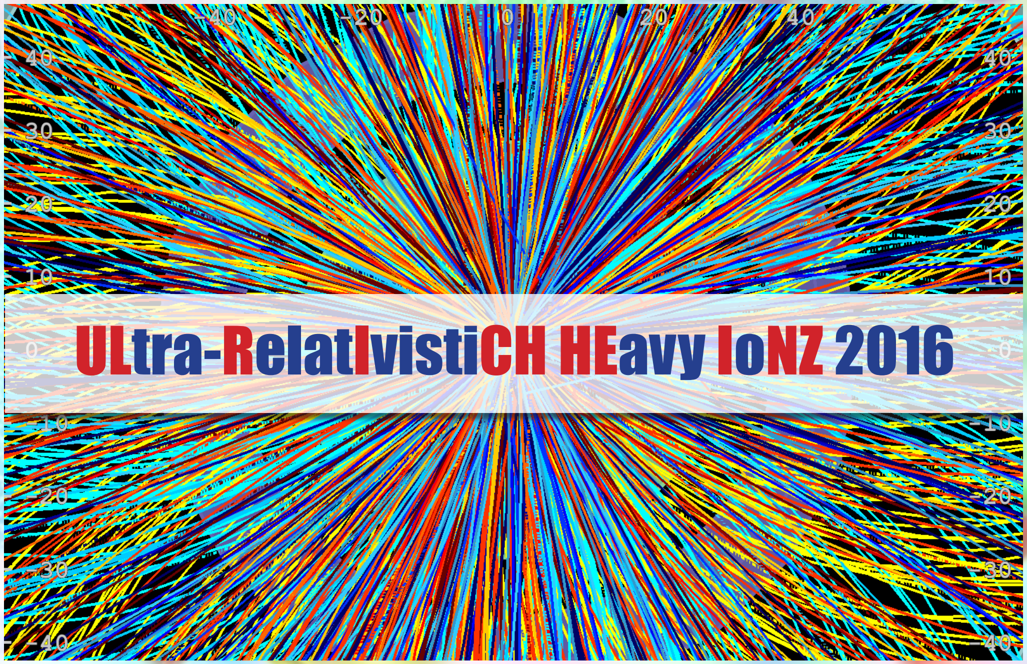
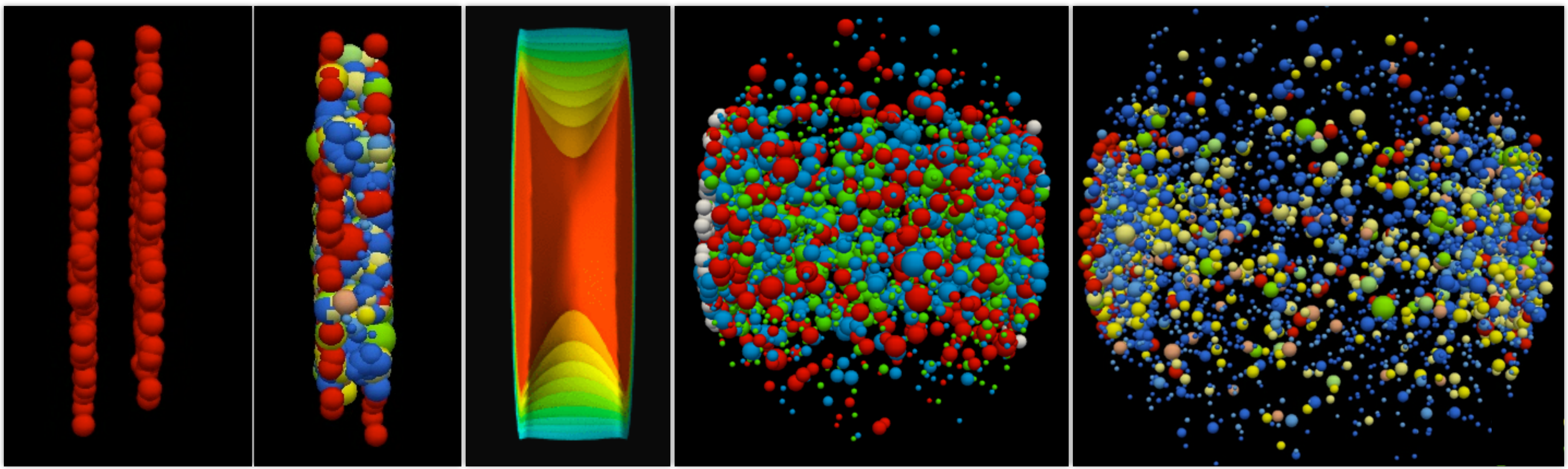
Hydrodynamics & Penetrating Radiation: Peering beyond freeze-out



Charles Gale
McGill University

[Image: physics.org]

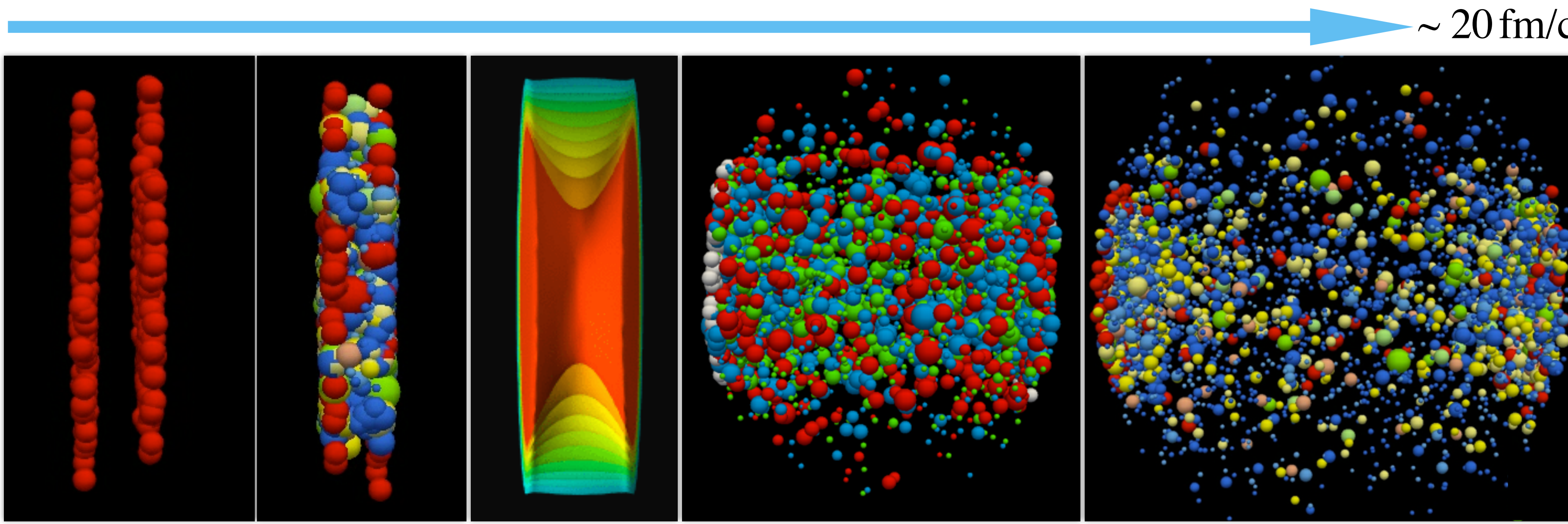
Relativistic nuclear collisions: The emergence of a "standard picture"



Initial state | Pre-equilibrium | QGP | Hadronization | Thermal freeze-out

Glasma

Relativistic nuclear collisions: The emergence of a "standard picture"



Initial state | Pre-equilibrium | QGP | Hadronization | Thermal freeze-out

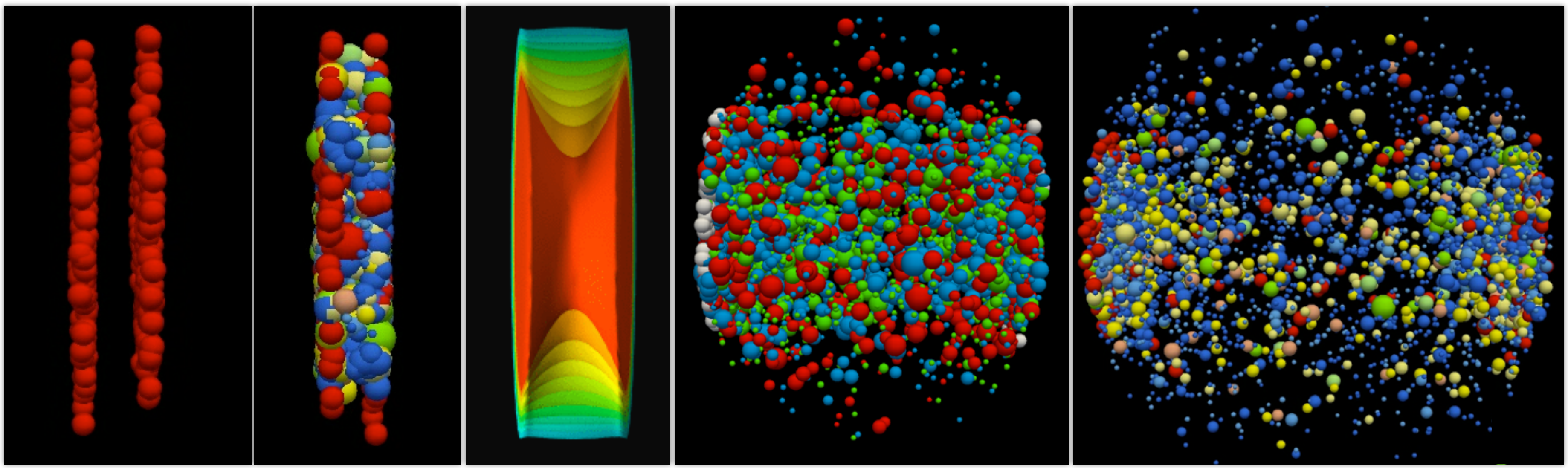
Glasma

ULtra-RelatIvistiCH HEavy IoNZ 2016

Charles Gale
McGill

Relativistic nuclear collisions: The emergence of a “standard picture”

~ 20 fm/c



Initial state

Pre-equilibrium

Glasma

QGP

Hadronization

Thermal freeze-out

Relativistic hydrodynamics

The success of fluid dynamics modelling at RHIC and at the LHC: The existence of collectivity

- Viscous relativistic fluid dynamics

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + T^{\mu\nu}_{\text{diss}}; \qquad T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}; \;\; T^{\mu\nu}_{\text{diss}} = \pi^{\mu\nu} - \Delta^{\mu\nu}\Pi$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

- To first order in the velocity gradient: Navier-Stokes
- To second order:

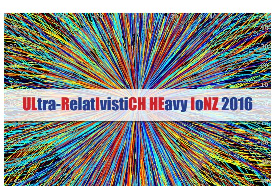
$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

Israël & Stewart, Ann. Phys. (1979);
Baier et al., JHEP (2008);
G. S. Denicol et al., PRD (2012);
G. S. Denicol et al., PRC (2014);
Jeon & Heinz, Int. J. Mod. Phys. E (2015)

η, ζ shear and bulk viscosities

- Resistance to deformation, and to volume expansion
- A fundamental property of QCD



Charles Gale
McGill

Matter behaves collectively. Is it in thermal equilibrium? Calculating transport coefficients

- Kubo relation:

$$\eta = \frac{1}{20} \lim_{\omega \to 0} \frac{1}{\omega} \int d^4 x \, e^{i\omega t} \langle [S^{ij}(t,\vec{x}), S^{ij}(0,\vec{0})] \rangle \theta(t)$$

$$S^{ij} = T^{ij} - \delta^{ij} P$$

For finite-temperature QCD, can be calculated

- Perturbatively:

  Arnold, Moore, Yaffe JHEP (2000, 2003)

- On the lattice:

  H. B. Meyer PRD(2007); (2009)
  Sakai, Nakamura LAT2007

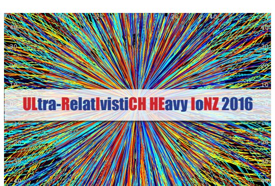
- Using FRG techniques

  Haas, Fister, Pawlowski PRD (2014)
  Christiansen et al., PRL (2015)

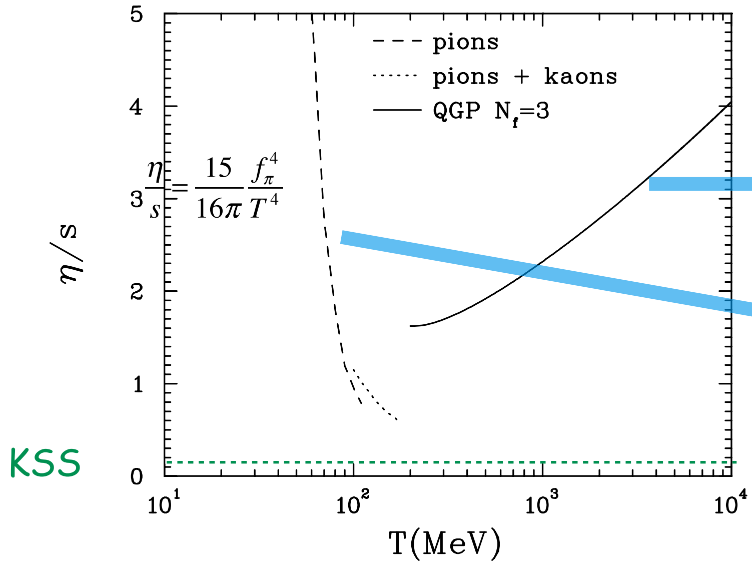
- Using strong-coupling AdS/CFT techniques:

$$\eta / s \geq \frac{1}{4\pi}$$

  Policastro, Son, Starinets PRL(2001)
  Kovtun, Son, Starinets (KSS) PRL(2003)



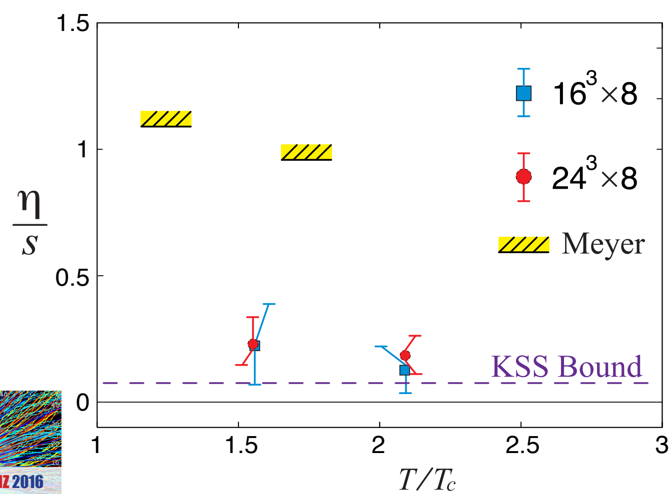
Calculating transport coefficients, II



Arnold, Moore, Yaffe JHEP (2003)

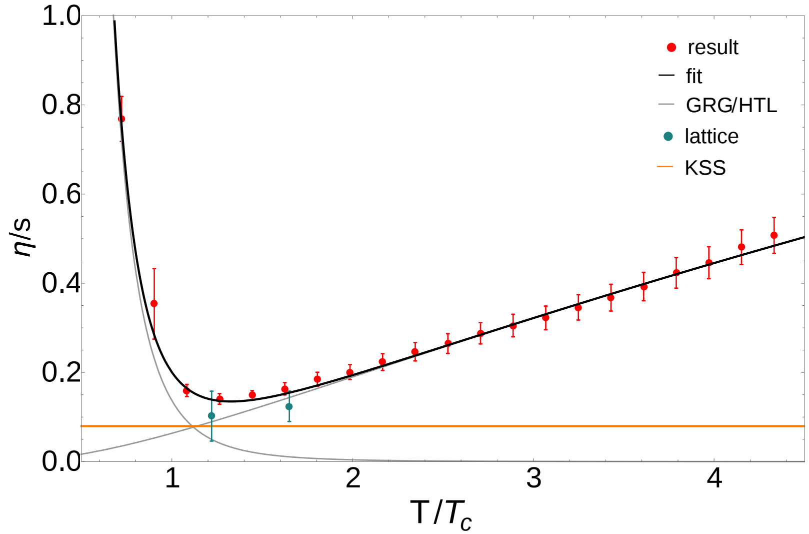
Prakash, Prakash, Venugopalan, Welke
Phys. Rep. (1993)

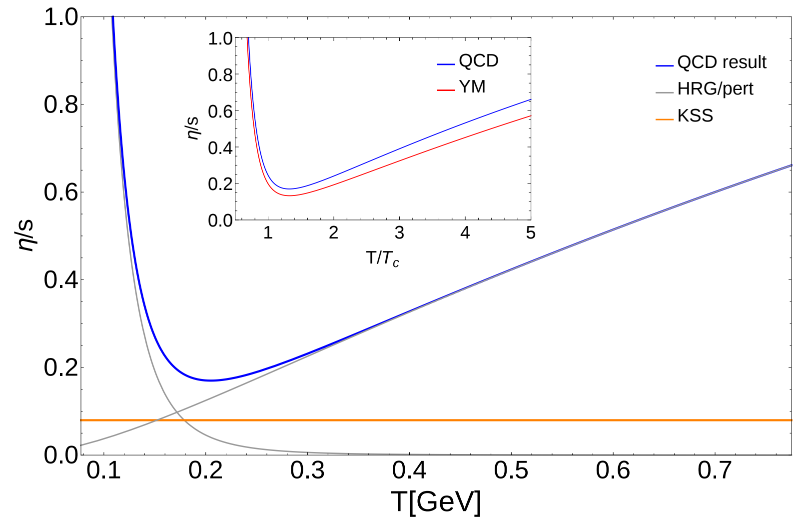
Csernai, Kapusta, McLerran PRL (2006)



Sakai, Nakamura LAT2007

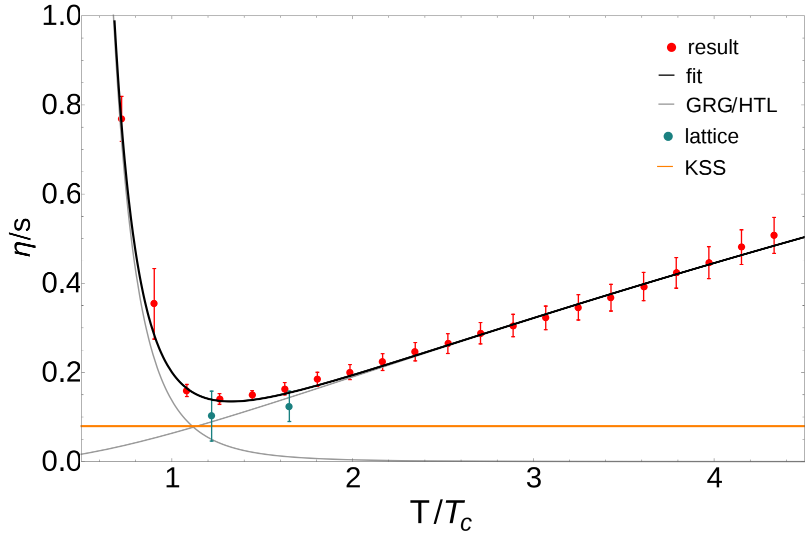
Calculating transport coefficients, III

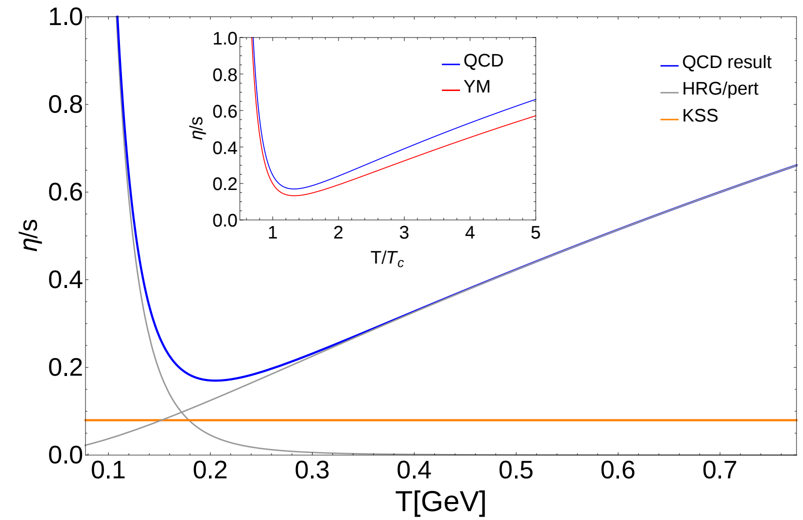




Christiansen, Haas, Pawlowski, Strodthoff PRL (2015)

Calculating transport coefficients, III





Christiansen, Haas, Pawlowski, Strodthoff PRL (2015)

- Constraints set by calculations not yet stringent
- Treat the transport coefficients as the parameters of a long-wavelength effective theory (fluid dynamics)
- Fix them by looking at data with relativistic hydro

Assessing collectivity with the differential single-particle spectrum

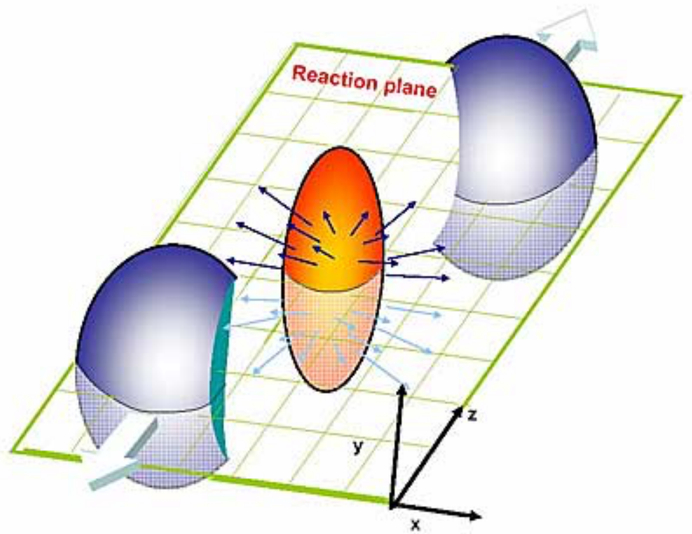
Quantifying the azimuthal asymmetries

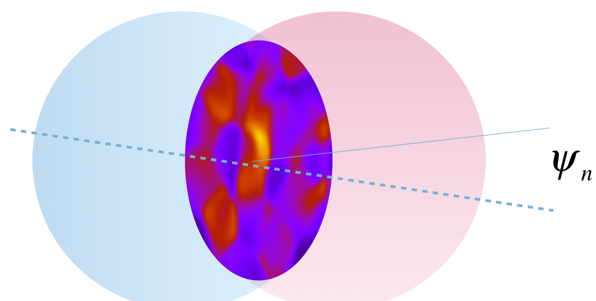
$$\frac{d^3N}{dyd^2p_T} = \frac{1}{\pi}\frac{d^2N}{dydp_T^2}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos n(\phi - \psi_n)\right]$$

v_1 = Directed flow

v_2 = Elliptic flow

v_3 = Triangular flow





$$(\epsilon + P)\frac{\partial \vec{v}}{\partial t} = -\vec{\nabla}P$$

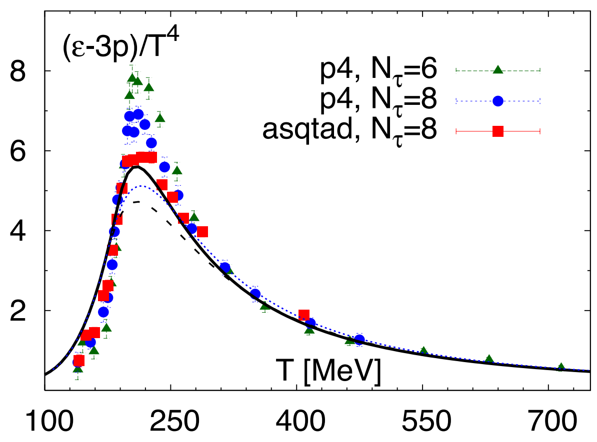
$$\nabla P(\Leftrightarrow) > \nabla P(\Updownarrow)$$

Anisotropies in coordinate space generate those in momentum space

ULtra-RelatIvistiCH HEavy IoNZ 2016

Charles Gale
McGill

Much work has been done studying the effects of shear viscosity. What about bulk?



Huovinen and Petreczky, Nucl. Phys. A (2010)

- For a non-conformal fluid, the bulk viscosity is not zero
- Around, and sightly above, T_c, the bulk viscosity will matter

Kharzeev, Tuchin PLB (2007); JHEP (2008)

$$T^{\mu\nu} = -Pg^{\mu\nu} + \omega u^{\mu} u^{\nu} + \Delta T^{\mu\nu}$$

The dissipative terms, to second order: $\Delta T^{\mu\nu} = \mathfrak{F}^{\mu\nu}[\eta, \zeta, \chi]$

- Some calculations now incorporate all of these

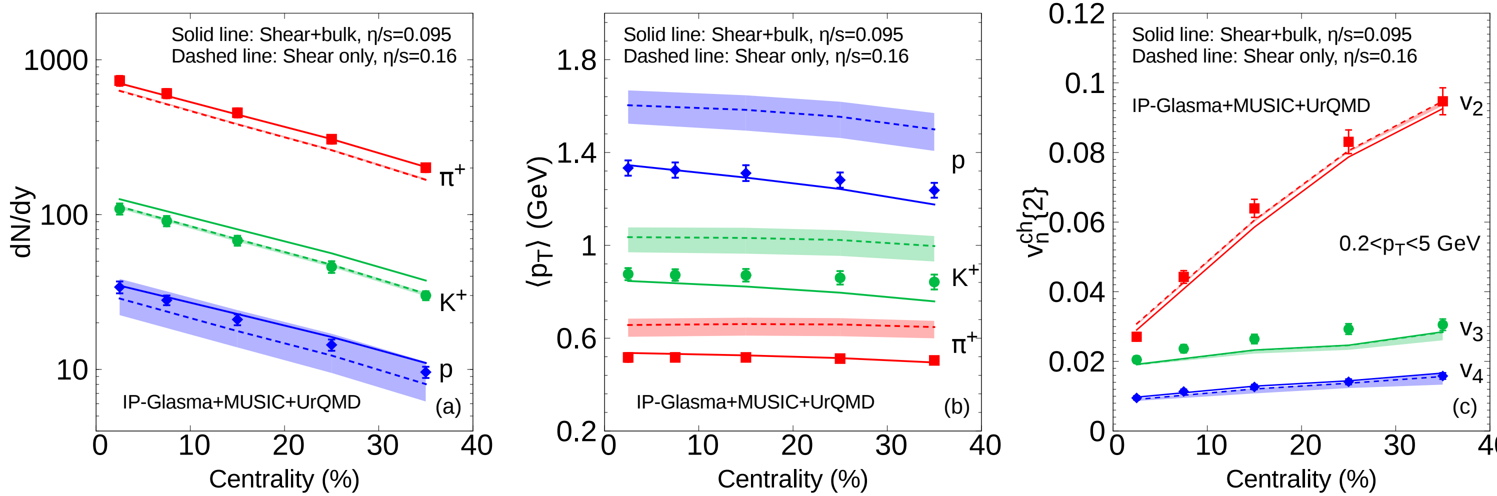
S. Ryu et al., PRL (2015); J. E. Bernhard et al., arXiv/1605.03954

- The hydro description is still very much in evolution

ULtra-RelatIvistiCH HEavy IoNZ 2016

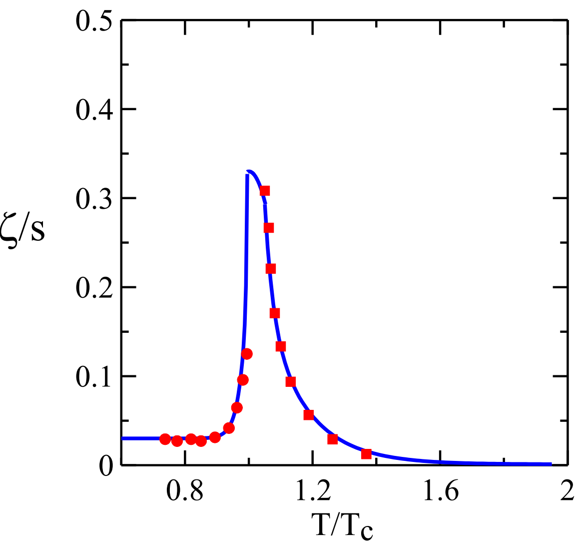
Charles Gale
McGill

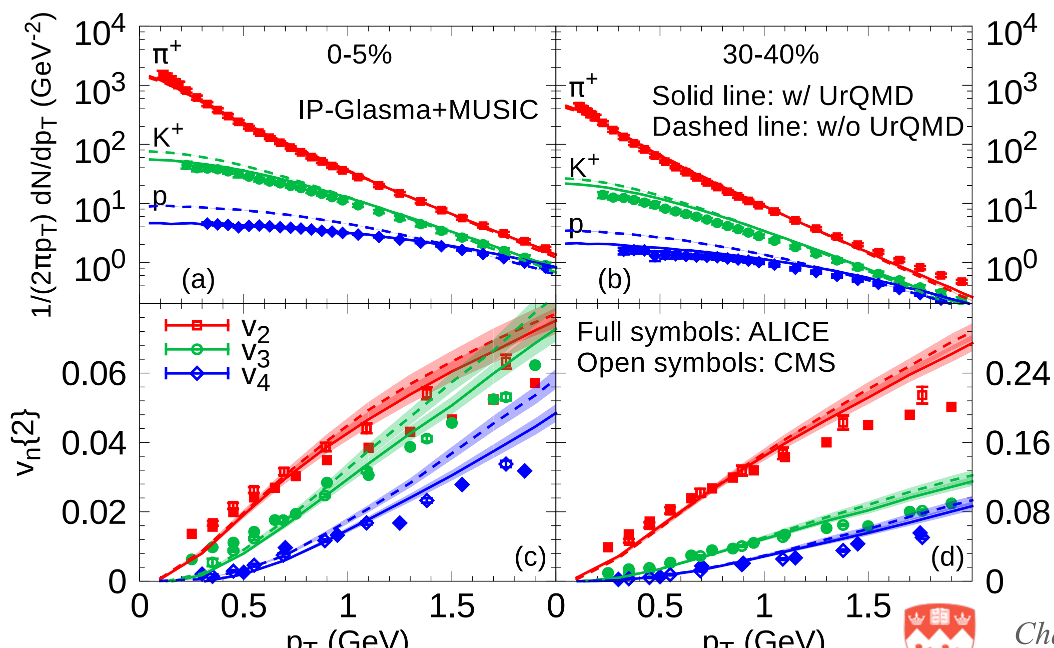
WHAT DOES THE BULK VISCOSITY DO FOR HADRONS?



- The bulk viscosity reduces the average p_T: it acts as a negative pressure $\quad \Pi \sim -\zeta\theta$

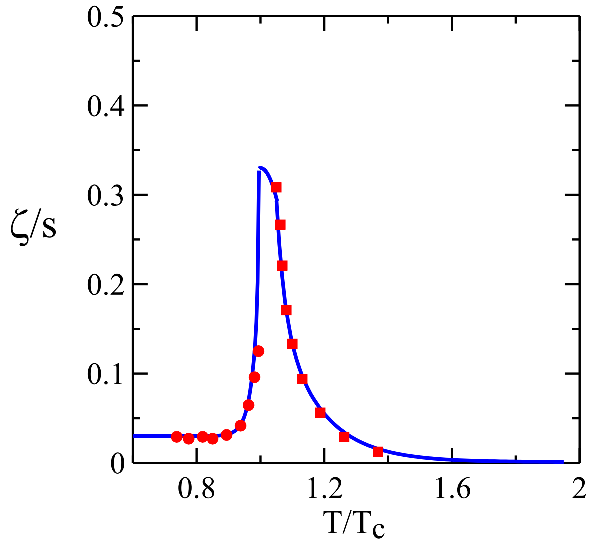
S. Ryu et al., PRL (2015)





Charles Gale
McGill

What we can say, from the hadrons



$$\eta / s = 0.095$$

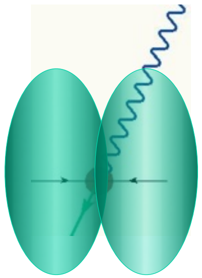
The inclusion of bulk viscosity affects the extraction of shear viscosity (here, ≈50%).

Uncertainty on these extracted values: MADAI-style statistical analysis: MADAI.MSU.EDU; Sangaline and Pratt, PRC (2016); J. E. Bernhard et al., arXiv/160503954; G. Denicol, QM 2015

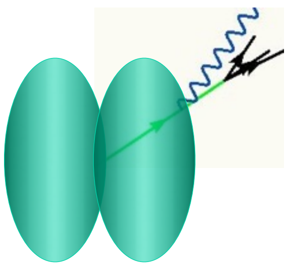
What about photons?
Update on the "Photon Flow Puzzle"

THE "PHOTON FLOW PUZZLE"

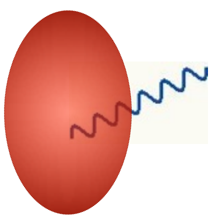
Photon Sources (real and/or virtual)



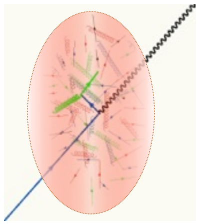
Hard direct photons. pQCD with shadowing
Non-thermal



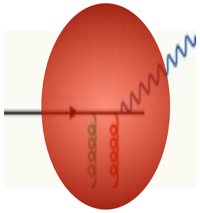
Fragmentation photons. pQCD with shadowing
Non-thermal



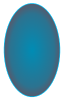
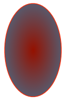
Thermal photons
Thermal



Jet-plasma photons
Thermal

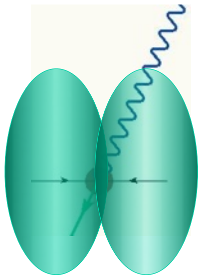


Jet in-medium bremsstrahlung
Thermal

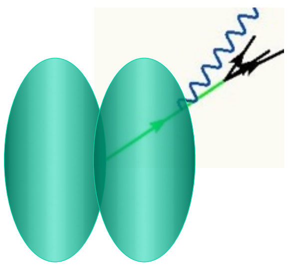
 Pre-equilibrium? 

The "Photon Flow Puzzle"

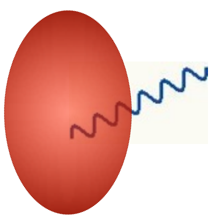
Photon Sources (real and/or virtual)



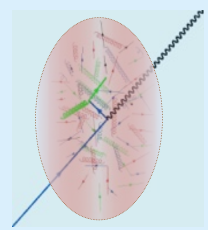
Hard direct photons. pQCD with shadowing
Non-thermal



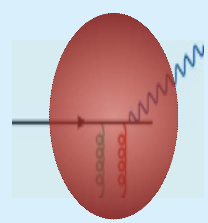
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal



Jet-plasma photons
Thermal



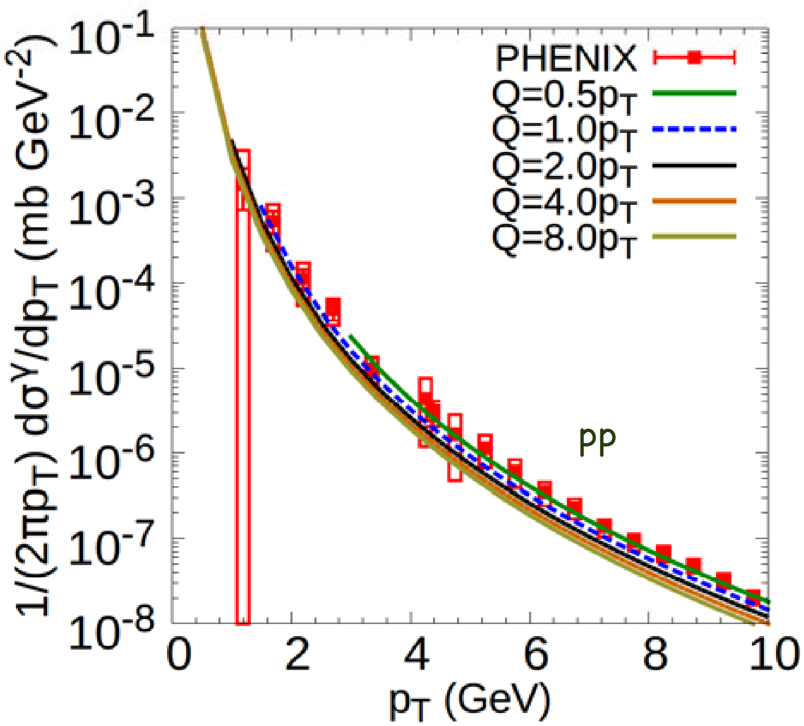
Jet in-medium bremsstrahlung
Thermal

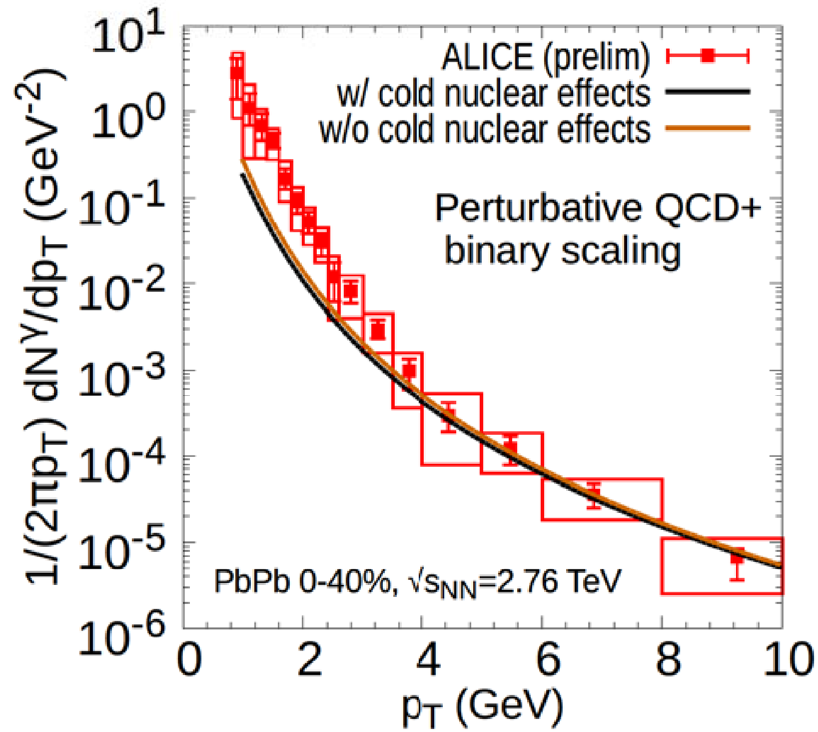
Pre-equilibrium?

Charles Gale
McGill

pQCD Photons

- Calculated at NLO in pQCD
  - INCNLO, P. Aurenche et al., Eur. PJC (2000)
  - CTEQ6.1m, BFG-2, Isospin, EPS09





J.-F. Paquet, PhD Thesis (2015)

Electromagnetic thermal emissivity

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1}$$

- Partonic rates @ LO: Arnold, Moore, Yaffe, JHEP (2001); Partonic rates @ NLO: J. Ghiglieri et al., JHEP (2013); Partonic rates [Lattice]: J. Ghiglieri et al., arXiv:1604.07544
- Hadronic rates: Turbide et al., PRC (2004); Heffernan et al., PRC (2015)

$$\begin{aligned} \mathcal{L} = {} & \frac{1}{8}F_\pi^2\,\mathrm{Tr}\,D_\mu U D^\mu U^\dagger + \frac{1}{8}F_\pi^2\,\mathrm{Tr}\,\mathrm{M}\left(\mathrm{U}+\mathrm{U}^\dagger\right) \\ & -\frac{1}{2}\mathrm{Tr}\left(F^L_{\mu\nu}F^{L\mu\nu} + F^R_{\mu\nu}F^{R\mu\nu}\right) + m_0^2\,\mathrm{Tr}\left(A^L_\mu A^{L\mu} + A^R_\mu A^{R\mu}\right) \\ & + \text{non-minimal terms} \end{aligned}$$

$$\left.\begin{aligned} & X+Y \to Z+\gamma \\ & \rho \to Y+Z+\gamma \\ & K^* \to Y+Z+\gamma \end{aligned}\right\} X,Y,Z \in \{\rho,\pi,K^*,K\}$$

$$\pi\pi \to \pi\pi\gamma,\ \Sigma \to \Lambda\gamma,\ \ f_1(1285) \to \rho^0\gamma \ldots$$

+ viscous corrections

"Viscous Thermal Photons" from a hot ensemble of hadrons

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

$$f \to f_0 + \delta f, \quad \delta f = f_0 (1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

$$q_0 \frac{d^3 R}{d^3 q} = \int \frac{d^3 p_1}{2(2\pi)^3 E_1} \frac{d^3 p_2}{2(2\pi)^3 E_2} \frac{d^3 p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1) f(E_2) \left[1 \pm f(E_3)\right]}{2(2\pi)^3}$$

- Recalculate all the rates
- Integrate rates with viscous hydro

$$E\frac{d^3 N}{d\mathbf{k}} = \int d^4 X \, E \frac{d^3 \Gamma}{d\mathbf{k}} (K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))$$

M. Dion, MSc Thesis (2011), Dion et al., PRC (2011);
Shen et al., PRC (2014), Paquet et al., (2016)

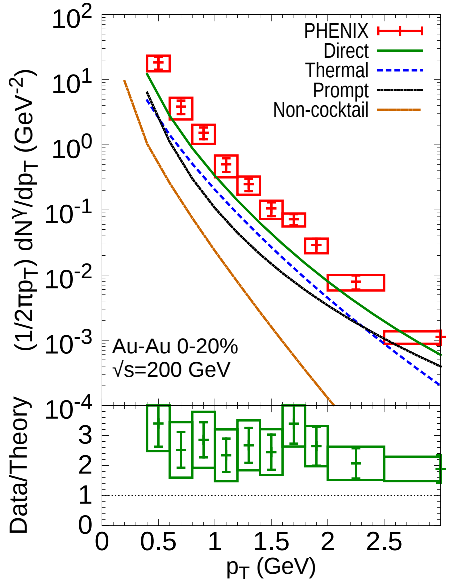
Where we are with "viscous photon" rates (no NLO)

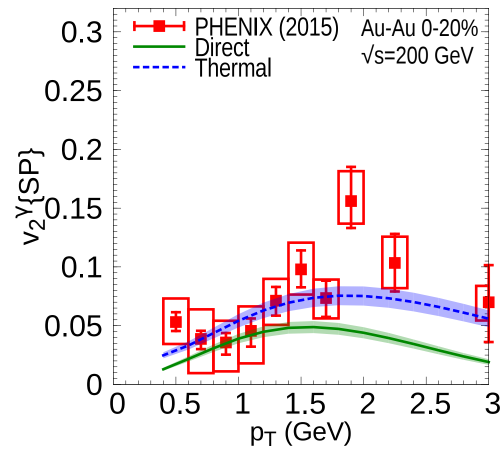
Rate/viscous correction	Ideal	I+Shear	I+S+Bulk
QGP: 2->2	AMY	Chen et al., PRC (2015)	Paquet etal., PRC (2016)
QGP: LPM-Brem.	AMY		
Hadronic: Meson reactions	• Turbide et al. , PRC (2004) • van Hees et al., PRC (2011)	• Dion et al., PRC (2011) • Paquet et al., PRC (2016)	Paquet etal., PRC (2016)
Hadronic: Meson-Meson Brem.	• Liu et al., NPA (2007) • Linnyk et al., PRC (2015)		
Hadronic: Baryons	• Rapp et al., ANP (2000) • Turbide et al., PRC (2004)		

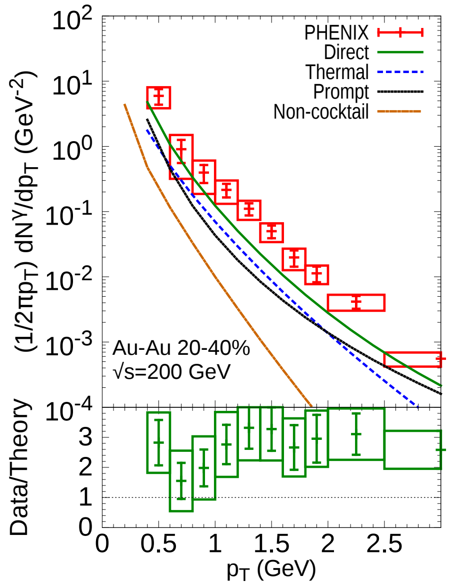
(An incomplete reference list)

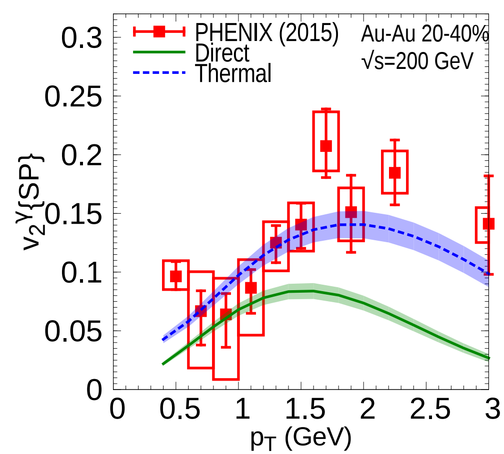
PHOTON RESULTS: A SUMMARY

PHENIX







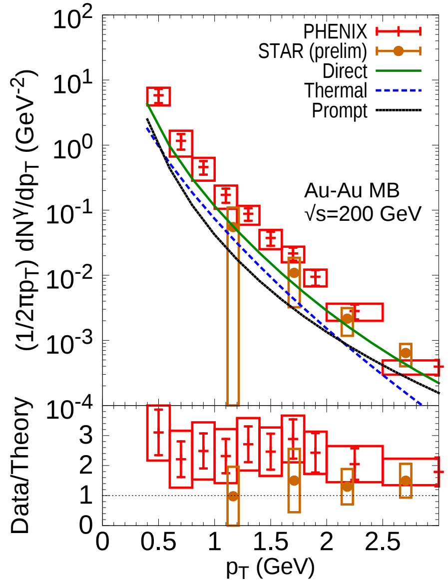


Paquet et al., PRC (2016)

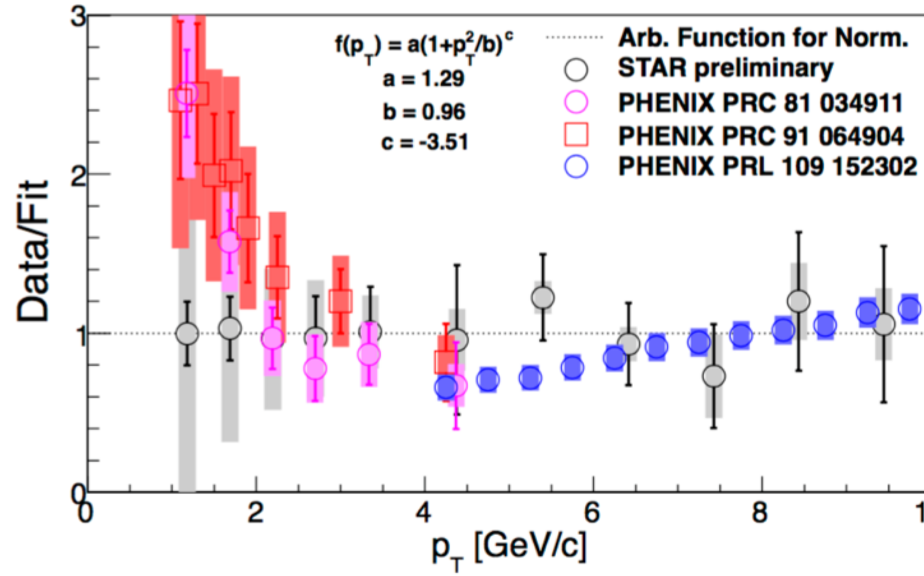
Charles Gale
McGill

Photon results: A summary

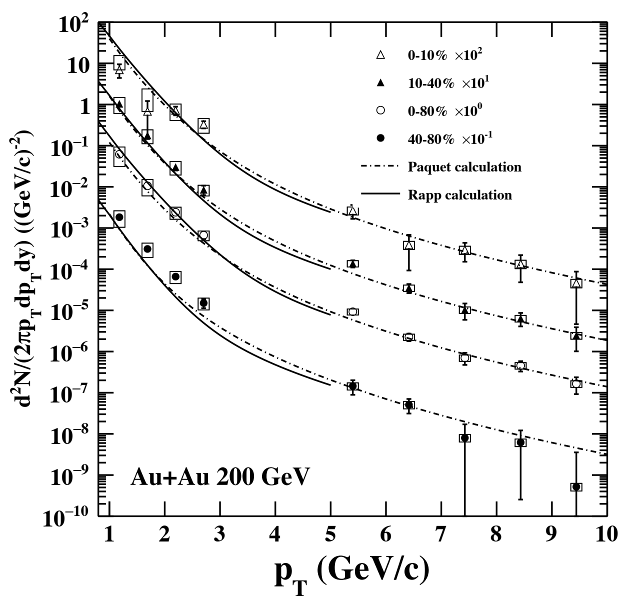
STAR



V. Novitzky HP 2015



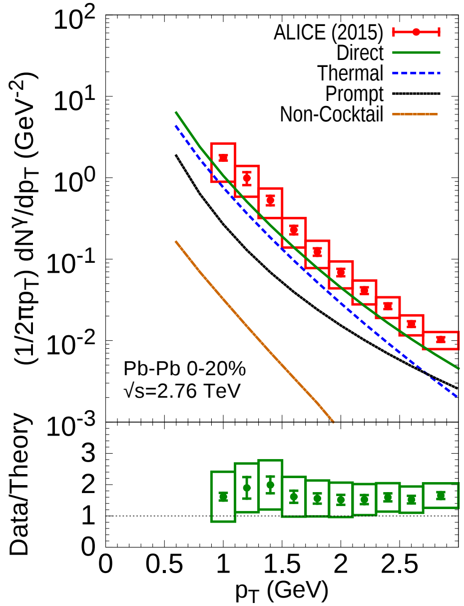
STAR arXiv:1607.01447

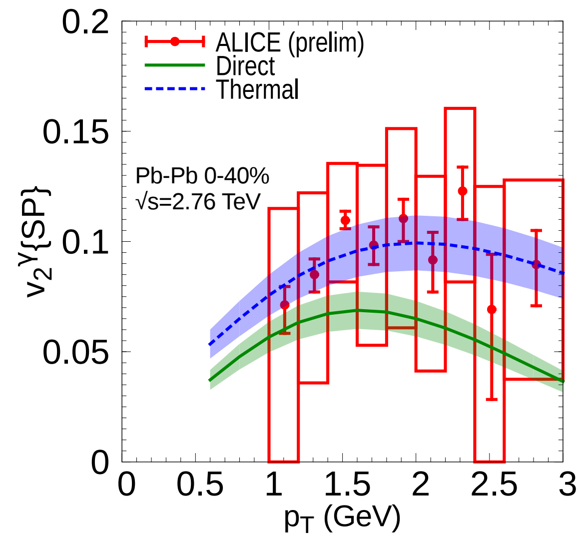


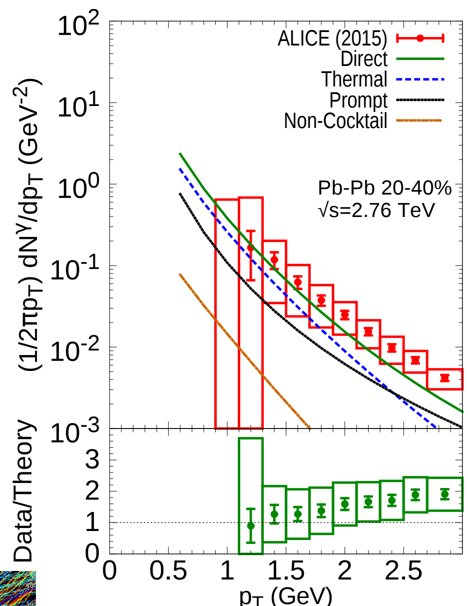
- MB: STAR 0-80%, PHENIX 0-92%
- Apparent tension between STAR and PHENIX photon data

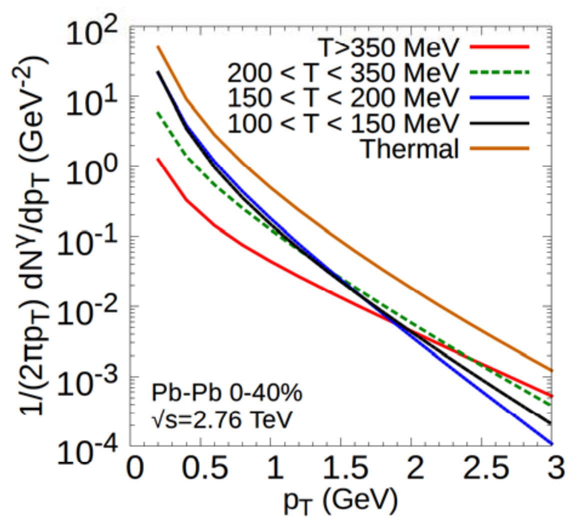
PHOTON RESULTS: A SUMMARY

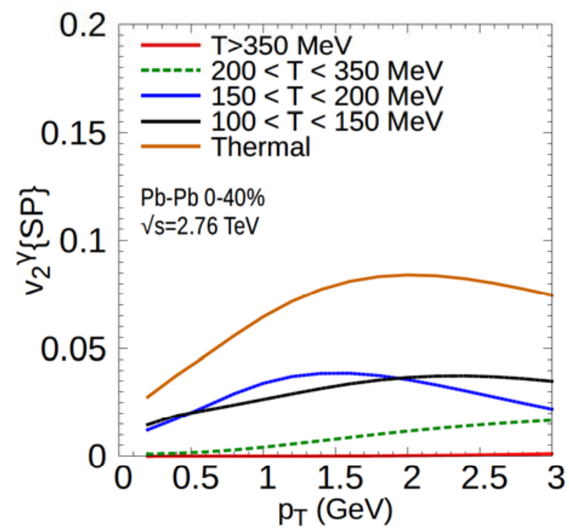
ALICE









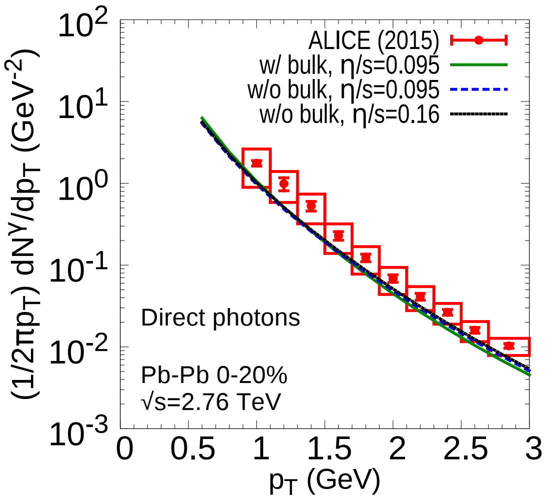


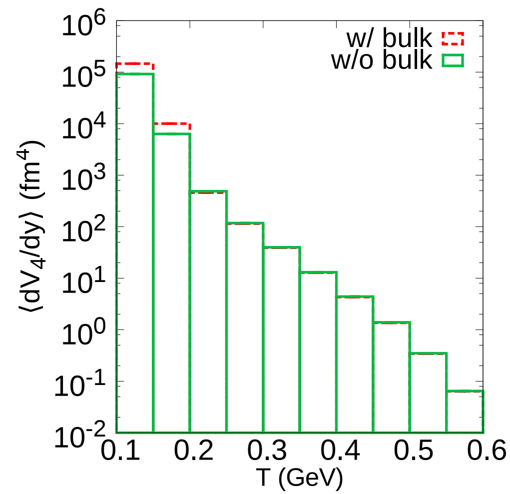
(n.b. F. Bock et al., arXiv:1606.06077)

Charles Gale
McGill

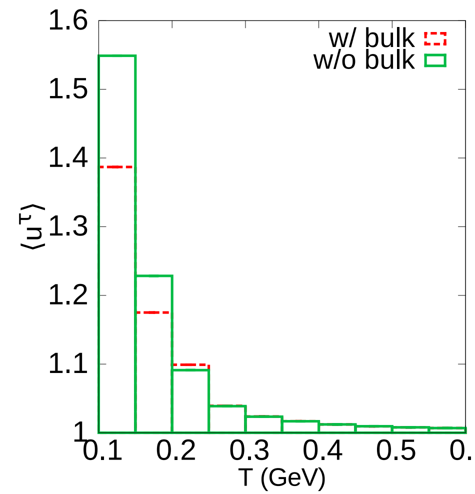
What does the bulk viscosity do for photons?

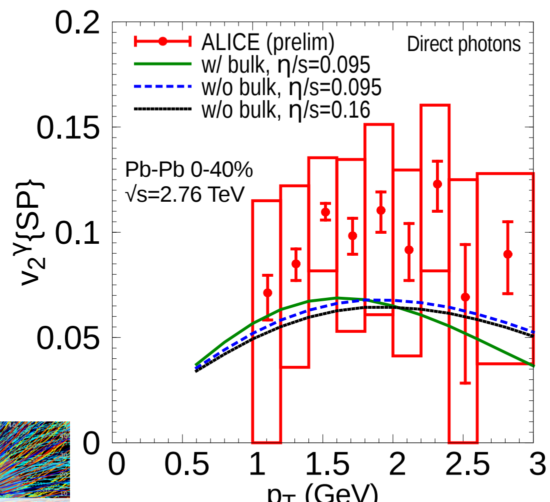
$$\delta f_i^{\Pi} = -\frac{\Pi}{T\hat{\zeta}} f_{0i}\,\tilde{f}_{0i}\left[\left(c_s^2 - \frac{1}{3}\right)E_i + \frac{m_i^2}{3E_i}\right]$$





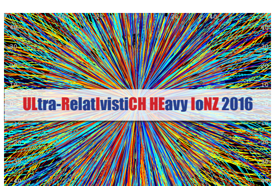
$u^{\tau} = \sqrt{1 + (u^x)^2 + (u^y)^2}$





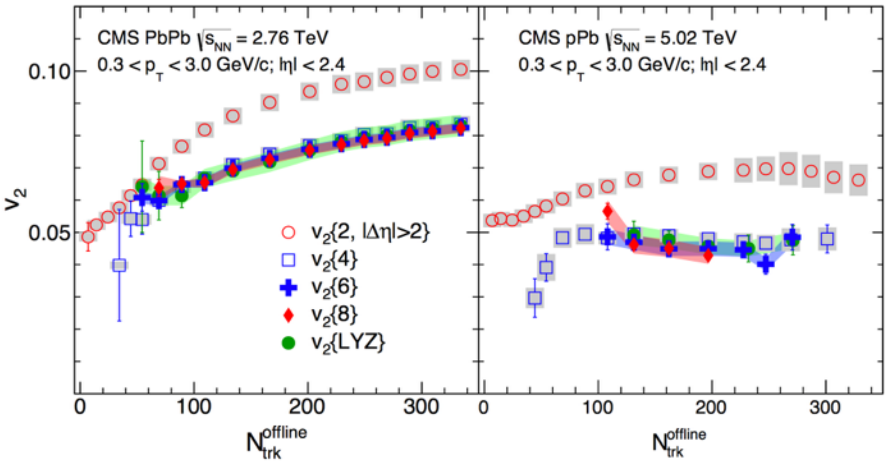
- The inclusion of bulk viscosity slows down the transverse expansion
- Shifts v_2 to lower pT
- Slightly larger spacetime volume in the late stages

J.-F. Paquet et al., PRC (2016)

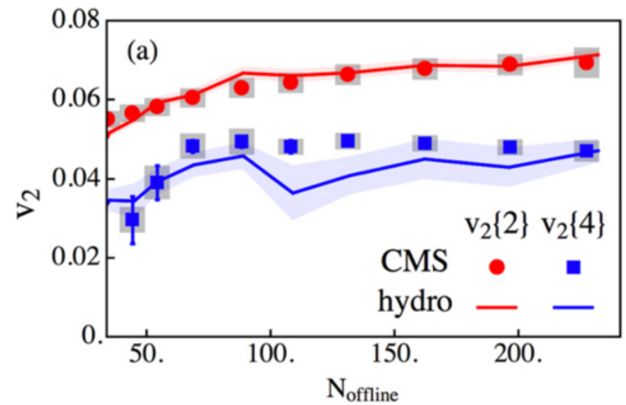


Charles Gale
McGill

Collectivity in small systems?



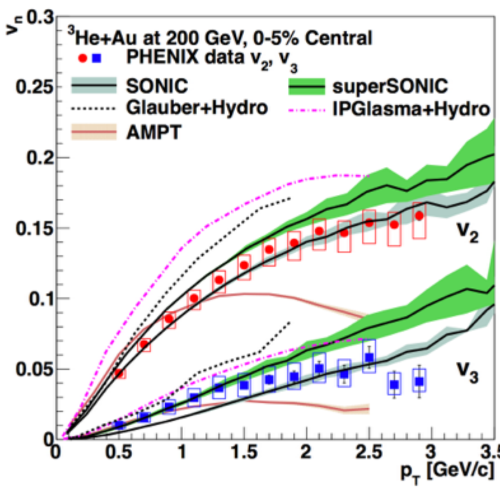
CMS Collab., PRL 2015



Kozlov *et al.*, NPA (2014)

LHC
pPb 5.02 TeV

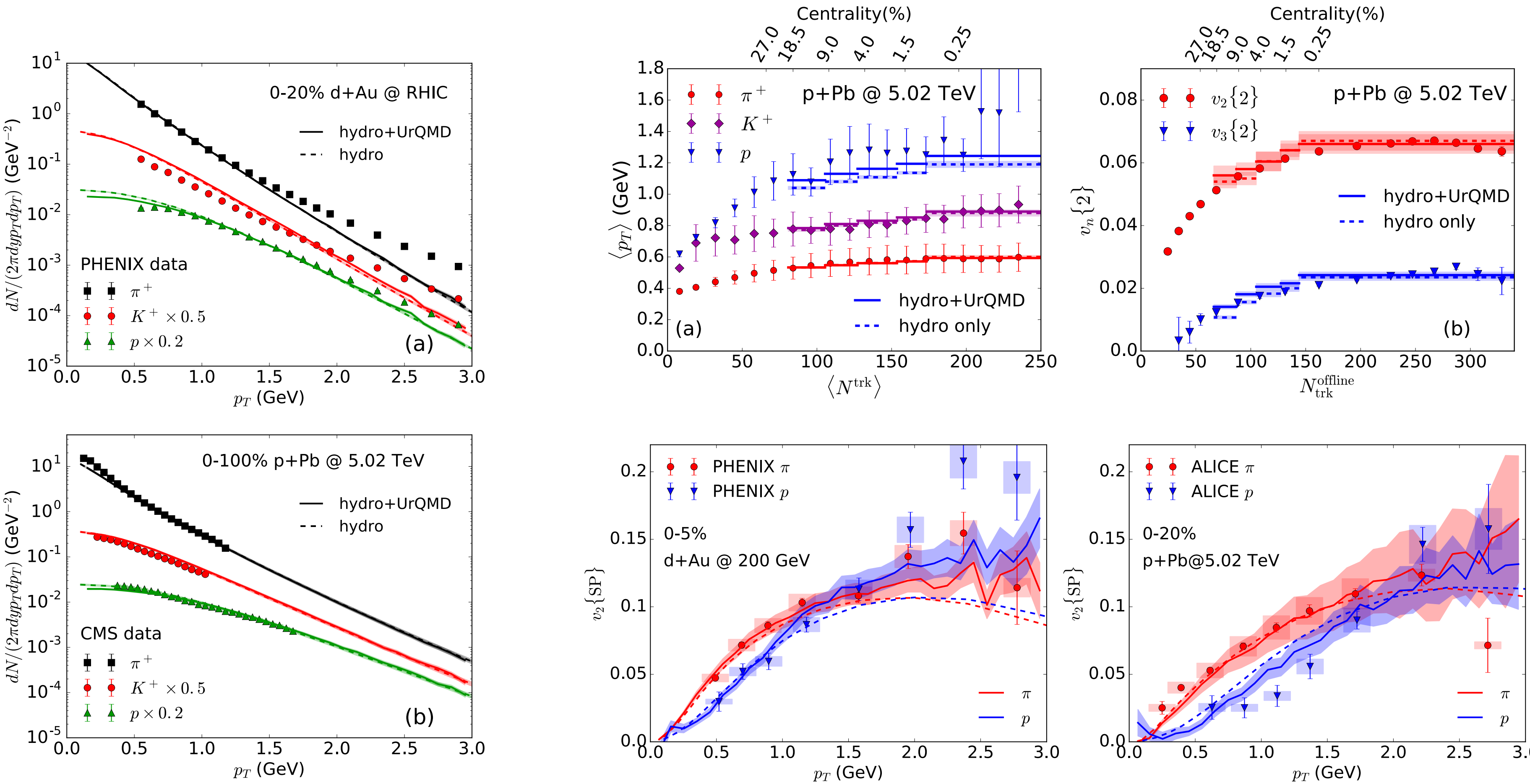
RHIC



PHENIX Collab., arXiv:1507.06273

- Magnitude and behaviour of flow coefficients consistent with fluid-dynamical modelling
- Pair correlation variable $r_n(p_T^a, p_T^b)$ confirmed by measurements (CMS)
- Some tension between AA and pA hydro calculations
- Initial state correlations; details of the shape of the proton/deuteron

Soft hadrons @ RHIC and @ LHC



C. Shen et al., PRL (2016), and in preparation

- Reasonable agreement between theory and measurement for spectra, centrality tracking, and flow
- $< p_T >$ values in agreement within uncertainties

Charles Gale
McGill

Pushing the limits of hydrodynamics? pA systems … and help from photons

One indicator, the Knudsen number, Kn $\quad \mathrm{Kn} = \dfrac{\ell_{\mathrm{micro}}}{L_{\mathrm{macro}}}$

For a dilute gas $\quad \ell_{\mathrm{micro}} = \lambda_{\mathrm{mfp}} \sim \tau_\pi = 5\dfrac{\eta}{\epsilon + P}$

For L_{macro}, use the local fields ϵ, u^μ to construct all possibilities

Denicol *et al.*, PRD (2012); Niemi, Denicol, *arXiv:1404.7327*

$\dfrac{1}{L^\theta_{\mathrm{macro}}} = \theta, \ \dfrac{1}{L^\epsilon_{\mathrm{macro}}} = \dfrac{1}{\epsilon}\sqrt{\nabla_\mu \epsilon \nabla^\mu \epsilon}$ are the larger ones $\quad \left(\theta = \nabla_\mu u^\mu\right)$

$$\mathrm{Kn} = \frac{\tau_\pi}{L}, \quad L = \min\left(L^\theta_{\mathrm{macro}}, L^\epsilon_{\mathrm{macro}}\right)$$

Pushing the limits of hydrodynamics? pA systems … and help from photons

One indicator, the Knudsen number, Kn

$$\mathrm{Kn} = \frac{\ell_{\mathrm{micro}}}{L_{\mathrm{macro}}}$$

For a dilute gas $\ell_{\mathrm{micro}} = \lambda_{\mathrm{mfp}} \sim \tau_\pi = 5\frac{\eta}{\epsilon + P}$

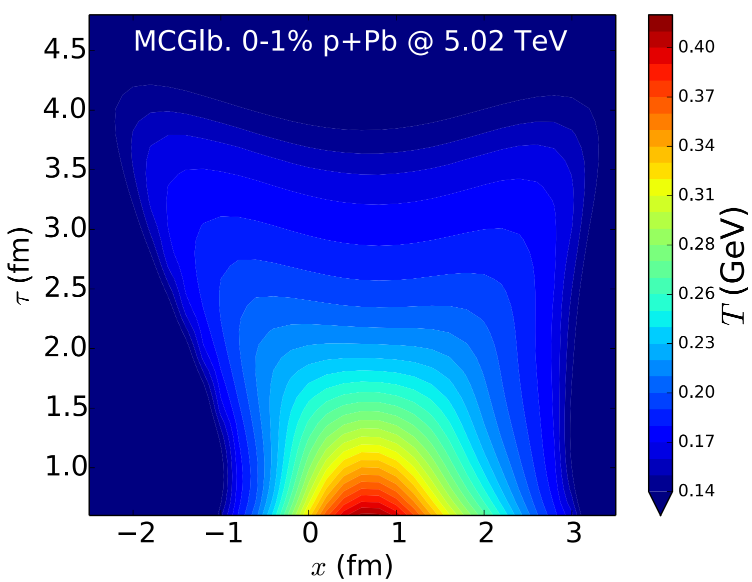
For L_{macro}, use the local fields ϵ, u^μ to construct all possibilities

Denicol *et al.*, PRD (2012); Niemi, Denicol, *arXiv:1404.7327*

$$\frac{1}{L^\theta_{\mathrm{macro}}} = \theta, \quad \frac{1}{L^\epsilon_{\mathrm{macro}}} = \frac{1}{\epsilon}\sqrt{\nabla_\mu \epsilon \nabla^\mu \epsilon}$$

are the larger ones $\left(\theta = \nabla_\mu u^\mu\right)$

$$\mathrm{Kn} = \frac{\tau_\pi}{L}, \quad L = \min\left(L^\theta_{\mathrm{macro}}, L^\epsilon_{\mathrm{macro}}\right)$$



Pushing the limits of hydrodynamics? pA systems … and help from photons

One indicator, the Knudsen number, Kn $\quad \mathrm{Kn} = \dfrac{\ell_{\mathrm{micro}}}{L_{\mathrm{macro}}}$

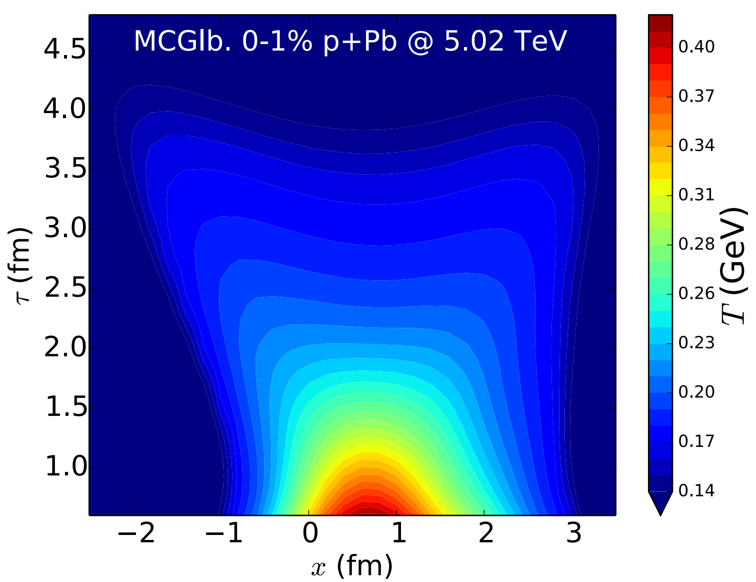
For a dilute gas $\quad \ell_{\mathrm{micro}} = \lambda_{\mathrm{mfp}} \sim \tau_\pi = 5\dfrac{\eta}{\epsilon + P}$

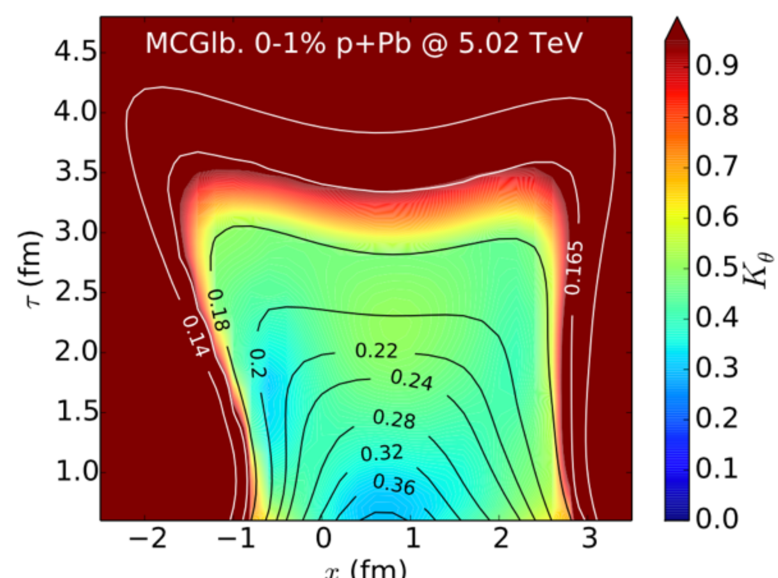
For L_{macro}, use the local fields ϵ, u^μ to construct all possibilities

Denicol *et al.*, PRD (2012); Niemi, Denicol, *arXiv:1404.7327*

$\dfrac{1}{L^\theta_{\mathrm{macro}}} = \theta, \quad \dfrac{1}{L^\epsilon_{\mathrm{macro}}} = \dfrac{1}{\epsilon}\sqrt{\nabla_\mu \epsilon \nabla^\mu \epsilon}$ are the larger ones $\quad \left(\theta = \nabla_\mu u^\mu\right)$

$$\mathrm{Kn} = \frac{\tau_\pi}{L}, \quad L = \min\left(L^\theta_{\mathrm{macro}}, L^\epsilon_{\mathrm{macro}}\right)$$





$\mathrm{Kn} > 1$

$\mathrm{Kn} \sim 1$

$\mathrm{Kn} < 1$

Charles Gale
McGill

Pushing the limits of hydrodynamics? pA systems
… and help from photons

One indicator, the Knudsen number, Kn $\quad \mathrm{Kn} = \dfrac{\ell_{\mathrm{micro}}}{L_{\mathrm{macro}}}$

For a dilute gas $\quad \ell_{\mathrm{micro}} = \lambda_{\mathrm{mfp}} \sim \tau_\pi = 5\dfrac{\eta}{\epsilon + P}$

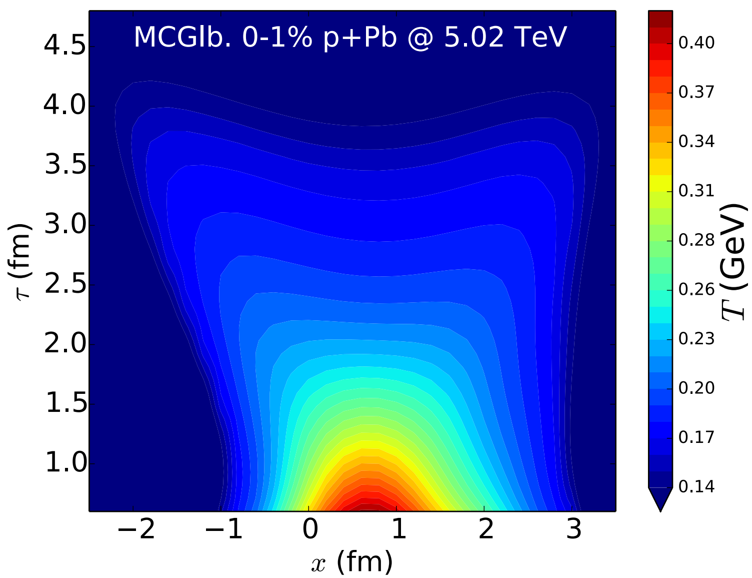
For L_{macro}, use the local fields ϵ, u^μ to construct all possibilities

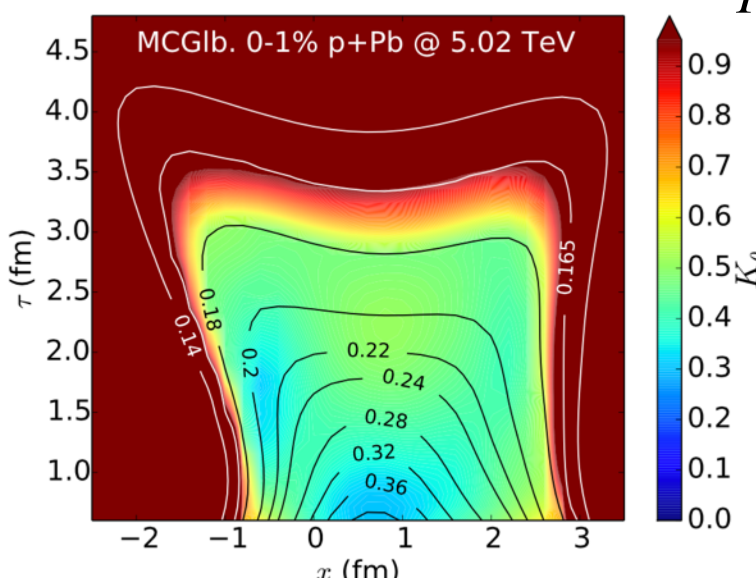
Denicol *et al.*, PRD (2012); Niemi, Denicol, *arXiv:1404.7327*

$$\frac{1}{L^\theta_{\mathrm{macro}}} = \theta, \quad \frac{1}{L^\epsilon_{\mathrm{macro}}} = \frac{1}{\epsilon}\sqrt{\nabla_\mu \epsilon \nabla^\mu \epsilon}$$ are the larger ones $\quad \left(\theta = \nabla_\mu u^\mu\right)$

$$\mathrm{Kn} = \frac{\tau_\pi}{L}, \quad L = \min\left(L^\theta_{\mathrm{macro}}, L^\epsilon_{\mathrm{macro}}\right)$$

Stop at $T_{\mathrm{dec}} = 165\ \mathrm{MeV}$





$\mathrm{Kn} > 1$

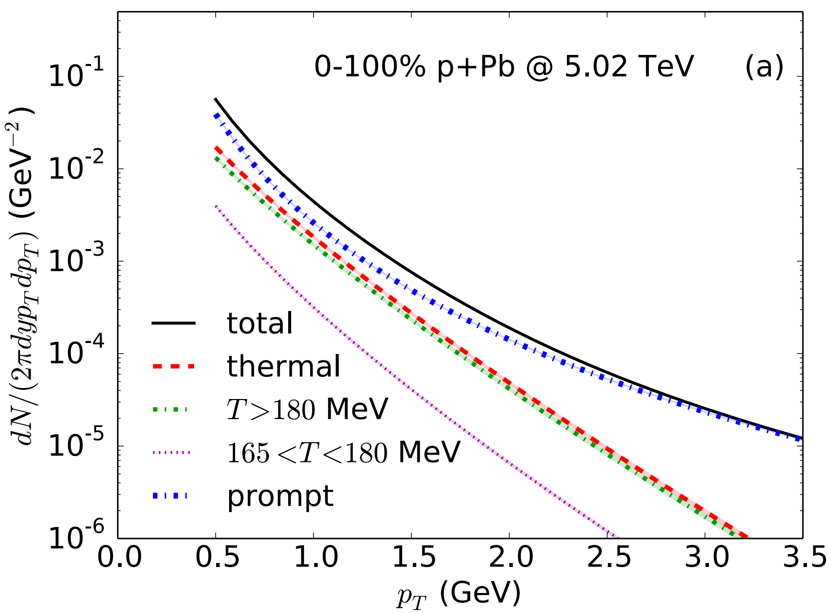
$\mathrm{Kn} \sim 1$

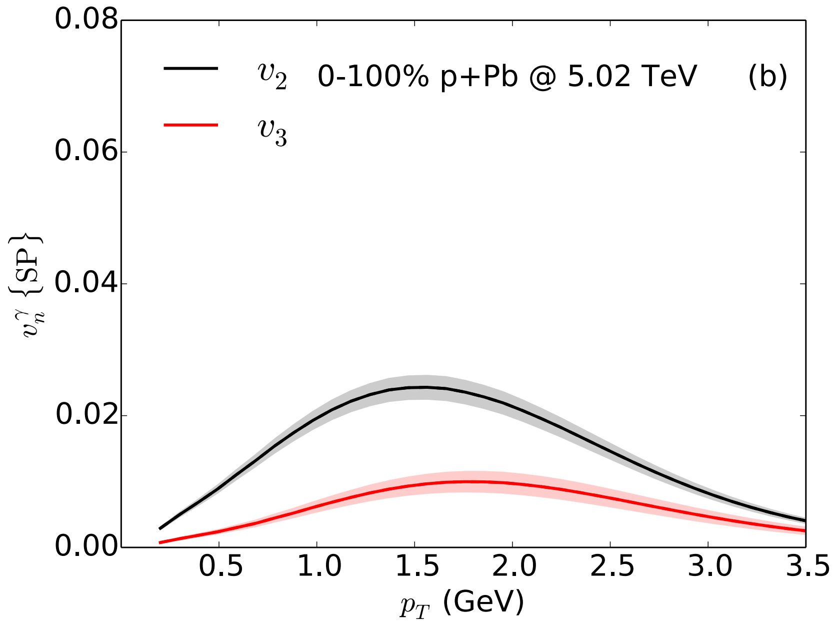
$\mathrm{Kn} < 1$

Charles Gale
McGill

Photon results

Min. bias

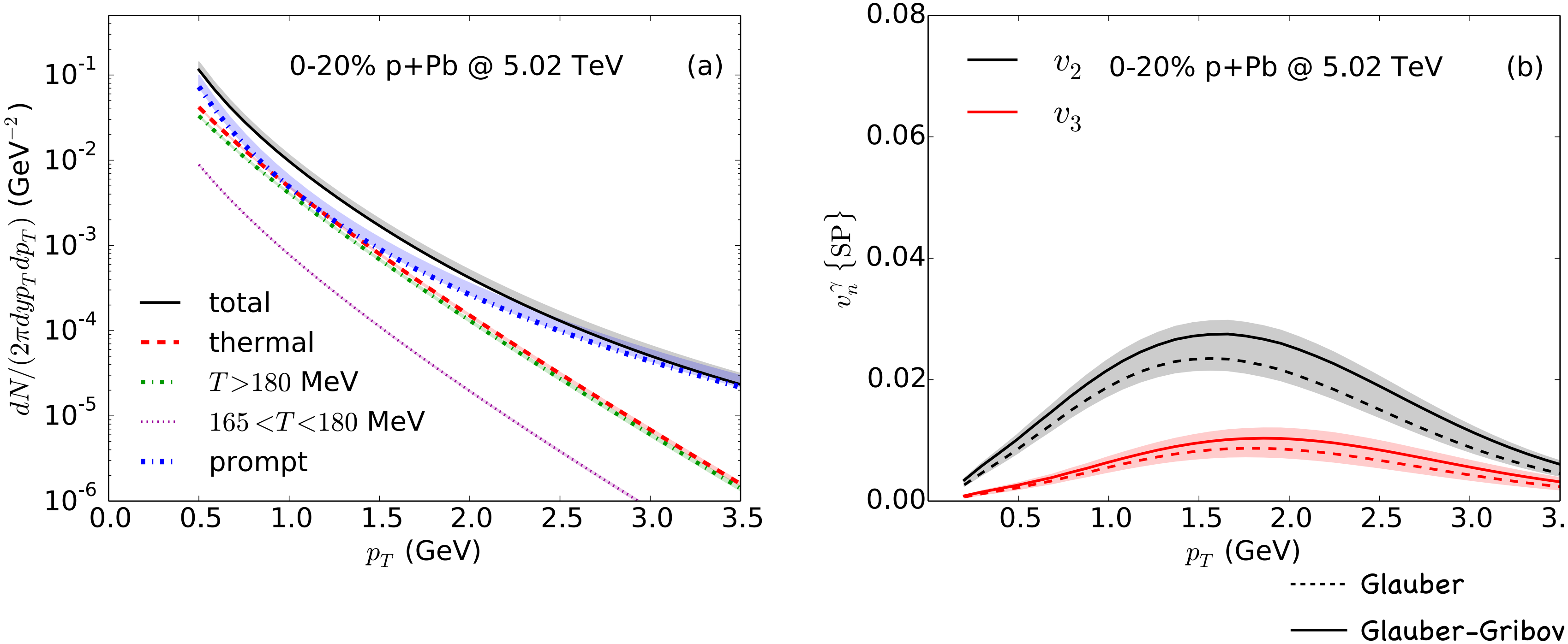




- For minimum bias p+Pb collisions, thermal photons are suppressed w.r.t. prompt photons, but are still visible in the total yield
- Prompt photons: NLO pQCD
- There is however a clear photon elliptic flow, and a photon triangular flow

Photon results

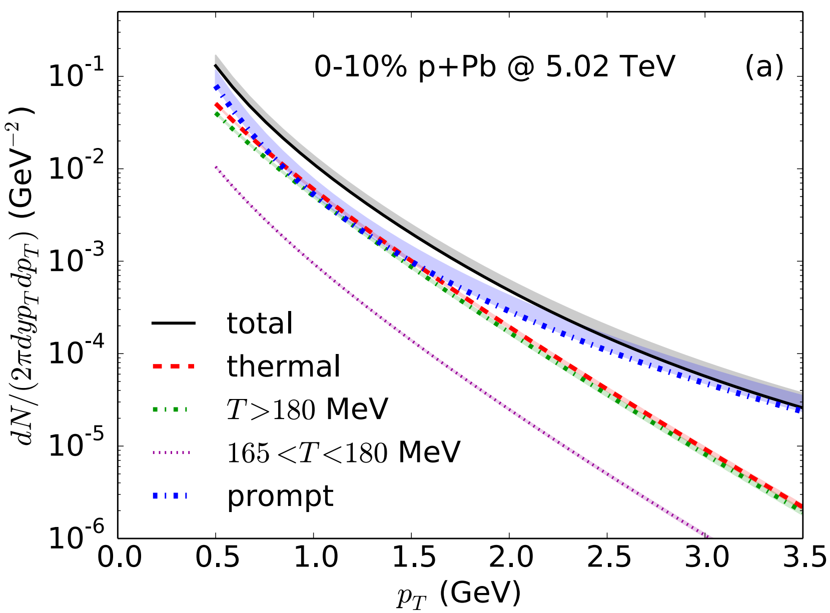
0-20%

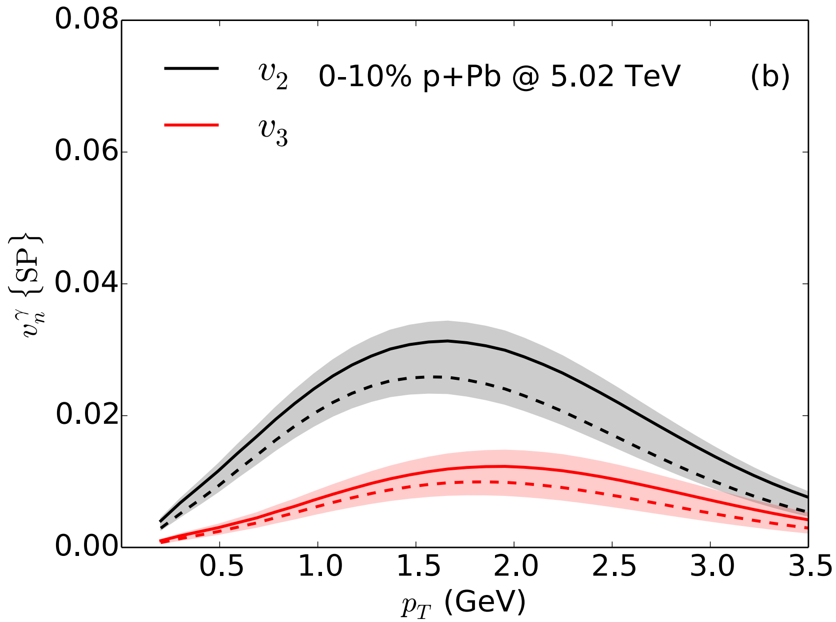


- In the 0-20% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows

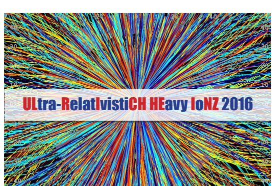
Photon results

0-10%



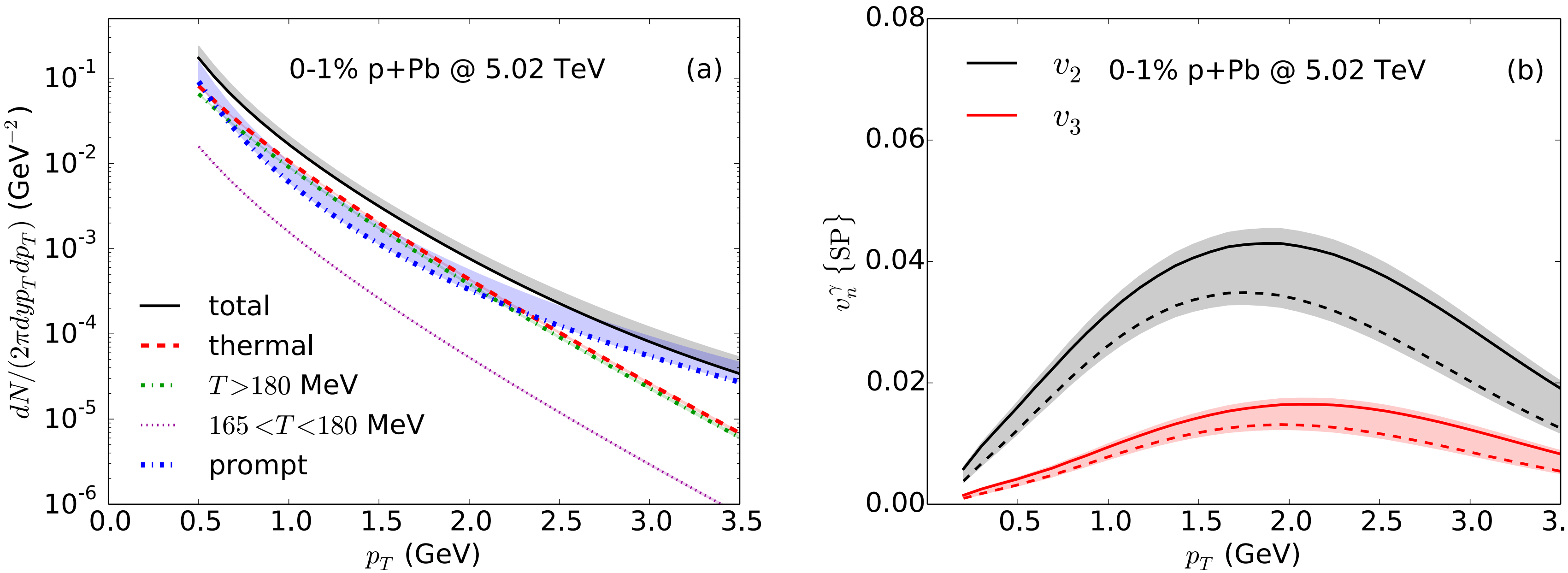


- In the 0-10% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows



Photon results

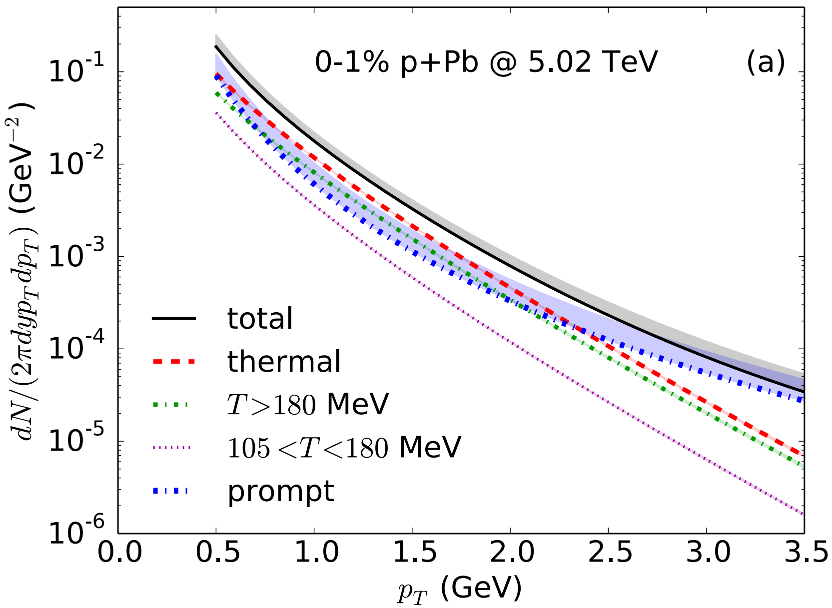
0-1%

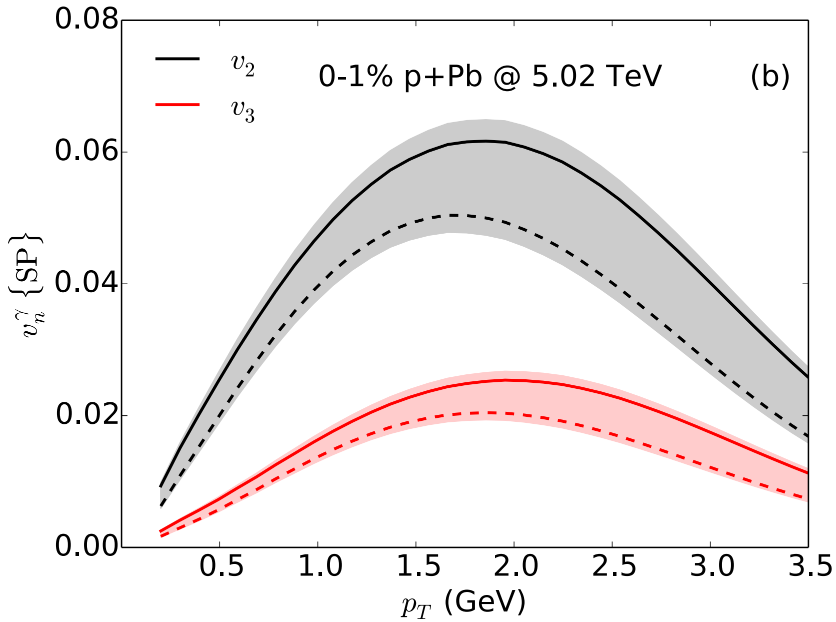


- In the 0-1% centrality range, a clear thermal photon signal over the prompt photon contribution; a factor of 3 @ 1.5 GeV
- There is a clear photon elliptic flow, and a photon triangular flow
- T_{dec} is kept high: arguably even a lower limit to the thermal contributions

Photon results

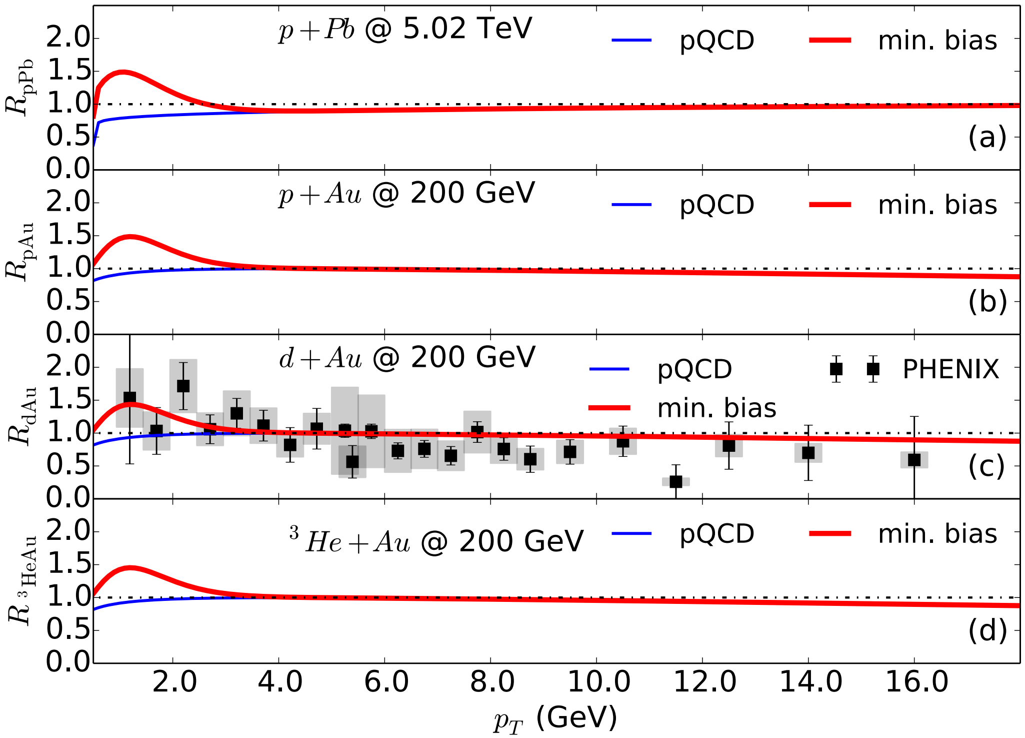
0-1%

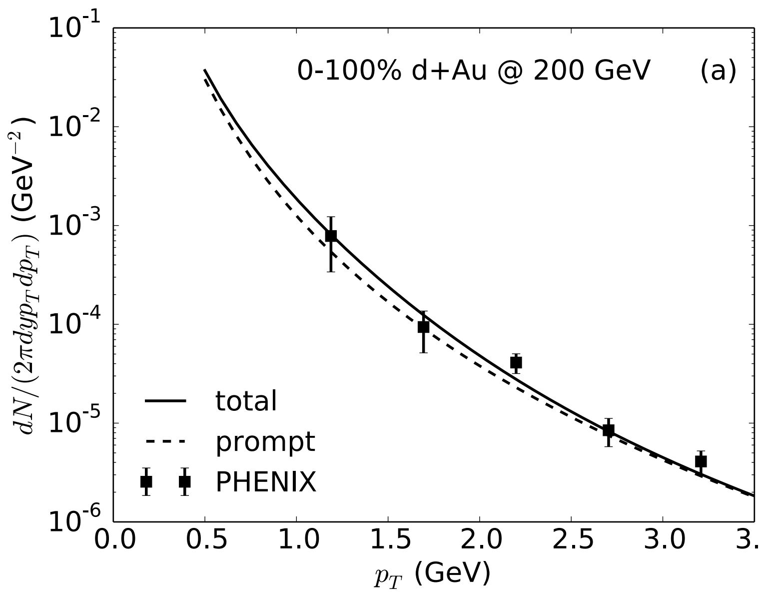




- In the 0-1% centrality range, a clear thermal photon signal over the prompt photon contribution
- There is a clear photon elliptic flow, and a photon triangular flow
- T_{dec} is kept high: arguably a lower limit to the thermal contributions

Comparing against what is currently known, and some predictions

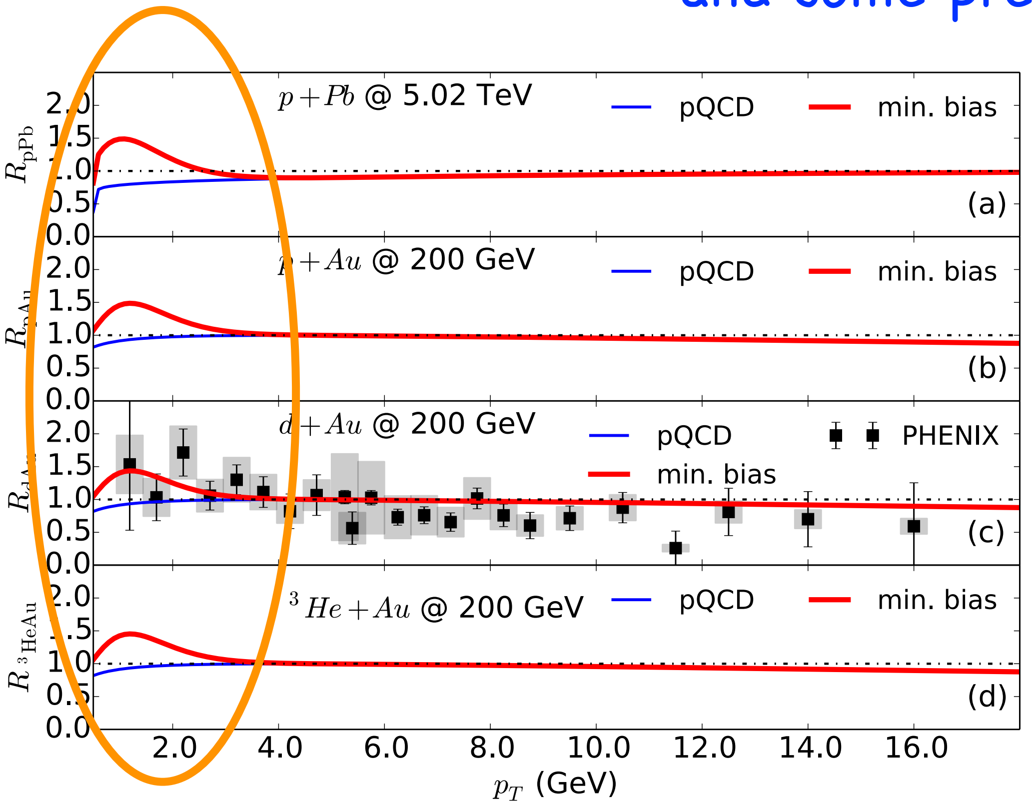


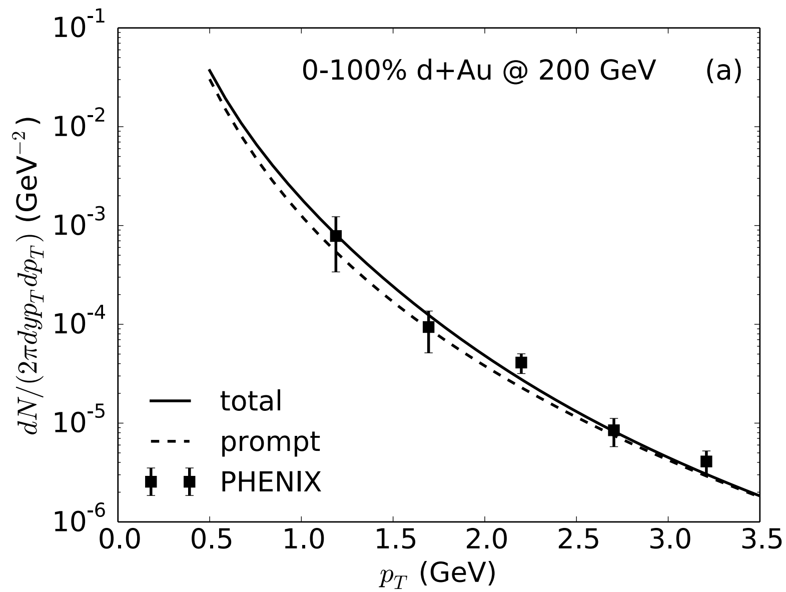


- Thermal radiation can leave a measurable imprint even on min. bias $R^{\gamma}_{\mathrm{pPb}}$
- An additional empirical support to the existence of a medium with collectivity features

C. Shen et al., PRL (2016)

Comparing against what is currently known, and some predictions





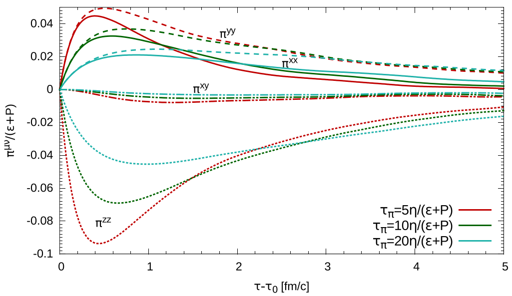
- Thermal radiation can leave a measurable imprint even on min. bias R^{γ}_{pPb}
- An additional empirical support to the existence of a medium with collectivity features

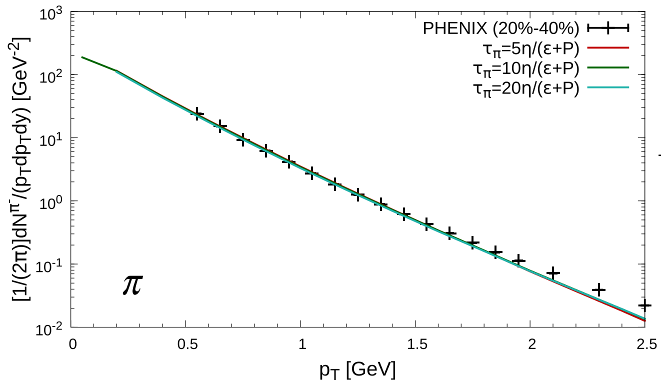
C. Shen et al., PRL (2016)

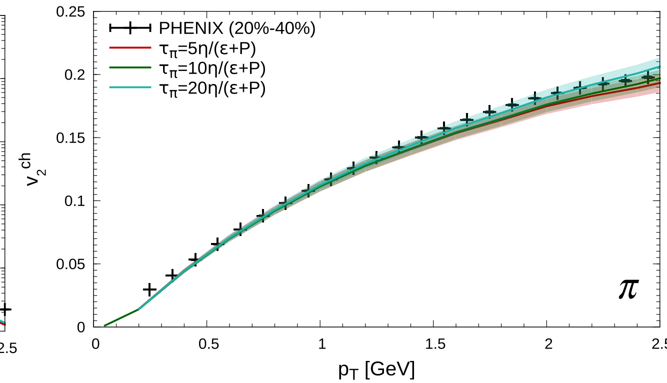
Charles Gale
McGill

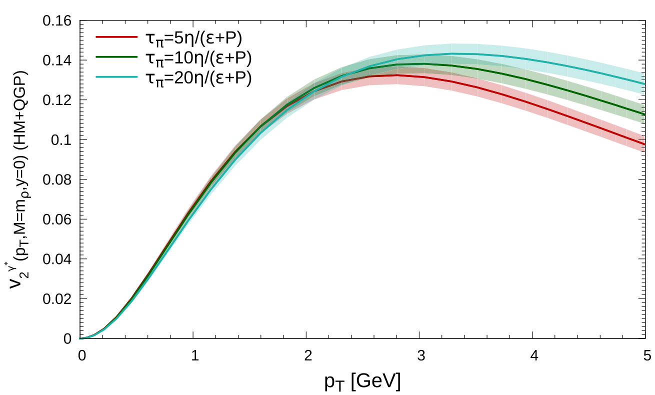
More fluid-dynamical insights from EM radiation

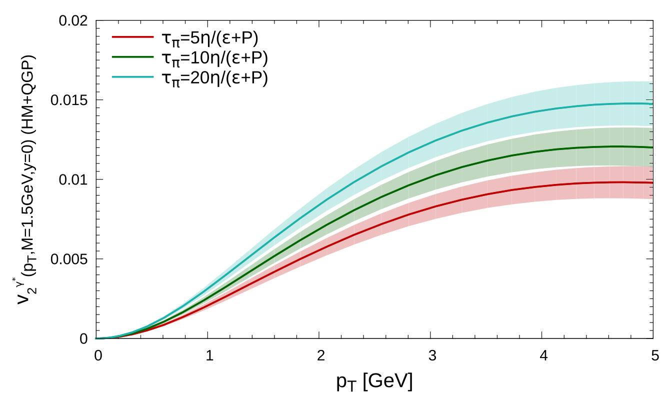
τ_π = Relaxation time in Israel-Stewart Hydrodynamics



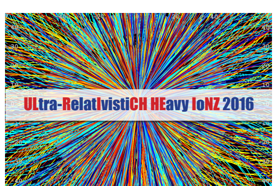








Thermal dileptons have access to regions opaque to hadrons



G. Vujanovic et al., PRC (2016)

Conclusions

- EM radiation & fluid-dynamical modelling: a powerful combination. Photon is a penetrating, soft probe
- Photons, some of the things I didn't talk about:
    - Uncertainty of rates near T_c:
        - Semi-QGP, Pisarski et al.; Gale et al., PRL (2015)
        - PHSD, Linnyk, Bratkovskaya, Cassing, PNPP (2016)
        - Enhancement near T_c, van Hees, He, Rapp, NPA (2015)
    - Influence of the early chemistry
        - A. Monnai, PRC (2014)
        - V. Vovchenko et al., arXiv:1604.06346
        - P. Moreau et al., arXiv:1512.02875
    - Pre-equilibrium photons
        - M. Grief et al., in preparation
    - Uncertainty in pQCD photon calculations
        - M. Klasen et al., JHEP (2013)
    - ...

Where and when did I first meet Ulrich?

Where and when did I first meet Ulrich?

QUARK MATTER 1987

Sixth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions
24 – 28 August 1987 · Nordkirchen · West Germany

Topics to be discussed will include Quark Matter formation and other nonperturbative QCD phenomena, very high energy nuclear collisions, and cosmological and astrophysical implications.

Organising Committee

R. Santo	Münster
H. Satz	Bielefeld/BNL
H. J. Specht	Heidelberg
R. Stock (Chairman)	Frankfurt

Conference Secretary

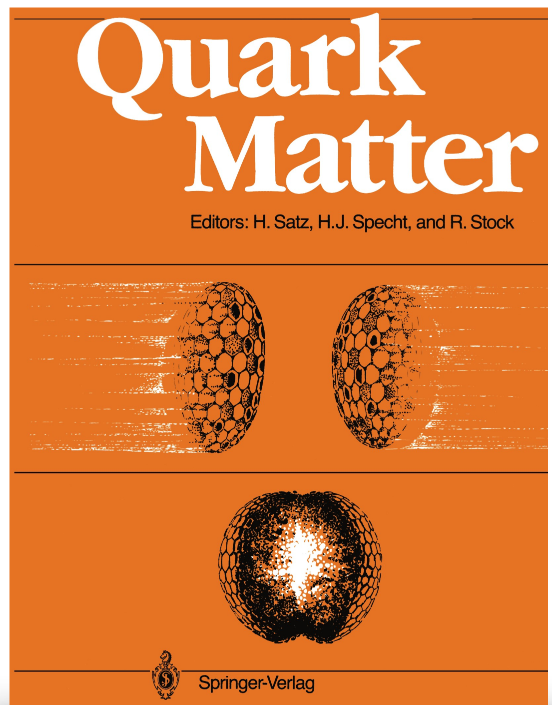
Mrs. Petra Behrens
Institute of Nuclear Physics
University of Frankfurt
D-6000 Frankfurt, W. Germany
Tel. 49 - 69 - 7 98 42 39

Advisory Committee

G. Baym	Urbana
J. D. Bjorken	Fermilab
R. Bock	GSI Darmstadt
M. Gyulassy	LBL Berkeley
K. Kajantie	Helsinki
G. W. London	Saclay
T. W. Ludlam	BNL Brookhaven
S. Nagamiya	Columbia N. Y.
I. Otterlund	Lund
D. Schramm	Chicago
B. Sinha	Calcutta
L. Van Hove	CERN Genève
W. Willis	CERN Genève

Quark Matter 1987
NordKirchen, Germany

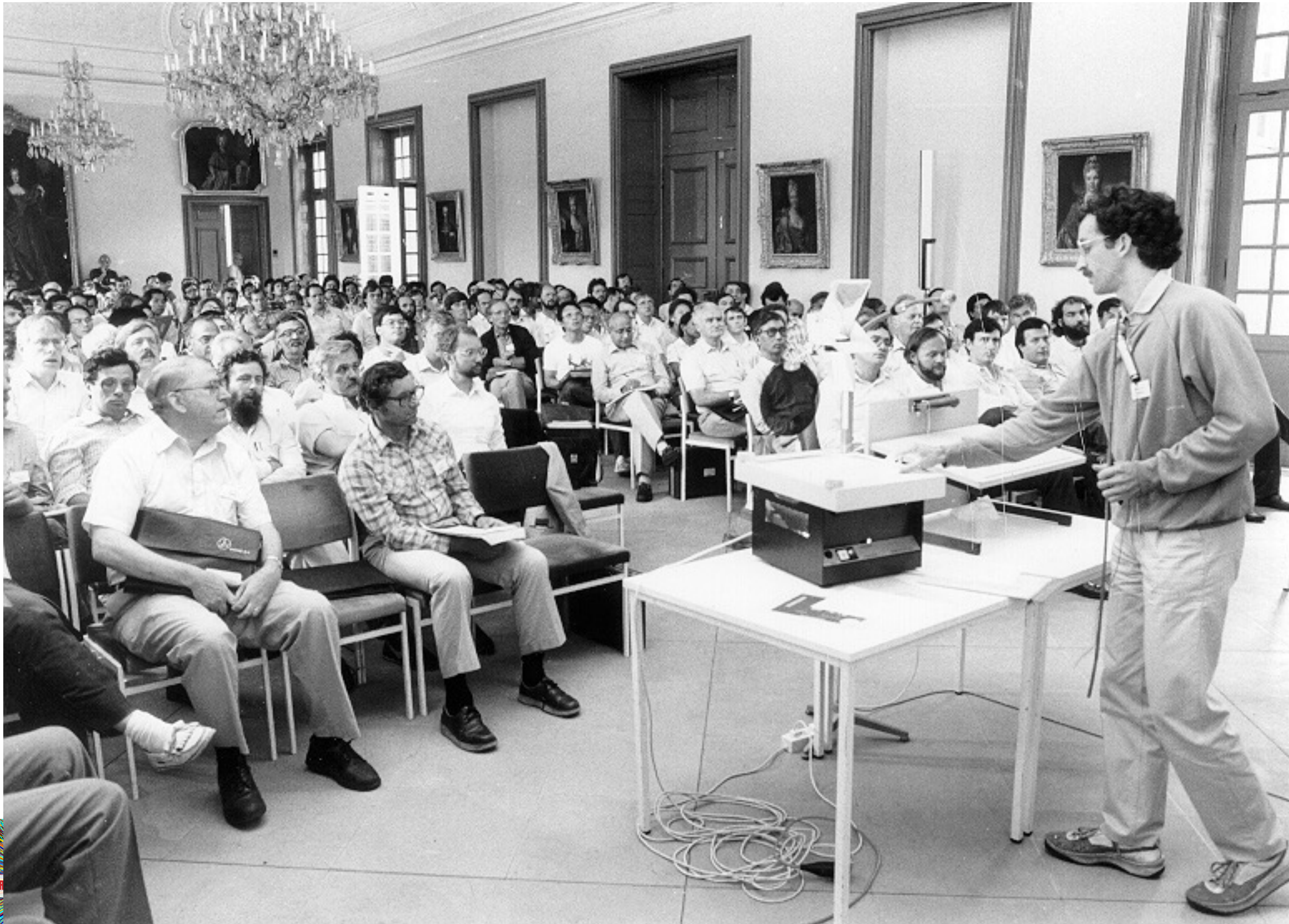
… almost 30 years ago



ULtra-RelatIvistiCH HEavy IoNZ 2016

Charles Gale
McGill

Where and when did I first meet Ulrich?



1987...

1987…

Top 5 movies of 1987

1. Beverly Hills Cop III
2. Dirty Dancing
3. Dragnet
4. Fatal Attraction
5. Full Metal Jacket

1987…

Top 5 movies of 1987

1. Beverly Hills Cop III
2. Dirty Dancing
3. Dragnet
4. Fatal Attraction
5. Full Metal Jacket

Top 5 songs of 1987

1. "Open Your Heart" … Madonna
2. "Livin' on a Prayer" … Bon Jovi
3. "Jacob's Ladder" … Huey Lewis and the News
4. "Lean on Me" … Club Nouveau
5. "Nothing's Going to Stop Us Now" … Starship

1987...

Top 5 movies of 1987

1. Beverly Hills Cop III
2. Dirty Dancing
3. Dragnet
4. Fatal Attraction
5. Full Metal Jacket

Top 5 songs of 1987

1. "Open Your Heart" ... Madonna
2. "Livin' on a Prayer" ... Bon Jovi
3. "Jacob's Ladder" ... Huey Lewis and the News
4. "Lean on Me" ... Club Nouveau
5. "Nothing's Going to Stop Us Now" ... Starship

Top 5 non-fiction books of 1987

1. "The Eight-Week Cholesterol Diet" by Robert Kowalski
2. "Talking Straight" by Lee Iacocca
3. "A Brief History of Time" by Stephen Hawking
4. "Trump" by Donald Trump
5. "Gracie: A Love Story" by George Burns

1987...

1987…

Top Selling US Autos and Prices 1987

Ford Escort $6,895
Ford Taurus $11,808
Honda Accord $10,925
Chevrolet Cavalier $7,395
Chevrolet Celebrity $11,010
Hyundai $5,395
Oldsmobile Ciera $11,420
Nissan Sentra $6,449
Ford Tempo $9,056
Chevrolet Corsica / Berreta $9,955
Pontiac Grand AM $10,269
Toyota Camry $11,248
Chevrolet Caprice $12,510
Honda Civic $6,195
Ford Mustang $9,209

1987…

Physics?

QM 1987: 3 "hydro talks"/51

Concluding remarks (M. Gyulassy):
"As emphasized by Feinberg, local equilibration may result from strong multiparticle interactions. In that case, simple hydrodynamics $\partial_\mu T^{\mu\nu} = 0$, may provide a better dynamical framework than current two body kinetic arguments would indicate."

1987…

Happy Birthday!

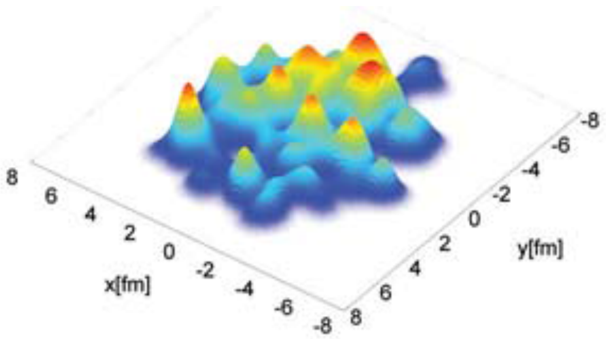
Physics?

QM 1987: 3 "hydro talks"/51

Concluding remarks (M. Gyulassy):
"As emphasized by Feinberg, local equilibration may result from strong multiparticle interactions. In that case, simple hydrodynamics $\partial_\mu T^{\mu\nu} = 0$, may provide a better dynamical framework than current two body kinetic arguments would indicate."

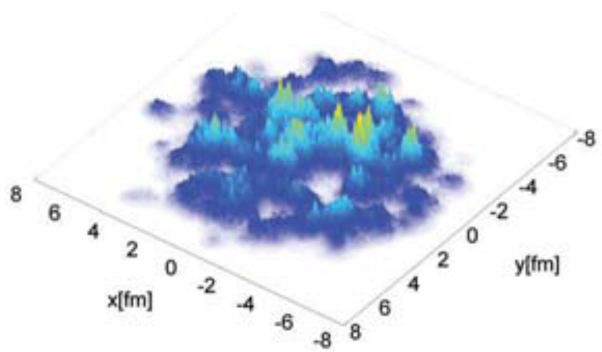
Much progress in the calculation of the initial state

Energy density



MC-Glauber

Fluctuations in the nucleon positions



IP-Glasma

Fluctuations in the nucleon positions +

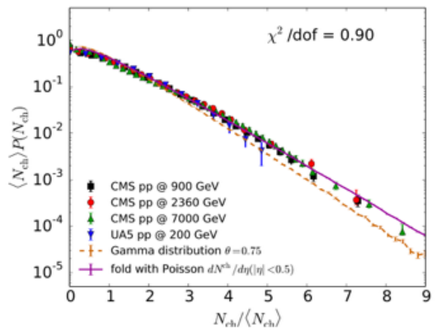
Fluctuations in the colour fields

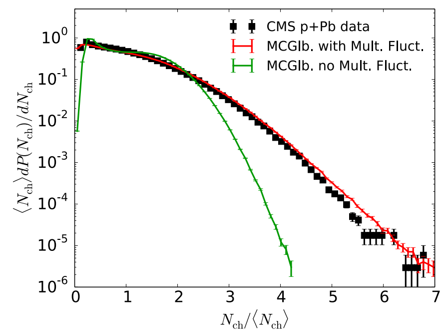
Schenke, Tribedy, and Venugopalan, PRL (2012)

Gale, Jeon, Schenke, Tribedy, and Venugopalan, PRL (2013)

Fluid-dynamical simulation

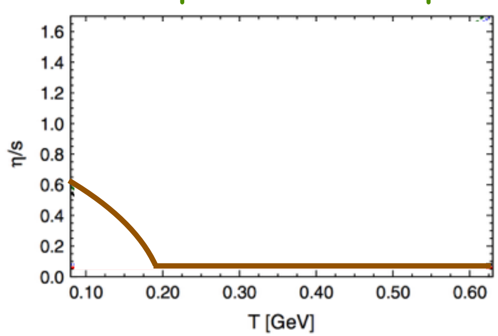
- Event-by-event simulations
- Initial state entropy density fluctuates according to a Gamma distribution





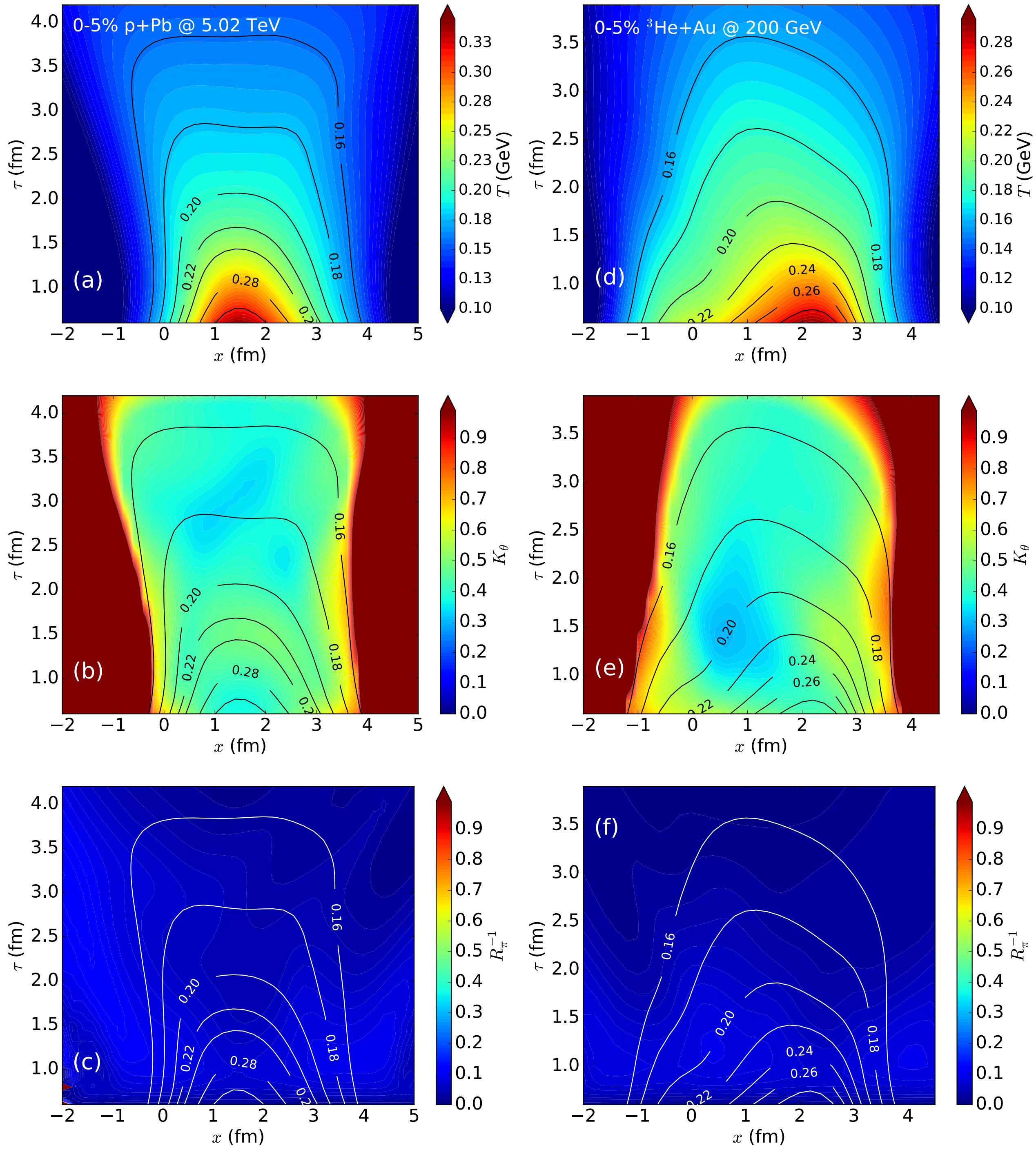
C. Shen *et al.*, arXiv:1409.8164

- Temperature-dependent shear viscosity

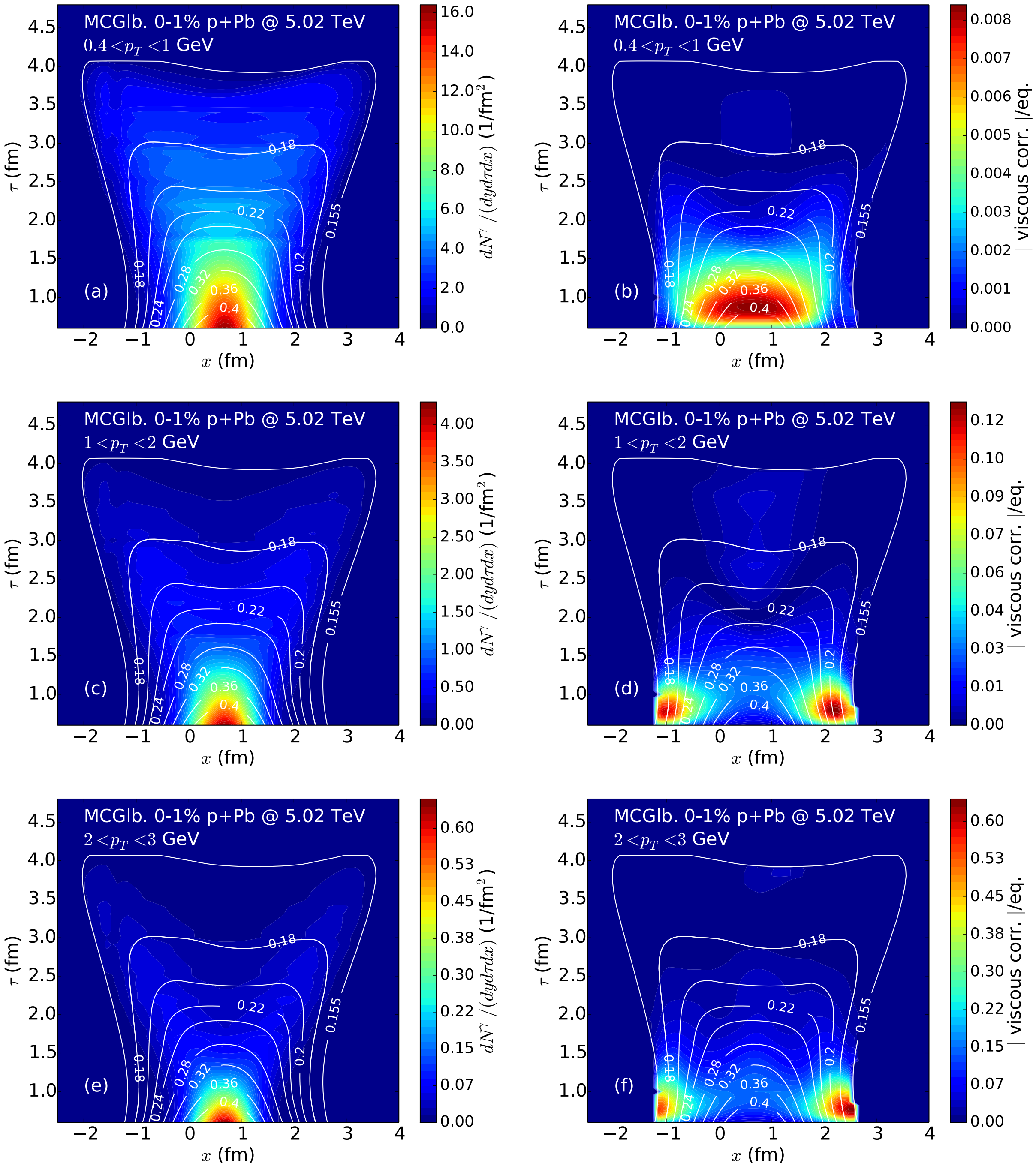


H. Niemi *et al.*, PRL (2011)

- Owing to compact fireball sizes (v.s. AA) pA collisions have larger pressure gradients, driving a larger expansion rate



Charles Gale
McGill



Charles Gale
McGill