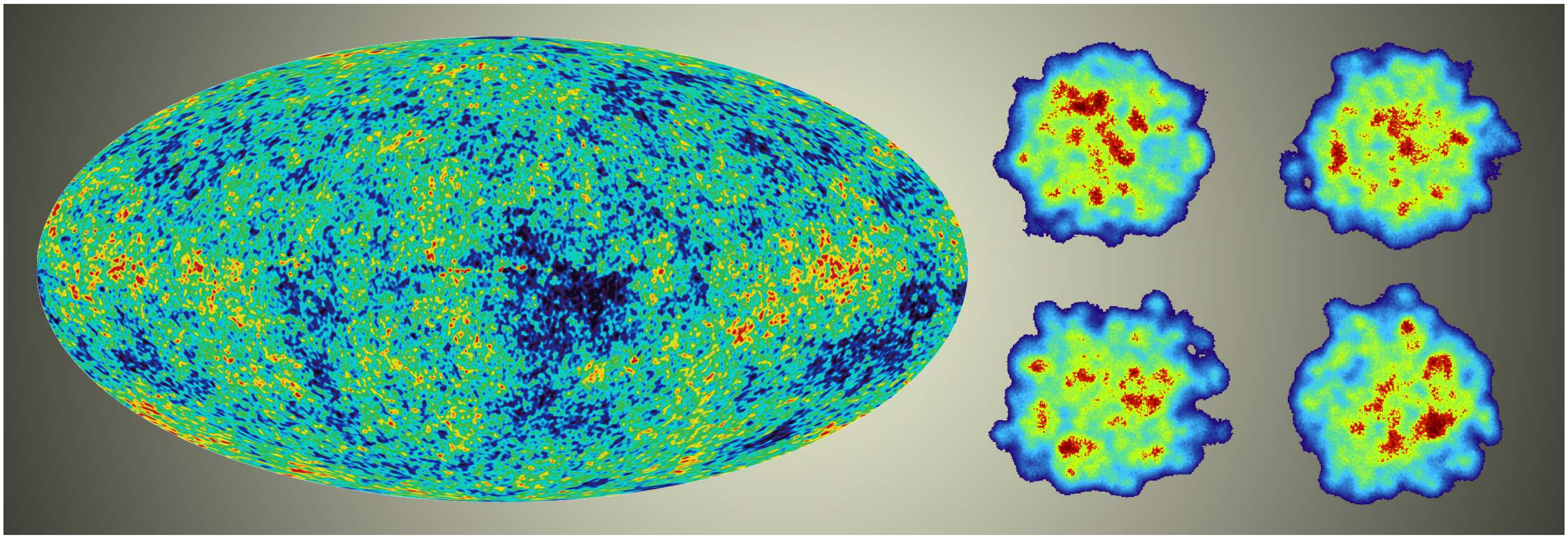
# The Physics of Heavy-Ion Collisions – Recent Insights and Open Questions*

Ulrich Heinz (The Ohio State University)



**Discovery Physics at the LHC (Kruger2014), Kruger Gate, South Africa, 1-6 Dec. 2014**

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

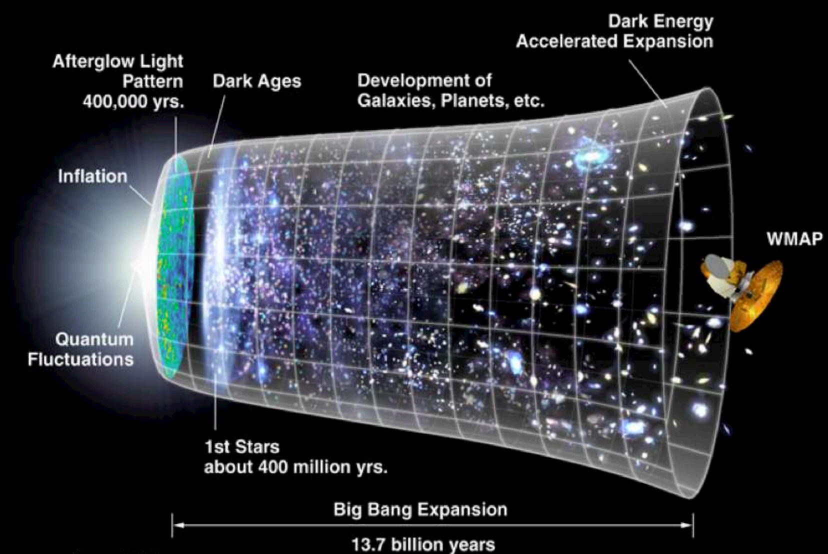
*Supported by the U.S. Department of Energy

JET Collaboration

# Two big questions driving the field:

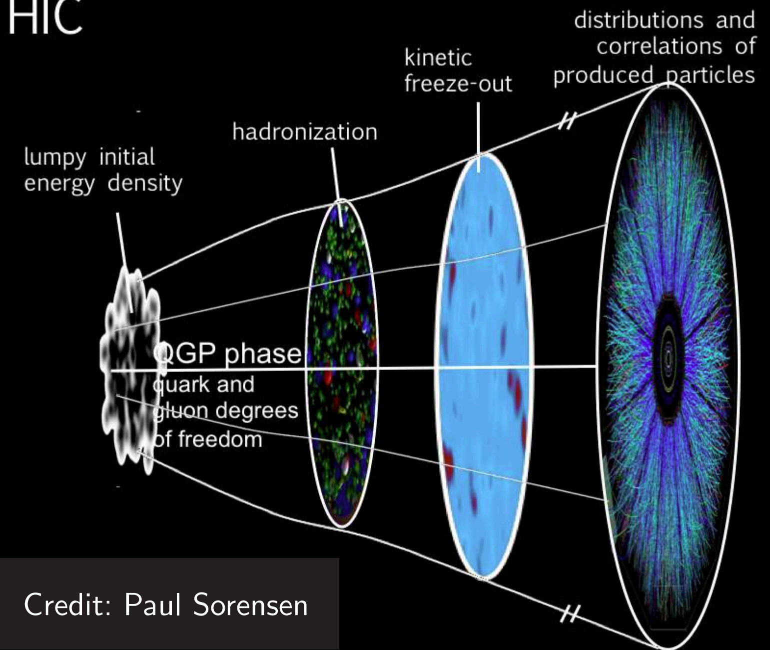
# 1. Studying the Big Bang with Little Bangs

The Universe

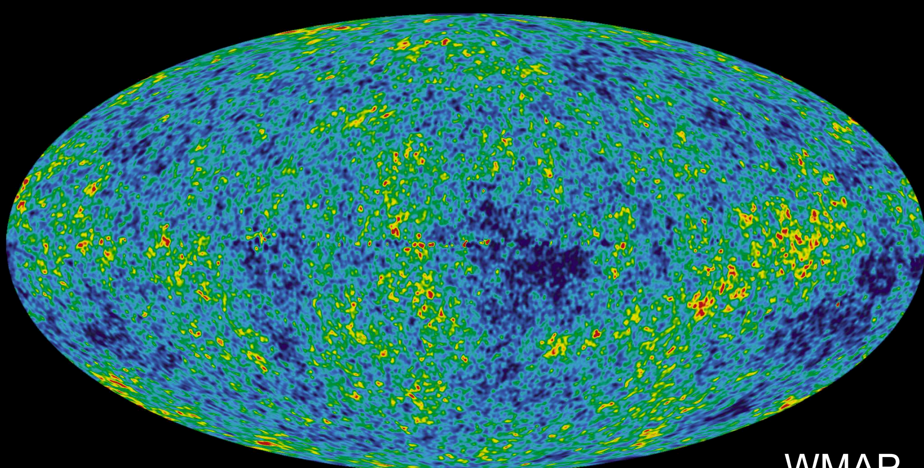



Credit: NASA

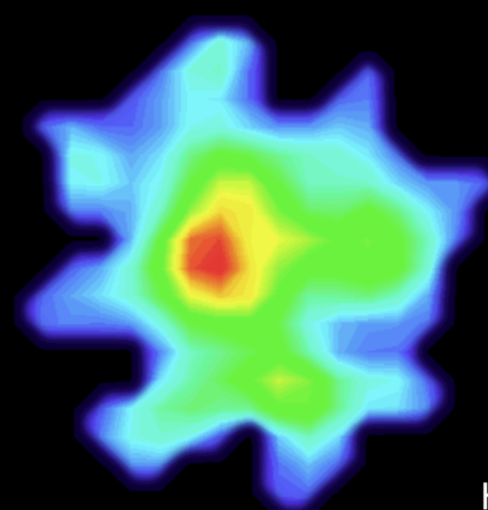
HIC




Credit: Paul Sorensen

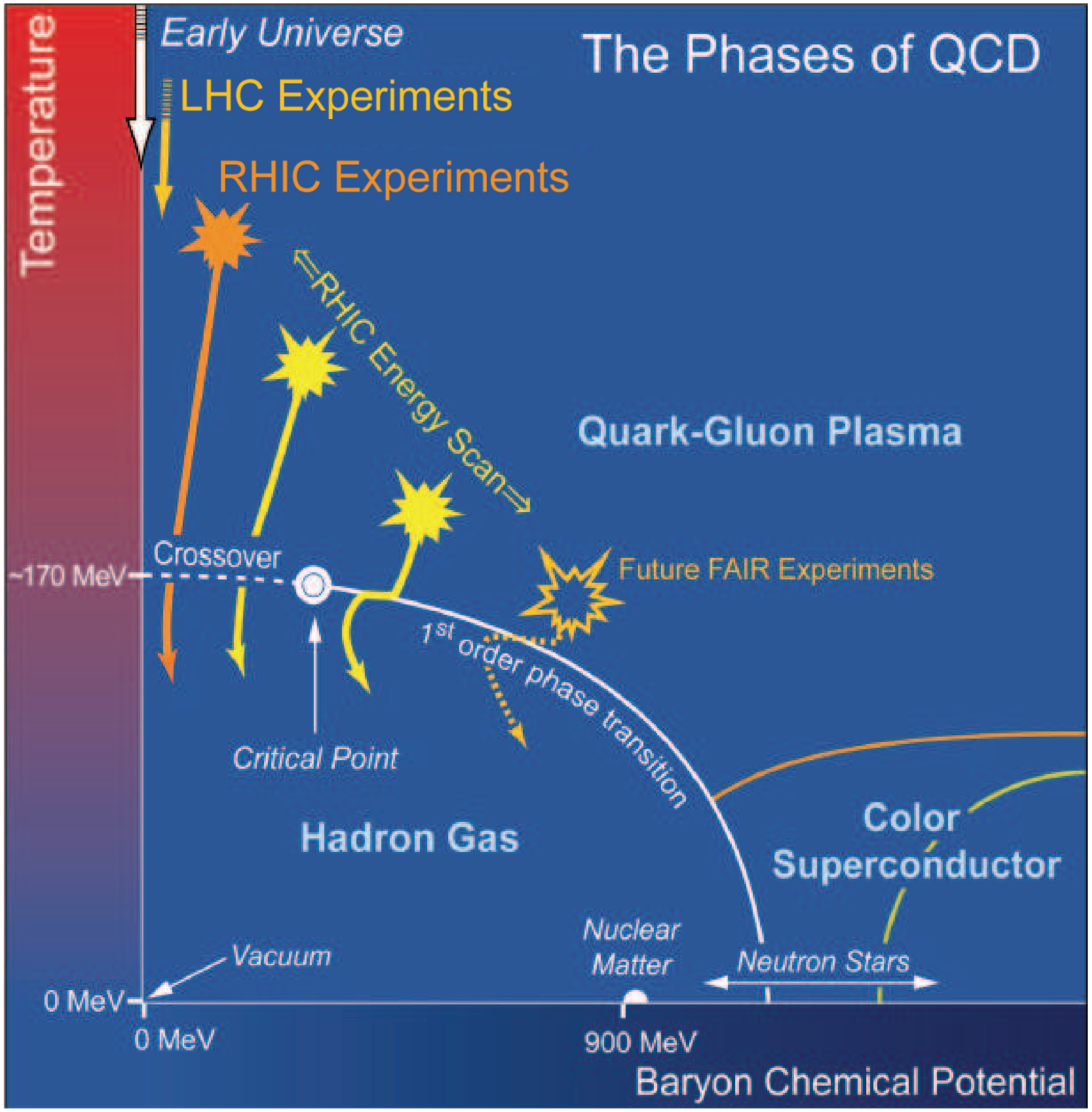


WMAP



HIC

# 2. Exploring the QCD phase diagram: emergent phenomena in non-Abelian media



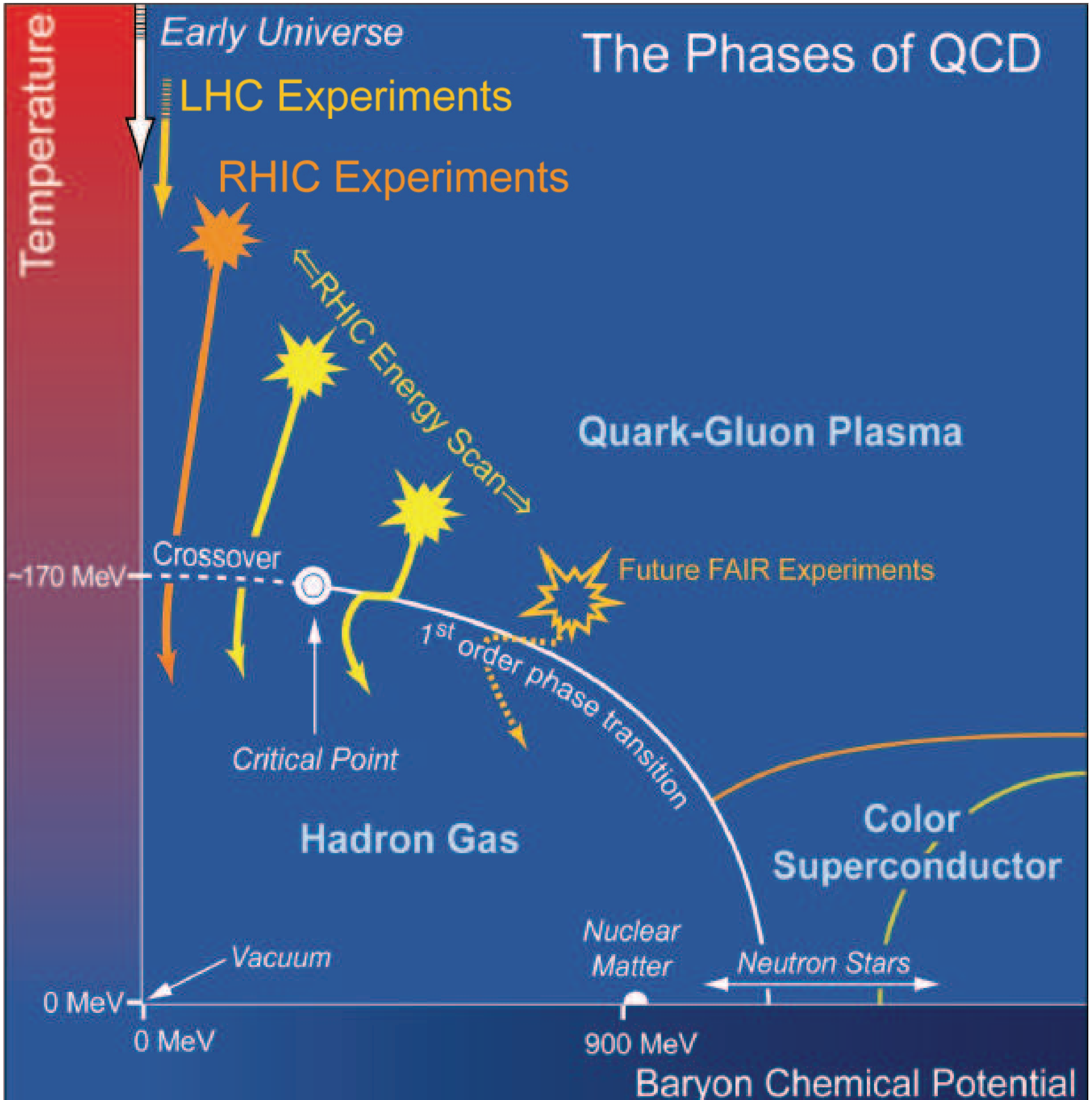

## Phenomena:

- (De-)confinement (clustered vs. homogeneous states)
- chiral symmetry restoration
- (almost) perfect fluidity
- order of the phase transition(s)
- critical end point?

What happened in the early universe about 10 $\mu$s after the Big Bang?

What changes when you dope the matter that filled the early universe with extra quarks/baryon number?

# 2. Exploring the QCD phase diagram: emergent phenomena in non-Abelian media




## Probes:

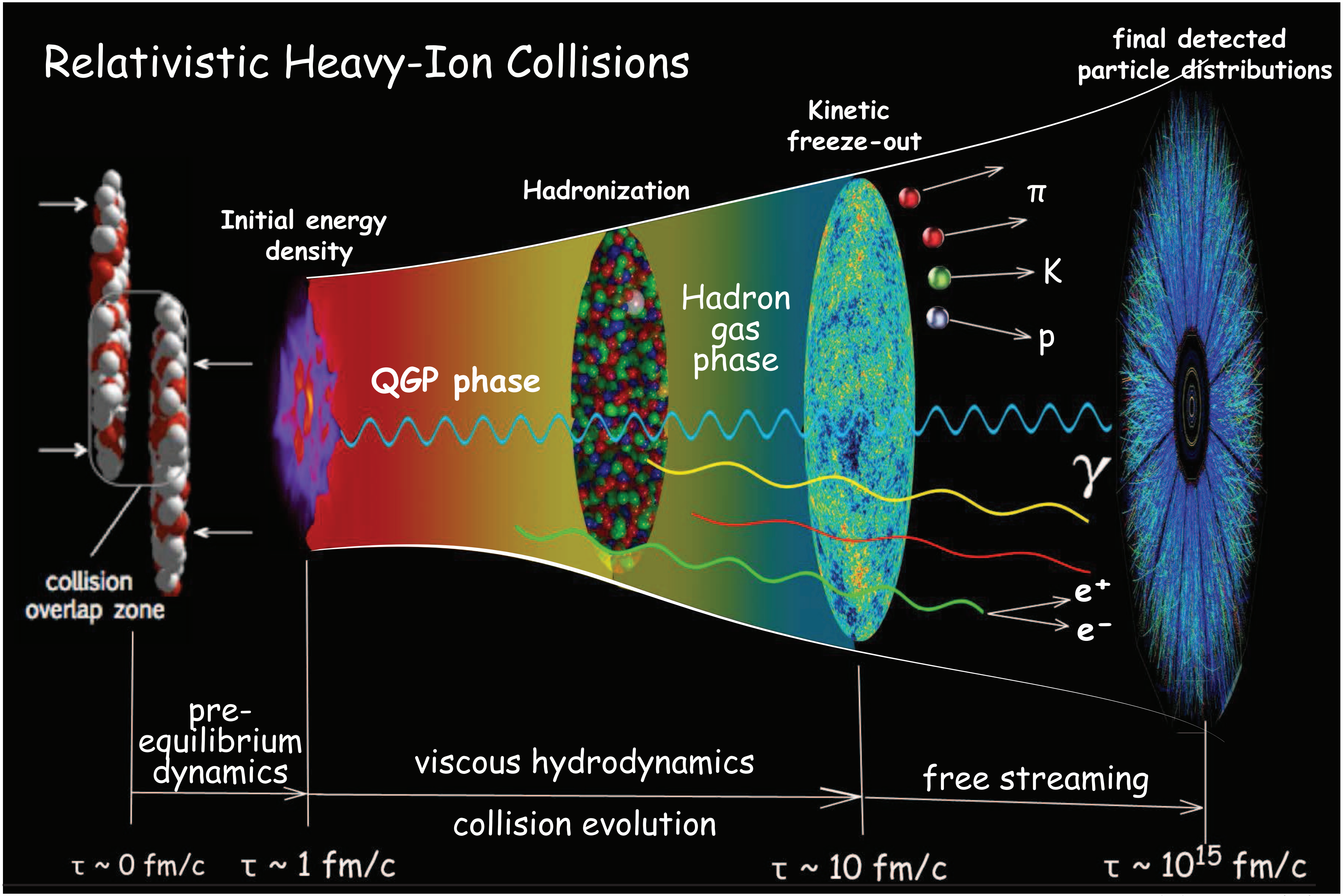
- Collective flow
- Jet modification and quenching
- Thermal electro-magnetic radiation
- Critical fluctuations
- . . .

# Key questions:

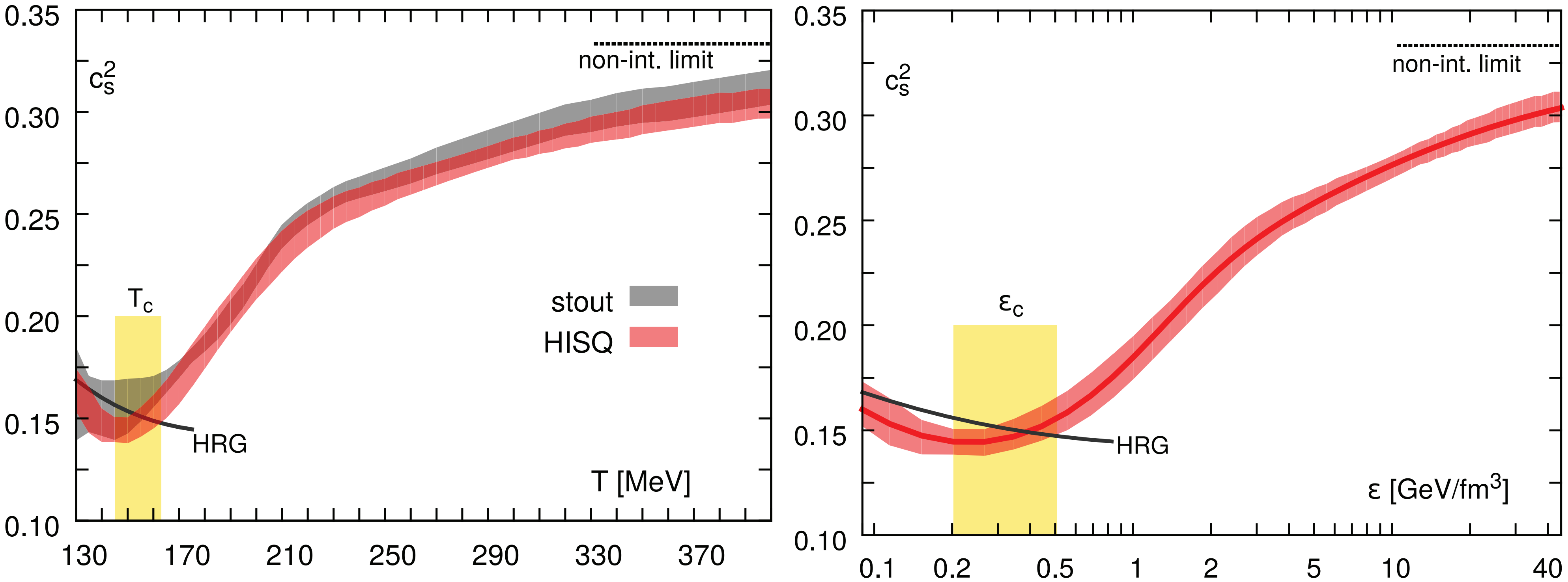
- What are the transport properties of the QGP? How do they change when the plasma is heated or doped with excess quarks?
- How do the collective properties of the QGP liquid, one of the most strongly coupled forms of matter now known, emerge from the interactions among the individual quarks and gluons that we know must be visible if the liquid is probed with sufficiently high resolution?
- What is the precise nature of the initial state from which this liquid forms, and how does it reach approximate local thermal equilibrium in the short time and rapidly expanding environment provided by heavy-ion collisions?
- Can dense systems of quarks and gluons act like strongly coupled liquids without thermalizing? Does the Color Glass Condensate state that manifests itself when fast-moving atomic nuclei are probed at very small longitudinal momentum fraction exhibit collective behavior?
- What is the structure of the QCD phase diagram? Does it, like that of water, feature a critical end point that connects a line of first-order phase transitions at large baryon density with the rapid but continuous cross-over found by lattice QCD at low baryon density?
- How does the observed structure of the QGP change when it is probed at different length scales, with photons, jets, and heavy quark flavors? What is the shortest length scale on which the plasma fluid looks liquid-like?
- What is the smallest size and density of a droplet of QCD matter that behaves like a liquid?

# A standard framework for heavy-ion collision dynamics

(credit: Paul Sorensen/Chun Shen)



# New: converged results on lattice EOS and $T_c$

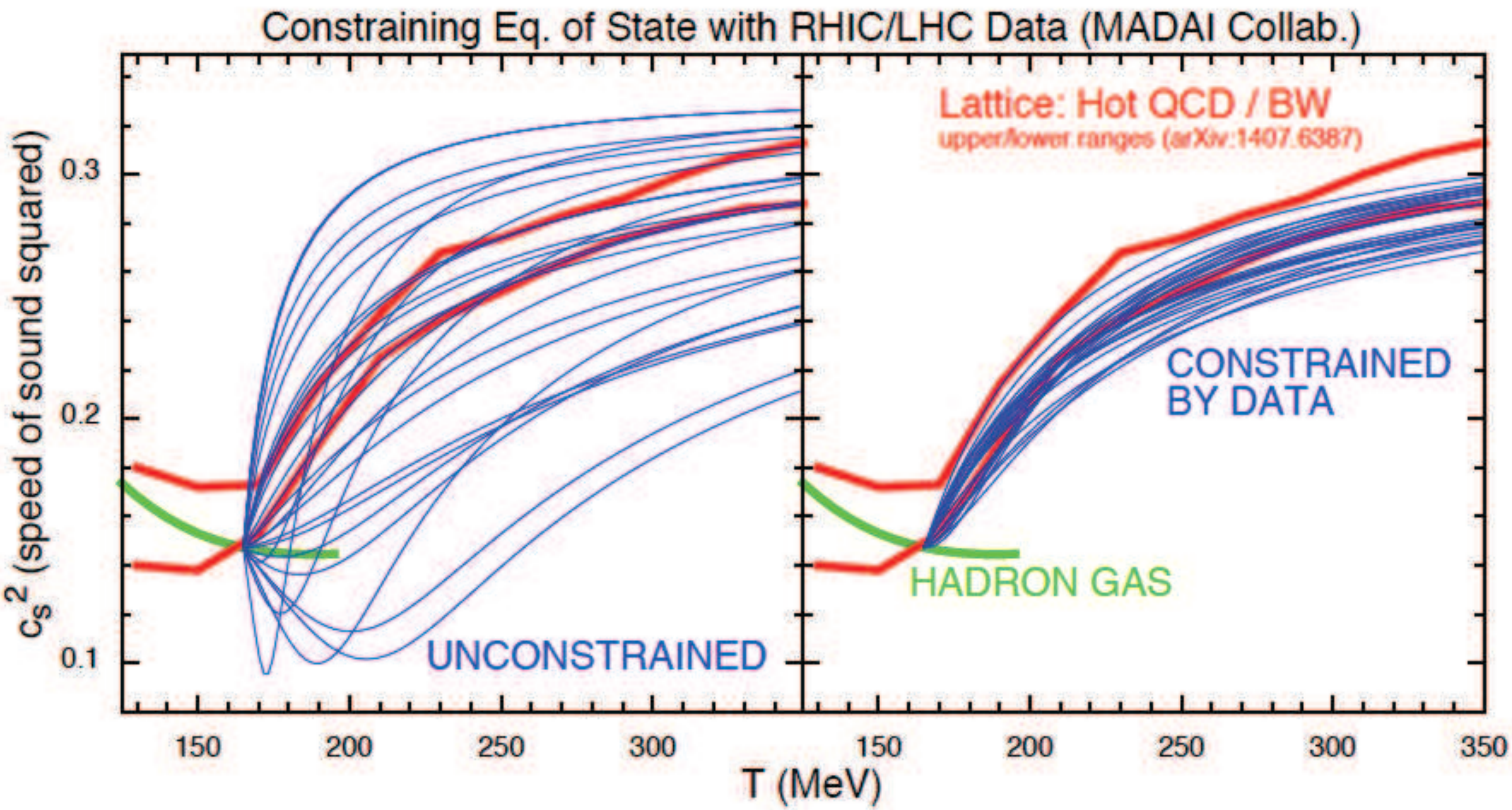



HOT QCD and BMW collaborations now have converged. New critical parameters at zero baryon density from HOT QCD (Bazavov et al., PRD 90 (2014) 094503):

$$T_c = 154(9)\,\mathbf{MeV},\ 180 < e_c < 500\,\mathbf{MeV/fm^3}$$

# . . . and we are on the verge of reconstructing it from experiment!

MADAI Collaboration, S. Pratt et al., QCD Town Mtg., Temple U., Sep. 13-15, 2014

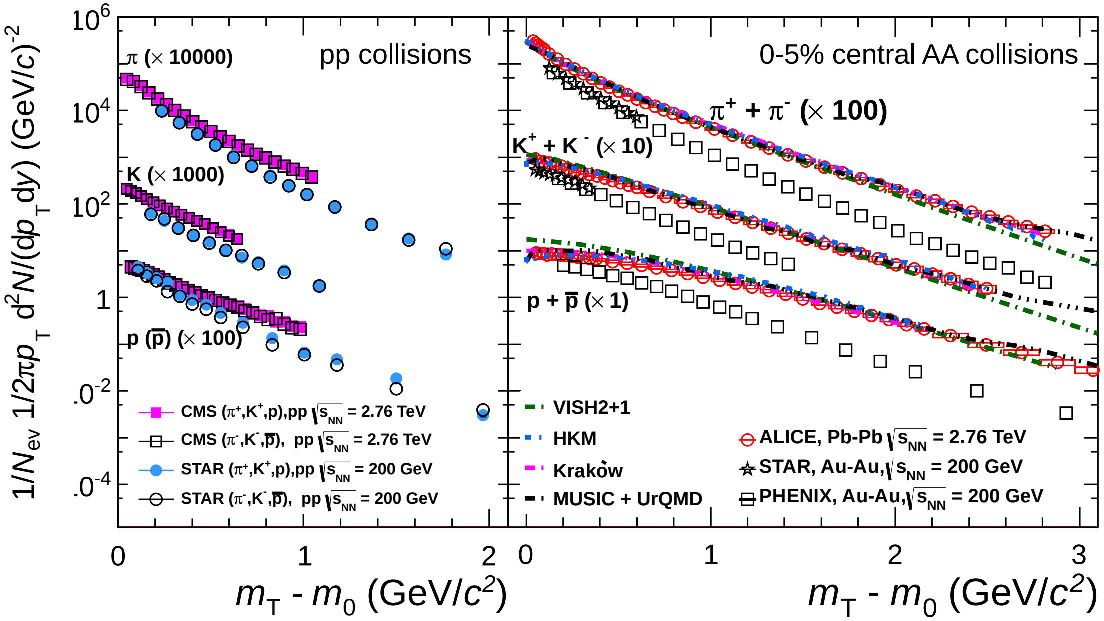



Exptl. input: hadron spectra, elliptic flow, HBT radii in Au+Au@RHIC and Pb+Pb@LHC
Constraints: asymptotic values of $c_s^2$ at $T_c$ and $T = \infty$, fixed $\eta/s$.

# Successes of the Little Bang Standard Model

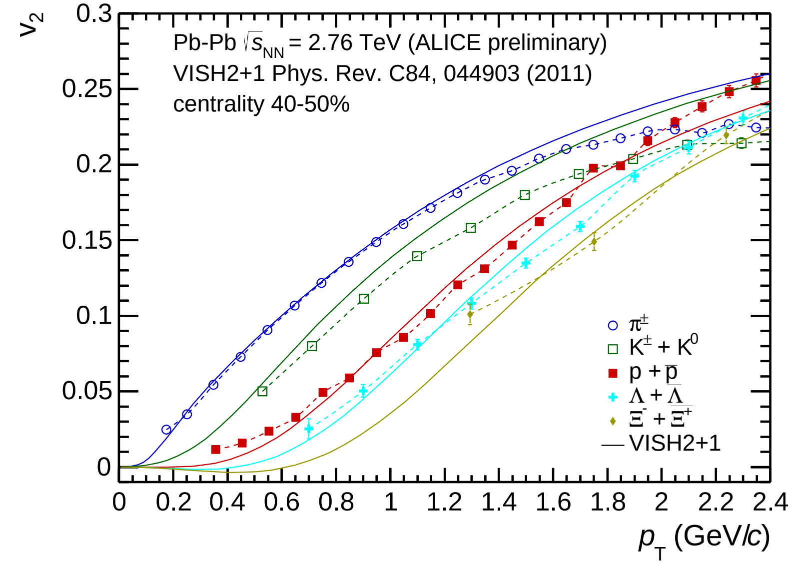
identified hadron $p_T$-spectra

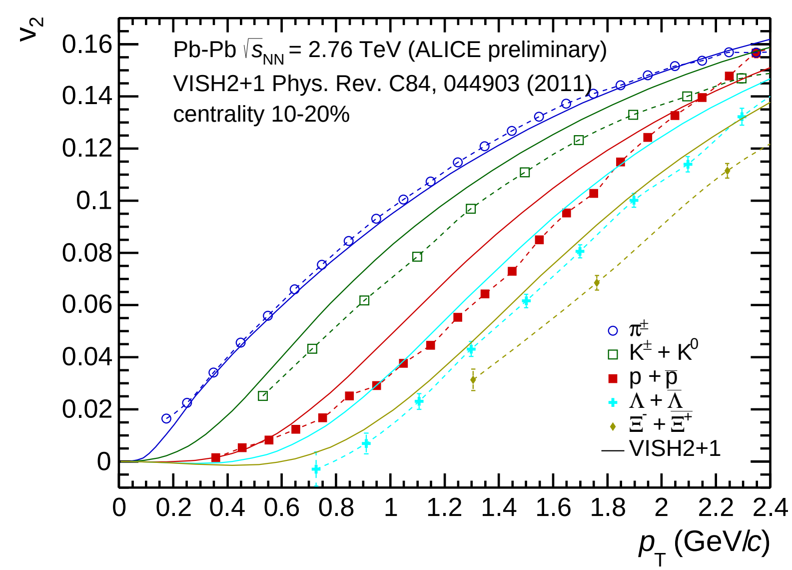
Data: ALICE. VISH2+1 pre-diction: PRC 84 (2011) 044903




A purely hydrodynamic description does not produce quite enough radial flow in central collisions (although it qualitatively reproduces the much larger mass splitting of $v_2(p_T)$ due to stronger radial flow at LHC compared to RHIC)

identified hadron elliptic flow
(R. Snellings, RSN@CT (Catania 2014))

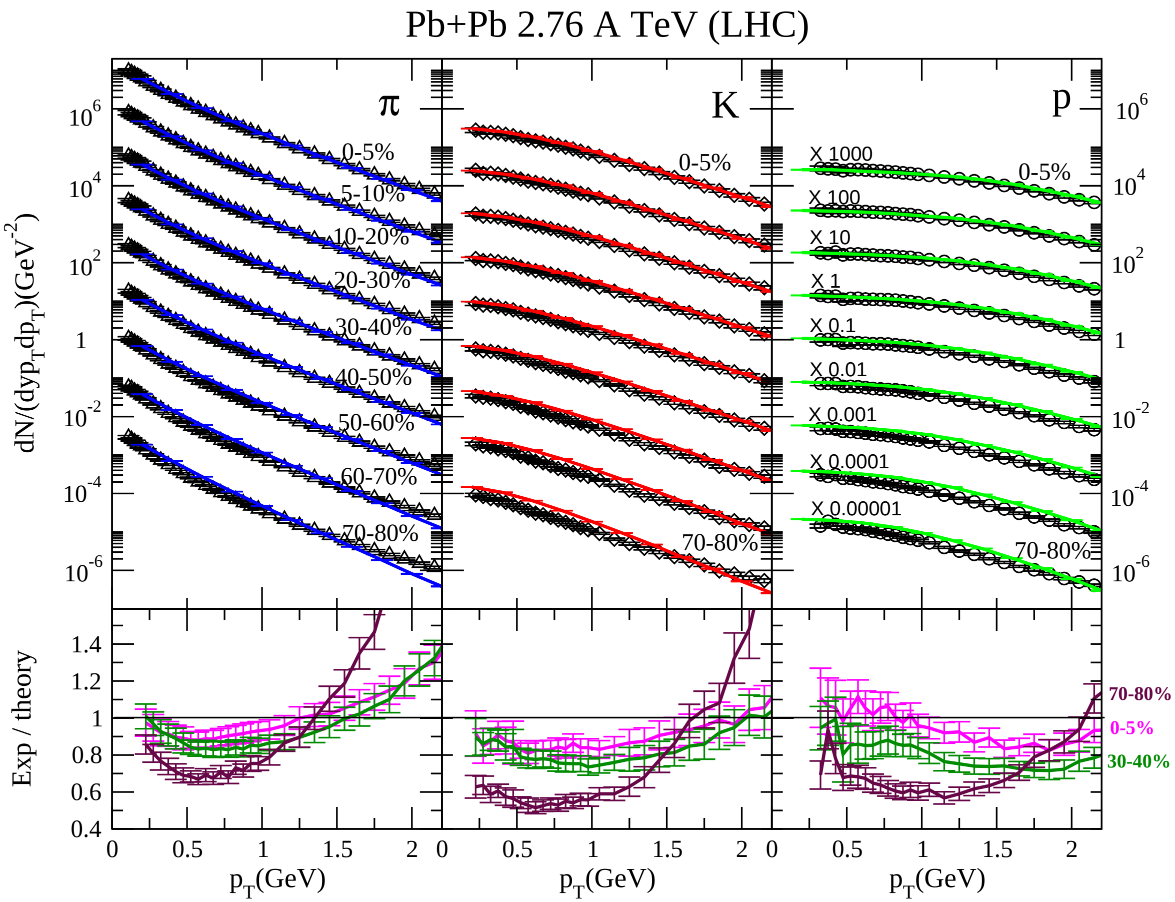


# Successes of the Little Bang Standard Model

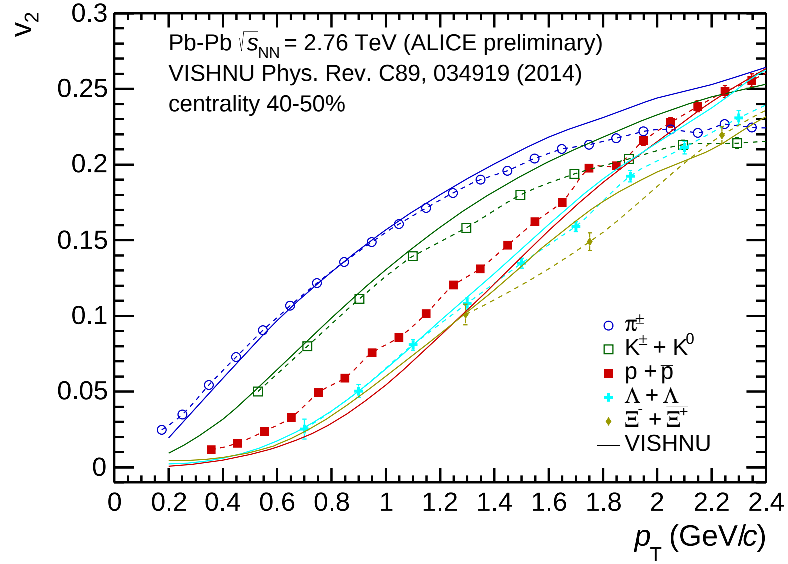
identified hadron $p_T$-spectra

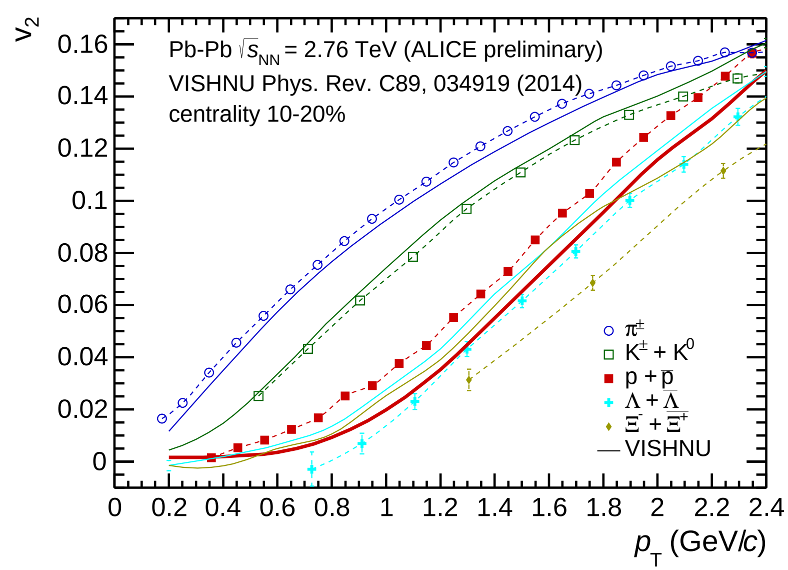
Data: ALICE. Theory: VISHNU (PRC 89 (2014) 034919)




identified hadron elliptic flow

(R. Snellings, RSN@CT (Catania 2014))

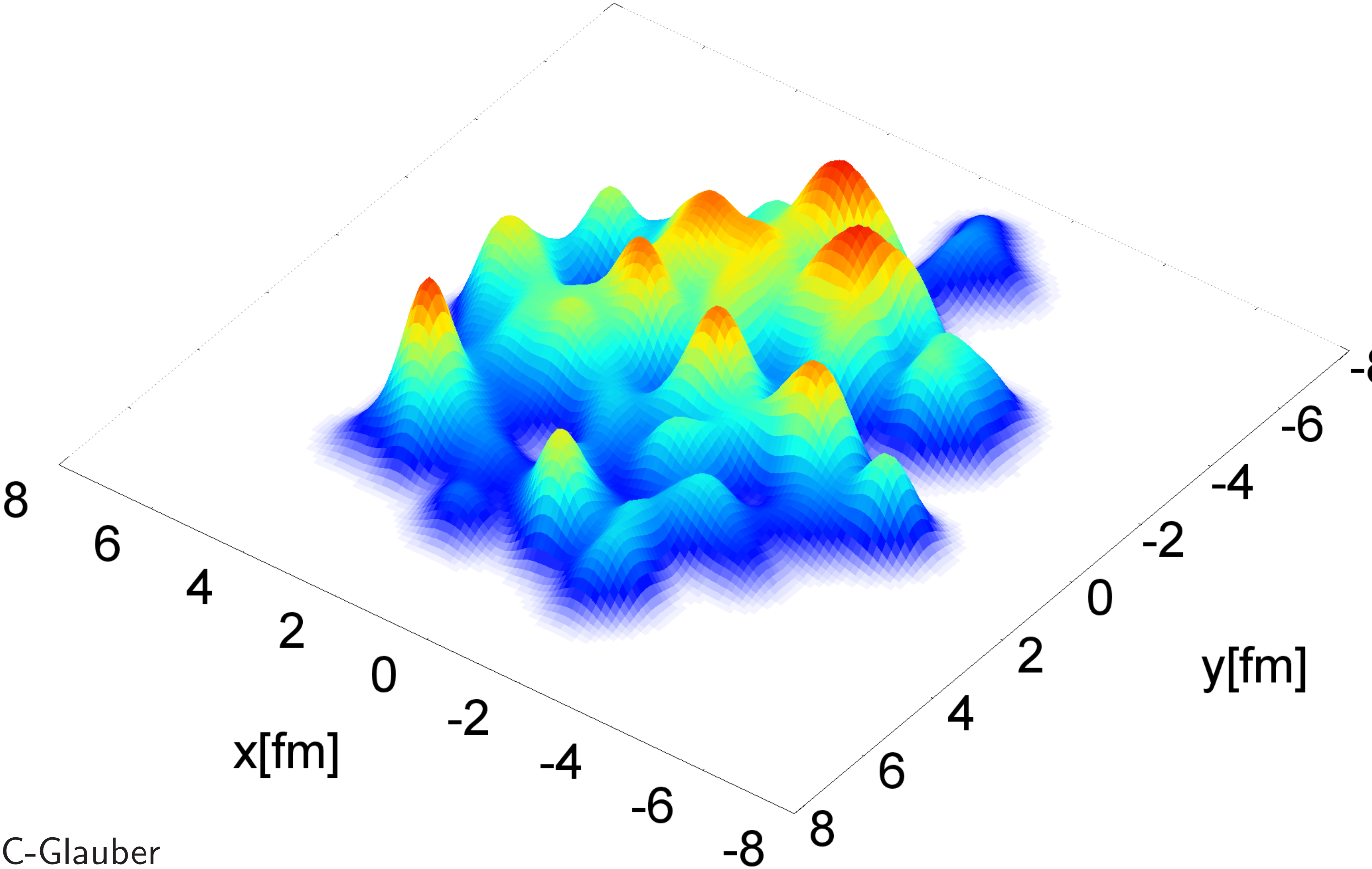



A hybrid approach (viscous hydro plus hadronic cascade) produces a bit too much radial flow for protons in central collisions but, due to smaller cross sections, hyperons don't fully pick it up, yielding inverted mass-ordering ($\Lambda$-$\Xi$-$p$, instead of $p$-$\Lambda$-$\Xi$ as experimentally measured)

# Adding sub-nucleonic quantum fluctuations

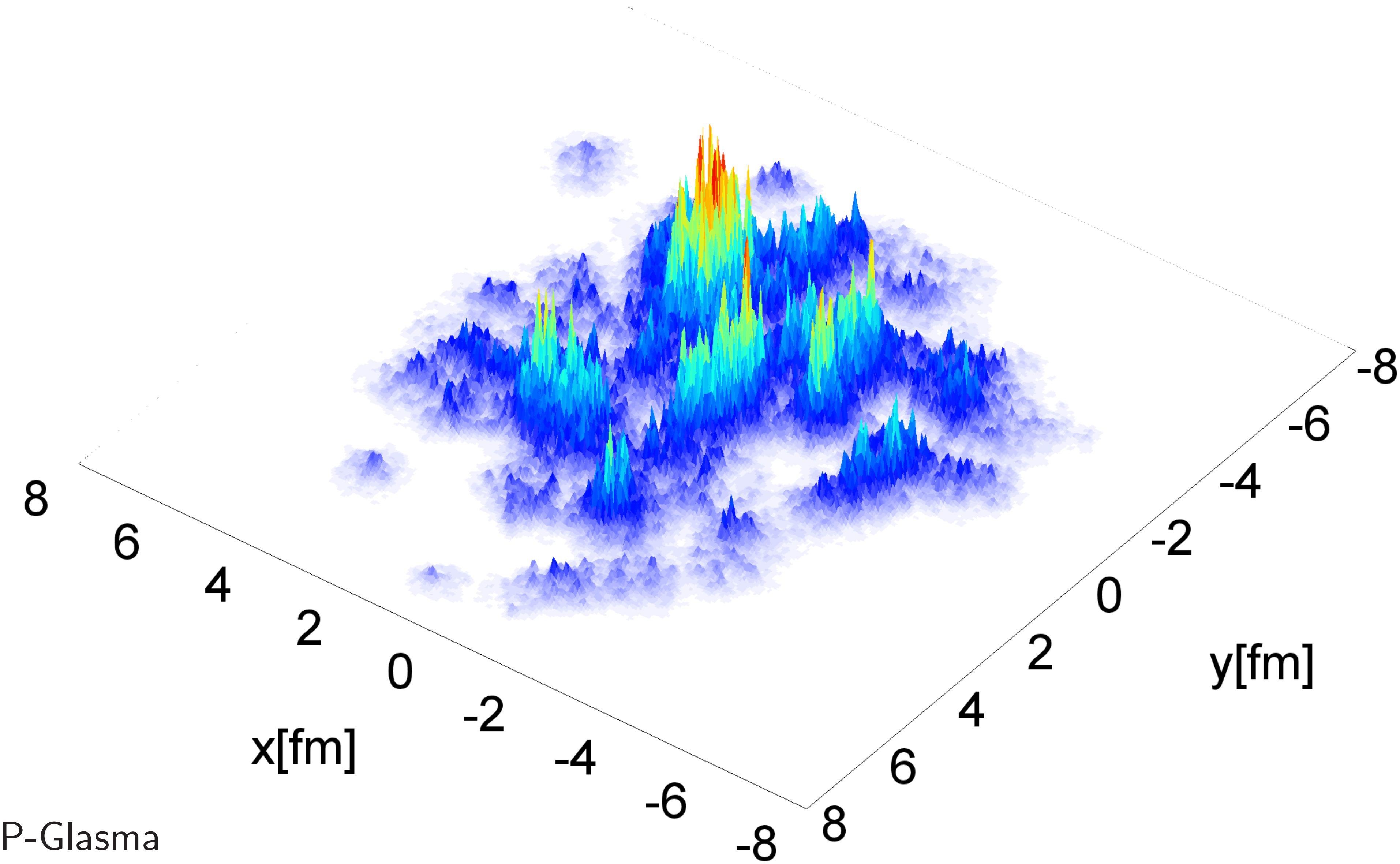
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)




MC-Glauber

# Adding sub-nucleonic quantum fluctuations

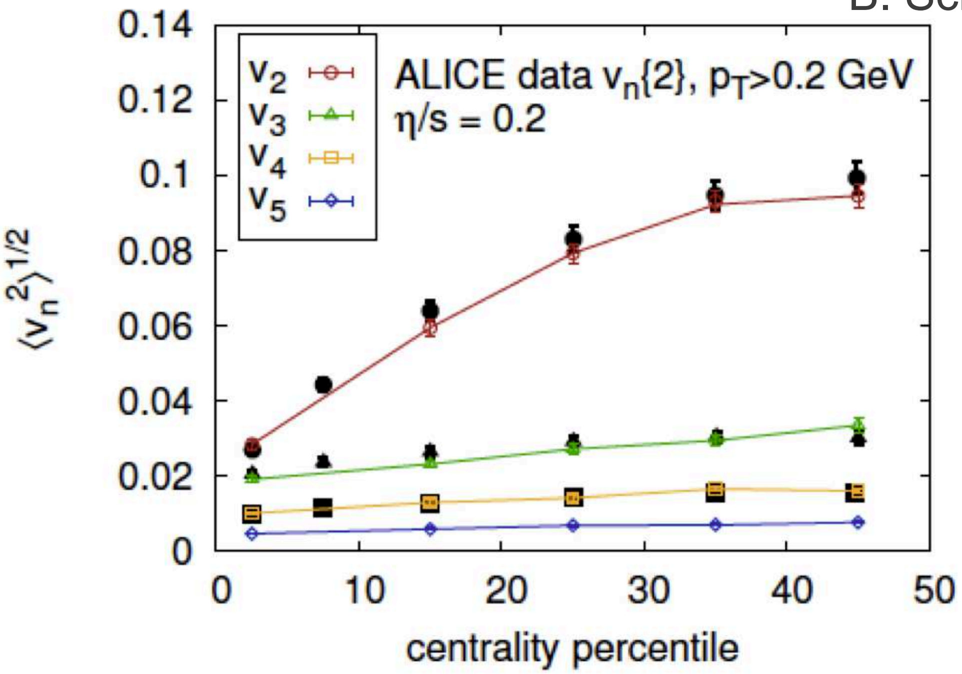
Schenke, Tribedy, Venugopalan, PRL108, 252301 (2012)

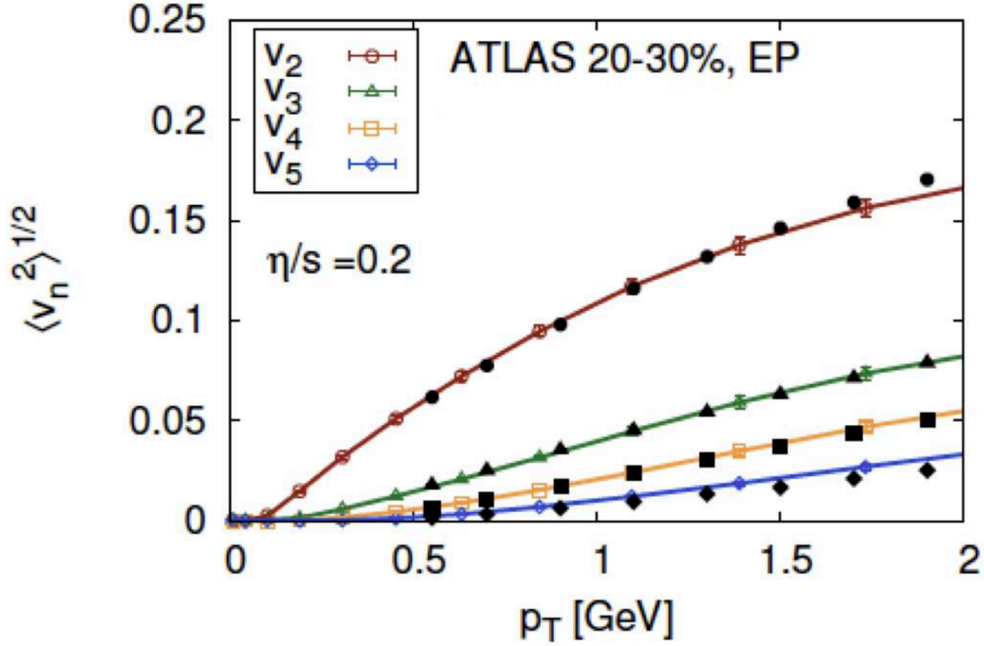



IP-Glasma

# 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:

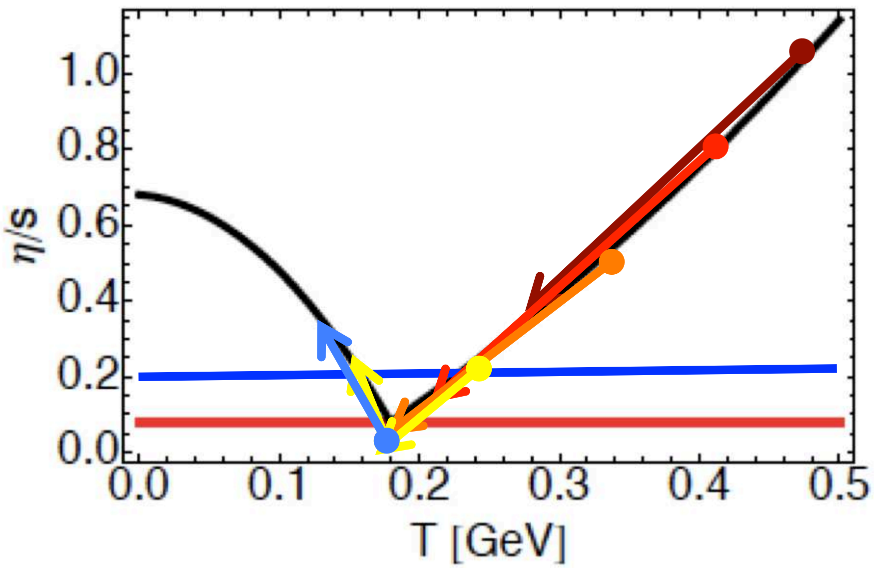
→ outstanding agreement between data and model

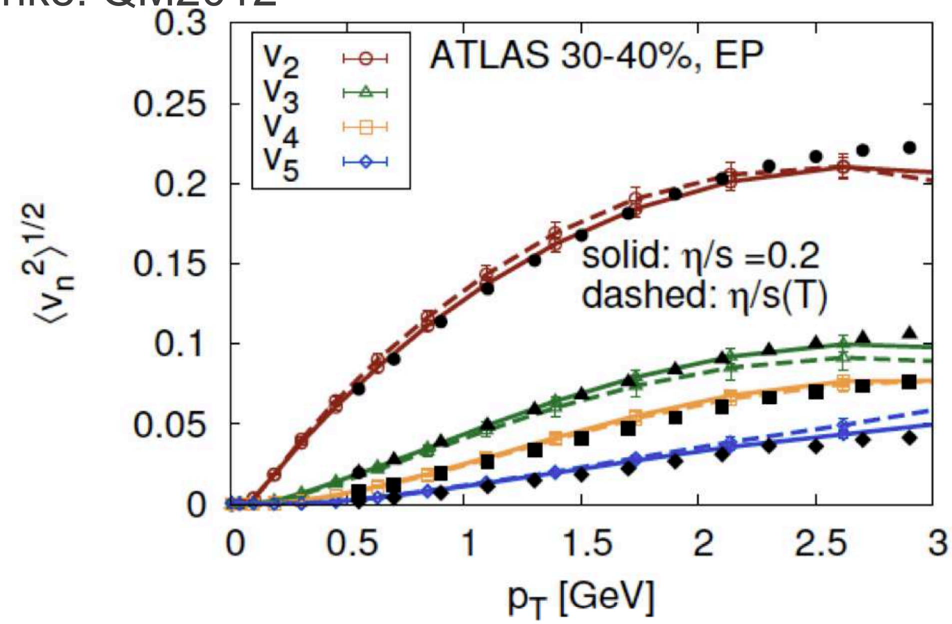
**Rapid convergence on a standard model of the Little Bang!**

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



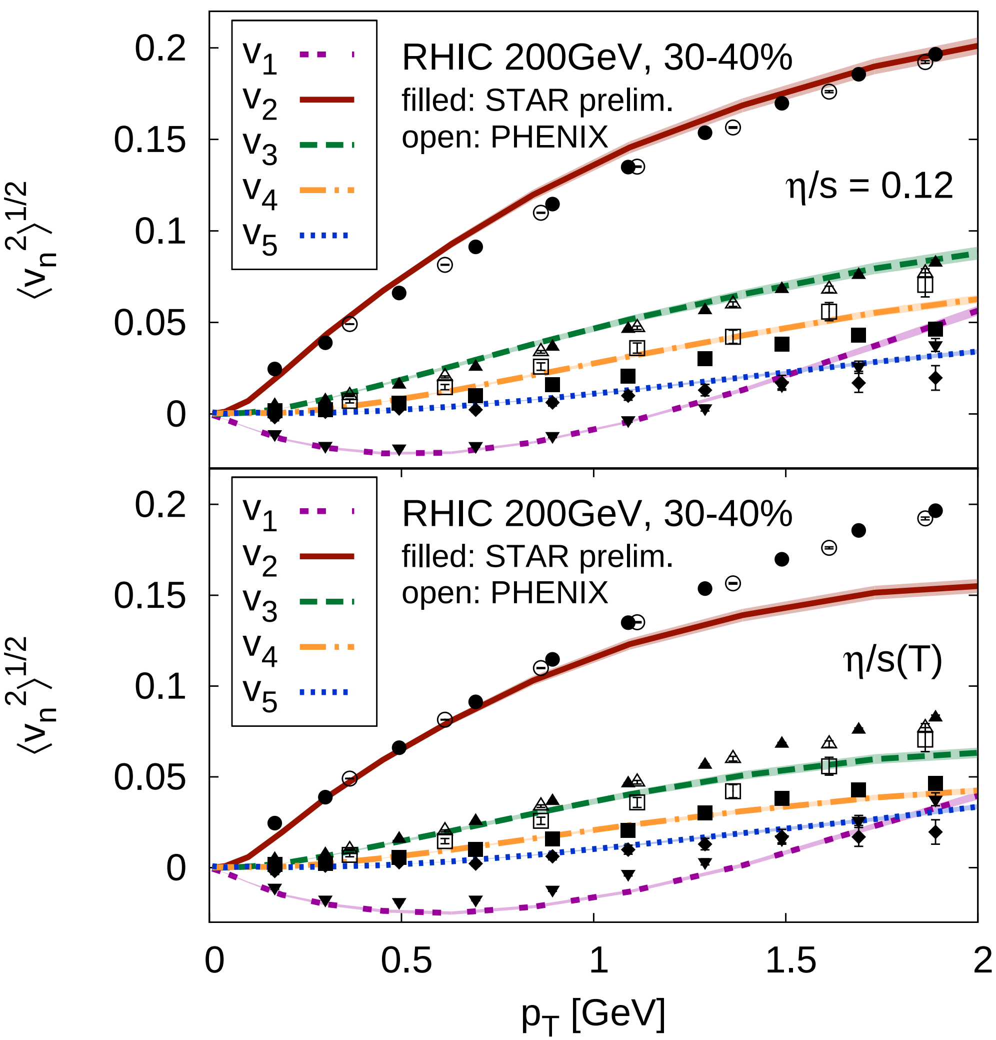



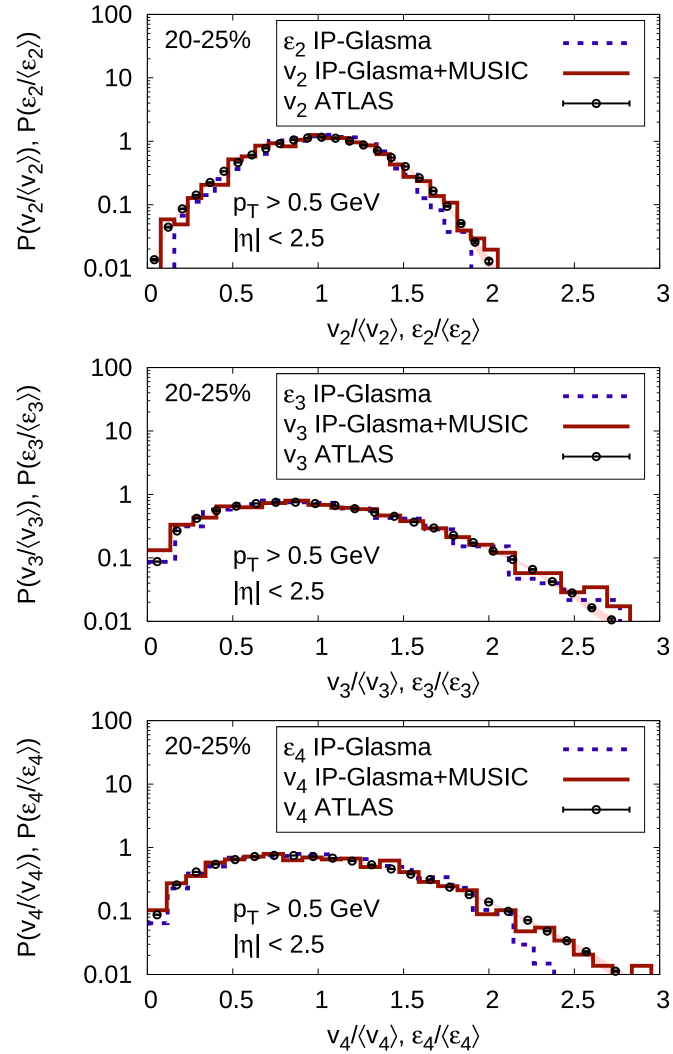

Model doesn't distinguish between a constant η/s of 0.2 or a temperature dependent η/s with a minimum of 1/4π

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)

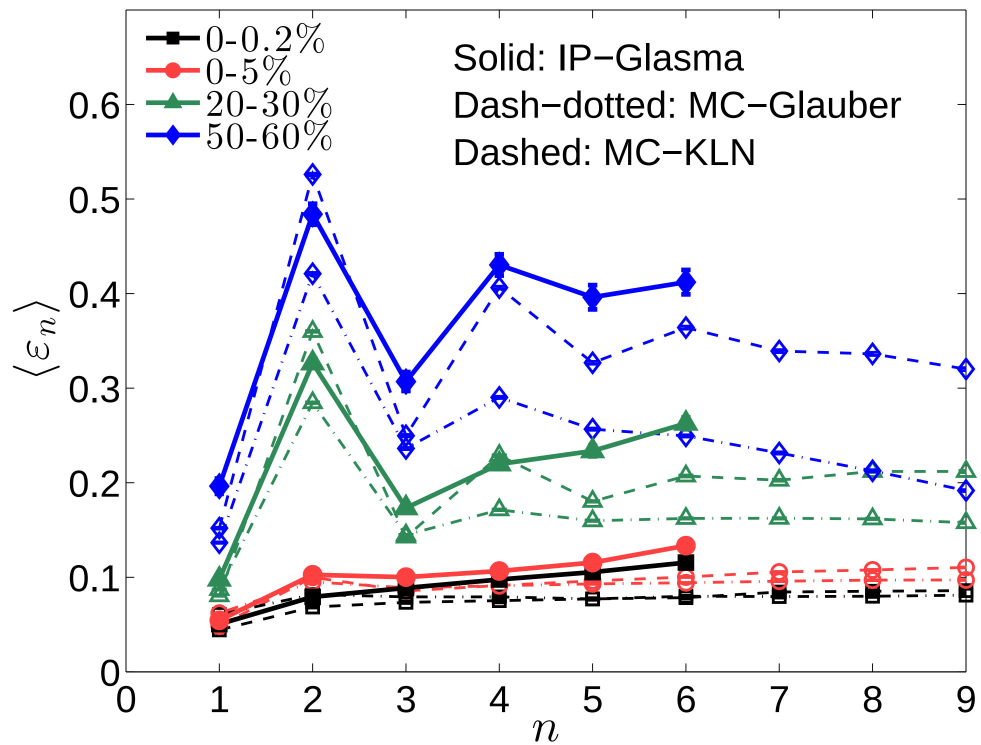



- Model describes RHIC data with lower effective specific shear viscosity $\eta/s = 0.12$
- In contrast to MC-Glauber and MC-KLN, IP-Sat initial conditions correctly reproduce the final flow fluctuation spectrum, generated from initial shape fluctuations by viscous hydrodynamics

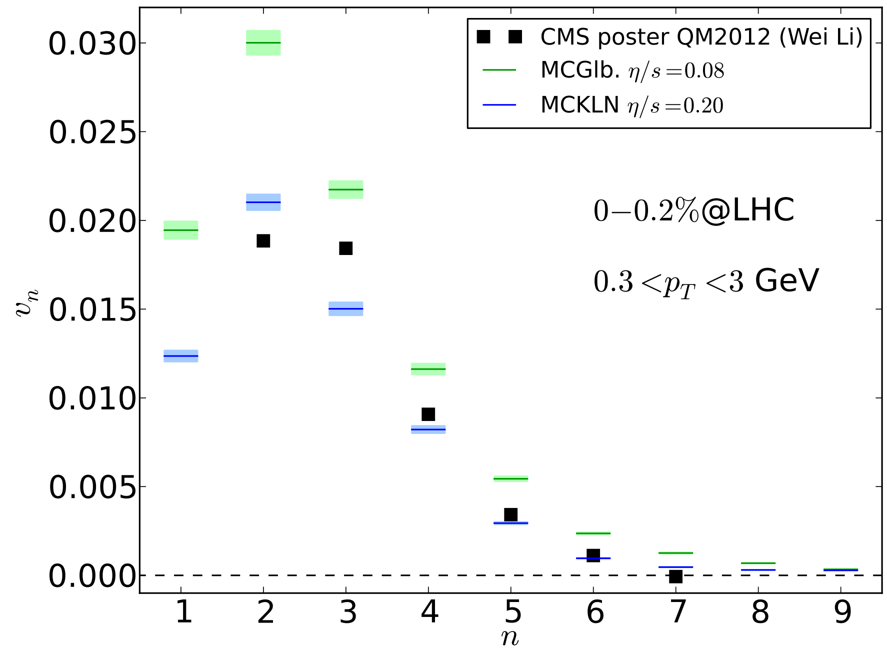
# The Little Bang fluctuation power spectrum: initial vs. final

Little Bang density power spectra




Flow power spectrum for ultracentral PbPb Little Bangs

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



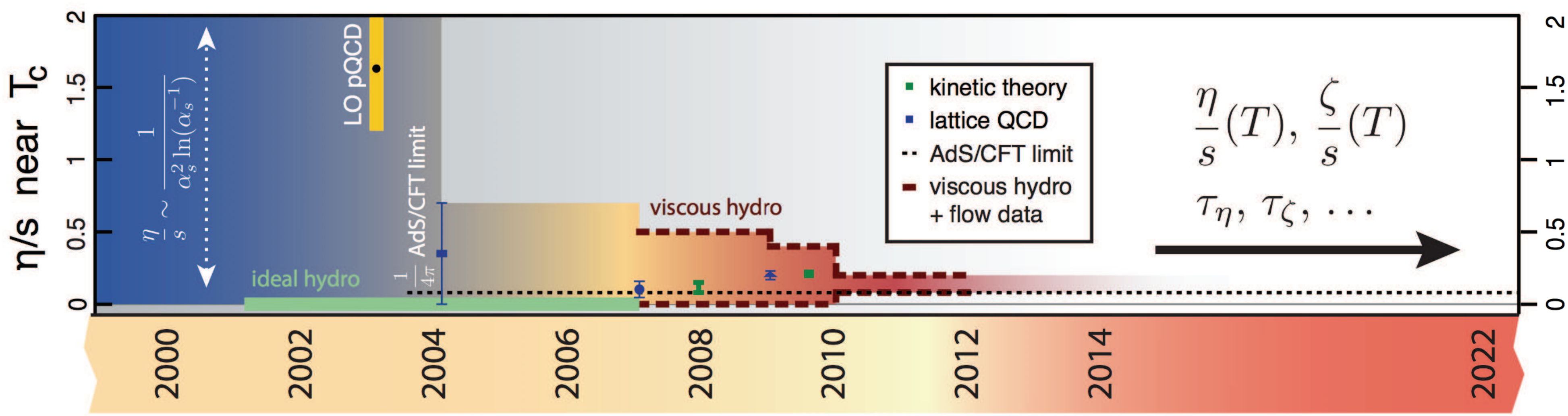

Higher flow harmonics get suppressed by shear viscosity

**Neither MC-Glb nor MC-KLN gives the correct initial power spectrum! † R.I.P.**

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

# Progress to date in constraining $(\eta/s)_{\mathrm{QGP}}$

(Adapted from "Hot and Dense QCD Matter – Unraveling the Mysteries of the Strongly Interacting Quark-Gluon-Plasma", S. Bass et. al., 2012)




**What is needed to further reduce the uncertainty band?**

# How to further constrain $(\eta/s)_{\rm QGP}$ and the initial fluctuation spectrum

The $v_n$-data are in principle precise enough to extract $(\eta/s)_{\rm QGP}$ with $\sim 5\%$ precision, were it not for the model uncertainties in the initial density fluctuation spectrum.

$\Longrightarrow$ must determine the initial fluctuation spectrum simultaneously with the QGP transport coefficients!

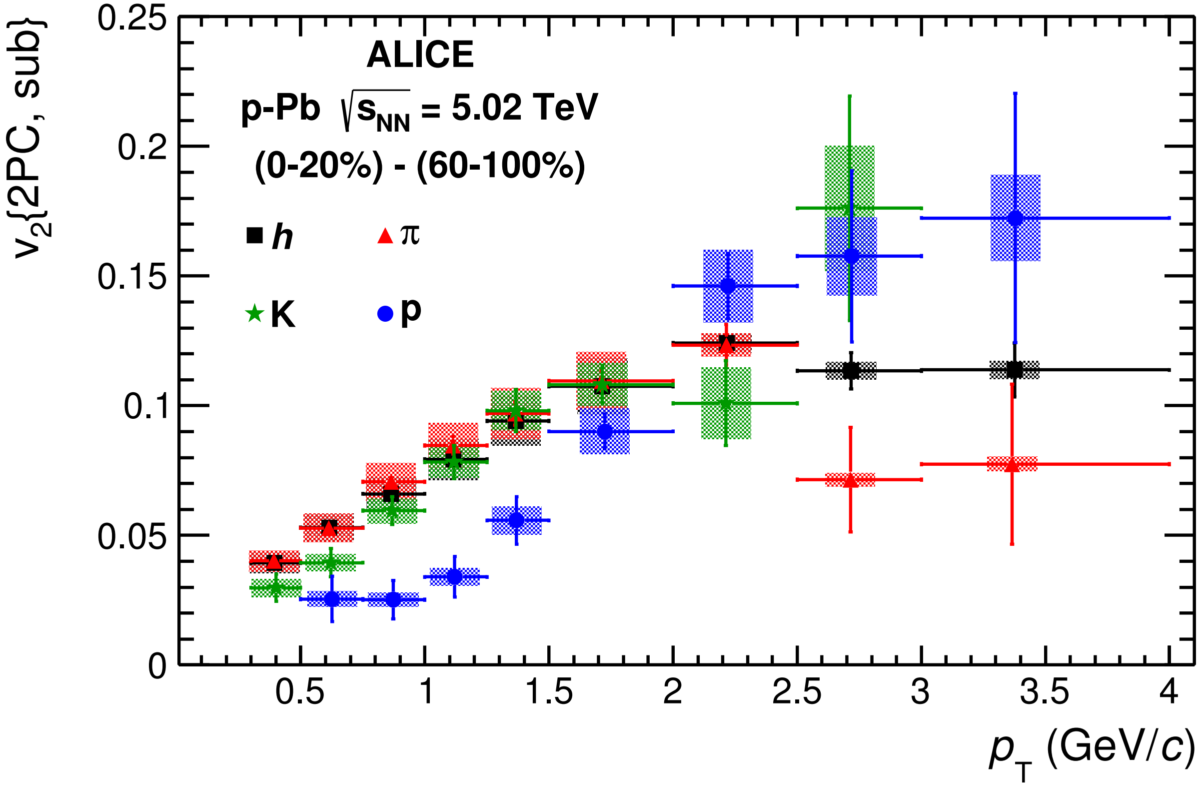
To this end we can additionally measure and compute

- flow-angle correlations (PLB 717 (2012) 261)
- the fluctuation-induced breaking of factorization of two-particle anisotropy coefficients (PRC87 (2013) 034913)
- different variants of particle-identified anisotropic flow coefficients (to separate fluctuations in flow magnitude from flow-angle fluctuations) (PRC87 (2013) 034913)
- the decorrelation of flow planes in rapidity due to longitudinal fluctuations (J. Jia, QM2014)
- the anisotropic (elliptic, triangular) flow of photons (probes earlier stages of the evolution than hadronic flow)(arXiv:1308.2111)
- flow in p+Au(Pb), d+Au(Pb), He3+Au(Pb) (seen in d+Au at RHIC and in p+Pb at the LHC!)
- flow, flow fluctuations and flow correlations at lower beam energies at RHIC (BES)
- . . .

**Ultimate goal: to determine the |initial wave function|$^2$ of the Little Bang!**

# Collectivity in p+A! How small can a drop of QGP be and still behave like a liquid?

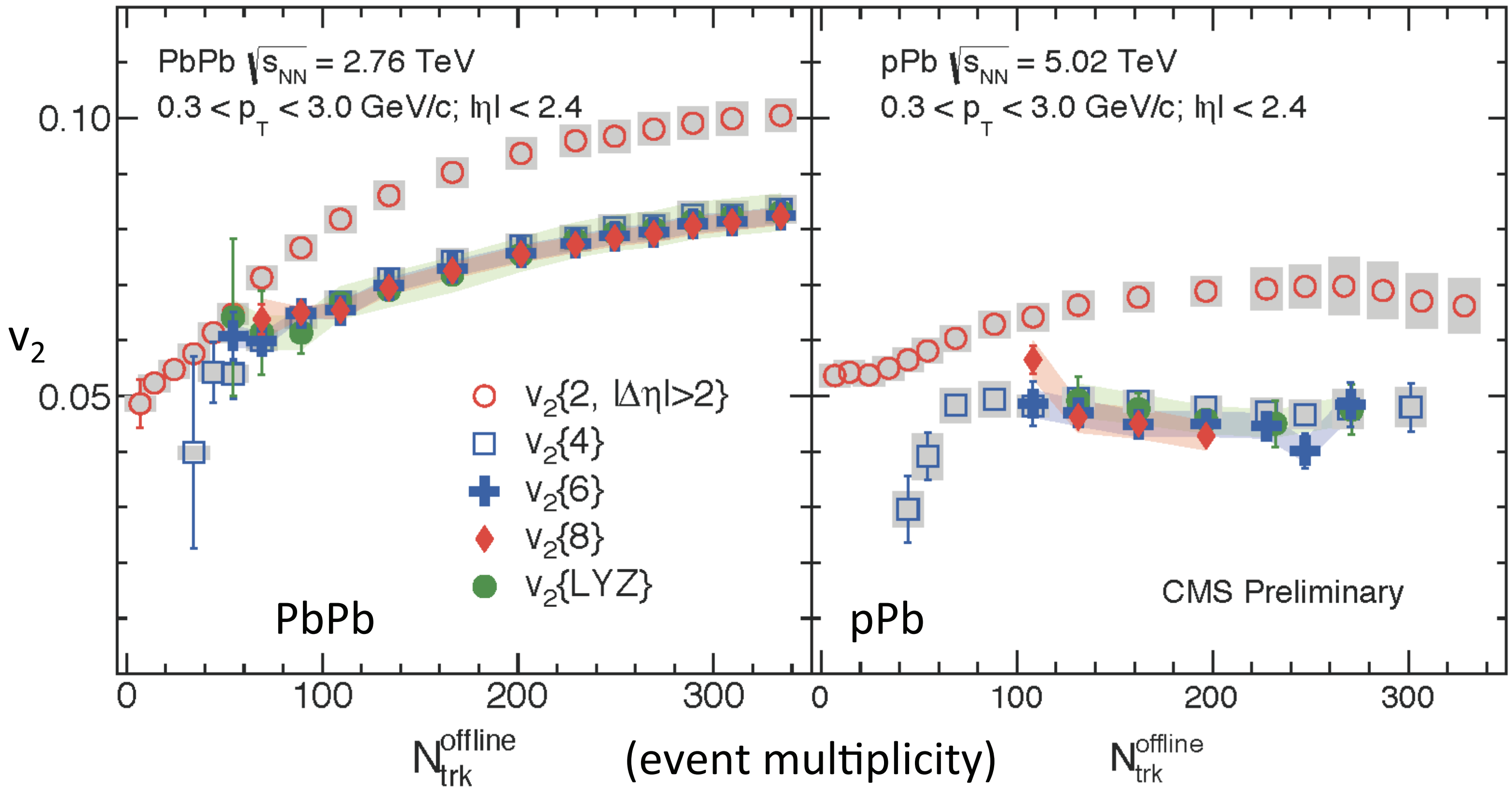
ALICE, arXiv:1307.3237v4




Similar mass splitting of differential elliptic flow for identified hadrons as seen in Au+Au, Pb+Pb, where it is a hallmark of hydrodynamic behavior.
Can one get this **without** hydrodynamics?!

# Collectivity in p+A! How small can a drop of QGP be and still behave like a liquid?

**CMS,** Quark Matter 2014



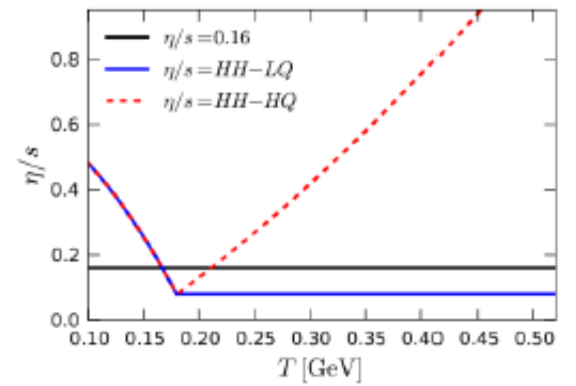

Elliptic flow is **collective**, not only in Pb+Pb, but also in p+Pb!

p+Pb data not yet quantitatively understood theoretically. Will teach us new things mostly about the fluctuating internal structure of the proton at high energies.

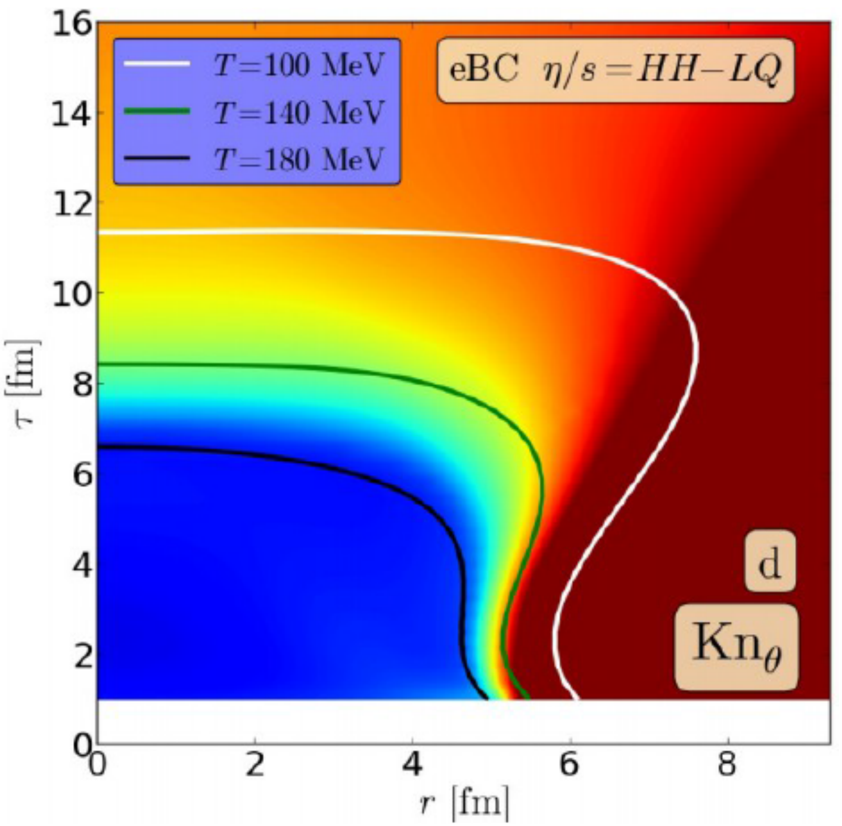
# Validity of viscous hydro: Knudsen number check

Niemi & Denicol, arXiv:1404.7327

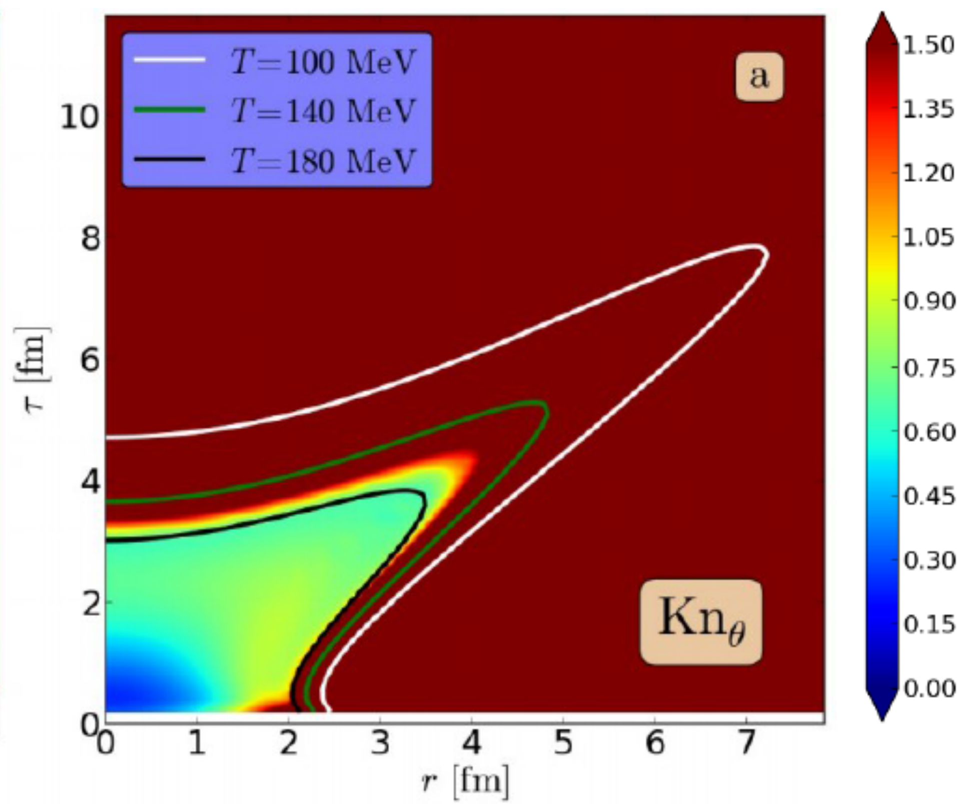
$$Kn = \tau_{micro}\,\theta = \tau_{micro}/\tau_{macro}$$




**Pb+Pb**




**p+Pb**

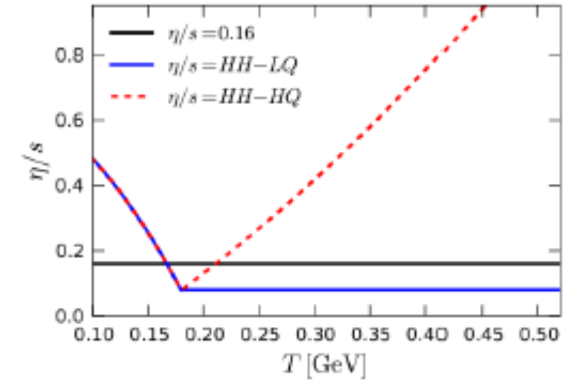



Predicts freeze-out at higher temperature in p+Pb than in Pb+Pb

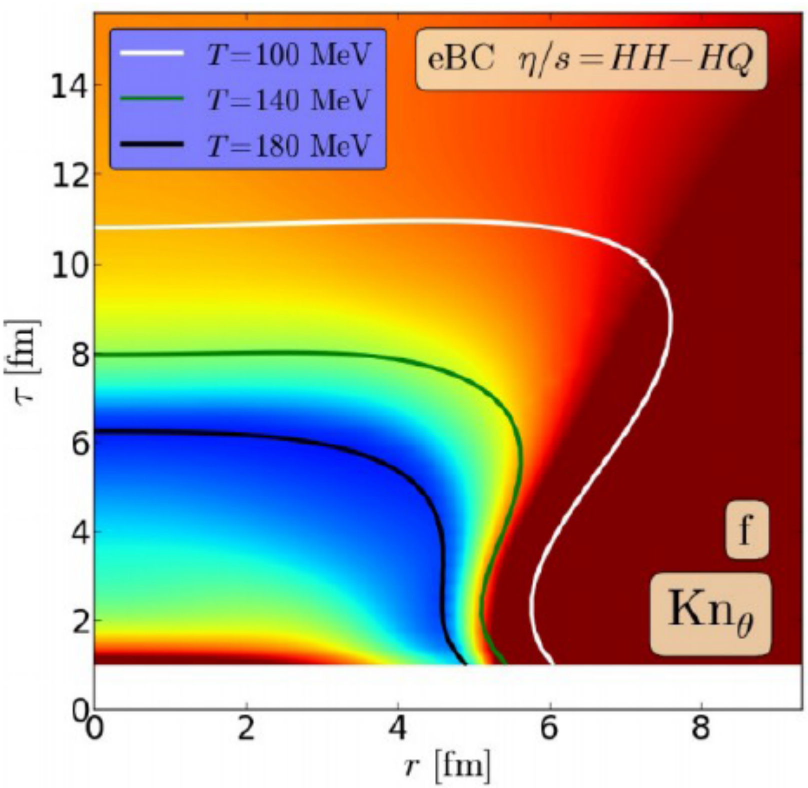
# Validity of viscous hydro: Knudsen number check

Niemi & Denicol, arXiv:1404.7327

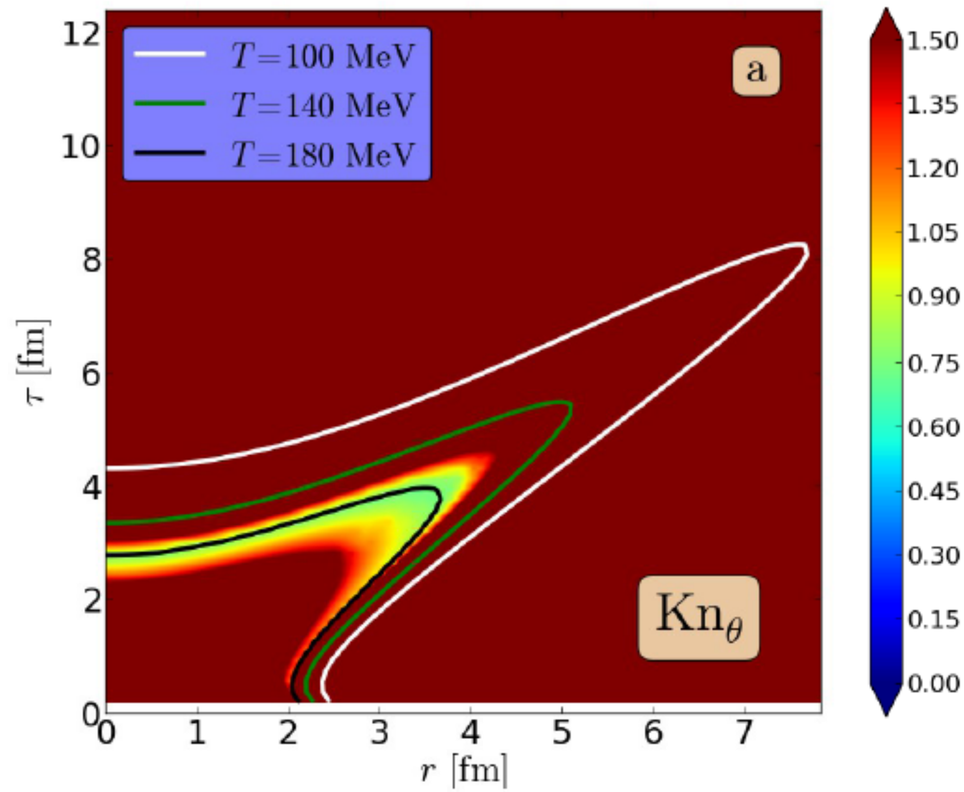
$$Kn = \tau_{micro}\,\theta = \tau_{micro}/\tau_{macro}$$




**Pb+Pb**




**p+Pb**




A strong increase above $T_c$ of $(\eta/s)(T)$ basically invalidates hydro for p+Pb at the LHC!

# Anisotropic hydrodynamics

## Viscous hydrodynamics expansion

$$f(\tau, \mathbf{x}, \mathbf{p}) = \underbrace{f_{\rm eq}(\mathbf{p}, T(\tau, \mathbf{x}))} + \delta f_1 + \delta f_2 + \cdots$$

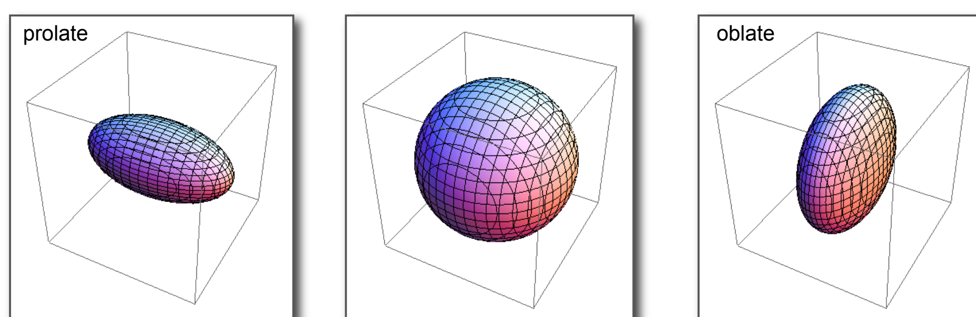
Isotropic in momentum space

## Anisotropic hydrodynamics (vaHydro) expansion

(Strickland, Martinez, Bazow, Heinz, …)

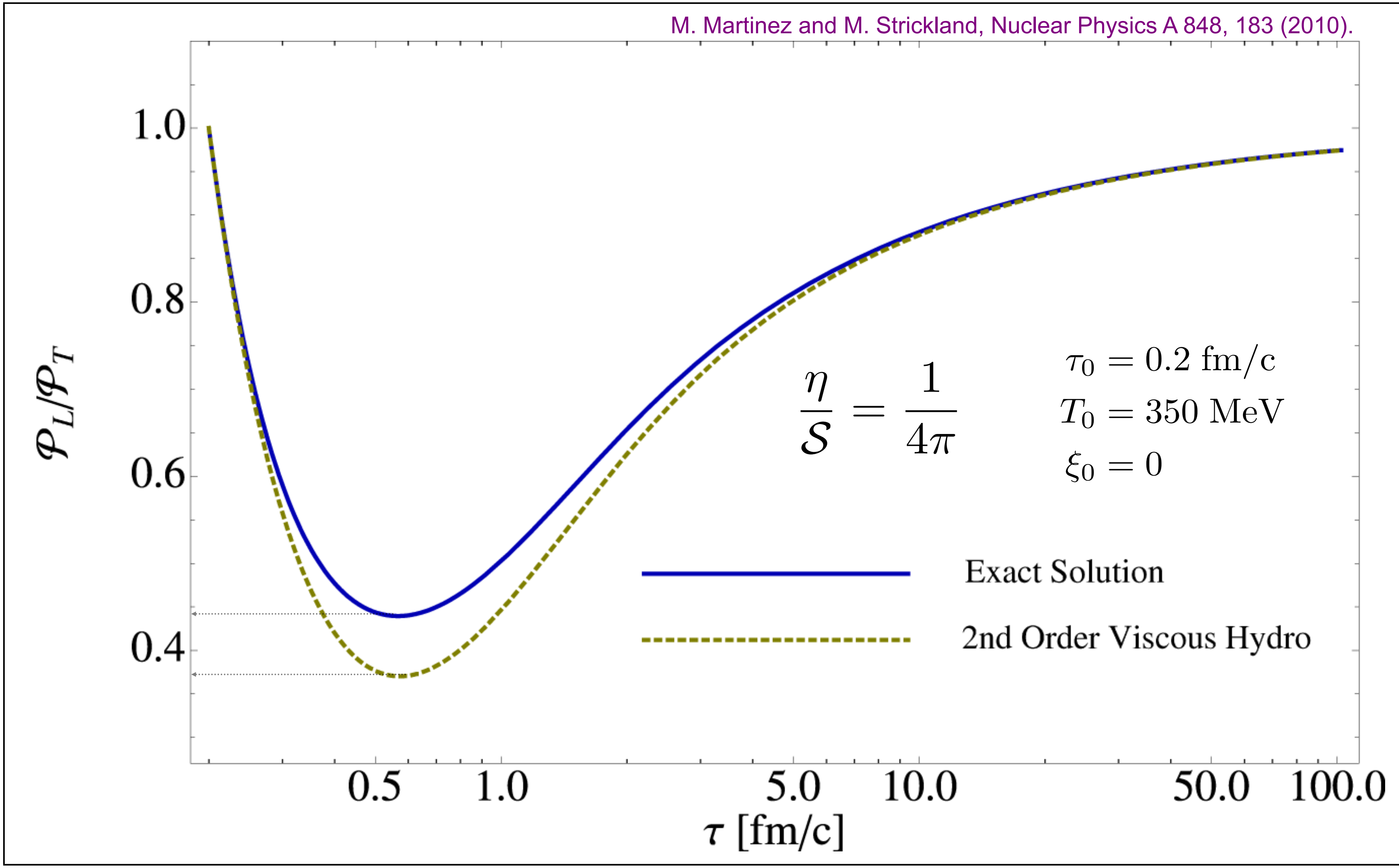
$$f(\tau, \mathbf{x}, \mathbf{p}) = f_{\rm aniso}(\mathbf{p}, \underbrace{\Lambda(\tau, \mathbf{x})}_{T_\perp}, \underbrace{\xi(\tau, \mathbf{x})}_{\text{anisotropy}}) + \delta f_1' + \delta f_2' + \cdots$$

$$\xi = \frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} - 1$$

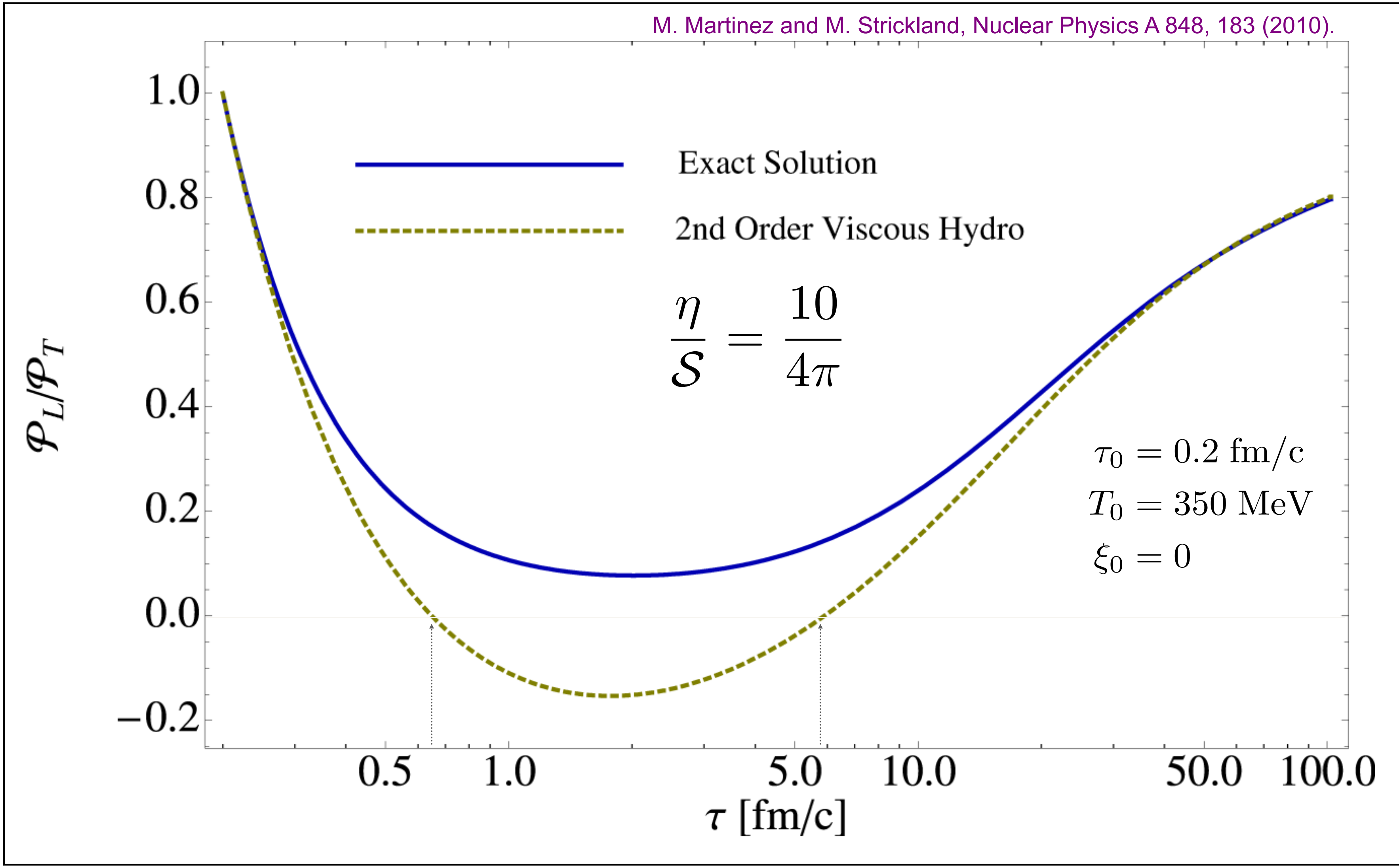



$-1 < \xi < 0$   $\xi = 0$   $\xi > 0$

# vHydro vs. aHydro: strong coupling



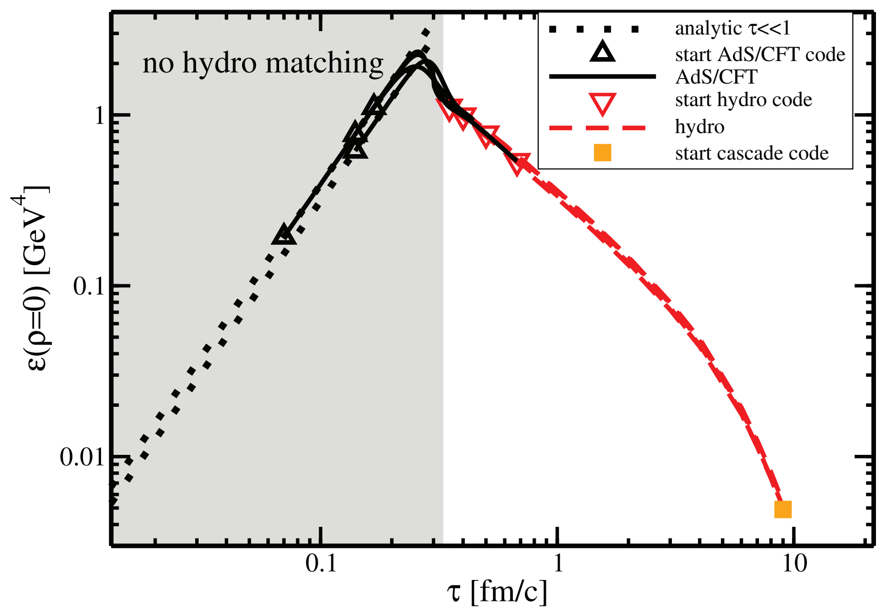
# vHydro vs. aHydro: weak coupling

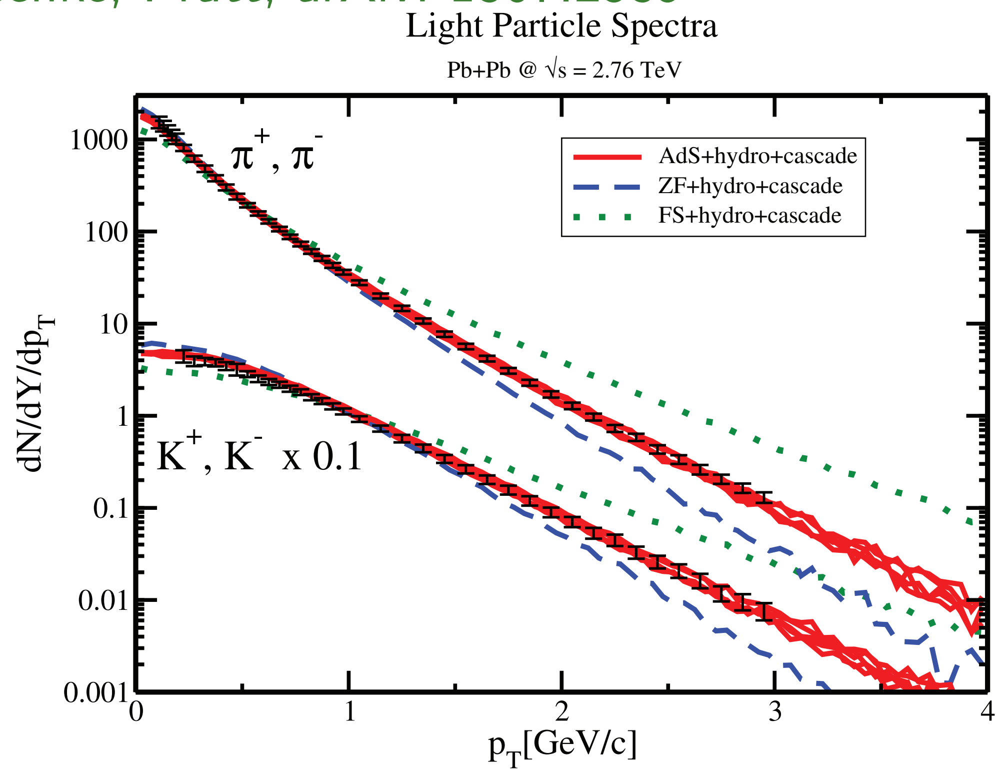


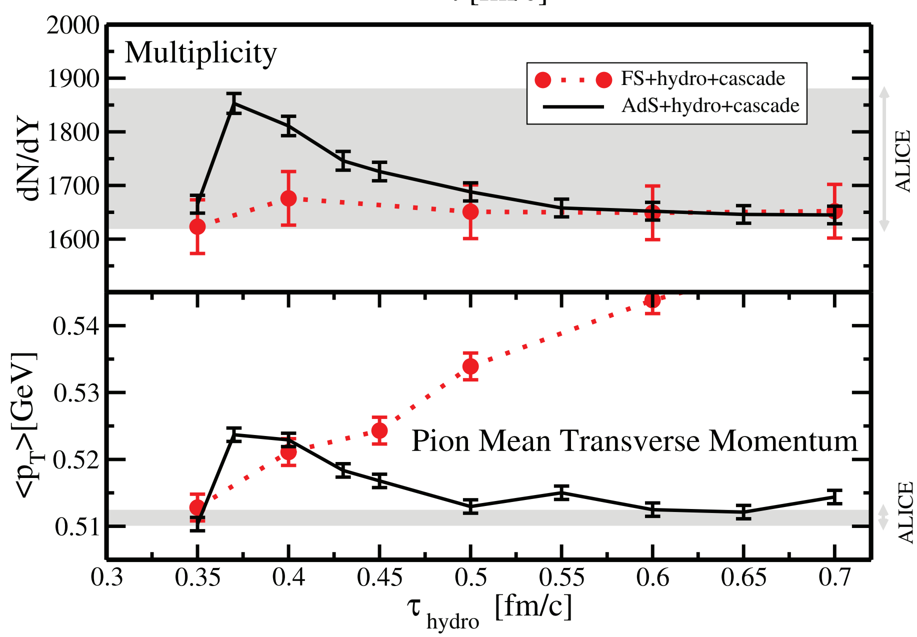

Test in (0+1)-d against exact soln. of Boltzmann equation: Improved hydrodynamic behavior at early times when anisotropic expansion drives system far away from local momentum isotropy

# Pre-equilibrium flow

van der Schee, Romatschke, Pratt, arXiv: 1307.2539




Pre-equilibrium flow significantly affects slope of single-particle $p_T$-spectra; radial flow is created earlier, leaving less room for radial push from final hadronic rescattering.

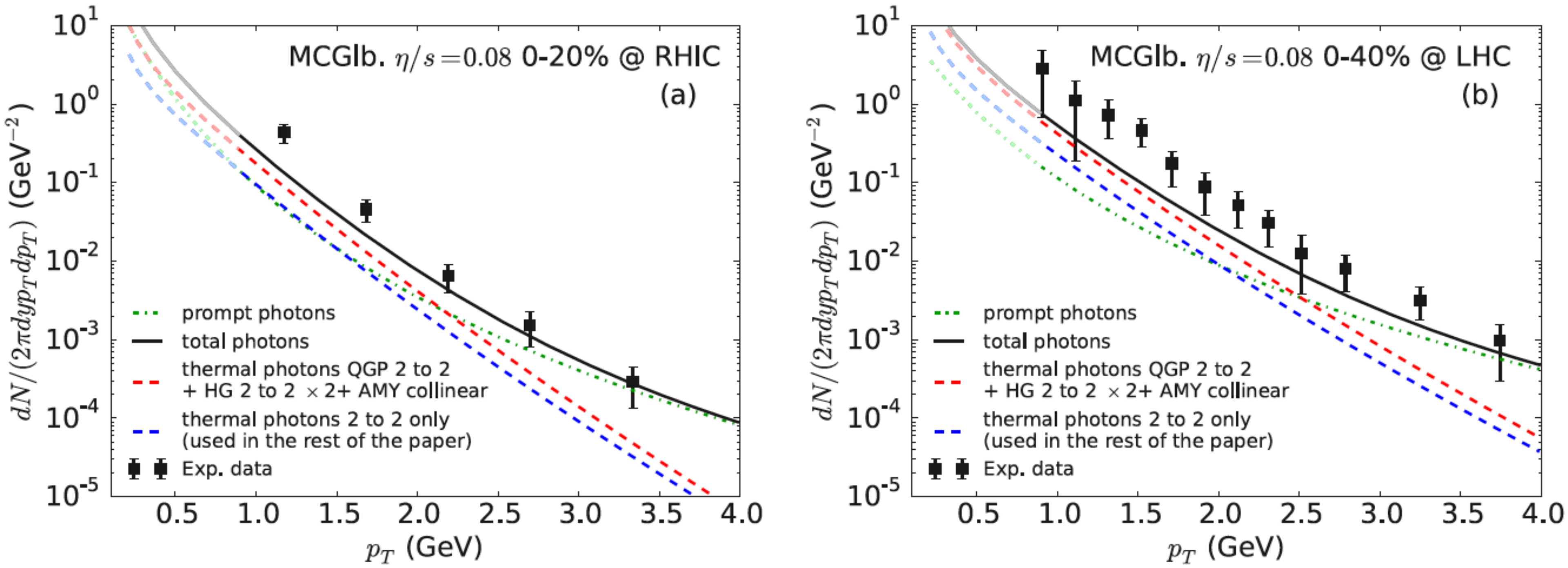
AdS/CFT leads to fast hydrodynamization; after 0.35 fm/$c$, final results are insensitive to switching time between pre-equilibrium and hydro-dynamics.

# Directly probing the dense fireball at earlier times:

# Electromagnetic radiation and quarkonium suppression

# Photon spectra from event-by-event viscous hydrodynamics

C. Shen et al. PRC 89 (2014) 044910




The photon yields at $p_T < 2$ GeV/c are seriously underpredicted (by a factor > 4)

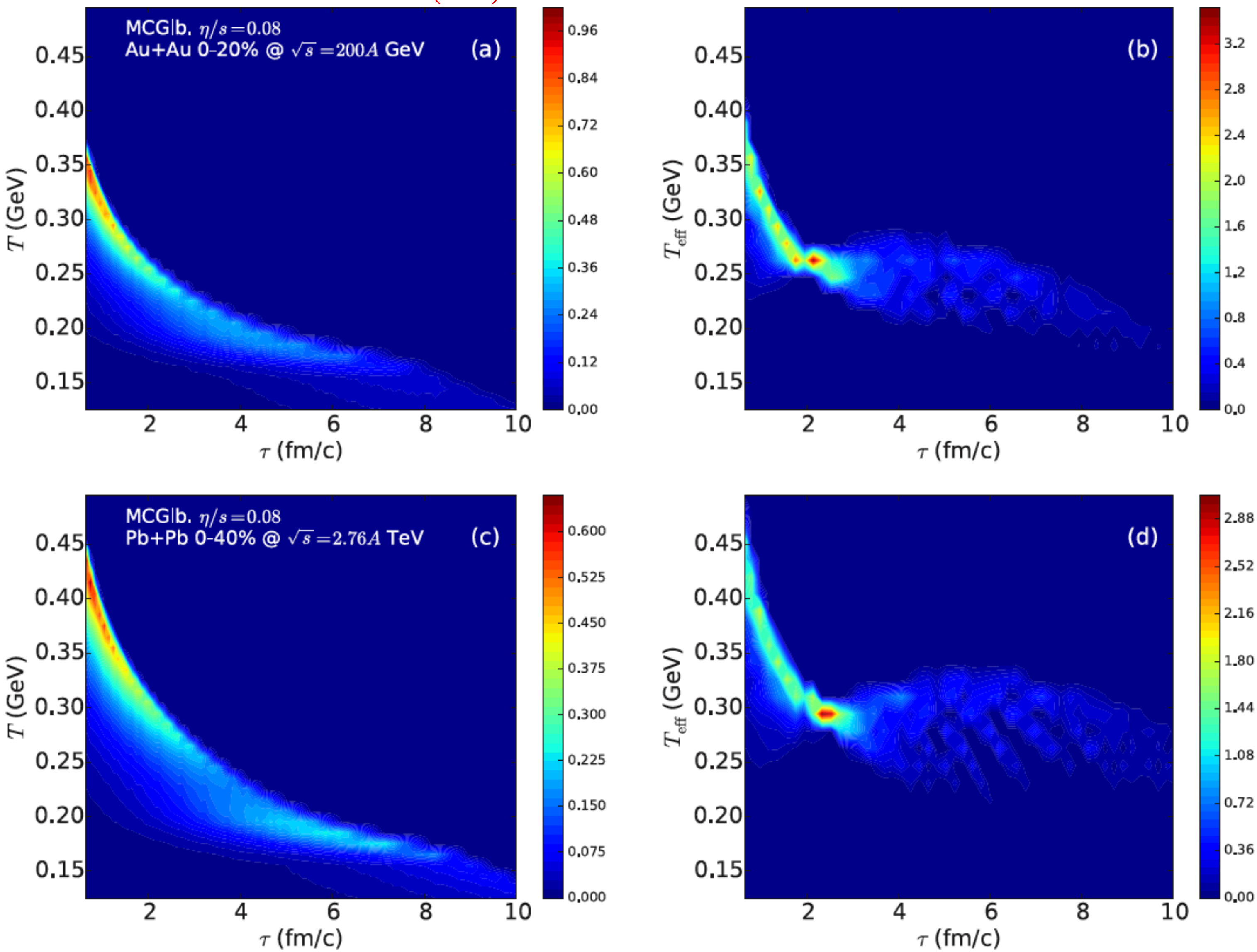
# Photon tomography of space-time and temperature evolution

$dN^{\gamma}/(dy\,d\tau\,dT_{(\mathrm{eff})})$

C. Shen et al., PRC 89 (2014) 044910

RHIC

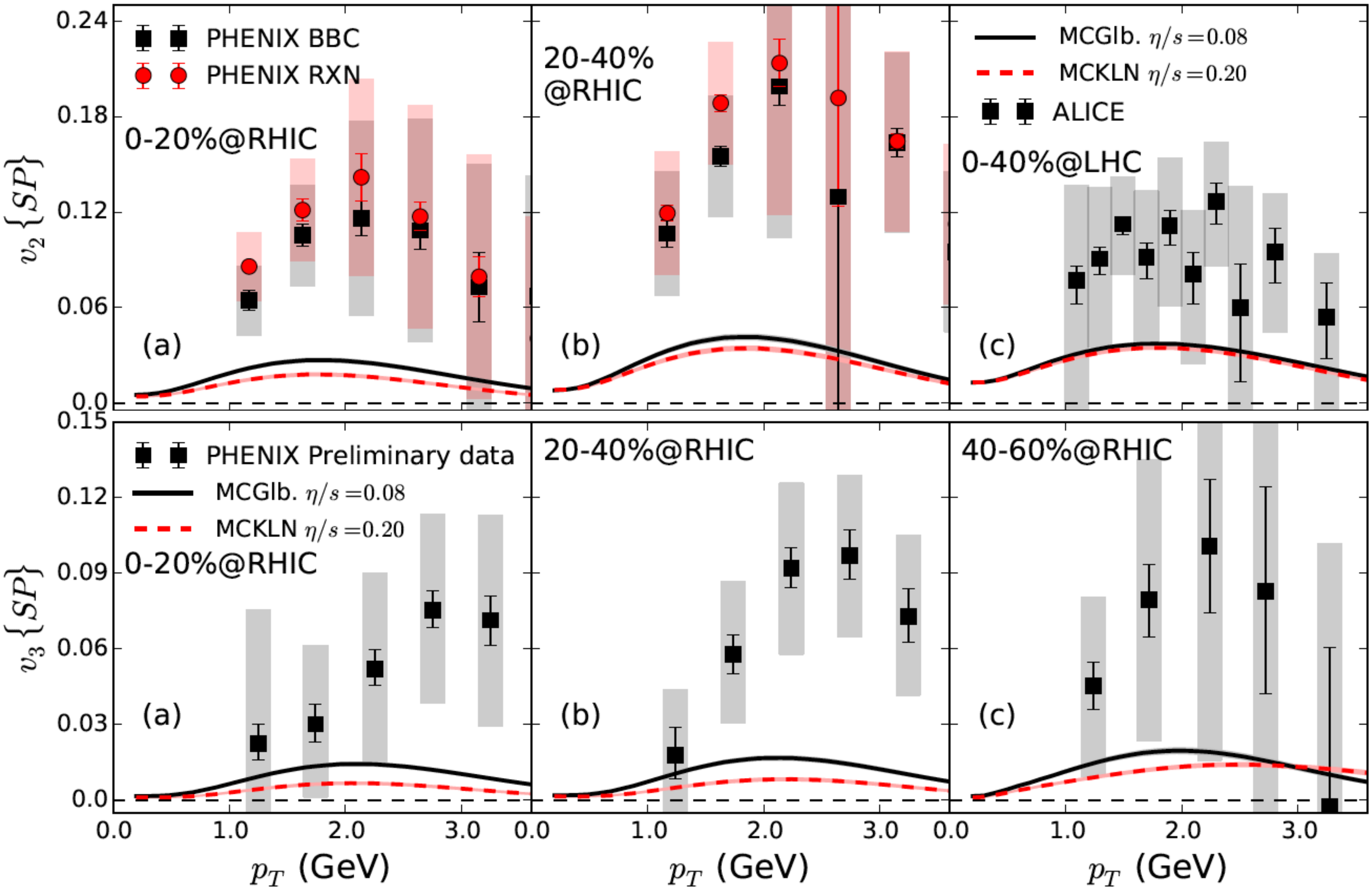
LHC




Two-wave emission pattern. Emission at later times and lower temperature strongly blue-shifted by radial flow, to "effective temperatures" around 230 MeV (RHIC) and 300 MeV (LHC) .

# Photon $v_2$ and $v_3$ from event-by-event viscous hydrodynamics

C. Shen et al., arXiv:1308.2111v3




The photon elliptic and triangular flows are also seriously underpredicted (by factors 2-4);

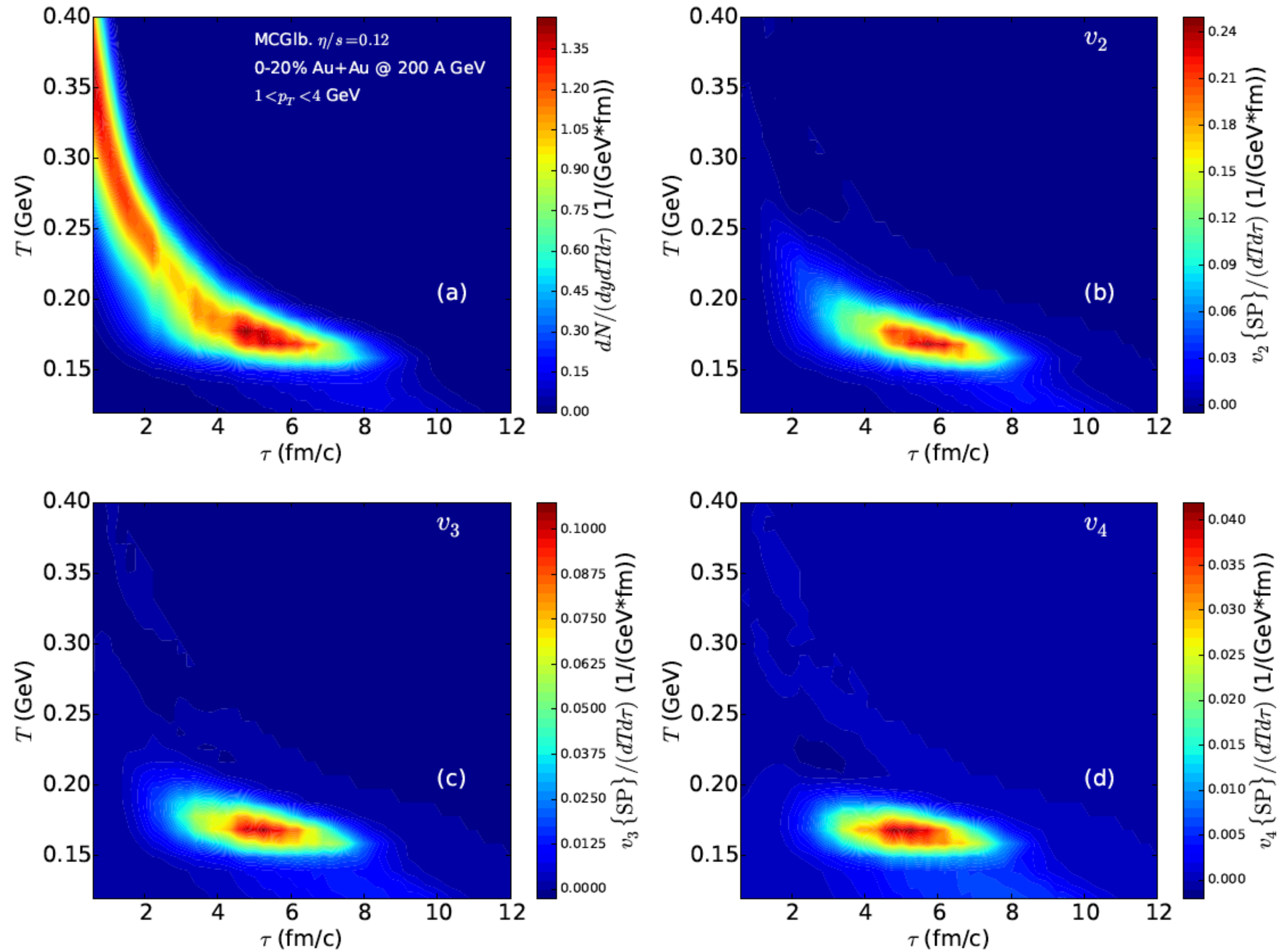
→ missing photon yield from relatively late times/low temperatures?

# Photon tomography of $v_n$ evolution in viscous hydrodynamics

C. Shen et al., arXiv:1308.2111v3

$$\frac{dN^{\gamma}}{dy\, d\tau\, dT}$$

$$\frac{dv_n^{\gamma}}{d\tau\, dT}$$

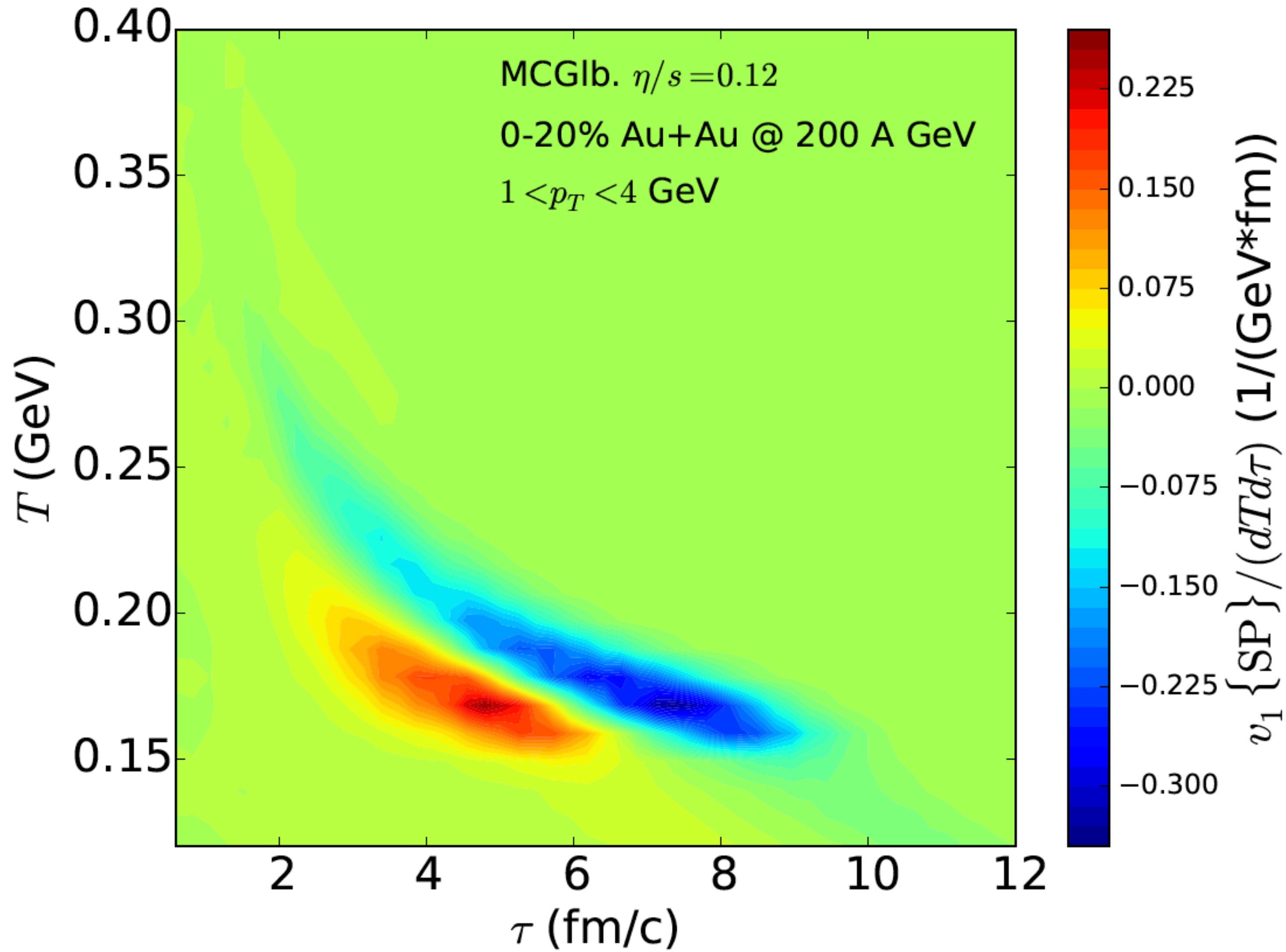



The largest contribution to photon $v_n$ (n=2-4) comes from the second emission wave, near $T_c$ !

# Photon tomography of $v_1$ evolution in viscous hydrodynamics

C. Shen et al., arXiv:1308.2111v3

$$\frac{dv_1^\gamma}{d\tau\, dT}$$

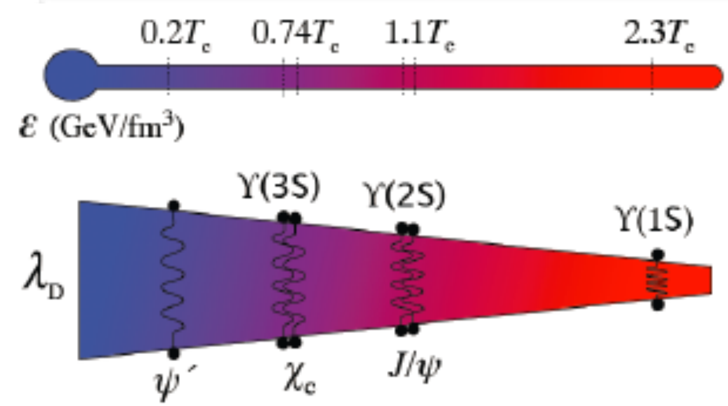



Photon directed flow flips sign in course of evolution! Photons emitted from regions that reach $T_c$ earlier have positive, those from regions that reach $T_c$ later have negative directed flow relative to charged hadrons.

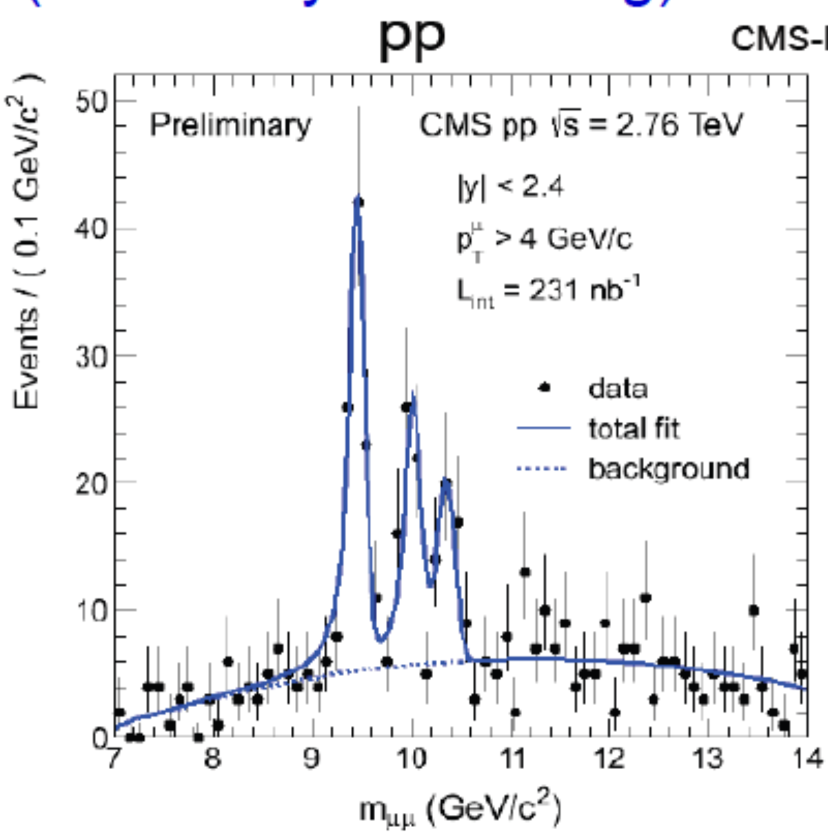
# A Calibrated Length Scale in the Plasma

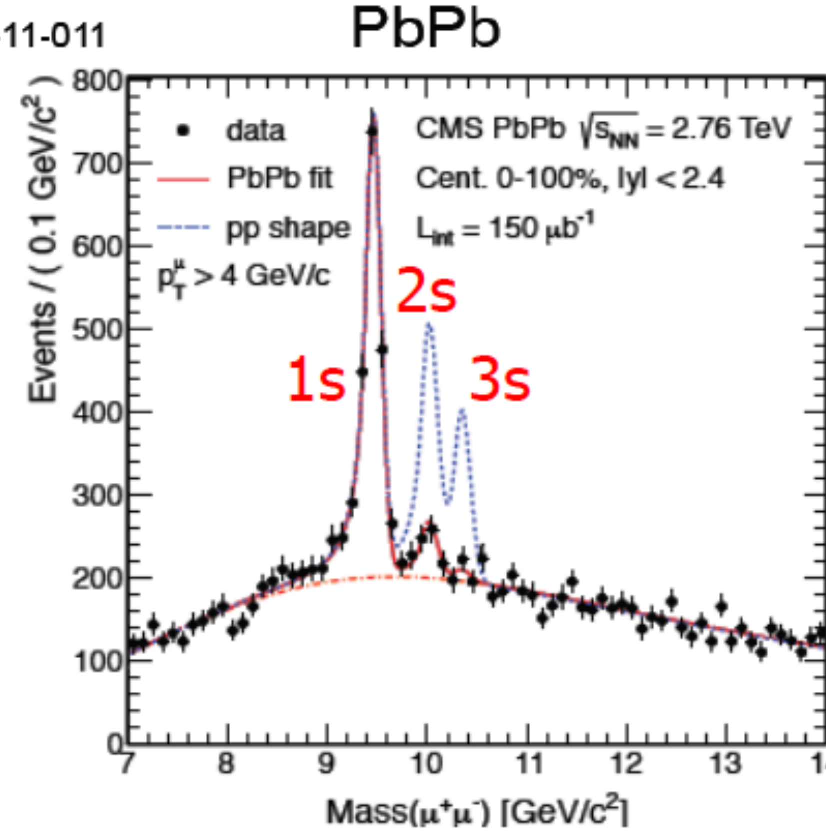


- Wide range of Bohr radii of quarkonium states:
  - Ψ' 0.88 fm → Υ(1s) 0.23 fm
- Should lead to sequential melting (from Debye screening)



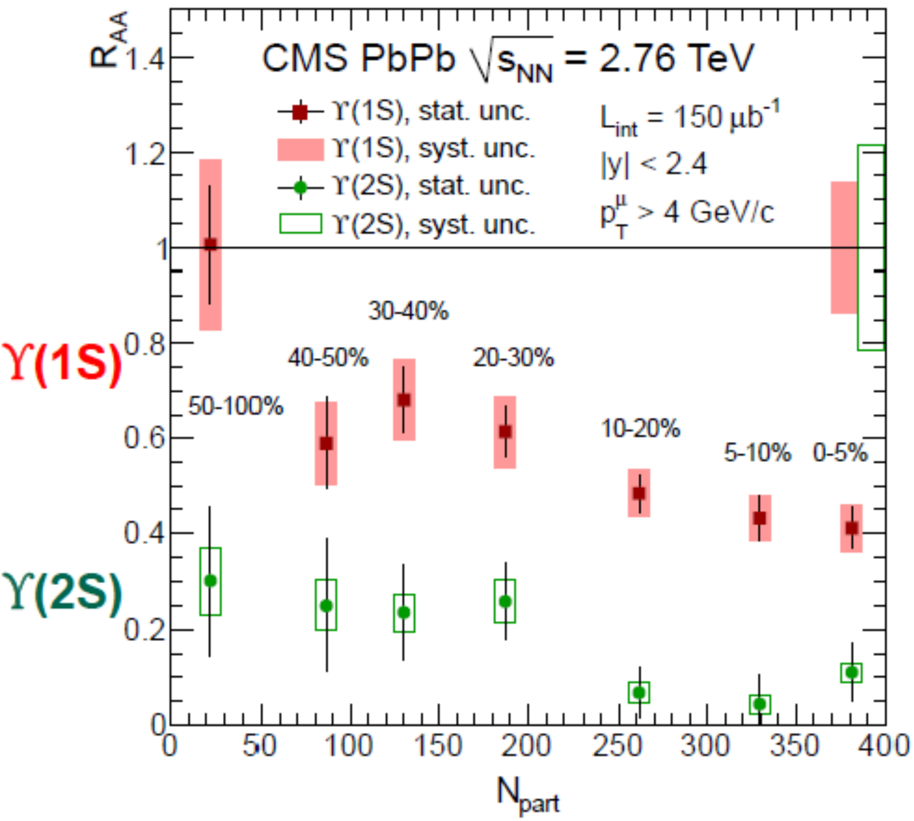

CMS-HIN-11-011

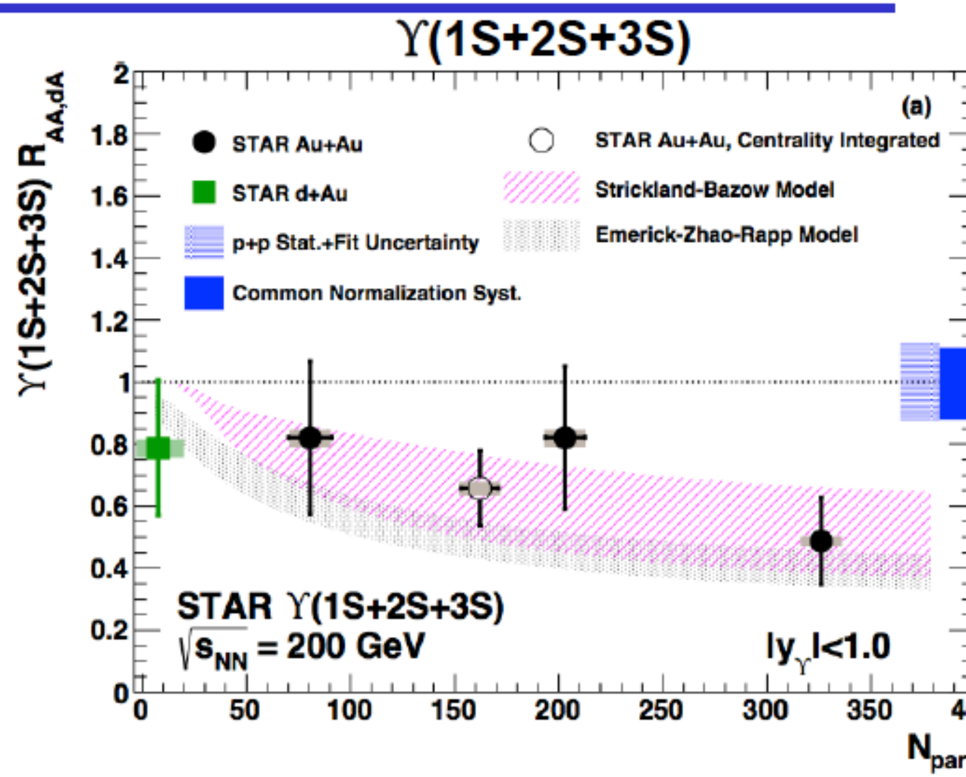



W. A. Zajc, QCD Town Meeting, Sep. 2014

# Sequential melting for different Υ



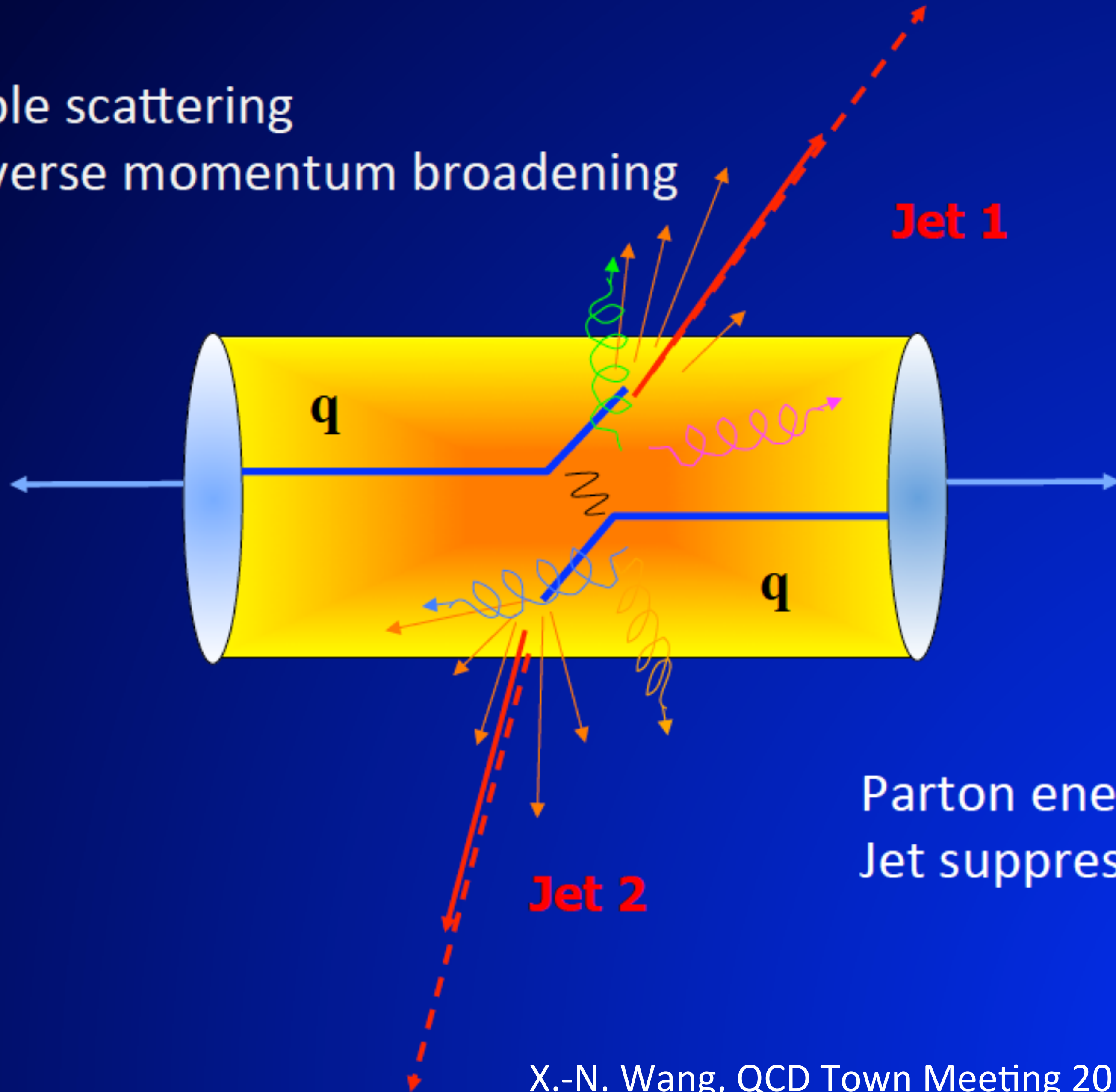

**Υ(1s) suppression magnitude consistent with excited states suppression.**
**Υ(2S) strongly suppressed, Υ(3S) completely melted.**

CMS: PRL109(2012)222301
STAR: PLB735(2014)127

# Probing the dense fireball at shorter length scales: Jets and heavy flavor

# Jets in heavy-ion collisions

Multiple scattering
Transverse momentum broadening




Parton energy loss
Jet suppression

X.-N. Wang, QCD Town Meeting 2014

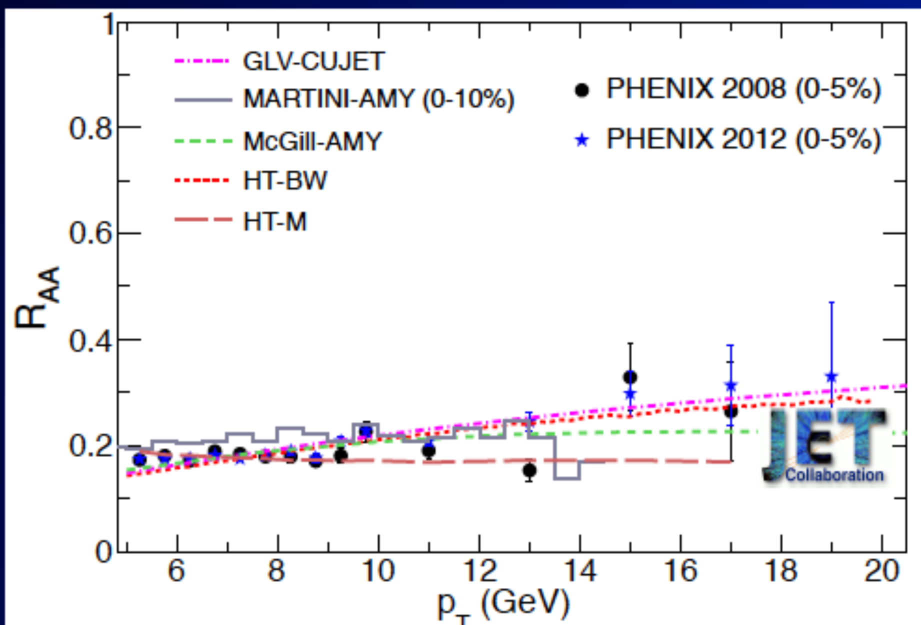
# What properties of QGP jets probe

- Space-time profile: $T_{\mu\nu}(x) : T(x), u(x)$
- EOS: $T_{\mu\nu} \Longleftrightarrow \epsilon, P, s, c_s^2 = \partial p / \partial \epsilon$
- Bulk transport: $\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt dx e^{i\omega t} \langle [T_{xy}(0), T_{xy}(x)] \rangle$
- EM response: $W_{\mu\nu}(q) = \int \frac{d^4x}{4\pi} e^{iq\cdot x} \langle j_\mu(0) j_\nu(x) \rangle$
- Jet transport: $\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{\sigma +}(0) F_\sigma^{\ +}(y) \rangle$
- … $\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{+-}(0) F_{+-}(y) \rangle$

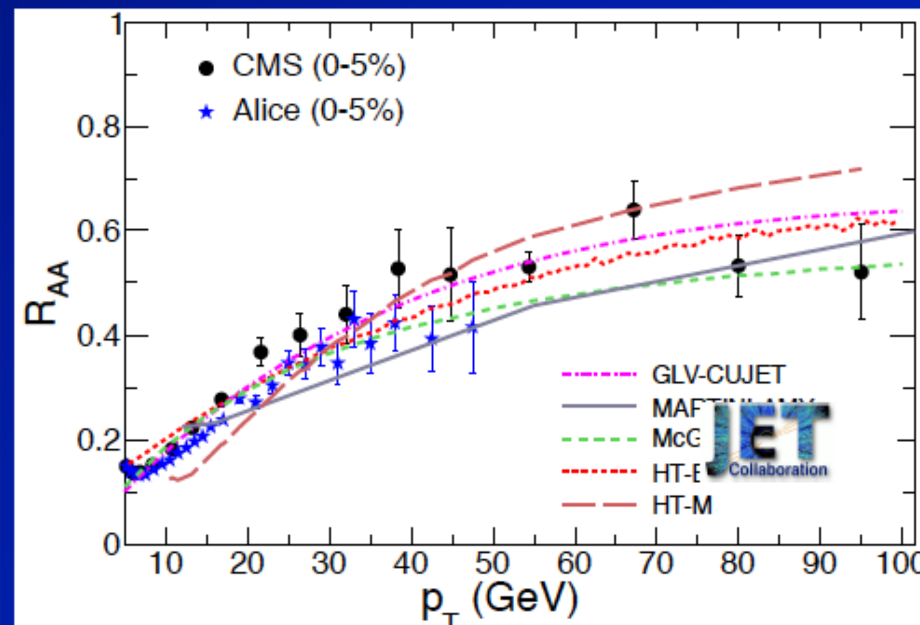
# Jet quenching phenomenology

Suppression of single hadron spectra at RHIC and LHC

Best $\chi^2$ fits with different model calculations :



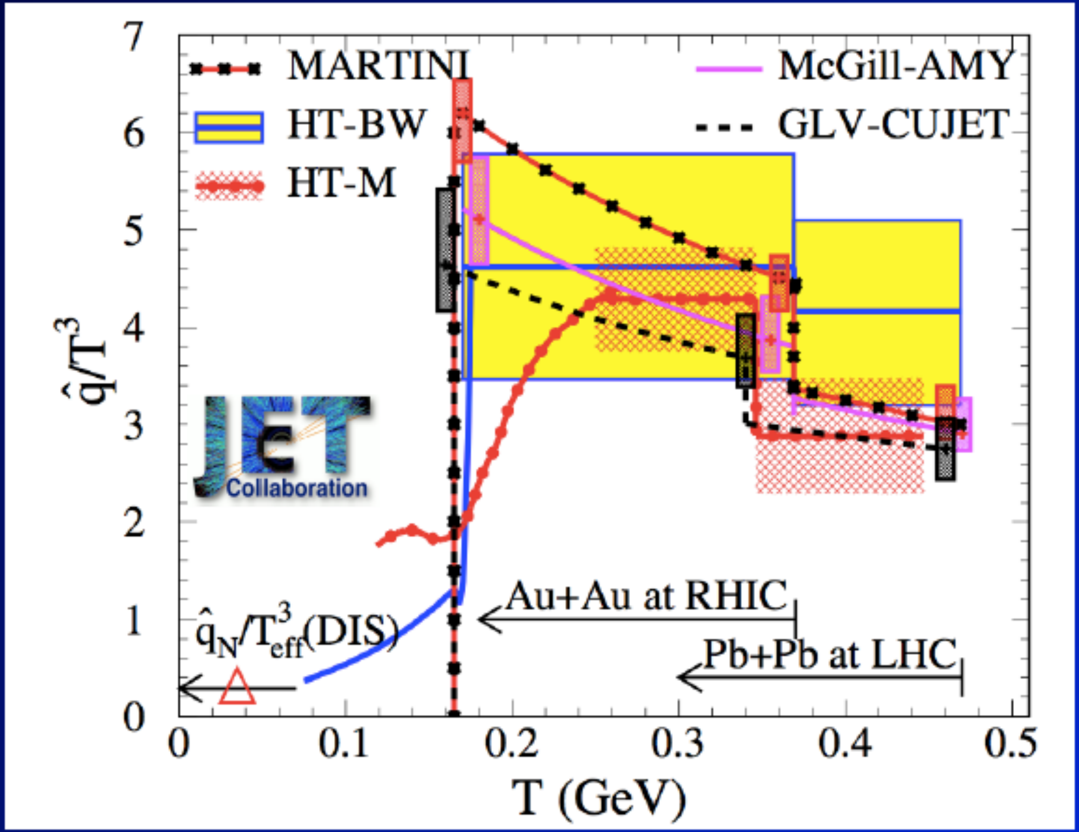

RHIC




LHC

# Jet transport coefficient

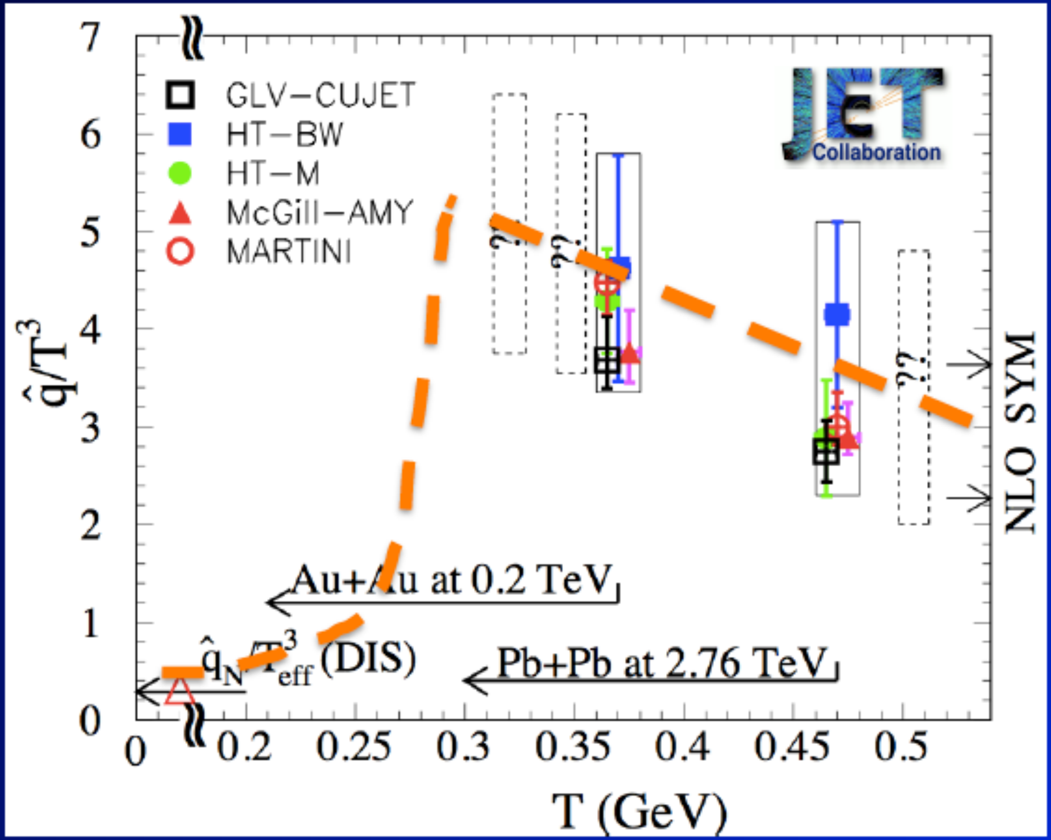
JET Collaboration: **arXiv:1312.5003**




$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{array}{l} \text{T=370 MeV, RHIC} \\ \text{T=470 MeV, LHC} \end{array}$$

# T-dependence of jet transport coefficient ?

JET Collaboration: arXiv:1312.5003




Majumder et al. (2007):

$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Scan over the initial T at RHIC and LHC higher energies

Reduction of uncertainties: dihadron, gamma-hadron, flavor dependence, anisotropy, jet observables

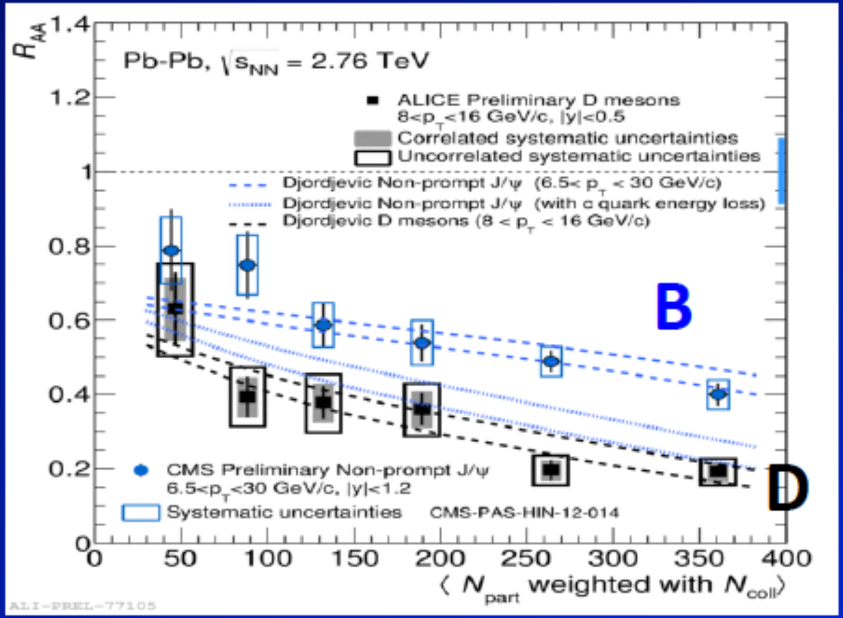
X.-N. Wang, QCD Town Meeting 2014

# Quasi-particles seen by heavy quarks

Mass effect: dead-cone in gluon radiation
(Dokshitzer & Kharzeev (2001)

$$\frac{dN_g}{d\ell_T^2} \sim \frac{\alpha_s}{\ell_T^2} \to \frac{\alpha_s \ell_T^2}{(\ell_T^2 + z^2 M^2)^2}$$

Smaller radiative energy loss
(Should be similar to light quarks $p_T$>> M)



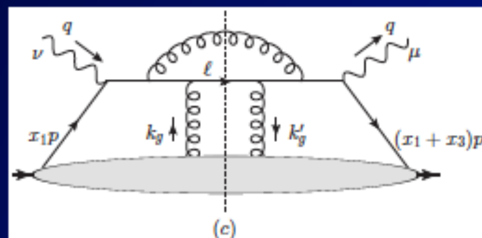

$$R^h_{AA} \approx R^D_{AA} < R^B_{AA}$$

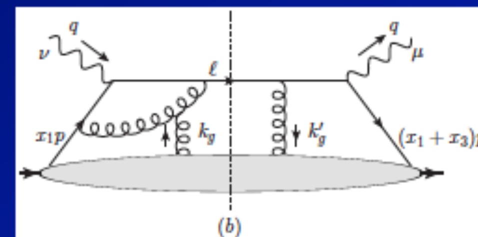
Detailed study of Interplay between elastic and radiative energy loss

$\hat{e}/\hat{q}$ → Properties of quasi-particles in QGP
(close to Tc and at highest T )

# NLO and Q-evolution of qhat

- Uncertainty in scale dependence of collinear LO results




- Cancellation of soft-collinear divergence
- Factorization of the collinear divergence

PRL 112, 102001(2014)

$$\frac{d\langle k_\perp^2 \sigma\rangle_{\rm NLO}}{dz_h} = \sigma_0 D_h(z,\mu_f^2) \otimes H_{\rm NLO}(x, x_B, Q^2, \mu_f^2) \otimes T_{qg}(x, x_1, x_2, \mu_f^2)$$

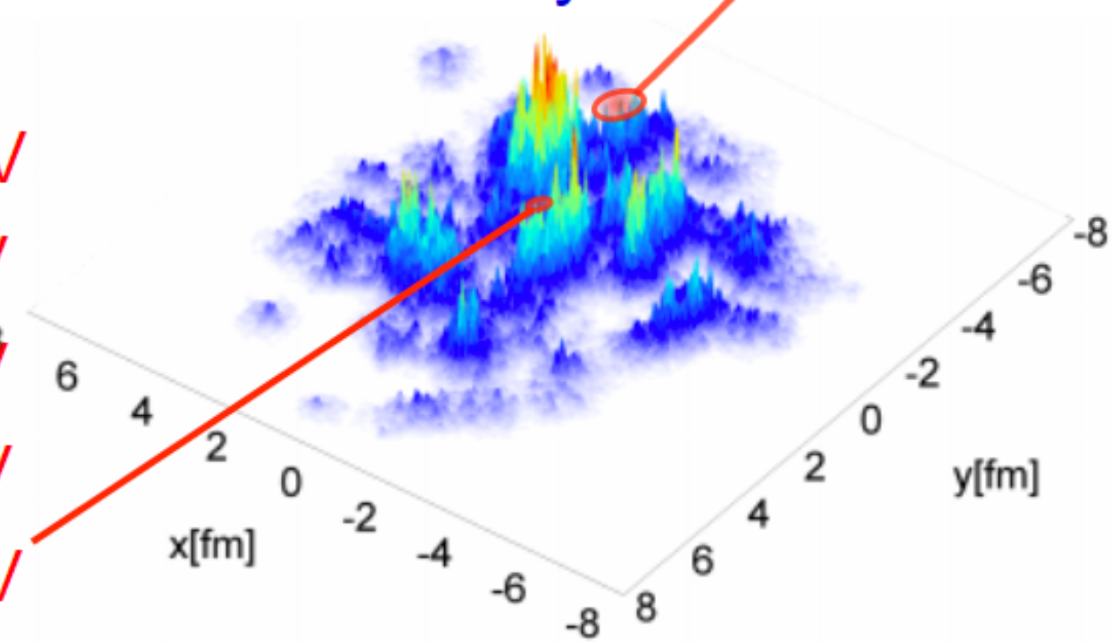
$$\frac{\partial}{\partial \ln \mu_f^2} T_{qg}(x_B, 0, 0, \mu_f^2) = \frac{\alpha_s}{2\pi}\int_{x_B}^{1} \frac{dx}{x}\left[\mathcal{P}_{qg\to qg} \otimes T_{qg} + P_{qg}(\hat{x}) T_{gg}(x, 0, 0, \mu_f^2)\right].$$

$$\hat{q} \Longrightarrow \hat{q}(E, Q^2)$$

Structure of the medium at different scales

# Plasma diagnostics at different length scales

- Needed: Tools to interrogate QGP at small distances
- Intrinsic scales of the QGP:
  - T ~ 200 MeV
  - gT ~ 500 MeV ~ gluon effective mass
- Hard processes provide a wide variety of perturbative scales:
  - $M_c$ ~ 1.3 GeV
  - $M_b$ ~ 4.2 GeV
  - $M_W$ ~ 80 GeV
  - $M_Z$ ~ 90 GeV
  - Q ~ 10-300 GeV




W. A. Zajc, QCD Town Meeting, Sep. 2014

# Summary

- We have a successful standard dynamical framework for heavy-ion collisions, which is being improved continuously (pre-equilibrium flow, anisotropic viscous hydro, baryon number transport, etc.). Now we must turn it into the "Little Bang Standard Model", by determining its parameters phenomenologically. New sophisticated tools to perform such a quantitative model/data comparison, determining a substantial number of parameters simultaneously from comprehensive sets of experimental data, are being developed and show first fruit.
- We now know the QGP shear viscosity $\eta/s$ with about 50% precision, aiming for 10%:

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

  There are indications that it depends on temperature and rises weakly above $T_c$ and strongly below $T_c$. To make further progress, we must perform additional measurements to fully constrain the spectrum of quantum fluctuations of the gluon fields in the initial state, and on the theory side include effects from bulk viscosity.
- We now know one of the jet transport parameters, $\hat{q}/T^3 = (d\langle p_T^2\rangle/dL)/T^3$, to within about a factor 3. To make further progress, we are developing tools to describe the evolution of fully reconstructed jets in the evolving medium. To access the resolution dependence of $\hat{q}$ and other hard probes, the theories of energy loss and jet modifications must be improved to NLO accuracy.
- We have made much progress, conceptually and quantitatively, on using direct photons for electromagnetic tomography of the Little Bang. To resolve the photon flow puzzle, we need to find additional sources of photons in the critical region near $T_c$ and below.
- Satisfactory answers to the compelling questions raised by the findings to date require the full flexibility of the combined LHC, RHIC and FAIR programs, to cover a broad range of energies and collision systems (including small ones at high energies).

# Thank you!

# Thank you!

# Thank you!