Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

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

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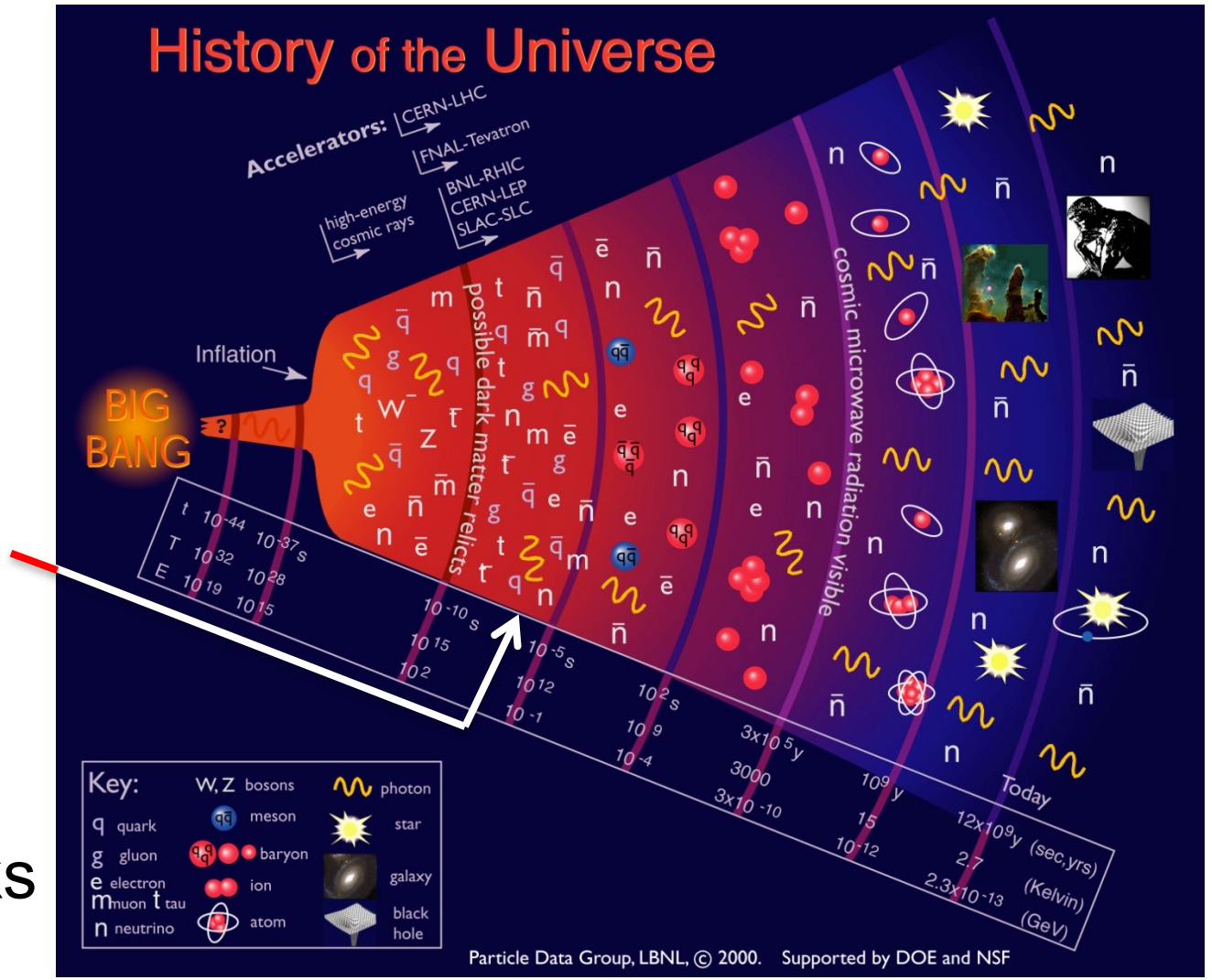
@BrookhavenLab

RHIC: recreating the Early Universe in the Lab

The purpose of the
- Relativistic
- Heavy
- Ion
- Collider

To recreate conditions as they existed 1 μs after the Big Bang

Quark Gluon Plasma:
- Hot soup of free quarks and gluons



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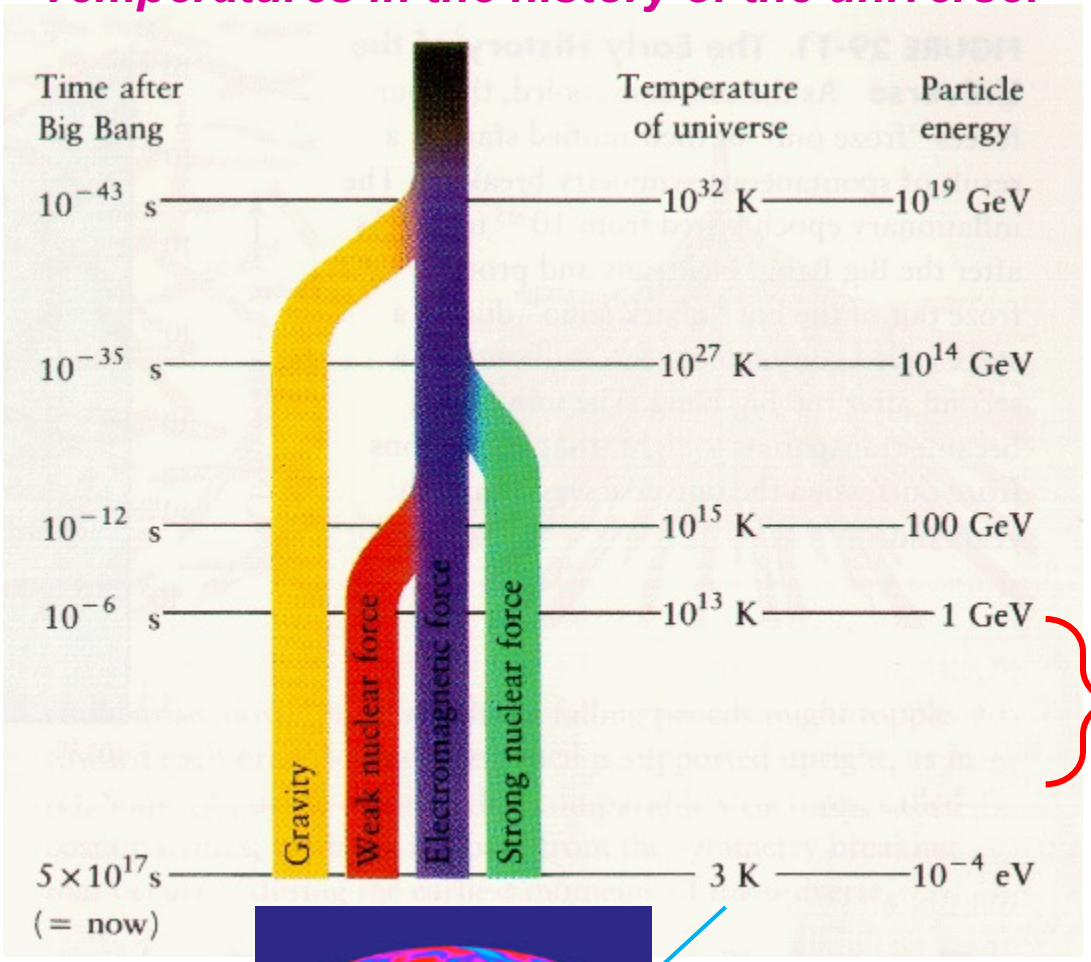
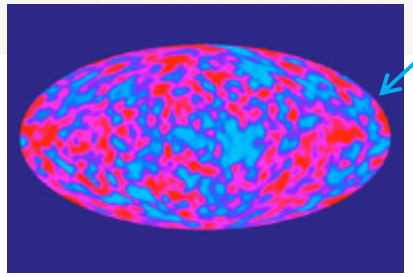
How Hot Is It?

Temperatures in the history of the universe:



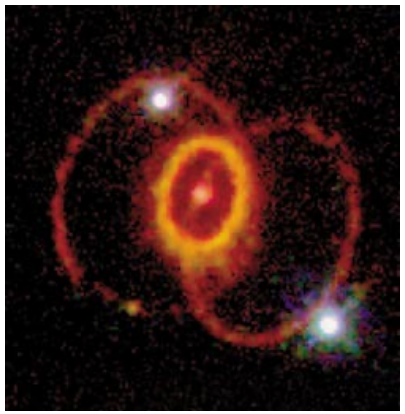


Cosmic microwave background

~4 × 10^{12} K : RHIC matter

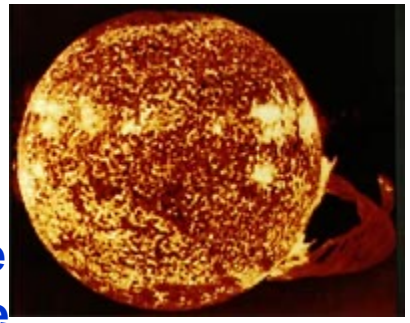
~2 × 10^{12} K : predicted melting temp. for neutrons & protons

~1 × 10^{11} K : typical core temp. of Type II supernova



1.5 × 10^{7} K : center of Sun

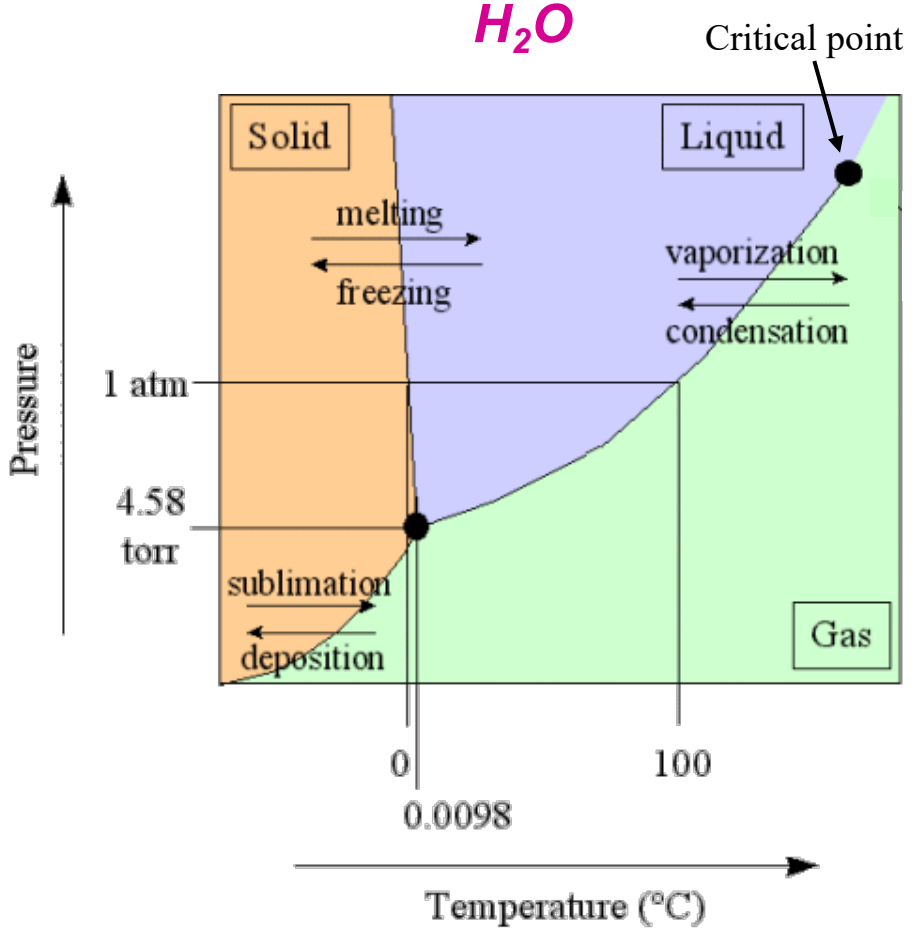
5.8 × 10^{3} K : Sun's surface ≈ Earth's core

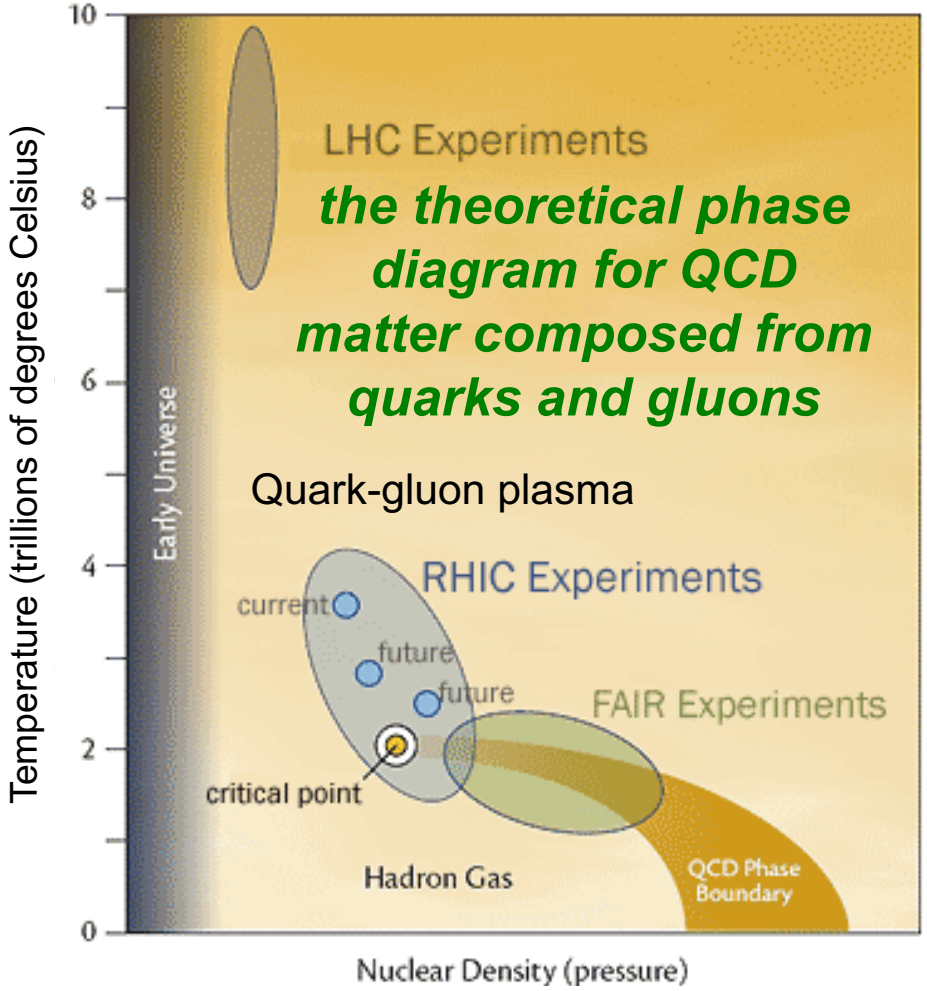


1.8 × 10^{3} K : iron melts

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

e.g., the phase diagram for H_2O

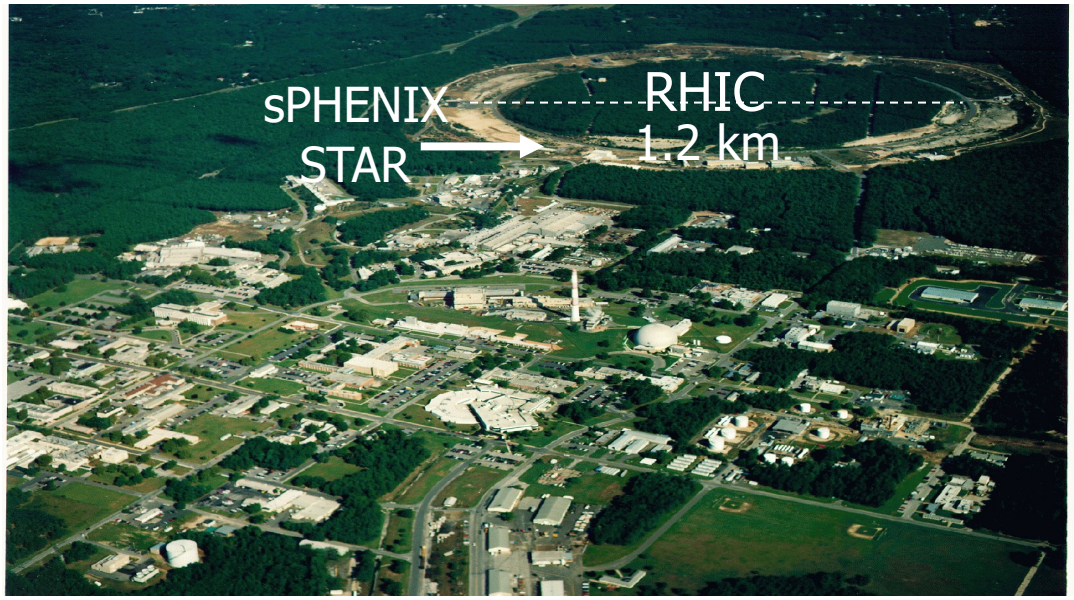


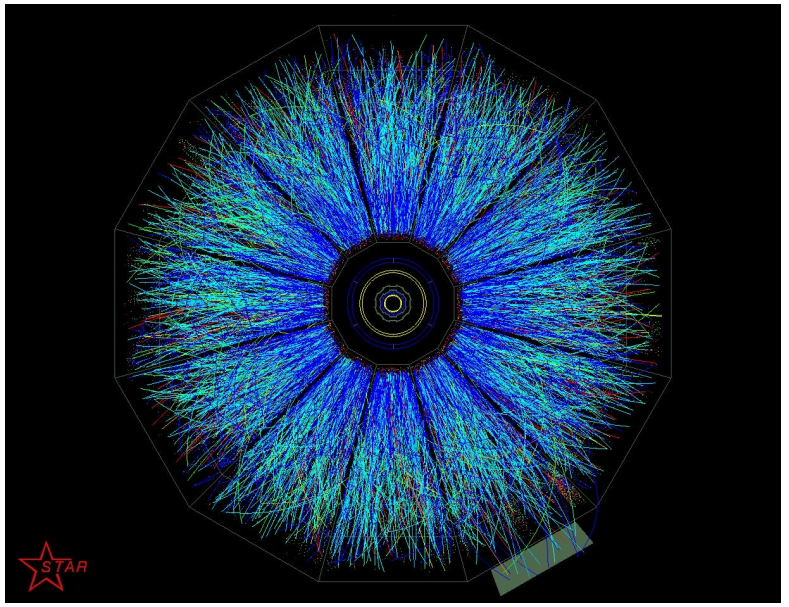


We now know that RHIC collisions produce quark-gluon plasma that expands, cools and condenses into hadrons that reach the detectors

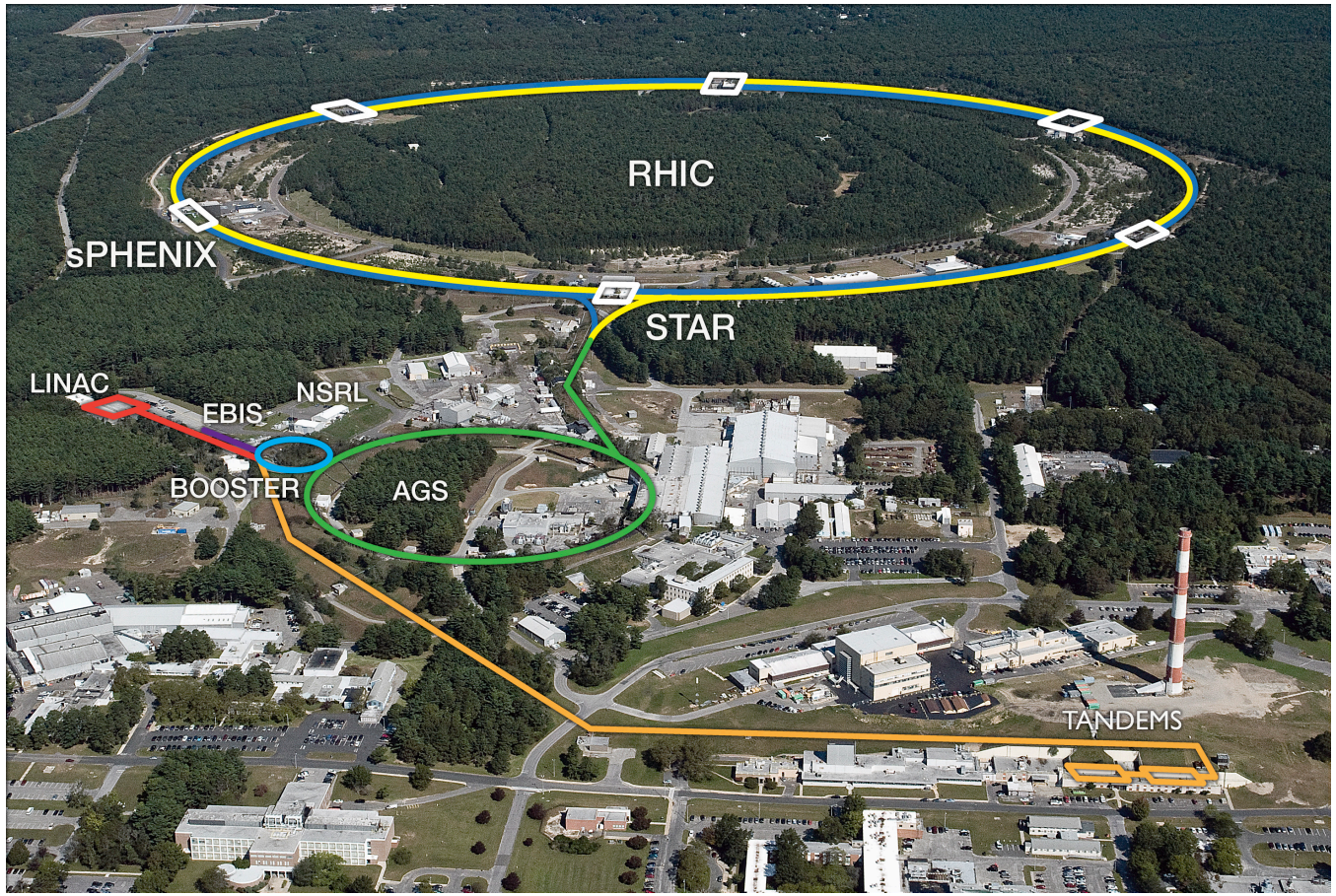
How to do this: RHIC Implementation

- 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)



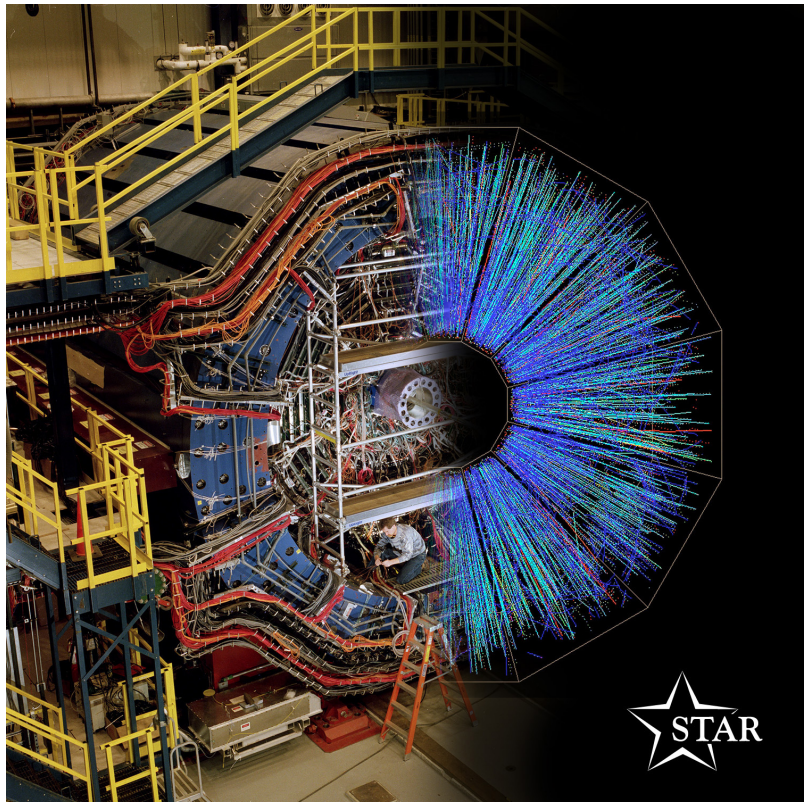


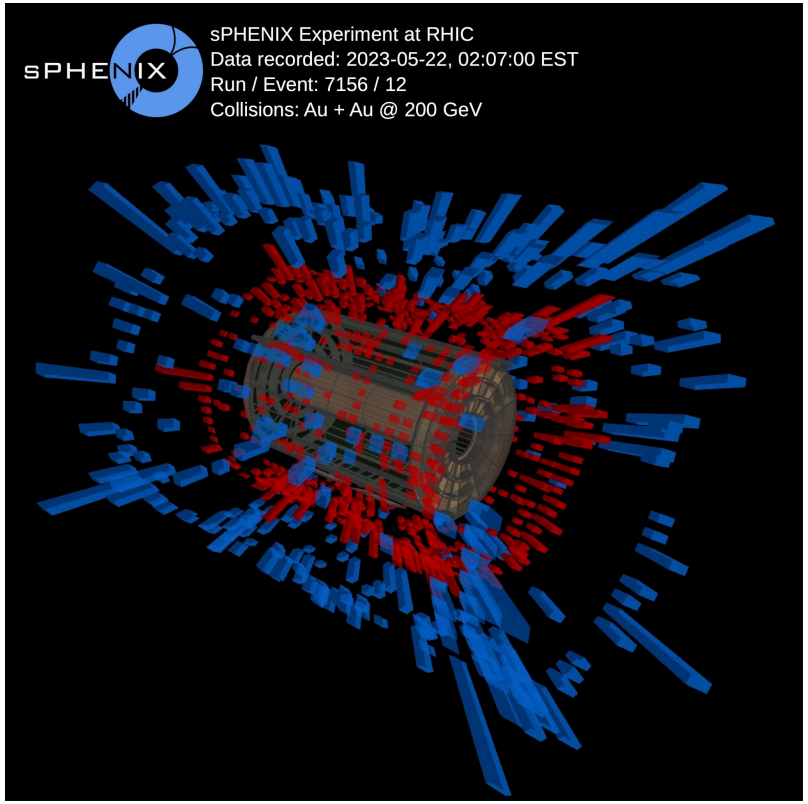
RHIC Complex

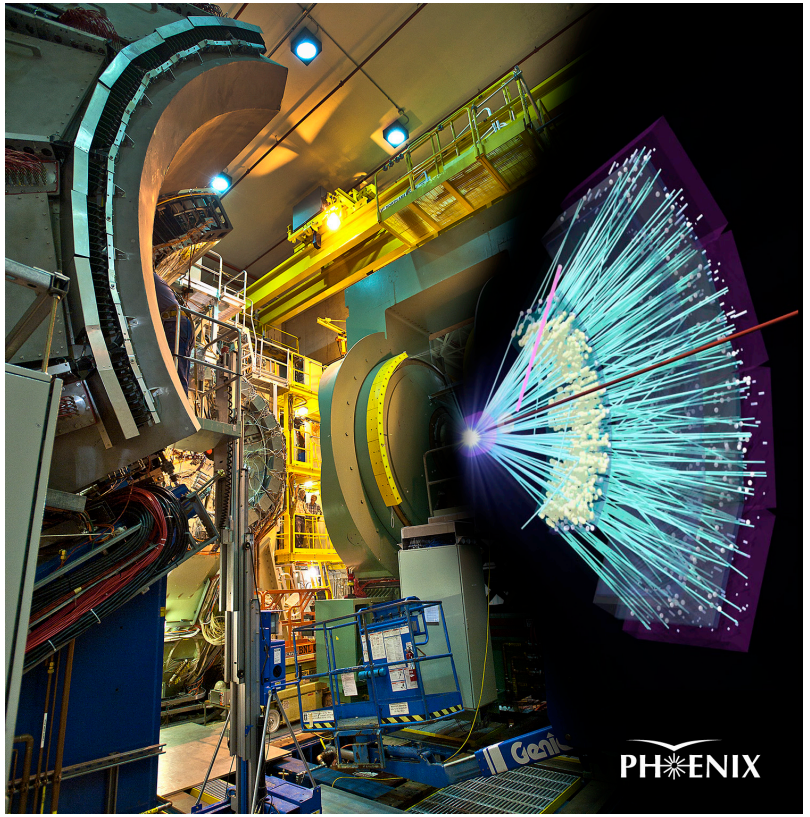


RHIC will have been in operation from 2000 to 2025
Most flexible collider in the world, from protons to Uranium
over two orders of magnitude in energy and 100x design luminosity

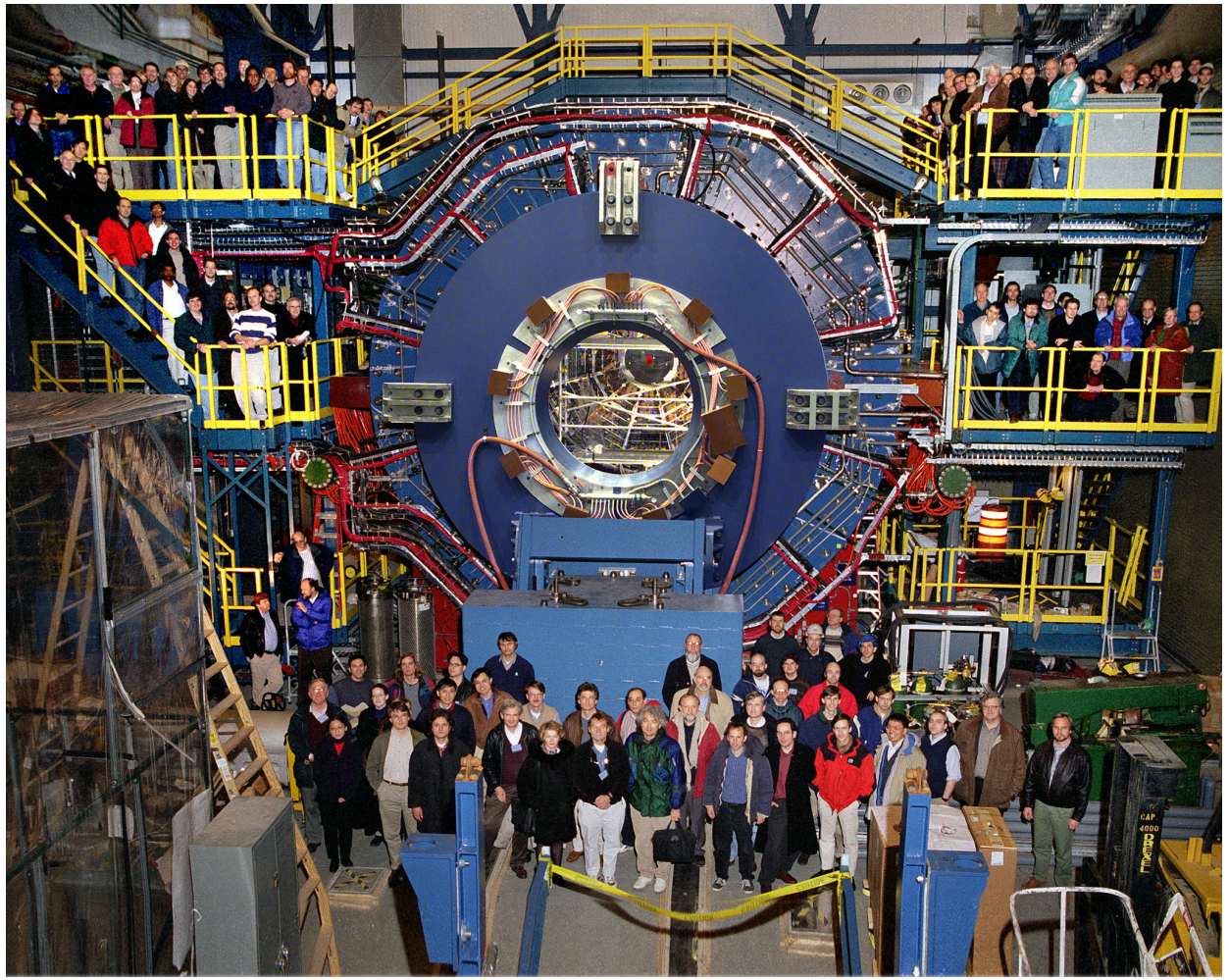
Detectors


STAR


sPHENIX
sPHENIX Experiment at RHIC
Data recorded: 2023-05-22, 02:07:00 EST
Run / Event: 7156 / 12
Collisions: Au + Au @ 200 GeV


PHENIX

People

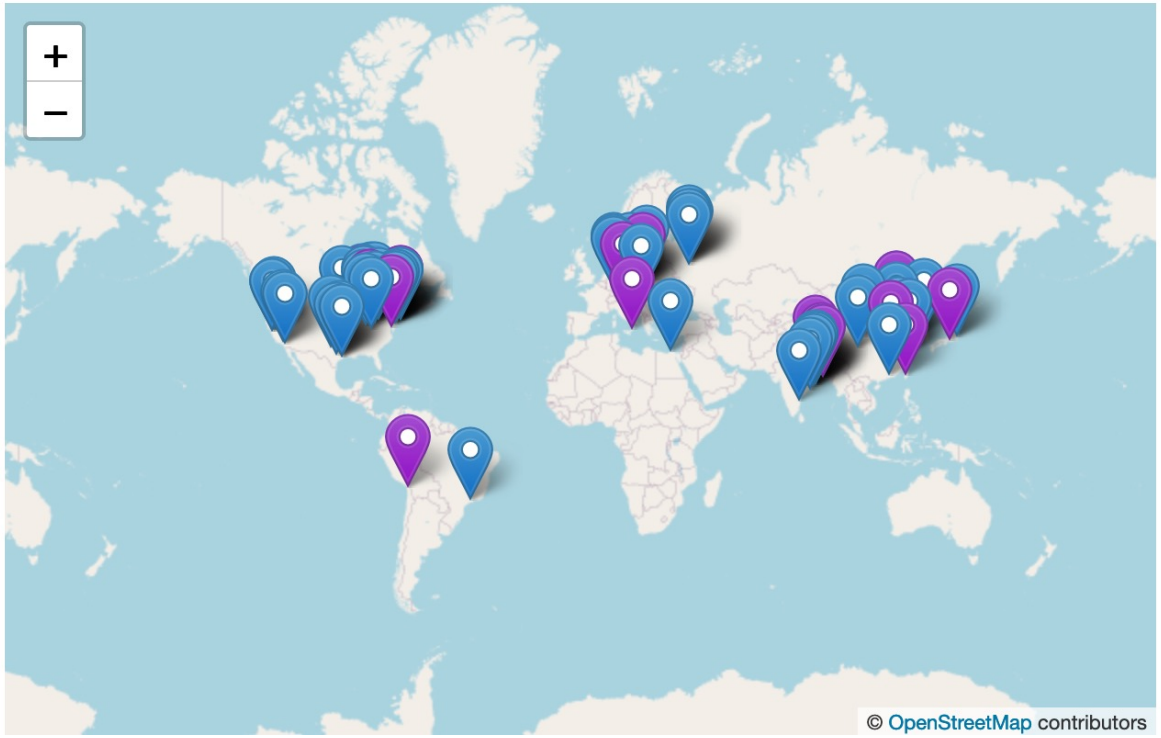


The STAR experiment

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

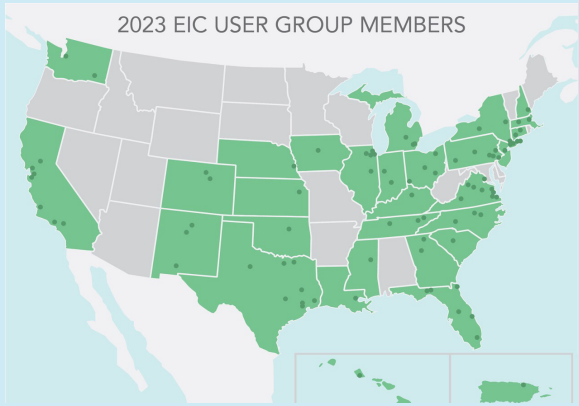
Sidebar 3.8 EIC Network for Discovery Science and Workforce Development

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].

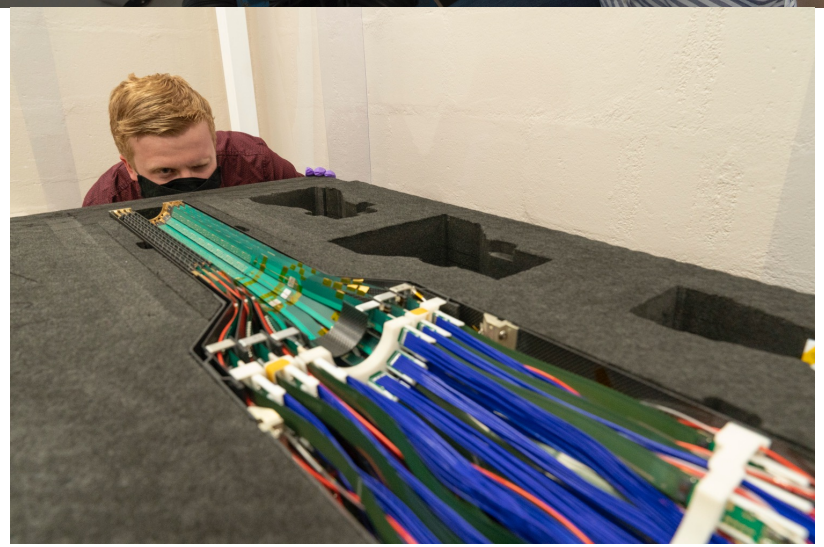


[S23]

[S24]

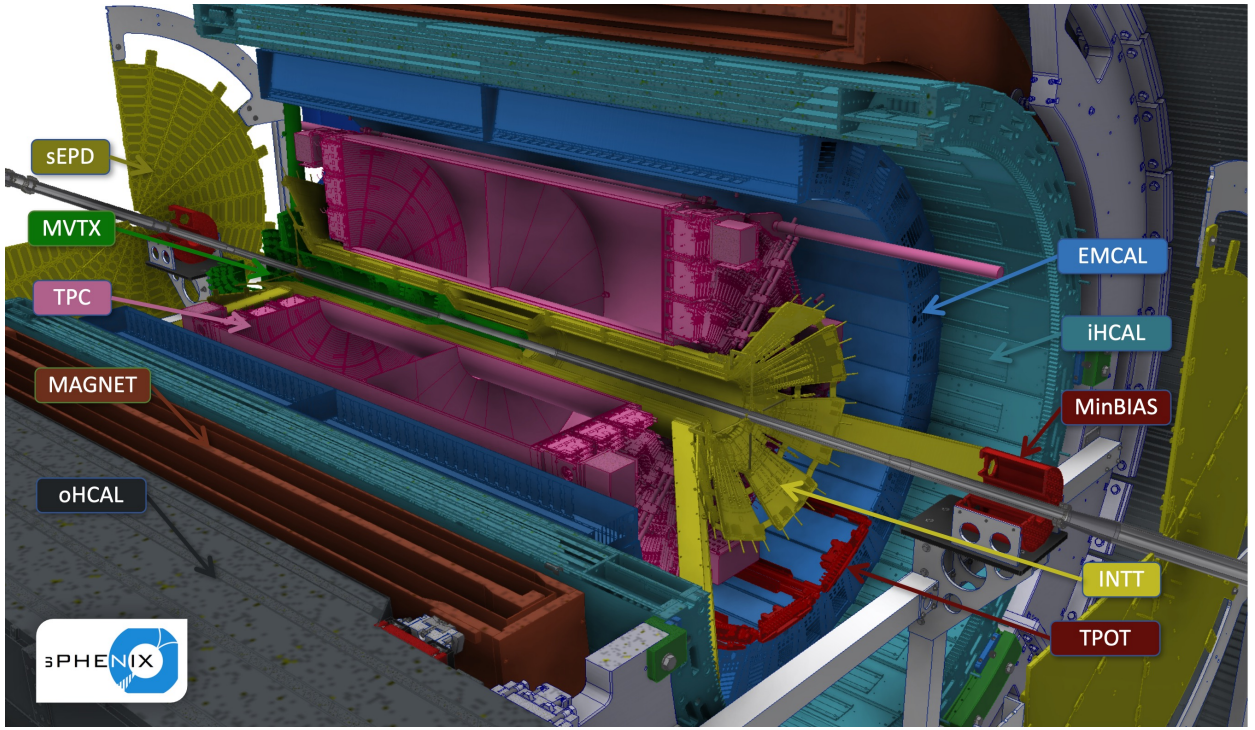
From Nuclear Science Advisory Council 2023 Long Range Plan for Nuclear Science

Detector Construction

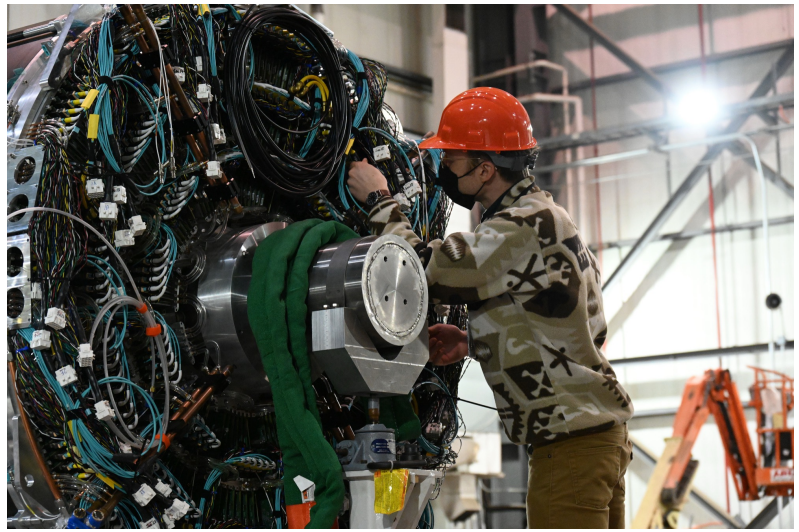


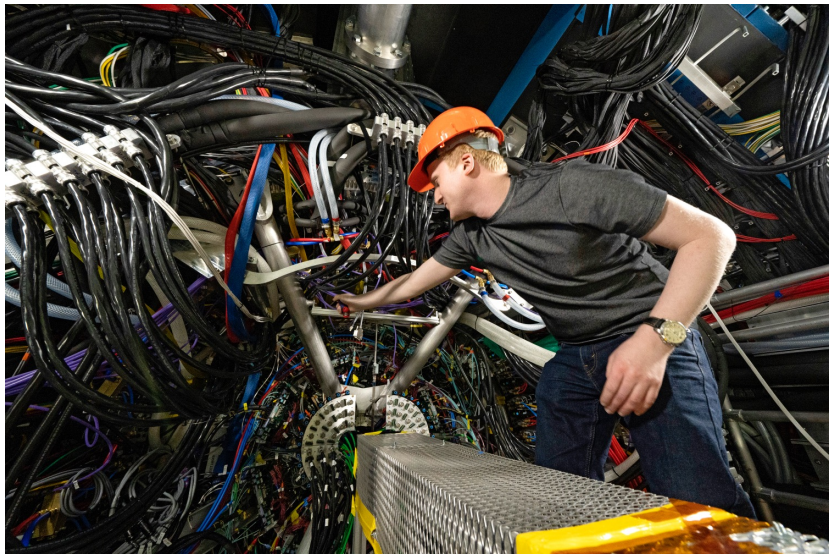
sPHENIX construction and installation:
Sept. 2019 to May 2023

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

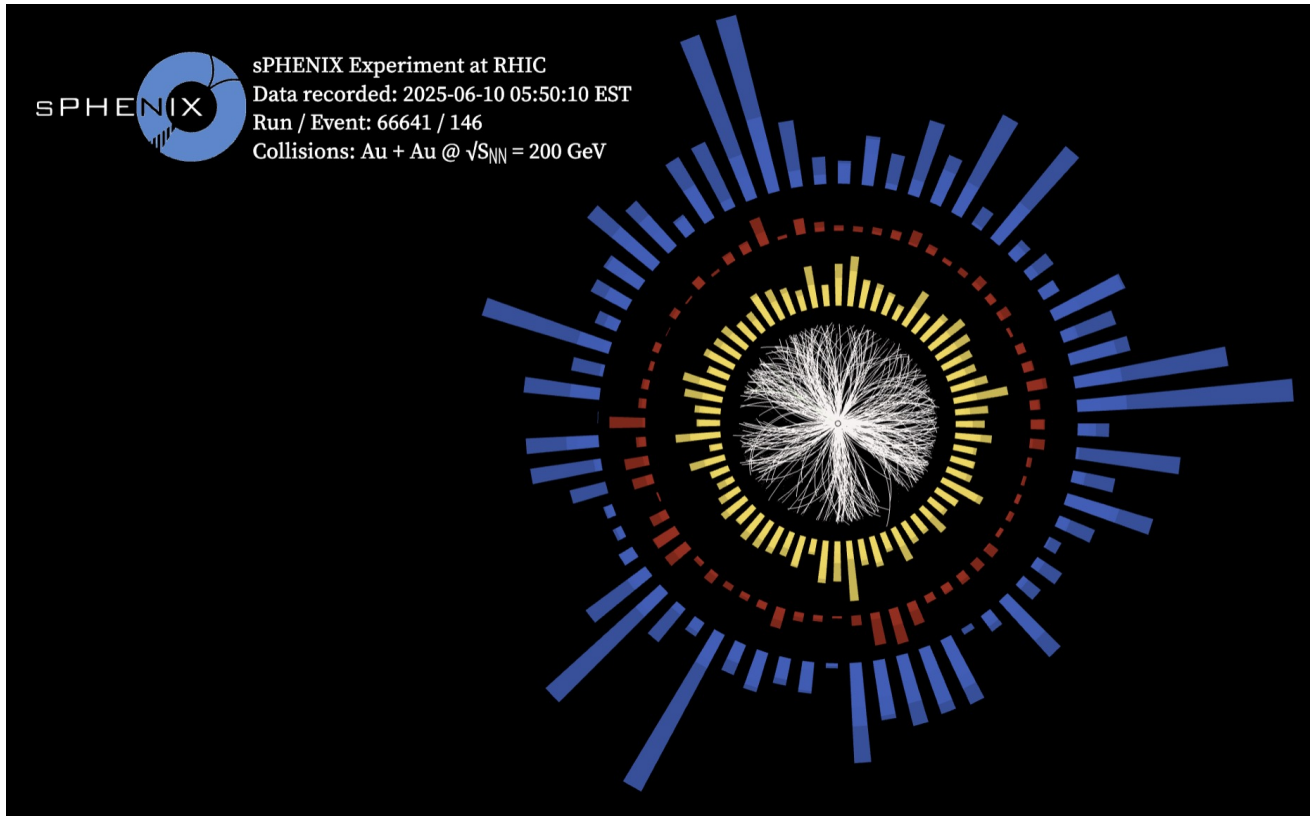


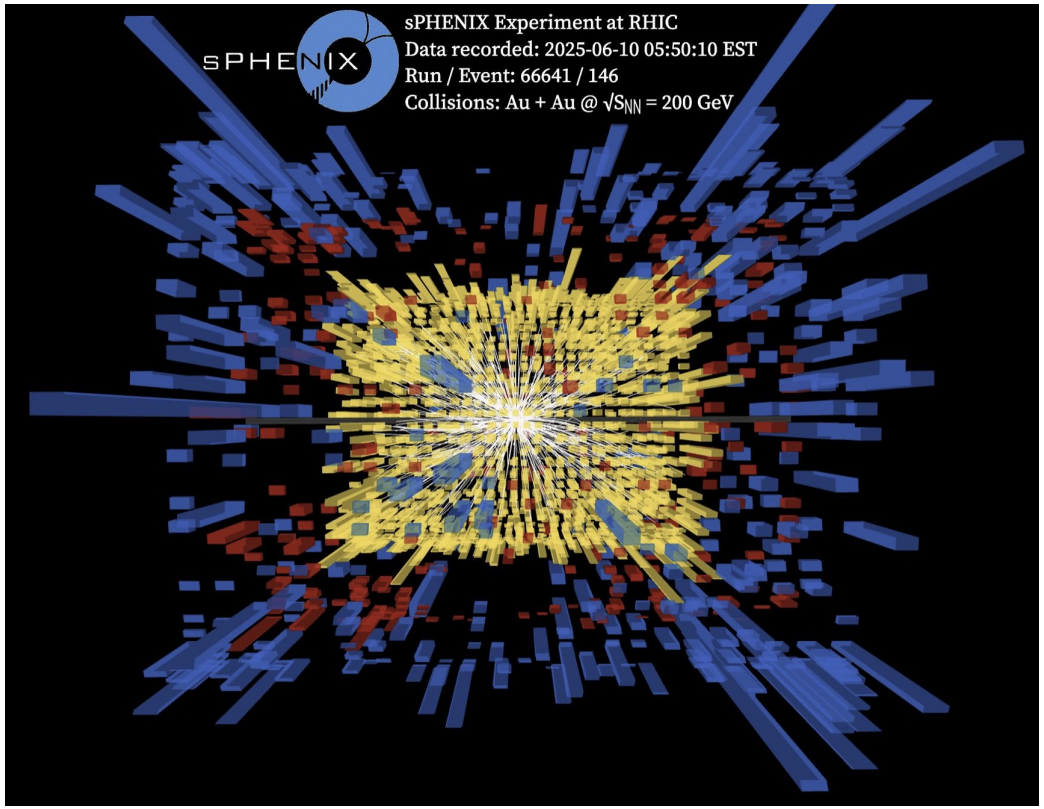
sPHENIX: Installing a detector





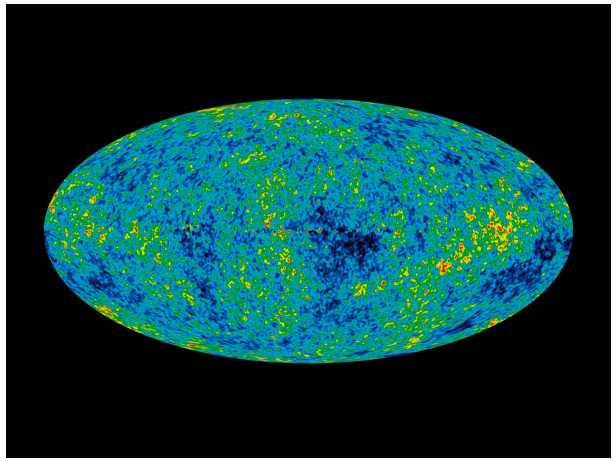
An sPHENIX Event

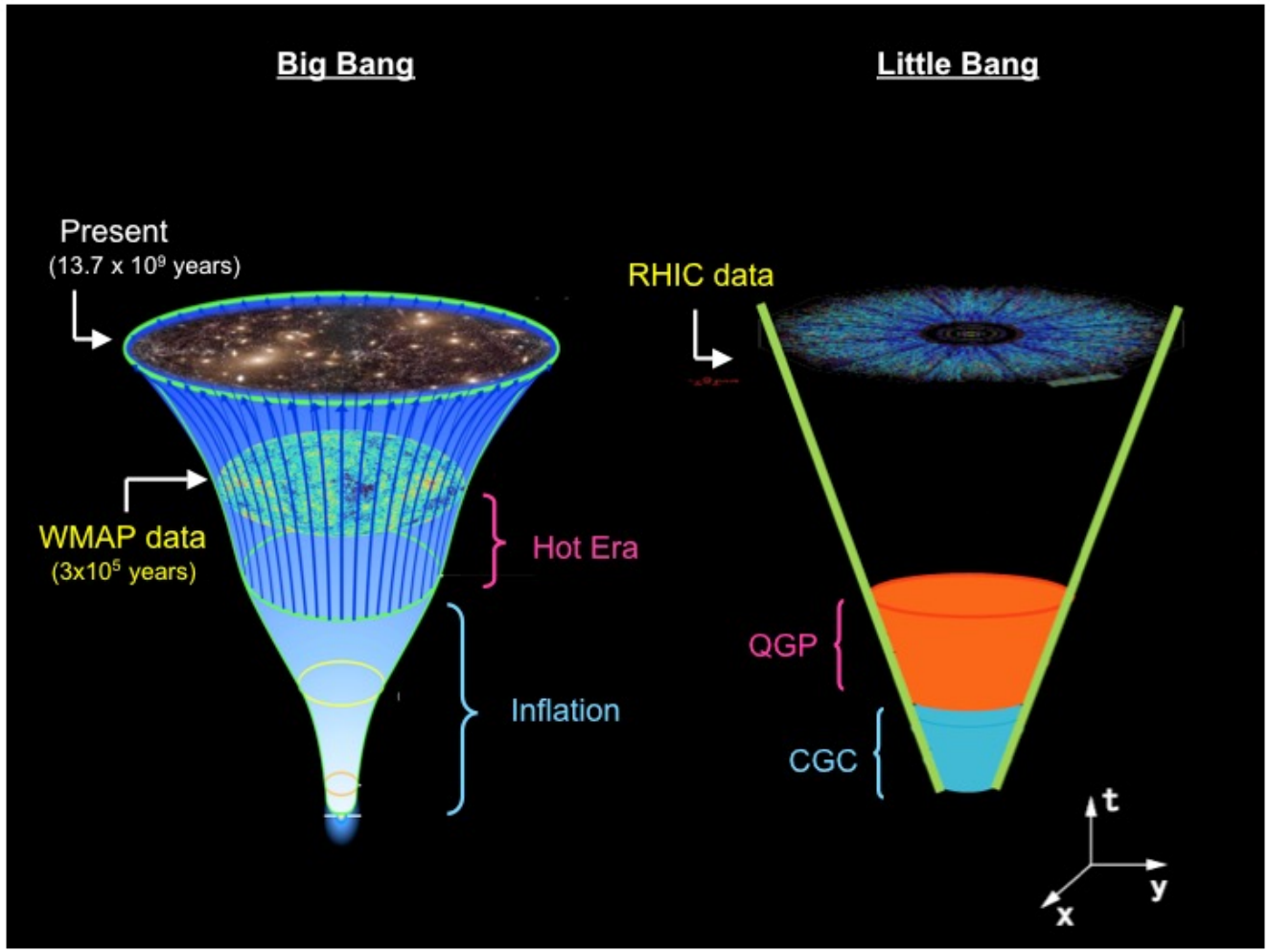




- Particles deposit energy in detector systems
- Reconstruct 3D trajectories and energy patterns
  - Expecting few hundred petabytes of data this year

What to Measure: Patterns

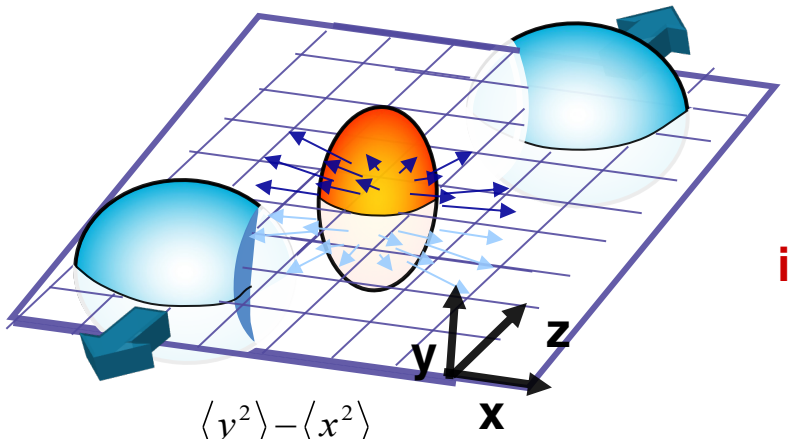


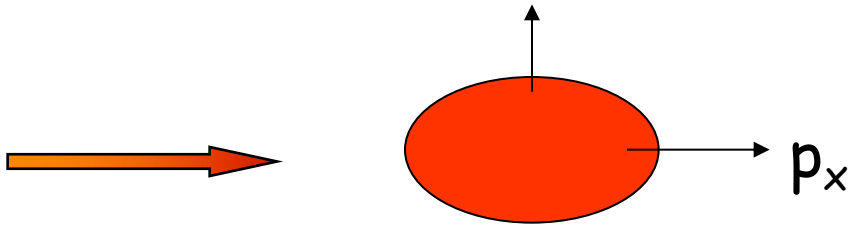


- Collisions produce thousands of particles: $E=mc^2$
- Patterns in produced particles: properties of the matter

Collective Behavior: Azimuthal Anisotropy v_2

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





initial spatial anisotropy anisotropy in momentum space

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

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

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

isotropic directed elliptic higher harmonics

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

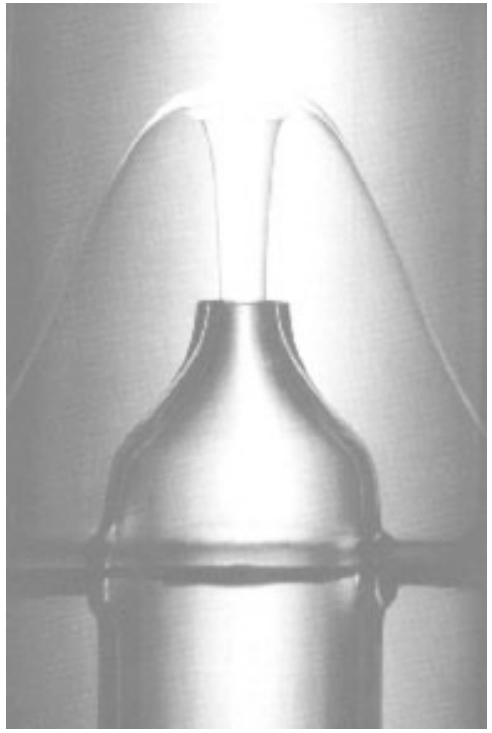
= Correlation to the reaction plane

≡"anisotropic flow"

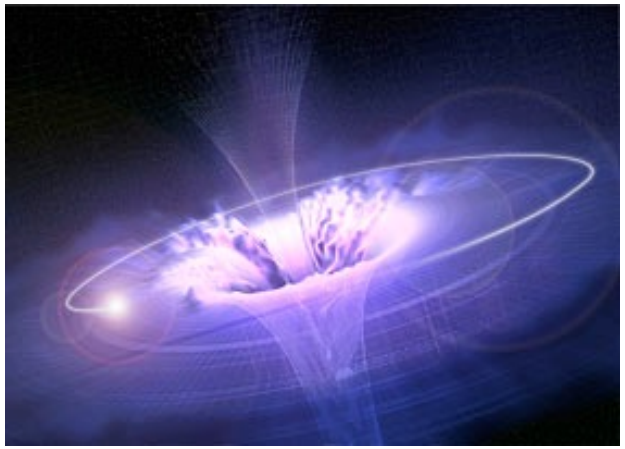
Viscosity

Molasses:
High viscosity

Superfluid helium:
Low viscosity



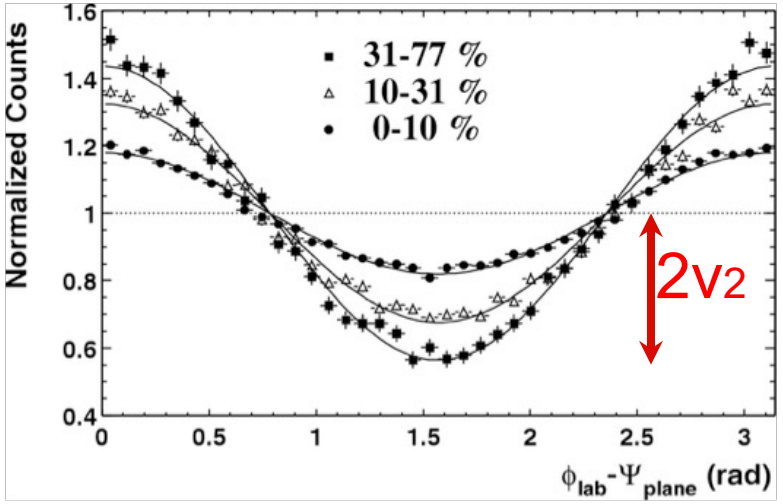
“Perfect” Fluid:
No viscosity

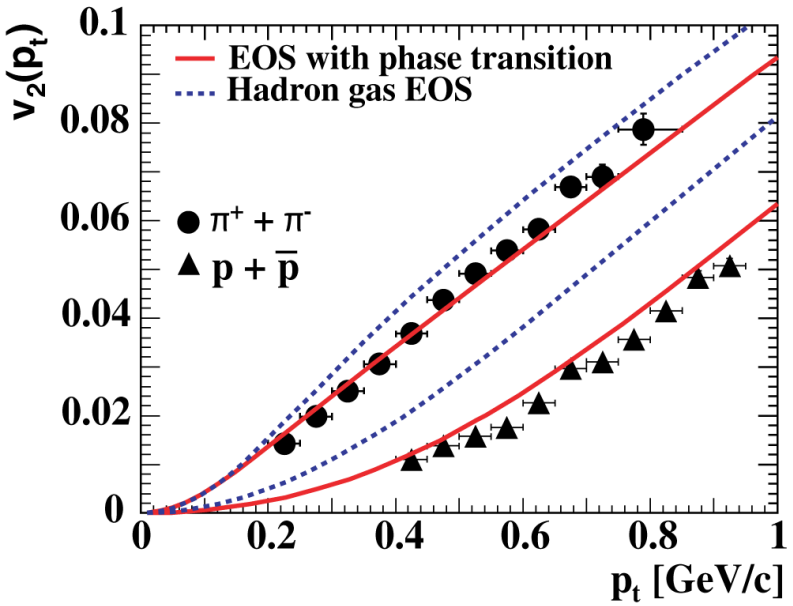


viscosity |ˌviˈskäsitē|noun (pl. **-ties)**

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

The Flow is ~Perfect

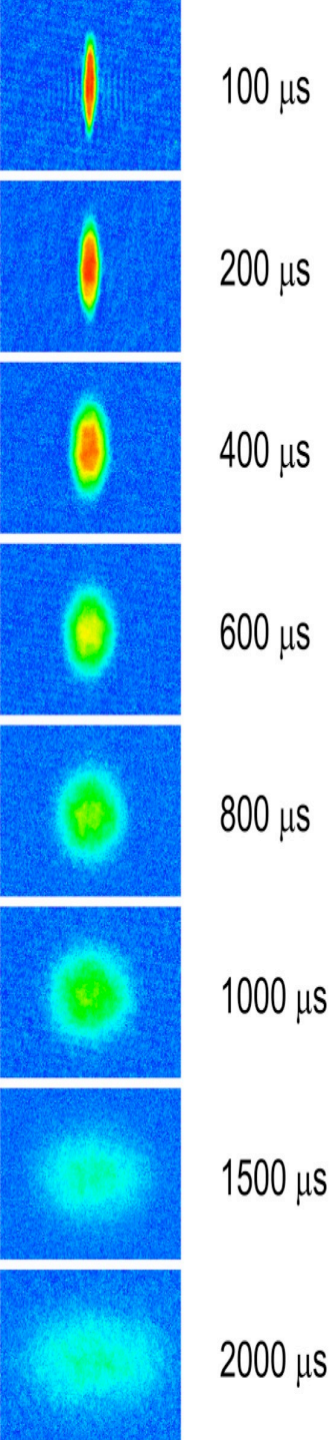




Hydro calculations: Kolb, Heinz and Huovinen

- 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, λ=0) hydrodynamics
- "perfect liquid"
- Appealing picture:
  Nearly perfect fluid with local thermal equilibrium established at <~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

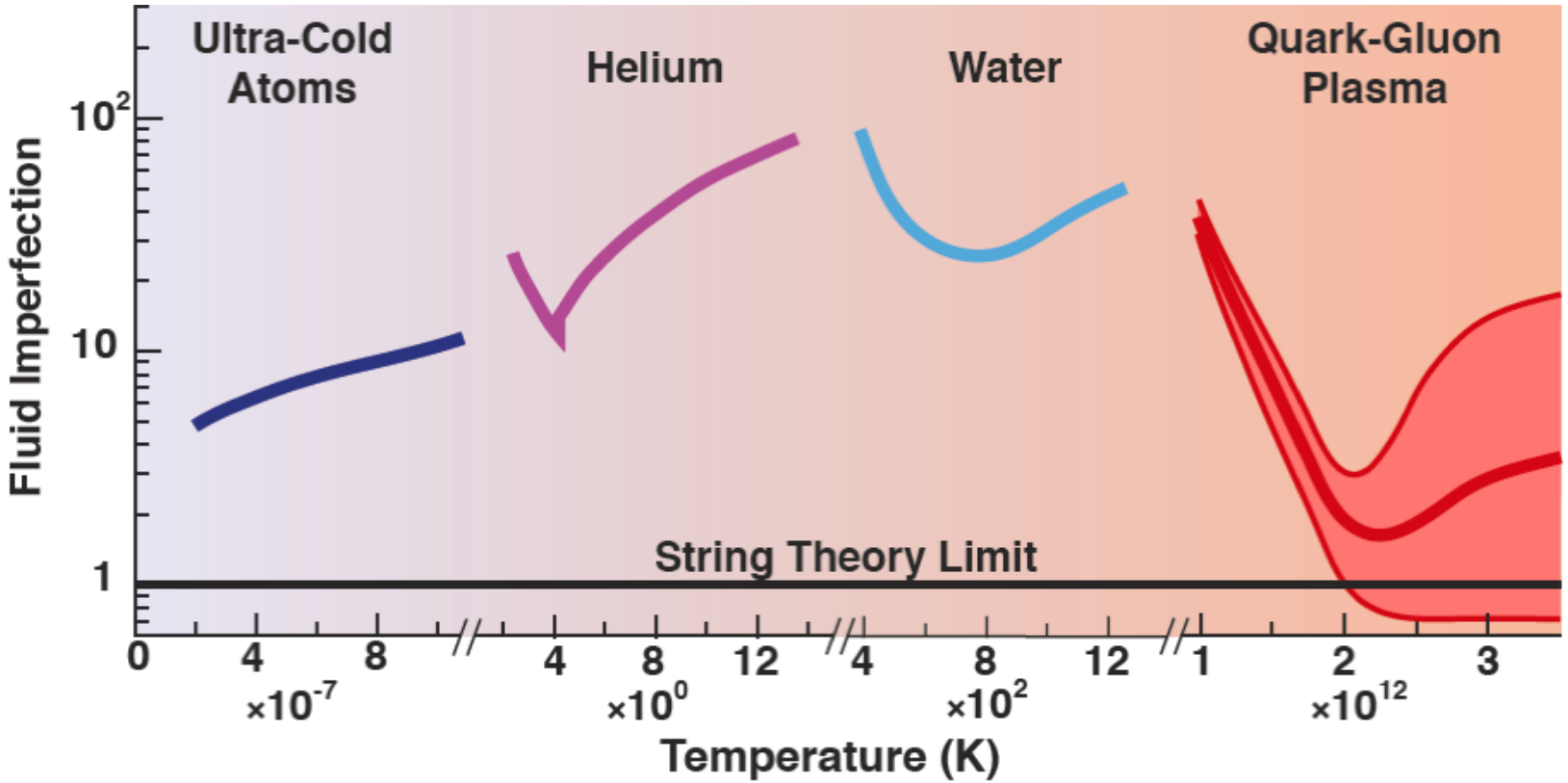
Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime

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?

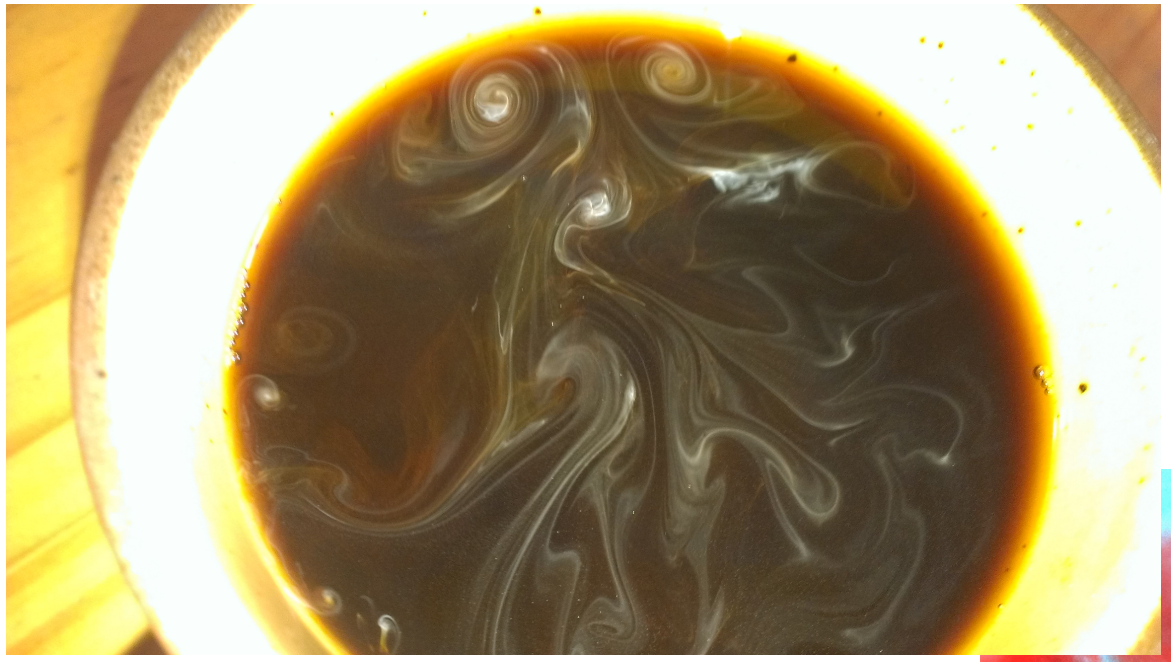
Viscosity in strongly interacting quantum field theories from black hole physics P. Kovtun, D. Son, A. Starinets, Phys. Rev. Lett. 94 (2005) 111601



None more perfect!

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

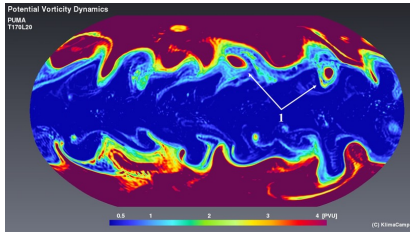
Beyond Flow: Vorticity

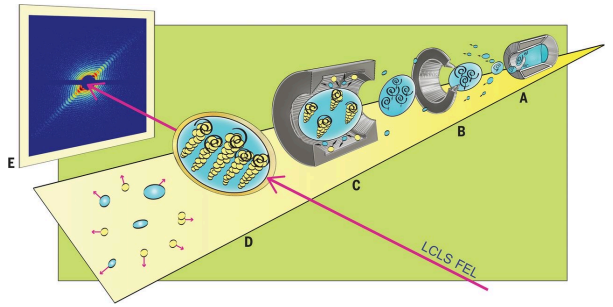


- Vortices naturally form in fluids
- "Vorticity" a measure of how rapidly the fluid spins locally
- Units: s^{-1}

Vorticity in other systems: Scale

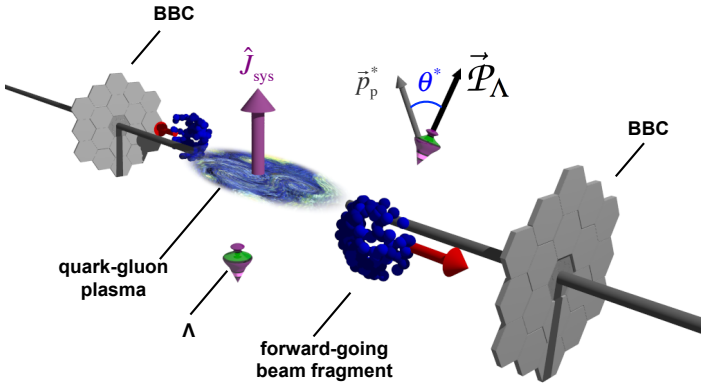
- Solar subsurface flow: 10^{-7} s^{-1}
- Terrestrial atmospheric patterns: 10^{-5}-10^{-7} s^{-1}
- Great red spot of Jupiter: 10^{-4} s^{-1}
- Supercell tornado cores: 10^{-1} s^{-1}
- Bulk superfluid He II: 150 s^{-1}
- Superfluid nanodroplets: 10^{7} s^{-1}
- RHIC: 10^{22} s^{-1}





The measurements: spin polarization

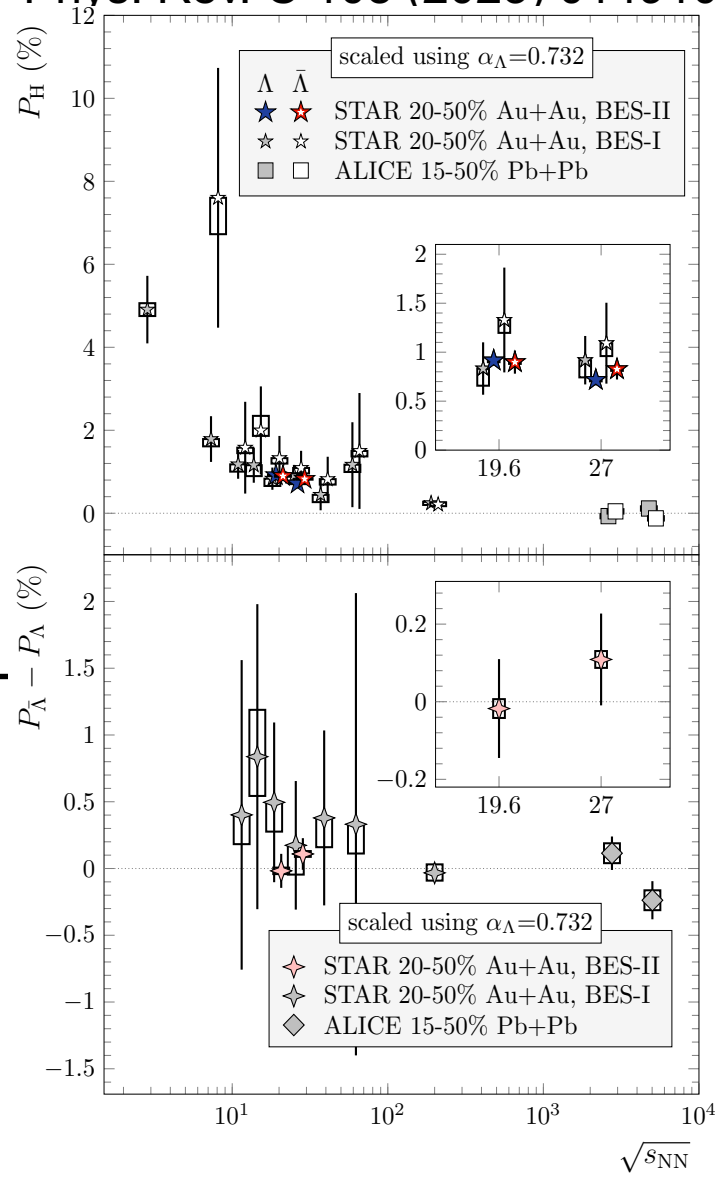
Nature **548** (2017) 62



Most Vortical Fluid ever observed

Exploring Magnetization:
Limit on magnetic field < ~1 x 10^{13} T

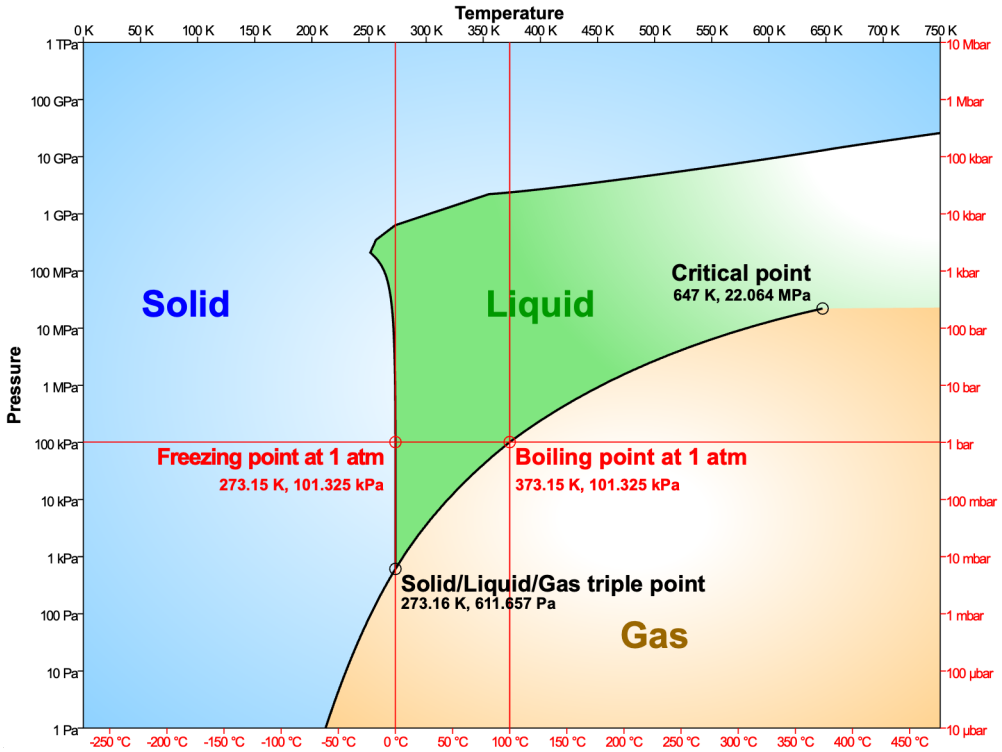
Phys. Rev. C 108 (2023) 014910



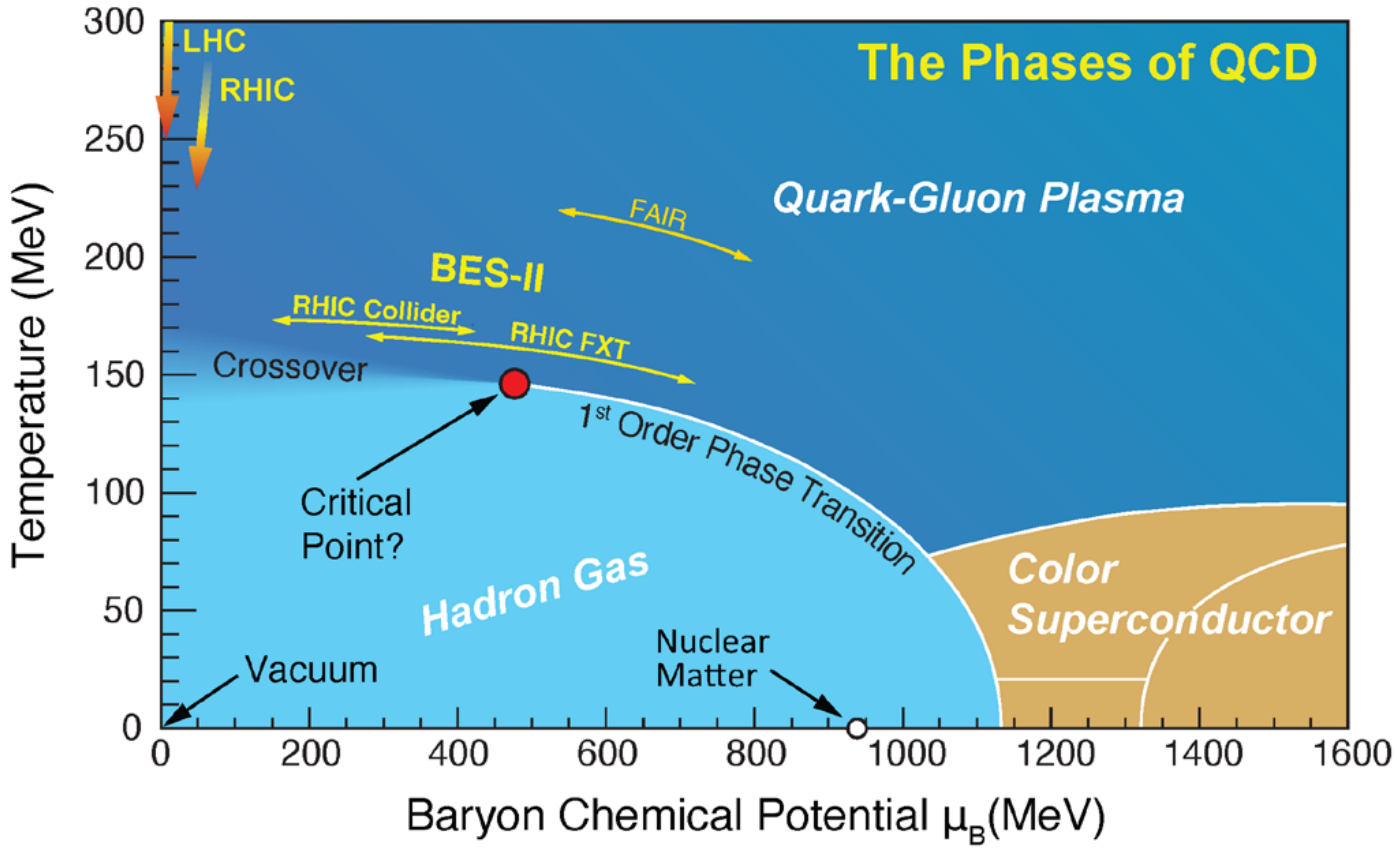
Many other detailed measurements probe vortical structure

Phases of matter

Example of QED Matter: Water



QCD Matter: explored at accelerators



Phase Transitions

Boiling Water

1st order phase transitions:

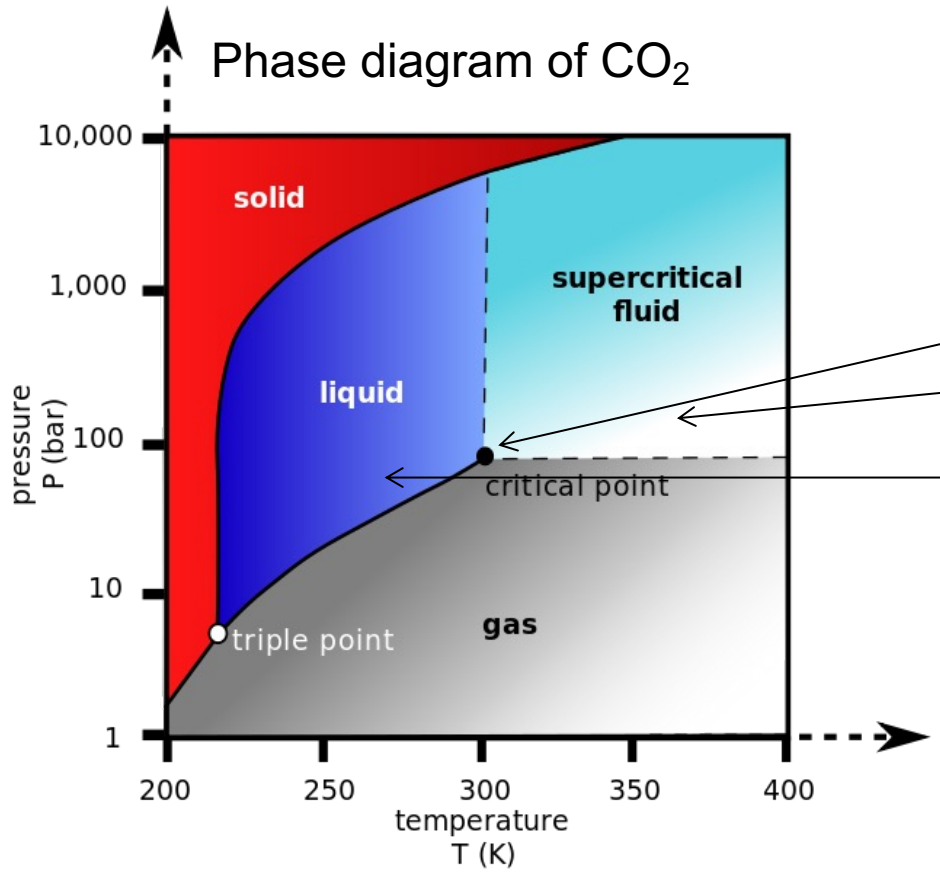
Phase Coexistence (“Bubbles”)
Latent Heat

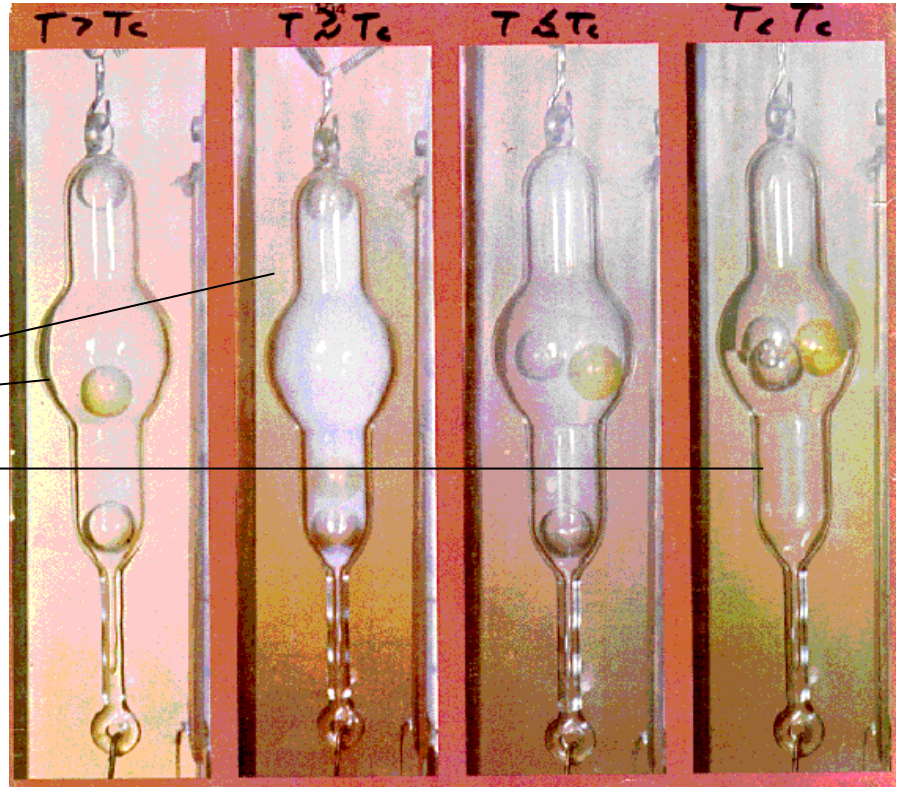
CO_2 near critical point

2nd order phase transitions:

Critical behavior

Critical Behavior

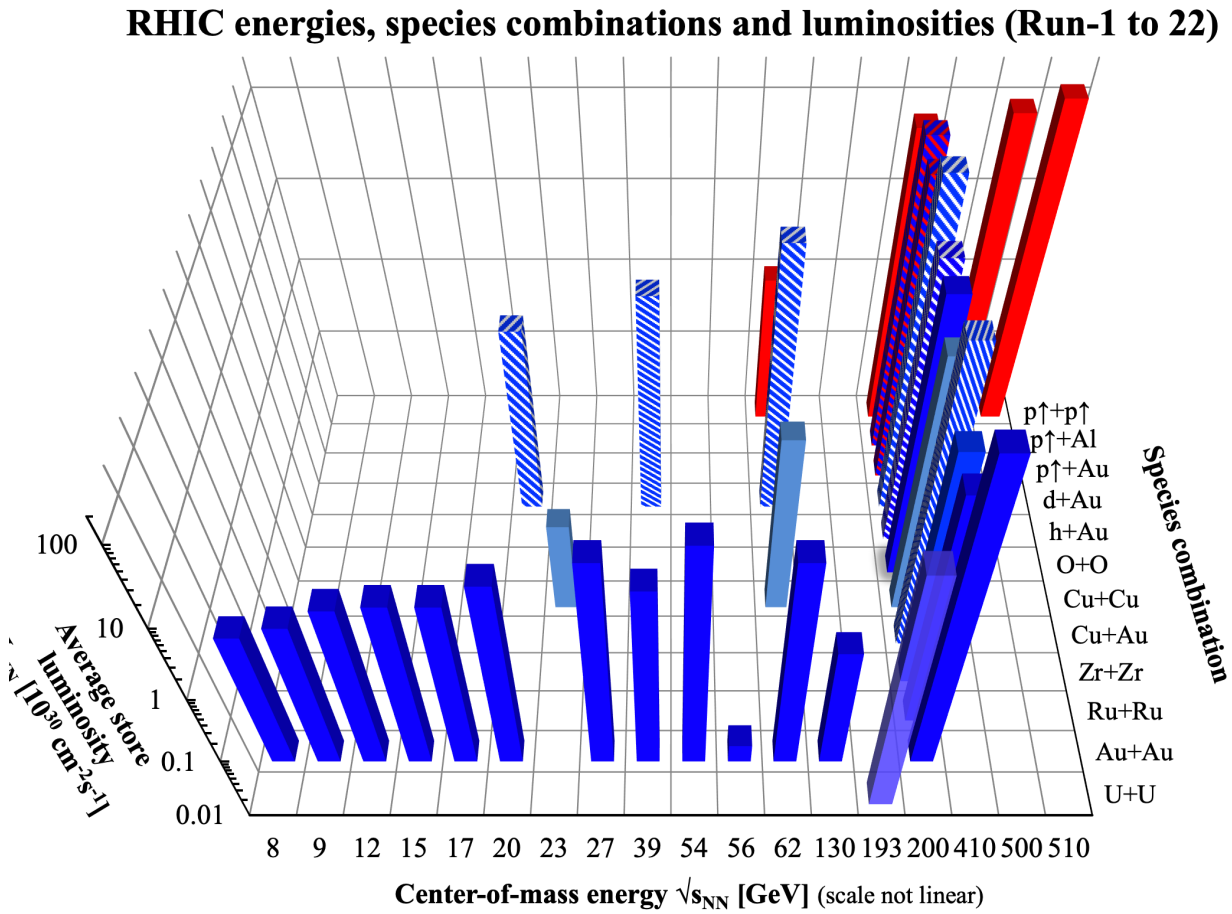




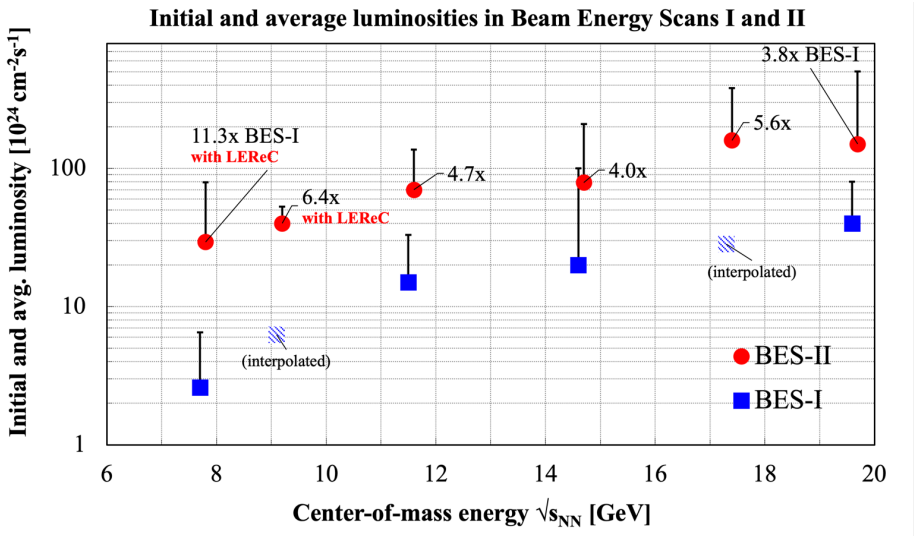
http://www.mit.edu/~8.334/grades/projects/projects08/TheodoreGolfinopoulos/text3a.html

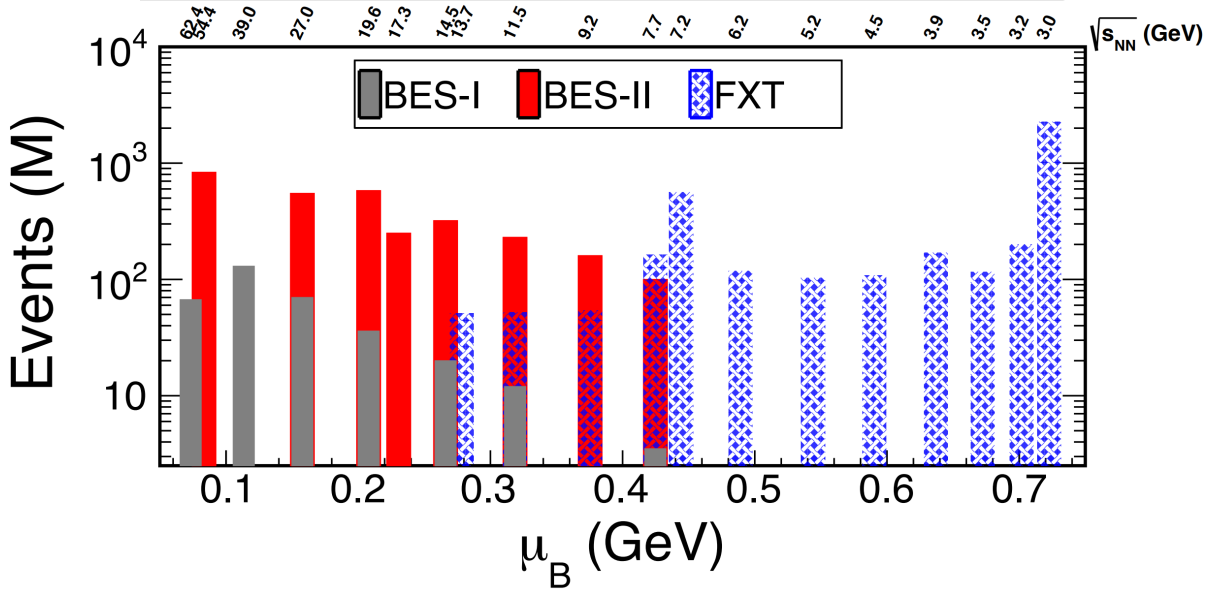
Critical Opalescence (i.e. long-range correlations) near a critical point

The Versatility of RHIC



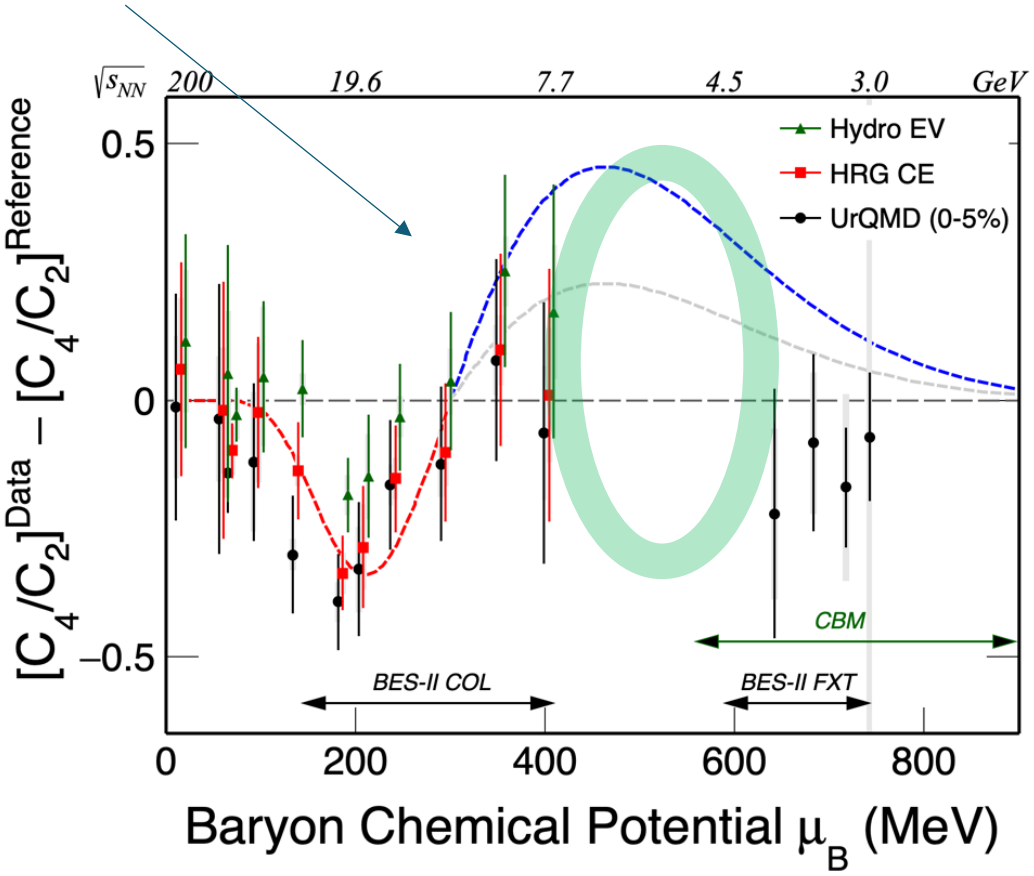
Only polarized hadron collider in the world!





Current Status of Critical Point Search

Curve to guide the eye:
Dip and rise expected from presence of critical point



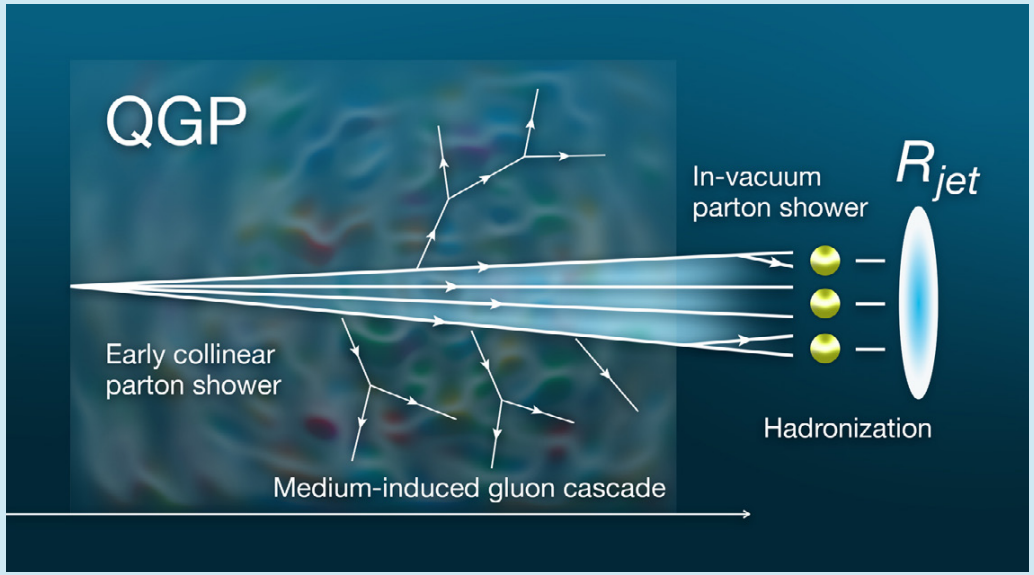
Lesson:

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

S. Esumi, Quark Matter 2025
https://indico.cern.ch/event/1334113/contributions/6209751/attachments/3050082/5390661/QM25Apr11_CP_Esumi.pdf

Next chapter of RHIC: Jets and Emergence of fluid behavior

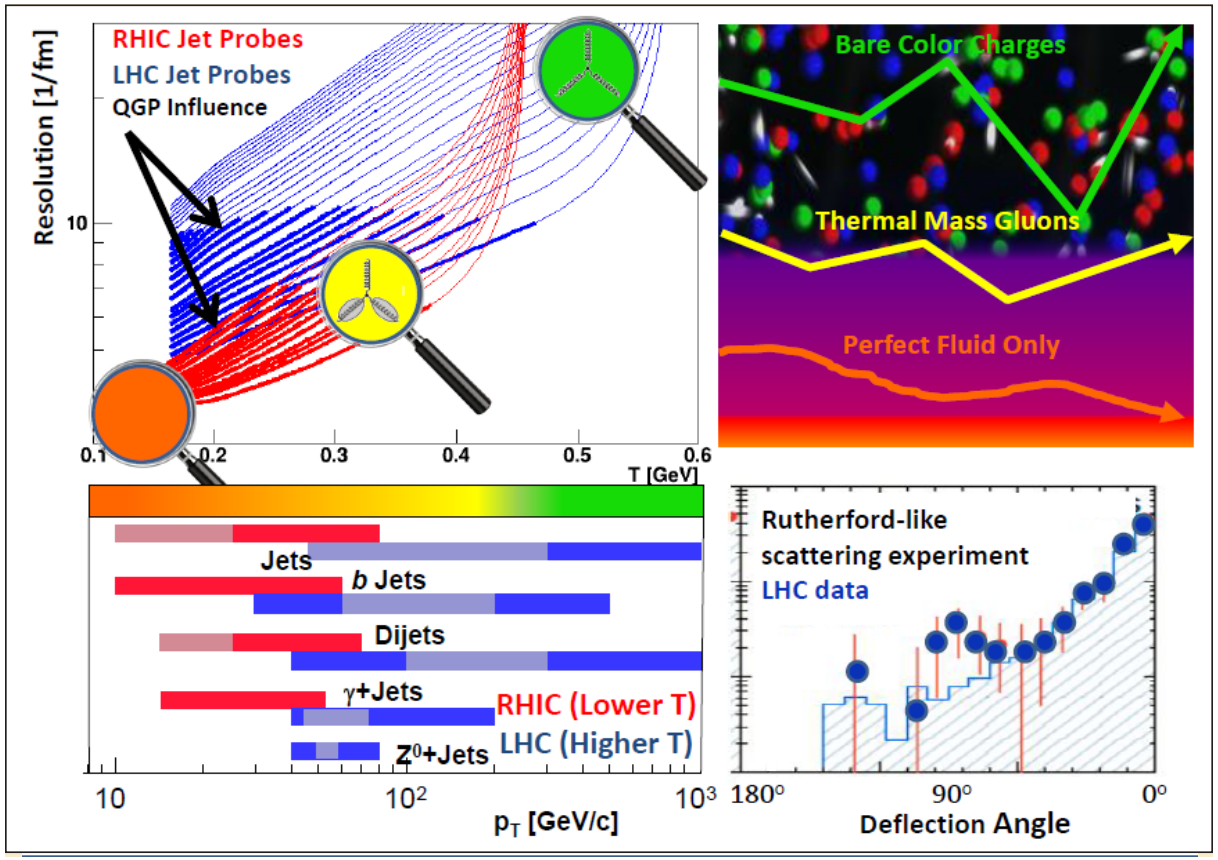
NSAC 2023 Long Range Plan



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



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 >500 PhD’s over its lifetime