Elliptic Flow at RHIC

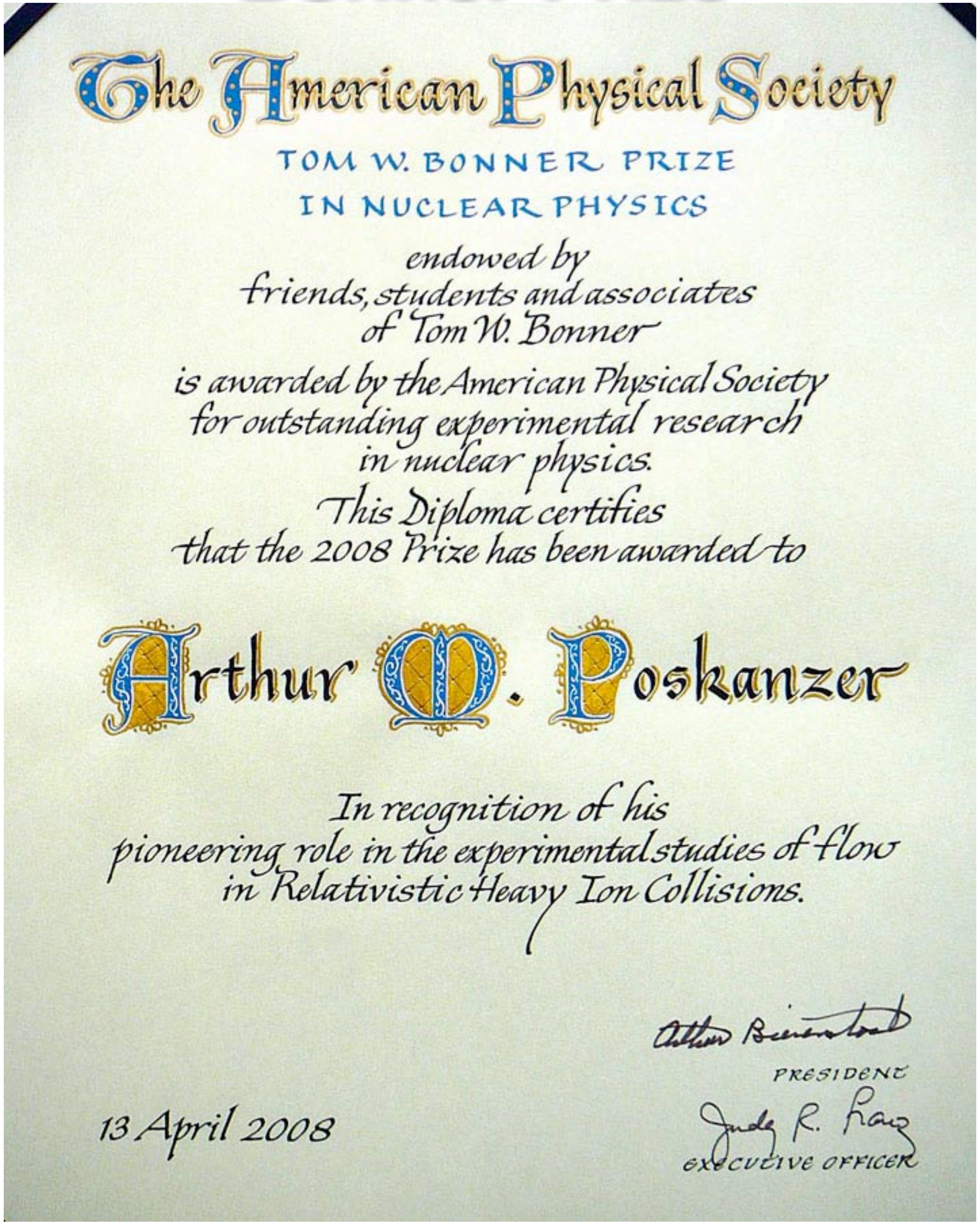
Color by Roberta Weir

Tom W. Bonner Prize
2008

Art Poskanzer

Lawrence Berkeley
National Laboratory

Bonner Prize



The American Physical Society

TOM W. BONNER PRIZE
IN NUCLEAR PHYSICS

endowed by
friends, students and associates
of Tom W. Bonner
is awarded by the American Physical Society
for outstanding experimental research
in nuclear physics.
This Diploma certifies
that the 2008 Prize has been awarded to

Arthur M. Poskanzer

In recognition of his
pioneering role in the experimental studies of flow
in Relativistic Heavy Ion Collisions.

Arthur Bienenstock
PRESIDENT

13 April 2008

Judy R. Franz
EXECUTIVE OFFICER

Many Thanks

- Sergei Voloshin
  - collaborated on most of the prize-winning work
- Hans-Georg Ritter
  - key person in discovery of collective flow
- Lucille Poskanzer
  - tremendous support and understanding

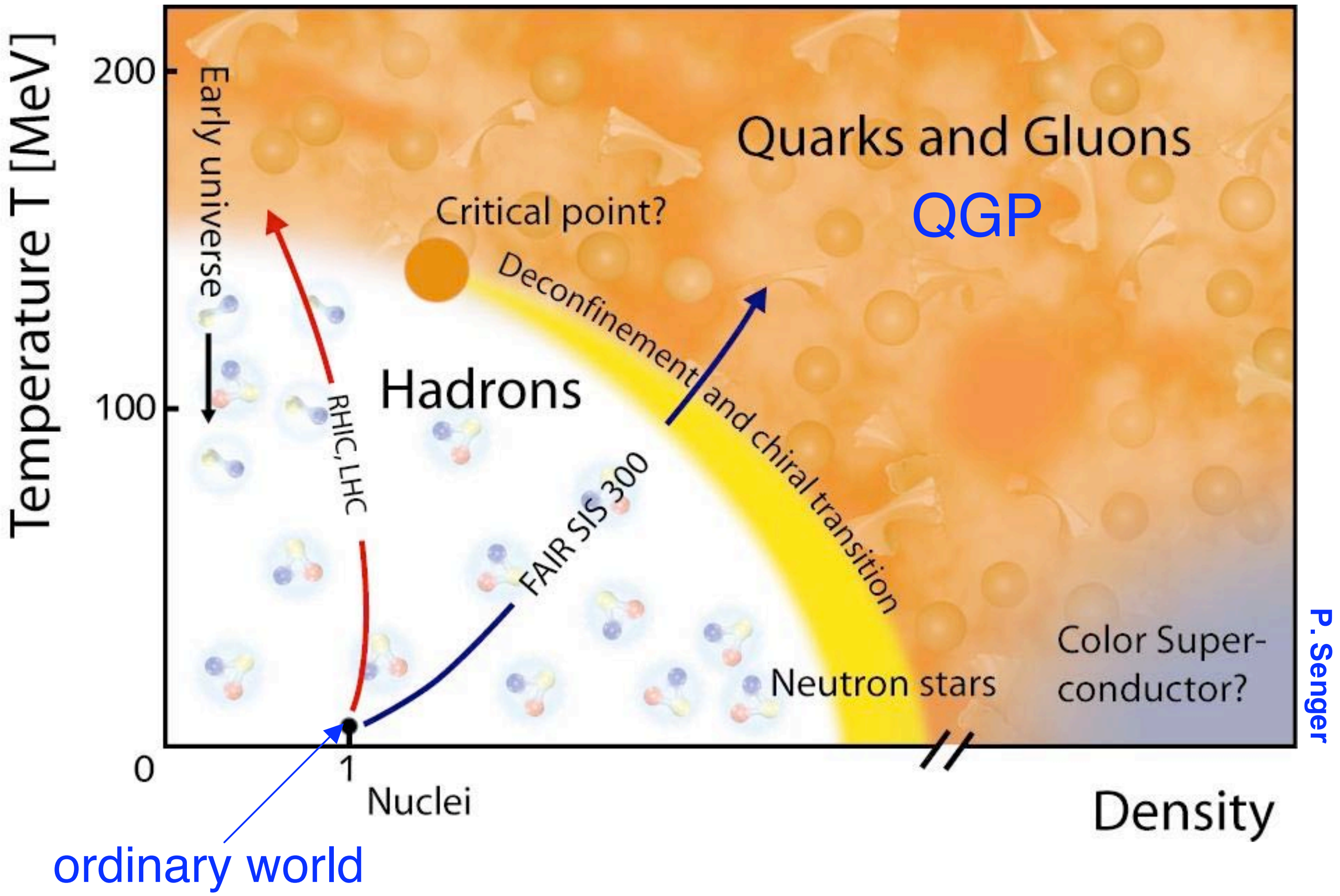
Sergei

Hans-Georg

Lucille

Importance

- **Physics of hot dense matter**
- **Evolution of the universe**



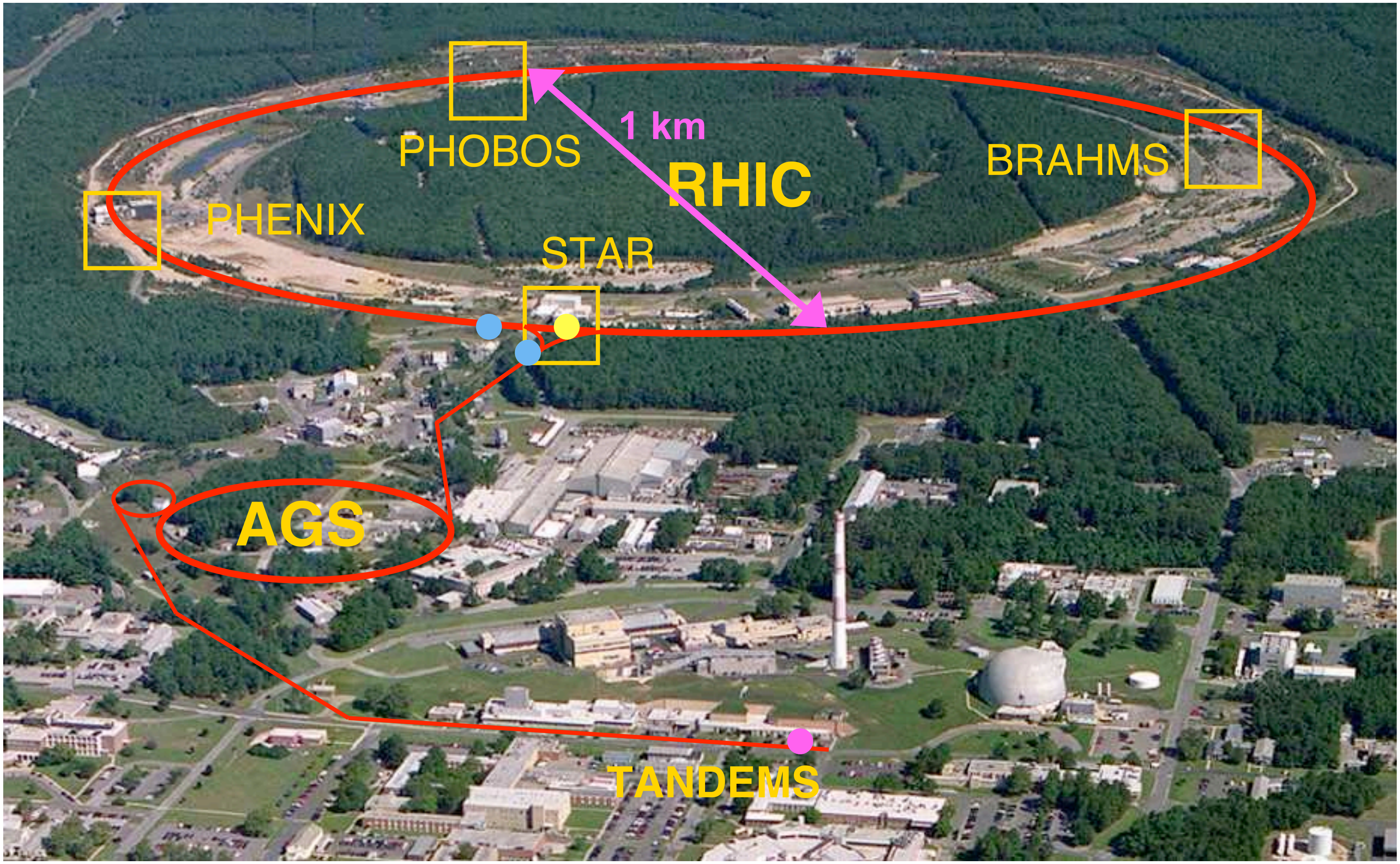
Quark-Gluon Plasma

- We want to study the QGP phase
  - deconfined quarks and gluons
  - interacting gas
  - equilibrated

↓

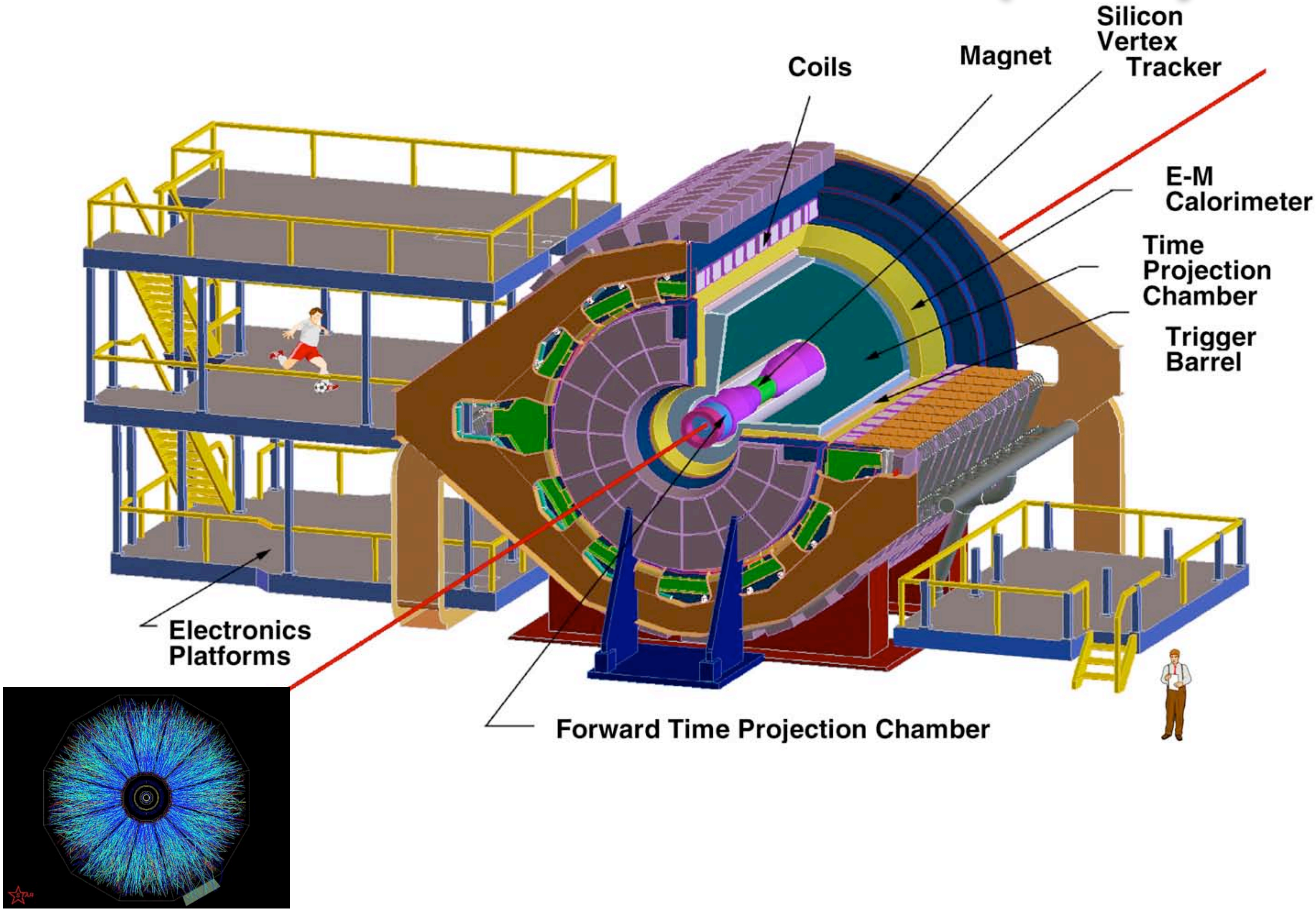
- We find it is a sQGP
  - strongly coupled perfect liquid

Relativistic Heavy Ion Collider (RHIC) at Brookhaven

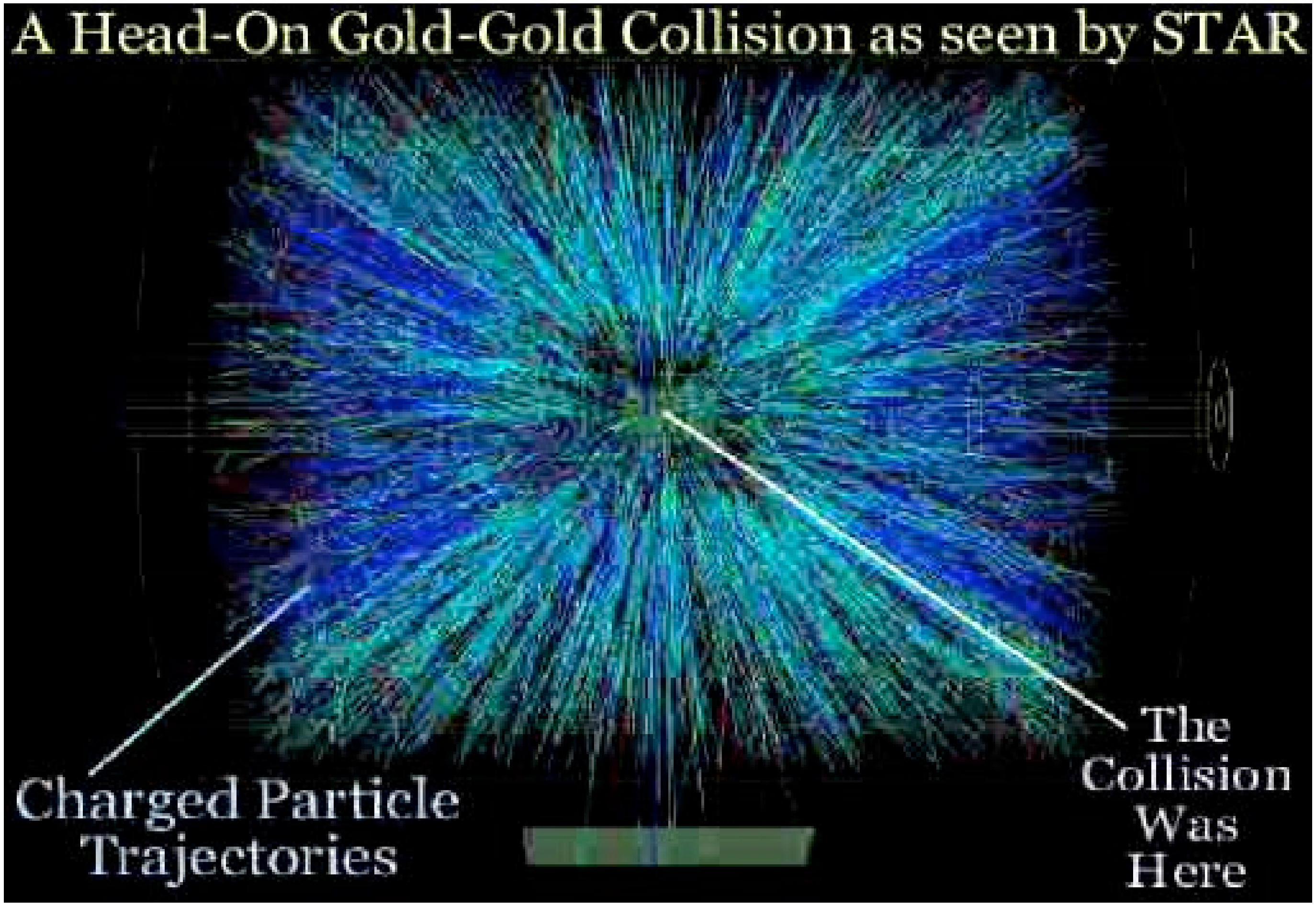


animation by Mike Lisa

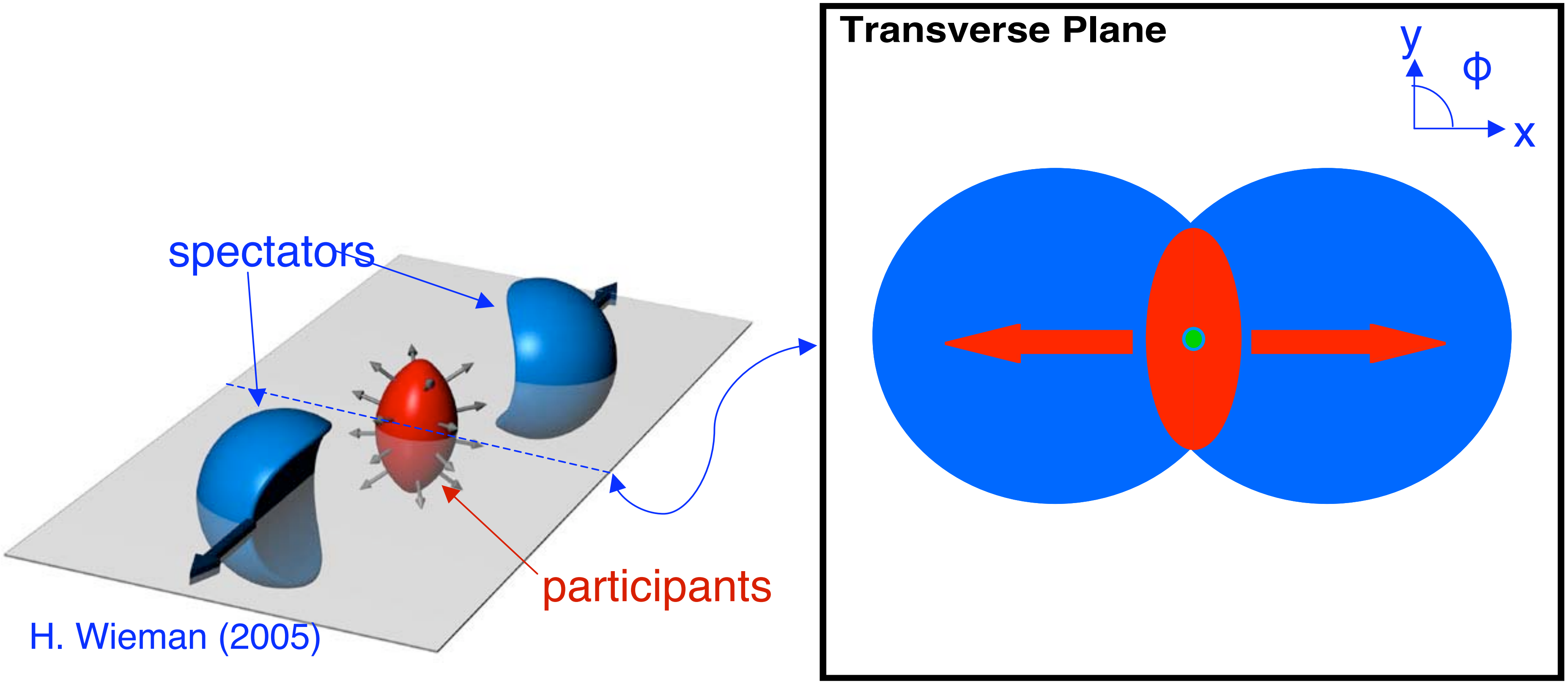
Solenoidal Tracker at RHIC (STAR)



STAR Detector



Hadronic Probe of Early Time



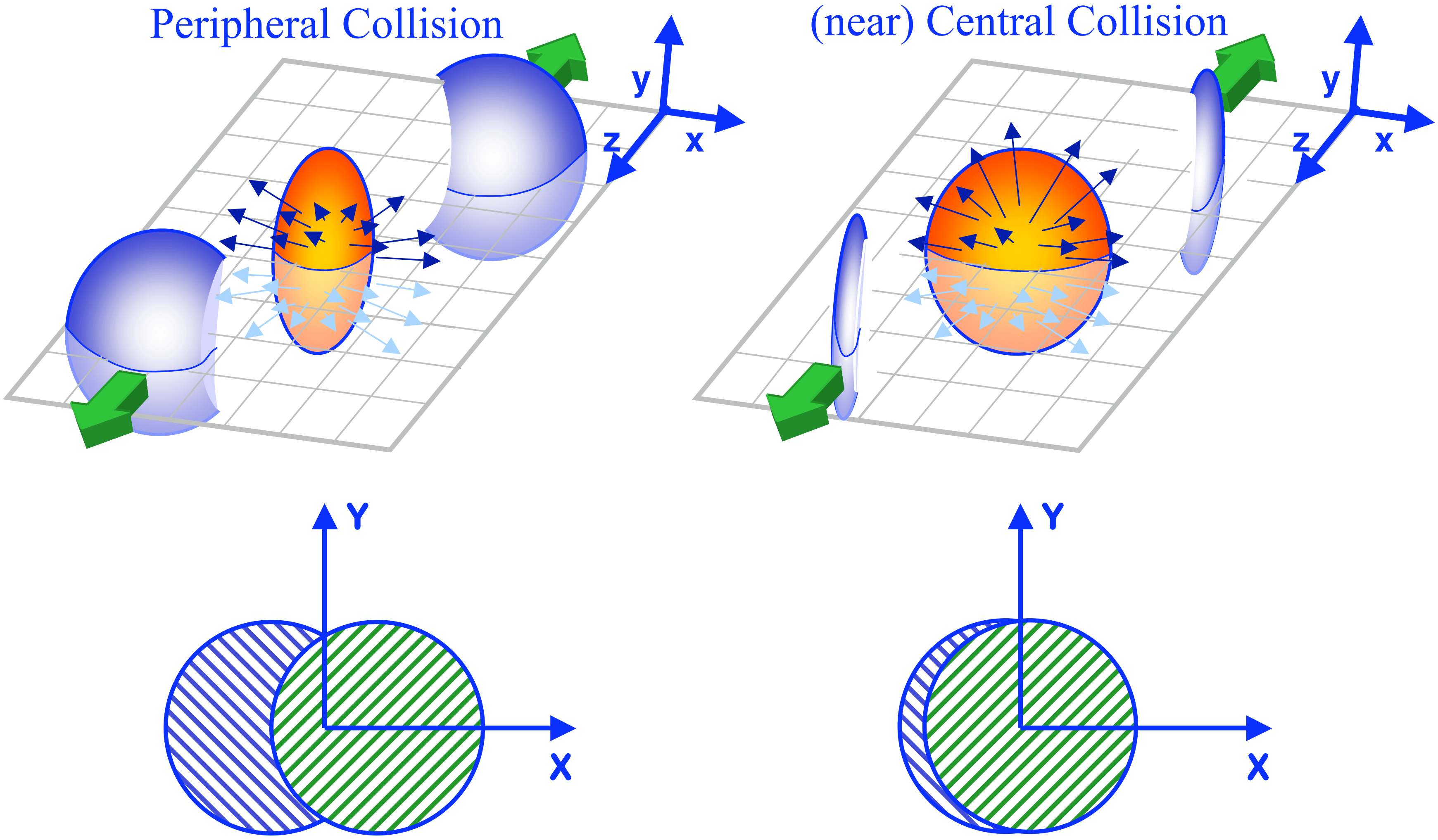
azimuthal angle around the beam axis

density gradient -> pressure for anisotropic expansion

It is self quenching

$$\epsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle} \qquad A : \pi \sqrt{\langle x^2\rangle \ \langle y^2\rangle}$$

Centrality Dependence

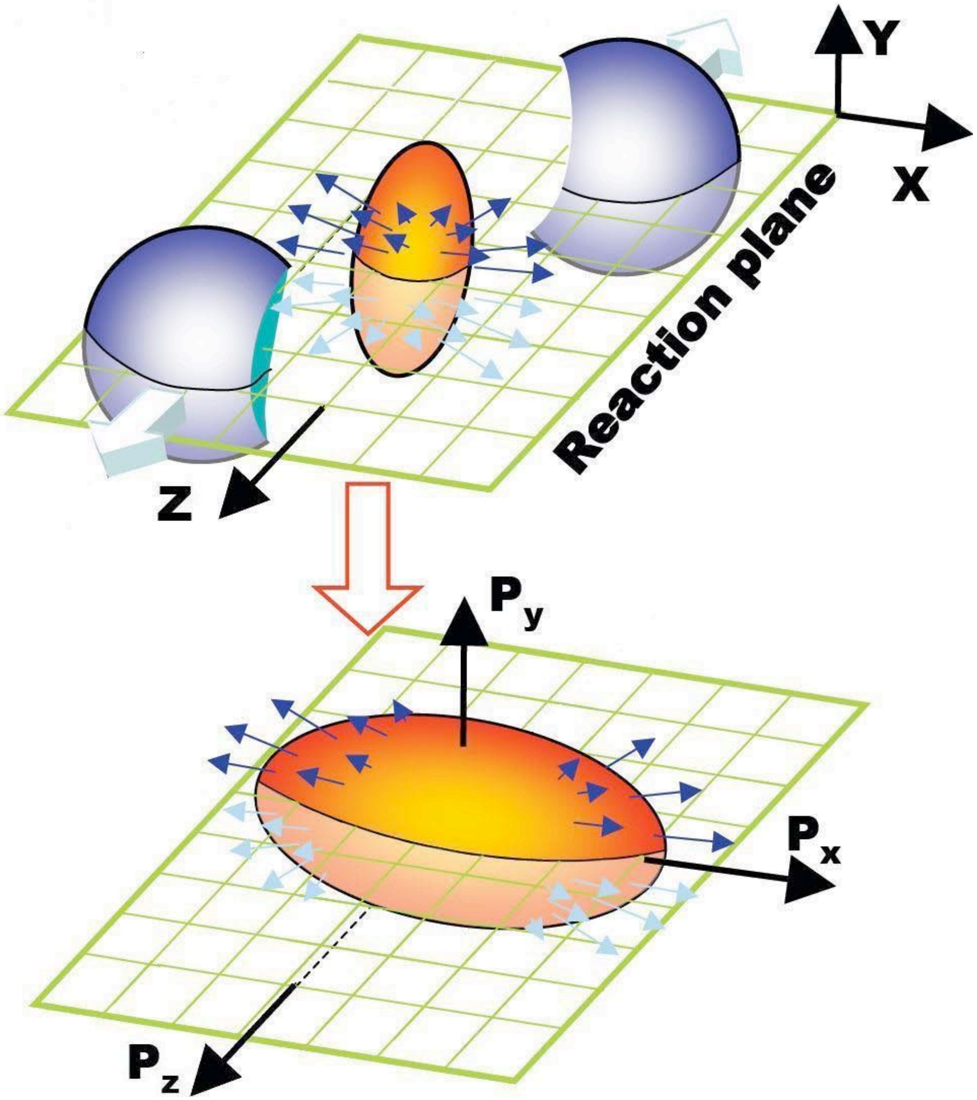


Peripheral Collision

(near) Central Collision

Centrality measured by the multiplicity of charged particles

Expansion In Plane



spatial anisotropy ε_2

↓ ↓

momentum anisotropy v_2

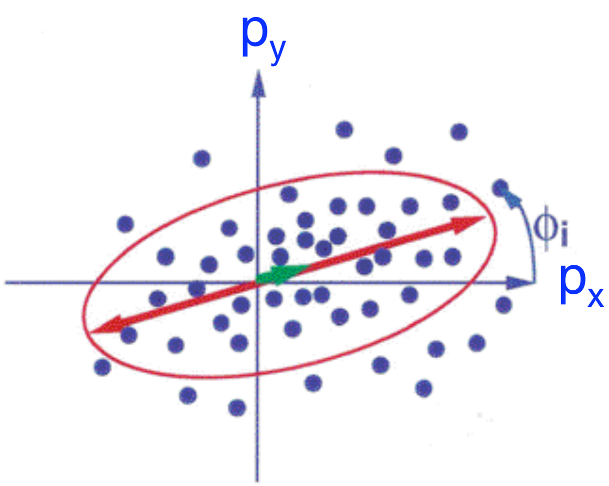
Elliptic Flow

Animation by Jeffery Mitchell

Flow Vector

Sum of vectors of all the particles

Transverse Plane



$$\Psi_{plane} = \tan^{-1}\frac{\Sigma \sin(\phi_i)}{\Sigma \cos(\phi_i)}$$

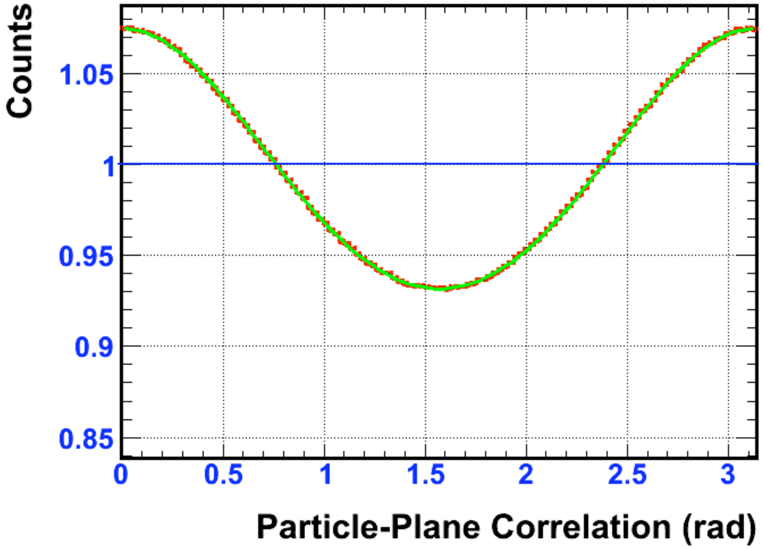
$$2\,\Psi_{ellipse} = \tan^{-1}\frac{\Sigma \sin(2\phi_i)}{\Sigma \cos(2\phi_i)}$$

For each harmonic n:

$$Q_n \cos(n\Psi_n) = \sum [w_i \cos(n\phi_i)]$$
$$Q_n \sin(n\Psi_n) = \sum [w_i \sin(n\phi_i)]$$

Q is a 2D vector
for odd harmonics $w_i(-y) = -w_i(y)$

azimuthal anisotropy:



S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996)

Fourier Harmonics

$$1 + 2\underset{\substack{\uparrow\\ \text{directed flow}}}{v_1}\cos(\phi - \Psi_{\mathrm{RP}}) + 2\underset{\substack{\uparrow\\ \text{elliptic flow}}}{v_2}\cos[2(\phi - \underset{\substack{\uparrow\\ \text{reaction plane}}}{\Psi_{\mathrm{RP}}})] + \cdots$$

$$v_n = \langle \cos[n(\phi_i - \Psi_{\mathrm{RP}})] \rangle$$

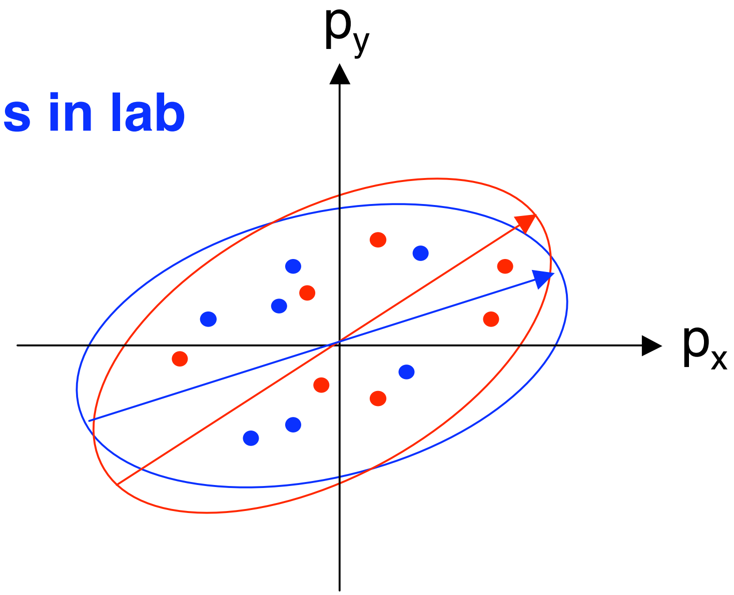
- angle of Q-vector, ψ_n, is experimental event plane angle
- ψ_{RP} is real reaction plane angle
- event plane resolution tells how well the event plane angle approximates the reaction plane angle:

$$\mathrm{res} \equiv \langle \cos(n(\Psi_n - \Psi_{\mathrm{RP}})) \rangle$$

S. Voloshin and Y. Zhang, hep-ph/940782; Z. Phys. C **70**, 665 (1996)
See also, J.-Y. Ollitrault, arXiv nucl-ex/9711003 (1997)
and J.-Y. Ollitrault, Nucl. Phys. **A590**, 561c (1995)

Standard Event Plane Method

- Define 2 independent groups of particles
- Flatten event plane azimuthal distributions in lab
  - to remove acceptance correlations
- Correlate subevent planes:



- Subevent plane resolution is the square root of this correlation
- Event plane resolution (res) is √2 times subevent plane resolution
- Correlate particles with the event plane to get v_n^{obs}
- Correct for the event plane resolution

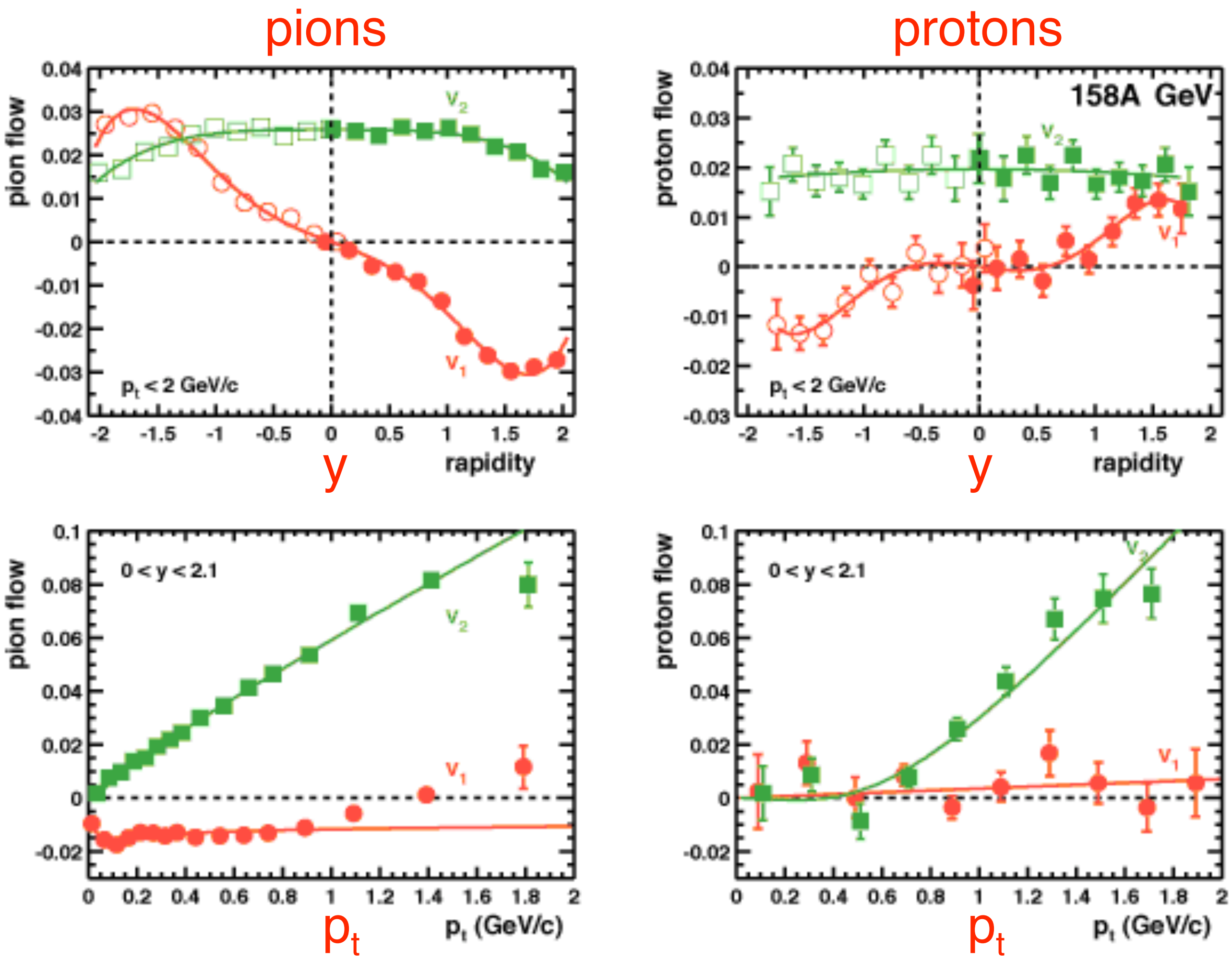
$$v_n(\eta, p_t) = v_n^{obs}/res$$

- Average differential $v_n(\eta,p_t)$ over η, p_t, or both (with yield weighting)

A.M. Poskanzer and S.A. Voloshin, PRC **58**, 1671 (1998)

Directed and Elliptic Flow at the SPS

y = relativistic velocity along beam direction
p_t = transverse momentum

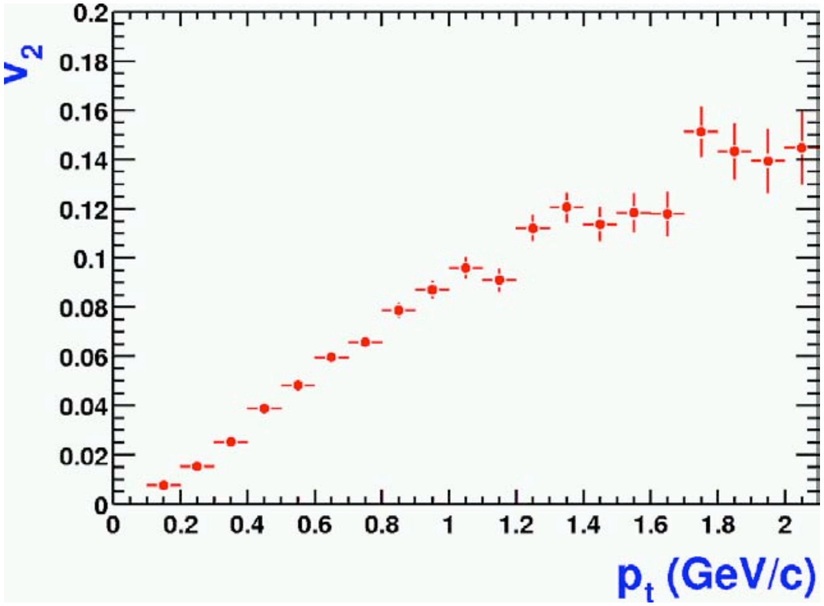


pions

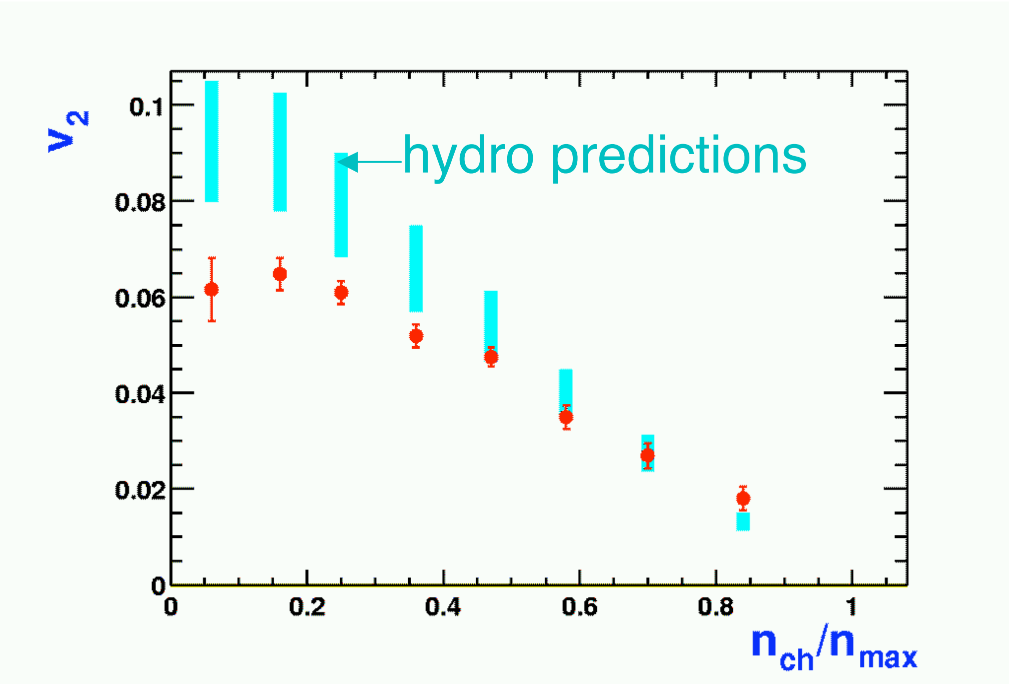
protons

NA49, C. Alt et al., PRC **68**, 034903 (2003)

Discovery of Elliptic Flow at RHIC



First paper from STAR
22 k events



peripheral ⟶ central

Dramatic effect:

peak / valley = $(1 + 2\ v_2) / (1 - 2\ v_2)$
= 1.8

Significant that data approach hydro for central collisions
Was not true at lower beam energies

STAR, K.H. Ackermann et al., PRL **86**, 402 (2001)

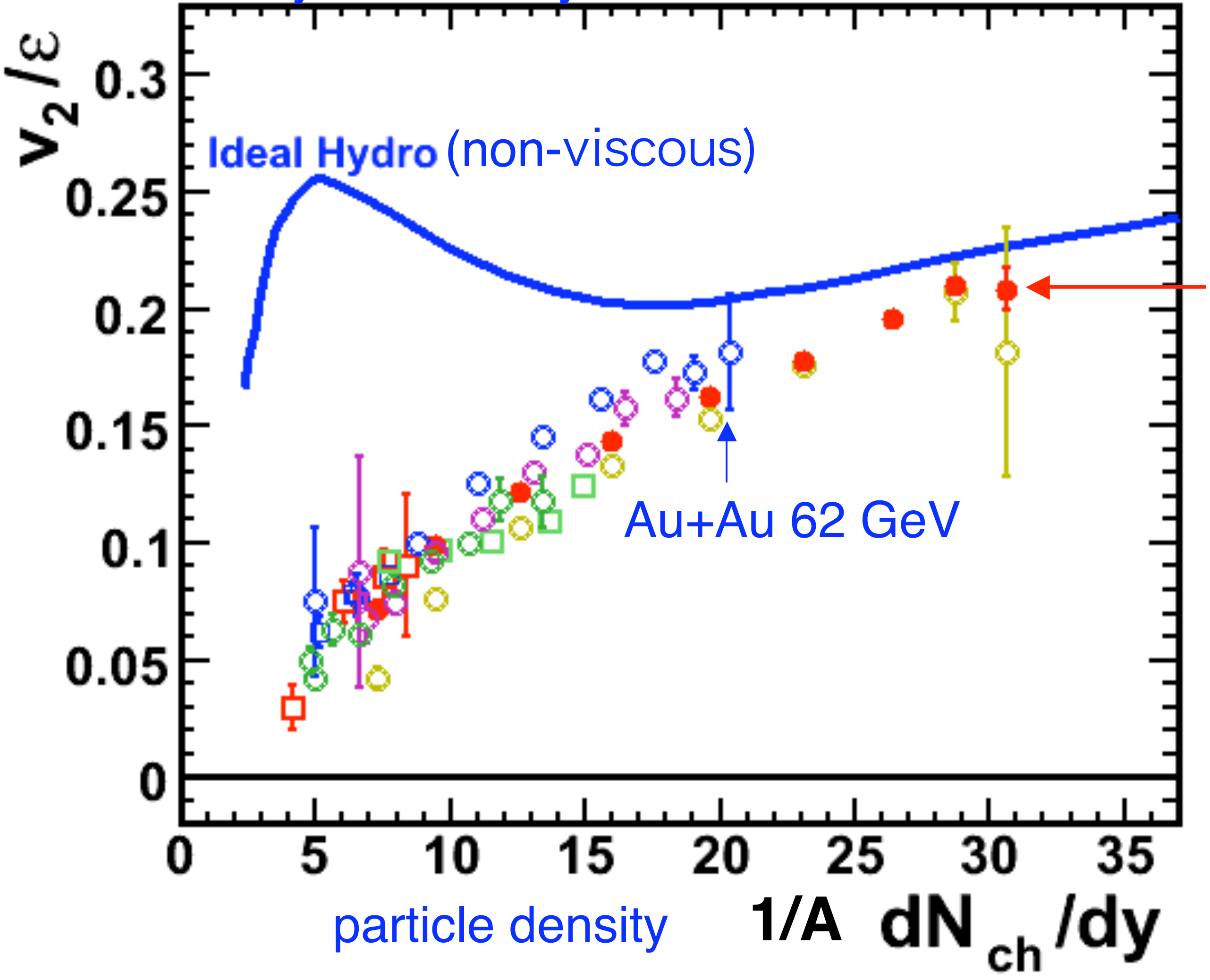
Ideal Hydrodynamics

- Needs initial conditions and Equation of State
    - Fitted to spectra from central collisions
- Then deterministic
- Uses relativistic kinematics
- Assumes early local equilibration and strong coupling
- Gives maximum effect for elliptic flow

Kolb and Heinz, arXiv:nucl-th/0305084
Huovinen and Ruuskanen, ARNPS **56**, 1056 (2006)
Ollitrault, arXiv:0708.2433

Approach to Hydro

flow scaled by eccentricity



(non-viscous)

Au+Au 200 GeV

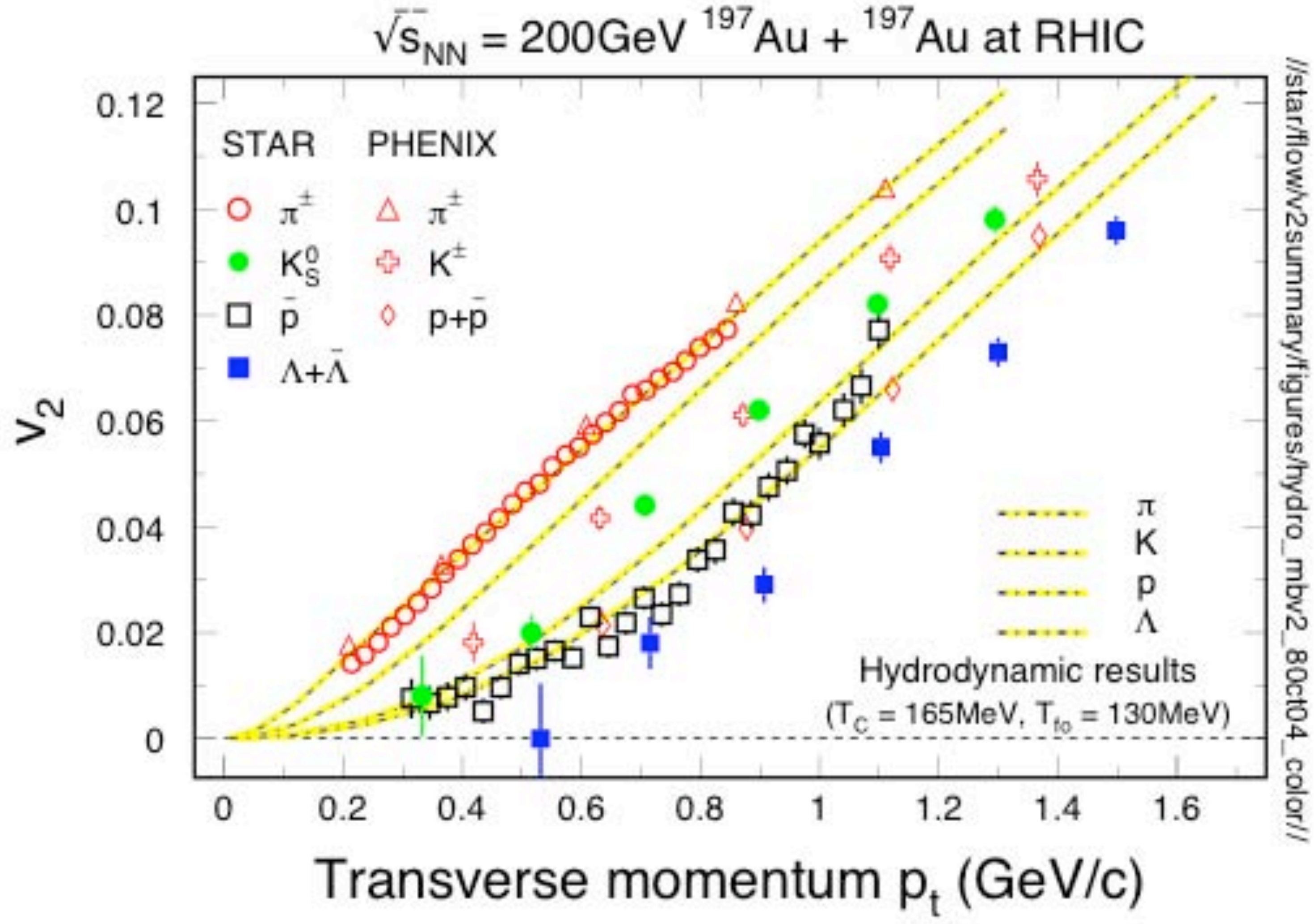
Au+Au 62 GeV

particle density

For hydro, need early equilibration and strong coupling

Sergei Voloshin, QM06, S883 (2007)
Hydro: Kolb, Sollfrank, and Heinz PRC **62**, 0544909 (2000)

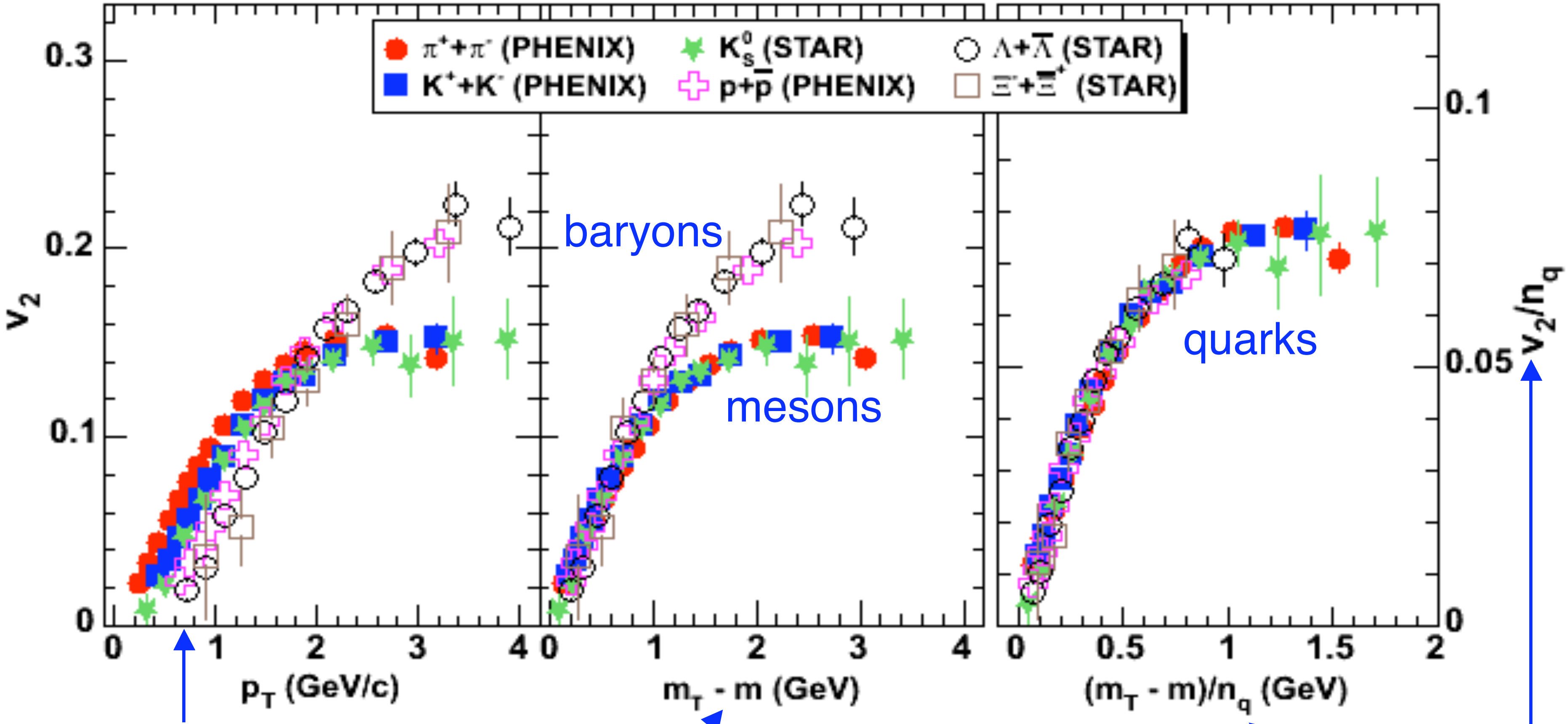
Particle Mass Dependence



Described by ideal hydro

STAR, J. Phys. G. **31,** S437, (2005)
Huovinen, private communication

Scaling with Number of Quarks



particle mass
dependence

plotted vs.
trans. kinetic energy

both axes scaled by number
of constituent quarks

n_q = 2 for mesons
n_q = 3 for baryons

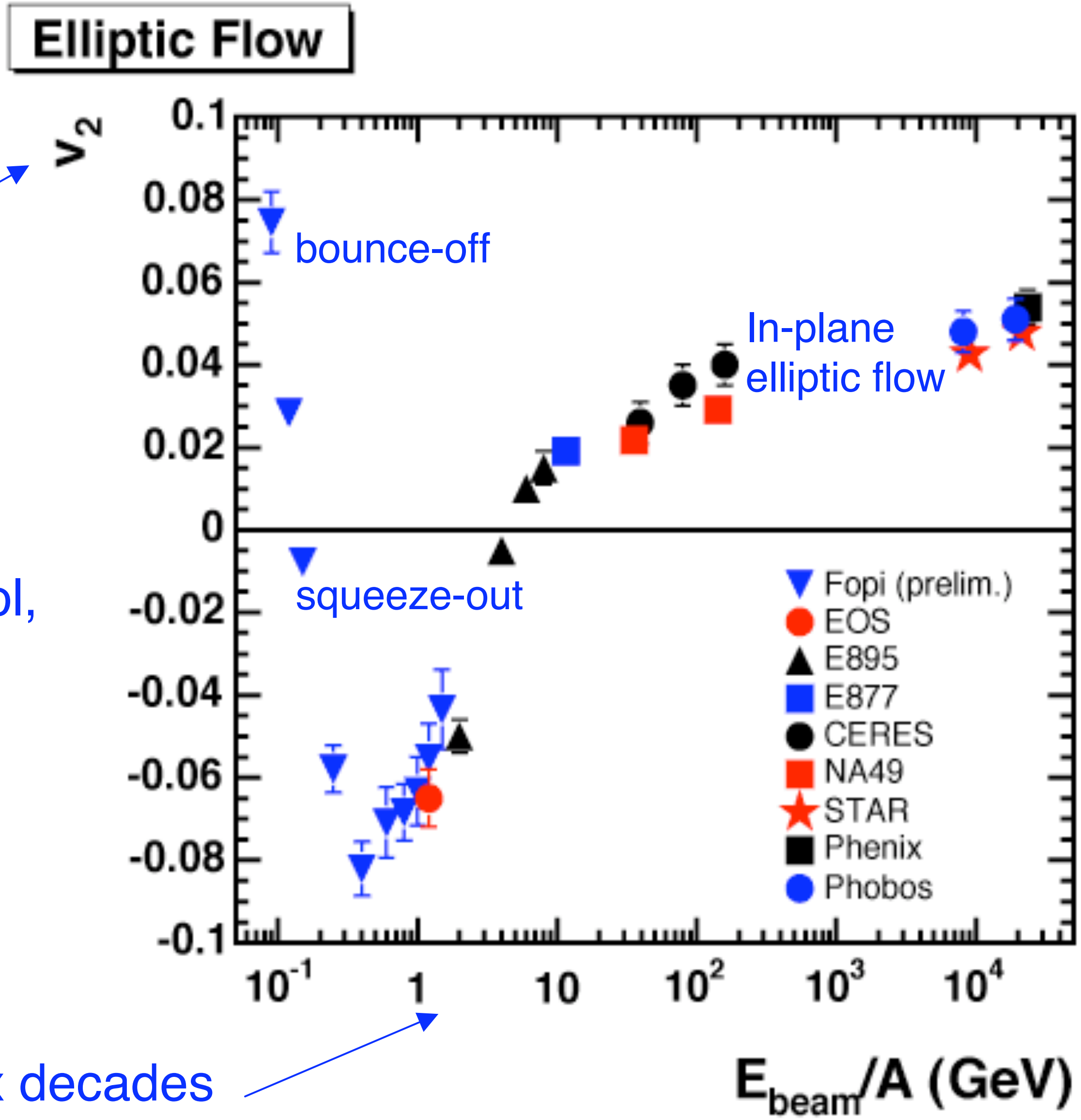
recombination of quarks
quarks have v_2 before hadronization

S. Voloshin, QM02, 379c (2003)
STAR, PRL **95**, 122301 (2005)   PHENIX, PRL **98**, 162301 (2007)

Elliptic Flow vs. Beam Energy

25% most central
mid-rapidity

all $v_2\{EP\}$



bounce-off

In-plane
elliptic flow

squeeze-out

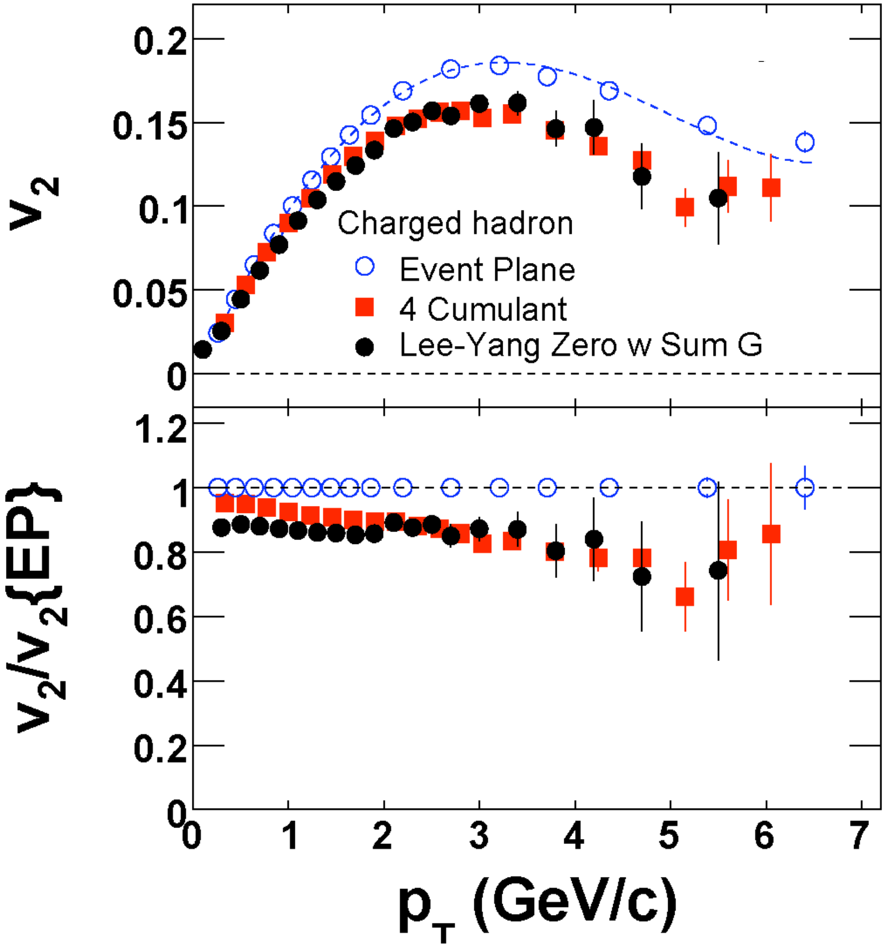
powerful, widely-used tool,
to study EOS of
nuclear matter

six decades

A. Wetzler (2005)

Non-Flow Effects

Non-flow effects are correlations not associated with the reaction plane.
(They include resonance decays, 2-particle small angle correlations, and jets of particles.)



Non-flow effects are caused by few-particle correlations

Multi-particle methods remove non-flow.

STAR, B.I. Abelev et al., arXiv:0801.3466; PRC, submitted (2008)

Shear Viscosity

$$\frac{\text{shear viscosity}}{\text{entropy density}} \qquad \frac{\eta}{S} \geq \frac{1}{4\pi}$$

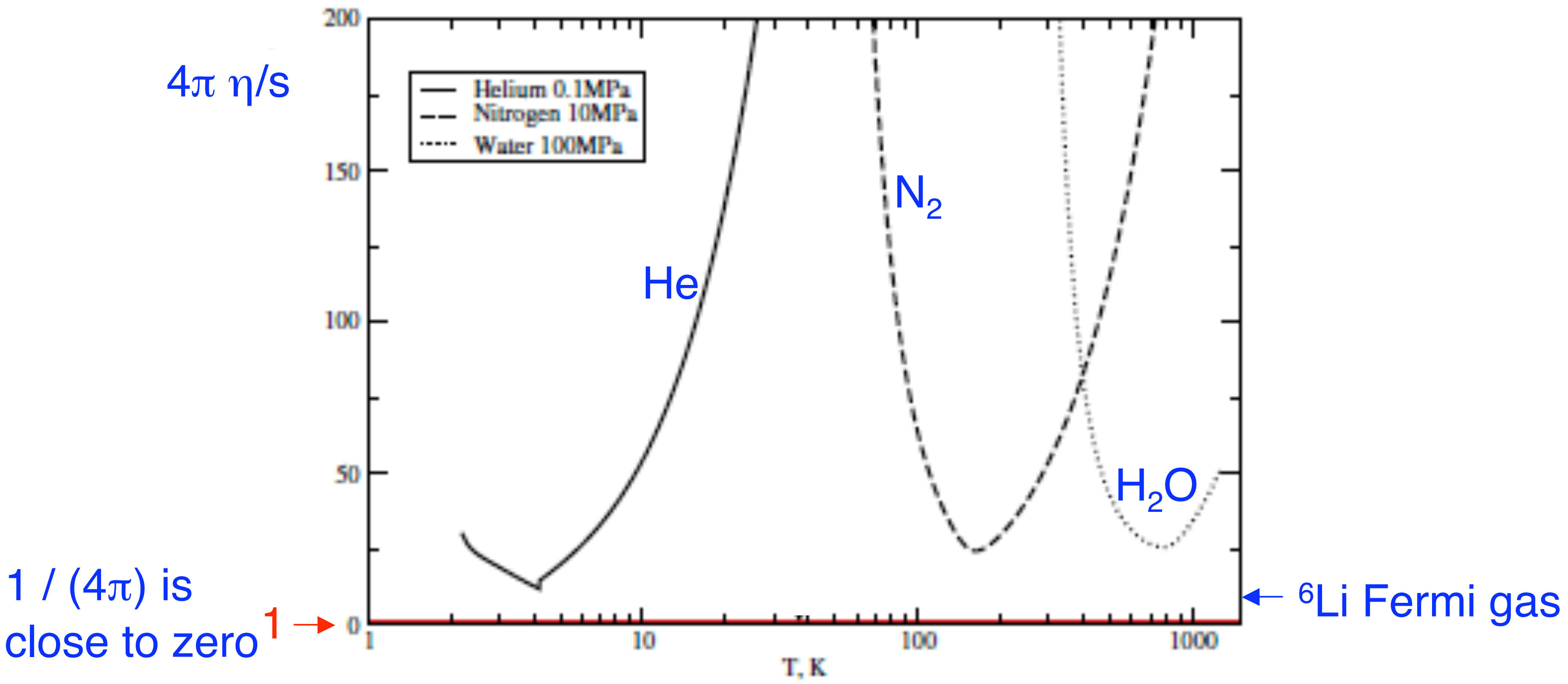
Conjecture was derived from string theory but has simple interpretation based on the uncertainty principle:

Mean free path must be bigger than De Broglie wavelength. Larry McLerran

Small shear viscosity means
small mean free path, which means
strongly coupled

Danielewicz and Gyulassy, PRD **31**, 53 (1985)

Perfect Fluid



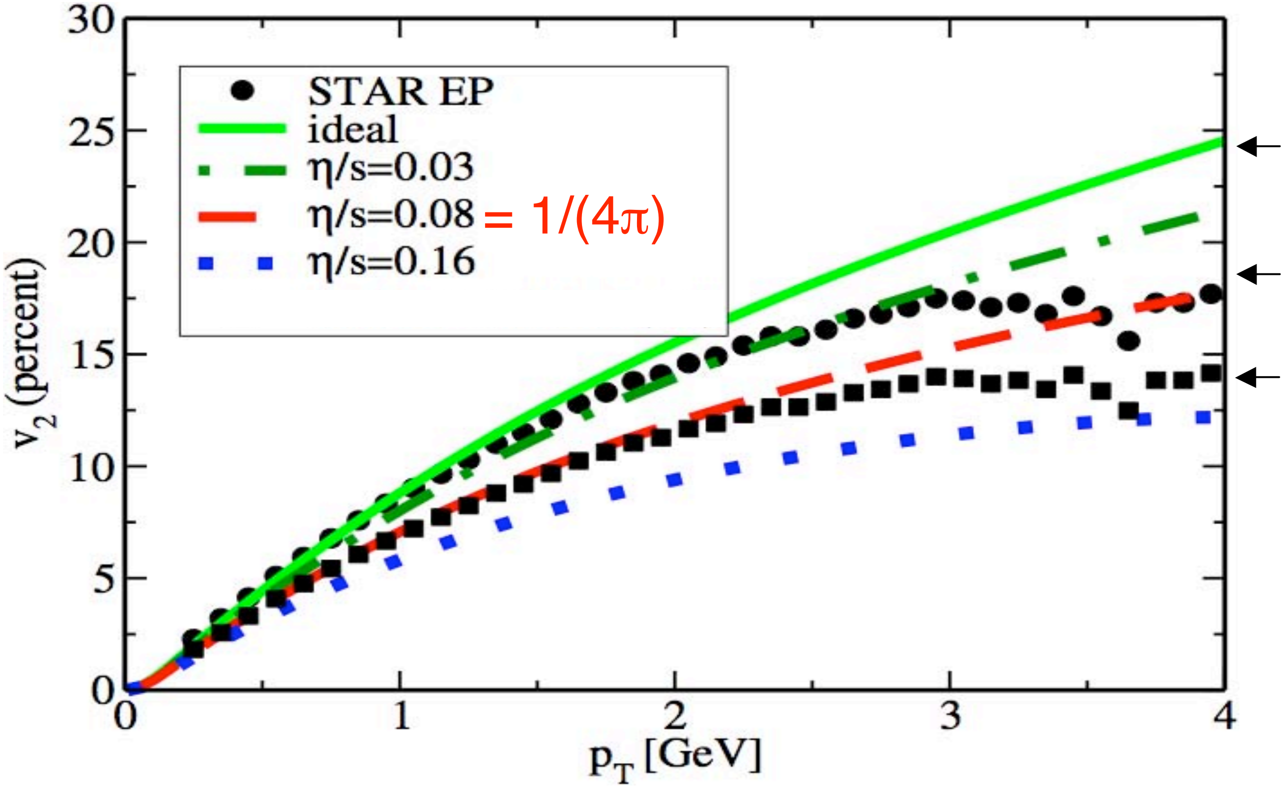
$1\ /\ (4\pi)$ is close to zero 1 →

← ^{6}Li Fermi gas

Perfect fluids have no shear stresses, viscosity, or heat conduction.

Turlapov et al., J. Low Temp Physics **150**, 567 (2008)
Kovtun, Son, and Starinets, PRL **94**, 111601 (2005)

Viscous Hydrodynamics



= 1/(4π)

← non-viscous

← STAR data

← estimated removal of non-flow

Data: removing non-flow lowers v_2

Hydro: viscosity lowers v_2

Both data and hydro need more work on these effects

- But approximately at the uncertainty principle value
- Thus η/s is at least 5 times smaller than any other known substance

Romatschke², PRL **99**, 172301 (2007)
STAR, B.I. Abelev et al., arXiv:0801.3466; PRC, submitted (2008)

Conclusions

- Early Equilibration
    - because elliptic flow approaches ideal hydro
- Partonic when flow develops
    - suggested by number-of-quark scaling
- Strongly Coupled Liquid
    - because of qualitative success of ideal hydrodynamics
- Nearly Perfect
    - because of probable low shear viscosity

- Therefore: a Perfect Liquid
    - sQGP, strongly coupled quark-gluon plasma

- What will happen at the Large Hadron Collider?
    - 15 x higher energy