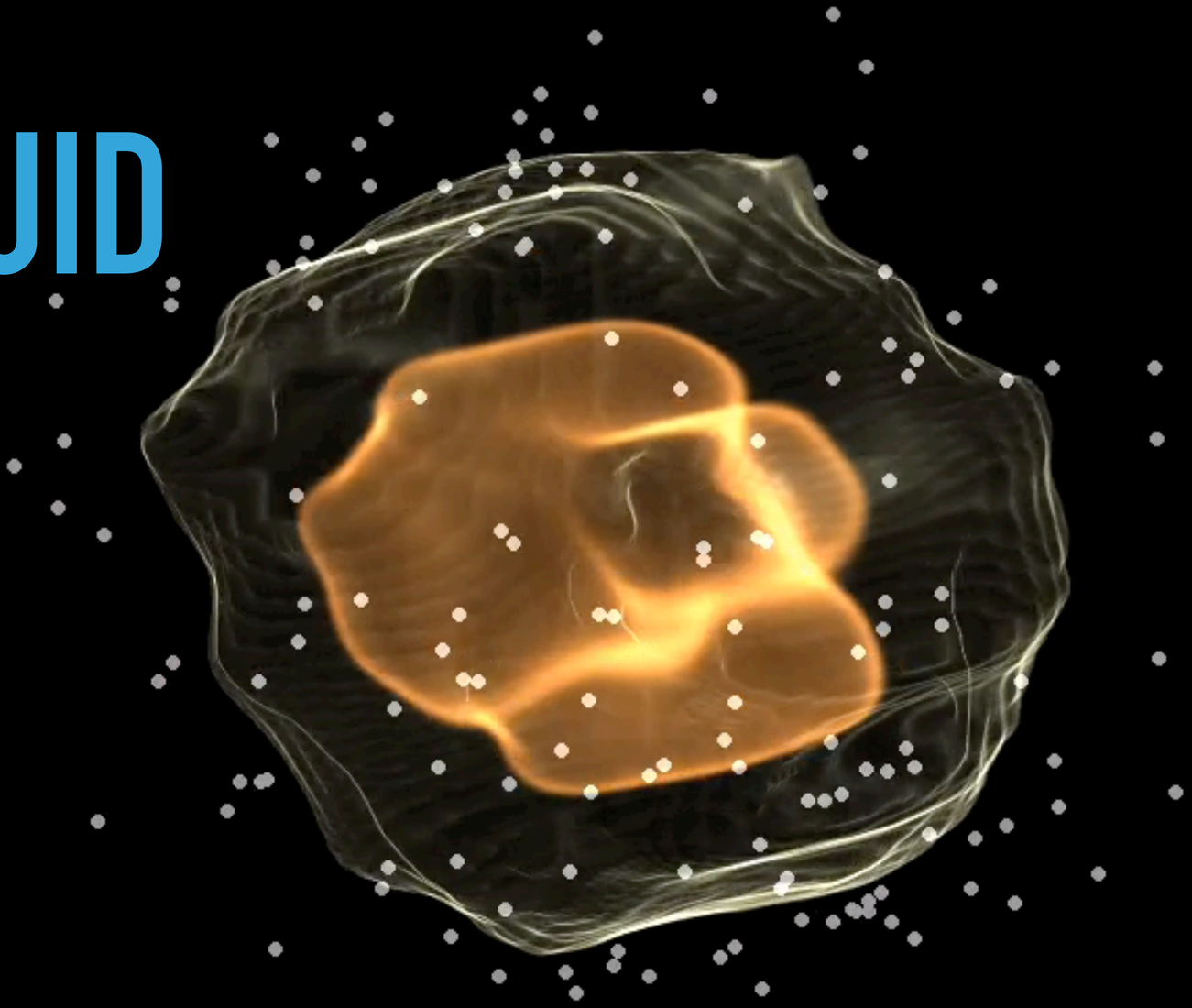
RBRC
RIKEN BNL Research Center

THE HOTTEST FLUID ON EARTH

CHUN SHEN



Wayne State Academy of Scholars
Nov. 15, 2023

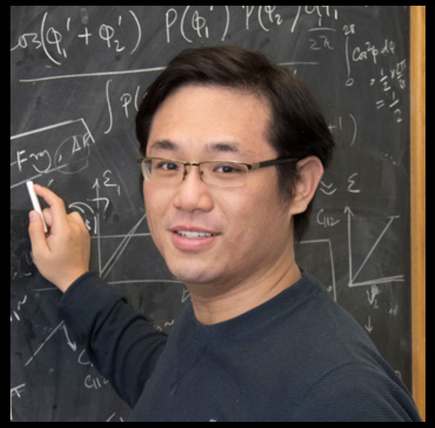
MY ACADEMIC TRAJECTORY

- 2014 Ph. D from Ohio State University
- 2014-2016 Postdoc fellow at McGill University
- 2016-2018 Goldhaber fellow at Brookhaven National Laboratory
- 2018-present Wayne State University

- 2016 APS Dissertation Award in Nuclear Physics
- 2019 IUPAP Young Scientist Award in Nuclear Physics
- 2021 DoE Early Career Award

WHY WAYNE STATE?

- Theory Group:

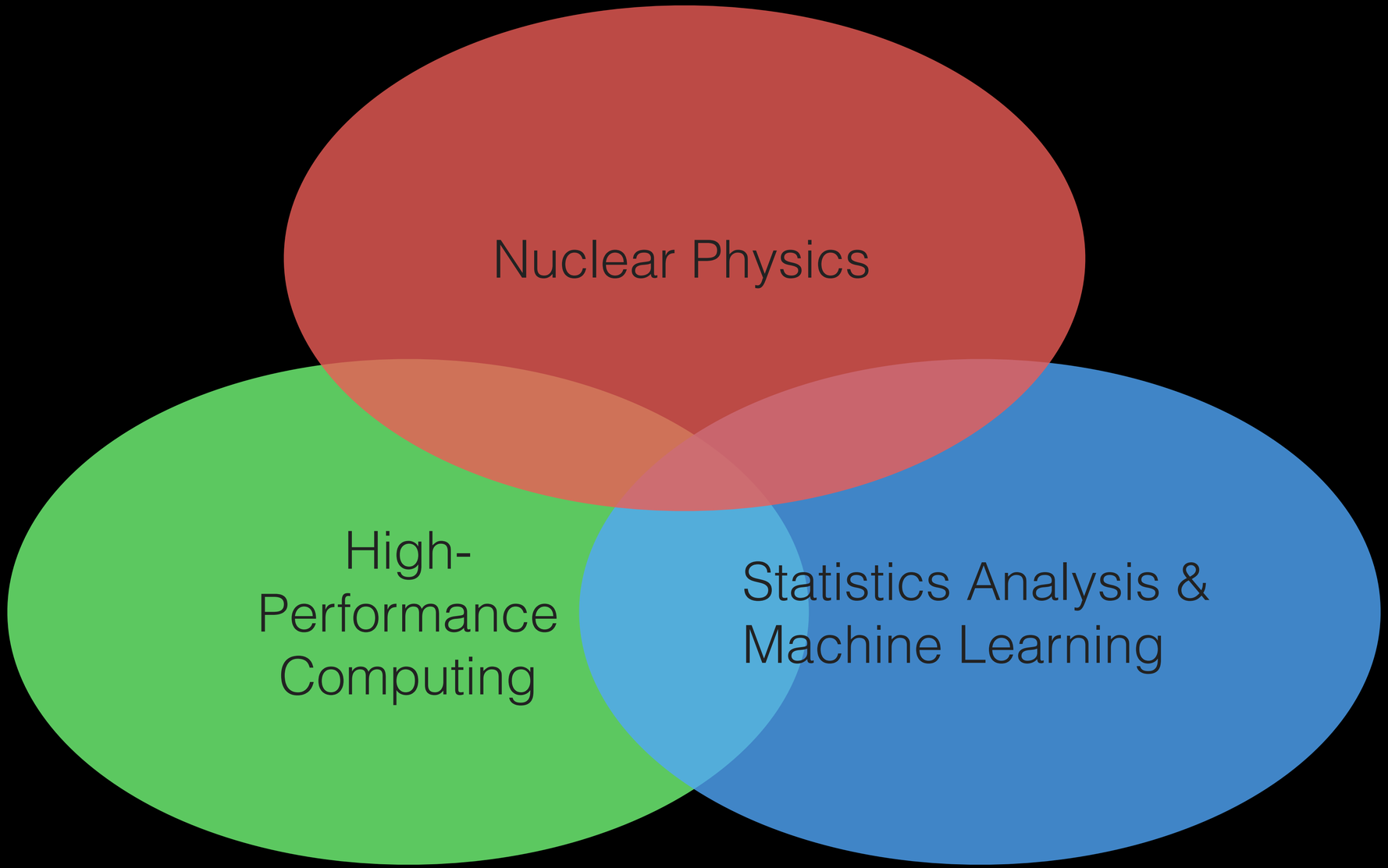




- Experimental Group:

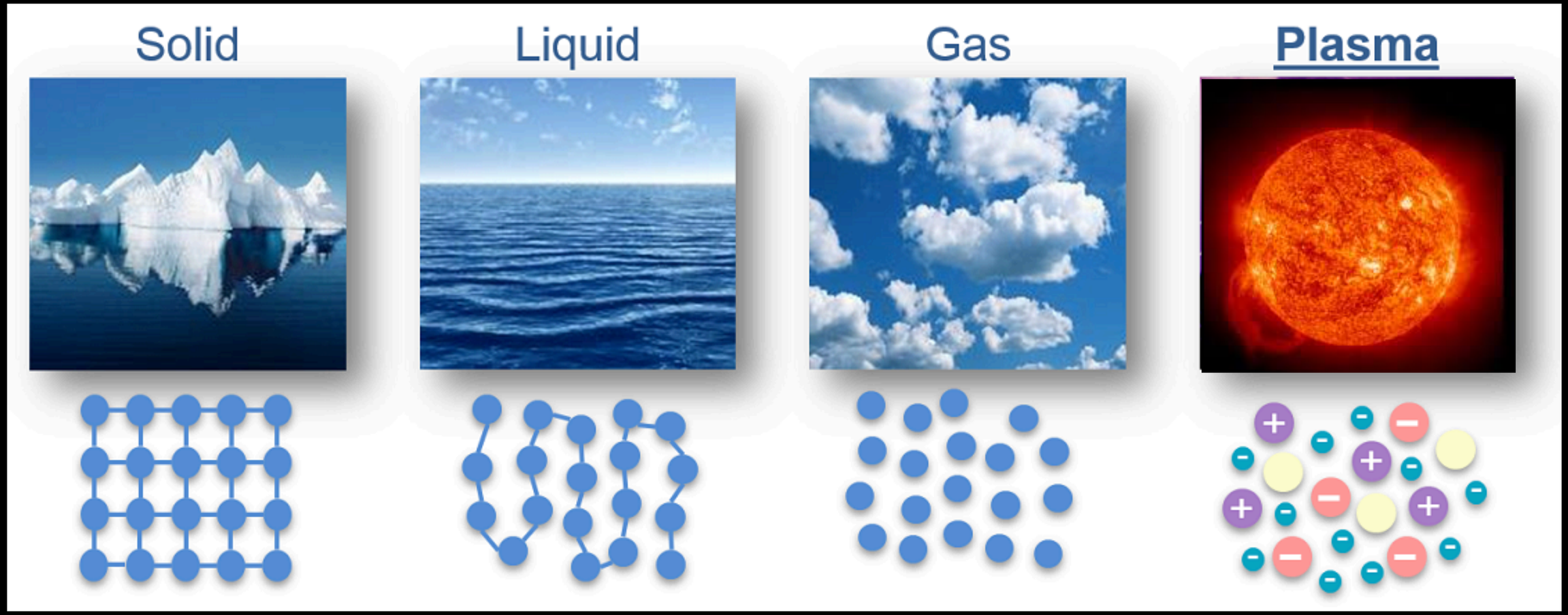



A **world-leading center** for high-energy nuclear physics

MY RESEARCH INTERESTS



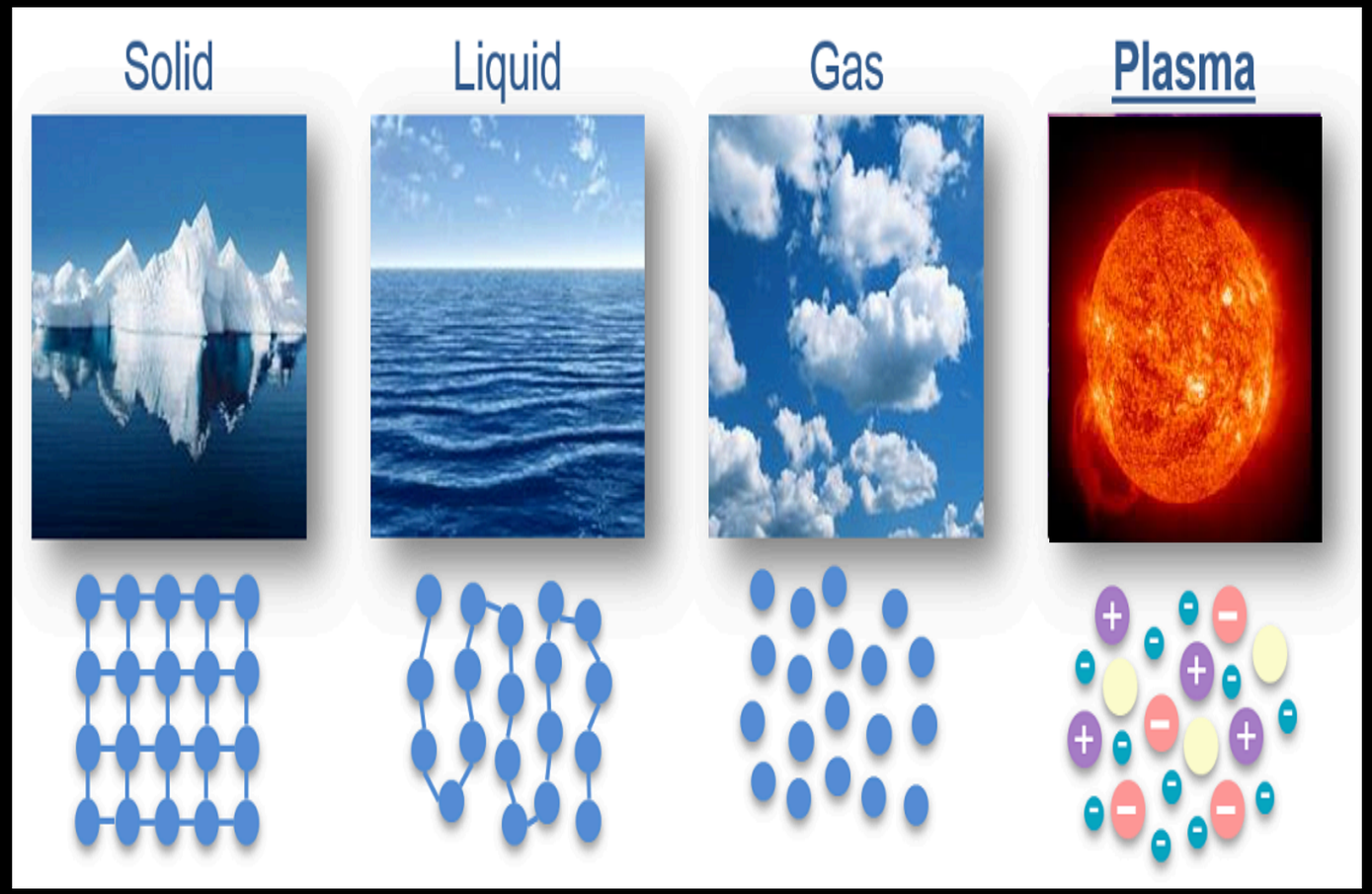
EXPLORING THE PHASE OF MATTER



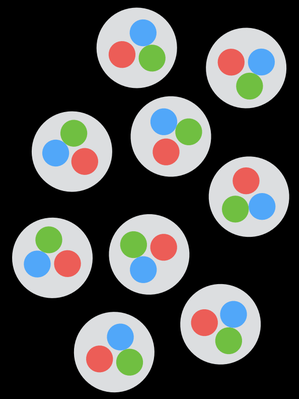
Temperature

T~10^5-10^7 K

EXPLORING THE PHASE OF MATTER



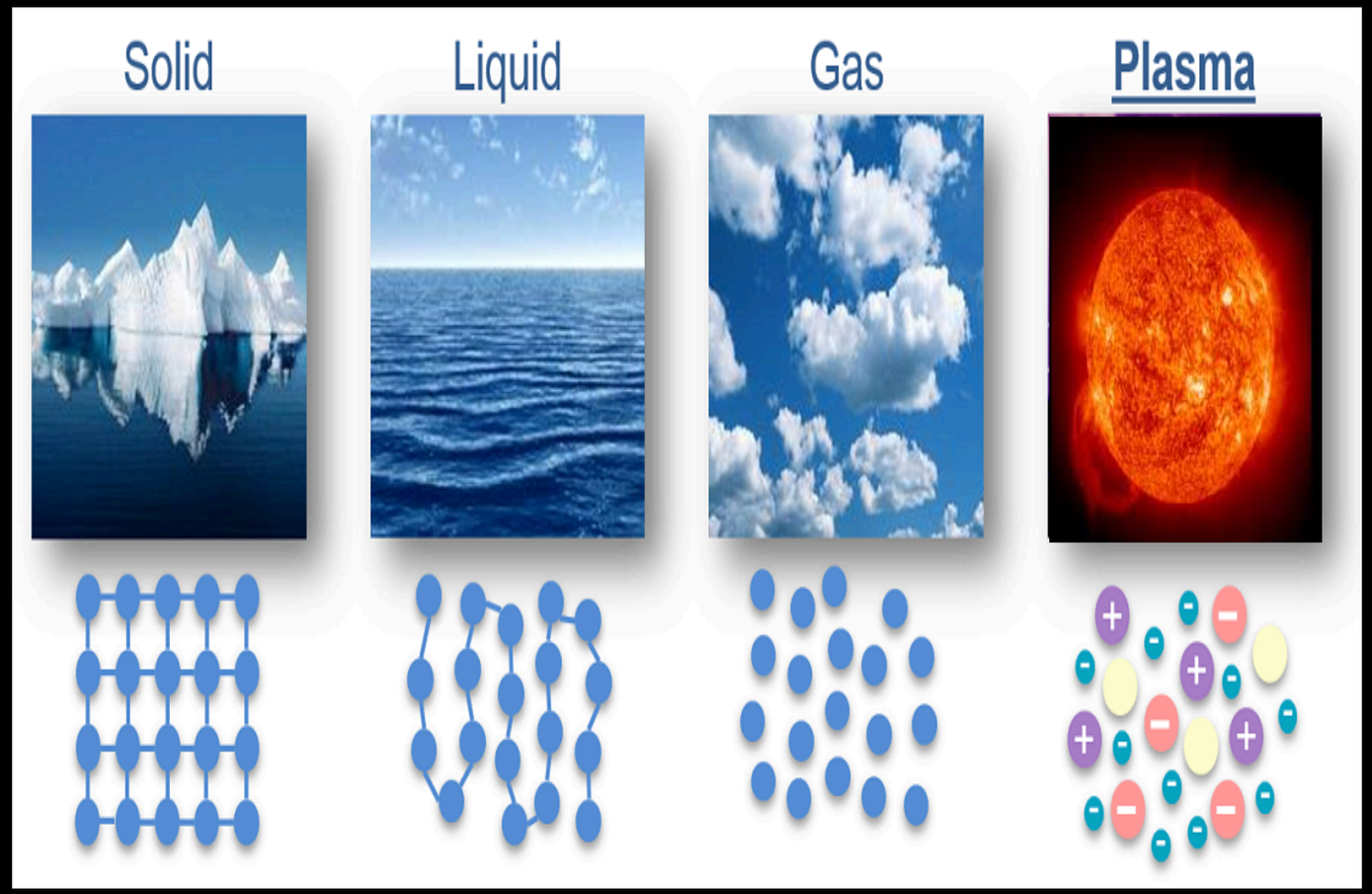
Hadron Gas



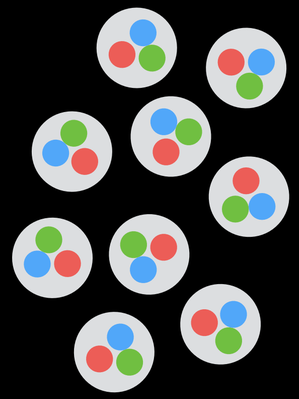
T~10^5-10^7 K T~10^{10}-10^{11}K

Temperature

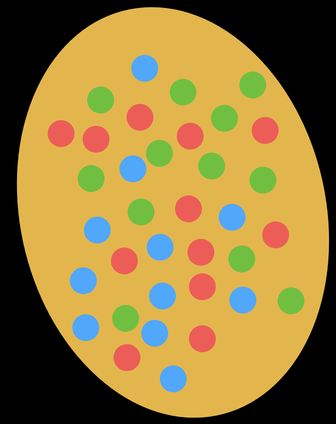
EXPLORING THE PHASE OF MATTER



Hadron Gas



Quark-Gluon Plasma



$T \sim 10^{5}\text{-}10^{7}$ K

$T \sim 10^{10}\text{-}10^{11}$K

$T > 10^{12}$K

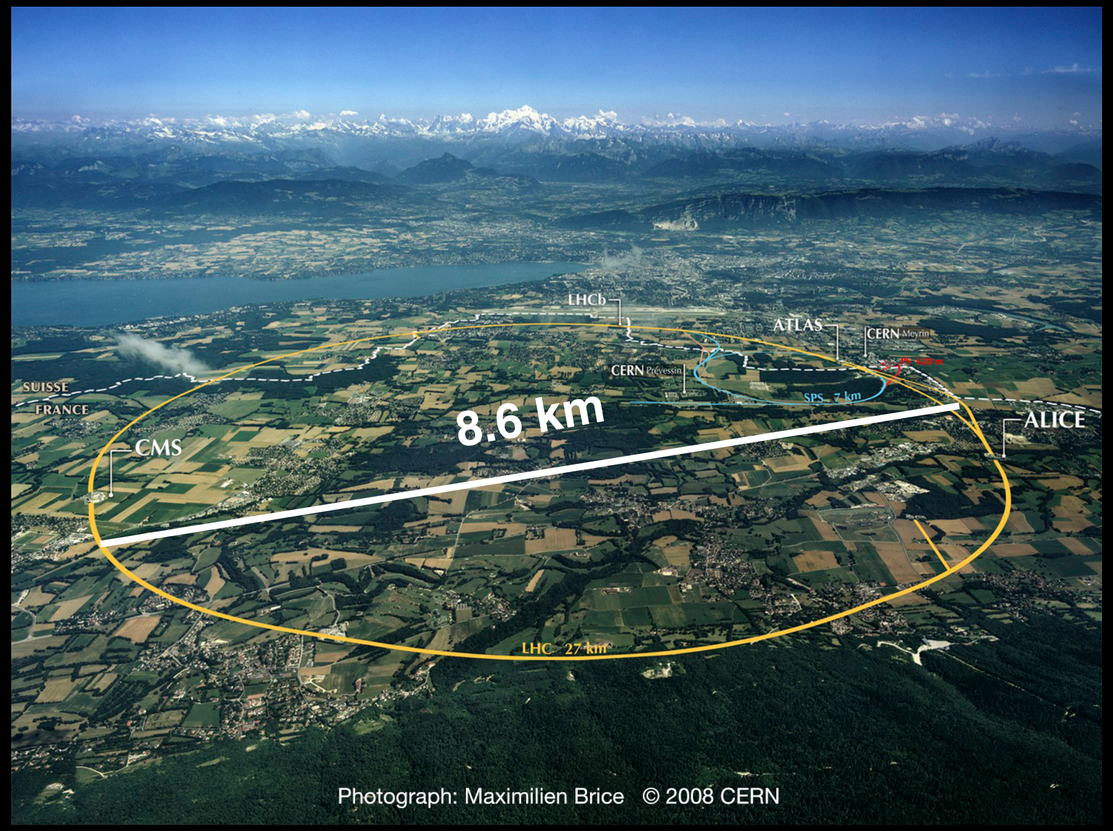
Temperature

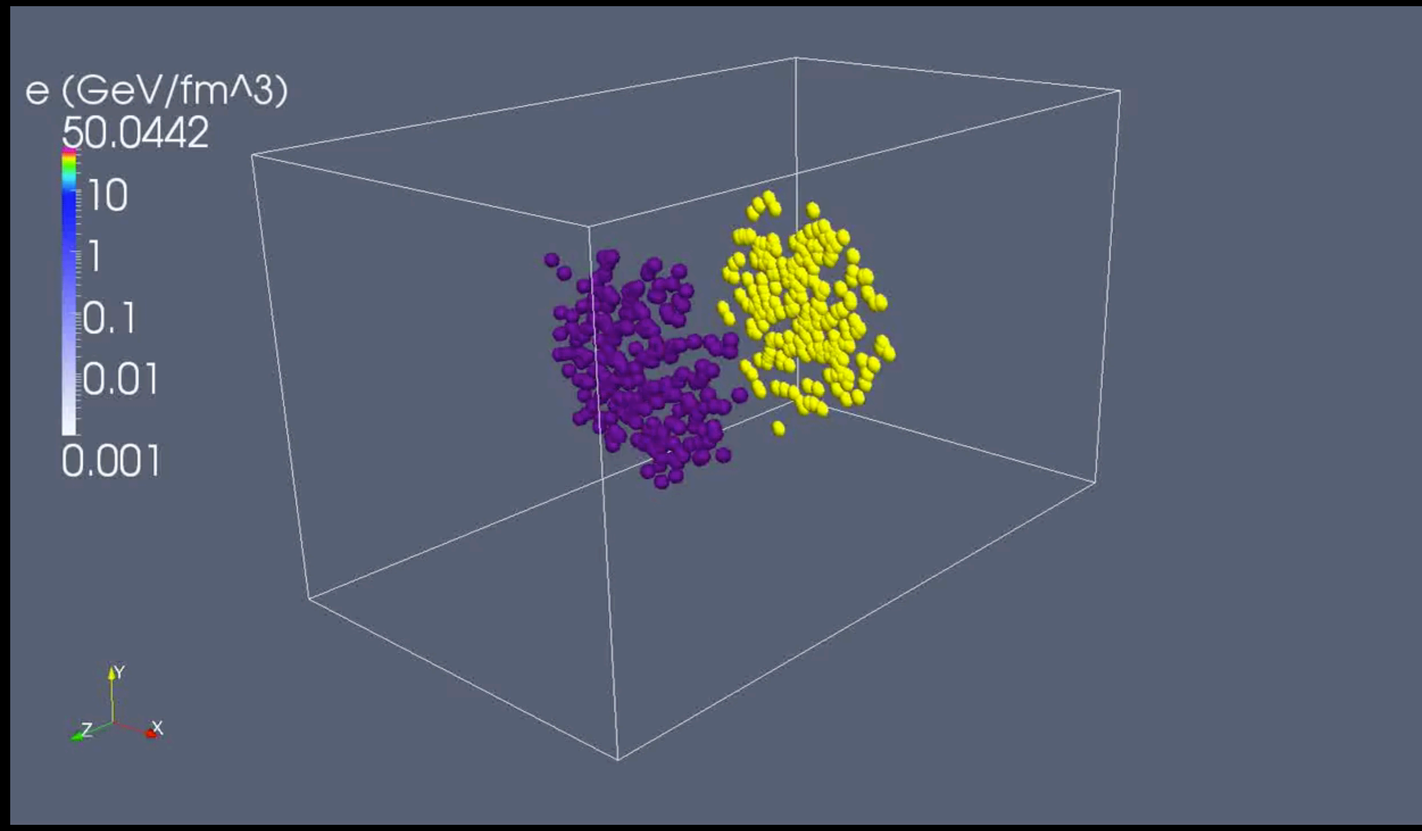
NUCLEAR MATTER UNDER EXTREME CONDITIONS

$T>10^{12}K$, $P>10^{30}ATM$

Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab

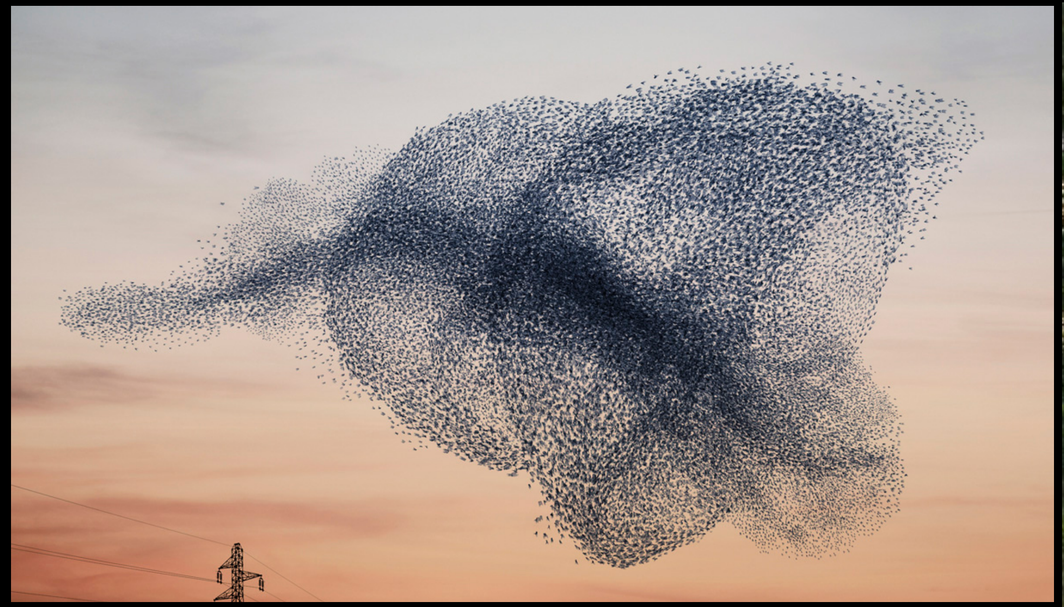
Large Hadron Collider (LHC) at CERN

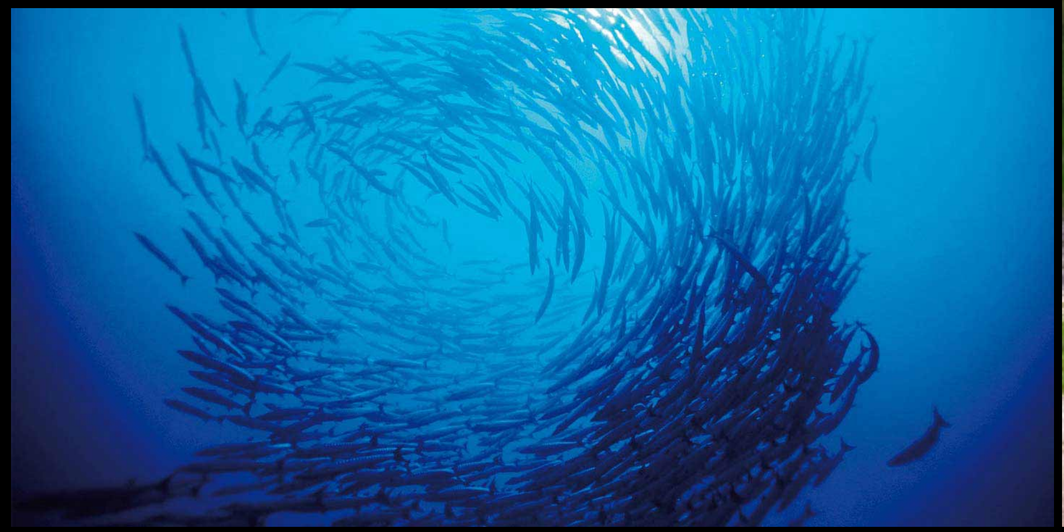




http://youtu.be/W3h5vQOUJTg

MORE IS DIFFERENT

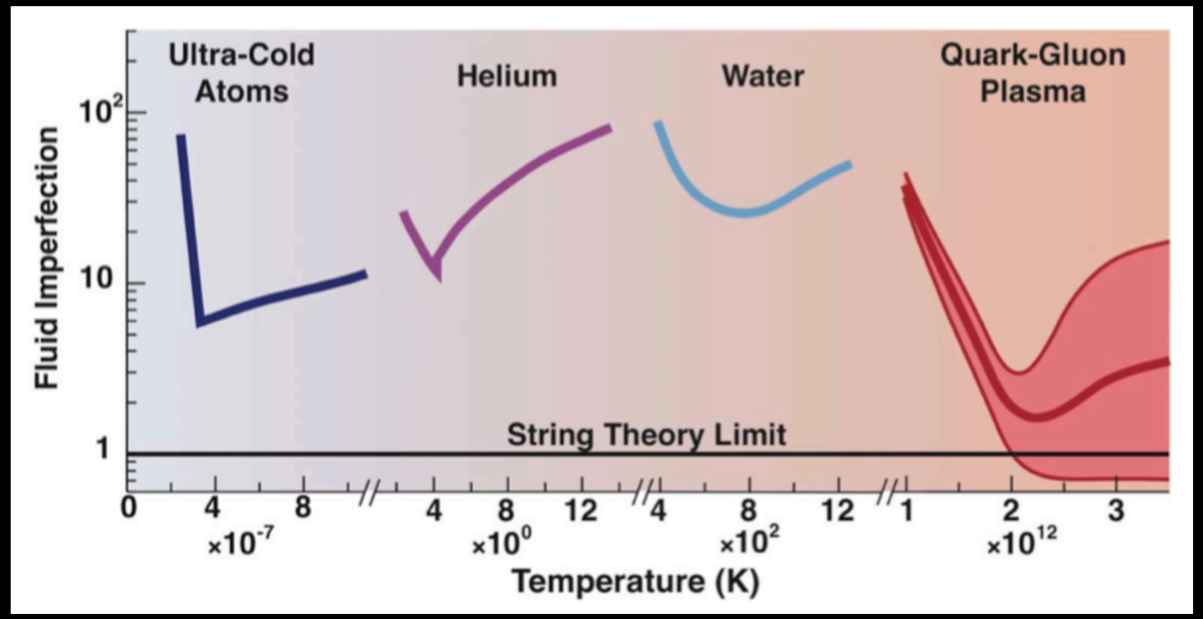


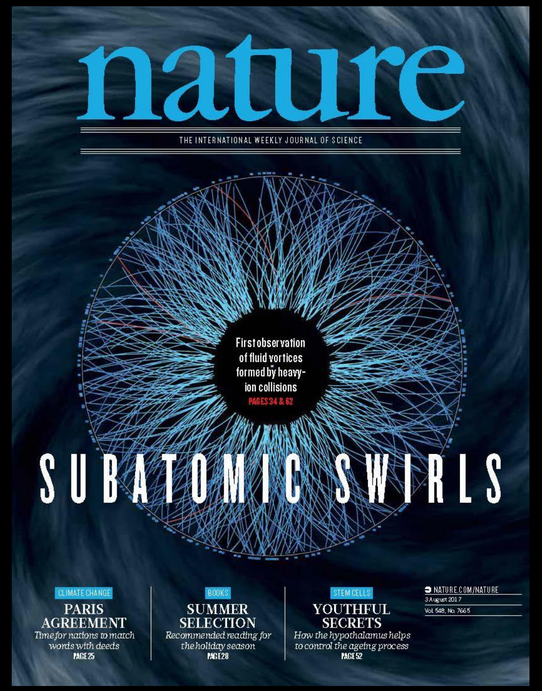


QUARK-GLUON PLASMA (QGP)

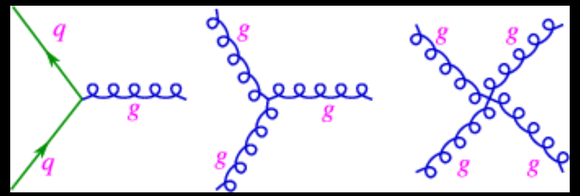
- Quark-Gluon Plasma is the hottest, smallest, and the most perfect and vortical fluid in nature!

Burrows A et al. 2013 Implementing the 2007 Long Range Plan

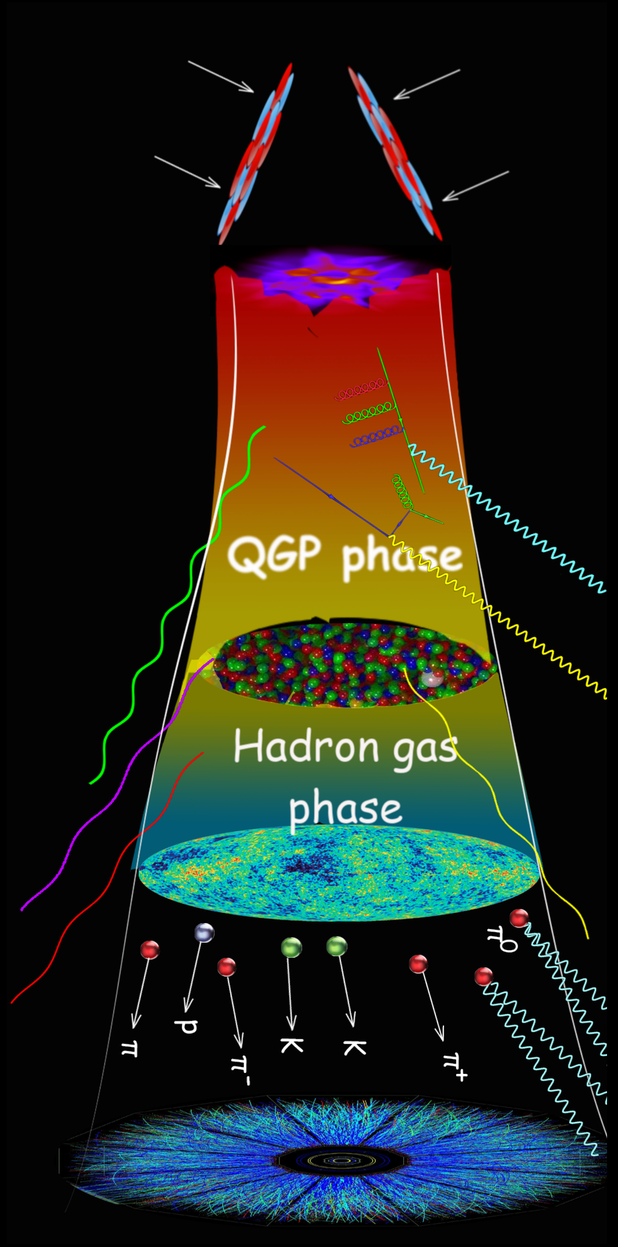




- How does this emerge from QCD?



DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$$c_s^2 = \partial P/\partial e|_{s/n}$$

Shear and bulk viscosities $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$

Spectra, collective flow, femtoscopy

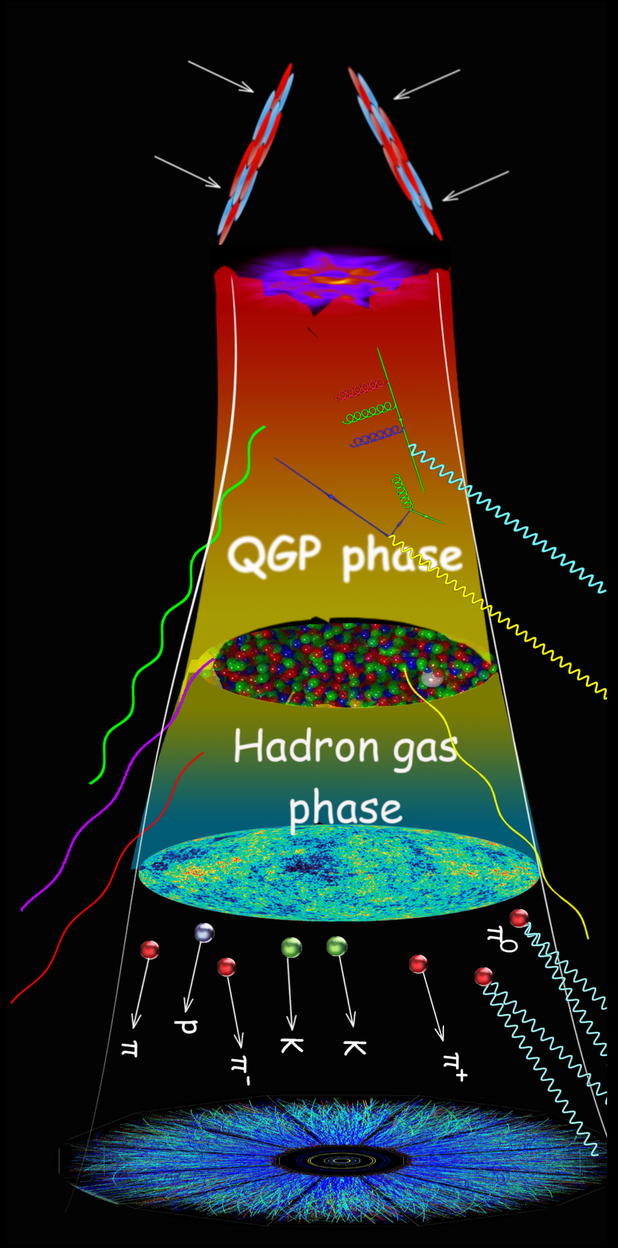
Anisotropic flow v_n
Flow correlations

Balance functions

Photons and dileptons

Jets and heavy-quarks

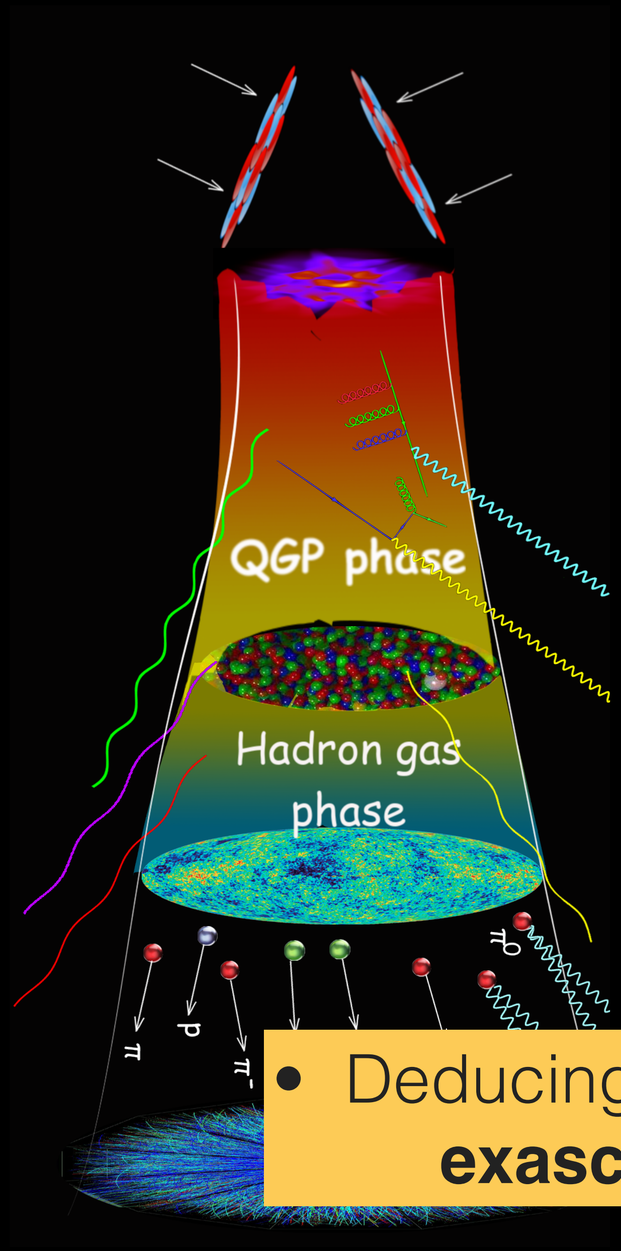
DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$ $c_s^2 = \partial P/\partial e\|_{s/n}$	Spectra, collective flow, femtoscopy
Shear and bulk viscosities $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$	Anisotropic flow v_n Flow correlations
Charge diffusion D_B, D_Q, D_S	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$c_s^2 = \partial P/\partial e|_{s/n}$

Shear and bulk viscosities

$\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Spectra, collective flow, femtoscopy

Anisotropic flow v_n

Flow correlations

Balance functions

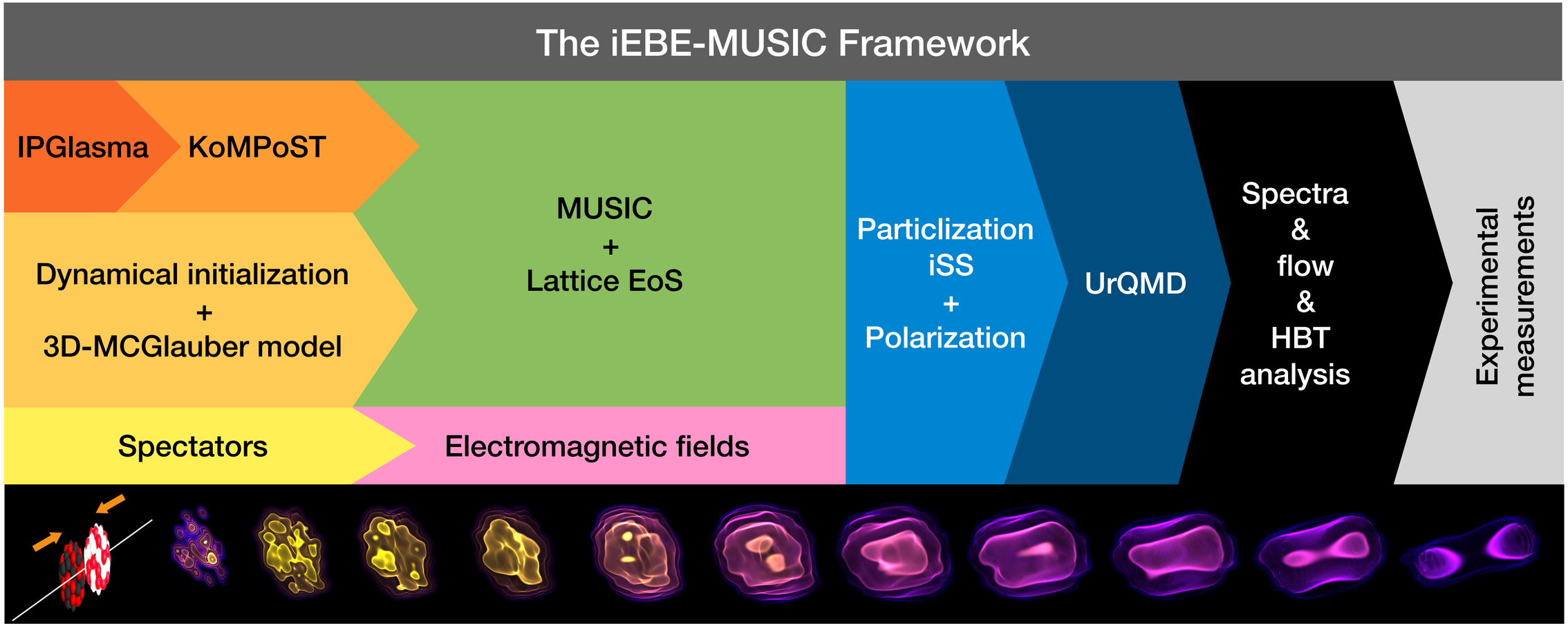
Photons and dileptons

quarks

- Deducing the QGP properties from experimental data requires **exascale computing** with advanced statistical methods

AN OPEN SOURCE HYBRID FRAMEWORK—IEBE-MUSIC

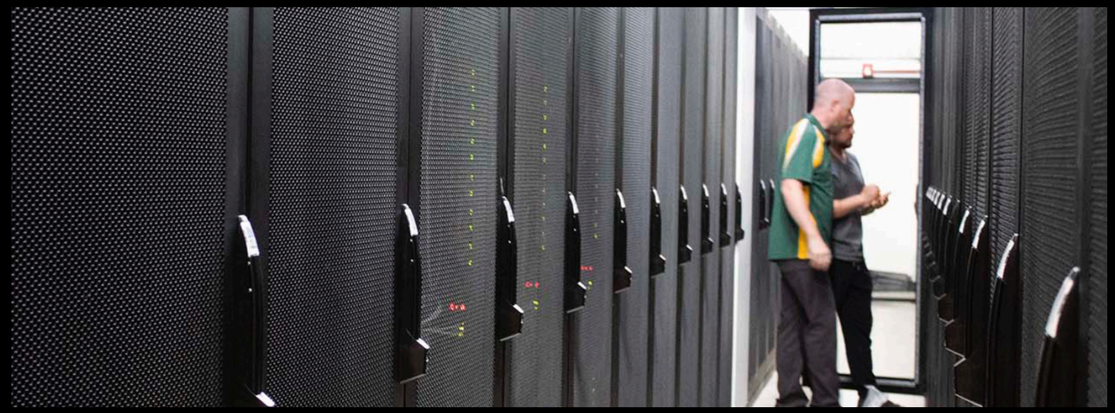
https://github.com/chunshen1987/iEBE-MUSIC



The state-of-the-art event-by-event simulations for relativistic heavy-ion collisions

HIGH PERFORMANCE COMPUTING

The top 1 user at Wayne State Grid



Open Science Grid

BAYESIAN INFERENCE ANALYSIS

- Data driven approach to calibrate all model parameters
- Determine the best values and their probability distributions

A: exp data; B: theory params

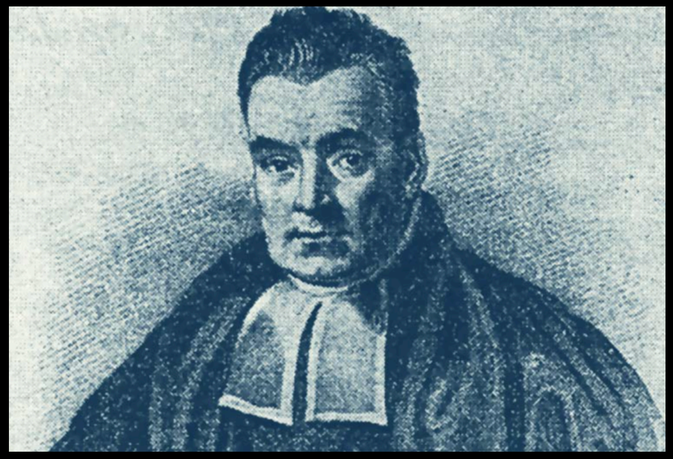
Bayes' Theorem

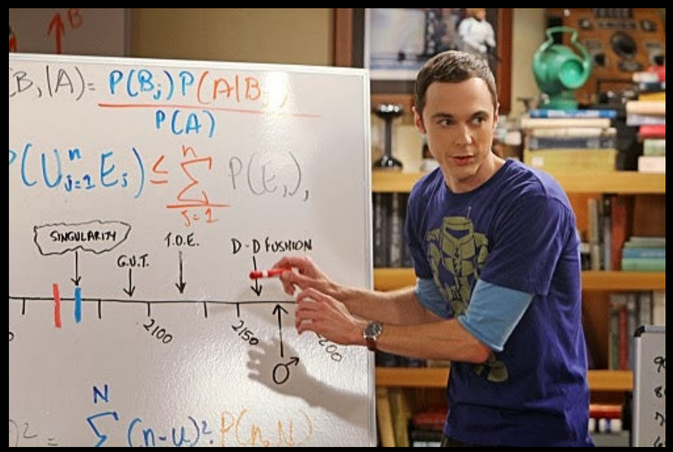
$$P(B|A) \propto P(A|B)P(B)$$

P(A|B): (likelihood) probability of data given theory(parameters)

P(B|A): (posterior) probability of theory(parameters) given data

P(B): (prior) initial knowledge about the theory parameters



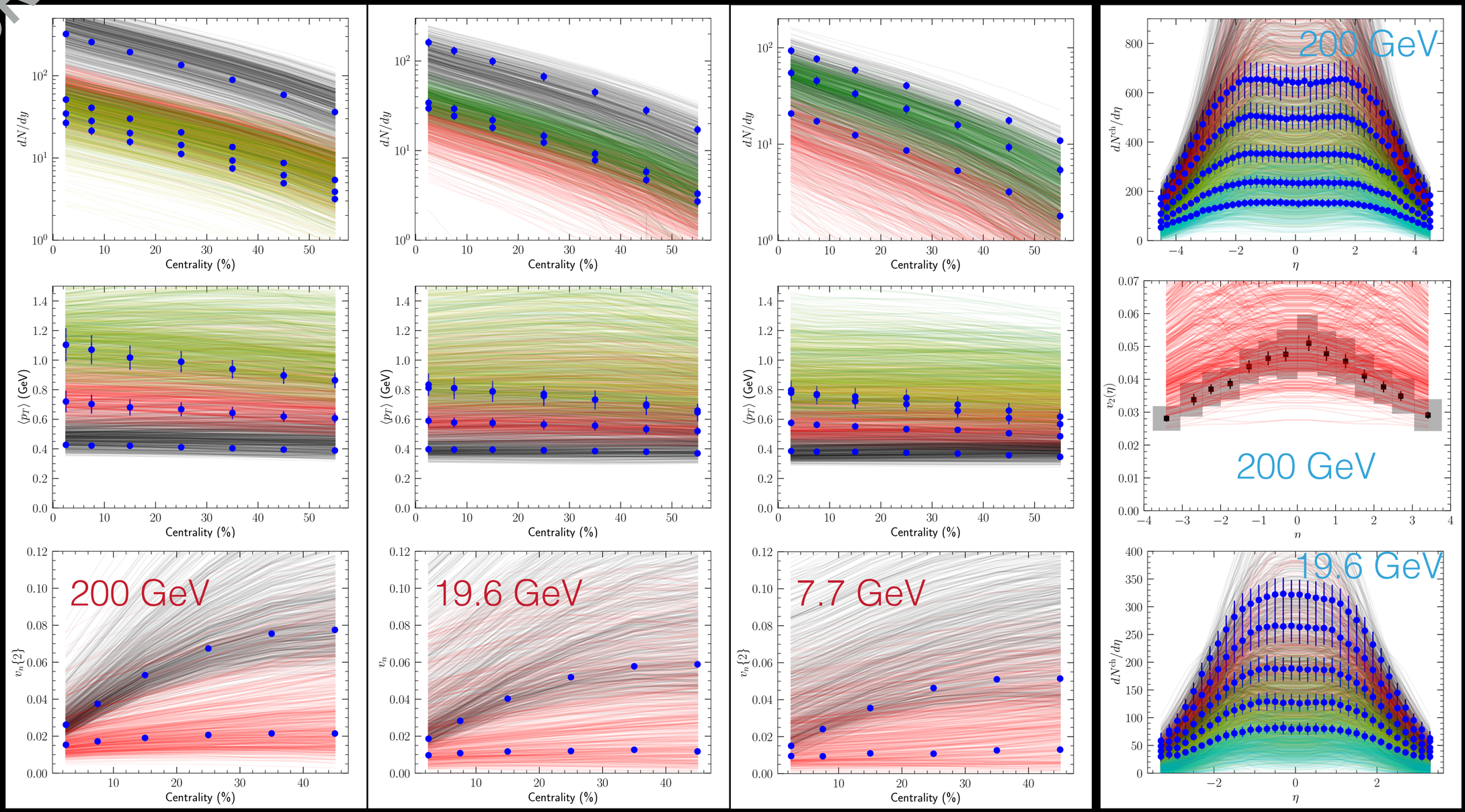


BAYESIAN INFERENCE AT RHIC BES ENERGIES

PRIOR

STAR

PHOBOS

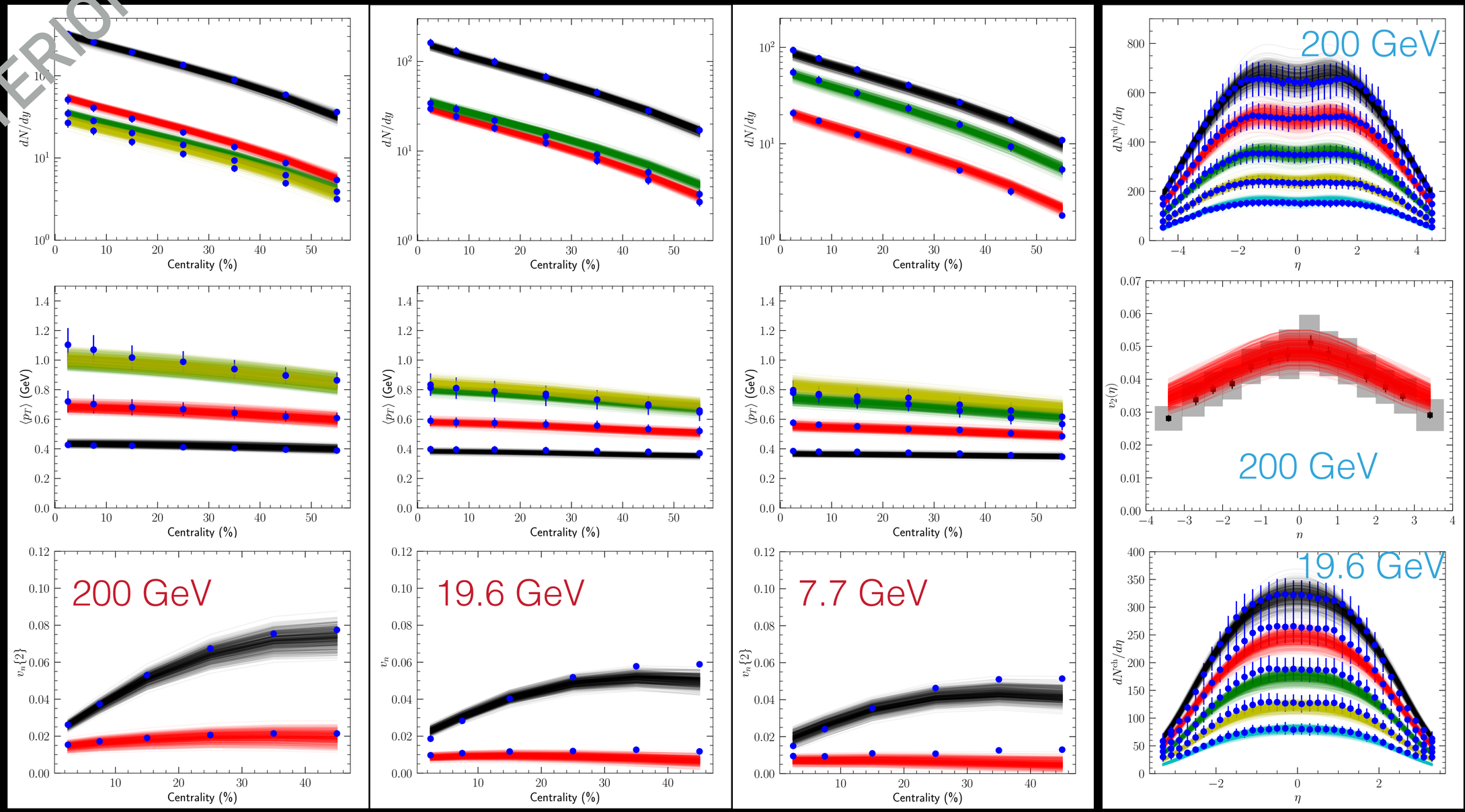


BAYESIAN INFERENCE AT RHIC BES ENERGIES

POSTERIOR

STAR

PHOBOS

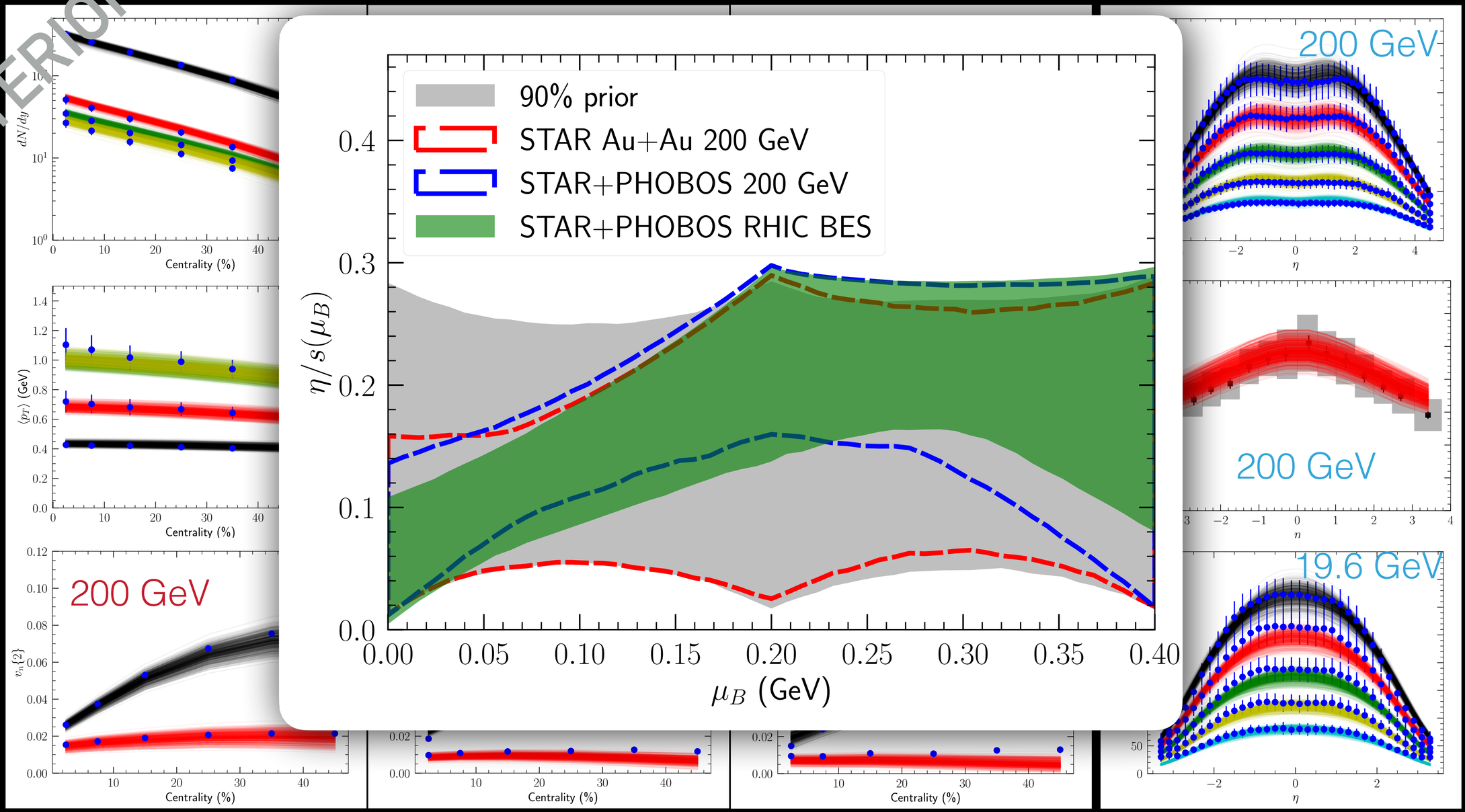


BAYESIAN INFERENCE AT RHIC BES ENERGIES

POSTERIOR

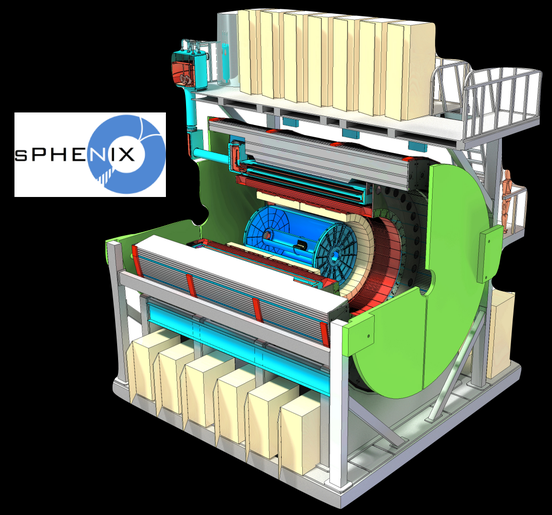
STAR

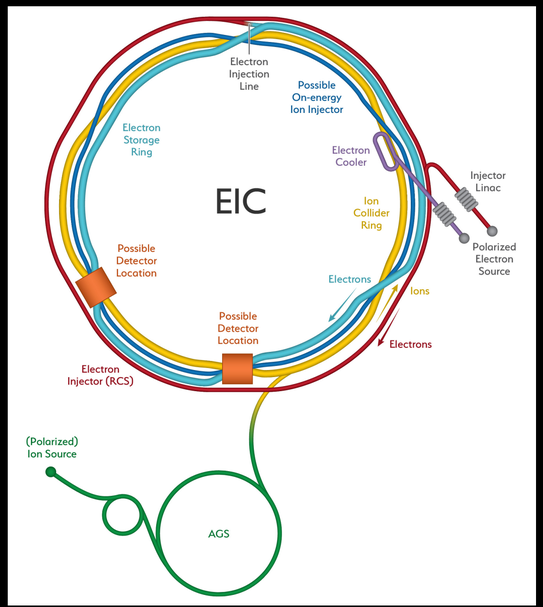
PHOBOS



THE ERA OF PRECISION HEAVY-ION PHYSICS

- RHIC: STAR upgrade and sPHENIX program
  - Probing QCD at high net baryon density
  - Study fully resolved jets, Upsilon states, and heavy quarks as QGP structure probes
- LHC: ALICE, CMS, ATLAS upgrades
  - High energy and high luminosity frontier
  - Precision measurements for rare probes
- HADES, FAIR, J-PAC-HI
  - Phase structure of hot QCD matter
- Future Electron-Ion Collider
  - Tomography of nucleon and nucleus
  - smallest QGP droplet?





SUMMARY

- Quark-Gluon Plasma is the hottest, smallest, and the most perfect fluid ever created in the laboratory
  - relativistic, strongly coupled, and nonlinear system
  - exhibits universal collective behavior
- Fluid dynamic paradigm is remarkably successful in quantitative determination of the QGP transport properties
  - first principles inputs
  - statistical analysis and machine learning
- Dynamically modelling of relativistic heavy-ion collisions is the cornerstone of study the phase structure of nuclear matter