From fundamental quantum fields to properties of matter

Heavy Ions Theory Overview

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CERN PH-TH

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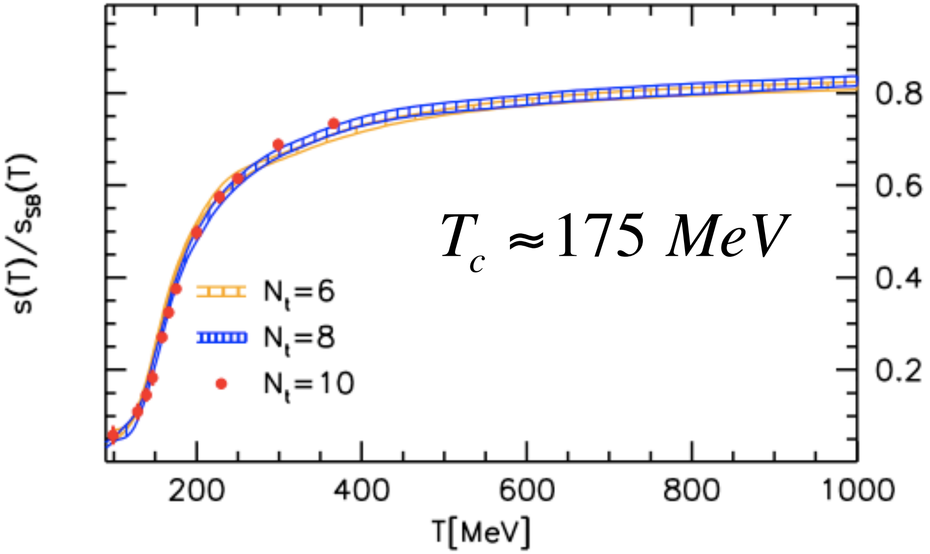
What do we know from 1st principles about hot and dense QCD?

Rapid cross-over at T_c

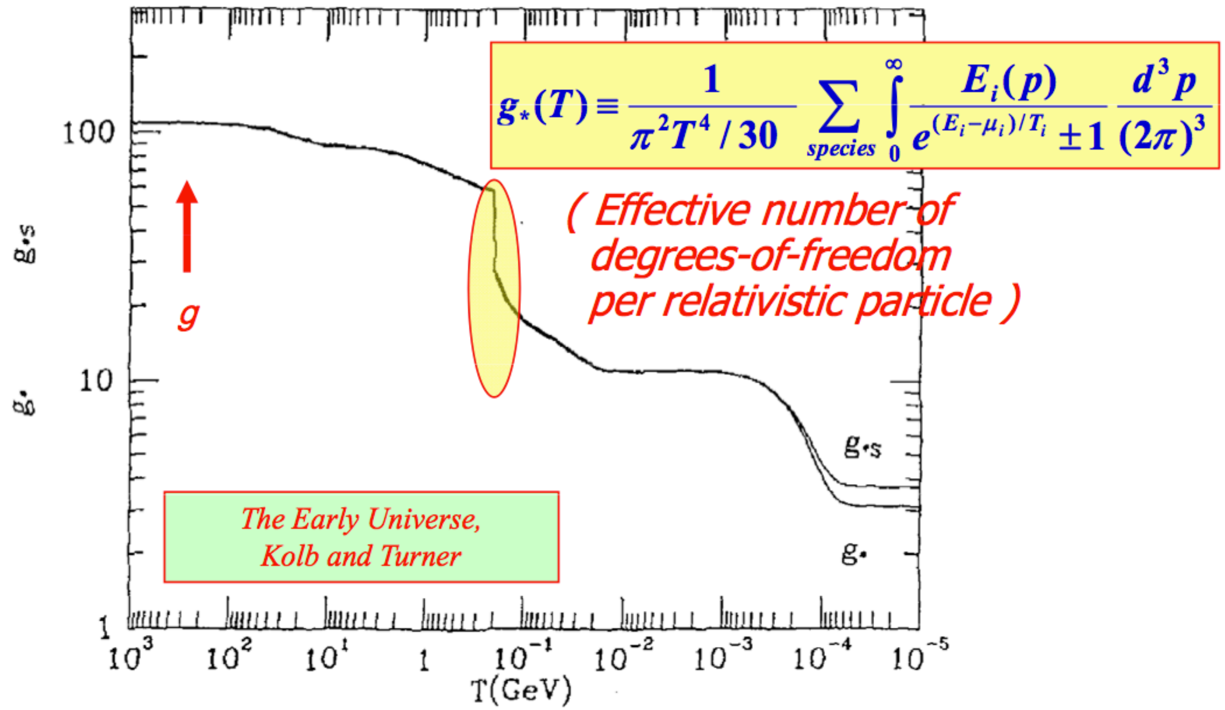
- QCD 'phase transition' at

$$\varepsilon_c \approx (3-5)\ \varepsilon^{cold}_{nuclear\ matter}$$

Wuppertal-Budapest,
arXiv:1005.3508,
arXiv:1007.2580



- change of effective number of degrees of freedom

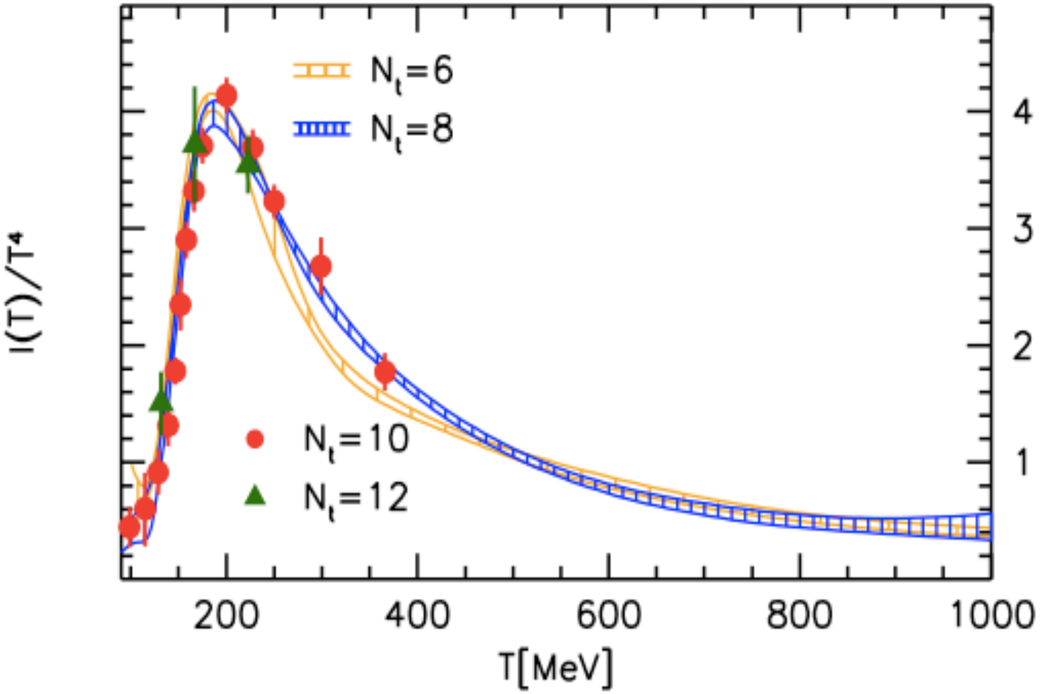


QCD equation of state (eos)

- EOS is known

Interaction measure $I = (\varepsilon - 3p)/T^4$

Wuppertal-Budapest,
arXiv:1005.3508,
arXiv:1007.2580



- access to sound velocity in QCD plasma

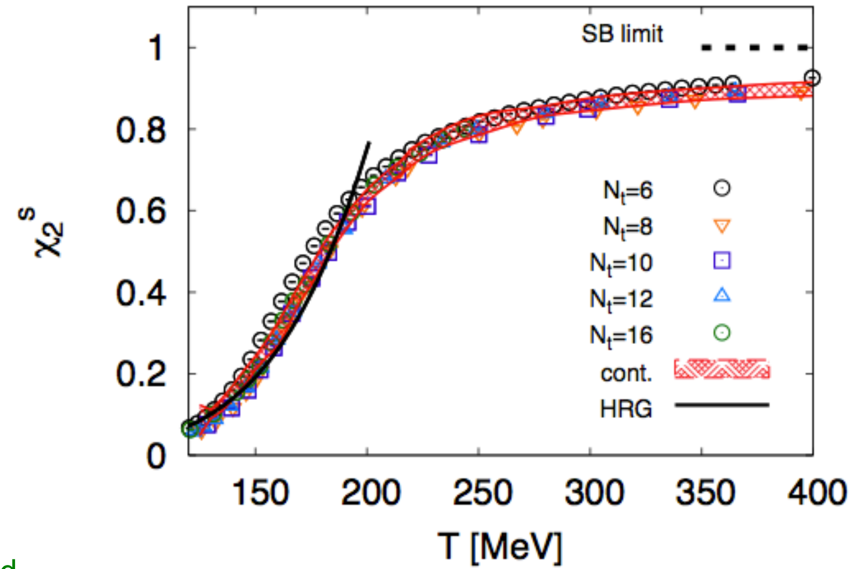
$$c_s = \partial p / \partial \varepsilon$$

- characterizes deviations from conformality

more from finite temperature lattice QCD…

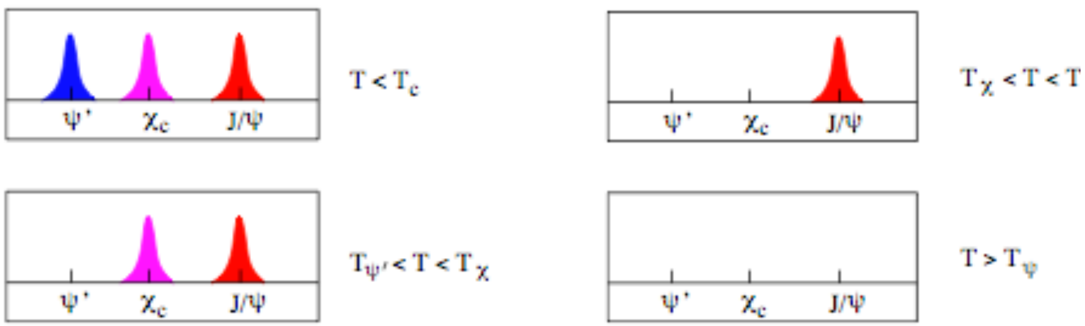
- various fluctuation measures such as quark number susceptibilities

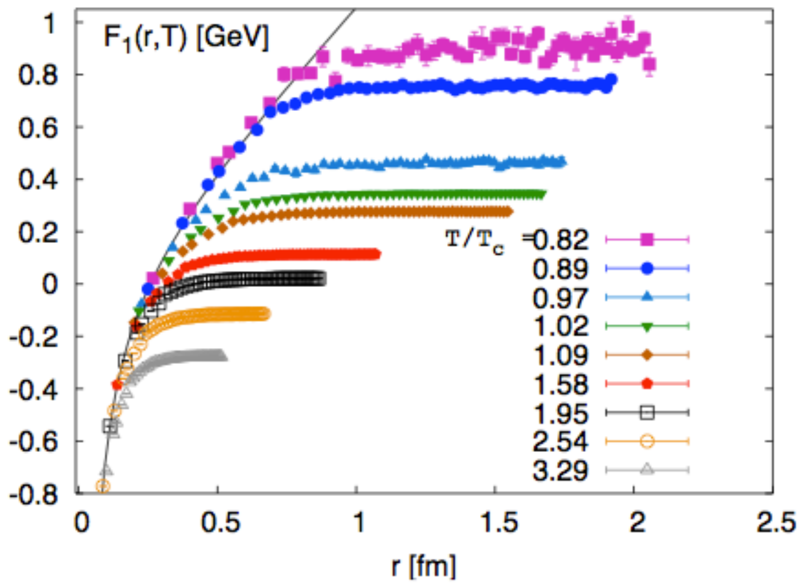
Wuppertal-Budapest,
arXiv:1112.4416



- Results relevant for sequential (T-dependent) suppression of quarkonia. Here: singlet free energy

Bielefeld,
arXiv:1001.5284





AdS/CFT insights into strongly couples non-abelian plasmas

- equilibration time-scales
- transport properties
- propagating probes in hot QCD

Finite T Lattice QCD difficult to apply to
- Real time dynamics
- Hydrodynamic properties
  ($2\pi T$ is lowest Matsubara frequency, problem for limit $\omega \to 0$)

Gauge/gravity duality (AdS/CFT correspondence) Maldacena, 1997

Strong coupling problems in non-abelian QFT $\Longleftrightarrow$ Classical Problem in a curved higher-dimensional space

g^2, N_c

$\lambda \equiv g^2 N$ T' Hooft coupling

$g_s, \alpha' = l_s^2$ String coupling and string tension

applicable to non-abelian plasmas of QFTs with gravity dual

$$\boxed{T_H = \frac{r_0}{\pi R^2} = T}$$

Black hole horizon

Curvature radius

$$\boxed{\frac{R^2}{\alpha'} = \sqrt{\lambda} = \sqrt{g^2 N_c}}$$

But: gravity dual of QCD not known. How can this be relevant? =>

QFTs with gravity duals vs QCD at T=0

N=4 SYM theory

- conformal
- no asymptotic freedom
  no confinement
- supersymmetric
- no chiral condensate
- no dynamical quarks, 6 scalar and 4 Weyl fermionic fields in adjoint representation

Physics near vacuum and at very high energy is very different from that of QCD

… and at finite temperature …

N=4 SYM theory at finite T	QCD at T ~ few x T_c
• conformal	• near conformal (lattice)
• no asymptotic freedom no confinement	• not intrinsic properties of QGP at strong coupling
• supersymmetric (badly broken)	• not present
• no chiral condensate	• not present
• no dynamical quarks, 6 scalar and 4 Weyl fermionic fields in adjoint representation	• may be taken care of by proper normalization

In solid state physics, materials of different microscopic composition and interaction show similar thermal properties.
Here: **non-abelian gauge theories of different particle content and symmetries show similar thermal properties above T_c.**

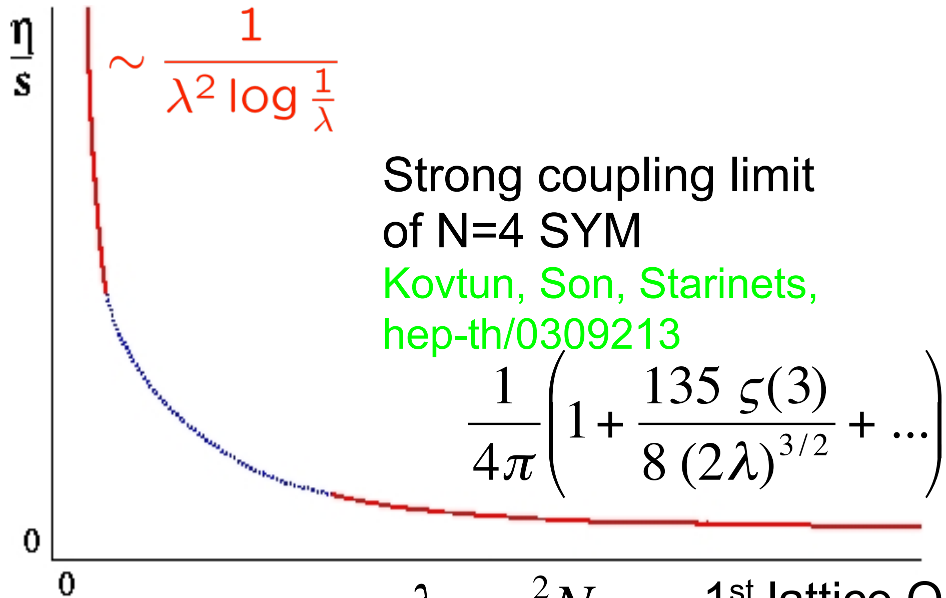
Dissipative properties: shear viscosity

Calculable from first principles in quantum field theory (QCD)

$$G^R_{xy,xy}(\omega,0) \equiv \int dt\, dx\, e^{i\omega t}\, \Theta(t) \left\langle \left[T_{xy}(t,x), T_{xy}(0,0) \right] \right\rangle_{eq}$$

$$\eta \equiv -\lim_{\omega \to 0} \frac{1}{\omega} \mathrm{Im} G^R_{xy,xy}(\omega,0)$$

Arnold, Moore, Yaffe,
JHEP 11 (2000) 001



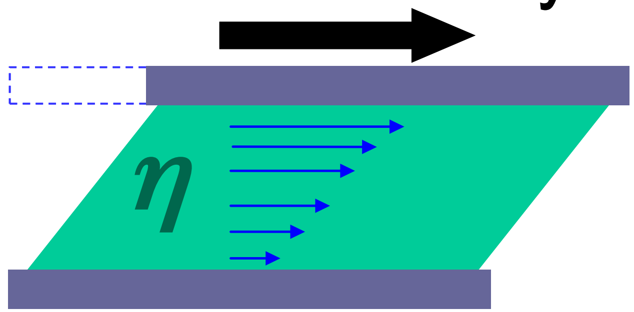
Strong coupling limit
of N=4 SYM
Kovtun, Son, Starinets,
hep-th/0309213

$$\frac{1}{4\pi}\left(1 + \frac{135\,\varsigma(3)}{8\,(2\lambda)^{3/2}} + \ldots\right) \qquad \frac{\eta}{s} > \frac{1}{4\pi}$$

$$\lambda \equiv g^2 N_c$$

1st lattice QCD study
H. Meyer, 0805.4567

Shear viscosity:



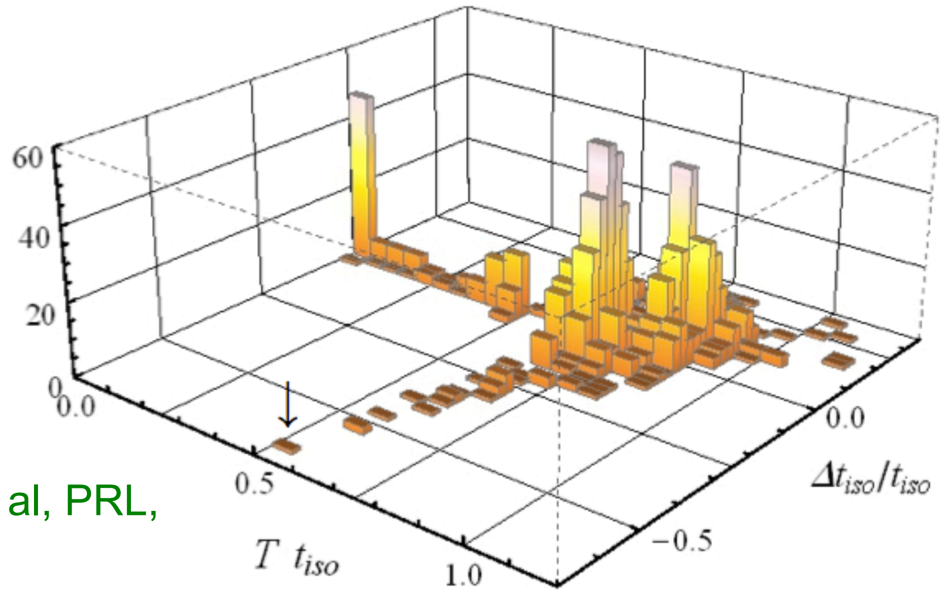
acts against the buildup of flow anisotropy

First rigorous example that a finite T QFT can evolve with minimal dissipation.

Far from equilibrium dynamics at strong coupling

- Model-dependent in QCD but a rigorously calculable problem of numerical gravity in AdS/CFT

- Results show extremely short **non-perturbative isotropization**



$$\boxed{\tau_{iso} < \frac{1}{T}}$$

M. Heller et al, PRL, 1202.0981

- The first rigorous field theoretic set-up in which fluid dynamics applies at very short time scales

$$\alpha_s >> 1 \quad \Rightarrow \boxed{0.65 \leq \tau_0\, T_0}$$

Chesler, Yaffe, PRL 102 (2009) 211601

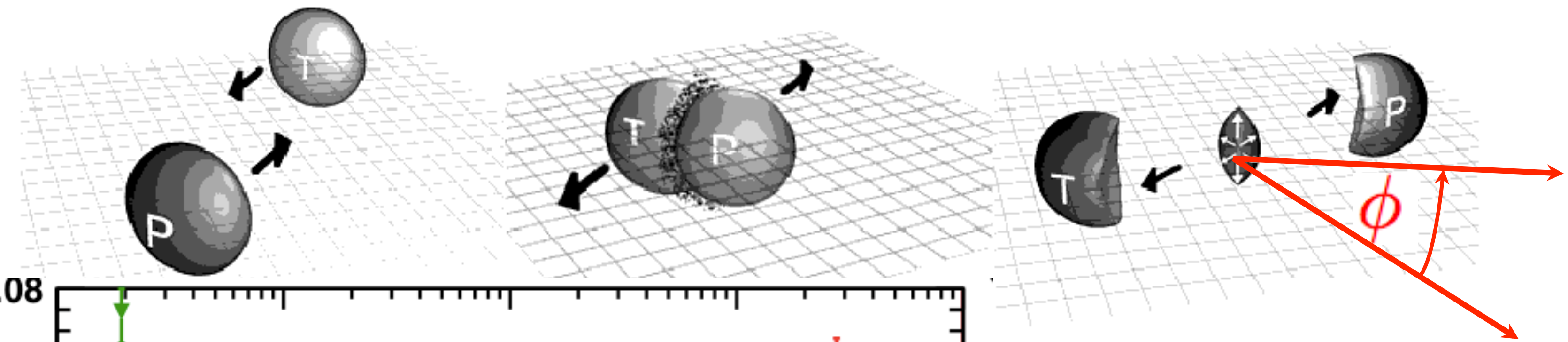
- These non-abelian plasma are unique in that they do not carry quasi-particle excitations:

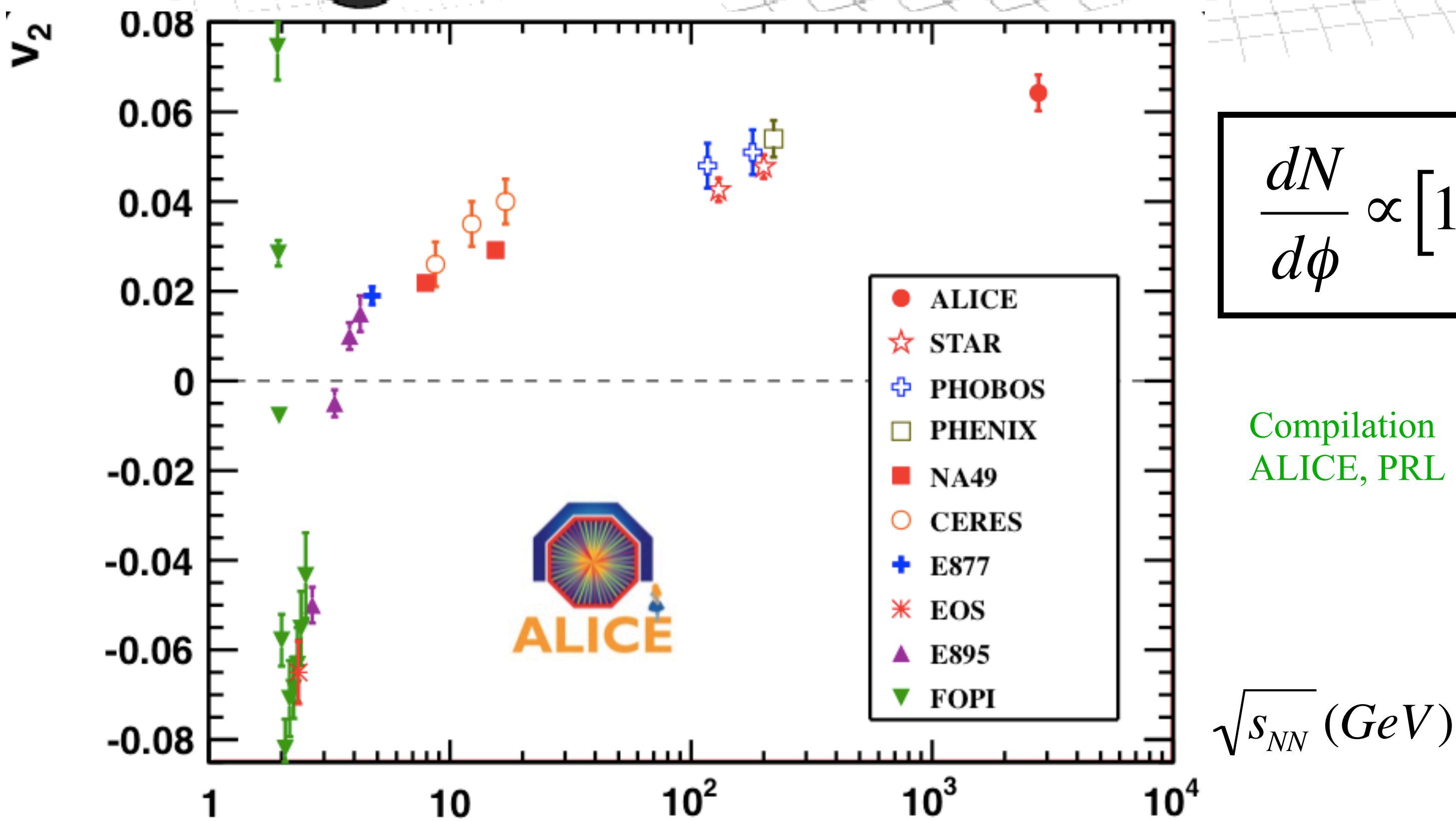
perturbatively require $\quad \tau_{quasi} \sim \dfrac{1}{\alpha_s^2 T} >> \dfrac{1}{T}$

but $\quad \tau_{quasi} \approx \dfrac{const}{T}\dfrac{\eta}{s}$

Turning now to phenomenology of heavy ion collisions

Elliptic Flow: hallmark of a collective phenomenon





$$\frac{dN}{d\phi} \propto \left[1 + 2 v_2 \cos(2\phi)\right]$$

Compilation
ALICE, PRL 105, 252302 (2010)

Fluid dynamic simulations of heavy ion collisions

Based on 2nd order **Israel-Stewart** relativistic fluid dynamic equations of motion. Under simplifying assumptions, …

$$(\varepsilon + p) D u^{\mu} = \nabla^{\mu} p - \Delta^{\mu}_{\nu} \nabla^{\sigma} \Pi^{\nu\sigma} + \Pi^{\mu\nu} D u_{\nu}$$

$$D\varepsilon = -(\varepsilon + p)\nabla_{\mu} u^{\mu} + \tfrac{1}{2} \Pi^{\mu\nu} \left\langle \nabla_{\nu} u_{\mu} \right\rangle$$

$$\tau_{\pi} \Delta^{\mu}_{\alpha} \Delta^{\nu}_{\beta} D \Pi^{\alpha\beta} + \Pi^{\mu\nu} = \eta \left\langle \nabla^{\mu} u^{\nu} \right\rangle - 2\tau_{\pi} \Pi^{\alpha(\mu} \omega^{\nu)}_{\alpha}$$

In general, dissipative dynamics involves several **relaxation times** and **transport coefficients**.

Dissipative fluid dynamics relates flow to fundamental properties of matter

- based *only* on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- sensitive *only* to properties of matter that are

calculable from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

AdS/CFT =>

EOS: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

transport coefficients: shear η, bulk ξ viscosity, conductivities …

$$\eta = \lim_{\omega\to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

relaxation times: τ_π, τ_Π, …

Fluid dynamics of initial density fluctuations

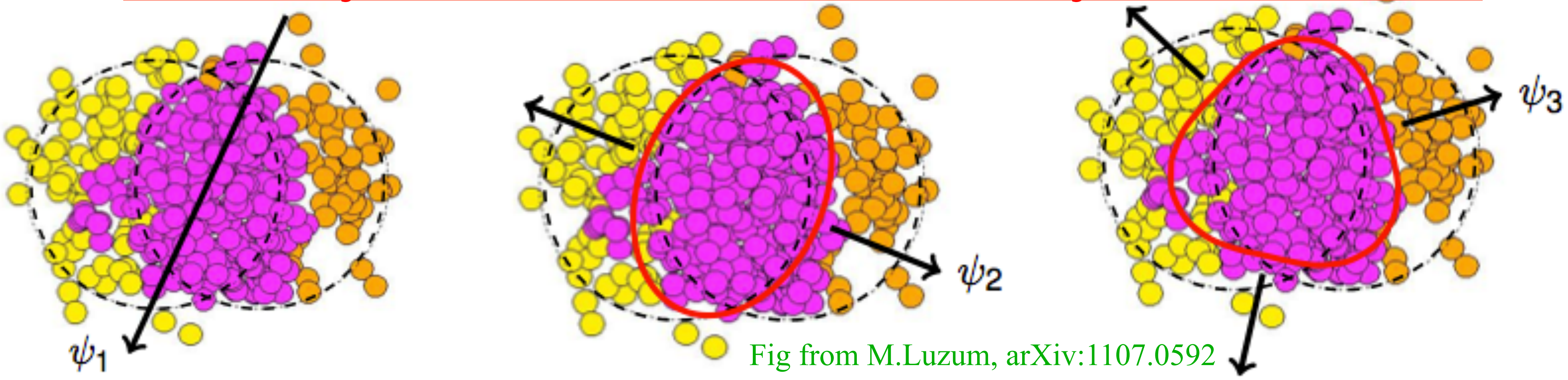
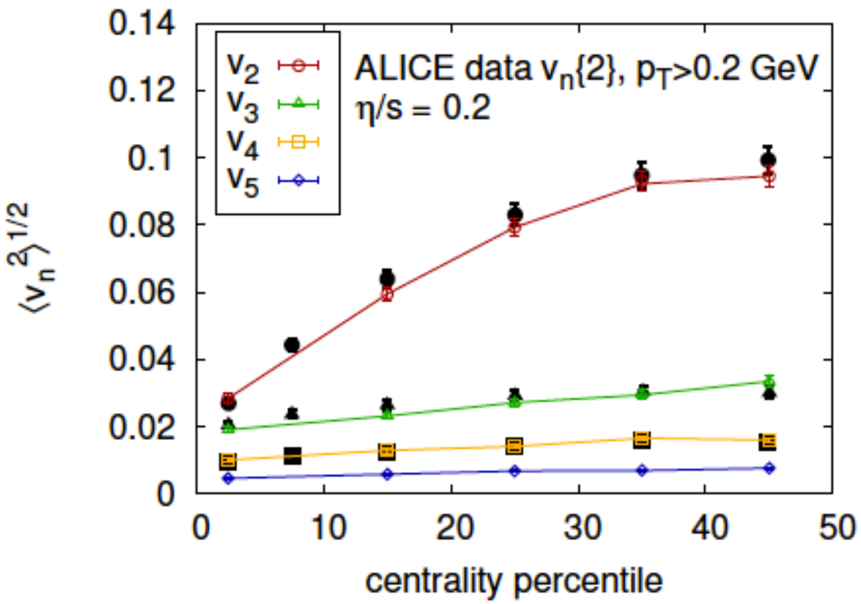
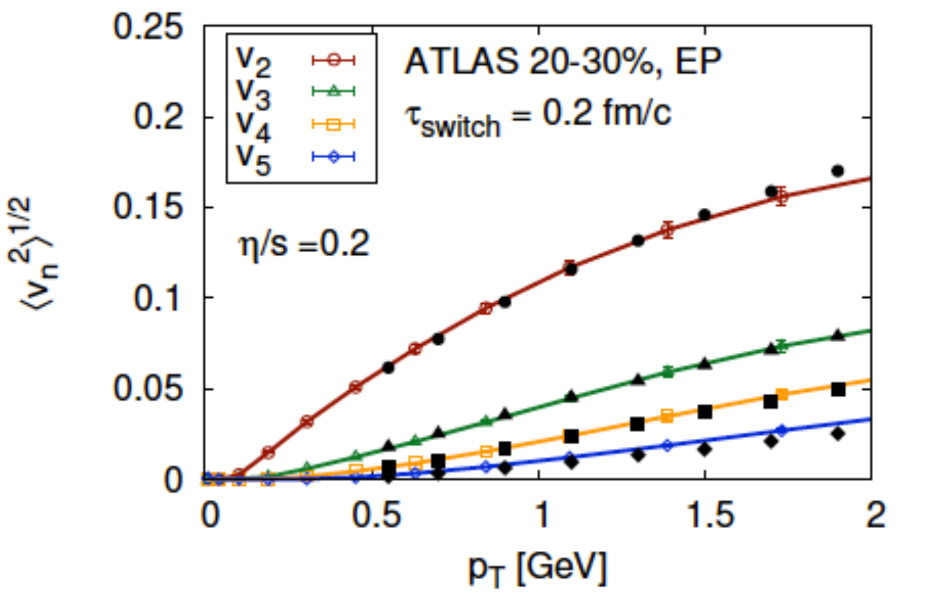


Fig from M.Luzum, arXiv:1107.0592

- Fluid dynamics maps initial spatial eccentricities onto measured v_n
- 3+1 D viscous hydro reproduces v_2,v_3,v_4,v_5 in p_T and centrality

B. Schenke, MUSIC, .QM2012

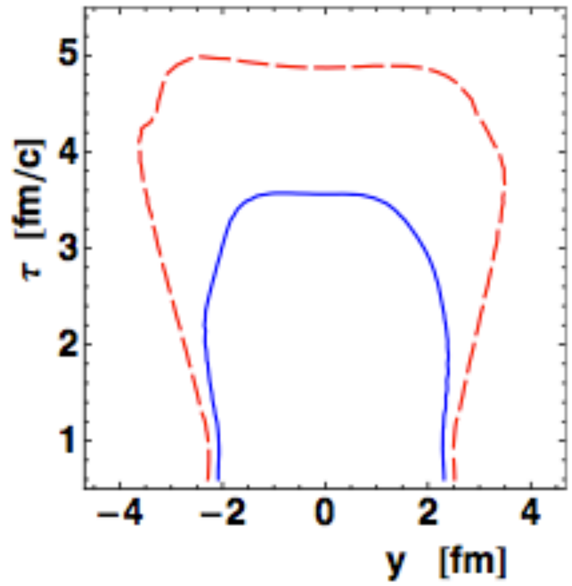


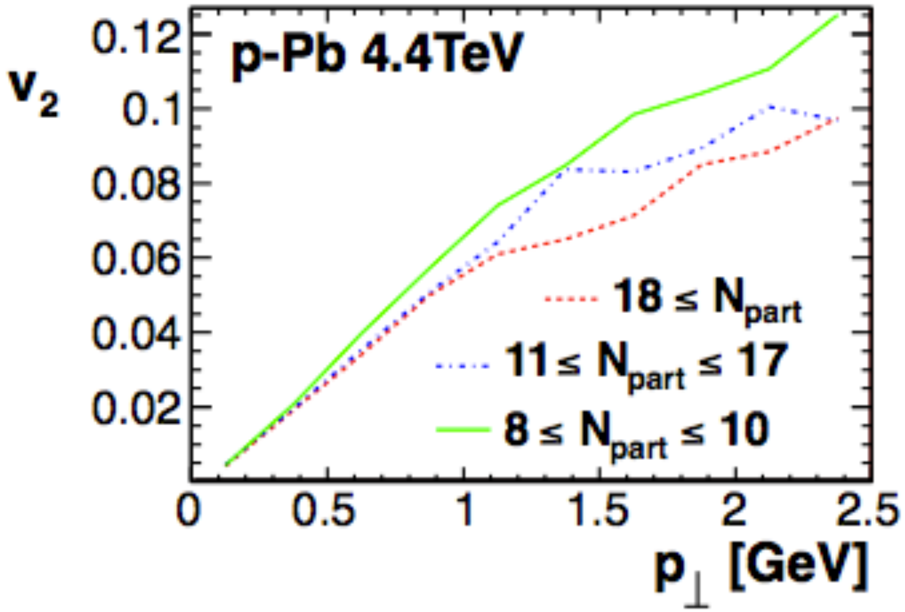


Do smaller systems show flow: pPb?

P. Bozek, 1112.0915

And if one treats evolution of pPb@LHC fluid dynamically?



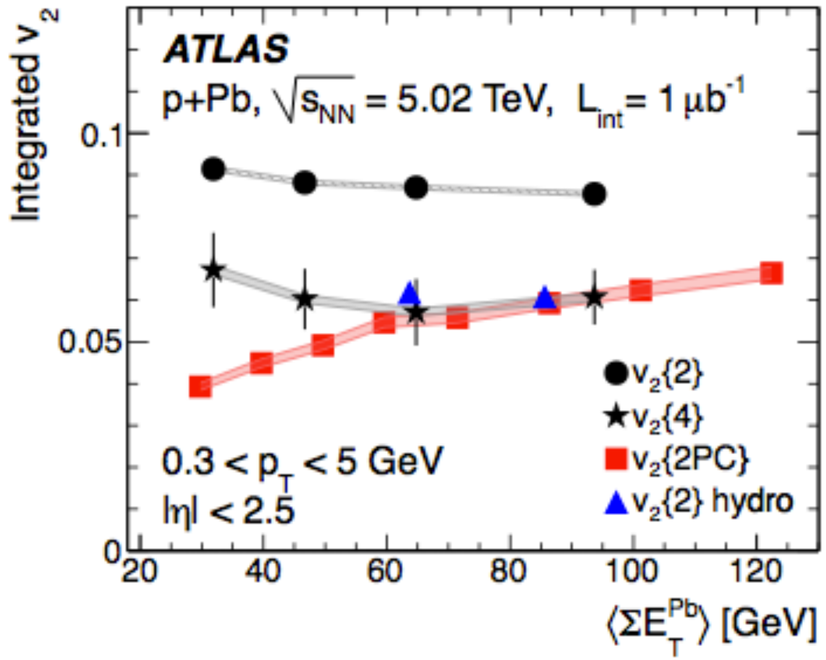


Fluid dynamics compares surprisingly well with

$$v_2\{2\}, v_2\{4\}, v_3\{2\}$$

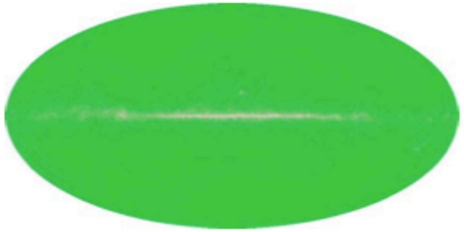
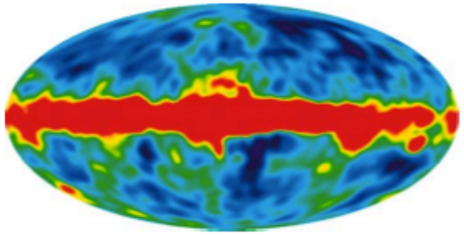
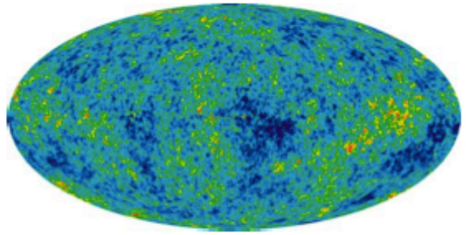
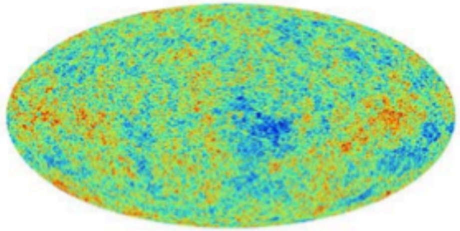
in pPb@LHC.

ATLAS, 1303.2084
CMS, 1305.0609



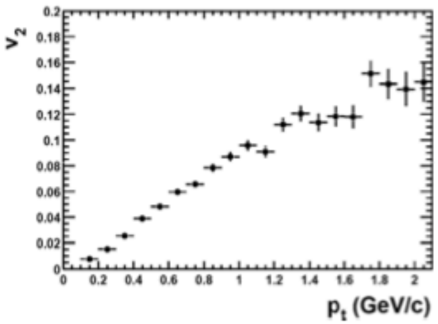
A (valid) analogy

Penzias/Wilson 1965	COBE 2003	WMAP 2007	Planck 2012

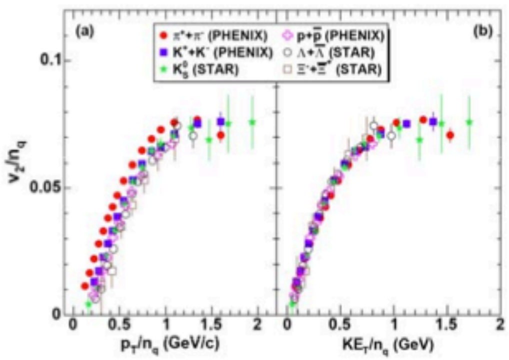





D I S C O V E R Y.....

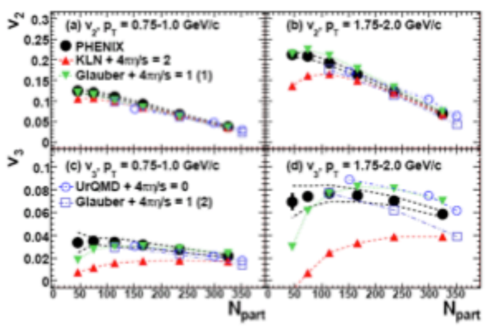
..... P R E C I S I O N



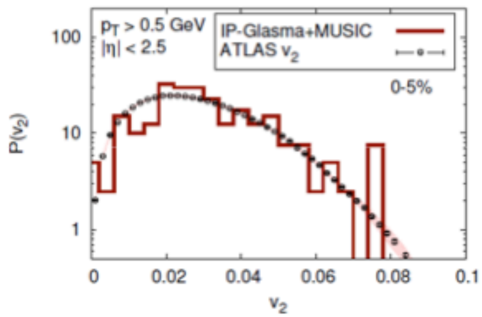
2001



2004



2008



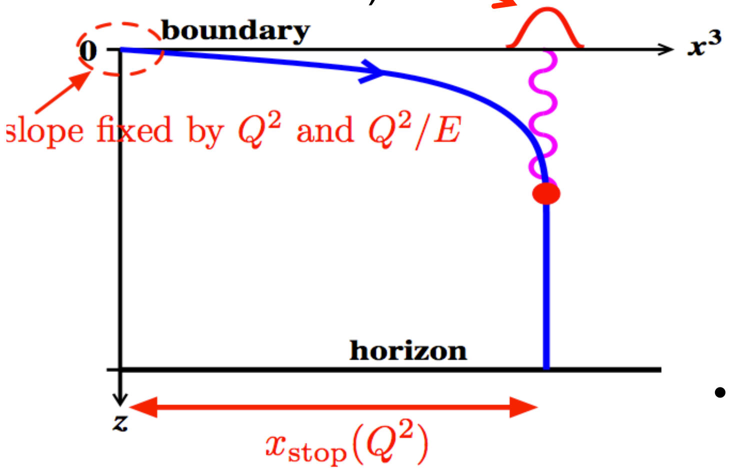
2012

Slide from W. Zajc

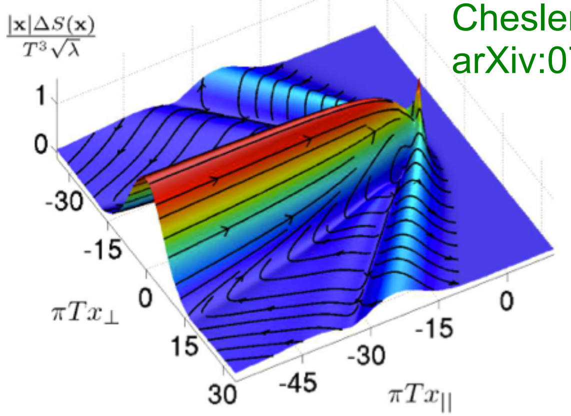
How do high-momentum partons propagate?- theory

In a perfect liquid (AdS/CFT view)

- Light partons/jets **thermalize** (no collinear structure remains)



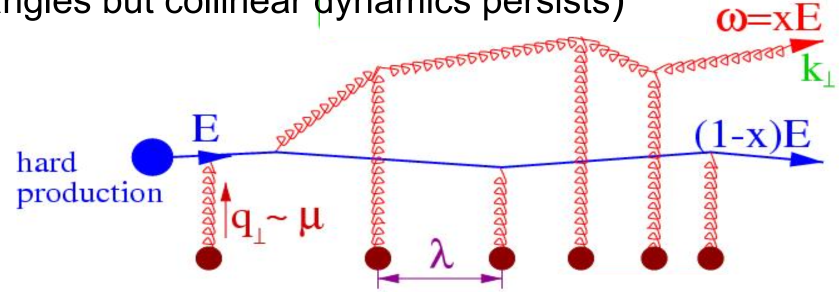
- Heavy quarks loose momentum via sound modes and wake



Chesler, Yaffe arXiv:0712.0050

In system with finite mean free path

- Light hard partons **fragment** in medium (Energy moved to softer scales/larger angles but collinear dynamics persists)



- Heavy quarks **fragment** with smaller branching probabilities (*dead-cone effect*)

$$\frac{1}{k_T^2} \Rightarrow \frac{k_T^2}{\left(k_T^2 + \frac{M^2}{E^2}\omega^2\right)^2}$$

testable hierarchy in mass and color charge

$$\Delta E_{gluon} > \Delta E_{quark,m=0} > \Delta E_c > \Delta E_b$$

- For $M << E$, mass unimportant. In high energy limit (eikonal limit) ΔE determined by $\hat{q}$

Motivates experimental study of medium-dependent jet fragmentation

Open heavy flavor at low pt

- 'No-quasiparticle conjecture' implies that light low-momentum dressed quarks do not exist (i.e. do not propagate beyond $L \approx 1/T$)

  In contrast, charm & bottom propagate (consequence of flavor conservation). How?

- At low pt, Langevin dynamics determines how charm & beauty quarks move: The perfect liquid is source of **random forces**

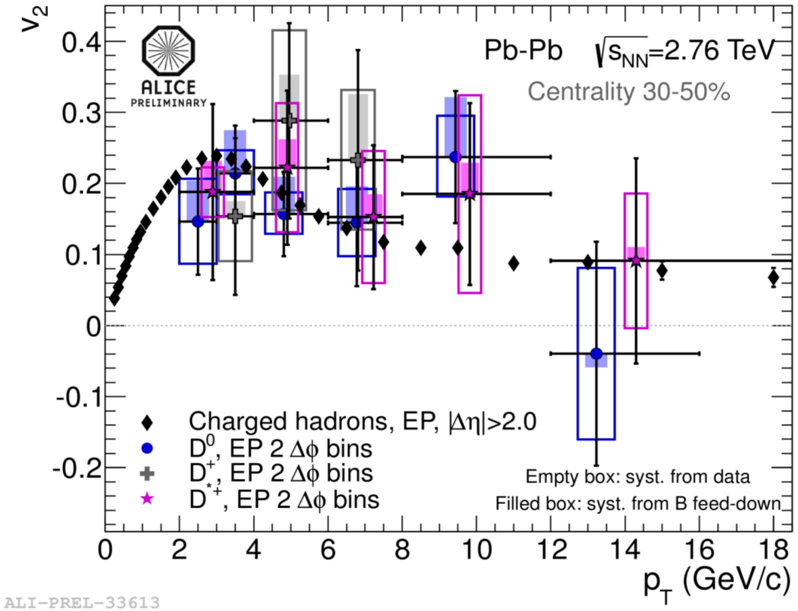
$$\frac{dp_L}{dt} = \xi_L(t) - \mu(p_L)p_L, \qquad \langle \xi_L(t)\xi_L(t')\rangle \equiv \kappa_L(p_L)\,\delta(t-t')$$

$$\frac{dp_T}{dt} = \xi_L(t) \qquad \langle \xi_{Ti}(t)\xi_{Tj}(t')\rangle \equiv \kappa_T(p_L)\,\delta_{ij}\delta(t-t')$$

calculable from 1st principles in quantum field theory, e.g. in strong coupling limit:

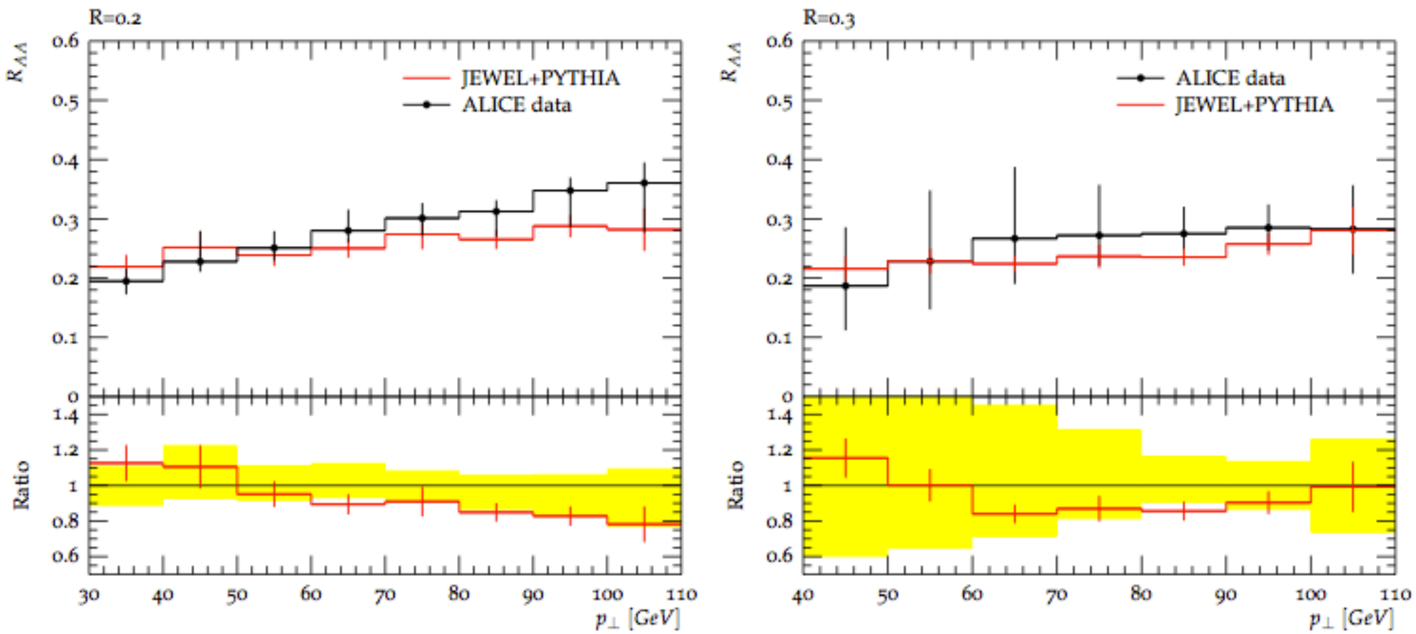
$$\kappa_T = \pi\sqrt{\lambda}T^3\sqrt{\gamma} \qquad \kappa_L = \pi\sqrt{\lambda}T^3\gamma^{5/2}$$

- This hard probe is unique in that we know already that it is moved by the flow.



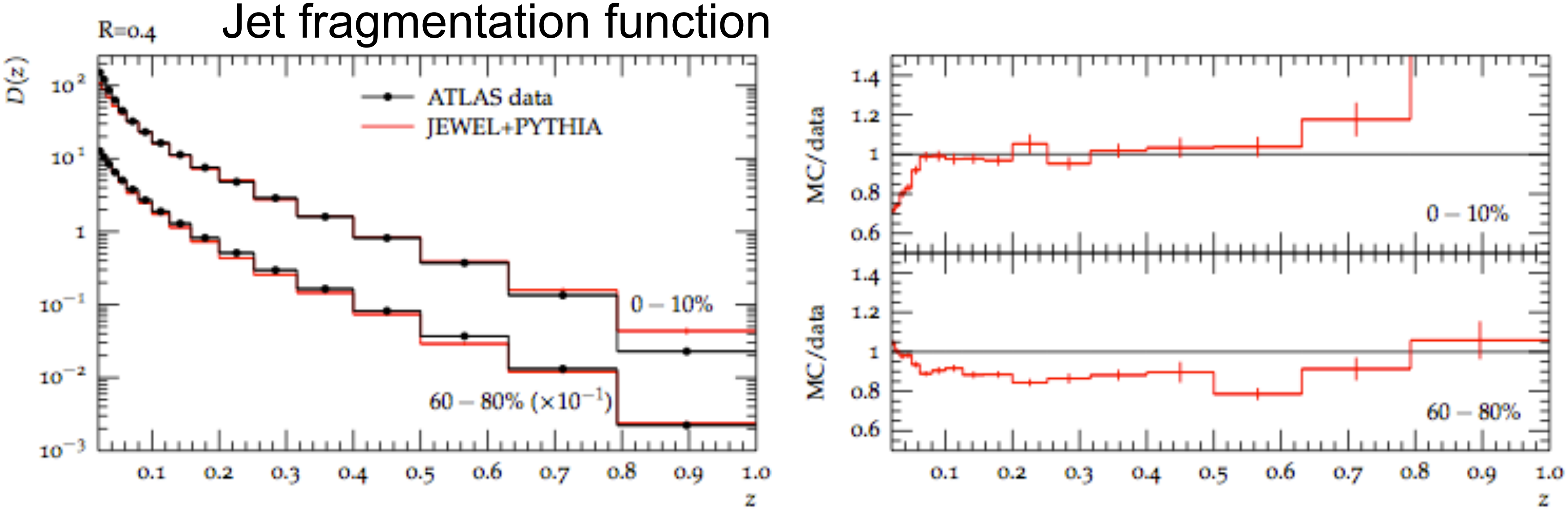
Perturbative description of 'high-pt' jet quenching fairs well

Nuclear Modification factor

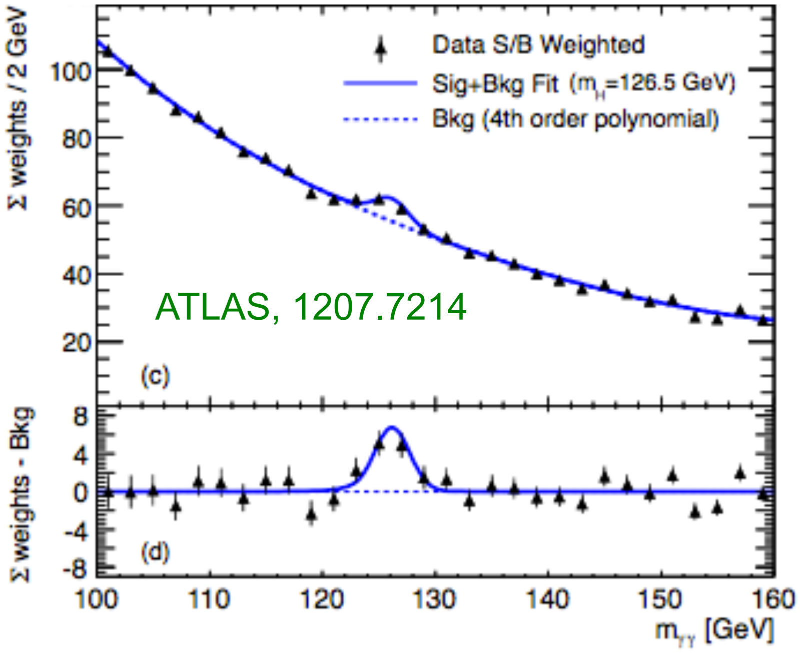


K. Zapp, F. Krauss, UAW, JHEP 1303 (2013) 080

Jet fragmentation function

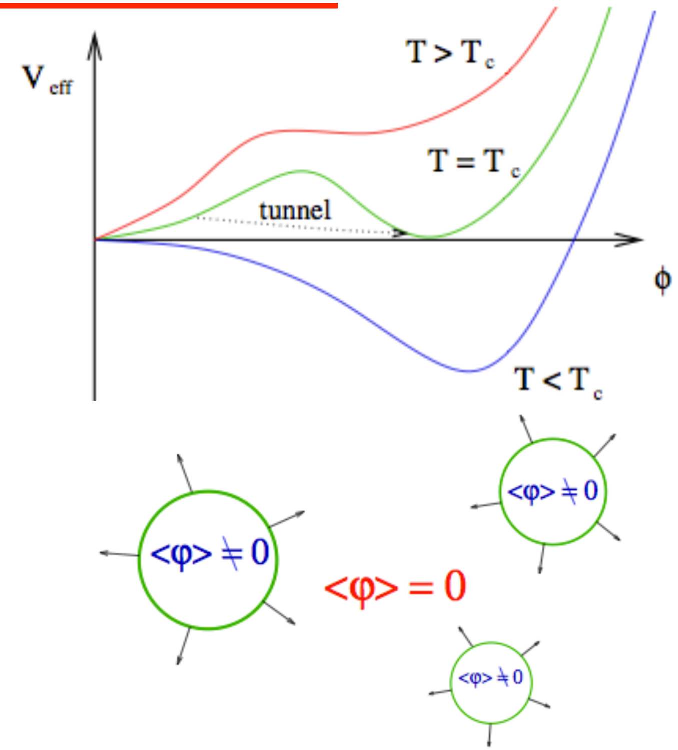


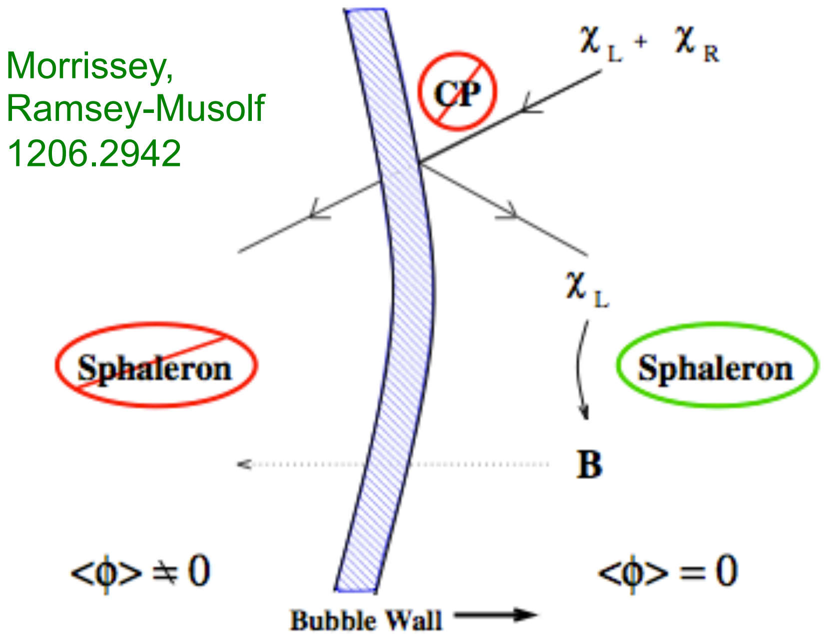
From quantum fields to properties of matter



Early

Universe





If the particle content of the fundamental lagrangian is known,

We ask how collective phenonema and properties of matter arise from it.

The LHC heavy ion programme addresses this question for the theory of strong interactions.

End