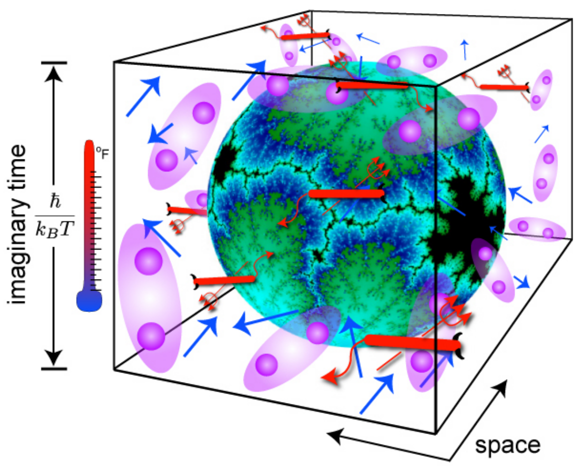
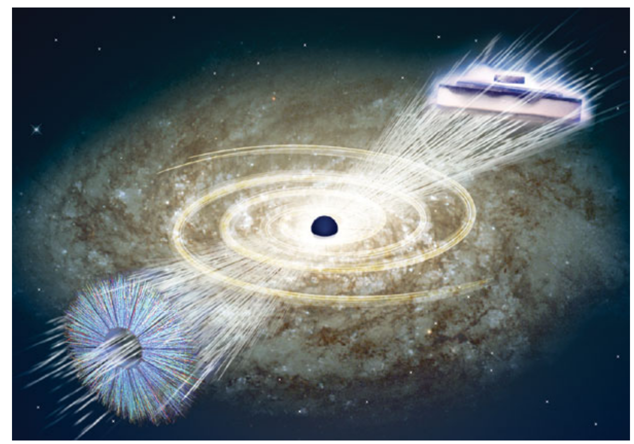
Observing the origin of superconductivity in quantum critical metals.

Jan Zaanen





Nederlandse Organisatie voor Wetenschappelijk Onderzoek

Universiteit Leiden

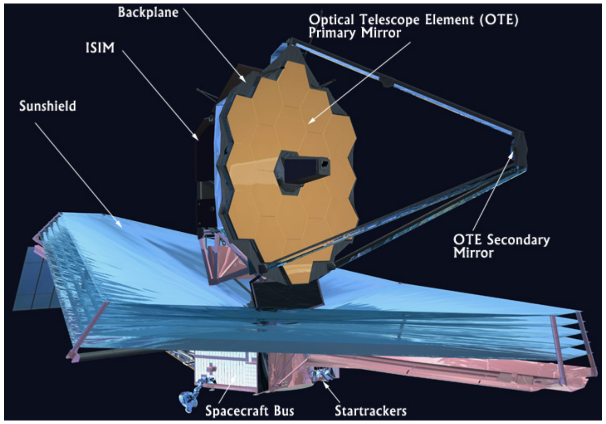
Instituut-Lorentz for theoretical physics

FOM

Plan of the talk

A proposal to build the condensed matter incarnation of

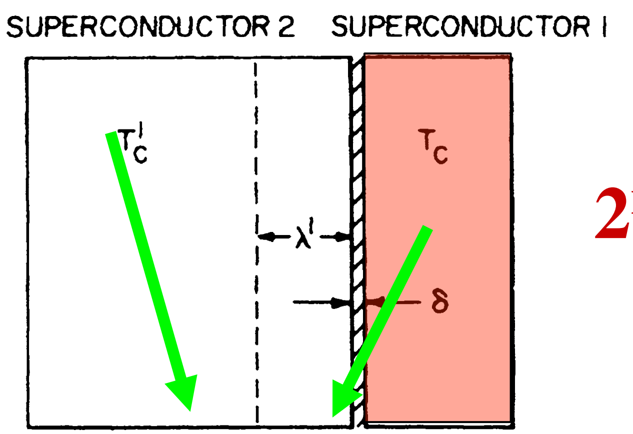
The James Webb Space Telescope



To either: - Embarrass string theorists.

Or: - Win Nobel Prize(s) together with string theorists for high Tc superconductivity, quantum gravity, …

Observing the origin of the pairing mechanism



$$\Delta c^\dagger c^\dagger$$

$$T_c' > T > T_c$$

2nd order Josephson effect

Ferrell Scalapino

1969 1970

$$I_s(\mathbf{H}, V) \sim \frac{1}{R_N^2} \mathrm{Im}\chi_{\mathrm{pair}}(\mathbf{k}, \omega) \qquad \omega = 2eV$$

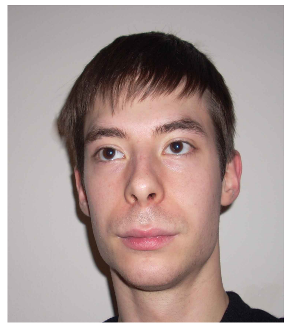
Promiscuous Leiden physics …

J.-H. She et al., arXiv:1105.5377

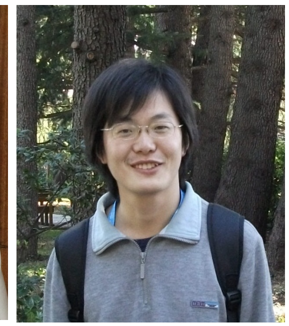
Stringy folks


Schalm


Parnachev


Cubrovic


Sun


Liu

Condensed matter people


She

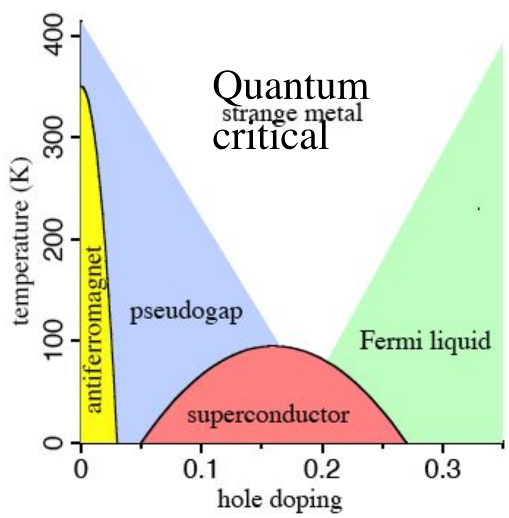

Overbosch


Mydosh

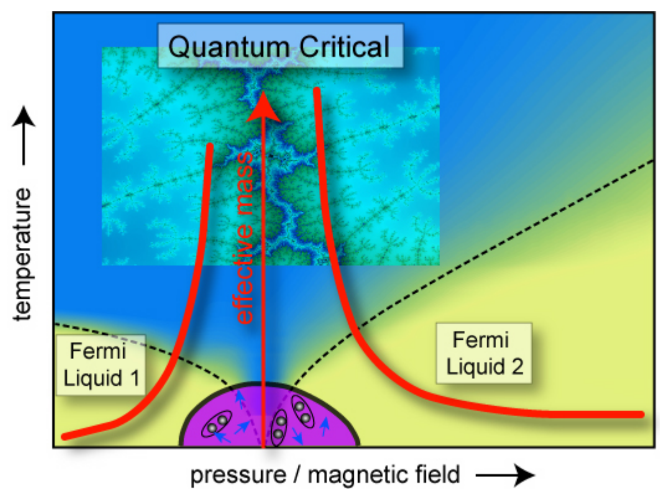

Hilgenkamp

A universal phase diagram

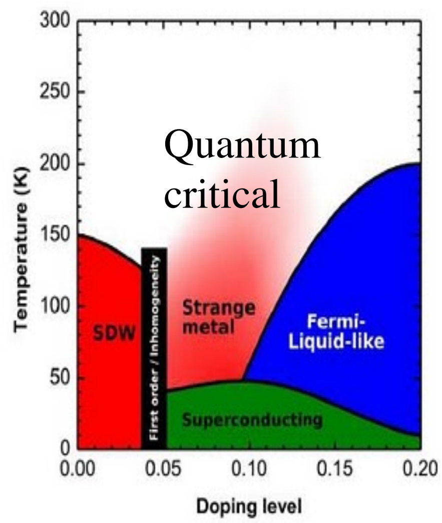
High Tc superconductors



Heavy fermions

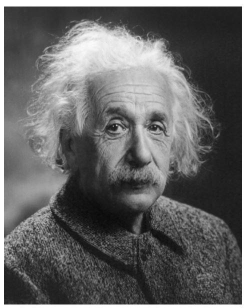


Iron superconductors (?)

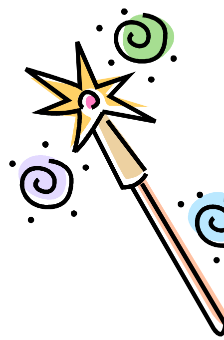


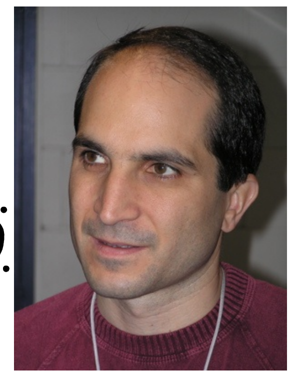
General relativity "=" quantum field theory

Gravity



In Anti-de-Sitter space



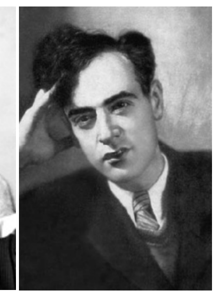


Maldacena 1997

=

AdS/CFT correspondence

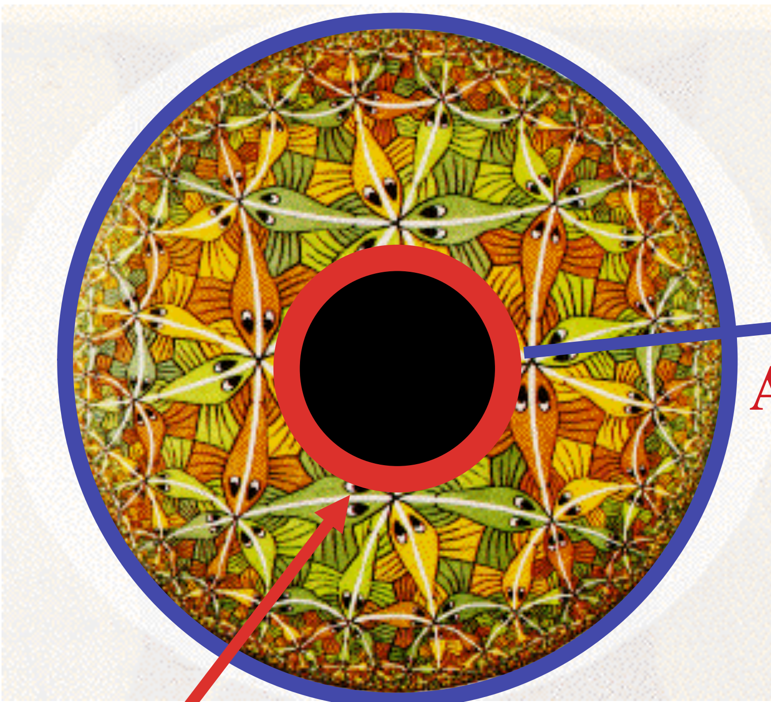
Quantum fields



When they are conformal = quantum critical

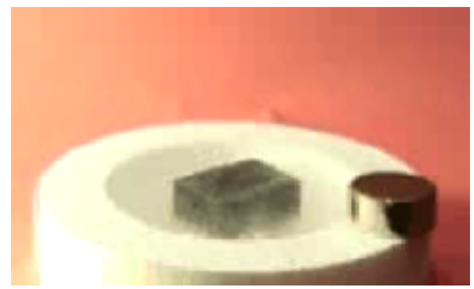
The holographic superconductor

Gubser; Hartnoll, Herzog, Horowitz



Condensate (superconductor, …) on the boundary!

AdS-CFT



‘Super radiance’: in the presence of matter the extremal BH is unstable => zero T entropy always avoided by low T order!!!

(Scalar) matter ‘atmosphere’

Plan

1. On susceptibility, quantum criticality and instability.

2. A template: BCS and Hertz-Millis-Chubukov.

3. Pair susceptibility versus holographic superconductivity.

4. Scaling toy model: quantum critical BCS.

5. How to build the pairing telescope?

Observing the pairing mechanism …

Claim: the maximal knowledge on the pairing mechanism is encoded in the temperature evolution of the normal state dynamical pair susceptibility,

$$\chi_p(q,\omega) = -i\int_0^\infty dt\, e^{i\omega t - 0^+ t}\left\langle\left[b^+(q,0),b(q,t)\right]\right\rangle$$

$$b^+(q,t) = \sum_k c^+_{k+q/2,\uparrow}(t)\,c^+_{-k+q/2,\downarrow}(t)$$

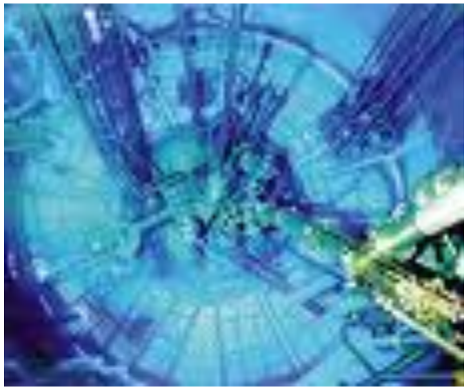
Observing the origin of magnetism …

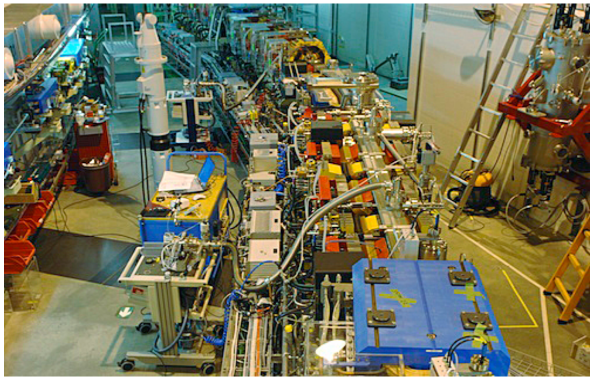
The origin of magnetism: dynamical magnetic susceptibility.

$$\chi_M(q,\omega) = -i\int_0^\infty dt\, e^{i\omega t - 0^+ t}\left\langle\left[\vec{S}\ (q,0),\vec{S}(q,t)\right]\right\rangle$$

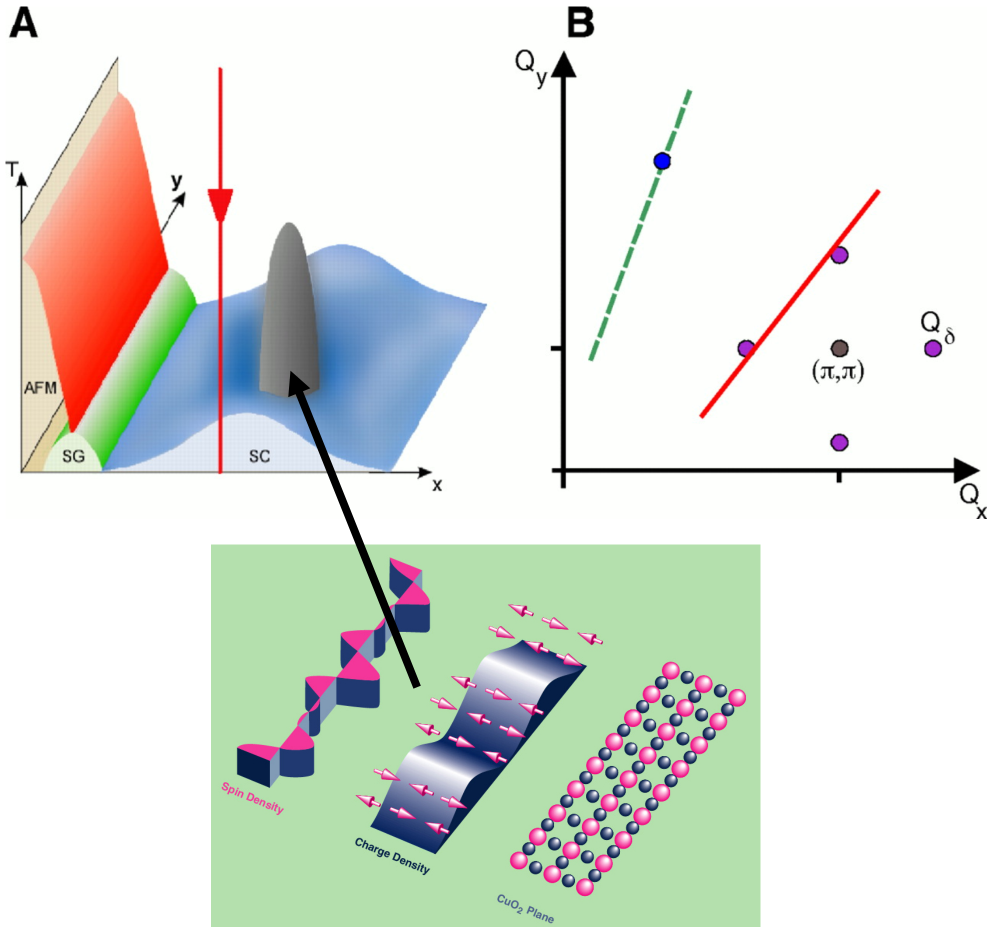
$$\vec{S}(q,t) = \sum_{k\alpha\beta} c^+_{k+q,\alpha}(t)\vec{\sigma}_{\alpha\beta}c_{k,\beta}(t)$$

Measured by inelastic neutron scattering:





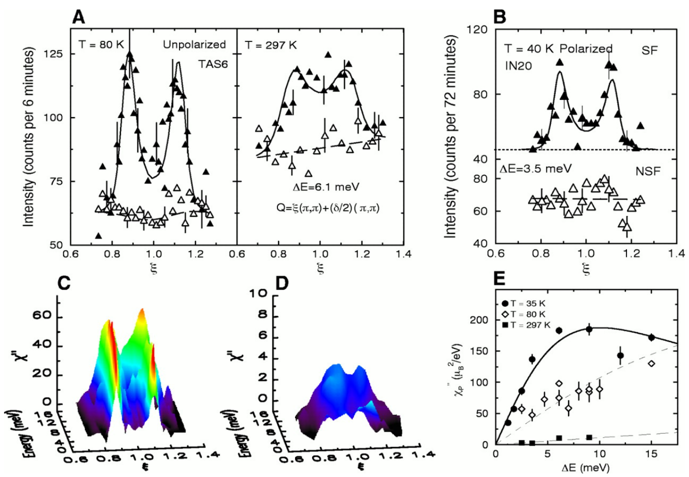
Quantum critical spin fluctuations in underdoped cuprates

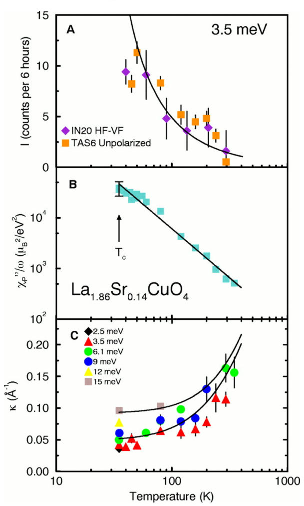


Aeppli et al.
Science 1997.

Quantum critical spin fluctuations in underdoped cuprates

Aeppli et al. Science 1997.

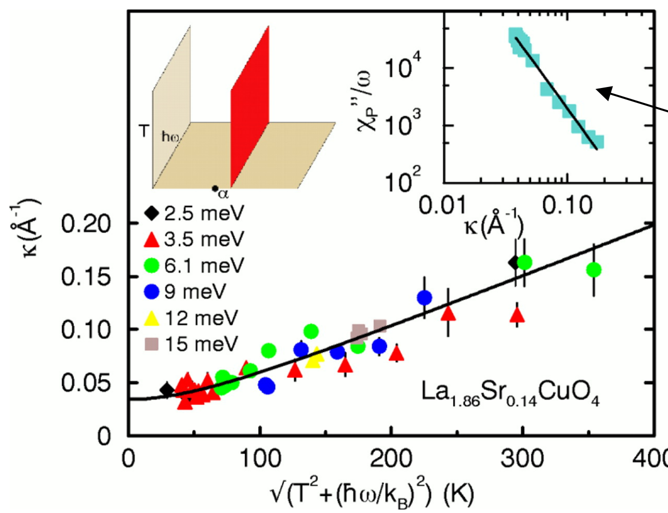




Peak widths reveal z=1 energy-temperature (conformal) scaling:

$$\kappa^2 = \kappa_0^2 + a_0^{-2}\left(\frac{(k_B T)^2 + (\hbar\omega)^2}{(E_T)^2}\right)^{1/z} \quad \mathbf{Z=1}$$

Real data



Amplitude suggests

$$\eta \approx 0$$

2+1D Heisenberg

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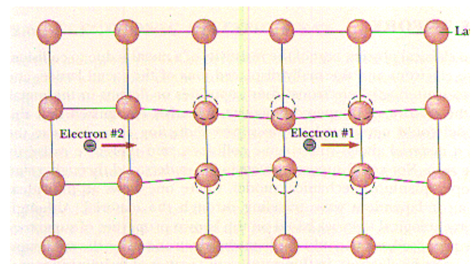
$$b^+\left(q,t\right) = \sum_k c^+_{k+q/2,\uparrow}(t)\, c^+_{-k+q/2,\downarrow}(t)$$

BCS theory: fermions turning into bosons

Bardeen Cooper Schrieffer

Fermi-liquid + attractive interaction

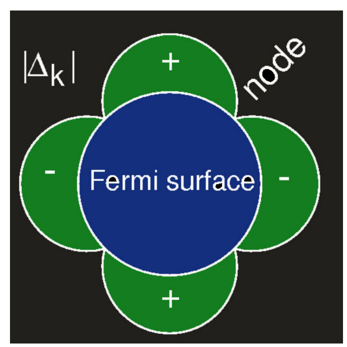


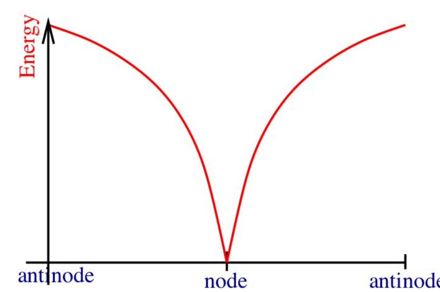
Quasiparticles pair and Bose condense:

Ground state

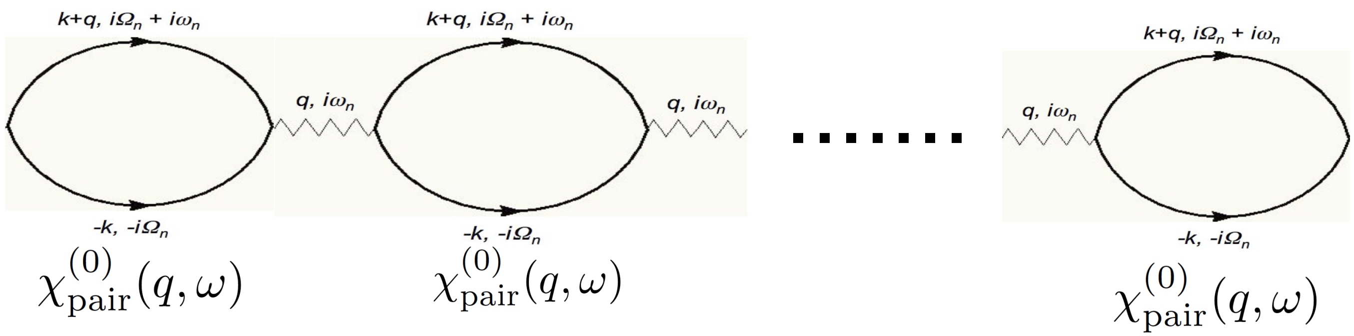
$$\Psi_{BCS} = \Pi_k \left(u_k + v_k c^+_{k\uparrow} c^+_{-k\downarrow} \right) \left| vac. \right\rangle$$

D-wave SC: Dirac spectrum





BCS and the pair susceptibility



$$\chi_{\text{pair}}(\omega) = \frac{\chi^{(0)}_{\text{pair}}(\omega)}{1 - g\chi^{(0)}_{\text{pair}}(\omega)} \rightarrow 1 - g\text{Re}\chi^{(0)}_{\text{pair}}(\omega = 0) = 0$$

$$\text{Im}\,\chi^{(0)}_{pair}(\omega) = \frac{1}{2E_F}\tanh\left(\frac{\hbar\omega}{4k_BT}\right) \rightarrow \text{Re}\chi(\omega = 0) = 2\int_0^{\omega_c} d\omega' \frac{\text{Im}\chi(\omega')}{\omega'}$$

$$\Delta = 2\omega_B e^{-1/\lambda}$$

Computing the pair susceptibility: full Eliashberg

$$\chi(k,k';q) = \chi_0(k,k';q) + u^2 \sum_{k_1,k_2} \chi_0(k,k_1;q) D(k_2 - k_1) \chi(k_2,k';q)$$

$$\Gamma(k;q) = \sum_{k'} \chi(k,k';q)$$

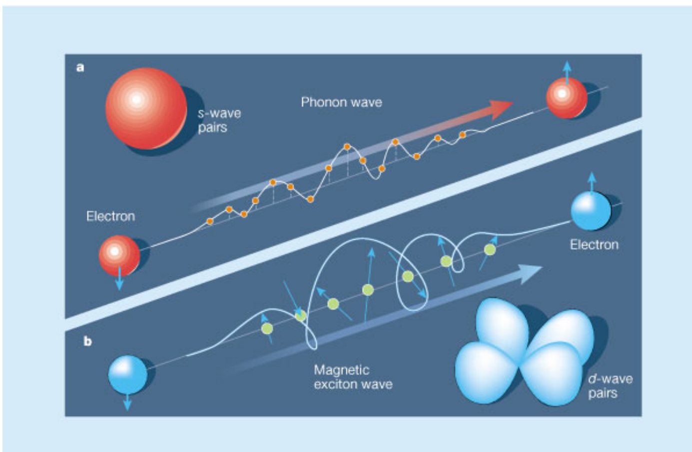
$$\Gamma(i\nu;i\Omega) = \Gamma_0(i\nu;i\Omega) + \mathcal{A}\,\Gamma_0(i\nu;i\Omega) \sum_{\nu'} \lambda(i\nu' - i\nu)\Gamma(i\nu';i\Omega)$$

$$\chi_{\text{pair}}(i\Omega, \mathbf{q}=0) = \sum_{\nu} \Gamma(i\nu;i\Omega)$$

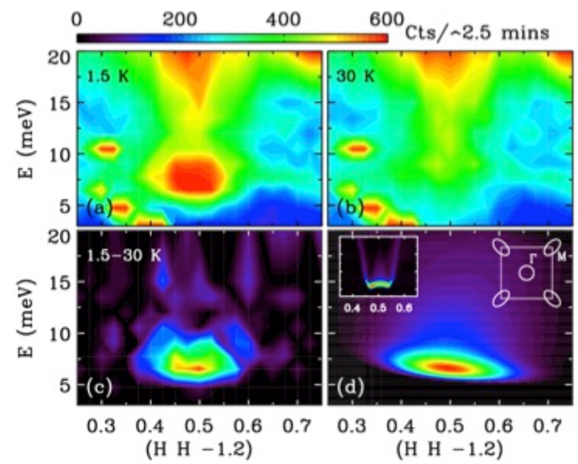
$$i\Omega \to \omega + i\delta$$

$$\chi_{\text{pair}}(\omega, \mathbf{q}=0)$$

Superglue !



Magnetic resonance …

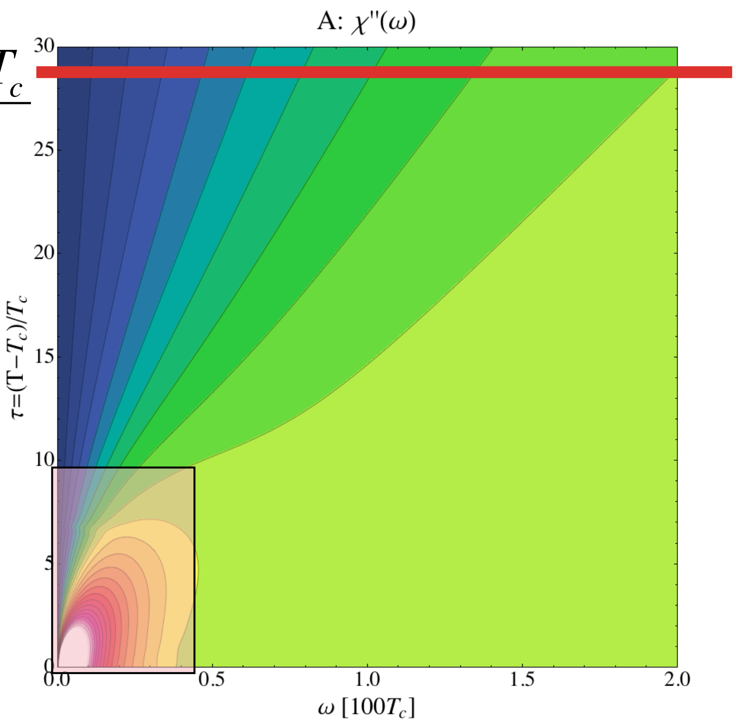


$$\lambda(i\Omega) = \frac{g}{A}\frac{\omega_b^2}{\omega_b^2 + \Omega^2}$$

Imaginary part of the "regular" BCS pair susceptibility

$$\lambda(i\Omega) = \frac{g}{\mathcal{A}} \frac{\omega_b^2}{\omega_b^2 + \Omega^2}$$

$$\frac{T - T_c}{T_c}$$



High temperature: the Fermi gas

$$\mathrm{Im}\,\chi_{pair}^{(0)}(\omega) = \frac{1}{2E_F}\tanh\left(\frac{\hbar\omega}{4k_BT}\right)$$

Close to Tc: "relaxational peak"

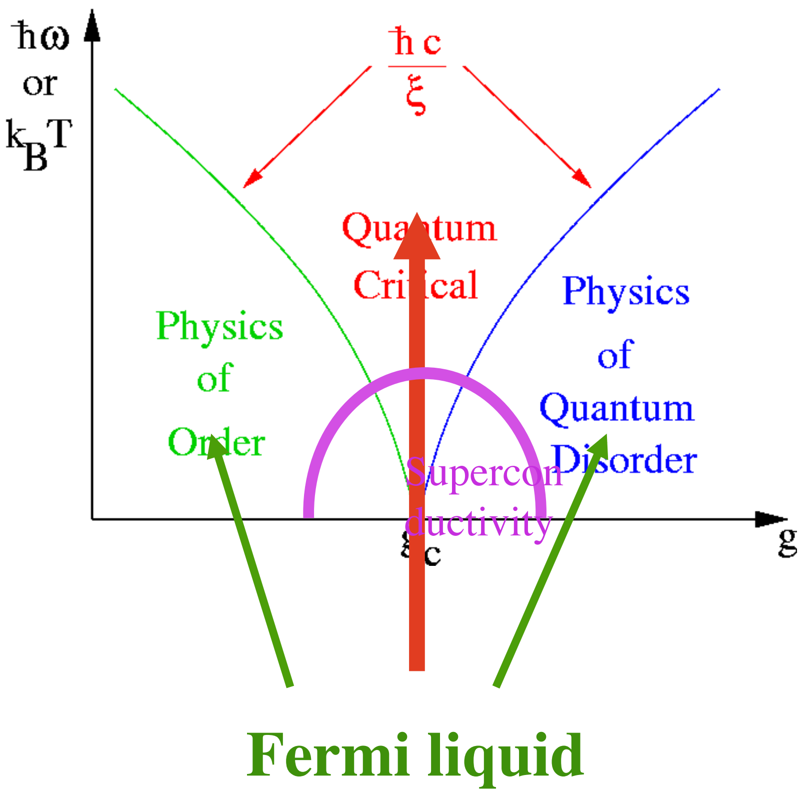
$$L = \frac{1}{\tau_r}\Psi\partial_t\Psi + |\nabla\Psi|^2 + \alpha_0(T - T_c)|\Psi|^2 + w|\Psi|^4 + \cdots$$

Assume mean-field thermal transition (true in all cases)

$$\chi_{pair}''(\omega) = \frac{\chi_{pair}'(\omega = 0, T)}{1 - i\omega\tau_r}$$

$$\chi_{pair}'(\omega = 0, T) = 1/\left[\alpha_0(T - T_c)\right] \quad \tau_r = \frac{8}{\pi}\frac{\hbar}{k_B(T - T_c)}$$

Hertz-Millis and Chubukov's "critical glue" (Metlitski talk)



Bosonic (magnetic, etc.) order parameter drives the phase transition

Electrons: fermion gas = heat bath damping bosonic critical fluctuations

Bosonic critical fluctuations 'back react' as pairing glue on the electrons

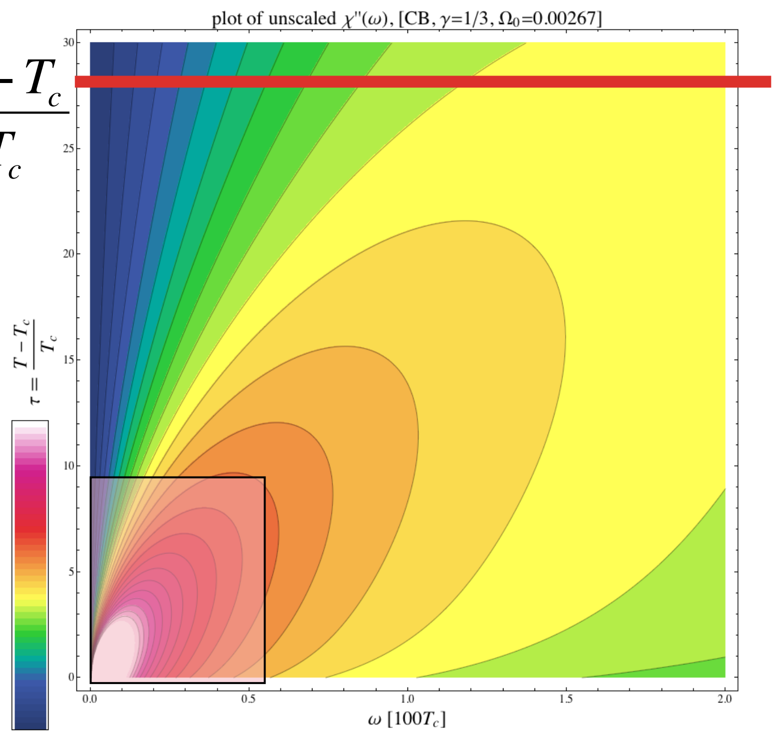
$$\lambda(i\Omega) = \left(\frac{\Omega_0}{|\Omega|} \right)^{\gamma}$$

E.g.: Moon, Chubukov, J. Low Temp. Phys. 161, 263 (2010)

The Hertz-Millis-Chubukov "critical glue" pair susceptibility

$$\lambda(i\Omega) = \left(\frac{\Omega_0}{|\Omega|}\right)^{\gamma}$$

$\frac{T - T_c}{T_c}$



High temperature: effectively strongly coupled, self energies produce a peak (yellow).

Close to Tc: "relaxational peak"

$$\chi_{pair}''(\omega) = \frac{\chi_{pair}'(\omega = 0, T)}{1 - i\omega\tau_r}$$

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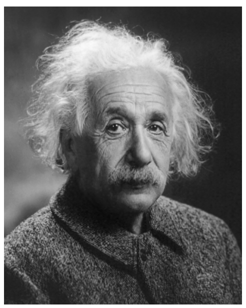
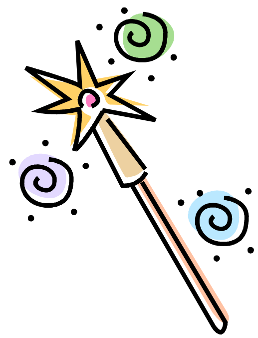
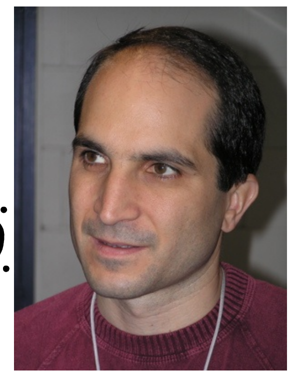
General relativity “=“ quantum field theory

Gravity



In Anti-de-Sitter space





Maldacena 1997

=

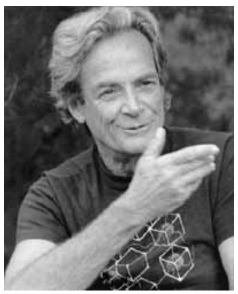
AdS/CFT correspondence

Quantum fields

When they are conformal = **quantum critical**

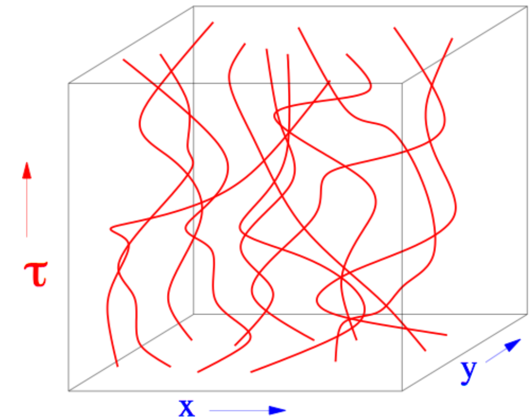
Fermion sign problem

Imaginary time path-integral formulation



$$\mathcal{Z} = \operatorname{Tr} \exp(-\beta \hat{\mathcal{H}}) = \int d\mathbf{R} \rho(\mathbf{R}, \mathbf{R}; \beta)$$

$$\mathbf{R} = (\mathbf{r}_1, \ldots, \mathbf{r}_N) \in \mathbb{R}^{Nd}$$



$$\rho_{B/F}(\mathbf{R}, \mathbf{R}; \beta) = \frac{1}{N!} \sum_{\mathcal{P}} (\pm 1)^{\mathcal{P}} \rho_D(\mathbf{R}, \mathcal{P}\mathbf{R}; \beta) = \frac{1}{N!} \sum_{\mathcal{P}} (\pm 1)^{\mathcal{P}} \int_{\mathbf{R} \to \mathcal{P}\mathbf{R}} \mathcal{D}\mathbf{R}(\tau) \exp\left\{ -\frac{1}{\hbar} \int_0^{\hbar/T} d\tau \left(\frac{m}{2} \dot{\mathbf{R}}^2(\tau) + V(\mathbf{R}(\tau)) \right) \right\}$$

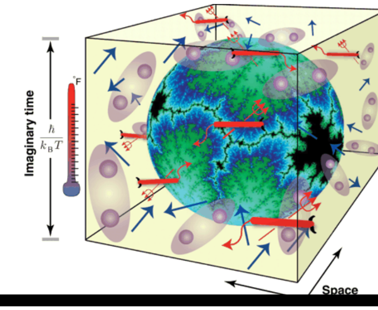
Boltzmannons or Bosons:

- integrand non-negative
- probability of equivalent classical system: (crosslinked) ringpolymers

Fermions:

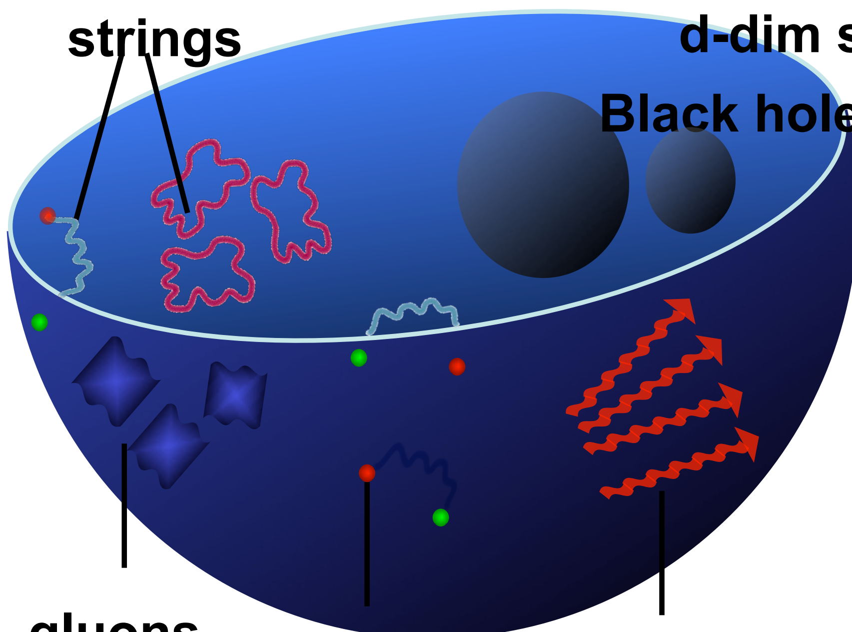
- negative Boltzmann weights
- non probablistic: NP-hard problem (Troyer, Wiese)!!!

Fermionic renormalization group

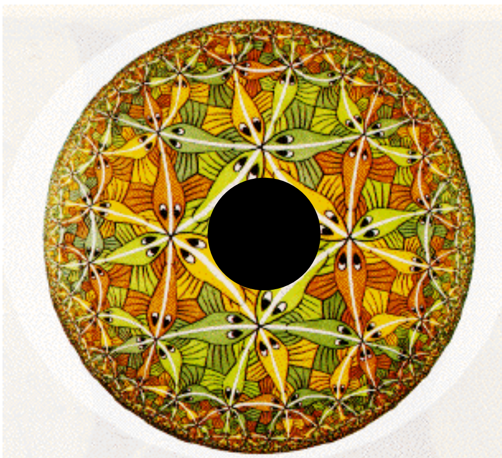


Wilson-Fisher RG:
based on Boltzmannian
statistical physics

The Magic of AdS/CFT!



Planckian dissipation

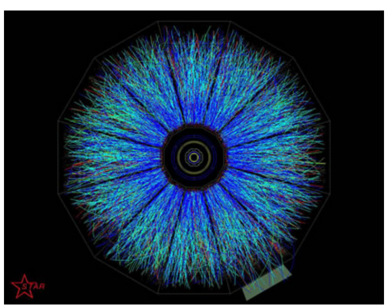


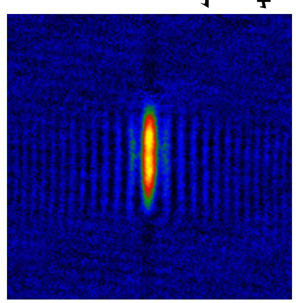
Schwarzschild Black Hole: encodes for the finite temperature dissipative quantum critical fluid.

Universal entropy production time:

$$\tau = \tau_\hbar \approx \frac{\hbar}{k_B T}$$

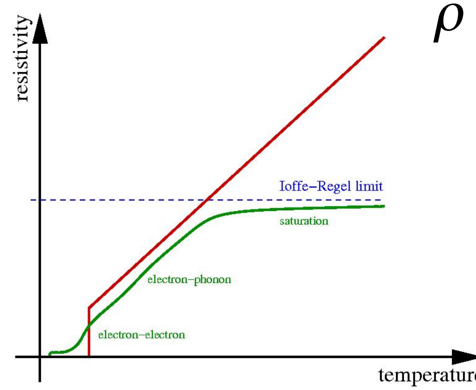
Minimal viscosity: quark gluon plasma, unitary cold atom fermion gas $\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$





Linear resistivity high Tc metals:

$$\rho \propto \frac{1}{\tau_\hbar} \propto k_B T$$

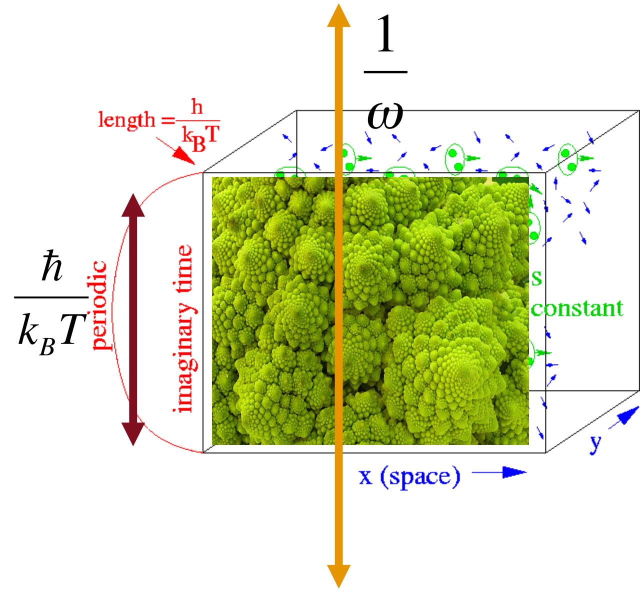


Quantum critical hydrodynamics: Planckian dissipation & viscosity

Planckian dissipation:

Sachdev, 1992

In a finite temperature quantum critical state the time it takes to convert work in heat (relaxation time) has to be



$$\tau = \tau_{\hbar} \approx \frac{\hbar}{k_B T}$$

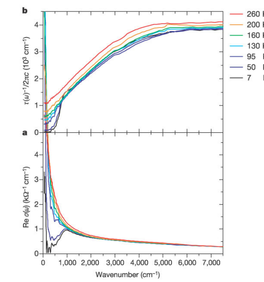
Viscosity, entropy density: $\eta = (\varepsilon + p)\tau,\ s = \dfrac{\varepsilon + p}{T} \Rightarrow \dfrac{\eta}{s} = T\tau$

Planckian viscosity: $\dfrac{\eta}{s} \approx \dfrac{\hbar}{k_B}$

Critical Cuprates are Planckian Dissipators

van der Marel, JZ, … Nature 2003:

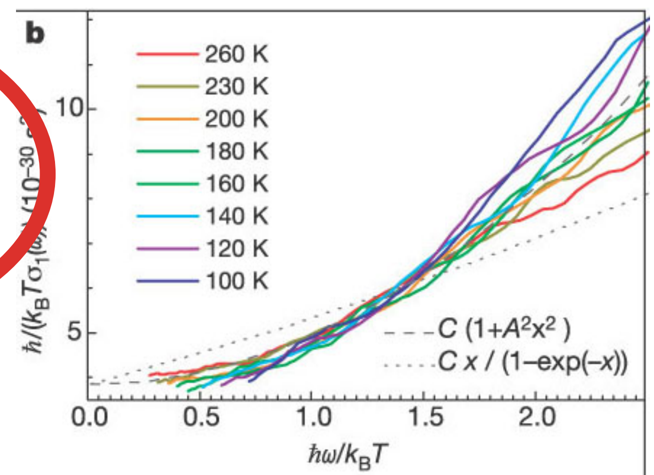
Optical conductivity QC cuprates



Frequency less than temperature:

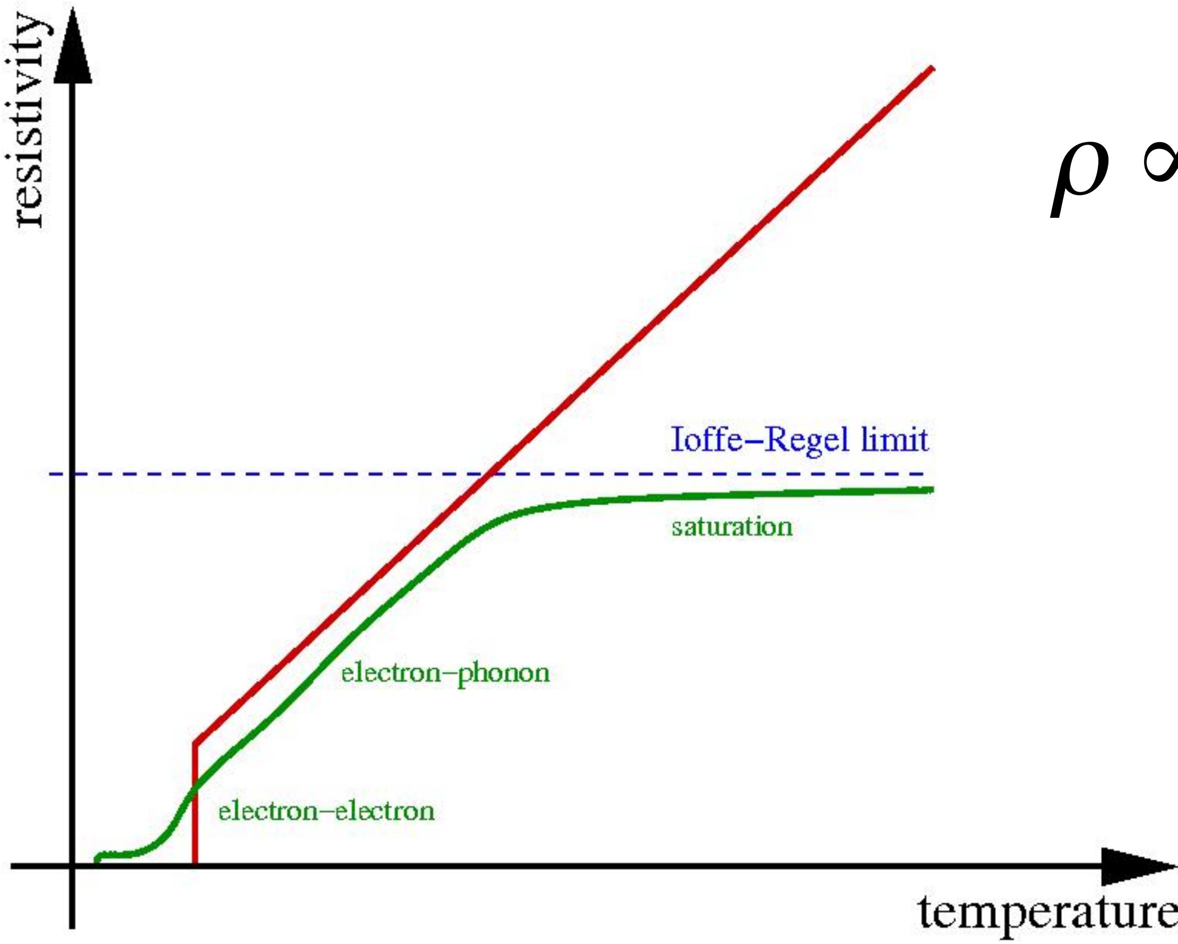
$$\sigma_1(\omega,T) = \frac{1}{4\pi}\frac{\omega_{pr}^2\tau_r}{1+\omega^2\tau_r^2}, \quad \tau_r = A\frac{\hbar}{k_B T}$$

$$\Rightarrow \quad [\frac{\hbar}{k_B T\sigma_1}] = const.(1 + A^2[\frac{\hbar\omega}{k_B T}]^2)$$



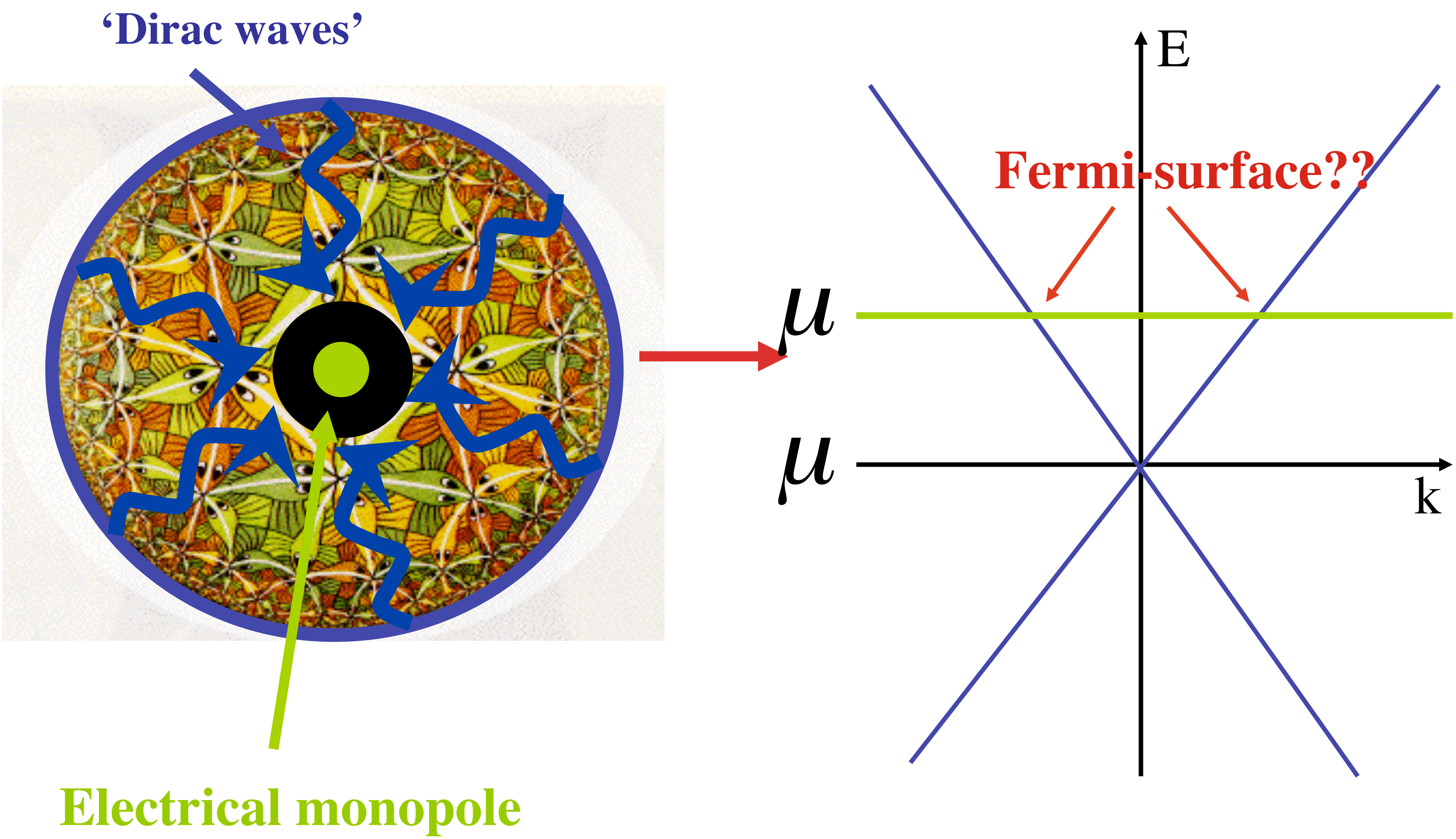
A= 0.7: the normal state of optimallly doped cuprates is a Planckian dissipator!

Divine resistivity = Planckian Dissipation!



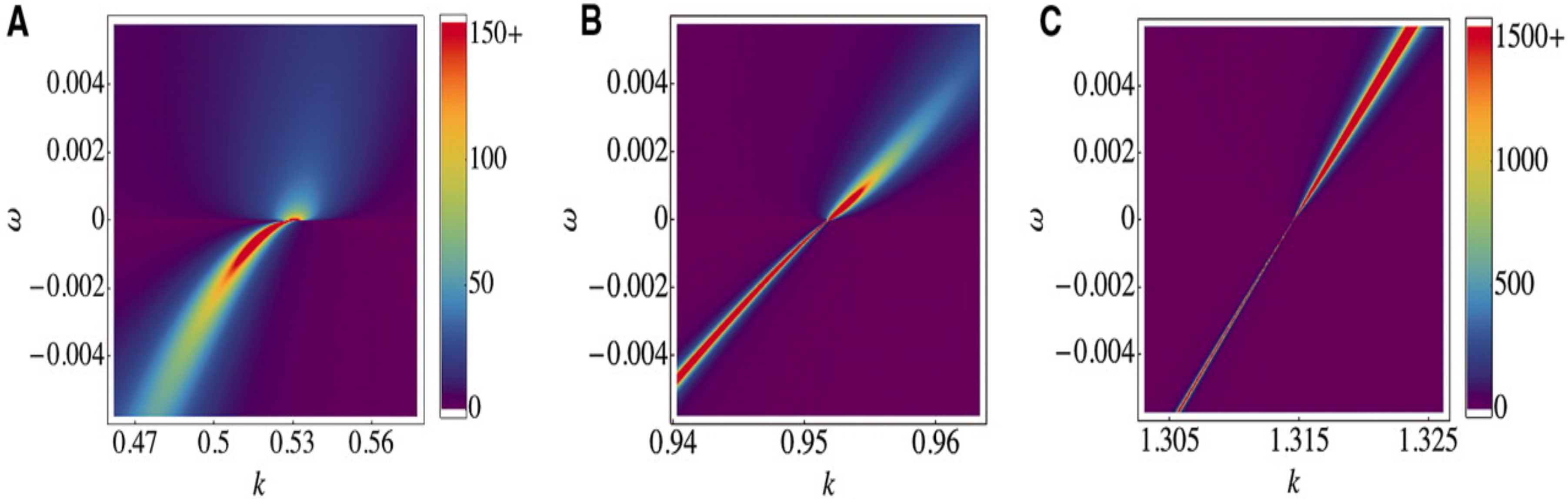
$$\rho \propto \frac{1}{\tau_\hbar} \propto k_B T$$

Breaking fermionic criticality with a chemical potential



AdS/ARPES for the Reissner-Nordstrom non-Fermi liquids

Fermi surfaces but no quasiparticles!

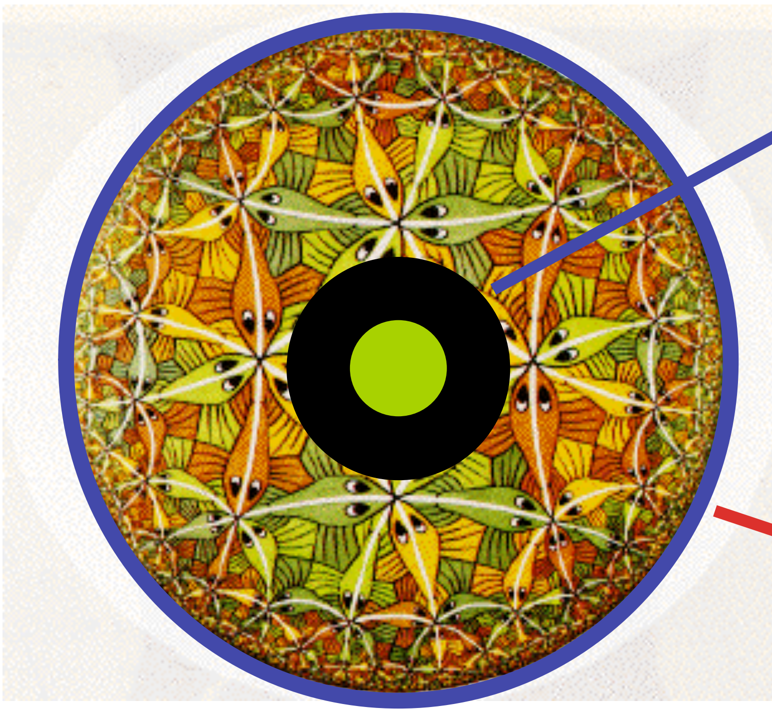


Critical FL

Marginal FL

Non Landau FL

The zero temperature extensive entropy ‘disaster’



The ‘extremal’ charged black hole with AdS^2 horizon geometry has zero Hawking temperature but a finite horizon area.

AdS-CFT

The ‘seriously entangled’ quantum critical matter at zero temperature should have an extensive ground state entropy (?*##!!)

Why is Tc high?

"Because there is superglue binding the electrons in pairs"

Wrong!

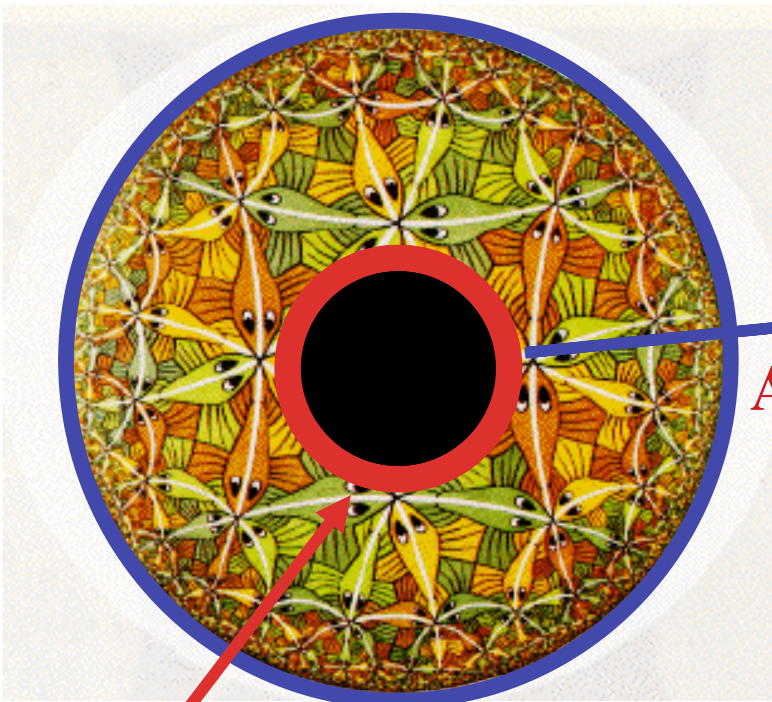
The superfluid density is tiny, it is very easy to 'bend and twist' a high Tc superconductor. **Its cohesive energy sucks.**

Tc's are set by the competition between the two sides …

The theory of the mechanism should explain why the free energy of the metal is seriously BAD.

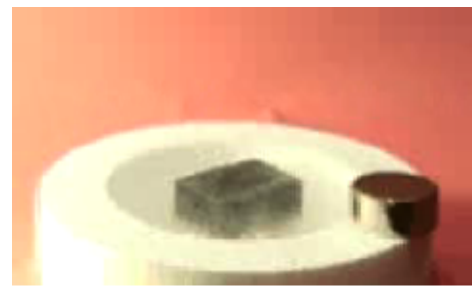
The holographic superconductor

Gubser; Hartnoll, Herzog, Horowitz



Condensate (superconductor, …) on the boundary!

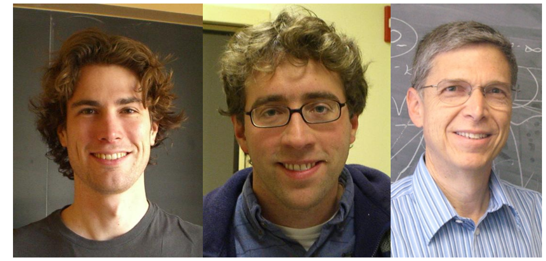
AdS-CFT



'Super radiance': in the presence of matter the extremal BH is unstable => zero T entropy always avoided by low T order!!!

(Scalar) matter 'atmosphere'

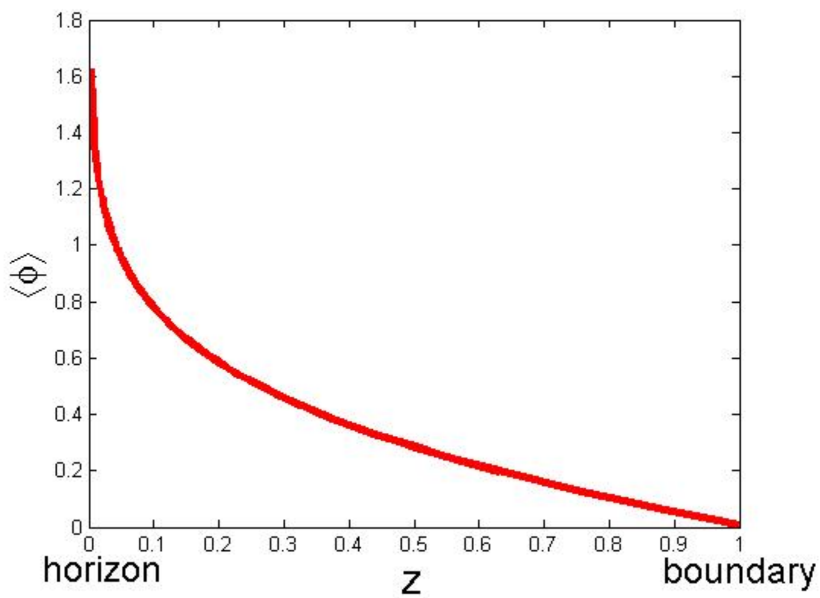
The Bose-Einstein Black hole hair

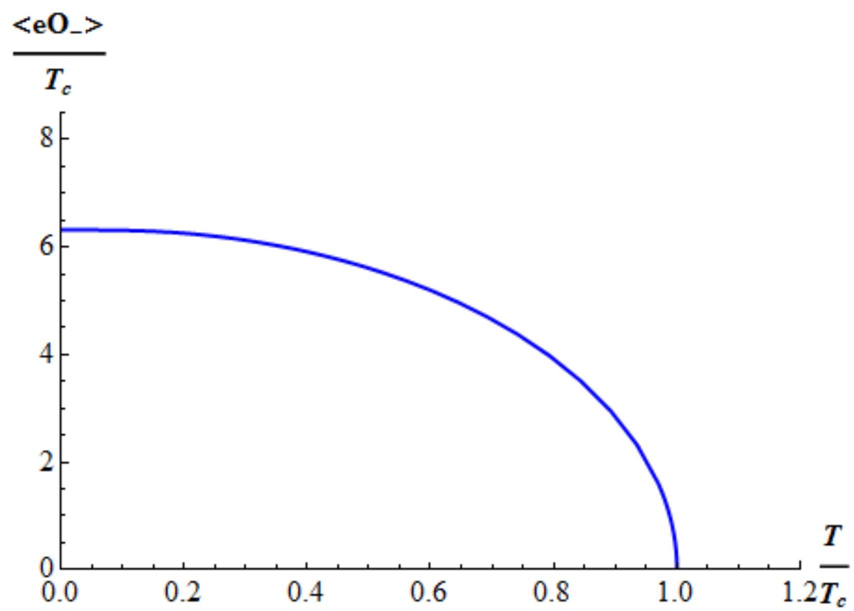


Hartnoll Herzog Horowitz

Scalar hair accumulates at the horizon

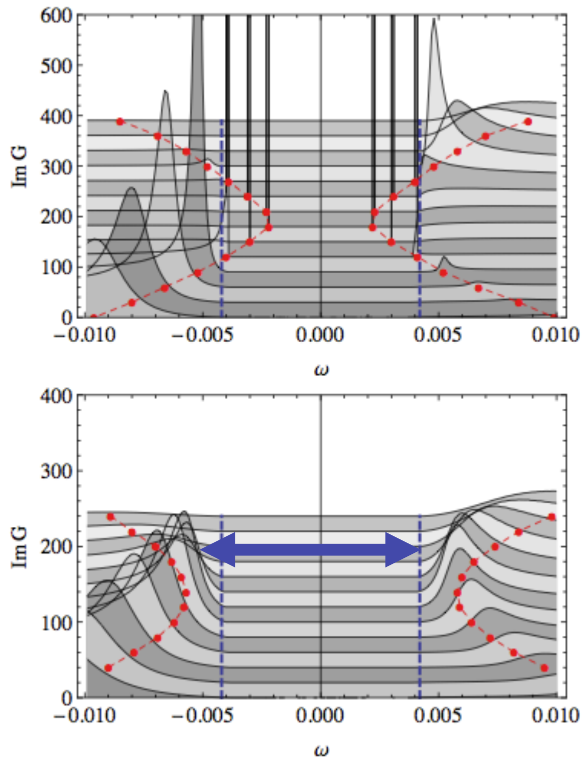
Mean field thermal transition.



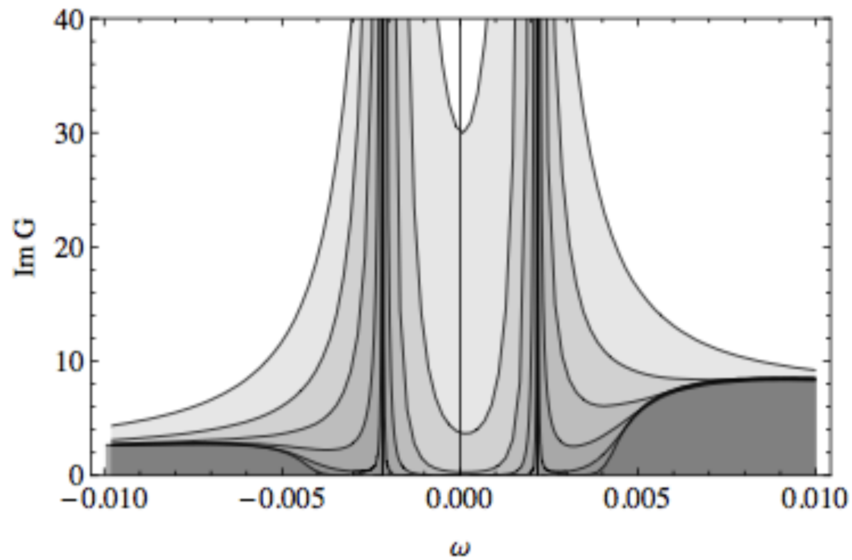


Holographic superconductivity: stabilizing the fermions.

Fermion spectrum for scalar-hair black hole (Faulkner et al., 911.340):



'BCS' Gap in fermion spectrum !!

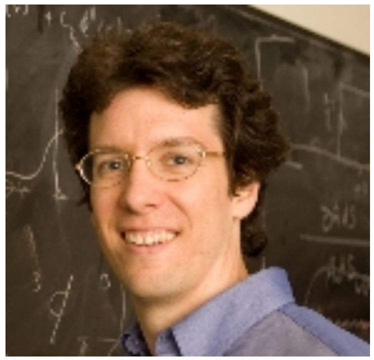


"Pseudogap" Temperature dependence

The top-down holographic superconductors

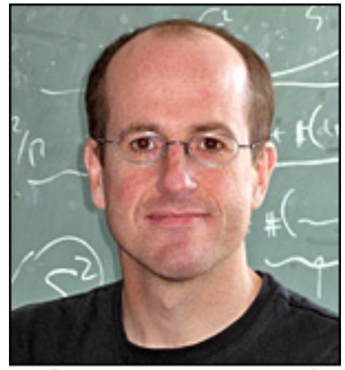
Erdmenger et al.:

D3/D7 brane intersections, (arXiv:0810.2316)



Gubser et al.:

type II sugra (arXiv:0907.3510)

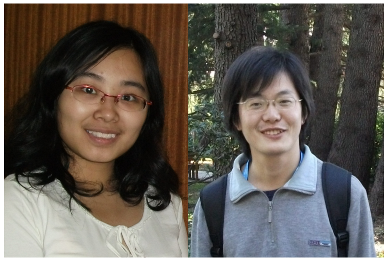


Professor Jerome Gauntlet

Gauntlett et al.:

M-theory, Sasaki-Einstein (arXiv: 0907.3796).

Holographic superconductivity: the equations



"**Double trace**": Roberts, Faulkner, Horowitz, arXiv:1008.1581

Bulk action:

$$S = \int d^4x \sqrt{-g}\left[R + \frac{6}{L^2} - \frac{1}{4}(1 + g_0|\Psi|^2) F_{\mu\nu}F^{\mu\nu} - m^2|\Psi|^2 - |\nabla^\mu \Psi - ieA^\mu \Psi|^2 \right]$$

R = Ricci scalar, L= AdS radius, $F_{\mu\nu}$ Maxwell tensor, Ψ scalar field dual to pair field

Near boundary asymptotics: $\Psi(r) \approx \frac{\psi_-}{r^{\Delta_-}} + \frac{\psi_+}{r^{\Delta_+}}, r \to \infty \quad \left(\Delta_\pm = \frac{3}{2} \pm \frac{\sqrt{9 + 4m^2}}{2} \right)$

Pair susceptibility CFT: $\chi_{pair} = \frac{(\psi_- / \psi_+)}{1 - \kappa(\psi_- / \psi_+)}$

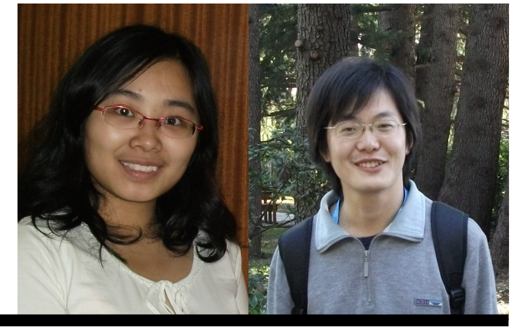
"pair breaking" interaction, like RPA!!

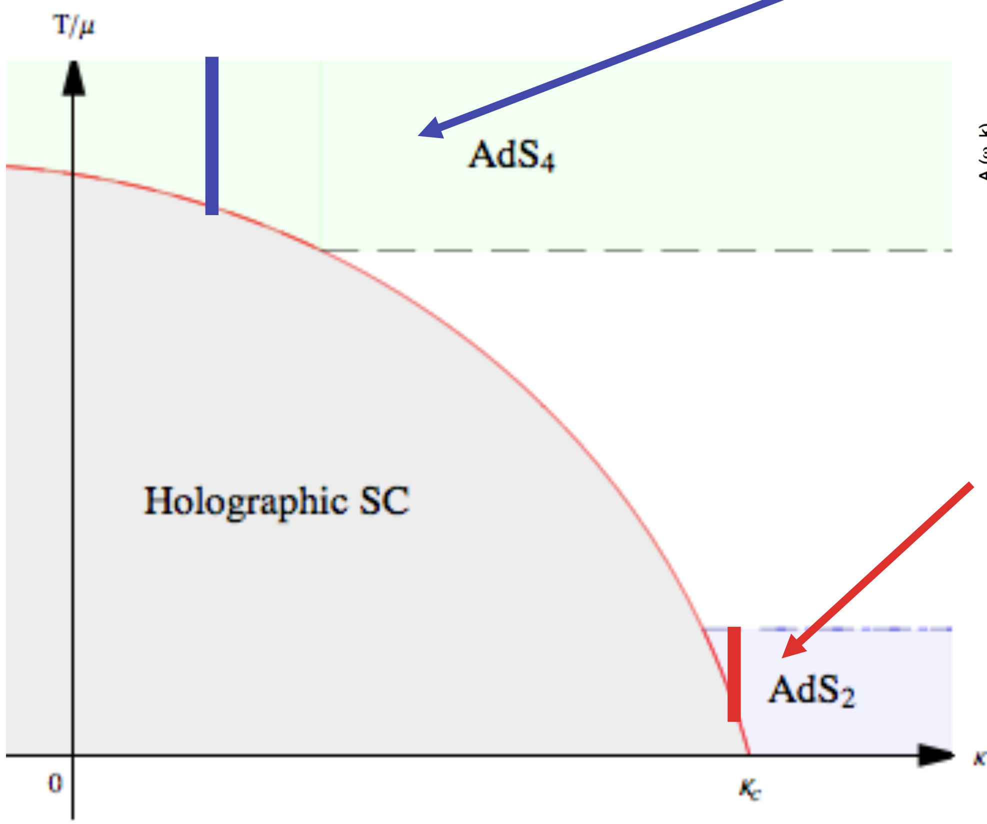
$$S_{\text{int}} \propto \kappa \int d^3x\, c^+ c^+ c\, c$$

"AdS⁴": $e >> 1, \kappa = 0$ **like "local pair SC",** $T_c \approx \mu$

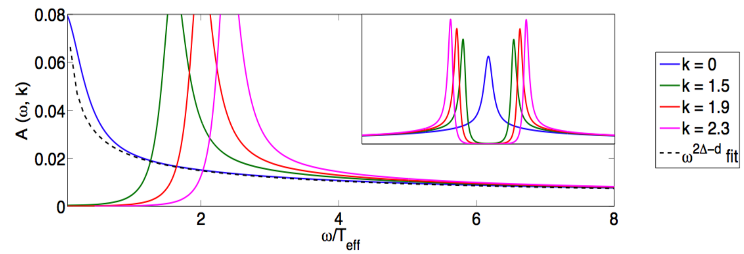
"AdS²": $e << 1, \kappa < 0$ **"BCS from AdS2 metal",** $T_c << \mu$

“Double trace” Phase Diagram

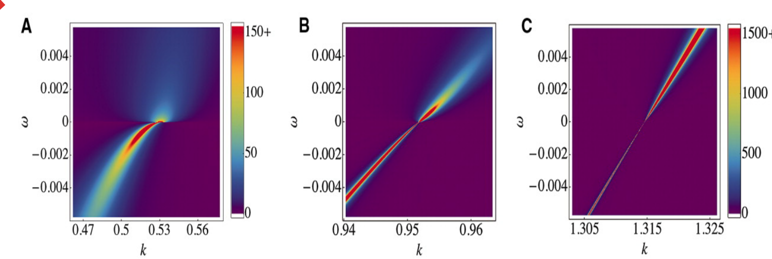




This looks like “quantum critical graphene” at zero density



This is the “marginal Fermi-liquid” Liu style



More fanciful: Iqbal, Liu, Mezei

arXiv:1108.0425

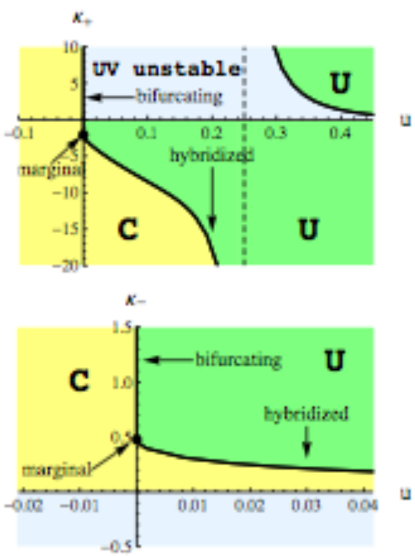
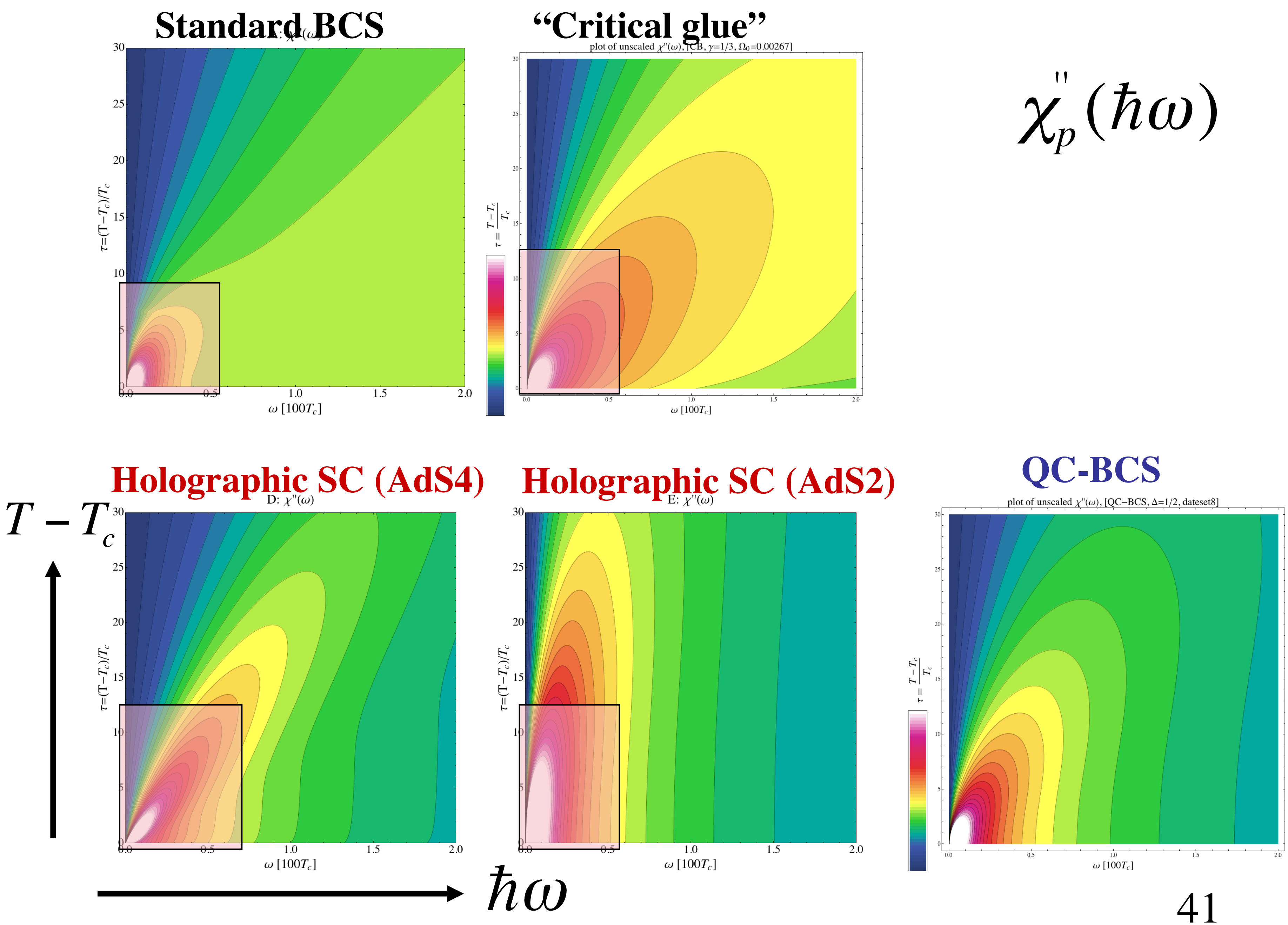


FIG. 7. The full phase diagram of the system for a neutral scalar. C (U) denotes regions with (without) IR instabilities. *Top plot*: standard quantization. For $u < 0$, i.e. $m^2R^2 < -\frac{3}{2}$ the system is always unstable in the IR with $u = 0$ the critical line for a bifurcating QCP. For $-\frac{3}{2} < m^2R^2 < 0$, i.e. $0 < u < \frac{1}{4}$, the system develops an IR instability for $\kappa_+ < \kappa_c(m^2) < 0$ with $\kappa_c(m^2)$ giving the critical line for hybridized QCP. The marginal critical point lies at the intersection for the critical lines for bifurcating and hybridized instabilities. The system has a vacuum UV instability for $\kappa_+ > 0$. For $m^2 > 0$, i.e. $u > \frac{1}{4}$, as discussed in the caption of Fig. 6, the vacuum instability is cured by finite density effect for sufficiently large κ_+. *Bottom plot*: phase diagram for the alternative quantization (for $\nu_U \in (0,1)$, hence the limited range in u compared to the top plot, $u < \frac{1}{24}$), which can be obtained from that of the standard quantization by using the relation (3.4). In the vacuum, the system has an IR instability for $\kappa_- < 0$, i.e. with $\kappa_- = 0$ the critical line. At a finite density the critical line is pushed into the region $\kappa_- > 0$.

Quite different behaviors of the holographic quantum phase transitions by tuning the holographic SC down by mass or double trace deformation



Standard BCS
"Critical glue"
plot of unscaled χ''(ω), [CB, γ=1/3, Ω0=0.00267]
χ''p(ħω)
Holographic SC (AdS4)
D: χ''(ω)
Holographic SC (AdS2)
E: χ''(ω)
QC-BCS
plot of unscaled χ''(ω), [QC−BCS, Δ=1/2, dataset8]
τ=(T−Tc)/Tc
ω [100Tc]
T − Tc
ħω

Plan

1. On susceptibility, quantum criticality and instability.

2. A template: BCS and Hertz-Millis-Chubukov.

3. Pair susceptibility versus holographic superconductivity.

4. Scaling toy model: quantum critical BCS.

5. How to build the pairing telescope?

Quantum Critical BCS

PRB80, 184518 (2009)

J.-H. She

Depart from BCS:

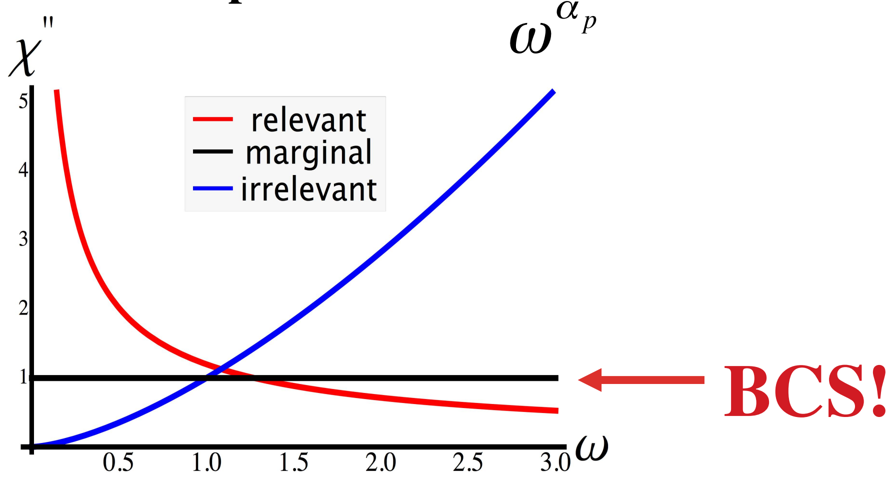
$$\chi_{\text{pair}}(\omega) = \frac{\chi^{(0)}_{\text{pair}}(\omega)}{1 - g\chi^{(0)}_{\text{pair}}(\omega)}$$

$$\lambda(i\Omega) = \frac{g}{\mathcal{A}} \frac{\omega_b^2}{\omega_b^2 + \Omega^2}$$

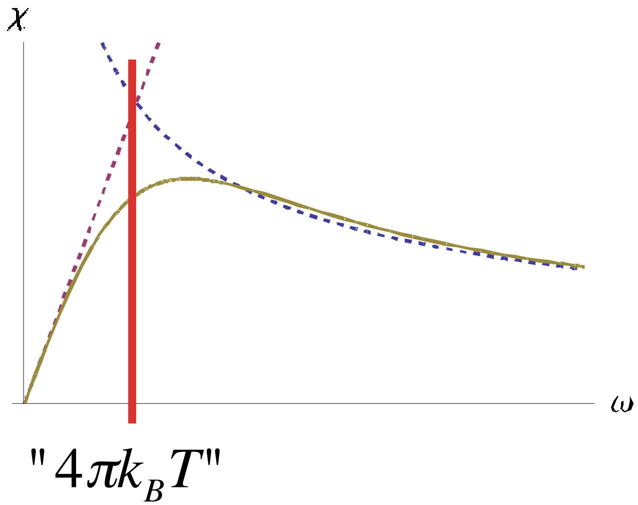
Conformal ansatz for $\chi^{(0)}_{\text{pair}}(\omega, T) = \frac{1}{T^{\alpha_p}} \mathcal{F}\left(\frac{\omega}{T}\right)$

E.g. 1+1D scaling function + gymnastics to account for retardation

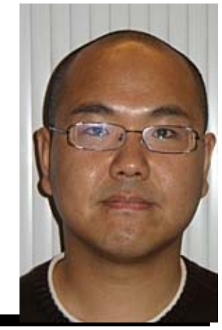
Zero temperature $\propto \frac{1}{\omega^{\alpha_p}}$



Finite temperature



Scaling versus the BCS gap



J.-H. She

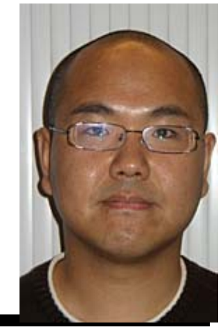
Gap equation: $$1-\frac{g}{\omega_c}\int_{\tilde{\Delta}_0}^{2\hbar\tilde{\omega}_B}\frac{d\tilde{\omega}}{\tilde{\omega}^{\alpha}}=0$$

Fermi-liquid: $$\omega_c=E_F,\lambda=\frac{g}{E_F},\alpha=1 \quad \Rightarrow \Delta_0=2\hbar\omega_B e^{-1/\lambda}$$

Critical case: $$\lambda=\frac{g}{\omega_c},\ \alpha=\frac{2-\eta_{pp}}{z} \quad \Rightarrow$$

'Huang's equation': $$\Delta_0=2\hbar\omega_B\left(\frac{\lambda}{\lambda+\left(2\omega_B/\omega_c\right)^{\left(2-z-\eta_{pp}\right)/z}}\right)^{\frac{z}{2-z-\eta_{pp}}}$$

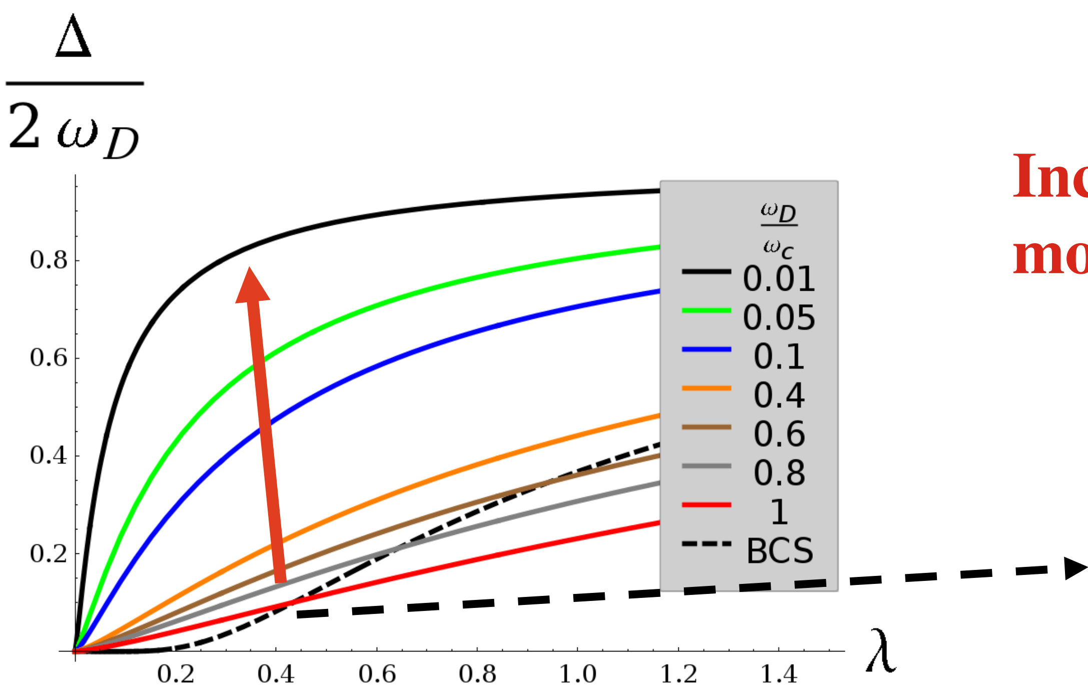
Huang's equation at work



J.-H. She

$$\Delta_0 = 2\hbar\omega_B \left(\frac{\lambda}{\lambda + (2\omega_B/\omega_c)^{(2-z-\eta_{pp})/z}} \right)^{\frac{z}{2-z-\eta_{pp}}}$$

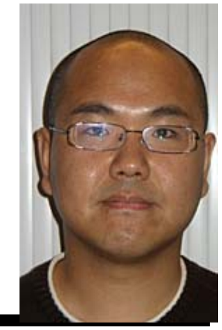
Strongly interacting critical state, e.g. 1+1D Ising: $\eta_{pp} = 1/4, \quad z = 1$



Increasing retardation: more bang for the bucks!

Standard BCS

Huang's equation versus high Tc



J.-H. She

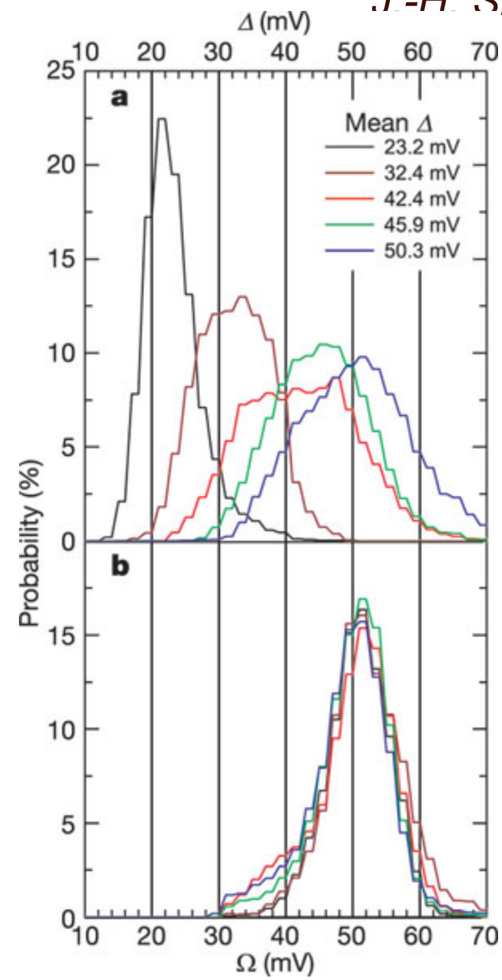
E.g. 1+1D Ising: $\eta_{pp} = 1/4, \quad z = 1$

Typical phonon-, cut-off energy: $\dfrac{\omega_B}{\omega_c} = \dfrac{50\ meV}{500\ meV}$

Typical gap: $\Delta_0 = 40\, meV$

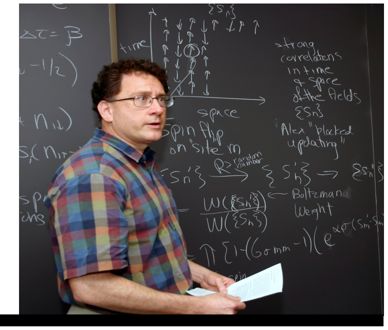
Fermi-liquid: $\lambda \approx 1.1$

Critical case: $\lambda \approx 0.3$!!!

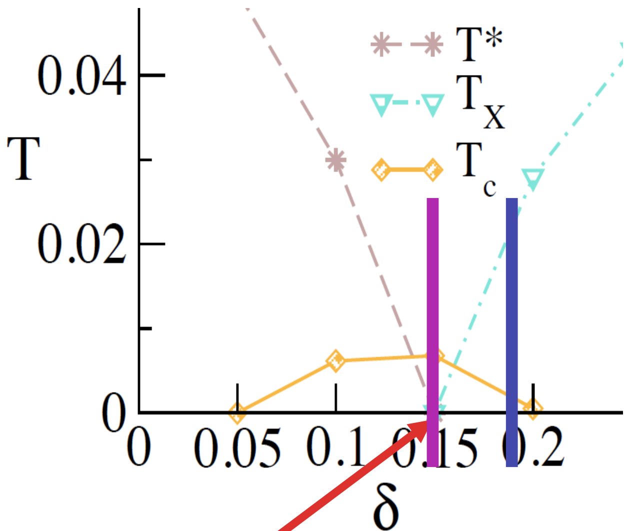


Davis, Balatsky

Jarrell's DCA quantum criticality (PRL **106**, 047004, 2011)

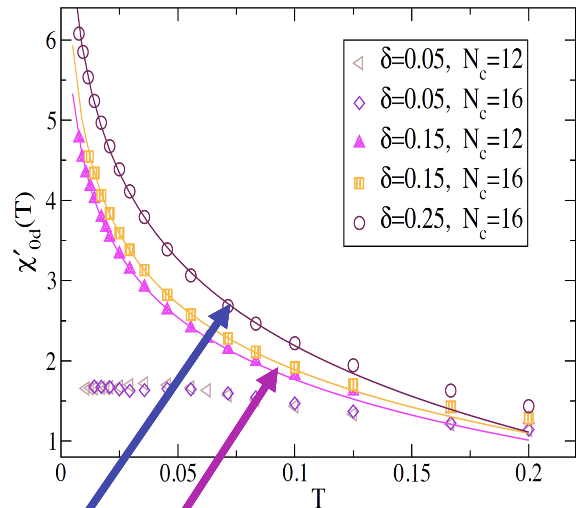


2D Hubbard model:



Phase separation quantum critical end point

Real part "bare" pair susceptibility:



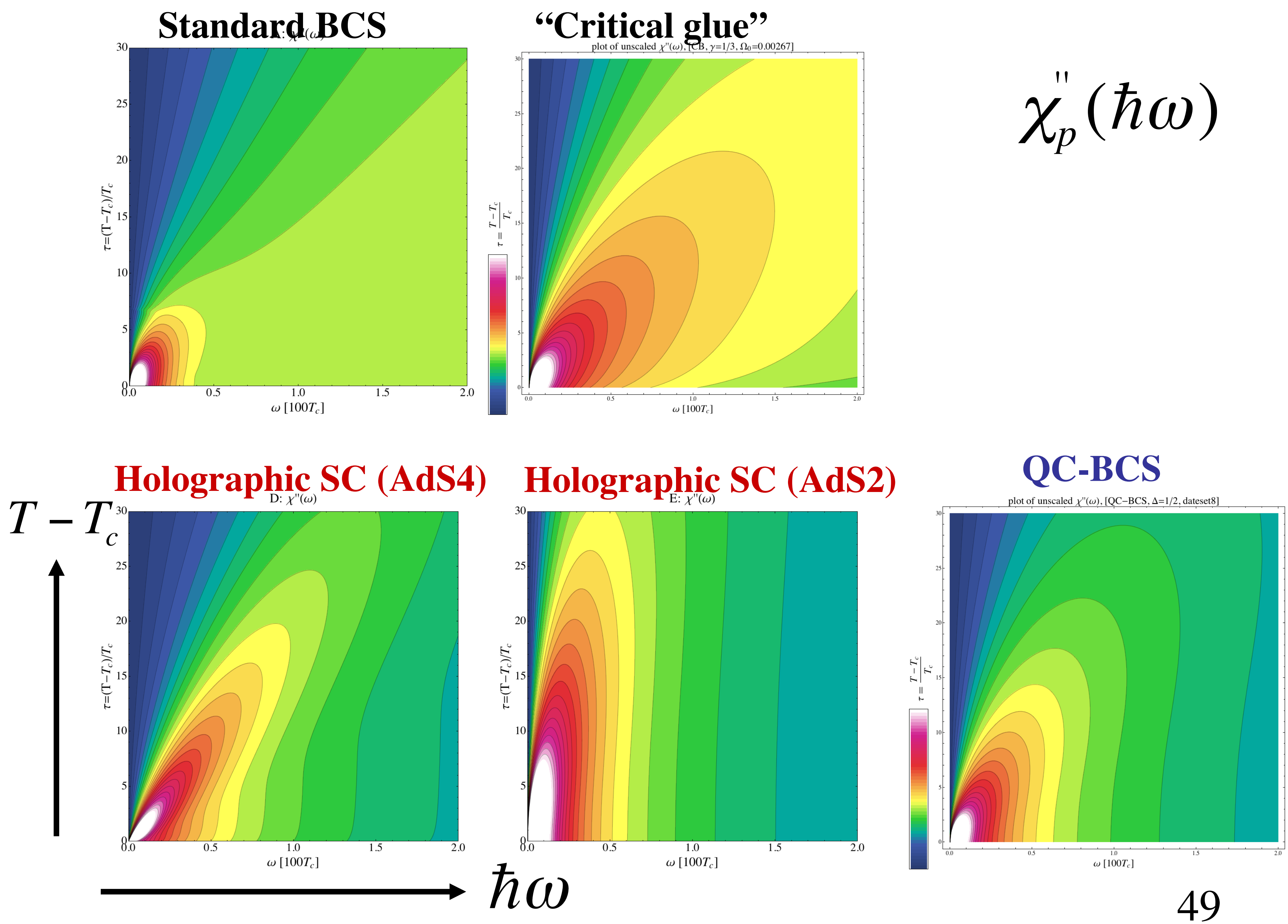
Overdoped: $\chi'_{0d}(\omega = 0) = A \ln(\omega_c/T)$

Optimally doped:

$$\chi'_{0d}(\omega = 0) = B/T^{0.5}$$

Holographic smoking gun …

Check the "energy-temperature" (conformal) scaling properties of the pair susceptibility away from the superconducting transition!


Standard BCS
"Critical glue"
plot of unscaled χ''(ω), [CB, γ=1/3, Ω₀=0.00267]
χ''_p(ħω)
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D: χ''(ω)
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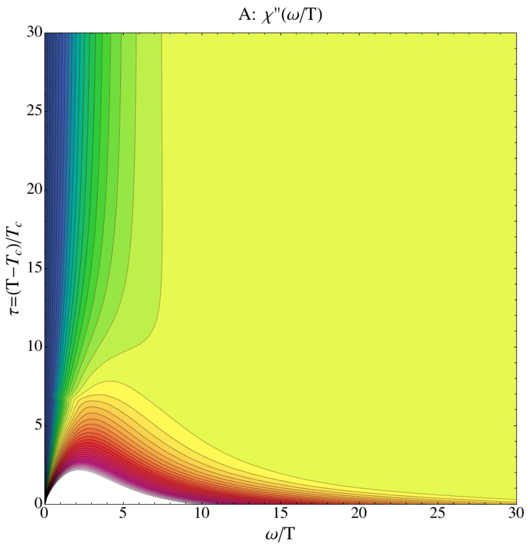
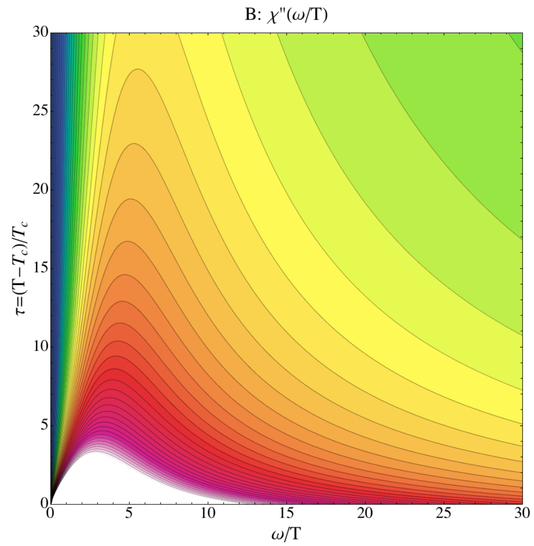
plot of unscaled χ''(ω), [QC−BCS, Δ=1/2, dataset8]
τ=(T−T_c)/T_c
ω [100T_c]
T − T_c
ħω

Standard BCS



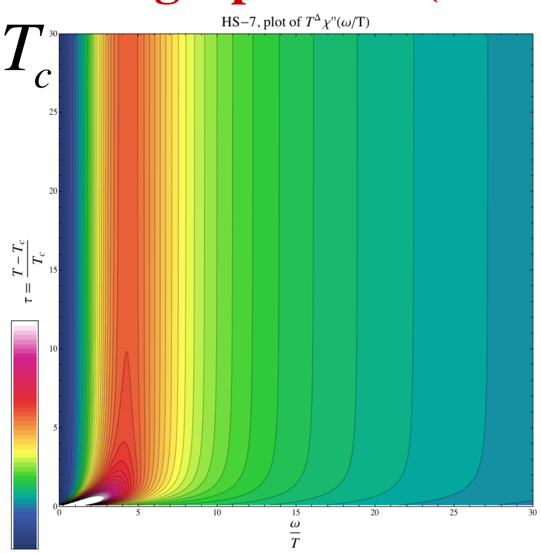
"Critical glue"



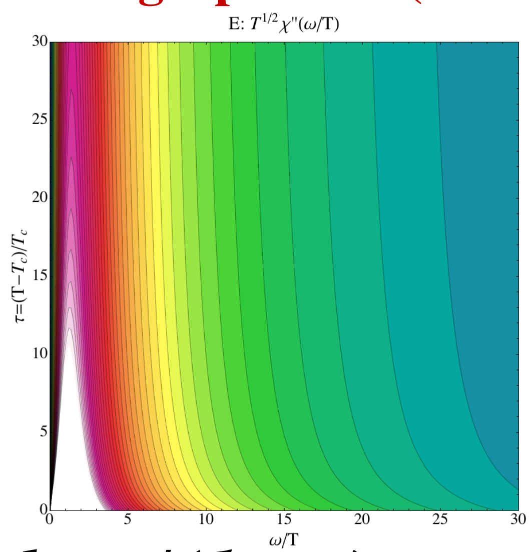
$$T^{\Delta}\chi_p''\left(\frac{\hbar\omega}{k_B T}\right)$$

$T - T_c$

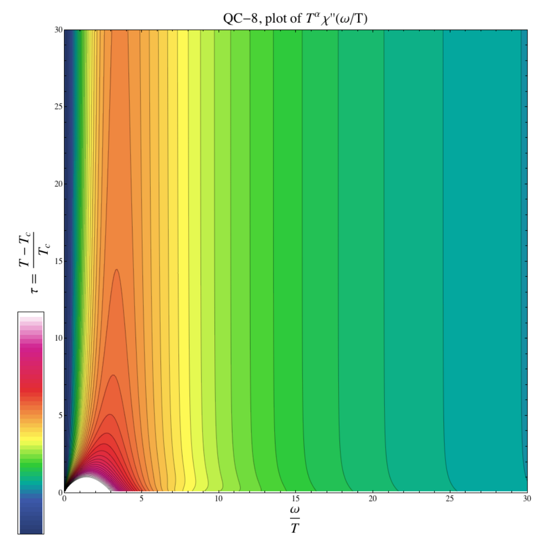
Holographic SC (AdS4)



Holographic SC (AdS2)



QC-BCS



$\hbar\omega/(k_B T)$

Holographic smoking gun …

- Fermi gas shaken from below ("Hertz-Millis"): emergent conformal metal only in deep IR. $T > T_c$: non-conformal but interesting cross-over regime knowing about E_F (Metlitski talk, Chubukov, D.H. Lee, …).

Dress the BCS fermion loop with a marginal self energy.

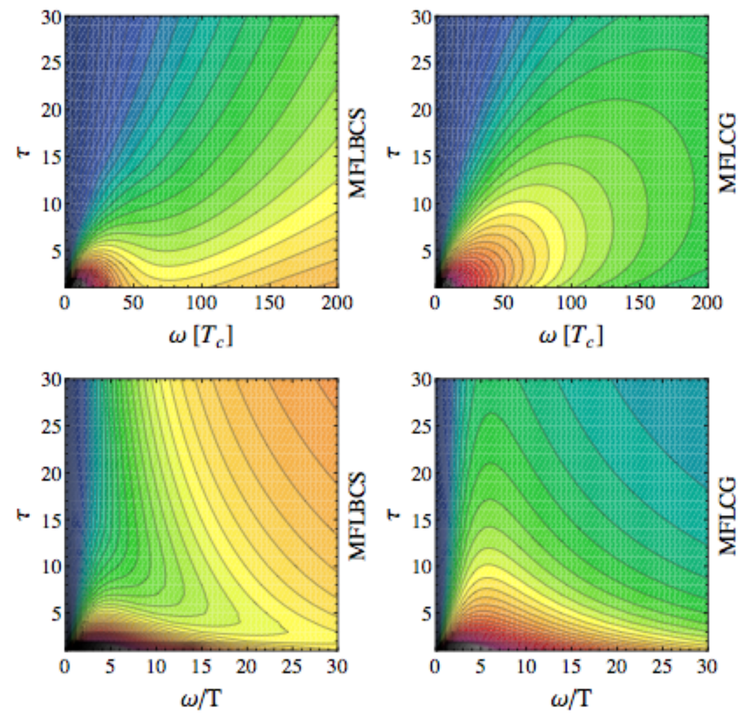


FIG. 8: (Color online) **Marginal Fermi liquid pair susceptibility with smooth density of states.** *Top*: False-color plot of the imaginary part of the pair susceptibility χ'' as function of frequency ω (in units of T_c) and reduced temperature $\tau = (T - T_c)/T_c$, for two different models: marginal Fermi-liquid with BCS pairing and marginal Fermi-liquid with critical glue. In both cases, the density of states is taken to be constant. *Bottom*: the same plot, but now the horizontal axis is rescaled by temperature while the magnitude is rescaled by temperature to a certain power: we are plotting $T^{\delta}\chi''(\omega/T, \tau)$, in order to show energy-temperature scaling at high temperatures. Here for both models $T_c = 0.01$ and $\delta = 0$. The color scheme is the same as used in the main text. For MFLBCS, the parameters are $a = 0.3, \omega_E = 1, g = 0.9627, \omega_b = 0.5$. For MFLCG, we take $a = 0.4, \omega_E = 0.2, \gamma = 1/3, \Omega_0 = 0.0134$.

Holographic smoking gun …

- Fermi gas shaken from below ("Hertz-Millis"): emergent conformal metal only in deep IR. $T > T_c$: non-conformal but interesting cross-over regime knowing about E_F (Melitski talk, Chubukov, D.H. Lee, …).

- Holographic superconductor: robust "intermediate" conformal (AdS_2) metal, collective pair response (conformal !!) completely detached from single fermion (marginal FL) response. Favorite metaphor: Luttinger liquid.

- Glue or not glue? Quantum critical BCS as poor man's double trace deformation …

Conformal metal versus the "quantum critical BCS" glue

The width of the relaxational peak knows about the glue scale:

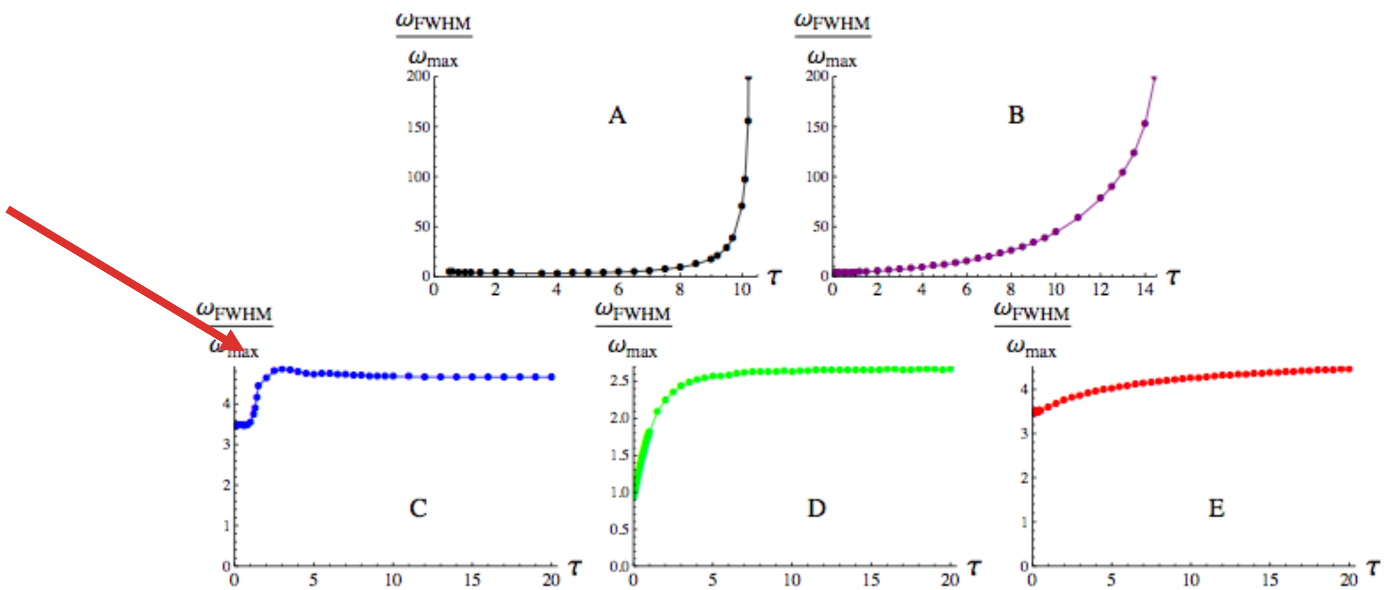


FIG. 7: (Color online) **Peak width crossover.** Evolution of the relative peak width, i.e., the ratio of the full width at half maximum (FWHM) of the peak and peak location ω_{max}, as a function of reduced temperature $\tau = (T - T_c)/T_c$ for the five different models. For FLBCS (A) and CGBCS (B), the ratio diverges at high temperature. For QCBCS (C) there is a sudden change from the low temperature relaxational behavior to the high temperature conformal field theory behavior. For the two holographic superconductors (D–E), the crossover from high temperature region to low temperature region is more smooth.

Holographic smoking gun …

- Fermi gas shaken from below ("Hertz-Millis"): emergent conformal metal only in deep IR. T > $T_{c:}$ non-conformal but interesting cross-over regime knowing about E_F (Melitski talk, Chubukov, D.H. Lee, …).

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Experiment can tell the difference!

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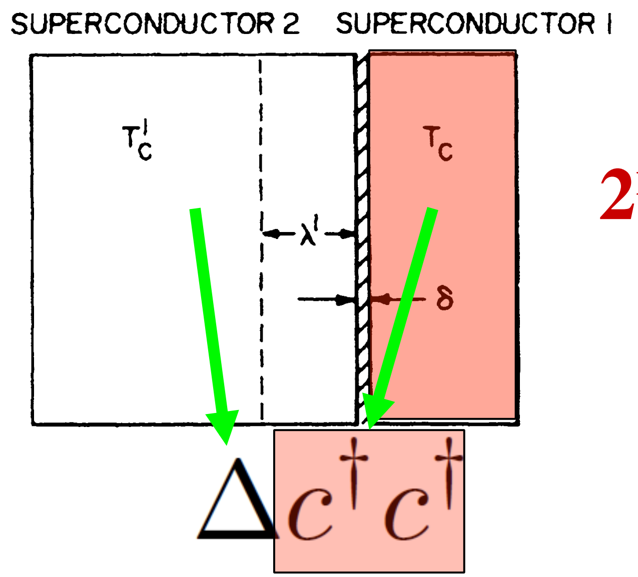
Observing the origin of the pairing mechanism



$$T_c' > T > T_c$$

2nd order Josephson effect


Ferrell Scalapino

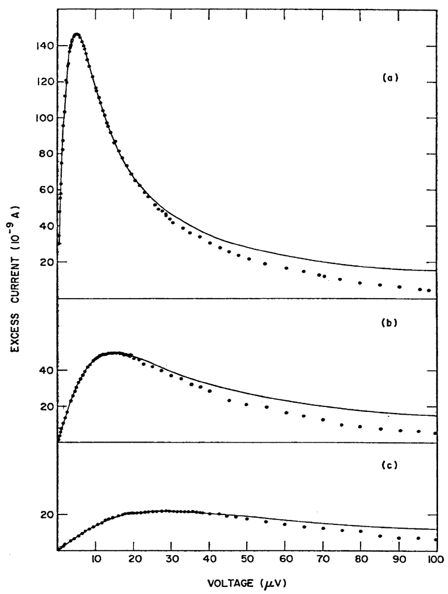
1969 1970

$$I_s(\mathbf{H}, V) \sim \frac{1}{R_N^2} \mathrm{Im}\chi_{\mathrm{pair}}(\mathbf{k}, \omega) \qquad \omega = 2eV$$

Proof of principle ....

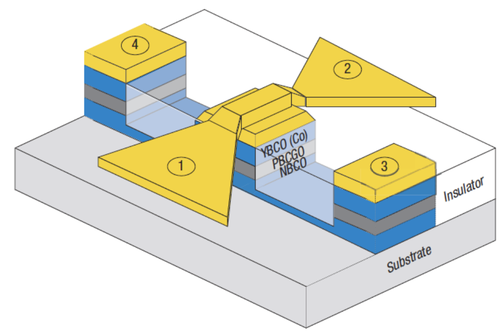
Goldman
1970's

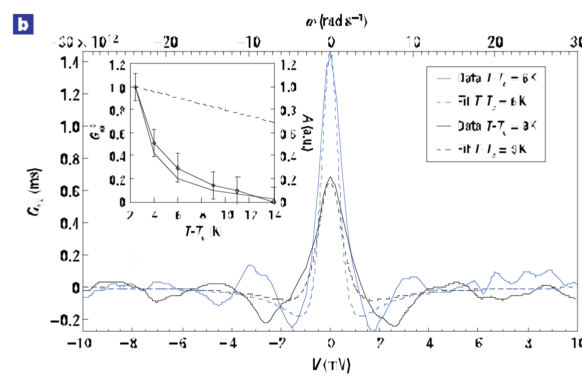
Al-Pb junction: "Relaxational peak" Al near the BCS transition



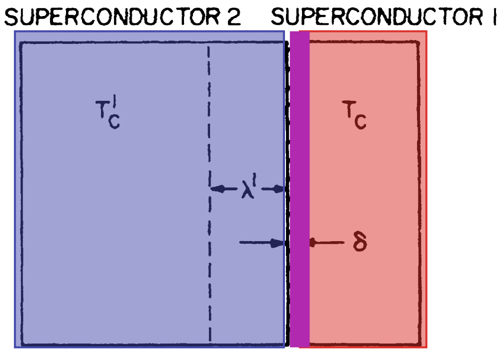
$$I_s(V) = \frac{4eA|C|^2}{dN_0\varepsilon}\frac{\omega/\Gamma_0}{1+(\omega/\Gamma_0)^2}$$

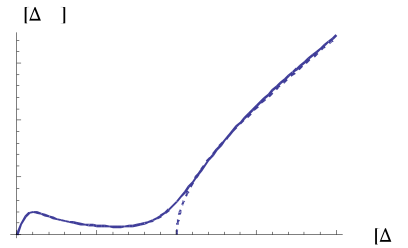
Recent: 60K-90K cuprate superconductors (Bergeal, Nature Physics 2008).





Why Webb Pairing telescope?



$$I_{tun}(V) = I_{qp}(V) + I_{pair}(V)$$

QC metal:

Need large dynamical range:

$$T, \omega \propto 10 - 100\, T_c$$

QC superconductor at ambient conditions with low Tc:

$CeIrIn_5$, $T_c = 0.4K$

Probe superconductor:

High T_c

Tunneling into d(?)-wave channel

Cuprate ?

Full gap to suppress QP current (?)

MgB_2 (Tc=40K)?

Barrier is the challenge!

Holographic smoking gun …

- Fermi gas shaken from below ("Hertz-Millis"): emergent conformal metal only in deep IR. T > $T_{c:}$ non-conformal but interesting cross-over regime knowing about E_F (Melitski talk, Chubukov, D.H. Lee, …).

- Holographic superconductor: robust "intermediate" conformal (AdS_2) metal, collective pair response (conformal !!) completely detached from single fermion (marginal FL) response. Favorite metaphor: Luttinger liquid.

- Glue or not glue? Quantum critical BCS as poor man's double trace deformation …

Experiment can tell the difference!

Further reading

AdS/CMT tutorials:

J. Mc Greevy, arXiv:0909.0518; S. Hartnoll, arXiv:0909.3553

AdS/CMT fermions:

Hong Liu et al., arXiv:0903.2477,0907.2694,1003.0010; M. Cubrovic et al. Science 325,429 (2009), arXiv:1011.xxxx; T. Faulkner et al., Science 329, 1043 (2010).

Condensed matter:

High Tc: J. Zaanen et al., Nature 430, 512, Nature Physics 2, 138; C.M. Varma et al., Phys. Rep. 361, 267417

Heavy Fermions: J. Zaanen, Science 319, 1205; von Loehneisen et al, Rev. Mod. Phys. 79, 1015