Recent Applications of the Gauge/Gravity Correspondence to QCD and Condensed Matter Physics.

Andreas Karch (University of Washington, Seattle)

(talk at STRINGS 2012, Munich, 7/23/12)

Goal:

Why do people outside the string theory community care about the gauge/gravity correspondence = holography?

Holography = Solvable Toy Model

Solvable models of strong coupling dynamics.

- Study Transport, real time
- Study Finite Density

Common Theme: Experimentally relevant, calculations impossible.

Gives us qualitative guidance/intuition.

Challenge for Computers:

We do have methods for strong coupling:

e.g. Lattice QCD

But: typically relies on importance sampling.

Monte-Carlo techniques.

e^{-S} weighting in Euclidean path integral.

FAILS FOR DYNAMIC PROCESSES OR AT FINITE DENSITY (sign problem)

Holographic Toy models.

Can we at least get a qualitative understanding of what dynamics look like at strong coupling?

Holographic Toy models.

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Holographic Theories:

Examples known:

- in d=1, 2, 3, 4, 5, 6 space-time dimensions
- with or without super-symmetry
- conformal or confining
- with or without chiral symmetry breaking
- with finite temperature and density

Holographic Theories:

Holographic toy models have two key properties:

"Large N": theory is essentially classical

"Large λ": large separation of scales in the spectrum

$$m_{\text{spin-2-meson}} \sim \lambda^{1/4}\ m_{\text{spin-1-meson}}$$

QCD: **1275 MeV** **775 MeV**

(note: there are some exotic examples where the same parameter N controls both, classicality and separation of scales in spectrum)

Applications to QCD Transport.

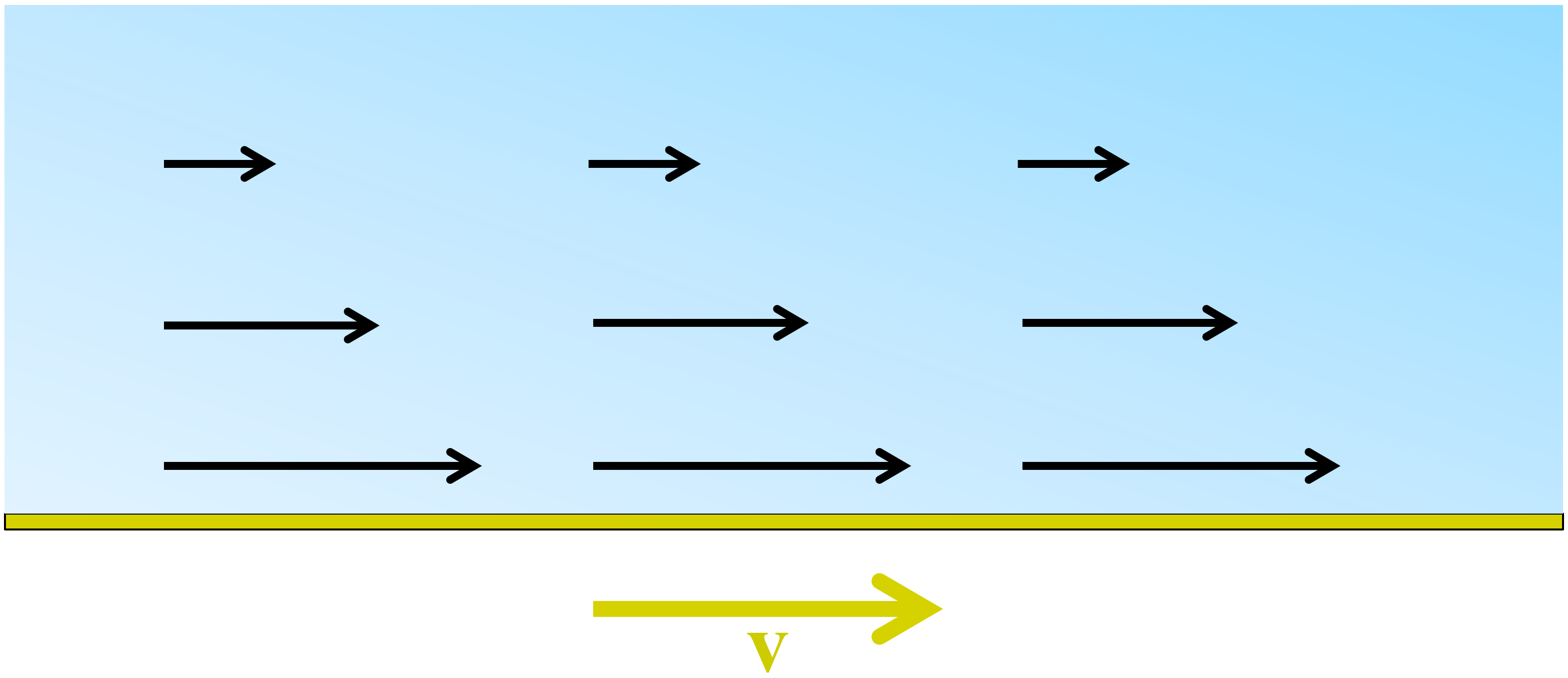
Applications to QCD Transport

(as experimentally probed in Heavy Ion Collisions)

- Viscosity and Hydrodynamics
- Energy Loss
- Thermalization

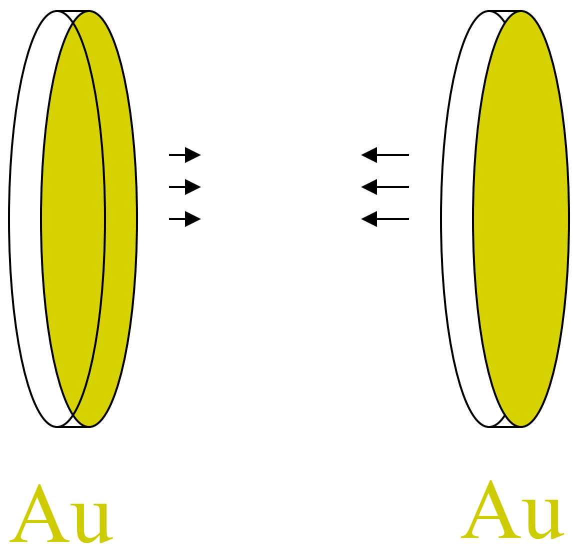
Shear Viscosity

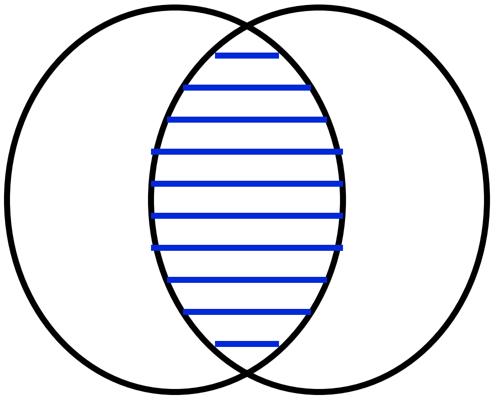
Viscosity = Diffusion constant for momentum



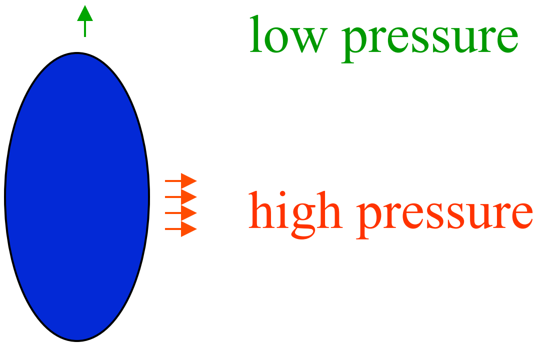
Viscosity = [(force/area)] per unit velocity gradient

Viscosity in Heavy Ions.





How does the almond shaped fluid expand?



Viscosity

Viscosity can be quantified:

water: 1 centipoise (cp)
air: 0.02 cp
honey: 2000-10000 cp

(1 cp = 10^{-2} P = 10^{-3} Pa·s)

Measuring Viscosity - an example

Pitch drop experiment

Started in 1930

8 drops fell so far

but no one has ever witnessed a drop fall

2005 Ig Nobel Prize in Physics

Viscosity of pitch: 230 billions times that of water

(2.3 10^{11}cp)

Measuring Viscosity - an example

Recall: Viscosity of pitch: ~ 2.3 10^{11}cp

Measuring Viscosity - an example

Recall: Viscosity of pitch: ~ 2.3 10^{11}cp

RHIC's measurement of QGP (confirmed by LHC):

$$\eta \sim \frac{\hbar}{4\pi} s \sim \frac{10^{-27}\text{erg}\cdot\text{s}}{(10^{-13}\text{cm})^3} \sim 10^{14}\text{cp}$$

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BNL press release 2005:

"The degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being form at RHIC makes this the most nearly perfect liquid ever observed."

Viscosity in Holography:

In a large class of systems:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

(Kovtun, Son, Starinets)

- pinpoints correct observable
- in contrast to QGP, η/s enormous for pitch
- gives ball-park figure
- large at weak coupling: bound?

Viscosity – Recent Developments

Not a bound! (Kats, Petrov, 2007)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 - \frac{1}{2N}\right)$$

$\mathcal{N} = 2$ Sp(N)
4 fundamental
1 antisymmetric traceless

Higher Curvature corrections violate bound.

(Brigante, Liu, Myers, Shenker, Yaida, Buchel, Sinha, ….)

Calculations only reliable if violations are small.

Hydro – Recent Developments

Viscosity is not the only hydro transport coefficient that can be calculated holographically.

- 2^{nd} order hydro
  - Calculated in 2007 (Romatschke et. al., Batthacharyya et. al.)
  - Needed for stable hydro simulation (causality!)
  - Holographic values/structure routinely used
- anomalous transport

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}\left[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}\right]$$

Anomalous Transport in Hydro

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$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

J: conserved current

1) Baryon Number or

2) Electric Charge

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

B: magnetic field
"Chiral Magnetic Effect"

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

ω: vorticity (= curl of velocity)
"Chiral Vortical Effect"

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

axial chemical potential
(requires non-zero axial charge)

$$\langle \mu_5 \rangle = 0$$

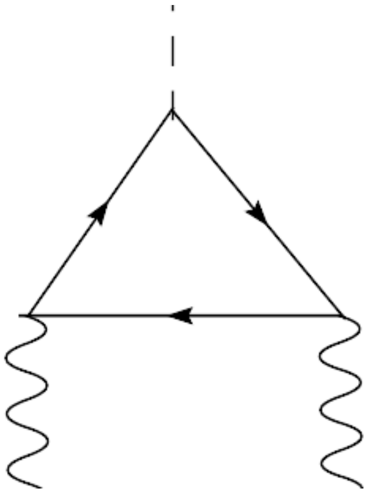
$$\langle {\mu_5}^2 \rangle \neq 0$$

relies on event
by event fluctuations

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$



Coefficients determined by anomaly!

Relative size of baryon versus charge asymmetry unambiguous.

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

$$J_E^{CME} \sim \frac{2}{3} \quad (N_f = 3) \quad \text{or} \quad \frac{5}{9} \quad (N_f = 2)$$

$$J_B^{CME} = 0 \quad (N_f = 3) \quad \text{or} \quad \sim \frac{1}{9} \quad (N_f = 2).$$

$$J_E^{CVE} = 0 \quad (N_f = 3) \quad \text{or} \quad \sim \frac{1}{3} \quad (N_f = 2);$$

$$J_B^{CVE} \sim 1 \quad (N_f = 3) \quad \text{or} \quad \sim \frac{2}{3} \quad (N_f = 2).$$

Predictions (Kharzeev and Son)

- There should be a baryon number separation of the same sign as the electric charge separation;
- The ratio between the baryon asymmetry and charge asymmetry should increase as the center of mass energy is lowered;
- The magnitude of the ratio of charge and baryon asymmetries allows to discriminate between the CME and CVE mechanisms.

Anomaly and the CVE

connection between CME and anomaly was quantitatively understood before (Kharzeev, …)

How does the anomaly know about vorticity?

(Erdmenger, Haack, Kaminski, Yarom;
Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka)

In holographic models CVE completely determined in terms of

Chern-Simons term = anomaly.

Anomaly and the CVE

How does the anomaly know about vorticity?

Son, Surowka: True in general.

axial anomaly in background electromagnetic fields

+

entropy current with non-negative divergence

= CVE

Beyond the Entropy Current

(Jensen, Kaminski, Kovtun, Meyer, Ritz, Yarom;
Banerjee, Bhattacharya, Bhattacharyya, Minwalla, Sharma)

Idea: "Static Configuration" should exist in "non-trivial backgrounds".

Beyond the Entropy Current

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Idea: Static Configuration should exist in non-trivial backgrounds.

Metric with timelike Killing Vector

$$ds^2 = -e^{2\sigma(\vec{x})}\left(dt + a_i(\vec{x})dx^i\right)^2 + g_{ij}(\vec{x})dx^i dx^j$$

$$\mathcal{A}^\mu = (A^0(\vec{x}), A^i(\vec{x}))$$

Beyond the Entropy Current

Can be described by Euclidean Generating Functional

Idea: Static Configuration should exist in non-trivial backgrounds.

Metric with timelike Killing Vector

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$$\mathcal{A}^\mu = (A^0(\vec{x}), \mathcal{A}^i(\vec{x}))$$

Beyond the Entropy Current

- Reproduces Son/Surowka results for CVE
- Conjectured to be equivalent to existence of entropy current
- Equivalent to Ward identities on correlators
  (including "global" ones related to time circle) - **(Jensen)**
- Byproduct: subset of transport coefficient given by static correlation functions.

And a puzzle:

(Landsteiner, Megias, Melgar, Pena-Benitez)

$$(\sigma^{\mathcal{V}})_A = \frac{1}{8\pi^2} d_{ABC}\, \mu^B \mu^C + \frac{T^2}{24} b_A \,.$$

vortical conductivity.
A,B,C: labels axial/vector

μ_5, μ dependence of CVE

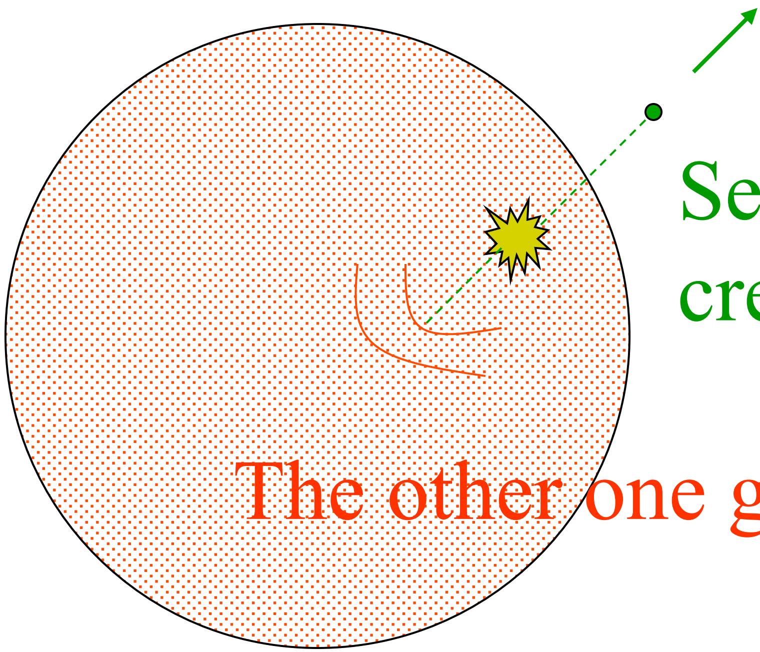
MIXED GAUGE/ GRAVITATIONAL ANOMALY

Coefficient of gravitational anomaly shows up both at weak and strong coupling. WHY?

(would give 10^4 fold enhancement of CVE at RHIC)

Energy Loss

Energy Loss in Heavy Ions.

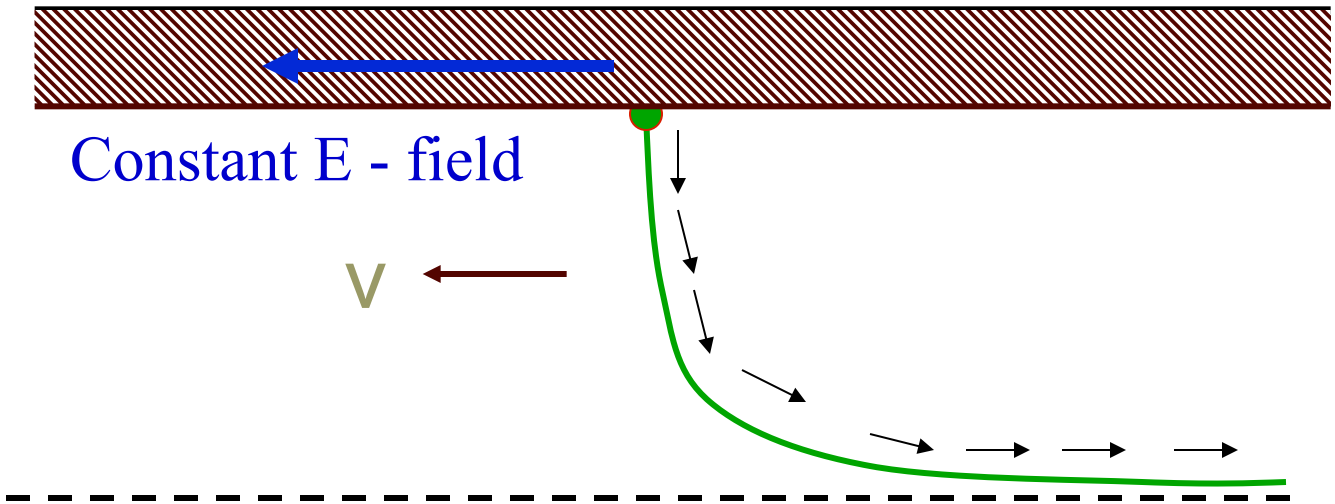


See one of two back-to-back created particles.

The other one got "stuck" in the fireball

Jet quenching is a direct indication of large drag.

Energy Loss (2006): Heavy quarks

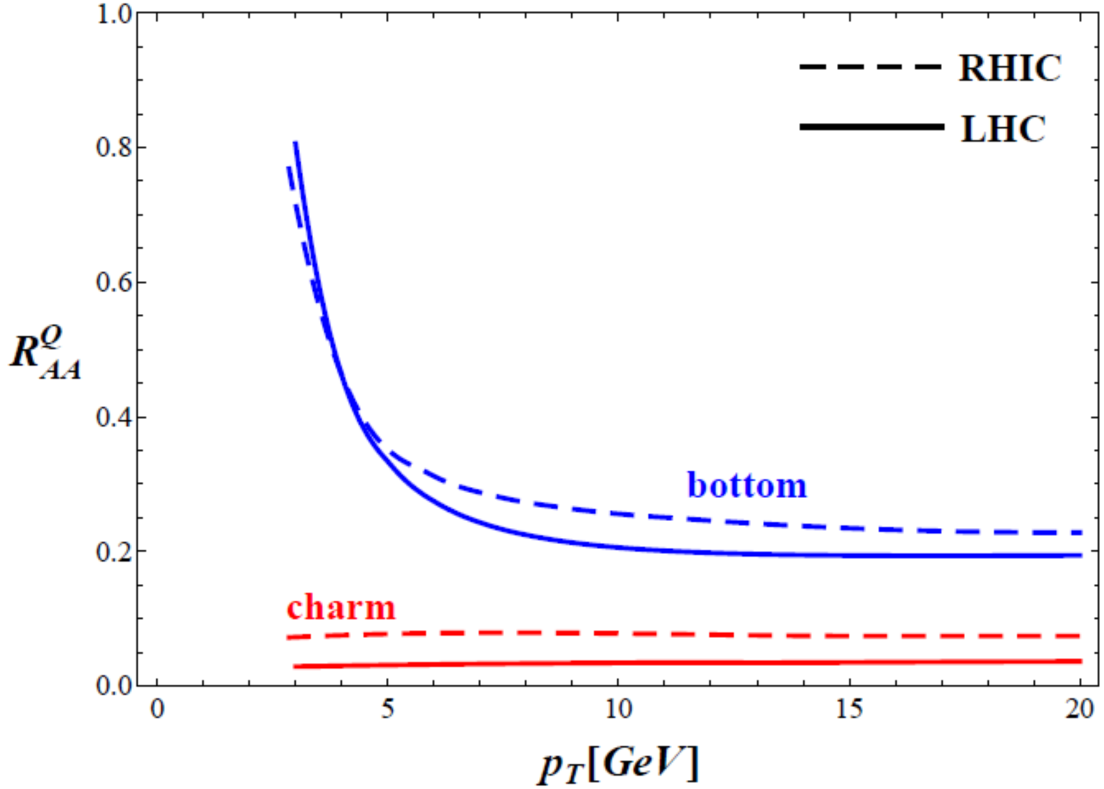


$$\frac{dp}{dt} = -\mu\, p \qquad \mu = \pi T\, \frac{\Delta m(T)}{m} \qquad \Delta m(T) \equiv \tfrac{1}{2}\sqrt{\lambda}T$$

(Casalderrey-Solana & Teaney; Herzog, AK,Kovtun,Koczkaz,Yaffe; Gubser)

Energy Loss, Recent Developments:

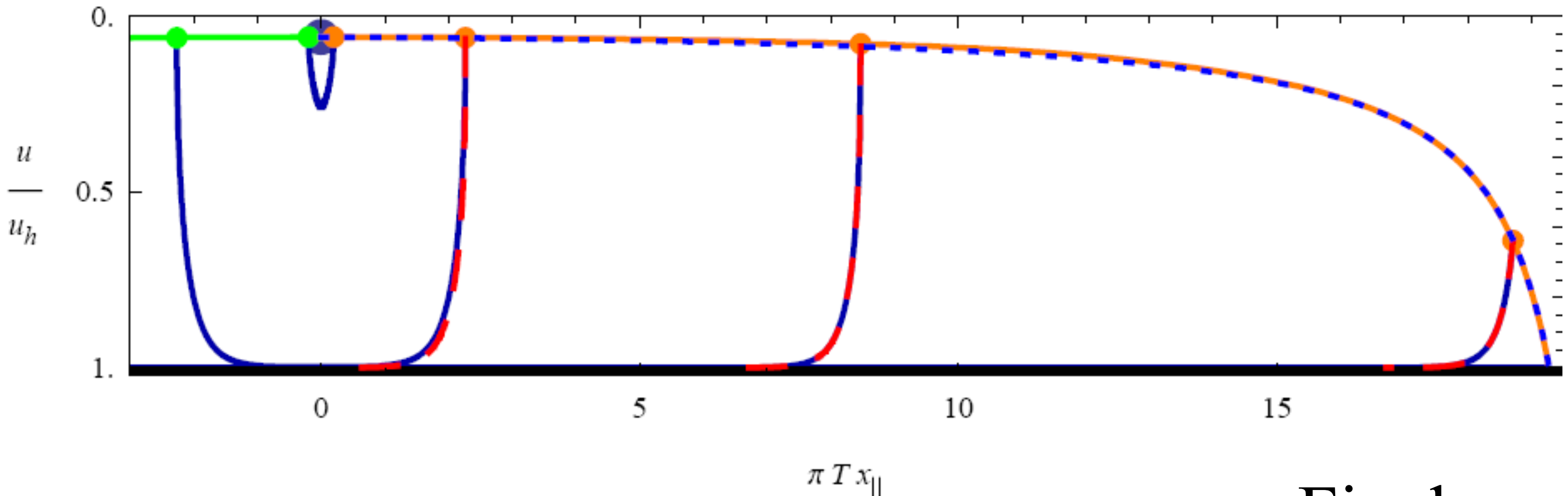
Use holographic models to make LHC "predictions":



(Ficnar, Noronha, Gyulassy)

Energy Loss, Light Quarks (2010)

(Chesler, Jensen, AK, Yaffe; Gubser, Gulotta, Pufu, Rocha)

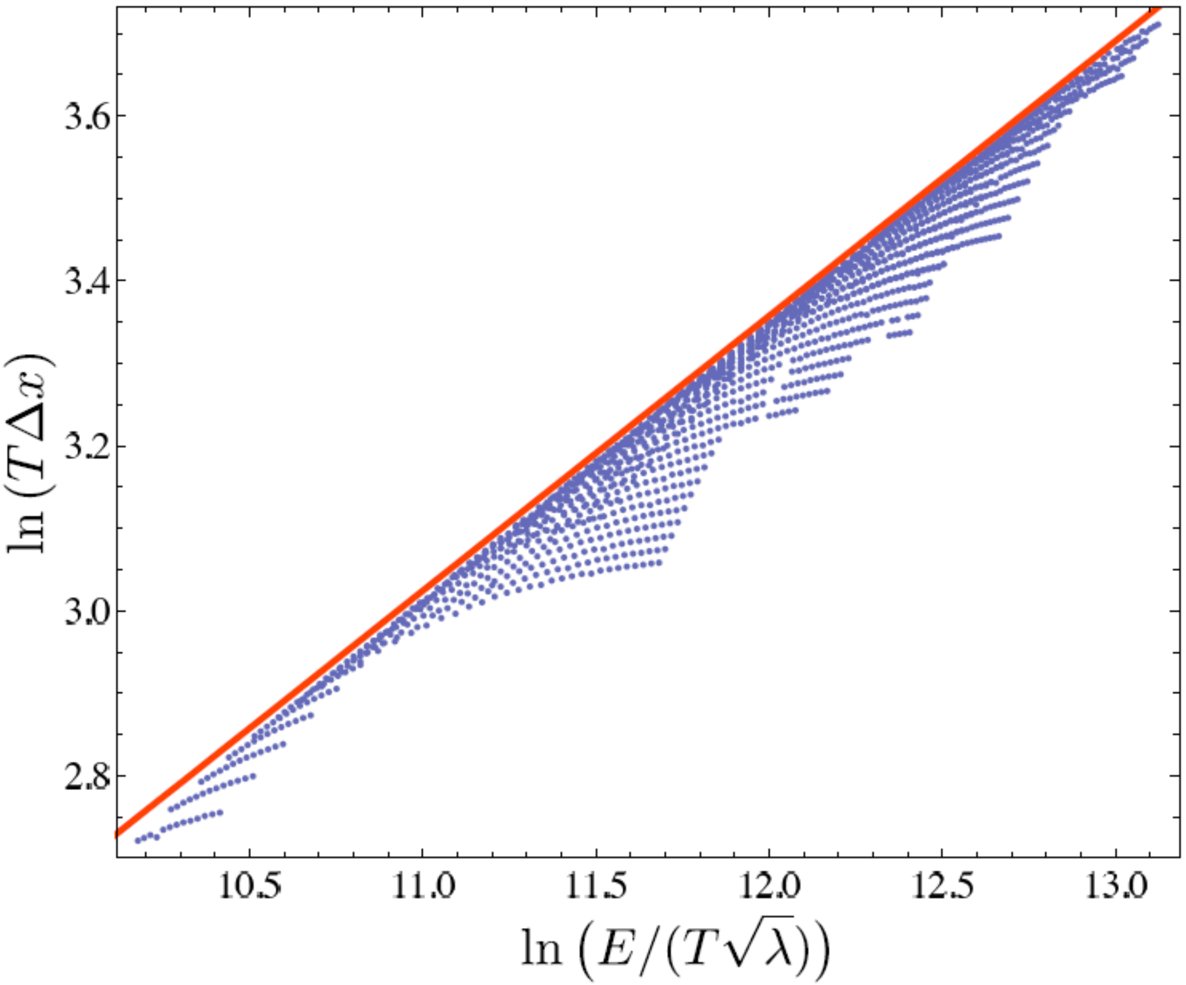


Zero T Jets

Quasiparticle in Plasma (for E >> T)

Final Diffusion

Stopping Distance vs Energy



(Chesler, Jensen, AK, Yaffe)

Stopping Distance:

Perturbative QCD: **$L \sim E^{1/2}$** (BDMPS, …)

Holography:

Maximal Stopping Distance: **$L \sim E^{1/3}$**

Typical Stopping Distance: **$L \sim E^{1/4}$**

(Arnold, Vaman - 2011)

Experiment: **?????**

Stopping Distance: **Exponents!**

Perturbative QCD: **$L \sim E^{1/2}$** (BDMPS, …)

Holography:

Maximal Stopping Distance: **$L \sim E^{1/3}$**

Typical Stopping Distance: **$L \sim E^{1/4}$**

(Arnold, Vaman - 2011)

Experiment: **?????**

Thermalization

Why does the QCD fireball thermalize so rapidly?

Thermalization

Why does the QCD fireball thermalize so rapidly?

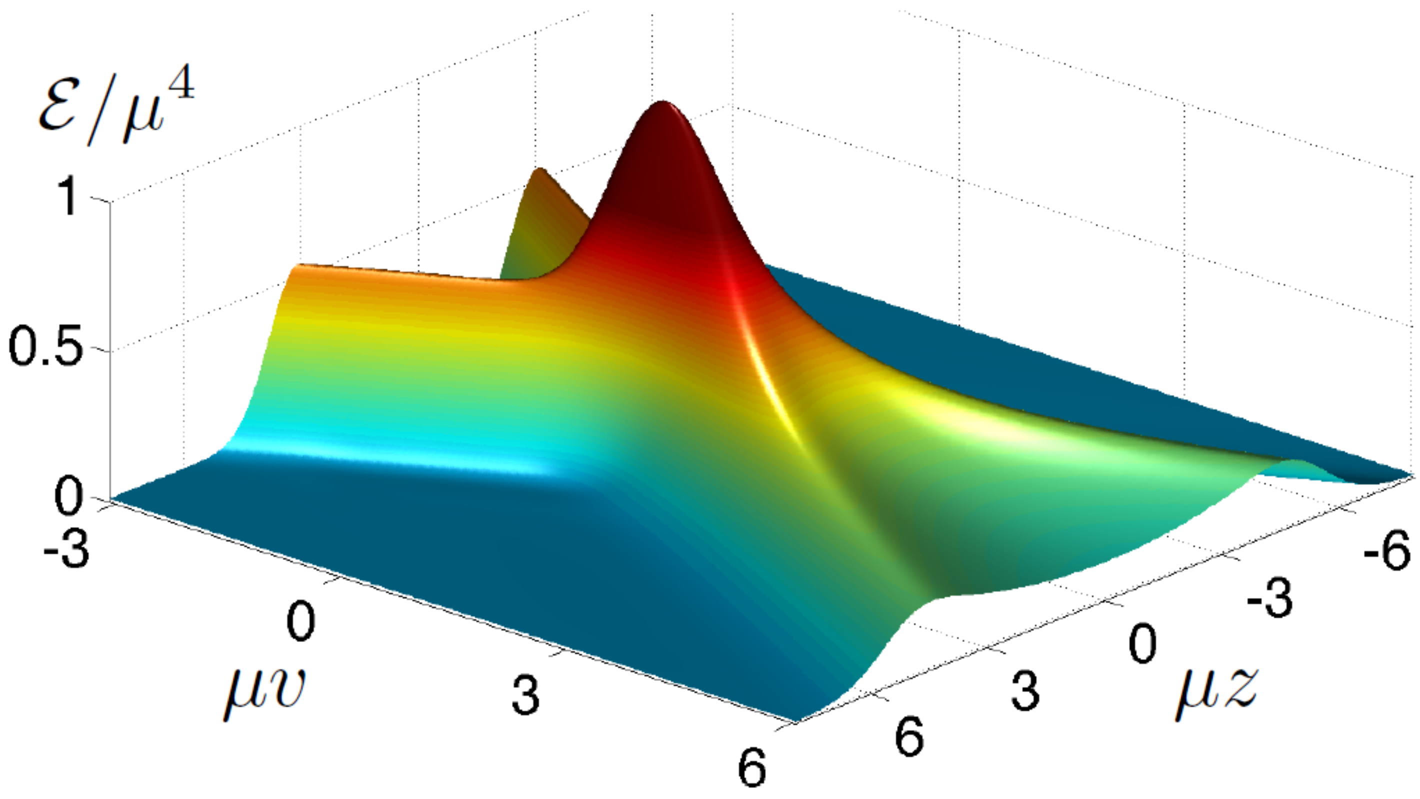
too hard!

Thermalization

How quickly does the holographic fireball thermalize?

Shockwave-collision to black hole

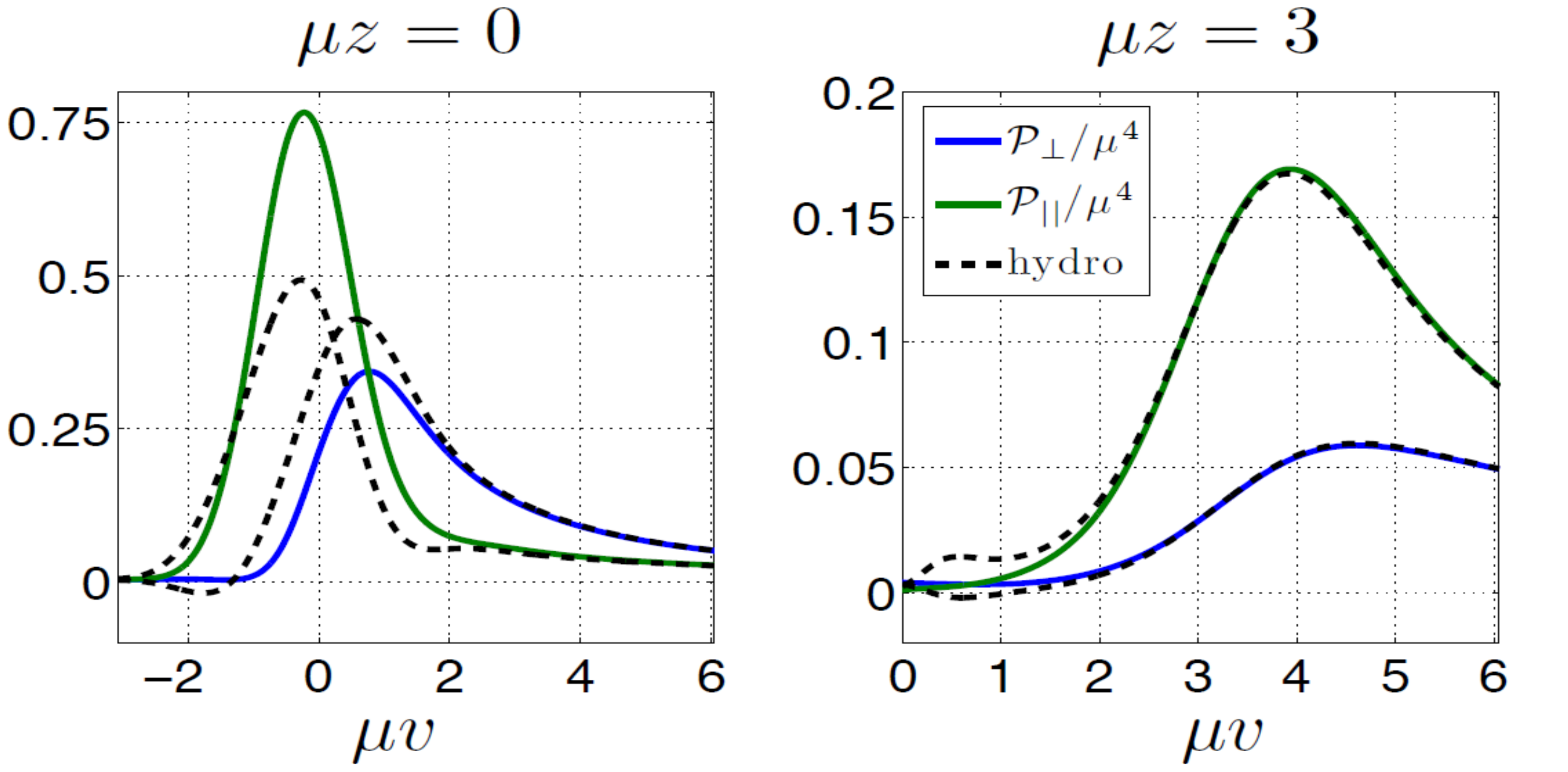
(Chesler, Yaffe)



Energy/area in shock ~ μ^3

Shockwave-collision to black hole

(Chesler, Yaffe)



Shockwave-collision to black hole

(Chesler, Yaffe)

"RHIC":

$\mu \sim 2.3$ GeV

Hydro valid ~ 0.35 fm/c << 1 fm/c

But: there is so much more info in this plot!

What do you want to know?

Hydrolization vs Thermalization

(Chesler, Teaney)

Note: Hydro works when transverse and
longitudinal pressure differ by
a factor of 2.

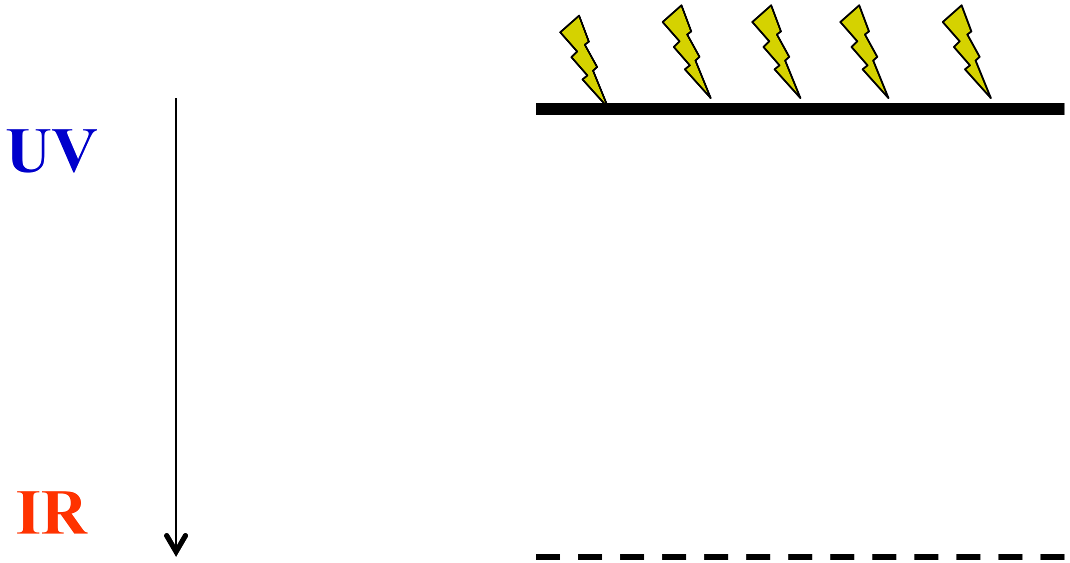
Hydrolization before Thermalization!

↑

Hydro works. **No well defined temperature.**

Hydrolization vs Thermalization

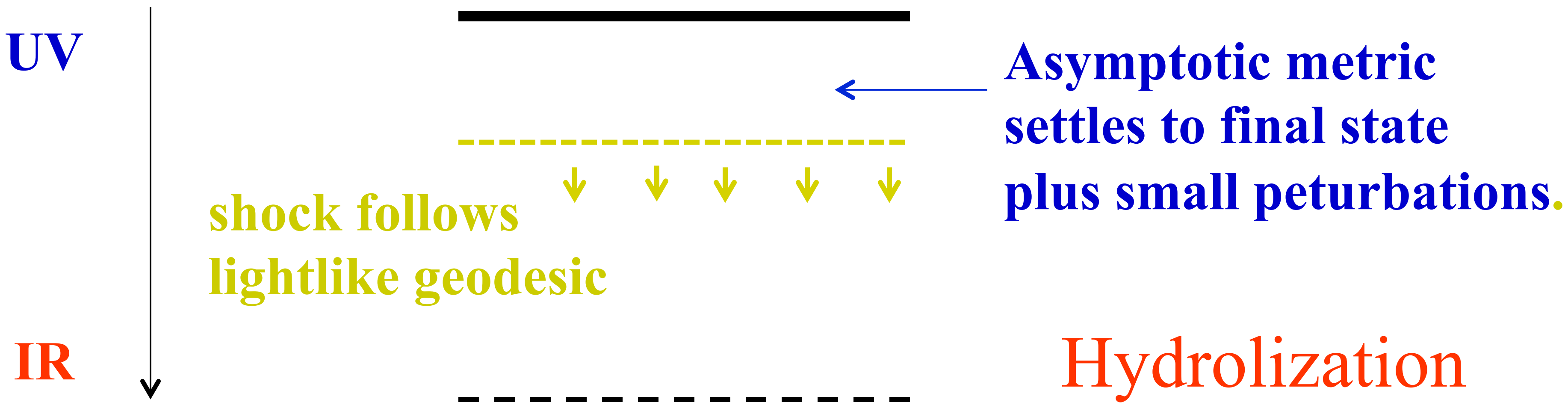
(Chesler, Teaney)



t=0
initial perturbation

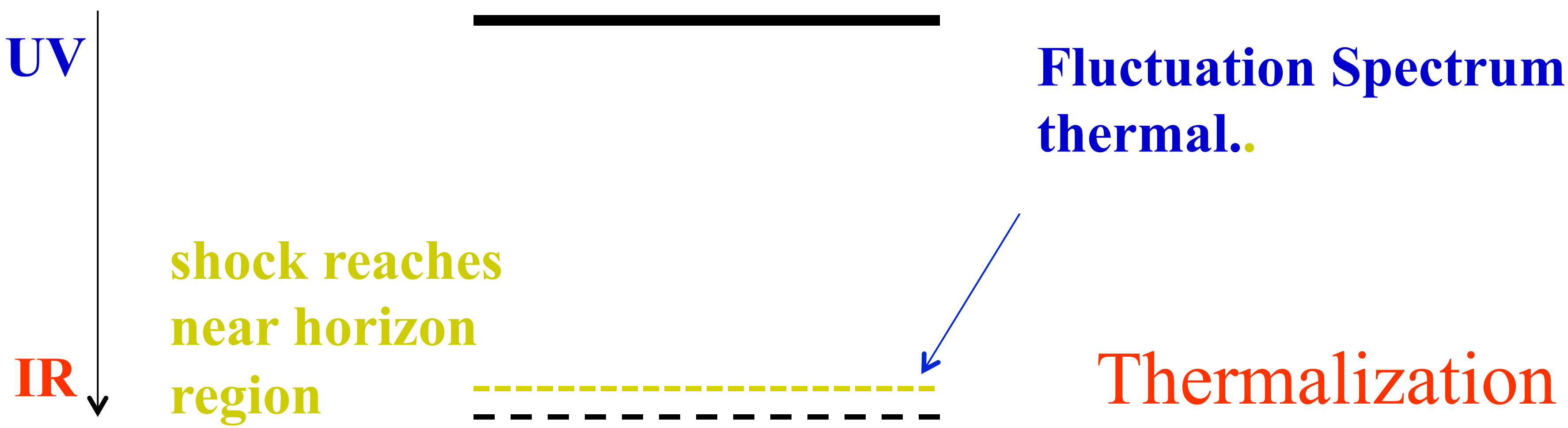
Hydrolization vs Thermalization

(Chesler, Teaney)



Hydrolization vs Thermalization

(Chesler, Teaney)



Hydrolization vs Thermalization

(Chesler, Teaney)

- Generically Hydrolization and Thermalization differ by "infall" time

- For suitable initial condition (lightlike geodesic skimming boundary) thermalization time can be **parametrically large** compared to hydrolization time.

Applications to Condensed Matter Physics.

Strong Coupling in CM.

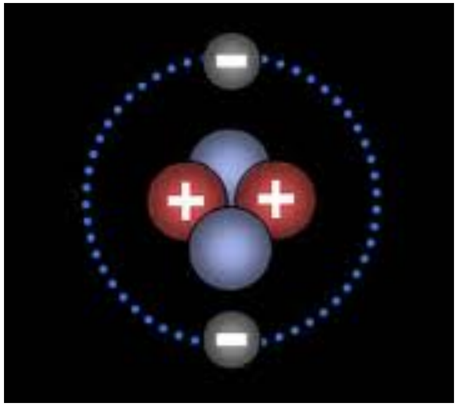
The theory of everything:

$$H = \sum_{Nuclei,A} \frac{{P_A}^2}{m_A} + \sum_{electron,i} \frac{{p_i}^2}{m_e} - \sum_{A,i} \frac{e^2}{|x_i - x_A|} + \sum_{i \neq j} \frac{e^2}{|x_i - x_j|}$$

How hard can it be?

Strong Coupling in CM

Already Helium too difficult to solve analytically.



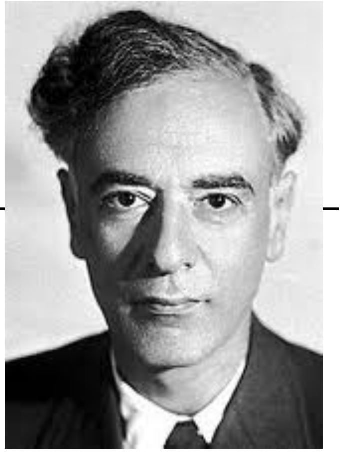
electron/electron Coulomb repulsion not weak!

if it is negligible, we have good theory control:

Band structure! Insulators and conductors.

but what to do when it is not?

Landau's paradigms:



- Identify physical candidates for low energy degrees of freedom.

  ← **dominate transport**

- Write down most general allowed interactions

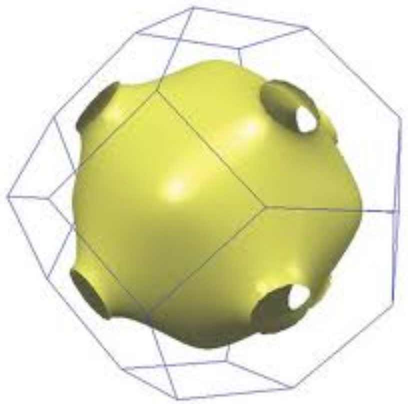
  many interactions "irrelevant" = scale to zero

  ↓

- See how interactions scale in low energy limit

What could they be?

1) weakly coupled fermions.



Landau Fermi Liquid

- Fermi Surface
- Low energy excitations near Fermi Surface
- Only Cooper Pair Instability survives at low energies, all other interactions scale to zero

at low temperatures resistivity grows as T^2

← **universal!**

What could they be?

1) weakly coupled bosons.

Landau's Theory of Phase Transitions

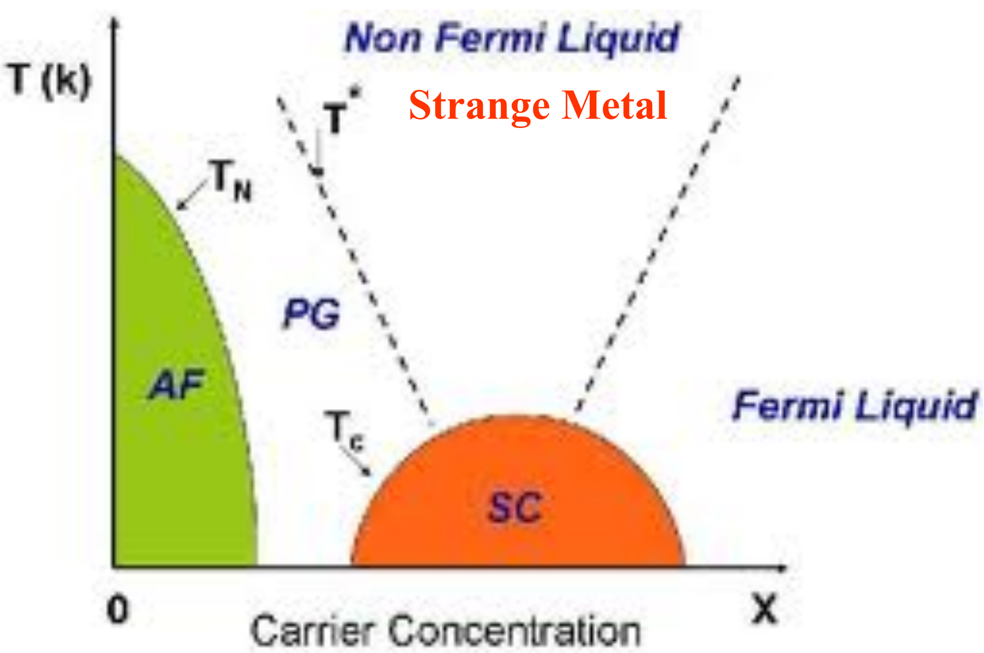
$$G(m,T) = \frac{b_0}{2}(T - T_c)m^2 + \frac{c}{4}m^4 + \frac{d}{6}m^6 + \cdots .$$

free energy

order parameter = scalar field.

Scalar mass relevant; dominates at low energies. Can be tuned to zero close to a phase transition.

Is this all?



Degrees of freedom in high Tc superconductors are neither!

Non-Fermi Liquid

at low temperatures resistivity grows as T

What else could it be?

This is the perfect question to ask a solvable toy model:

Studying matter in holographic toy models, what are the possible low energy behaviors?

Matter=finite density of some conserved charge.

MIT/Leiden Fermions.

(Lee)
(Liu, McGreevy, Vegh)
(Cubrovic, Zaanen, Schalm)

Holographic Realization of a large class of non-Fermi Liquids.

Fermions in a charged black hole background.

MIT/Leiden Fermions.

Characteristic Features:

Fermi surface

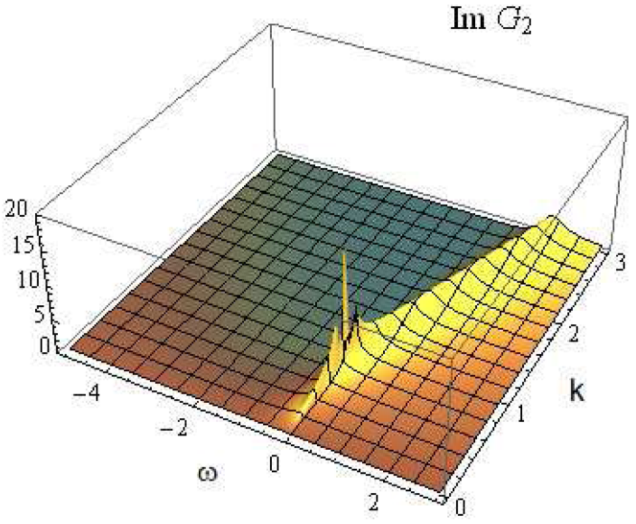
(singularity in wavevector dependence of correlation functions).

No well defined particle excitation.

(not a Fermi-liquid).

Low temperature resistivity grows as $T^{2\Delta-1}$

(Δ free parameter in model).



Interactions don't scale away?

Fermi-surface, but interactions not irrelevant?

Low energy physics = fermions coupled to other light degrees of freedom!

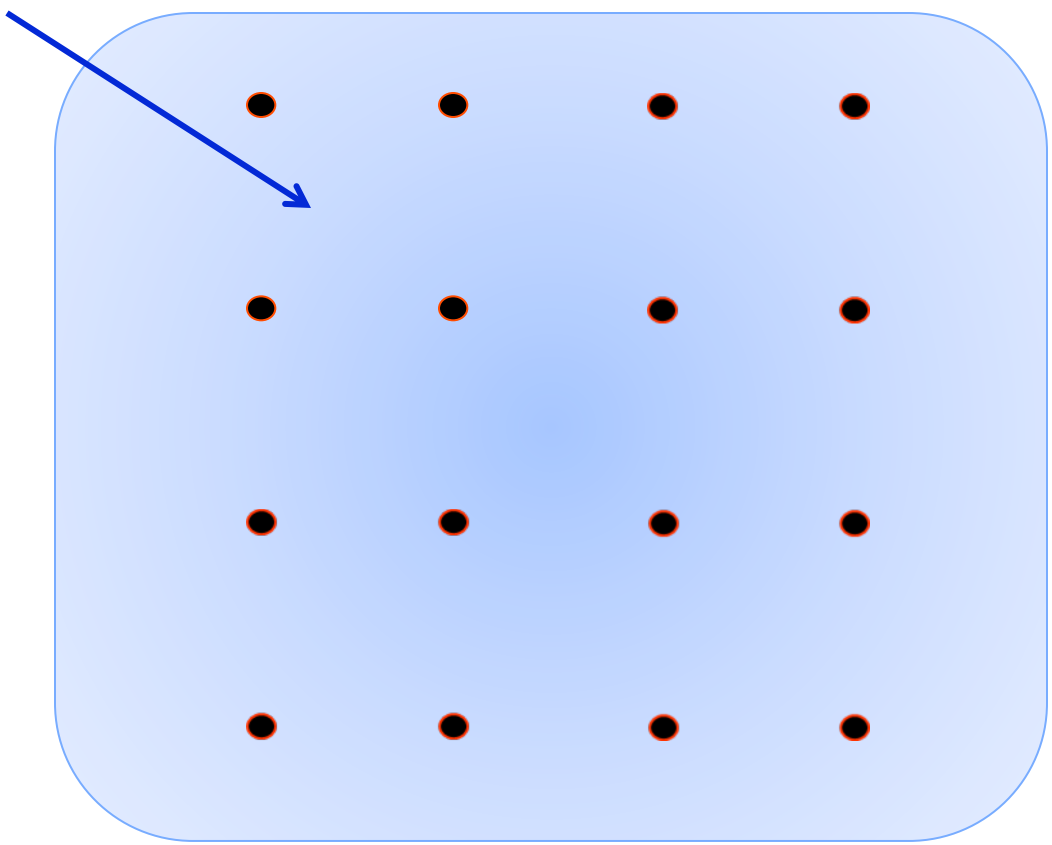
Local Quantum Criticality.
0+1 dimensional theories close to a Landau-like phase transition.

$$= \mathbf{AdS_2}$$

Local Criticality:

Lattice Kondo model

bulk fermions



Lattice of localized defects.

$$H_J = \sum_{i<j} J_{ij} \hat{S}_i^a \, \hat{S}_j^a + \dots$$

$\downarrow$

Quantum Critical Point.

Lattice Kondo model.

CM model for strange metal (heavy fermions)

Supersymmetric Lattice Kondo model gives particularly nice realization of MIT fermions

(Kachru, AK, Yaida)

(Kachru, AK, Polchinski, Silverstein)

- **Explicit Lagrangian of Field Theory is known.**
- **Δ=1 (resistivity as T) arises naturally.**

Instabilities

It is perhaps fortunate, therefore, that low temperature charged AdS black holes are found to be unstable towards a range of processes that discharge the black hole and can lead to spacetimes without black hole horizons. The instabilities include condensation of charged scalar fields [26], Cooper pairing of charged fermions [27], emission of D branes [28, 29, 14], backreaction of a bulk fermionic charge density induced by the local chemical potential [14], confinement [30, 31, 32], and perhaps the emergence of underlying lattice degrees of freedom [33]. It is not clear at this stage whether all zero temperature charged AdS black holes with a finite size horizon are unstable [34]. If they are, this fact may be closely tied up with a version of the 'weak gravity' conjecture [35]. The instabilities lead to

(from Hartnoll and Tavanfar)

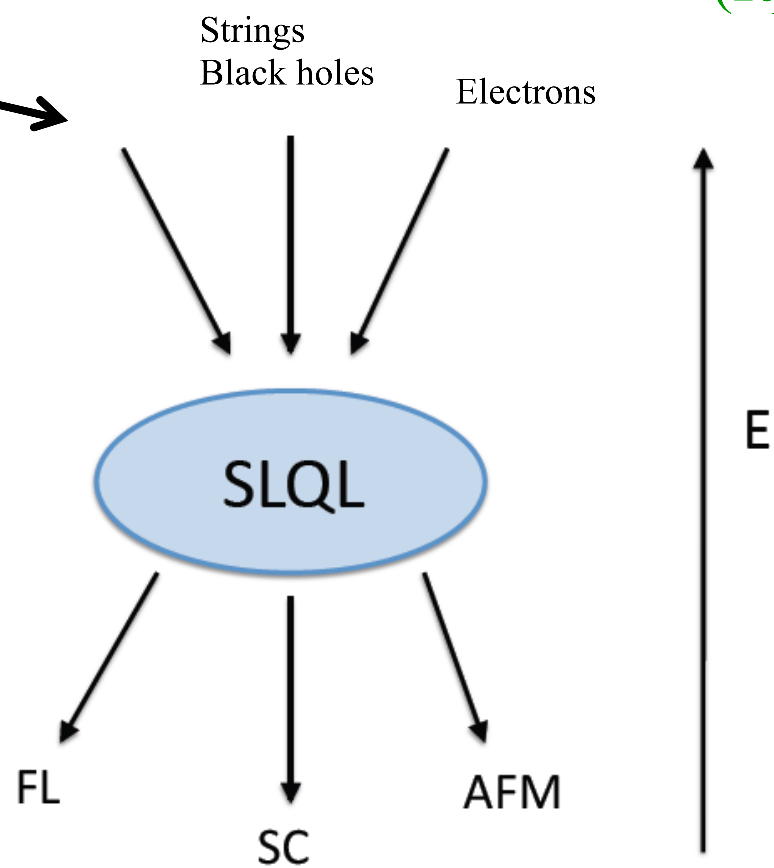
Universal Intermediate Phase

(Iqbal, Liu, Mezei)

UV Physics

MIT/Leiden fermions

The various deep IR phases.

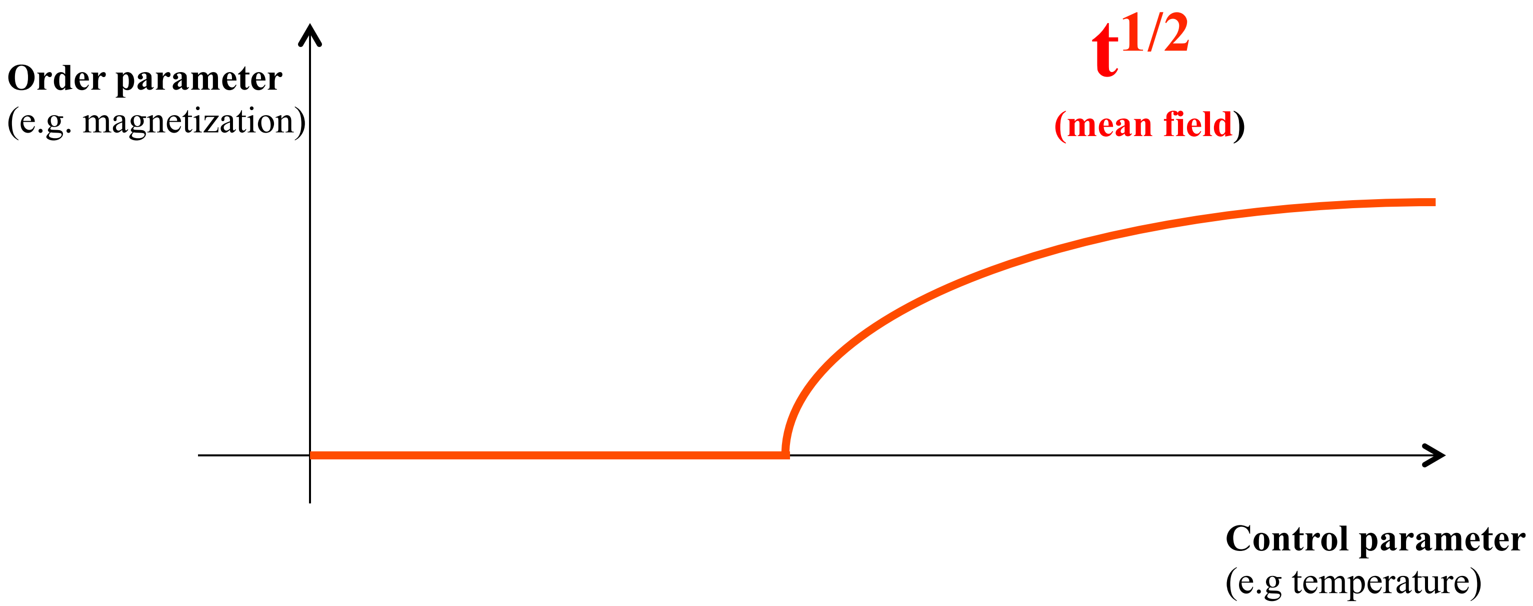


Local Criticality and Bosons

MIT fermions = Local criticality + Landau fermions

????? = Local criticality + Light Scalar

Phase transitions beyond Landau



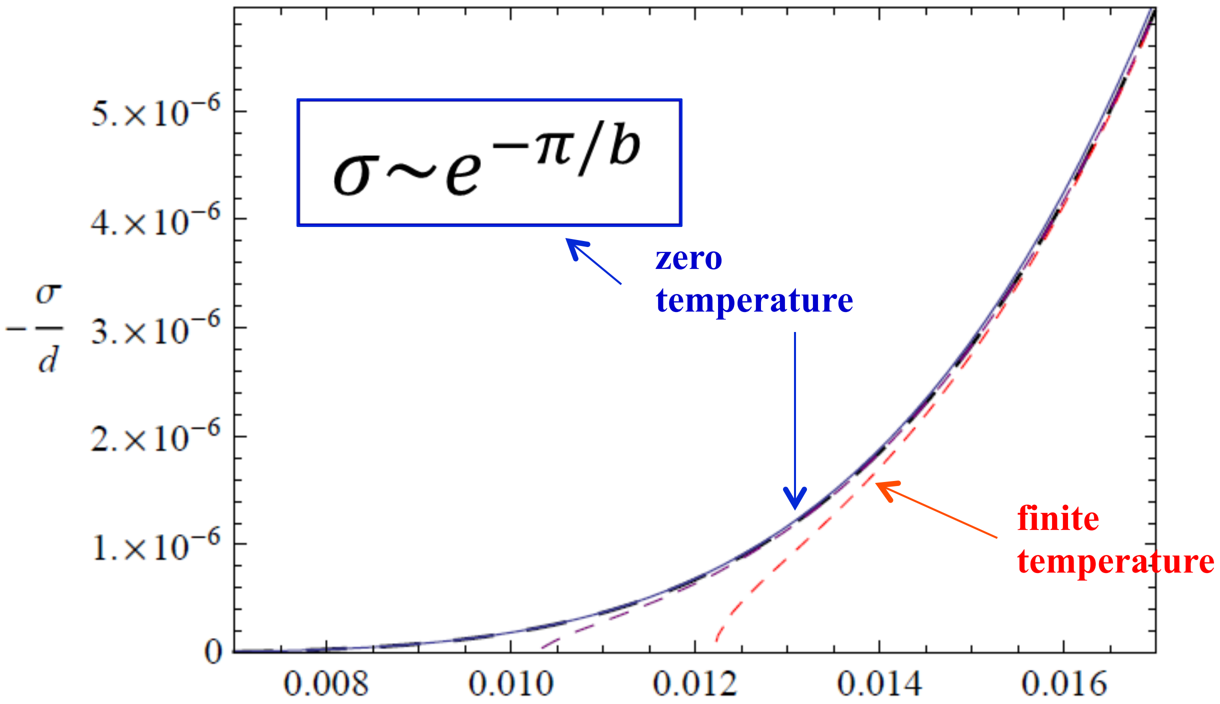
Landau phase transitions:

- **Power Laws**
- **Critical Exponents**

Phase transitions beyond Landau

(Jensen, AK, Son, Thompson; Iqbal, Liu, Mezei, Si)

Order parameter
(e.g. magnetization)



Control parameter
(e.g. magnetic field)

b = $\frac{B}{\rho} - \frac{1}{\sqrt{7}}$

- **BKT scaling (but real 2+1 d quantum phase transition)**
- **Infinite order**

The big question:

Holography provides controlled examples of novel quantum matter.

Is any of this realized (to some approximation) in real systems?

Summary.

Holography

=

Solvable models of strong coupling dynamics.