Parton transport and collectivity

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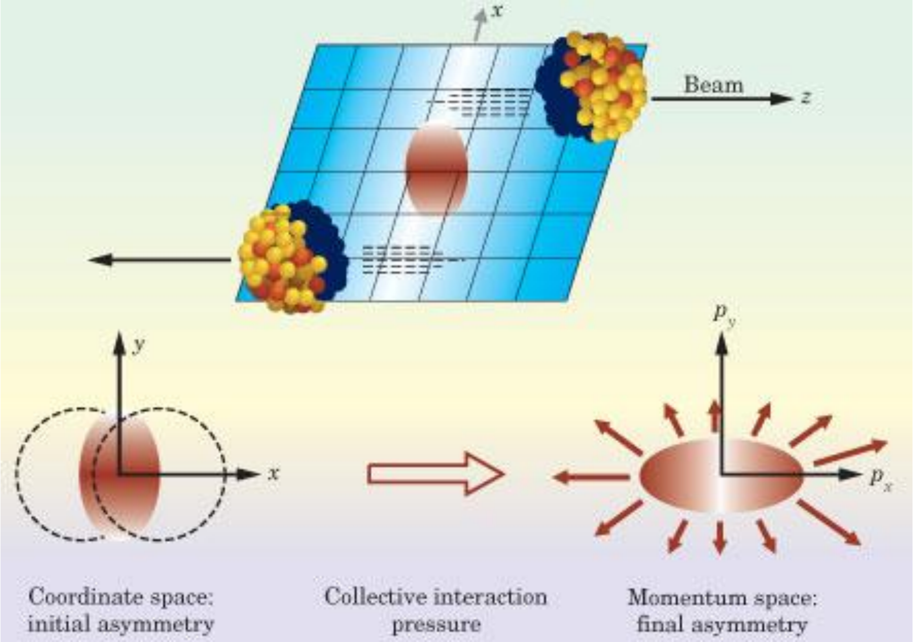
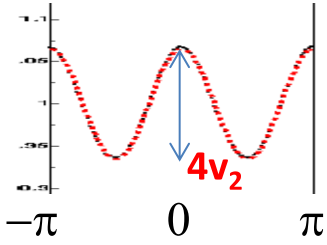
Preamble

- Large azimuthal anisotropy and jet quenching have been measured. We seem to have well established the perfect fluid paradigm. We do not question it anymore.
- We have created little bangs: quark gluon plasma / local equilibrium / hydro expansion / collectivity / perfect fluid. We are studying QCD at extreme conditions.
- Parton transport and hydrodynamics can both successfully describe data, and that's no surprise to many of us. The system is so dense and strongly interacting that parton transport has reached hydro limit.
- Why do I want to talk about them? What are the problems?
- Can we ever address the problems?

Azimuthal Anisotropy

$\vec{x}$-anisotropy $\quad\Rightarrow\quad$ $\vec{p}$-anisotropy



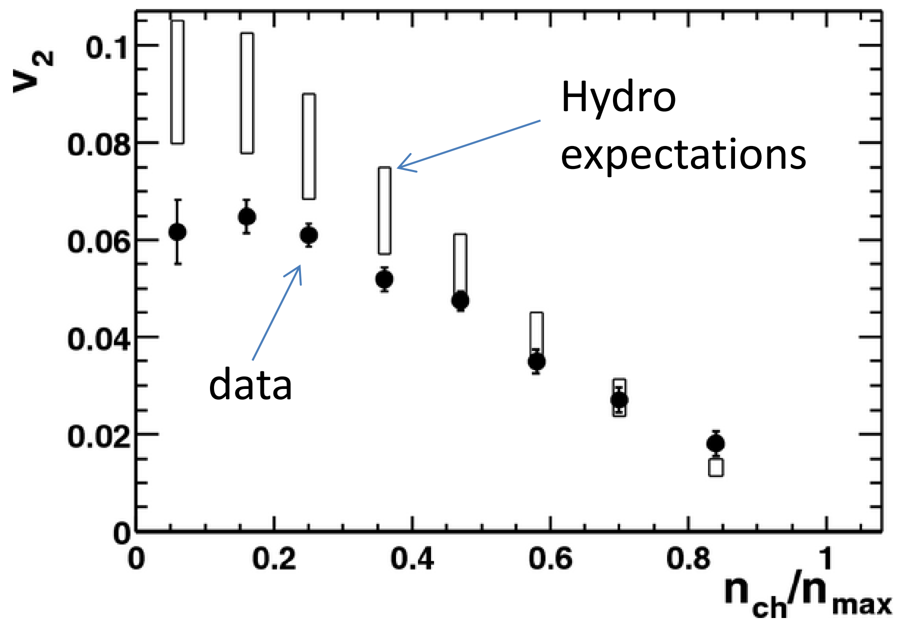


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

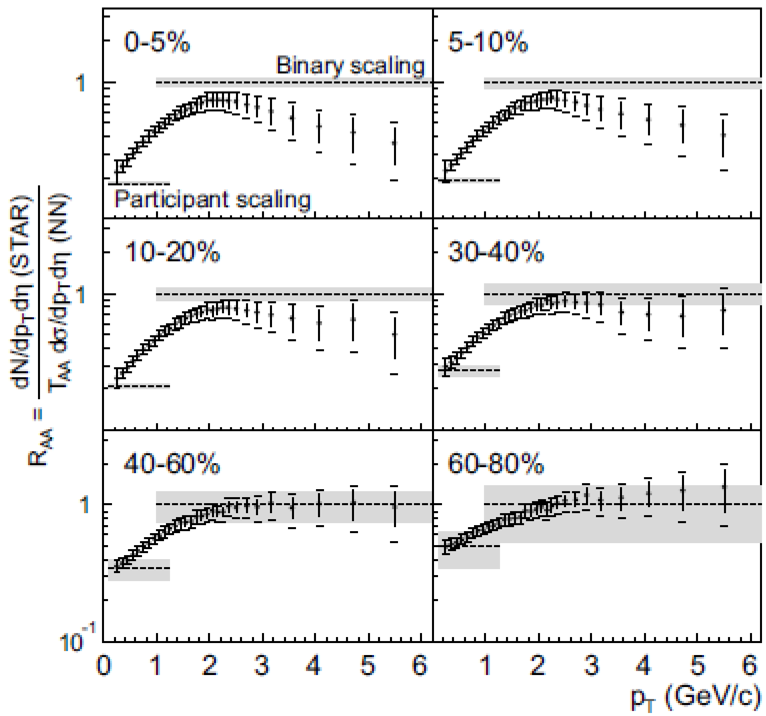
Large flow, large energy loss

Au+Au 130 GeV

STAR, PRL**86** (2001) 402

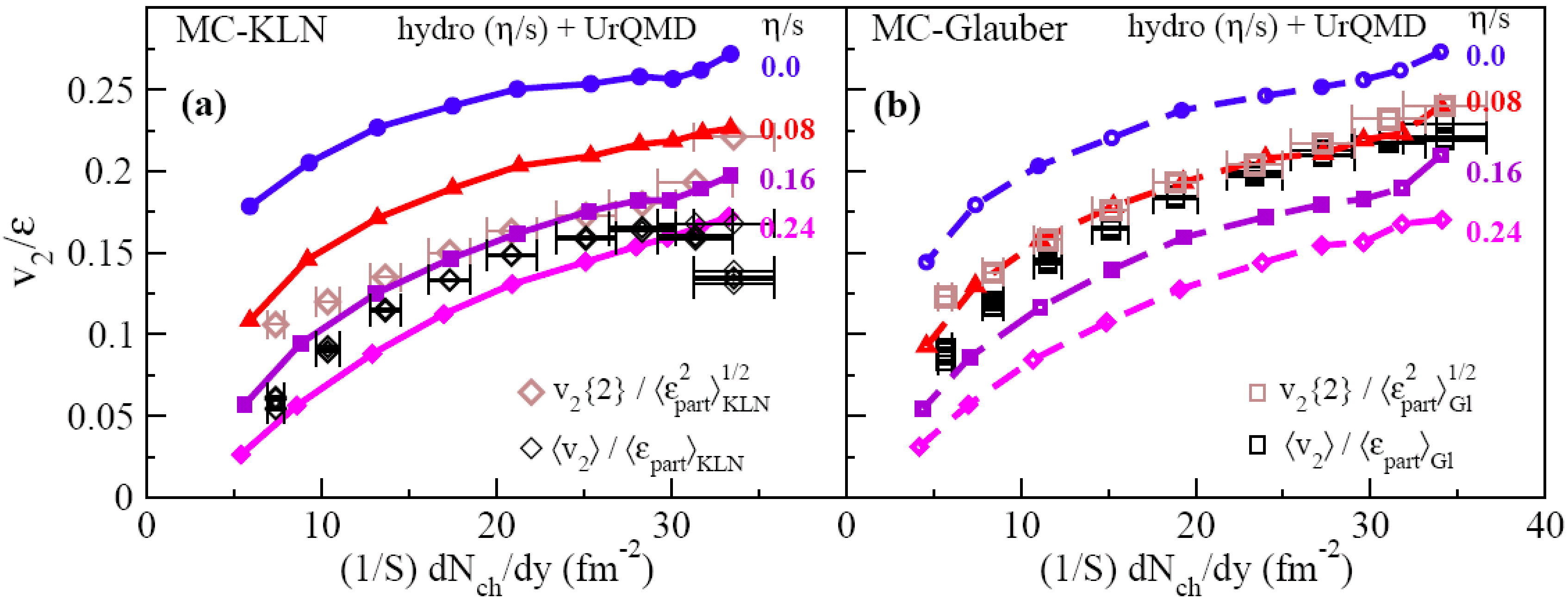


STAR, PRL**89** (2002) 202301



Comparison to Hydrodynamics

Large elliptic anisotropy



➔ ***Small value*** of specific viscosity over entropy density ***η/s***

➔ Model uncertainty dominated by ***initial eccentricity ε***

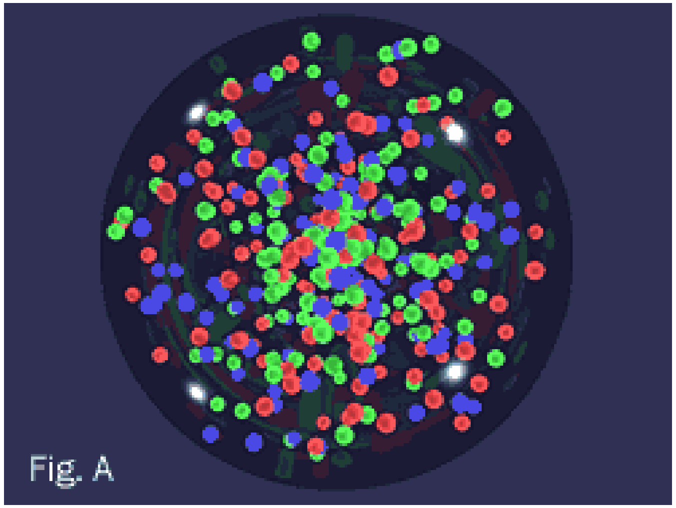
Model: Song *et al. arXiv:1011.2783*

Our Paradigm

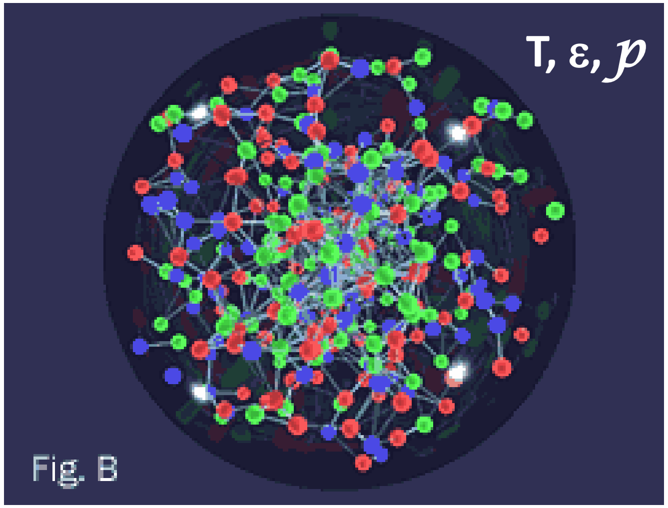
ca 2005

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions



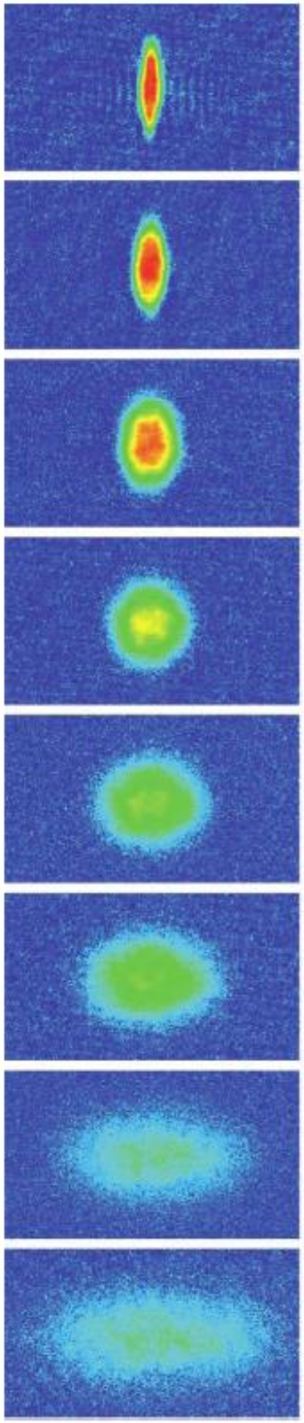
Infinite viscosity



Very low viscosity

Local equilibrium, Collective velocity field

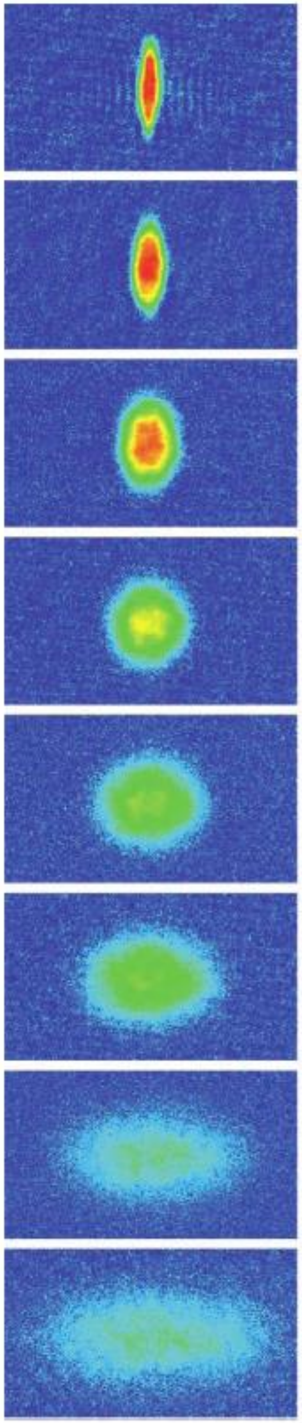
Another system with large anisotropy



K. M. O'Hara *et al.*, Science 298, 2179 (2002)

Large elliptic anisotropy
in heavy ion collisions
consistent with hydrodynamic flow

Large elliptic anisotropy
in cold atom systems
consistent with hydrodynamic flow



Opacity

Mean free path: $L_{mfp} = 1/\rho\sigma$, Prob. = $\exp(-L/L_{mfp}) = \exp(-\rho\sigma L)$

Opacity = $L/L_{mfp} = \rho\sigma L$

Cold atom system:

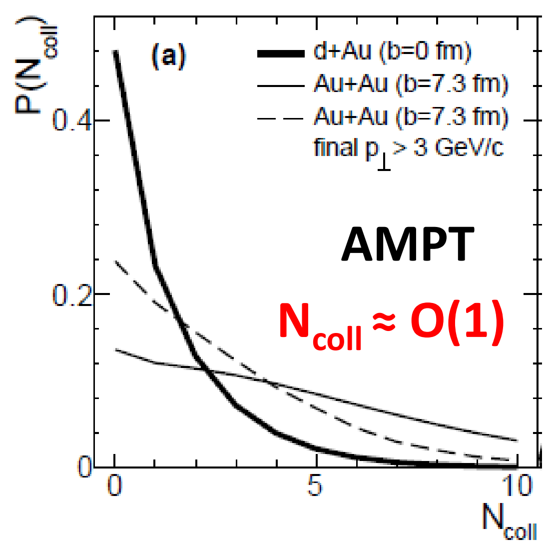
$a \approx 5\times10^{-5}$ cm
$\sigma_{int} \approx 10^{-8}$ cm^2
$\rho \approx 5\times10^{13}$ /cm^3
$L_{mfp} \approx 2\times10^{-6}$ cm
$L \approx 2\times10^{-3}$ cm
$L/L_{mfp} \approx 1000$

Very high opacity for the cold atom system

Indeed hydro!

Heavy ion collision:

dN/dy ~ 1000
$\rho \sim 1000/\pi R^2\tau \sim 7$ fm^{-3}
$\rho\sigma L$ ~ 7fm^{-3}*3mb*3fm **~ 6**

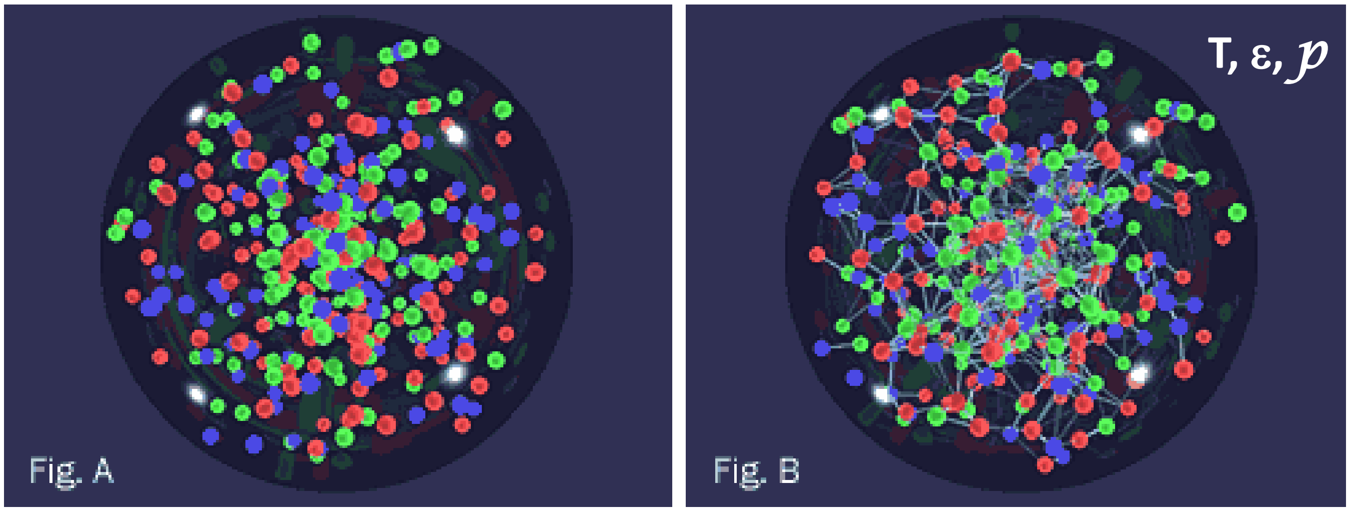


Low opacity in AMPT

Hydro??

Our Paradigm

ca 2005



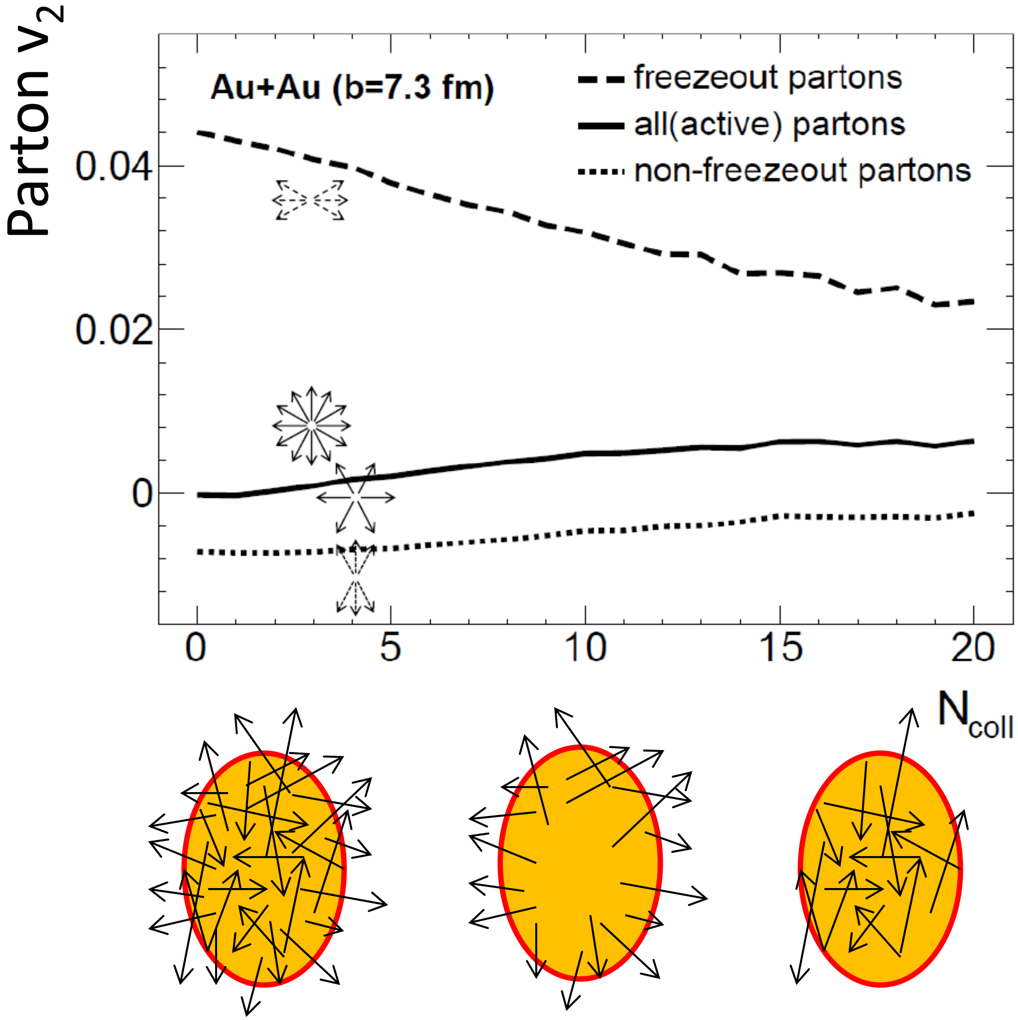
Local equilibrium**??**
Collective velocity field**??**

Ncoll ~ a few:

Already enough to equilibrate and generate large hydrodynamic flow?
Might there be another mechanism to generate large anisotropy?

How is anisotropy developed in AMPT?

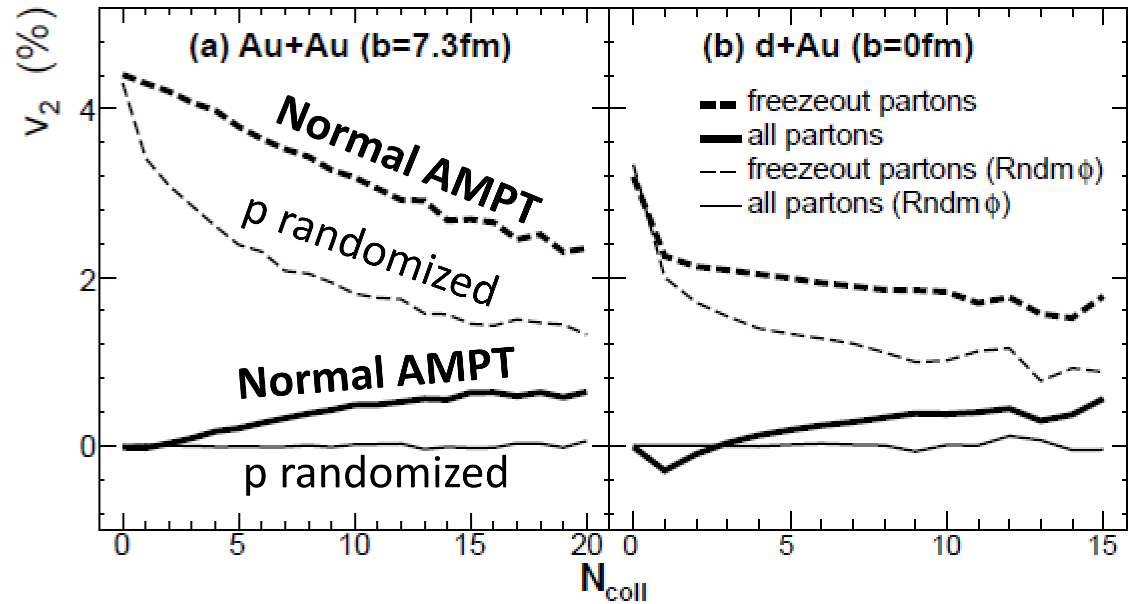
L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, FW, arXiv:1502.05572, PLB753(2016)506



- Partons freeze out with large positive v_2, even when they do not interact at all.
- This is due to larger escape probability along x than y.
- Remaining partons start off with negative v_2, and become ~isotropic (v_2~0) after one more collision.
- Process repeats itself.
- Similar for v_3.
- Similar for d+Au collisions.

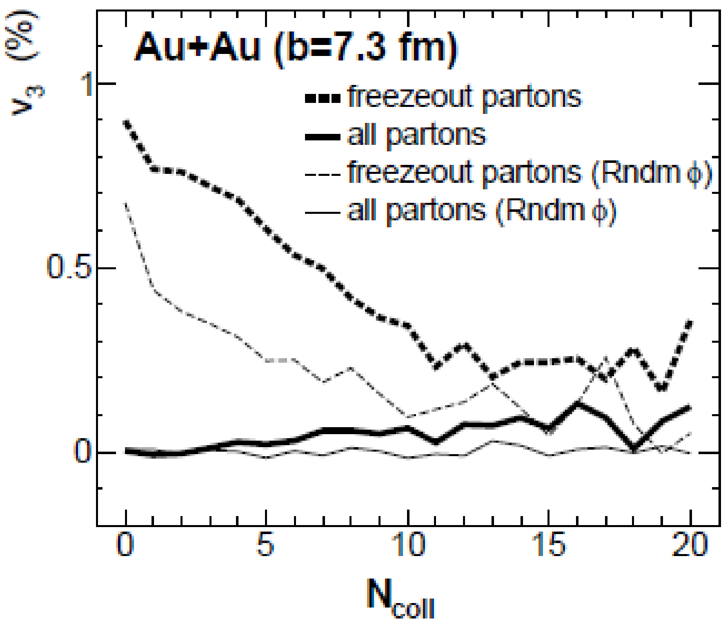
Majority anisotropy from escape

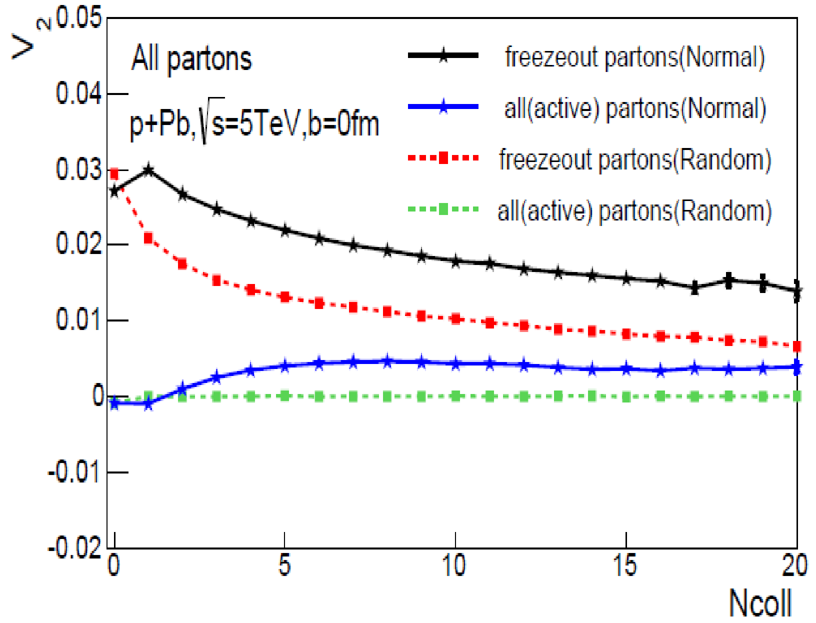
L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, FW, arXiv:1502.05572, PLB753(2016)506



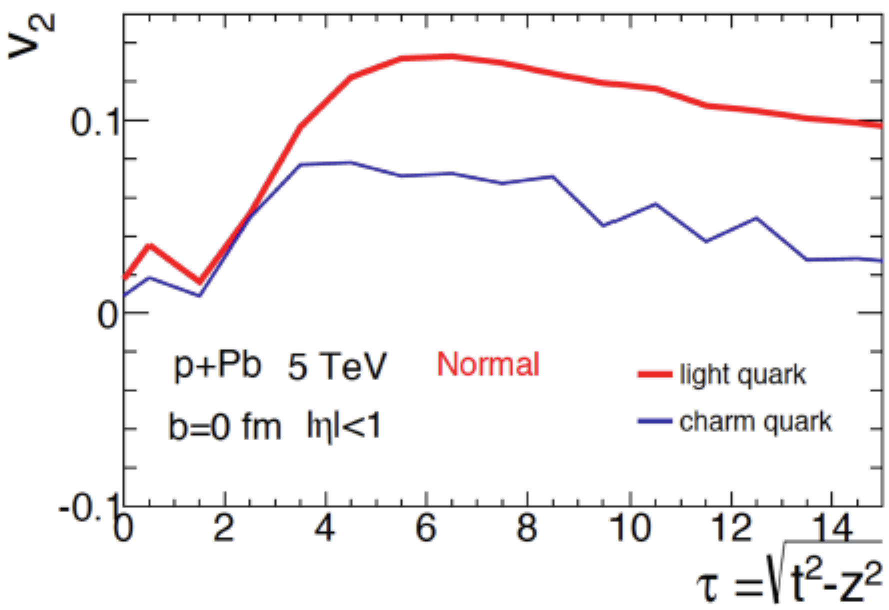
- **Majority of anisotropy comes from the final-step "escape" mechanism.**
- The small dynamic v_2 is result of hydrodynamic pressure push. It is this flow that is most relevant. However it plays a minor role.
- **May explain small system data and weak energy dependence.**

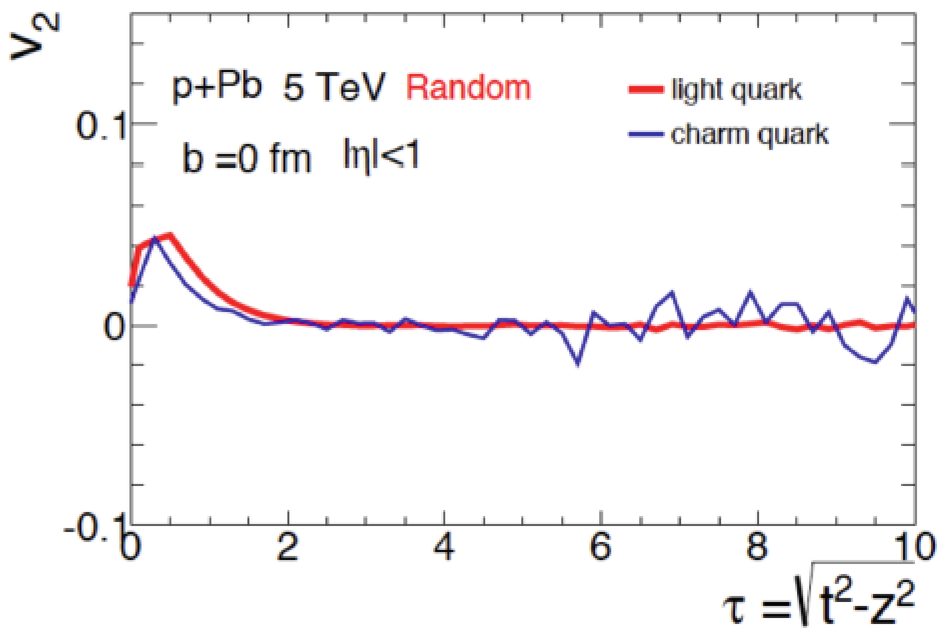
Similar for v_3 & LHC p+Pb



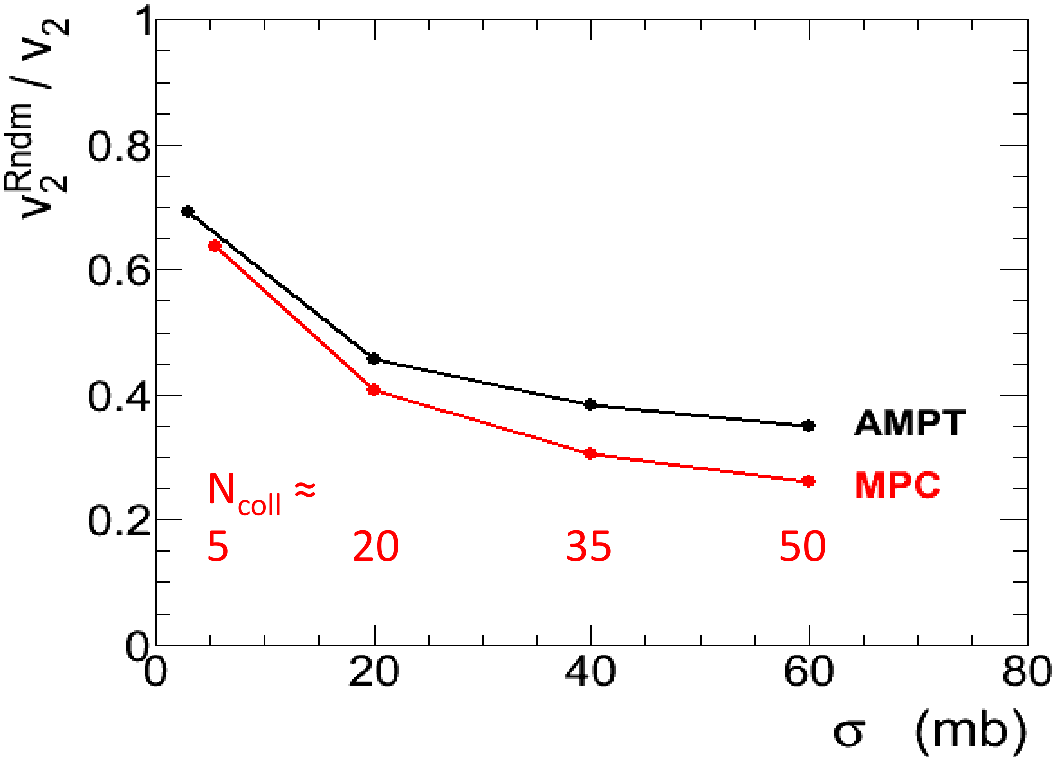


Charm "flow" in p+Pb



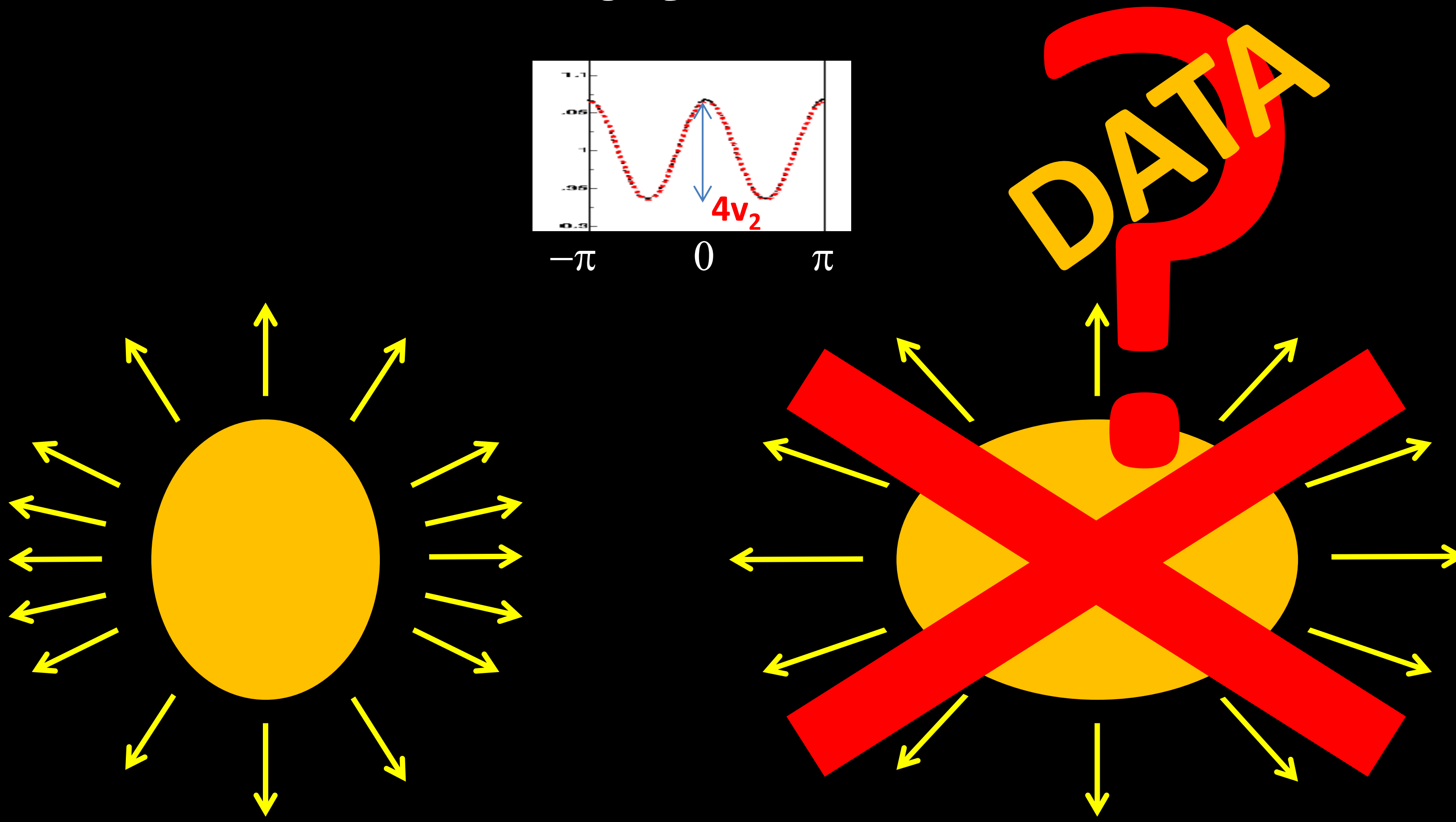


Relative escape contribution



- **Escape contribution still sizeable even at x10 larger x-sections.**

Anisotropy mechanism



No expansion **Expansion, flow**

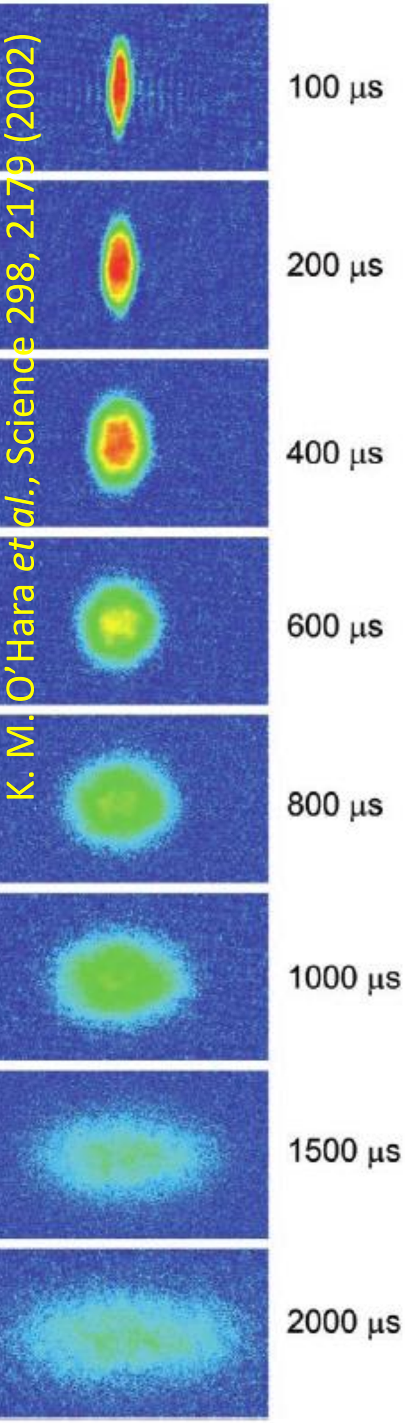
Heavy ion collisions

Low density/opacity
Mundane physics

Perfect liquid
Hydrodynamics

Need experimental test!

To emulate QGP with cold atoms



Opacity: ρσL

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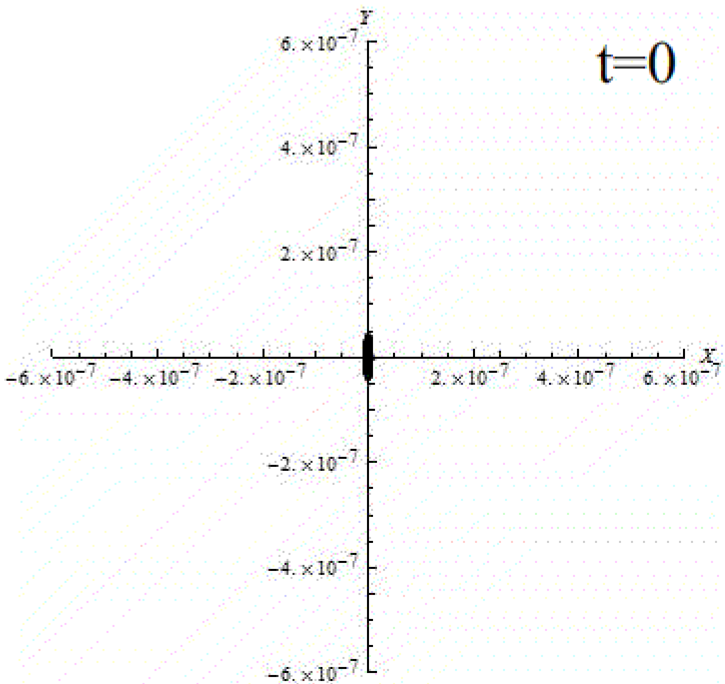
Very high opacity for the cold atom system

$\rho\sigma_{int}L$: reduce opacity by 10^3
1000 → 1

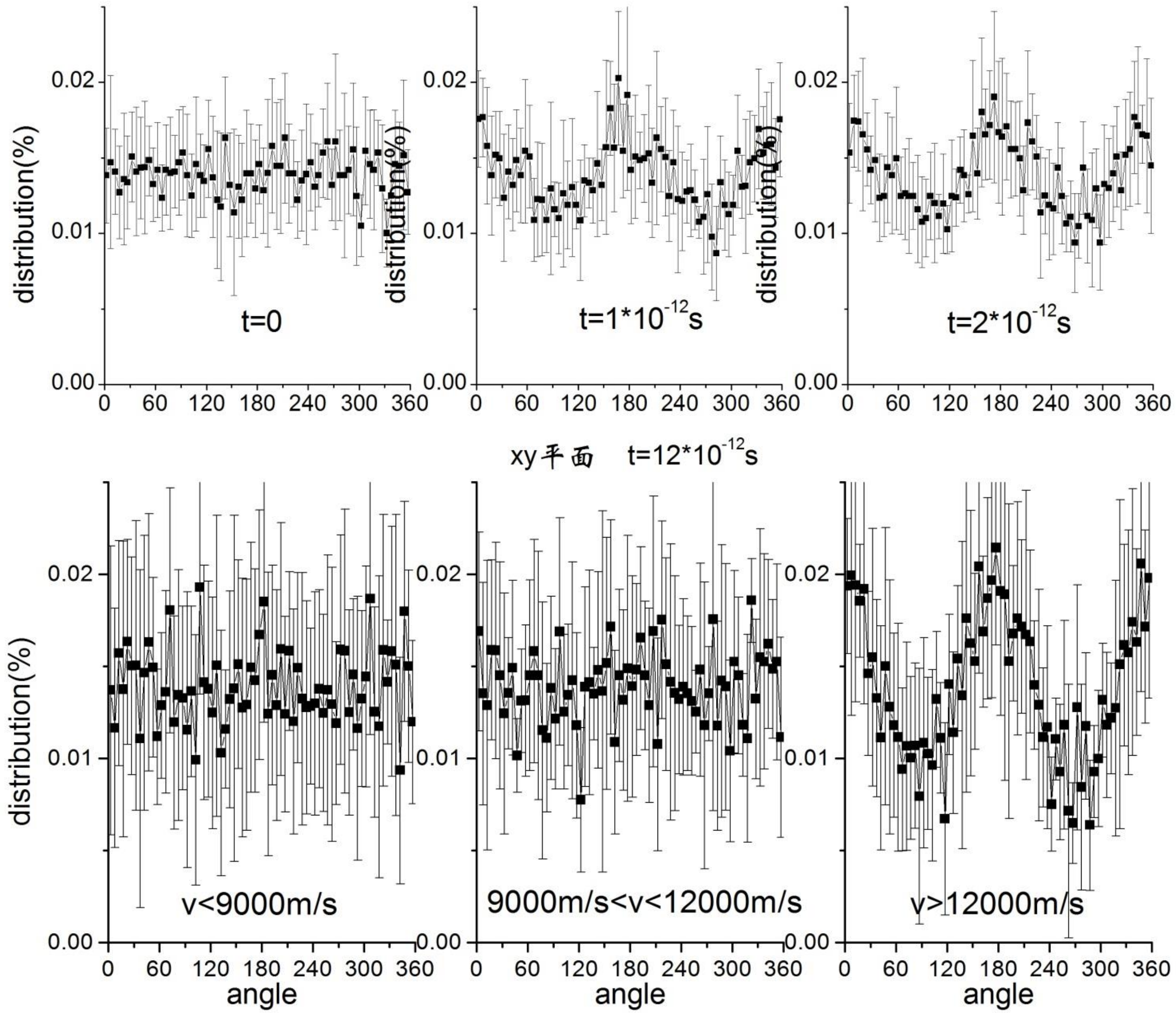
Anisotropic ion trap is also viable



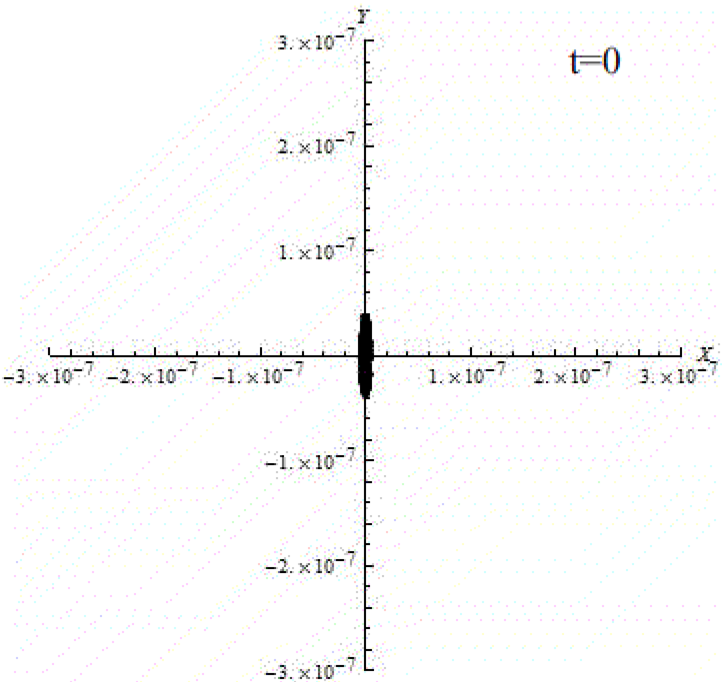
- Coulomb interactions
- Can change trap size and anisotropy, and ion density

Ion trap: Coulomb

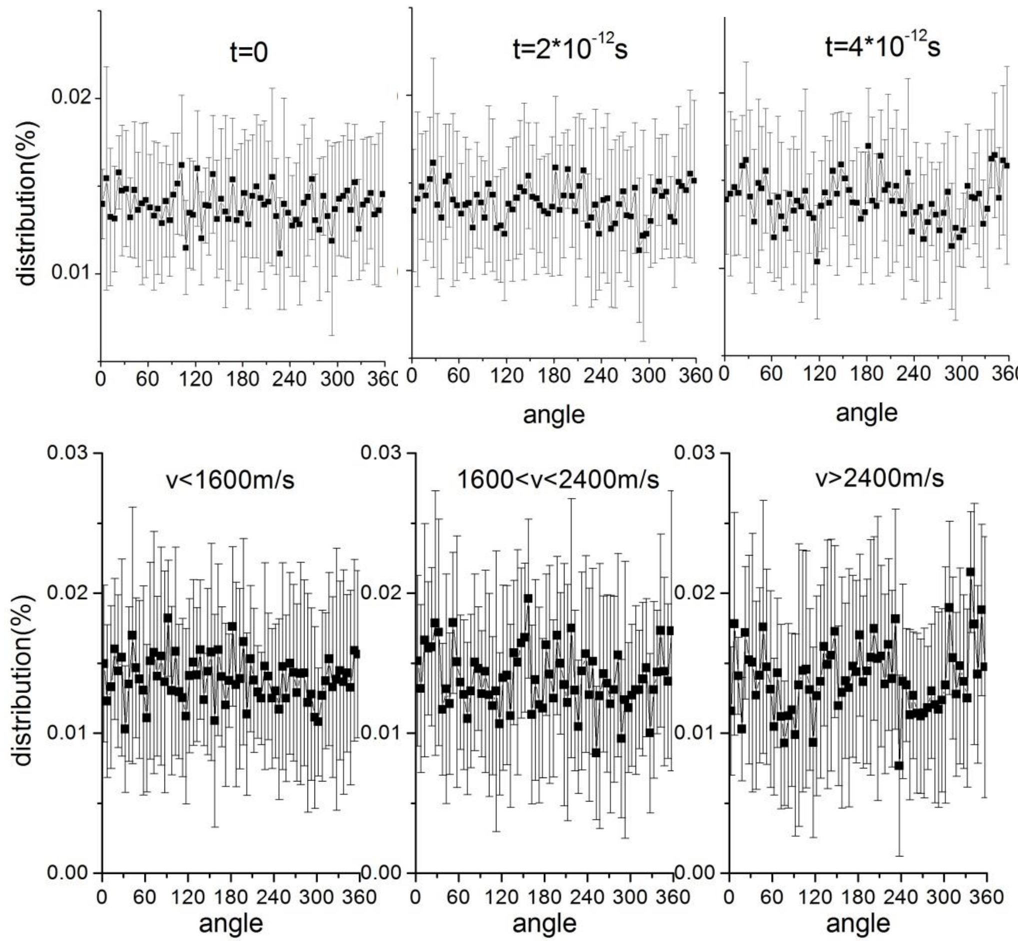
- Lx=10nm
  Ly=80nm
  Lz=100nm
- Number of ions =1000
- Initial thermal velocity 2000m/s



Ion trap: Coulomb with hard core



$\rho\sigma_{int}L \sim 1$



Final remarks

- The more I think, the more skeptical I am about our established paradigm.

- What have we learned from heavy ion collisions?
  Spontaneously, I can give you a long list of findings.
  What *fundamental* physics have we learned?
  I cannot give you a clear answer.

- We must be self critical. We must ask hard questions. We must think out of the box.

- **We need a Higgs in heavy ion collisions…and better soon.**