Title: Coexistence of Antiferromagnetism and Superconductivity on Honeycomb Lattice

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Abstract: Motivated by results of DMRG and tensor network simulations on doped
t-J model on honeycomb lattice, we study superconductivity of singlet and triplet pairing in this model. We show that a superconducting state with coexisting spin-singlet and spin-triplet pairings is induced by the antiferromagnetic order near half-filling. The superconducting state we obtain has a topological phase transition that separates a topologically trivial state and a non-trivial state with Chern number two.


Unconventional Superconductivity
in Honeycomb Lattice
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Collaborators:
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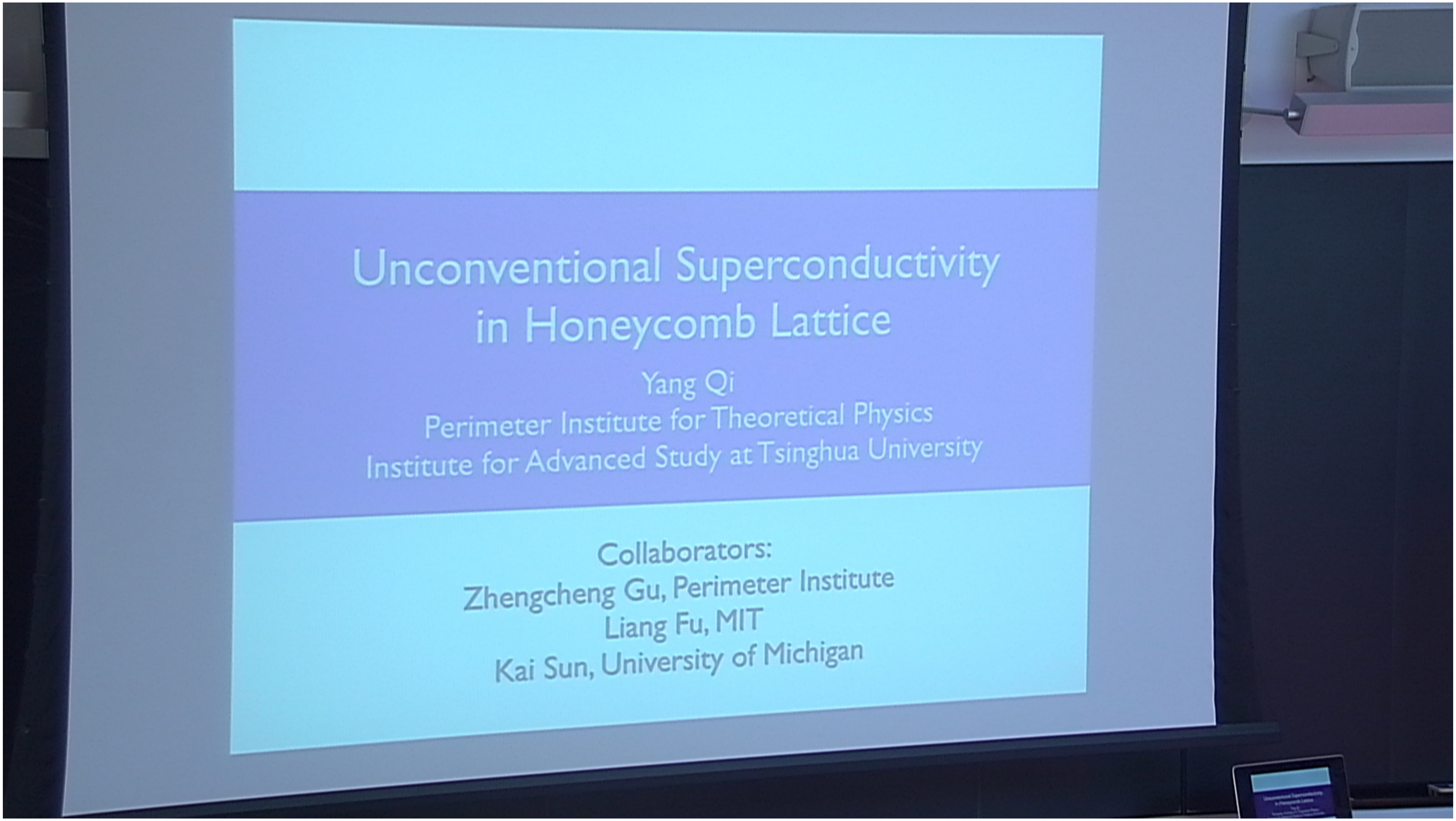
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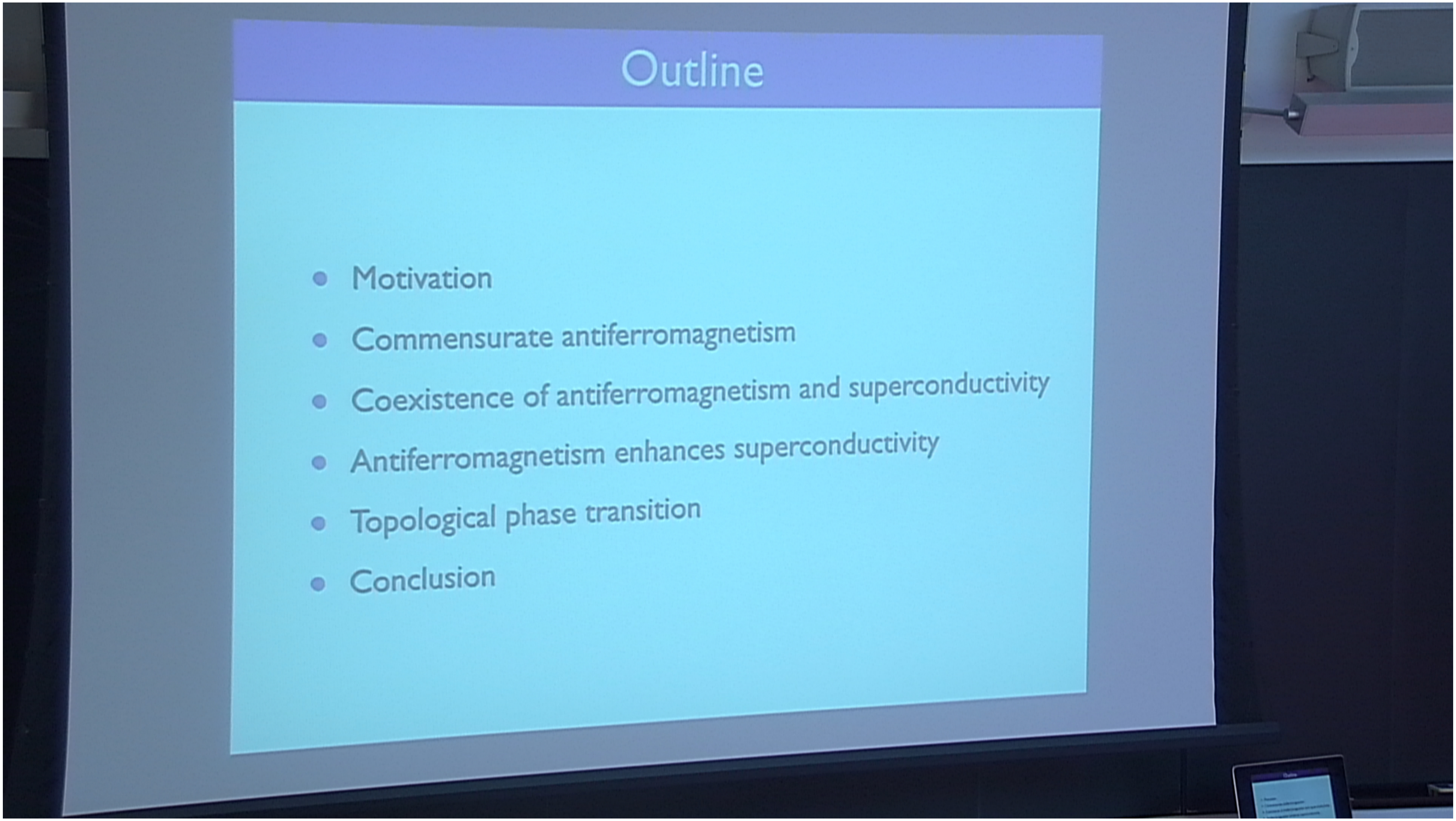
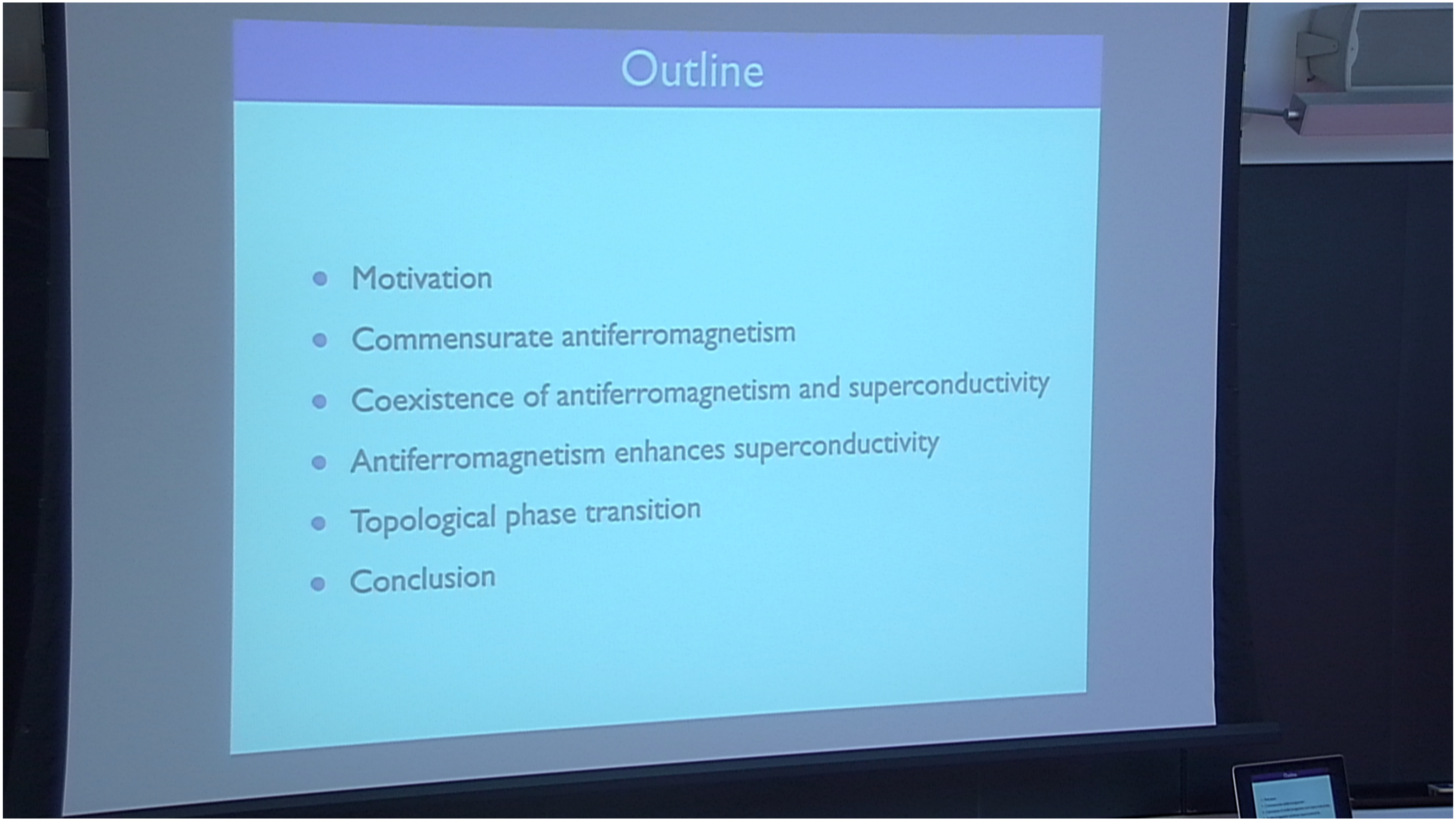

Outline
Motivation
Commensurate antiferromagnetism
Coexistence of antiferromagnetism and superconductivity
Antiferromagnetism enhances superconductivity
Topological phase transition
Conclusion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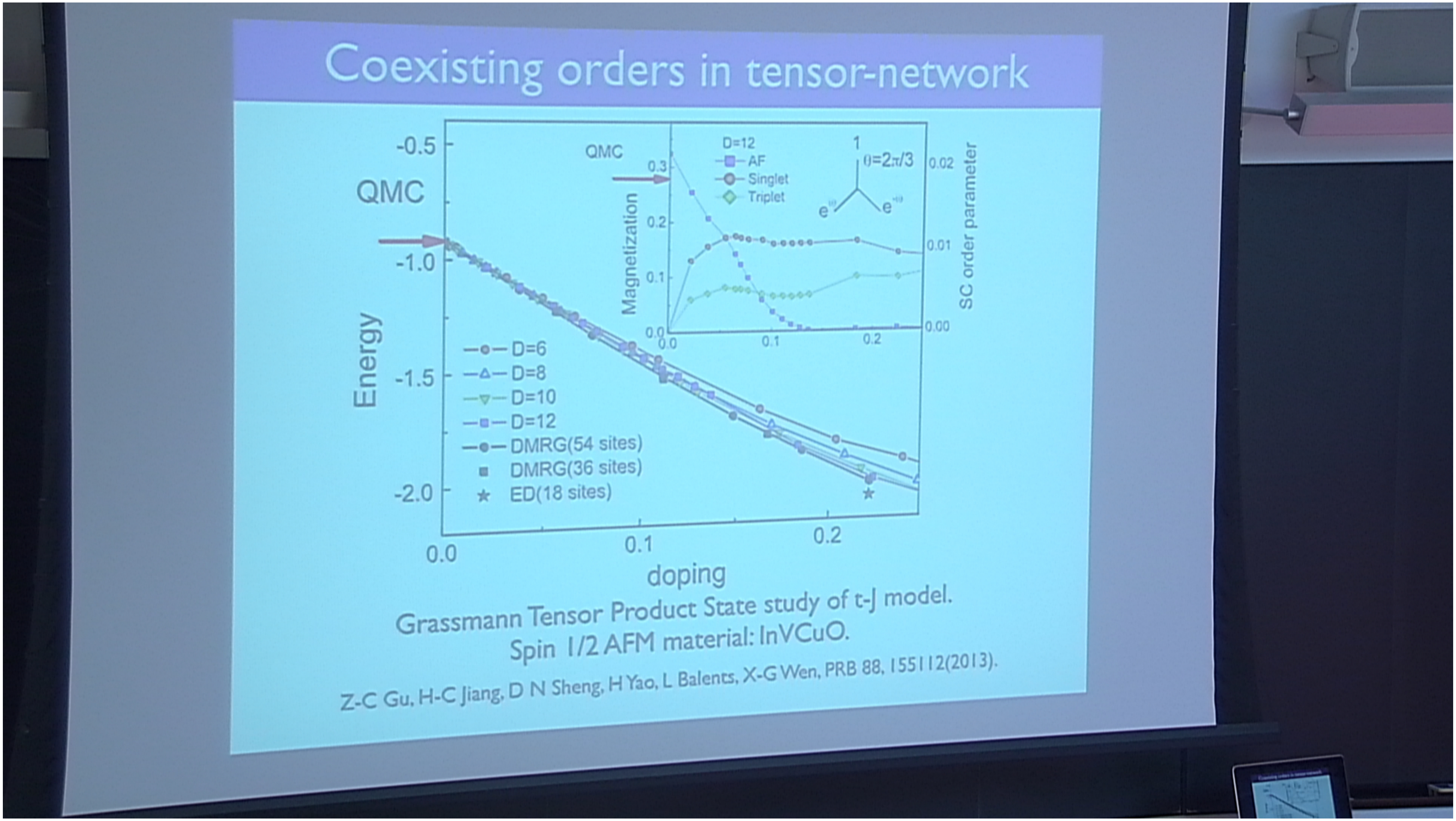
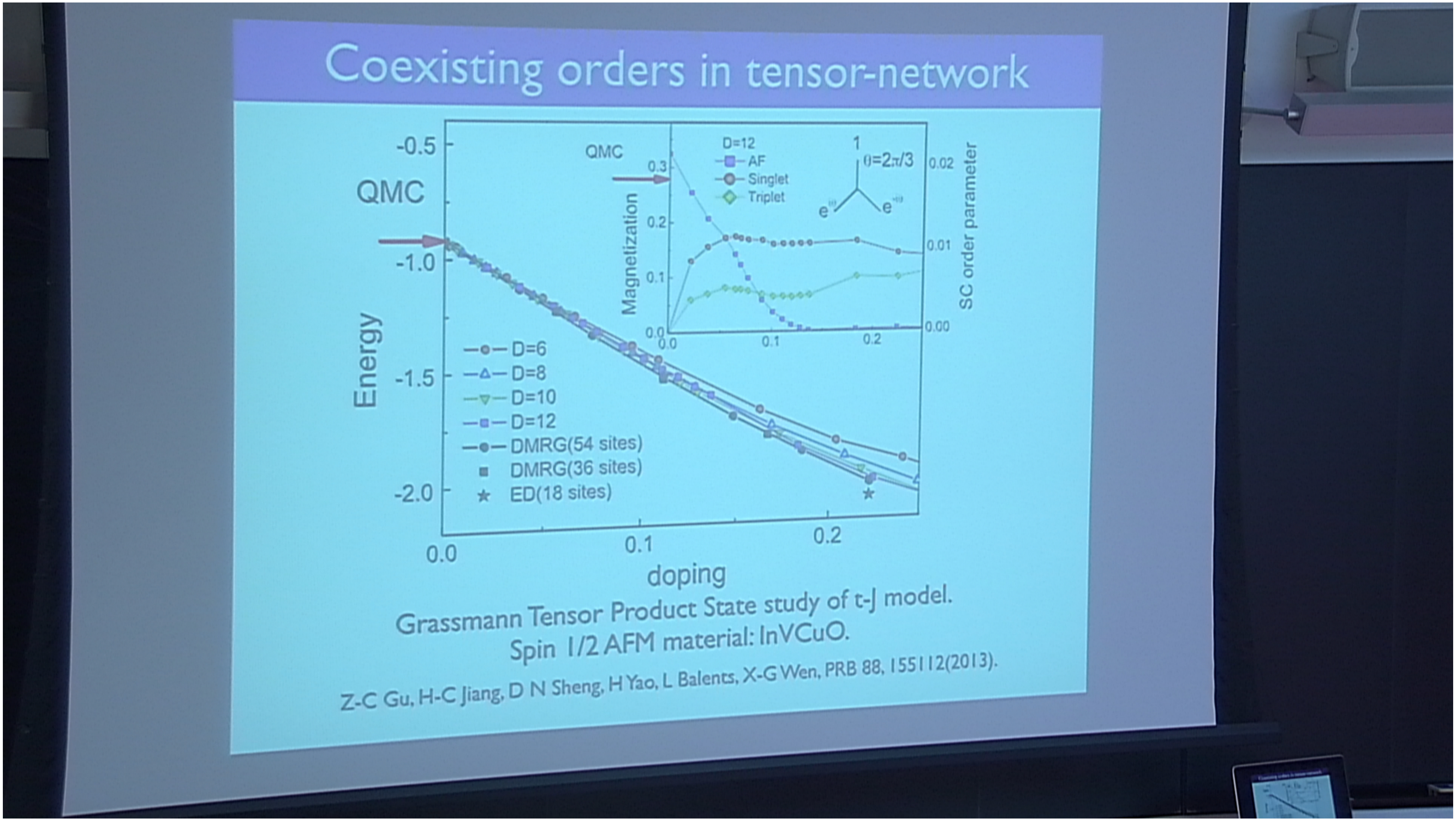

Coexisting orders in tensor-network
QMC
Energy
-0.5
-1.0
-1.5
-2.0
0.0
0.1
0.2
doping
D=6
D=8
D=10
D=12
DMRG(54 sites)
DMRG(36 sites)
ED(18 sites)
Magnetization
SC order parameter
D=12
AF
Singlet
Triplet
θ=2π/3
Grassmann Tensor Product State study of t-J model.
Spin 1/2 AFM material: InVCuO.
Z-C Gu, H-C Jiang, D N Sheng, H Yao, L Balents, X-G Wen, PRB 88, 155112(2013).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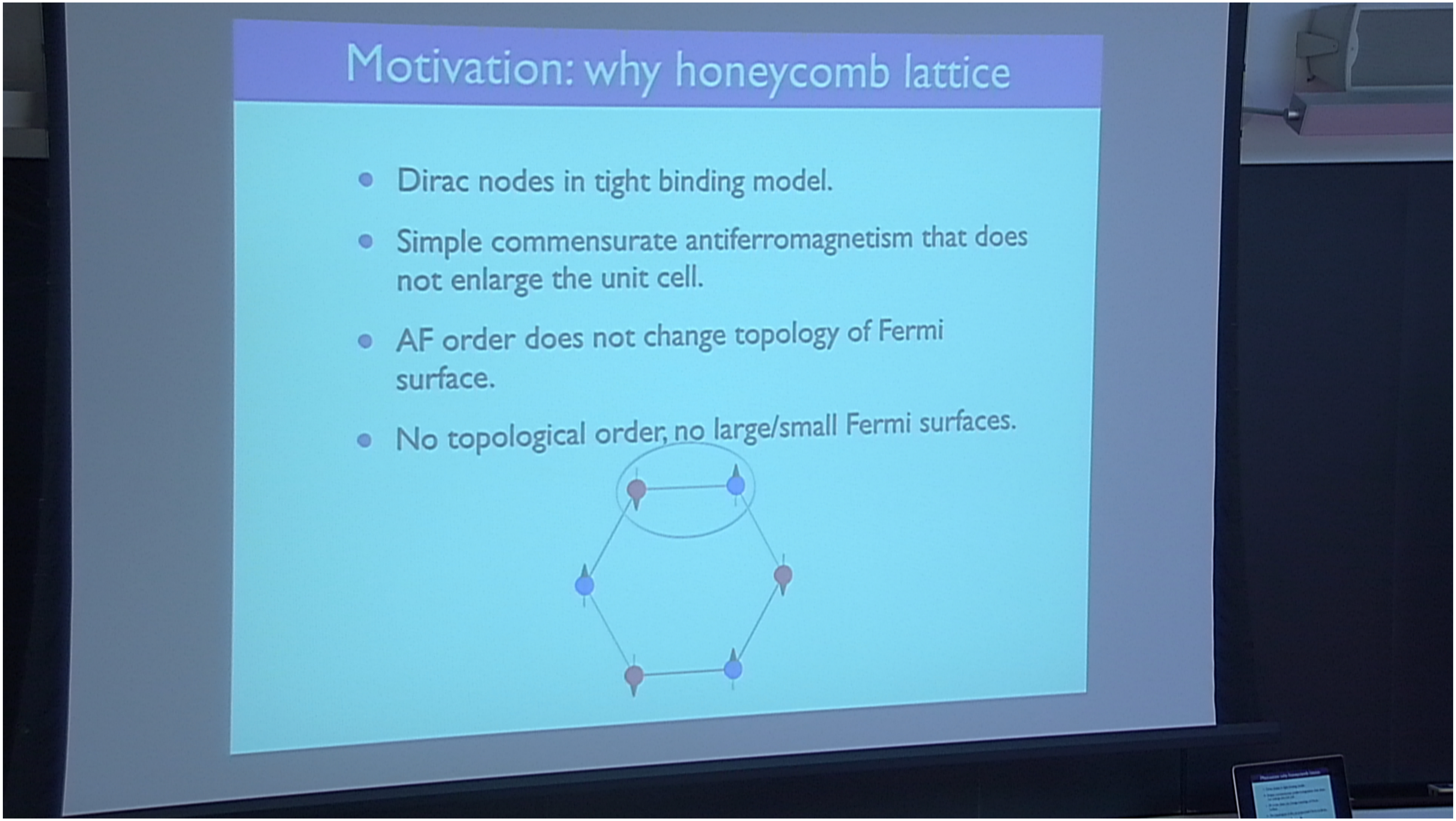
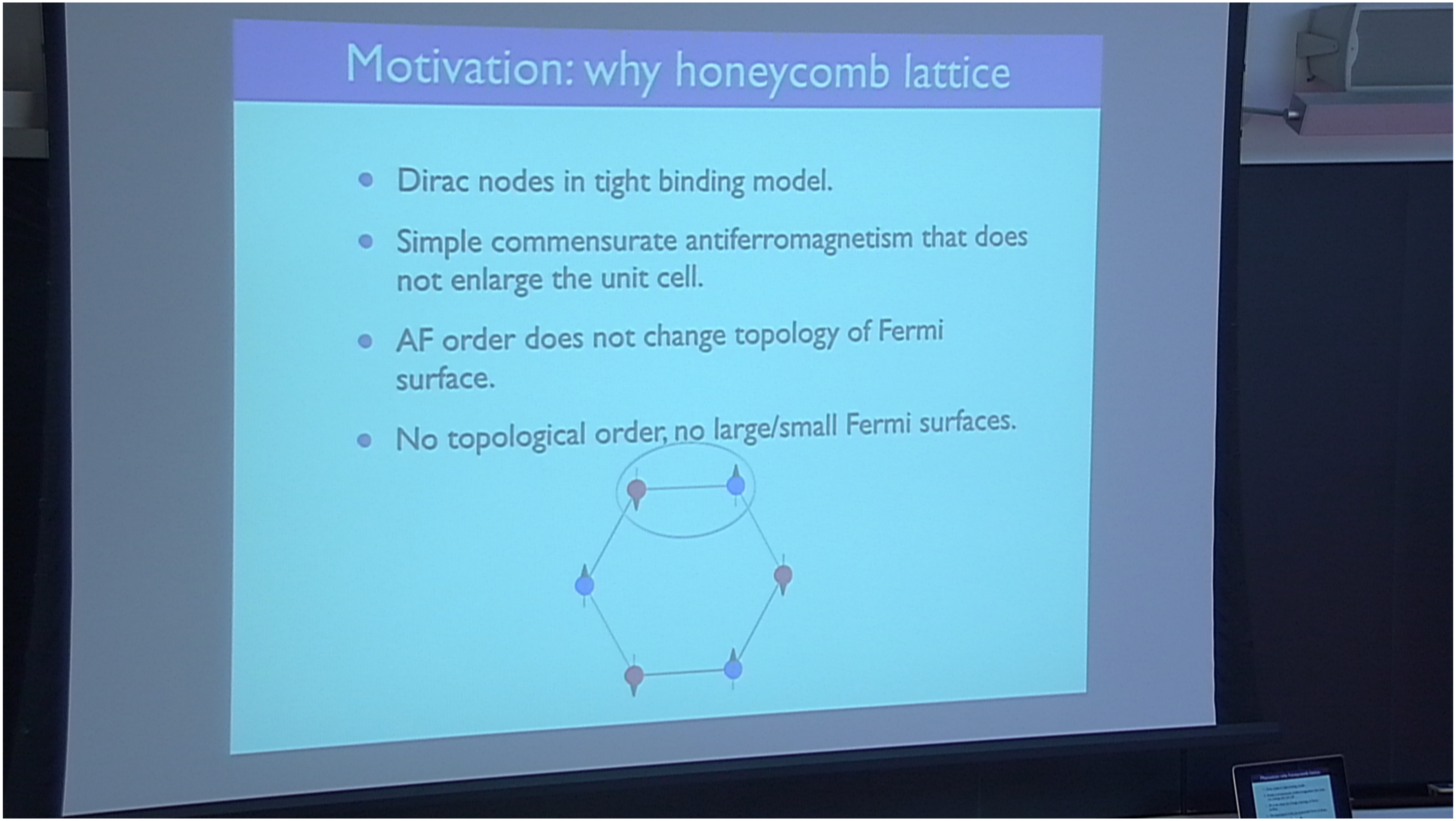

Motivation: why honeycomb lattice
Dirac nodes in tight binding model.
Simple commensurate antiferromagnetism that does not enlarge the unit cell.
AF order does not change topology of Fermi surface.
No topological order, no large/small Fermi surfaces.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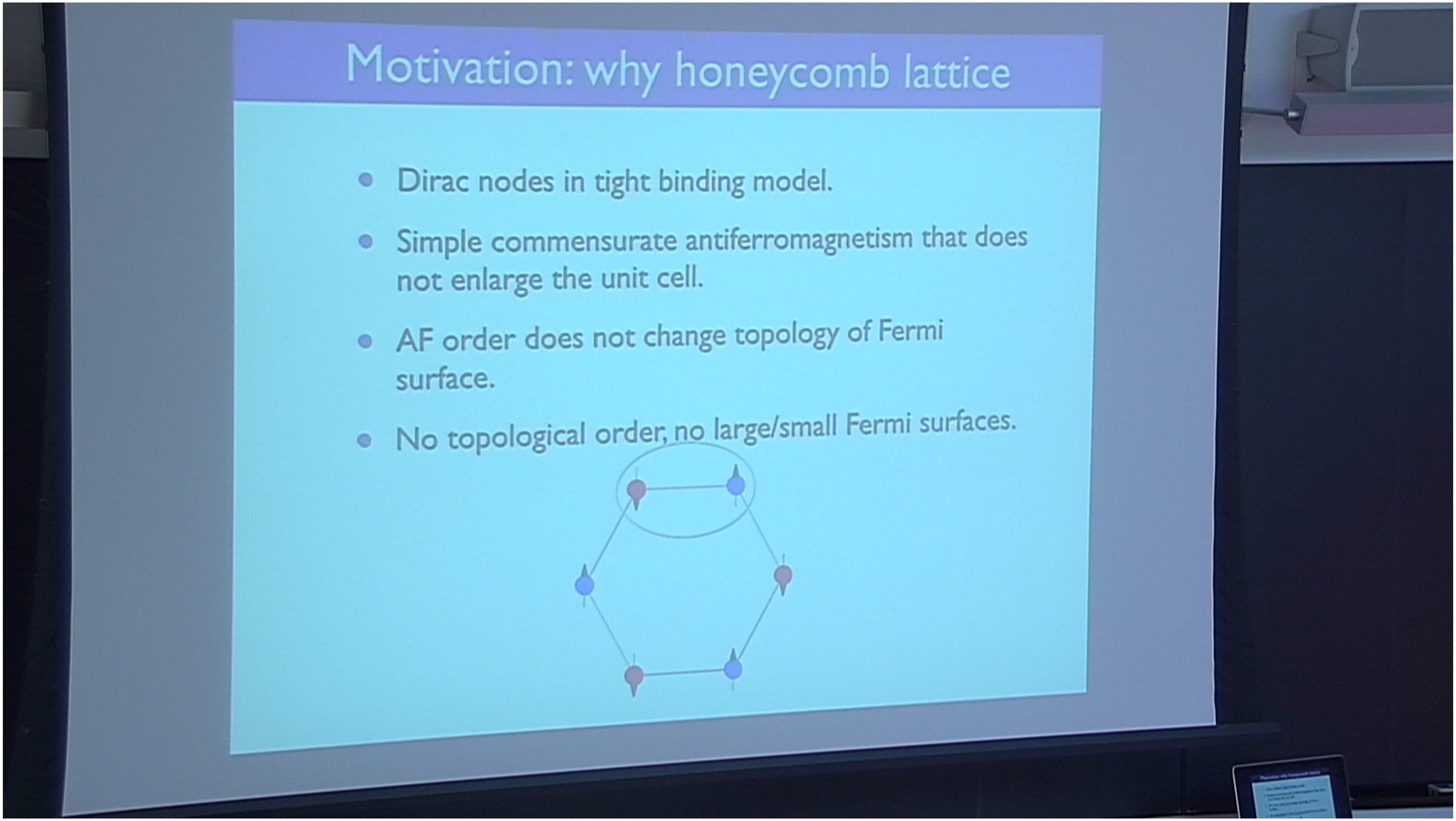
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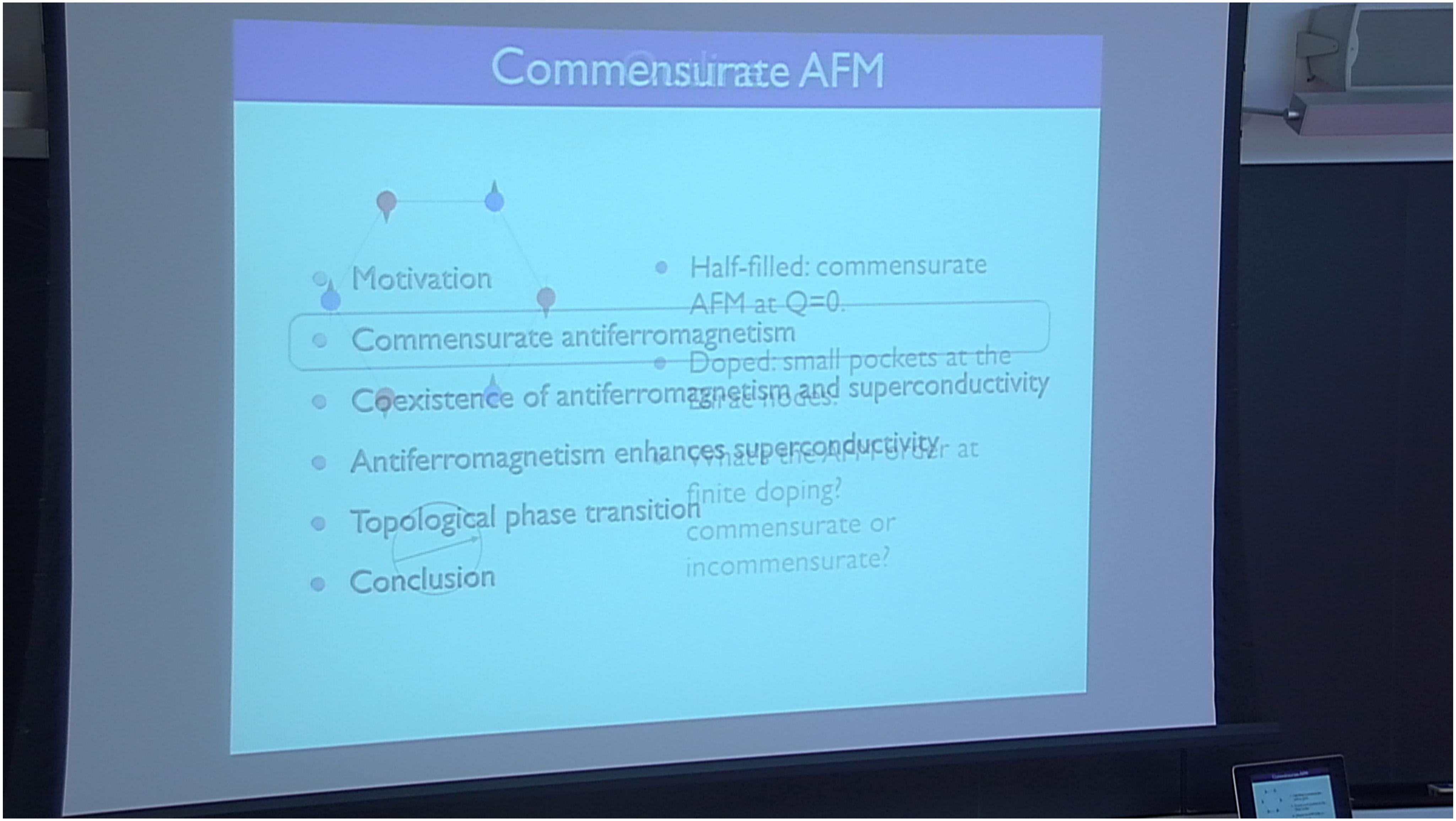
Commensurate AFM
Outline
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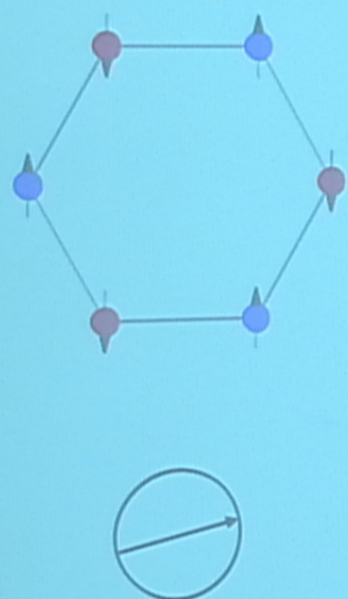
Half-filled: commensurate AFM at Q=0.
Doped: small pockets at the Dirac nodes.
What's the AFM order at finite doping? commensurate or incommensurate?

Commensurate AFM



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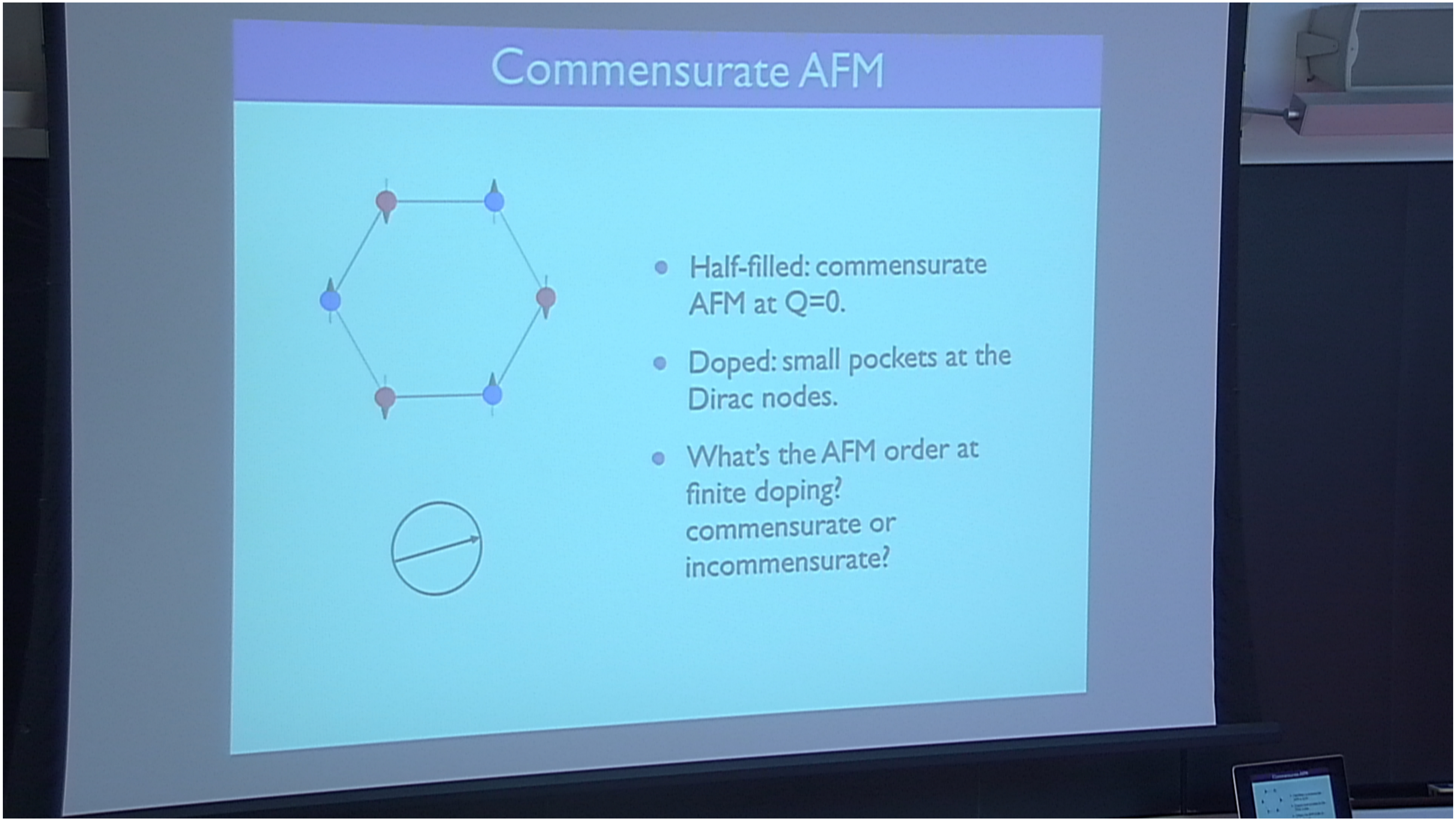
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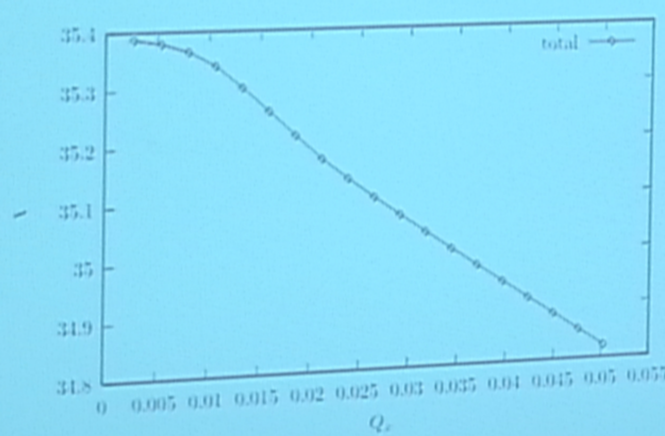
Magnetic susceptibility

- We calculated the susceptibility for the AFM order using a tight binding model with finite doping.
- Commensurate AFM.

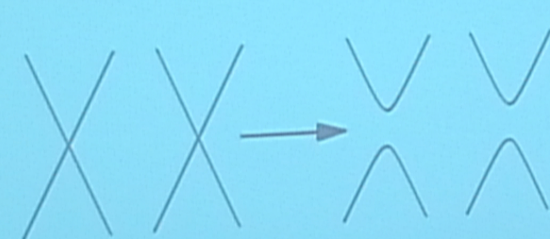


Mean field treatment of AF

- We start from the Hubbard model on honeycomb lattice,

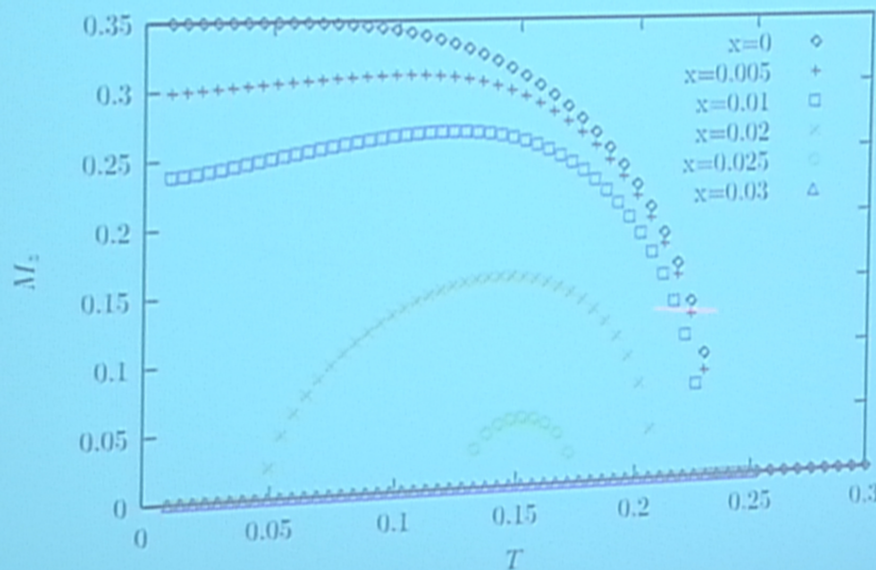
$$H = -t \sum_{\langle ij \rangle} \left(c^\dagger_{i\alpha} c_{j\alpha} + \text{h. c.} \right) + U \sum_i n_{i\uparrow} \cdot n_{i\downarrow}$$

- AF order gaps the Dirac nodes,

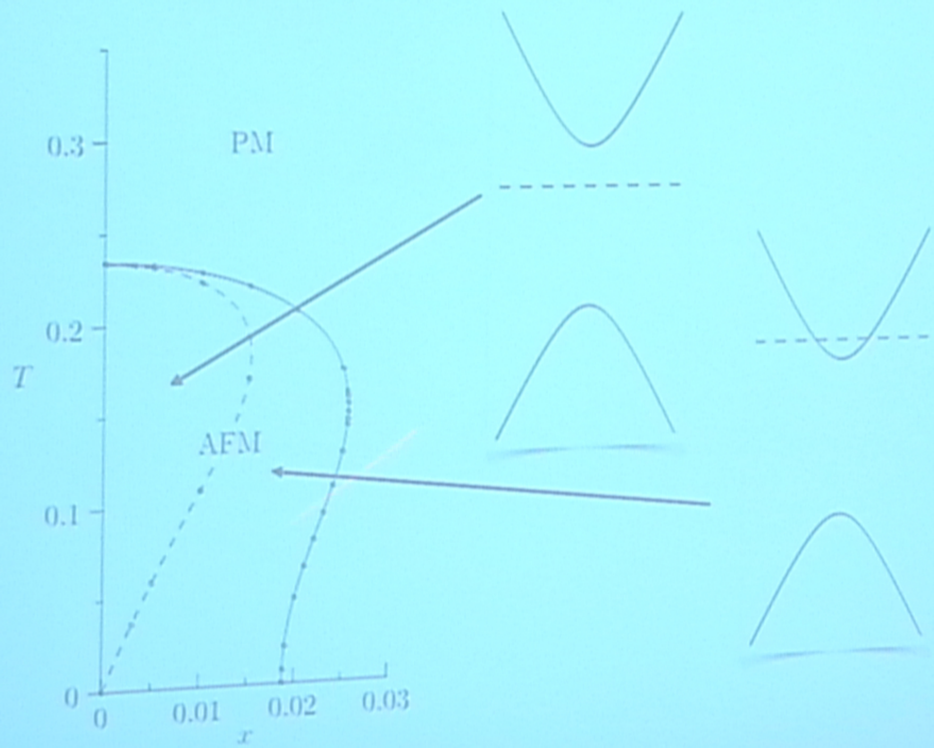


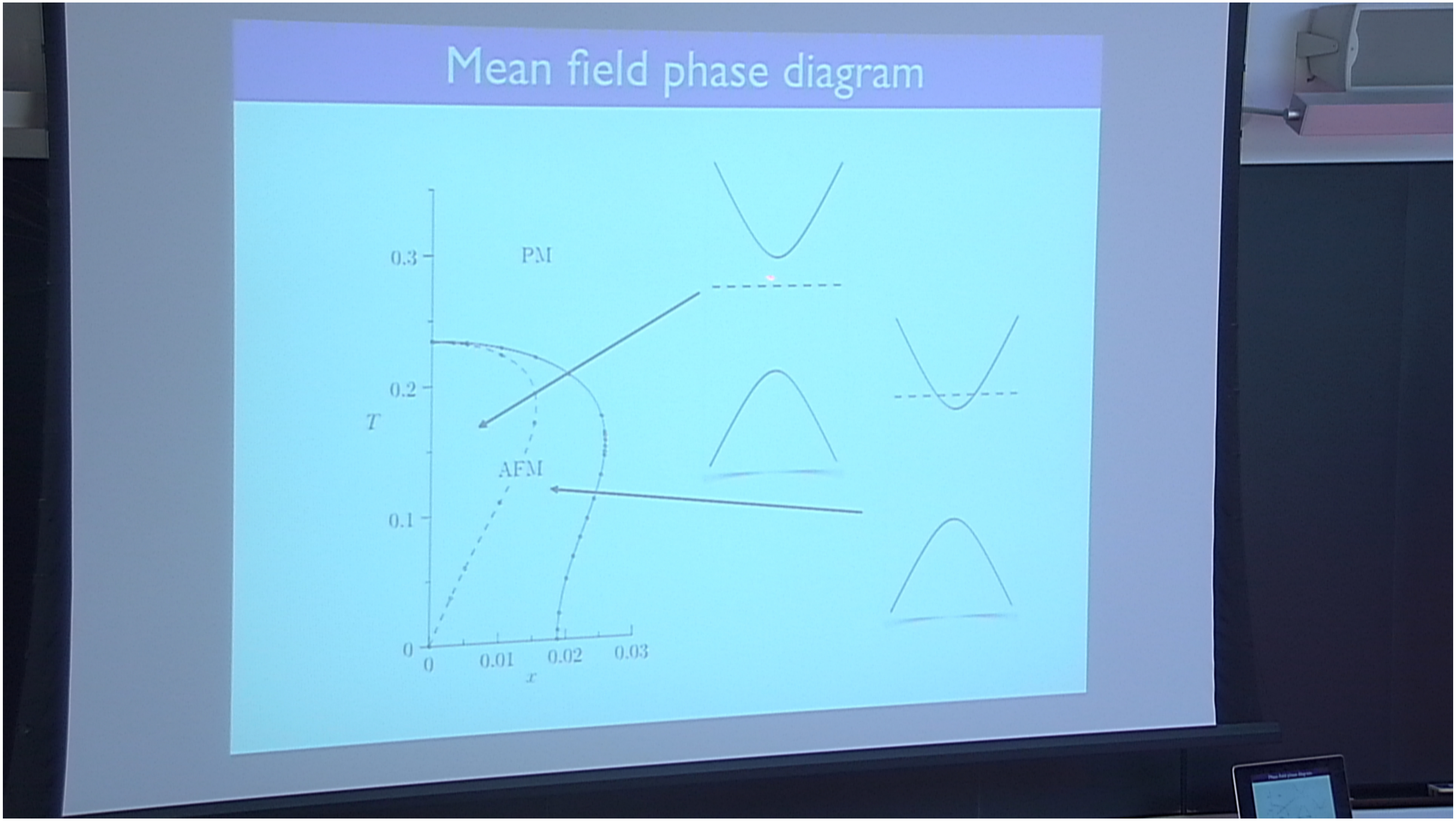
Result of mean field theory

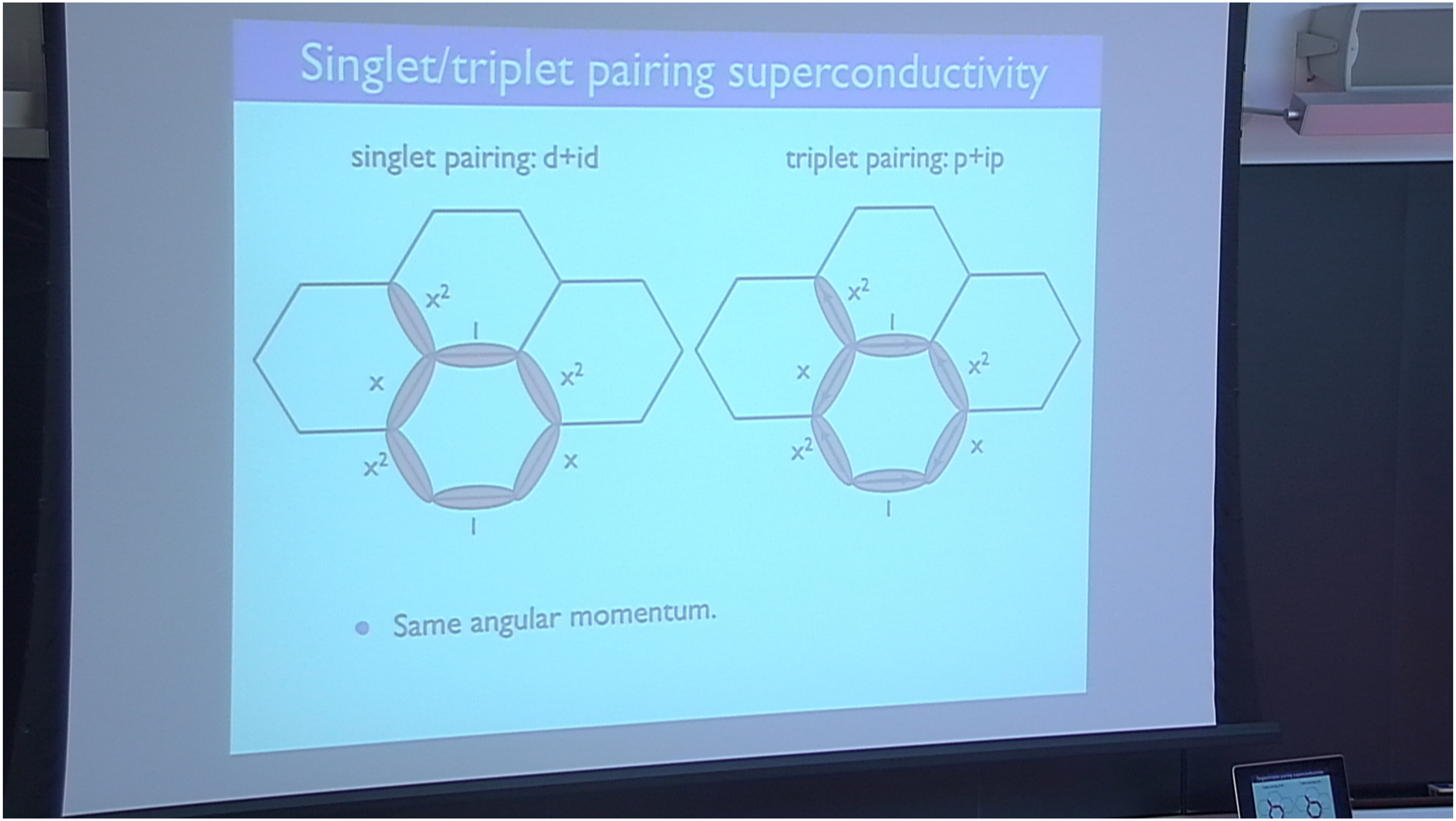
- AFM is suppressed at finite doping.
- Suppression is bigger at lower T.

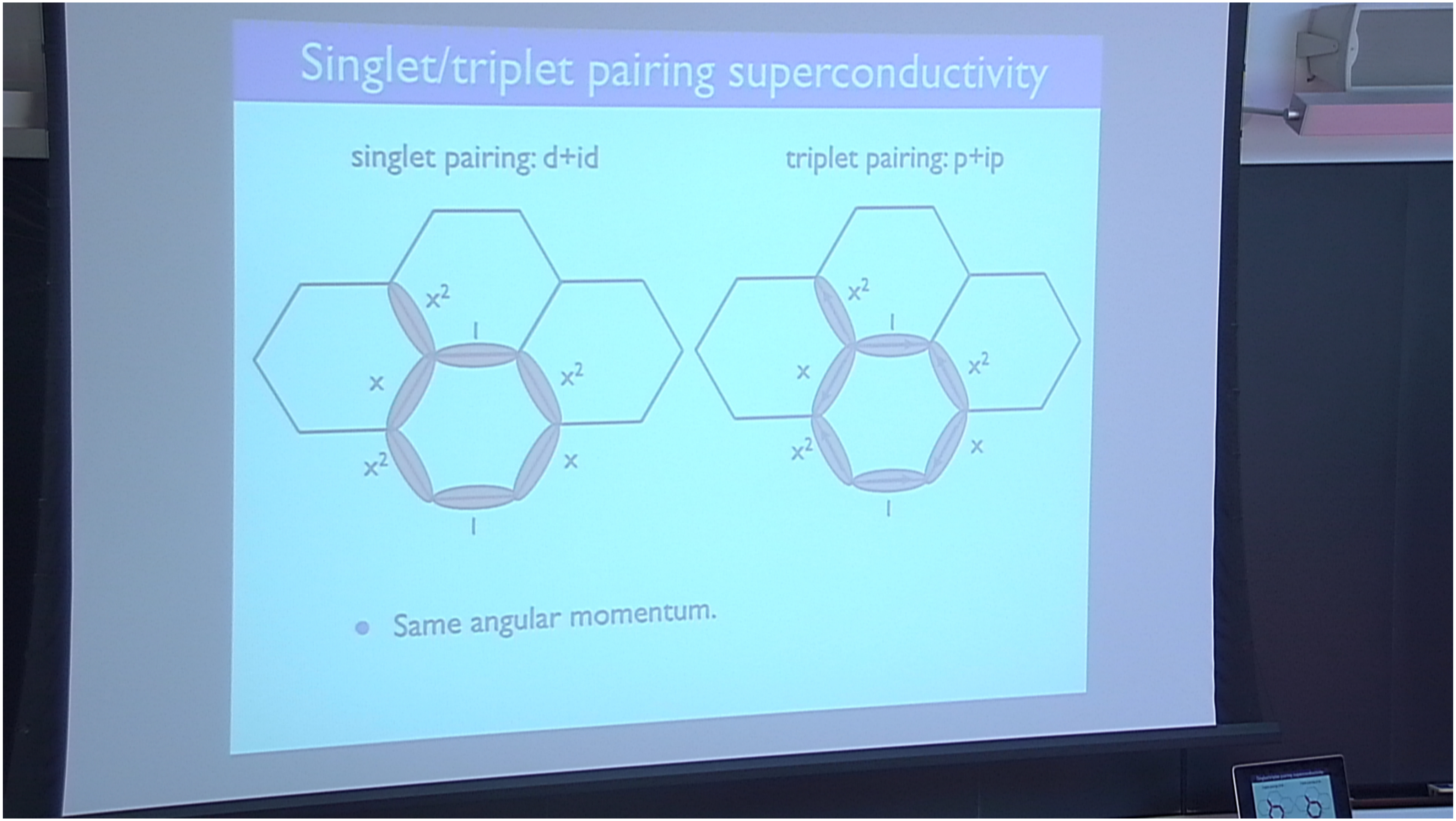


Mean field phase diagram




Mean field phase diagram
PM
AFM
T
x
0.3
0.2
0.1
0
0
0.01
0.02
0.03


Singlet/triplet pairing superconductivity
singlet pairing: d+id
triplet pairing: p+ip
x^2
1
x
x^2
x^2
x
1
Same angular momentum.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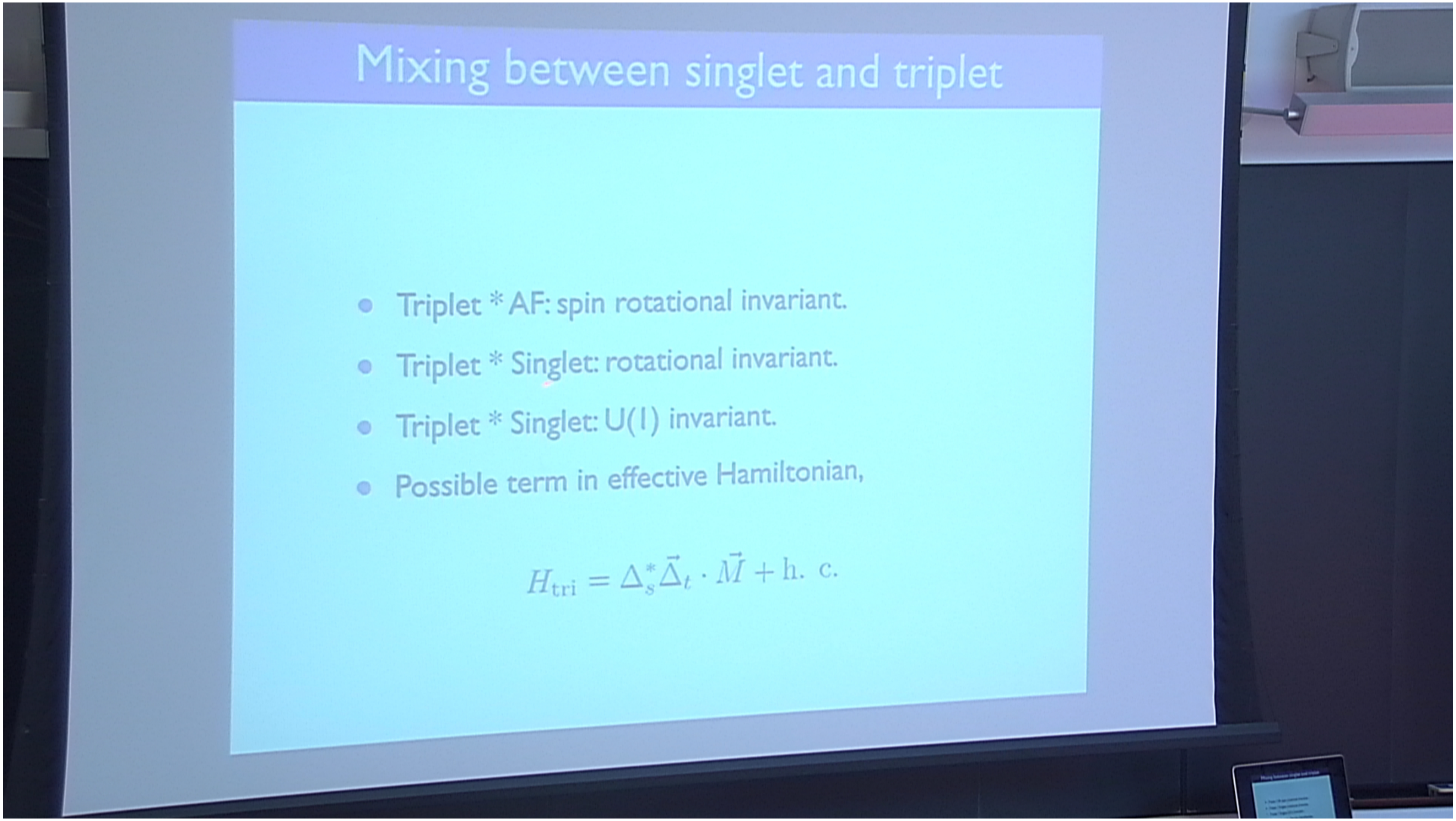
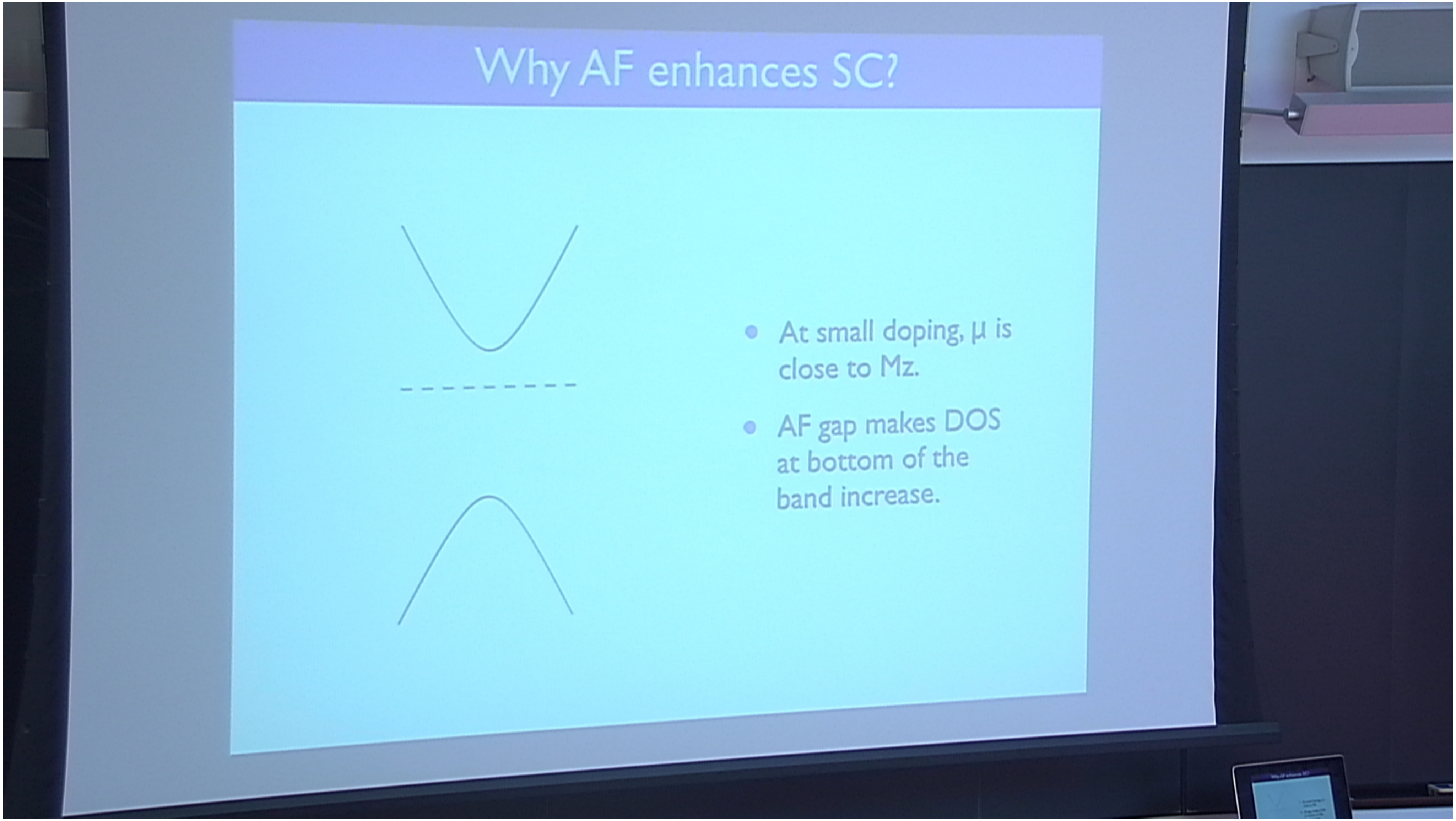
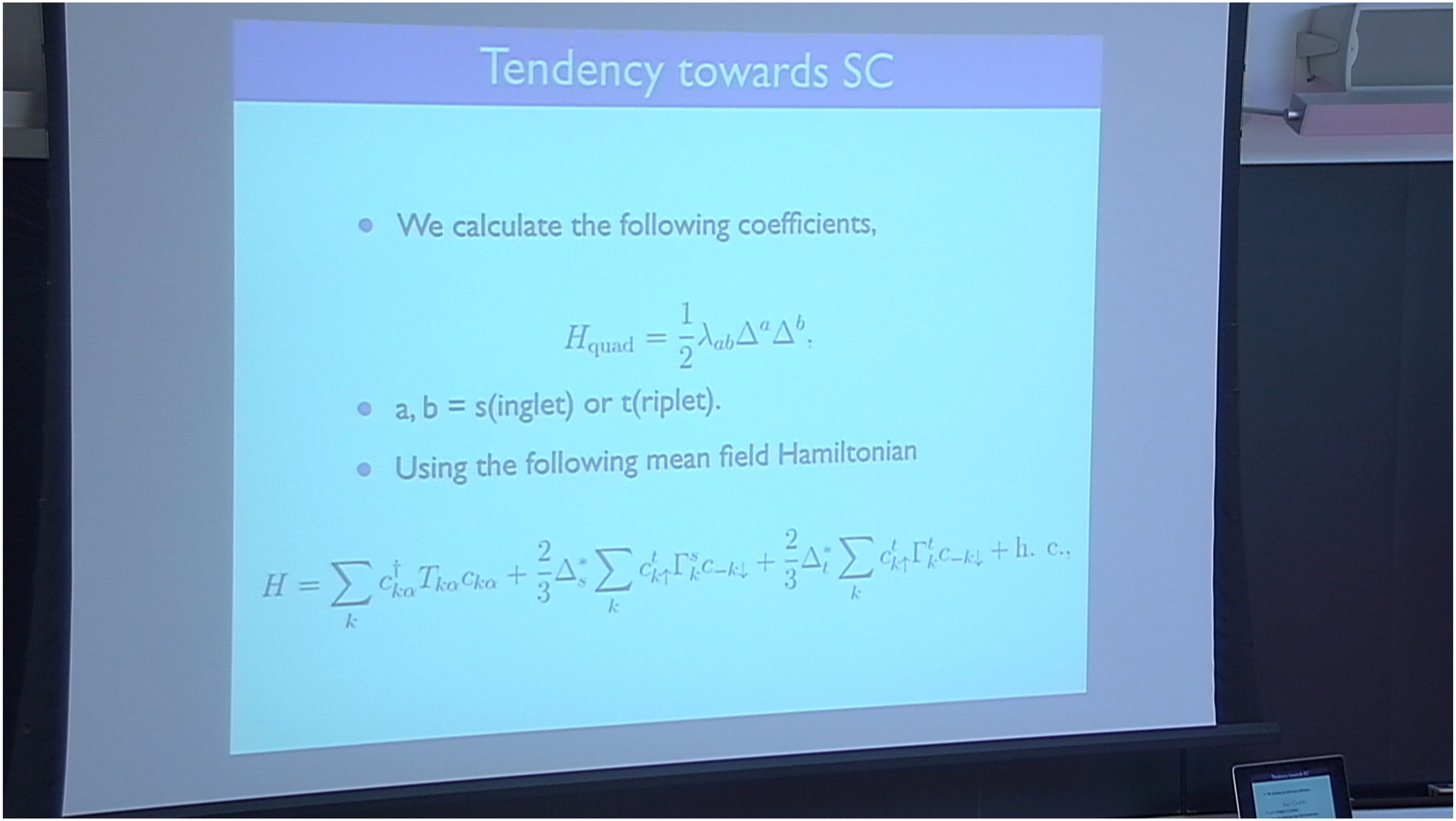
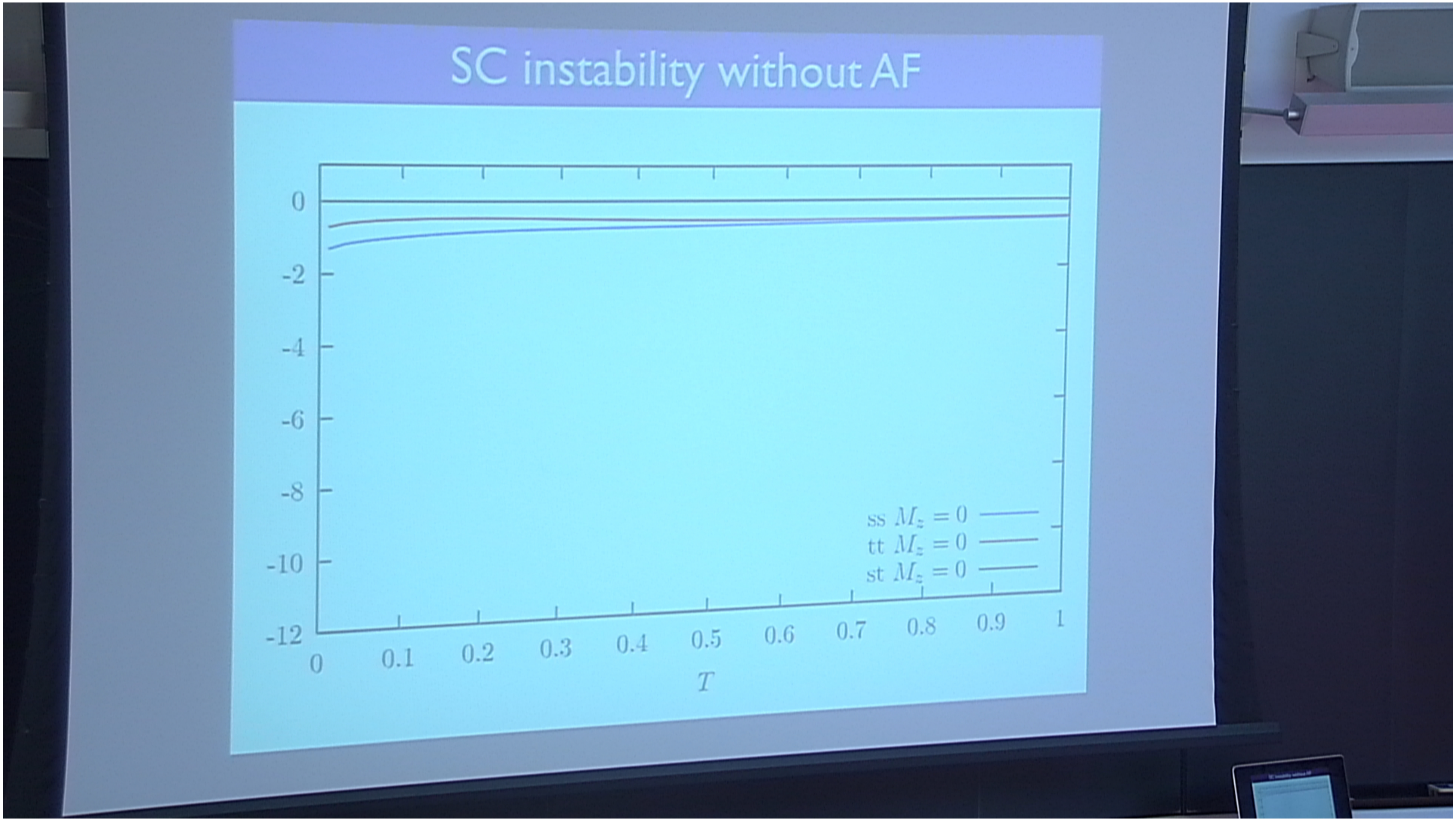
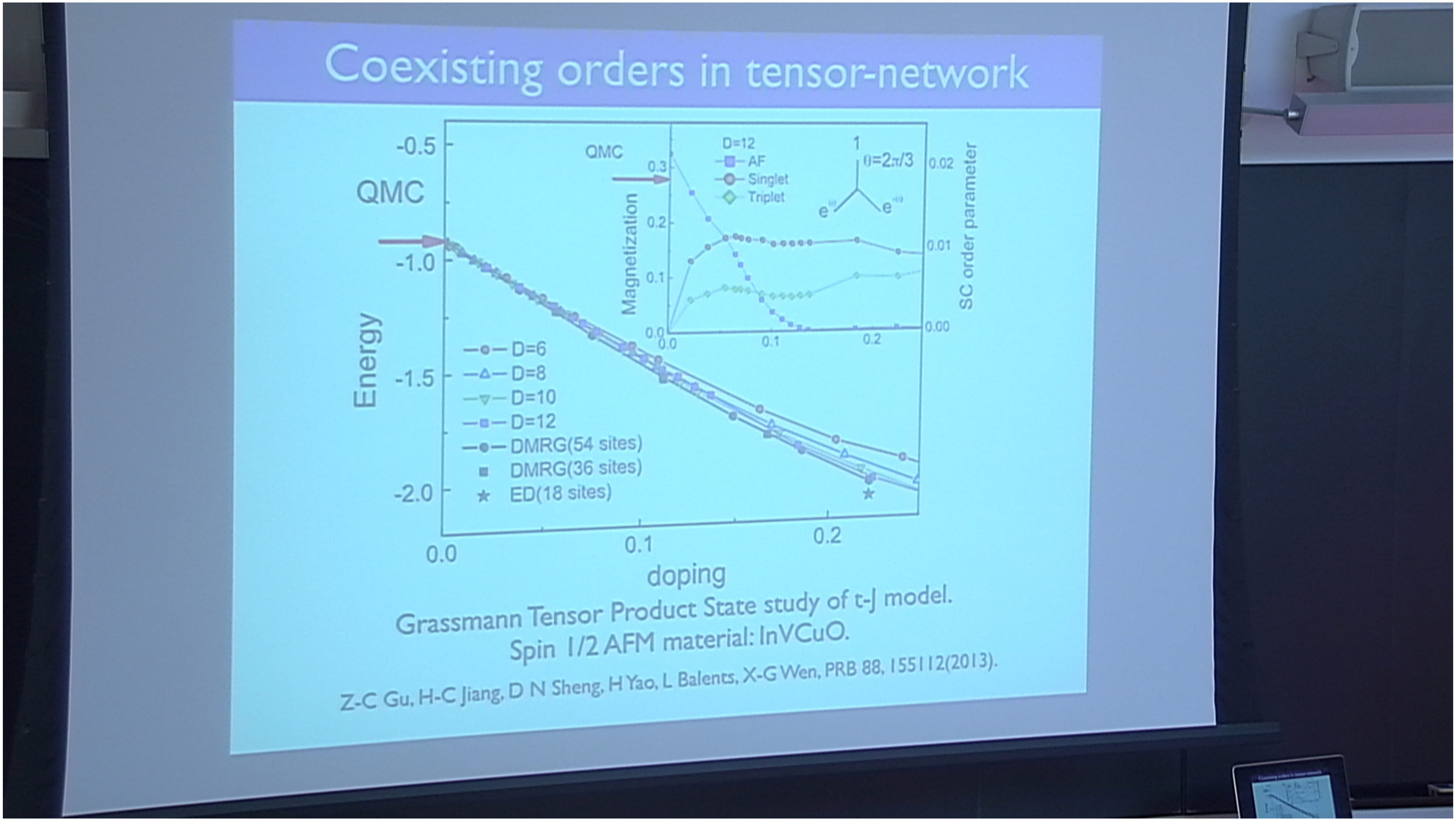

Mixing between singlet and triplet
Triplet * AF: spin rotational invariant.
Triplet * Singlet: rotational invariant.
Triplet * Singlet: U(1) invariant.
Possible term in effective Hamiltonian,
$H_{\rm tri} = \Delta_s^* \vec{\Delta}_t \cdot \vec{M} + \mathrm{h.\ c.}$


Why AF enhances SC?
At small doping, μ is close to Mz.
AF gap makes DOS at bottom of the band increase.


Tendency towards SC
We calculate the following coefficients,
$H_{\text{quad}} = \frac{1}{2}\lambda_{ab}\Delta^a\Delta^b,$
a, b = s(inglet) or t(riplet).
Using the following mean field Hamiltonian
$H = \sum_k c^\dagger_{k\alpha} T_{k\alpha} c_{k\alpha} + \frac{2}{3}\Delta^*_s \sum_k c^t_{k\uparrow}\Gamma^s_k c_{-k\downarrow} + \frac{2}{3}\Delta^*_t \sum_k c^t_{k\uparrow}\Gamma^t_k c_{-k\downarrow} + \text{h. c.},$


SC instability without AF
0
-2
-4
-6
-8
-10
-12
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
T
ss $M_z = 0$
tt $M_z = 0$
st $M_z = 0$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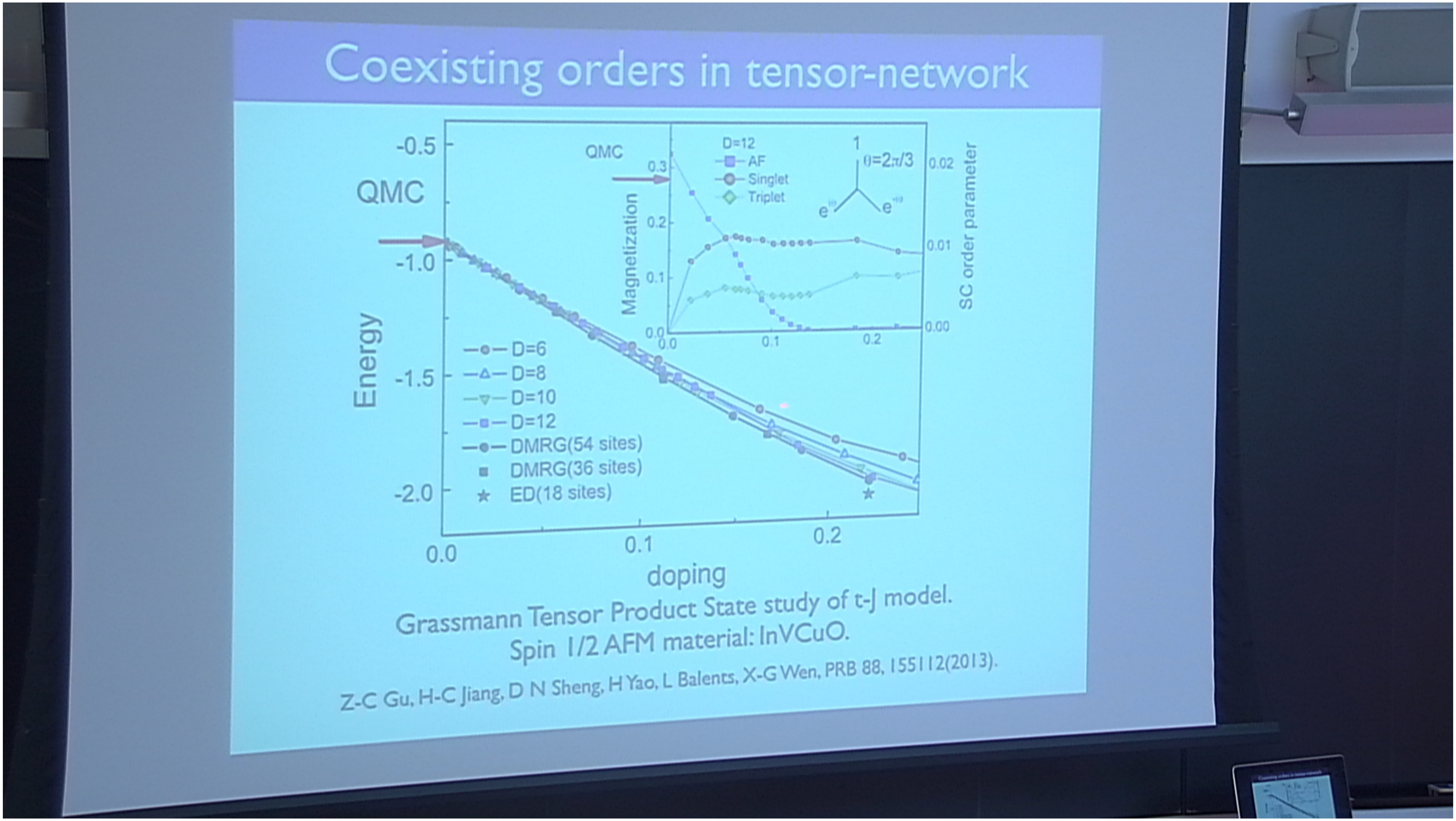

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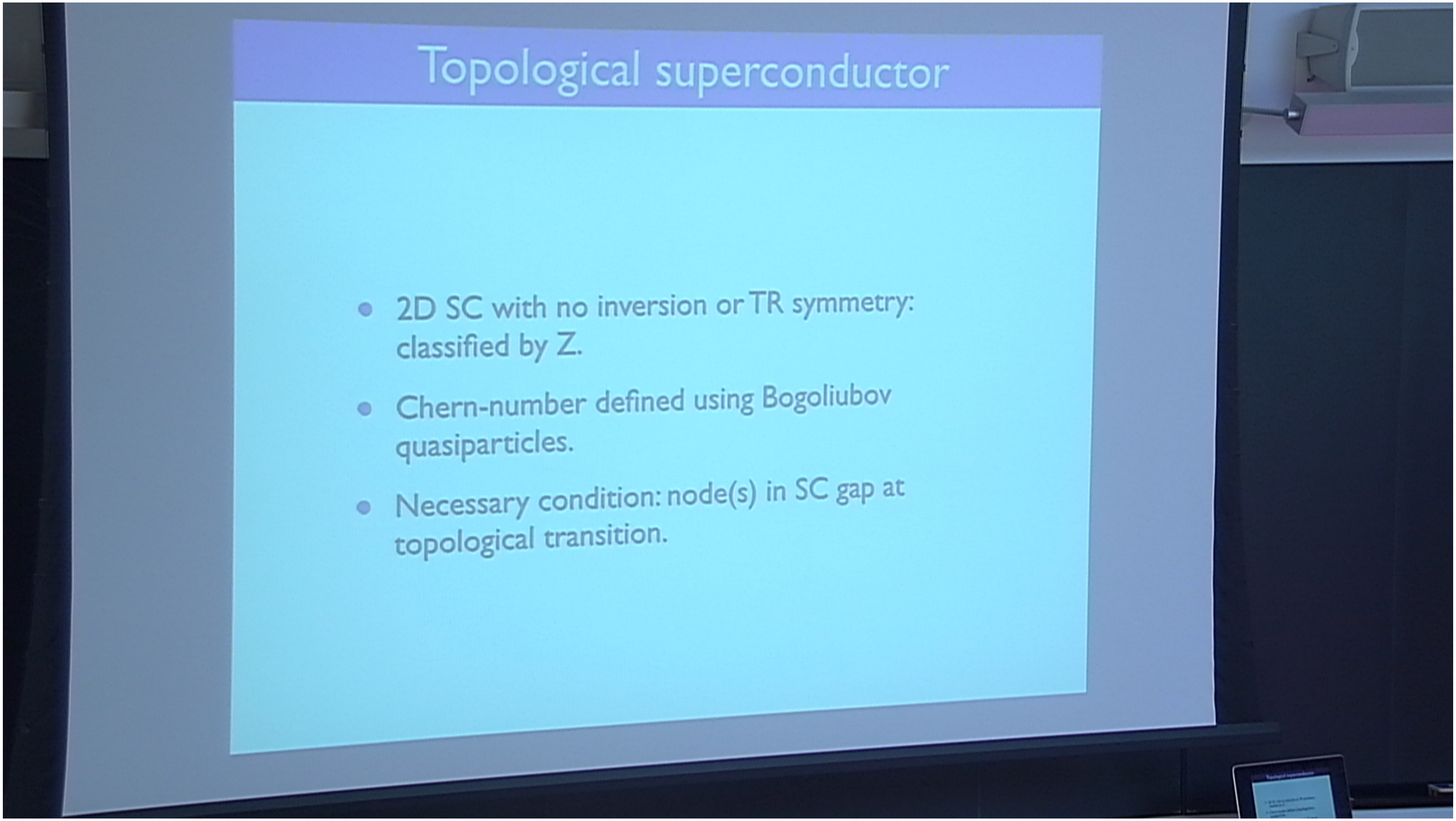
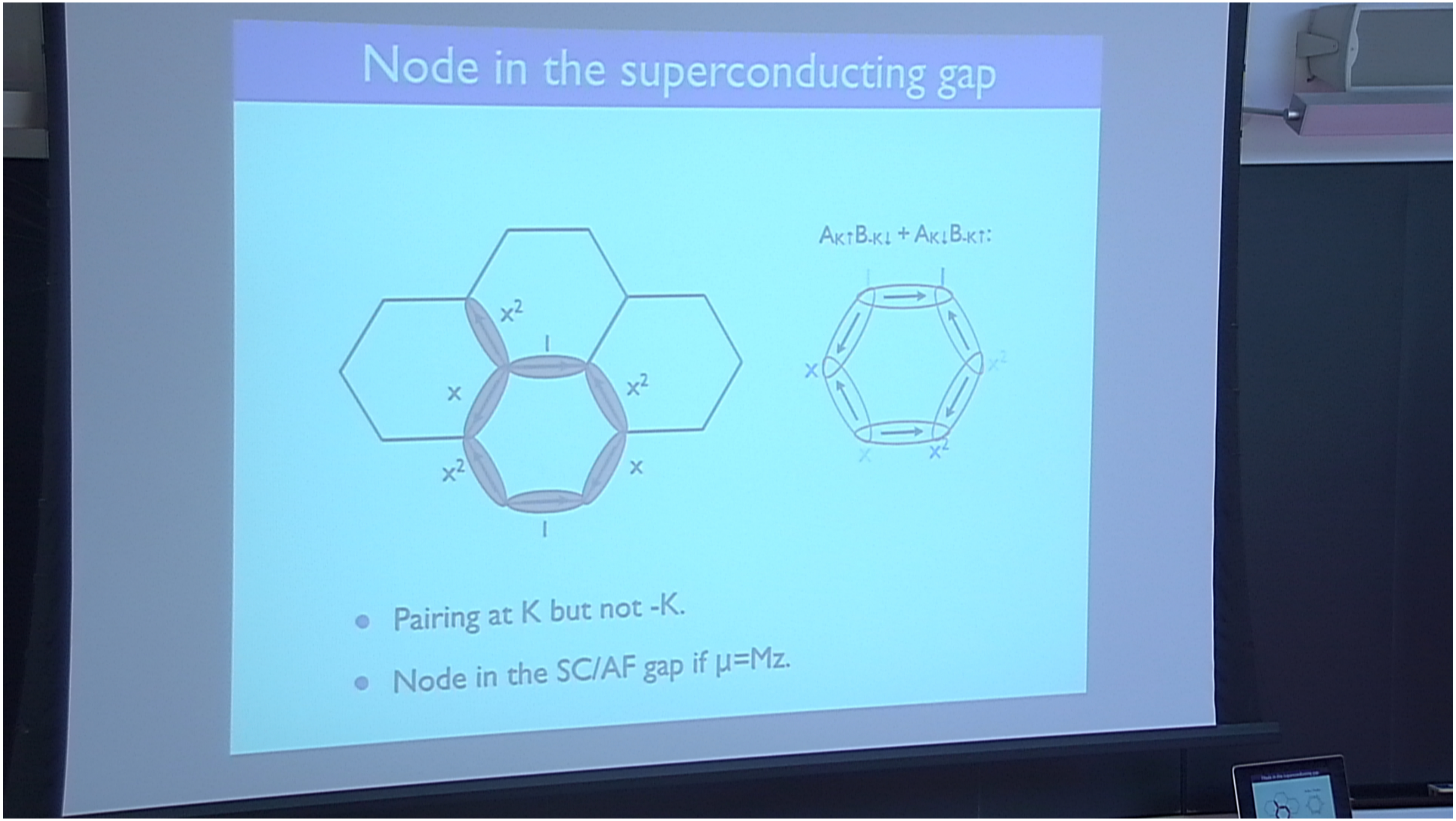
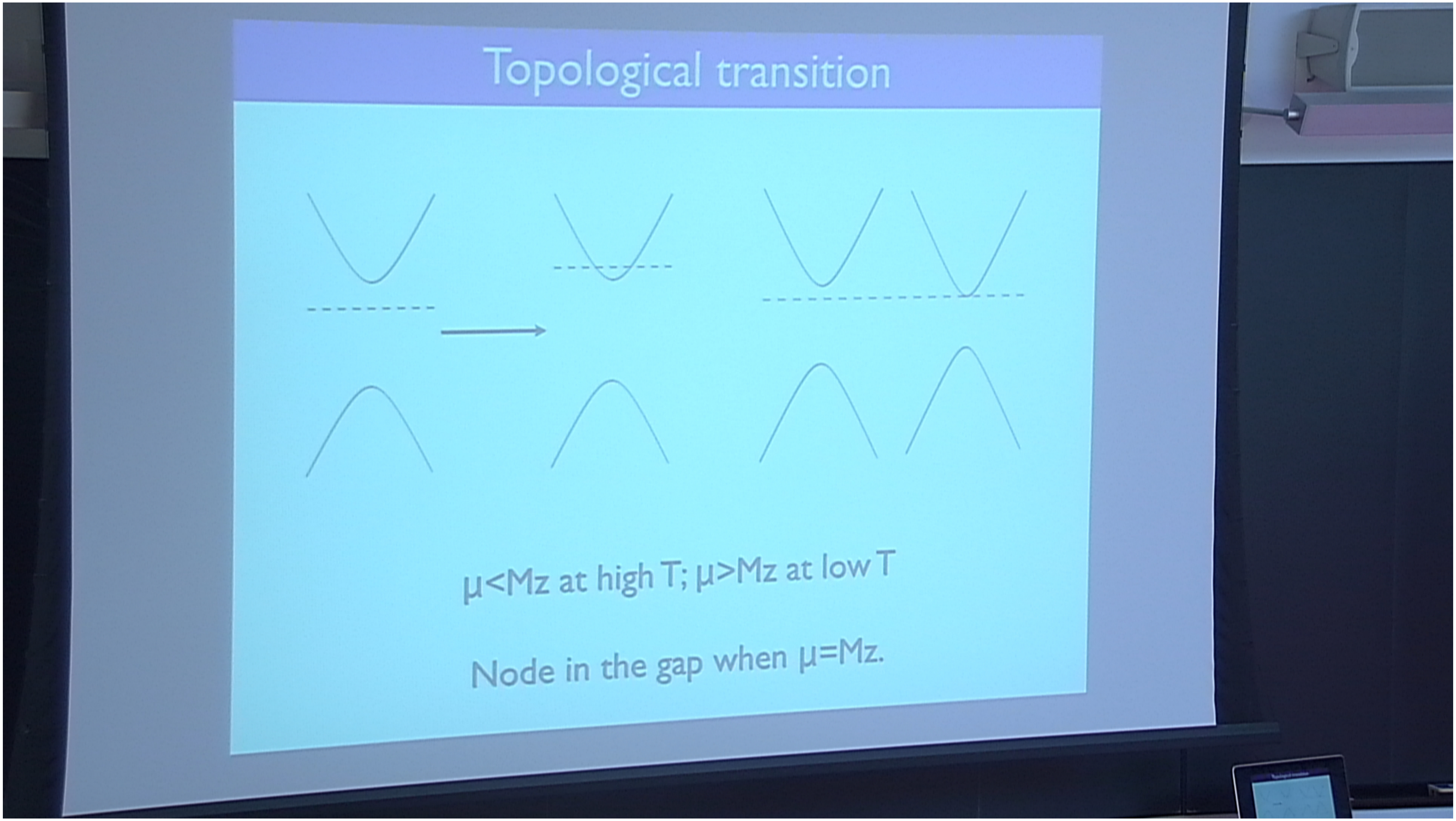
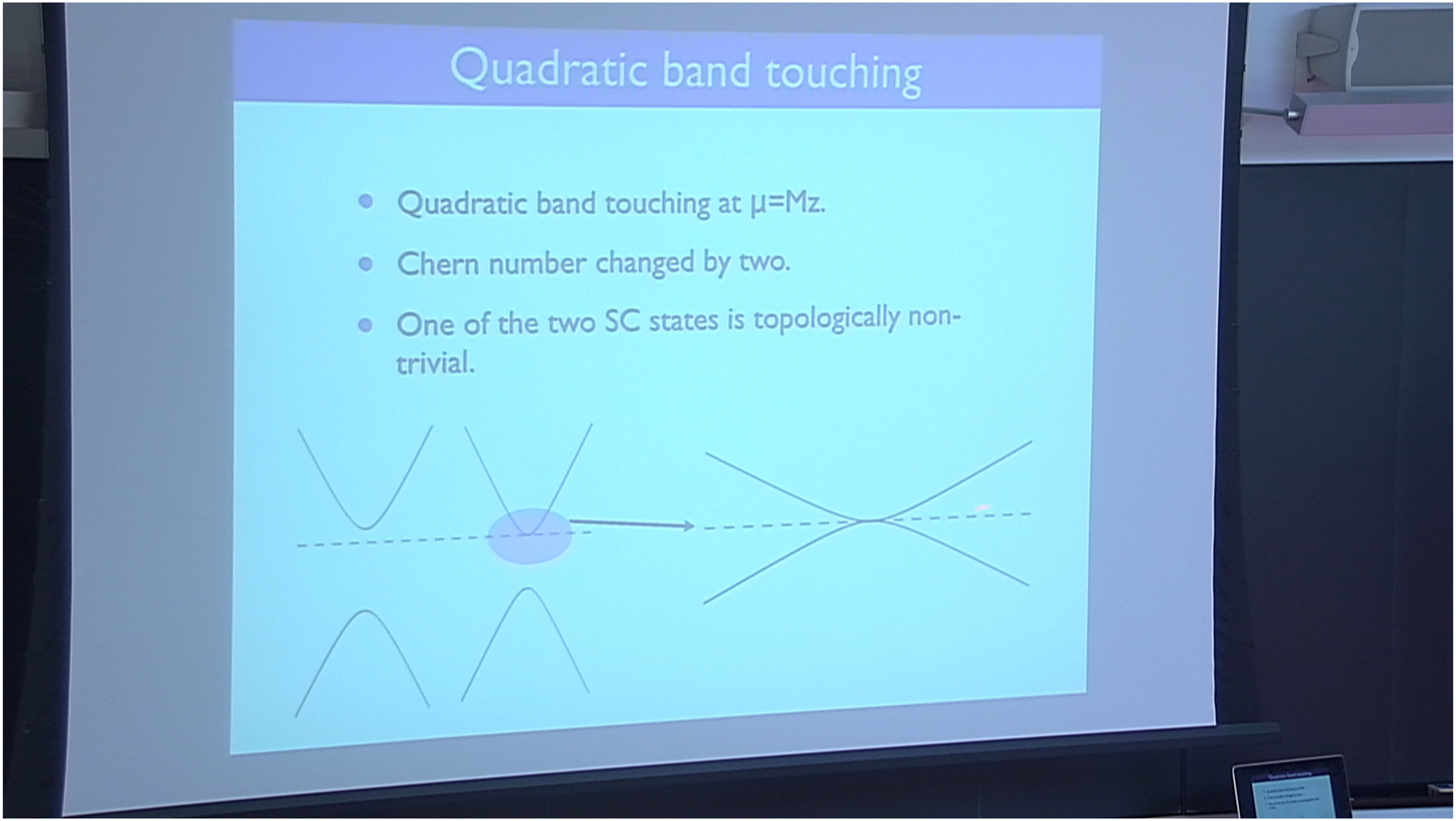
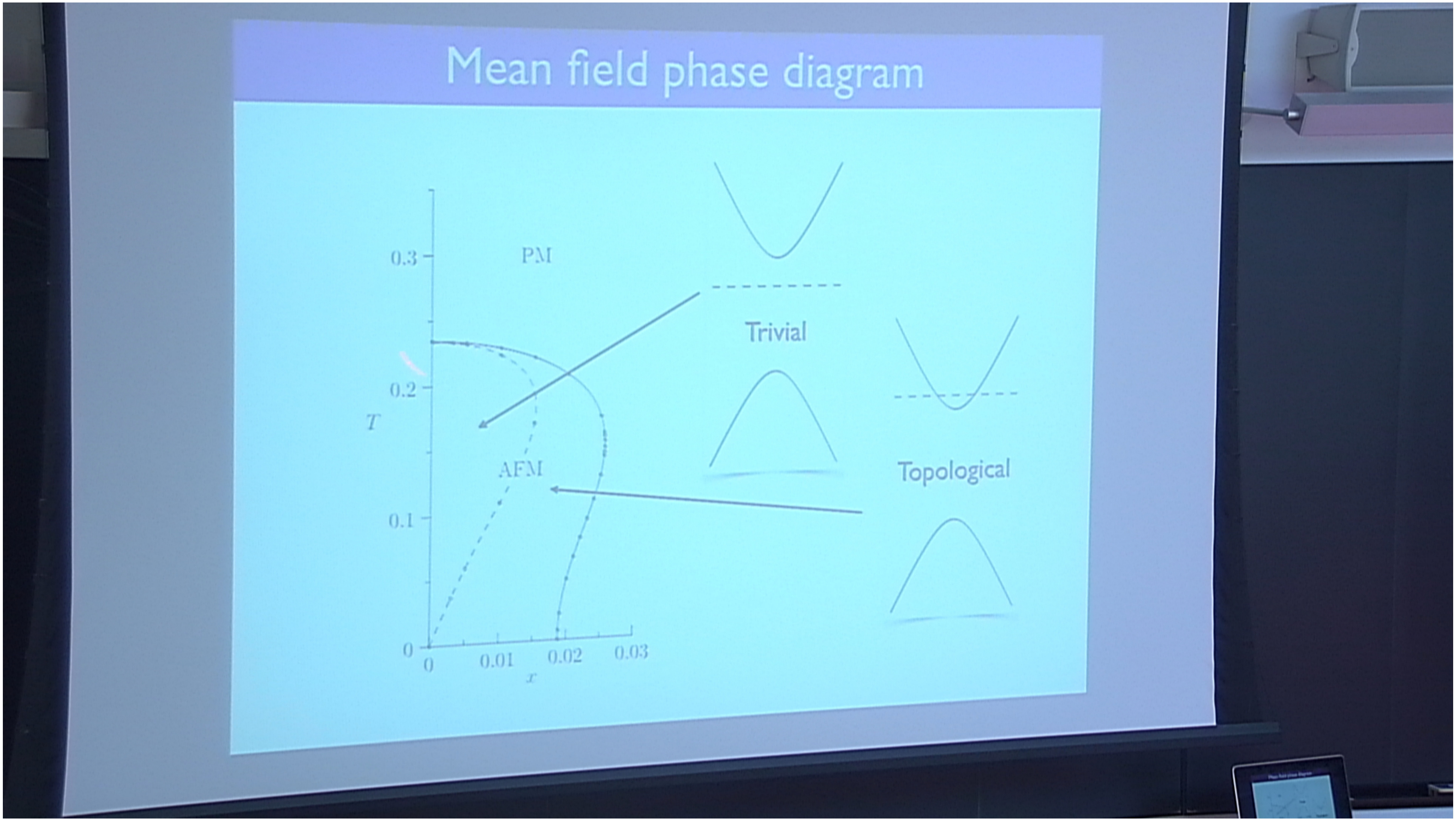
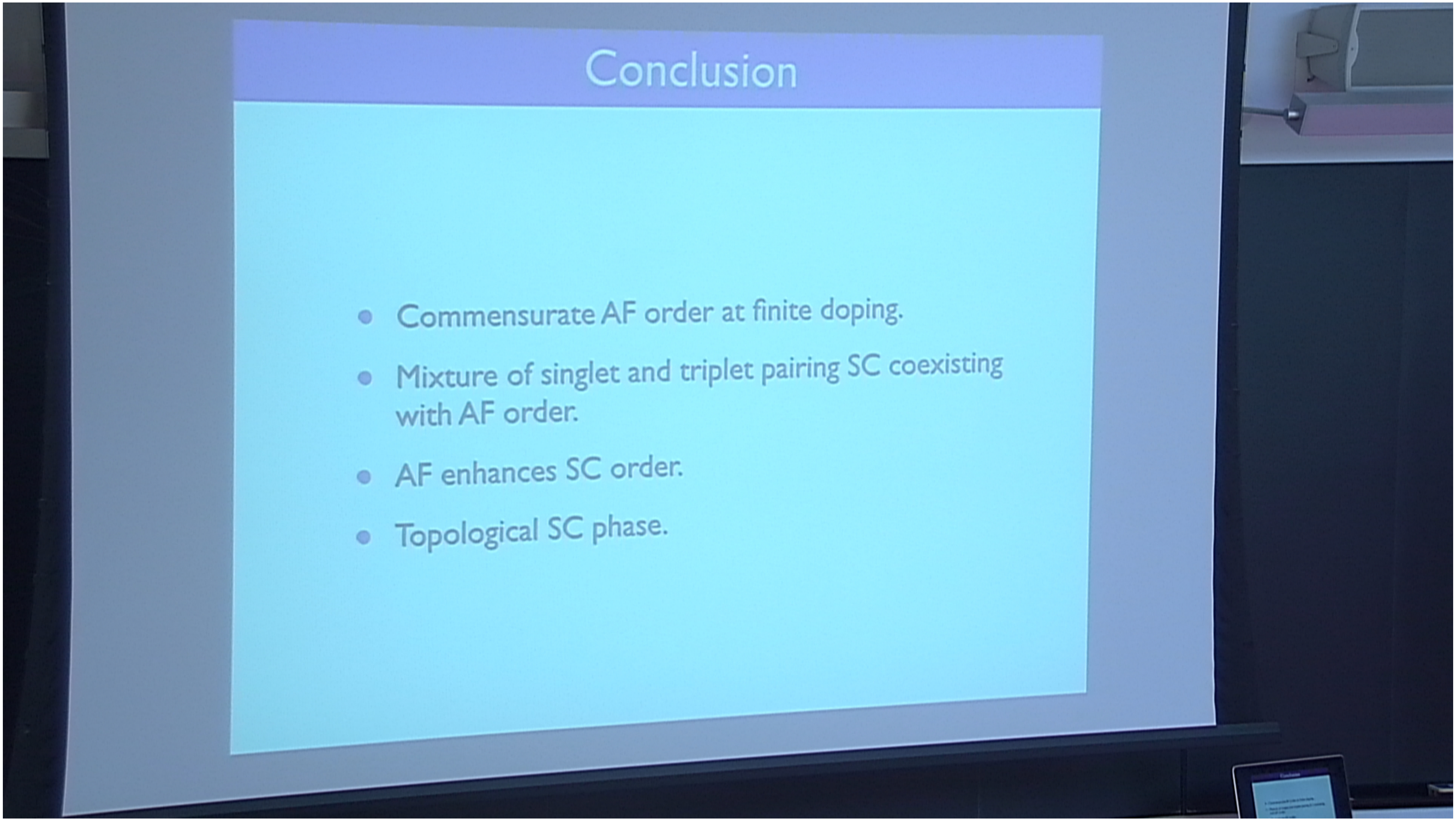

Topological superconductor
2D SC with no inversion or TR symmetry: classified by Z.
Chern-number defined using Bogoliubov quasiparticles.
Necessary condition: node(s) in SC gap at topological transition.


Node in the superconducting gap
AK↑B-K↓ + AK↓B-K↑:
x²
1
x
x²
x²
x
1
x
x²
x
x²
Pairing at K but not -K.
Node in the SC/AF gap if μ=Mz.


Topological transition
μ<Mz at high T; μ>Mz at low T
Node in the gap when μ=Mz.


Quadratic band touching
Quadratic band touching at μ=Mz.
Chern number changed by two.
One of the two SC states is topologically non-trivial.


Mean field phase diagram
PM
AFM
Trivial
Topological
0.3
0.2
0.1
0
0.01
0.02
0.03
T
x


Conclusion
Commensurate AF order at finite doping.
Mixture of singlet and triplet pairing SC coexisting with AF order.
AF enhances SC order.
Topological SC phase.