

# Small systems in heavy-ion collisions: creating droplets of the early universe?

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THE UNIVERSITY *of* NORTH CAROLINA  
**GREENSBORO**

## Утро в сосновом лесу





# Утро в сосновом лесу



# Outline

- Part 0: introduction
  - History lesson, units, physical constants, some basics
- Part I: the large
  - Overview of conventional heavy ion physics with large nuclei
- Part II: the small
  - Some recent results from heavy ion physics with small nuclei
- Part III: the future
  - A brief look at the next US-based experiment in heavy ions

# Key points for Part 0

- A bit of a history lesson
- Natural units
- A basic sense of scale
- Fundamentals of quantum chromodynamics (QCD)
  - quarks
  - gluons
  - hadrons and confinement

# Historical Perspective

"Those who do not remember George Santayana are condemned to paraphrase him." - Unknown

- 400 BCE Democritus hypothesizes atoms
- 1687 Newton publishes *Philosophiae Naturalis Principia Mathematica*
- 1900 Planck's Law
- 1905 Einstein's 4 papers
- 1911 Rutherford scattering
- 1913 Bohr atom
- 1924 de Broglie wavelength
- 1925 Heisenberg's Matrix mechanics
- 1926 Schrödinger equation
- 1927 Dirac's relativistic quantum mechanics

# Historical Perspective

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- 1963 Gell-Mann's Quark Model (particle zoo)
- 1965 Additional degree of freedom postulated for quarks by Han and Nambu
- 1969 Deep inelastic scattering experiments prove the existence of quarks
- 1972 Color charge and basic framework of **quantum chromodynamics**
- 1973 Asymptotic Freedom discovered by Gross, Politzer, and Wilczek
- 1975 Collins and Perry formulate a QCD plasma
- 1980 Shuryak coins term quark-gluon plasma (QGP)
- 2000 RHIC is operational
- 2010 First heavy ion collisions at LHC

# What we've learned so far

Three generations of matter (fermions)

	I	II	III	
mass	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name	u up	c charm	t top	Y photon
	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	Z <sup>0</sup> Z boson
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	$\mu$ muon	$\tau$ tau	W <sup>±</sup> W boson
				Gauge bosons

- **Electromagnetic force:** interactions among charged particles
- **Weak force:** flavor changes, e.g. lepton decays and nuclear beta decays
- **Strong force:** binds protons and neutrons together into nuclei (residual) and quarks together into hadrons (fundamental)
- **Gravitational force:** not part of the standard model

# What we've learned so far

Which view of the world is the right one? It depends!

	slow	fast
large	<b>Classical Physics</b> (most of our daily life is here)	<b>Special Relativity</b> (effects noticeable in GPS and air travel)
small	<b>Quantum Mechanics</b> (solid state devices are based on small stuff)	<b>Quantum Field Theory</b> (only self-consistent way to combine QM and SR)

Note: GR effects **also** noticeable for GPS and air travel



# Physical constants and units

- High energy physics makes physical constants very easy to remember!
- Planck's constant  $\hbar = 1$ 
  - Shows up often quantum mechanics
- Speed of light  $c = 1$ 
  - Shows up often in special relativity
- Boltzmann's constant  $k_B = 1$ 
  - Shows up often in thermal physics and stat mech

# Typical sizes and scales for heavy ion physics

- Mass of proton = 938.3 MeV = 1.007 amu =  $1.673 \times 10^{-27}$  kg
- Typical energy = 1 GeV =  $1.602 \times 10^{-10}$  J
- Typical size = 1 fm =  $10^{-15}$  m
- Typical time = 1 fm =  $3.336 \times 10^{-24}$  s
- Typical temperature = 200 MeV =  $2.321 \times 10^{12}$  K

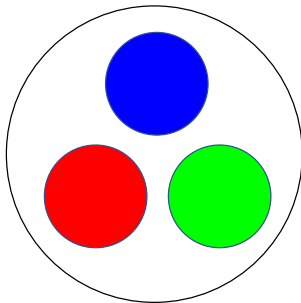
# QCD as explained by approximate analogy to QED

QED		QCD	
electric charge	$\leftrightarrow$	color charge	coupling
electrons	$\leftrightarrow$	quarks	matter fermions
photons	$\leftrightarrow$	gluons	exchange bosons
atoms	$\leftrightarrow$	nucleons	(stable) bound states
molecules	$\leftrightarrow$	nuclei	compound states

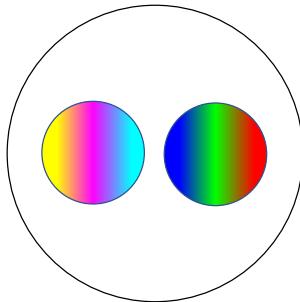
- One kind of electric charge, three kinds of color charge
- Photons do not have electric charge, gluons do have color charge
- Only one photon, eight different gluons

# QCD bound states

## Baryon



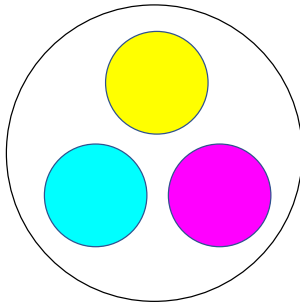
## Meson



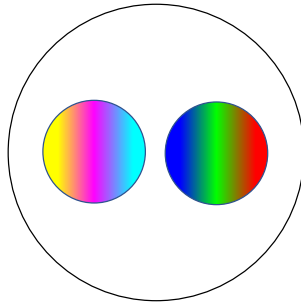
- Color-charged particles (quarks and gluons) are generically called **partons**
- QCD bound states are generically called **hadrons**, divided into **baryons** and **mesons**
- All observables must be in color singlet state—no partons can be found in isolation in nature

# QCD bound states

## Antibaryon



## Antimeson



- Color-charged particles (quarks and gluons) are generically called **partons**
- QCD bound states are generically called **hadrons**, divided into **baryons** and **mesons**
- All observables must be in color singlet state—no partons can be found in isolation in nature

# QCD Potential and confinement

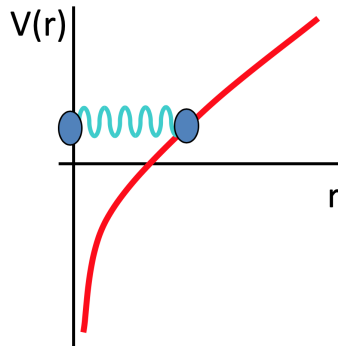
- The QED potential

$$V(r) = -\frac{\alpha_{EM}}{r}$$

- The QCD potential for  $q\bar{q}$

$$V(r) = -\frac{4}{3} \frac{\alpha_S}{r} + kr$$

- Coulomb part and confining part
- New pairs of quarks are created when energy exceeds mass



# QCD Potential and confinement

- The QED potential

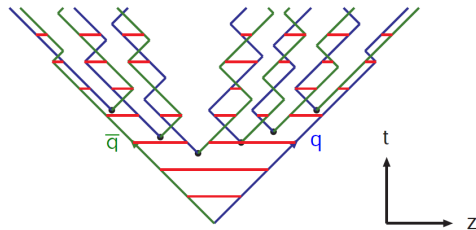
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- The QCD potential for  $q\bar{q}$

$$V(r) = -\frac{4}{3} \frac{\alpha_S}{r} + kr$$

- Coulomb part and confining part
- New pairs of quarks are created when energy exceeds mass

Motion of quarks and antiquarks in a  $q\bar{q}$  system:



gives simple but powerful picture of hadron production



# The six flavors of quarks

flavor	charge	mass
down	$-1/3 e$	3.0–7.0 MeV
up	$2/3 e$	1.5–3.0 MeV
strange	$-1/3 e$	$95 \pm 25$ MeV
charm	$2/3 e$	$1.25 \pm 0.09$ GeV
bottom	$-1/3 e$	$4.70 \pm 0.07$ GeV
top	$2/3 e$	$174.2 \pm 3.3$ GeV

# Summary for Part 0

- QCD is the theory of strong interactions
- Quarks and gluons (partons) are the fundamental particles
- There are three colors (and eight kinds of gluon)
- QCD exhibits confinement, meaning can only be found in bound states (hadrons)

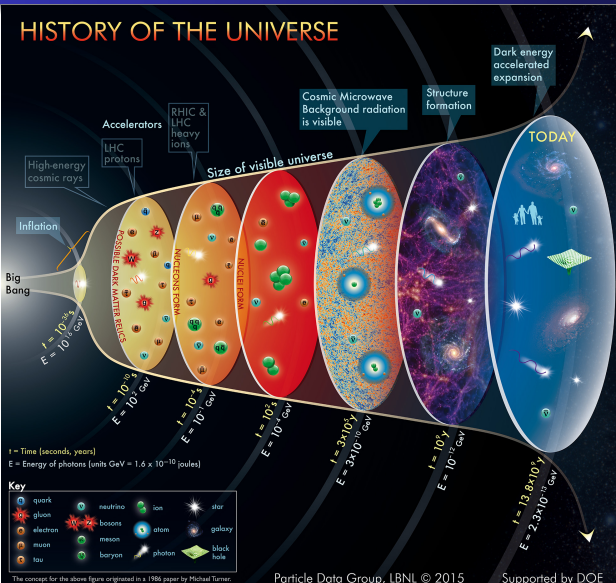
# Key points for Part I

The quark gluon plasma:

- Is a phase of matter with deconfined quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
  - Examples include  $^{197}_{79}\text{Au} + ^{197}_{79}\text{Au}$  and  $^{208}_{82}\text{Pb} + ^{208}_{82}\text{Pb}$
- Is hot and dense
- Behaves like a liquid
  - The initial-state geometry is translated into the final state

# The history of the universe

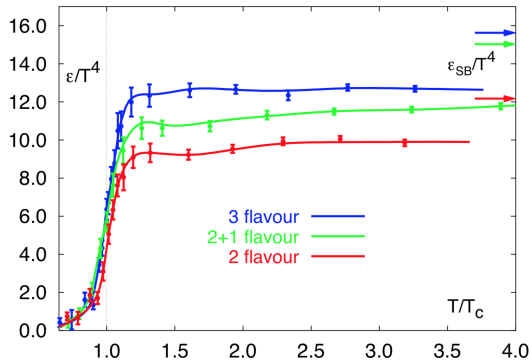
## HISTORY OF THE UNIVERSE



- The early universe (few microseconds) was a quark-gluon plasma (QGP)
- The QGP is a system of deconfined quarks and gluons
- We can recreate the QGP in the lab in collisions of heavy nuclei at relativistic speeds
- Goal of heavy-ion physics: create, identify, and study the QGP

# Phases of QCD matter

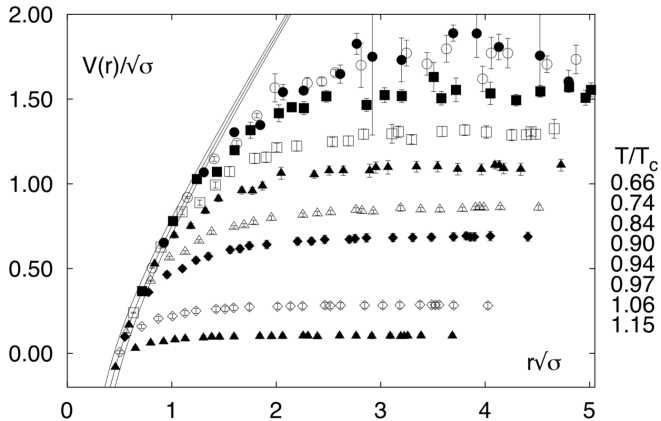
- Lattice QCD predicts a phase transition from nuclear matter to QGP
- Large increase energy density at  $T_C \approx 155$  MeV due to large increase in number of degrees of freedom



$$\epsilon_{SB} = g \frac{\pi^2}{30} T^4$$

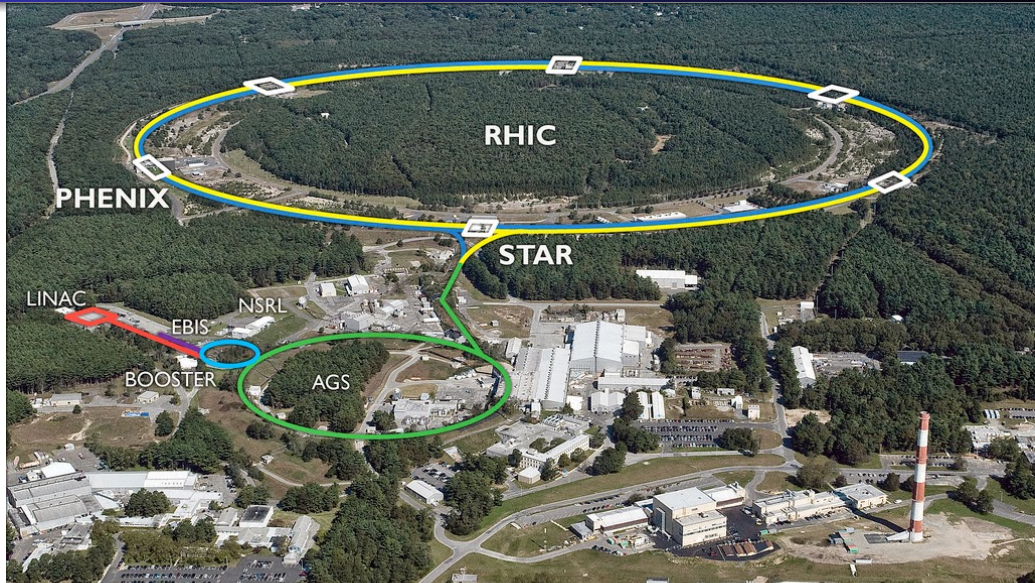
- Below  $T_C$ :  $g = 3$   
3 pions with spin 0
- Above  $T_C$ :  $g = 37$   
8 gluons with spin 1,  
2 (anti)quarks with spin 1/2

# Phases of QCD matter



- The confining part of gets weaker with increasing temperature
- More or less gone at the critical temperature ( $T_C \approx 155$  MeV)

# The Relativistic Heavy Ion Collider





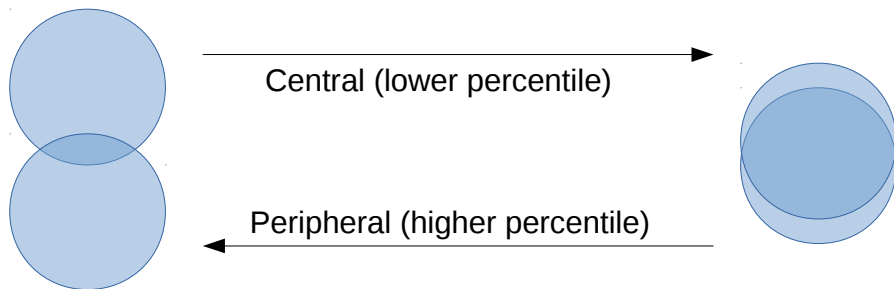
# The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC
- RHIC is a dedicated ion collider and is designed to collide many different species of ions at many different energies—vastly more flexible than the LHC

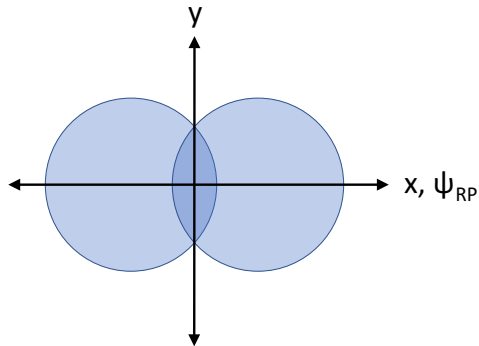
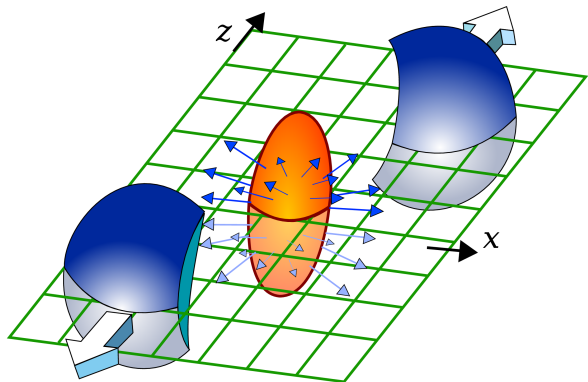
Collision Species	Collision Energies (GeV)
$p\uparrow + p\uparrow$	510, 500, 200, 62.4
$p + \text{Al}$	200
$p + \text{Au}$	200
$d + \text{Au}$	200, 62.4, 39, 19.6
$^3\text{He} + \text{Au}$	200
$\text{Cu} + \text{Cu}$	200, 62.4, 22.5
$\text{Cu} + \text{Au}$	200
$\text{Au} + \text{Au}$	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
$\text{U} + \text{U}$	193

And lots more to come!

# Centrality



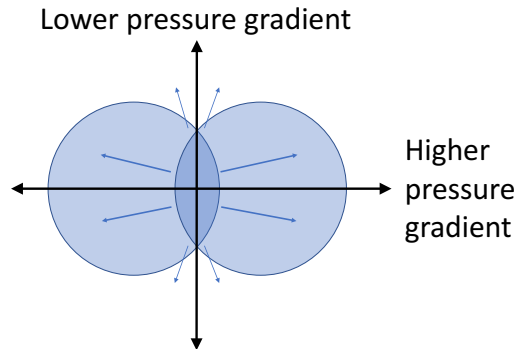
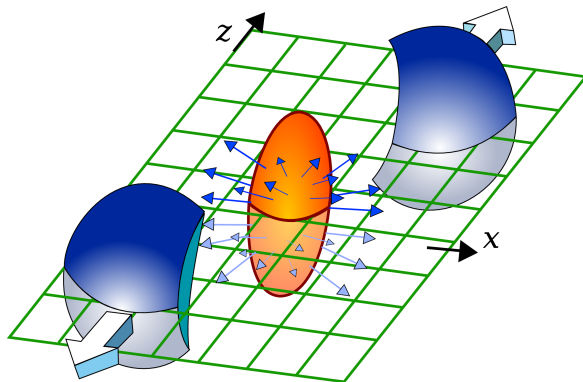
# Azimuthal anisotropy measurements



$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \quad v_n = \langle \cos n\varphi \rangle \quad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi \rangle + \langle r^2 \sin n\varphi \rangle}}{\langle r^2 \rangle}$$

- Hydrodynamics translates initial shape ( $\varepsilon_n$ ) into final state distribution ( $v_n$ )
- Overlap shape approximately elliptical, expect  $v_2$  to be the largest

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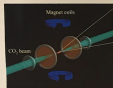
# Ultracold Fermi Gas

## Ultracold Fermi Gases as Paradigms for Strongly Correlated Matter

J. E. Thomas, Physics Department, North Carolina State University, Raleigh NC 27695

### 1 Fermi Gases – A Universal Model

Ultra-cold Fermi gases with magnetically tunable interactions are a paradigm for interacting systems in nature. When tuned to a broad collisional (Feshbach) resonance, the atoms enter a unitary regime where the properties of the gas are *universal* functions of only the density  $n$  and temperature  $T$ .



In our lab, we start with an equal mixture of the two lowest hyperfine states of fermionic  $^7\text{Li}$  atoms. After pre-cooling in a magneto-optical trap, atoms are loaded into an optical dipole trap formed by a far red-detuned  $\text{CO}_2$  laser beam. By lowering the  $\text{CO}_2$  laser intensity, we evaporatively cool the atoms to quantum degeneracy.

### 2 String Theory Limit: “Perfect” Fluids

Viscosity measurement in a unitary Fermi gas is motivated by a recent conjecture derived using string theory methods. The conjecture states that for a broad class of strongly interacting fields, the ratio of shear viscosity  $\eta$  to the entropy density  $s$  has a universal minimum:

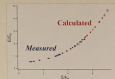
$$\frac{\eta}{s} \geq \frac{1}{4\pi} \frac{\hbar}{k_B}$$

$\eta$ : Shear viscosity  
 $s$ : Entropy density

A fluid with the minimum ratio is referred to as a *perfect fluid*. In a Fermi gas, we are able to measure both the entropy and the viscosity, connecting thermodynamics and hydrodynamics in strongly correlated systems.

### 3 Measurement of Entropy and Energy

Entropy is measured from the cloud size by exploiting the virial theorem, which holds for a unitary gas. Entropy is measured from the cloud size after an adiabatic sweep to a weakly interacting regime.



### 4 Measurement of Quantum Viscosity

Viscosity  $\eta$  has a dimension of momentum/area. In a unitary gas, the natural momentum is of order  $\hbar k$  and the natural area is the s-wave collision cross section  $4\pi k^{-2} = \hbar^2/m^2$ . The Fermi momentum sets the length scale  $k \sim 1/L$ , with  $L$  the interparticle spacing. Thus, the natural scale of viscosity is  $\hbar^2/m^2$ . Measuring the aspect ratio of an elliptically expanding atom cloud as a function of time after release from the optical trap determines the shear viscosity at high temperature (red). For low temperatures, we measure the damping rate of a radial breathing mode (blue), which smoothly joins.



Viscosity vs Energy



Viscosity/entropy density vs Energy  
Inset: Perfect fluid red dashed line

C. Cao, E. Eliot, J. Joseph, H. Wu, J. Patricke, T. Schaefer and J. E. Thomas, Universal quantum viscosity in a unitary Fermi gas, Science 331 58 (2011)

### 5 Optical Control of Feshbach Resonances

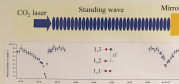
Optical fields, tuned to resonance on a singlet molecular transitions allow “dark-state” control of interactions.



- “Designer” interactions
- control width of narrow FB resonance
- control interactions in 3-state systems
- Random interactions in space and time
- Non-equilibrium Fermi gases—Fermi time
- “Designer” dispersion relations

### 6 Quasi-Two-Dimensional Fermi Gases

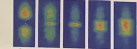
We create a 2D gas by trapping atoms in a  $\text{CO}_2$  laser standing-wave, with a few hundred atoms per site,  $5.3 \mu\text{m}$  spacing.



- Entropy measurement by IR-sweep, site-to-site correlations
- Collective modes—quantum pressure
- Confinement-induced many-body interactions
- Parametric resonance excitation of fermionic atom pairs
- Radio frequency spectra—shown above.

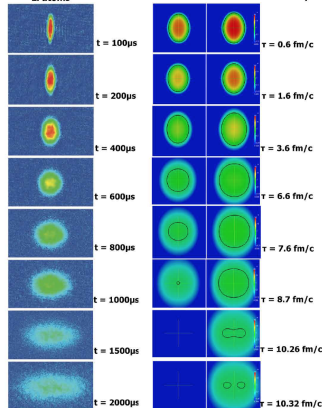
### 7 Shock Waves

Colliding Fermi gas clouds—LHC!



- Nonlinear hydrodynamics in strongly interacting quantum matter

### Degenerate Fermi Gas of Ultracold Li atoms<sup>1</sup>



# Ultracold Fermi Gas

## 2 String Theory Limit: “Perfect” Fluids

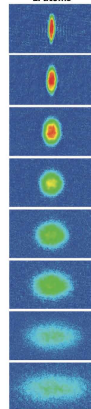
Viscosity measurement in a unitary Fermi gas is motivated by a recent conjecture derived using string theory methods. The conjecture states that for a broad class of strongly interacting fields, the ratio of shear viscosity  $\eta$  to the entropy density  $s$  has a universal minimum:

$$\frac{\eta}{s} \geq \frac{1}{4\pi} \frac{\hbar}{k_B}$$

$\eta$  : Shear viscosity  
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A fluid with the minimum ratio is referred to as a *perfect* fluid. In a Fermi gas, we are able to measure both the entropy and the viscosity, connecting *thermodynamics* and *hydrodynamics* in strongly correlated systems.

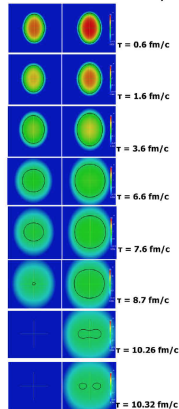
Degenerate Fermi Gas of Ultracold Li atoms<sup>1</sup>



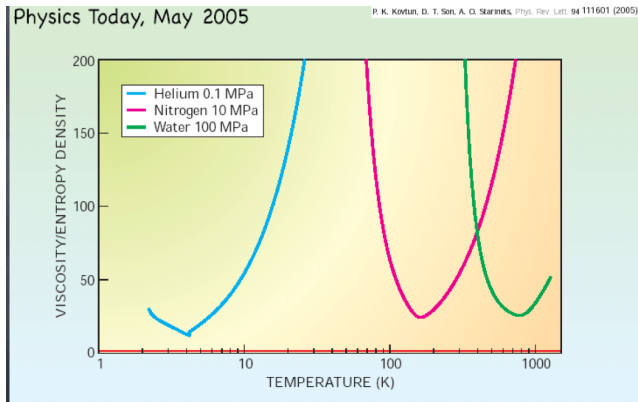
RHIC

LHC

20~30% Centrality



# Viscosity (over entropy density)



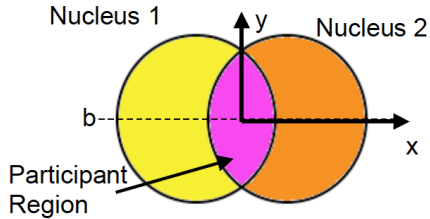
Ultracold Fermi gases: few times the lower bound  
Quark-gluon plasma: very close to the lower bound



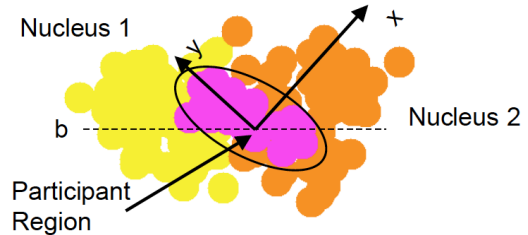
# Important discovery in 2005

G. Roland, PHOBOS Plenary, Quark Matter 2005

## Standard Eccentricity



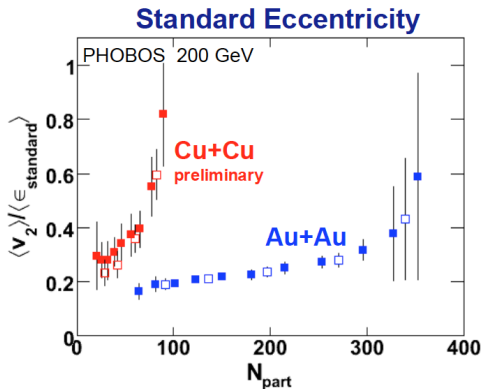
## Participant Eccentricity



A nucleus isn't just a sphere

# Important discovery in 2005

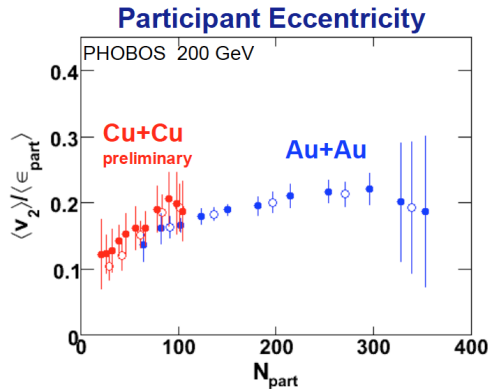
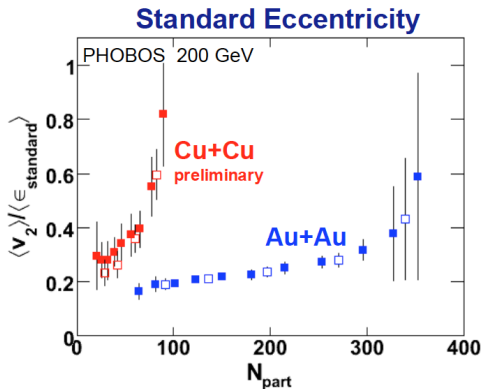
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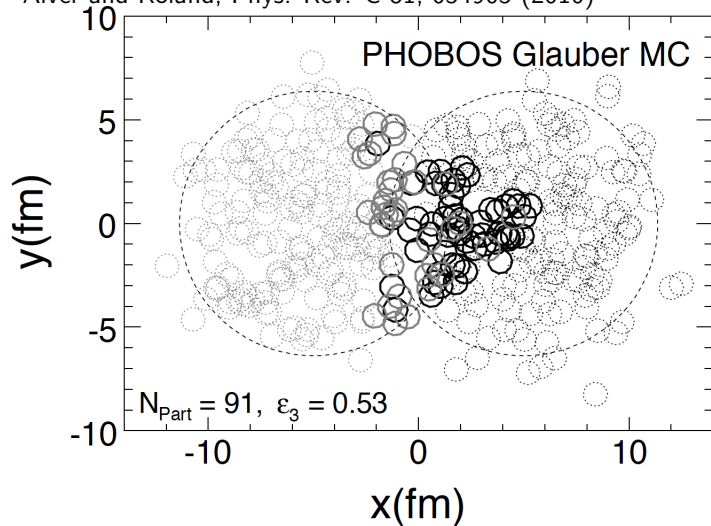
G. Roland, PHOBOS Plenary, Quark Matter 2005



A nucleus isn't just a sphere

# Important discovery in 2010

Alver and Roland, Phys. Rev. C 81, 054905 (2010)



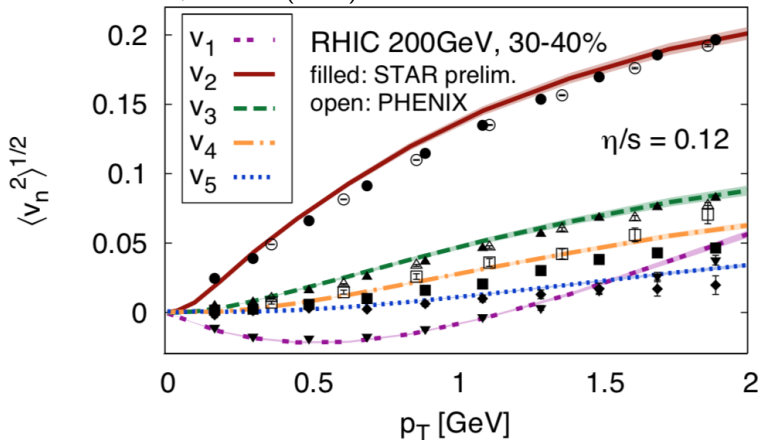
Nucleon fluctuations can produce non-zero  $\epsilon_n$  for odd  $n$

Symmetry planes  $\psi_n$  can be different for different harmonics

$$\varphi = \phi_{lab} - \psi_n$$

# Data and theory for $v_n$

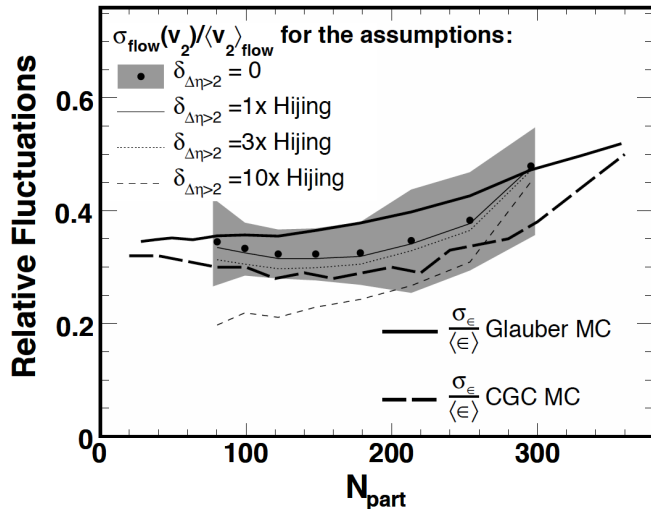
Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



$$\frac{dN}{d\varphi} \propto 2v_1 \cos \varphi + 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + 2v_5 \cos 5\varphi$$

# Fluctuations in large systems

PHOBOS, Phys. Rev. C 81, 034915 (2010)



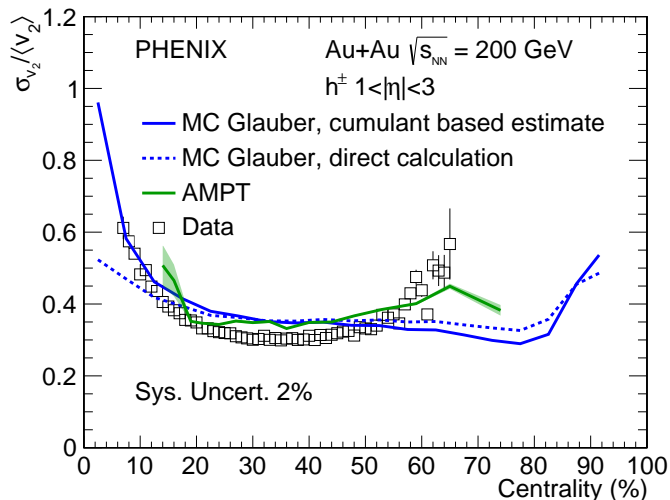
Fluctuations should also be translated, so measure  $\sigma_{v_2}/\langle v_2 \rangle$

$$|\eta| < 1$$

Generally good agreement with models of initial geometry

# Fluctuations in large systems

PHENIX, arXiv:1804.10024 (accepted by Phys. Rev. C)



Fluctuations should also be translated, so measure  $\sigma_{v_2}/\langle v_2 \rangle$

$$1 < |\eta| < 3$$

Generally good agreement with models of initial geometry

# Summary for Part I

The quark-gluon plasma:

- Is a phase of matter with deconfined quarks and gluons
- Existed in the very early universe
- Is created in the lab in collisions of large nuclei
- Evolves hydrodynamically
  - The initial-state geometry is translated into the final state



# Key points for Part II

- A major component of heavy ion physics nowadays is “small systems”
  - Nuclear collisions of small+large or even small+small
  - Examples include d+Au, p+Pb, and even p+p
- The matter created in small systems looks a lot like the matter in large systems
- Roughly speaking, two competing pictures
  - QGP droplets being created in small systems
  - Initial state effects from color-glass condensate (CGC)

# Media Attention

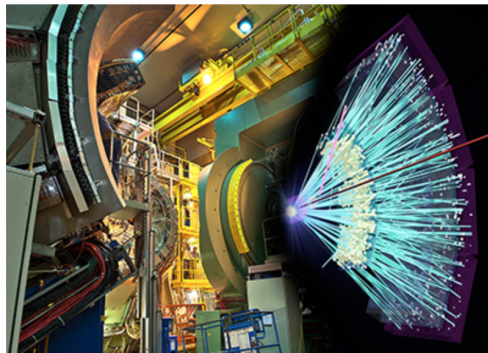
Physics World, September 22, 2017

Phys.org, September 18, 2017

PHENIX colleague **Ron Belmont** of the University of Colorado says it is still possible that the elliptical emission they have observed is due not to the formation of tiny QGPs but instead down to nuclear properties prior to collision. When accelerated close to light speed, time slows down for the heavy nuclei, which means, according to quantum chromodynamics, that they appear as a dense wall of gluons. The fact that these condensates are thicker in the centre of the nuclei might explain why particles generated in the collisions are not emitted in random directions, he says.

## Collider serves up drop of primordial soup

Sep 22, 2017



**Tiny drop: PHENIX and reconstructed particle tracks from a QGP**

# A very brief history of recent heavy ion physics

- 1980s and 1990s—AGS and SPS... QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS. d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p??  
QGP in d+Au even at low energies???

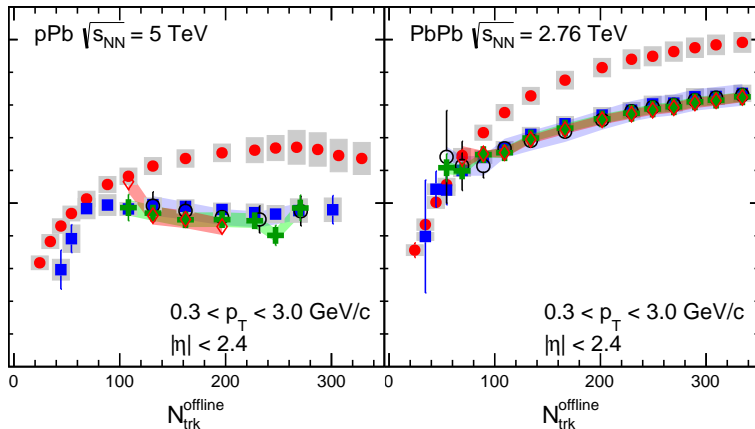
# A very brief history of recent heavy ion physics

- 1980s and 1990s—AGS and SPS... QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS. d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p??  
QGP in d+Au even at low energies???

“Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it.” —Jürgen Schukraft, QM17

# Multiparticle correlations in large and small systems

CMS, Phys. Lett. B 765 (2017) 193-220

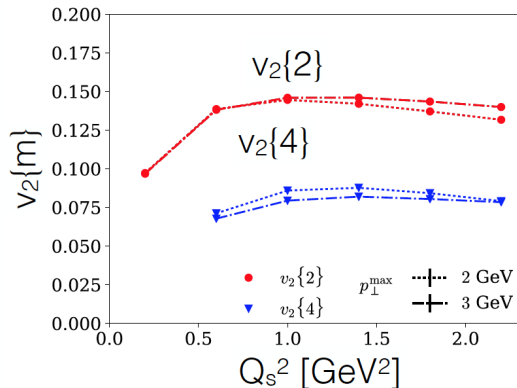


$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma^2$$

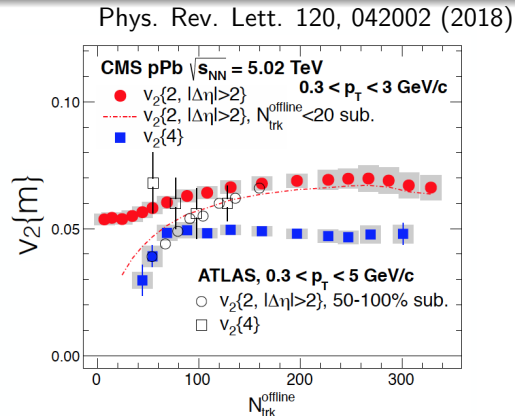
$$v_n^2\{4, 6, 8\} \approx \langle v_n \rangle^2 - \sigma^2$$

- Multiparticle correlations reflect global correlation from geometry in Pb+Pb, Au+Au, Cu+Cu, etc
- The p+Pb has a remarkably similar pattern as the Pb+Pb

# CGC results on small systems



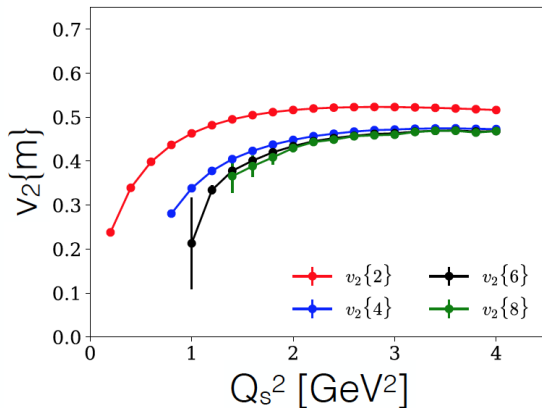
Dusling, MM, Venugopalan PRL 120 (2018)



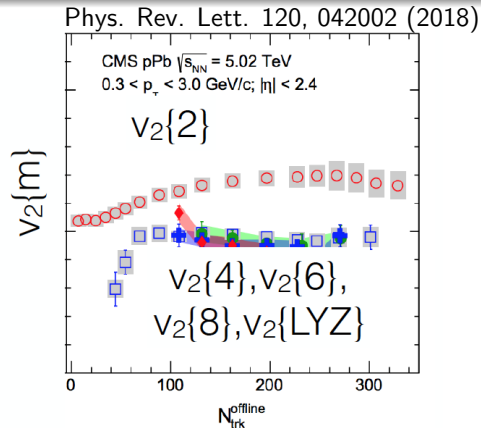
CMS PLB 724 (2013) 213

- Can reproduce  $v_2\{2\}$  and  $v_2\{4\}$
- Disagreement with data by a factor of 2, but qualitative features match

# CGC results on small systems



Dusling, MM, Venugopalan PRL 120 (2018)



CMS PRL 115 (2015) 012301

- Abelian calculations can produce  $v_2\{2\}$ ,  $v_2\{4\}$ ,  $v_2\{6\}$ ,  $v_2\{8\}$
- Disagreement with data by factor of 5, but qualitative features match

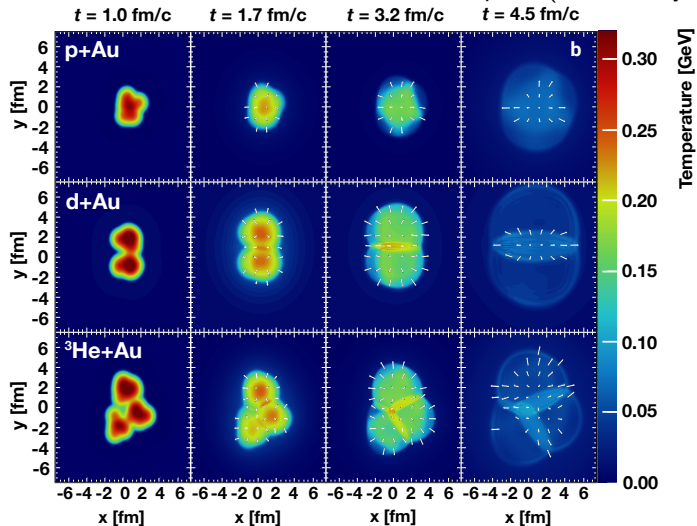
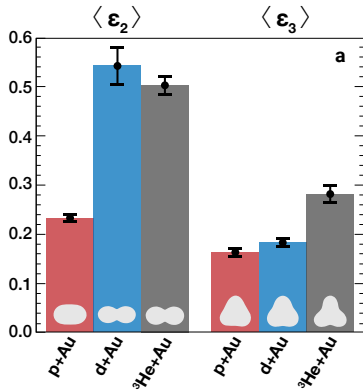
# Intermission

Small systems geometry scan



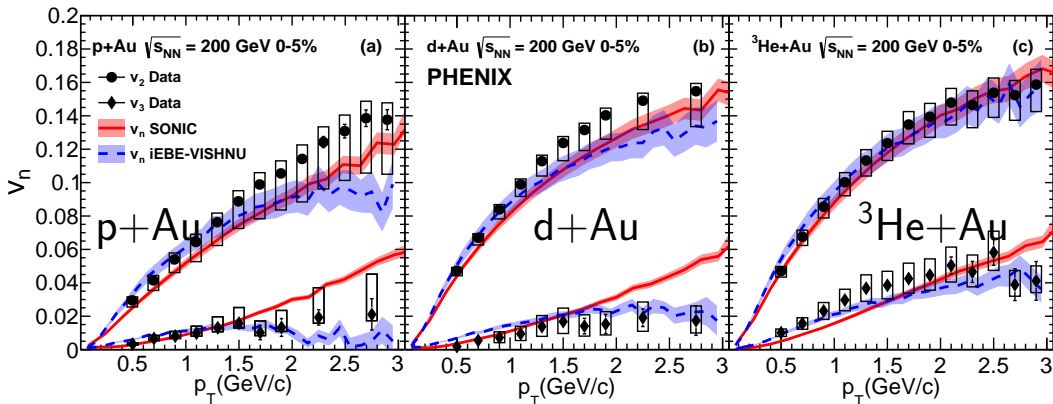
# Testing hydro by controlling system geometry

arXiv:1805.02973, in press (Nature Physics)



# Testing hydro by controlling system geometry

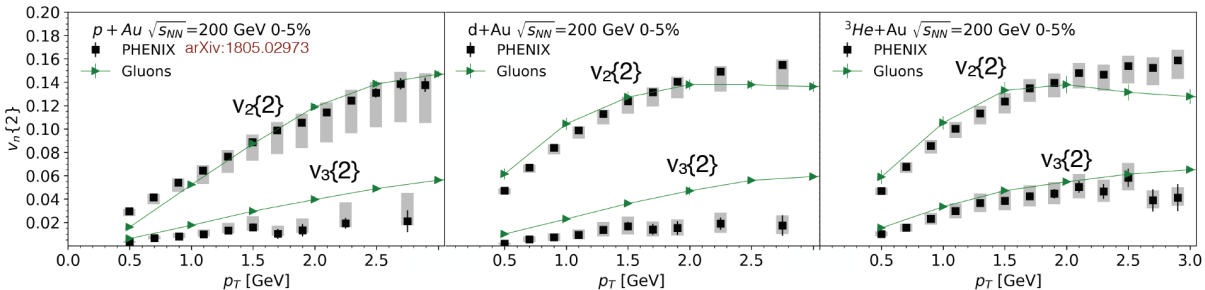
arXiv:1805.02973, submitted to Nature Physics



- $v_2$  and  $v_3$  vs  $p_T$  described very well by hydro in all three systems  
—Suggests QGP droplets in hydro evolution(?)

# CGC results on small systems

M. Mace et al, Phys. Rev. Lett. 121, 052301 (2018)

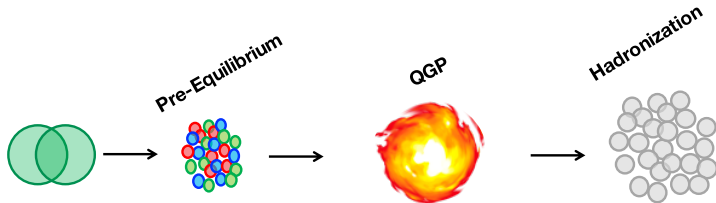


- $v_2$  is quite well-described
- $v_3$  is in the right ballpark, though hydro does better

# Intermission

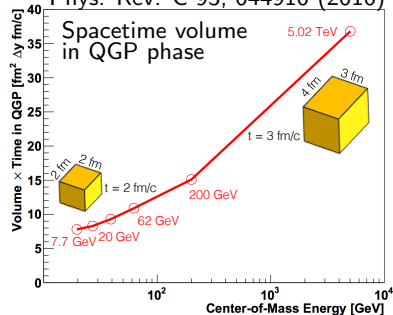
Small systems beam energy scan

# Testing hydro by controlling system size and life time



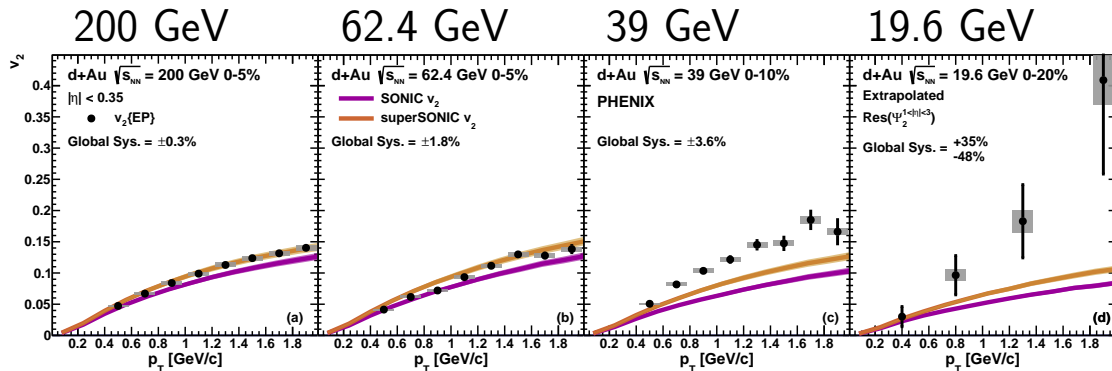
- Standard picture for A+A: QGP in hydro evolution
- What about small systems? And lower energies?
- Use collisions species and energy to control system size, test limits of hydro applicability

J.D. Orjuela Koop et al  
Phys. Rev. C 93, 044910 (2016)



# d+Au beam energy scan

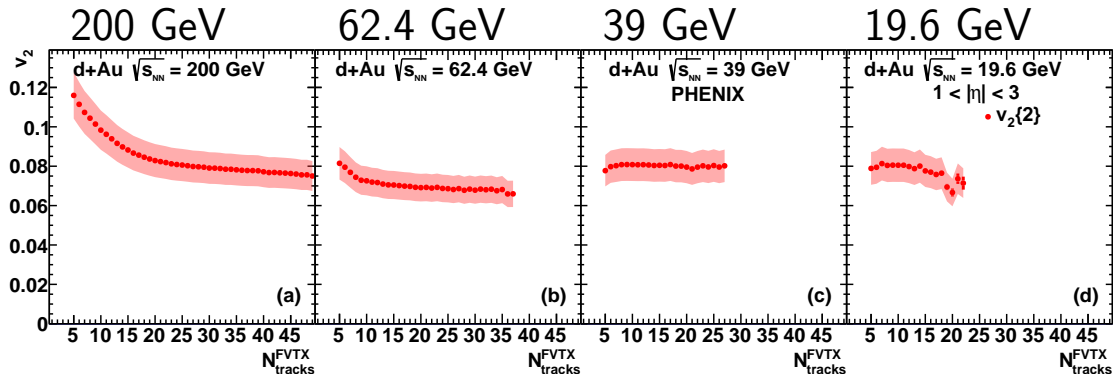
Phys. Rev. C 96, 064905 (2017)



- Hydro theory agrees with higher energies very well, underpredicts lower energies
  - Breakdown of hydro?
  - Predominance of other correlations?

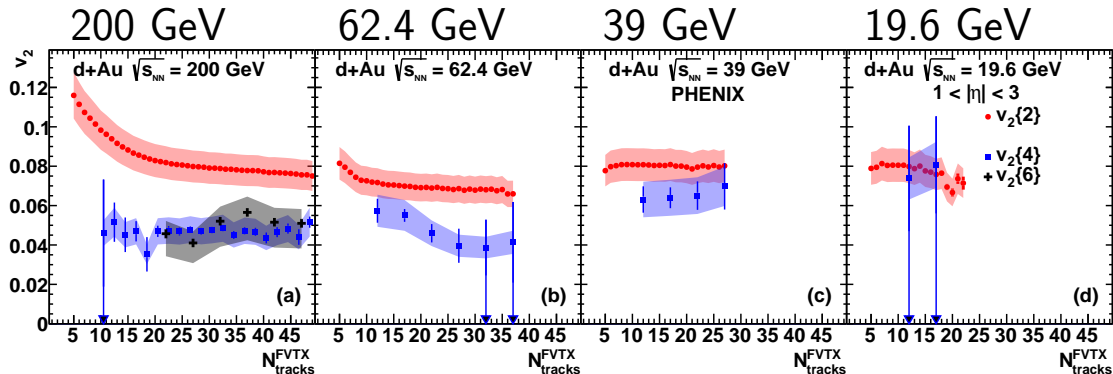
# d+Au beam energy scan

Phys. Rev. Lett. 120, 062302 (2018)



# d+Au beam energy scan

Phys. Rev. Lett. 120, 062302 (2018)

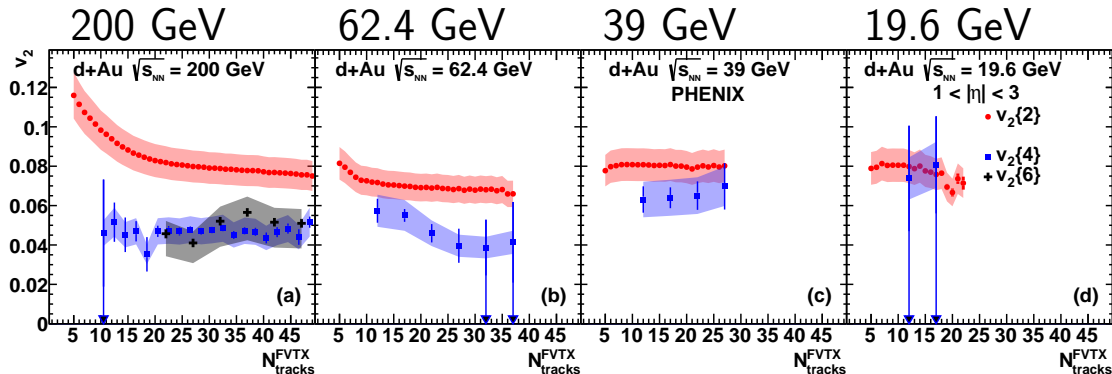


- Measurement of  $v_2\{6\}$  in d+Au at 200 GeV and  $v_2\{4\}$  in d+Au at all energies



# d+Au beam energy scan

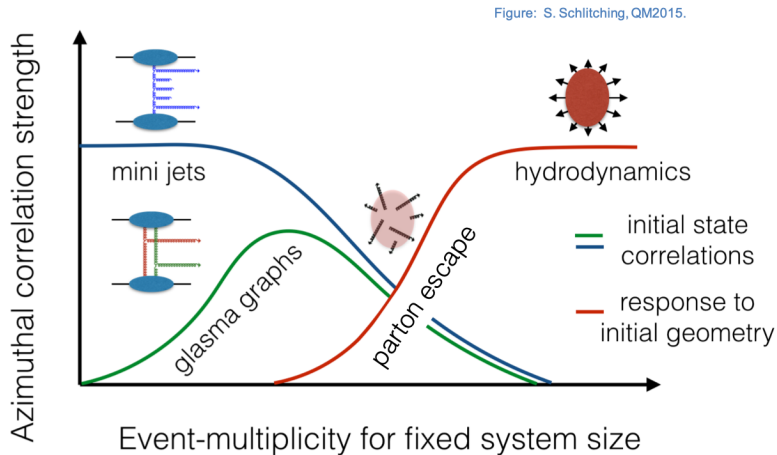
Phys. Rev. Lett. 120, 062302 (2018)



- Measurement of  $v_2\{6\}$  in d+Au at 200 GeV and  $v_2\{4\}$  in d+Au at all energies
- No theory comparisons available (yet...)

# Competing theories

Where are we?



# Summary for Part II

- Small systems is a hot topic in heavy ion physics
- We've even gotten some media attention for it
- The system created in small systems looks a like the one in large systems
- Two competing pictures: CGC and QGP
  - QGP picture ahead by points, but no knockout yet

# Intermission

Part III: the future

# The 2015 Long Range Plan for Nuclear Science

[https://www.science.energy.gov/~media/np/nsac/pdf/2015LRP/2015\\_LRPNS\\_091815.pdf](https://www.science.energy.gov/~media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf)

**Recommendation I: The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**

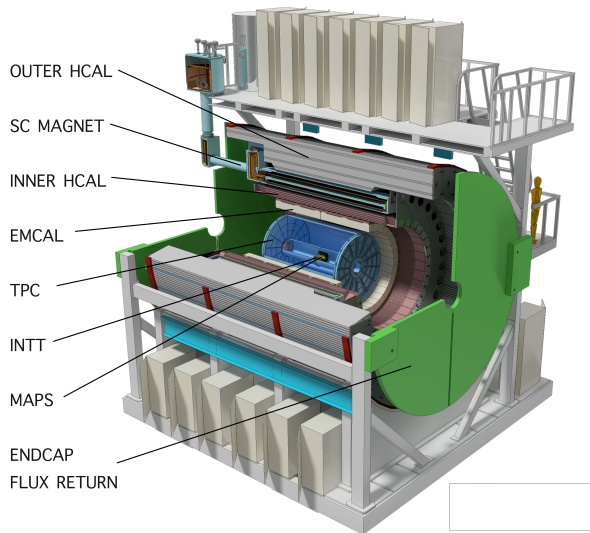
—CEBAF, FRIB, Symmetries & Neutrinos, RHIC (BES II & sPHENIX)

Recommendation II: We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

**Recommendation III: We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.**

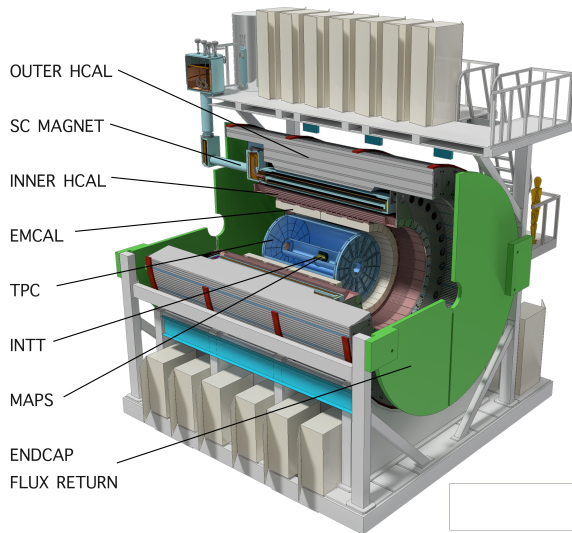
Recommendation IV: We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

# sPHENIX: QGP microscope



From the LRP: **[The goal is to] probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.... essential to this goal... is a state-of-the-art jet detector at RHIC, called sPHENIX.**

# sPHENIX: QGP microscope



Resolving power  $d \propto \lambda$   
 de Broglie wavelength  $\lambda = h/p$

$p$	$\lambda$
2.5 eV	500 nm
100 keV	12 pm
200 MeV	6.2 fm
1 GeV	1.2 fm
10 GeV	0.12 fm
50 GeV	0.025 fm

# sPHENIX: timeline

## Past and present

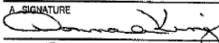
- Magnet purchase July 2013
- Magnet delivery April 2015
- DOE OPA CD-0 September 2016
- Order for Outer HCal steel March 2018
- DOE OPA CD-1/CD-3a August 2018

## Future

- DOE OPA CD-2/CD-3b Review May 2019
- Authorization for CD-2/CD-3b July 2019
- Fabrication orders August 2019
- Installation begins April 2021
- Installation complete July 2022
- Initial commissioning complete September 2022
- First collisions January 2023



# sPHENIX: magnet

STANDARD FORM 122 JUNE 1974 GENERAL SERVICES ADMINISTRATION FPMR (41 CFR) 101-32.306 FPMR (41 CFR) 101-43.315		<b>TRANSFER ORDER</b> <b>EXCESS PERSONAL PROPERTY</b>		1. ORDER NO. SLAC 2013-07-18		
				2. DATE July 18, 2013		
3. TO: GENERAL SERVICES ADMINISTRATION*			4. ORDERING AGENCY (Full name and address)* Brookhaven National Lab Attention: John Haggerty; haggerty@bnl.gov Upton, NY 11973-5000			
5. HOLDING AGENCY (Name and address)* SLAC National Accelerator Laboratory 2575 Sand Hill Road, MS 85A Menlo Park, CA 94025			6. SHIP TO (Consignee and destination)* Same as block 4			
7. LOCATION OF PROPERTY SLAC National Accelerator Laboratory C/O Mike Racine 2575 Sand Hill Road, MS 53 Menlo Park, CA 94025 650 926-3543 racine@slac.stanford.edu			8. SHIPPING INSTRUCTIONS BNL to arrange for shipping			
9. ORDERING AGENCY APPROVAL A. SIGNATURE 			10. APPROPRIATION SYMBOL AND TITLE transfer from DE-AC02-76SFO0515 transfer to DE-AC02-98CH10886			
B. DATE 7-19-13			11. ALLOTMENT		12. GOVERNMENT B/L NO.	
C. TITLE Property Manager						
13. PROPERTY ORDERED						
GSA AND HOLDING AGENCY NOS. (a)	ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST	
					UNIT (f)	TOTAL (g)
	1	BaBar Solenoid and Components Date of Mfr: 1996 (See attached list)	ea	1	12,000,000.00	\$ 12,000,000.00

# sPHENIX: magnet



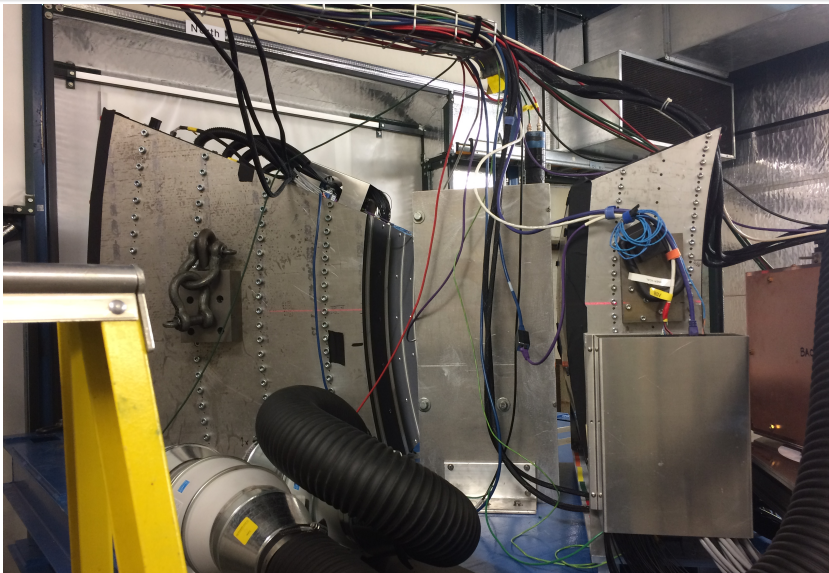
# sPHENIX: magnet



# sPHENIX: beam tests

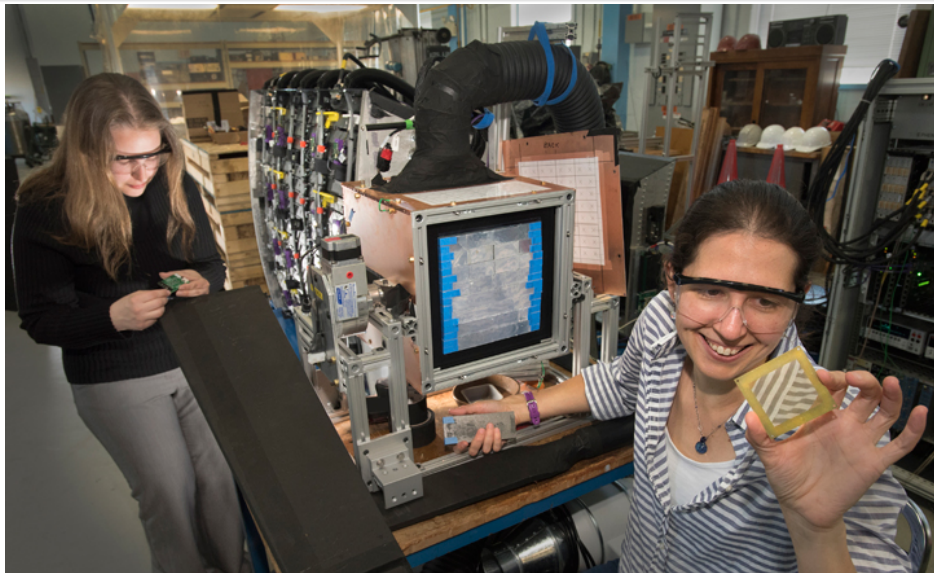


# sPHENIX: beam tests

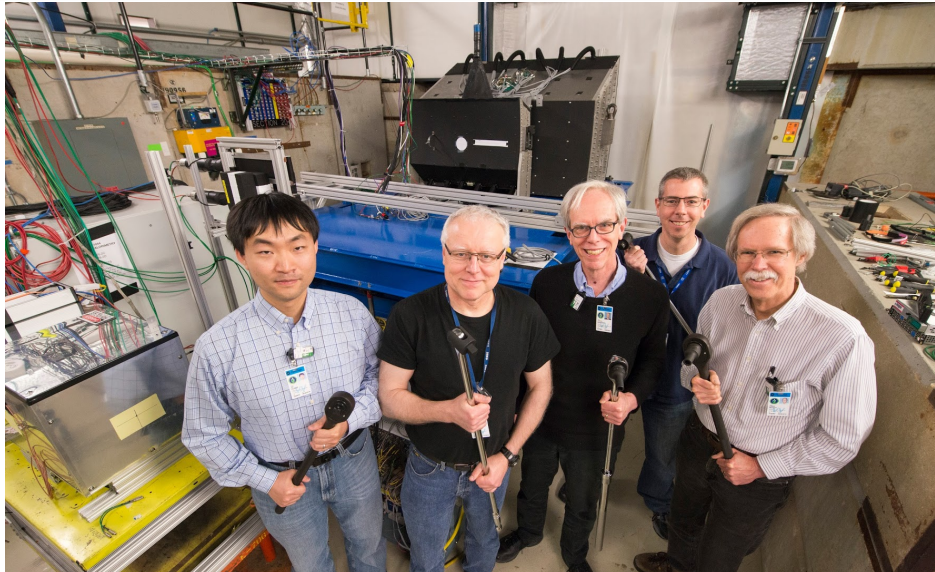




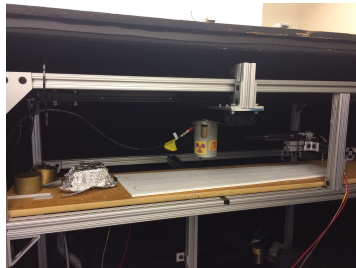
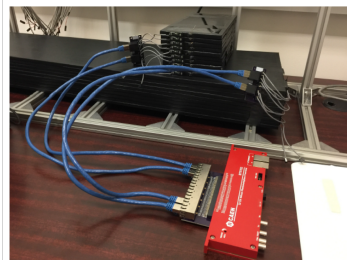
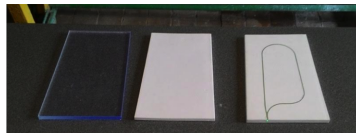
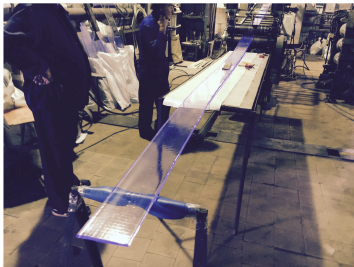
# sPHENIX: beam tests



# sPHENIX: beam tests



# sPHENIX: HCal tiles





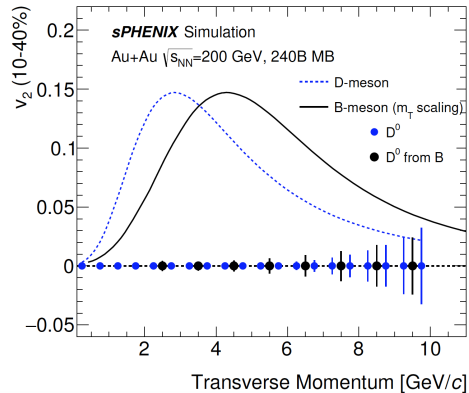
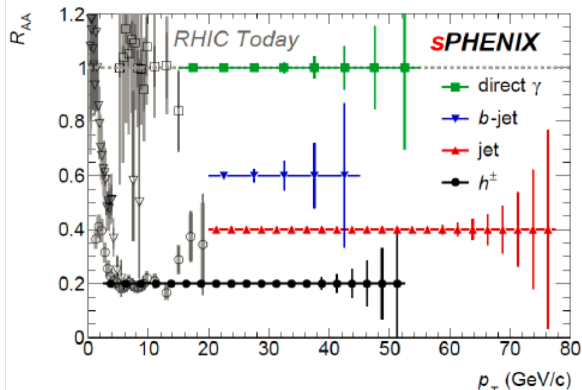
# sPHENIX: jets!



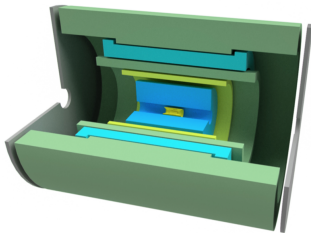
# sPHENIX: heavy flavor!



# sPHENIX: projections

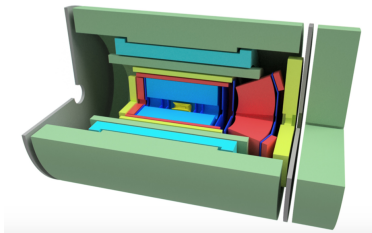


# sPHENIX: day one EIC detector



EIC white paper: [arXiv:1212.1701](https://arxiv.org/abs/1212.1701)

sPHENIX EIC proposal: [arXiv:1402.1209](https://arxiv.org/abs/1402.1209)



## An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

# Summary and outlook

- We can recreate the early universe in the lab using collisions of large nuclei
- Small systems have had a lot of surprises for us
  - Many similarities to large systems, but theoretical picture less clear
  - How to disentangle CGC from QGP?
- It's an exciting time for nuclear physics in the US

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“The optimist regards the future as uncertain.”—Eugene Wigner