Title: New Paths to Unconventional Topological Superconductivity

Date: Nov 07, 2011 02:00 PM

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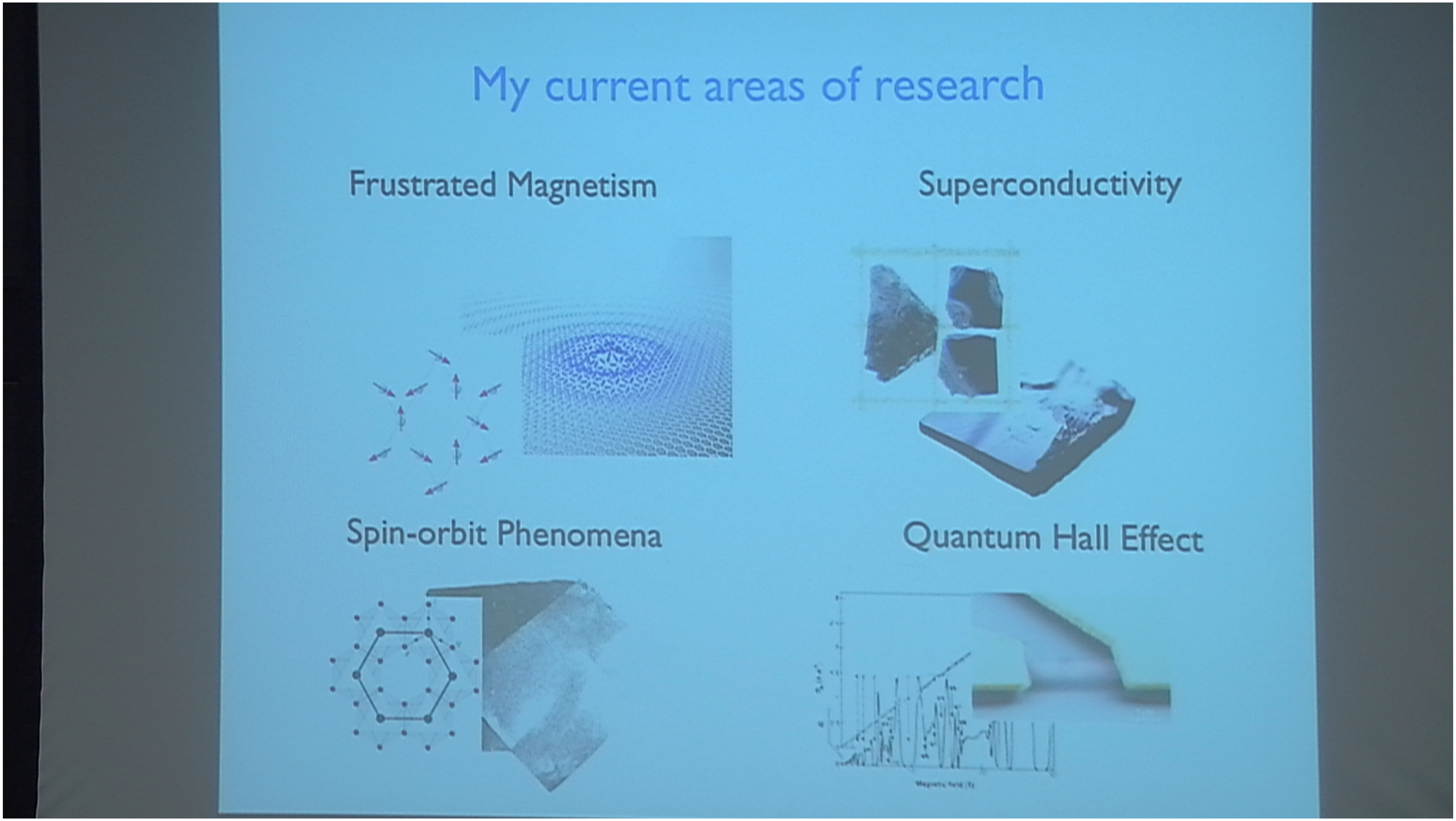
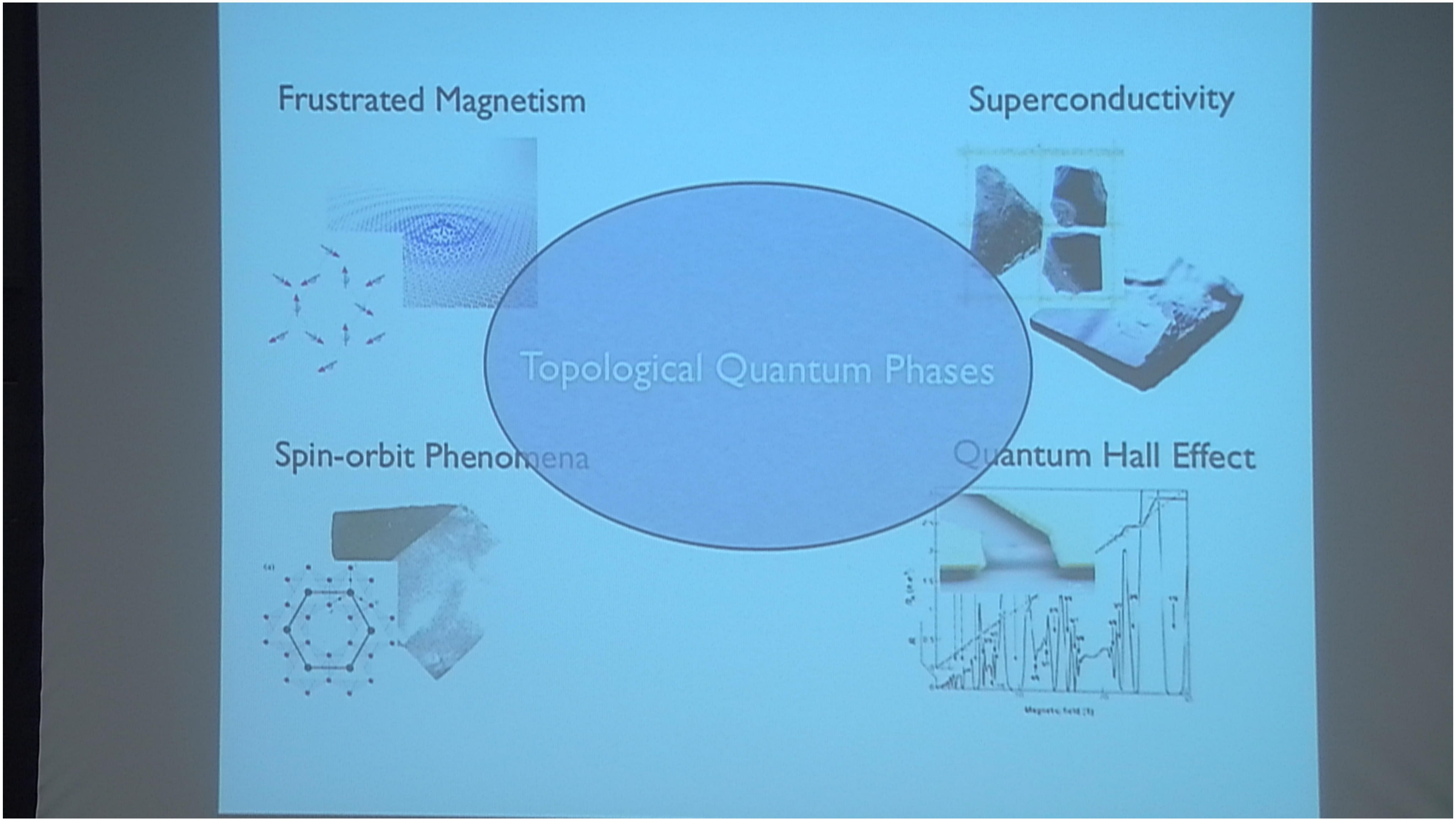
Abstract: We report on our recent progress to investigate materials classes exhibiting d+id superconductivity, where topologically nontrivial pairing phases can emerge. Specifically, motivated by recent experimental progress, we show that graphene doped to the van Hove regime can give rise to a plethora of interesting ordering instabilities such as spin density wave and superconductivity. As a function of system parameters such as doping and range of Coulomb interaction, we explain which instability is favored by the system, and analyze the effect of long-range interactions on superconductivity giving rise to a competition between singlet d+id and triplet f wave. We also outline our work in progress for other materials classes which we believe are promising to stabilize such interesting topological superconducting states of matter.


New paths to unconventional topological superconductivity
Ronny Thomale
Stanford University
Die Junge Akademie
LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891
Deutsche Forschungsgemeinschaft
DFG
Perimeter Institute, Nov 7th 2011


My current areas of research
Frustrated Magnetism
Superconductivity
Spin-orbit Phenomena
Quantum Hall Effect


Frustrated Magnetism
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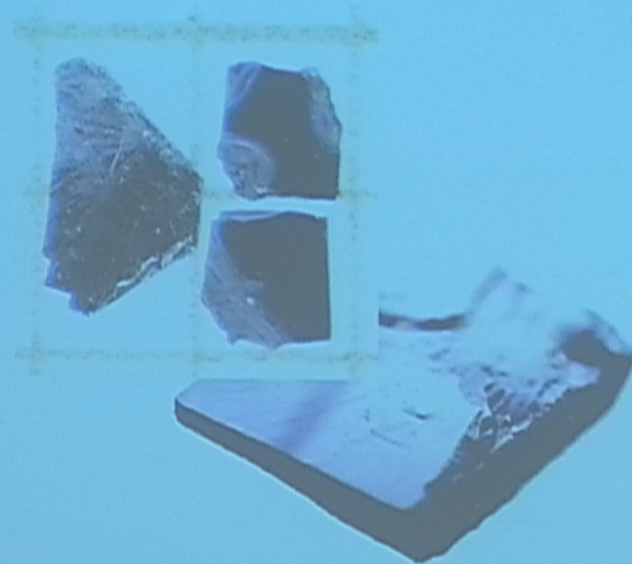
This talk:



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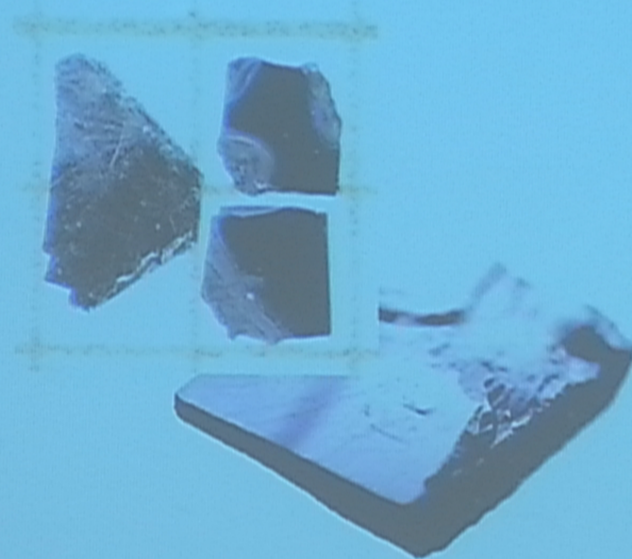

How to find topological superconductivity?

Collaborators

- C. Platt, M. Kiesel, W. Hanke (Würzburg)
- D.A. Abanin (Harvard, Perimeter)

Thanks for discussions:
G. Baskaran, S. Kivelson, S. Raghu, X.-L. Qi, S. C. Zhang,
J. Analytis, I. Fisher

Outline

- Topological superconductivity – order parameter, edge modes, vortex cores, phase transitions

- Functional renormalization group – from a microscopic material description to collective many-body phases

- Graphene – d+id superconductivity and helical magnetic order at van Hove filling

- Cobaltates – d+id superconductivity and multi-orbital anisotropy

Superconductivity formalism in a nutshell

Electronic model with a pairing instability mean field:

$$H_{\mathrm{BCS}}^{\mathrm{MF}} = \sum_{\boldsymbol{k},\sigma} \xi_{\boldsymbol{k}} c_{\boldsymbol{k}\sigma}^{\dagger} c_{\boldsymbol{k}\sigma} - \sum_{\boldsymbol{k}} \Delta_{\boldsymbol{k}} c_{\boldsymbol{k}\uparrow}^{\dagger} c_{-\boldsymbol{k}\downarrow}^{\dagger} - \sum_{\boldsymbol{k}} \Delta_{\boldsymbol{k}}^{*} c_{-\boldsymbol{k}\downarrow} c_{\boldsymbol{k}\uparrow}$$

Order parameter of broken $U(1)/\mathbb{Z}_2$ symmetry: $\Delta_{\boldsymbol{k}} \sim \langle c_{-\boldsymbol{k}\downarrow} c_{\boldsymbol{k}\uparrow} \rangle$

Ground state wave function: $|\Phi_0\rangle = \prod_{\boldsymbol{k}} \left(u_{\boldsymbol{k}} + v_{\boldsymbol{k}} c_{\boldsymbol{k}\uparrow}^{\dagger} c_{-\boldsymbol{k}\downarrow}^{\dagger} \right) |0\rangle$

Quasiparticle description:

$$H_{\mathrm{BCS}}^{\mathrm{MF}} = \sum_{\boldsymbol{k}} E_{\boldsymbol{k}} \gamma_{\boldsymbol{k}}^{\dagger} \gamma_{\boldsymbol{k}} \quad E_{\boldsymbol{k}} = \sqrt{\xi_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2} \quad Q_{\gamma,\boldsymbol{k}} = -e \frac{\xi_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}$$

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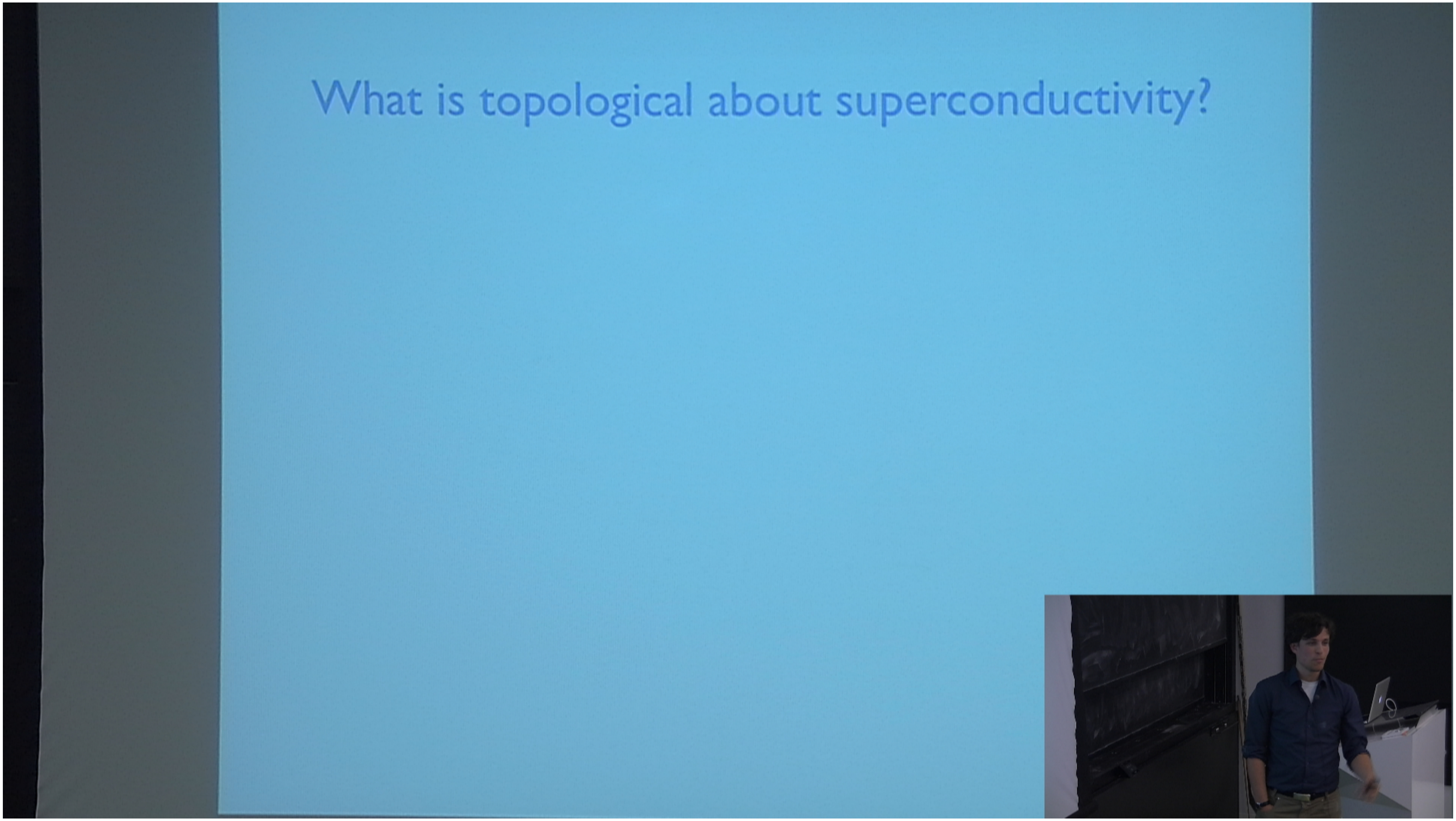
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$$\phi(\boldsymbol{r}) := \langle \psi_\downarrow(\boldsymbol{r}) \psi_\uparrow(\boldsymbol{r}) \rangle$$

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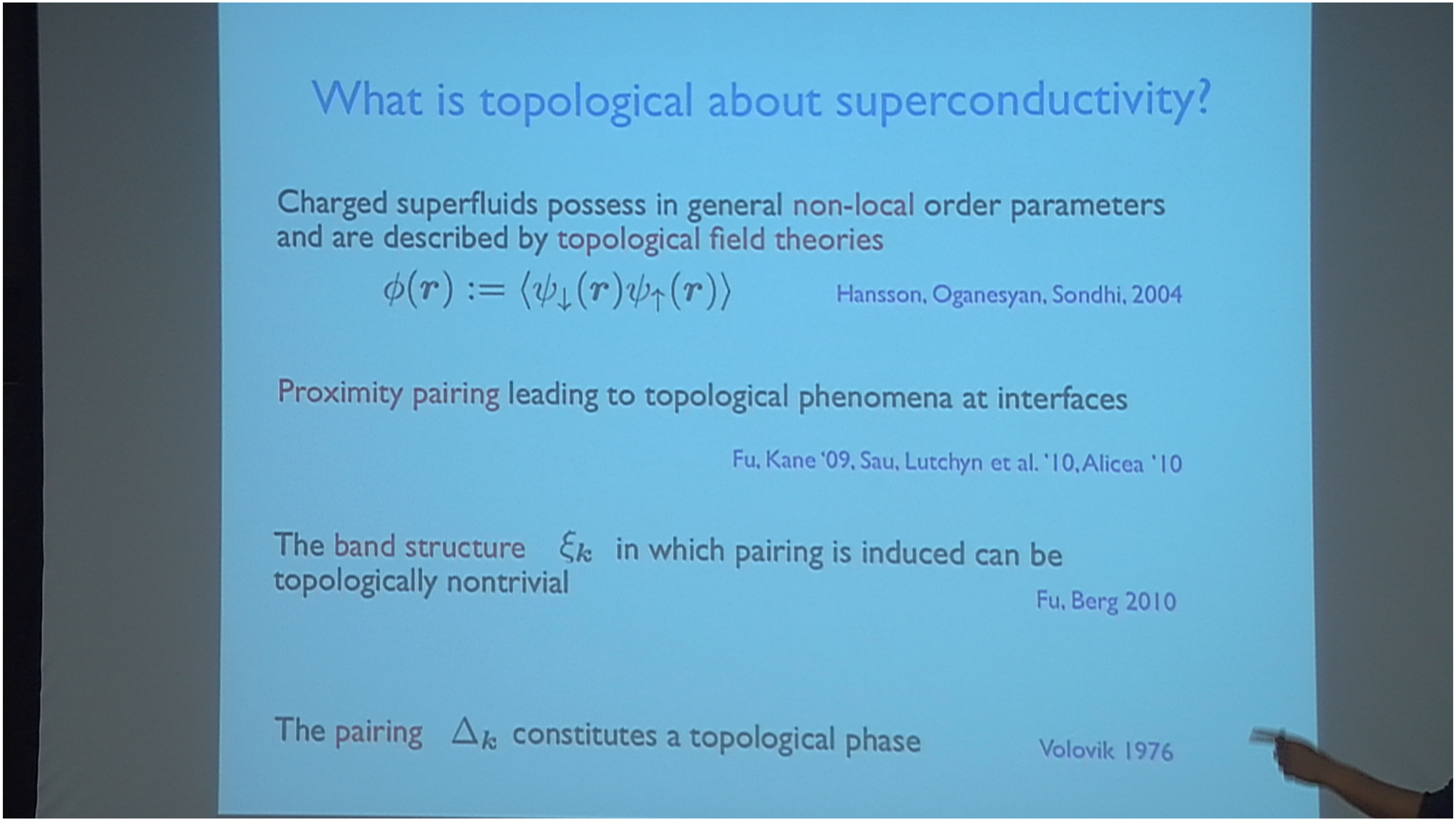
Proximity pairing leading to topological phenomena at interfaces

Fu, Kane '09, Sau, Lutchyn et al. '10, Alicea '10



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The band structure $\xi_{\boldsymbol{k}}$ in which pairing is induced can be topologically nontrivial
Fu, Berg 2010
The pairing $\Delta_{\boldsymbol{k}}$ constitutes a topological phase
Volovik 1976

p+ip superconductivity

$$\Delta_{\boldsymbol{k}} \sim \hat{\boldsymbol{z}}(k_x \pm i k_y)$$

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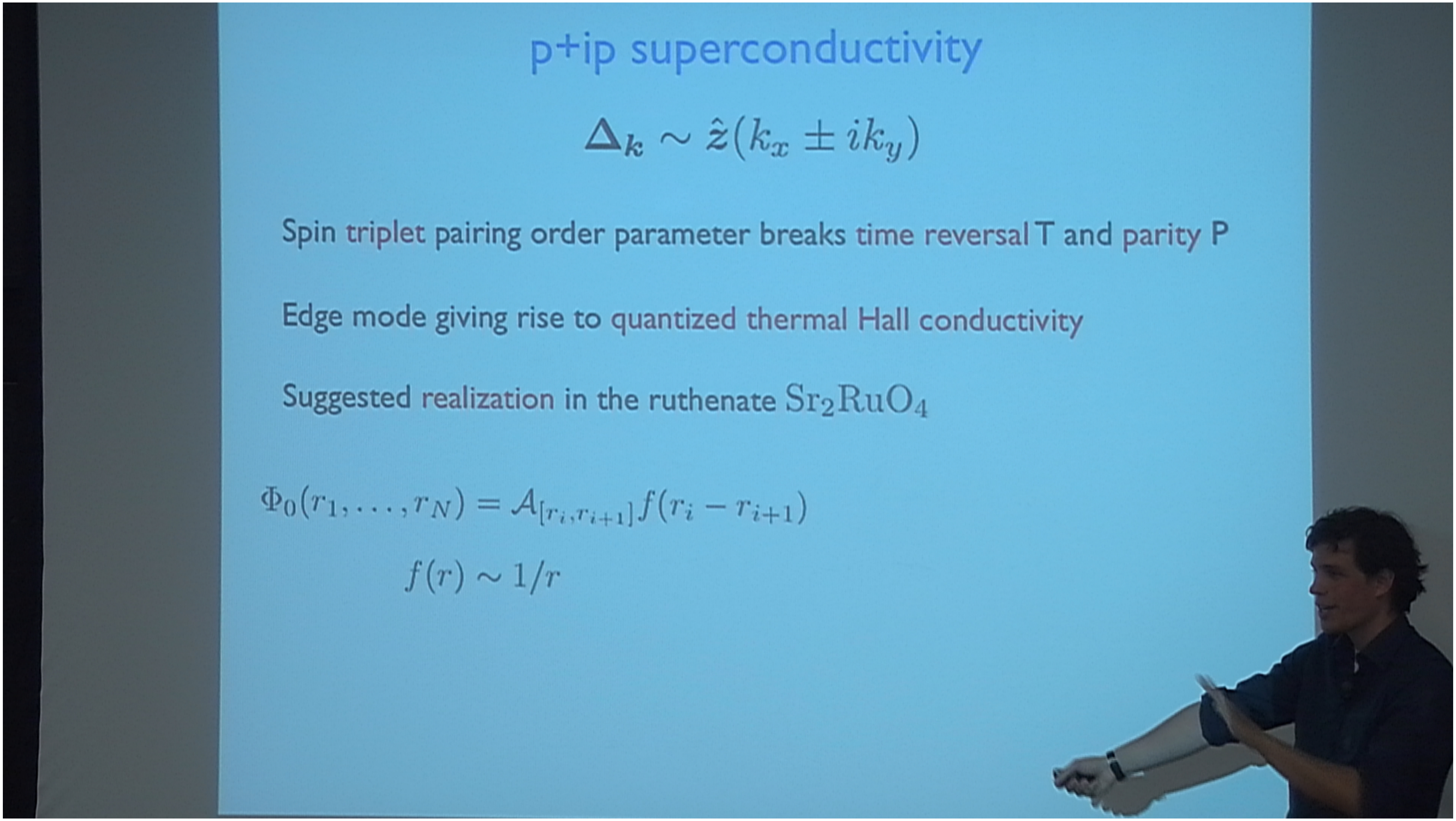
Suggested realization in the ruthenate $\mathrm{Sr_2RuO_4}$

$$\Phi_0(r_1, \ldots, r_N) = \mathcal{A}_{[r_i, r_{i+1}]} f(r_i - r_{i+1})$$

$$f(r) \sim 1/r$$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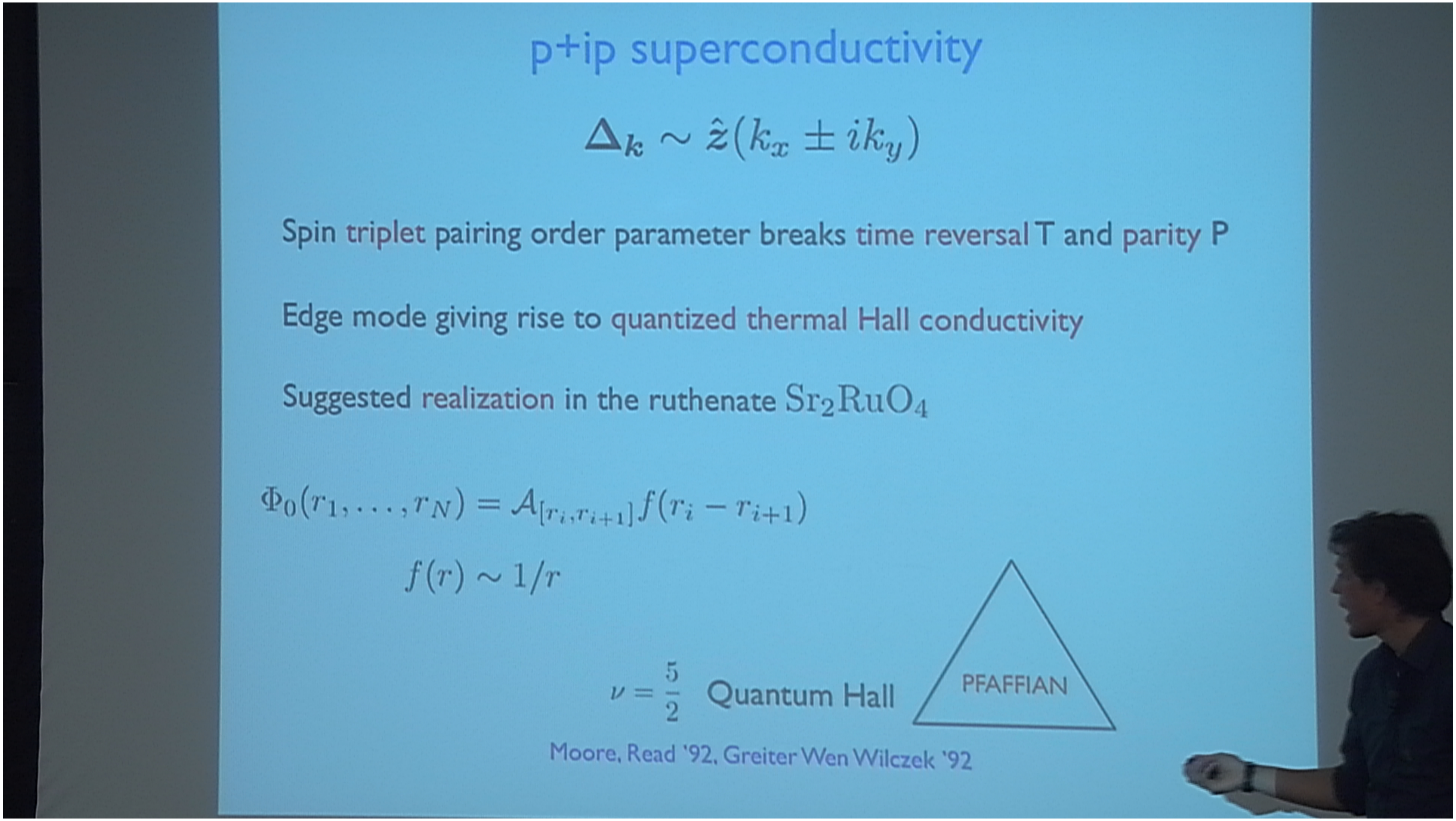
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PFAFFIAN
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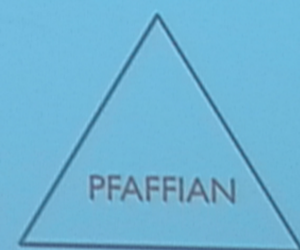


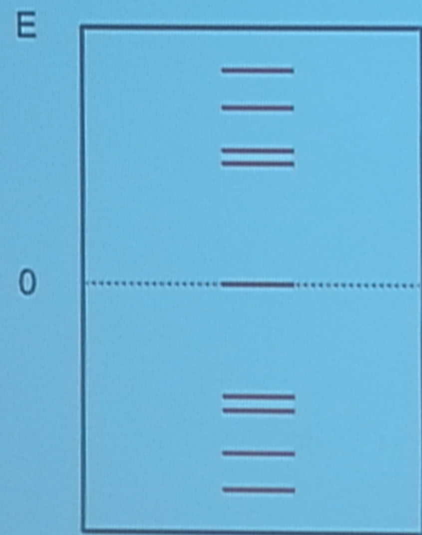
p+ip SC

Moore, Read '92, Greiter Wen Wilczek '92

Read, Green '00

Non-Abelian statistics in the p+ip vortex core

D.A. Ivanov '01



$$[H,\gamma] = E\gamma$$

$$[H,\gamma^\dagger] = -E\gamma^\dagger$$

$$\gamma = \gamma^\dagger$$

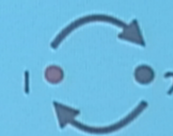
Majorana zero mode
in the vortex core

Braiding of vortices induces non-commutative rotations in the internal Hilbert space of Majorana zero modes

Topological quantum computation

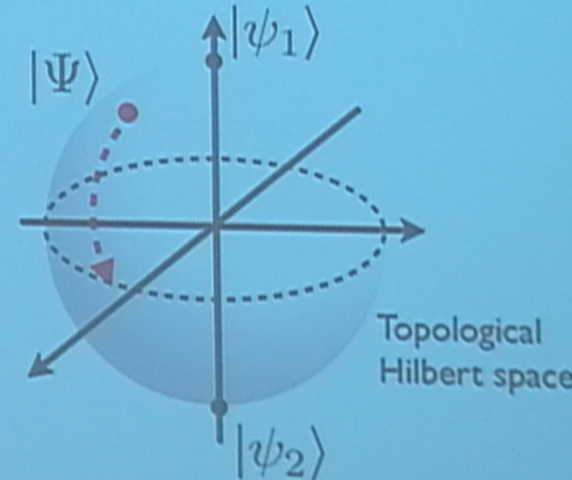
Non-Abelian statistics: action on topological ground state manifold $|\psi_a\rangle$

$$|\psi_a\rangle = \mathcal{W}^{12}_{ab}\,|\psi_b\rangle \qquad [\mathcal{W}^{ij}, \mathcal{W}^{kl}] \neq 0$$



Freedman, 2003

Braiding of particles: rotation in the ground state sector (topological qubit)



d+id superconductivity

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Two edge mode branches giving rise to quantized thermal Hall conductance and quantized spin Hall conductance

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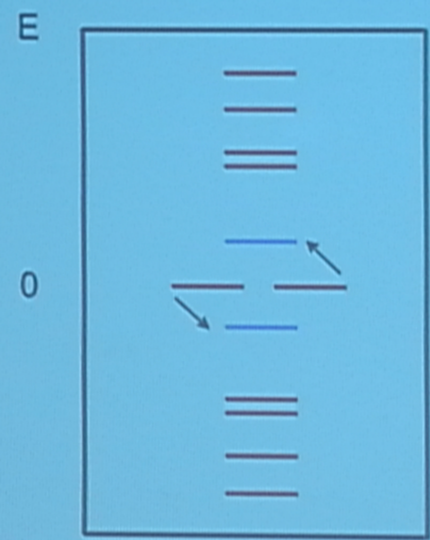
Non-Abelian statistics in the d+id vortices?

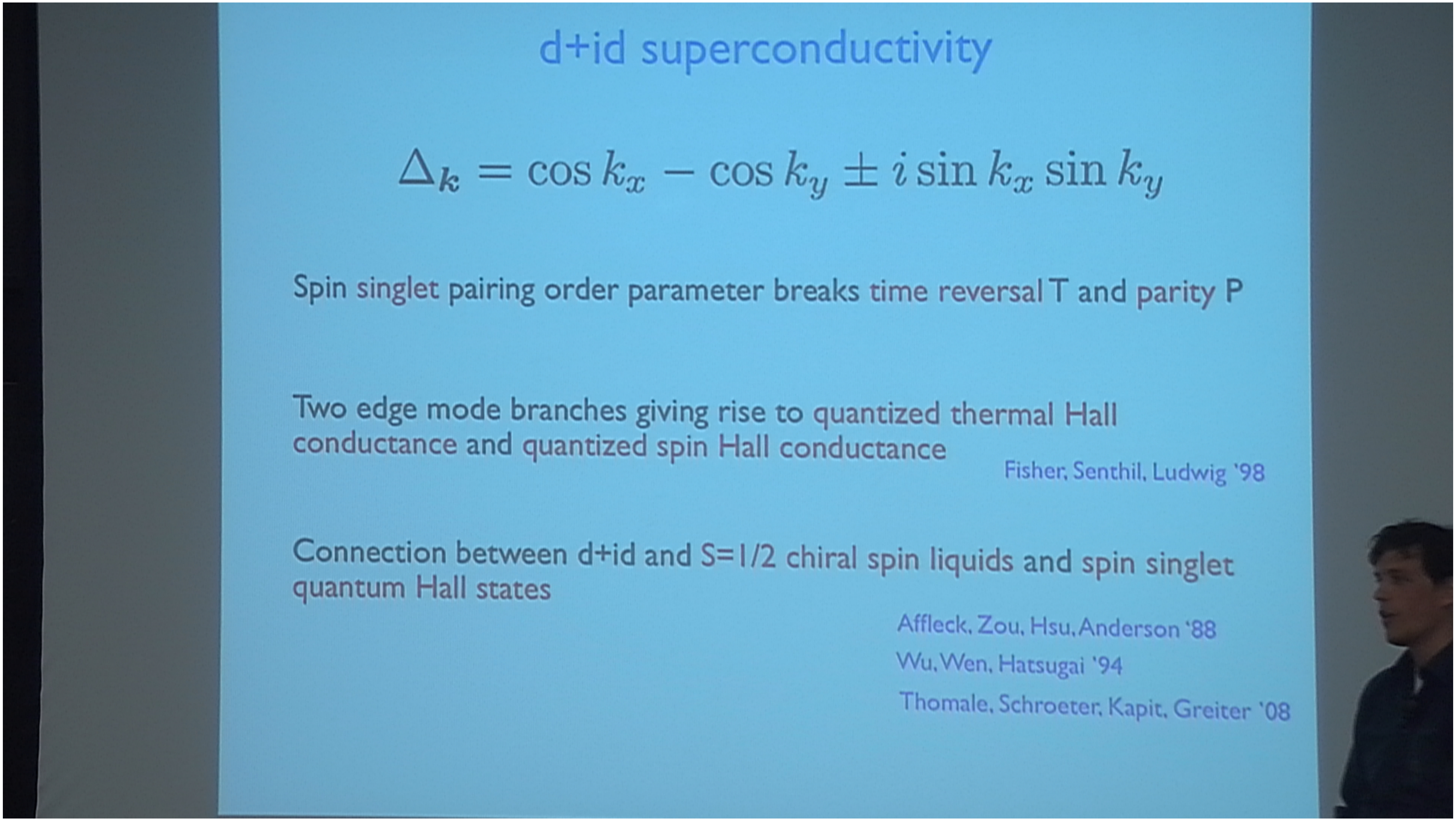
Sato, Takahashi, Fujimoto 2010



even number of modes in the vortex core: no topological protection

Claim: Addition of Rashba coupling and Zeeman field can drive a topological phase transition from TKNN 2 to 1

Advantage d+id: only a small Zeeman field needed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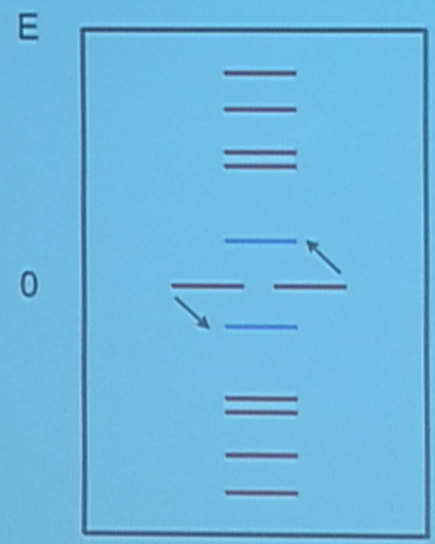

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Recipe for finding X+iX SC order

Platt, Thomale, in prep.

The favored real space pairing function $\Delta_{i,j} \sim \langle c_i^\dagger c_j^\dagger \rangle$

transforms under irreducible point group representations

Layered square lattice (tetragonal)

C_{4v}	E	C_2	$2C_4$	$2\sigma_v$	$2\sigma_d$
A_1	1	1	1	1	1
A_2	1	1	1	-1	-1
B_1	1	1	-1	1	-1
B_2	1	1	-1	-1	1
E	2	-2	0	0	0

px, py

Layered honeycomb lattice (hexagonal)

C_{6v}	E	C_2	$2C_3$	$2C_6$	$3\sigma_v$	$3\sigma_d$
A_1	1	1	1	1	1	1
A_2	1	1	1	1	-1	-1
B_1	1	-1	1	-1	1	-1
B_2	1	-1	1	-1	-1	1
E_1	2	-2	-1	1	0	0
E_2	2	2	-1	-1	0	0

d(x2-y2), d(xy)

When different separately nodal SC solutions are degenerate, the system gains condensation energy by forming X+iX

Recipe for finding d+id SC order

Kiesel, Platt, Hanke, Thomale, in prep.

Choose a system with a triangular or honeycomb lattice and a sufficiently large single pocket Fermi surface

Achieve an electronically driven pairing mechanism through spin fluctuations

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Achieve an electronically driven pairing mechanism through spin fluctuations

Dope the system away from magnetically favorable nesting or adjust the interaction/bandwidth ratio (pressure)

Functional renormalization group

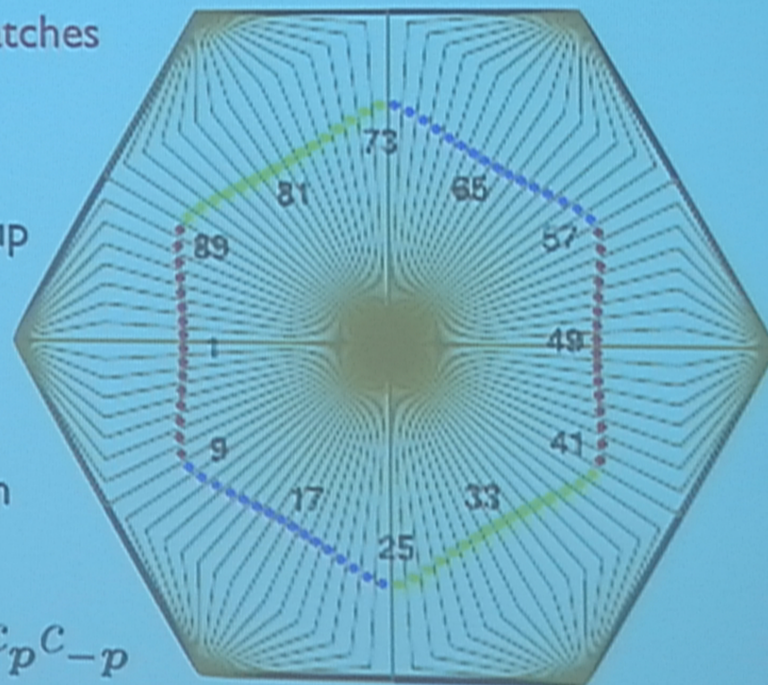
SC instability in the FRG

Zanchi Schulz '99; Honerkamp, Salmhofer, Rice '01; Wang et al '09; Thomale et al '09

Discretize the BZ into different patches along the Fermi surface

Integrate out high energy modes up to Λ and approach the FS

If the pairing channel diverges, extract the leading SC gap function



$$V(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{p}, -\boldsymbol{p}, \Lambda) c^{\dagger}_{\boldsymbol{k}} c^{\dagger}_{-\boldsymbol{k}} c_{\boldsymbol{p}} c_{-\boldsymbol{p}}$$

$$V(k, p, \Lambda) = \sum_{n} c_n(\Lambda) \Delta_{n,\boldsymbol{k}} \Delta_{n,\boldsymbol{p}}$$

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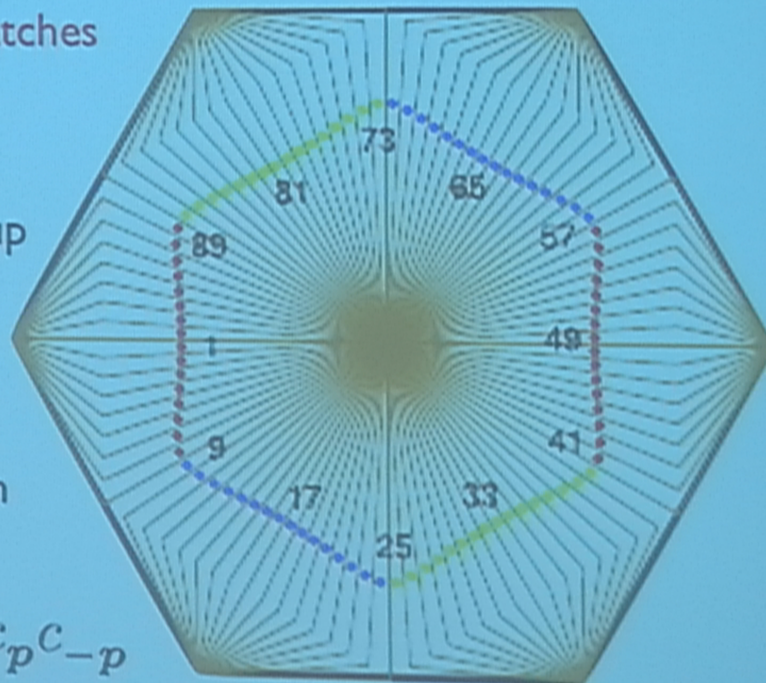

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$$V(\boldsymbol{k}, -\boldsymbol{k}, \boldsymbol{p}, -\boldsymbol{p}, \Lambda) c^\dagger_{\boldsymbol{k}} c^\dagger_{-\boldsymbol{k}} c_{\boldsymbol{p}} c_{-\boldsymbol{p}}$$

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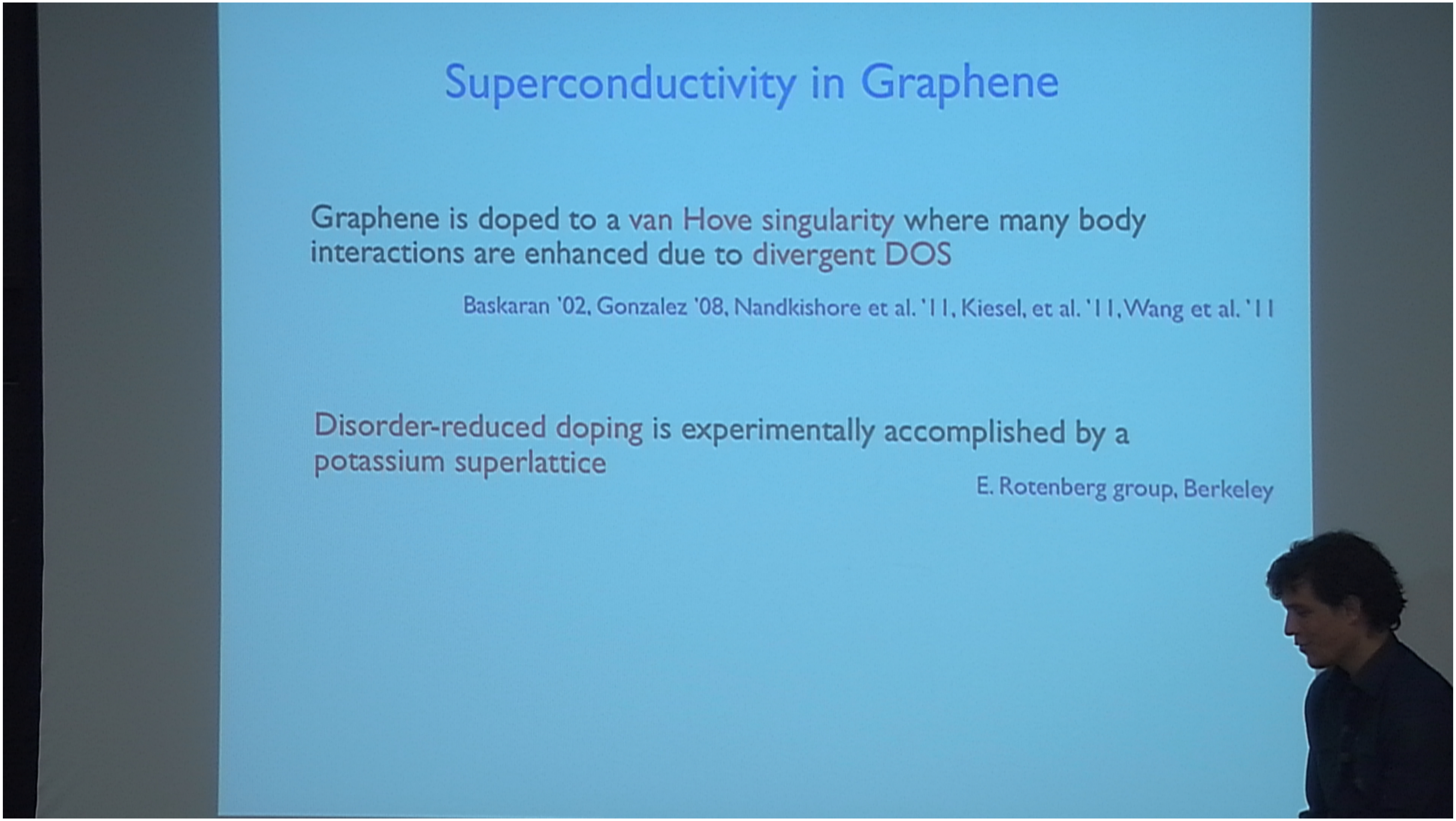
Superconductivity in Graphene
Graphene is doped to a van Hove singularity where many body interactions are enhanced due to divergent DOS
Baskaran '02, Gonzalez '08, Nandkishore et al. '11, Kiesel, et al. '11, Wang et al. '11
Disorder-reduced doping is experimentally accomplished by a potassium superlattice
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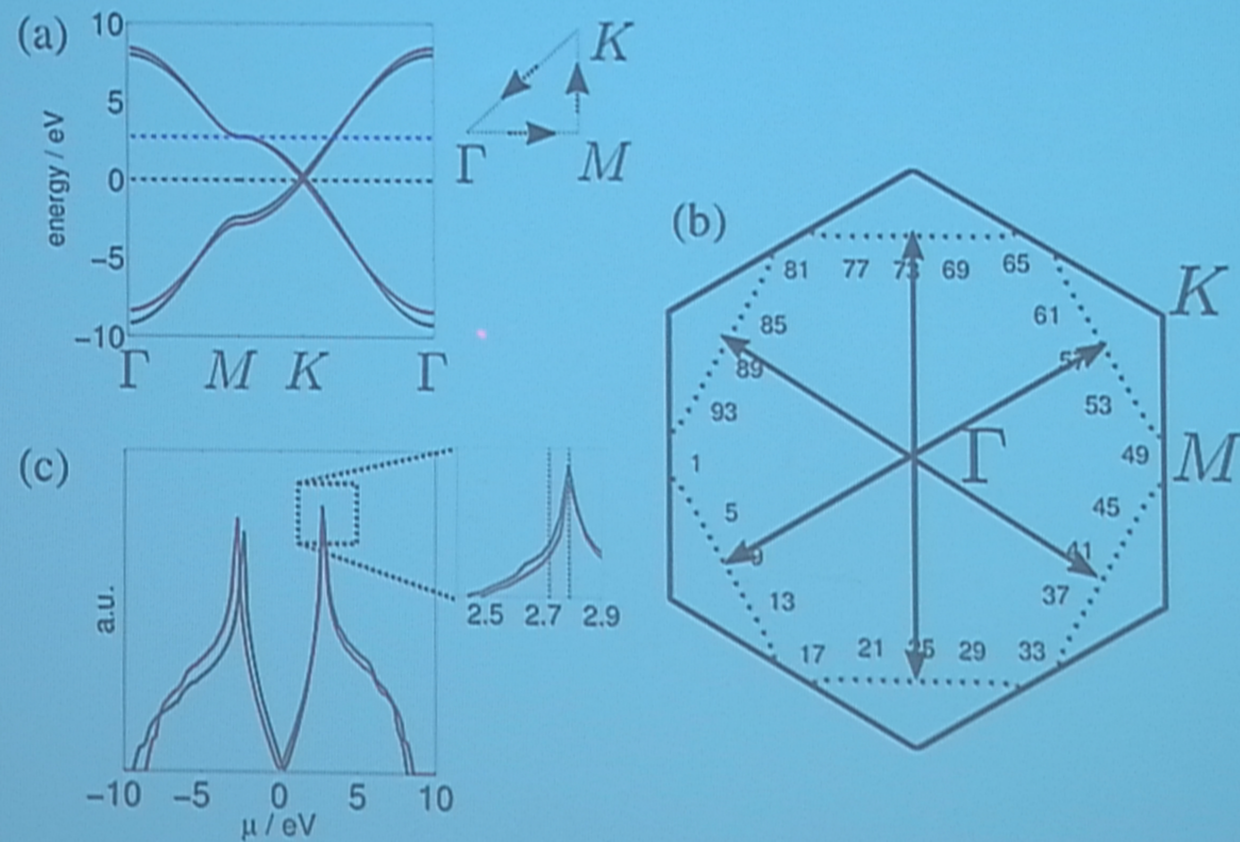
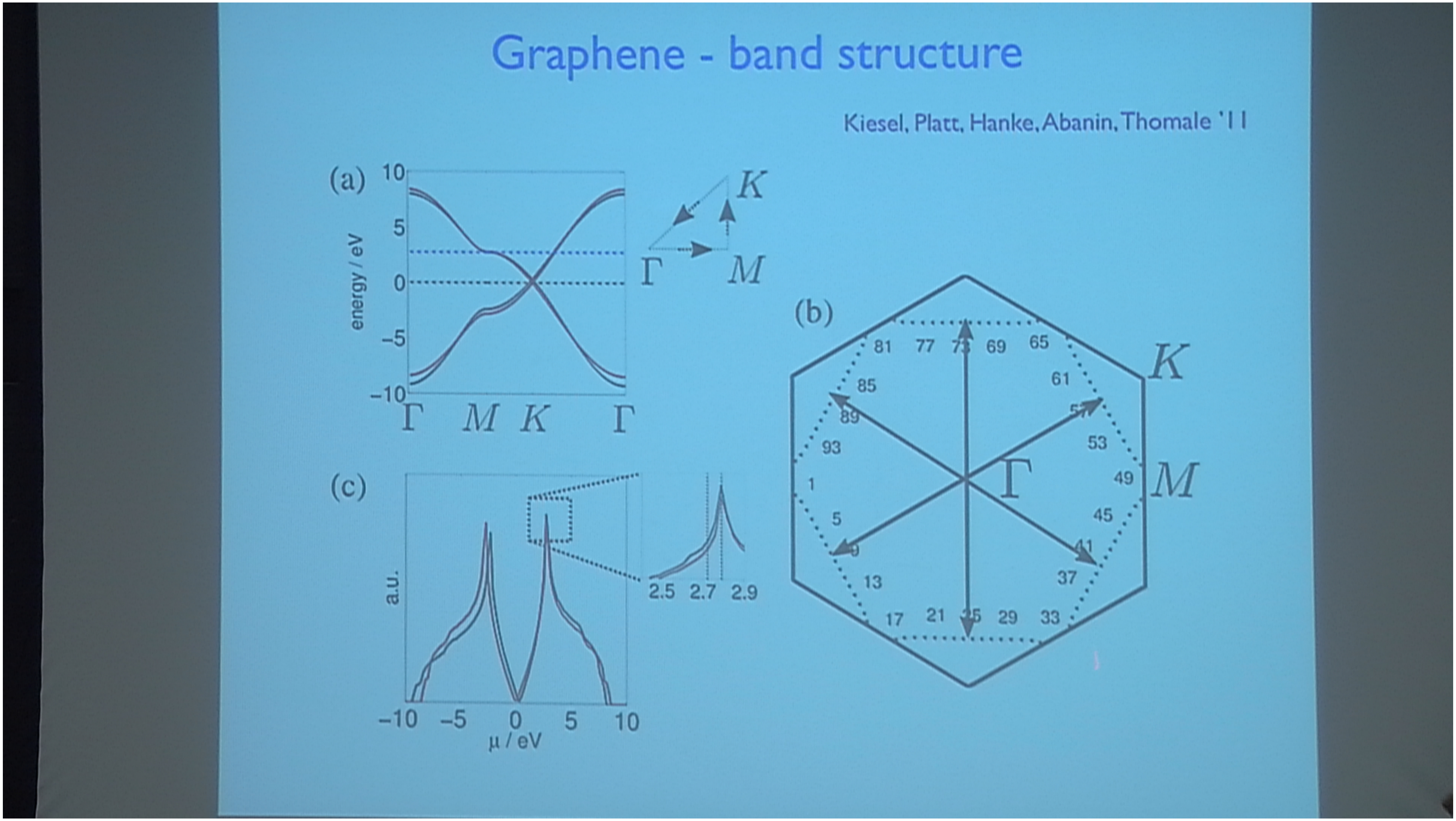
A variety of competing many body phases is found with high tunability via kinetic and interaction parameters

Kiesel, et al. '11

Graphene - band structure

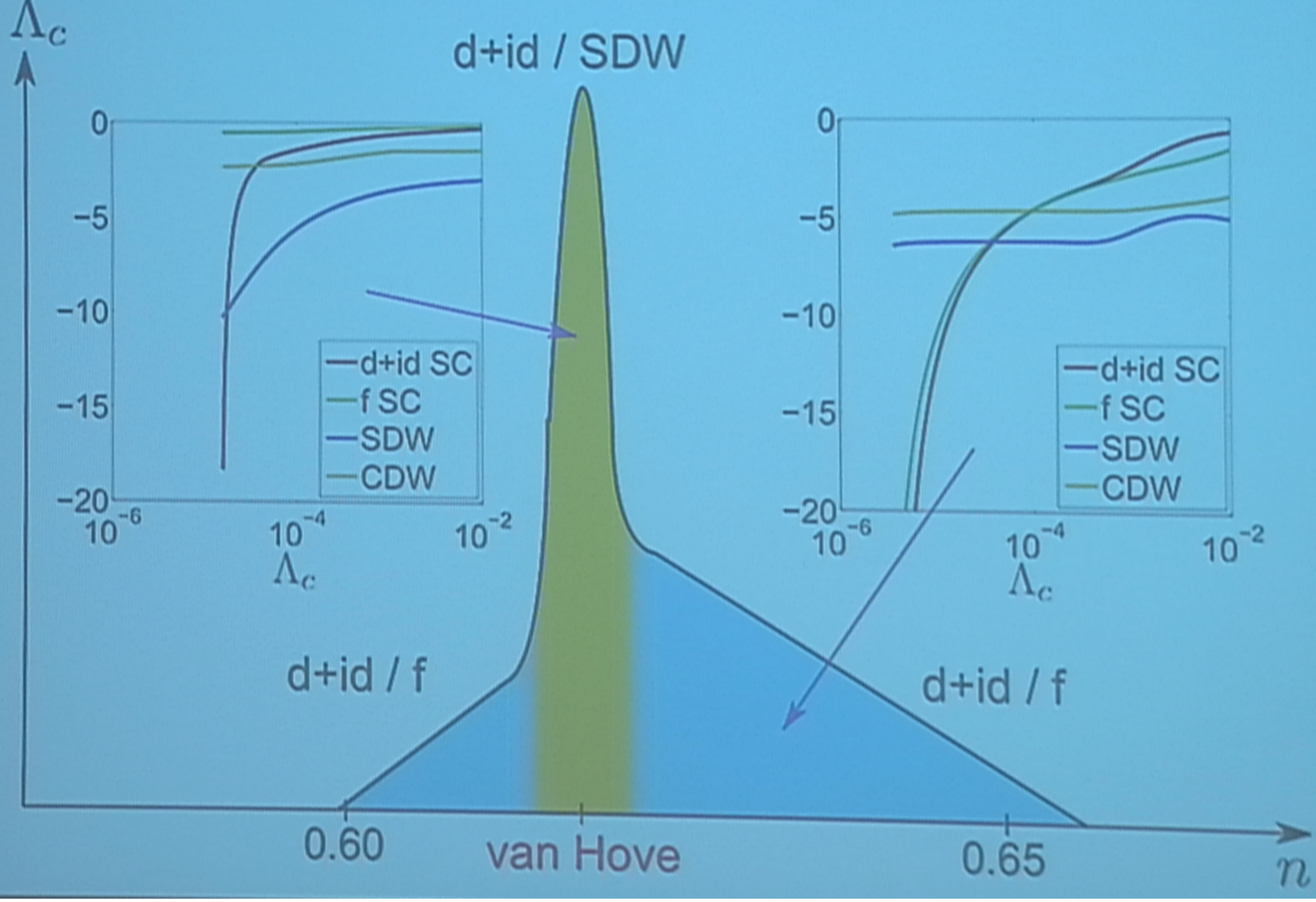
Kiesel, Platt, Hanke, Abanin, Thomale '11

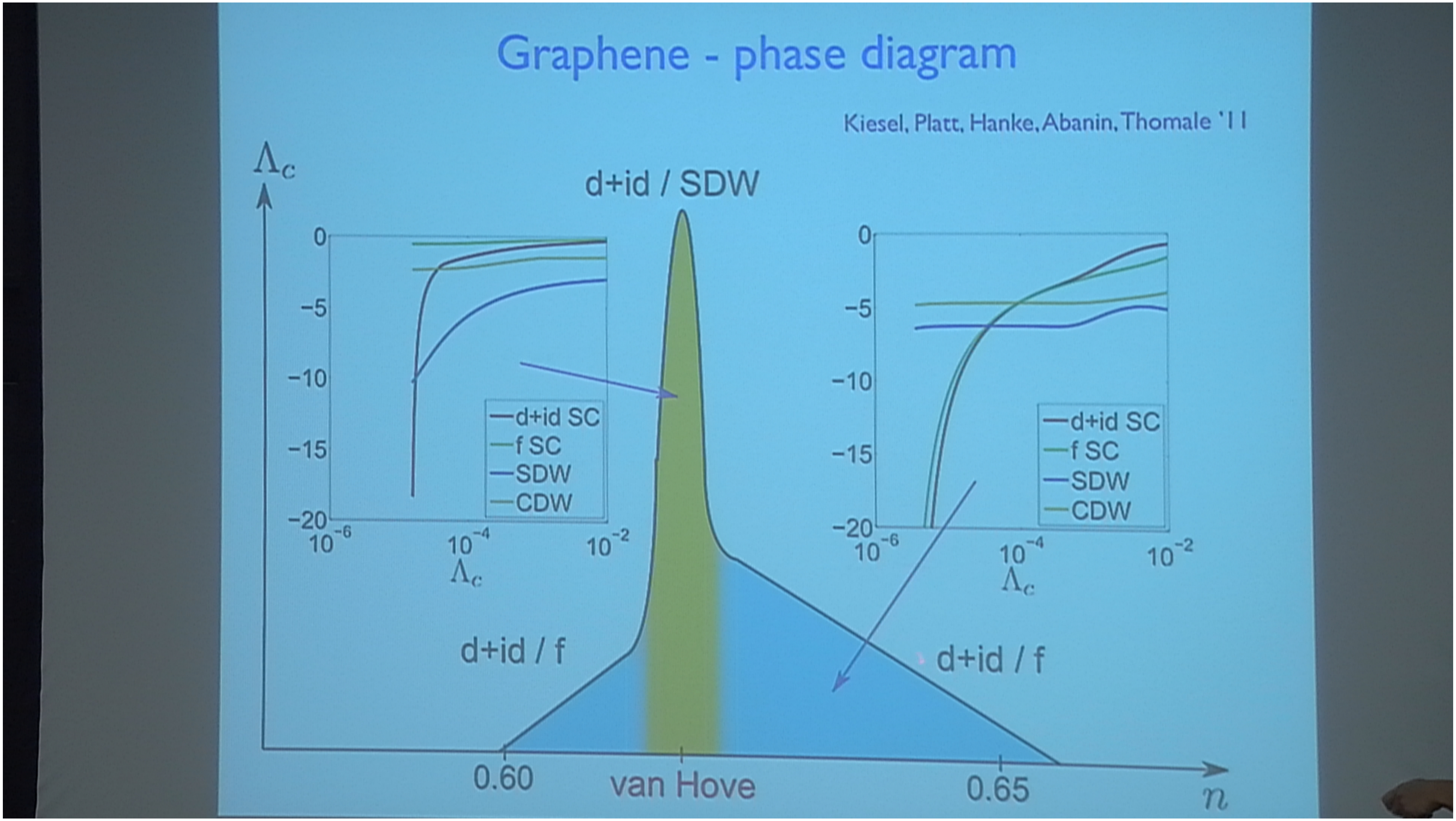



Graphene - band structure
Kiesel, Platt, Hanke, Abanin, Thomale '11
(a)
energy / eV
10
5
0
−5
−10
Γ M K Γ
K
Γ M
(b)
81 77 73 69 65
85 61
89 57
93 53
1 49
5 45
9 41
13 37
17 21 25 29 33
K
Γ
M
(c)
a.u.
−10 −5 0 5 10
μ / eV
2.5 2.7 2.9

Graphene - phase diagram

Kiesel, Platt, Hanke, Abanin, Thomale '11

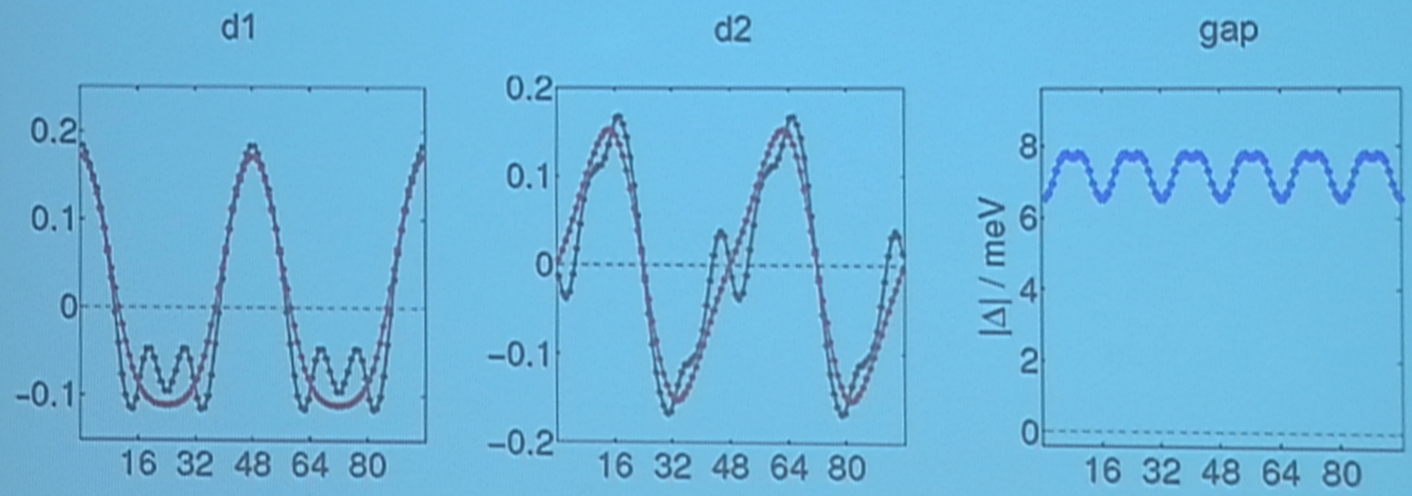




Graphene - phase diagram
Kiesel, Platt, Hanke, Abanin, Thomale '11
Λ_c
d+id / SDW
0
−5
−10
−15
−20
10^{-6}
10^{-4}
10^{-2}
Λ_c
d+id SC
f SC
SDW
CDW
d+id / f
d+id / f
0.60
van Hove
0.65
n

Graphene - d+id superconductivity

Kiesel, Platt, Hanke, Abanin, Thomale '11



Free energy functional analysis: d+id is favored by the system, as also seen by a fully gapped Fermi surface

Gap anisotropy and competition to SDW and f-wave depends on details of doping, interaction, and kinetic parameters

Superconductivity in the Cobaltates

Kiesel, Platt, Hanke, Thomale, in prep.

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Takada et al. '03; Baskaran '03

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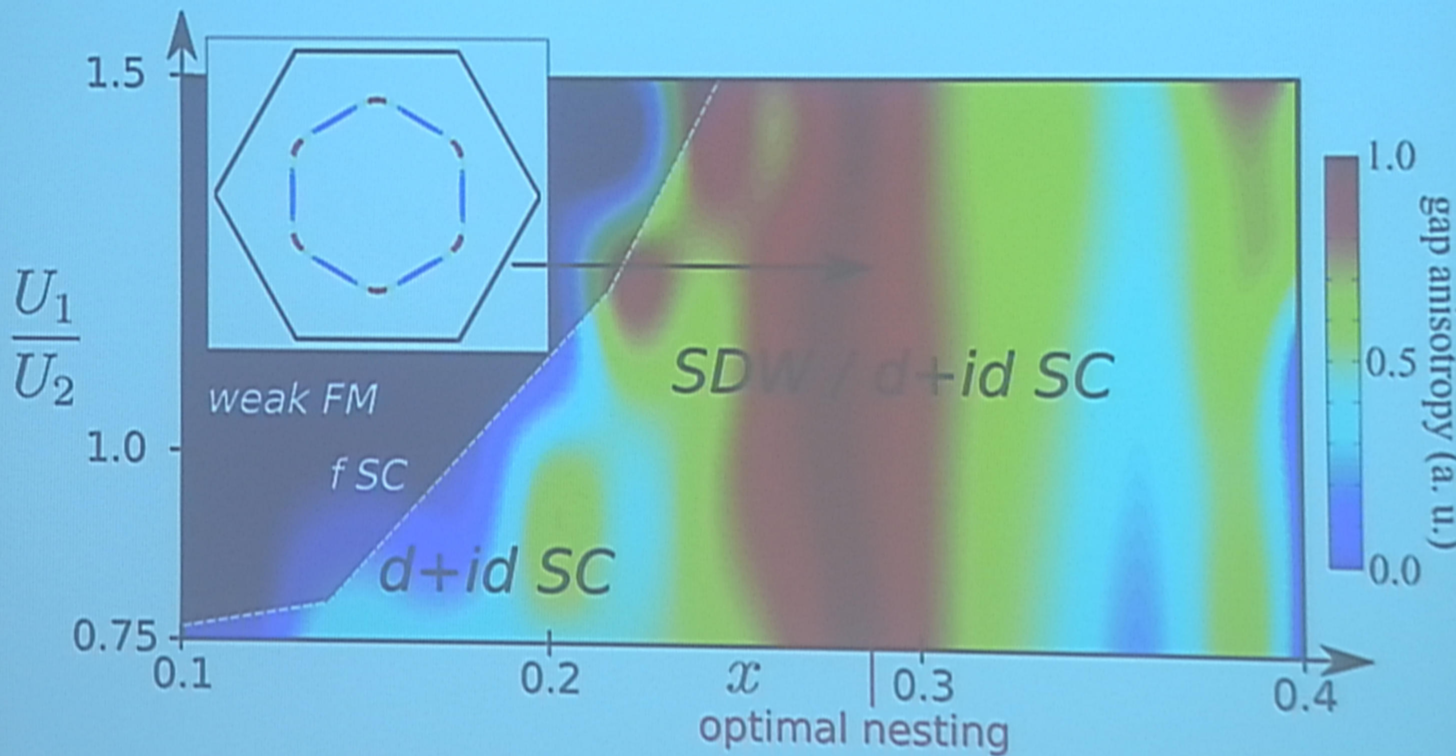
Anisotropy profile of the d+id phase



Summary

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Aside from chiral triplet SC, chiral singlet SC promises intricate topological properties that can also be driven into the triplet SC universality class

d+id superconductivity is predicted for (i) graphene doped to van Hove filling and (ii) water-intercalated cobaltates where the controversy on the nodal gap is resolved by a large order parameter anisotropy

Exotic singlet superconductivity can be realized in a large class of materials and promises new discoveries of potentially topological unconventional superconductors

Investigate Fermi instabilities in electronic systems

- Polchinski's flow equations: hierarchy of m-point functions

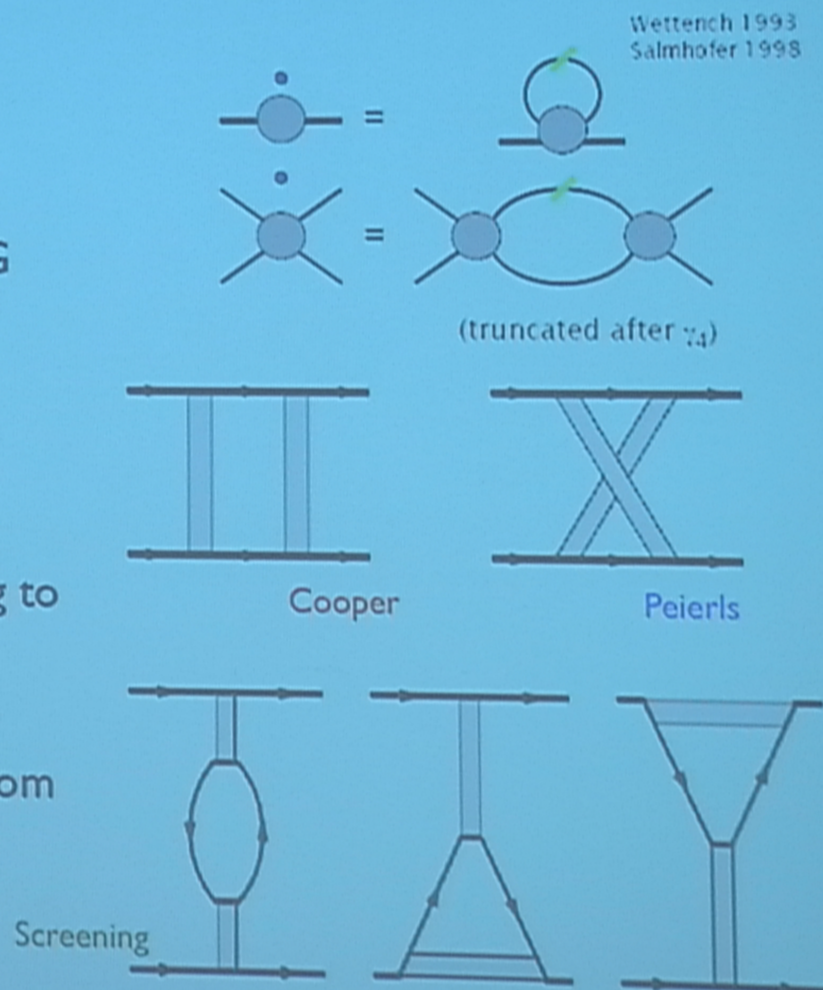
- Infinitesimal steps of mode integration via cutoff flow Λ: FRG solution of fermionic action

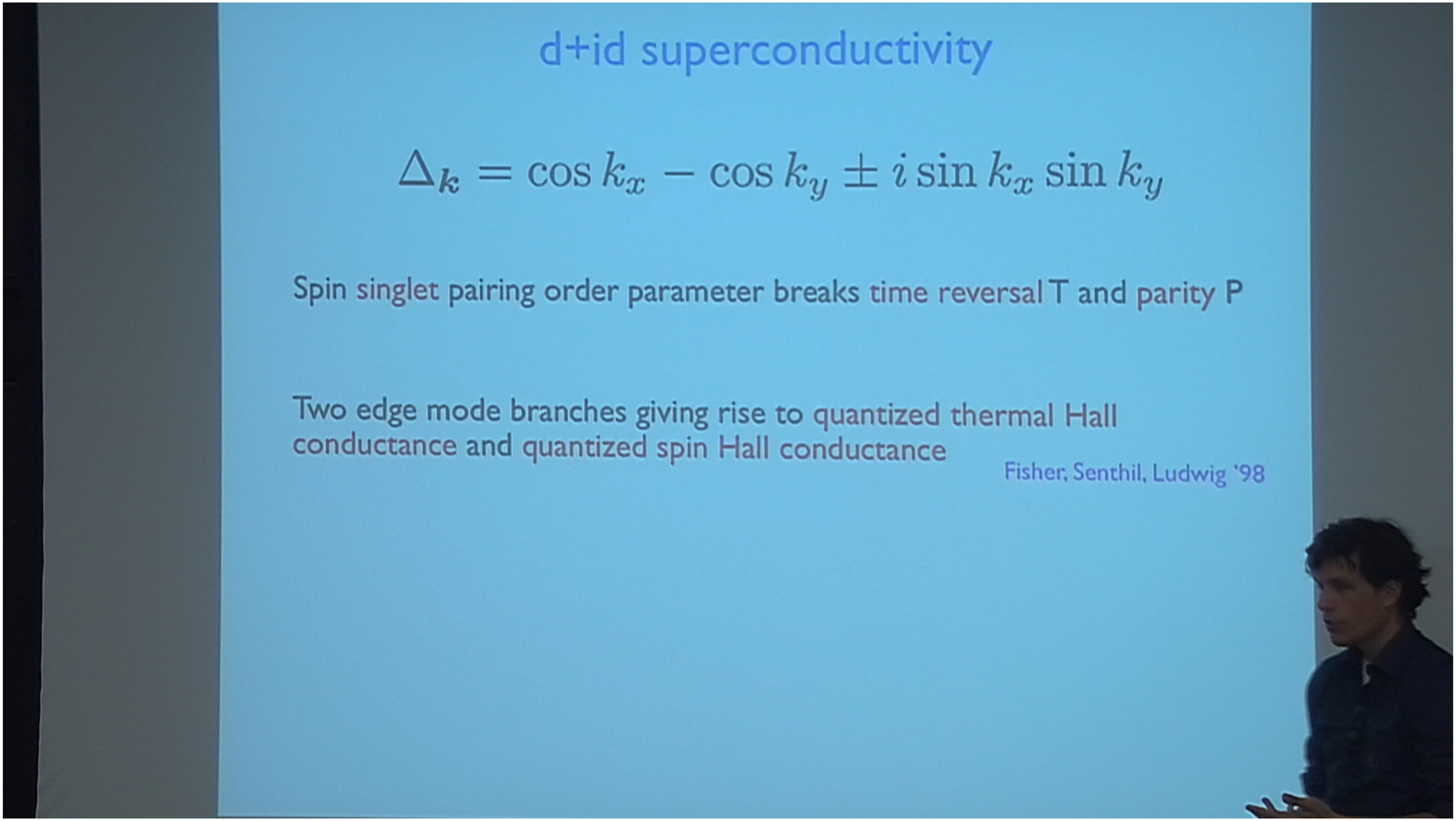
$$Z = \int \mathcal{D}\bar{\Psi}\mathcal{D}\Psi \; e^{S\{\Psi\}}$$

- Consider diagrams contributing to 4 point function V(k1,k2,k3,k4): 2nd order plaquet terms

- Asymptotically exact starting from bare weak coupling

- Kohn-Luttinger physics




d+id superconductivity
$\Delta_{\boldsymbol{k}} = \cos k_x - \cos k_y \pm i \sin k_x \sin k_y$
Spin singlet pairing order parameter breaks time reversal T and parity P
Two edge mode branches giving rise to quantized thermal Hall conductance and quantized spin Hall conductance
Fisher, Senthil, Ludwig '98