Broken Paradigms

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Our Tony?

Thank you Haruko and Tony for your tremendous hospitality and for keeping in touch year after year through your annual letters

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AJL@80: Challenges in Quantum Foundations, Condensed Matter Physics and Beyond, March 29,30 2018

- How to ask “good” questions
- How to make them sharper

Quantum Matter: Emergence

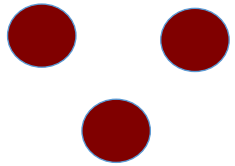
electron

Electron=charge+spin

Spin wave (magnon) S=1

$$\nabla \cdot B = 0$$

No monopoles



fractionalization

Fractional Quantum Hall effect

spin-charge separation

Luttinger Liquids

Fractionalization: S=1/2 spinons: (neutral) spinon Fermi surface

Monopoles in spin liquids

One story.....

Disorder driven Superconductor-Insulator Transition SIT

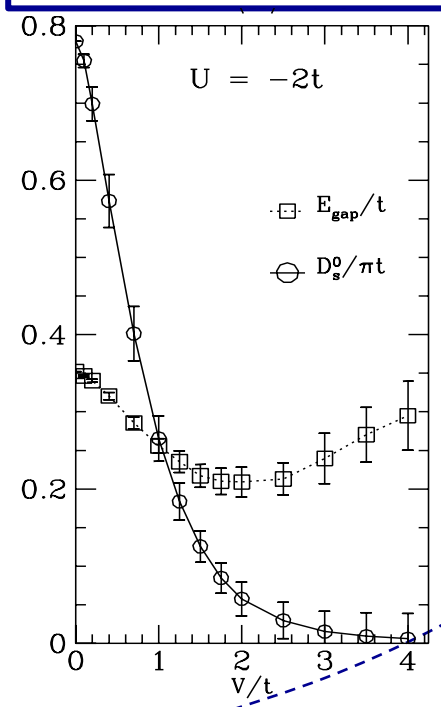
Anderson Localization

?

BCS s-Superconductivity

Breakdown of both paradigms!

Phase Diagram
Disorder tuned SIT



ρ_s

E_{gap}

ω_{pair}

g_c

Non-magnetic Disorder g

ρ_s

E_{gap}

BCS

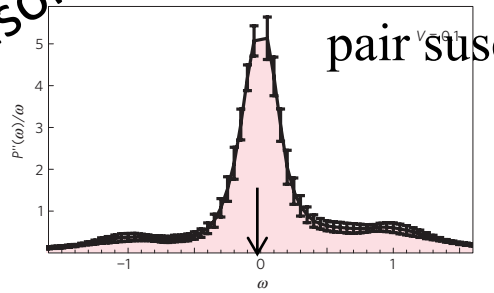
Tc

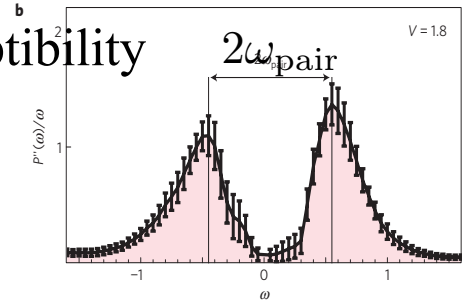
T

$T_c = \min(E_{gap}, \rho_s)$

$T^* \sim E_{gap}$

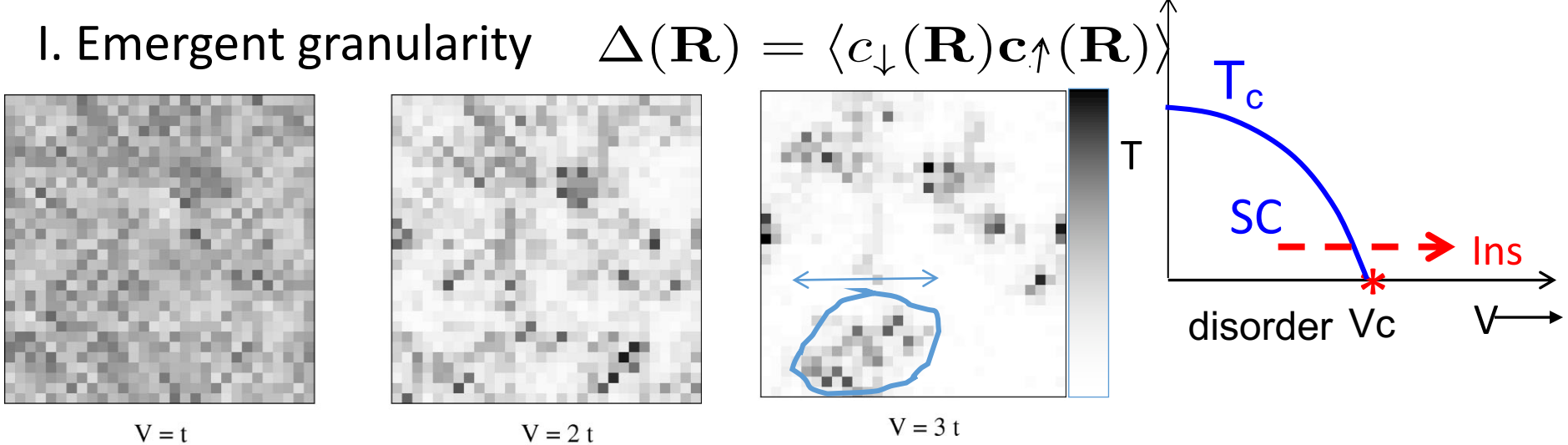
pair susceptibility





K. Bouadim, Y. L. Loh, M. Randeria, and N. Trivedi, Nat. Phys., 7, 884 (2011).
A. Ghosal, M. Randeria, and N. Trivedi, PRL 81, 3940 (1998); PRB 65, 014501 (2001).

I. Emergent granularity $\Delta(\mathbf{R}) = \langle c_\downarrow(\mathbf{R}) c_\uparrow(\mathbf{R}) \rangle$



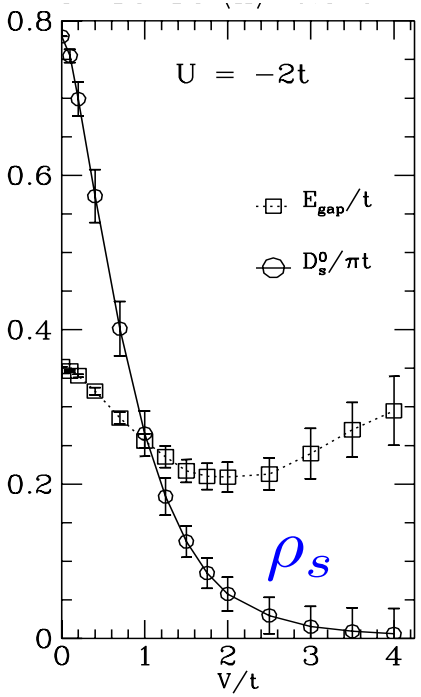
Structural disorder: atomic scale

increasing disorder

Patches~ ξ

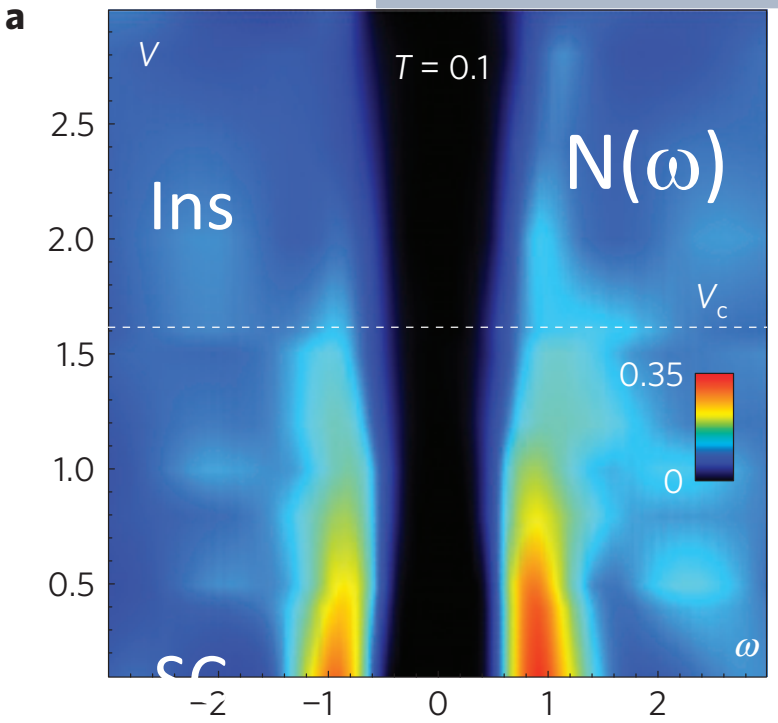
Prediction of robust Cooper pairs in insulator starting with a fermion model

Pairing of exact eigenstates; Bogoliubov de-Gennes inhomohenous mean field theory
Ghosal, Randeria & NT, PRL 81, 3940 (**1998**); PRB65, 014501 (2001)



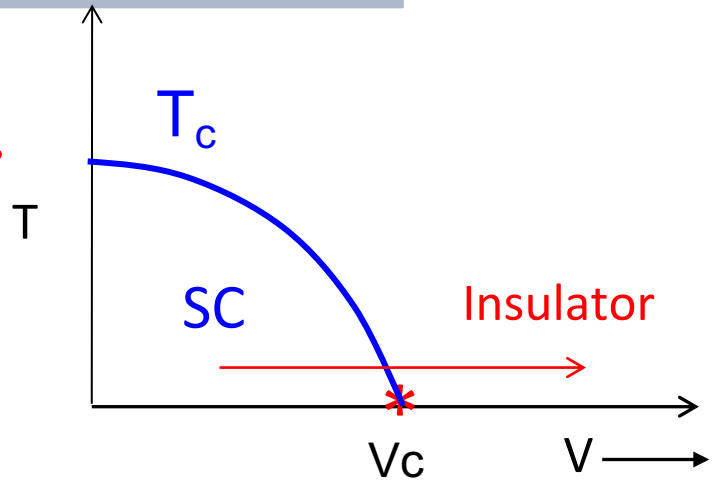
Model: Attrractive U Hubbard model with potential disorder

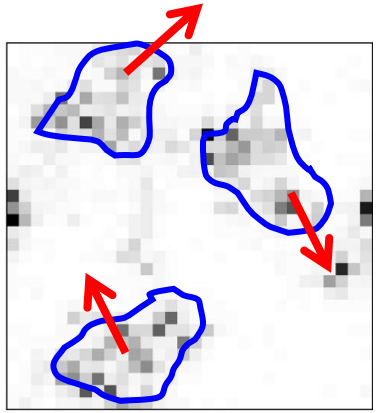
Single Particle Density of States



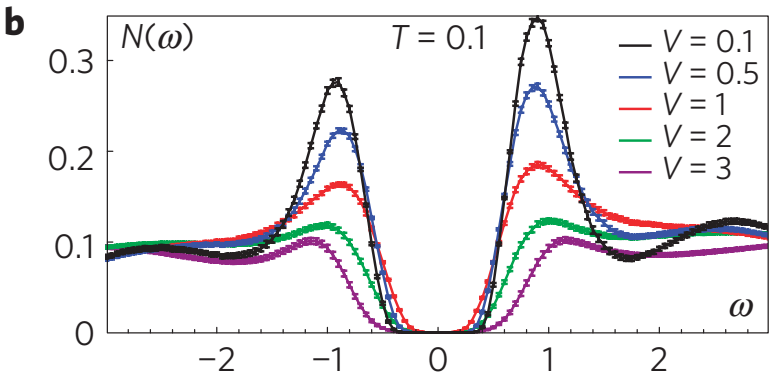
Destroyed by quantum phase fluctuations

Increasing Disorder V





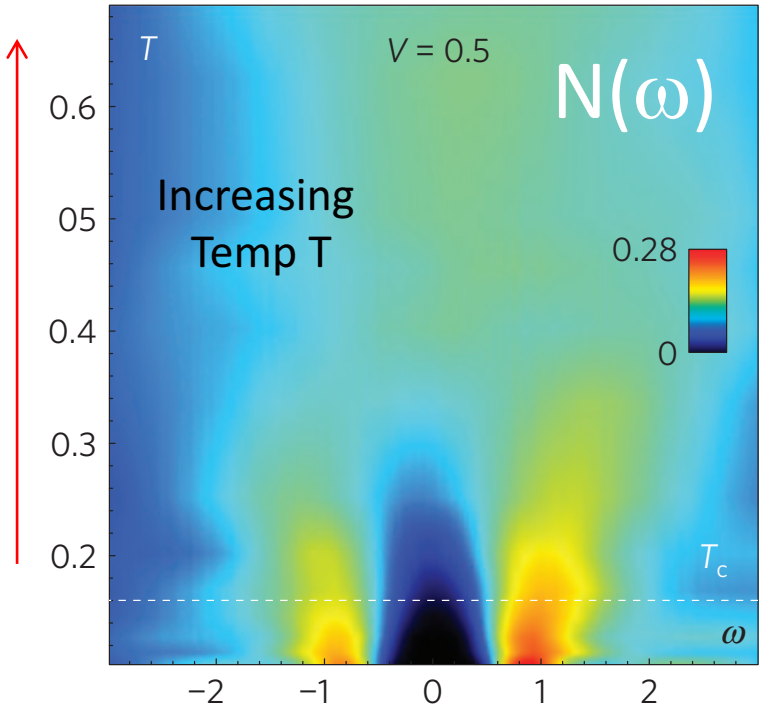
V = 3 t



Quantum Monte Carlo simulations and analytic continuation

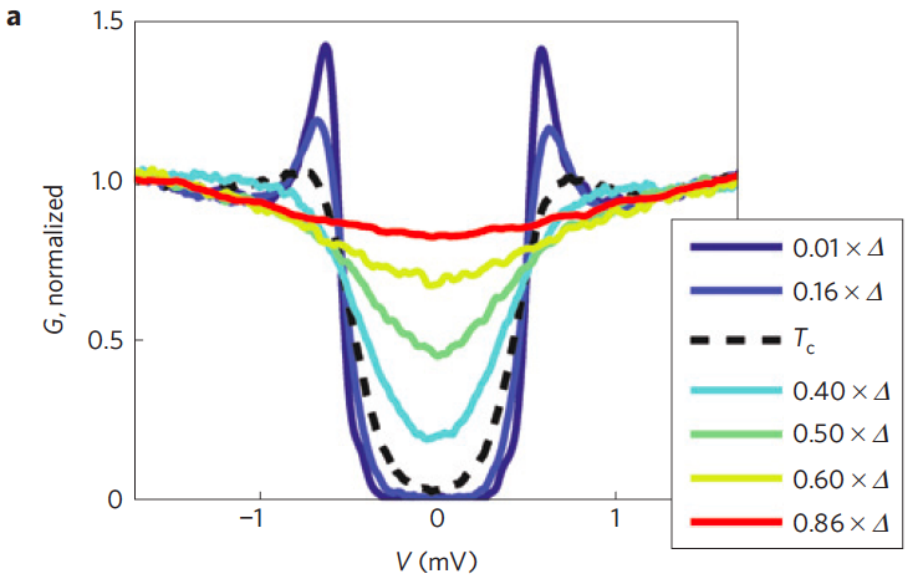
Bouadim, Loh, Randeria & Trivedi Nature Phys. 7, 884 (**2011**)

Pseudogap persists above Tc

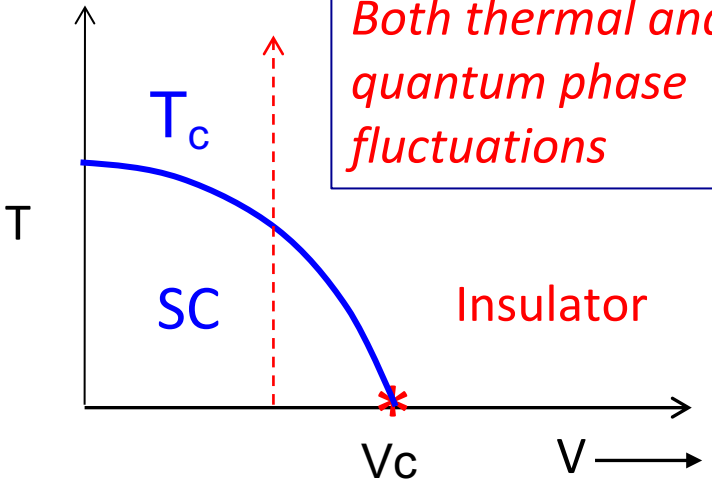


$$\rho_s \sim T_c < \omega_{\rm dos}$$

Scanning tunneling spectroscopy



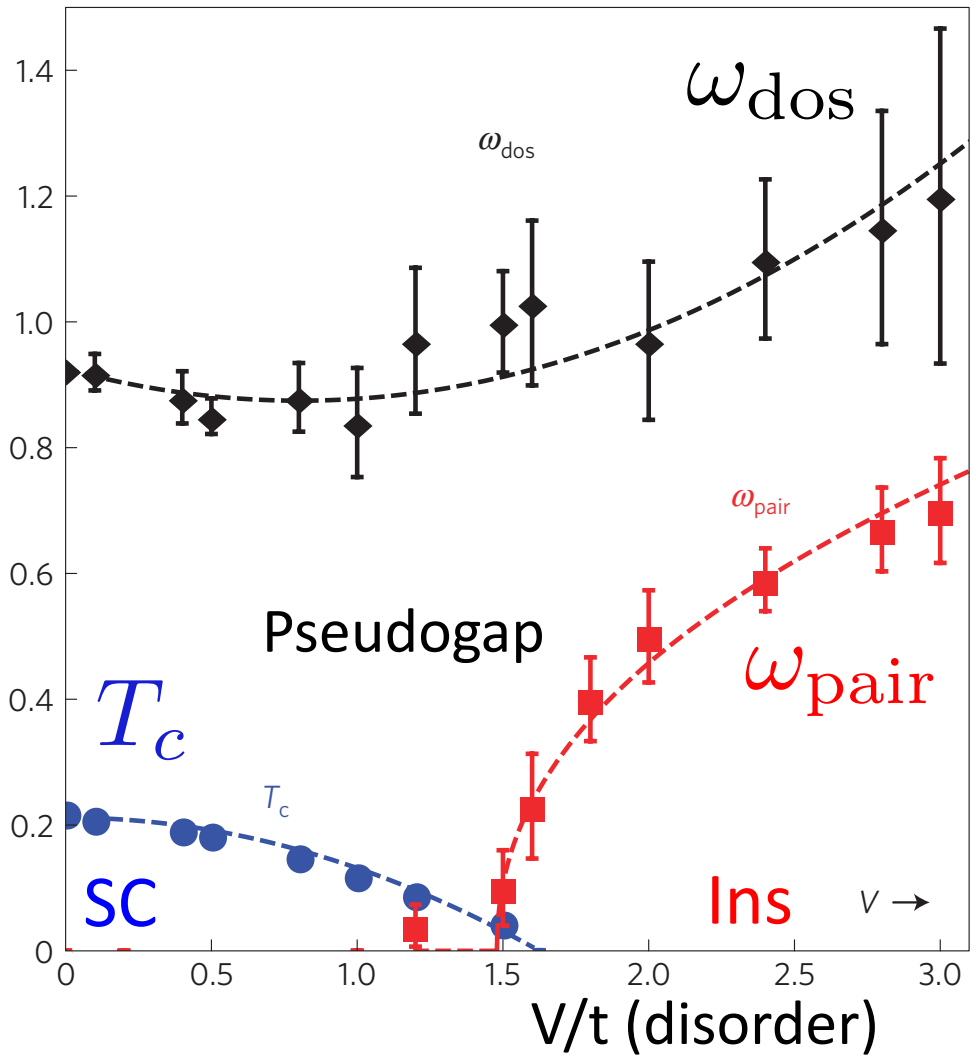
Sacépé, Dubouchet, Chapelier, Sanquer, Ovadia, Shahar, Feigel'man and Ioffe, Nat. Phys **7** 239 (2011)



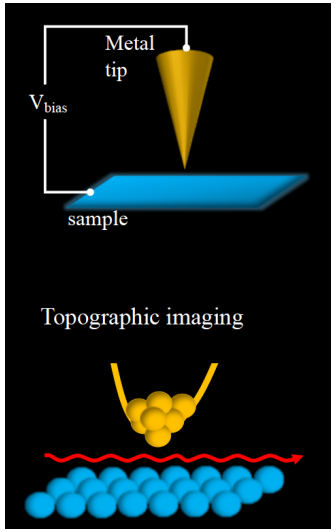
Both thermal and quantum phase fluctuations

Bouadim, Loh, Randeria & Trivedi Nature Phys. 7, 884 (**2011**)

Superconductor-Insulator Transition: Energy & T scales



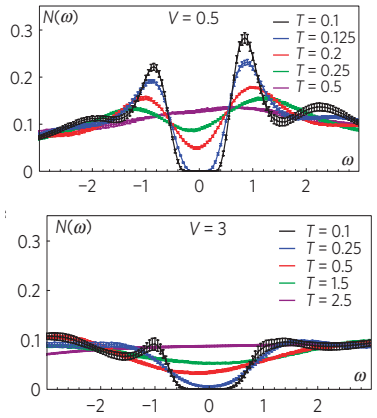
Local gap and Local superfluid density



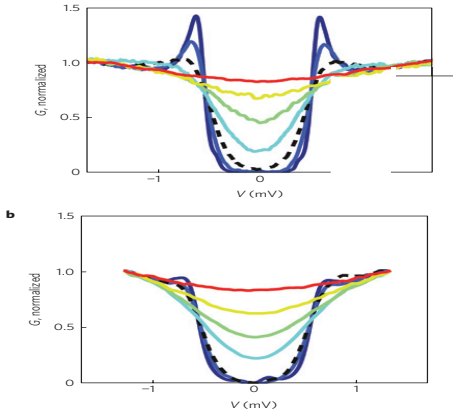
Scan-tunneling

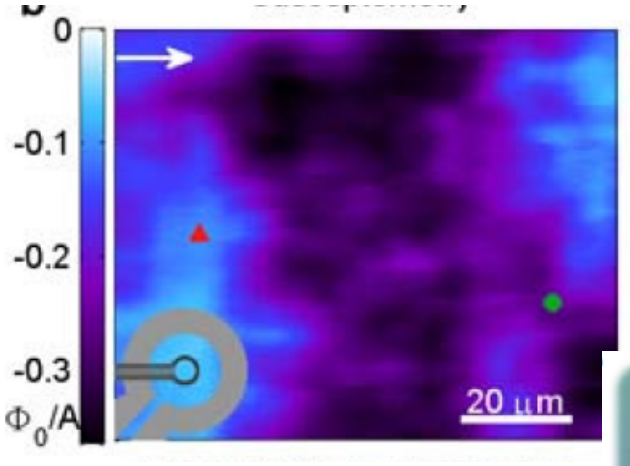
DOS gapped on *both* sides of transition

Theory

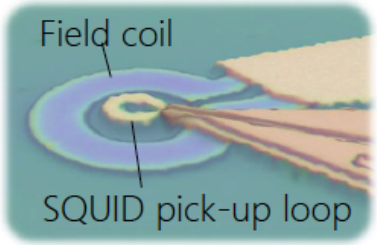


Experiment

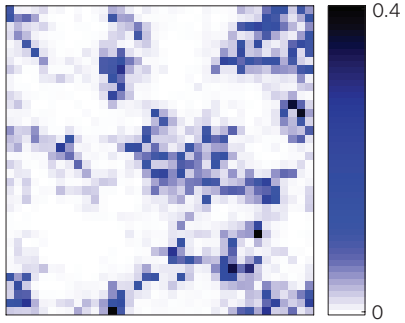


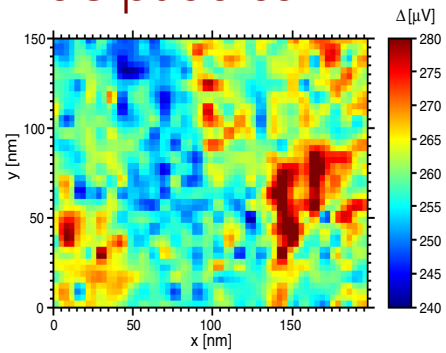


Scan-squid



Disorder leads to "SC puddles"





Theory: Ghosal *et al*, PRB 65 014501 (2001) PRL 81 3940 (1998)
Bouadim *et al*, Nat. Phys. 7, 884 (2011)

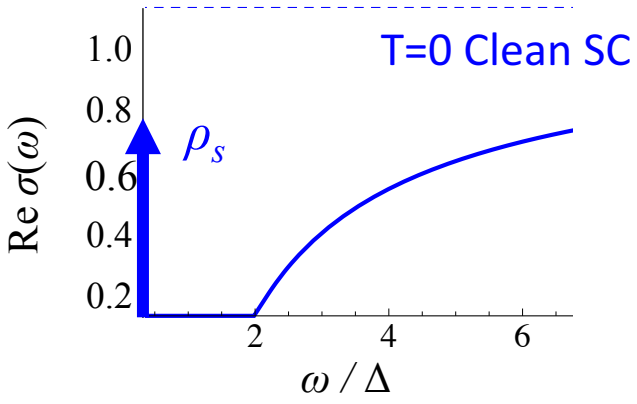
Experiment: Sacepe, *et al*, Nat. Phys **7** 239 (2011), PRL **101**, 157006 (2008)

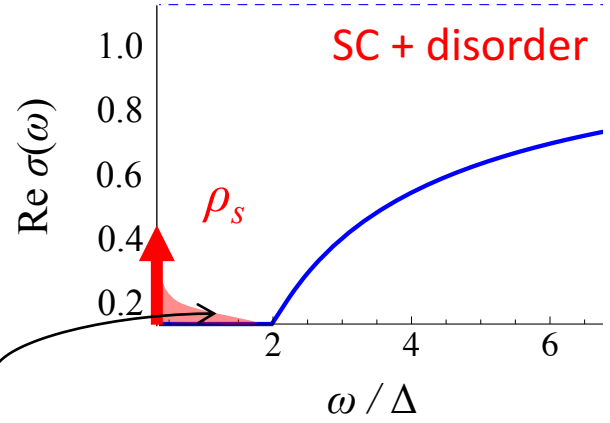
Dynamical Conductivity

With increasing disorder:

- DOS gapped on *both* sides of transition
- Superfluid density is vanishing at the transition

$$\rho_s + 2\int_{0+}^{\infty} \frac{d\omega}{\pi} \mathrm{Re}\sigma(\omega) = \langle -k_x \rangle$$



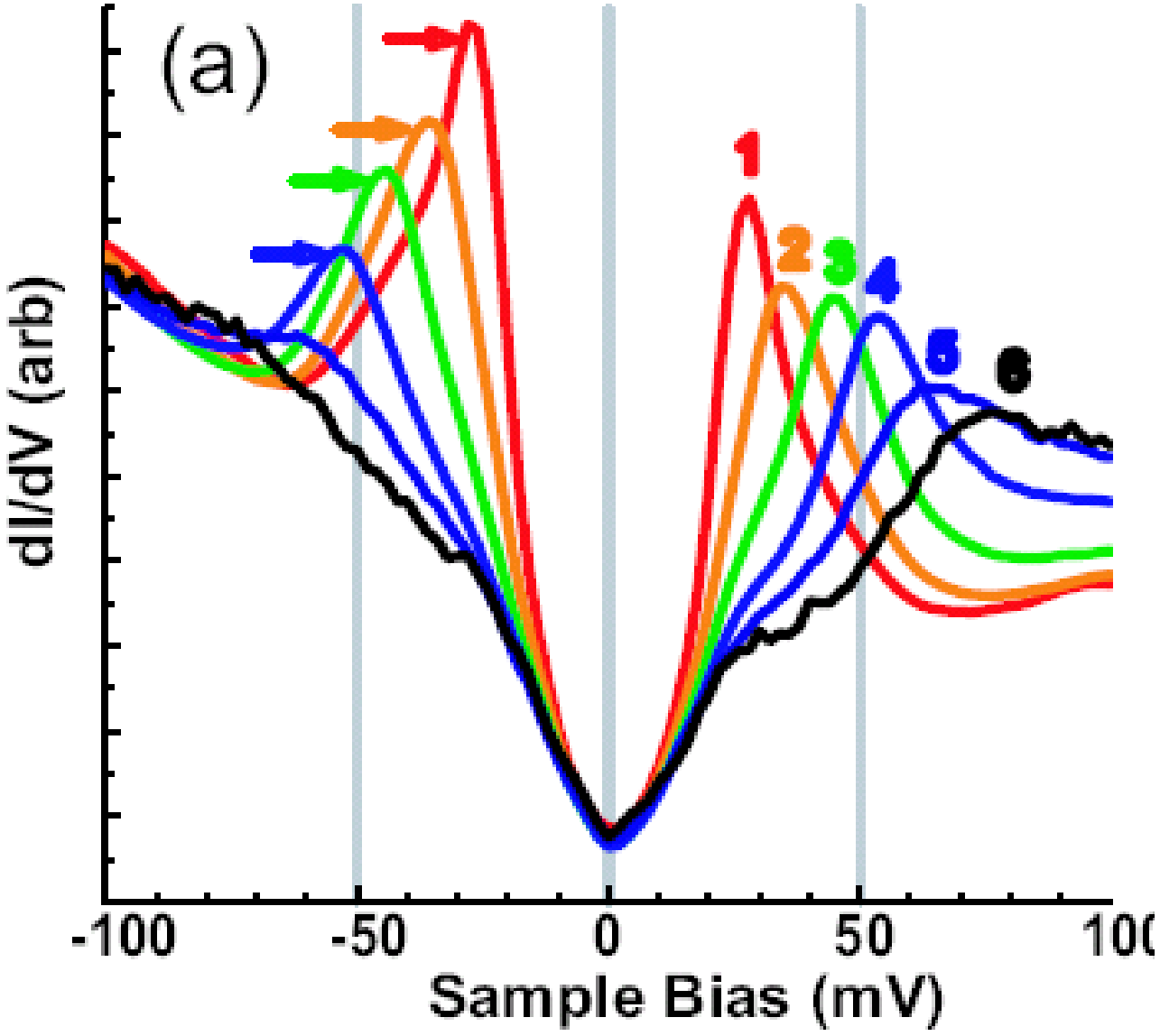


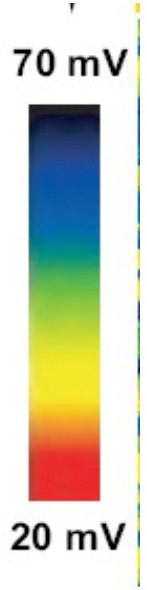
Bosonic model

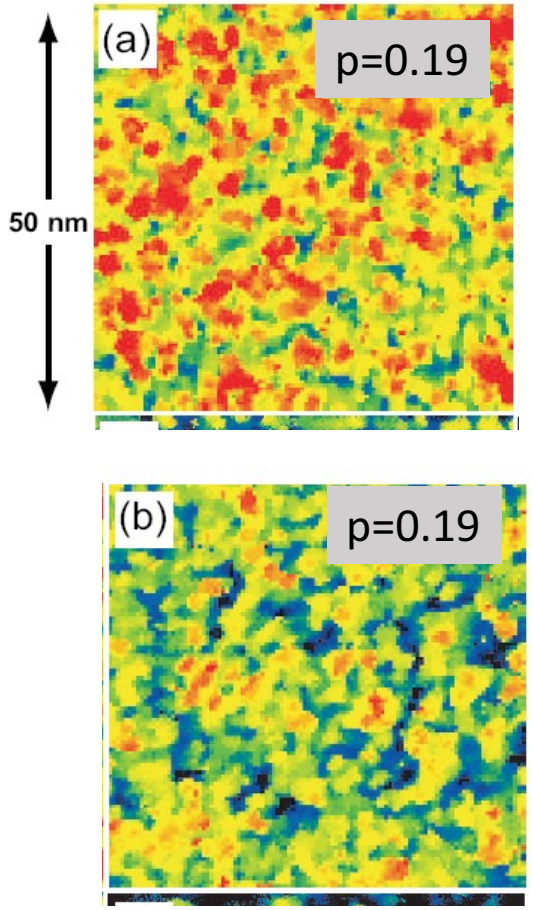
$2\Delta \to \infty$

What processes contribute to the spectral weight at low freq?

Whatever happened to d-wave and disorder?







McElroy et. al.
PRL 94, 197005
(2005)

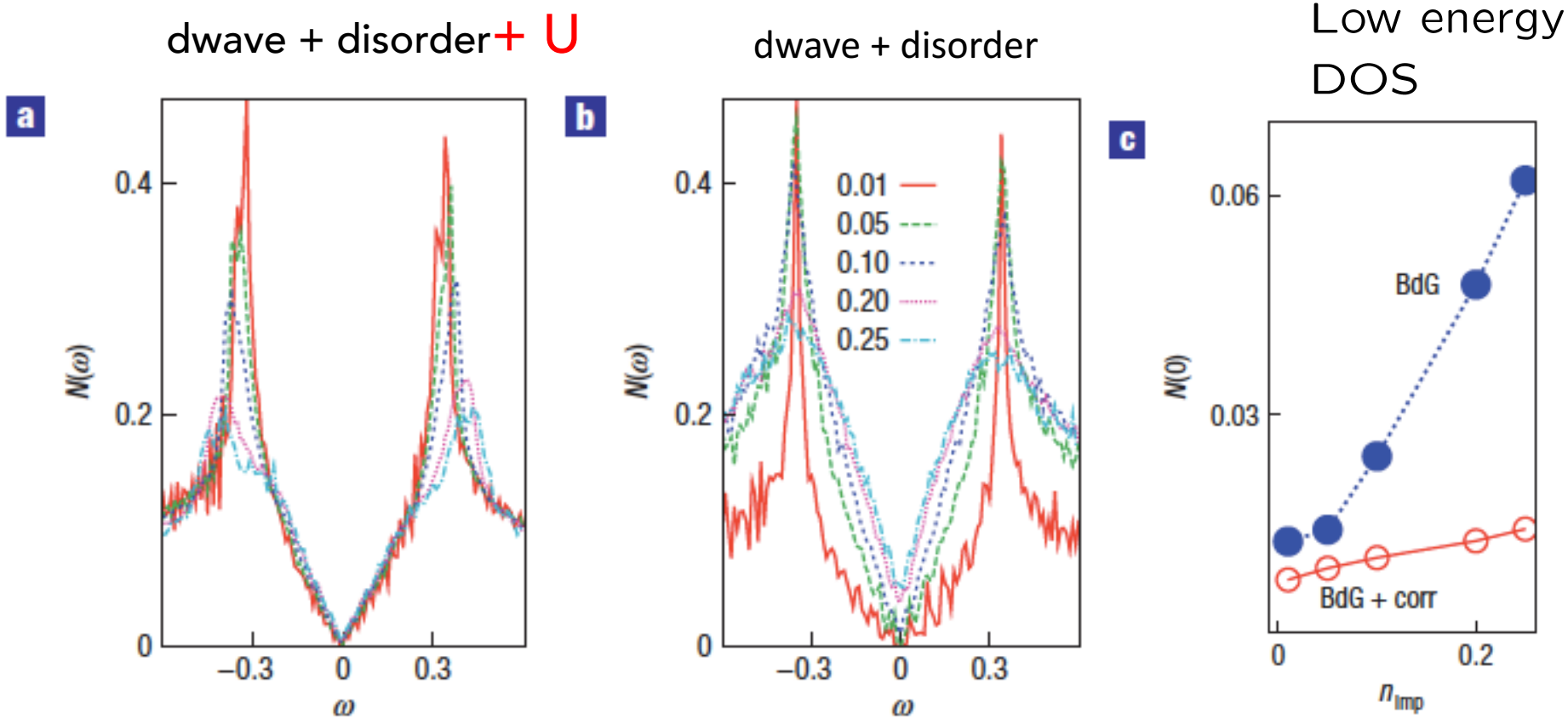
$$BSCCO = Bi_2Sr_2CaCu_2O_{8+\delta}$$

Why is the low energy V –shaped dos unaffected by disorder??

Spatially averaged DOS

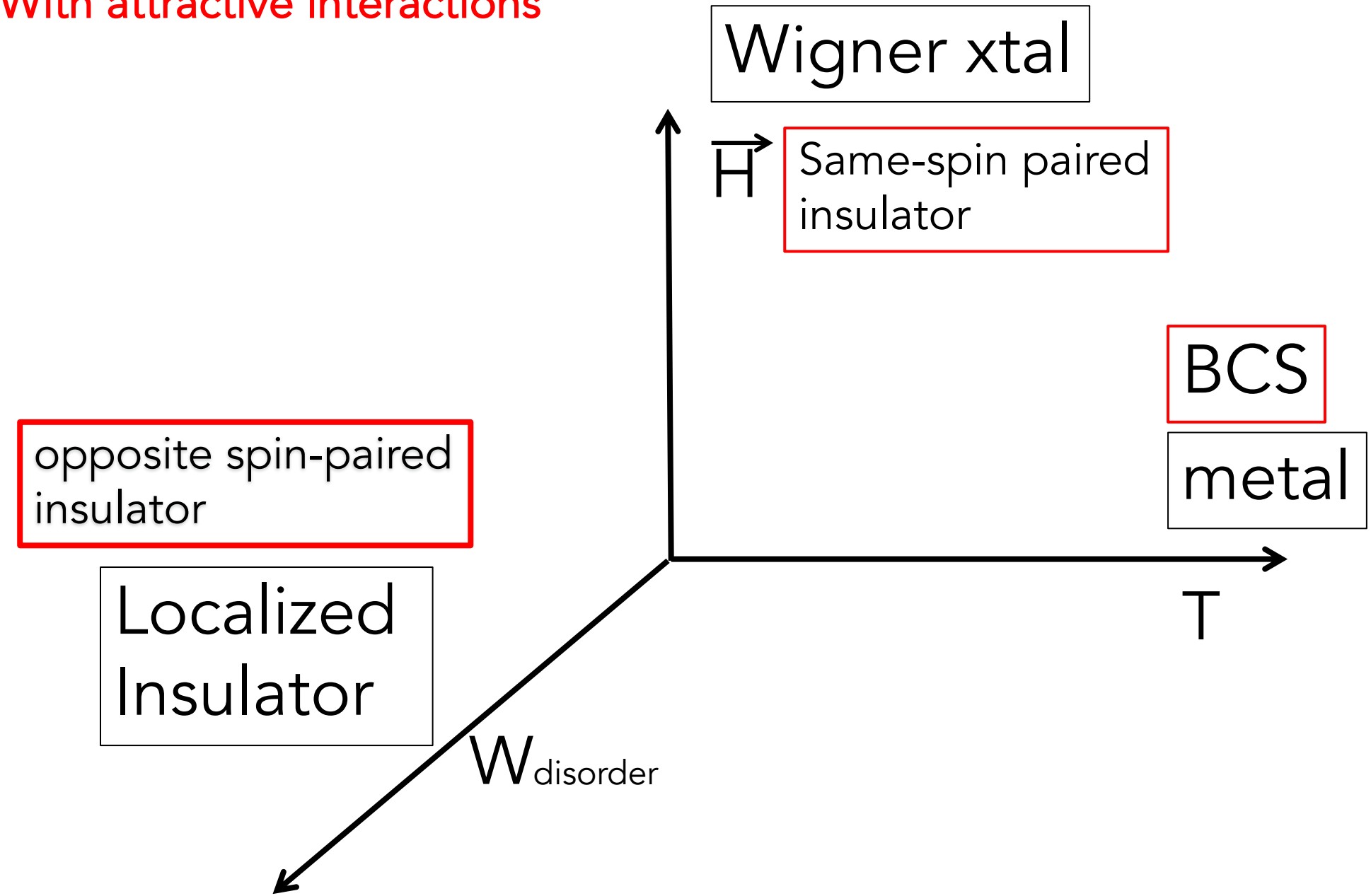
$\overline{N(\omega \approx 0)}$

Low energy DOS

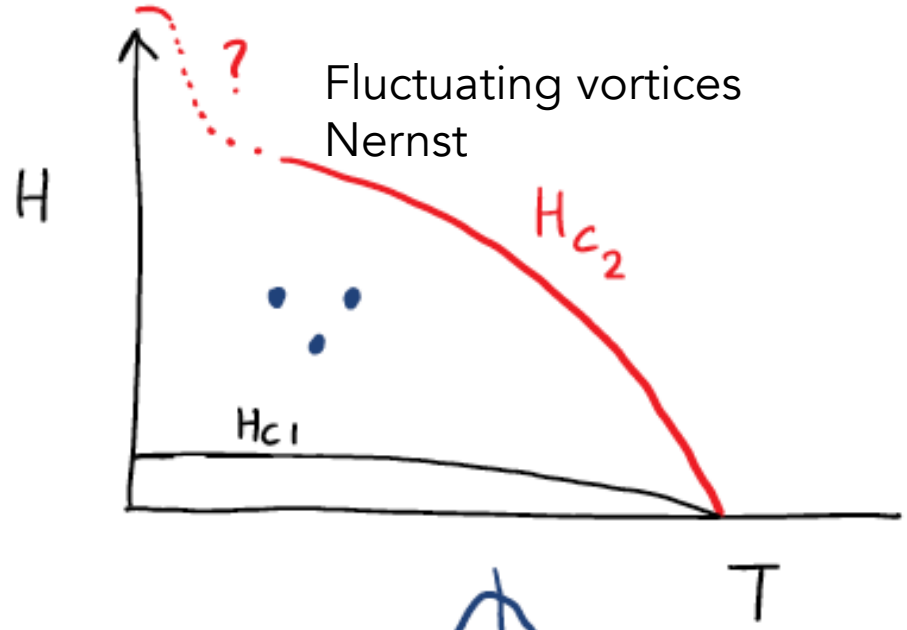


"Strong correlations make high-temperature superconductors robust against disorder"
A. Garg, M. Randeria and N. Trivedi, Nature Physics 4, 762 (2008)

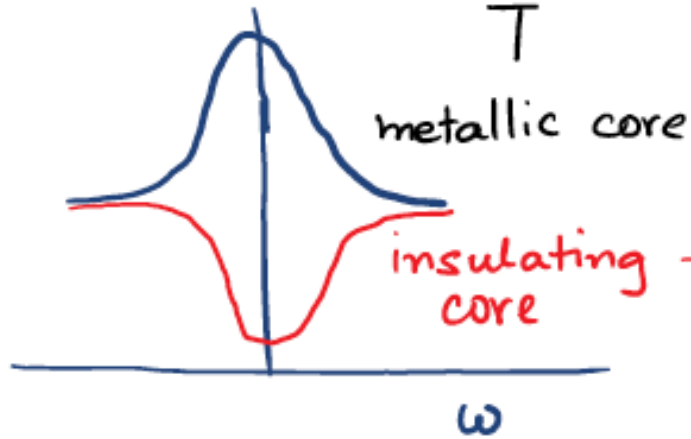
With attractive interactions



Magnetic field Puzzles :



vortex core :

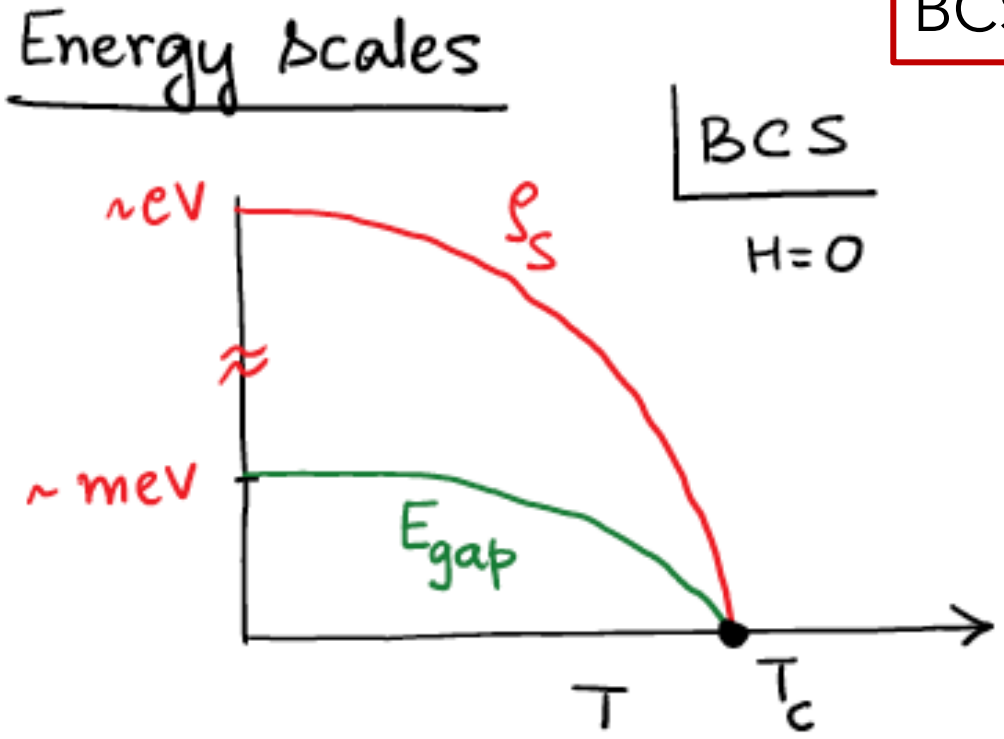


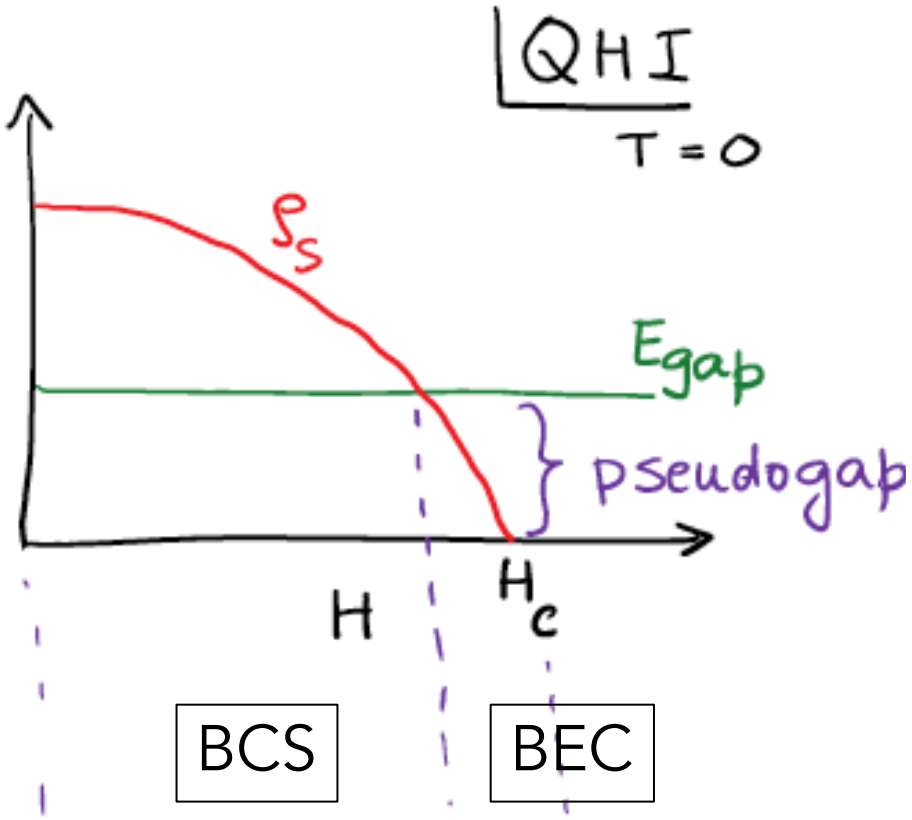
→ What kind ?

underlying state that goes SC : QH Insulator (with interactions)

Need measurements of the superfluid density (mutual inductance) as a function of magnetic field at low T

BCS--BEC crossover in a field



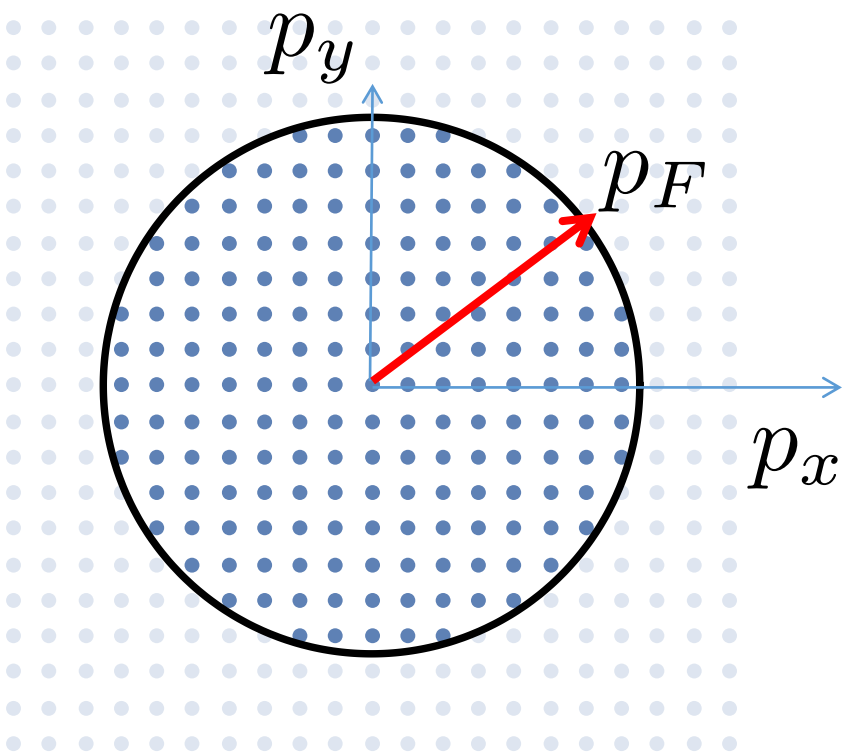


Vortex cores?

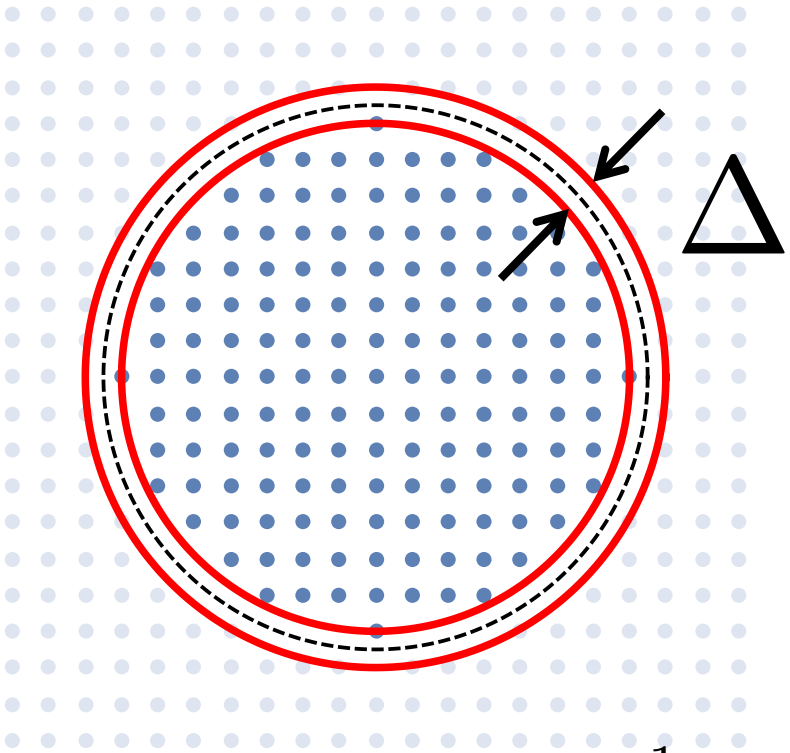
- How to ask “good” questions
- How to make them sharper

Metal: Electron Waves

Instability of Fermi surface



g



Binding energy of pair

$p = h/\lambda$ wave length of electron wave

$$\Delta \sim E_m \; e^{-\frac{1}{g}}$$

$$E_F = \frac{p_F^2}{2m}$$ Fermi energy

$$\Delta < E_m < E_F$$

How can the BCS paradigm break down?

(1) Strong coupling to glue:

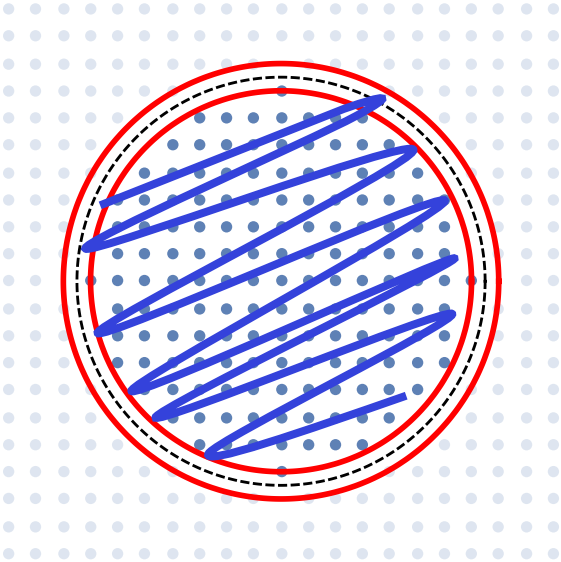
Fermi sphere greatly perturbed

$$T_c \not\propto \Delta$$

(2) Non-adiabatic limit:

electrons are ***slower*** than the mode

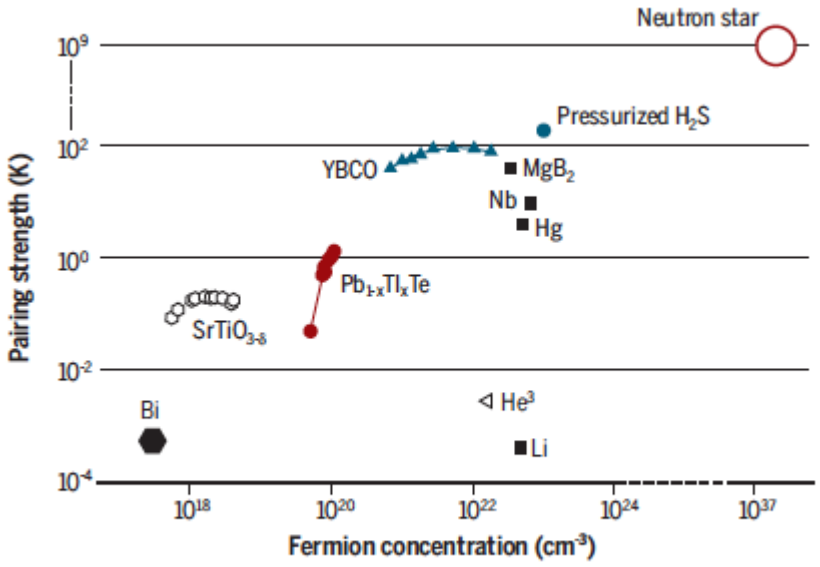
$$\Delta \not\propto E_m \; e^{-\frac{1}{g}}$$



BCS paradigm $T_c \ll E_{mode} \ll E_F$

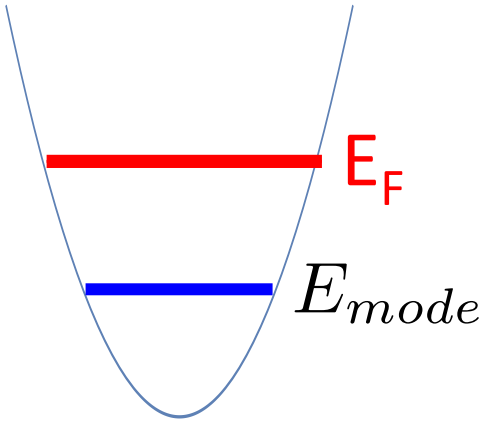
non-adiabatic limit:

electrons are slower than the mode



$\tau_e > \tau_{mode}$

$E_F < E_{mode}$



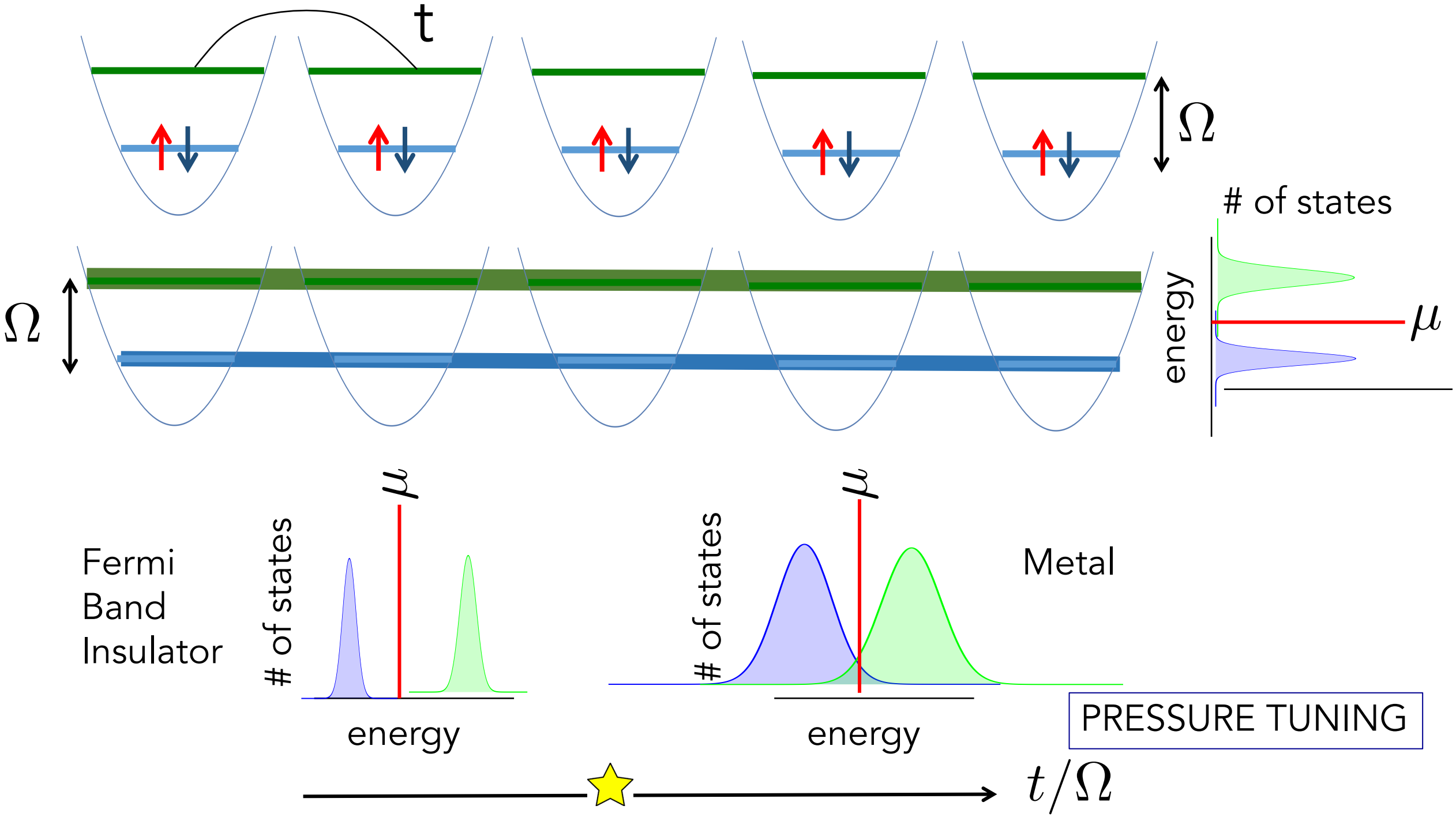
Bismuth: E_F=25 meV

E_{mode}=12 meV

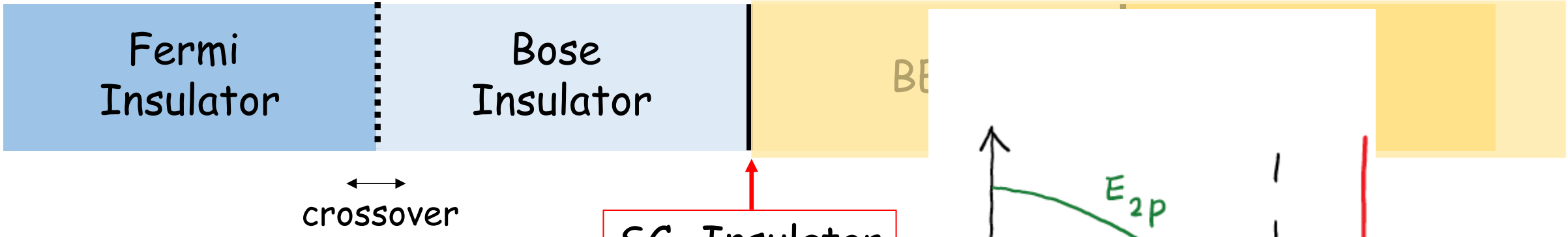
Tc= 0.5 mK~0.05 meV

Prakash, Kumar, Thamizhavel, Ramakrishnan, Science 355, 52–55 (2017)

Can an insulator become a SC? [*at same doping*]
How does SC arise when there is ***no*** Fermi surface?


t
Ω
Ω
# of states
energy
μ
Fermi
Band
Insulator
# of states
μ
energy
# of states
μ
energy
Metal
PRESSURE TUNING
t/Ω

Fixed attraction U

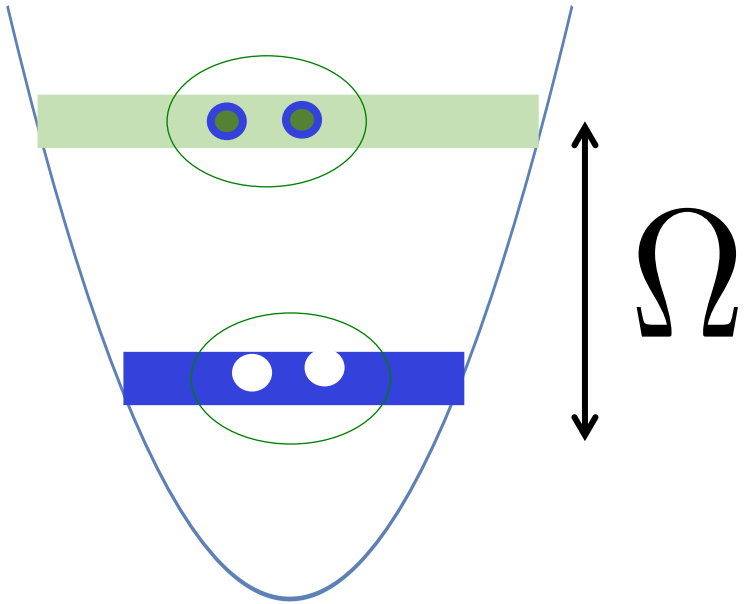


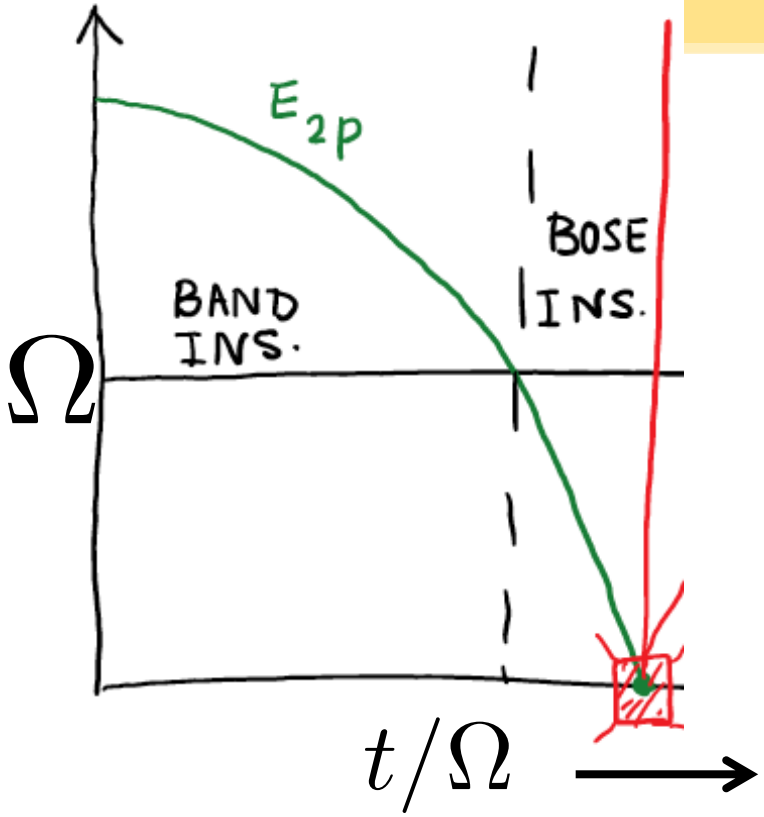
U=0

$$E_{1p} = \Omega$$

$$E_{2p} = 2\Omega$$

$U \neq 0$





Increase hopping t between wells

Insulator-Superconductor Transition:

Fermi Insulator	Bose Insulator	BEC	BCS

crossover

SC- Insulator Transition

crossover

Lowest energy excitation is a charge e fermion

Lowest energy excitation has charge 2e -- "boson"

→ goes soft at SIT

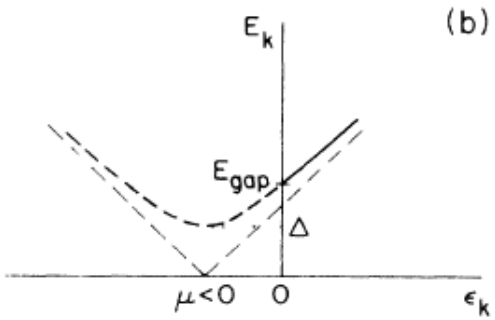
Minimum Gap locus is a Point

Minimum Gap locus is a Contour

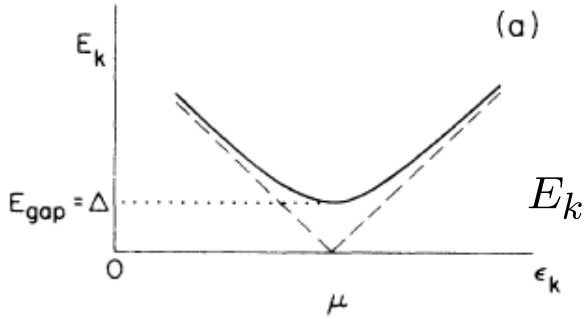
* Topology of minimum gap locus
* Gap-edge singularity in DOS

Loh, Randeria, Trivedi, Chen, Scalettar, Phys. Rev. X 6, 021029 (2016)

BEC regime ("strong pairing")



BCS regime ("weak pairing")



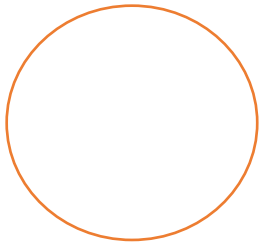
$$E_k = \sqrt{(\epsilon_k - \mu)^2 +}$$

Minimum gap locus in k-space

point

$$\epsilon_k = 0$$

or $k = 0$

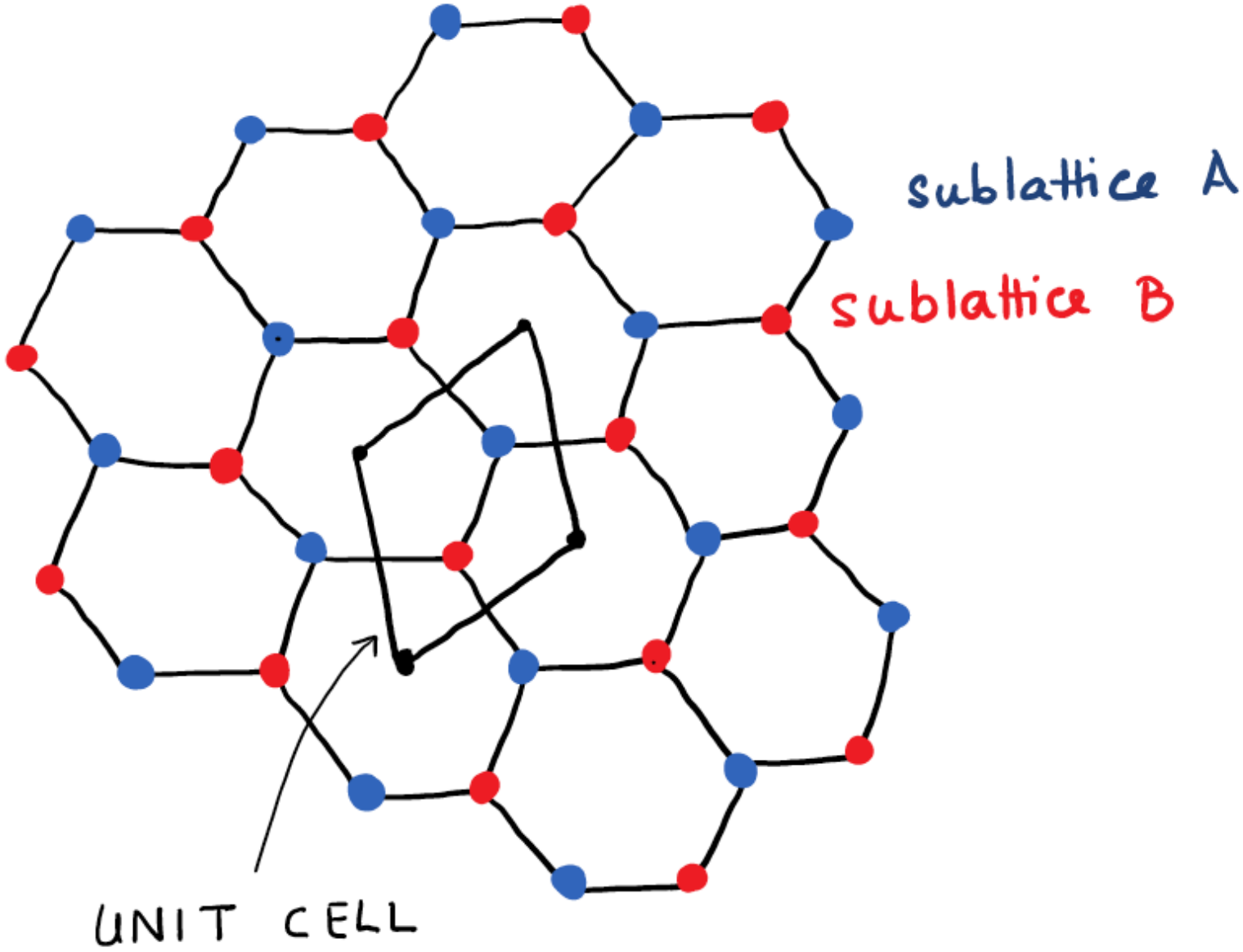


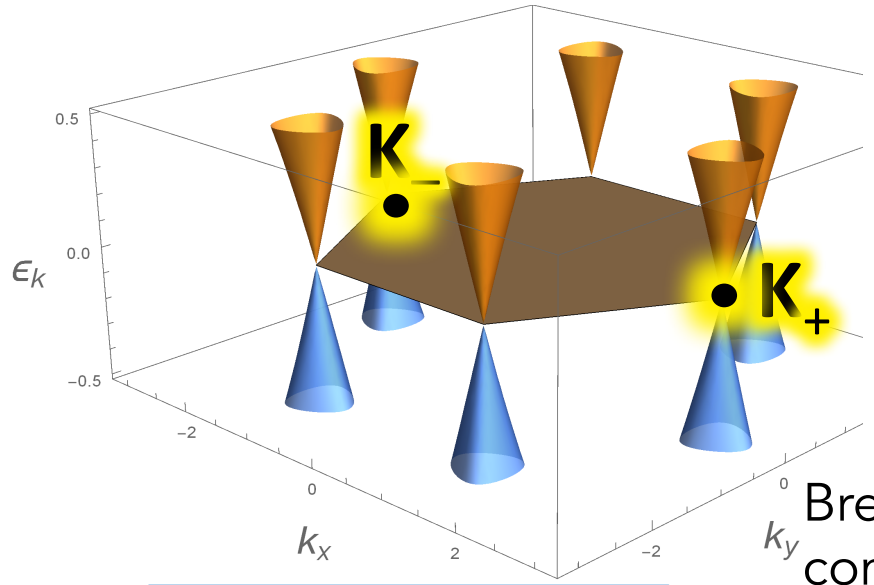
contour

$$\epsilon_k = \mu$$

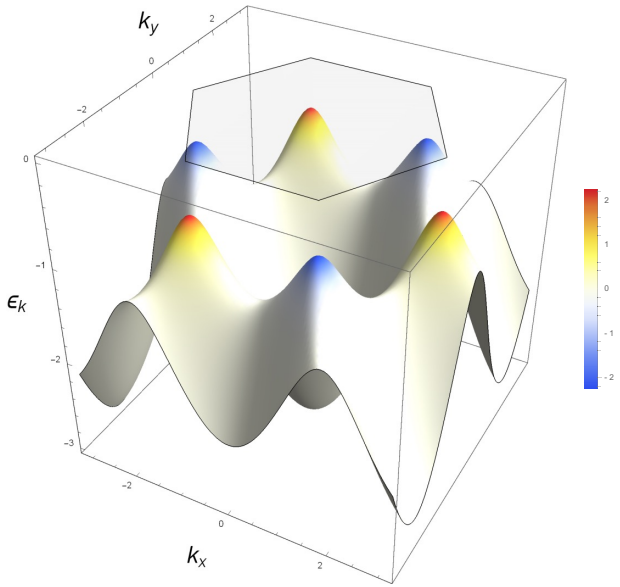
or $k =$ "k_F"

Can a topological insulator become a SC?
Is the SC topological?
What is the role of the Berry phase?

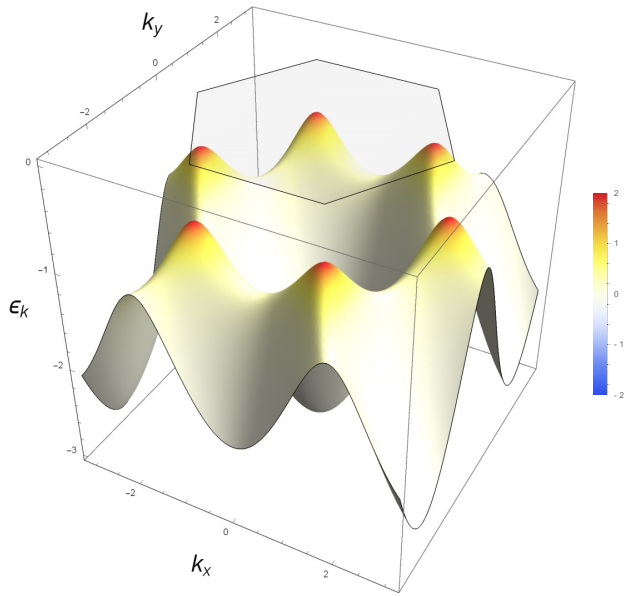

sublattice A
sublattice B
UNIT CELL



Break inversion
Sublattice potential



Break TR
complex nn hopping



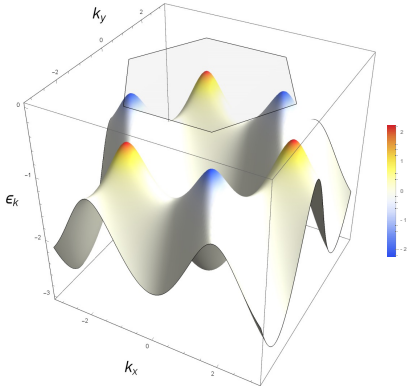
Dirac points protected by inversion and time reversal symmetry

(Color: Berry curvature = Berry flux density)

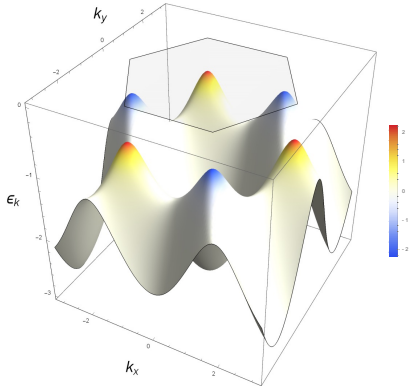
Trivial Insulator

Topological Insulator

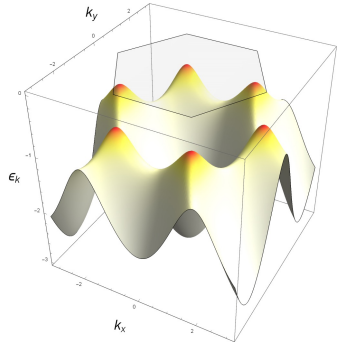
λ/m



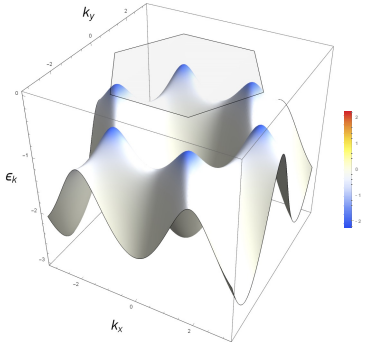
spin ↑



spin ↓



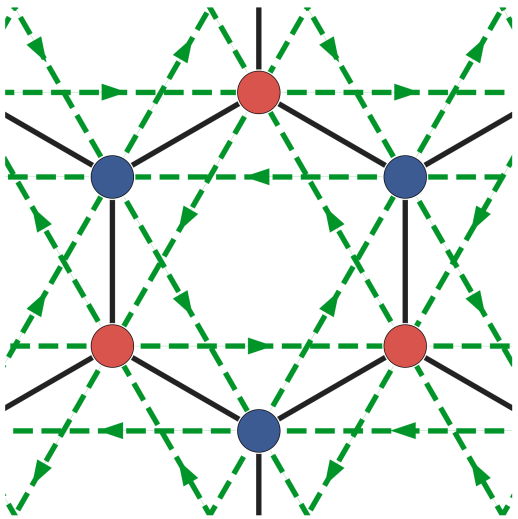
spin ↑



spin ↓

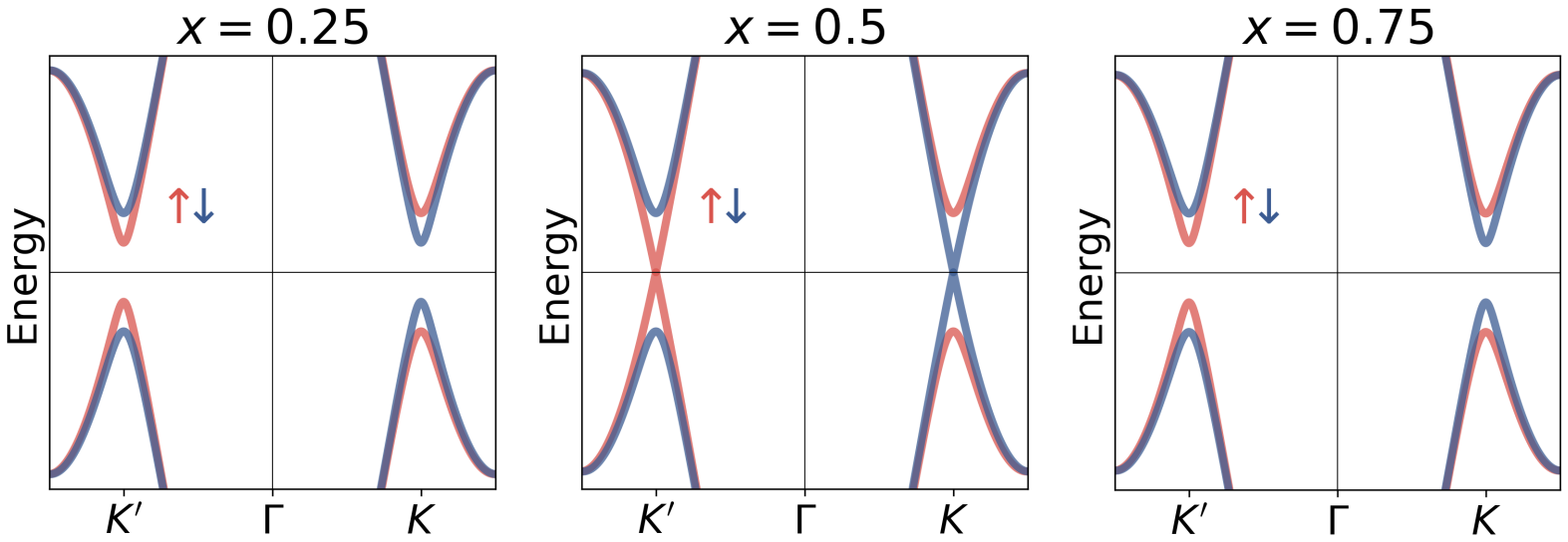
Band Structure: Kane-Mele M

topological phase transition



trivial phase

topological phase



$$H_{\mathrm{KM}} = -t \sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i\sigma} c_{j\sigma}$$

$$-i\lambda \sum_{\langle\langle i,j\rangle\rangle,\sigma} \nu^{\sigma}_{ij} c^{\dagger}_{i\sigma} c_{j\sigma}$$

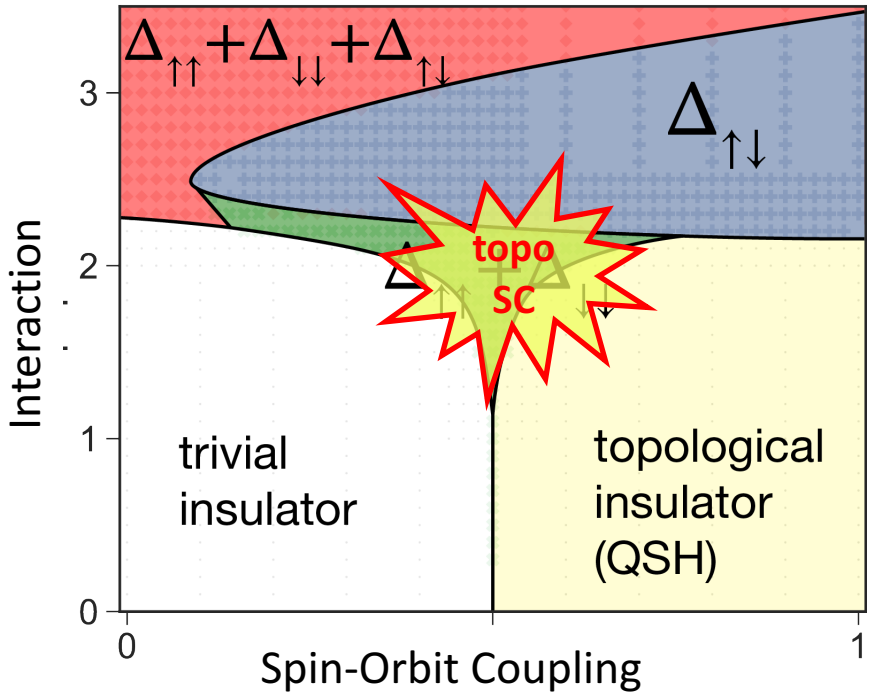
$$+m_{\mathrm{AB}} \sum_{i\in A,\sigma} c^{\dagger}_{i\sigma} c_{i\sigma} - m_{\mathrm{AB}} \sum_{i\in B,\sigma} c^{\dagger}_{i\sigma} c_{i\sigma}$$

$m_{\mathrm{AB}} > 3\sqrt{3}\lambda$

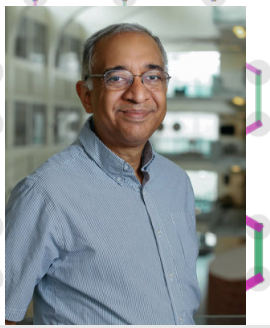
$m_{\mathrm{AB}} < 3\sqrt{3}\lambda$

$$x \equiv \frac{3\sqrt{3}\lambda}{3\sqrt{3}\lambda + m_{\mathrm{AB}}}$$

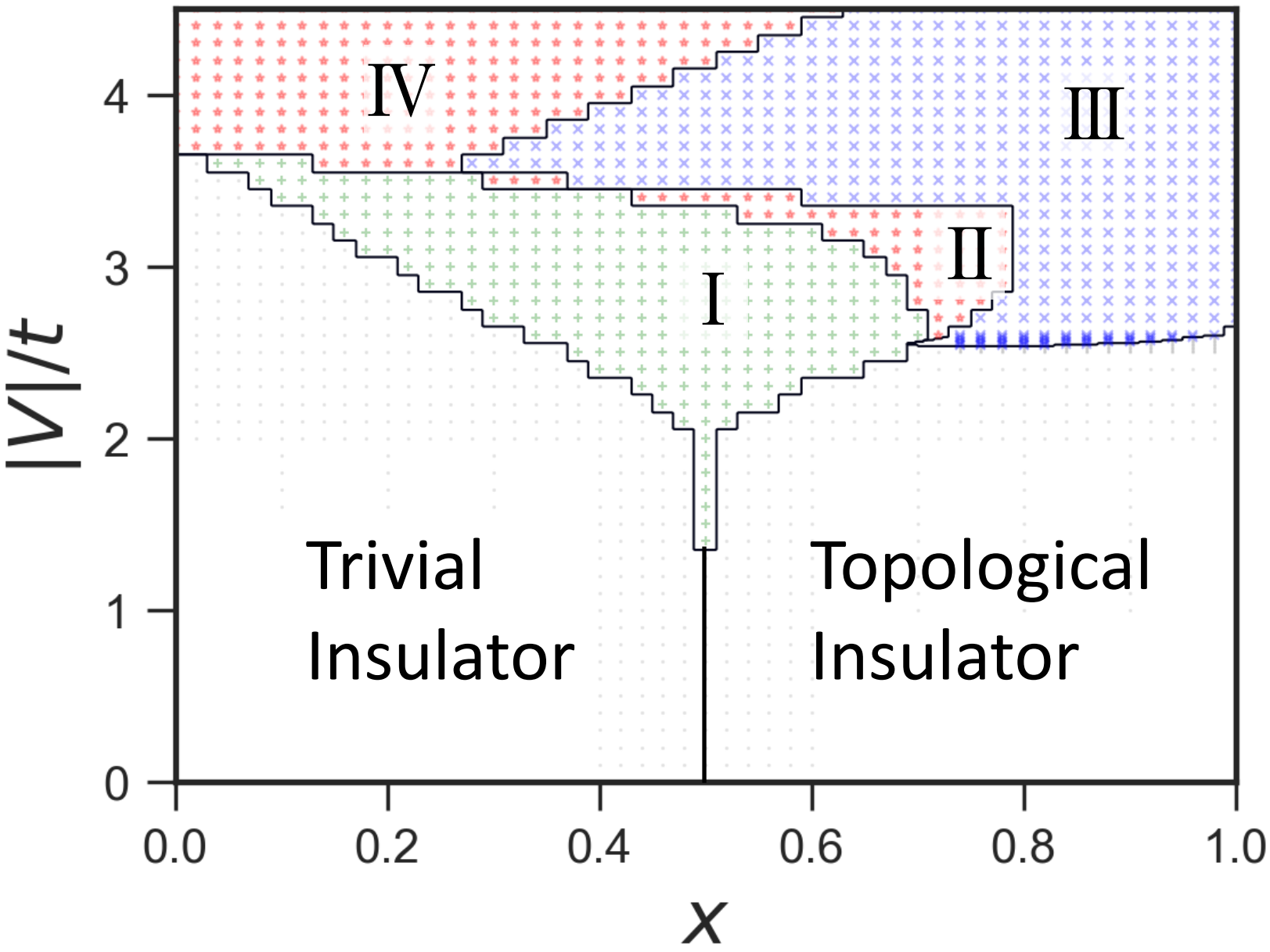
Pairing Instabilities at Bulk and Edge of Topological Insulator





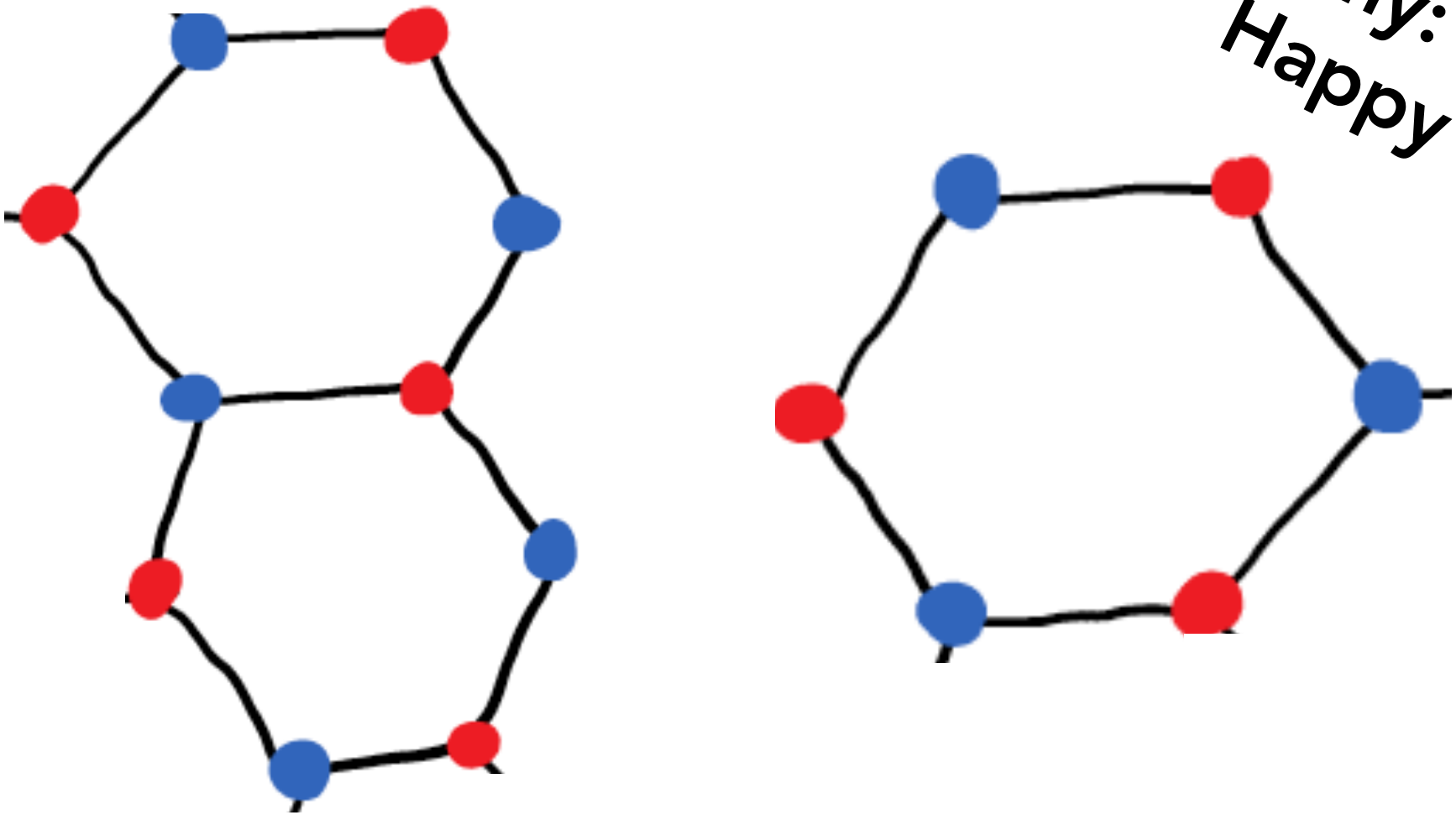


Tamaghna Hazra Kyungmin Lee Mohit Randeria



Phases

- I
  - Time-reversal Invariant
  - Topological SC ($\tilde{\nu} = 1$)
- II
  - Time-reversal breaking
  - Topological SC ($\tilde{C} = \pm 1$)
- III
  - Time-reversal invariant
  - Trivial SC ($\tilde{\nu} = 0$)
- IV
  - Time-reversal breaking
  - Trivial SC ($C = 0$)



Tony:
Happy Birthday