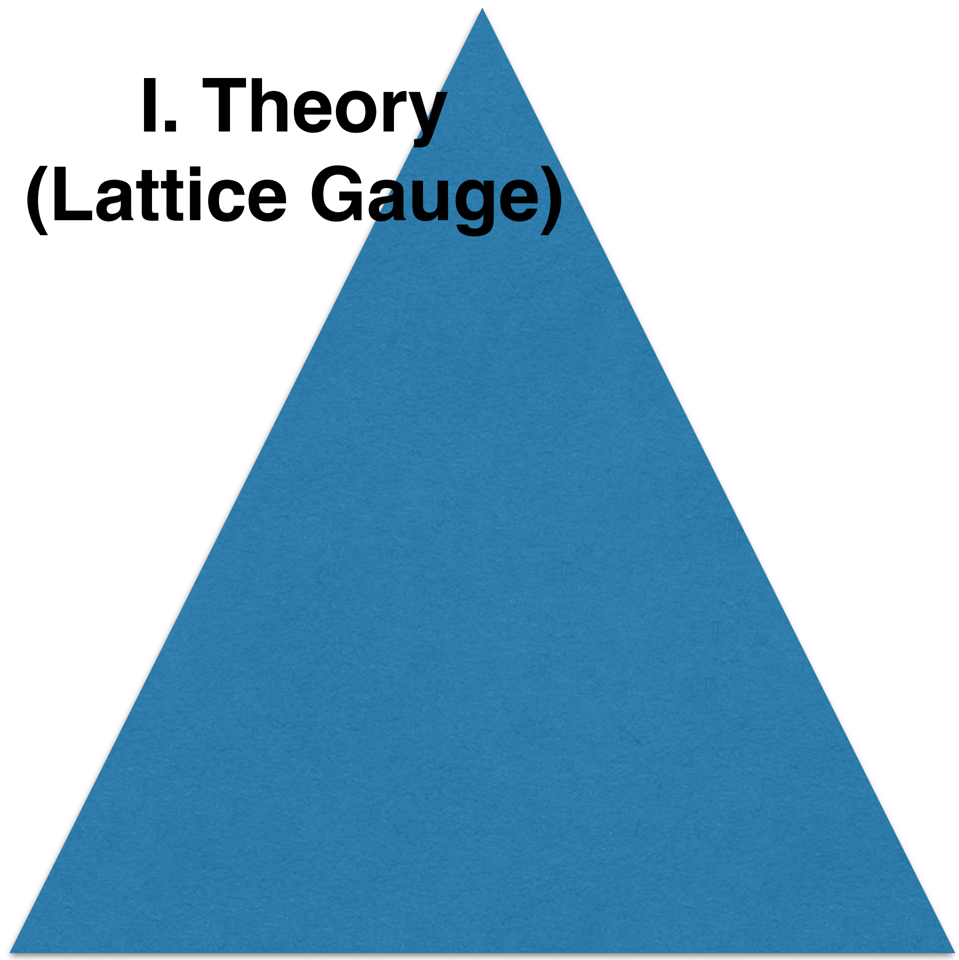
Relativistic Heavy Ion Collisions



Theory Basics

As you heat the vacuum…

- **Density depends only on T**

$$\rho_{\text{hadrons}} = \sum_{\alpha} (2S_{\alpha}+1) \int \frac{d^3p}{(2\pi\hbar)^3} \frac{e^{-E_p/T}}{1 \mp e^{-E_p/T}}$$

hadrons=π,K,p…

- **When T≳165 MeV, ρ≳1/V_{hadron} and quarks are confused**
- **For T>>165 MeV,**

$$\rho_{\text{partons}} = \sum_{a} (2S_{a}+1) \int \frac{d^3p}{(2\pi\hbar)^3} \frac{e^{-E_p/T}}{1 \mp e^{-E_p/T}}$$

partons=u,d,s,gluons (56 deg.s of freedom)

Theory Basics

For $T \gtrsim 165$ MeV,

- **Create QGP (Quark Gluon Plasma)**
- **Restore Chiral Symmetry**
  - **Symmetry related to ~massless quarks**
  - **Dissolve quark-antiquark condensate**

Lattice Gauge Theory

Integrate over field configurations —> Partition function

$$Z(\beta = 1/T) = \sum_i \langle i | e^{-\beta H} | i \rangle$$

$$= \sum_{i_1 \cdots i_N} \langle i_1 | e^{-\delta\beta H} | i_2 \rangle \langle i_2 | e^{-\delta\beta H} \cdots | i_N \rangle \langle i_N | e^{-\delta\beta H} | i_1 \rangle, \quad \delta\beta = \beta / N$$

Change basis to “fields”

$$| \phi \rangle = \exp\left\{ i\phi a - \phi^* a^\dagger) \right\} | 0 \rangle, \ \ \phi = p + iq$$

$$\sum_i | i \rangle \langle i | \to \int dp\, dq \ | \phi \rangle \langle \phi |$$

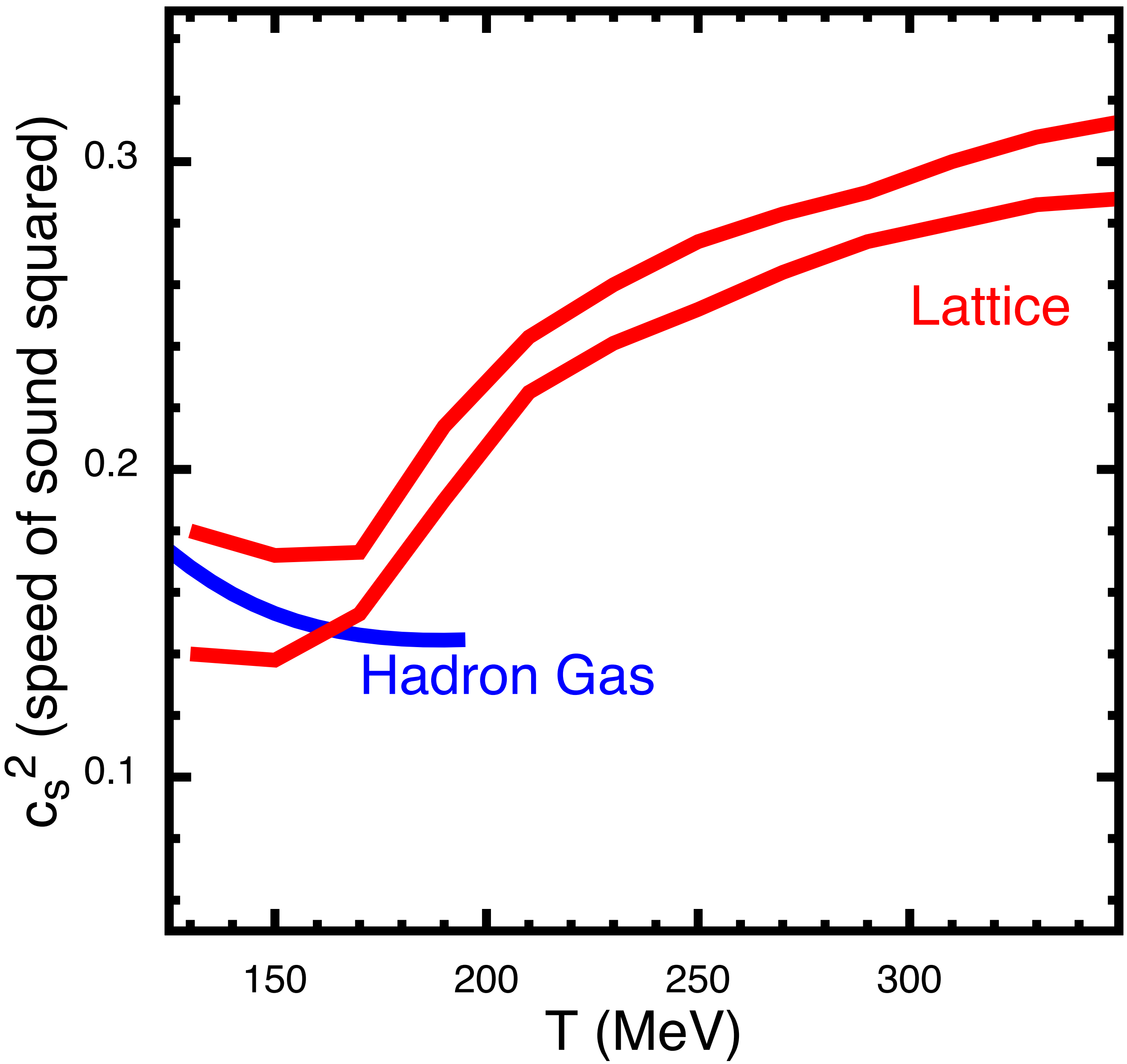
$$\langle \phi(t) | \phi(t + \delta t) \rangle = \exp\left\{ (ip\dot{q} - iq\dot{p}) \delta t / 2 \right\}, \sim\sim\sim \langle \phi(t) | e^{-iH\delta t} | \phi(t + \delta t) \rangle = \exp\left\{ iL(p,q) \delta t \right\}$$

Problem reduced to high-dimensional integral

$$Z(\beta) = \prod_{i_1 i_2 \cdots i_N} \int dp_1 dq_1 dp_2 dq_2 \cdots dp_N dq_N \exp\left\{ i \int_0^{i\beta} d\tau \ L(p(\tau), q(\tau)) \right\}$$

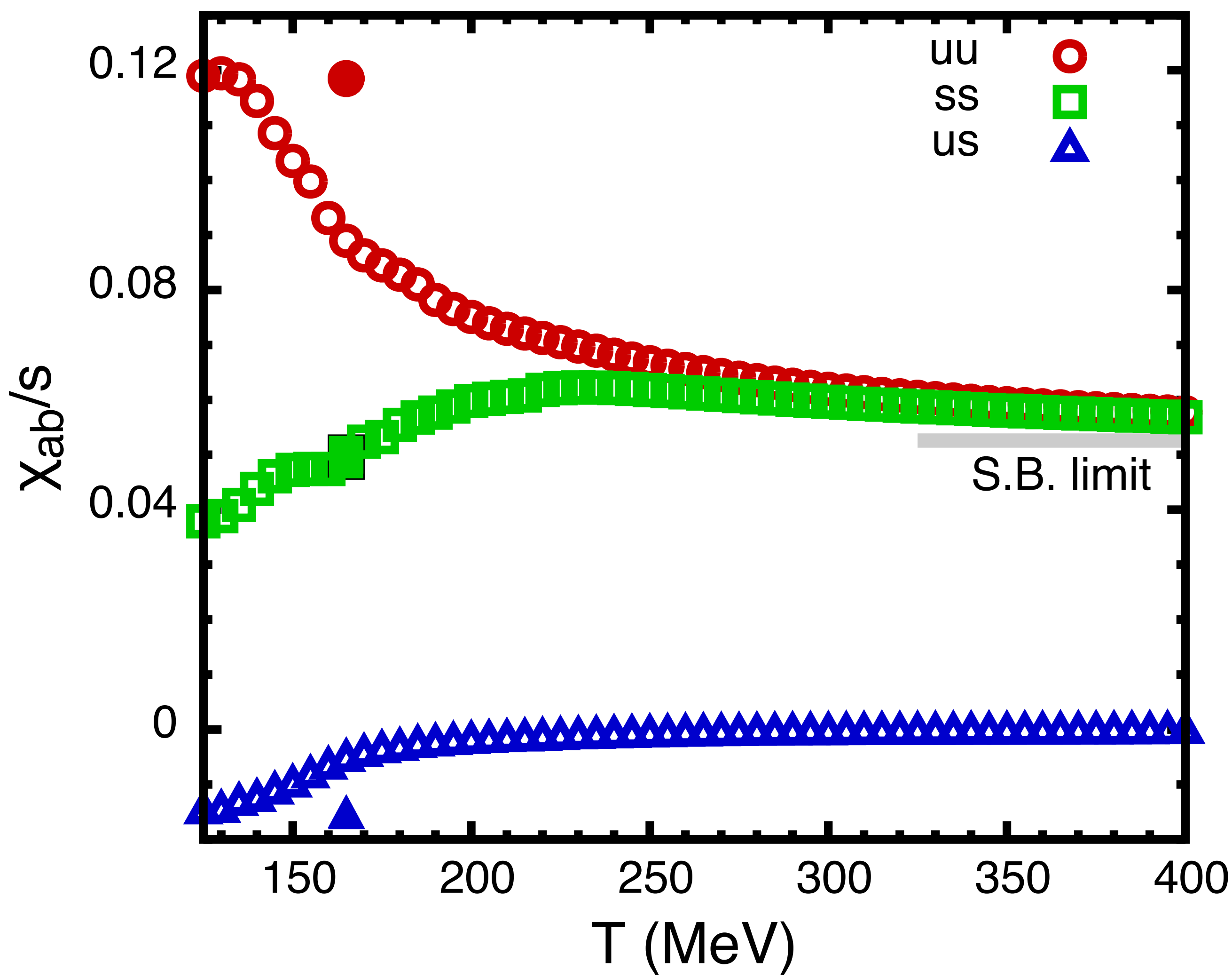
Three Lattice Results

1. Equation of State



Three Lattice Results

2. Charge Fluctuations

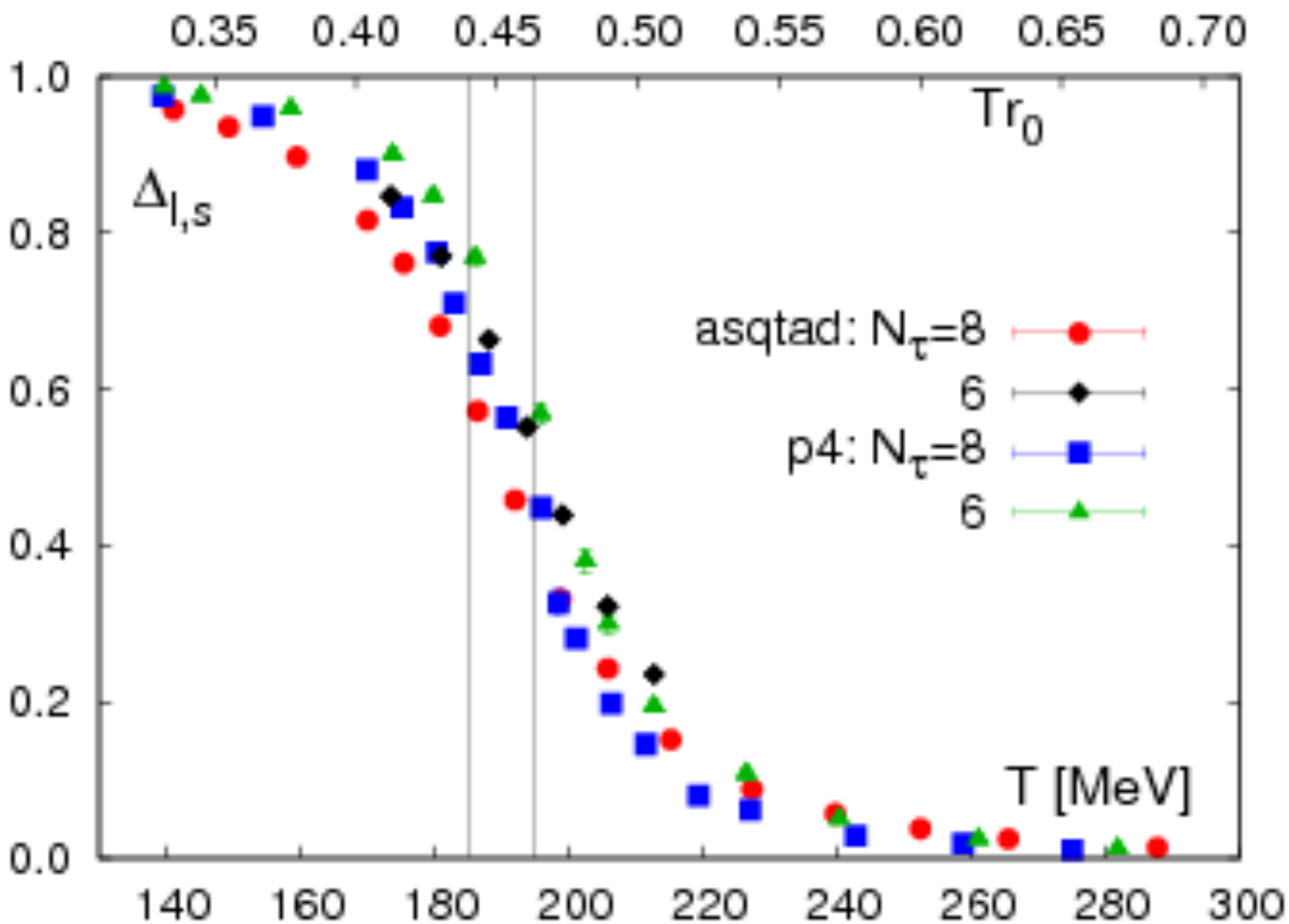


$$\chi_{ab} = \frac{\langle Q_a Q_b \rangle}{V}$$

$$\chi_{ab}(T \to \infty) = \delta_{ab}(n_a + n_{\bar{a}})$$

Three Lattice Results

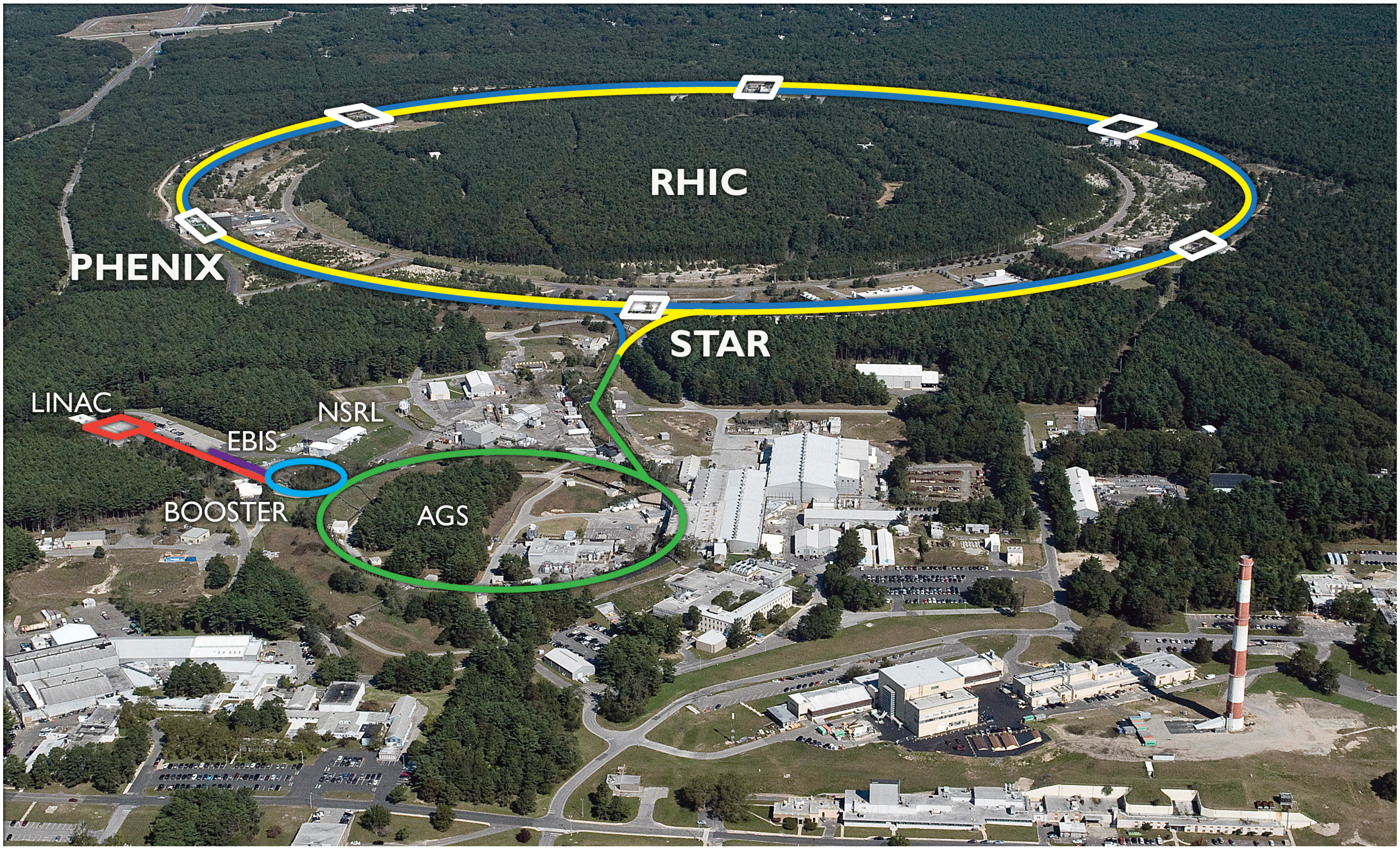
3. Melt the q-qbar condensate,
aka ⟨σ⟩ condensate, aka restore chiral symmetry



Condensate couples to quarks and gives them mass

Facilities (RHIC)

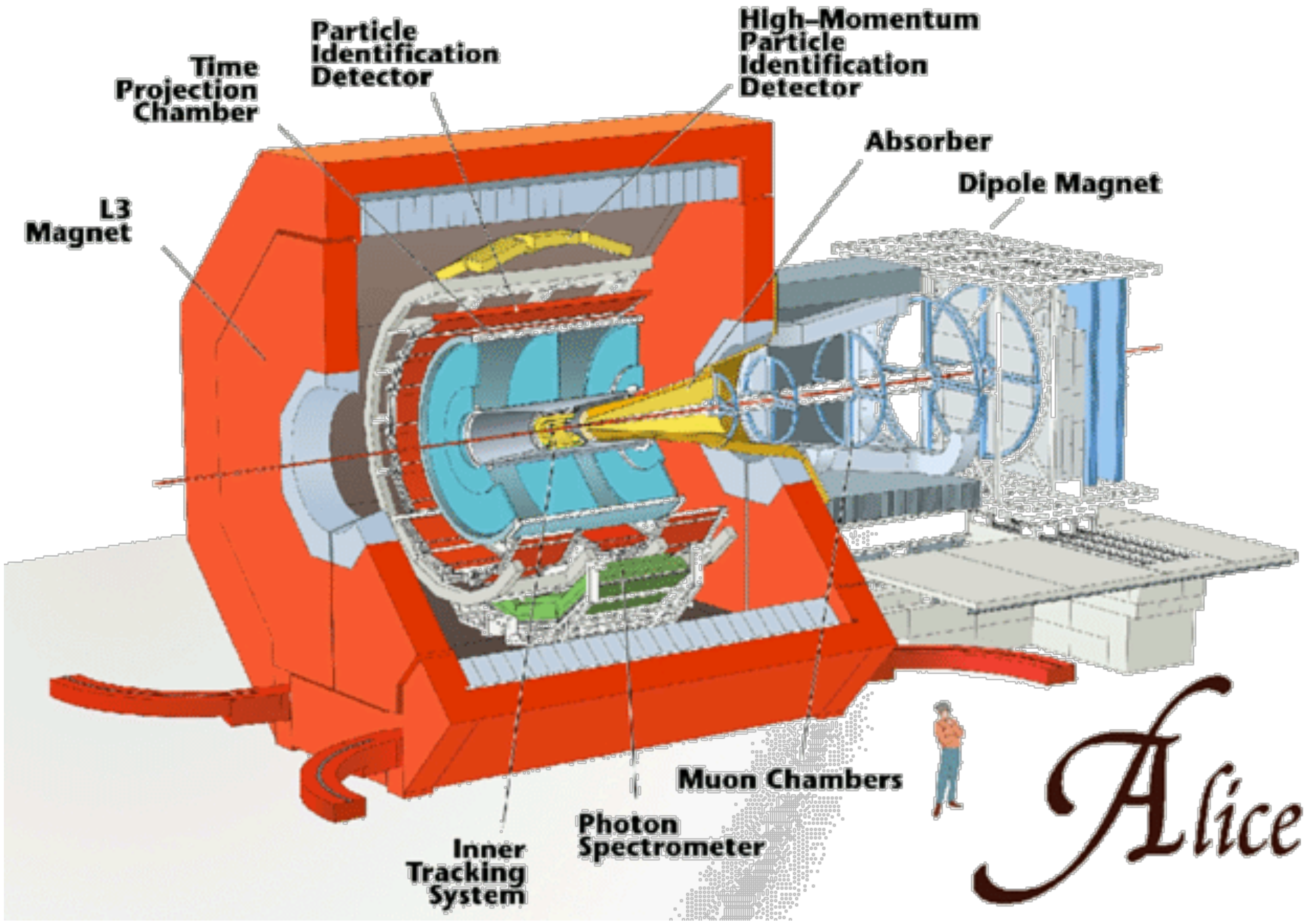
100 GeV Au + 100 GeV , can vary beams and energy



Collaborations: STAR, PHENIX

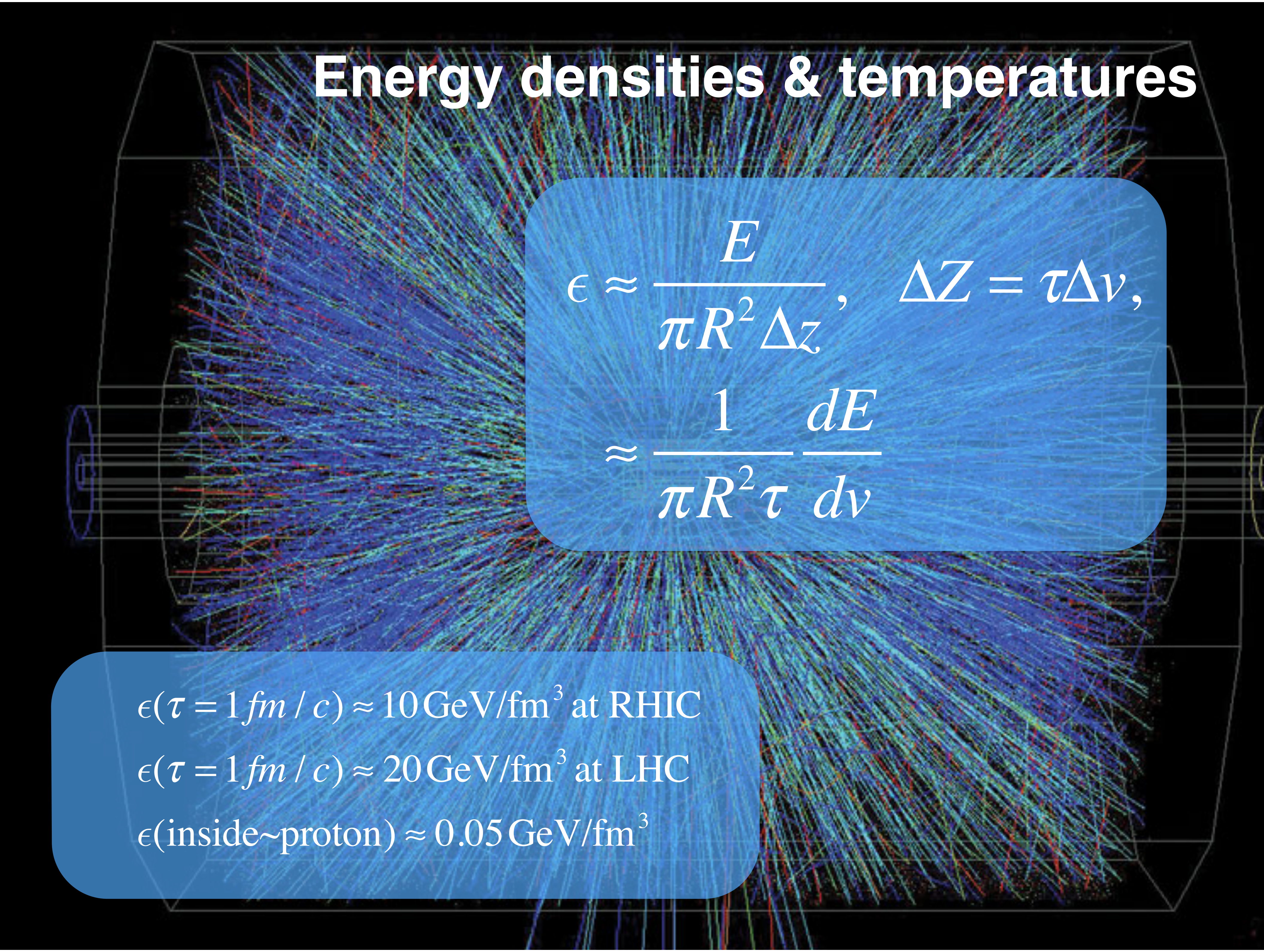
Facilities (LHC)

6.5*A* TeV Pb +6.5*A* TeV Pb



Collaborations: ALICE, ATLAS CMS

Energy densities & temperatures



$$\epsilon \approx \frac{E}{\pi R^2 \Delta z}, \quad \Delta Z = \tau \Delta v,$$

$$\approx \frac{1}{\pi R^2 \tau} \frac{dE}{dv}$$

$\epsilon(\tau = 1\, fm/c) \approx 10\,\mathrm{GeV/fm}^3$ at RHIC

$\epsilon(\tau = 1\, fm/c) \approx 20\,\mathrm{GeV/fm}^3$ at LHC

$\epsilon(\text{inside~proton}) \approx 0.05\,\mathrm{GeV/fm}^3$

Observables

- **Spectra**
  driven by radial flow and final temperature
- **Elliptic Flow**
  $v_n \equiv \langle \cos n\phi \rangle$
- **Femtoscopic correlations**
  measure spatial extent of final *f(p,r,t)*
- **Jets**
  strongly damped by QGP
- **rare probes**
  charmonium states should be dissolved
- **numerous other correlations**
  related to chemistry or phase transition
- **direct photons and dileptons**
  known as penetrating probes
- **tens of PB of data are stored yearly**

MODELS

- **Pre-Equilibrium (0<τ<1 fm/c)**
  mixture of gluonic fields and partons
  not decisively understood

- **Hydrodynamic (T>160 MeV)**
  relativistic, viscous
  most strongly affects results

- **Hadronic cascade (T<160)**
  microscopic evolution of *f(p,r,t)* for each species
  hydro can't handle 100 species flowing differently

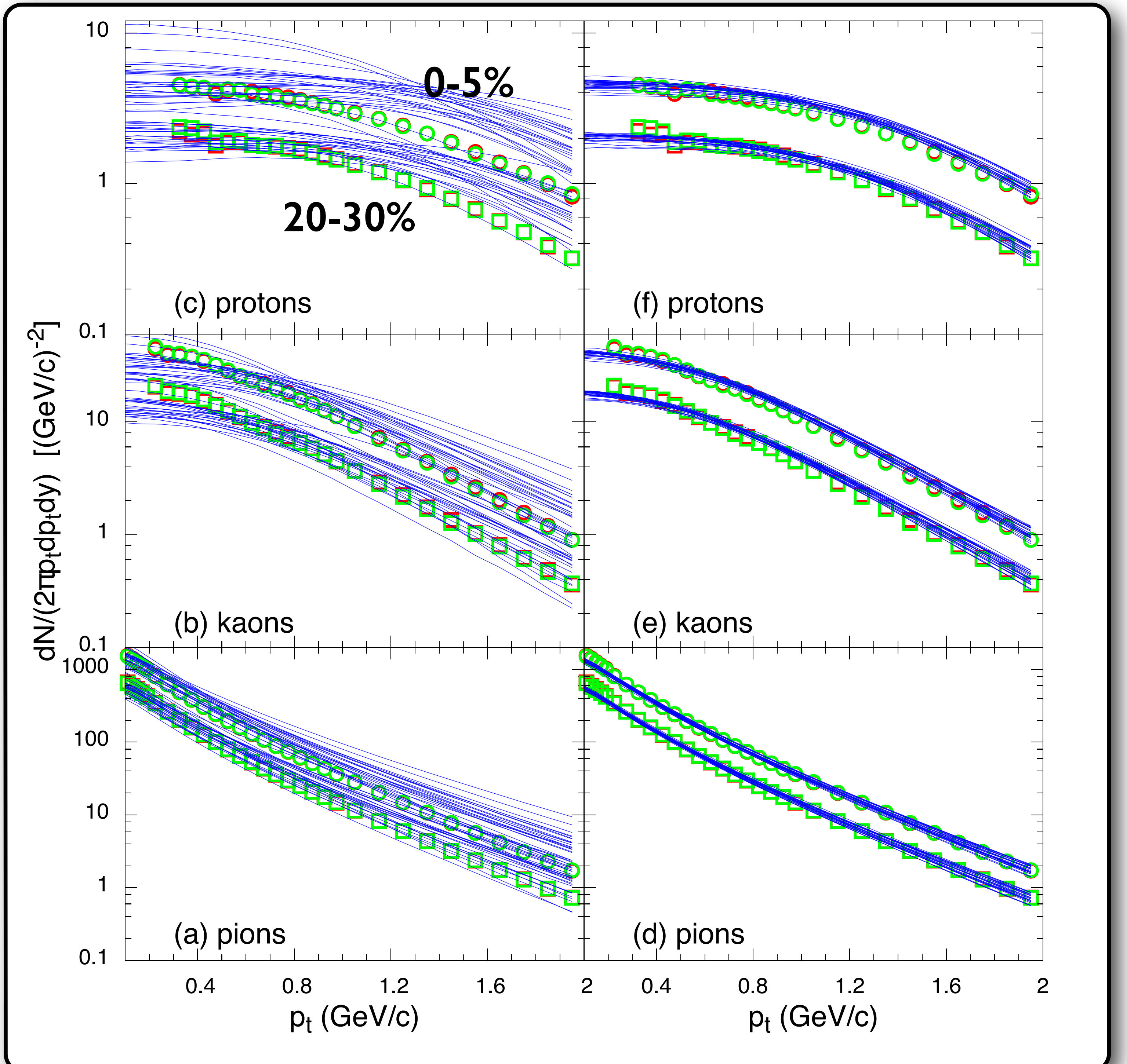
- **Jets, rare probes, bulk correlations & EM probes**
  calculations overlaid on hydro evolution

- **Femtoscopic correlations**
  calculated from final *f(p,r,t)*

Comparing to Experiment

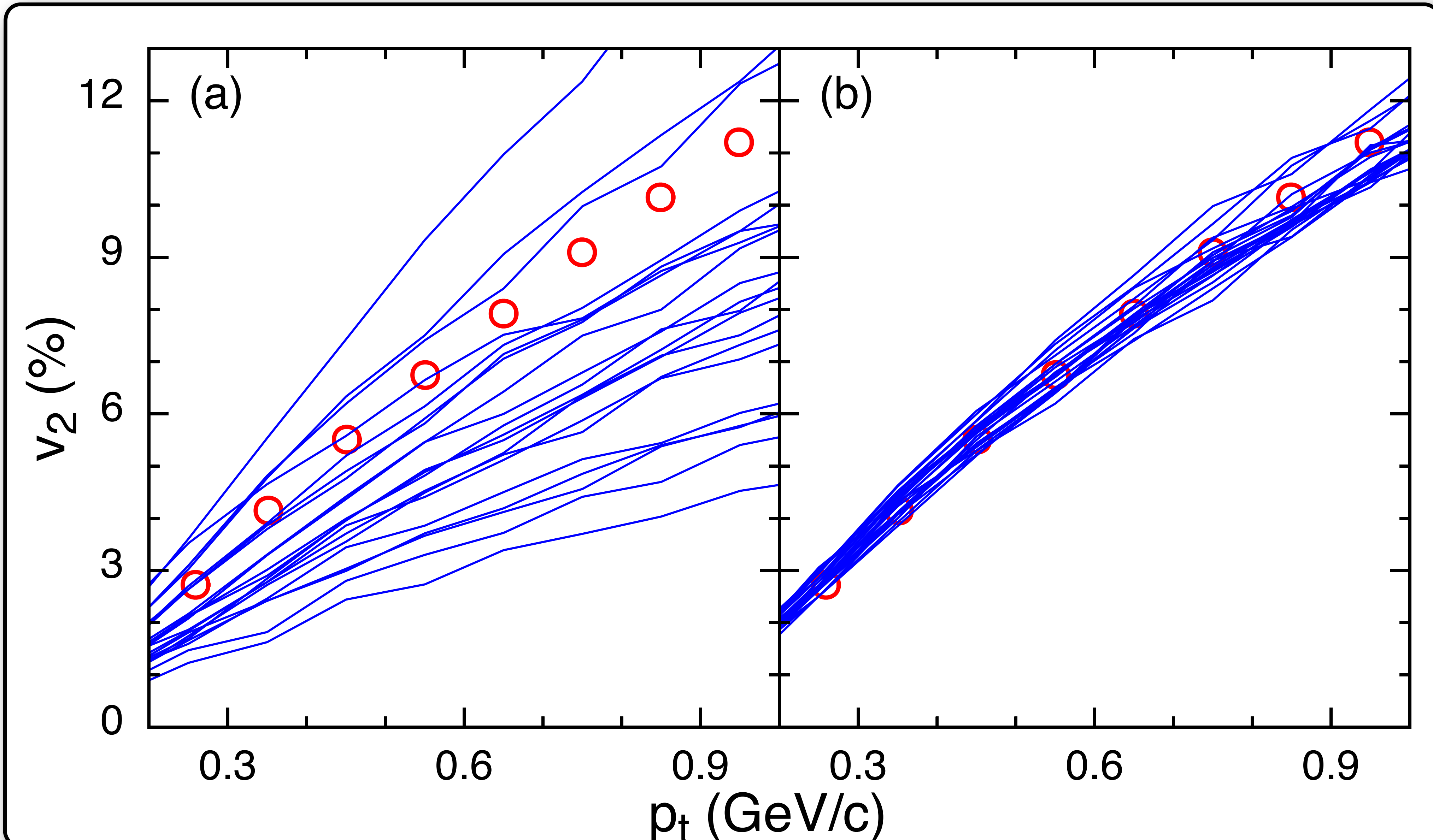
- **Spectra**
  sensitive to eq. of state, initial ε
- **Elliptic flow**
  strongly affected by viscosity
- **Femtoscopy**
  sensitive to eq. of state
- **Jets, rare probes, EM probes**
  related physics
- **Correlations**
  sensitive to chemistry, phase structure

Spectra

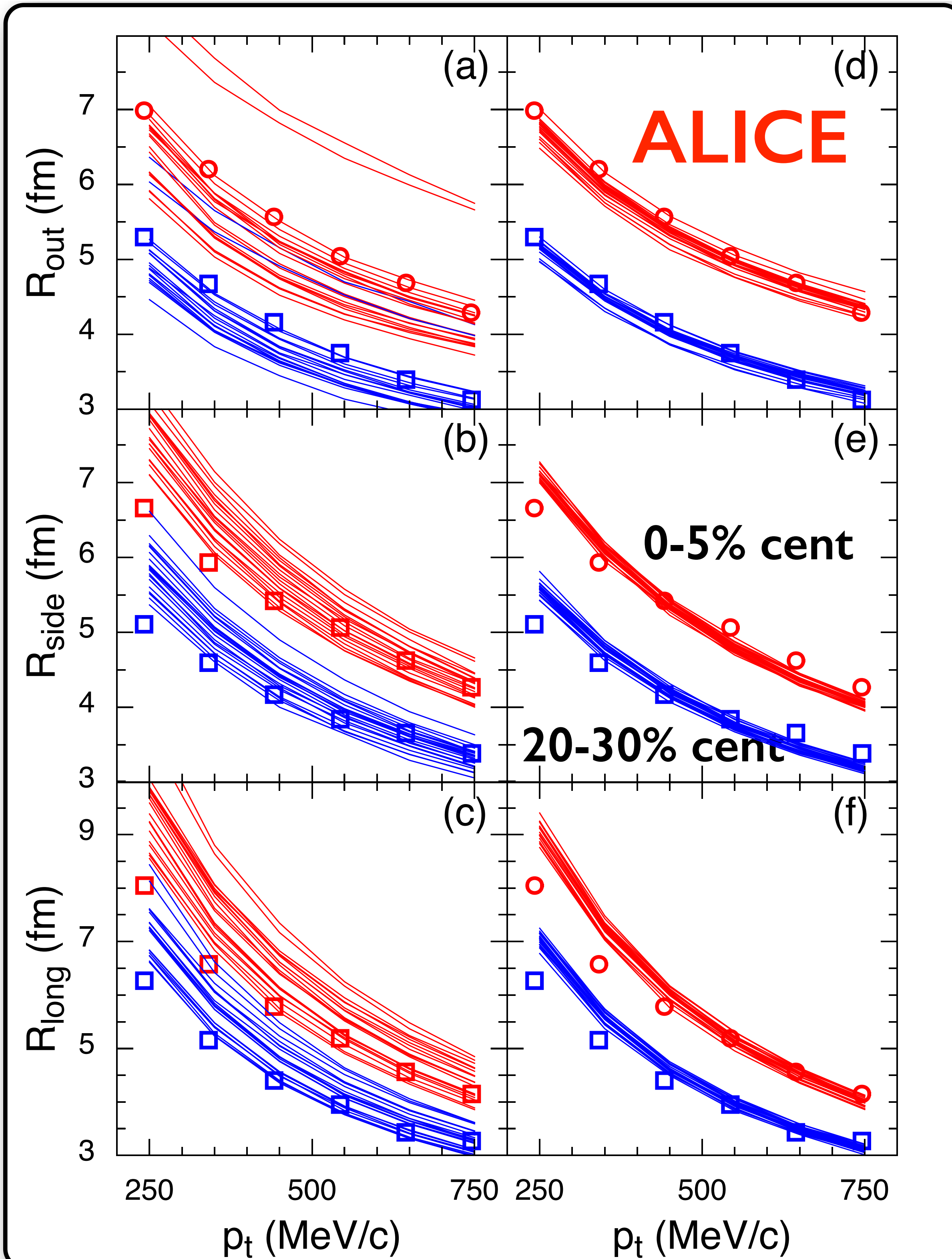


0-5%
20-30%
(c) protons
(f) protons
(b) kaons
(e) kaons
(a) pions
(d) pions
dN/(2πp_t dp_t dy) [(GeV/c)^-2]
p_t (GeV/c)
10
1
0.1
10
1
0.1
1000
100
10
1
0.1
0.4
0.8
1.2
1.6
2

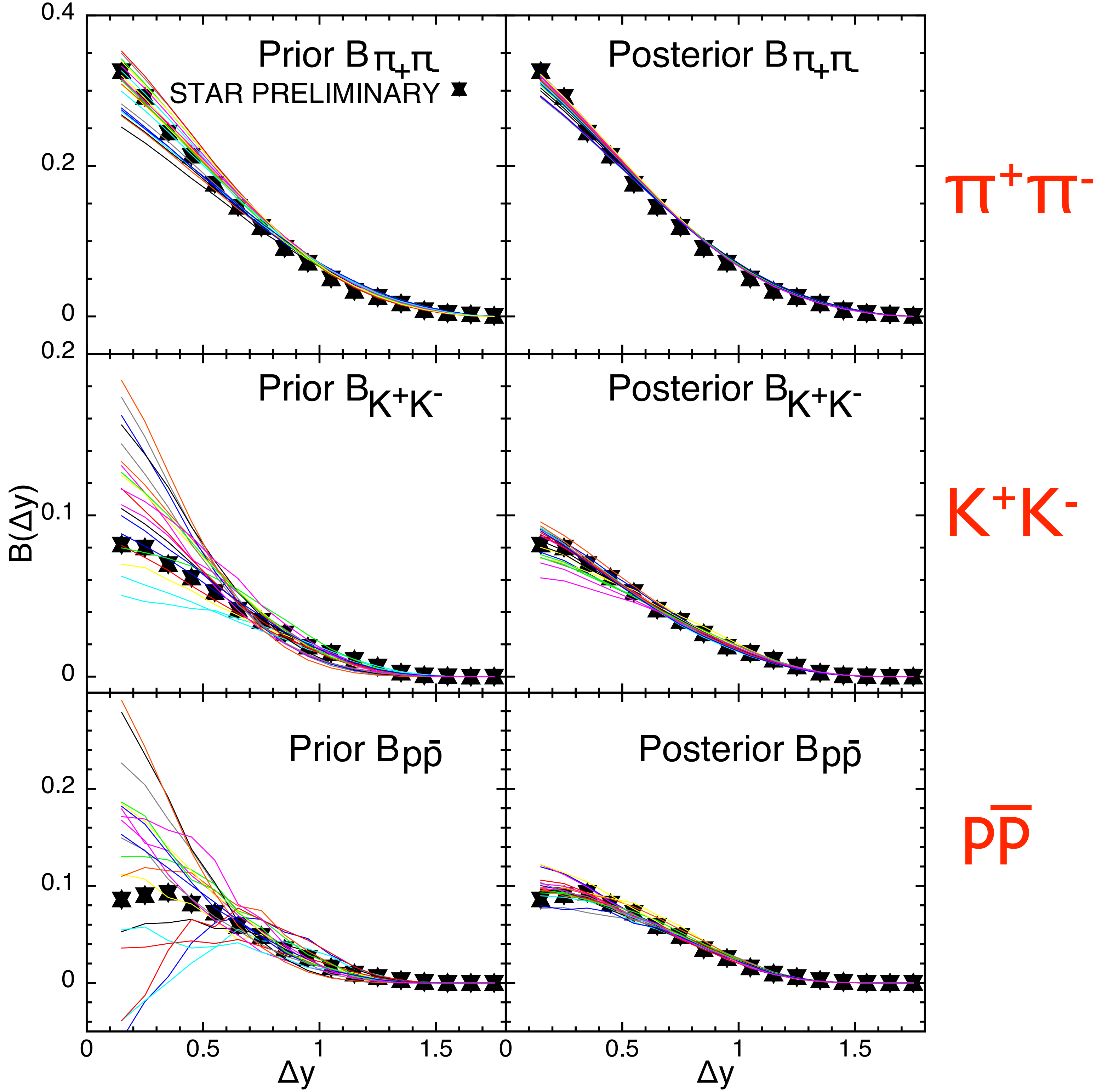
V_2 (elliptic flow)

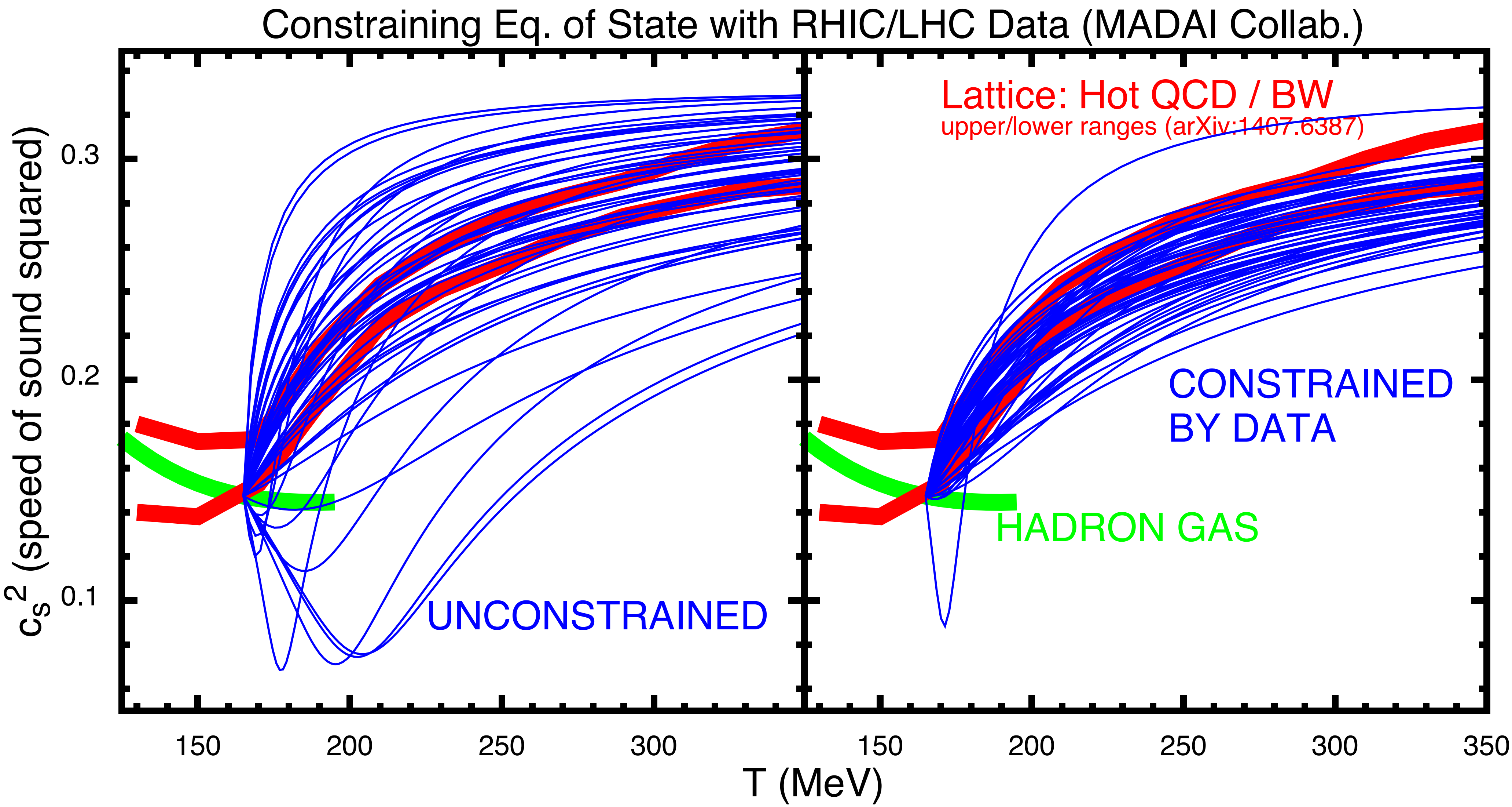


Femtoscopic Radii



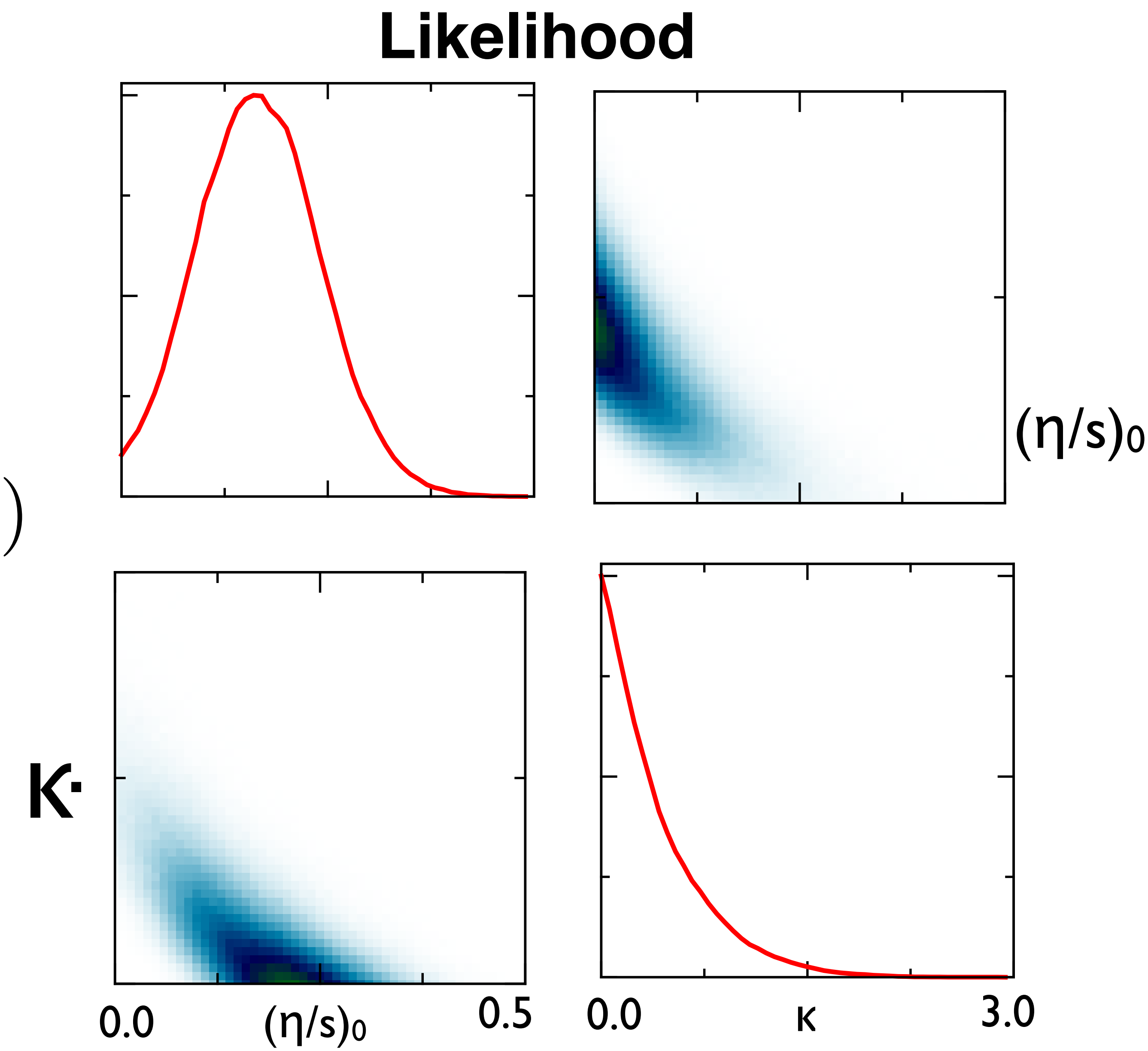
Charge Correlations




Constraining Eq. of State with RHIC/LHC Data (MADAI Collab.)
Lattice: Hot QCD / BW
upper/lower ranges (arXiv:1407.6387)
CONSTRAINED
BY DATA
HADRON GAS
UNCONSTRAINED
c_s^2 (speed of sound squared)
0.1
0.2
0.3
150
200
250
300
350
T (MeV)

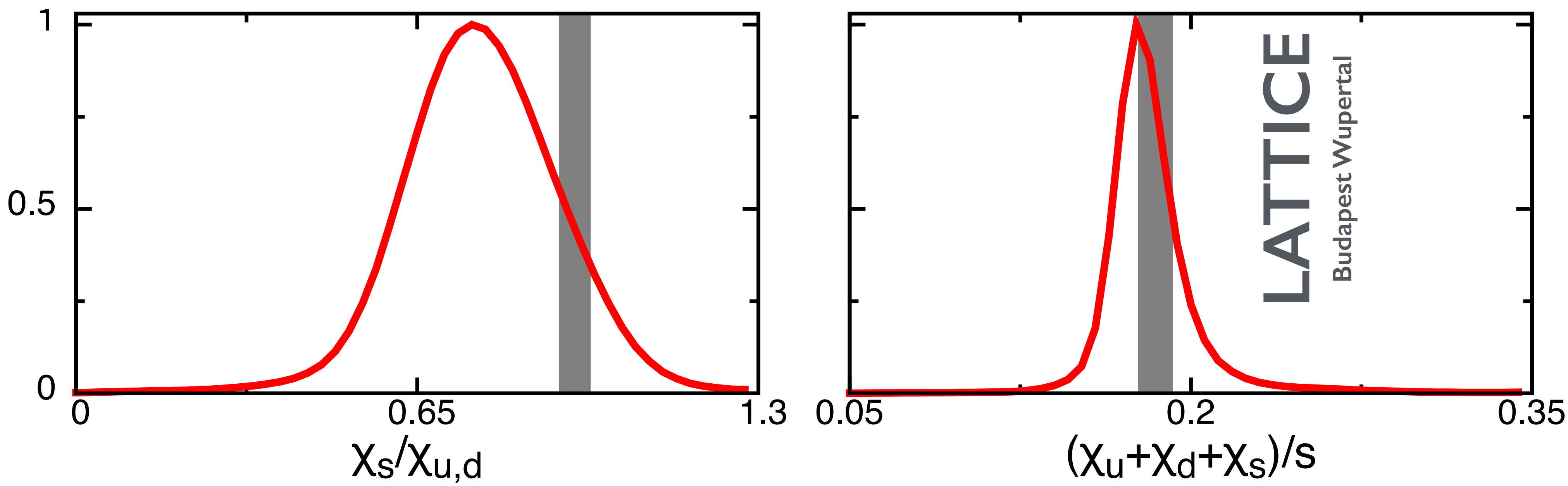
Viscosity from spectra, femtoscopy, elliptic flow at RHIC & LHC

$$\eta/s = (\eta/s)_0 + \kappa \ln(T/165)$$



Charge fluctuations from charge correlation measurements

Likelihood from Data Comparison



Summary

Strong Evidence for:

- SE tensor(**pressure**) near **equilibration**
- **chemically equilibrated** QGP
- extremely good **liquid** with low viscosity
- strong jet damping ➔ **strongly interacting** liquid