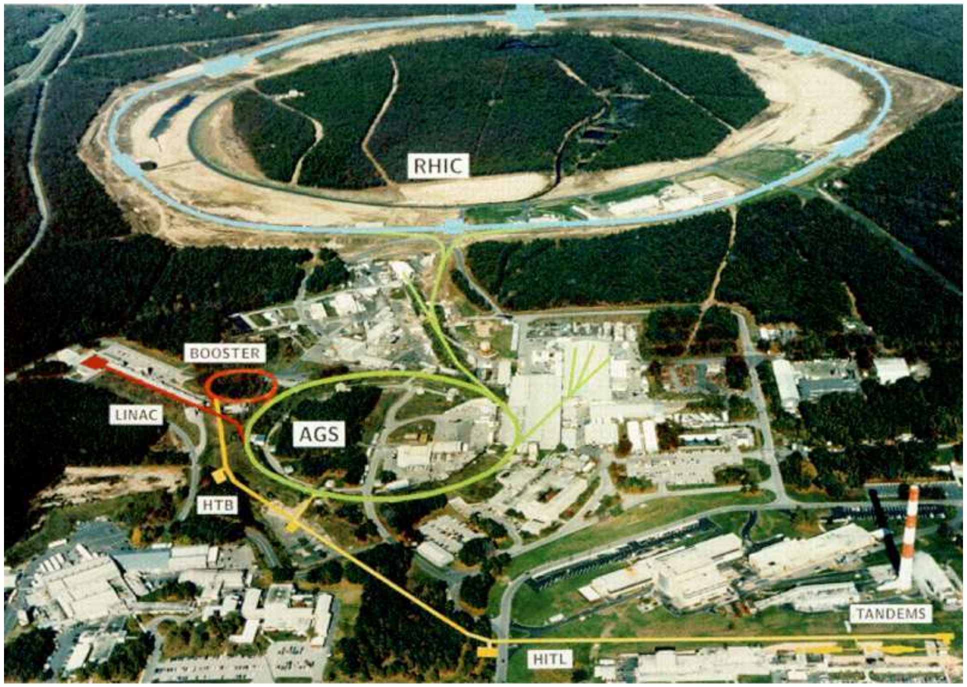
Towards the Little Bang Standard Model*

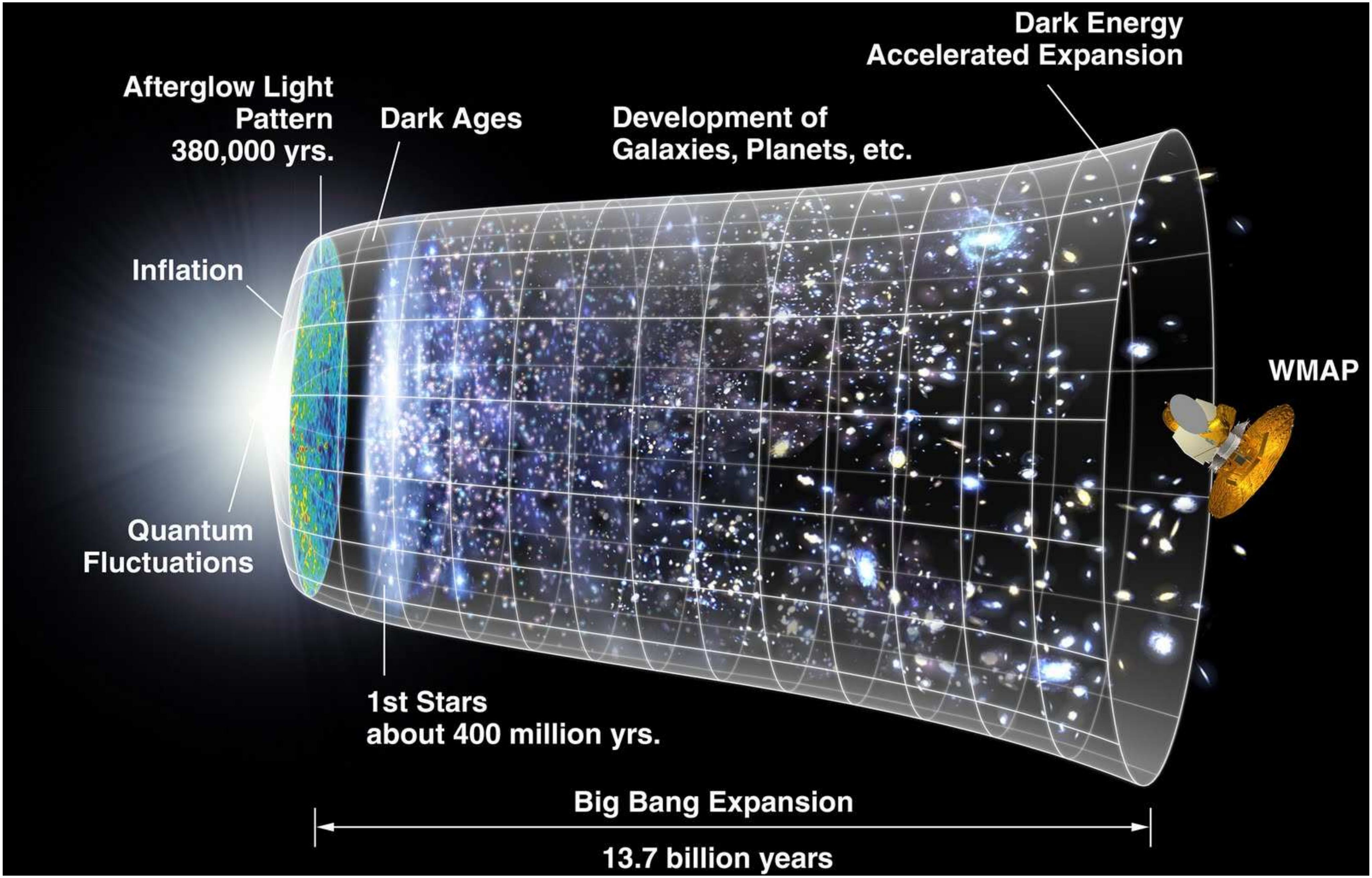
Ulrich Heinz, The Ohio State University



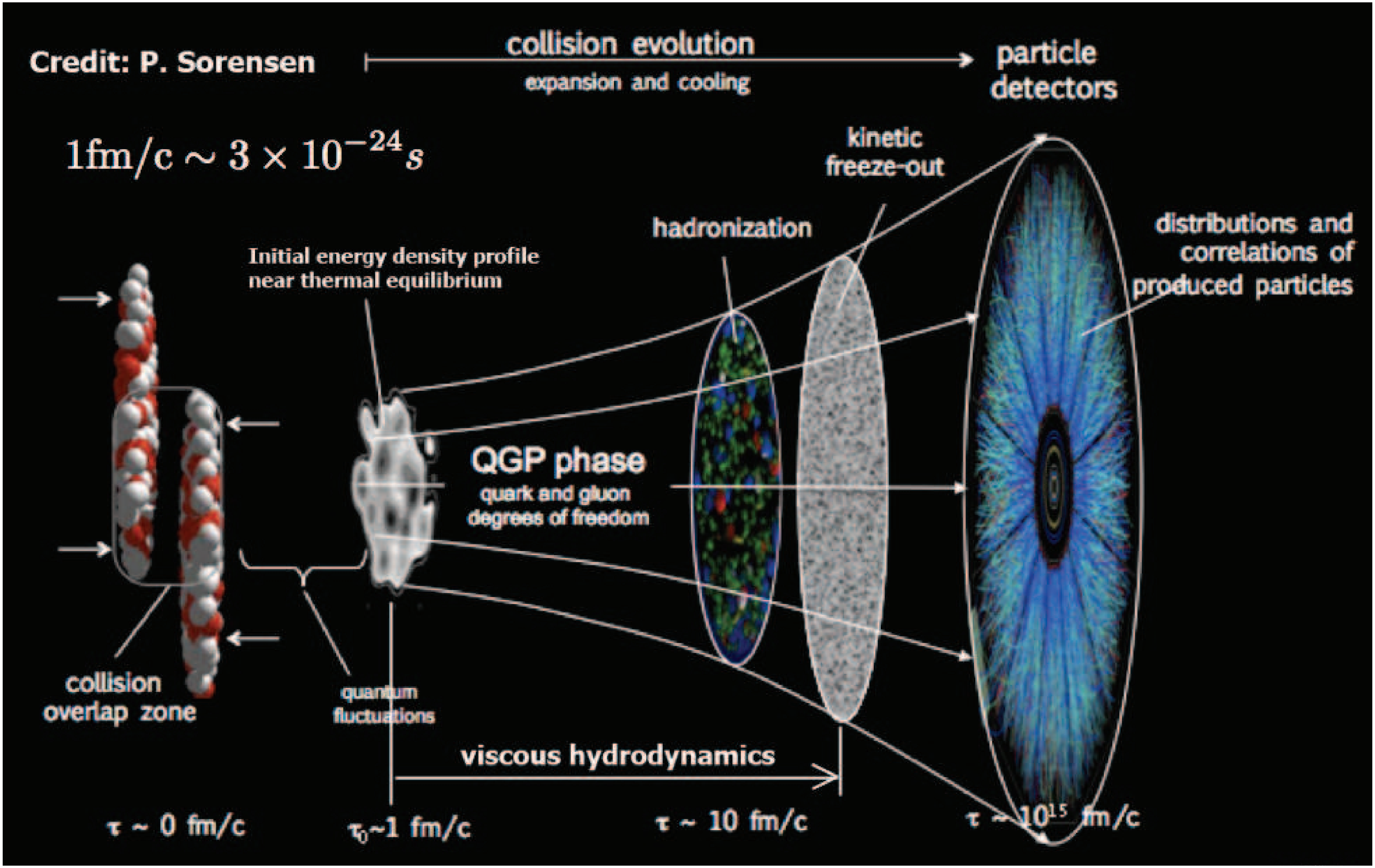
International Workshop on Discovery Physics at the LHC (Kruger2012)
Krueger Park, South Africa, Dec. 3-7, 2012

*Supported by the U.S. Department of Energy

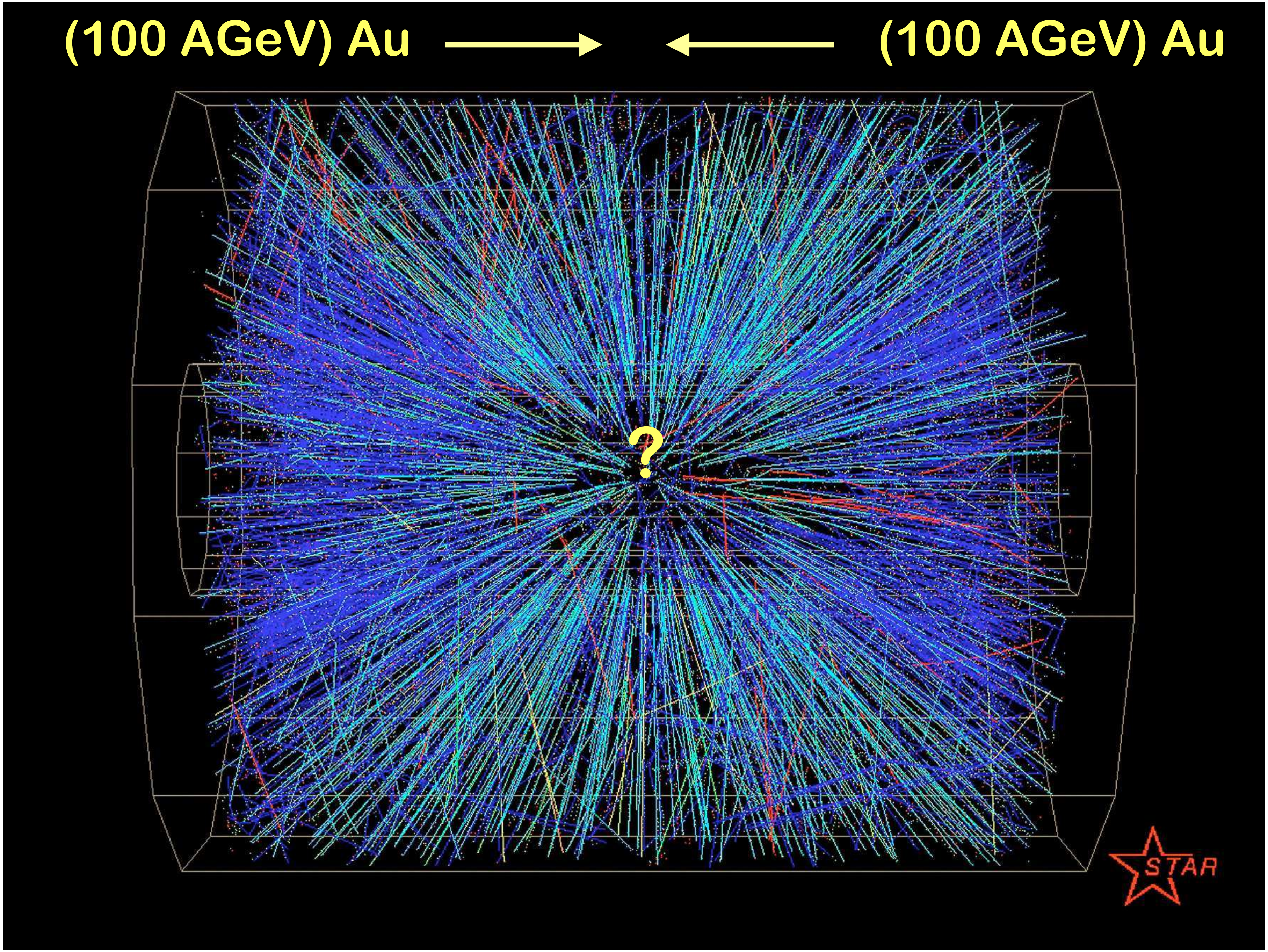
The Big Bang


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

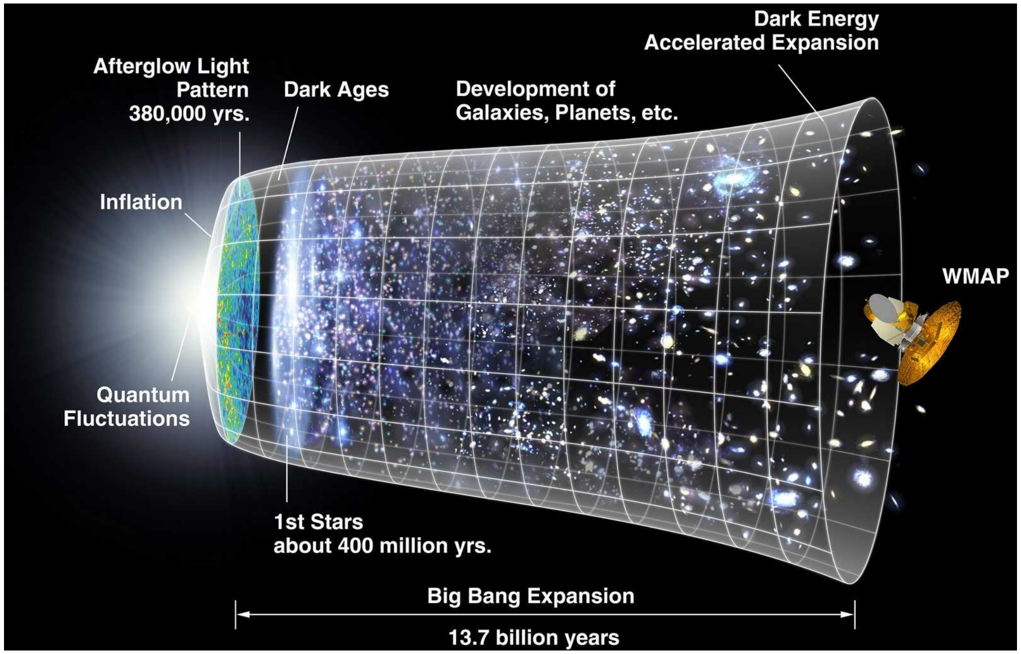
The Little Bang

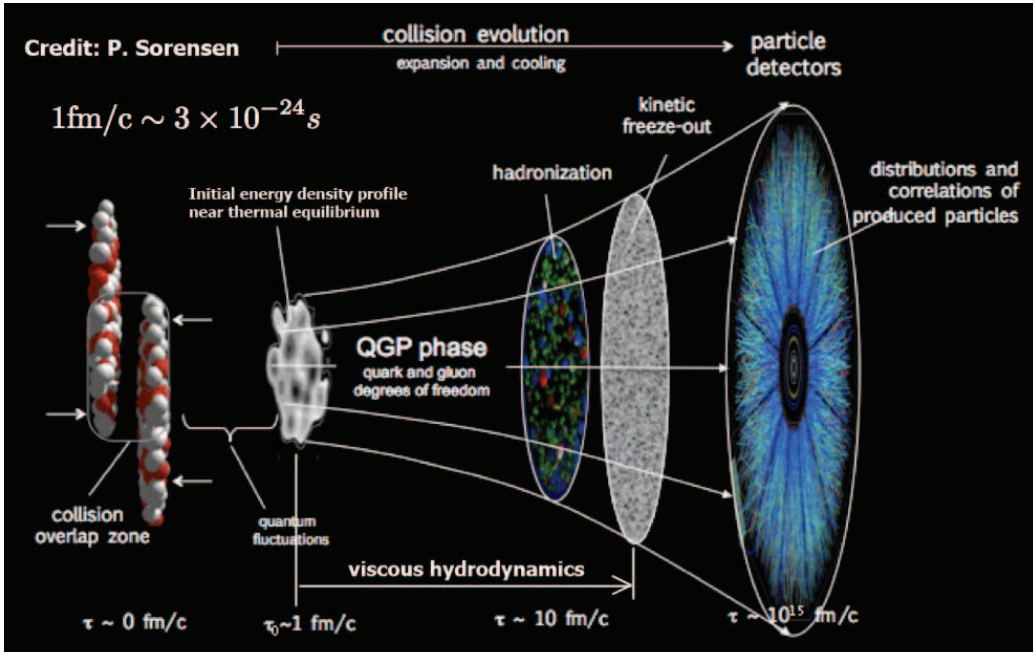


A Little Bang in the STAR Detector:



Big Bang vs. Little Bang



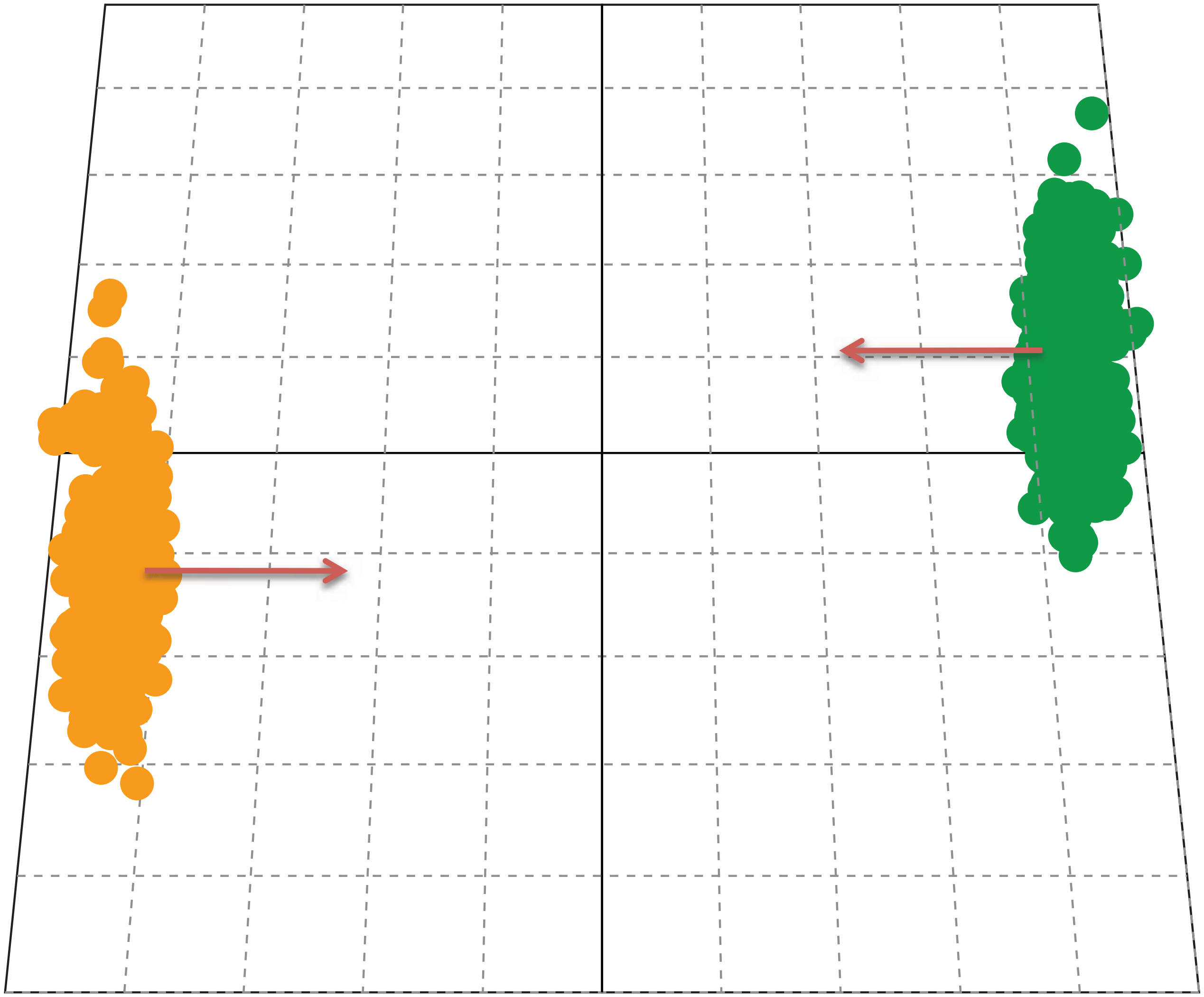


Similarities: Hubble-like expansion, expansion-driven dynamical freeze-out
chemical freeze-out (nucleo-/hadrosynthesis) before thermal freeze-out (CMB, hadron p_T-spectra)
initial-state quantum fluctuations imprinted on final state

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**

Relativistic Nucleus-Nucleus Collisions

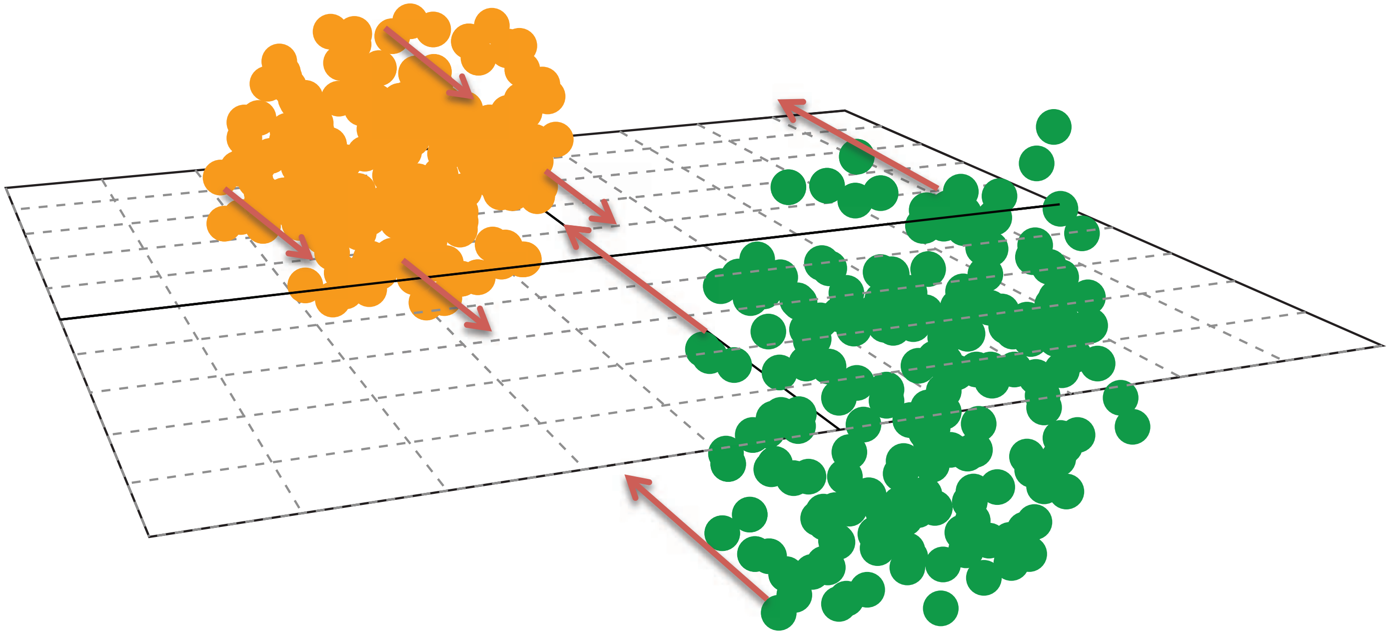
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

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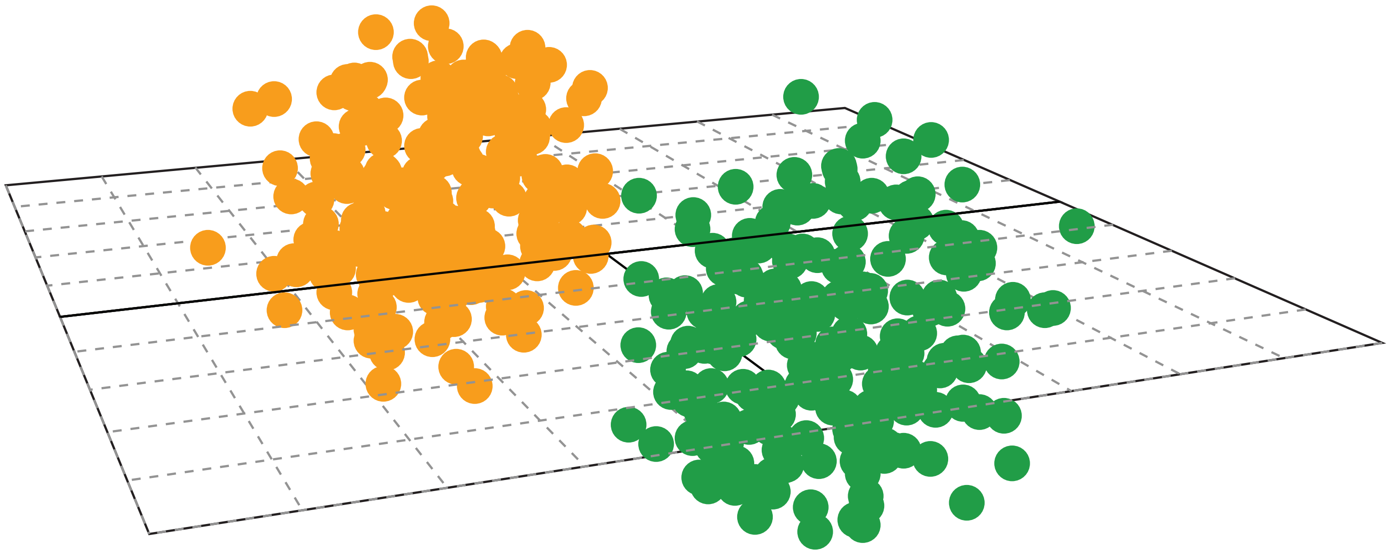

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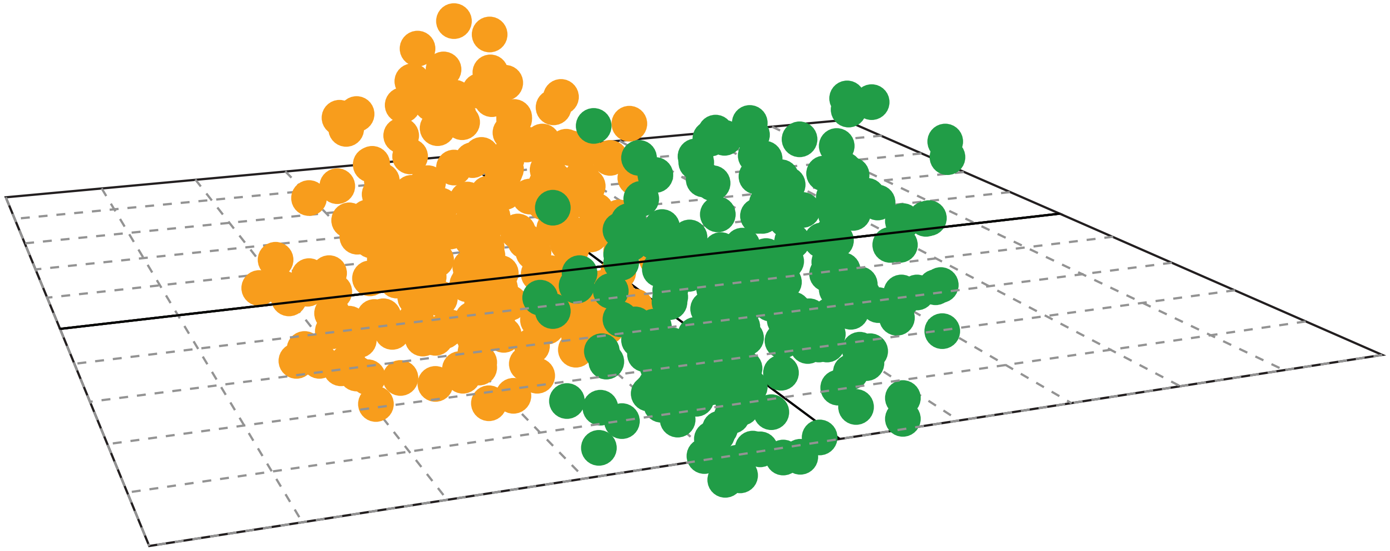

Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

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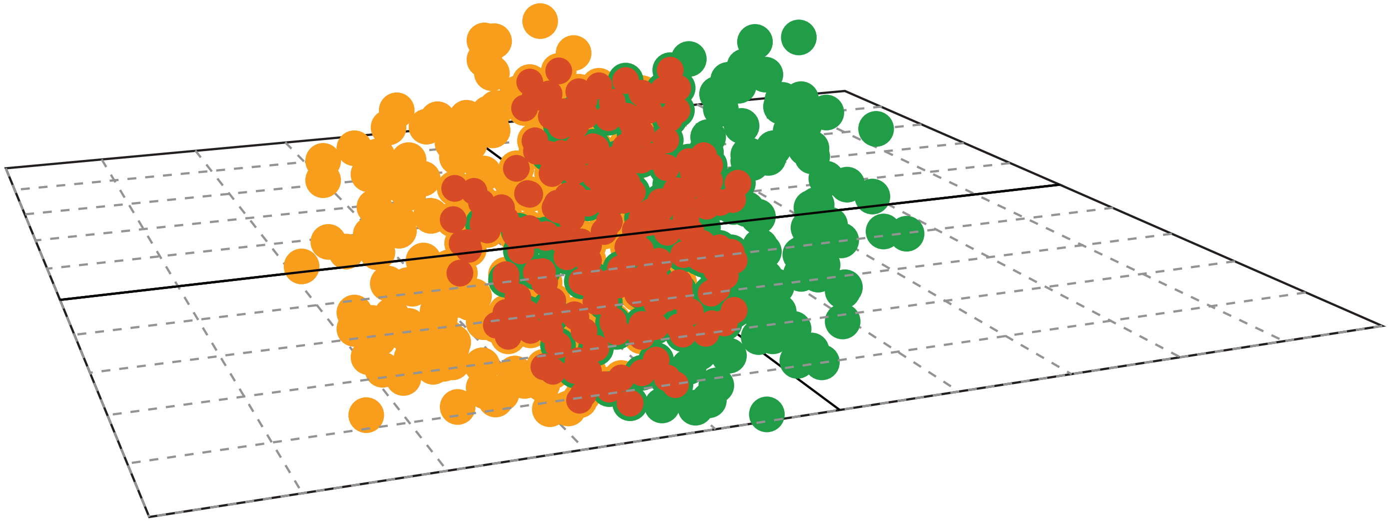
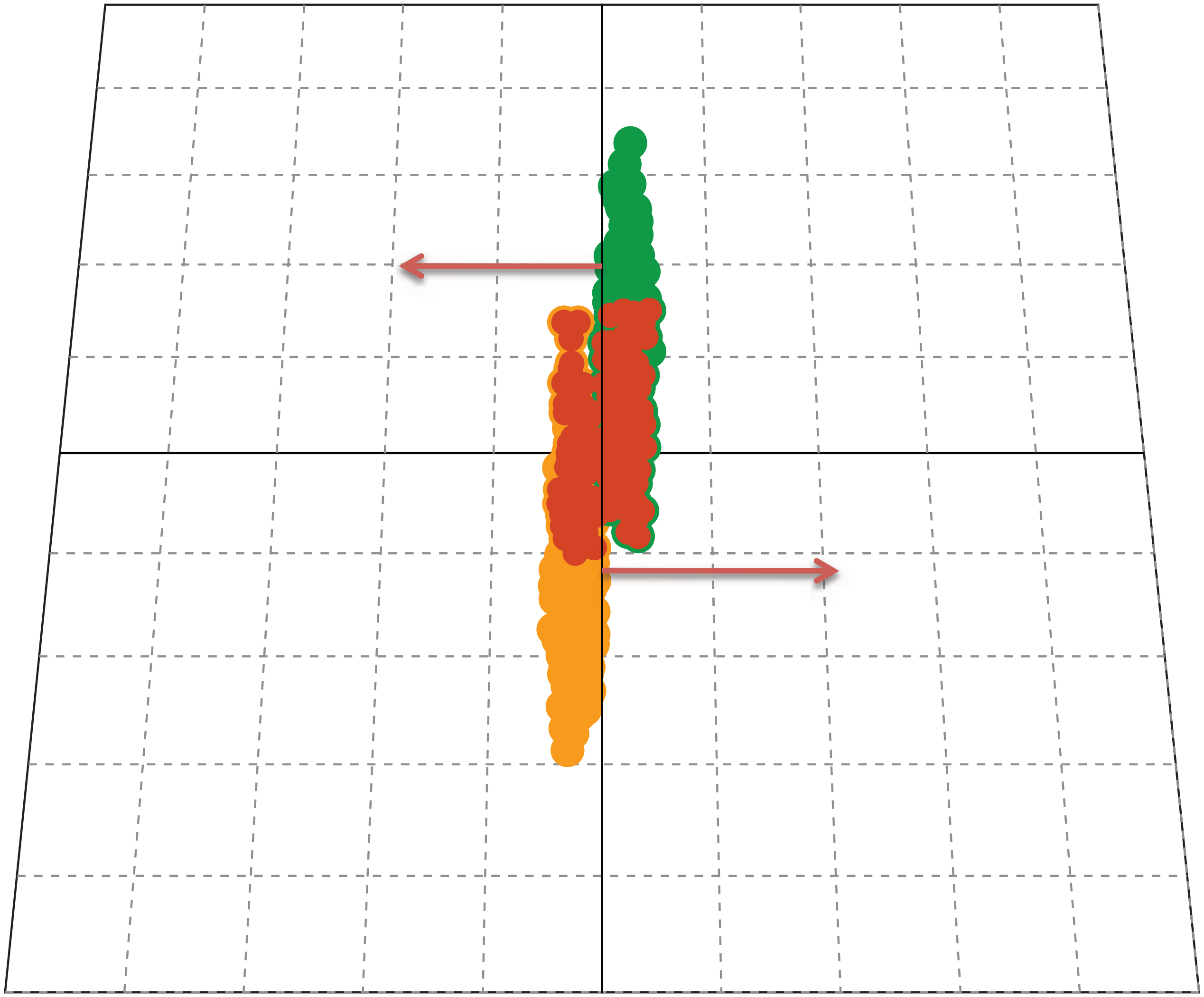


Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

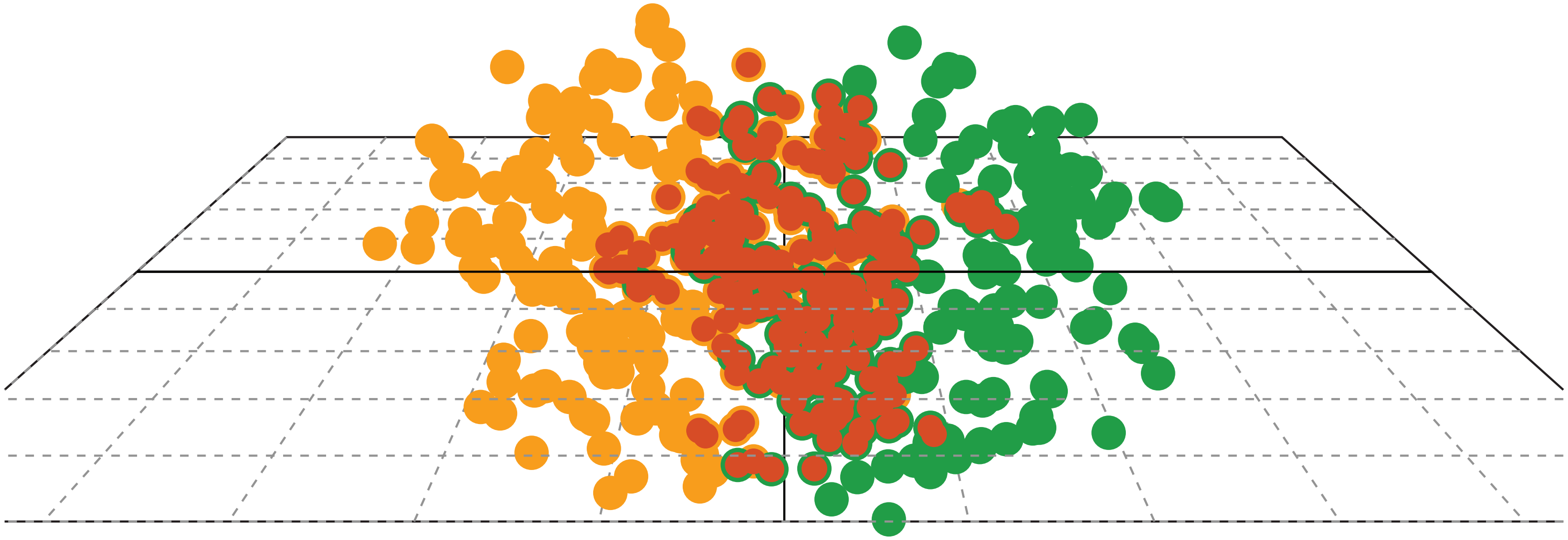
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen

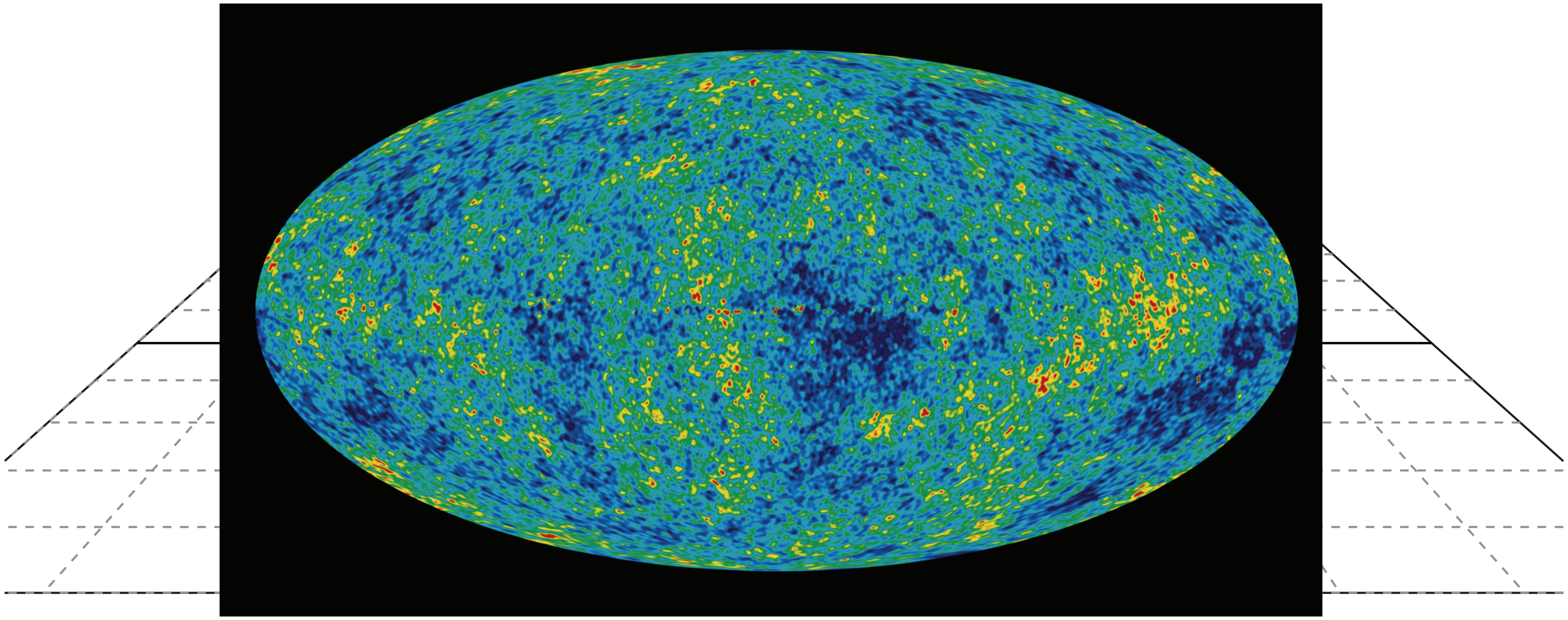


Produced fireball is ~10^{-14} meters across and lives for ~5×10^{-23} seconds

Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen

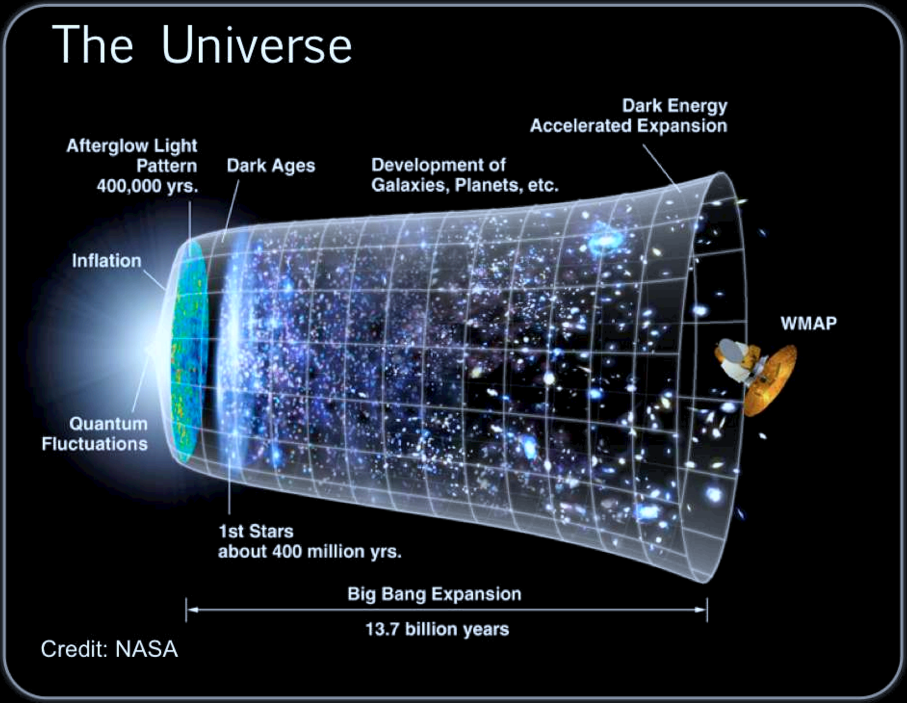


Produced fireball is ~10^{-14} meters across and lives for ~5x10^{-23} seconds

Collision of two Lorentz contracted gold nuclei

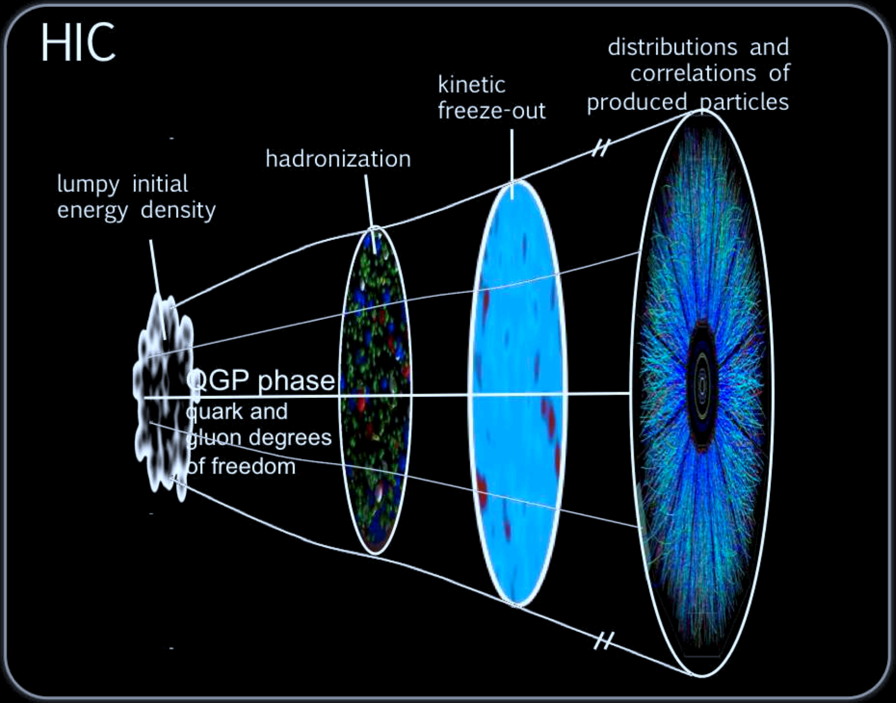
The Big Bang vs the Little Bangs

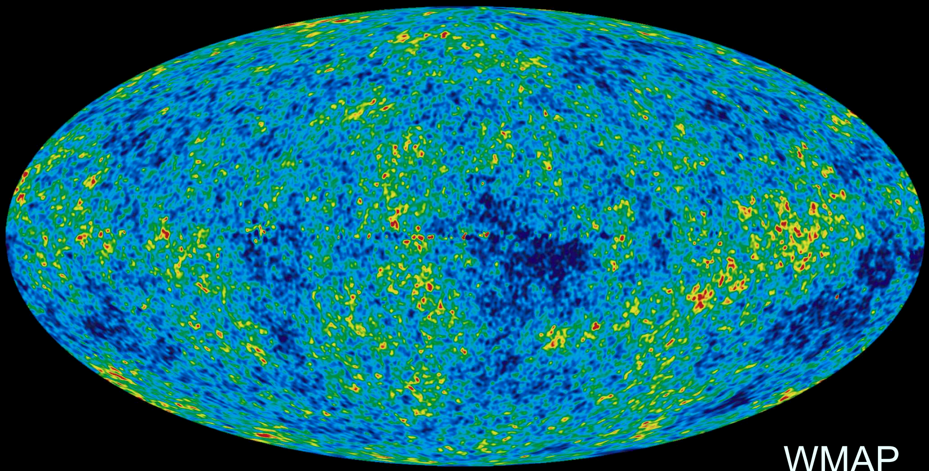
The Universe



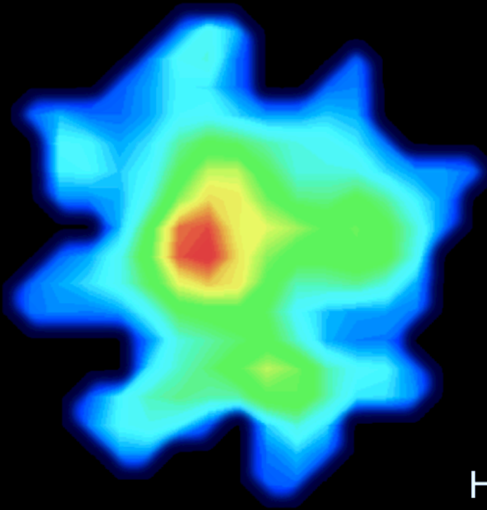
Credit: NASA

HIC





WMAP

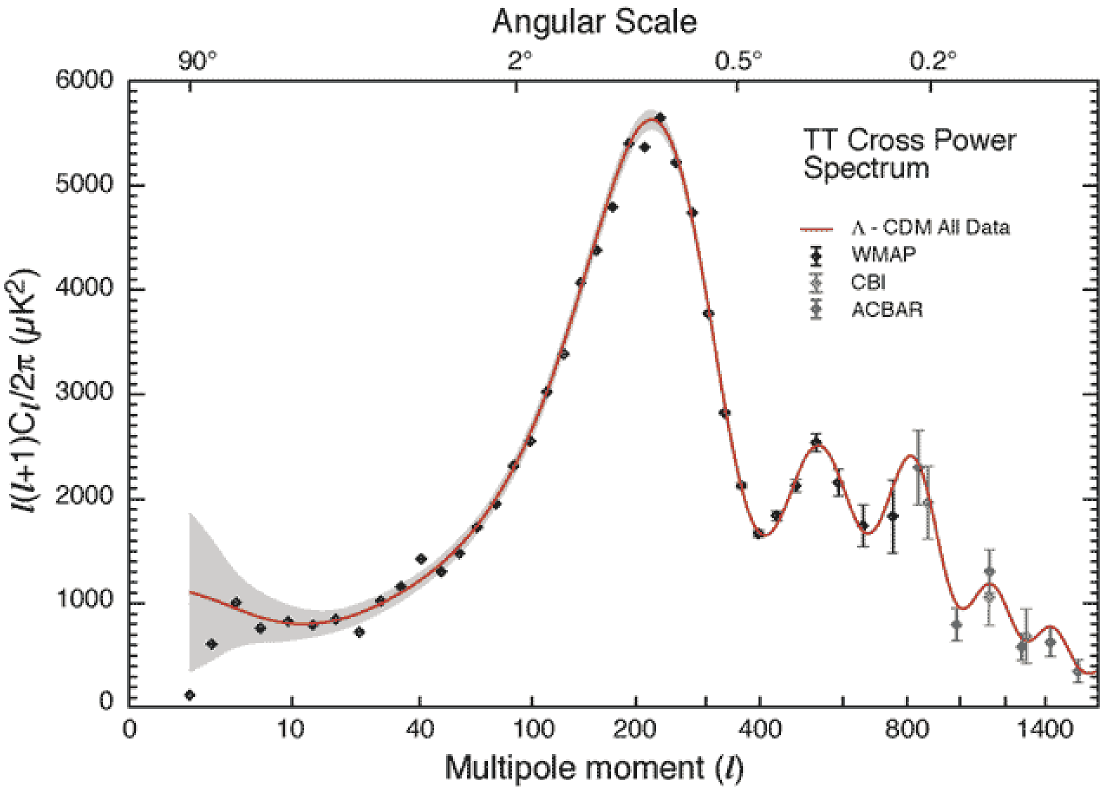


HIC

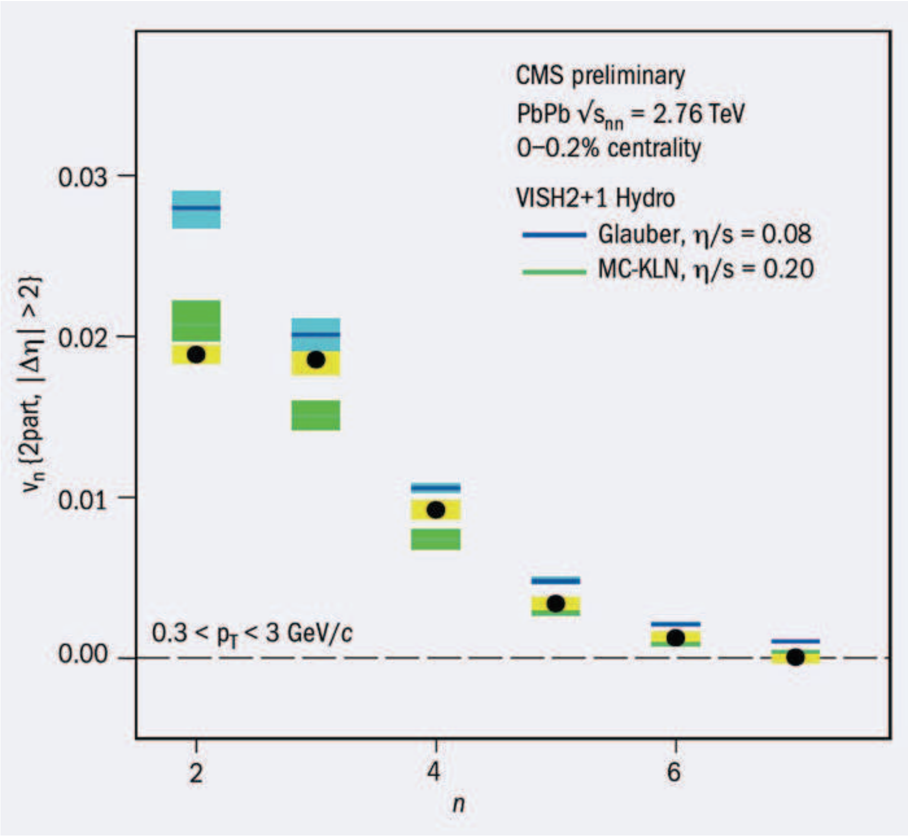
Big vs. Little Bang: The fluctuation power spectrum

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

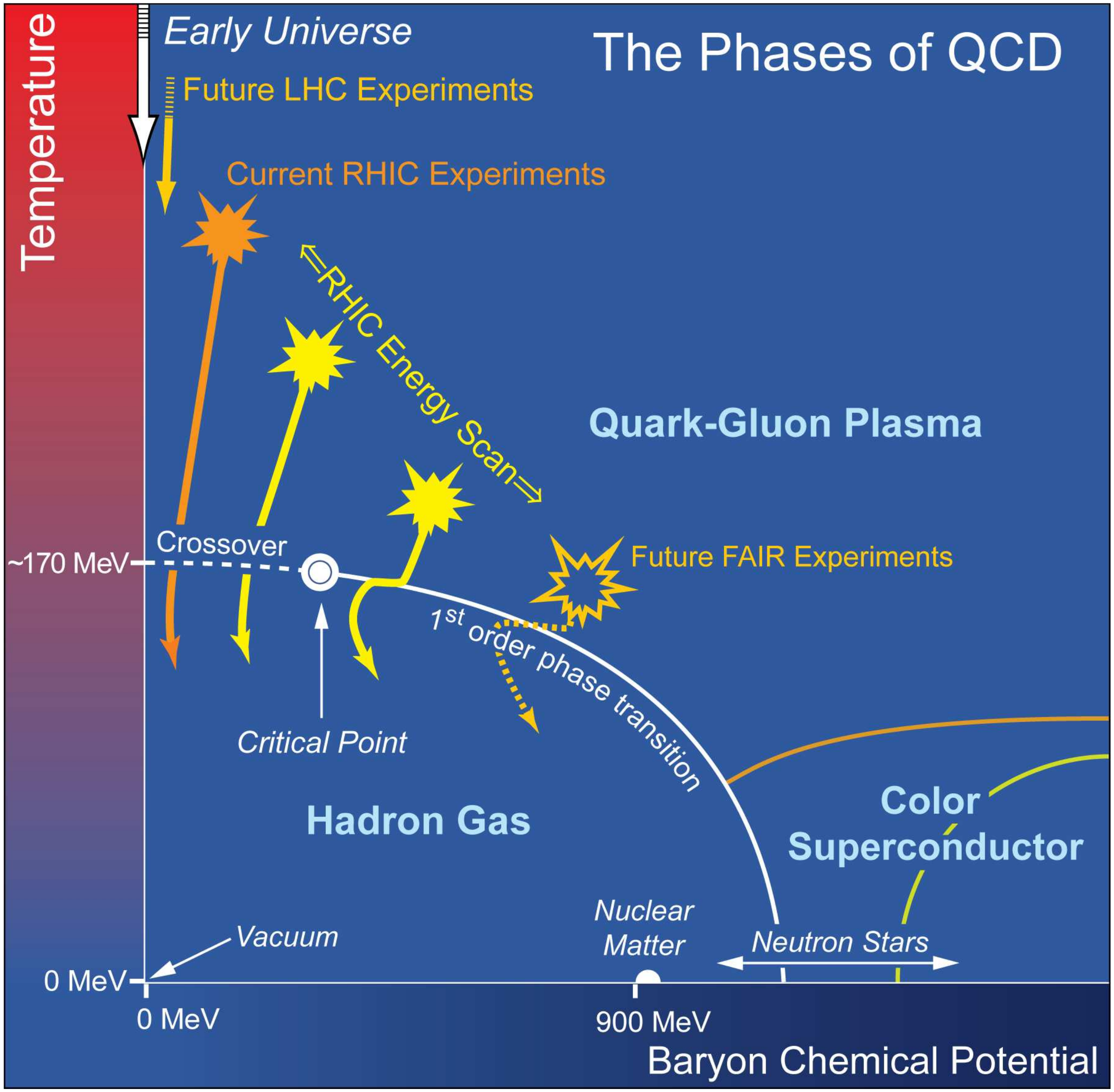
Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71



Status: Quark Matter 2012



The landscape of QCD matter: The future is now



Probes:

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

The University of Queensland pitch drop experiment

SI unit for shear viscosity:

$$[\eta] = \text{Poise} = \text{kg}/(\text{m}\cdot\text{s})$$

$$\eta_{\text{water}} = \mathcal{O}(10^{-2}\,\text{Poise})$$

$$\eta_{\text{pitch}} \approx 2.3{\times}10^{11}\,\eta_{\text{water}} = \mathcal{O}(10^{9}\,\text{Poise})$$

(∼ one drop per decade –
next drop expected to fall in 2013!)

$$\eta_{\text{QGP}} \approx 10^{3}\,\eta_{\text{pitch}} = \mathcal{O}(10^{12}\,\text{Poise})$$

A measure of fluidity

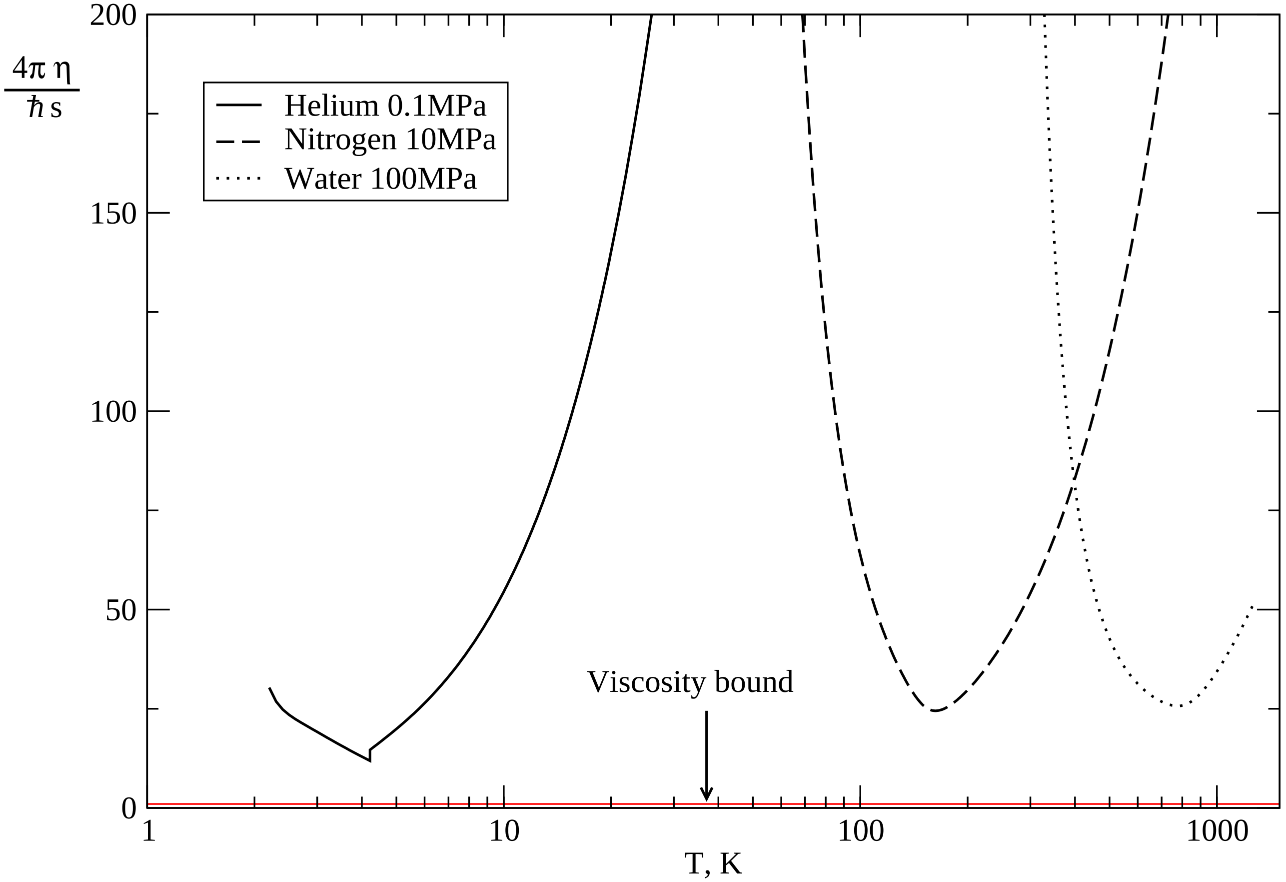
$$\frac{\eta}{e+p} \times \partial\cdot u = \frac{\Gamma_{\mathrm{exp}}}{\Gamma_{\mathrm{sound}}} \sim \frac{\eta}{s}\,\frac{1}{T\tau}$$

The **specific viscosity** η/s (s=entropy density) is conceptually related to the "kinematic viscosity" η/n in Navier-Stokes theory

QGP – the most perfectly fluid liquid ever observed!

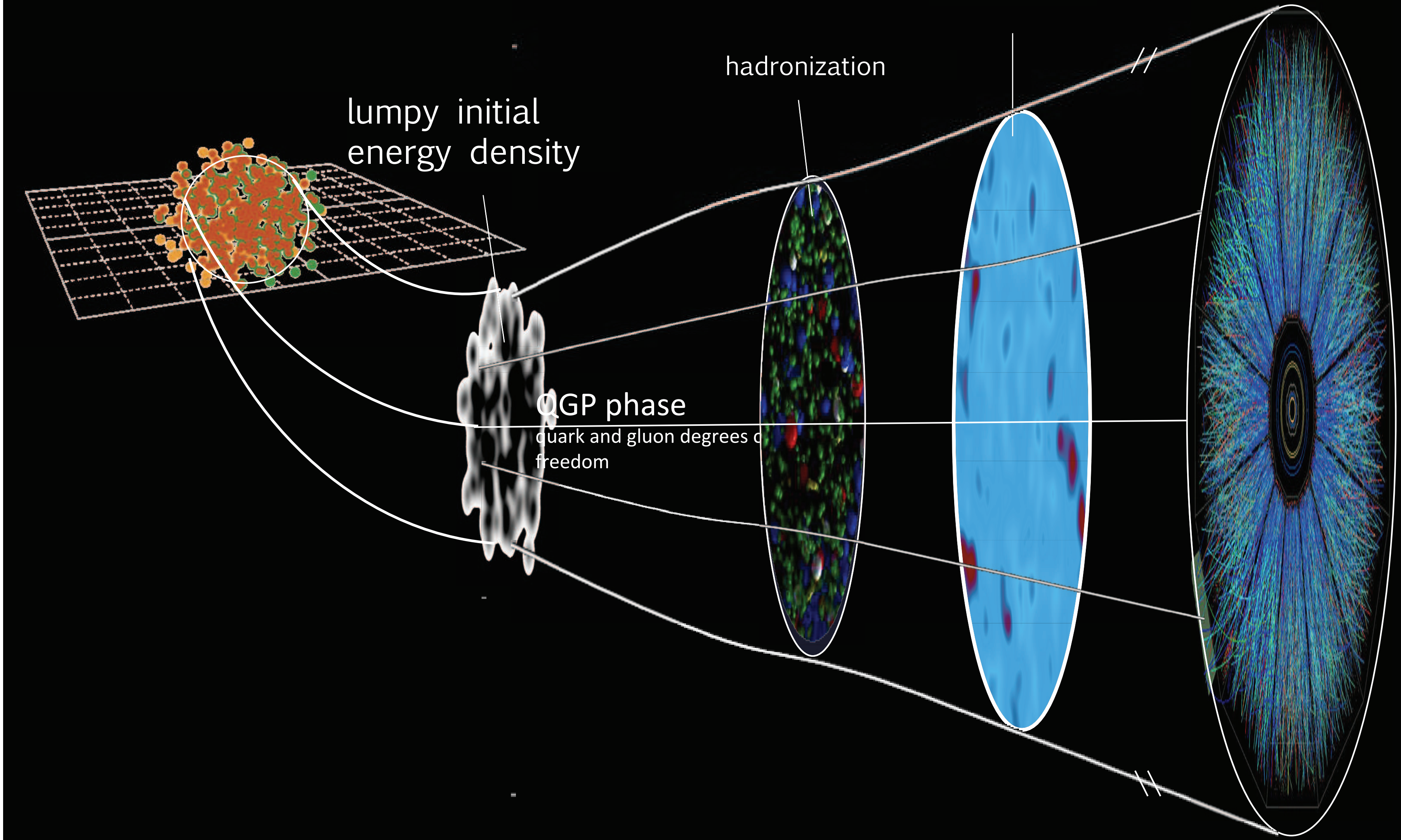
AdS/CFT universal lower viscosity bound conjecture: $\boldsymbol{\frac{\eta}{s} \gtrsim \frac{\hbar}{4\pi k_B}}$

Kovtun, Son, Starinets, PRL 94 (2005) 111601



Will show that the QGP viscosity is close to this bound!

Expansion of the Little Bang



distributions and
correlations of
produced particles

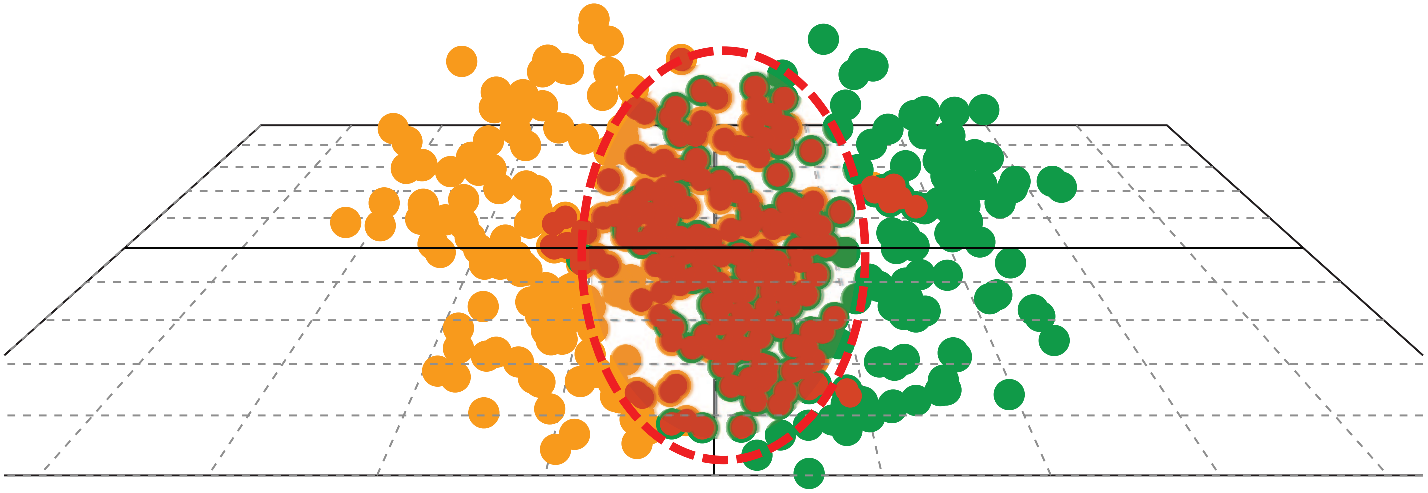
kinetic
freeze-out

hadronization

lumpy initial
energy density

QGP phase
quark and gluon degrees o
freedom

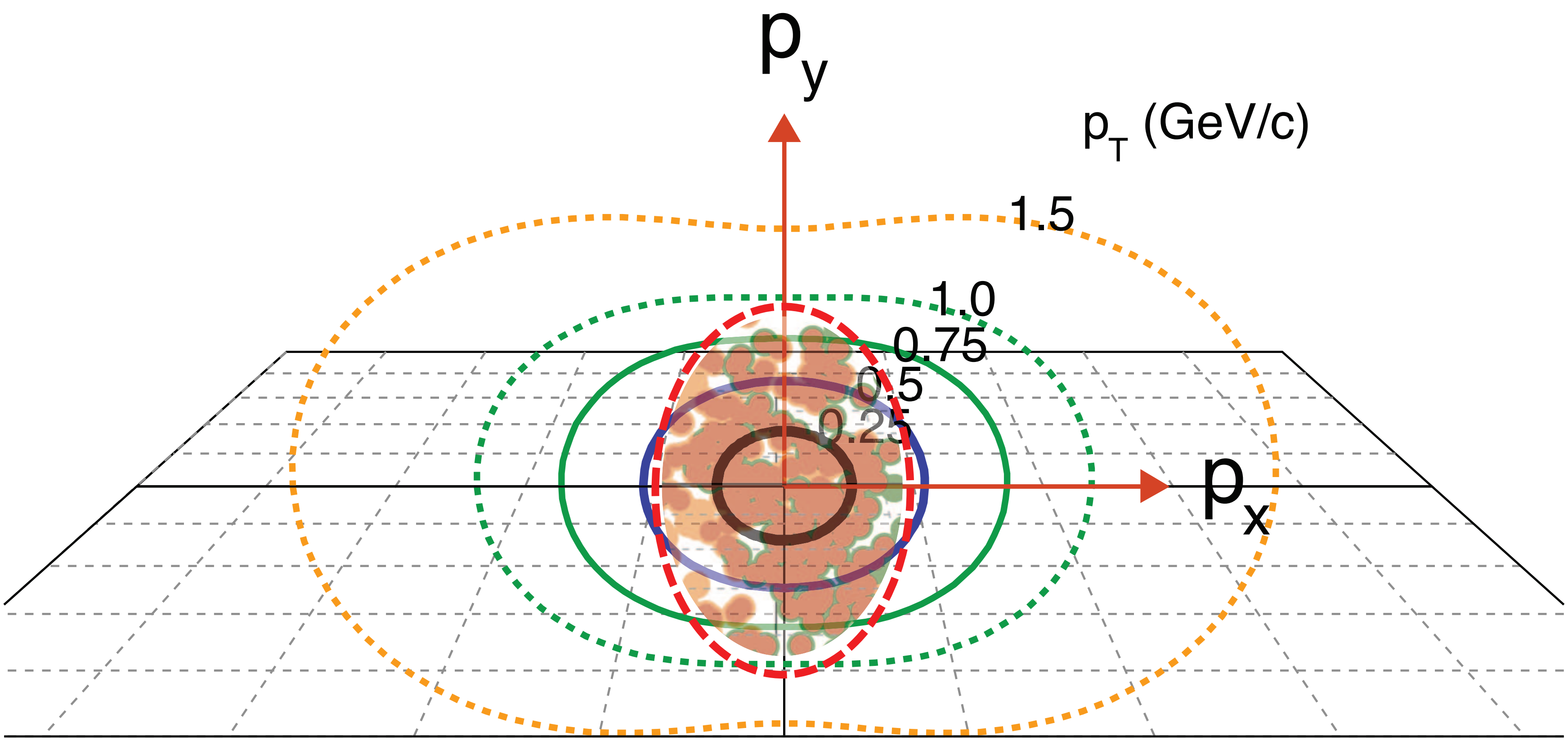
Azimuthal Distributions: x-space



Are particles emitted at random angles?

No. They remember the initial geometry!

Azimuthal Distributions: p-space

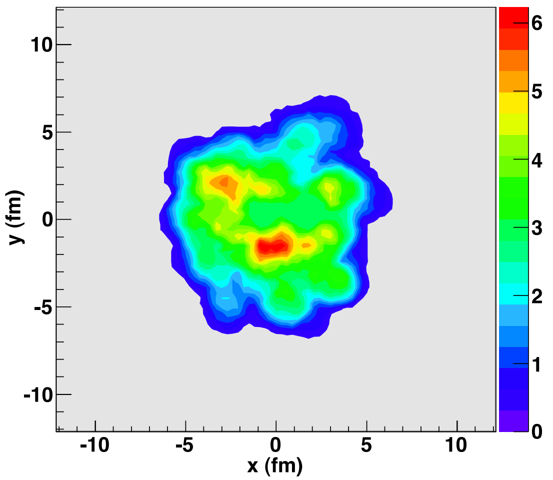


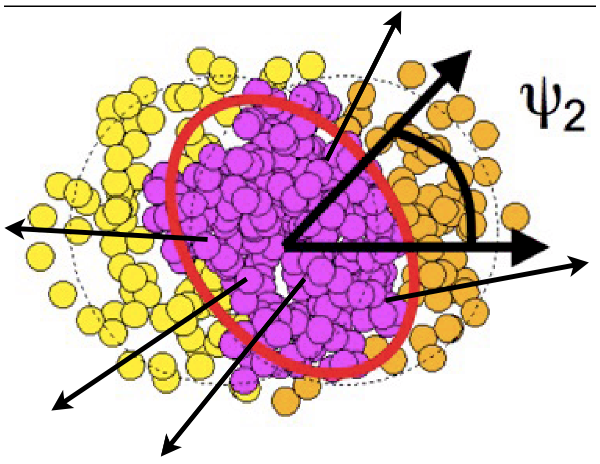
Are particles emitted at random angles?

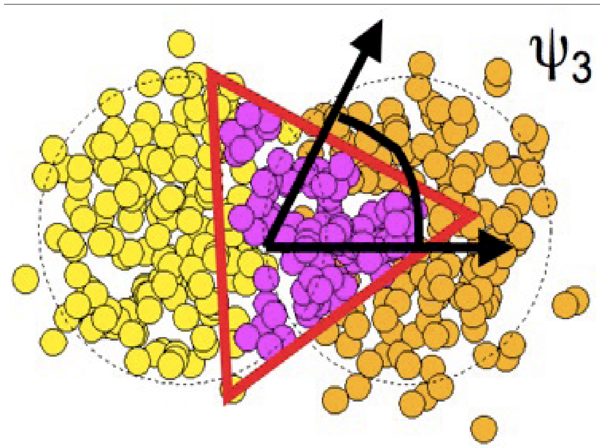
No. They remember the initial geometry!

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)

How anisotropic flow is measured:

Definition of flow coefficients:

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

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

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:

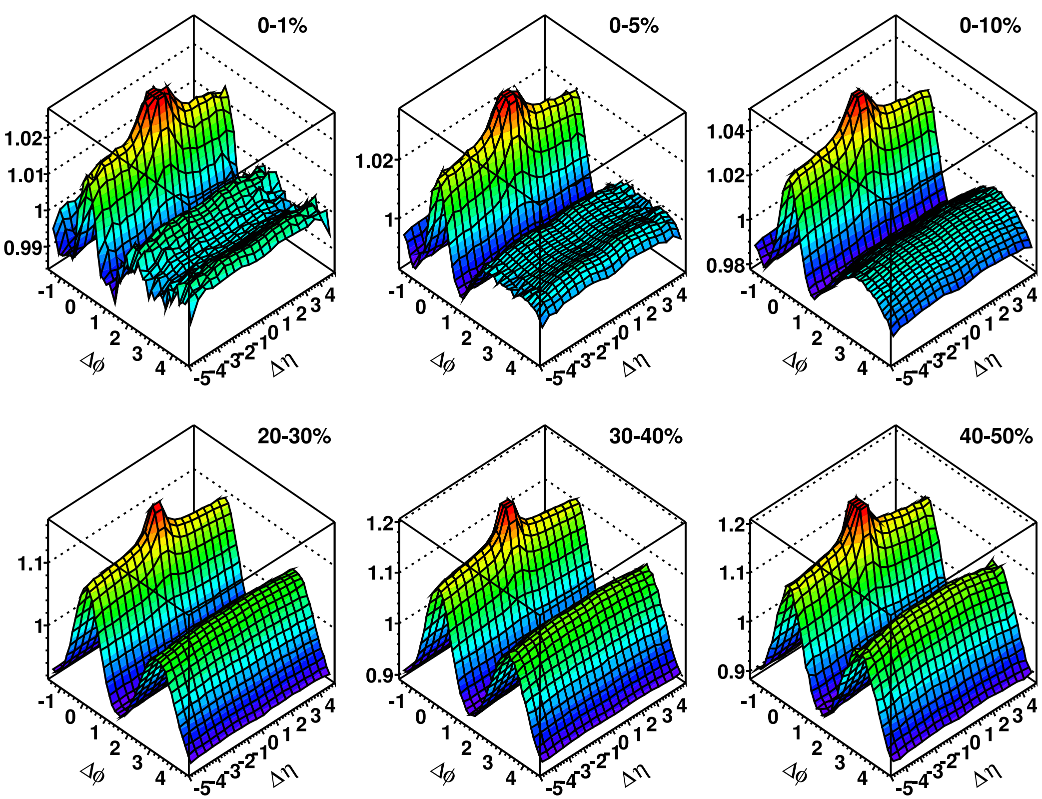
$$\langle v_2^2\rangle = \langle v_2\rangle^2 + \sigma^2, \qquad \langle v_2^4\rangle = \langle v_2\rangle^4 + 6\sigma^2\langle v_2\rangle^2$$

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

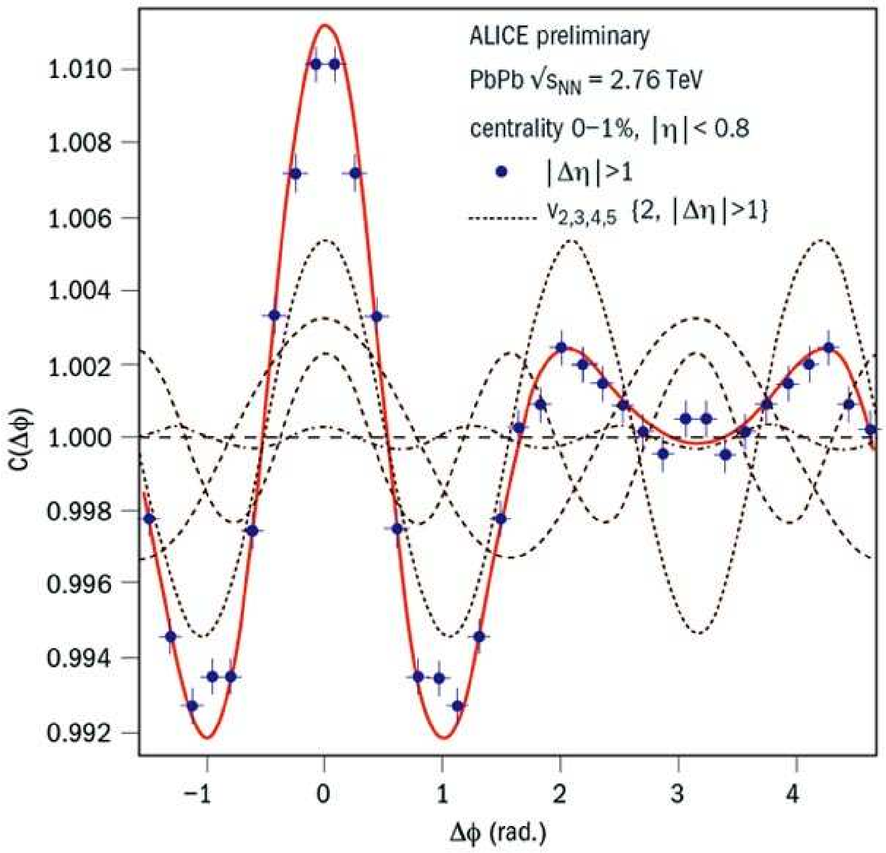
$$v_2\{2\} = \sqrt{\langle v_2^2\rangle}, \qquad v_2\{4\} = \sqrt[4]{2\langle v_2^2\rangle^2 - \langle v_2^4\rangle}$$

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!

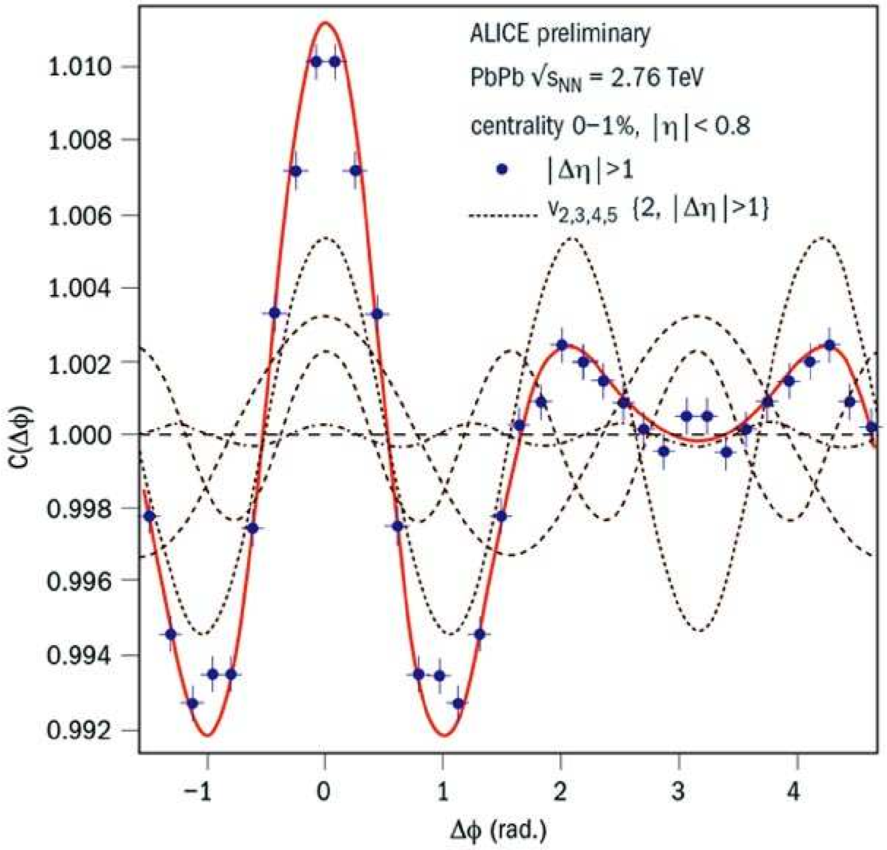
  M. Luzum, PLB 696 (2011) 499: All long-range rapidity correlations seen at RHIC are consistent with being entirely generated by hydrodynamic flow.

- in the 1% most central collisions $v_3 > v_2$

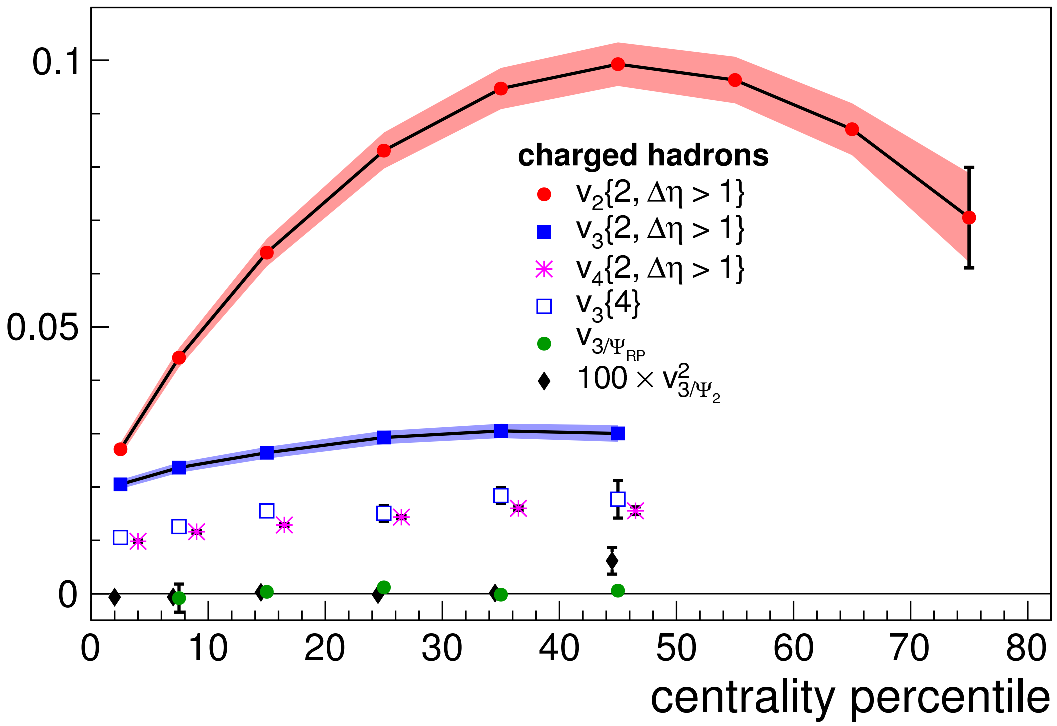
  $\Longrightarrow$ prominent “Mach cone”-like structure!

  $\Longrightarrow$ 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

Viscous relativistic hydrodynamics (Israel & Stewart 1979)

Include shear viscosity η, neglect bulk viscosity (massless partons) and heat conduction ($\mu_B \approx 0$); solve

$$\partial_\mu T^{\mu\nu} = 0$$

with modified energy momentum tensor

$$T^{\mu\nu}(x) = \big(e(x)+p(x)\big)u^\mu(x)u^\nu(x) - g^{\mu\nu}p(x) + \pi^{\mu\nu}.$$

$\pi^{\mu\nu}$ = traceless viscous pressure tensor which relaxes locally to 2η times the shear tensor $\nabla^{\langle\mu}u^{\nu\rangle}$ on a microscopic kinetic time scale τ_π:

$$D\pi^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle}\right) + \dots$$

where $D \equiv u^\mu\partial_\mu$ is the time derivative in the local rest frame.

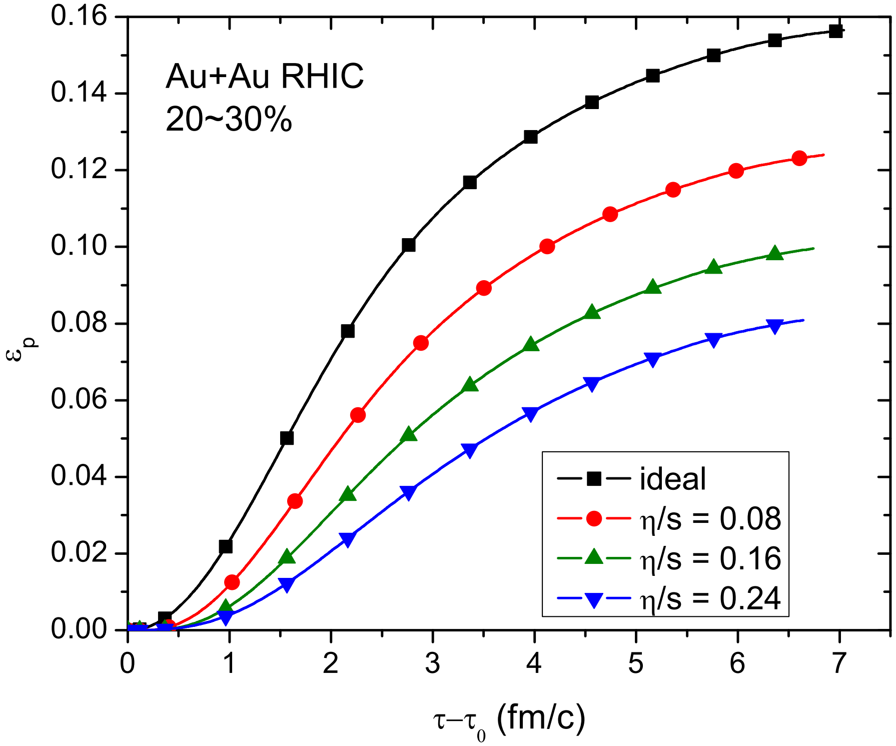
Kinetic theory relates η and τ_π, but for a strongly coupled QGP neither η nor this relation are known $\Longrightarrow$ treat η and τ_π as independent phenomenological parameters. For consistency: $\tau_\pi\theta \ll 1$ ($\theta = \partial^\mu u_\mu =$ local expansion rate).

Converting initial shape fluctuations into final flow anisotropies – the QGP shear viscosity

$$(\eta/s)_{\mathrm{QGP}}$$

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

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^{ch}**:

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

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

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

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

but: $v_2^{(i)}(p_T)$, $\frac{dN_i}{dyd^2p_T}$ 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)

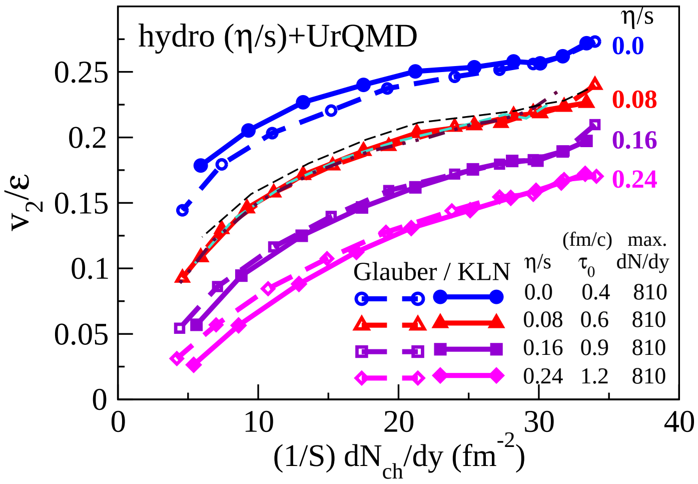
$\Rightarrow$ need hybrid code that couples viscous hydrodynamic evolution of QGP to **realistic microscopic dynamics** of late-stage hadron gas phase

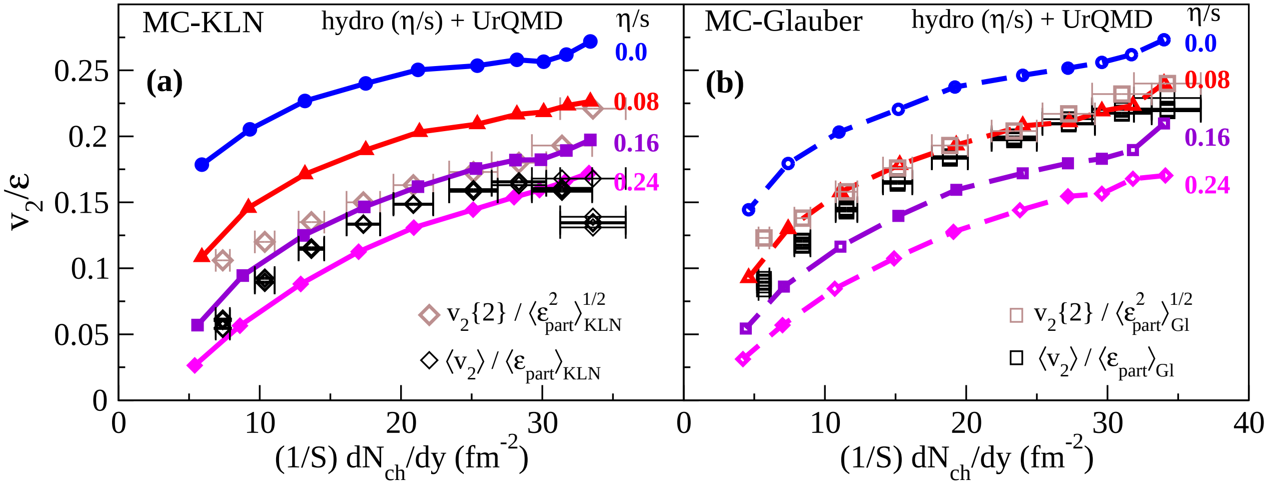
$\Rightarrow$ **VISHNU** ("Viscous Israel-Stewart Hydrodynamics 'n' UrQMD")

(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



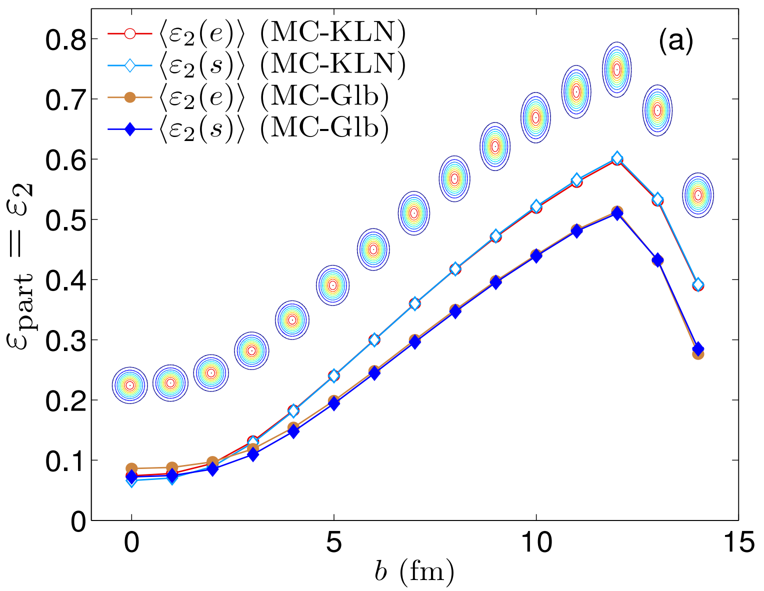


$$1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$$

- 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** $\boldsymbol{\eta/s}$ 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. $\varepsilon_x^{\rm KLN}$ ⟶
- smaller effects: *early flow* → increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % → larger η/s

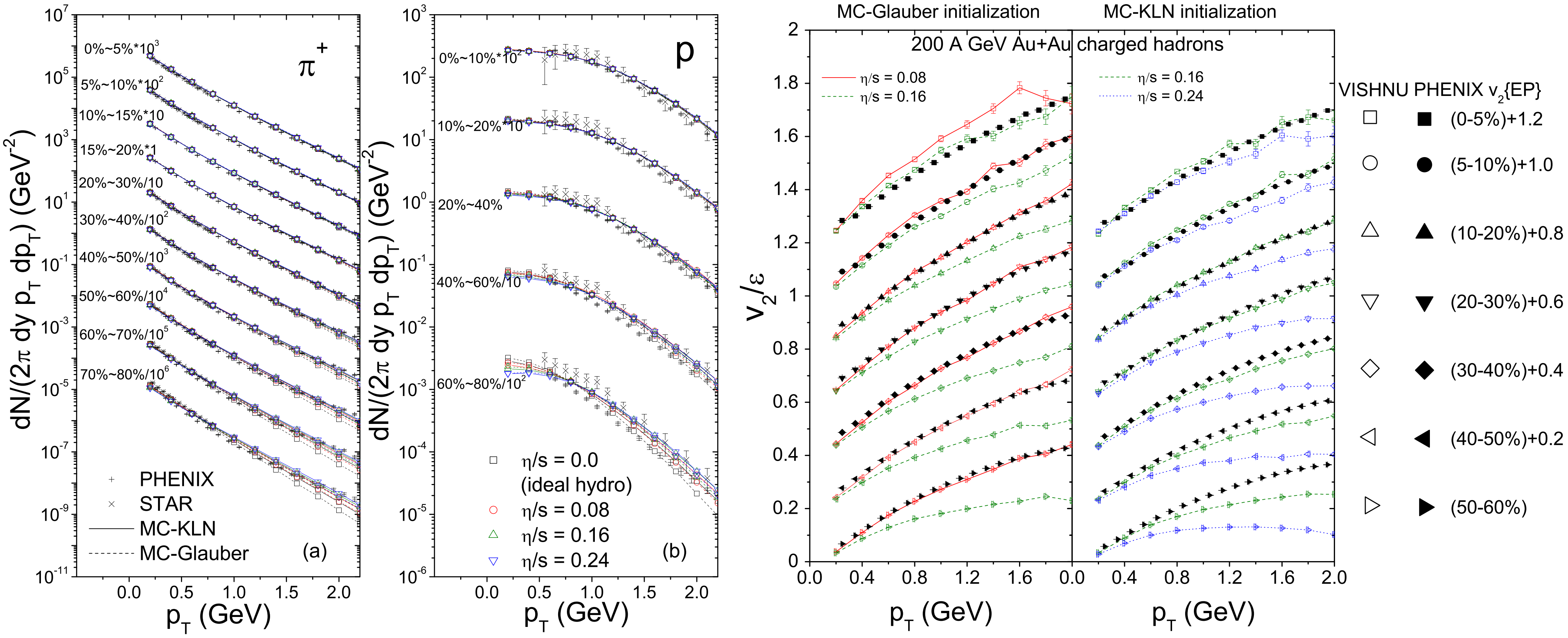
  bulk viscosity → affects $v_2^{\rm ch}(p_T)$, but ≈ not $v_2^{\rm ch}$

Zhi Qiu, UH, PRC84 (2011) 024911



Global description of AuAu@RHIC spectra and v_2

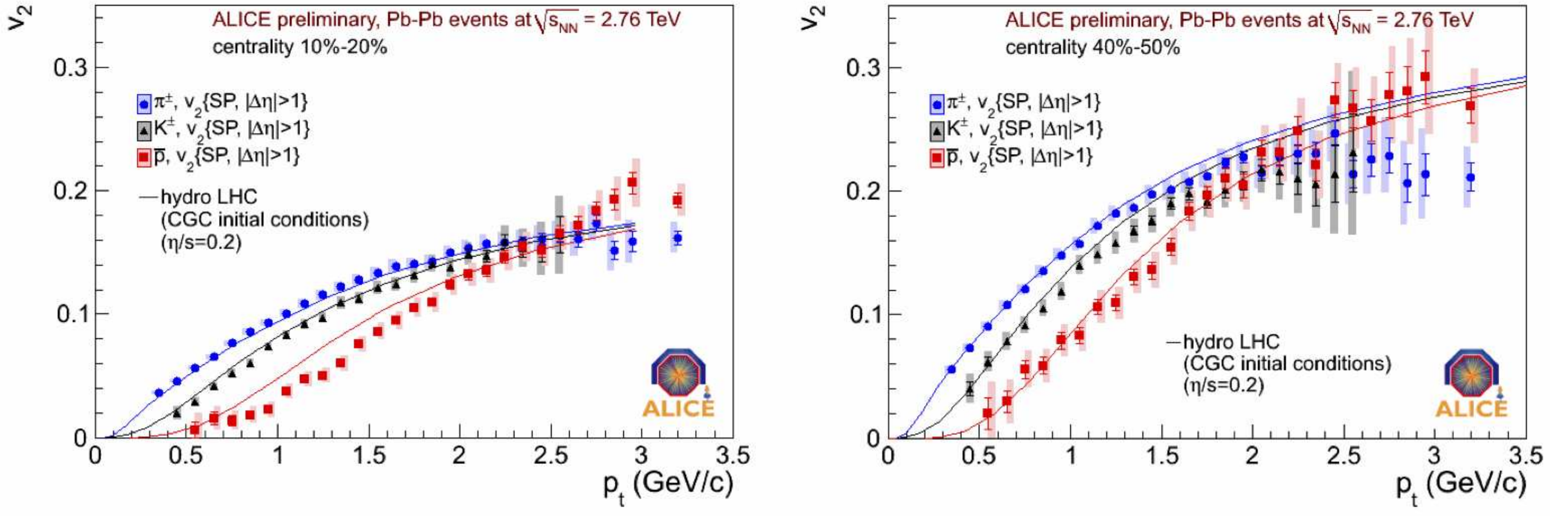
VISHNU (H. Song, S.A. Bass, UH, T. Hirano, C. Shen, PRC83 (2011) 054910)



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

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)



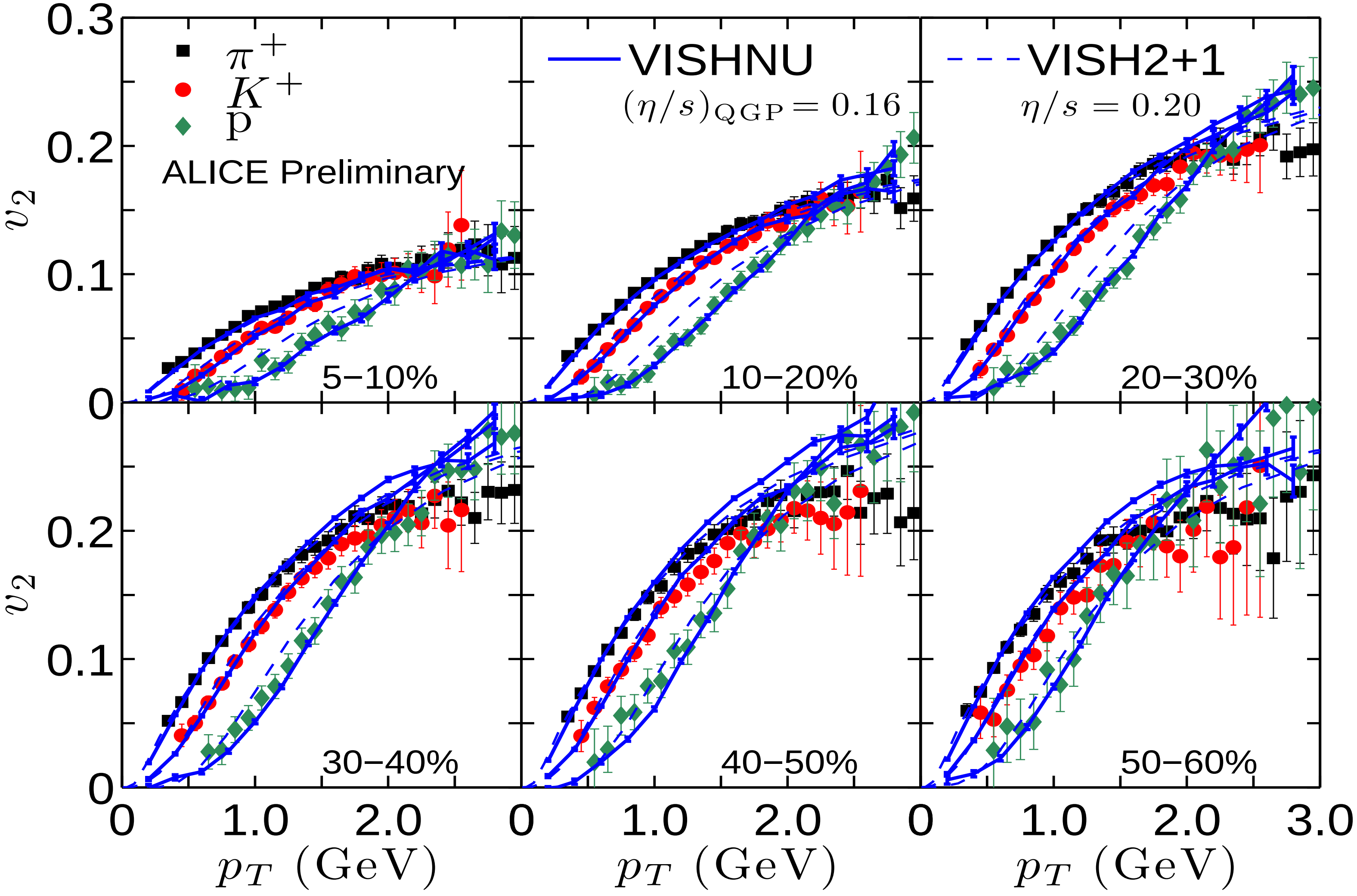
Perfect fit in semi-peripheral collisions!

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. VISHNU

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



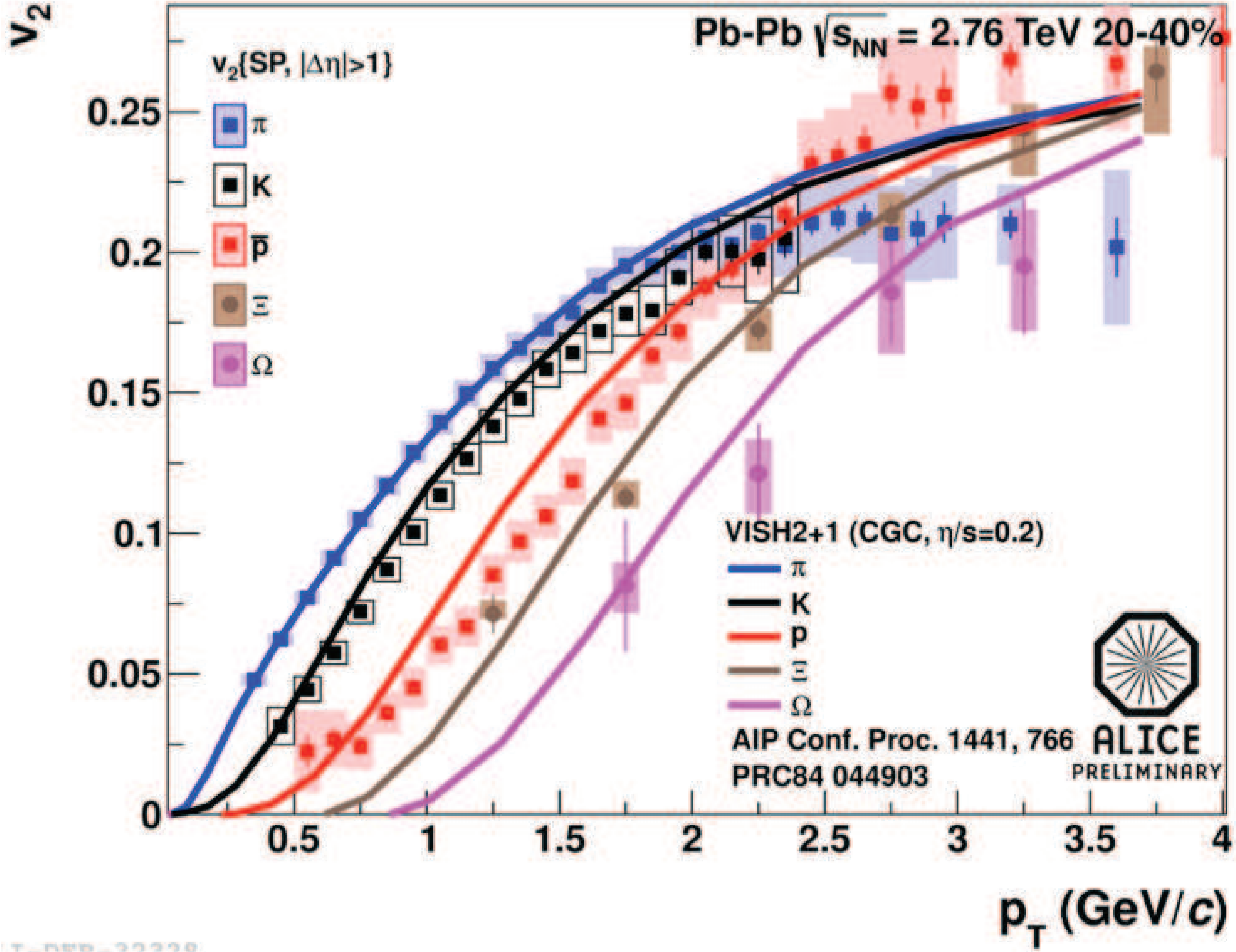
VISHNU yields correct magnitude and centrality dependence of $v_2(p_T)$ for pions, kaons **and protons!**

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

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

Data: ALICE, Quark Matter 2012

Prediction: Shen et al., PRC84 (2011) 044903 (VISH2+1)



Radial flow pushes v_2 for heavier hadrons to larger p_T

Theory curves are true predictions, without any parameter adjustment

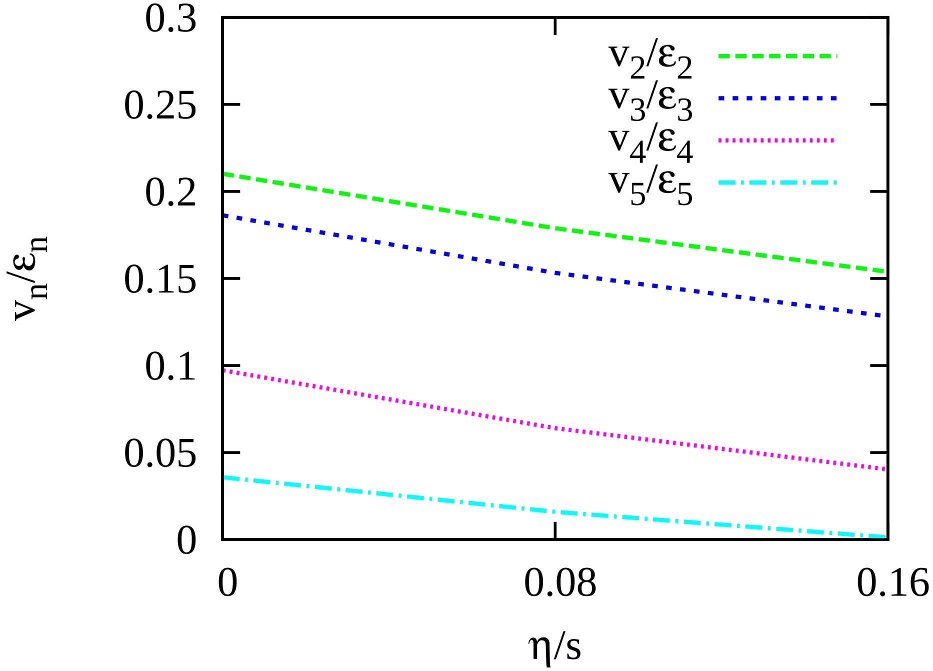
Back to the “elephant in the room”: How to eliminate the large model uncertainty in the initial eccentricity?

Two observations:

I. Shear viscosity suppresses higher flow harmonics more strongly

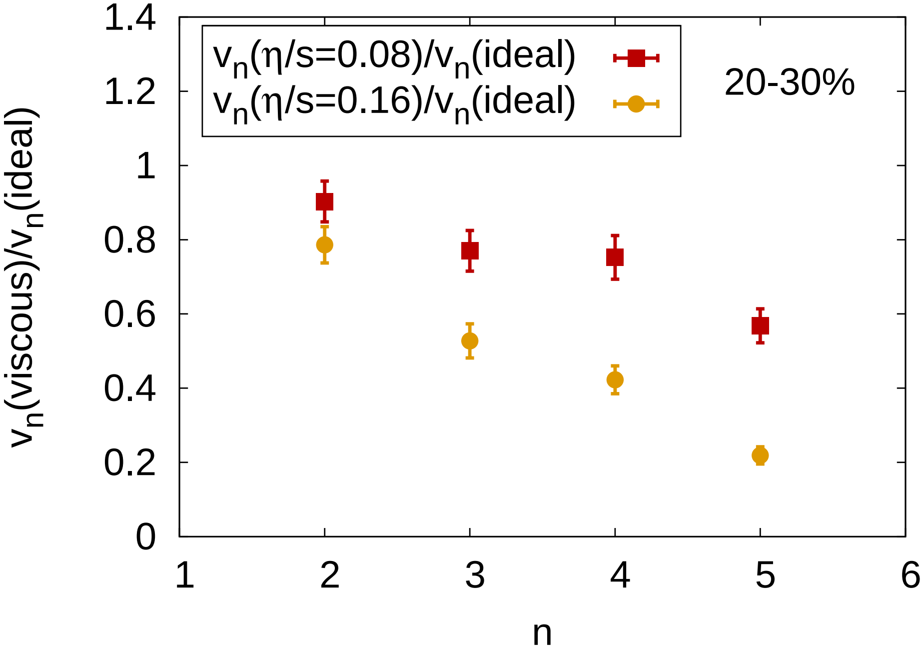
Alver et al., PRC82 (2010) 034913

(averaged initial conditions)



Schenke et al., arXiv:1109.6289

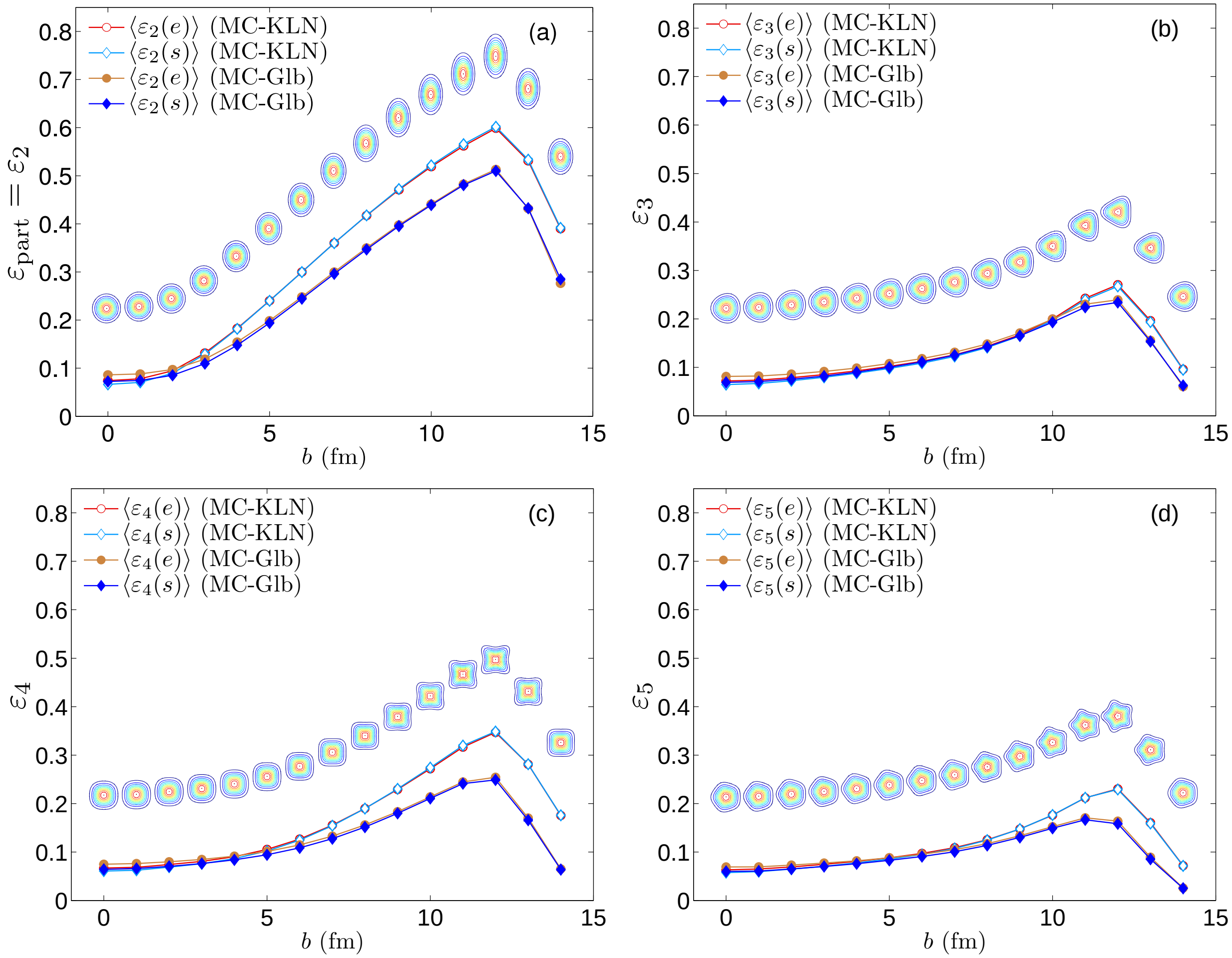
(event-by-event hydro)



⟹ **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:

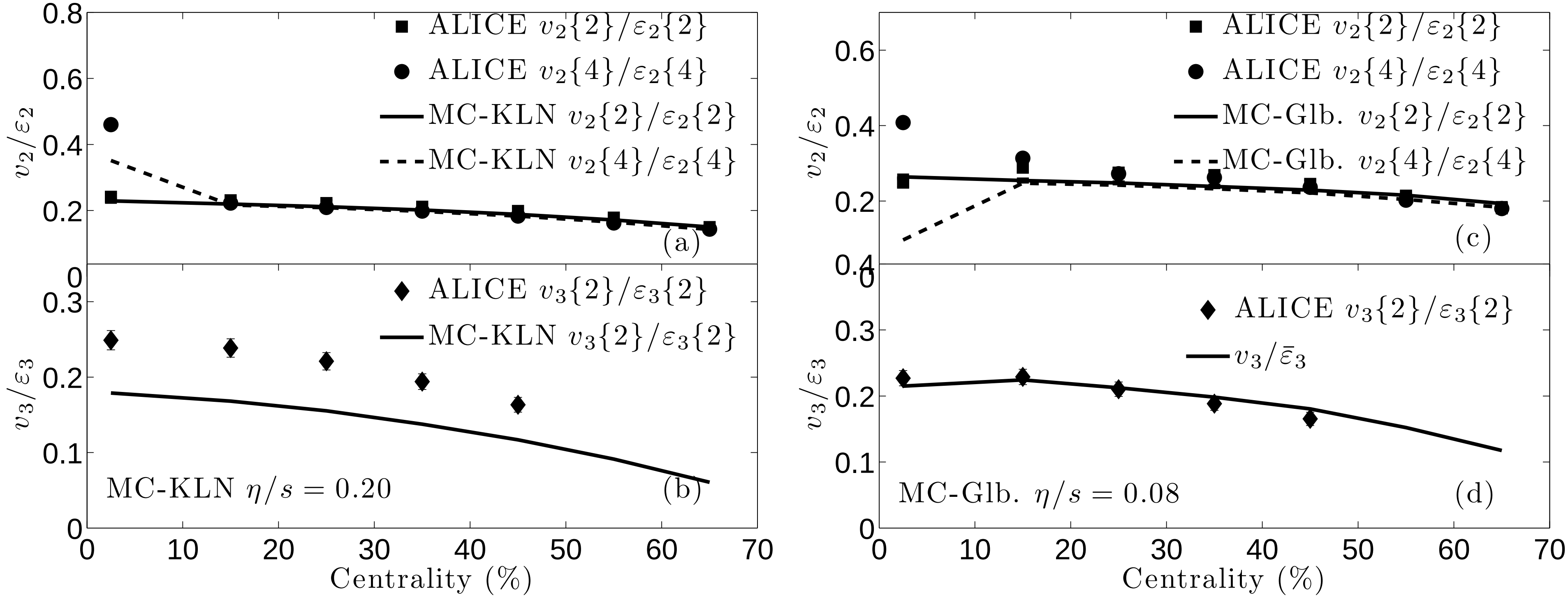
$$\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$$

- 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!

Combined v_2 & v_3 analysis: η/s is small!

Zhi Qiu, C. Shen, UH, PLB707 (2012) 151 and QM2012 (e-by-e VISH2+1)

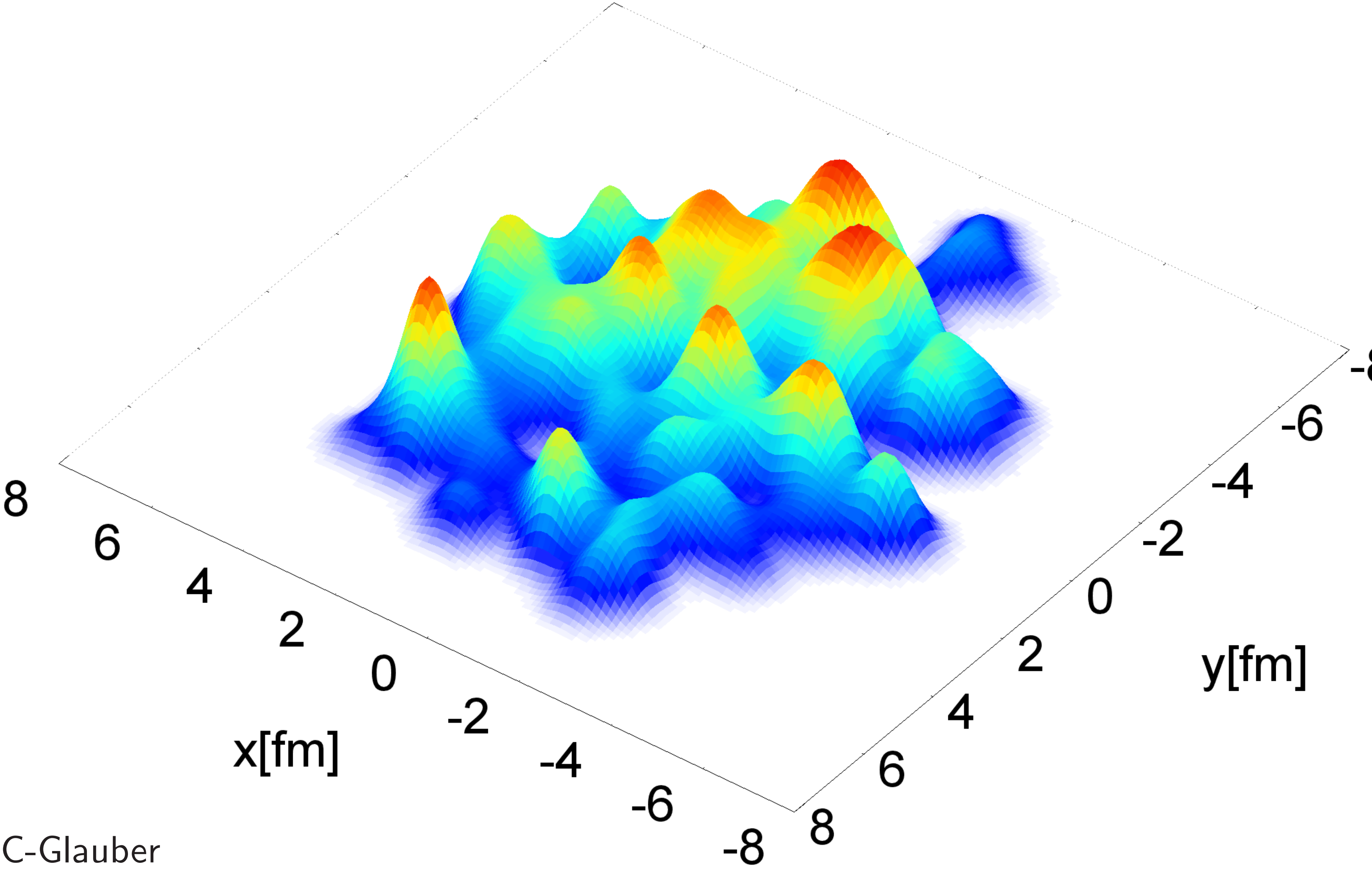


- Both MC-KLN with $\eta/s = 0.2$ and MC-Glauber with $\eta/s = 0.08$ give very good description of v_2/ε_2 at all centralities.
- **Only $\eta/s = 0.08$ (with MC-Glauber initial conditions) describes v_3/ε_3!**
  PHENIX, comparing to calculations by Alver et al. (PRC82 (2010) 034913), come to similar conclusions at RHIC energies (Adare et al., arXiv:1105.3928, and Lacey et al., arXiv:1108.0457)
- **Large v_3 measured at RHIC and LHC requires small $(\eta/s)_{\mathrm{QGP}} \simeq 1/(4\pi)$** unless the fluctuations in these models are completely wrong and ε_3 is really 50% larger than these models predict!

Sub-nucleonic fluctuations

Adding sub-nucleonic quantum fluctuations

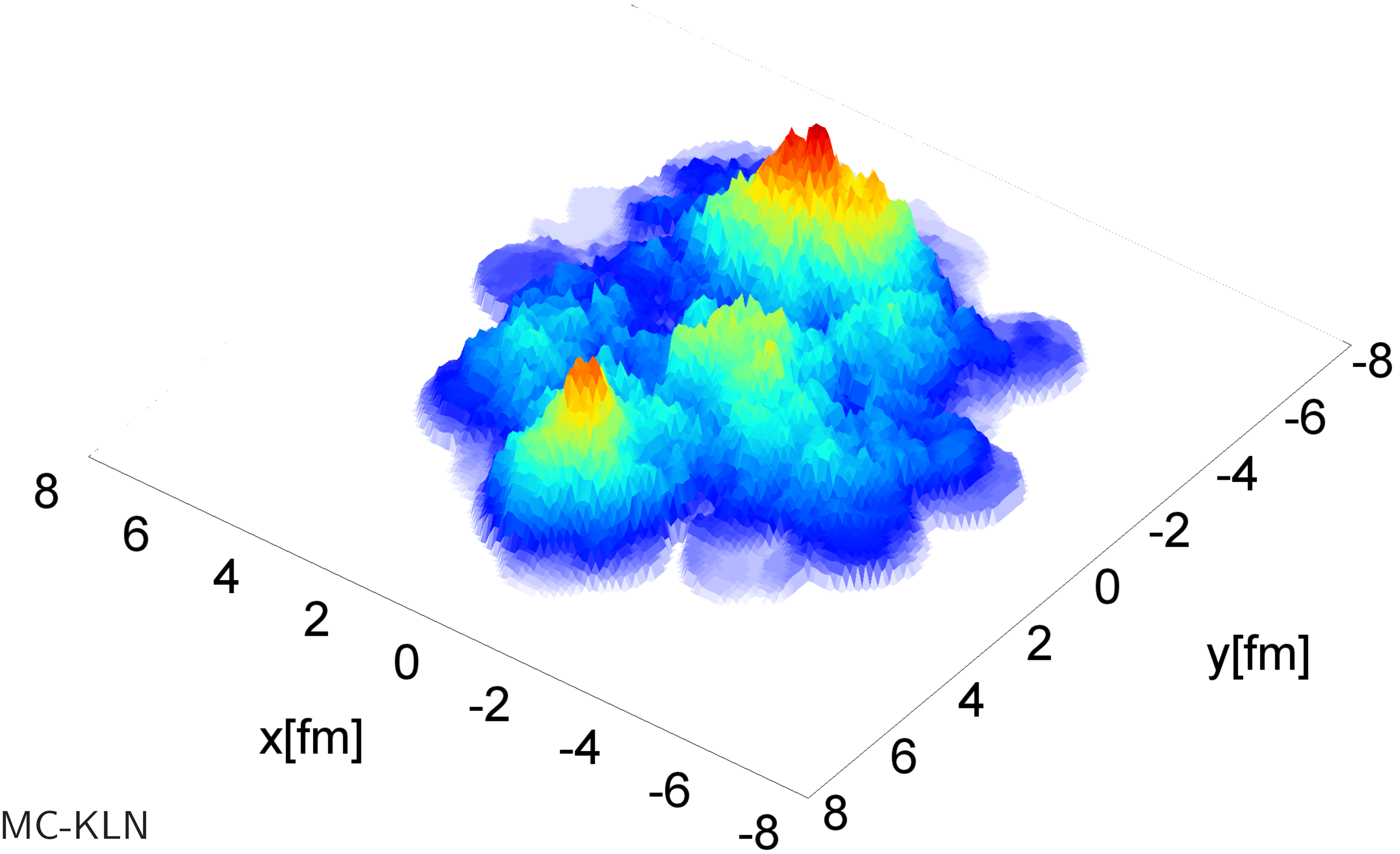
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)



MC-Glauber

Adding sub-nucleonic quantum fluctuations

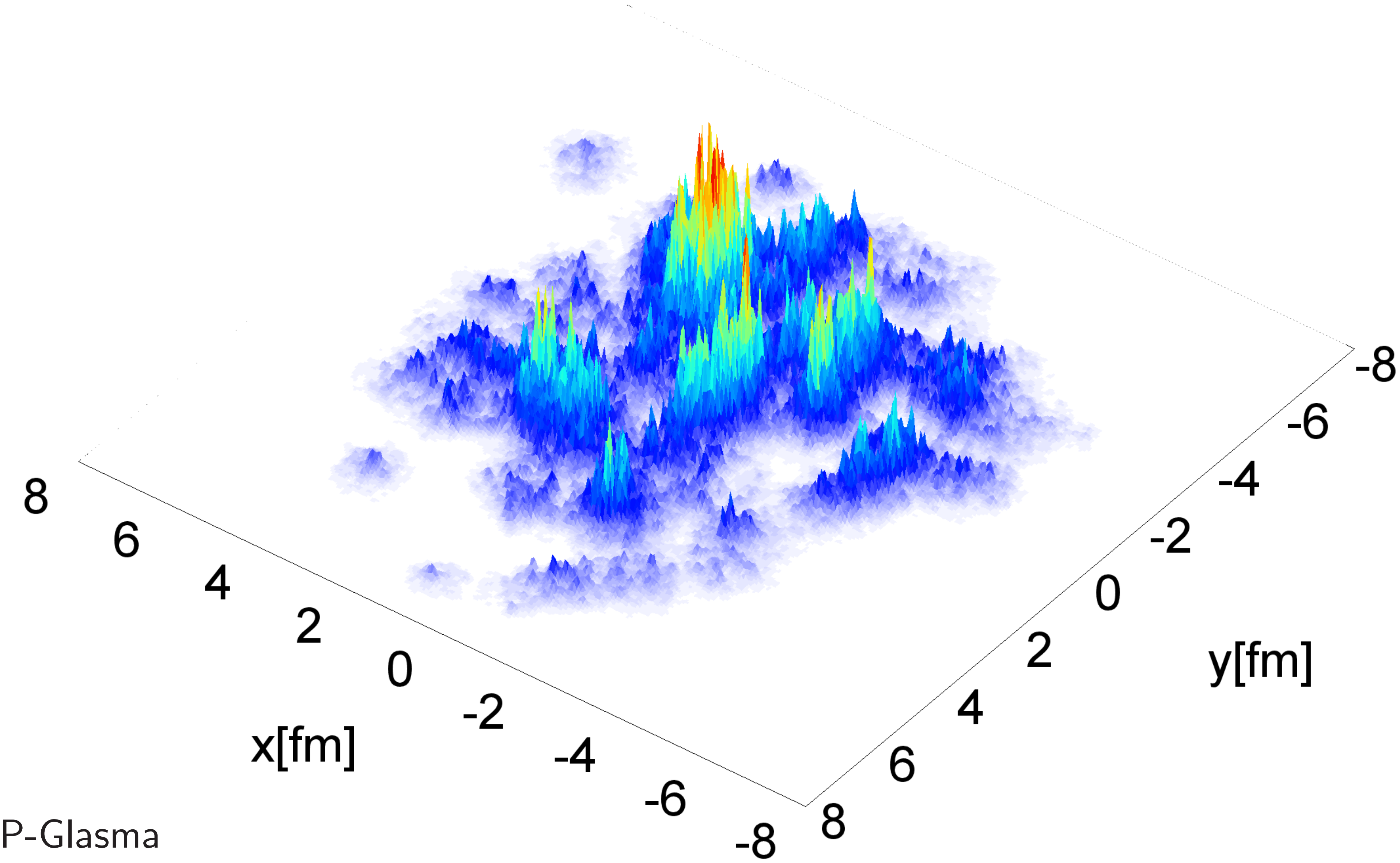
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)



MC-KLN

Adding sub-nucleonic quantum fluctuations

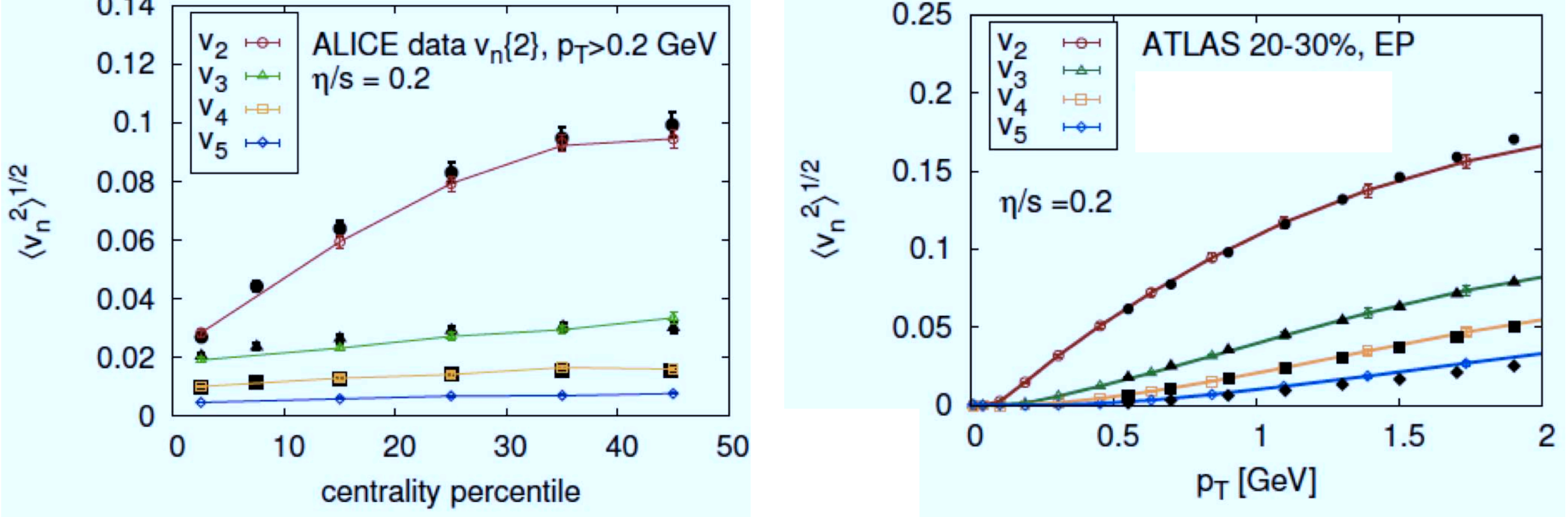
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)



IP-Glasma

Towards a Standard Model of the Little Bang

B. Schenke: QM2012



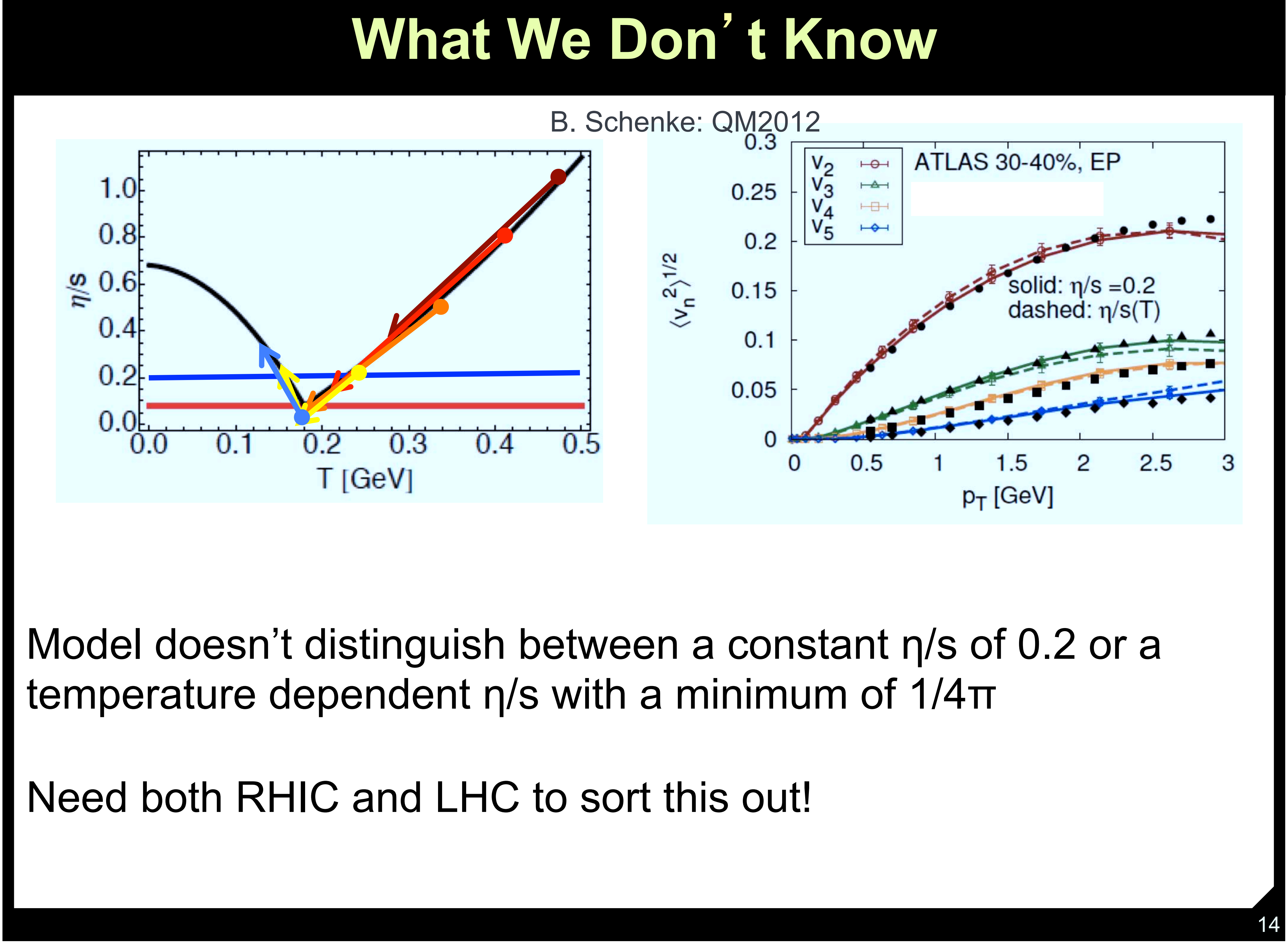
Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

With inclusion of sub-nucleonic quantum fluctuations and pre-equilbrium dynamics of gluon fields:

→ outstanding agreement between data and model

Rapid convergence on a standard model of the Little Bang!

Perfect liquidity reveals in the final state initial-state gluon field correlations of size $1/Q_s$ (sub-hadronic)!



What We Don't Know

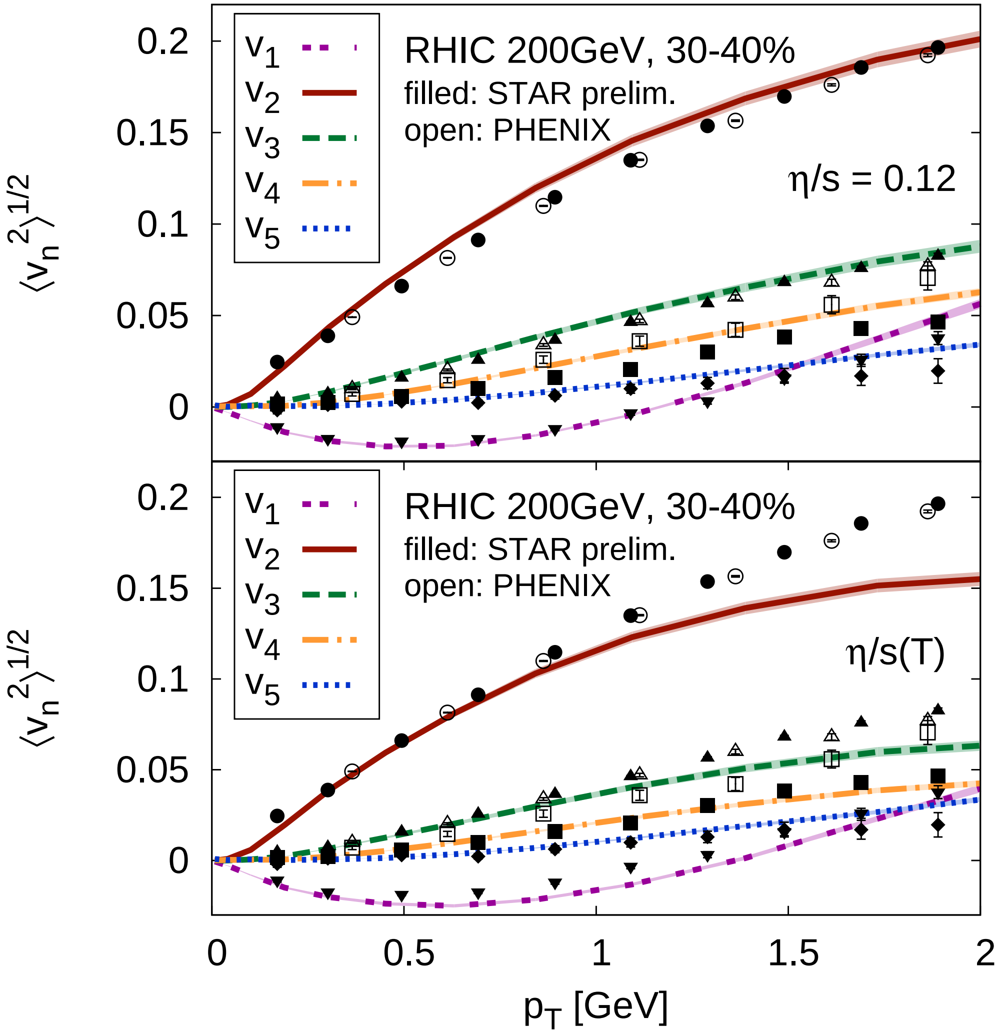
B. Schenke: QM2012

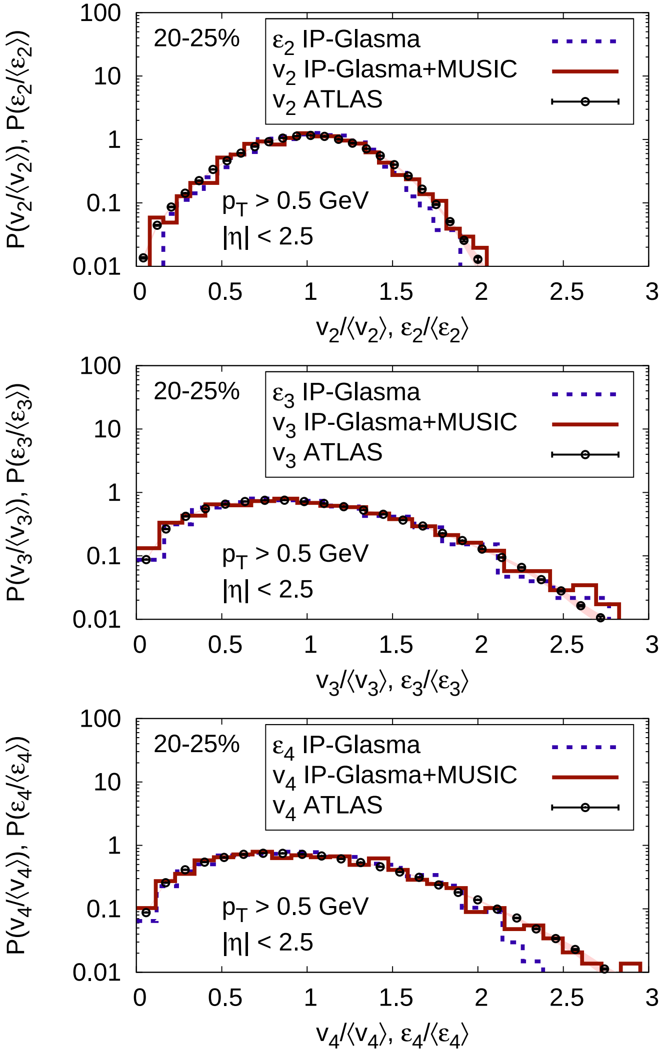
Model doesn't distinguish between a constant η/s of 0.2 or a temperature dependent η/s with a minimum of 1/4π

Need both RHIC and LHC to sort this out!

Other successes of the Little Bang Standard Model

Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330 (PRL 2012)





- Model describes RHIC data with lower effective specific shear viscosity $\eta/s = 0.12$
- In contrast to MC-Glauber and MC-KLN, IP-Sat initial conditions correctly reproduce the final flow fluctuation spectrum, generated from initial shape fluctuations by viscous hydrodynamics

Conclusions

- Quark-Gluon Plasma is by far the hottest and densest form of matter ever observed in the laboratory. Its properties and interactions are controlled by QCD, not QED.
- It is a liquid with almost perfect fluidity. Its specific shear viscosity at RHIC and LHC energies is

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

  This is significantly below that of any other known real fluid.
  Precision comparison of harmonic flow coefficients at RHIC and LHC provides first serious indications for a moderate increase of the specific QGP shear viscosity between $2T_c$ and $3T_c$.
- Viscous relativistic hydrodynamics provides a quantitative description of QGP evolution.
- By coupling viscous fluid dynamics for the QGP stage to microscopic evolution models of the dense early pre-equilibrium and dilute late hadronic freeze-out stages, a complete dynamical description of the strongly interacting matter created in ultra-relativistic heavy-ion collisions has been achieved. This dynamical theory has made successful predictions for the first Pb+Pb collisions at the LHC that were quantitatively precise and non-trivial (in the sense that they disagreed with other predictions that were falsified by the data).
- The Color Glass Condensate theory (IP-Sat model) appears to give the correct spectrum of initial-state gluon field fluctuations.

We are rapidly converging on the Standard Model for the Little Bang

Thanks to:

Paul Sorensen for the animations and artwork

Chun Shen for the movie

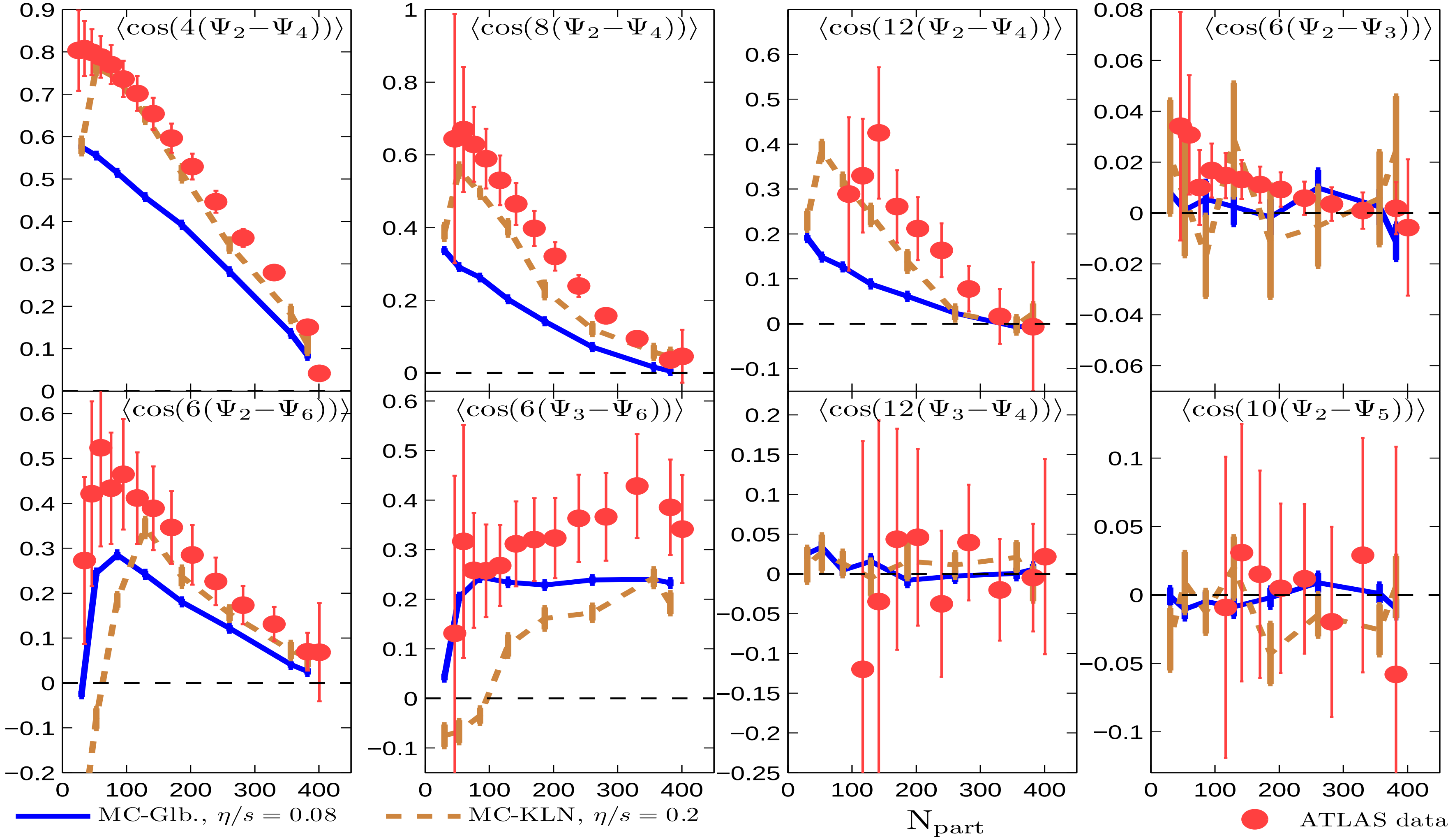
Huichao Song, Steffen Bass, Zhi Qiu, Chun Shen, Pasi Huovinen, Tetsu Hirano, and Peter Kolb for their collaboration

Supplements

Higher order event plane correlations in PbPb@LHC

Data: ATLAS Coll., J. Jia et al., Hard Probes 2012

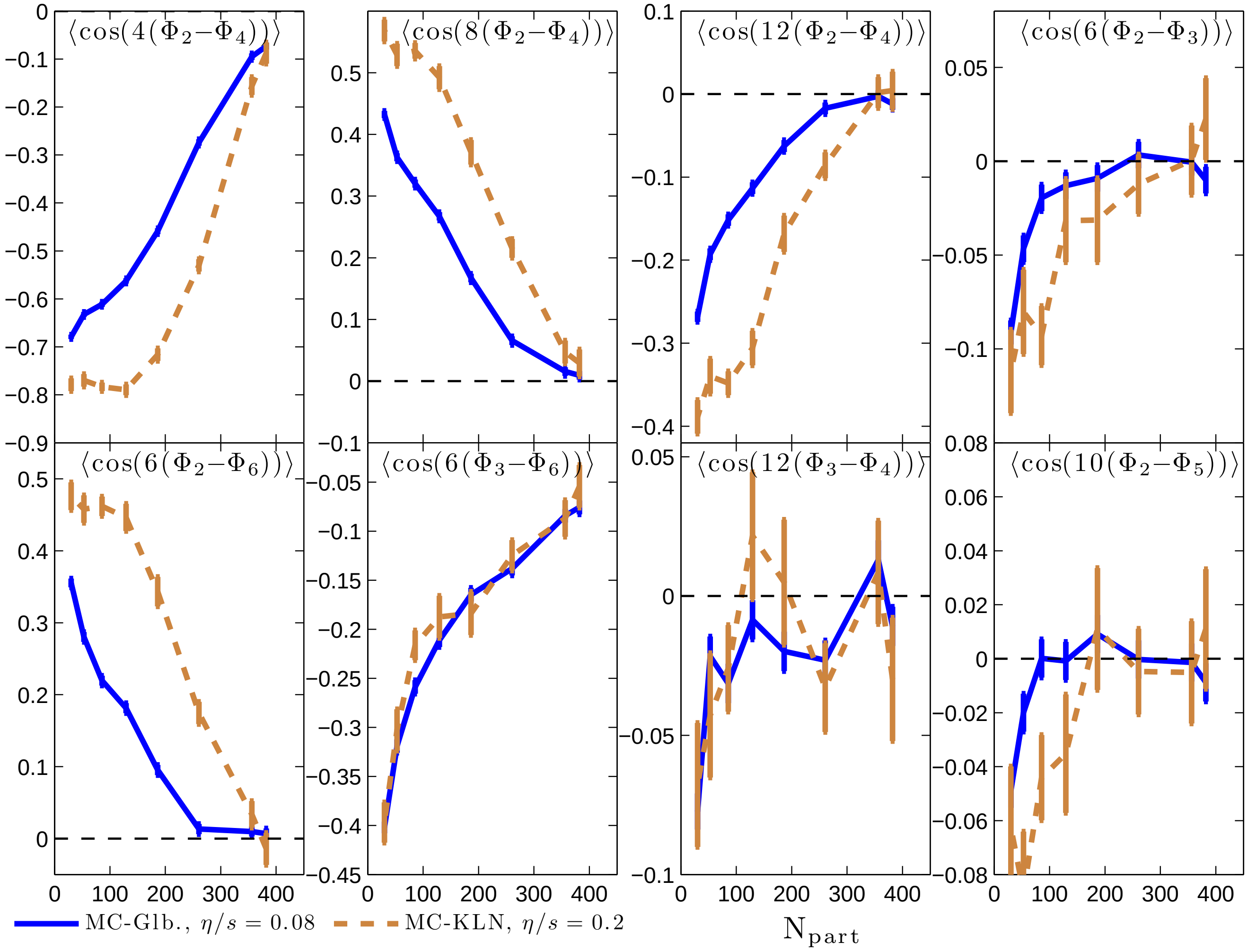
Event-by-event hydrodynamics: Zhi Qiu, UH, PLB 717 (2012) 261 (VISH2+1)



VISH2+1 reproduces qualitatively the centrality dependence of all measured event-plane correlations

Higher order event plane correlations in PbPb@LHC

Zhi Qiu, UH, PLB 717 (2012) 261



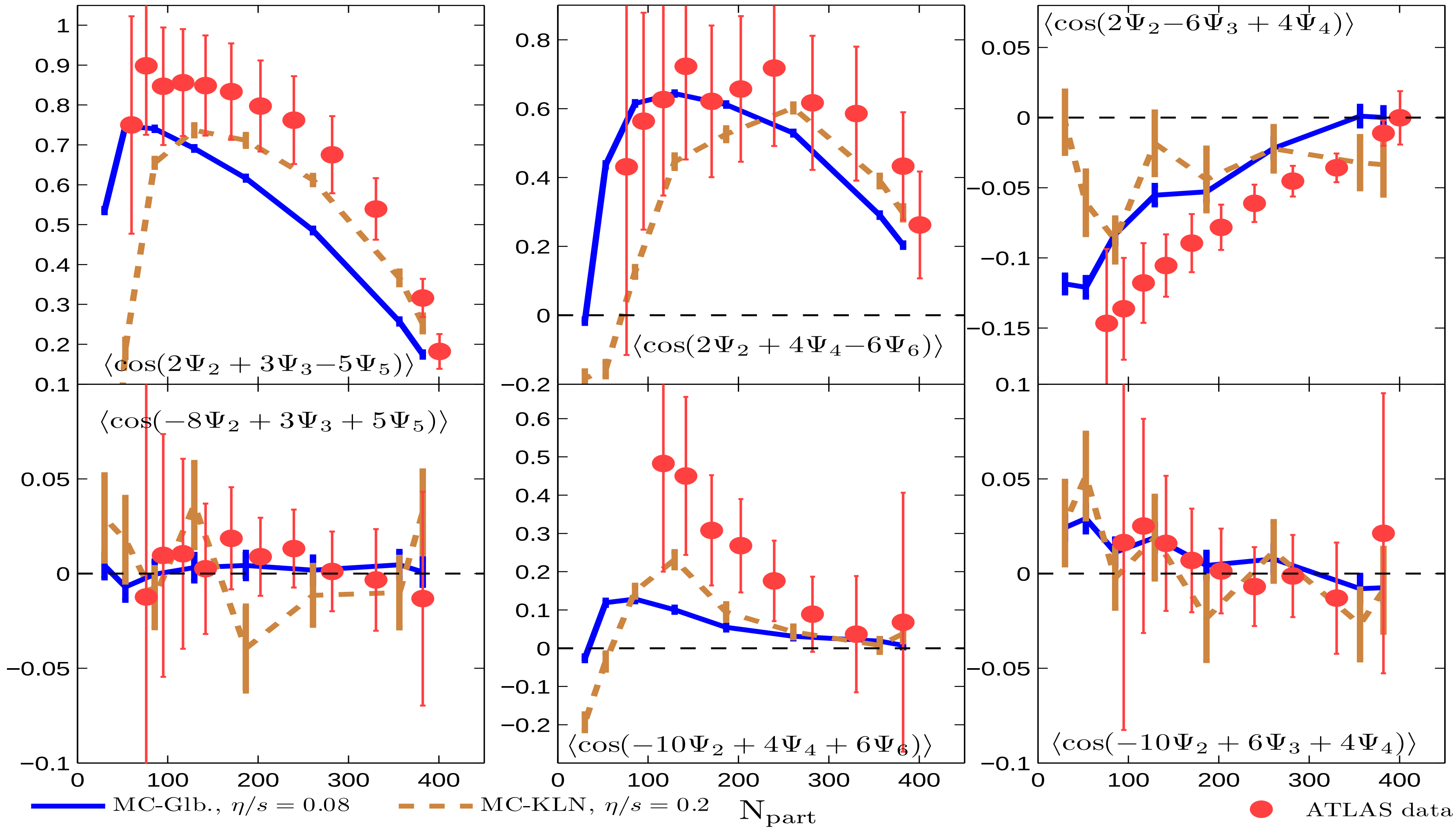
Initial-state participant plane correlations disagree with final-state flow-plane correlations

$\Longrightarrow$ Nonlinear mode coupling through hydrodynamic evolution essential to describe the data!

Higher order event plane correlations in PbPb@LHC

Data: ATLAS Coll., J. Jia et al., Hard Probes 2012

Event-by-event hydrodynamics: Zhi Qiu, UH, PLB 717 (2012) 261 (VISH2+1)



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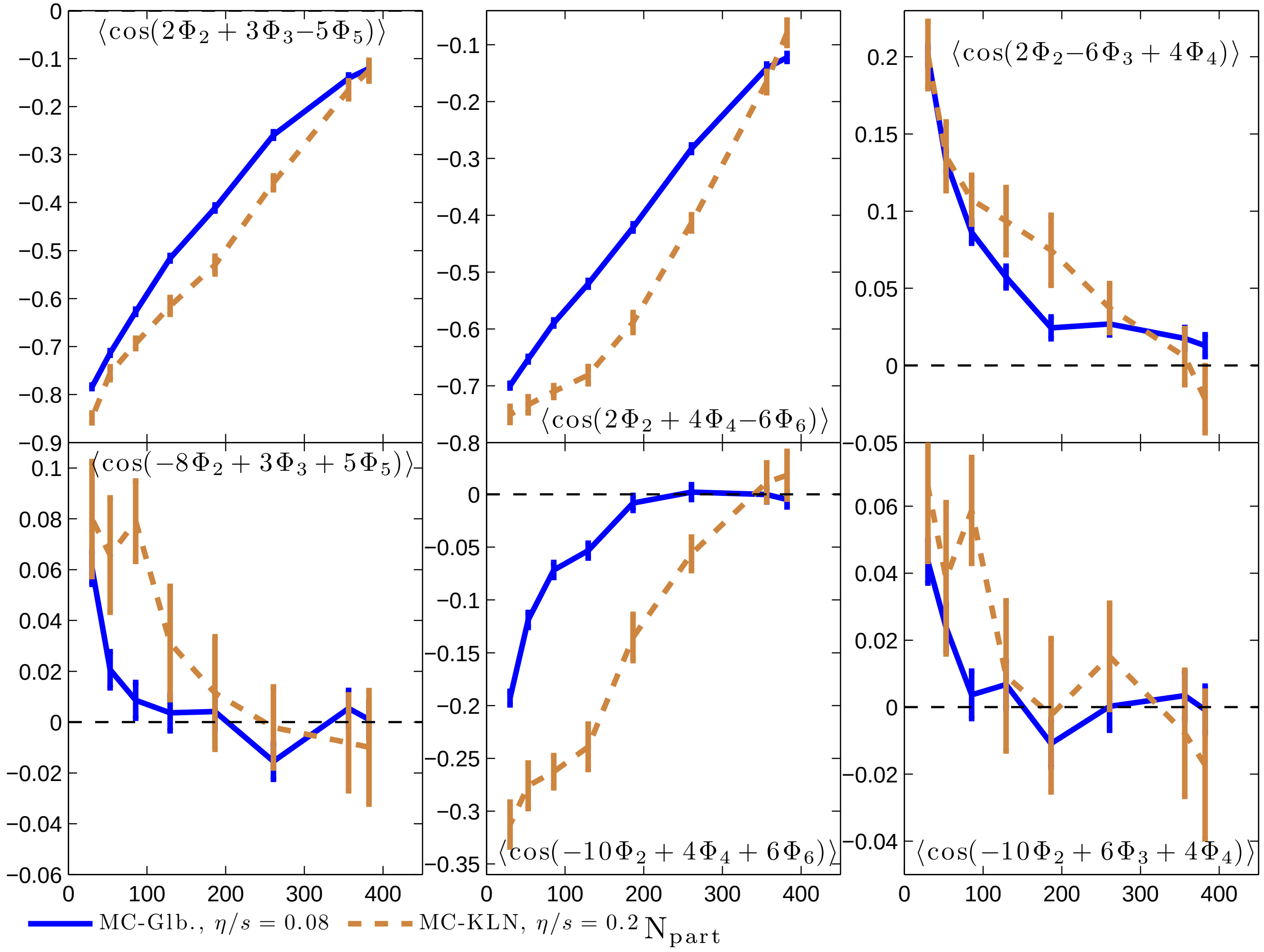
Higher order event plane correlations in PbPb@LHC

Zhi Qiu, UH, PLB 717 (2012) 261

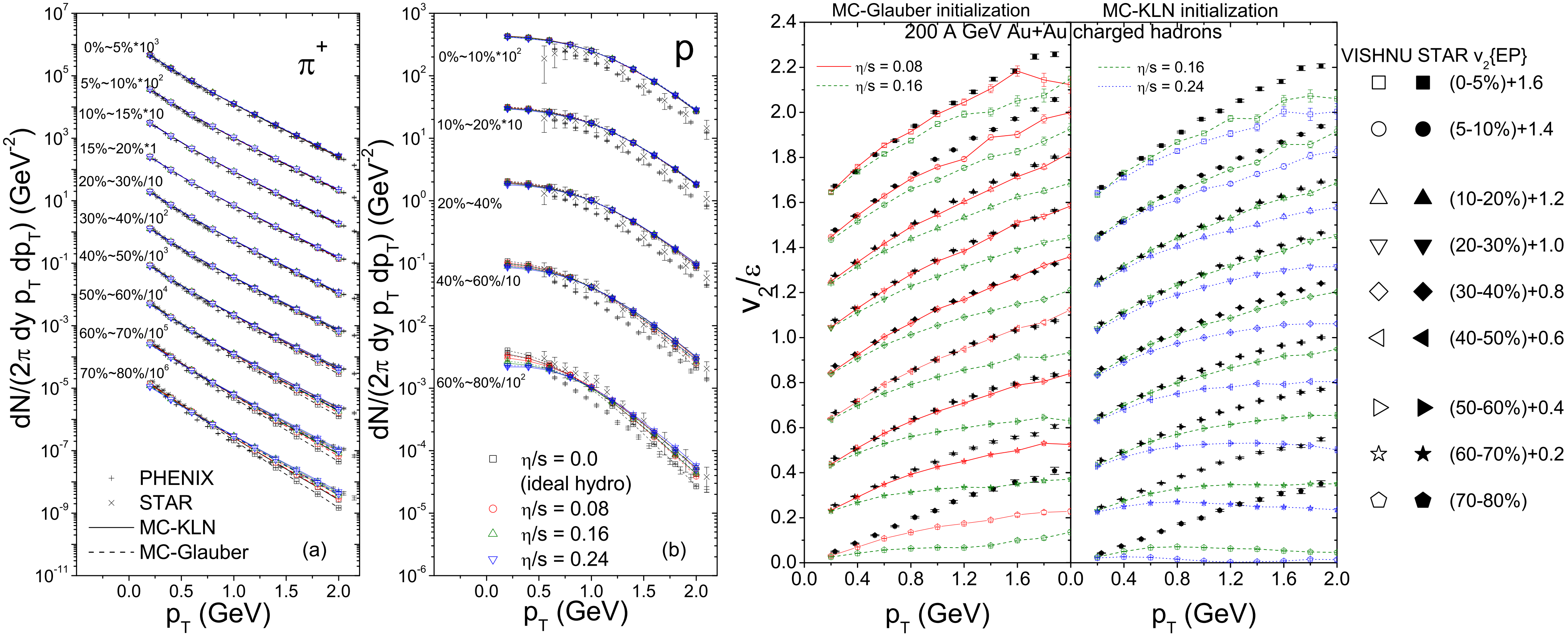


Initial-state participant plane correlations disagree with final-state flow-plane correlations

$\Longrightarrow$ Nonlinear mode coupling through hydrodynamic evolution essential to describe the data!

Global description of AuAu@RHIC spectra and v_2

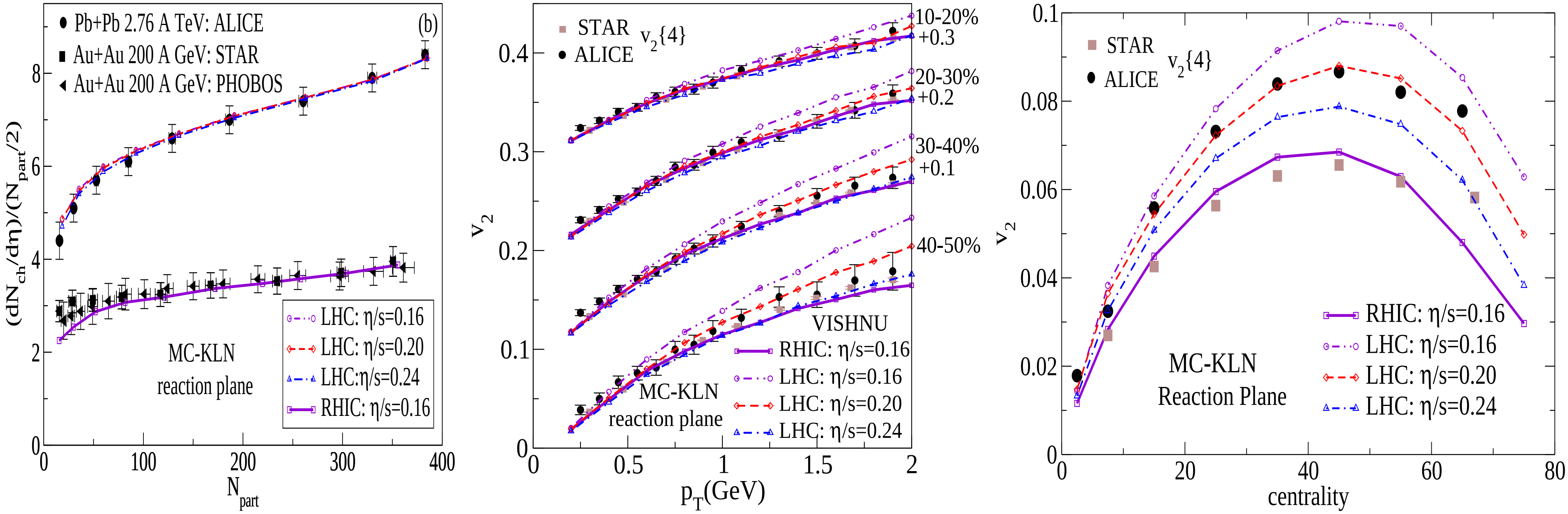
VISHNU (H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRC83 (2011) 054910)



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

Pre- and postdictions for PbPb@LHC

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

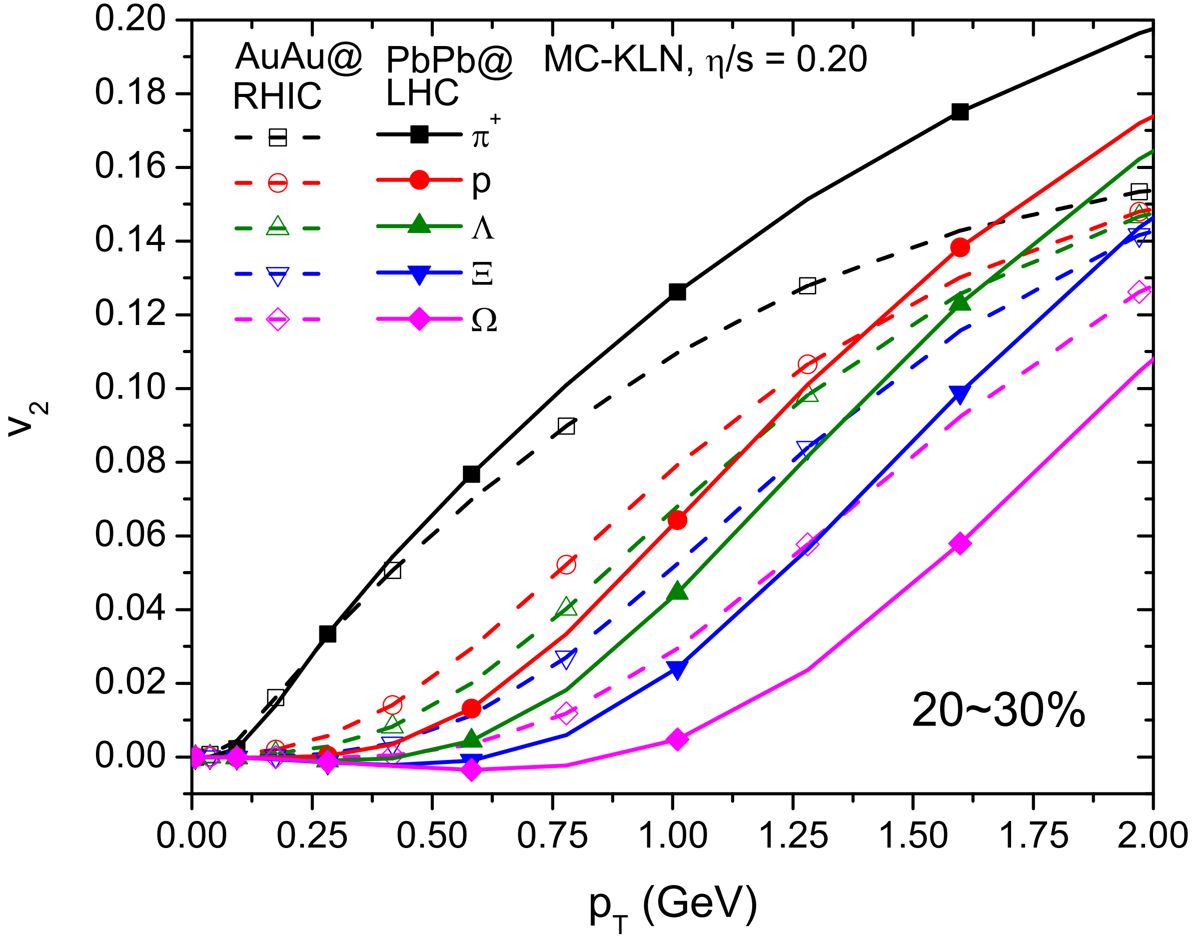


- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of $dN_{\rm ch}/d\eta$ well in both AuAu@RHIC and PbPb@LHC
- $(\eta/s)_{\rm QGP} = 0.16$ for MC-KLN works well for charged hadron $v_2(p_T)$ 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 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 & UH EPJC61 (2009) 545; Shen & UH, PRC85 (2012) 054902)

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

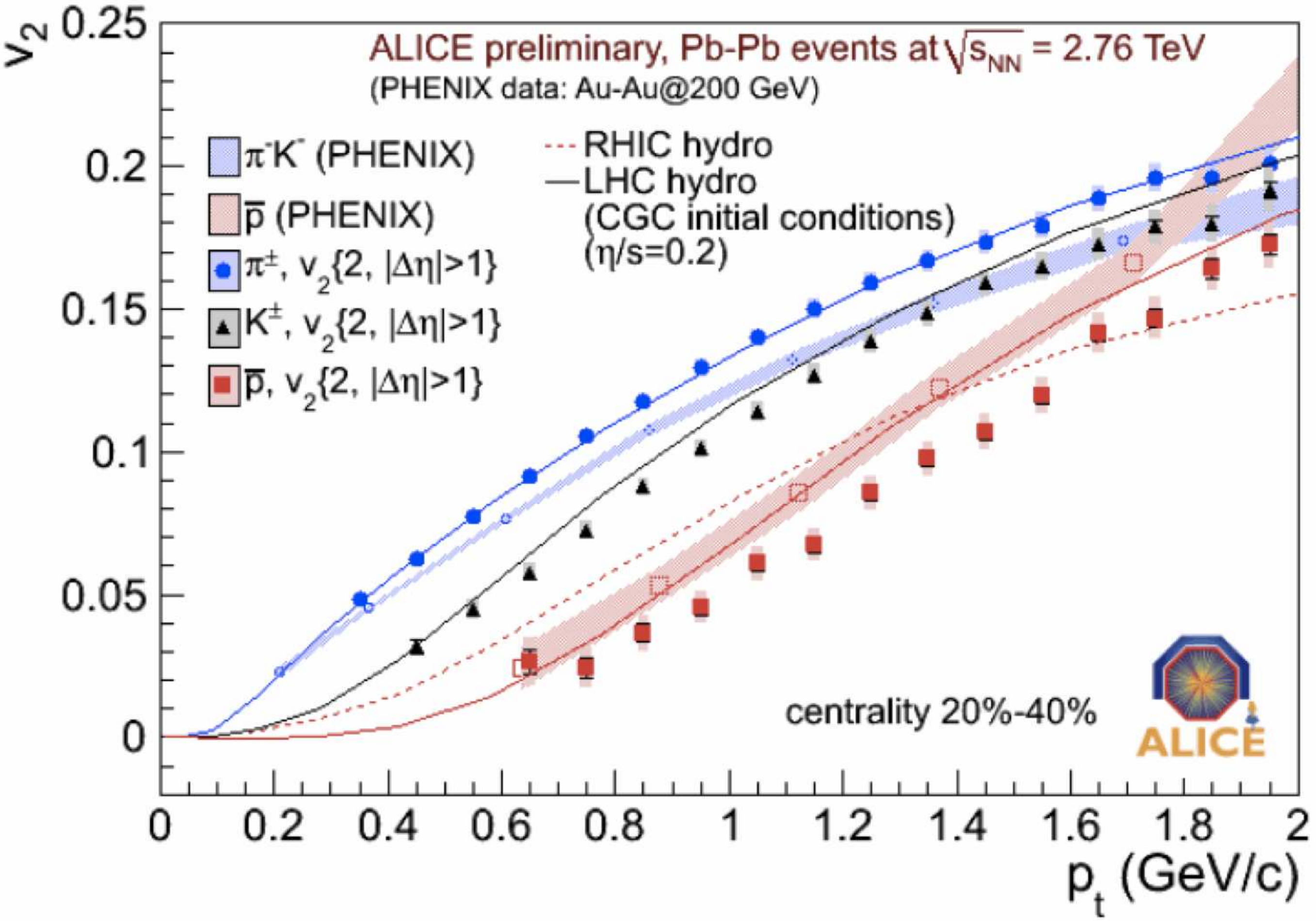
(radial flow pushes momentum anisotropy of heavy hadrons to larger p_T)

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)

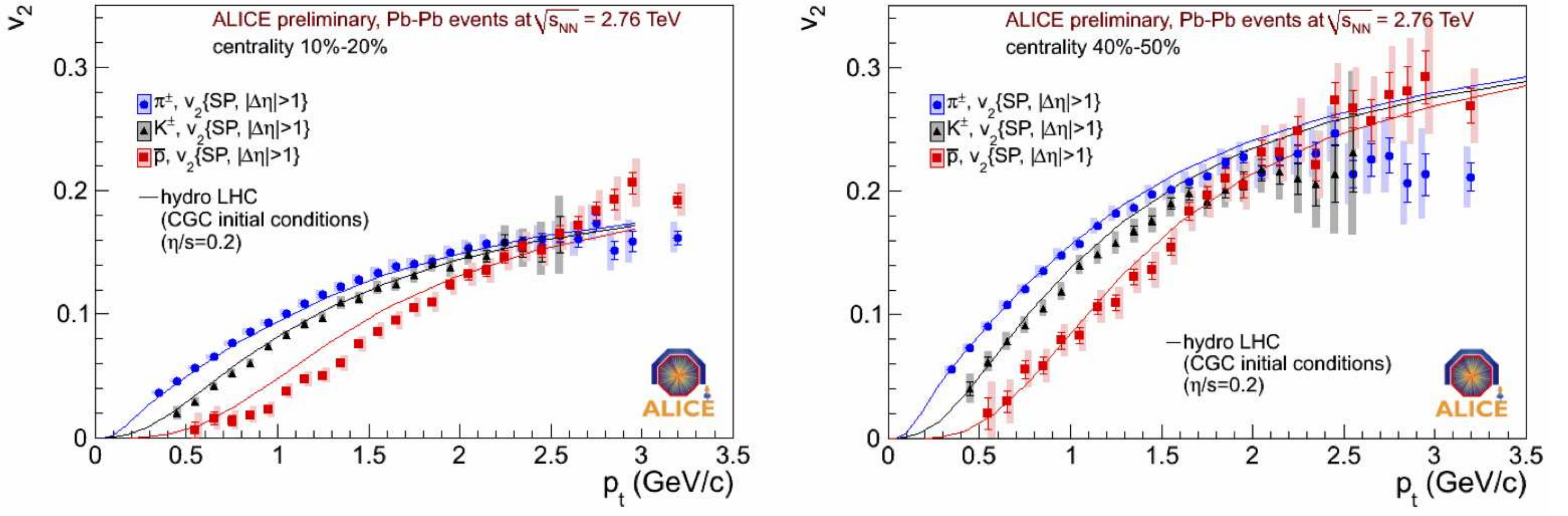
Lines: Shen et al., PRC84 (2011) 044903 (VISH2+1 + MC-KLN, η/s=0.2)



- 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)



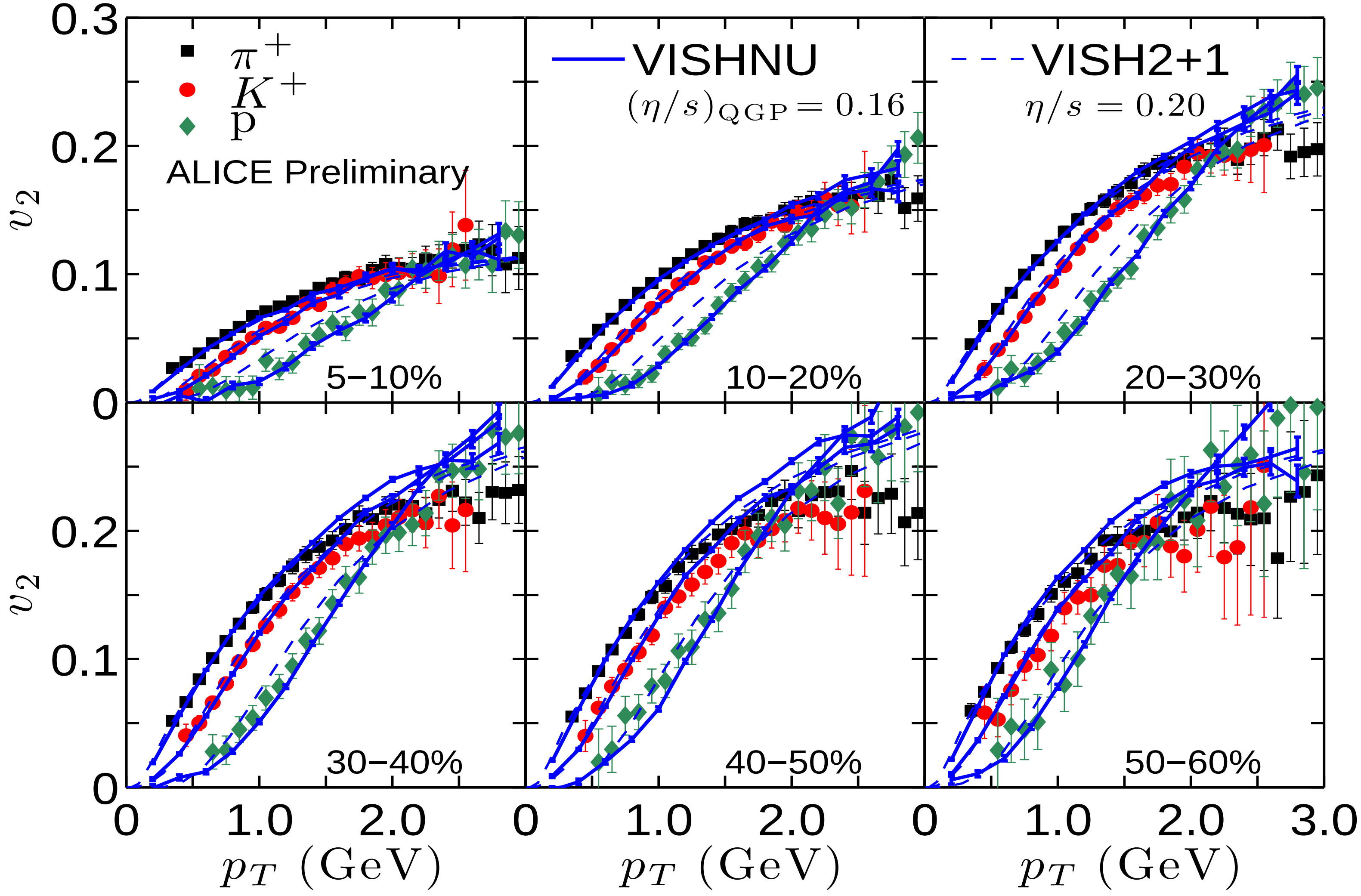
Perfect fit in semi-peripheral collisions!

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. VISHNU

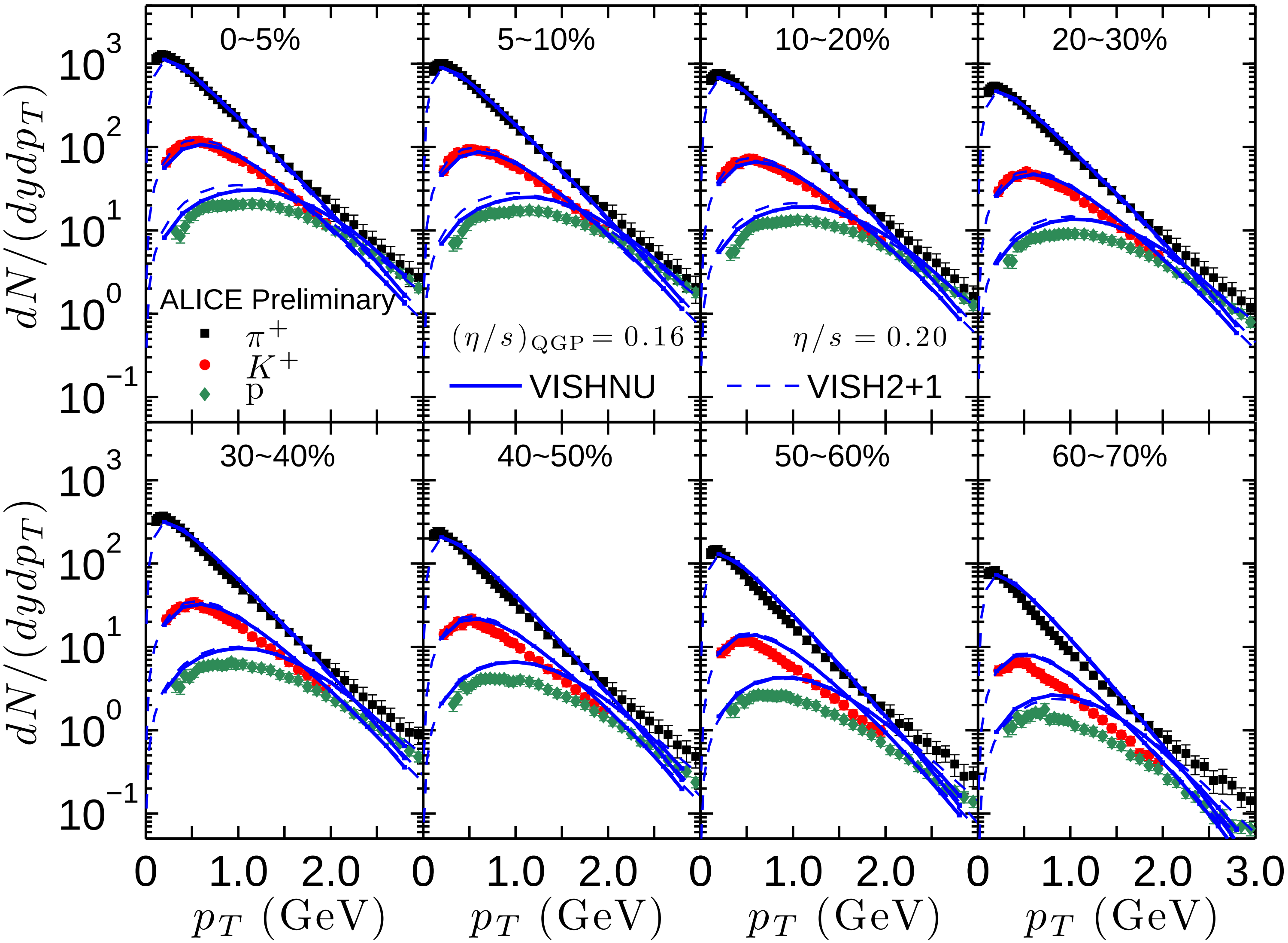
Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)
Dashed lines: Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, $(\eta/s)_{\rm QGP}$=0.2)
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{\rm QGP}$=0.16)



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

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

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

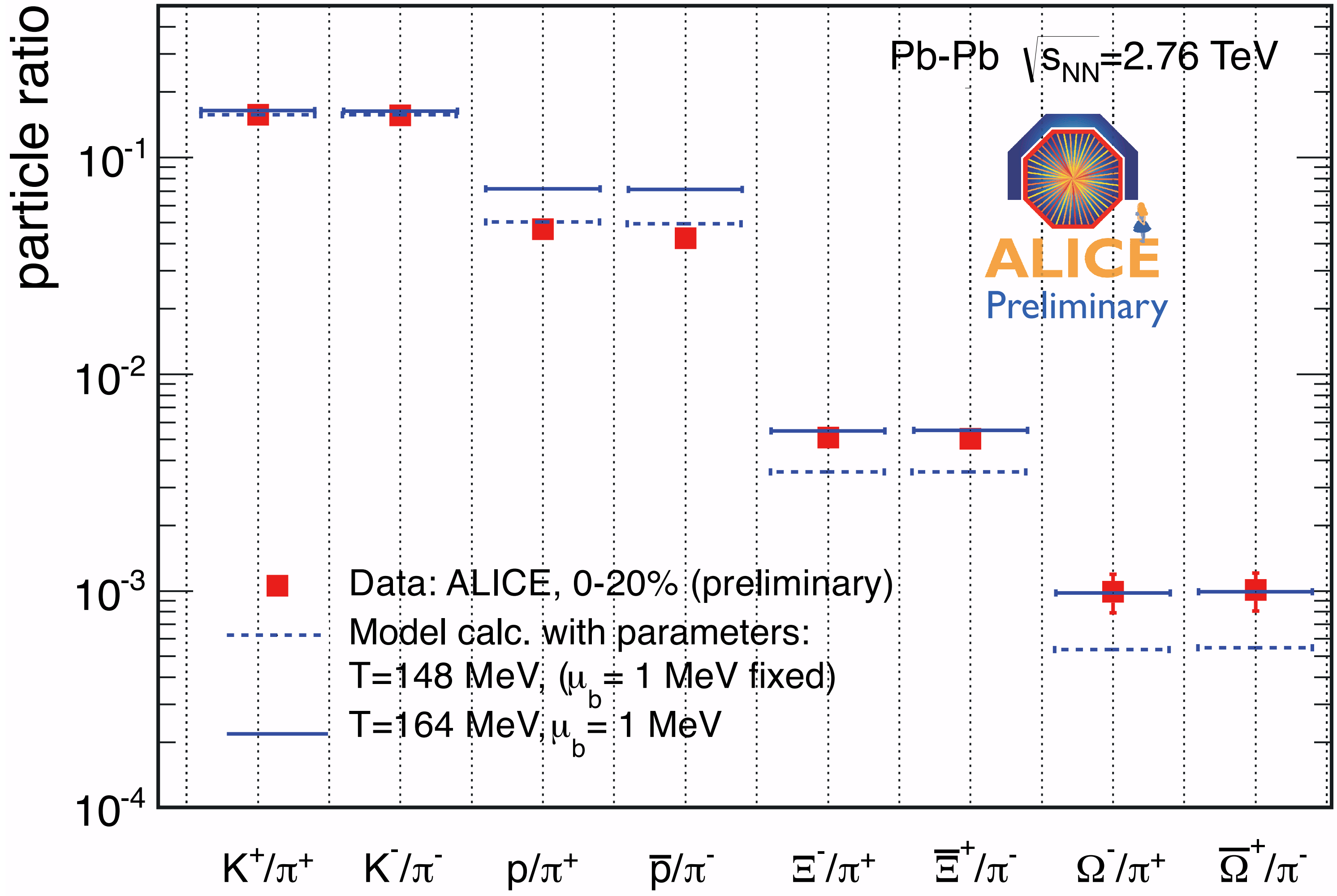


- Good description also of identified hadron spectra for centralities $< 50\%$
- VISHNU better than VISH2+1 in central collisions (more radial flow)
- Both models give too much radial flow in peripheral collisions $\Longrightarrow$ initial conditions?
- Both models overpredict proton yield by 50-70%!?

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



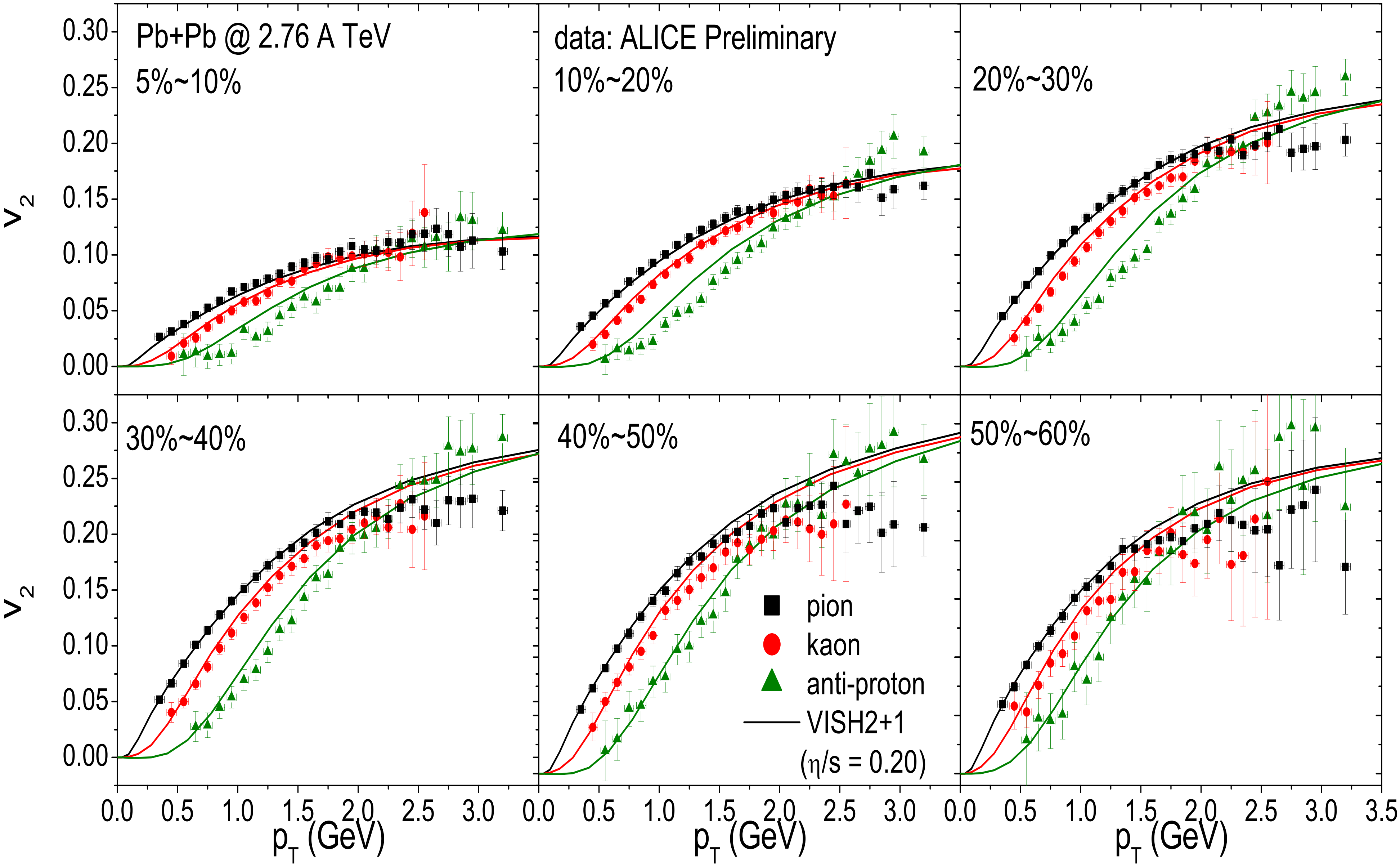
- “Standard” $T_{\text{chem}} = 164$ MeV reproduces strange hadrons but overpredicts (anti-)protons by 50%!
- $p\bar{p}$ annihilation in UrQMD not strong enough to repair this
- Similar problem already seen at RHIC but not taken seriously (STAR/PHENIX disagreement)

???

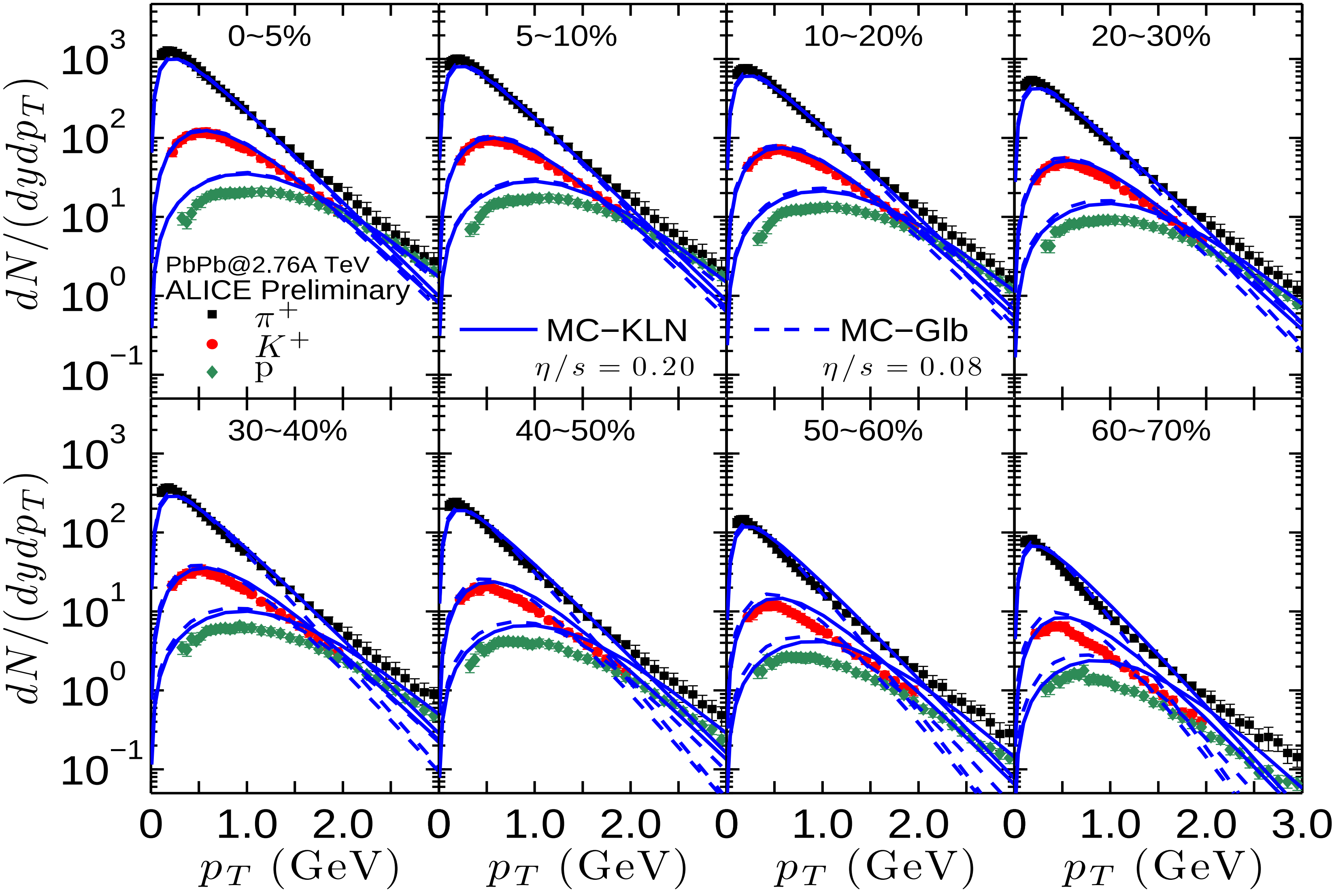
Comparison of ALICE PbPb@LHC v_2 data with VISH2+1

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

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



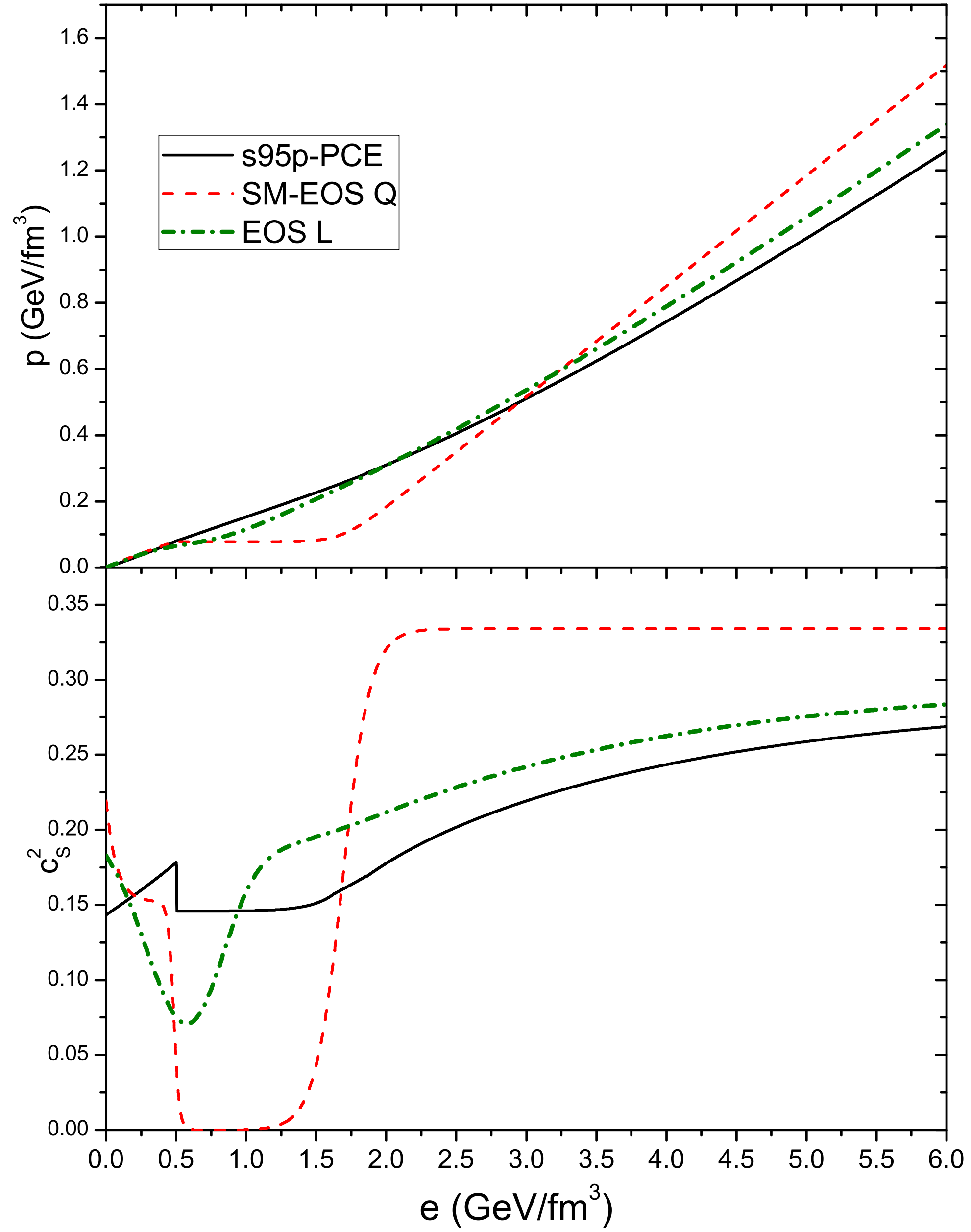
PbPb@LHC p_T-spectra: Glauber vs. KLN



- 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

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

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



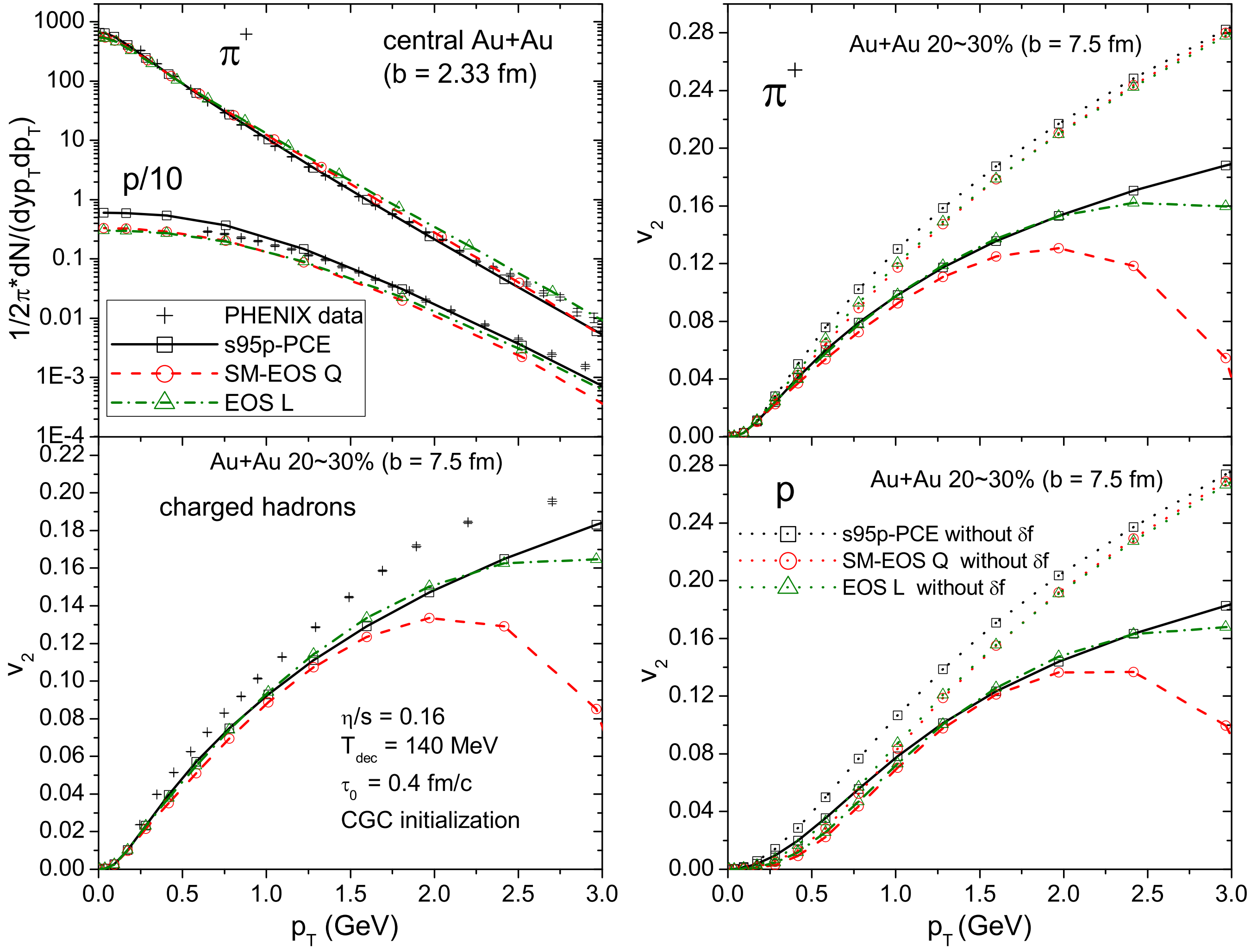
High T: Lattice QCD (latest hotQCD results)

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

No softest point!

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

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



Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy

Smooth transition leads to smaller δf at freeze-out

$\Longrightarrow$ larger v_2