Turbulent Thermalization in Non-Abelian Plasmas

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Sebastian Scheffler

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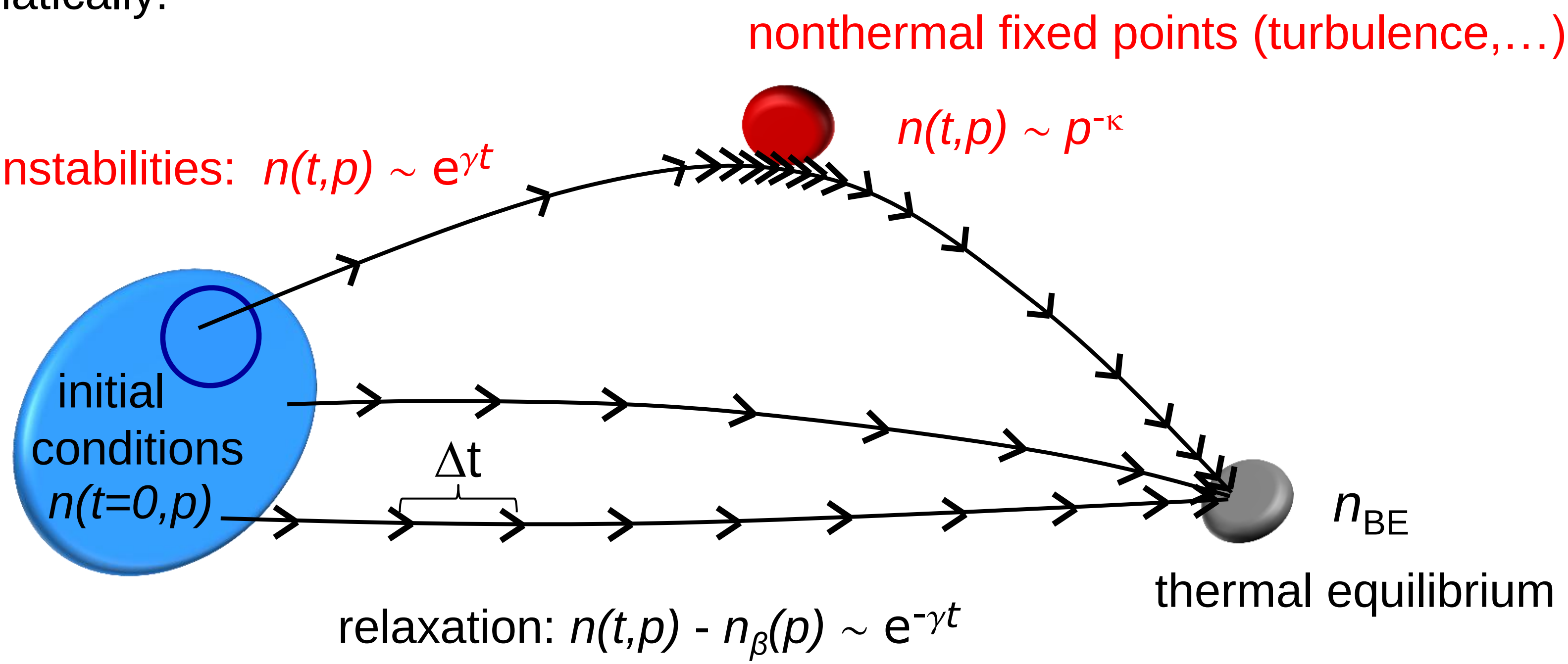
Thermalization process in quantum many-body systems

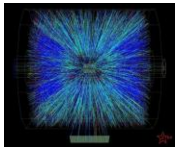
Schematically:



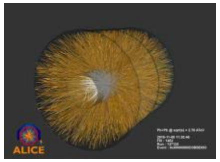
- Relaxation? Instabilities? Nonthermal fixed points?

Universality far from equilibrium?

Heavy Ion Collisions



- fluid-like behavior from very early time on
- very special transport properties, such as small η/s



How is local isotropization/thermalization achieved?

a) strong coupling? $\alpha_s \sim 0.3 - 0.4$ at RHIC or LHC

Strong anisotropy at transition to hydrodynamic regime

Heller, Janik, Witaszczyk; Chesler, Yaffe …

b) weak coupling but highly occupied? CGC: McLerran, Venugopalan, …

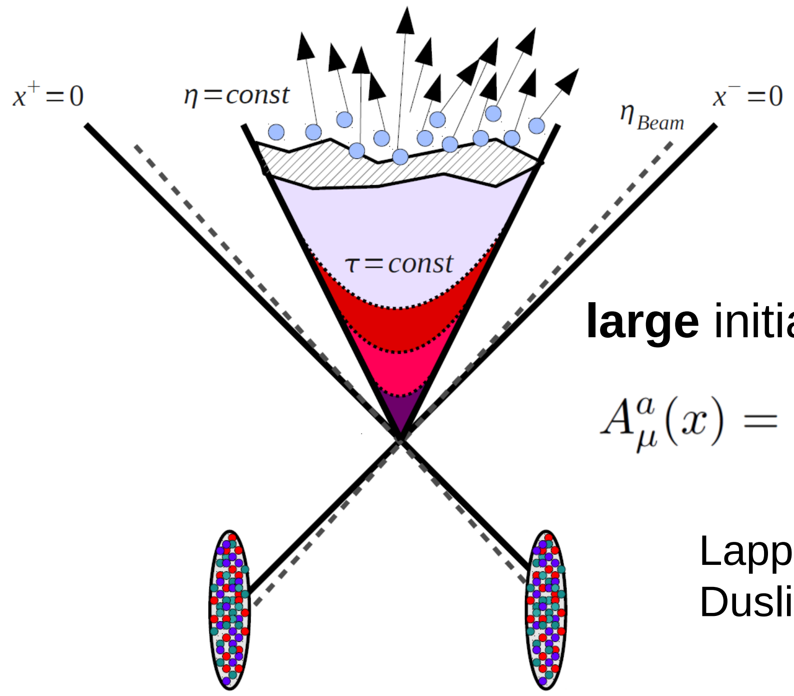
Energy density of gluons with typical momentum Q_s (at time $\sim 1/Q_s$)

$$\epsilon \sim \frac{Q_s^4}{\alpha_s}$$ i.e. 'occupation numbers' $$n(p \lesssim Q_s) \sim \frac{1}{\alpha_s}$$

Strongly correlated/nonperturbative even for weak coupling $\alpha_s \ll 1$

CGC and the Glasma

- particle production in the presence of large fields



$g \ll 1$

large initial fields:

$$A_\mu^a(x) = \langle \hat{A}_\mu^a(x) \rangle \sim \mathcal{O}(1/g)$$

Lappi, McLerran,
Dusling, Gelis, Venugopalan,…

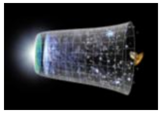
- **small** initial (vacuum) fluctuations:

$$F_{\mu\nu}^{ab}(x,y) = \frac{1}{2}\left\langle\left\{\hat{A}_\mu^a(x), \hat{A}_\nu^b(y)\right\}\right\rangle - A_\mu^a(x)A_\nu^b(y)$$

$$\sim \mathcal{O}(1)$$

→ ***instability!***

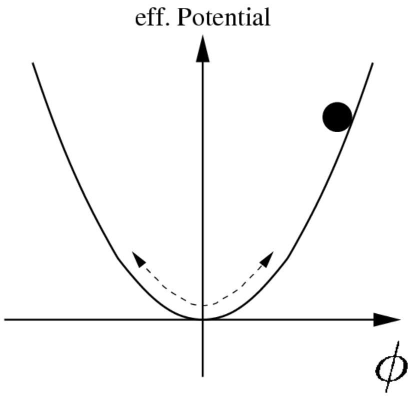
Mrowczynski; Rebhan,
Romatschke, Strickland;
Arnold, Moore, Yaffe …



A well understood *quantum* example

Early universe preheating:

Kofman, Linde, Starobinsky, PRL 73 (1994) 3195



Scalar $\lambda\Phi^4$ inflaton: $\lambda \ll 1$

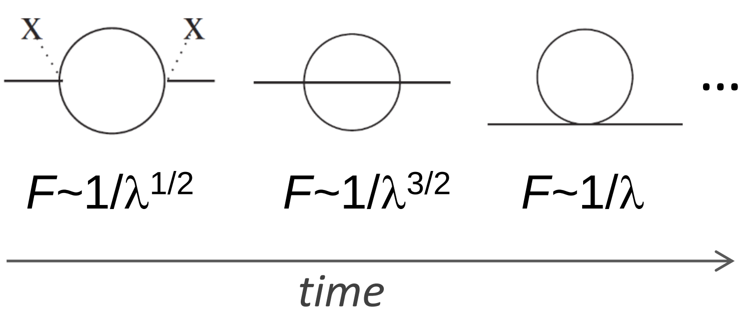
- **large** initial field $\phi = \langle\Phi\rangle \sim 1/\lambda^{1/2}$
- **small** fluctuation $F \sim \langle\{\Phi,\Phi\}\rangle - \phi\phi \sim 1$

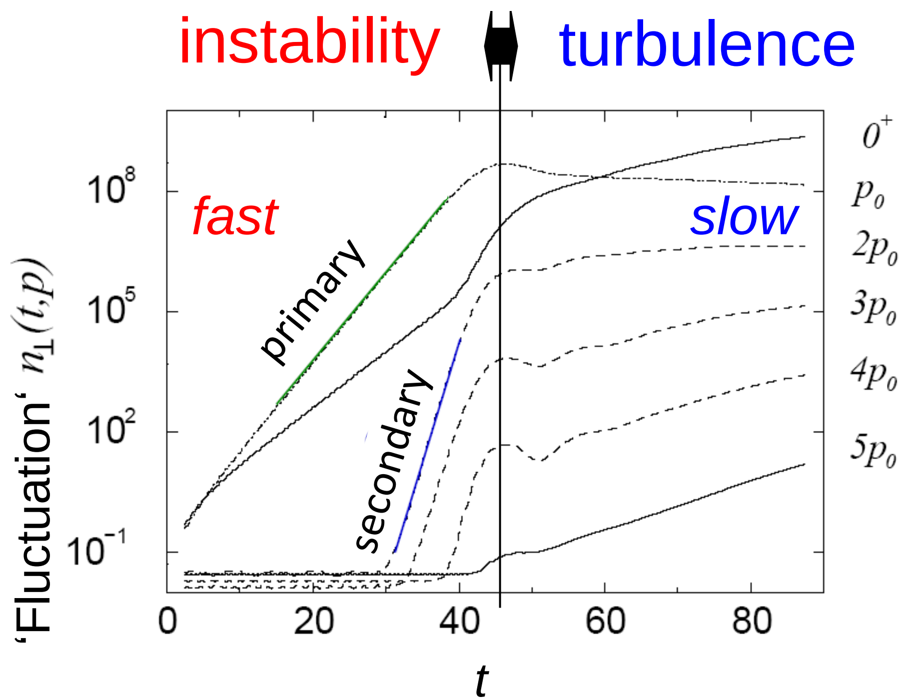
Instability: $F(t) \sim e^{\gamma t}$ $(\gamma > 0)$

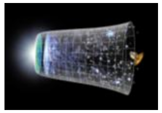
Quantum field theory:

Berges, Serreau, PRL 91 (2003) 111601

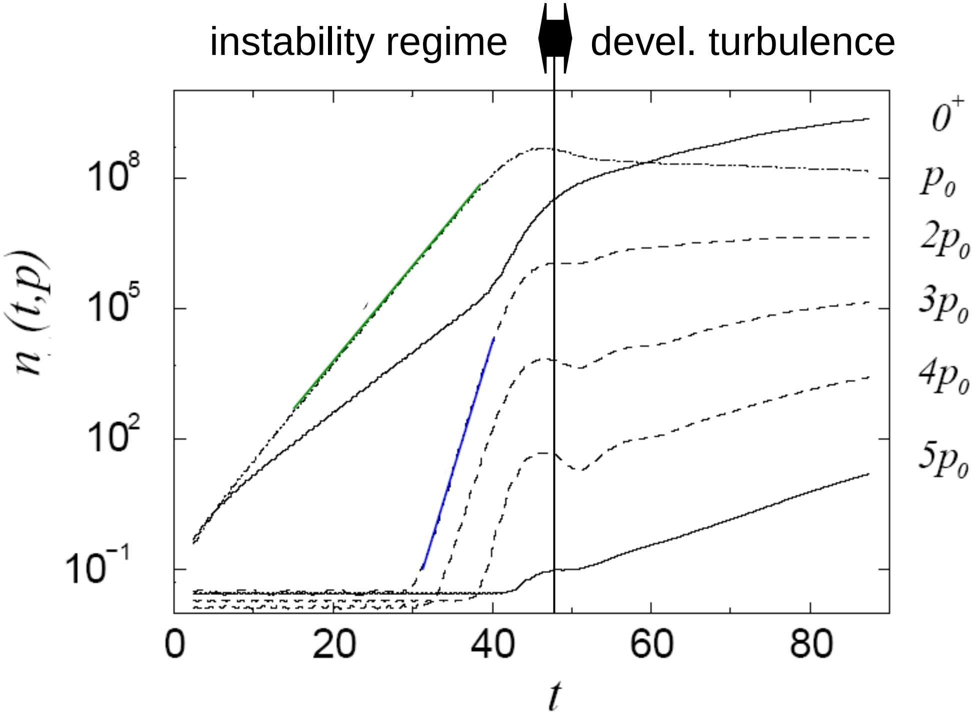
Dynamical power counting (2PI):



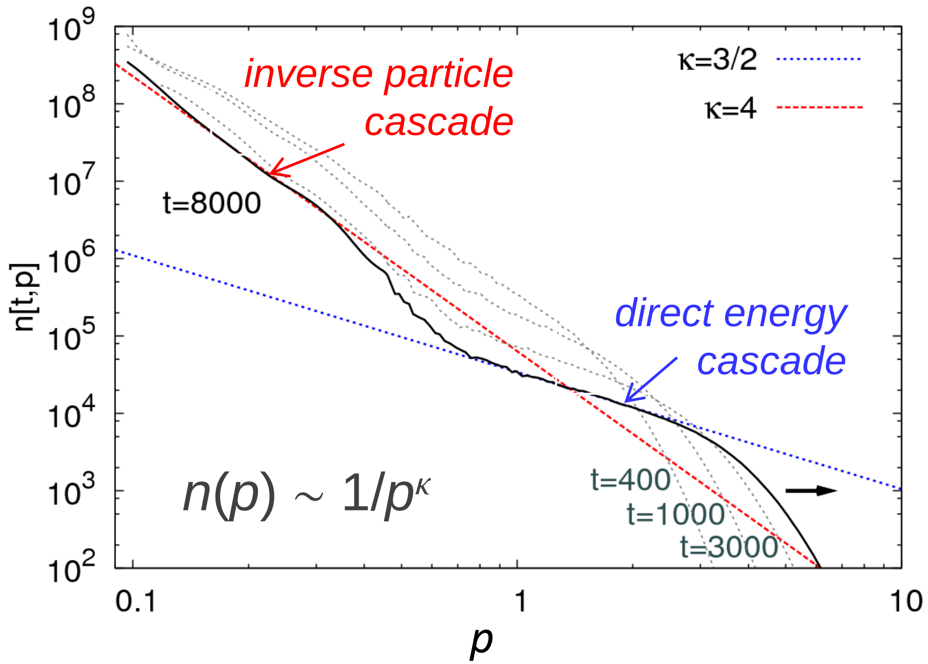




Turbulent thermalization



dual cascade:



Direct cascade: Micha, Tkachev, PRL 90 (2003) 121301, …(no condensate: $\kappa = 5/3, 4/3$)

Inverse cascade: Berges, Rothkopf, Schmidt, PRL 101 (2008) 041603, … ($\kappa = d+z-\eta$)

Bose condensation: Berges, Sexty, PRL 108 (2012) 161601, …

Cascade dynamics described by universal scaling laws!

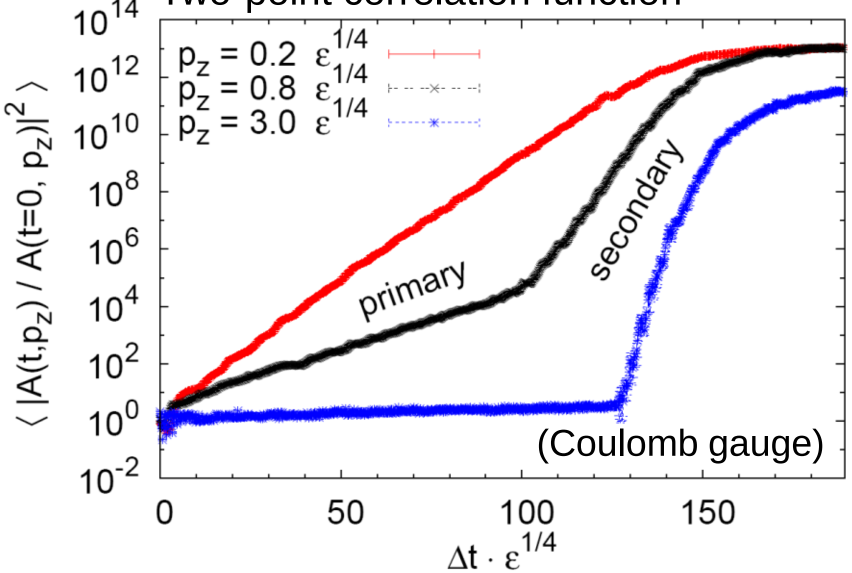
self-similar evolution, same universality class as classical-statistical field theory

Classical-statistical lattice gauge theory

Romatschke, Venugopalan, PRL 96 (2006) 062302, …

SU(2) – fixed box

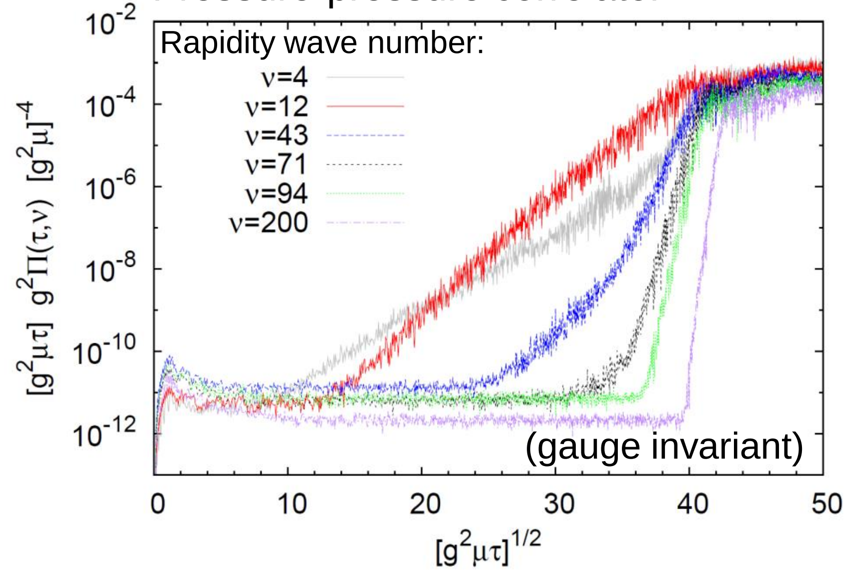
Two-point correlation function



Berges, Scheffler, Sexty, PRD 77 (2008) 034504
SU(3): Berges, Gelfand, Scheffler, Sexty (2009)

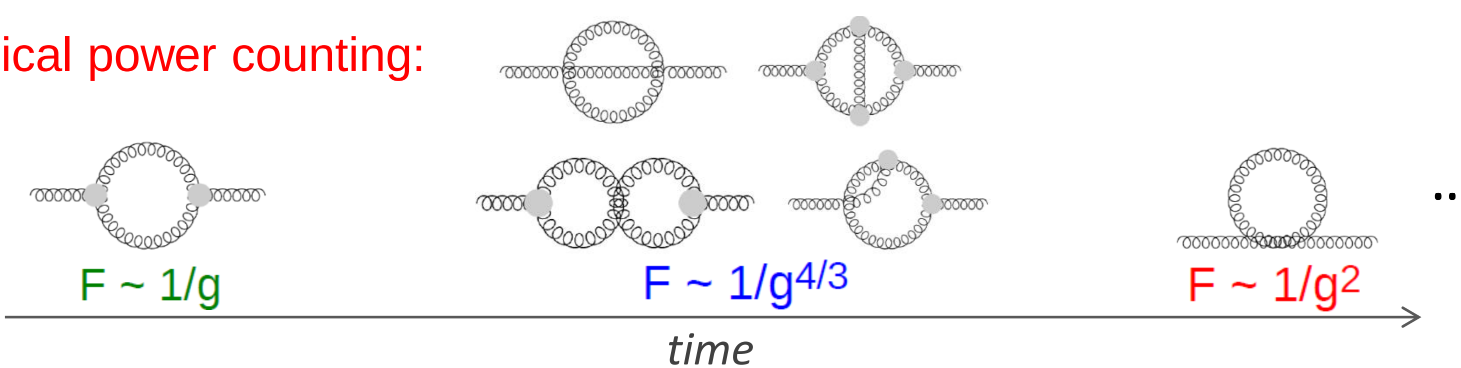
SU(2) – CGC expanding

Pressure-pressure correlator



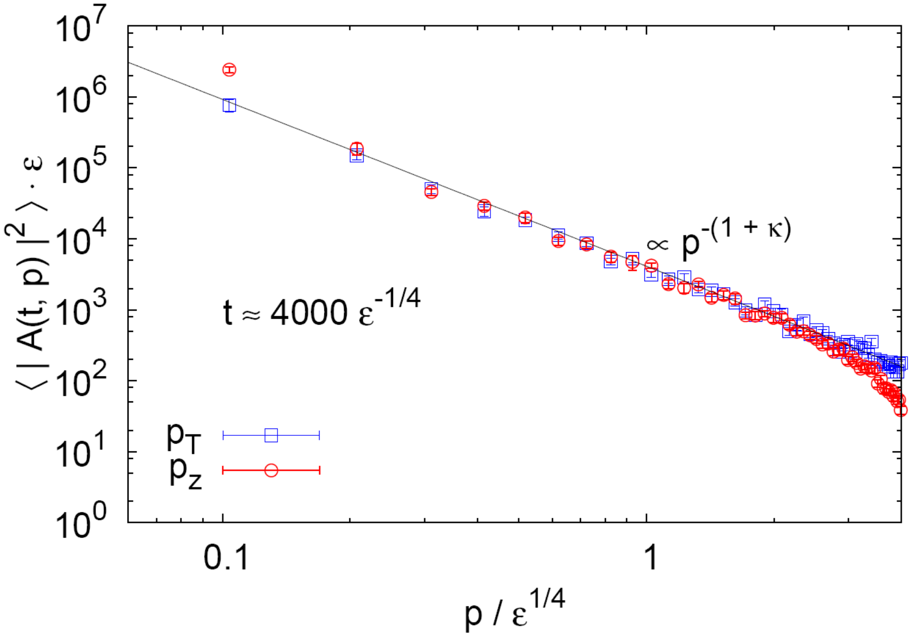
Berges, Schlichting
arXiv:1209.0817 [hep-ph]

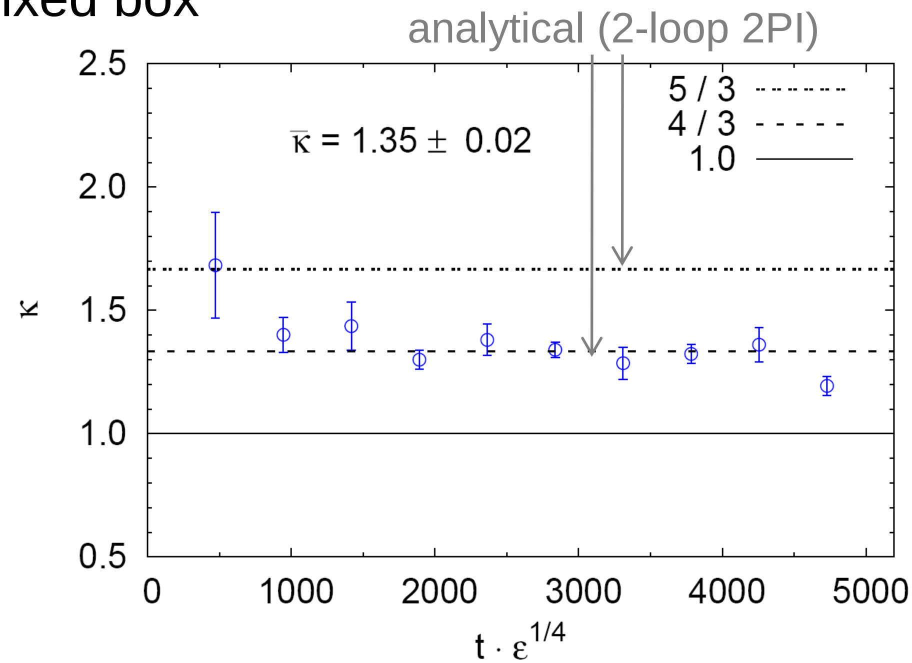
Dynamical power counting:



Turbulent thermalization

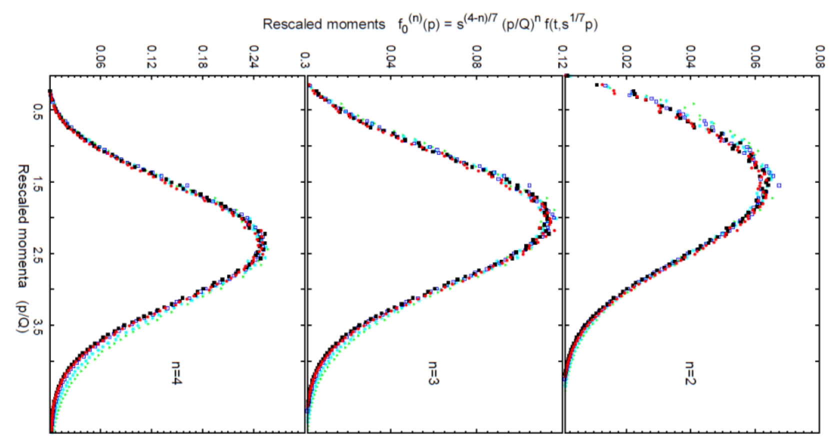
SU(2) – fixed box





turbulence exponent as for scalars (without condensate): $\kappa = 4/3$

Berges, Scheffler, Sexty, PLB 681 (2009) 362



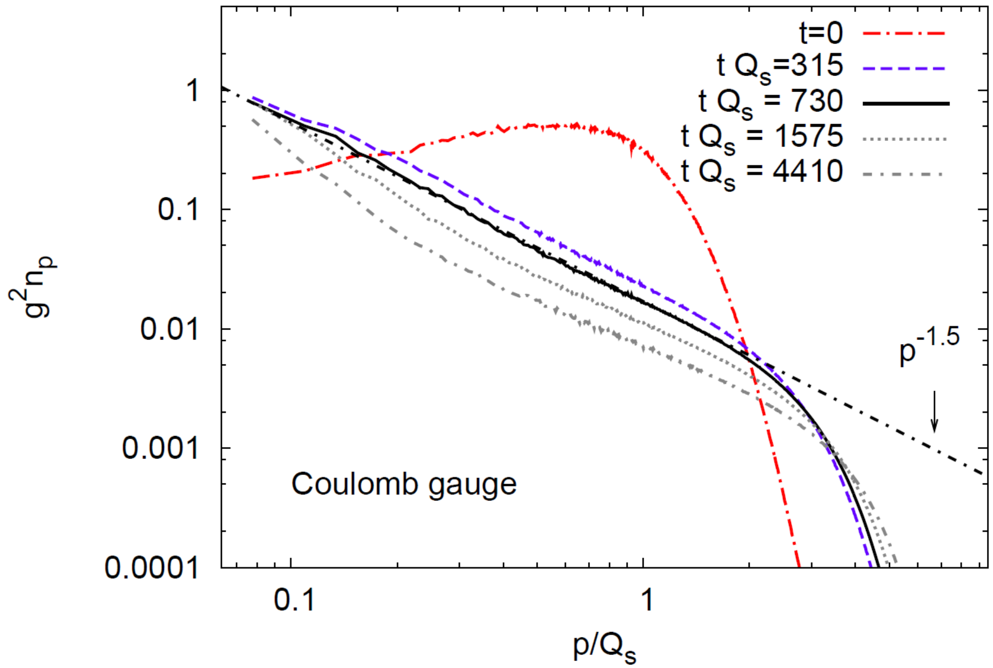
→ self-similar evolution

Schlichting, PRD 86 (2012) 065008

Kurkela, Moore, PRD 86 (2012) 056008

Bose condensation?

Occupancy: $\sim \sqrt{\langle|A^2(p)|\rangle\langle|E^2(p)|\rangle}$

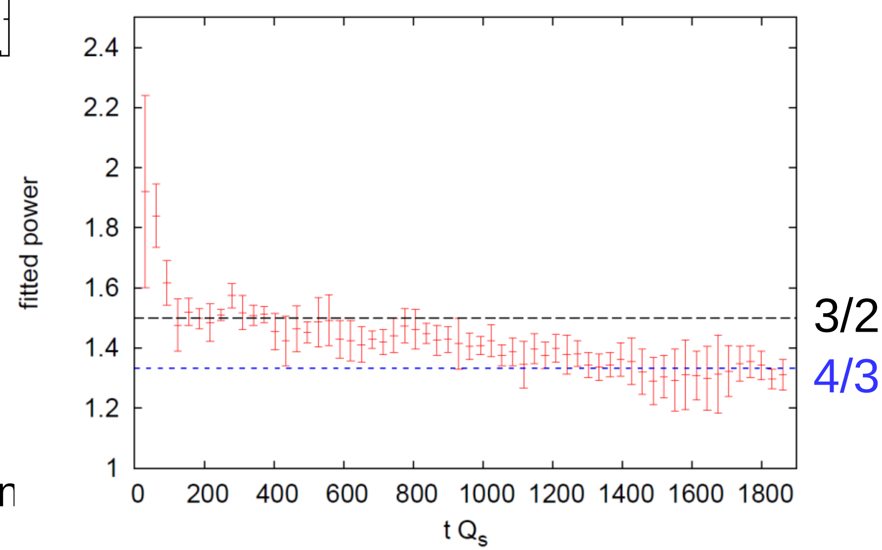


SU(2) – fixed box

starting from initial overpopulation:

$$\epsilon \sim \frac{Q_s^4}{g^2} \quad \text{i.e.} \quad n(p \simeq Q_s) \sim \frac{1}{g^2}$$

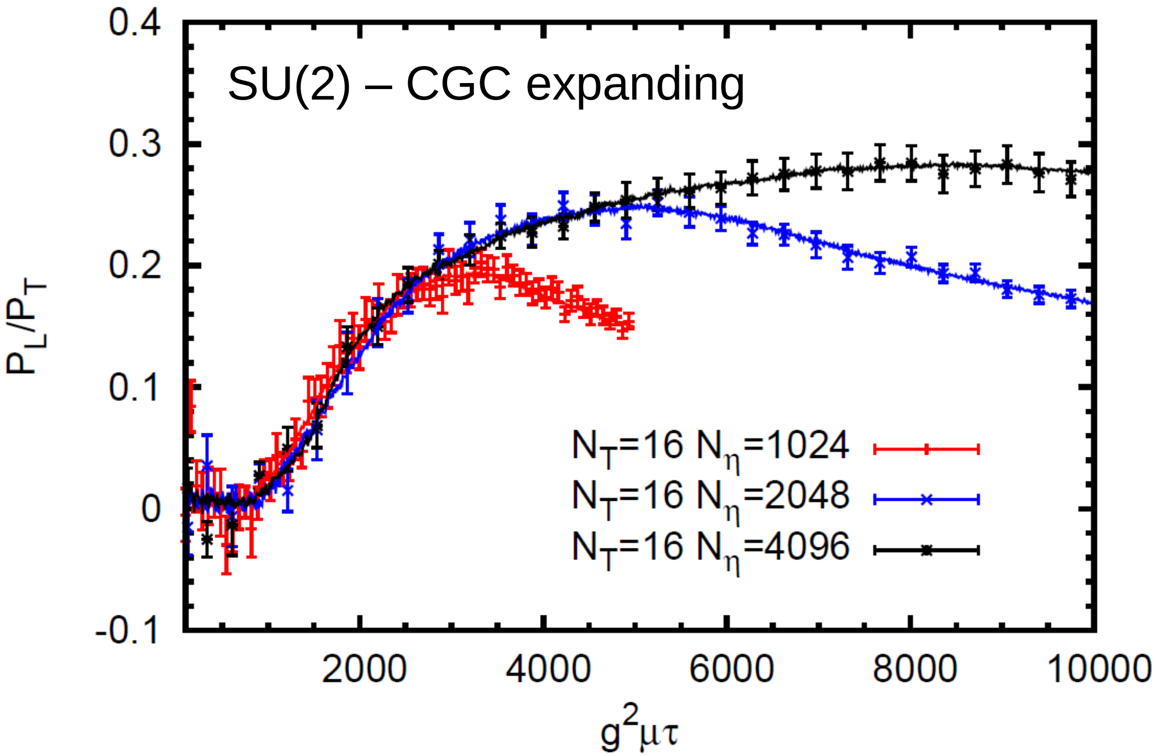
Berges, Schlichting, Sexty,
PRD 86 (2012) 074006



intermediate exponent 3/2 as for scalars with condensate!?

c.f. Blaizot, Gelis, Liao, McLerran, Venugopalan
NPA 873 (2012) 68

Turbulent thermalization with expansion?



Berges, Schlichting arXiv:1209.0817 [hep-ph]

Strong anisotropy for large times!

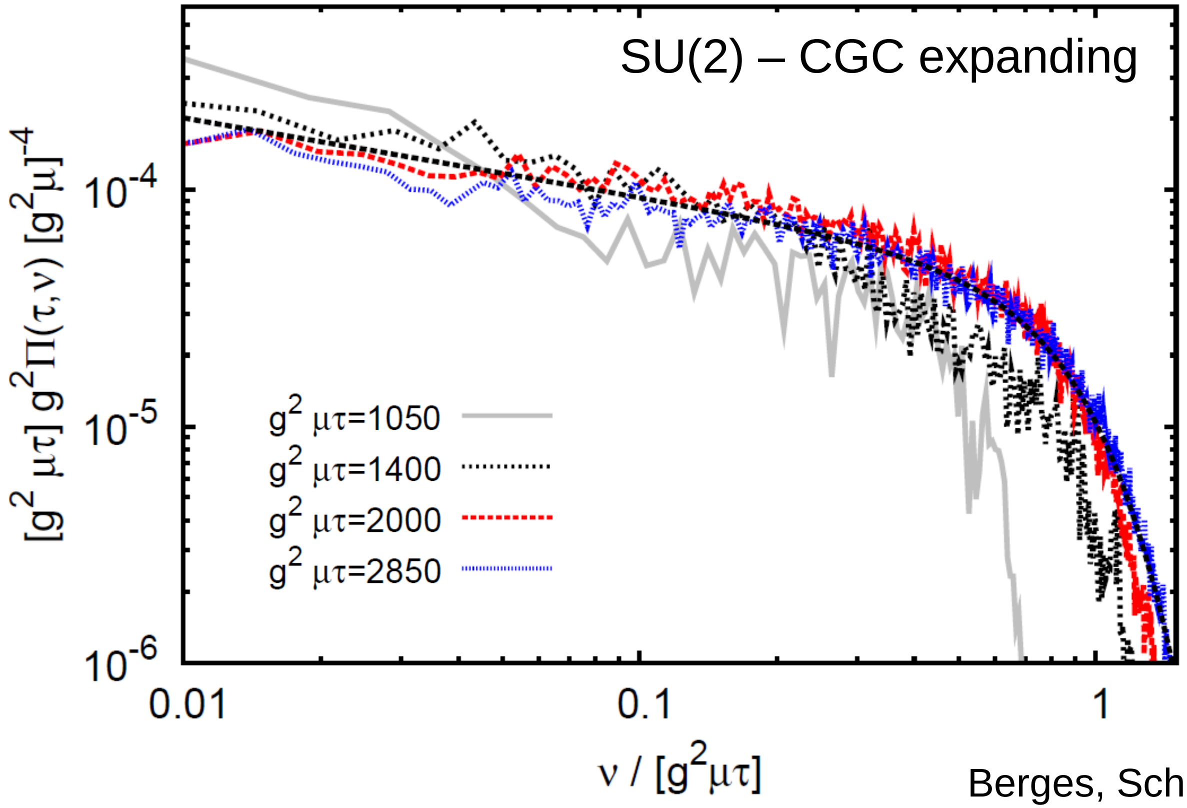
(dependence on tranverse lattice size? → work in progess)

Attractor solutions scenarios with small/large anisotropy?

c.f. Kurkela, Moore, JHEP 1111 (2011) 120

Turbulent thermalization with expansion?

Pressure-pressure correlator:



Fit (cf. scalars):

$$\frac{A\, x^{-\beta}}{1+\exp[Bx^2]}$$

$$\beta \simeq 1/3$$

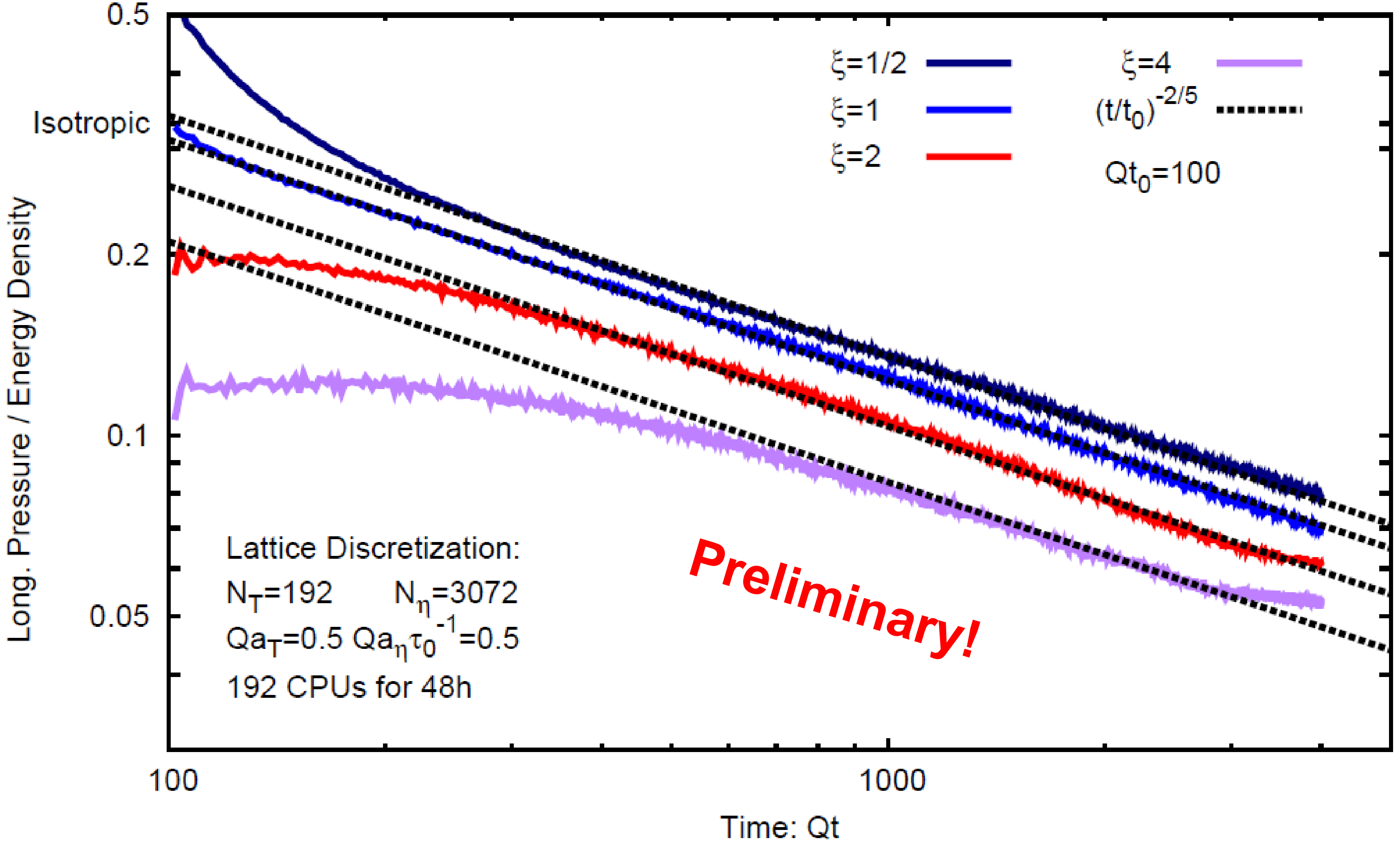
$\sim \nu\, n(\nu) \;\rightarrow\; n(\nu) \sim 1/\nu^{4/3}$

Berges, Schlichting arXiv:1209.0817 [hep-ph]

Turbulent scaling behavior despite strong anisotropy!?

c.f. also Fukushima, Gelis, NPA 874 (2012) 108

Power-law behavior with expansion



S.Schlichting, R. Venugopalan, K. Boguslavski, J.Berges, in preparation

Conclusions

- Thermalization dynamics at weak coupling:

large initial fields/small fluctuations

instabilities with non-linear amplification

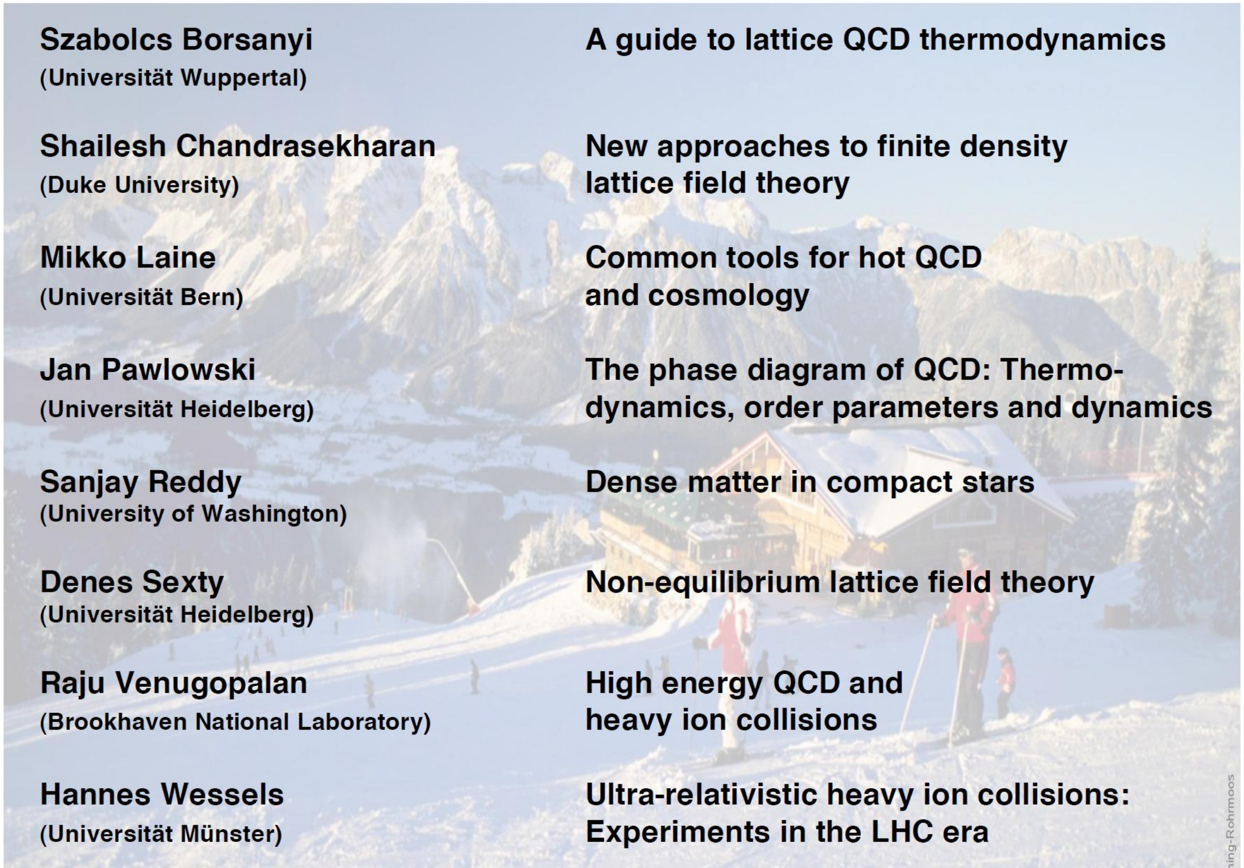
turbulent thermalization

well established for fixed box, still some open questions $\longrightarrow$ expansion

- Same far-from-equilibrium scaling exponents for scalars/gauge fields
- Scalars: inverse particle cascade leads to Bose condensation
- Gauge fields: no Bose condensation for parametrically long times
- CGC: Expansion at weak α_s leads to strong anisotropy for long times

Extreme QCD in and out of Equilibrium

Schladming, Austria, February 23 – March 2, 2013



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Shailesh Chandrasekharan (Duke University)	**New approaches to finite density lattice field theory**
Mikko Laine (Universität Bern)	**Common tools for hot QCD and cosmology**
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Denes Sexty (Universität Heidelberg)	**Non-equilibrium lattice field theory**
Raju Venugopalan (Brookhaven National Laboratory)	**High energy QCD and heavy ion collisions**
Hannes Wessels (Universität Münster)	**Ultra-relativistic heavy ion collisions: Experiments in the LHC era**

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