Summary of the Workshop: String Theory and Extreme Matter

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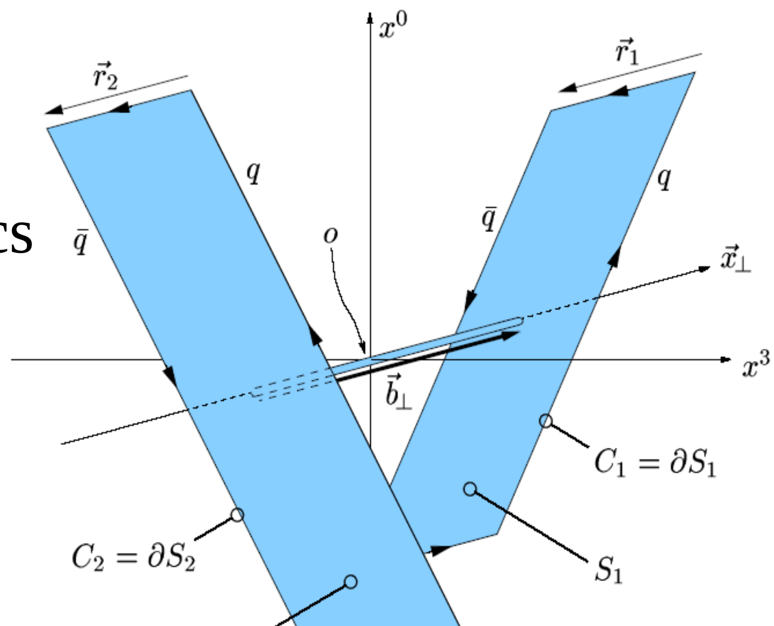
Thursday night 22.00, H. Forkel has not yet presented correlators, P. Kerner p-wave superfluids, D. Antonov a field strength model

Loop Loop Correlation Model

- The loop loop correlation model gives high energy scattering of color dipoles (mesons)

which are described by string surfaces in 4d

My own way
To stringy physics



A. I. Shoshi, F. D. Steffen and H. J. Pirner, Nucl. Phys. A **709** (2002) 131.
O. Nachtmann, Annals Phys. **209** (1991) 436.

Three Topics :

- Construction of a gravity dual theory which describes confinement/deconfinement transition with temperature (Kiritsis, Kajantie, Megias)
- D3/D7 Branes give a possibility to introduce flavoured quarks and be close to Superstring theory in 10-dimensions (Erdmenger, O´Bannon)
- String Theory makes contact with reality especially finite density: AdS/QCD:Nickel,Schade,Zaanen,Alanen,Kerner

1. Confinement/Deconfinement

- Instead of strong coupling (unsolvable/lattice) and weak coupling (solvable in pQCD) there is only one world of hadron physics.
- Do not replicate this separation with top down and bottom up approach
- Both must approach reality/ experiment
- Now, Gravity dual theories perhaps in better position

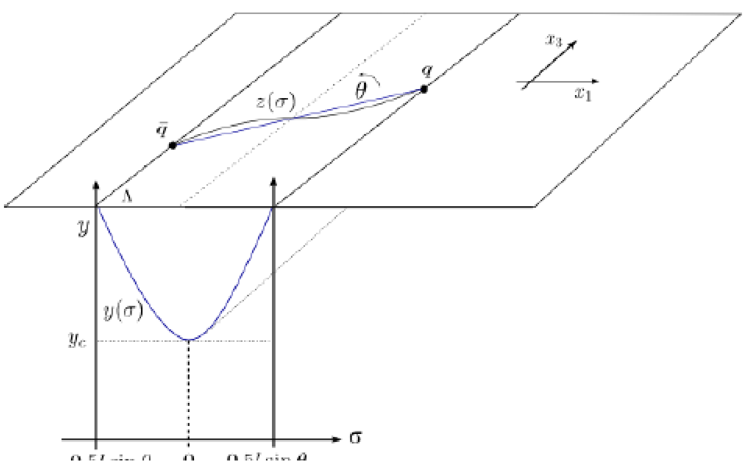
Start with Wilson loop calculations:

Screening Length in a hot moving plasma

- Static quark-antiquark pair in a hot moving plasma „wind“ blowing in $-x_3$ – direction
- velocity $v = \tanh\eta$
- orientation angle θ

Schade
Ewerz
Megias
Kajantie

Quark-antiquark configuration



Nambu-Goto action:

$$S = \frac{1}{2\pi\alpha'} \int d\sigma d\tau \sqrt{-\det g_{\alpha\beta}}$$

with $g_{\alpha\beta} = G_{\mu\nu}\partial_\alpha x^\mu \partial_\beta x^\nu$

Improved Holographic QCD: a model

• We would like to write down a model that captures the holographic behavior of YM:

• The basic fields will be $g_{\mu\nu}, \phi, a$. We can neglect a when studying the basic vacuum solution (down by N_c^{-2}).

• In the IR the action should have two derivatives and admit solutions with weak curvature (in the string frame)

$$S_{\text{Einstein}} = M^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V(\lambda) \right] \quad , \quad \lambda = N_c \, e^{\phi}$$

• Although in the UV we expect higher derivatives to be important we will extend this by demanding that the solution is asymptotically AdS_5 and the 't Hooft coupling will run logarithmically.

• Although we do not expect this simple model to capture all aspects of YM dynamics we will see that it goes a long way.

Black hole factors f(r) in conformal theory and in Ads/QCD

The gauge-theory at finite temperature

- The finite temperature ground state of the gauge theory corresponds to a different solution in the dual string theory: the AdS-Black-hole solution

E. Witten, 1998

$$ds^2 = \frac{\ell^2_{AdS}}{r^2}\left[\frac{dr^2}{f(r)} + f(r)dt^2 + dx^i dx_i\right] + \ell^2_{AdS}\,(d\Omega_5)^2 \quad , \quad f(r) = 1 - (\pi T)^4 r^4$$

(2) "black-hole" solutions

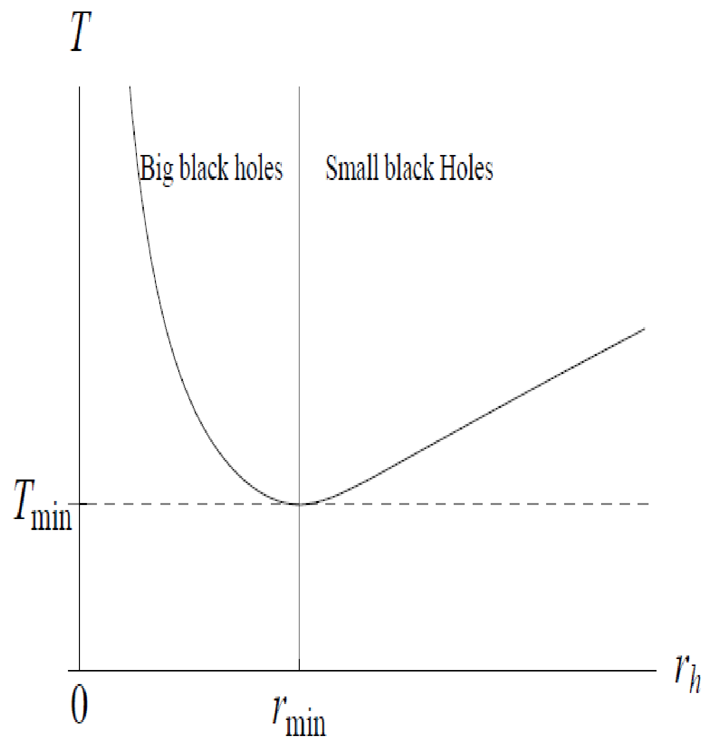
- $$ds^2 = b(r)^2\left[\frac{dr^2}{f(r)} - f(r)dt^2 + dx^i dx^i\right], \qquad \lambda = \lambda(r)$$

Temperature black hole radius

- The relation between temperature and black hole radius r_h : (z -Kajantie= r Kiritsis)

$$\frac{1}{4\pi T} = b^3 \int_0^z \frac{dz}{b^3}$$

Temperature versus horizon position



How to calculate?

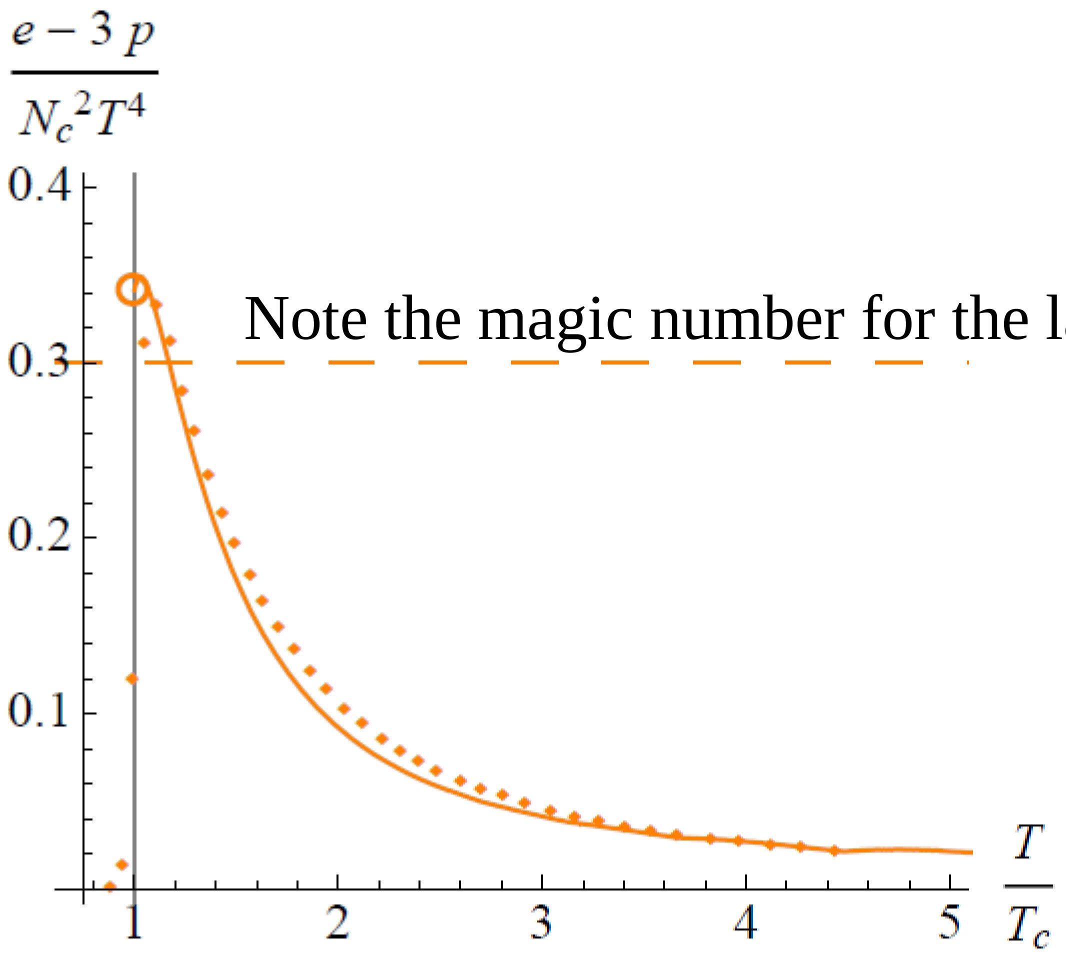
Keijo Kajantie gave a detailed description how to solve:

$$6\frac{\dot{b}^2}{b^2} + 3\frac{\ddot{b}}{b} + 3\frac{\dot{b}}{b}\frac{\dot{f}}{f} = \frac{b^2}{f}V(\phi)$$

$$6\frac{\dot{b}^2}{b^2} - 3\frac{\ddot{b}}{b} = \tfrac{4}{3}\,\dot{\phi}^2,$$

$$\frac{\ddot{f}}{\dot{f}} + 3\frac{\dot{b}}{b} = 0,$$

Equation of state

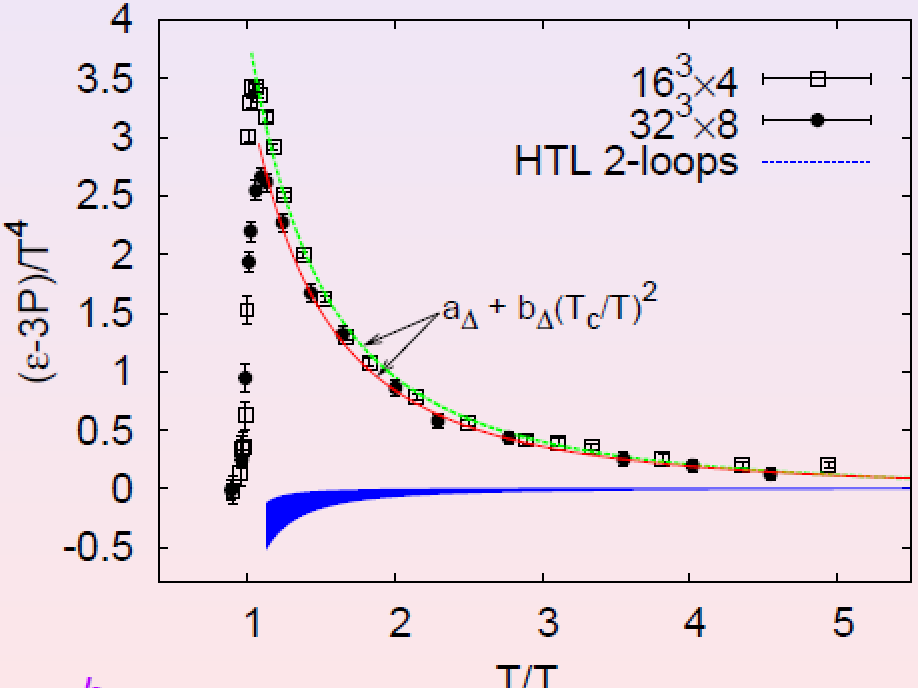


Note the magic number for the latent heat

Panero and Megias observed not yet understood 1/T^2 behviour

Trace Anomaly $N_c = 3, N_f = 0$

G. Boyd et al., Nucl. Phys. B469, 419 (1996).



$$\frac{\epsilon - 3P}{T^4} = a_\Delta + \frac{b_\Delta}{T^2}, \quad b_\Delta = (3.46 \pm 0.13) T_c^2, \qquad 1.13 T_c < T < 4.5 T_c .$$

Where do we see conformal invariance in experiment?

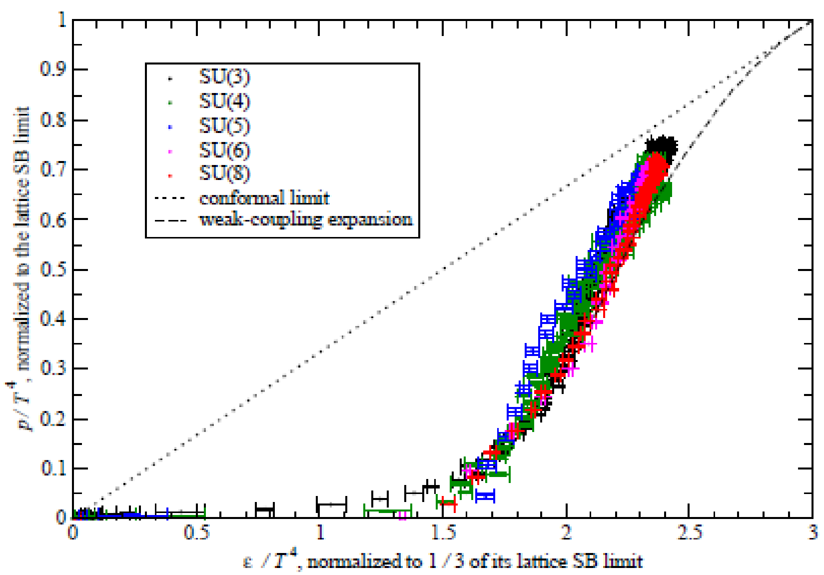
AdS/CFT *vs.* lattice data in a 'quasi-conformal' regime

T larger –equal three times T critical, but then also close to perturbation theory

For $T \simeq 3T_c$, the lattice results reveal that the deconfined plasma, while still strongly interacting and far from the Stefan-Boltzmann limit, approaches a scale-invariant regime . . .

$p(\varepsilon)$ equation of state and approach to conformality

Panero

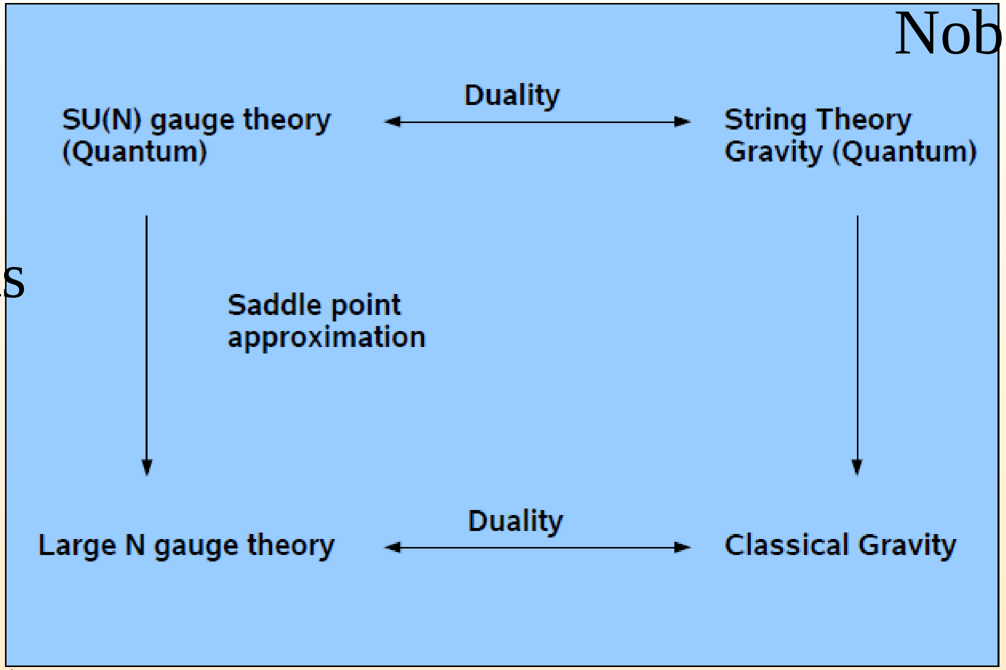


Can we see indications in the radiation pattern of partons? (Nickel)

2. D3/D7 Branes and Quarks

Nobody knows how to

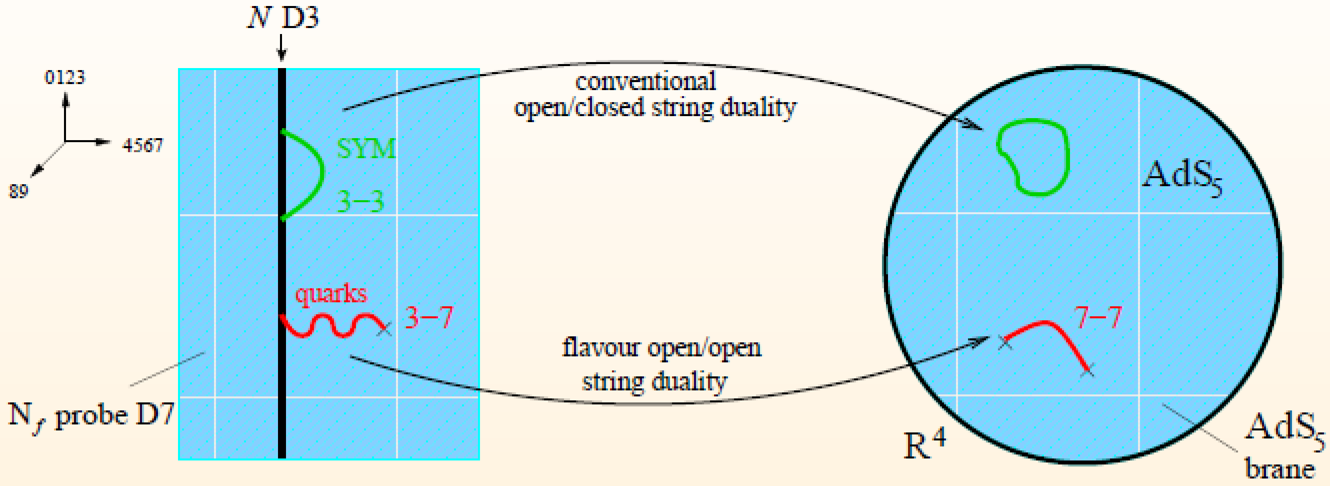
Panero showed some results without quarks



QCD(N large)

Here we can work

Quarks (fundamental fields) from brane probes



$N \to \infty$ (standard Maldacena limit), N_f small (probe approximation)

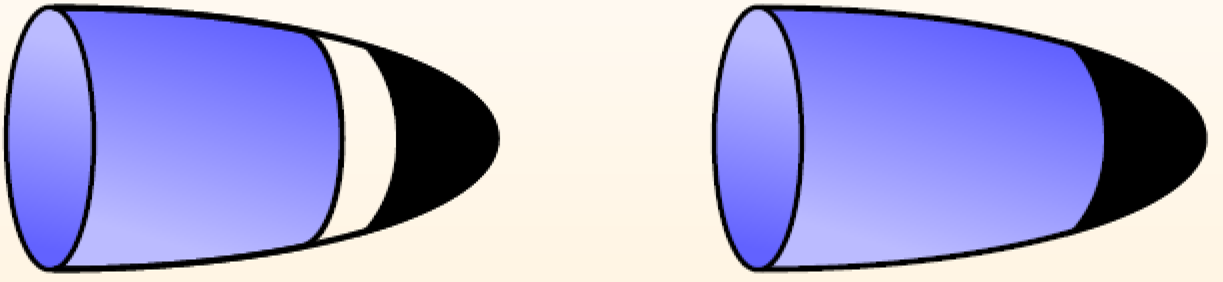
duality acts twice:

$\mathcal{N} = 4$ SU(N) Super Yang-Mills theory coupled to $\mathcal{N} = 2$ fundamental hypermultiplet	$\longleftrightarrow$	IIB supergravity on $AdS_5 \times S^5$ + Probe brane DBI on $AdS_5 \times S^3$

Karch, Katz 2002

D7 brane embedding in black hole background

When we encounter rh black hole, D7 can stop before : mq



Here we change rho^2 =w1^2+w2^2+w3^2+w4^2 UV→IR

First order phase transition

Babington, J.E., Evans, Guralnik, Kirsch
Mateos, Myers, Thomson

The magic of the many dimensions:

0 1 2 3   4 5 6 7 8 9 = 10 dimensions

x x x x   = where we live (D3)

q q q q   q q q q   =where the quarks are hooked onto (D7)

w1 to w6 with polar coordinate rho

Finite baryon density due to U(1)

Finite $U(1)$ baryon density

Baryon density melts condensate easier than T alone

Mateos, Myers, Matsuura et al

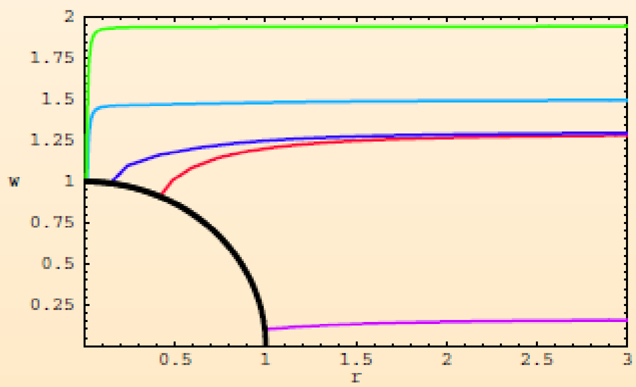
Baryon density n_B and $U(1)$ chemical potential μ
from VEV for gauge field time component:

Near the boundary Rho =infinity :

$$\bar{A}_0(\rho) \sim \mu + \frac{\tilde{d}}{\rho^2}, \qquad \tilde{d} = \frac{2^{5/2}}{N_f \sqrt{\lambda} T^3} n_B$$

At finite baryon density, all embeddings are black hole embeddings

Condensate/rho^2



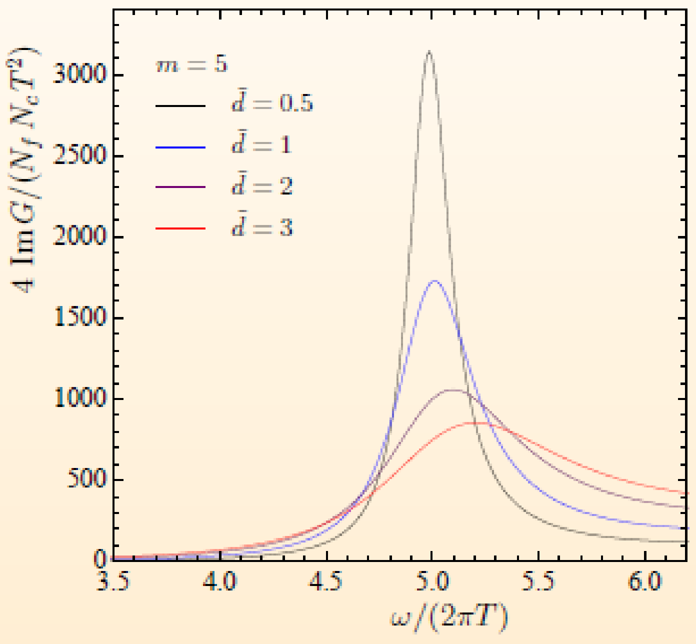
Fixed quark mass/T

Would expect two parameters ?

Spectral function of vector meson

Parameter d = baryondensity/T^3

- Vector meson which couples to baryonic current = omega meson, has no width in vacuum, because correlated two pion=rho +one pion decay is suppressed
- In medium with finiteT not seen yet

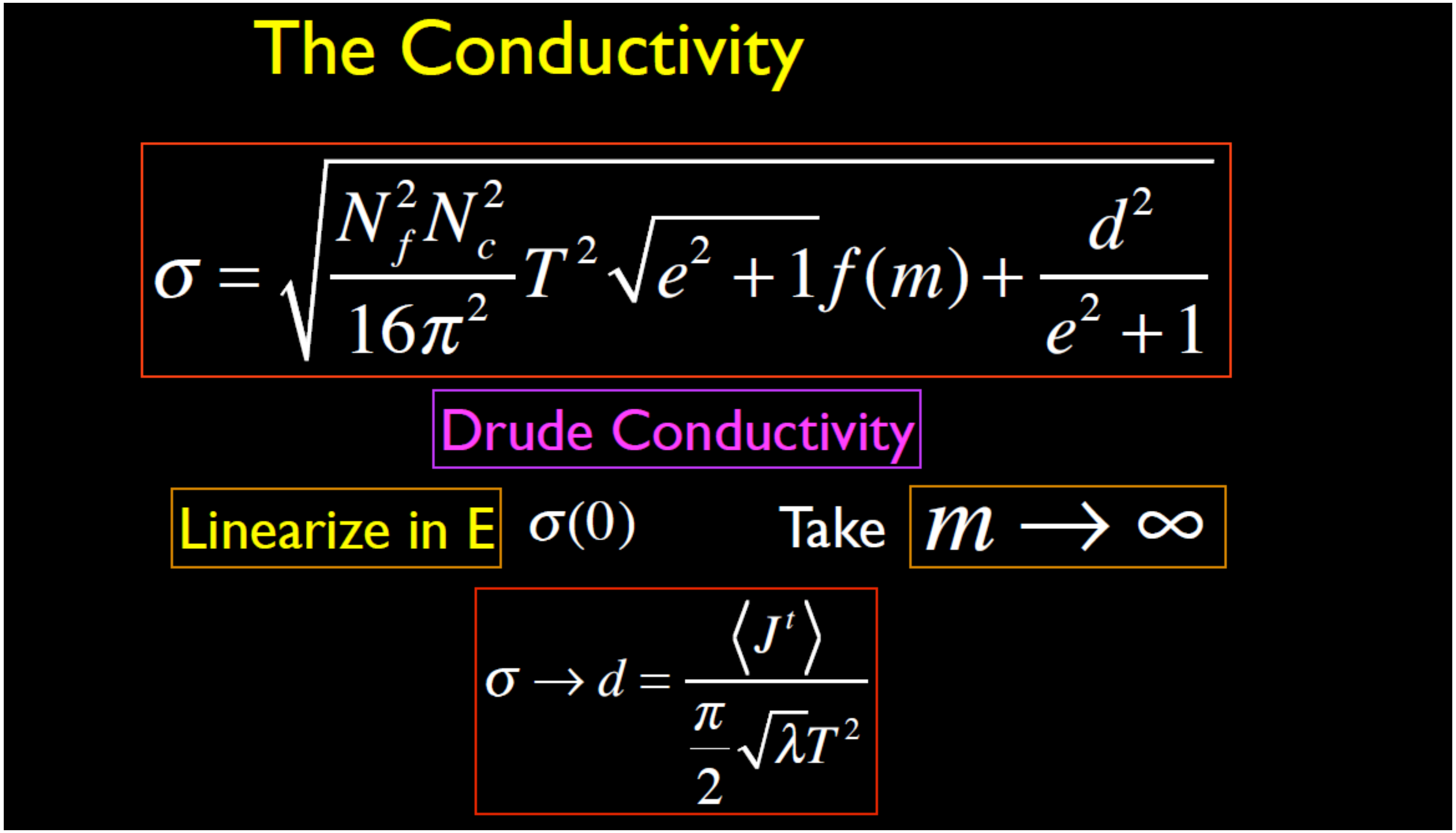


AdS/CFT result

(J.E., Kaminski, Kerner, Rust 2008)

Conformal y and x axis scales with T

O‘Bannons interesting result about conductivity :



3. Emergence of new physics

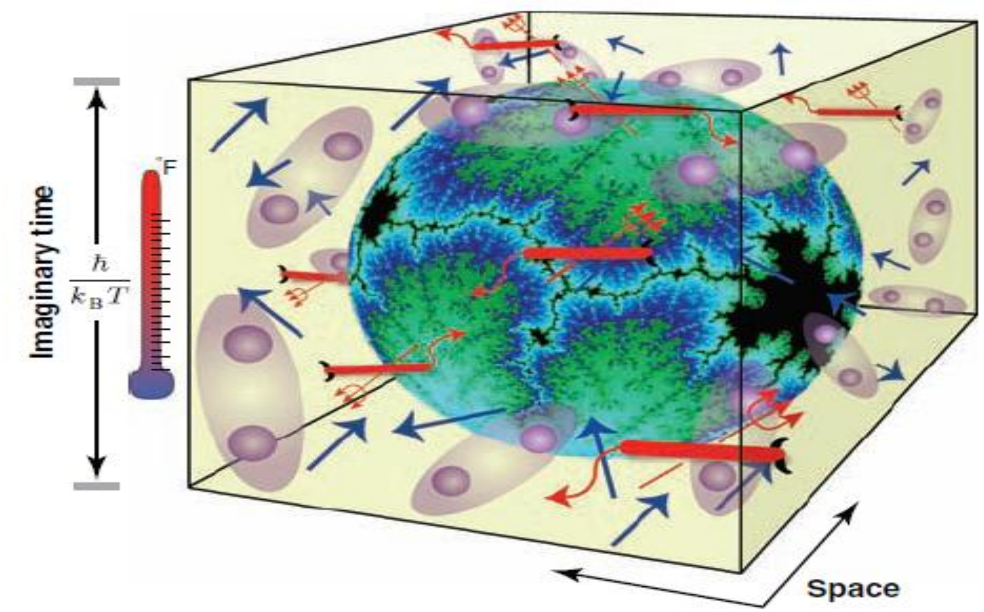


Fig. 1. Illustrating the Feynman path integral, the mathematical tool of choice to address emergence phenomena in many-particle quantum systems (*2*). Near a quantum phase transition, the world inside space-time turns scale-variant at shorter scales, like the Julia set of this cartoon, whereas at larger scales a stable form of quantum matter takes over. Dealing with fermions, the devilish minus signs obscure, however, any detailed understanding of these space-time worlds. The duration of imaginary time is determined by $\hbar$ (Planck's constant divided by 2π) and the product of Boltzmann's constant k_B and absolute temperature T.

Zaanen:
The devilish minus sign for Fermions,
Conformality in Viscosity/éntropy
Quantum critical systems

Emergence of the fermi-liquid

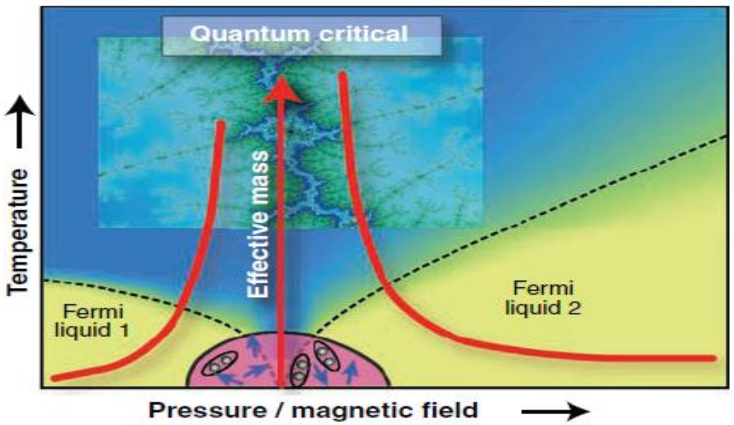


Fig. 2. Typical phase diagram observed in the heavy-fermion metals in the proximity of a quantum phase transition (*3–6*). The thermal phase transition to a magnetic state is driven to zero temperature by varying a magnetic field or pressure, and this is the anchor point of a regime of finite-temperature quantum critical fluid behavior fanning out for increasing temperature. The fermionic weirdness manifests itself through the effective mass of the quasi-electrons in the Fermi liquids on both sides, which increases without bound approaching the quantum phase transition. Invariably one finds that at a low temperature, an exotic superconductor (or even a quantum liquid crystal state) takes over at the last minute.

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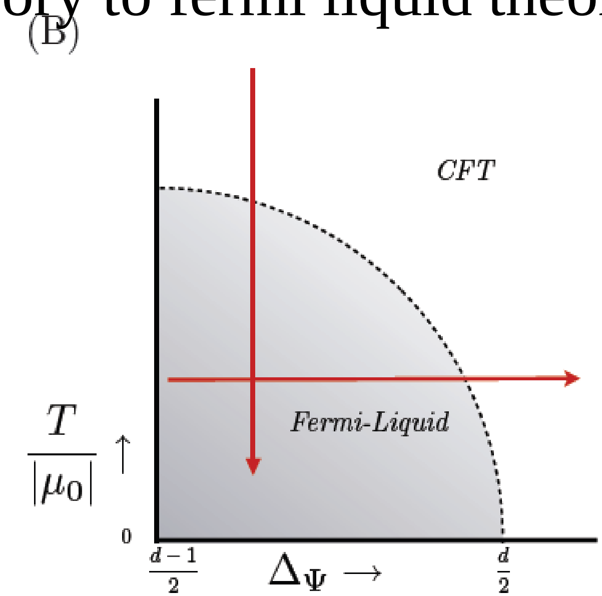
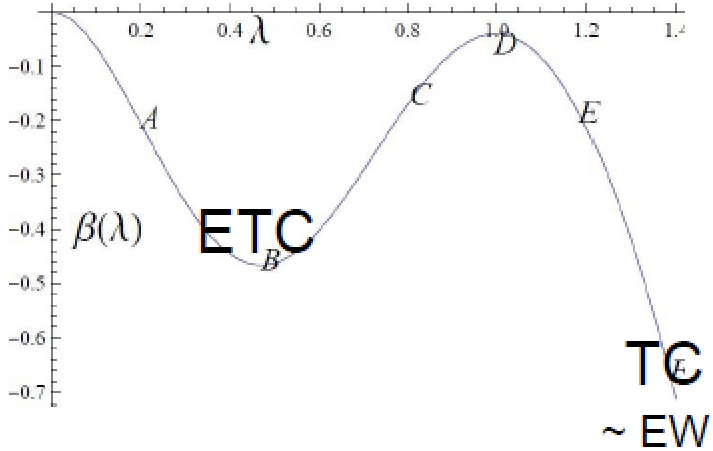
AdS4- Calculation of transition from conformal theory to fermi liquid theory



Cubrovicz, Zaanen, Schalm

8.2 Walking technicolor:



TC ~ 246 GeV
ETC ~ 1000 TC

To get big top quark mass while avoiding strangeness changing neutral currents the techniquark condensate must vary a lot:

$$\langle \bar{Q}Q(\mathrm{ETC})\rangle = \exp\left(\int_{\mathrm{TC}}^{\mathrm{ETC}} \frac{d\mu}{\mu}\gamma(g^2(\mu))\right)\langle \bar{Q}Q(\mathrm{TC})\rangle$$

$$[\log(\mathrm{ETC}/\mathrm{TC})]^{\mathrm{const}}$$ coupling runs

$$(\mathrm{ETC}/\mathrm{TC})^{\gamma(g_*^2)}$$ coupling walks

Technicolor/Gravity now gives thermodynamics – in terms of unknown parameters !

Alanen-Kajantie-Tuominen

We have learned the great potential of the new technique of the string/gravity dual theory.
With this optimism in a bright future , I close the workshop.

Let me thank all participants for their active and lively discussions and presentations,
And we hope to see you soon again in Heidelberg
And/or and in the extreme matter institute .