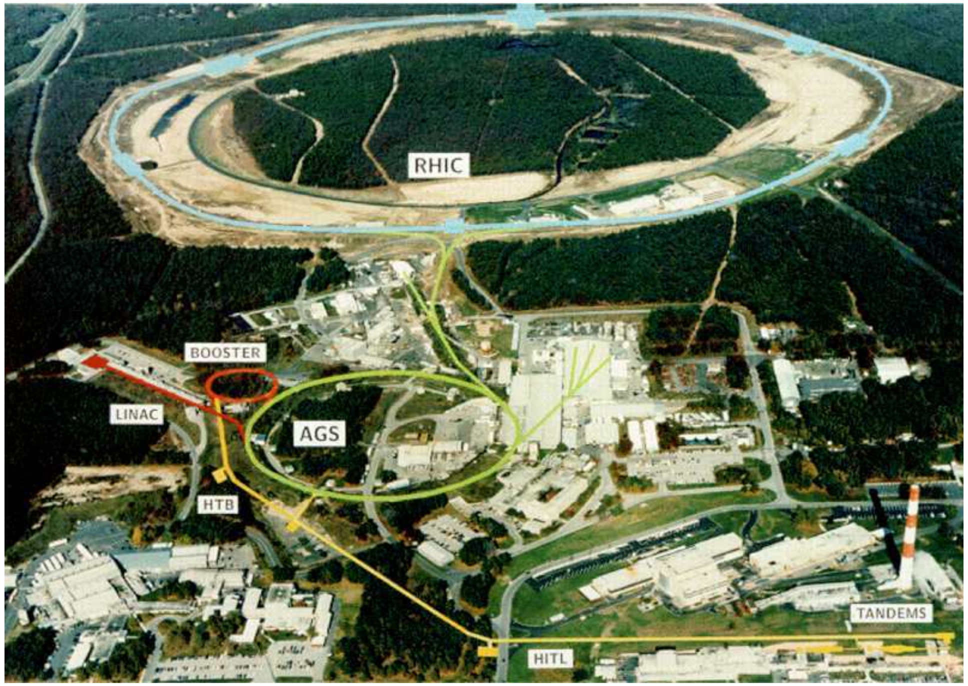
Phenomenological limits on the QGP shear viscosity and what they imply for QGP thermalization*

Ulrich Heinz, The Ohio State University



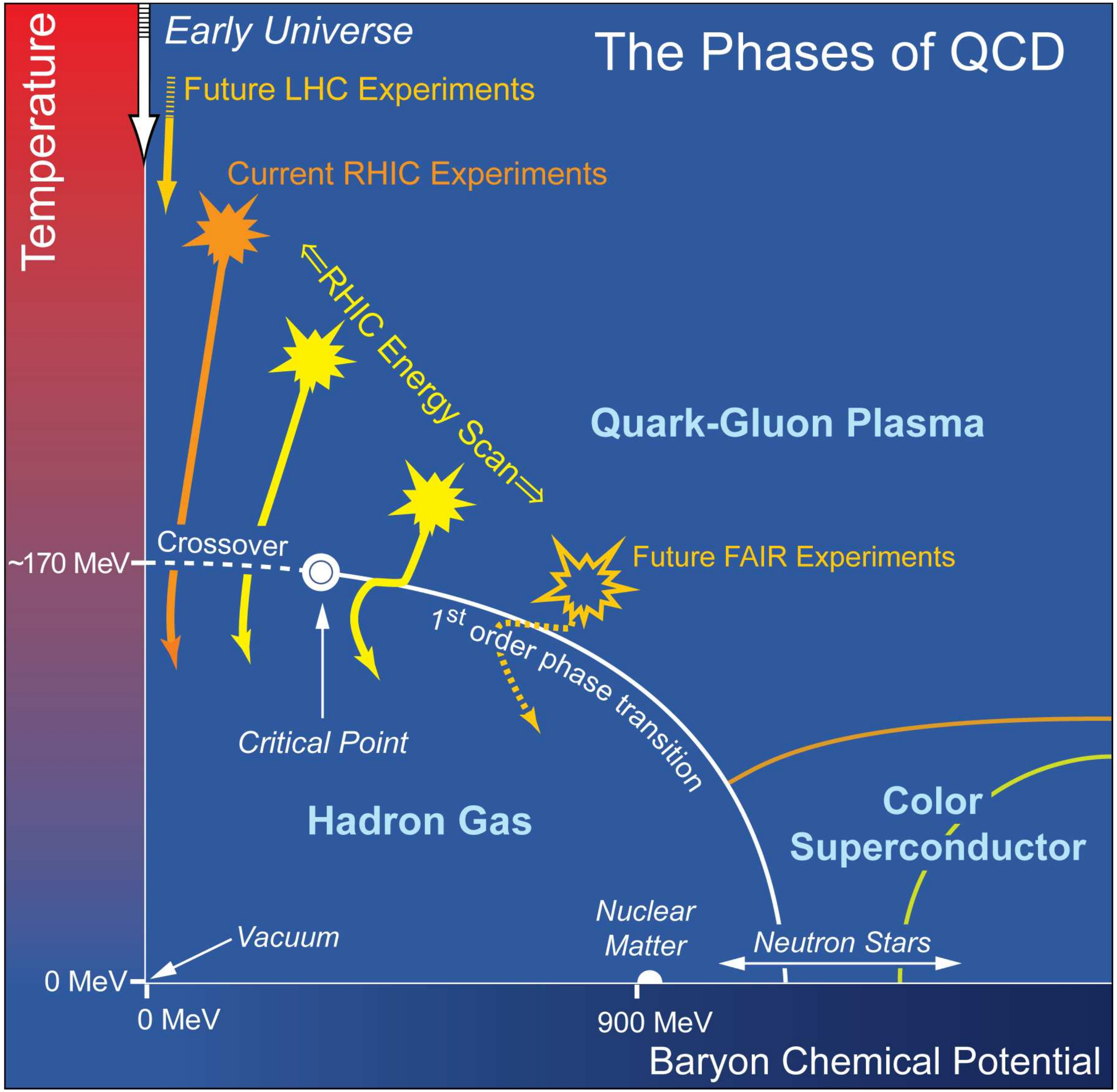
Gauge Field Dynamics In and Out of Equilibrium, INT, March 19, 2012

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

*Work supported by the U.S. Department of Energy

JET Collaboration

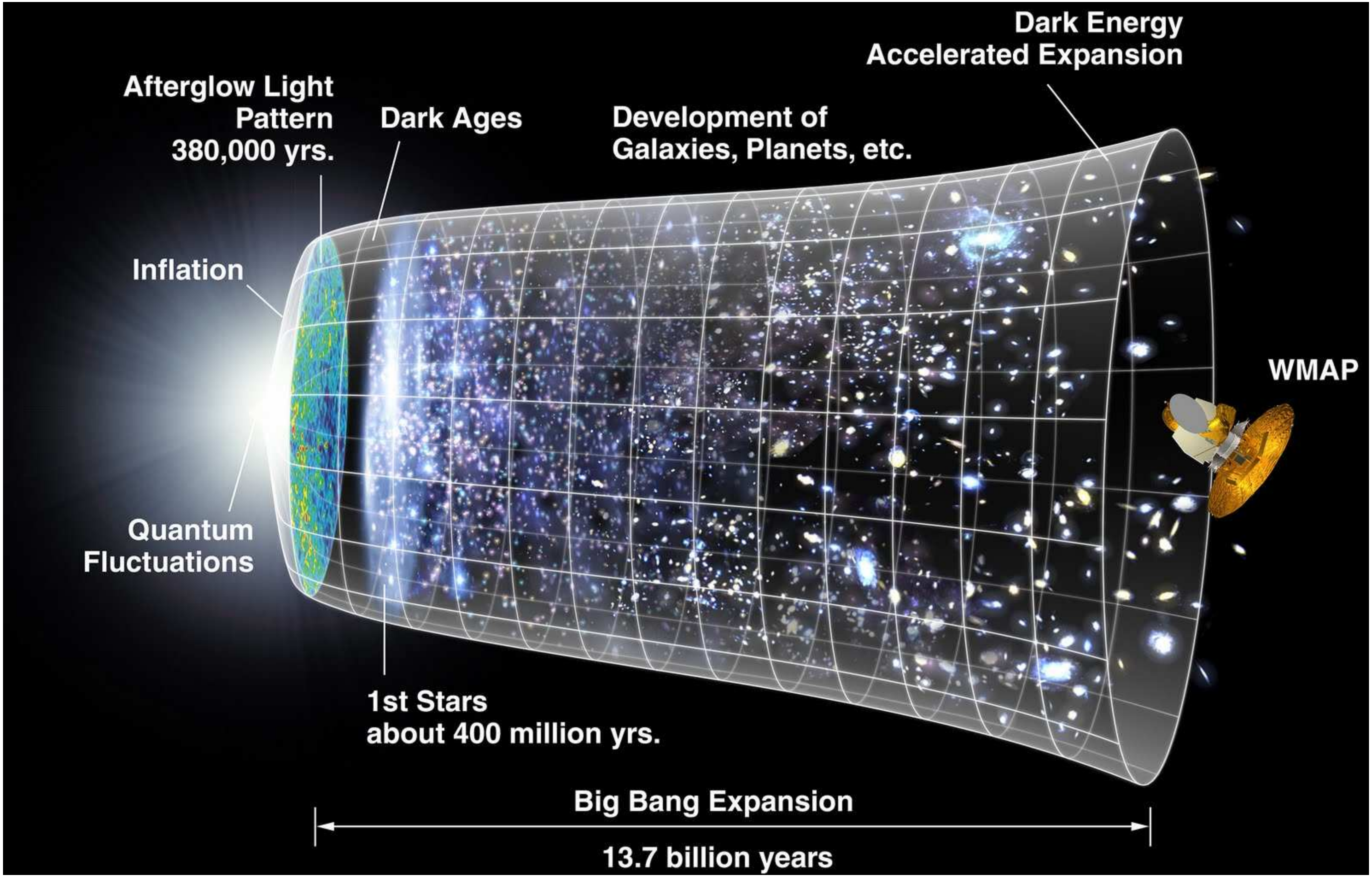
Probing the landscape of QCD matter: The future is now!



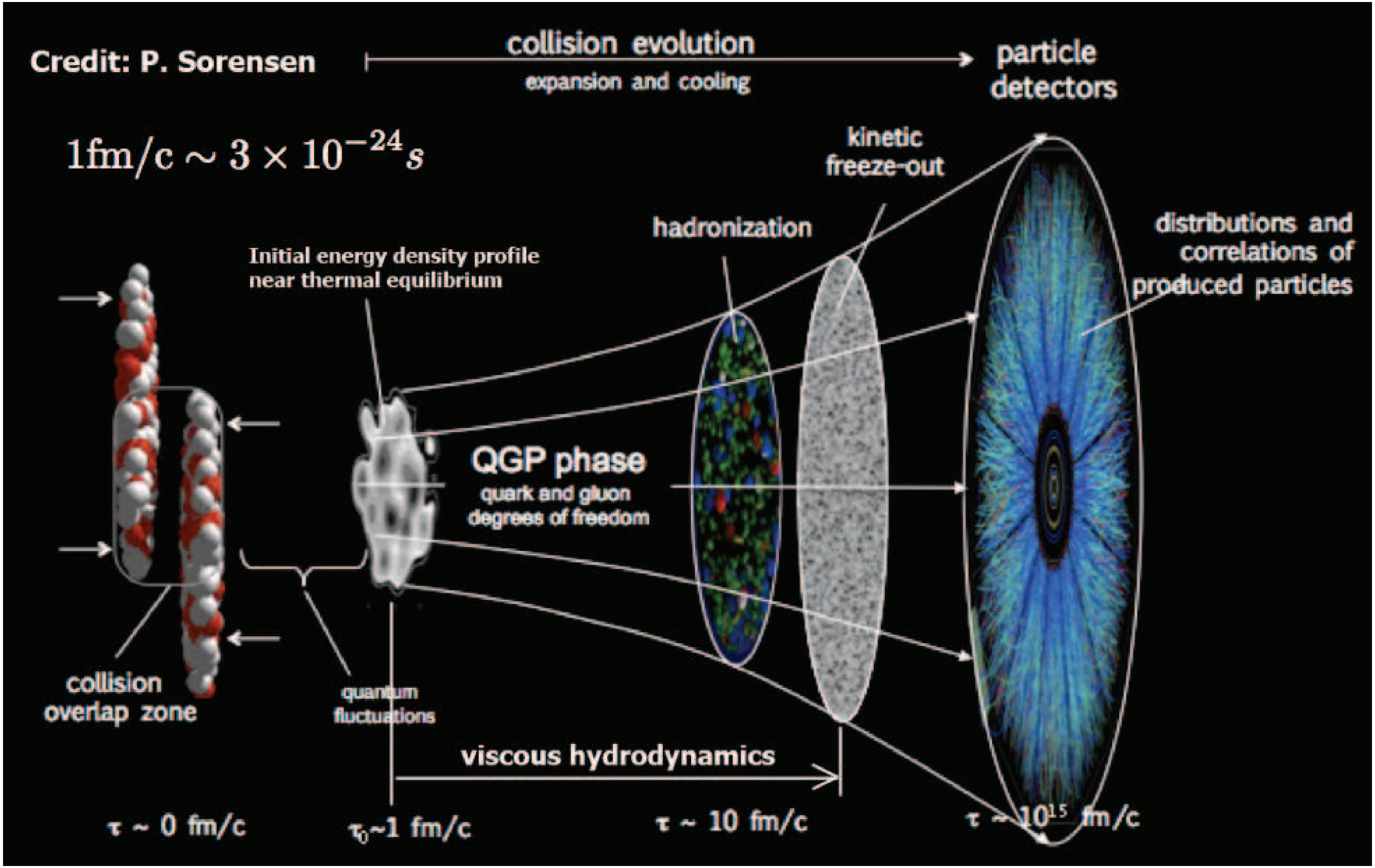
Probes:

- Collective flow
- Jet modification and quenching
- Thermal electro-magnetic radiation
- Critical fluctuations
- . . .

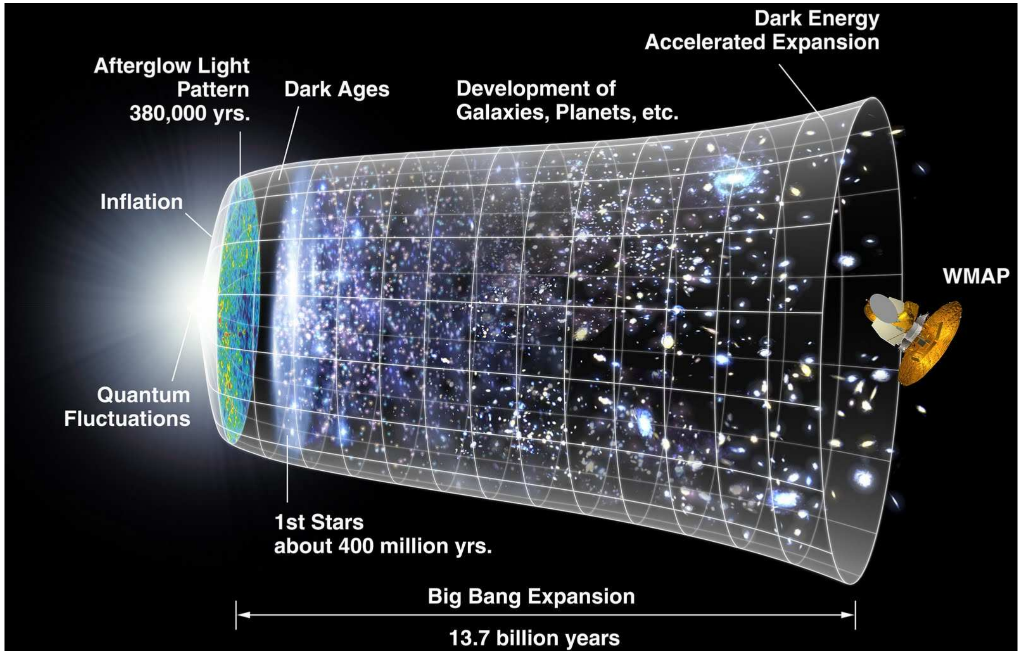
The Big Bang

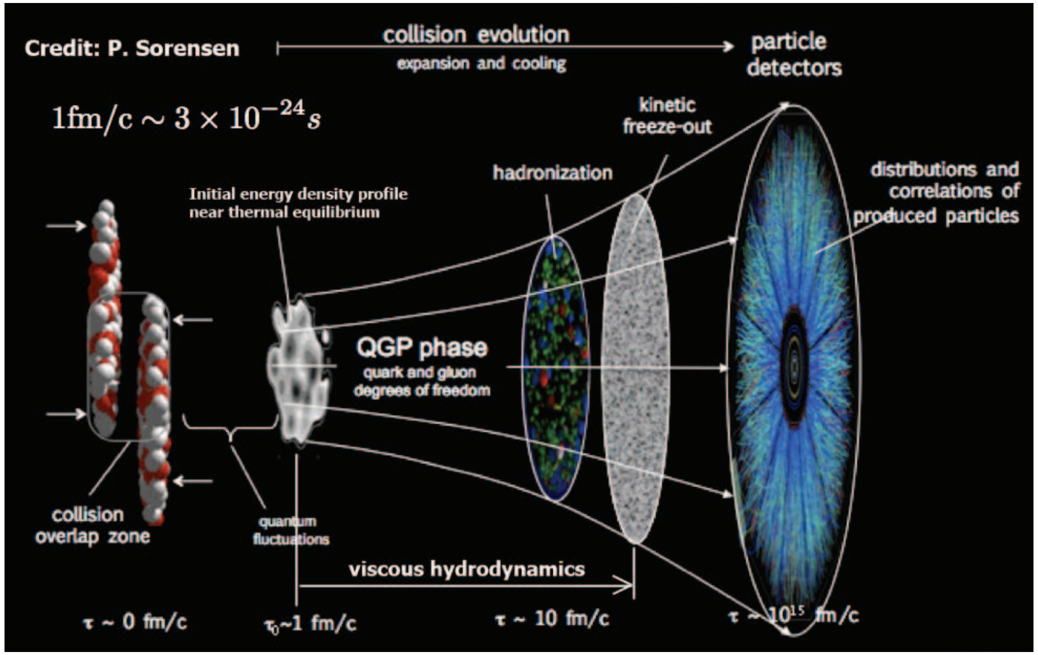

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

The Little Bang



Big Bang vs. Little Bang





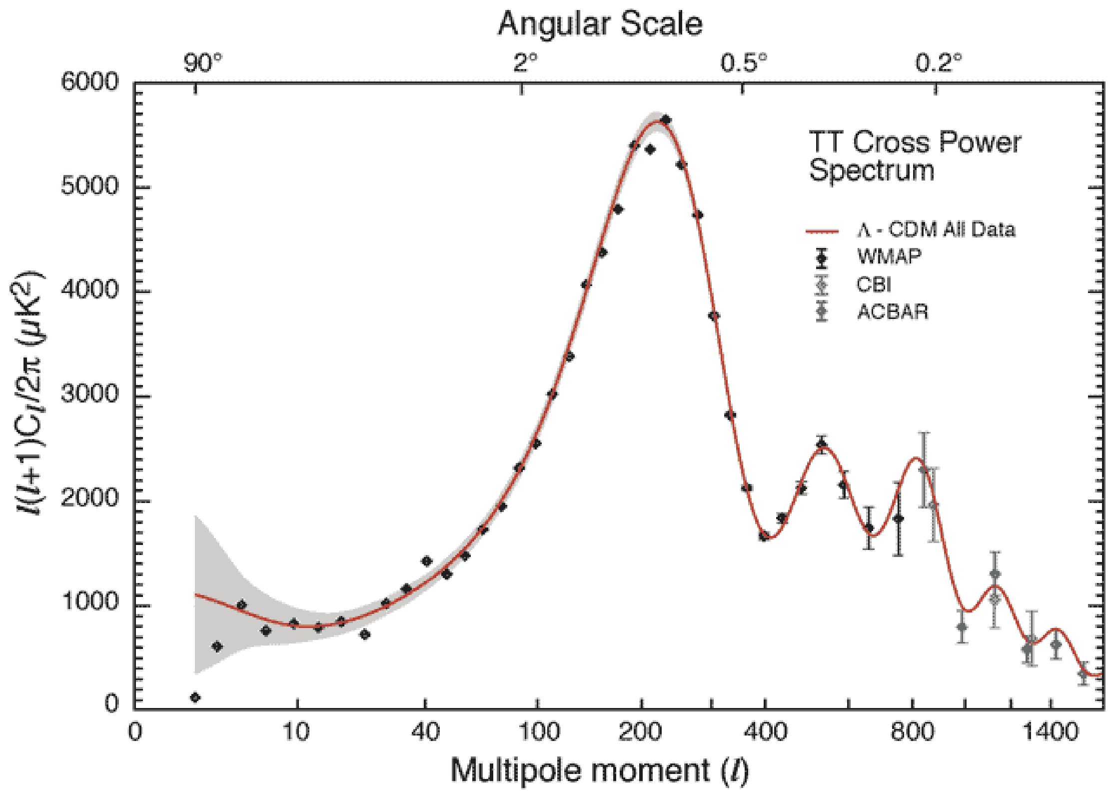
Similarities: Hubble-like expansion, expansion-driven dynamical freeze-out
chemical freeze-out (nucleo-/hadrosynthesis) before thermal freeze-out (CMB, hadron p_T-spectra)
initial-state quantum fluctuations imprinted on final state

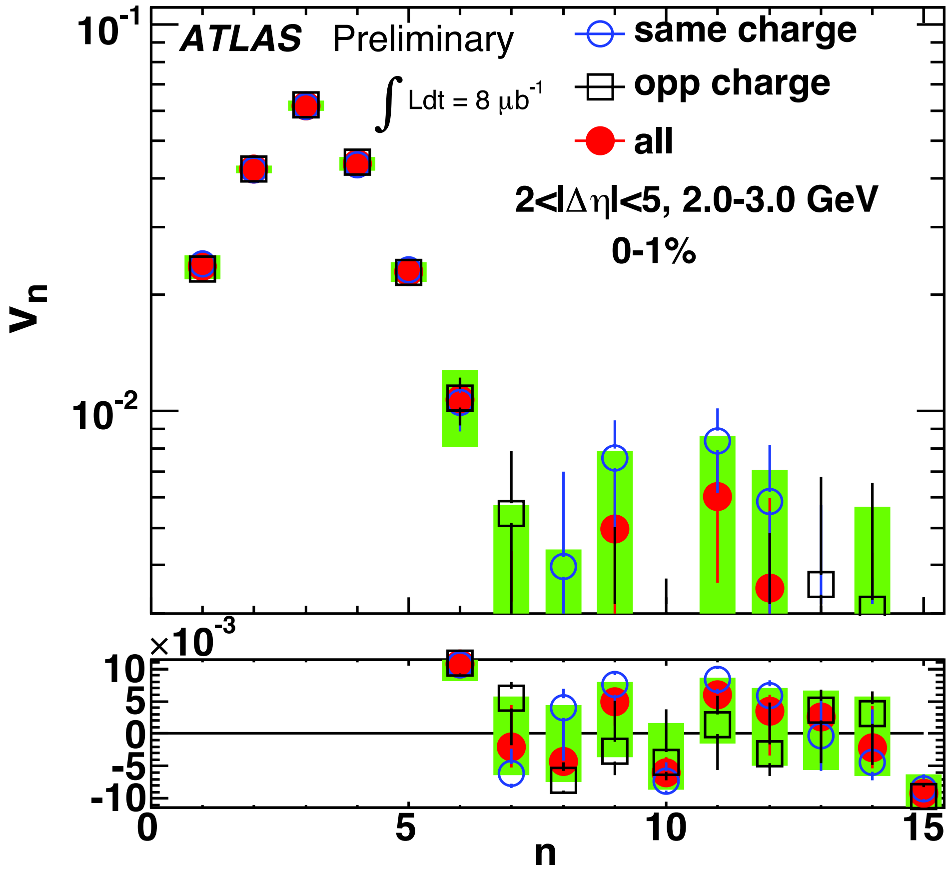
Differences: Expansion rates differ by 18 orders of magnitude
Expansion in 3d, not 4d; driven by pressure gradients, not gravity
Time scales measured in fm/c rather than billions of years
Distances measured in fm rather than light years
"Heavy-Ion Standard Model" still under construction $\Longrightarrow$ **this talk**

Big vs. Little Bang: The fluctuation power spectrum

Mishra, Mohapatra, Saumia, Srivastava, PRC77 (2008) 064902 and C81 (2010) 034903

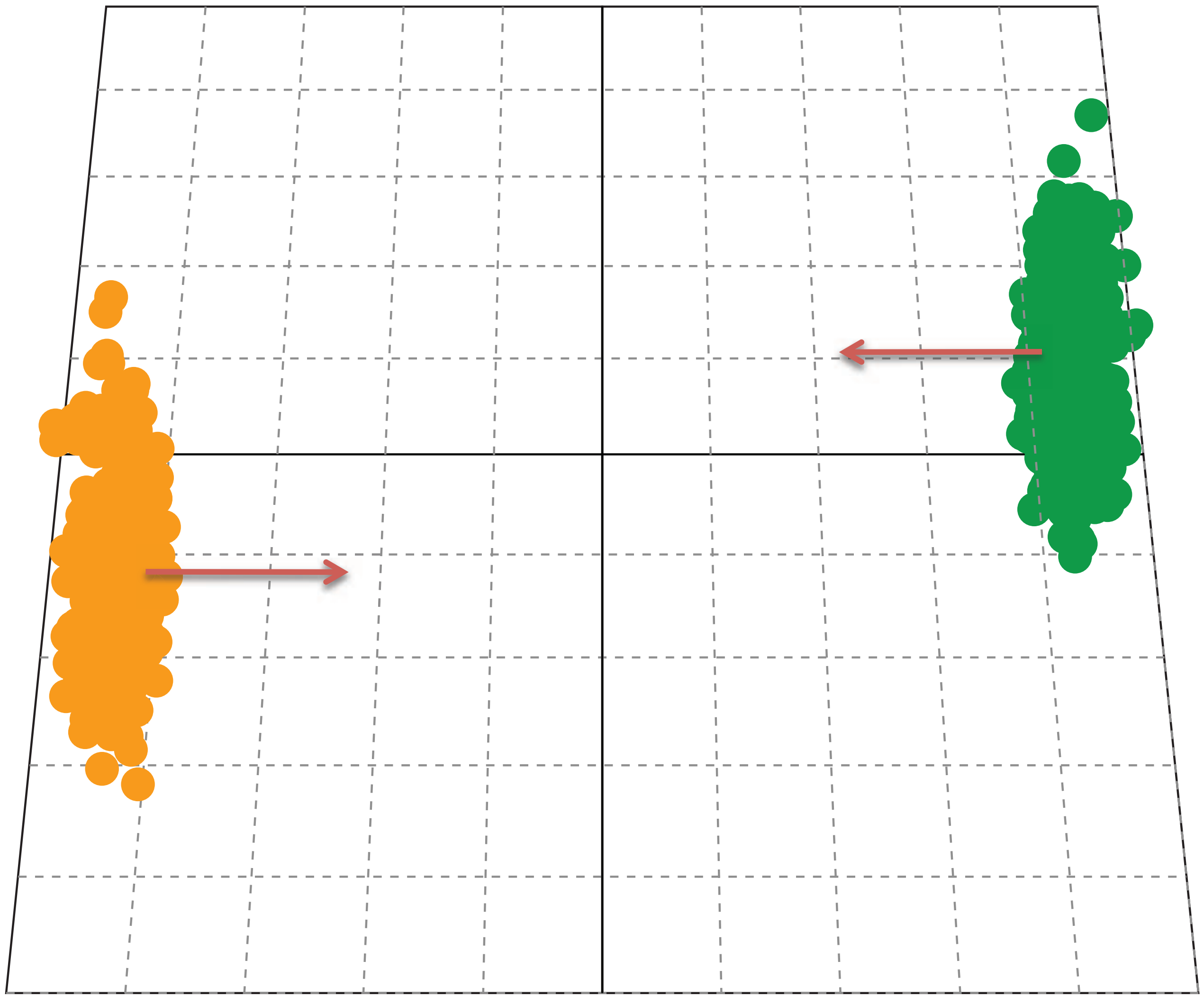
Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71





Relativistic Nucleus-Nucleus Collisions

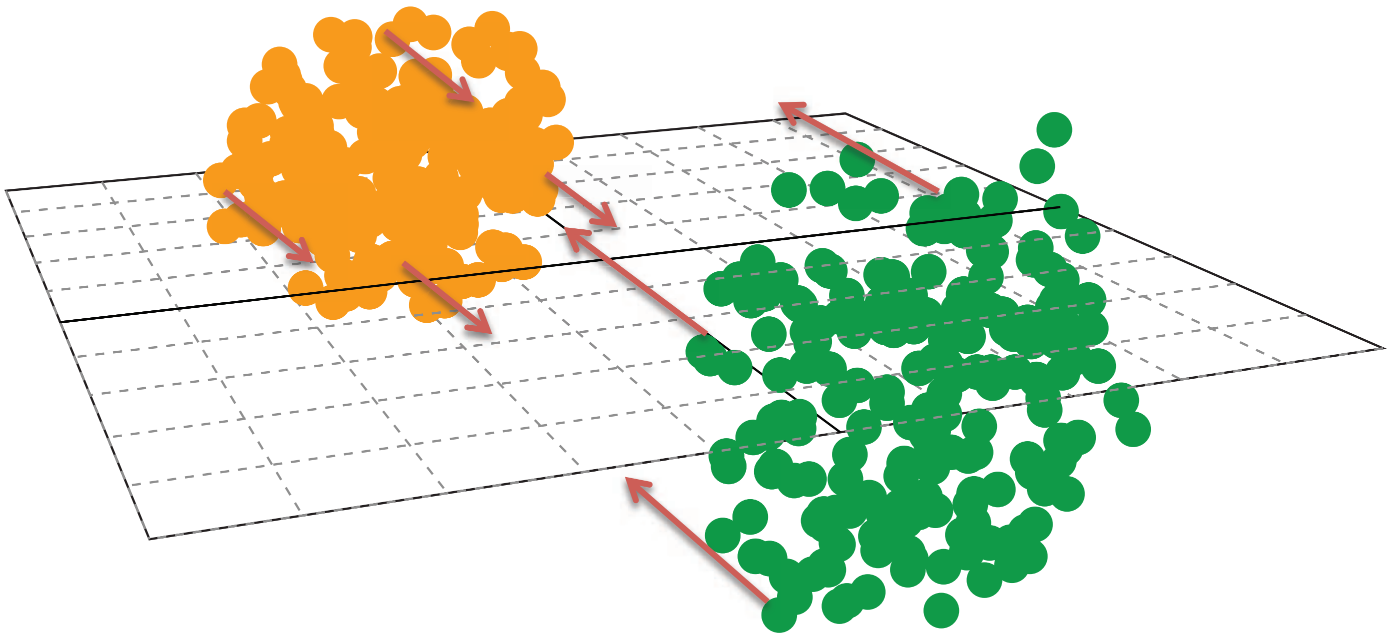
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen



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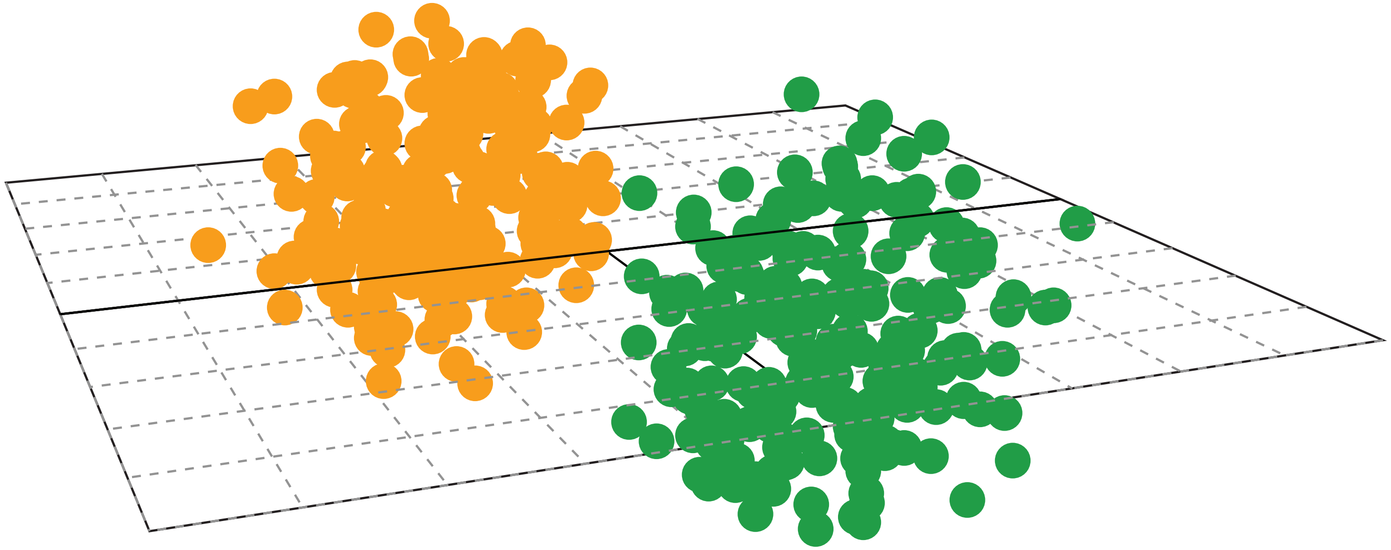

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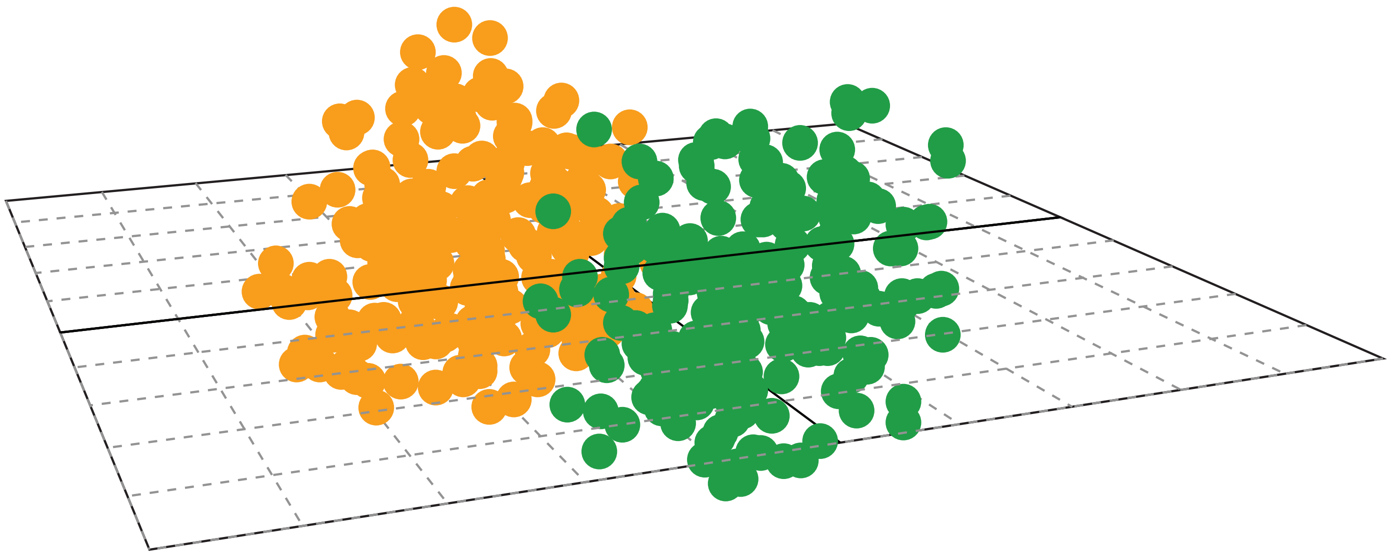

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Relativistic Nucleus-Nucleus Collisions

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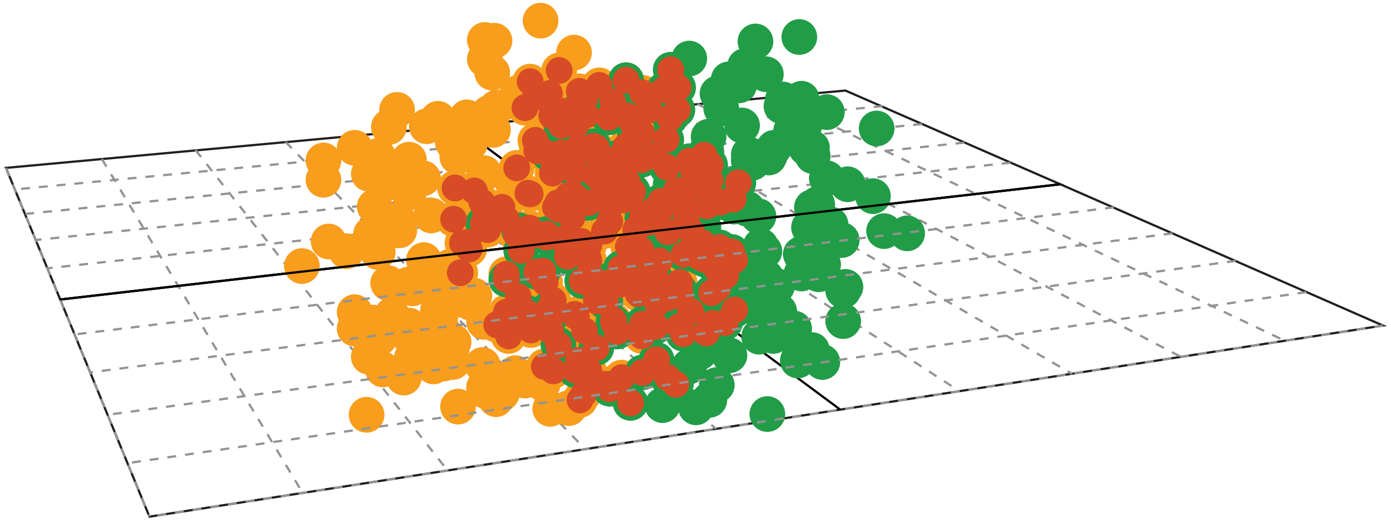

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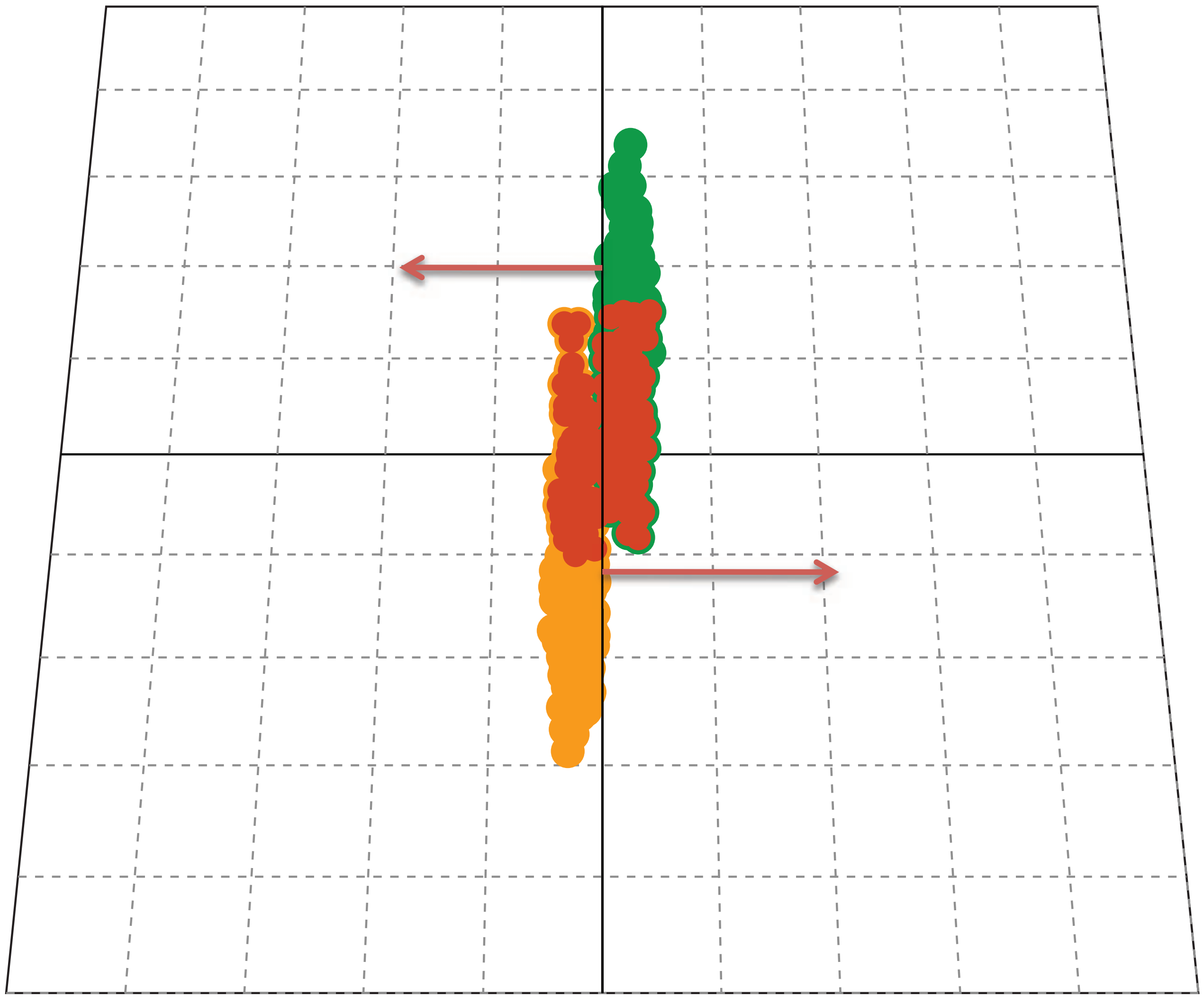

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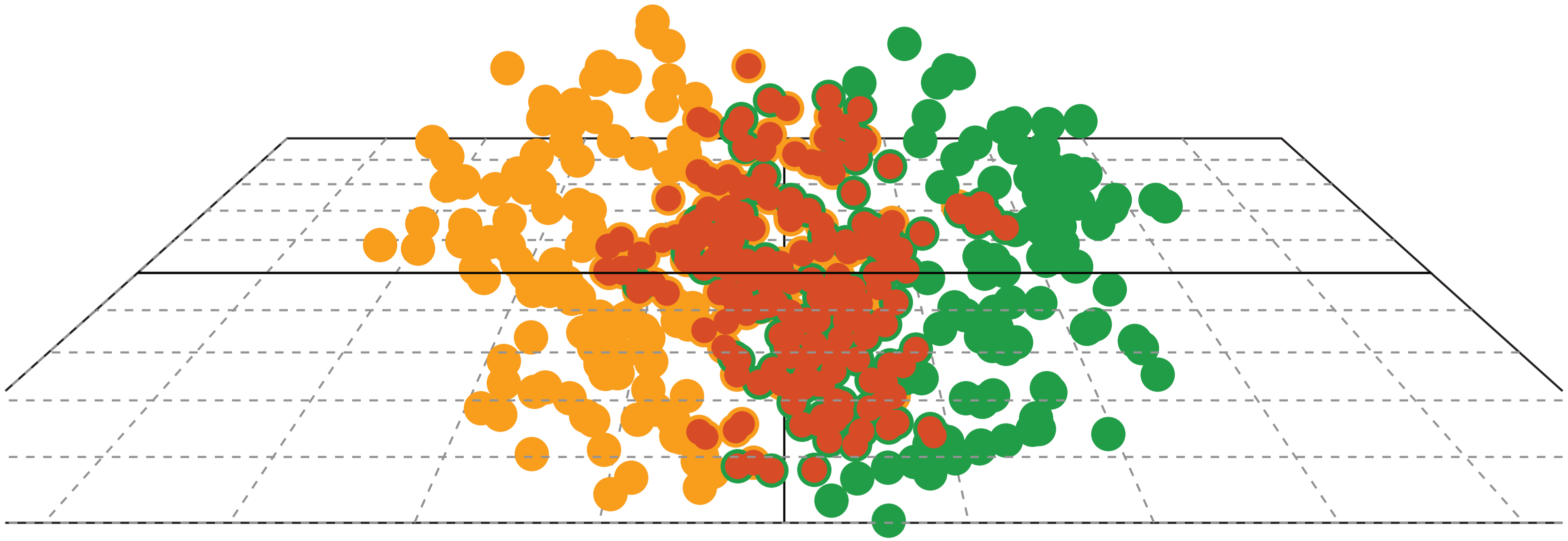
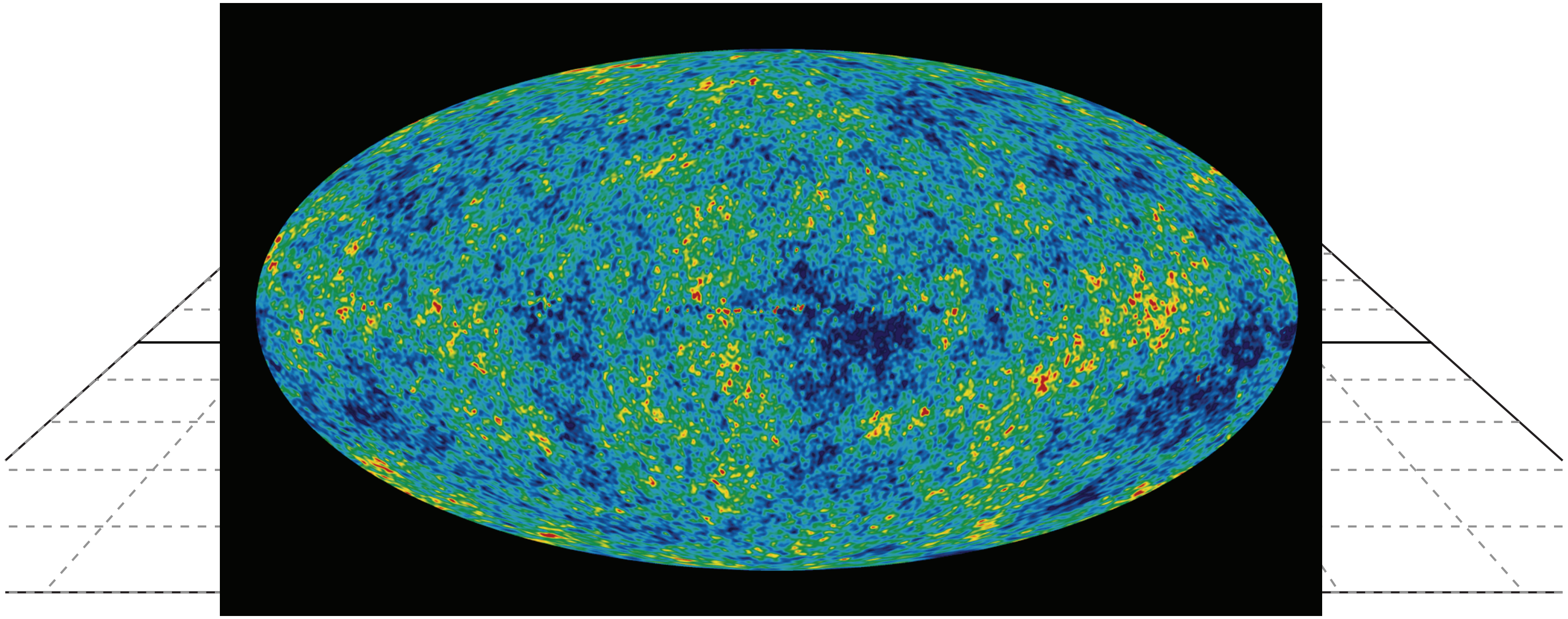


Produced fireball is ~10^{-14} meters across and lives for ~5×10^{-23} seconds

Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen



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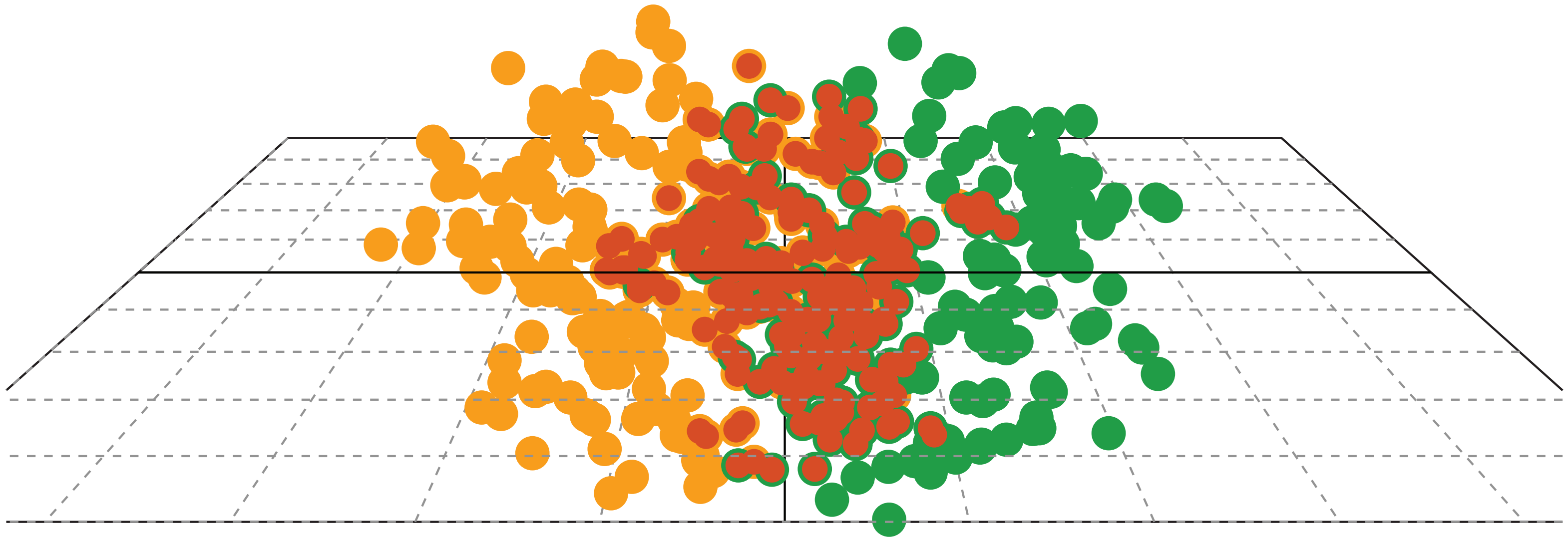
Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

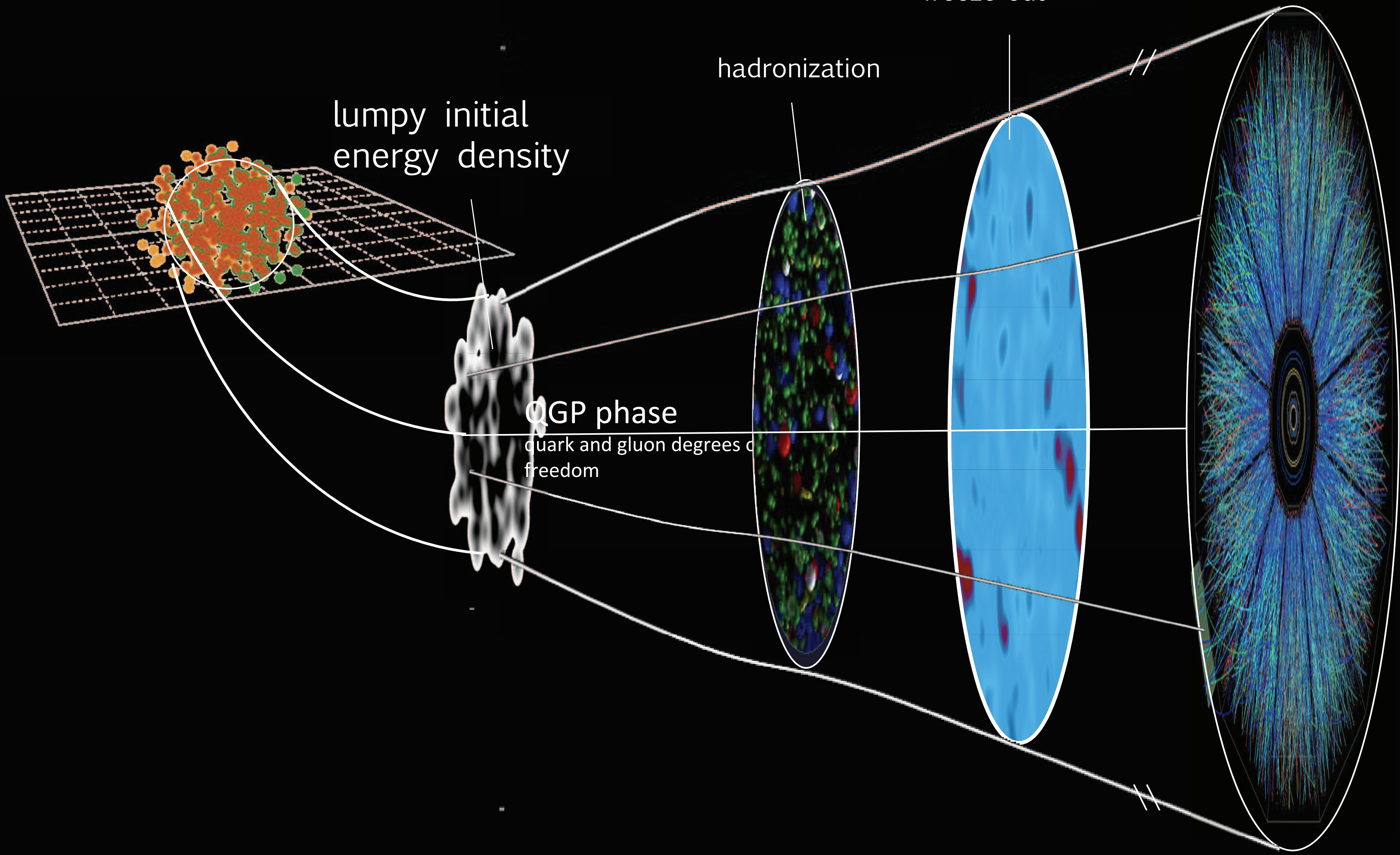
Animation: P. Sorensen



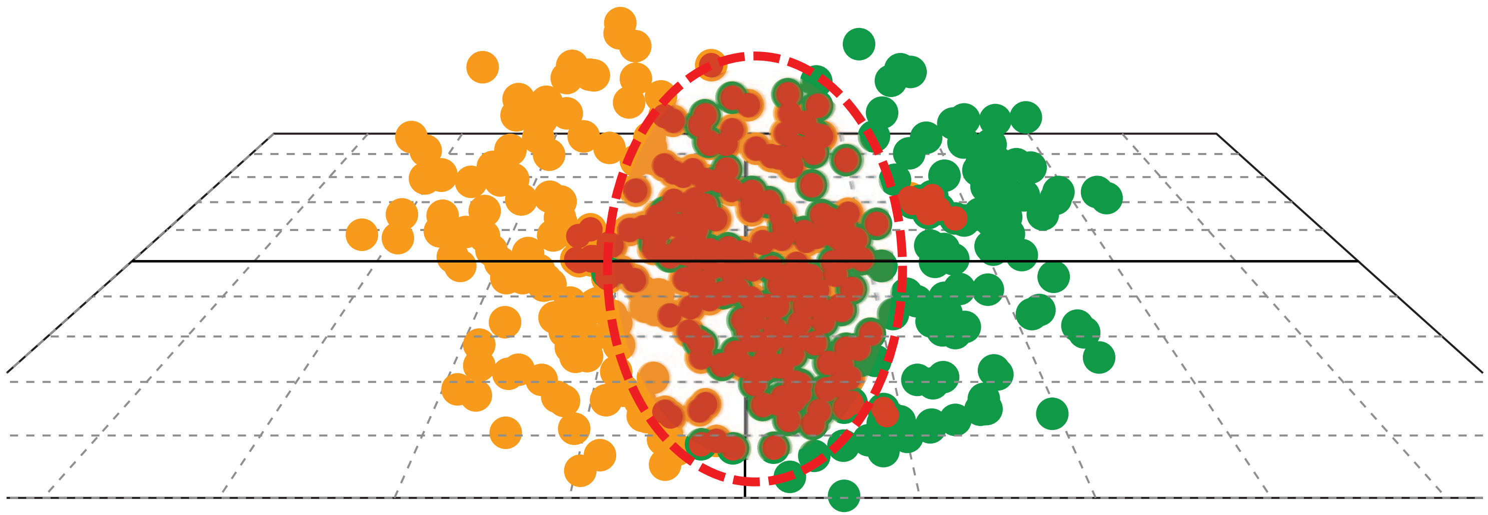
Produced fireball is ~10^{-14} meters across and lives for ~$5\text{x}10^{-23}$ seconds

Collision of two Lorentz contracted gold nuclei

Expansion of the Little Bang



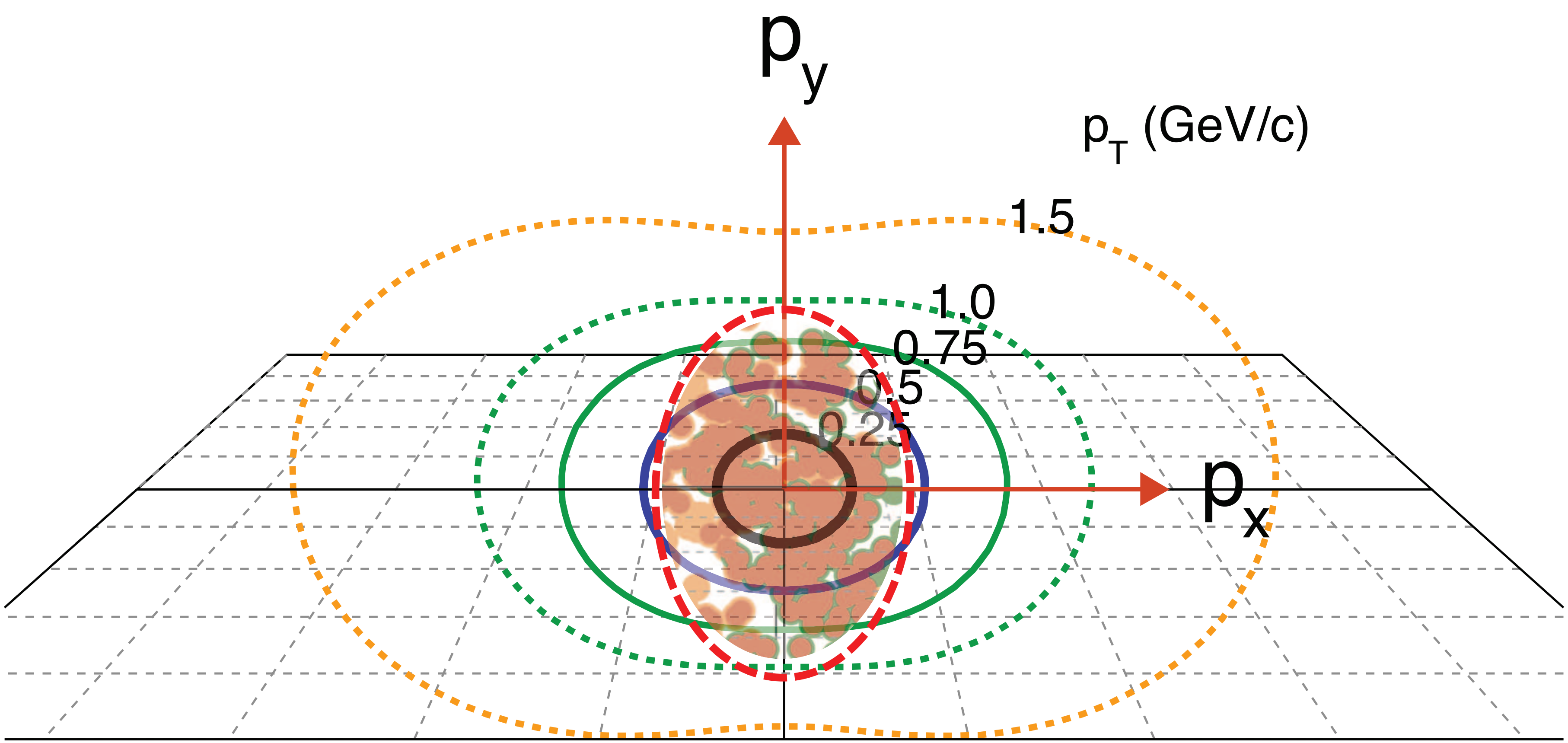
Azimuthal Distributions: x-space



Are particles emitted at random angles?

No. They remember the initial geometry!

Azimuthal Distributions: p-space



Are particles emitted at random angles?

No. They remember the initial geometry!

The Little Bang:

The Movie

How anisotropic flow is measured:

Definition of flow coefficients:

$$\frac{dN^{(i)}}{dy\, p_T dp_T\, d\phi_p}(b) = \frac{dN^{(i)}}{dy\, p_T dp_T}(b) \left(1 + 2\sum_{n=1}^{\infty} \boldsymbol{v_n^{(i)}(y, p_T; b)} \cos(\phi_p - \Psi_n^{(i)})\right).$$

Define event average $\{\ldots\}$, ensemble average $\langle \ldots \rangle$

Flow coefficients v_n typically extracted from azimuthal correlations (k-particle cumulants). E.g. $k = 2, 4$:

$$c_n\{2\} = \langle\{e^{ni(\phi_1-\phi_2)}\}\rangle = \langle\{e^{ni(\phi_1-\psi_n)}\}\{e^{-ni(\phi_2-\psi_n)}\} + \delta_2\rangle = \langle v_n^2 + \delta_2\rangle$$
$$c_n\{4\} = \langle\{e^{ni(\phi_1+\phi_2-\phi_3-\phi_4)}\}\rangle - 2\langle\{e^{ni(\phi_1-\phi_2)}\}\rangle = \langle -v_n^4 + \delta_4\rangle$$

v_n is correlated with the event plane while δ_n is not ("non-flow"). $\delta_2 \sim 1/M$, $\delta_4 \sim 1/M^3$. 4^{th}-order cumulant is free of 2-particle non-flow correlations.

These measures are affected by event-by-event flow fluctuations:

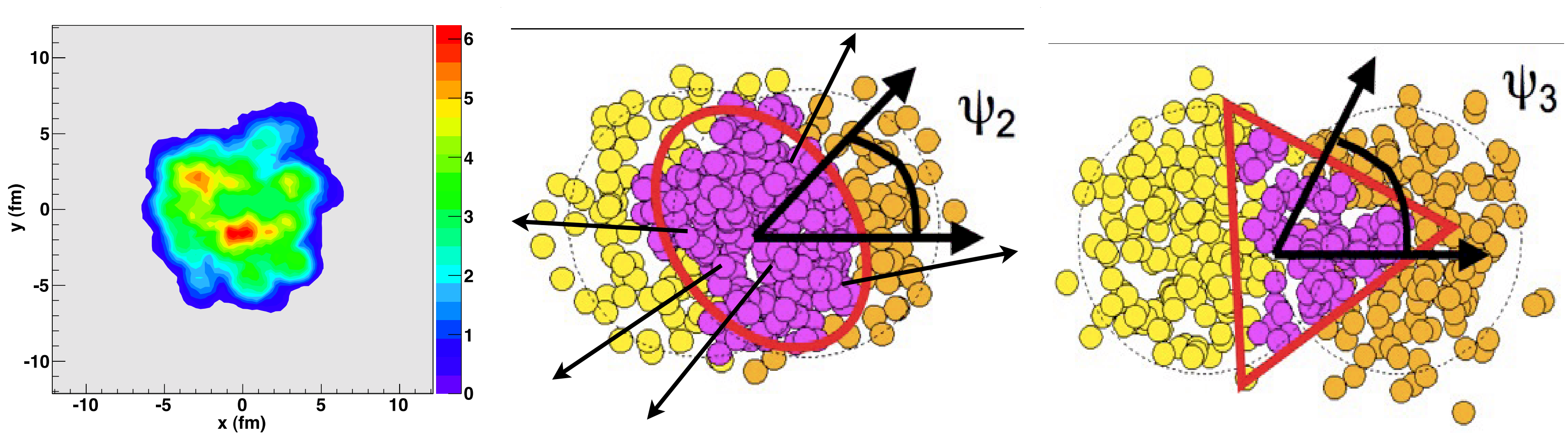
$$\langle v_2^2\rangle = \langle v_2\rangle^2 + \sigma^2, \qquad \langle v_2^4\rangle = \langle v_2\rangle^4 + 6\sigma^2\langle v_2\rangle^2$$

$\boldsymbol{v_n\{k\}}$ denotes the value of v_n extracted from the k^{th}-order cumulant:

$$v_2\{2\} = \sqrt{\langle v_2^2\rangle}, \qquad v_2\{4\} = \sqrt[4]{2\langle v_2^2\rangle^2 - \langle v_2^4\rangle}$$

Event-by-event shape and flow fluctuations rule!

(Alver and Roland, PRC81 (2010) 054905)



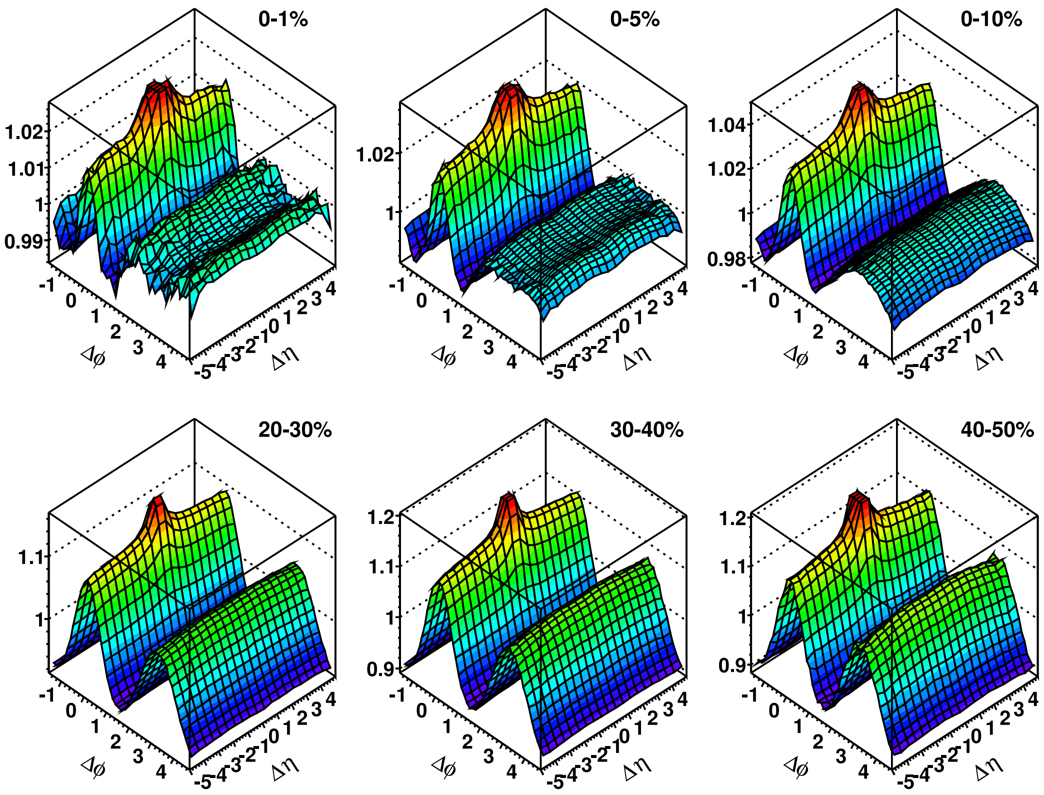
- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n

- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n

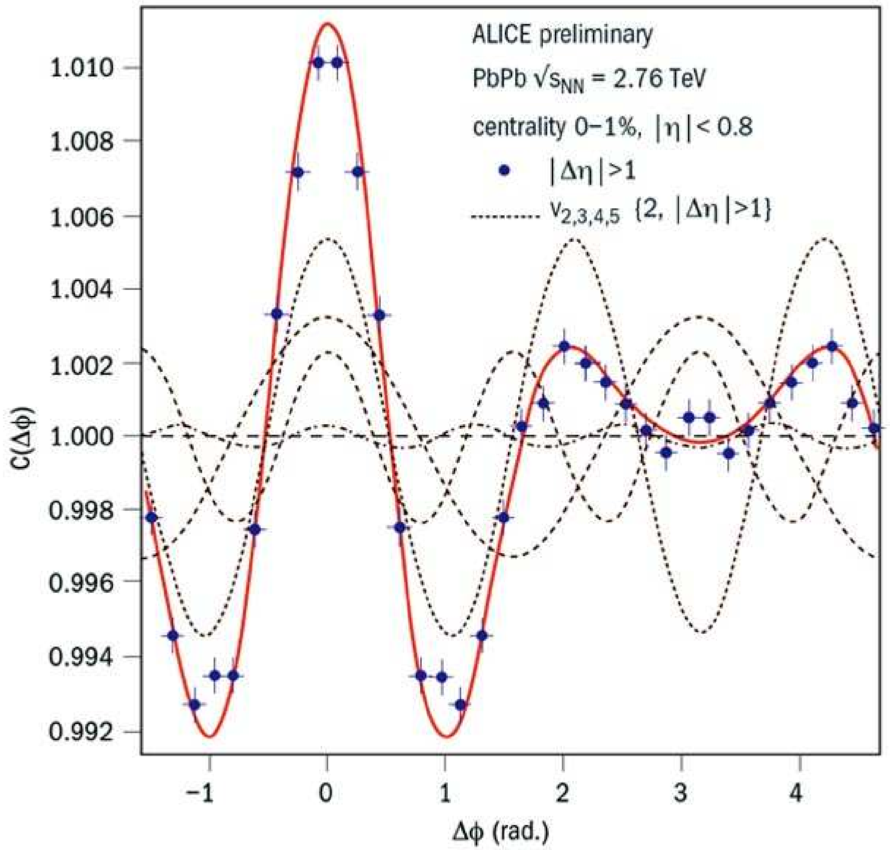
- At small impact parameters fluctuations ("hot spots") dominate over geometric overlap effects
(Alver & Roland, PRC81 (2010) 054905; Qin, Petersen, Bass, Müller, PRC82 (2010) 064903)

Panta rhei: "soft ridge"="Mach cone"=flow!

ATLAS (J. Jia), Quark Matter 2011



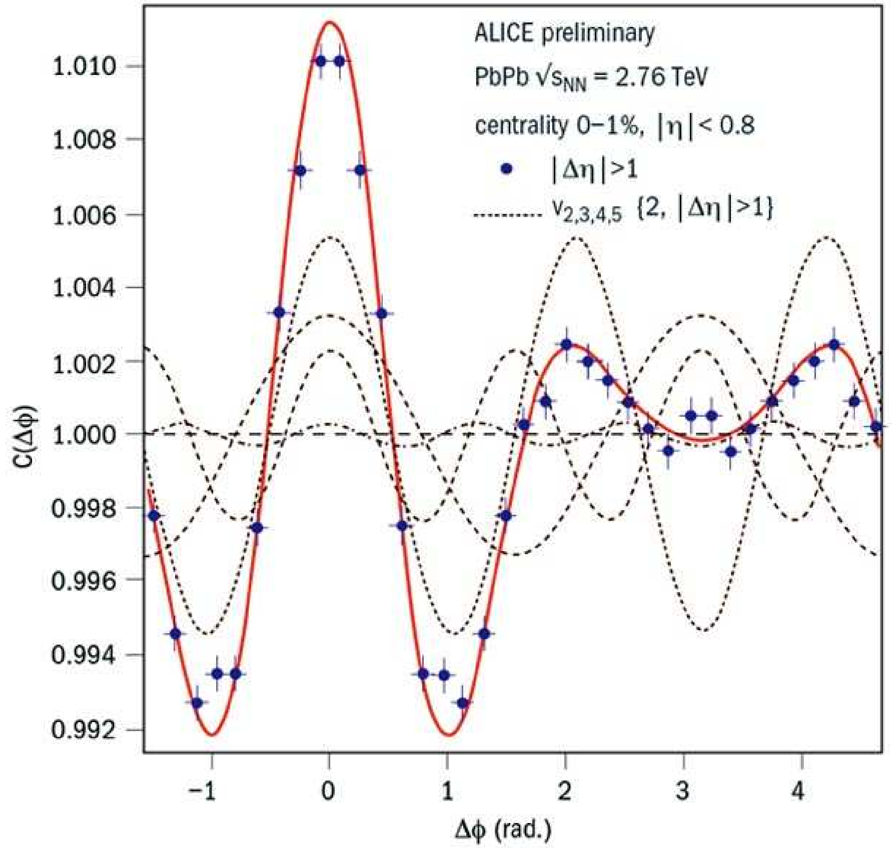
ALICE (J. Grosse-Oetringhaus), QM11



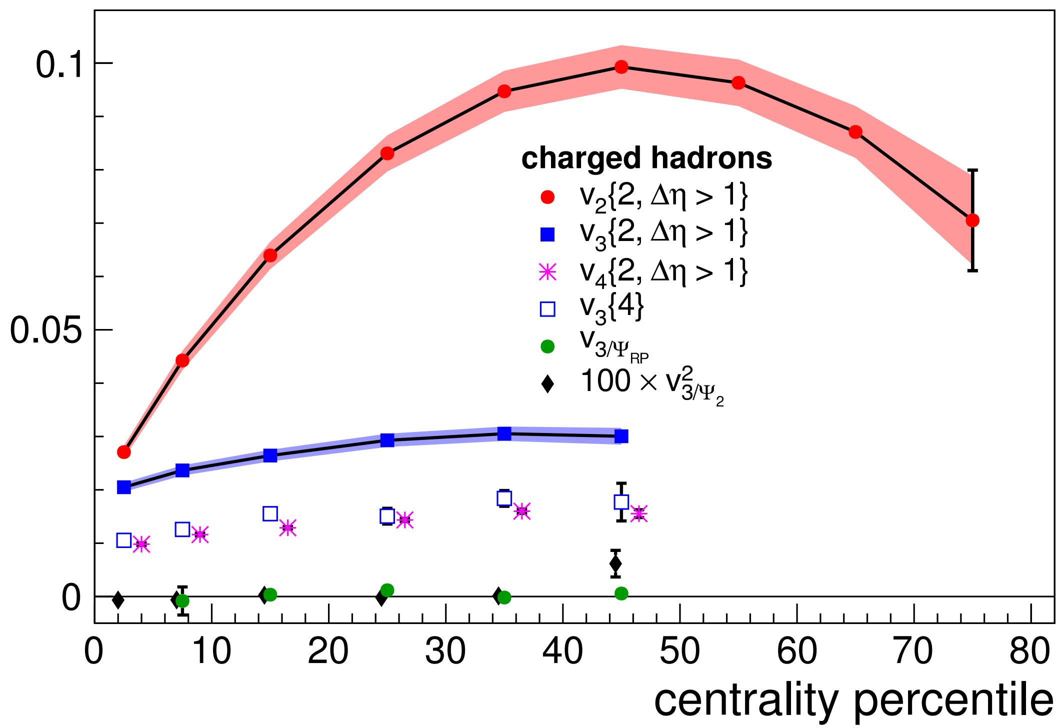
- anisotropic flow coefficients v_n and flow angles ψ_n correlated over large rapidity range!
  M. Luzum, PLB 696 (2011) 499: All long-range rapidity correlations seen at RHIC are consistent with being entirely generated by hydrodynamic flow.

- in the 1% most central collisions $v_3 > v_2$
  $\Longrightarrow$ prominent "Mach cone"-like structure!
  $\Longrightarrow$ event-by-event eccentricity fluctuations dominate!

Event-by-event shape and flow fluctuations rule!



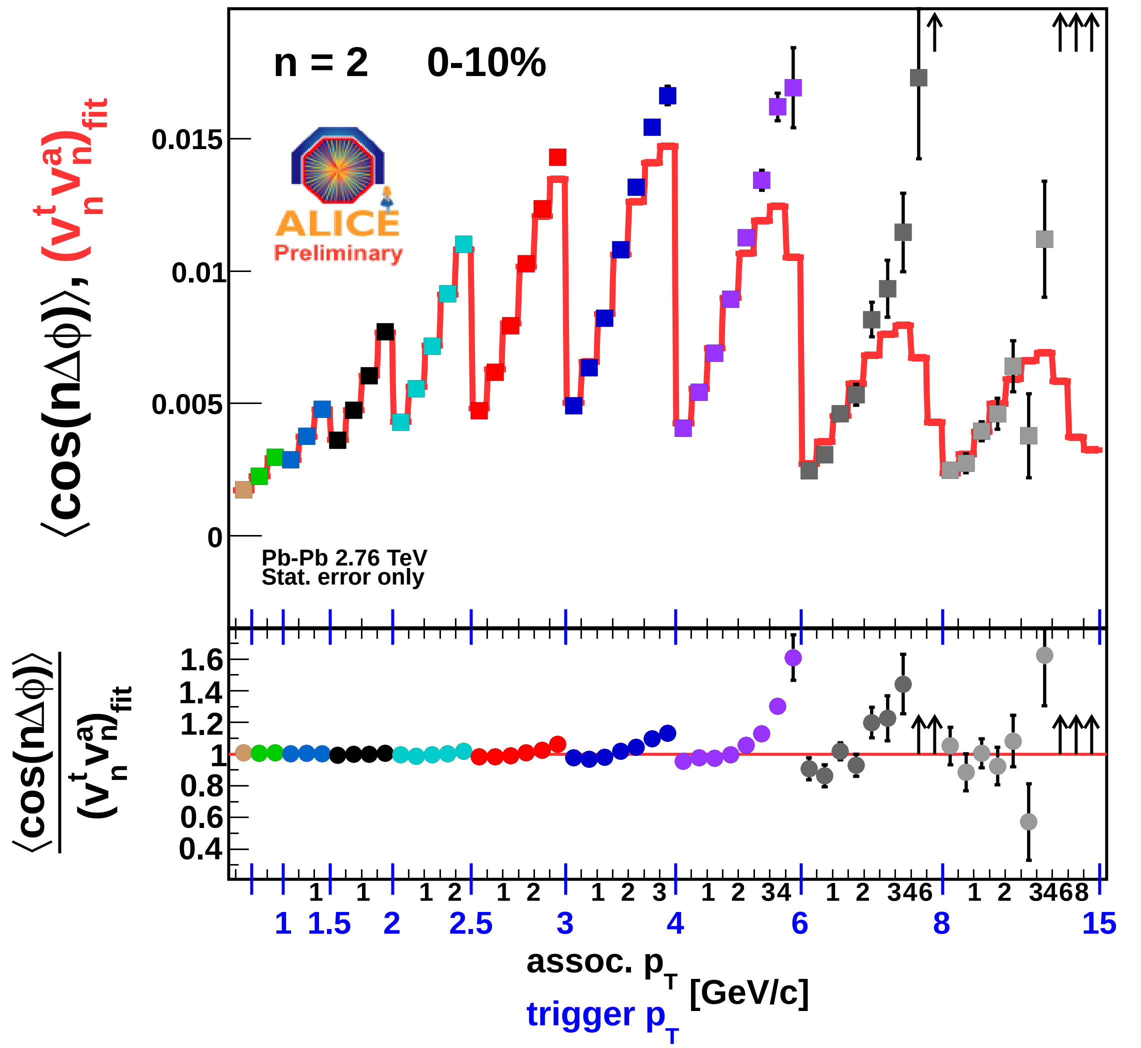
ALICE (A. Bilandzic) Quark Matter 2011



- in the 1% most central collisions $v_3 > v_2 \Longrightarrow$ prominent "Mach cone"-like structure!
- triangular flow angle uncorrelated with reaction plane and elliptic flow angles
  $\Longrightarrow$ due to event-by-event eccentricity fluctuations which dominate the anisotropic flows in the most central collisions

Fluctuation-driven anisotropic flow is indeed collective!

ALICE (J. Grosse-Oetringhaus) Quark Matter 2011

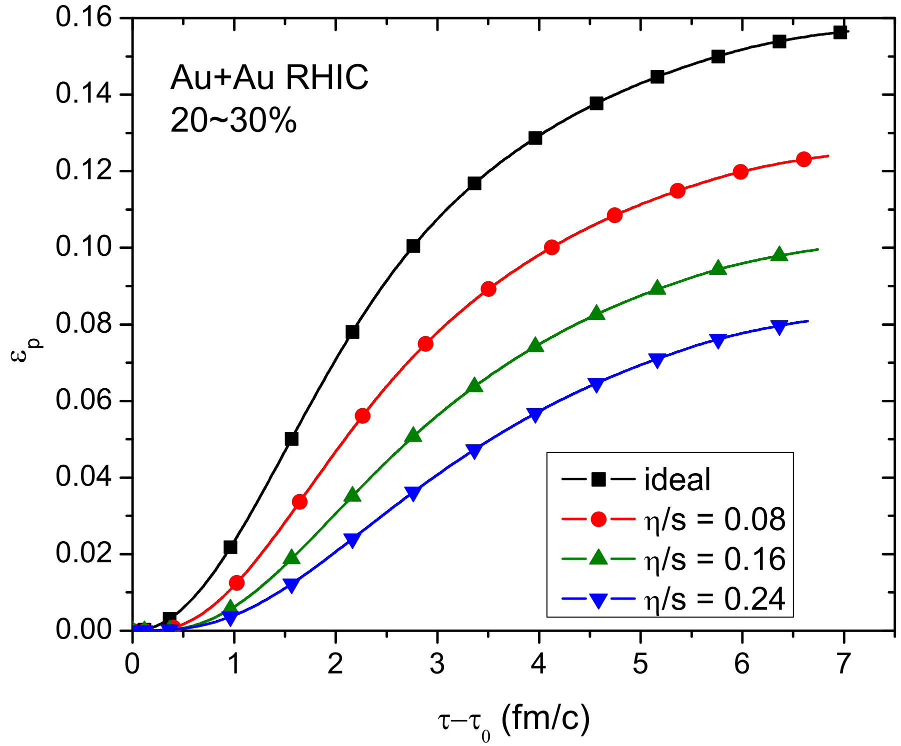


- Two-particle Fourier coefficients factorize ($v_{n\Delta}(p_{T1}, p_{T2}) = v_n(p_{T1}) v_n(p_{T2})$) as required
- Factorization shown to work for $n = 2, 3, 4, 5$ as long as both $p_{T1}, p_{T2} < 3\,\text{GeV}/c$ (bulk matter)

Converting initial shape fluctuations into final flow anisotropies – the QGP shear viscosity $(\eta/s)_{\rm QGP}$

How to use elliptic flow for measuring $(\eta/s)_{\rm QGP}$

Hydrodynamics converts
spatial deformation of initial state $\Longrightarrow$
momentum anisotropy of final state,
through anisotropic pressure gradients



Shear viscosity degrades conversion efficiency

$$\varepsilon_x = \frac{\langle\langle y^2-x^2\rangle\rangle}{\langle\langle y^2+x^2\rangle\rangle} \Longrightarrow \varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle}$$

of the fluid; the suppression of ε_p is monotonically related to η/s.

The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow $v_2^{\rm ch}$**:

$$\varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle} \Longleftrightarrow \frac{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \cos(2\phi_p)\, \frac{dN_i}{dy p_T dp_T d\phi_p}}{\sum_i \int p_T dp_T \int d\phi_p\, p_T^2\, \frac{dN_i}{dy p_T dp_T d\phi_p}} \Longleftrightarrow v_2^{\rm ch}$$

How to use elliptic flow for measuring $(\eta/s)_{\rm QGP}$ (contd.)

- **If** ε_p **saturates** before hadronization (e.g. in PbPb@LHC (?))

$\Rightarrow$ $v_2^{\rm ch} \approx$ not affected by details of hadronic rescattering below $T_{\rm c}$

but: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dy d^2p_T}$ change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)

$\Rightarrow$ $v_2(p_T)$ of a single particle species **not** a good starting point for extracting η/s

- **If** ε_p **does not saturate** before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of ε_p over hadronic species and in p_T, but even the final value of ε_p itself (from which we want to get η/s)

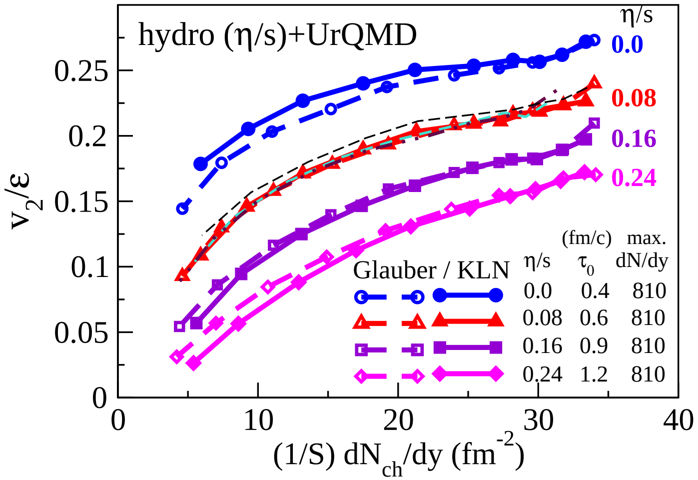
$\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

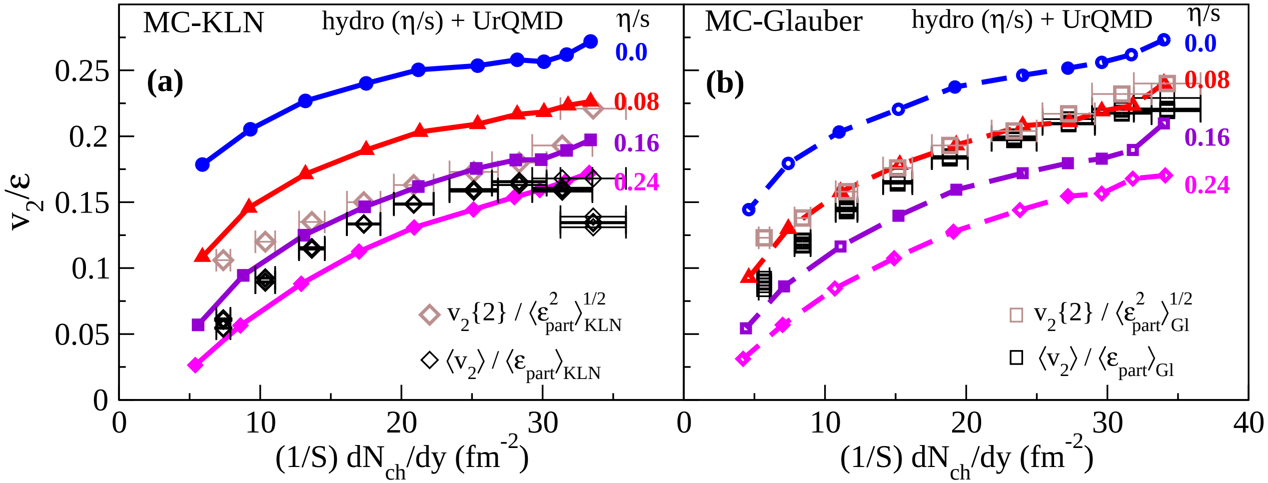
$\Rightarrow$ **VISHNU** ("Viscous Israel-Steward Hydrodynamics 'n' UrQMD")

(Song, Bass, UH, PRC83 (2011) 024912) Note: this paper shows that UrQMD $\neq$ viscous hydro!

Extraction of $(\eta/s)_{\rm QGP}$ from AuAu@RHIC

H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRL106 (2011) 192301



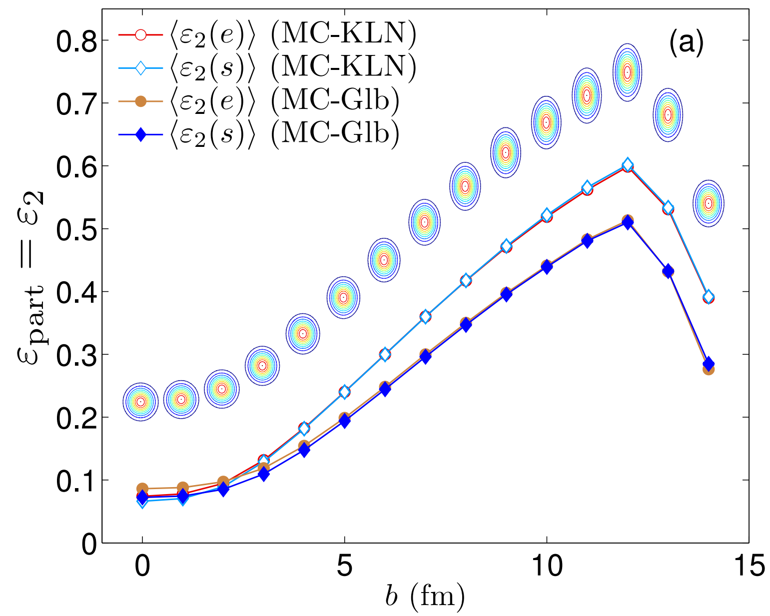


$$1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$$

- All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as p_T-spectra of charged hadrons, pions and protons at all centralities
- $v_2^{\rm ch}/\varepsilon_x$ vs. $(1/S)(dN_{\rm ch}/dy)$ is "universal", i.e. depends **only on** η/s but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- dominant source of uncertainty: $\varepsilon_x^{\rm Gl}$ vs. $\varepsilon_x^{\rm KLN}$ $\longrightarrow$
- smaller effects: *early flow* $\to$ increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % $\to$ larger η/s

  bulk viscosity $\to$ affects $v_2^{\rm ch}(p_T)$, but $\approx$ not $v_2^{\rm ch}$

Zhi Qiu, UH, PRC84 (2011) 024911



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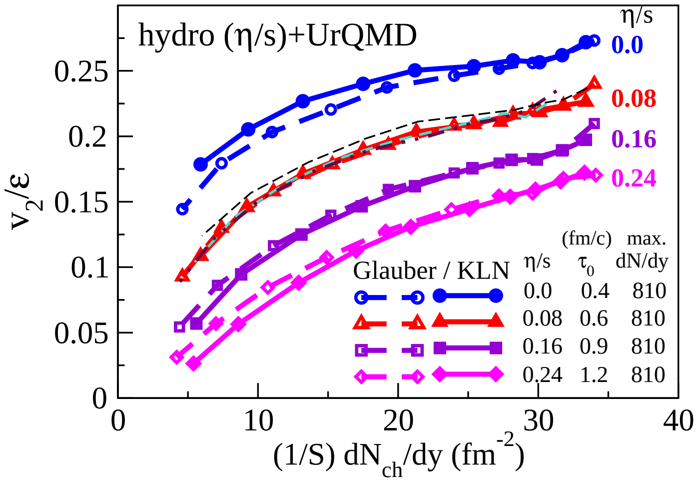
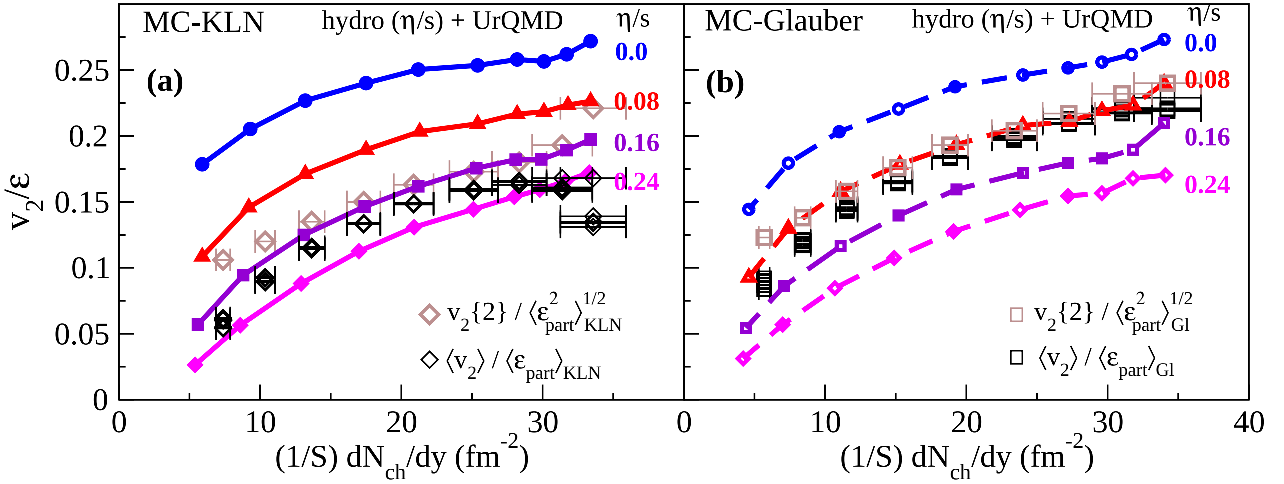
H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRL106 (2011) 192301





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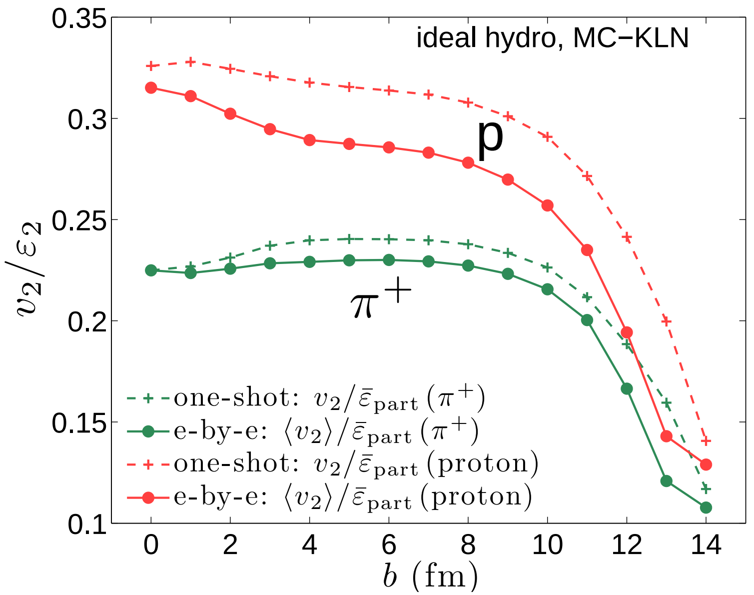
- smaller effects: *early flow* $\to$ increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % $\to$ larger η/s

  bulk viscosity $\to$ affects $v_2^{\rm ch}(p_T)$, but $\approx$ not $v_2^{\rm ch}$

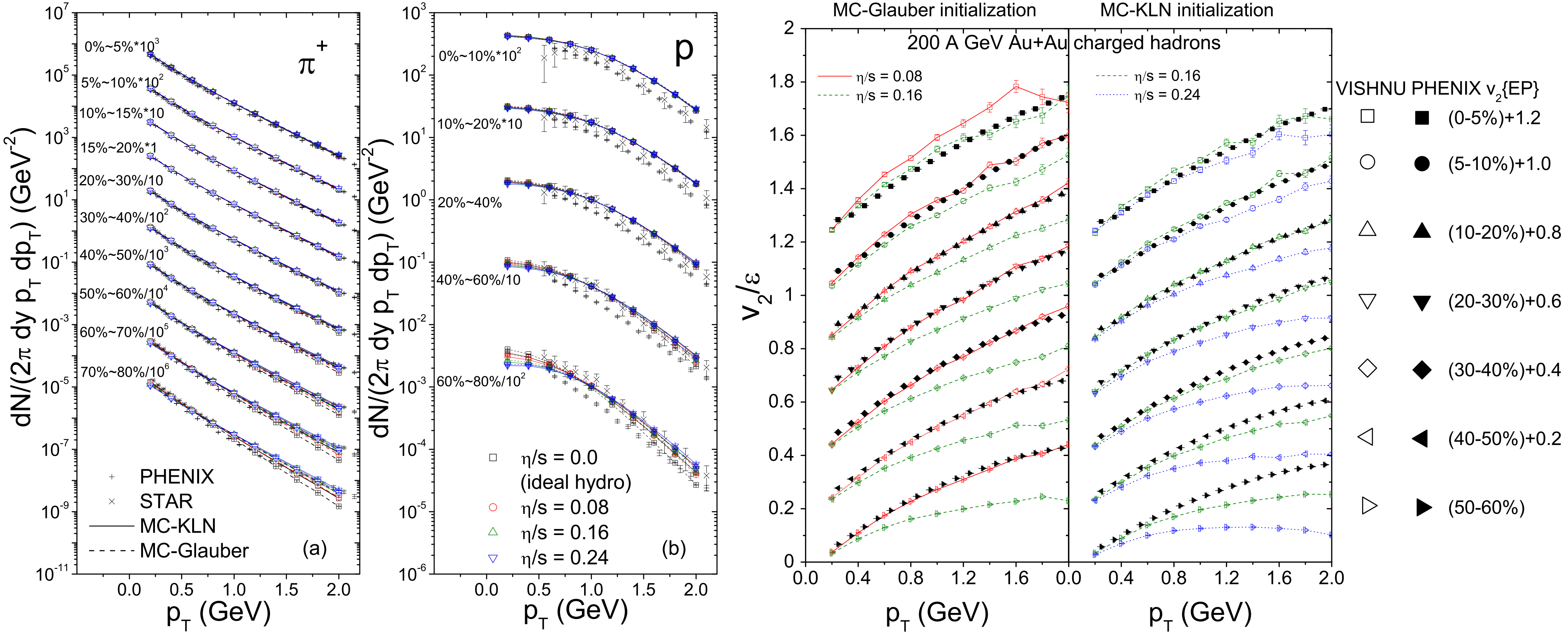
  e-by-e hydro $\to$ decreases $\frac{v_2^{\rm ch}}{\varepsilon}$ by $\lesssim 5\%$ (dep. on η/s)

Zhi Qiu, UH, PRC84 (2011) 024911



Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)

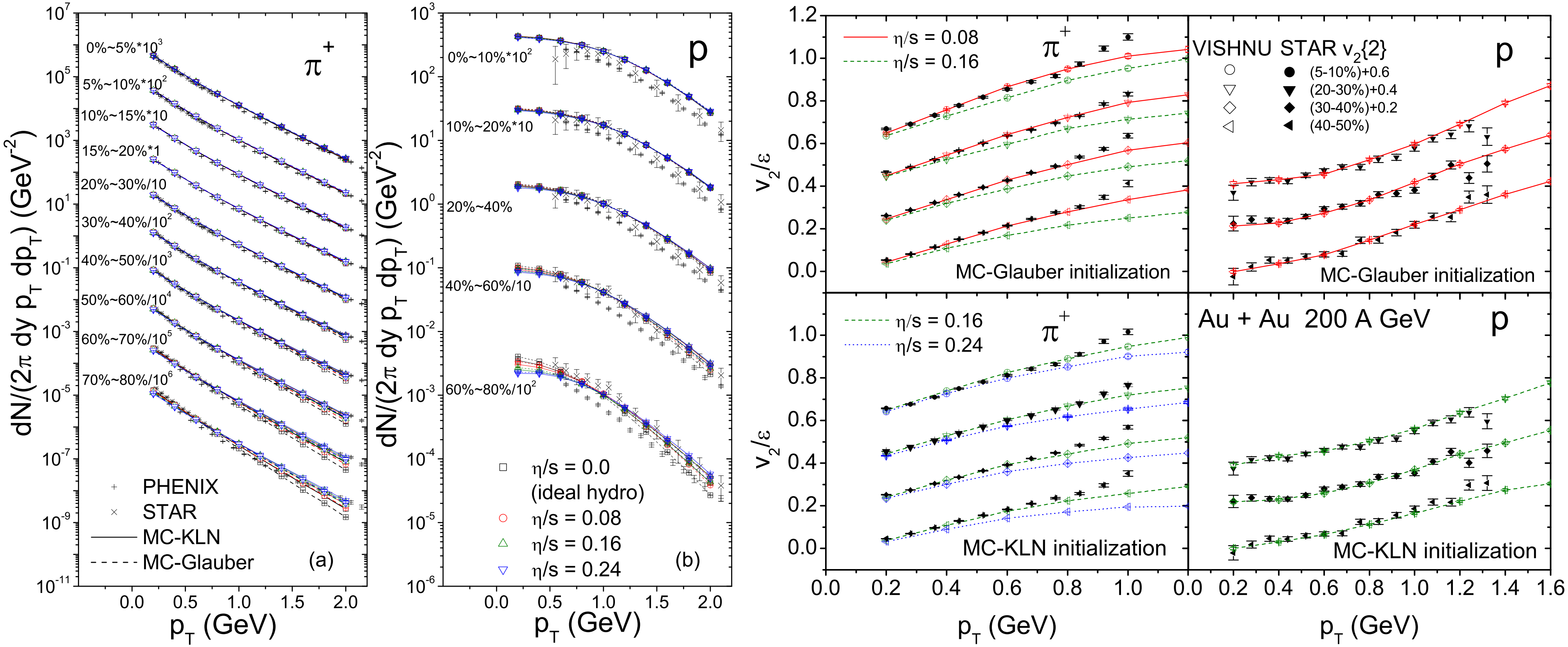


- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

- Note: $T_{\rm chem} = 165$ MeV reproduces the proton spectra from STAR, but not from PHENIX! $\Longrightarrow$ Slightly incorrect chemical composition in hadronic phase? Not enough $p\bar{p}$ annihilation in UrQMD?

Global description of AuAu@RHIC spectra and v_2

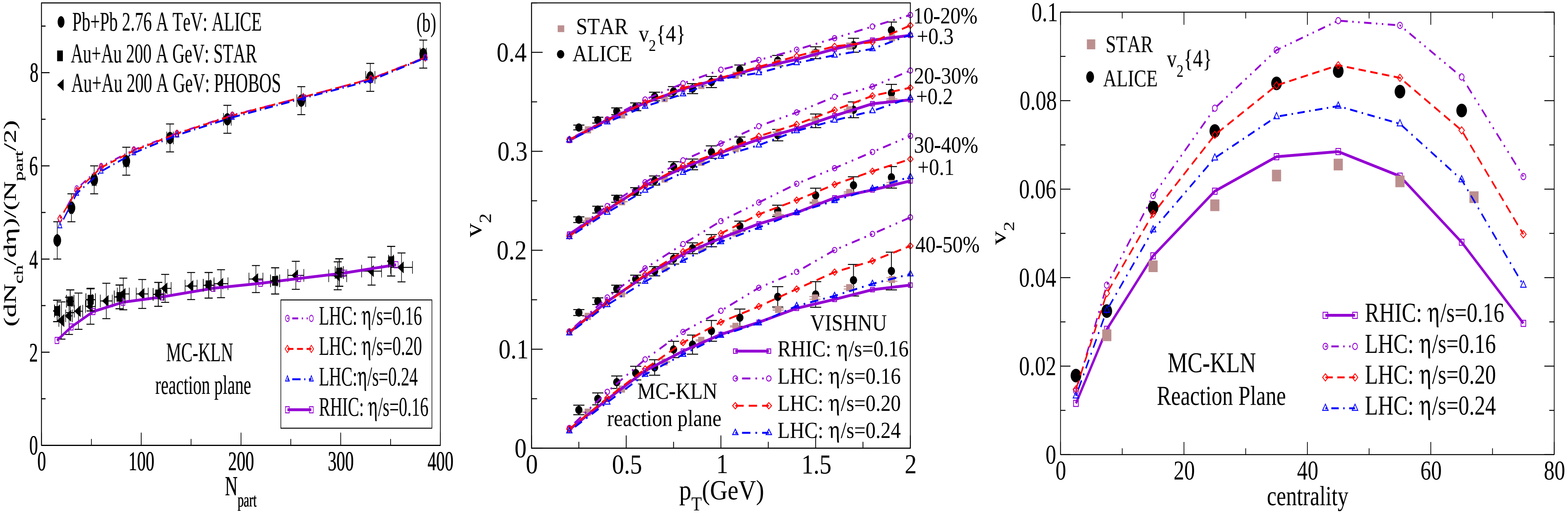
VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
- A purely hydrodynamic model (without UrQMD afterburner) with the same values of η/s does almost as well (except for centrality dependence of proton $v_2(p_T)$) (C. Shen et al., PRC84 (2011) 044903)
  Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ($\tau_0 = 0.6$ instead of 1.05 fm$/c$), otherwise proton spectra are too steep
- These η/s values agree with Luzum & Romatschke, PRC78 (2008), even though they used EOS with incorrect hadronic chemical composition $\Longrightarrow$ shows robustness of extracting η/s from total charged hadron v_2

Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (Song, Bass, UH, PRC83 (2011) 054912)



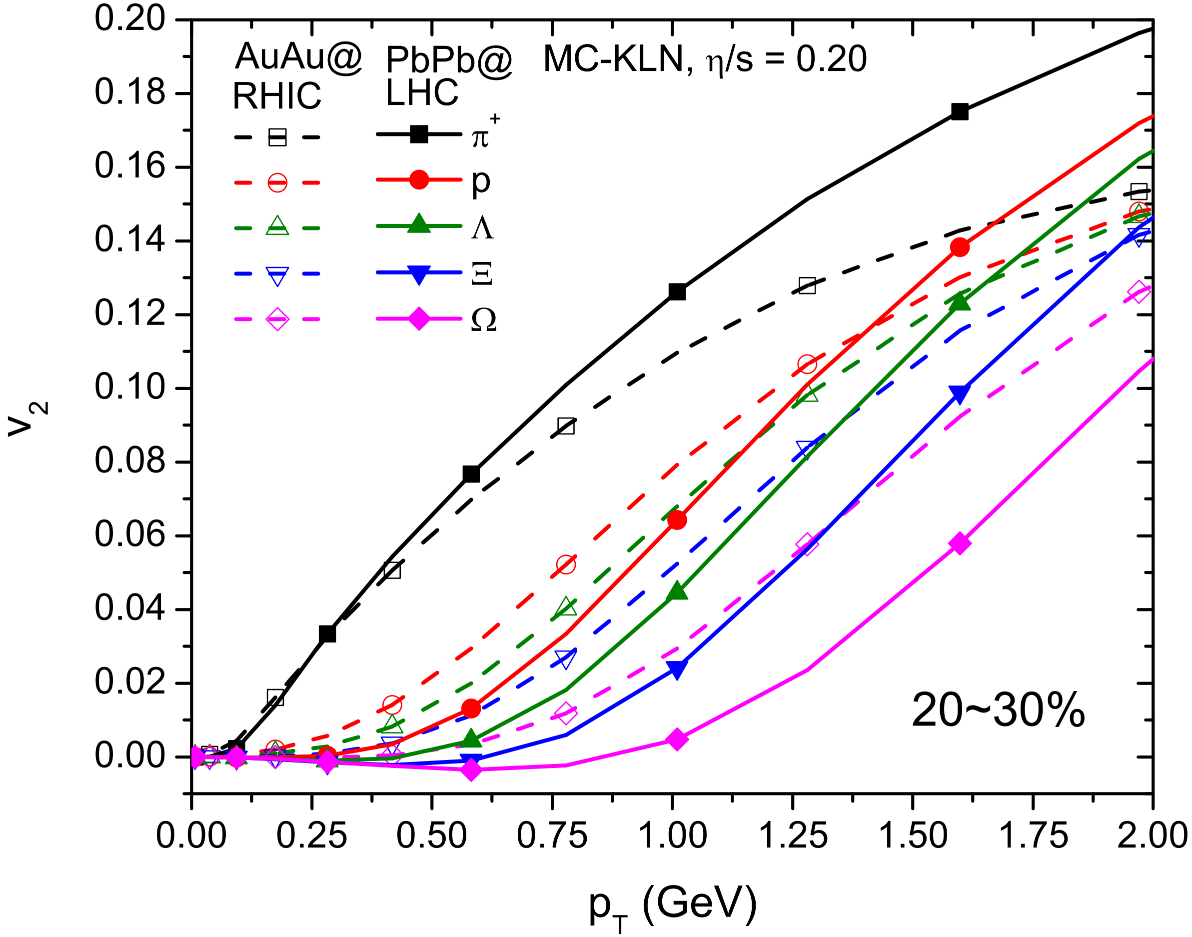
- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\mathrm{ch}}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\mathrm{QGP}} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ and integrated v_2 in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC
- Similar results from predictions based on pure viscous hydro (C. Shen et al., PRC84 (2011) 044903)
- **but:** At LHC significant sensitivity of v_2 to initialization of viscous pressure tensor $\pi^{\mu\nu}$ (Navier-Stokes or zero) $\Longrightarrow$ need pre-equilibrium model.

  $\Longrightarrow$ **QGP at LHC definitely not much more viscous than at RHIC!**

Why is $v_2^{\mathrm{ch}}(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)

C. Shen, UH, P. Huovinen, H. Song, PRC84 (2011) 044903



$v_2^{\pi}(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed p_T decreases

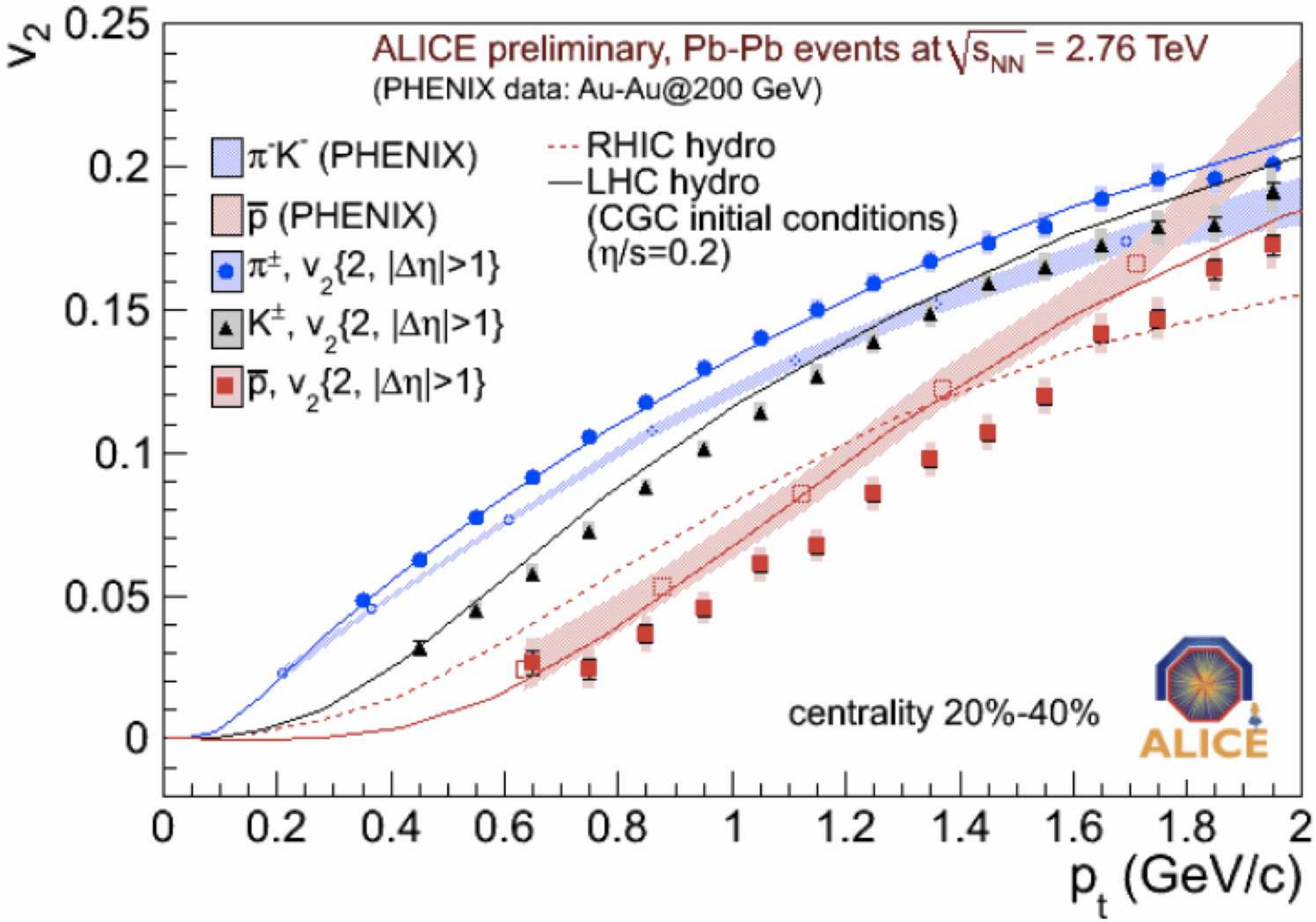
(radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

This is a hard prediction of hydrodynamics! (See also Nagle, Bearden, Zajc, NJP13 (2011) 075004)

Confirmation of increased mass splitting at LHC

Data: ALICE @ LHC, Quark Matter 2011 (symbols), PHENIX @ RHIC (shaded)

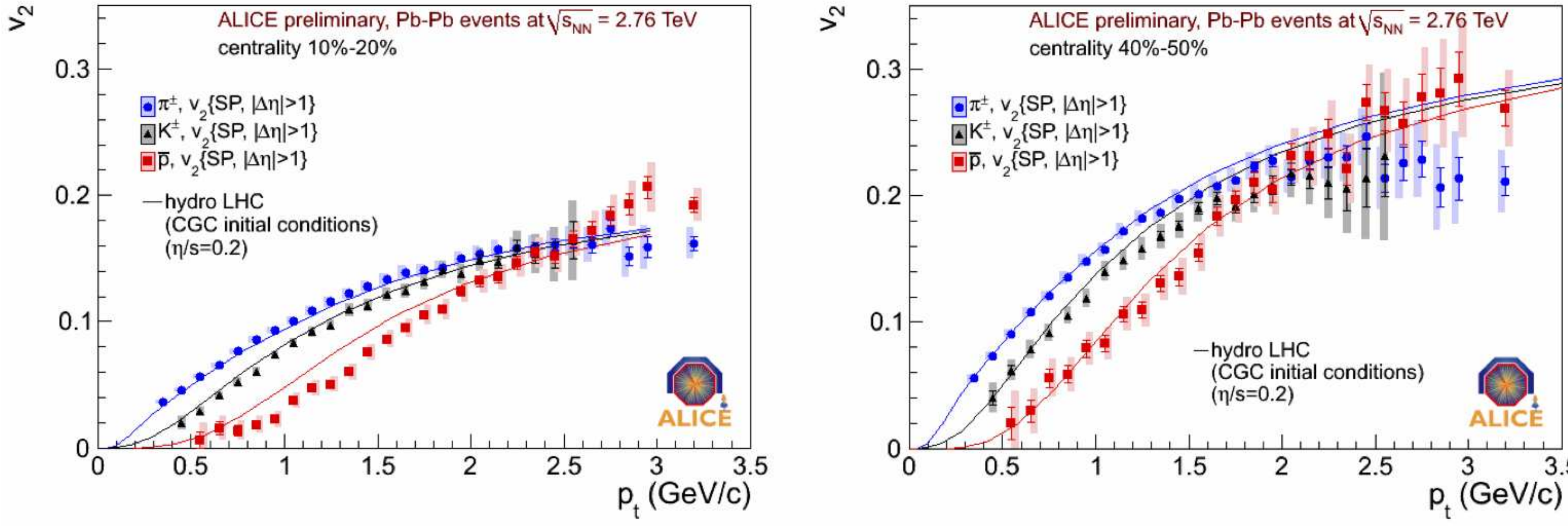
Lines: Shen et al., PRC84 (2011) 044903 (VISH2+1 + MC-KLN, η/s=0.2)



- Qualitative features of data agree with VISH2+1 predictions
- VISH2+1 does not push proton v_2 strongly enough to higher p_T, both at RHIC and LHC
- At RHIC we know that this is fixed when using VISHNU – is the same true at LHC?

Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE, Quark Matter 2011 Prediction: Shen et al., PRC84 (2011) 044903 (VISH2+1)



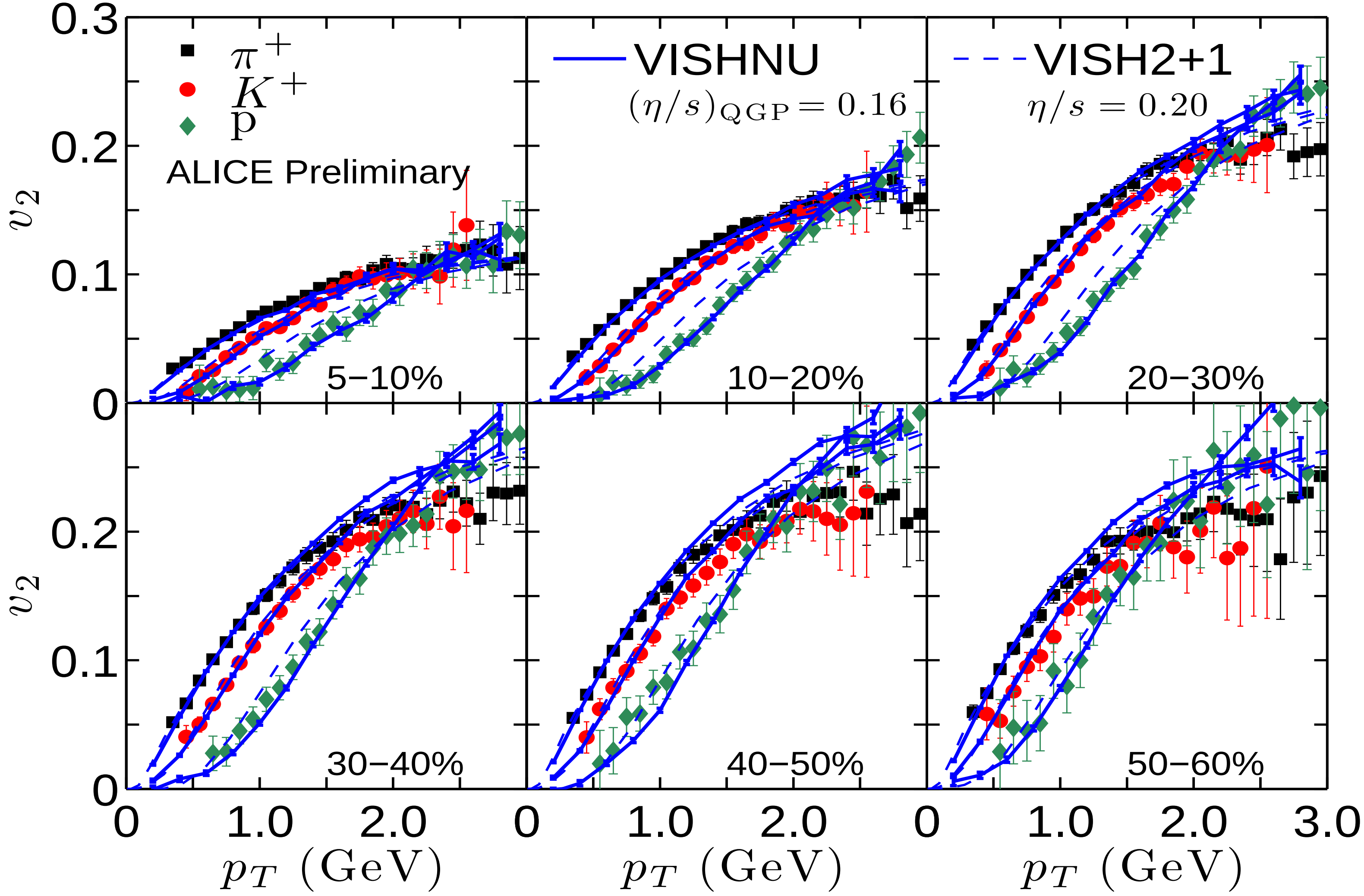
Perfect fit in semi-peripheral collisions!

The problem with insufficient proton radial flow exists only in more central collisions

Adding the hadronic cascade (VISHNU) helps:

$v_2(p_T)$ in PbPb@LHC: ALICE vs. VISH2+1 & VISHNU

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)
Dashed lines: Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, $(\eta/s)_{\mathrm{QGP}}=0.2$)
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{\mathrm{QGP}}=0.16$)



VISHNU yields correct magnitude and centrality dependence of $v_2(p_T)$ for pions, kaons **and protons!**

Same $(\eta/s)_{\mathrm{QGP}} = 0.16$ (for MC-KLN) at RHIC and LHC!

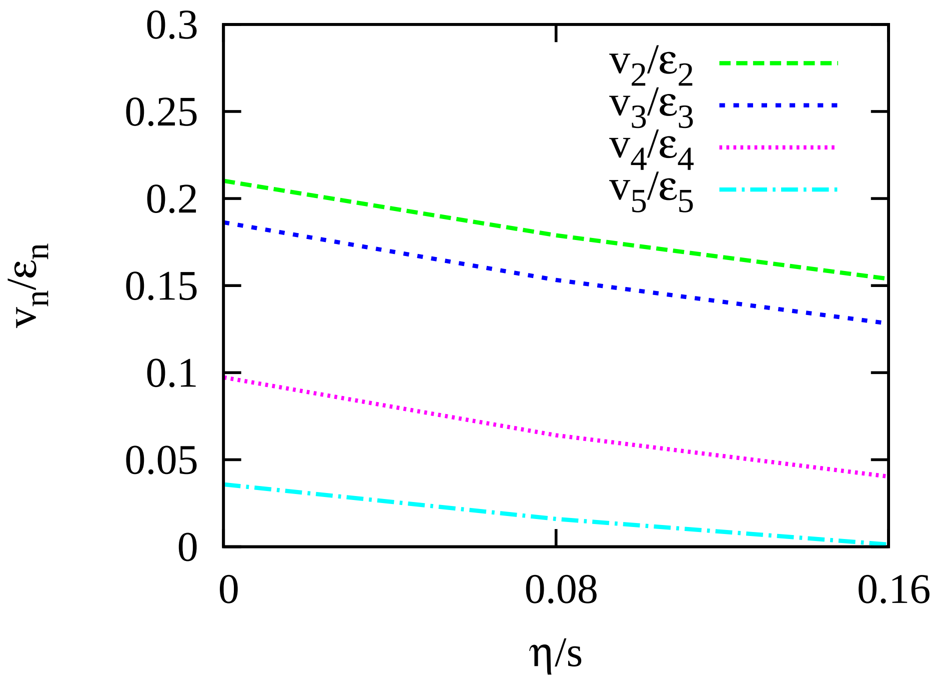
Back to the “elephant in the room”: How to eliminate the large model uncertainty in the initial eccentricity?

Two observations:

I. Shear viscosity suppresses higher flow harmonics more strongly

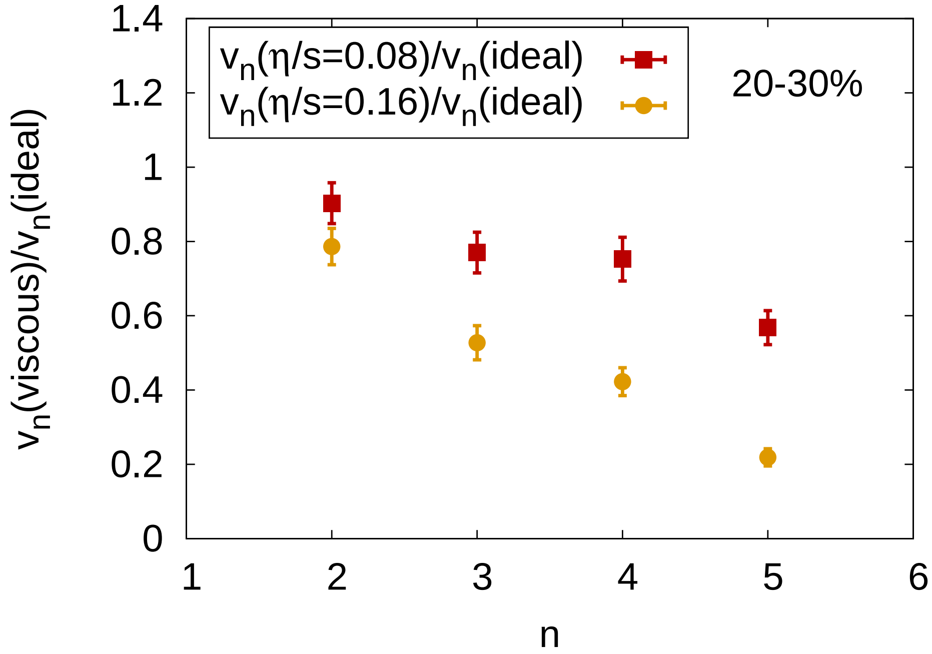
Alver et al., PRC82 (2010) 034913

(averaged initial conditions)



Schenke et al., PRC85 (2012) 024901

(event-by-event hydro)

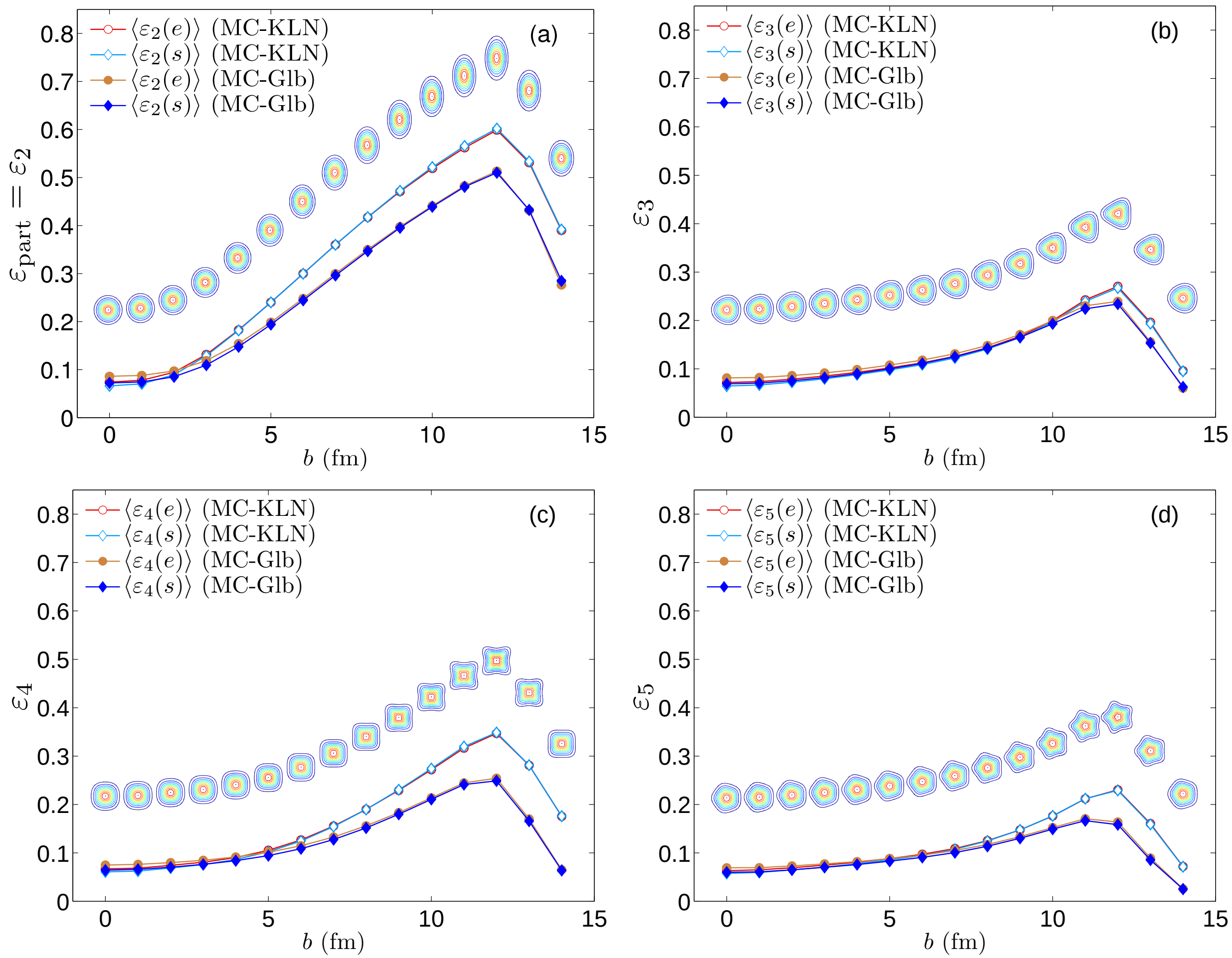


$\Longrightarrow$ **Idea:** Use simultaneous analysis of elliptic and triangular flow to constrain initial state models (see also Bhalerao, Luzum Ollitrault, PRC 84 (2011) 034910)

Two observations:

II. ε_3 is $\approx$ model independent

Zhi Qiu, UH, PRC84 (2011) 024911



Initial eccentricities ε_n and angles ψ_n:

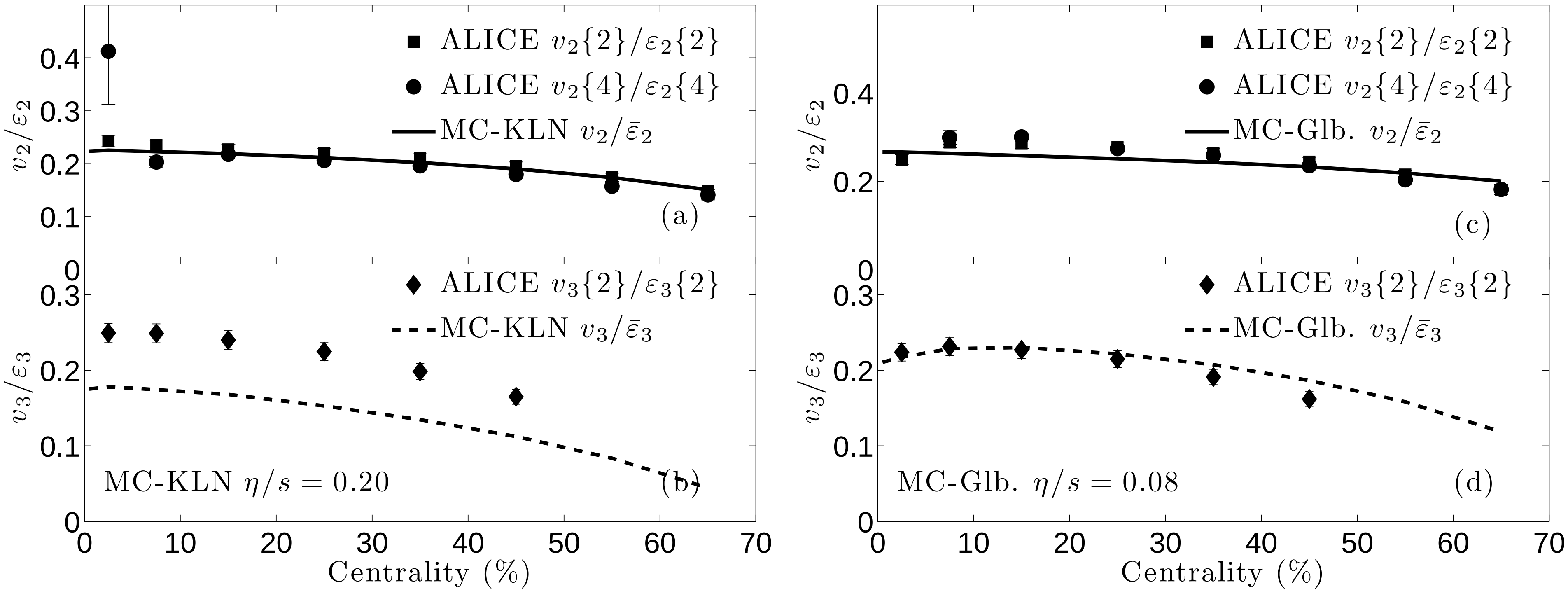
$$\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$$

- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber
- Angles of ε_2 and ε_4 are correlated with reaction plane by geometry, whereas those of ε_3 and ε_5 are random (purely fluctuation-driven)
- While v_4 and v_5 have mode-coupling contributions from ε_2, v_3 is almost pure response to ε_3 and $v_3/\varepsilon_3 \approx$ const. over a wide range of centralities

$\Longrightarrow$ **Idea:** Use total charged hadron $v_3^{\rm ch}$ to determine $(\eta/s)_{\rm QGP}$, then check $v_2^{\rm ch}$ to distinguish between MC-KLN and MC-Glauber!

Large measured v_3 requires small $(\eta/s)_{\rm QGP} \simeq 1/(4\pi)$!

Zhi Qiu, Chun Shen, UH, PLB707 (2012) 151 (VISH2+1)



- Both MC-KLN with $\eta/s = 0.2$ and MC-Glauber with $\eta/s = 0.08$ give very good description of v_2/ε_2 at all centralities.
- **Only MC-Glauber initial conditions with $\eta/s = 0.08$ describe v_3/ε_3**

  PHENIX, comparing to calculations by Alver et al. (PRC82 (2010) 034913), come to similar conclusions at RHIC energies (PHENIX Coll., PRL107 (2011) 252301, and Lacey et al., arXiv:1108.0457 (QM11))
- **Large v_3 measured at RHIC and LHC requires small $(\eta/s)_{\rm QGP} \simeq 1/(4\pi)$** unless the fluctuations predicted by both models are completely wrong and ε_3 is really 50% larger than we presently believe!

The "Little Bang Standard Model": Status 2012

- We have come a long way over the last couple of years:
  I believe that the issue of the QGP shear viscosity at RHIC and LHC energies is now settled:

$$(\eta/s)_{\rm QGP}(T_c < T < 2T_c) = \frac{1}{4\pi} \pm 50\%$$

  A moderate increase between $2T_c$ and $3T_c$ can at present not be excluded but is not mandated by the data.

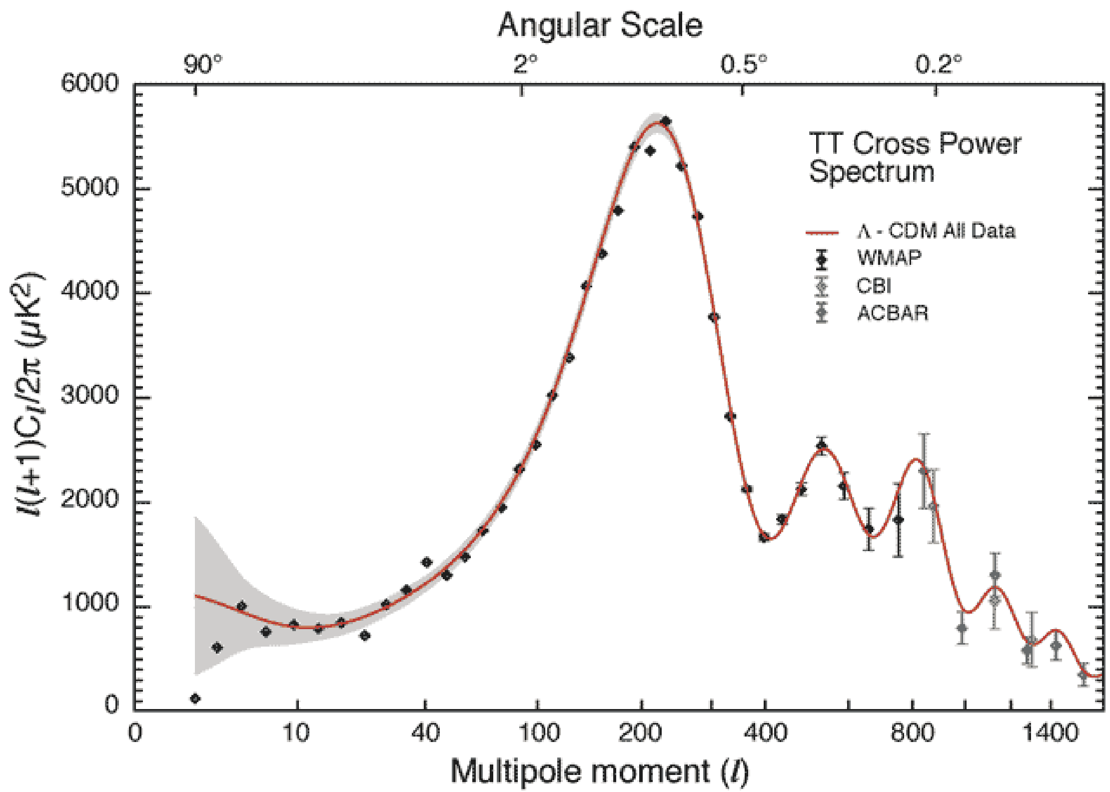
- Ingredients that matter at the 50% level and are under control:
  - relativistic viscous fluid dynamics
  - realistic EOS with correct non-equilibrium composition in HG phase
  - microscopic description of the highly dissipative hadronic stage, including all resonance decays
  - fluctuating initial conditions, simultaneous study of v_2 and v_3

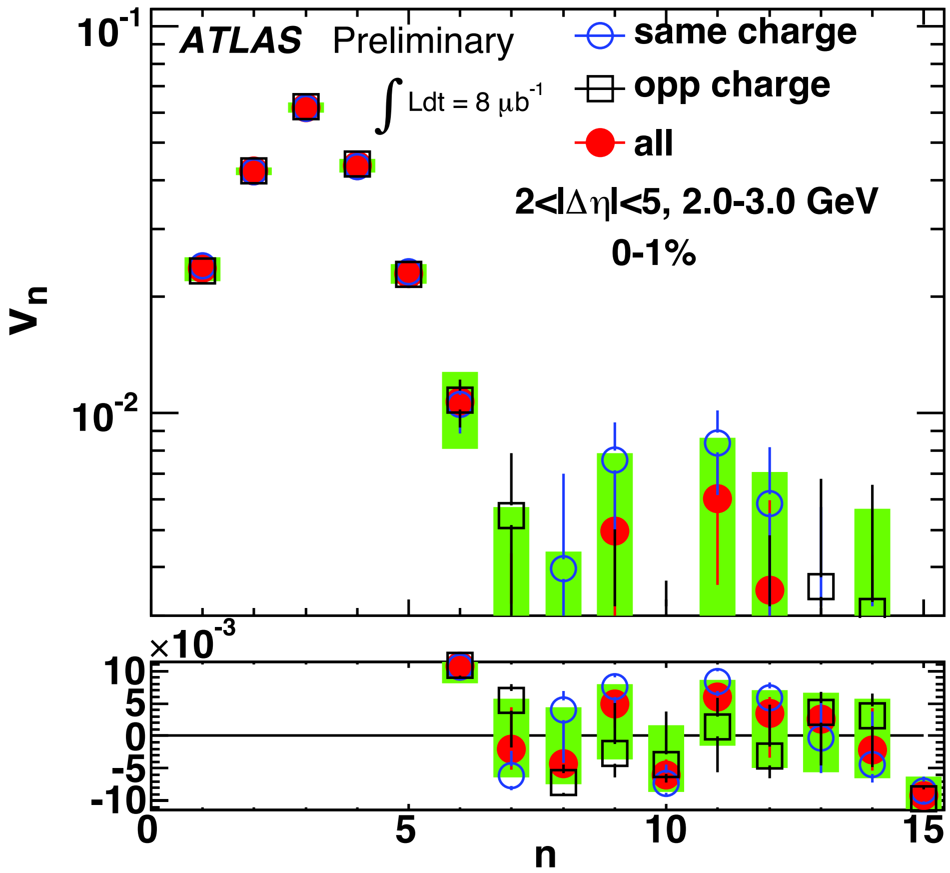
- Ingredients that matter at the $< 25\%$ level and require more work:
  - bulk viscosity
  - temperature dependence of $(\eta/s)_{\rm QGP}$
  - pre-equilibrium flow
  - event-by-event hydro + cascade evolution
  - (3+1)-d vs. (2+1)-d evolution
  - study of higher harmonics; influence of nucleon growth with $\sqrt{s}$ on fluctuations
  - flow fluctuations and flow angle correlations for different harmonics

The ultimate theoretical question:

Why is $(\eta/s)_{\rm QGP}$ as small as it is?

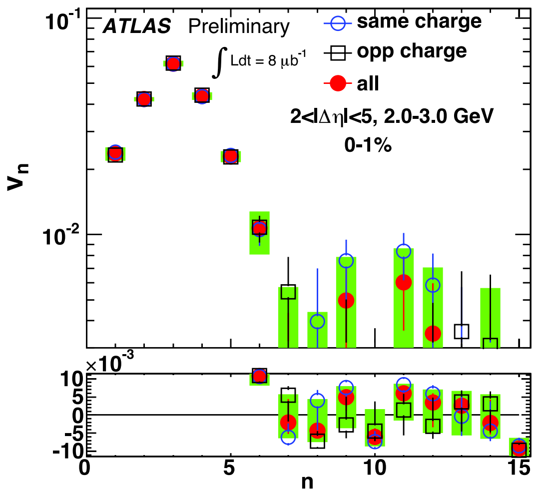
Outlook: The fluctuation power spectrum



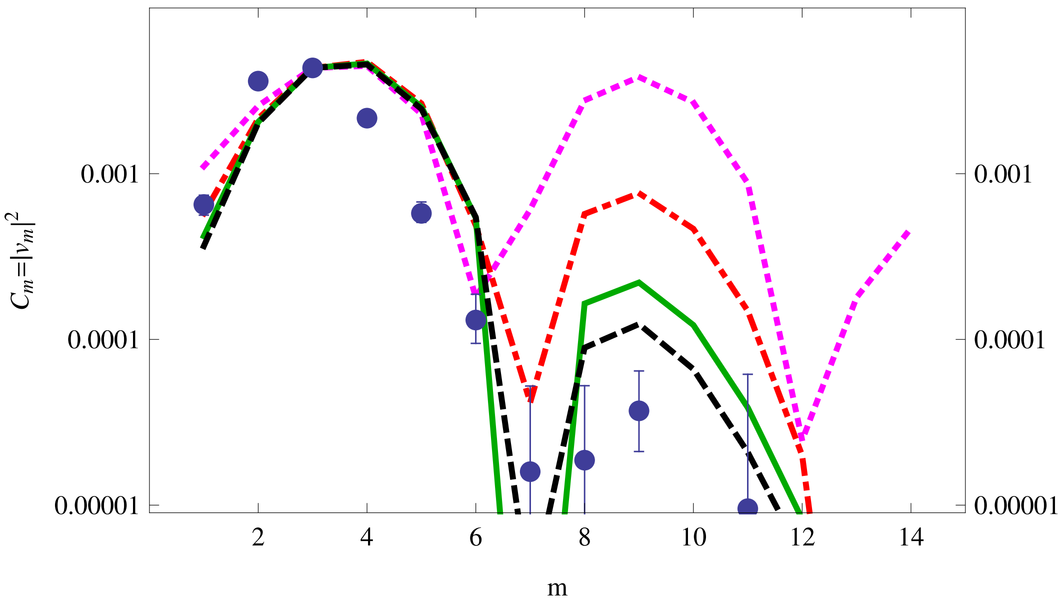


We need theory curves through the right plot!

The fluctuation power spectrum of the Little Bang: a first try



Staig & Shuryak, Quark Matter 2011



- Collisions between different species, at different collision centralities, and at different $\sqrt{s}$ create Little Bangs with characteristically different power spectra
- The final flow power spectra depend on p_T – rich experimental information!
- Relating the measured "anisotropic flow power spectrum" (i.e. v_n vs. n) to the "initial fluctuation power spectrum" (i.e. ε_n vs. n) provides access to the QGP transport coefficients (likely not just η/s, but also ζ/s, τ_π, τ_Π ...)
- Power spectrum of initial fluctuations (in particular its $\sqrt{s}$ dependence) can (probably) be calculated from first principles via CGC effective theory (Dusling, Gelis, Venugopalan, NPA872 (2011) 161; Schenke, Tribedy, Venugopalan, arXiv:1202.6646)

$\longrightarrow$ The Concordance Model of Little Bang Cosmology!

Thanks to:

Paul Sorensen for the animations

Chun Shen for the movie

Huichao Song, Steffen Bass, Zhi Qiu, Chun Shen, Pasi Huovinen, Tetsu Hirano, and Peter Kolb for their collaboration

Supplements

Eccentricity definitions:

Define event average $\{\ldots\}$, ensemble average $\langle\ldots\rangle$

Two choices for weight function in event average: (i) Energy density $e(\boldsymbol{x}_\perp;b)$
(ii) Entropy density $s(\boldsymbol{x}_\perp;b)$

Define $\sigma_x^2=\{x^2\}-\{x\}^2,\ \sigma_{xy}=\{xy\}-\{x\}\{y\}$, etc.,
where x,y are reaction-plane coordinates ($\boldsymbol{e}_x \parallel \boldsymbol{b}$)

1. Standard eccentricity: $\varepsilon_s \equiv \bar\varepsilon_{\rm RP} = \frac{\langle\sigma_y^2-\sigma_x^2\rangle}{\langle\sigma_y^2+\sigma_x^2\rangle}$ (calculated from RP-averaged $\langle e\rangle$ or $\langle s\rangle$)

2. Average reaction-plane eccentricity: $\langle\varepsilon_{\rm RP}\rangle = \left\langle\frac{\sigma_y^2-\sigma_x^2}{\sigma_y^2+\sigma_x^2}\right\rangle$

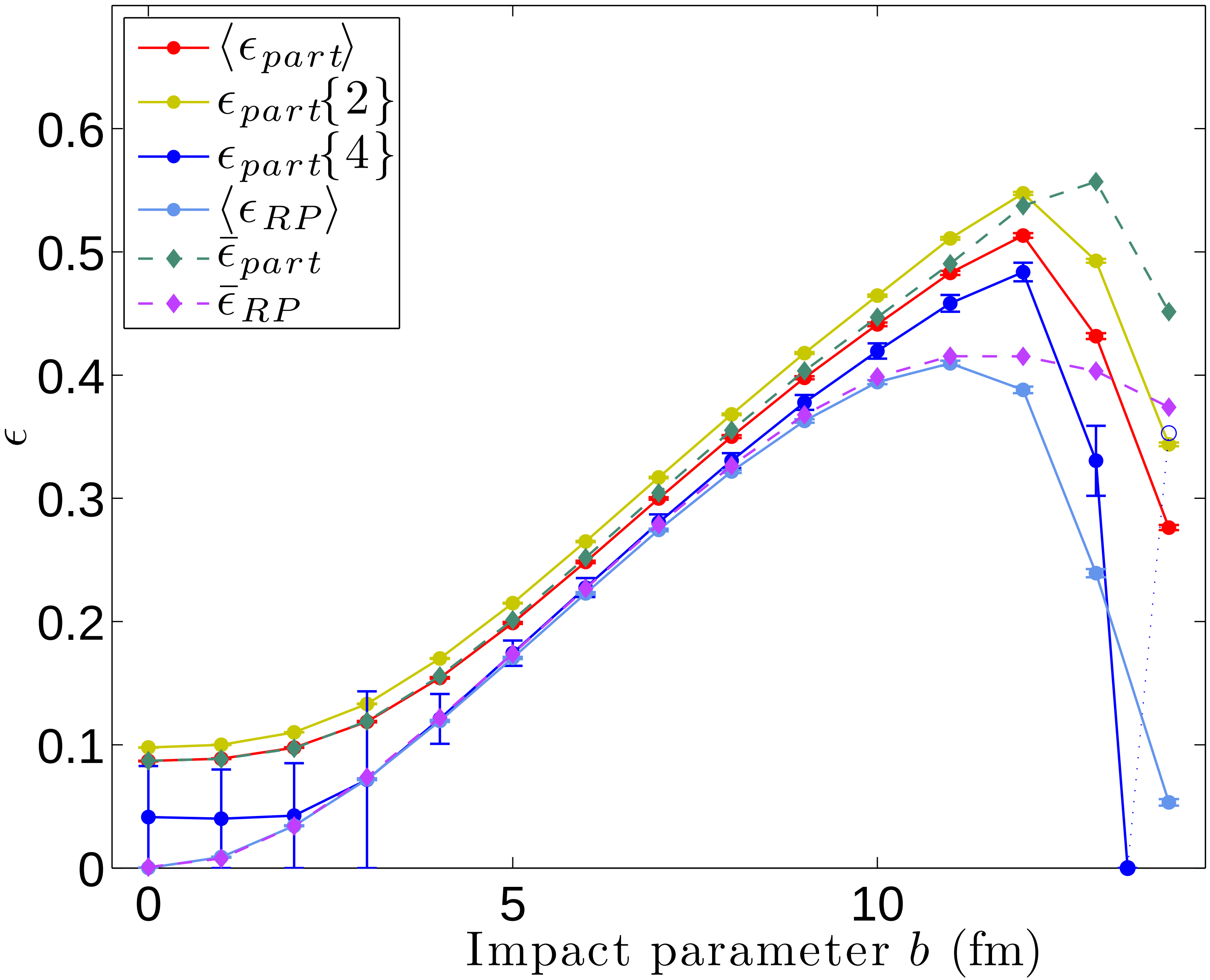
3. Eccentricity of the participant-plane averaged source: $\bar\varepsilon_{\rm part} = \frac{\left\langle\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}\right\rangle}{\langle\sigma_y^2+\sigma_x^2\rangle}$

4. Average participant-plane eccentricity: $\langle\varepsilon_{\rm part}\rangle = \left\langle\frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_y^2+\sigma_x^2}\right\rangle$

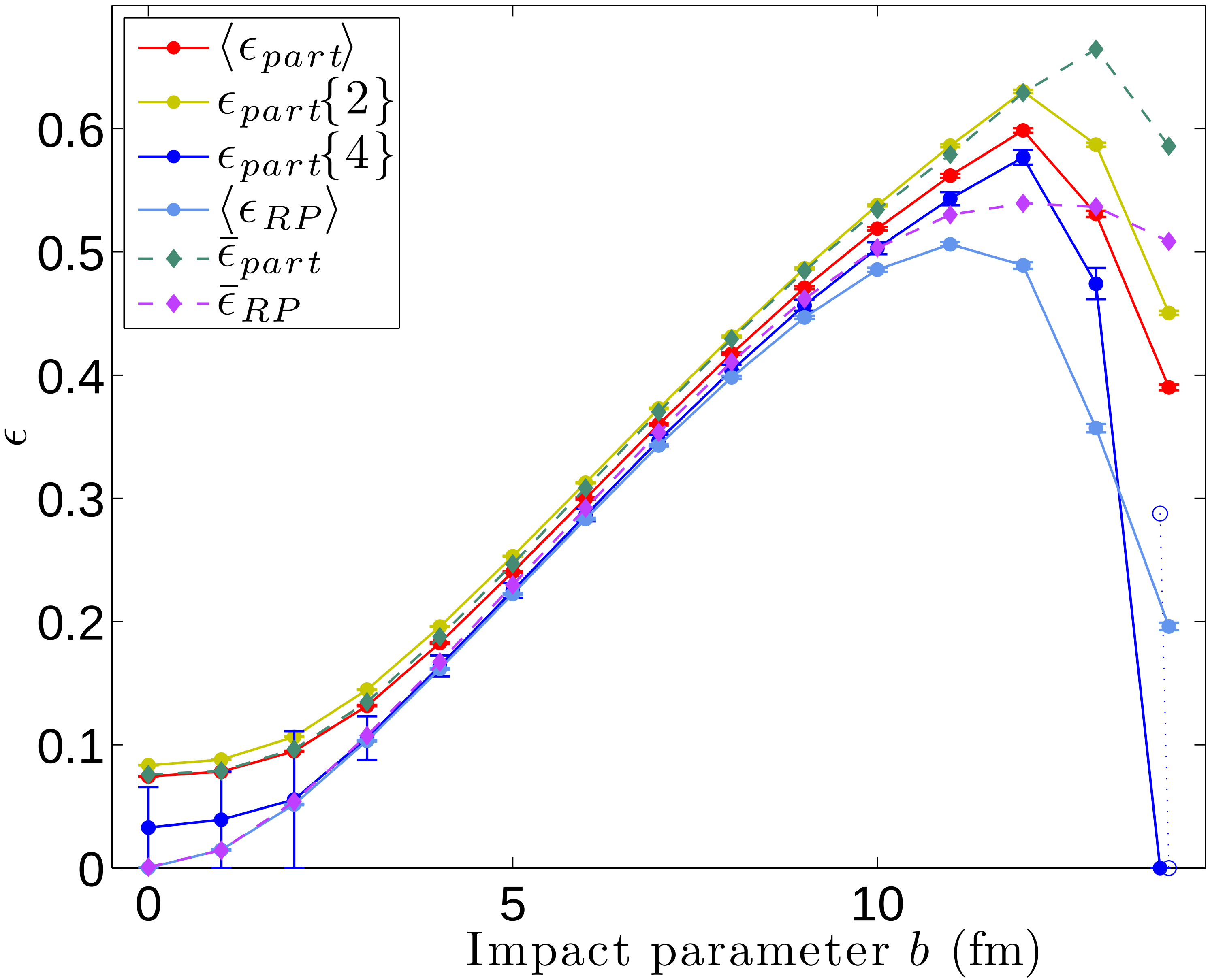
5. r.m.s. part.-plane eccentricity: $\varepsilon_{\rm part}\{2\} \equiv \sqrt{\langle\varepsilon_{\rm part}^2\rangle}$ $\left(=\sqrt{\langle\varepsilon_{\rm part}\rangle^2+\sigma_\varepsilon^2/2}\right.$ for Gauss. fl.)

6. 4th cumulant eccentricity: $\varepsilon_{\rm part}\{4\} \equiv \left[\langle\varepsilon_{\rm part}^2\rangle^2 - \left(\langle\varepsilon_{\rm part}^4\rangle-\langle\varepsilon_{\rm part}^2\rangle^2\right)\right]^{1/4}$
$\left(=\sqrt{\langle\varepsilon_{\rm part}\rangle^2-\sigma_\varepsilon^2/2}\right.$ for Gauss. fl.)

MC-Glauber eccentricities (e-weighted):

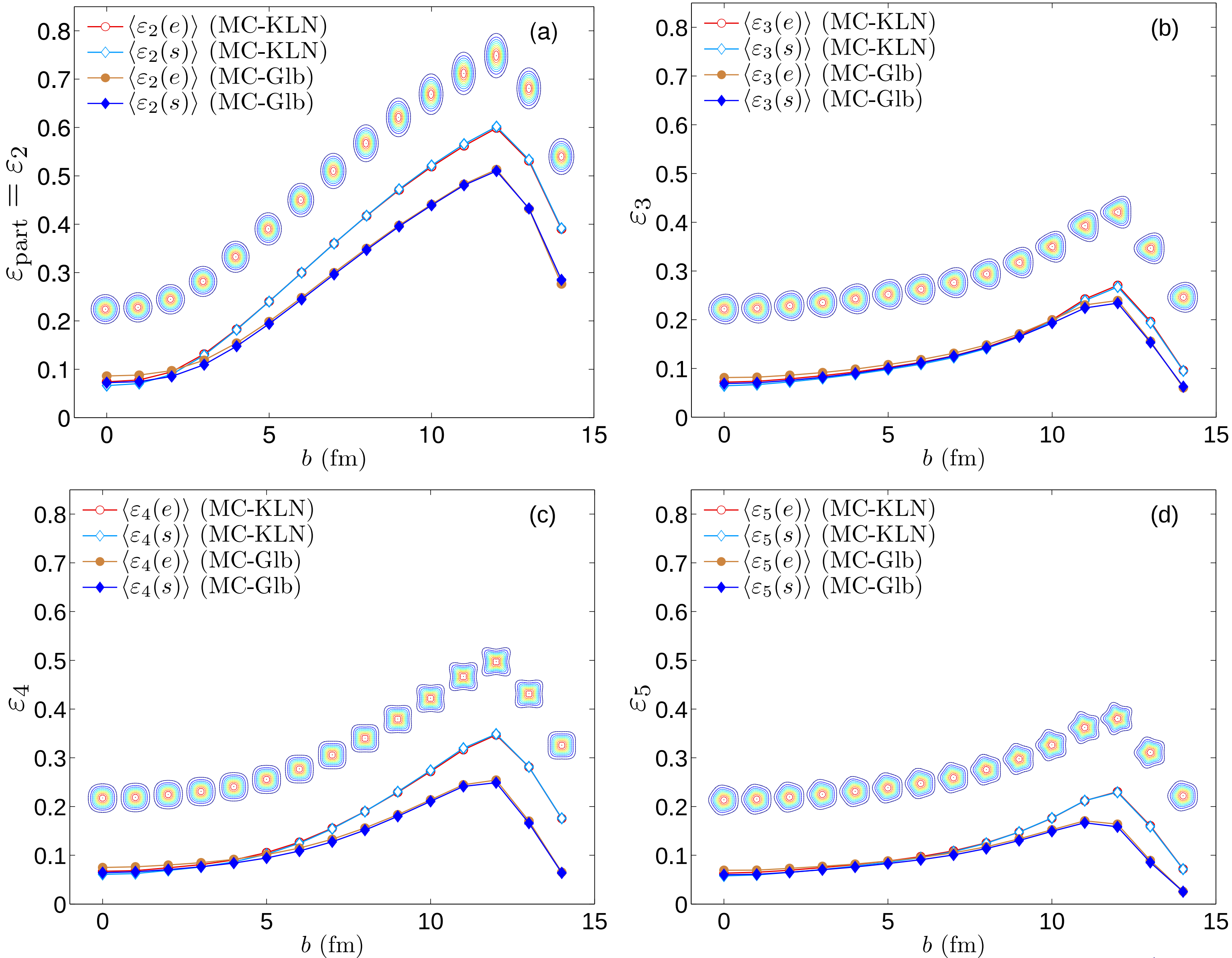


MC-KLN eccentricities (e-weighted):



Initial eccentricities $\varepsilon_n(n=2-5)$ vs. impact parameter

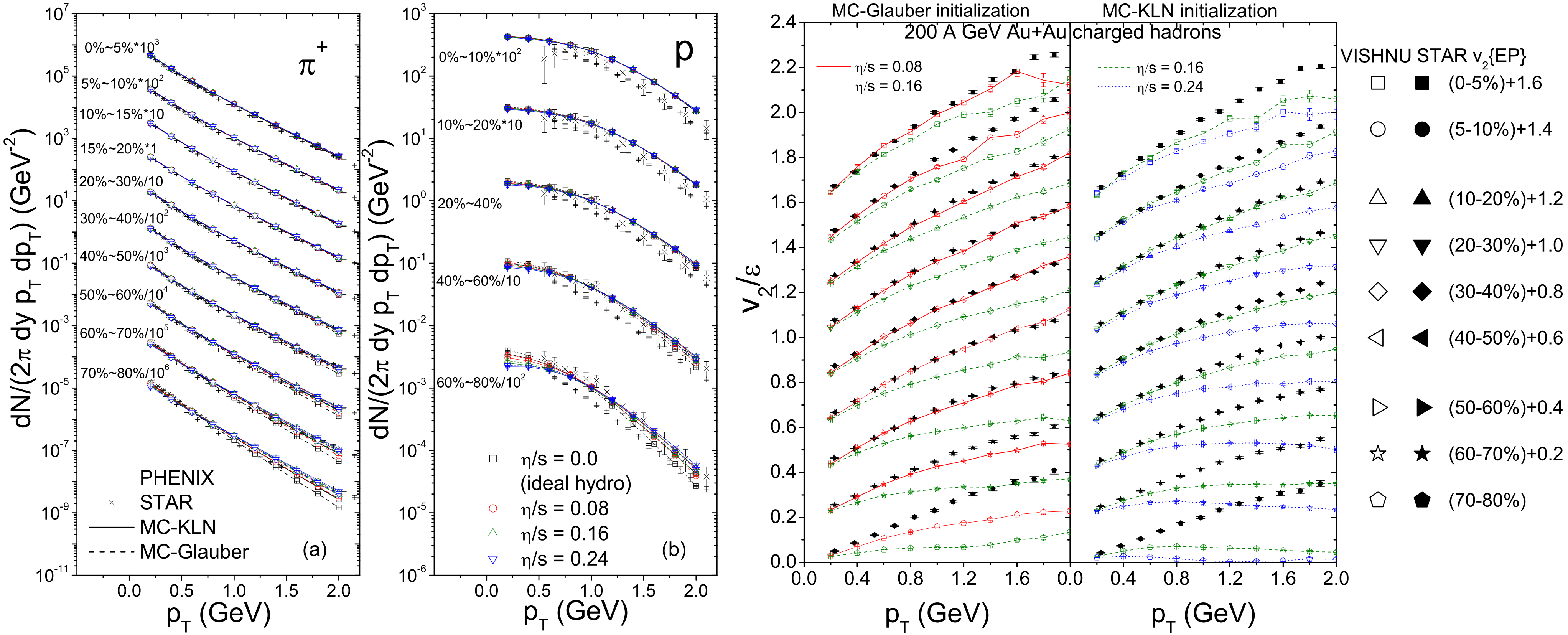
Zhi Qiu, UH, PRC84 (2011) 024911



- Contours: $e(r,\phi) = e_0 \exp\left[-\frac{r^2}{2\rho^2}\left(1+\varepsilon_n\cos(n(\phi-\psi_n))\right)\right]$ where $\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$
- MC-KLN has larger ε_2 and ε_4, but similar ε_5 and almost identical ε_3 as MC-Glauber ($\varepsilon_{3,5}$ are purely fluctuation-driven!)

Global description of AuAu@RHIC spectra and v_2

VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC, arXiv:1101.4638)

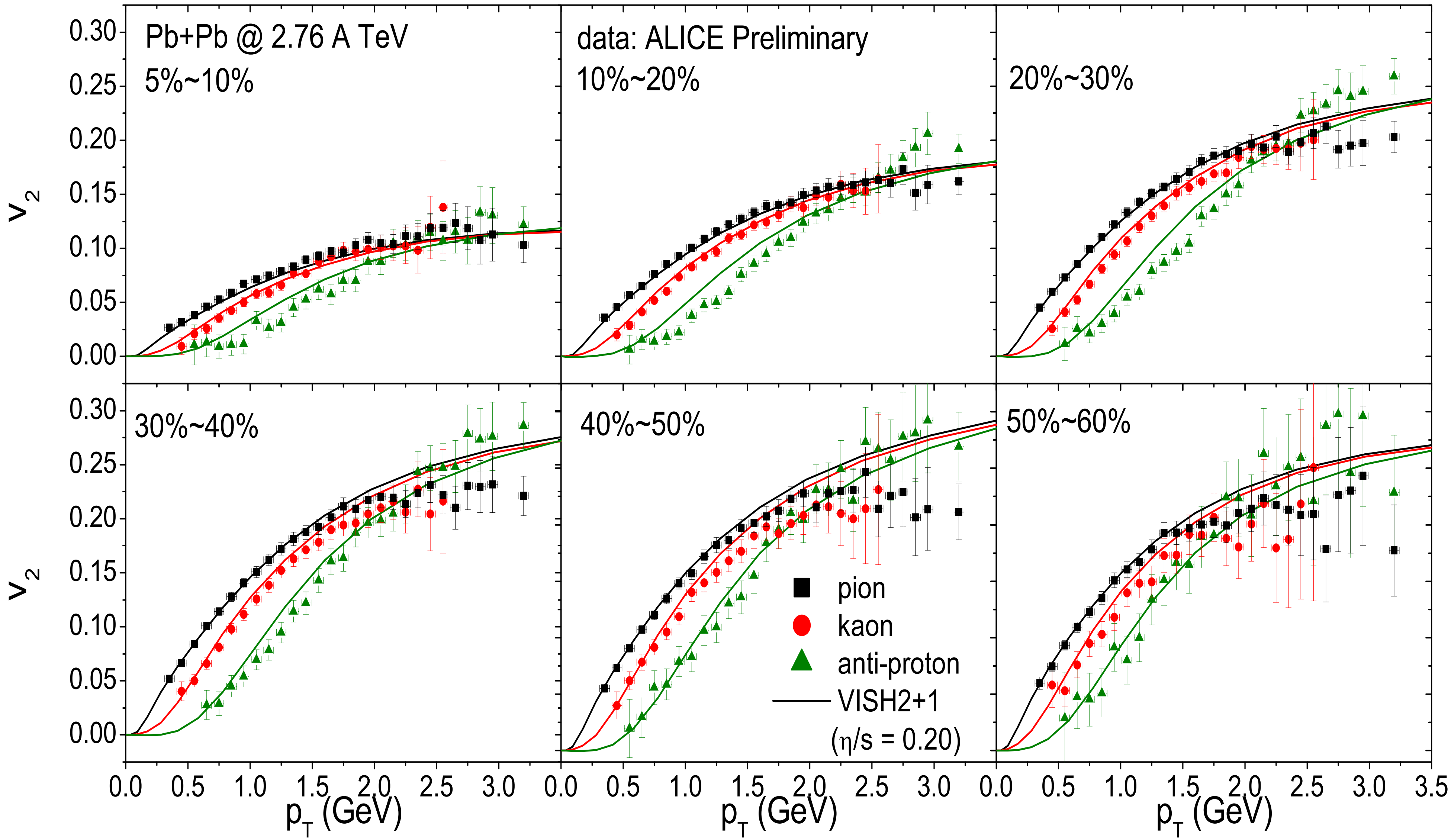


- $(\eta/s)_{\rm QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities

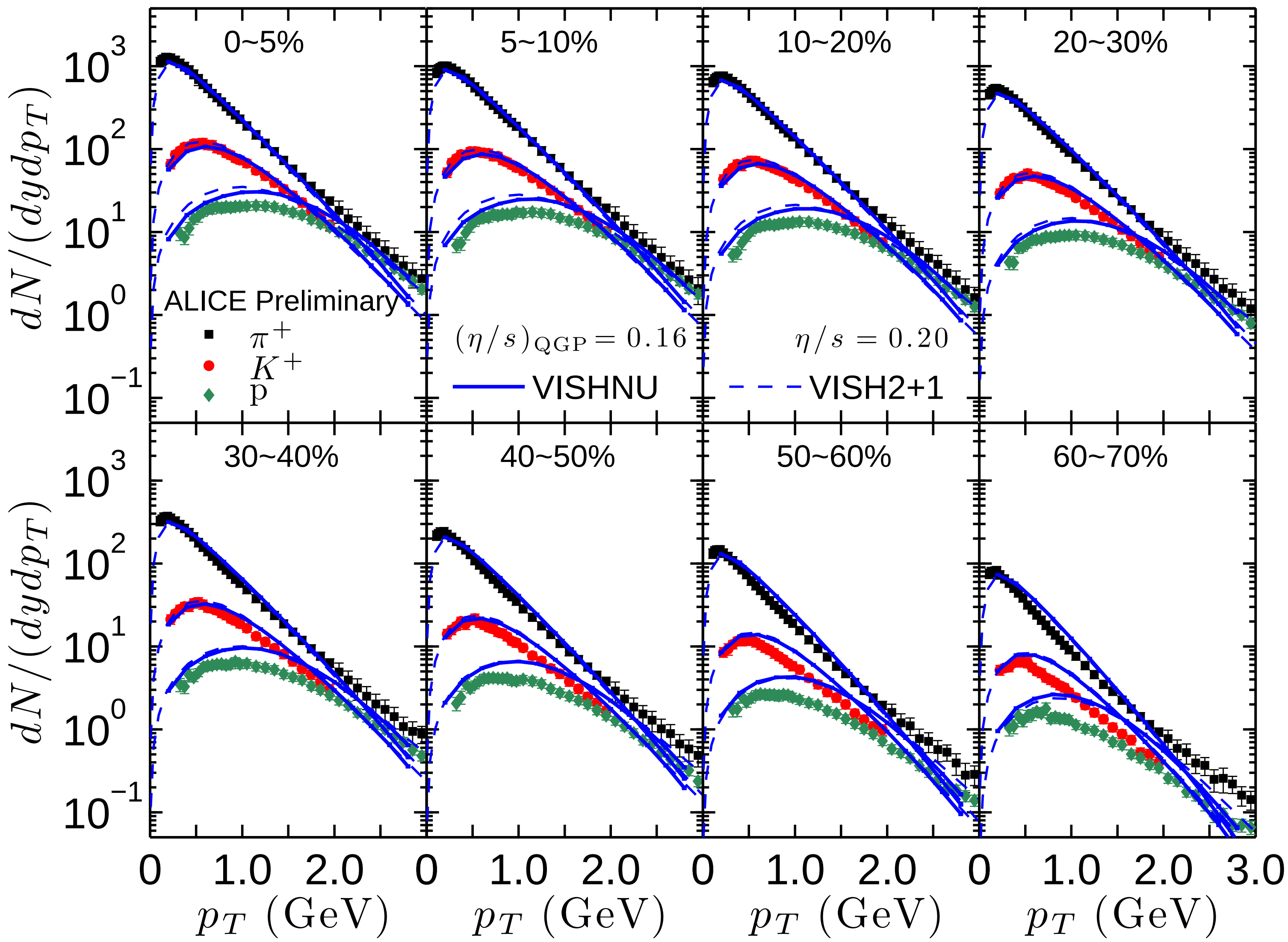
Comparison of ALICE PbPb@LHC v_2 data with VISH2+1

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)

Prediction: C. Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, η/s=0.2)



PbPb@LHC p_T-spectra: ALICE vs. VISH2+1 and VISHNU:

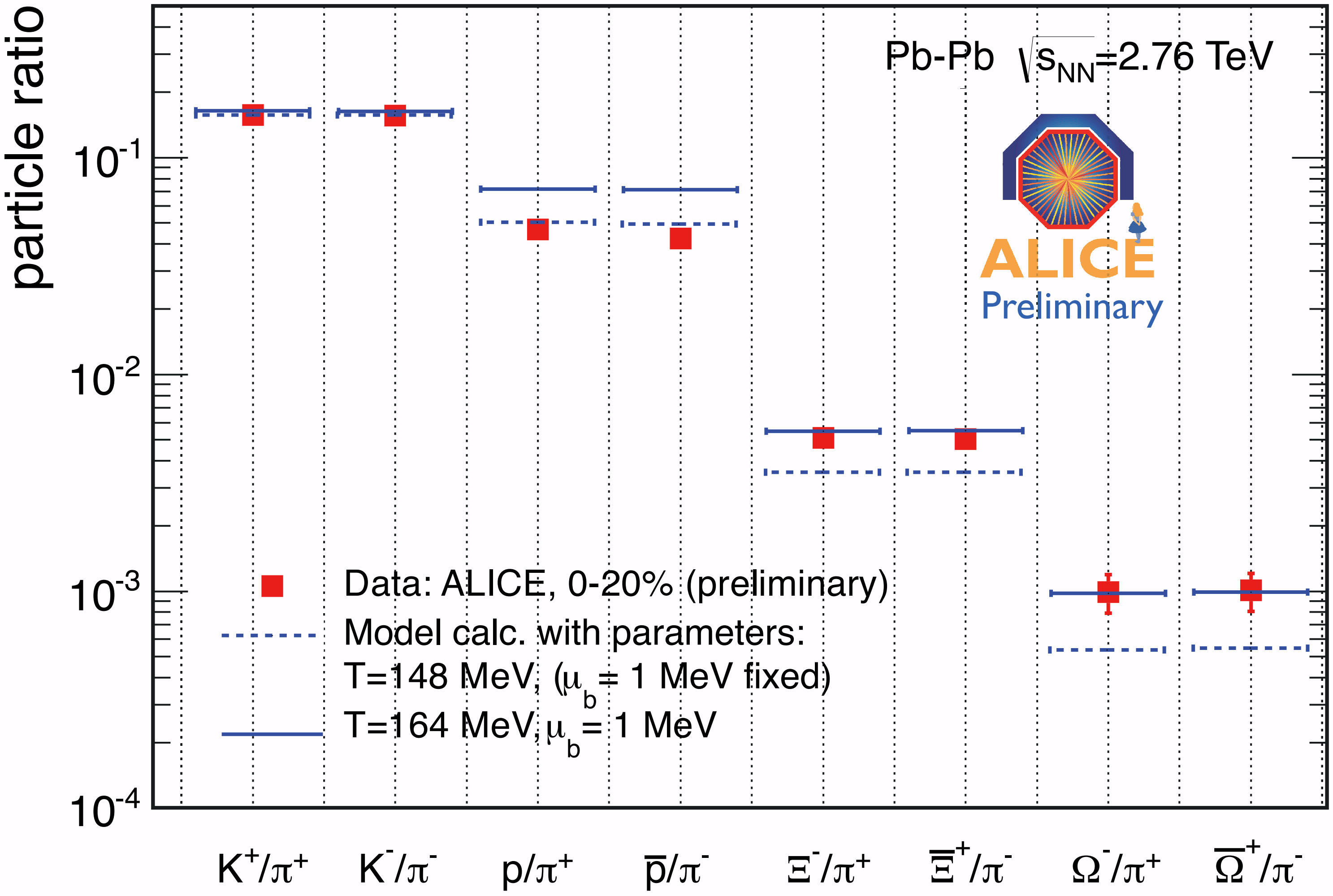


- Good description also of identified hadron spectra for centralities $< 50\%$
- VISHNU better than VISH2+1 in central collisions (more radial flow)
- Both models give too much radial flow in peripheral collisions $\Longrightarrow$ initial conditions?
- Both models overpredict proton yield by 50-70%!?

The new "proton anomaly": disagreement with the thermal model

Data: ALICE, preliminary (A. Kalweit, Strange Quark Matter 2011)

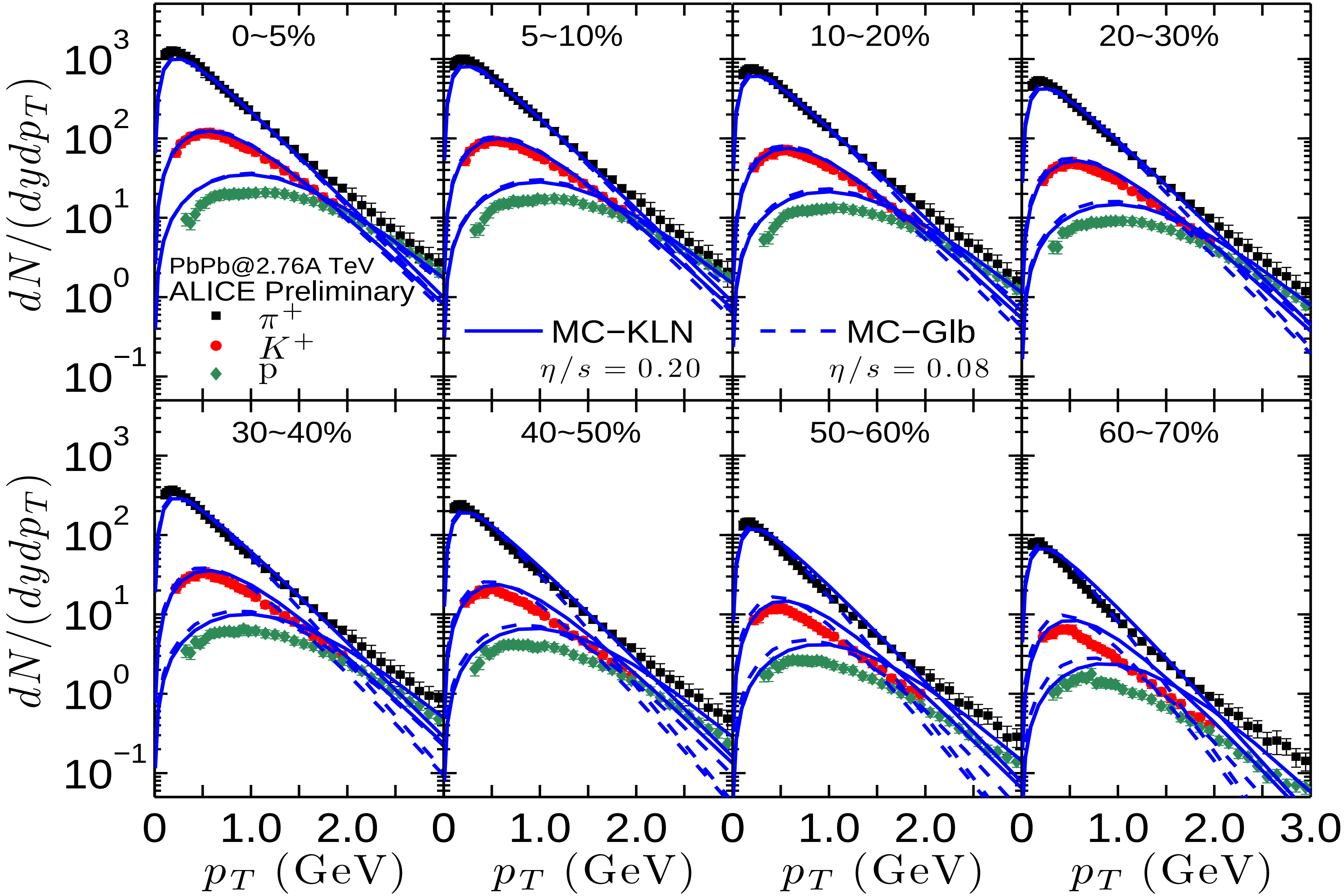
Model: A. Andronic et al., PLB673 (2009) 142; similar: S. Wheaton et al. (THERMUS), Comp. Phys. Comm. 180 (2009) 84



- "Standard" $T_{\rm chem} = 164$ MeV reproduces strange hadrons but overpredicts (anti-)protons by 50%!
- $p\bar{p}$ annihilation in UrQMD not strong enough to repair this
- Similar problem already seen at RHIC but not taken seriously (STAR/PHENIX disagreement)

???

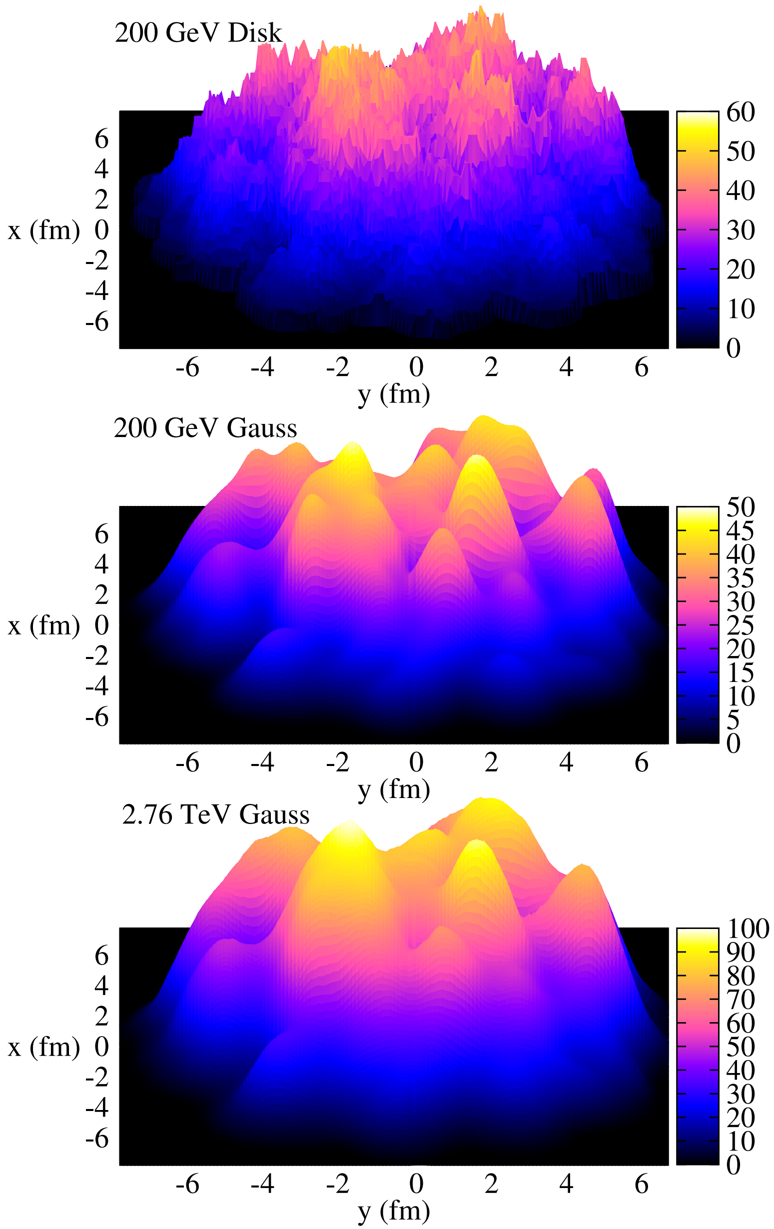
PbPb@LHC p_T-spectra: Glauber vs. KLN

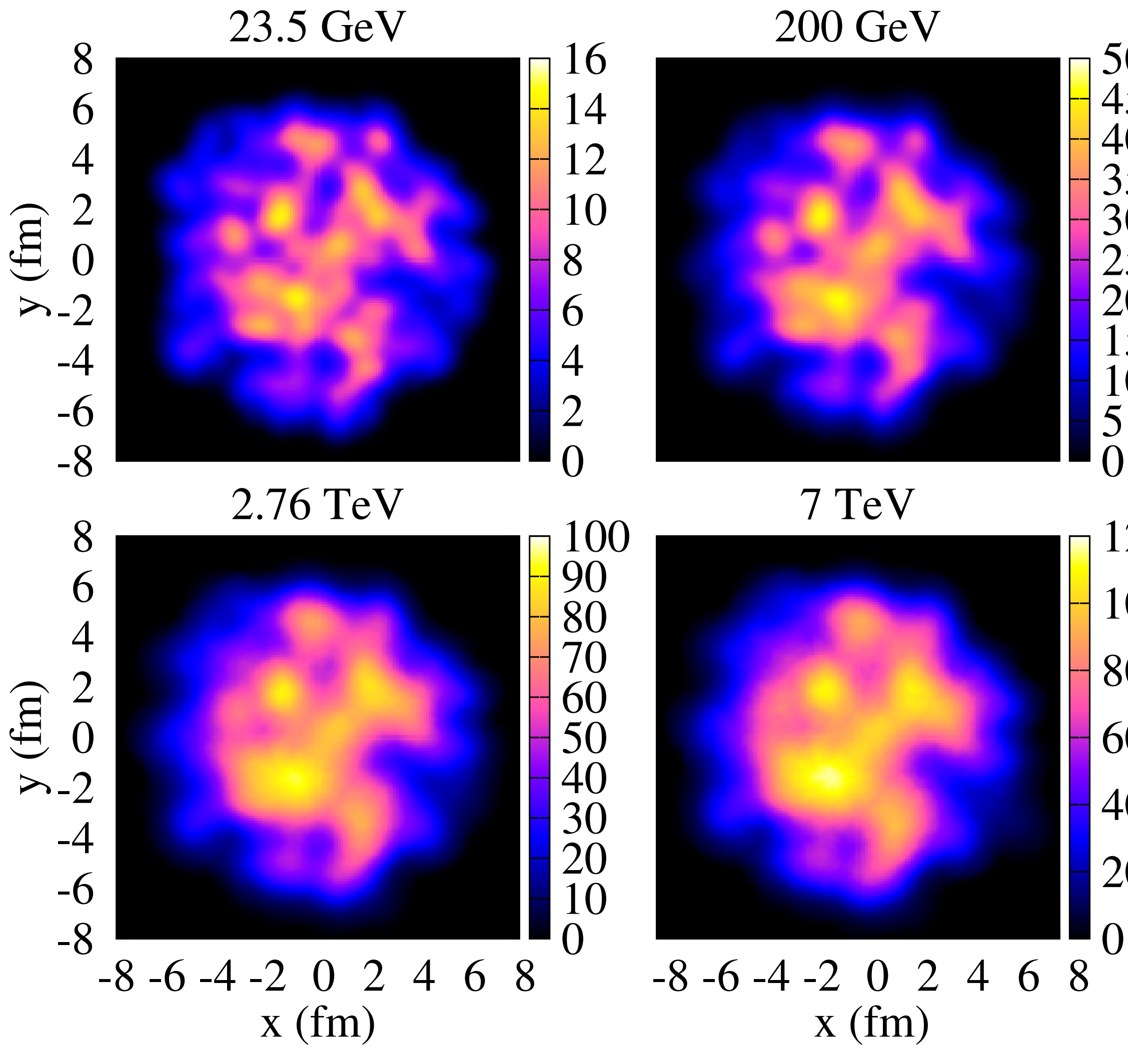


- In central collisions no difference between the models.
- In peripheral collisions p_T-spectra from MC-Glauber IC too steep!
  This is an artifact of single-shot hydro with averaged initial profile; for small $\eta/s = 0.08$ (but not for $\eta/s = 0.2$!), e-by-e hydro gives flatter p_T-spectra in peripheral collisions, due to hot spots

Smearing effects from nucleon growth at high energies

U. Heinz & Scott Moreland, arXiv:1108.5379

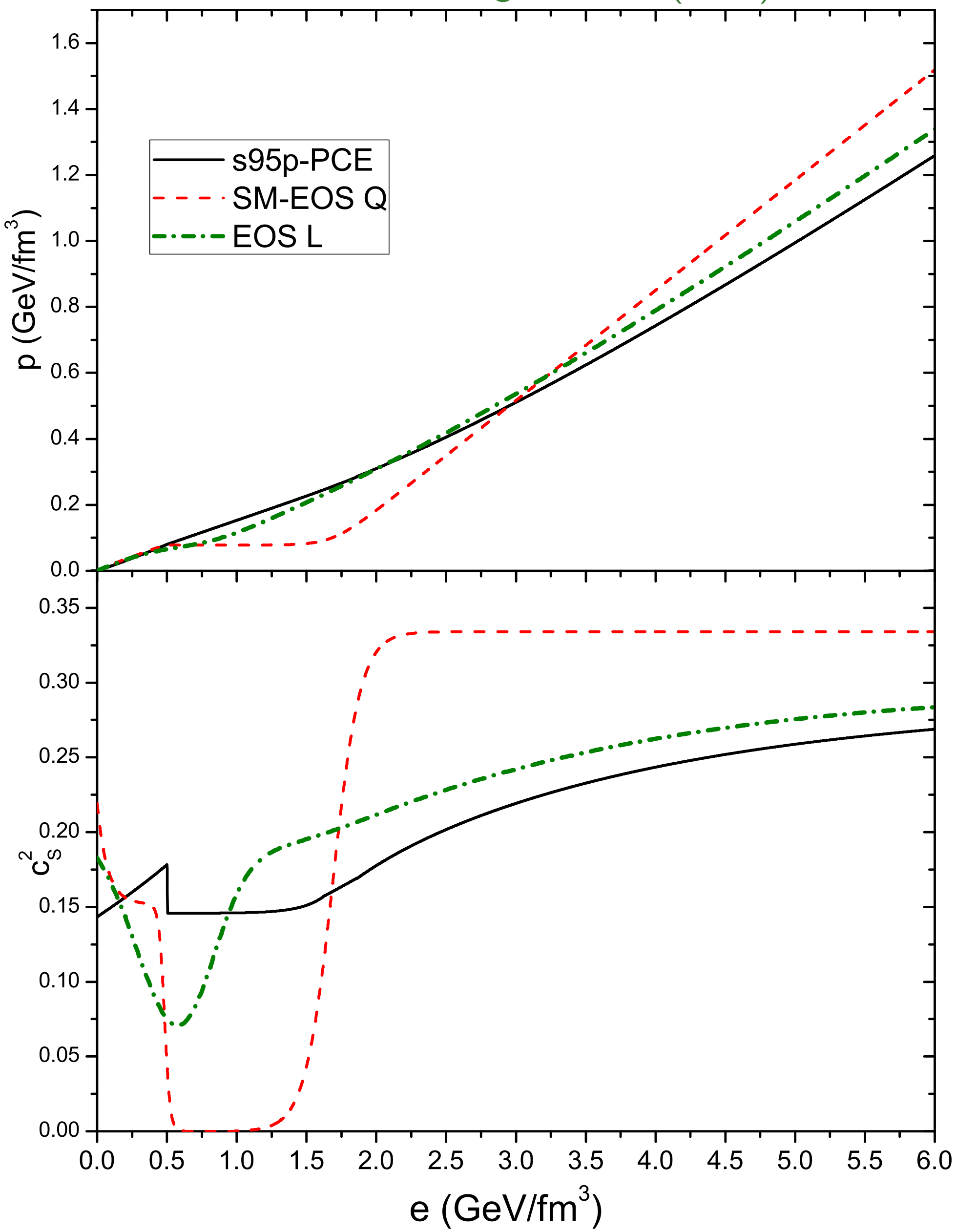




Between $\sqrt{s} = 23.5$ and 7,000 GeV, nucleon area grows by factor $\mathcal{O}(2) \Longrightarrow$ significant smoothing of event-by-event density fluctuations from RHIC to LHC

s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904



High T: Lattice QCD (latest hotQCD results)

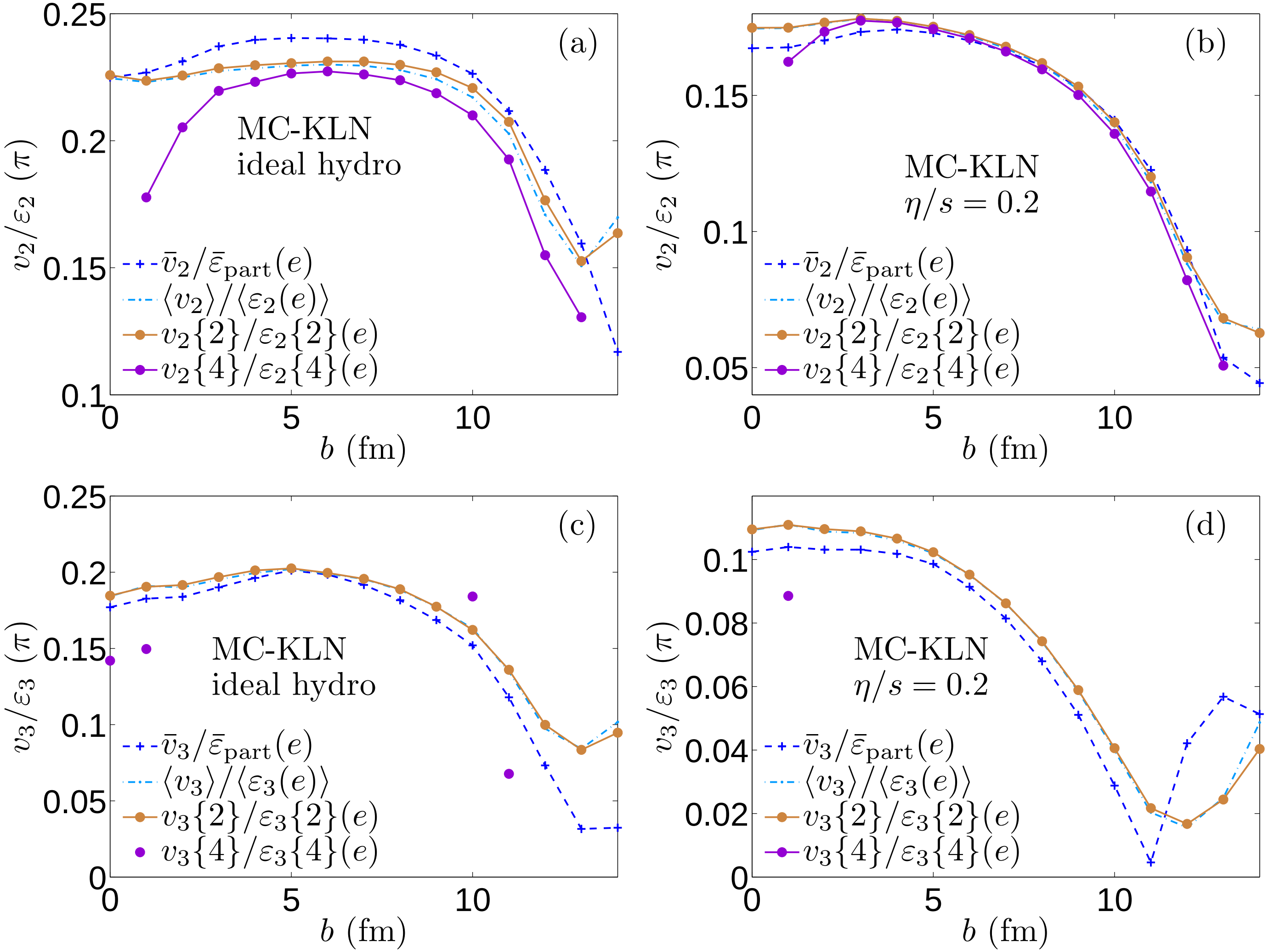
Low T: Chemically frozen HRG ($T_{\rm chem} = 165\,\text{MeV}$)

No softest point!

Event-by-event vs. single-shot hydro

Eccentricity-scaled $v_{2,3}$ flow from e-by-e and single-shot hydro

Zhi Qiu, UH, in preparation



- For most centralities, eccentricity-scaled $v_{2,3}$ from e-by-e and single-shot hydro agree within 5-10%
- Agreement between $\langle v_{2,3}\rangle/\langle\varepsilon_{2,3}\rangle$ and $v_{2,3}\{2\}/\varepsilon_{2,3}\{2\}$ is excellent at all centralities
- Agreement between $v_2\{2\}/\varepsilon_2\{2\}$ and $v_2\{4\}/\varepsilon_2\{4\}$ is good over most of the centrality range, but the analog relation for triangular flow does not work (note, however, limited statistics)
- **$\Longrightarrow$ Can use single-shot hydro to compute $\langle v_{2,3}\rangle/\langle\varepsilon_{2,3}\rangle = v_{2,3}\{2\}/\varepsilon_{2,3}\{2\}$**