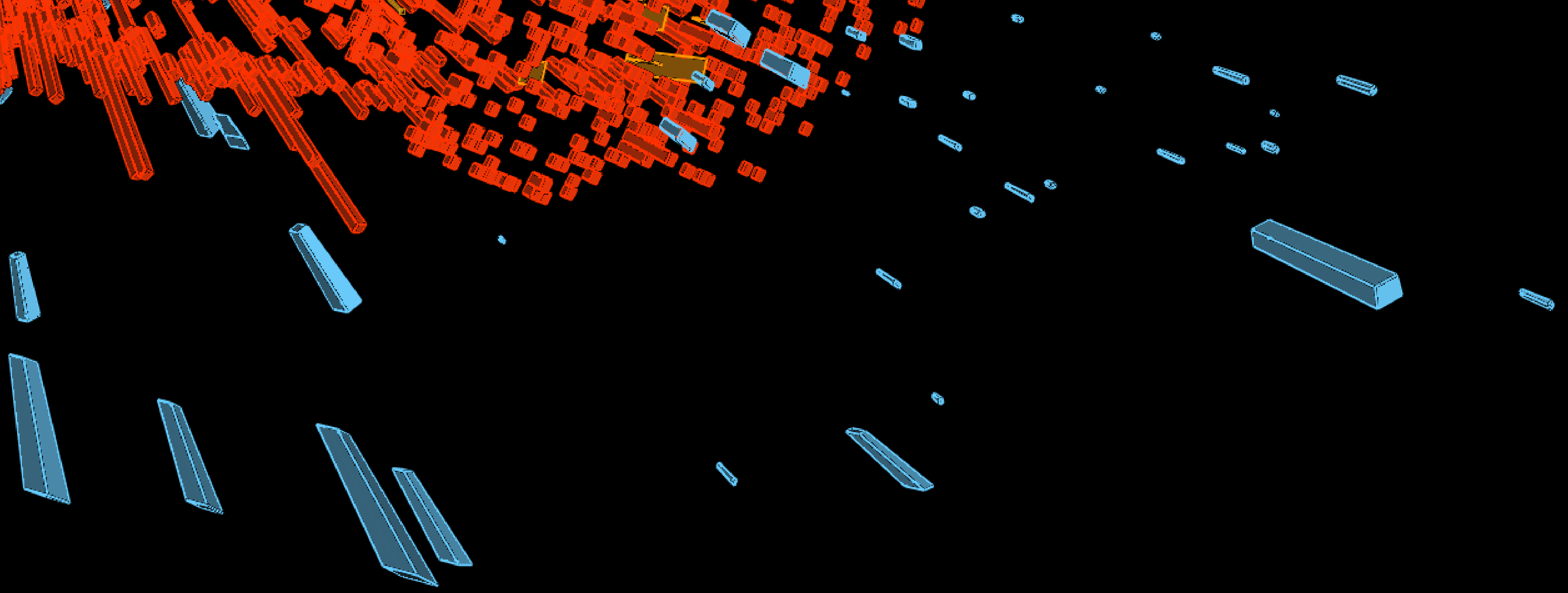


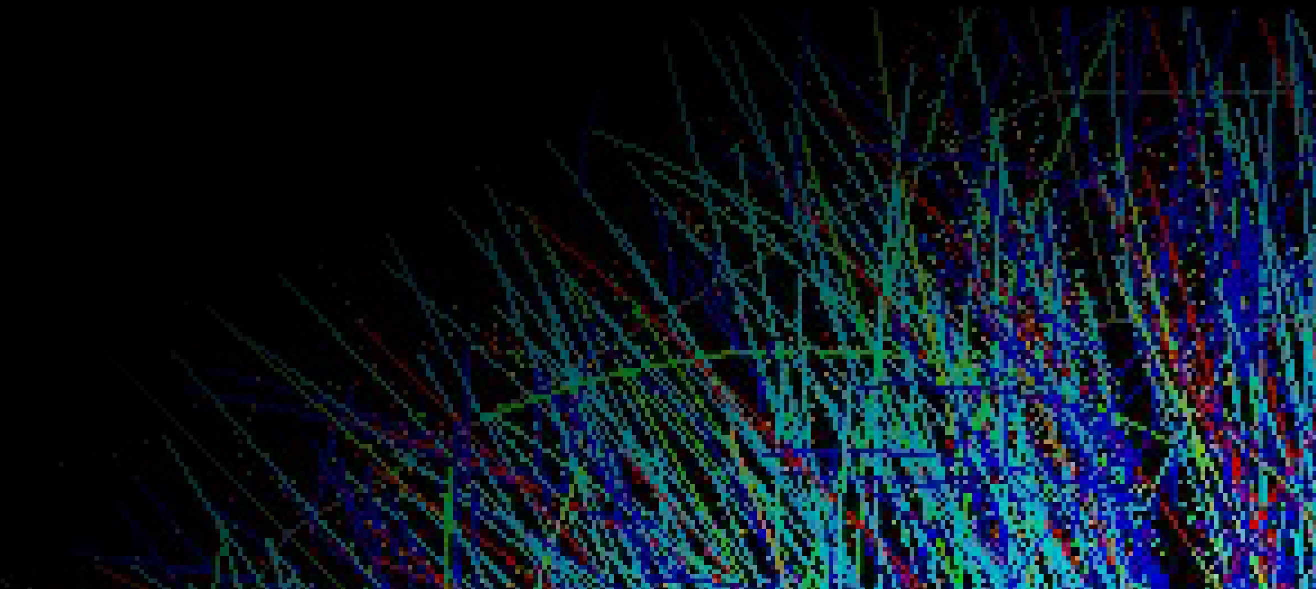
Duke
UNIVERSITY

Precision Extraction of QGP Properties with Quantified Uncertainties

Steffen A. Bass
Jonah E. Bernhard

arXiv:1605.03954

J. Scott Moreland
Jia Liu
Ulrich Heinz
+ many other collaborators

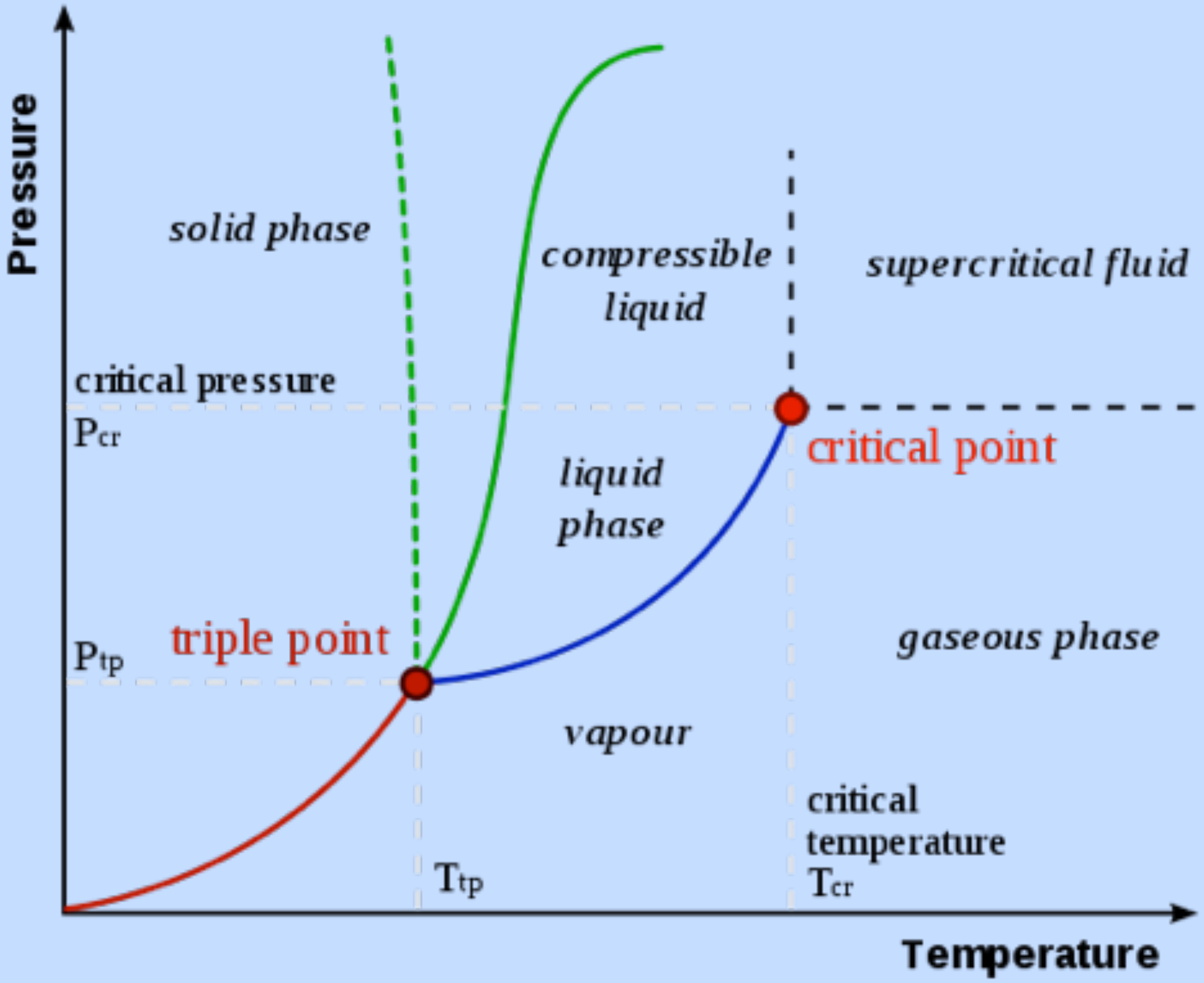


Introduction

Phases of Matter

Ordinary Matter:

- phases determined by (electro-magnetic) interaction
- apply heat & pressure to study phase-diagram



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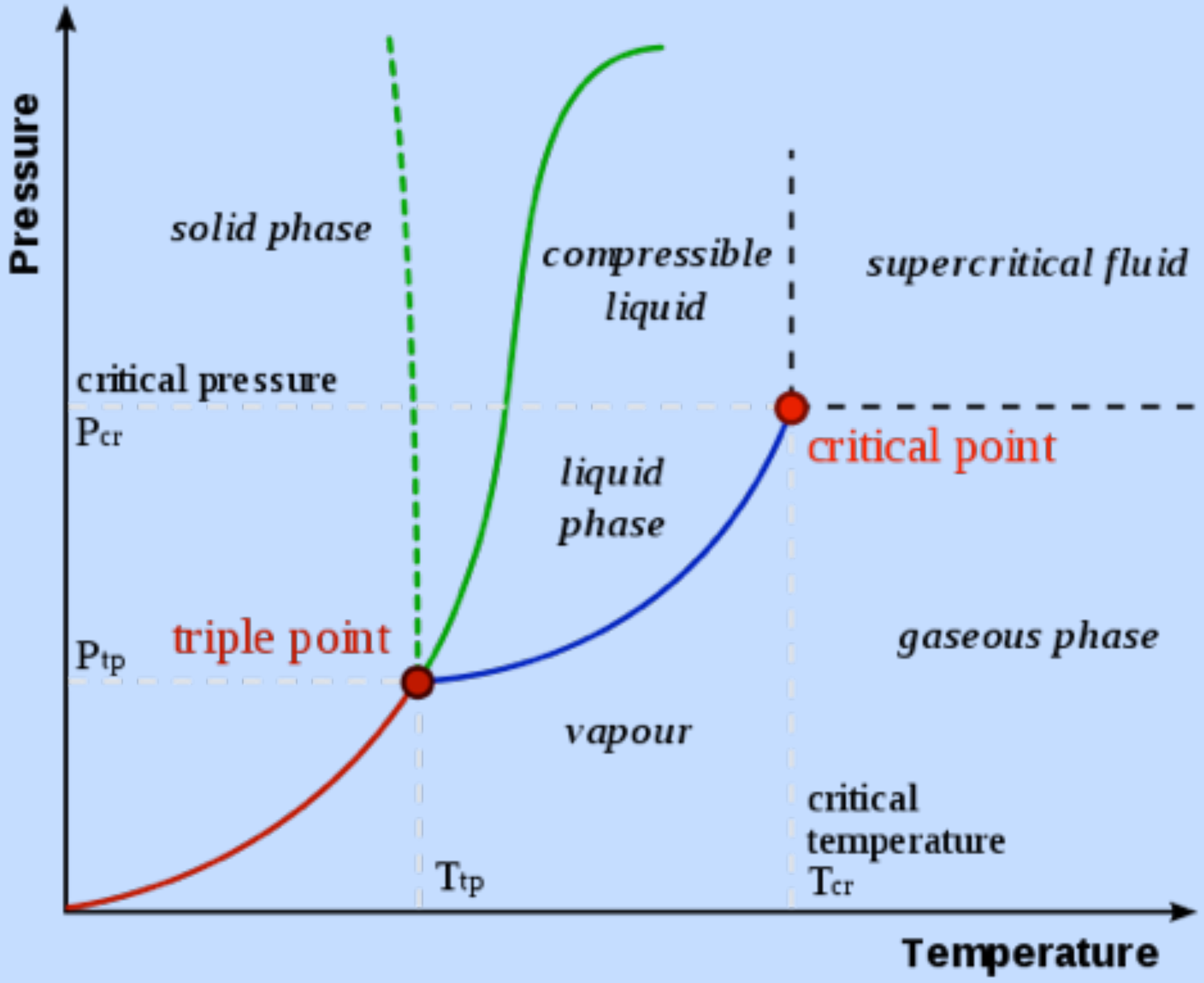
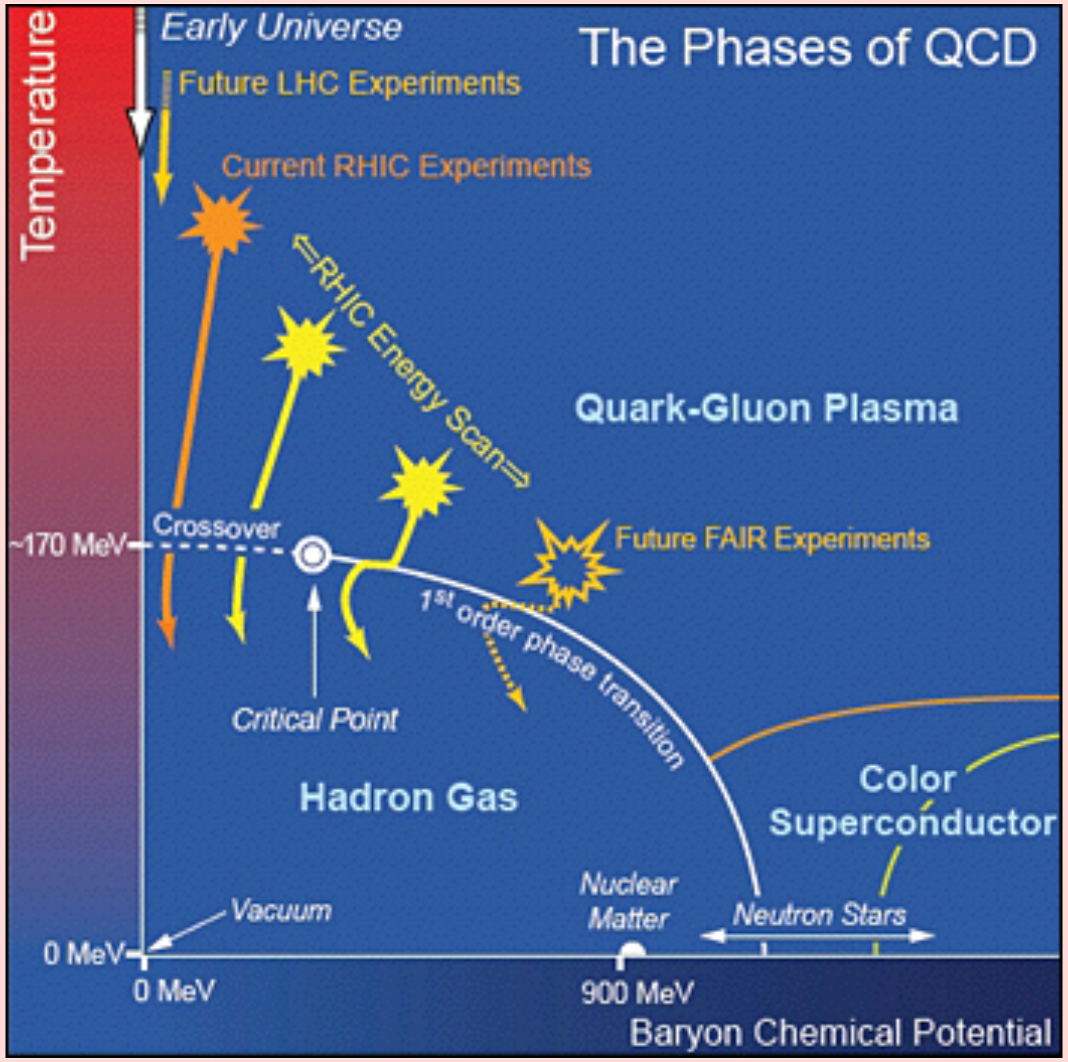


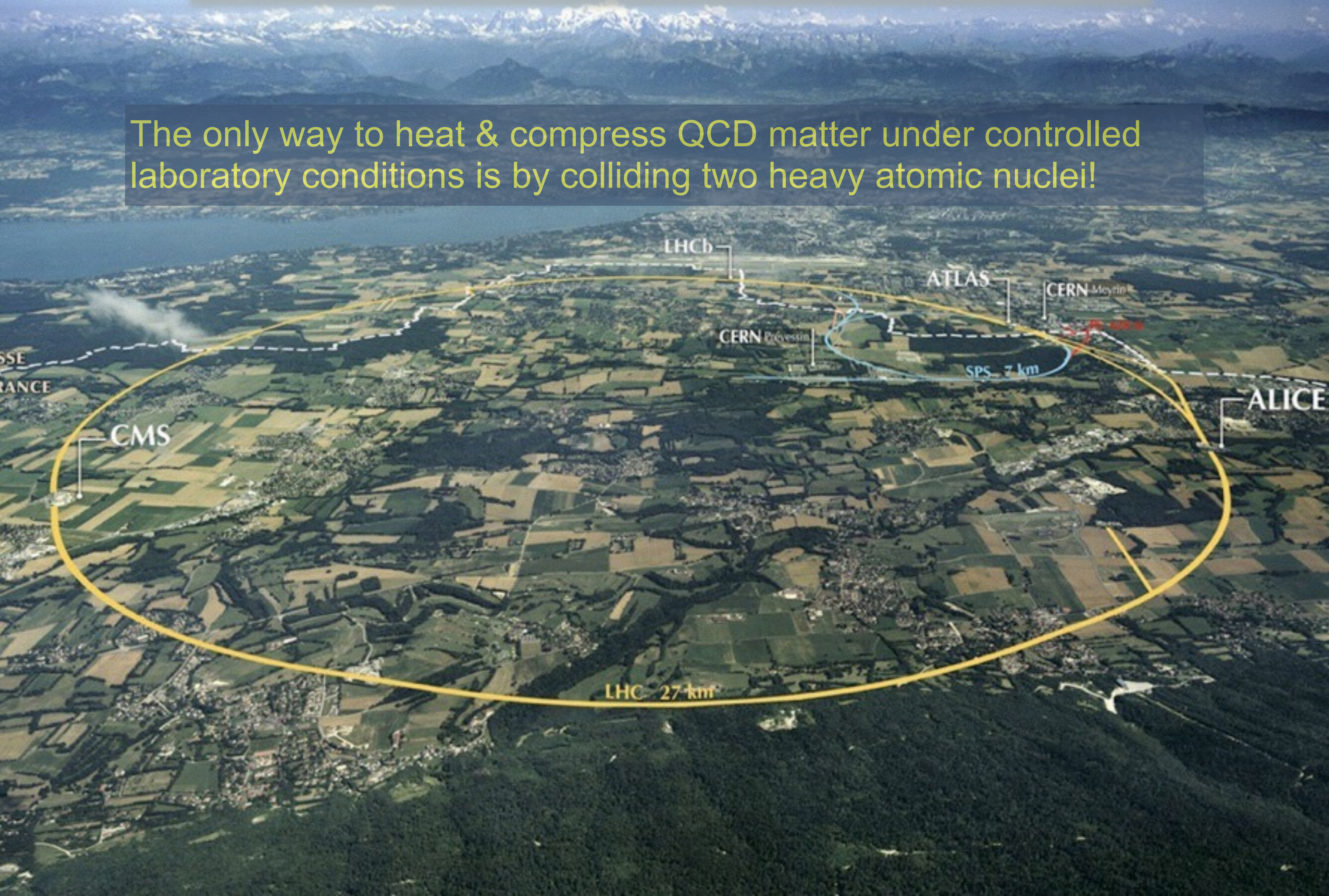
Phases of QCD matter:

- heat & compress QCD matter:
  - collide heavy atomic nuclei
- numerical simulations:
  - solve partition function (Lattice)



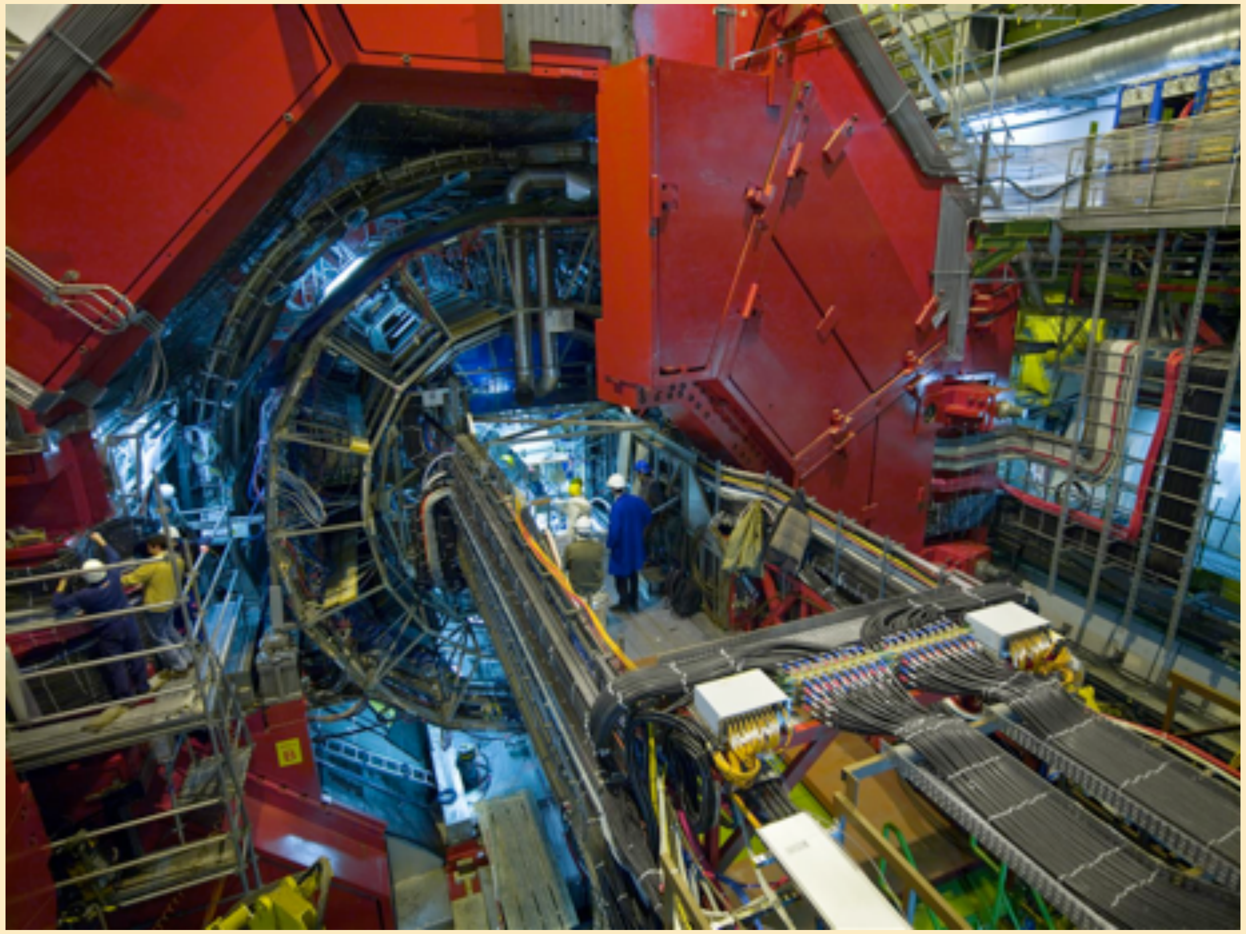
Heating & Compressing QCD Matter

The only way to heat & compress QCD matter under controlled laboratory conditions is by colliding two heavy atomic nuclei!



Heating & Compressing QCD Matter

ALICE experiment @ CERN:



- 1000+ scientists from 105+ institutions
- dimensions: 26m long, 16m high, 16m wide
- weight: 10,000 tons

two more experiments w/ Heavy-Ions:

- CMS, ATLAS

QCD matter under controlled
g two heavy atomic nuclei!

Heating & Compressing QCD Matter

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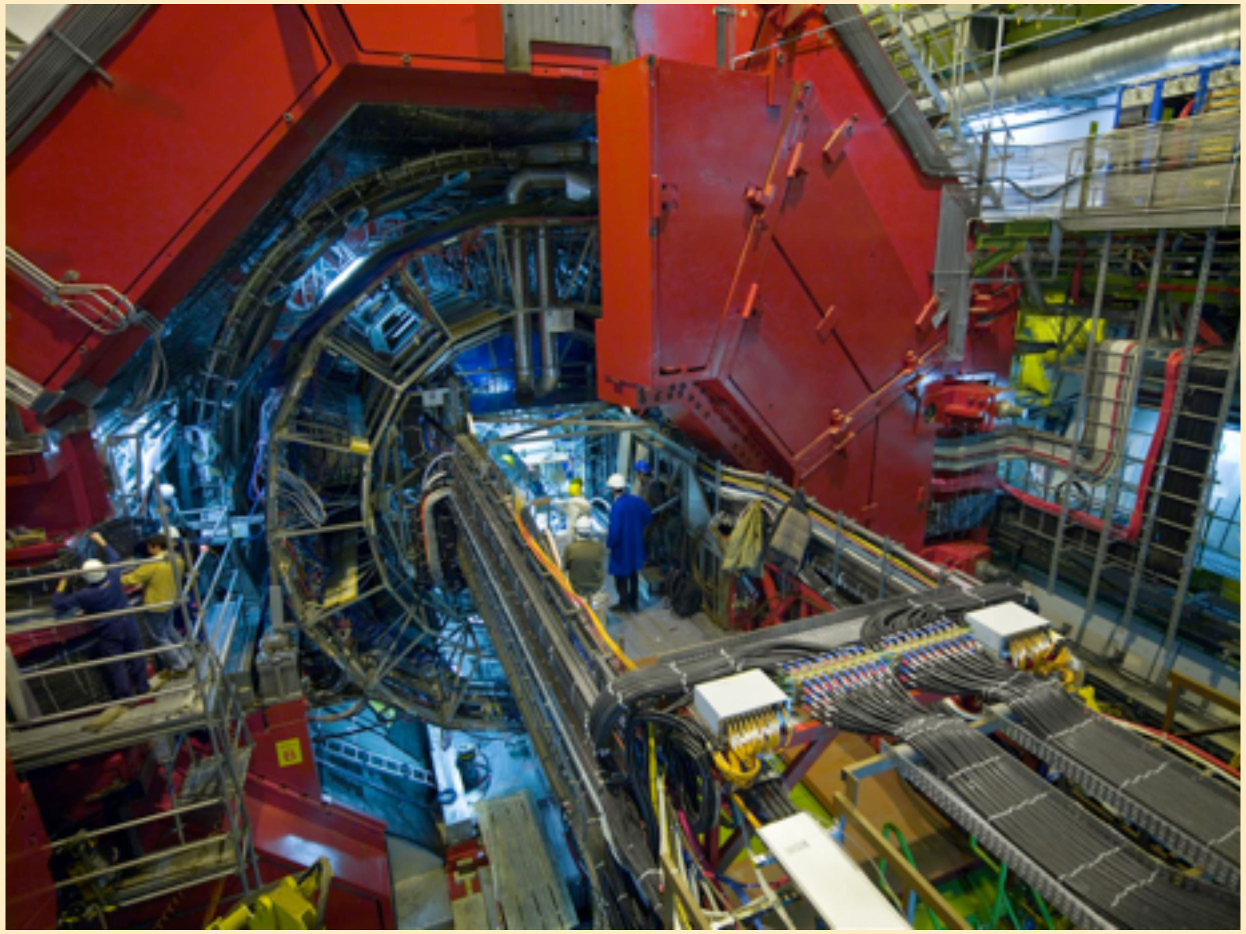

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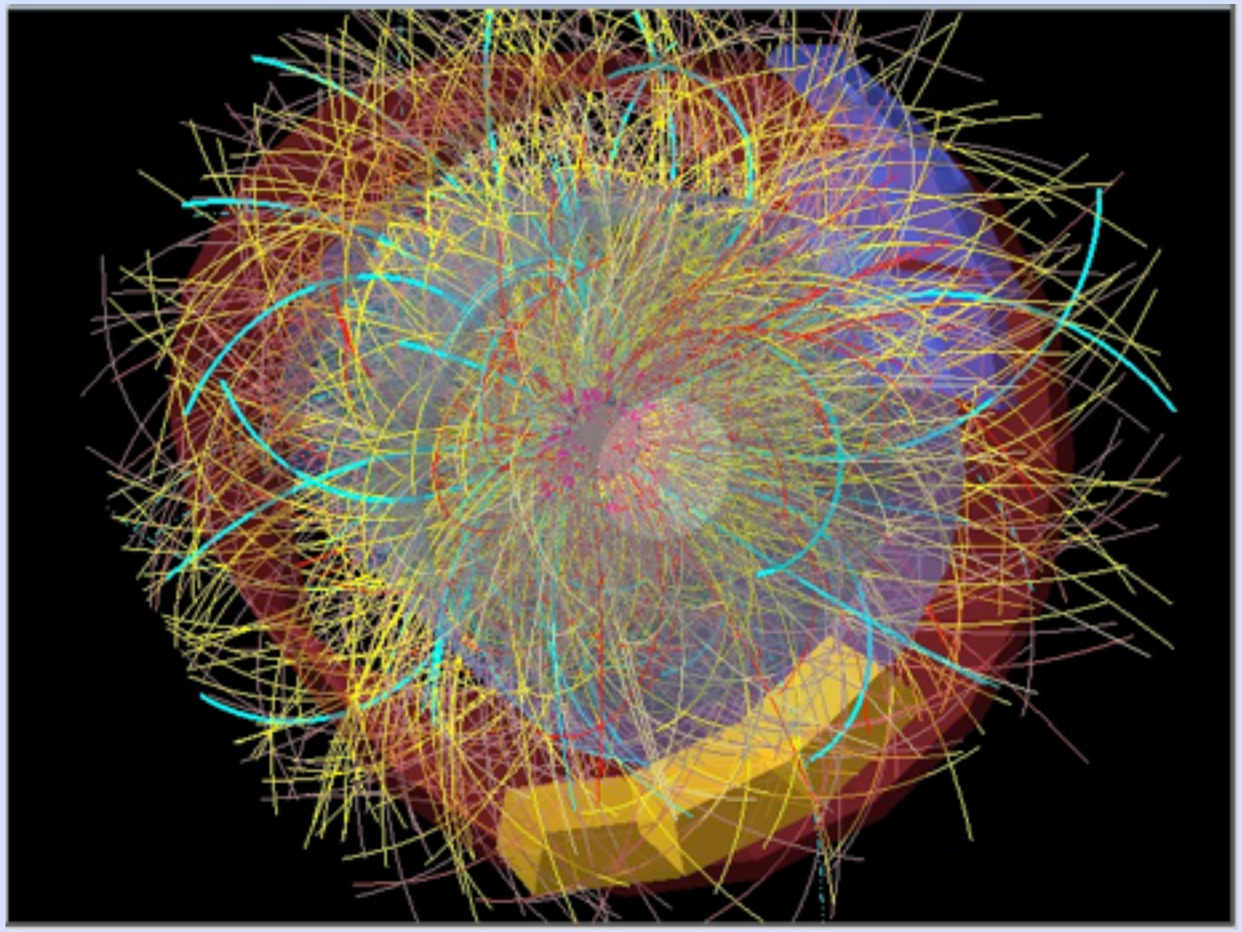
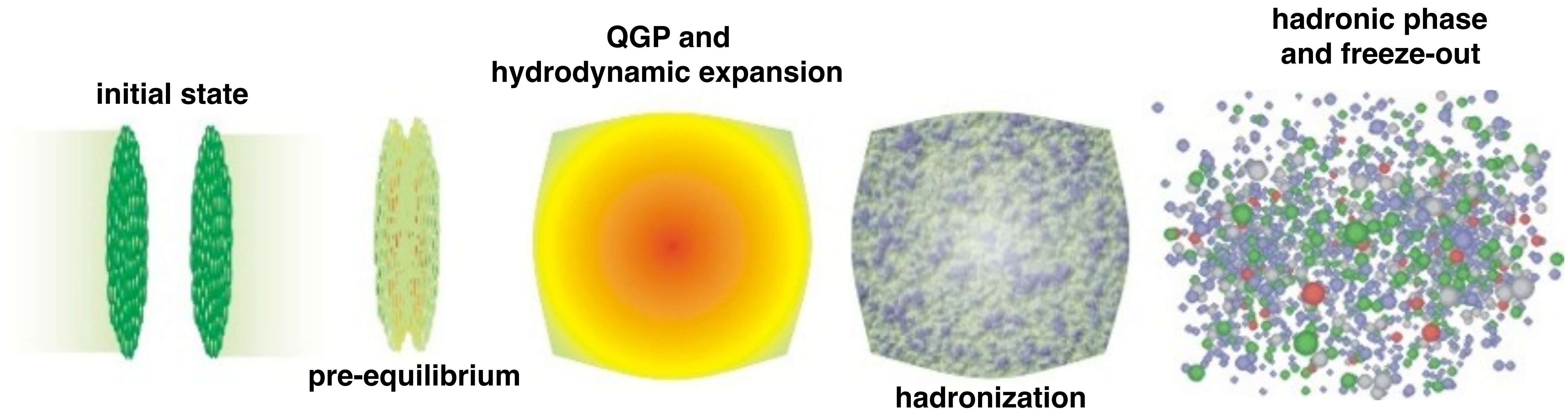
typical Pb+Pb collision @ LHC:



- 1000s of tracks
- task: reconstruction of final state to characterize matter created in collision

Time Evolution of a Heavy-Ion Collision



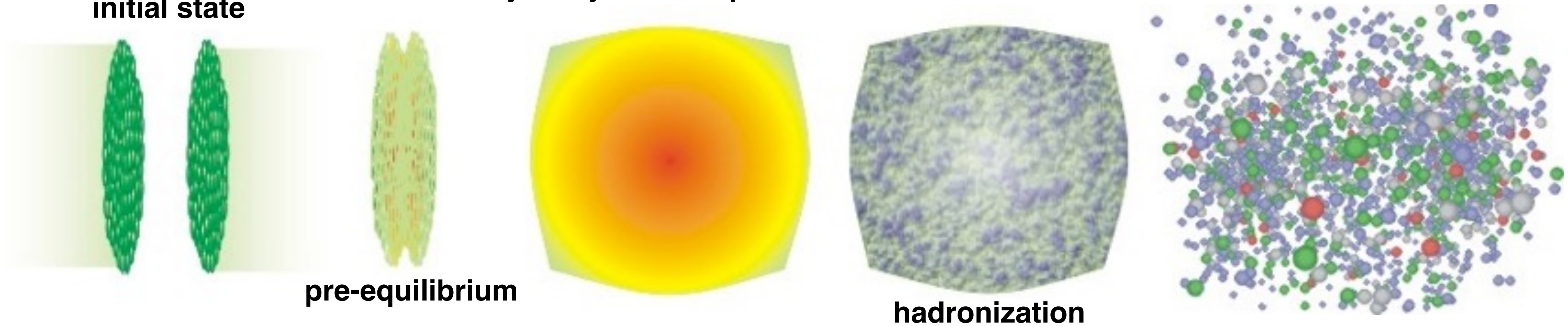
- **Initial State:**
  - fluctuates event-by-event
  - classical color-field dynamics

- **QGP and hydrodynamic expansion:**
  - proceeds via 3D viscous RFD
  - EoS from Lattice QCD

- **Pre-equilibrium:**
  - rapid change-over from glue-field dominated initial state to thermalized QGP
  - time scale: 0.15 to 2 fm/c in duration
  - significant conceptual challenges!

- **hadronic phase & freeze-out**
  - interacting hadron gas
  - separation of chemical and kinetic freeze-out

Time Evolution of a Heavy-Ion Collision



- Initial State:

- QGP and hydrodynamic expansion:

Principal Challenges of Probing the QGP with Heavy-Ion Collisions:

- time-scale of the collision process: 10^{-24} seconds! [too short to resolve]
- characteristic length scale: 10^{-15} meters! [too small to resolve]
- confinement: quarks & gluons form bound states, experiments don’t observe them directly

▸**computational models are need to connect the experiments to QGP properties!**

- time scale: 0.15 to 2 fm/c in duration
- significant conceptual challenges!

kinetic freeze-out

Modeling of Heavy-Ion Collisions

microscopic transport models based on the **Boltzmann Equation**:

- transport of a system of microscopic particles
- all interactions are based on binary scattering

$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p}, \vec{r}, t) = \sum_{processes} C(\vec{p}, \vec{r}, t)$$

diffusive transport models based on the **Langevin Equation**:

- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

$$\vec{p}(t + \Delta t) = \vec{p}(t) - \frac{\kappa}{2T} \vec{v} \cdot \Delta t + \vec{\xi}(t) \Delta t$$

(viscous) relativistic fluid dynamics:

- transport of macroscopic degrees of freedom
- based on conservation laws:

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

$$\begin{aligned} T_{ik} &= \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) \\ &- \eta\left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik}\nabla \cdot u\right) \\ &+ \varsigma\, \delta_{ik} \nabla \cdot u \end{aligned}$$

(plus an additional 9 eqns. for dissipative flows)

hybrid transport models:

- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling

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hybrid transport models:

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- current state of the art for RHIC modeling

Each transport model relies on roughly a dozen physics parameters to describe the time-evolution of the collision and its final state. These physics parameters act as a representation of the information we wish to extract from RHIC & LHC.

QCD Transport Coefficients: Shear Viscosity

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shear and bulk viscosity are defined as the coefficients in the expansion of the stress tensor in terms of the velocity fields:

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assuming matter to be quasi-particulate in nature:

microscopic kinetic theory:
η is given by the rate of momentum transport

$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f = \frac{\bar{p}}{3\sigma_{\mathrm{tr}}}$$

unitary limit on cross sections suggests a lower bound for η

$$\sigma_{\mathrm{tr}} \le \frac{4\pi}{\bar{p}^2} \quad \Rightarrow \quad \eta \ge \frac{\bar{p}^3}{12\pi}$$

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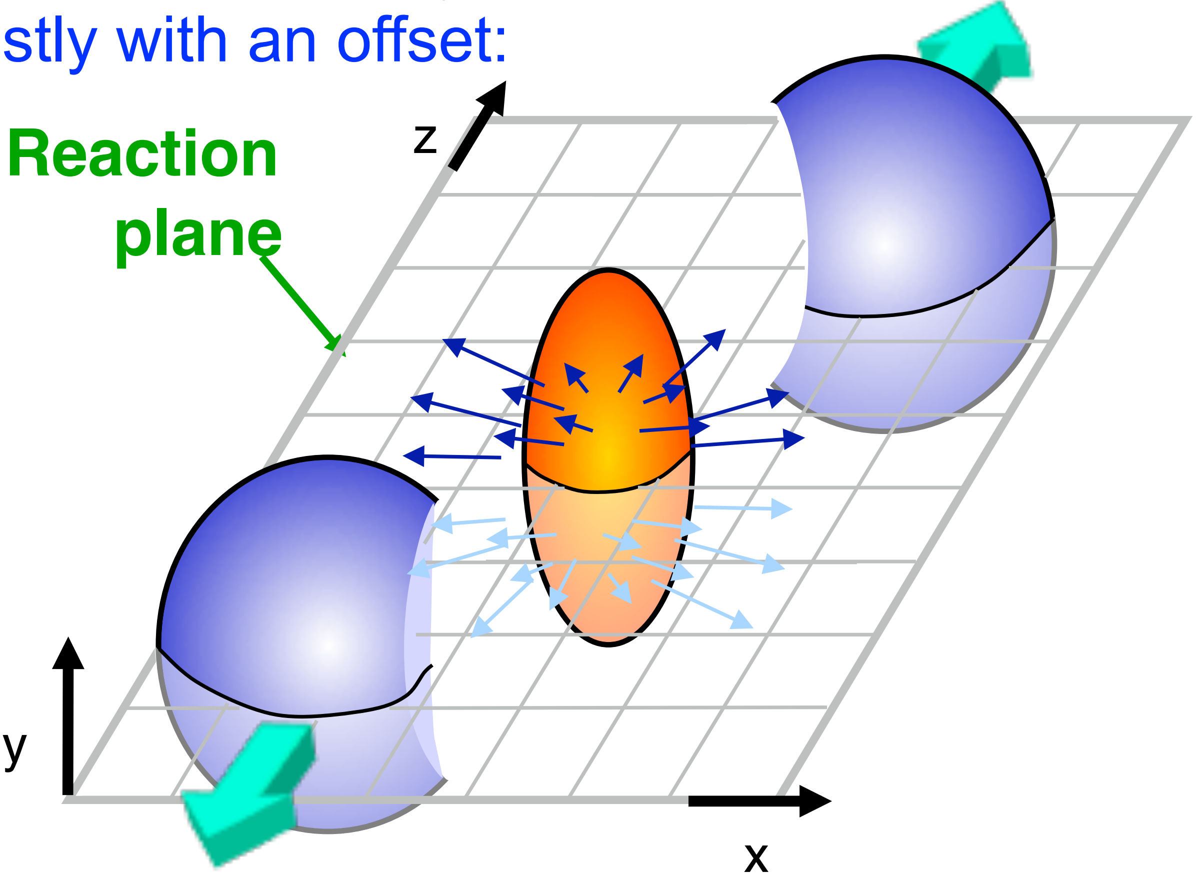
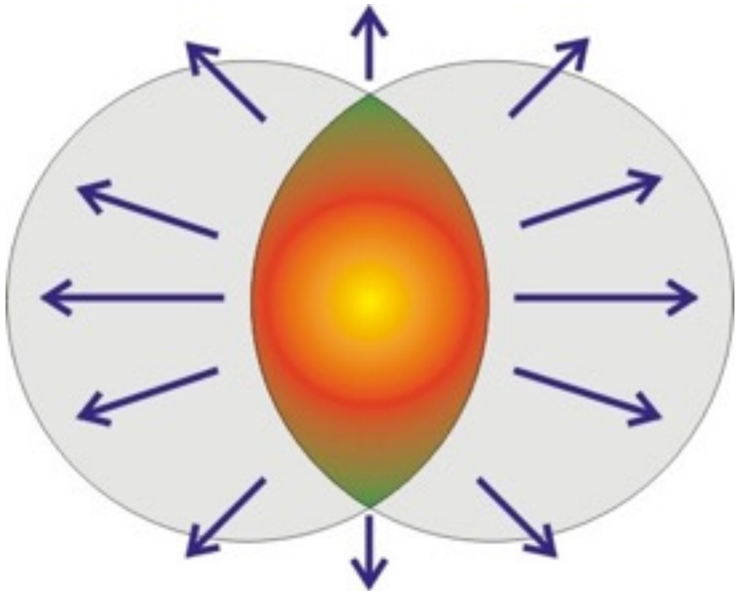
The determination of the QCD transport coefficients is one of the key goals of the US relativistic heavy-ion effort!

Collision Geometry: Elliptic Flow

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated up

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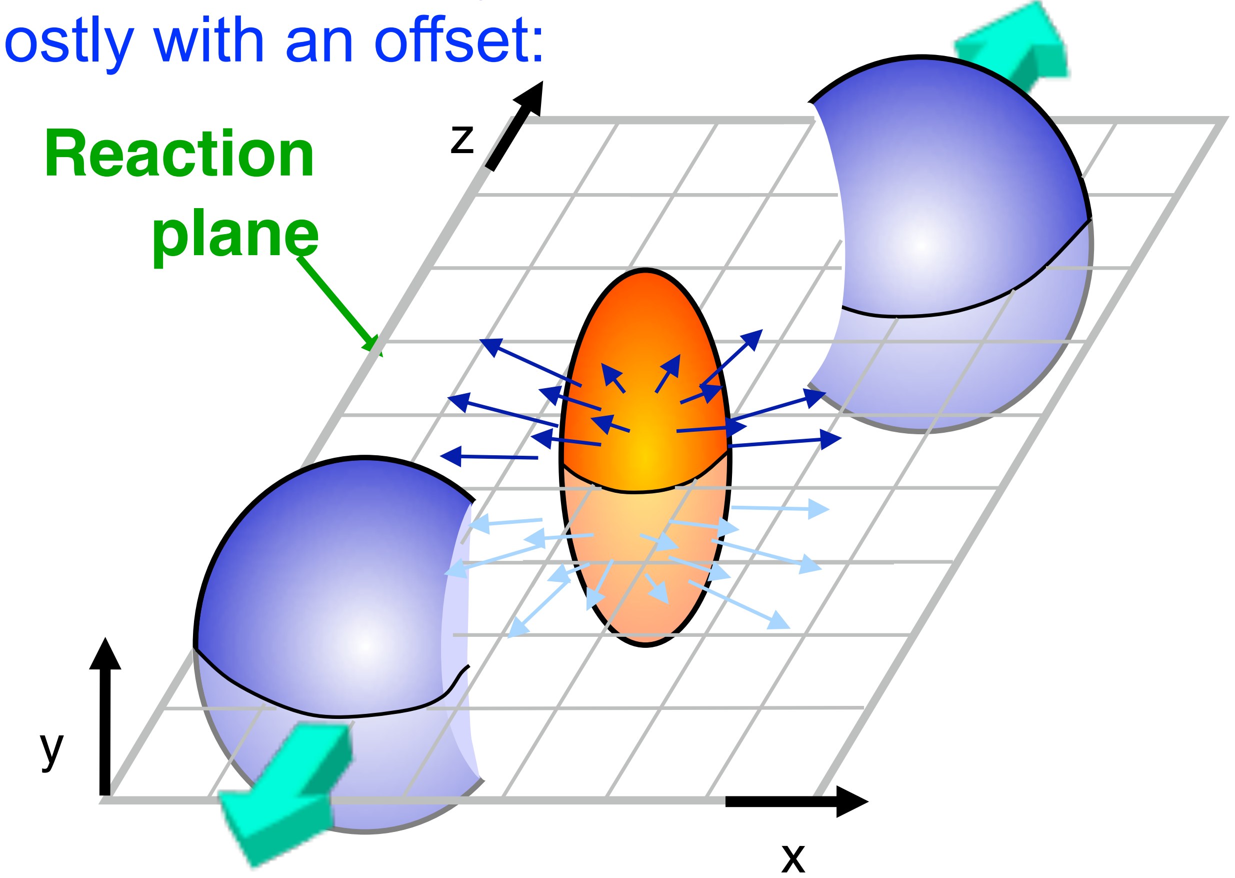

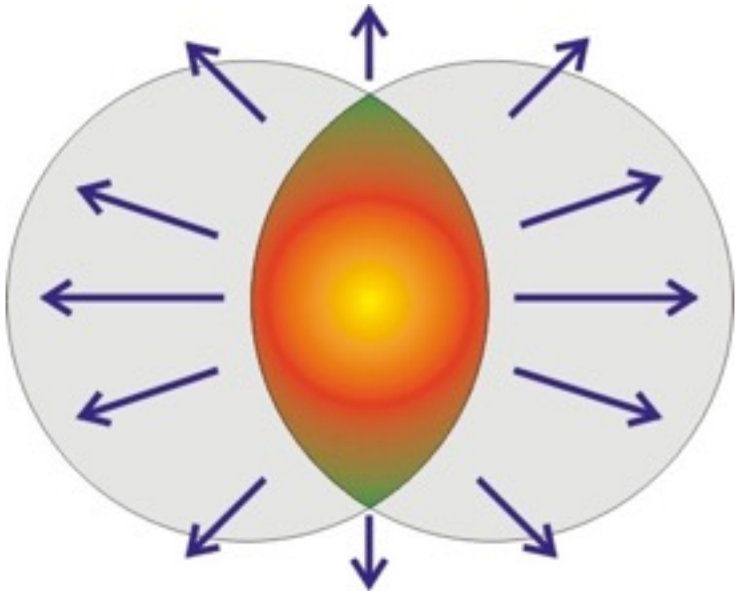

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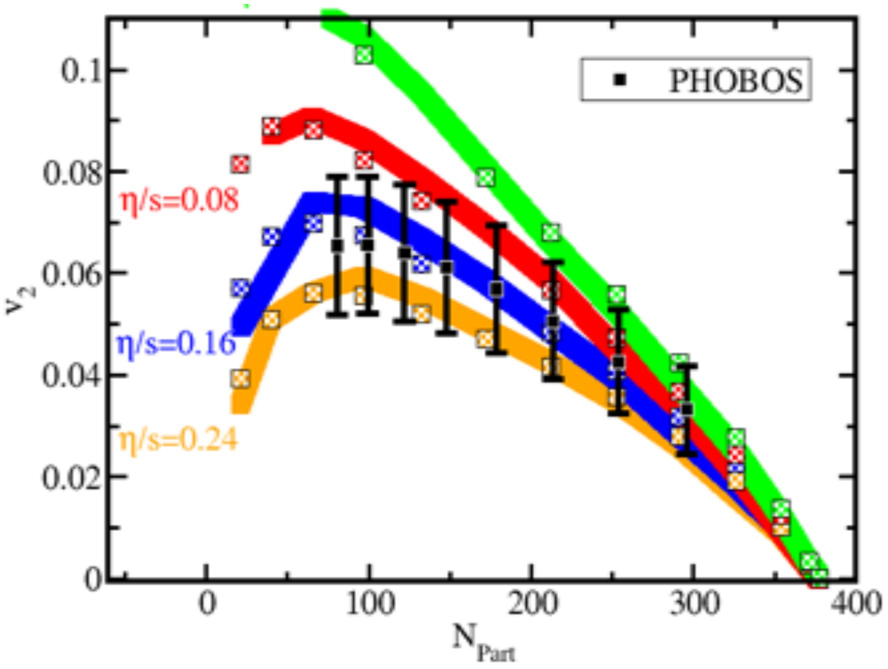
elliptic flow (v_2):

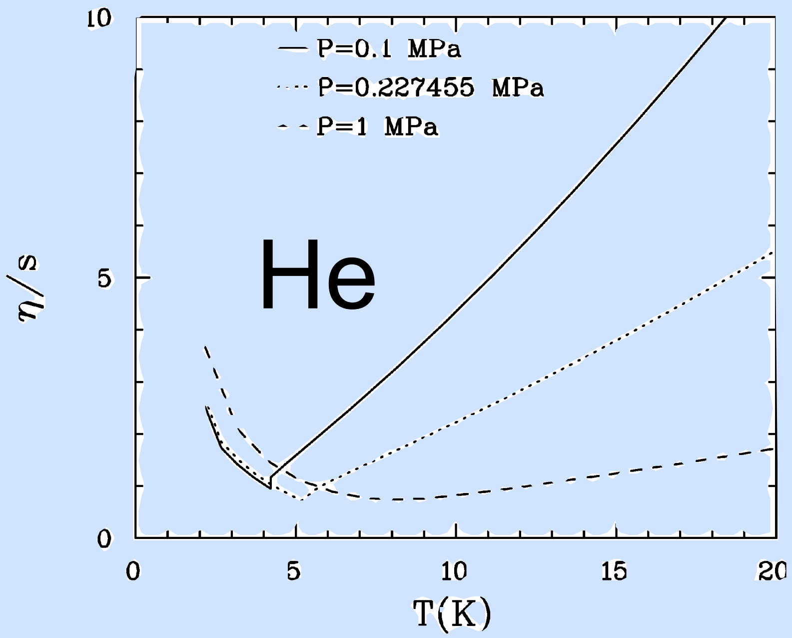
- gradients of almond-shape surface will lead to preferential emission in the reaction plane
- asymmetry out- vs. in-plane emission is quantified by 2nd Fourier coefficient of angular distribution: v_2

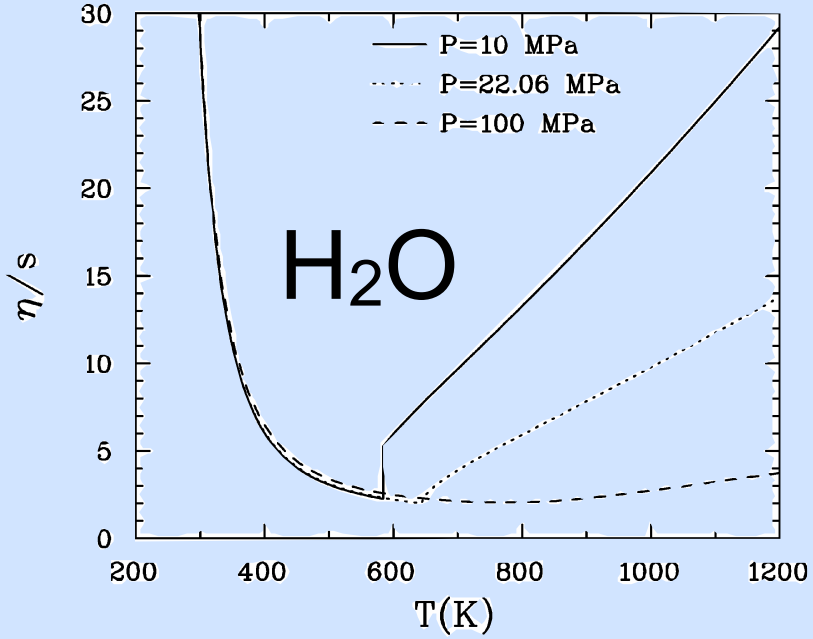
➢ **vRFD: good agreement with data for very small η/s**



Temperature Dependence of η/s

what can ordinary matter, e.g. He or H_2O teach us about η/s?





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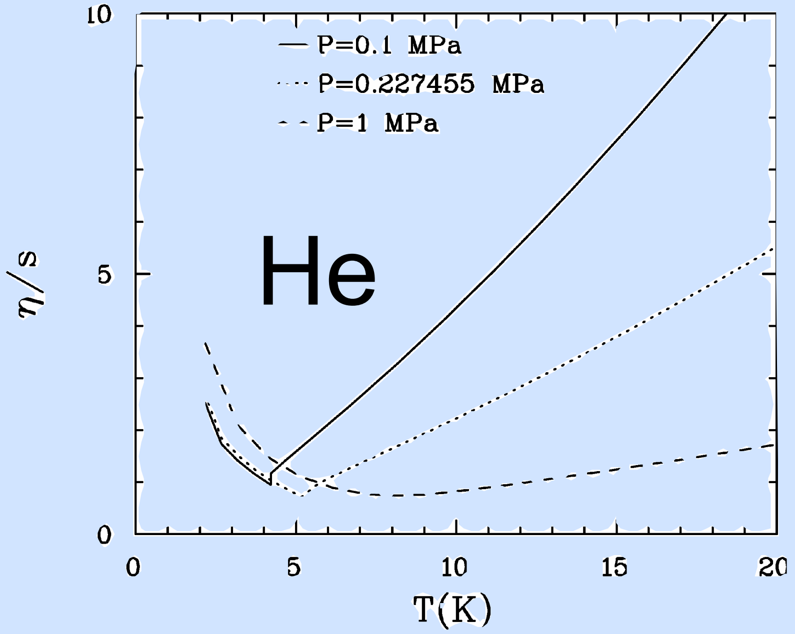
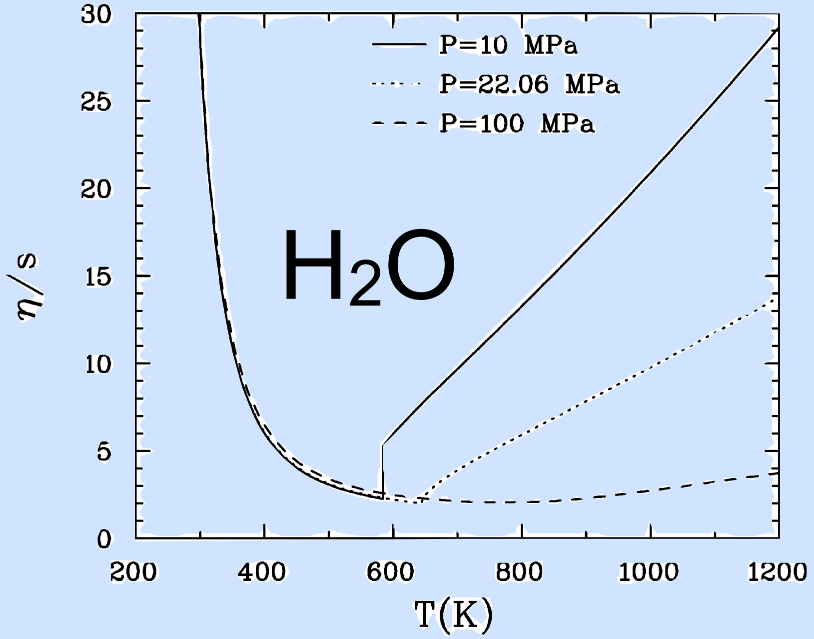
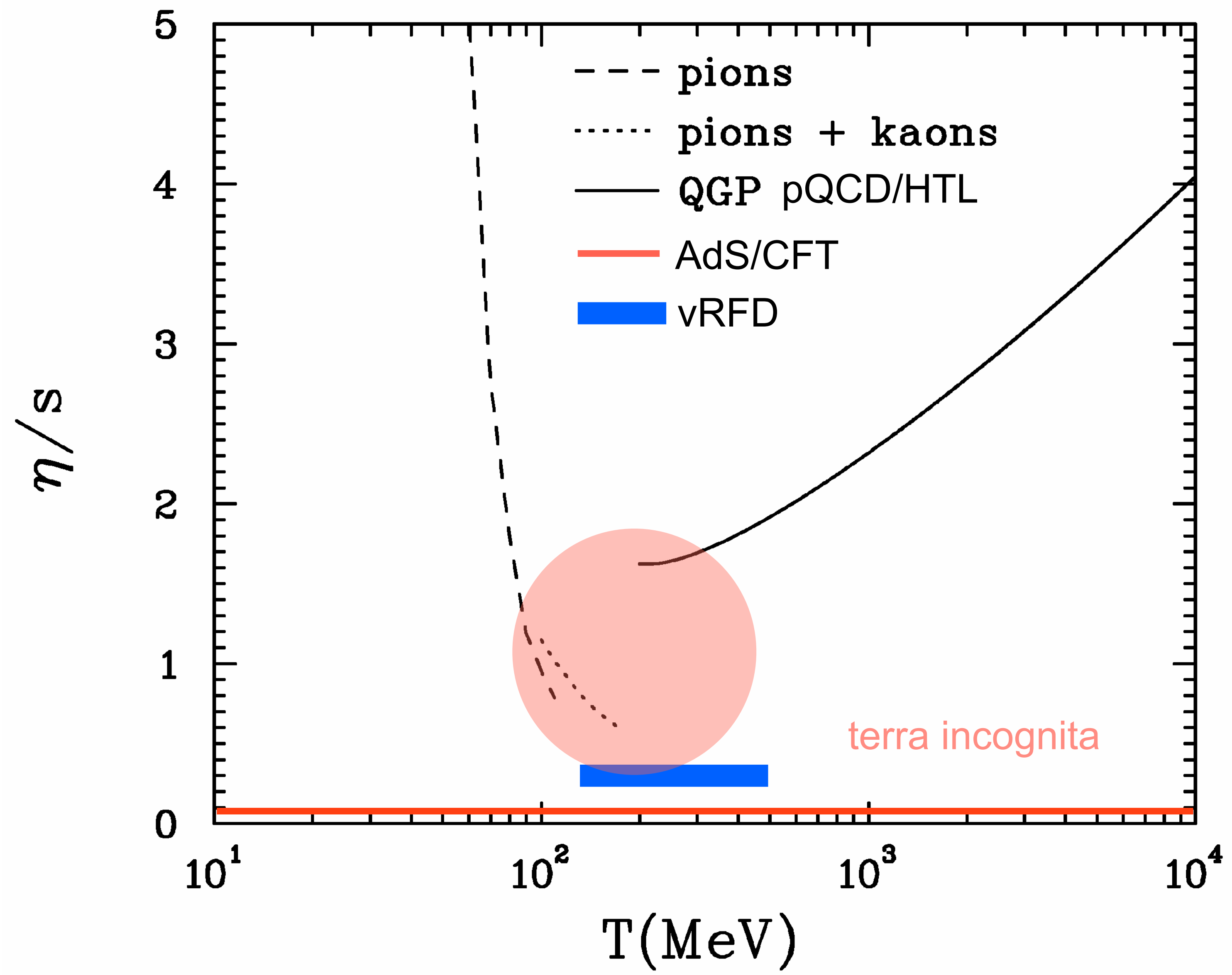




- η/s has minimum & discontinuity at T_c

temperature dependence of η/s in QCD can be estimated in low- and high-temperature limit:

- low temperature: chiral pions
- high temperature: QGP in HTL approximation



L.P. Csernai, J.I. Kapusta & L. McLerran: Phys. Rev. Lett. **97**: 152303 (2006)
M. Prakash, M. Prakash, R. Venugopalan & G. Welke: Phys. Rept. **227**, 321 (1993)
P. Arnold, G.D. Moore & L.D. Yaffe: JHEP **05**: 051 (2003)

The Challenge of a rigorous Model to Data Comparison

Model Parameter:

eqn. of state

shear viscosity

initial state

pre-equilibrium dynamics

thermalization time

quark/hadron chemistry

particlization/freeze-out

experimental data:

π/K/P spectra

yields vs. centrality & beam

elliptic flow

HBT

charge correlations & BFs

density correlations

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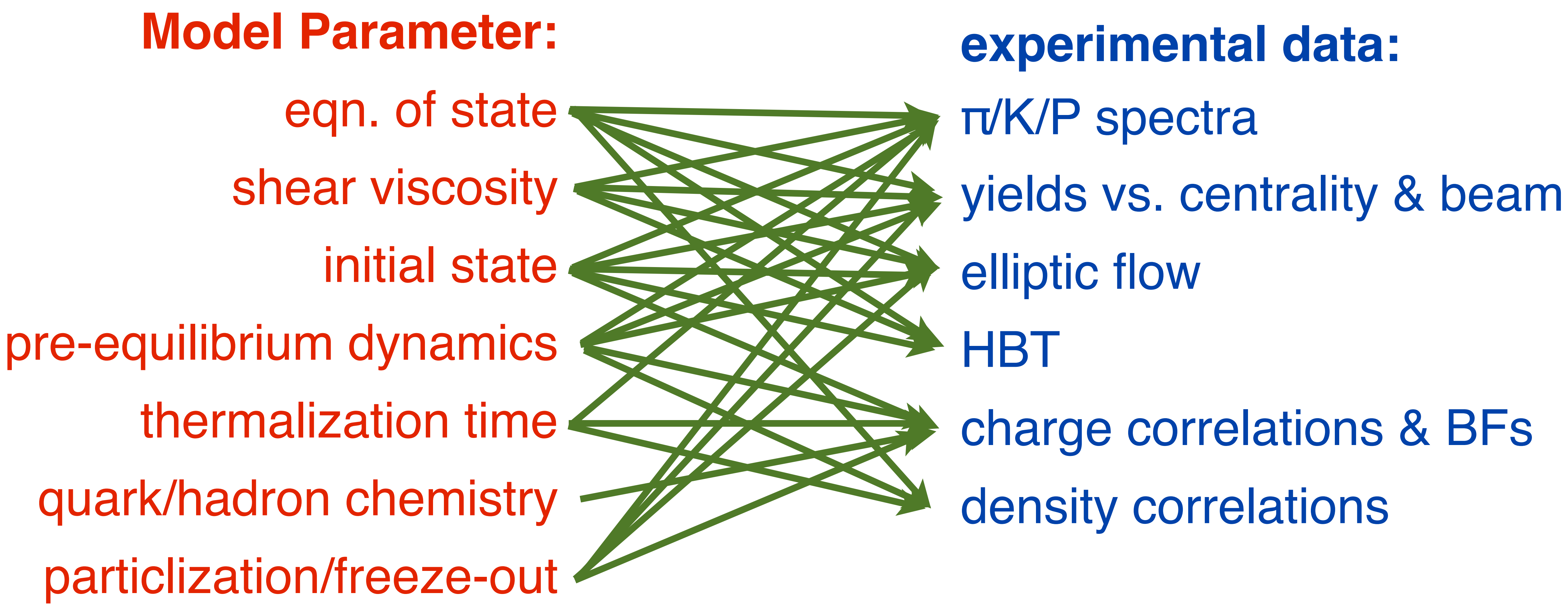

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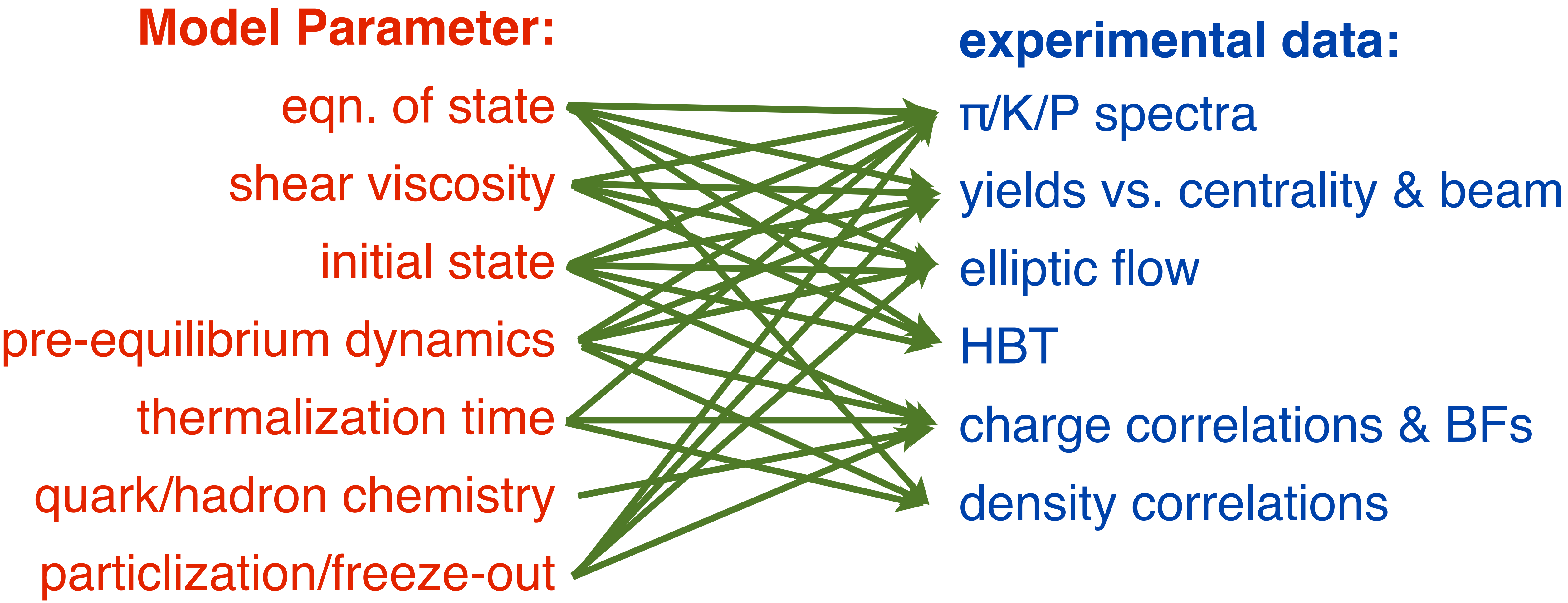

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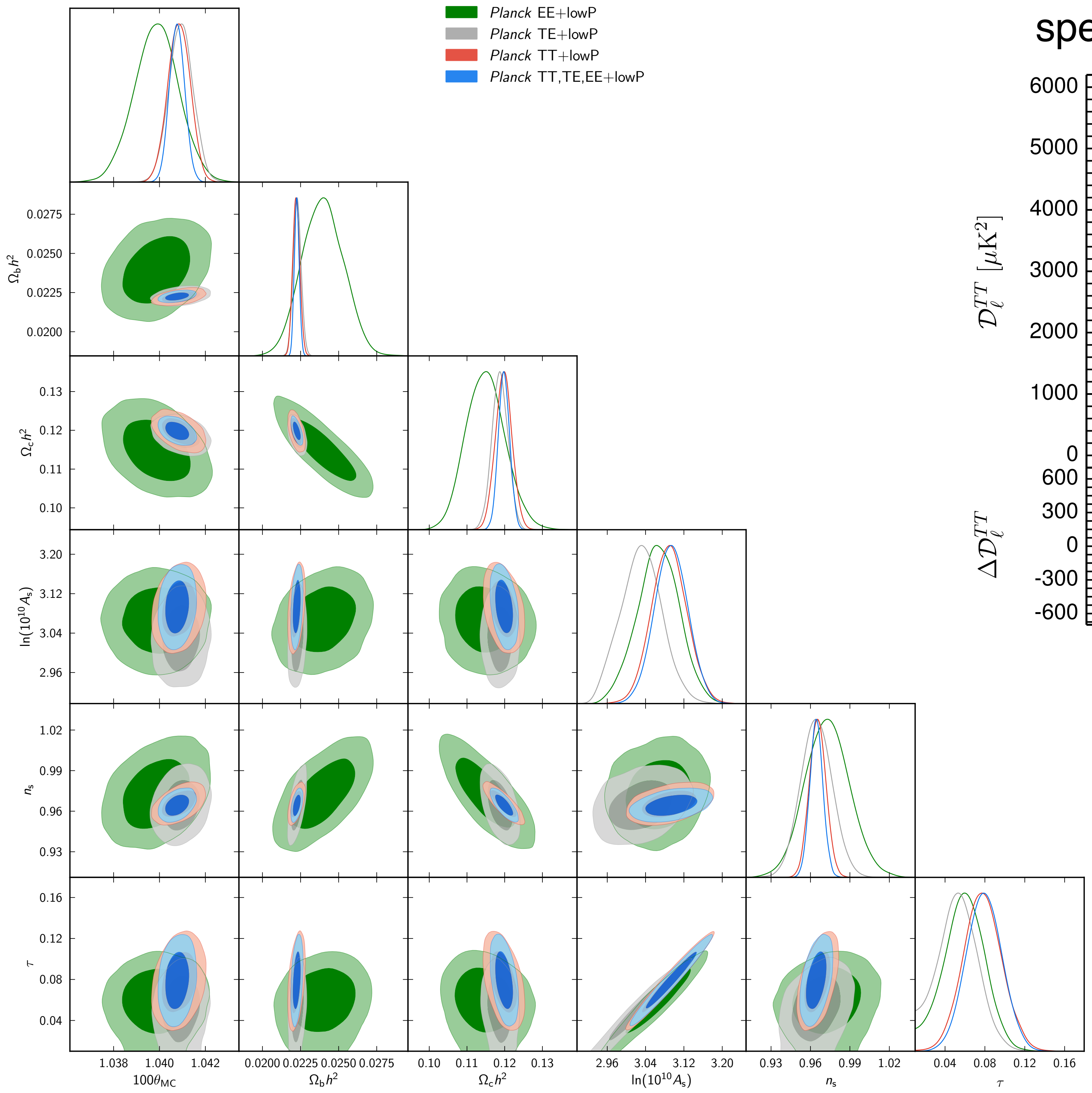
- large number of interconnected parameters w/ non-factorizable data dependencies
- data have correlated uncertainties
- develop novel optimization techniques: Bayesian Statistics and MCMC methods
- transport models require too much CPU: need new techniques based on emulators
- general problem, not restricted to RHIC Physics

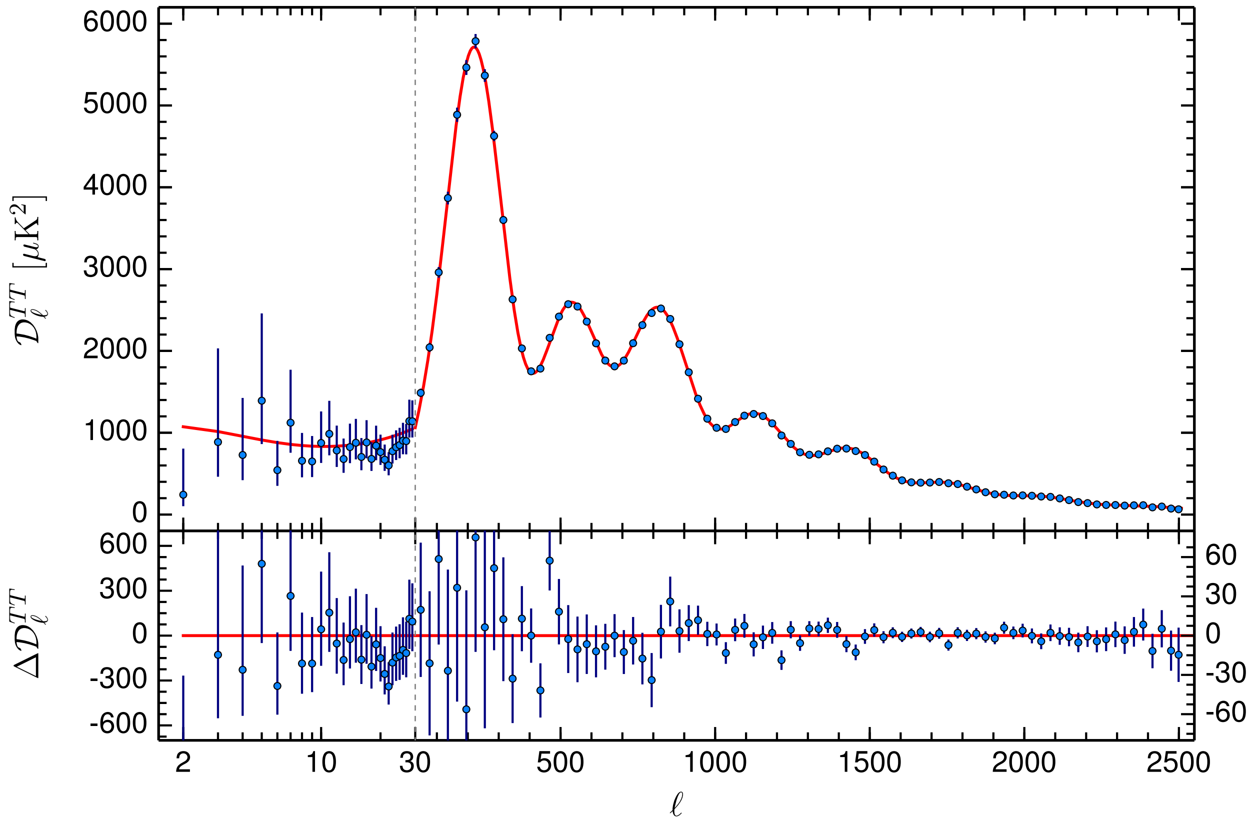
→collaboration with Statistical Sciences

Precision Cosmology



calibrated posterior distribution of ΛCDM model parameters with *Planck* data

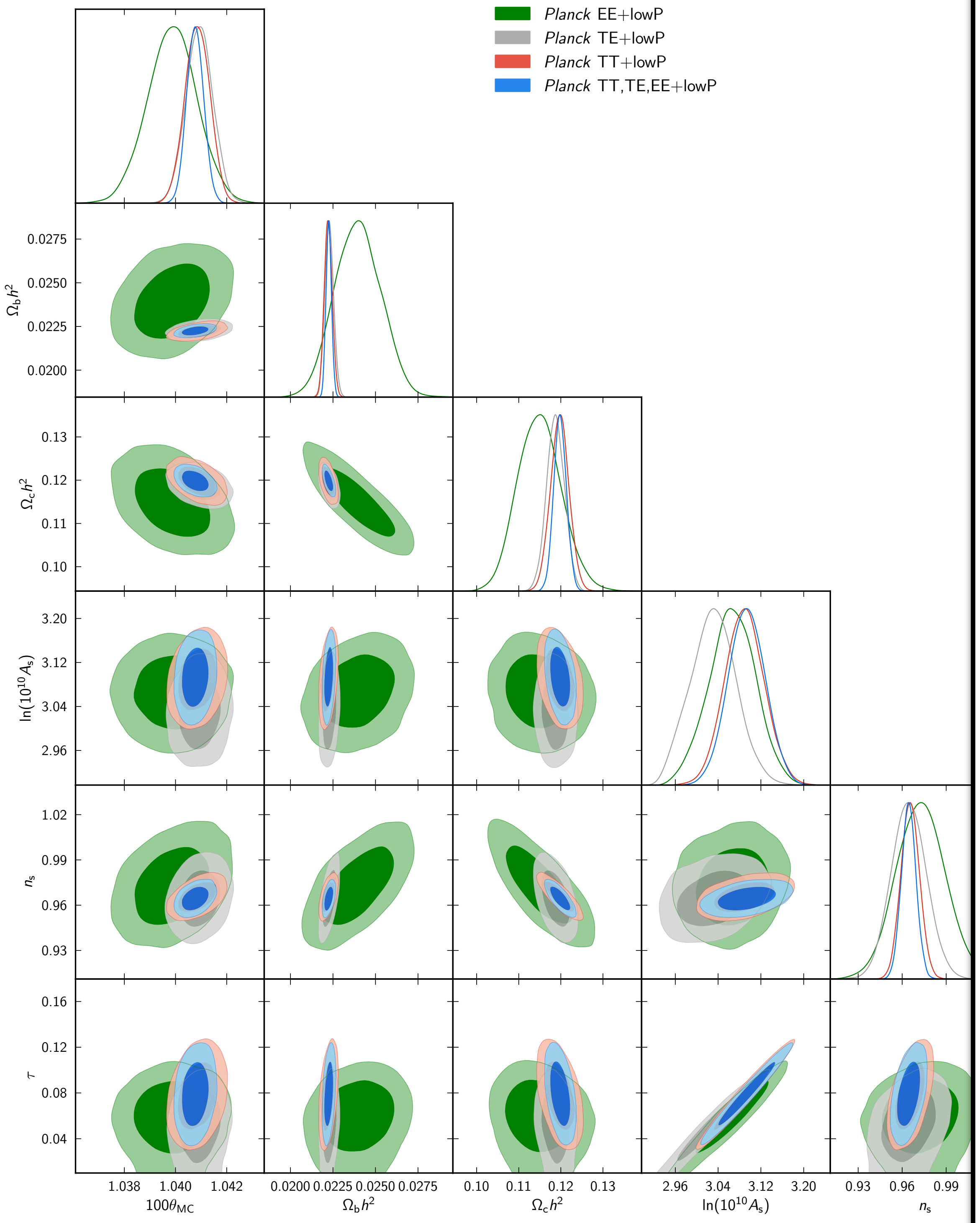
comparison of *Planck* 2015 temperature power spectrum with the ΛCDM cosmological model:



high precision *Planck* data on the CMB has allowed for the verification of the standard cosmological model and the most accurate determination of cosmological parameters to date

- **Is Heavy-Ion Physics capable of this type of Precision Science?**

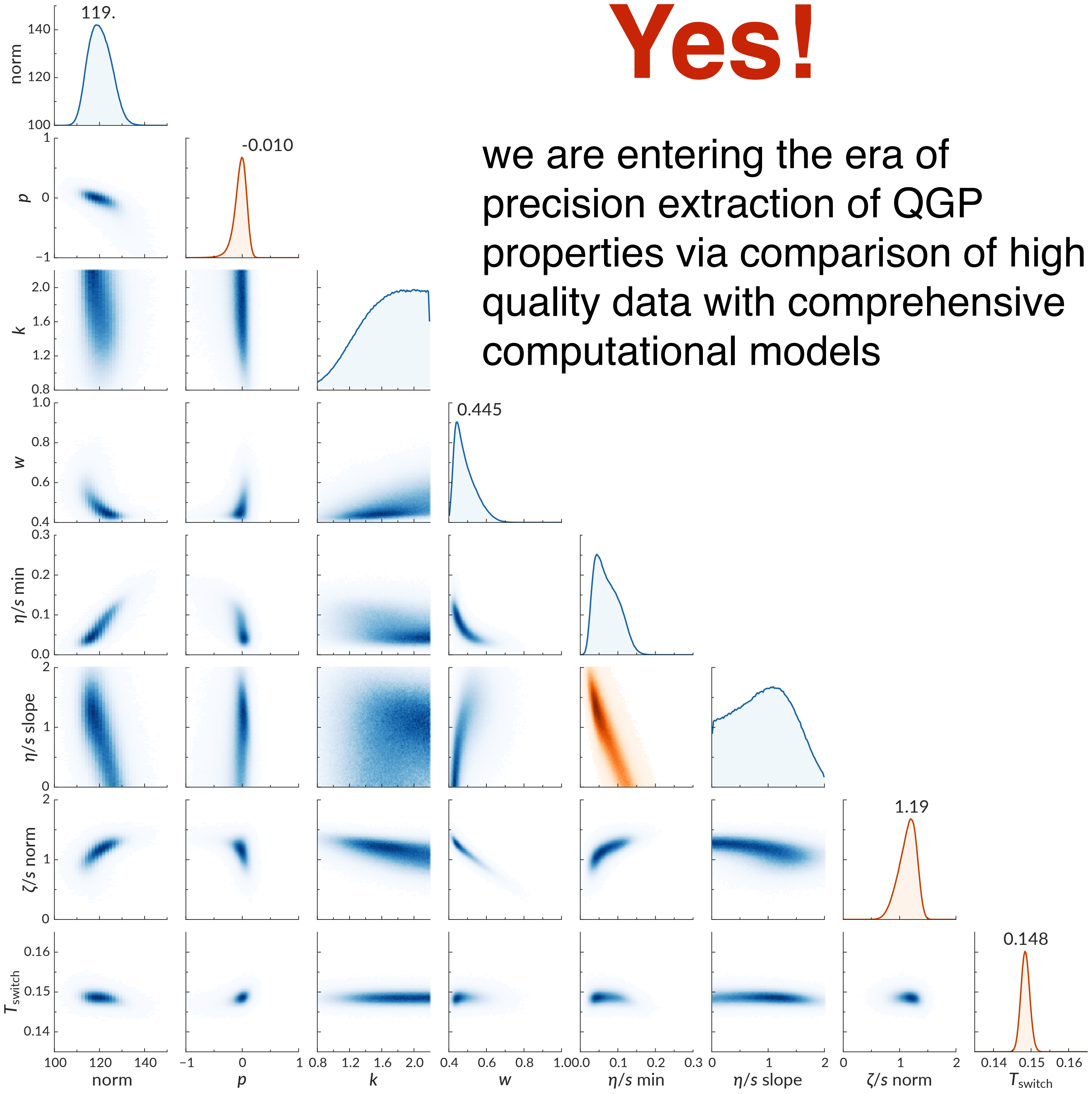
Precision Cosmology



calibrated posterior distribution of ΛCDM model parameters with *Planck* data

Yes!

we are entering the era of precision extraction of QGP properties via comparison of high quality data with comprehensive computational models



calibrated posterior distribution of hybrid vRFD+micro model parameters with LHC data