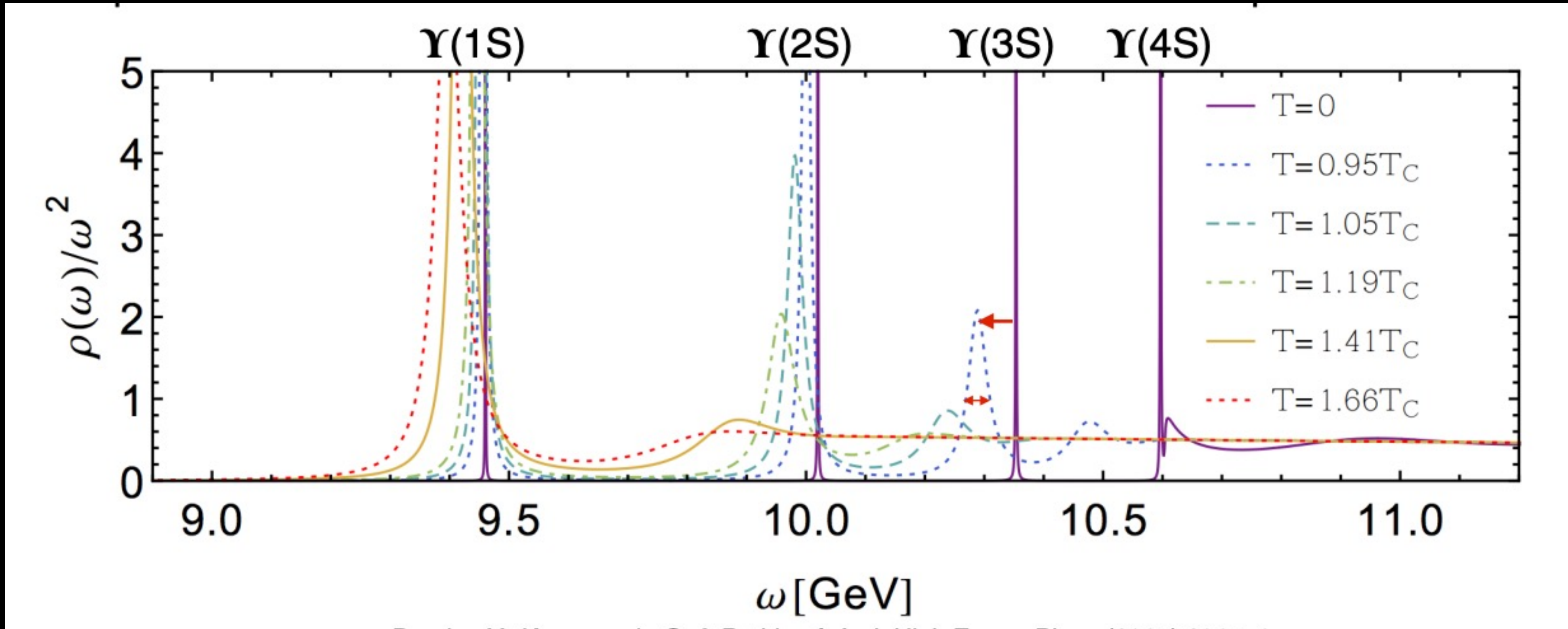
QGP Properties: What about deconfinement?





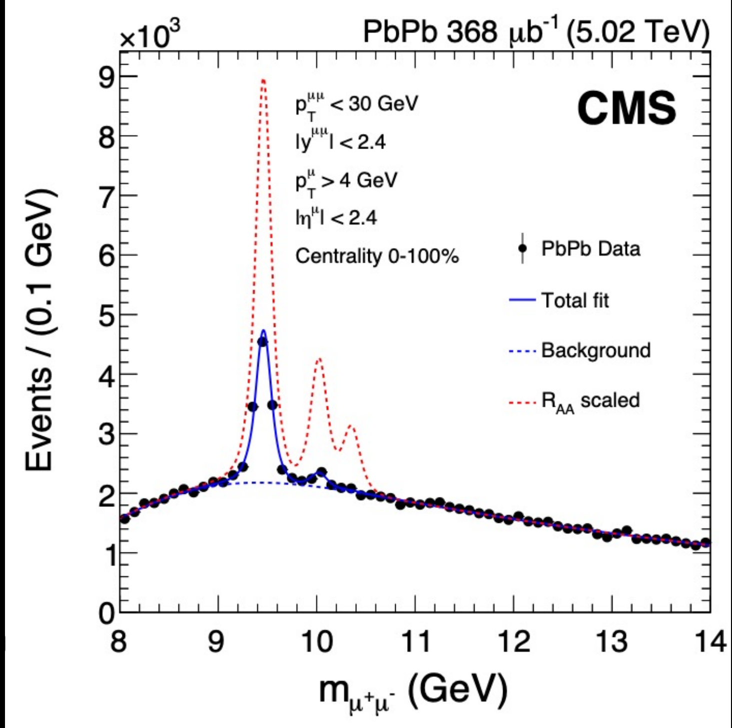
Quarkonia probe a specific length scale of the medium.

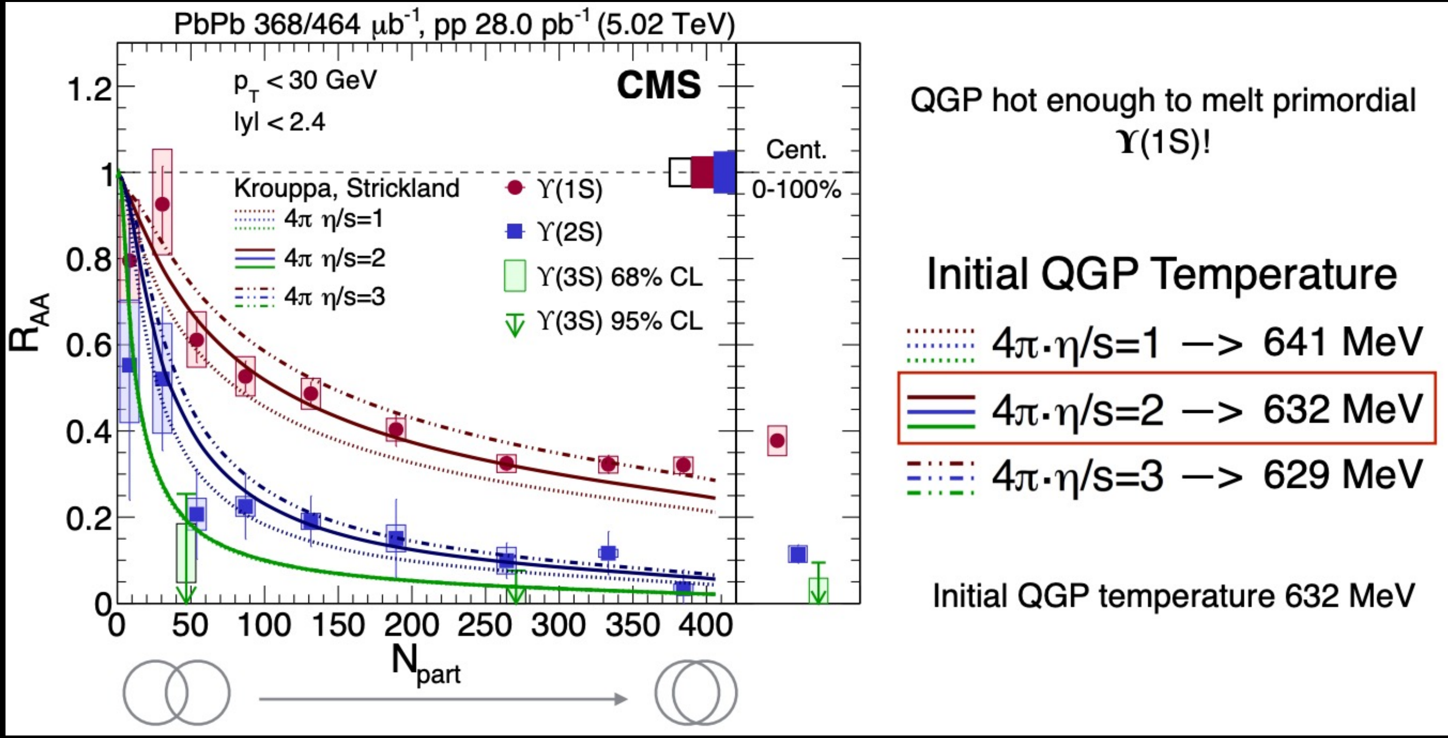
The Debye screening length is a fundamental parameter for plasmas



Burnier, Y., Kaczmarek, O. & Rothkopf, A. J. High Energ. Phys. (2015) 2015: 1.

Is Upsilon suppression a definitive observation of deconfinement?





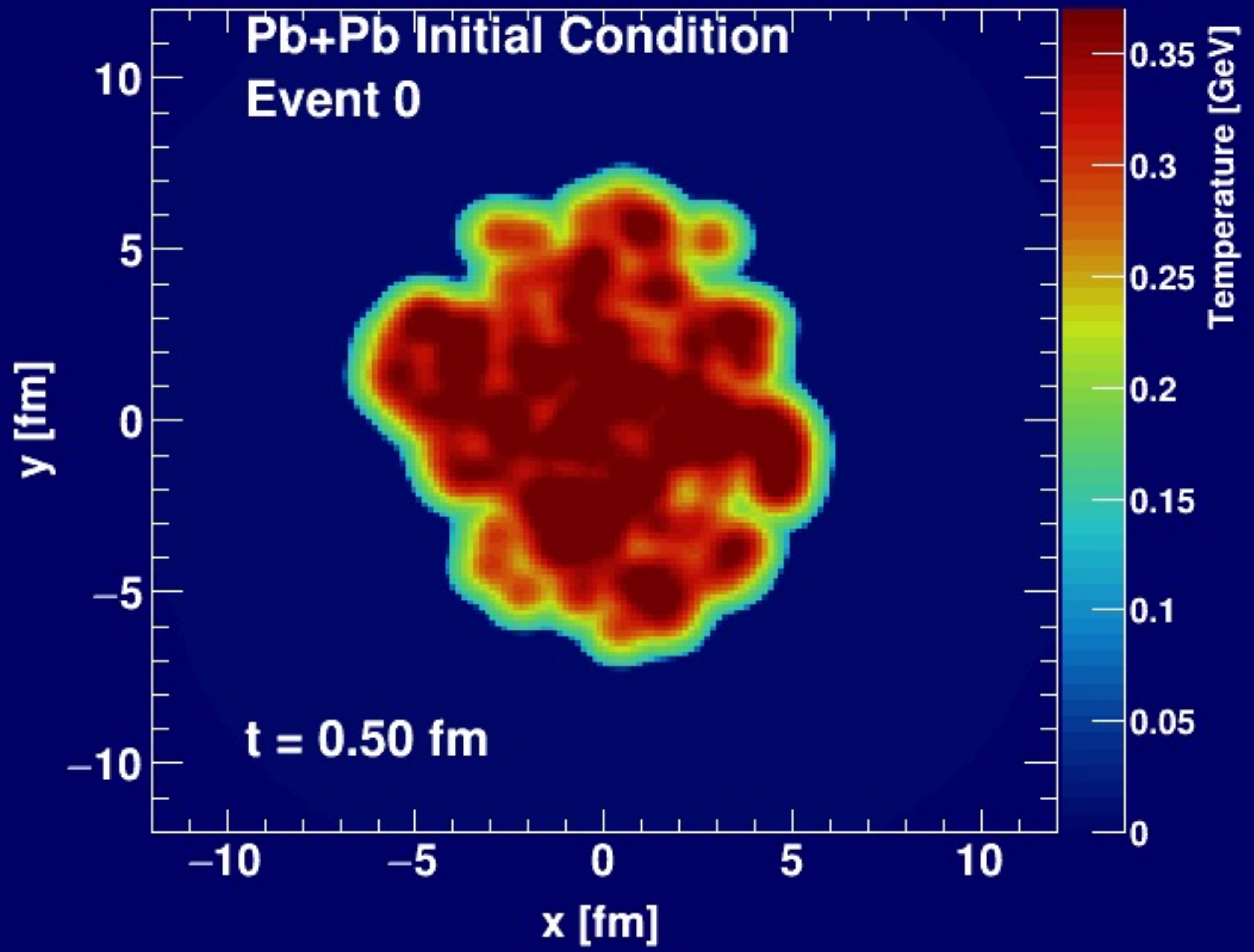
"Because the more excited states melt at lower temperatures, the sequential suppression is an excellent indicator of the temperature of the nuclear medium produced in PbPb collisions."

I am less interested in the temperature.

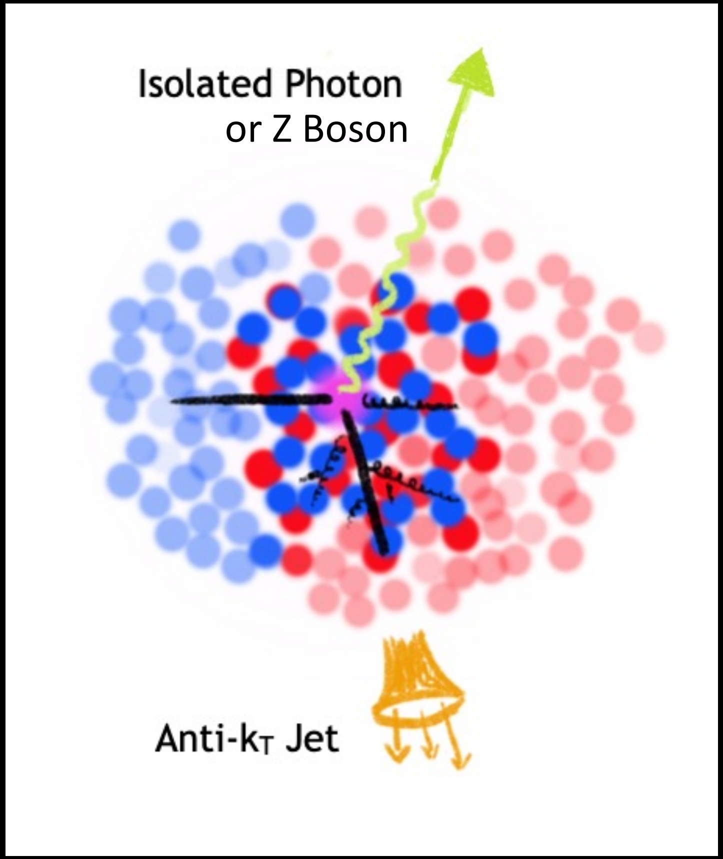
Indirect assessment: $T > 2.5\ T_c$ and thus must be QGP

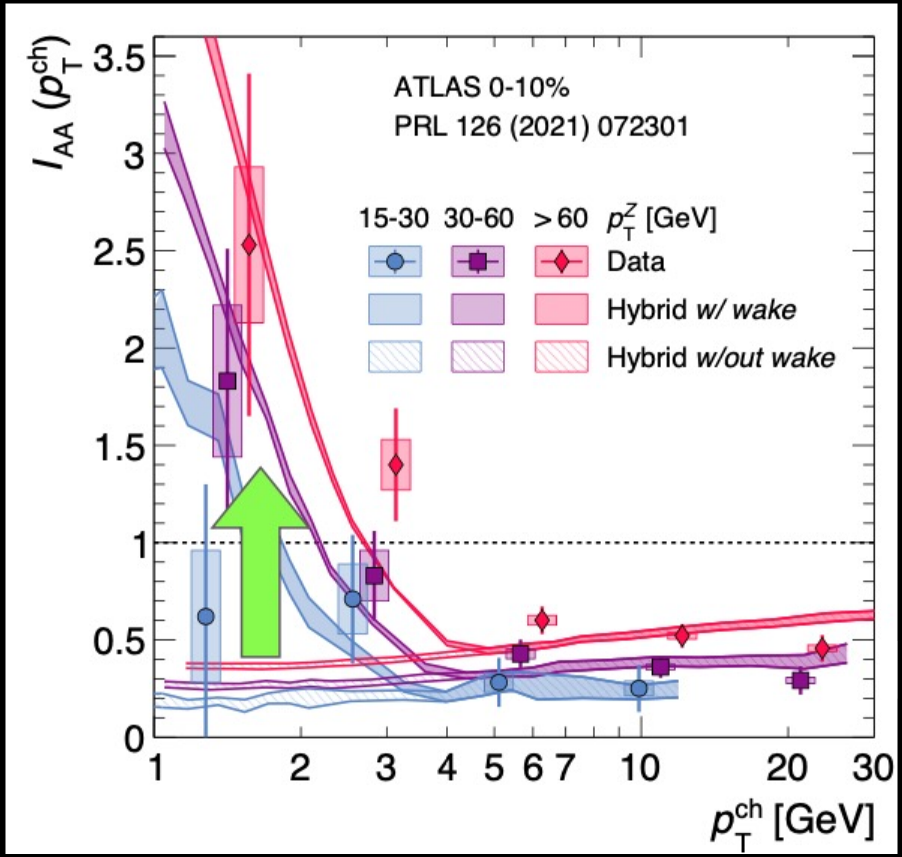
Direct assessment: Melting tells us something fundamental about color screening in QGP

Jet Quenching Signature of QGP

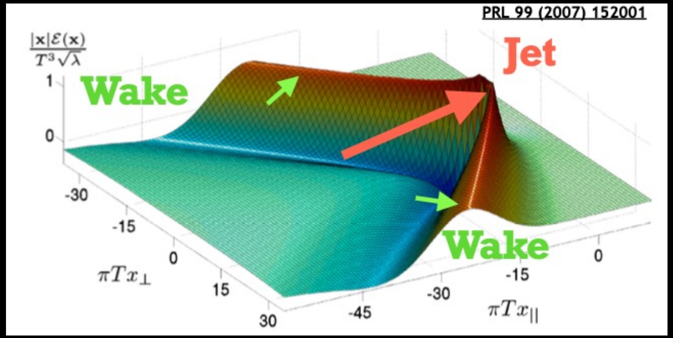


Scales and quasiparticles probed by jets



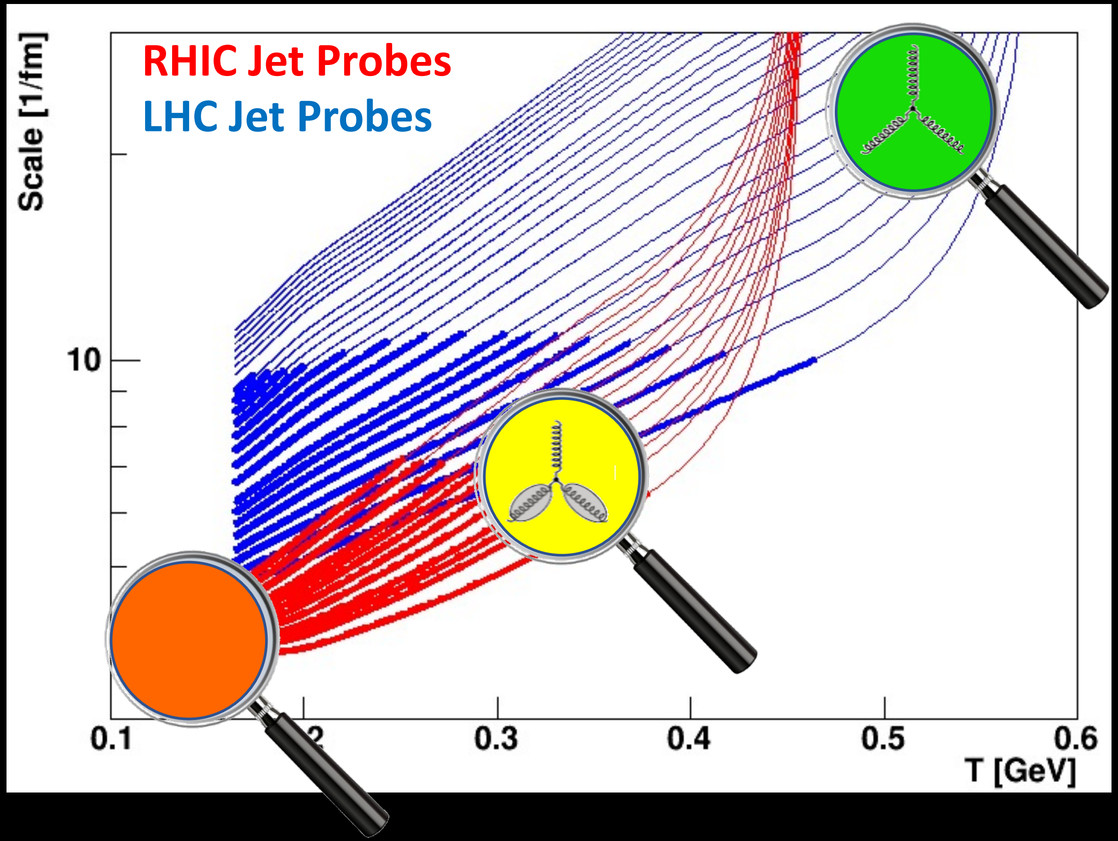


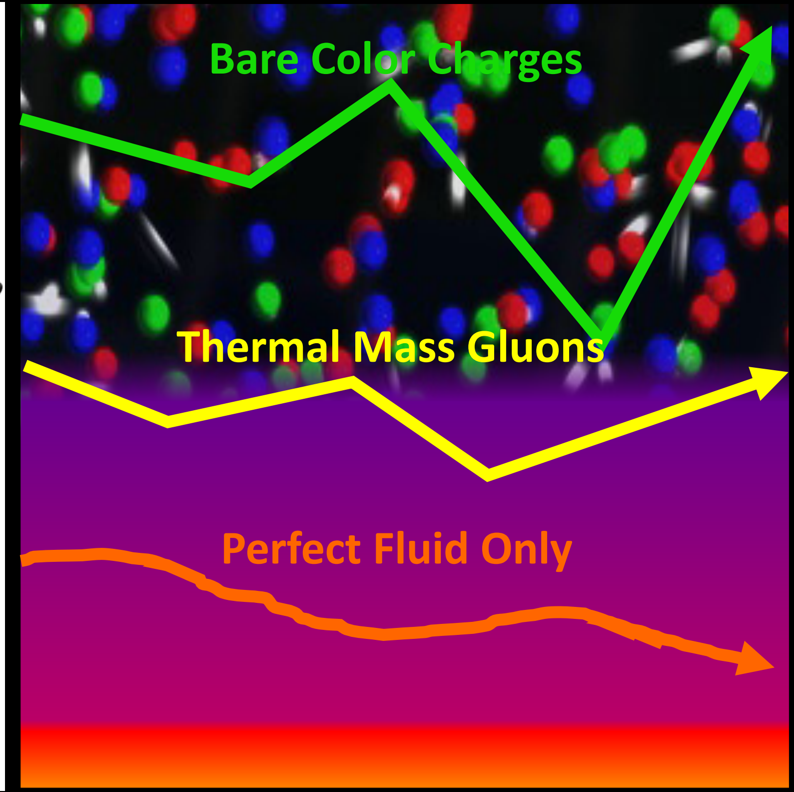
Jet yield suppressed at high p_T (quenching) and enhanced at low p_T (medium response)



Does not necessarily mean color charges are deconfined and rather the coupling strength as a function of scale sPHENIX will measure jets and heavy quark probes with precision complementing LHC measurements

Initial hard scatterings act as a microscope on the QGP with varying resolution scale





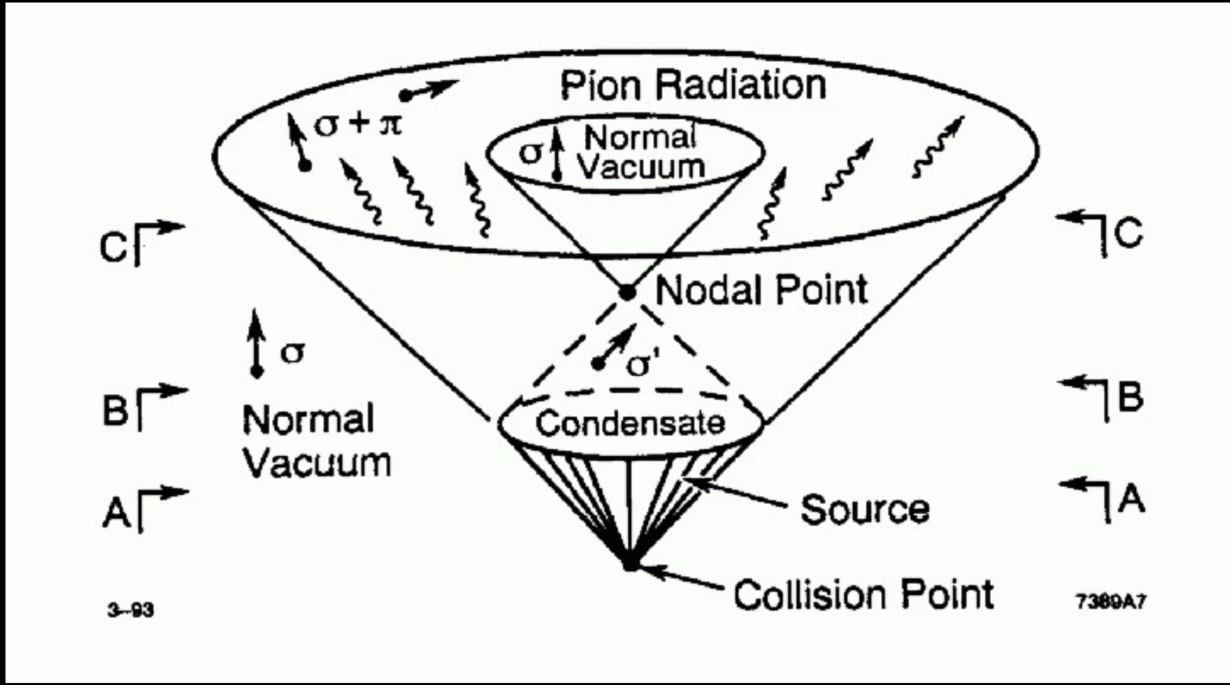
sPHENIX being assembled

sPHENIX first data taking in 2023!

What else did we want to learn?

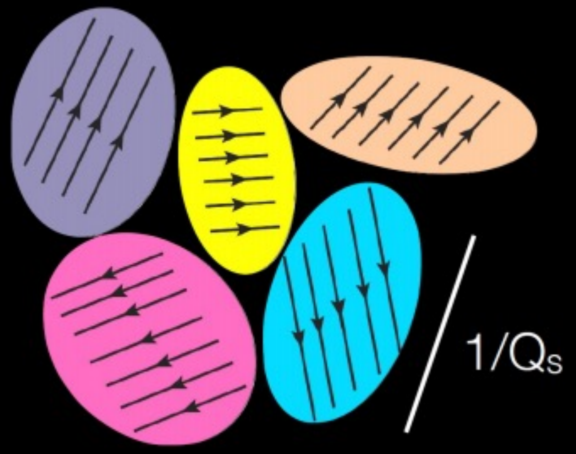
Domains within Droplets

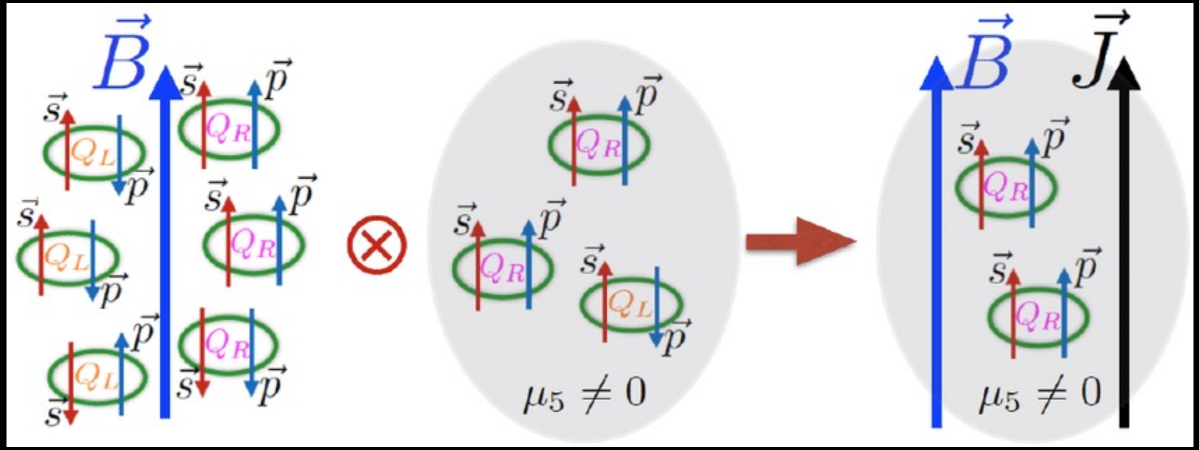
Bjorken speculated that in the
"interiors of large fireballs produced in very high-energy pp collisions; vacuum states of the strong interactions are produced with anomalous chiral order parameters."

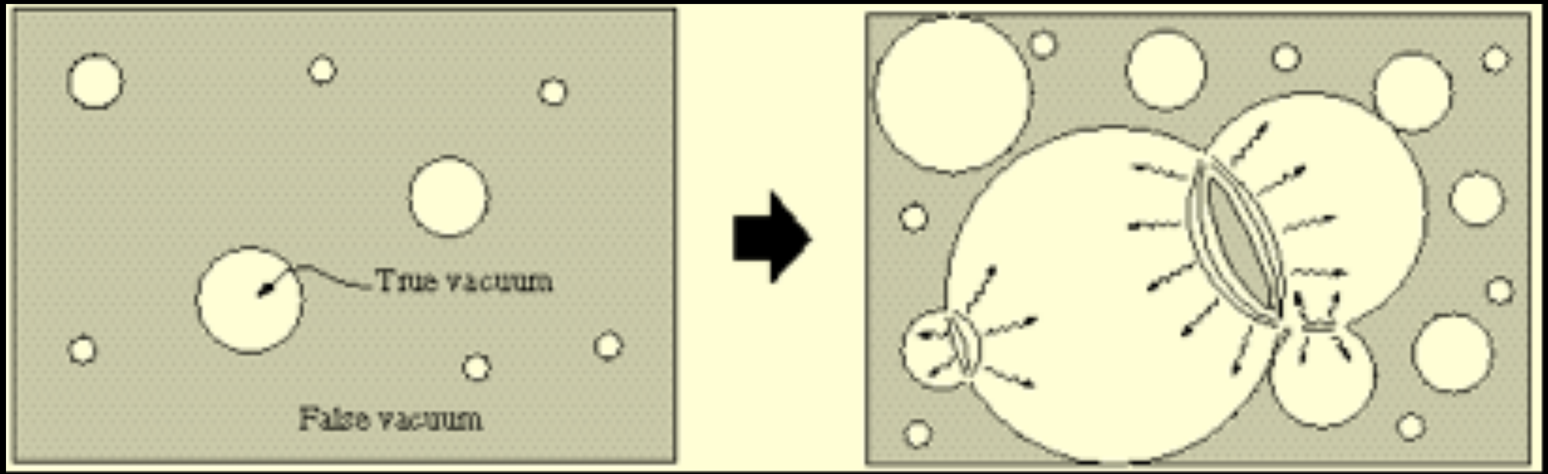


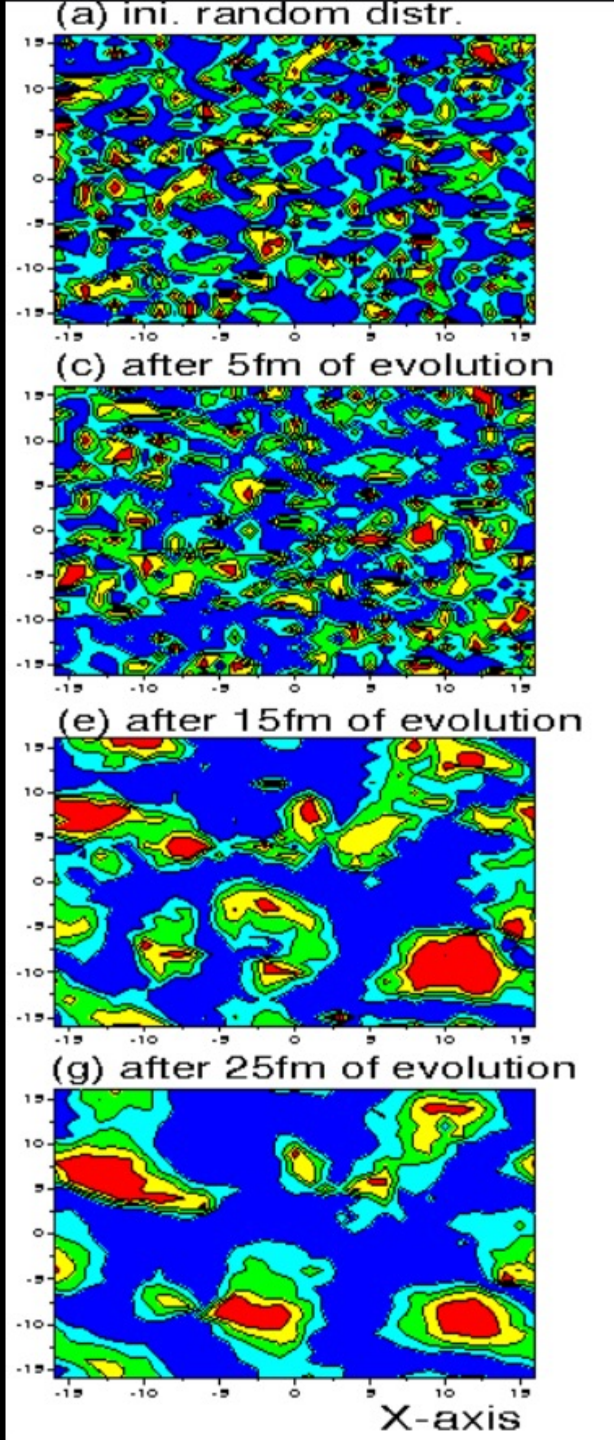
"Disoriented Chiral Condensate" Domains

Other types of "domains"









Color Domains - a post-modern view of CGC

Saturation physics sets a scale Q_s corresponding to gluon occupation number exceeding unity.

Beautiful weak-coupled theory with phenomenology that has been used to explain *literally* everything at RHIC
(read the 20+ year literature).

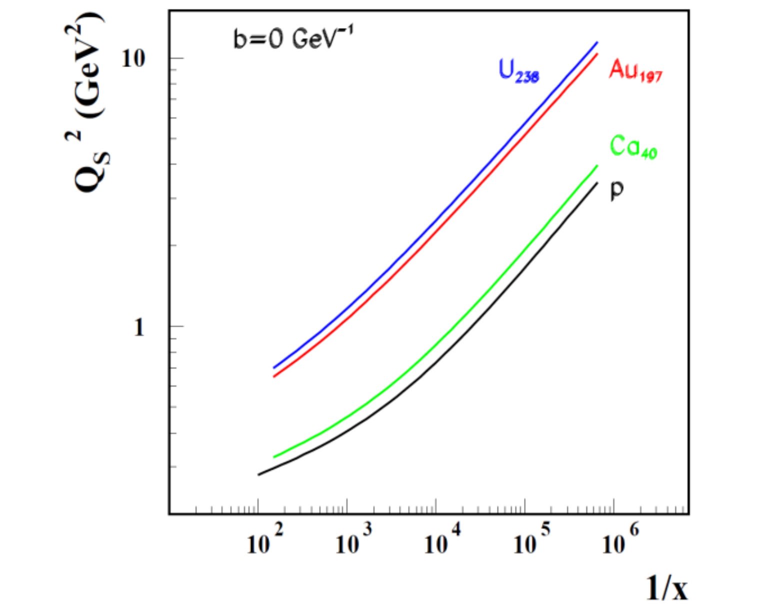
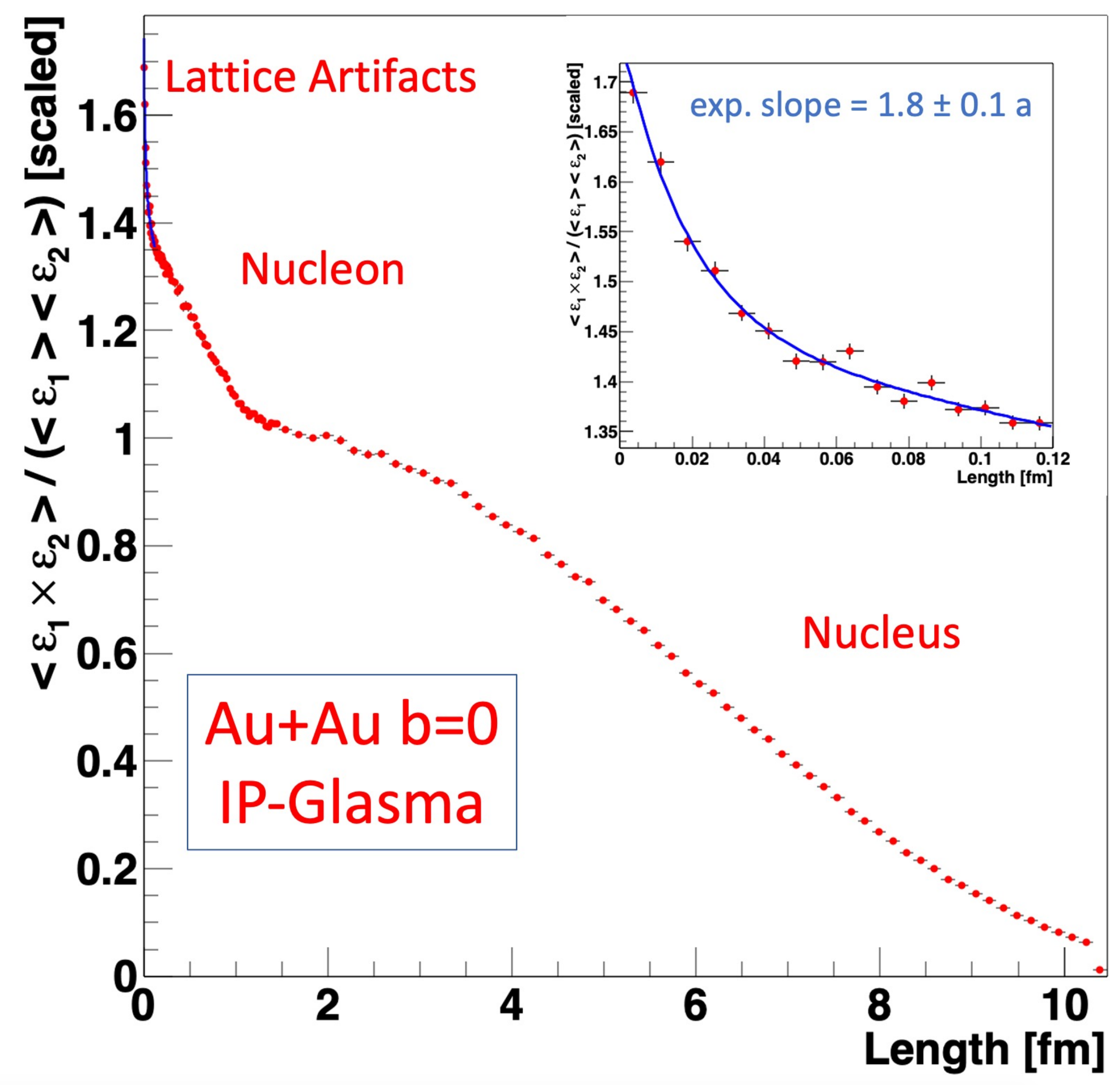


FIG. 25: The quark saturation scale $(Q_s^2)_q$ at $b = 0$ as a function of x for various nuclei . The gluon saturation scale is $(Q_s^2)_g = \frac{N_c}{C_F}(Q_s^2)_q \approx 2.25\,(Q_s^2)_q$.

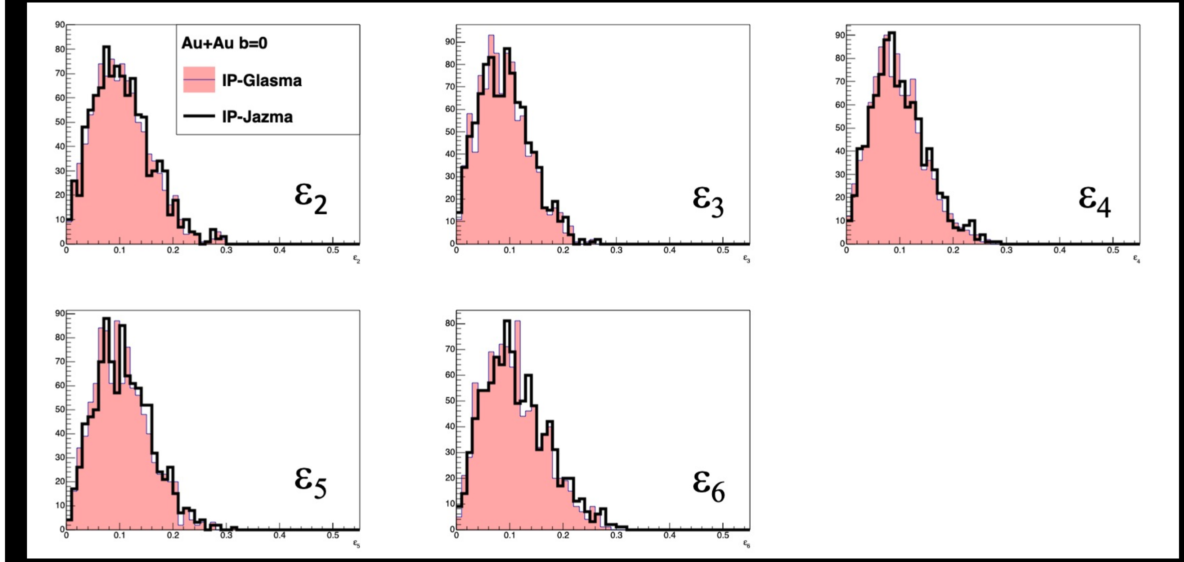
Now it is clear there is no evidence that saturation regime extends to physics of RHIC or LHC.

What are the EIC detector design implications?

IP-Glasma "color domains"



Apples to Apples Comparison at τ=0.000015 fm/c

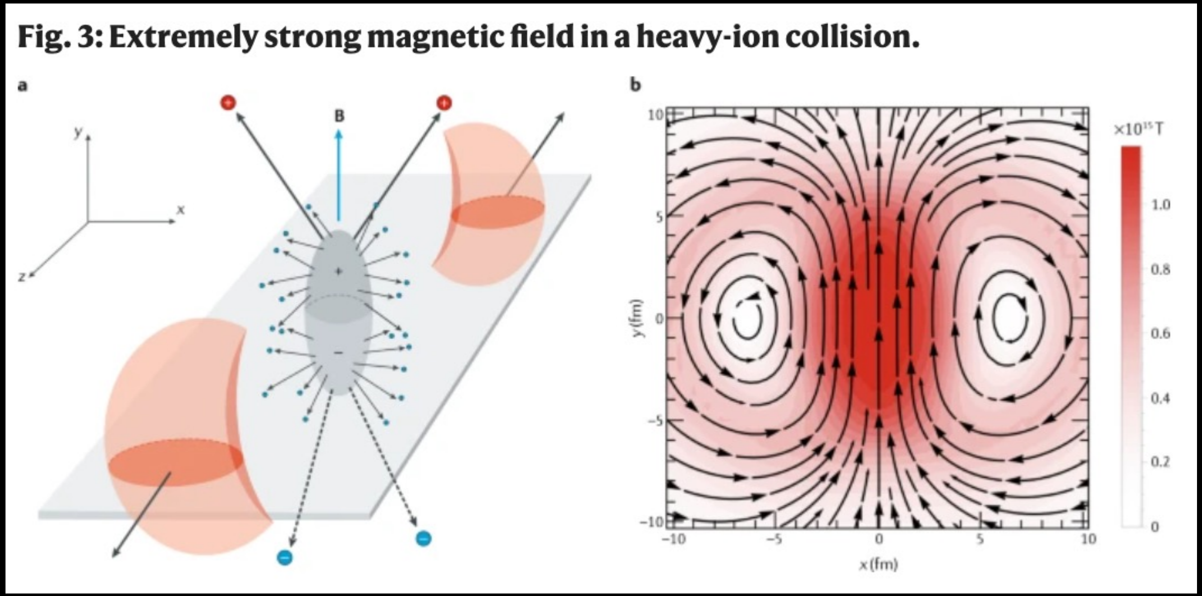


None of the features tested by IP-Glasma + hydrodynamics give any evidence of saturation physics or color domains.

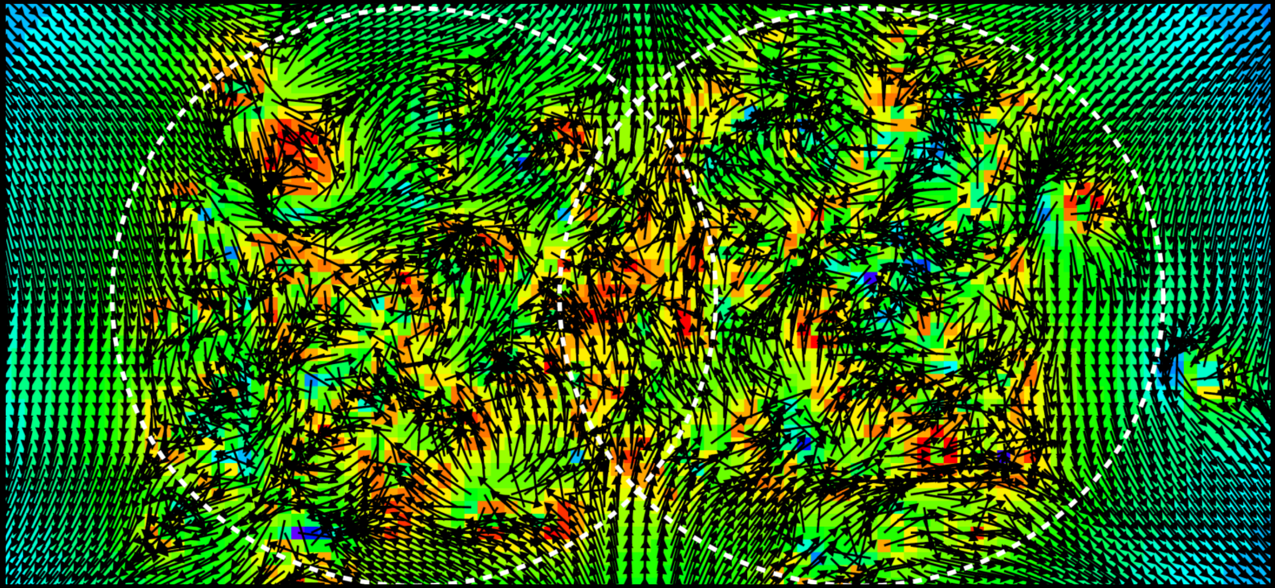
Only feature not seen in IP-Jazma is the lattice artifact component in the correlator.

Other types of "domains"

https://www.nature.com/articles/s42254-020-00254-6



https://journals.aps.org/prc/abstract/10.1103/PhysRevC.96.024901



Simplified pictures, even as schematic, often mislead the field in its critical thinking.

Much harder to imagine observing a CME effect here.

Deep dive…

1) Is there any experimental evidence for CGC effects at RHIC (or LHC)?

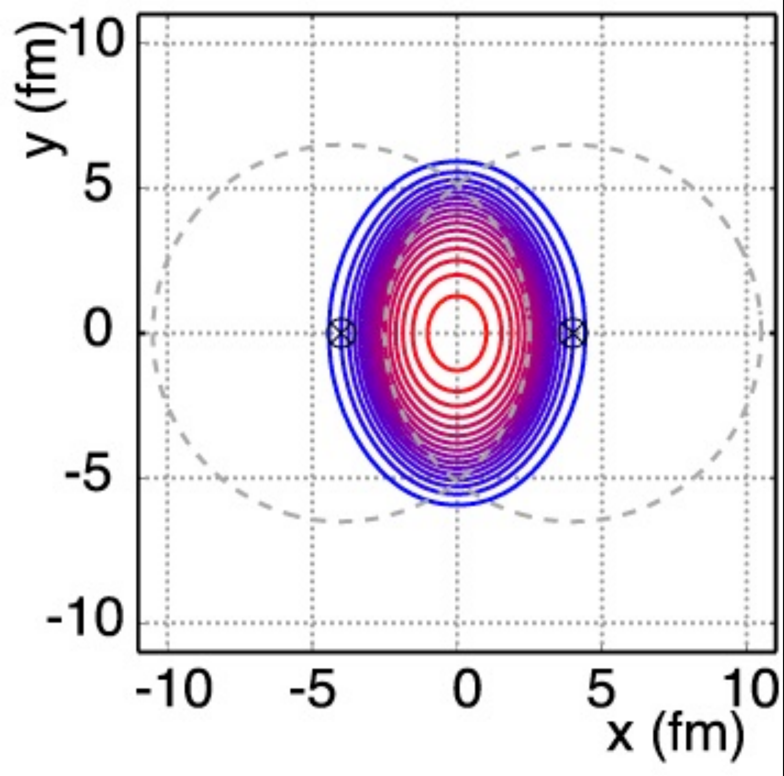
2) Is there any experimental evidence for weak-coupled initial stage between strongly coupled incoming nuclei and strongly coupled QGP?

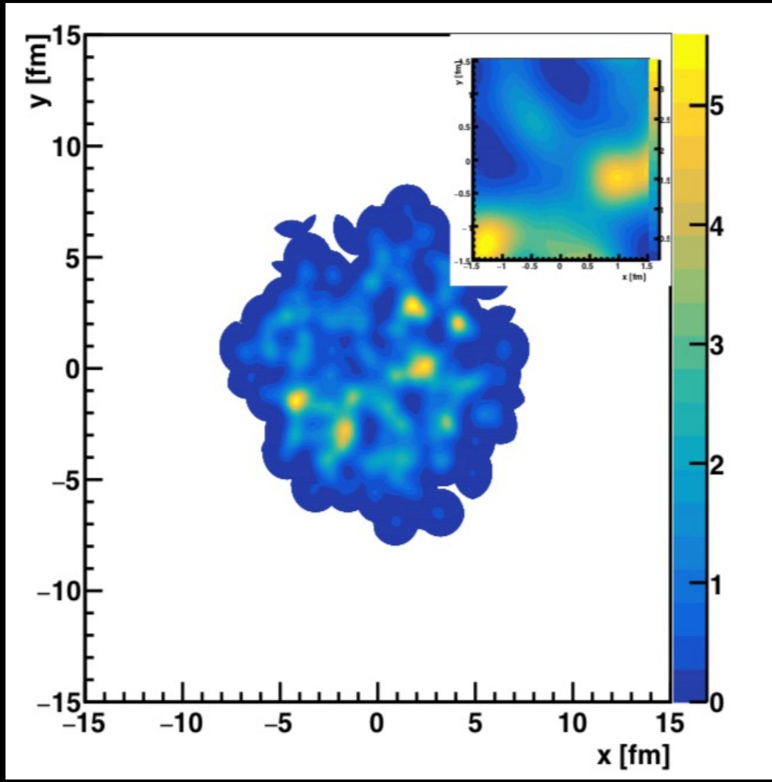
3) Is there any experimental (or theoretical) evidence for equilibration?

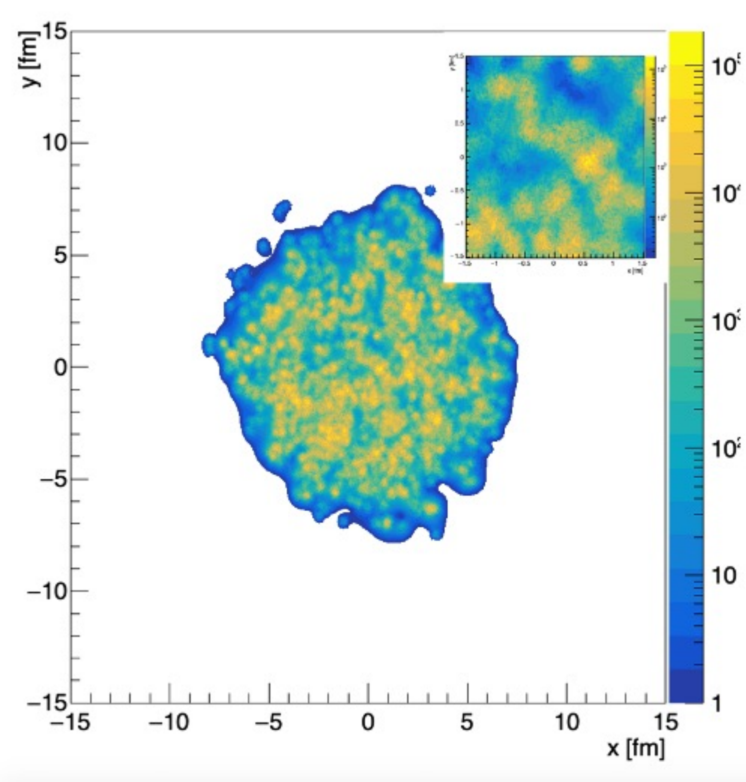
The answers have important implications for what we have (and also can) learn about QCD from heavy ion collisions.

So, what have we learned?

- ✓ Nuclei are not smooth.
- ✓ Nucleon fluctuations are important.
- ✓ Sub-nucleonic geometry is important.
- ✗ Three valance quarks are the important DOF?
- ✗ Color Glass Condensate Domains are important?
- ✗ Chiral Magnetic Domains are important?







Are we unlearning things: "hot spots"

State-of-the-Art
JETSCAPE Bayesian analysis

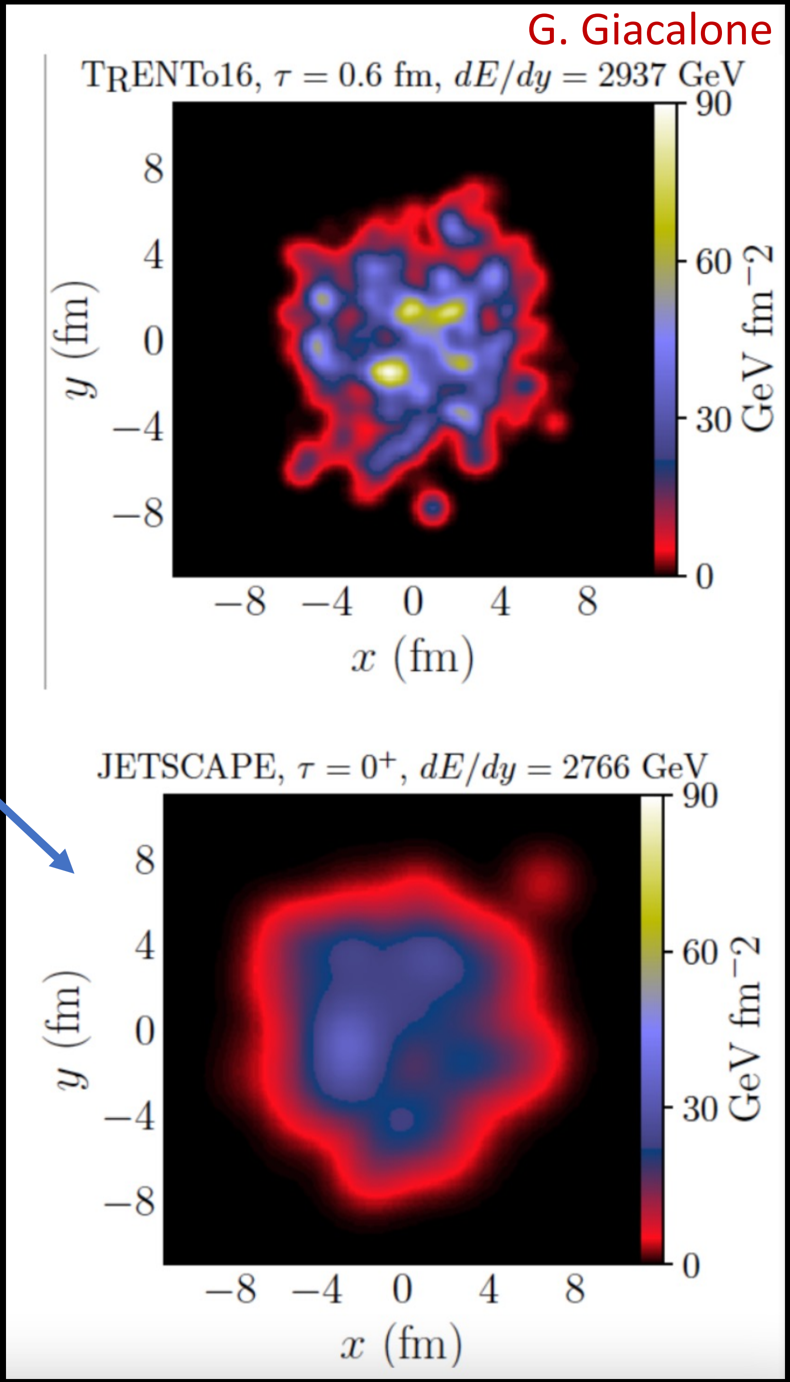
https://journals.aps.org/prc/pdf/10.1103/PhysRevC.103.05490

New parameters:

w = 1.12 fm - really big proton

d_{min} = 1.44 fm - nice and even spacing

- cannot be hard core repulsion



Important progress with Bayesian analyses, but losing sight of the goals of the field.

Treating too many parameters like nuisance parameters

Physics goals of RHIC

- Achieve highest energy densities in extended matter for relatively long times

- Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout

- Search for collective effects beyond individual pp scattering, or pA scattering

- Study role of new degrees of freedom

- Produce and study quark-gluon plasma with large A at E above a few GeV/fm^3

- Extract nuclear equation of state, application to astrophysics

G. Baym, 1/95

What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales (ρ_0=0.16/fm^3, E_0=0.15GeV/fm^3) to orders of magnitude beyond?

- What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.

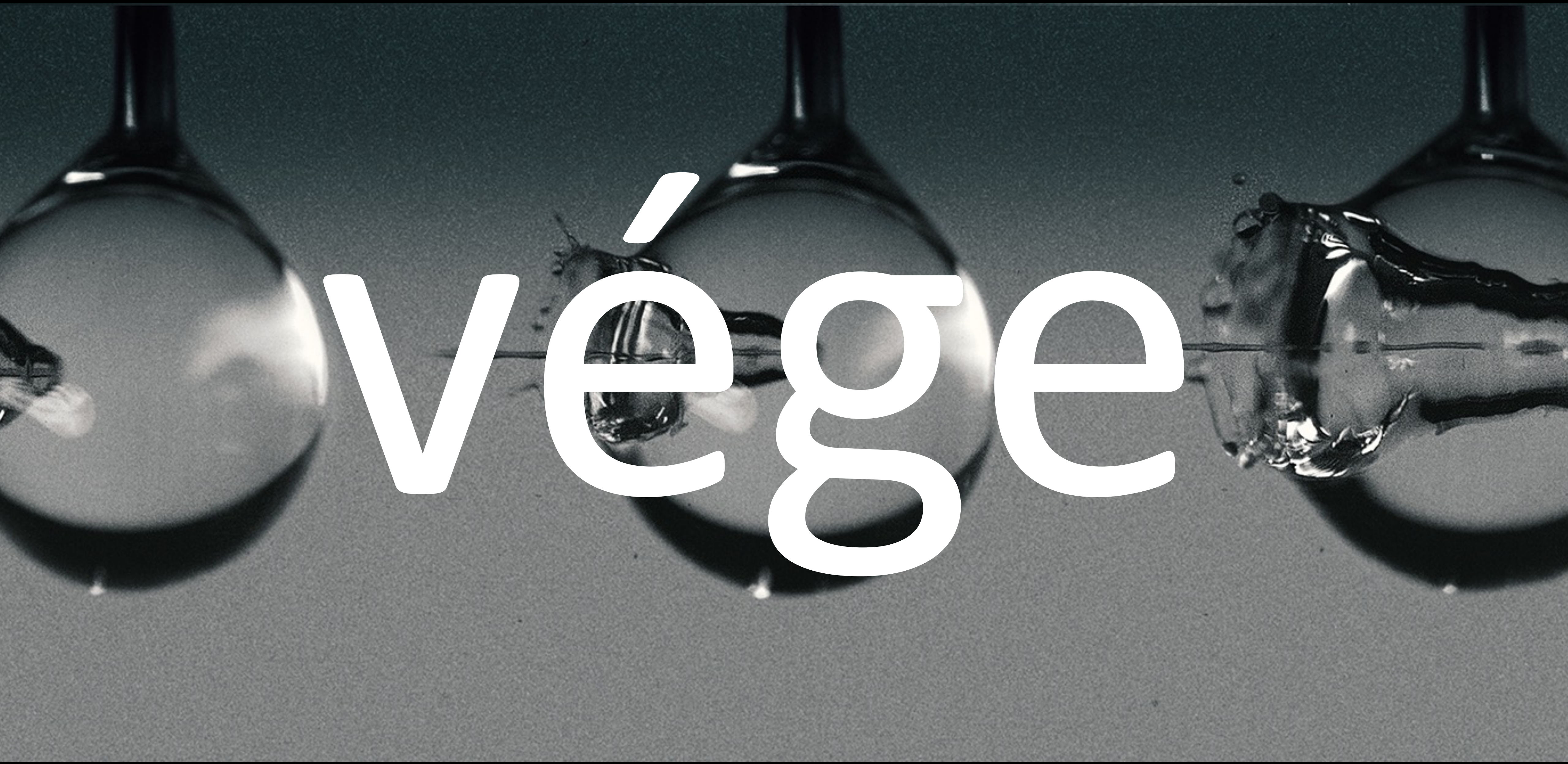
- What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?

- What is the structure of qcd on large distance scales? Phase transitions? Monopoles?

- Surprises!

Terra incognita

G. Baym, 1/95



vége

Jamie Nagle
University of Colorado Boulder

December 09, 2021

Extras

University of Colorado Boulder Group

Key additional contributors
Professor Ron Belmont (UNCG) and
Professor Sanghoon Lim (PNU),
both former postdocs in Boulder

U.S. DEPARTMENT OF ENERGY | Office of Science

University of Colorado Boulder
College of Arts and Sciences

College Scholar Award

P2IO
Physique des 2 Infinis et des Origines

Emilie du Chatelet
grant from P2IO at
CEA / Saclay

6:00 AM → 6:45 AM **Ortvay Colloquium** 7.22 Kari Tanácsterem (7th flo...

6:00 AM **What is the QGP really?** 45m

Speaker: James Lawrence Nagle (University of Colorado Boulder)

35+10