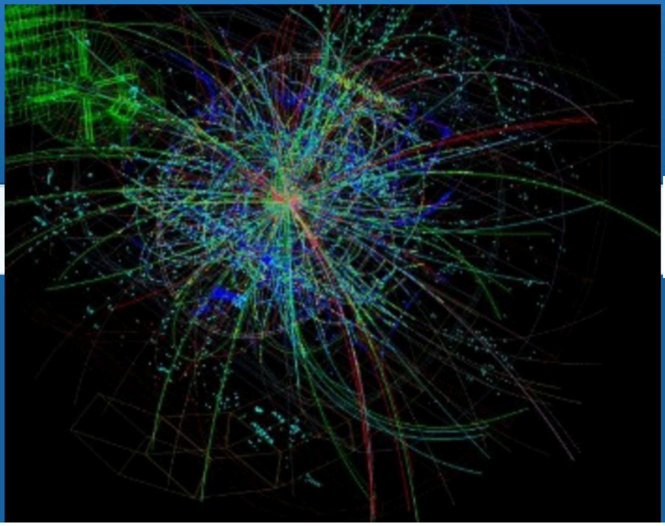
Incontro sulla fisica con ioni pesanti a LHC



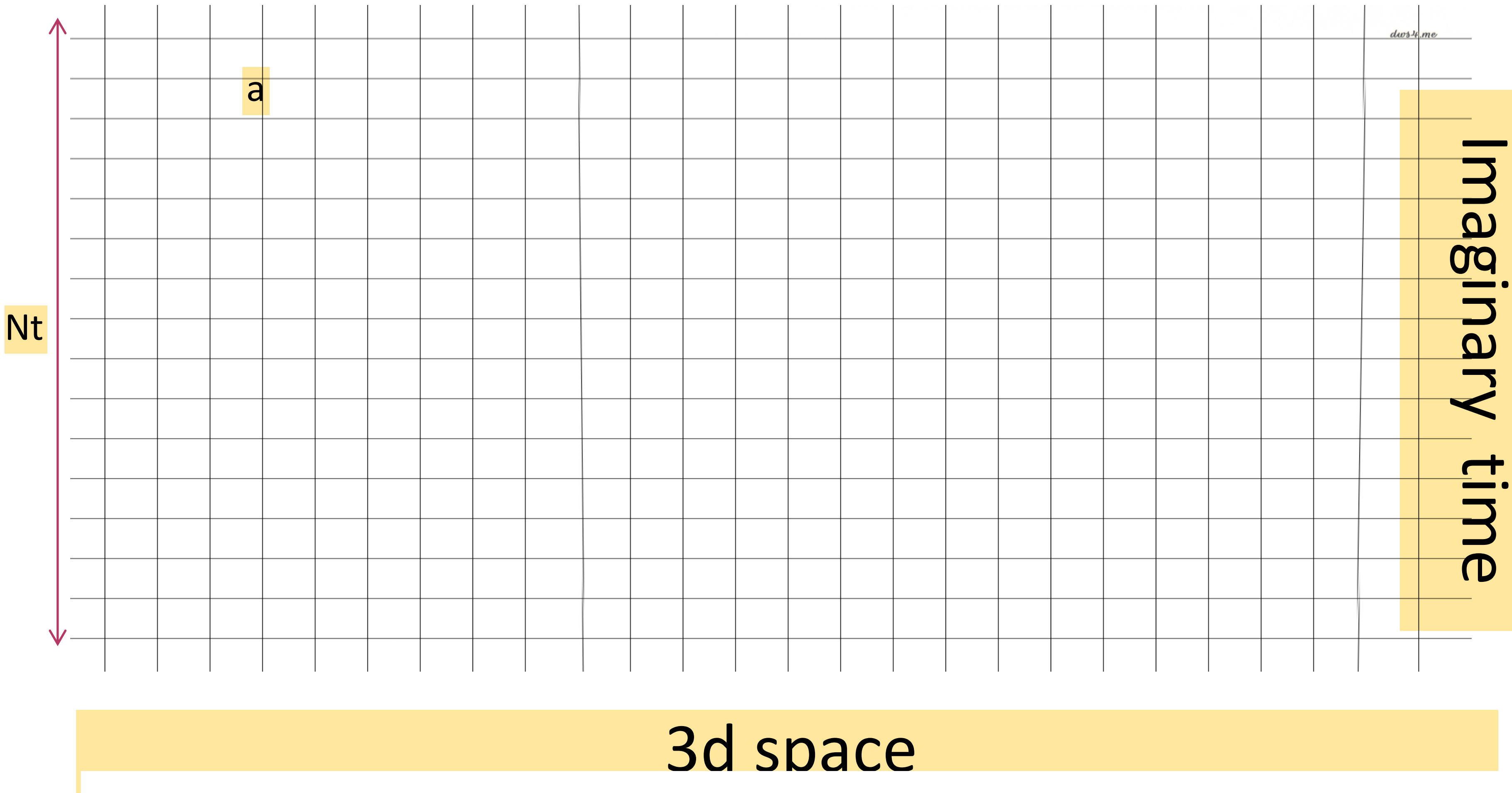
Bologna 26-27 Maggio 2015

Maria Paola Lombardo

Equation of state and transport from the lattice

The lattice:

With a rotation to imaginary time and
(anti)periodic boundary condition in time:
Statistical system in 3+1 dimension
Temperature = 1/ Nt a



Spectrum and EoS

Lattice: tool for computing Partition Function

$$\mathcal{Z} = Tr\hat{\rho}$$
$$\hat{\rho} = e^{-(H-\mu\hat{N})/T}$$

$$< O >= TrO\hat{\rho}/\mathcal{Z}$$

Spectrum

$$P = T\frac{\partial ln\mathcal{Z}}{\partial V}$$
$$N = T\frac{\partial ln\mathcal{Z}}{\partial \mu}$$
$$S = \frac{\partial T ln\mathcal{Z}}{\partial T}$$
$$E = -PV + TS + \mu N$$

EoS

Designing a simulation

$$Z(N_\sigma, N_\tau, \beta, m_q, \tilde{\mu}) = \int \prod_{n\nu} \mathrm{d}U_{n,\nu} (\det Q^{KS}(m_q, \tilde{\mu}))^{n_f/4} \mathrm{e}^{-\beta S_G}$$

Physical choice:
Active Quarks

Technical choice:
Lattice Action

QCD Symmetries, lattice and the real world

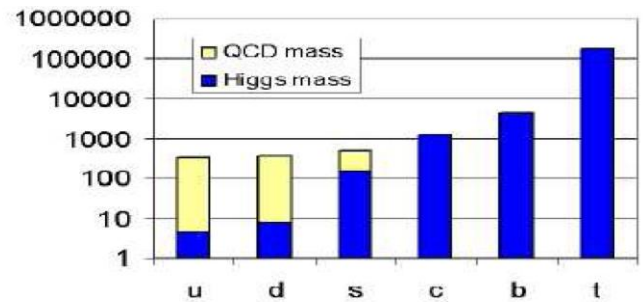
High T

$SU(N_f)_R$ X $SU(N_f)_L$ X $U_A(1)$

$SU(N_f)_V$

Low T

c,b,t do not participate in the chiral dynamics around the critical temperature. Lattice simulations **around Tc** are then performed with up,down,strange quarks – Nf = 2+1



	SU(N)XSU(N)	$U_A(1)$
Staggered	Remnant U(1)	Broken
Wilson	Broken	Broken
Domain Wall	Exact (for L $\to\infty$)	Exact (for L $\to\infty$)
Overlap	Exact	Exact
Wilson twisted	As good as staggered	Broken

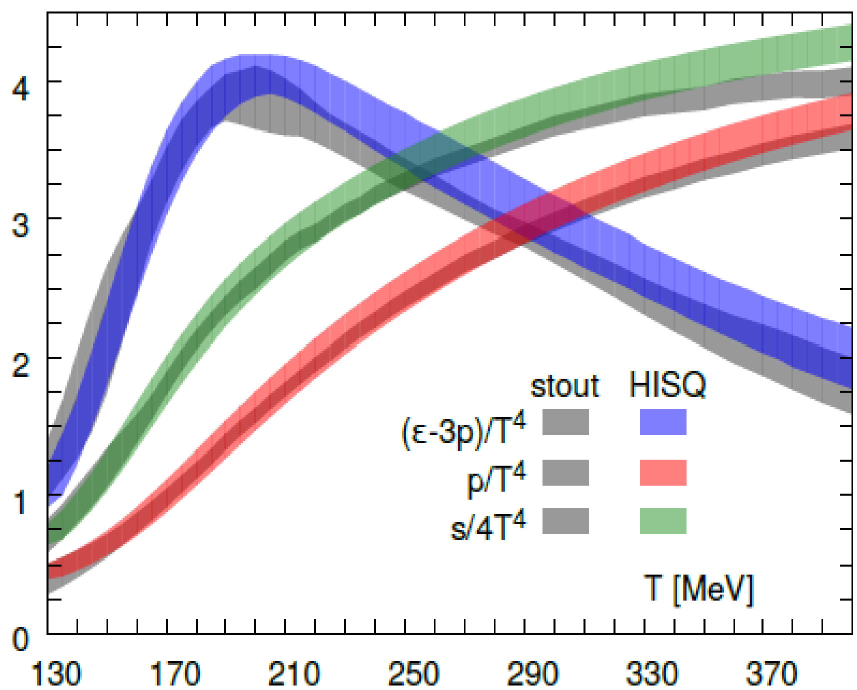
Input to Hydro:

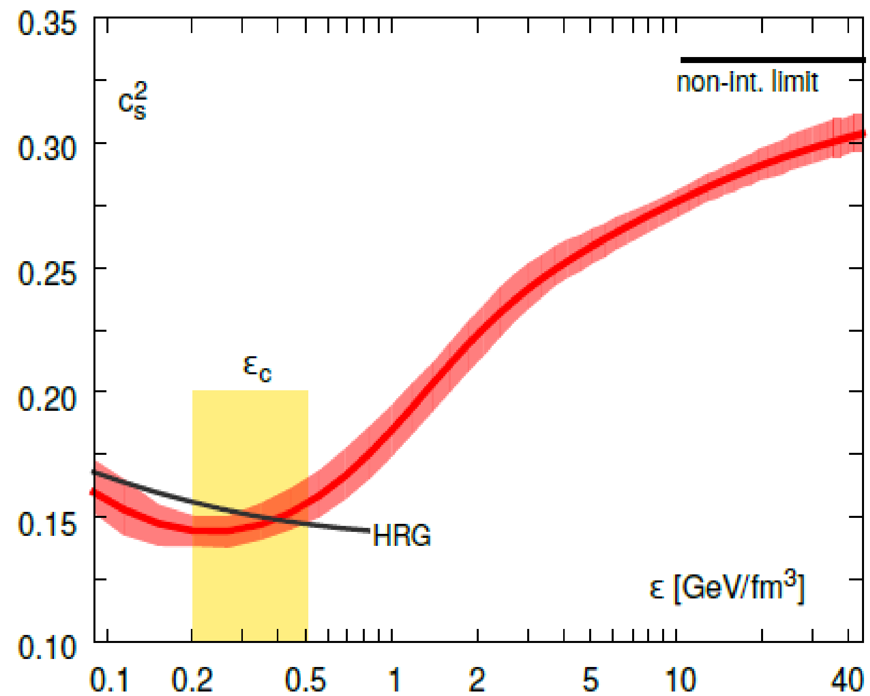
EOS

Nf = 2 + 1

Eos Current Status

$$\langle\theta\rangle = \mathcal{E} - 3P$$



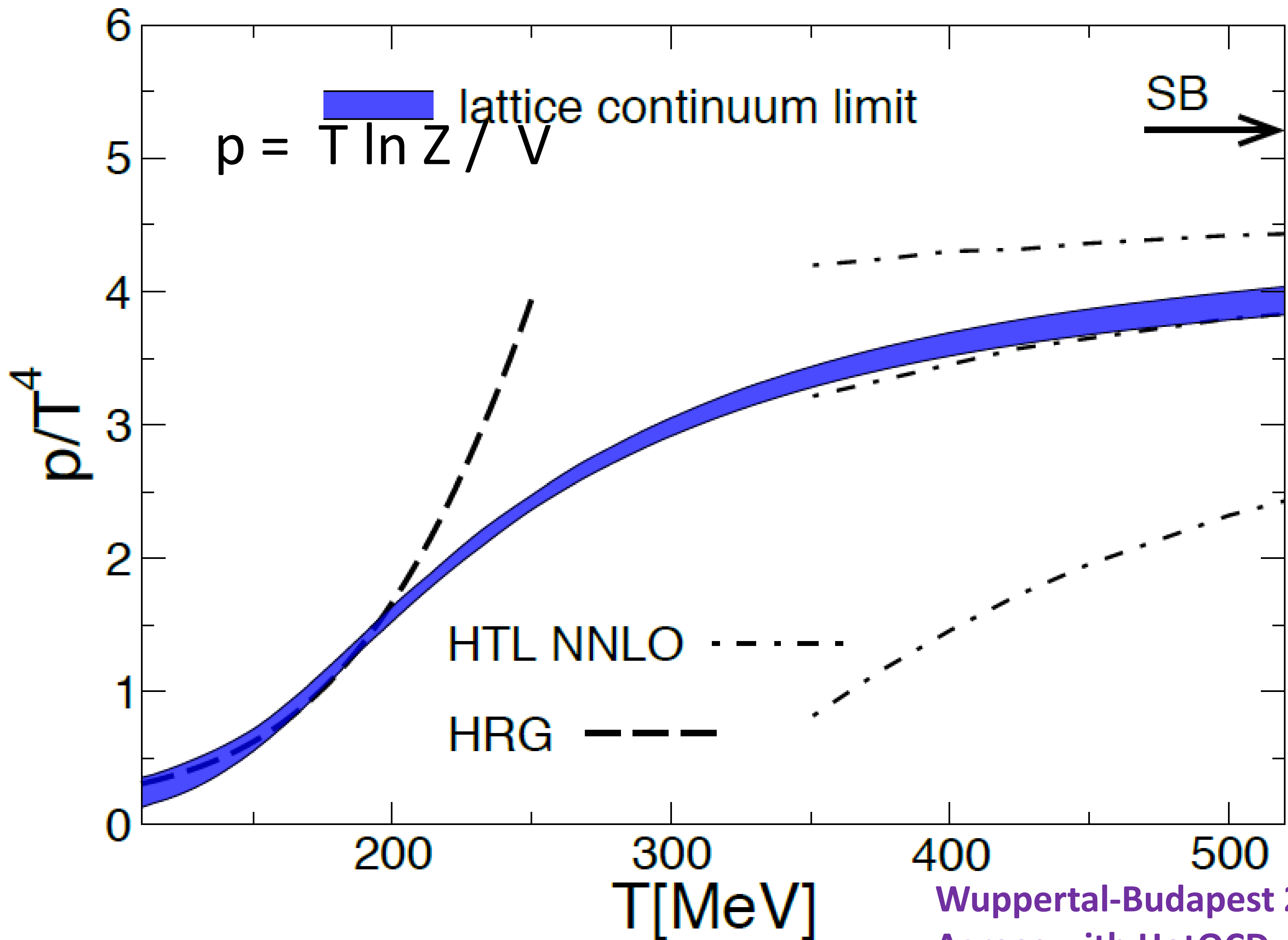


$$\frac{\zeta}{\eta} \geq 2\left(\frac{1}{3} - c_s^2\right)$$

Wuppertal-Budapest 2014
Agrees with HotQCD
(Ding and Bazavov at QM2014)

Nf = 2+1

EoS Current Status



Wuppertal-Budapest 2014
Agrees with HotQCD
(Ding and Bazavov at QM2014)

Tc

≈200MeV

340 –380 MeV
RHIC AuAu
200 GeV

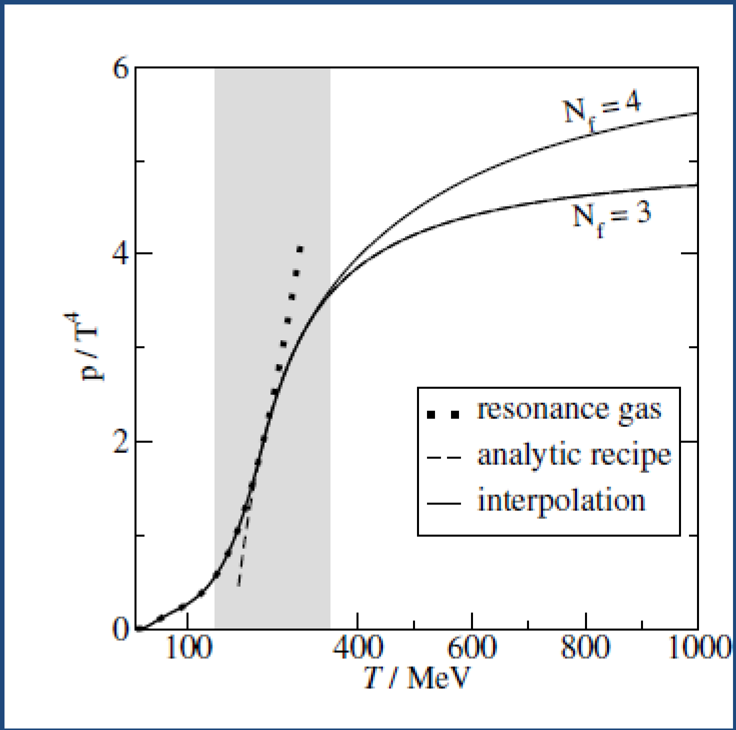
420-480 MeV
LHC
2.76 TeV

500- 600MeV
LHC hot spots
2.76 TeV

1 GeV
LHC
7 TeV

[Expected]

Quark Gluon Plasma @ Colliders

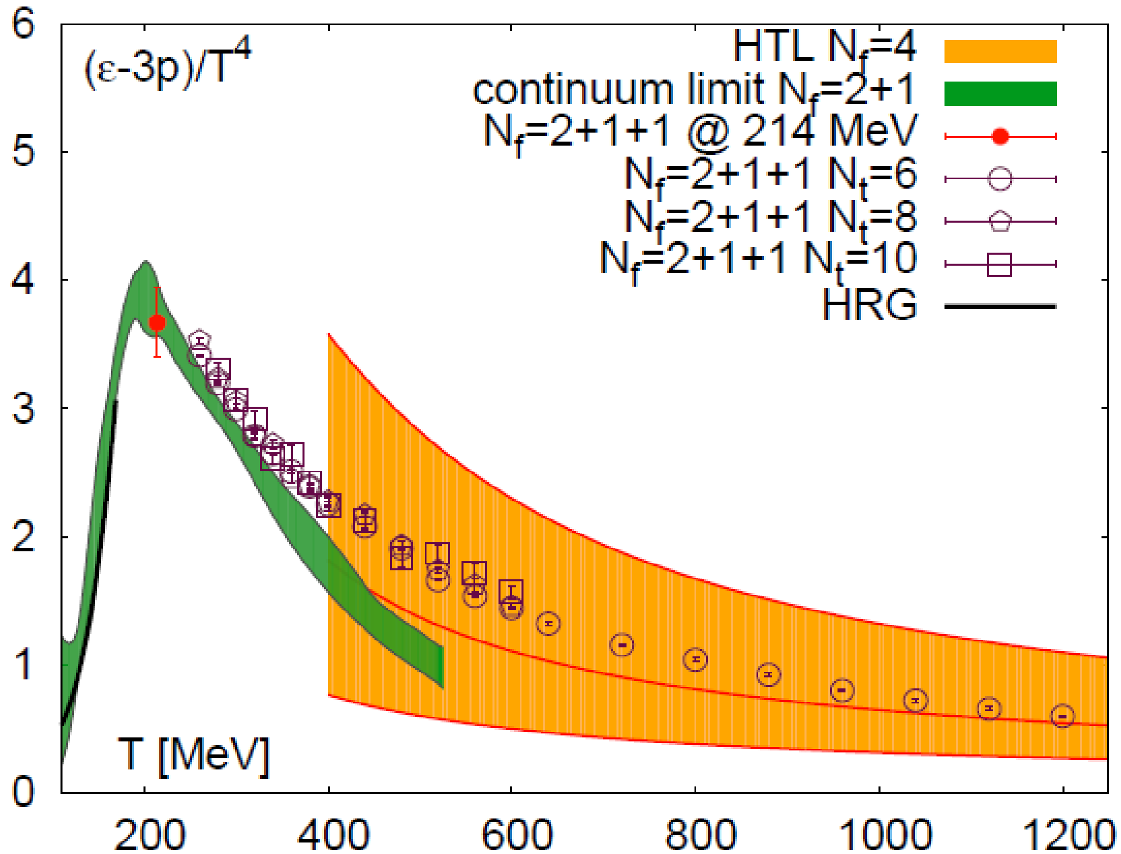


Analytic studies suggest that a dynamical charm becomes relevant above 400 MeV, well within the reach of LHC

Laine Schroeder 2006

Thermodynamics with a dynamical charm : Nf = 2+1+1:

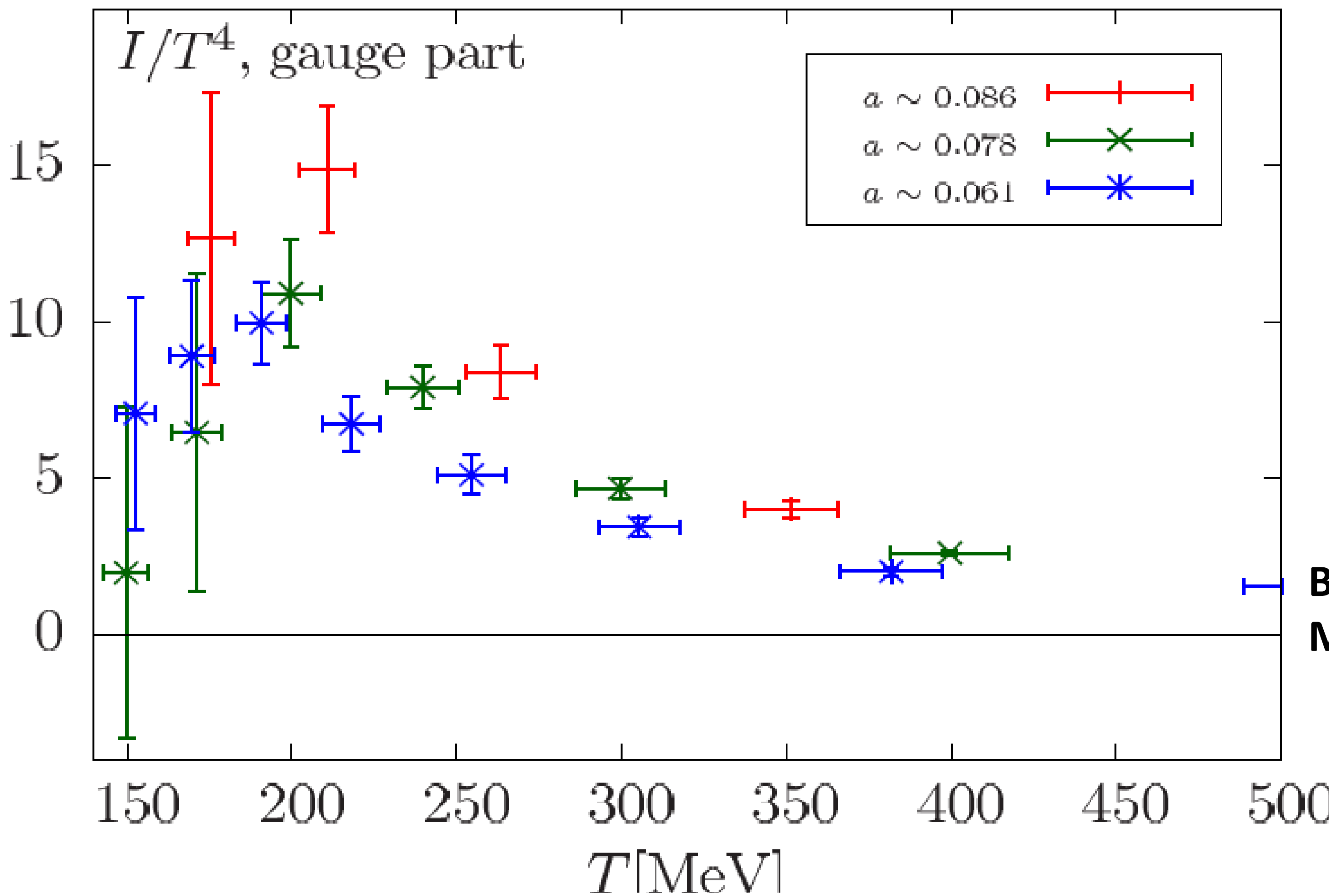
Staggered fermions (fixed Nt, varying spacing)



Budapest Wuppertal 2014

Thermodynamics with a dynamical charm : Nf = 2+1+1:

Wilson fermions (fixed a, varying Nt)



Burger, Ilgenfritz, MpL, Mueller-Preussker 2014

In progress

EoS finished for T < 400 MeV!

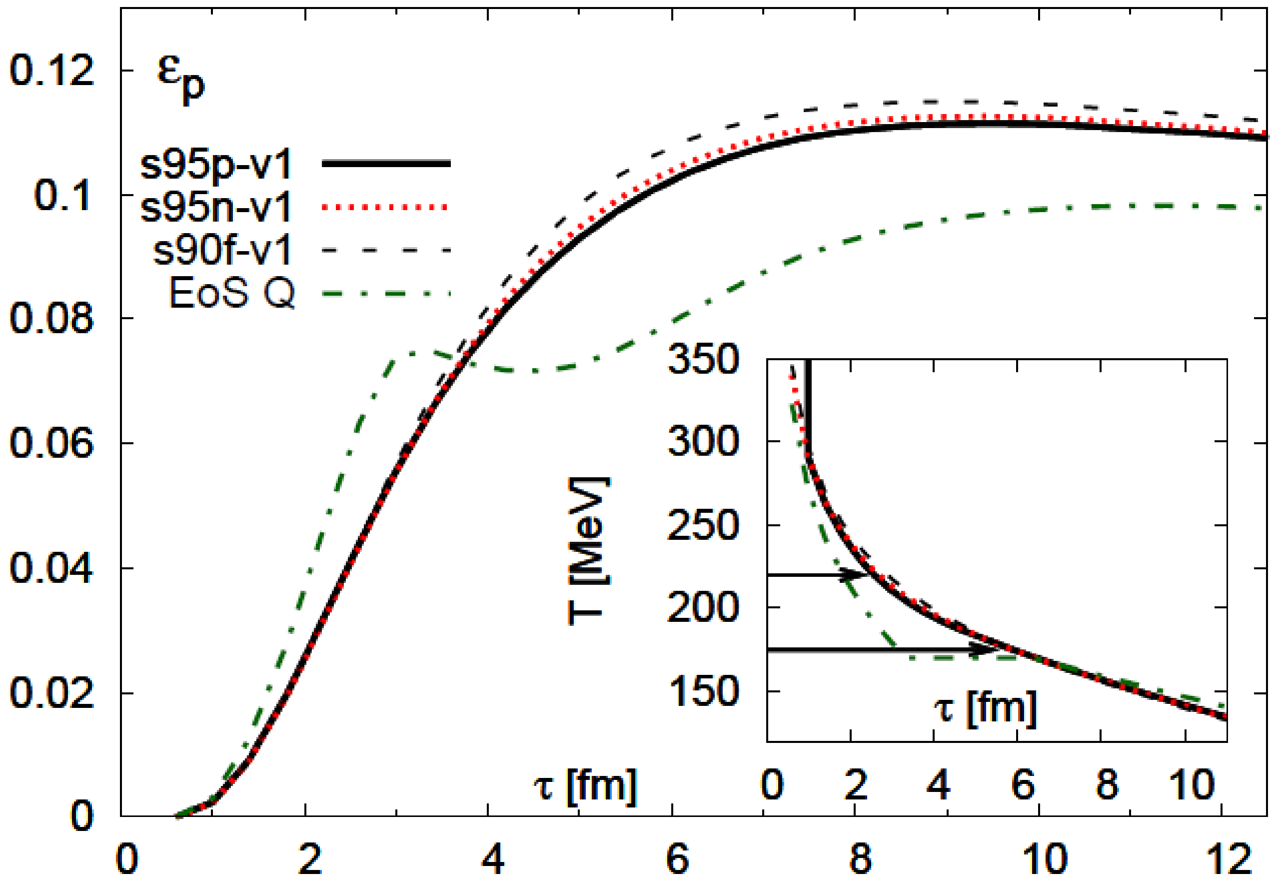
A controlled calculation of the Equation of State for T > 400 MeV requires a dynamical charm.

Studies with staggered and Wilson fermions are in progress

Is it possible to estimate the required accuracy from a phenomenological point of view?

For instance:

Impact of EoS on time evolution?



Huovinen Petreczky 2010

Beyond ideal hydro

TRANSPORT

Transport on the lattice

Real time

Imaginary time

Analytic continuation in principle possible

Transport on the lattice

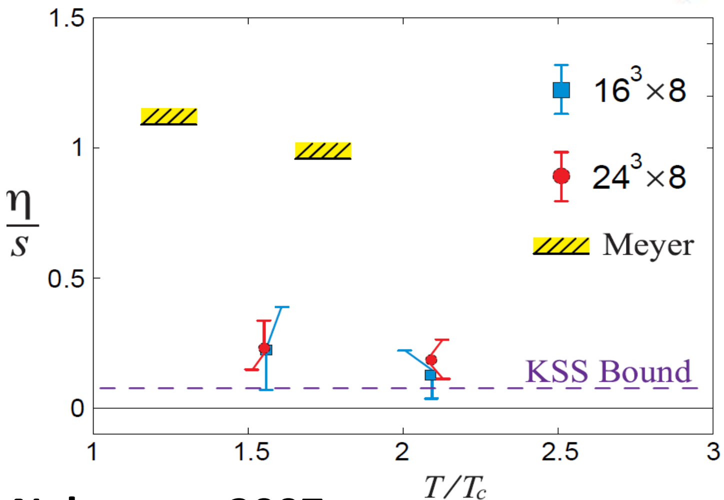
Imaginary time:

Green-Kubo relations

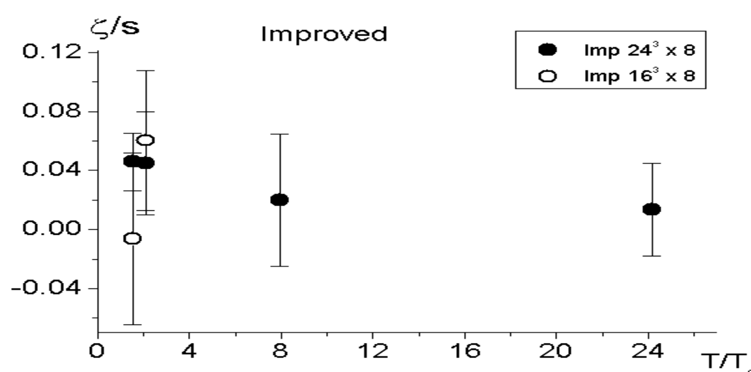
In practice, so far: **Spectral functions** from Euclidean correlators computed in imaginary time

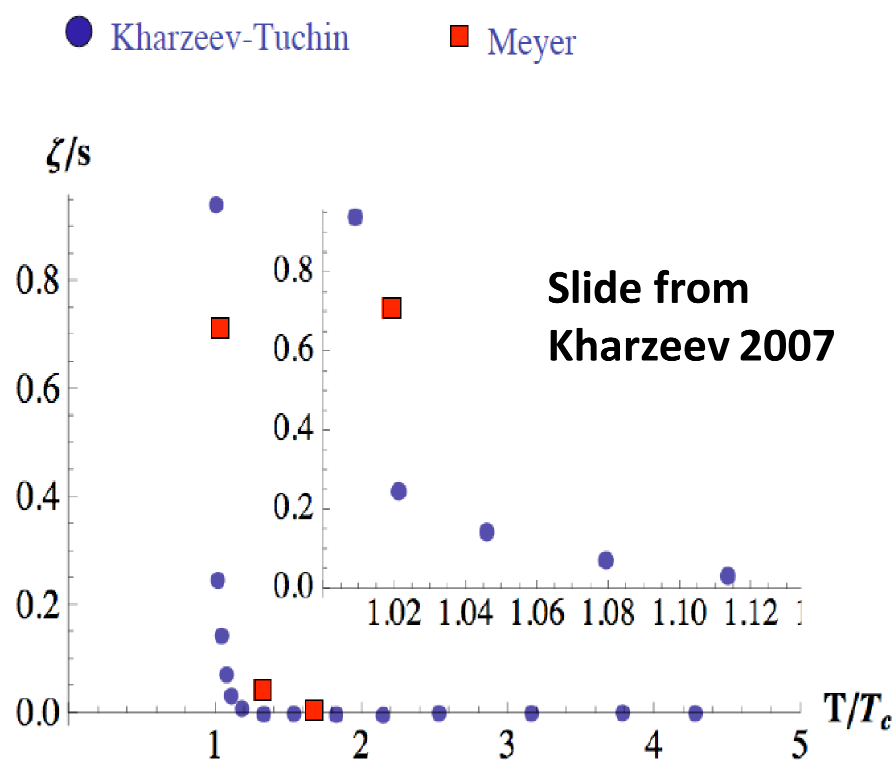
2007: Golden year for lattice trasport...

$$\theta_{ij} = P_{eq}(\epsilon)\delta_{ij} - \eta \left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u_k\right) - \zeta\, \delta_{ij}\vec{\nabla}\cdot\vec{u}$$



Nakamura 2007

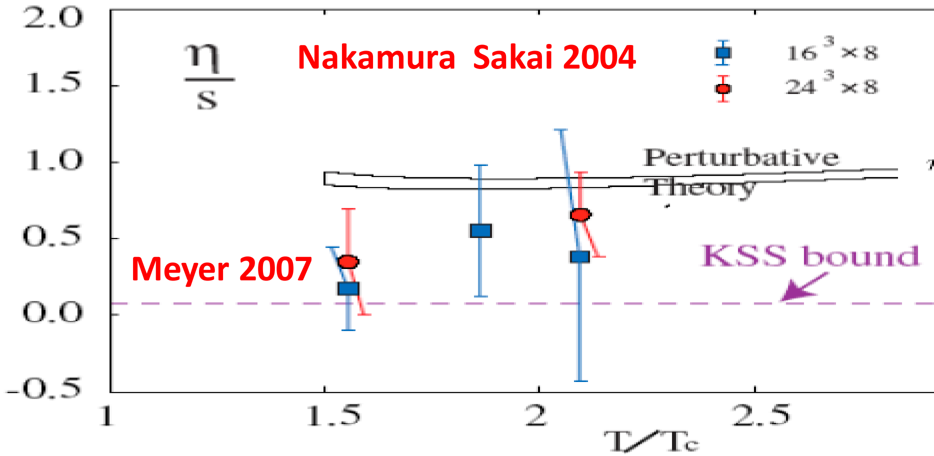




Lattice and transport

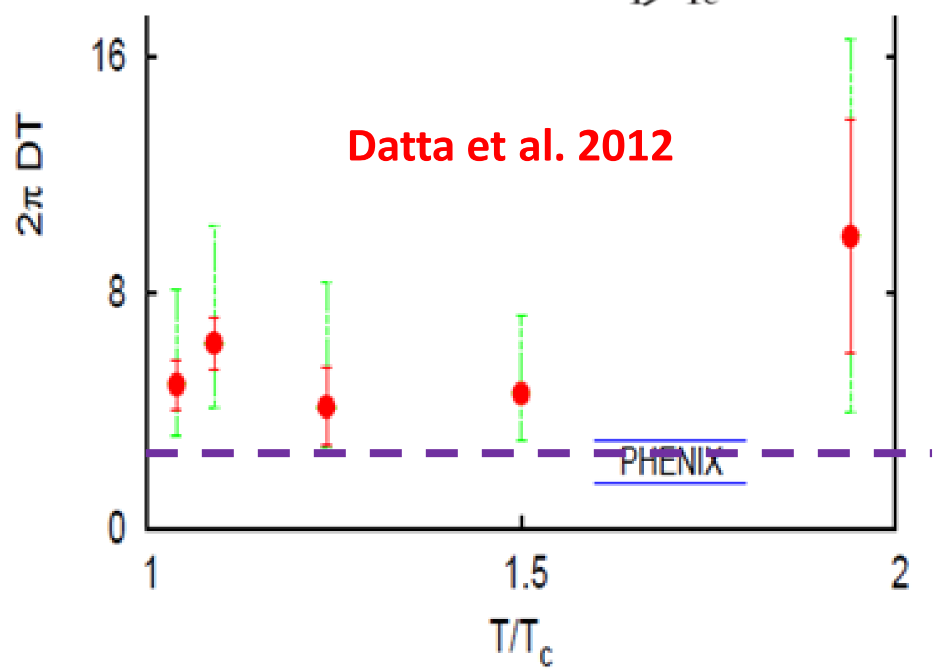
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

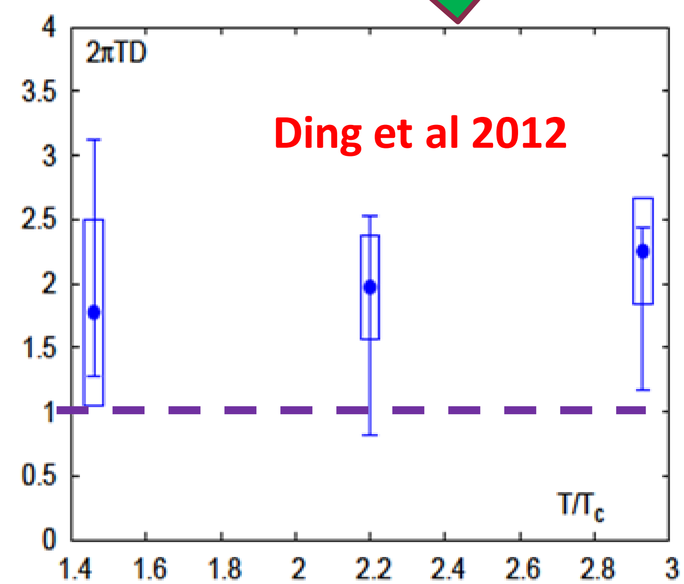
2012 status



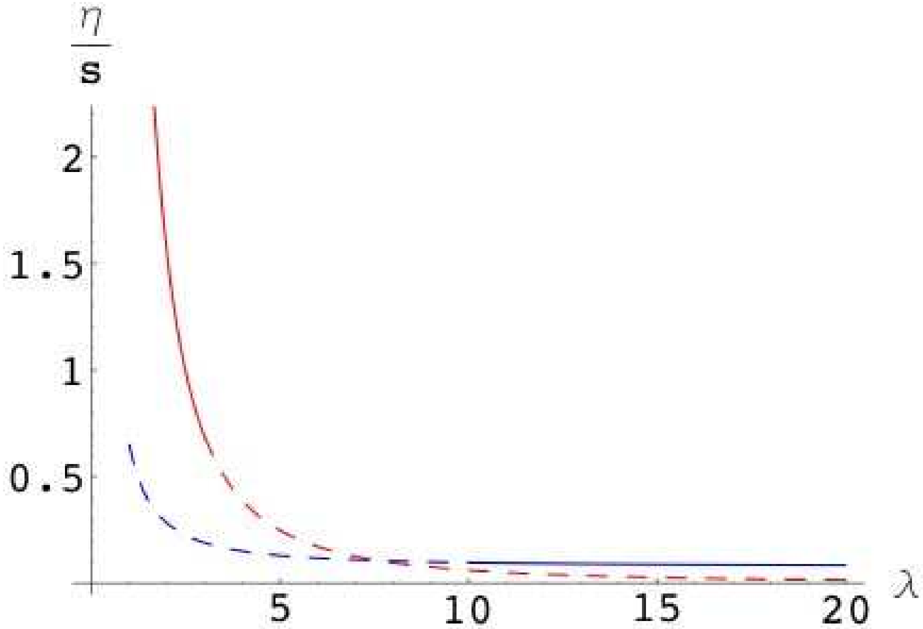
Early evidence for sQGP (slide from D. Kharzeev, 2007)

Recent results for the HQ diffusion coeff.





η/s



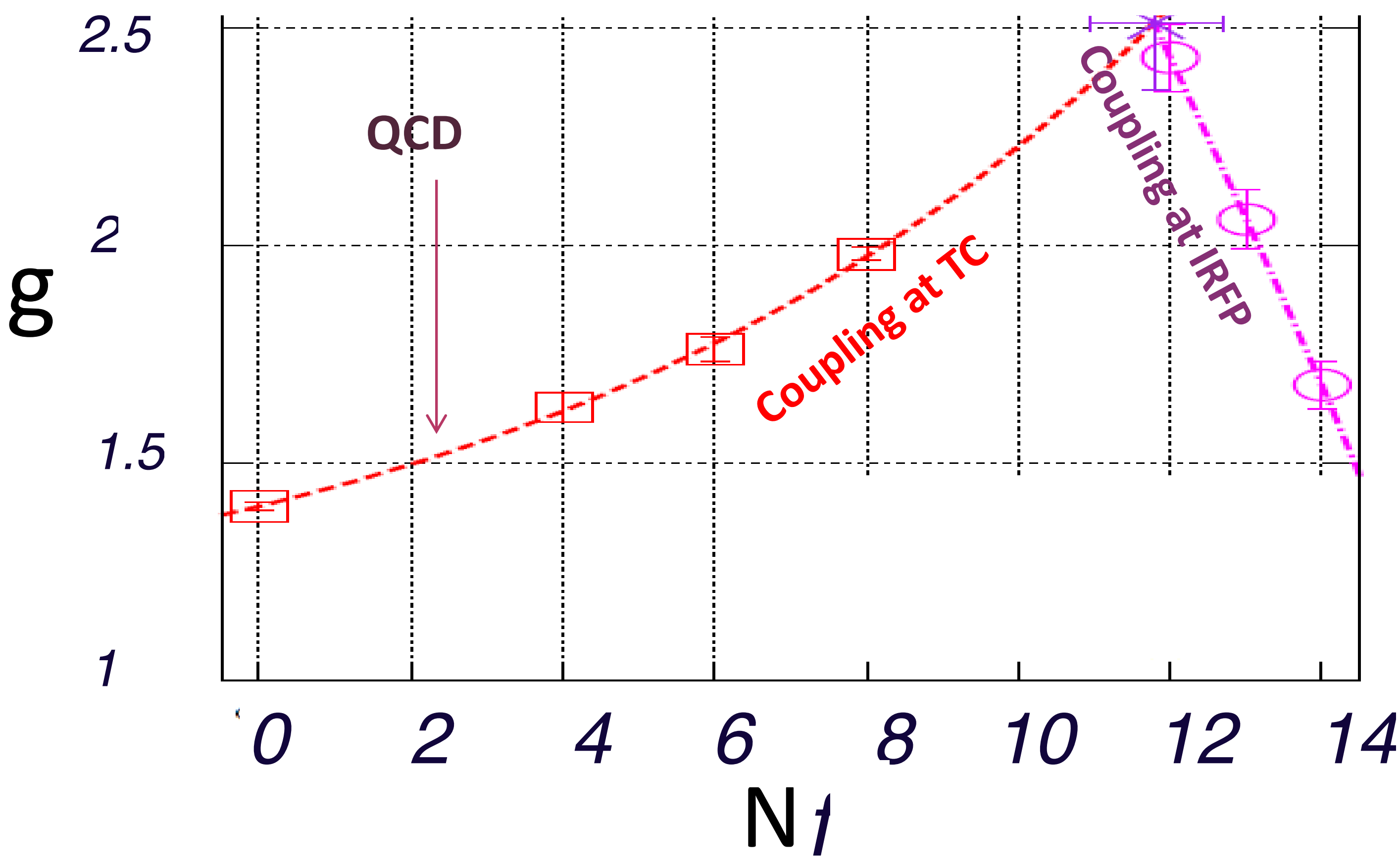
behaviour of η/s as a function of the 't Hooft coupling $\lambda = g^2_{YM} N_c$

Kovtun-Son-Starinets (KSS) bound:

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

$\frac{\eta}{s} \approx 0.5$: border-value between sQGP and pQGP ?

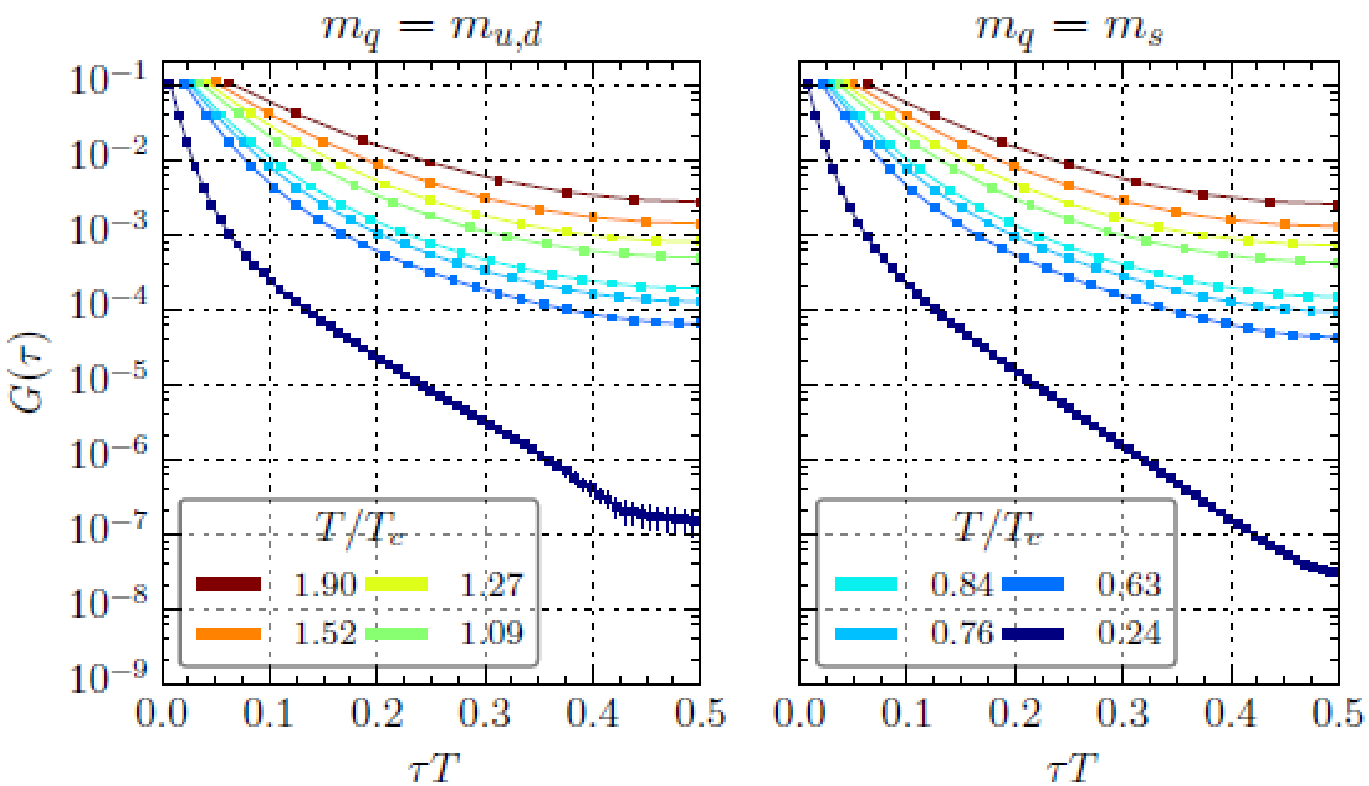
Strength of the sQGP vs Nf



Miura, MpL 2013

2015: trasport on the lattice coming of age? Conductivity

$$G^{\rm em}_{\mu\nu}(\tau) = \frac{1}{V}\int d^3x\, \langle j^{\rm em}_\mu(\tau,\mathbf{x})\, j^{\rm em}_\nu(0,0)^\dagger \rangle$$

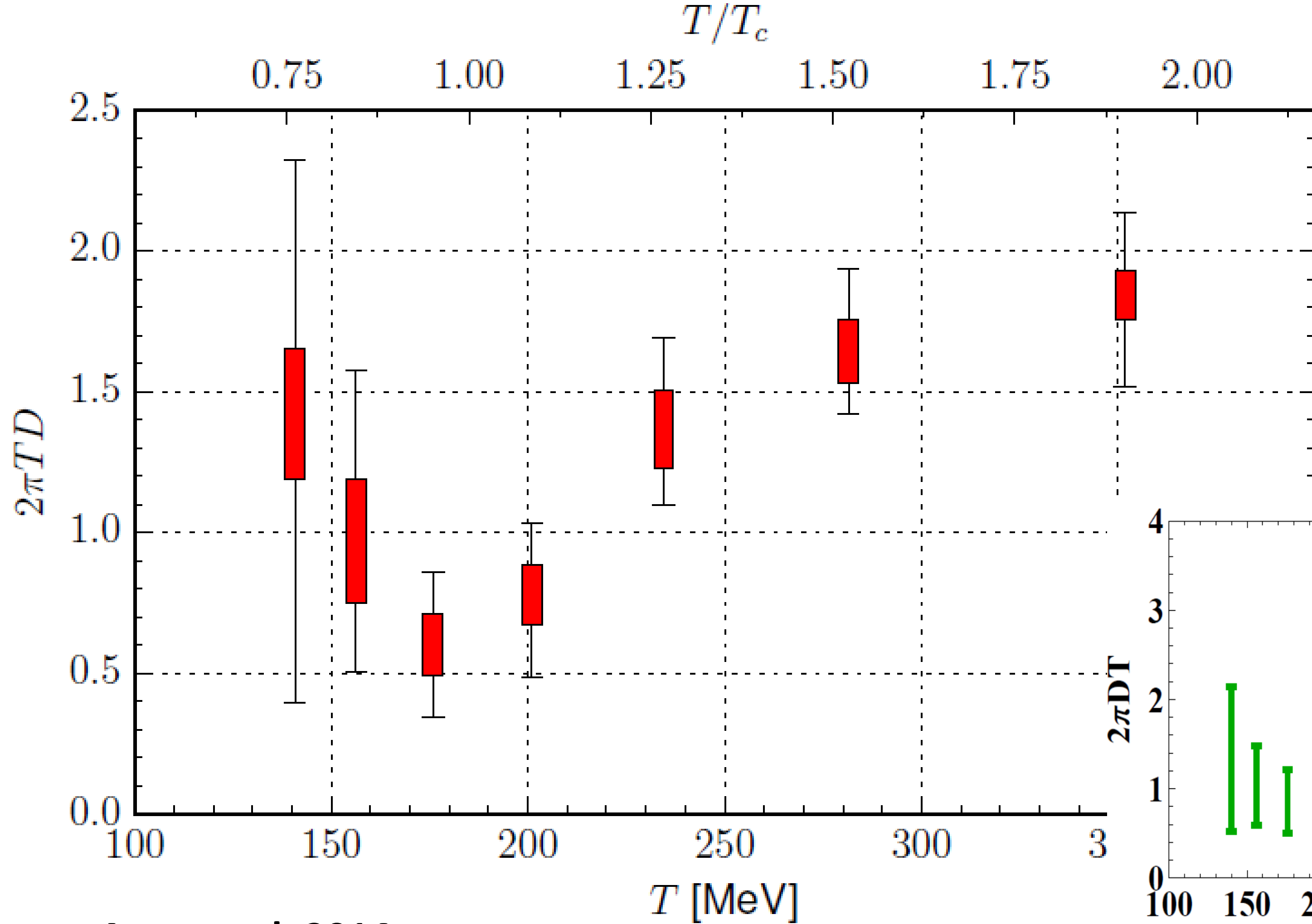


$$j^{\rm em}_\mu = \sum_f (eq_f) j^f_\mu = \frac{2e}{3} j^u_\mu - \frac{e}{3} j^d_\mu - \frac{e}{3} j^s_\mu$$

Aarts et al. 2014

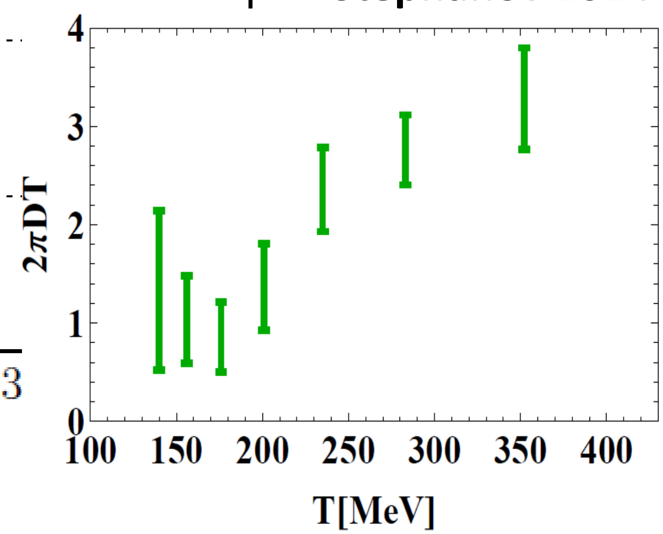
FASTSUM Collaboration

Charge diffusion coefficient $D = \sigma / \chi_Q$



Aarts et al. 2014

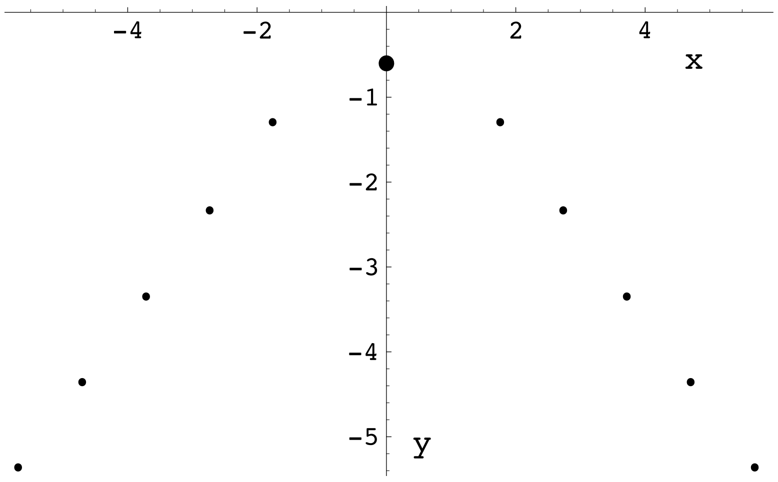
Ling, Springer Stephanov 2014

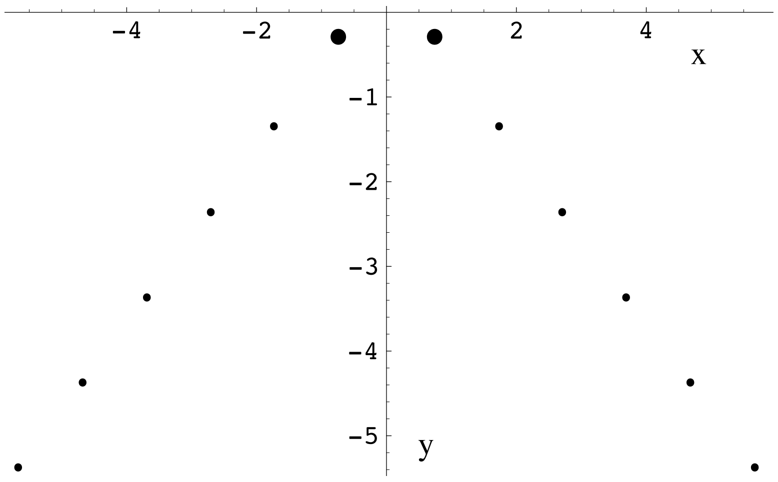


Beyond Hydro?

Quasinormal modes

hydrodynamic modes





quasinormal spectrum of black brane gravitational fluctuations in the shear and sound channels at fixed spatial momentum as a function of complex frequency

[Kovtun and Starinets (2005)]

hydrodynamic poles are marked by full dots, e.g. shear

$$\omega = -i\frac{\eta}{Ts}q^2 + O(q^3) = -i\frac{1}{4\pi T}q^2 + O(q^3)$$

approach the real frequency axis for $q \to 0$

[Kovtun, Son and Starinets (2005)]

Questions:

Equation of State: which is the needed accuracy

Transport coefficients: -which is the needed accuracy
-how many of them are needed

Approach to hydro: -quasinormal modes?

Physics mechanisms: -qualitative differences
between QGP and sQGP?
-Characterization of sQGP

Emerging field: lattice + holography + near-conformal model field theories