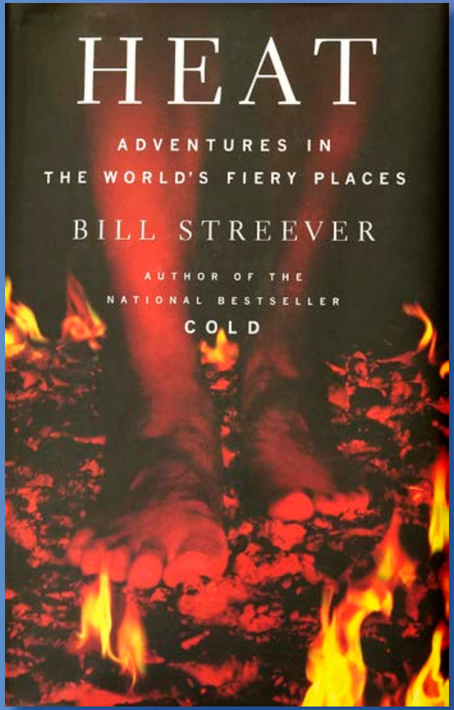
The “Hot” (and Cold) Science of RHIC



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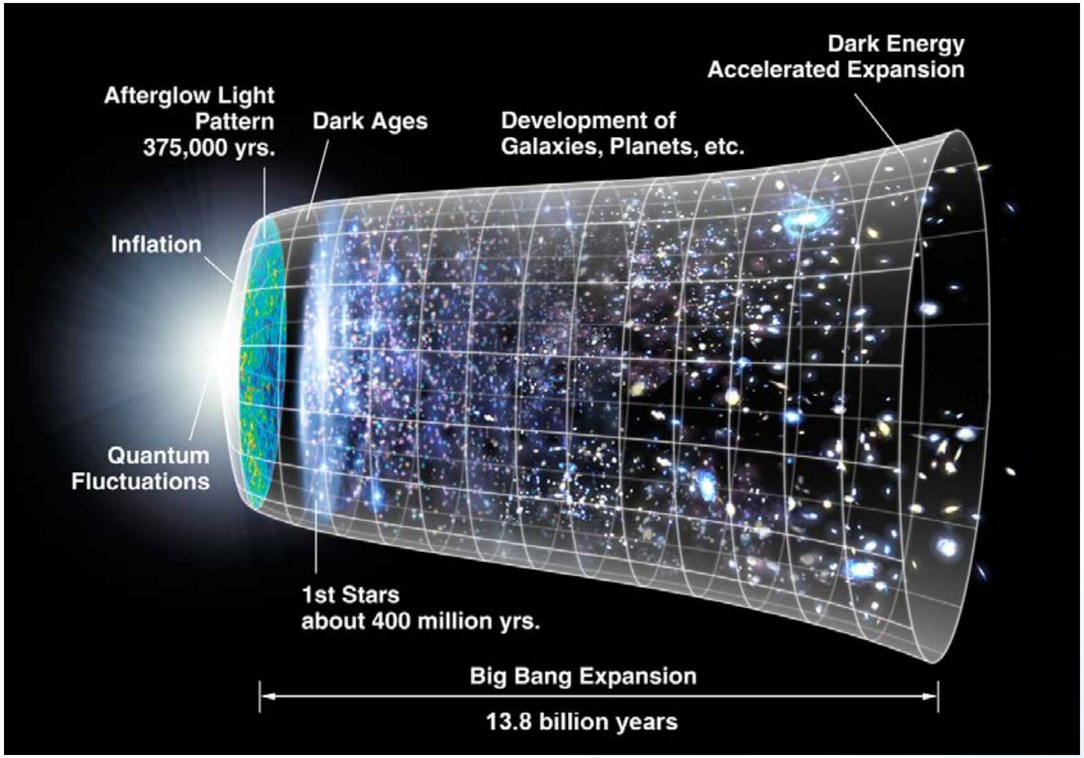
The "Hot" (and Cold) Science of RHIC

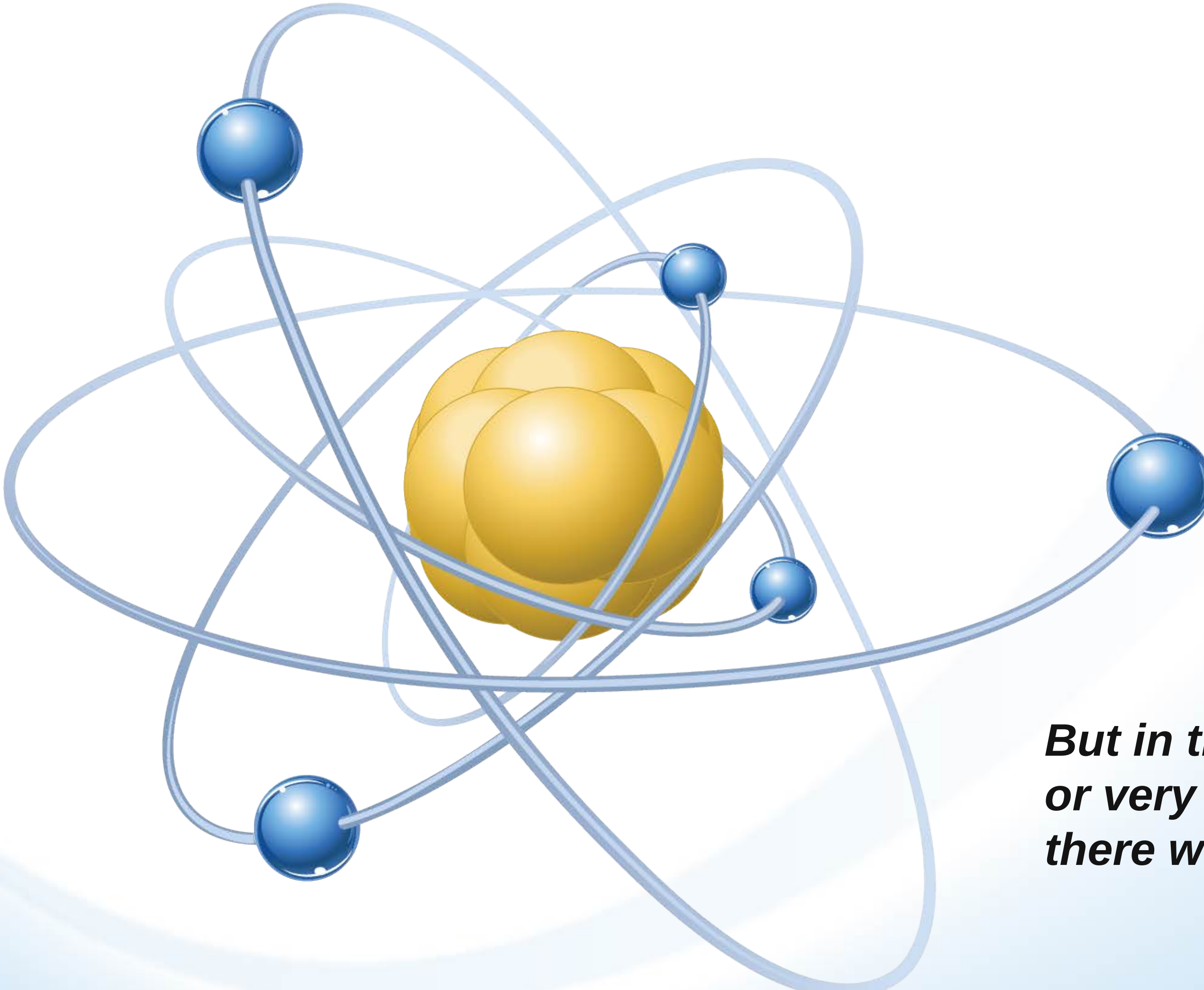
RHIC looks back to the dawn of time…



…to explore the origins of mass and matter…

…and the evolution of our universe.

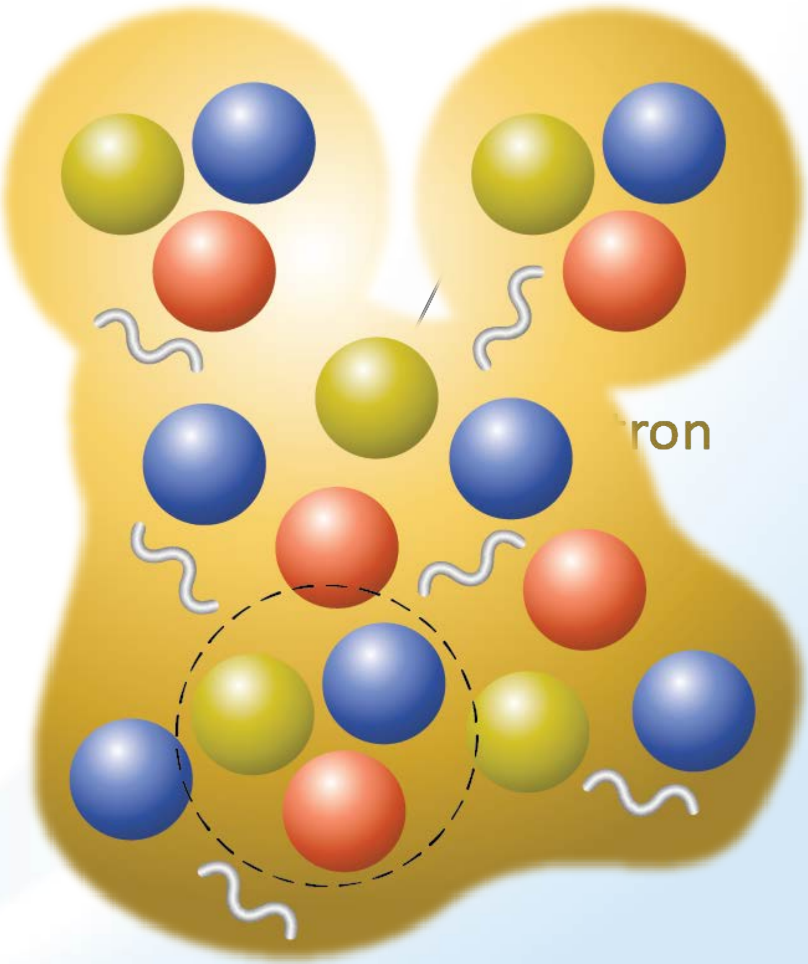
Today our world is built of atoms



But in the beginning— or very close to it— there were no atoms…

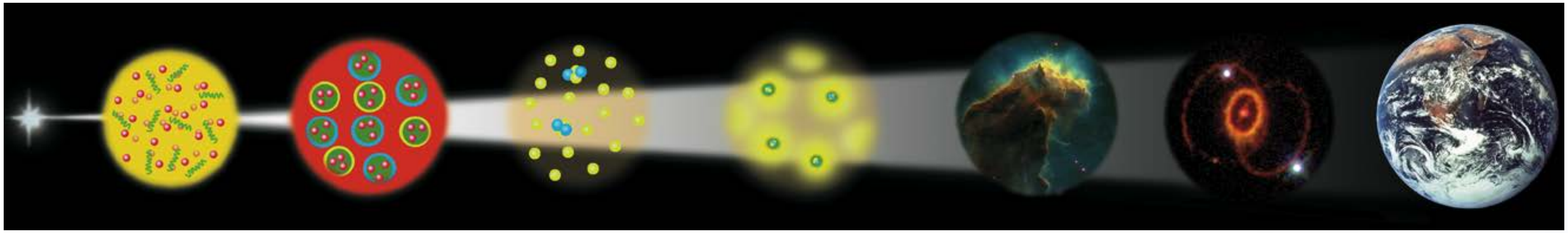
…not even the building blocks of atoms

- No protons or neutrons (the particles that make up the nucleus of an atom)
- Just a sea of subatomic particles including:
    - *quarks* – the building blocks of protons and neutrons
    - and *gluons* – the “glue” that ordinarily holds quarks together in bigger particles

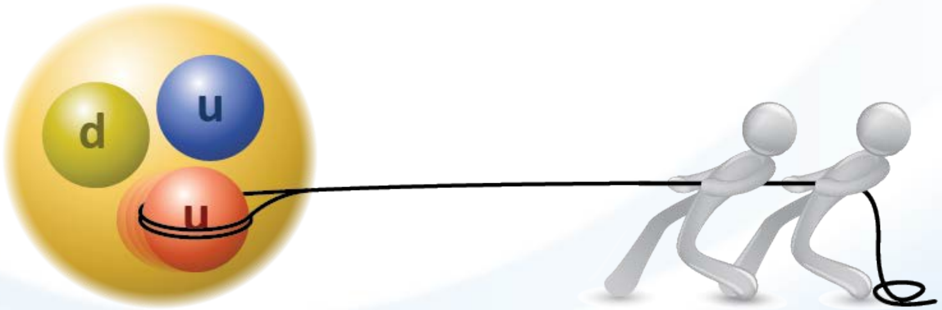


The whole universe was a seething soup of quark-gluon plasma.

Quarks (and gluons)…

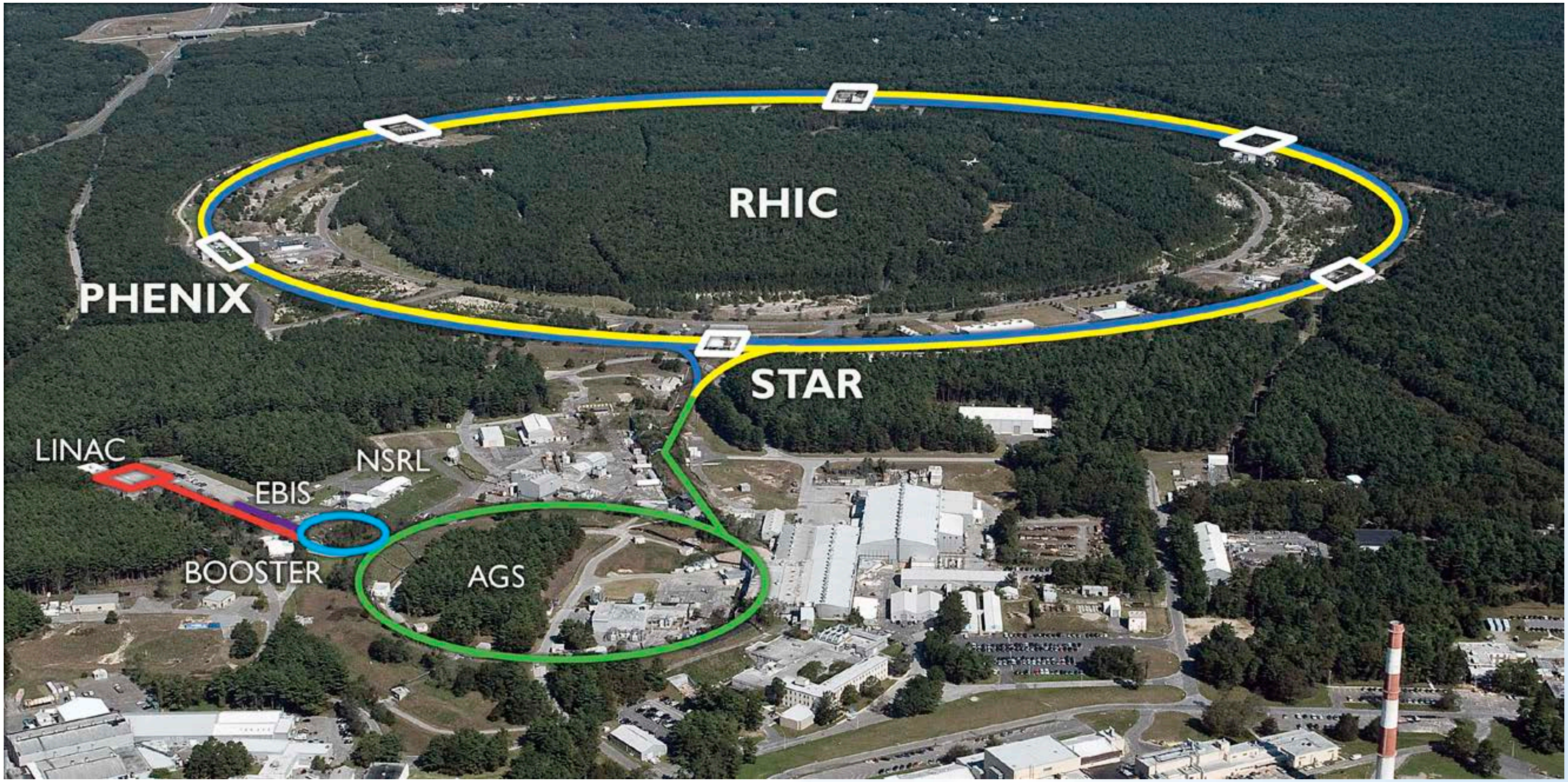


- Make up 99 percent of the mass of the matter visible in the universe today—everything from stars, to planets and people
- Nearly impossible to study when locked inside protons, neutrons, and nuclei
  - Can't pull them out: the force that holds them together—the strongest force in Nature—gets stronger when we try



We needed another way to explore their role in the structure of our world!

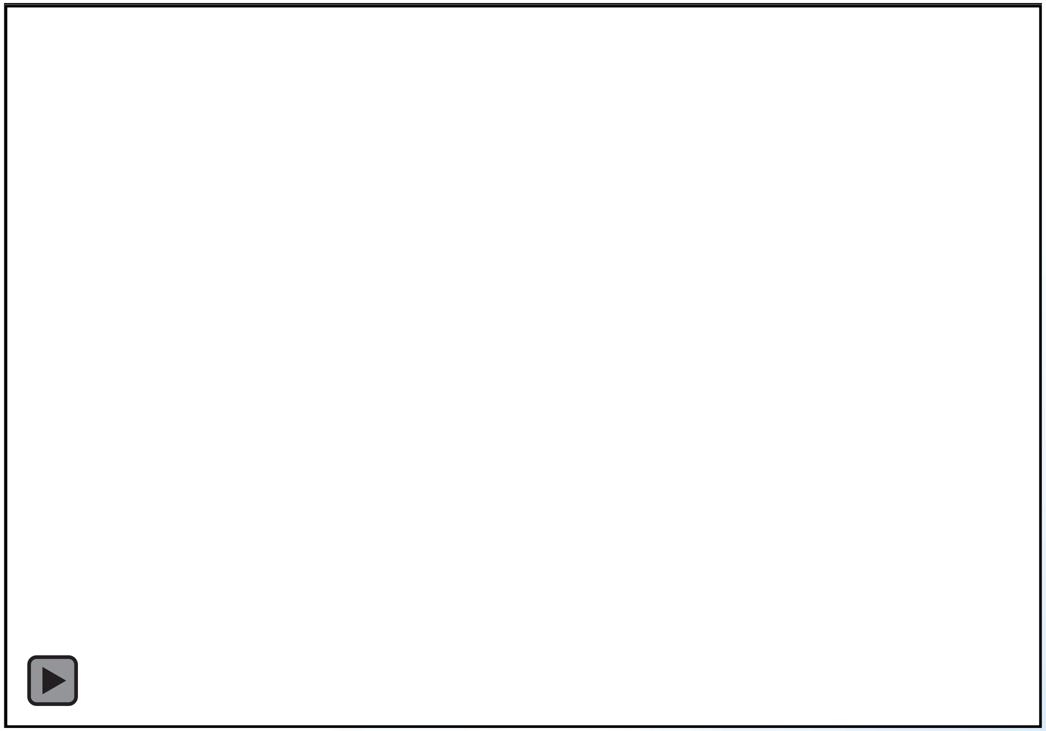
The Relativistic Heavy Ion Collider: RHIC turns back the clock



- 2.4-mile circular particle racetrack for atom-scale smashups

The Relativistic Heavy Ion Collider: RHIC turns back the clock

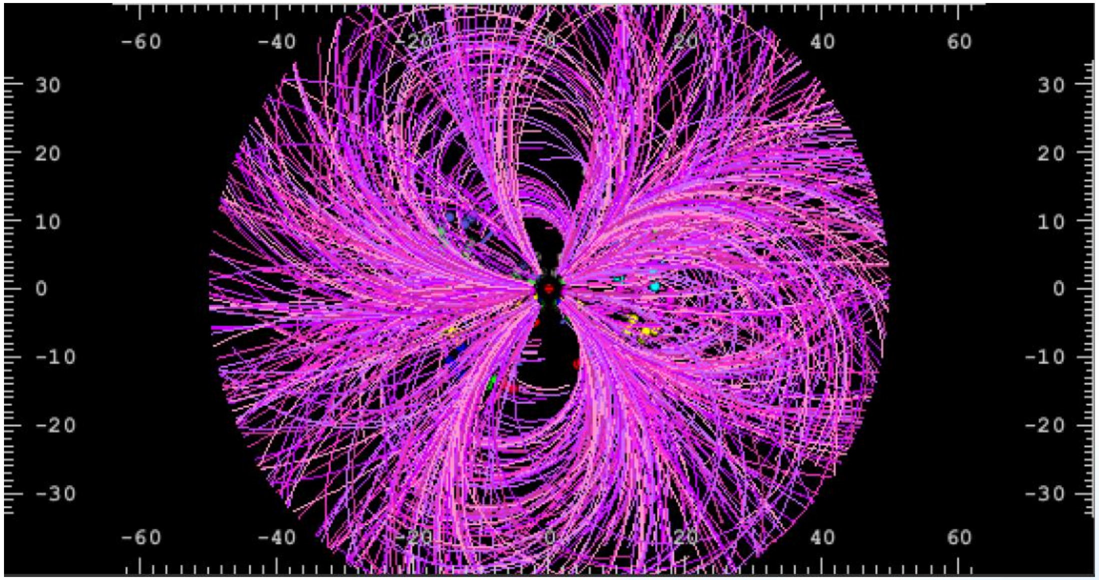
- RHIC accelerates bits of ordinary matter (nuclei of heavy atoms such as gold, *heavy ions*) to *relativistic* speeds (close to the speed of light), and steers them into head-on *collisions*
- Recreates conditions of the early universe, some 13.8 billion years ago



A fleeting chance to see how the building blocks behaved before cooling off and joining up to form the ordinary stuff that surrounds us now.

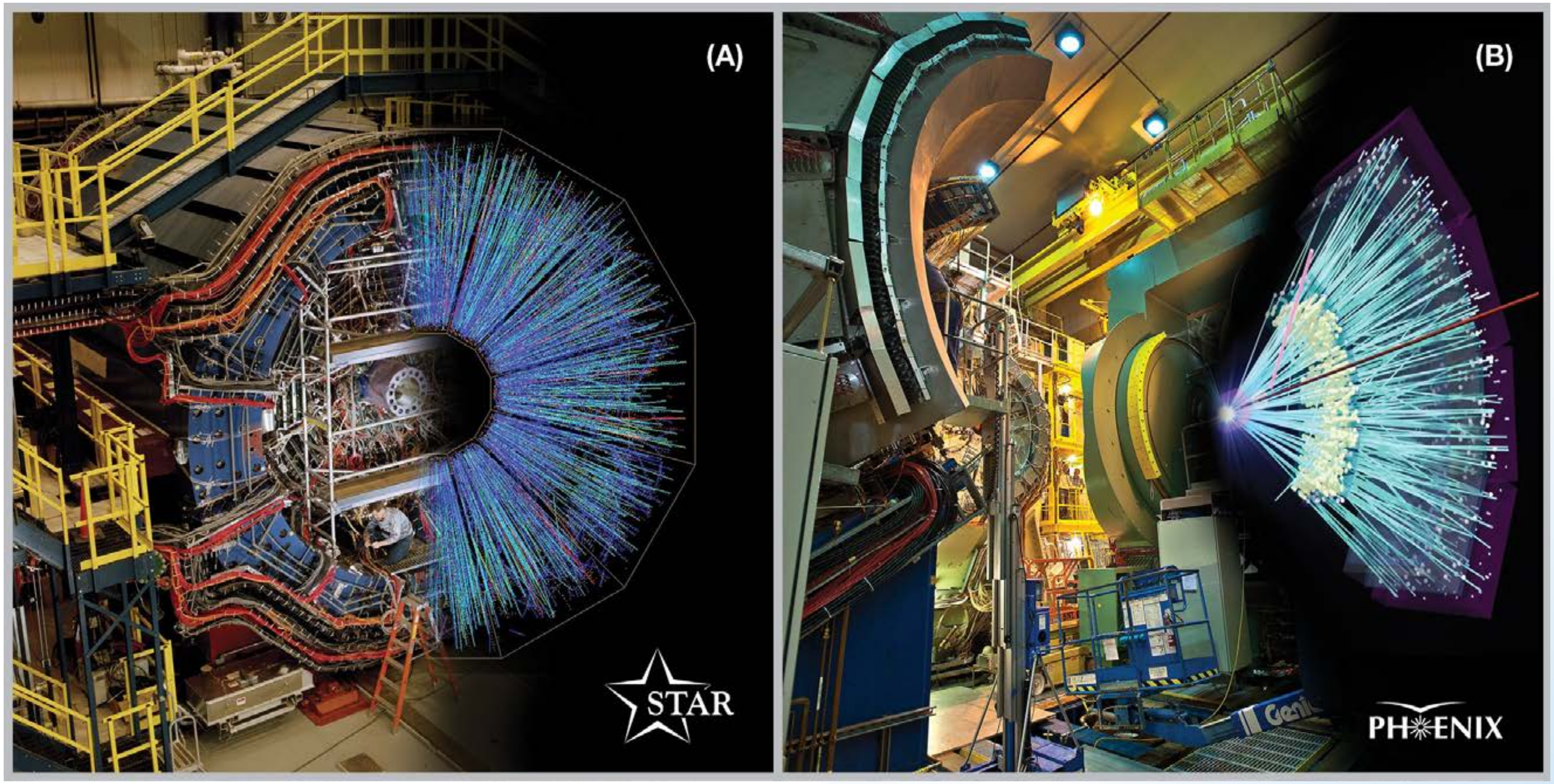
Detectors, computers, and scientists capture and track the action

- Hot quark soup lasts 0.00000000000000000000001 second—less than ten *millionths* of a *billionth* of a *billionth* of a second
  - very hot (trillions of degrees)
  - lots of matter squeezed into a very tiny space



We learn what quark-gluon plasma (and the early universe) was like by looking at the "debris"—thousands of particles created by each energetic collision, converted to mass via Einstein's $E=mc^2$.

RHIC's detectors



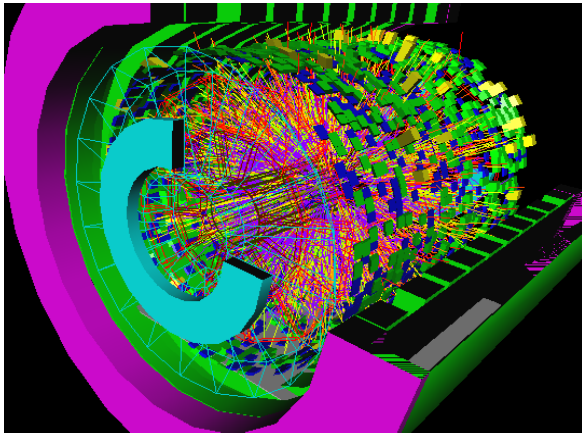
STAR like a giant, 3-D, digital camera

PHENIX layers tease out different particles

Plus two earlier detectors,
PHOBOS and **BRAHMS**,
mission complete

Complexity pushes the limits

- Measure/count which particles come out
  (some particles created in the matter interact with it and get “stuck”)
- Requires LOTS of collisions
  (thousands per second)
- Yields LOTS of data
  (15 petabytes so far, enough to fill 5 million DVDs)



Pushes the limits of particle detection.

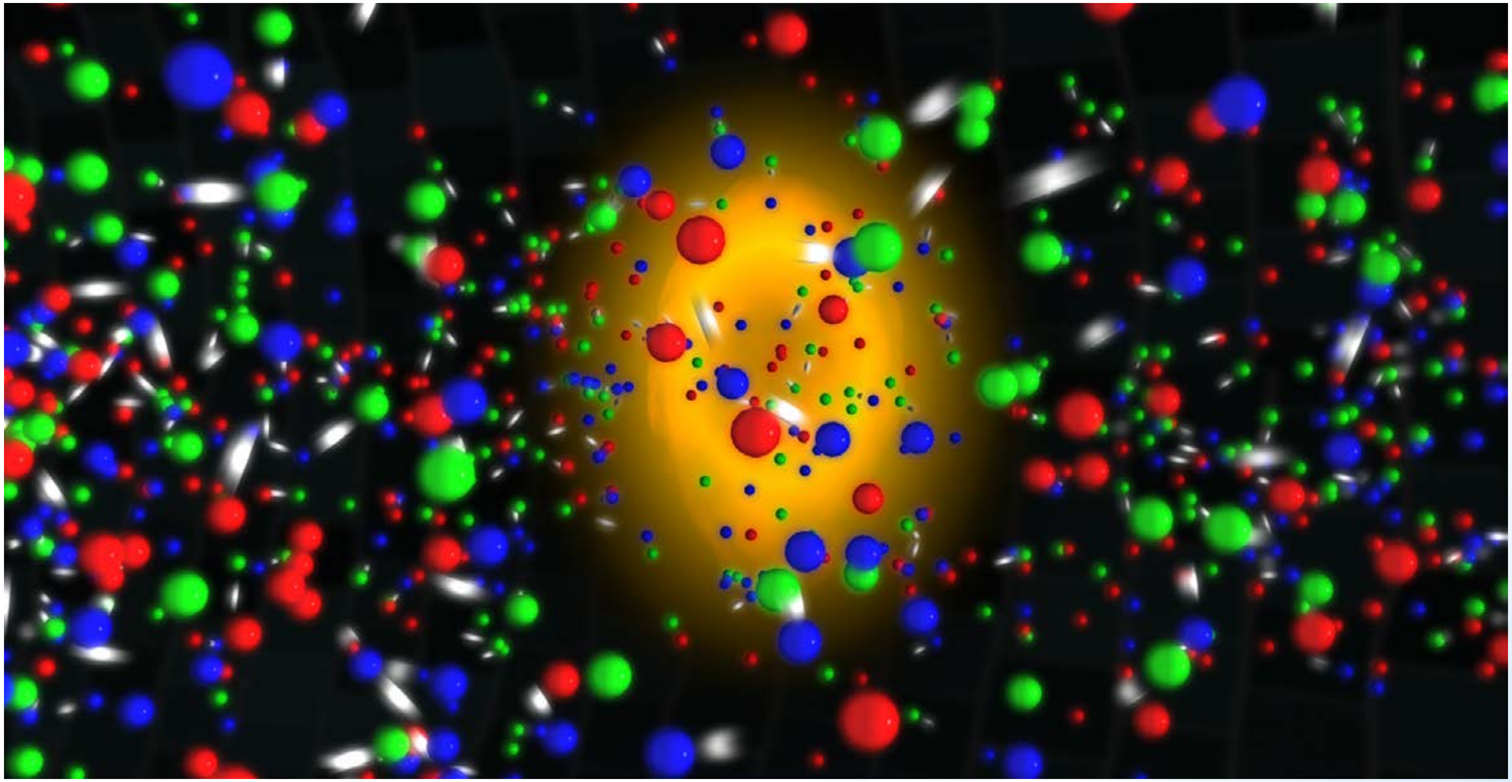
Pushes the limits of accelerator design.

Pushes the limits of computer storage, processing, and data analysis.

Complexity pushes the limits

- Attracts 1,000+ collaborators from around the world who figure out what questions to ask of all that data!
  - *Physicists gravitate to the biggest challenges!*
  - *Many go on to address other technological and data challenges in physics, medicine (accelerators for cancer treatment), national security (detectors for dangerous materials), and other fields.*

Big surprise:
RHIC's quark-gluon plasma is a *liquid*



- More than 4 trillion degrees Celsius—250,000 times hotter than the center of the sun—a Guinness World Record!

We expected a gas…

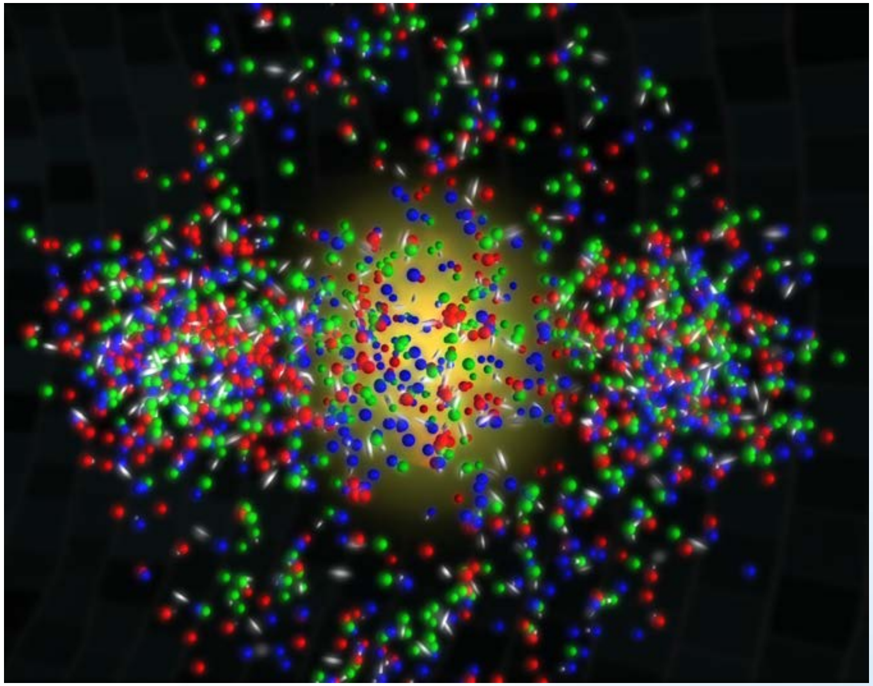
Big surprise: RHIC's quark-gluon plasma is a *liquid*

- Imagine:

  … heating nuclear matter until it turns into a gas of protons and neutrons (at 100 billion degrees)

  …but when you heat it to 20 times this temperature, the gas suddenly becomes a liquid again!

  …and not just any liquid, but the most perfect liquid ever observed—it *flows with almost no friction!*

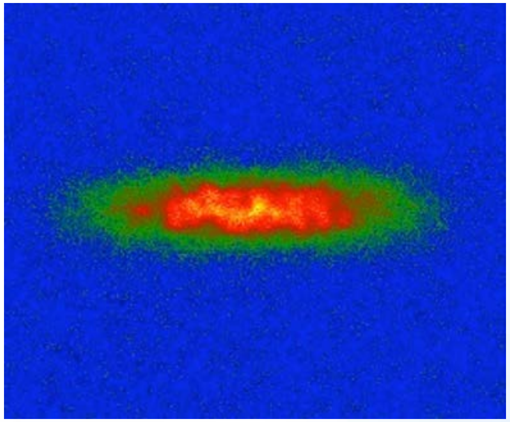


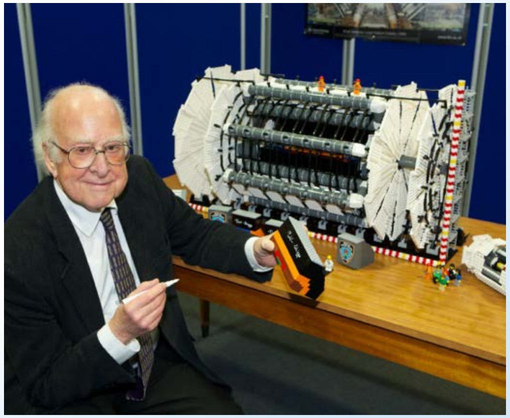
- Viscosity even lower than that of matter created in higher-energy/temperature collisions at the Large Hadron Collider in Europe

No other liquid is known with such a low value!

Connections to other fields (some unexpected!)

- Cold atomic gases (also perfect liquids) and condensed matter (superconductors)
- String theory in action
- Black holes! They act like perfect liquid at event horizon when swallowing information
- Probing the vacuum—it's not empty!
- Origin of mass—Higgs particle gives mass to fundamental particles (e.g. quarks), but the interaction of quarks via gluons accounts for 99 percent of the mass of visible matter!

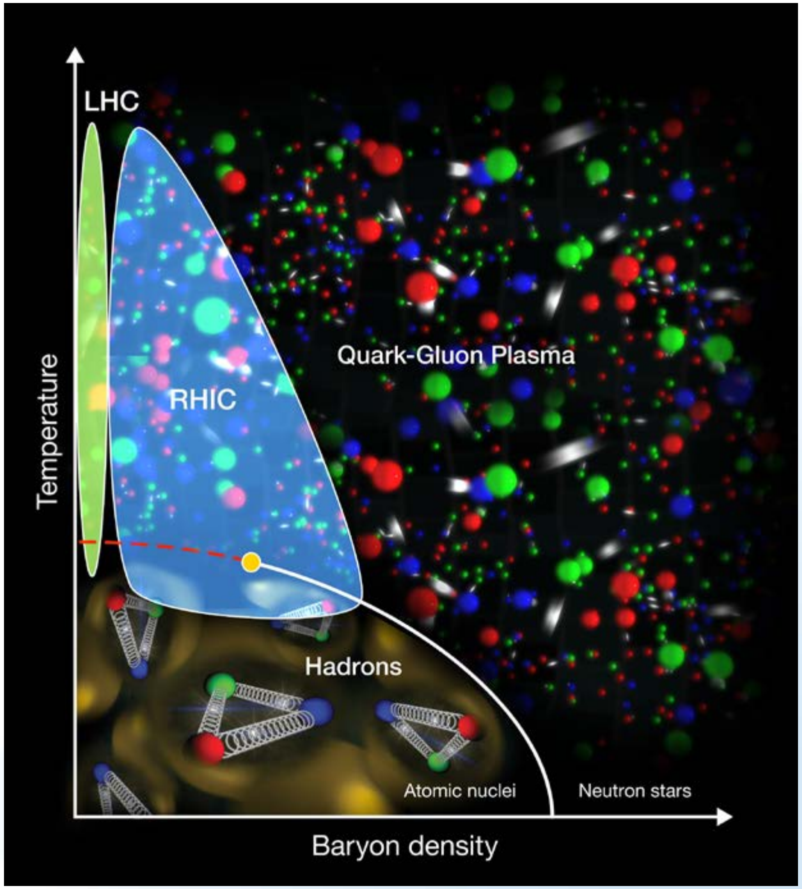




We want to know more about those subatomic interactions and how RHIC's perfect liquid works.

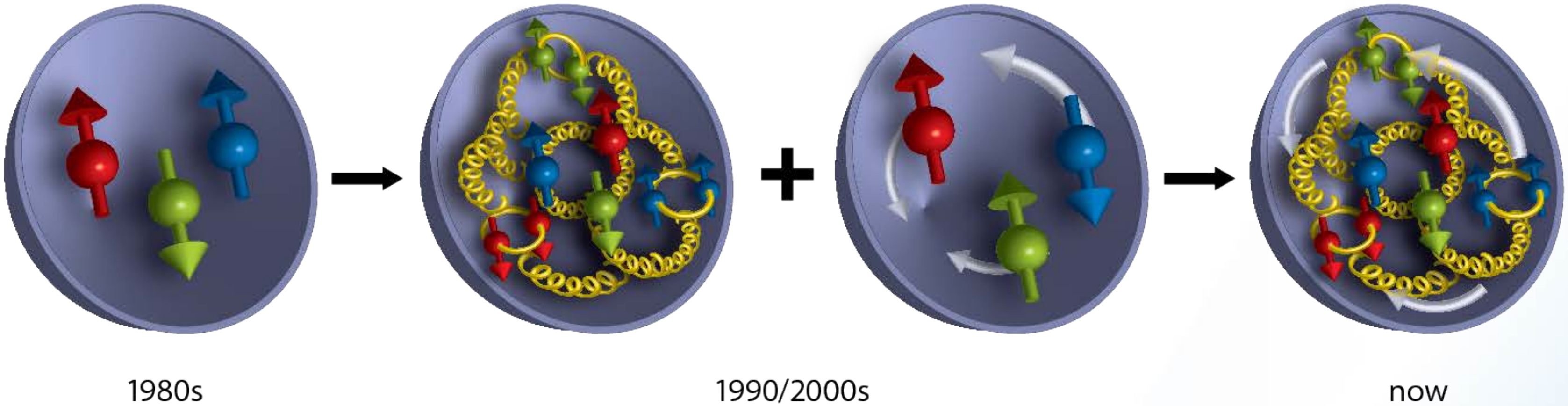
RHIC's versatility puts it in the "sweet spot" for studying nuclear matter

- "Mapping" the phase diagram
- Wide range of beam energies
- Ability to create temperatures above and below the transition from ordinary matter to quark-gluon plasma
- Different sizes and shapes of ions (from protons to copper, gold, and uranium)
- Control and study subtle effects (e.g., dependence on temperature, quark density)



RHIC explores matter with the most unusual properties.

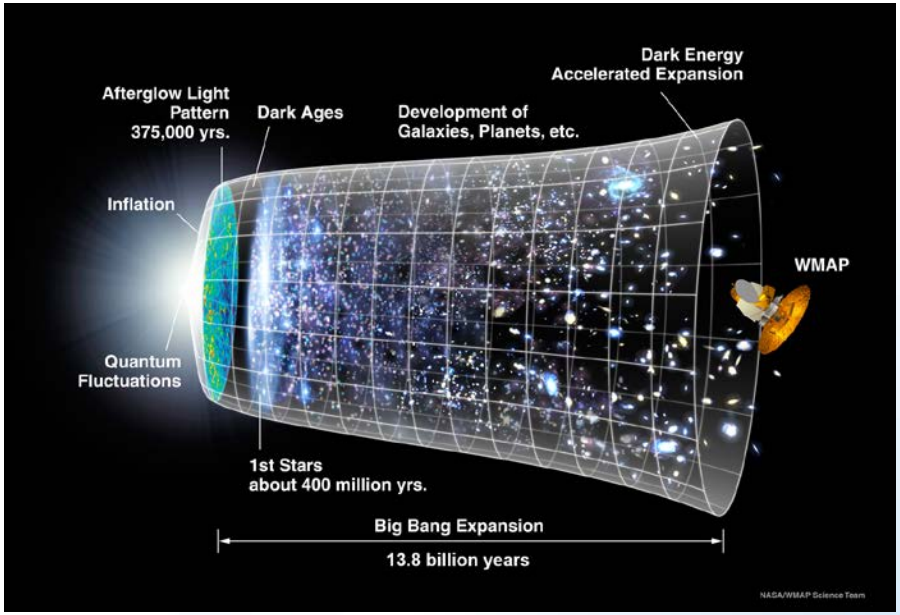
The world's ONLY polarized proton collider



- Enables detailed exploration of a long-standing physics mystery: missing proton "spin"
    - spin doesn't just come from quarks
    - measure gluon contribution for the first time (they're a big part of the story)
    - measure "sea" quarks
    - measure interactions and angular momentum of quarks

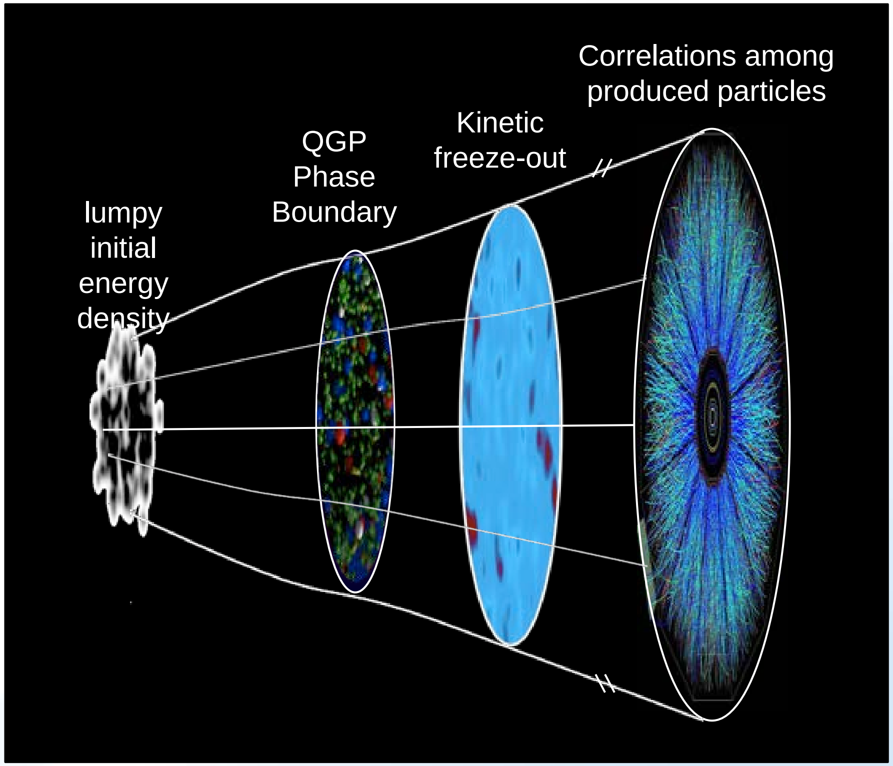
"Fingerprints" of early-state conditions

- Similar to how cosmologists learn about the very early universe by looking at the "cosmic microwave background" radiation
  - tiny fluctuations in the universe's temperature long after the Big Bang contain clues about what the universe looked like the instant after its birth
  - certain aspects of that early-universe structure are "frozen out," leaving an imprint on these temperature measurements and the large-scale structure of the universe today



“Fingerprints” of early-state conditions

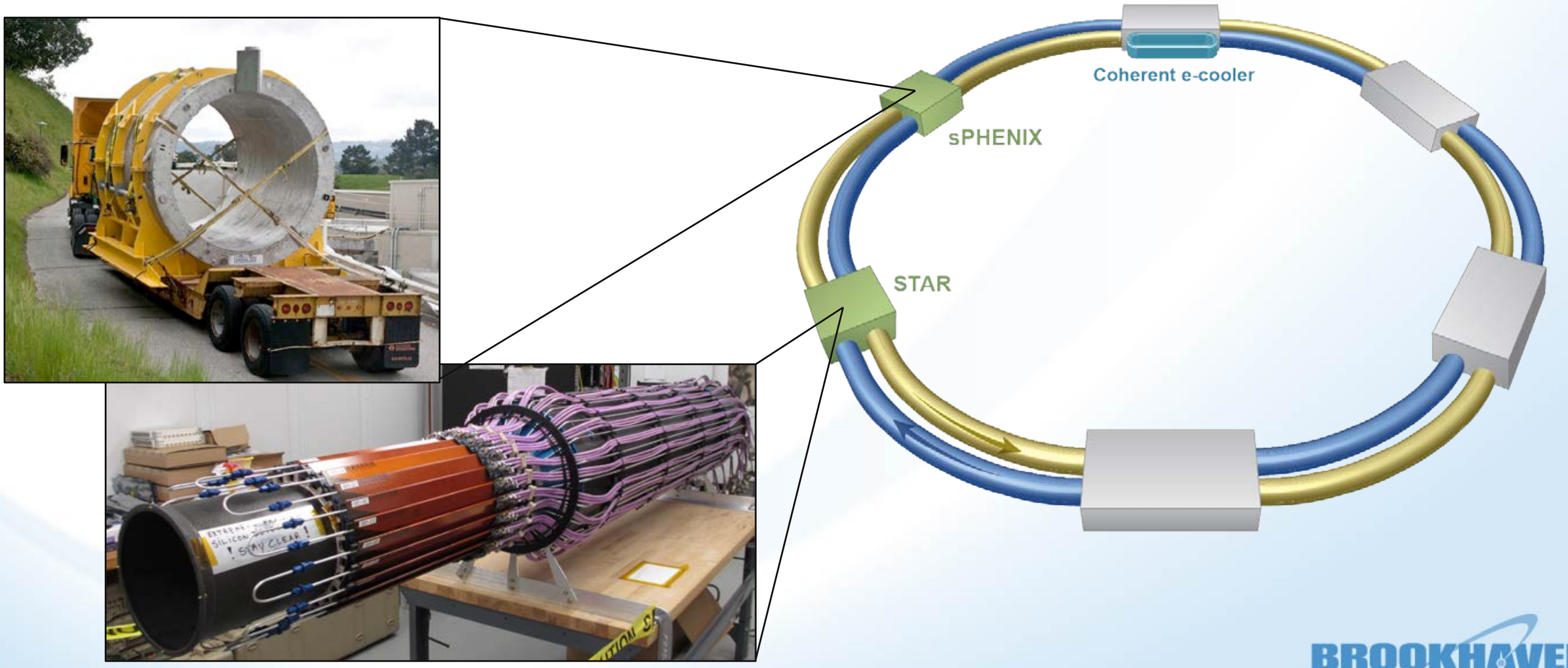
- At RHIC, the spatial structure of the collision is very sensitive to the earliest moments of the collisions
  - colliding walls of gluons
  - measurements of flow
  - tiny fluctuations in gluon fields and collision “geometry” are frozen out and left as “fingerprints” in the flow pattern of particles



We can learn a lot by looking back, but also want to look at early stages directly with an electron-ion collider (eRHIC).

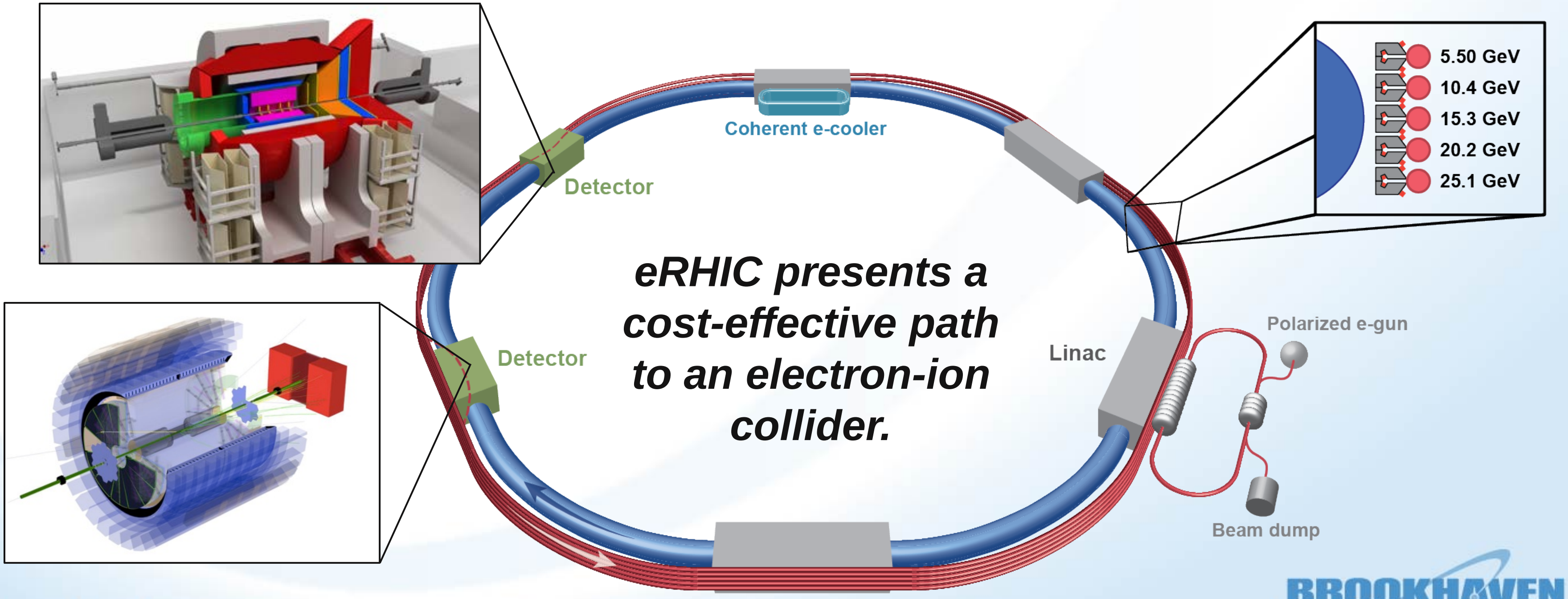
Upgrades will make RHIC more powerful

- New detector components for tracking new kinds of particles
- 10x higher collision rates
- “Electron cooling” to keep beams tightly bunched and maximize beam life



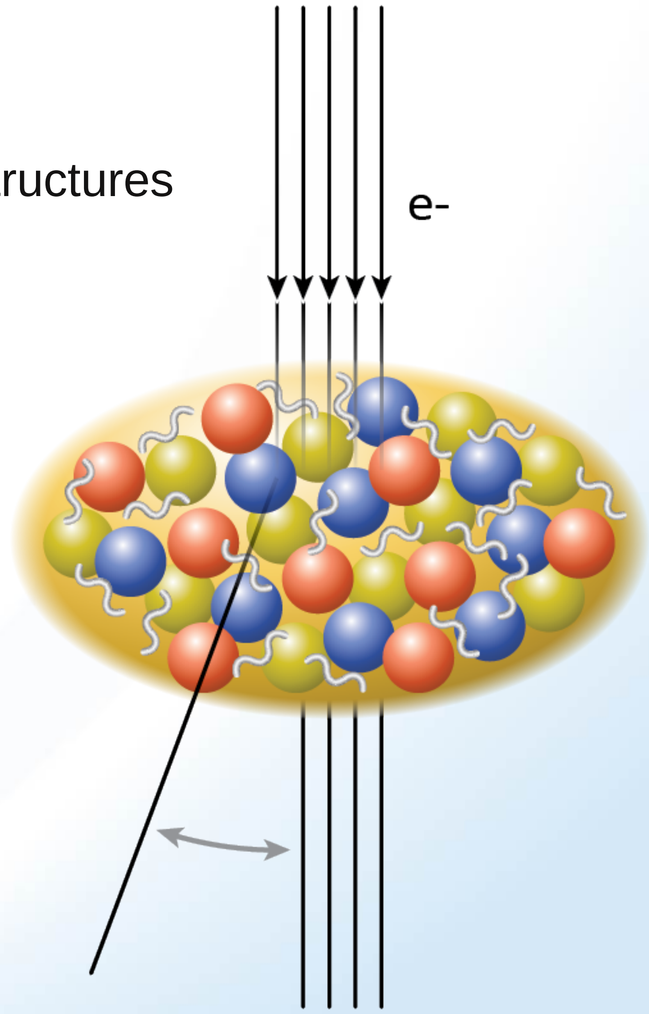
eRHIC: The world's first polarized electron-ion collider

- Adding an electron ring to the RHIC complex
- Builds on existing RHIC infrastructure
- Novel accelerator and detector technologies
- Leverages Brookhaven's scientific and technical expertise



eRHIC probes cold nuclear matter

- Highly collimated electrons penetrate heavy ions and protons
  - similar to how a microscope sees internal structures
  - deflection of electrons gives information about internal structure in 3-D
- Explores conditions before the particles collide
  - behavior is dominated by gluons, constantly moving
  - light-speed motion “freezes” sample so you can see the gluons
  - dense gluon walls (another new form of matter: color glass condensate)

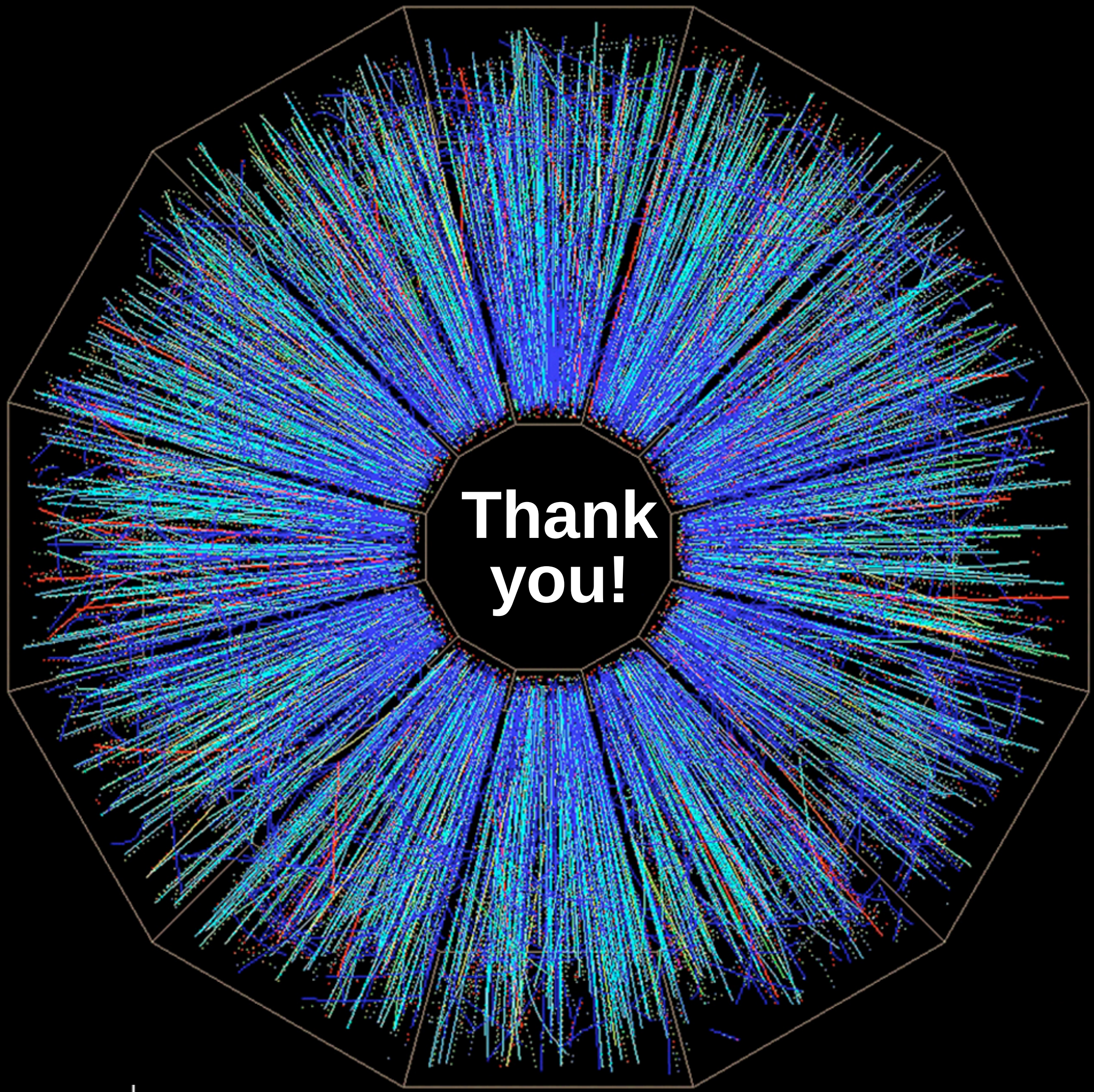


Allows detailed studies of how gluons create quark-gluon plasma and contribute to proton spin with unprecedented precision.

Summary: RHIC is irreplaceable

- ONLY collider operating in the U.S.
- Continuing high productivity
  - >350 scientific papers (on perfect liquid, heaviest antimatter, gluon role in proton spin, and more)
  - >30,000 references made to these papers in other research
- A magnet for the brightest minds
  - >350 PhDs based on work at RHIC; hundreds more in the pipeline
- $2B infrastructure uniquely capable of exploring quark-gluon matter and proton spin
- Lays the foundation (scientifically and infrastructurally) for a future electron-ion collider (eRHIC)
- RHIC & eRHIC will help ensure U.S. preeminence in nuclear physics for 2-3 decades!

Expertise and tangential benefits
our nation can't afford to lose!



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