CCCQS, Evora, October 2014

Transport theory of short coherence length superconductors

Assa Auerbach, Technion, Israel

1. Signatures of breakdown of BCS theory
2. Higgs mode in Superconducting films
3. Optical conductivity and Linear resistivity

Netanel Lindner and AA, ***PRB 81, (2010).***
Netanel Lindner, AA and Dan Arovas, ***PRB 82, (2010)***
Daniel Podolsky, AA and Dan Arovas, ***PRB 84, (2011)***
Snir Gazit, Daniel Podolsky, AA PRL 110 (2013) + arxiv 1407.1055
Snir Gazit, Daniel Podolsky, AA, D. Arovas (PRB 2013).

Bardeen Cooper Schrieffer, 1957

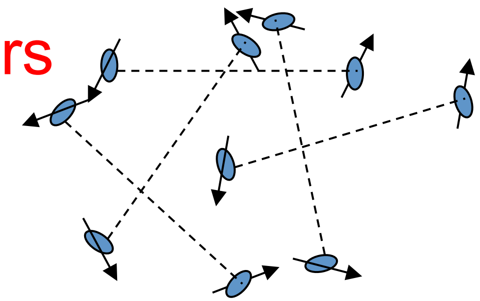
1972

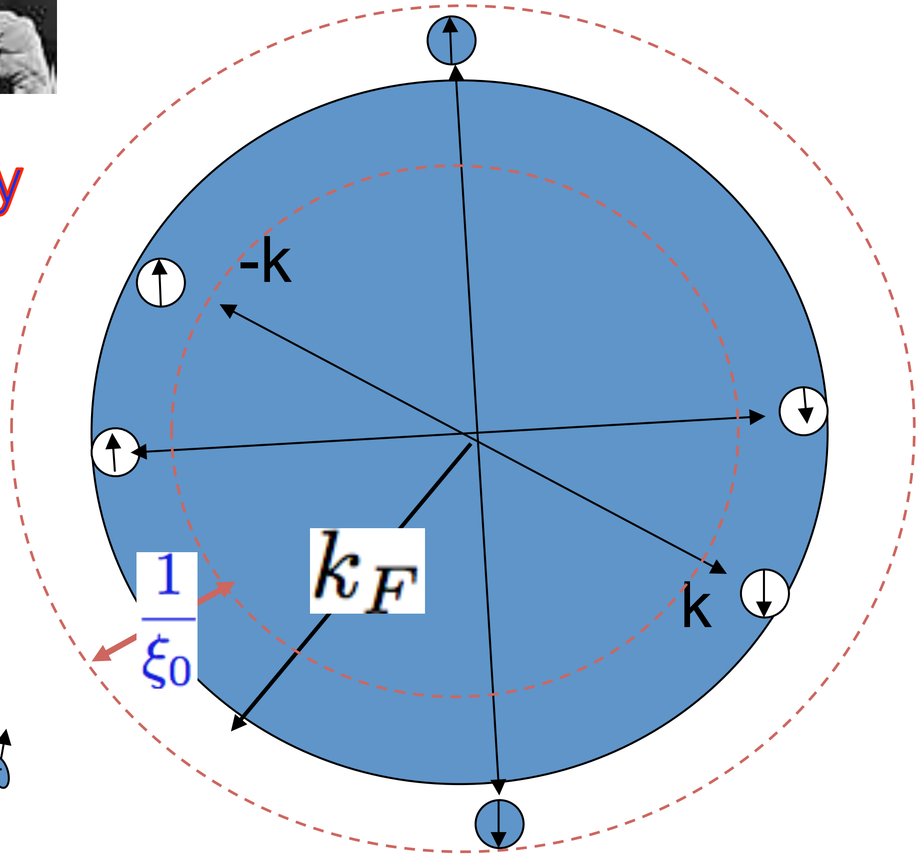
k-space pairing instability

$$\langle c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} \rangle = \Delta$$

$$k_F \xi_0 \sim \epsilon_F / \Delta >> 1$$

large pairs

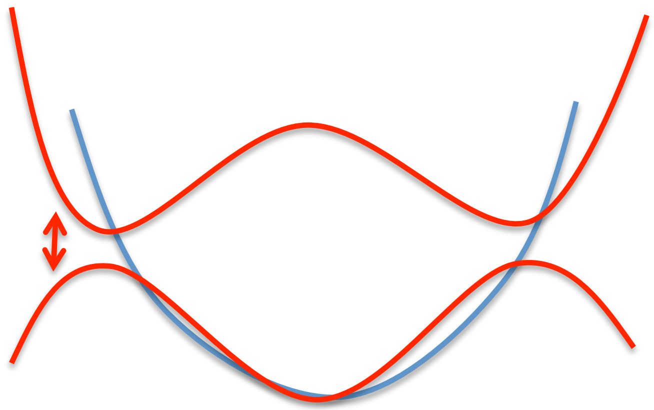




Schrieffer's ballroom dance

BCS relations

$$\langle c^{\dagger}_{k\uparrow} c^{\dagger}_{-k\downarrow} \rangle = \Delta$$



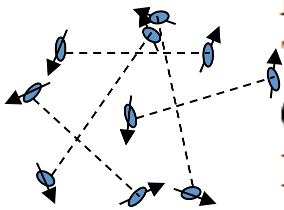
1. order parameter ~ excitation gap ~ Tc

2. superfluid density ~ Fermi energy (suppressed phase fluctuations)

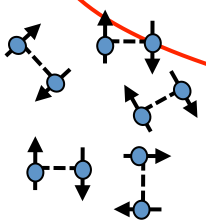
1. large coherence length (overlapping pairs)

Superconductors coherence length (by H_{c2})

Guy Deutscher & Bok 1993

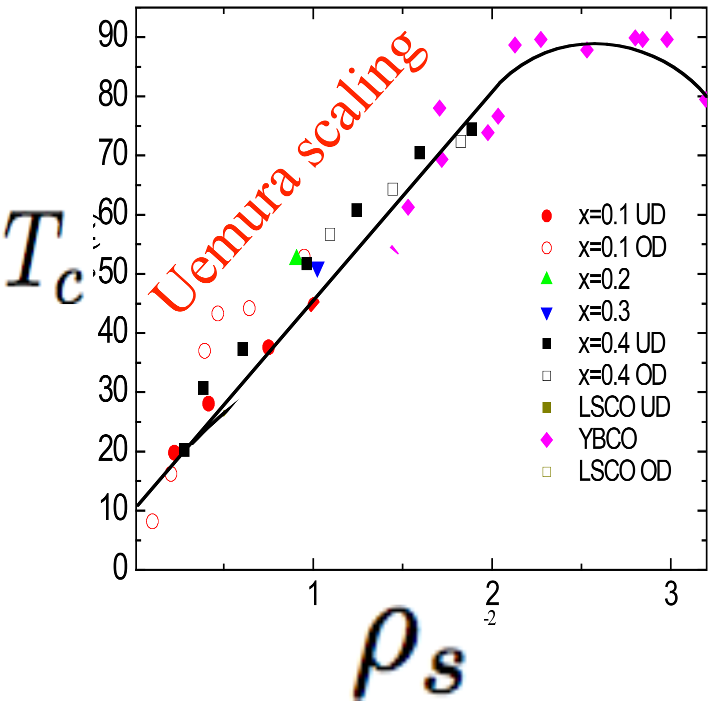


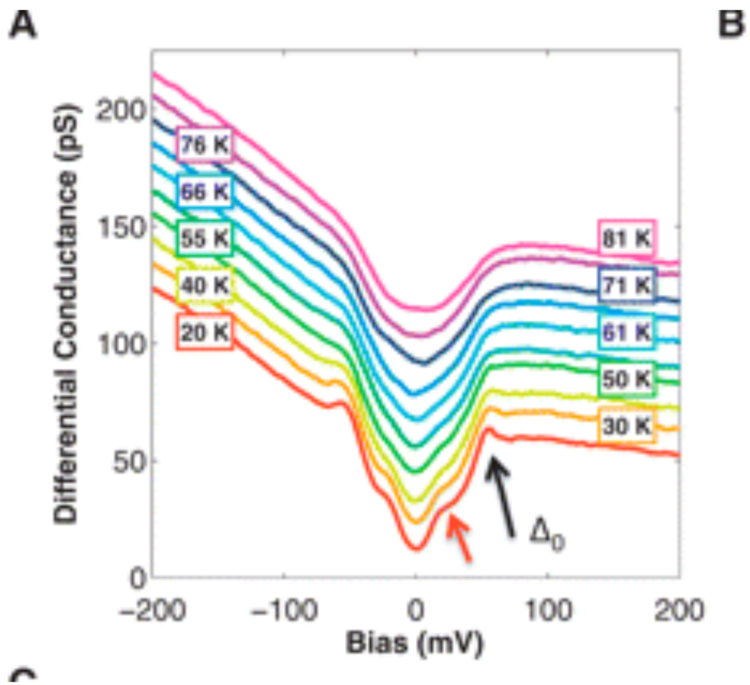
	T_c (K)		ξ (μm)	$k_F \xi$
Aluminium (1)	1.19	BCS regime	1.20	~1000
Indium (1)	3.40		0.33	
Tin (1)	3.72		0.26	~100
Callium (1)	5.90		0.16	
Lead (1)	7.20		0.080	
Niobium (1)	9.25		0.035	~10
$PbMoS_8$ (2)	15		0.0025	
Nb_3Sn (1)	17		0.0040	
$C_{60}K_3$ (3)	19	bosonic	0.0030	
$C_{60}Rb_3$ (3)	31		0.0023	~1
$Pr_{.4}Y_{.6}Ba_2Cu_3O_7$ (4)	40		0.007	
$YBa_2Cu_3O_7$ (1)	93		0.0015	
$BaFe_{1.8}Co_{0.2}As_2$	Yi Yin et. al. PRL 2009		0.0027	



Breakdown of BCS and Fermi Liquid Theory

Cuprates: Keren et al.

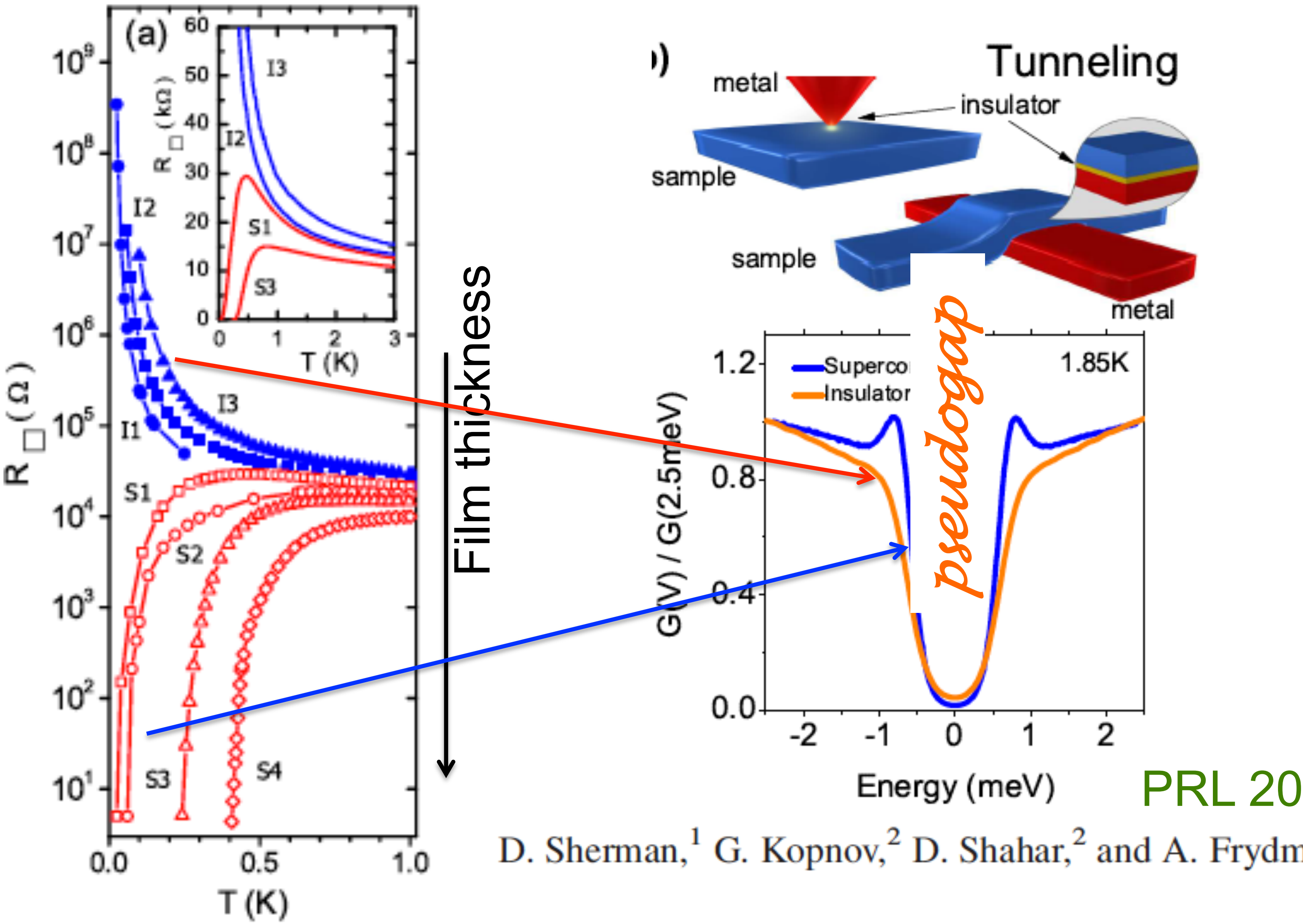




1. T_c driven by phase (bosonic) fluctuations

2. Pairing gap survives above T_c

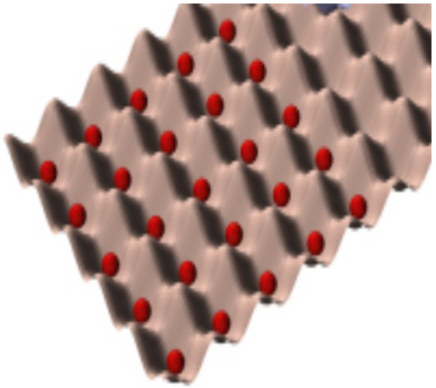
Superconductor to Insulator transition



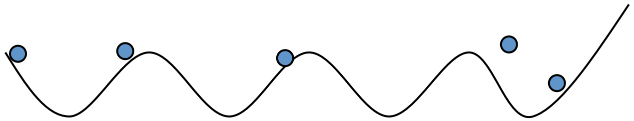
PRL 2012

D. Sherman,[1] G. Kopnov,[2] D. Shahar,[2] and A. Frydman[1]

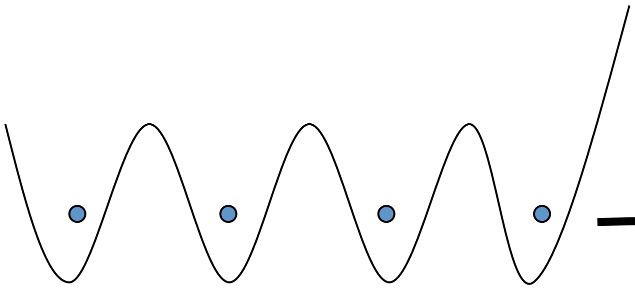
SF – Mott in Cold Atoms



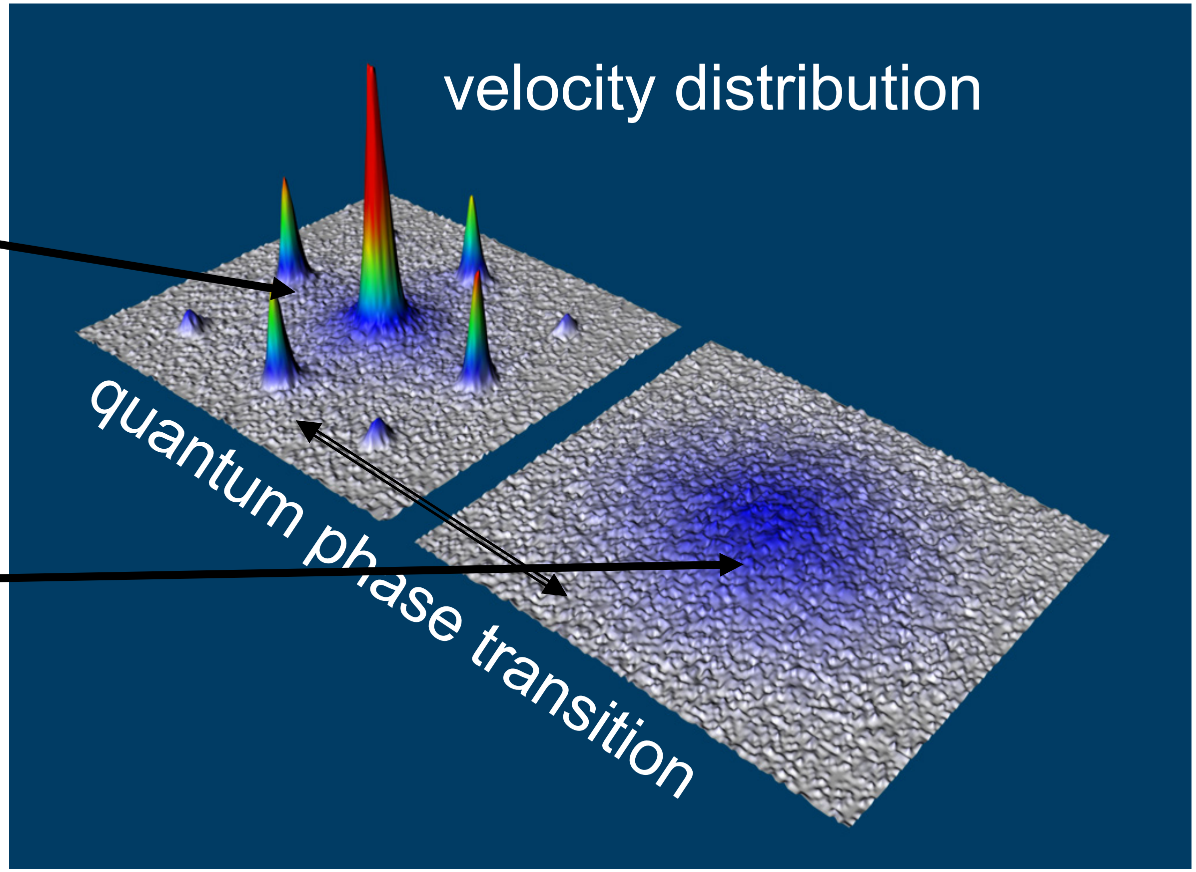
I. Bloch



superfluid



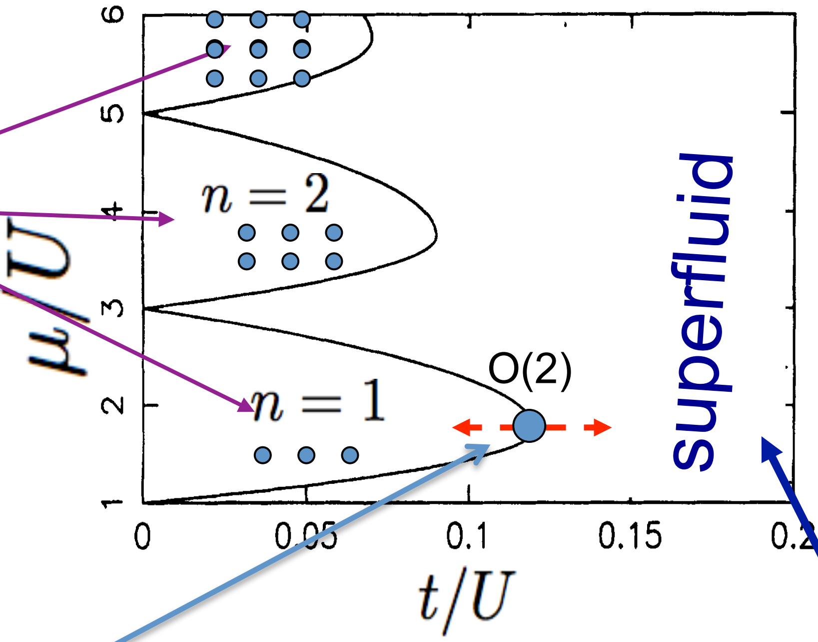
Mott insulator



Bose Hubbard Model

$$\mathcal{H} = -t\sum_{ij} a_i^\dagger a_j + U\sum n_i{}^2 - \mu\sum_i n_i$$

Zimanyi et. al (1994)



Mott insulators

incompressible

$\langle \psi^\dagger \rangle = 0$

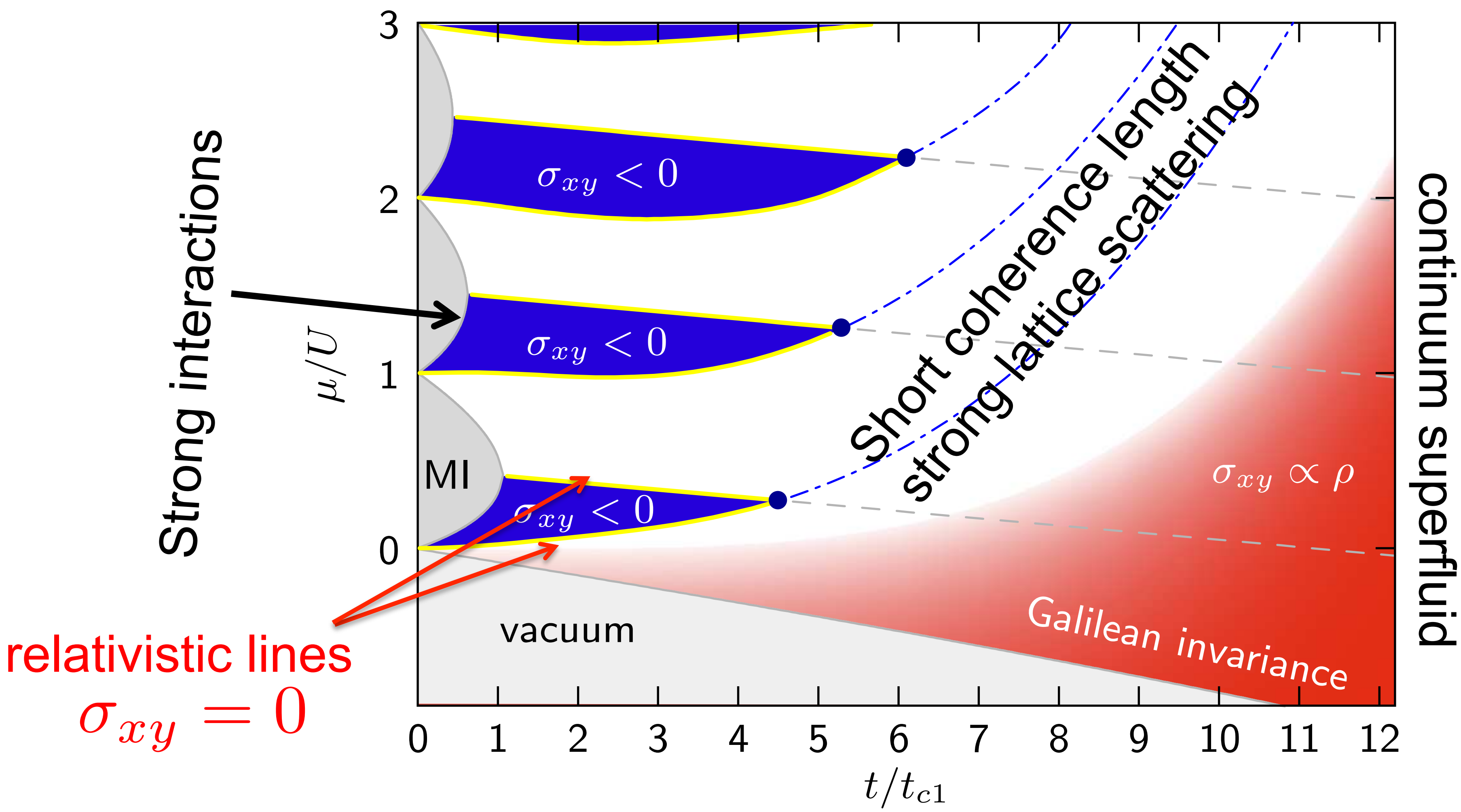
$\langle n_j^2 \rangle \approx (\langle n_i \rangle)^2$

d+1 Quantum Critical Point

Continuum
Gross Pitaevskii
Theory $\psi(x)$

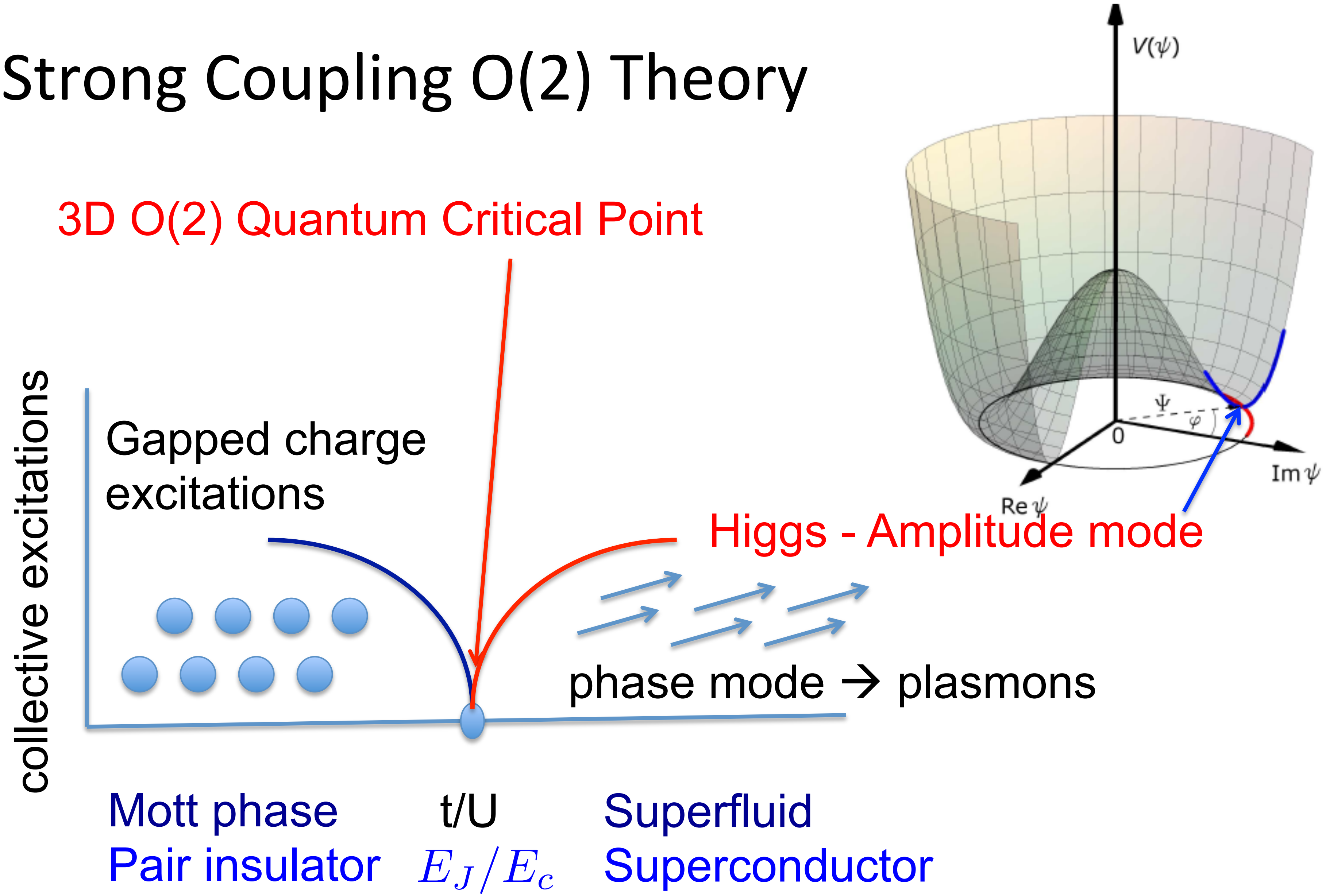
Hall Coefficient Map

Sebi Huber, Netanel Lindner, PNAS 2011



Lattice-induced Hall sign reversals

Strong Coupling O(2) Theory

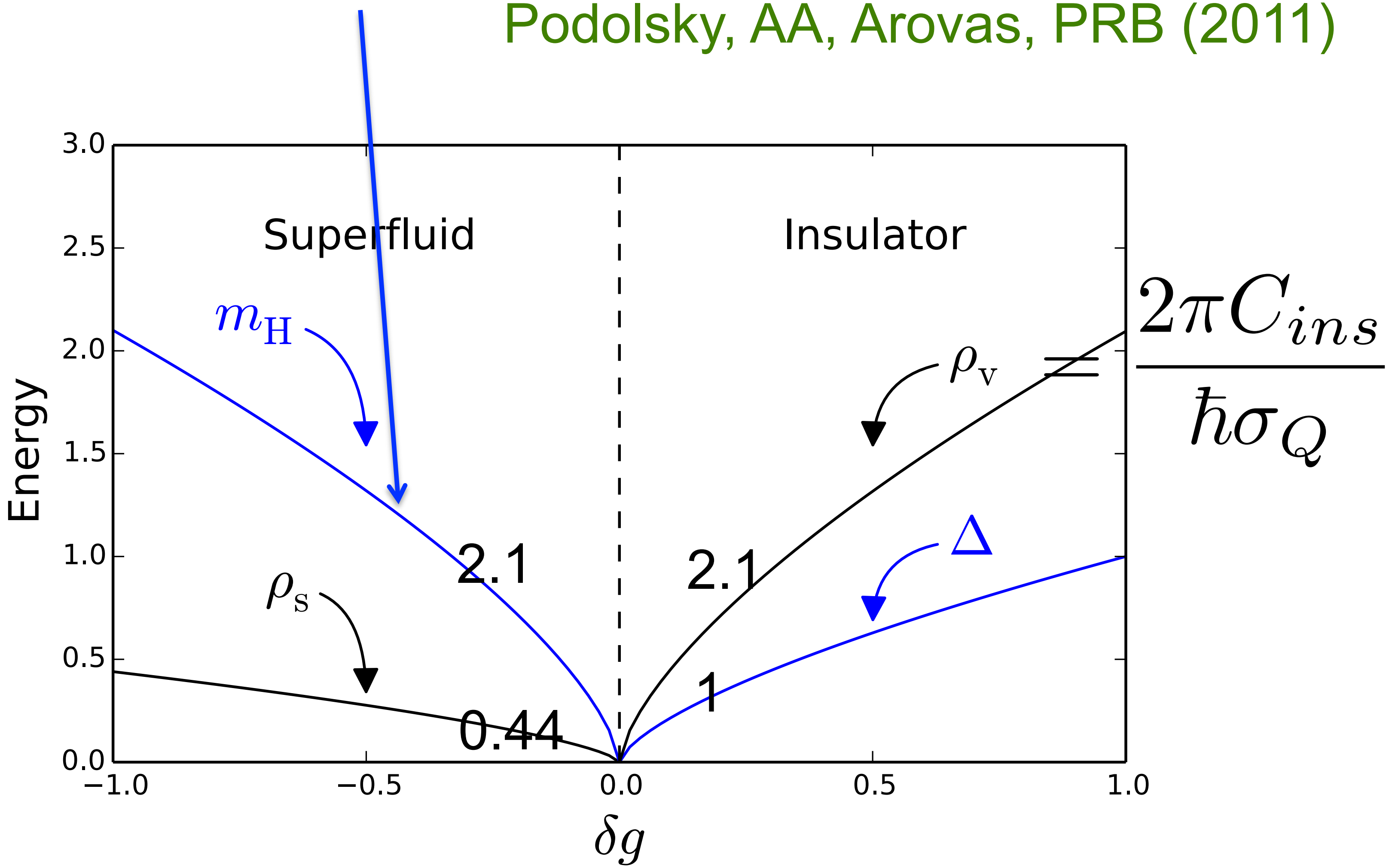


Charge-Vortex duality?

Critical Energy Scales

Recent results: Higgs mode is not overdamped in d=2!

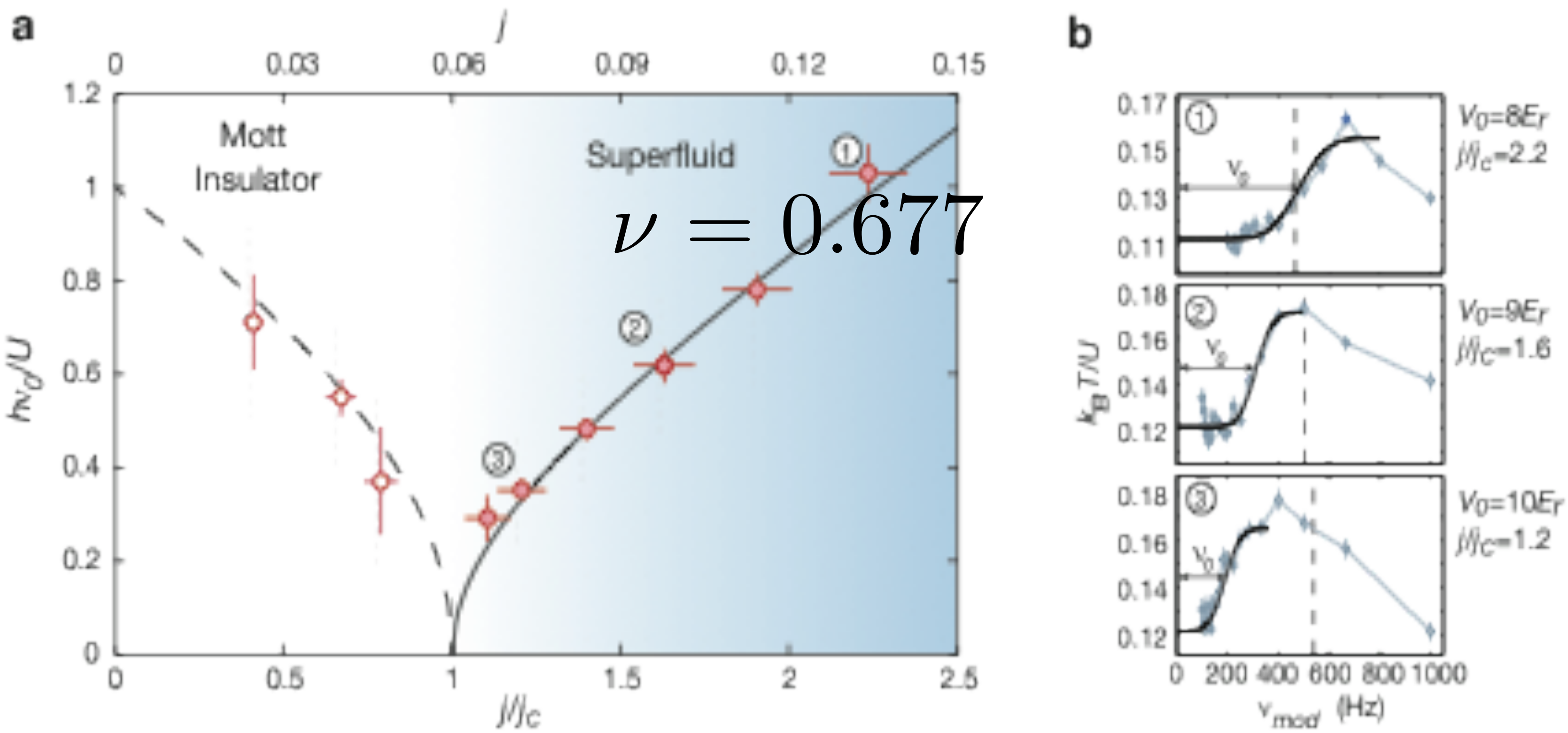
Podolsky, AA, Arovas, PRB (2011)



Approximate Charge-Vortex Duality: Gazit et. al. Arxiv 1407.1055

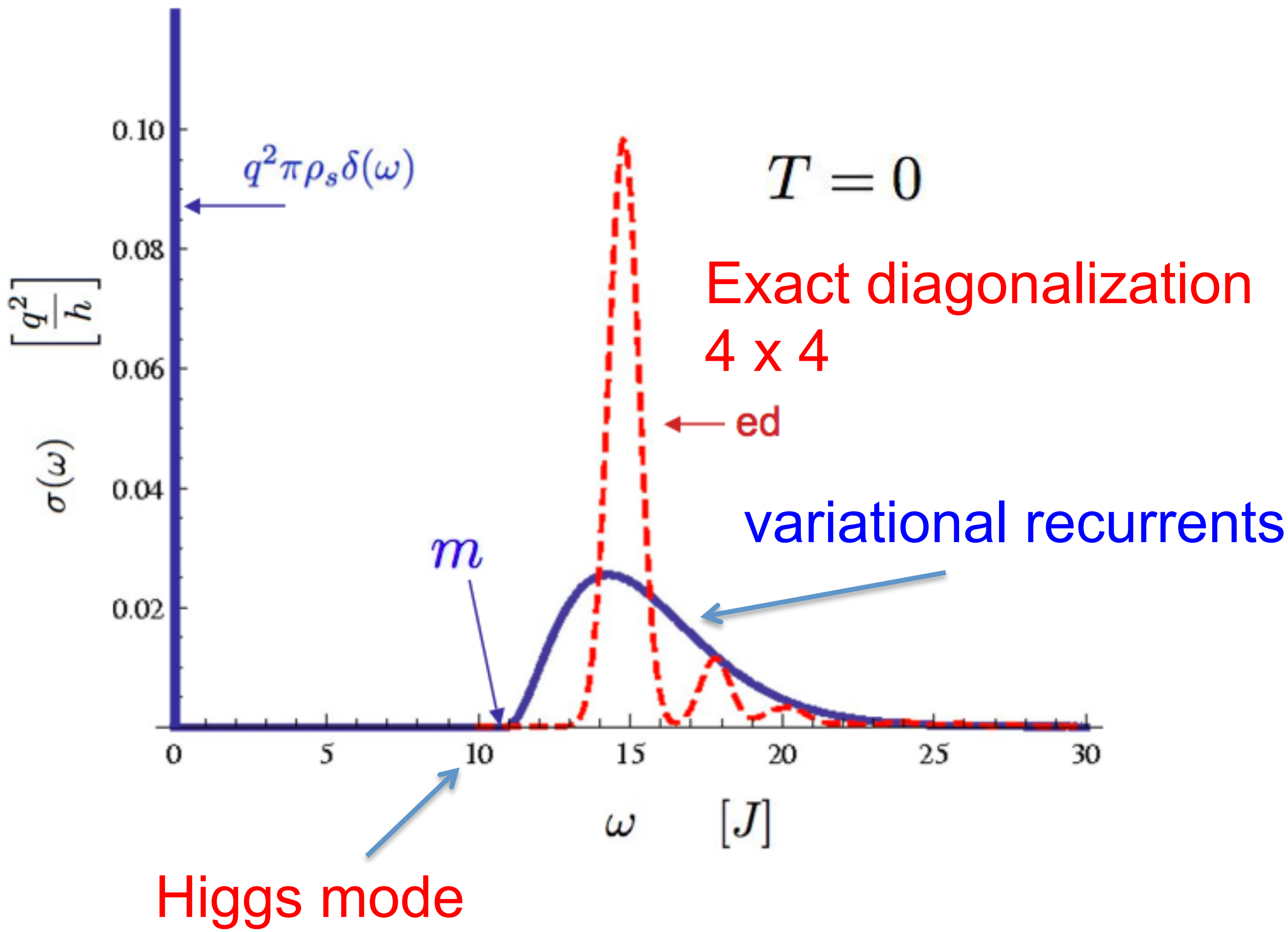
Higgs mode in cold atoms

Experiments at MPI: Endres *et al.* (Nature, 2012)



T=0 AC Conductivity of Hard Core Bosons

Lindner AA, *Phys. Rev. B81, 054512, (2010).*

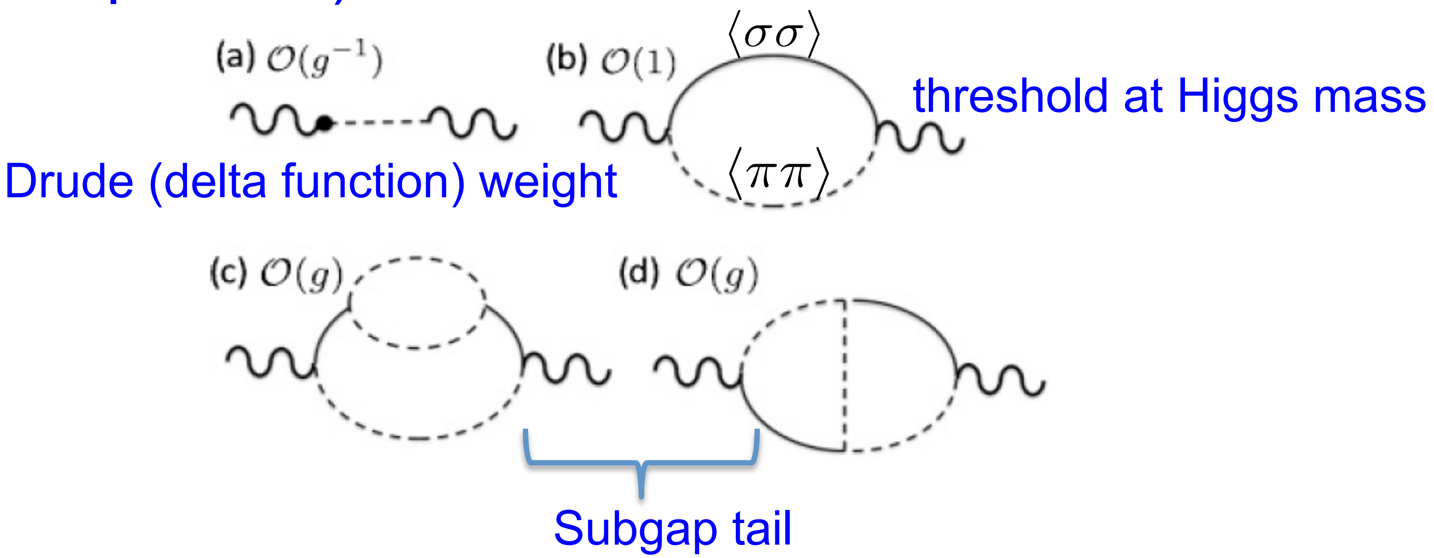


Conductivity of O(2) superfluid

Daniel Podolsky, AA and Dan Arovas, ***PRB 84, (2011)***

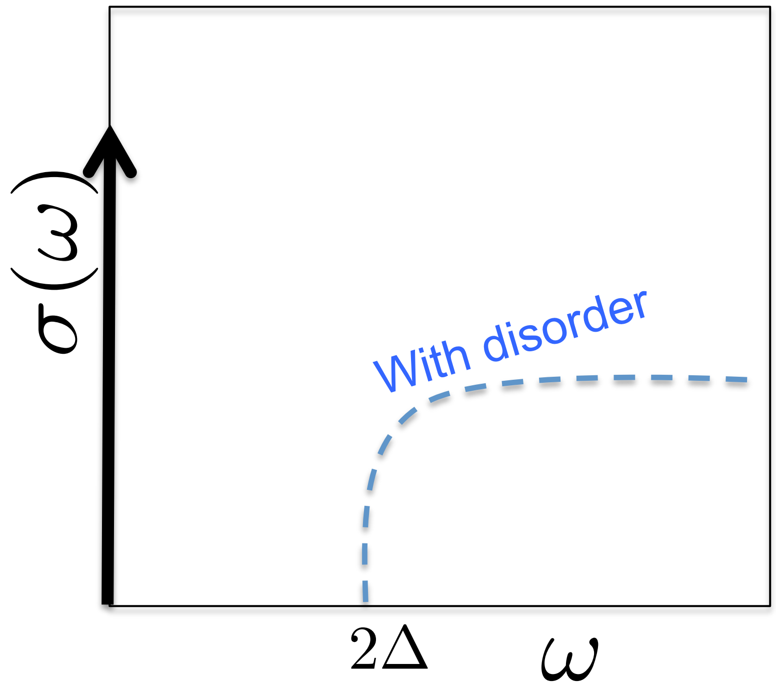
$$L_{\rm em} = q\mathbf{A}\cdot(\nabla\pi)(|\bar{\psi}|^2 + 2\sigma|\bar{\psi}| + \ldots)$$

Small g (loop expansion)



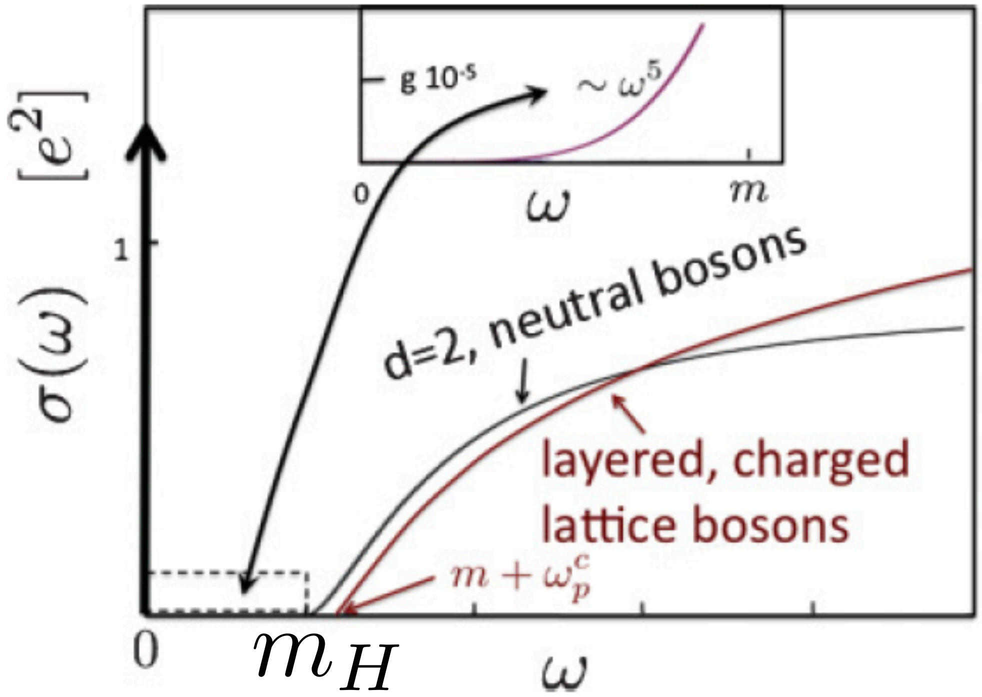
AC conductivity of superconductors

BCS / Mattis-Bardeen

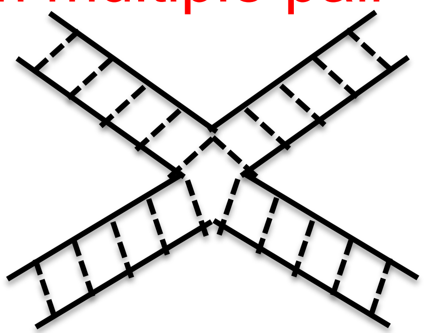


O(2) (bosonic) theory

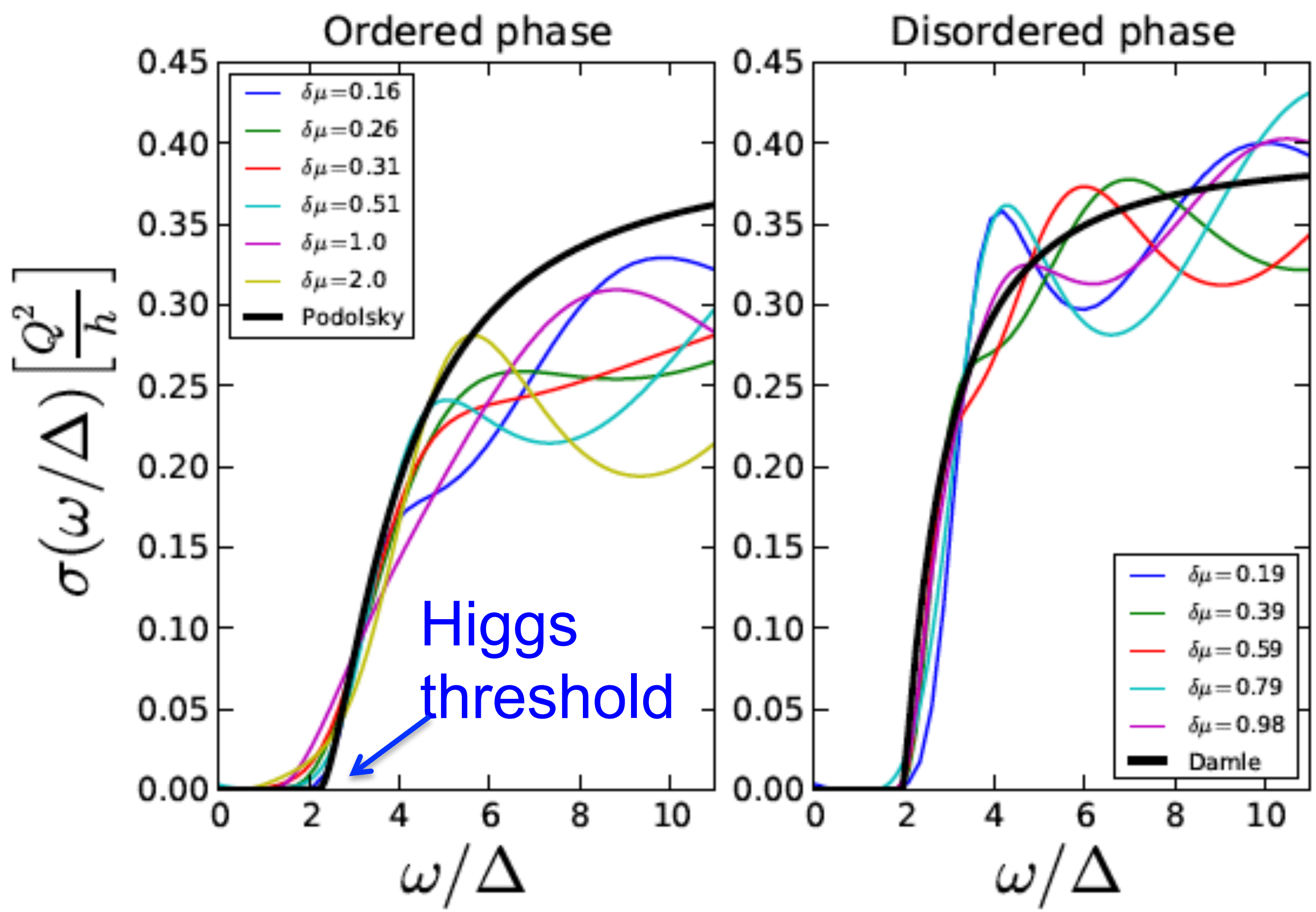
Podolsky, AA Arovas, PRB (2011)



Higgs mode arises from multiple pair interactions



AC Conductivity – QMC numerics

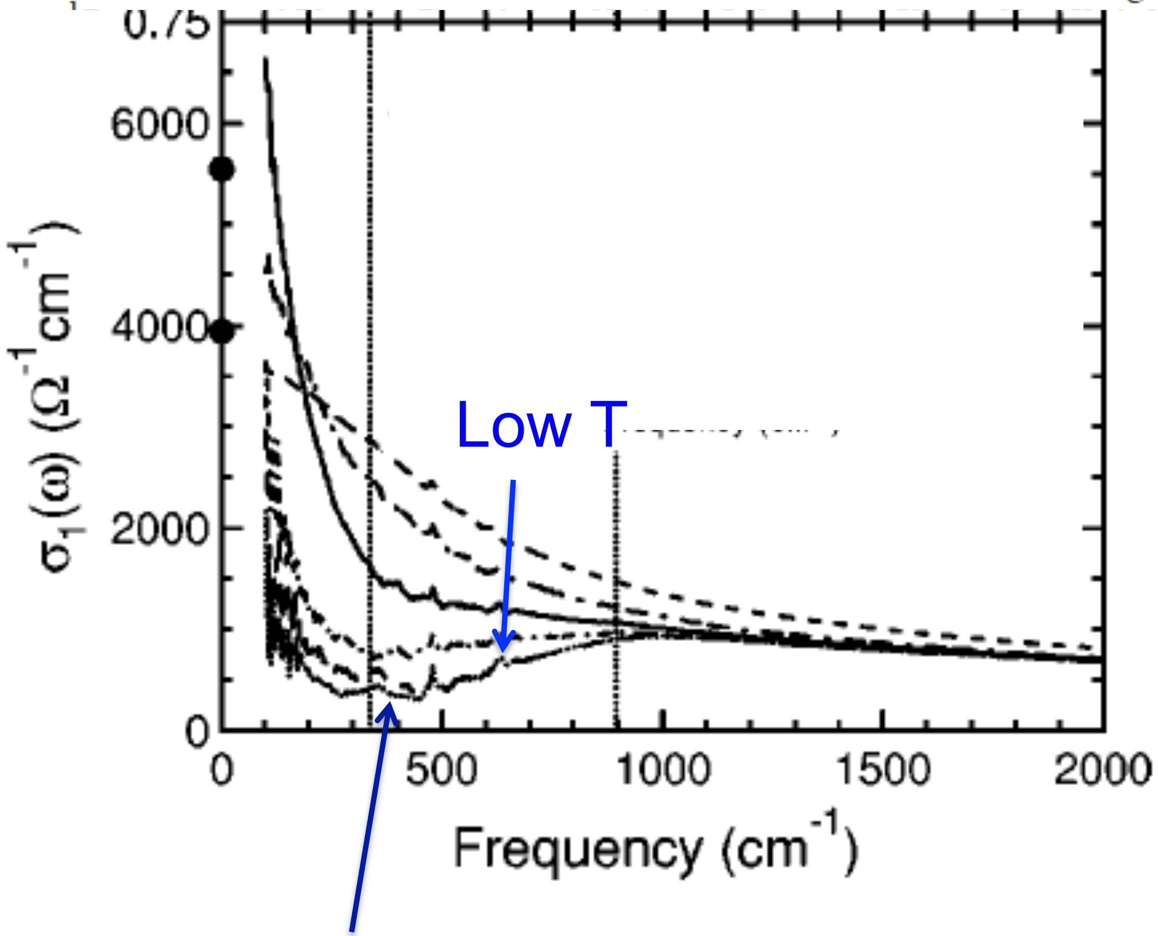


Worm-QMC: Snir Gazit, Ph.D. Thesis, Technion

PHYSICAL REVIEW B **66**, 144514 (2002)

Optical studies of charge dynamics in optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

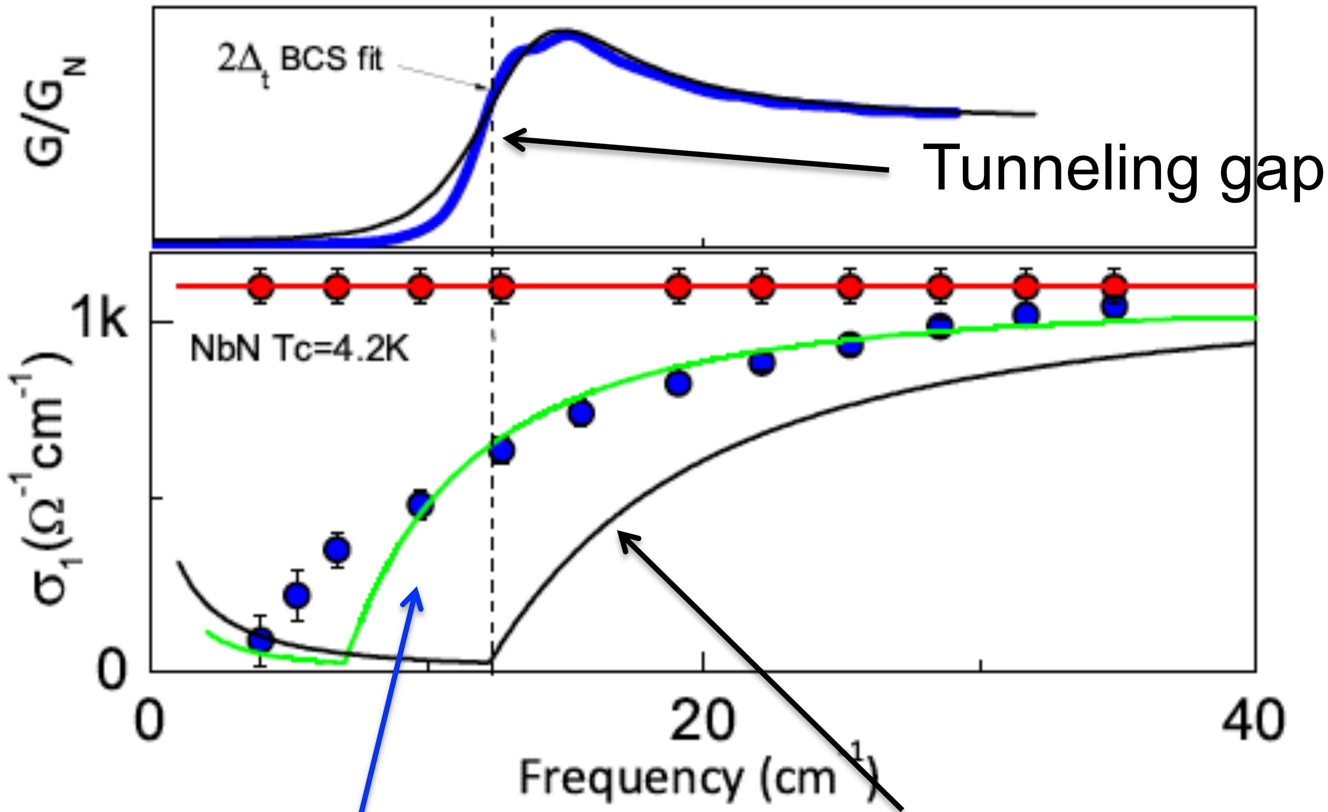
J. J. Tu,[1,*] C. C. Homes,[1] G. D. Gu,[1] D. N. Basov,[2] and M. Strongin[1]



Is the mid IR threshold at 400 cm-1 the superconductor Higgs mode?

Higgs threshold in SC Films

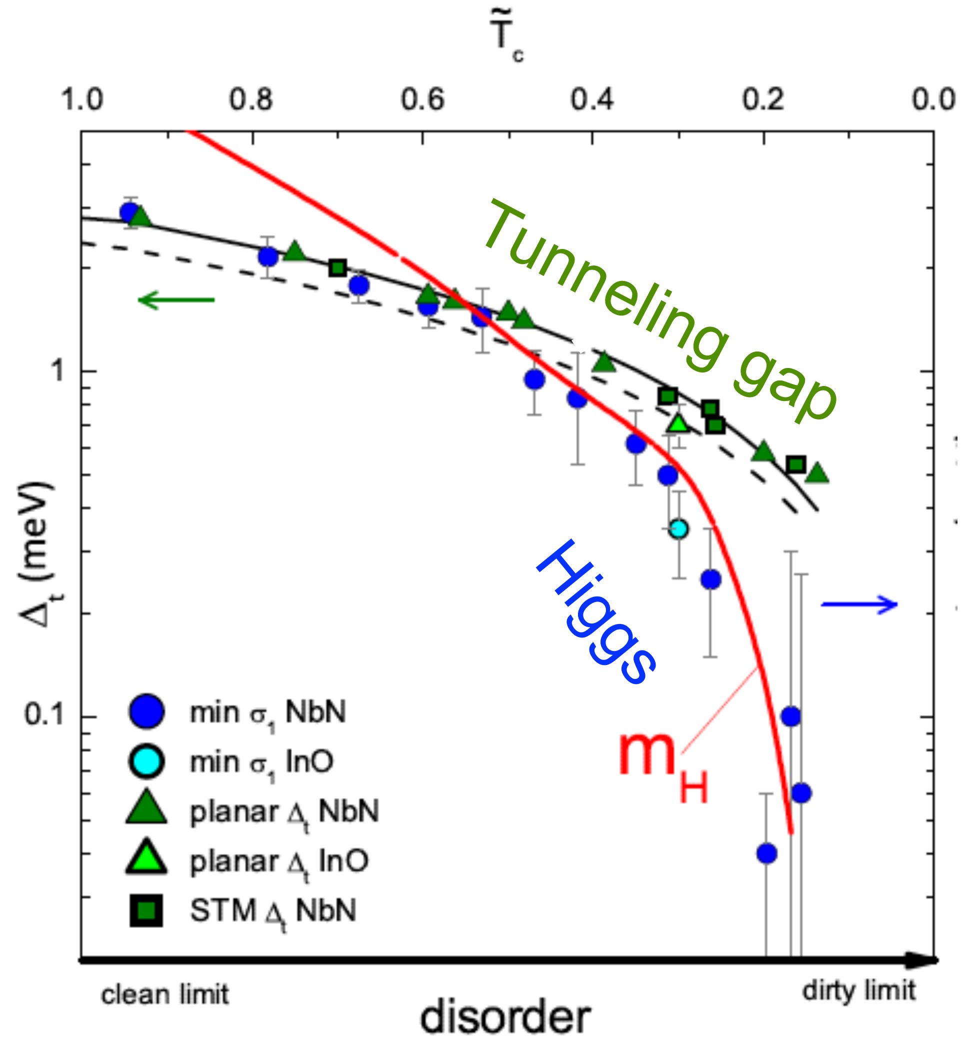
Sherman et al. (under review)



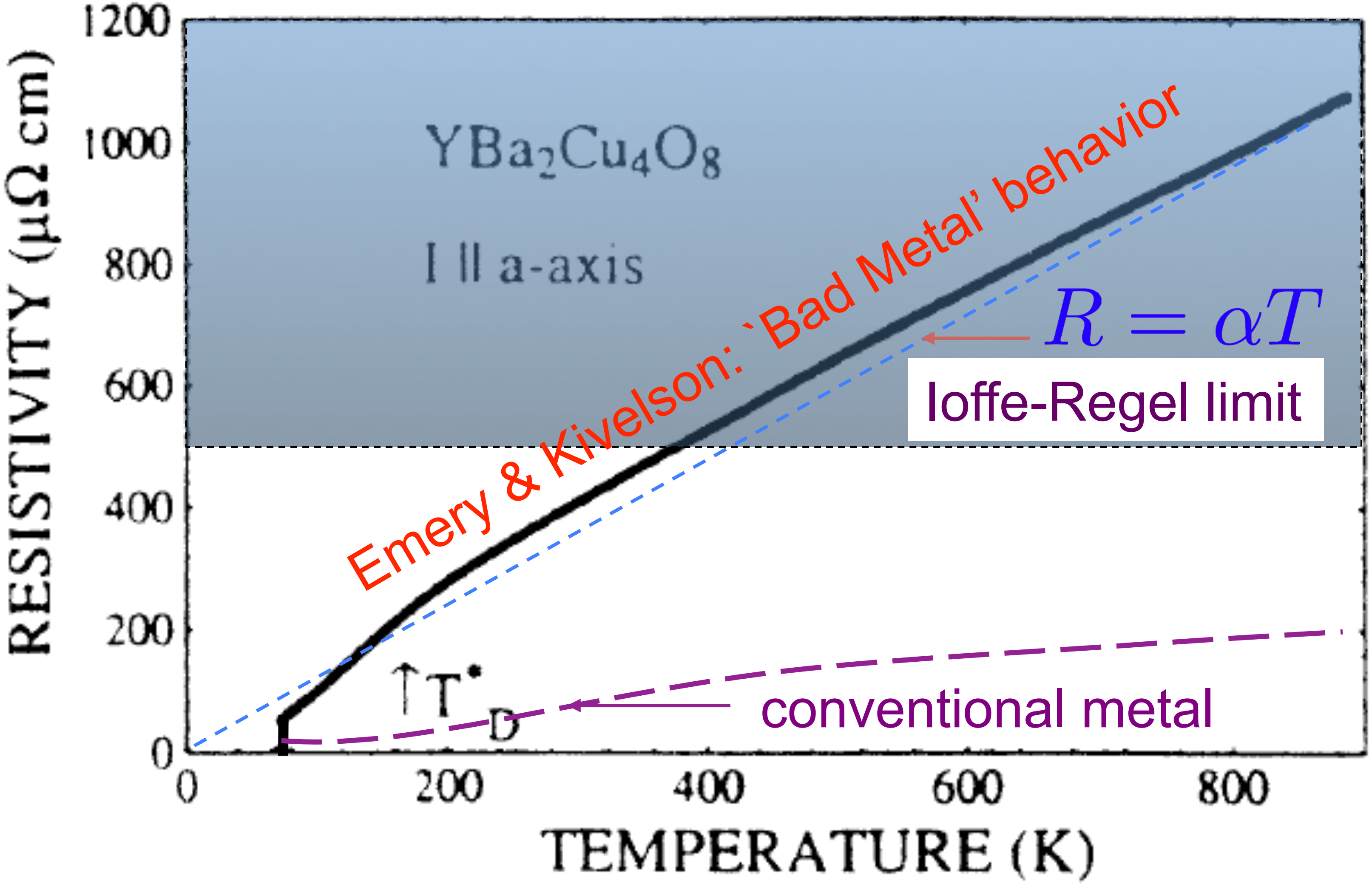
Extra optical spectral weight below tunneling gap. Higgs mode !!

Mattis Bardeen conductivity using tunneling gap

Signature of Quantum Criticality

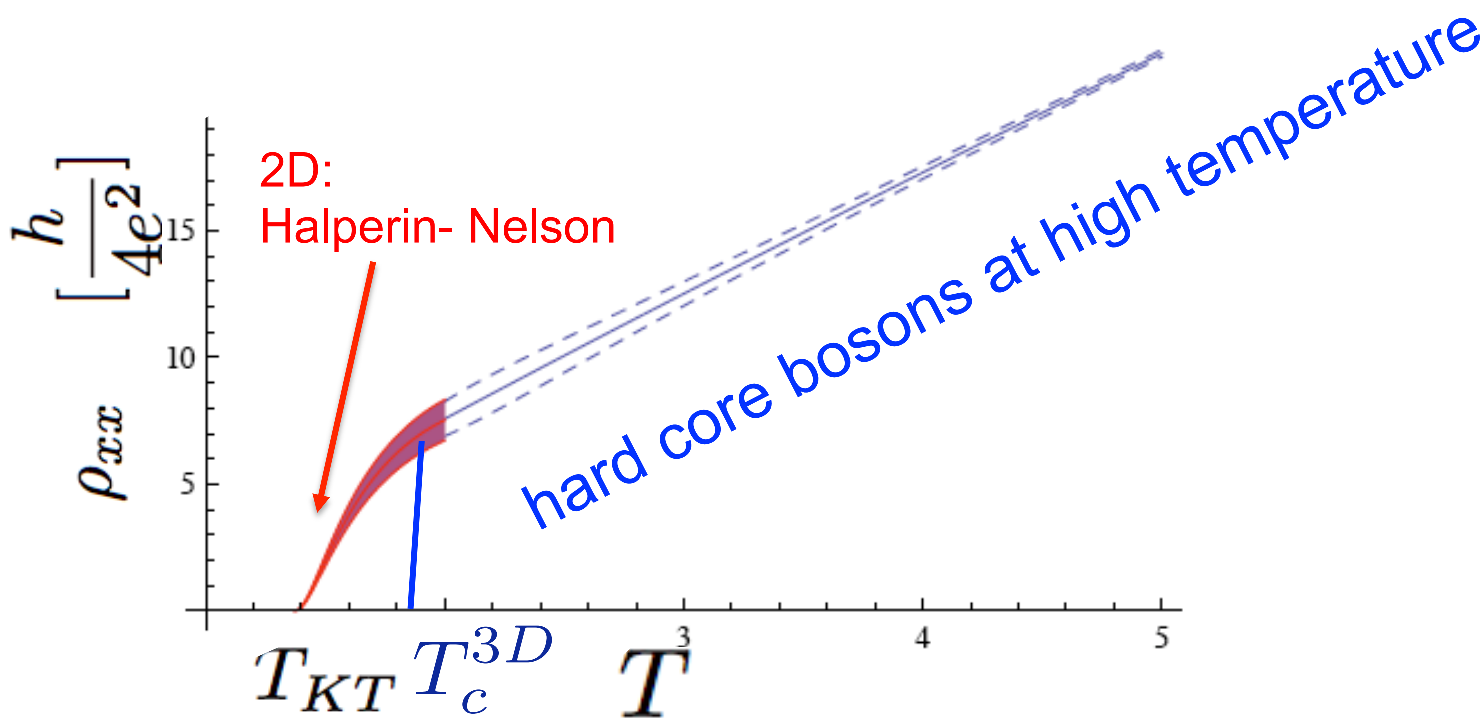


The "Linear Resistivity Problem"



Resistivity of Hard Core Bosons

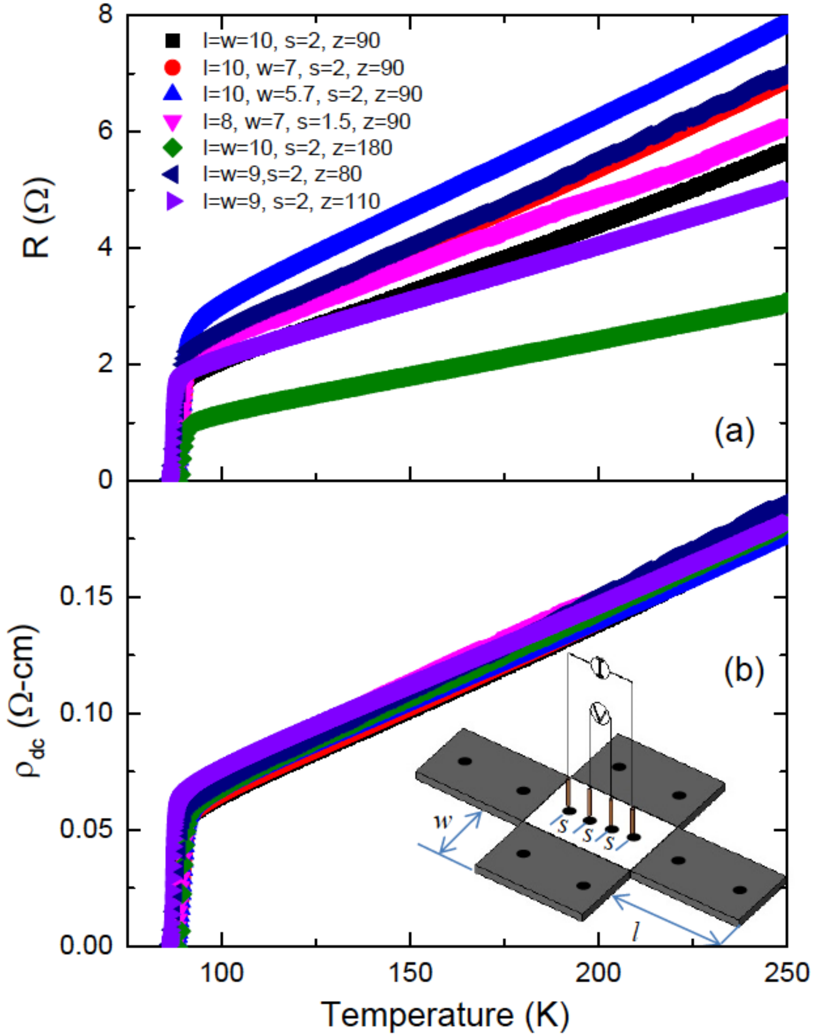
N. Lindner and AA, PRB 81, (2010).
Continued Fractions Kubo calculation

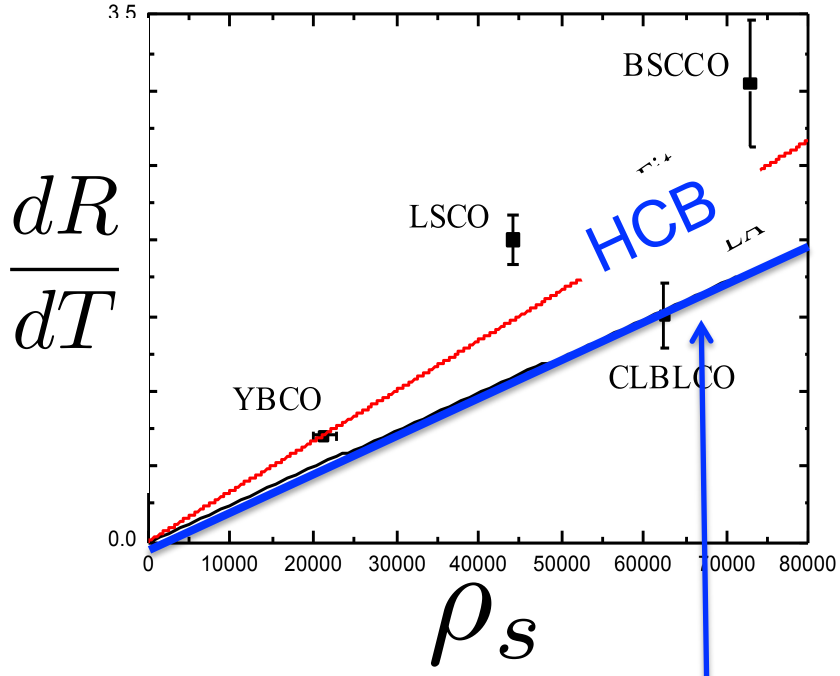


Predicts a relation: $\rho_s(0) = 0.245 \frac{h}{4e^2} \left(\frac{dR}{dT} \right)^{-1}$

Cuprates: universality of Resistivity slopes

Amit Keren's group





hard core bosons

$$\rho_s(0) = 0.245 \frac{h}{4e^2} \left(\frac{dR}{dT} \right)^{-1}$$

Summary

Short coherence length superconductors have different dynamics and transport than conventional BCS theory.

- Breakdown of BCS relations between gap, OP, and Tc
- Hall sign reversals
- A soft (critical) amplitude / Higgs mode.
- Higgs threshold in optical conductivity.
- Asymptotic linear resistivity above Tc.
- Linear resistivity, with a slope related to SF density.