



Re-Engineering the Big Bang: the Physics of Heavy Ion Collisions

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RHIC: recreating the Early Universe in the Lab

The purpose of the
Relativistic

Heavy

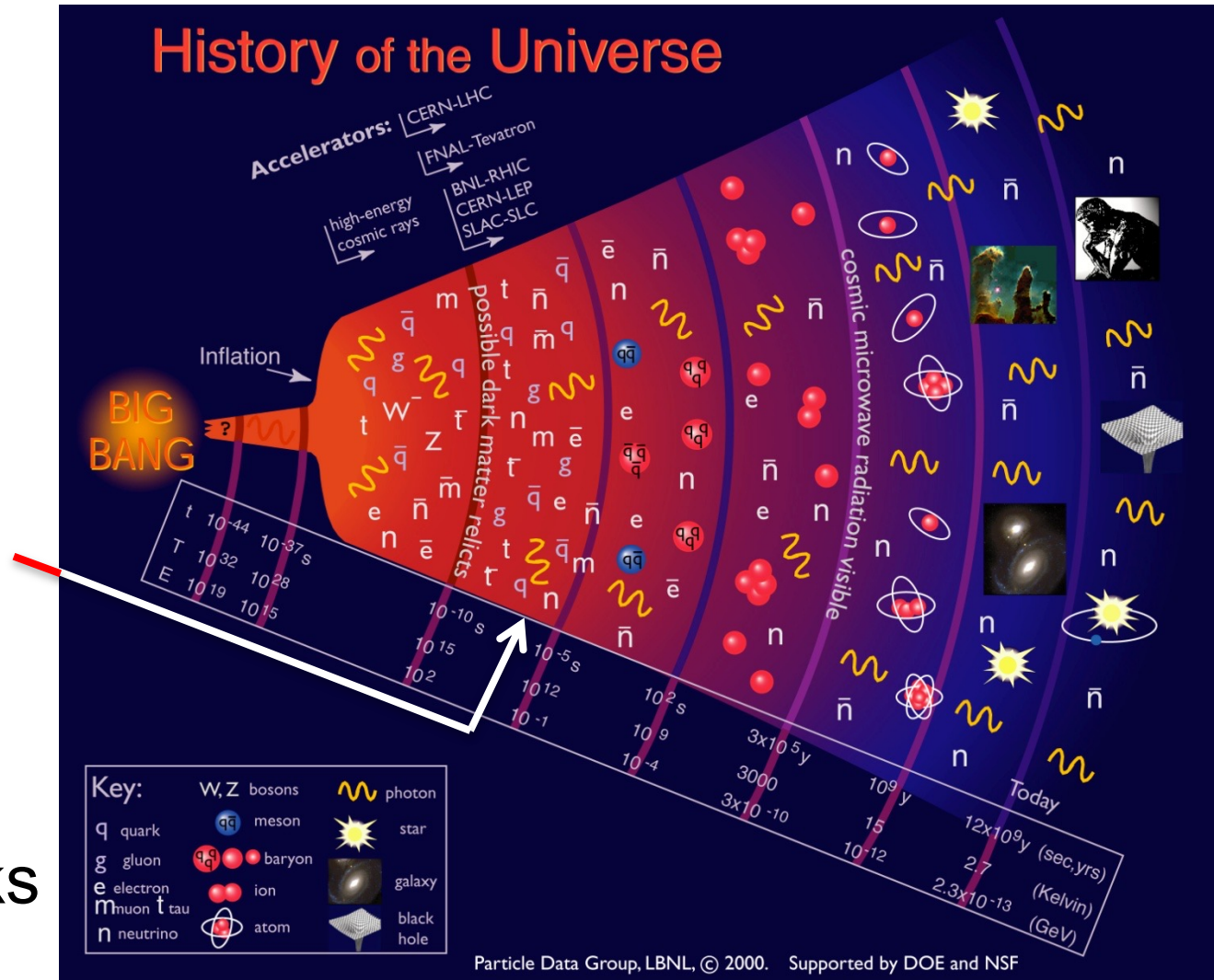
Ion

Collider

To recreate conditions
as they existed 1 μ s
after the Big Bang

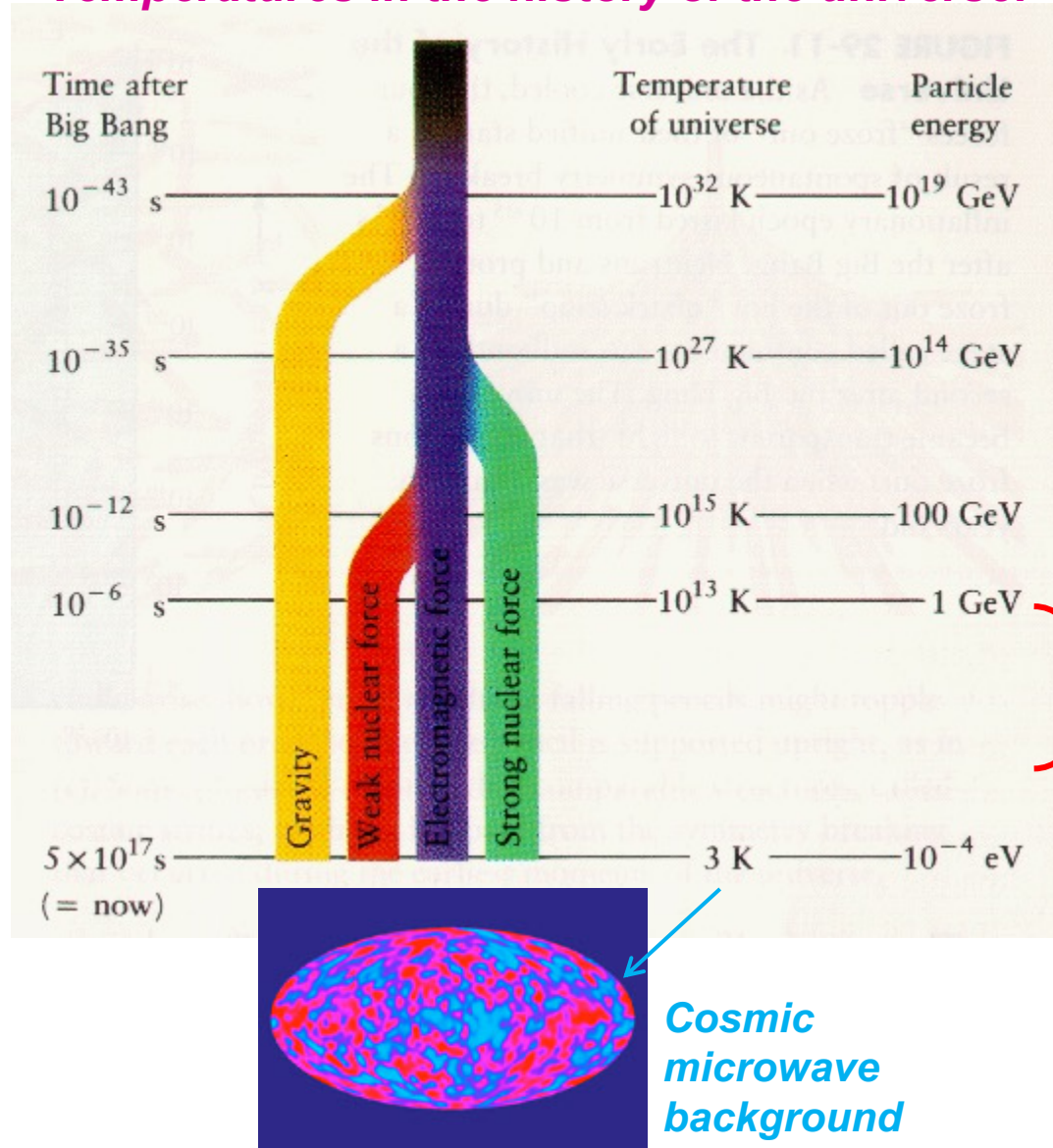
Quark Gluon Plasma:

Hot soup of free quarks
and gluons



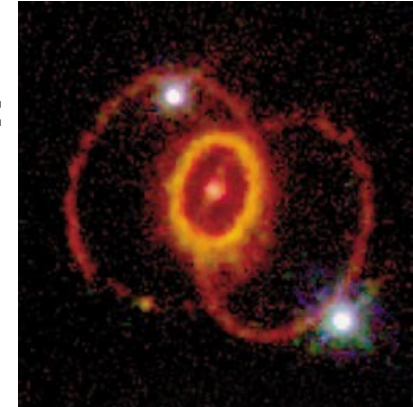
How Hot Is It?

Temperatures in the history of the universe:

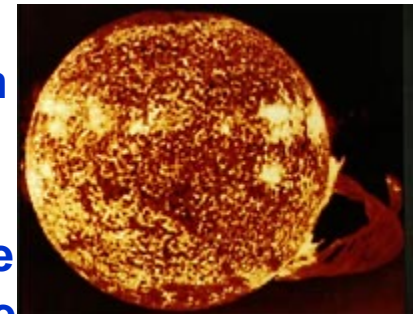


$\sim 4 \times 10^{12}$ K : RHIC matter
 $\sim 2 \times 10^{12}$ K : predicted melting temp. for neutrons & protons

$\sim 1 \times 10^{11}$ K : typical core temp. of Type II supernova



1.5×10^7 K : center of Sun

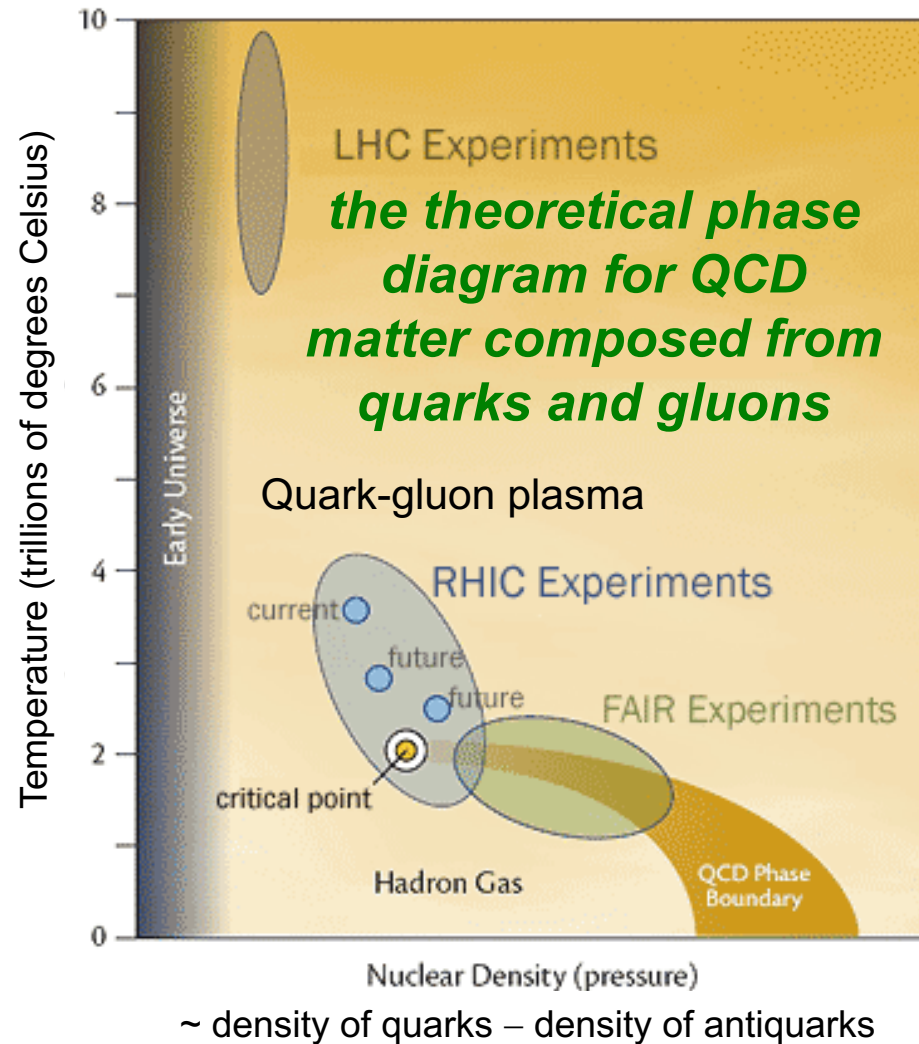
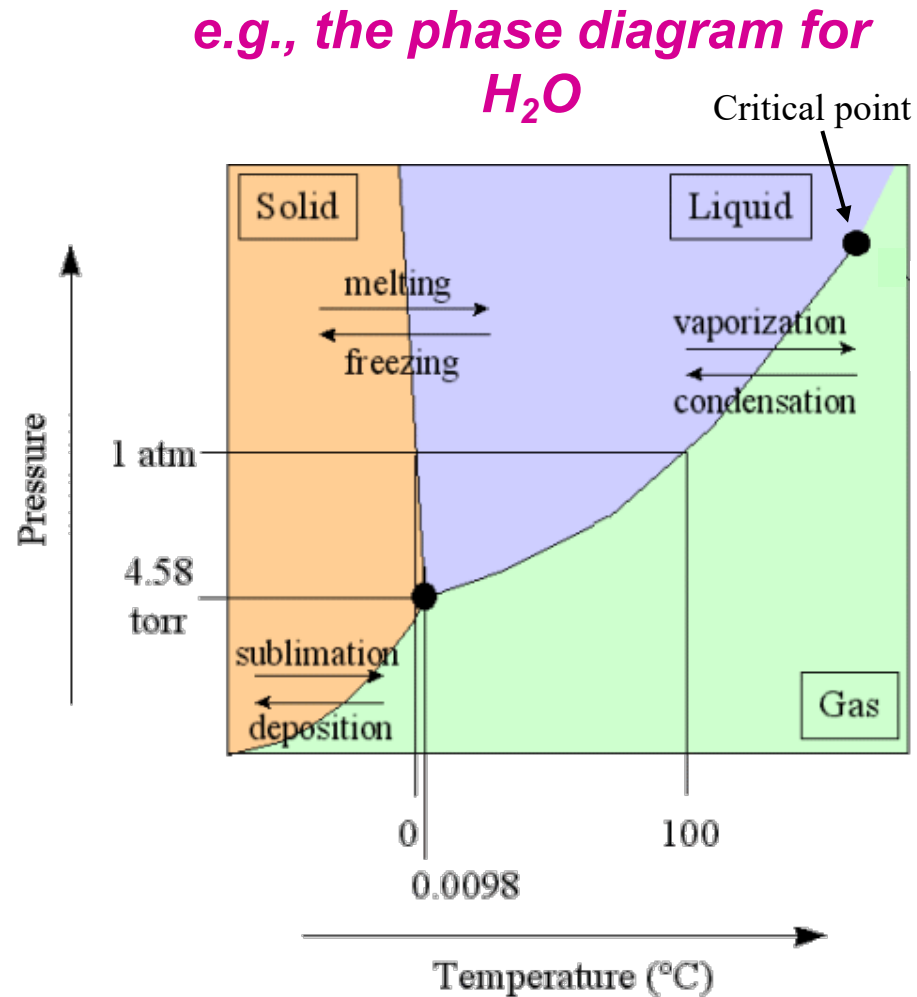


5.8×10^3 K : Sun's surface $\approx$ Earth's core

1.8×10^3 K : iron melts



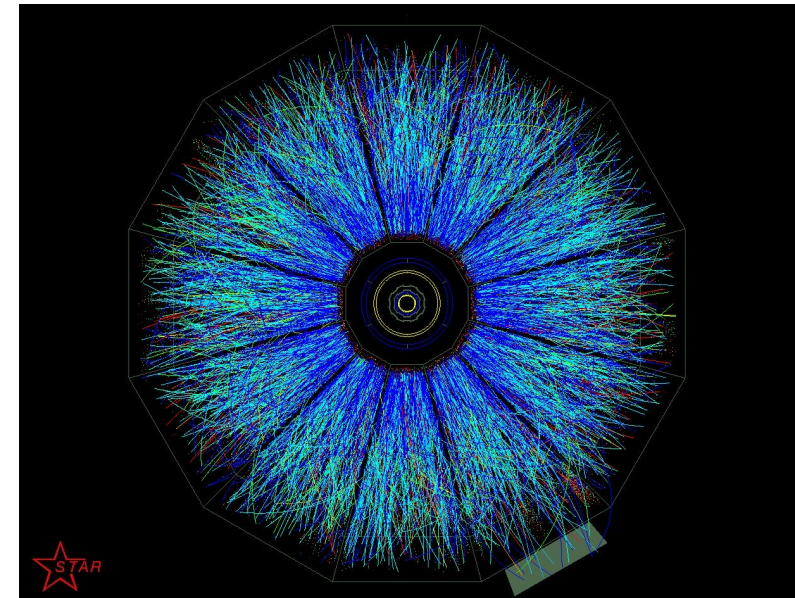
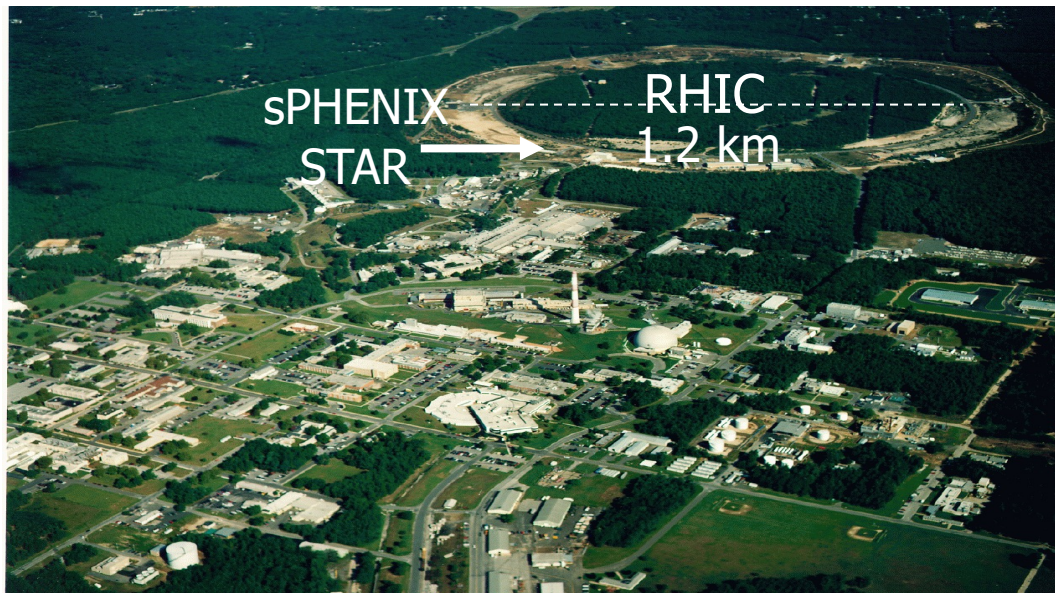
Matter Can Exist in Various Phases with Transitions Between Them Marked by Fluctuations, Like Bubbles in Boiling Water



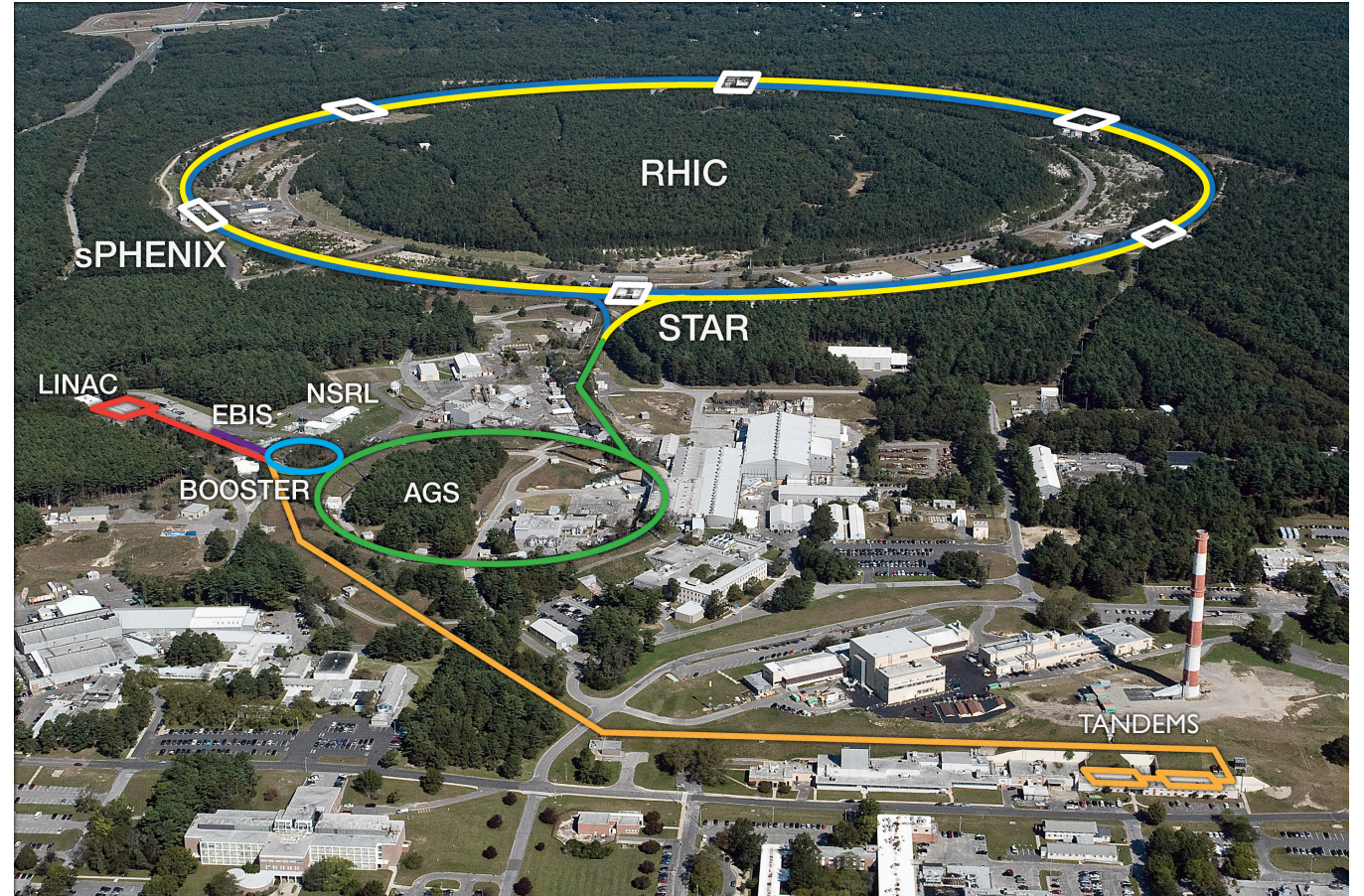
We now know that RHIC collisions produce quark-gluon plasma that expands, cools and condenses into hadrons that reach the detectors

How to do this: RHIC Implementation

- Accelerate nuclei as heavy as Au to high energies (99.996% speed of light) and steer them to collide
- Produces matter:
 - At temperature of 4 Trillion °C
 - For ~30 yoctoseconds (10^{-24} seconds)
 - Of radius 10 femtometers (10^{-15} meters)

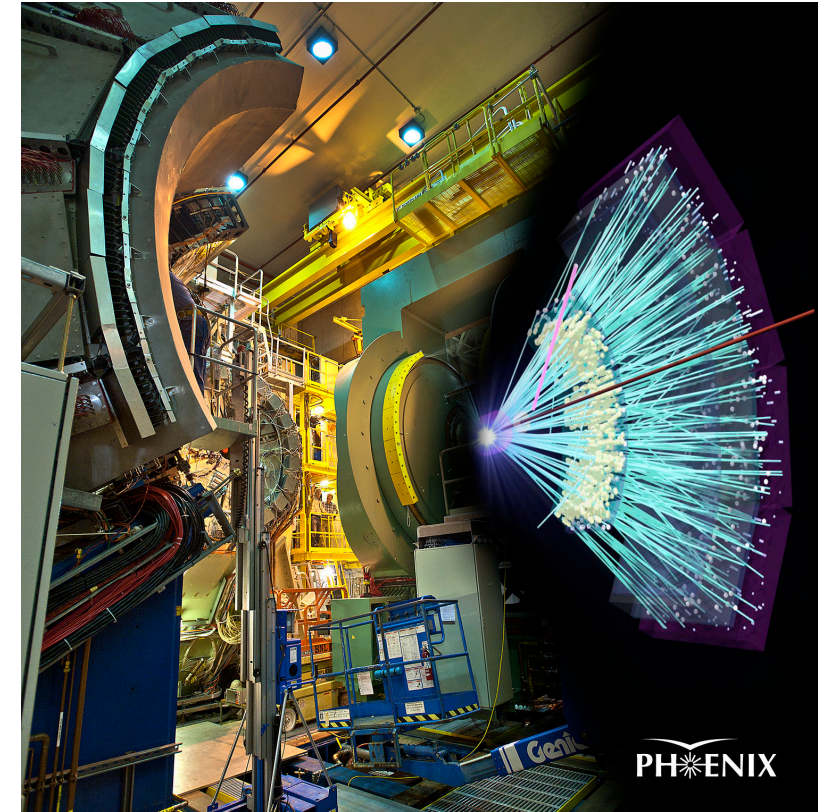
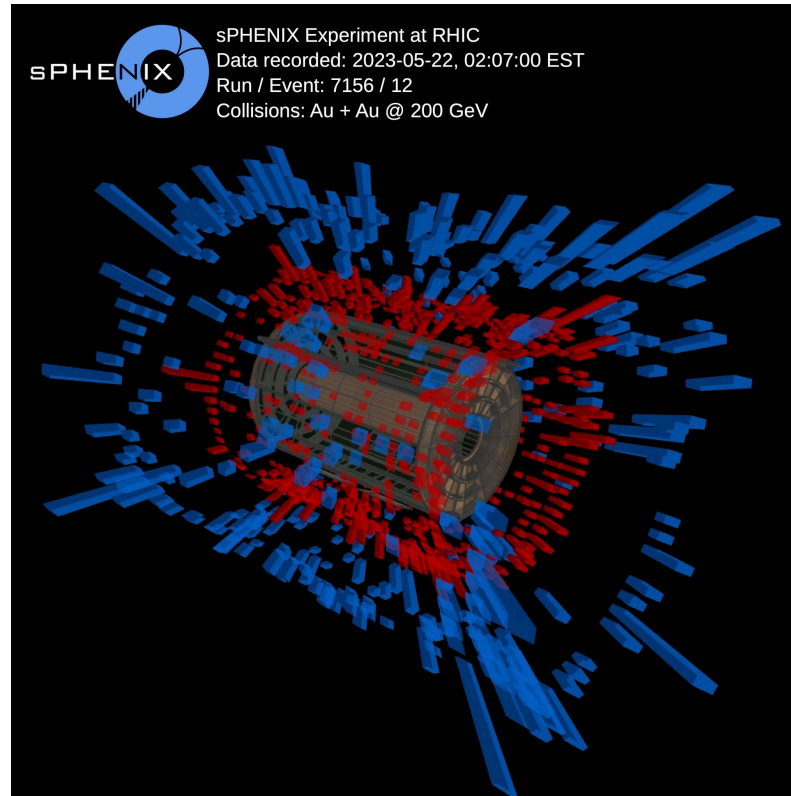
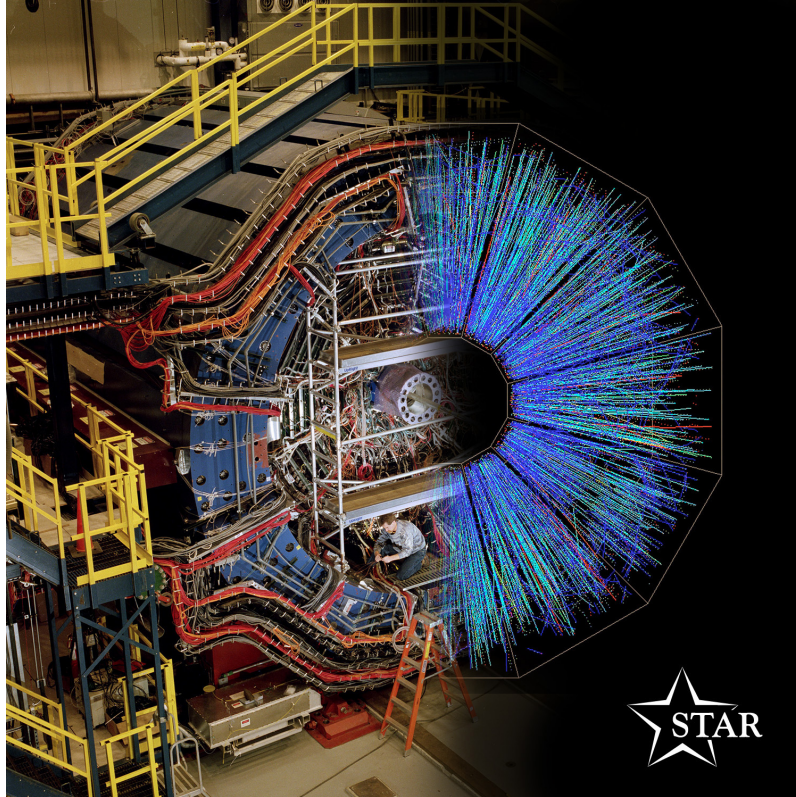


RHIC Complex

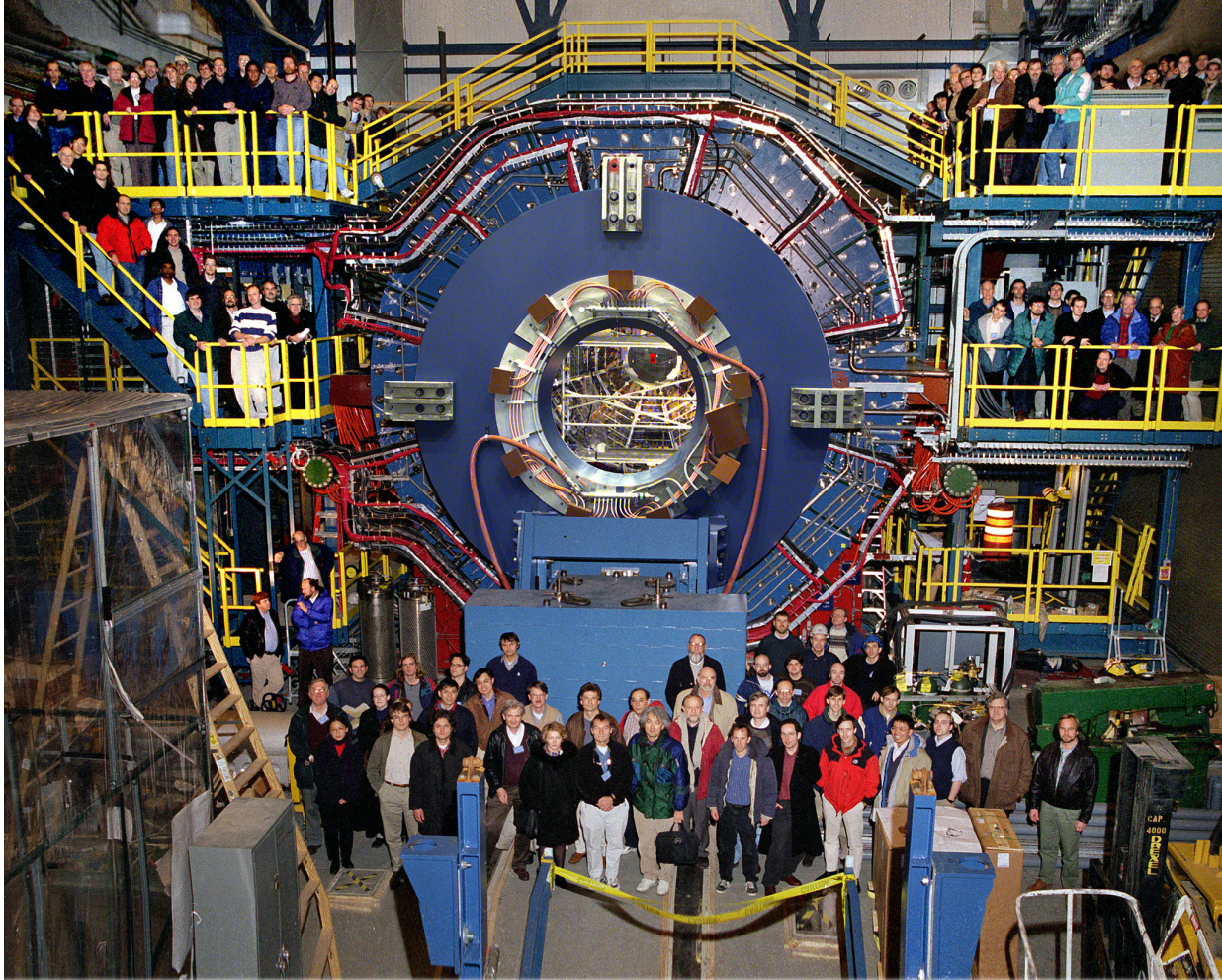


RHIC will have been in operation from 2000 to 2025
Most flexible collider in the world, from protons to Uranium
over two orders of magnitude in energy and 100x design luminosity

Detectors



People



The STAR experiment

at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

★ star member institutions

STAR is composed of 74 institutes from 15 countries, with a total of 746 collaborators.



Large multipurpose detectors require large collaborations for construction, operation, and analysis

People

Sidebar 3.8 EIC Network for Discovery Science and Workforce Development

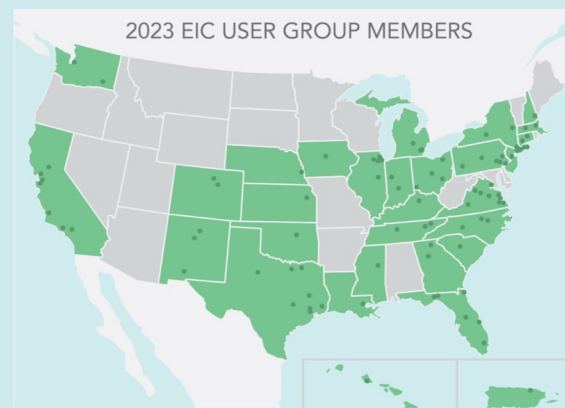
An EIC network would empower discovery science at the EIC while strengthening and building nuclear physics research at U.S. institutions, especially those with limited research capacities, and supporting training of a STEM workforce for the nation from a broad pool of talent.

The network would promote partnerships between U.S. national labs and universities and support students and postdoctoral fellows. Additionally, the network would foster collaborations between experimentalists and theorists, organize traineeships, and provide mentoring and career development programs.

In addition to discovery science, the nation benefits from a highly skilled STEM workforce for advances in fields such as energy, environment, health, and national security.



One of our DOE-NP Traineeship (NPT) students, Ambar Rodriguez Alicea. She was an undergraduate at Univ of Puerto Rico, and worked with Luca Cultrera from Instrumentation Division at BNL on “spin polarized electron emission studies”, to investigate numerically finding better photocathodes for producing polarized electrons. She is now a graduate student at Michigan State University pursuing a PhD in nuclear physics [S22].



[S23]



[S24]

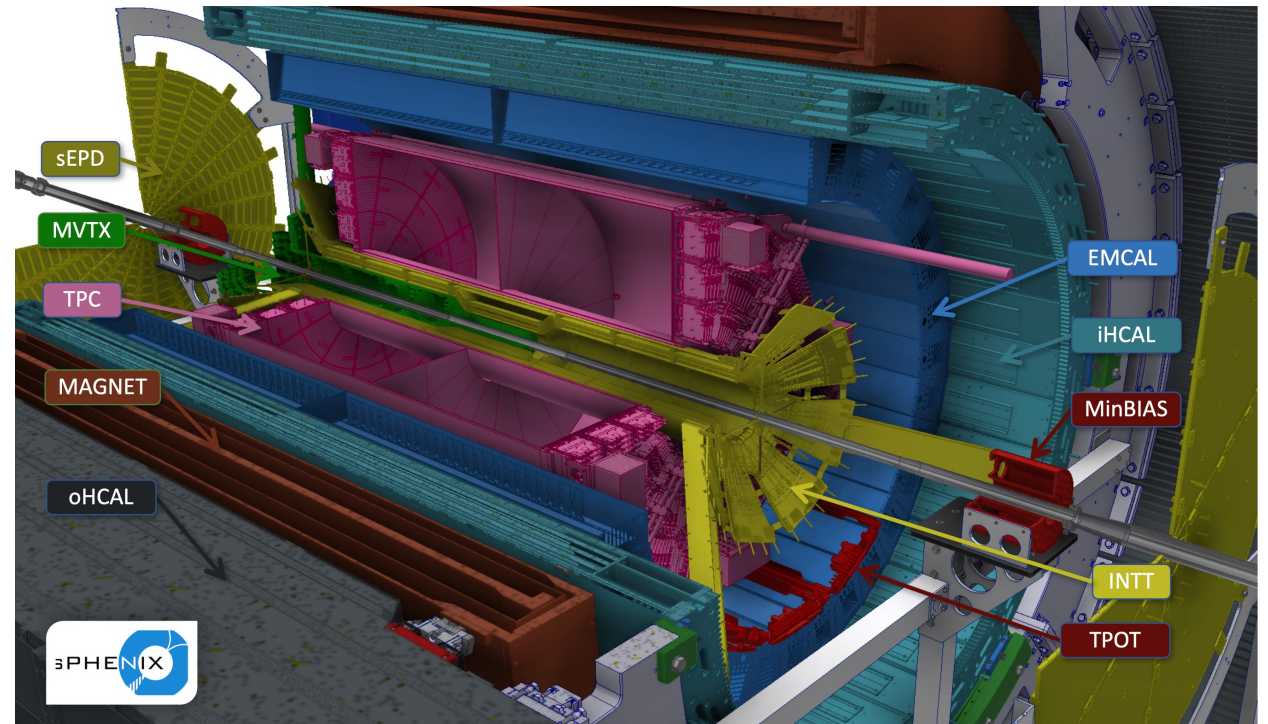
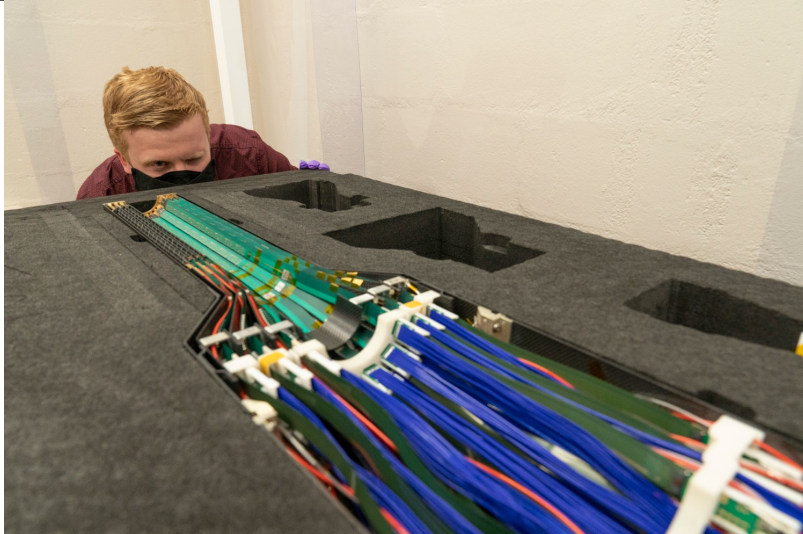
From
Nuclear
Science
Advisory
Council
2023
Long
Range
Plan
for
Nuclear
Science

Detector Construction

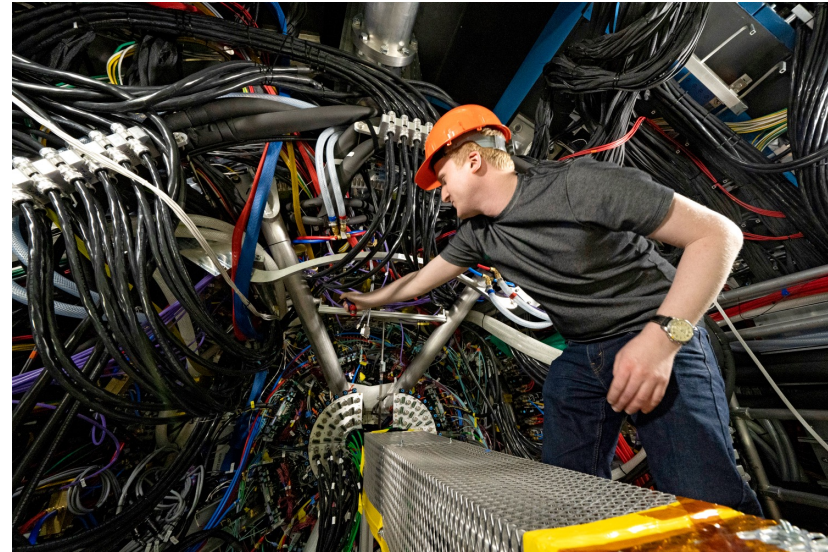


sPHENIX construction and installation:
Sept. 2019 to May 2023

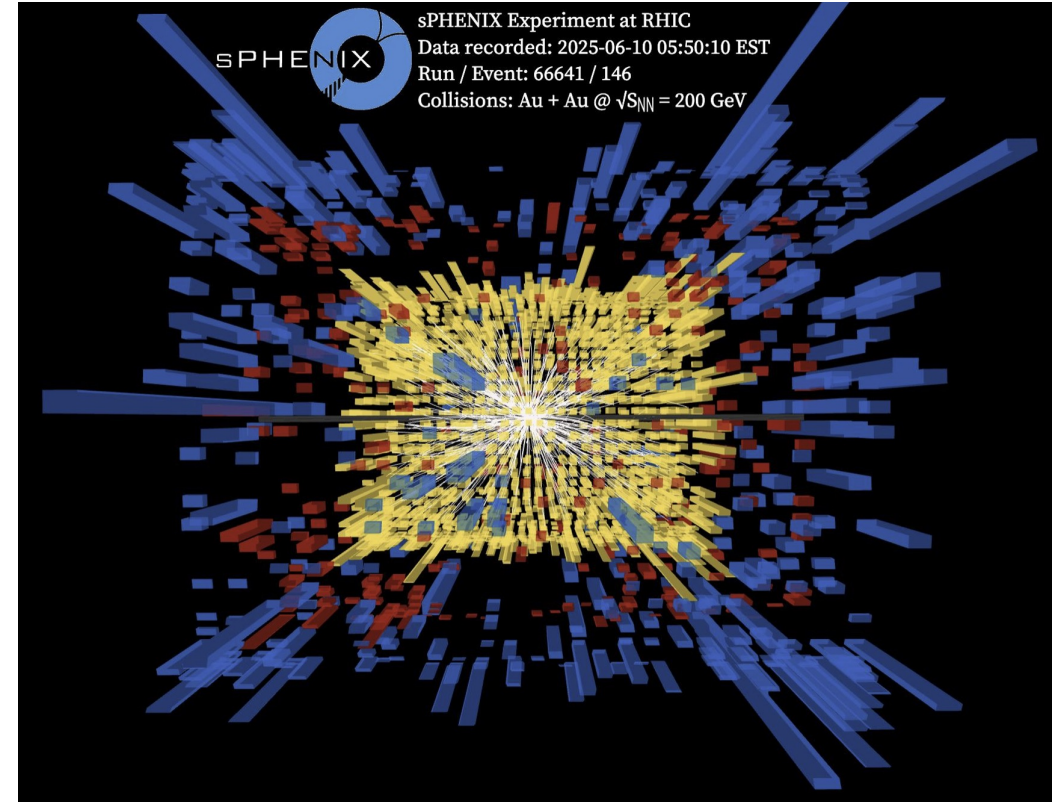
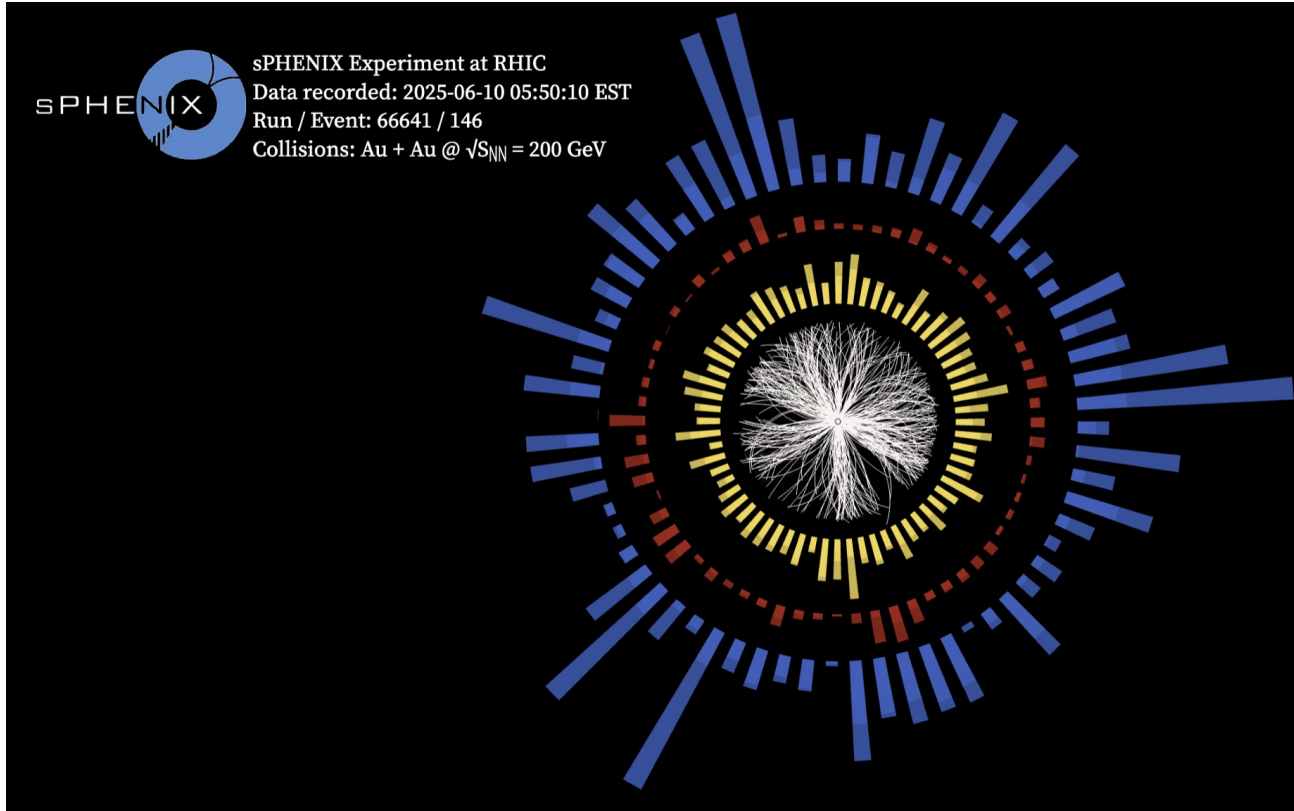
Many subsystems and substantial effort from
partner institutions, including subsystem
construction at those institutions



sPHENIX: Installing a detector

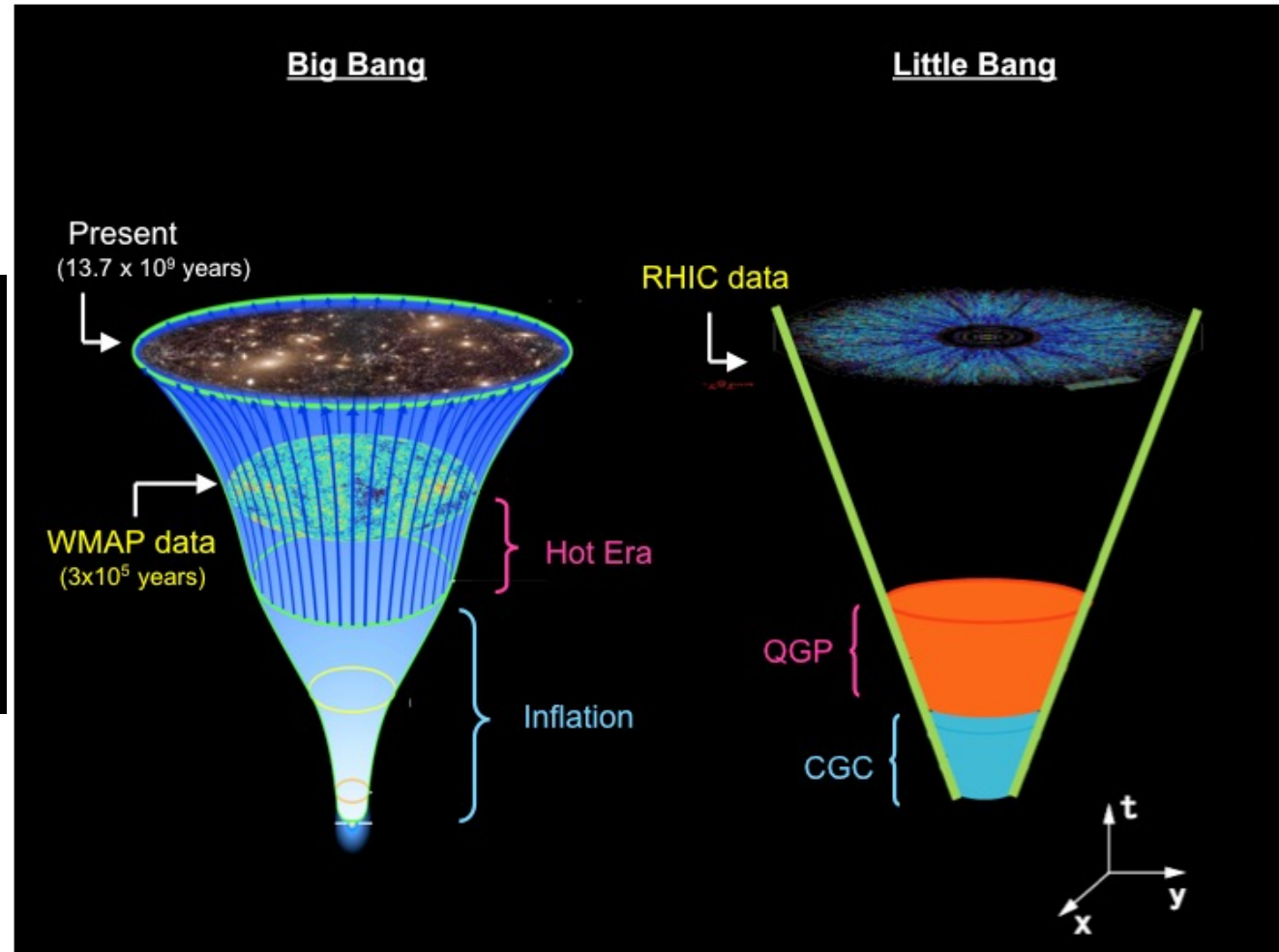
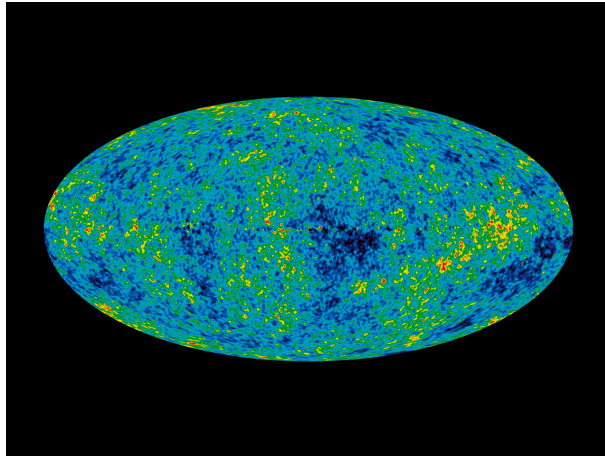


An sPHENIX Event



- Particles deposit energy in detector systems
- Reconstruct 3D trajectories and energy patterns
 - Expecting few hundred petabytes of data this year

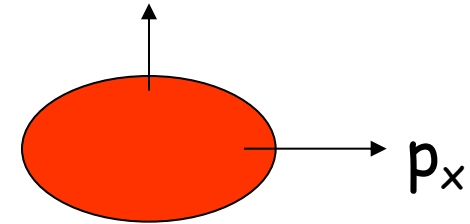
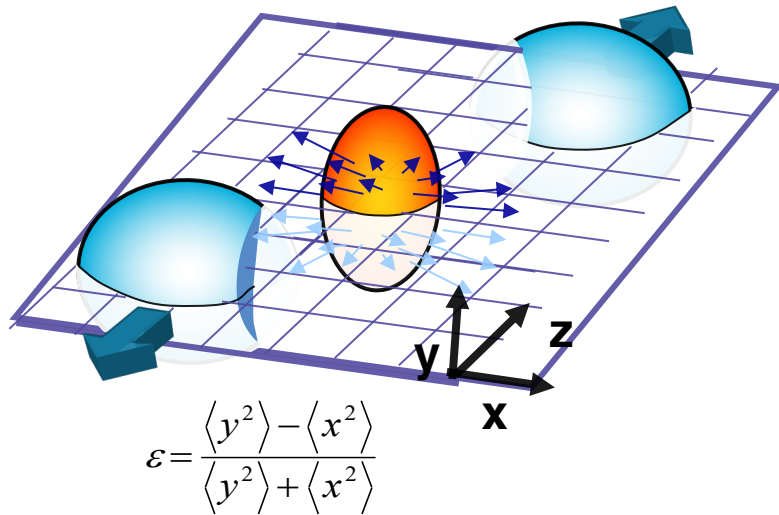
What to Measure: Patterns



- Collisions produce thousands of particles: $E=mc^2$
- Patterns in produced particles: properties of the matter

Collective Behavior: Azimuthal Anisotropy v_2

Pressure converts initial coordinate-space anisotropy into final momentum-space anisotropy



initial spatial anisotropy

anisotropy in momentum space

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

$$E \frac{dN^3}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} (1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 \cos(2(\phi - \Psi_R)) + \dots)$$

isotropic

directed

elliptic

higher harmonics

$$v_n = \left\langle \cos(n(\phi - \psi_{RP})) \right\rangle = \left\langle e^{in(\phi - \psi_{RP})} \right\rangle$$

= Correlation to the reaction plane

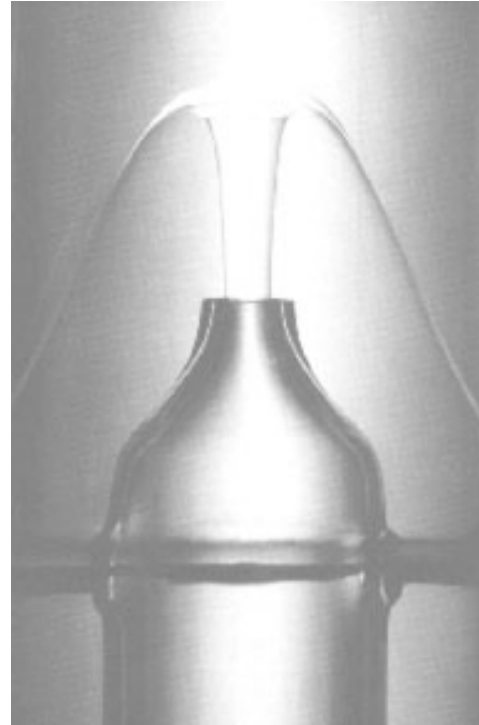
≡ "anisotropic flow"

Viscosity

Molasses:
High viscosity



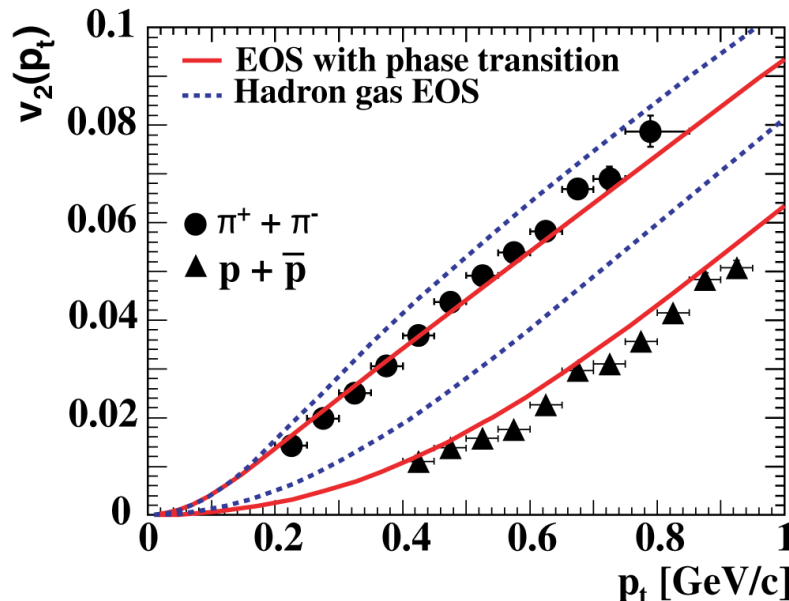
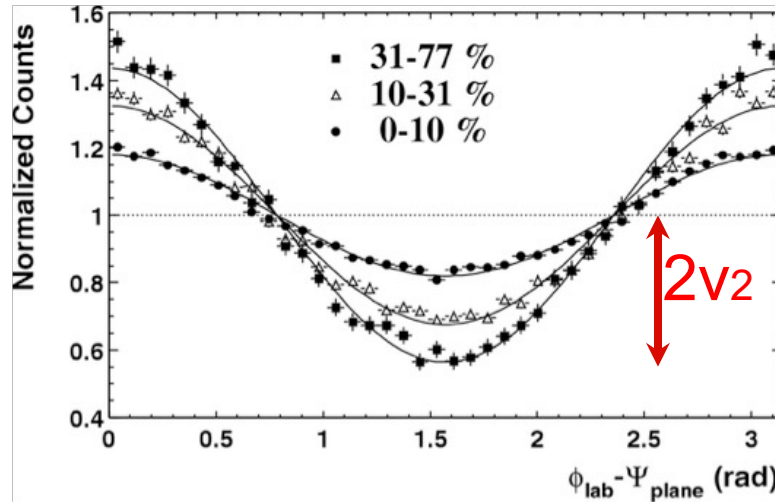
Superfluid helium: “Perfect” Fluid:
Low viscosity No viscosity



viscosity |,vi'skäsītē|noun (pl. **-ties**)

- **the state of being thick, sticky, and semifluid in consistency, due to internal friction.**

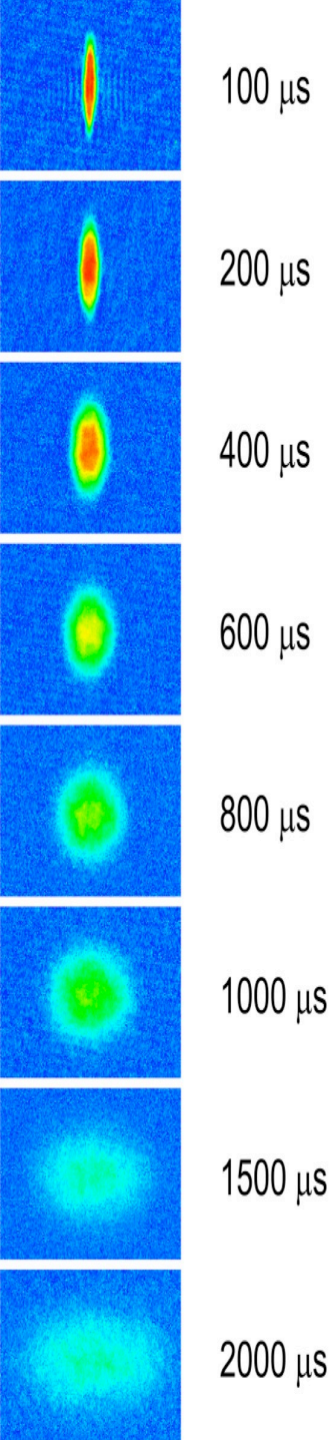
The Flow is ~Perfect



Hydro calculations: Kolb, Heinz and Huovinen

- ◆ Huge asymmetry found at RHIC
 - ▶ massive effect in azimuthal distribution w.r.t reaction plane
 - ▶ At higher p_T : Factor 3:1 peak to valley from 25% v_2
- ◆ The “fine structure” $v_2(p_T)$ below ~ 2 GeV/c for different mass particles shows good agreement with ideal (zero viscosity, $\lambda=0$) hydrodynamics
- “perfect liquid”
- Appealing picture:
 - Nearly perfect fluid with local thermal equilibrium established at $< \sim 1$ fm with a soft equation of state containing a QGP stage

Analogy to Ultracold Atoms



Extremely cold system at $T=10$ nK or 10^{-12} eV can produce micro-bang

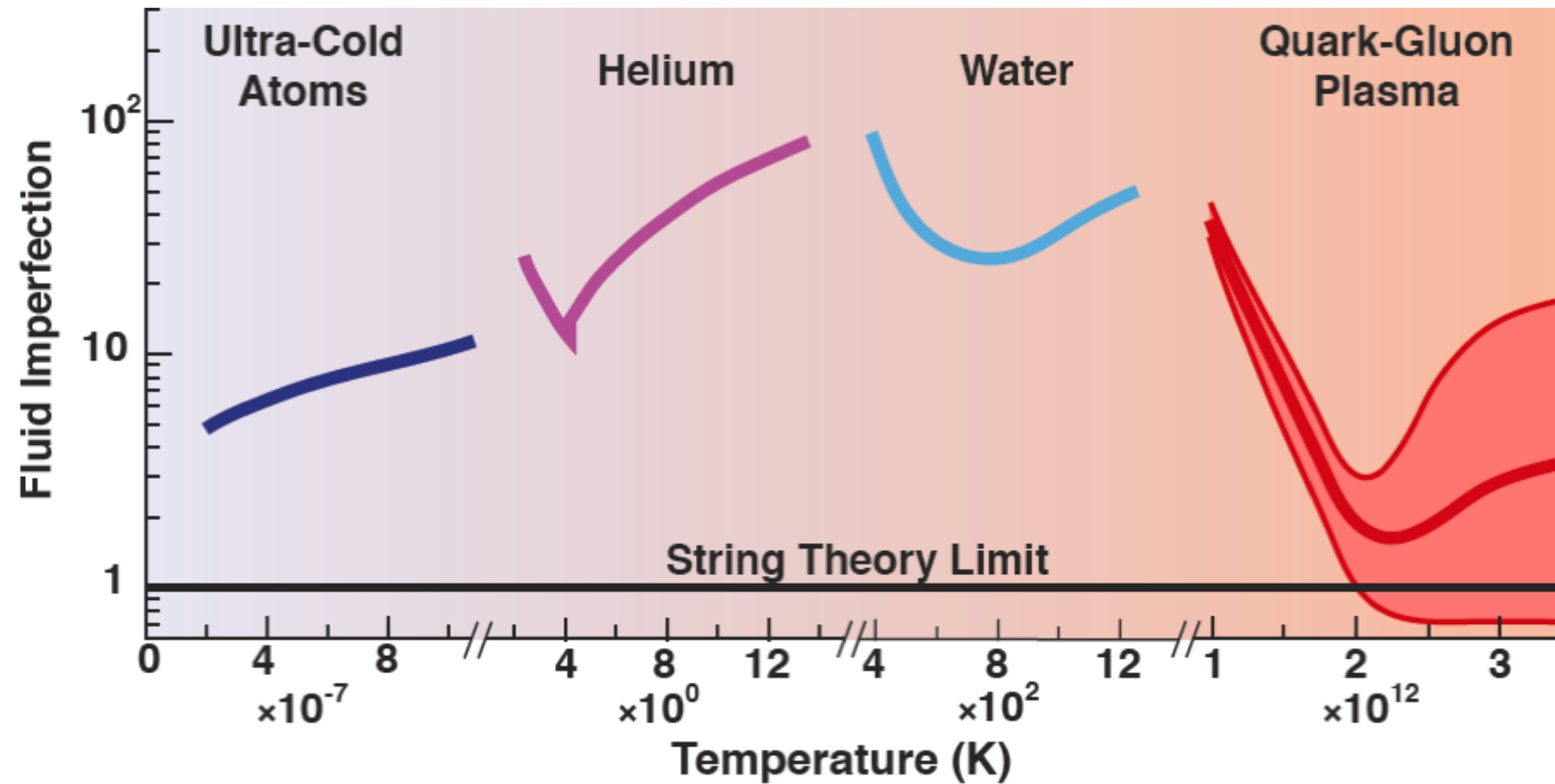
**Elliptic flow with ultracold trapped
Li6 atoms, $a \rightarrow \infty$ regime**

**The system is extremely dilute, but
can be put into a hydro regime, with
an elliptic flow, if it is specially tuned
into a strong coupling regime via the
so called Feshbach resonance**

Analogy pointed out by Shuryak

How perfect is perfect?

Viscosity in strongly interacting quantum field theories from black hole physics P. Kovtun, D. Son, A. Starinets,
Phys. Rev. Lett. 94 (2005) 111601



None more perfect!

Actually, we're still working to make the red curve better

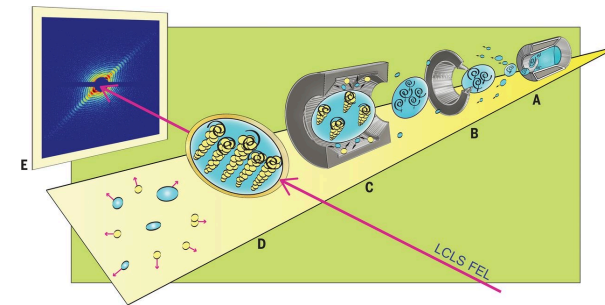
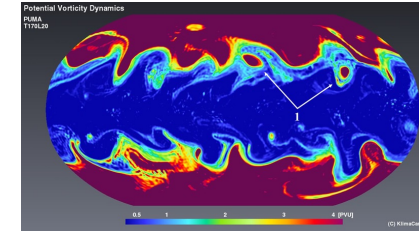
Beyond Flow: Vorticity



- Vortices naturally form in fluids
- “Vorticity” a measure of how rapidly the fluid spins locally
- Units: s^{-1}

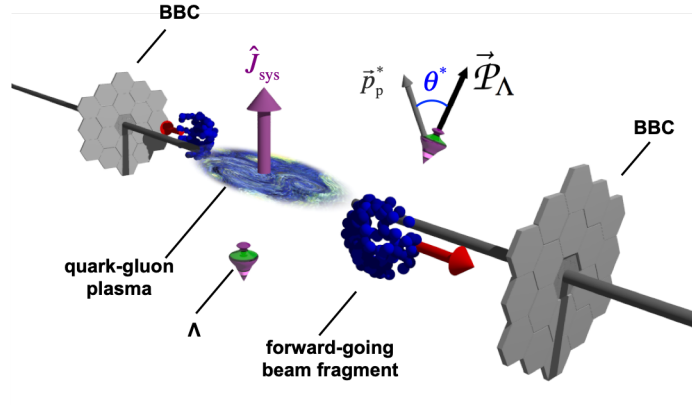
Vorticity in other systems: Scale

- Solar subsurface flow: 10^{-7} s^{-1}
- Terrestrial atmospheric patterns: 10^{-5} - 10^{-7} s^{-1}
- Great red spot of Jupiter: 10^{-4} s^{-1}
- Supercell tornado cores: 10^{-1} s^{-1}
- Bulk superfluid He II: 150 s^{-1}
- Superfluid nanodroplets: 10^7 s^{-1}
- RHIC: 10^{22} s^{-1}



The measurements: spin polarization

Nature **548** (2017) 62

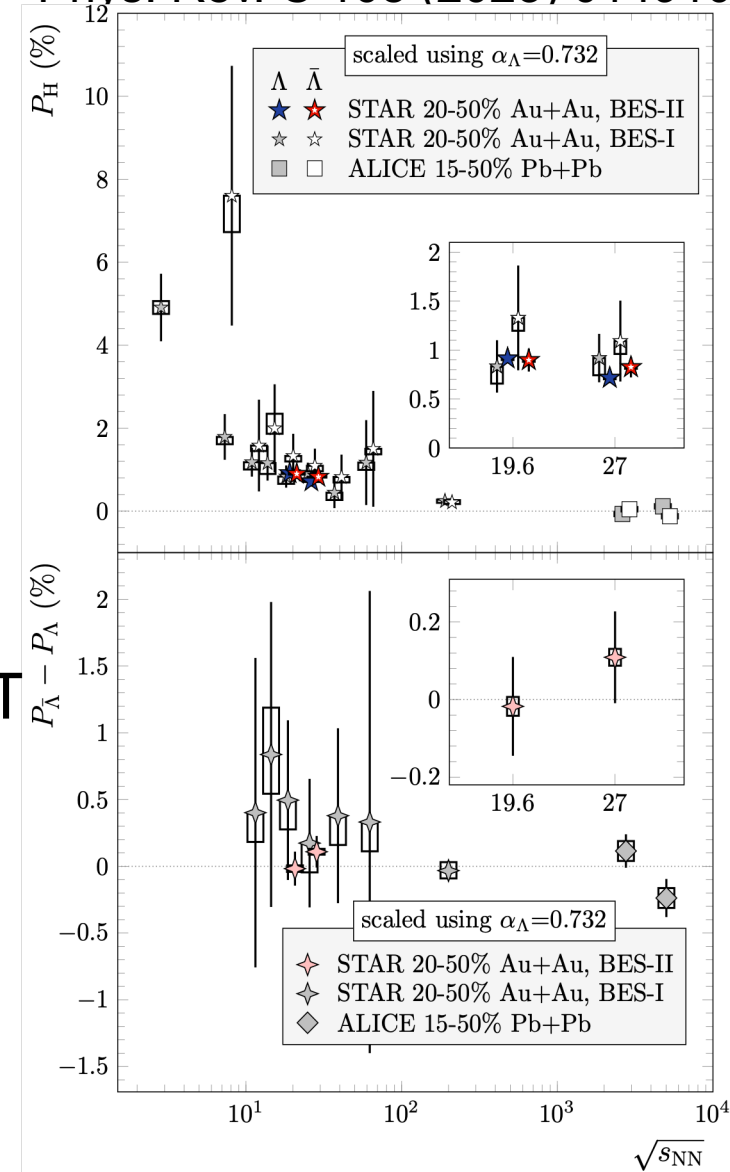


Most Vortical Fluid ever observed

Exploring Magnetization:
Limit on magnetic field $< \sim 1 \times 10^{13}$ T

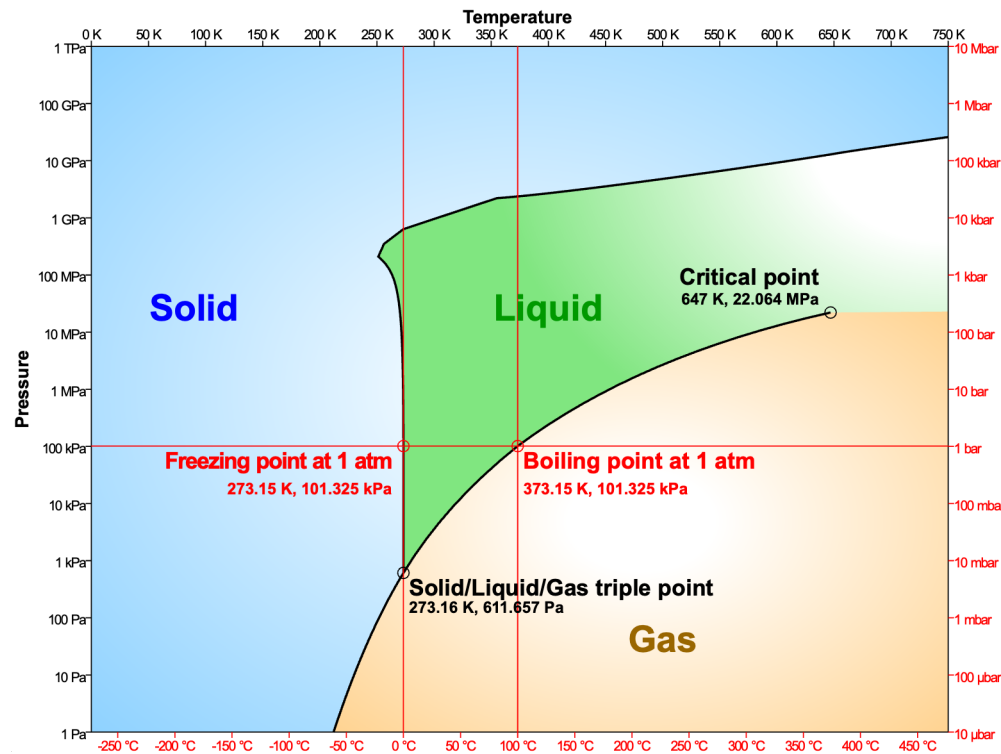
Many other detailed measurements probe vortical structure

Phys. Rev. C 108 (2023) 014910



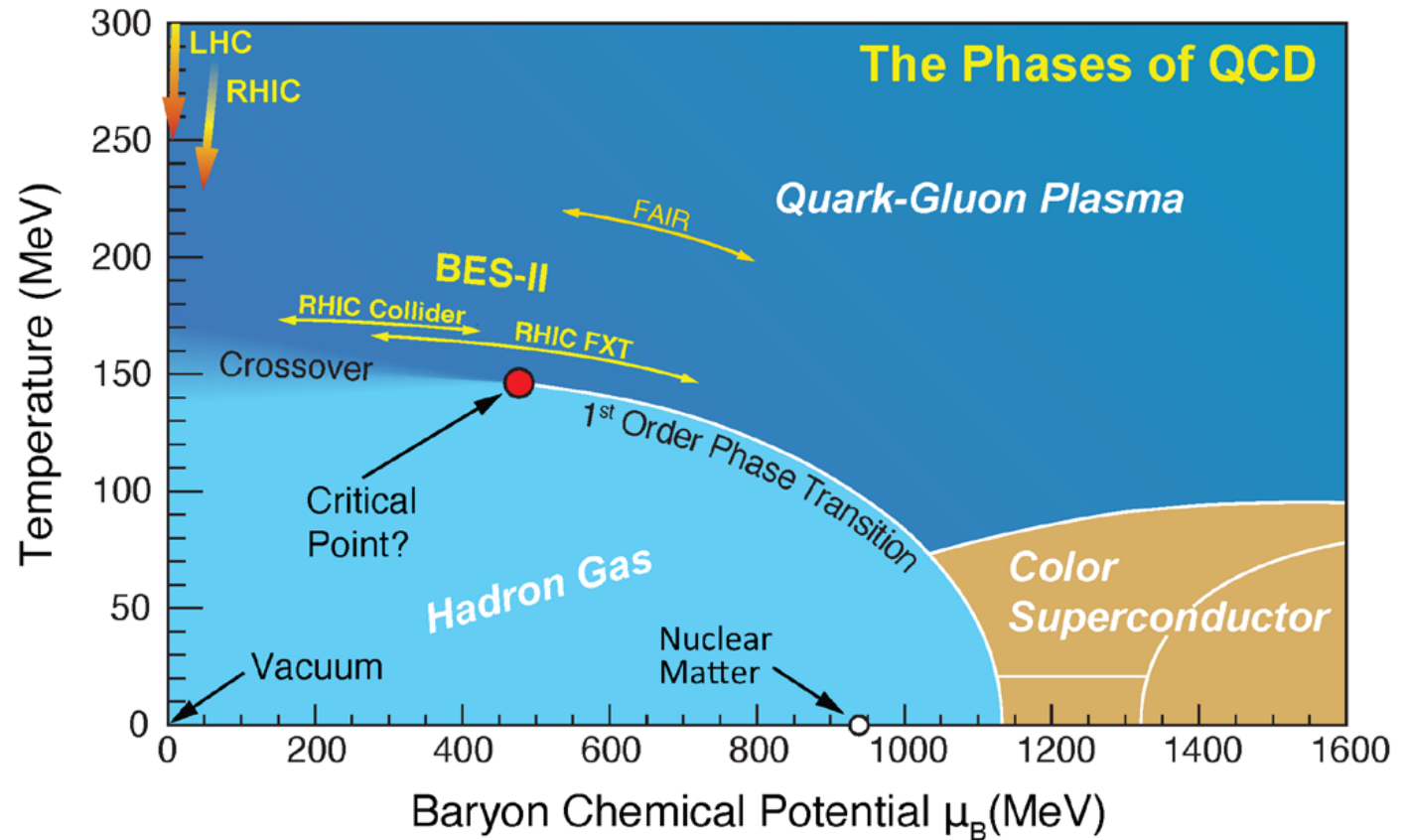
Phases of matter

Example of QED Matter: Water



By author of the original work: Cmgleetranslator: Manlleus (ca) - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=34865054>

QCD Matter: explored at accelerators



Phase Transitions

Boiling Water



1st order phase transitions:

Phase Coexistence (“Bubbles”)
Latent Heat

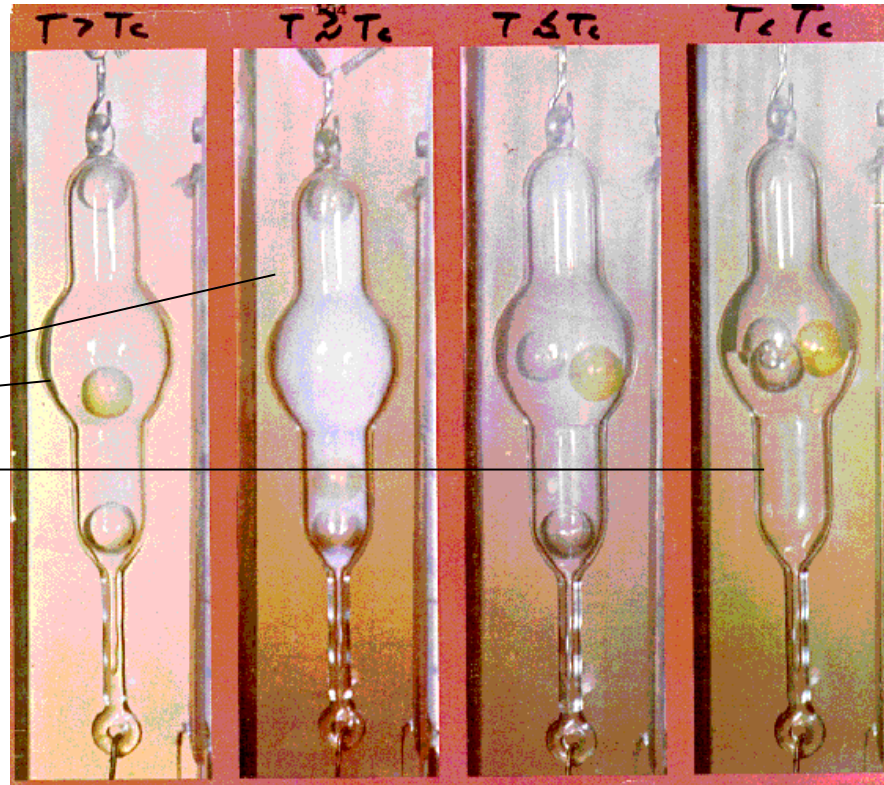
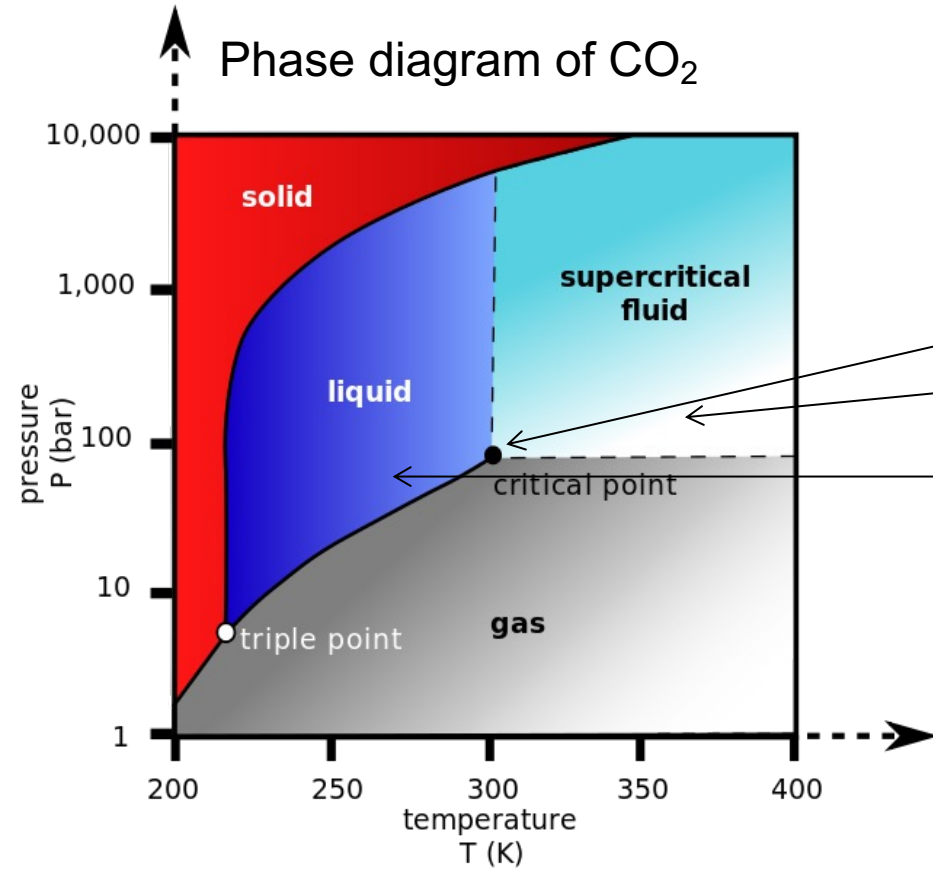
CO₂ near critical point



2nd order phase transitions:

Critical behavior

Critical Behavior

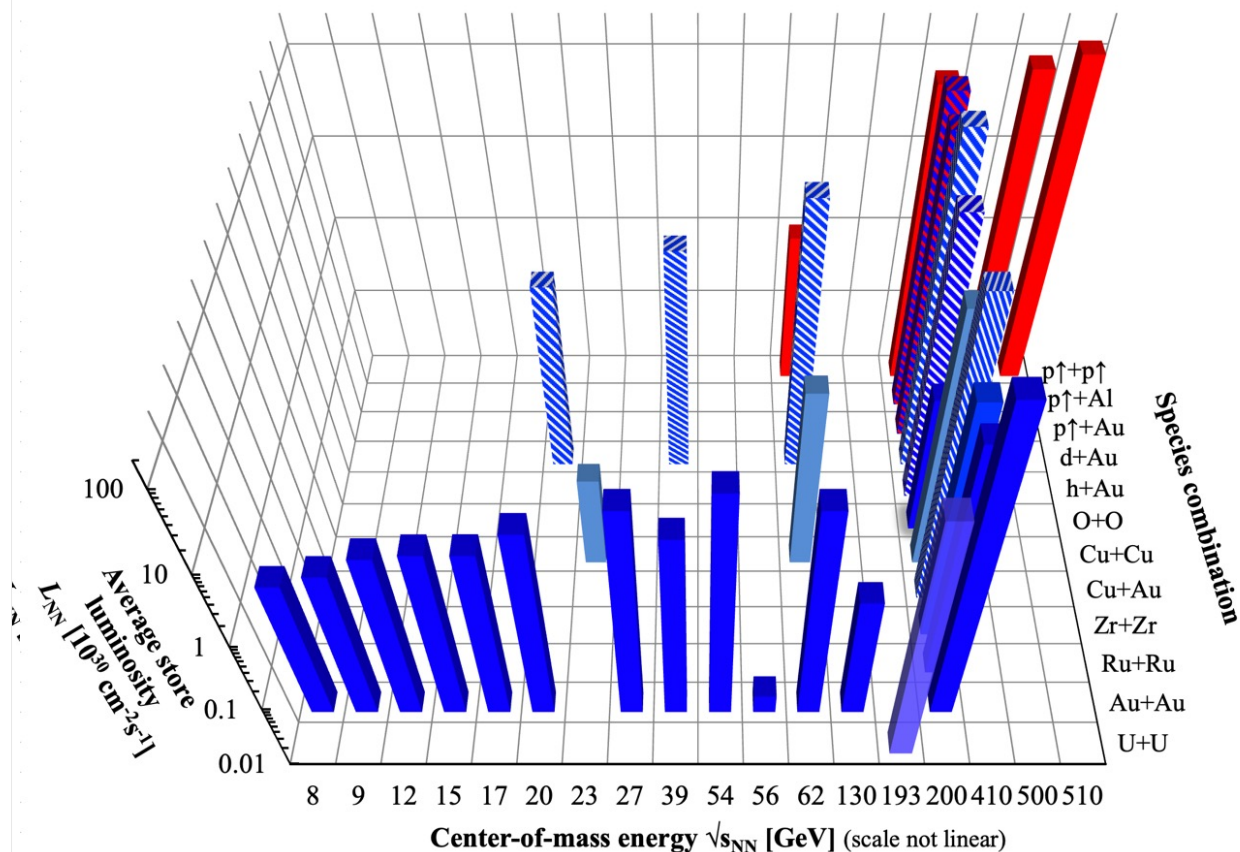


<http://www.mit.edu/~8.334/grades/projects/projects08/TheodoreGolfinopoulos/text3a.html>

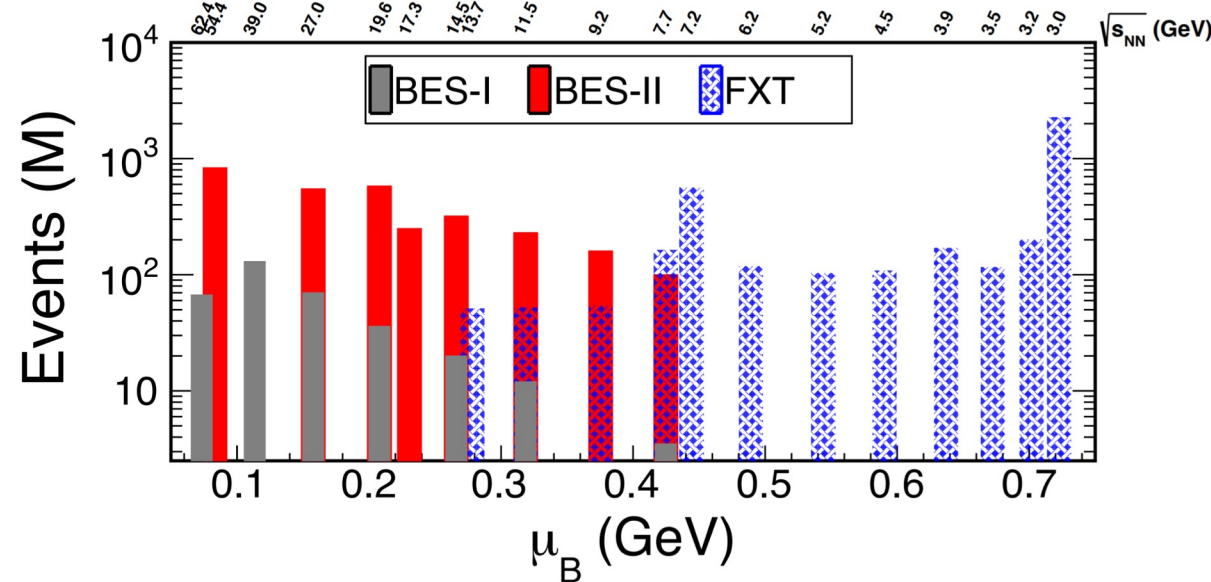
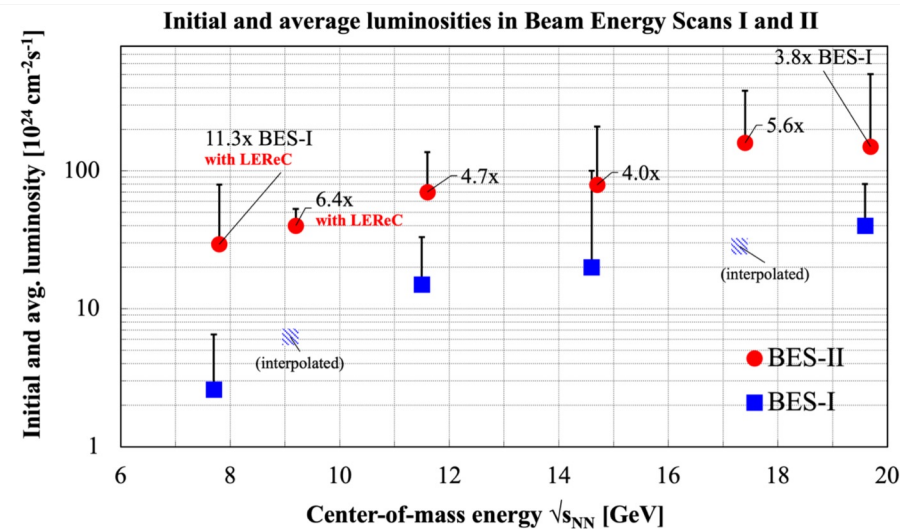
Critical Opalescence (i.e. long-range correlations) near a critical point

The Versatility of RHIC

RHIC energies, species combinations and luminosities (Run-1 to 25)



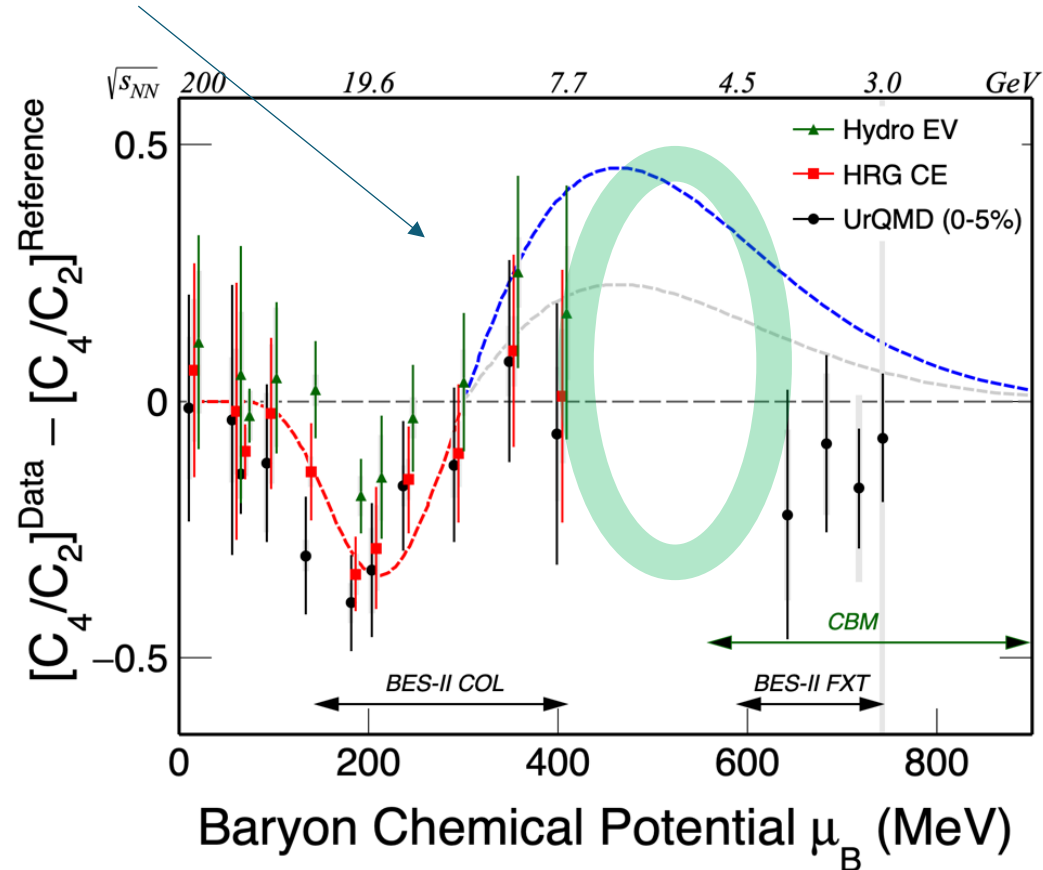
Only polarized hadron collider in the world!



Current Status of Critical Point Search

Curve to guide the eye:

Dip and rise expected from presence of critical point



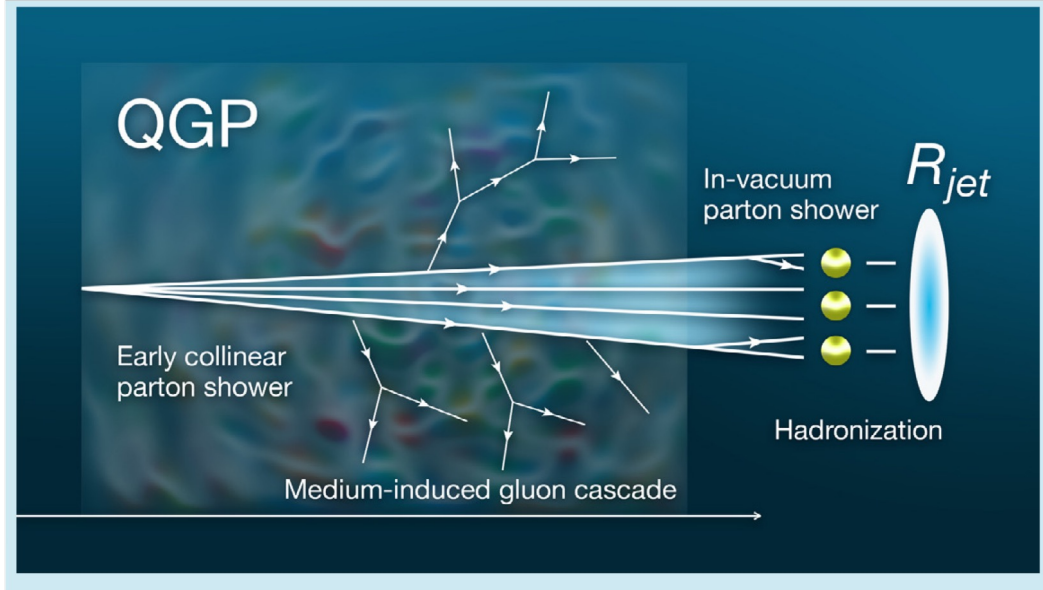
Lesson:

Even after much effort one can be left with ambiguous hints of new physics

High precision data taken in last days of RHIC at $\sqrt{s_{NN}} = 4.2, 4.5, 5.2$ GeV

Next chapter of RHIC: Jets and Emergence of fluid behavior

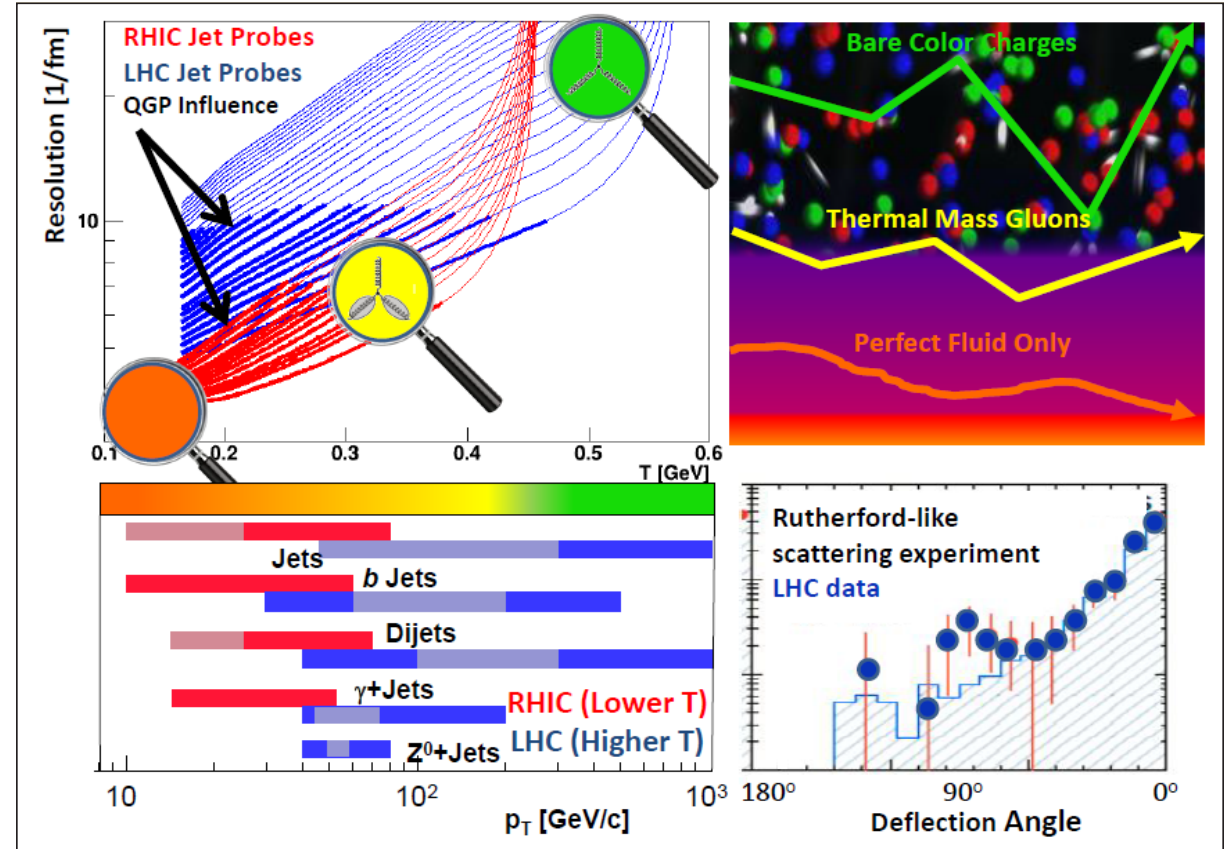
NSAC 2023 Long Range Plan



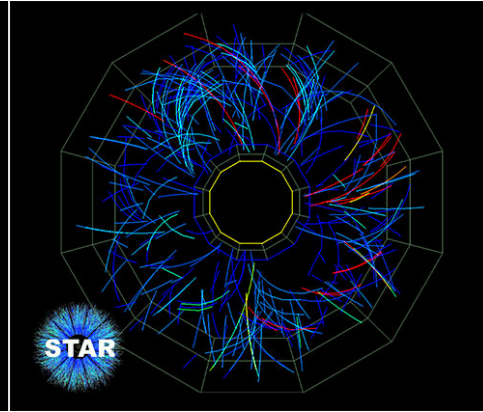
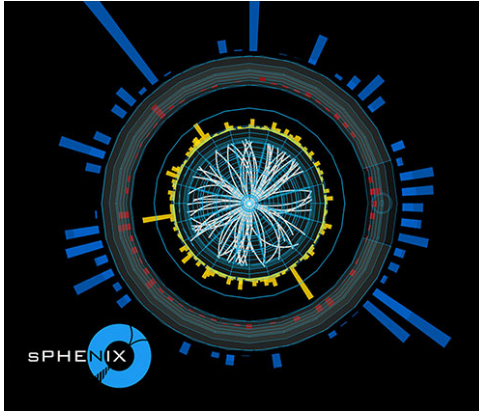
Embedded in the fluid are high-momentum showers from before the formation of QGP

Use these showers to probe QGP “granularity” and more generally the emergence of fluidity

NSAC 2015 Long Range Plan



The future of RHIC science



While RHIC ended beam operations on Feb 6, 2026...

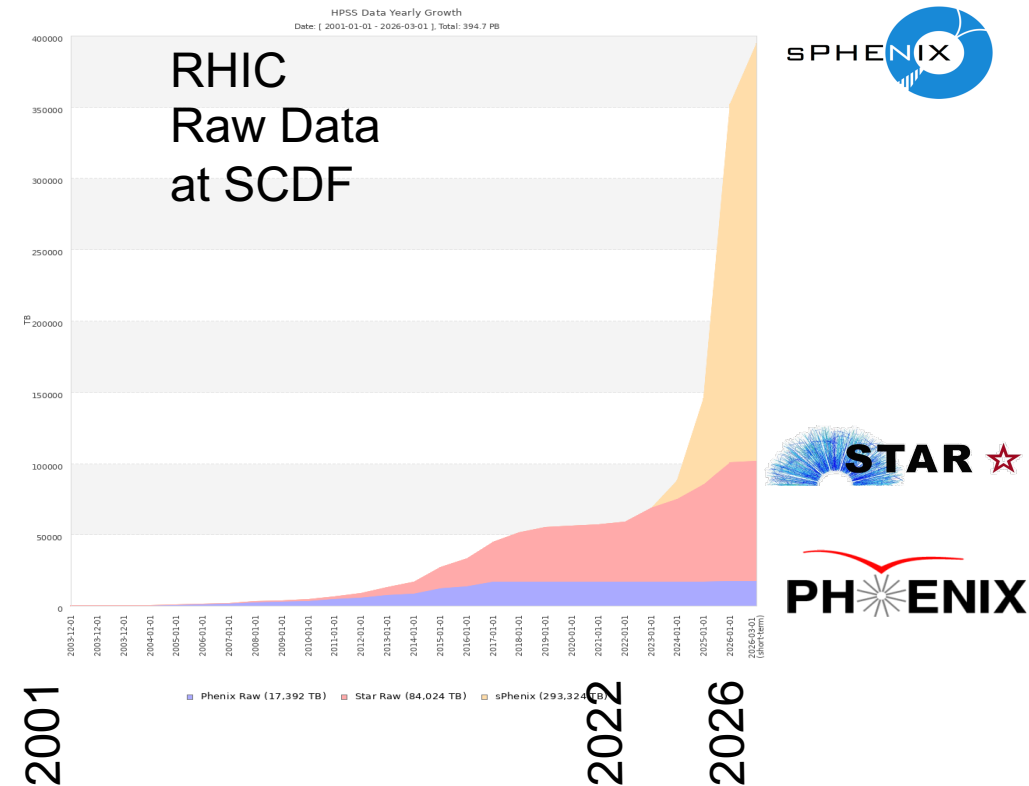
Very large datasets were taken in its final years: more data were taken in its final year than in all previous years combined

Harvesting of the science from this data will continue well into the 2030's

400 PB

100 PB

50 PB



Summary

After more than 25 years field of Heavy Ion physics still making discoveries, and will continue to do so for the next decade

Even as we transition to the next facility, the EIC

Lots of room for the next generation

RHIC has produced >640 PhD's over its lifetime