Large-scale QCD at RHIC
An *experimental* overview

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Similar but somehow different…

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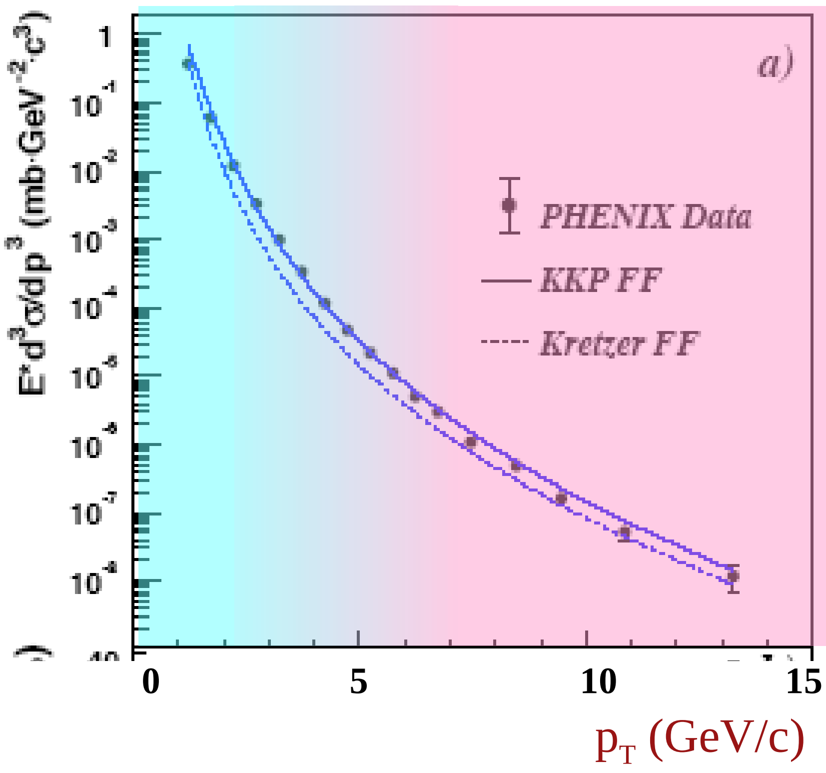
Outline - Achievements & Issues in 3 Regimes

Brief motivation. Then...

low-p_T ("soft")

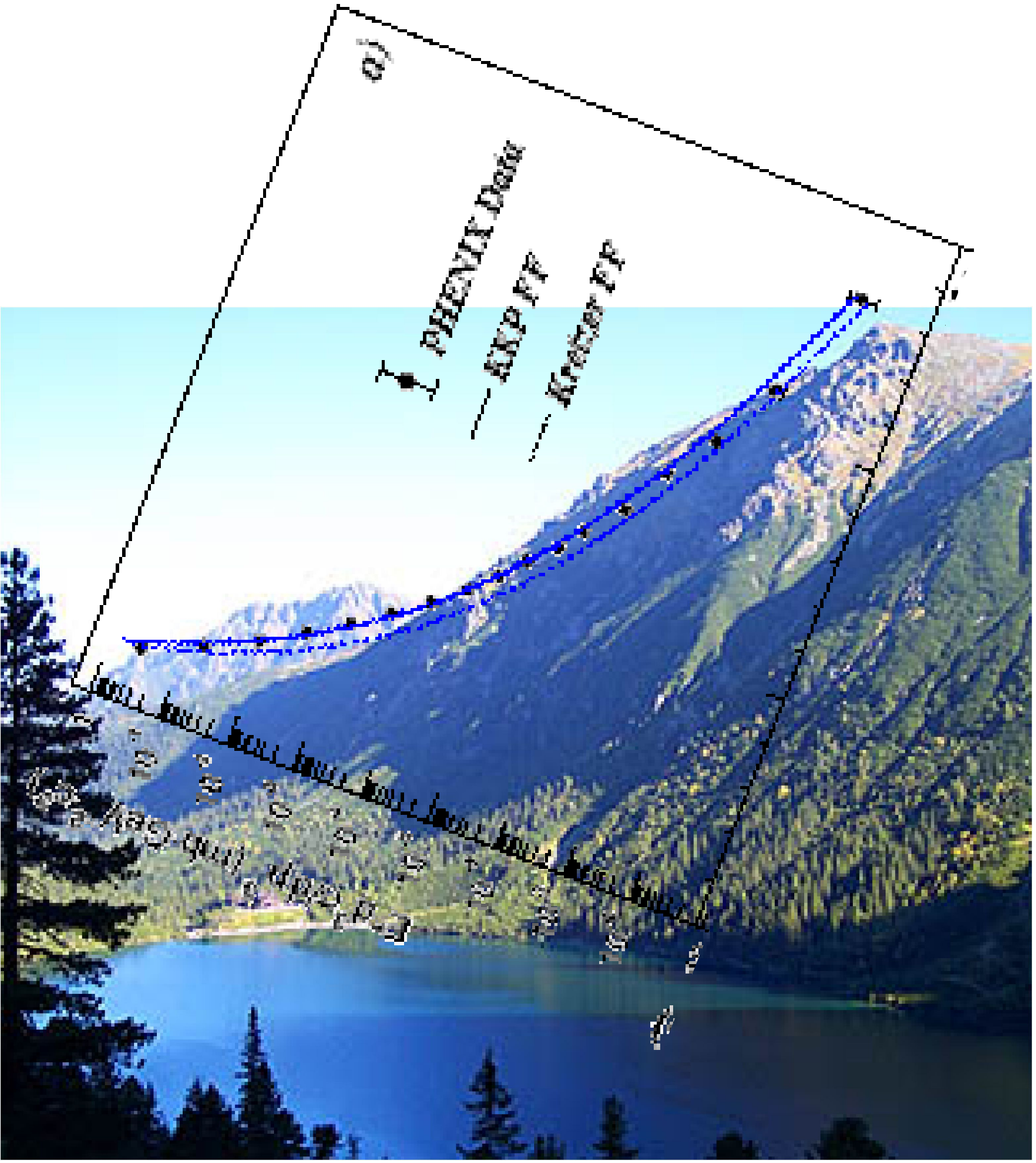
high-p_T ("hard")

mid-p_T ("firm")



PHENIX PRL 91 241803 (2003)

Outline - Achievements & Issues in 3 Regimes



Achievements

high-p_T ("hard") : thin air
- density? deconfinement?
- nuclear modification
- jet quenching

mid-p_T ("firm"): the journey
- degrees of freedom?
- non-hydro "flow"
- recombination

low-p_T ("soft") : base camp
- bulk? matter? Equ. of State?
- chemistry
- femtoscopy
- collectivity

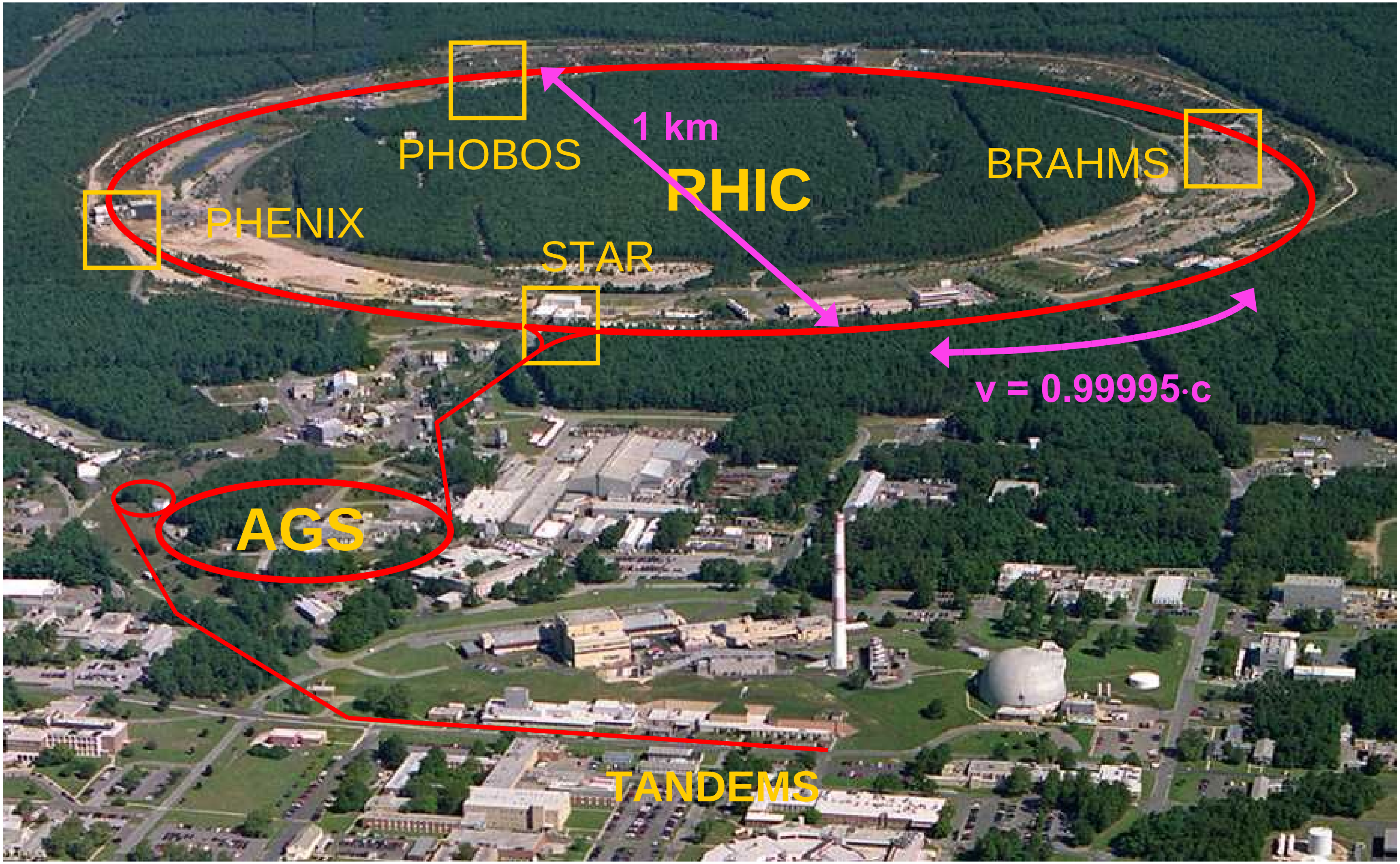
Open Issues

“RHIC is big”

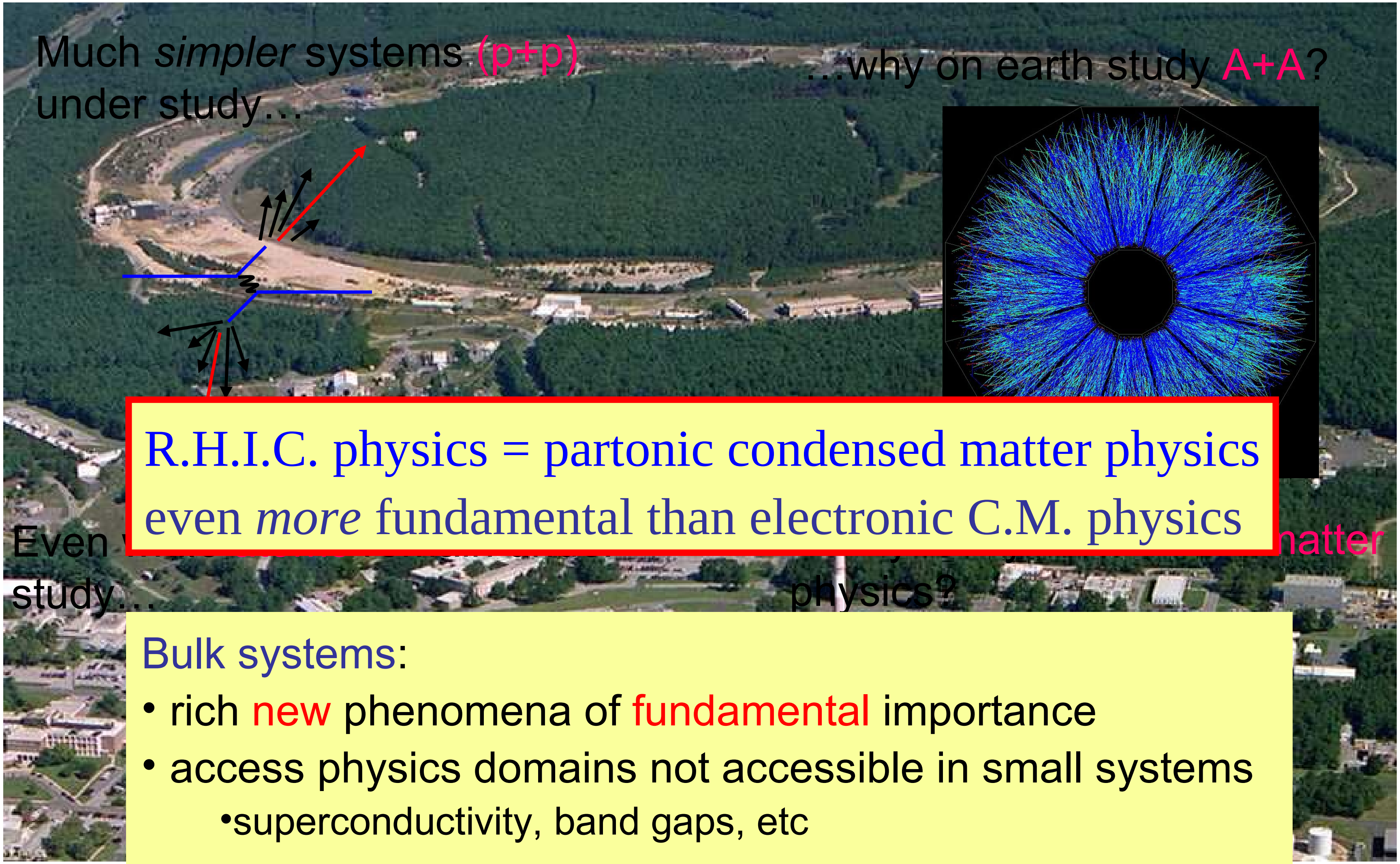
- big facility
- big detectors
- big collaborations
- “big” collisions

as seen by the Landsat-4 satellite…


Nuclear
Particle


PHOBOS
1 km
RHIC
BRAHMS
PHENIX
STAR
v = 0.99995·c
AGS
TANDEMS

Nuclear → Particle



R.H.I.C. physics = partonic condensed matter physics
even *more* fundamental than electronic C.M. physics

Bulk systems:

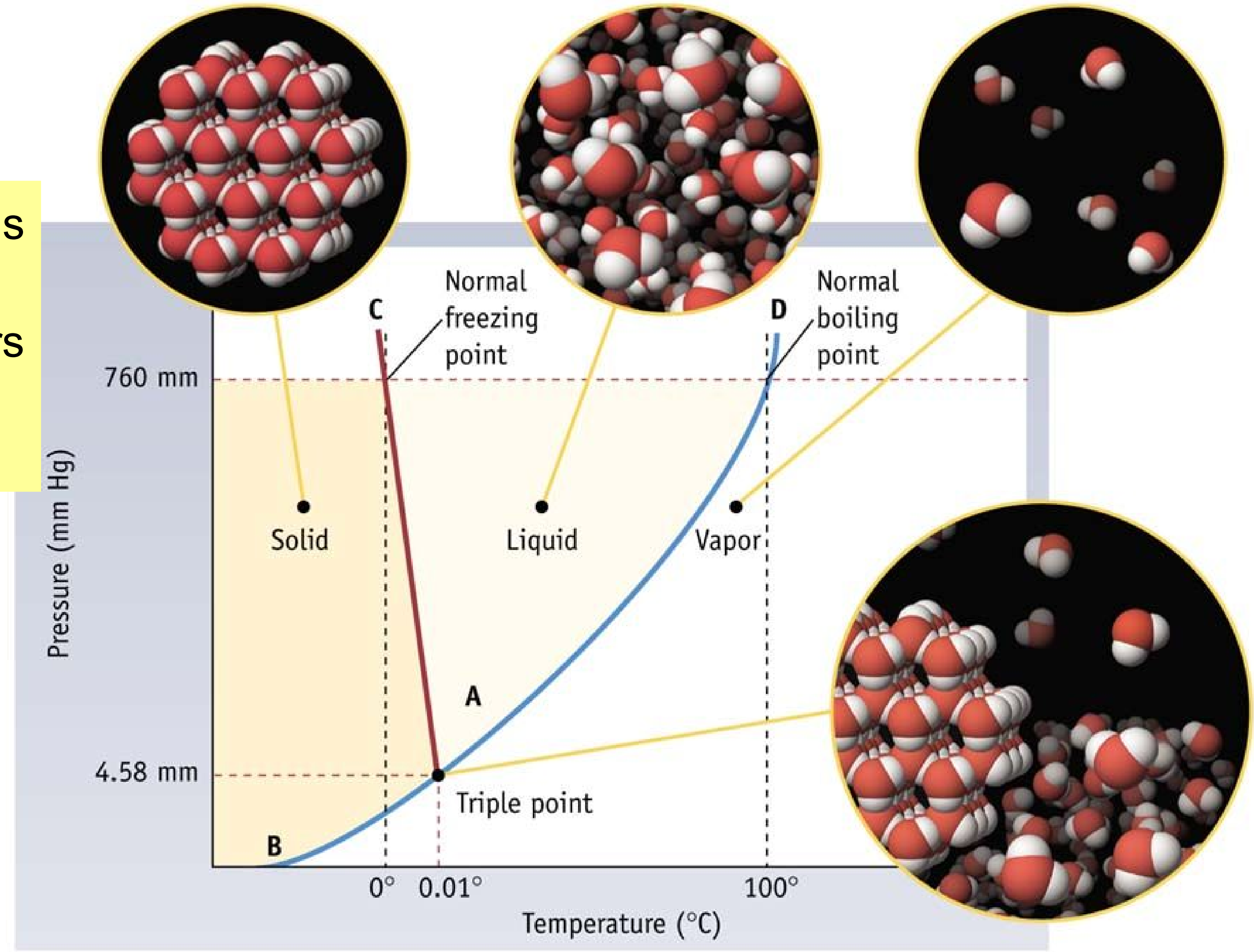
- rich new phenomena of fundamental importance
- access physics domains not accessible in small systems
    - superconductivity, band gaps, etc

(connection between simple and bulk systems nontrivial & theoretically intractable)

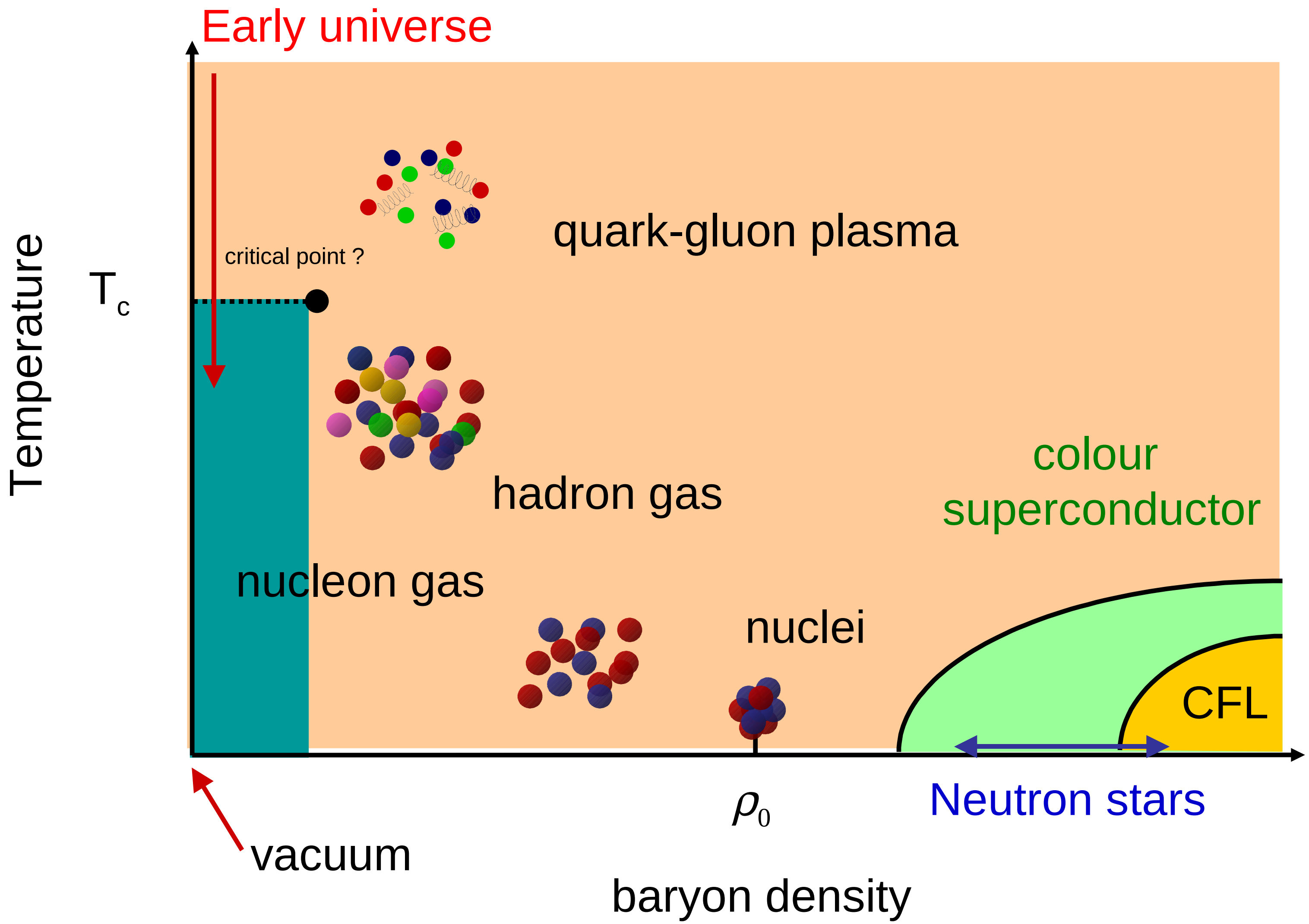
The phase diagram of water

Analogous graphs

- superfluids
- superconductors
- metal/insulator
- …

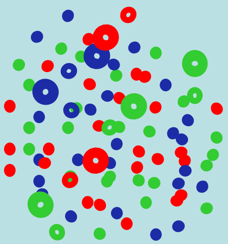


The phase diagram of QCD

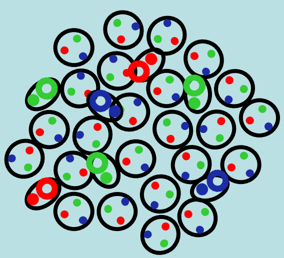


Lattice Calculations

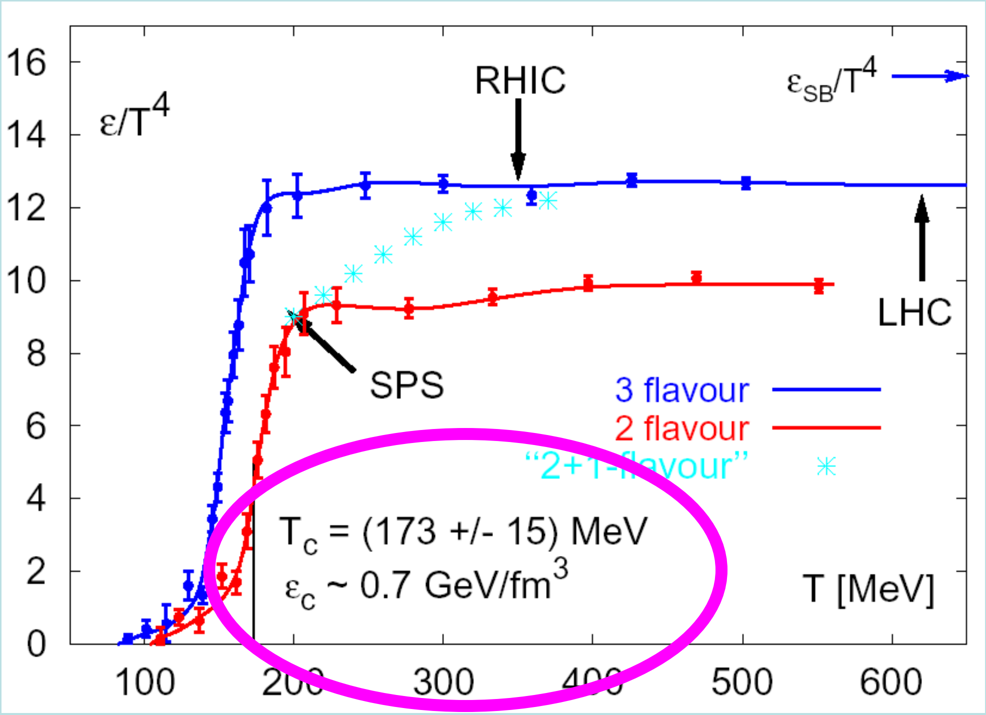
ε/T^4 ~ # degrees of freedom



deconfined:
many d.o.f.



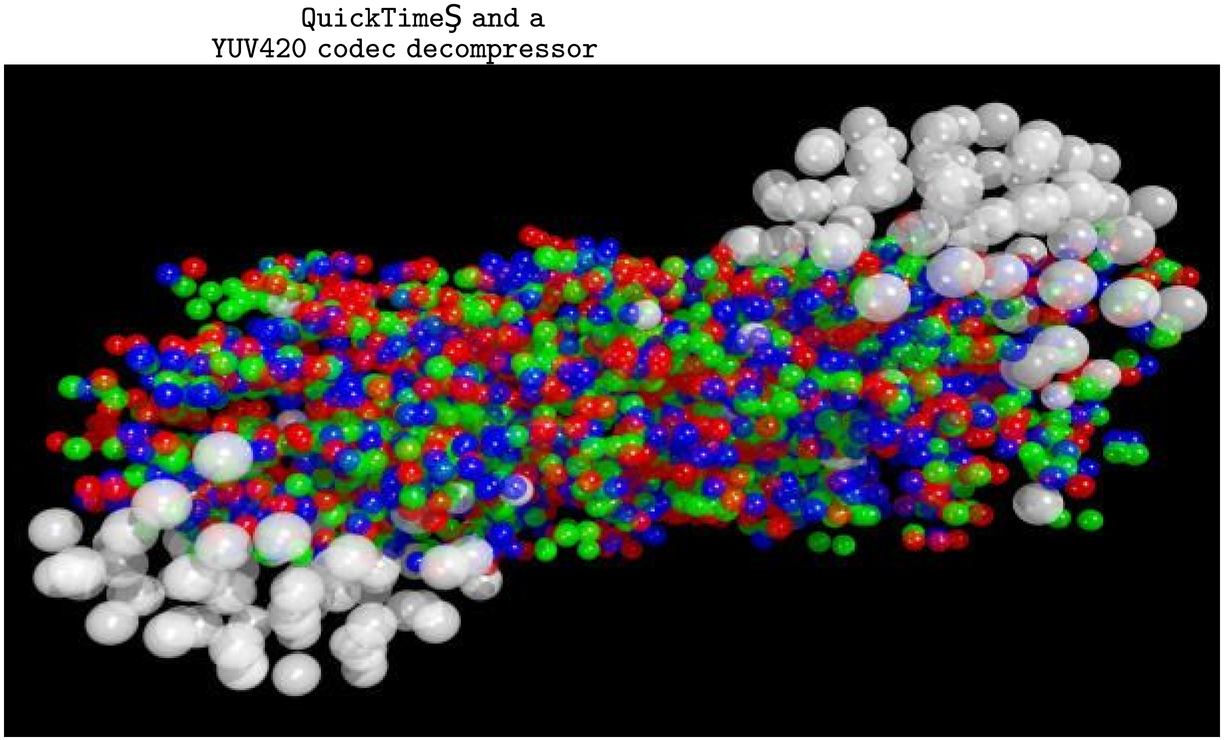
confined:
few d.o.f.



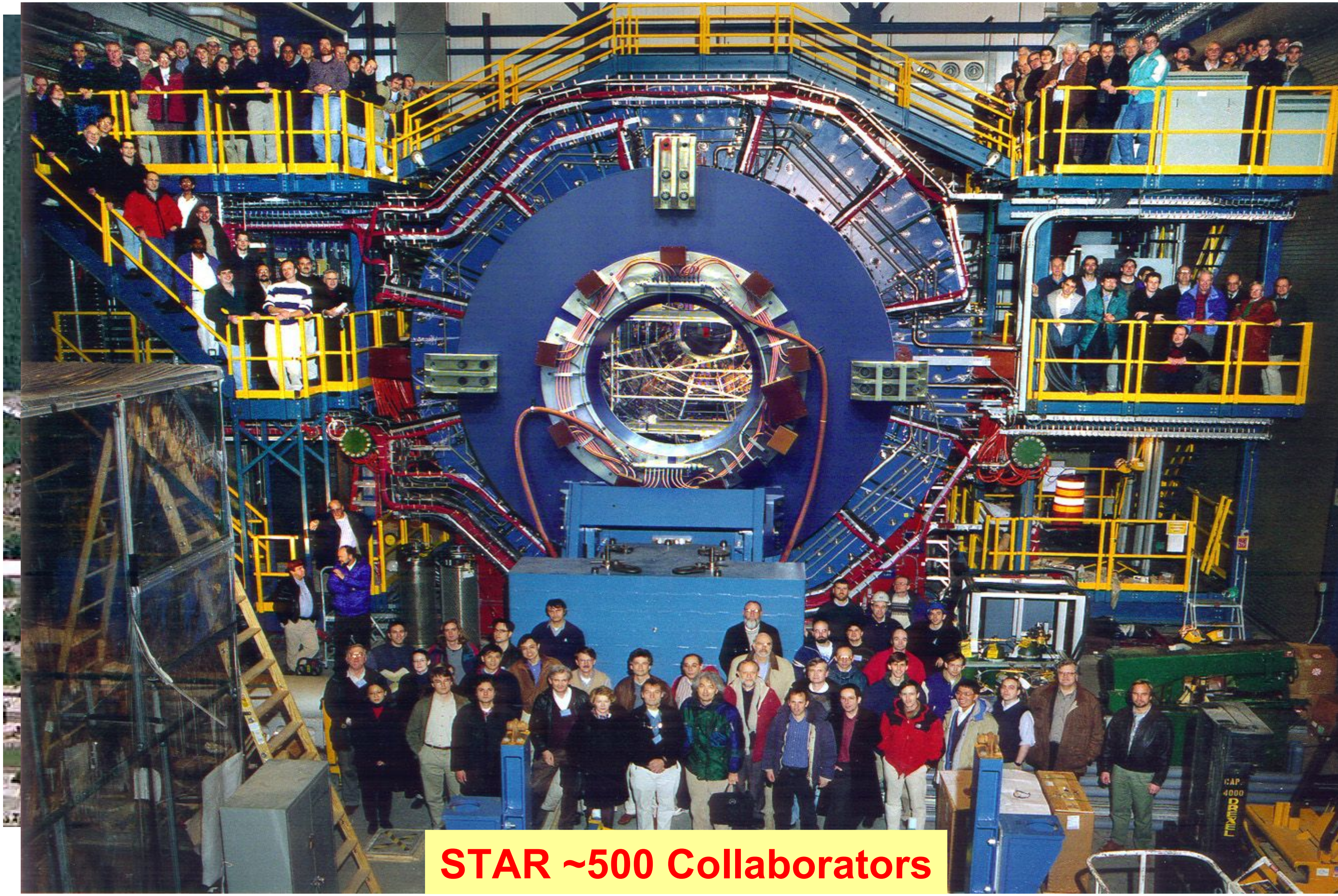
Bulk Matter

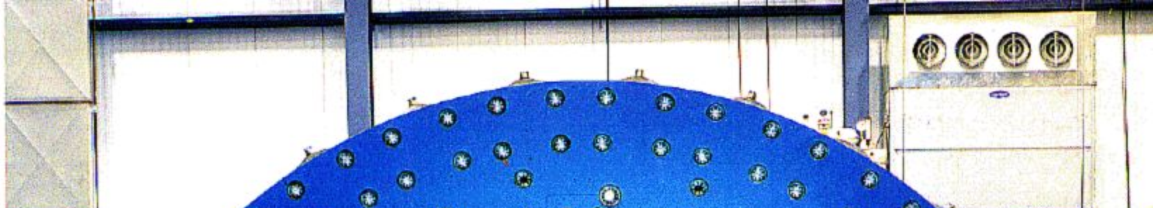
- We must create/compress/heat a **bulk** (geometrically large) system
  - freeze/melt a single H_20 molecule?
  - fundamental distinction from particle physics
- *Only* achievable through collisions of the heaviest nuclei (Au, Pb) at the highest available energy– at Relativistic Heavy Ion Collider (RHIC)

1000's of particles produced in *each* collision



Relativistic Heavy Ion Collider (RHIC)

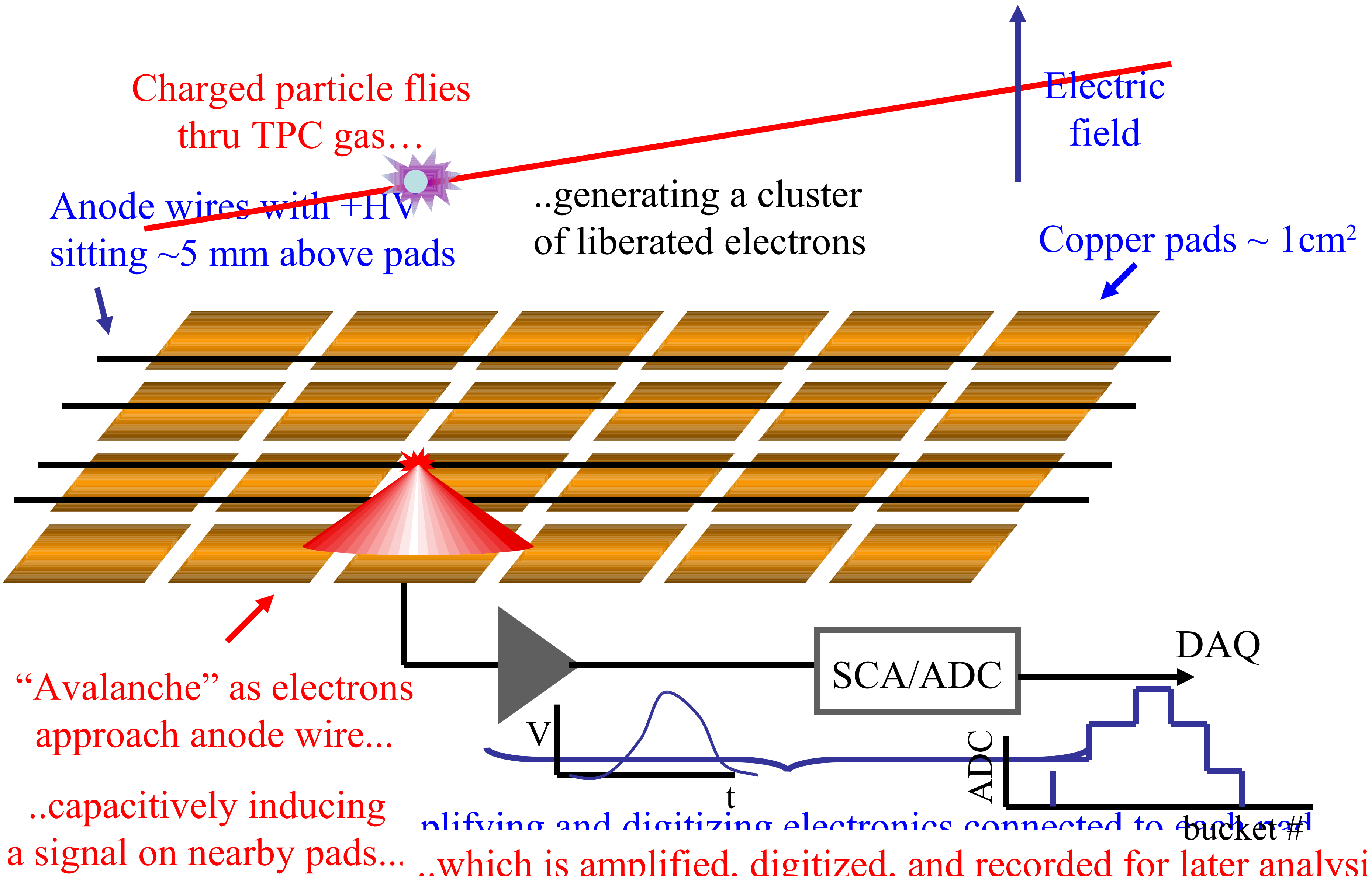




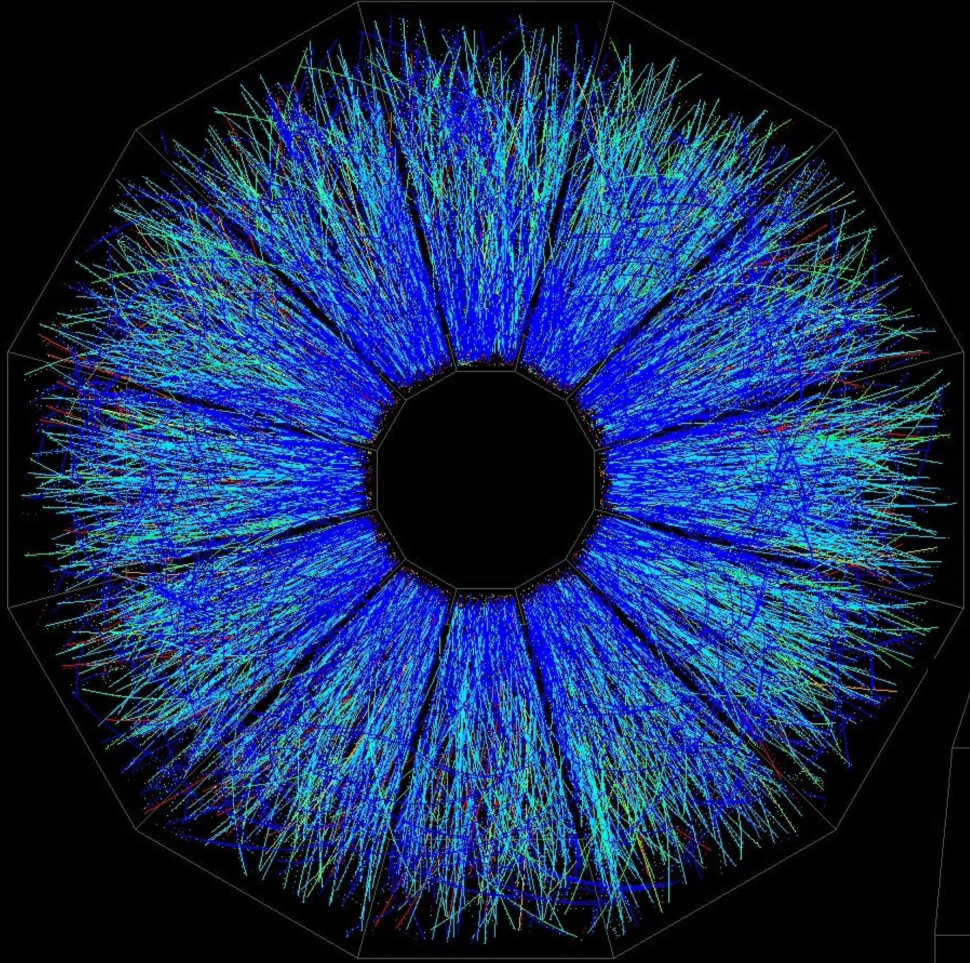
Solenoidal Tracker At RHIC

goal: track “all” charged hadrons (bags of quarks) emitted in each collision

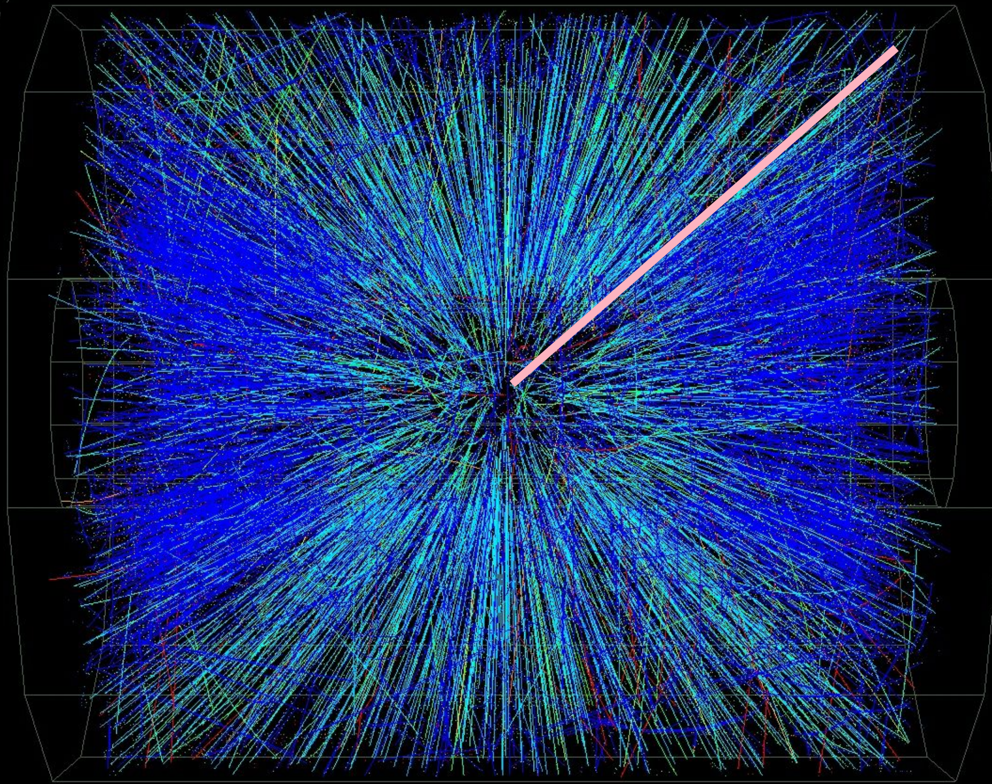
Operation of a Time Projection Chamber



One collision seen by STAR TPC



Momentum determined by track curvature in magnetic field…



…and by direction relative to beam

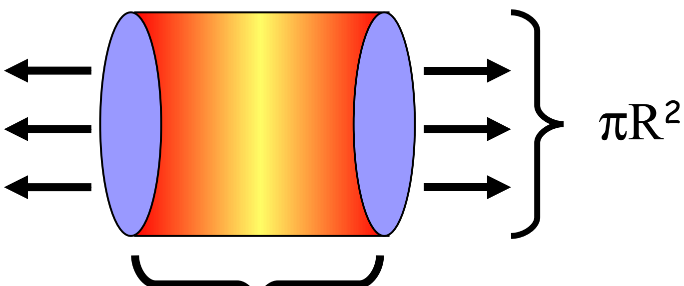
Crudest, day-1 estimate of ε

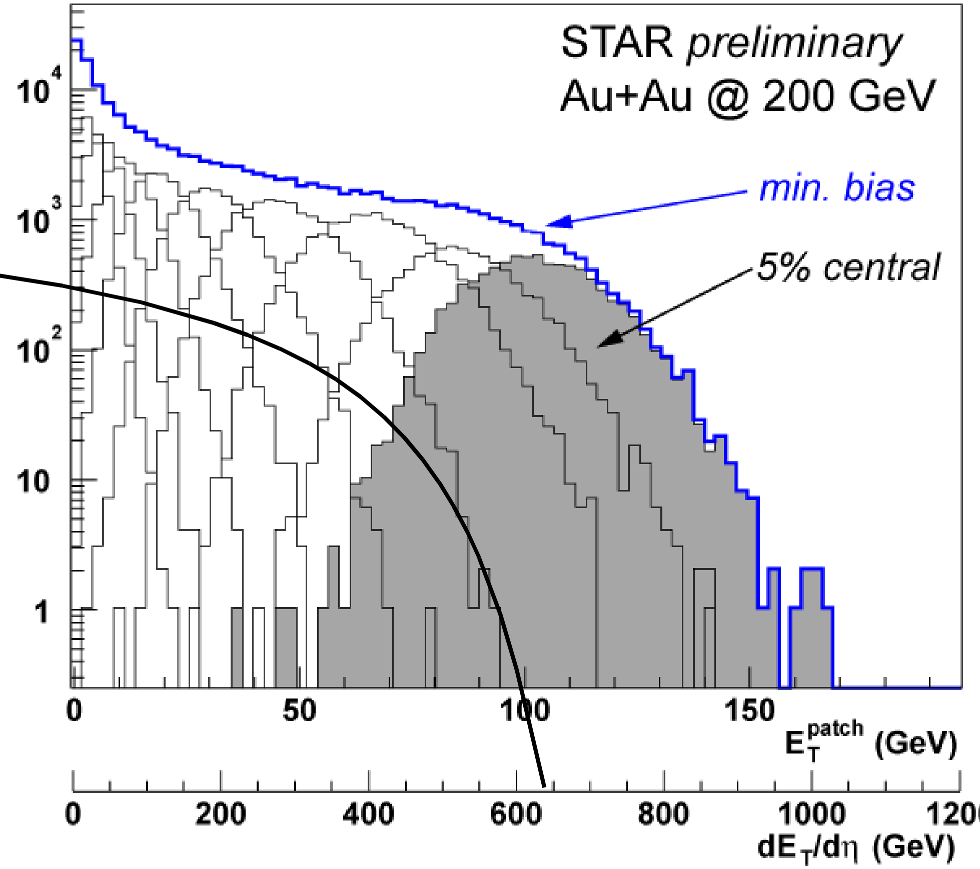
Bjorken-Formula for Energy Density:
PRD 27, 140 (1983) – watch out for typo (factor 2)

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

~6.5 fm

Time it takes to thermalize system ($\tau_0 \sim$ 1 fm/c)

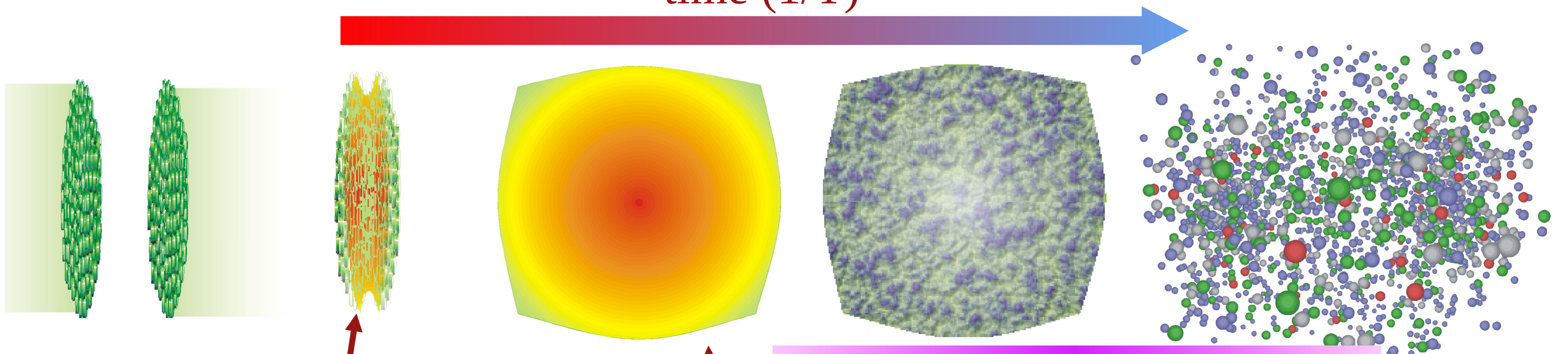




Central Au+Au (Pb+Pb) Collisions:
17 GeV: $\varepsilon_{BJ} \approx 3.2$ GeV/fm³
130 GeV: $\varepsilon_{BJ} \approx 4.6$ GeV/fm³
200 GeV: $\varepsilon_{BJ} \approx 5.0$ GeV/fm³

Note: τ_0 (RHIC) < τ_0 (SPS)
commonly use 1 fm/c in both cases

Stages of the collision



Chemical freezeout
- particle yields are fixed

hadronization
- c
- c

Kinetic freezeout
- particle momenta are fixed

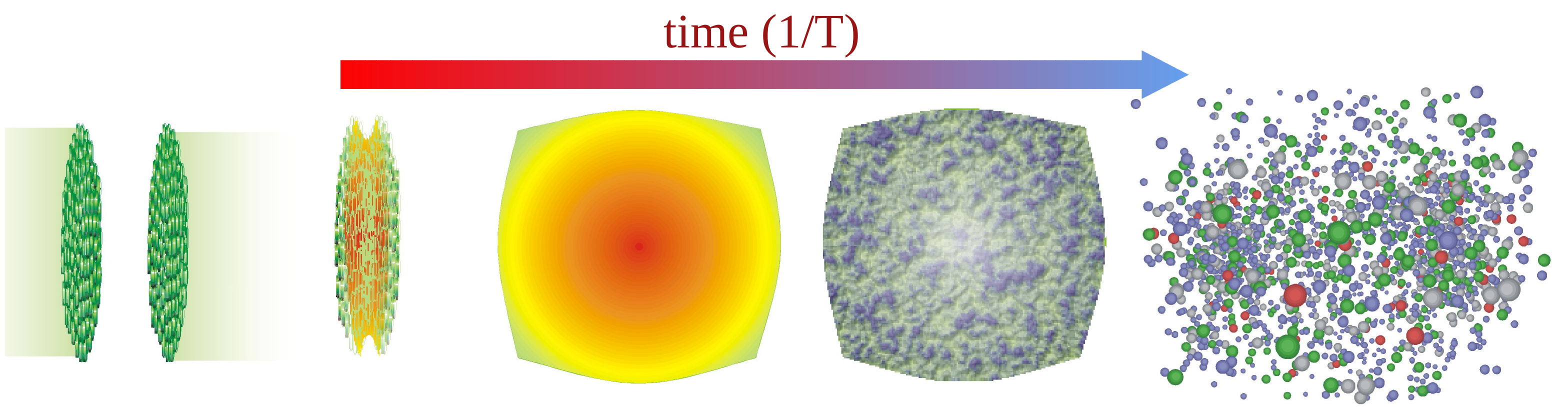
interpenetration “t=0”
- jets, hard processes
- pre-equilibrium

partonic structure t<0
- color glass condensate?

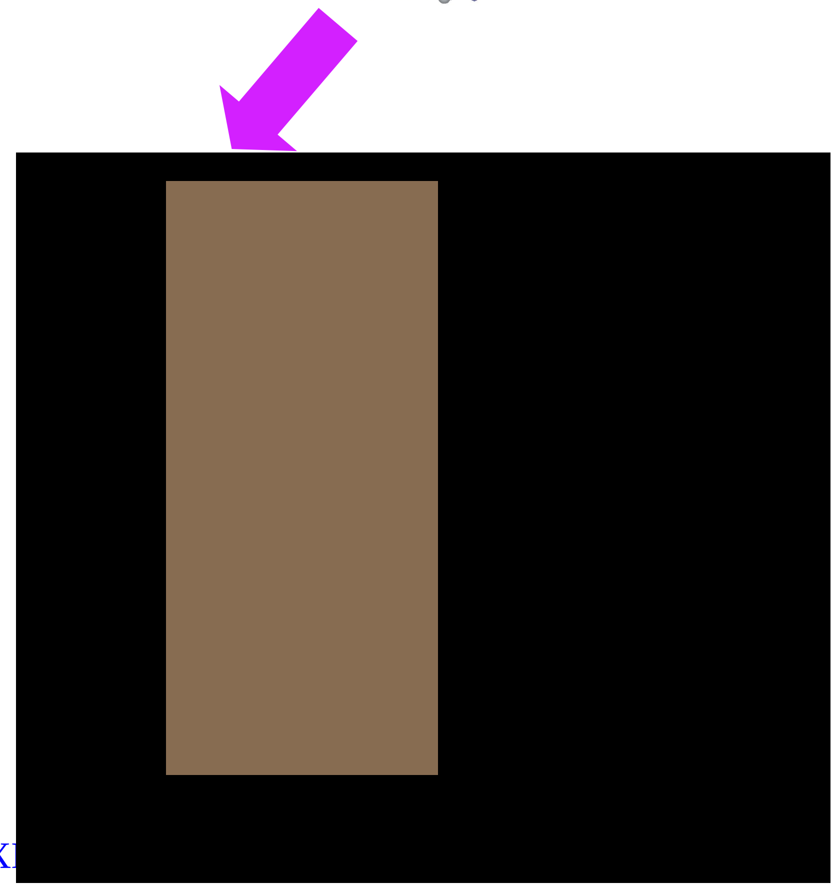
energy partition
- thermalization?
- QGP?

hadronic rescattering
- “must” be there?
- obscuring mist

Soft sector - ashes of the QGP

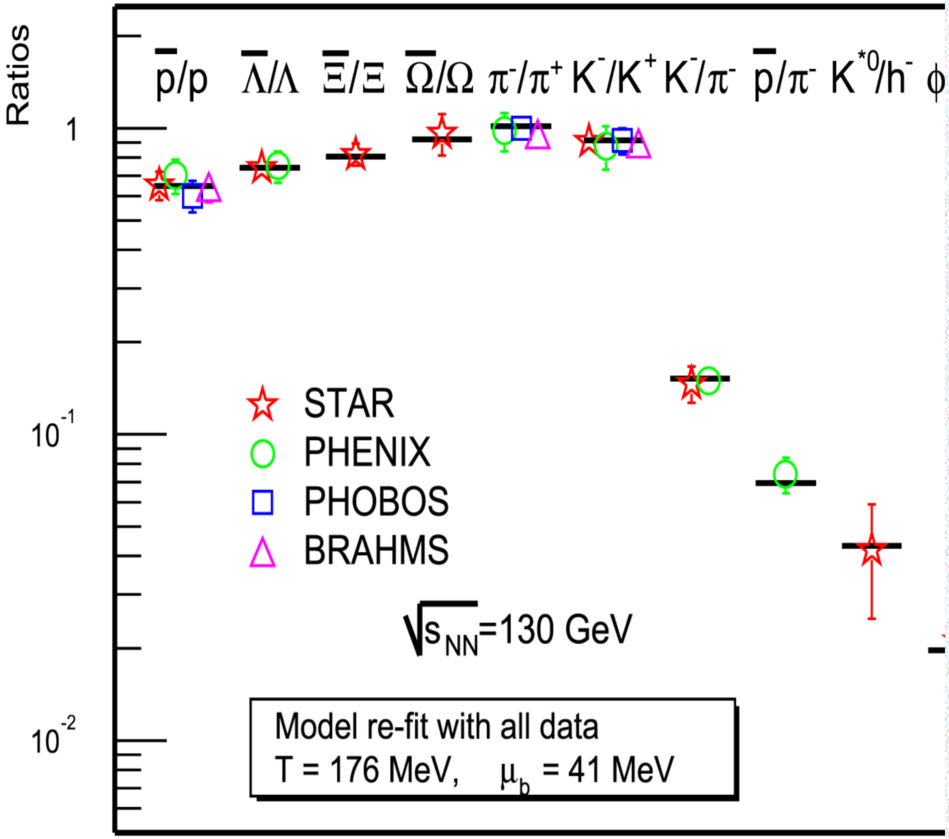


- high-pT tail ("pQCD") not thermalized
- medium (?) itself decays into low momentum particles ("soft sector")
  - QGP is non-perturbative, low-Q phenomenon (need expt'l info)
  - dynamics - difficult but crucial here

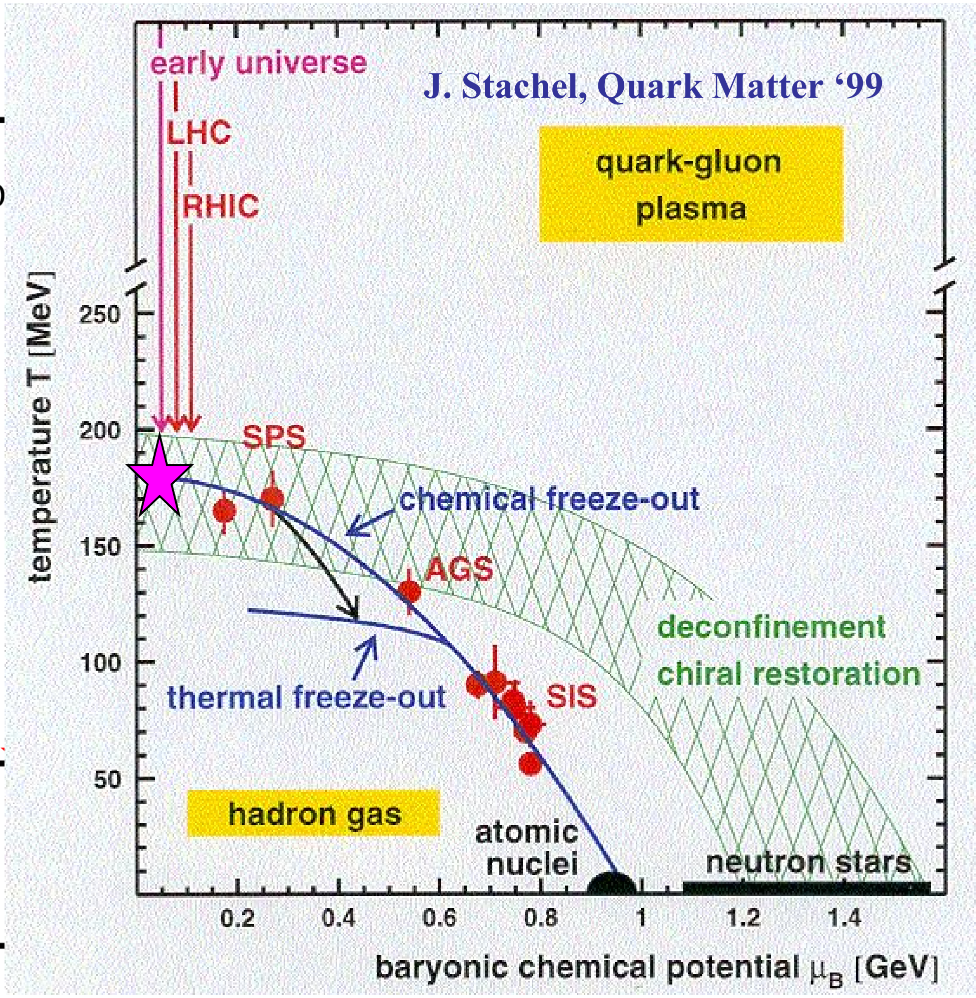


- *Is* it a "big" "system/medium"?
  - bulk, collective behaviour
- Thermo properties
  - potentials, temperature (EoS)
- How does it evolve in spacetime?
  - dynamic response to pressure, (EoS)

Chemical freezeout



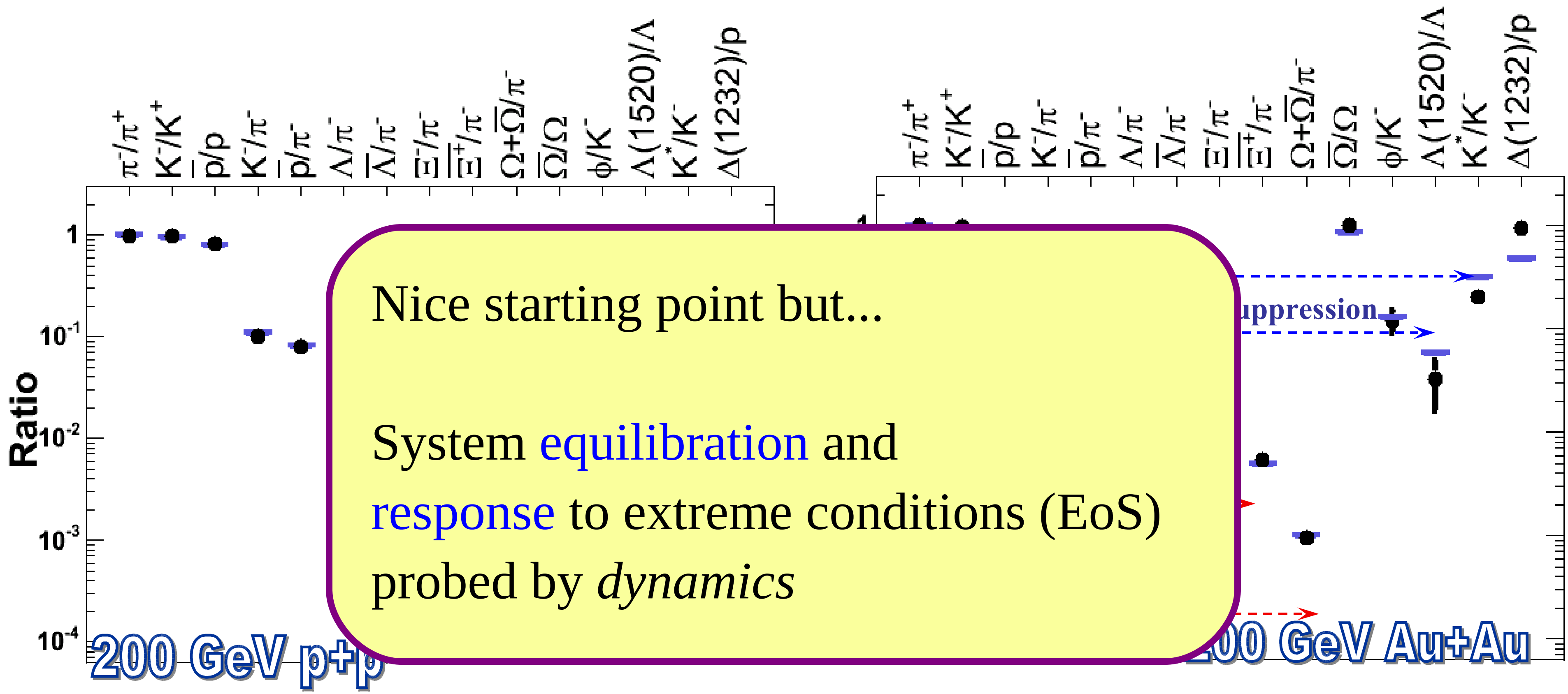
Braun-Munzinger et al., PLB 518 (2001) 41



$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \qquad \lambda_s = \exp(\mu_s/T_{ch})$$

Careful: need not be "system" "thermalization"



Nice starting point but…

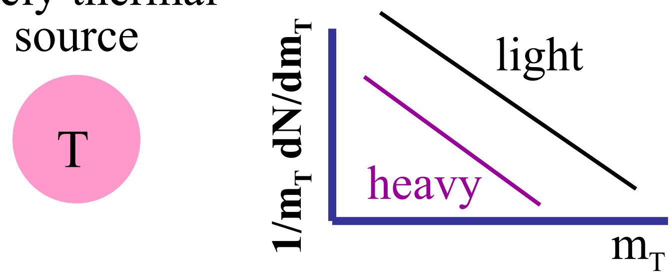
System equilibration and response to extreme conditions (EoS) probed by *dynamics*

– pp, AuAu described by *same* T, μ
  – phasespace dominance? / "born" into max entropy?
– differences
  – "strangeness enhancement" (loss of canonical suppression) in AA
  – *measured* short-lived resonance yields suppressed (hadronic rescattering)

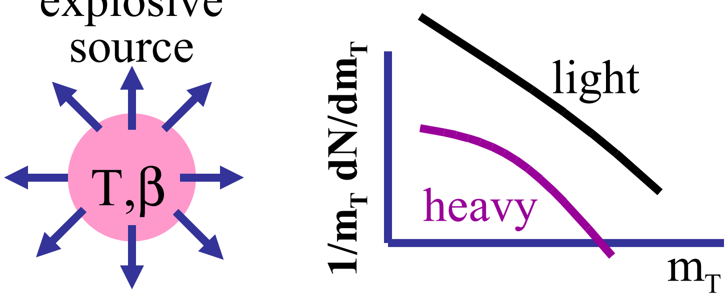
Collective motion in p_T spectra

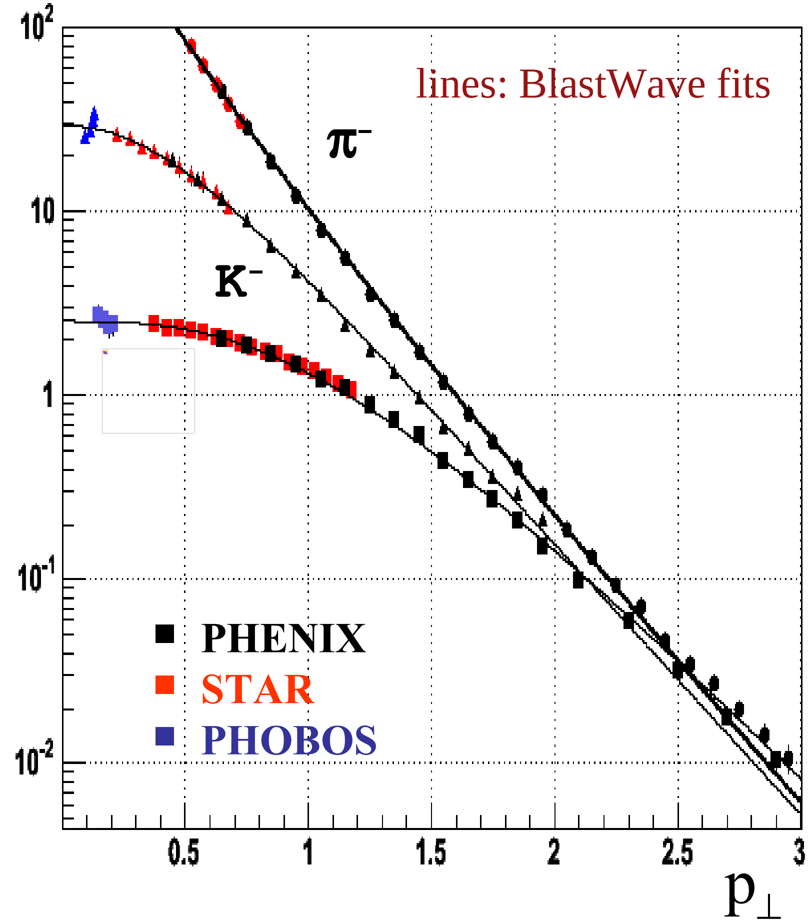
- various experiments agree well
- different spectral shapes for particles of differing mass
  $\rightarrow$ strong collective radial flow

purely thermal source

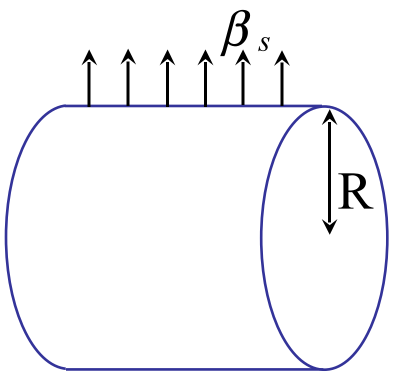


explosive source



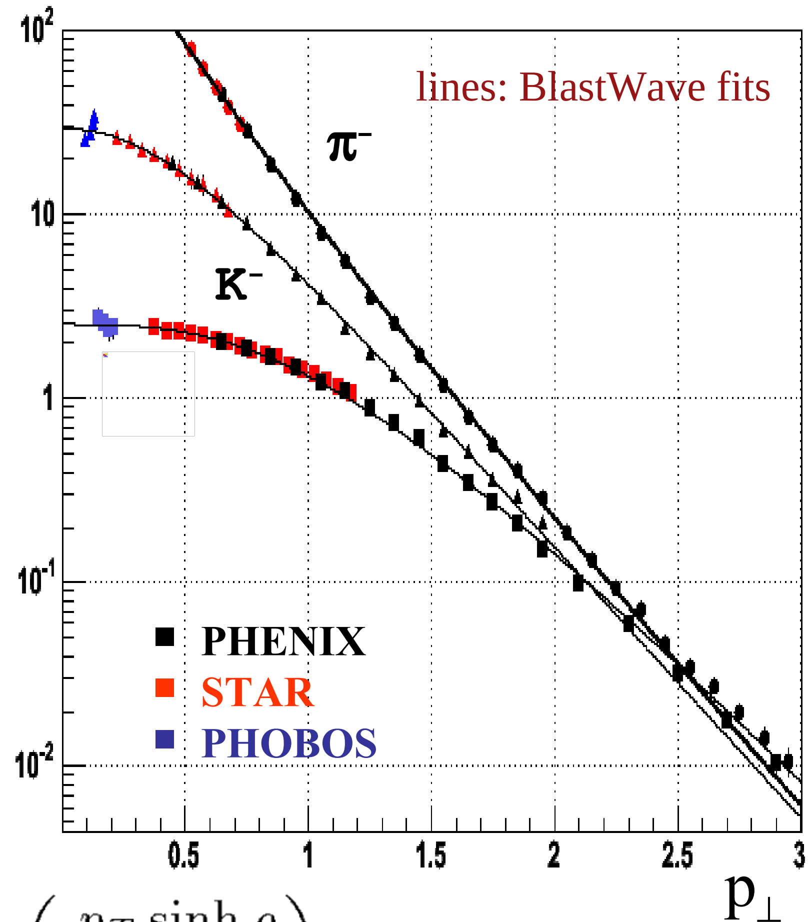


Thermal motion superimposed on radial flow



$$E\frac{d^3n}{dp^3} \propto \int_\sigma e^{-(u^\nu p_\nu)/T_{th}} p^\lambda d\sigma_\lambda$$

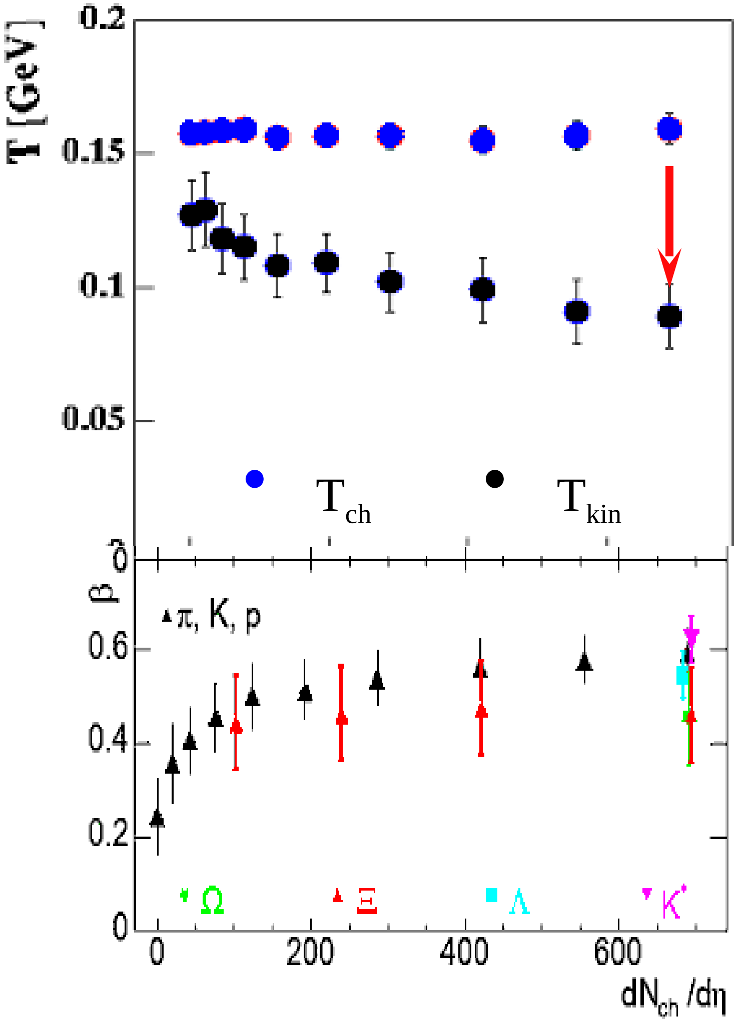
$$\upsilon^\nu(\tau,\rho,\zeta=0) = (\cosh\rho, \varepsilon_\rho \sinh\rho, 0)$$

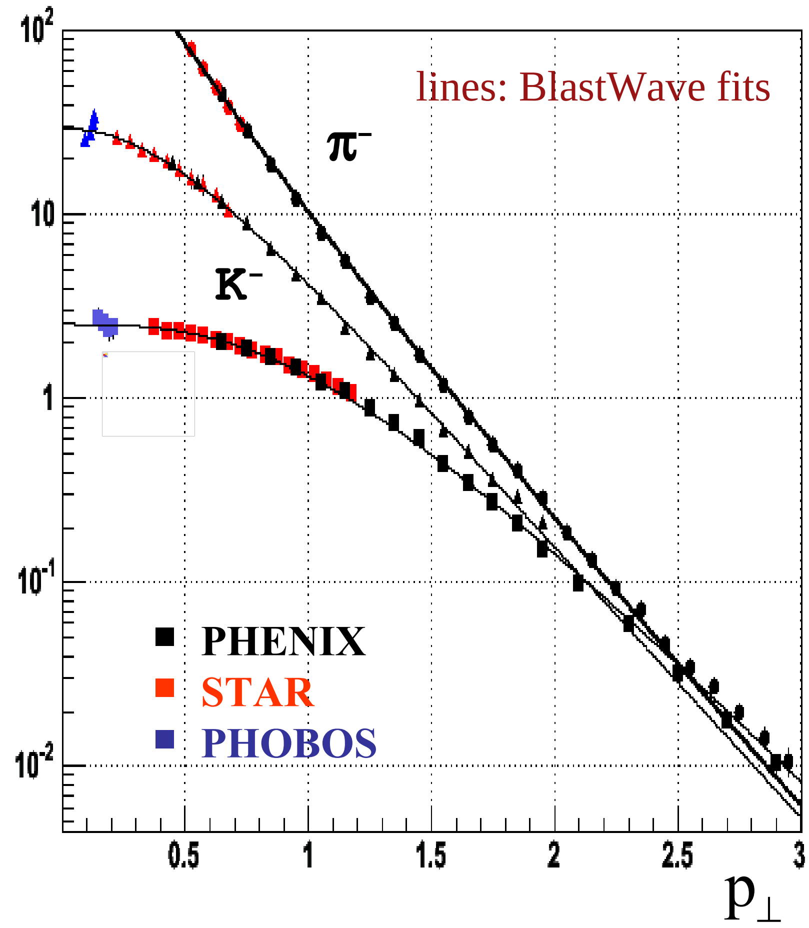


$$\frac{dn}{m_T dm_T} \propto \int_0^R r\,dr\, m_T K_1\left(\frac{m_T \cosh\rho}{T_{th}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{th}}\right)$$

E.Schnedermann et al, PR**C48** (1993) 2462
F. Retiere & MAL PR**C70:**044907,2004

Kinetic F.O. - p_T spectra





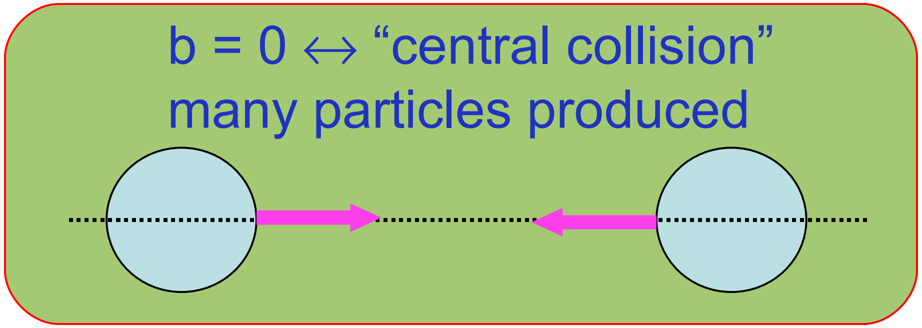
- explosive collective velocity ~0.6c
- cooling chemical → kinetic FO

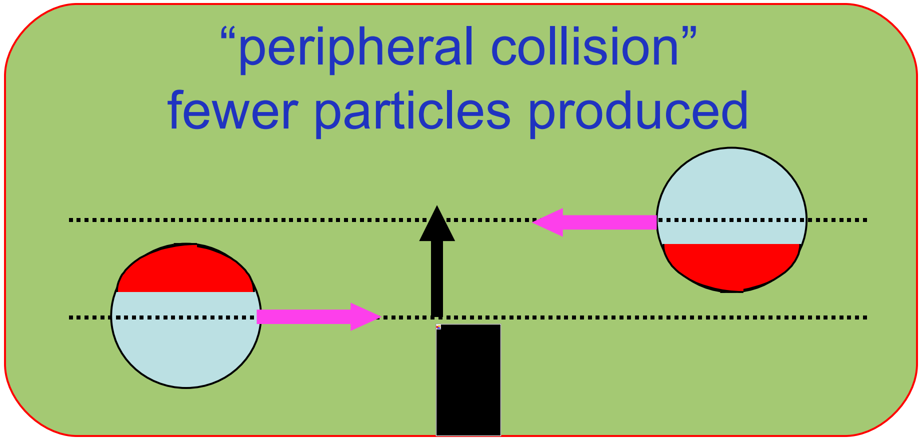
Impact parameter & Reaction plane

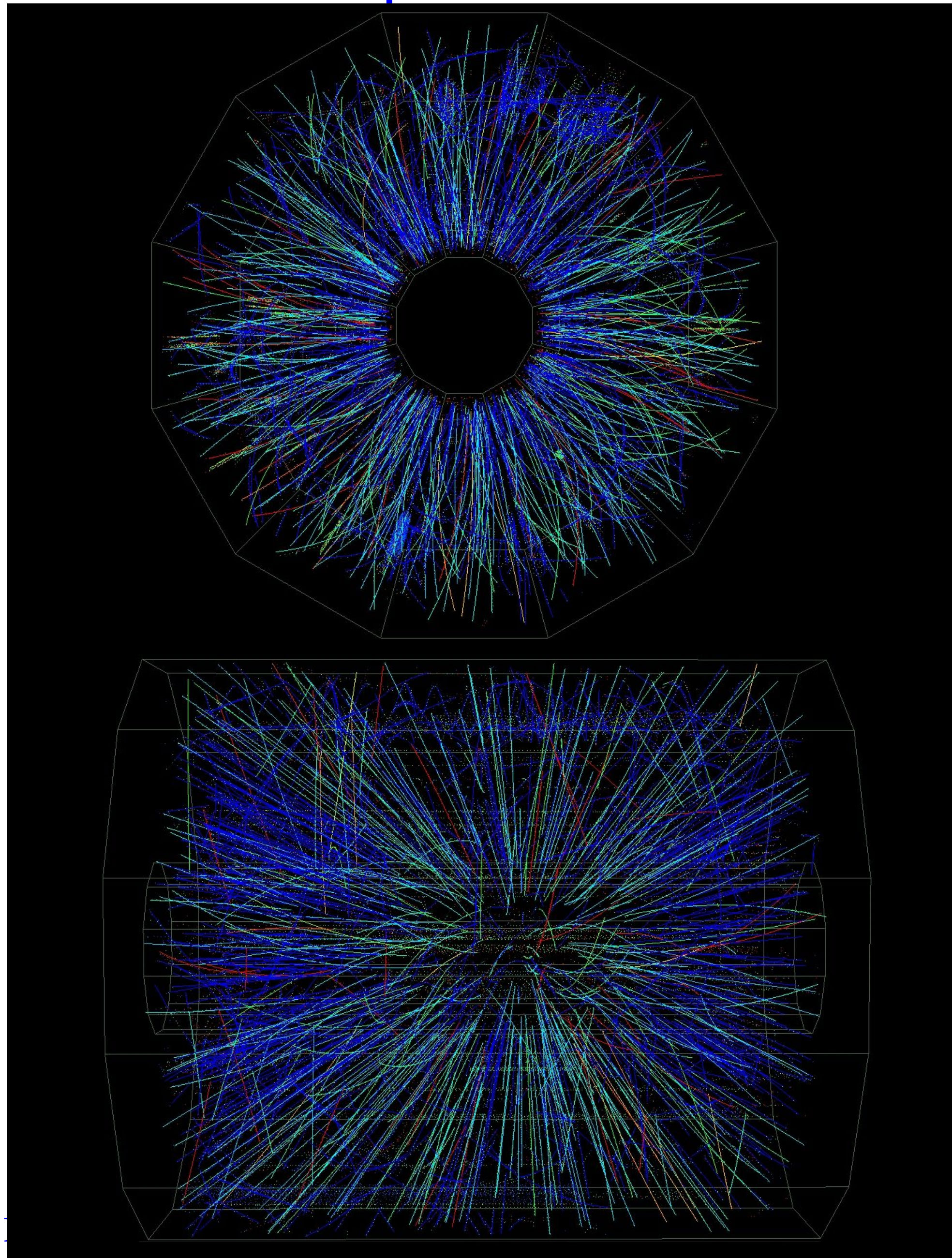
Impact parameter vector $\vec{b}$:

g $\perp$ beam direction

gconnects centers of colliding nuclei







Impact parameter & Reaction plane

Impact parameter vector $\vec{b}$:

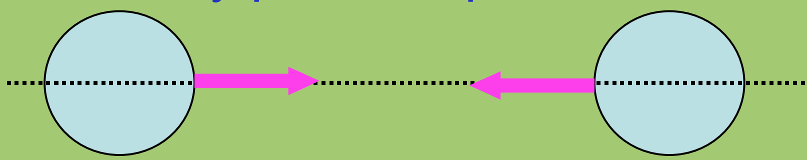
g ⊥ beam direction

gconnects centers of colliding nuclei

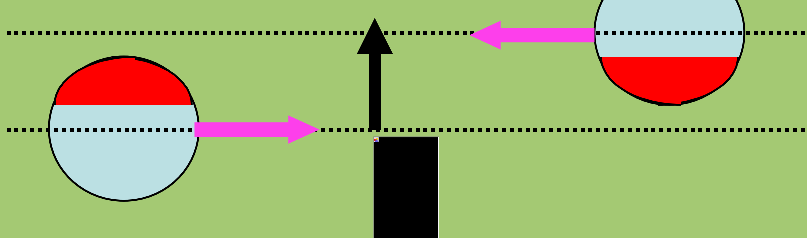
Reaction plane:

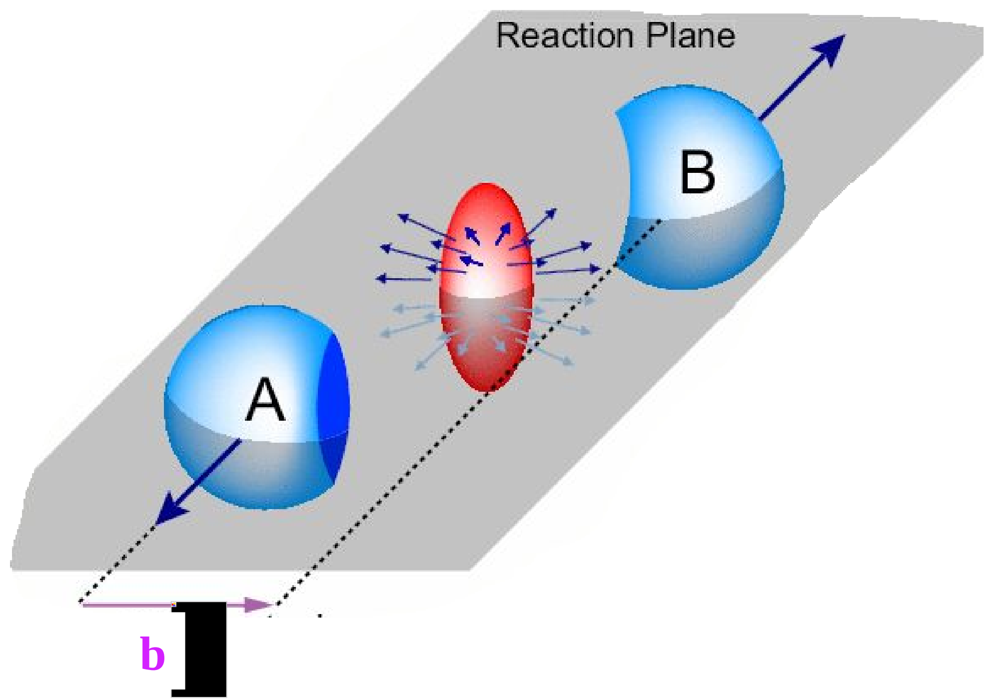
spanned by beam direction and $\vec{b}$

b = 0 ↔ “central collision”
many particles produced



“peripheral collision”
fewer particles produced

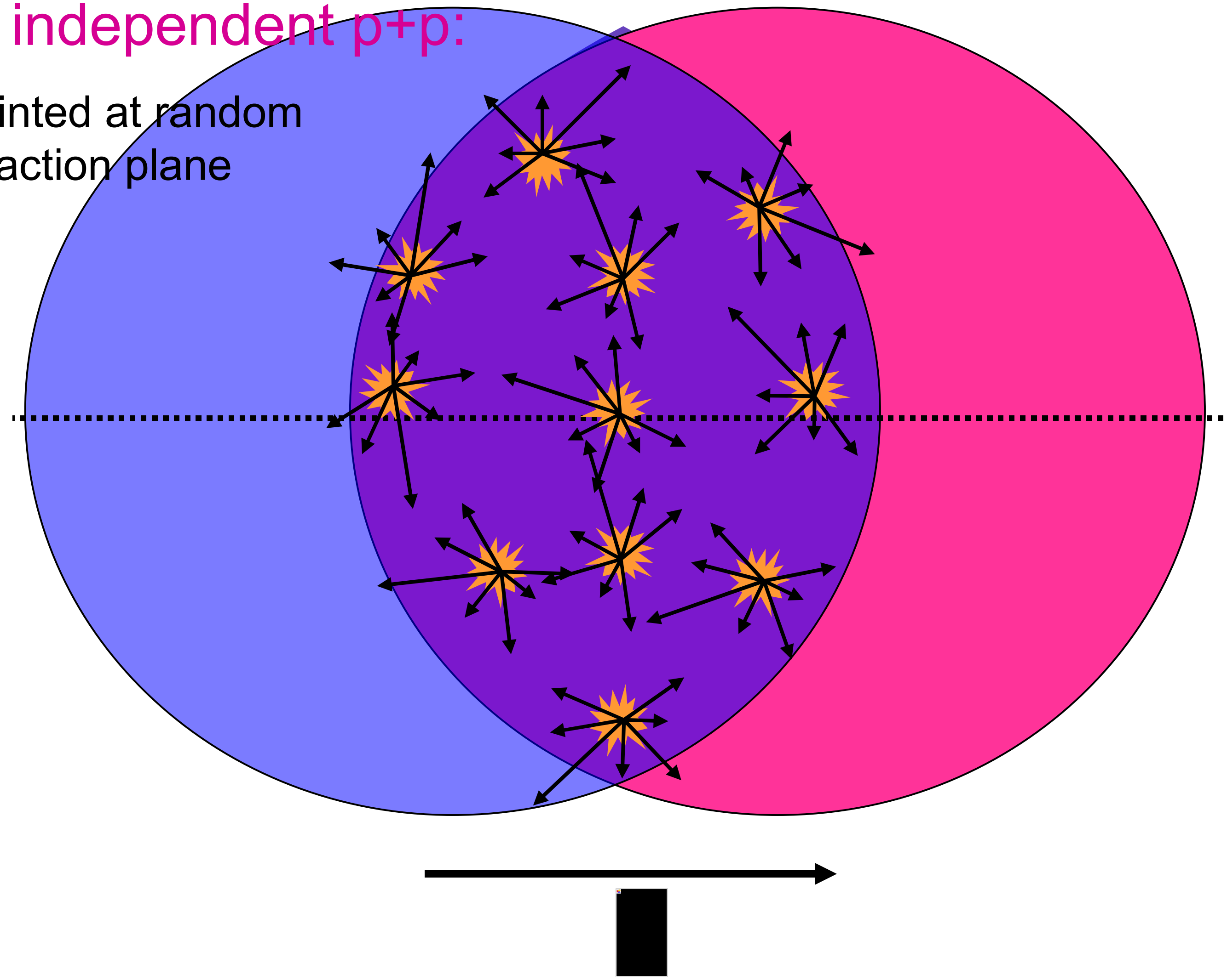




How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane



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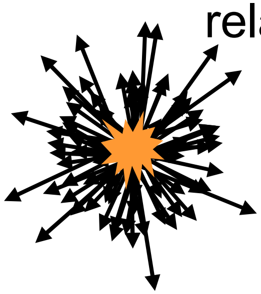
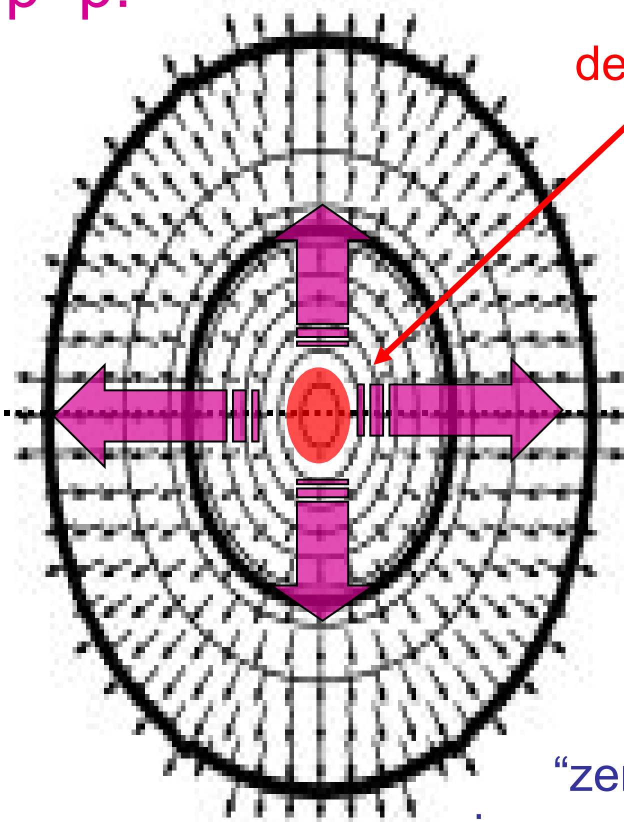


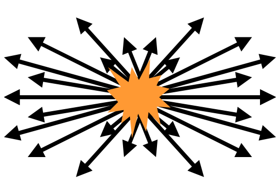
high
density / pressure
at center



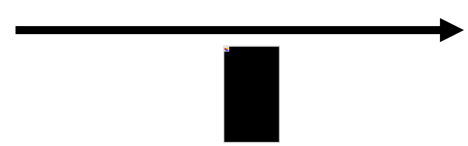
"zero" pressure
in surrounding vacuum

2) Evolution as a **bulk system**

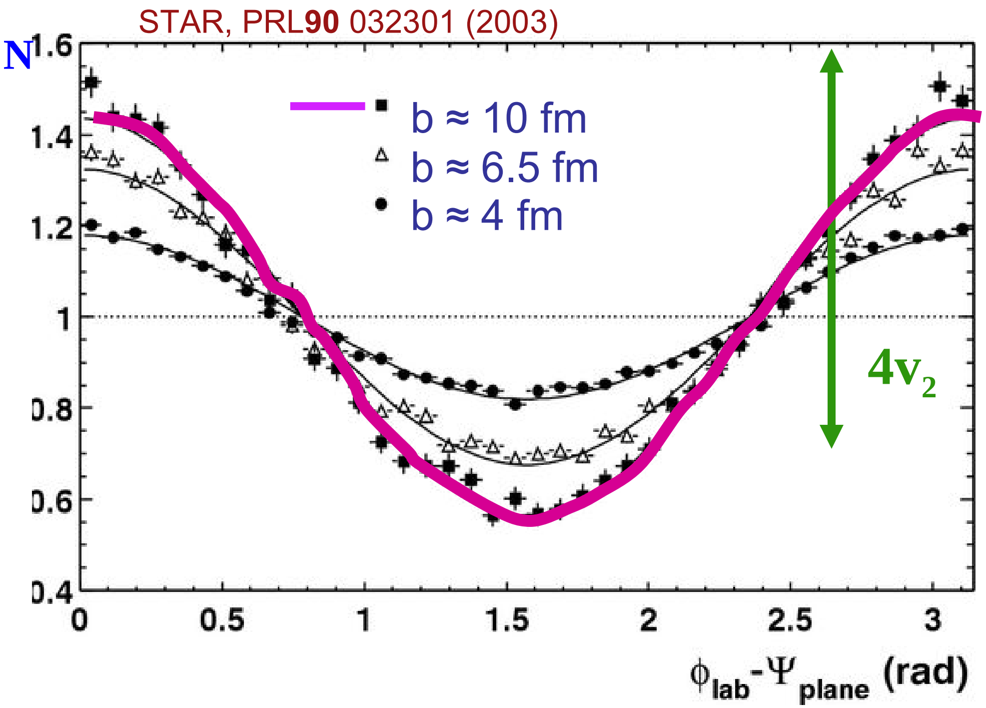
Pressure gradients (larger in-plane)
push bulk "out" → "flow"

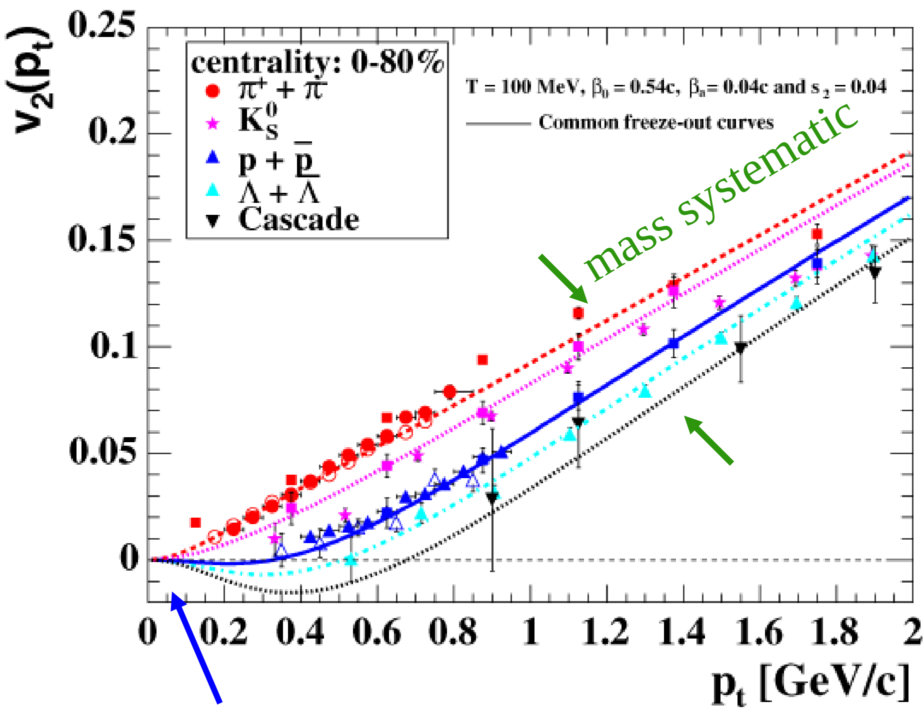


more, faster particles
seen in-plane



Elliptic flow v_2

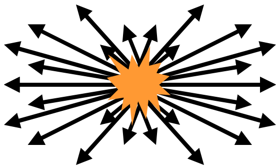




symmetry, thermal smearing

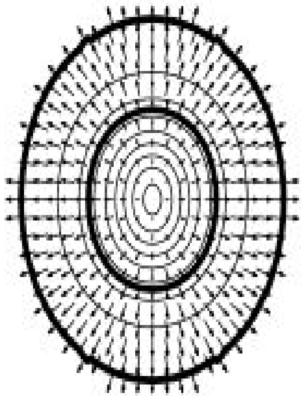
2) Evolution as a **bulk system**

Pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane

$v_2(p_T,m)$ consistent with anisotropic *velocity* field (i.e. property of *bulk*)



Elliptic flow – collectivity & sensitivity to *early* system

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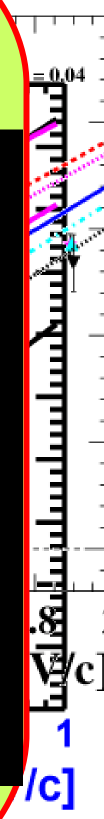
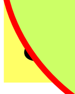
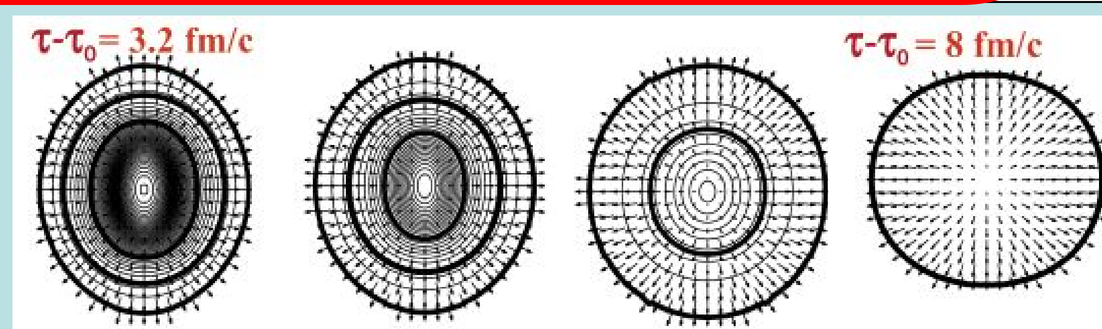
RHIC energies: the **first** quantitative success of hydro

• direct access to EoS (phase transitions, lattice, etc.)



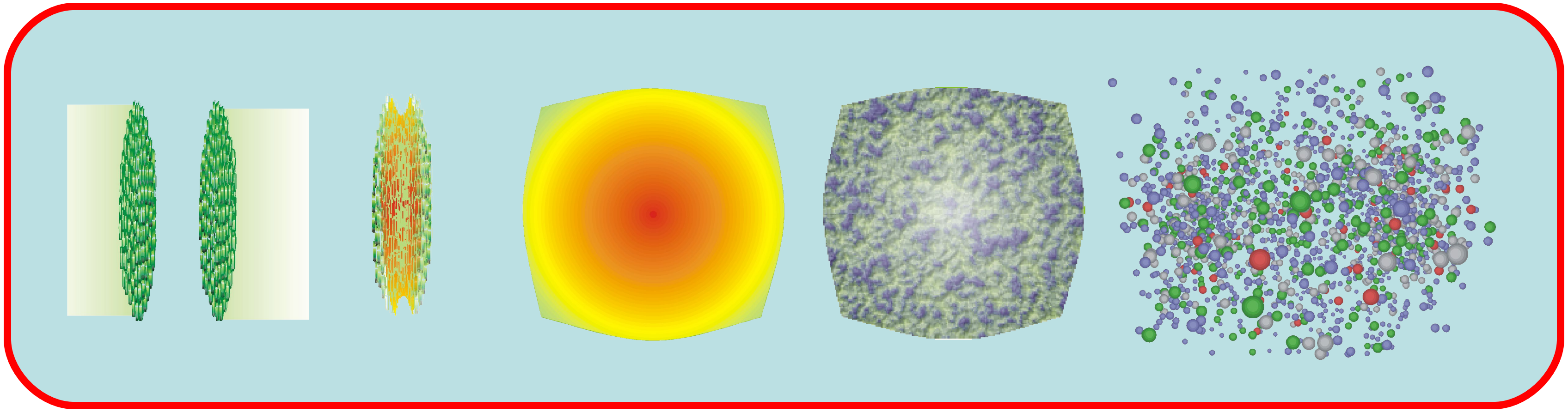


Hydrodynamic calculation of *system* evolution



A more direct *geometric* handle?

- elliptic flow (v_2) → evidence towards QGP at RHIC
  - –accounts for ~1/3 of RHIC HI experimental papers
  - –oblique connection to crucial issue of dynamics/spacetime geometry
  - –theoretical (hydro) dynamical evolution: “peering through the mist”



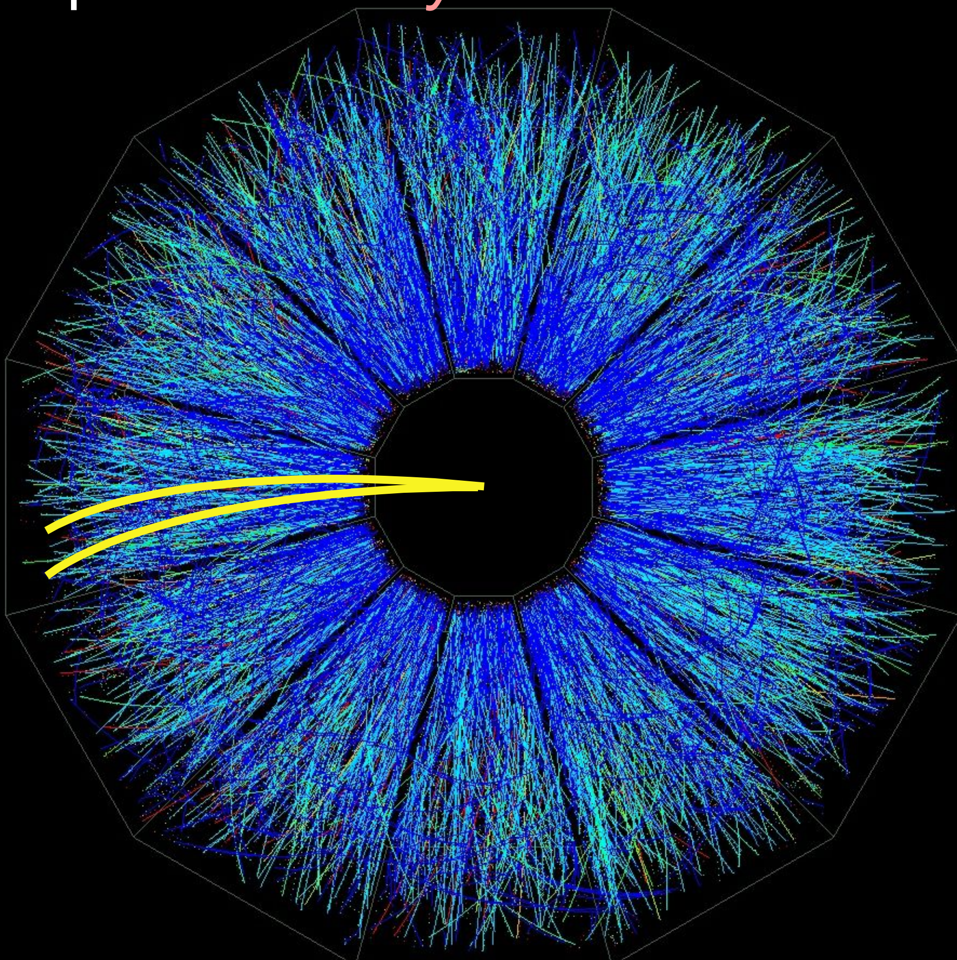
Two particle intensity interferometry: a more direct handle on spacetime

Recent review: MAL, S. Pratt, R. Soltz, U. Wiedemann nucl-ex/0505014

Probing source geometry through interferometry

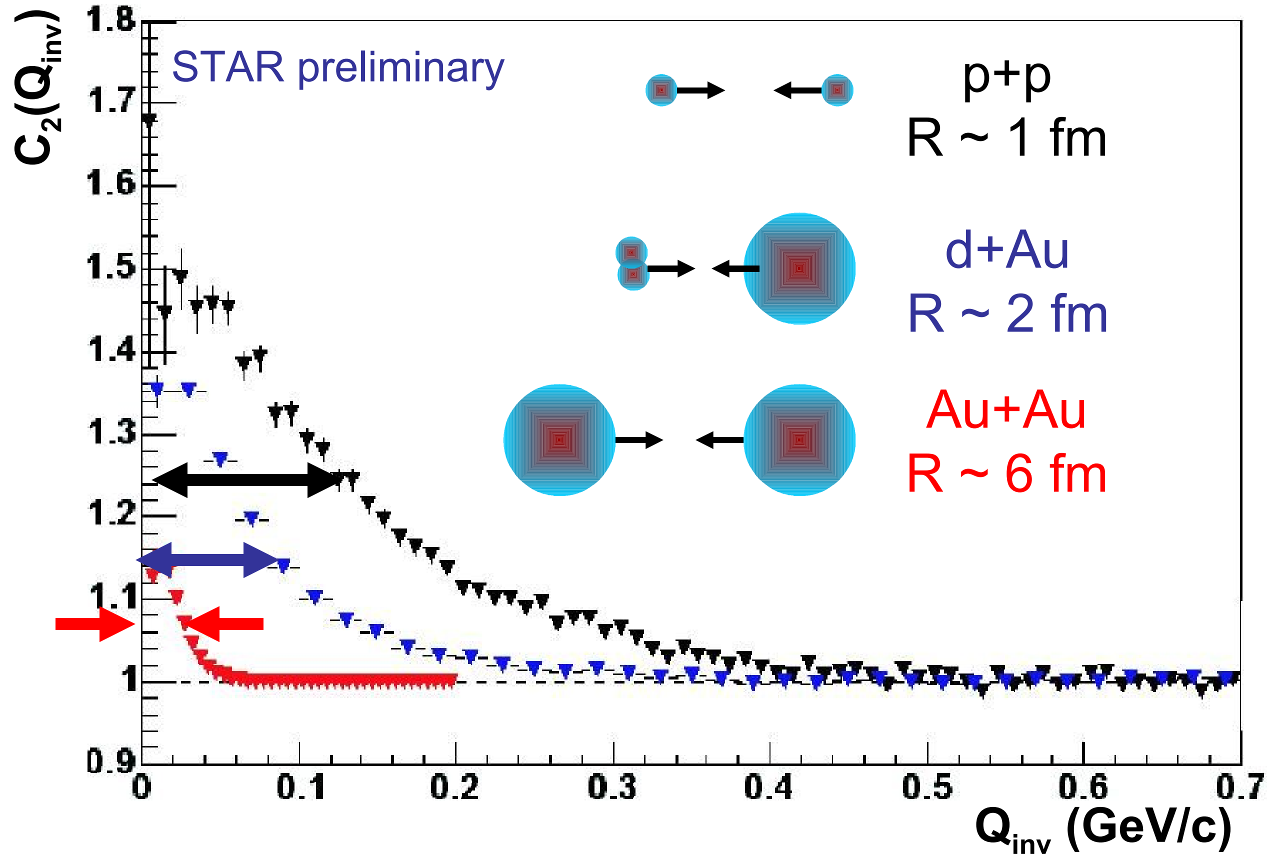
HBT: The Bottom line…

if a pion is emitted, it is more likely to emit another pion *with very similar momentum* if the source is small



experimentally measuring this enhanced probability: quite challenging

Correlation functions for different colliding systems



(Still amazing to me…)

Interferometry probes the smallest scales ever measured !

More detailed geometry

Relative momentum between pions is a **vector** $\vec{q} = \vec{p}_1 - \vec{p}_2$

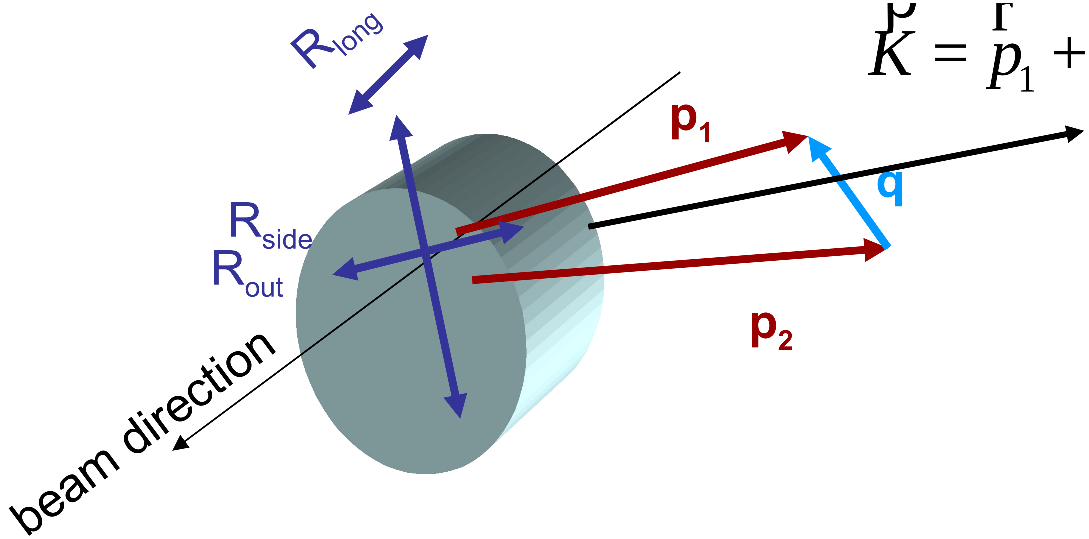
→ can extract 3D shape information

R_{long} – along beam direction

R_{out} – along “line of sight”

R_{side} – ⊥ “line of sight”

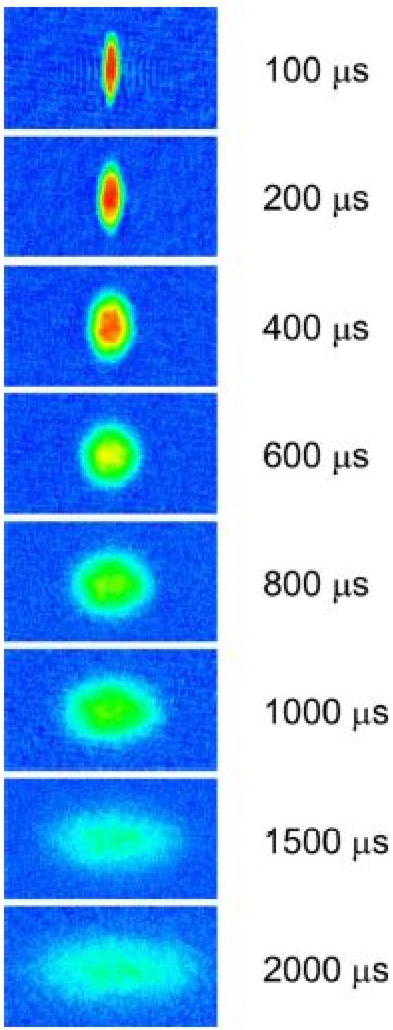
$$\vec{K} = \vec{p}_1 + \vec{p}_2$$



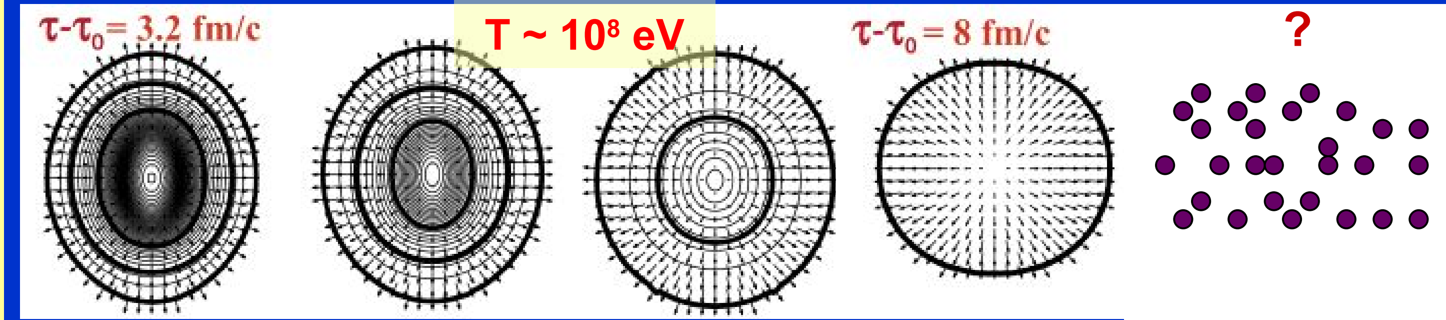
$$\mathrm{HBT}(\sqrt{s};p_T,y,|\vec{b}|,\phi_{\vec{p}},m_1,m_2,A_{sys})$$

Strongly-interacting ^6Li released from an asymmetric trap
O'Hara, *et al*, Science **298** 2179 (2002)
T ~ 10^{-12} eV

What can we learn?

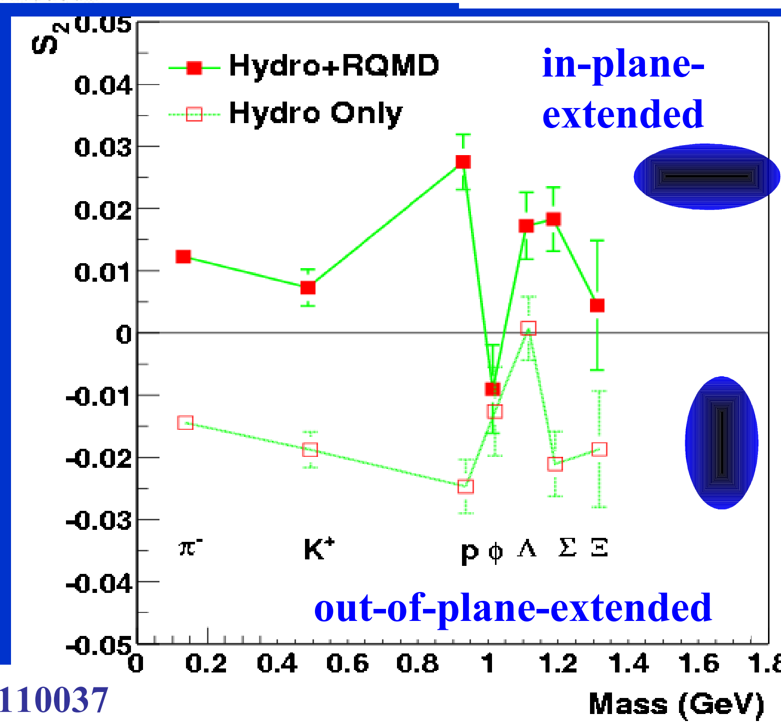


T ~ 10^8 eV



transverse FO shape
+ collective velocity
→ evolution time estimate

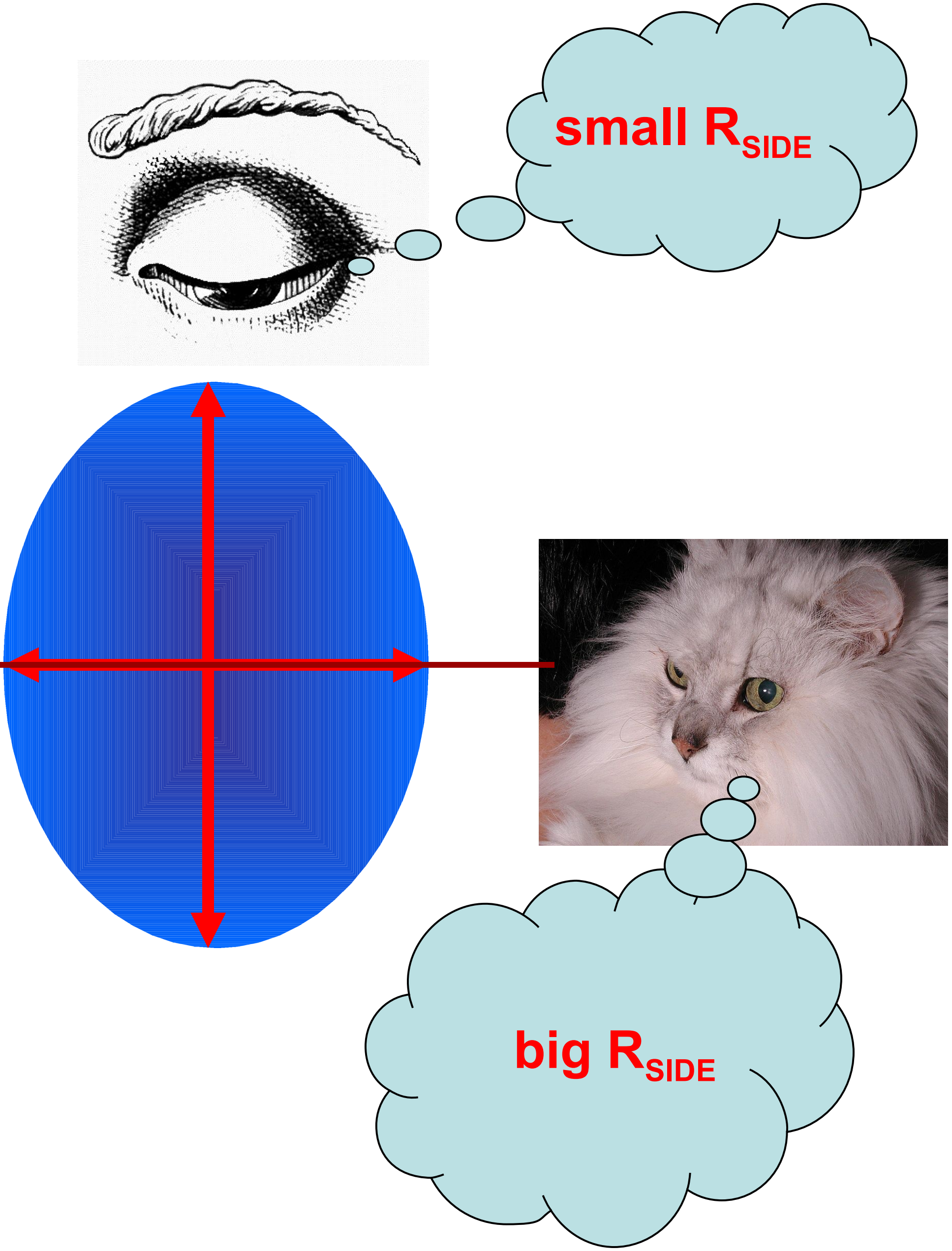
check independent of $R_L(p_T)$

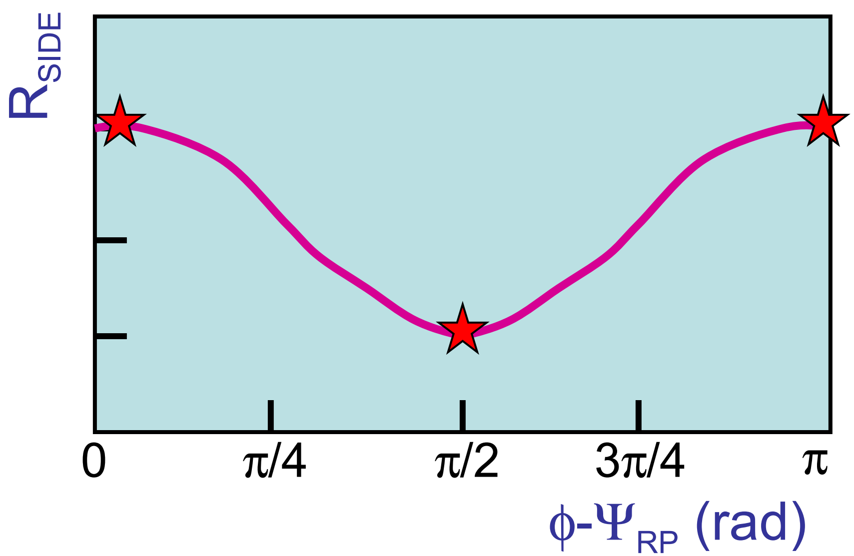


Teaney, Lauret, & Shuryak nucl-th/0110037

Source shape

- "observe" the source from all angles relative to the reaction plane
- expect oscillations in radii for non-round sources

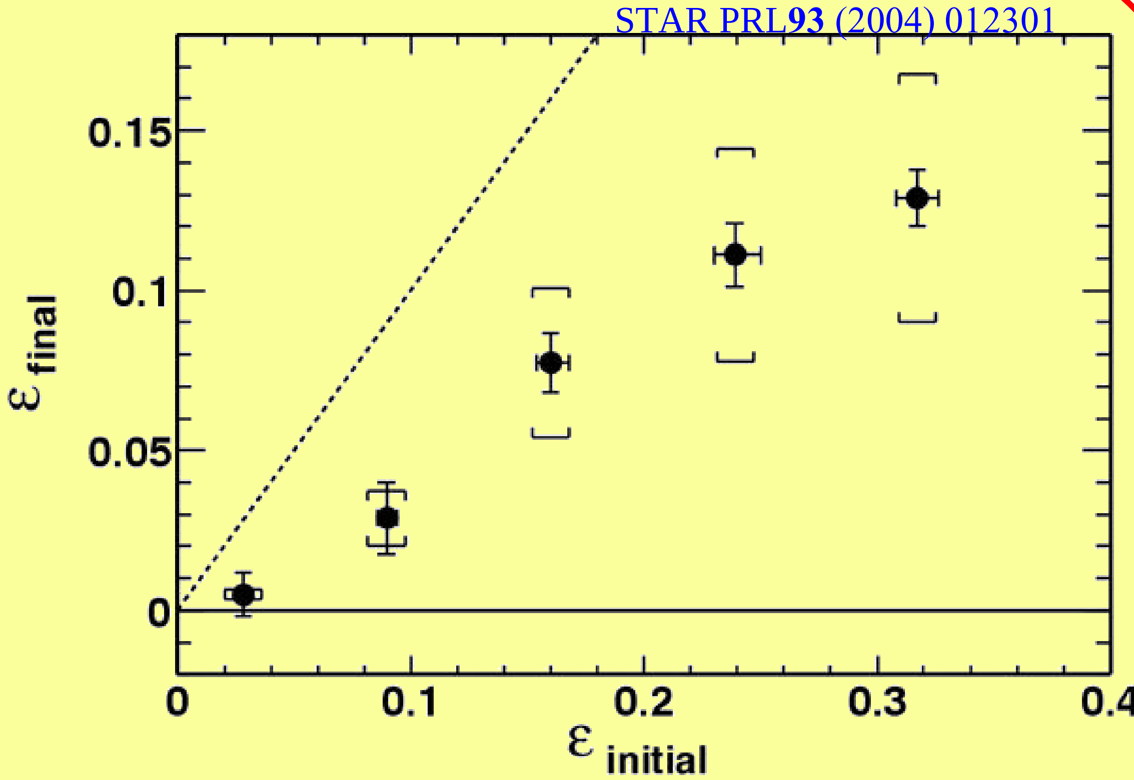




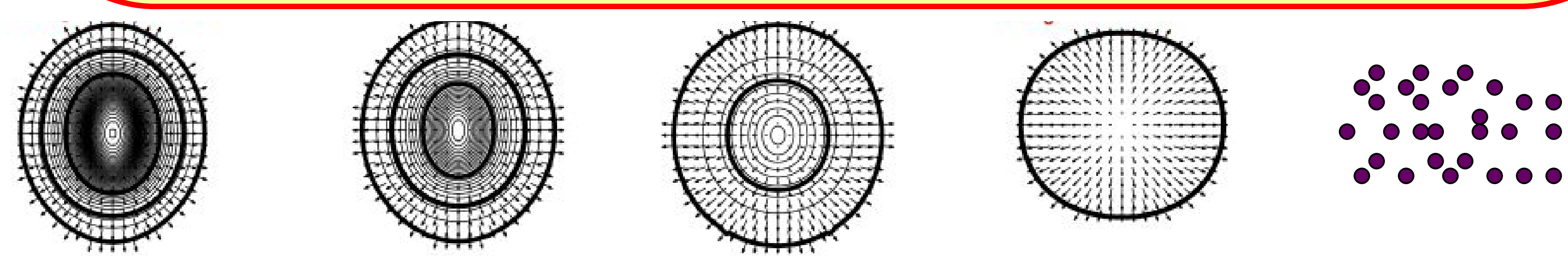
Measured *final* source shape

$$\varepsilon \ \S\ \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

- estimate ε_{INIT} from Glauber
- from asHBT: $\varepsilon_{FO} \approx 2\frac{R_{S,2}^2}{R_{S,0}^2}$



Shape **evolution**:

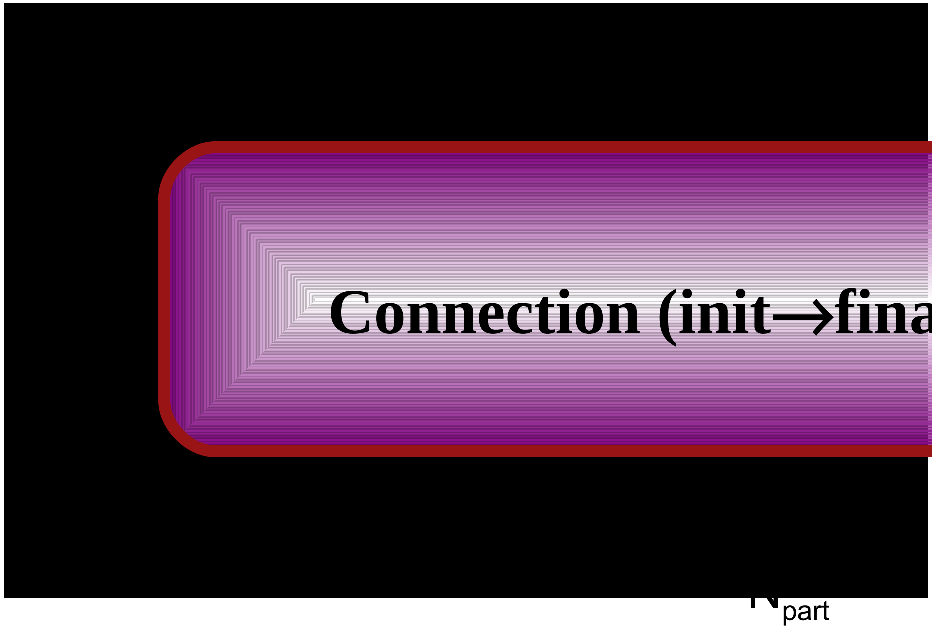


Evolution of size and shape

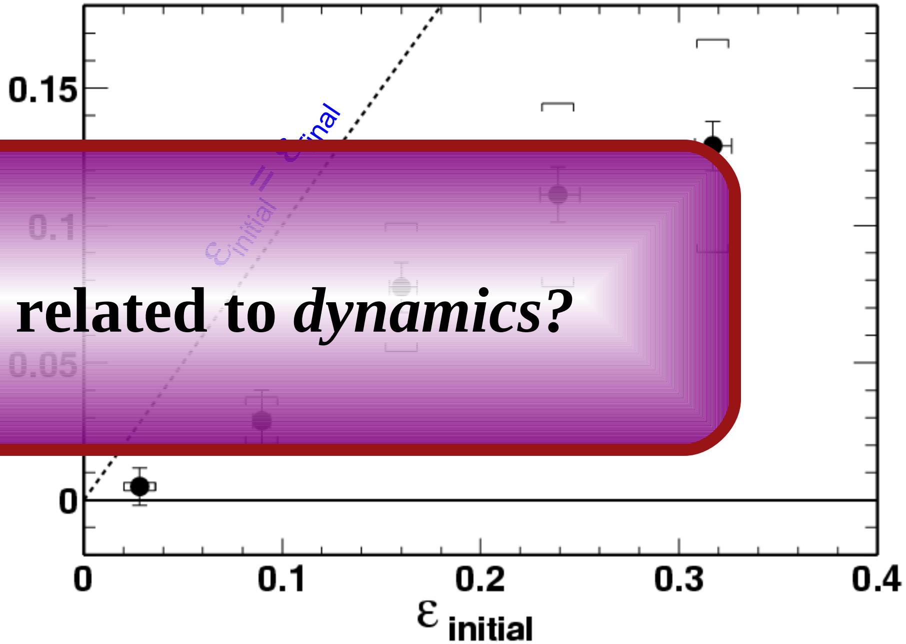
$$R(\sqrt{s}; p_T, y, \vec{b}, AB, f_{\theta}, m_1, m_2)$$

@RHIC

STAR PRC71 044906 (2005)



STAR PRL93 012301 (2004)



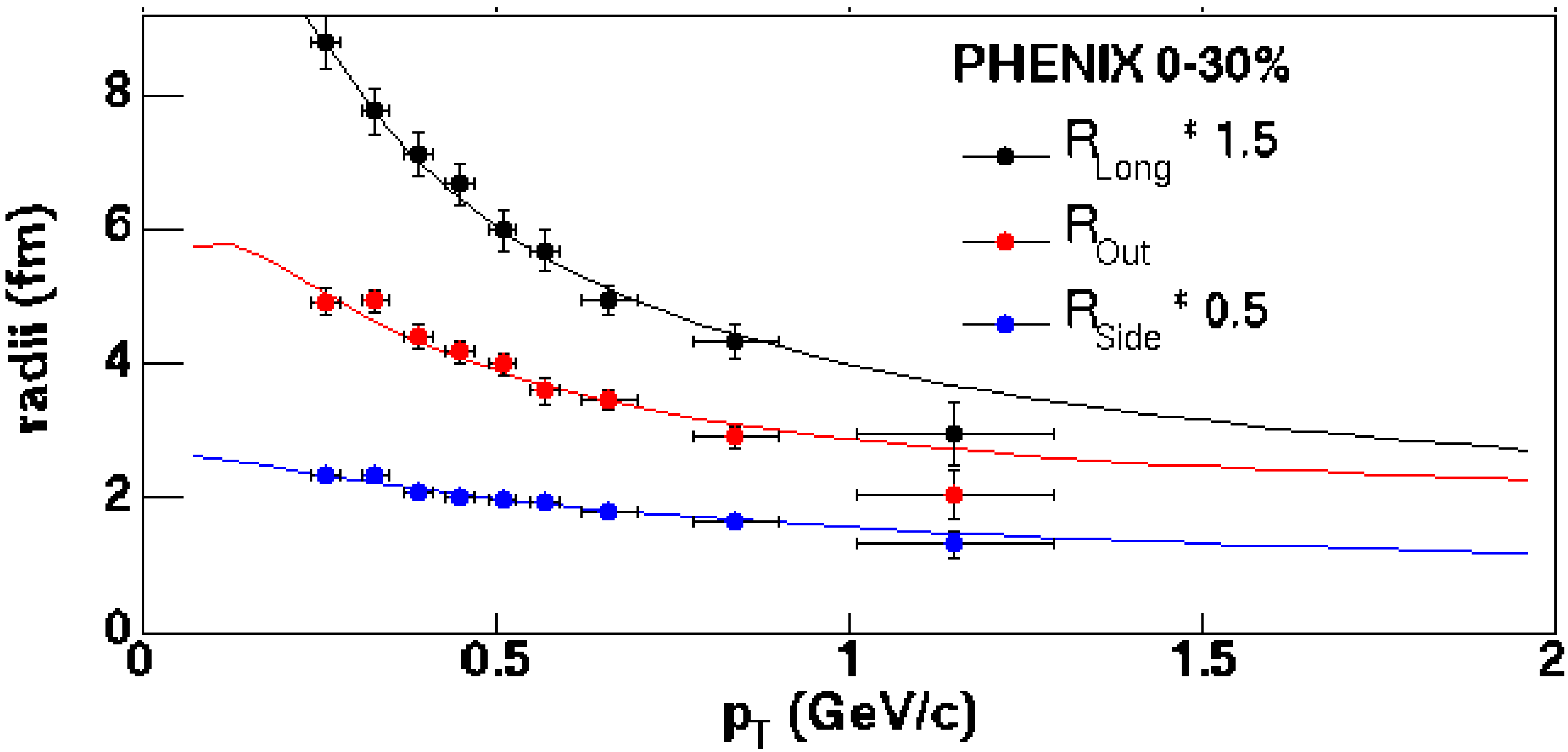
Connection (init→final) related to *dynamics?*

~ x2 size increase

~ 1/2 anisotropy reduction

Initial size/shape estimated by Glauber calculation

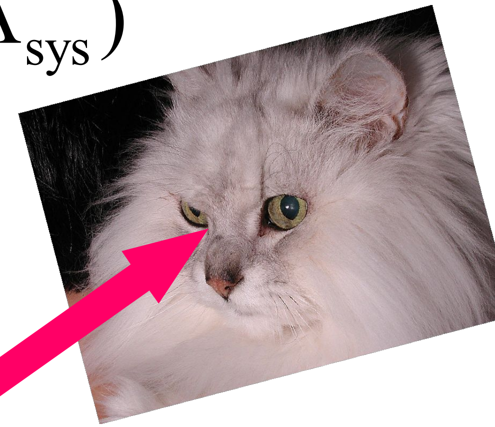
Why do the radii fall with increasing momentum ??

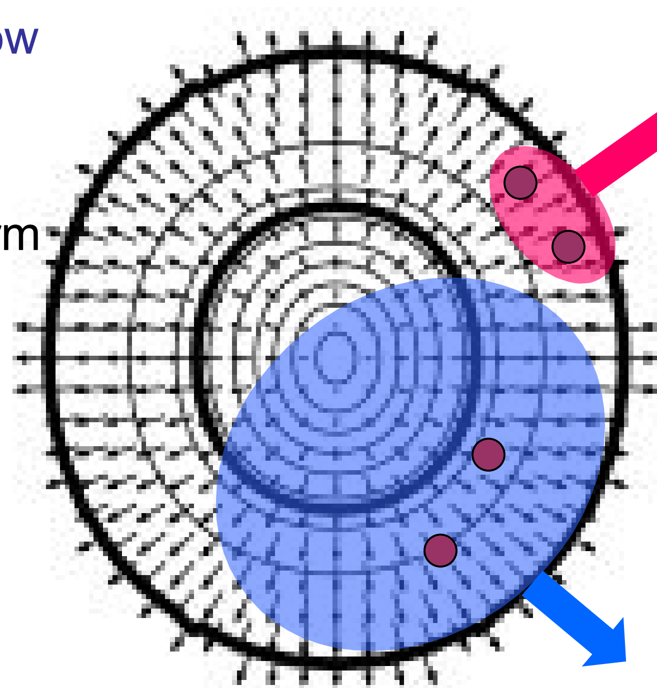


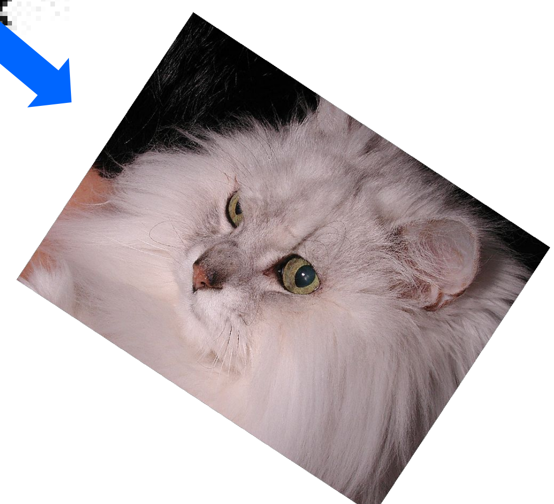
$$HBT(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{\hat{b}}, m_1, m_2, A_{sys})$$

Decreasing $R(p_T)$

- usually attributed to **collective** flow
- flow integral to our understanding of R.H.I.C.; taken for granted
- femtoscopy the *only* way to confirm **x-p** correlations – impt check







Kolb & Heinz, QGP3 nucl-th/0305084

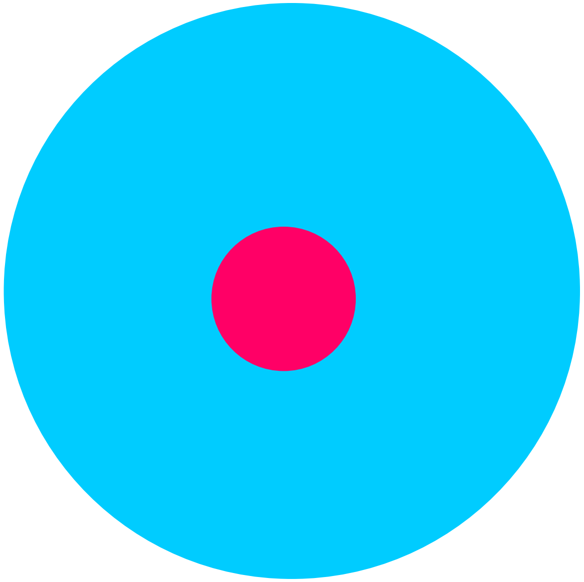
$$\mathrm{HBT}(\sqrt{s};\, p_T,\, y,\, |\vec{b}|,\, \phi_{\ddot{p}},\, m_1,\, m_2,\, A_{sys})$$

Decreasing $R(p_T)$

- usually attributed to collective flow
- flow integral to our understanding of R.H.I.C.; taken for granted
- femtoscopy the *only* way to confirm **x-p** correlations – impt check

Non-flow possibilities

- cooling, *thermally* (not collectively) expanding source
    - combo of x-t and t-p correlations



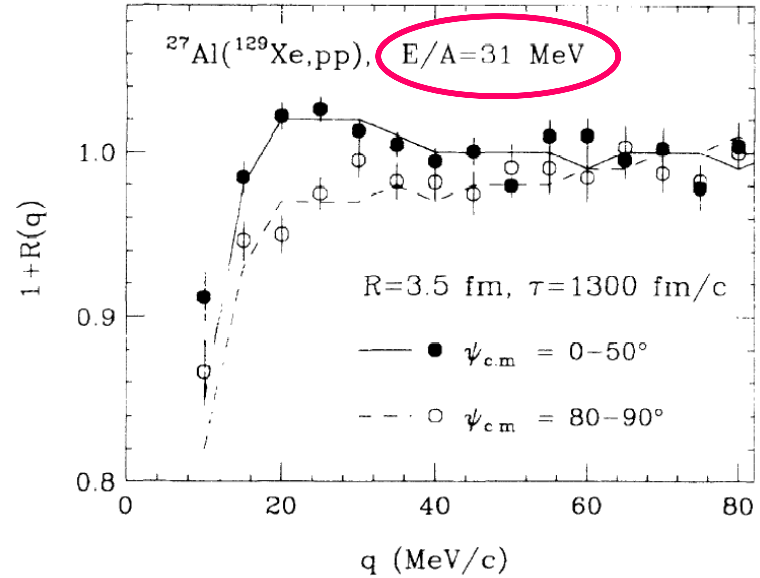
early times: small, hot source

late times: large, cool source

$HBT(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{p}, m_1, m_2, A_{sys})$

Decreasing $R(p_T)$

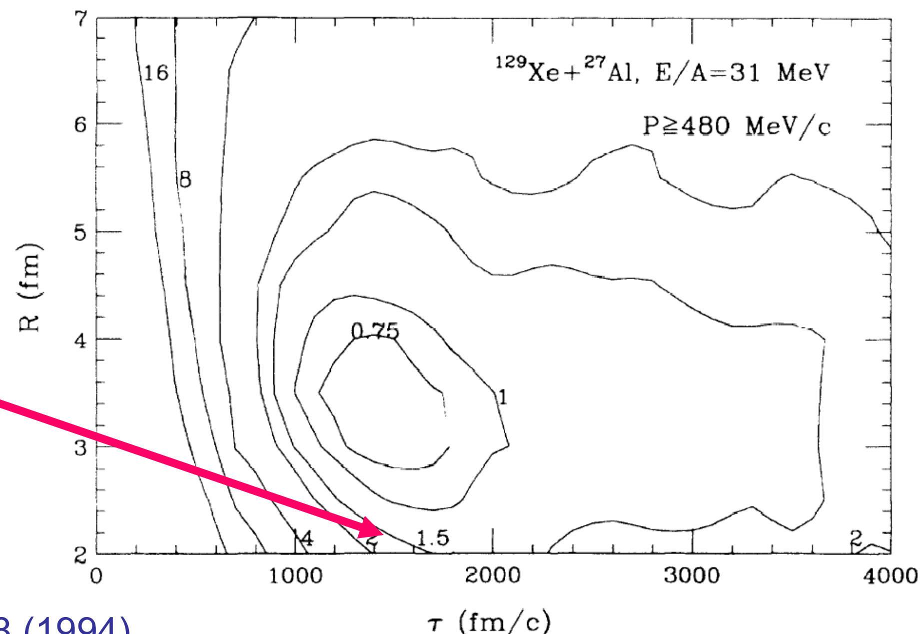
- usually attributed to collective flow
- flow integral to our understanding of R.H.I.C.; taken for granted
- femtoscopy the *only* way to confirm **x-p** correlations – impt check



Non-flow possibilities

- cooling, *thermally* (not collectively) expanding source
  - combo of x-t and t-p correlations

1500 fm/c (!)



MAL et al, PR**C49** 2788 (1994)

$$\mathrm{HBT}(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{p}, m_1, m_2, A_{sys})$$

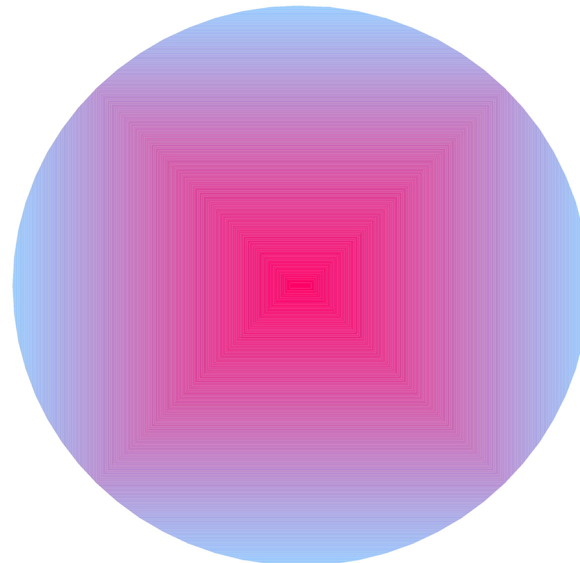
Decreasing $R(p_T)$

- usually attributed to collective flow
- flow integral to our understanding of R.H.I.C.; taken for granted
- femtoscopy the *only* way to confirm **x-p** correlations – impt check

Non-flow possibilities

- cooling, *thermally* (not collectively) expanding source
  - combo of x-t and t-p correlations

- hot core surrounded by cool shell
  - important ingredient of Buda-Lund hydro picture
    e.g. Csörgő & Lörstad
    PR**C54** 1390 (1996)

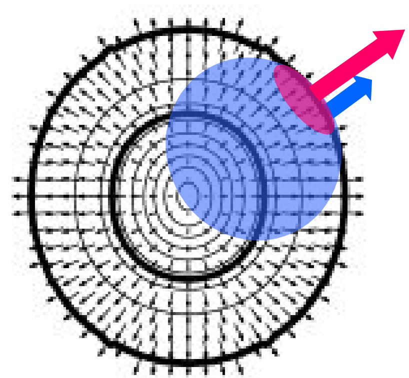


$$\mathrm{HBT}(\sqrt{s};p_T, y, |\vec{b}|, \phi_{\hat{p}b}, m_1, m_2, A_{sys})$$

Each scenario generates x-p correlations but…

Decreasing $R(p_T)$

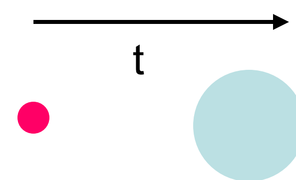
- usually attributed to collective flow
- flow integral to our understanding of R.H.I.C.; taken for granted
- femtoscopy the *only* way to confirm **x-p** correlations – impt check



$\langle x^2\rangle$-p correlation: yes
$\langle x\rangle$-p correlation: yes

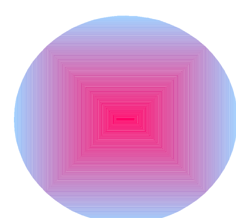
Non-flow possibilities

- cooling, *thermally* (not collectively) expanding source
  - combo of x-t and t-p correlations



$\langle x^2\rangle$-p correlation: yes
$\langle x\rangle$-p correlation: no

- hot core surrounded by cool shell
  - important ingredient of Buda-Lund hydro picture
    e.g. Csörgő & Lörstad
    PR**C54** 1390 (1996)



$\langle x^2\rangle$-p correlation: yes
$\langle x\rangle$-p correlation: no

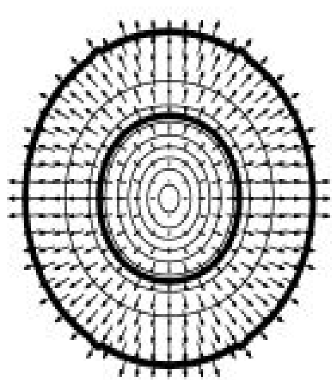
$HBT(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{p}, m_1, m_2, A_{sys})$

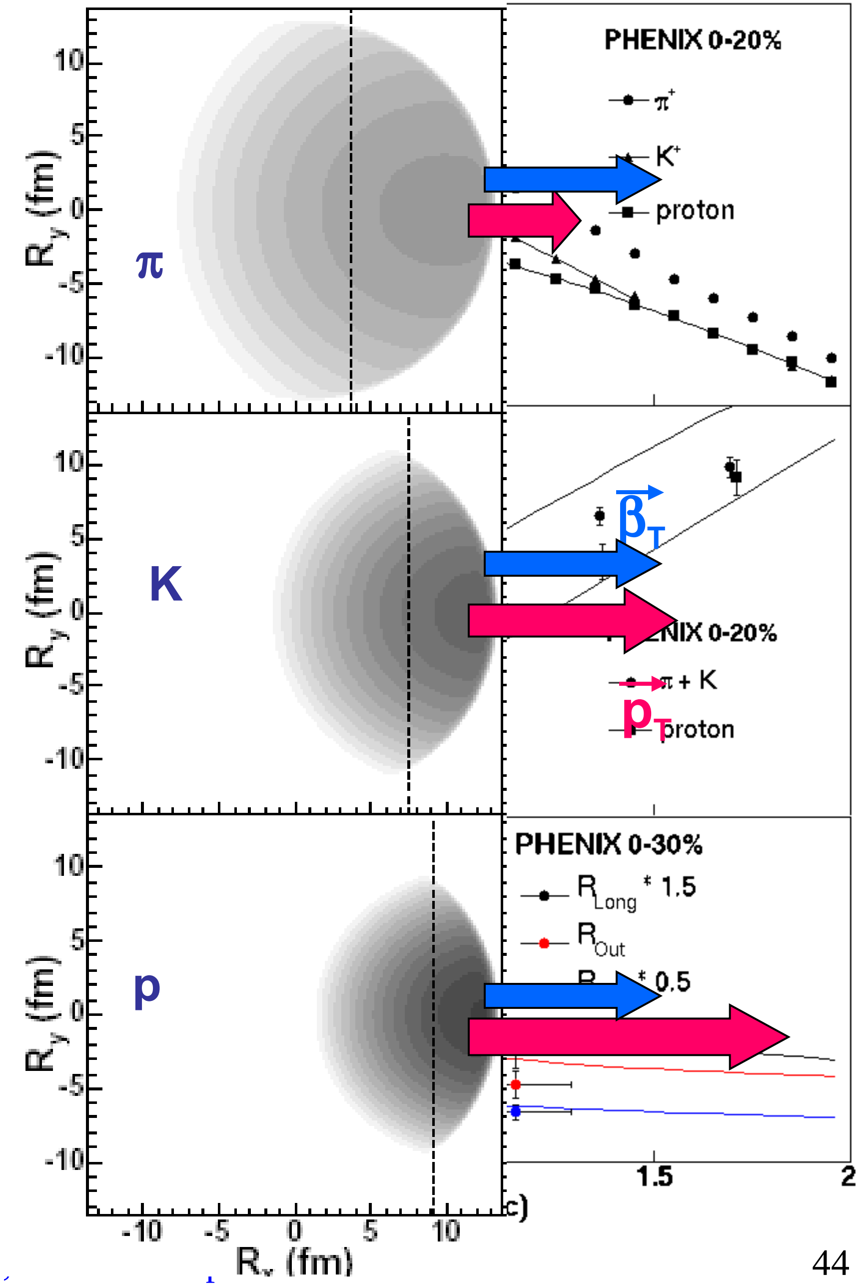
- flow-dominated "models" can reproduce soft-sector x-space observables
    - imply short timescales

- however, are we on the right track? [flow]
    - puzzles? → check your assumptions!
    - look for flow's "special signature"
      ⟨x⟩-p correlation

- In flow pictures (BlastWave), low-p_T particles emitted closer to source's center
- non-identical particle correlations (FSI at low Δv) probe:
    - $\forall\langle(x_1-x_2)^2\rangle$ (as does HE
    - $\nabla\langle x_1-x_2\rangle$

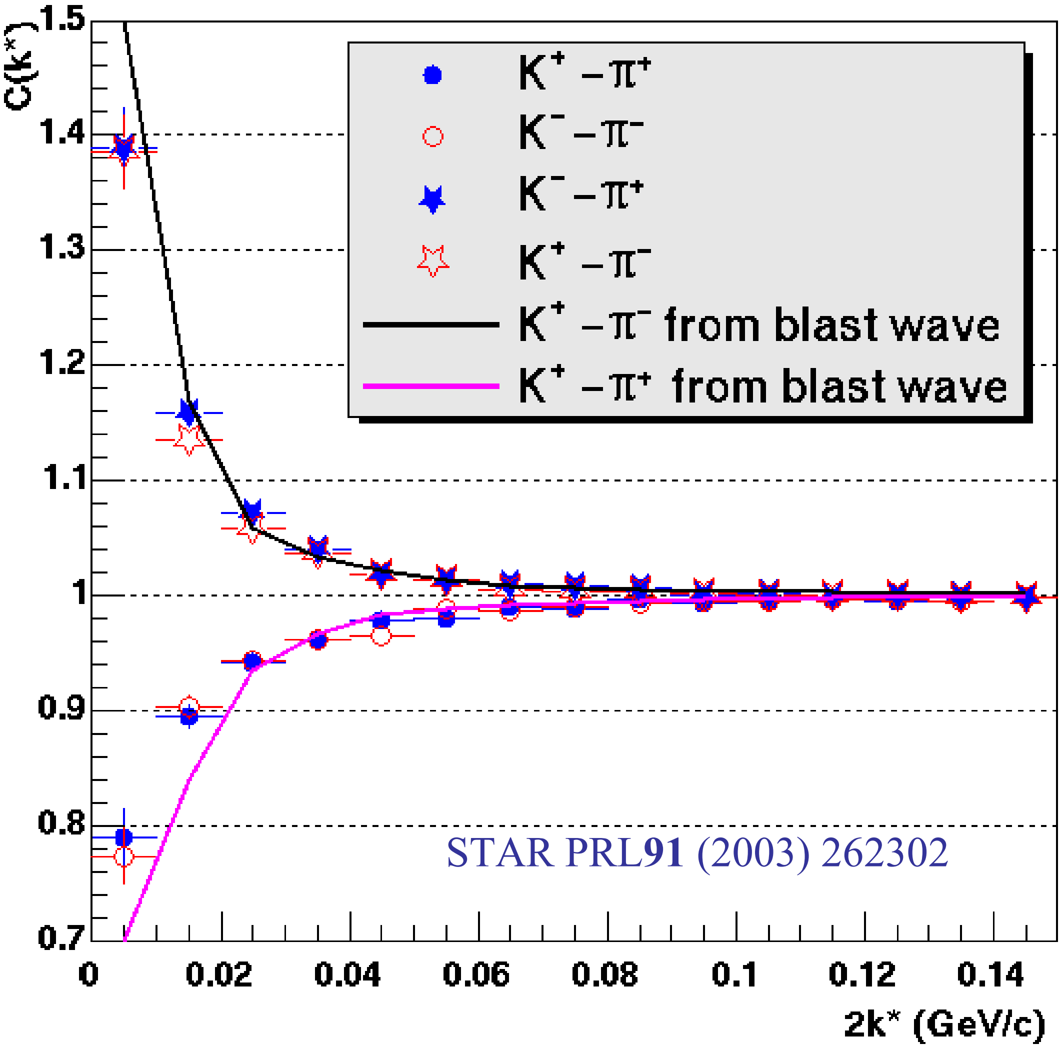
Blast-Wave
R~13 fm, τ~2,9 fm/c
T~110 MeV, β_{edge}~0.8





F. Retiere & MAL, PRC**70** 044907 (2004)

Kaon – pion correlations: dominated by Coulomb interaction



Smaller source → stronger (anti)correlation

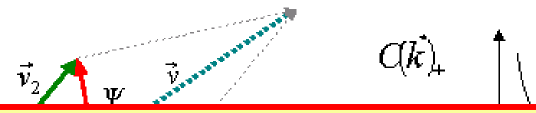
K-p correlation well-described by:

- Blast wave with same parameters as spectra, HBT

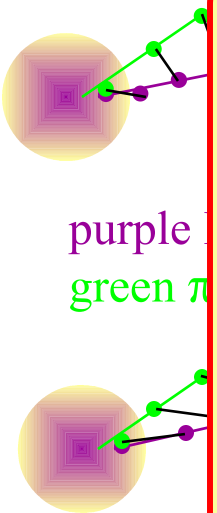
But with non-identical particles, we can access more information…

Initial idea: probing emission-time ordering

purple K emitted first
green π is *faster*

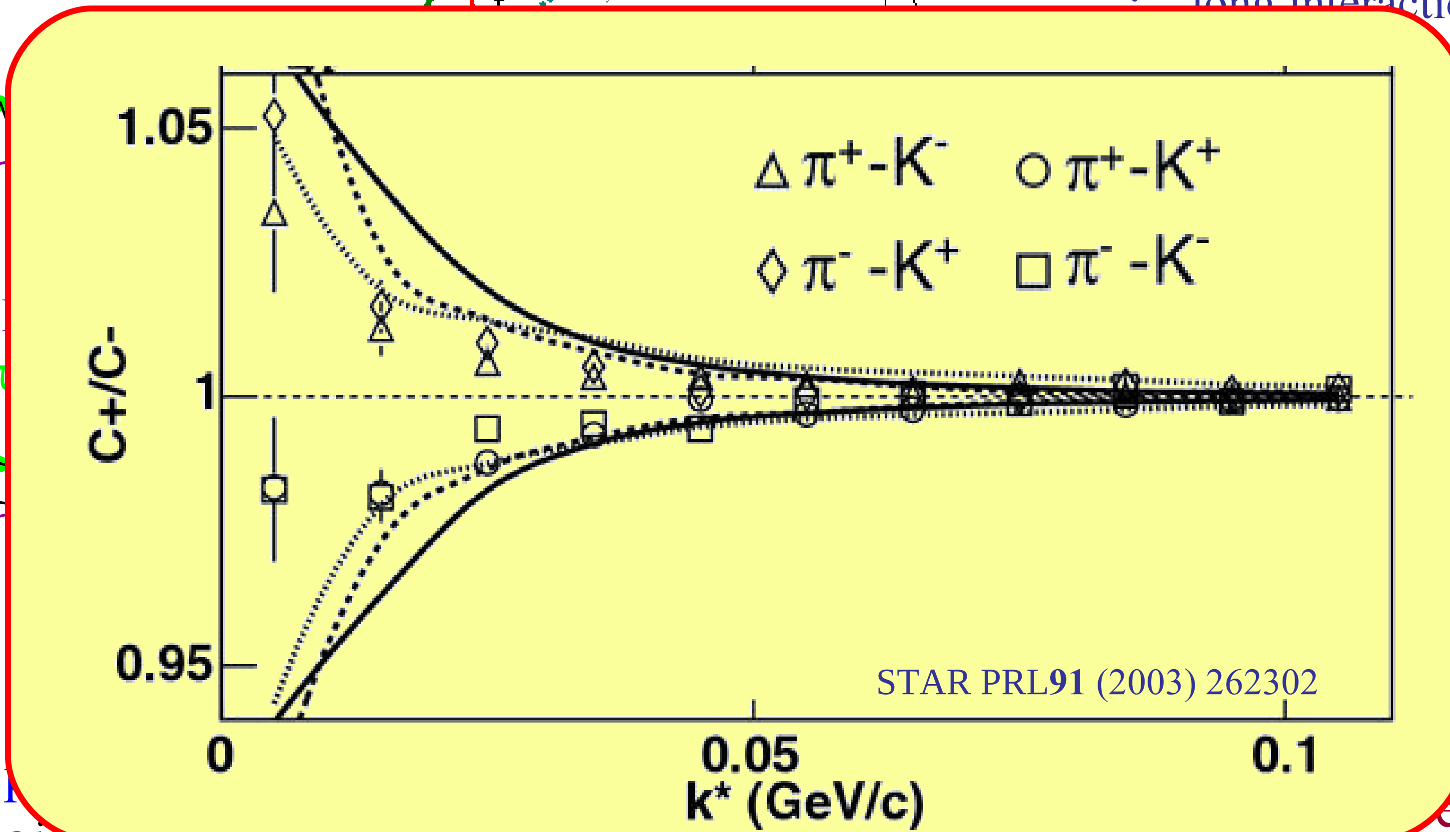


- Catching up: cosΨ ⟩ 0
  - long interaction time
  - ...tion



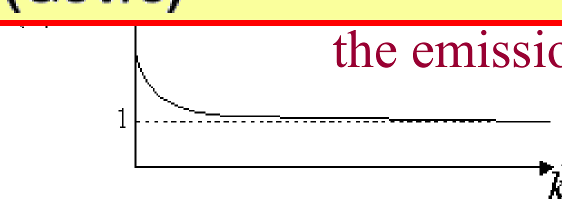
purple ...
green π ...

- ...sΨ ⟨ 0
  - ...n time
  - ...on



Crucial ...
kaon *begins* farther in "out" direction
(in this case due to time-ordering)

...arios
...e study of
the emission asymmetry



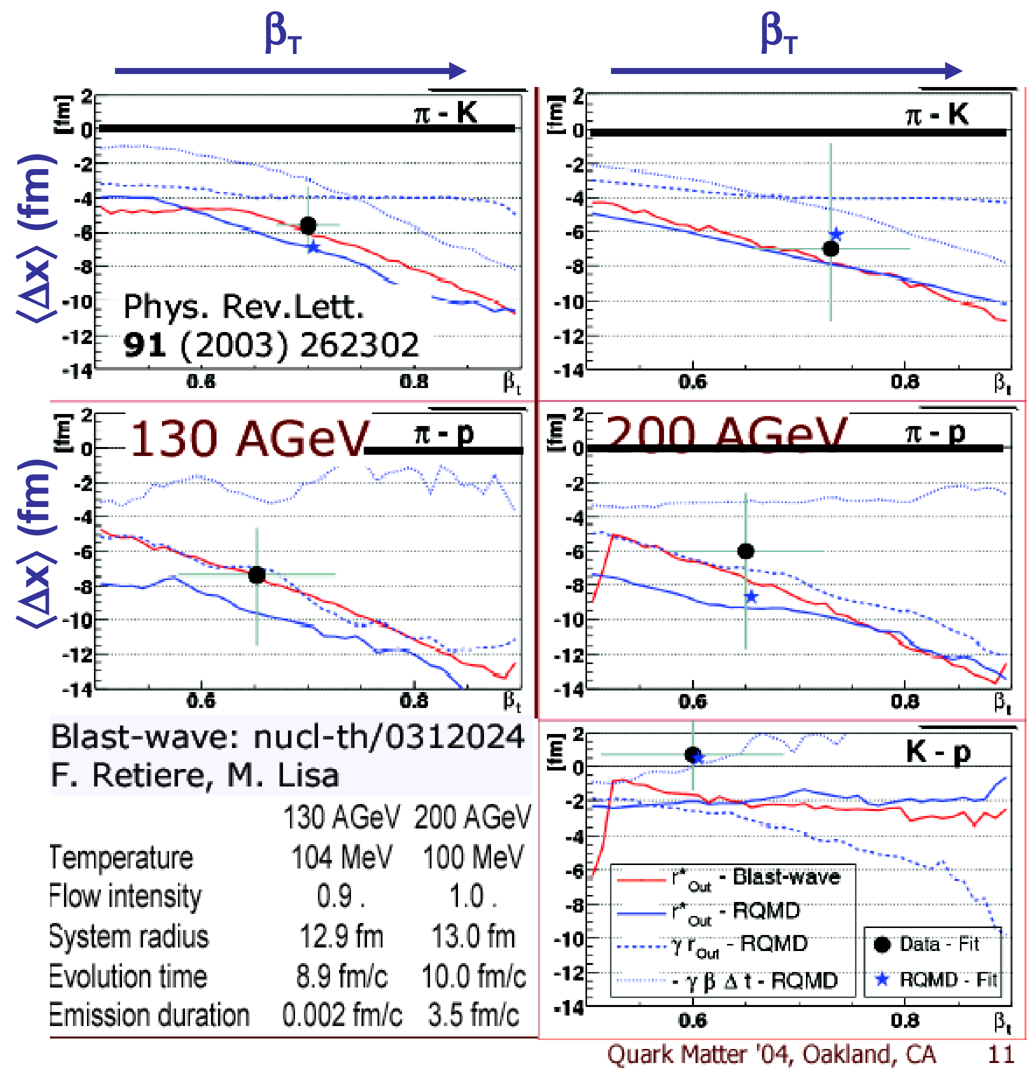
e.g. Lednicky et al Phys. Lett. B373:30–34, 1996

$$\mathrm{HBT}(\sqrt{s}; p_T, y, |\vec{b}|, \phi_{\vec{p}}, m_1, m_2, A_{sys})$$

- extracted shift in emission point $\langle x_1 - x_2 \rangle$
- In flow pictures, low-p_T particles emitted closer to source's center (along "out")

consistent w/ flow-dominated blastwave

- non-identical particle correlations (FSI at low Δv) probe:
  - $\forall \langle (x_1-x_2)^2 \rangle$ (as does HBT)
  - $\forall \langle x_1-x_2 \rangle$ √



Blast-wave: nucl-th/0312024
F. Retiere, M. Lisa

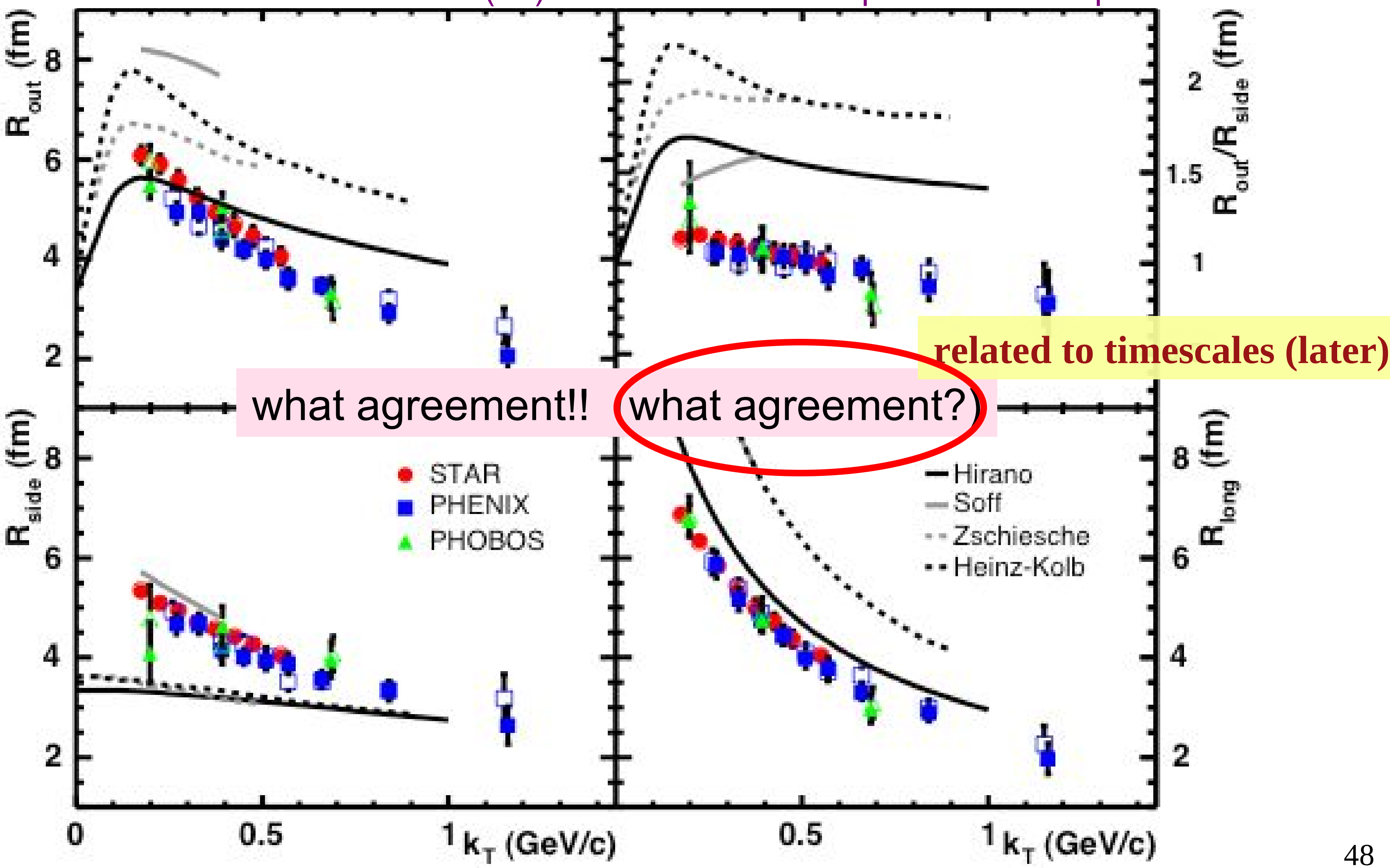
	130 AGeV	200 AGeV
Temperature	104 MeV	100 MeV
Flow intensity	0.9 .	1.0 .
System radius	12.9 fm	13.0 fm
Evolution time	8.9 fm/c	10.0 fm/c
Emission duration	0.002 fm/c	3.5 fm/c

A. Kisiel (STAR) QM04

Strong flow confirmed by all expts...

$$R(\sqrt{s}; p_T, y, |\vec{b}|, AB, \phi, m_1, m_2)$$

LPSW(05) - DATA in color-- experimentalist's plot



Initial thoughts for your coffee...

- We are on the right track: The system *is* a system
  - consistent with thermochemical equilibrium
    - chemical freezeout on expected phase boundary
    - T_{ch}~170 MeV; μ_b~30 MeV
  - bulk collective behaviour
    - explosive, anisotropic evolution to T_{kin}~100 MeV, β_{flow}~0.7c
    - momentum- and coordinate-space aspects of flow substructure (**x-p**)
    - initial versus final size/shape : *system* evolution

- Ideal hydro works for the **first time** at RHIC energies
  - evidence for early thermalization
  - mass, p_T systematics well-fit assuming:
    - EoS with HG -> QGP PT

    $\forall \varepsilon_{init}$ ~ 10 GeV/fm^3

Chemical Freeze-Out Model: Fit Results

Hadron resonance gas + decay effects

Chemical freeze-out parameters

T_{ch} = 170±4 MeV

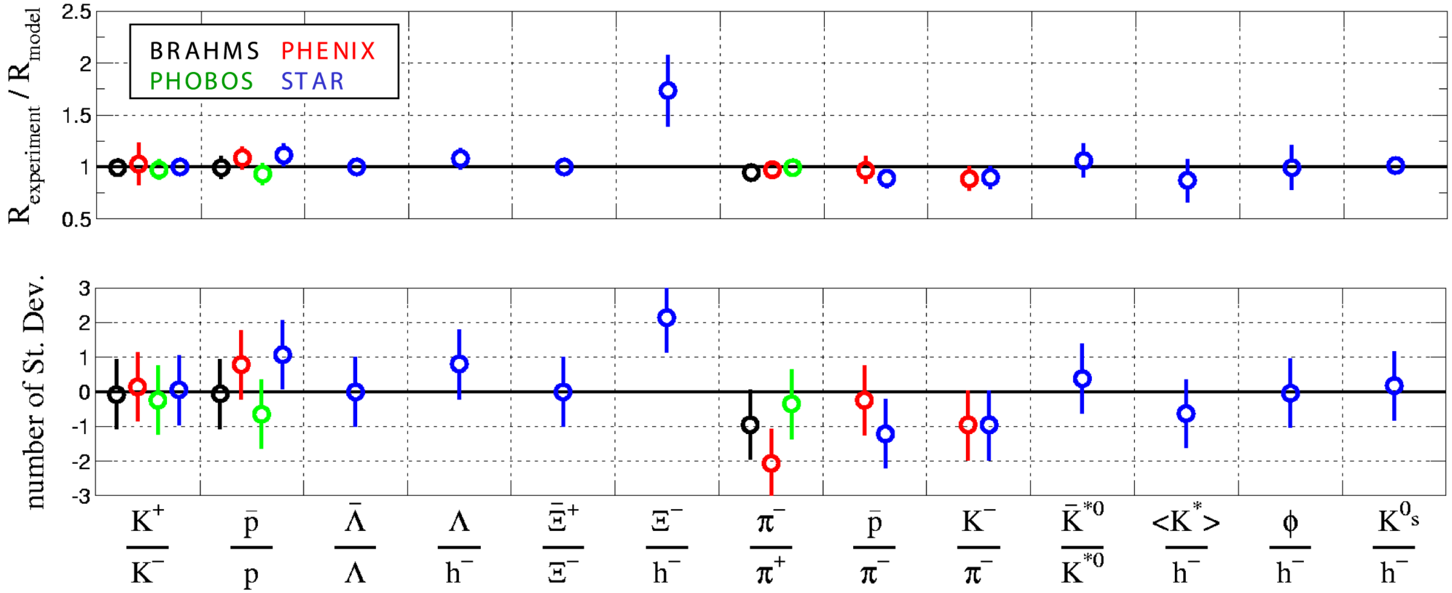
$\mu_B = 3\mu_{u(d)}$ = 40±4 MeV

μ_s = 1.1±2.0 MeV

γ_s = 1.09 ±0.06

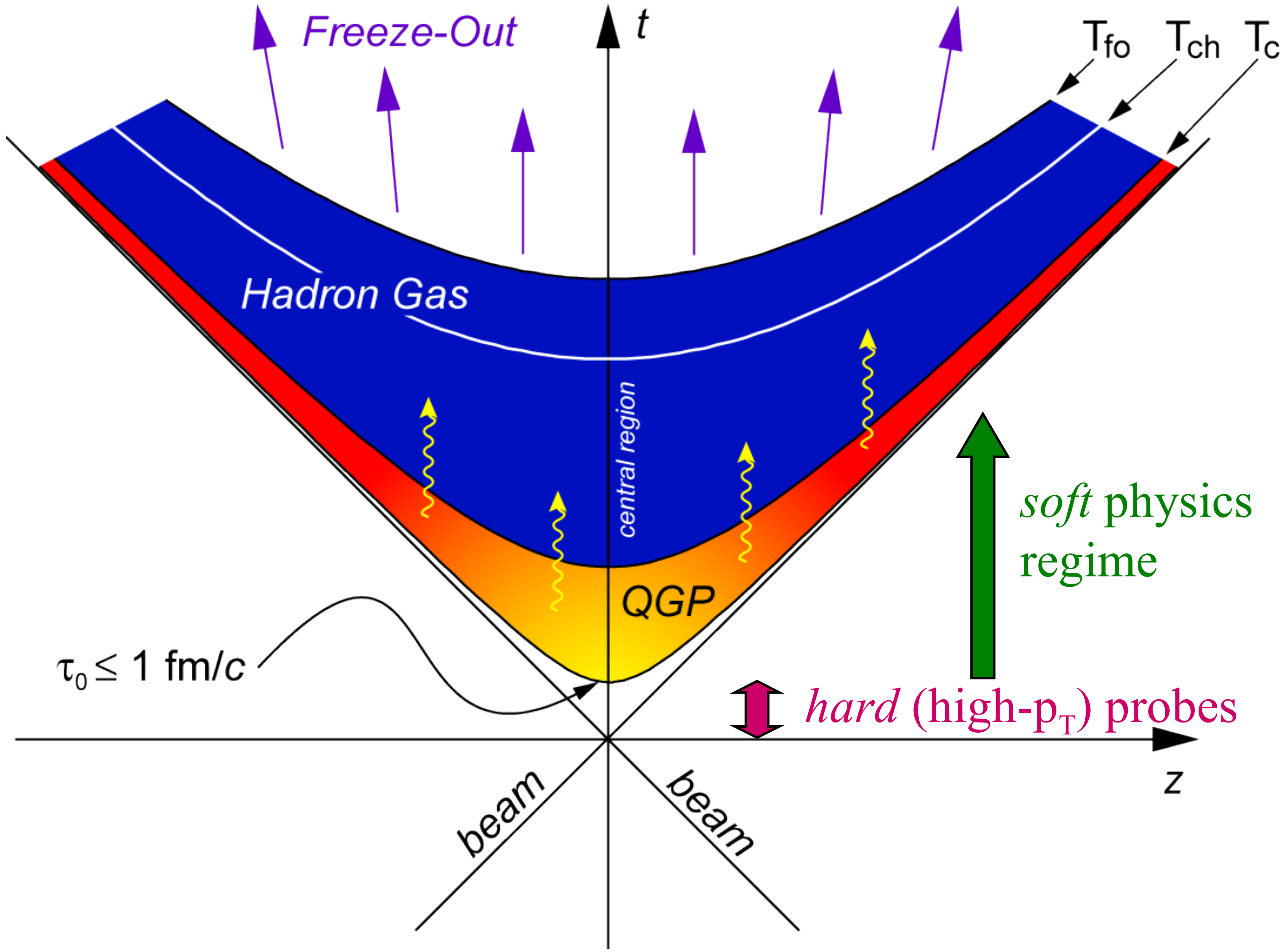
χ^2/dof = 16.7/9

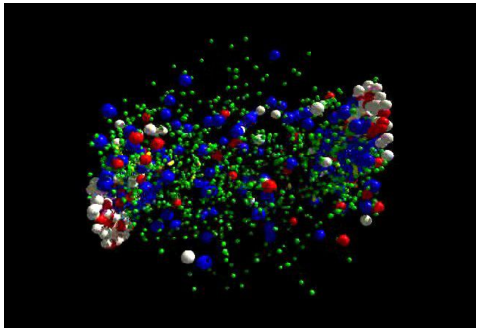
(χ^2/dof = 12.2/8 w/o Ξ^-/h^-)

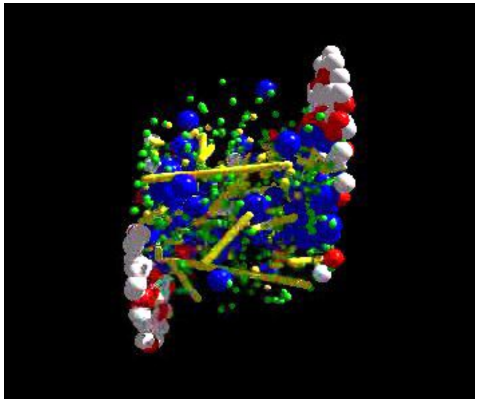


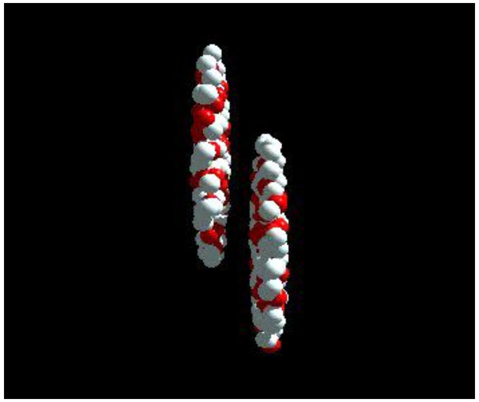
M. Kaneta, N. Xu, LBL, 2002
(Thermal Fest BNL 2001 and nucl-ex/0104021)

Stages of collision









Chemical freezeout ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases