COMSATS Institute
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Flow in Quark Gluon Plasma

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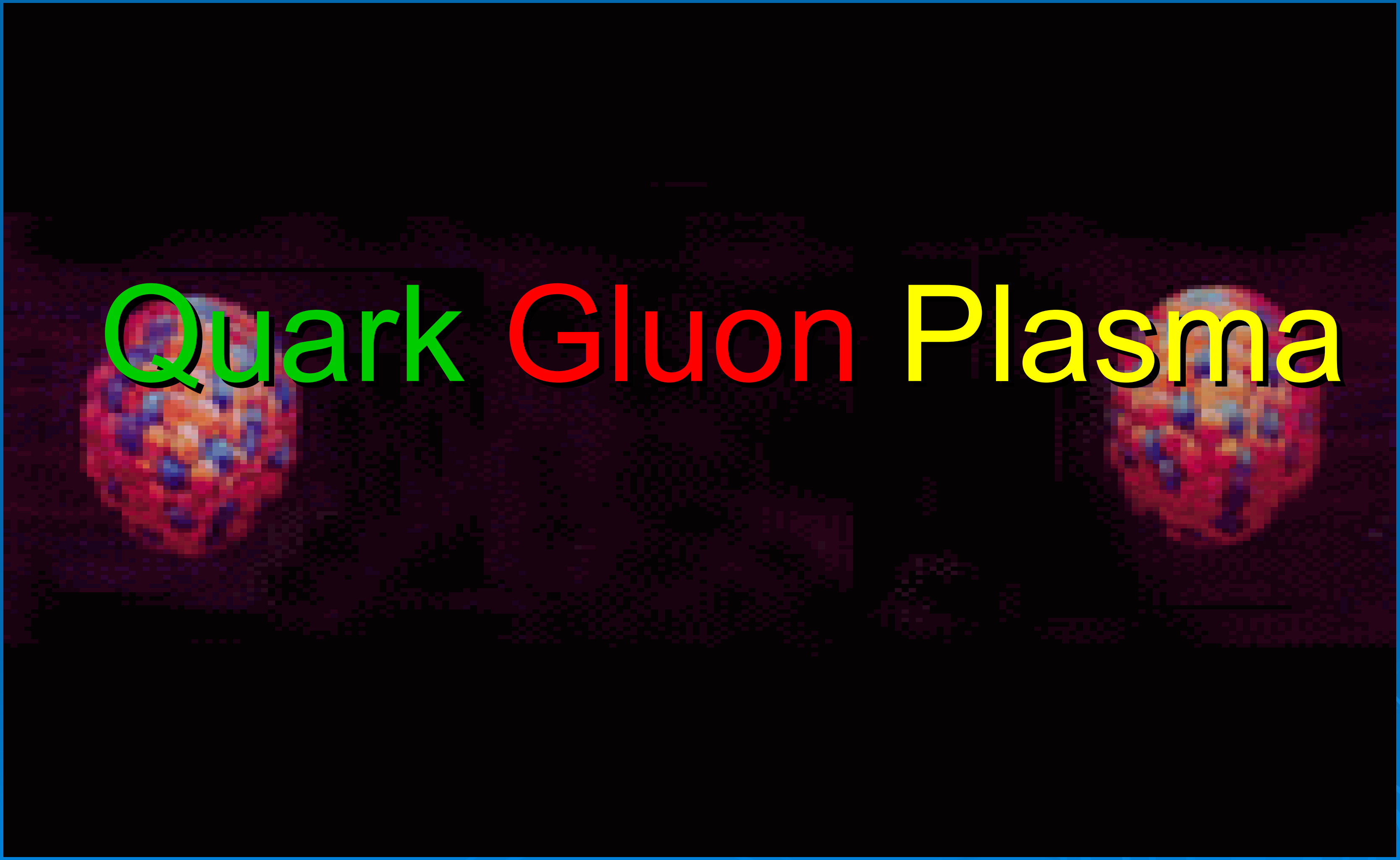
Ultra Relativistic Heavy Ion Collisions



Quark Gluon Plasma

Where WAS the QGP?

History of the Universe

⇕

History of the matter

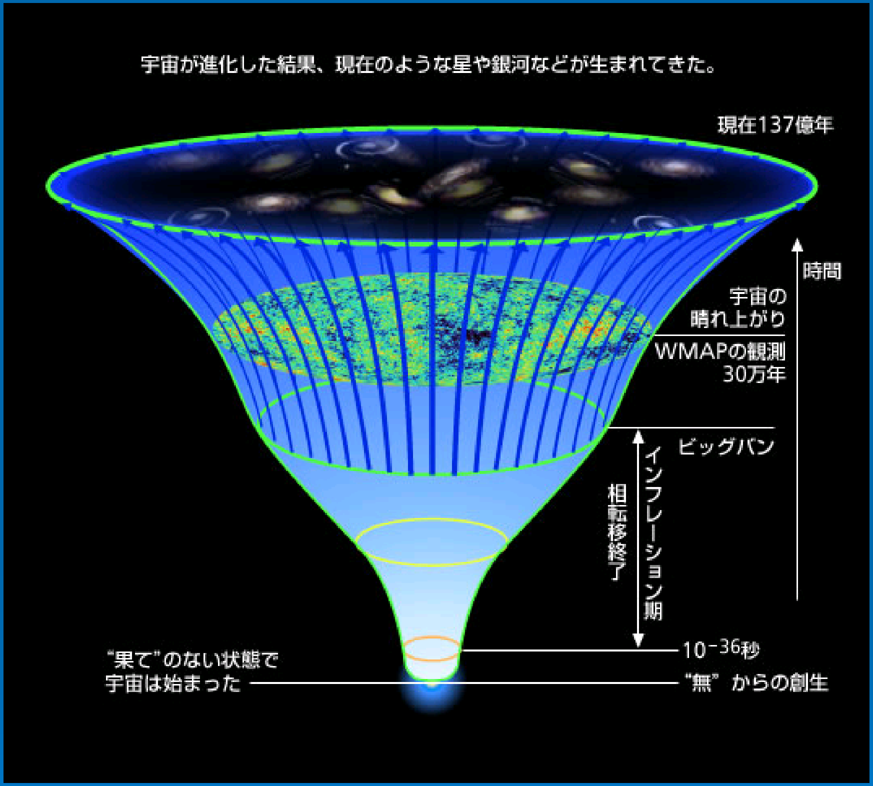
Nucleosynthesis

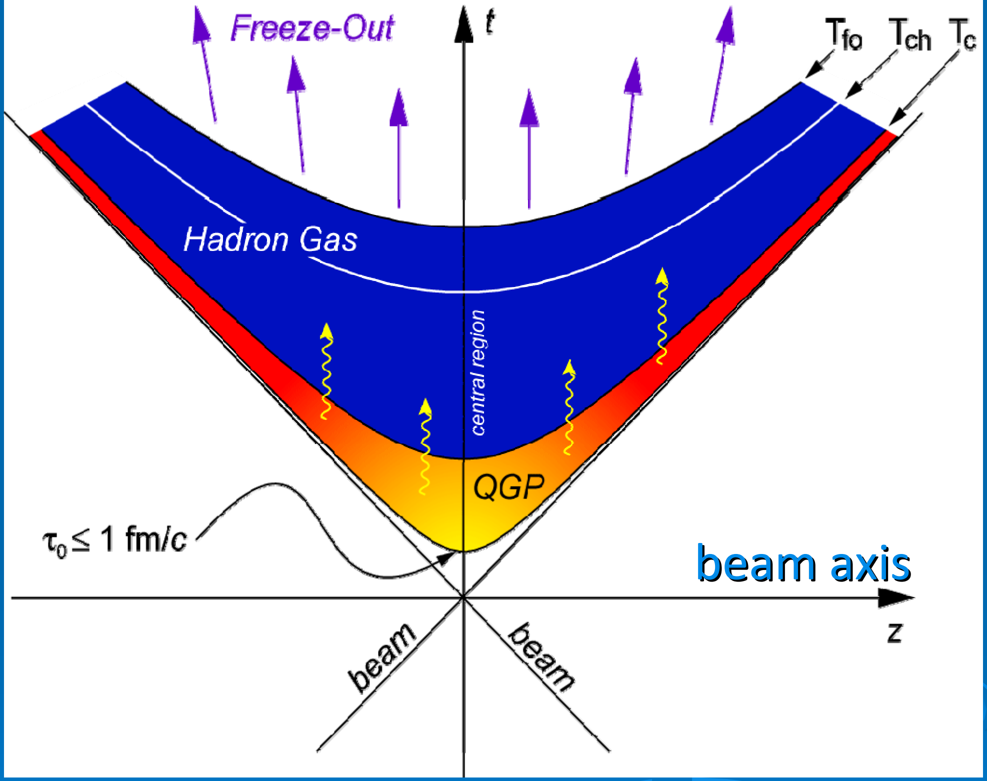
Hadronization

Quark Gluon Plasma

(after micro seconds of Big Bang)

Big Bang vs. Little Bang



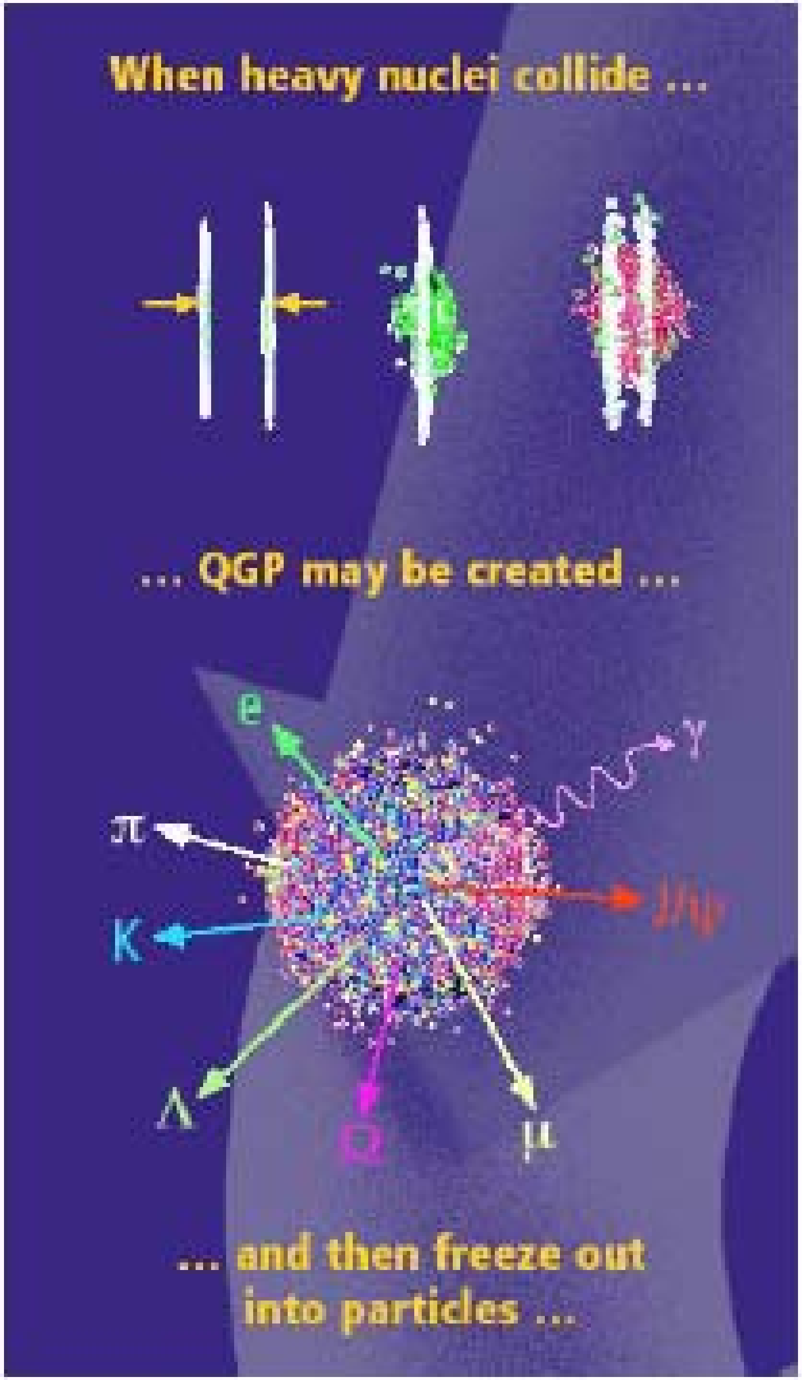


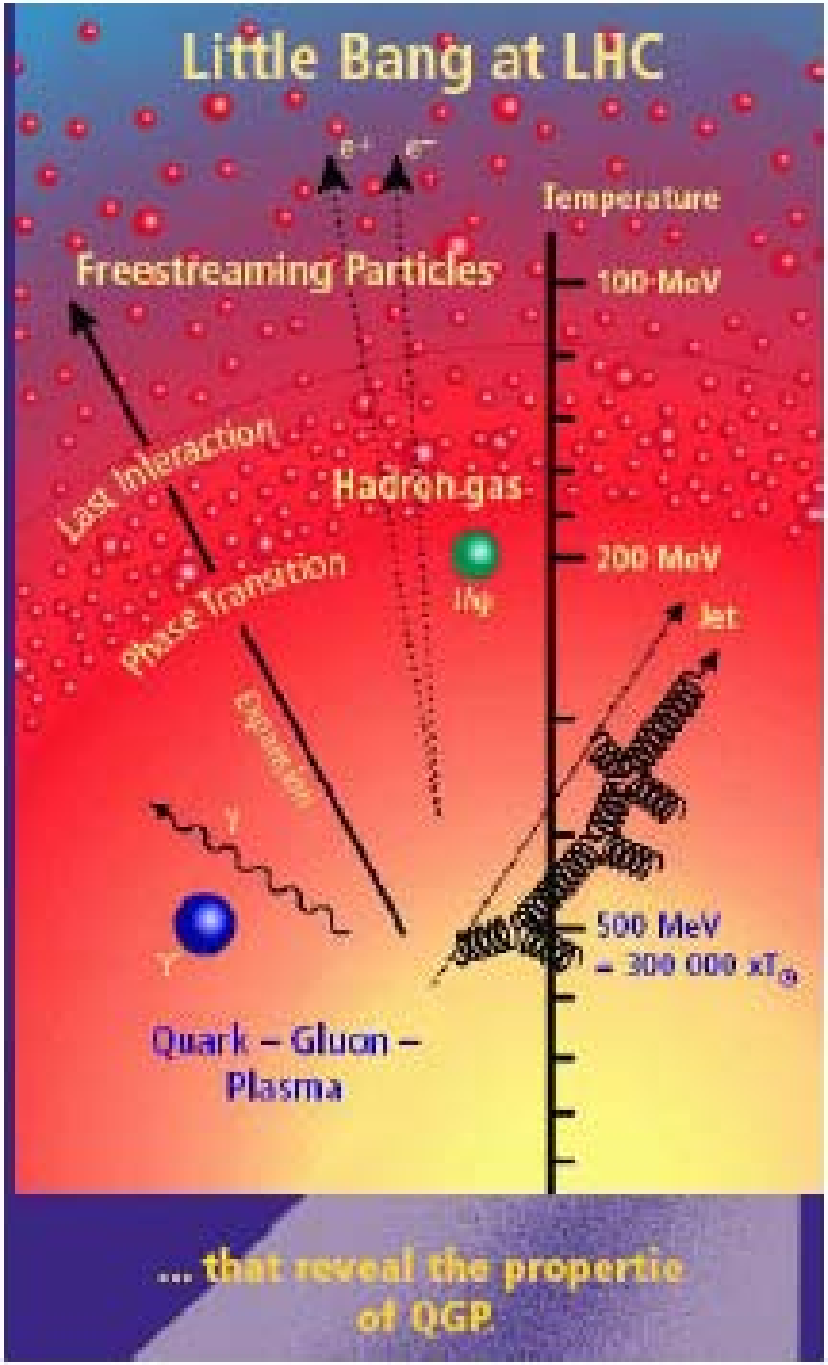
3D Hubble expansion

Nearly 1D Hubble expansion*
+ 2D transverse expansion

Figure adopted from
http://www-utap.phys.s.u-tokyo.ac.jp/~sato/index-j.htm

*Bjorken('83)


When heavy nuclei collide ...
... QGP may be created ...
e
γ
π
J/ψ
K
Λ
Ω
μ
... and then freeze out into particles ...


Little Bang at LHC
e+
e−
Temperature
Freestreaming Particles
100 MeV
Last Interaction
Hadron gas
200 MeV
Phase Transition
J/ψ
Jet
Expansion
γ
ϒ
500 MeV
= 300 000 x T☉
Quark – Gluon – Plasma
... that reveal the propertie of QGP

Quark-Gluon Plasma

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

↓

- Find it is a sQGP
  - strongly coupled perfect liquid

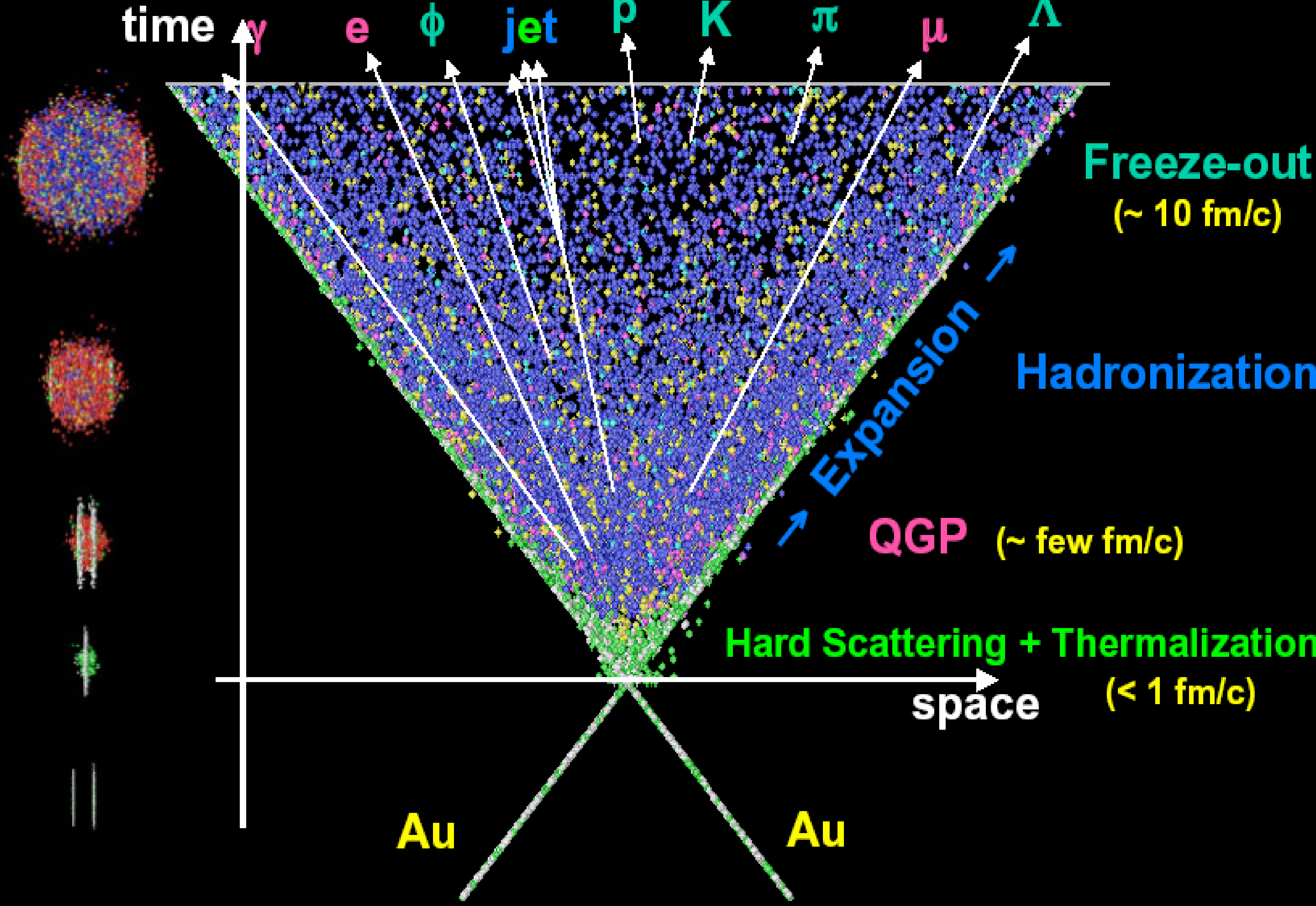
SCIENTIFIC
AMERICAN

MAY 2006
WWW.SCIAM.COM

Quark Soup

PHYSICISTS RE-CREATE
THE LIQUID STUFF OF
**THE EARLIEST
UNIVERSE**

Space-time Evolution of RHIC Collisions



Freeze-out
(~ 10 fm/c)

Hadronization

QGP (~ few fm/c)

Hard Scattering + Thermalization
(< 1 fm/c)

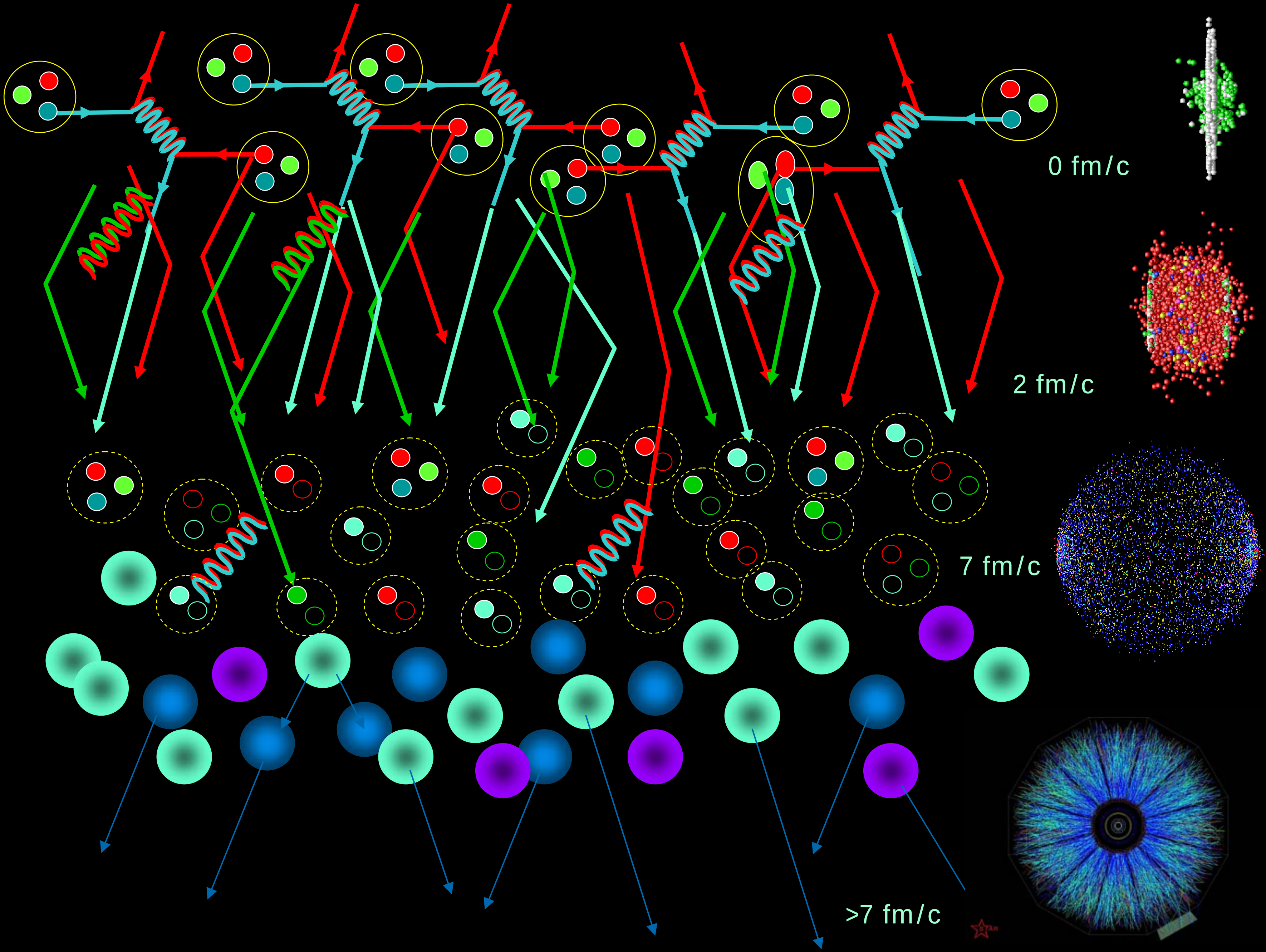
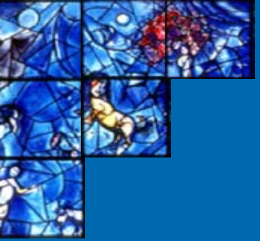
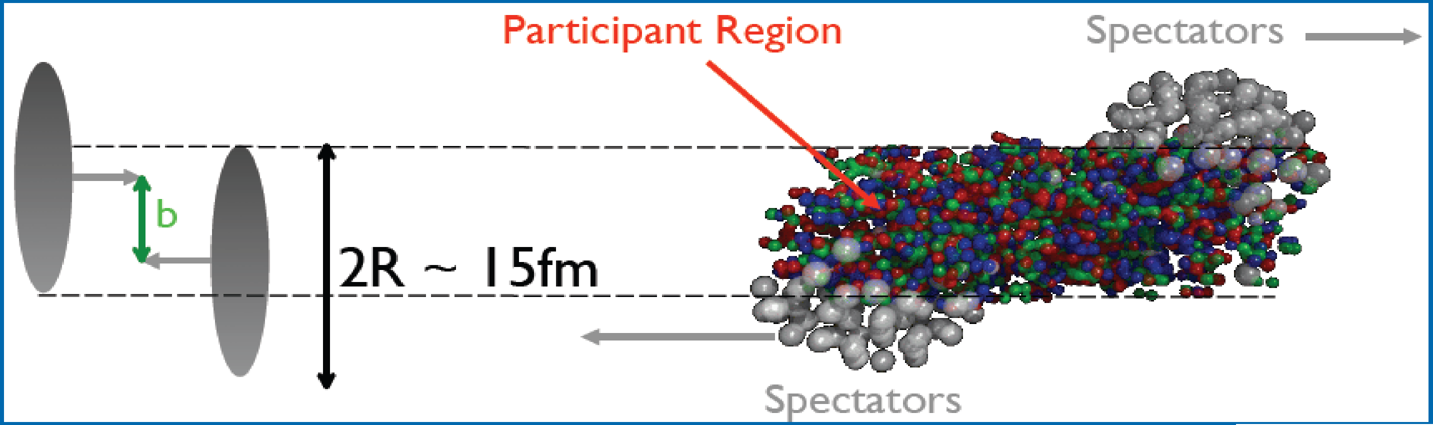
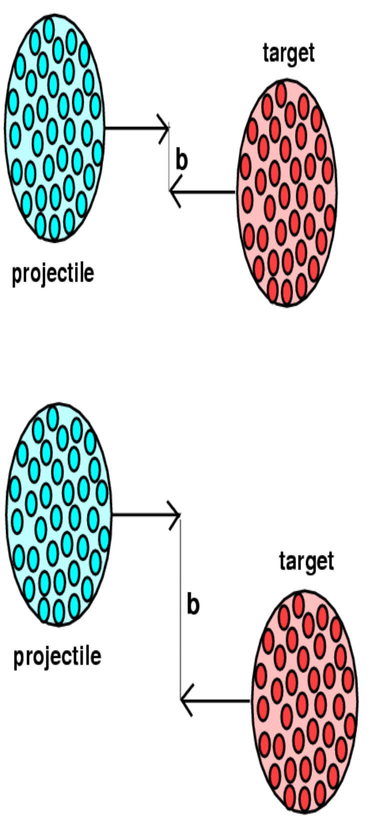


Diagram from Peter Steinberg



Multiplicity and collision centrality

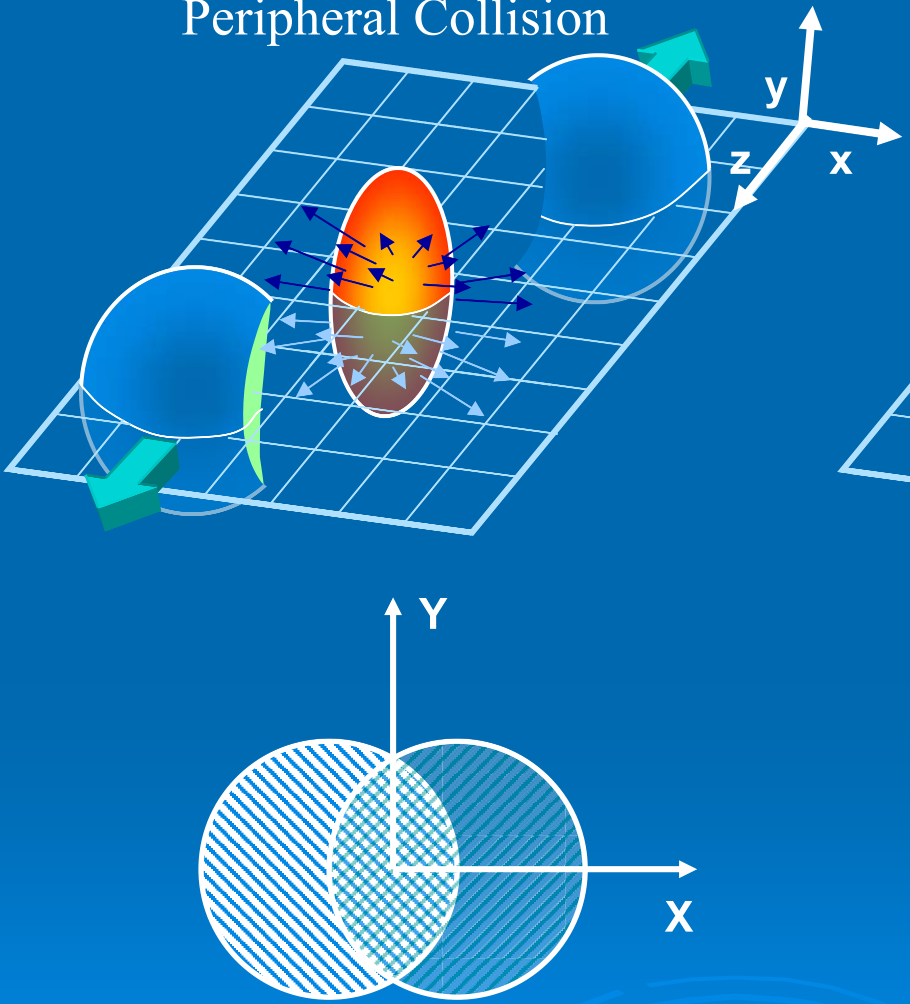




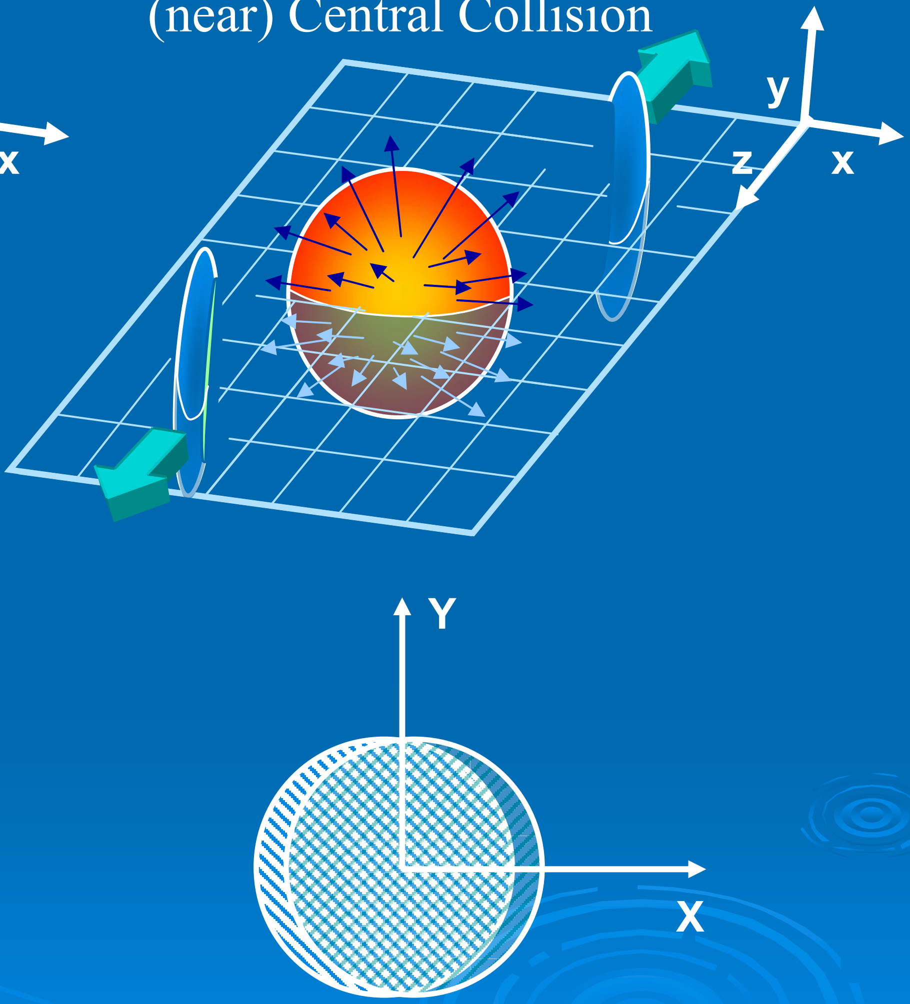
- The *impact parameter b* determines "centrality" of the event
- SMALL IMPACT PARAMETER (Central events)
  - Many participant nucleons (large N_{part}) and few spectators
  - Many nucleon-nucleon collisions (large N_{coll})
  - Big system
  - Many produced particles (~ 5000 at top RHIC energy)
- LARGE IMPACT PARAMETER (Peripheral events)
  - Few participant nucleons (small N_{part}) and many spectators
  - Few nucleon-nucleon collisions (small N_{coll})
  - Small system
  - Few produced particles

Centrality Dependence

Peripheral Collision



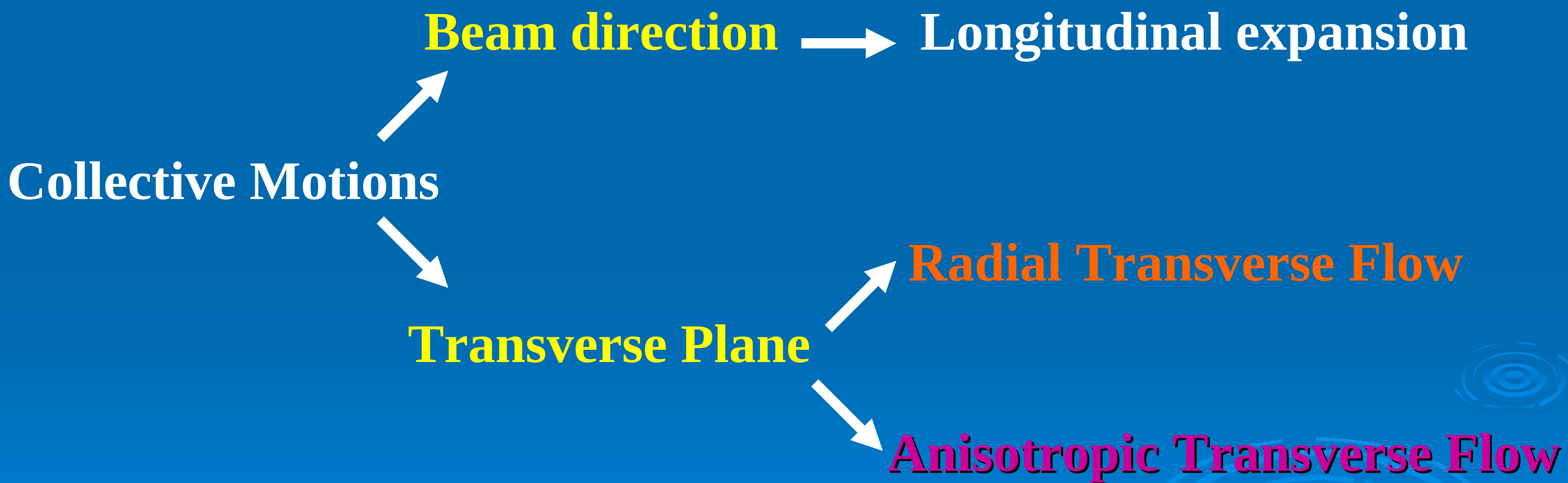
(near) Central Collision



Centrality measured by the multiplicity of charged particles

Flow in heavy ion collisions

Flow = collective motion of particles (due to high pressure arising from compression and heating of nuclear matter) superimposed on top of the thermal motion



Beam direction → **Longitudinal expansion**

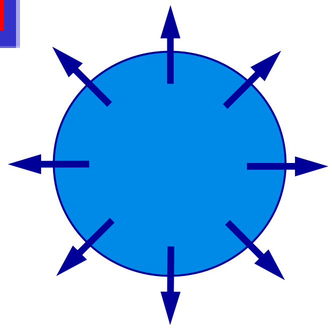
Collective Motions

Radial Transverse Flow

Transverse Plane

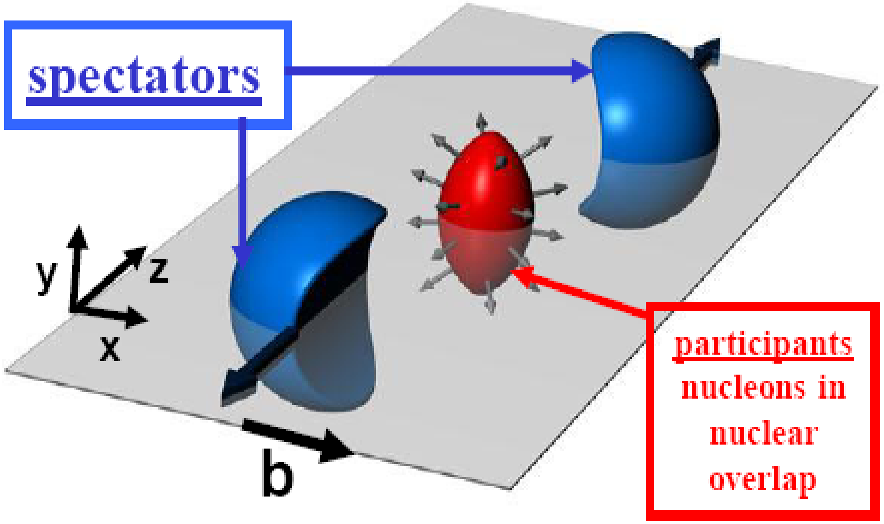
Anisotropic Transverse Flow

Types of flow in nuclear collisions



- radial flow
  - driven by **pressure gradient**
    - increases for central collisions
  - acts over **long time**
    - until freeze-out

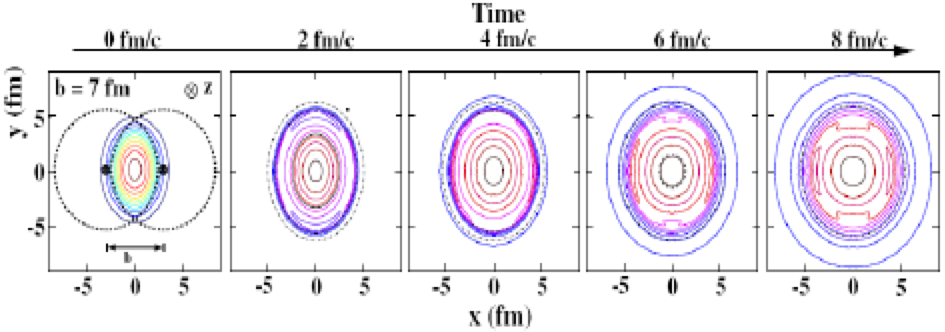
not so interesting



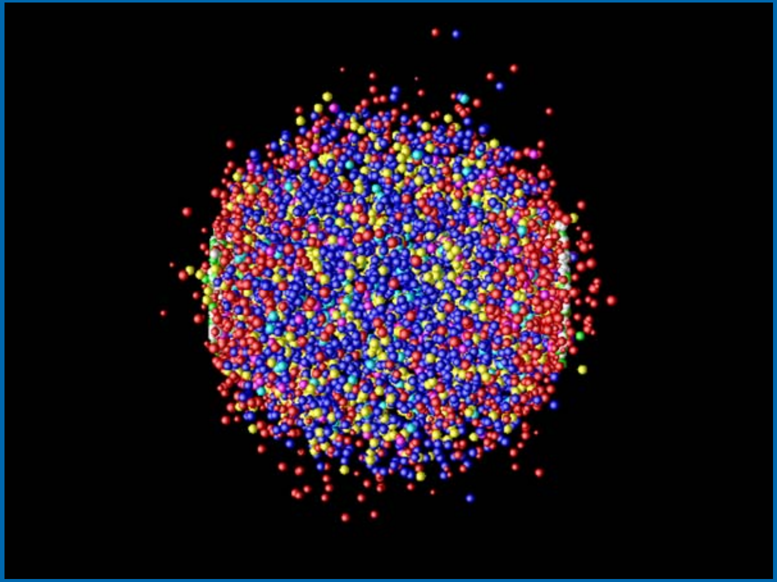
spectators

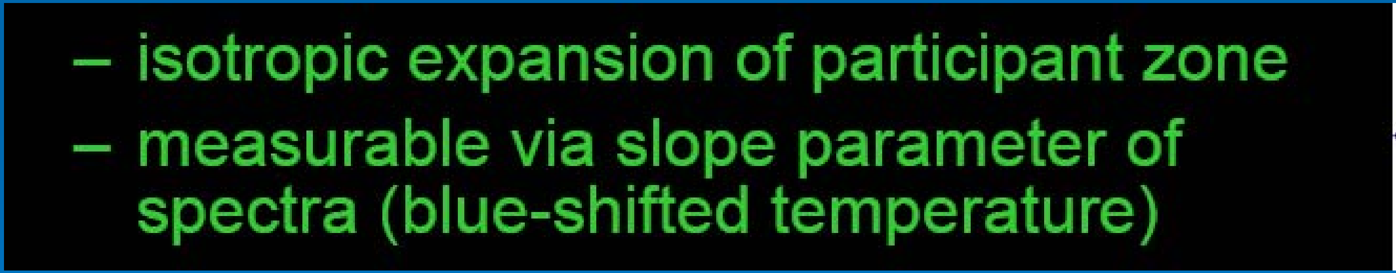
participants
nucleons in nuclear overlap

- elliptic flow **very interesting !**
  - **spatial anisotropy** => pressure anisotropy
    - azimuthal dependence of flow
    - strong for peripheral, zero for central
  - acts at **early times**
    - until anisotropy disappears

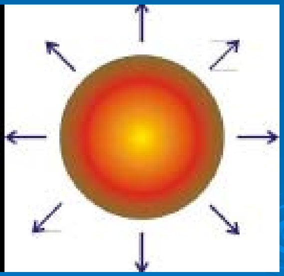


Radial Flow





- isotropic expansion of participant zone
- measurable via slope parameter of spectra (blue-shifted temperature)

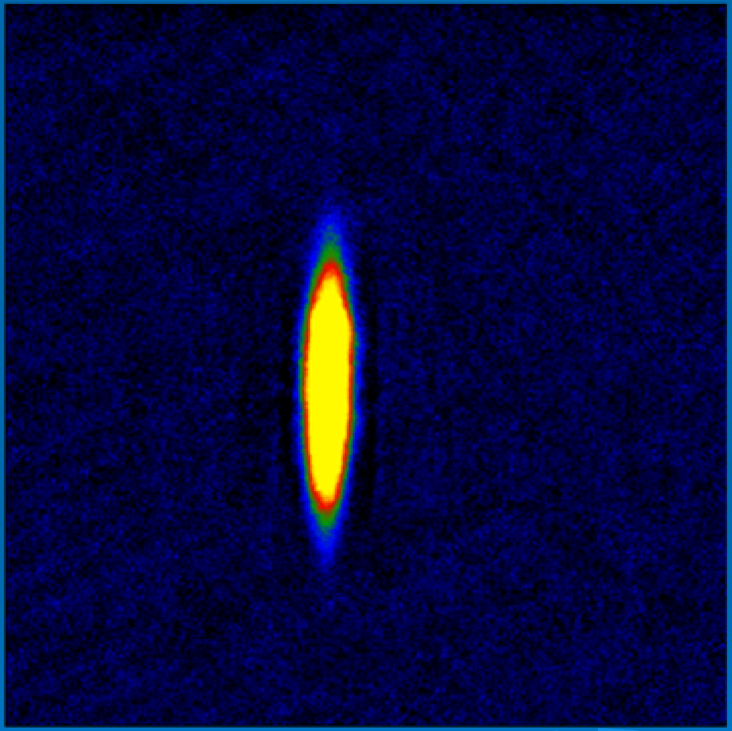


Partonic: parton-parton scattering, QGP EOS

Hadronic: hadron-hadron scattering, hadron gas

Isotropic expansion

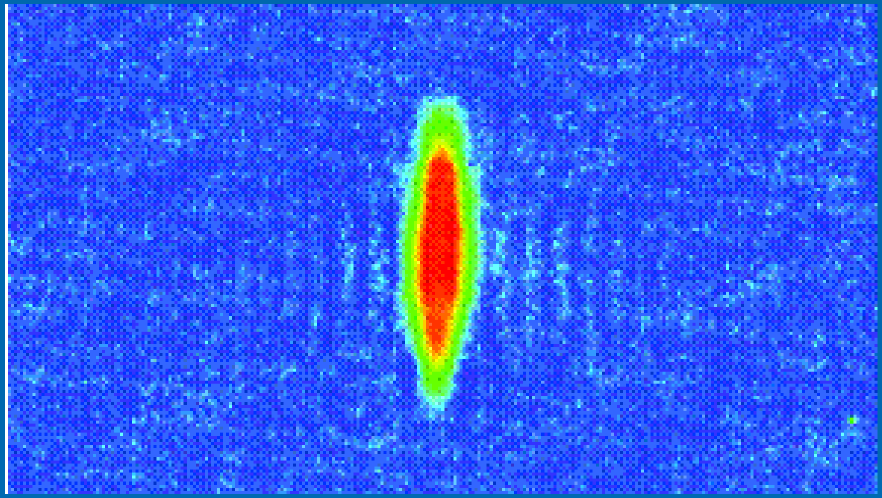
- nano-Kelvin gas of ^{6}Li atoms
- magnetic trap
- small scattering length leads to viscous hydrodynamics
- isotropic expansion when trapping field dropped



Ken O'Hara (Penn. St.)

Anisotropic expansion

- resonance tuned for large scattering length
- nearly ideal hydrodynamics
- anisotropic expansion when trapping field dropped

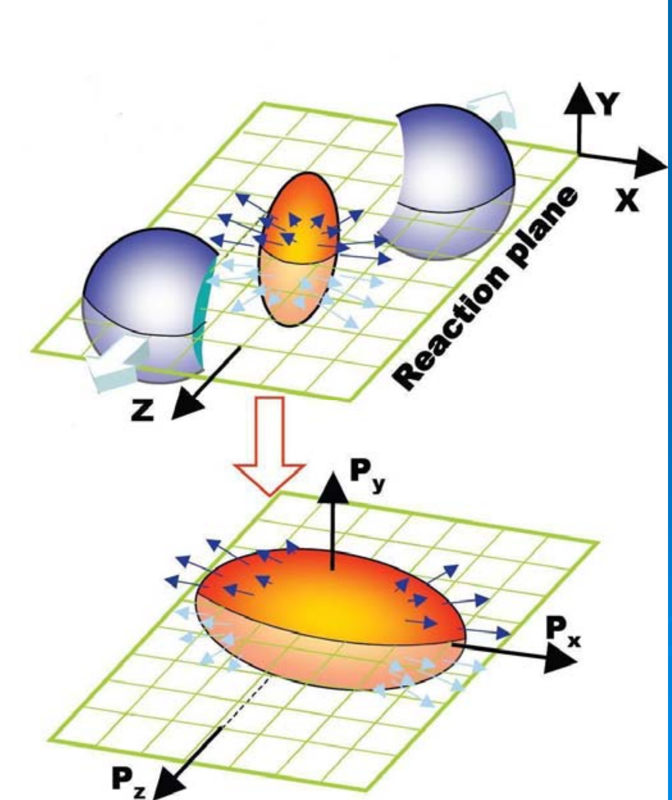


Julia Velkovska

Anisotropic transverse flow

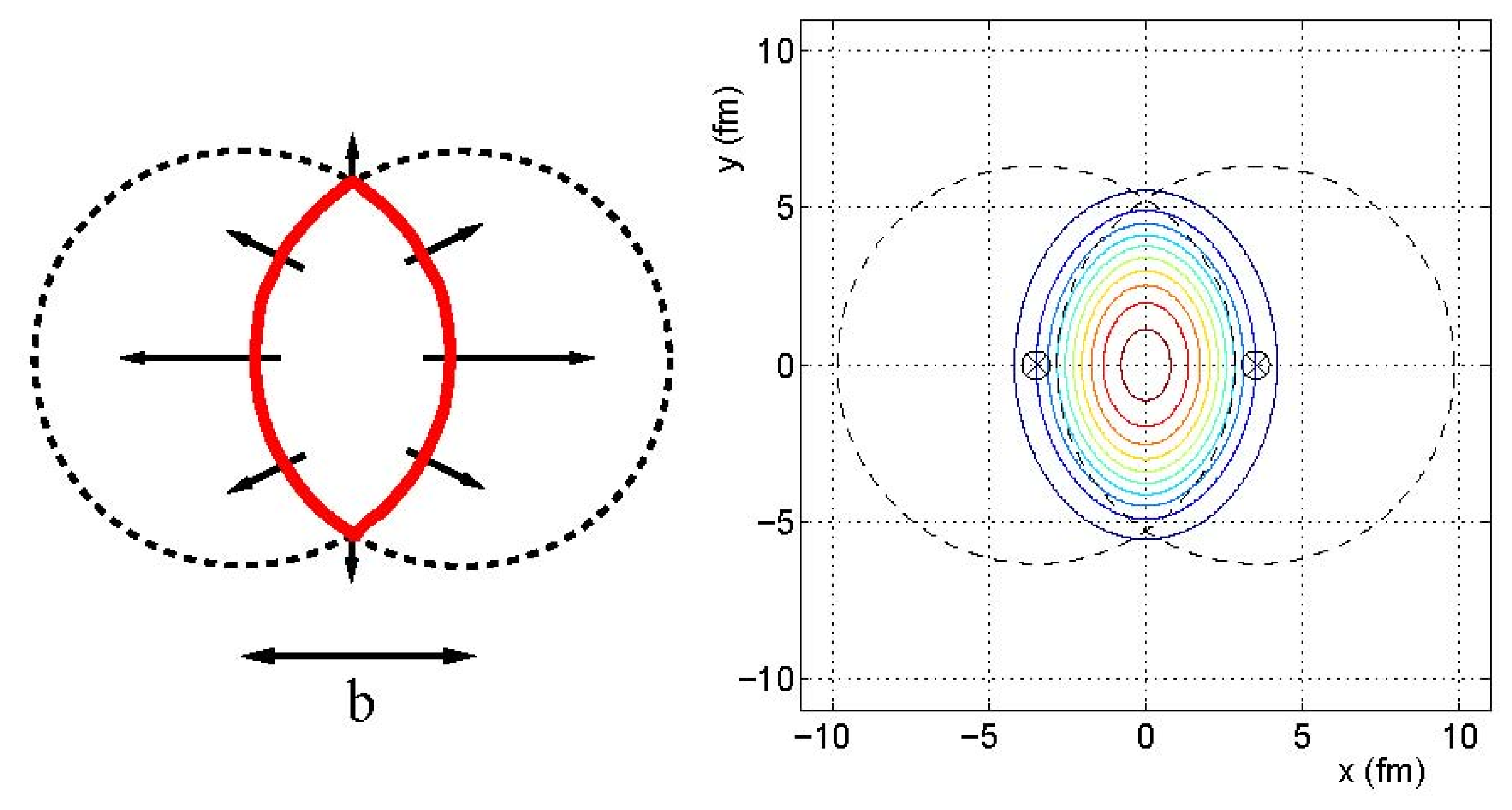
→ **Correlation between azimuthal angles of outgoing particles and the direction of the impact parameter**

Peripheral nucleus-nucleus collisions produce an asymmetric particle source



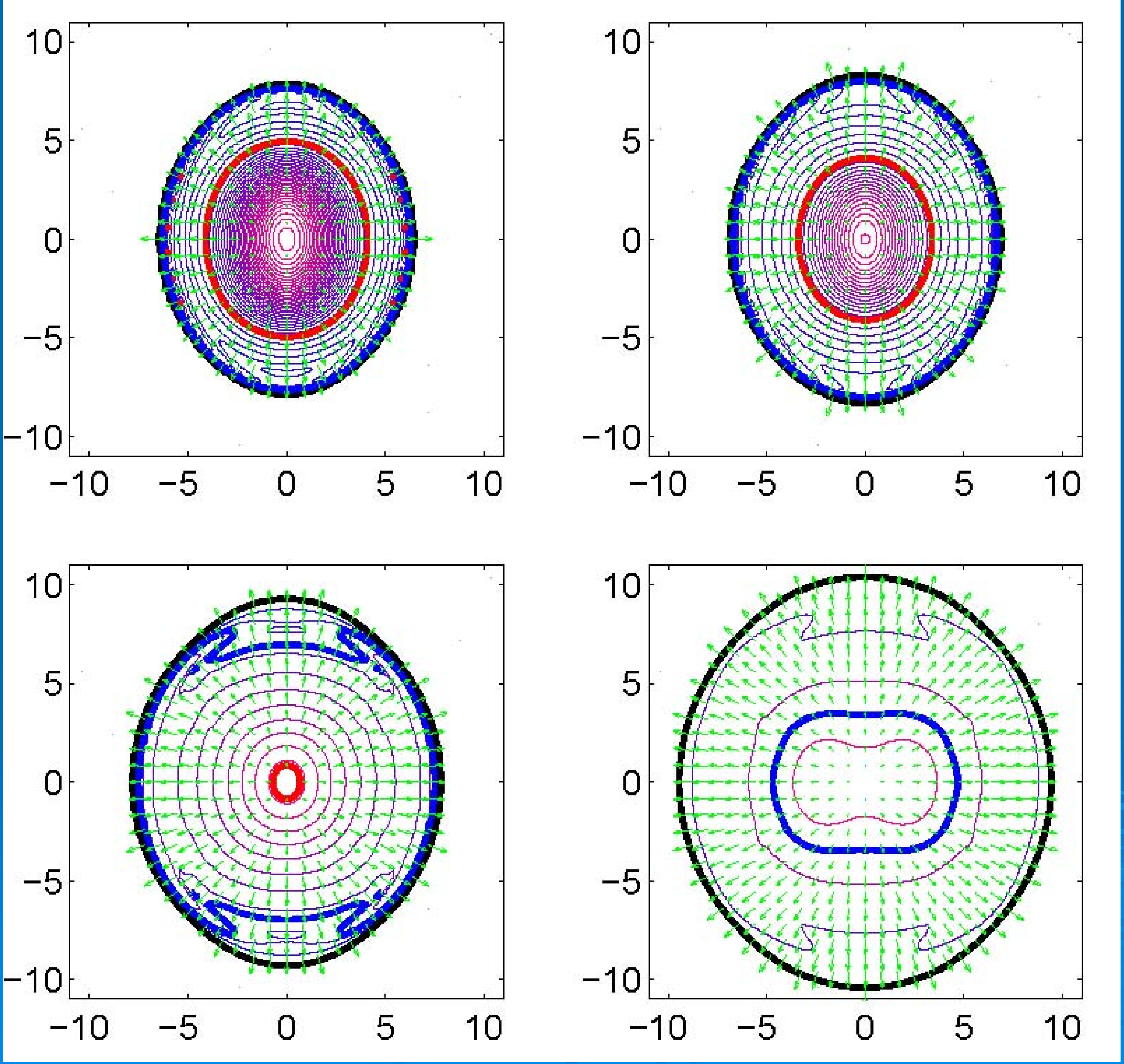
- "Almond-shaped" overlap region
  - → Larger pressure gradient in x-z plane than in y direction
  - → Pressure gradients in the transverse plane
- Particle rescatterings
  - → Convert the initial spatial anisotropy ε_2 into an observed momentum anisotropy v_2
- Asymmetry disappears with time
  - → Sensitive to the early stages of collision evolution EOS

Initial Geometry Important

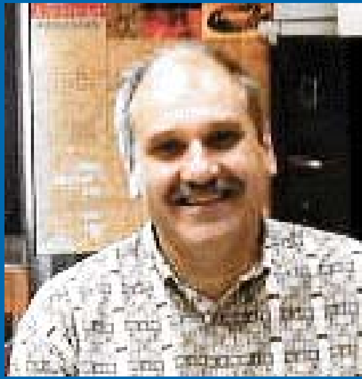


Eccentricity $\varepsilon = \dfrac{y^2 - x^2}{y^2 + x^2}$

Time Evolution of the Asymmetry



Fourier Harmonics



Voloshin

First to use Fourier harmonics:

$$1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos[2(\phi - \Psi_{RP})] + \cdots$$

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

Event plane resolution correction made for each harmonic

Unfiltered theory can be compared to experiment!

First to use mixed harmonics

First to use the terms directed and elliptic flow for v_1 and v_2

S. Voloshin and Y. Zhang, hep-ph/940782; Z. Phys. C **70**, 665 (1996)

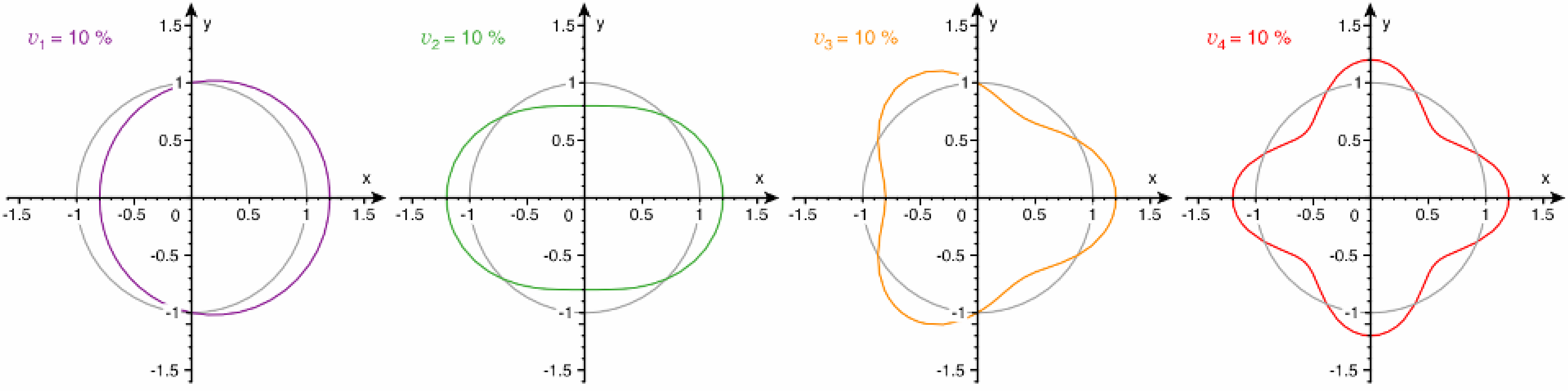
See also, J.-Y. Ollitrault, arXiv nucl-ex/9711003 (1997)
and J.-Y. Ollitrault, Nucl. Phys. **A590**, 561c (1995)

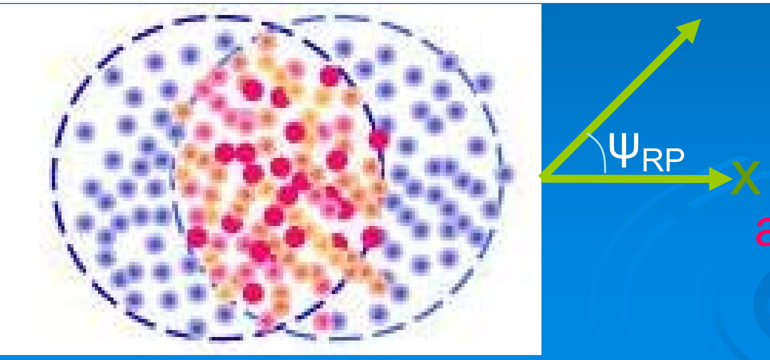
Anisotropic flow

Anisotropic flow v_n

$$E\frac{d^3N}{d^3\vec{p}} = \frac{dN}{p_T\,dp_T\,d\varphi\,dy} = \frac{1}{2\pi}\frac{dN}{p_T\,dp_T\,dy}\left[1+\sum_{n=1}^{\infty}2v_n(p_T,y)\cos(n\varphi)\right]$$

Sine terms vanish due to reflection symmetry wrt reaction plane in A+A collisions





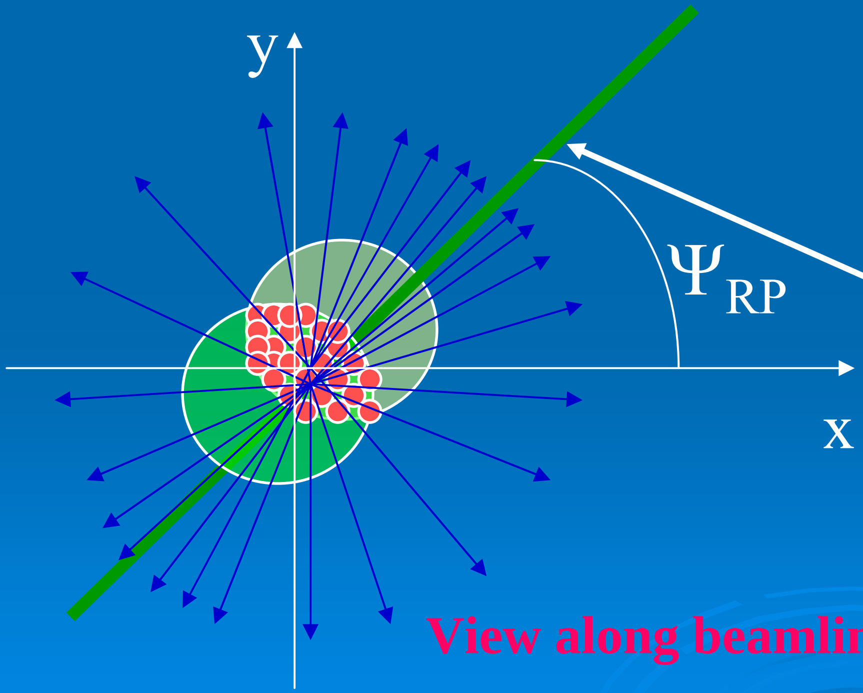
Initial spatial anisotropy ⇨ Pressure gradient anisotropy ⇨ Anisotropic flows

Flow parametrization

- Fourier expansion of azimuthal particle distribution

(Poskanzer and Voloshin, Phys. Rev. C58, 1998)

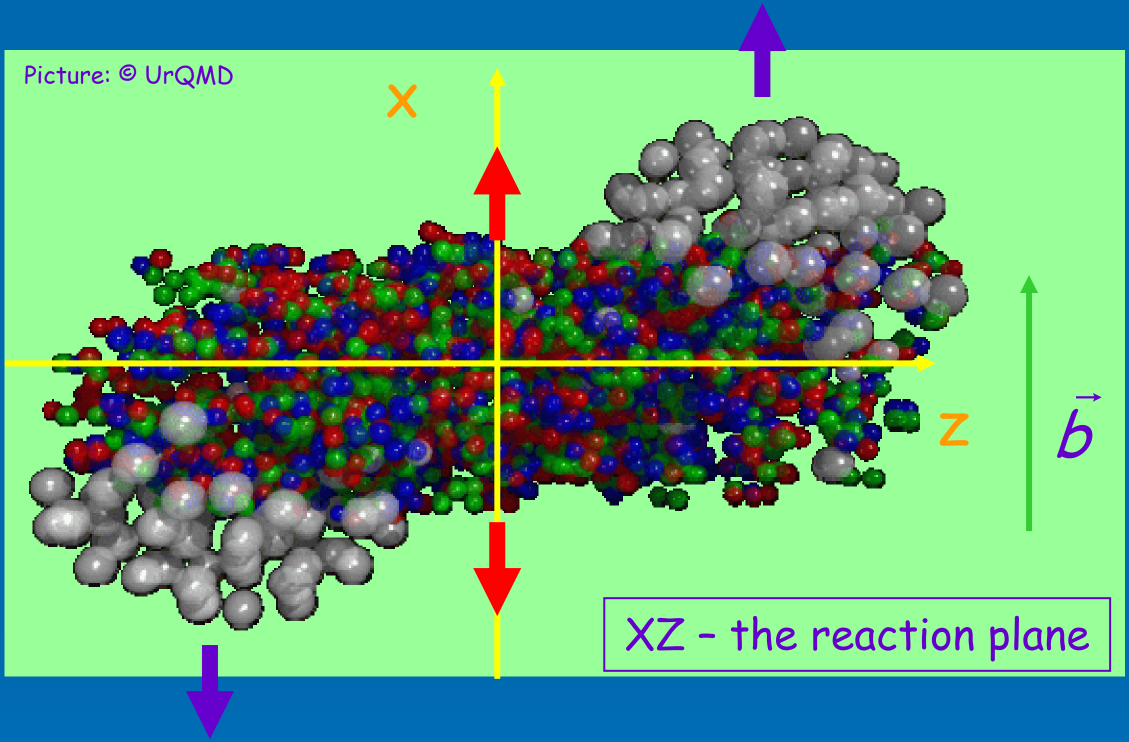
$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + \ldots.\right)$$



View along beamline

REACTION PLANE = plane defined by beam direction and impact parameter

The coefficients v_1 and v_2



Picture: © UrQMD

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \left\langle \cos\left(\phi - \Phi_R\right) \right\rangle$$

$$v_2 = \left\langle \left(\frac{p_x^2}{p_t^2} - \frac{p_y^2}{p_t^2} \right) \right\rangle = \left\langle \cos 2(\phi - \Phi_R) \right\rangle$$

$$p_t = \sqrt{p_x^2 + p_y^2}$$

$$\phi = \tan^{-1} \frac{p_y}{p_x}$$

Anisotropic flow ≡ correlations with respect to the reaction plane

$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\,\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \dots\right)$$

Directed flow

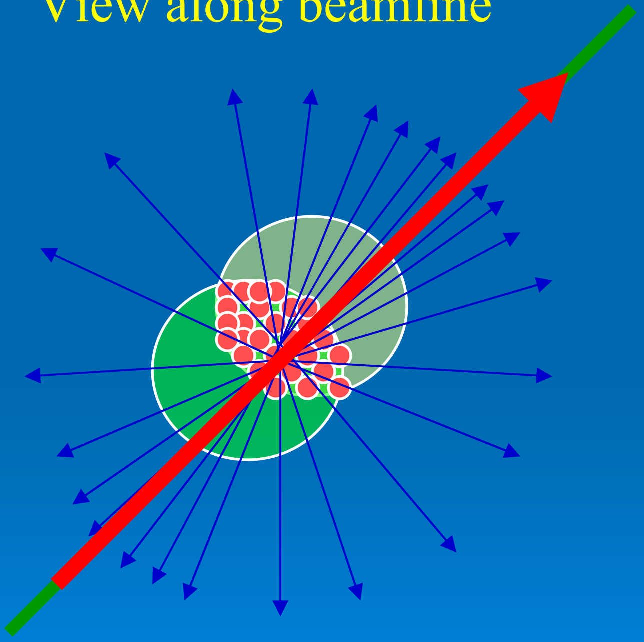
Elliptic flow

Directed Flow

$$\frac{dX}{d\varphi}=\frac{X_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos\left(2\left(\varphi-\Psi_{RP}\right)\right)+....\right)$$

Directed flow coefficient

$$v_1=\left\langle\cos\left(\varphi-\Psi_{RP}\right)\right\rangle$$



View along beamline

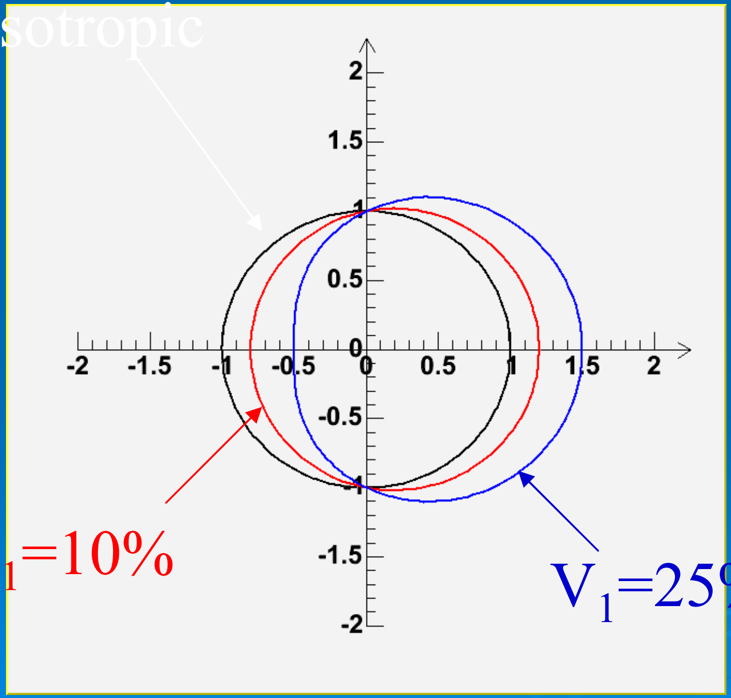
- Due to pressure built up between nuclei during the time of overlap
- Affects mostly particles at forward and backward rapidities
- Established very early
- Time scale = overlap time of the 2 nuclei (decreases with increasing beam energy)

Directed Flow

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + \boxed{2v_1} \cos(\varphi - \Psi_{RP}) + 2v_2 \cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + \ldots.\right)$$

Directed flow coefficient

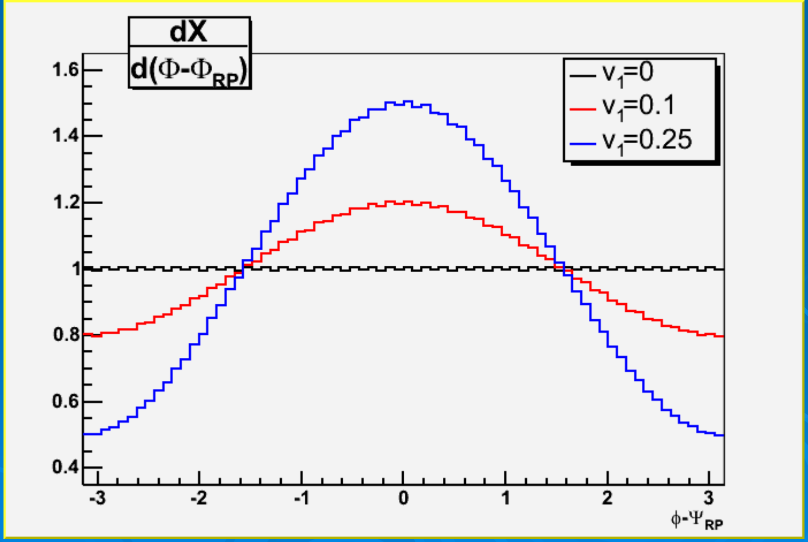
$$v_1 = \left\langle \cos\left(\varphi - \Psi_{RP}\right)\right\rangle$$



Isotropic

V_1=10%

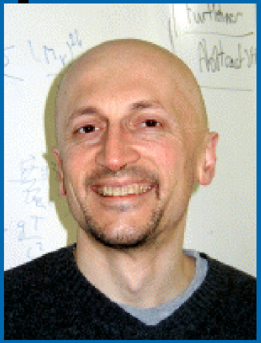
V_1=25%



Prediction of positive elliptic flow

Jan '93, Jean-Yves Ollitraut predicted in-plane elliptic flow at high beam energies. Poskanzer had just discovered out-of-plane elliptic flow

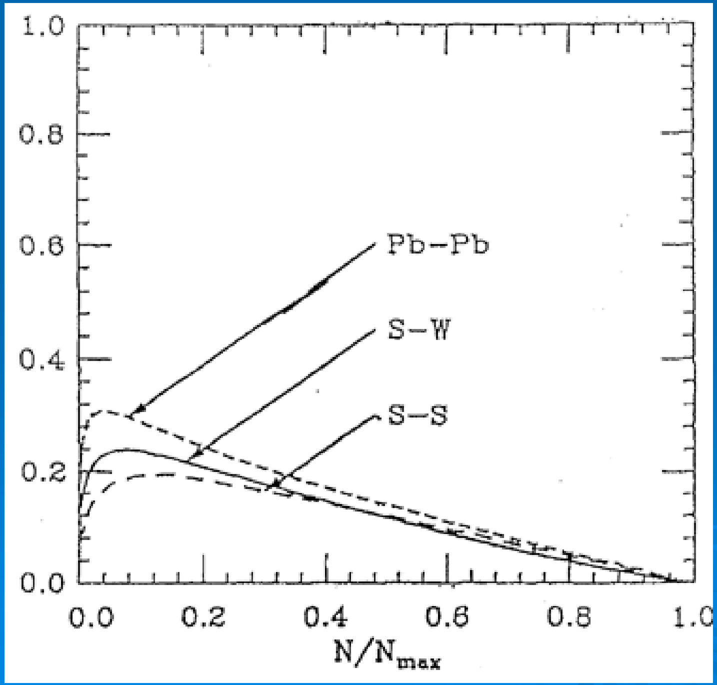
2-dimensional transverse sphericity analysis



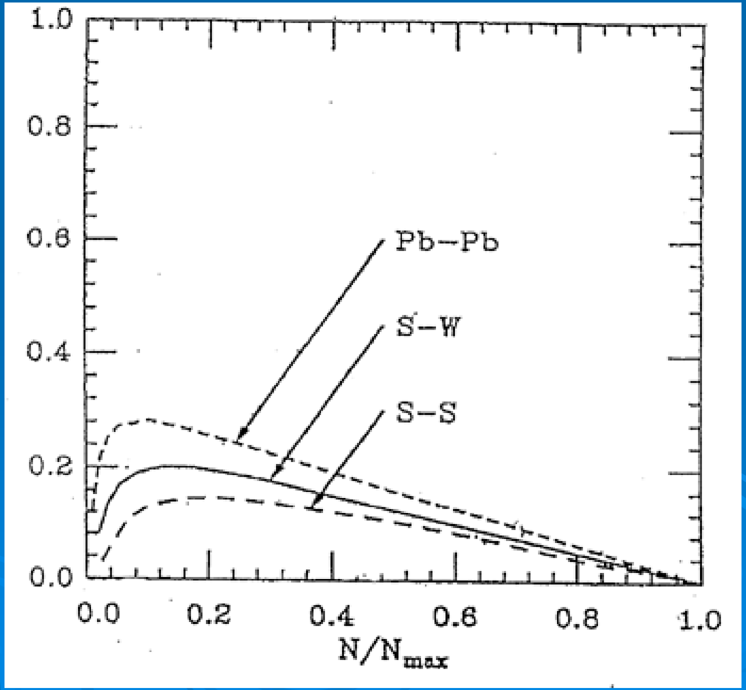
Ollitrault

Poskanzer

space elliptic anisotropy



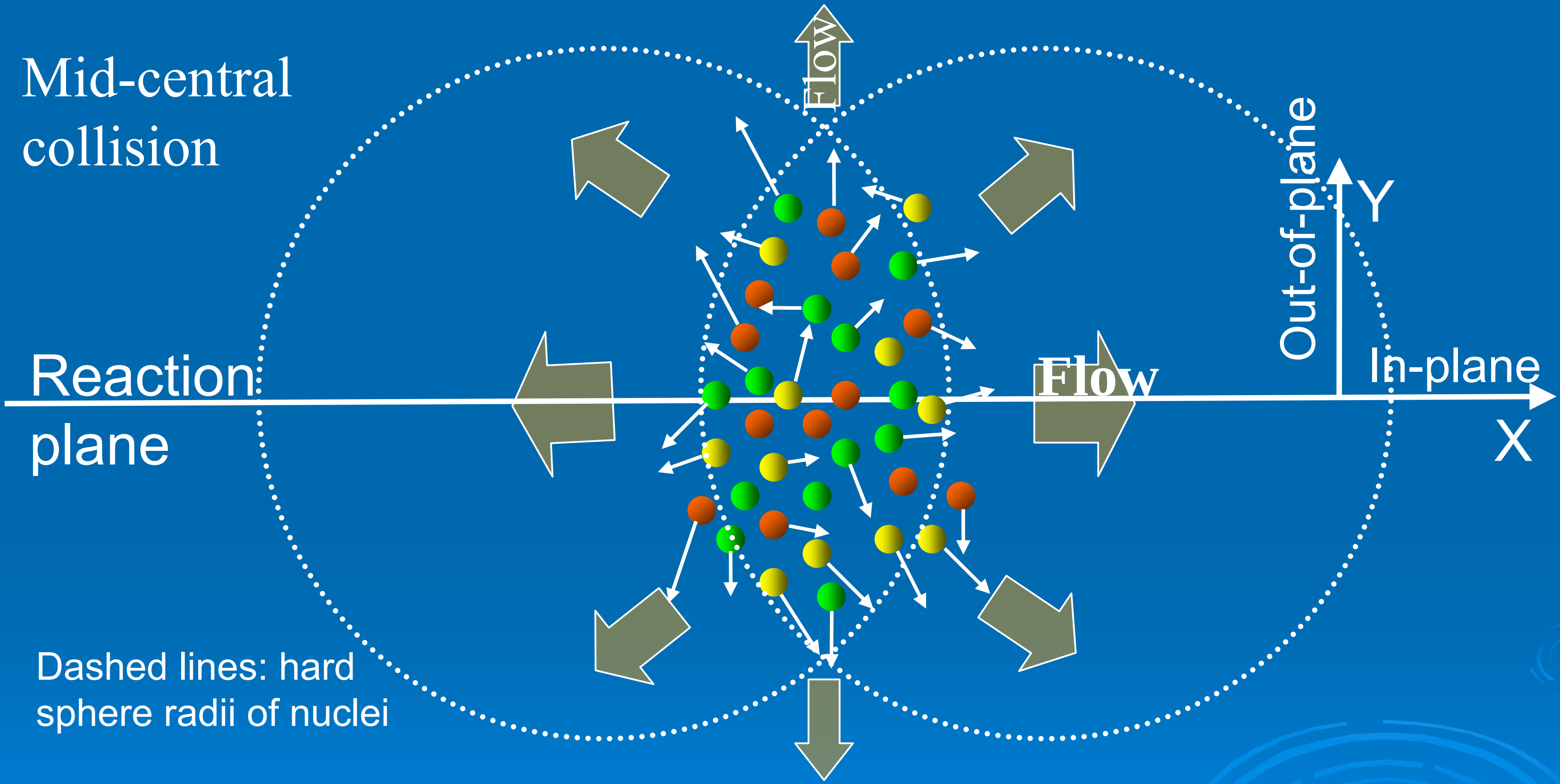
momentum elliptic anisotropy



J.-Y. Ollitrault, PRD **46**, 229 (1992), PRD **48**, 1132 (1993)

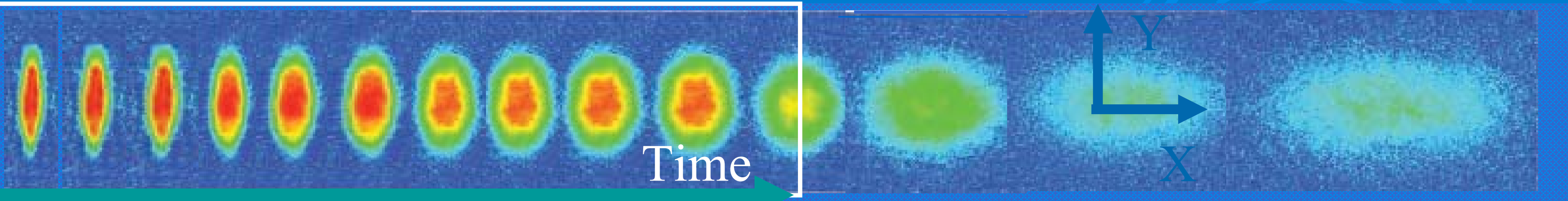
Collective behavior

Mid-central
collision



Reaction
plane

Dashed lines: hard
sphere radii of nuclei



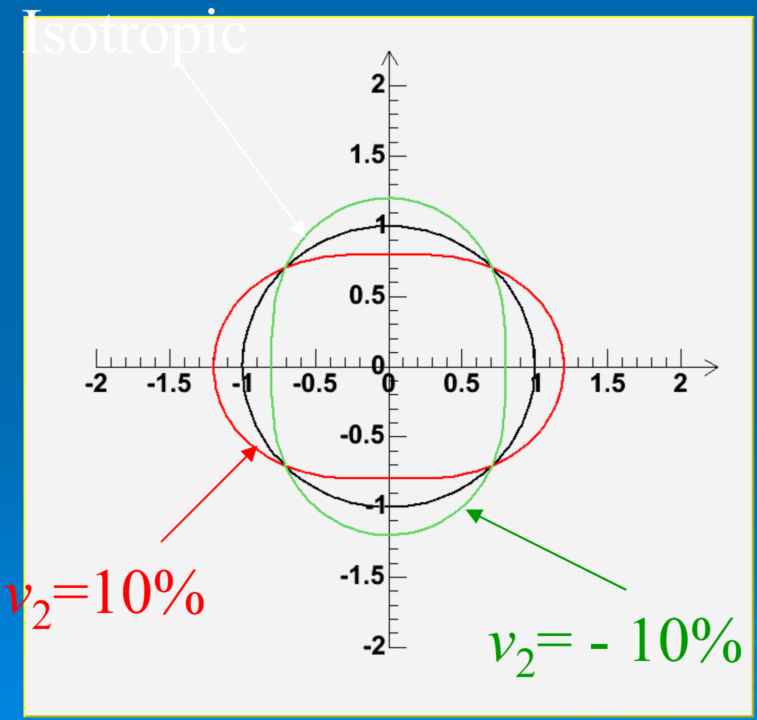
In Plane vs Out of Plane

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+\boxed{2v_2}\cos\left(2\left(\varphi-\Psi_{RP}\right)\right)+....\right)$$

Elliptic flow coefficient:

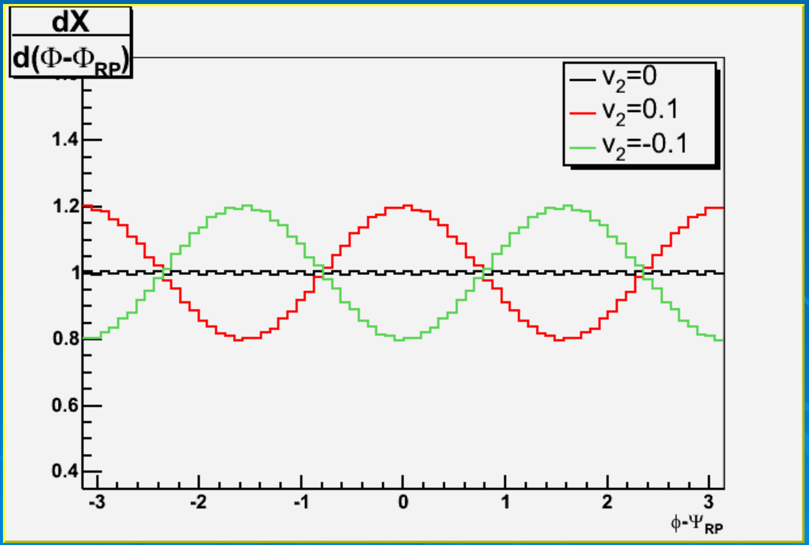
$v_2>0$ In plane elliptic flow

$v_2<0$ Out of plane elliptic flow


Isotropic

v_2=10%

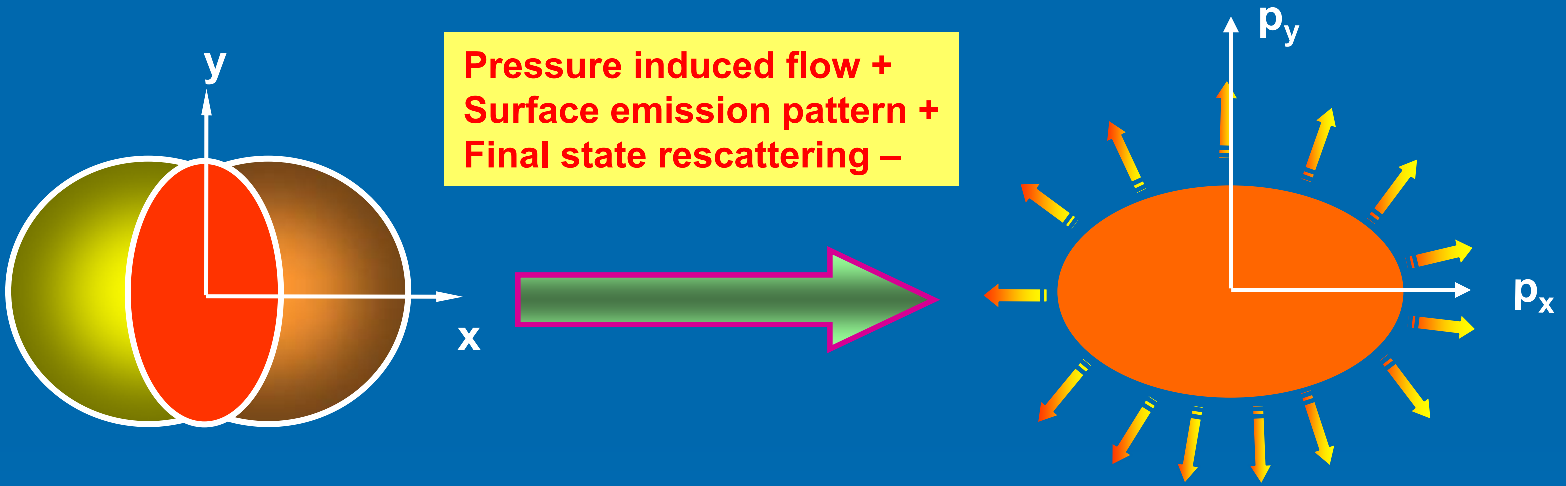
v_2= - 10%



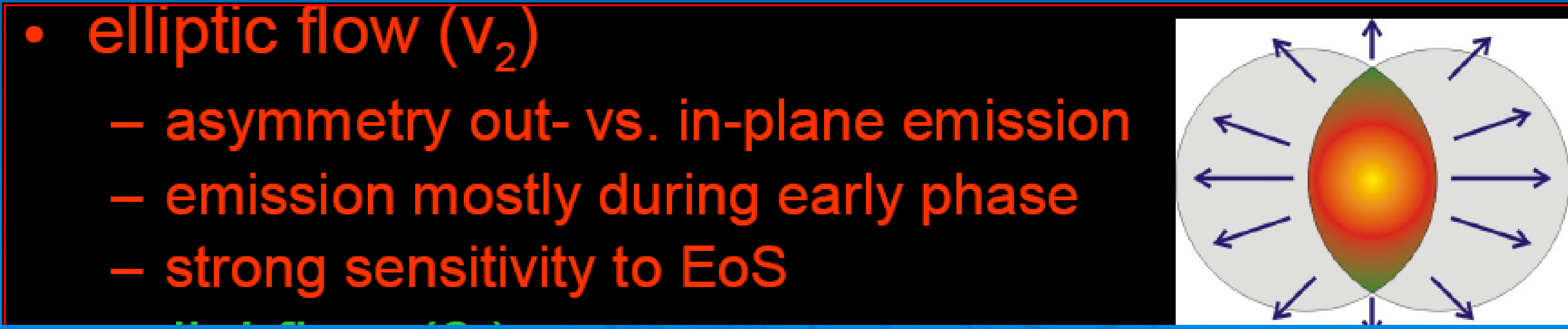
Elliptic Flow v_2 and Early Dynamics

Coordinate space:
initial asymmetry

Momentum space:
final asymmetry



Pressure induced flow +
Surface emission pattern +
Final state rescattering –



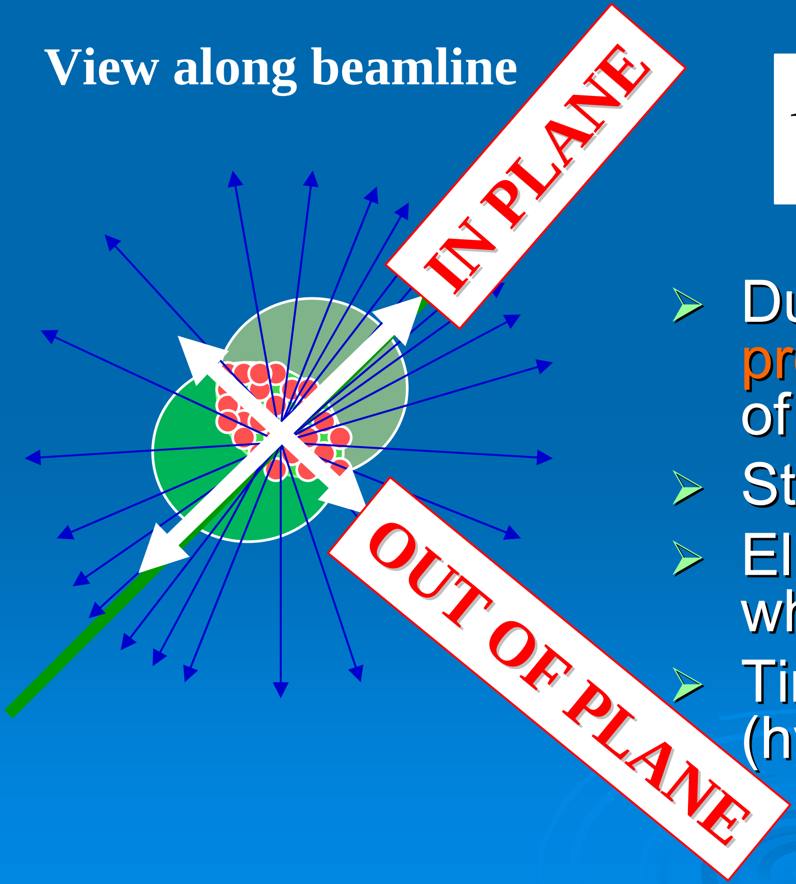
- elliptic flow (v_2)
  - asymmetry out- vs. in-plane emission
  - emission mostly during early phase
  - strong sensitivity to EoS

Elliptic Flow

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2}\cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + ...\right)$$

Elliptic flow coefficient

$$v_2 = \left\langle \cos\left(2\left(\varphi - \Psi_{RP}\right)\right)\right\rangle$$



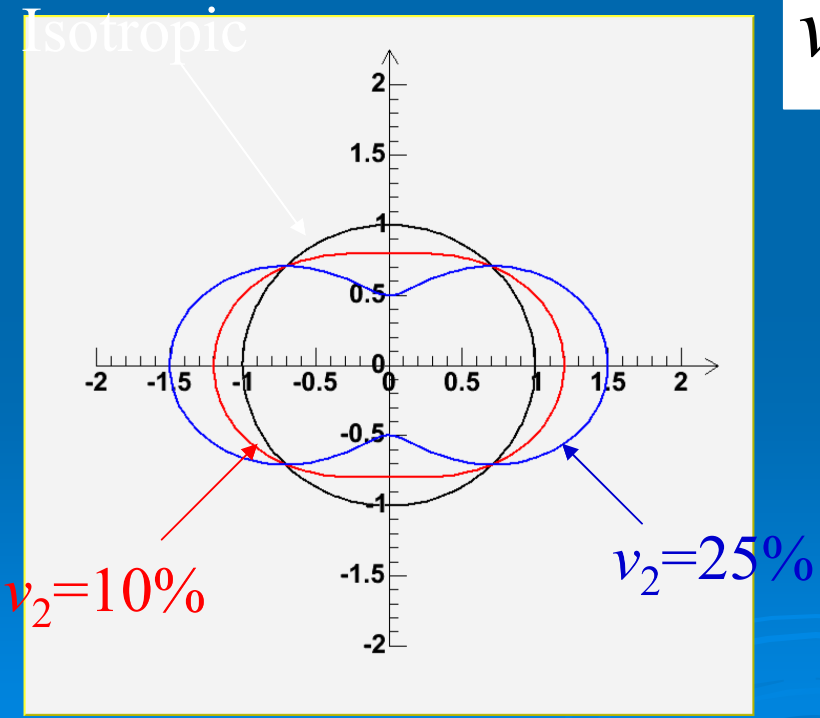
- Due to azimuthal anisotropy of transverse pressure gradient caused by deformation of reaction region in the transverse plane
- Strongest near midrapidity
- Eliminates the geometrical asymmetry which generates it
- Time scale > than for directed flow (hydrodynamics may describe it)

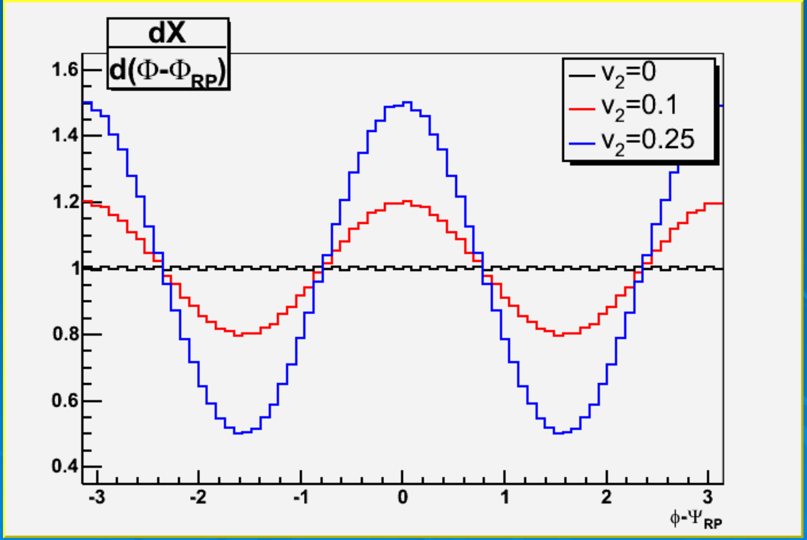
Elliptic Flow

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + \ldots.\right)$$

Elliptic flow coefficient

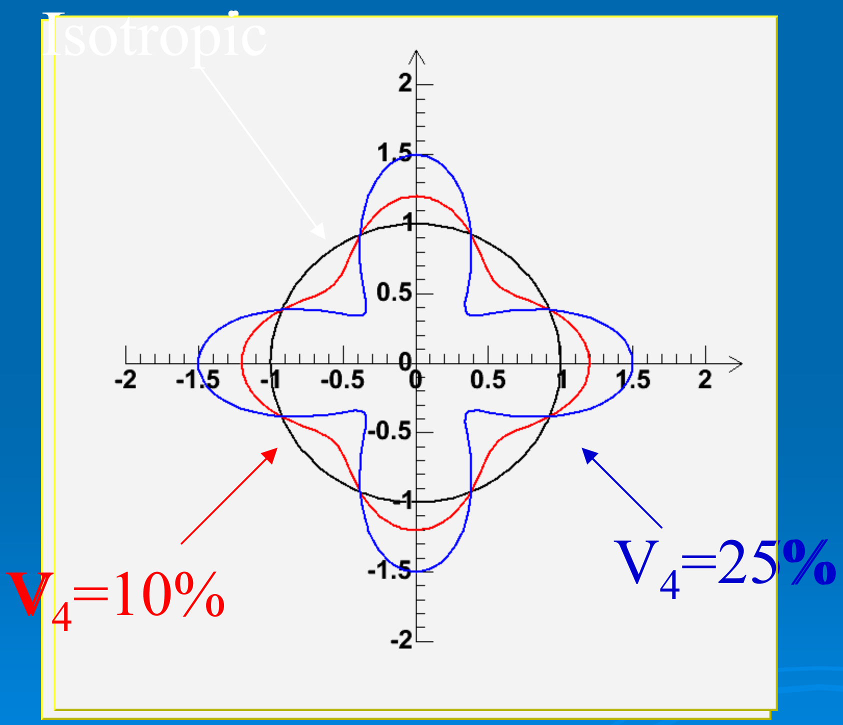
$$v_2 = \left\langle \cos\left(2\left(\varphi - \Psi_{RP}\right)\right)\right\rangle$$





Higher order harmonics

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + \boxed{....}\right)$$



- ***Fourth order coefficient v_4:***
  - *Restore the elliptically deformed shape of particle distribution*
  - *Magnitude and sign sensitive to initial conditions of hydro*
  - *Strong potential to constrain model calculations*
  - *Carry information on the dynamical evolution of the system*

(Peter Kolb, PRC 68, 031902(R))

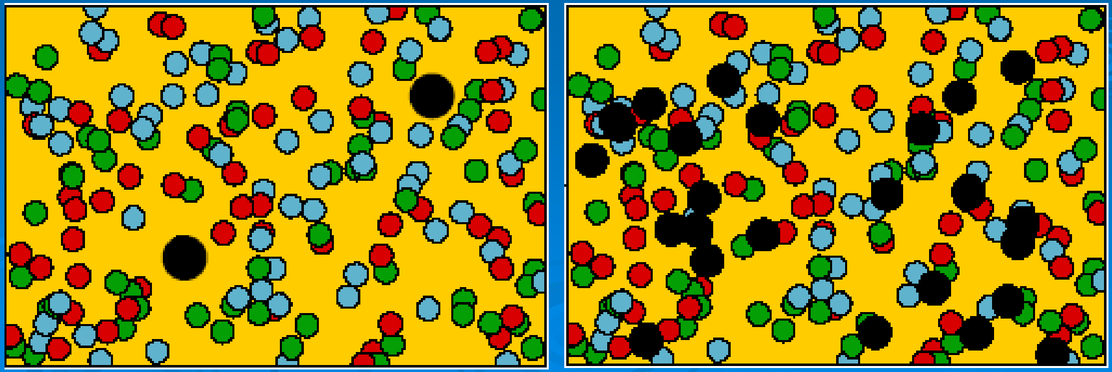
- An almost perfect fluid and opaque QCD matter is created at RHIC for the first time.
  - Concept of strongly interacting quark-gluon many body system has been established.
- Toward comprehensive understanding of the collision as a whole and the QGP at LHC
- Some exotic phenomena are anticipated
  - Something like perfect fluidity or shock wave (Mach cone)

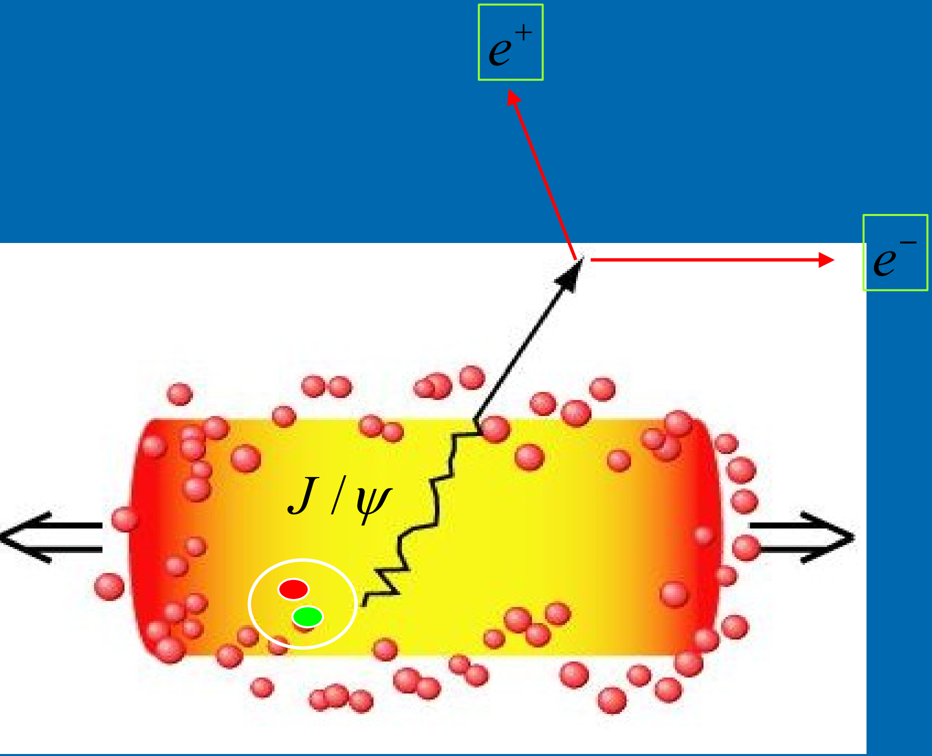
BACKUP SLIDES

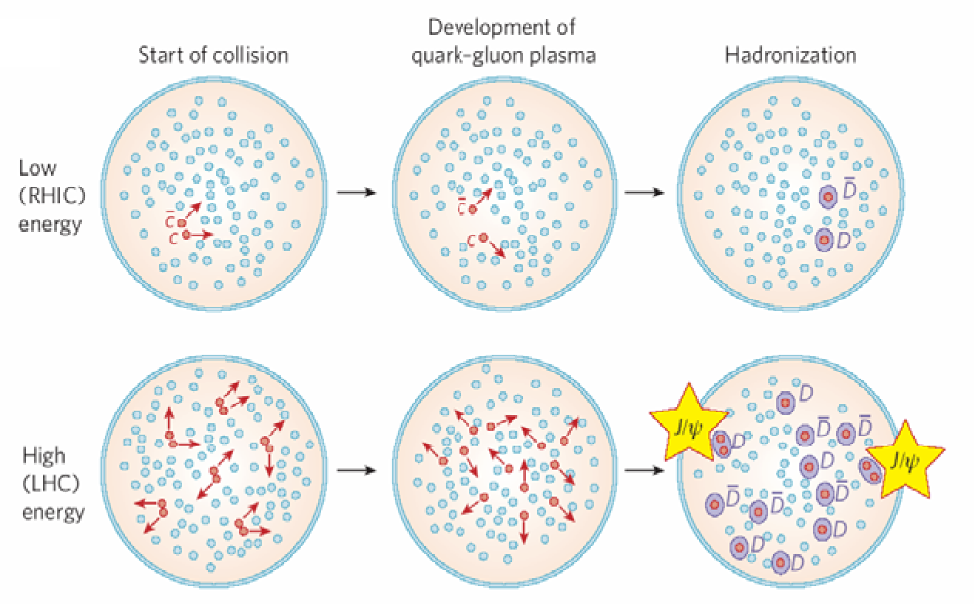
Heavy Quarks

- J/ ψ suppression is one of the oldest signature of deconfinementimportant signal of creation of hot and dense matter
- Heavy quarks live longer than QGP itself (10^{-11} vs 10^{-22} s) and travel far

  - way to sample plasma
- Lose less energy than light quarks
- More production at higher energies







J/Ψ Suppression

- **1986: Matsui and Satz claimed J/ψ suppression is a signature of formation of Quark Gluon Plasma in Heavy Ion collision**
- **2003: Asakawa and Hatsuda claimed J/ψ will survive up to 1.6 T_c**
- **Dynamic screening caused by long range confining QCD potential should cause J/ ψ suppression: quarks break apart into DDbar pairs**