QCD under extreme conditions: Hot, shiny fluids and sticky business

Charles Gale McGill University

Canadian Association of Physicists
Association canadienne des physiciens et physiciennes

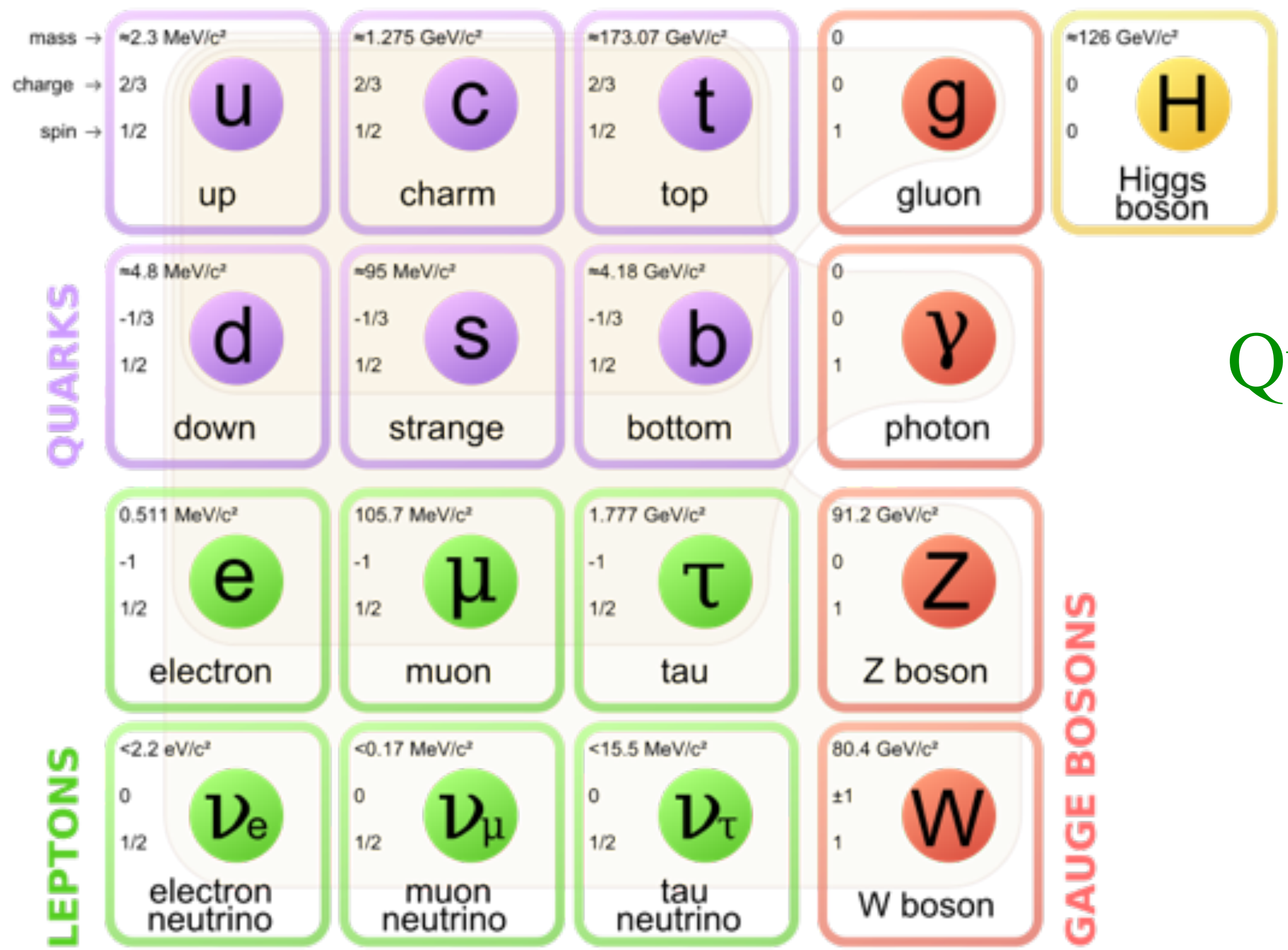
[Image: physics.org]

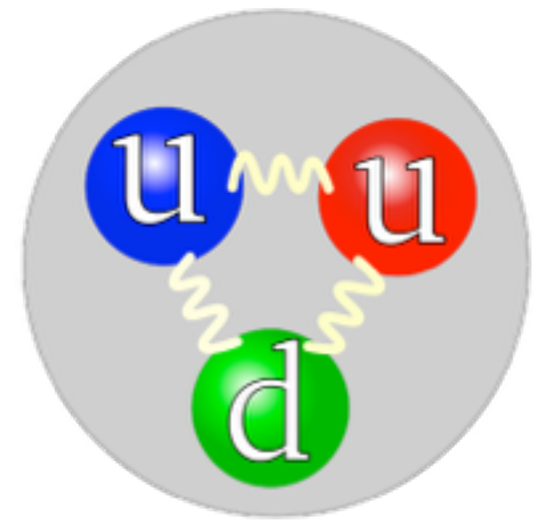
Outline

- The study of nuclear ("heavy ions") collisions furthers our understanding of the bulk features of QCD. Characterizing the quark-gluon plasma.
  - How do we do this?
    - Observe the collective hadronic dynamics
    - Send penetrating probes & observe response: Tomography
- The RHIC and LHC heavy-ion programs: Surprises and new physics
  - The quantitative success of relativistic hydrodynamics
  - RHIC and the LHC as viscometers
  - RHIC and the LHC as thermometers
- Conclusion

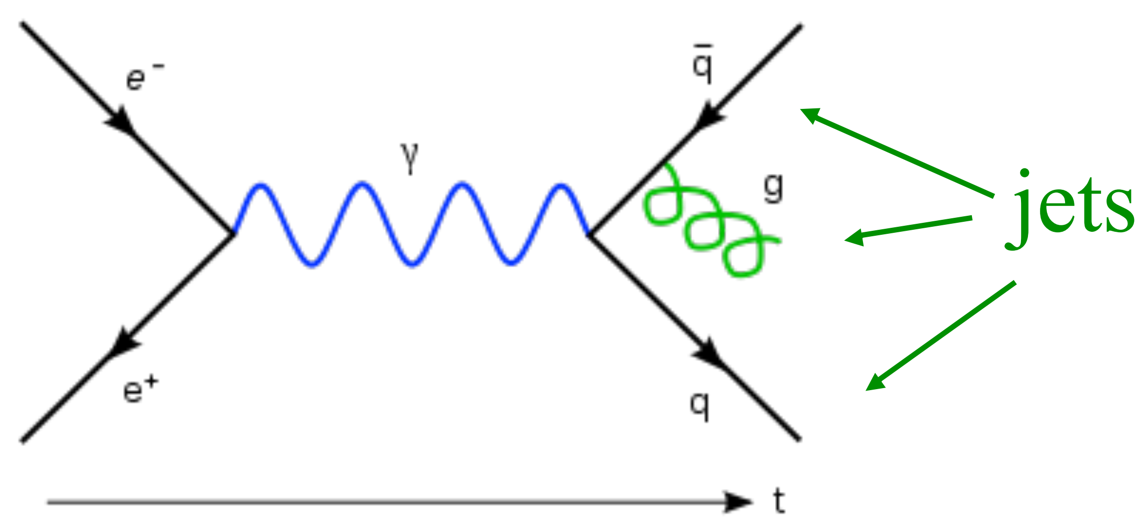
The theory of the strong interaction is QCD (Quantum ChromoDynamics)

The cast of characters:





Quark structure of the proton



Bosons mediate interaction

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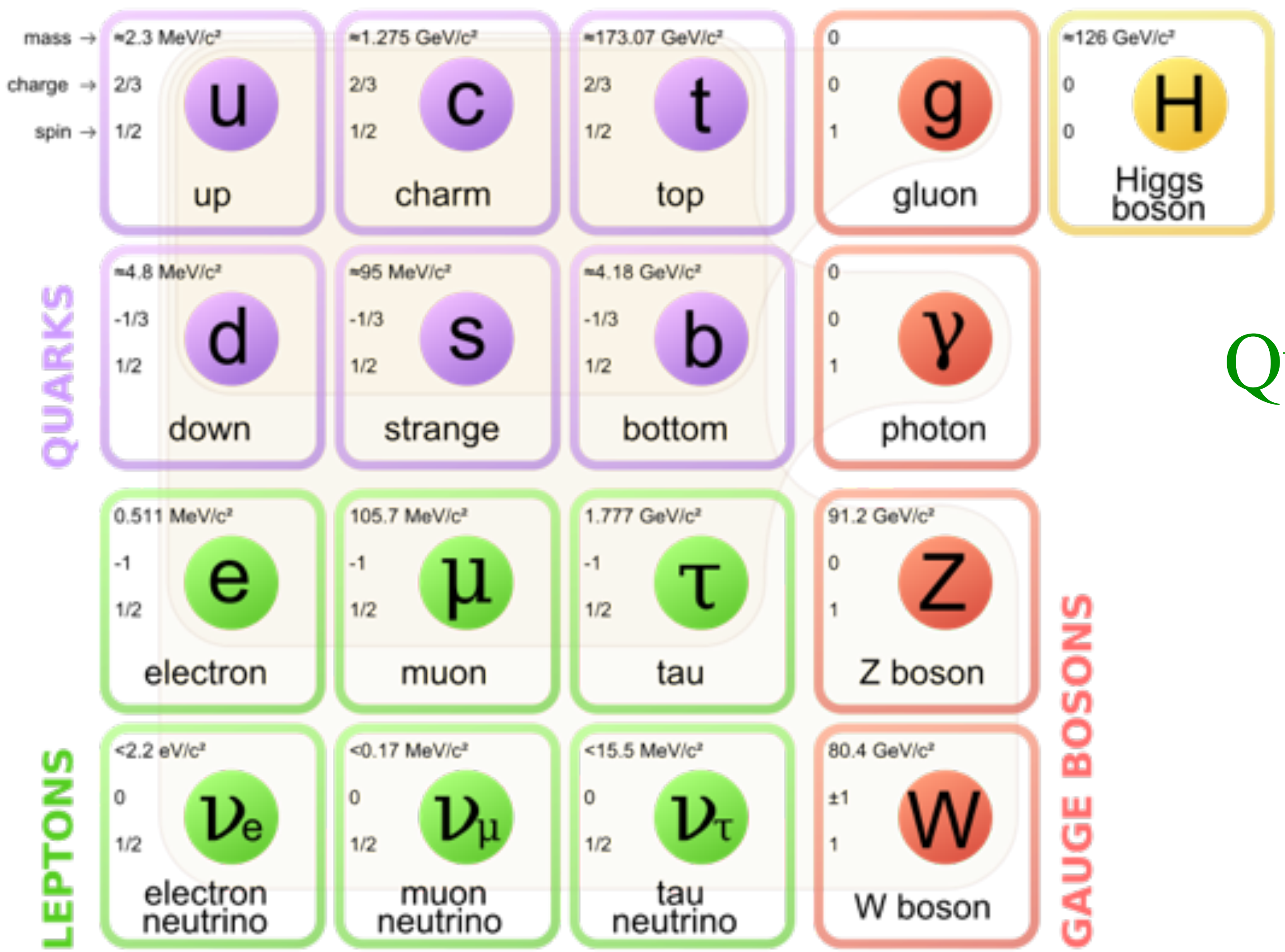

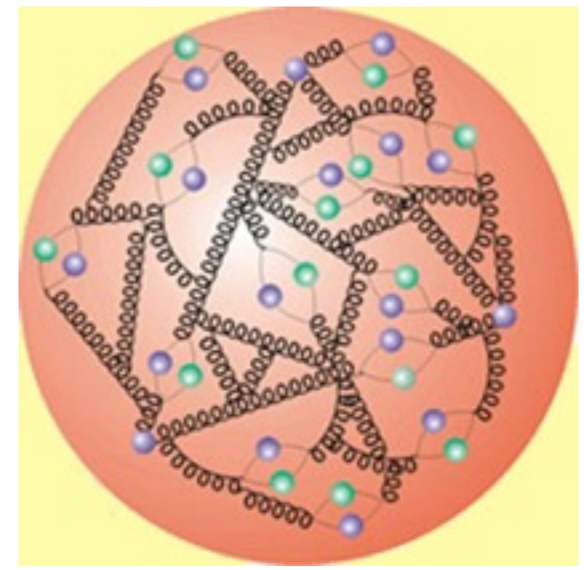

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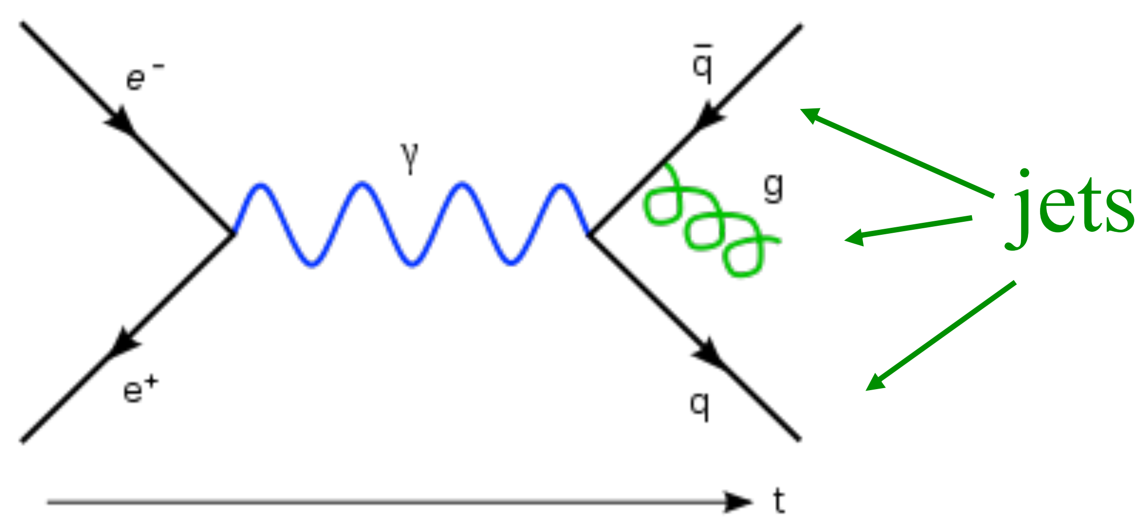

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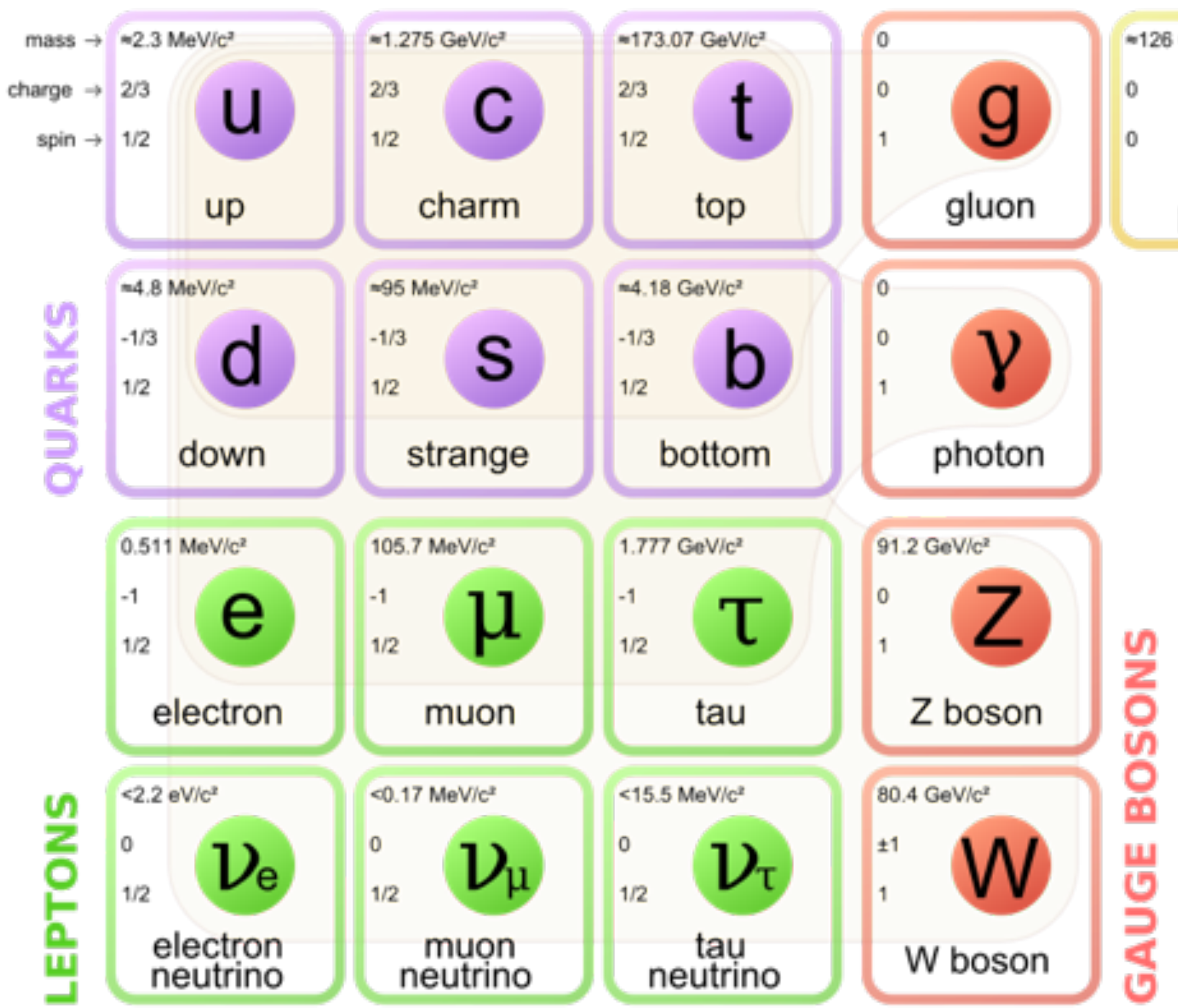

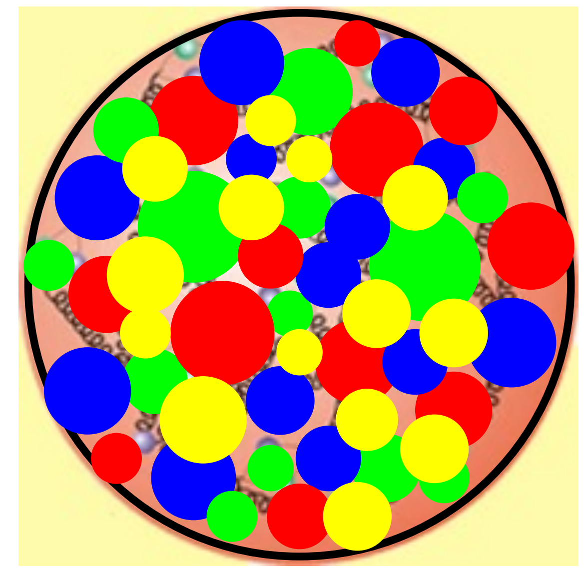

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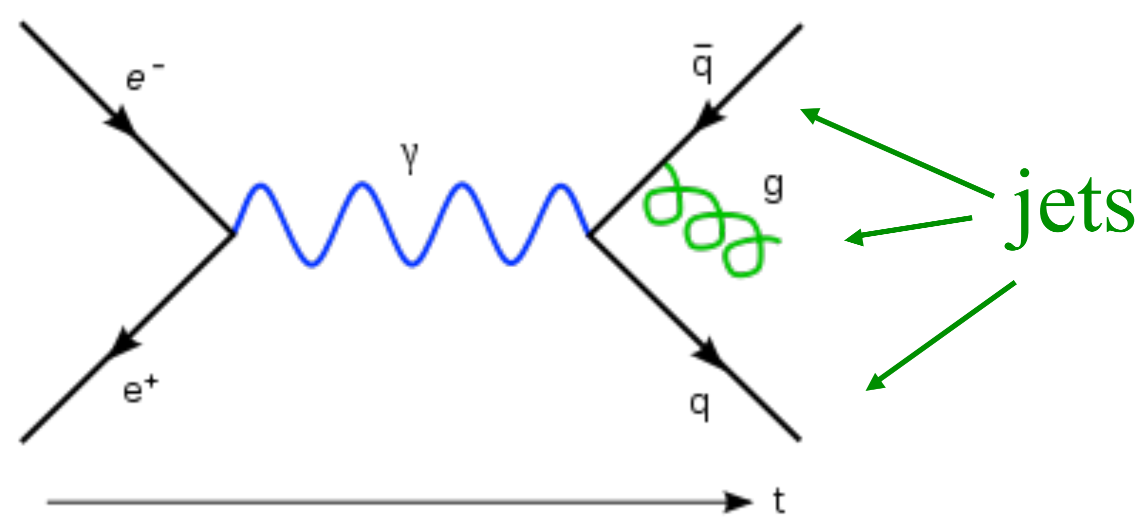

Bosons mediate interaction

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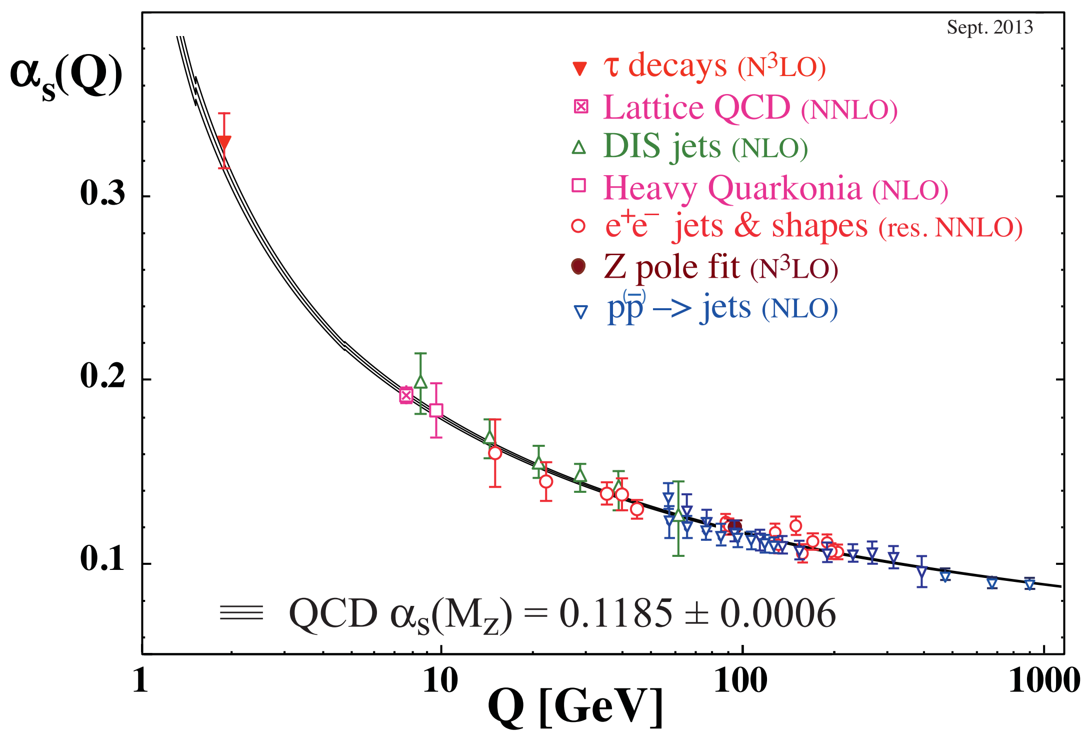
"…Further our understanding of QCD…"
Don't we know about QCD??

$$\mathcal{L} = \overline{\psi}(i\not{\partial} - M - g \not{A}_a G^a)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$



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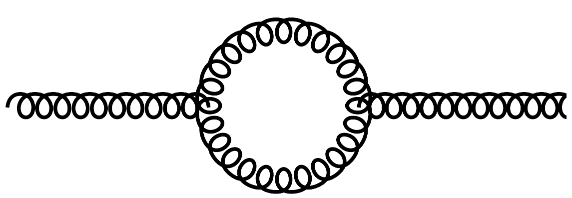

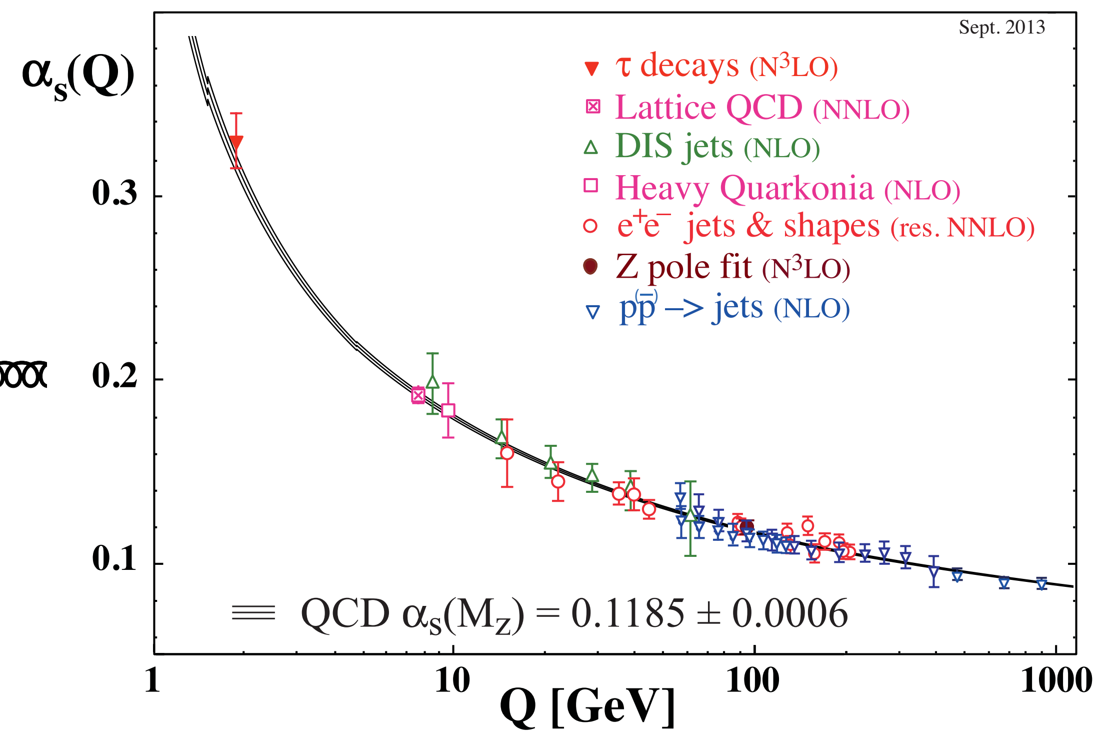

$$\alpha_s(Q) = \frac{g_s^2}{4\pi} = \frac{1}{\ln(Q/\Lambda)}(1 + \ldots)$$

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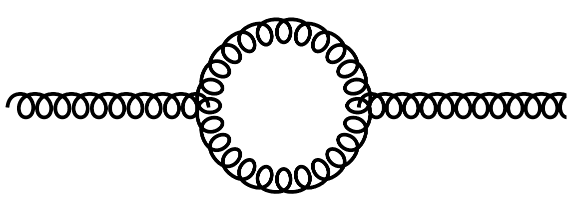

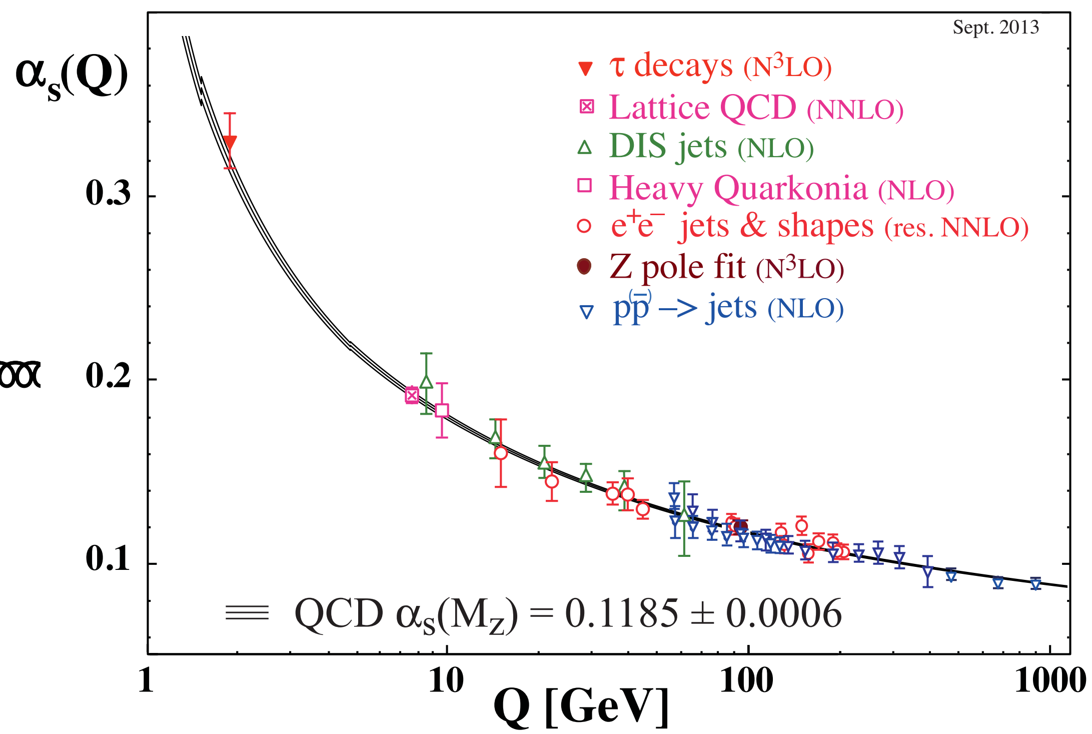

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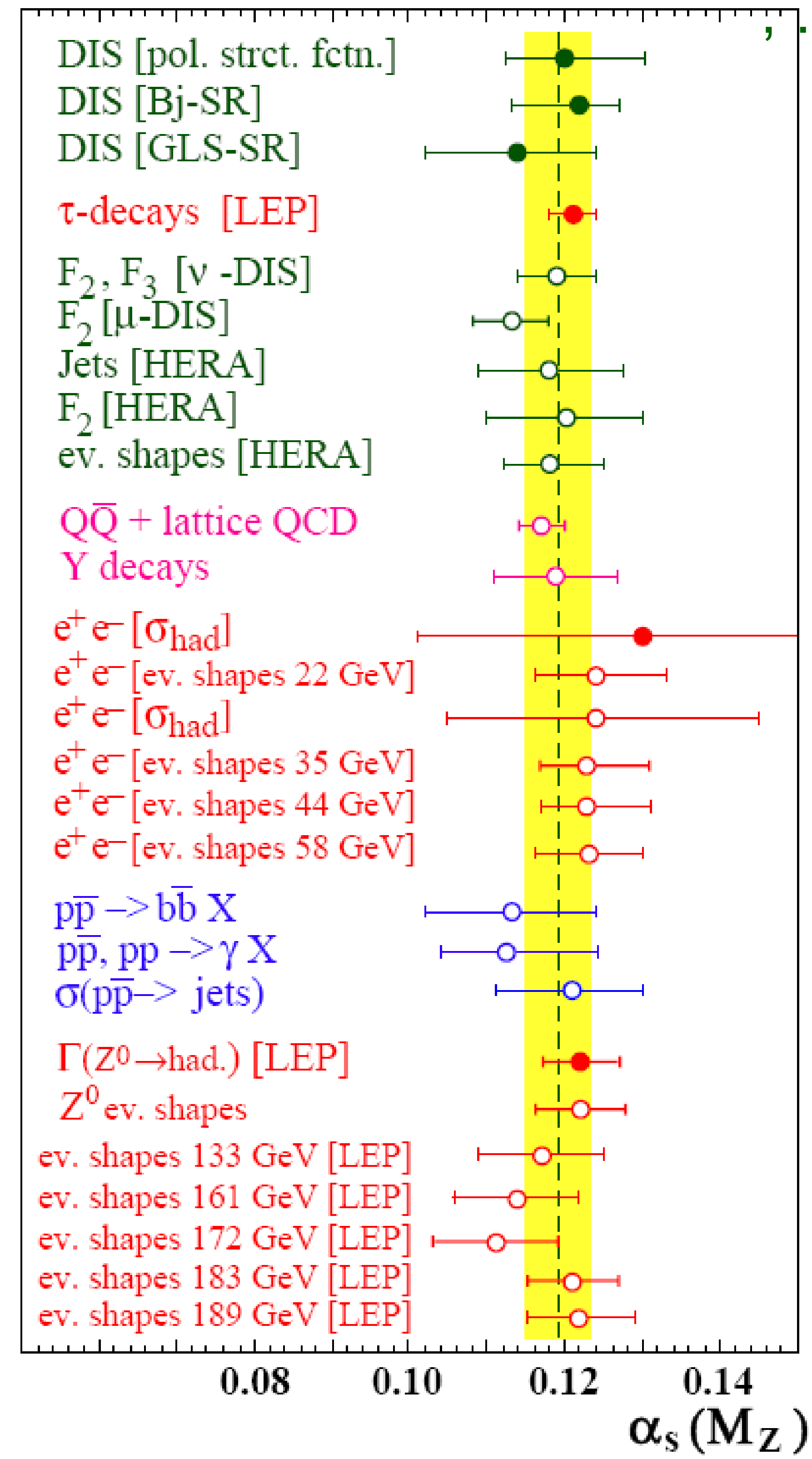
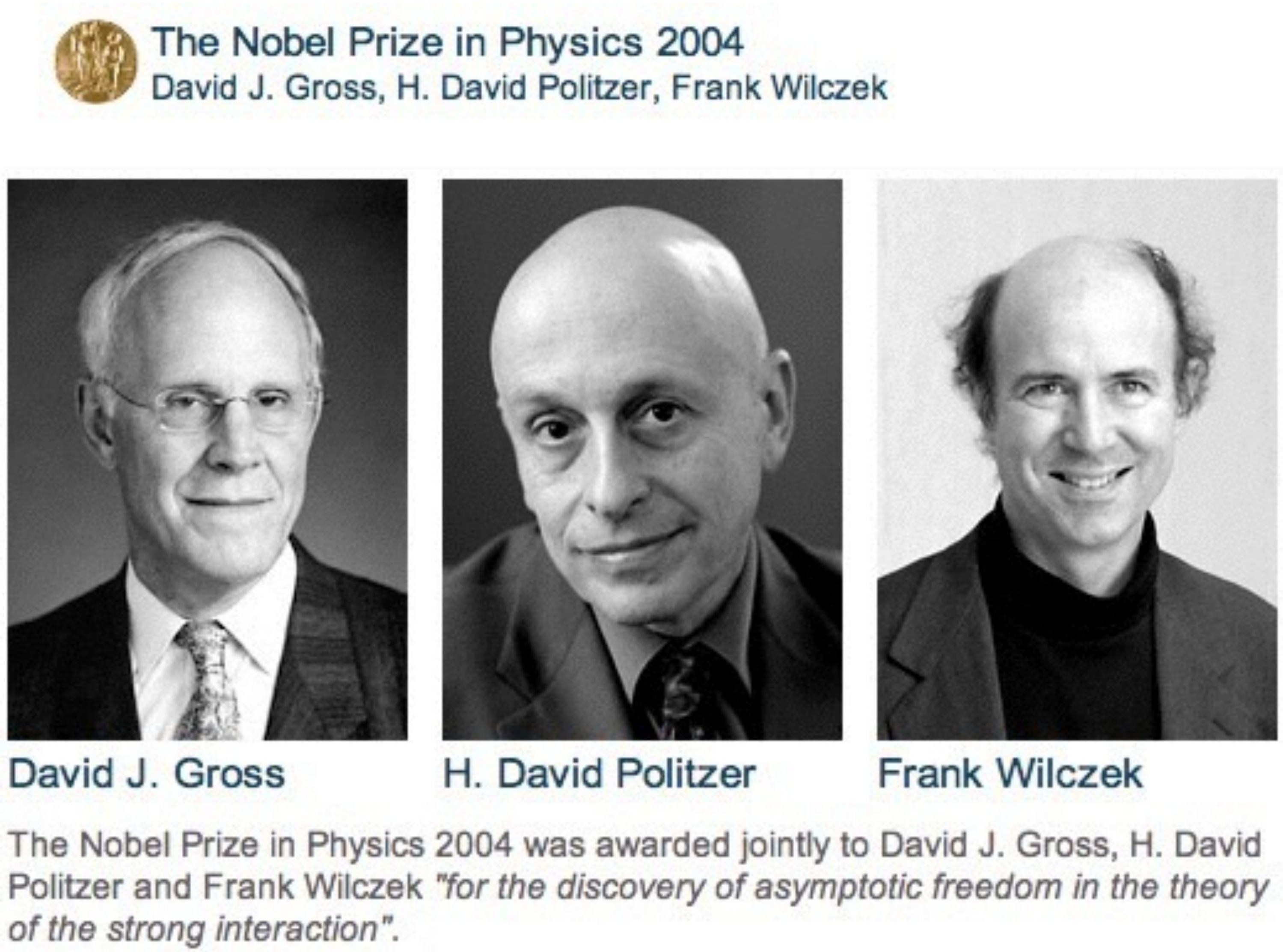
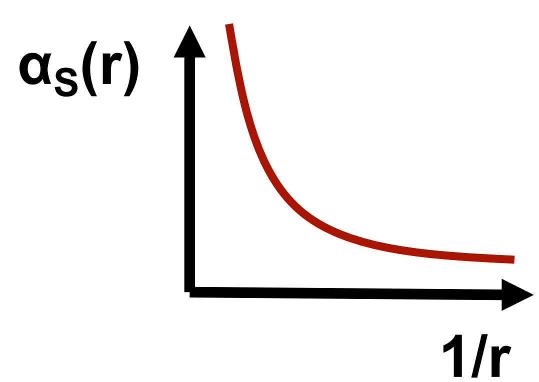




Asymptotic Freedom

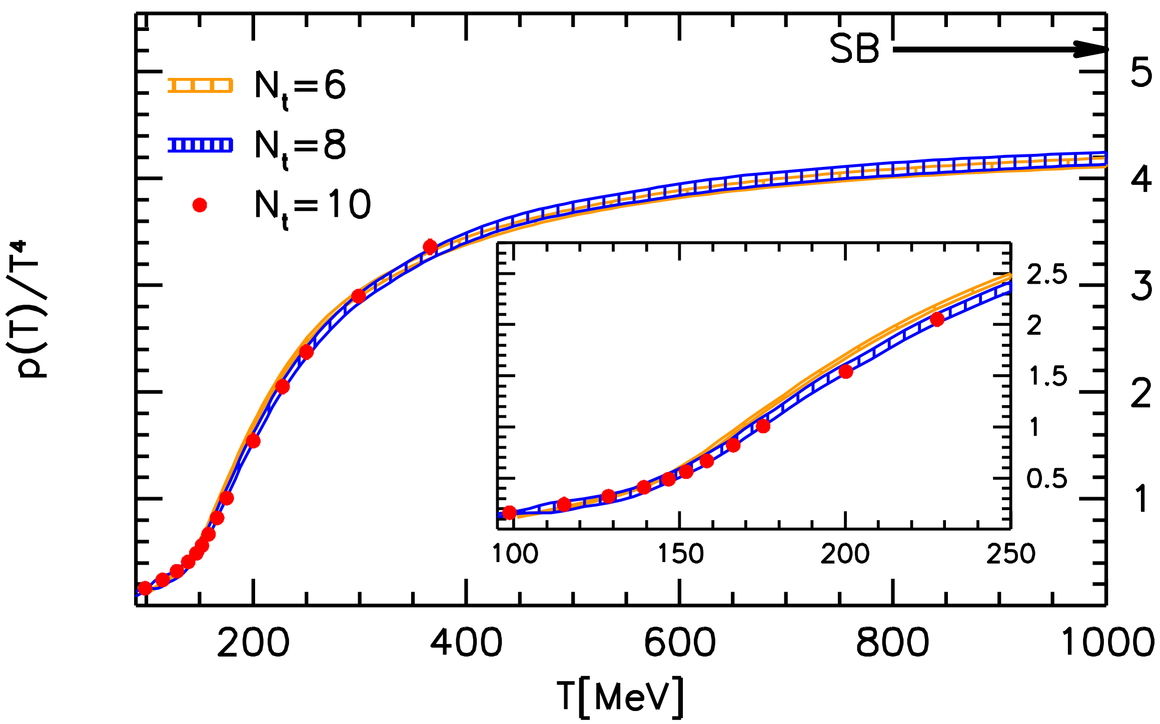
"What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called 'asymptotic freedom'. The converse is true when the quarks move apart: the force becomes stronger when the distance increases."

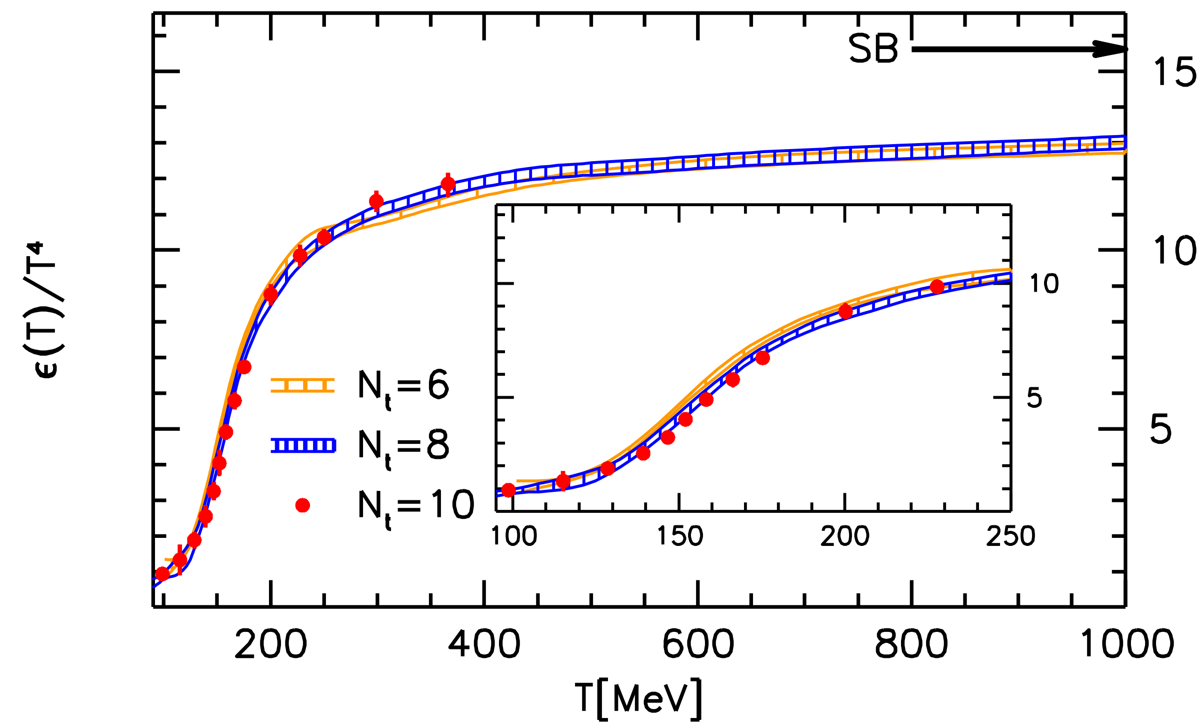


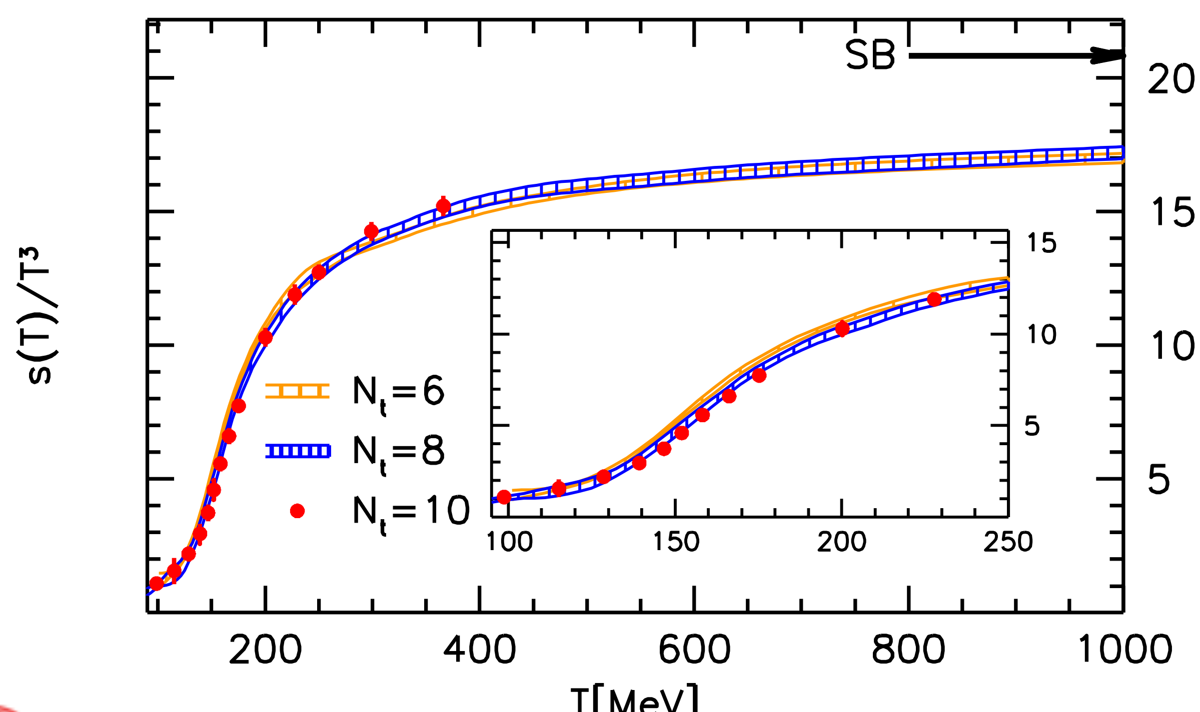
QCD: What we know less…

- Phase transitions in QCD? What is the phase diagram? Equilibration?
- Dynamics of deconfinement, hadronization
- Are there collective features (many-body) effects that are present in QCD at high density/temperatures that are not there at T=0? ("emergent features")
- Does features of the QCD phase diagram have implications for cosmology and for dense stellar objects?

Some aspects of the phase diagram, we do know from first principles: Lattice QCD (at μ_B=0)





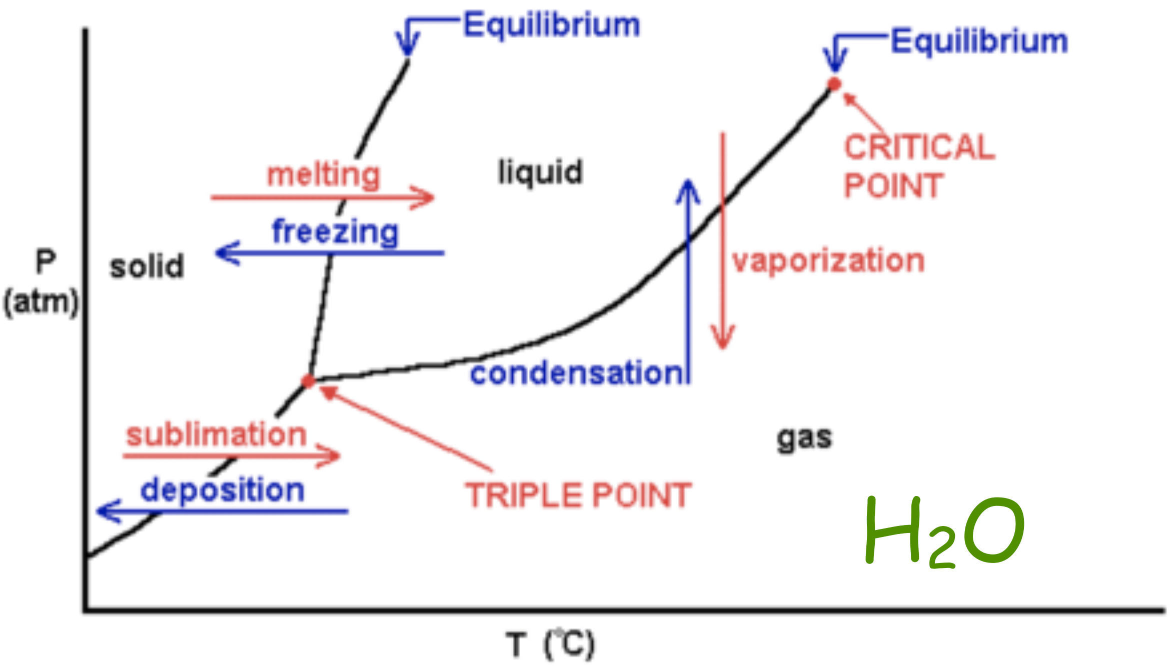


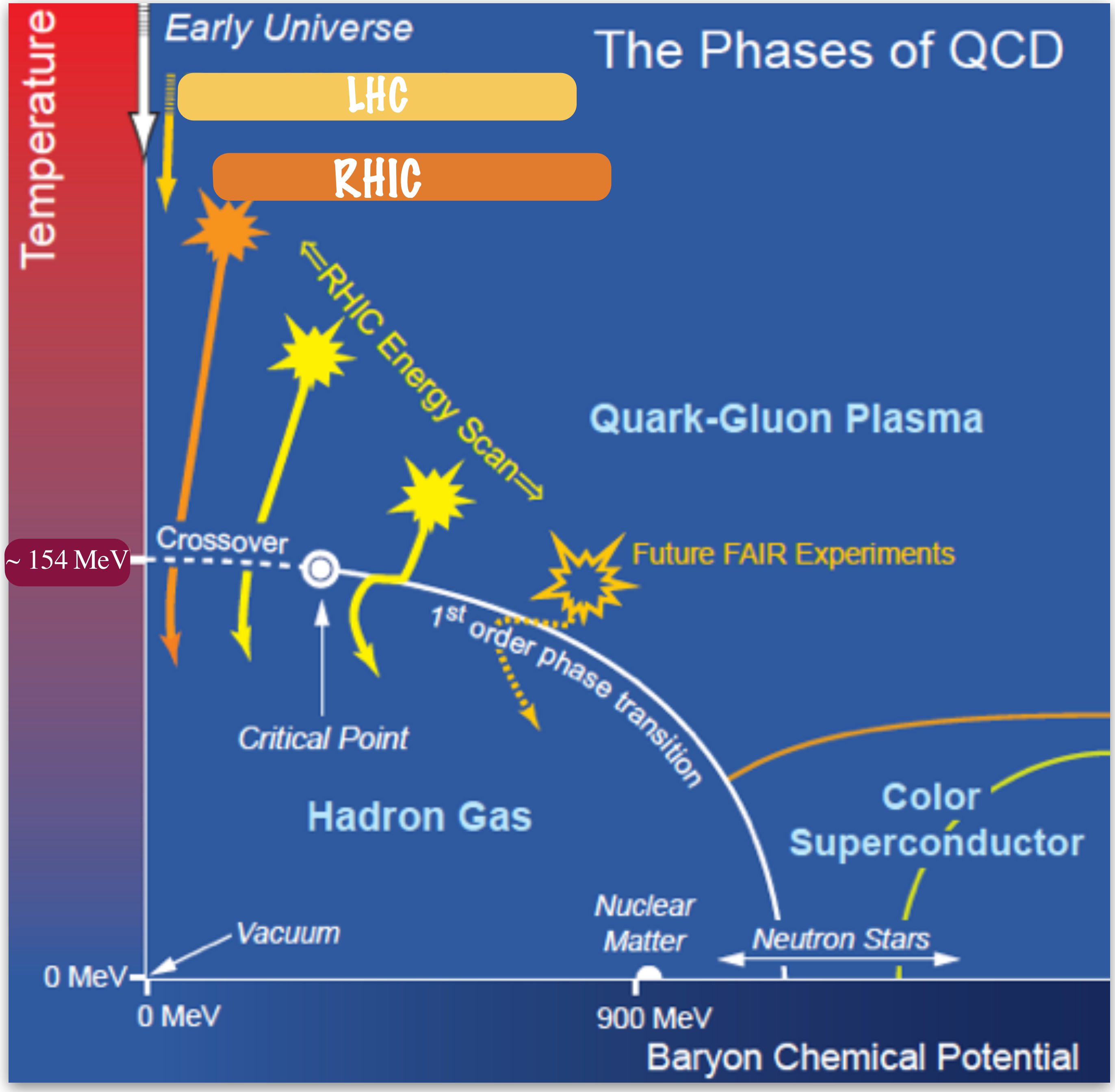
$$\frac{\epsilon}{T^4} = g_{\mathrm{Eff}} \frac{\pi^2}{30}$$

- Slow convergence to SB
- Transition is not sharp

Borsanyi et al.,arXiv:1007.2580

Exploring the QCD phase diagram: Has to be done dynamically





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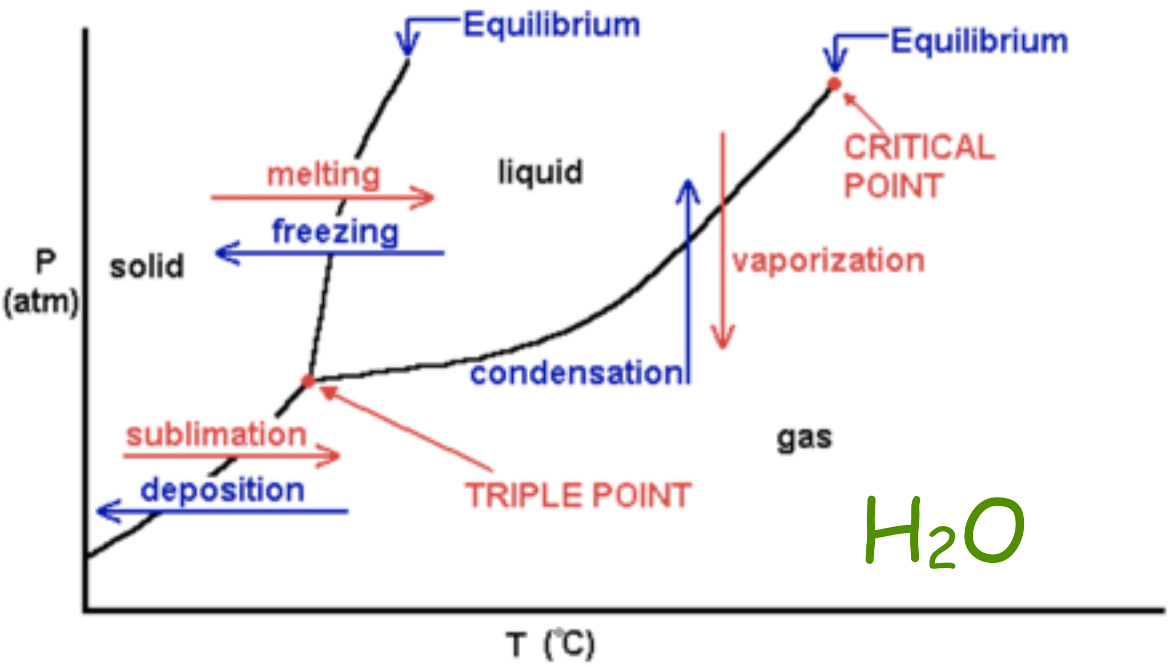
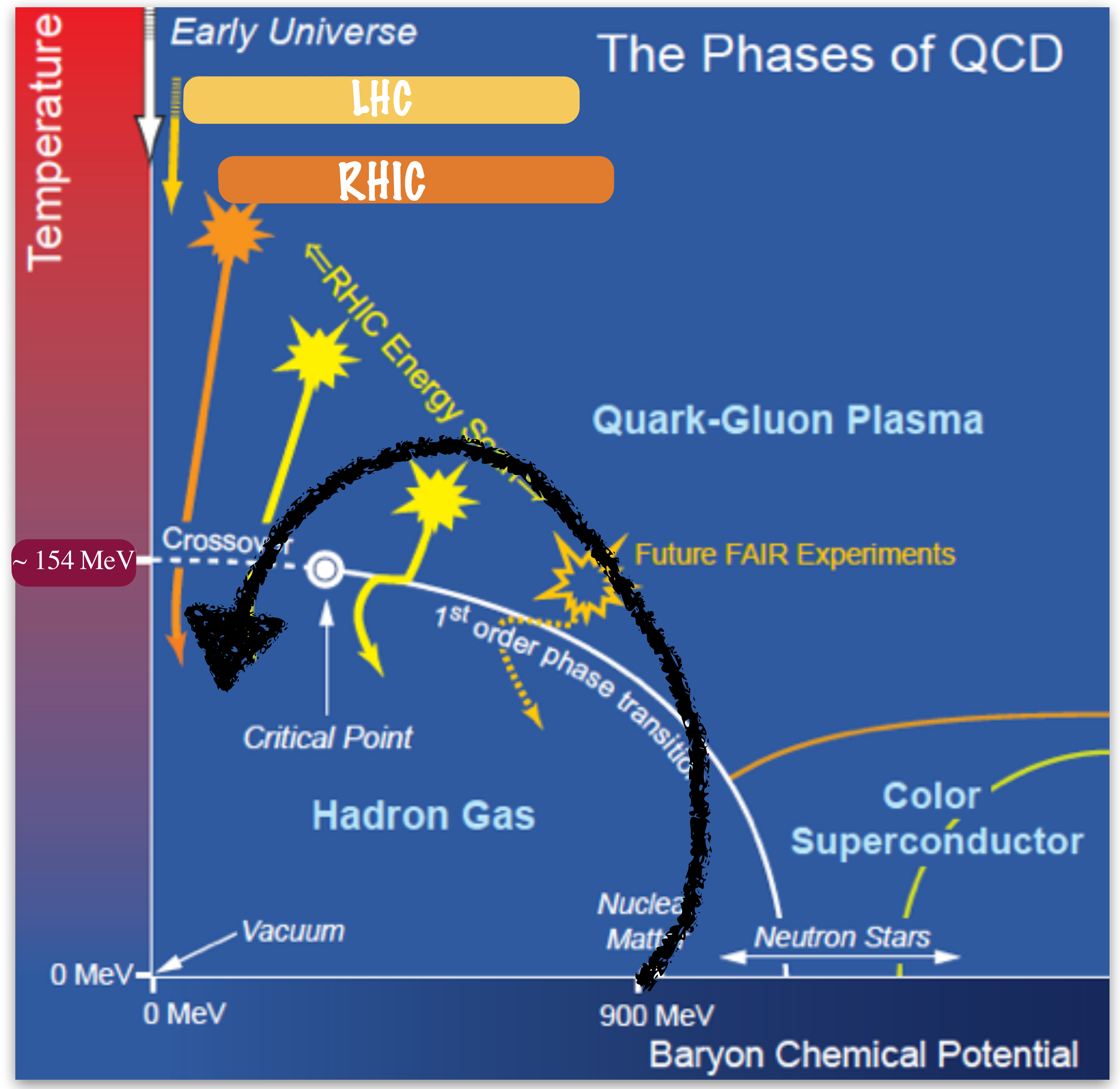
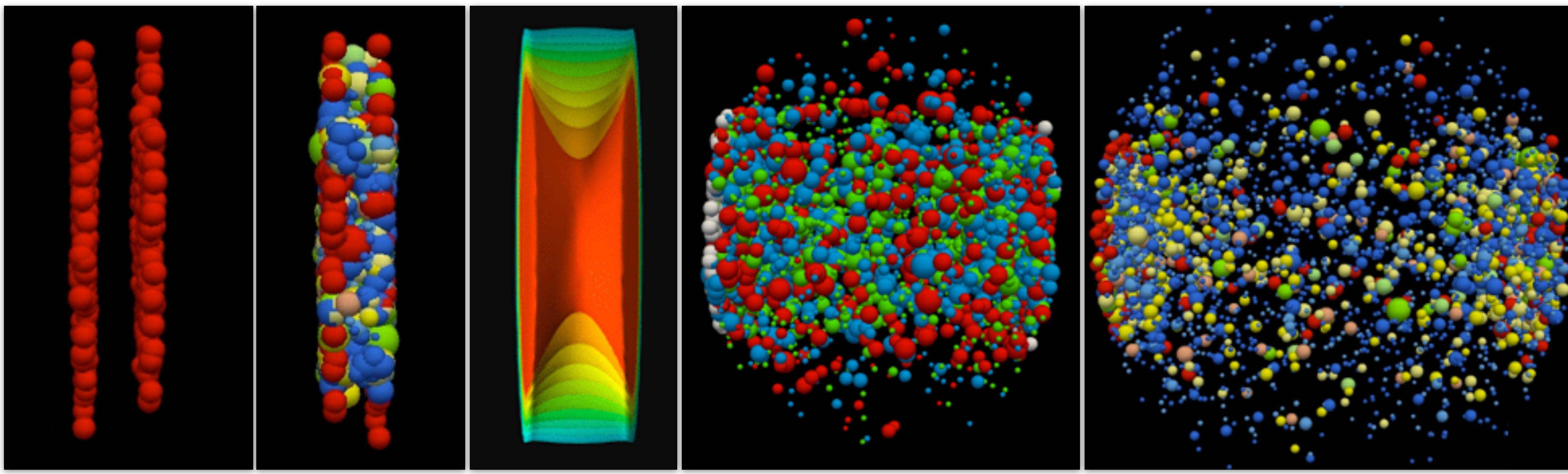


H_2O



How to compress and heat strongly interacting matter: Relativistic nuclear collisions

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



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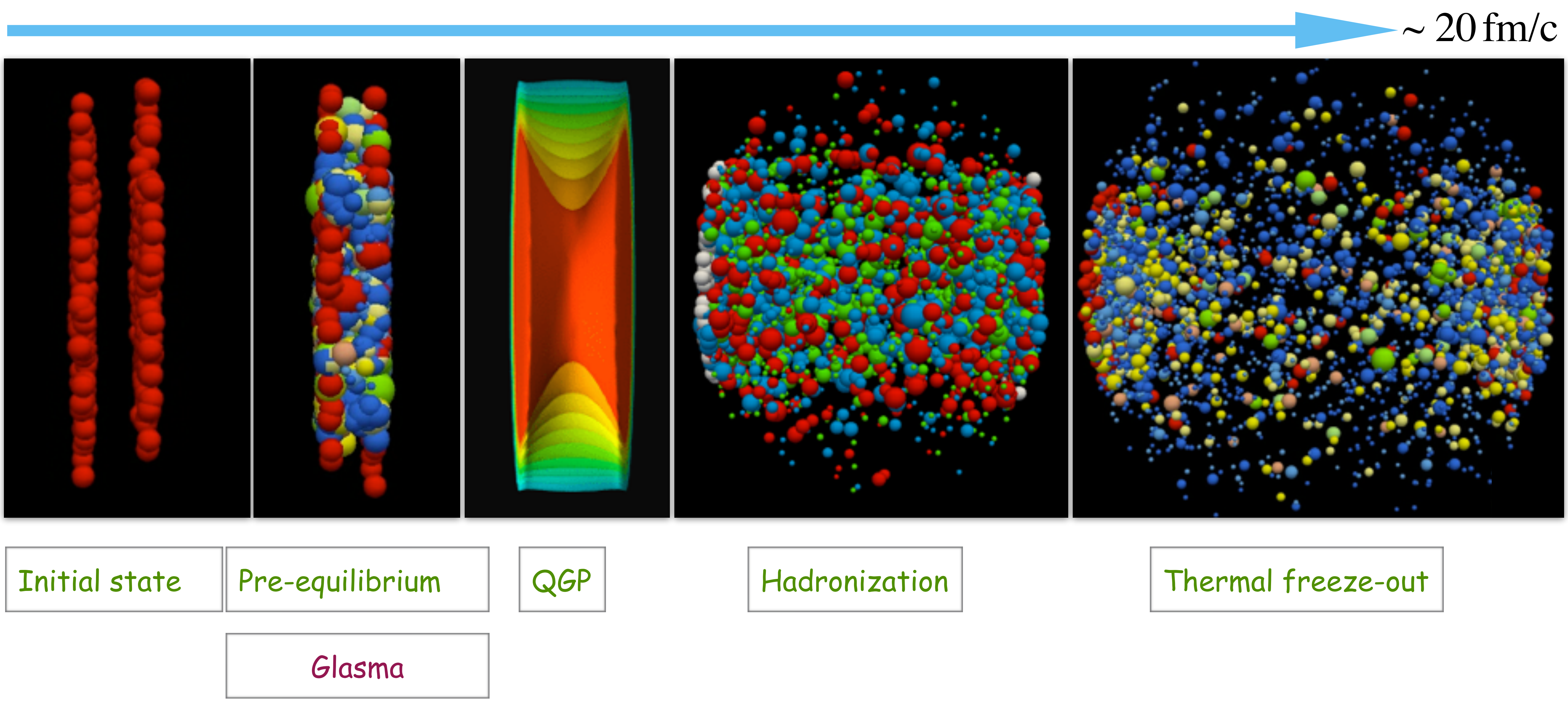

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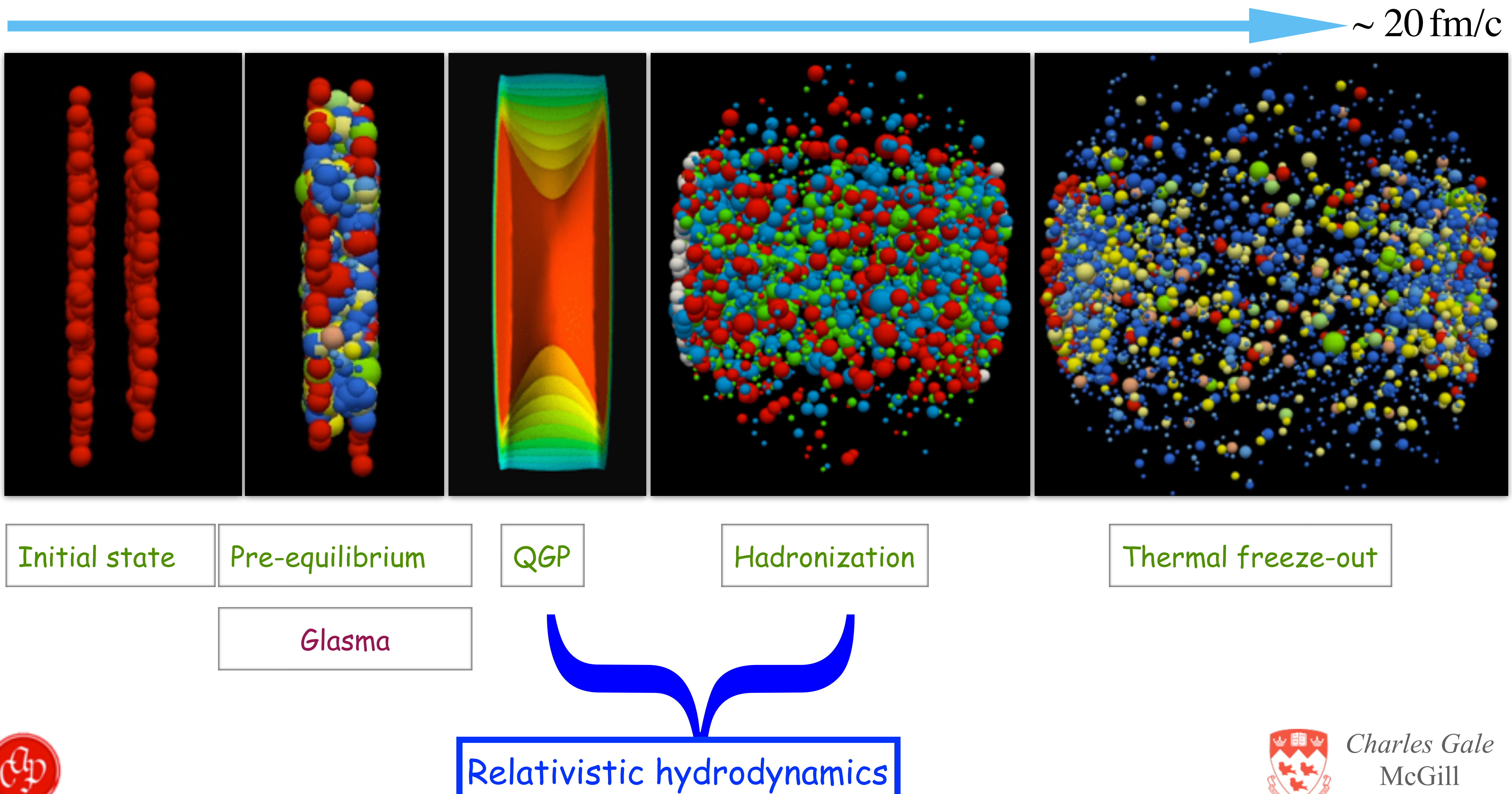

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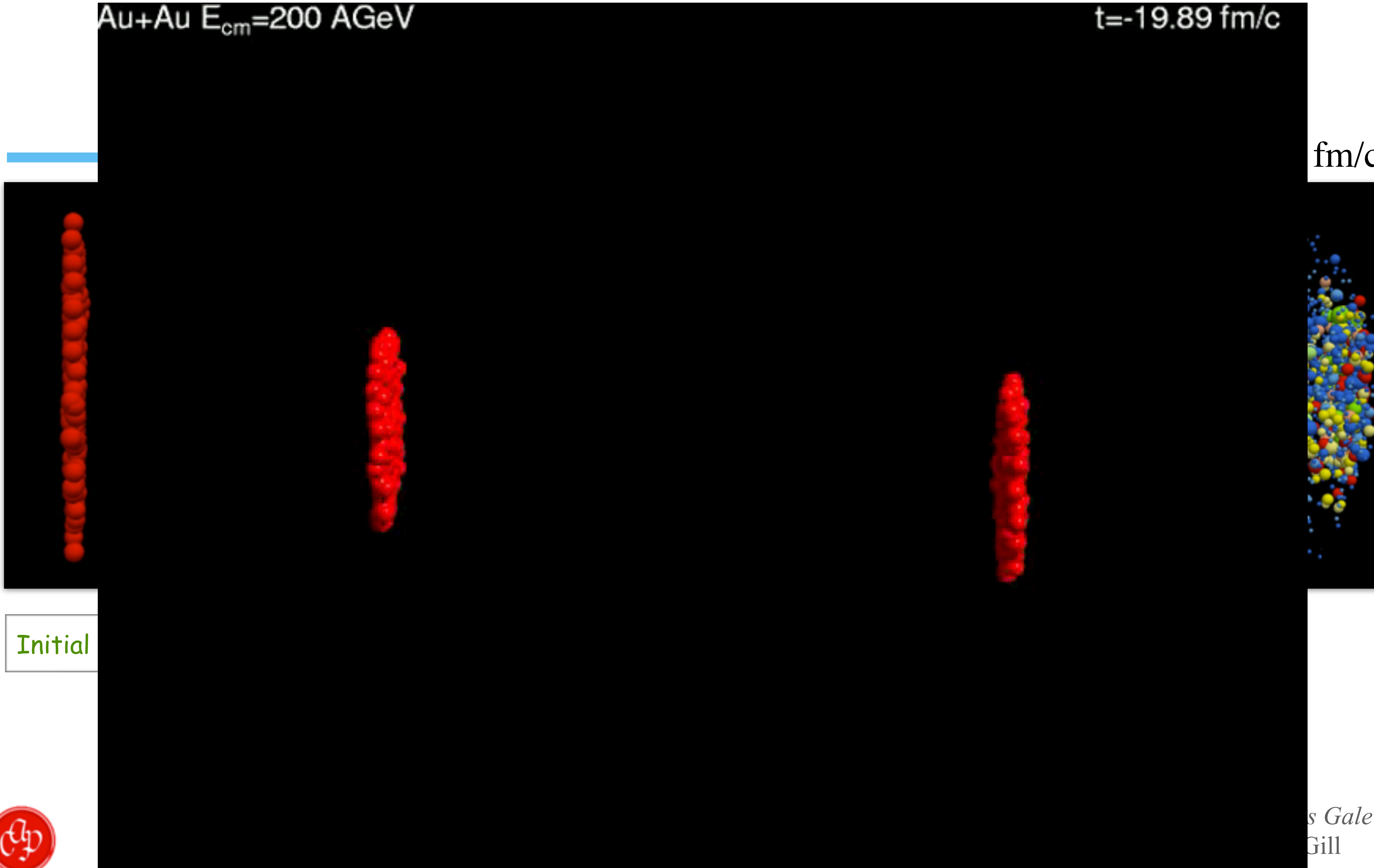
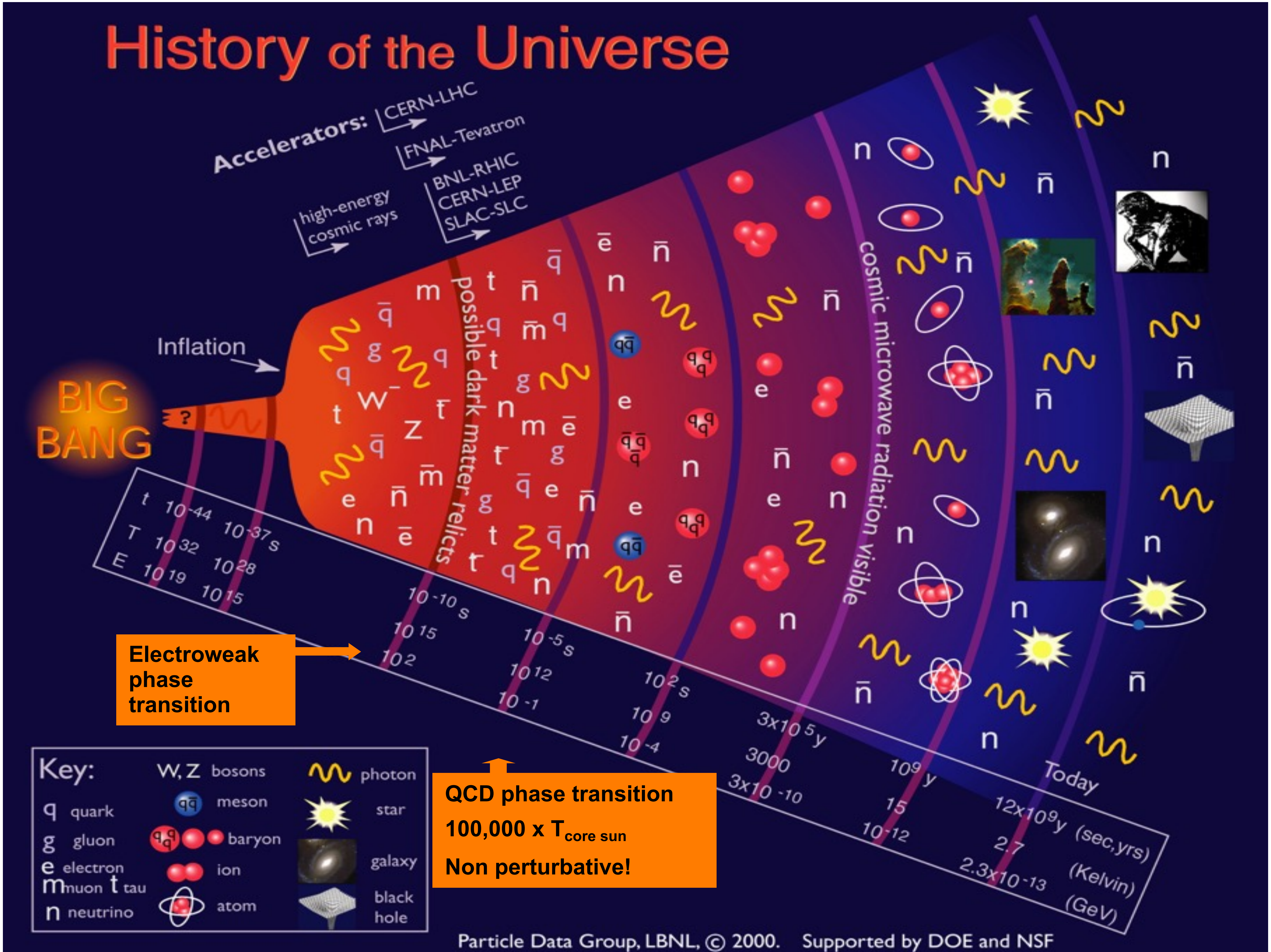


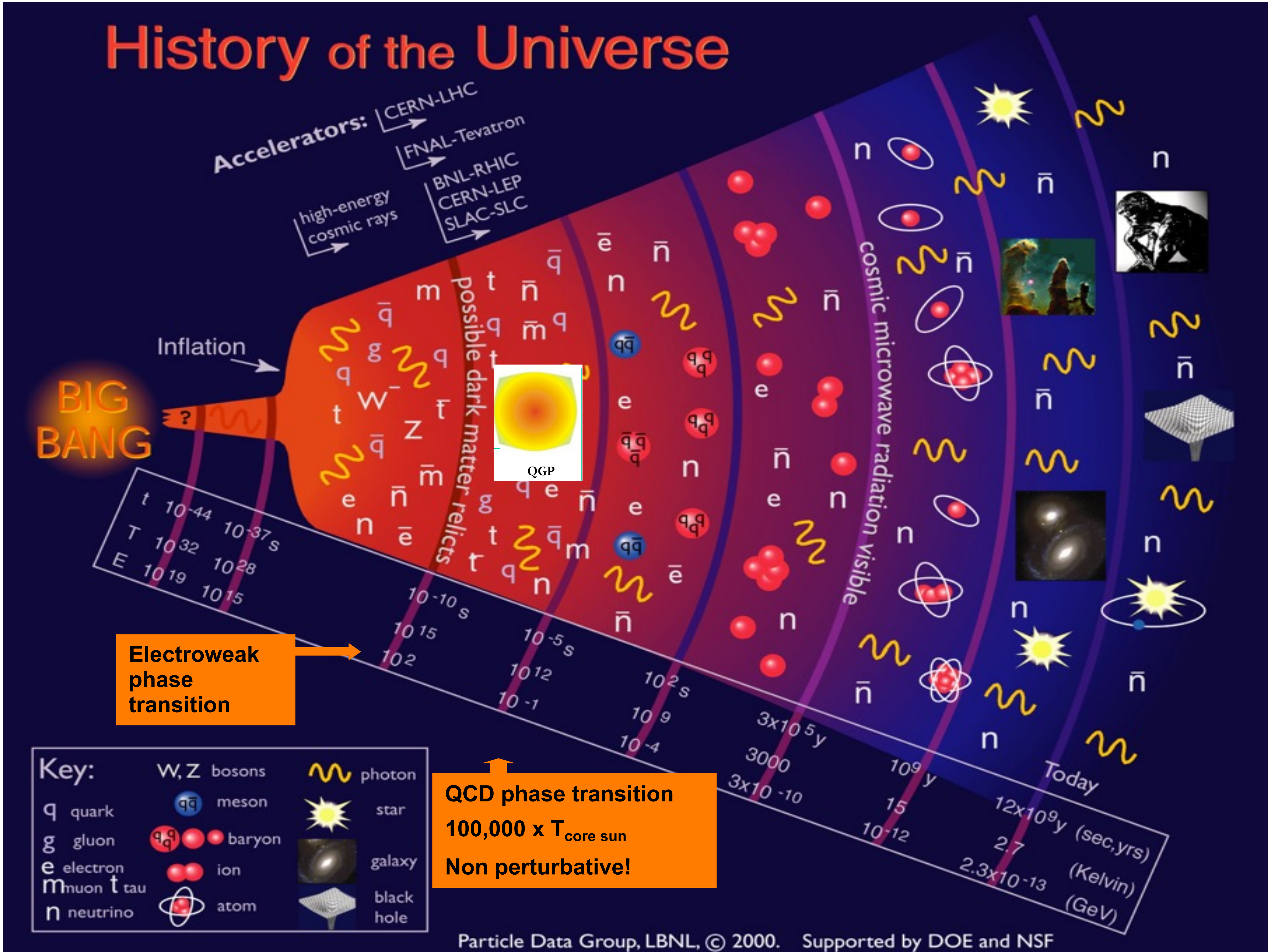


Electroweak phase transition

QCD phase transition

100,000 x $T_{core\ sun}$

Non perturbative!


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
QGP
cosmic microwave radiation visible
Today
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
Electroweak phase transition
QCD phase transition
100,000 x $T_{core\ sun}$
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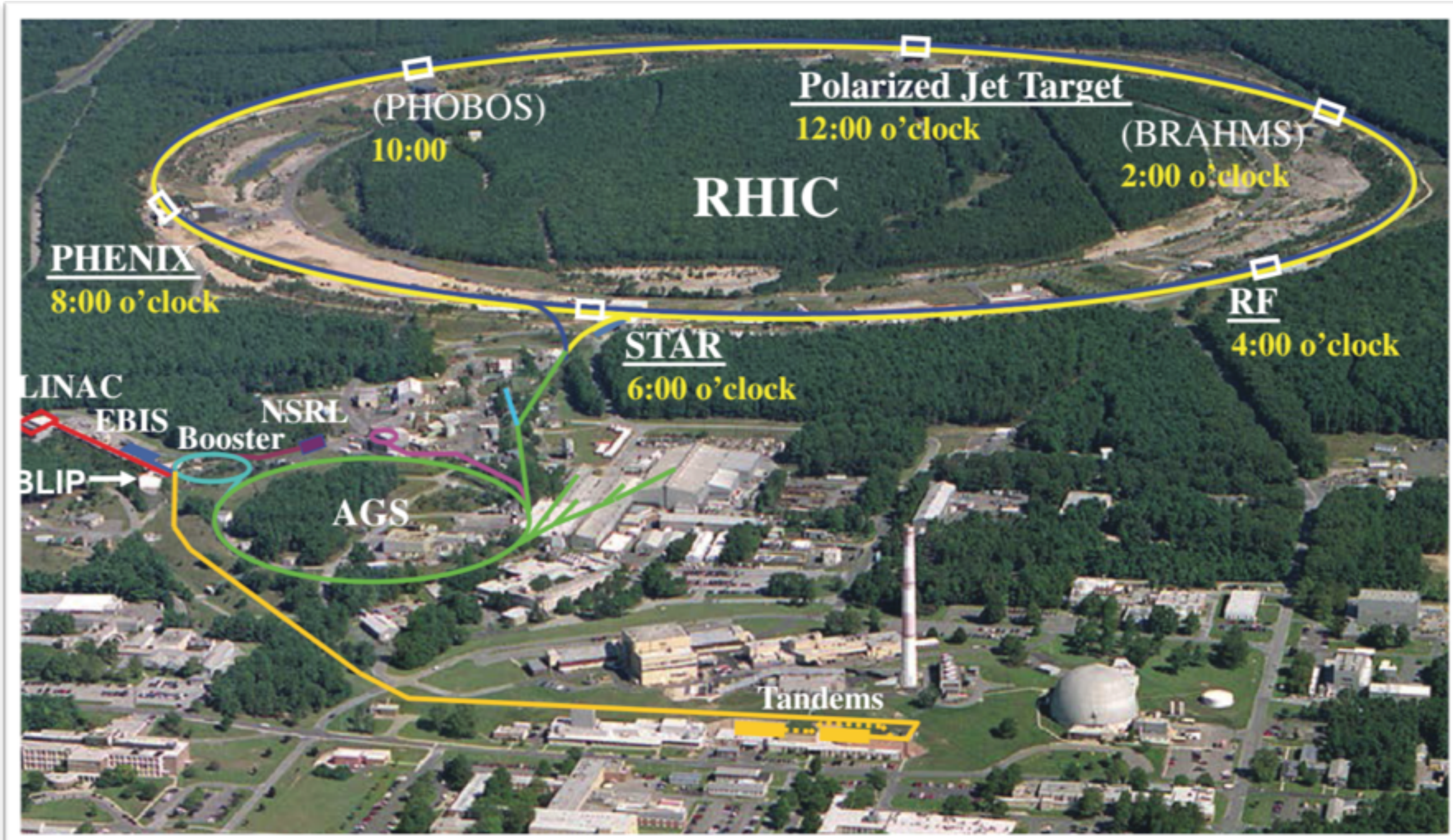
Looking into the distant past:
RHIC, Brookhaven National Laboratory



3.83 km circumference
Two independent rings

- 200 GeV for Au-Au (per N-N collision)
- 500 GeV for p-p (polarized)

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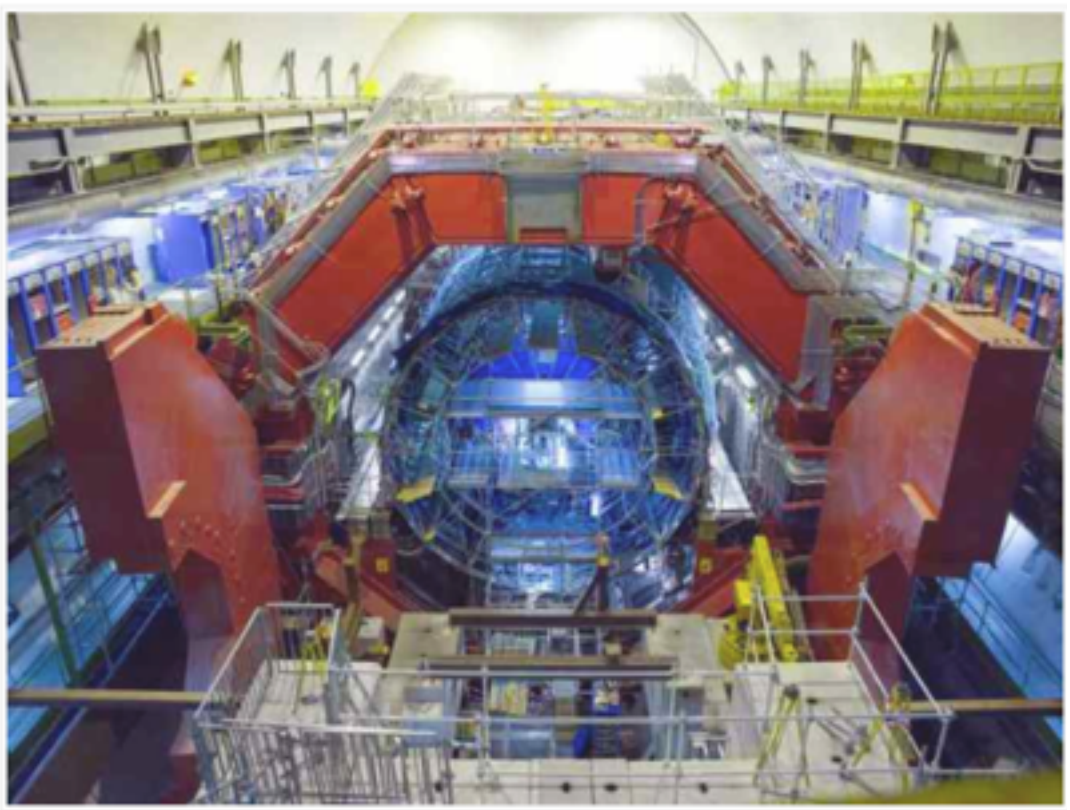
The LHC, CERN, Geneva

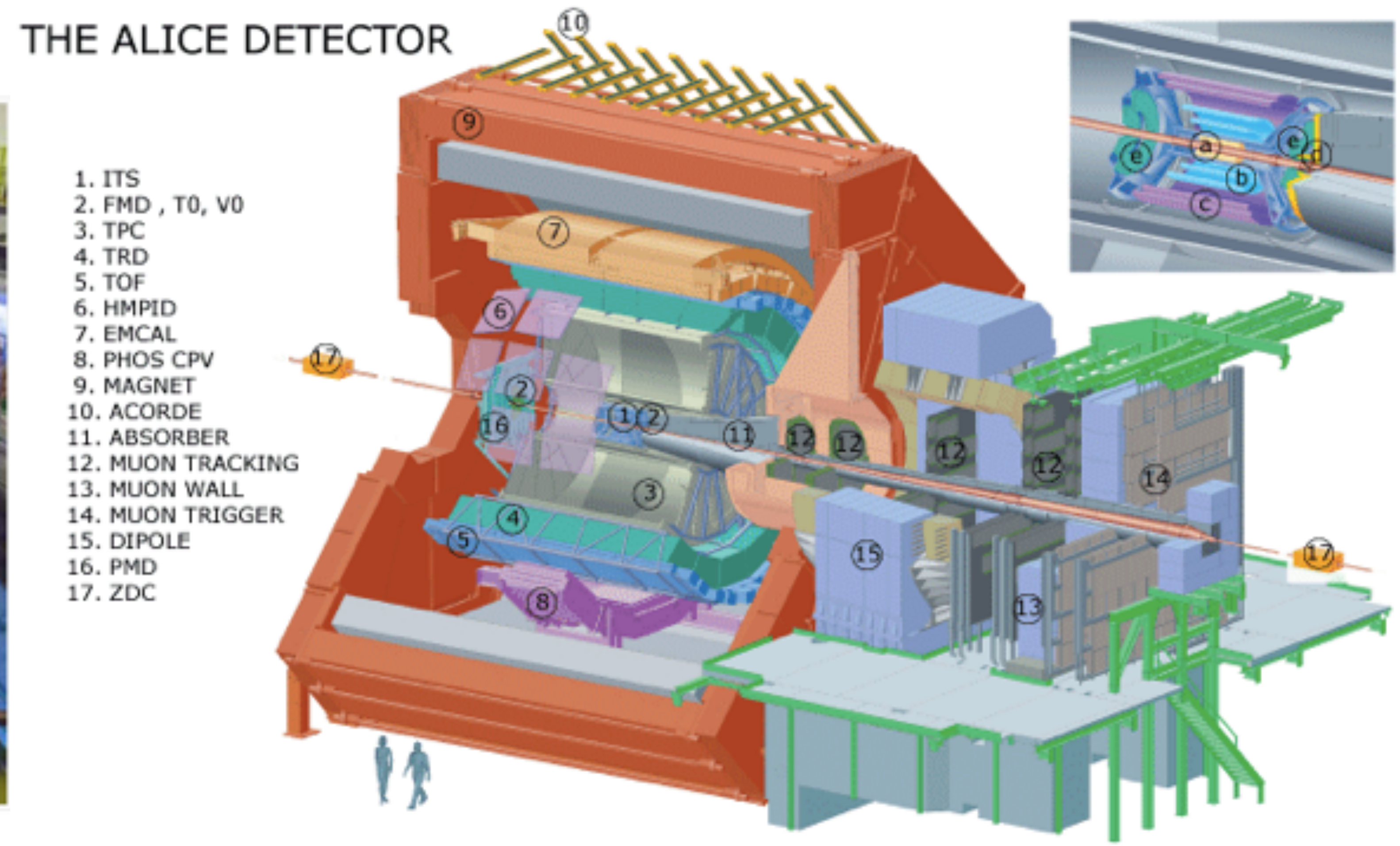
- p+p @ $\sqrt{s}$=7(14) TeV
- Au+Au@$\sqrt{s}$=2.76(5.5)TeV

The scale of these experiments: ALICE

ALICE – A Large Ion Collider Experiment

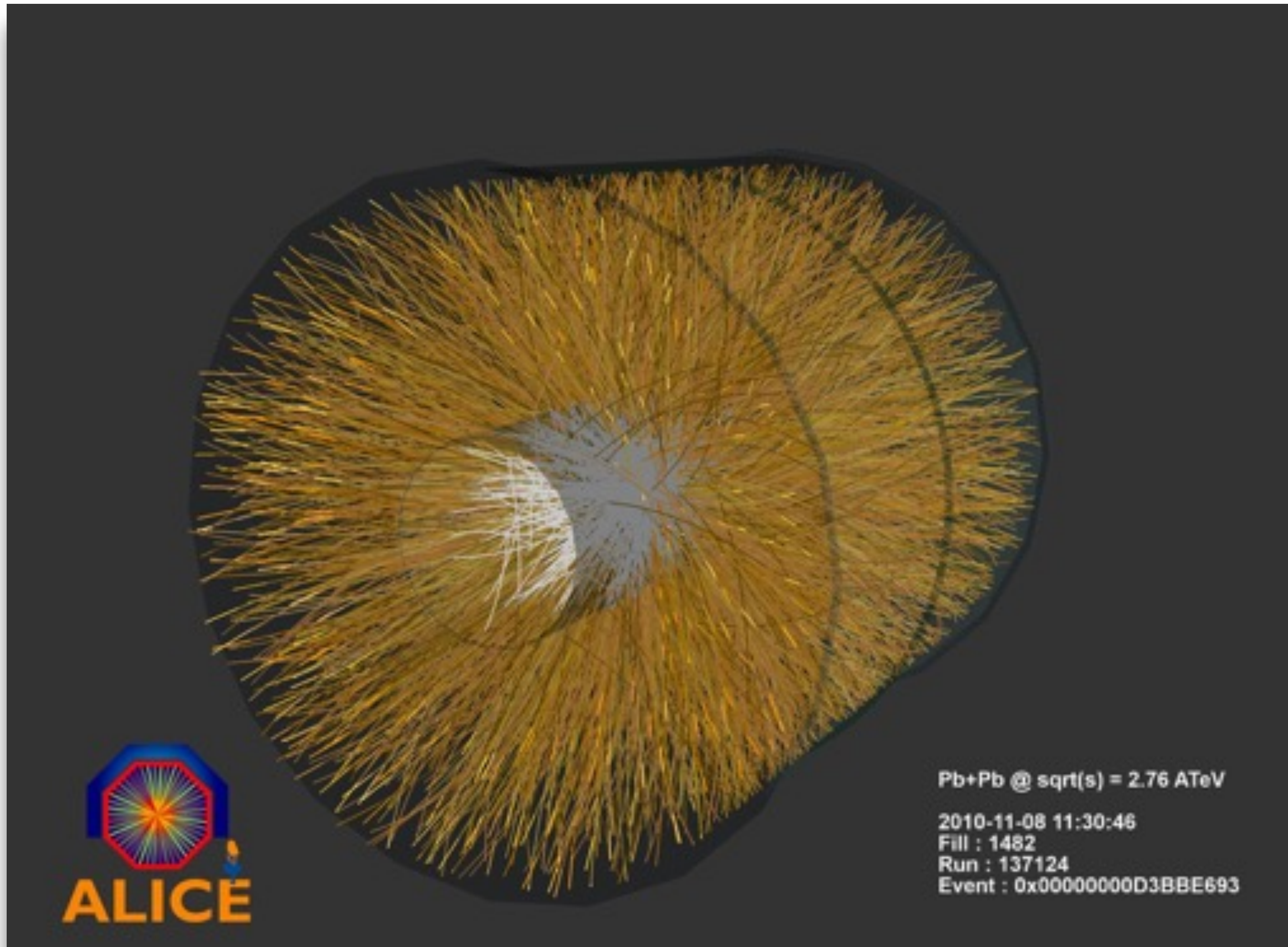


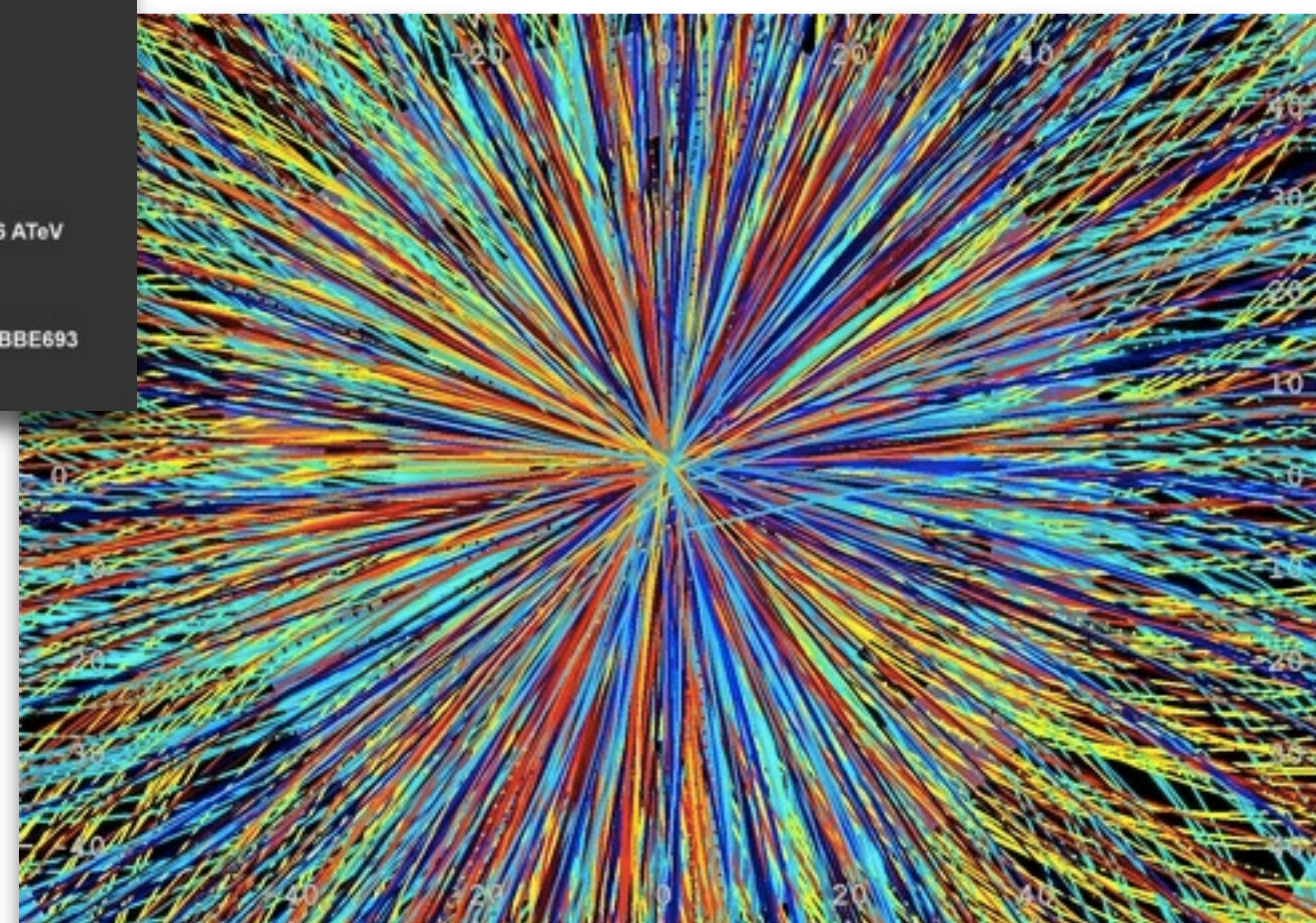
ALICE



An international collaboration of more than 1200 physicists, engineers and technicians, including around 200 graduate students, from 132 physics institutes in 36 countries across the world.

One ALICE event…



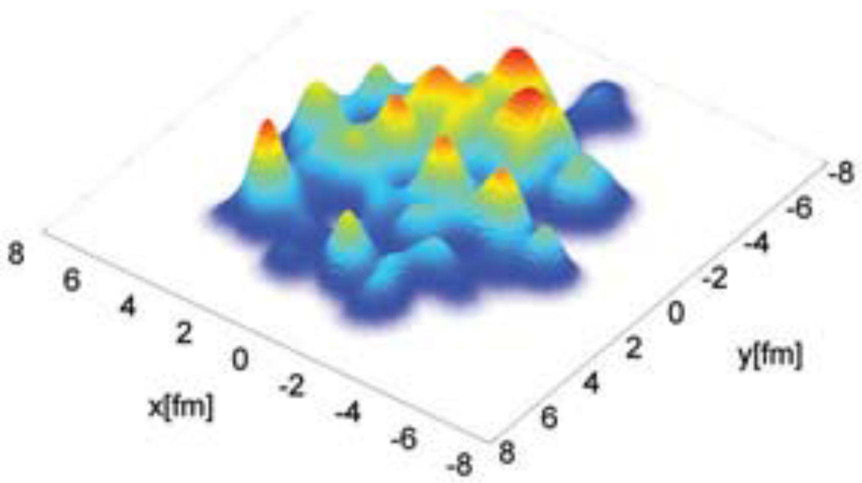


RHIC and LHC: new physics and many surprises!

- The success of hydrodynamics
  - Hot and dense matter flows like a liquid
  - Specific viscosity is ***very*** low
    - A connection with other strongly coupled systems:
      - » Cold fermionic atoms
      - » String theory (!)
  - System is strongly coupled
- Matter is surprisingly opaque
  - Jets are quenched by the strongly interacting system
- Electromagnetic signals

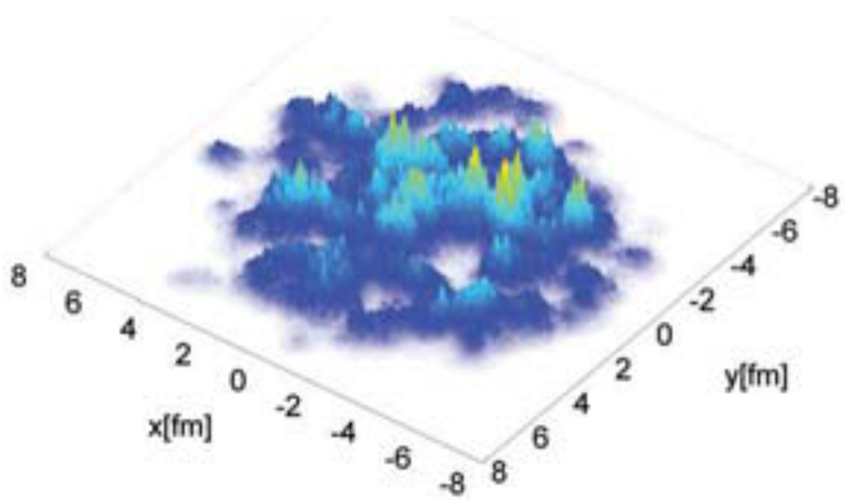
Much progress in the calculation of the initial state

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)

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

- Viscous relativistic fluid dynamics

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

- 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

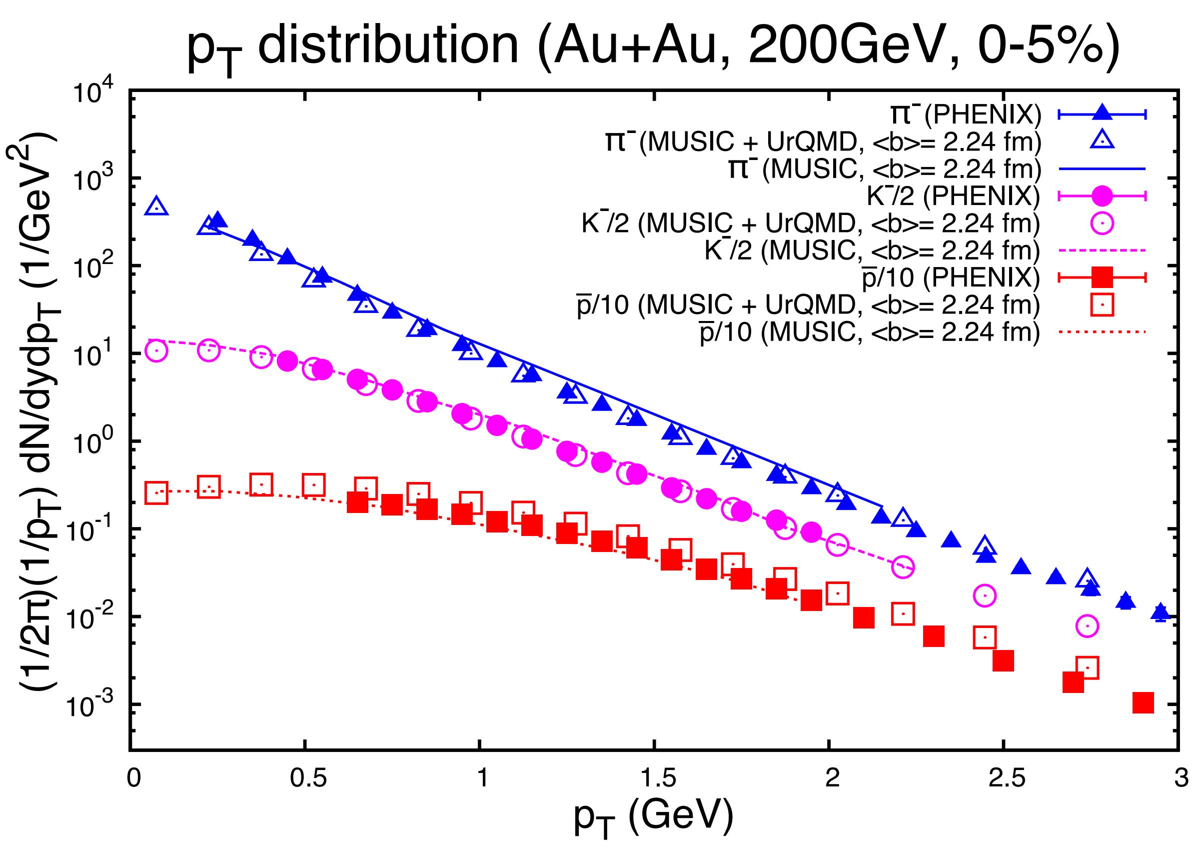
- Measures the resistance to deformation
- Is a fundamental property of QCD

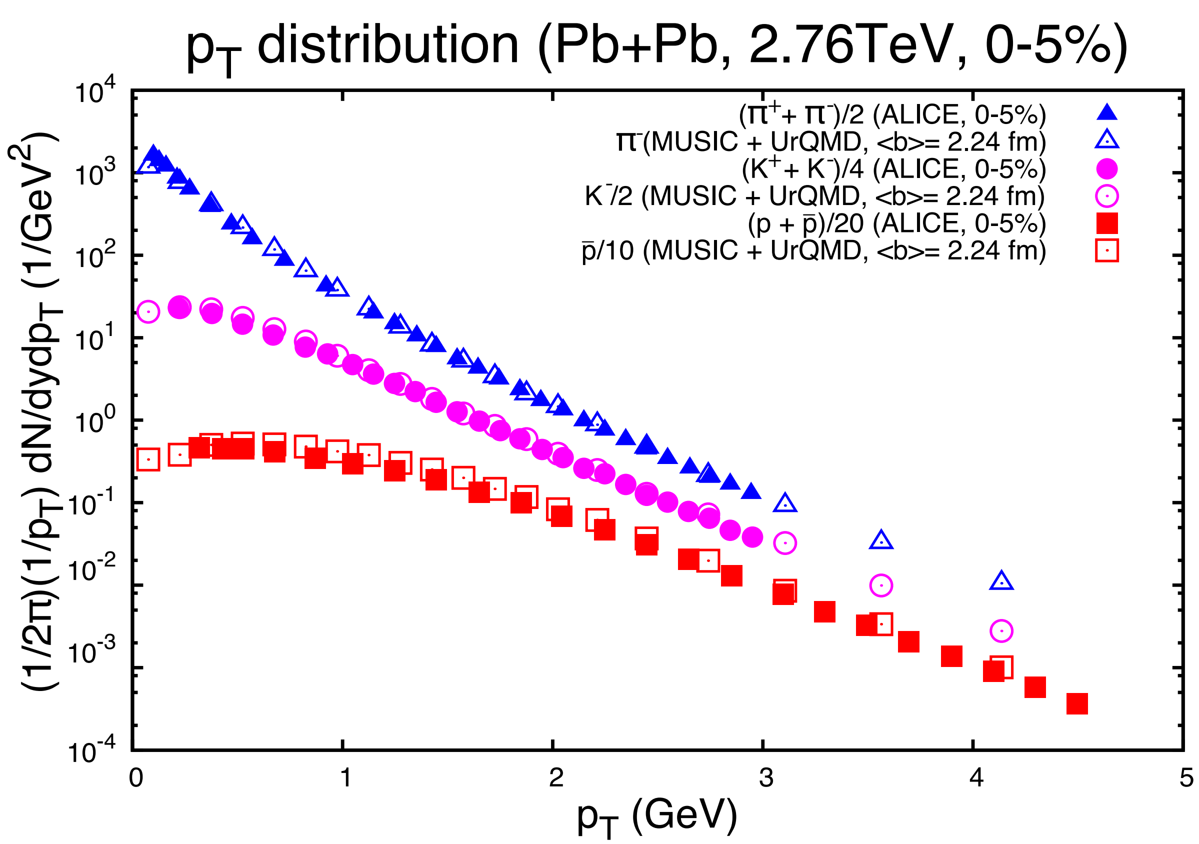
Relativistic hydrodynamics: An effective theory for the soft, long wavelength, modes

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

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

+ lQCD EOS





MUSIC: 3D relativistic hydro: Schenke, Jeon, and Gale, Int. J. Mod. Phys. A (2013); idem PRL (2011); idem PRC (2010)

Assessing collectivity further:
The differential single-particle spectrum

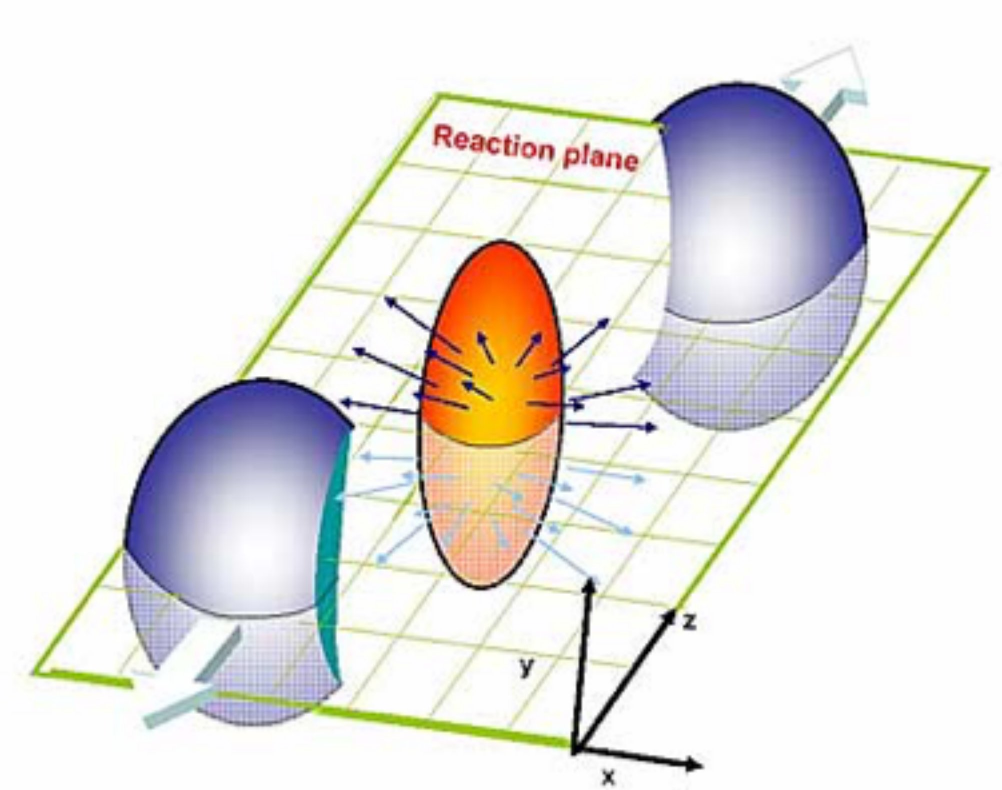
Quantifying the azimuthal asymmetries

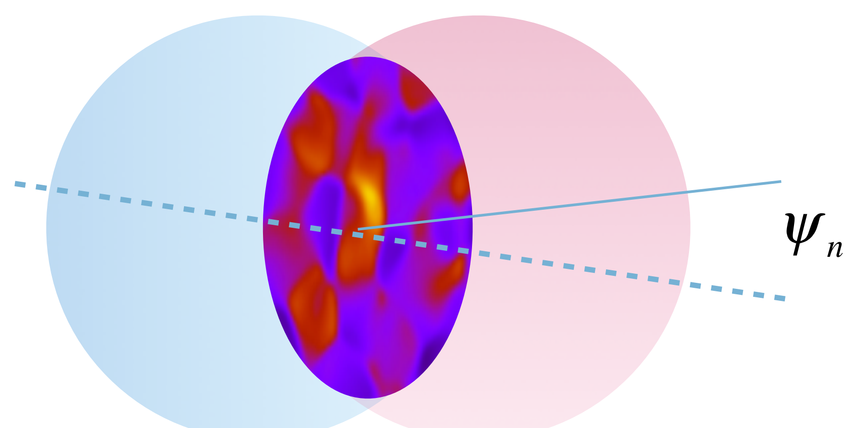
$$\frac{d^3N}{dyd^2p_T} = \frac{1}{\pi}\frac{d^2N}{dydp_T^2}\left[1+2\sum_{n=1}^{\infty} v_n(p_T)\cos n(\phi-\psi_n)\right]$$

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

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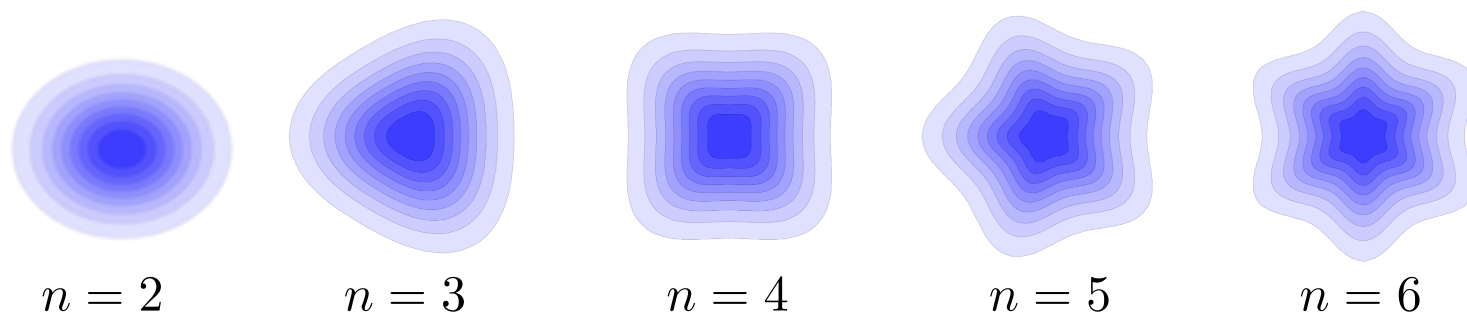
The relativistic hydro, continued

Flow pattern harmonics:



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

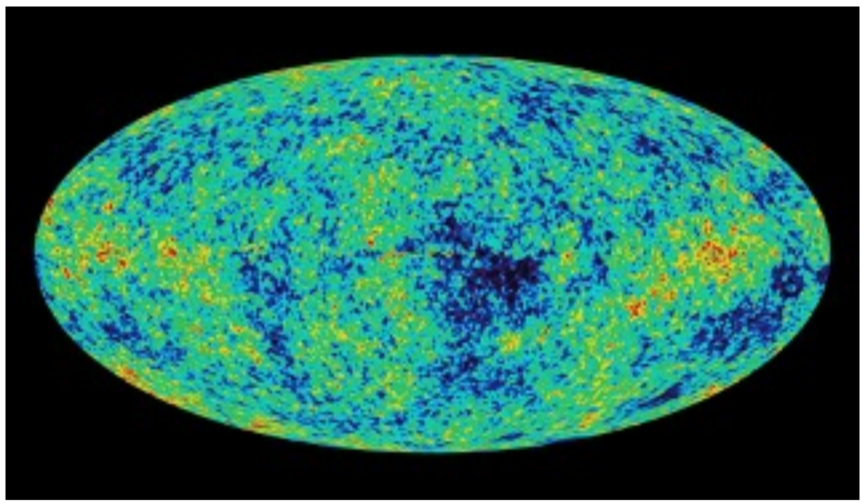
- Allows deviations from thermal equilibrium
- Includes fluctuations of initial states event-by-event
- Does not explain thermalization

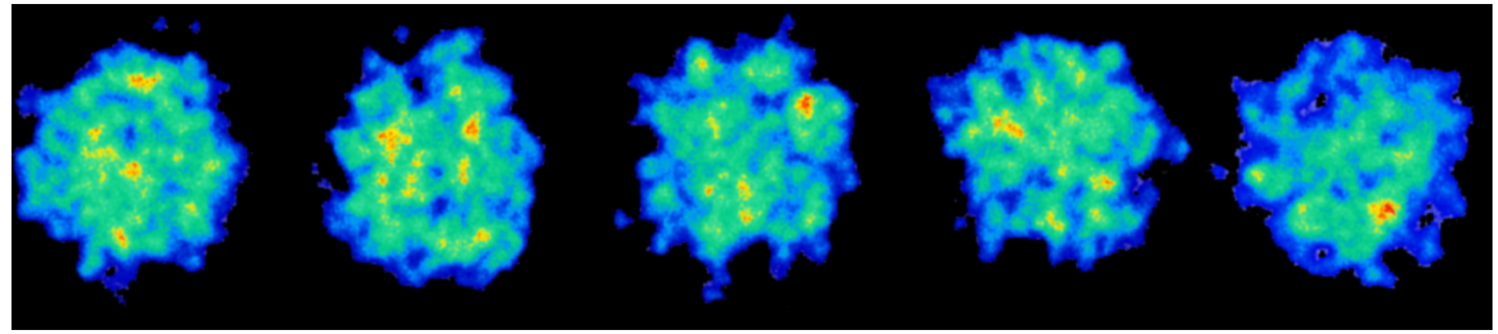
Gélis and Epelbaum, PRL (2013)

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

Analogy with cosmology

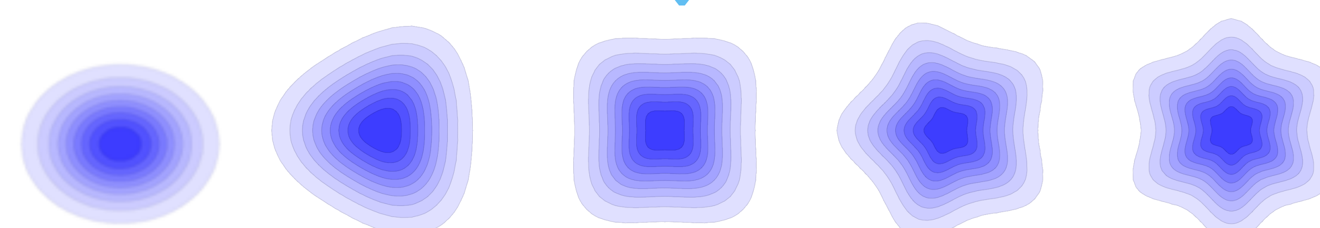
Temperature fluctuations, WMAP



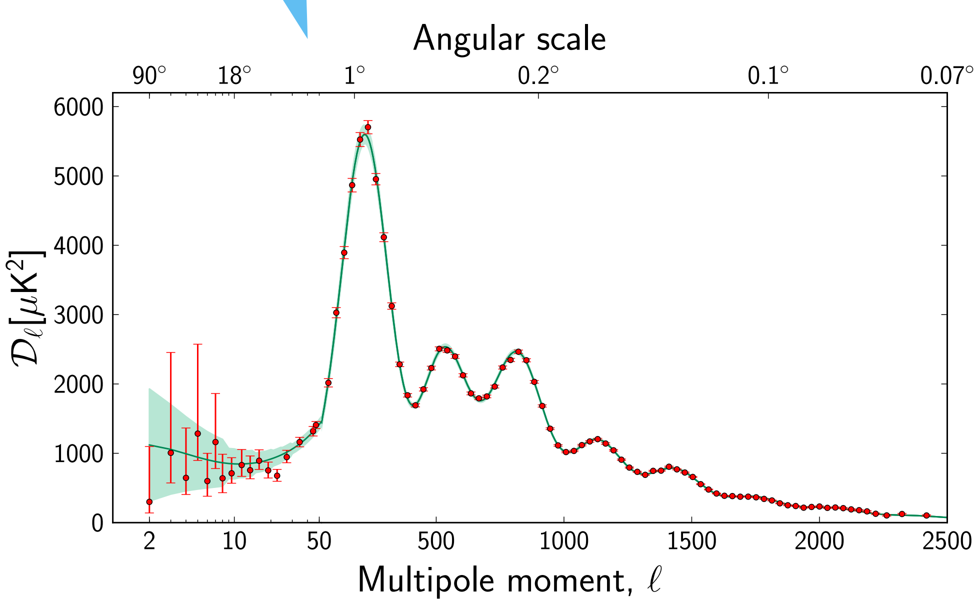


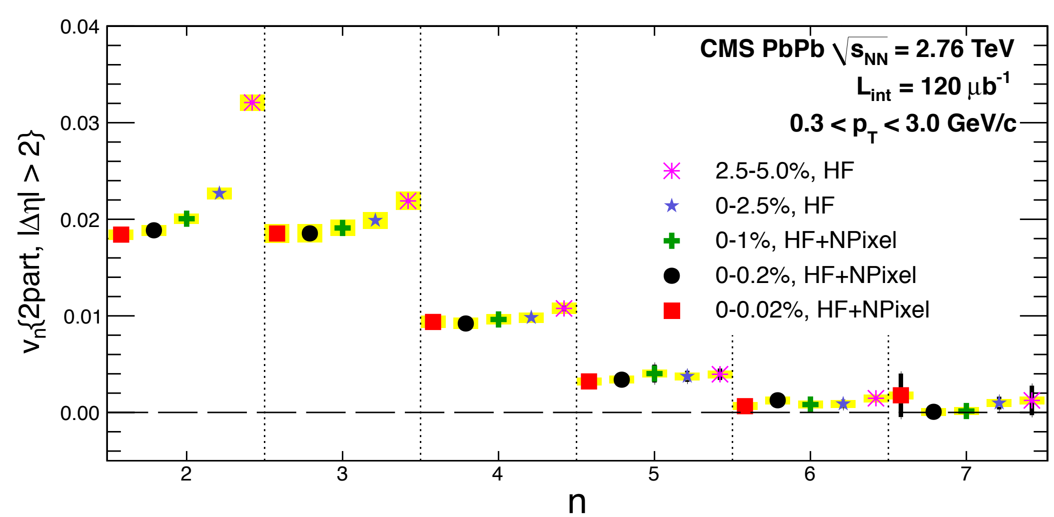
Energy density fluctuations, B. Schenke (BNL)

Hydro evolution



$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$





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

- Kubo relation:

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

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

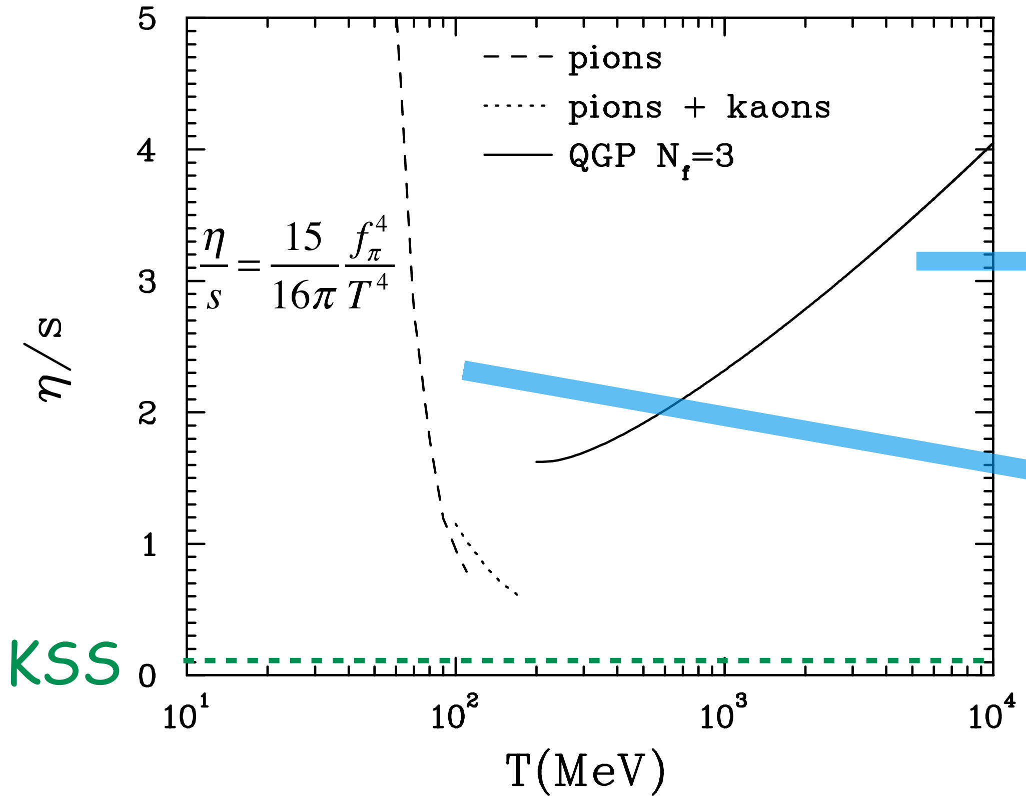
For finite-temperature QCD, can be calculated

- Perturbatively: Arnold, Moore, Yaffe JHEP (2000, 2003)
- On the lattice: H. B. Meyer PRD(2007)
  Sakai, Nakamura LAT2007
- Using strong-coupling AdS/CFT techniques:

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

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

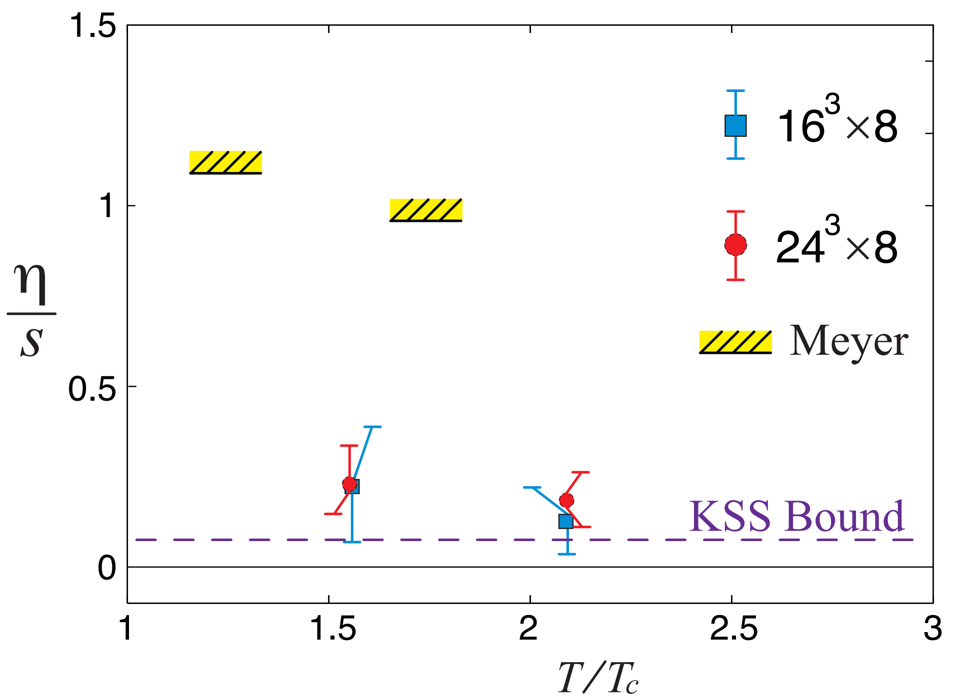
Calculating transport coefficients, II



Csernai, Kapusta, McLerran PRL (2006)

Arnold, Moore, Yaffe JHEP (2003)

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



Sakai, Nakamura LAT2007

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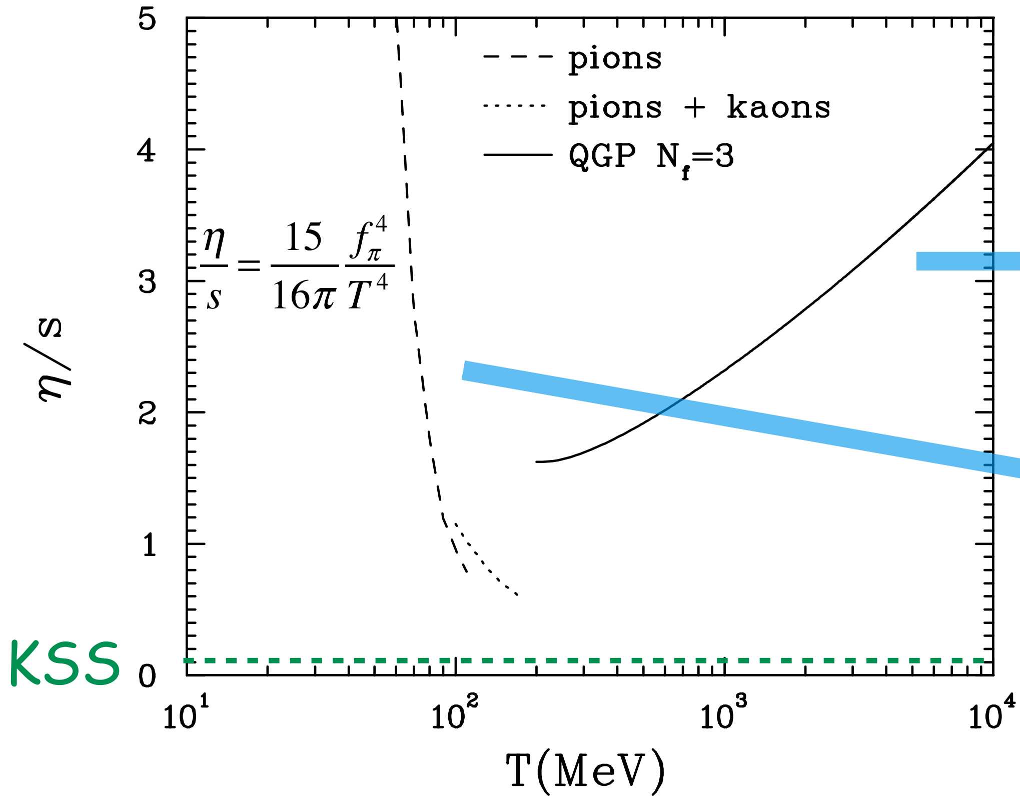
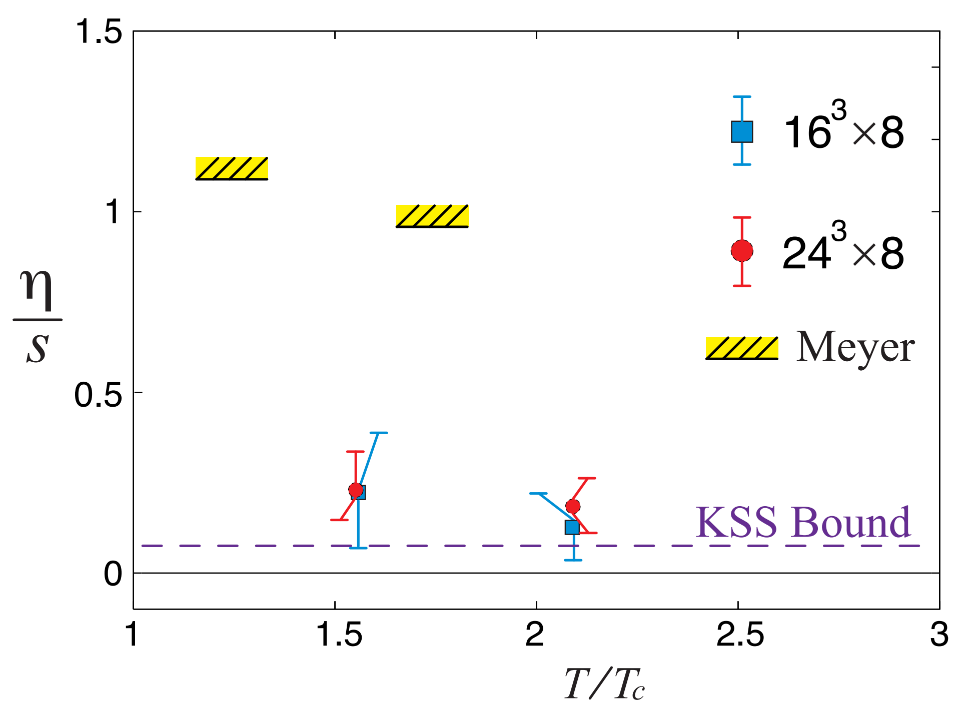
Calculating transport coefficients, II



Csernai, Kapusta, McLerran PRL (2006)

Arnold, Moore, Yaffe JHEP (2003)

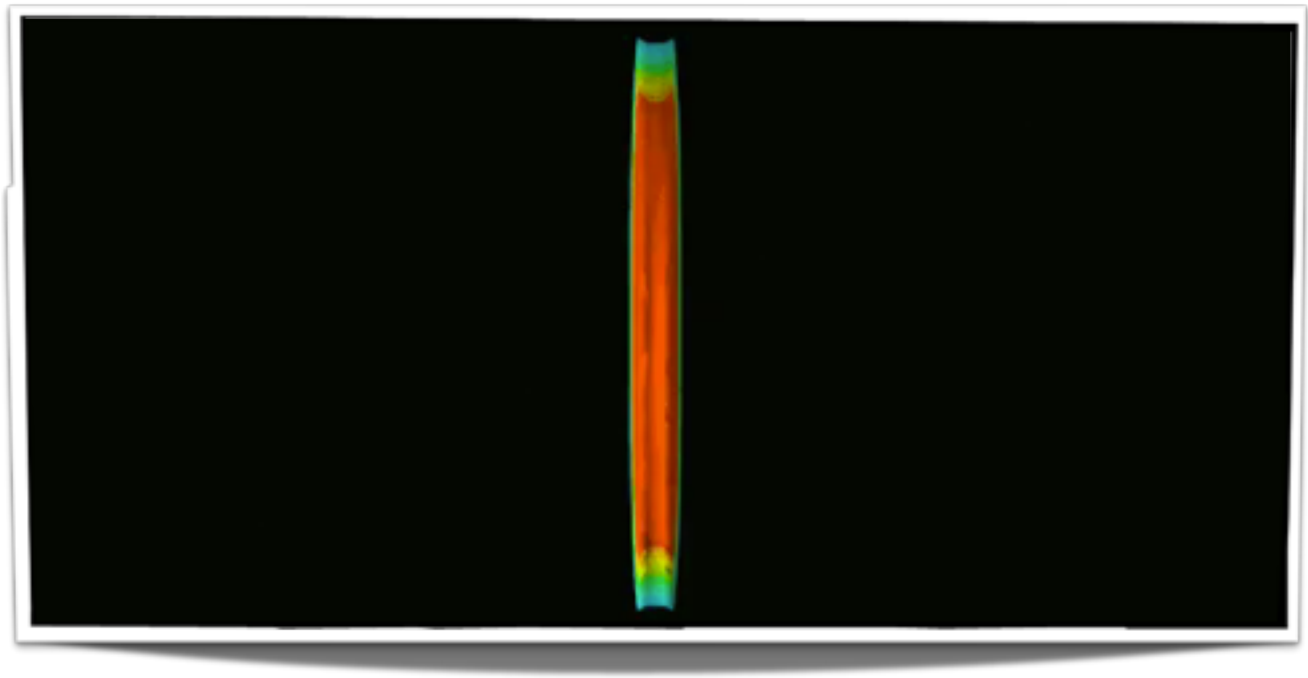
Prakash, Prakash, Venugopalan, Welke Phys. Rep. (1993)



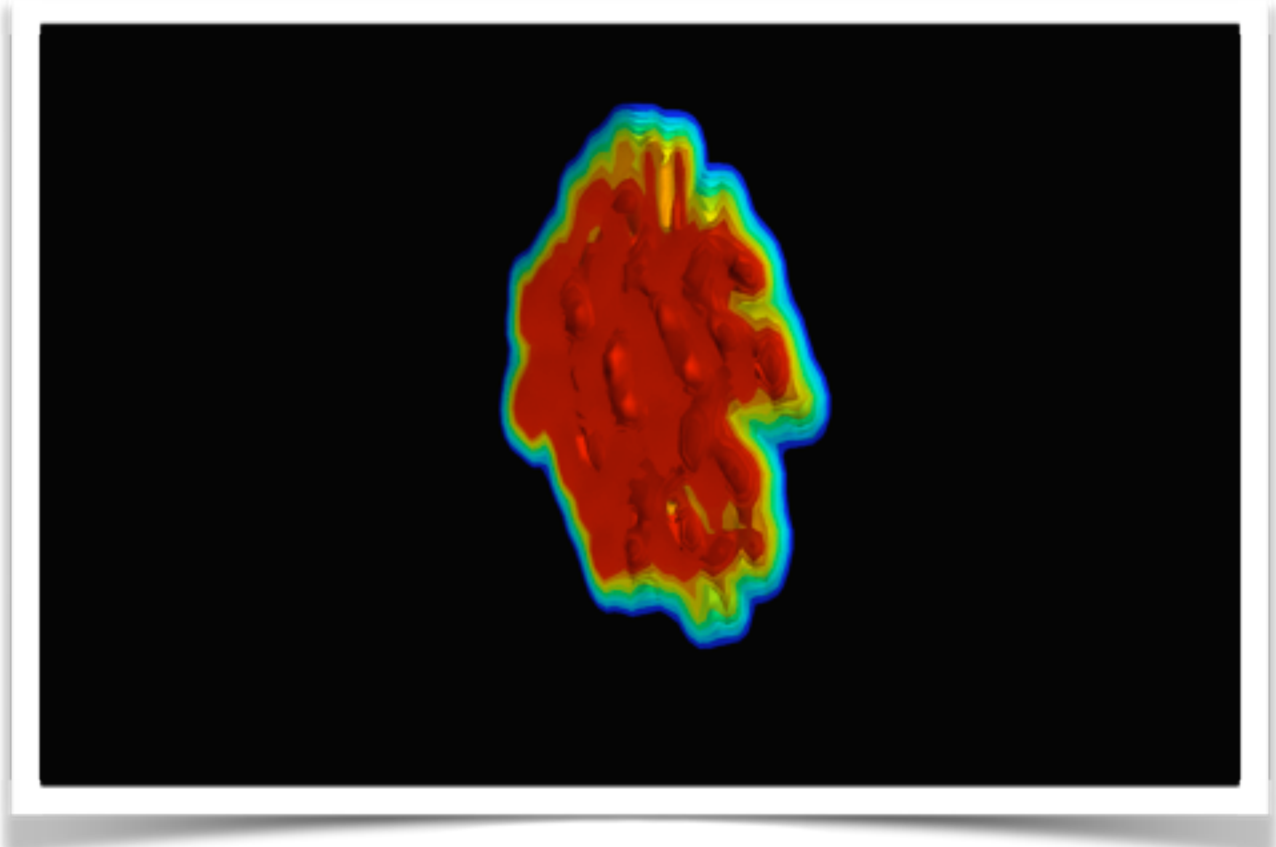
Sakai, Nakamura LAT2007

- Constraints not yet stringent: What does relativistic hydro say?

Relativistic hydrodynamics at work

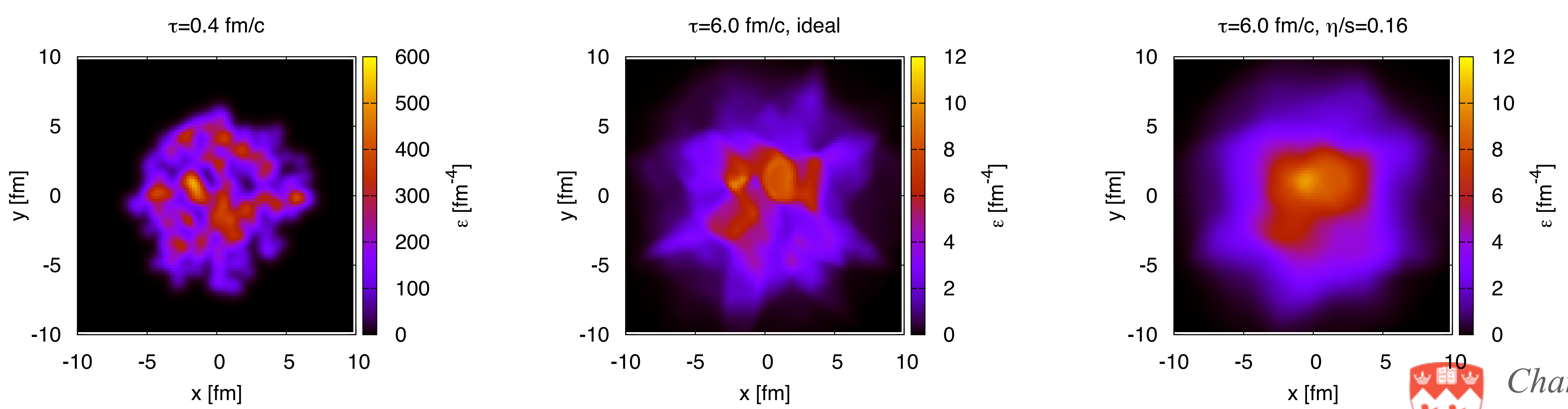


MUSIC



Lumpy MUSIC

Animations: B. Schenke (BNL)



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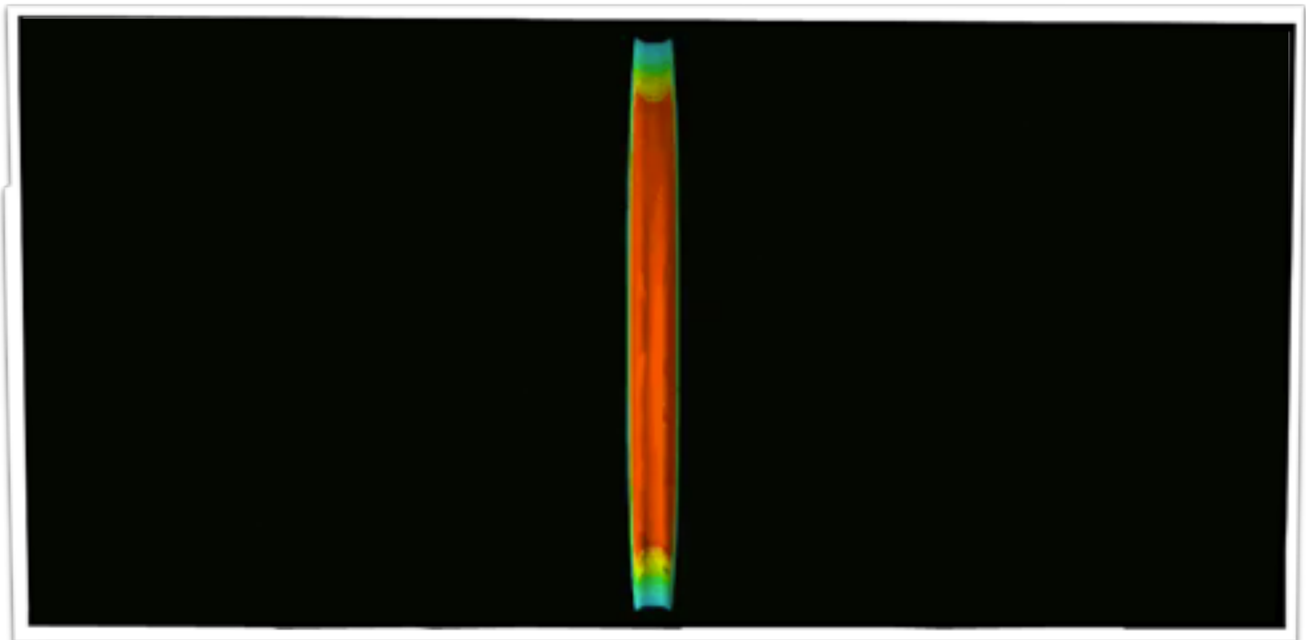
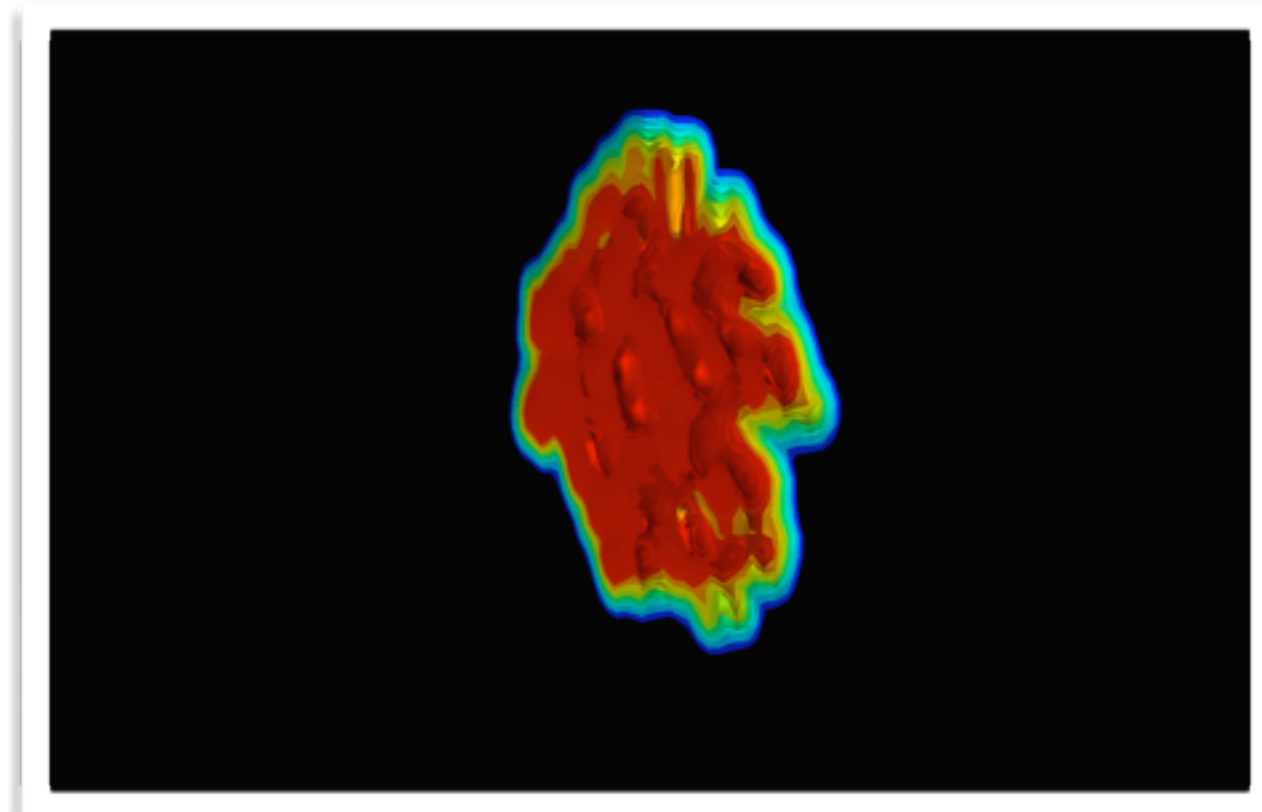
Relativistic hydrodynamics at work



MUSIC



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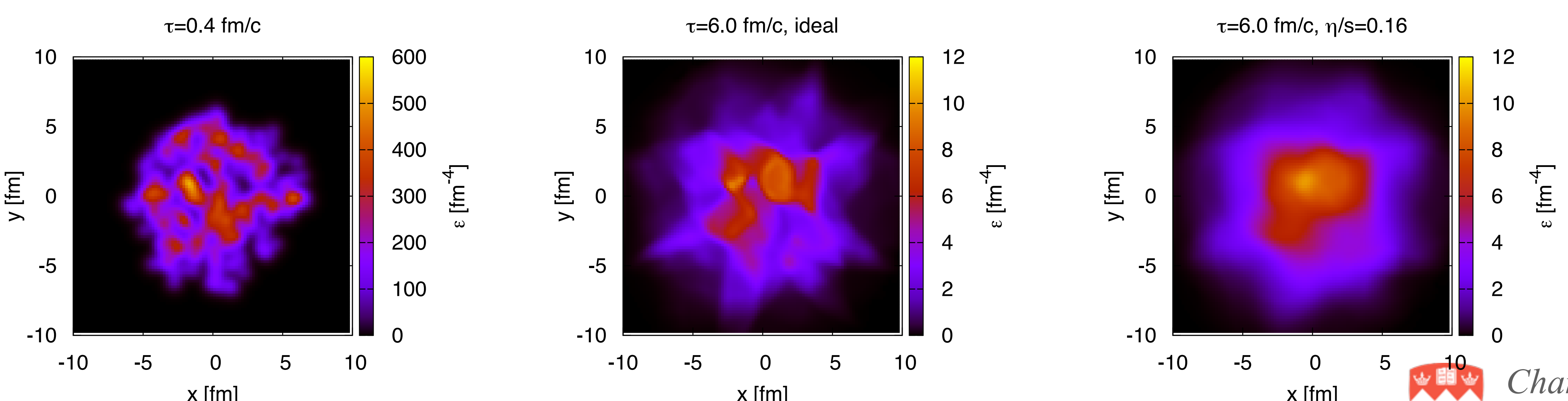
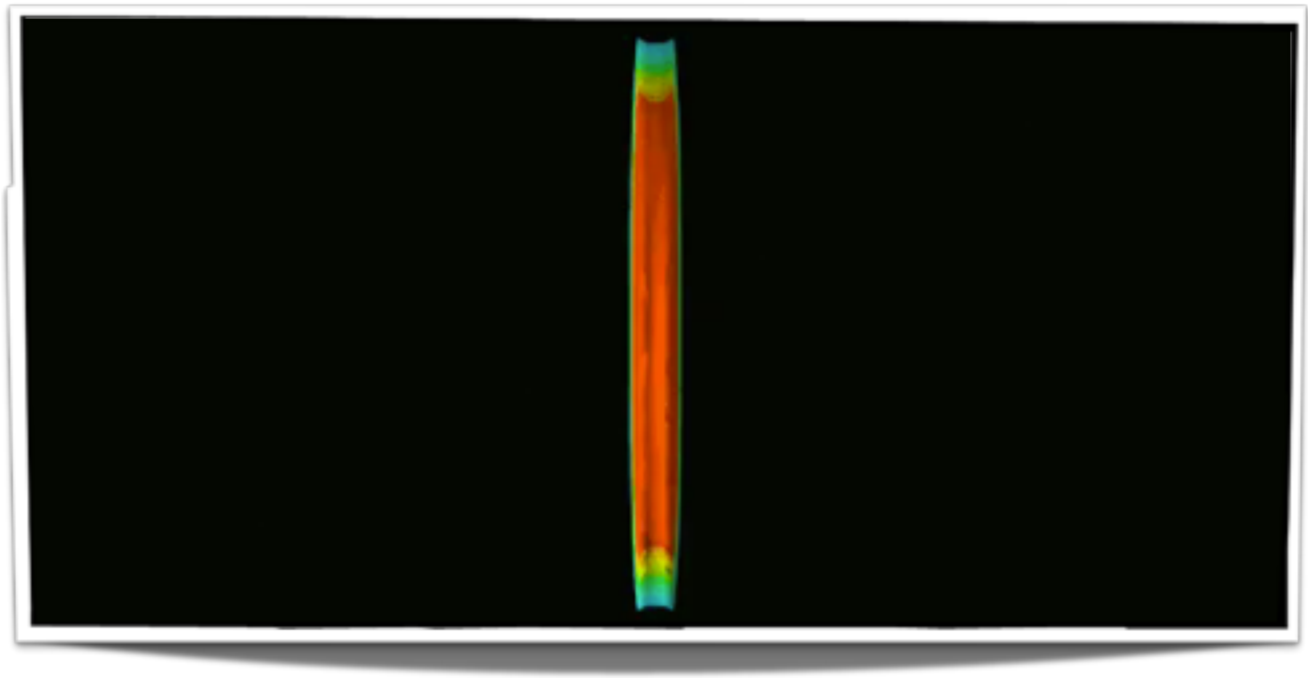
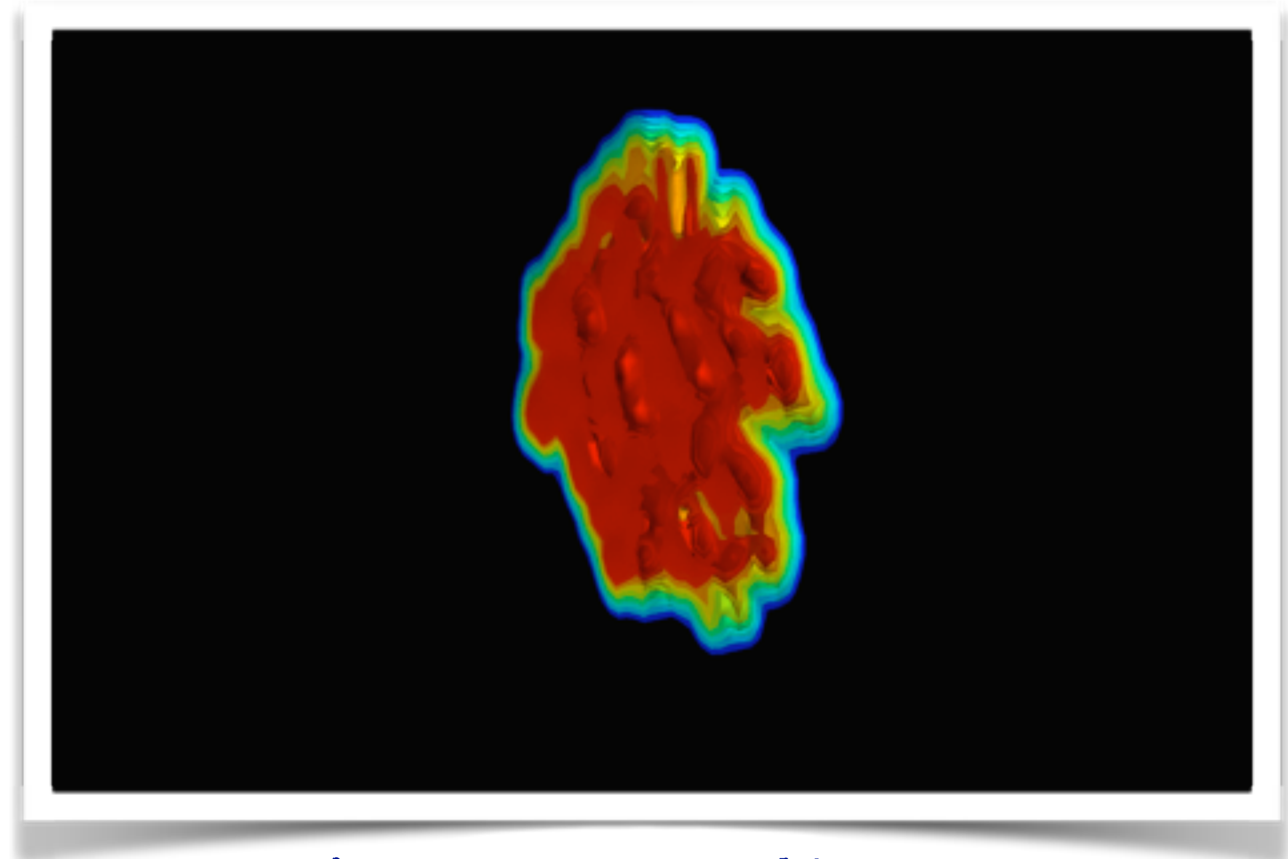


Relativistic hydrodynamics at work



MUSIC



Lumpy MUSIC

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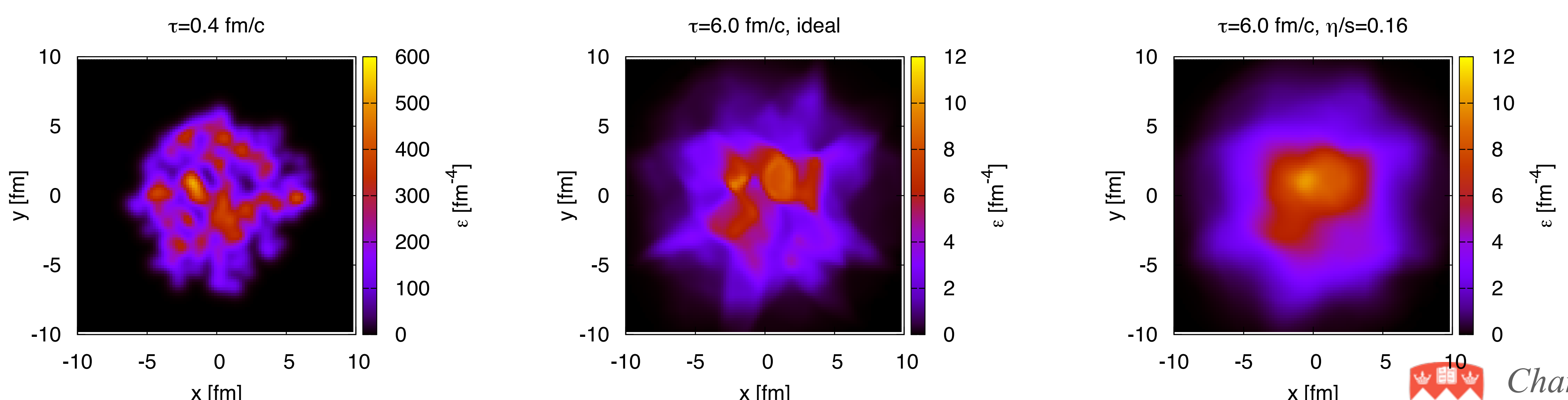

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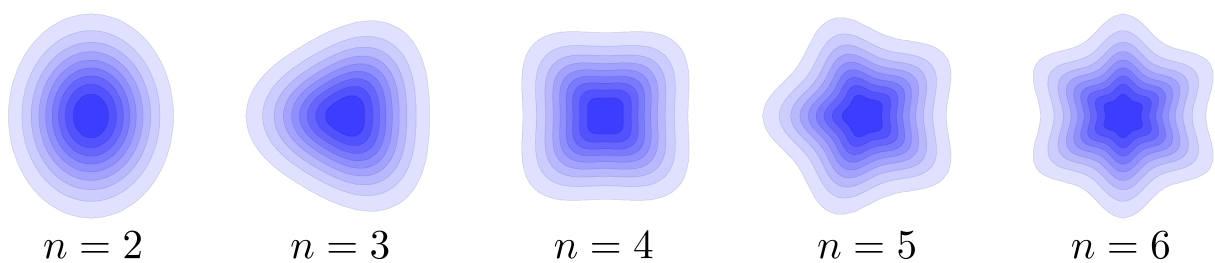
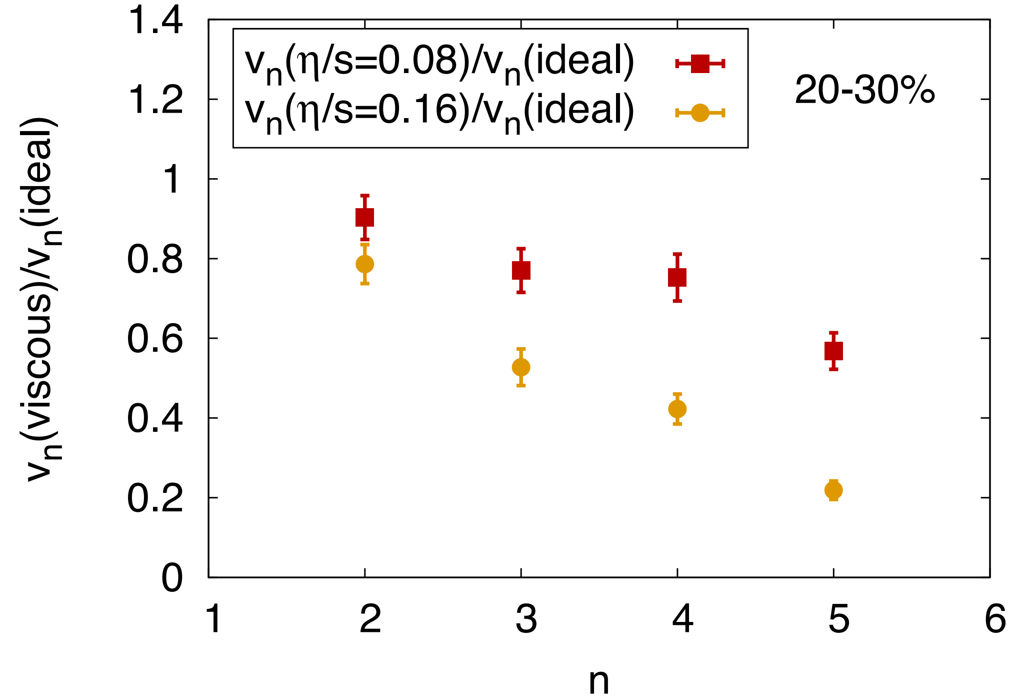
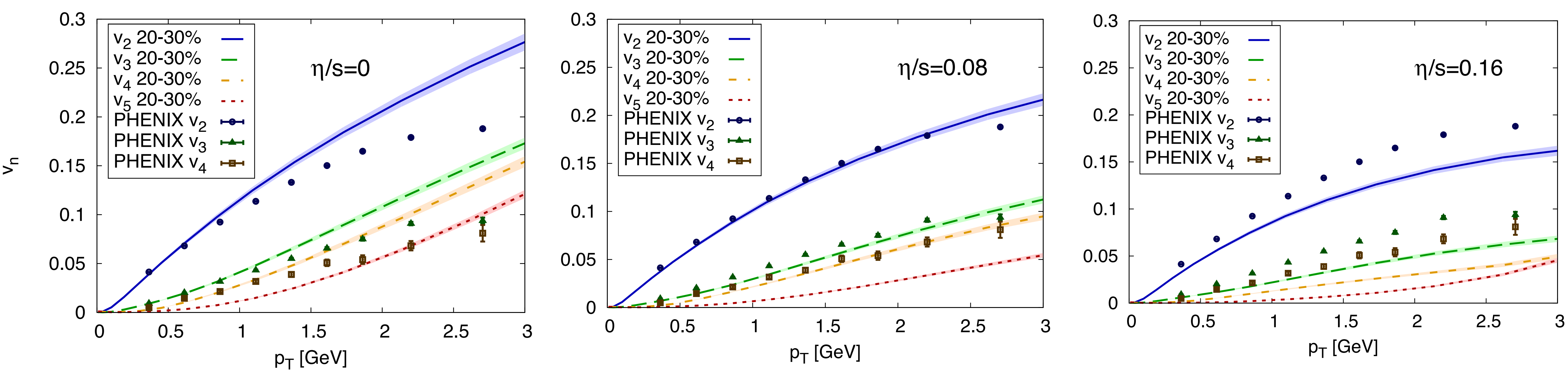
Measuring transport coefficients: The shear viscosity





Higher harmonics are more sensitive to shear viscous corrections

Schenke, Jeon, and Gale, PRC (2012)



The flow data can discriminate between values of η / s

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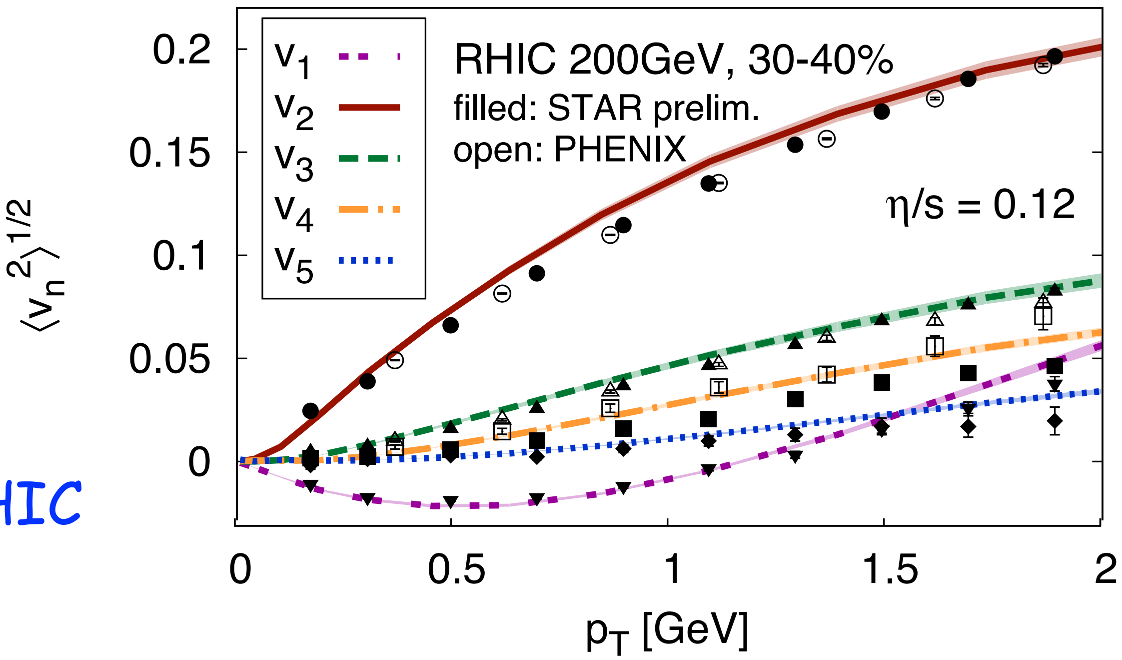
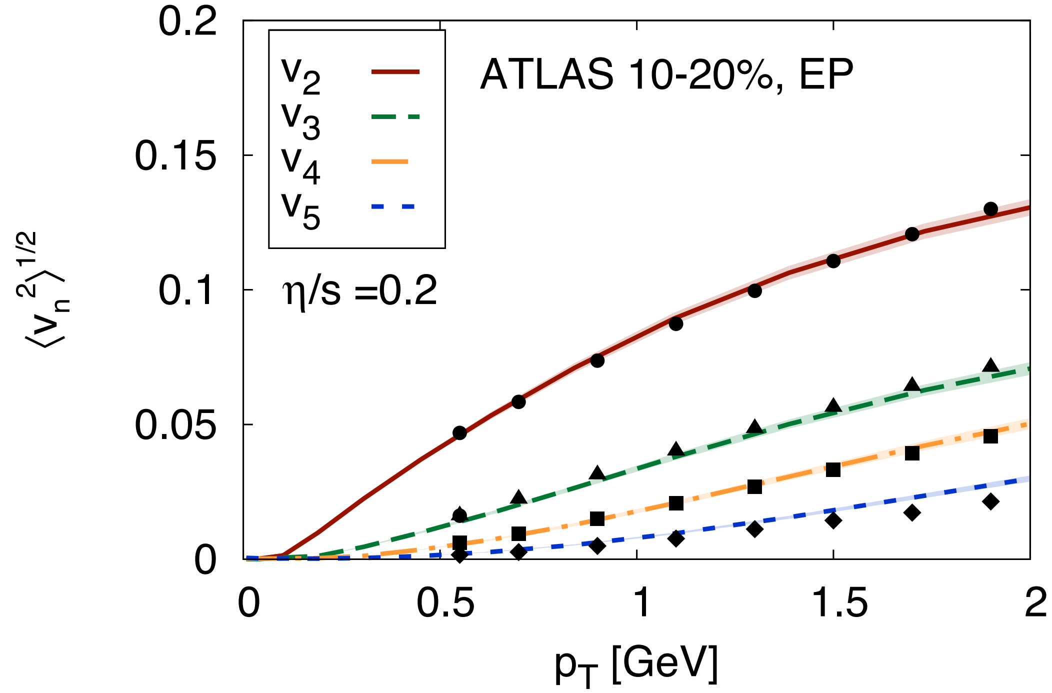
The story so far



RHIC

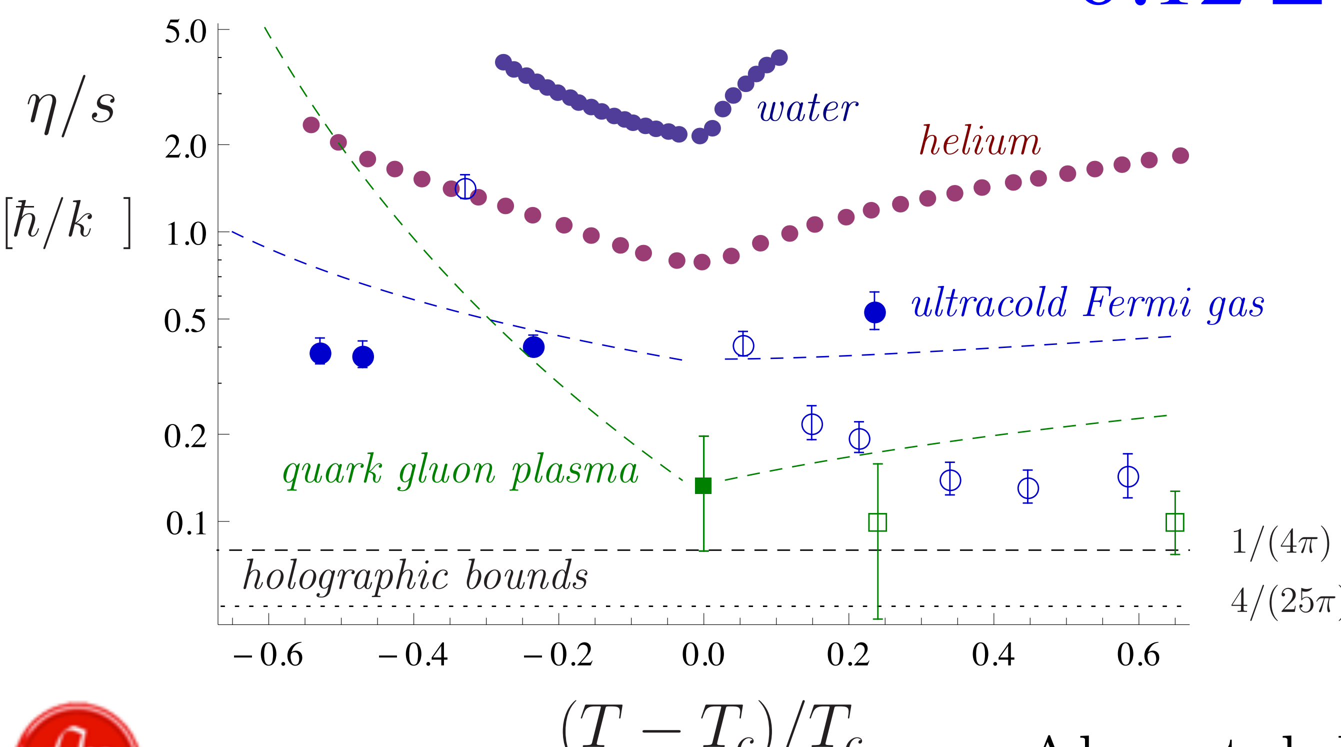


LHC

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

RHIC LHC

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



RHIC and the LHC are viscometers!

Adams et al., N. J. Phys (2012)

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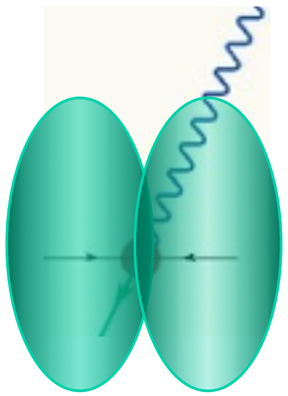
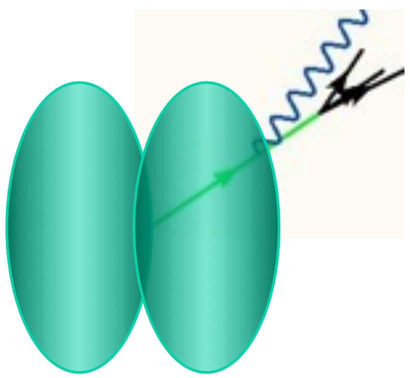
How about getting at the temperature?

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

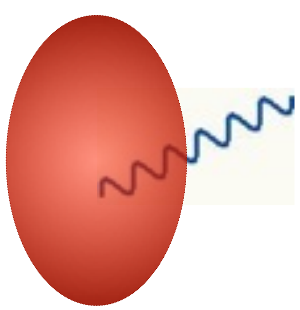
Photons (real and/or virtual)



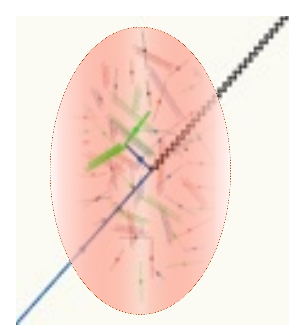
Hard direct photons. pQCD with shadowing
Non-thermal



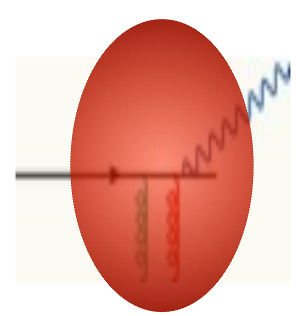
Fragmentation photons. pQCD with shadowing
Non-thermal



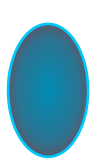
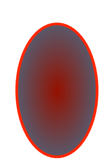
Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

 Pre-equilibrium? 

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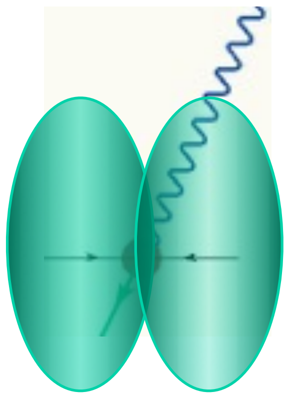
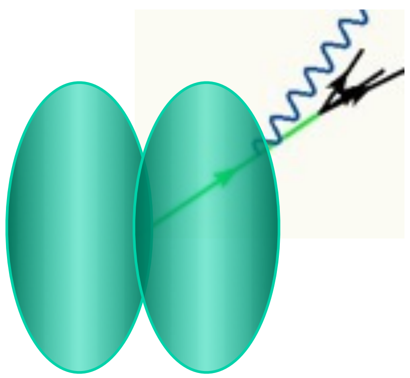
How about getting at the temperature?

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

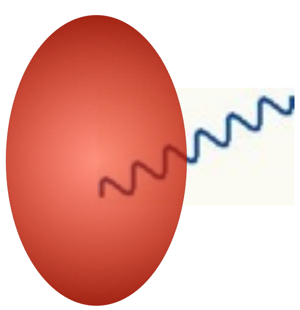
Photons (real and/or virtual)



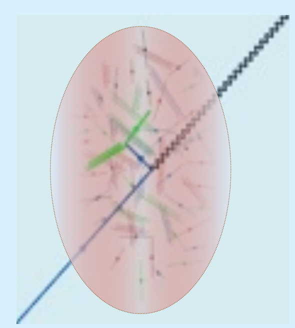
Hard direct photons. pQCD with shadowing
Non-thermal



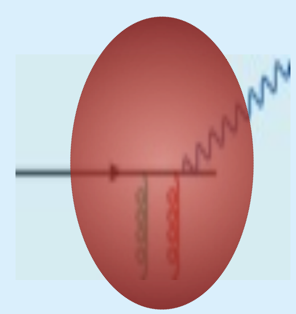
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
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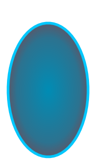
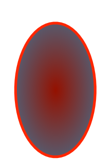
 Pre-equilibrium? 

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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)

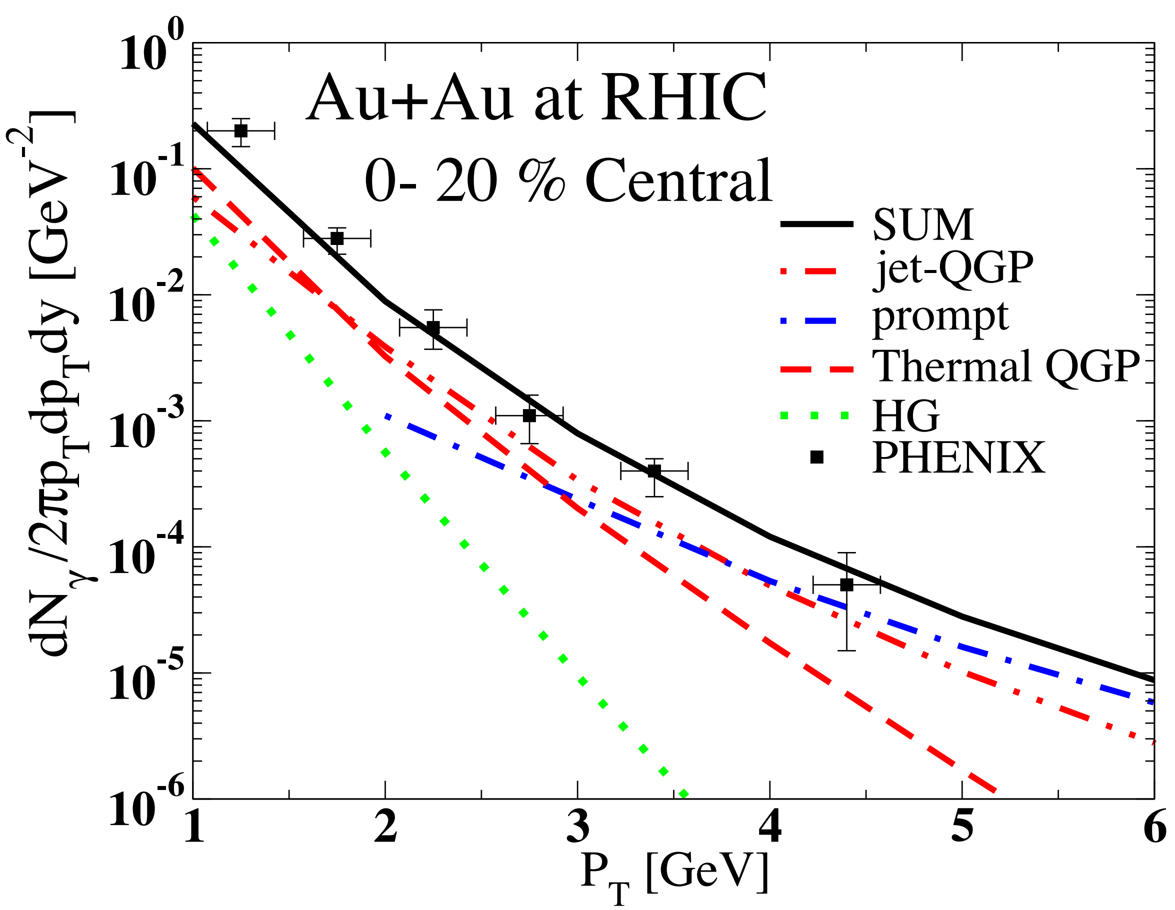
- QGP rates have been calculated up to NLO in α_s in FTFT:
  Ghiglieri et al., JHEP (2013); M. Laine JHEP (2013)

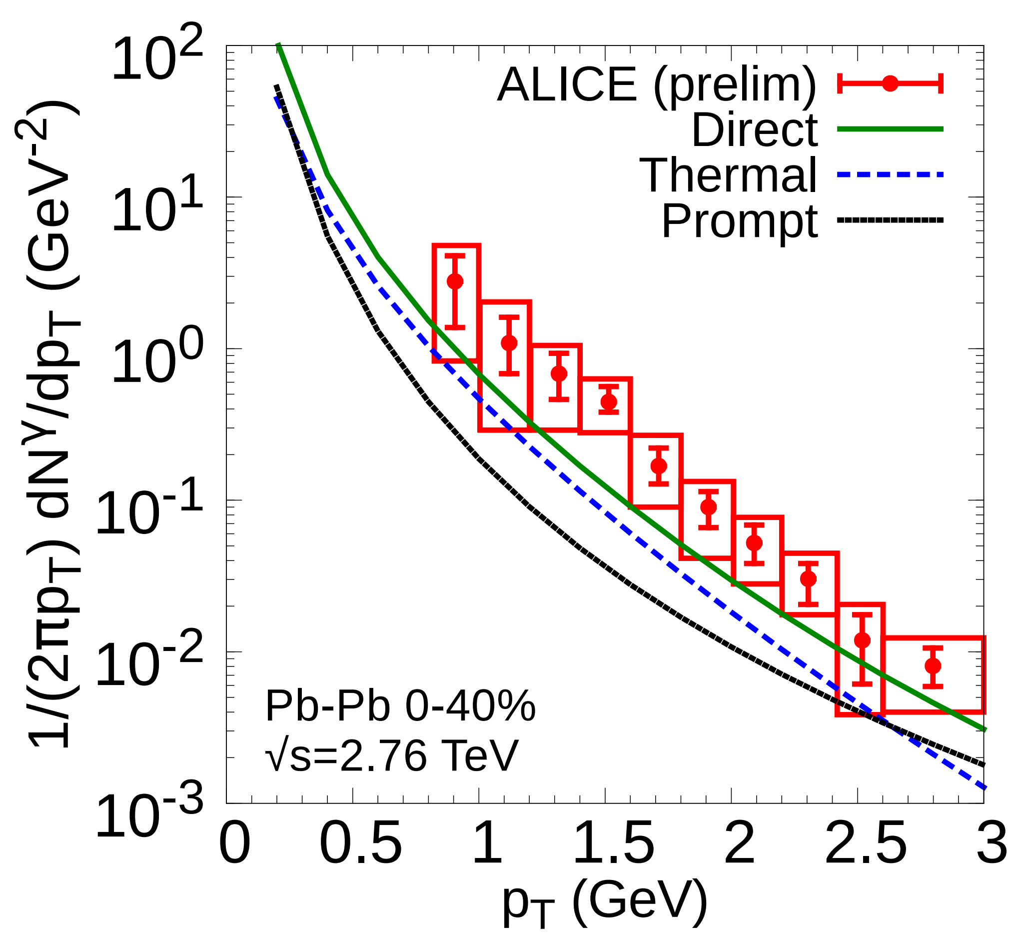
  ...and on the lattice (dileptons):
  Ding et al., PRD (2011)

- Hadronic rates: C. Gale, Landolt-Bornstein (2010)
  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

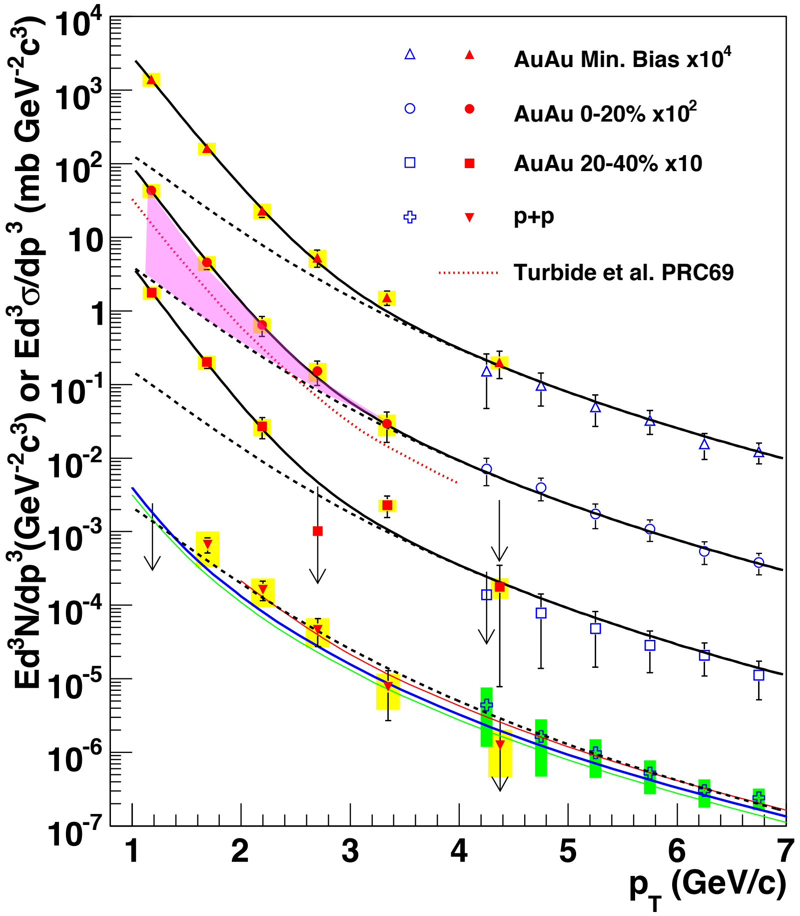


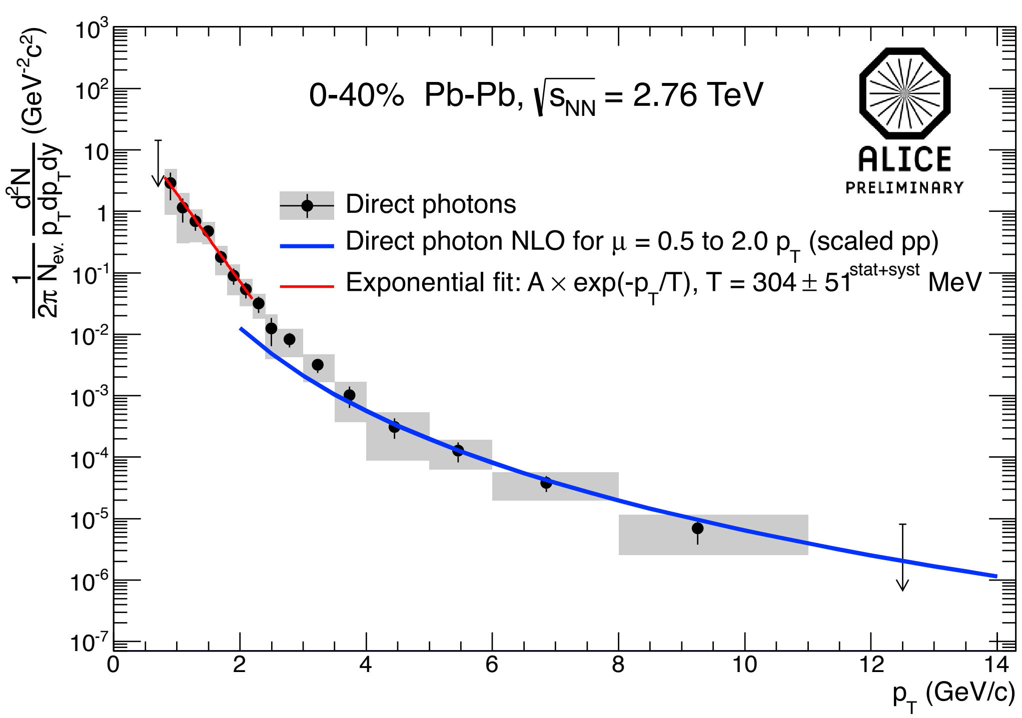


Turbide, Gale, Frodermann, Heinz, PRC (2008); Higher p_T: G. Qin et al., PRC (2009)

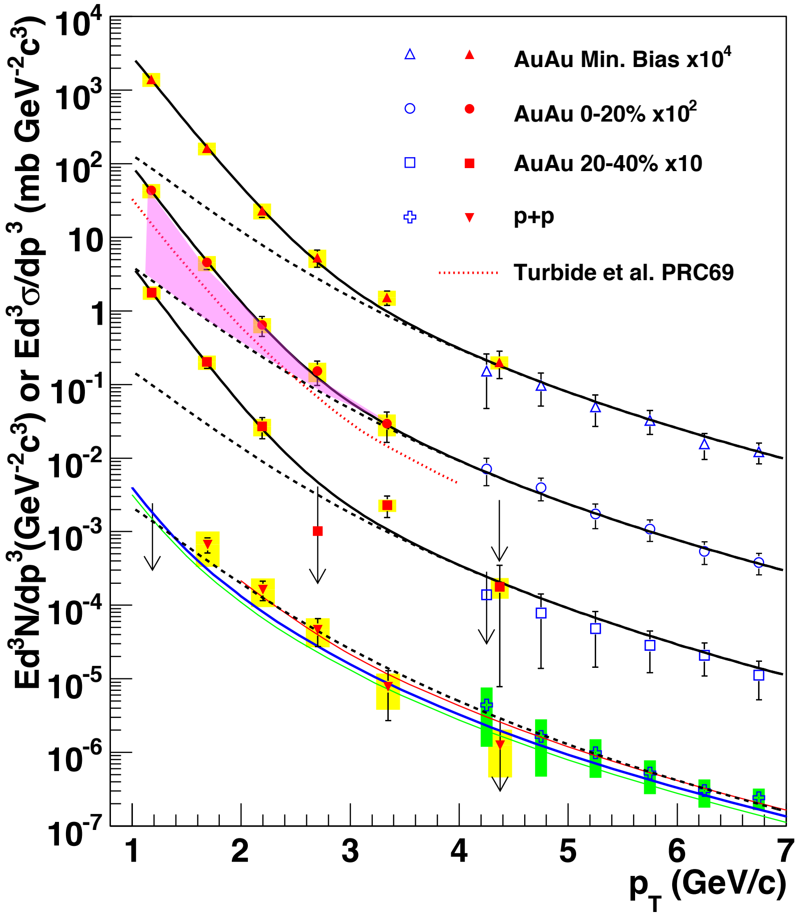
J.-F. Paquet McGill PhD (2015), and to be published

Characterizing the hot matter created at RHIC and at the LHC with photons

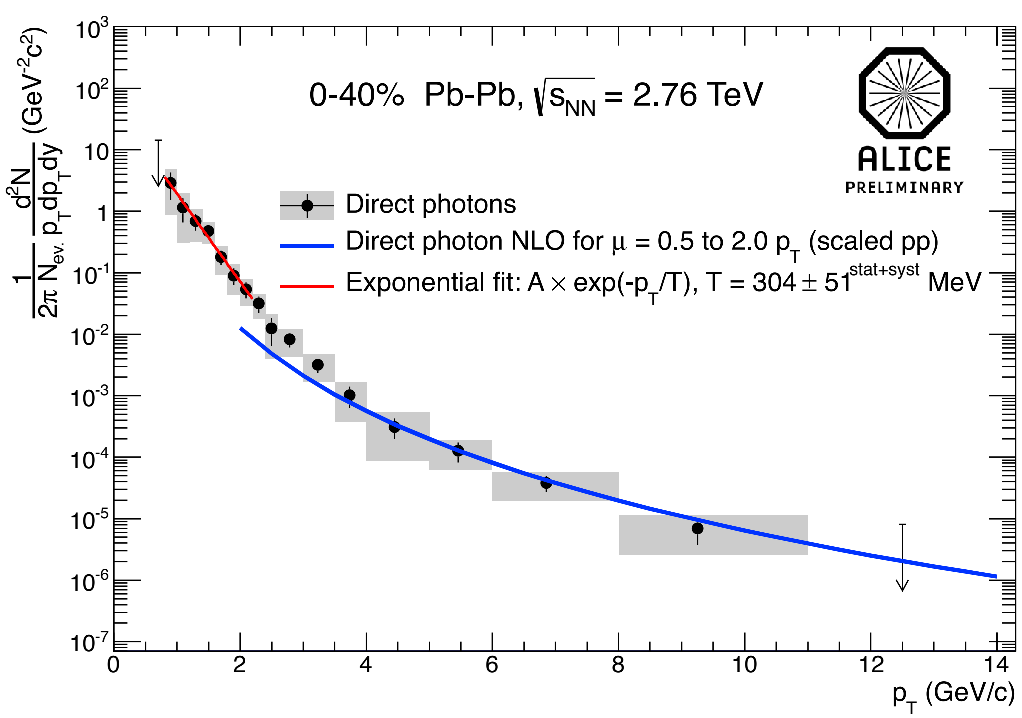




Characterizing the hot matter created at RHIC and at the LHC with photons



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



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

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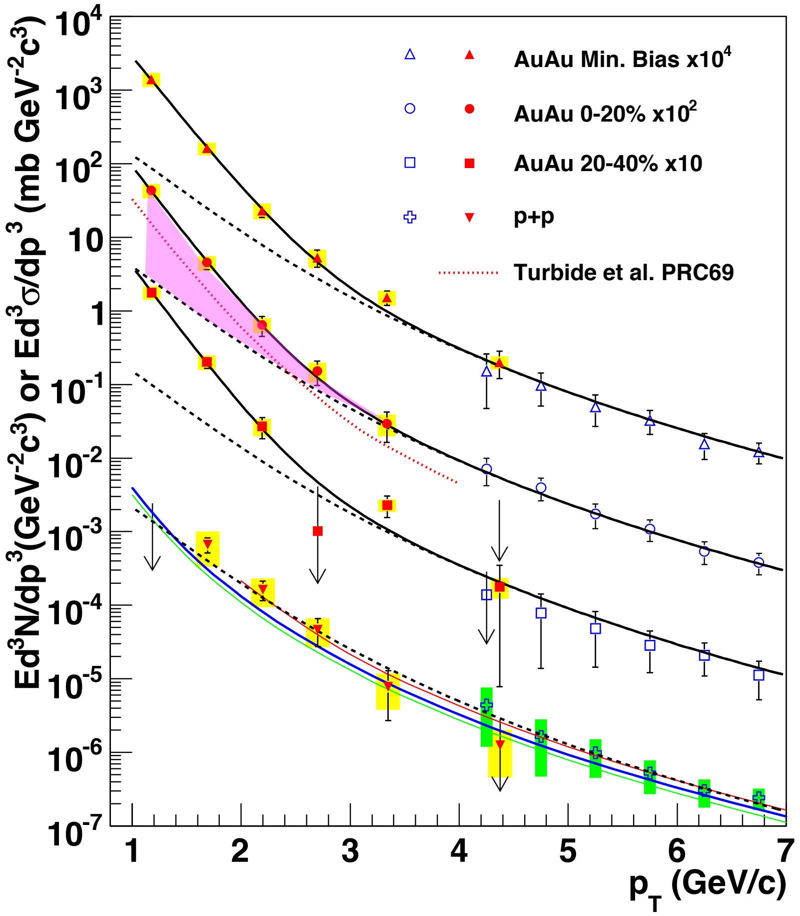
McGill

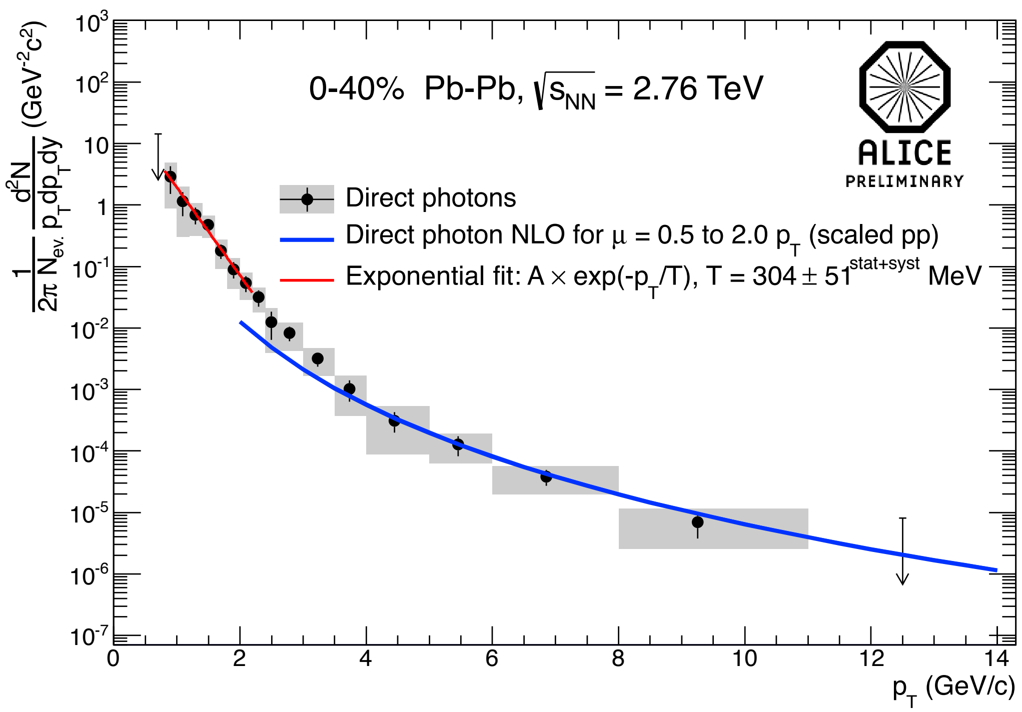
Characterizing the hot matter created at RHIC and at the LHC with photons



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

$$1\,\text{MeV} = 10^{10}\,\text{K}$$

$$T_{\odot}^{\text{core}} \approx 10^{7}\,\text{K}$$



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

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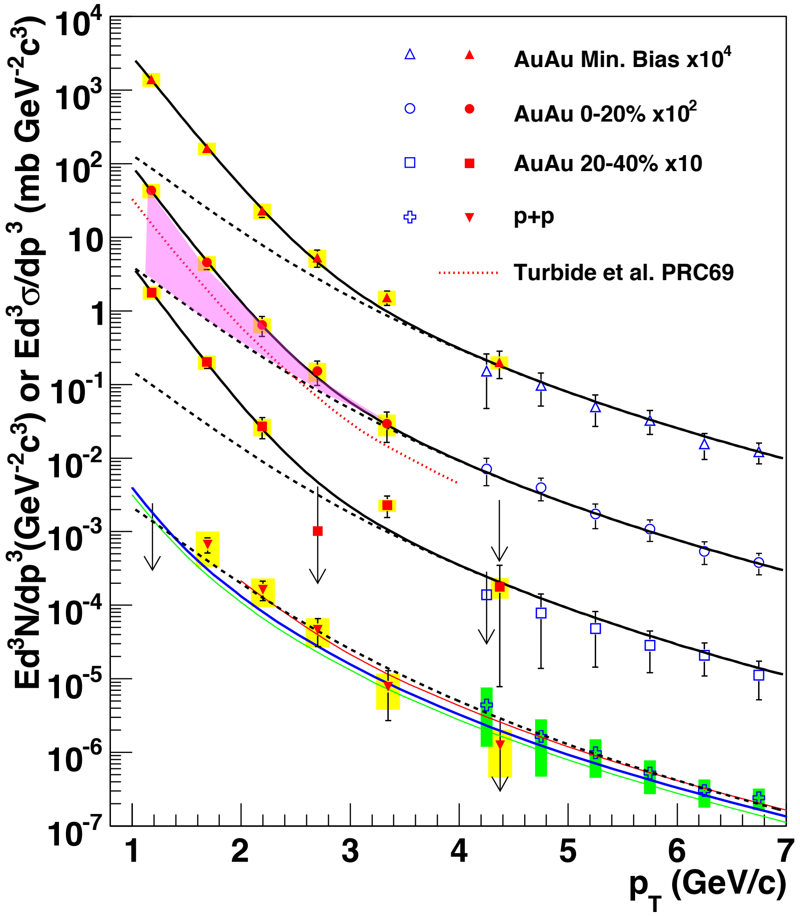
Characterizing the hot matter created at RHIC and at the LHC with photons



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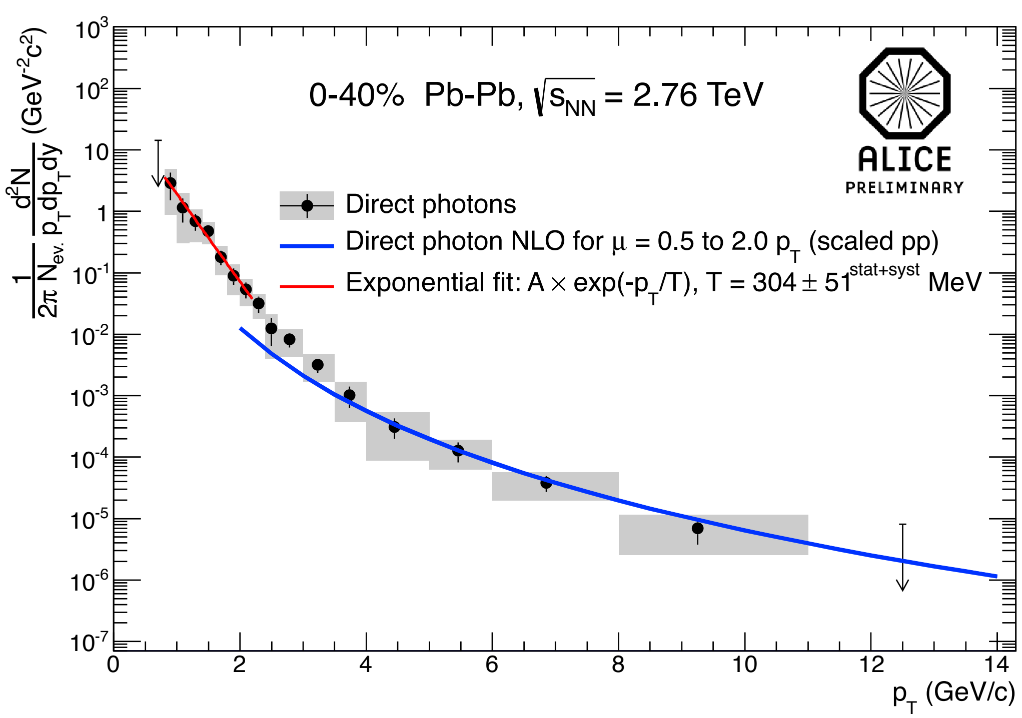

$$T_{\rm excess}^{\rm ALICE}({\rm LHC}) = 304 \pm 51\,{\rm MeV}$$

Flow effects will be important

van Hees, Gale Rapp, PRC (2011)
Shen, Heinz, Paquet, Gale, PRC (2014)

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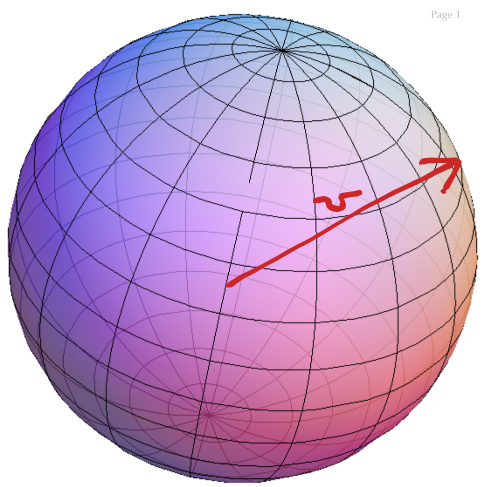
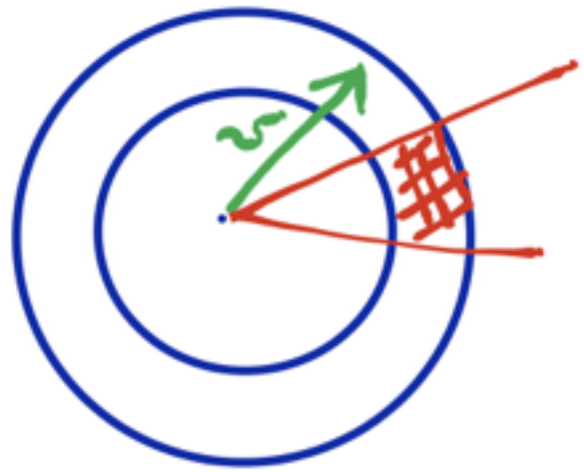
Suppose an expanding source at local temperature T:





Side view

$$E\frac{d^3n}{d^3p} \approx E\,e^{-\beta\gamma E+\beta\gamma v E}$$

$$T_e = \sqrt{\frac{1+v}{1-v}}\,T$$

Doppler shift

The effective temperature (deduced from the slope) is not the true temperature

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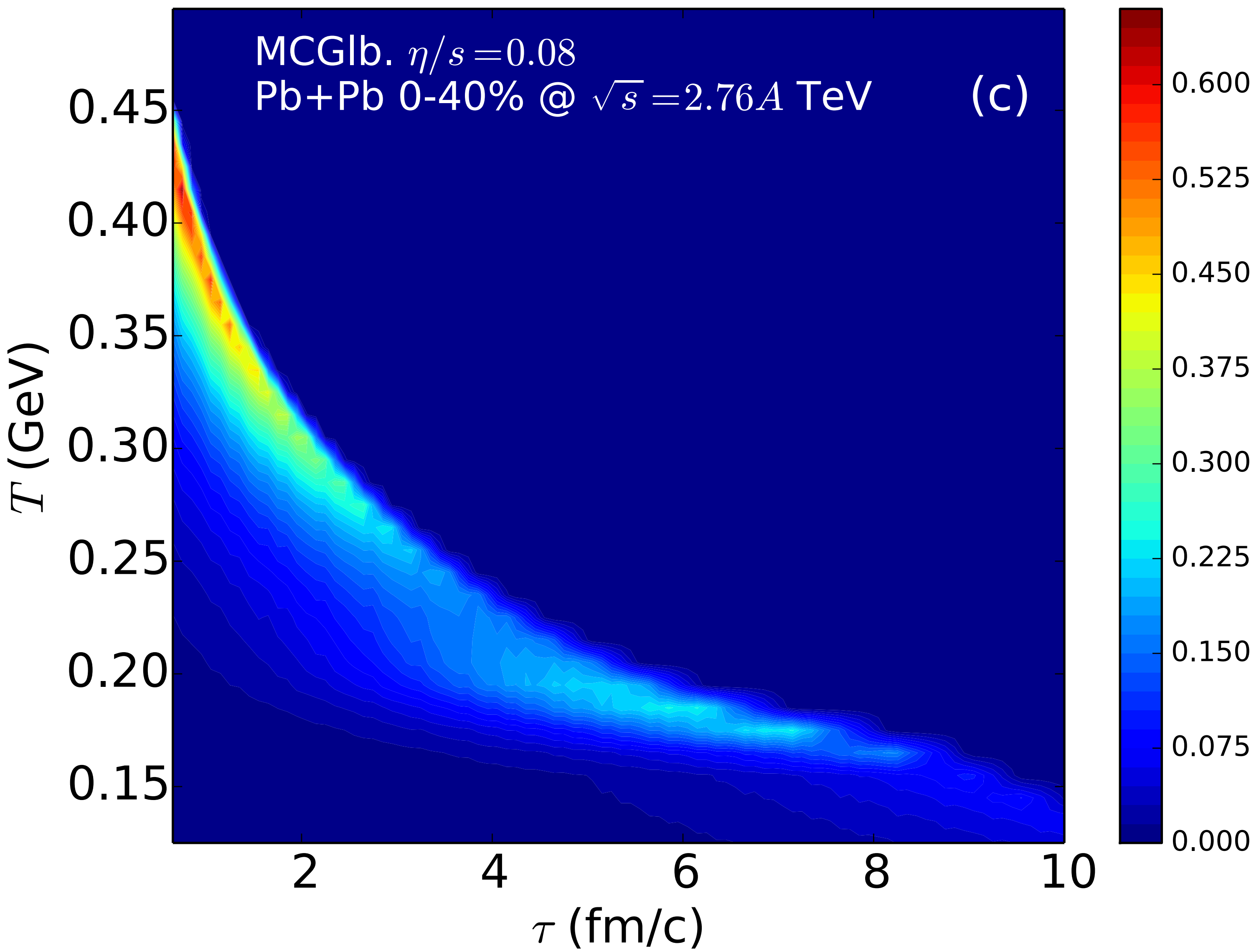
Studying the differential temperature distribution with a realistic fluid-dynamical calculation



LHC

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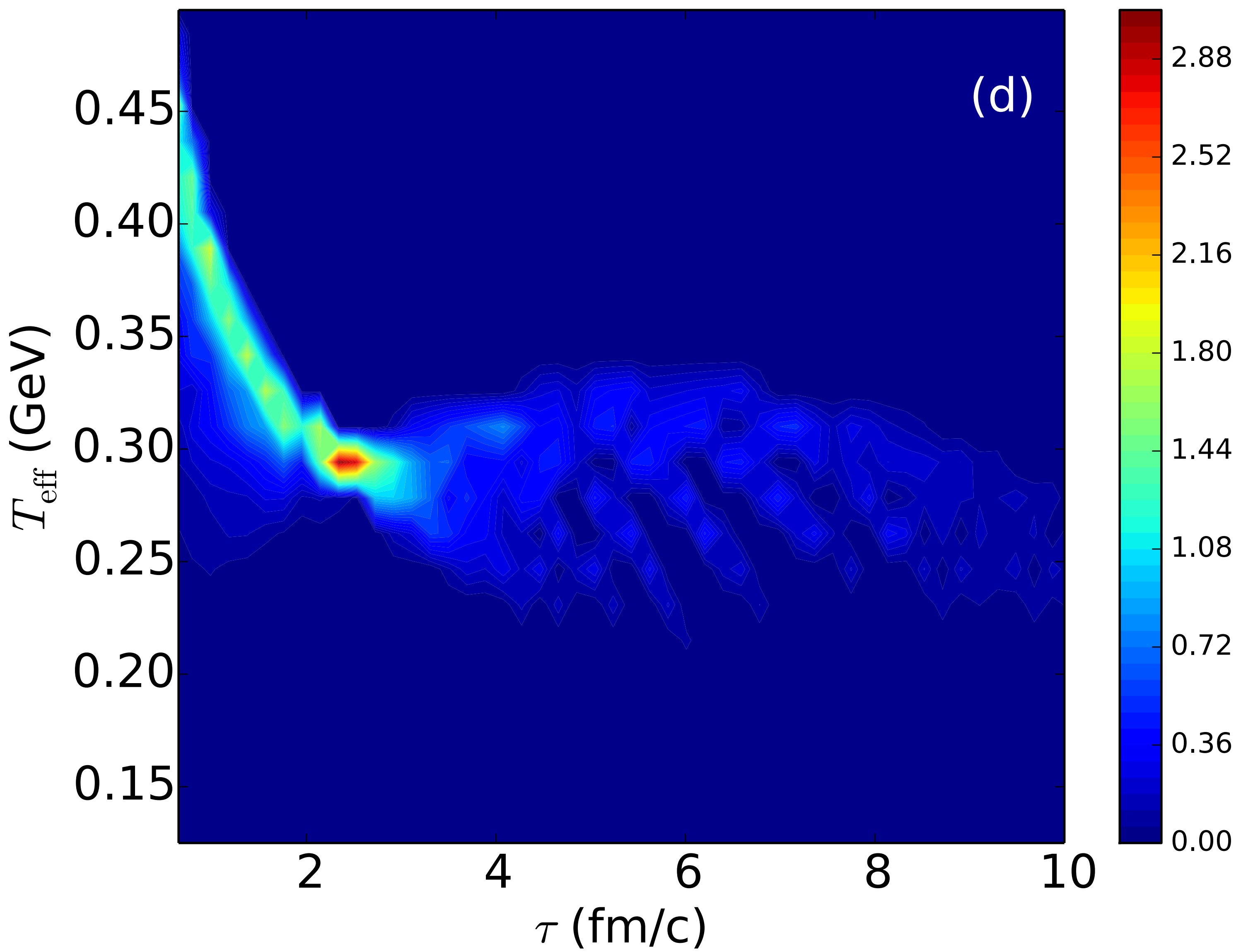
Studying the differential temperature distribution with a realistic fluid-dynamical calculation



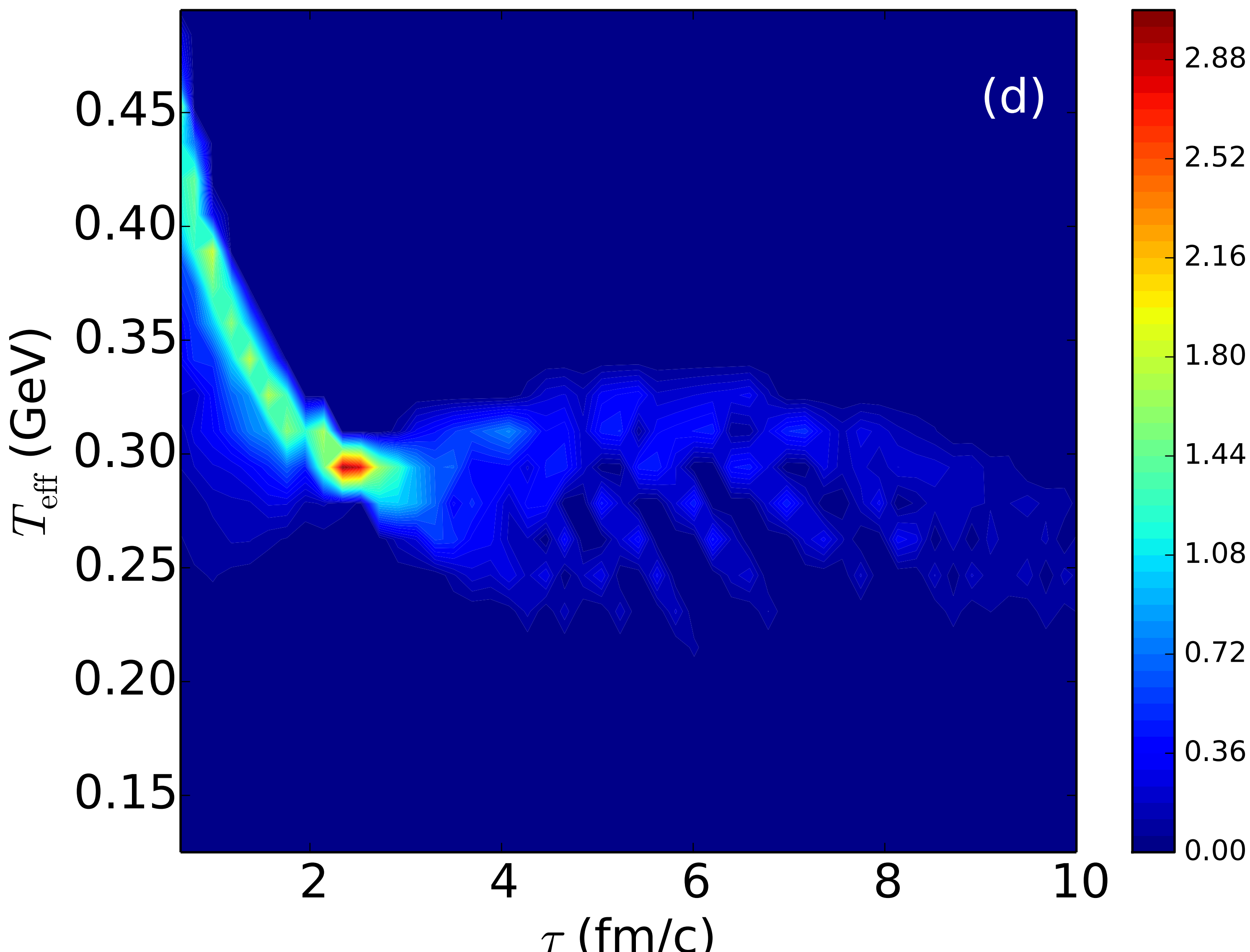
LHC

ALICE

NPA (2013)

$$T_{\mathrm{eff}} = 304 \pm 51\,\mathrm{MeV}$$

Studying the differential temperature distribution with a realistic fluid-dynamical calculation



LHC

ALICE

NPA (2013)

$$T_{eff} = 304 \pm 51 \, \text{MeV}$$

A summary:

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%

- Photons can be used as a thermometer!
- $T > T_c$ <u>is reached</u>

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

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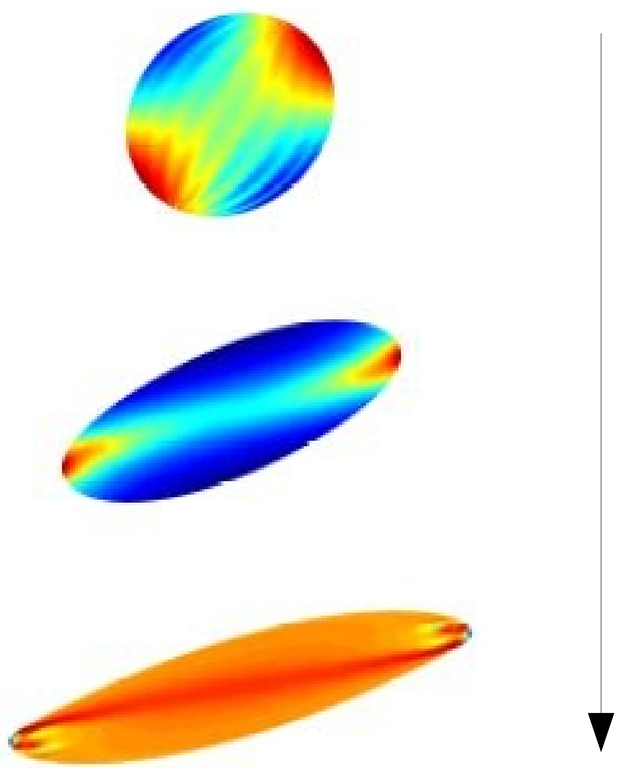
Is there more?

Shear

Resistance to deformation

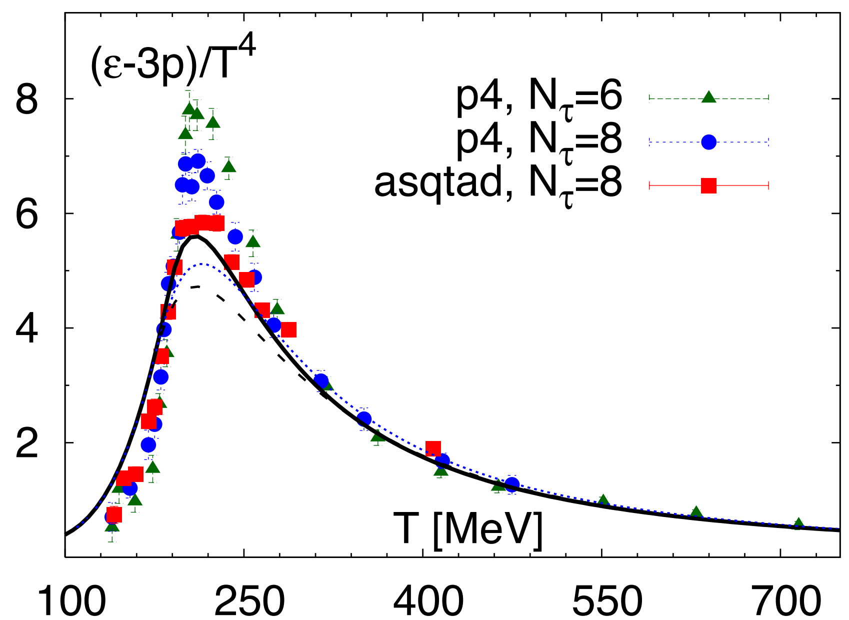


Bulk

Resistance to expansion

From G. Denicol (McGill)

Is the hydro modelling complete? More to the hydro!



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

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

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

The dissipative terms, to second order:

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

- Very few calculations incorporate all of these

  The importance of the bulk viscosity of QCD in ultrarelativistic heavy-ion collisions, S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, arXiv:1502.01675 [nucl-th].

- The hydro description is still very much in evolution

Conclusions

- Heavy-Ion collisions are teaching us about:
  - The initial state via the QCD nature of the nuclear wave function
  - The properties of the strongly coupled medium
  - The EOS of QCD, as it enters the hydro evolution
  - Transport coefficients of QCD
- The fluid dynamical paradigm is remarkably successful. The revolution is not over
- RHIC and the LHC have measured the largest temperatures, and the lowest specific shear viscosity ever produced.
- Moving closer to ab-initio modelling; exciting times ahead!

Thank you !