A Cold Atom Experiment

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Outline

Hydro flow or escape?

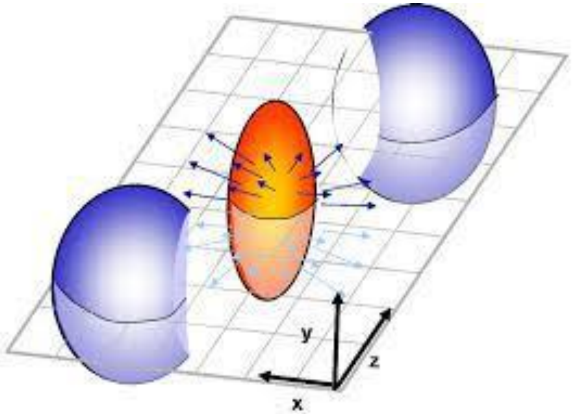
Motivation for a cold atom experiment

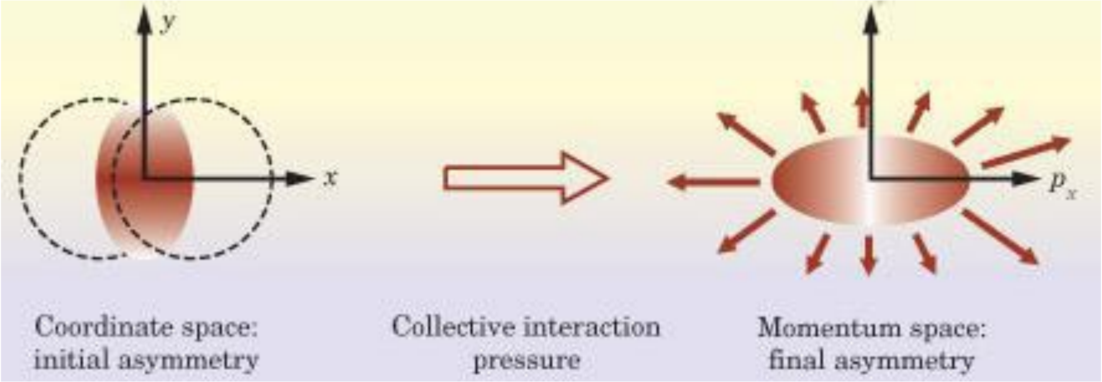
Cold atom laboratory

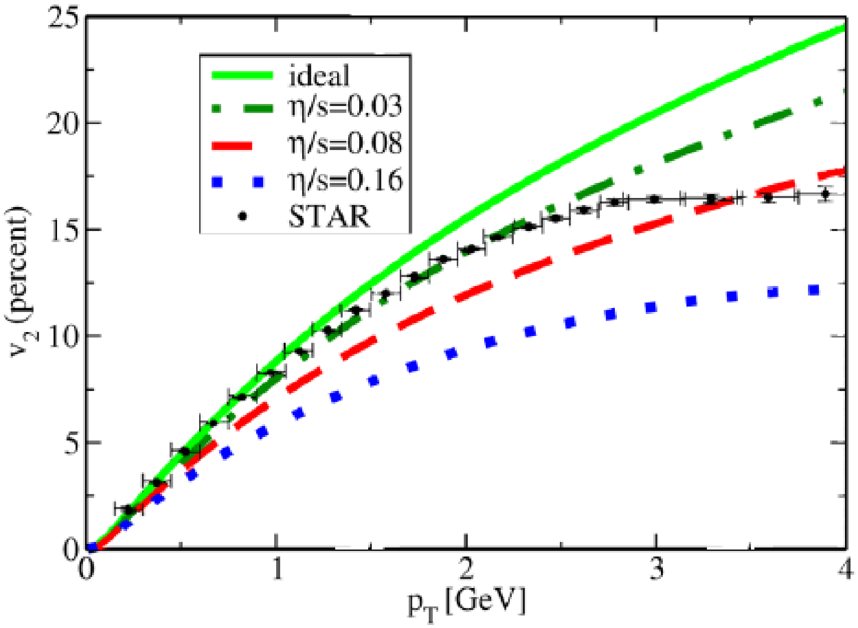
To verify the uncertainty principle*

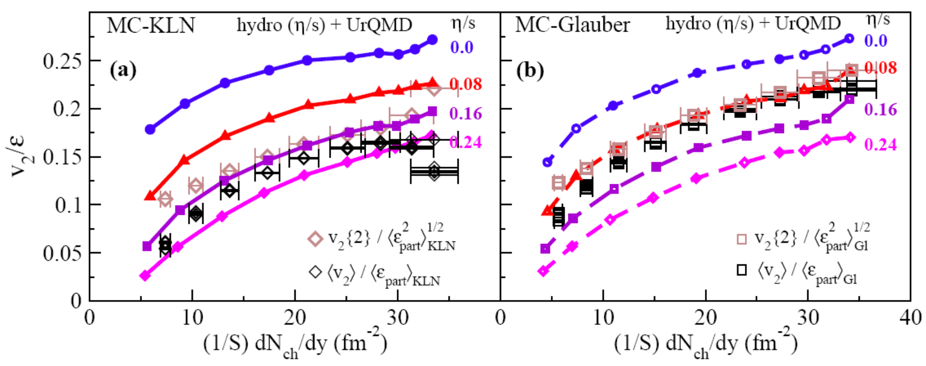
Summary

Heavy ion experiment









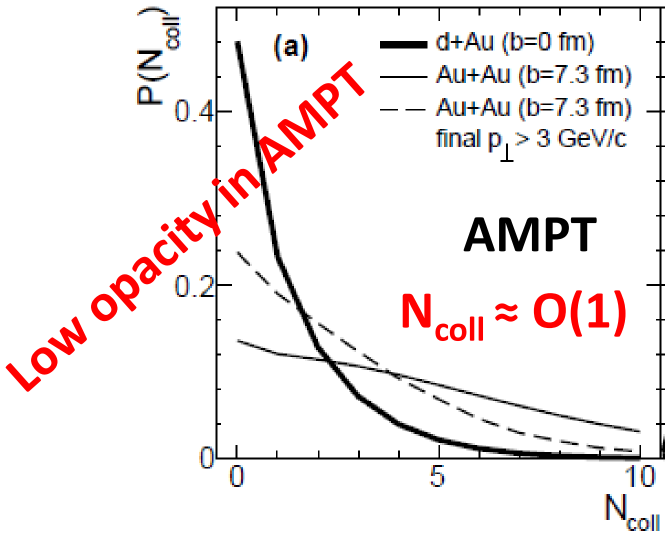
Model: Song *et al. arXiv:1011.2783*

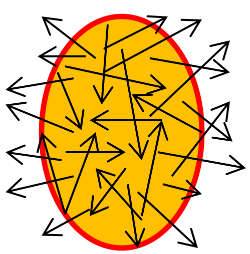
The Hydrodynamics Paradigm

Strong elliptic anisotropy
BNL press release 2005
Nearly perfect fluid (sQGP)

Is it really hydro?

Mean free path: $L_{mfp} = 1/\rho\sigma$
Ncoll = Opacity = $L/L_{mfp} = \rho\sigma L$

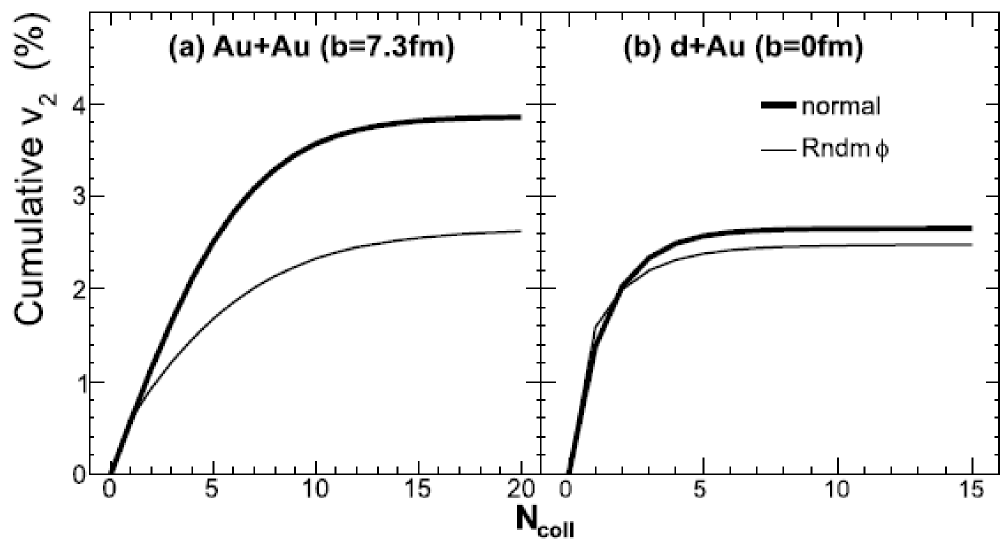




Heavy ion collision:

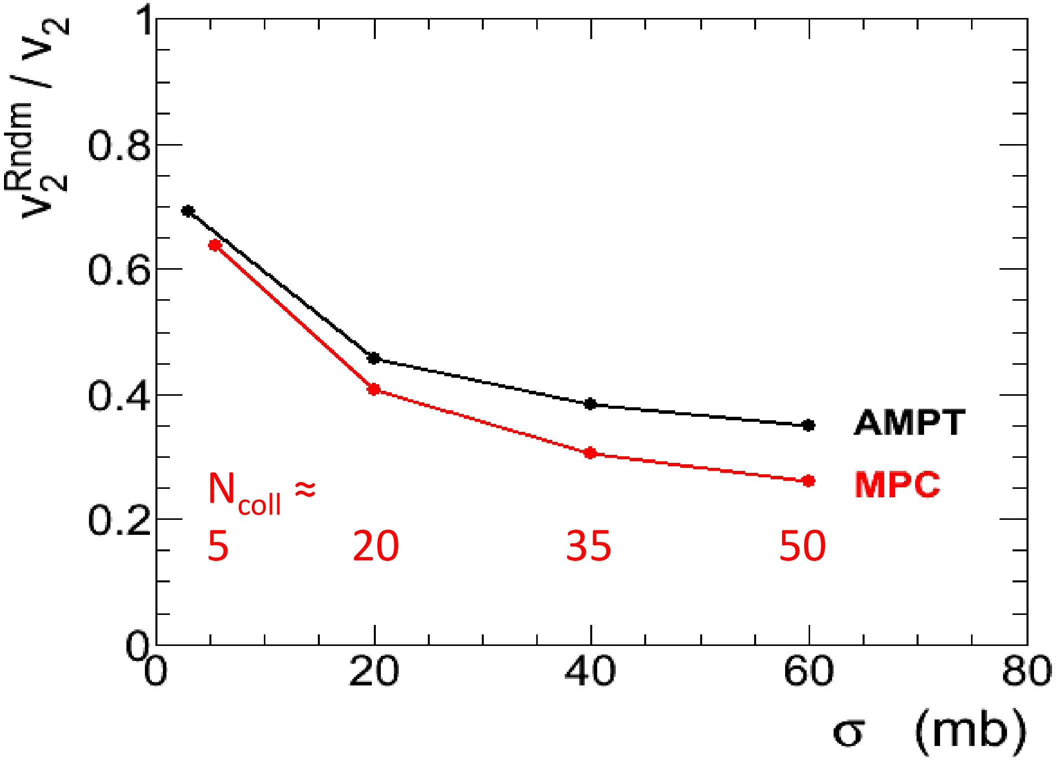
dN/dy ~ 1000, $\rho \sim 1000/\pi R^2\tau \sim 6\ \text{fm}^{-3}$
$\rho\sigma L \sim 7\text{fm}^{-3}*3\text{mb}*3\text{fm} \sim 5$

He, FW, et al. PLB753(16)506



Hydro questionable!

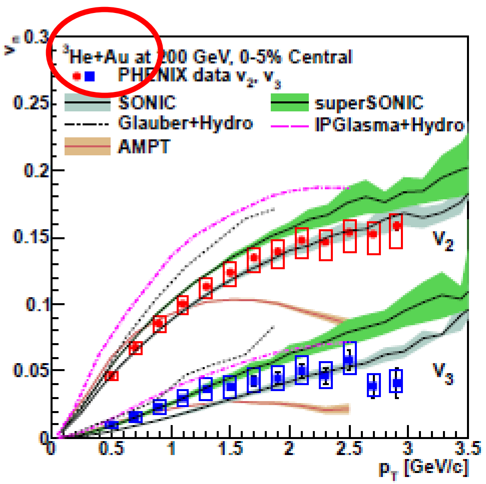
Relative escape contribution



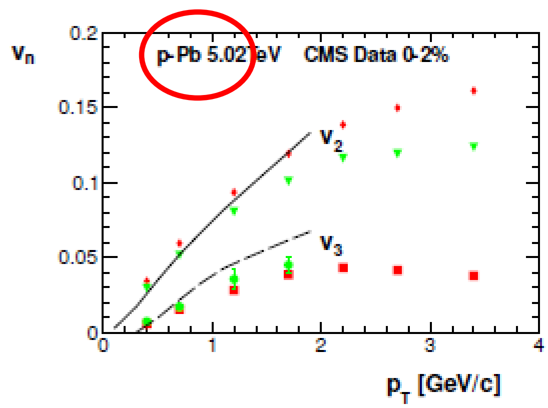
- **Escape contribution still sizeable even at x10 larger x-sections.**

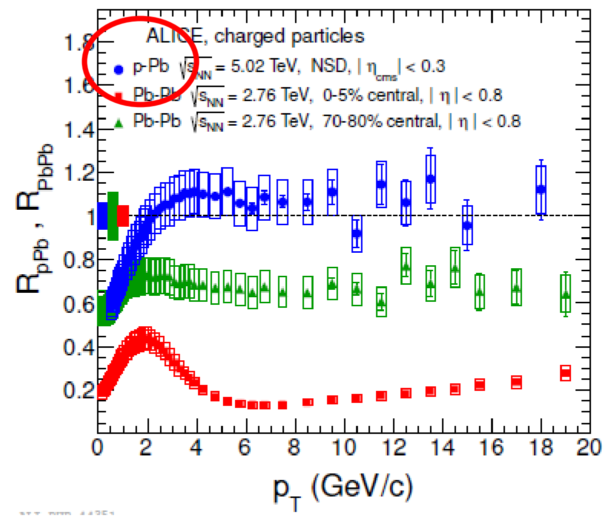
Strong anisotropy, but no energy loss

Small system collisions



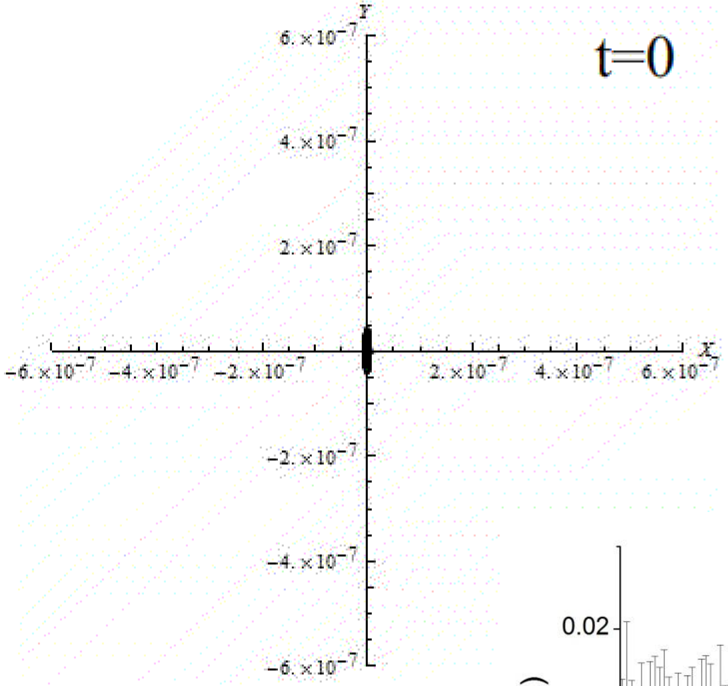
PHENIX, arXiv:1507.06273





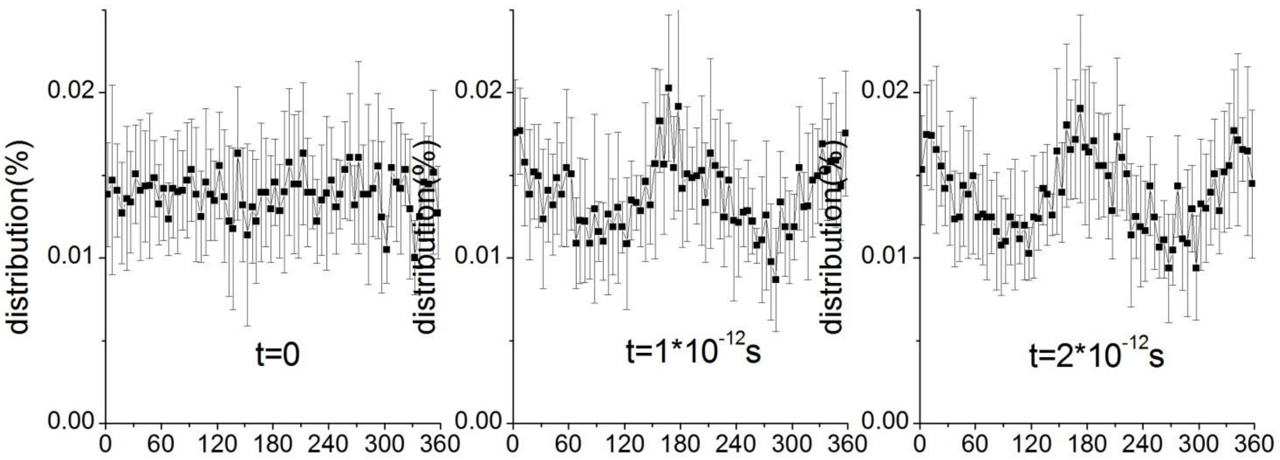
PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, K. Kawaguchi et al. Poster 206

Flow from Coulomb interaction

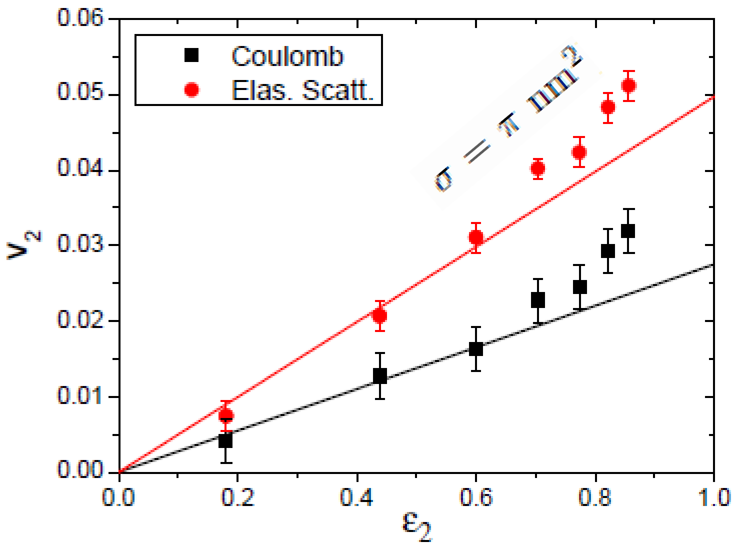


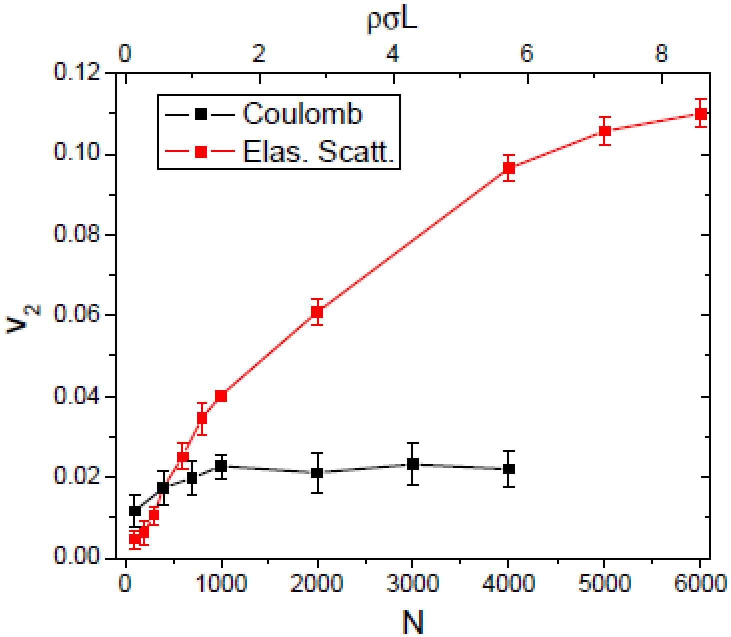
- Coulomb interactions
- Can change trap size and anisotropy, and ion density

- a = 10 nm, b = 80 nm, c = 100 nm
- Number of ions =1000
- Initial thermal velocity 2000m/s



Flow from Coulomb and Elastic scattering

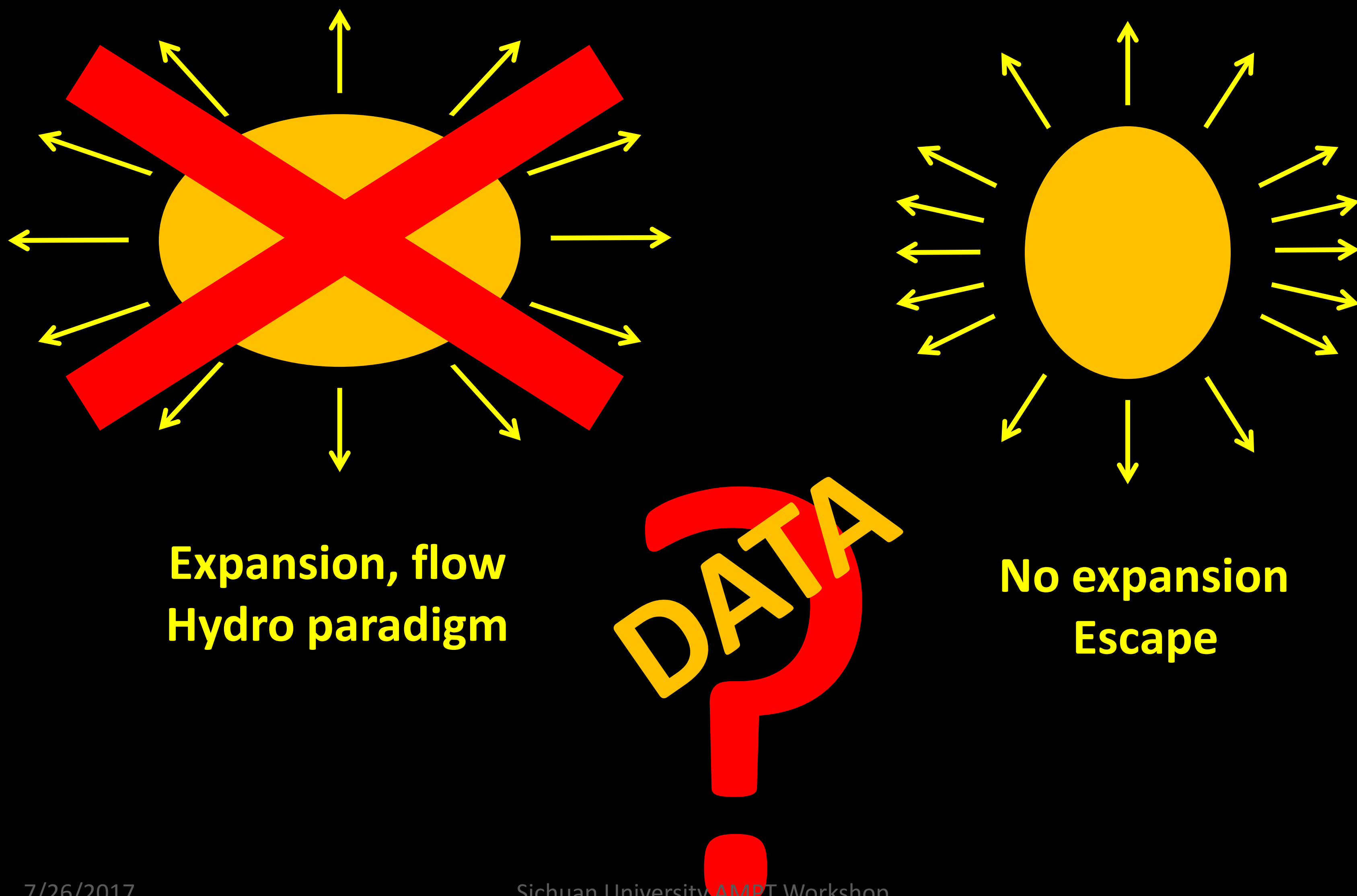


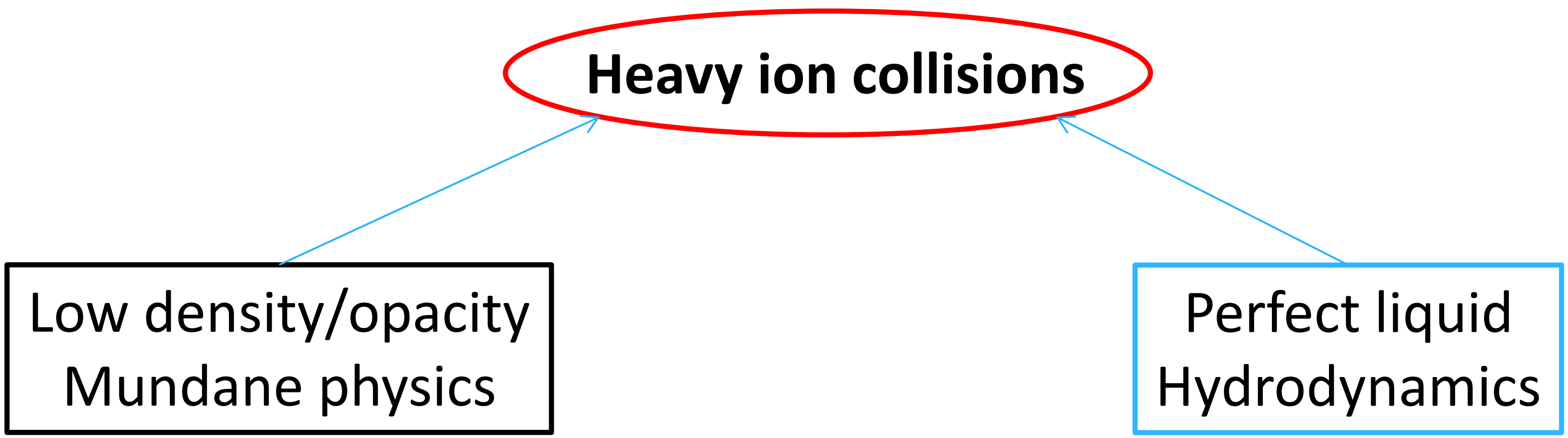


Trap size: ab = 240 nm^2, c = 50 nm.
Number of particles: 1000

a = 10 nm, b = 24 nm, c = 50 nm

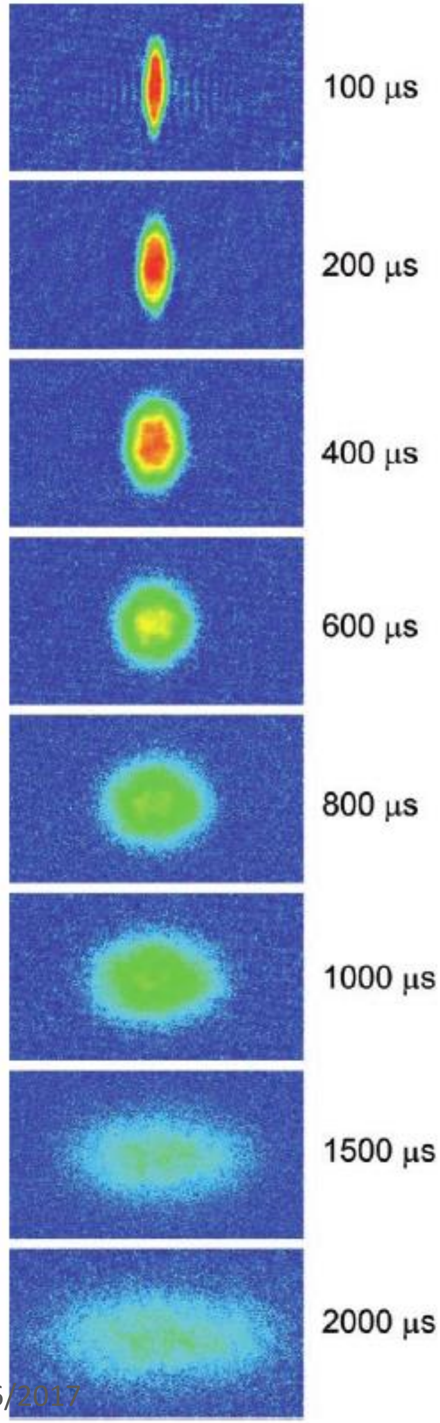
Anisotropy mechanism





Need experimental test!

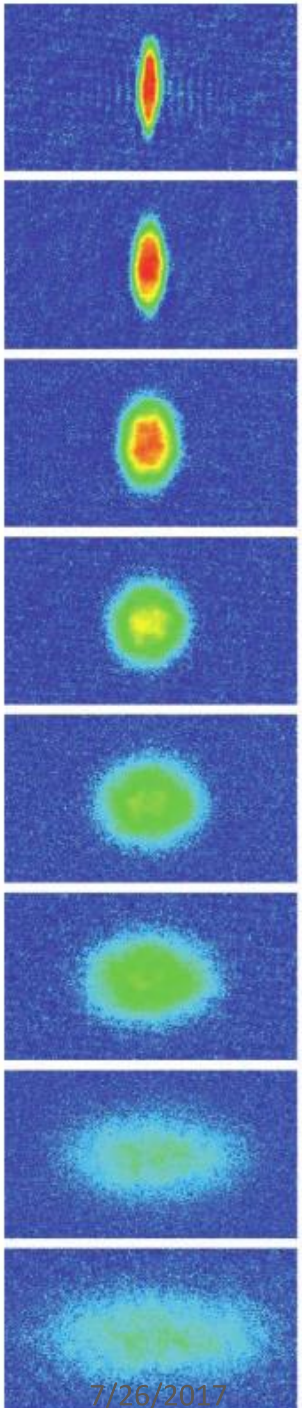
Another system with large anisotropy



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

Large elliptic anisotropy
in cold atom systems
consistent with hydrodynamic flow

Opacity



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

Mean free path: $L_{mfp} = 1/\rho\sigma$, Ncoll = Opacity = $L/L_{mfp} = \rho\sigma L$

Cold atom system:

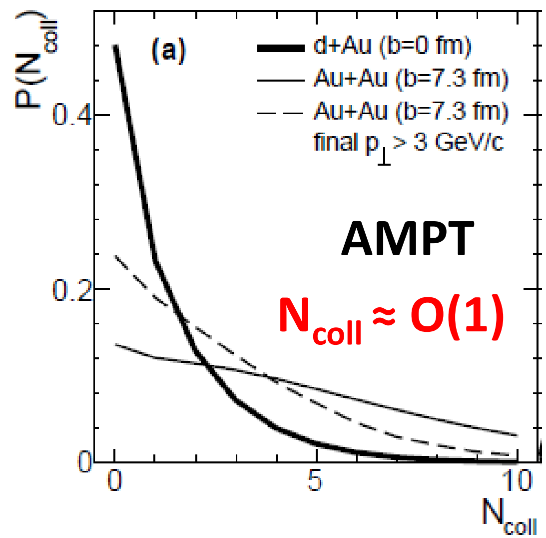
$a \approx 5\times10^{-5}$ cm
$\sigma_{int} \approx 10^{-8}$ cm^2
$\rho \approx 5\times10^{13}$ /cm^3
$L_{mfp} \approx 2\times10^{-6}$ cm
$L \approx 2\times10^{-3}$ cm
$L/L_{mfp} \approx 1000$

Very high opacity for the cold atom system

Indeed hydro!

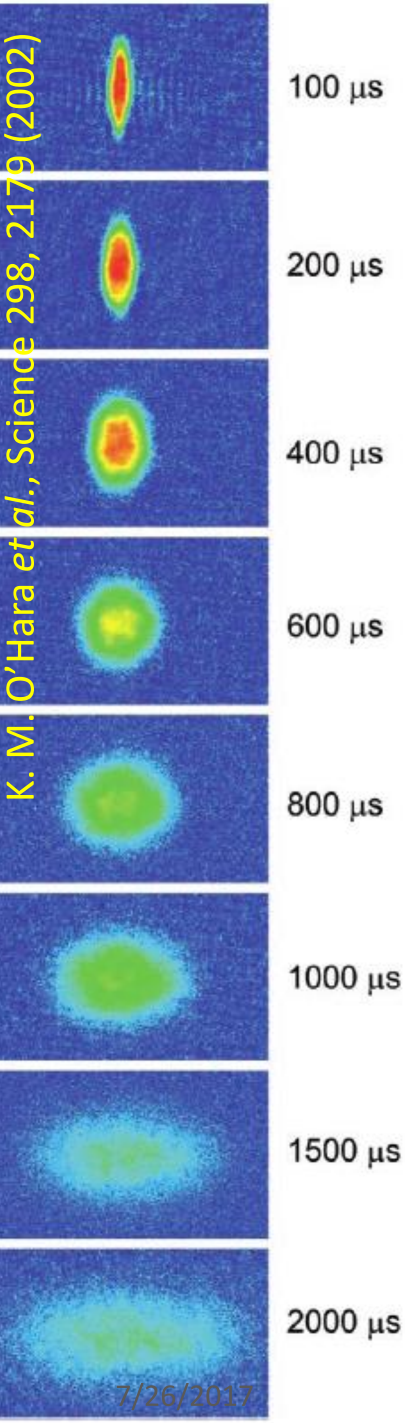
Heavy ion collision:

dN/dy ~ 1000, $\rho \sim 1000/\pi R^2\tau \sim 6$ fm^{-3}
$\rho\sigma L$ ~ 7fm^{-3}*3mb*3fm **~ 5**



Low opacity in AMPT

Hydro??



To emulate QGP with cold atoms

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

Opacity: $\rho\sigma L$

$a \approx 5\times10^{-5}$ 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~~
0-1

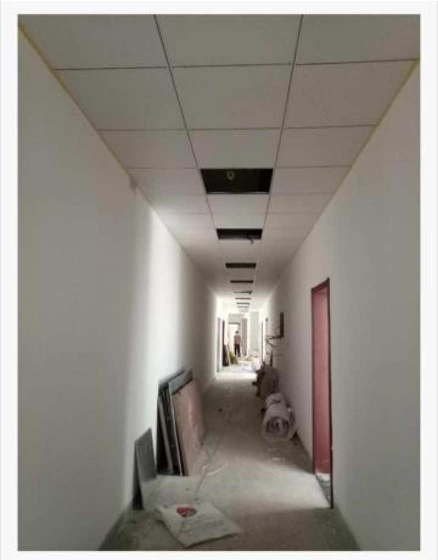
$X10^{-3}$

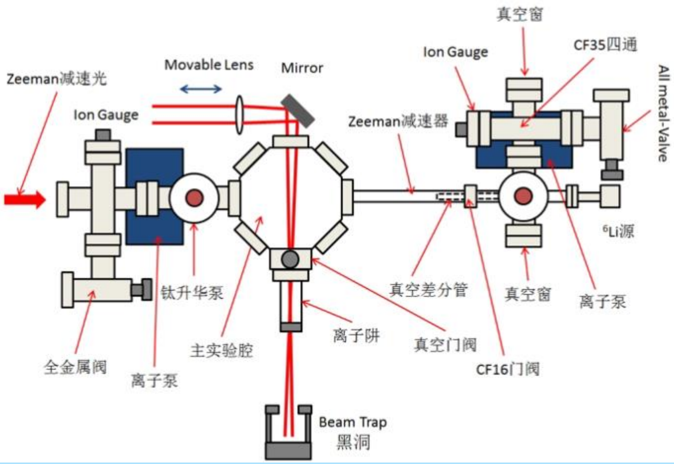
Very high opacity for the cold atom system

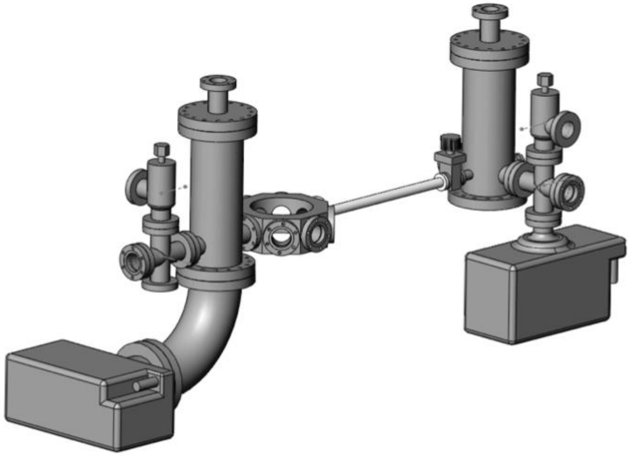
Low opacity for the cold atom system

A cold atom experiment

Setting up a cold atom experiment in Huzhou University







Summary

- Close connections between hot QGP and cold atoms.
- Cold atoms are hydrodynamical; QGP may not be.

  Make it less interacting, more dilute, or smaller to mimic QGP.

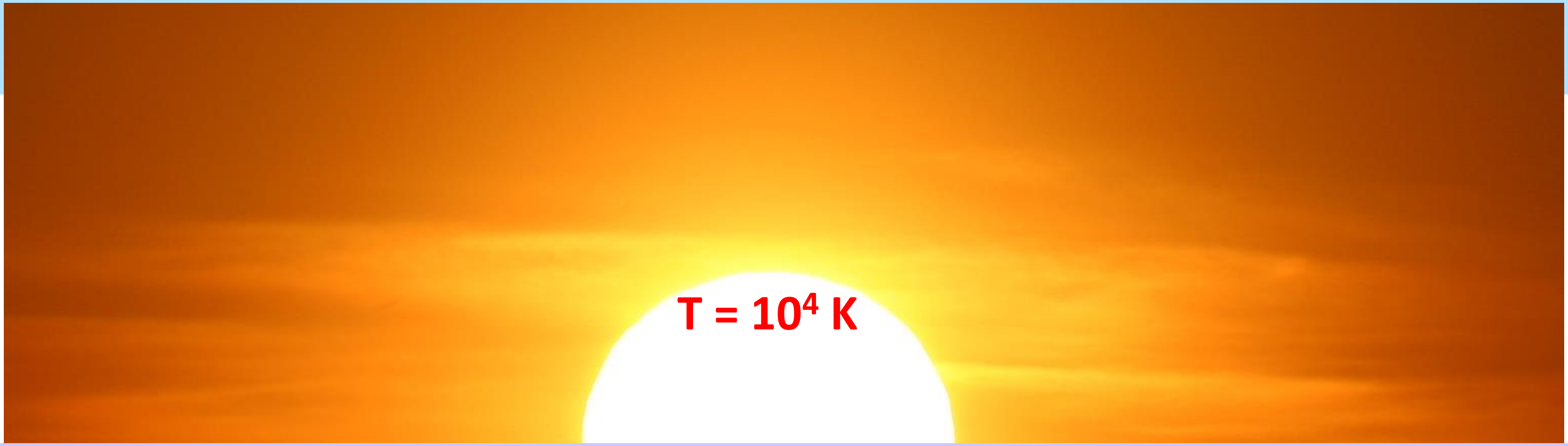
- QGP is quantum mechanical; cold atoms are “classical.”

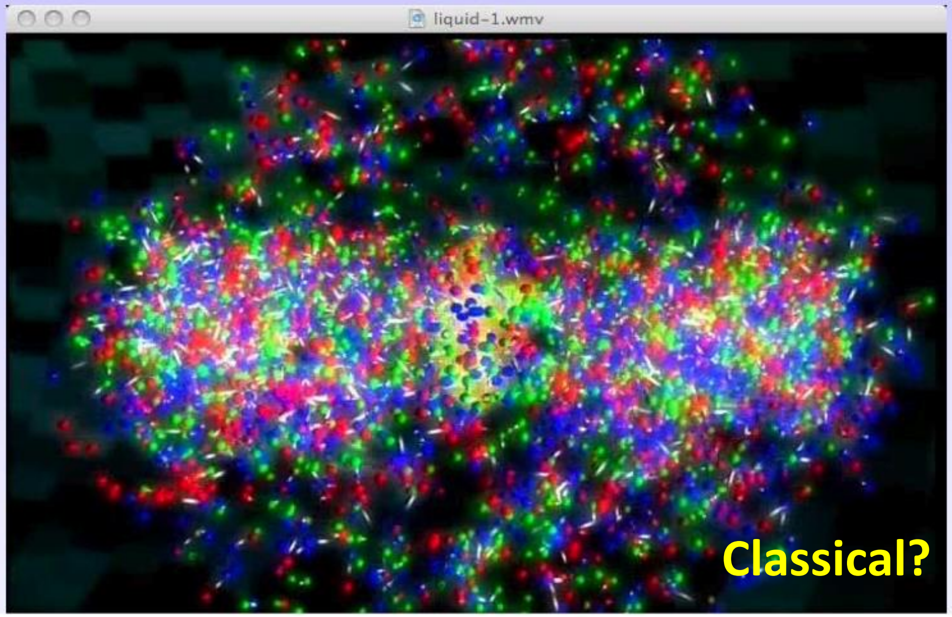
  Make it smaller, or colder to mimic QGP, and measure the uncertainty principle.

- Use controllability of cold atom system to address QGP questions

To verify the uncertainty principle*

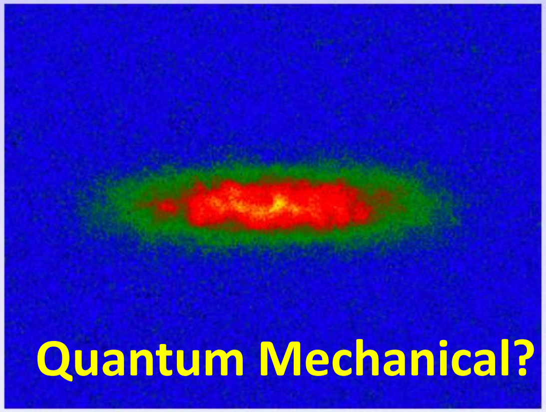
Hot QGP vs Cold Atoms





Quark-gluon plasma $T = 10^{12}$ K BIG BANG

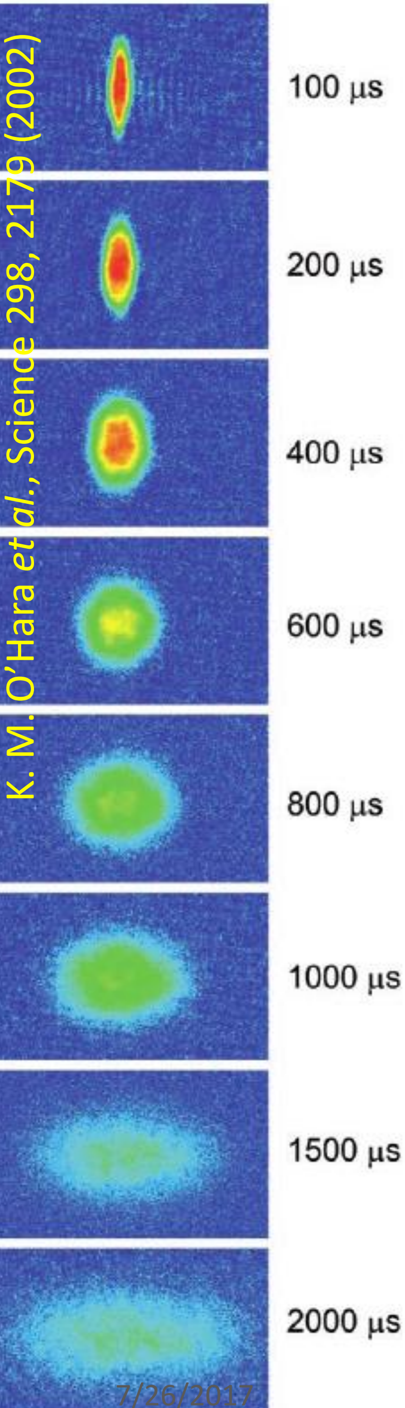
Computer simulation of RHIC collision

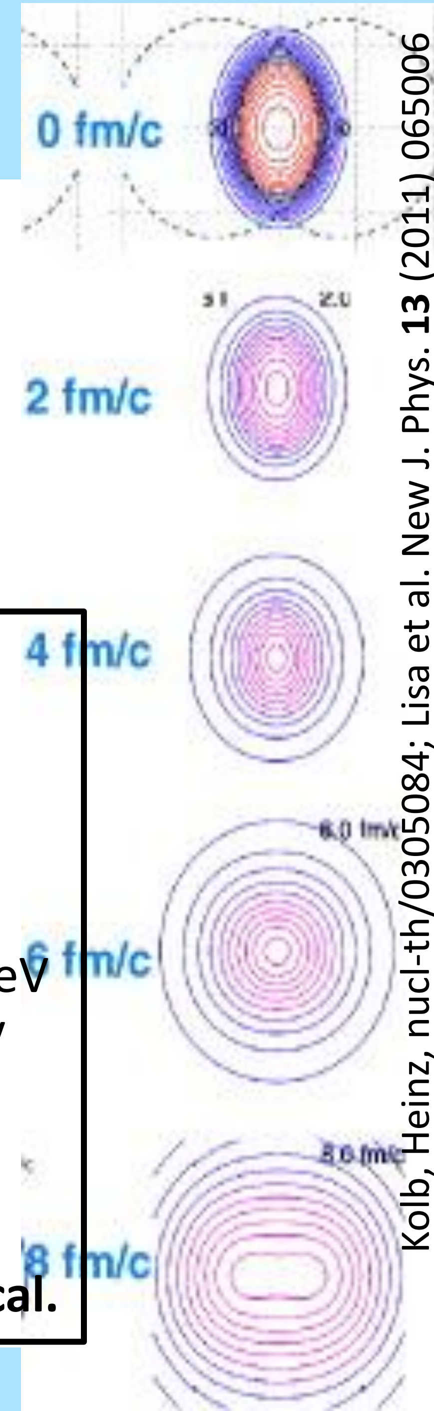


Ultracold atomic gas

$T = 10^{-7}$ K

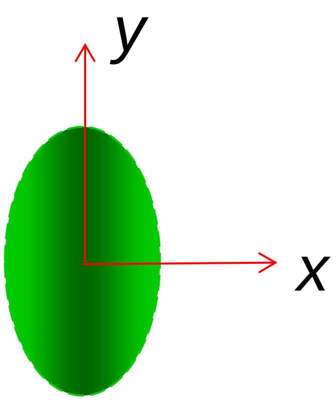
Is QGP classical?

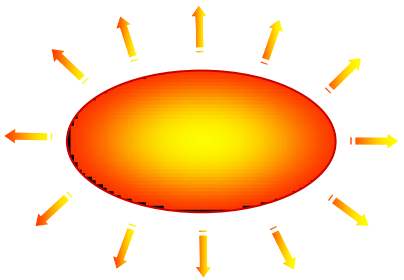




Li: M~6000 MeV T~1µK~10^{-16}MeV x~20µm, y~100µm p~$(TM)^{1/2}$~10^{-6}MeV p quan~1/r~10^{-8}MeV E quan~$1/(mr^2)$~10^{-20}MeV Negligible! **Cold atoms** are **hot**, **"classical" w.r.t. trap size.**	q,g: M~0 MeV T~200 MeV x~3fm, y~4fm p~200MeV p quan~1/r~200MeV E quan~200 MeV Comparable! **QGP** is **cold**, **quantum mechanical.**

QM uncertainty principle



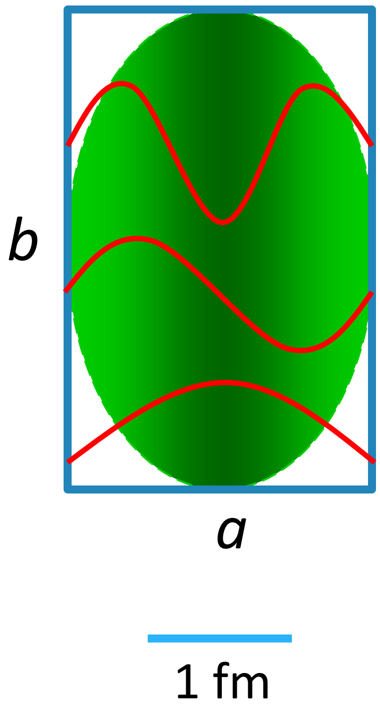


$$\Delta x \cdot \Delta p > \hbar / 2$$

$$p_x > p_y$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Infinite square well



$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi \quad \Rightarrow \quad \psi \propto \begin{cases} \cos\frac{n_{odd}\pi}{a}x \\ \sin\frac{n_{even}\pi}{a}x \end{cases}$$

Take even mode for example:

$$\langle p_x^2 \rangle = \hbar^2 k^2 \ ; \quad \langle x^2 \rangle = \frac{a^2}{4} - \frac{2}{k^2} \ ; \quad k = \frac{n_{odd}\pi}{a}$$

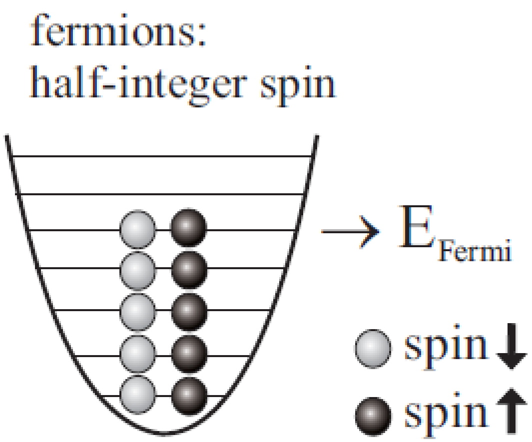
$$\sqrt{\langle p_x^2 \rangle \cdot \langle x^2 \rangle} = \hbar\sqrt{\frac{k^2 a^2}{4} - 2} = \hbar\sqrt{\frac{\pi^2}{4} n_{odd}^2 - 2} \ > \hbar / 2$$

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle} = \frac{b^2 - a^2}{b^2 + a^2} = \varepsilon \quad \text{for all } n.$$

Single state anisotropy

Harmonic oscillator

$$\left(-\frac{\hbar^2}{2m}\nabla^2+\frac{1}{2}m\omega^2x^2\right)\psi=E\psi\ ;\qquad E=\left(n+\frac{1}{2}\right)\hbar\omega$$



$$\left\langle\frac{p_x^2}{2m}\right\rangle=\left\langle\frac{1}{2}m\omega^2x^2\right\rangle=\frac{E}{2}=\frac{1}{2}\left(n+\frac{1}{2}\right)\hbar\omega$$

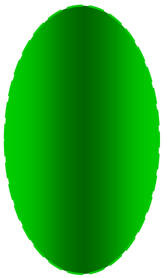
$$\sqrt{\left\langle p_x^2\right\rangle\left\langle x^2\right\rangle}=\left(n+\frac{1}{2}\right)\hbar$$

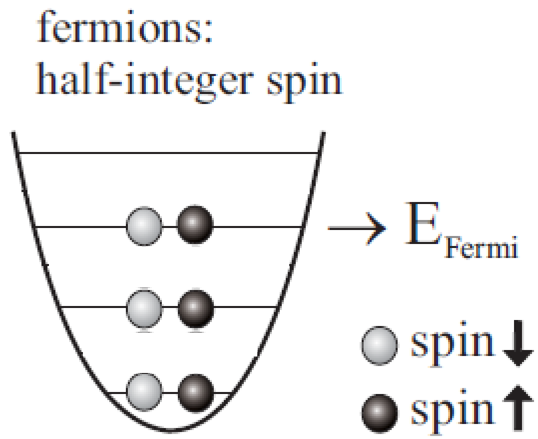
$$v_2=\frac{\left\langle p_x^2\right\rangle-\left\langle p_y^2\right\rangle}{\left\langle p_x^2\right\rangle+\left\langle p_y^2\right\rangle}=\frac{\omega_x-\omega_y}{\omega_x+\omega_y}$$

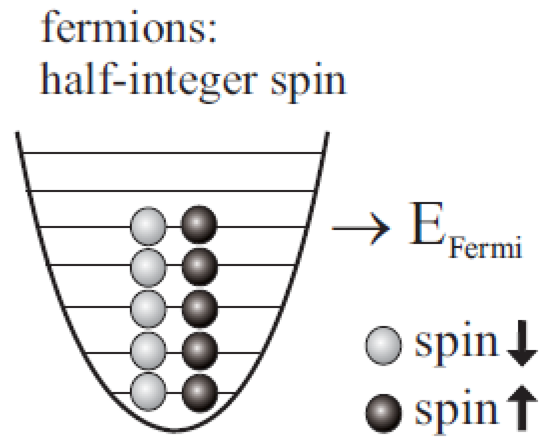
$$\varepsilon=\frac{\left\langle y^2\right\rangle-\left\langle x^2\right\rangle}{\left\langle y^2\right\rangle+\left\langle x^2\right\rangle}=\frac{\omega_x-\omega_y}{\omega_x+\omega_y}$$

$v_2=\varepsilon$ for each and all n

Thermal probability







x, y at same Fermi energy, so different number of filled energy levels.

At high temperature, classical limit, sum is approximated by integral:

$$\frac{dN}{d\mathbf{p}} = N\frac{\int d\mathbf{r}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}}{\int d\mathbf{r}\, d\mathbf{p}\, e^{-H_1(\mathbf{p},\mathbf{r})/T}} = N\frac{e^{-K(\mathbf{p})/T}}{\int d\mathbf{p}\, e^{-K(\mathbf{p})/T}}$$

then it's independent of potential.
It's isotropic at all temperature because $K=(p_x^2+p_y^2)/2m$ is isotropic.

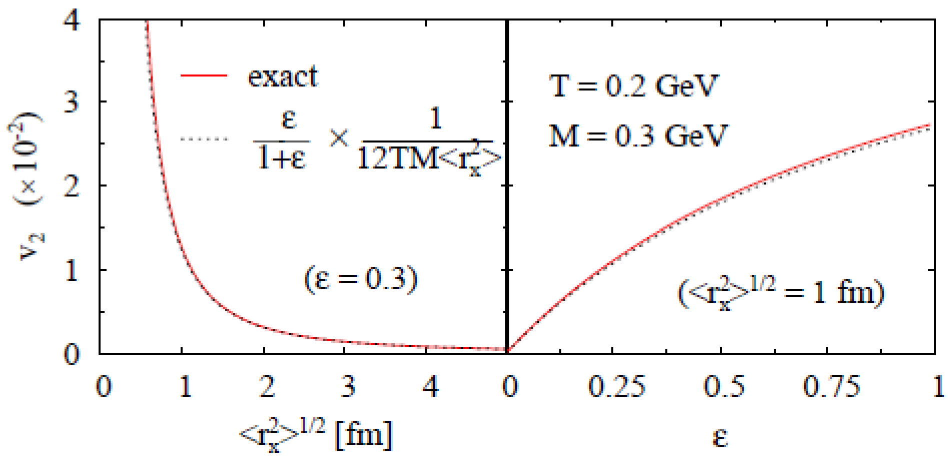
Thermal probability weight

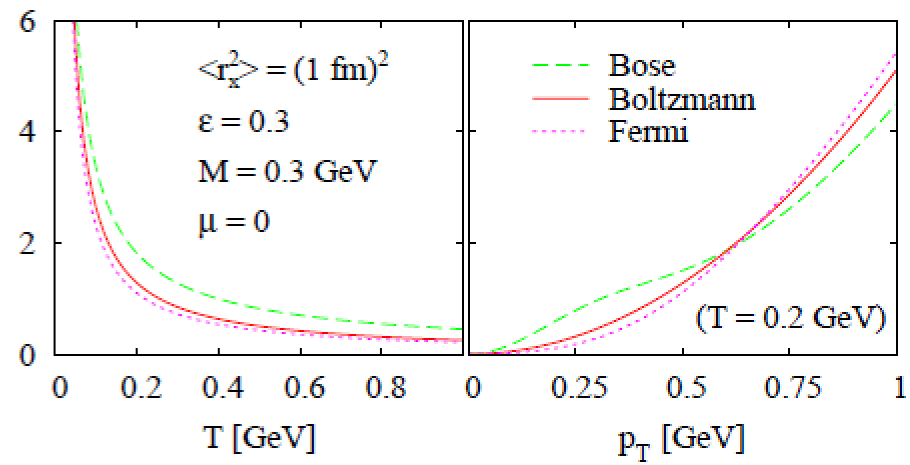
$$\rho(\mathbf{r}) \equiv \frac{dN}{d\mathbf{r}} = \frac{1}{Z} \sum_j |\psi_j(\mathbf{r})|^2 \, e^{-E_j/T} \qquad f(\mathbf{p}) \equiv \frac{dN}{d\mathbf{p}} = \frac{1}{Z} \sum_j |\psi_j(\mathbf{p})|^2 \, e^{-E_j/T}$$

$$Z \equiv \sum_j e^{-E_j/T}$$

$$\langle p_i^2 \rangle = \frac{M\omega_i}{2} \coth\frac{\omega_i}{2T} \,, \quad \langle r_i^2 \rangle = \frac{1}{2M\omega_i} \coth\frac{\omega_i}{2T} \,.$$

$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon}$$





Quantum physics anisotropy

D. Molnar, FW, and C.H. Greene, arXiv:1404.4119

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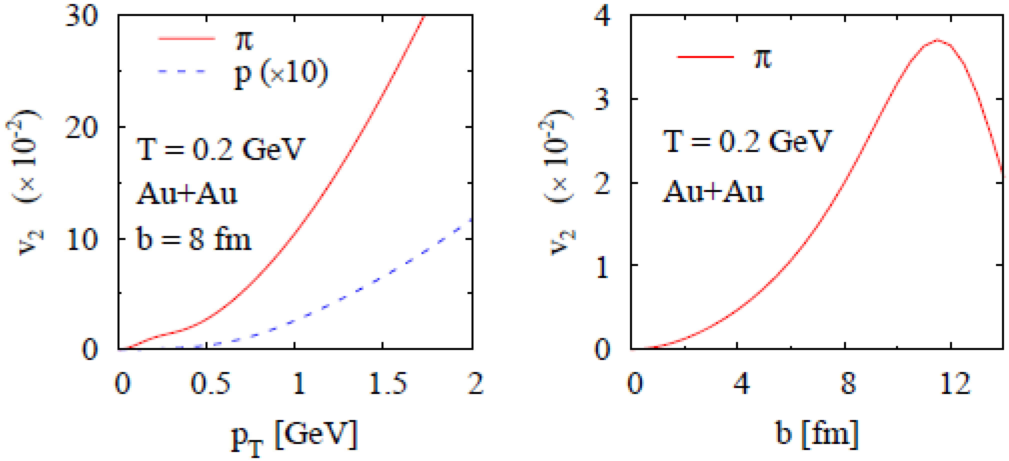
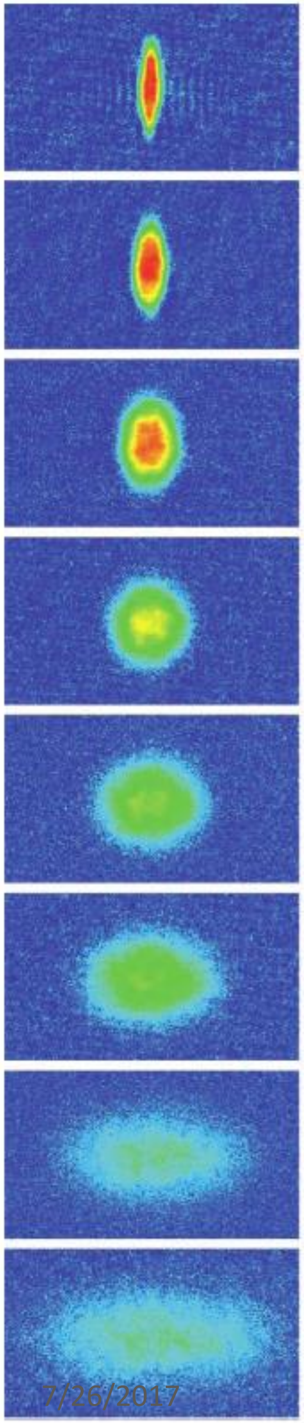


$b = 8$ fm: $\langle r_x^2 \rangle^{1/2} = 1.5$ fm and $\langle r_y^2 \rangle^{1/2} = 2.2$ fm

$$\rho(\mathbf{r}) \propto \exp\left(-\sum_i \frac{r_i^2}{2\langle r_i^2 \rangle}\right), \quad f(\mathbf{p}) \propto \exp\left(-\sum_i \frac{p_i^2}{2\langle p_i^2 \rangle}\right)$$



Cold atoms

Strong elliptic anisotropy

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

Lithium atoms M ~ 6000 MeV
Temperature T ~ 1 μK ~ 10^{-16} MeV
Trap size x ~ 20 μm, y ~ 100 μm

Typical momentum $(TM)^{1/2}$ ~ 10^{-6} MeV
Intrinsic momentum quantum ~ 1/r ~ 10^{-8} MeV, negligible.

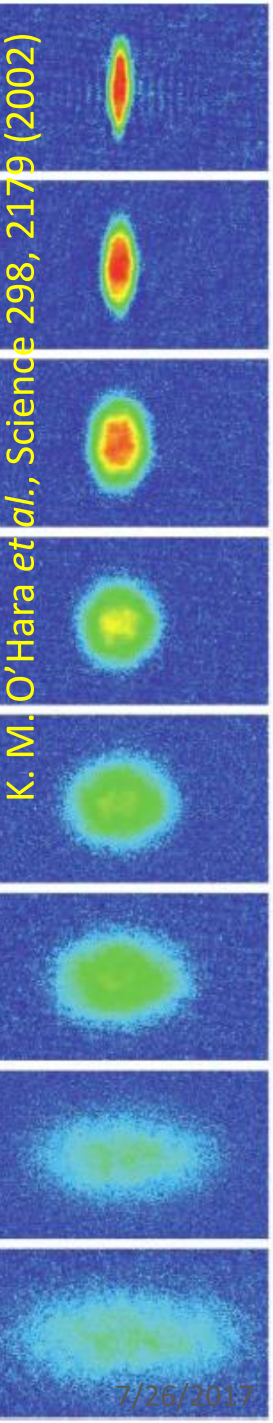
Typical energy ~ T ~ 10^{-16} MeV
Intrinsic energy quantum $1/(mr^2)$ ~ 10^{-20} MeV, negligible.

Cold Lithium atoms are actually "hotter" than the hot QGP.

$$\bar{v}_2 \approx \frac{\hbar^2}{12 k_B T M \langle r_x^2 \rangle} \cdot \frac{\varepsilon}{1+\varepsilon} \sim 10^{-5}$$

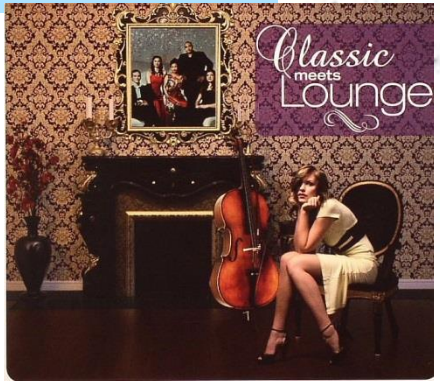
The observed large v_2 is indeed due to strong interactions.

Is quantum v_2 real in QGP?



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

- It should be... but need experiment to verify (cold atom experiment)
- Cold atoms are "classical." Make it Quantum Mechanical.
- Would be neat to verify QM and uncertainty principle



Li: M~6000 MeV	q,g: M~0 MeV
T~1µK~10^{-16}MeV	T~200 MeV
x~20µm, y~100µm	x~3fm,y~4fm
p~$(TM)^{1/2}$~10^{-6}MeV	p~200MeV
p quan~1/r~10^{-8}MeV	p quan~1/r~200MeV
E quan~$1/(mr^2)$~10^{-20}MeV	E quan~200 MeV
Negligible!	Comparable!
Cold atoms are **hot**, **classical.**	**QGP** is **cold**, **quantum mechanical.**

x10^{-4}

X10^{-2}

Kolb, Heinz, nucl-th/0305084; Lisa et al. New J. Phys. **13** (2011) 065006

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