Fluctuations and flow of the world's smallest and hottest fluid

Björn Schenke Brookhaven National Laboratory

in collaboration with Gabriel Denicol, Charles Gale, Sangyong Jeon, Jean-François Paquet, Sangwook Ryu (McGill), Sören Schlichting (BNL), Chun Shen (McGill), Prithwish Tribedy, Raju Venugopalan (BNL)

EuNPC 2015
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Groningen, Netherlands

BROOKHAVEN NATIONAL LABORATORY

10 years of perfectly fluid QCD

- **High energy heavy ion collisions:** From QCD we expect the creation of a weakly interacting gas of quarks and gluons (running coupling gets asymptotically small at high energies)

- **Surprise at RHIC:**
  The Quark Gluon Plasma (QGP) behaves like an
  almost perfect fluid

- Confirmed by results from LHC in 2010

2006

What have we learned since then?

2006

2015

What have we learned since then?

Significantly improved our understanding of many aspects.

I will focus on:

- Initial state and its fluctuations
- Transport properties such as shear and bulk viscosities
- Nuclear geometry, effects of deformed nuclei

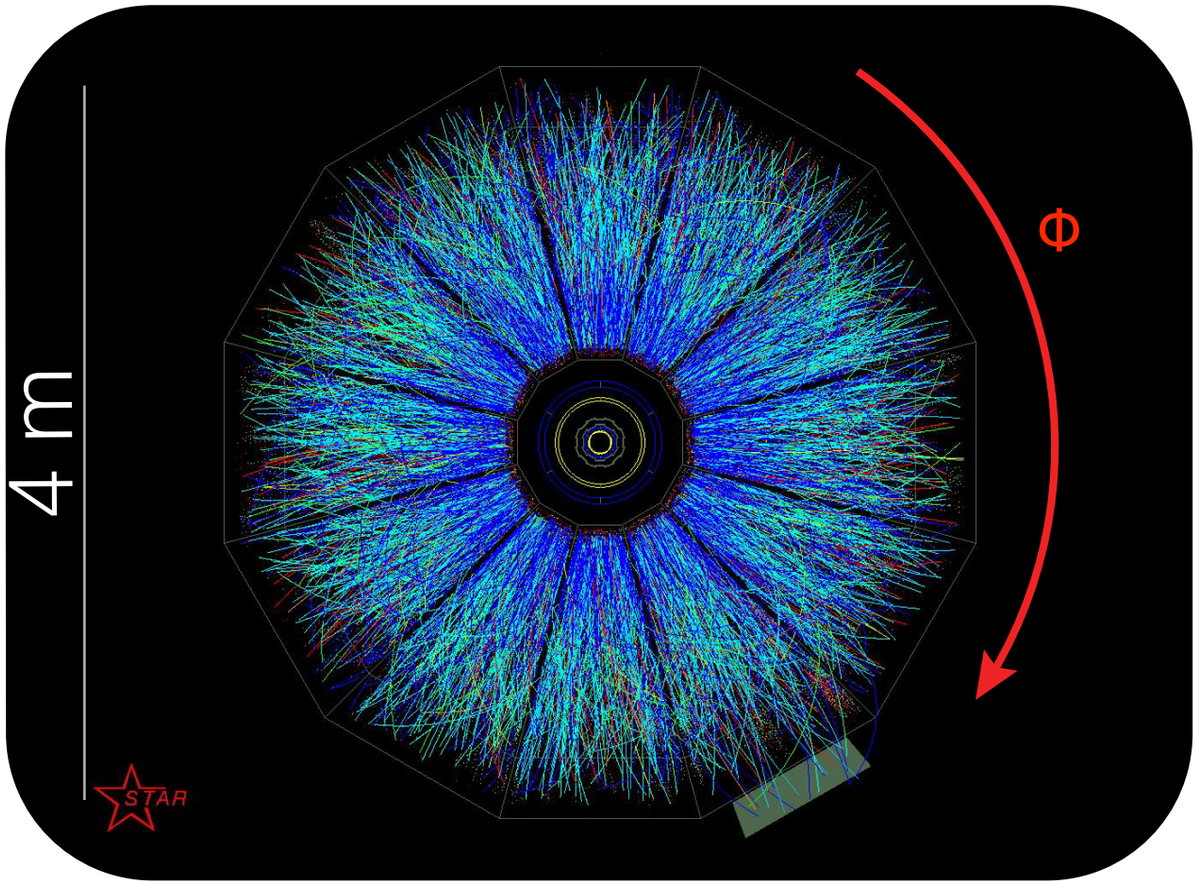
for hard probes see M. van Leeuwen's talk on Monday, for heavy flavors S. Masciocchi's talk Tuesday

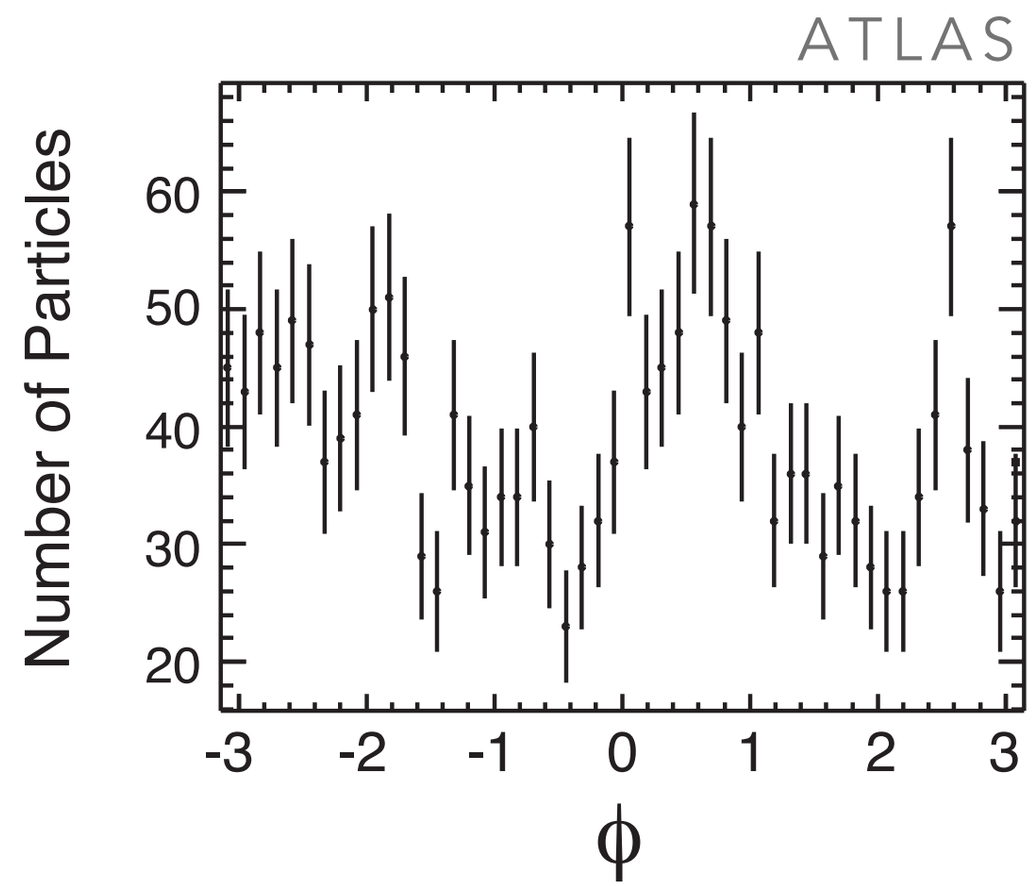
New challenge:

- Small systems: Flow in p+p and p+A collisions?

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra





Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2v_n \cos[n(\phi - \psi_n)]\right)$$

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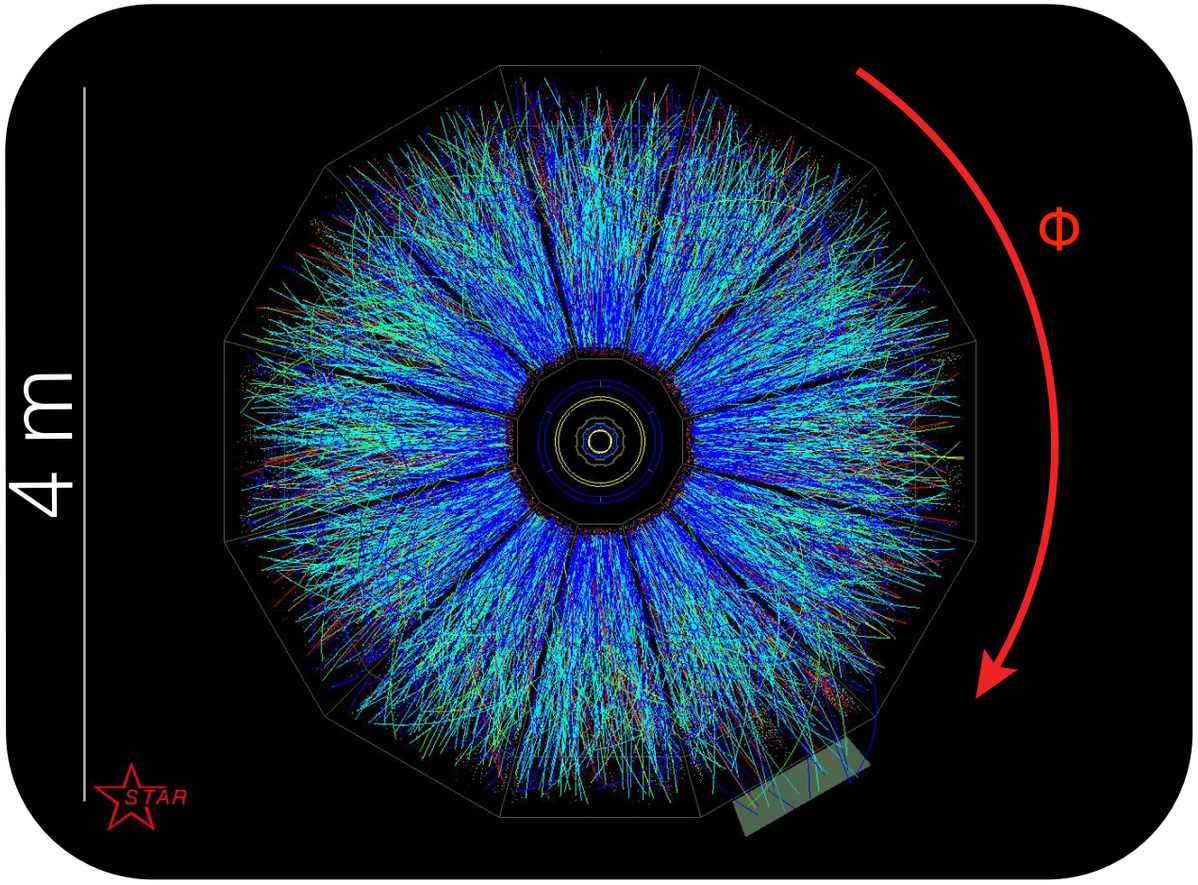

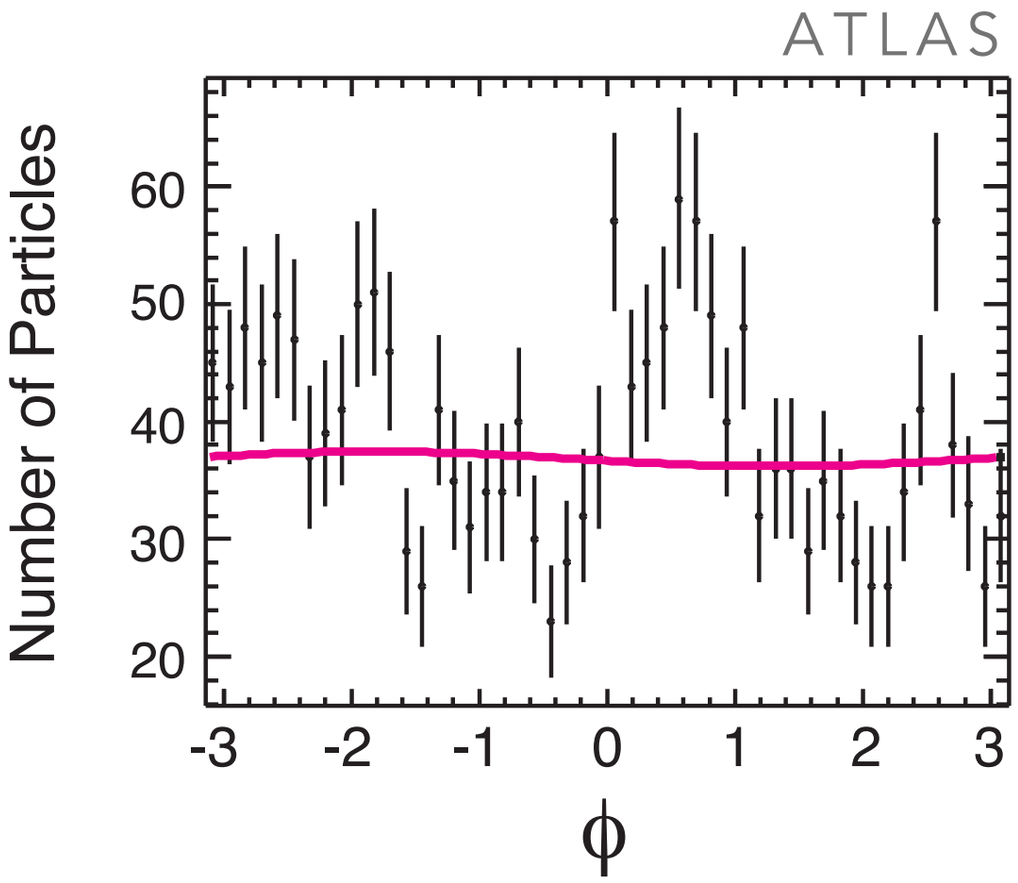

Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi))\Big)$$

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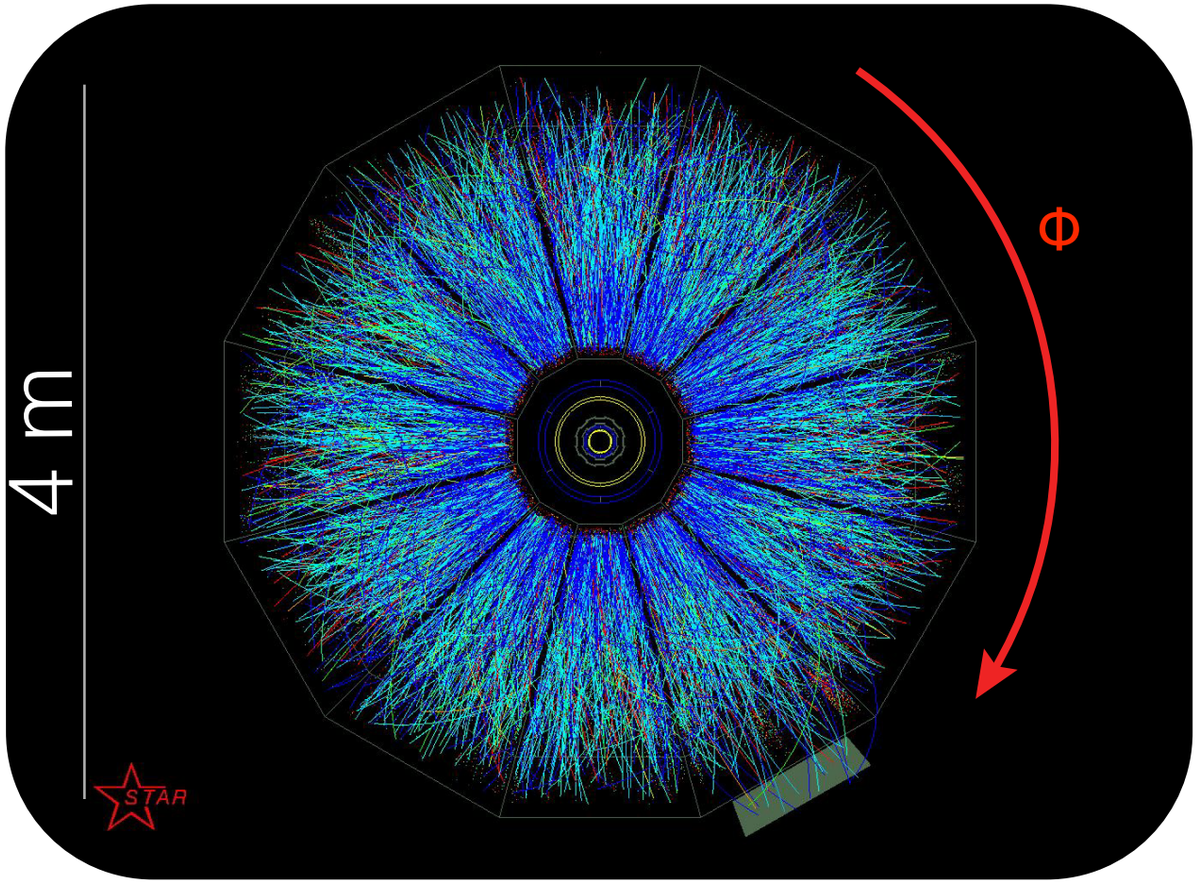

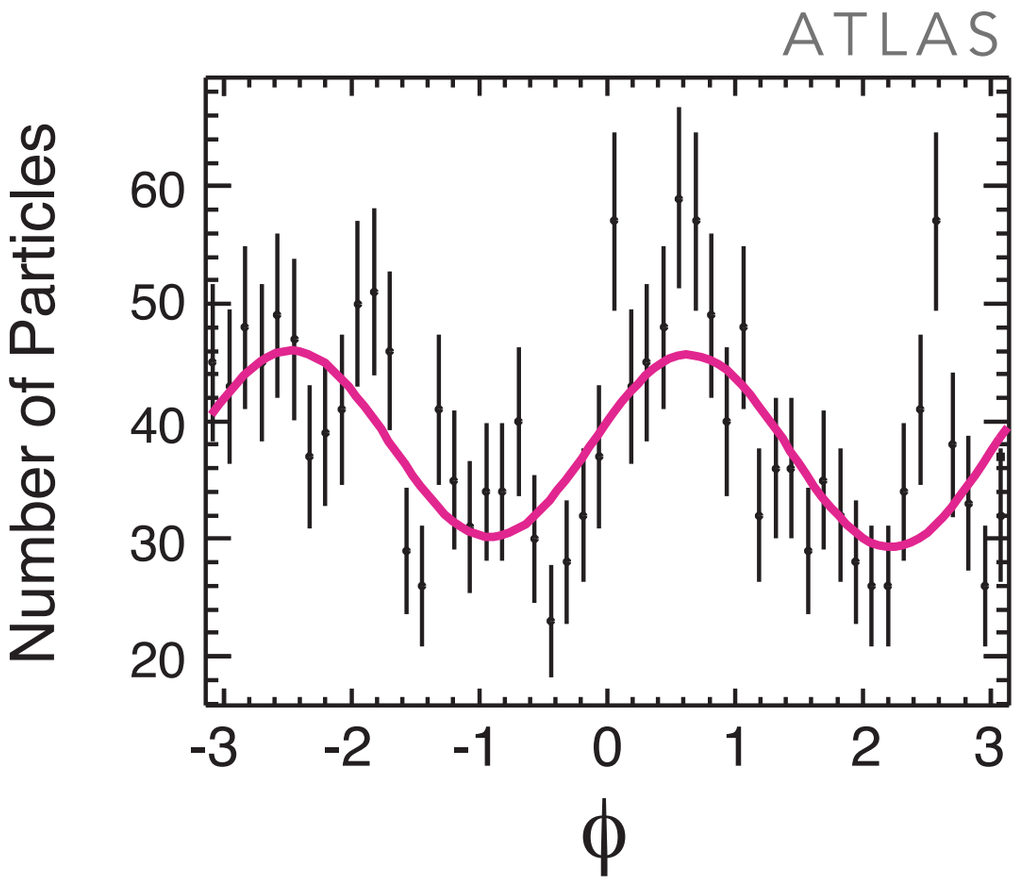

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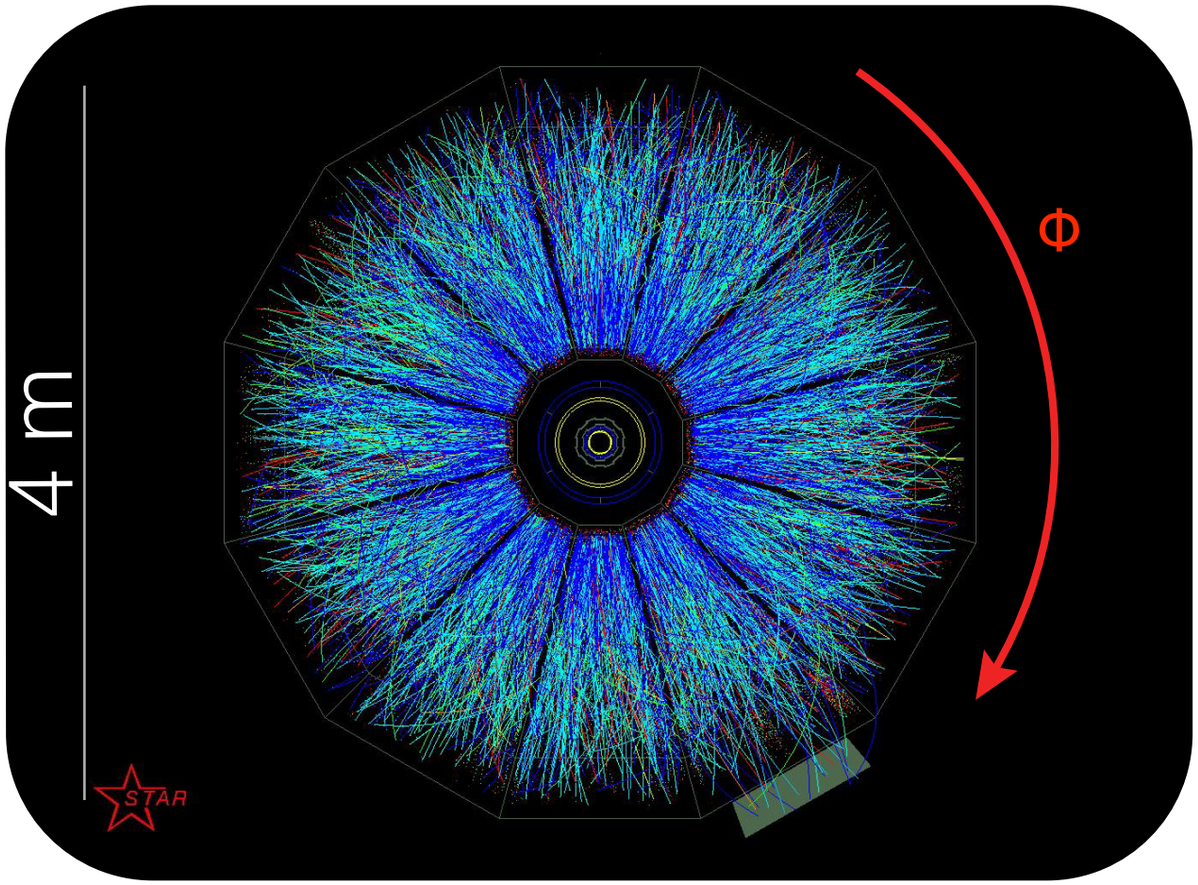

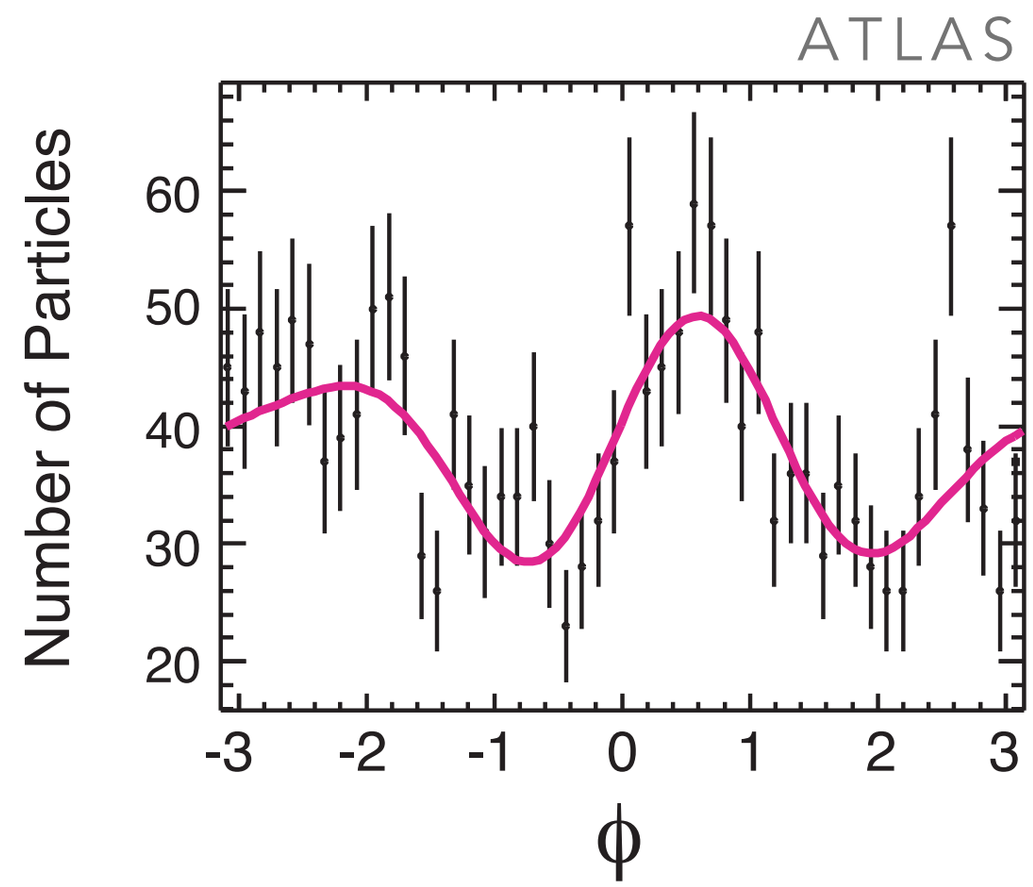

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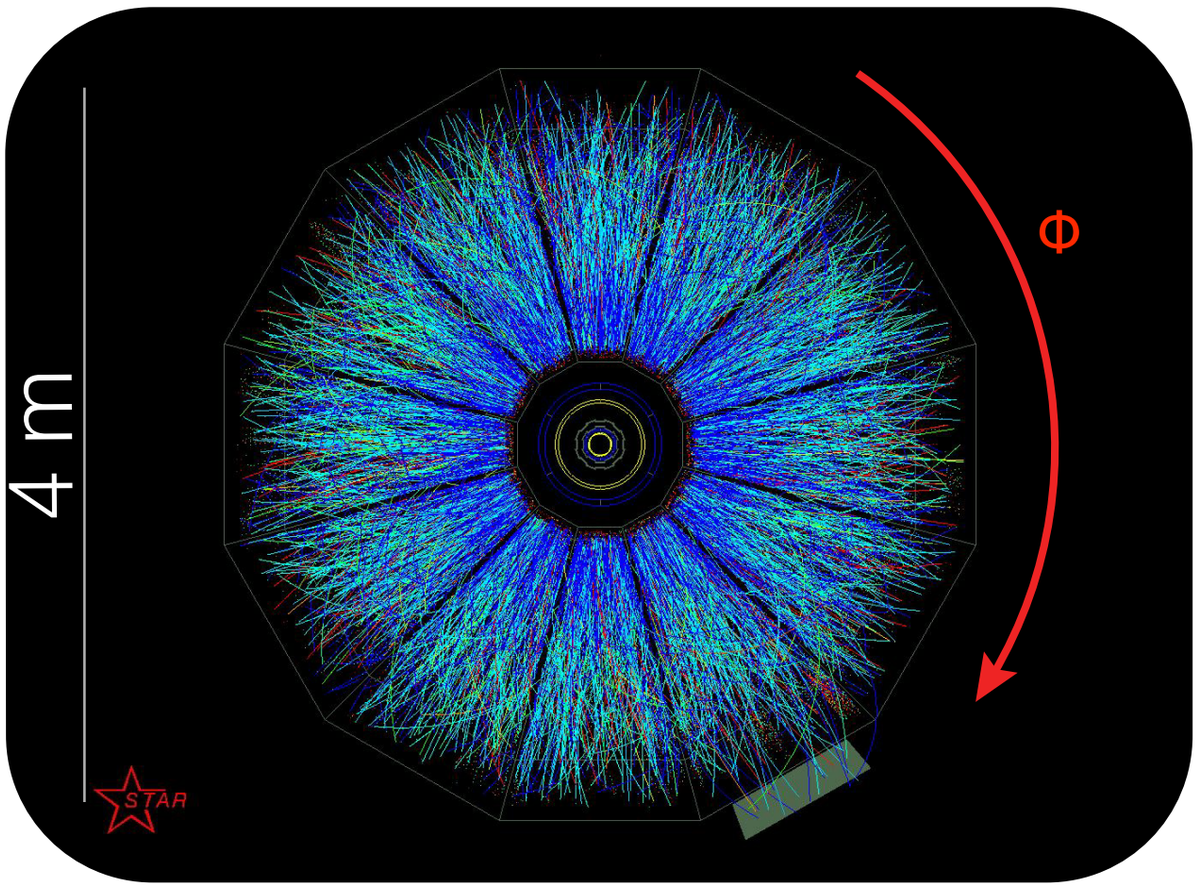

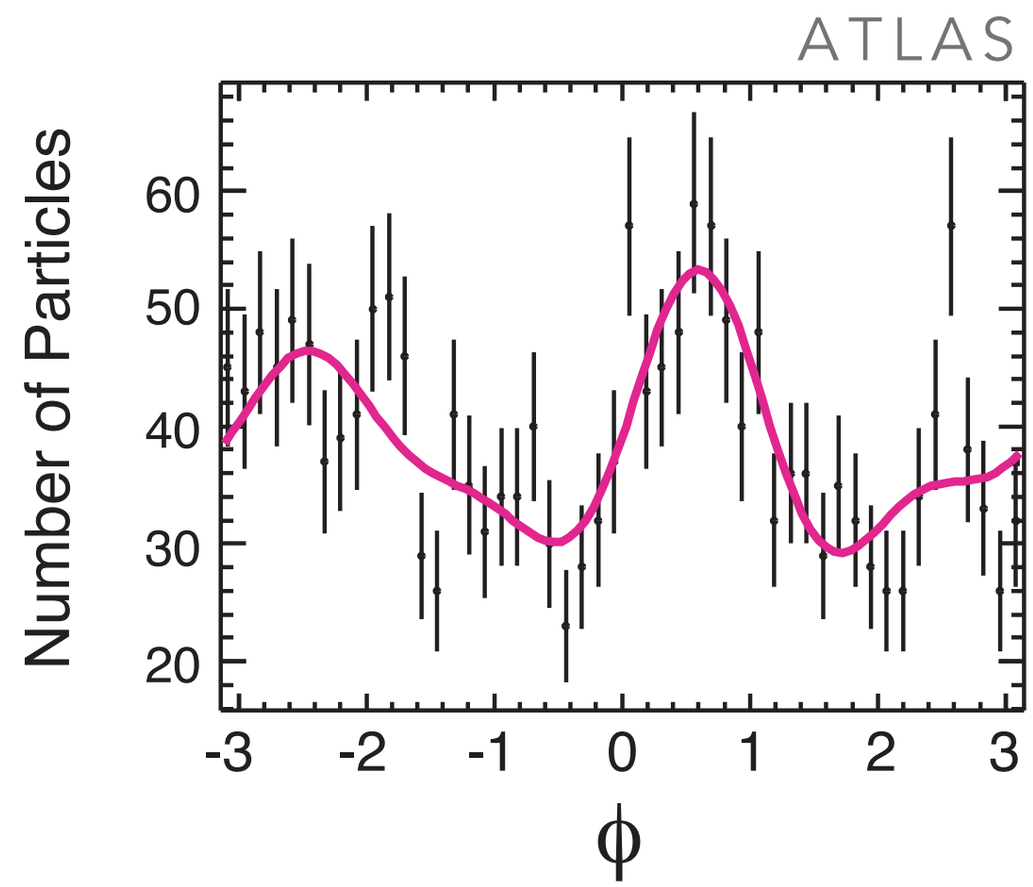

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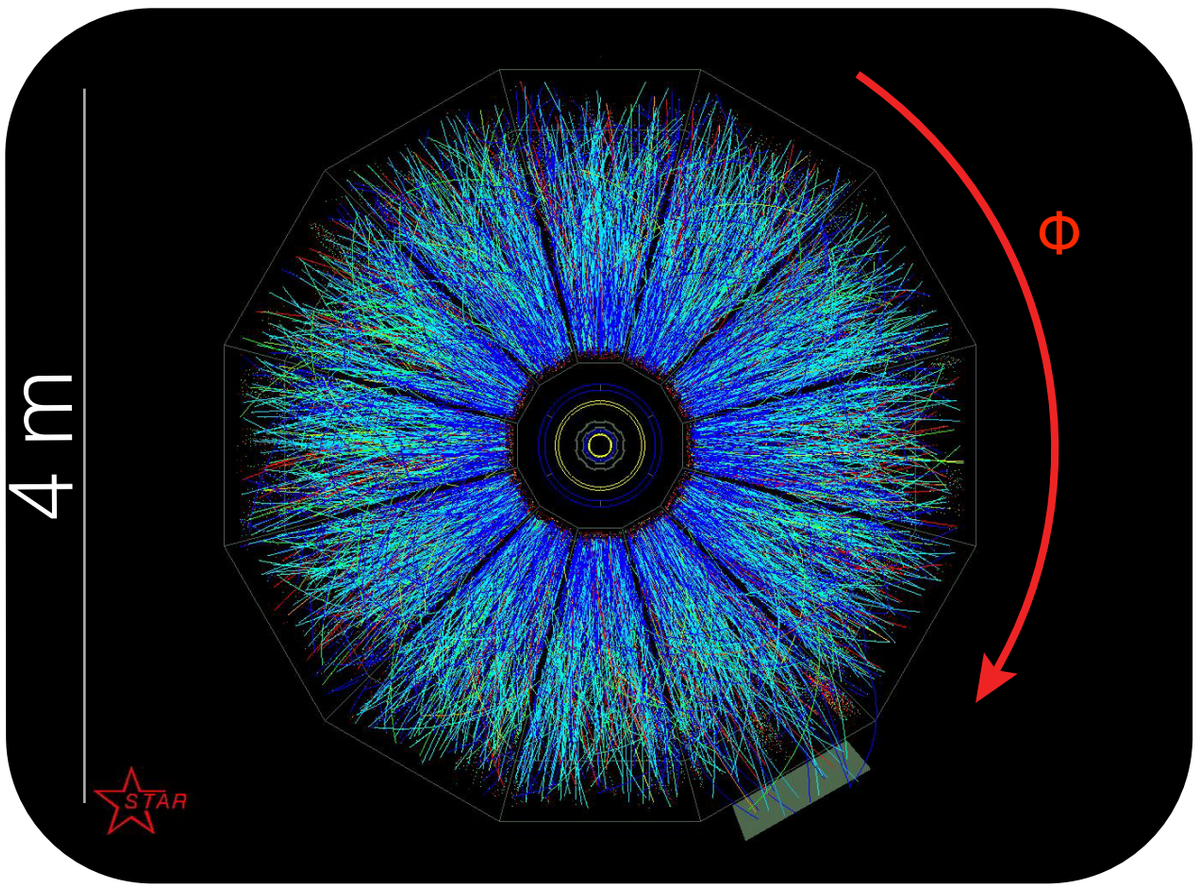

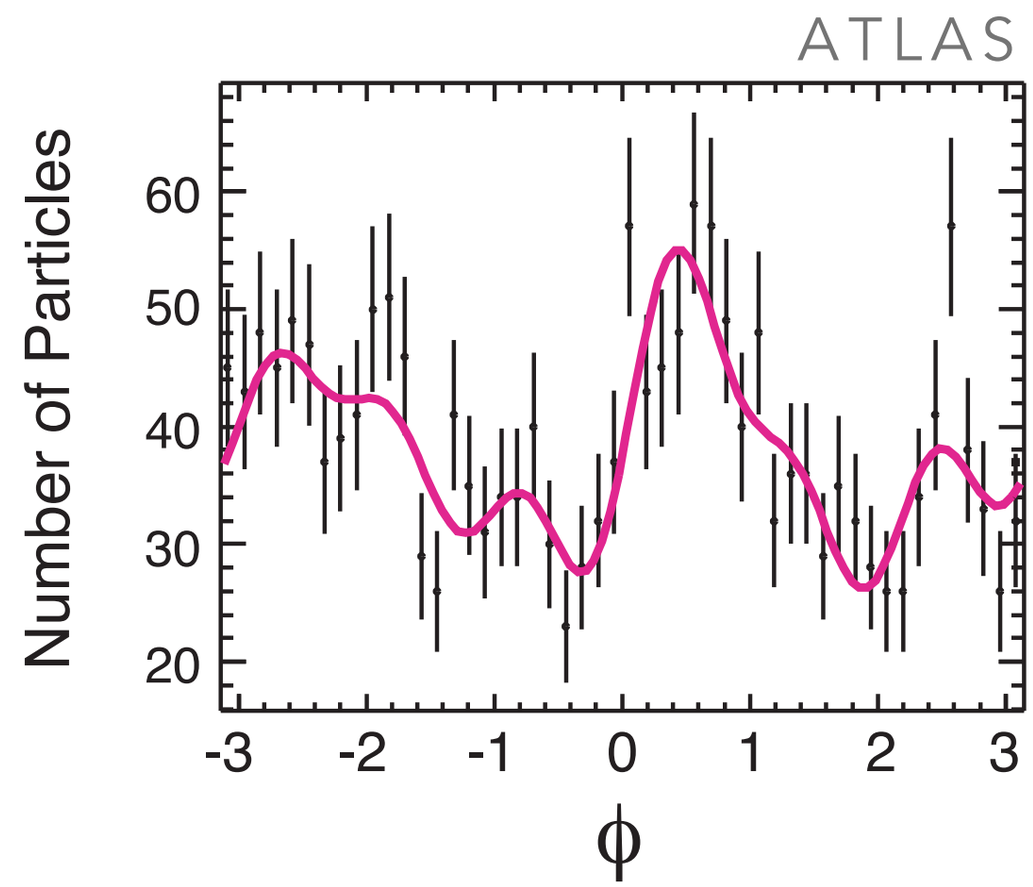

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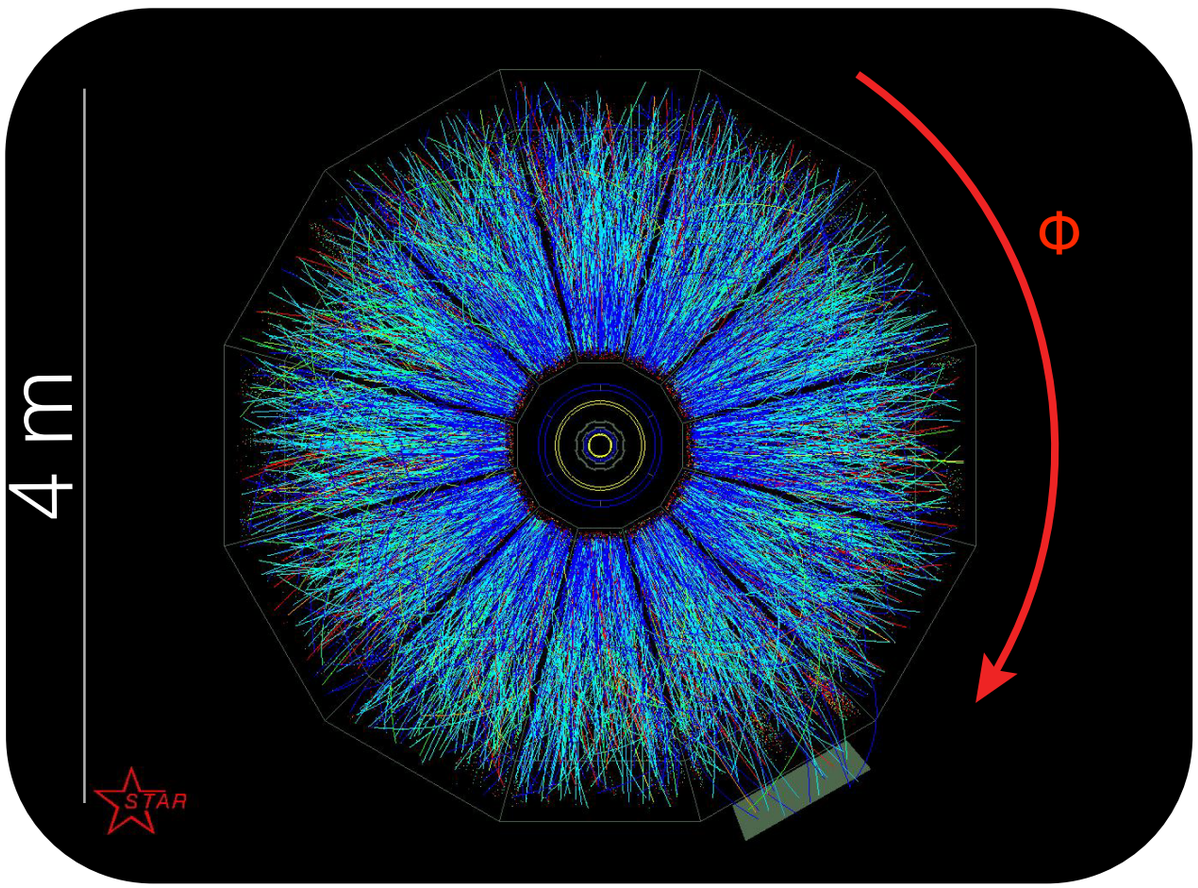

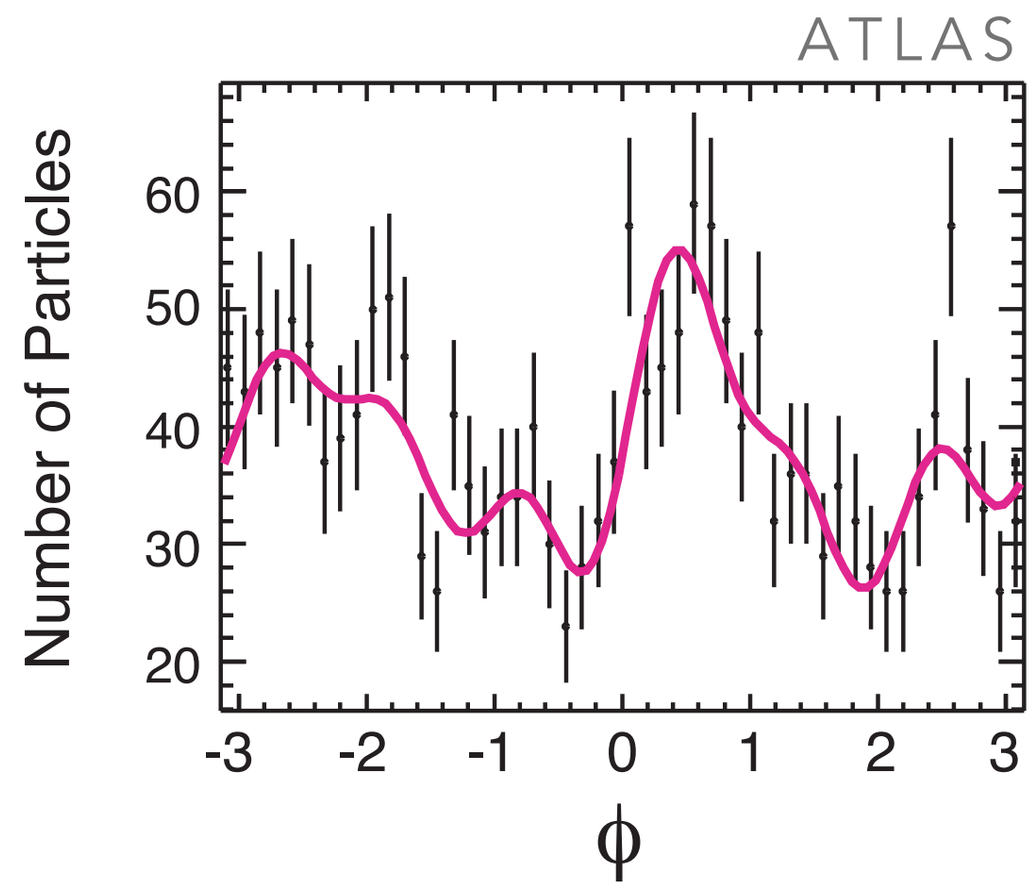

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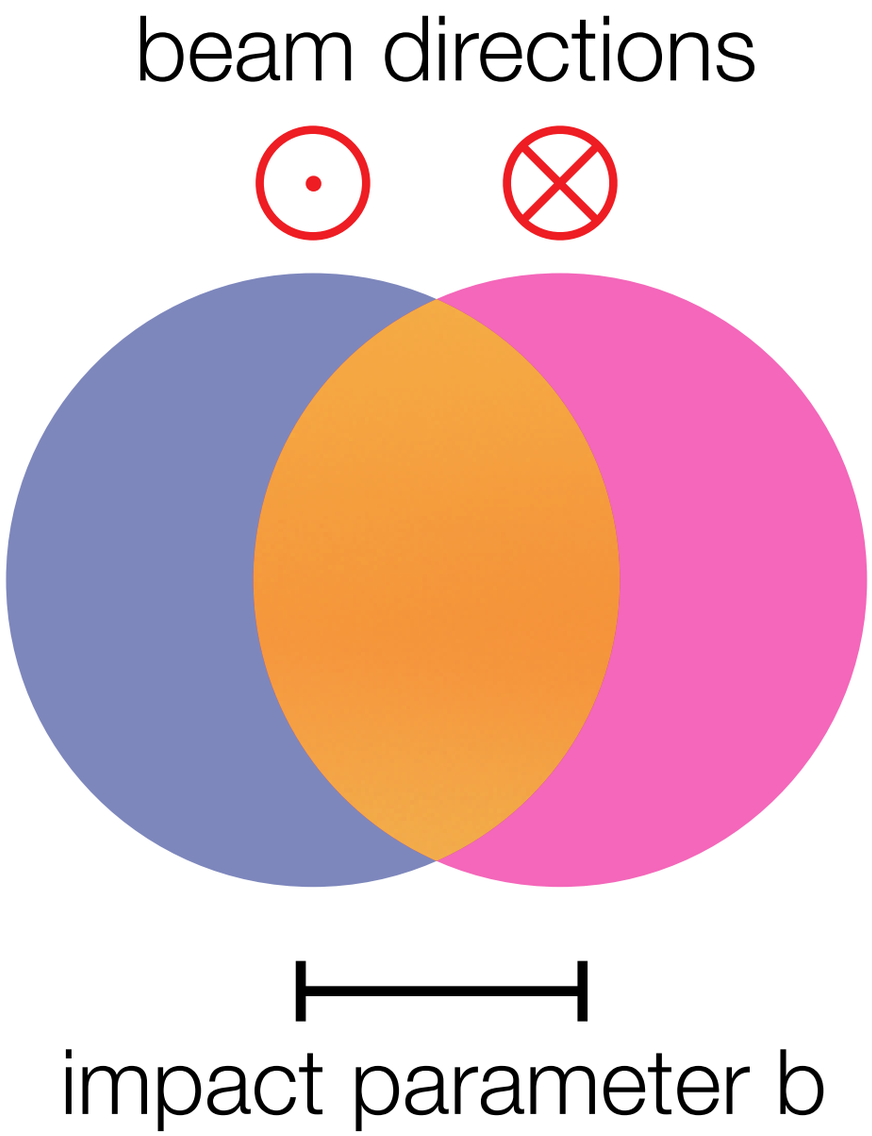
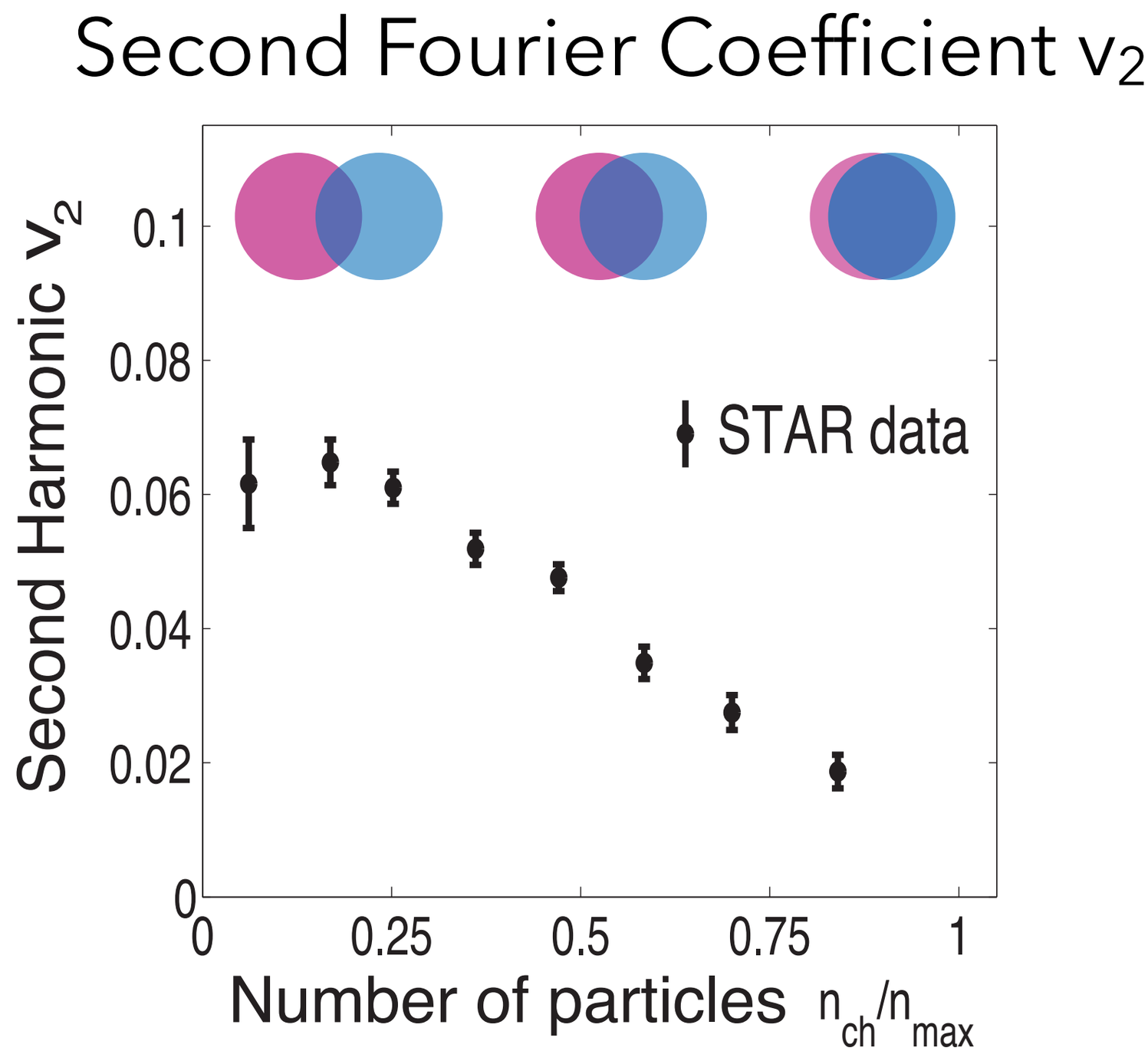
Fluid dynamic response to the initial shape





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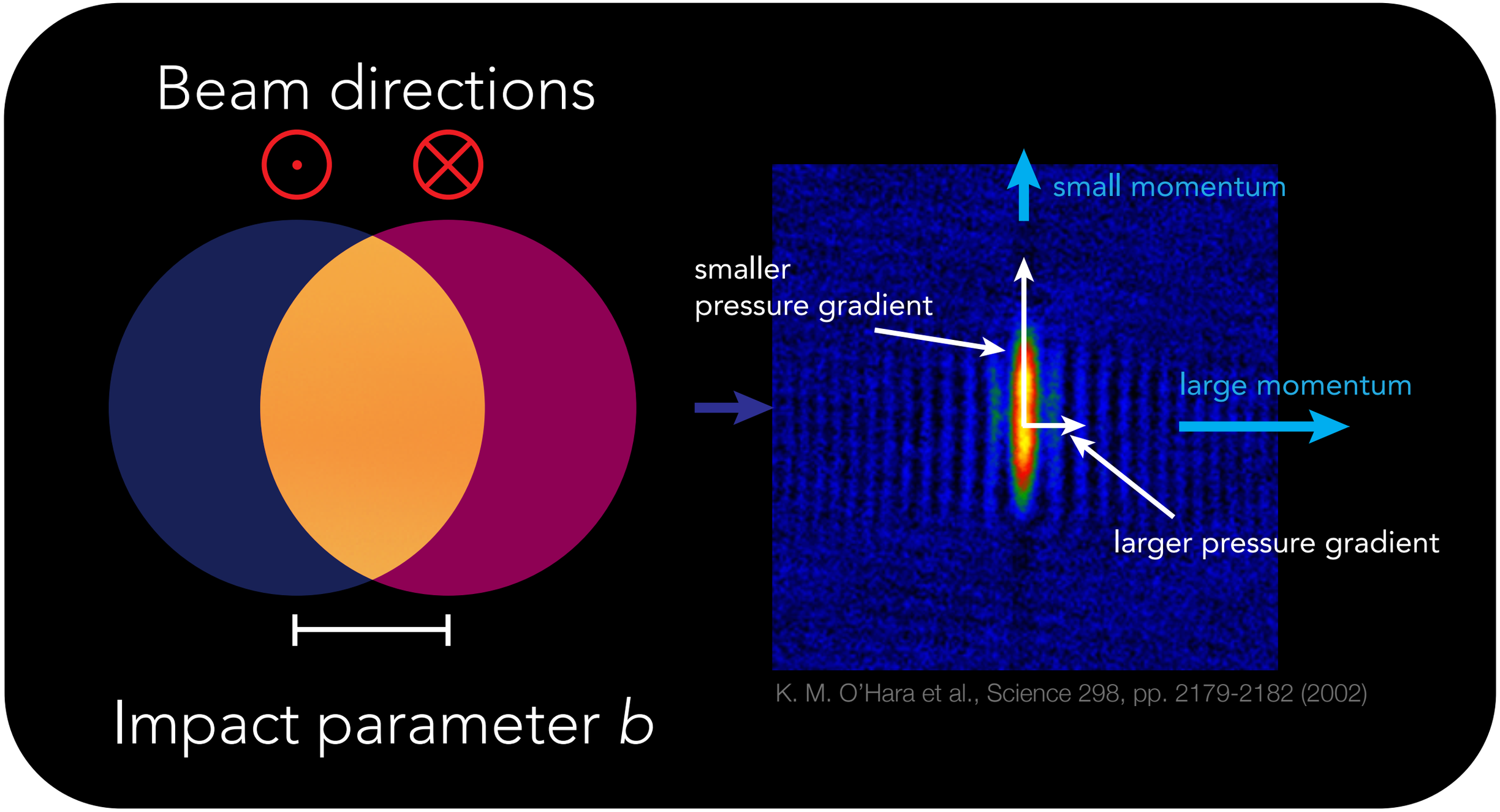

Cheating a little: Animation is an ultra cold quantum gas

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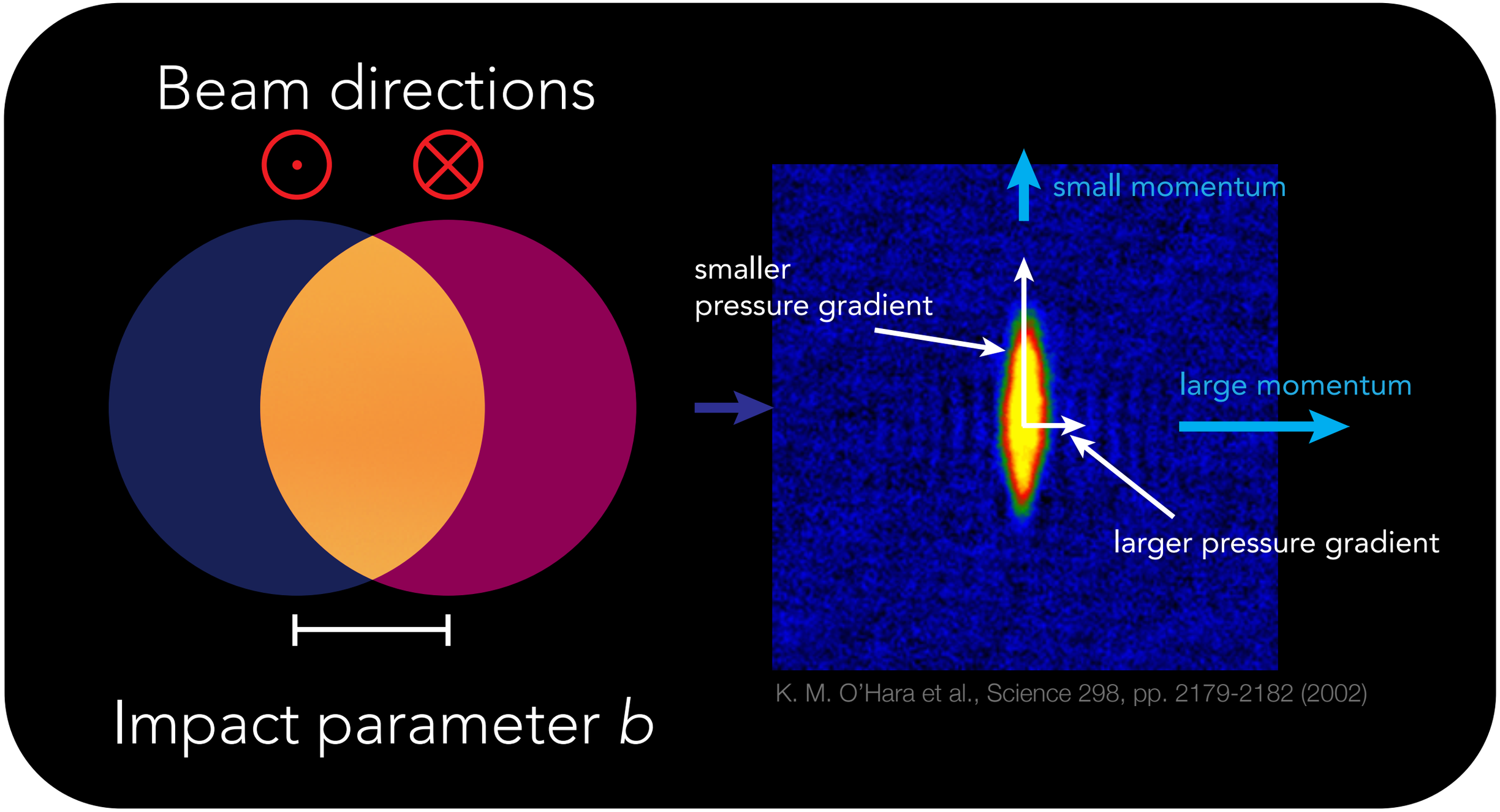

K. M. O'Hara et al., Science 298, pp. 2179-2182 (2002)

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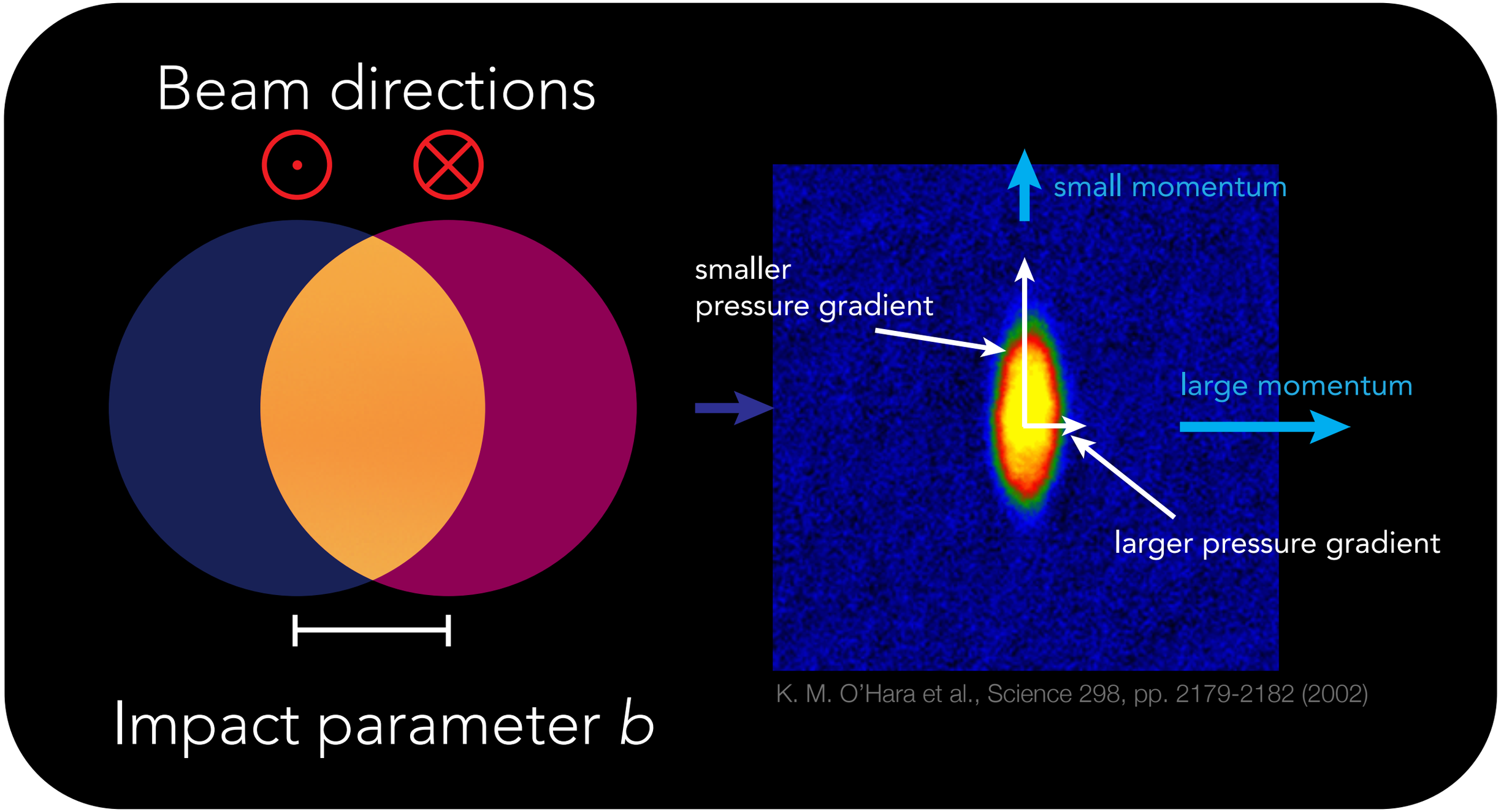

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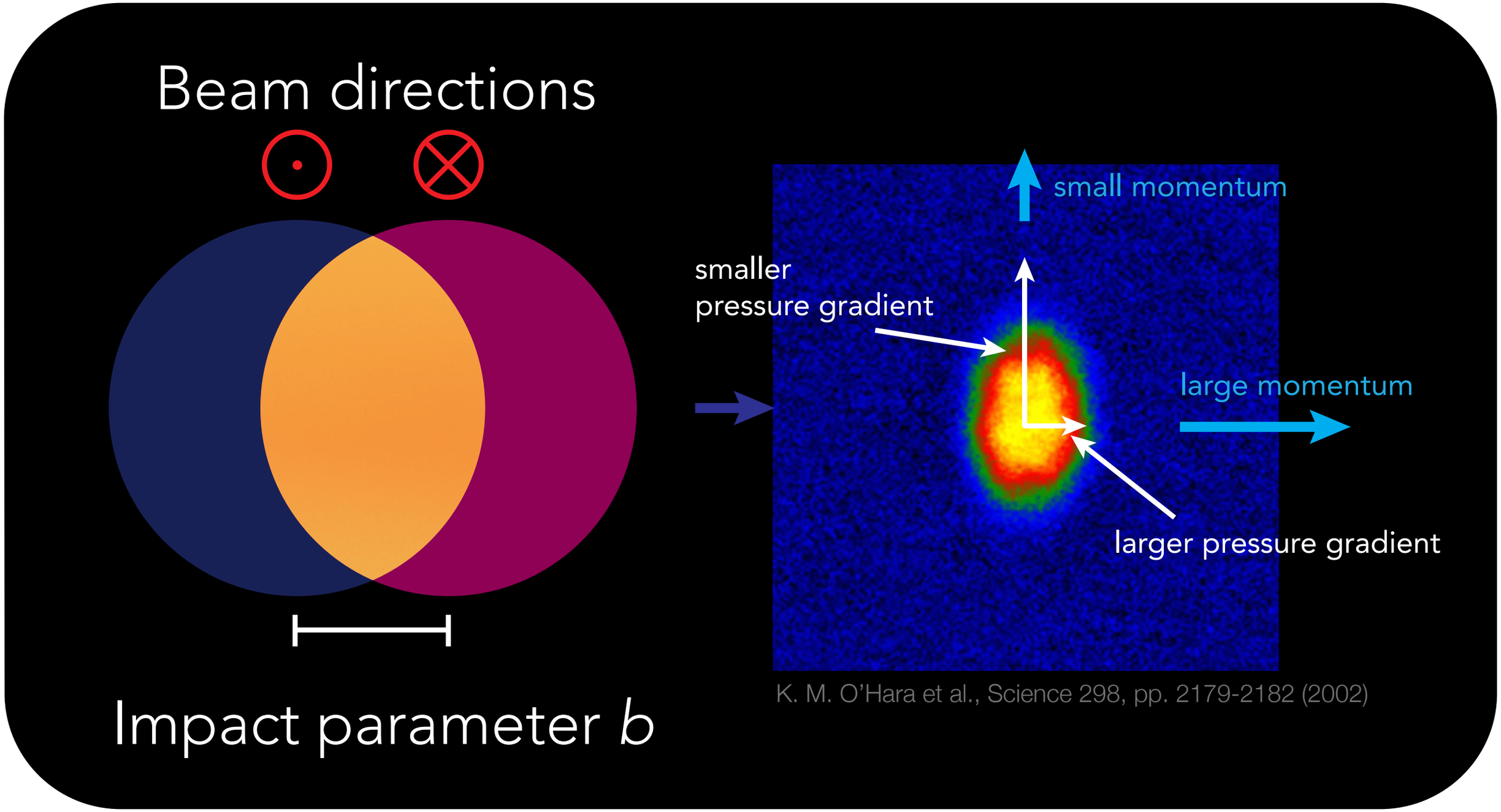

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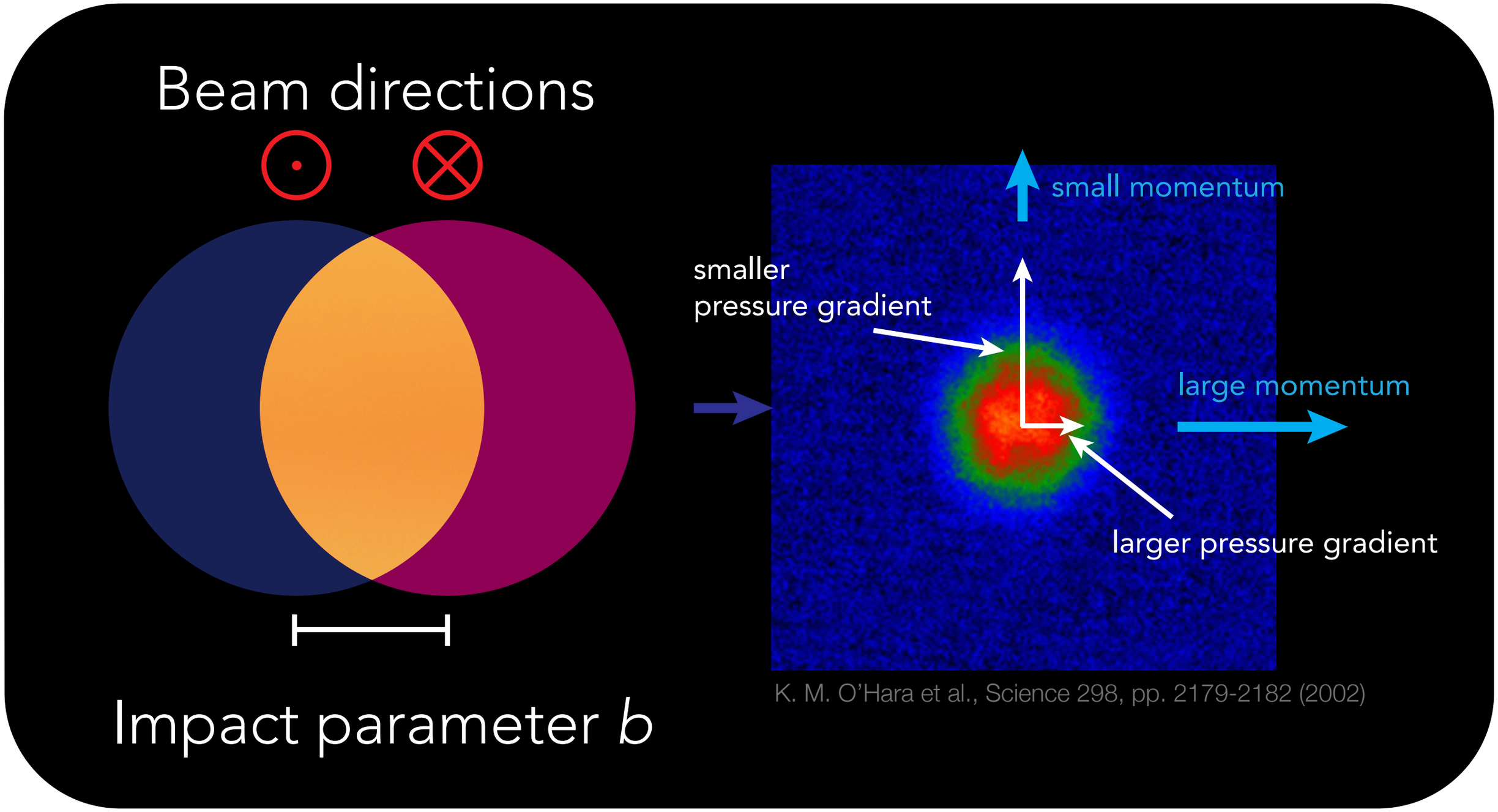

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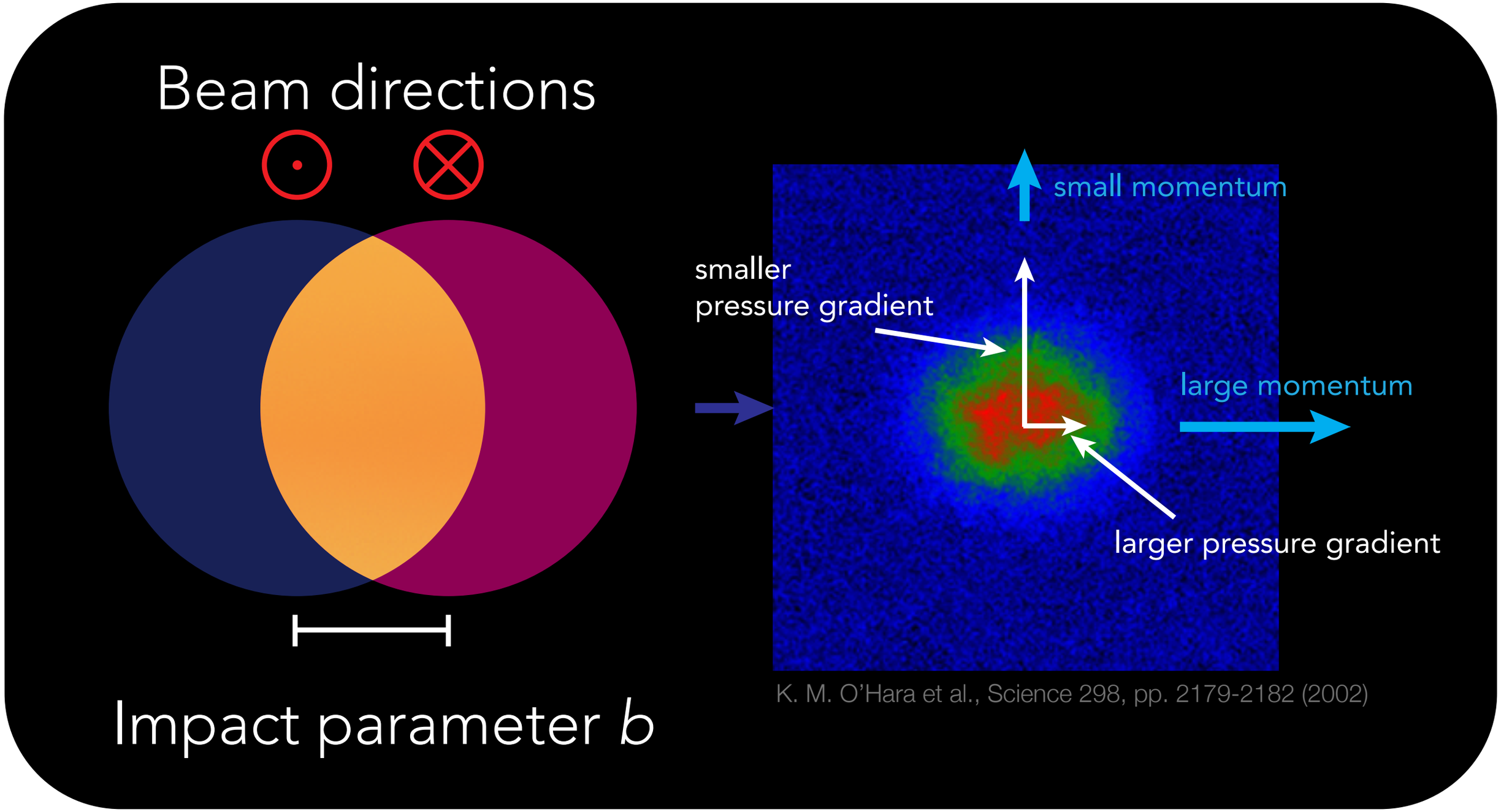

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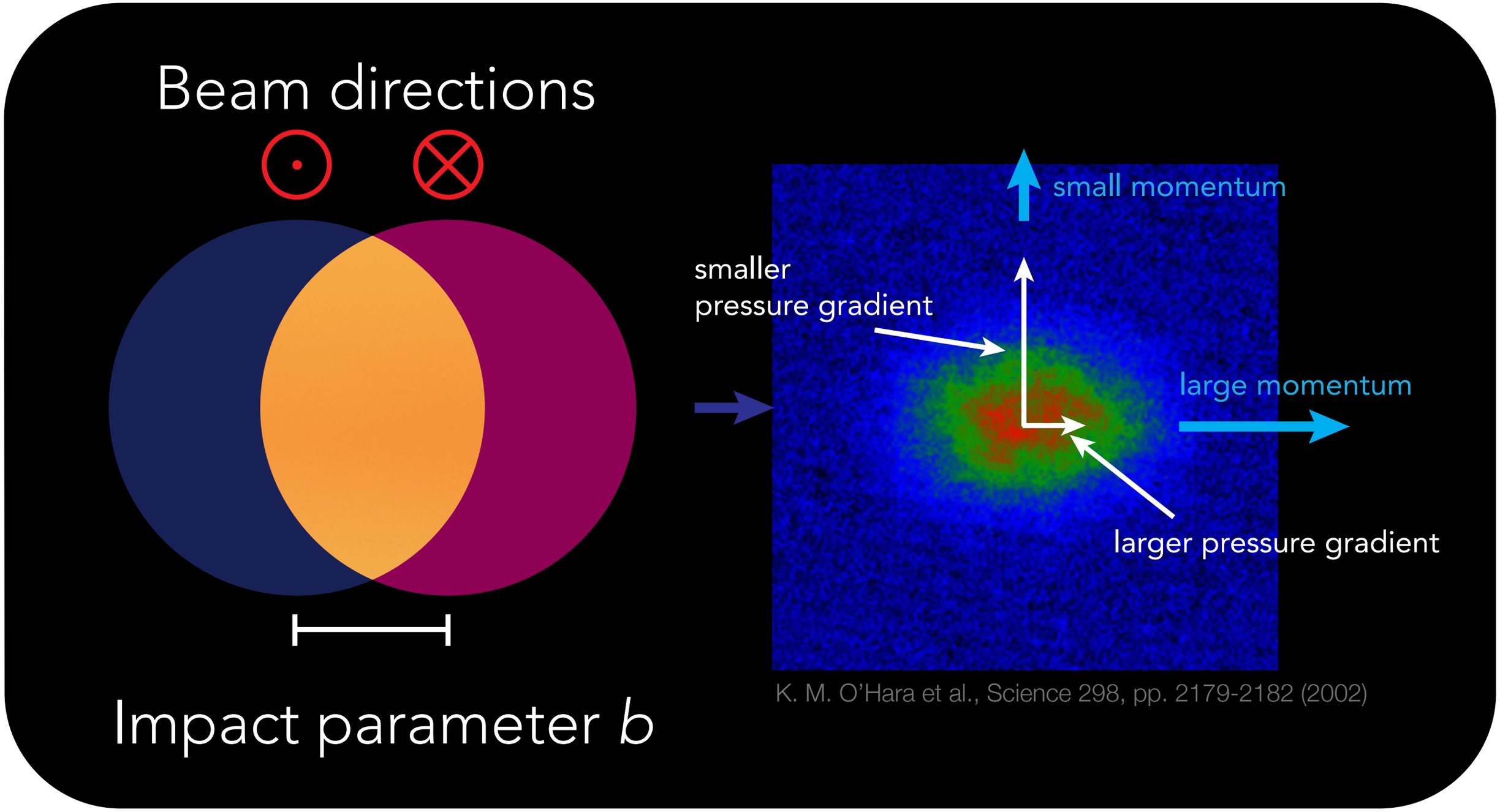

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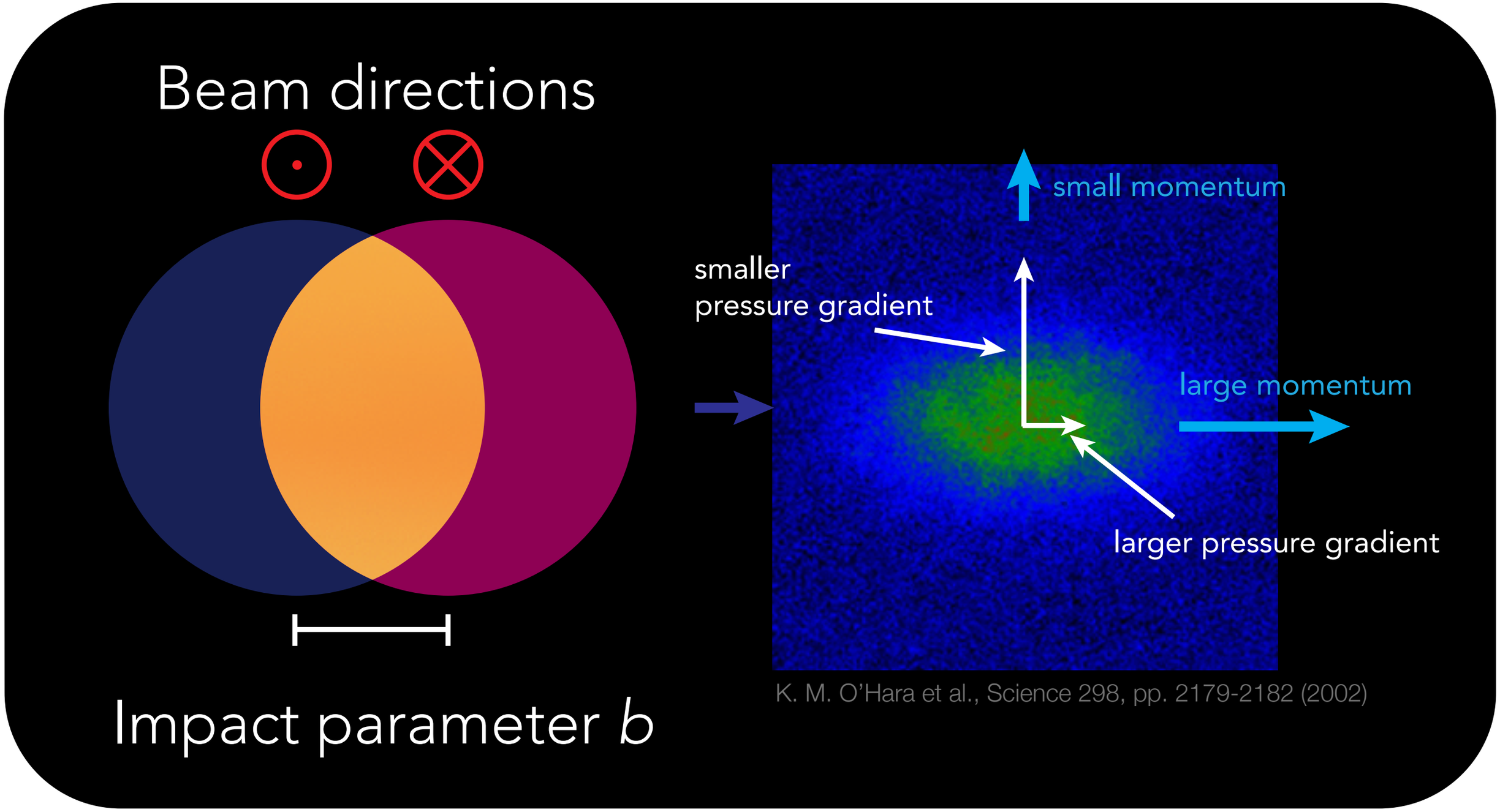

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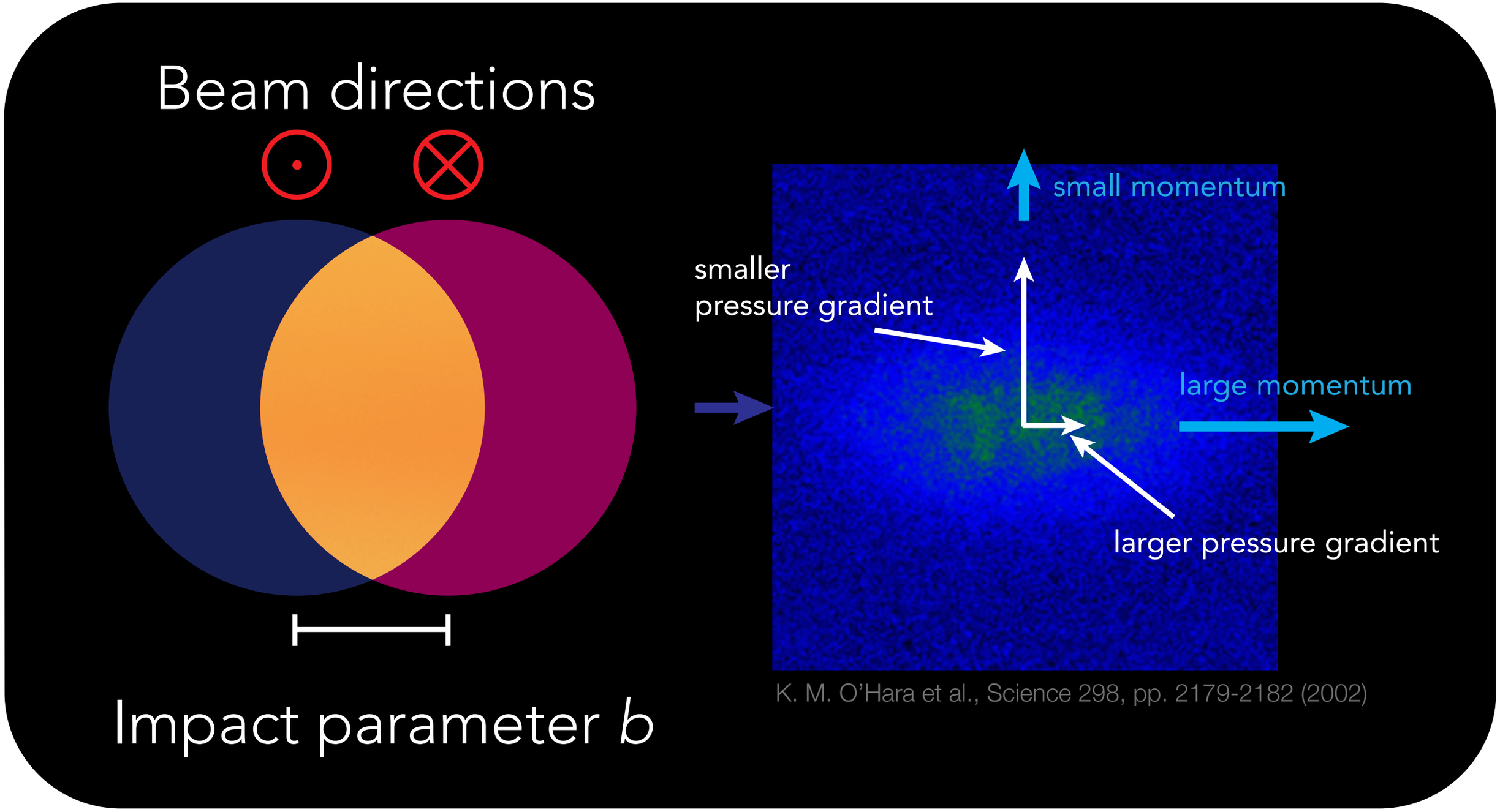


Cheating a little: Animation is an ultra cold quantum gas

Relativistic viscous fluid dynamics

- Effective theory for the long wavelength modes, valid for a strongly interacting system

- Basic equations: **energy and momentum conservation**

energy density pressure

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P) u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

flow velocity viscous correction

- Then there are constituent equations for $\Pi^{\mu\nu}$ (contain shear viscosity η and bulk viscosity $\boldsymbol{\zeta}$, heat conductivity and higher order transport coefficients)

- Equation of state $P(\varepsilon)$ from lattice QCD

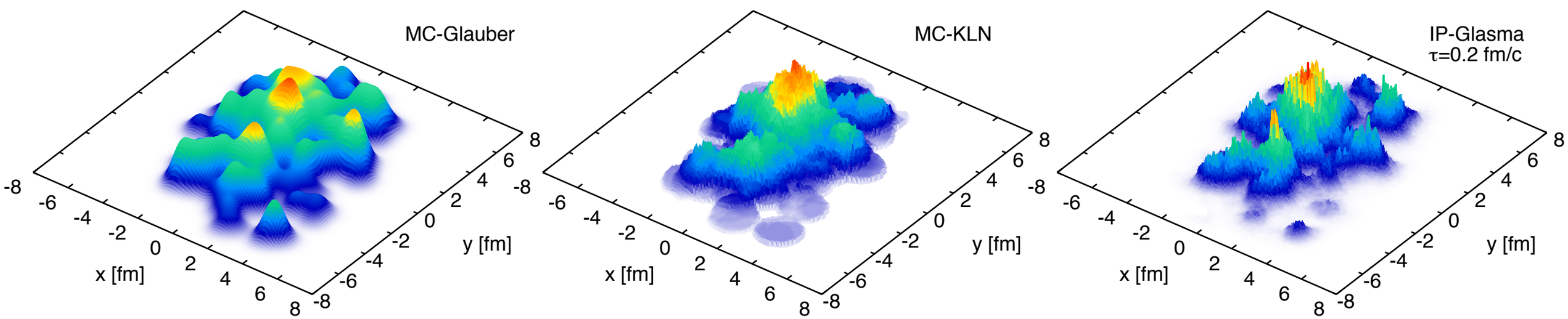
Initial conditions

- Models need to provide input for fluid dynamic simulations: initial energy density, flow velocities, shear stress tensor

- Initial conditions fluctuate from event to event
  no fluctuations, no odd harmonics like v_3

- Main source of fluctuations: nucleon positions

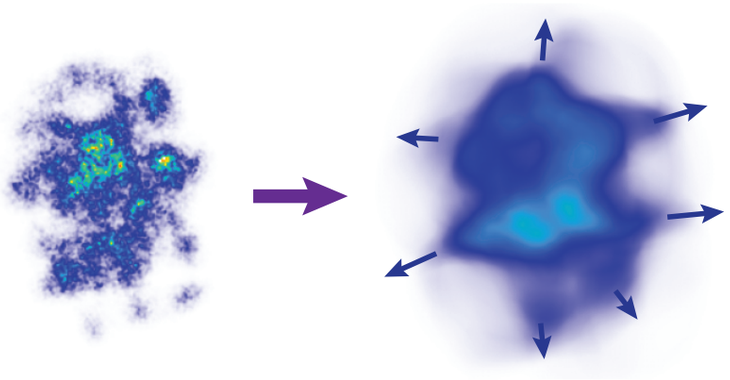
- Different models give different *energy density distributions*



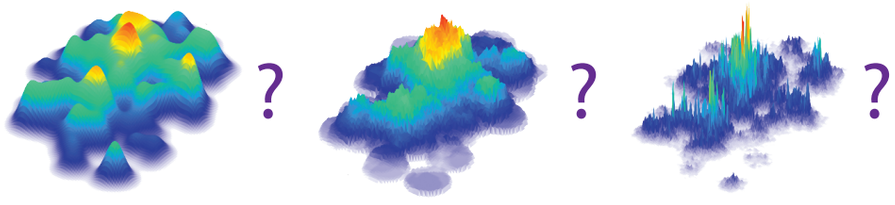
C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

Computing the initial state at high energies

Flow is driven by the initial geometry
Final result depends on what we start with

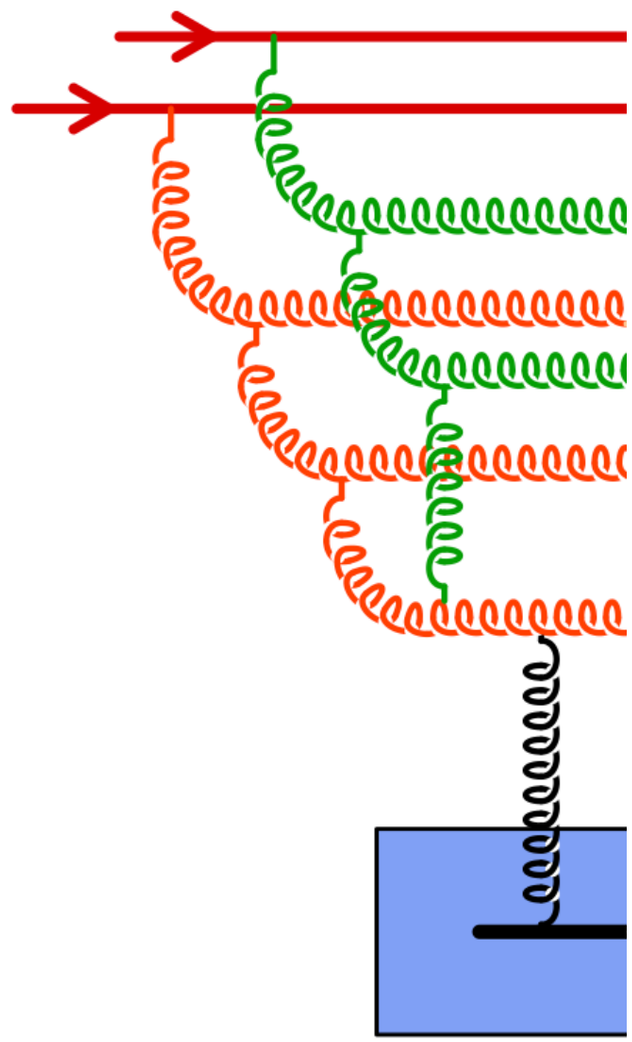


To learn about the medium we need rigorous understanding of the initial shape and its fluctuations



For high energy collisions we have achieved just that:
Instead of just a simple geometric model,
we can use **QCD in the high energy limit**
to calculate the initial state and its fluctuations

Nuclei at high energy: Gluon saturation



- Gluons that end up in central rapidity region: multiple splittings from valence quarks

- Eventually gluons in cascade overlap: Probability for recombination equal to splitting

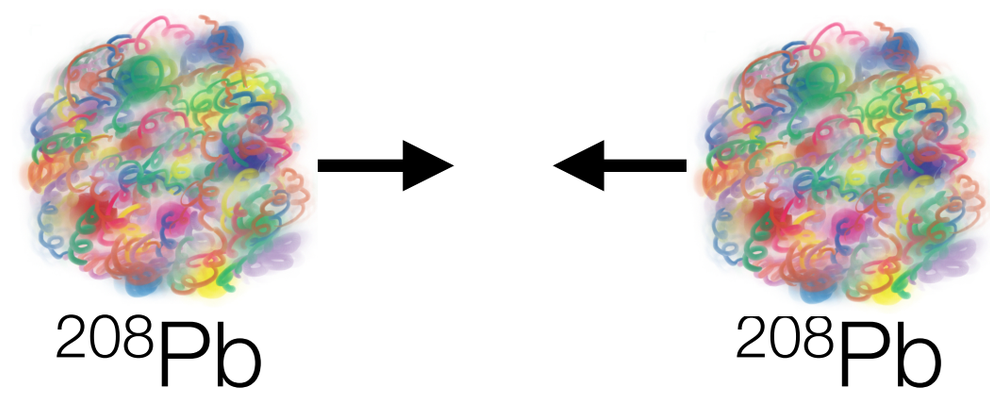
→ gluon saturation

Nuclei at high energy: Color glass condensate

Saturated regime: large occupation numbers: $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ with small α_s, which is true for $Q_S >> \Lambda_{QCD}$

Nuclear matter in this regime is called Color Glass Condensate

High energy heavy ion collisions are collisions of dense balls of gluons



⇒ At leading order we can use the classical field approximation

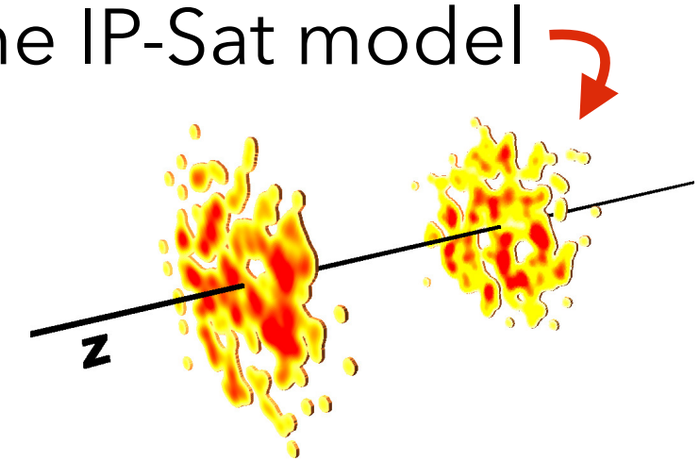
McLerran and Venugopalan, Phys.Rev. D49 (1994) 2233-2241

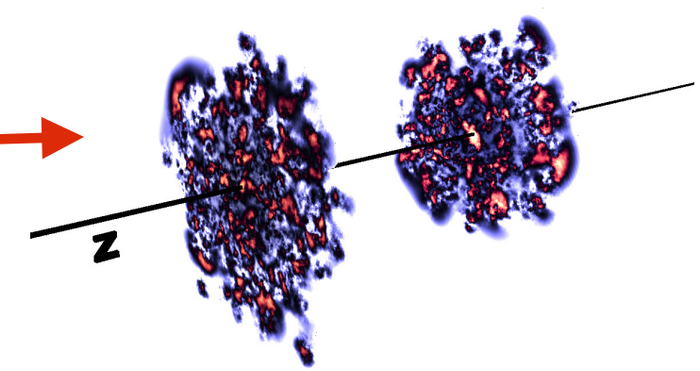
System created from two colliding CGCs is called Glasma

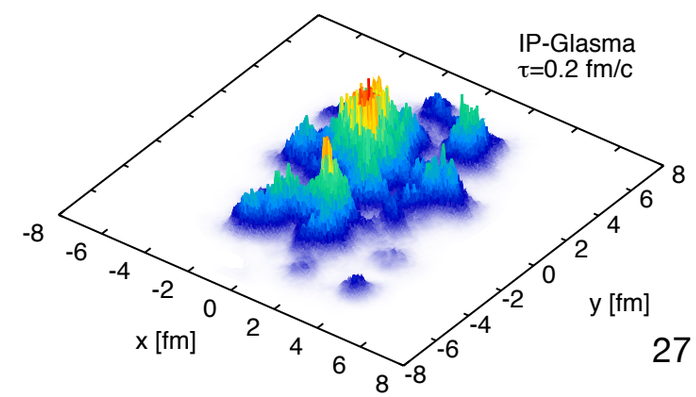
IP-Glasma initial conditions

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample nucleon positions from Woods-Saxon distribution
- Determine color charge distribution using the IP-Sat model
  H. Kowalski and D. Teaney, Phys.Rev. D68 (2003) 114005
- Sample color charges from that distribution
- Yang-Mills equations determine:
  - Initial gluon fields from color charges
    Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237
  - Early non-equilibrium time evolution
- Then match fields' $T^{\mu\nu}$ to hydrodynamics
  Here assumption of thermalization enters







Relativistic viscous fluid dynamics

For every fluctuating initial condition solve

energy density pressure

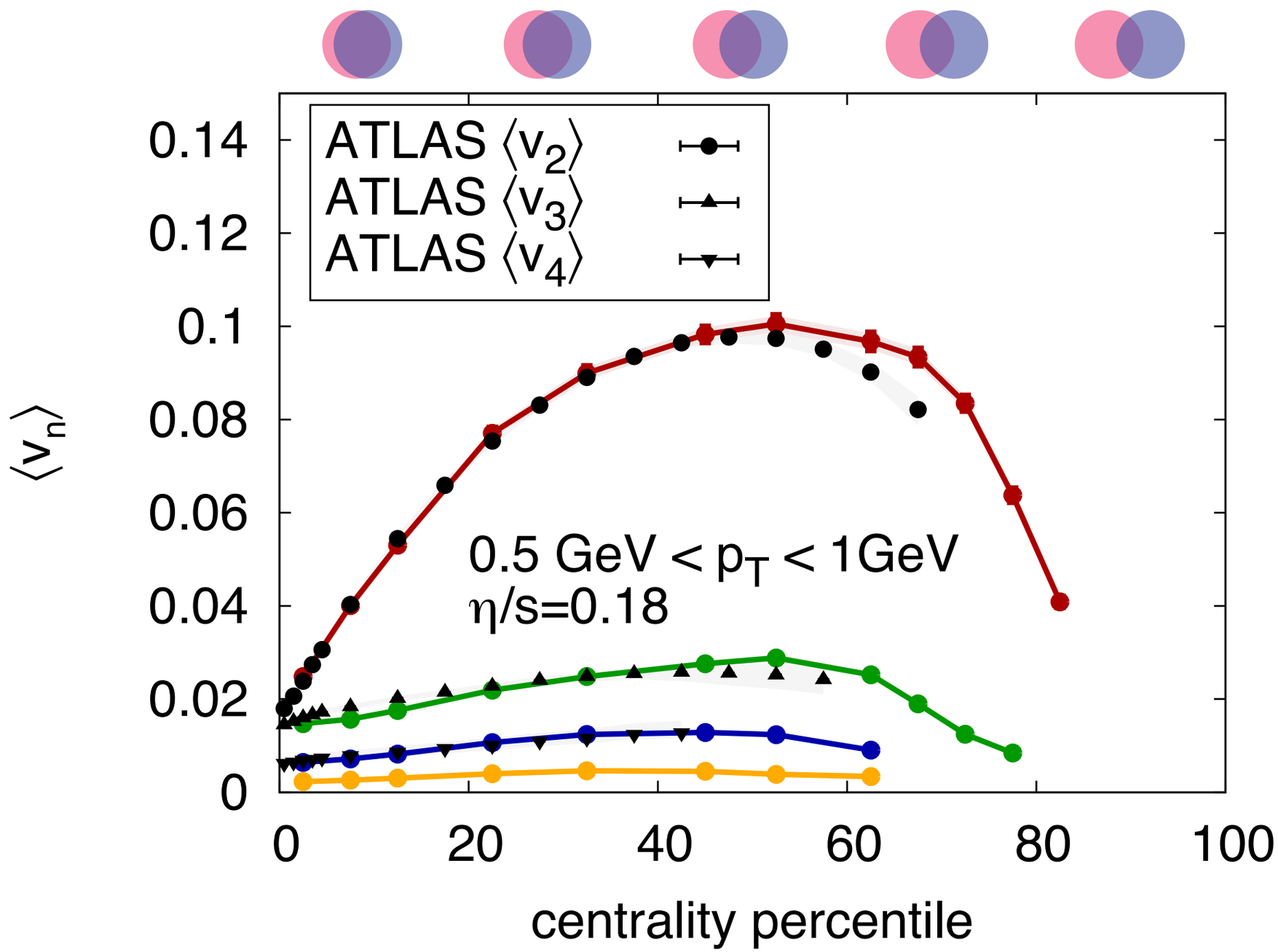
$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P) u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

flow velocity viscous correction

- and constituent equations for $\Pi^{\mu\nu}$
- Equation of state $P(\varepsilon)$ from lattice QCD:
  Contains Quark Gluon Plasma and hadron gas phase
- When temperature drops beyond a certain threshold
  freeze out particles, compute spectra, decay resonances

Results in Pb+Pb collisions: v_n of charged hadrons

Experimental Data: ATLAS Collaboration, JHEP 1311 (2013) 183
B.Schenke, R.Venugopalan, Phys. Rev. Lett. 113 (2014) 102301



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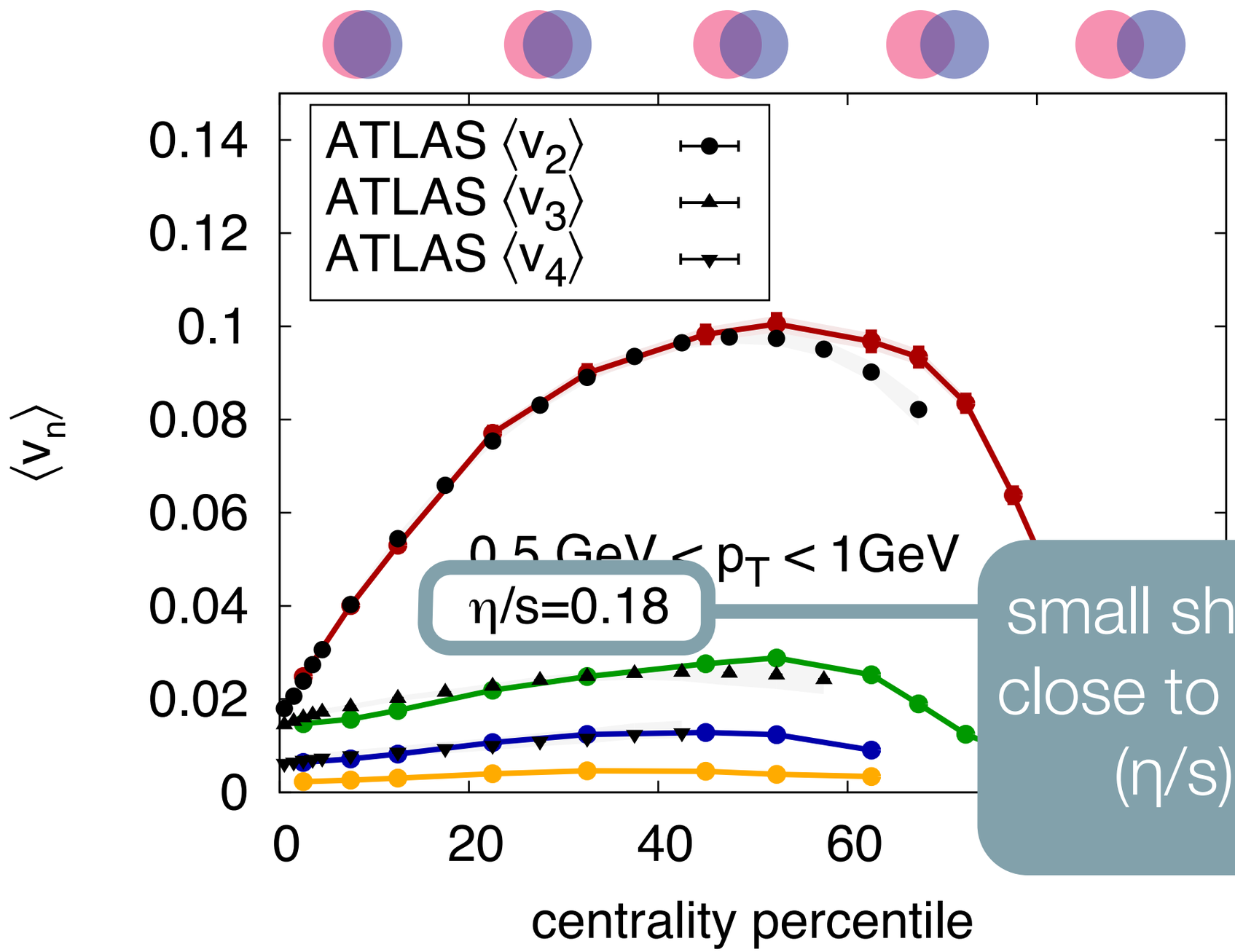
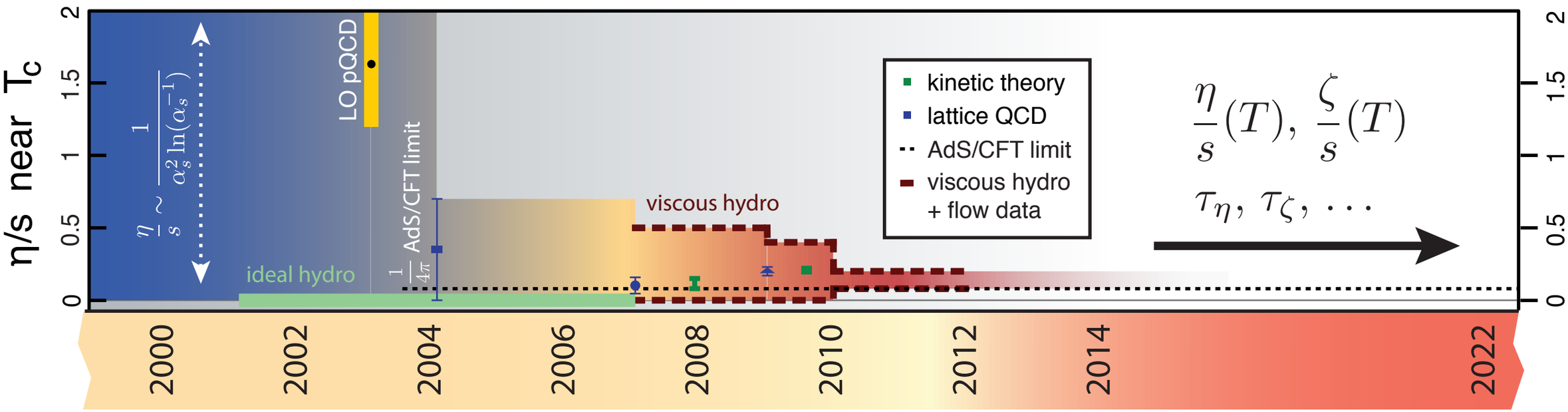


small shear viscosity close to lower bound $(\eta/s)_{min}=1/4\pi$

Our knowledge about the shear viscosity over time

Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



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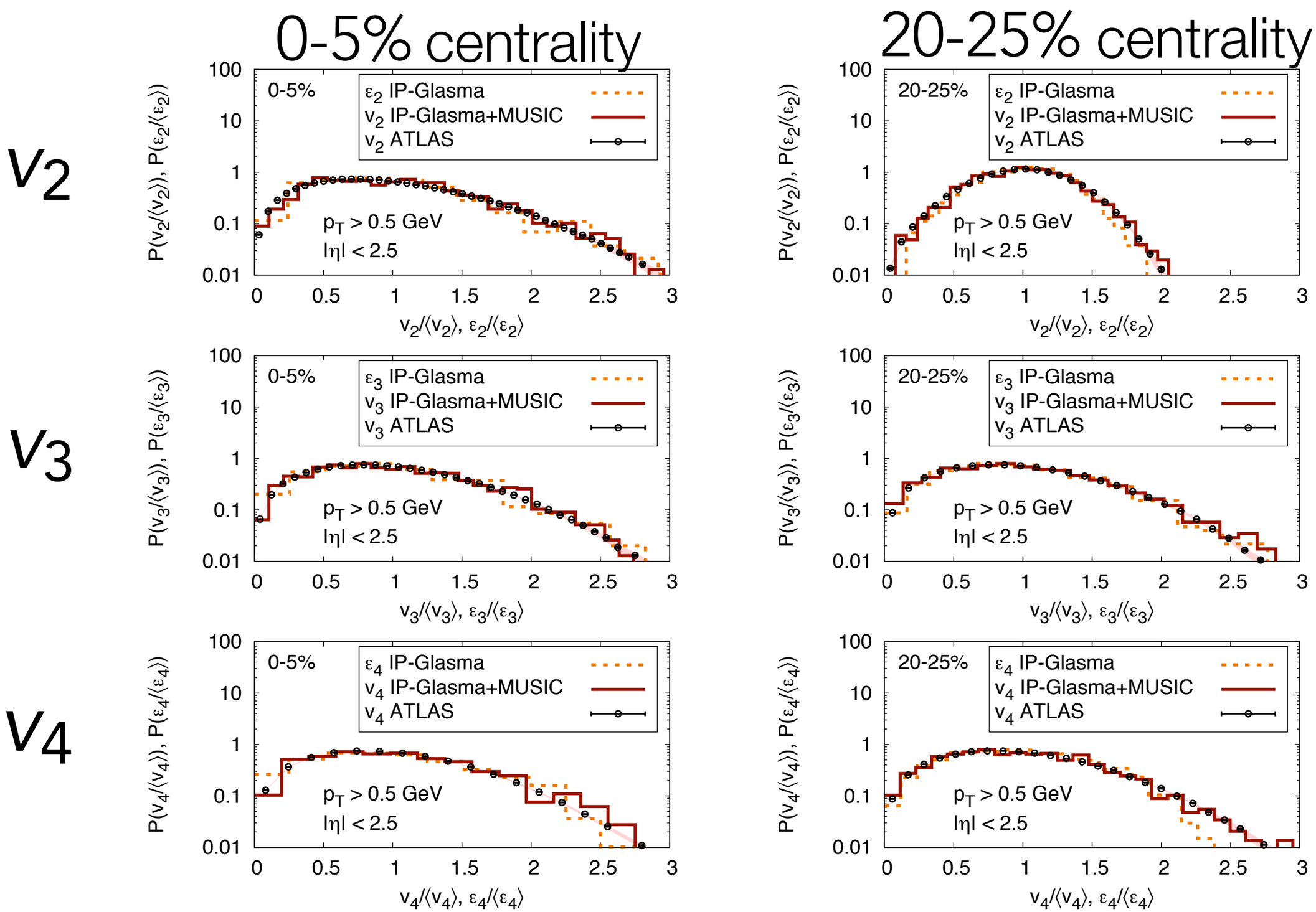
Event-by-event distributions of v_n

ATLAS Collaboration, JHEP 1311 (2013) 183
B.Schenke, R.Venugopalan, Phys. Rev. Lett. 113 (2014) 102301



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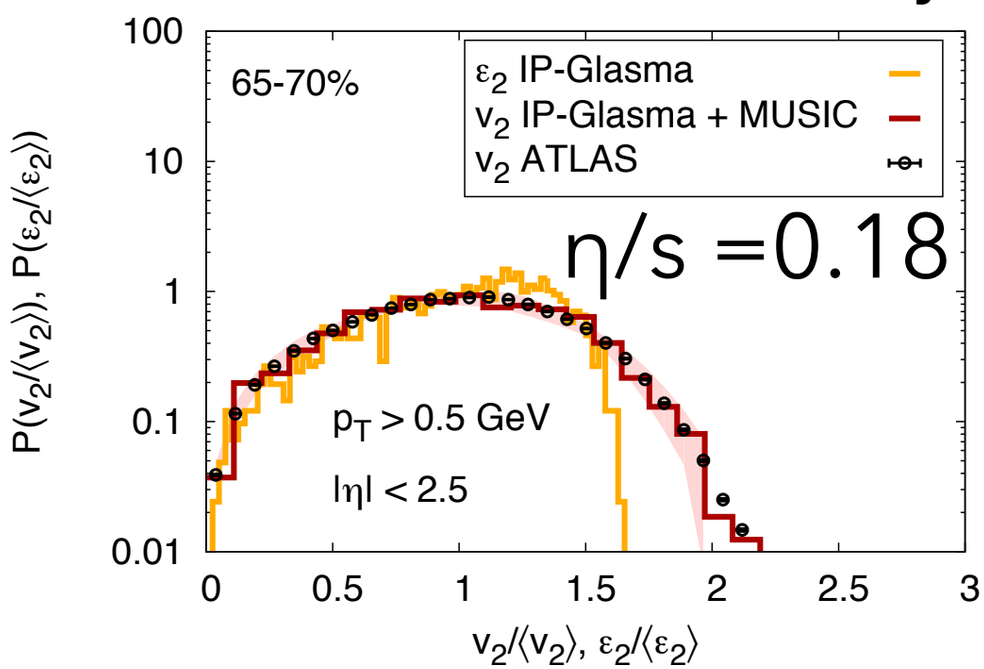
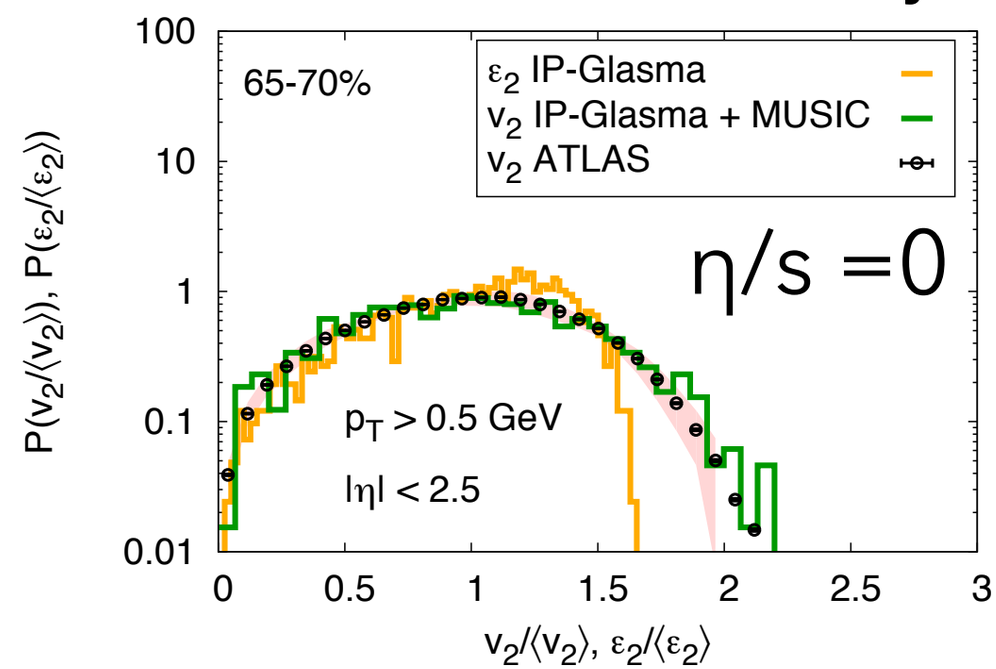
v_2

65-70% centrality



65-70% centrality



Non-linearities in hydrodynamics are important

But independent of the shear viscosity!

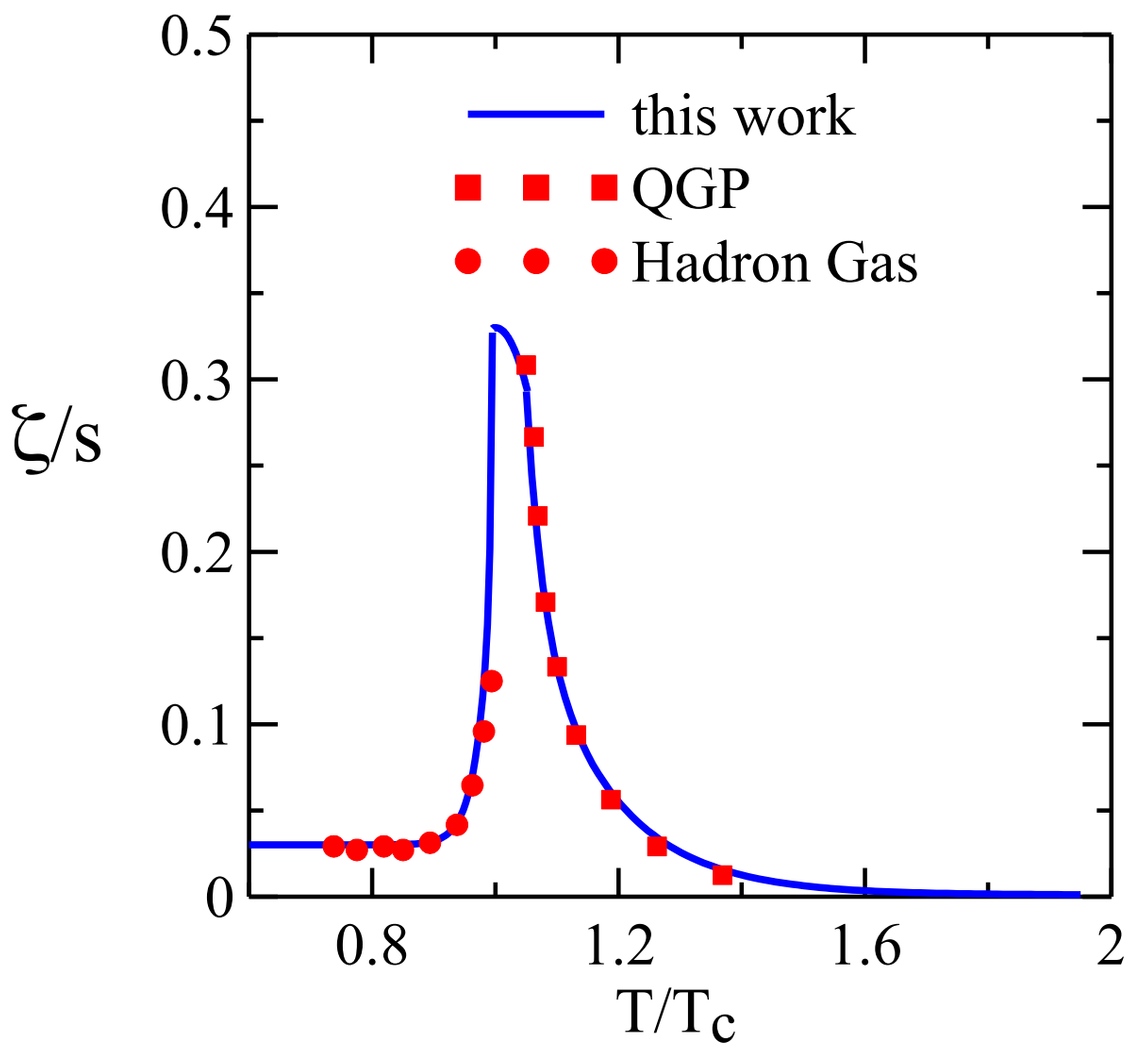
→ Can constrain initial state and its fluctuations

Bulk viscosity and hadronic cascade

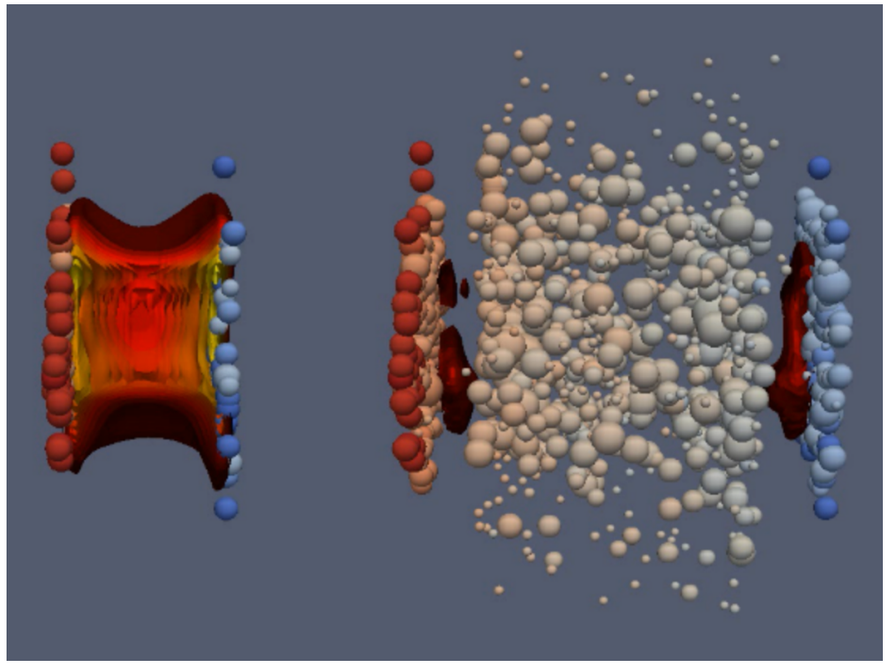
S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, arXiv:1502.01675 (2015), PRL, in print

Latest improvements consider more physics:

Bulk viscosity **ζ/s** should be non-zero



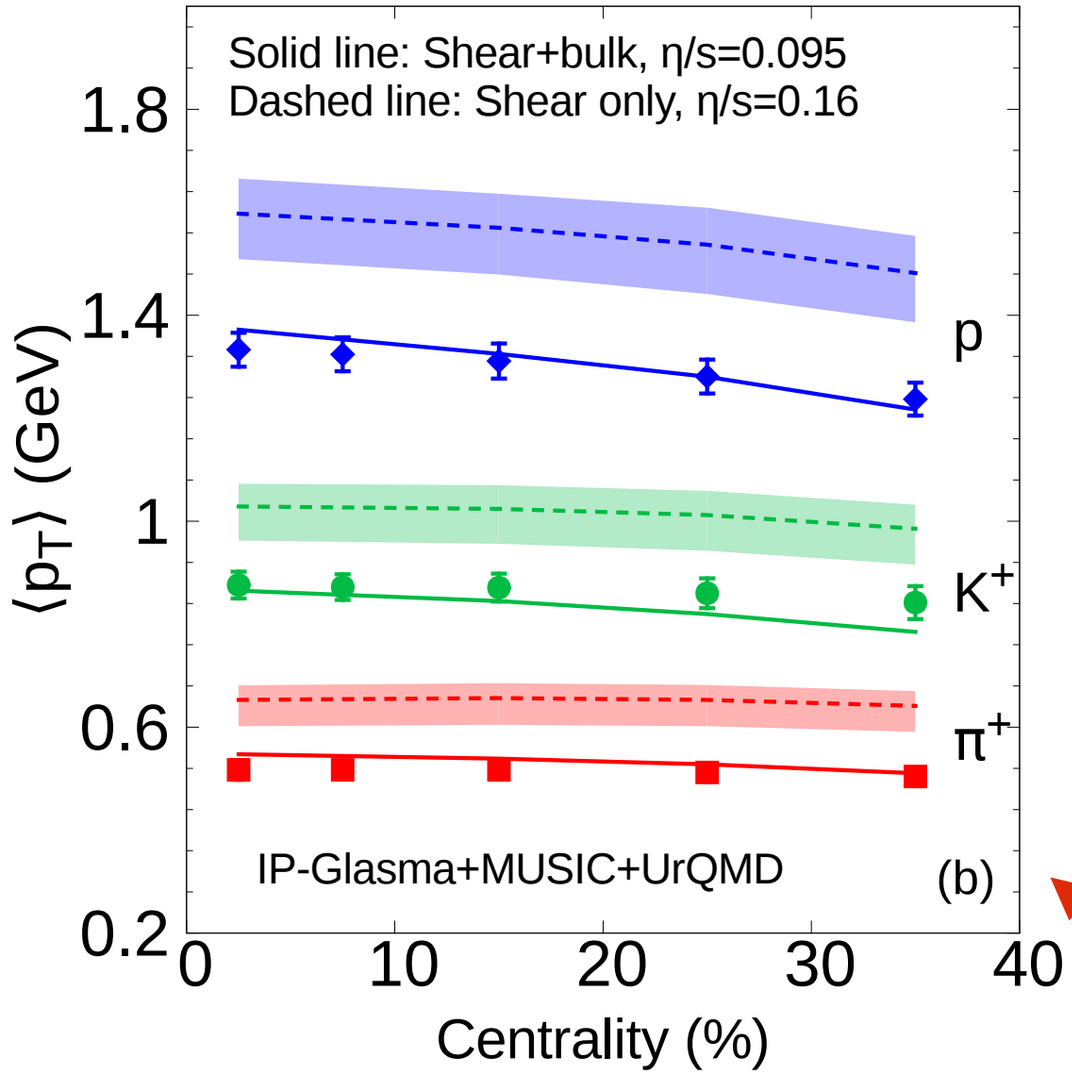
Evolution in the dilute regime is better described by microscopic transport

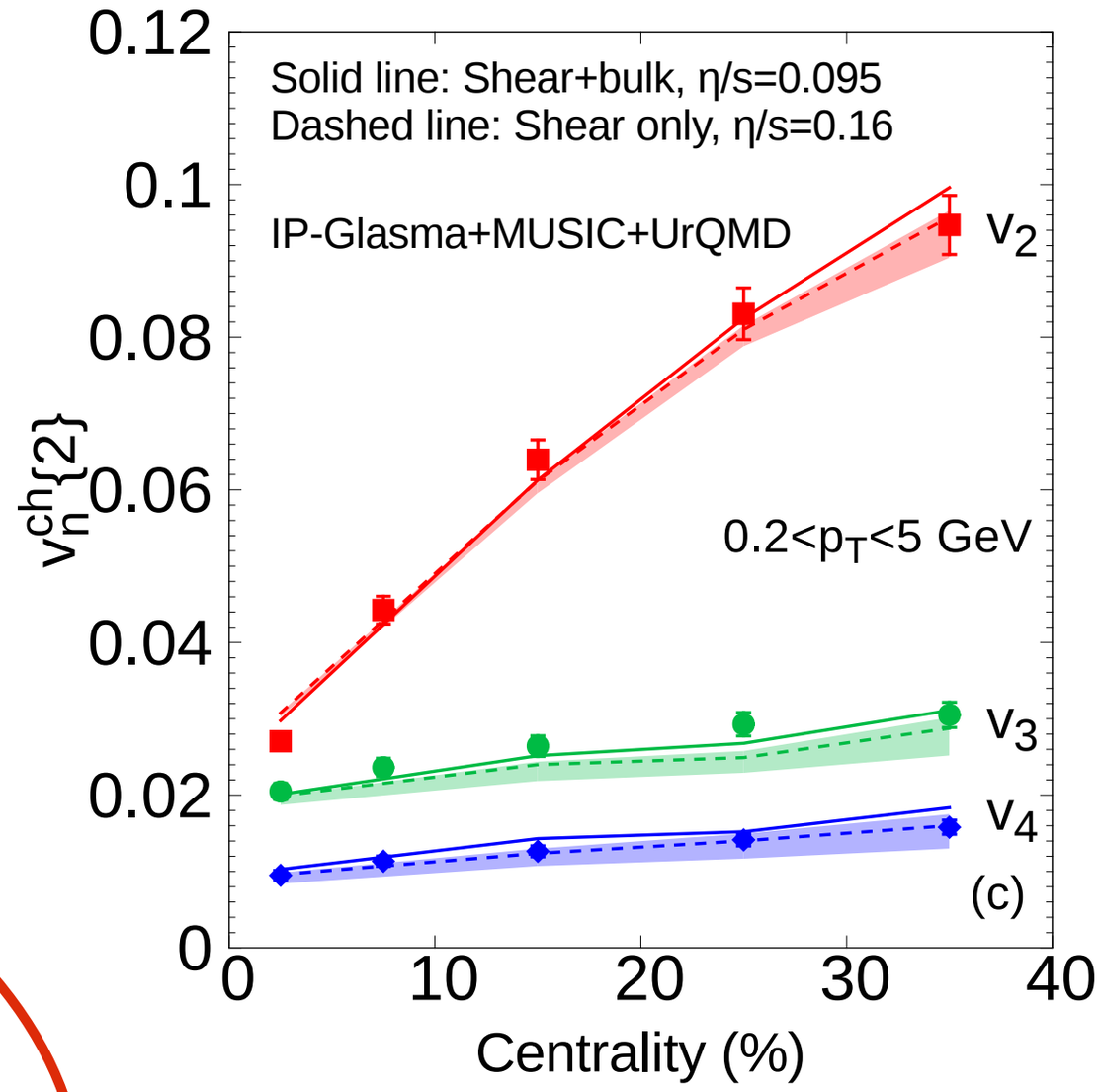


Credit: MADAI.us

Effect of bulk viscosity

S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, arXiv:1502.01675 (2015), PRL, in print





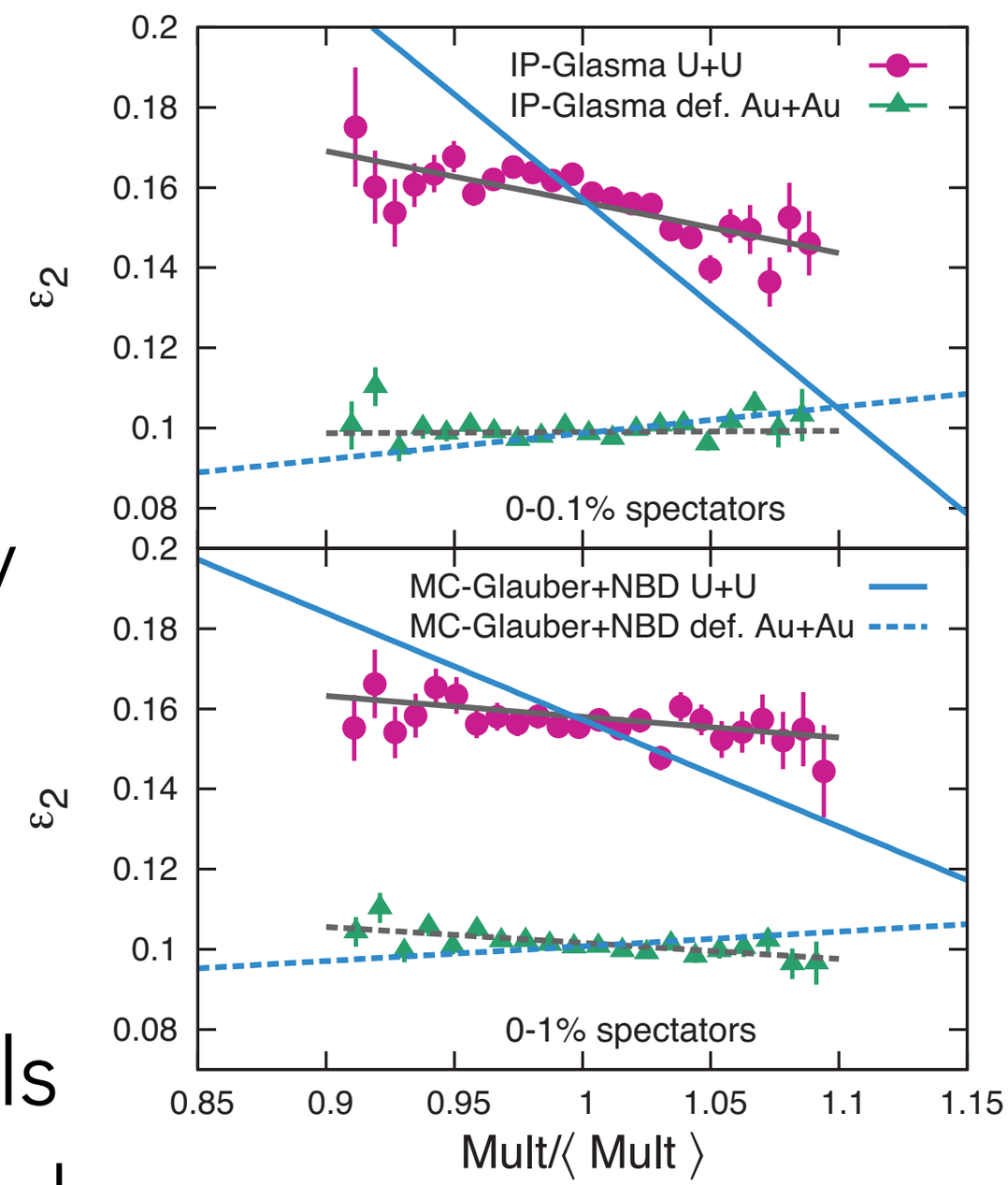
Main effect of bulk viscosity:
Slow down expansion - reduce mean transverse momentum

Experimental data: ALICE collaboration, Phys.Rev. C88 (2013) 044910; Phys.Rev.Lett. 107 (2011) 032301

Shape matters: Deformed nuclei

B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)

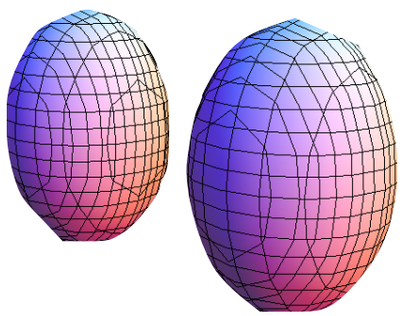
- Select ultra-central events based on neutrons in the ZDC
- Study correlation between v_2 and multiplicity
- Correlations are expected because nuclei are deformed
- Different initial state models predict different degree and even sign of the correlation



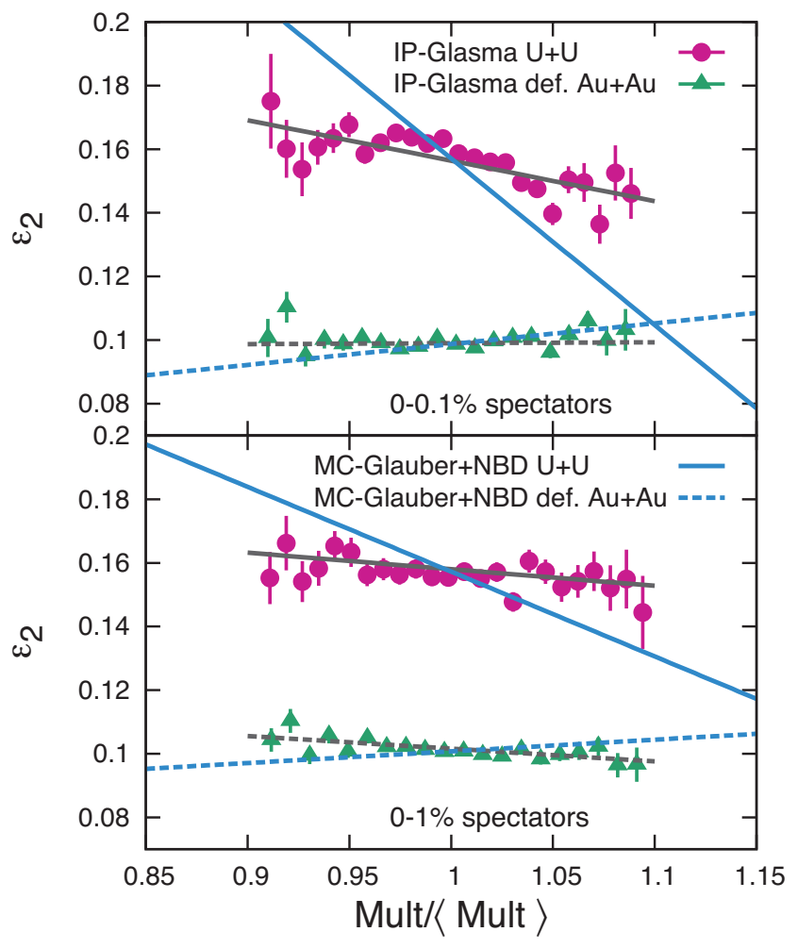
Deformed Nuclei

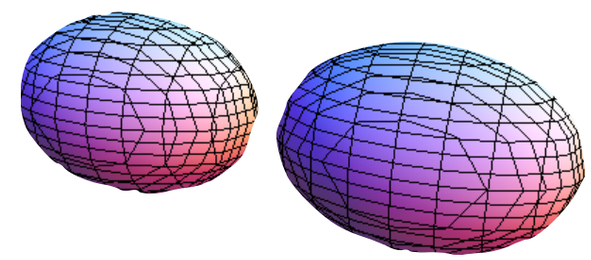
B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)

- Uranium: prolate
- Gold: oblate

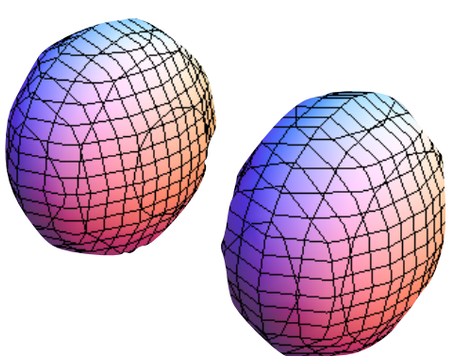


U+U, side-side

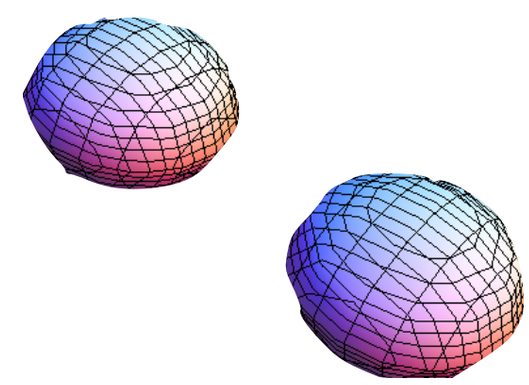




U+U, tip-tip



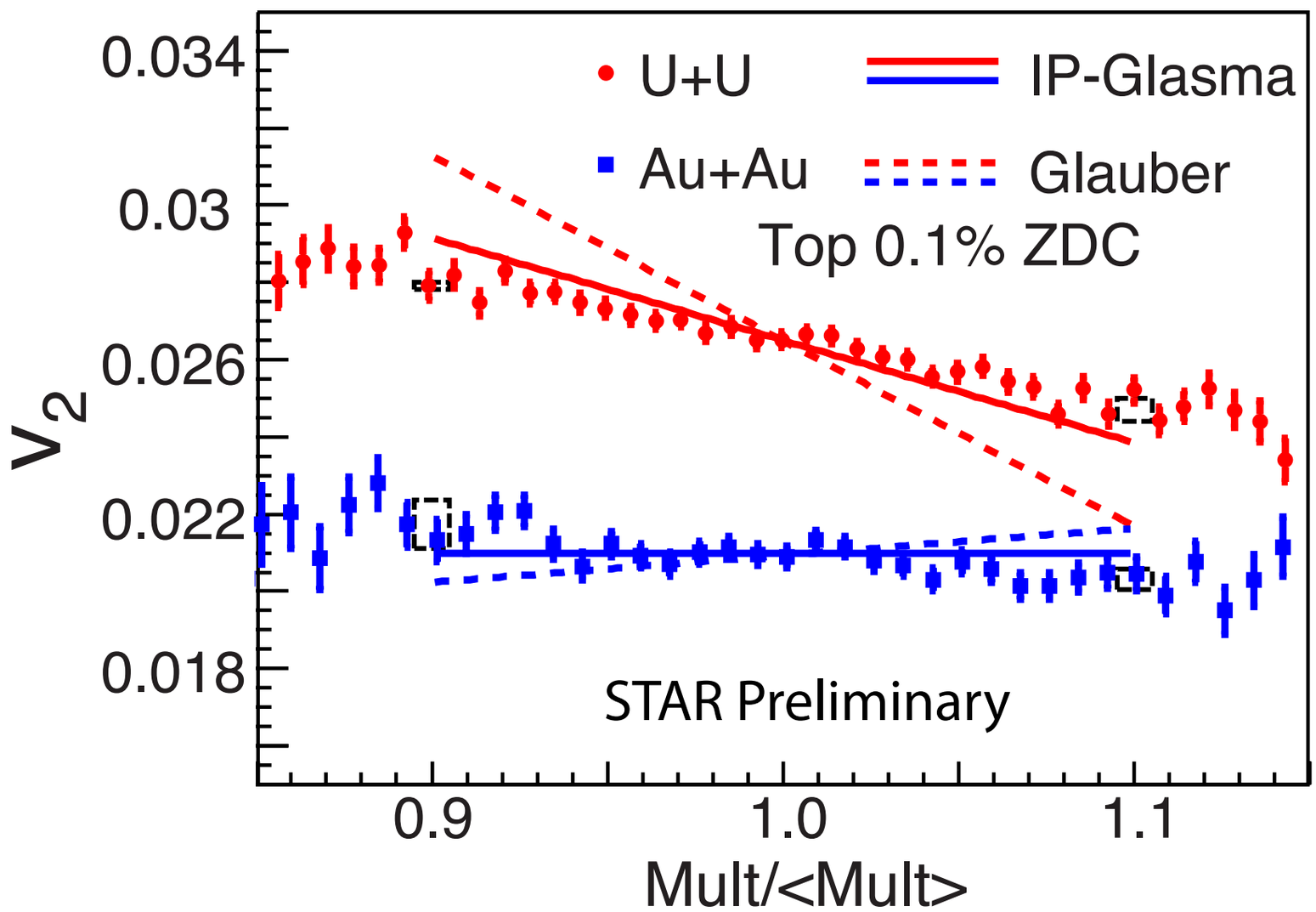
Au+Au, side-side



Au+Au, “tip-tip”

Testing the initial state model in U+U collisions

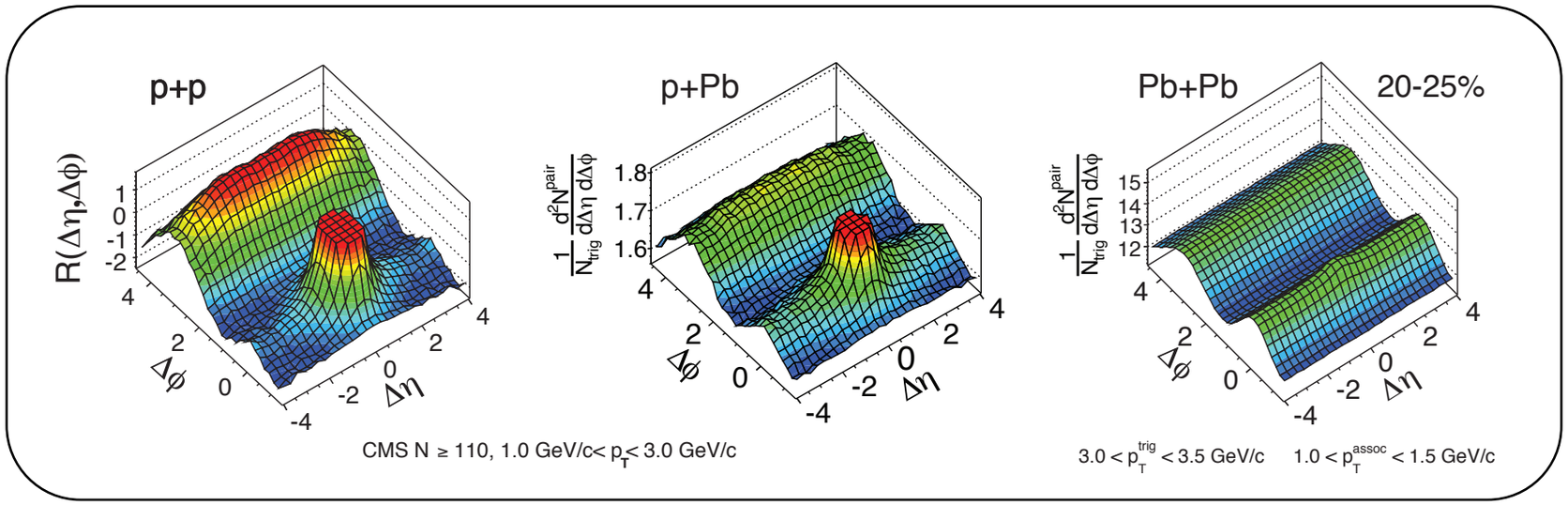
B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)
Experimental Data: STAR Collaboration, H. Wang, Nucl. Phys. A (in press, 10.1016/j.nuclphysa.2014.08.086)



Ultra-central collisions of deformed nuclei distinguish between different models of particle production

Small systems p+p, p+A, d+A, ^{3}He+A

- High multiplicity p+p and p+Pb collisions at LHC show similar features as Pb+Pb collisions (ridge, v_n)

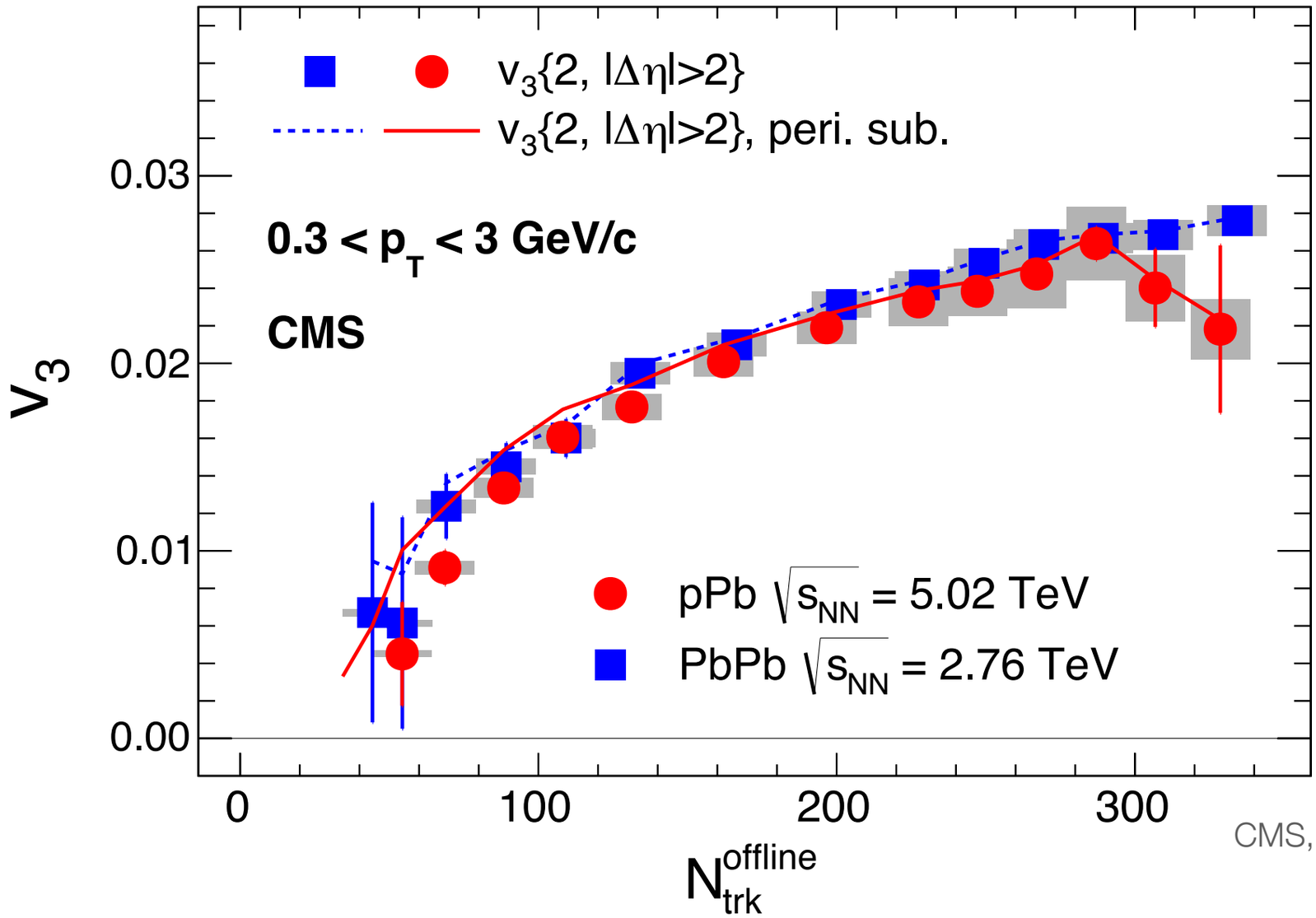


- Interpretation not yet clear:
  - Initial geometry + collective effects? Fluid dynamics?
  - Correlations present in the initial state?

CMS: JHEP 1009 (2010) 091, Phys.Lett. B718 (2013) 795-814, JHEP 1107 (2011) 076 , Eur.Phys.J. C72 (2012)

The experimental data was surprising:

- Similarity of experimental data in p+A and A+A collisions



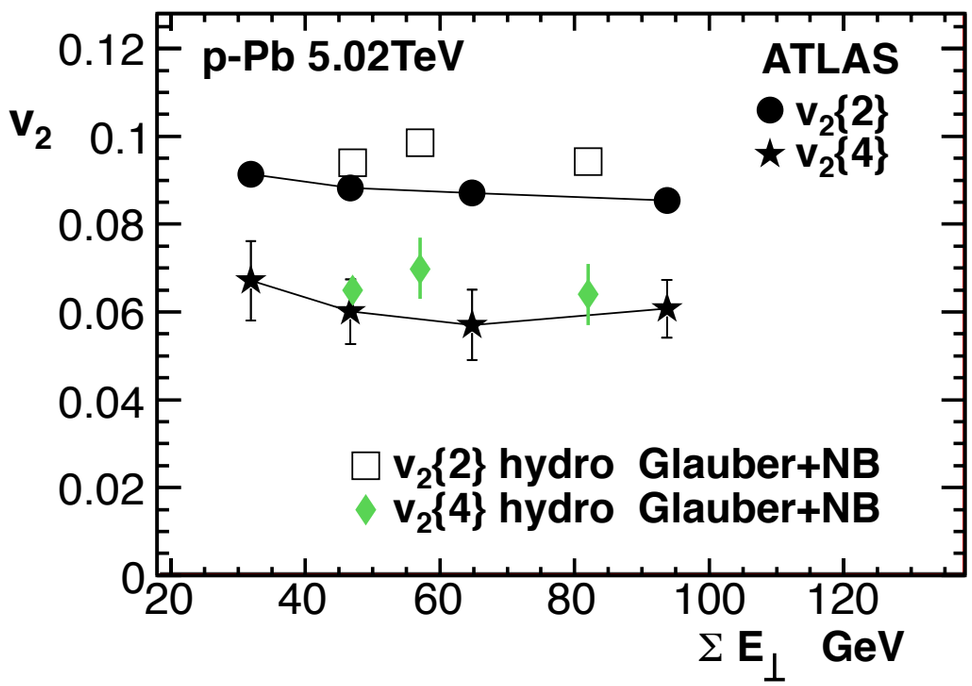
CMS, Phys. Lett. B 724 (2013) 213

see also
ALICE Coll., Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901
ATLAS Coll., Phys. Rev. Lett. 110, 182302 (2013), Phys. Lett. B 725 (2013) 60-78 , Phys. Rev. C 90.044906 (2014)
CMS Coll., arXiv:1502.05382

Different initial states: very different results

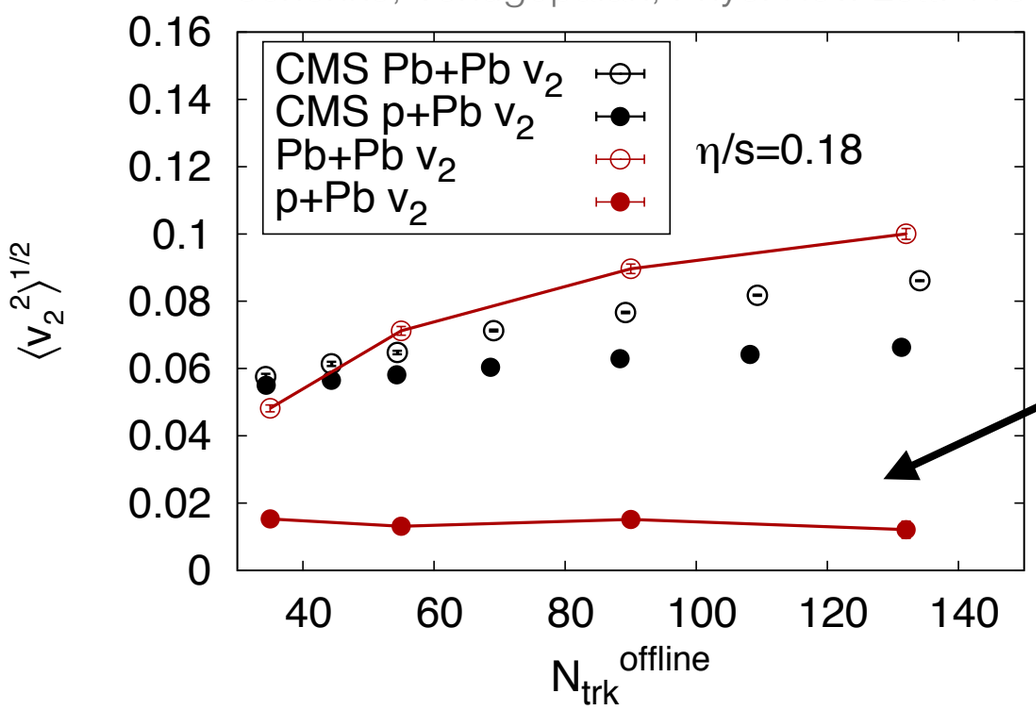
Model A (MC Glauber)

Bozek, Broniowski, Phys.Rev. C88 (2013) 014903

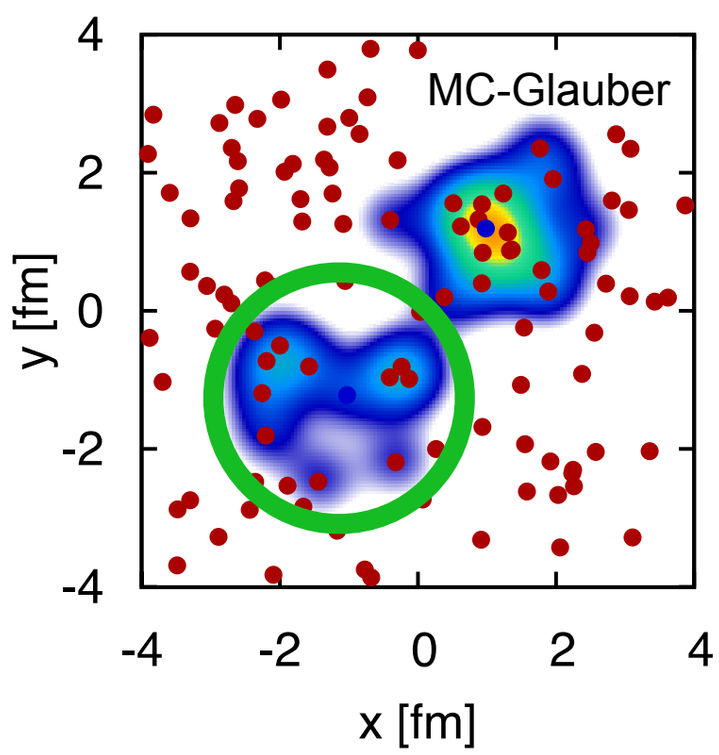


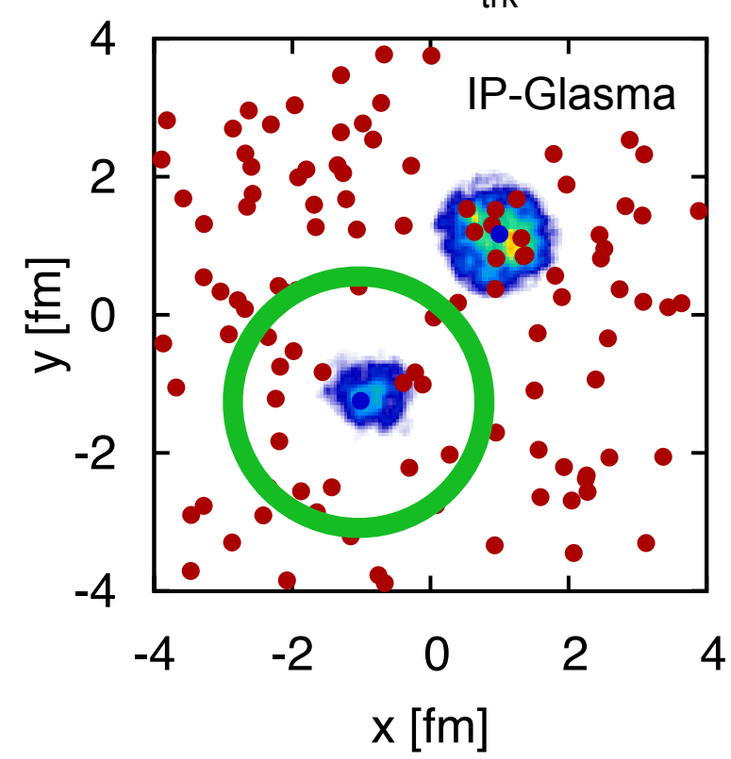
Model B (IP Glasma)

Schenke, Venugopalan, Phys. Rev. Lett. 113 (2014) 102301



p+Pb

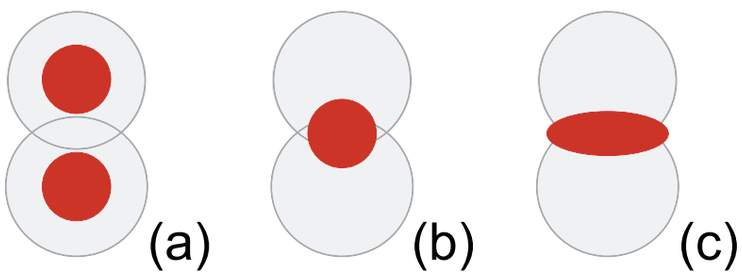




d+Au

Issues in small systems (p+p, p+A)

- MC-Glauber does not constrain energy density dist.



Where do we put the energy?

What shape does it have?

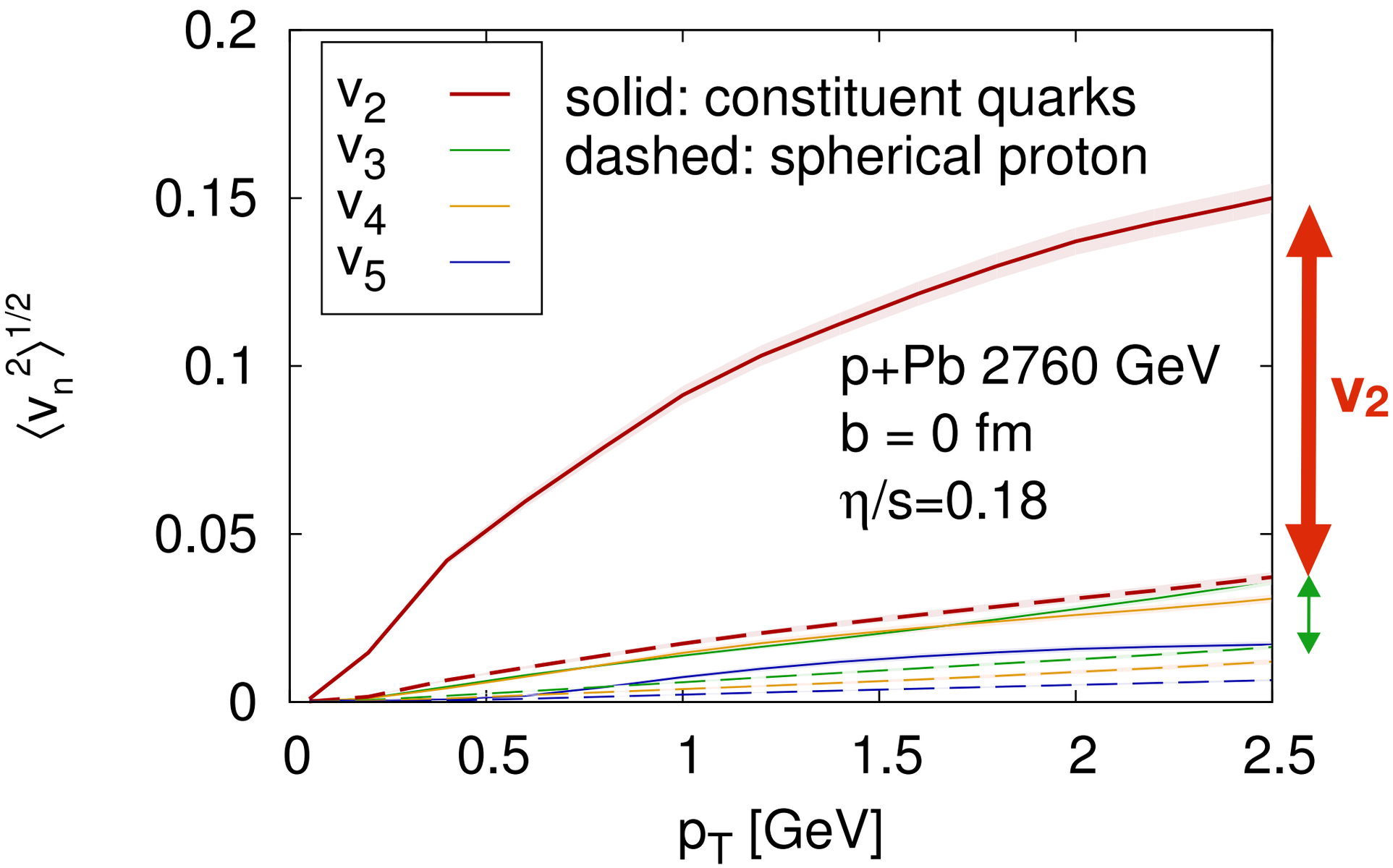
- IP-Glasma constrains energy density deposition

  However, it does not describe v_n in p+Pb

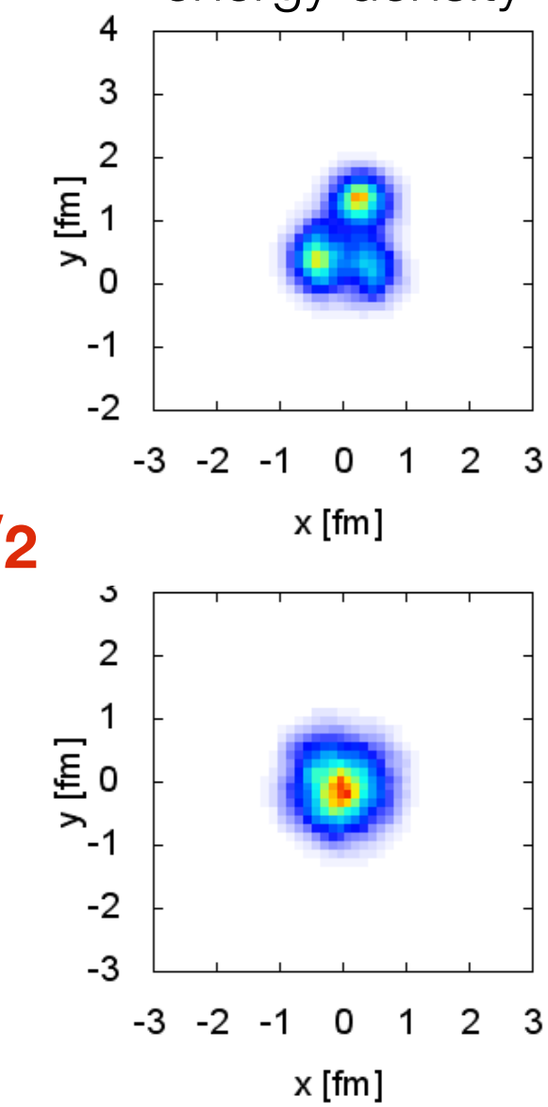
- Proton substructure should matter
- Give the proton some substructure, e.g. three denser regions representing valence quarks

S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)

Are we sensitive to the shape of the proton?



initial energy density



If there is flow in p+A collisions
we can see the fluctuating shape of the proton!

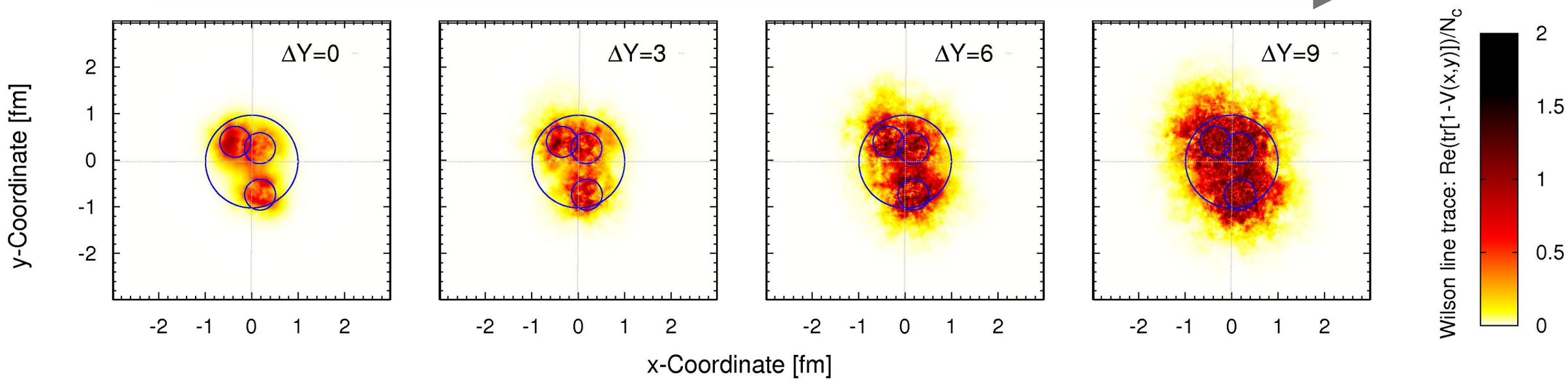
Isn't a proton at high energy pretty spherical?

S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)

- Three "Constituent quarks" at large *x*
- JIMWLK evolution to get gluon distribution at smaller *x*

J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Nucl. Phys. B504, 415 (1997), Phys. Rev. D59, 014014 (1999)
E. Iancu, A. Leonidov, and L. D. McLerran, Nucl. Phys. A692, 583 (2001)
E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A703, 489 (2002)
A. H. Mueller, Phys. Lett. B523, 243 (2001)

JIMWLK evolution: decreasing *x*



Hadron radius grows linearly with rapidity - "Gribov diffusion"
But even at small *x* the proton is not a sphere of gluons

But be careful with hydrodynamics…

H. Niemi, G.S. Denicol, e-Print: arXiv:1404.7327

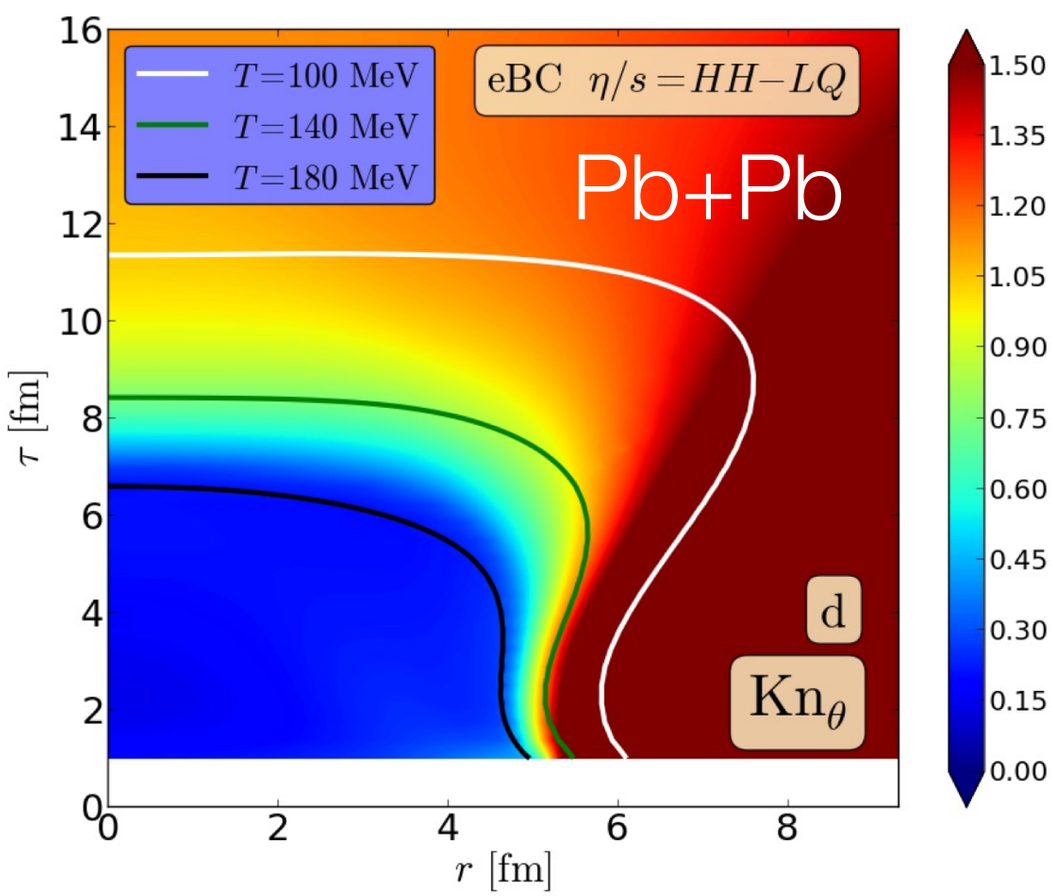
- Use the Knudsen number as a measure

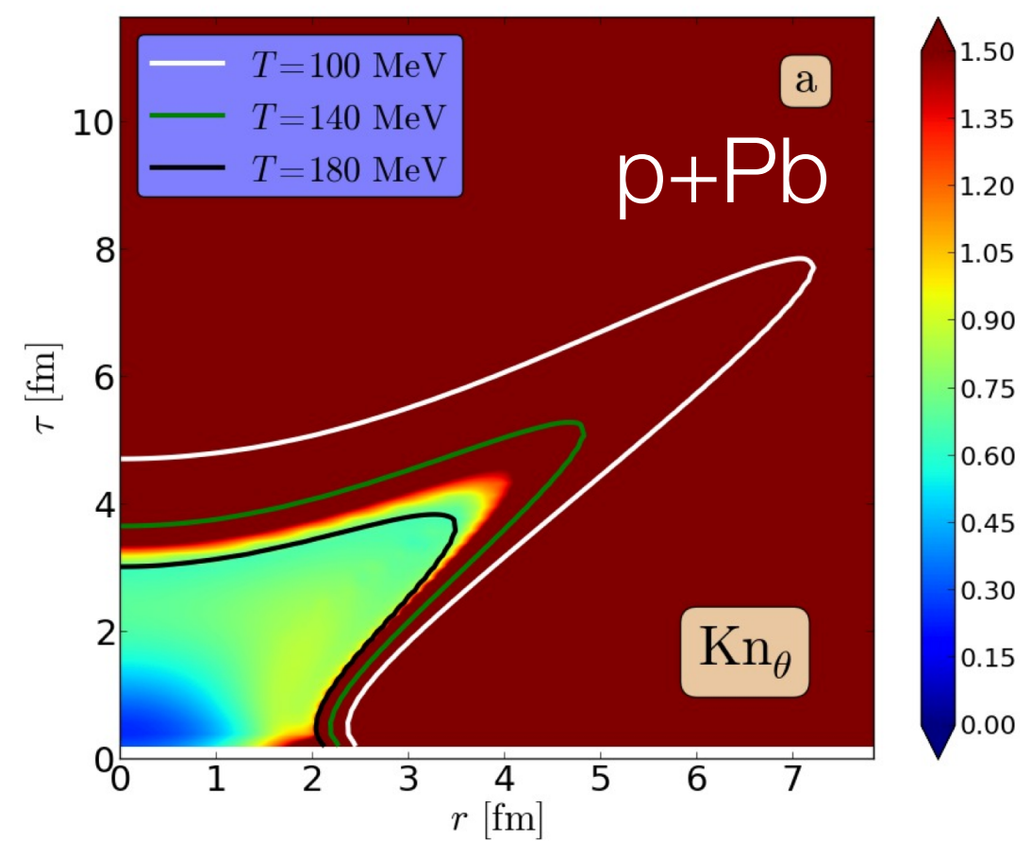
  $Kn_\theta = l_{\mathrm{micro}}/L^{\theta}_{\mathrm{macro}} = \tau_\pi/\theta$ (this is one specific choice)

  where τ_π is the shear relaxation time and $\theta = \partial_\mu u^\mu$

- Small Knudsen number (blue) means fluid dynamics is valid

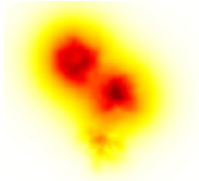
Temperature dependent η/s

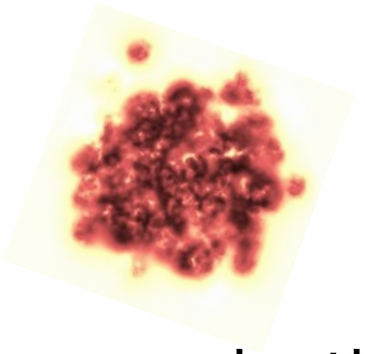




v_n p+Pb without hydrodynamics

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

Proton: Gluons located around constituent quarks 

Nucleus: IP-Glasma model 

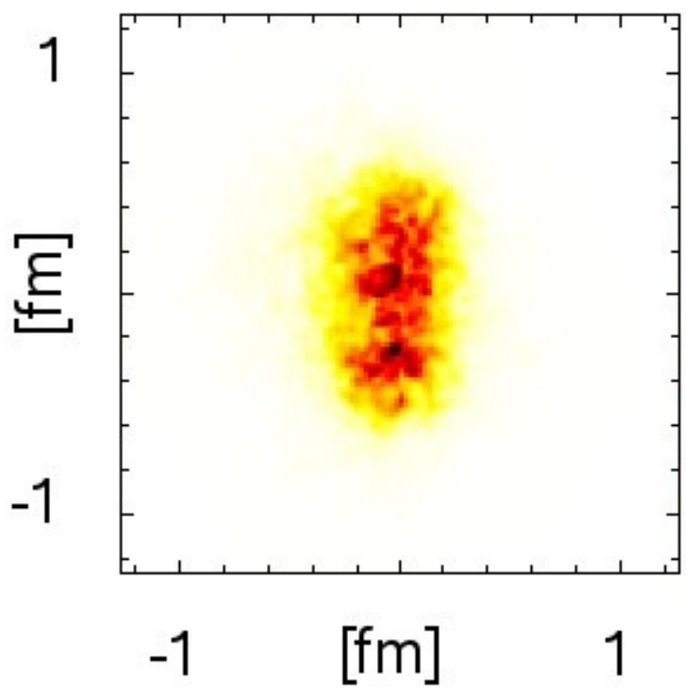
- Solve Yang-Mills equations as in the IP-Glasma model
- Extract gluon momentum distribution from field configuration in Coulomb gauge
- Compute pair distribution in angular difference $\Delta\Phi$
- Extract v_n

Initial state properties immediately after the collision

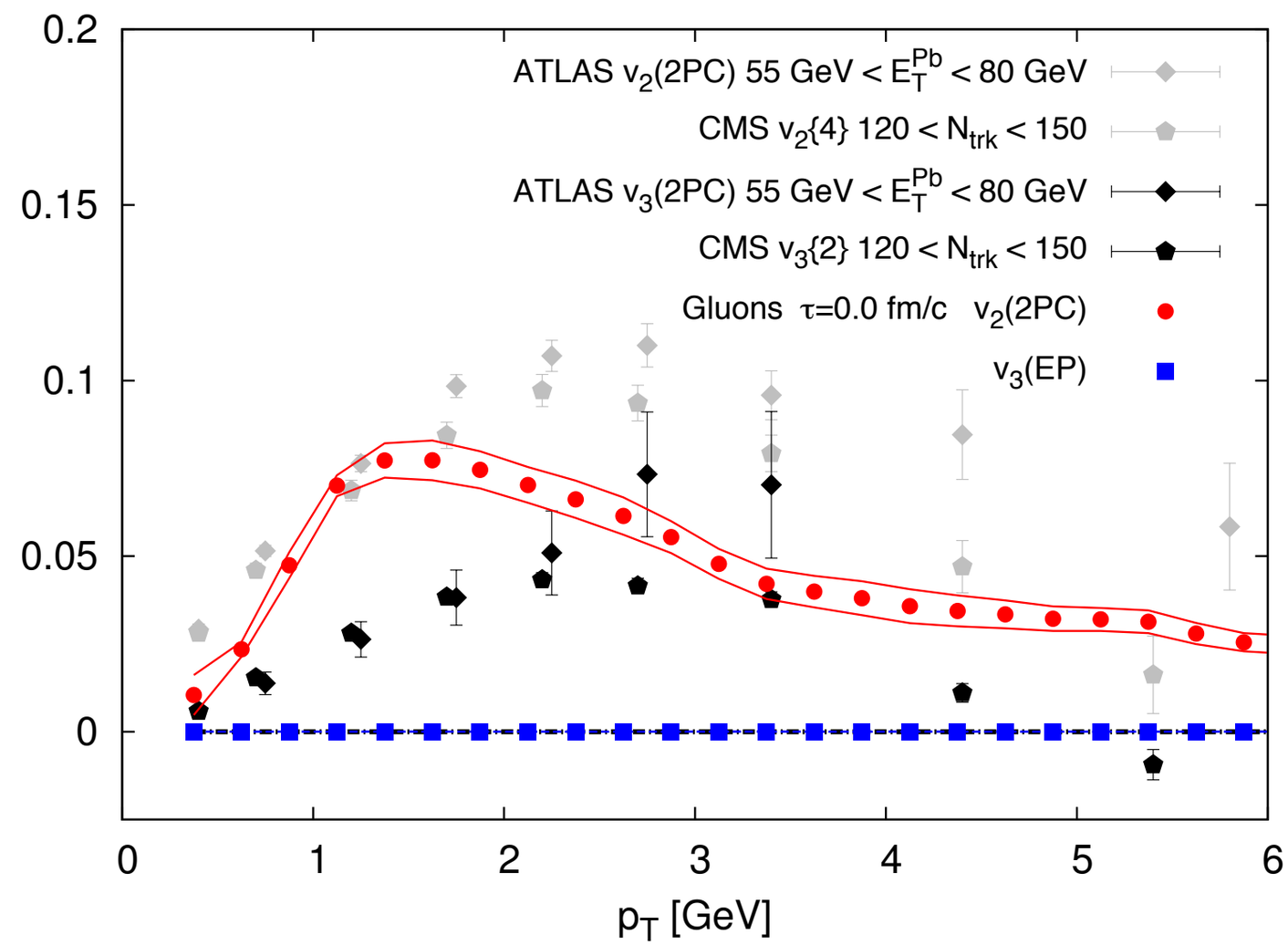
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.0 fm/c

Energy density profile
(single event)



Fourier harmonics *(gluons)*



Significant v_2 at time 0^+ - this is an intrinsic correlation

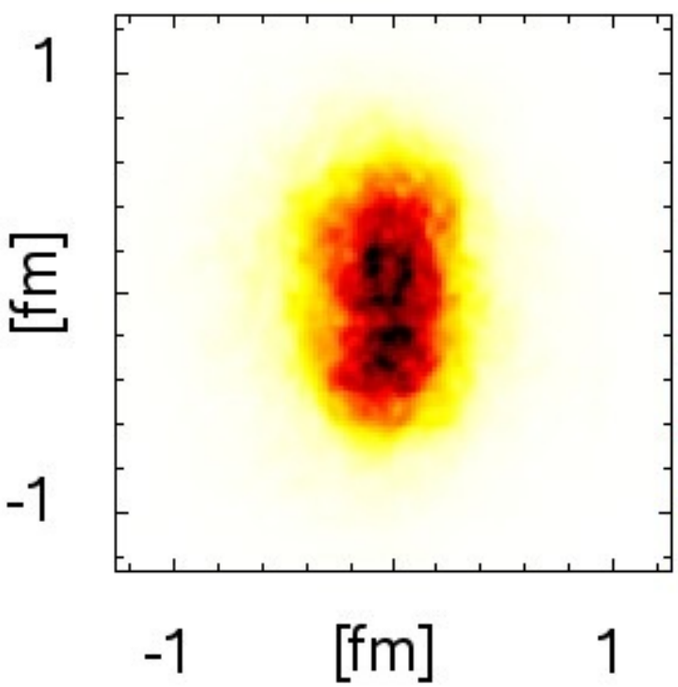
Due to domains of color fields that have particular directions

Initial state properties immediately after the collision

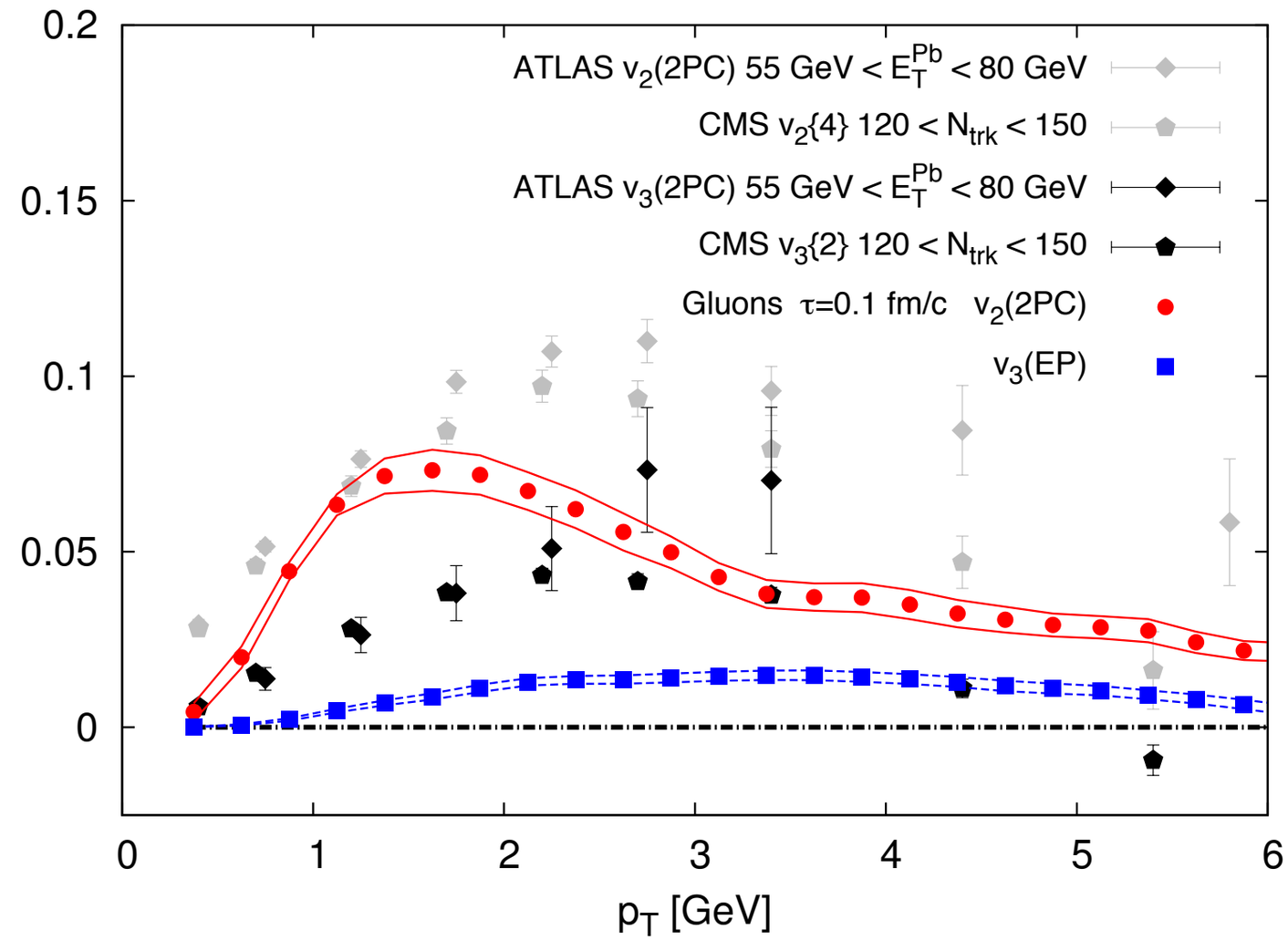
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.1 fm/c

Energy density profile
(single event)



Fourier harmonics *(gluons)*

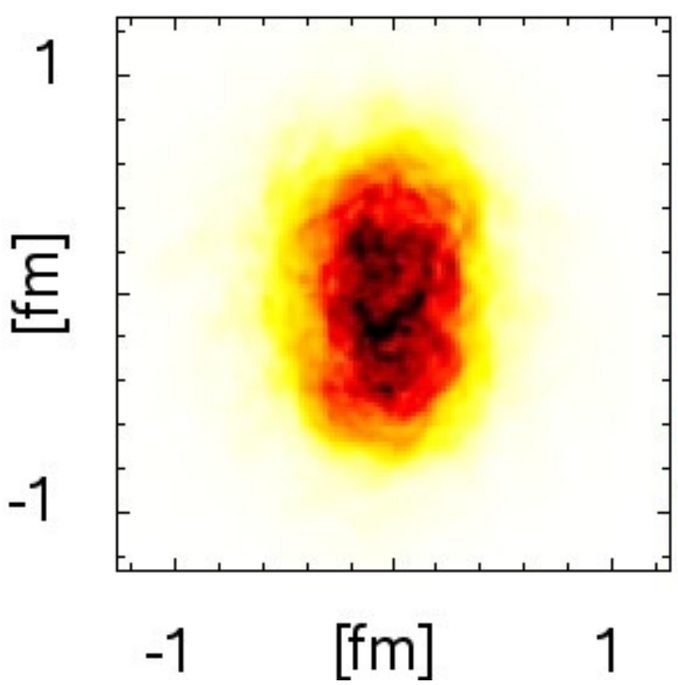


Initial state properties immediately after the collision

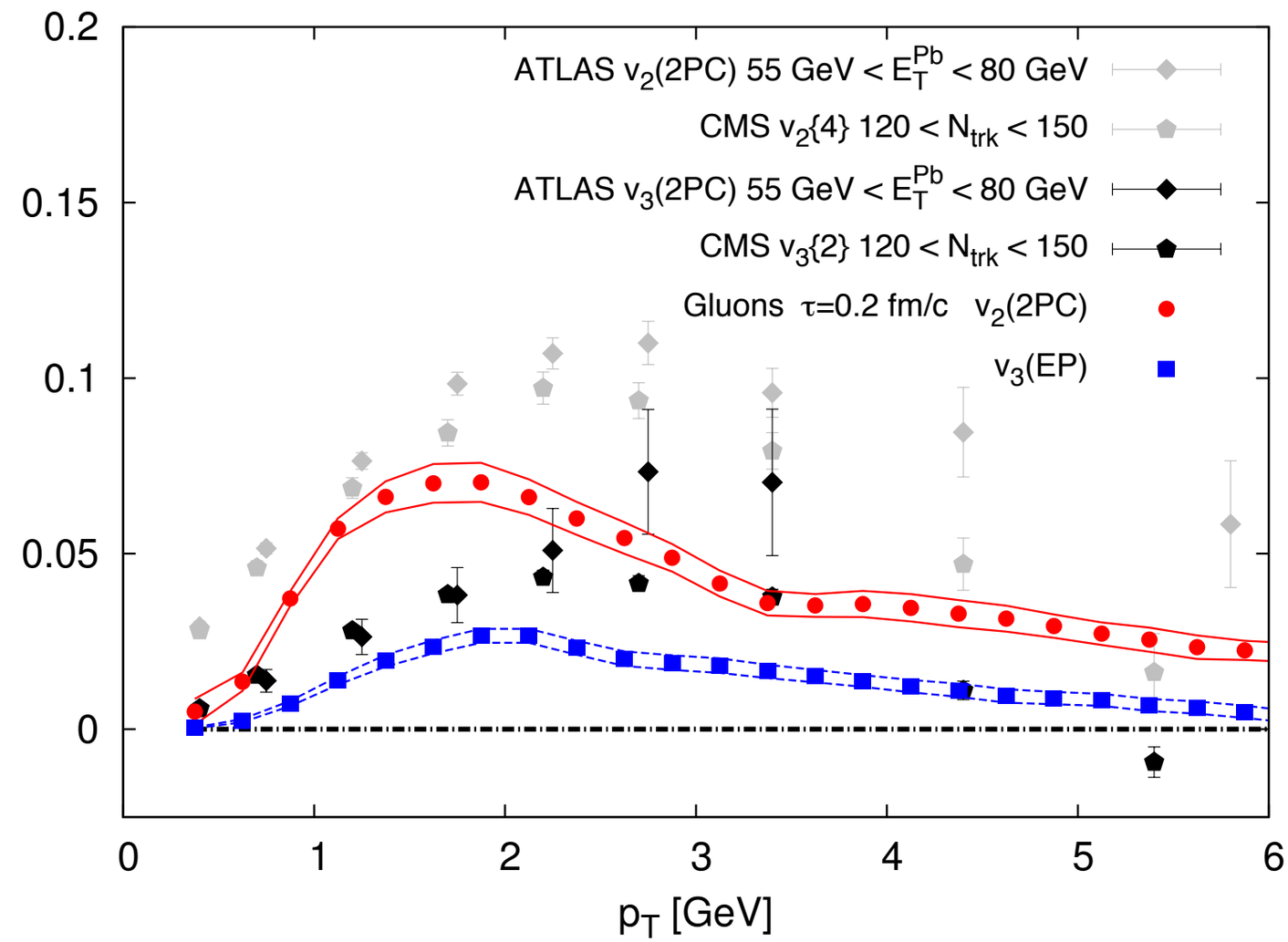
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.2 fm/c

Energy density profile
(single event)



Fourier harmonics *(gluons)*

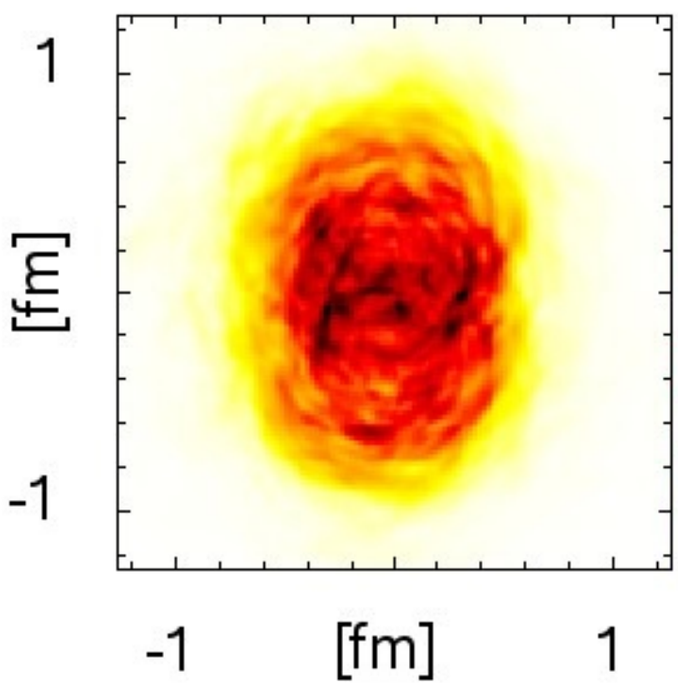


Initial state properties immediately after the collision

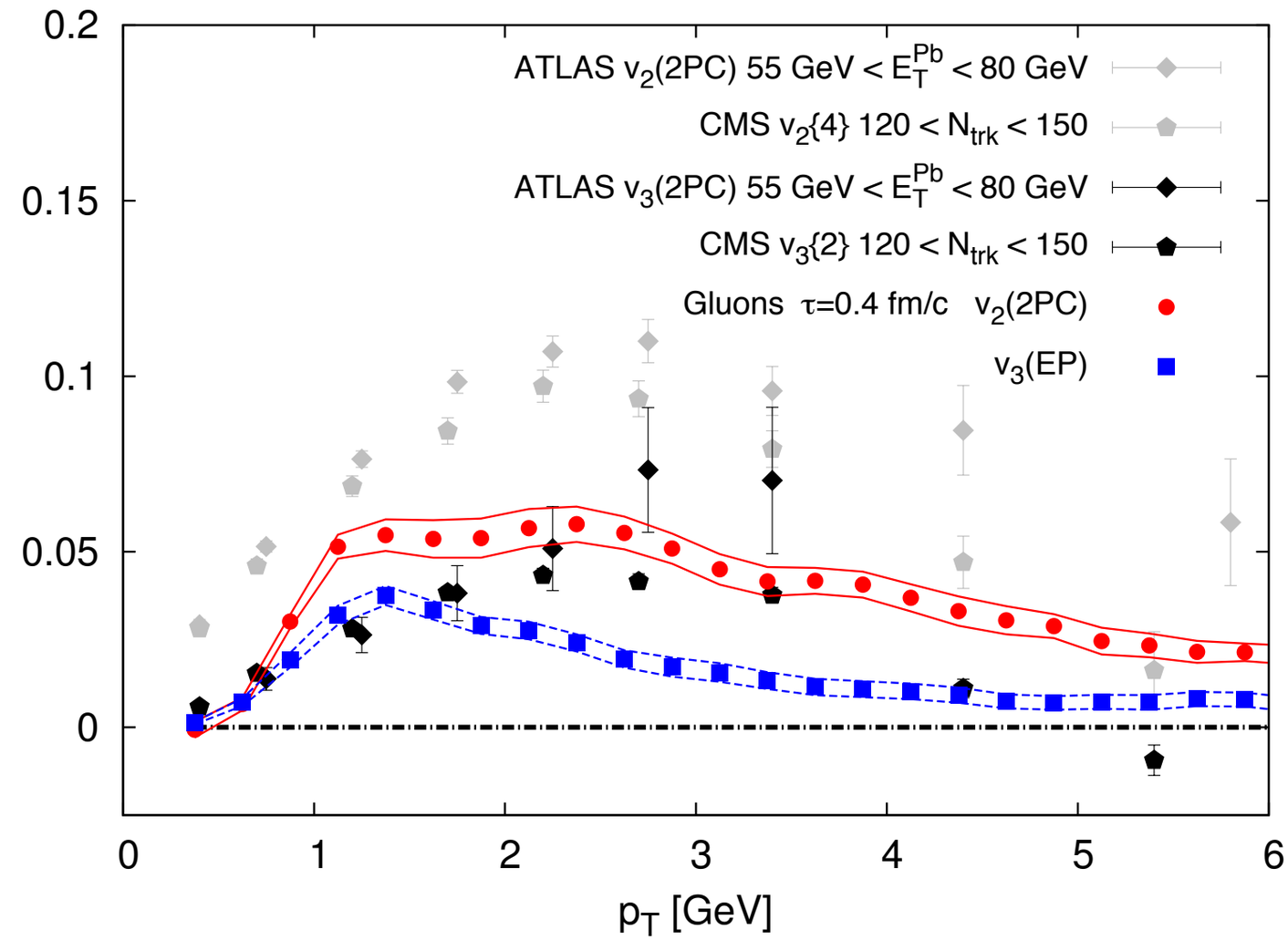
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.4 fm/c

Energy density profile
(single event)



Fourier harmonics *(gluons)*



Odd harmonics are generated by pre-equilibrium dynamics.

Conclusions

- We have learned a lot since the announcement of the discovery of the perfect fluid at RHIC
- At high energies the initial state can be computed in the classical limit of QCD: Leads to results compatible with all data
- Shear viscosity over entropy density ratio is very small
- Bulk viscosity also has important effects
- Deformed nuclei can teach us more about the initial state geometry and particle production mechanism
- Small systems show exciting results: What is the origin of azimuthal anisotropies in p+p and p+A collisions?

outlook

Outlook

- Determine the temperature dependence of transport coefficients such as shear and bulk viscosity
- Include analysis of the longitudinal (rapidity) fluctuations to learn more about the mechanism of particle production in heavy ion collisions
- Improve the theoretical description of nuclei before the collision and understand the early time dynamics better - Isotropization? Thermalization?
- Beam Energy Scan (BES) and BESII: Study the QCD phase diagram and locate the critical point if it exists

Outlook

BACKUP

Nuclei at high energy: Gluon saturation

The evolution towards smaller momentum fraction *x*
is described by the JIMWLK renormalization group equations:

high momentum quarks and gluons

intermediate momentum quarks and gluons

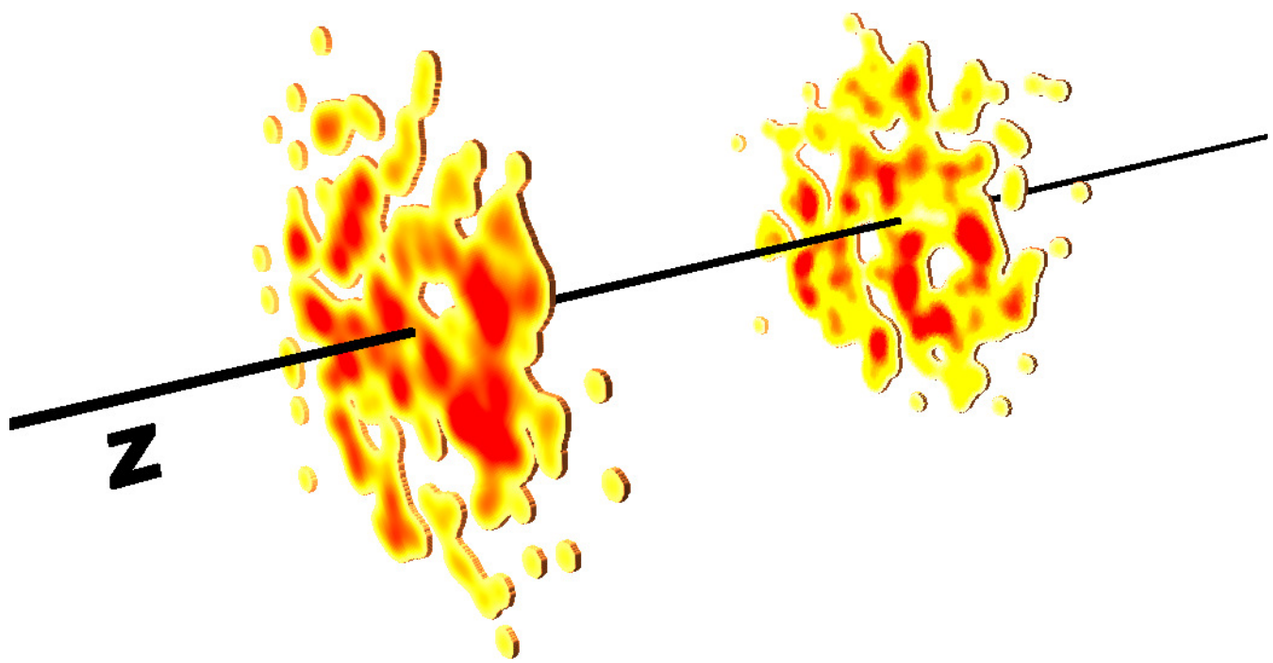
low momentum quarks and gluons

J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Nucl. Phys. B504, 415 (1997), Phys. Rev. D59, 014014 (1999)
E. Iancu, A. Leonidov, and L. D. McLerran, Nucl. Phys. A692, 583 (2001)
E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A703, 489 (2002)
A. H. Mueller, Phys. Lett. B523, 243 (2001)

IP-Glasma model

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample nucleon positions from Woods-Saxon distribution
- Determine color charge distribution using the IP-Sat model



- Sample color charges from that distribution

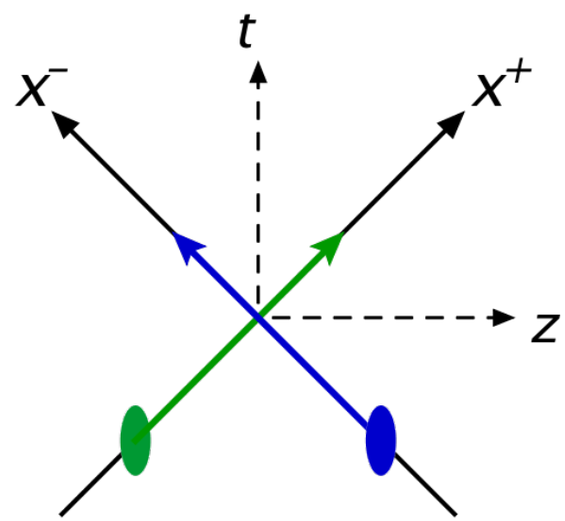
Classical gluon fields before the collision

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Moving color charges generate incoming currents

$$J_1^\mu = \delta^{\mu+}\rho_1(x^-, \mathbf{x}_T)$$

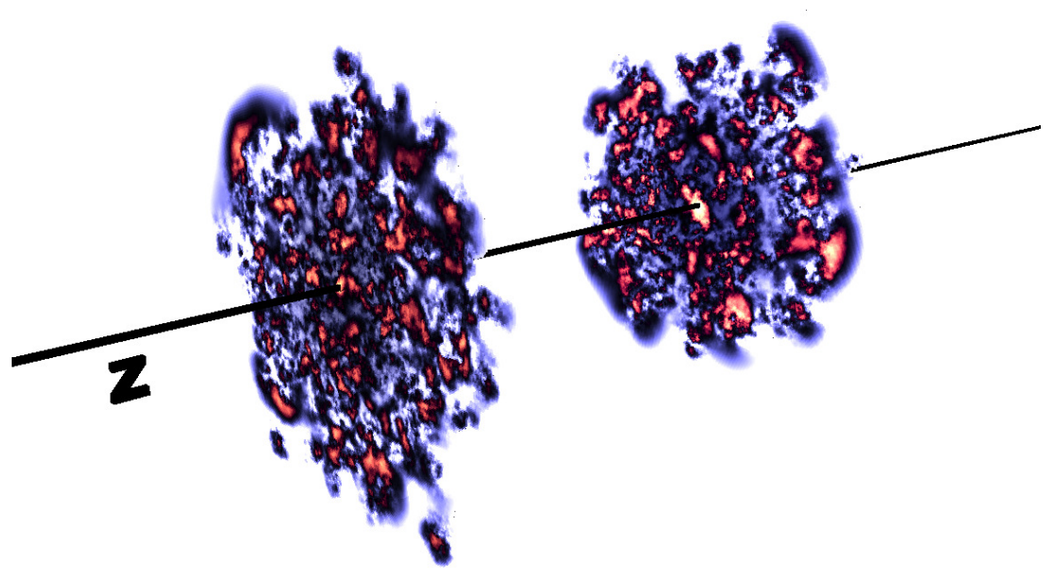
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$



$$J_2^\mu = \delta^{\mu-}\rho_2(x^+, \mathbf{x}_T)$$

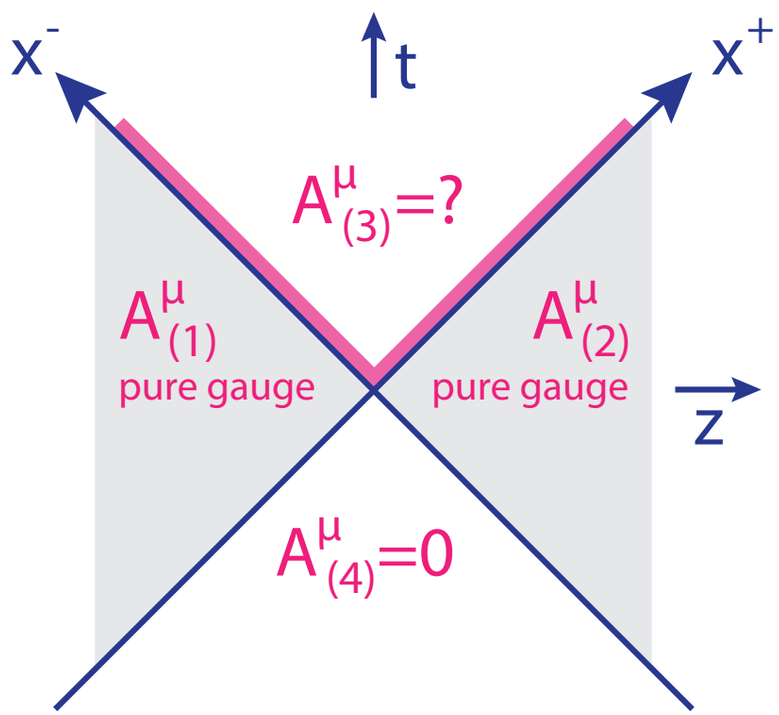
$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

Solve Yang-Mills equations for the gauge fields in the incoming nuclei



Gauge fields after the collision

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)



CONFIGURATION IN SCHWINGER GAUGE

Solution:

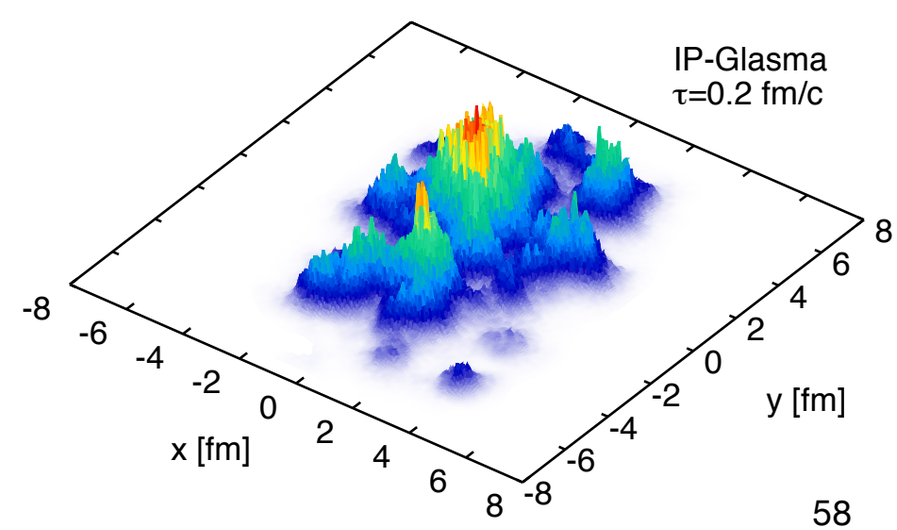
$$A^i_{(3)}|_{\tau=0+} = A^i_{(1)} + A^i_{(2)}$$

$$A^\eta_{(3)}|_{\tau=0+} = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

We solve for the gauge fields numerically

KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237

Leads to boost-invariant solution



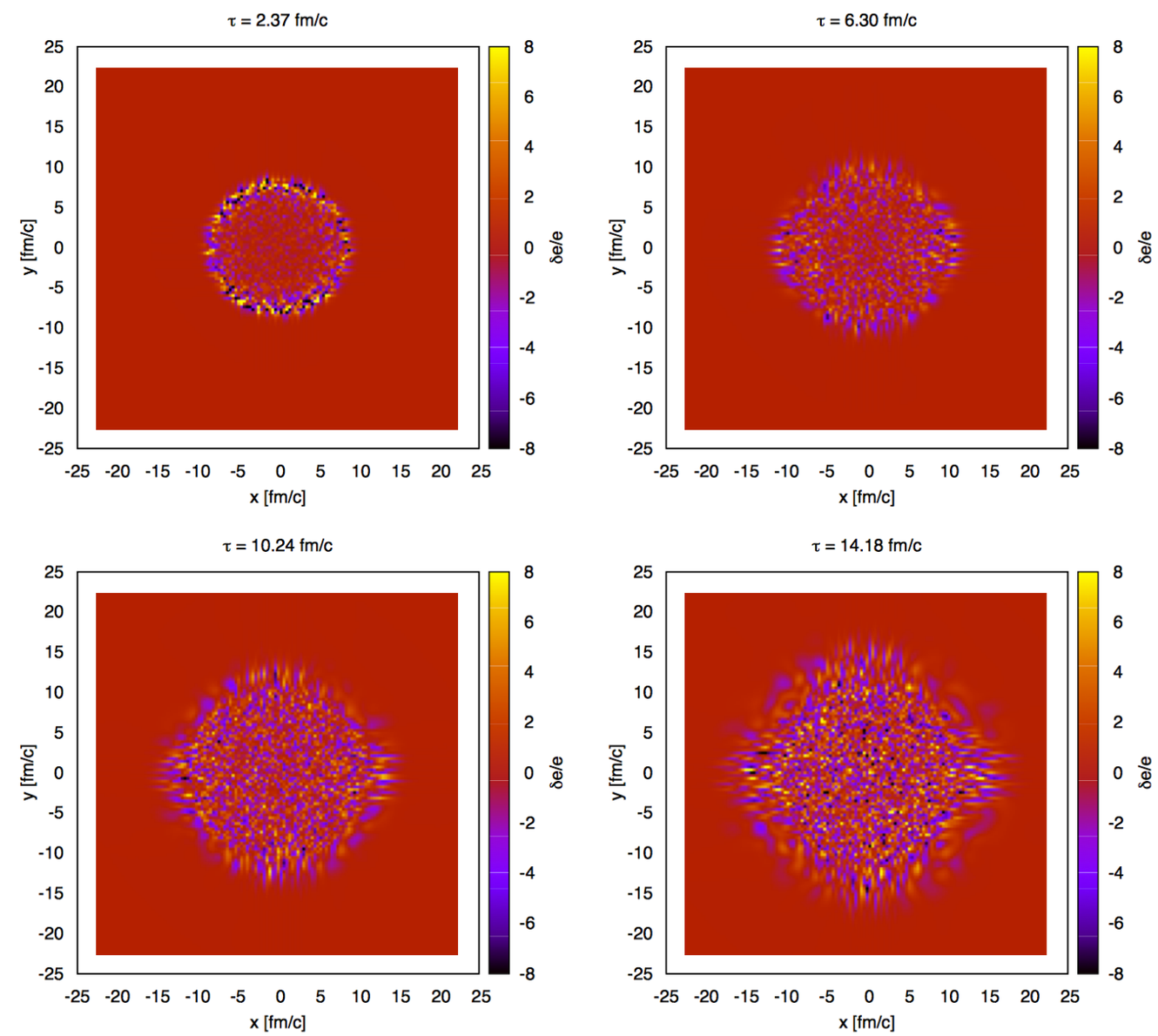
Hydrodynamic fluctuations

C. Young, J.I. Kapusta, C. Gale, S. Jeon, B. Schenke, arXiv:1407.1077

$$T^{\mu\nu}_{\rm tot} = T^{\mu\nu}_0 + \delta T^{\mu\nu}_{\rm id} + \delta W^{\mu\nu} + \Xi^{\mu\nu}$$ ← noise

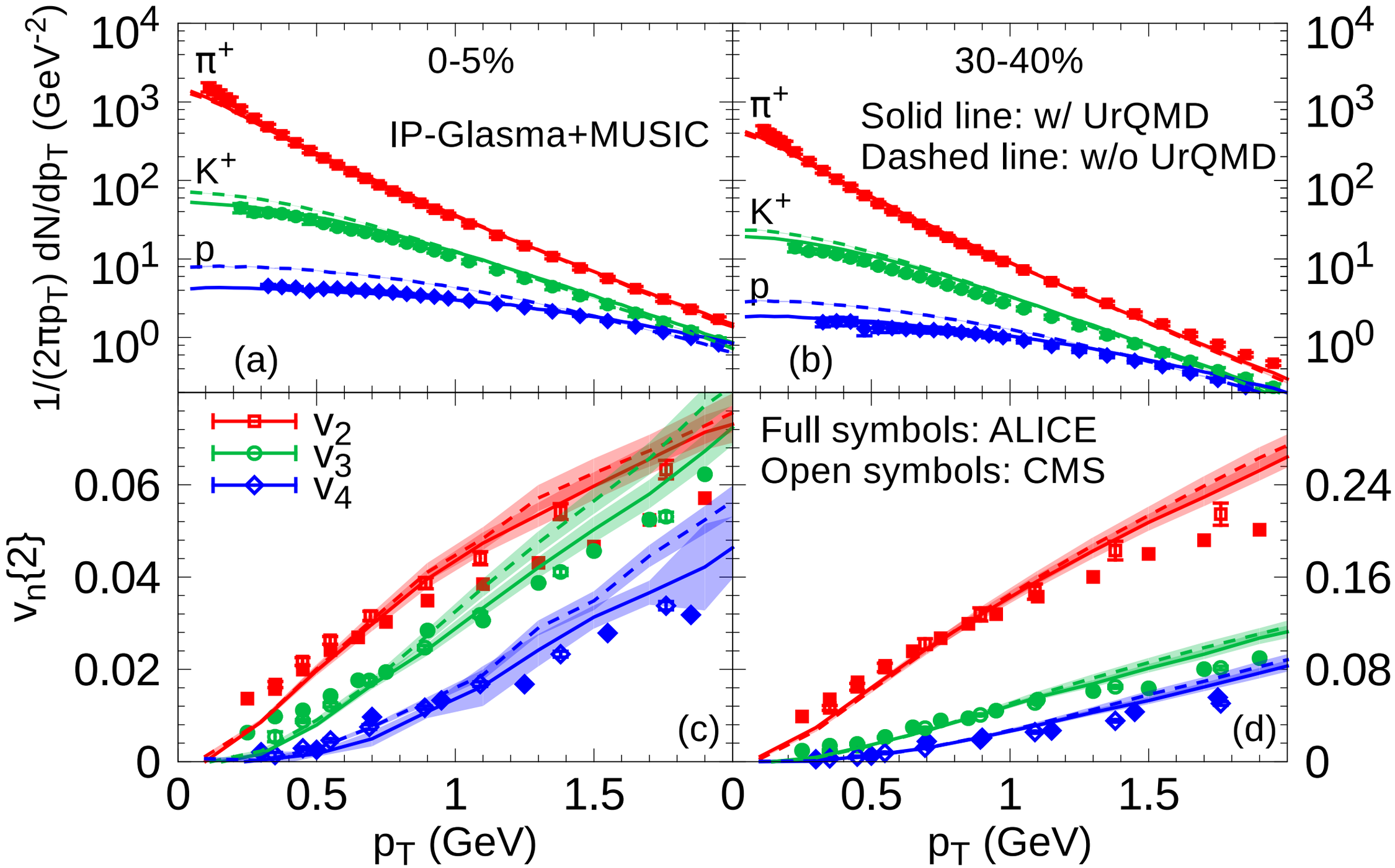
In linear response one can derive coupled equations for the evolution of the fluctuating parts of $T^{\mu\nu}$

They are separate from the evolution of the average quantities



Effect of the hadronic cascade (UrQMD)

S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, arXiv:1502.01675 (2015)



Experimental data: ALICE collaboration, Phys.Rev.Lett. 107 (2011) 032301;
CMS collaboration, Phys.Rev. C87 (2013) 1, 014902; Phys.Rev. C89 (2014) 4, 044906

Correlations from the initial state

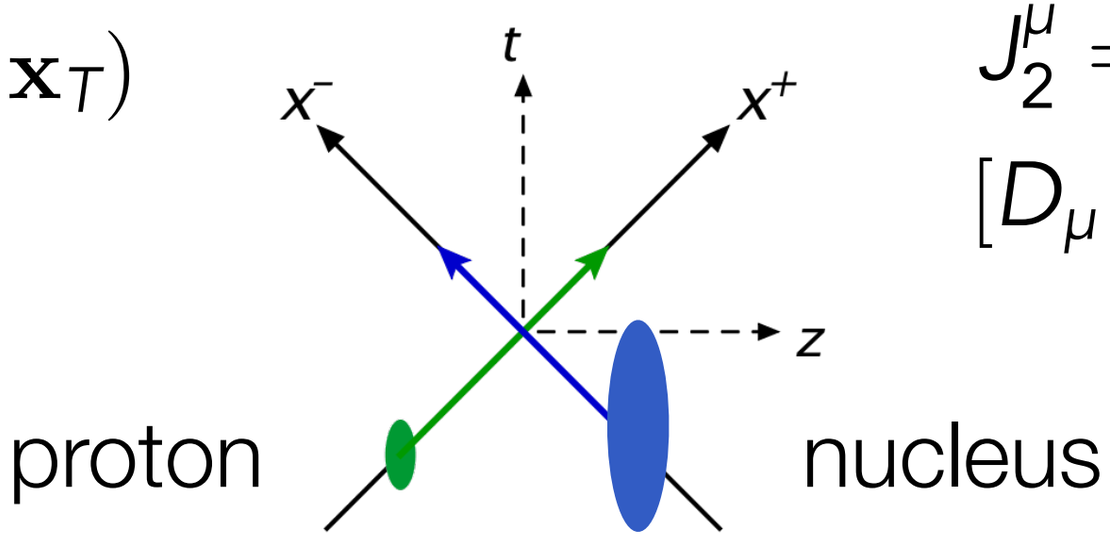
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

p+A collisions in the Color Glass Condensate framework:

For high multiplicity events, both target and projectile are best described as dense objects - like in the IP-Glasma framework

$$J_1^\mu = \delta^{\mu +} \rho_1(x^-, \mathbf{x}_T)$$
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$

$$J_2^\mu = \delta^{\mu -} \rho_2(x^+, \mathbf{x}_T)$$
$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$



Initial state and early time dynamics described by solution of classical Yang-Mills equations to leading order in α_s

Initial state properties immediately after the collision

Schenke, Schlichting, Venugopalan, arXiv:1502.01331

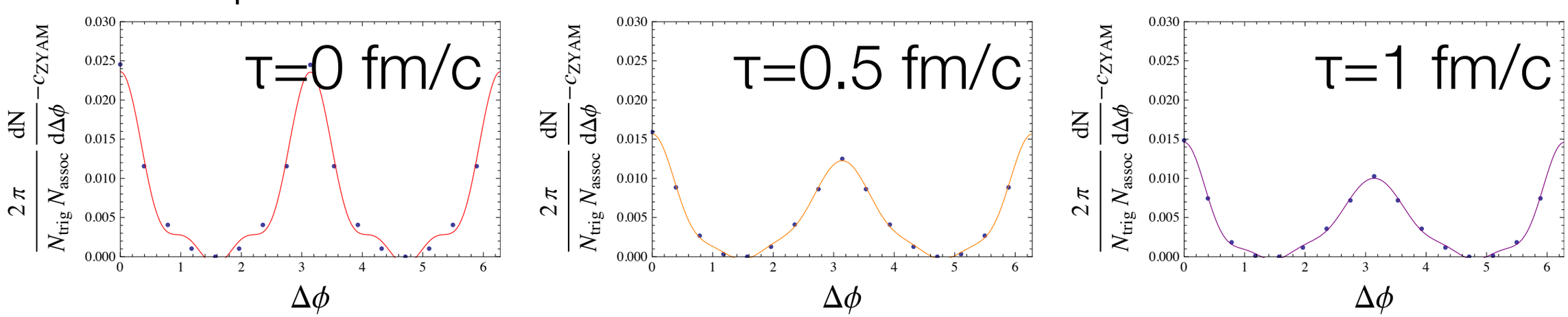
Fourier expand and fit values of $V_{n\Delta}$

$$\frac{2\pi}{N_{\rm trig}N_{\rm assoc}}\frac{dN^{\rm pair}}{d\Delta\phi}(k_1,k_2) = 1+\sum_n 2V_{n\Delta}(k_1,k_2)\cos(n\Delta\phi)$$

Then determine v_n as

$$v_n(2PC)(p_T) = \frac{V_{n\Delta}(p_T,p_T^{\rm ref})}{\sqrt{V_{n\Delta}(p_T^{\rm ref},p_T^{\rm ref})}}$$

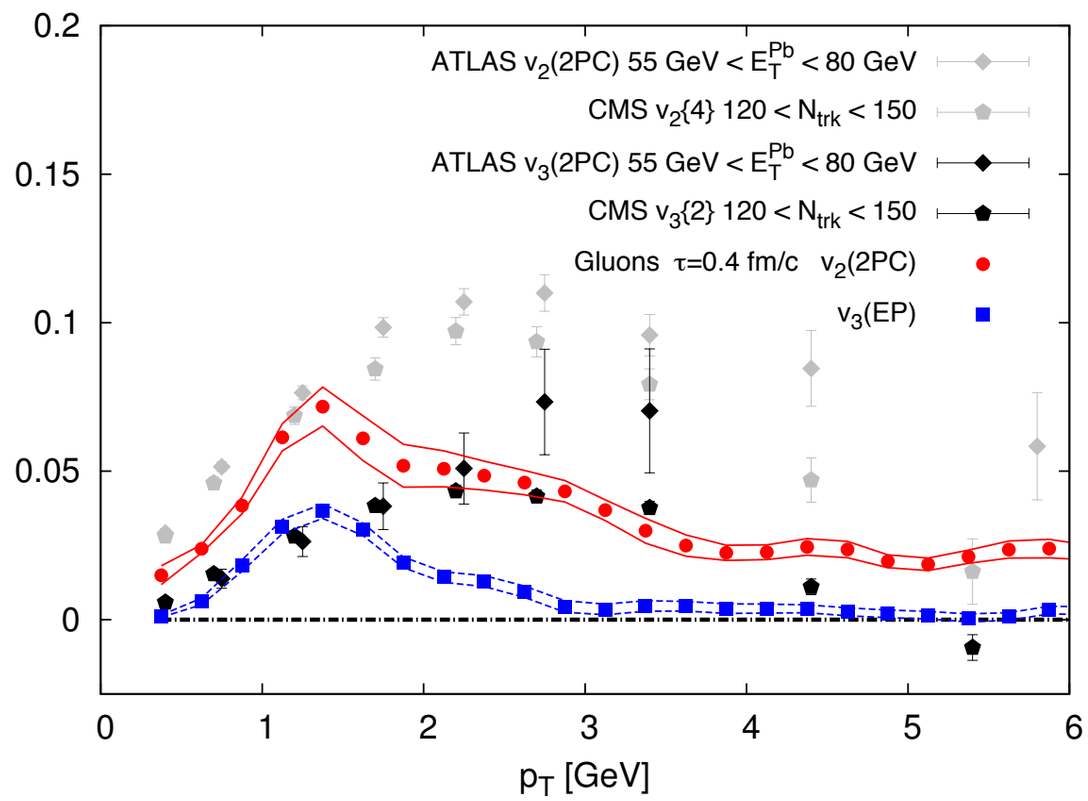
Example of distributions at different times



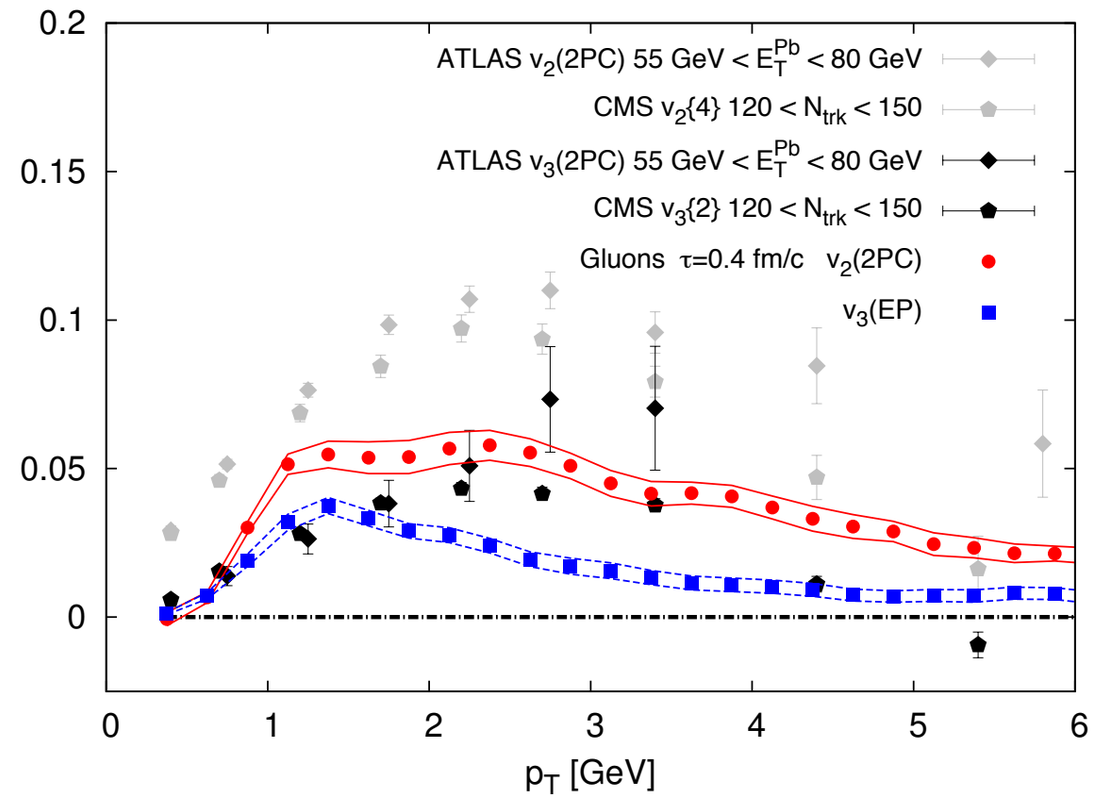
Sensitivity to proton shape

Schenke, Schlichting, Venugopalan, arXiv:1502.01331

Spherical proton



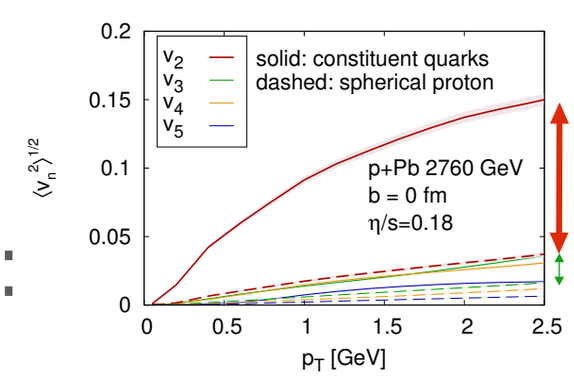
"Eccentric proton"



Small sensitivity to structure on the scale of the proton size

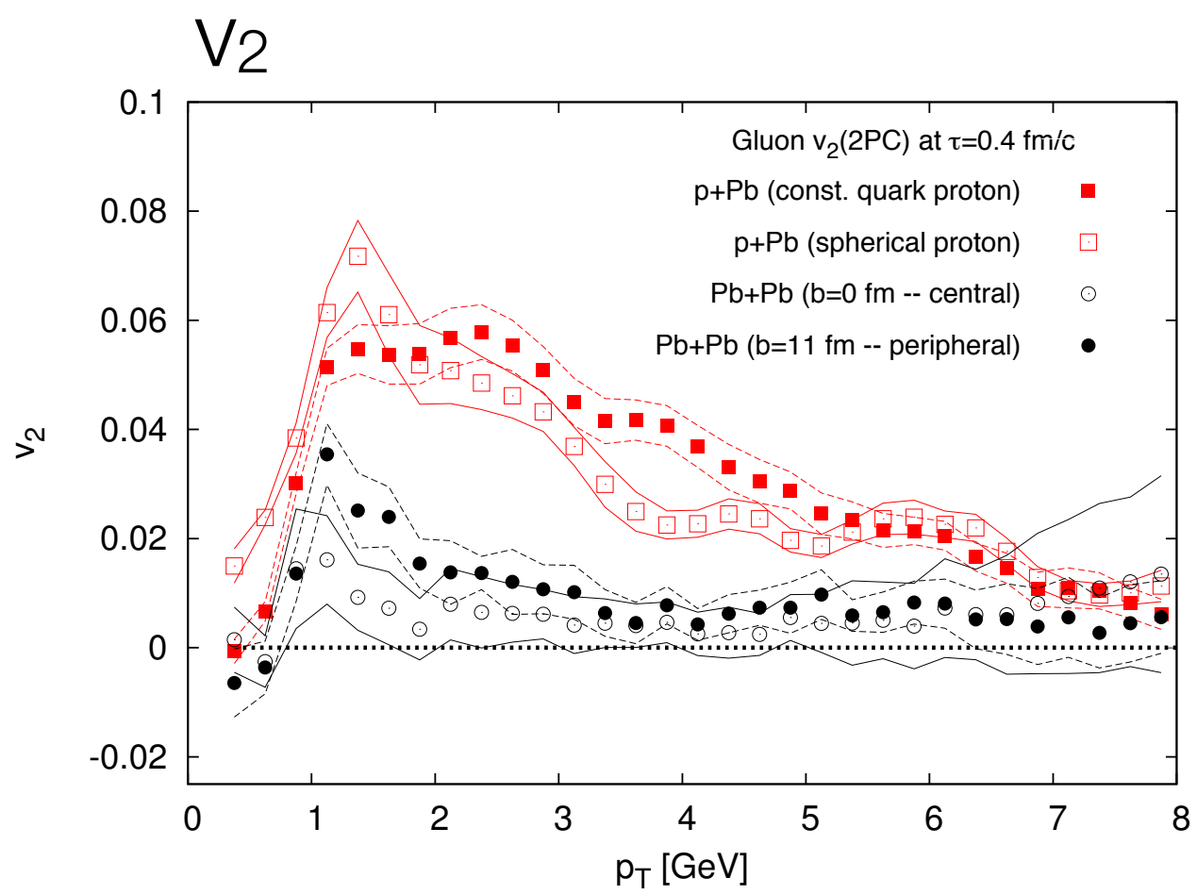
Very different from hydrodynamics

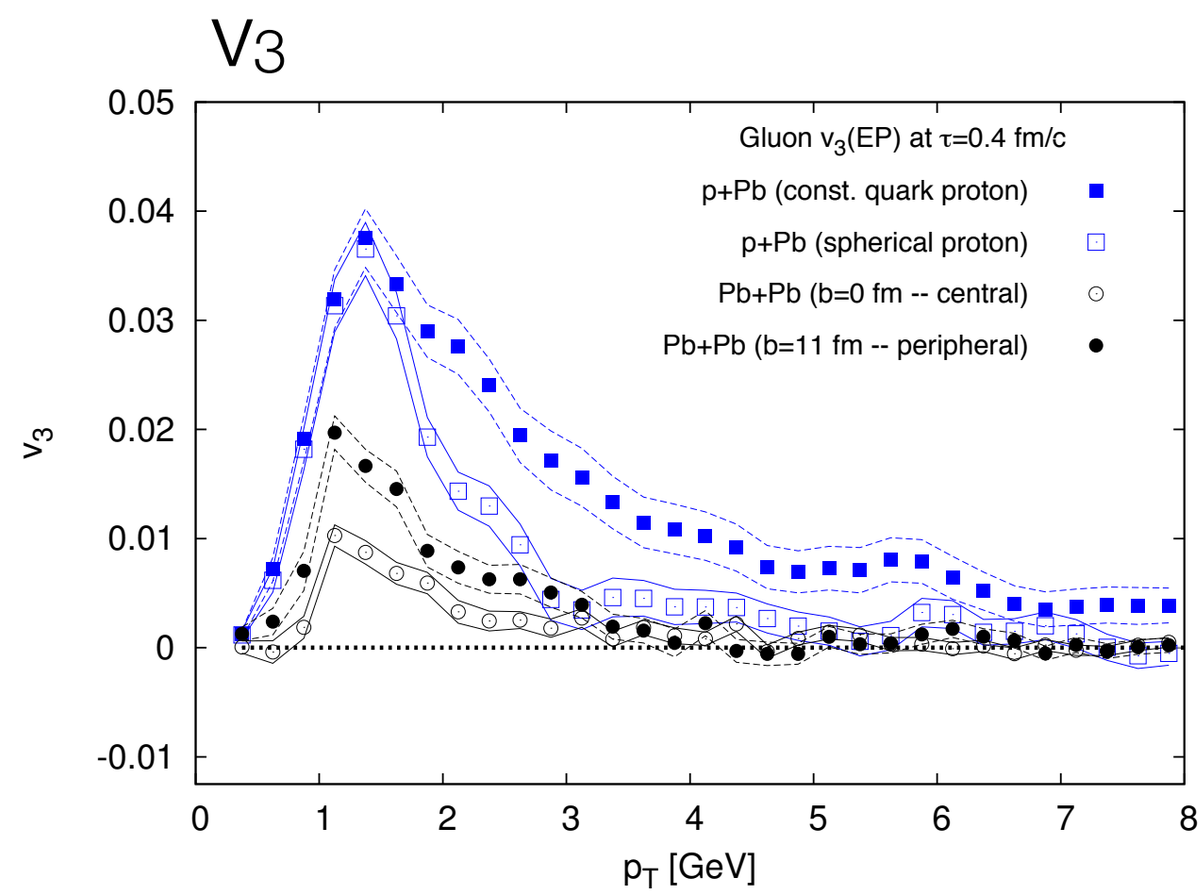
Remember hydro result:



Sensitivity to system size

Schenke, Schlichting, Venugopalan, arXiv:1502.01331



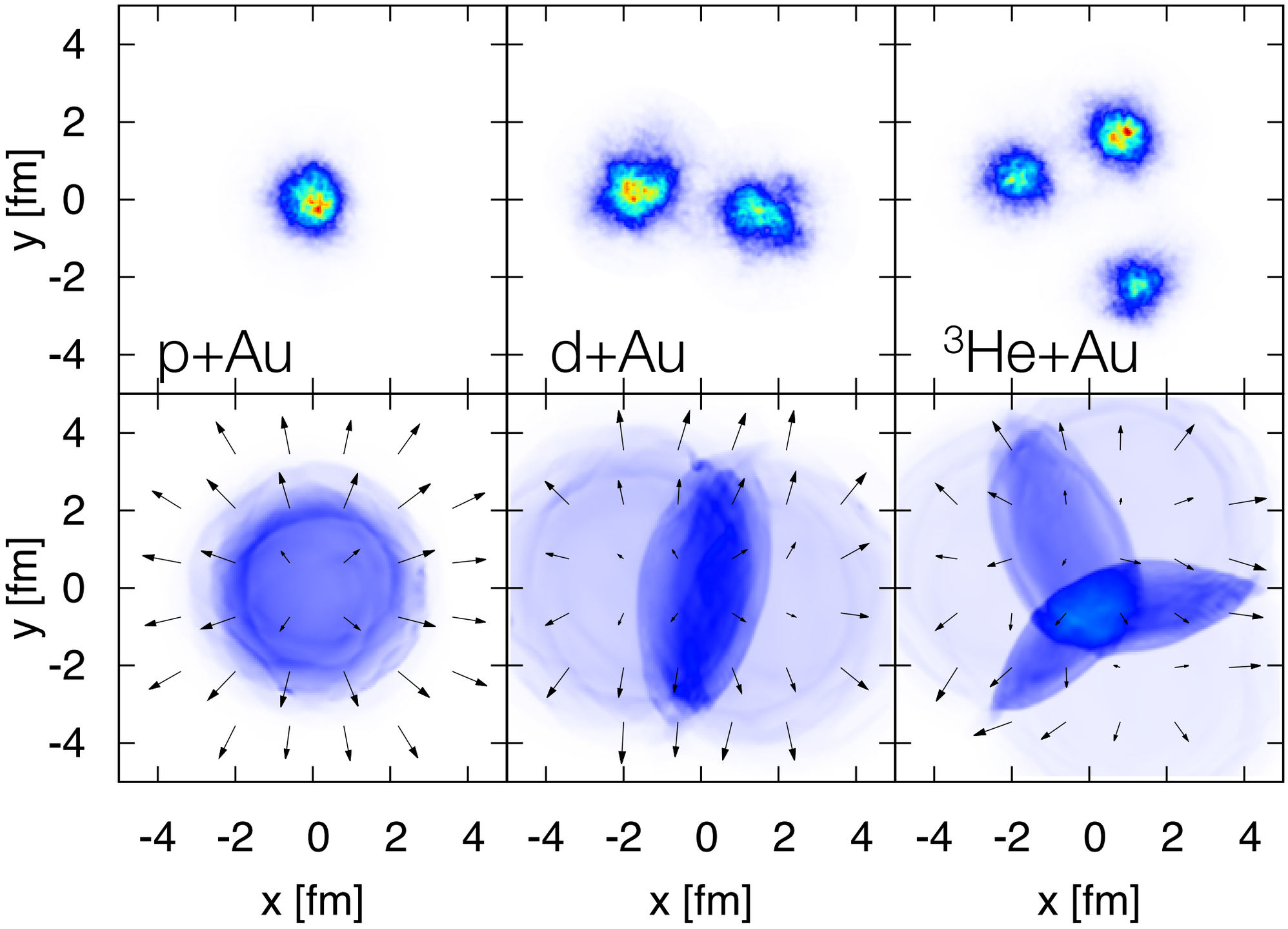


Black points: open: central Pb+Pb, solid: peripheral Pb+Pb

Small effect in Pb+Pb! Reason:

Gluons produced from many uncorrelated color field domains

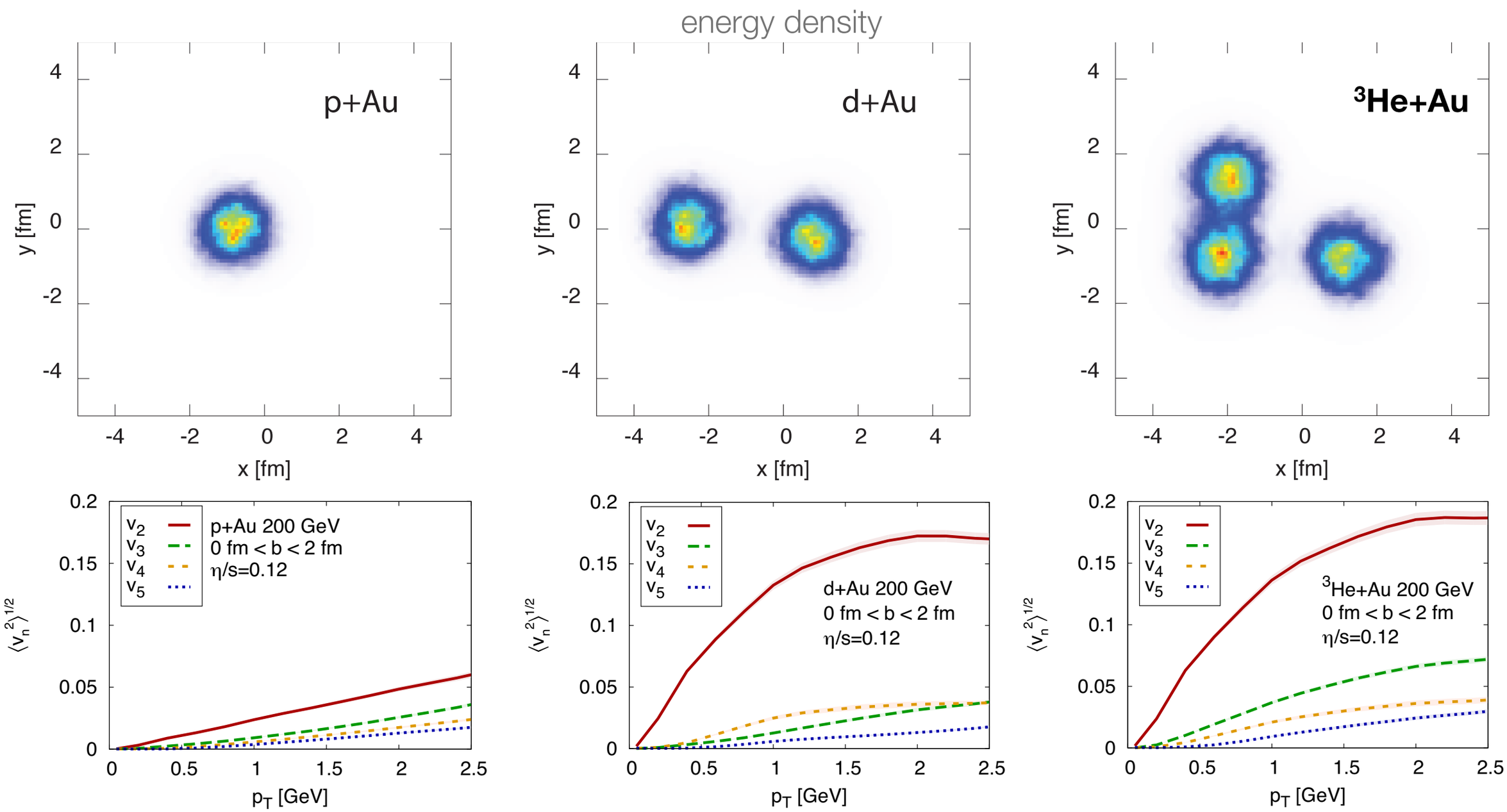
Various small collision systems: IP-Glasma + MUSIC



^{3}He+Au results from IP-Glasma + MUSIC

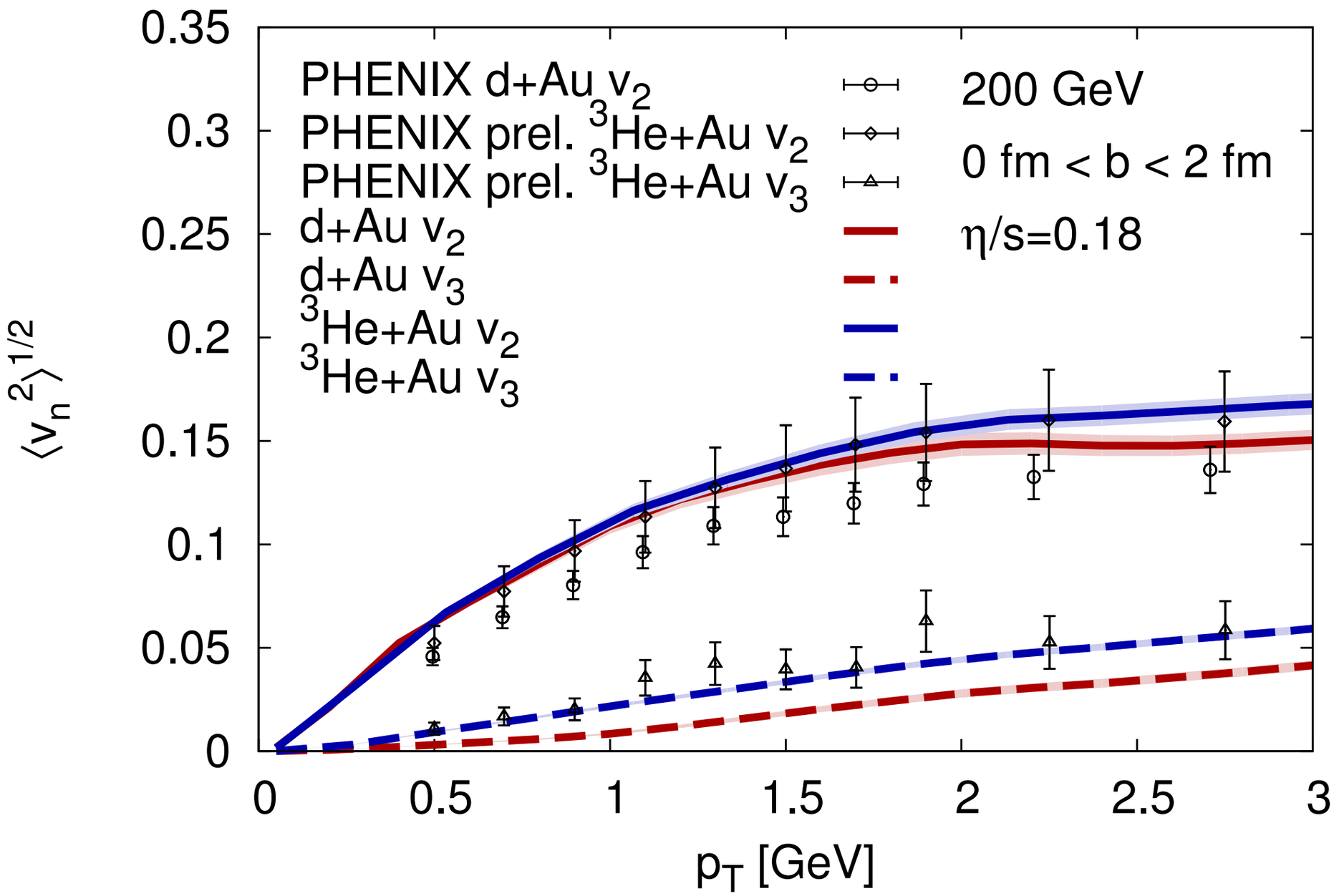
B. SCHENKE, R. VENUGOPALAN, NUCL.PHYS. A931 (2014) 1039-1044

Predictions for η/s = 0.12:



^{3}He+Au results from IP-Glasma + MUSIC

Adjust parameter: η/s = 0.18 - compare d+Au and ^{3}He+Au



Note: No realistic centrality selection