Anisotropies from Low Density Scattering

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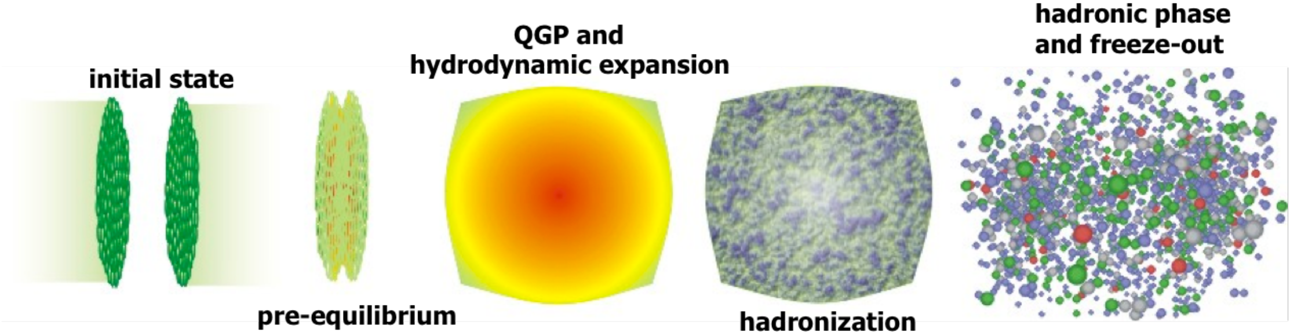
Outline

Introduction
Hydrodynamic flow
Escape mechanism
Summary

Azimuthal Anisotropy

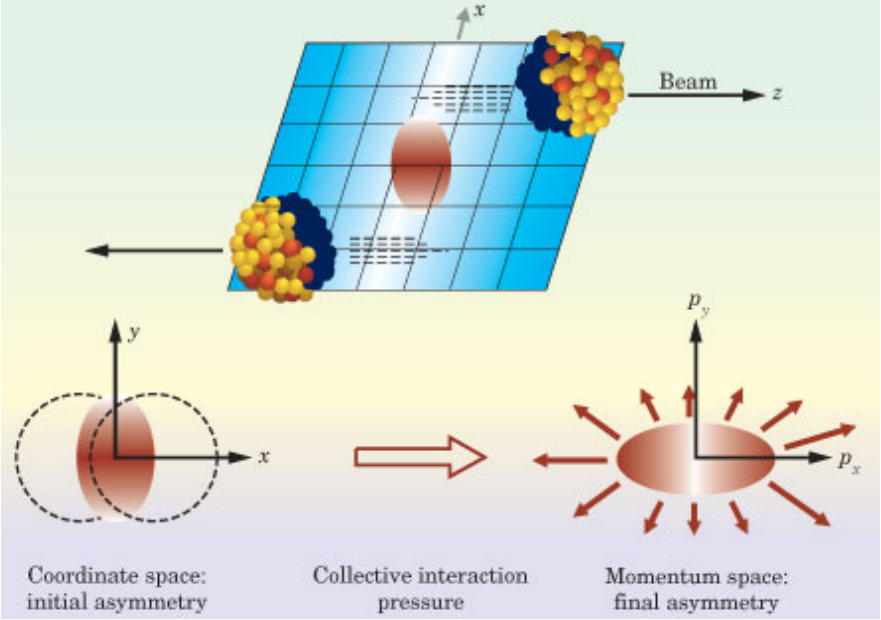


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

$$\equiv \langle \cos 2\varphi \rangle$$

$$\varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



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

interaction

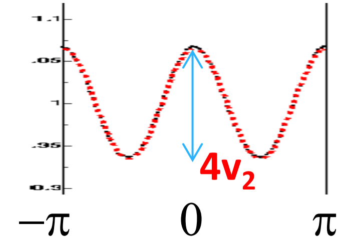
Common thinking:

High density, pressure

Pressure grad. anisotropy

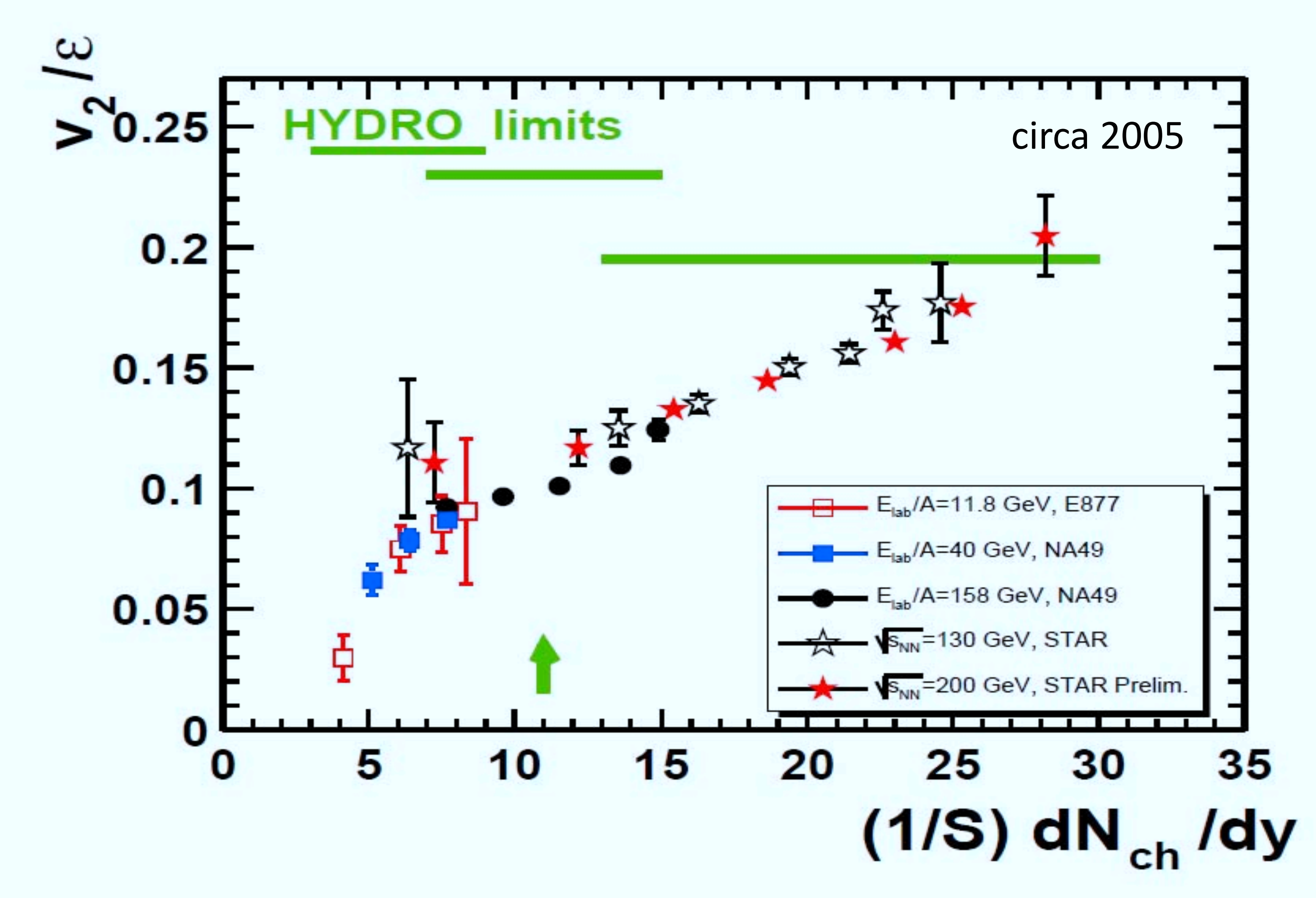
Hydrodynamic expansion

Strongly interacting QGP

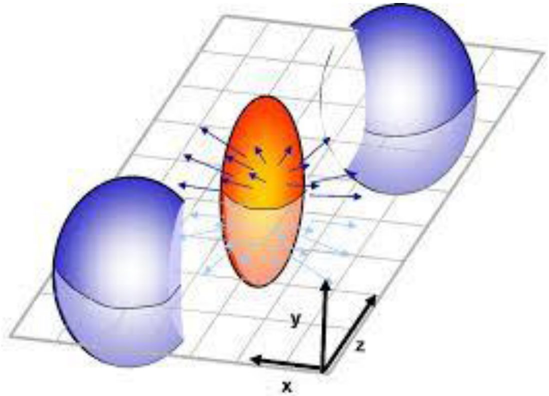


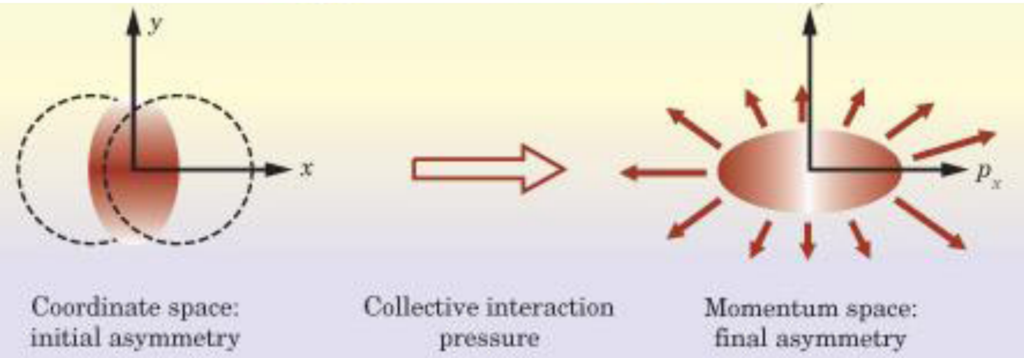
Finally "hydro" at RHIC…

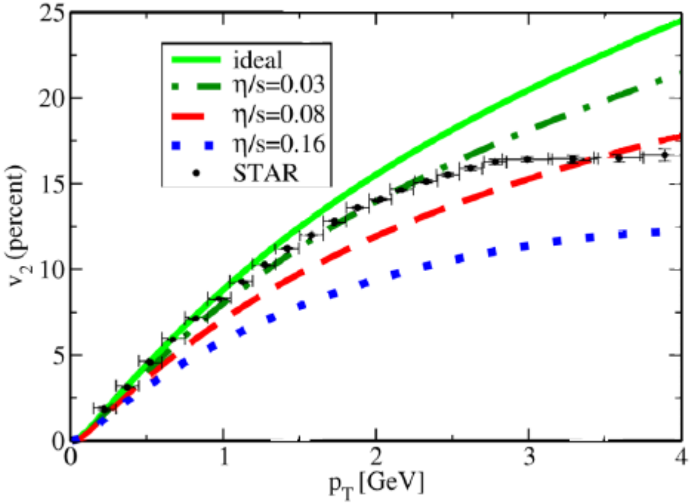
The question is: how strong is the interaction?

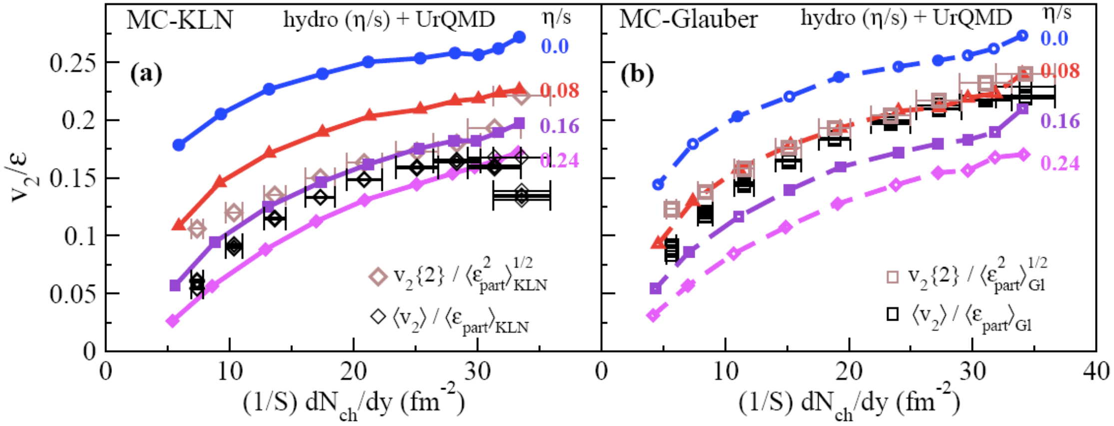


Hydrodynamic calculation









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

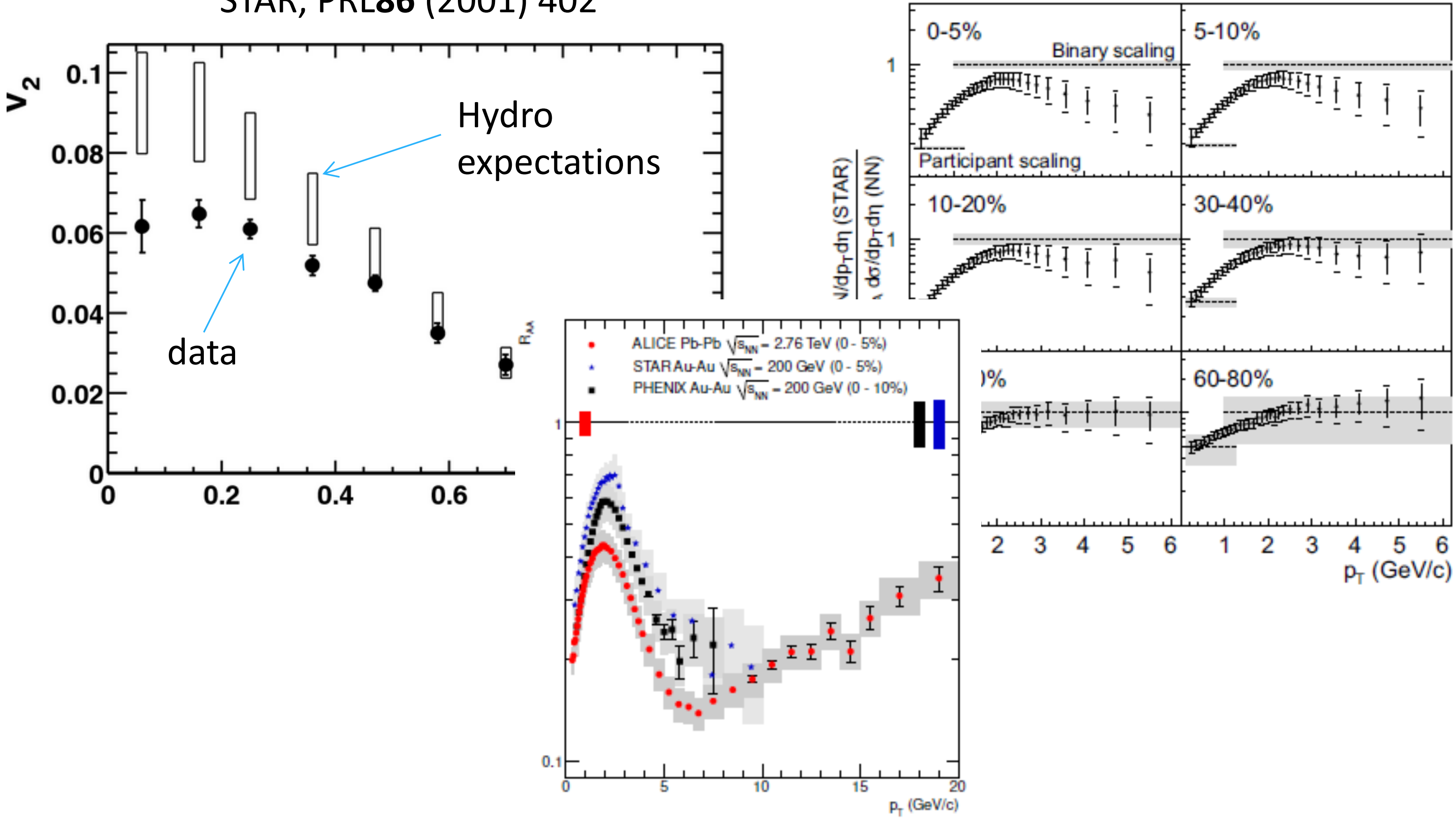
➔ Model uncertainty dominated by ***initial ecc. ε***

Model: Song *et al. arXiv:1011.2783*

Corroborated by large energy loss

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

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

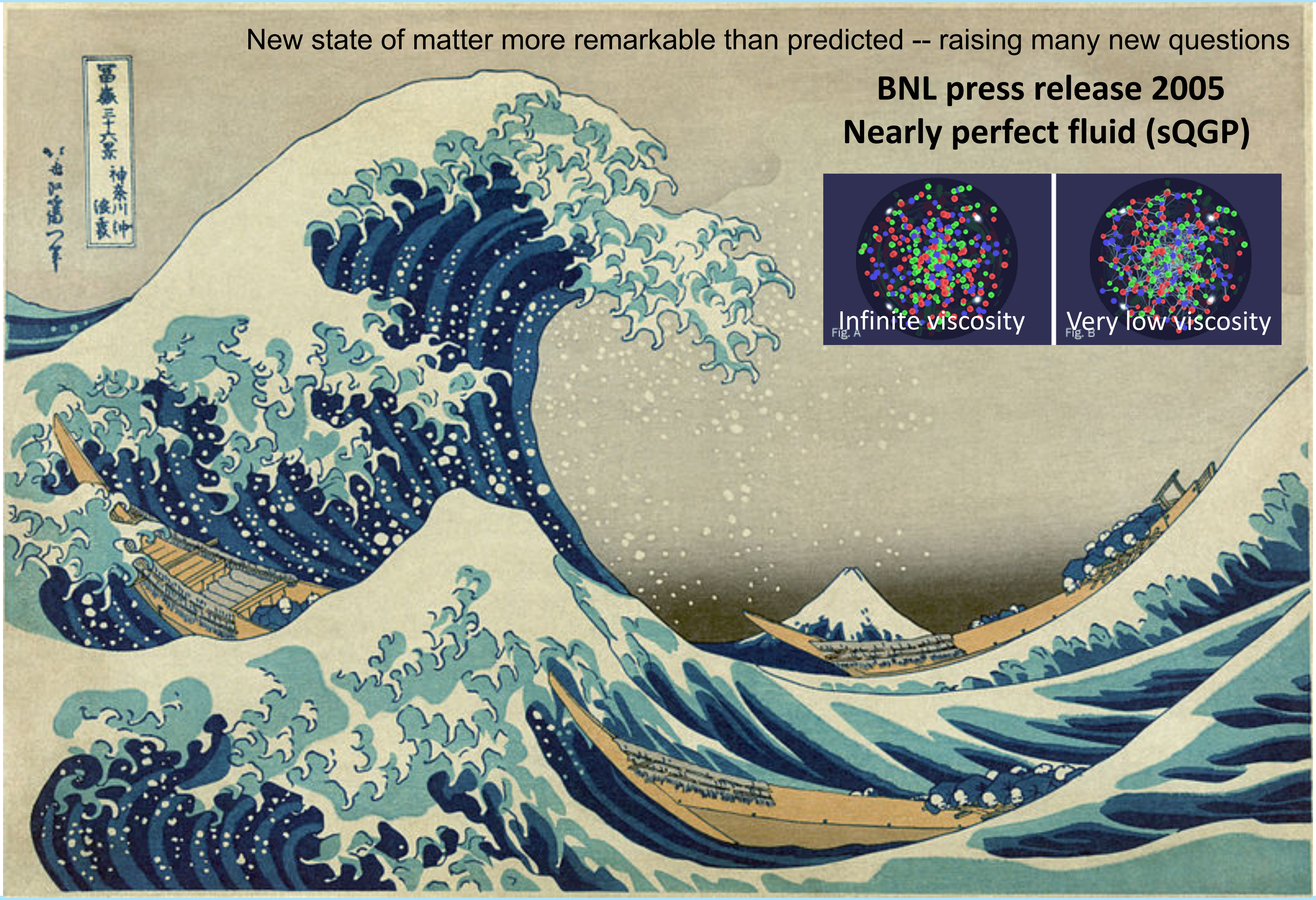


Hydro expectations

data

The Hydrodynamic Paradigm

ca 2005

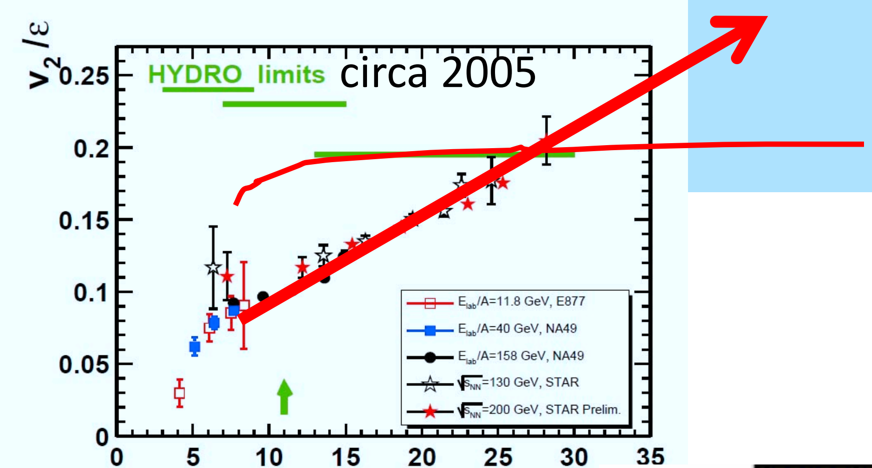


New state of matter more remarkable than predicted -- raising many new questions

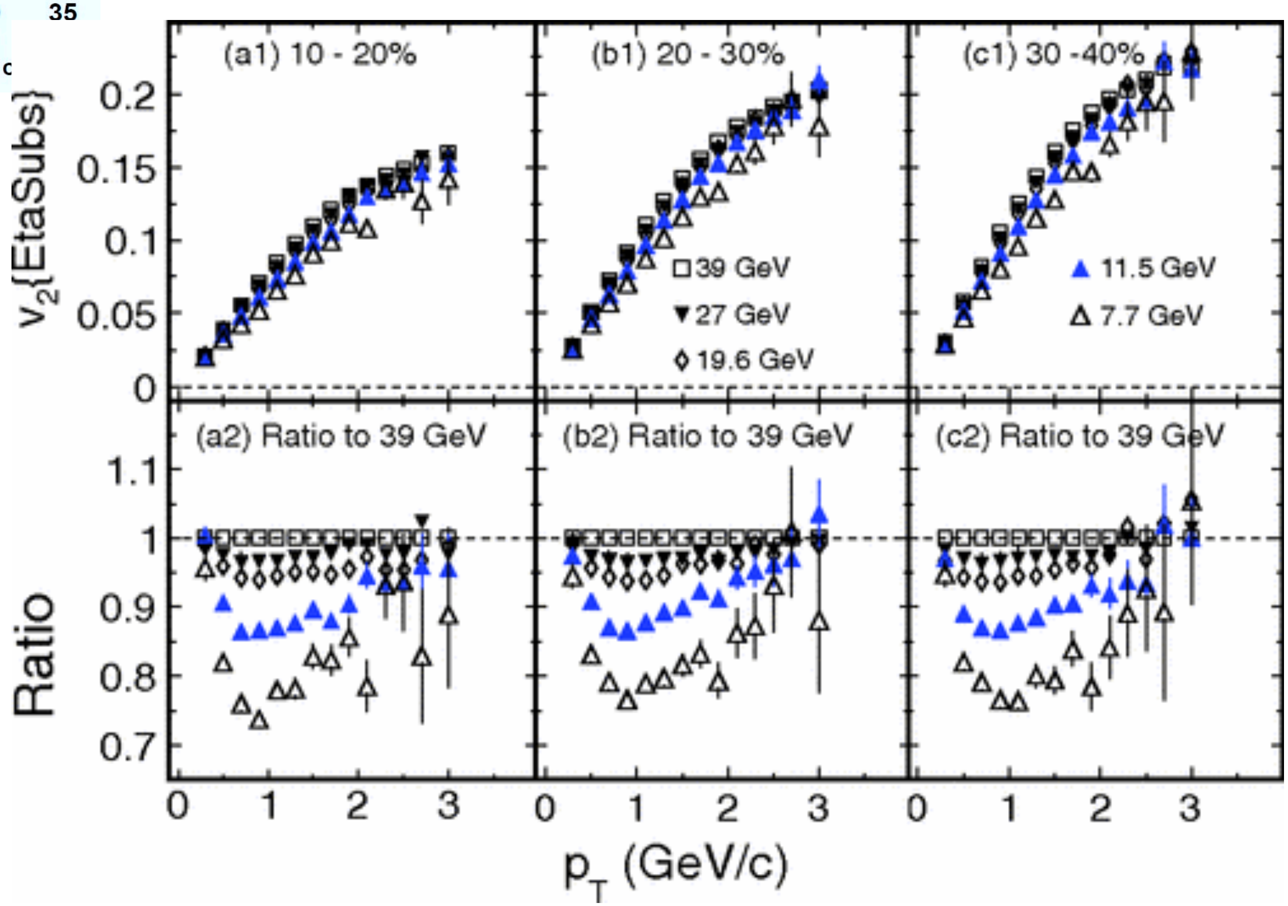
BNL press release 2005

Nearly perfect fluid (sQGP)

But actually very little energy dependence

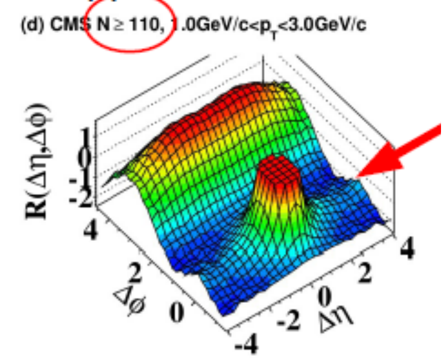


circa 2013

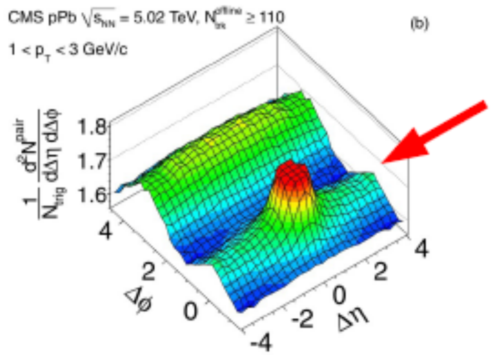


“flow” everywhere, even in small systems

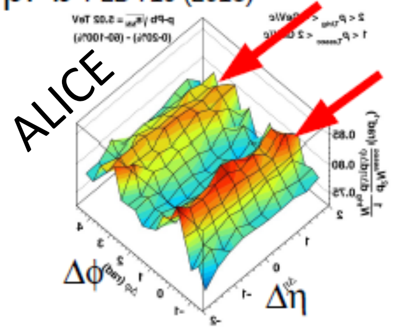
CMS pp JHEP 09 (2010) 091



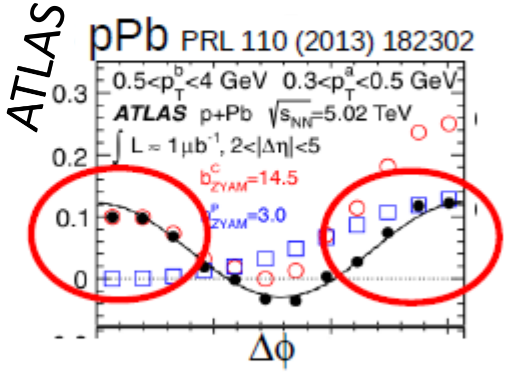
CMS pPb PLB 718 (2013) 795



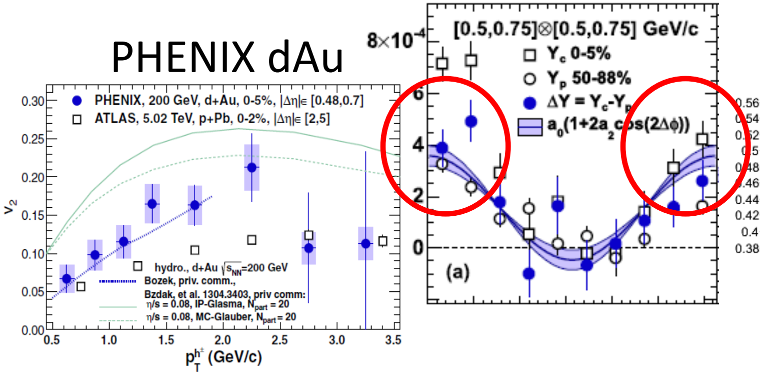
pPb PLB 719 (2013)



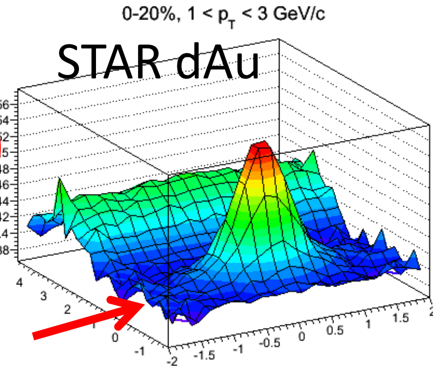
pPb PRL 110 (2013) 182302

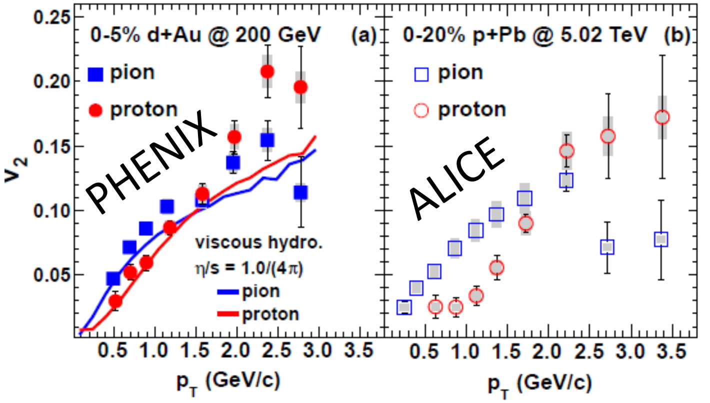


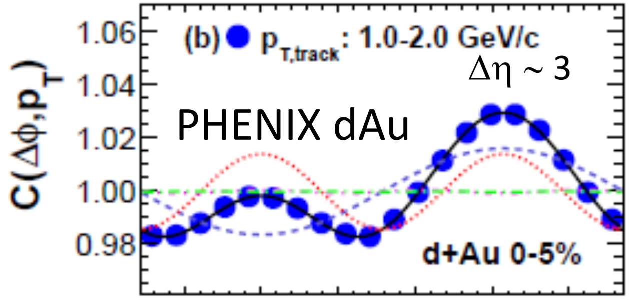
PHENIX dAu

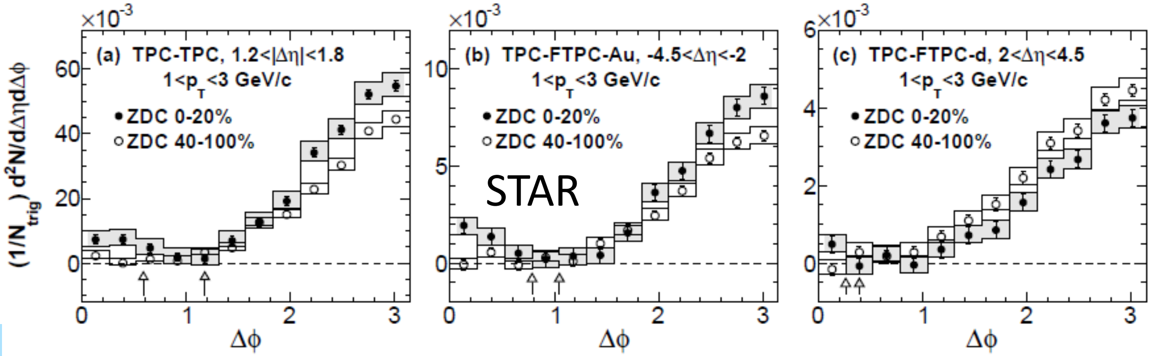


STAR dAu



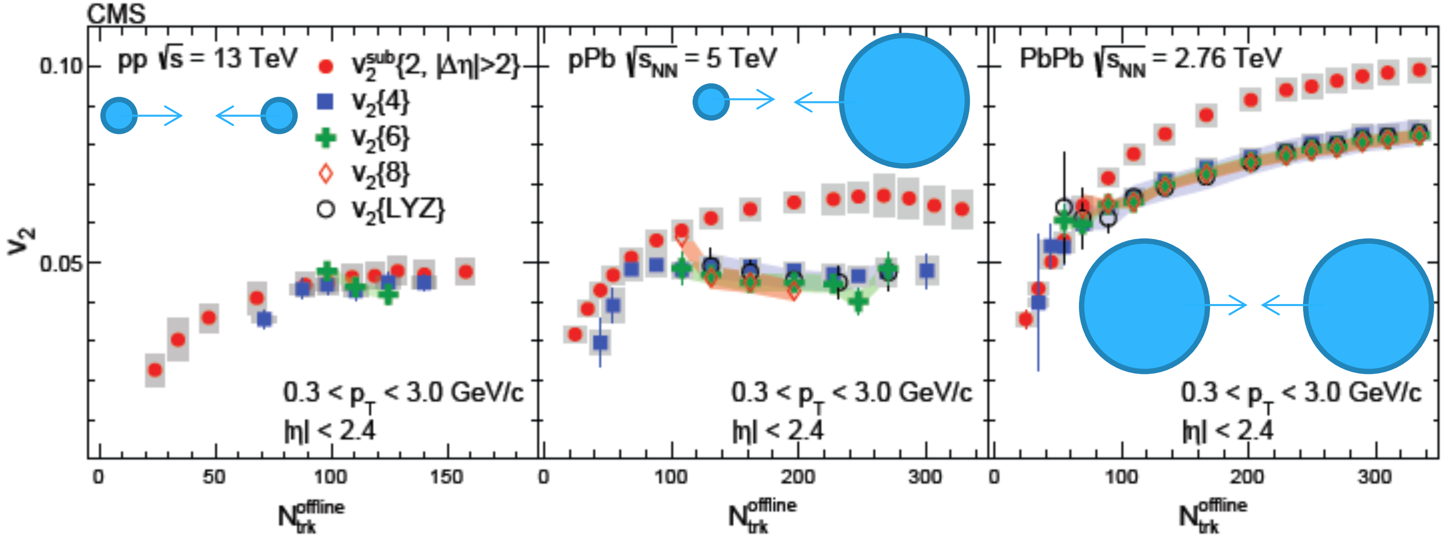


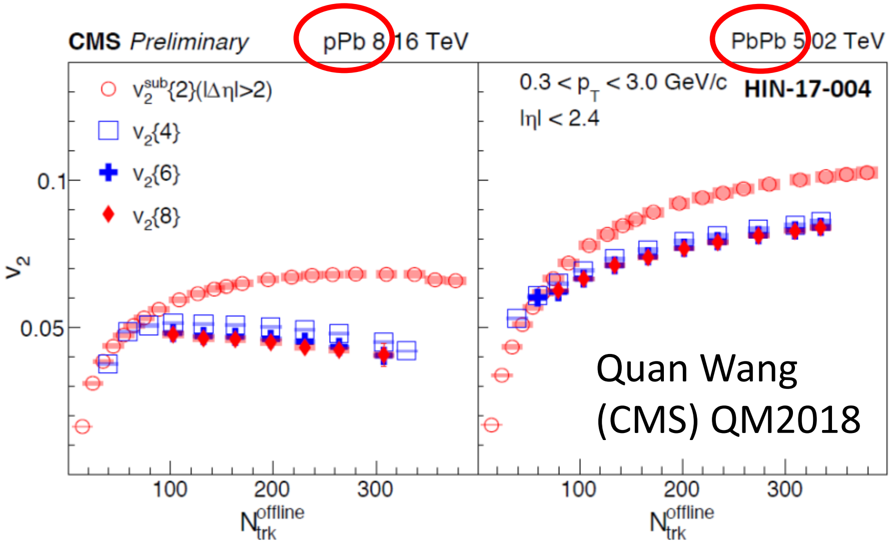




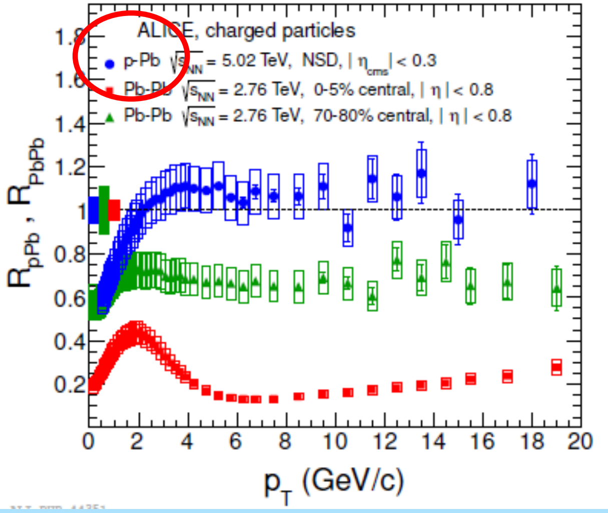
“Flow” in small systems, but no energy loss

CMS, PLB 765 (2017) 193



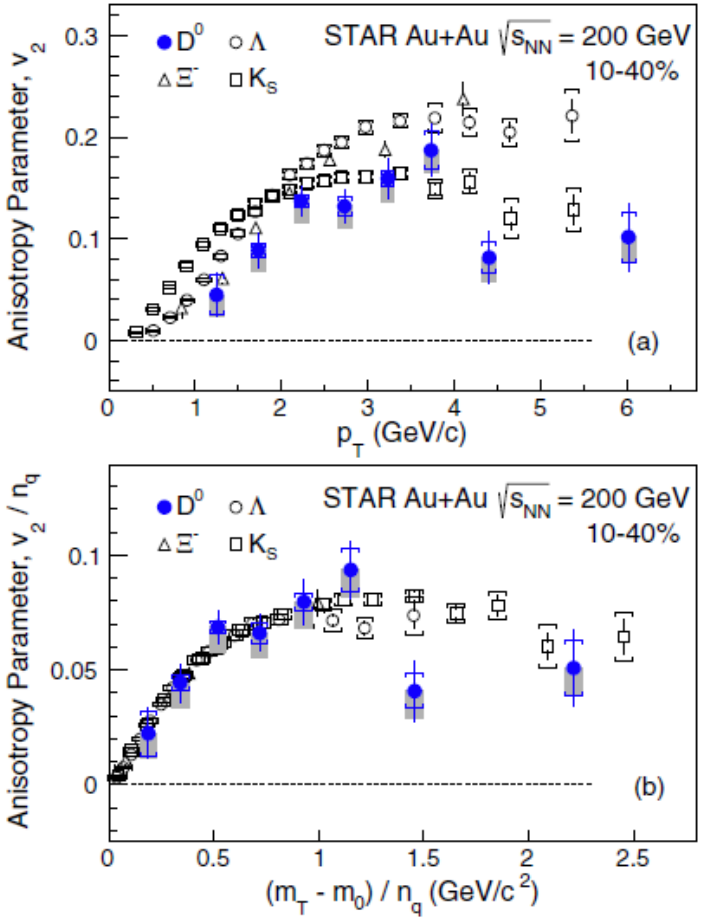


Quan Wang (CMS) QM2018

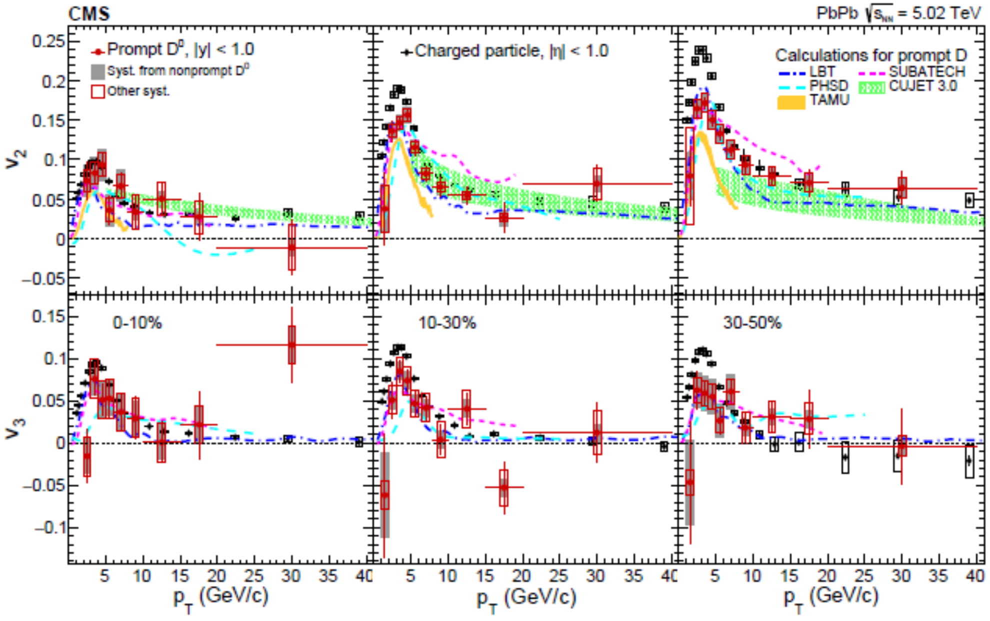


Heavy flavor “flows”

STAR, PRL 118, 212301 (2017)

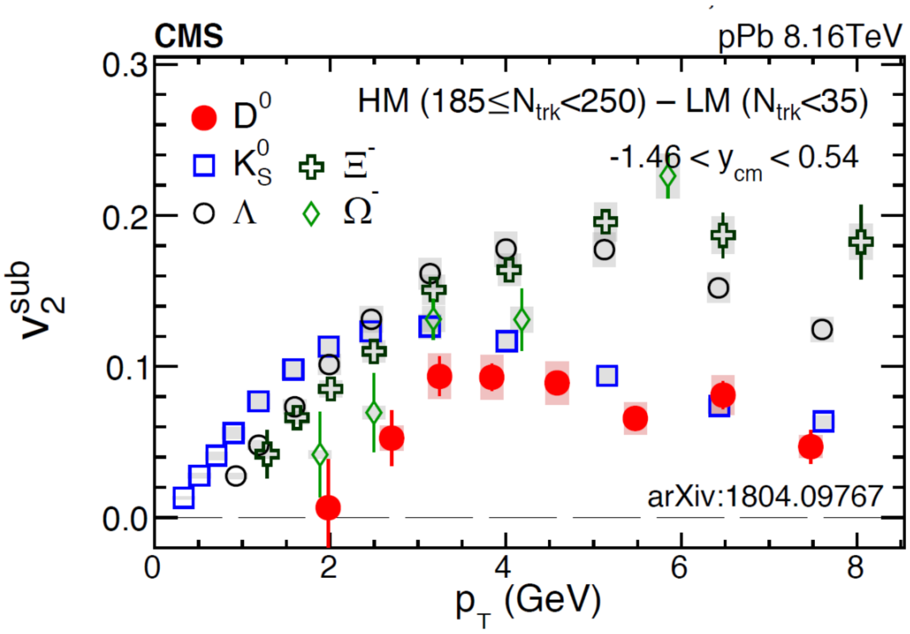


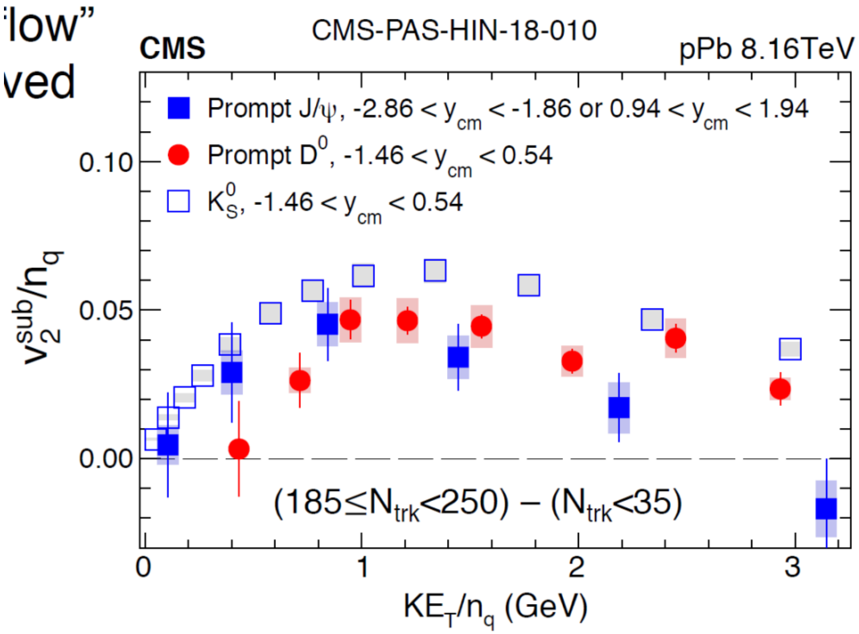
CMS, arXiv:1708.03497



Heavy flavor flows, AND in small systems

Wei Li (CMS), QM 2018

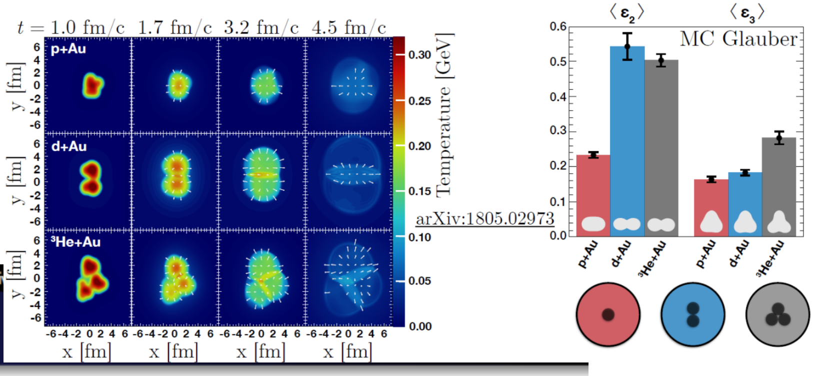




- Significant D0 v2, follow mass ordering at low pT
- D0 similar to K0s (both mesons) at higher pT
- Significant charmonium v2

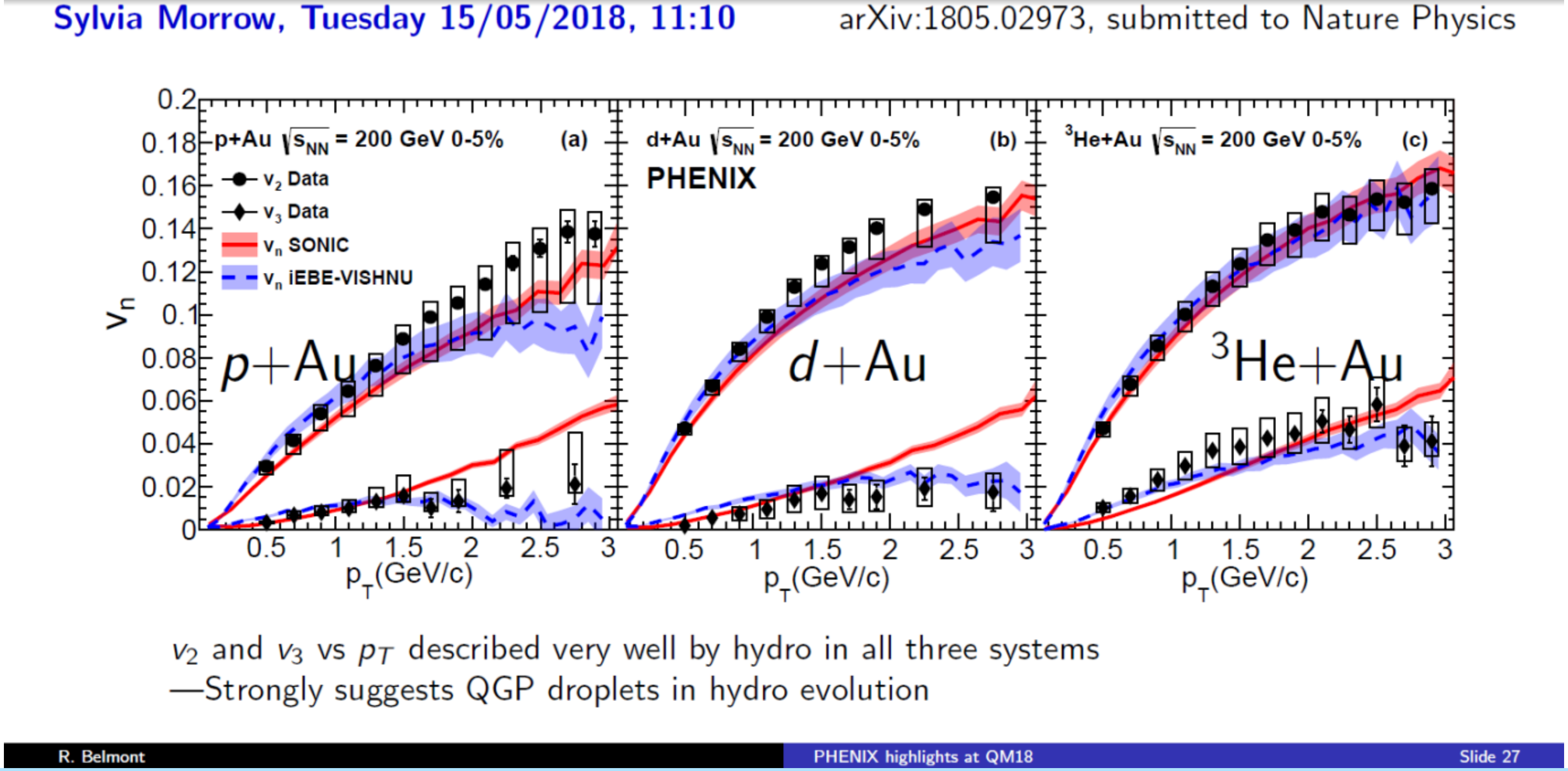
QGP droplets?

Belmont, QM 2018 PHENIX Highlights
Morrow (PHENIX) QM 2018



High-p_T hadrons Heavy flavor Collecti

Testing hydro by controlling system geometry



Sylvia Morrow, Tuesday 15/05/2018, 11:10 arXiv:1805.02973, submitted to Nature Physics

v_2 and v_3 vs p_T described very well by hydro in all three systems
—Strongly suggests QGP droplets in hydro evolution

R. Belmont PHENIX highlights at QM18 Slide 27

FLOW EVERYWHERE

Light quark flows, heavy quark flows

Different views

QGP in pp/pA? As strongly interacting?

Escape the room

Materials

Mostly based on:

L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F. Wang	Phys. Lett. **B735** (2016) 506
H. Li, L. He, Z.-W. Lin, D. Molnar, F. Wang, W. Xie	Phys. Rev. **C93** (2016) 051901(R)
H. Li, L. He, Z.-W. Lin, D. Molnar, F. Wang, W. Xie	Phys. Rev. **C96** (2017) 014901
Z.-W. Lin, L. He, T. Edmonds, F. Liu, D. Molnar, F. Wang	Nucl. Phys. **A956** (2016) 316
H. Li, Z.-W. Lin, , F. Wang	J.Phys.**779** (2017) 012063, SQM16
Z.-W. Lin, H. Li, F. Wang	charm anisotropy, SQM 2017
H. Li, Z.-W. Lin, F. Wang	arXiv:1804.02681

Parton cascade history

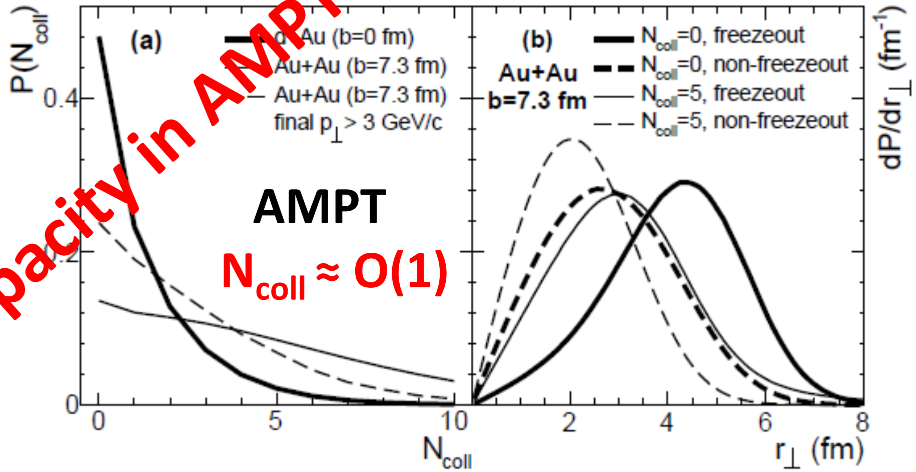
AMPT can describe bulk data well… both AA and pA

- Get into transport code
- Follow cascading history, microscopic interactions
- Investigate how parton v_n is generated

$L_{mfp} = 1/\rho\sigma$

Opacity:

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



Low opacity in AMPT

AMPT

$N_{coll} \approx O(1)$

$dN/dy \sim 1000$

$\rho \sim 1000/\pi R^2\tau$

$\sim 6\ fm^{-3}$

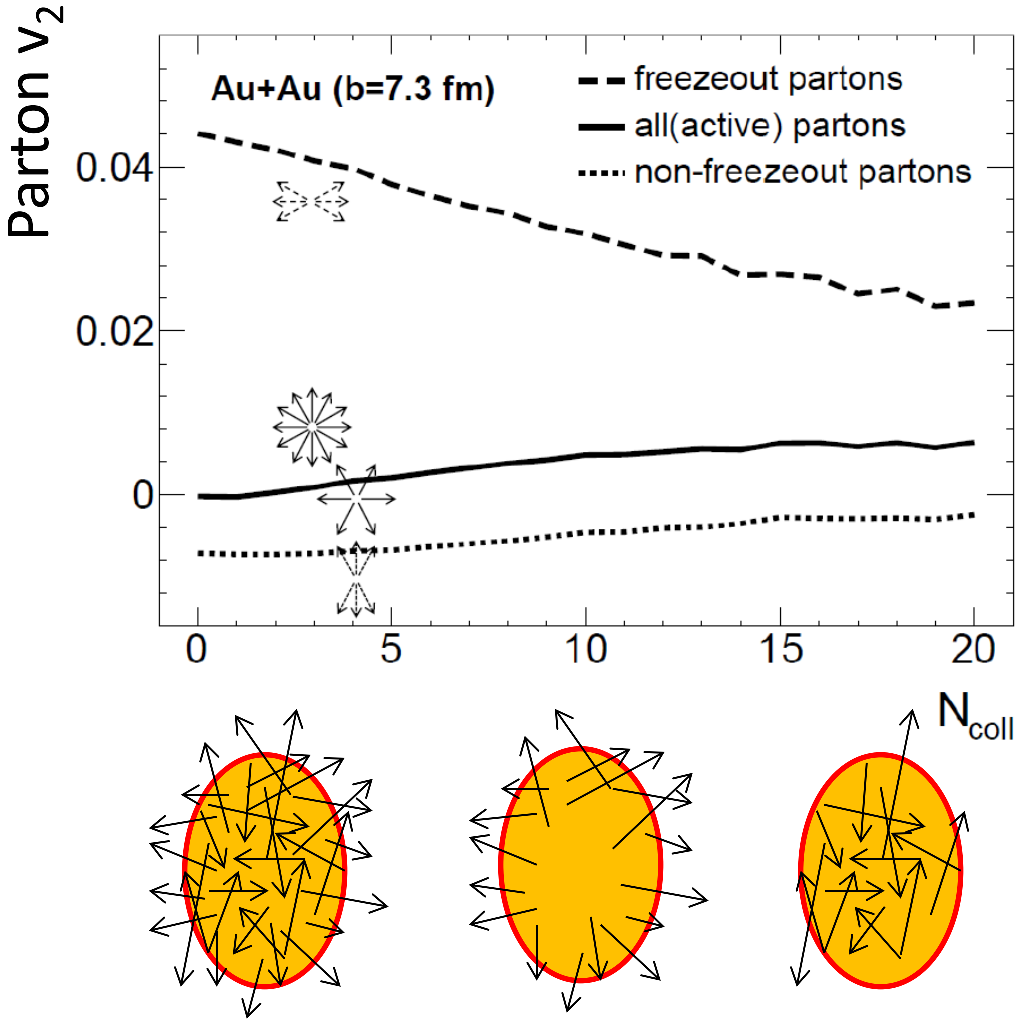
$\rho\sigma L \sim$

$6fm^{-3}*3mb*3fm$

~ 5

How is anisotropy developed in AMPT?

L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, FW, arXiv:1502.05572

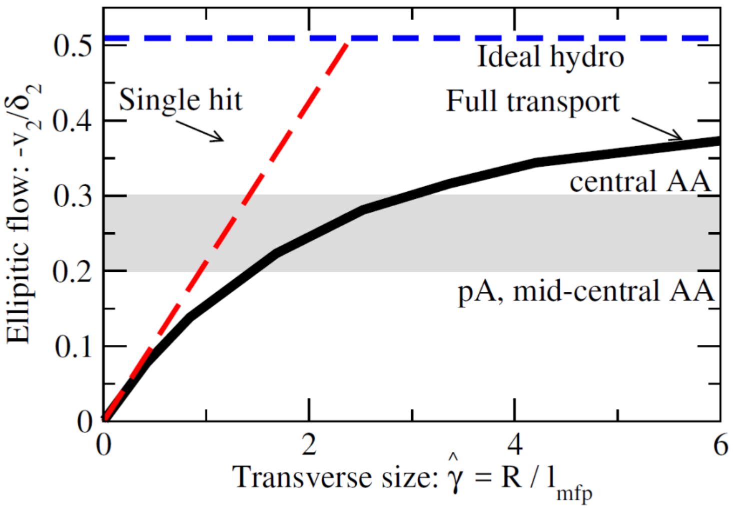


- Partons freeze out with large positive v_2, even when they do not interact at all.
- This is due to larger escape probability along x than y.
- Remaining partons start off with negative v_2, and become ~isotropic (v_2~0) after one more collision.
- Process repeats itself.
- Similar for v_3.
- Similar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

Analytical/numerical kinetic transport

Kurkela, QM 2018

Kurkela, Wiedemann, Wu, 1805.04081

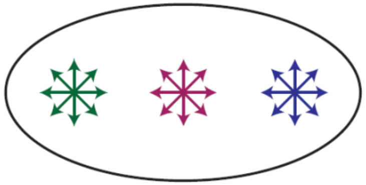


Central pA: $\frac{v_2}{\delta_2} \approx 0.2$, Central AA: $\frac{v_2}{\delta_2} \approx 0.3$

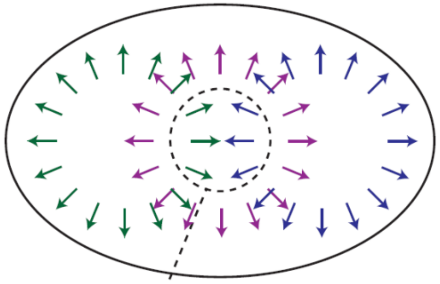
- Closer to single hit regime than ideal hydro

$$\eta/s \gtrsim 0.5$$

Kurkela, Wiedemann, Wu, 1803.02072



Initially isotropic momentum distribution



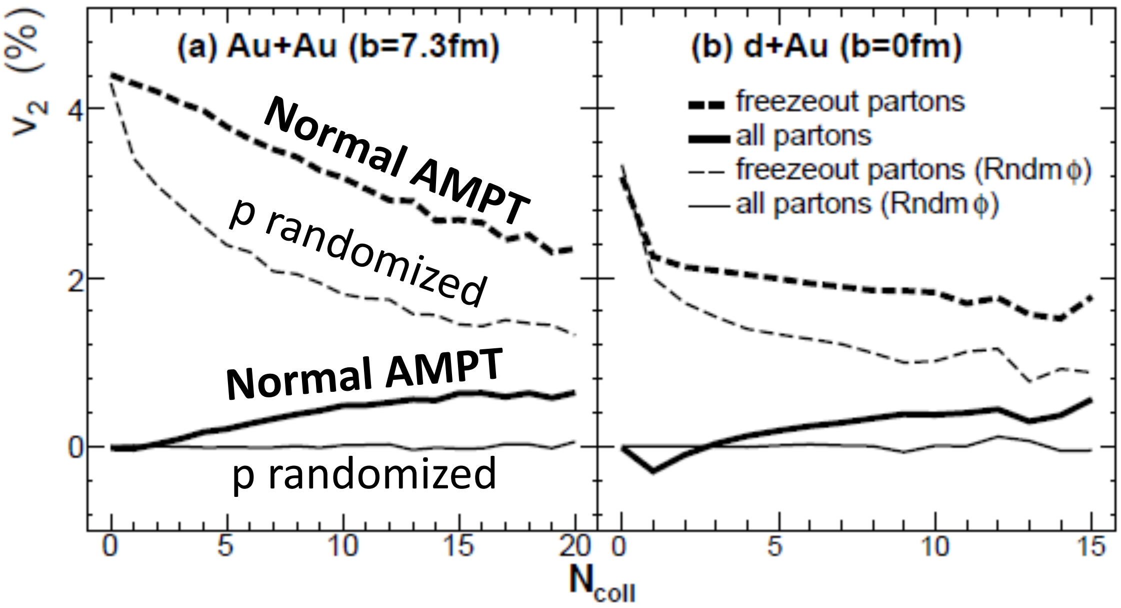
More particles moving in ±x-direction

- Initial condition initially isotropic in momentum space, anisotropic in coordinate space
- Free streaming makes local patches anisostropic
- Collisions isotropize the distribution in the center
  $\Rightarrow$ Reduction of horizontal movers and increase of vertical movers

Related closely to *anisotropic parton escape mechanism*, He et al. PLB753 (2016)

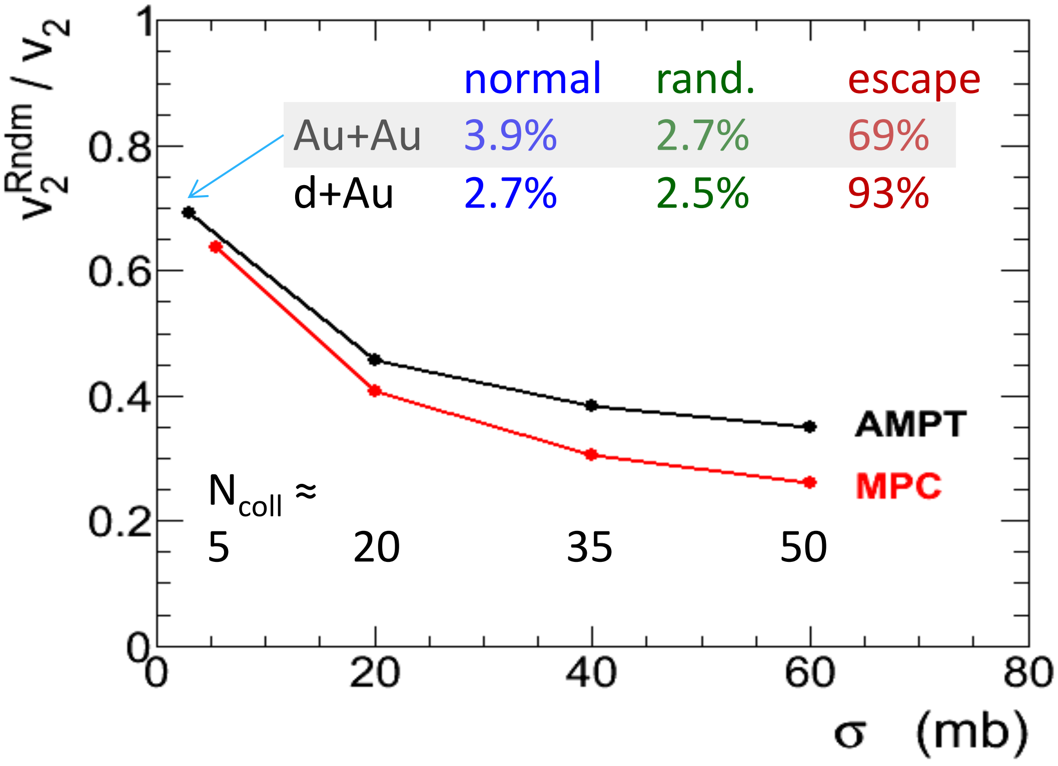
Majority anisotropy from escape

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.**

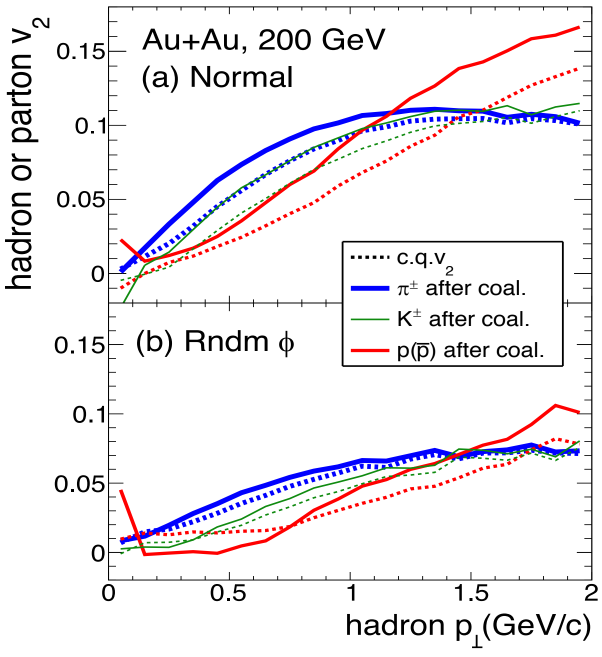
Relative escape contribution

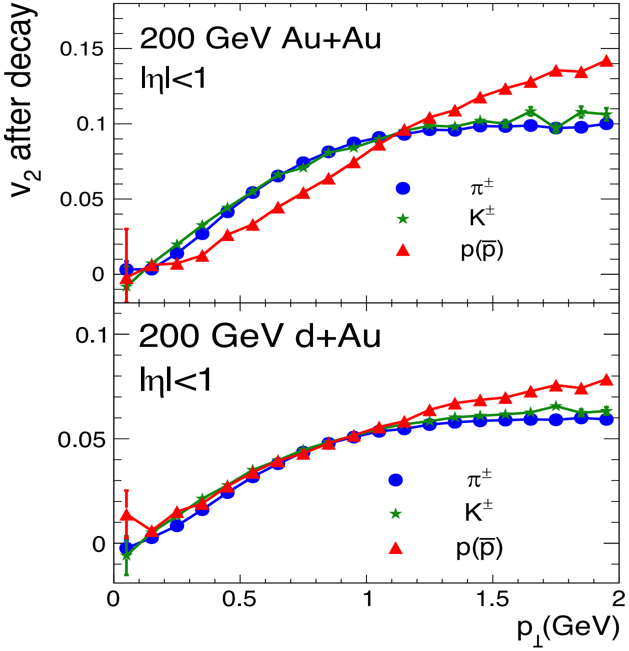


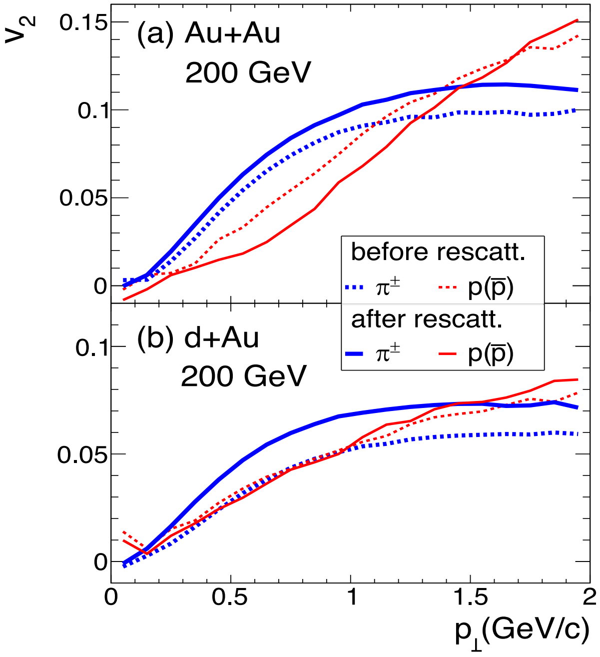
	normal	rand.	escape
Au+Au	3.9%	2.7%	69%
d+Au	2.7%	2.5%	93%

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

Mass splitting from hadronic rescattering



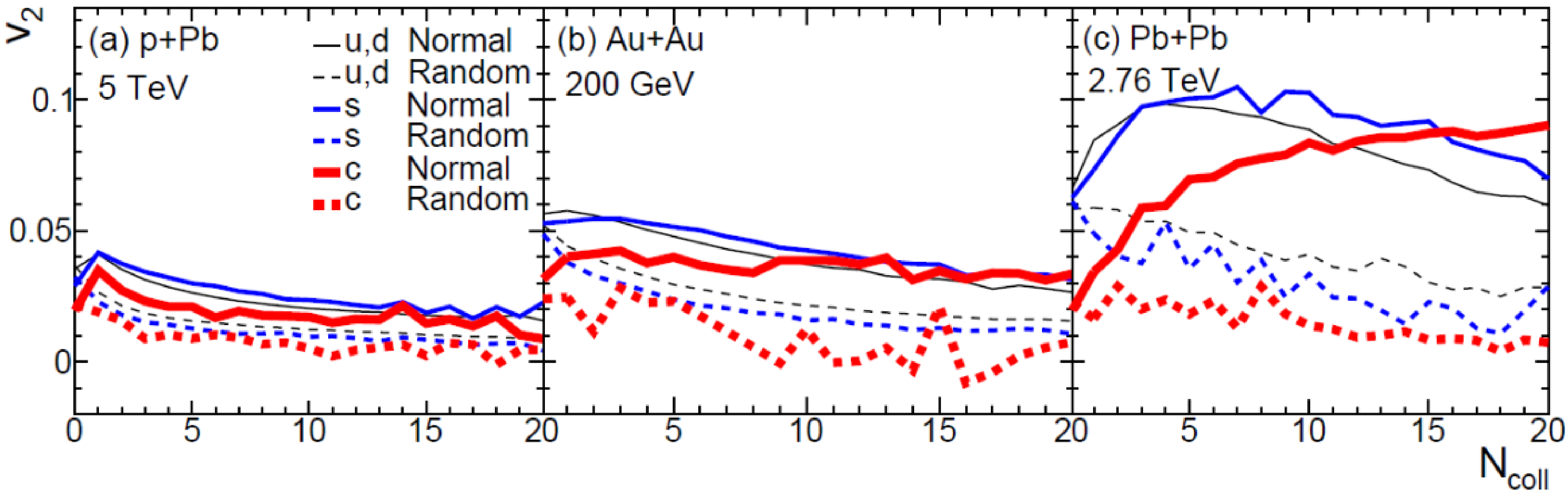




H.L. Li et al, Phys. Rev. C 93,051901(R)(2016)

The mass splitting is generated by coalescence, reduced by decays, and then significantly increased by hadronic scatterings.

The escape mechanism: *flavor dependence*



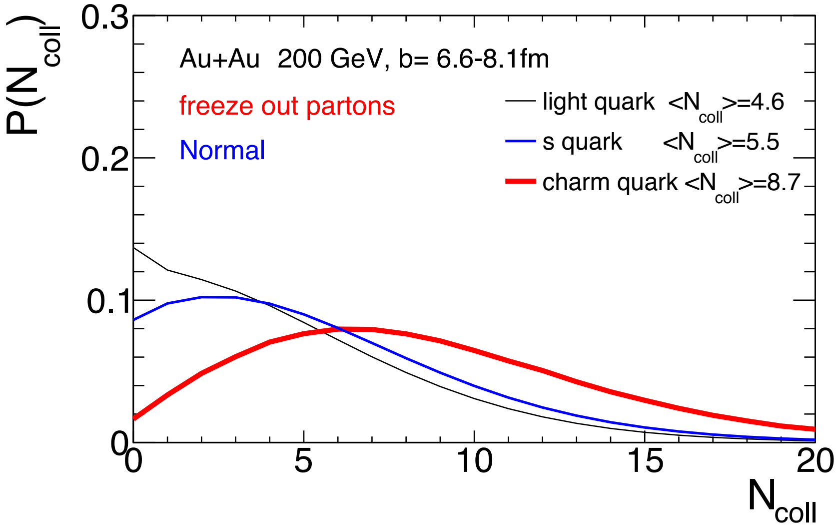
Mass ordering in v2(Ncoll):

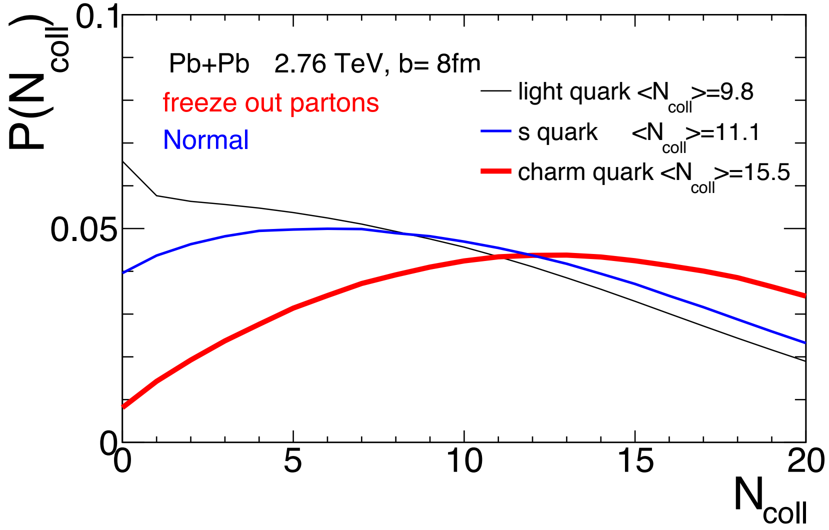
v2c < v2s < v2ud at small Ncoll

v2c > v2s > v2ud at large Ncoll, reversed

Escape mechanism is at work for all flavors

The escape mechanism: *flavor dependence*





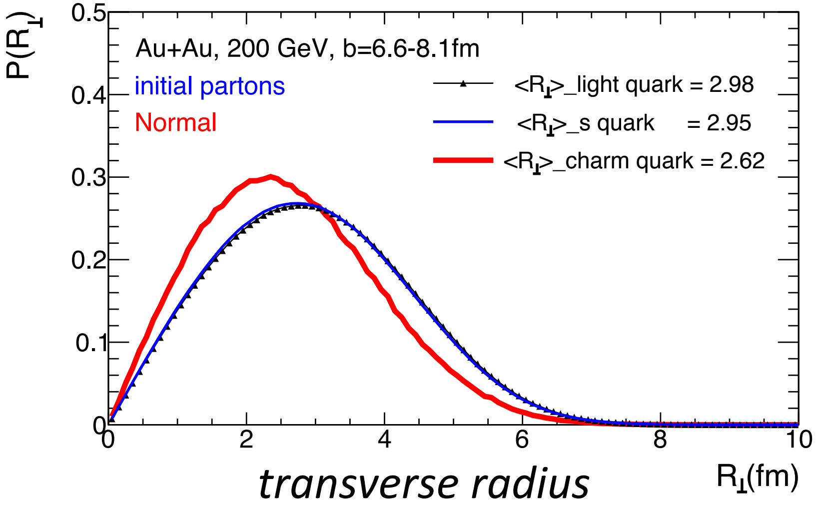
Quark mass ordering in the Ncoll distribution

for all 3 systems:

<Ncoll>c > <Ncoll>s > <Ncoll>ud

Related to the initial

(velocity &) spatial distribution



Toy model: *flavor dependence*

Initial $v_2 = 0$

The parton azimuth ϕ_f after <Ncoll> collisions

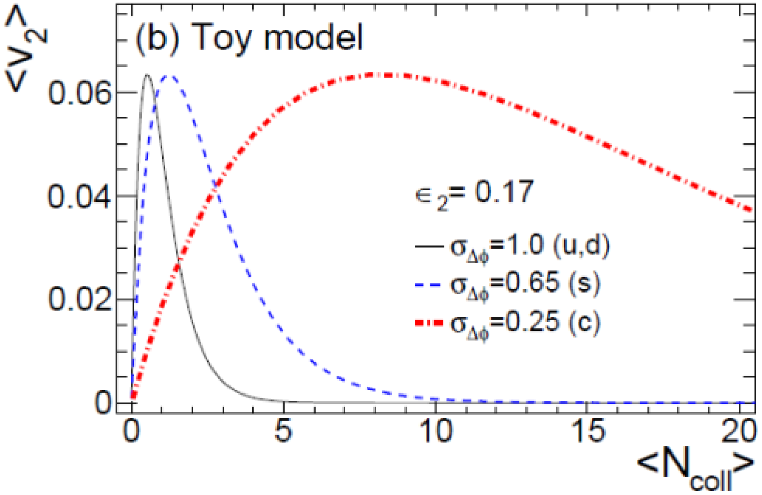
$$\phi_f = \phi_i + Gaus(\sqrt{N_{coll}(\phi_i)} \cdot \Delta\theta)$$

$$N_{coll}(\phi_i) = <N_{coll}> \cdot (1 - 2\varepsilon_2 \cdot \cos(2\phi_i))$$

$\Delta\theta$ parton average azimuthal deflection after each collision

Final $v_2 = <\cos(2\phi_f)>$

Hanlin Li, Z.W. Lin, FW, 1804.02681



With small N_{coll}, light quark v_2 > charm v_2. With large N_{coll}, it is the opposite. This is because light quarks are more randomized after each collision due to the large angle deflection.

Heavy quark flow

Followed the complete parton collision history to study light/strange/charm quark v_2 in AMPT

$\langle v_2 \rangle_{\text{random-}\varphi} / \langle v_2 \rangle_{\text{normal}}$ ratio ~ fraction from pure escape:

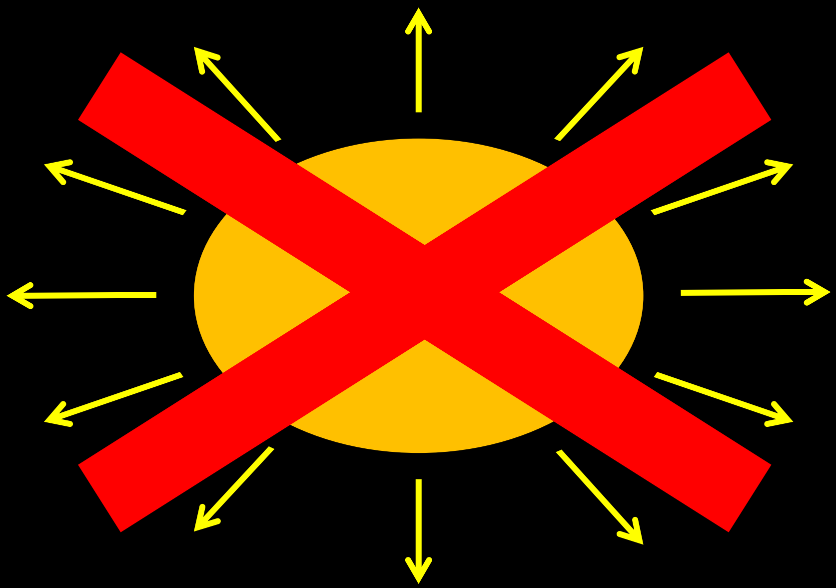
	dAu@200GeV b=0 fm	pPb@5TeV b=0 fm	AuAu@200GeV b=6.6-8.1 fm	PbPb@2.76TeV b=8 fm
u/d	93%(all quarks)	73%	66%	43%
s		59%	47%	27%
c		57%	22%	9%

Light quark v2:
escape more important for AuAu@RHIC, pPb@LHC, and smaller/lower-energy systems;
hydro-type flow more important for PbPb@LHC, although still significant escape contribution.

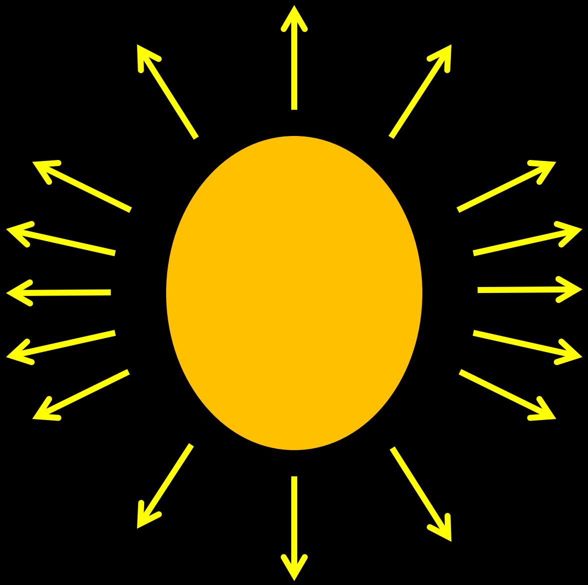
Charm v2 in AuAu@RHIC-200GeV & PbPb@LHC: mostly comes from **collective flow**

➔heavy quarks are more sensitive probes of collective flow & the medium

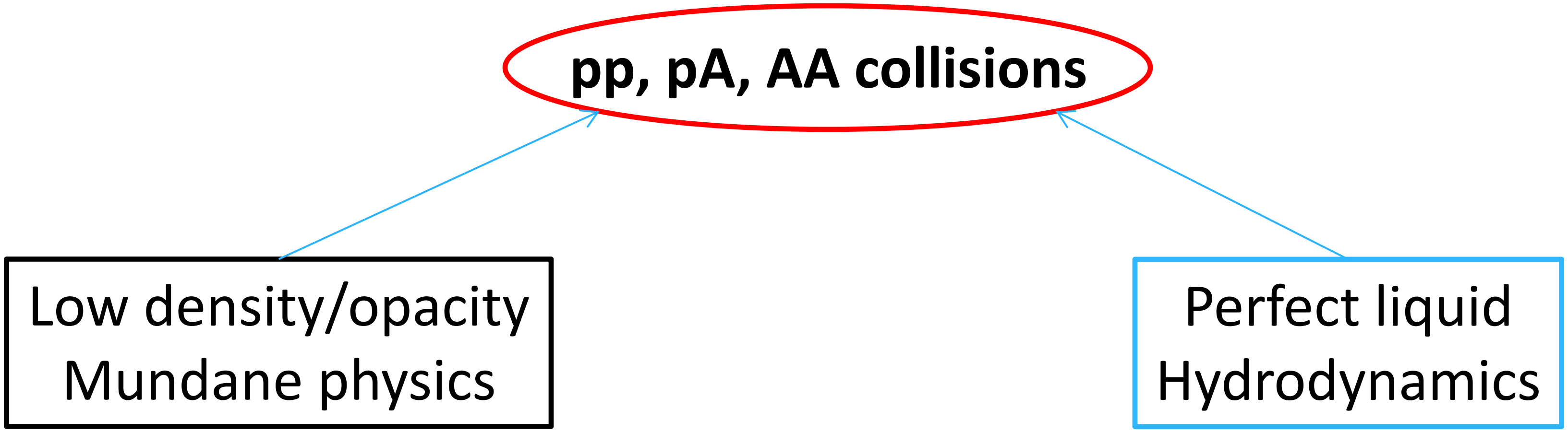
Anisotropy mechanism



Expansion, flow
Hydro paradigm



No expansion
But escape



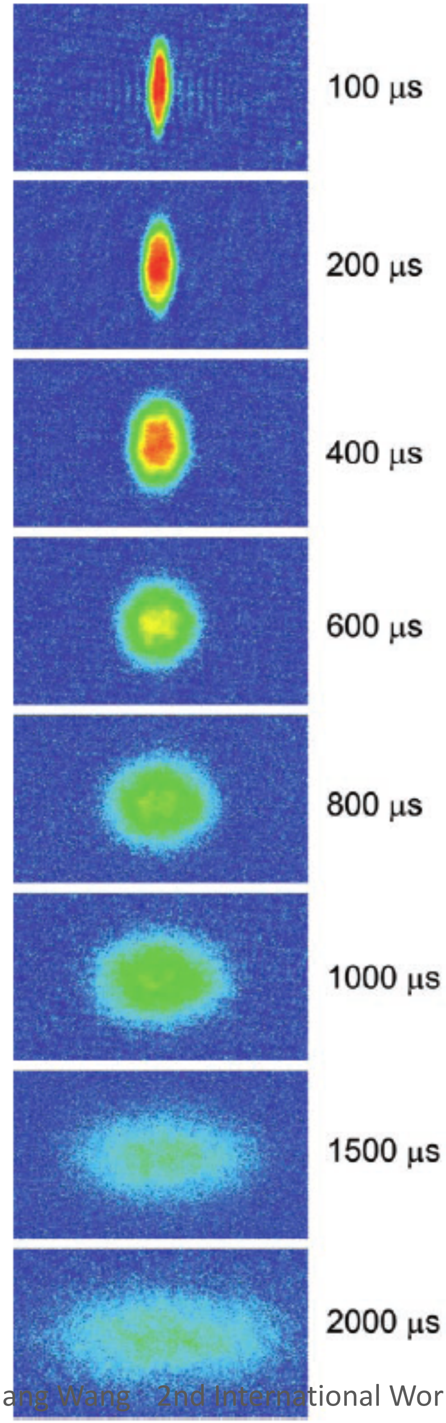
pp, pA, AA collisions

Low density/opacity
Mundane physics

Perfect liquid
Hydrodynamics

Need experimental test!

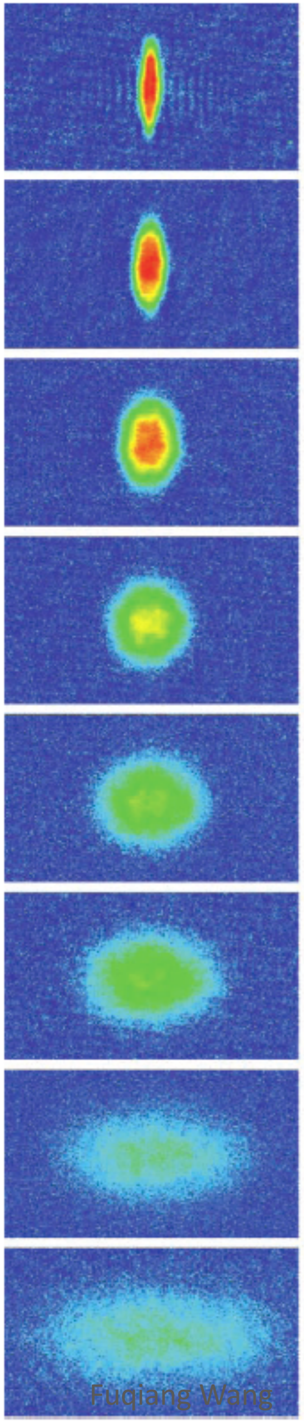
Cold atom experiment



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

$L/L_{mfp} \approx 1000$

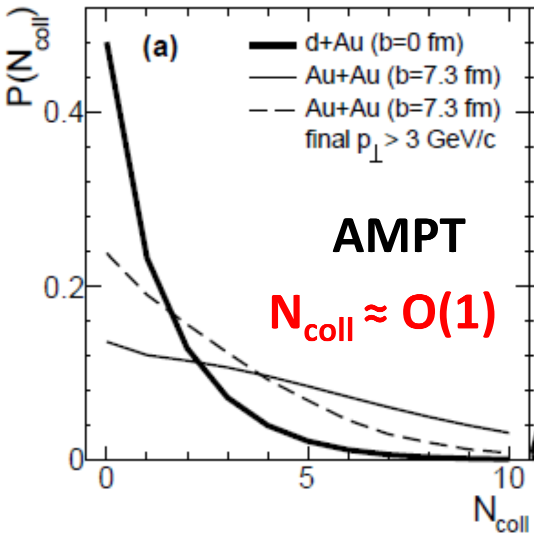
Very high opacity for the cold atom system

Indeed hydro!

Heavy ion collision:

$dN/dy \sim 1000$, $\rho \sim 1000/\pi R^2\tau \sim 6\ \text{fm}^{-3}$

$\rho\sigma L$ $\sim 7\text{fm}^{-3}*3\text{mb}*3\text{fm}$ **~ 5**

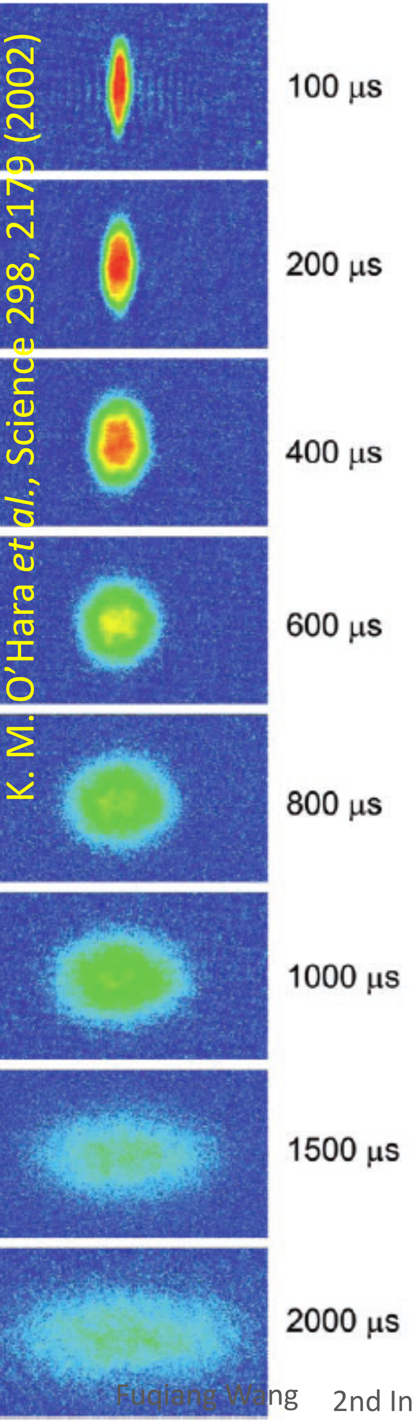


AMPT

$N_{coll} \approx O(1)$

Low opacity in AMPT

Hydro??



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

To emulate QGP with cold atoms

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

Opacity: $\rho\sigma L$

$a \approx 5\times10^{-5}$ cm
$\sigma_{int} \approx 10^{-8}\ \mathrm{cm}^2$
$\rho \approx 5\times10^{13}\ /\mathrm{cm}^3$
$L_{mfp} \approx 2\times10^{-6}$ cm
$L \approx 2\times10^{-3}$ cm
$L/L_{mfp} \approx$ ~~1000~~
0-1

$\mathrm{X}10^{-3}$

Very high opacity for the cold atom system

Low opacity for the cold atom system

Summary

- The escape mechanism can simultaneously, most naturally explain vn in small/large systems, at low/high energies, for light/heavy flavors.
- Cannot conclude from flow measurements that we have a “nearly perfect fluid.”
  Our paradigm “nearly perfect fluid” may be wrong.
- A questin we should all ask ourselves:
  What fundamental physics have we learned?