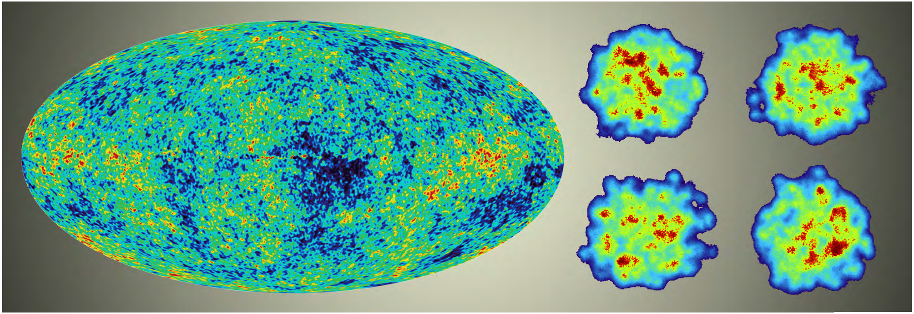
The Little Bang Standard Model

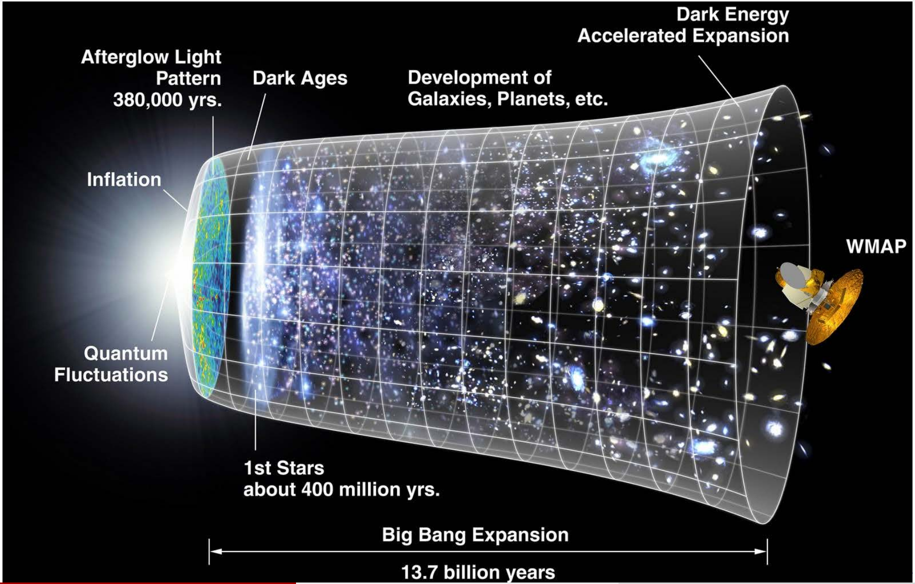
Ulrich Heinz

THE OHIO STATE UNIVERSITY

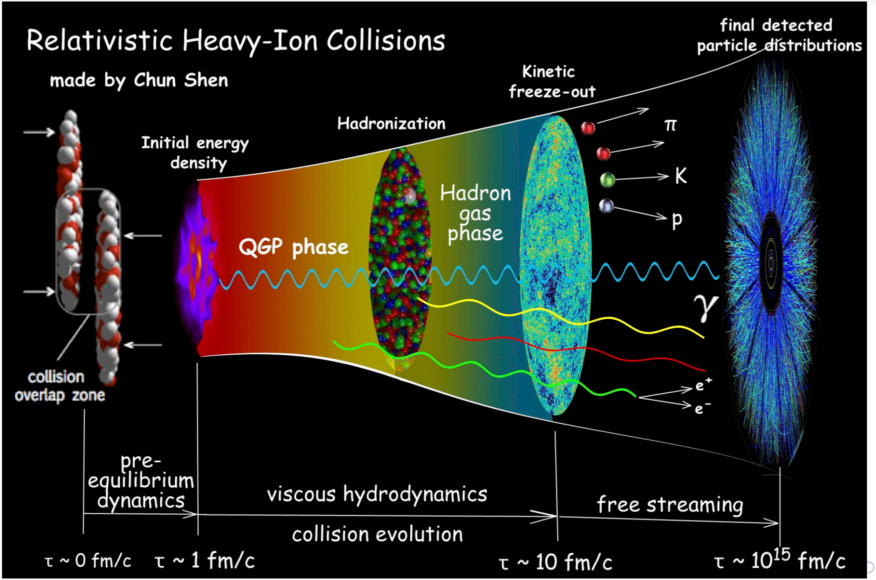


Physikalisches Kolloquium, GSI, 12. Juni 2018

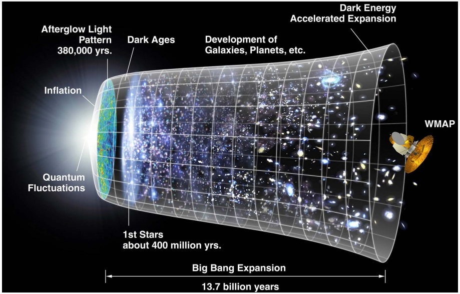
The Big Bang

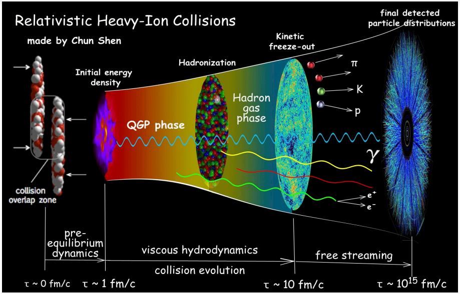

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

The Little Bang



Big Bang vs. Little Bang



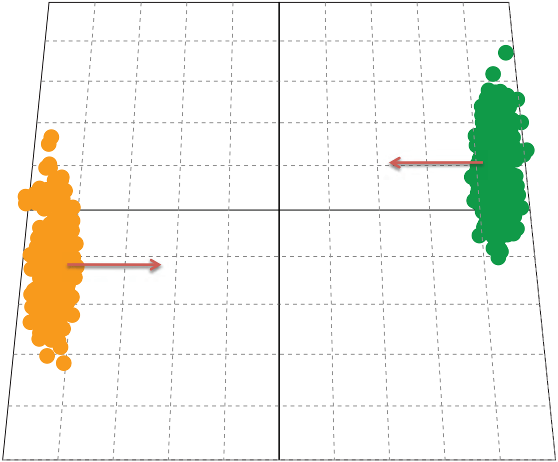


Similarities: Hubble-like expansion, expansion-driven dynamical freeze-out
chemical freeze-out (nucleo-/hadrosynthesis) before thermal freeze-out (CMB, hadron p_T-spectra)
initial-state quantum fluctuations imprinted on final state

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

Relativistic Nucleus-Nucleus Collisions

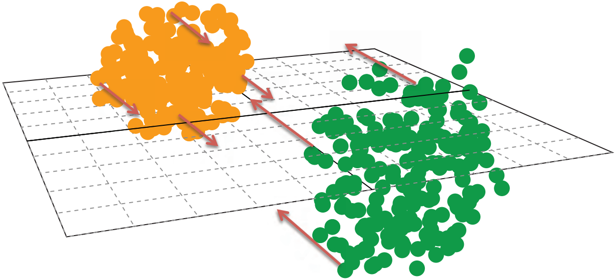
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen



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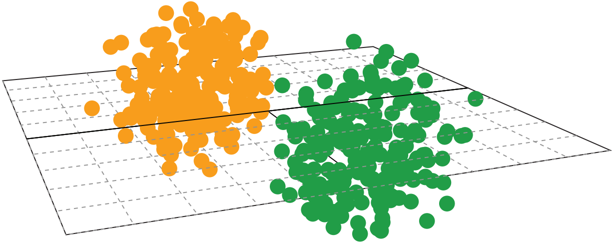

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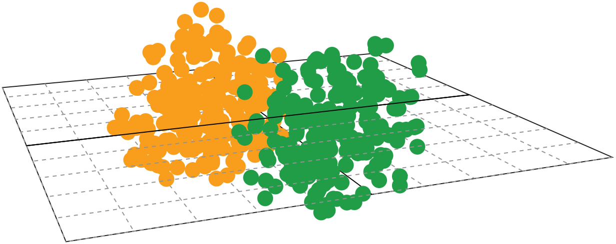

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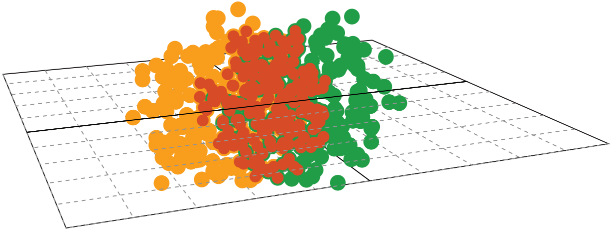

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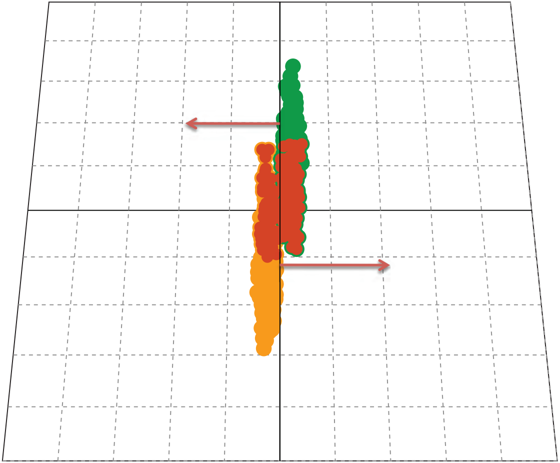
Relativistic Nucleus-Nucleus Collisions

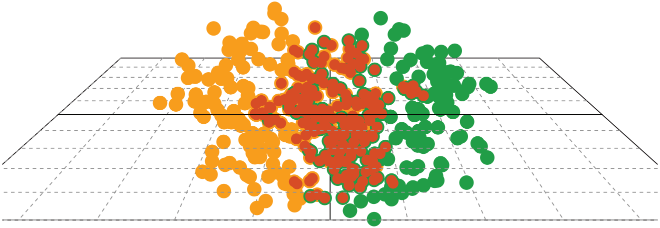
Animation: P. Sorensen



Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen

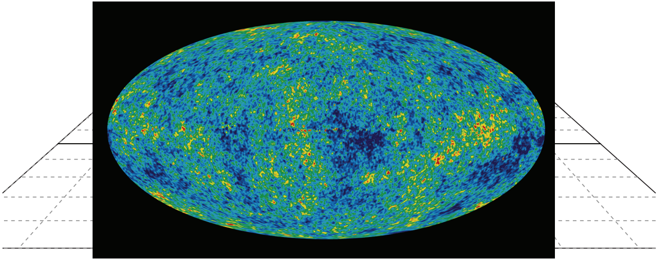


Produced fireball is ~10^{-14} meters across and lives for ~$5\text{x}10^{-23}$ seconds

Collision of two Lorentz contracted gold nuclei

Relativistic Nucleus-Nucleus Collisions

Animation: P. Sorensen



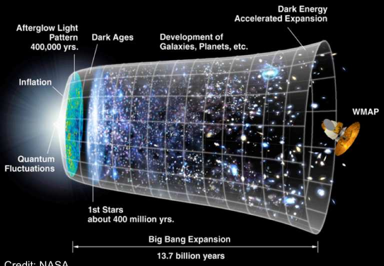
Produced fireball is ~10^{-14} meters across and lives for ~5×10^{-23} seconds

Collision of two Lorentz contracted gold nuclei

The Big Bang vs. the Little Bangs

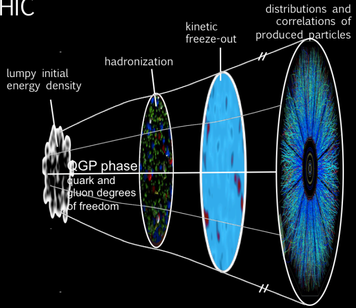
credit: Paul Sorensen

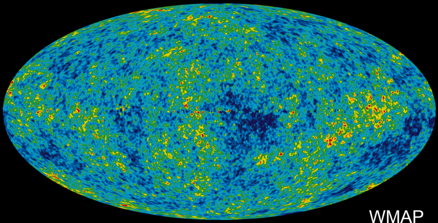
The Universe



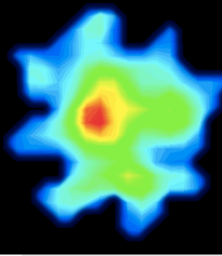
Credit: NASA

HIC





WMAP



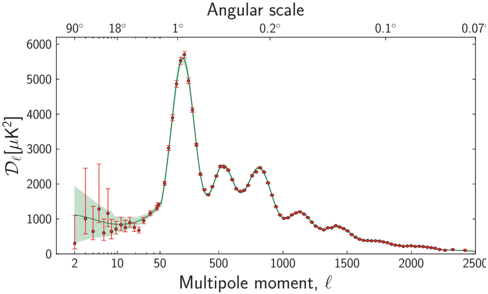
HIC

Big vs. Little Bang: The fluctuation power spectrum

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

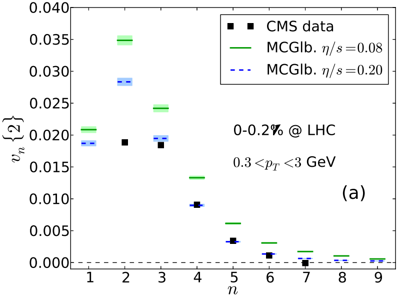
Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71

Big Bang temperature power spectrum (Planck 2013)



Flow power spectrum for ultracentral PbPb Little Bangs

(Data: CMS, Quark Matter 2012; Theory: OSU 2013)



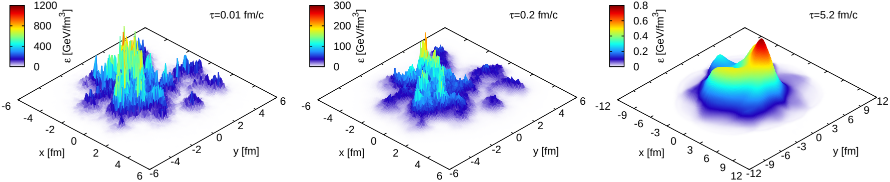
Higher flow harmonics get suppressed by shear viscosity

A detailed study of fluctuations is a powerful discriminator between models!

Every Little Bang evolves differently!

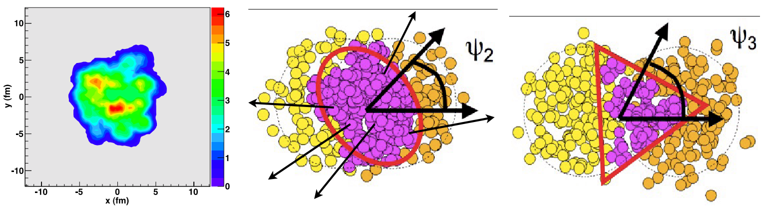
Density evolution of a single $b = 8$ fm Au+Au collision at RHIC, with IP-Glasma initial conditions, Glasma evolution to $\tau = 0.2\,\mathrm{fm}/c$ followed by (3+1)-d viscous hydrodynamic evolution with `MUSIC` using $\eta/s = 0.12 = 1.5/(4\pi)$

Schenke, Tribedy, Venugopalan, PRL 108 (2012) 252301:



Event-by-event shape and flow fluctuations rule!

(Alver and Roland, PRC81 (2010) 054905)



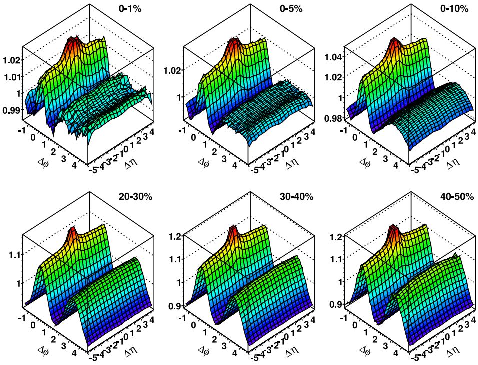
- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n
- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n
- At small impact parameters fluctuations ("hot spots") dominate over geometric overlap effects (Alver & Roland, PRC81 (2010) 054905; Qin, Petersen, Bass, Müller, PRC82 (2010) 064903)

Definition of flow coefficients:

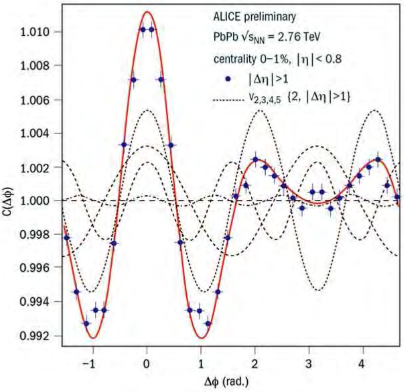
$$\frac{dN^{(i)}}{dy\,p_T dp_T\,d\phi_p}(b) = \frac{dN^{(i)}}{dy\,p_T dp_T}(b)\left(1+2\sum_{n=1}^{\infty} \boldsymbol{v_n^{(i)}(y,p_T;b)}\cos(\phi_p-\Psi_n^{(i)})\right).$$

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!

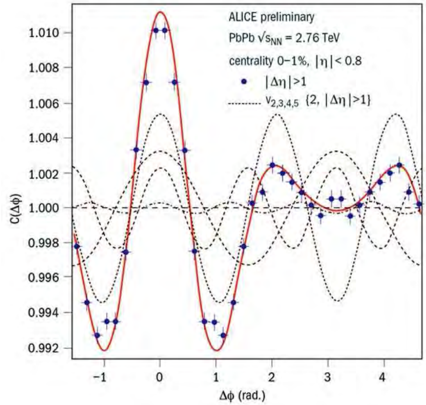
  M. Luzum, PLB 696 (2011) 499: All long-range rapidity correlations seen at RHIC are consistent with being entirely generated by hydrodynamic flow.

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

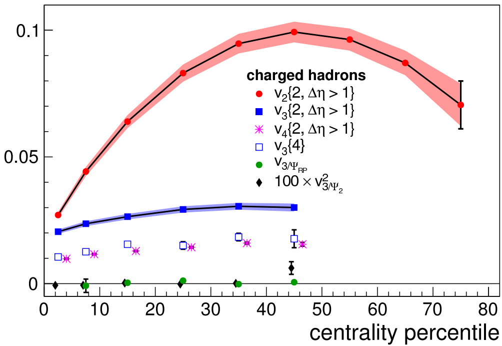
  $\Longrightarrow$ prominent "Mach cone"-like structure!

  $\Longrightarrow$ event-by-event eccentricity fluctuations dominate!

Event-by-event shape and flow fluctuations rule!



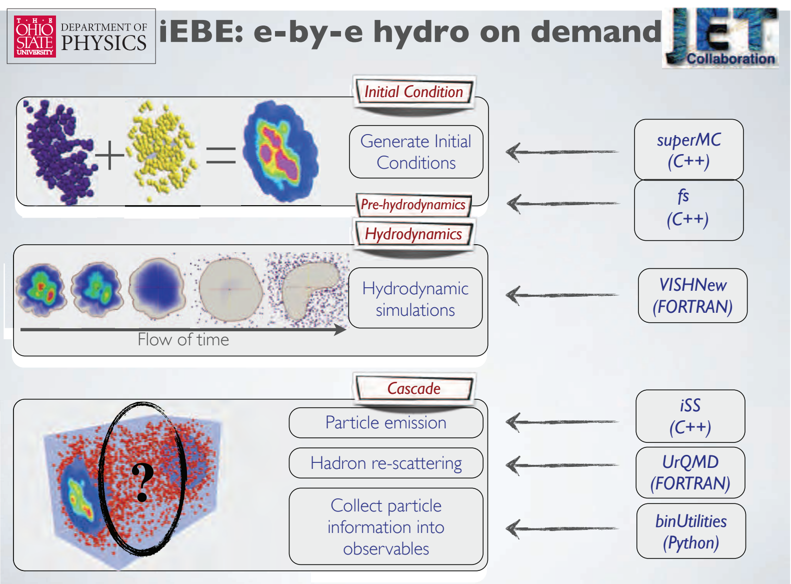
ALICE (A. Bilandzic) Quark Matter 2011



- 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

https://u.osu.edu/vishnu: A product of the JET Collaboration



iEBE: e-by-e hydro on demand

Initial Condition

Generate Initial Conditions ← *superMC (C++)*

Pre-hydrodynamics ← *fs (C++)*

Hydrodynamics

Hydrodynamic simulations ← *VISHNew (FORTRAN)*

Flow of time

Cascade

Particle emission ← *iSS (C++)*

Hadron re-scattering ← *UrQMD (FORTRAN)*

Collect particle information into observables ← *binUtilities (Python)*

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.

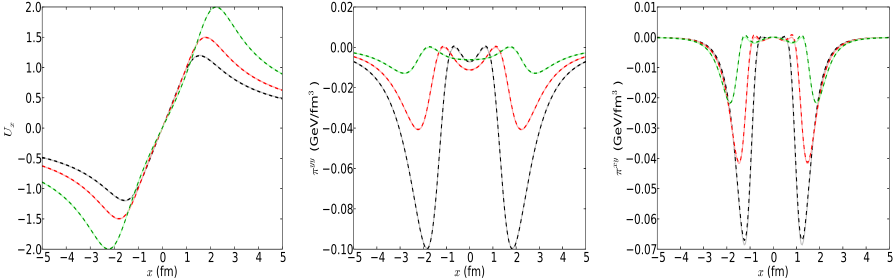
Kinetic theory relates η and τ_π, but for a strongly coupled QGP neither η nor this relation are known $\Longrightarrow$ treat η and τ_π as independent phenomenological parameters. For consistency: $\tau_\pi\theta \ll 1$ ($\theta = \partial^\mu u_\mu =$ local expansion rate).

Numerical precision: "Gubser-Test"

Gubser (PRD82 (2010) 085027) found analytical solution for relativistic Navier-Stokes equation with conformal EOS, boost-invariant longitudinal and non-zero transverse flow, corresponding to a specific transverse temperature profile.

Marrochio, Noronha *et al.* (arXiv:1307.6130) found semianalytical generalization of this solution for Israel-Stewart theory. This solution provides a stringent test for numerical Israel-Stewart codes (very rapid and non-trivial transverse expansion!)

VISH2+1 (C. Shen, 2013)



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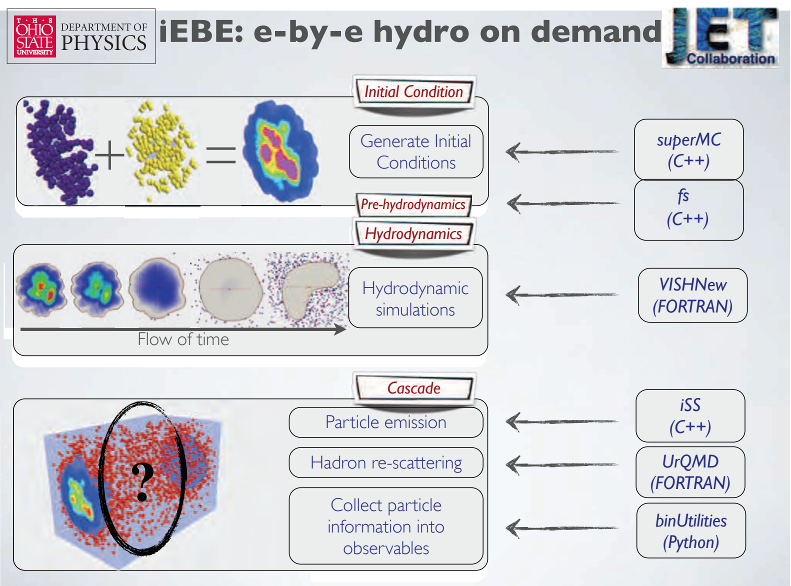

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

iEBE: e-by-e hydro on demand

JET Collaboration

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

The University of Queensland pitch drop experiment

SI unit for shear viscosity:

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

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

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

($\sim$ one drop per decade –
last drop fell in April 2014 – 2 years late!)

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

A measure of fluidity

(a.k.a. Knudsen number)

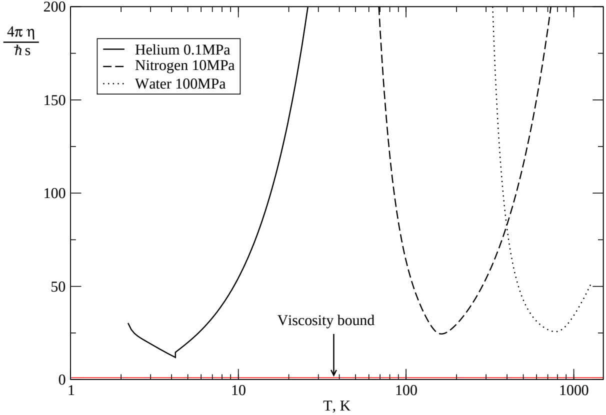
$$\boxed{\frac{\eta}{e+p} \times \partial{\cdot}u = \frac{\Gamma_{\mathrm{exp}}}{\Gamma_{\mathrm{sound}}} \sim \frac{\eta}{s}\,\frac{1}{T\tau}}$$

The **specific viscosity** η/s (s=entropy density) is conceptually related to the "kinematic viscosity" η/n in non-relativistic fluid dynamics

QGP – the most perfectly fluid liquid ever observed!

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

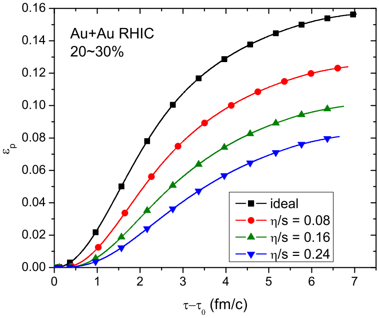
Kovtun, Son, Starinets, PRL 94 (2005) 111601



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

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

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

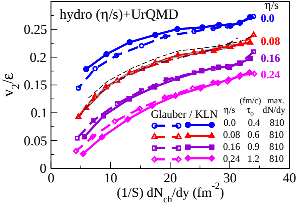
of the fluid; the suppression of ε_p is monotonically related to η/s.

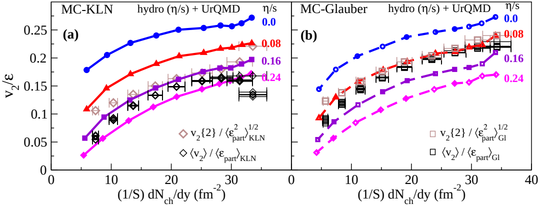
The observable that is most directly related to the total hydrodynamic momentum anisotropy ε_p is the **total (p_T-integrated) charged hadron elliptic flow v_2^{ch}**:

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

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

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



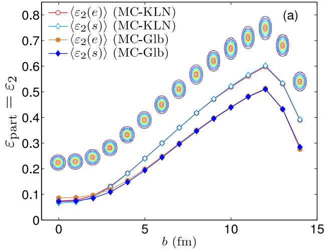


$$\boxed{\mathbf{1 < 4\pi(\eta/s)_{\mathrm{QGP}} < 2.5}}$$

- 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
- $v_2^{\mathrm{ch}}/\varepsilon_x$ vs. $(1/S)(dN_{\mathrm{ch}}/dy)$ 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: $\varepsilon_x^{\mathrm{Gl}}$ vs. $\varepsilon_x^{\mathrm{KLN}}$ $\longrightarrow$
- smaller effects: *early flow* → increases $\frac{v_2}{\varepsilon}$ by ∼ few % → larger η/s

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

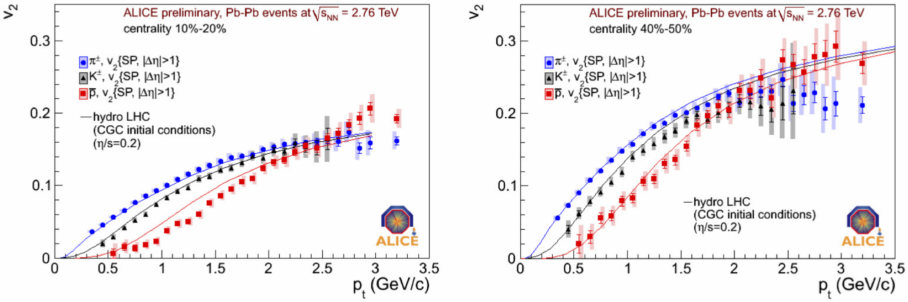
Zhi Qiu, UH, PRC84 (2011) 024911



Hydrodynamics – a theory with predictive power

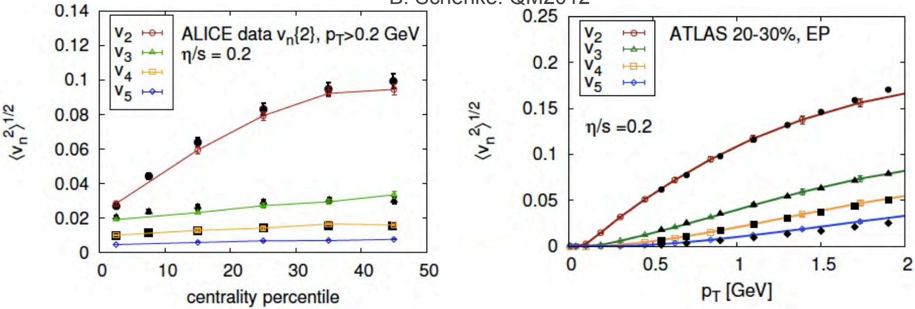
After tuning initial conditions and viscosity at RHIC to obtain a good description of all soft hadron data simultaneously (Song et al. 2010) the first LHC spectra and elliptic flow measurements were successfully **pre**dicted:

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



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-equilibrium dynamics of gluon fields:

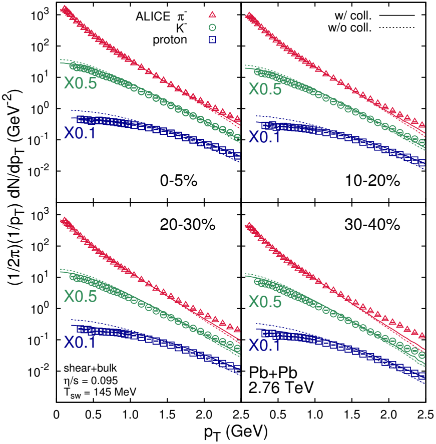
→ outstanding agreement between data and model

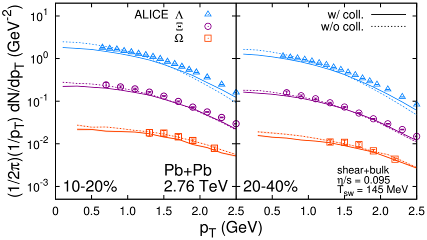
Rapid convergence on a standard model of the Little Bang!

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

Effect of “afterburning” on p_T-spectra::

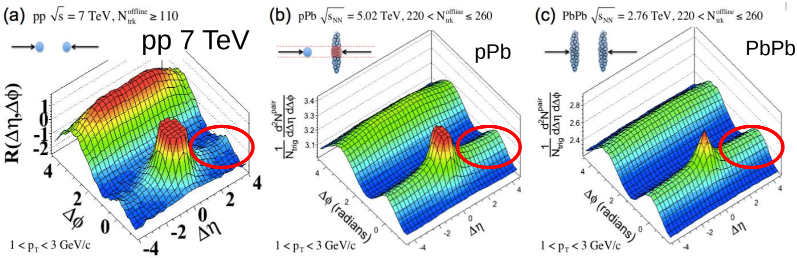
IP-Glasma + MUSIC + UrQMD, S. Ryu et al., PRC97 (2018) 034910



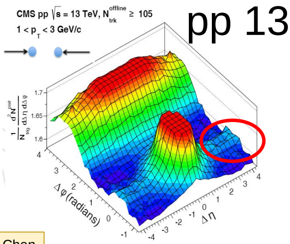


“Afterburning” builds additional radial flow, with little effect on abundance ratios

Ridge in pp, pPb and PbPb



NEW



pp 13 TeV

Ridge observed in high multiplicity pp collisions at 13 TeV !

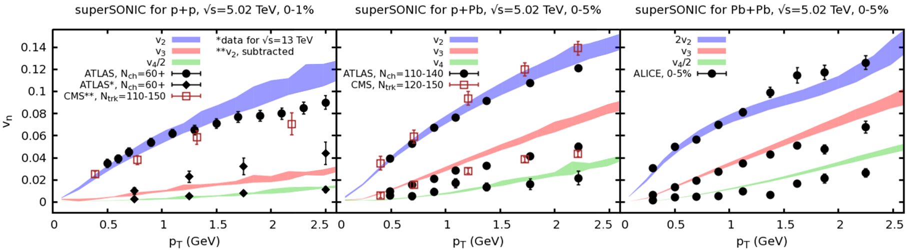
13 TeV vs. **7** TeV?

Zhenyu Chen

CMS-FSQ-15-002

Flow in Pb+Pb, p+Pb and even p+p at the LHC!

R.D. Weller, P. Romatschke, Phys. Lett. B 774 (2017) 351



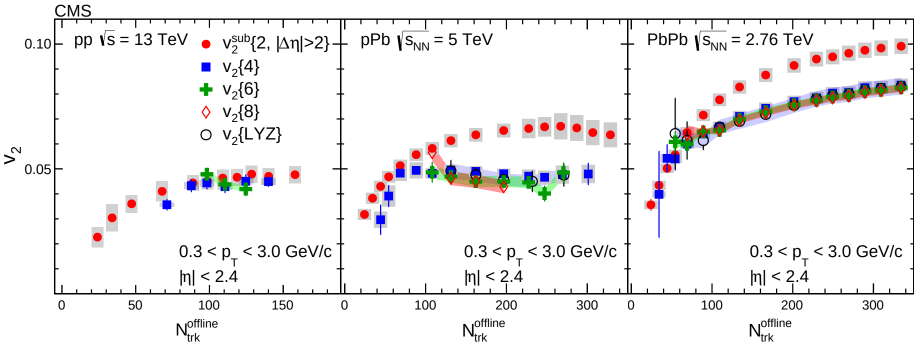
superSONIC for p+p, √s=5.02 TeV, 0-1%

superSONIC for p+Pb, √s=5.02 TeV, 0-5%

superSONIC for Pb+Pb, √s=5.02 TeV, 0-5%

Requires fluctuating proton substructure (gluon clouds clustered around valence quarks (K. Welsh et al. PRC94 (2016) 024919))

This is a collective effect!



Whatever its origin, the “flow signal” represents a collective response (to what?) of all particles!

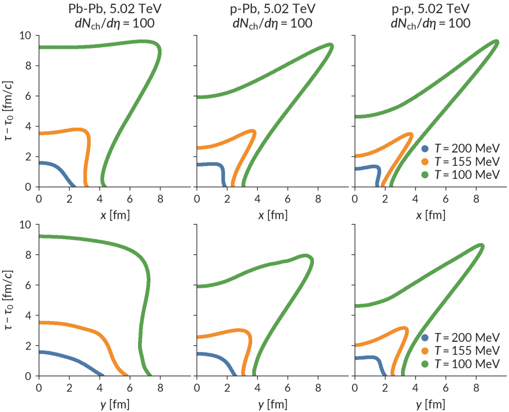
“Small” systems are so only initially:

Three collision systems with the same multiplicity $dN_{\rm ch}/d\eta = 100$

(iEBE-VISHNU, Scott Moreland)

short direction:

long direction:

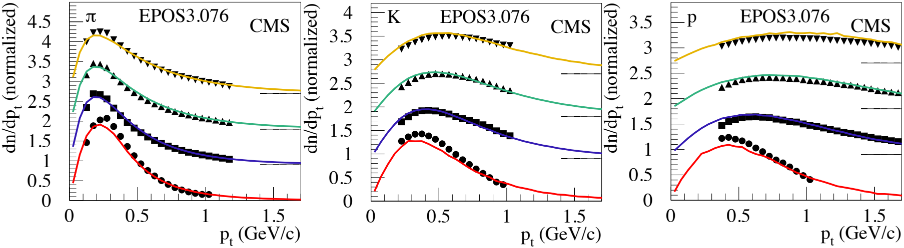


Collision systems with similar $dN_{\rm ch}/d\eta$ have similar freeze-out volumes!

$\Longrightarrow$ Stronger radial flow in initially smaller systems!

Strong radial flow in pp collisions at the LHC

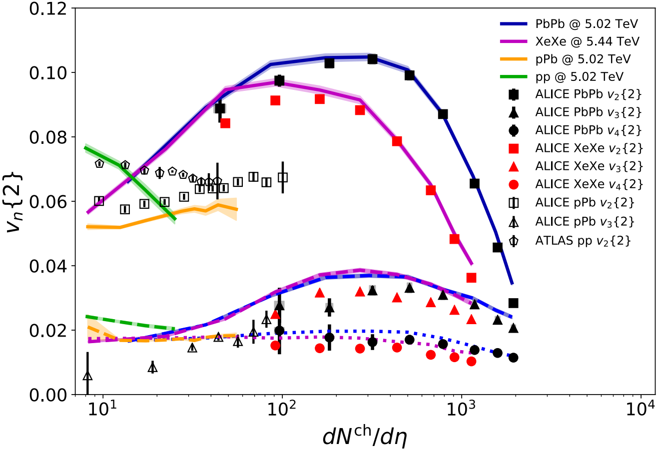
Werner, Guiot, Karpenko, Pierog (EPOS3), PRC 89 (2014) 064903;
Data: CMS Collaboration (8, 84, 160, 235 charged tracks)



Elliptic flow (double ridge) discovered in high-multiplicity pp by CMS at 7 TeV (and confirmed by ATLAS at 13 TeV) also reproduced by EPOS.

“One fluid that rules them all” (Weller & Romatschke 2017)

Schenke, Quark Matter 2018 (Schenke, Shen, Tribedy, in preparation)



Except for pp, hydro describes all collision systems at all “centralities”

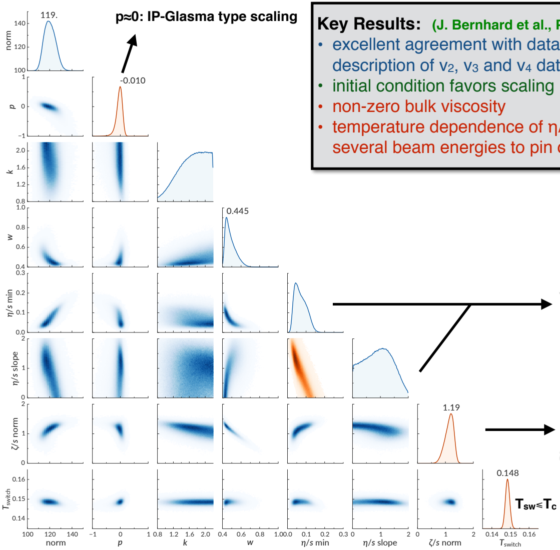
Towards quantitative quark-gluon plasma spectroscopy

- Relativistic viscous hydrodynamics (+ pre-hydrodynamic early stage and hadronic rescattering “afterburner”) has become the workhorse of dynamical modeling of ultra-relativistic heavy-ion collisions
- It has been successfully used in a Bayesian analysis of LHC Pb+Pb collision data for putting meaningful constraints on the initial conditions and medium properties of QGP created in heavy-ion collisions:

Calibrated Posterior Distribution

Key Results: **(J. Bernhard et al., PRC94 (2016) 024907)**

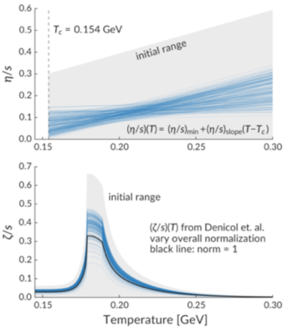
- excellent agreement with data, simultaneous description of v_2, v_3 and v_4 data
- initial condition favors scaling properties of IP-Glasma
- non-zero bulk viscosity
- temperature dependence of η/s requires data at several beam energies to pin down

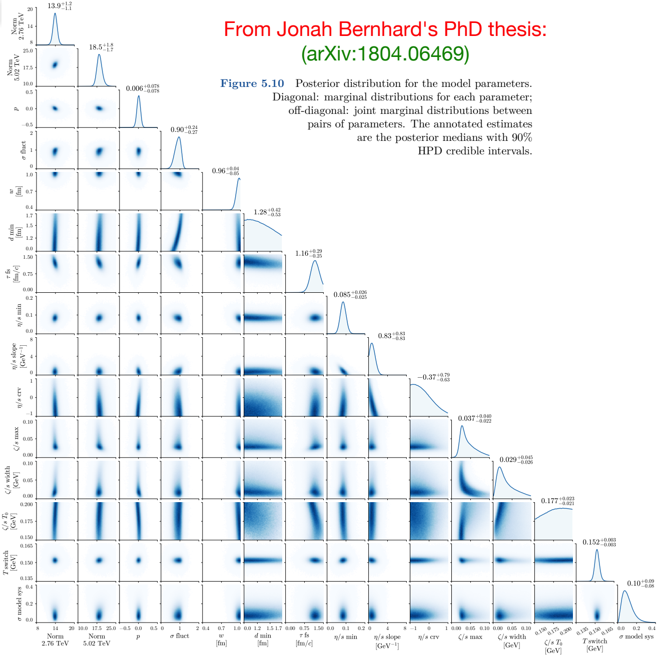


p≈0: IP-Glasma type scaling

$\mathbf{T_{sw} \leqslant T_c}$

temperature-dependent viscosities from the calibrated posterior:





From Jonah Bernhard's PhD thesis: (arXiv:1804.06469)

Figure 5.10 Posterior distribution for the model parameters. Diagonal: marginal distributions for each parameter; off-diagonal: joint marginal distributions between pairs of parameters. The annotated estimates are the posterior medians with 90% HPD credible intervals.

Challenges to the Little Bang Standard Model

- Flow-like signatures are also obtained from kinetic theory in the limit of *large Knudsen numbers* ("single scattering limit")

  Heiselberg & Levy '99, Kolb et al. '01, Alver et al. '10, Borghini & Gombeaud '11, Romatschke '18, Kurkela & Wiedemann '18, Borghini et al. '18, ...

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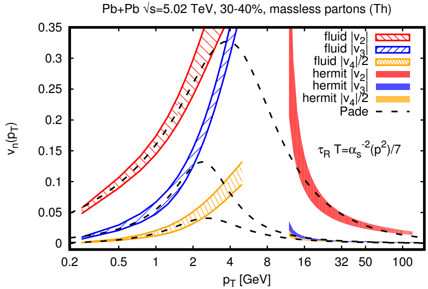
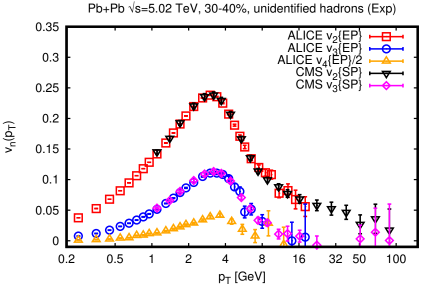
- This may actually explain the anisotropic flow measured at high p_T: (Romatschke '18)

Pb+Pb √s=5.02 TeV, 30-40%, massless partons (Th)



Pb+Pb √s=5.02 TeV, 30-40%, unidentified hadrons (Exp)



Challenges to the Little Bang Standard Model

- Flow-like signatures are also obtained from kinetic theory in the limit of *large Knudsen numbers* ("single scattering limit")
- Variation of this theme: the "escape mechanism" (studied extensively in AMPT: He et al. '15, Lin et al. '15, Orjuela-Koop et al. '15, Li et al. '16, '17, . . .)

Challenges to the Little Bang Standard Model

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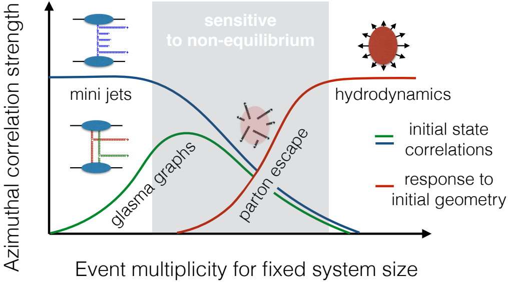
- Variation of this theme: the "escape mechanism" (studied extensively in AMPT: He et al. '15, Lin et al. '15, Orjuela-Koop et al. '15, Li et al. '16, '17, ...)
- Initial-state momentum correlations (Dusling & Venugopalan '13, Lappi et al. '15, Kovchegov & Skokov '18, Schlichting et al. '16, Greif et al. '17, '18, ...)



Much additional work needed to *quantitatively* understand small collision systems!

Conclusions

- Signs of hydrodynamic behavior are pervasive in heavy-ion collisions, from high to relatively low energies and from large to small collision systems.
- The **Little Bang Standard Model**, consisting of (1) QCD-motivated fluctuating initial conditions, (2) a short-lived pre-hydrodynamic stage, followed by (3) (anisotropic) relativistic dissipative fluid dynamics until hadronization and (4) a hadronic cascade to describe the final freeze-out, has been very successful and opens the door for precision spectroscopy of the quark-gluon plasma.
- Small collision systems still provide theoretical challenges: **Where does the hydrodynamic approach really break down?**
- Not covered in this talk: hard and penetrating probes ⟹ JETSCAPE

  Just released: JETSCAPE V1.0

Thanks!

(Also, of course, to the many collaborators and friends who contributed to the development of the LBSM)