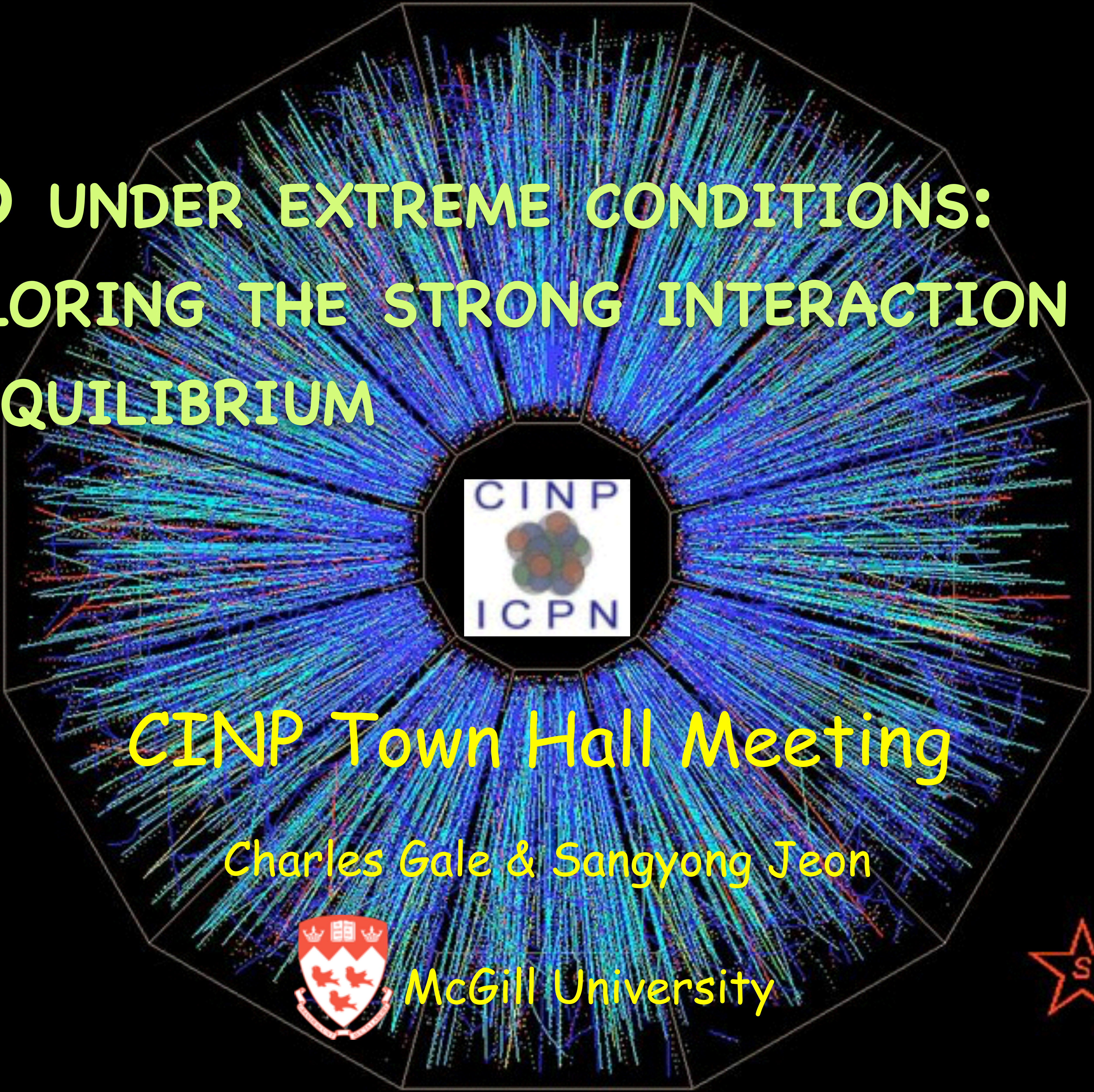
QCD under extreme conditions: Exploring the strong interaction out of equilibrium



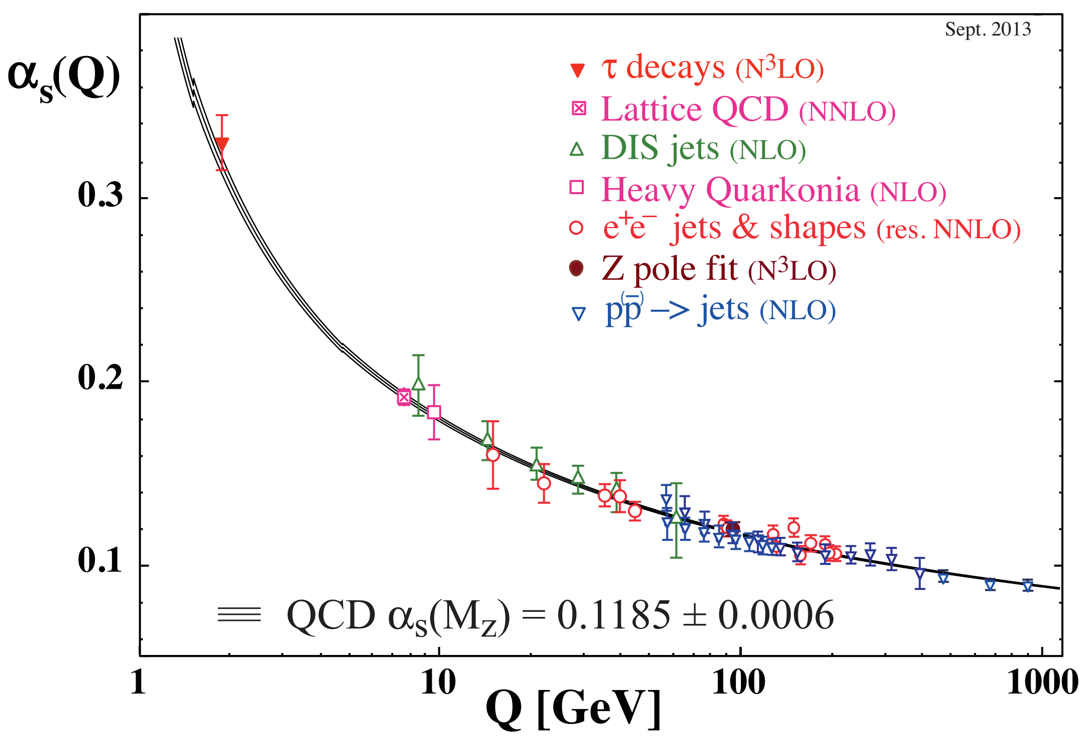
CINP Town Hall Meeting

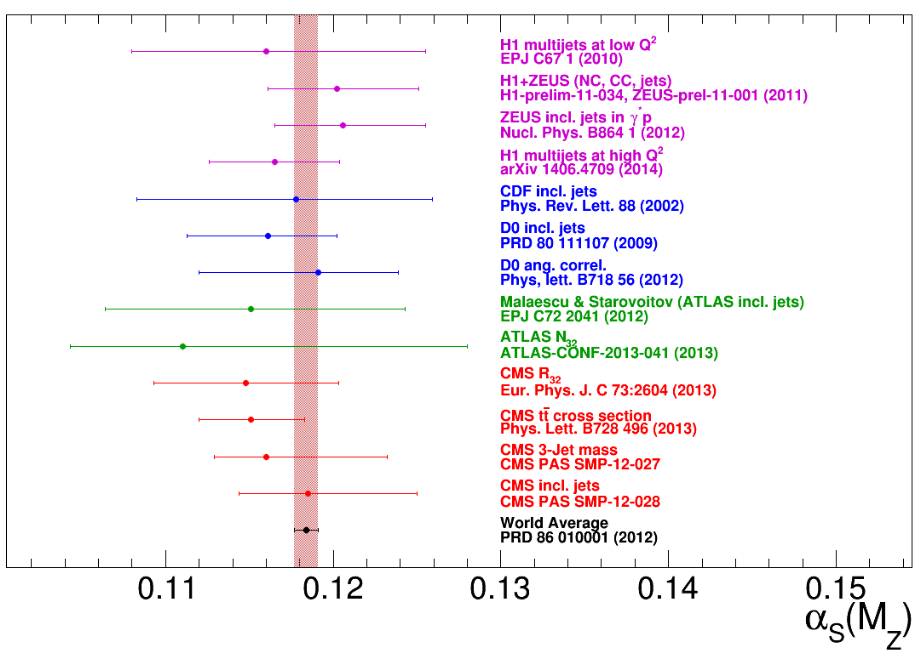
Charles Gale & Sangyong Jeon

McGill University

THE PROPERTIES OF STRONGLY INTERACTING SYSTEMS ARE DICTATED BY QCD

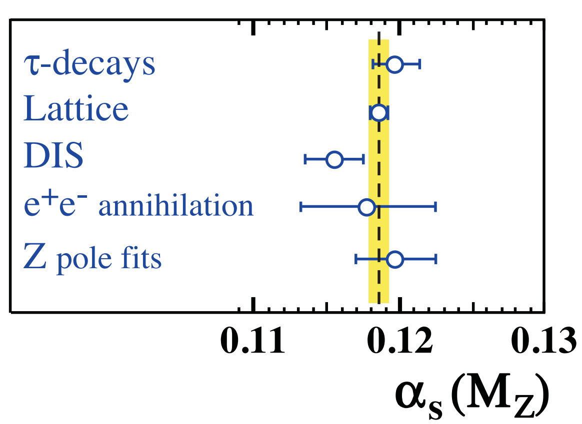
- Asymptotic freedom subtends the quantitative success and predictive power of a perturbation treatment, at high momenta or short distances. At long distances, infrared slavery





M. Mavromanolakis, ICHEP 2014

PDG (2013)



$$\alpha_s^{PDG} = 0.1185 \pm 0.0006$$

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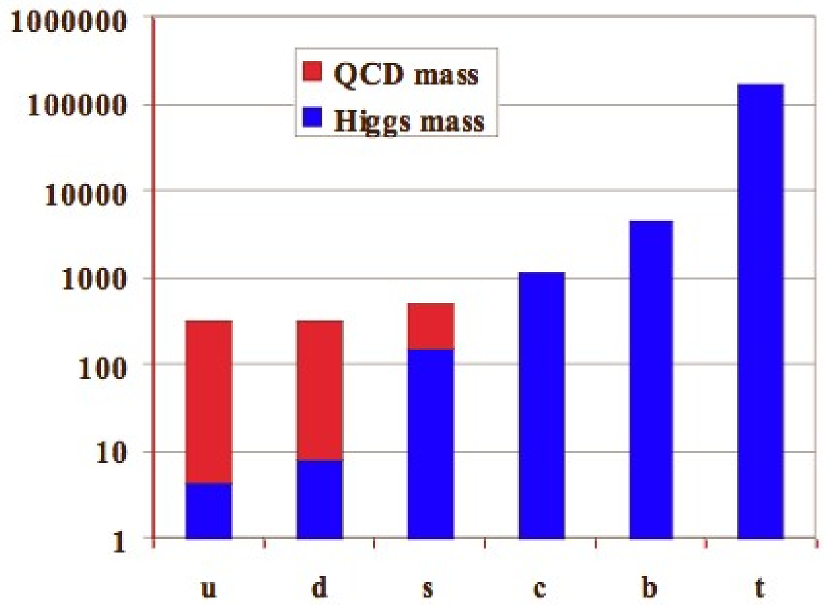
THE PROPERTIES OF STRONGLY INTERACTING SYSTEMS ARE DICTATED BY QCD (CONTN'D)

- A concise Lagrangian that yet yields a wide spectrum of phenomenology
- The QCD vacuum is characterized by condensates that spontaneously break chiral symmetry. As temperature increases, the symmetry is restored

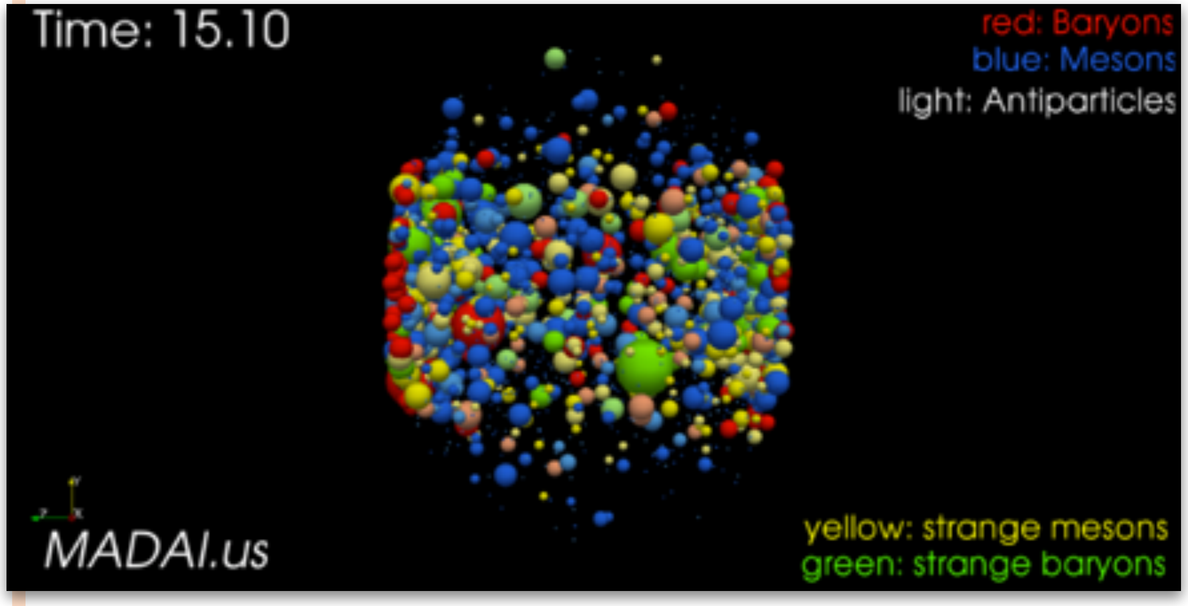


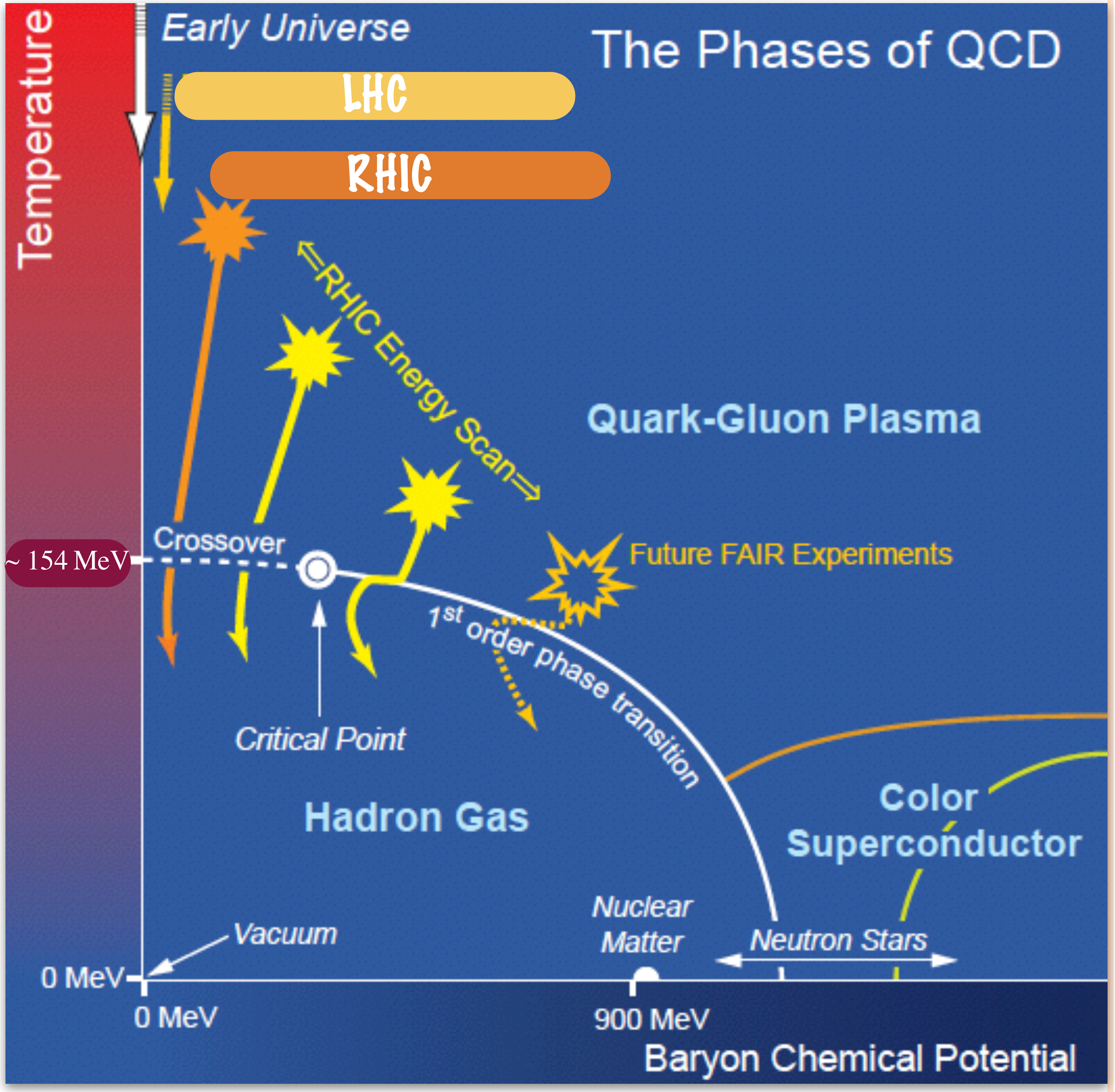
$$\langle \bar{\psi}\psi \rangle \neq 0$$

- What is the bulk behaviour of QCD? What are its collective features?
  - What is its phase diagram?

The QCD phase diagram

- Colliding heavy-ions (large nuclei) is the only practical way of heating and compressing nuclear matter in the laboratory





- Implies a time-dependent sampling of the phase diagram

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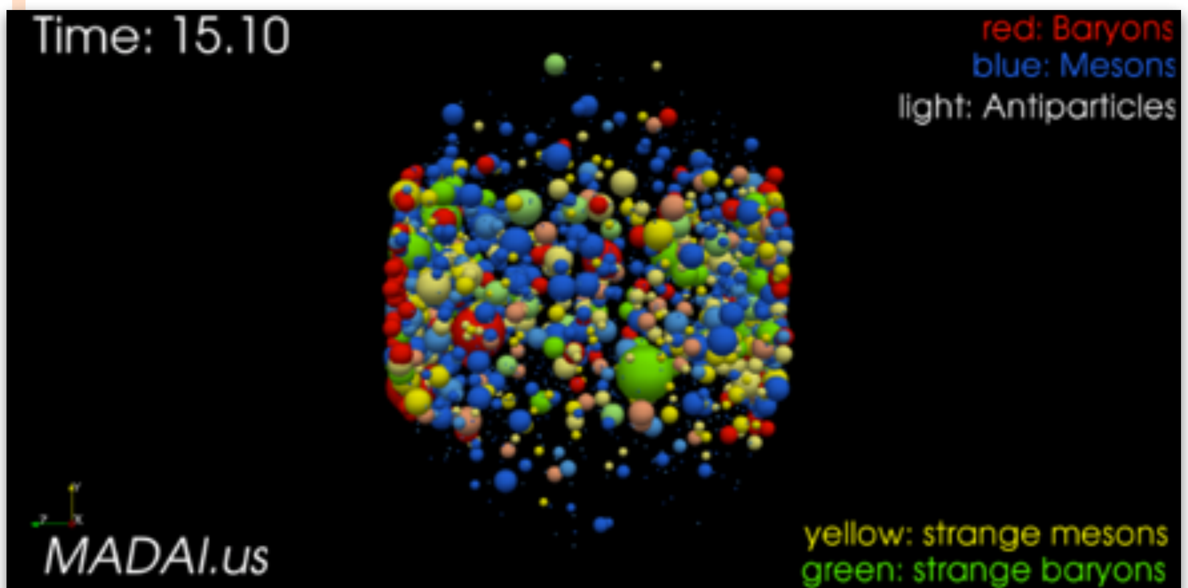
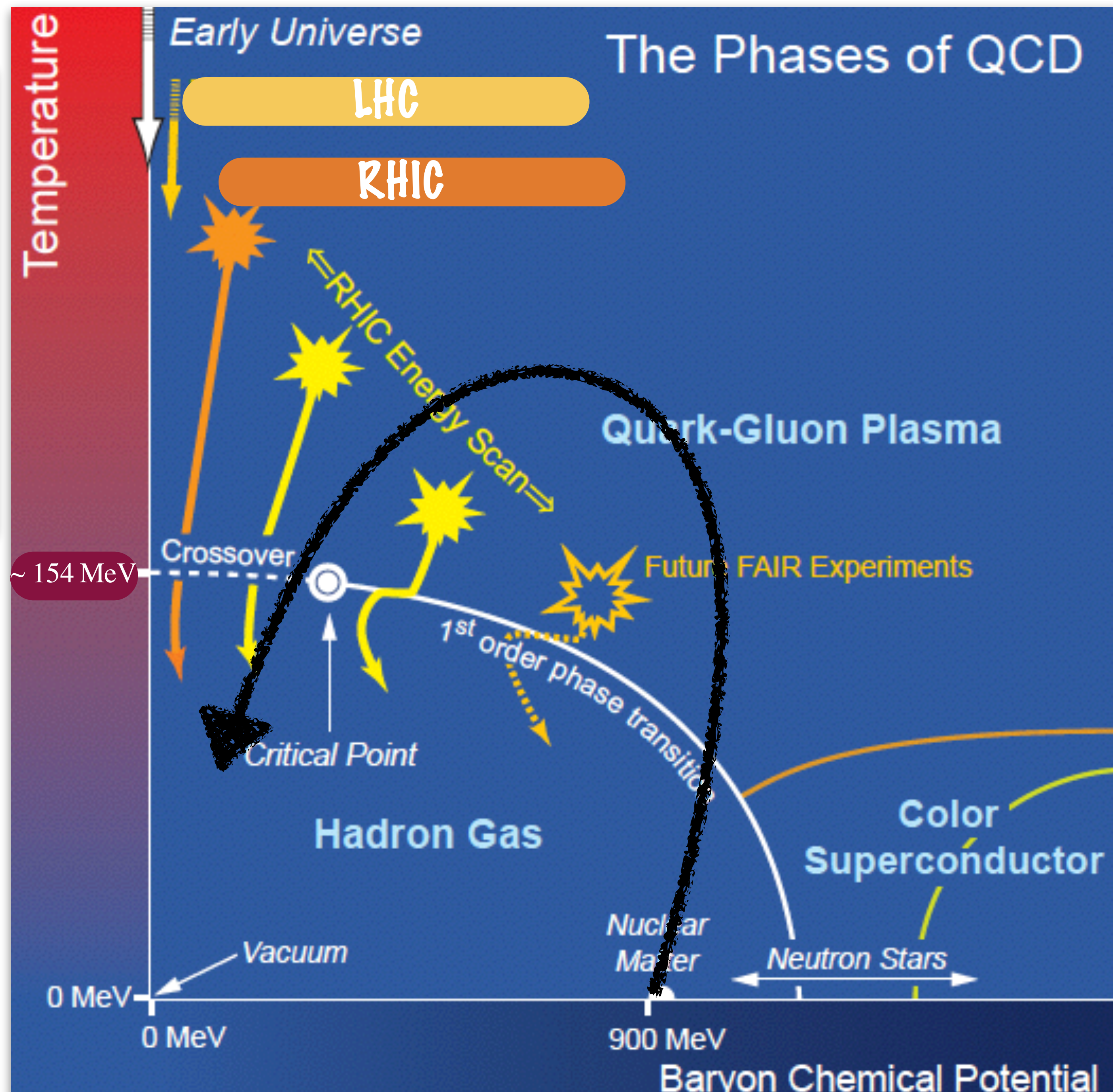
The QCD phase diagram

- Colliding heavy-ions (large nuclei) is the only practical way of heating and compressing nuclear matter in the laboratory



- Implies a time-dependent sampling of the phase diagram



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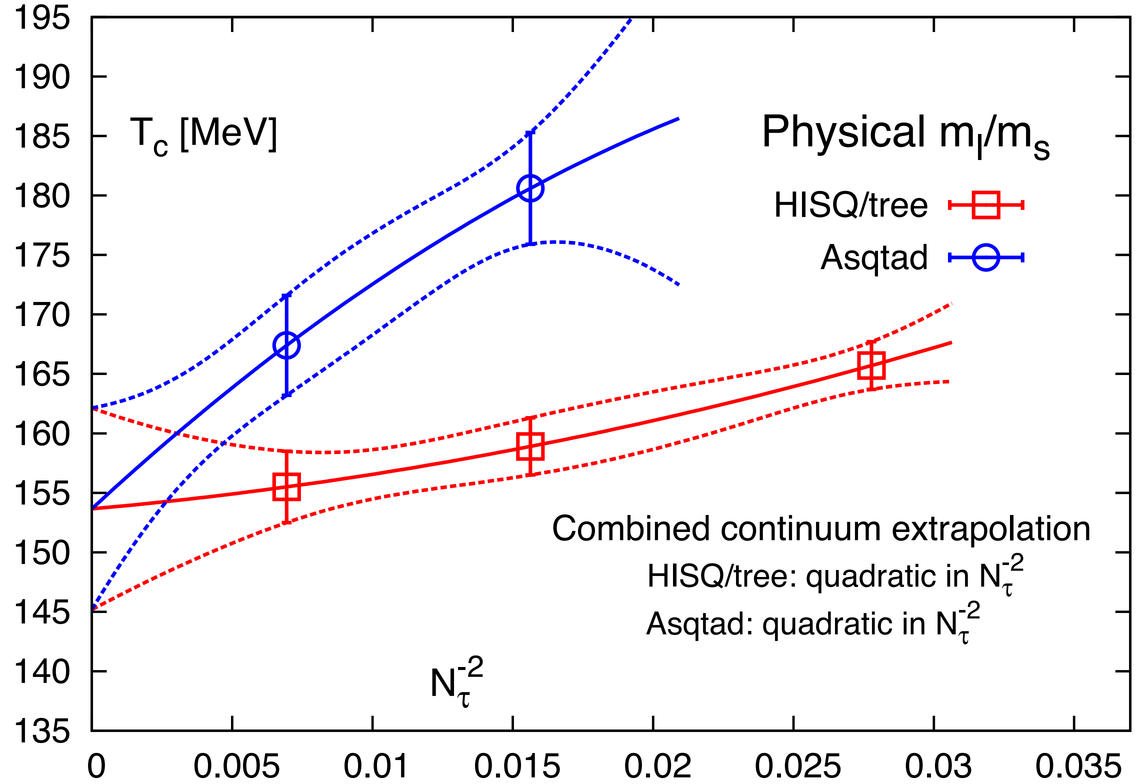
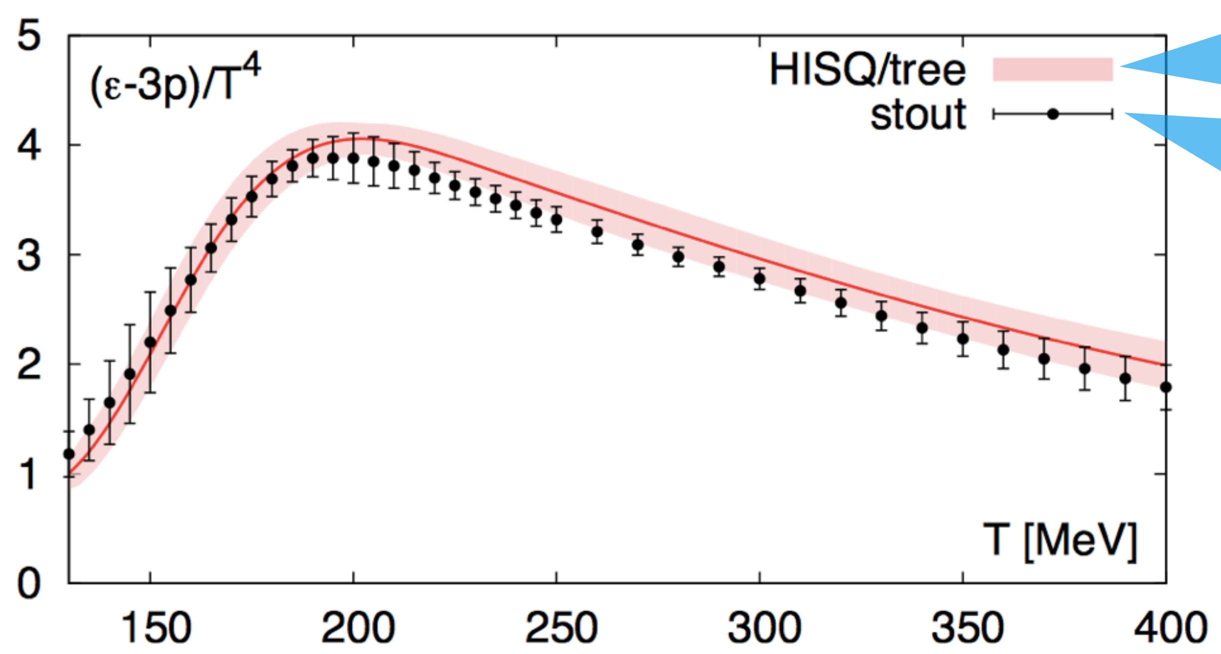
What is known from lattice QCD

- Wuppertal-Budapest/hotQCD difference in T_c resolved



$$T_c = 154 \pm 9\,\mathrm{MeV}$$

Transition at μ_B=0 is a cross-over

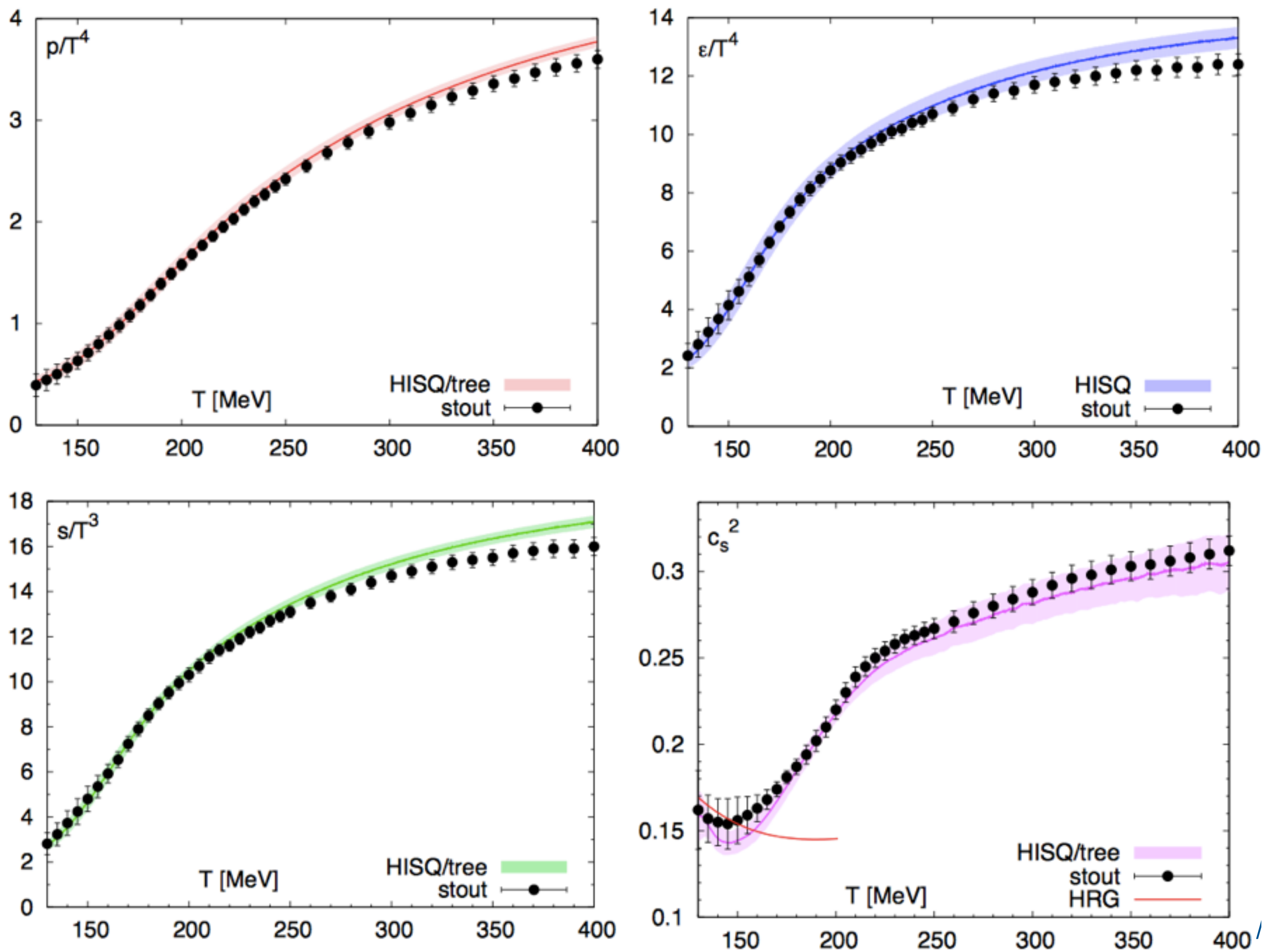


hotQCD

WB

A. Bazavov, QM 2014

Agreement extends to main thermodynamic equilibrium variables

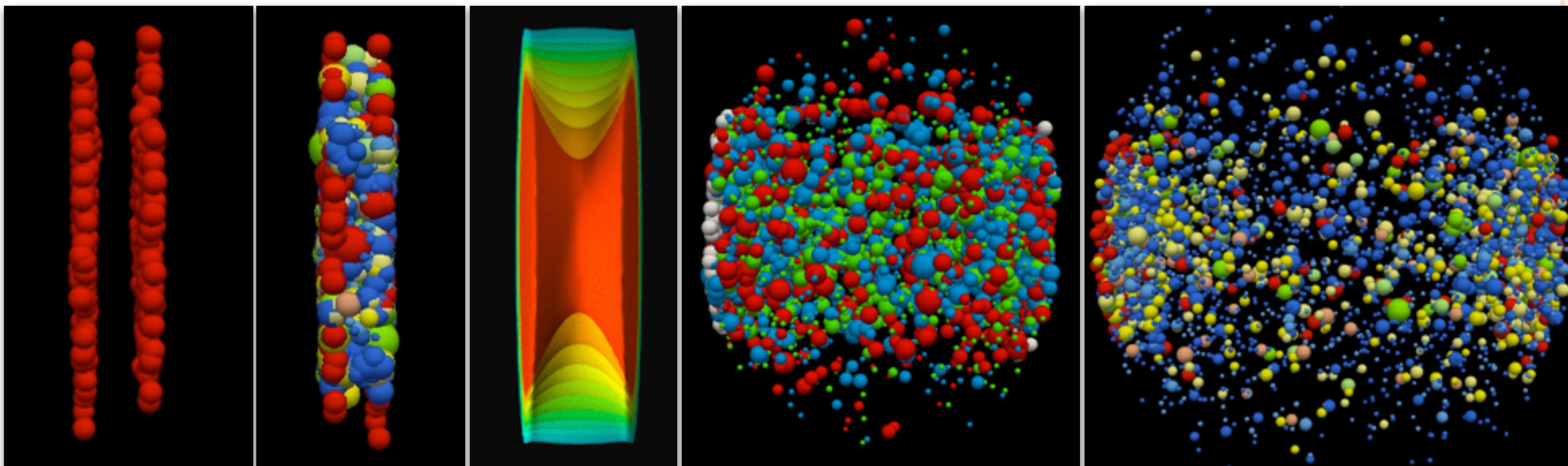


EOS @ μ_B=0 under control

Charles Gale

COLLECTIVITY IN RELATIVISTIC HEAVY-ION COLLISIONS

- The establishment of a "standard picture" of high-energy heavy-ion collisions

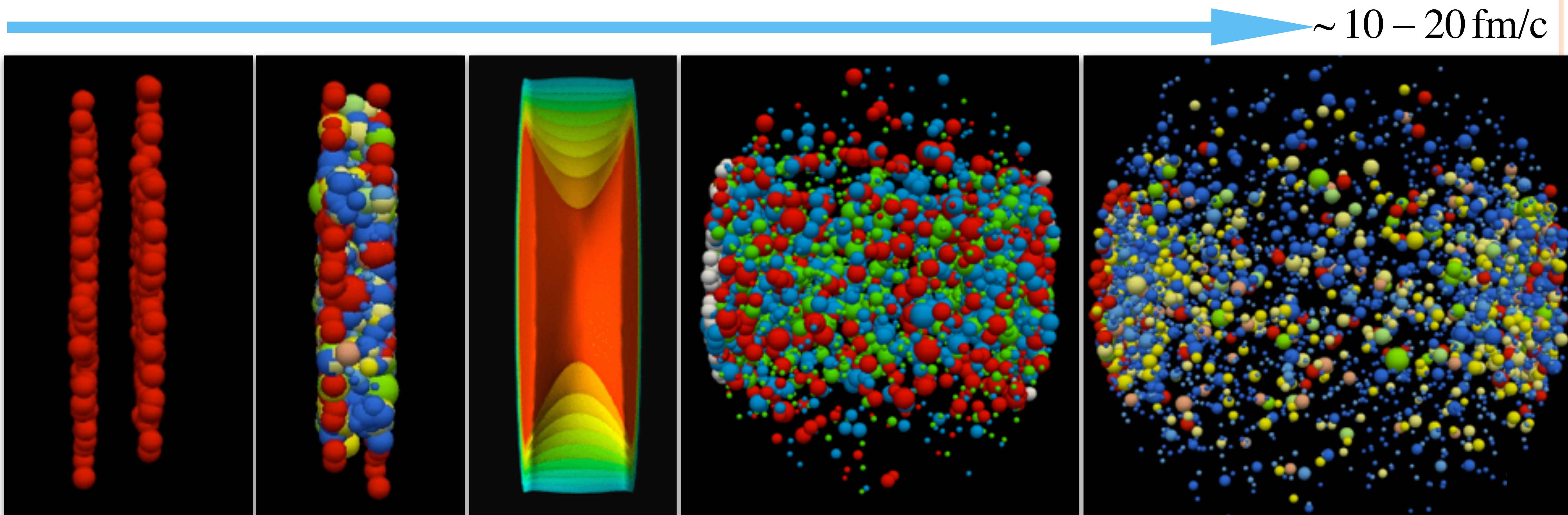


Initial state | Pre-equilibrium | QGP | Hadronization | Thermal freeze-out

Glasma

COLLECTIVITY IN RELATIVISTIC HEAVY-ION COLLISIONS

- The establishment of a "standard picture" of high-energy heavy-ion collisions



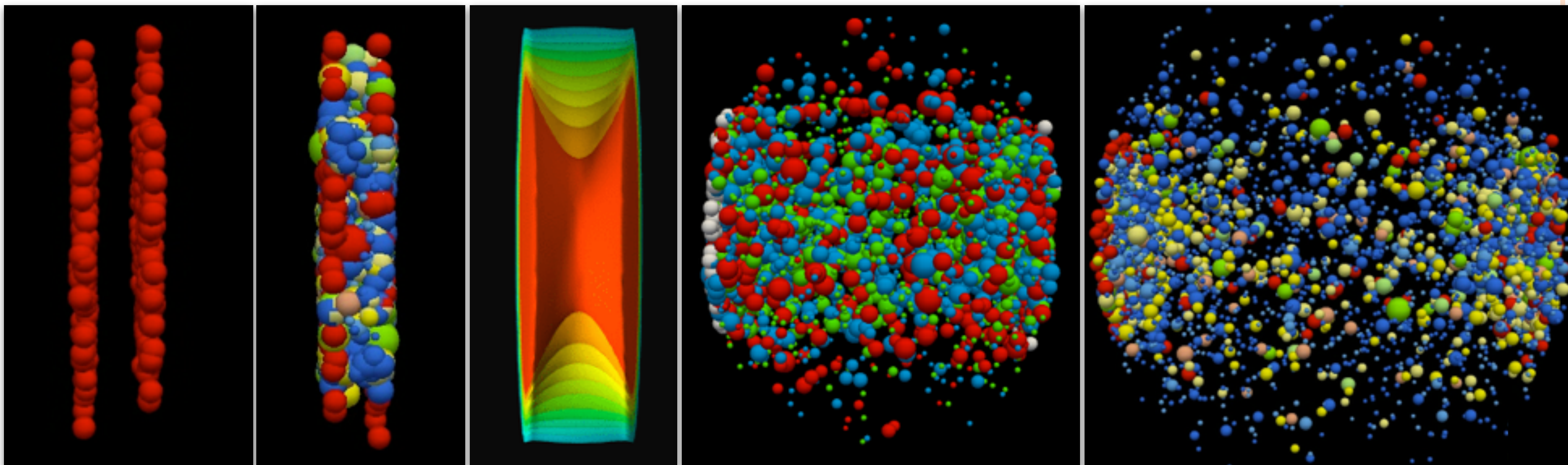
Initial state | Pre-equilibrium | QGP | Hadronization | Thermal freeze-out

Glasma

COLLECTIVITY IN RELATIVISTIC HEAVY-ION COLLISIONS

- The establishment of a "standard picture" of high-energy heavy-ion collisions

$\sim 10 - 20\,\mathrm{fm/c}$



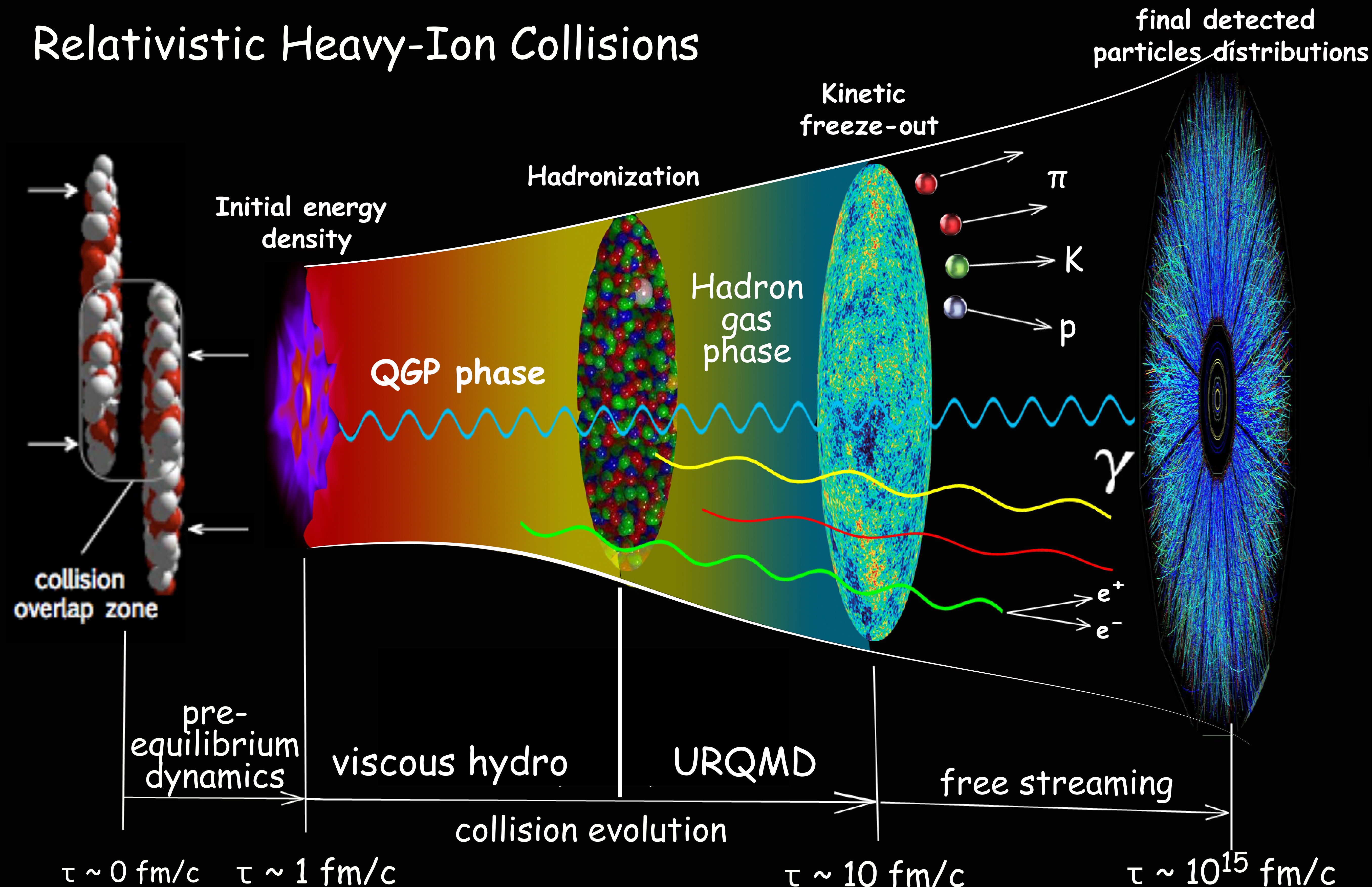
Initial state | Pre-equilibrium | QGP | Hadronization | Thermal freeze-out

Glasma

Relativistic hydrodynamics

Little Bang

(Chun Shen)



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

- Viscous relativistic fluid dynamics

$$T^{\mu\nu}_{\rm ideal} = (\varepsilon + P) u^\mu u^\nu - P g^{\mu\nu} \qquad T^{\mu\nu} = T^{\mu\nu}_{\rm ideal} + \pi^{\mu\nu}$$

- To first order in the velocity gradient: Navier-Stokes
- To second order: Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

$$\pi^{\mu\nu} = \eta \nabla^{<\mu} u^{\nu>} - \tau_\pi \left[\Delta^\mu_\alpha \Delta^\nu_\beta D \pi^{\alpha\beta} + \frac{4}{3} \pi^{\mu\nu} (\nabla_\alpha u^\alpha) \right]$$

$$(\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu, \quad D = u^\mu \partial_\mu)$$

η is the shear viscosity

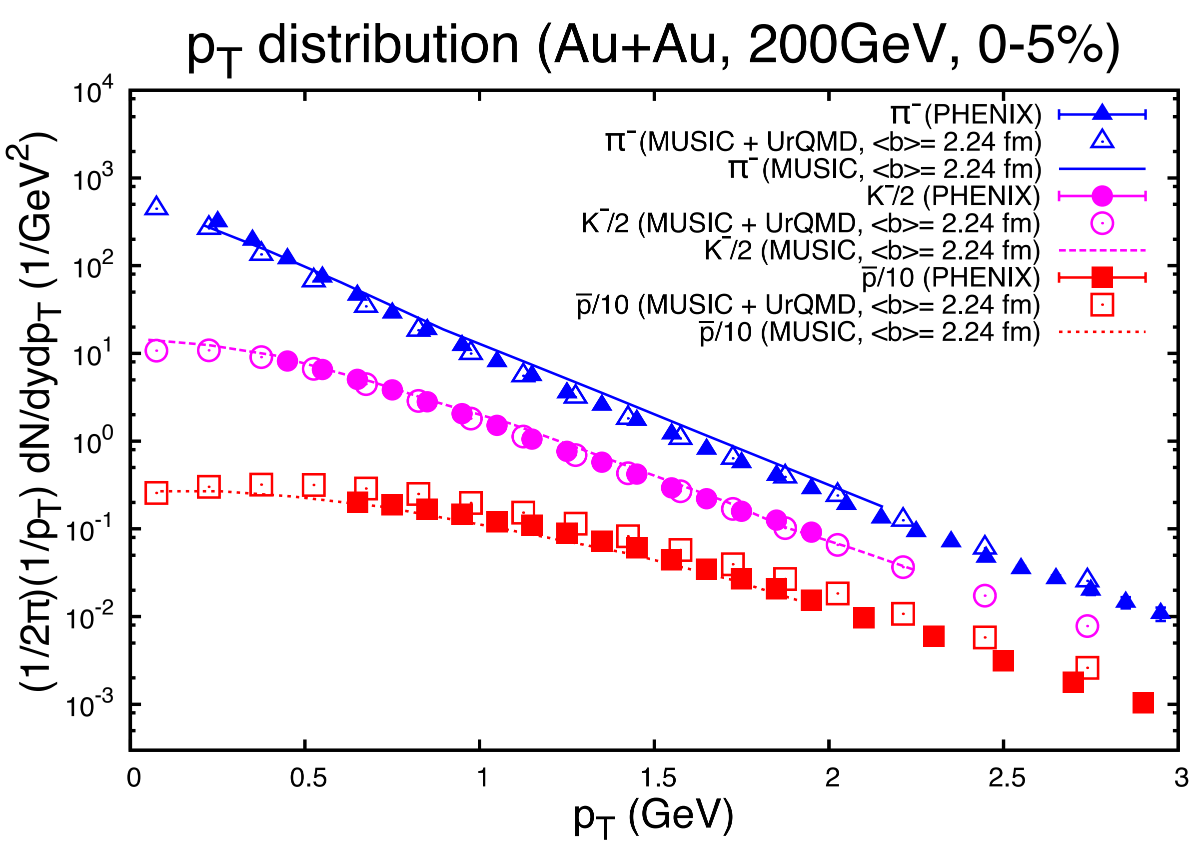
- Measures the resistance to deformation
- Is a fundamental property of QCD

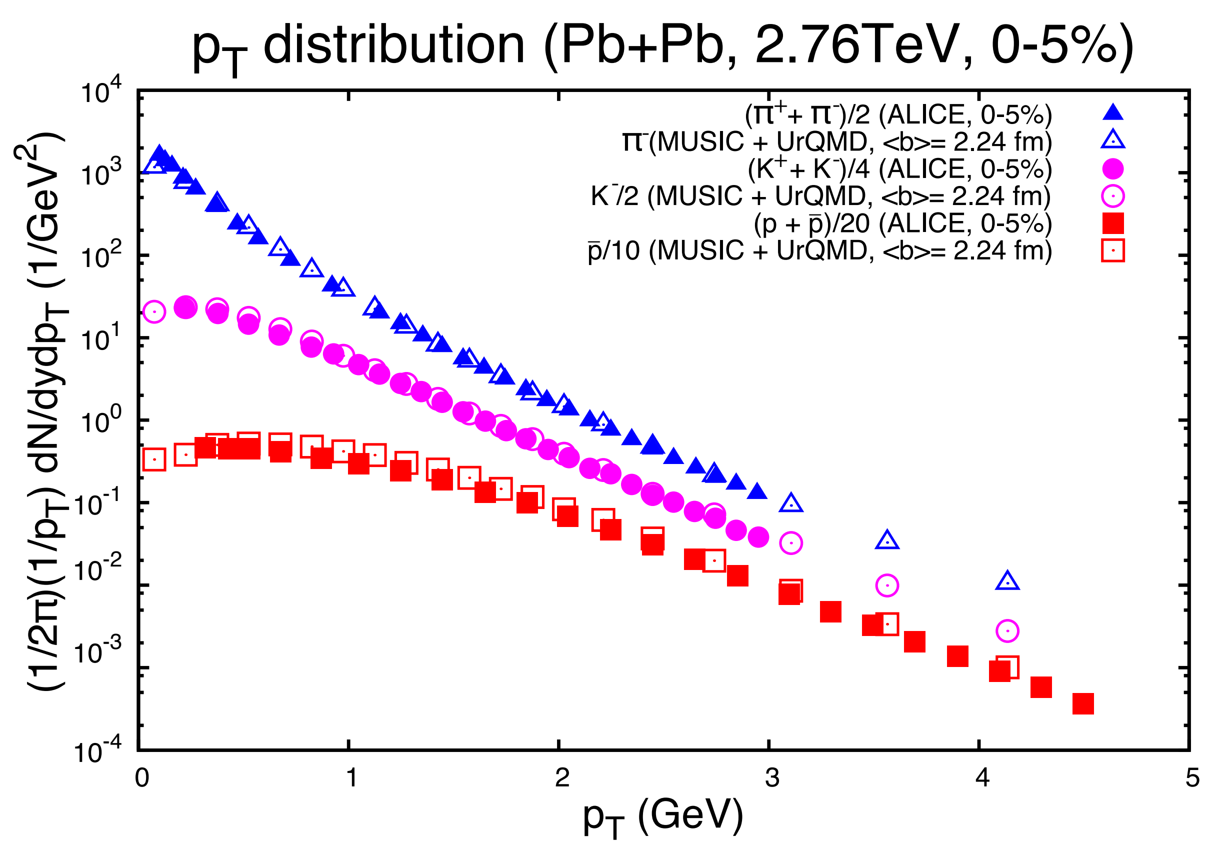
Relativistic hydrodynamics: An effective theory for the soft, long wavelength, modes

$$T^{\mu\nu} = T^{\mu\nu}_{\text{id}} + \pi^{\mu\nu} \qquad T^{\mu\nu}_{\text{id}} = (\epsilon + P)u^{\mu}u^{\nu} - g^{\mu\nu}P$$

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

+ lQCD EOS





MUSIC: 3D relativistic hydro: Schenke, Jeon, and Gale, Int. J. Mod. Phys. A (2013)

Assessing collectivity further:
The differential single-particle spectrum

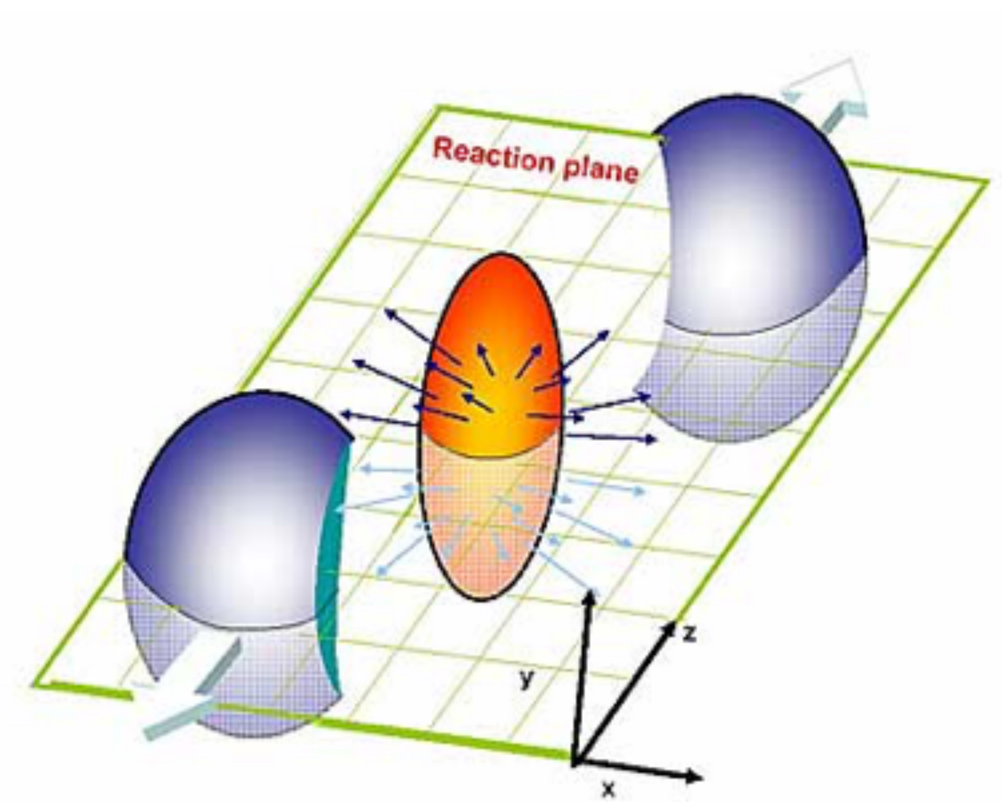
Quantifying the azimuthal asymmetries

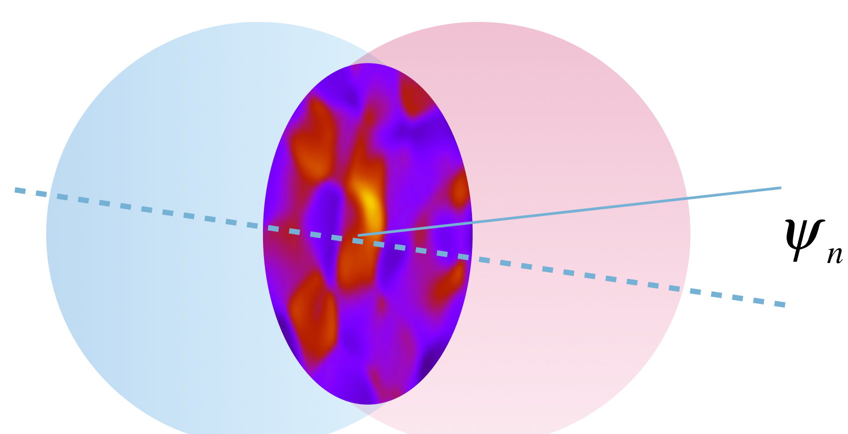
$$\frac{d^3N}{dy\,d^2p_T} = \frac{1}{\pi}\frac{d^2N}{dy\,dp_T^2}\left[1+2\sum_{n=1}^{\infty} v_n(p_T)\cos n(\phi-\psi_n)\right]$$

v_1 = Directed flow

v_2 = Elliptic flow

v_3 = Triangular flow





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

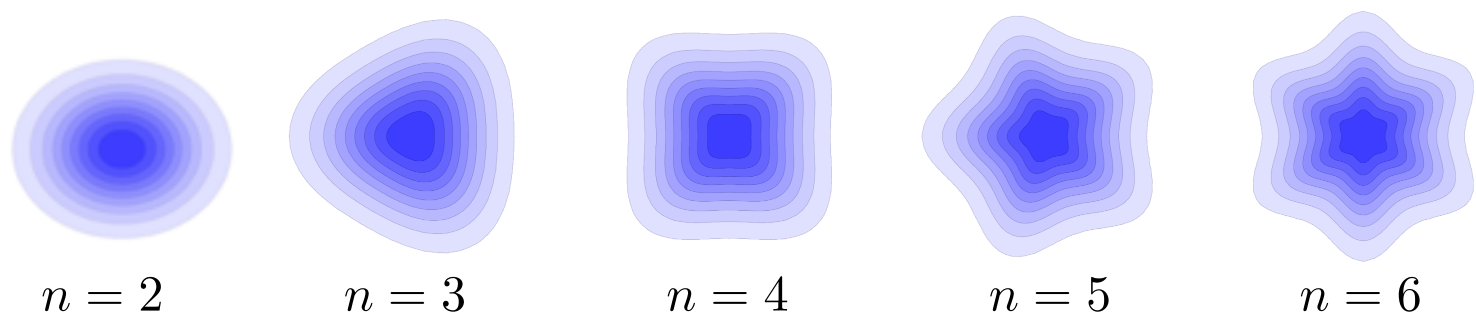
$$\nabla P(\Leftrightarrow) > \nabla P(\Updownarrow)$$

Anisotropies in coordinate space generate those in momentum space

Charles Gale
McGill

The relativistic hydro, continued

Flow pattern harmonics:



The current state-of-the-art fluid dynamical modelling:

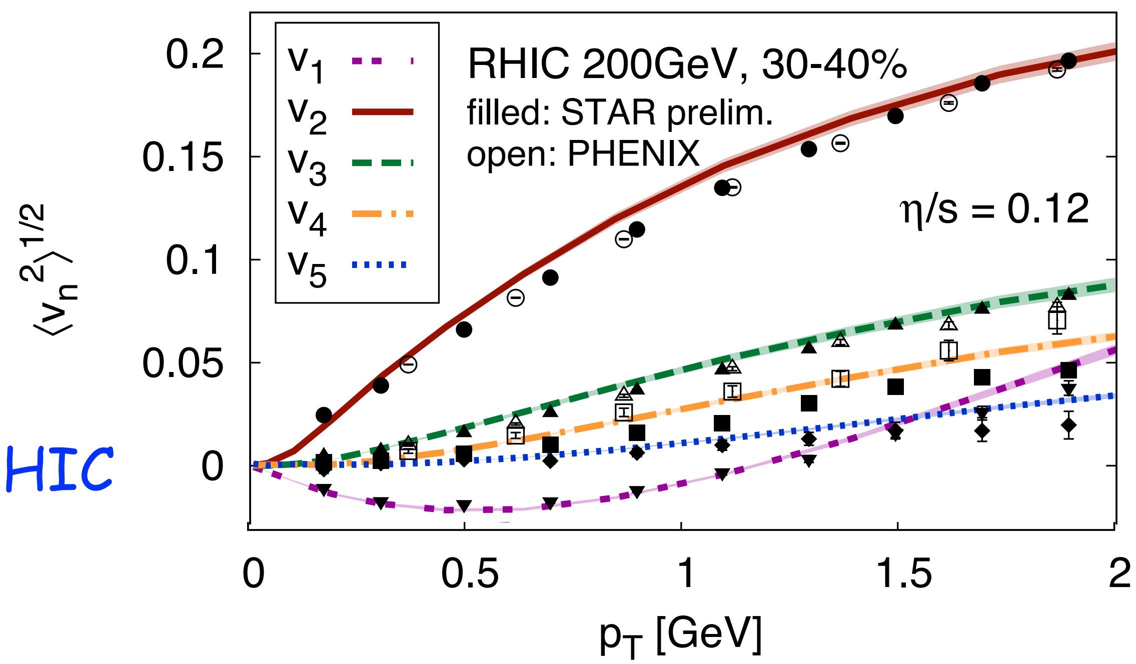
- Allows deviations from thermal equilibrium
- Includes fluctuations of initial states event-by-event; may use different initial states
- Does not explain thermalization

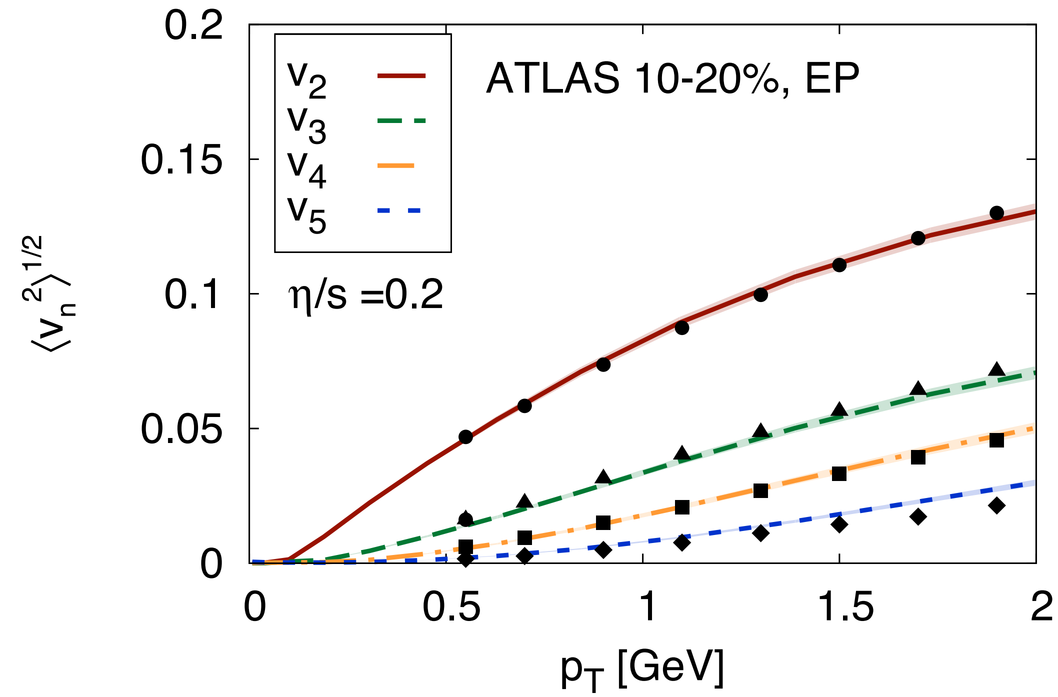
Gélis and Epelbaum, PRL (2013)

Berges, Boguslavski, Schlichting, Venugopalan, PRD (2014)

The story so far

RHIC





LHC

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

RHIC LHC

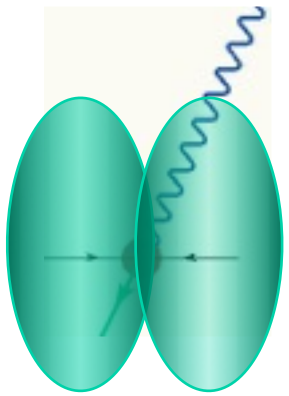
$$0.12 \leq \eta / s \leq 0.21$$

RHIC and the LHC are viscometers!

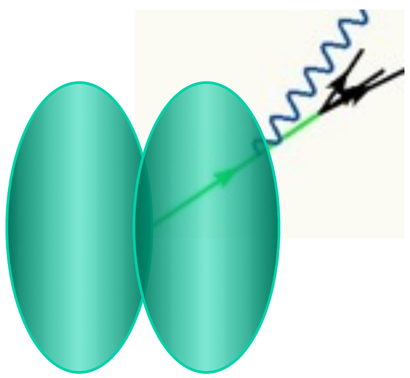
How about getting at the temperature?

Need a <u>penetrating probe</u> (tomography), with little final-state interaction:

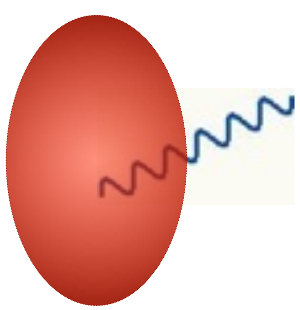
Photons (real and/or virtual)



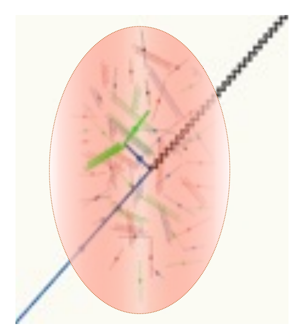
Hard direct photons. pQCD with shadowing
Non-thermal



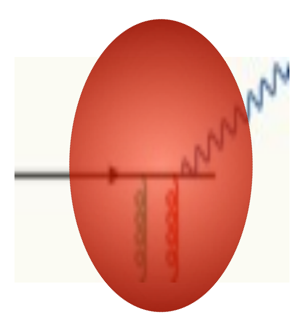
Fragmentation photons. pQCD with shadowing
Non-thermal



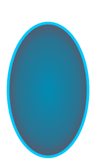
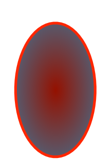
Thermal photons
Thermal



Jet-plasma photons
Thermal



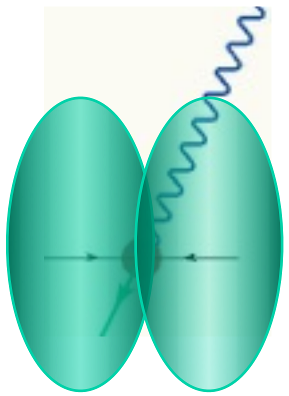
Jet in-medium bremsstrahlung
Thermal

 Pre-equilibrium? 

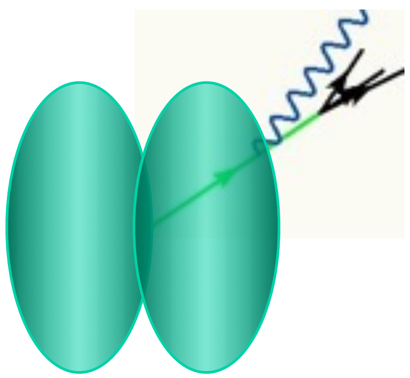
HOW ABOUT GETTING AT THE TEMPERATURE?

Need a penetrating probe (tomography), with little final-state interaction:

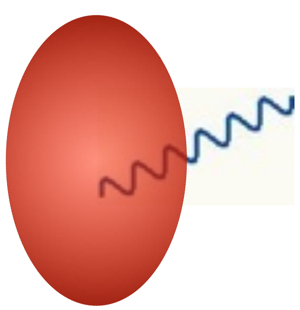
Photons (real and/or virtual)



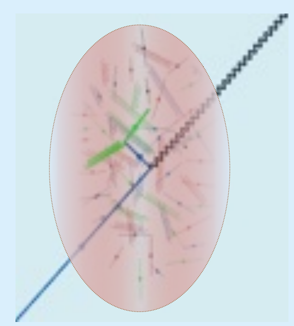
Hard direct photons. pQCD with shadowing
Non-thermal



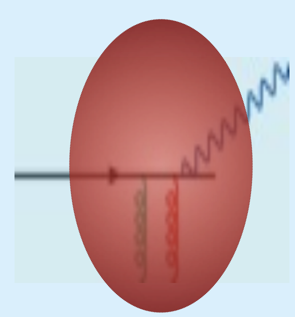
Fragmentation photons. pQCD with shadowing
Non-thermal



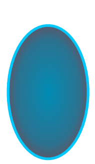
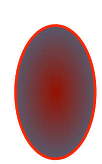
Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

 Pre-equilibrium? 

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Info Carried by the thermal radiation

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times \langle f | J_\mu | i\rangle\langle i | J_\nu | f\rangle$$

Thermal ensemble average of the current-current correlator

Emission rates:

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

$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(dileptons)}$$

Feinberg (76); McLerran, Toimela (85); Weldon (90); Gale, Kapusta (91)

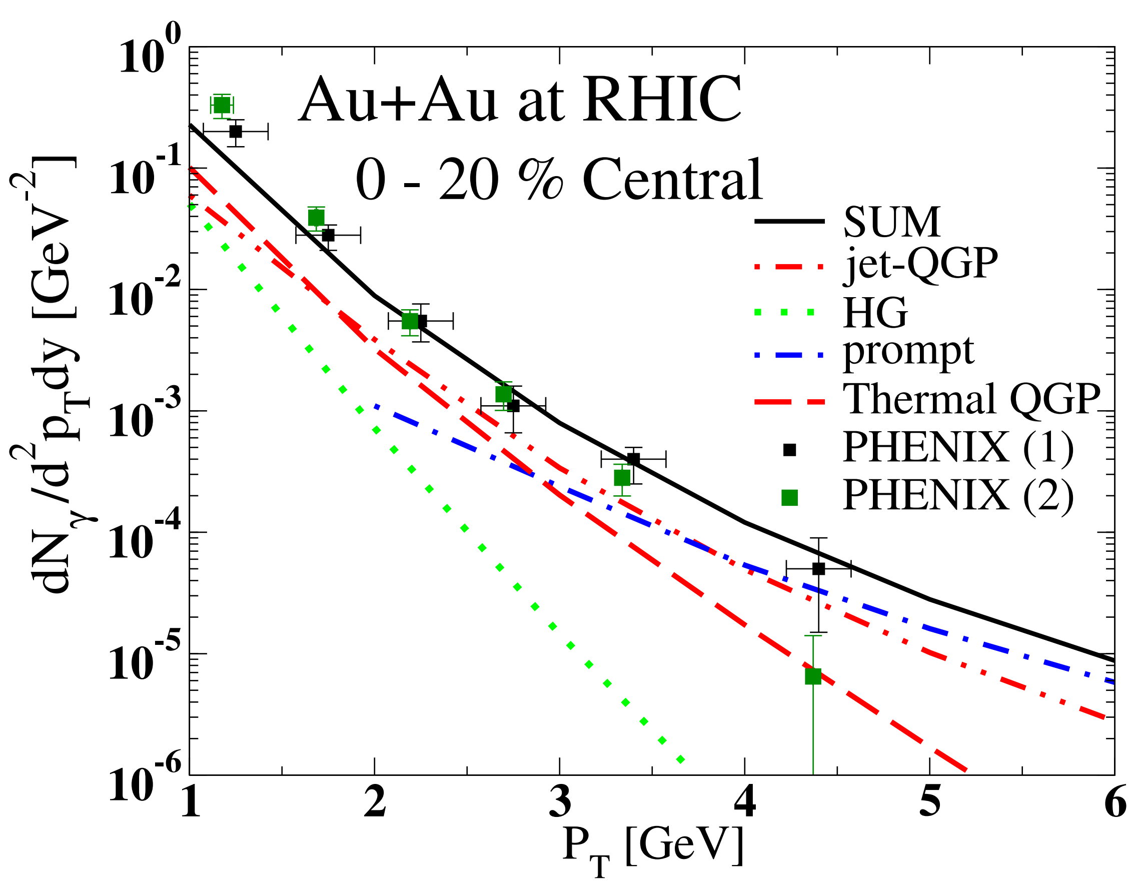
- QGP rates have been calculated up to NLO in α_s in FTFT:
  Ghiglieri et al., JHEP (2013); M. Laine JHEP (2013)

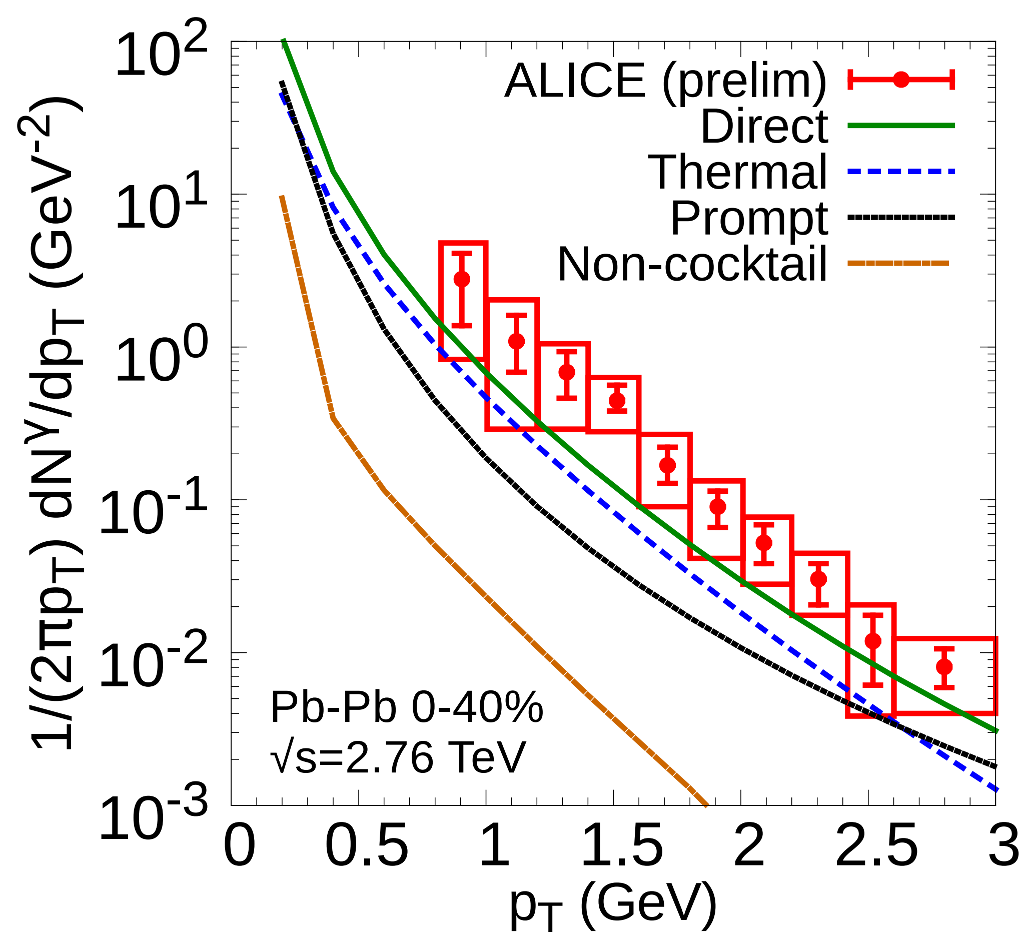
  ...and on the lattice:
  Ding et al., PRD (2011)

- Hadronic rates: Turbide, Rapp, Gale PRC (2009)

Rates are integrated using relativistic hydrodynamic modelling

- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD

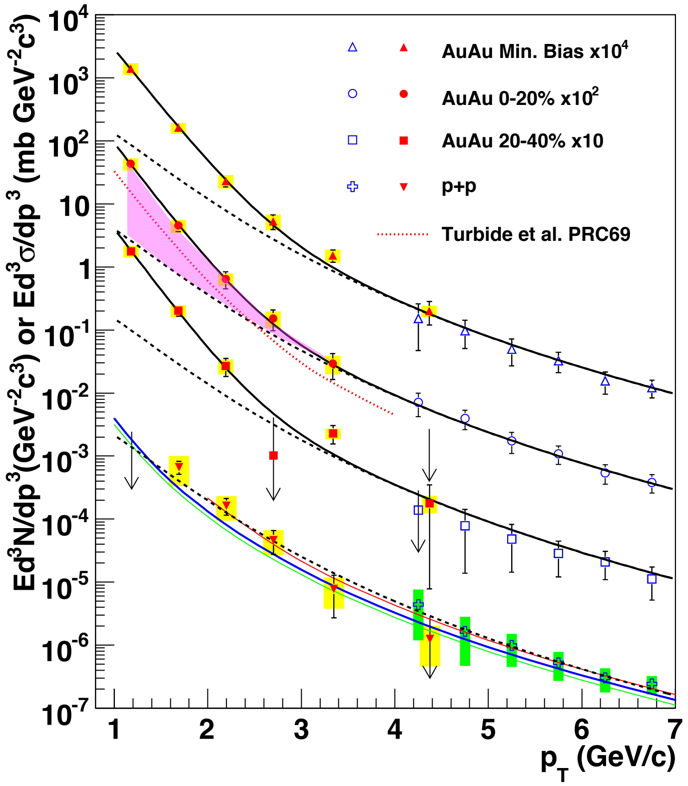


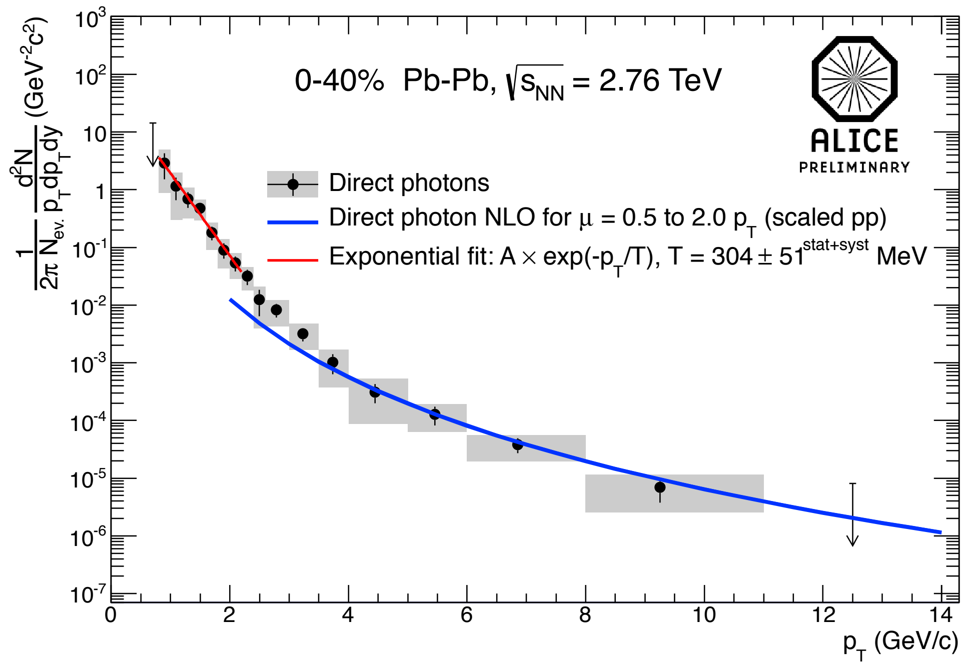


Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

J.-F. Paquet PhD (2015), and to be published

Getting to the temperature with photons





$T^{\text{PHENIX}}_{\text{excess}}(\text{RHIC}) = 239 \pm 25 \pm 7\,\text{MeV}$

$T^{\text{ALICE}}_{\text{excess}}(\text{LHC}) = 304 \pm 51\,\text{MeV}$

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Shen, Heinz, Paquet, Gale, PRC (2014)

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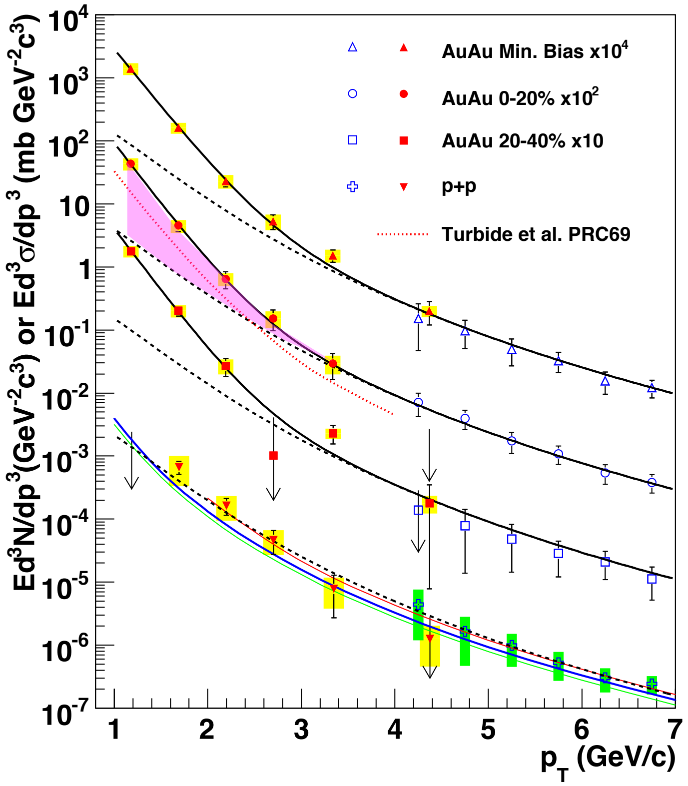
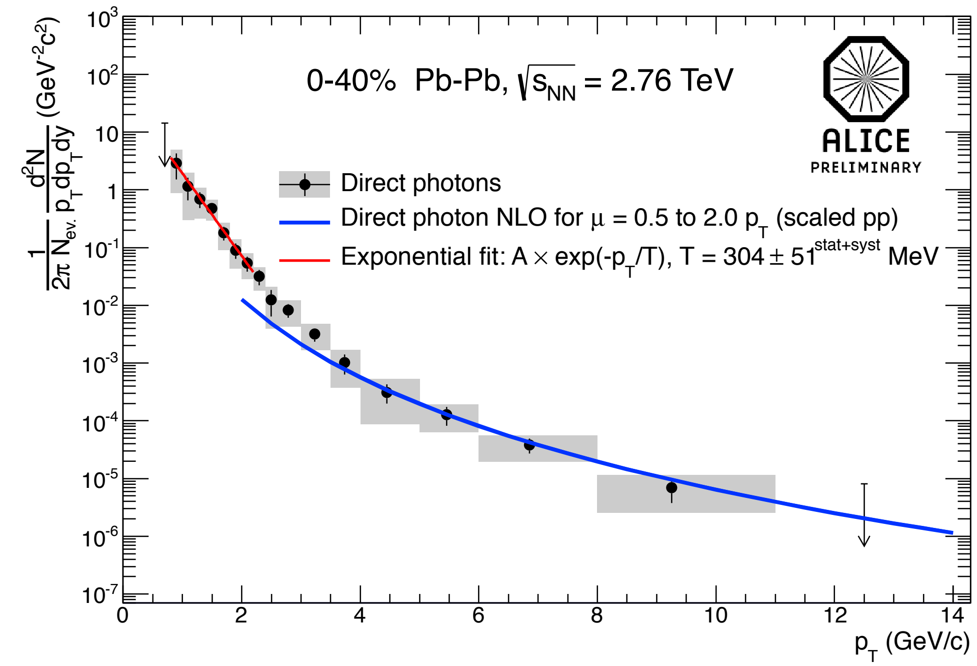




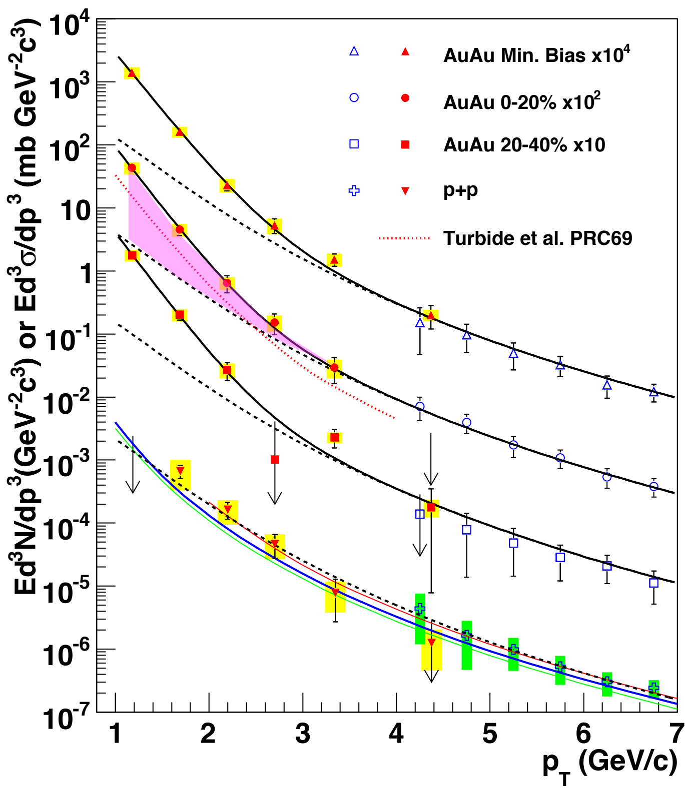
$T^{\rm PHENIX}_{\rm excess}({\rm RHIC}) = 239 \pm 25 \pm 7\,{\rm MeV}$

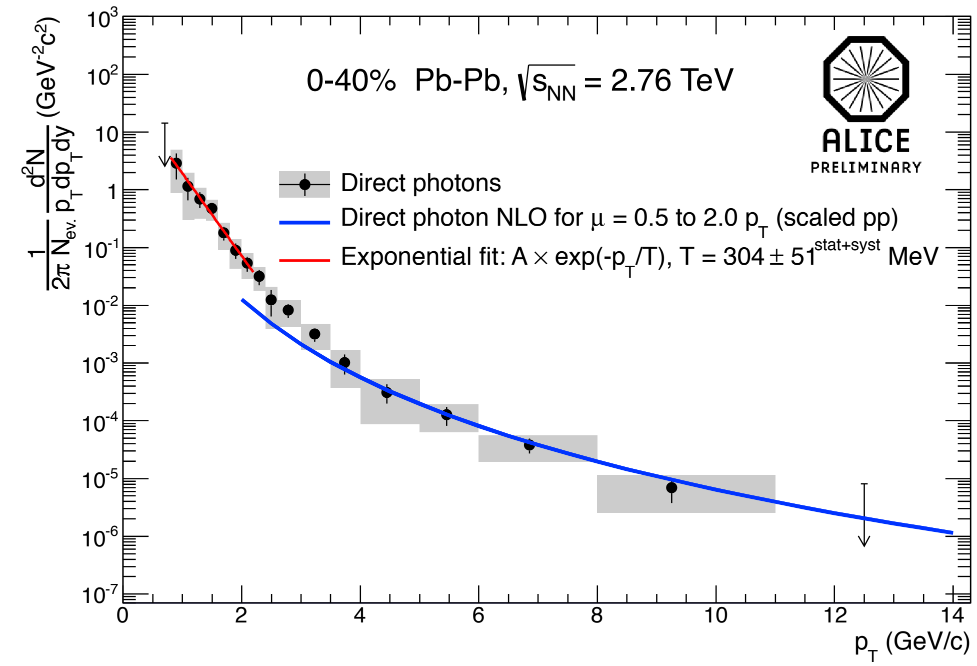
$T^{\rm ALICE}_{\rm excess}({\rm LHC}) = 304 \pm 51\,{\rm MeV}$

range of photon emission	fraction of total photon yield	
	AuAu@RHIC 0-20% centr.	PbPb@LHC 0-40% centr.
T = 120-165 MeV	17%	15%
T = 165-250 MeV	62%	53%
T > 250 MeV	21%	32%
$\tau = 0.6 - 2.0$ fm/c	28.5%	26%
$\tau > 2.0$ fm/c	71.5%	74%

Shen, Heinz, Paquet, Gale, PRC (2014)

Getting to the temperature with photons





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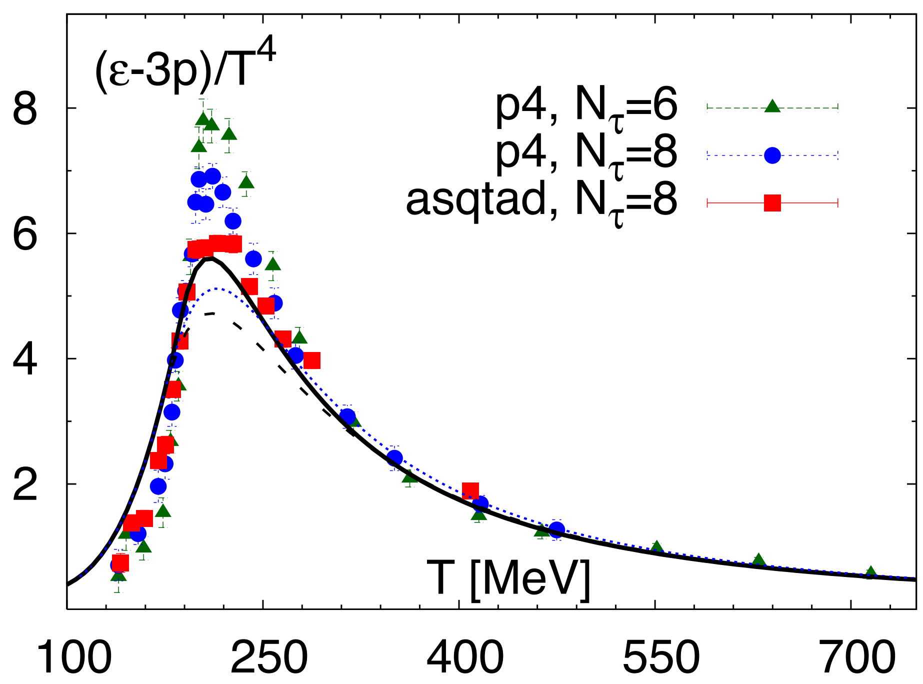
RHIC and the LHC are plasma thermometers and viscometers

Shen, Heinz, Paquet, Gale,PRC (2014)

THE FUTURE: (MUCH) MORE TO COME



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

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

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

The dissipative terms, to second order:

$$\Delta T^{\mu\nu} = \mathfrak{F}^{\mu\nu}[\eta, \zeta, \chi]$$

Moore and Sohrabi PRL (2011), JHEP (2012)
Molnar, Niemi, Denicol, and Rischke, PRD (2014)

- Our next generation of calculations will be able to simultaneously obtain shear **and** bulk viscosities, together with initial state properties (no current calculations incorporate all of these)
- pA program constitutes a missing link in the AA program
- The hydro description - essential in the determination of QGP properties - is still very much in evolution!
- Jet photons, dileptons, photon and dilepton flow

CINP ICPN

Charles Gale

Excellent opportunities for HQP
C. Gale, S. Jeon

- PDF
  - C. Shen (2014 -)
  - G. Denicol, *Banting Fellow* (2012 -)
  - M. Luzum (2012 - 13)
  - C. Young (2010 - 12)
  - T. Springer (2009 - 11)
  - J. Ruppert (2006 - 08)
  - S. Turbide (2006 - 07)
  - G. Torrieri (2004 - 06)
  - P. Jaikumar (2002 - 04)
- PHD
  - M. Singh (2015 -)
  - I. Kozlov (2010 -)
  - M. Richard (2010 -)
  - S. Ryu (2015)
  - J.-F. Paquet (2015)
  - G. Vujanovic (2015)
  - M. Mia (2011)
  - F. Fillion-Gourdeau (2009)
  - G. Qin (2008)
  - A. Bourque (2008)
  - S. Gagnon (2007)
  - S. Turbide (2006)
- MSc
  - S. Hauksson (2015 -)
  - S. Macdonald (2015 -)
  - S. Park (2013 -)
  - J.-B. Rose (2015)
  - K. El-Berouhmi (2014)
  - H. L. Gervais (2012)
  - J.-F. Paquet (2011)
  - S. Ryu (2011)
  - M. Dion (2011)
  - J. Coull (2011)
  - M. Richard (2010)
  - M. Cautun (2009)
  - R. Labrecque (2009)
  - A. Winkels (2009)
  - G. Vujanovic (2008)
  - M. Mia (2007)