Superfluids and superconductors in confinement

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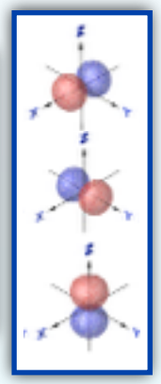
DMR-0954342
CAREER

Superfluid ^{3}He

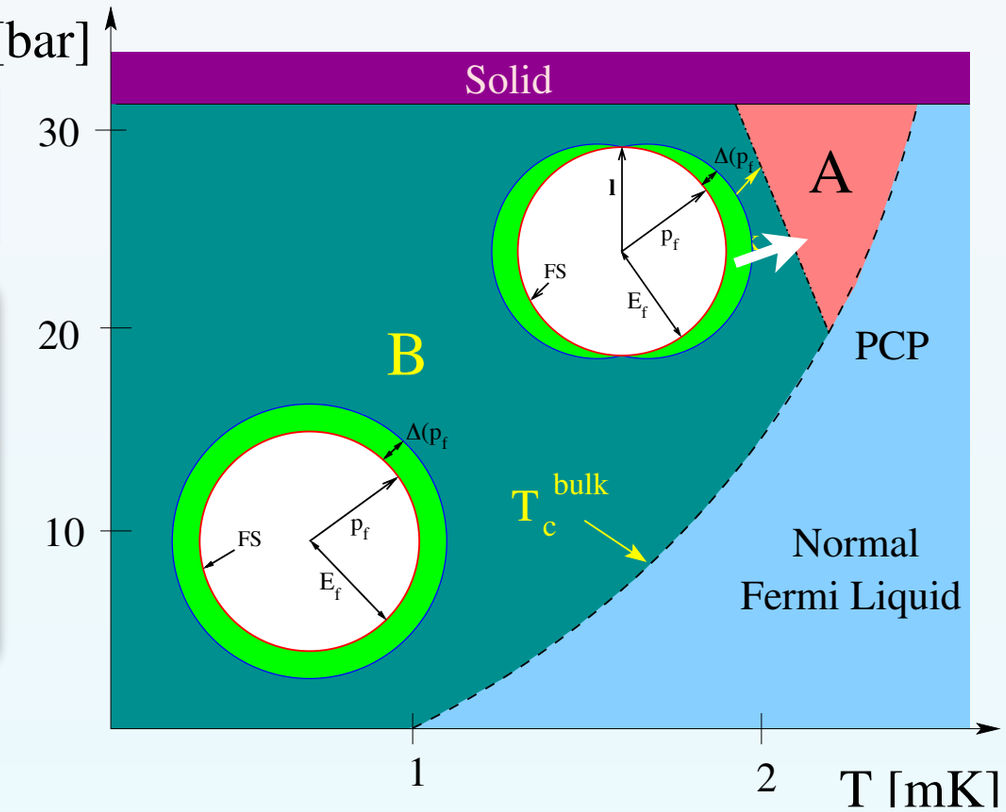
- *Multi-component (18) Order Parameter with Broken Spin- Orbital and Gauge Symmetries.*

$$\begin{pmatrix} |\uparrow\uparrow\rangle \\ \frac{1}{\sqrt{2}}|\uparrow\downarrow + \downarrow\uparrow\rangle \\ |\downarrow\downarrow\rangle \end{pmatrix} = \begin{pmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{yx} & A_{yy} & A_{yz} \\ A_{zx} & A_{zy} & A_{zz} \end{pmatrix}$$

S=1



L=1



Normal State Symmetry:

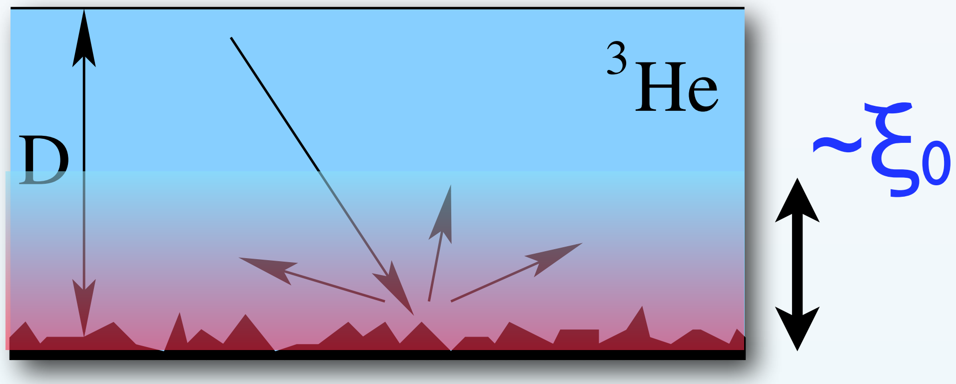
$\mathcal{G}_N = U(1) \times SO(3)_L \times P \times SO(3)_S \times \mathcal{T}$

gauge *orbital* *parity* *spin* *time reversal*

One of the most sophisticated and successful Condensed Matter Systems:

- *unconventional BCS pairing*
- *multiple condensed phases*
- *complex broken symmetries*
- *interactions: FL, dipole-dipole,…*
- *topological properties*

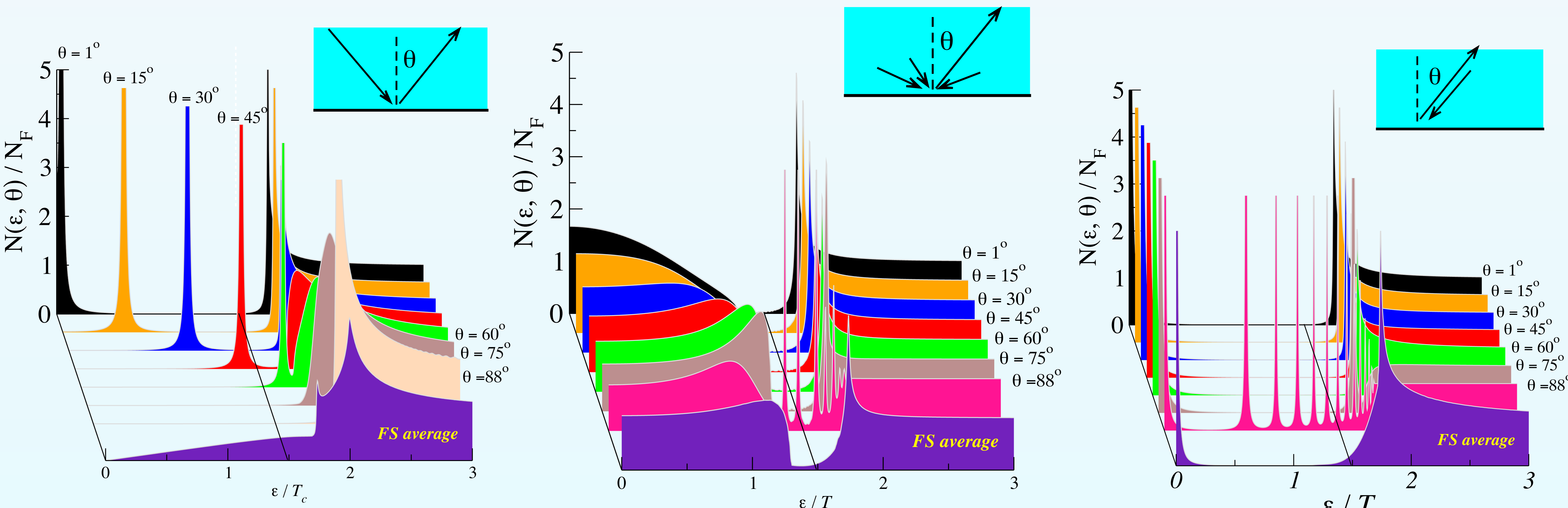
Surface states in ^3He



Normal State Film:

$$\mathcal{G}_N = U(1) \times [U(1)_{Lz} \times \mathcal{R}_x \times \mathcal{R}_y] \times SO(3)_S \times \mathcal{T}$$

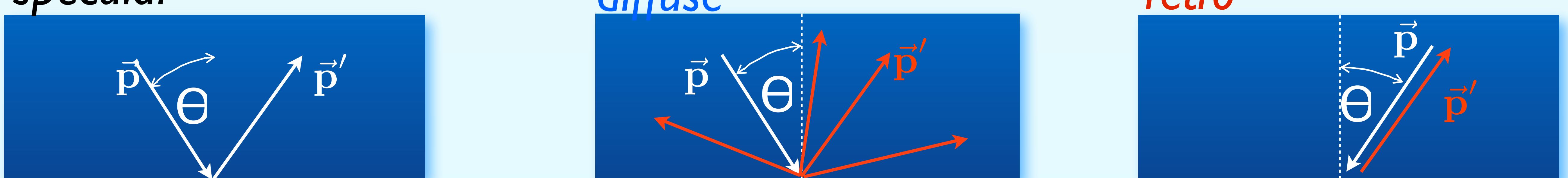
gauge | orbital rotations and reflections ($\mathcal{R}$) | spin | time reversal



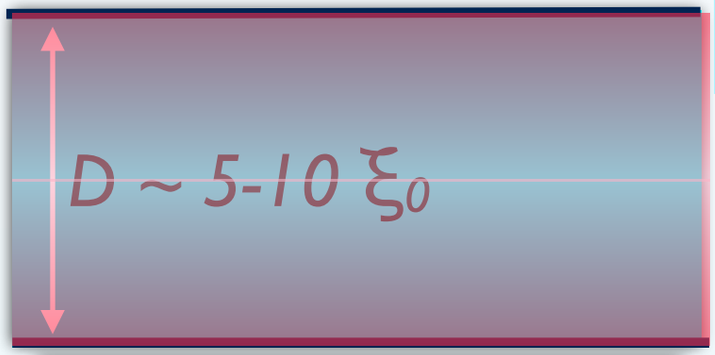
specular

diffuse

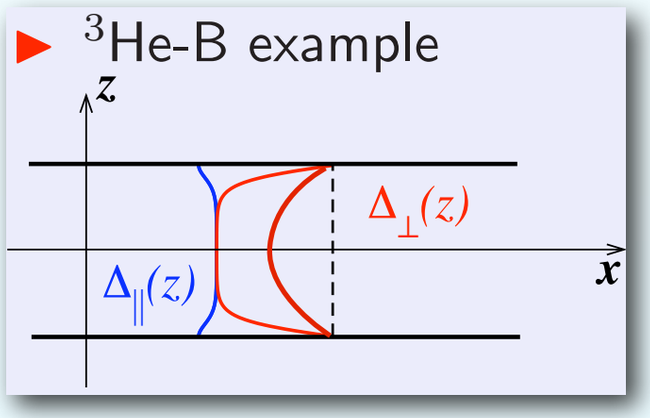
retro

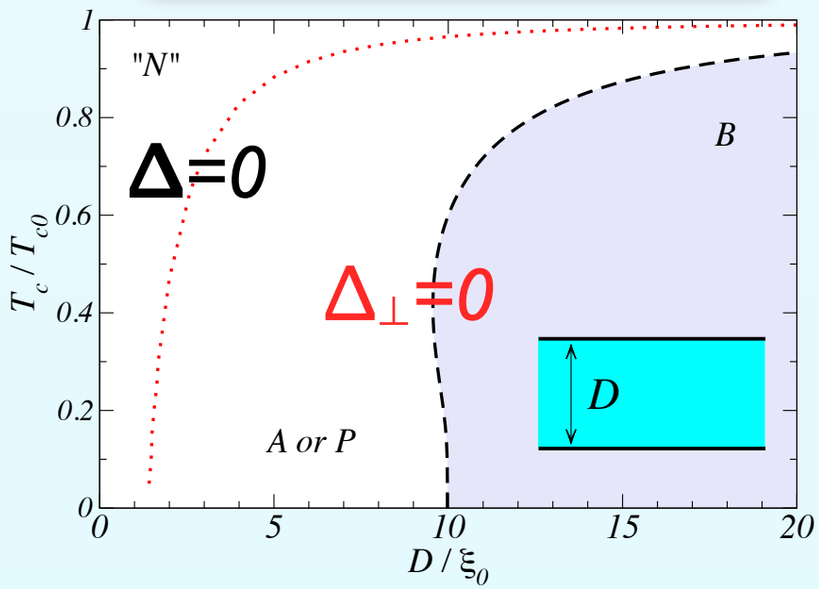


Superfluid in confinement



$$\xi_0 = \frac{\hbar v_f}{2\pi T_c} \approx 20 - 80\,\mathrm{nm}$$





- *surface states dominate the volume of the sample*

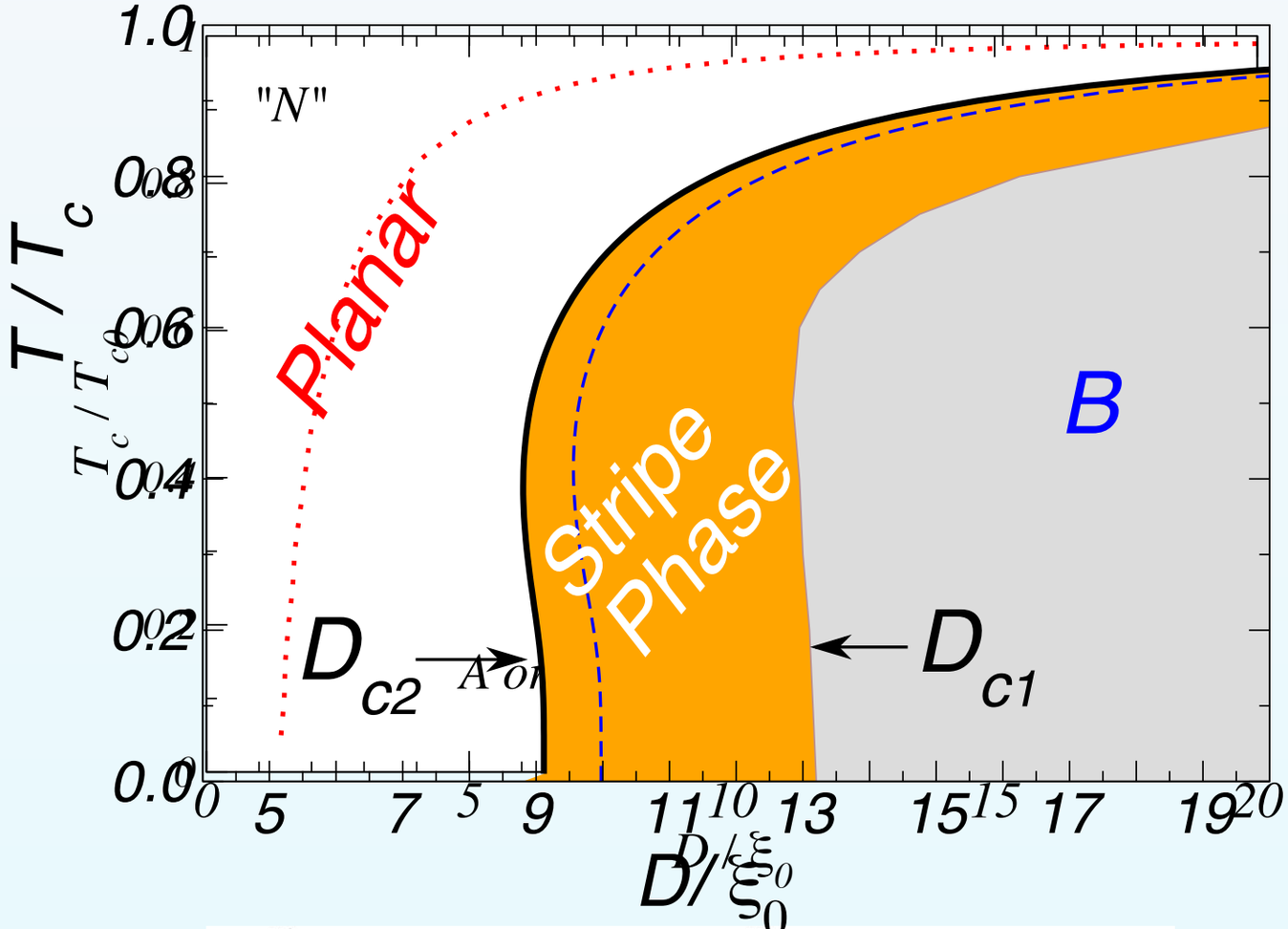
- *Surface states interactions, non-local physics (∇)*
- *Suppression of Order Parameter: `non-bulk' quasiparticle spectrum, new energy landscape*
- *Confinement driven transitions B-A, A-Normal*
- *Completely new OP configurations, phases with new symmetry properties*

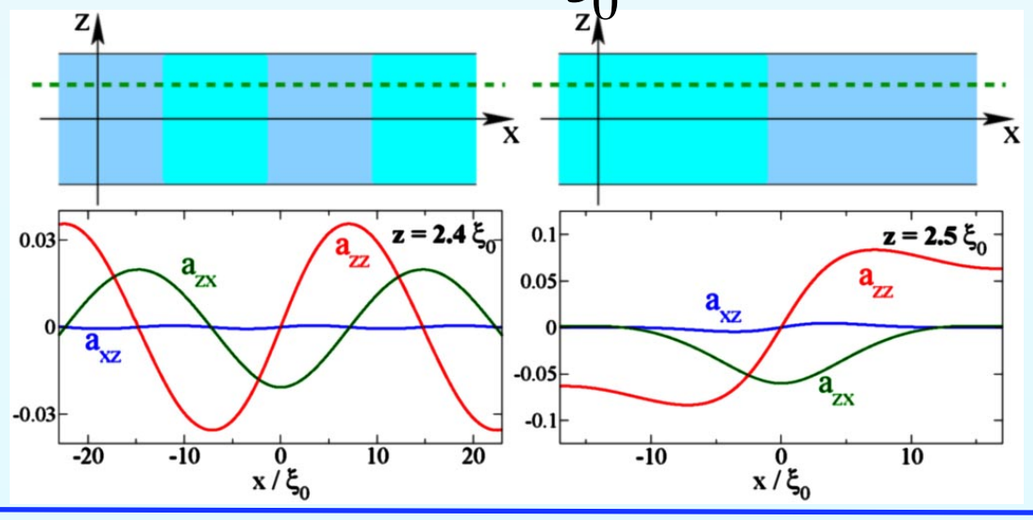
- ***Control** of Geometry & Spatial dimensions:*

- *Insight into pairing symmetries*
- *New phases*
- *New ways to access surface states: study and manipulation*
- *New technological devices*

Superfluid He-3 films

Confinement driven transition : *Stripe* phase





✳ *Transition is driven by re-structure of quasiparticle spectrum due to OP component suppression*

Hara, Nagai, Prog Theor.Phys 1986

✳ *Spontaneously Broken Translation Symmetry in the x-y plane of the film*

- *Competition of gradient and condensation energies*
- *Multiple "domain wall" configurations stabilized by the boundary conditions*

Salomaa, Volovik PRB 1988
Vorontsov, Sauls JLTP 2005

Vorontsov, Sauls, PRL 2007

New phases in other geometries

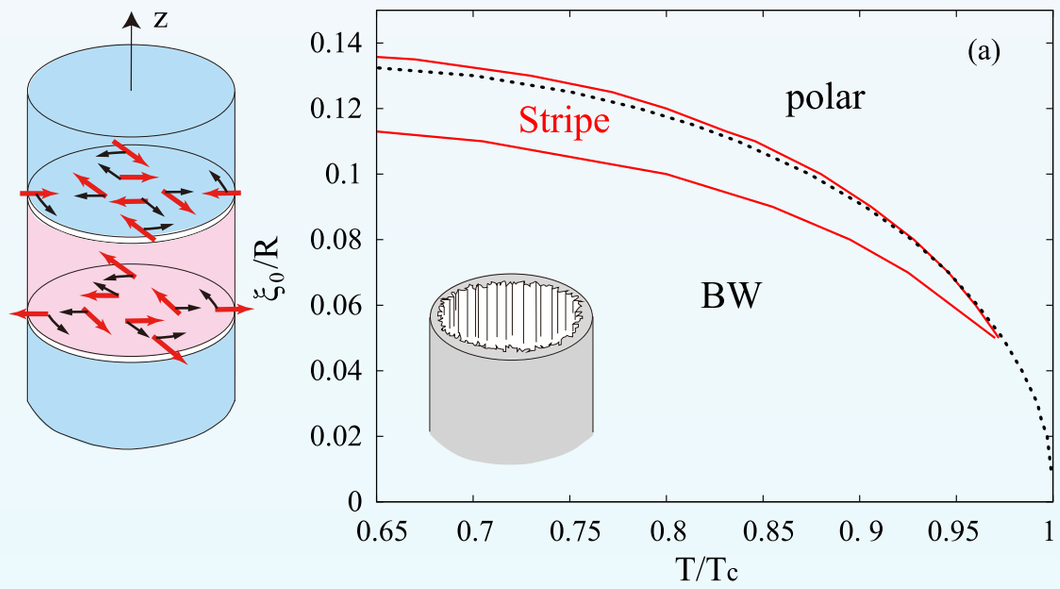
► Chiral ^{3}He-A ribbon

Hao Wu, J. Sauls *QFS'15 talk Aug 15, 9:40am*

↳ *Stripe order in multi-component OP*
↳ *Domain walls with non-trivial bound states and mass currents*

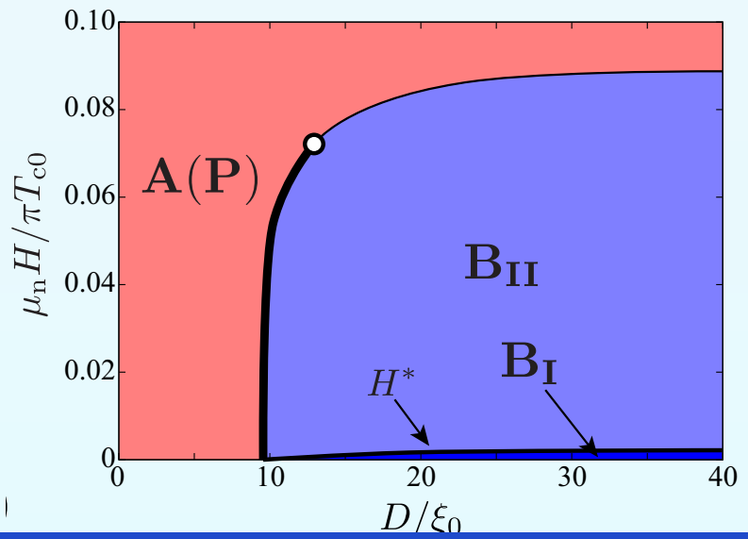
► Cylindrical pores

K. Aoyama, PRB 2014 *QFS'15 talk Aug 14 9am*



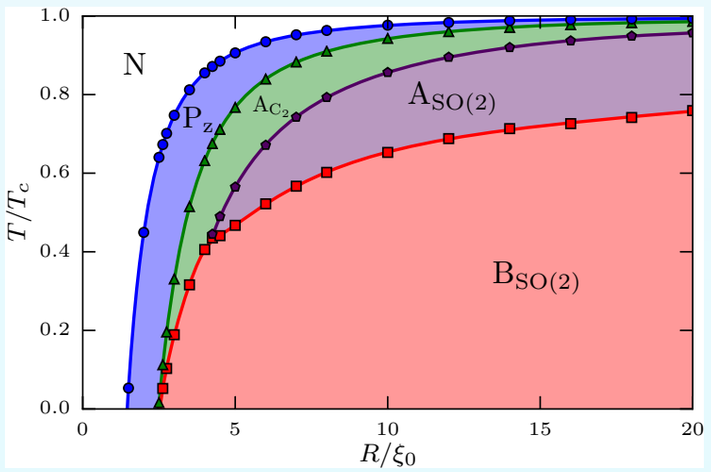
► Superfluid He-3 in magnetic field

T. Mizushima



↳ *Additional symmetries*
↳ *Protected topological phase in small **B***

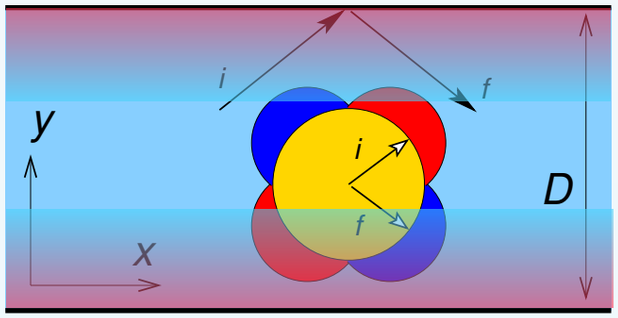
J. Wiman, J. Sauls *QFS'15 posters*



↳ *Several new phases*
↳ *"Spiral" order*

Spontaneous currents

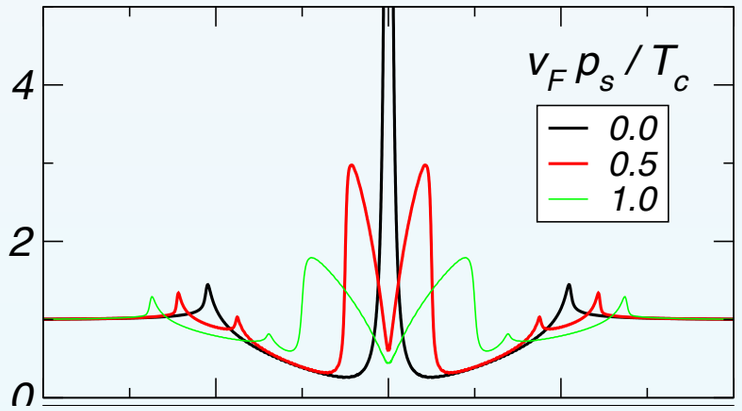
d-wave condensates

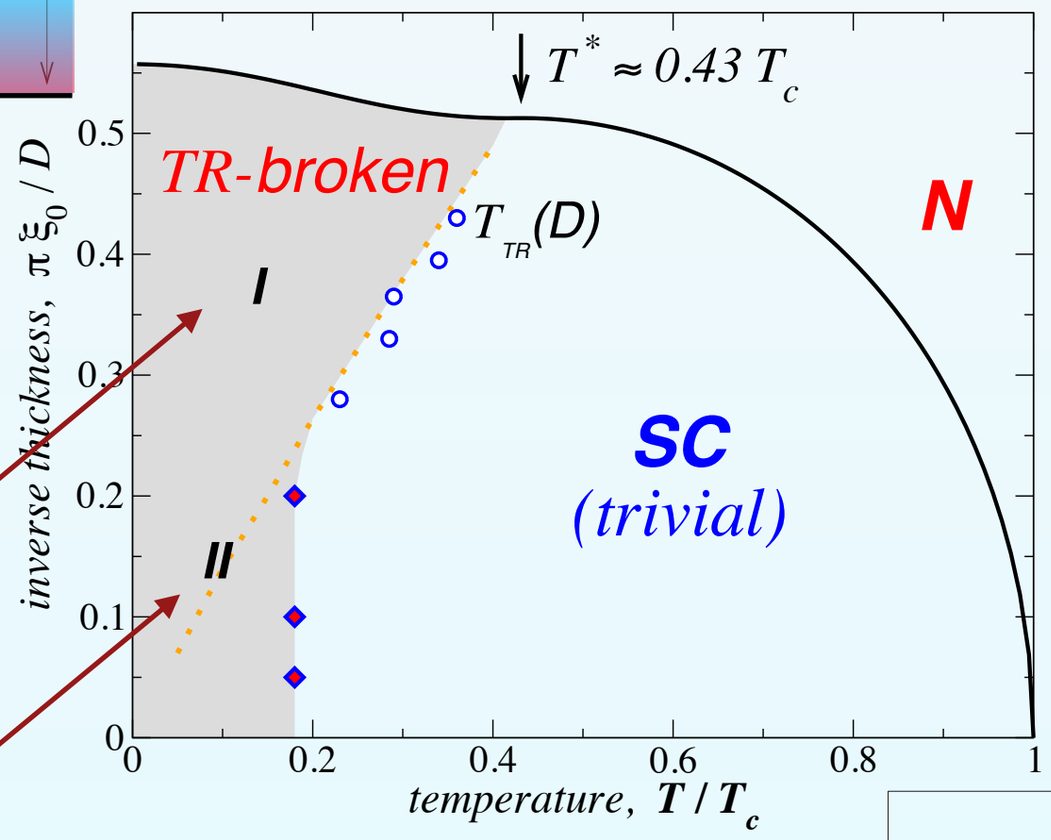


Zero-energy ABS

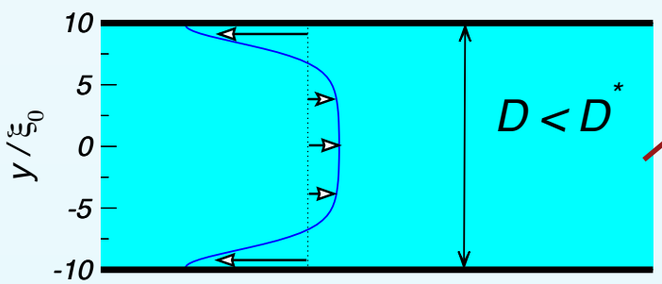
Energy gain due to shift of the bound states from zero energy $\varepsilon \Rightarrow \varepsilon - v_F p_s$

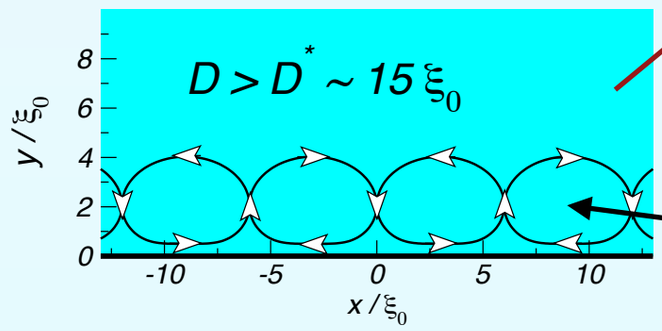
$p_{sy}=\pi/D$





Vorontsov, PRL 2009



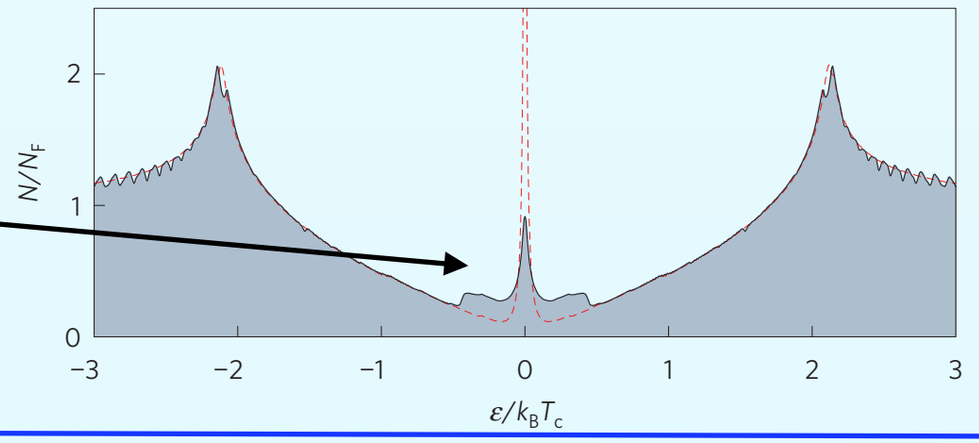


Hakansson et al, Nature Physics 2015

✳ *Spontaneously Broken Time-Reversal symmetry*

non-local ABS interaction

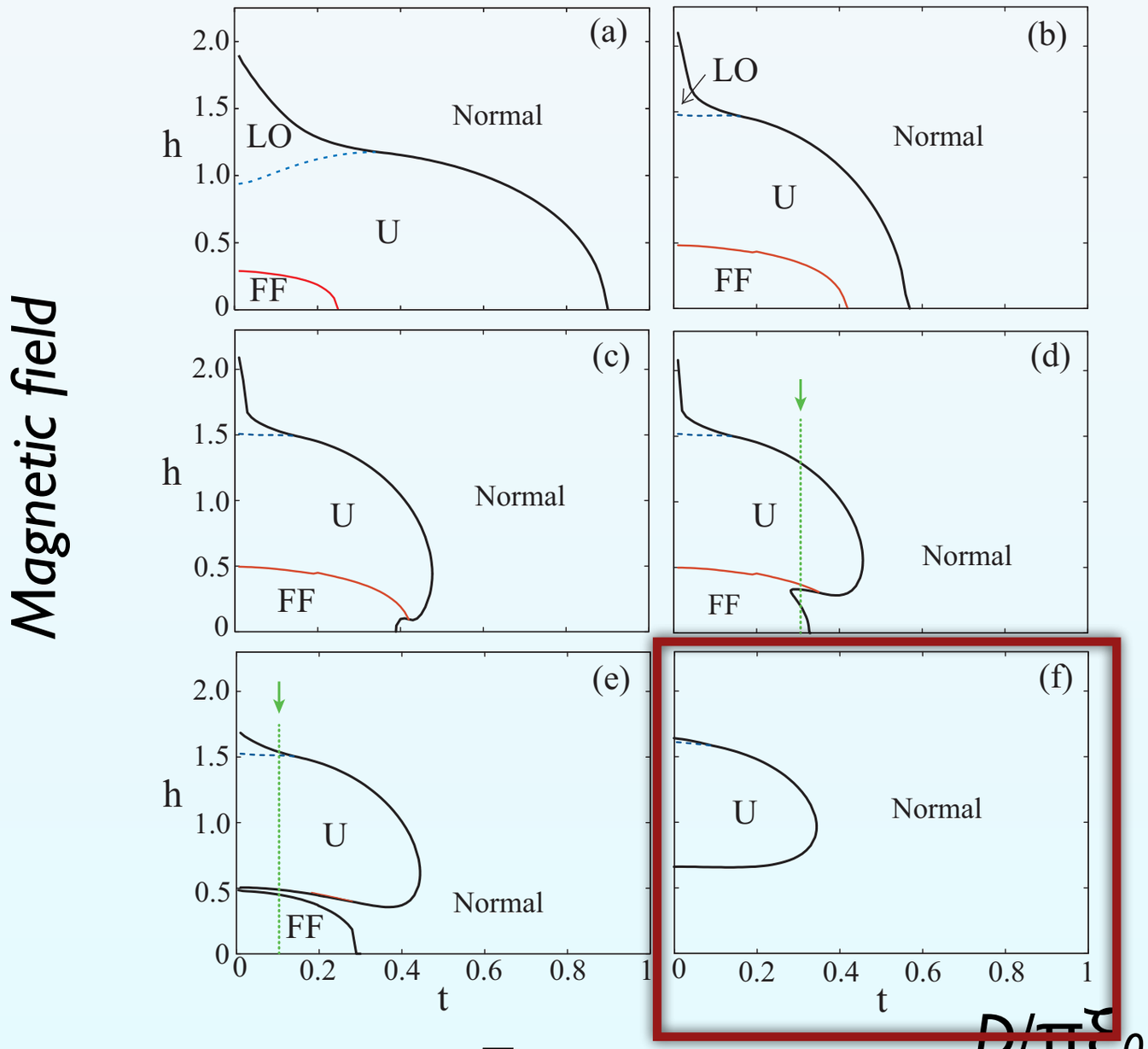
More complicated bound states structure



Re-entrant superconductivity

$D/\pi\xi_0=3.33$

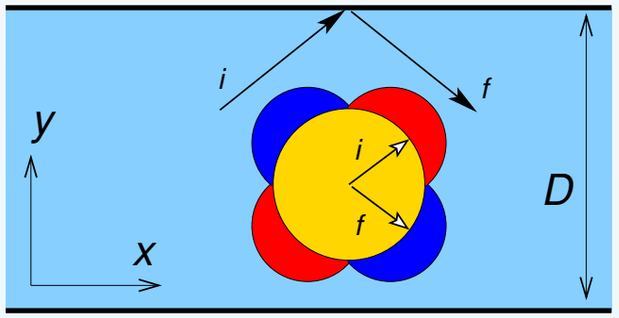
M. Hachiya, PRB 2013



$D/\pi\xi_0=1.79$

Confined geometry with Zeeman magnetic field:

$\varepsilon \Longrightarrow \varepsilon - v_F p_s - \mu_B H$



Zeeman magnetic field:
Fulde-Ferrell-Larkin-Ovchinnikov state

- *Real OP modulations, Currents, 'Uniform' phases*
- *Re-entrant superconductivity*
- *Induced by magnetic-field*

Grand Challenge 1

New phases are everywhere! - *WHERE are they?*

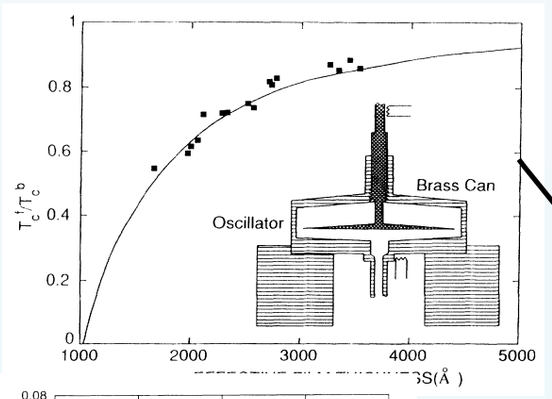
Prediction of signatures of bound states (surfaces and domain walls) and of new phases :

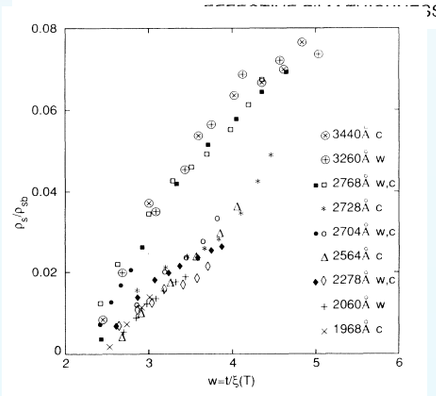
magnetic properties
connection to Majorana and Weyl quasiparticles
transport & non-equilibrium properties
condensate dynamics

Experimental challenges and development of new techniques: *low T, small volume, high B, surface physics*

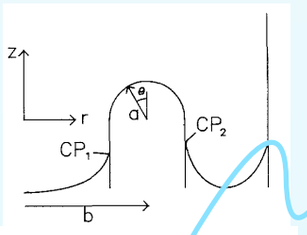
^{3}He thin films: experiments

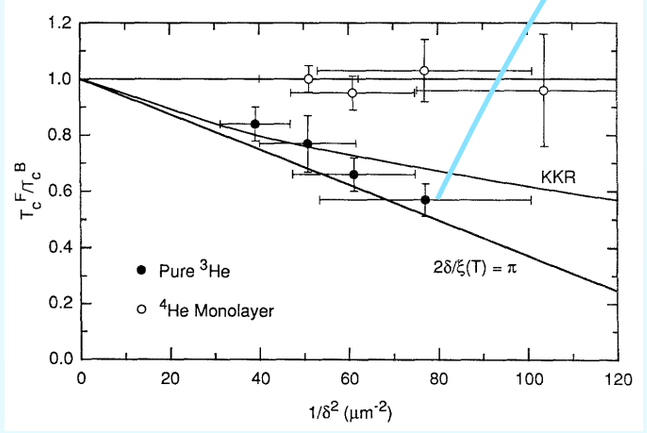
Xu, Crooker 1990



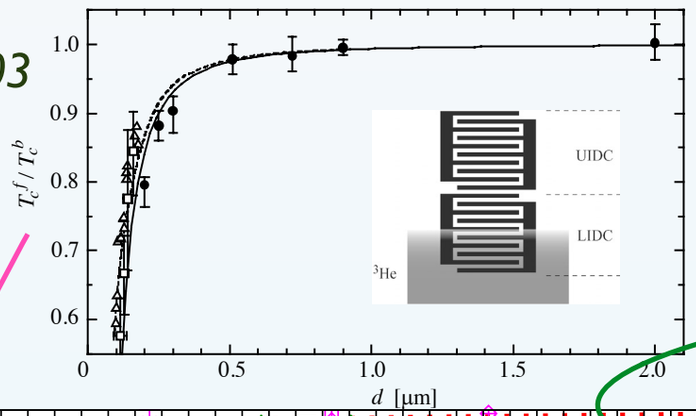


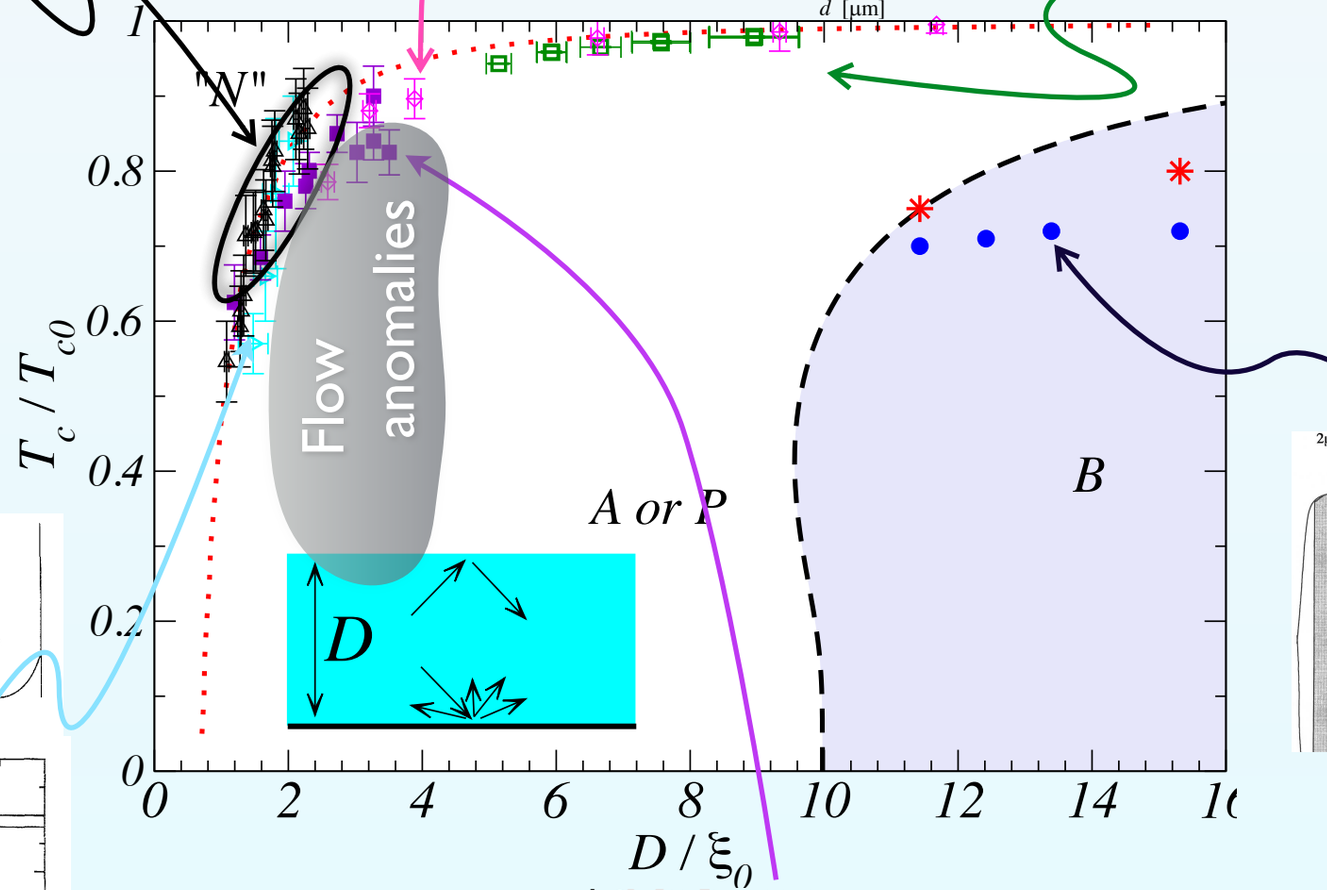
Steel et al 1994



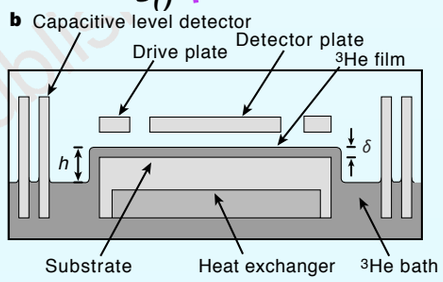


Saitoh et al 2003

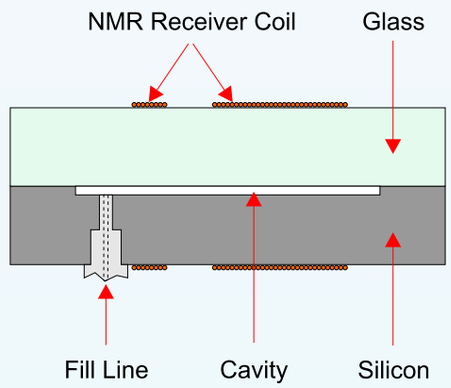




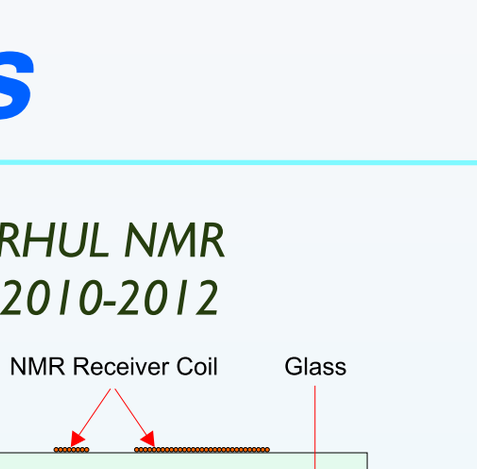
Schechter at al 1998 3rd sound



RHUL NMR 2010-2012



Kawae et al NMR 1998



Flow anomalies: below ~4ξ0
- Davis 1988
- Steel 1994
-Schechter 1998

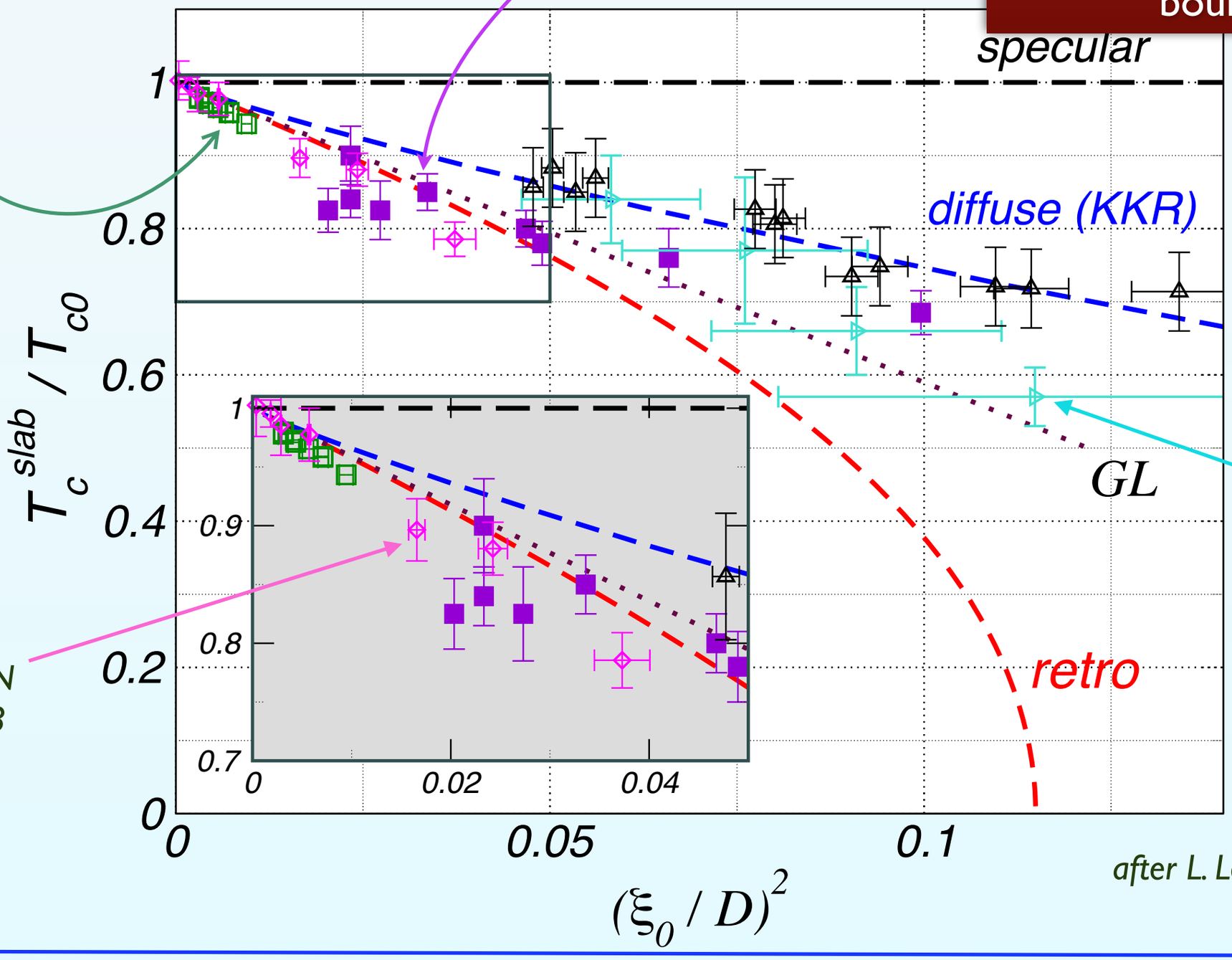
T_c suppression

Recent experiments:
Stronger suppression of Superfluidity than allowed by most pairbreaking boundary condition

Berkley 1998
RIKEN 2003
RHUL 2012

RHUL NMR
Levitin et al
2010-2012

Berkeley, 3rd sound
Schechter at al
1998

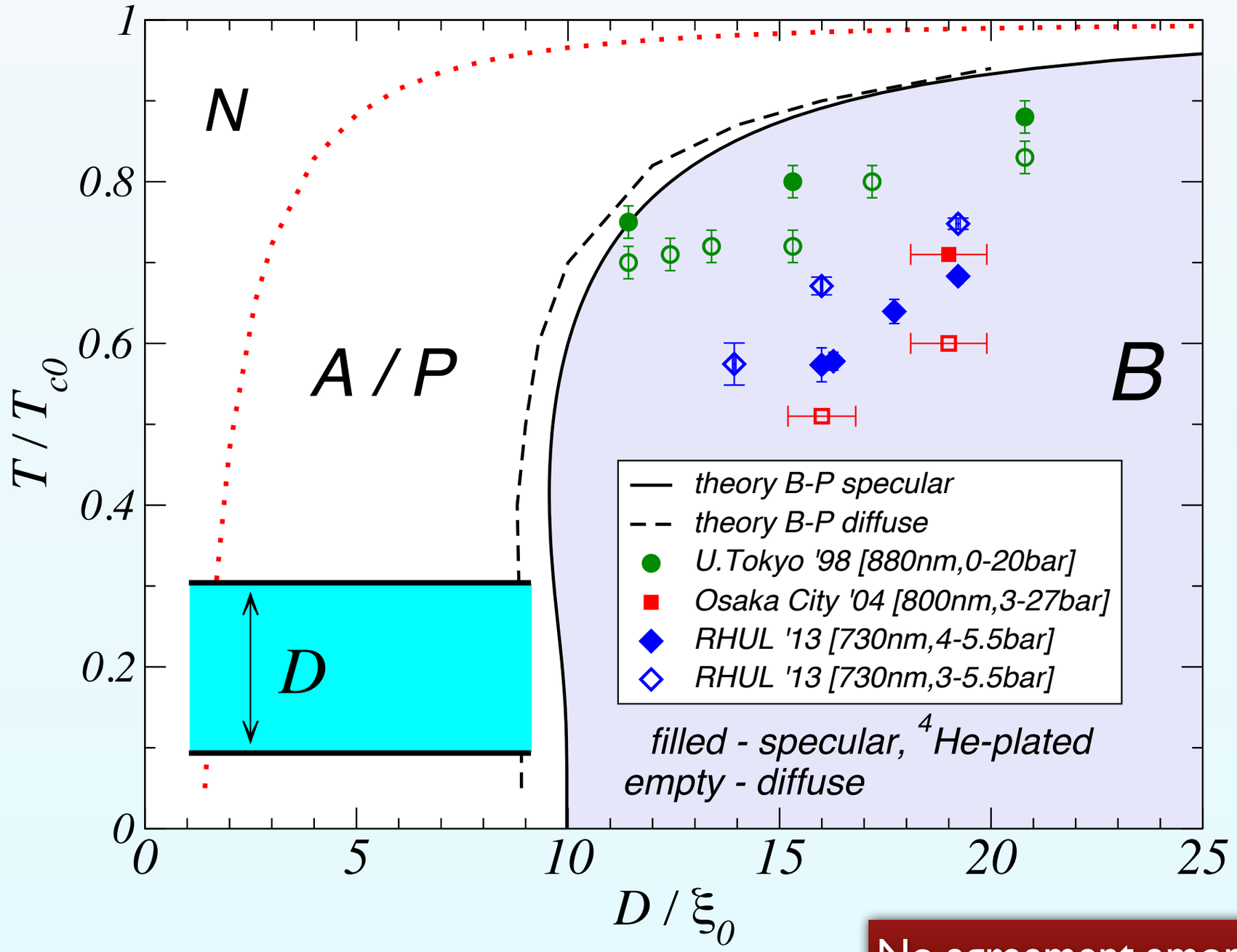


Queen's,
Steel et al
1994

RIKEN
2003

after L. Levitin et al, Science 2013

A-B transition: experiments

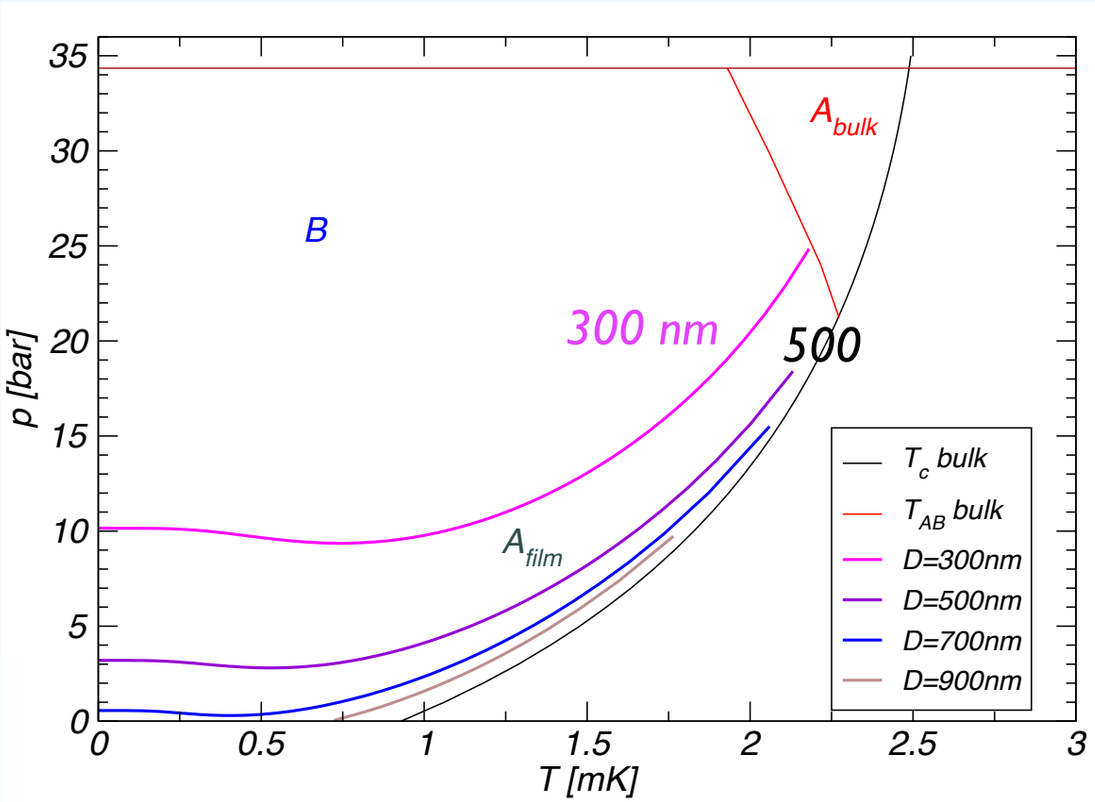


No agreement among measurements

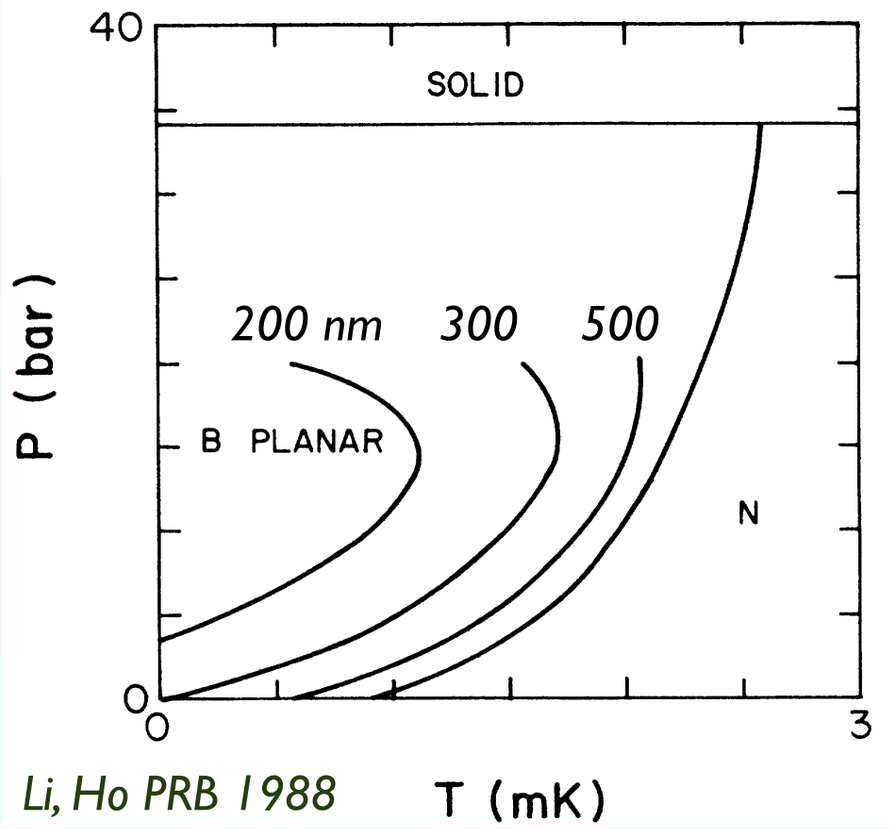
A-B transition: theory

No agreement in theory

Quasiclassical weak coupling



Ginzburg-Landau theory



Li, Ho PRB 1988

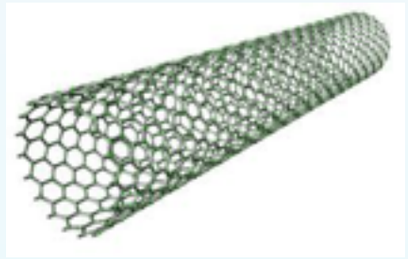
Grand Challenge 2

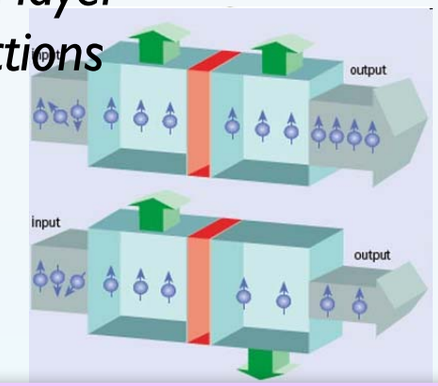
- ***Need for development of numerical approaches to model complex systems***
- ***Joint effort of several groups***

Broader connections

Nano-world:

- *enhanced role of surface atomic layer*
- *strongly modified DOS + interactions*
- *quantum discrete levels*
- *coherence effects*

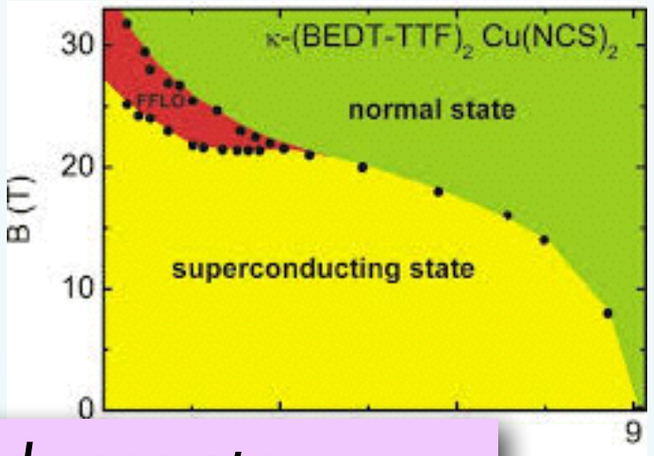


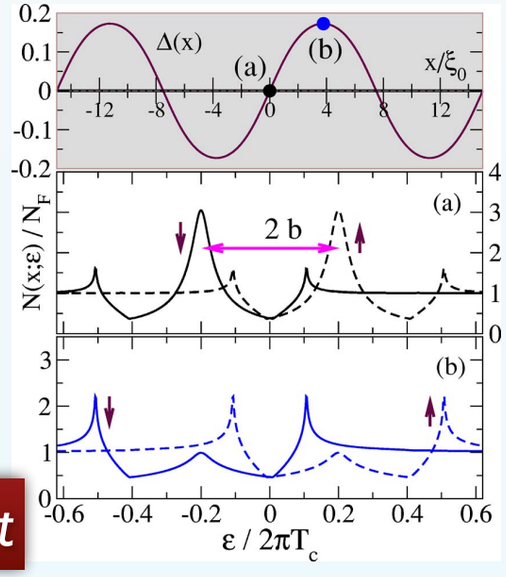


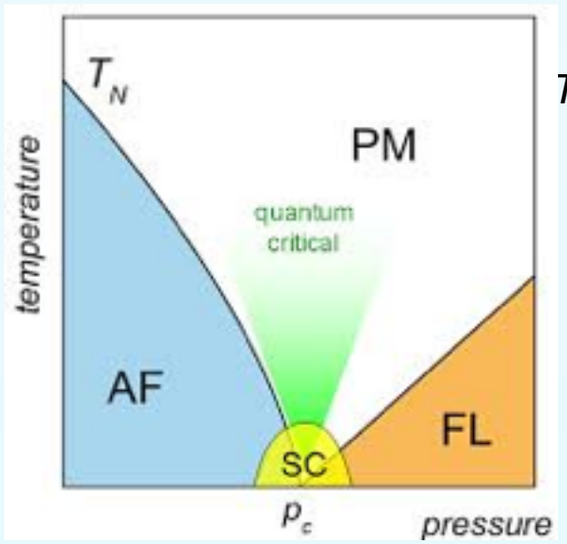
★ *physics in restricted geometry*
★ *non-uniform states: FFLO*
★ *confinement-driven transitions: QPT*
★ *thin films of topological insulators*

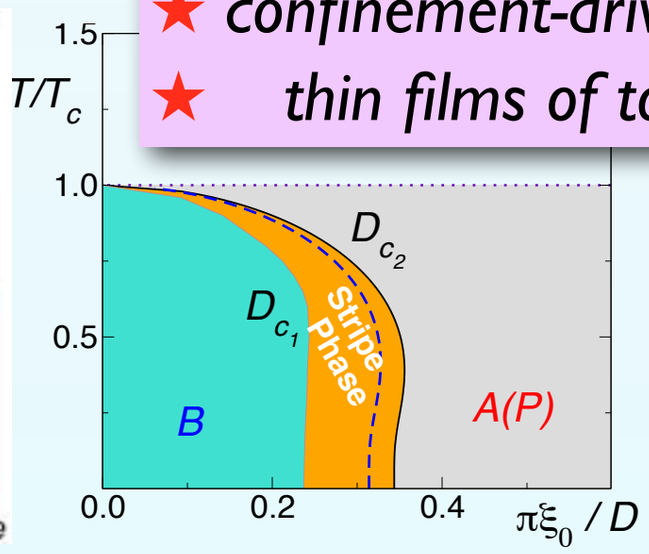
1964-present

Mayaffre et al 2015, QFS'15 talk Aug 11, 11am

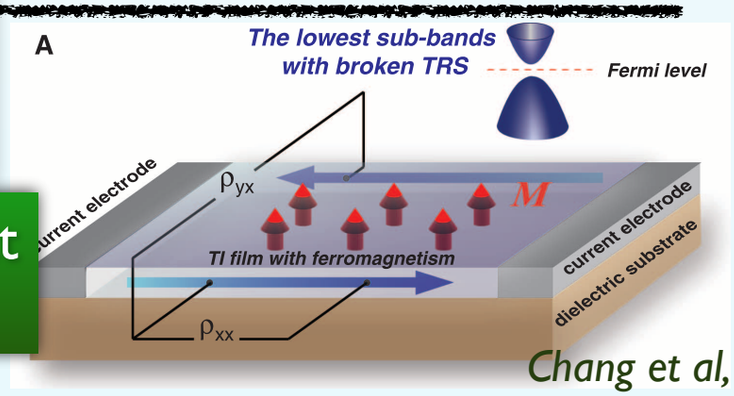




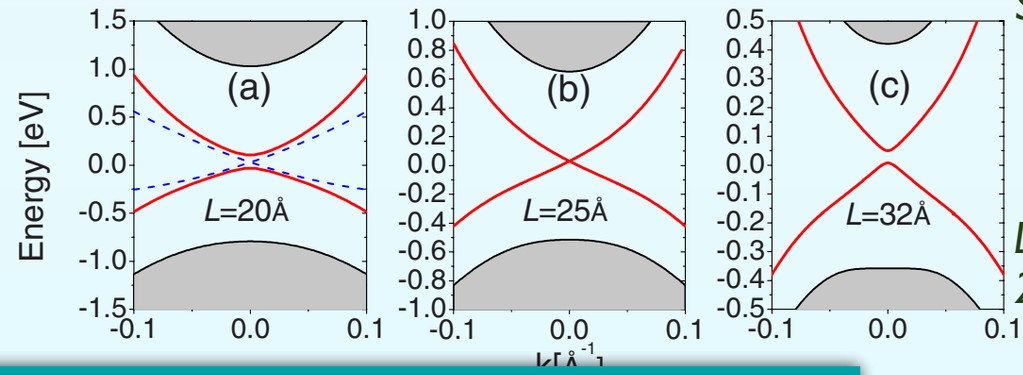




Anomalous Hall Effect in Magnetic TI



Chang et al, Science 2013



Lu et al, PRB 2010

Interaction of Dirac states in thin films

Quantum Critical Point:

- *change of ground state by external parameter*
- *appearance of new phases near QCP*

Vision for theory of restricted geometries

- *Superfluid He-3 is a model of unconventional pairing*
  - *1.1 9 x 2 order parameter components*
  - *1.2 symmetry and topology playground*
- ***Grand Challenge**: understanding surface states in confined geometry*
  - *2.1 properties of bound states*
  - *2.2 interactions with fields*
  - *2.3 connection to topological properties*
- ***Grand Challenge**: find agreement between theory and experiment (thin films)*
  - *3.1 numerical modeling - combined effort*
  - *3.2 connection to experiment*
- *Impact on various fields*
  - *4.1 States in confinement including FFLO*
  - *4.2 QPT and topological materials*

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