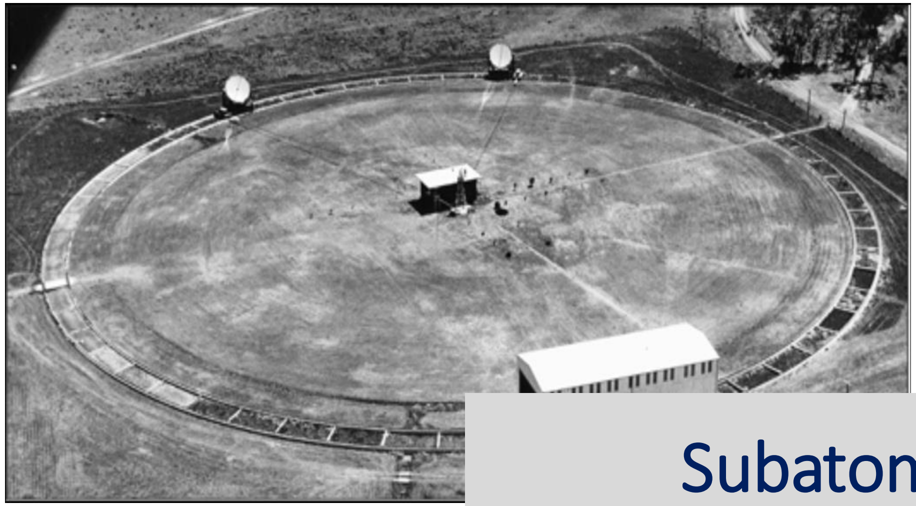
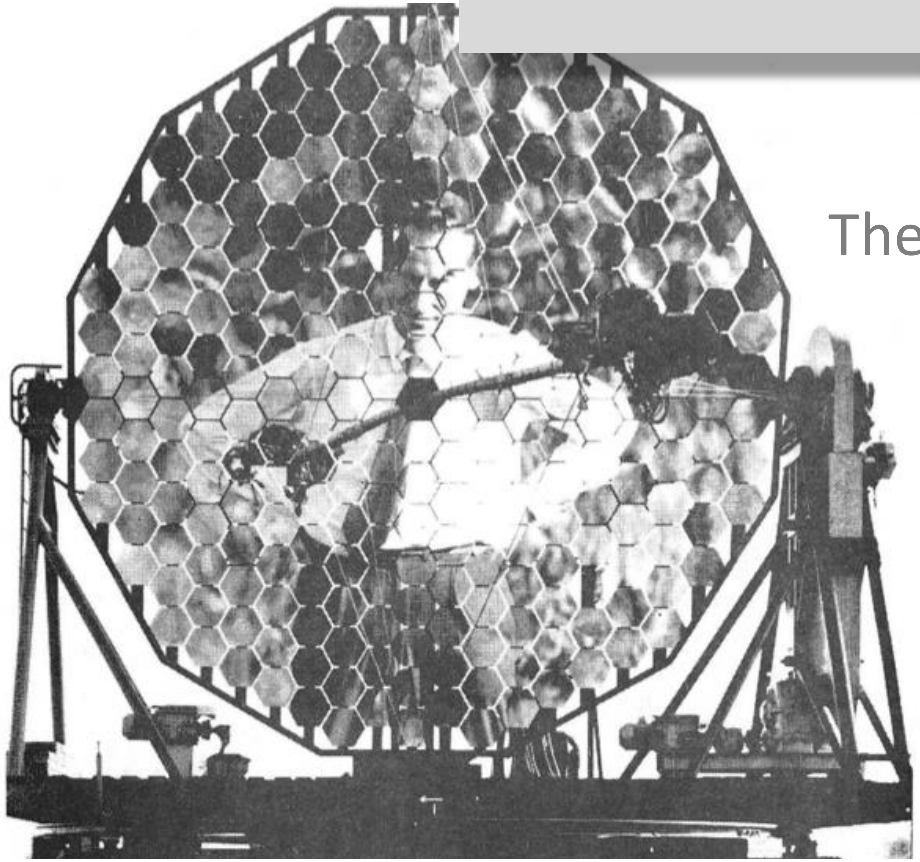
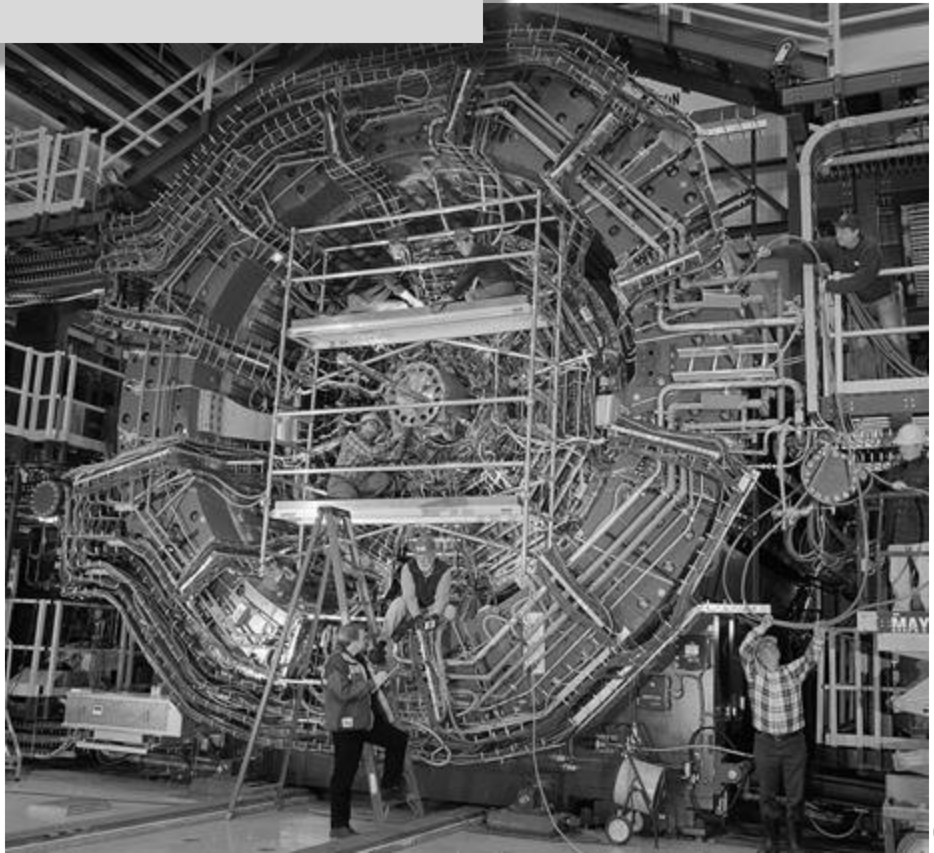


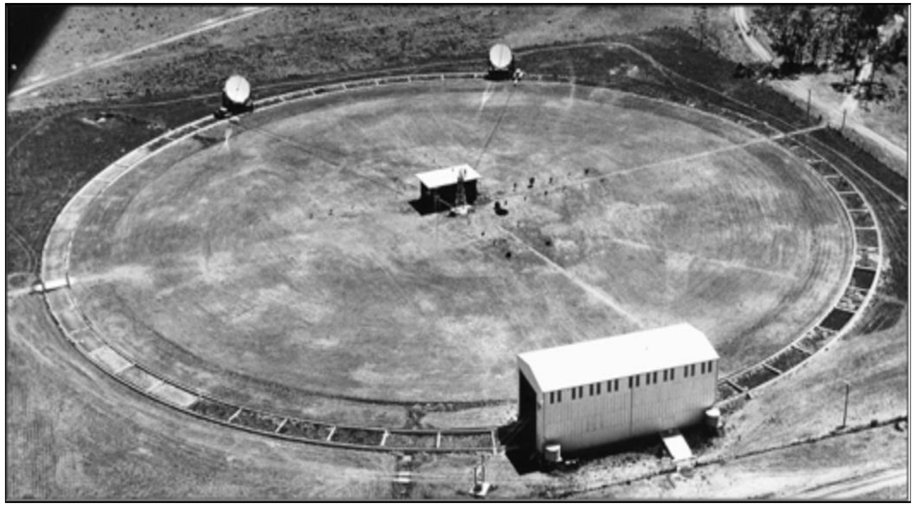
Subatomic Intensity Interferometry 101 for Stellar Intensity Interferometrists



Mike Lisa

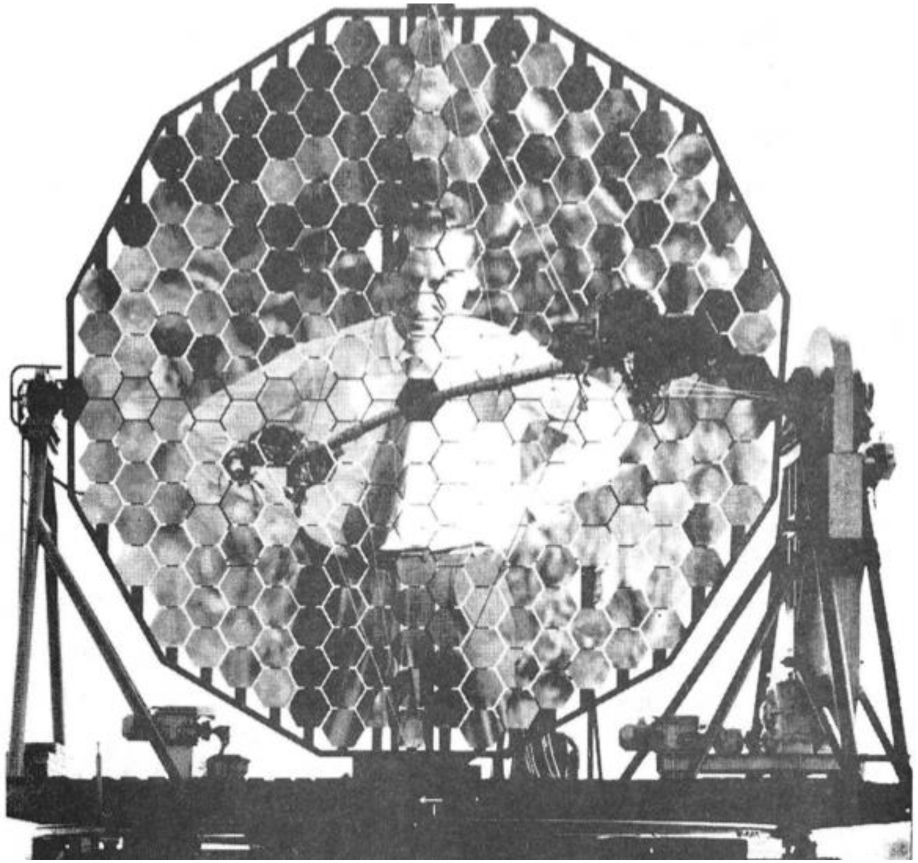
The Ohio State University





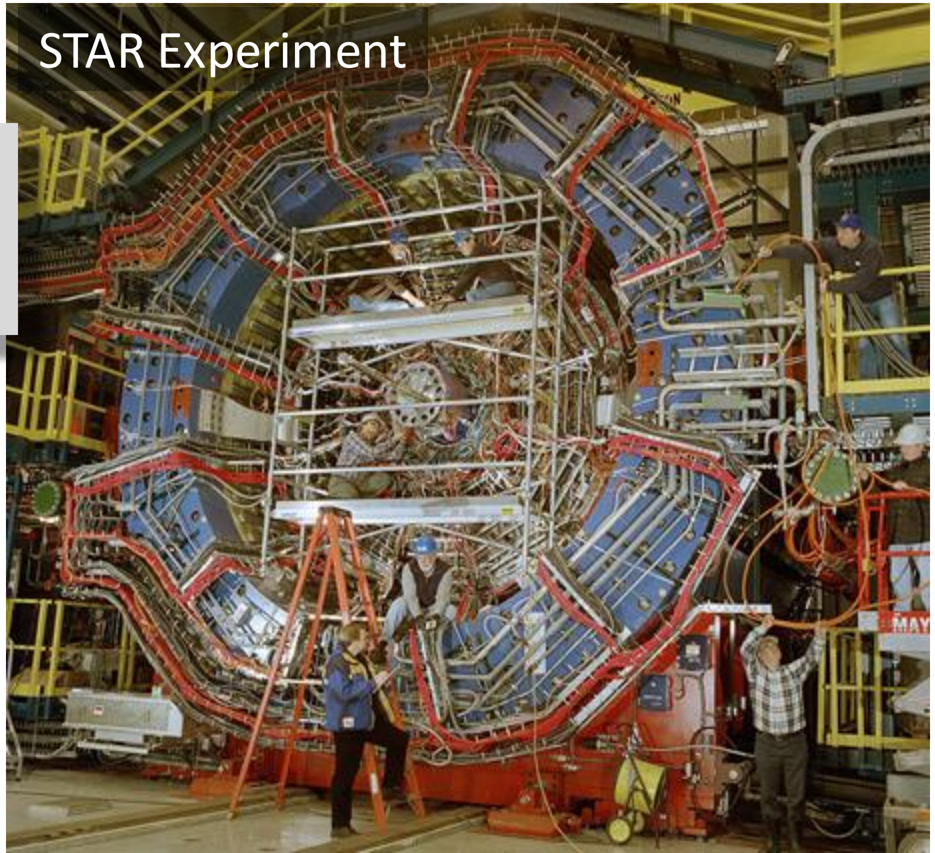
ring diameter

- Narrabri: 188 m
- RHIC* 1200 m

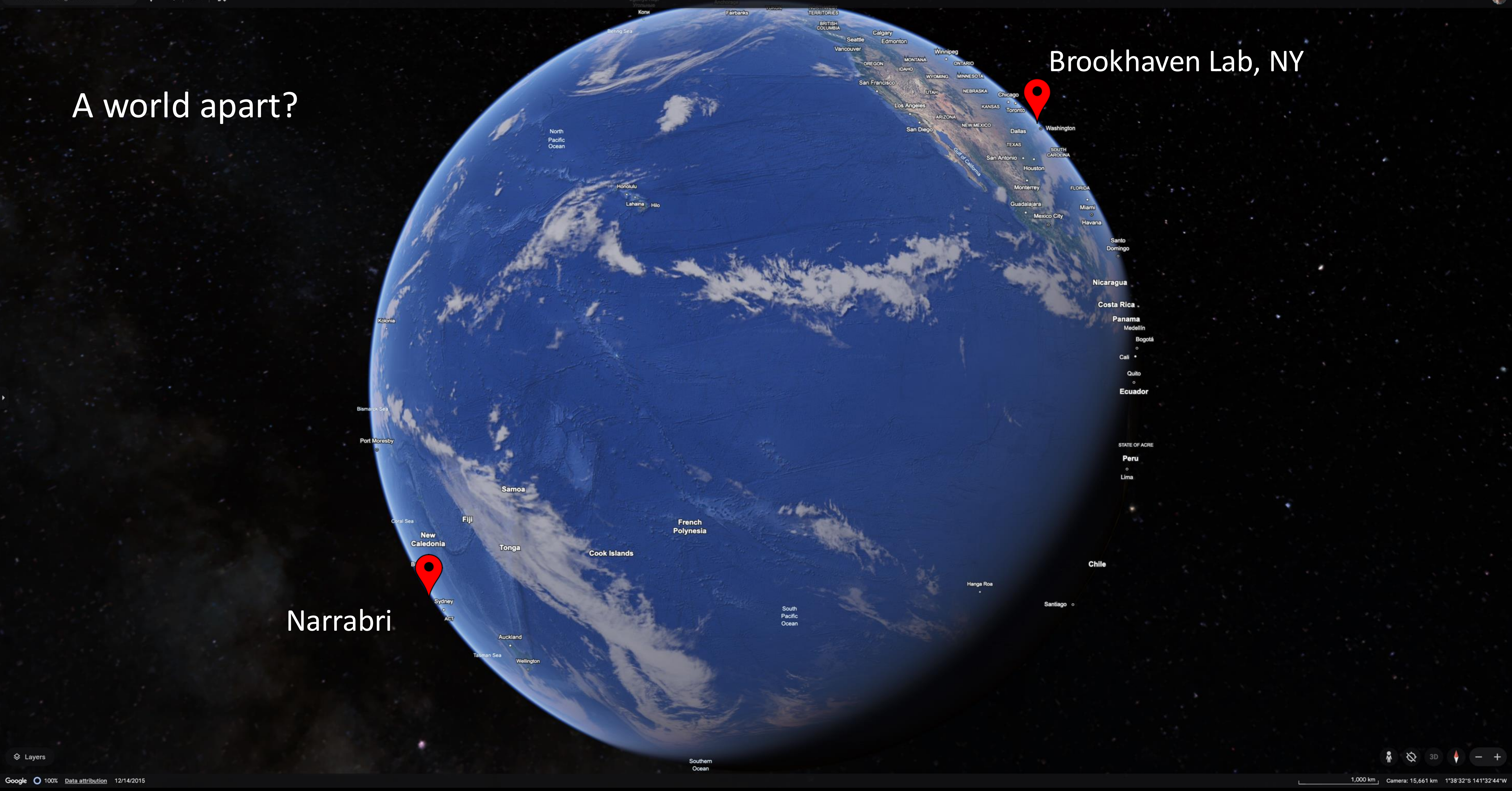


dodecagon detectors

- Narrabri mirrors: 6.5 m
- STAR detector: 6 m



A world apart?



CRIS '98 – Workshop on subatomic intensity interferometry. Catania Italy

Hanbury Brown’s one-sentence abstract:

The talk will give a brief history of the early development of Intensity Interferometry and its subsequent battle against common sense.

Outline

- Discovery of the "GGLP effect" & connection to HBT
- Relativistic heavy ion physics: motivation & importance of spacetime info
- Subatomic intensity interferometry (femtoscopy)
- Summary

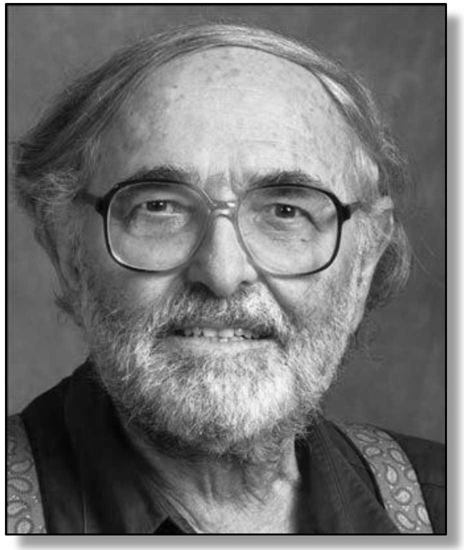
- Hanbury Brown & Twiss – 1954
- 1955 – discovery of antiproton
- 1960 – GGLP

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

GERSON GOLDHABER, SULAMITH GOLDHABER, WONYONG LEE, AND ABRAHAM PAIS†
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California

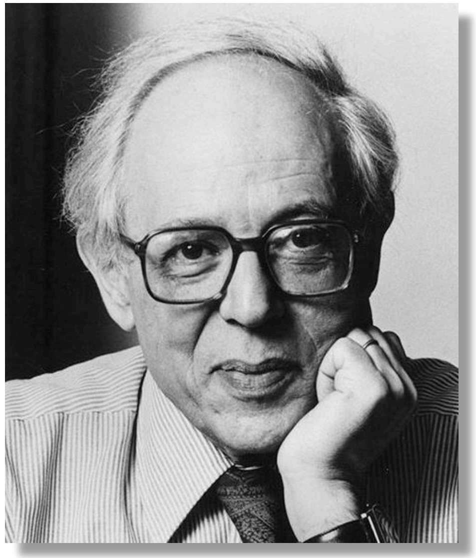
(Received May 16. 1960)



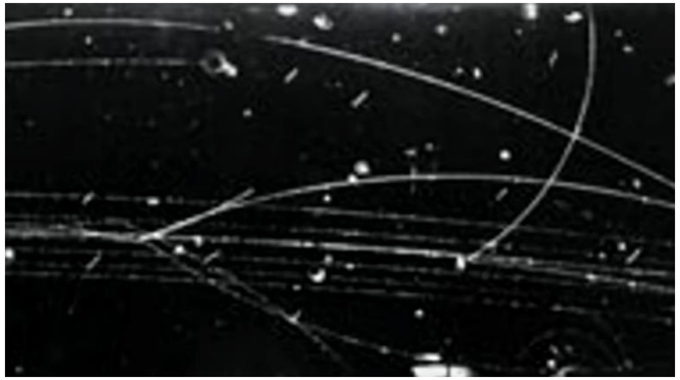
Gershon Goldhaber

Sulamith Goldhaber

Wonyong Lee



Abraham Pais

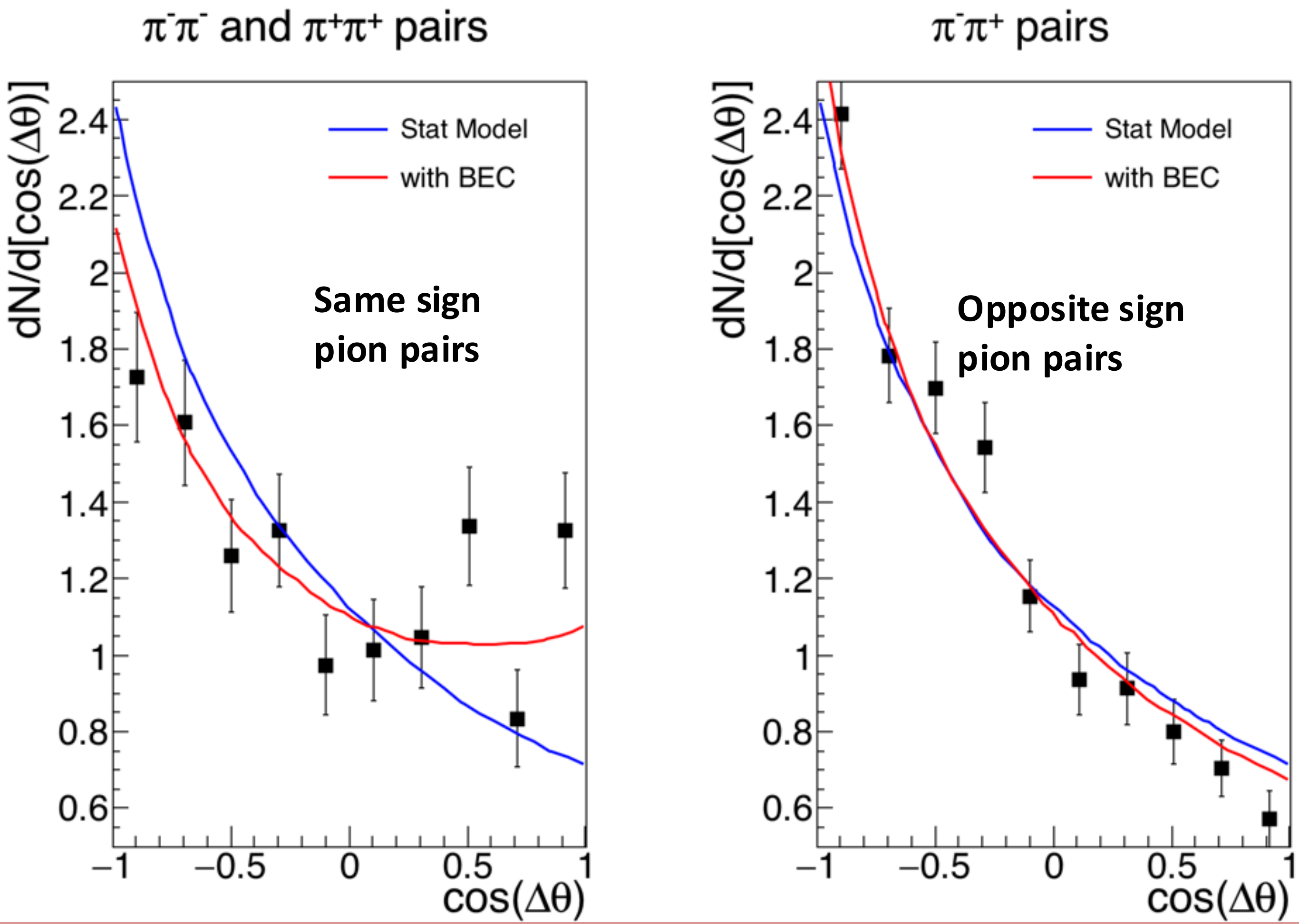


PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee, and Abraham Pais†
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16. 1960)

- low statistics!
- back-to-back preference lower for like-sign pairs
- Statistical Model captures main features (phasespace dominates)
- Agreement improves when Bose-Einstein correlations modify phasespace
  - R=0.75 fm used [reasonable enough]



- until recently, in particle physics the "GGLP effect" is relevant mostly inasmuch as it distorts the W mass (e.g. arXiv:hep-ph/9805223)
- in heavy ion physics, however, it plays a prominent role

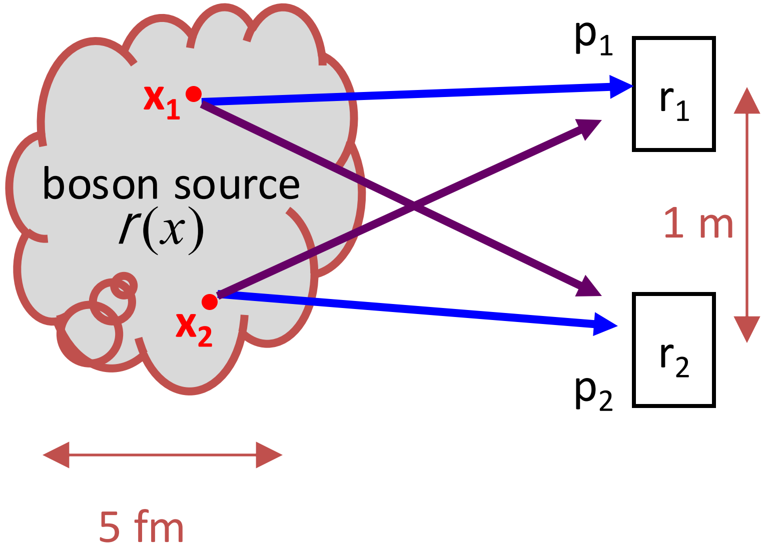
Phys. Lett. 44B (1973) 387

Evolution to heavy ion collisions

- early 1970's: connection between GGLP and HBT [Shuryak. Kopylov, Podgiretsky...]

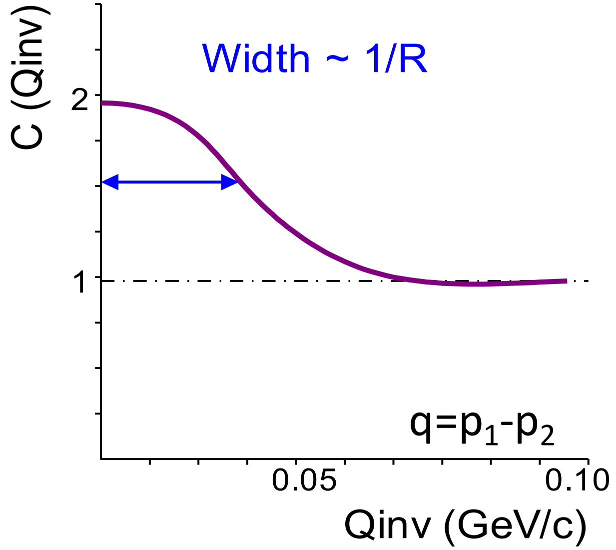

Edward Shuryak

Identical non-interacting bosons



$$\Psi = \frac{1}{\sqrt{2}}\Big[U(\vec{x}_1,\vec{p}_1)\,e^{i(\vec{r}_1-\vec{x}_1)\cdot\vec{p}_1/\hbar}\times U(\vec{x}_2,\vec{p}_2)\,e^{i(\vec{r}_2-\vec{x}_2)\cdot\vec{p}_2/\hbar} + U(\vec{x}_2,\vec{p}_1)\,e^{i(\vec{r}_1-\vec{x}_2)\cdot\vec{p}_1/\hbar}\times U(\vec{x}_1,\vec{p}_2)\,e^{i(\vec{r}_2-\vec{x}_1)\cdot\vec{p}_2/\hbar}\Big]$$

$$\Psi^*\Psi = \underbrace{U_1^*\,U_1}_{\text{Prob. }\#1}\cdot\underbrace{U_2^*\,U_2}_{\text{Prob. }\#2}\cdot\left[1+\cos\left((\vec{p}_1-\vec{p}_2)\cdot(\vec{x}_1-\vec{x}_2)/\hbar\right)\right]$$



$$C(\vec{p}_1,\vec{p}_2) \equiv \frac{P(\vec{p}_1,\vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = 1 + \left|\tilde{\rho}(\vec{q})\right|^2$$

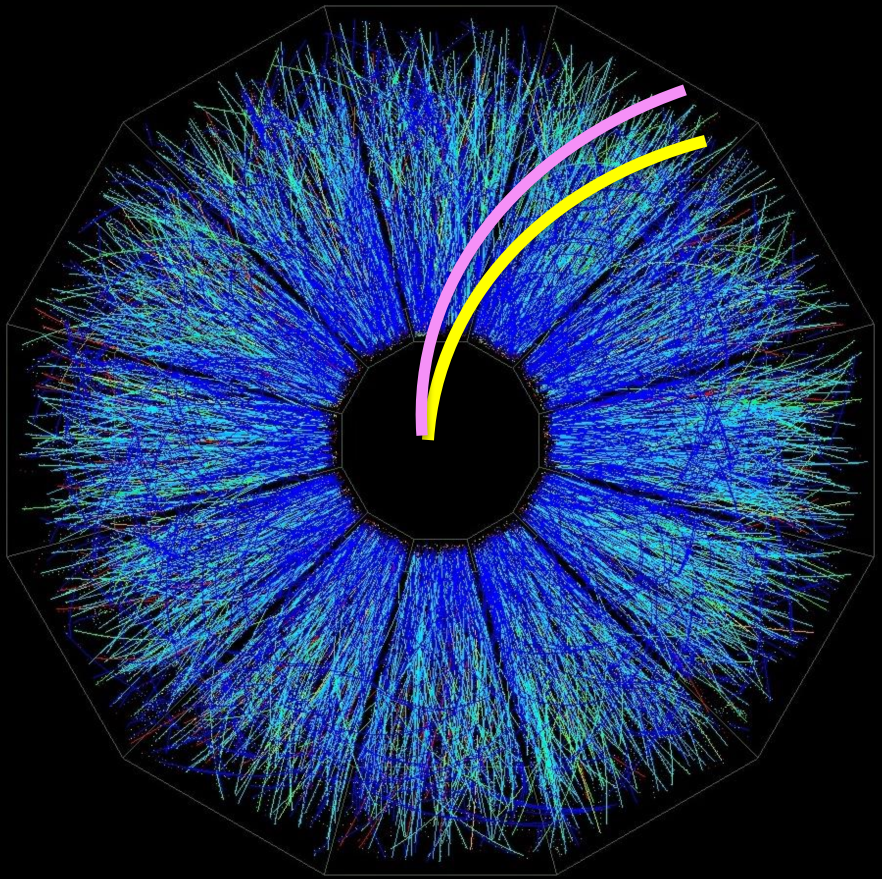
Measurable

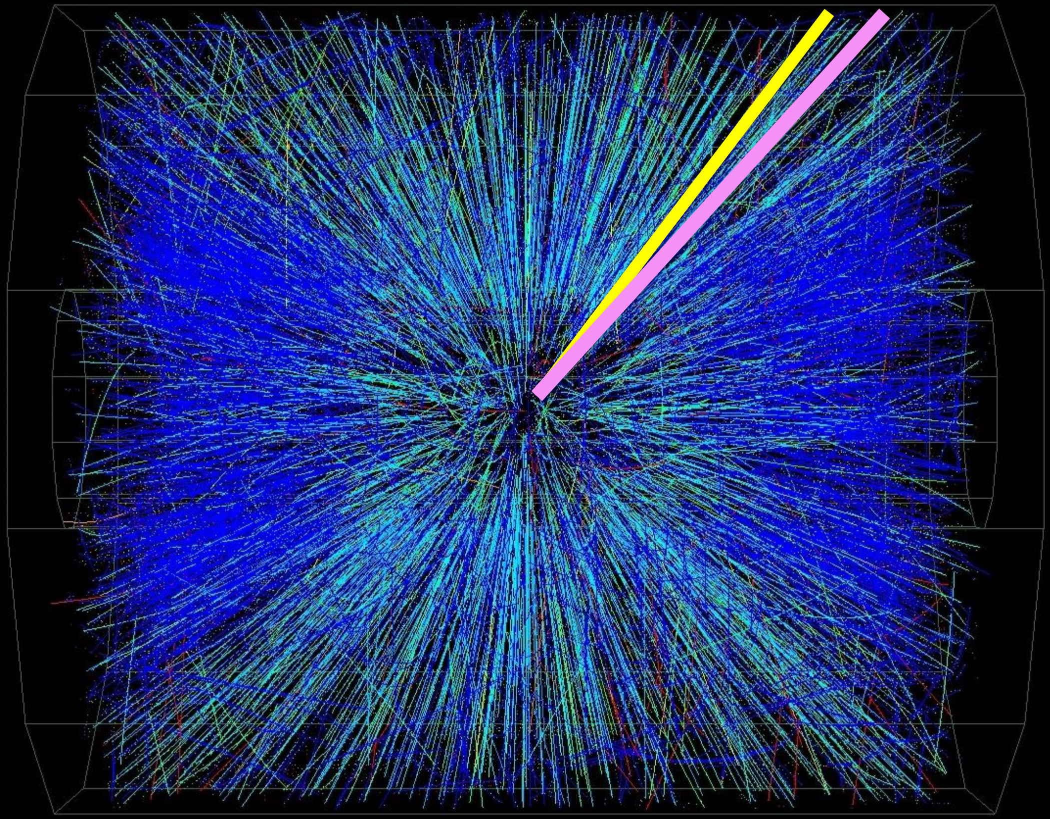
F.T. of pion source

$$C(\vec{q}) = 1 + \int d^3r\, S(\vec{r}) \cos(\vec{q}\cdot\vec{r}) \quad = \frac{N(\vec{p}_1, \vec{p}_2)}{N_{\rm mix}(\vec{p}_1, \vec{p}_2)}$$

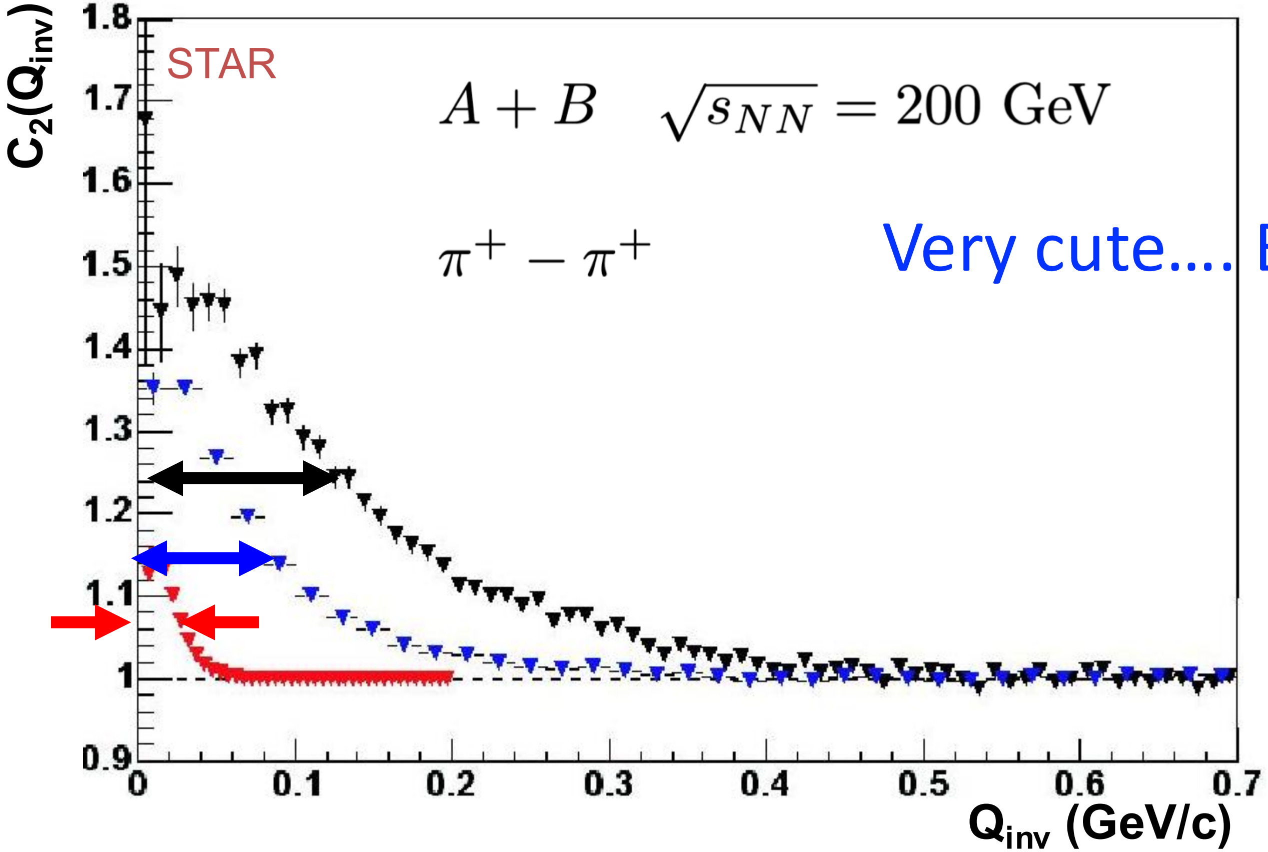
dominated by phasespace
MUCH more complicated than SII

Correlation expresses a conditional probability (~SII)

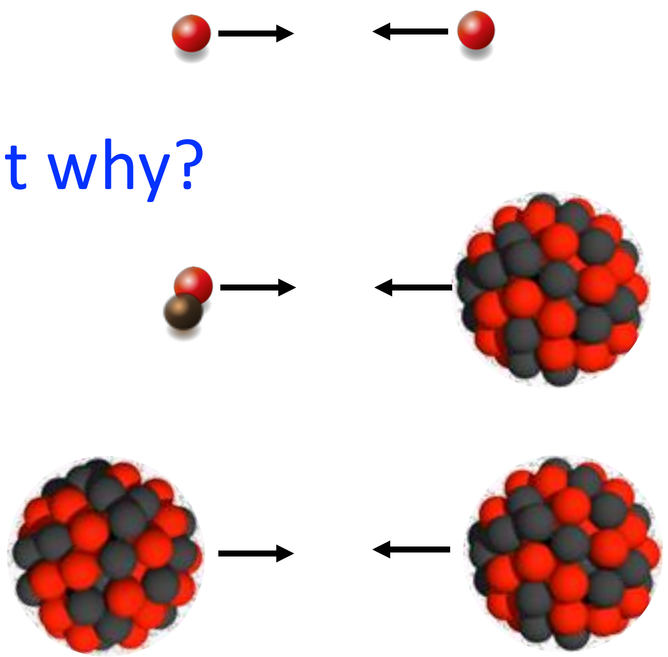




Sanity check: Intensity Interferometry for 3 systems

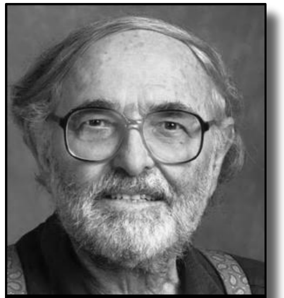


Very cute…. But why?



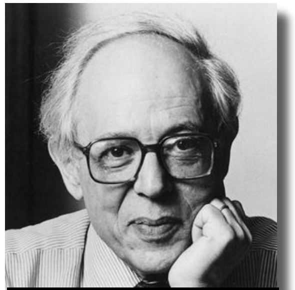
GGLP → Femtoscopy in heavy ion collisions

- 1960: GGLP observe small correlation between identical pions in p-pbar anhilation. Largely a curiosity

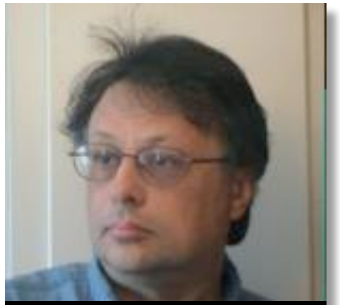

G.Goldhaber


S.Goldhaber


W. Lee


A. Pais

- early 1970's: connection between GGLP and HBT [Shuryak. Kopylov, Podgiretsky...]


Edward Shuryak

- late 1970's – early 1980's: explosive development in new field of heavy ion collisions


Miklos Gyulassy


Steve Koonin


Scott Pratt

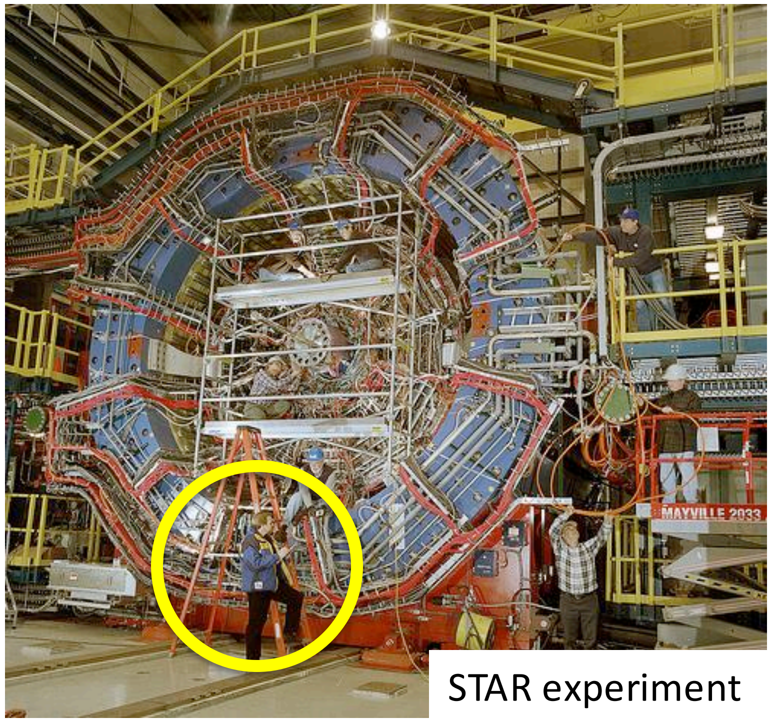

Richard Lednicky


Bill Zajc


Laura Fabbietti

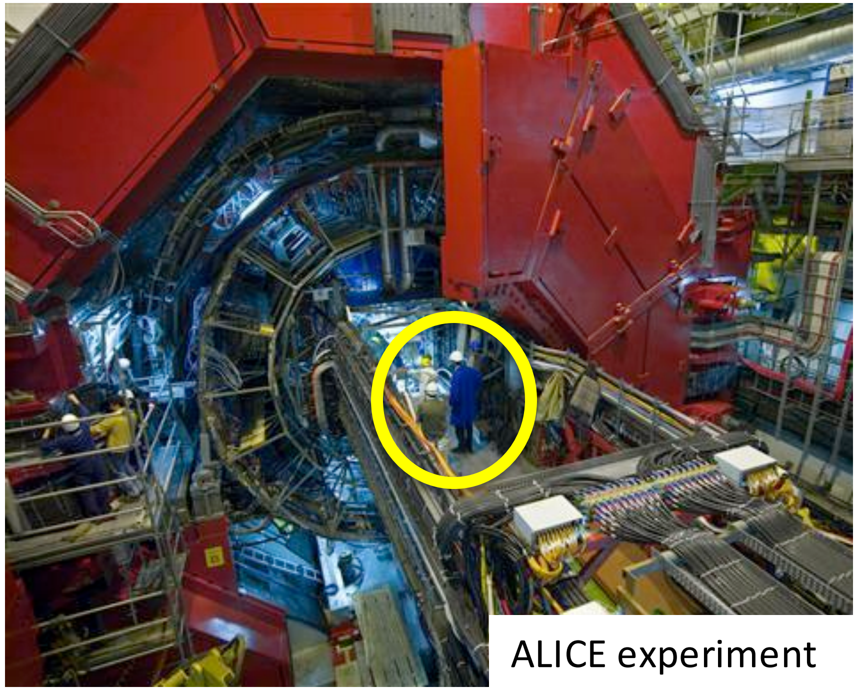
...

Relativistic Heavy Ion Collider (RHIC)
Brookhaven Lab, NY, USA



STAR experiment

Large Hadron Collider (LHC)
CERN, France/Switzerland



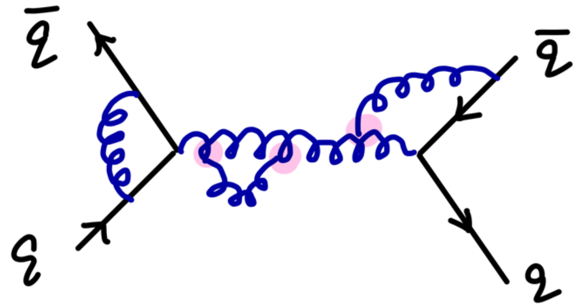
ALICE experiment

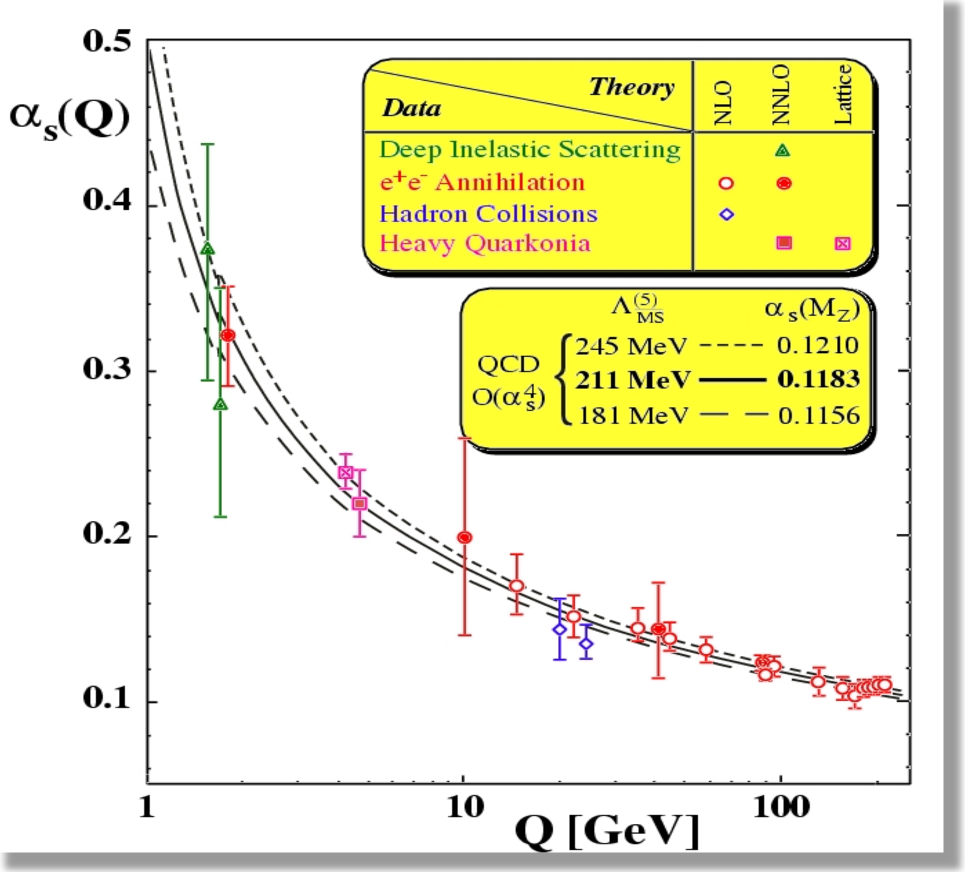
Ultrarelativistic collisions of:

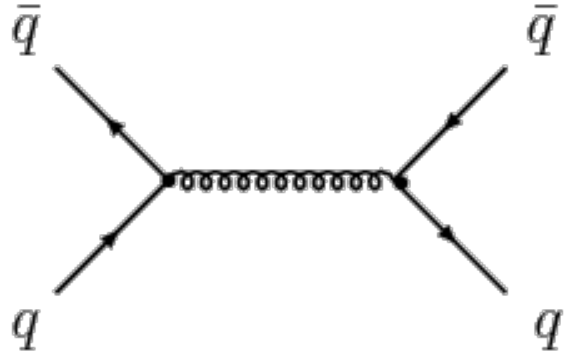
- p+p
- Au+Au / Pb+Pb

- (and p+Au, Cu+Cu, etc.)

- Theory of Strong Force between quarks: Quantum Chromodynamics (QCD)
- Strength of the Strong Force depends on momentum transfer (spatial scale)
- Complicated & least-well-understood interaction

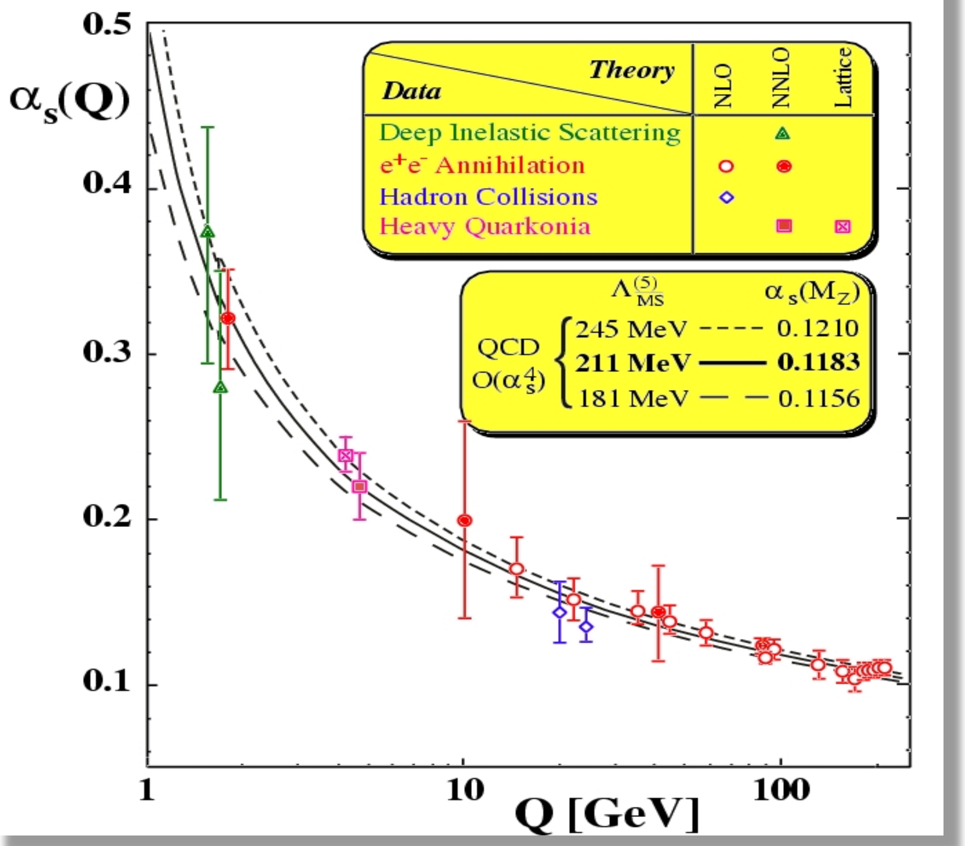






"Running" of the QCD coupling constant

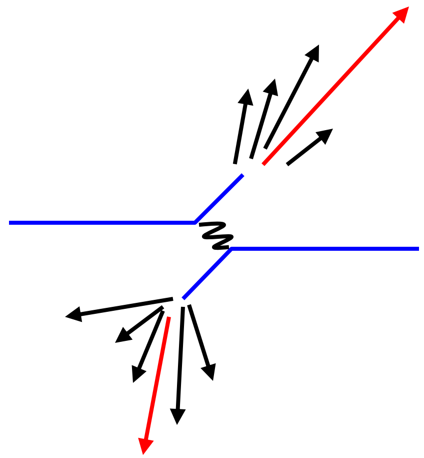
Particle Physics



focus on fundamental particles

Large Q : **Asymptotic Freedom**

- reduce “messy” QCD effects
- perturbative calculations work



✓ Smaller/simpler is better

✓ More energy is better

Heavy Ion Physics

Low Q: **Confinement**

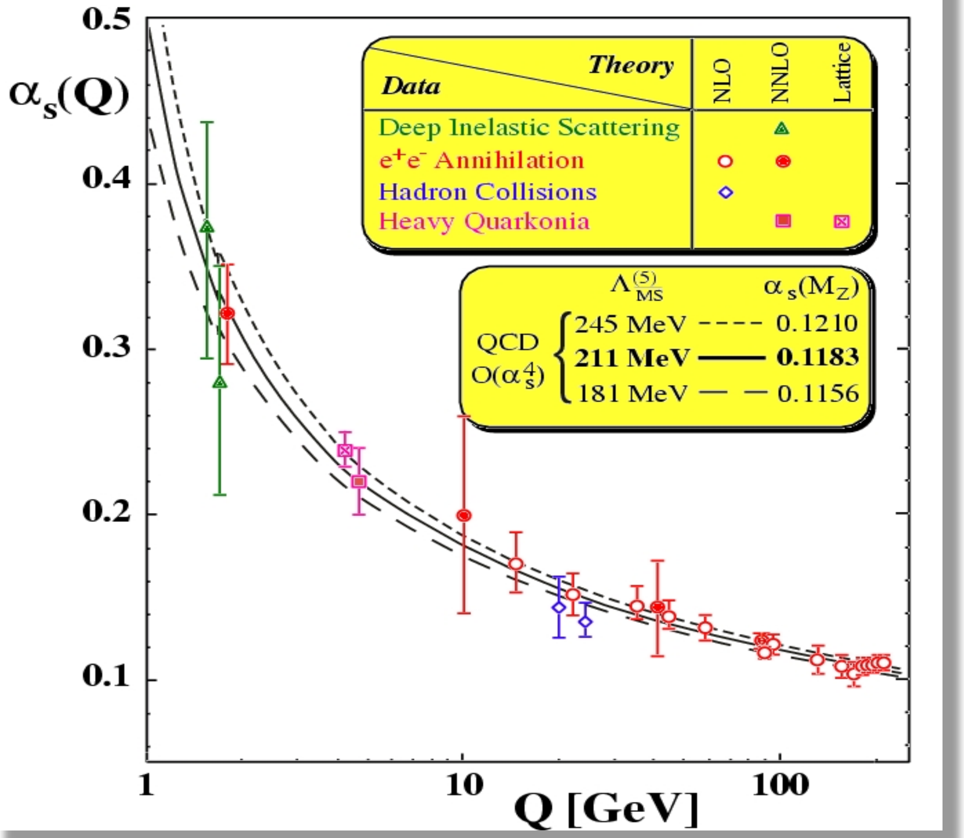
- dominates mass in universe
- theoretical insight limited

intrinsic scales of QCD→

✓ optimum energy range

✓ bigger is better (>> 1 fm)

focus on fundamental interaction

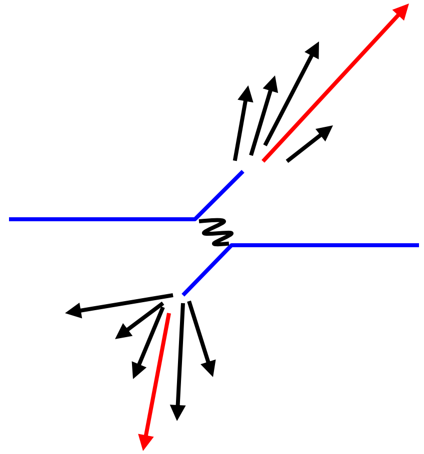


focus on fundamental particles

Particle Physics

Large Q : **Asymptotic Freedom**

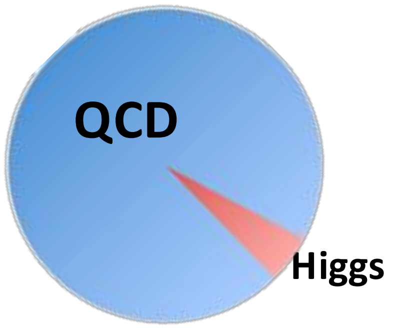
- reduce "messy" QCD effects
- perturbative calculations work

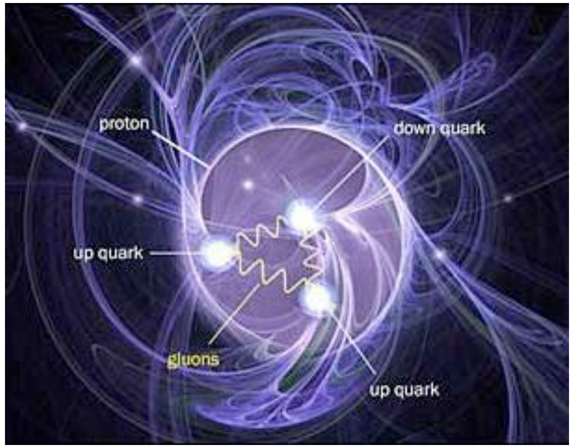


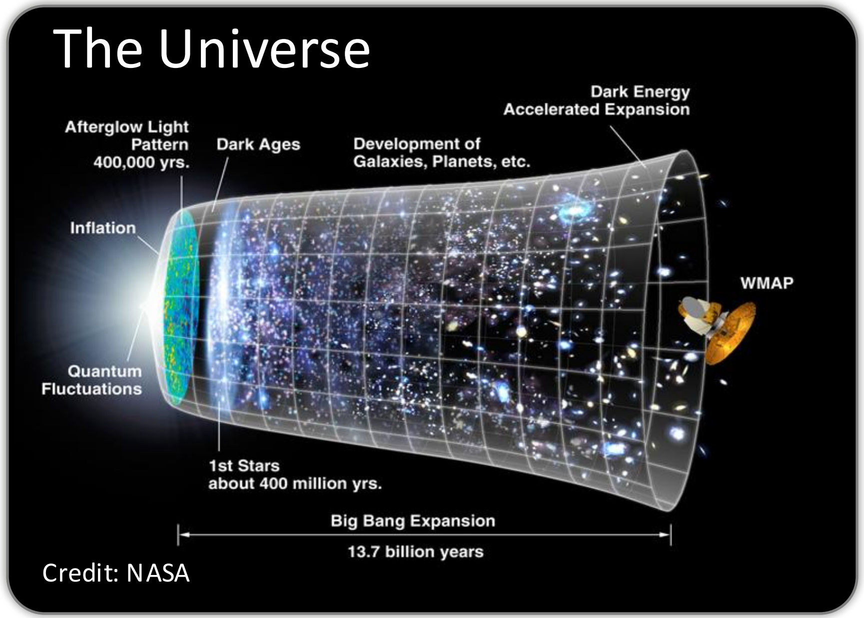
✓ Smaller/simpler is better

✓ More energy is better

Deconfinement transition

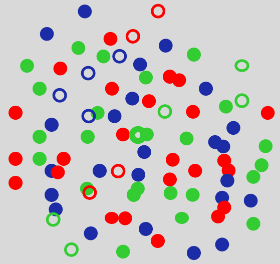




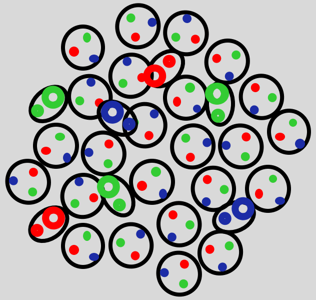


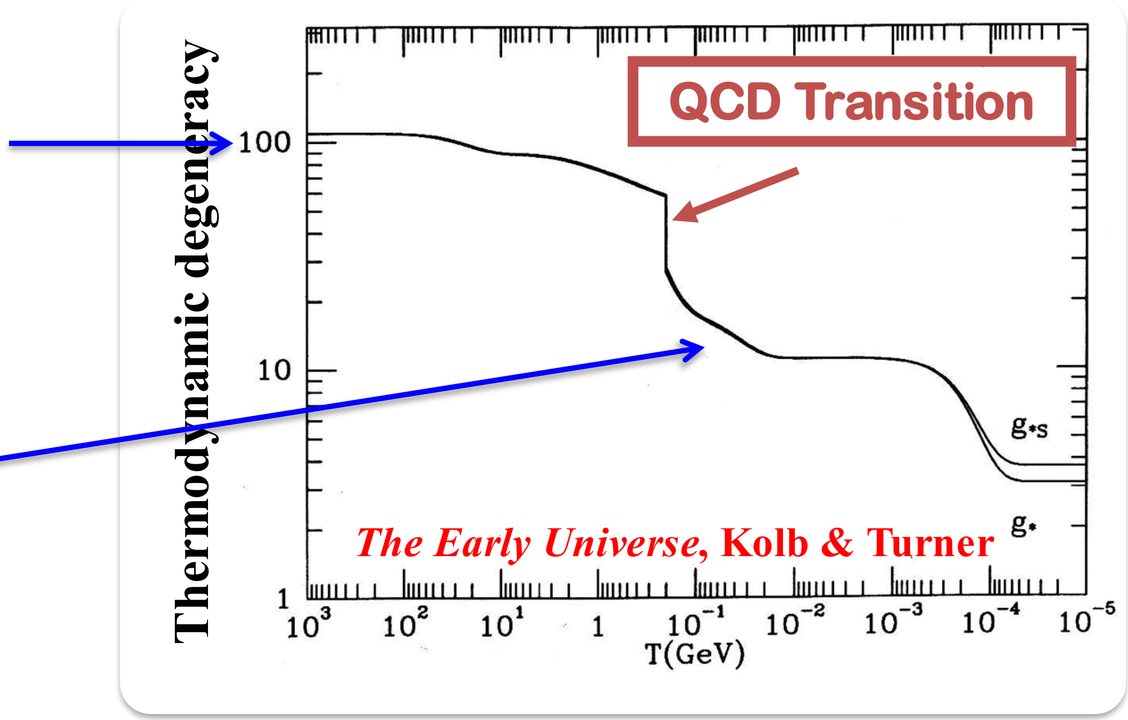
Deconfined color charges
Quark-gluon plasma

- first ~3 μs after Big Bang



Color confined inside
net-color-neutral **hadrons**
(e.g. proton)



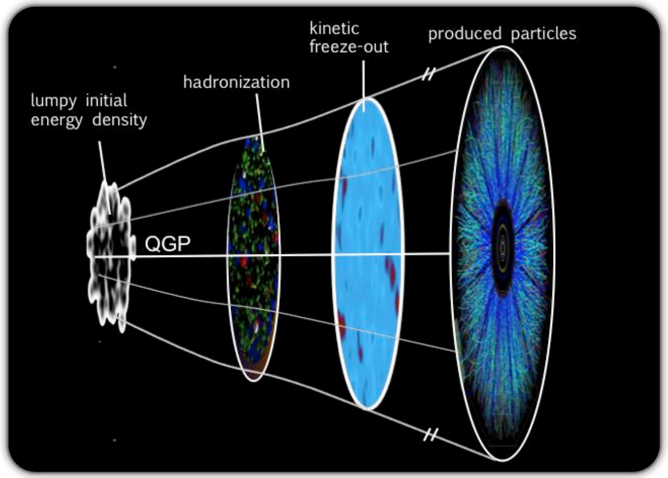


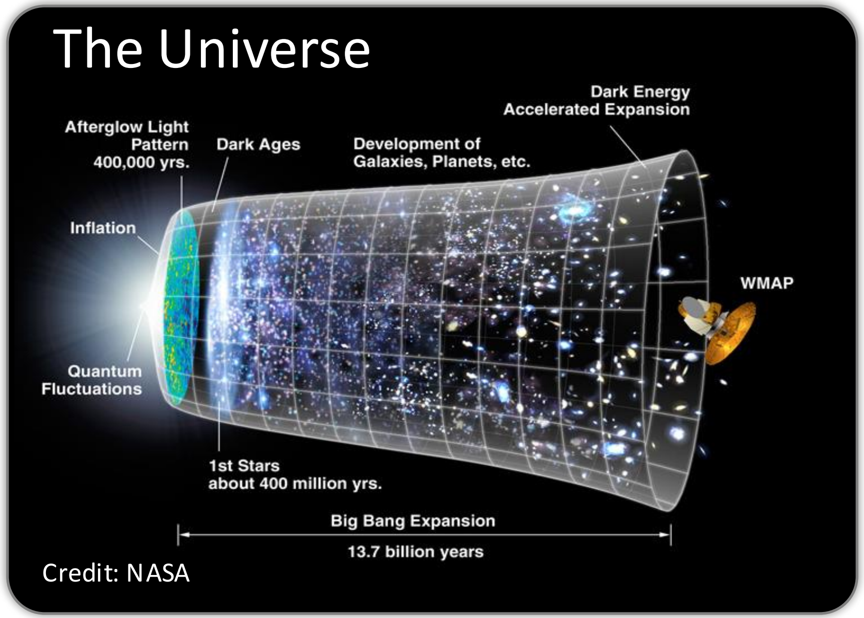
Deconfinement transition

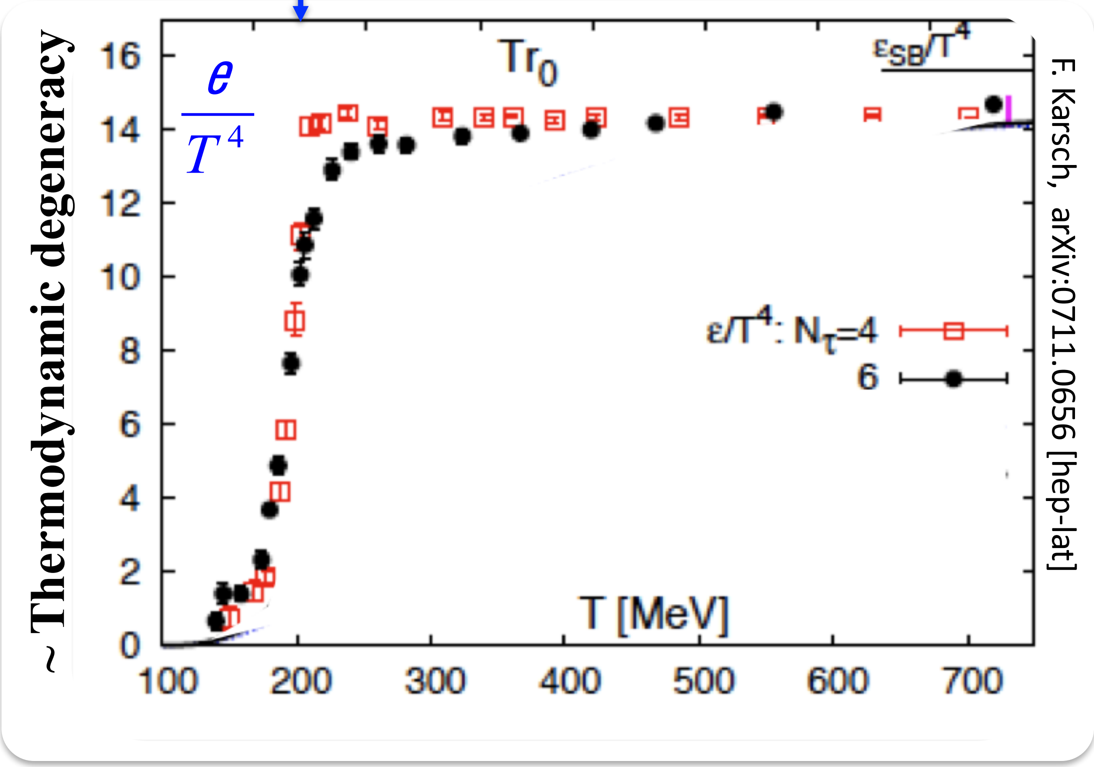
Lattice QCD calculation:

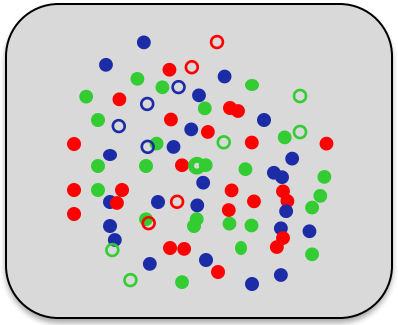
- T<150 MeV → interacting hadrons
- T>150 MeV → deconfined quarks

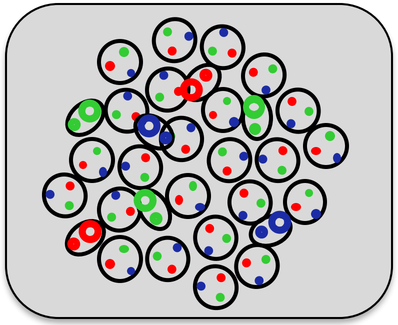
150 MeV = 2×10^{12} K ~ 10^5 $T_\odot$

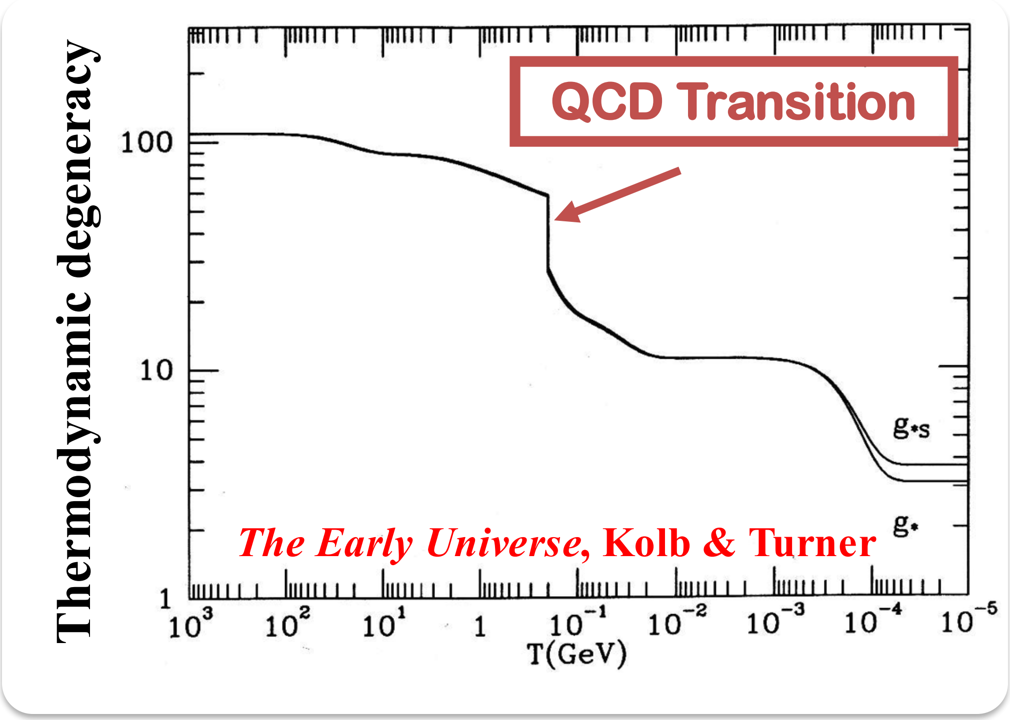






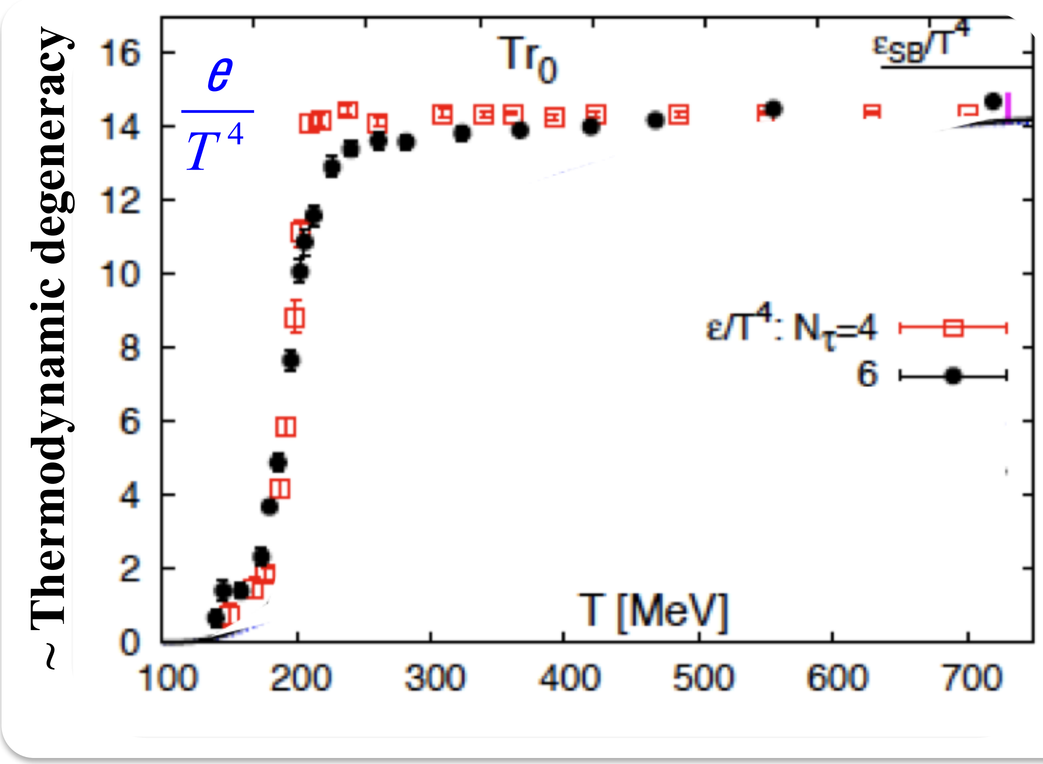




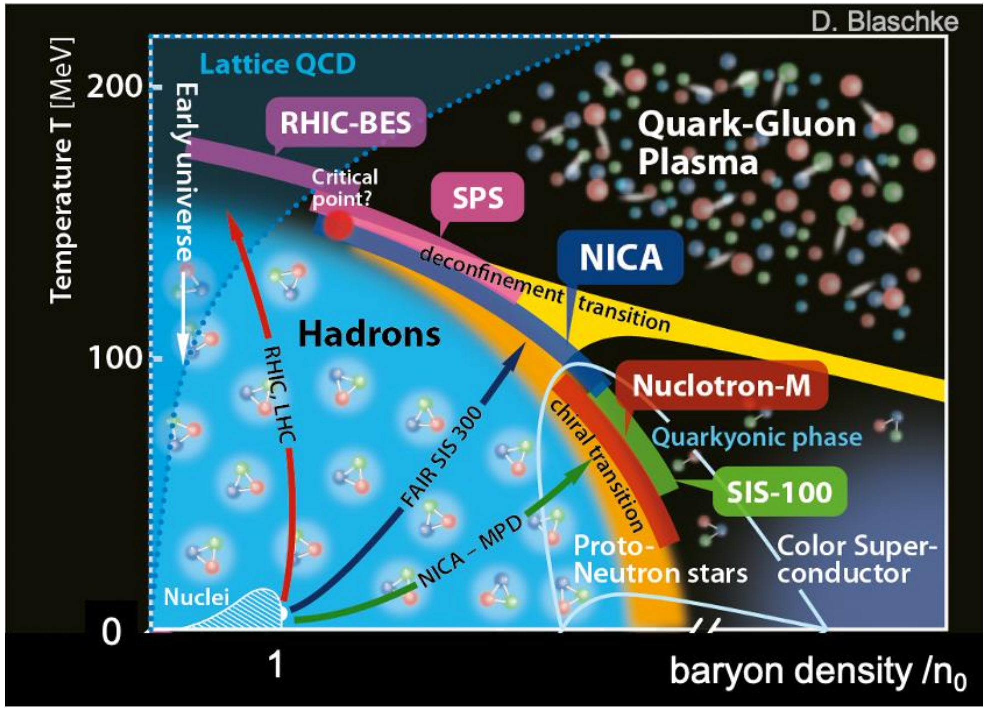


Equation of state – characterizing bulk matter

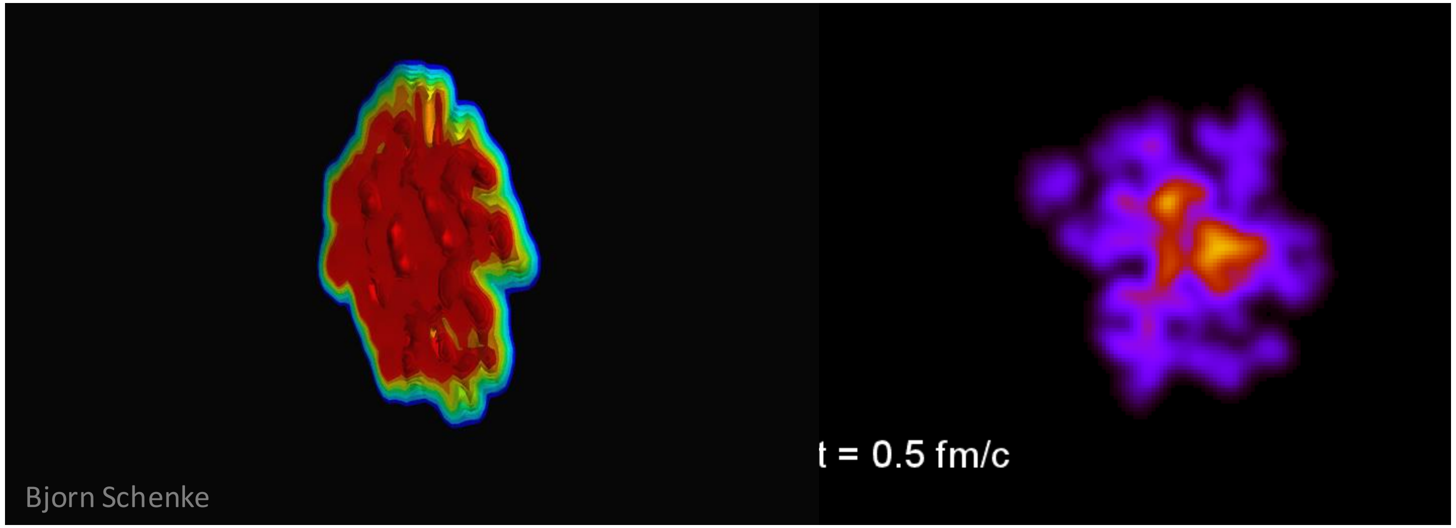
Lattice QCD calculation:



F. Karsch, arXiv:0711.0656 [hep-lat]



Equation of state – driving dynamic evolution




The New York Times

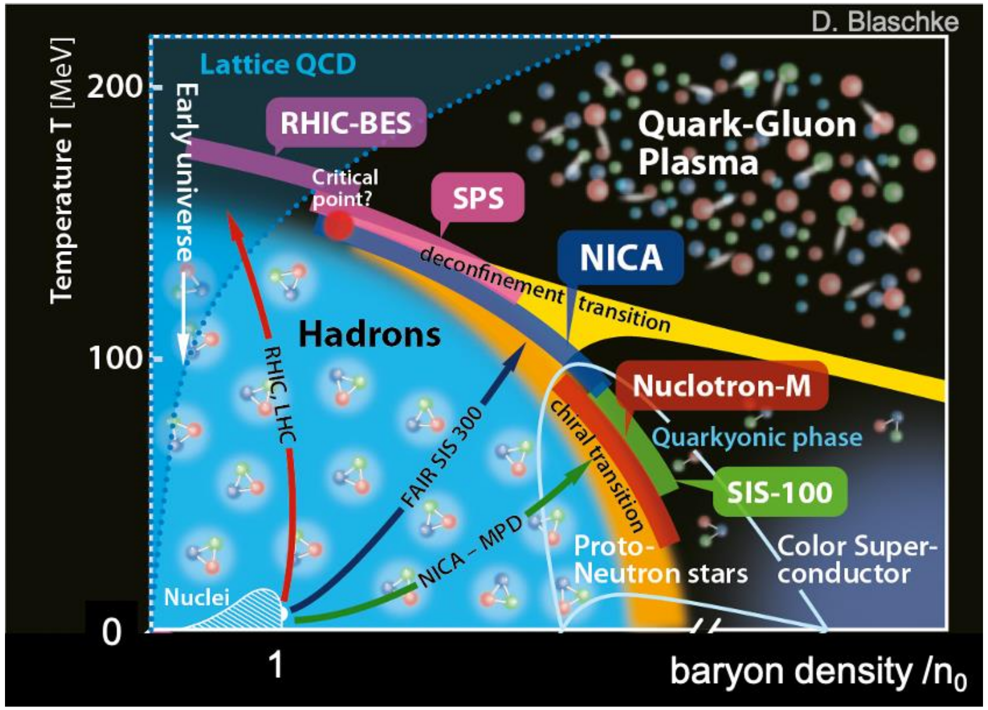
At One Trillion Degrees, Even Gold Turns Into the Sloshiest Liquid

By Kenneth Chang

April 19, 2005

SCIENTIFIC AMERICAN

RHIC serves the perfect fluid



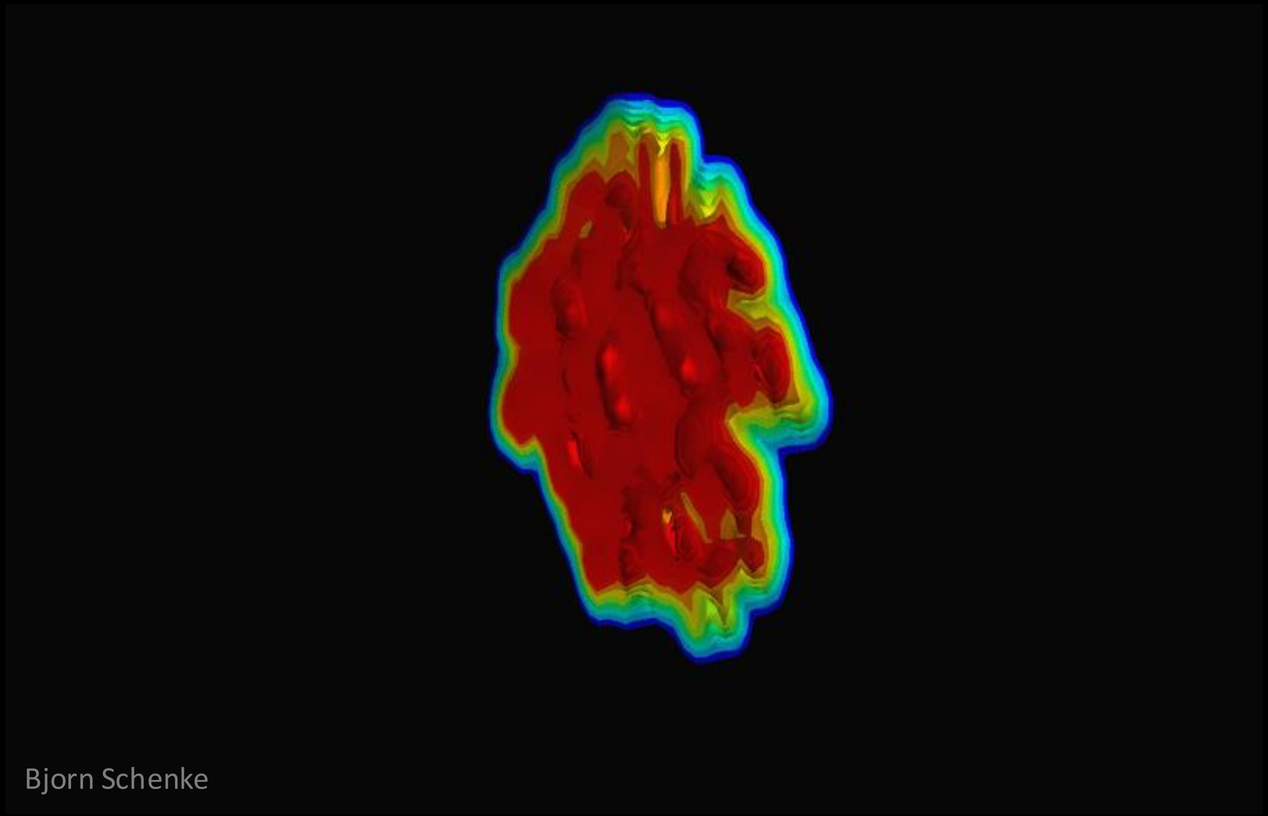
From a (lumpy) initial state, solve hydro equations:

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu,\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

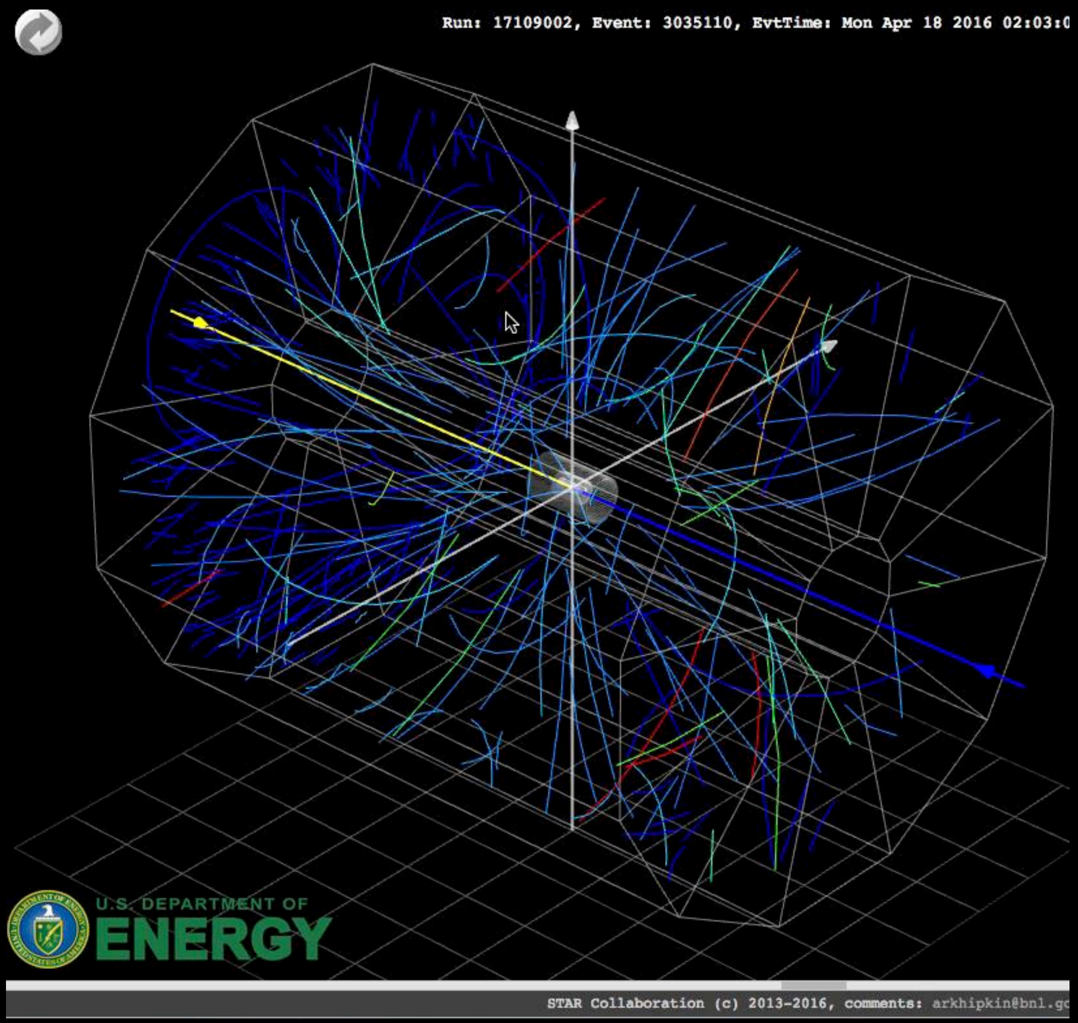
$$u^\mu \partial_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

& ….. the equation of state

Femto-scale simulation



Macro-scale reality

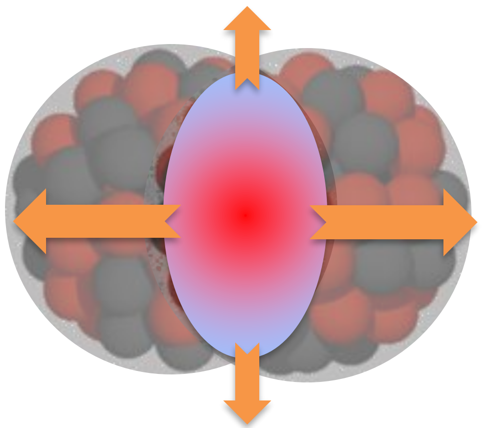


- Detectors record identities and *momenta* of emitted hadrons
- No direct spacetime information
  - "angular diameter" ~ nanoarcsecond
- Two-hadron intensity interferometry (femtoscopy) is crucial

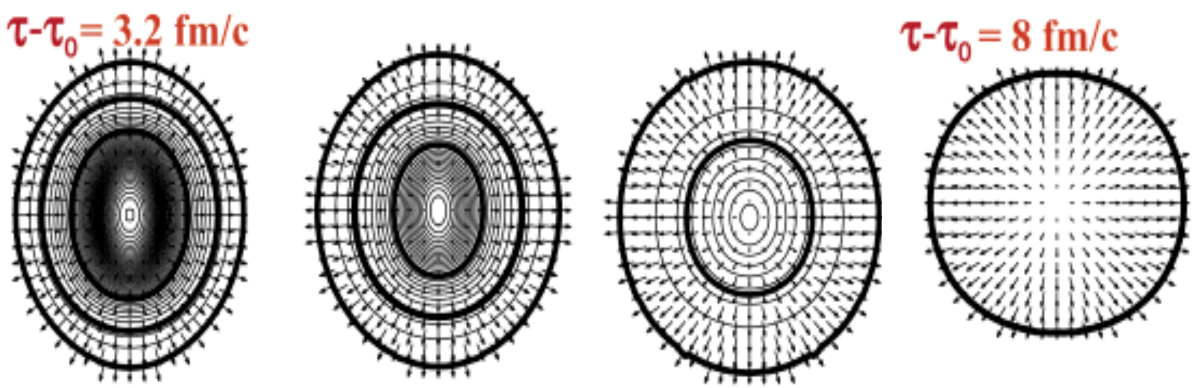
Geometry – the hallmark of heavy ion physics

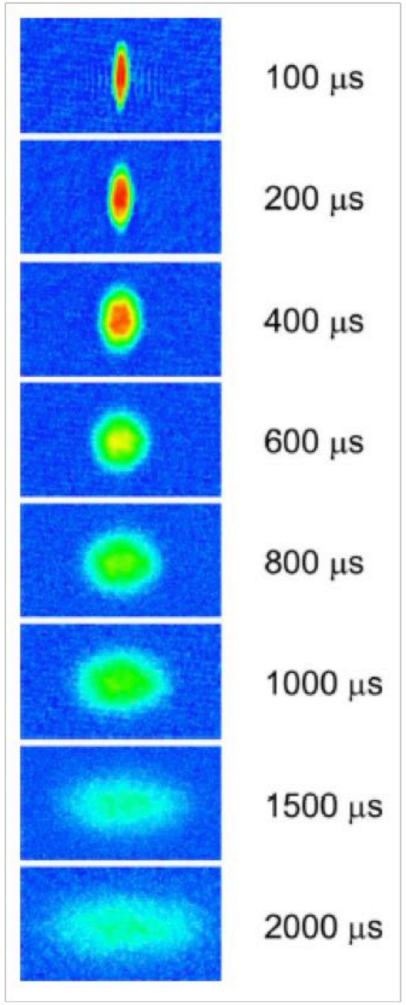
- Size matters – need a *bulk* system
- Shape matters – anisotropic geometry key

degenerate fermi gas (supercooled ^{6}Li) released from anisotropic magnetic trap



hydro calculations: Kolb & Heinz





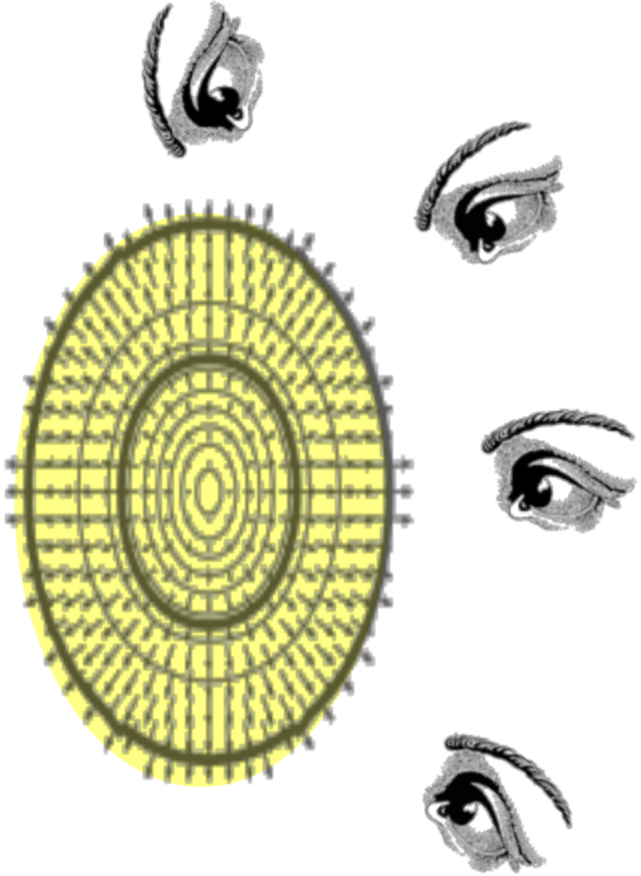
O'Hara et al, *Science* 2002

- "Elliptic flow" driven by anisotropic pressure gradients: sensitive to E.o.S. & viscosity
- universally observed for strongly-interacting systems

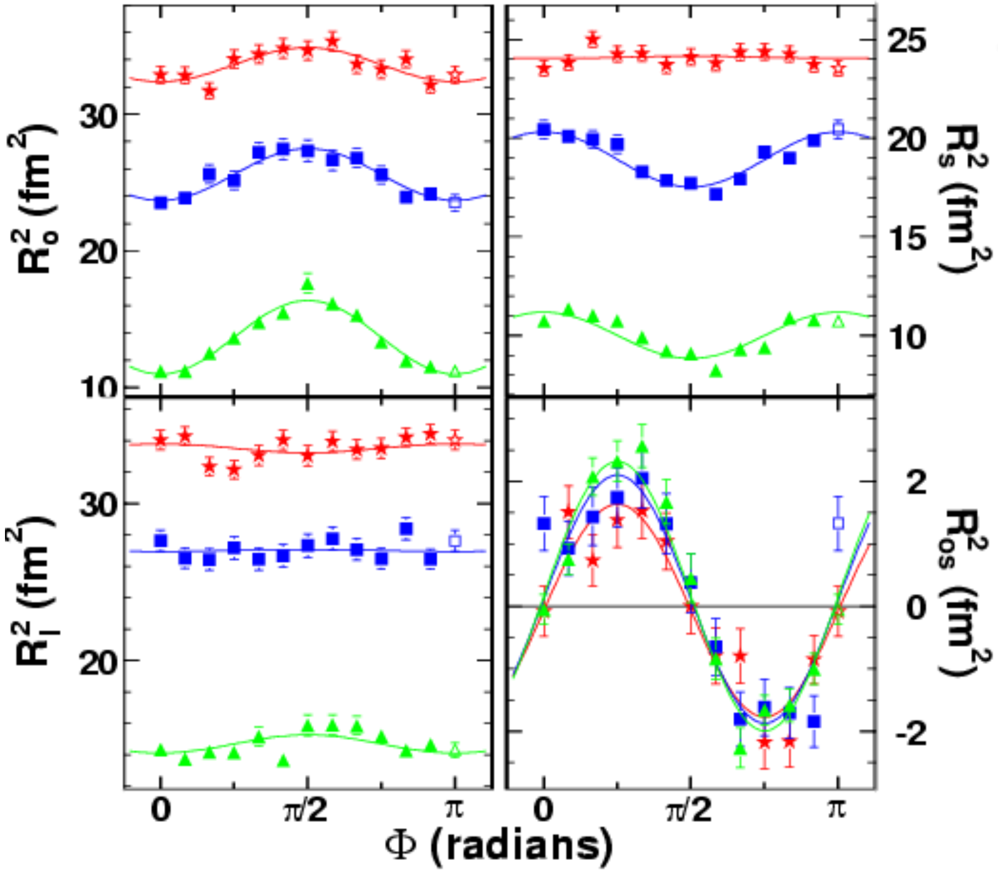
Spatial aspects of elliptic flow

- Size matters – need a *bulk* system
- Shape matters – anisotropic geometry key

complementary spatial information tightens constraints on hydro transport



STAR, PRL93 012301 (2004)



Central collisions

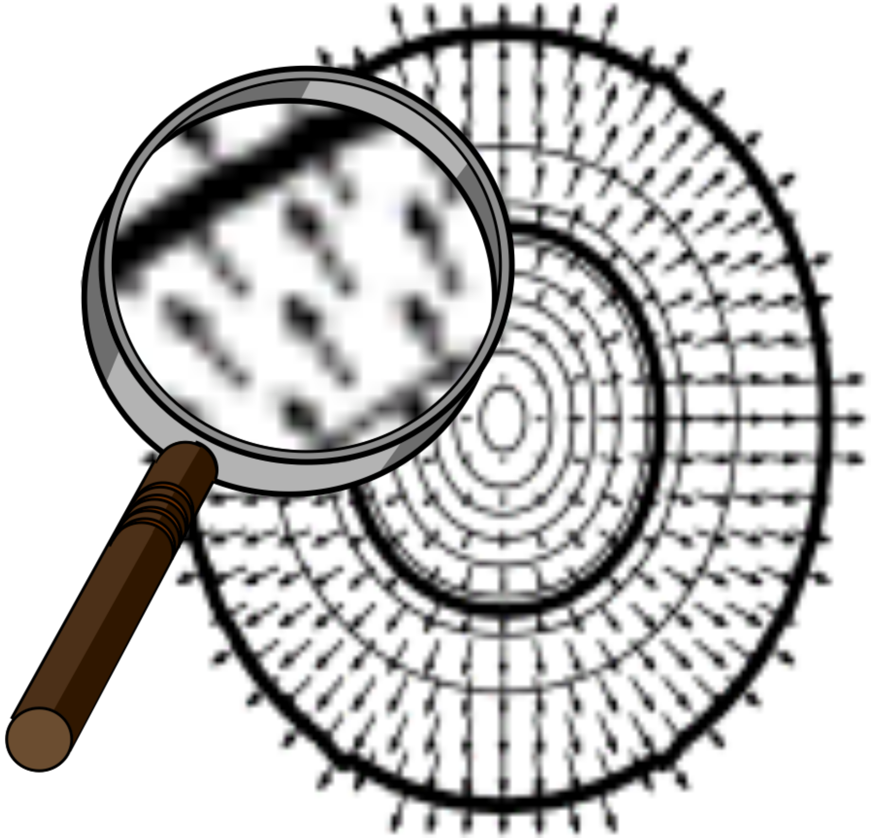
Mid-central collisions

Peripheral collisions

Geometry – the hallmark of heavy ion physics

- Size matters – need a *bulk* system
- Shape matters – anisotropic geometry key
- Substructure matters

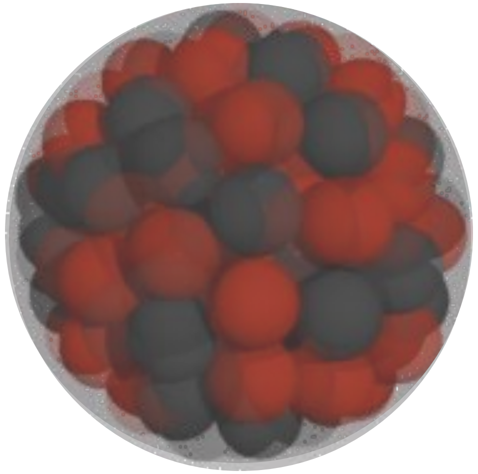
Intensity interferometry probes spacetime substructure in subatomic collisions



Geometric substructure

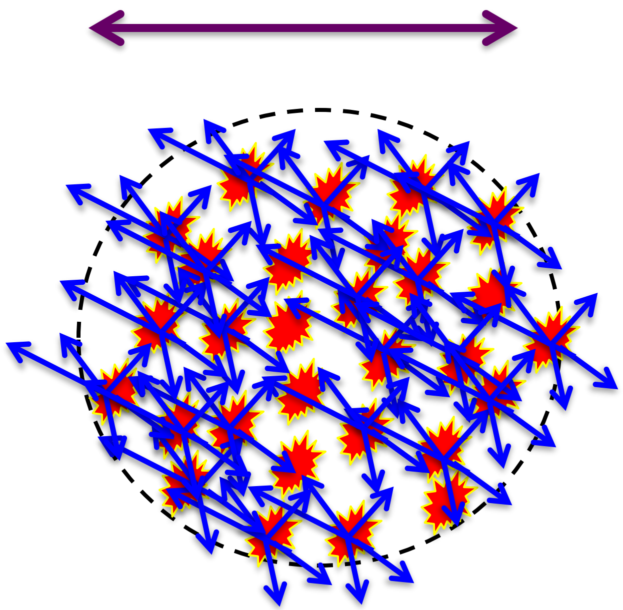
What type of system is formed?

Indeed, _is_ it a system?



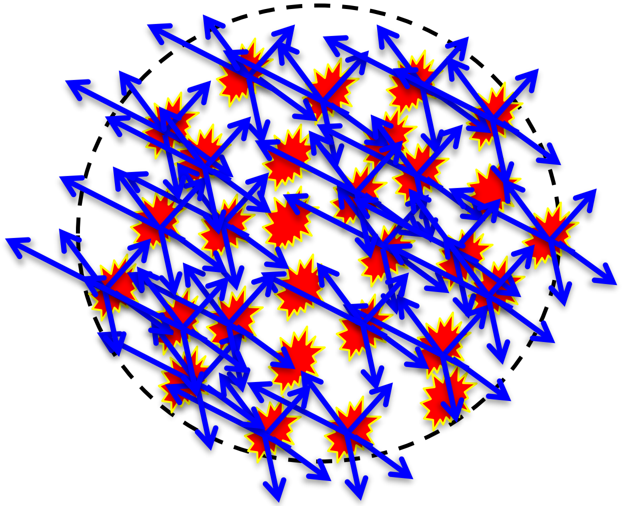
Geometric substructure

Size Independent of momentum



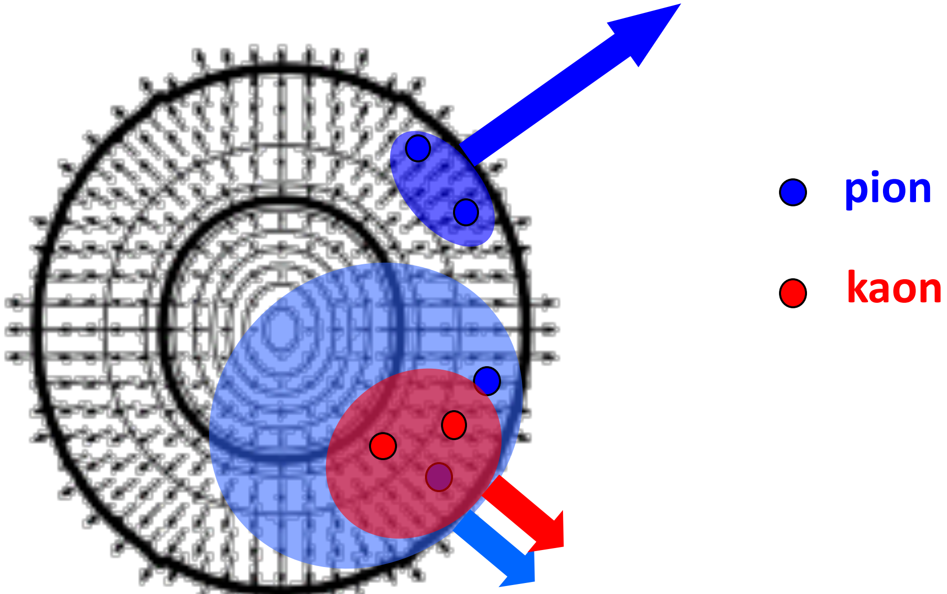
A collection of nearby, independent p+p collisions. **Not "matter"**

Geometric substructure



A collection of nearby, independent p+p collisions. **Not "matter"**

Hydrodynamic expectation:



selecting
fast particles

Matter is characterized by fields of **bulk** properties

selecting
slow particles

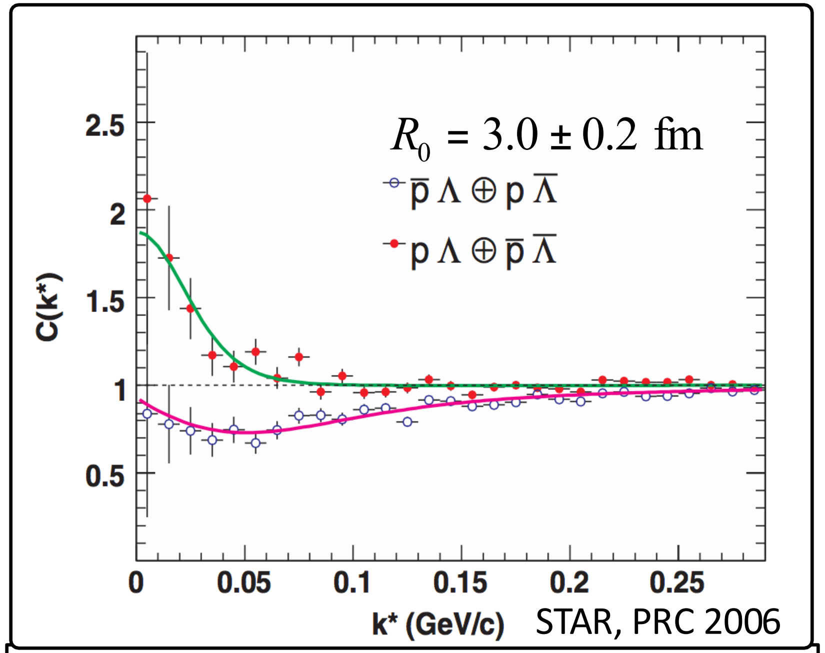
Beyond pions

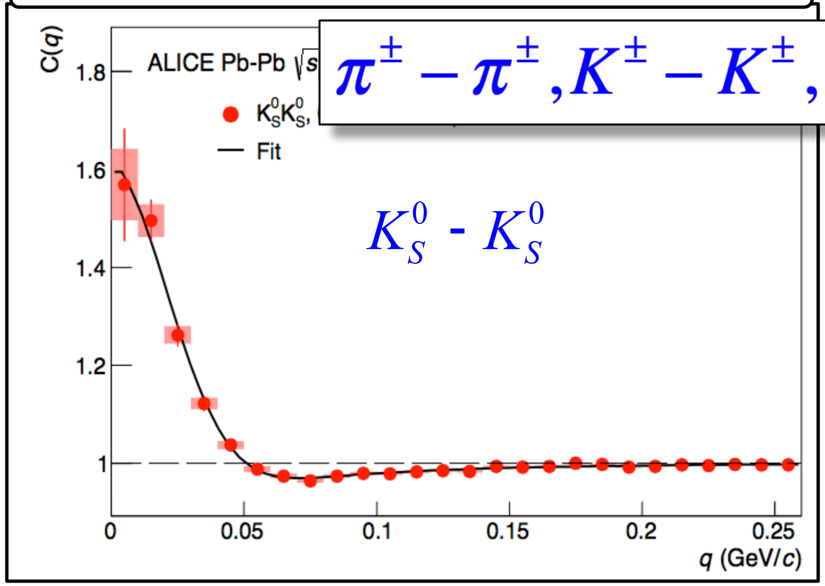
$$C(\vec{q}) = \int d^3r S(\vec{r})(1+\cos(\vec{q}\cdot\vec{r}))$$ ← non-interacting bosons

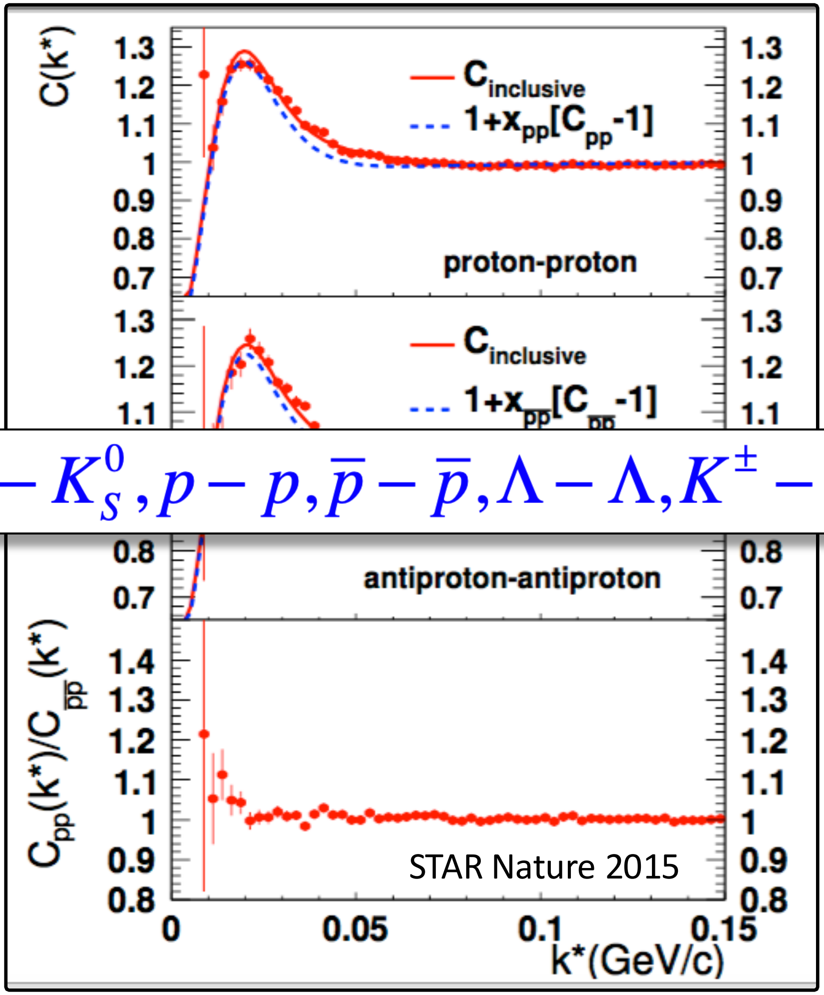
$$C(\vec{q}) = \int d^3r S(\vec{r})|\phi(\vec{q}\cdot\vec{r})|^2$$ ← in general (Koonin-Pratt eq.)

$\phi(\vec{q},\vec{r})$ = rel. wavefunction in pair c.m. including:

- (anti)symmetrization (for identical particles)
- final-state interactions



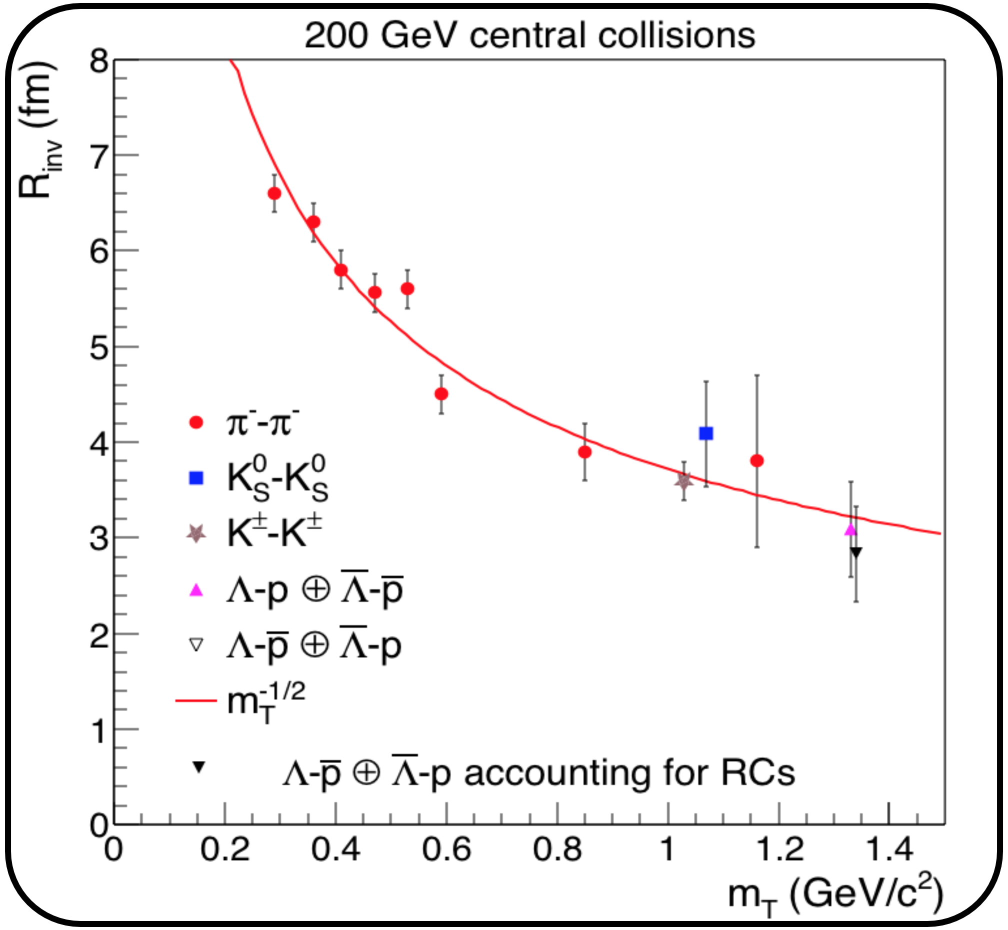




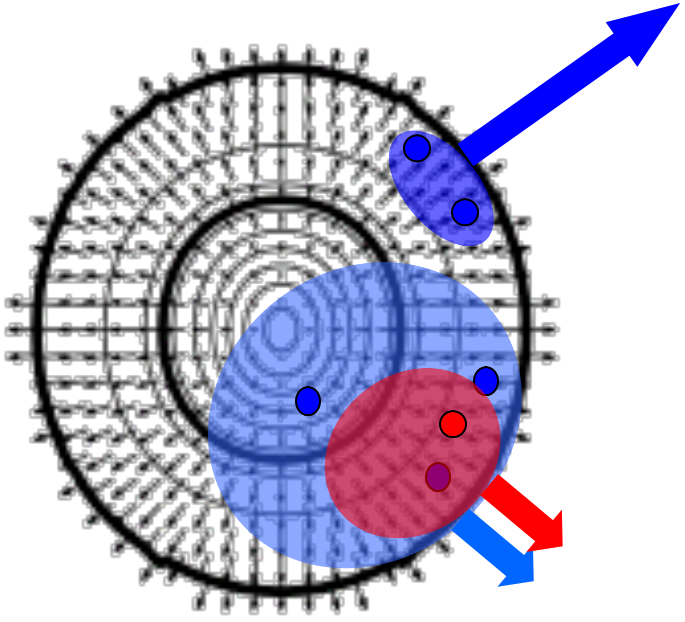
$$\pi^\pm-\pi^\pm, K^\pm-K^\pm, K^0_S-K^0_S, p-p, \bar{p}-\bar{p}, \Lambda-\Lambda, K^\pm-\pi^\pm, p-\Lambda, \Xi-\pi\ldots$$

Geometric substructure

Sizes for particles of different momentum & mass



Hydrodynamic expectation:

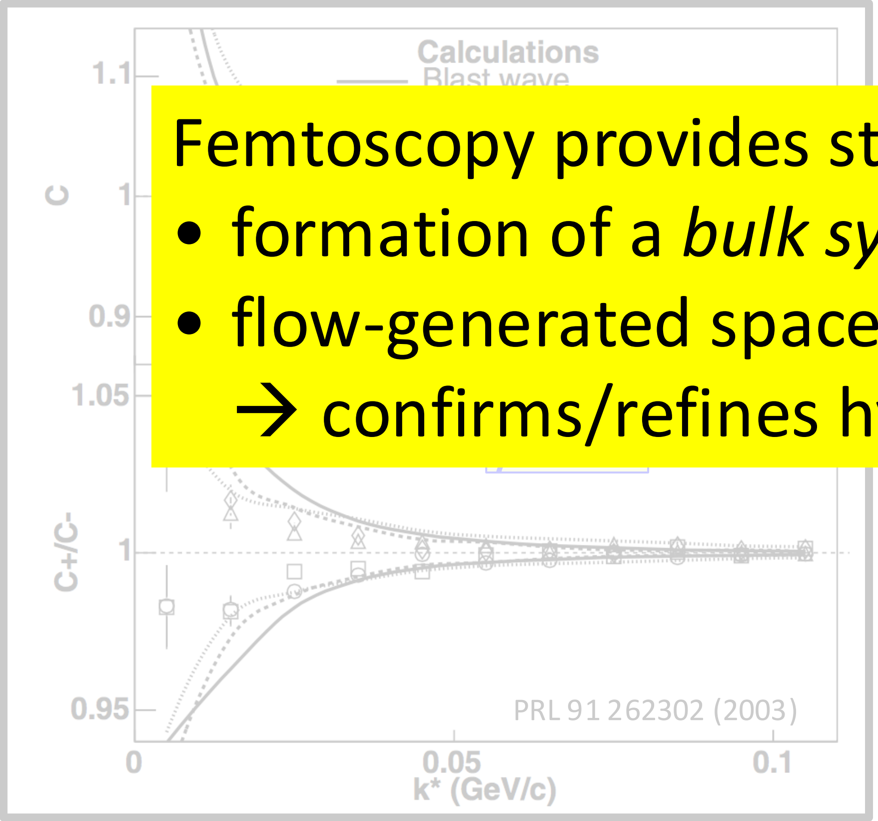


Matter is characterized by fields of **bulk** properties

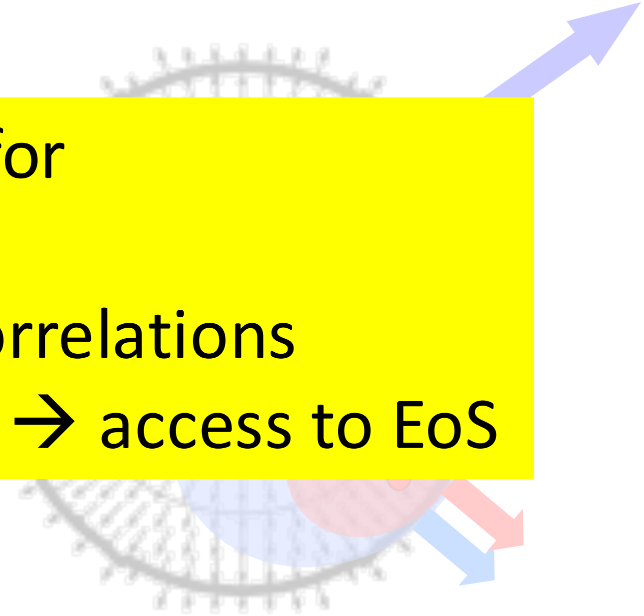
- pion
- kaon

Geometric substructure

$p^{\pm}$ - $K^{\pm}$ correlations reveal mass-ordered separation



Hydrodynamic expectation:



Femtoscopy provides strong evidence for

- formation of a *bulk system*
- flow-generated space-momentum correlations
  → confirms/refines hydro treatment → access to EoS

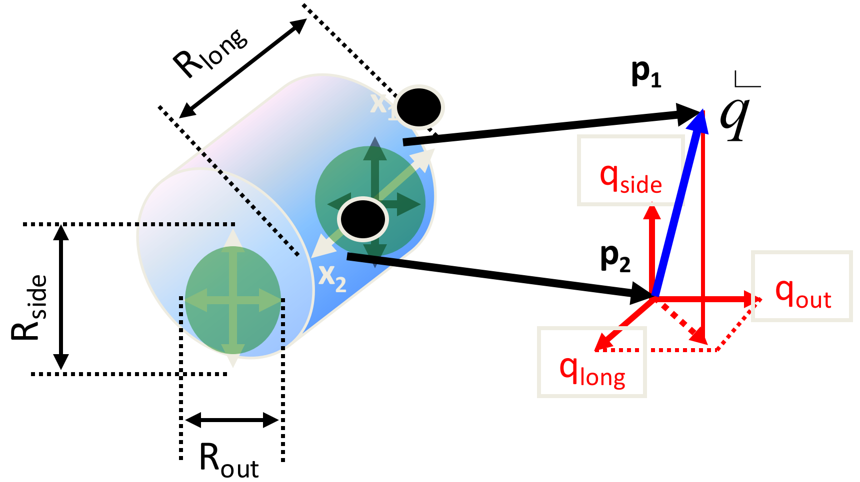
Matter is characterized by fields of **bulk** properties

pion

kaon

3D info and timescale

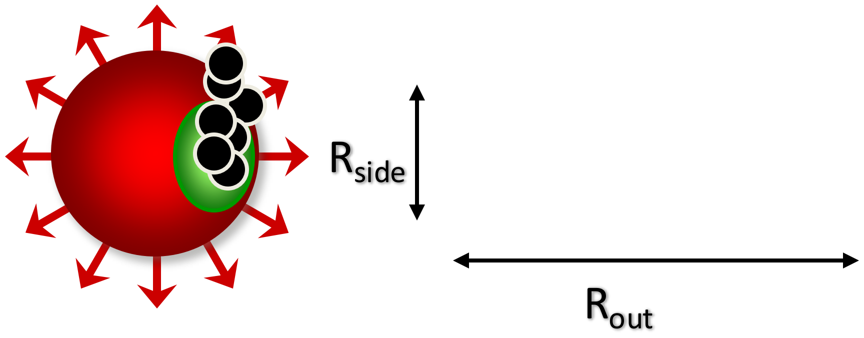
Bertsch-Pratt decomposition: R_{out}, R_{side}, R_{long}



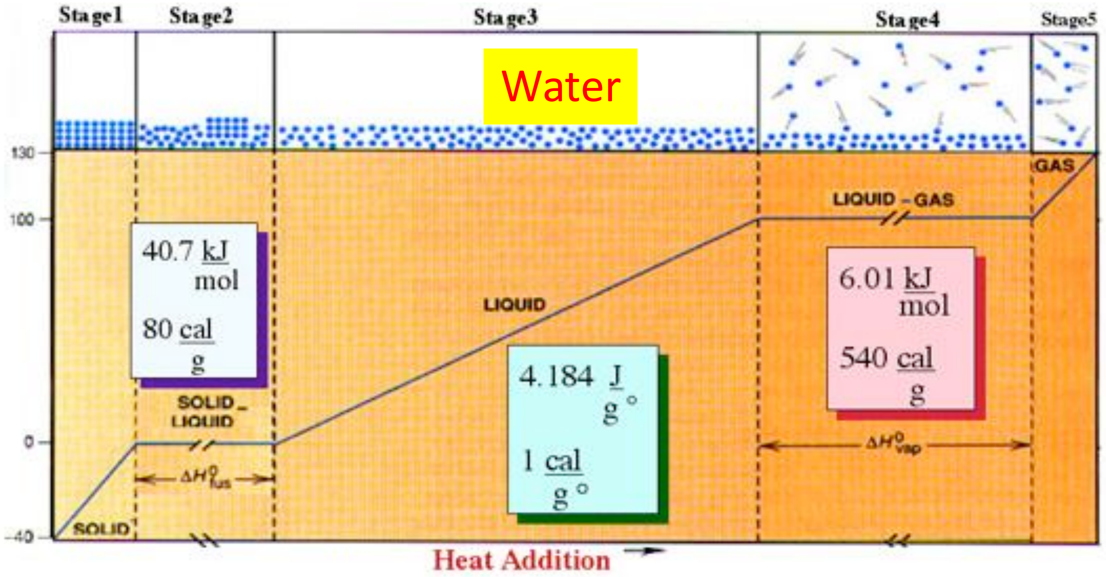
$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

$$\vec{k} = \frac{1}{2}\left(\vec{p}_2 + \vec{p}_1\right)$$

A long emission duration results in $R_{out} > R_{side}$



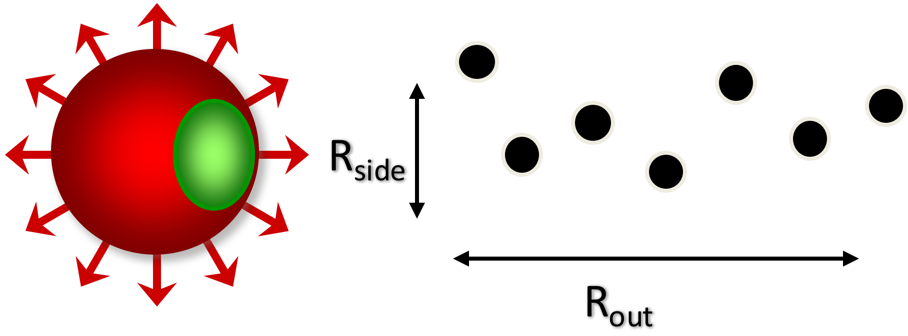
Phase transition? Order?



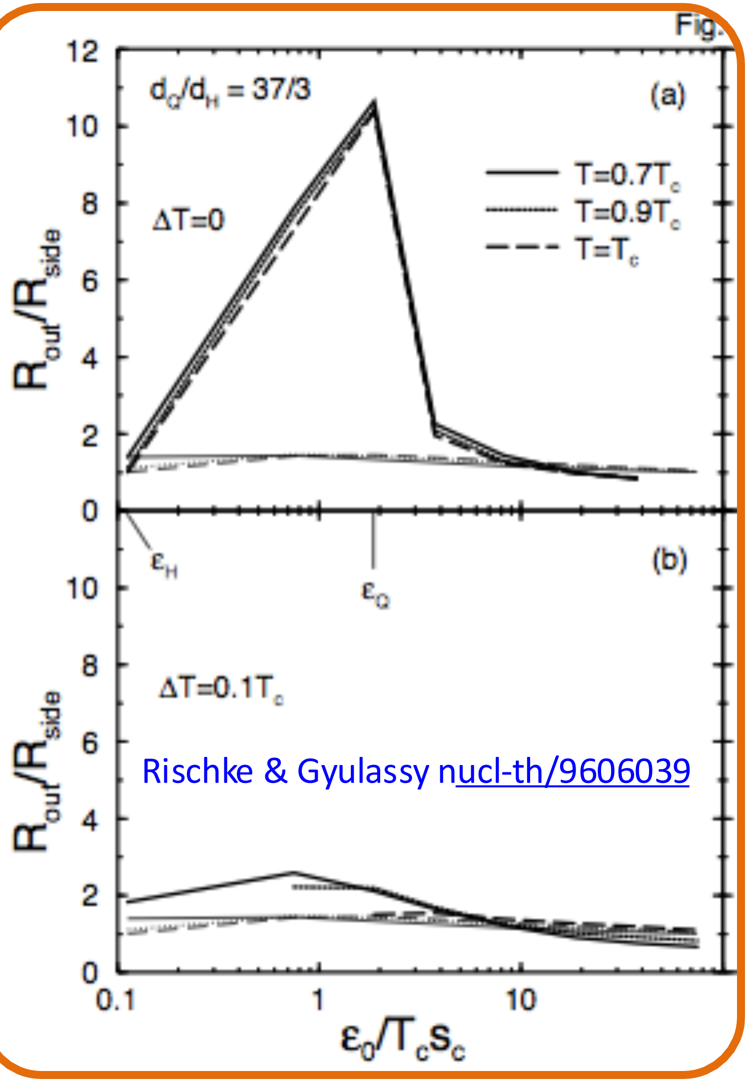
Probe for phase transition → vary conditions

RHIC Beam Energy Scan

A long emission duration results in $R_{out} > R_{side}$



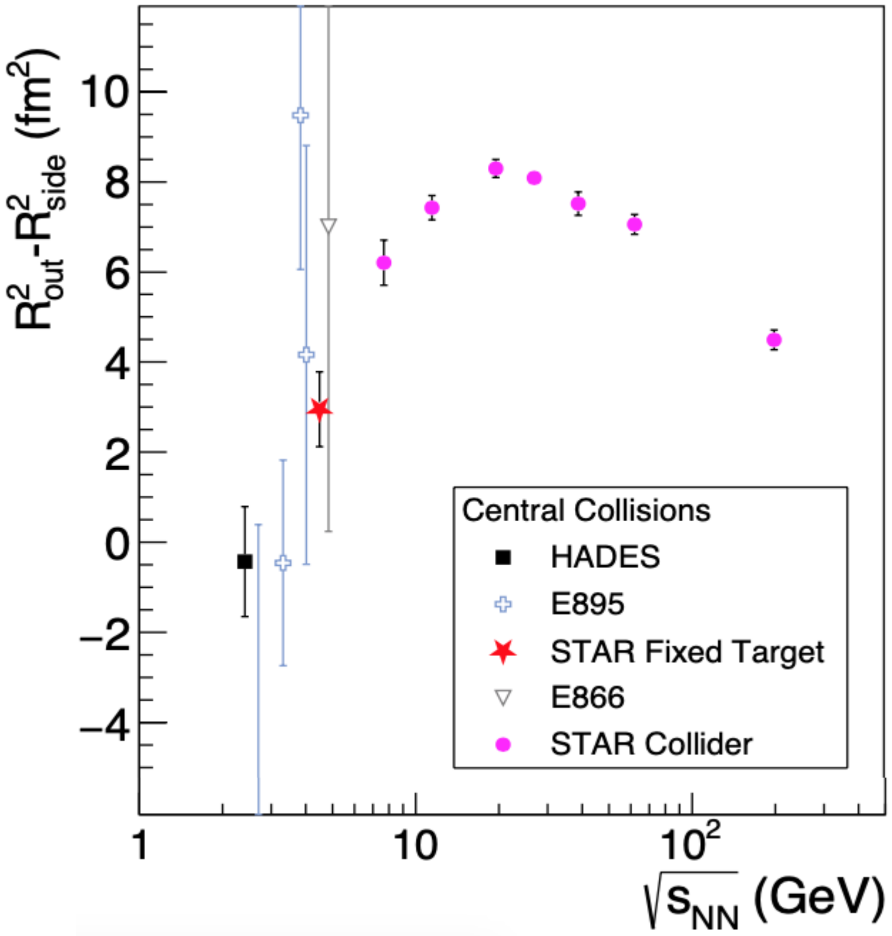
Early expectations at RHIC 200 GeV



Rischke & Gyulassy nucl-th/9606039

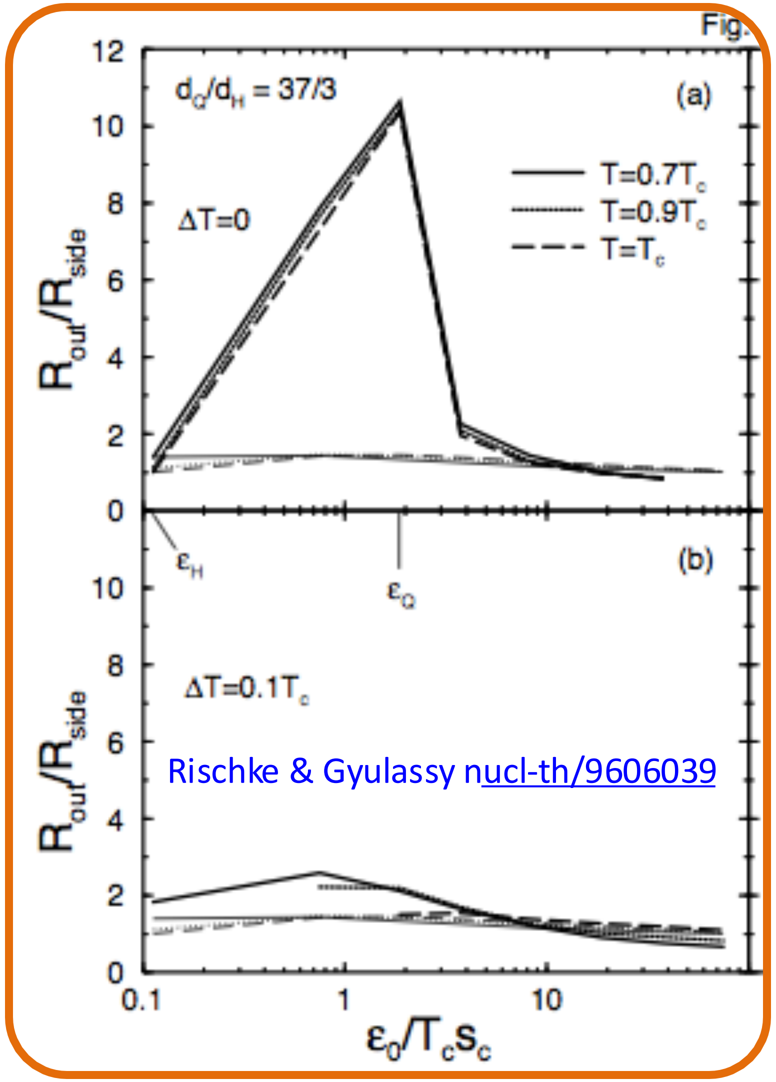
Phase transition? Order?

STAR Phys. Rev. C **103** (2021) 34908

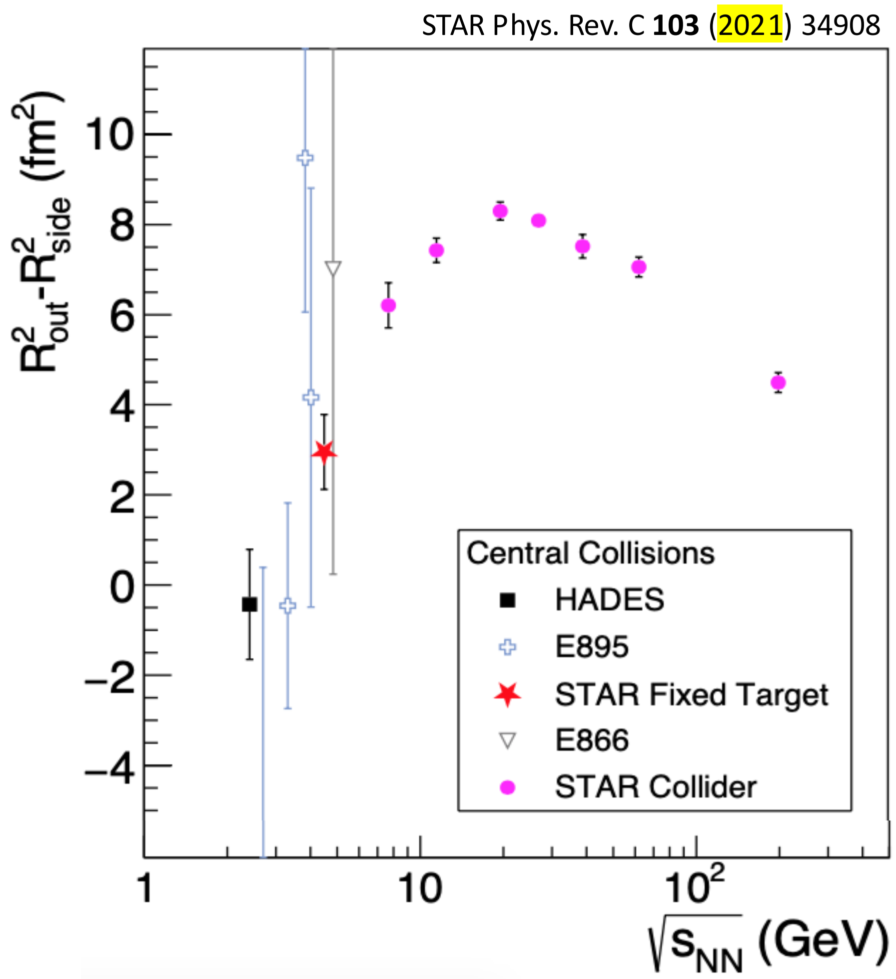


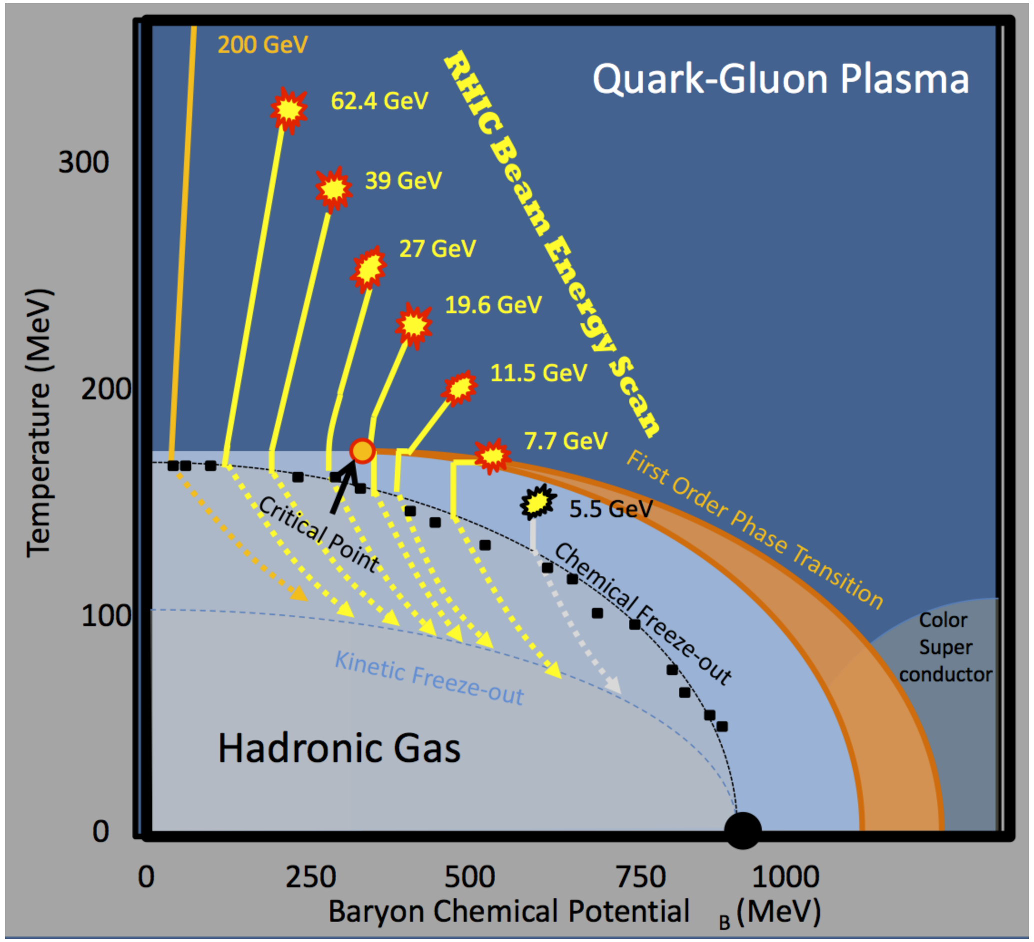
Multi-year program (BES) to vary the collision energy

Early expectations at RHIC 200 GeV



Phase transition? Order?





Evidence for

- cross-over at high energy (low chemical potential)
- first-order phase transition ~ 15 GeV

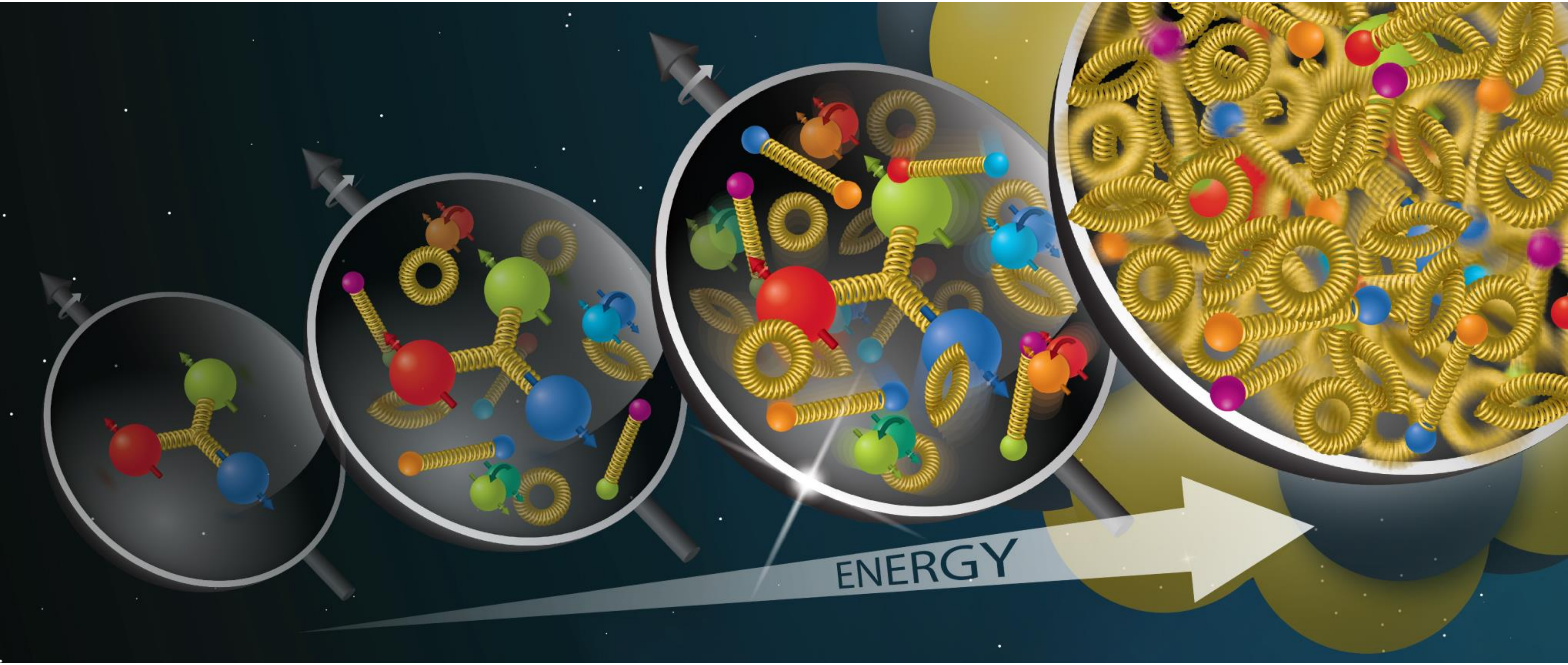
Summary

- Subatomic intensity interferometry (femtoscopy) deeply connected to HBT
  - Through Koonin-Pratt equation, sII has more probes than SII (”particle zoo” to correlate)
- Experimental access to spacetime features of relativistic heavy ion collisions is essential to understanding the quark-gluon plasma and QCD phase structure
- Active community of femtoscopists measuring
  - size, shape, orientation, emission duration, evolution time, flow substructure
- Cross-disciplinary discussion is interesting and can be fruitful!

Scales of SII and sII

SII – example: γ Cas	
$R \sim 10\, R_\odot \sim 10^{10}$ m	$2R/d \sim 4\times10^{-9}$ ~ milliarcsec
$d \sim 500$ ly $\sim 5\times10^{18}$ m	
$b \sim 100$ m	$\lambda/b \sim 4\times10^{-9}$ ~ milliarcsec
$\lambda \sim 4\times10^{-7}$ m	

sII (femtoscopy) – example Au+Au @ RHIC	
$R \sim 5$ fm $\sim 5\times10^{-15}$ m	$2R/d \sim 10^{-14}$ ~ 2 nanoarcsec
$d \sim 1$ m	
$b \sim 1$ m	$\lambda/b \sim 5\times10^{-16}$ ~ 0.1 nanoarcsec
$\lambda \sim hc/(400\text{ MeV}) \sim 5\times10^{-16}$ m	


ENERGY