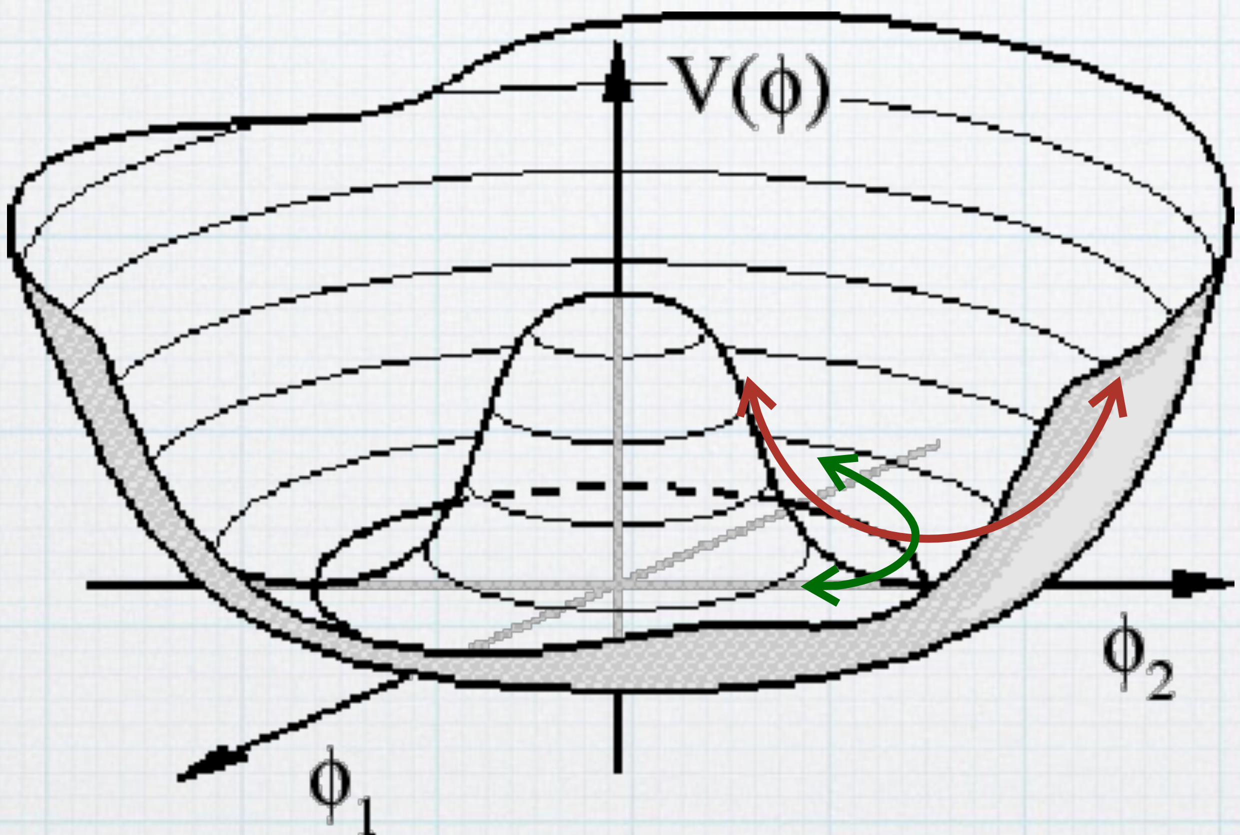
The Higgs particle in condensed matter

Assa Auerbach, Technion



N. H. Lindner and A. A, *Phys. Rev. B* **81**, 054512 (2010)
D. Podolsky, A. A, and D. P. Arovas, *Phys. Rev. B* **84**, 174522 (2011)S. Gazit, D. Podolsky, A.A, Phys. Rev. Lett. 110, 140401 (2013);
S. Gazit, D. Podolsky, A.A., D. Arovas, Phys. Rev. Lett. 117, (2016).
D. Sherman et. al., Nature Physics (2015)
S. Poran, et al., Nature Comm. (2017)

Outline

- Brief history of the Anderson-Higgs mechanism
- The vacuum is a condensate
- Emergent relativity in condensed matter
- Is the Higgs mode overdamped in d=2?
- Higgs near quantum criticality

Experimental detection:

Charge density waves
Cold atoms in an optical lattice
Quantum Antiferromagnets
Superconducting films

1955: T.D. Lee and C.N. Yang - massless gauge bosons

1960-61 Nambu, Goldstone: massless bosons in spontaneously broken symmetry

Where are the massless particles?

1962

Gauge Invariance and Mass

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts, and University of California, Los Angeles, California
(Received July 20, 1961)

It is argued that the gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong. This situation may permit a deeper understanding of nucleonic charge conservation as a manifestation of a gauge invariance, without the obvious conflict with experience that a massless particle entails.

1963

Plasmons, Gauge Invariance, and Mass

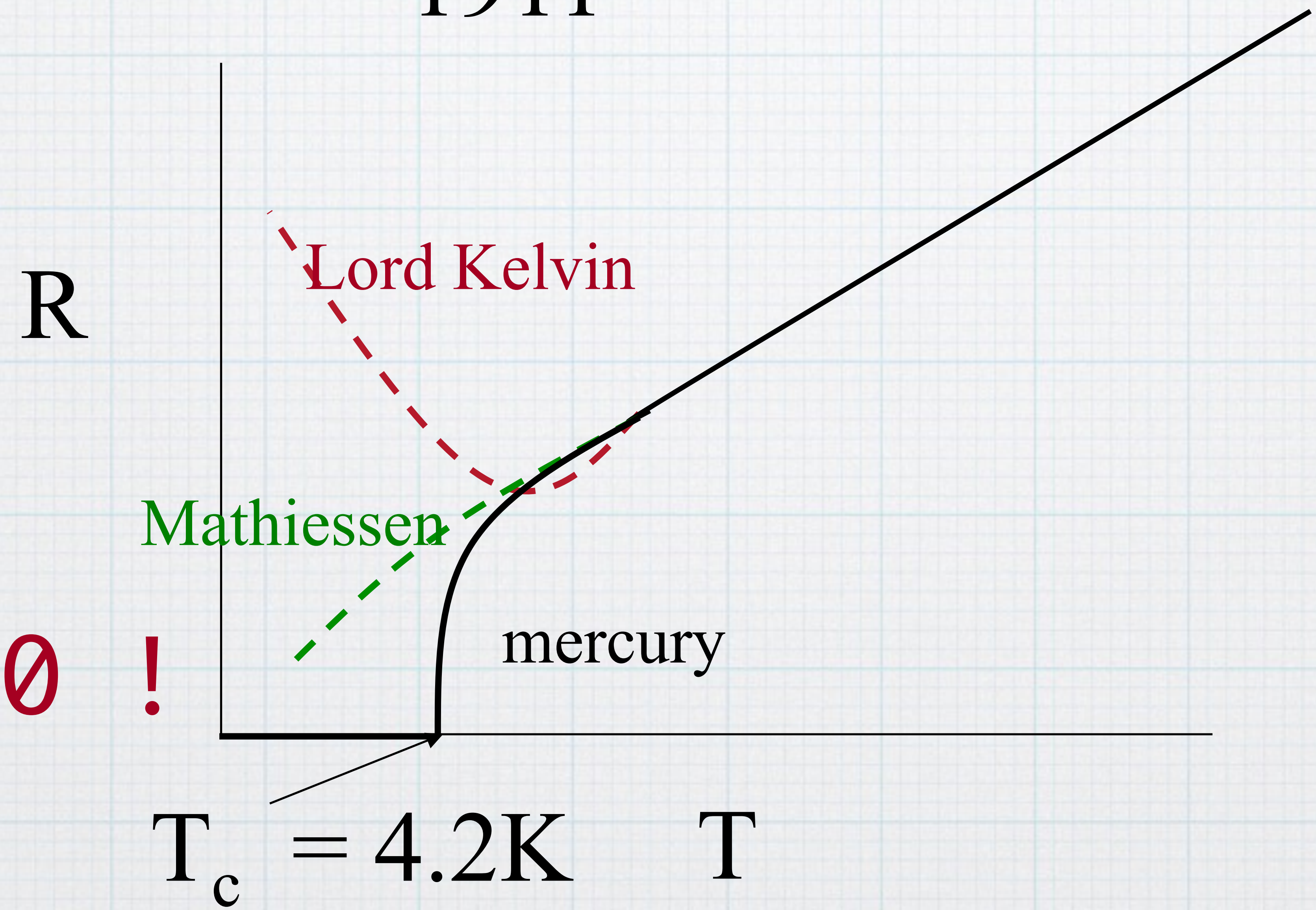
P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

The vacuum is not empty: it is stiff.
like a metal or a charged Bose condensate!

Rewind to 1911

Kamerlingh Onnes

Discovery of Superconductivity
1911

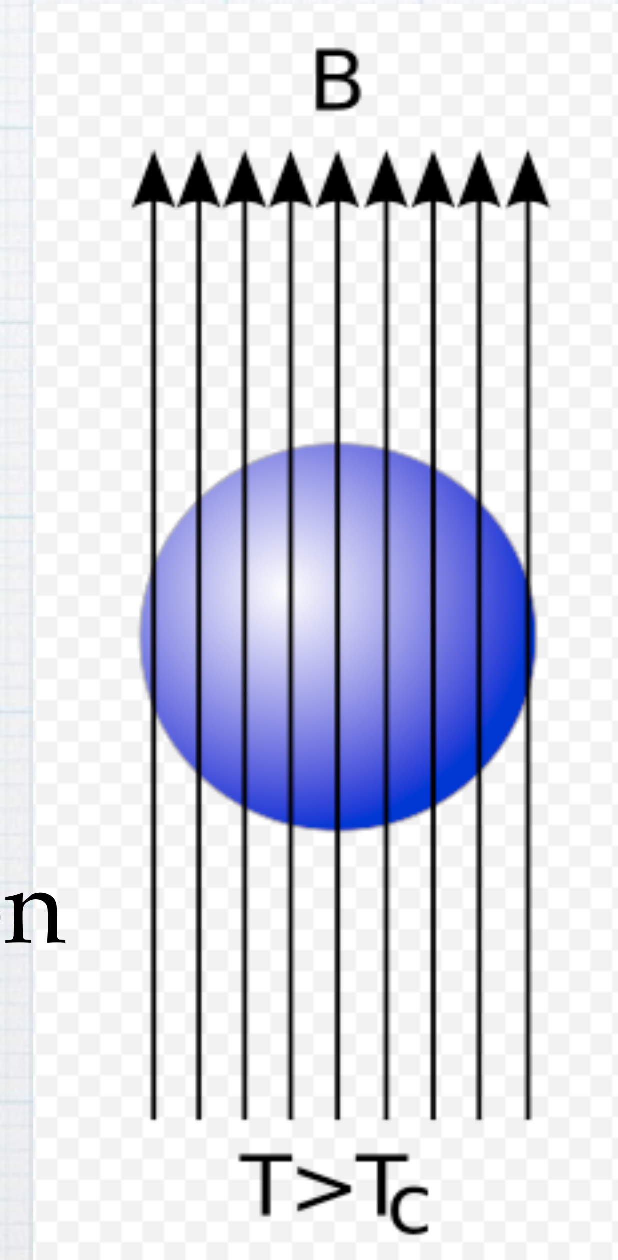


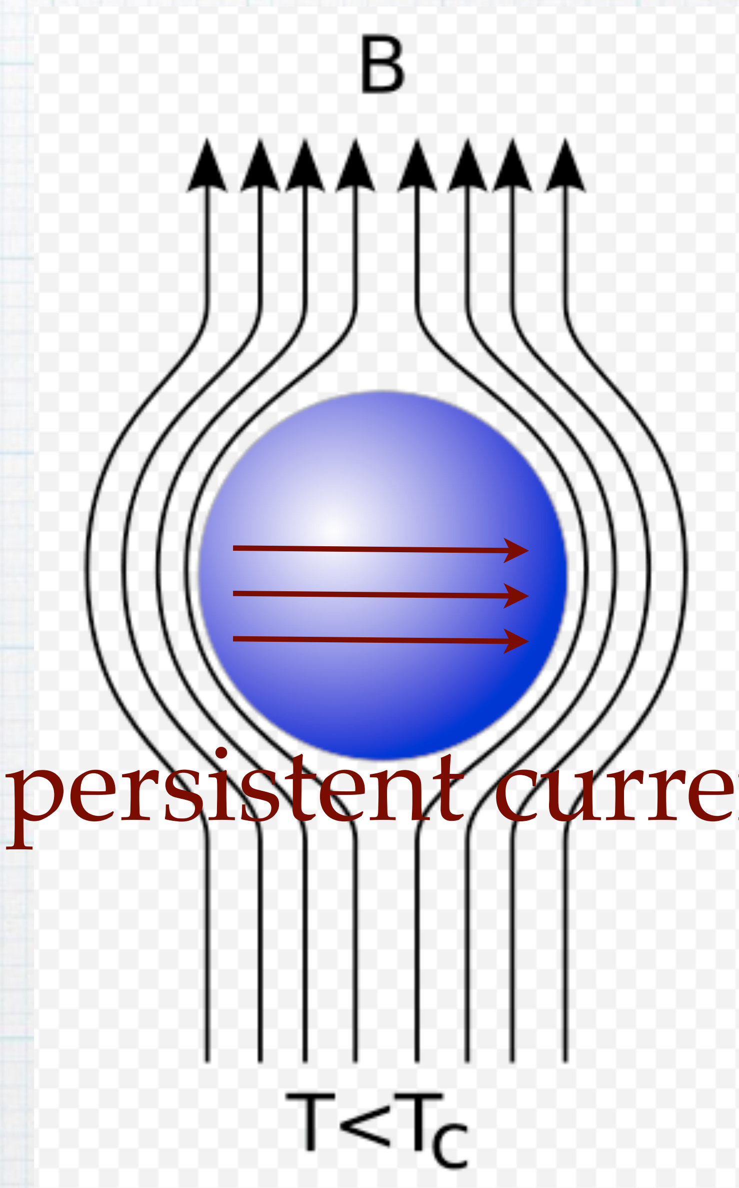
R=0 !

Meissner Effect, 1933

Metal

Superconductor





persistent currents

Phil Anderson

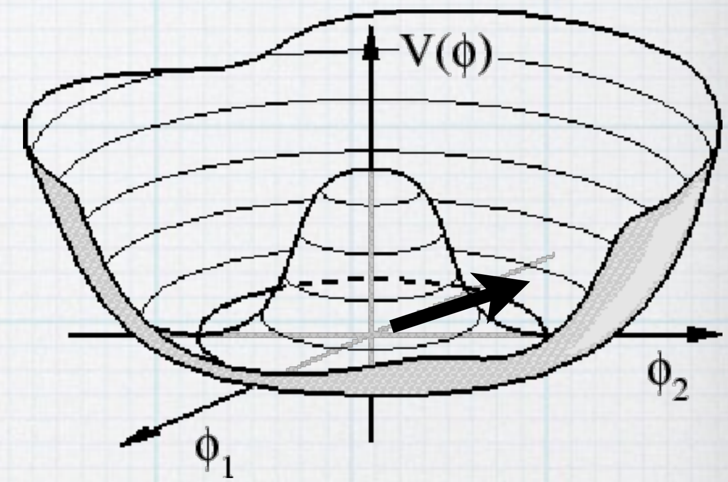
Meissner effect -> 1. Wave function rigidity

2. Photons get massive

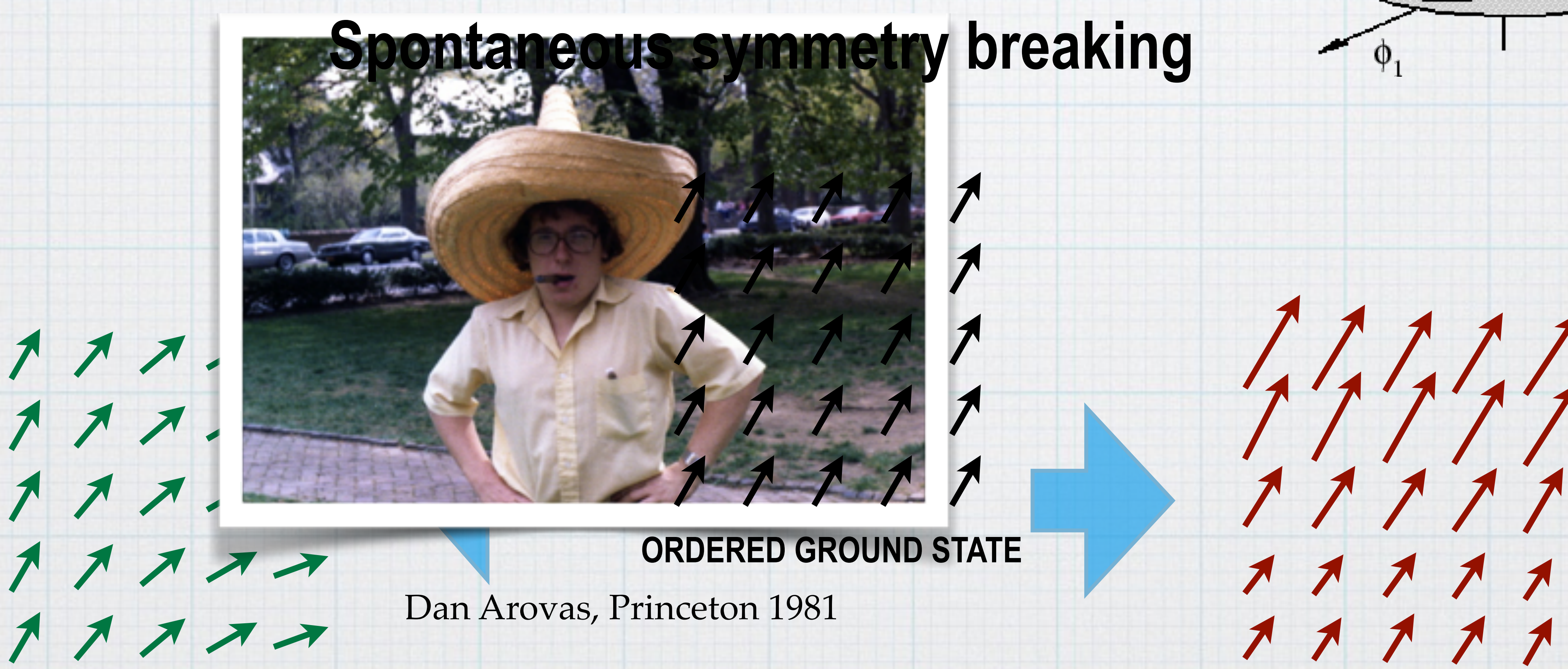
Symmetry breaking in O(N) theory

$N-$**component real scalar field :** $\phi^{\mathrm{t}} = (\phi_1, \ldots, \phi_N)$

"Mexican hat" potential : $V(\phi) = \dfrac{m_0^2}{8N}\left(\phi^2 - N\right)^2$



Spontaneous symmetry breaking



Dynamics of bosons

Galilean Gross Pitaevskii bosons (BEC) $\psi \simeq \sqrt{\rho} e^{i\varphi}$

$$\mathcal{L} = i\psi^* \dot{\psi} - |\nabla\psi|^2 - g(|\psi|^2 - \bar{n})^2$$

$$= \rho\dot{\varphi} - |\nabla\psi|^2 - g(\rho - \bar{n})^2$$

→ 1 massless phase-density phonon

→ NO Amplitude-Higgs mode

Relativistic O(2) theory $\psi = r(x)e^{i\varphi(x)}$

$$\mathcal{L}^{O(2)} = |\dot{\psi}|^2 - |\nabla\psi|^2 - \mu|\psi|^2 + g|\psi|^4 - i\alpha\psi^*\dot{\psi}$$

→ 1 massless phase mode

→ 1 Amplitude-Higgs mode

Both modes survive weak p-h symmetry breaking

Relativistic Dynamics in Lattice bosons

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

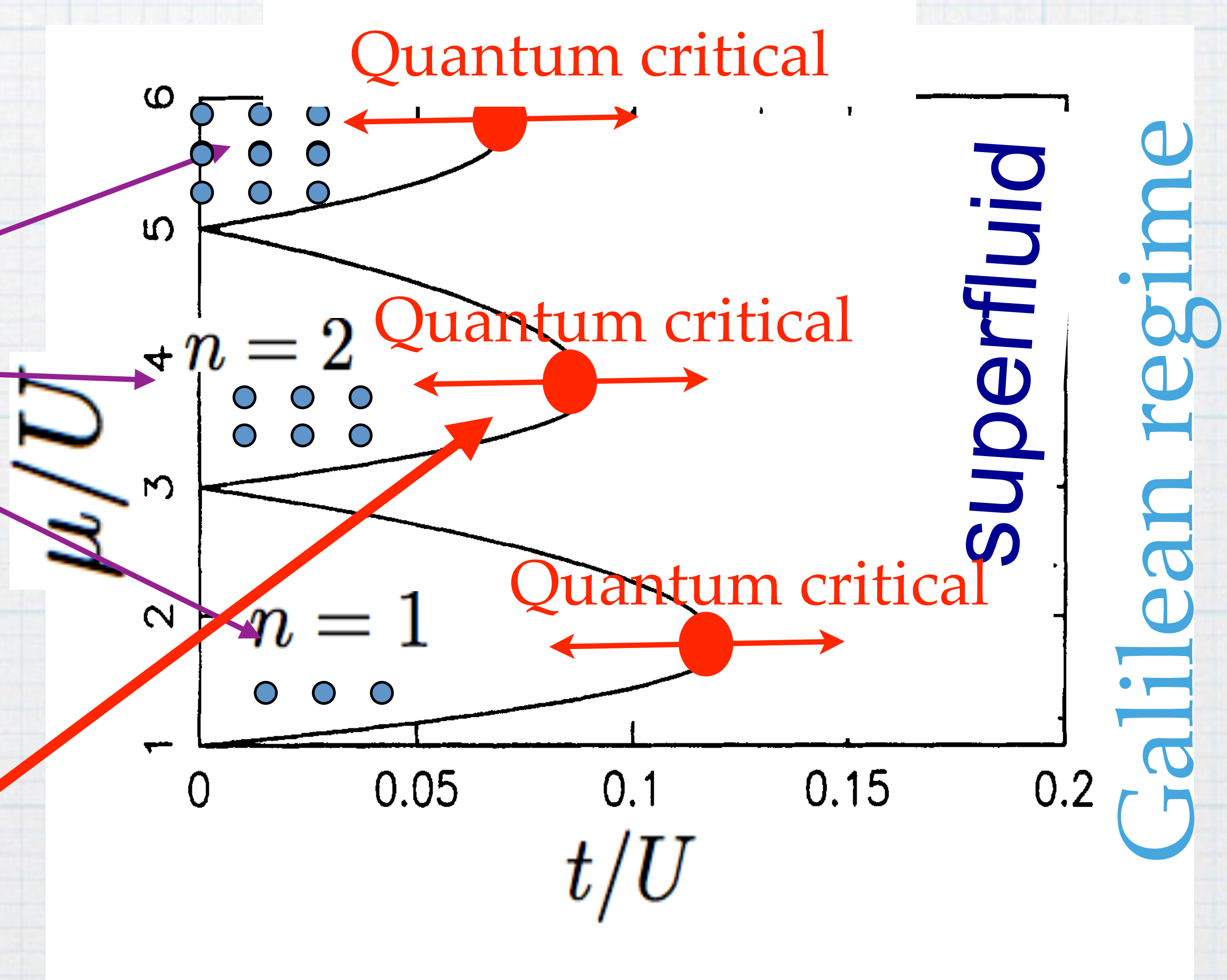
Large t/U : system is a superfluid, (Bose condensate).

Small t/U : system is a Mott insulator, (gap for charge fluctuations).

Mott insulators

incompressible

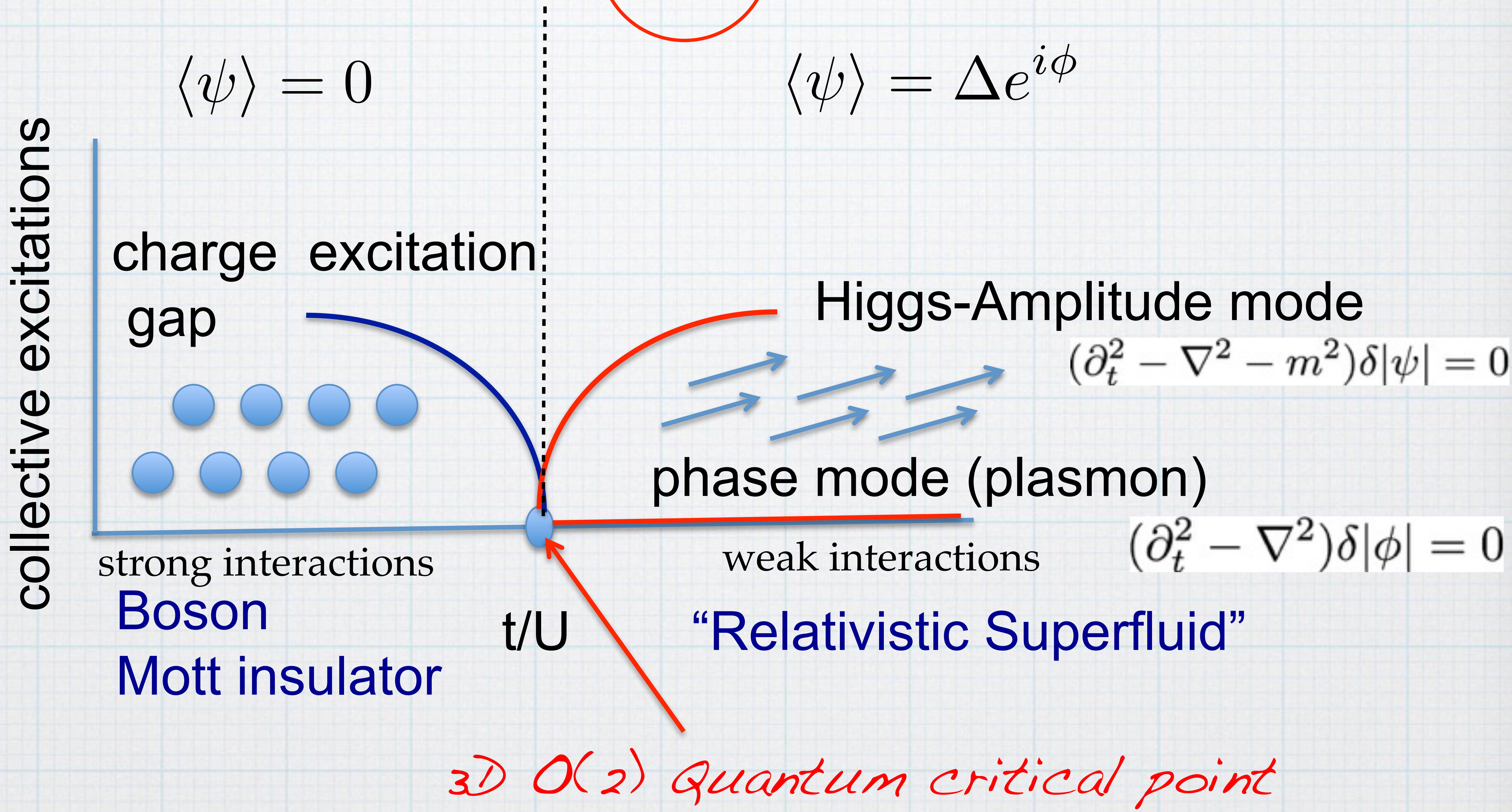
$$\langle \psi^\dagger \rangle = 0$$
$$\langle n_j^2 \rangle \approx (\langle n_i \rangle)^2$$



Relativistic Gross Pitaevskii $\mathcal{L} = |\partial_t \psi|^2 - c^2 |\nabla \psi|^2 + r|\psi|^2 - u|\psi|^4$

Relativistic Dynamics O(2) model

Relativistic Gross Pitaevskii $\mathcal{L} = |\partial_t \psi|^2 - c^2 |\nabla \psi|^2 + r|\psi|^2 - u|\psi|^4$

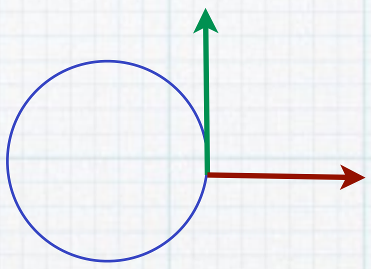


classical d+1 model at "temperature" U/t

Higgs - Goldstones coupling

$$S[\boldsymbol{\phi}] = \frac{1}{g}\int d^dx \int dt \left[\tfrac{1}{2}\left(\partial_t \boldsymbol{\phi}\right)^2 - \tfrac{1}{2}\left(\boldsymbol{\nabla}\boldsymbol{\phi}\right)^2 - V(\boldsymbol{\phi}) \right]$$

Fluctuations in the ordered state:



$$\boldsymbol{\phi} = \left(\sqrt{N} + \sigma, \boldsymbol{\pi}\right)$$

Harmonic theory

$$\mathcal{L}_0 = \frac{1}{2g}\left[(\partial_\mu \sigma)^2 - m^2\sigma^2 + (\partial_\mu \boldsymbol{\pi})^2\right]$$

Interactions

$$\mathcal{L}_1 = \frac{m^2}{2g}\left[\frac{1}{\sqrt{N}}\,\sigma\boldsymbol{\pi}^2 + \frac{1}{\sqrt{N}}\,\sigma^3 + \frac{1}{4N}\,\sigma^4 + \frac{2}{N}\,\sigma^2\boldsymbol{\pi}^2 + \frac{1}{4N}(\boldsymbol{\pi}^2)^2\right]$$

Higgs coupling to 2 Goldstones

Is the Higgs mode over damped in d=2?

PHYSICAL REVIEW B **84**, 174522 (2011)

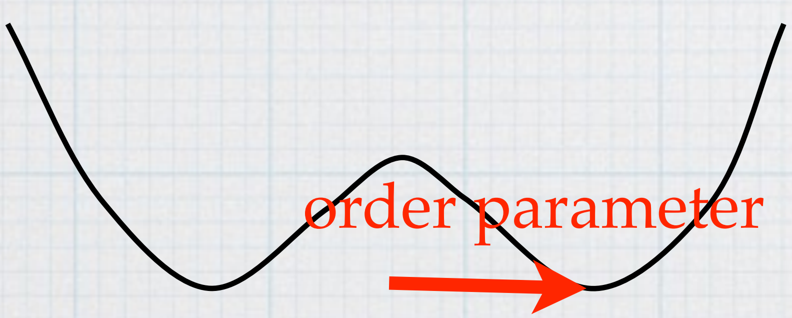
Visibility of the amplitude (Higgs) mode in condensed matter

Daniel Podolsky,[1] Assa Auerbach,[1,2] and Daniel P. Arovas[3]

$$S = \frac{1}{2g}\int_{\Lambda} d^{d+1}x \left[(\partial_\mu \mathbf{\Phi})^2 + \frac{m_0^2}{4N}(|\mathbf{\Phi}|^2 - N)^2 \right]$$

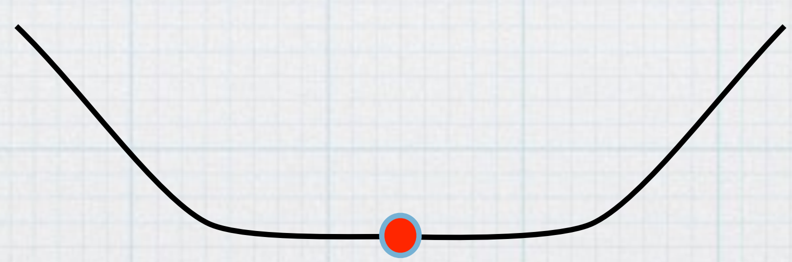
Quantum Critical point
Landau theory

Sponateously broken symmetry



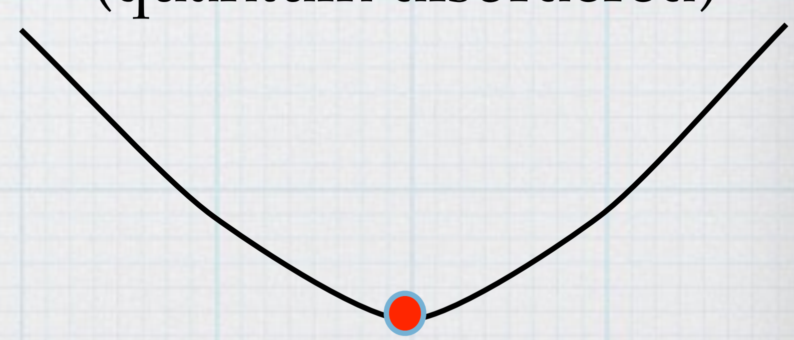
$g < g_c$

Quantum Critical point



$g = g_c$

Symmetric phase
(quantum disordered)

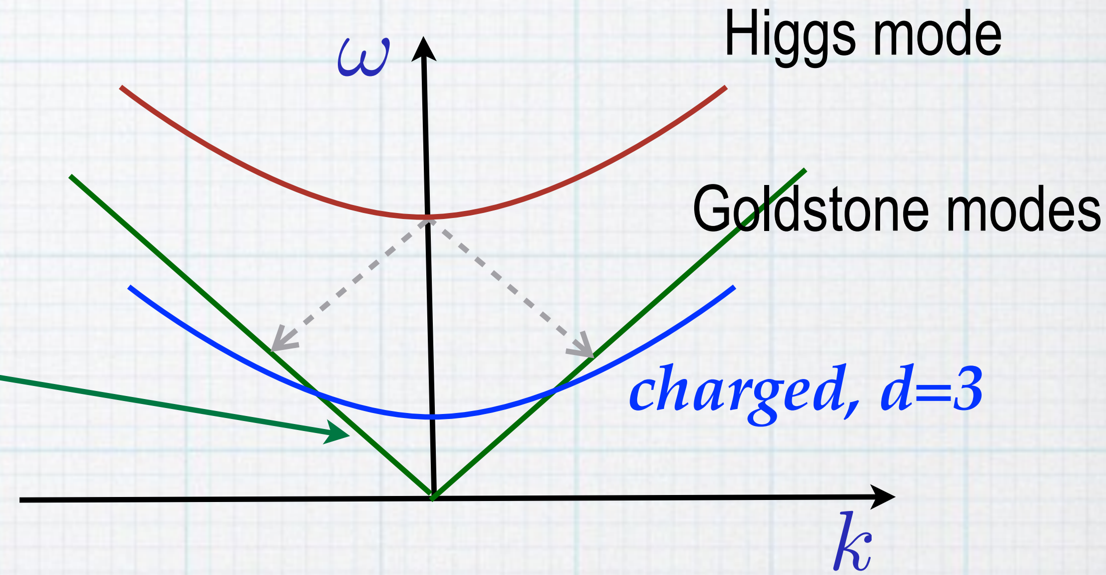


$g > g_c$

The Higgs decay

The Higgs mode can decay into a pair of Goldstone bosons :

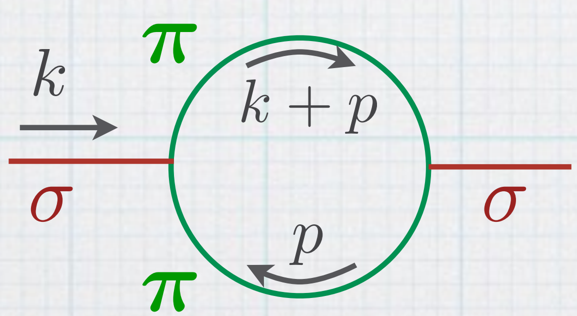
In neutral systems, and for 2D superconductors, the Goldstones are massless.



d=3 **Higgs decay rate is bounded even at strong coupling**

d=2 **self-energy diverges at low frequency, even at weak coupling :**

$$\Sigma_\sigma(k) =$$



$$\propto \int \frac{d^3p}{(2\pi)^3} \frac{1}{p^2(p+k)^2} = \frac{1}{8|k|}$$

$$\mathrm{Im}\Sigma(\omega) \propto \frac{1}{|\omega|}$$

infrared divergent!

(Nepomnyaschii)^2 (1978)
Sachdev (1999), Zwerger (2004)

Behavior of different dynamical correlation functions

order parameter susceptibility

(Nepomnyaschii)[2] (1978)
Sachdev (1999), Zwerger (2004)

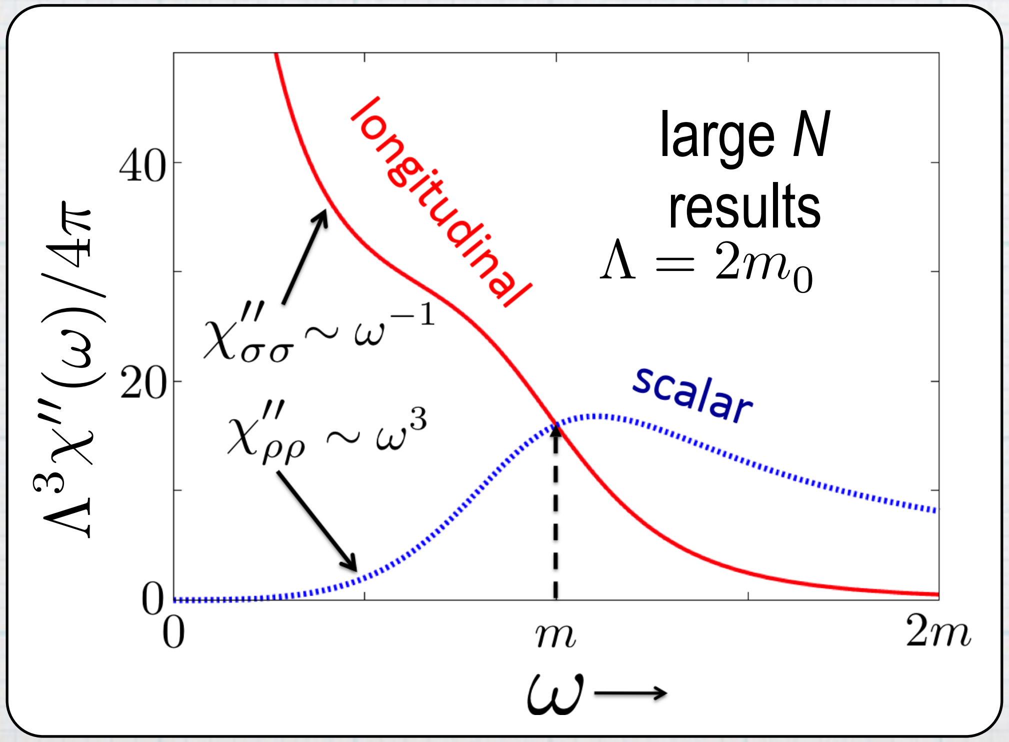
$$\chi_{11}(\omega) = \langle \psi_1(\omega)\psi_1(-\omega)\rangle \quad \sim \omega^{-1}$$

infrared divergent in d=2

scalar susceptibility **D. Podolsky, A. A, and D. P. Arovas, *PRB* (2011)**

$$\chi_{\rho\rho}(\omega) = \langle |\vec{\psi}|^2(\omega)|\vec{\psi}|^2(-\omega)\rangle \sim \omega^3$$

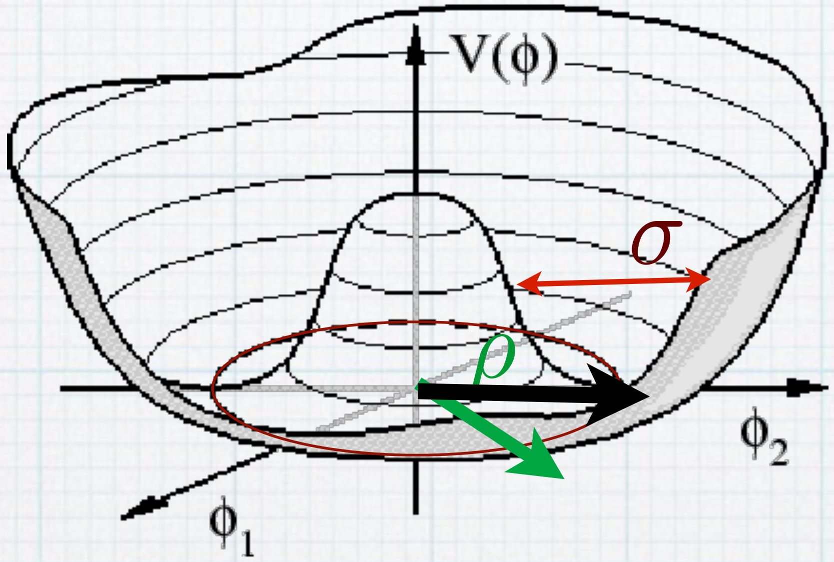
infrared regular in d=2



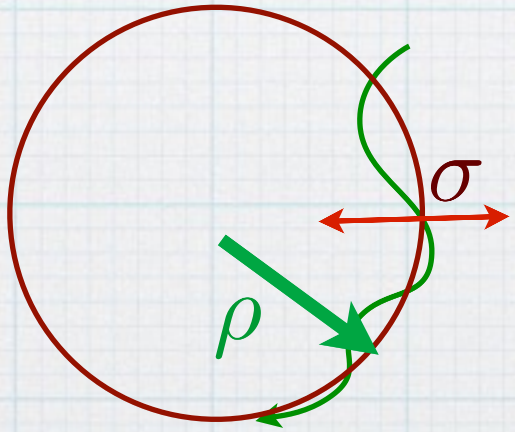
Higgs peak in scalar response is well defined!

vector vs **scalar** dynamical correlations

Longitudinal *versus* radial perturbations :



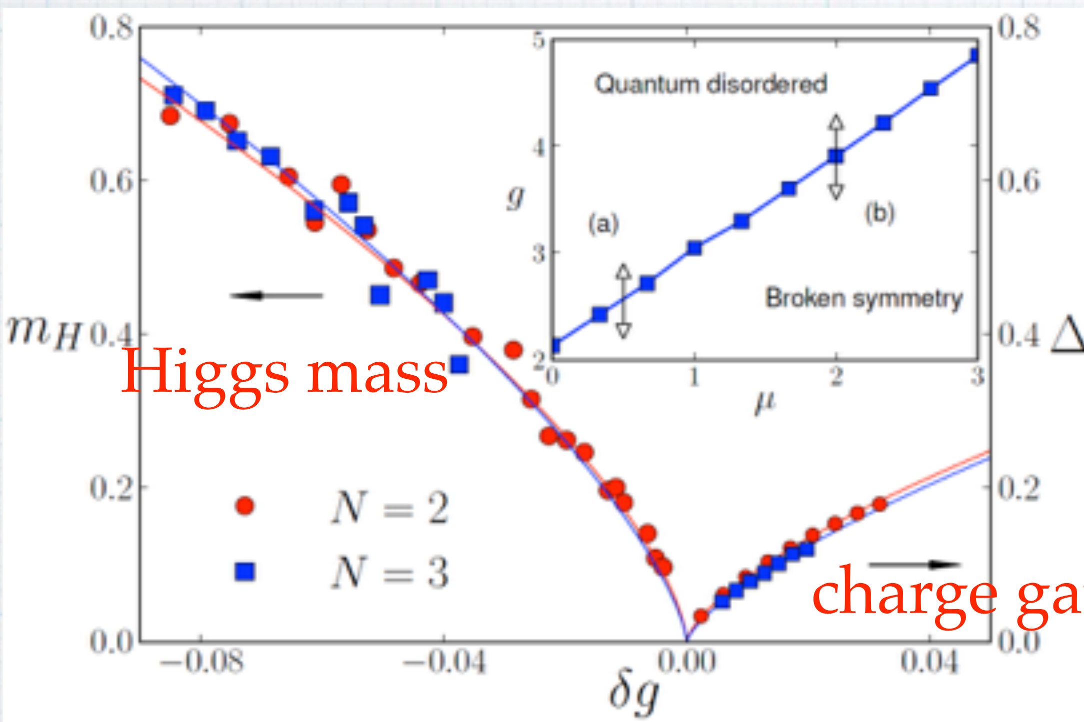
Radial motion is less damped, since it is not effected by azimuthal meandering.

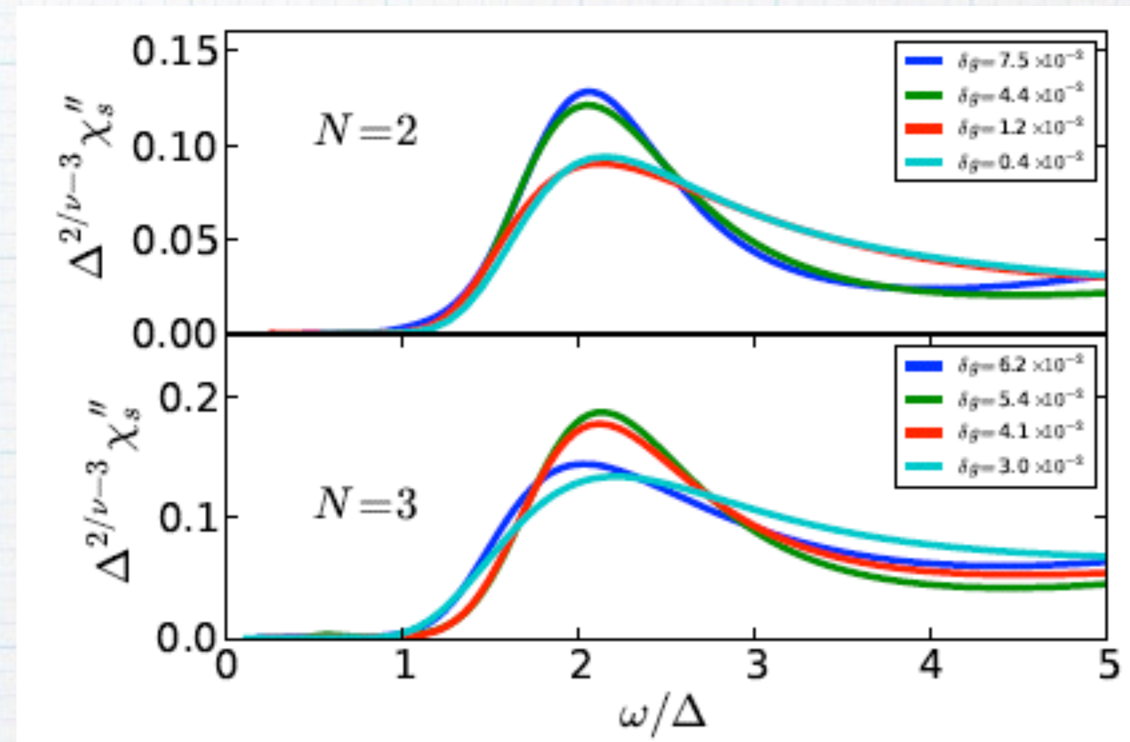


What happens to the spectral function near the quantum critical point?

Numerical simulations

Gazit Podolsky Auerbach PRL (2013), Gazit, Podolsky, AA, Arovas (in preparation)





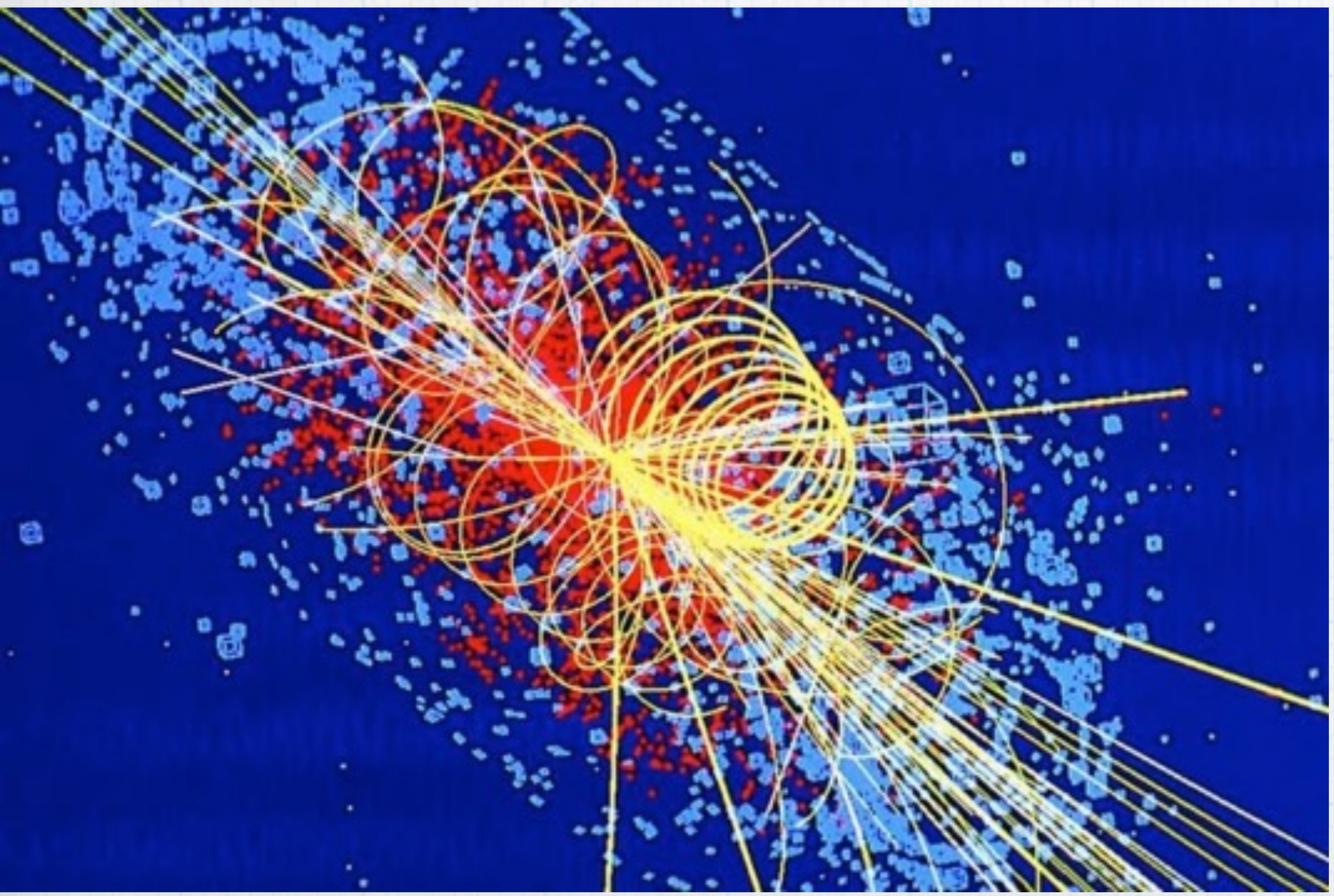
universal Higgs spectral function

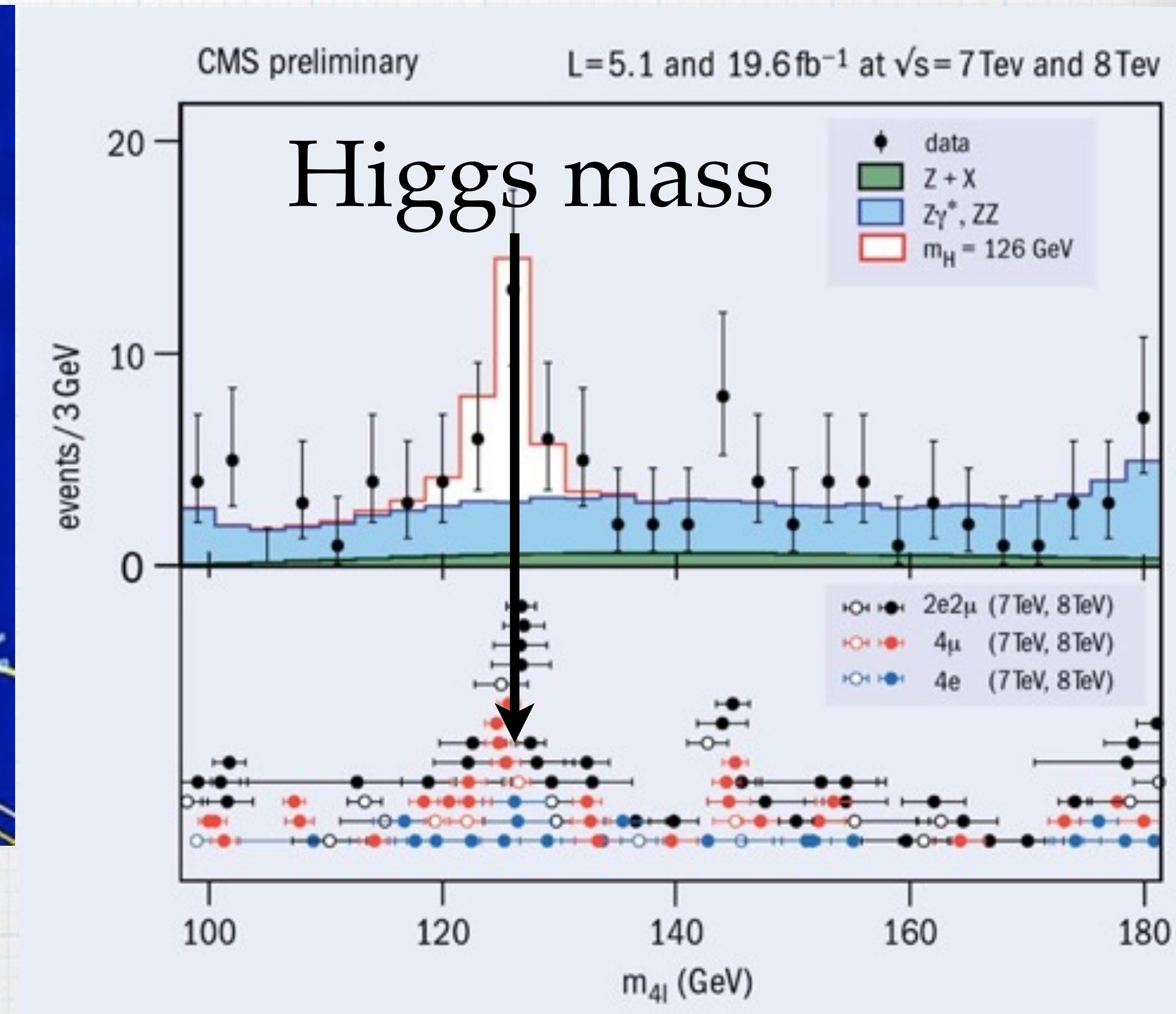
Conclusion: Higgs peak is ***visible*** *close to criticality in d=2*

Apr 26, 2013

Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a





Narrow Higgs peak —> vacuum is far from criticality

Experimental detection:

Charge density waves (coupled 1 dimensions)

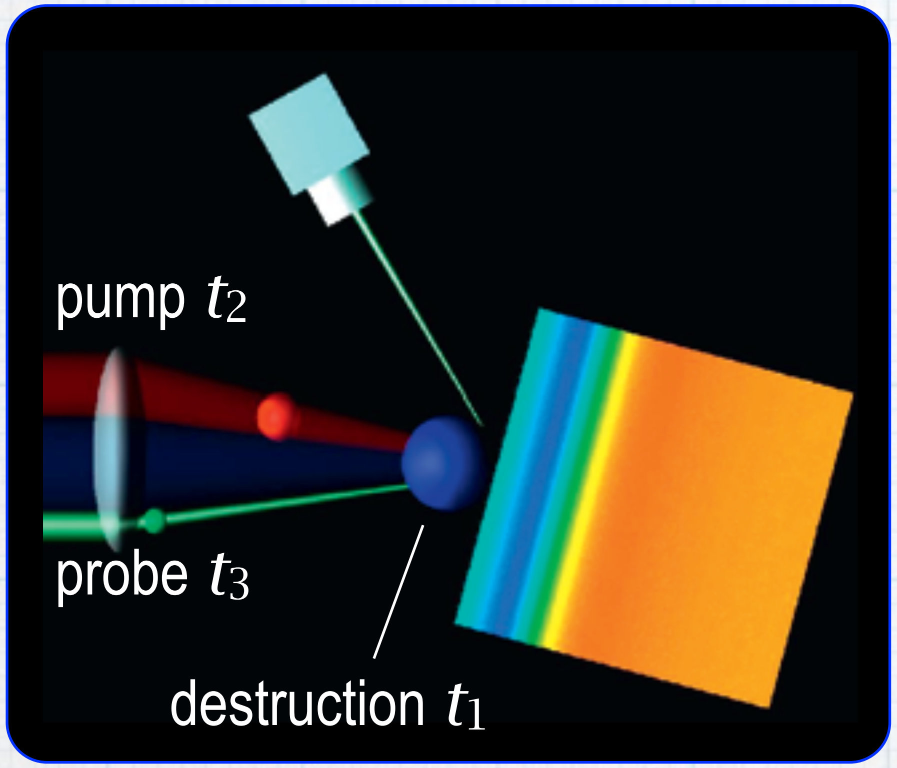
Quantum Antiferromagnets (3 dimensions)

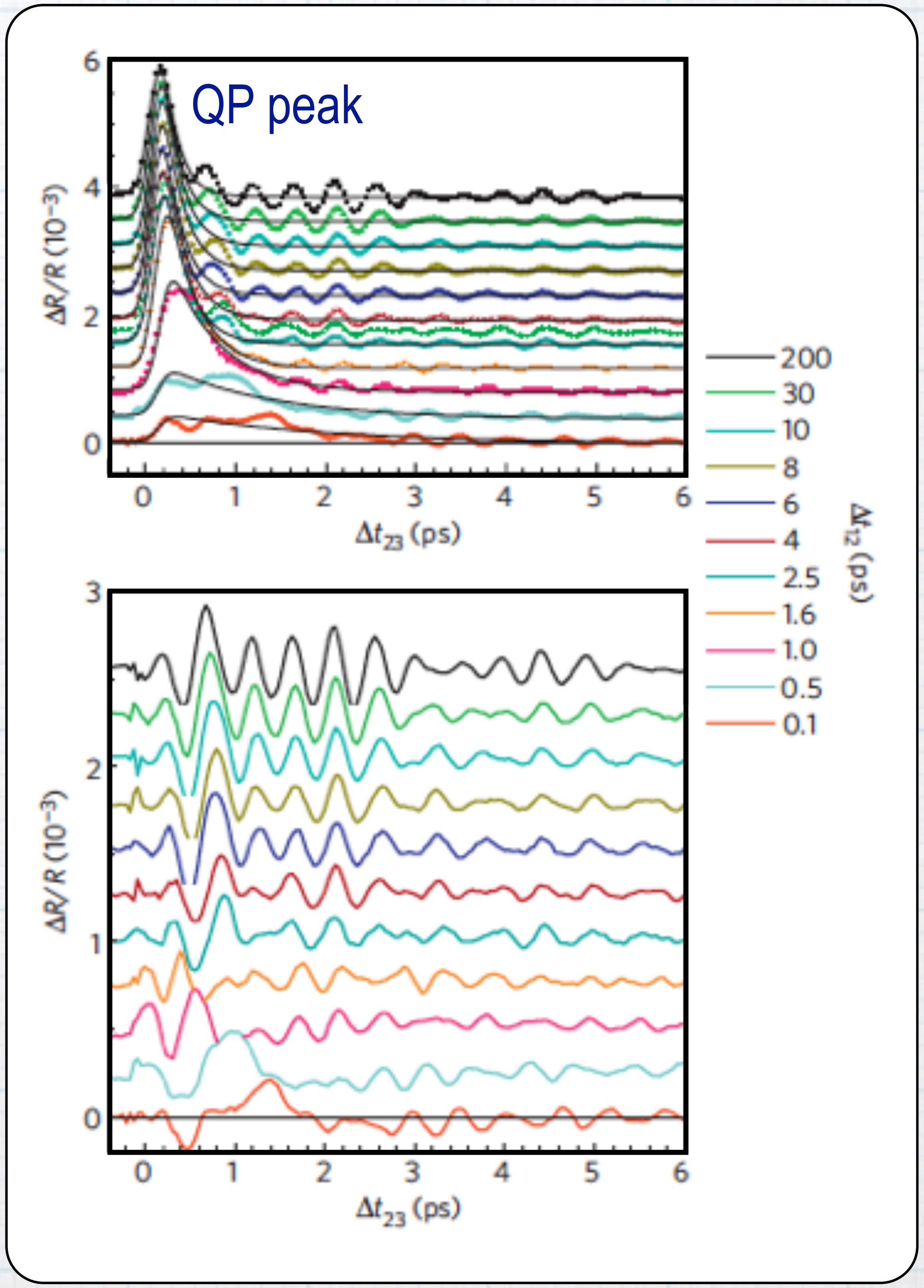
Cold atoms in an optical lattice (2 dimensions)

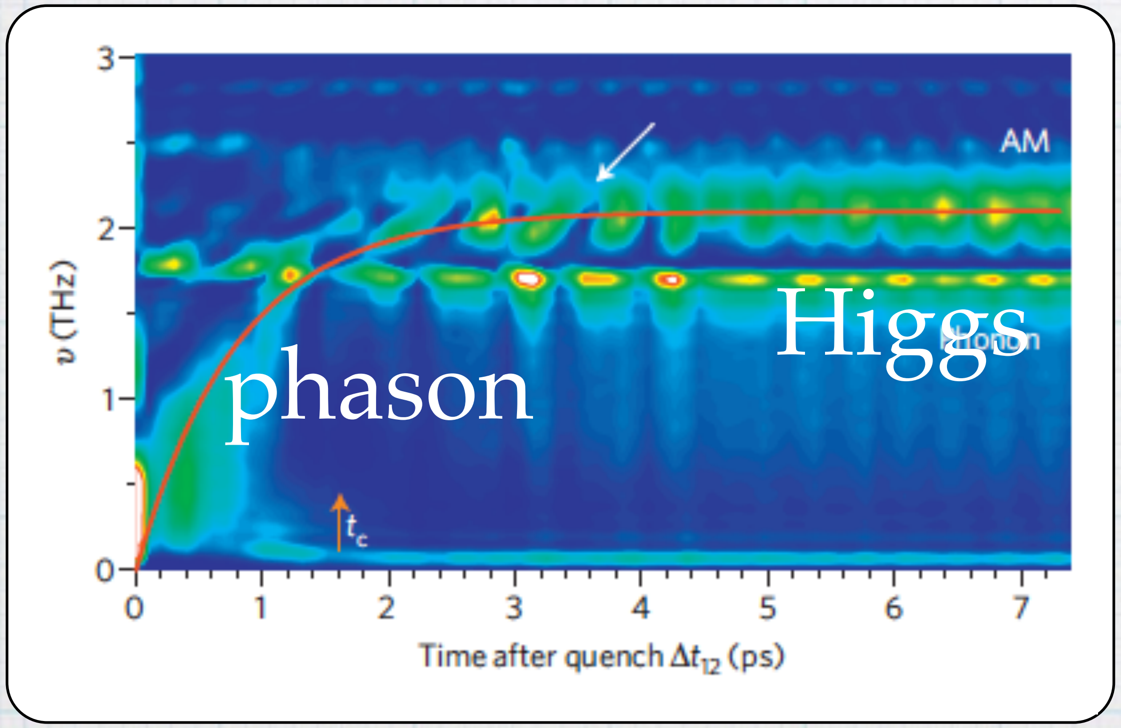
Superconducting films (2 dimensions)

CDW systems (TbTe$_3$, DyTe$_3$, *2H*-TaSe$_2$) :

R. Yusupov *et al*., *Nature Phys.* **6**, 681 (2010)





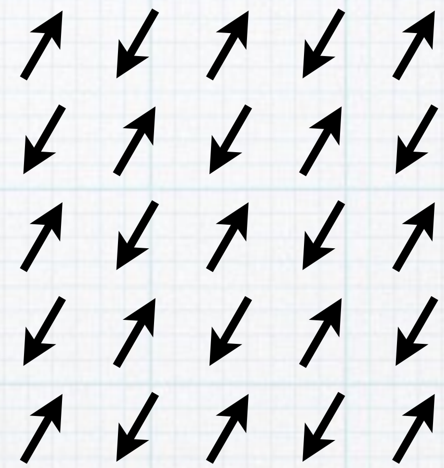


Fourier transform

Magnetic systems in 3 dimensions

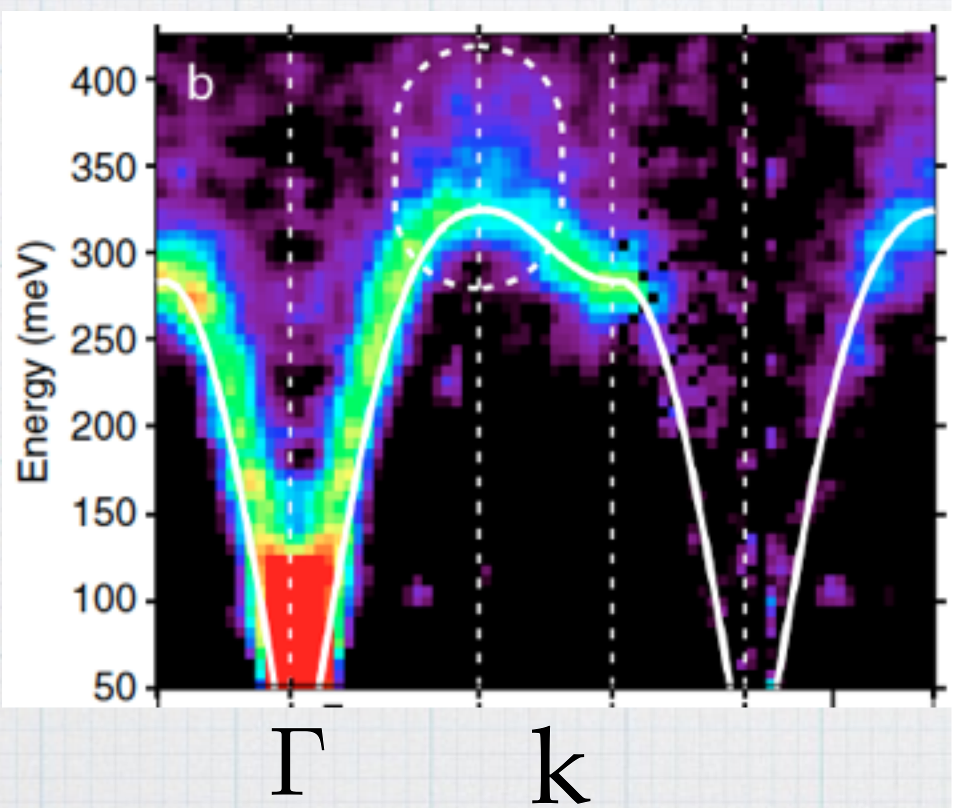
Heisenberg antiferromagnet

$$H = \sum_{\langle ij \rangle \rangle} \vec{S}_i \cdot \vec{S}_j$$

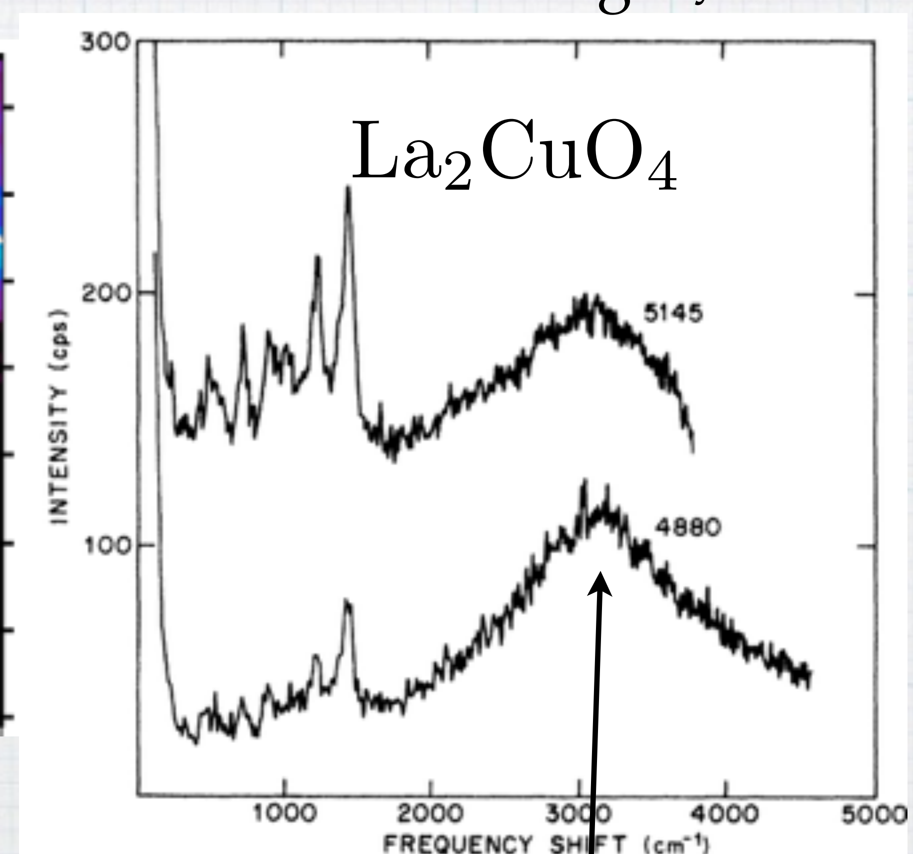


O(3) Relativistic
non linear sigma model

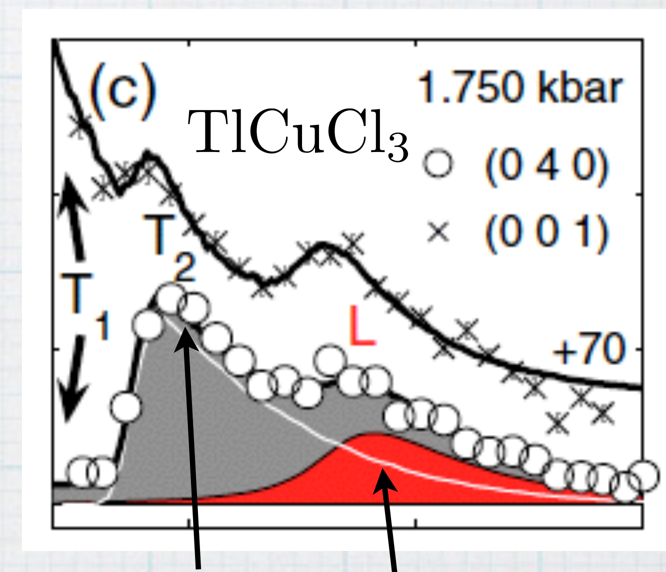
neutron scattering, Headings 2010



Raman scattering Lyons, 1988



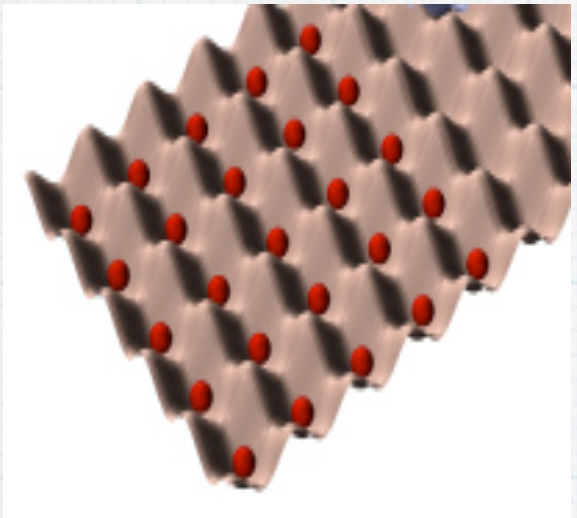
Neutrons, Ruegg, 2008



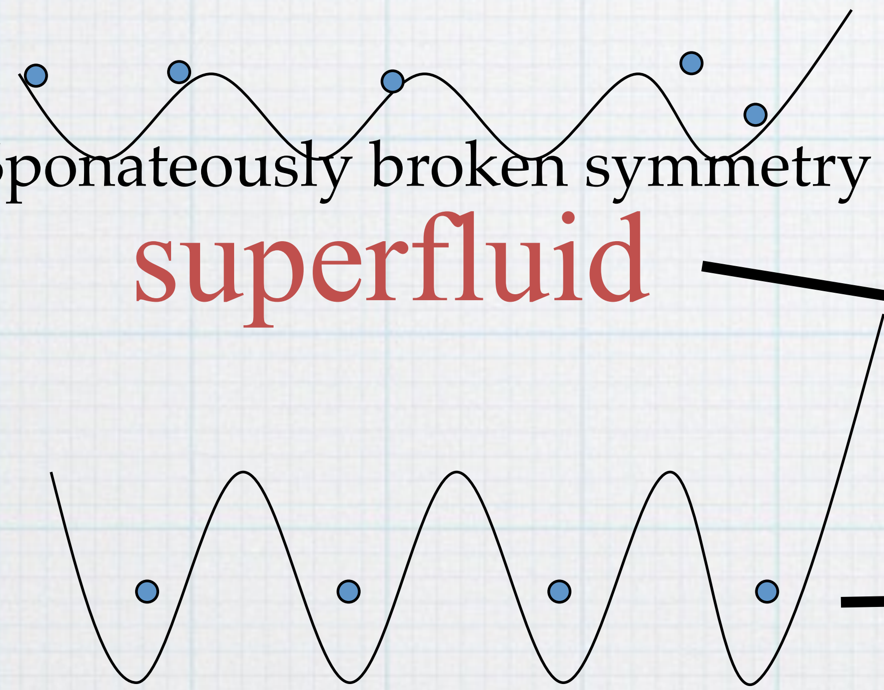
Spin waves = Goldstone modes

2 Magnon = Higgs mode

Cold atoms in *optical lattices*



Greiner et. al. Nature 2001



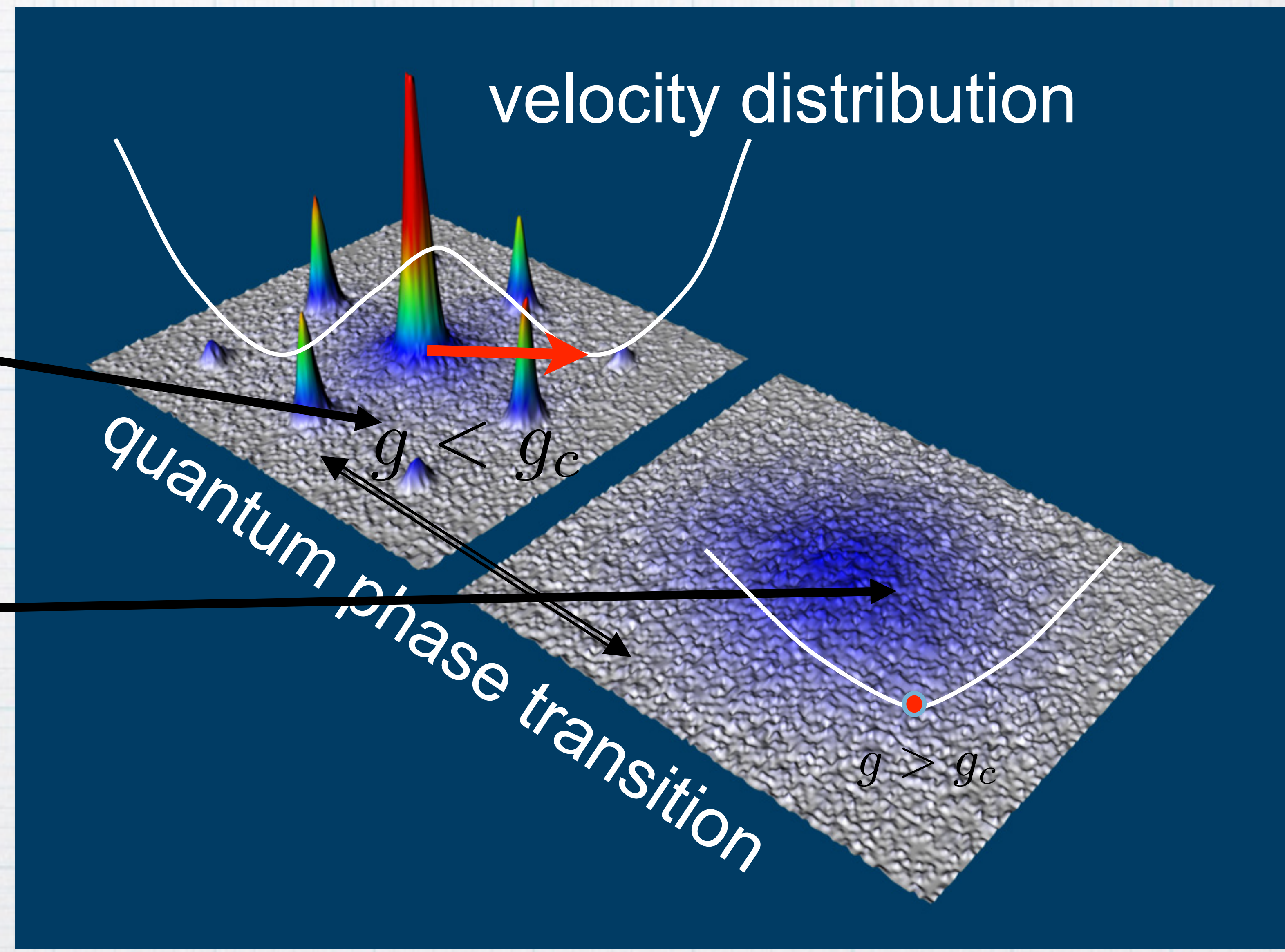
Sponateously broken symmetry

superfluid

Symmetric

Mott insulator

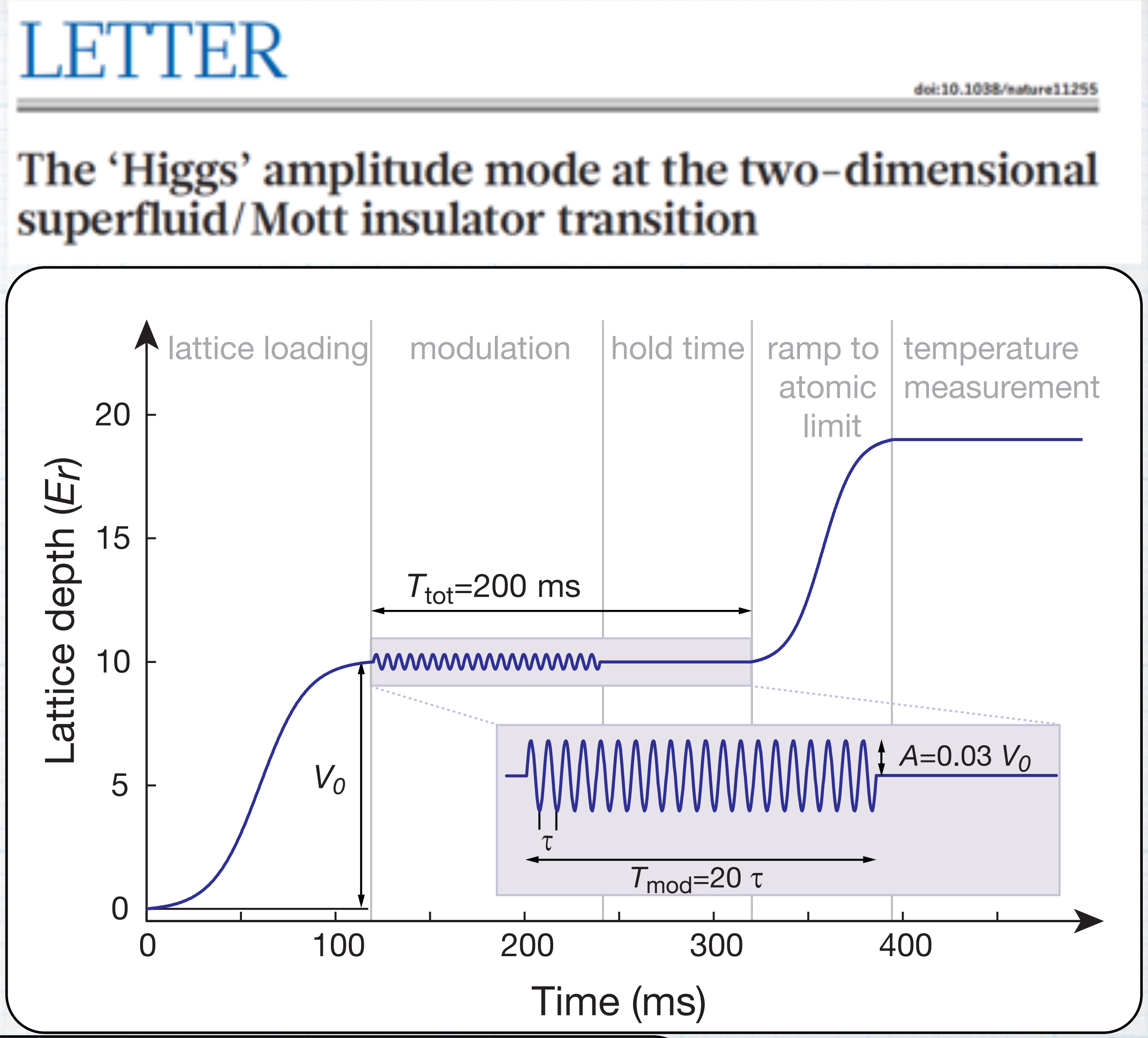
$g > g_c$



Relativistic Gross Pitaevskii $\mathcal{L} = |\partial_t \psi|^2 - c^2 |\nabla \psi|^2 + r|\psi|^2 - u|\psi|^4$

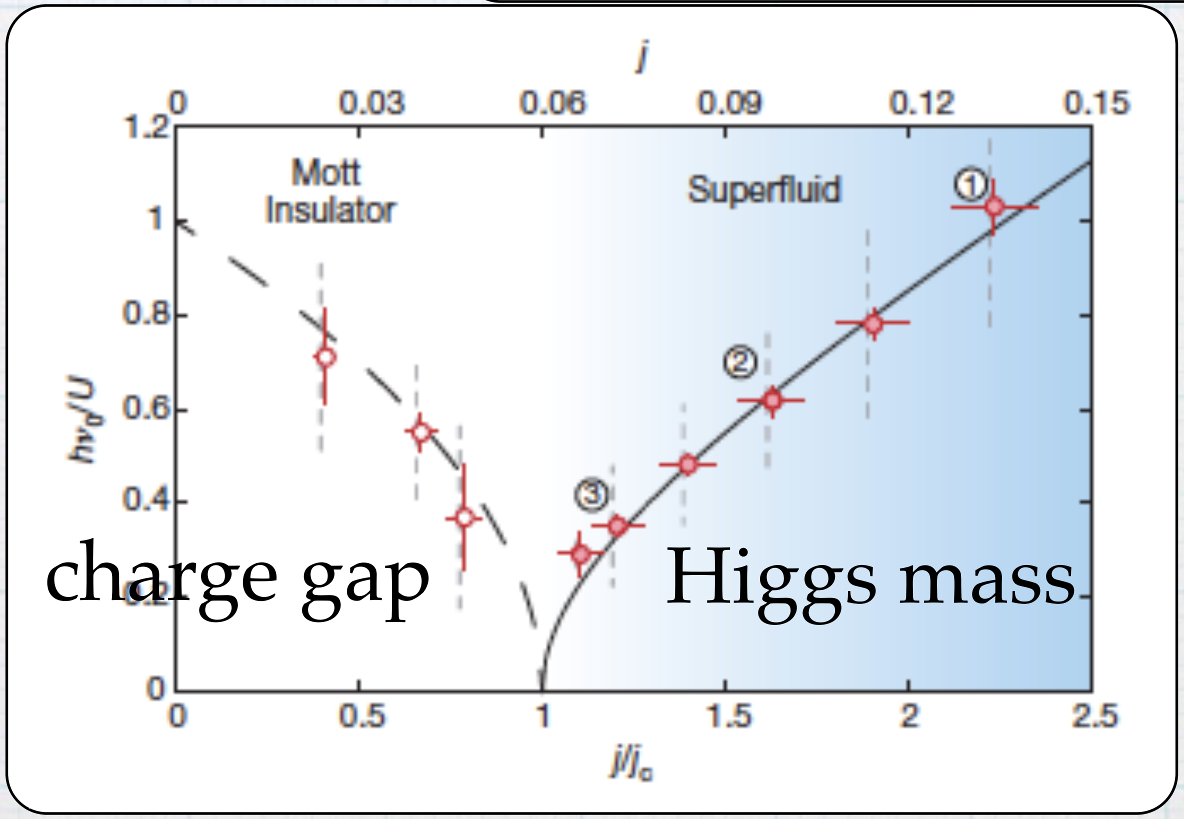
Higgs near criticality: ^{87}Rb

M. Endres *et al.*, *Nature* **487**, 454 (2012)

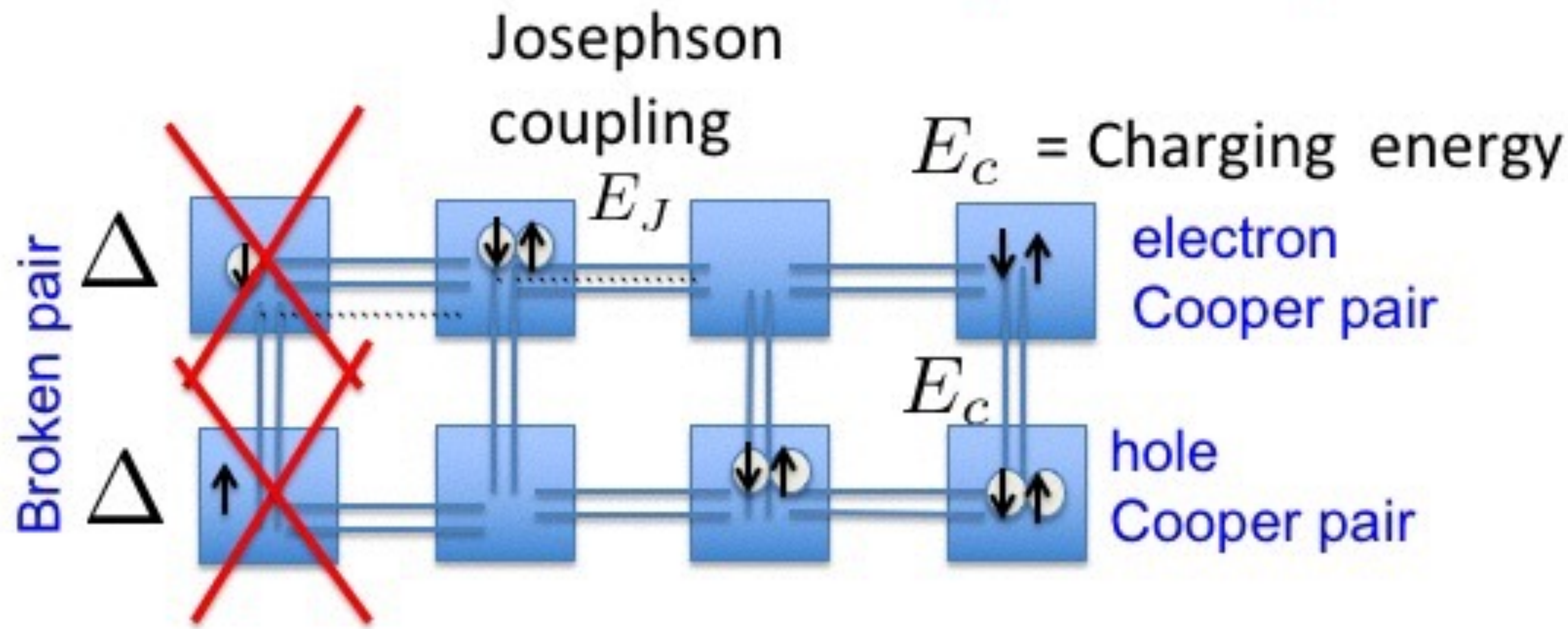


- Energy absorption rate of periodically modulated lattice $\propto \omega \chi''_{\rho\rho}(\omega)$

Critical gaps



Josephson Junction array *(no disorder)*



$E_c, E_J < 2\Delta$ ***Bosonic*** limit

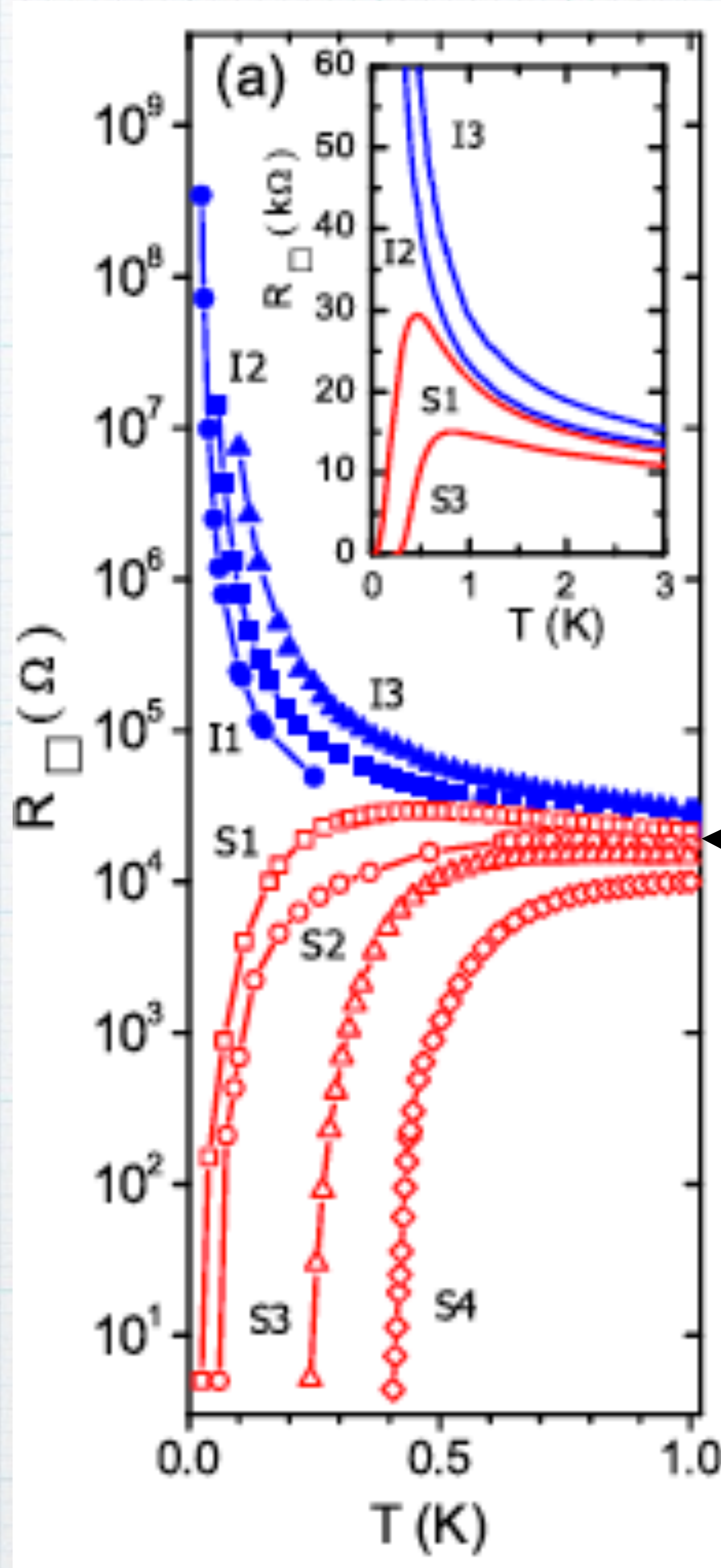
E_c-E_J model $H = E_c \sum (n_i - \bar{n})^2 - E_J \sum \cos(\phi_i - \phi_j)^2$

Relativistic Gross Pitaevskii $\mathcal{L} = |\partial_t \psi|^2 - c^2 |\nabla \psi|^2 + r|\psi|^2 - u|\psi|^4$

Superconductor to Insulator transition in thin films

Partial list:
Haviland et. al. PRL (1989)
Hebard Palaanen PRL (1990)
Yazdani & Kapitulnik (PRL (1995) MoGe
Sambandamurthy et. al. PRL (2004) InO
Baturina et. al. PRL 99 (2007)
M. Chand et. Al, PRB (2009)

Theory:
Finkelstein, Feigelman, Vinokur, Larkin, Ioffe, Trivedi, Randeria, Ghosal, Shimshoni, AA, Meir, Dubi, Michaeli



Insulator

R_c

Josephson coupling

Superconductor

O(2) Quantum phase transition at T=0

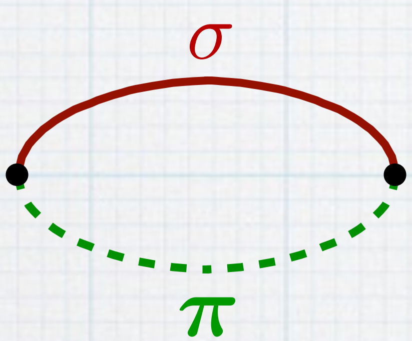
Collective modes would prove quantum criticality

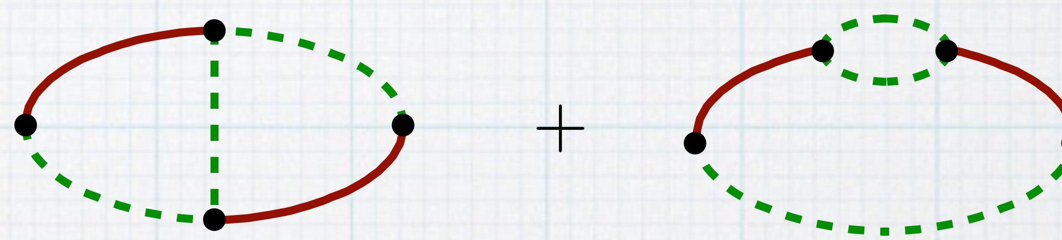
We find $\sigma(\omega) = A\,\delta(\omega) + \widetilde{\sigma}(\omega)$ with $A = Ne^2 g^{-1} + \mathcal{O}(g^0)$.

The finite frequency part is computed from

$$\widehat{K}^{\mathsf{P}}_{\mu\nu}(k) = \frac{1}{(N-1)g^2}\int d^{d+1}x\; e^{ik\cdot(x-x')}\big\langle(\sigma\,\partial_\mu\boldsymbol{\pi} - \boldsymbol{\pi}\,\partial_\mu\sigma)_x \cdot (\sigma\,\partial_\nu\boldsymbol{\pi} - \boldsymbol{\pi}\,\partial_\nu\sigma)_{x'}\big\rangle$$

We evaluate this perturbatively in the coupling *g*. Conductivity diagrams :

$\mathcal{O}(g^0)$: 

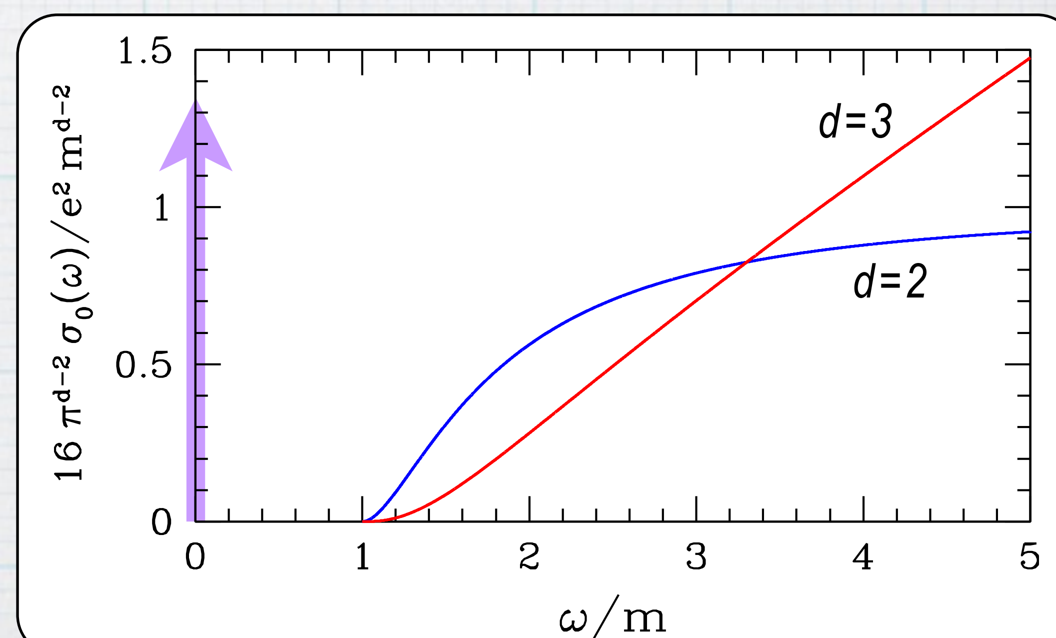
$\mathcal{O}(g^1)$: 

To lowest order, $\quad \widetilde{\sigma}_0(\omega) = \dfrac{\pi \mathcal{S}_d e^2}{d\omega^2}\left(\dfrac{\omega^2 - m^2}{4\pi\omega}\right)^d \Theta(\omega^2 - m^2)$

This yields a threshold at the Higgs mass, with

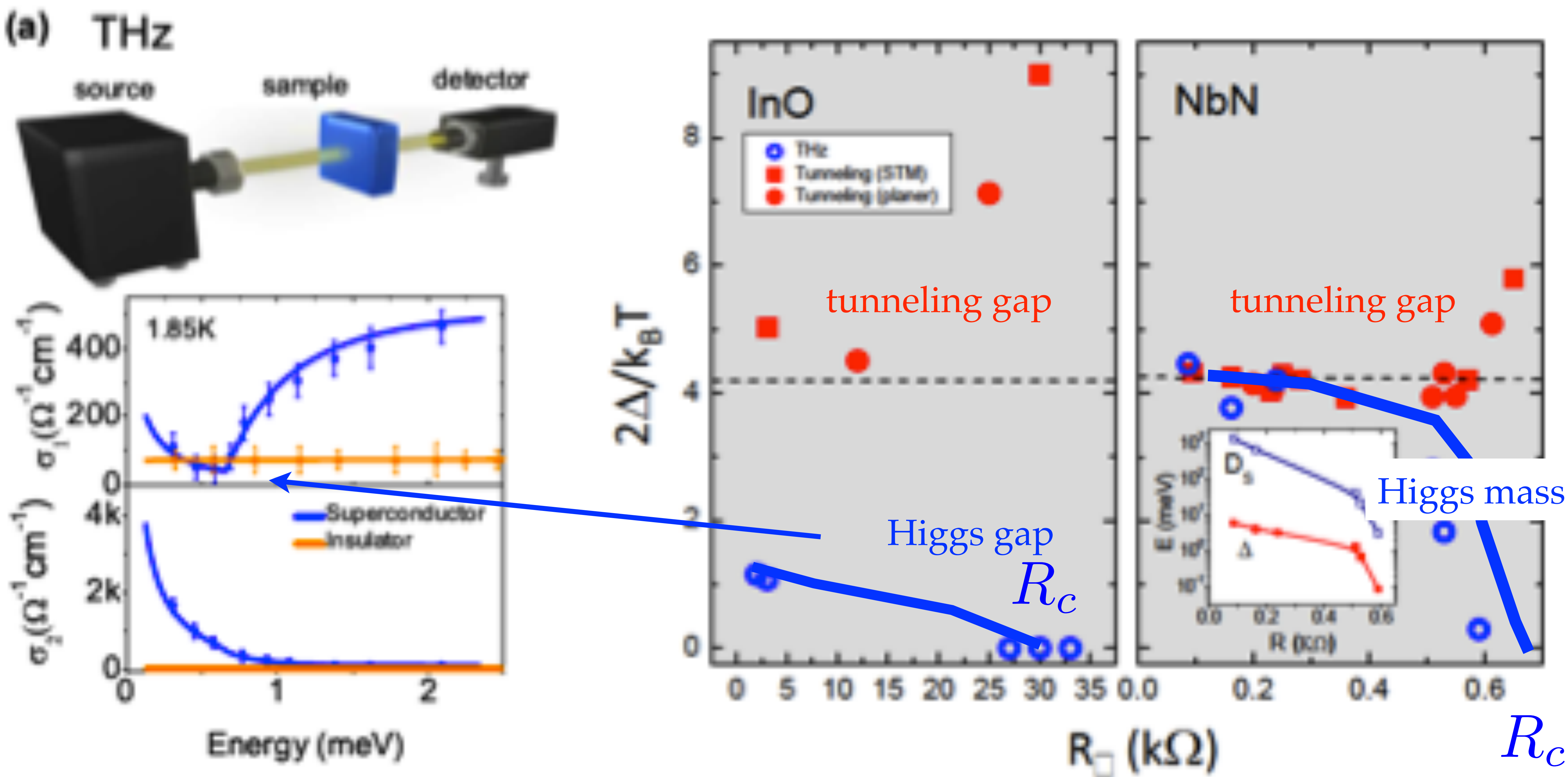
$$\sigma(\omega) \propto (\omega - m)^d$$

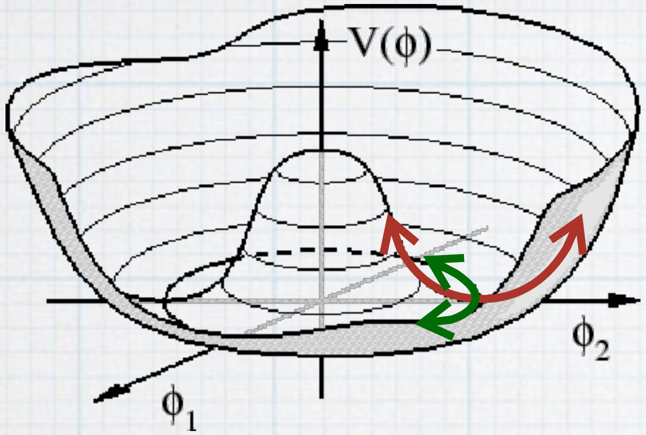
Does this change qualitatively at higher orders?



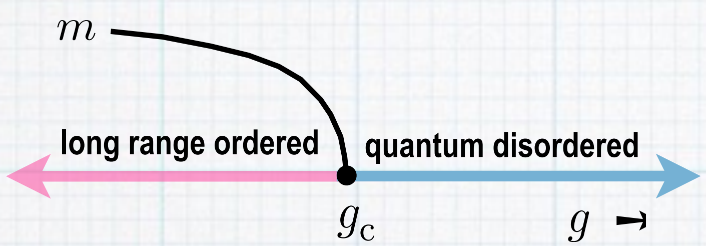
Sherman et.al. THZ spectroscopy

D. Sherman et. al., Nature Physics (2015)



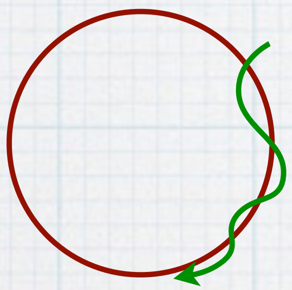


O(N) model



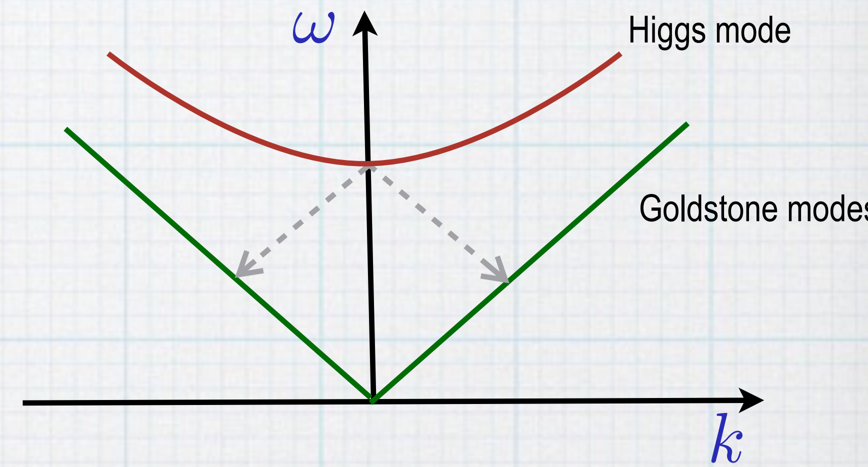
Cartesian *vs.* polar

$$\phi = \begin{cases} (r\sqrt{N} + \sigma \, , \, \boldsymbol{\pi}) \\ r\sqrt{N}\,(1+\rho)\,\hat{\boldsymbol{n}} \end{cases}$$

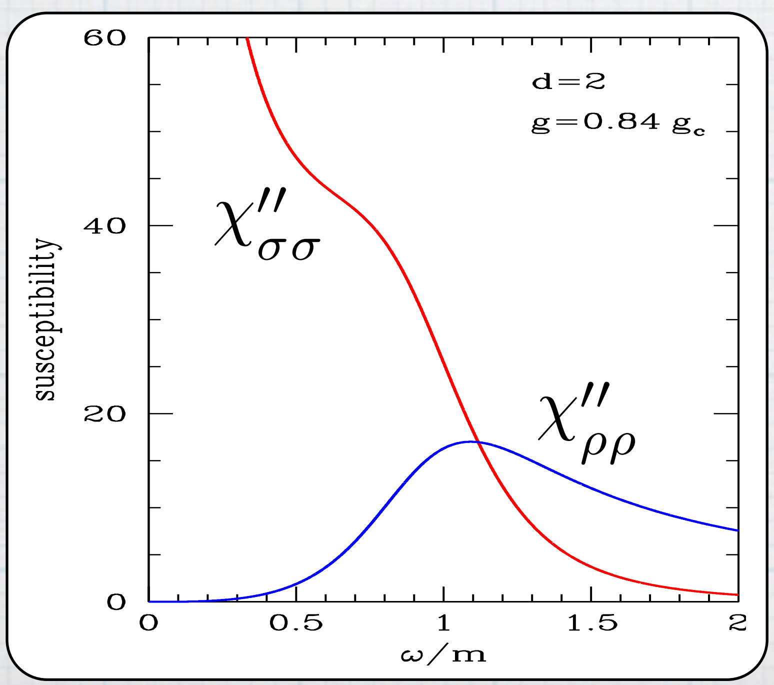


Summary

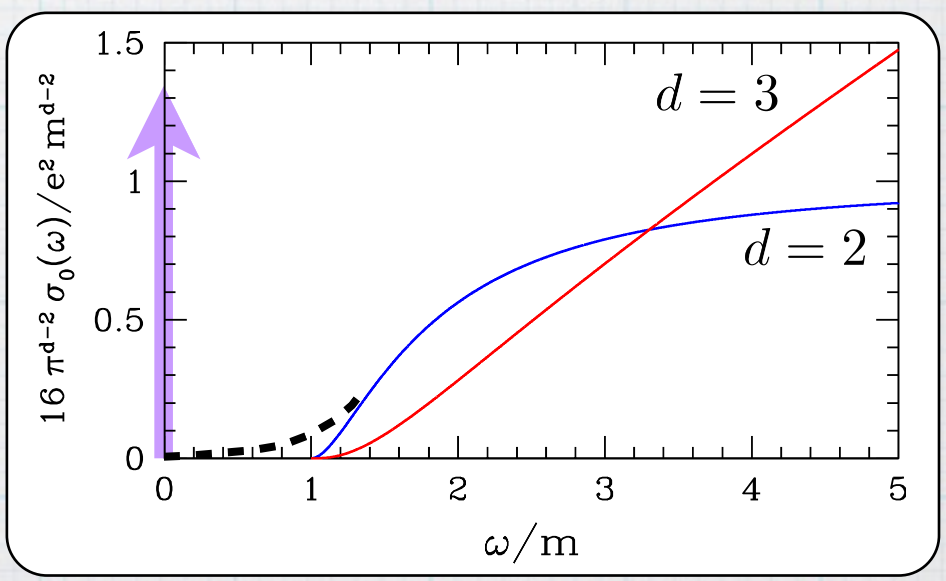
Higgs decay into Goldstone bosons



scalar $\chi''_{\rho\rho}$ is sharper than longitudinal $\chi''_{\sigma\sigma}$



conductivity pseudogap



Summary

A Higgs (amplitude) mode in condensed matter appears when

1. The dynamics are *relativistic*. (*granular superconductors, cold atoms on optical lattices, antiferromagnets)*.

2. Near a *quantum critical point*, when the Higgs mass is low.

In two dimensional superconductors, the Higgs mode is visible as a threshold for the AC conductivity.

At criticality, the Higgs spectral function scales as a *universal peak*