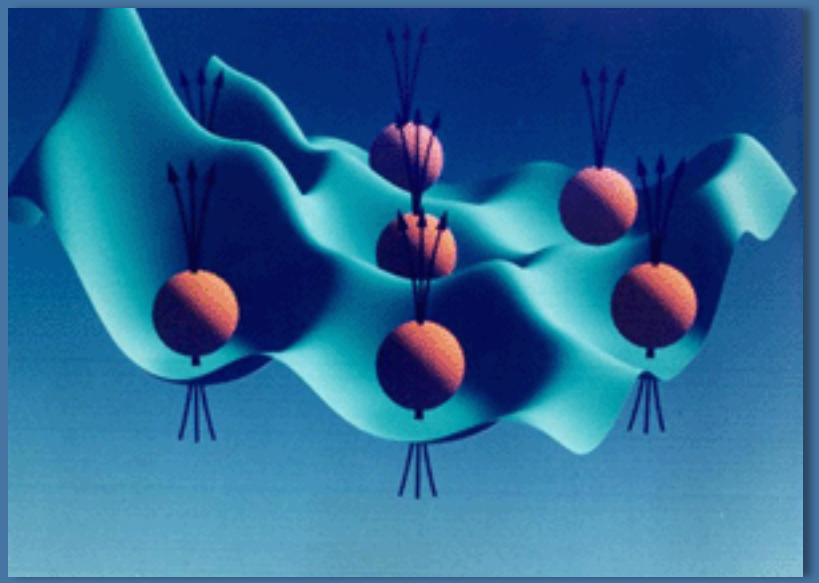
Engineering Quantum Matter: From Superfluids to Low-Dimensional Electrons



Johannes Pollanen

MICHIGAN STATE UNIVERSITY

IQIM
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

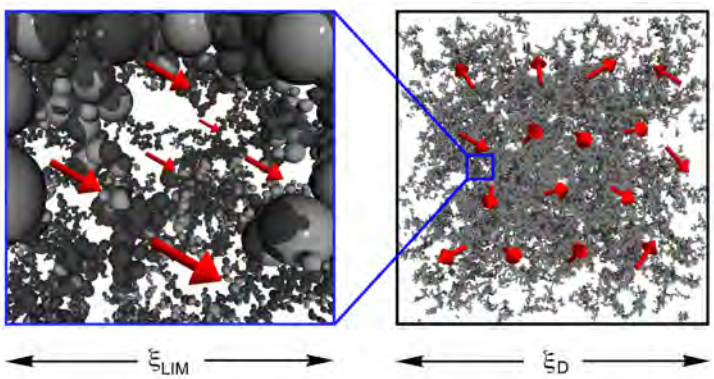
Many-body quantum engineering

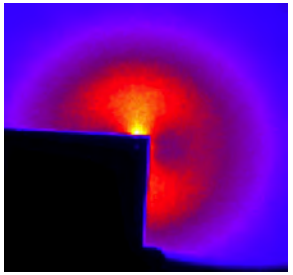
NORTHWESTERN UNIVERSITY

"Disorder" + quantum fluids

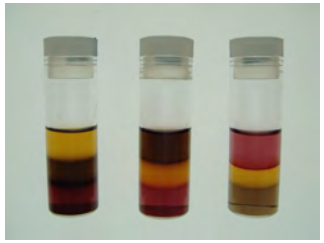
– New chiral superfluid phases of ^{3}He

– Superfluid glass state





– Aerogel microstructure x-rays + optics

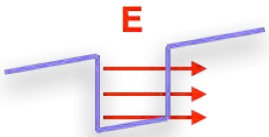


– nanoparticle aerogel composites

Electrons in flatland

– Demag cooling 2-d electrons

– Pulsed SAW + 2-d electrons



– QW symmetry + quantum Hall nematic phases

– 2-d e^- w/ tunable interaction (GaAs)

– graphene

Outline

Creating novel quantum matter:

– Engineering superfluid states with disorder

Controlling quantum matter:

– 2 dimensional electrons with tunable interactions

What does the future hold?

– Create and control hybrid quantum systems:

Electrons on helium + nano-scale devices & topological states of matter

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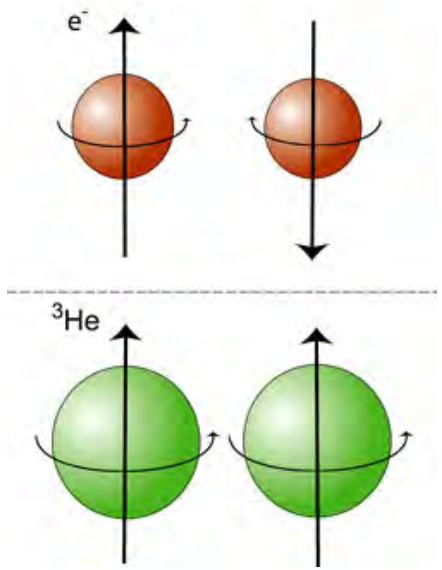
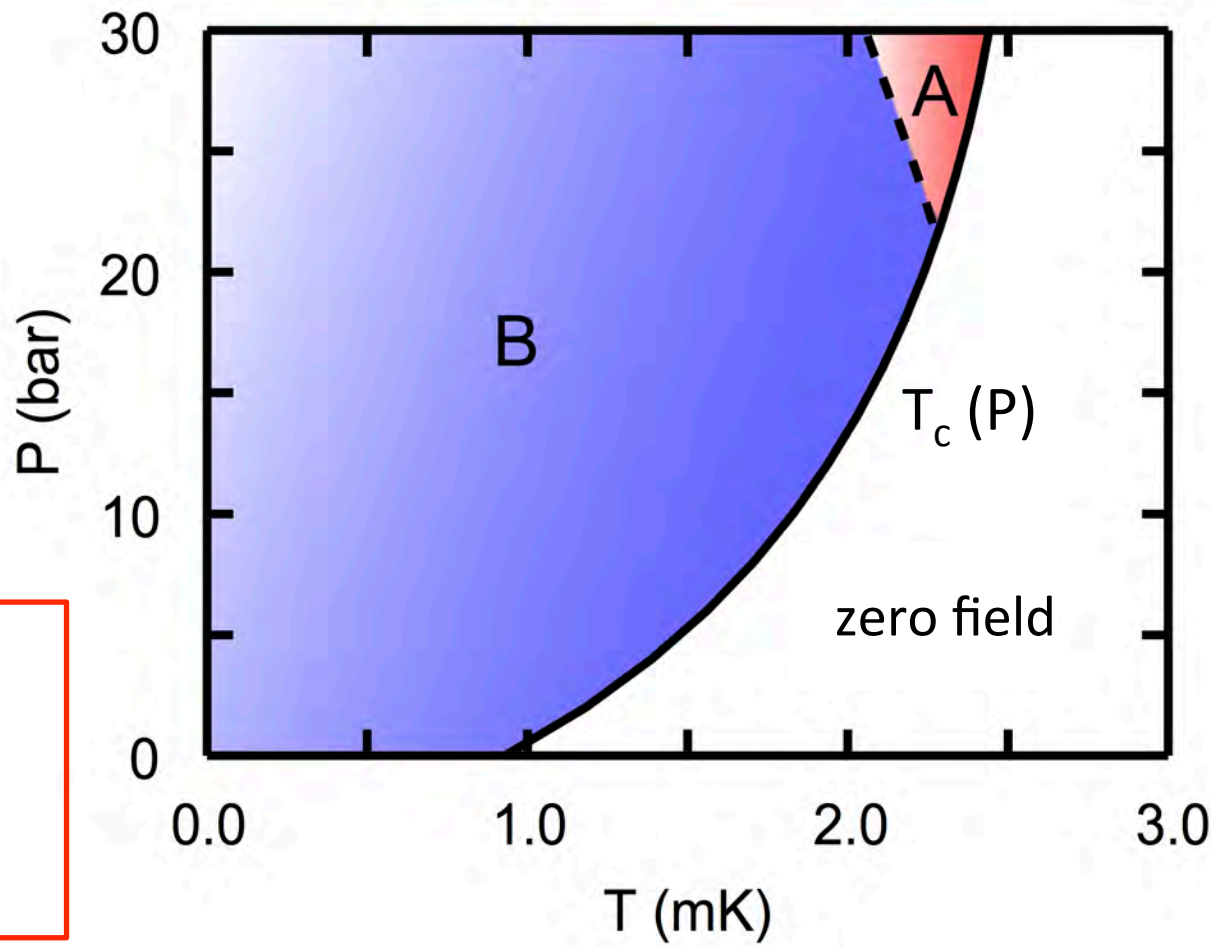
Superfluid of ^{3}He fermion pairs



The Royal Swedish Academy of Sciences

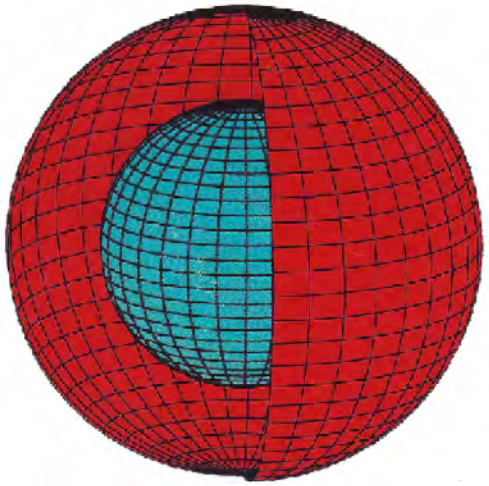
Ultra clean quantum fluid!



$L = 1$ orbital

$S = 1$ nuclear spin

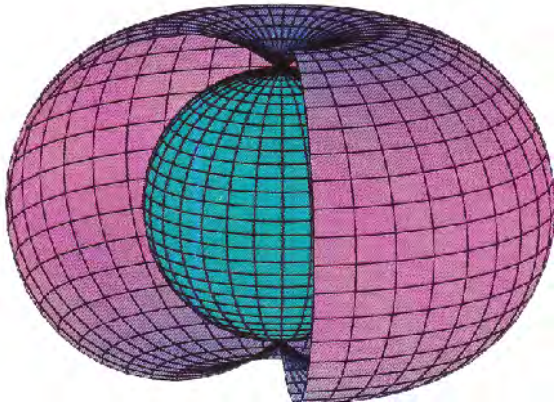
B and A phases



<u>B–phase</u>:

orbitally **isotropic** state

spin structure: $|\uparrow\uparrow\rangle \quad |\downarrow\downarrow\rangle \quad |\uparrow\downarrow + \downarrow\uparrow\rangle$



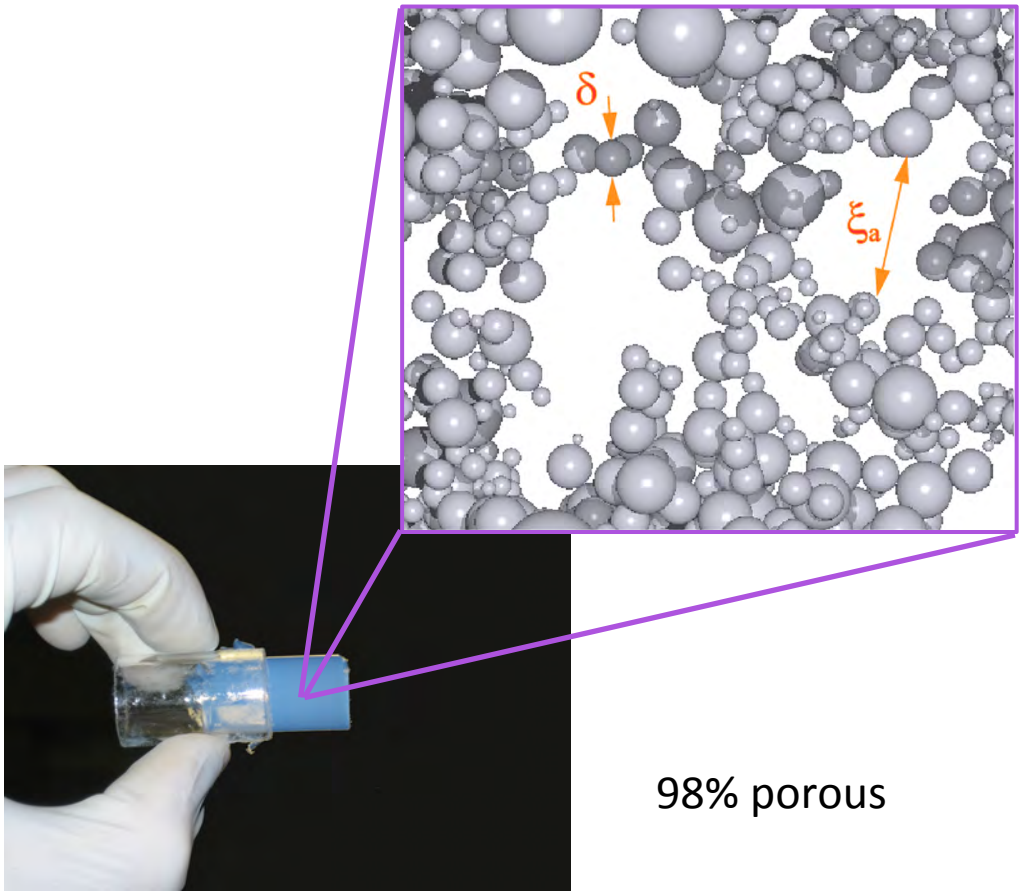
<u>A–phase</u>: $p_x + ip_y$

orbitally **anisotropic** state (chiral)

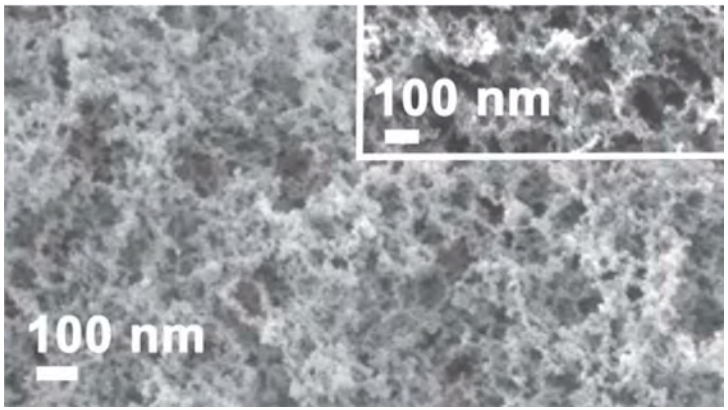
spin structure: $|\uparrow\uparrow\rangle \quad |\downarrow\downarrow\rangle$

Silica aerogel: quenched disorder

Kim *et al.*, Small **7**, 2568 (2011)



98% porous



- silica particles:

$$\delta \approx 3 - 5\, nm$$

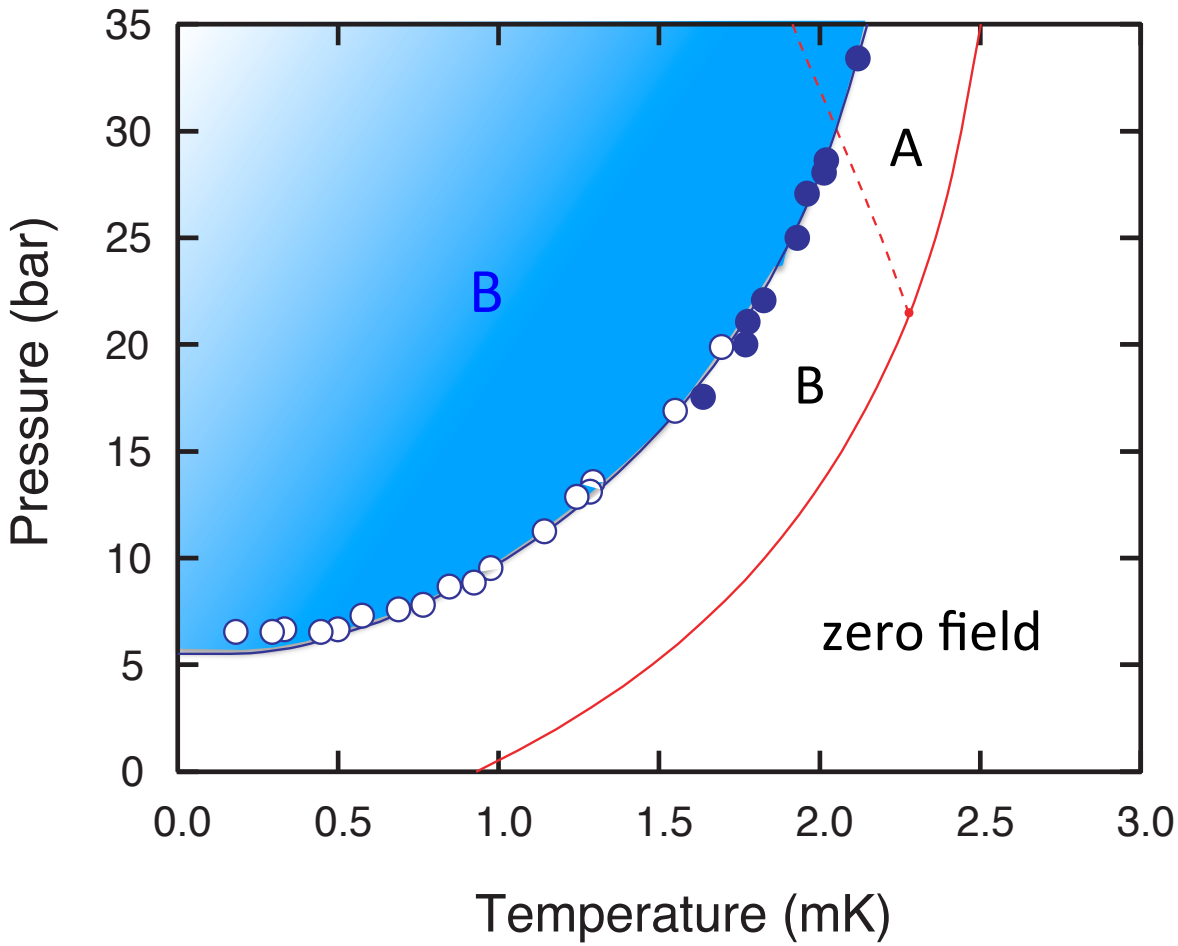
- correlation length:

$$\xi_a \sim 10\, nm$$

- superfluid pair size:

$$\xi \simeq 20 - 80\, nm$$

Superfluid ^{3}He in 98% porous aerogel



suppressed superfluidity

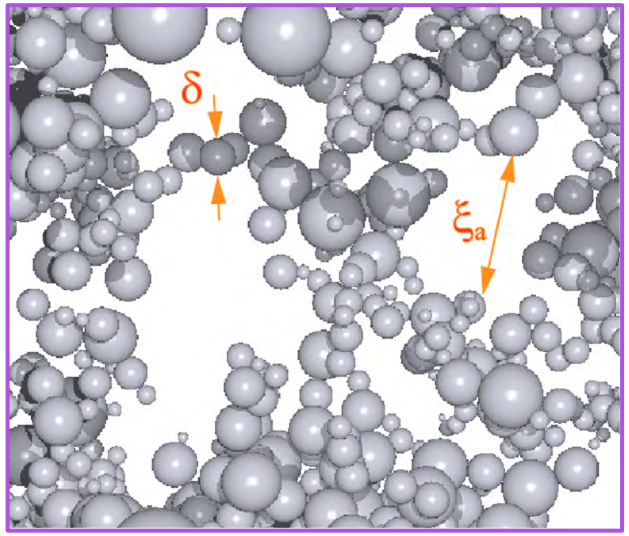
isotropic scattering favors **isotropic** states

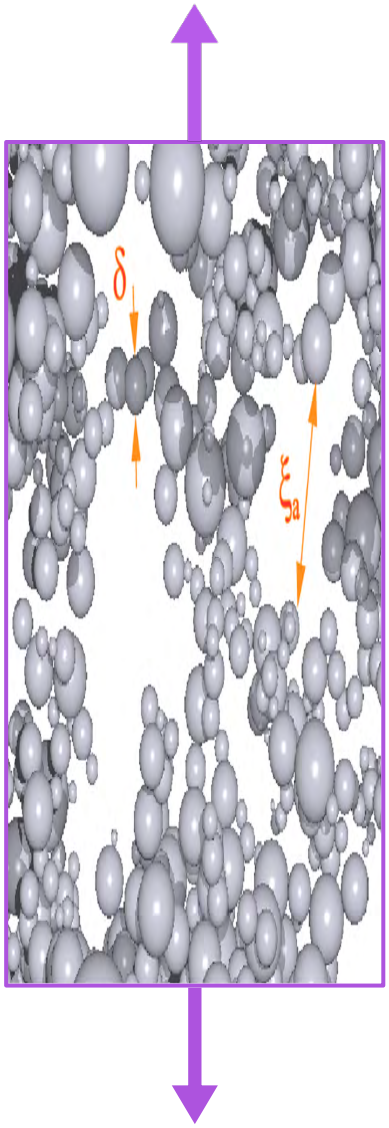
What about **anisotropic** scattering?

Thuneberg *et al.*, PRL **80**, 2861 (1998)

Vicente *et al.*, PRB **72**, 075301 (2005)
Aoyama & Ikeda., PRB **76**, 104512 (2007)

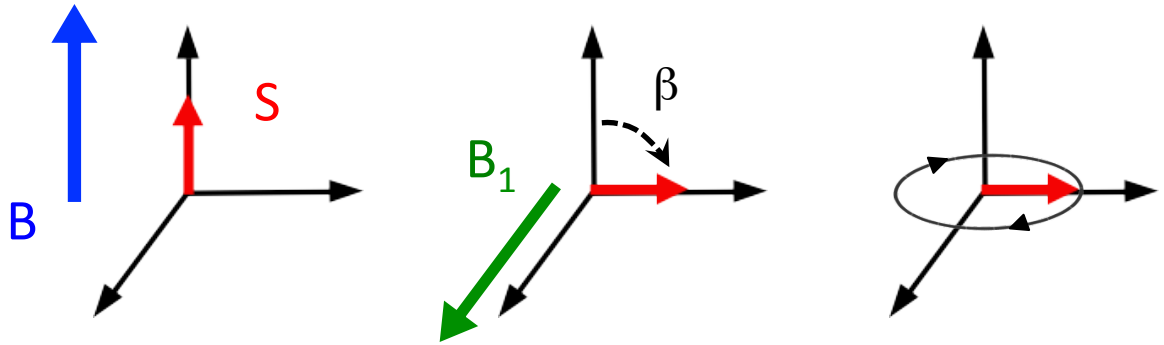
Anisotropy: “stretched” aerogel





Pollanen *et al*., JNCS **354**, 4668 (2008)

Experiment: NMR



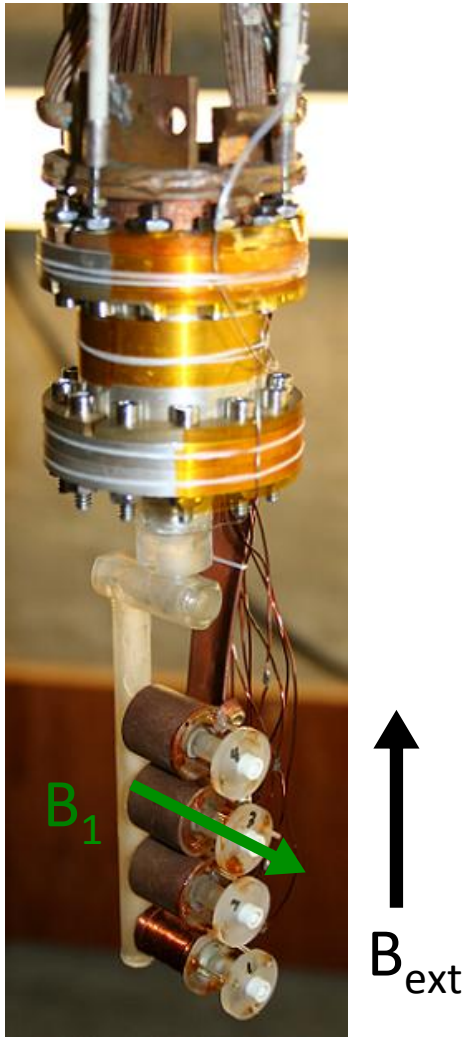
$$\omega = \gamma B$$

$$B = B_{ext} + \boxed{B_{sf}}$$

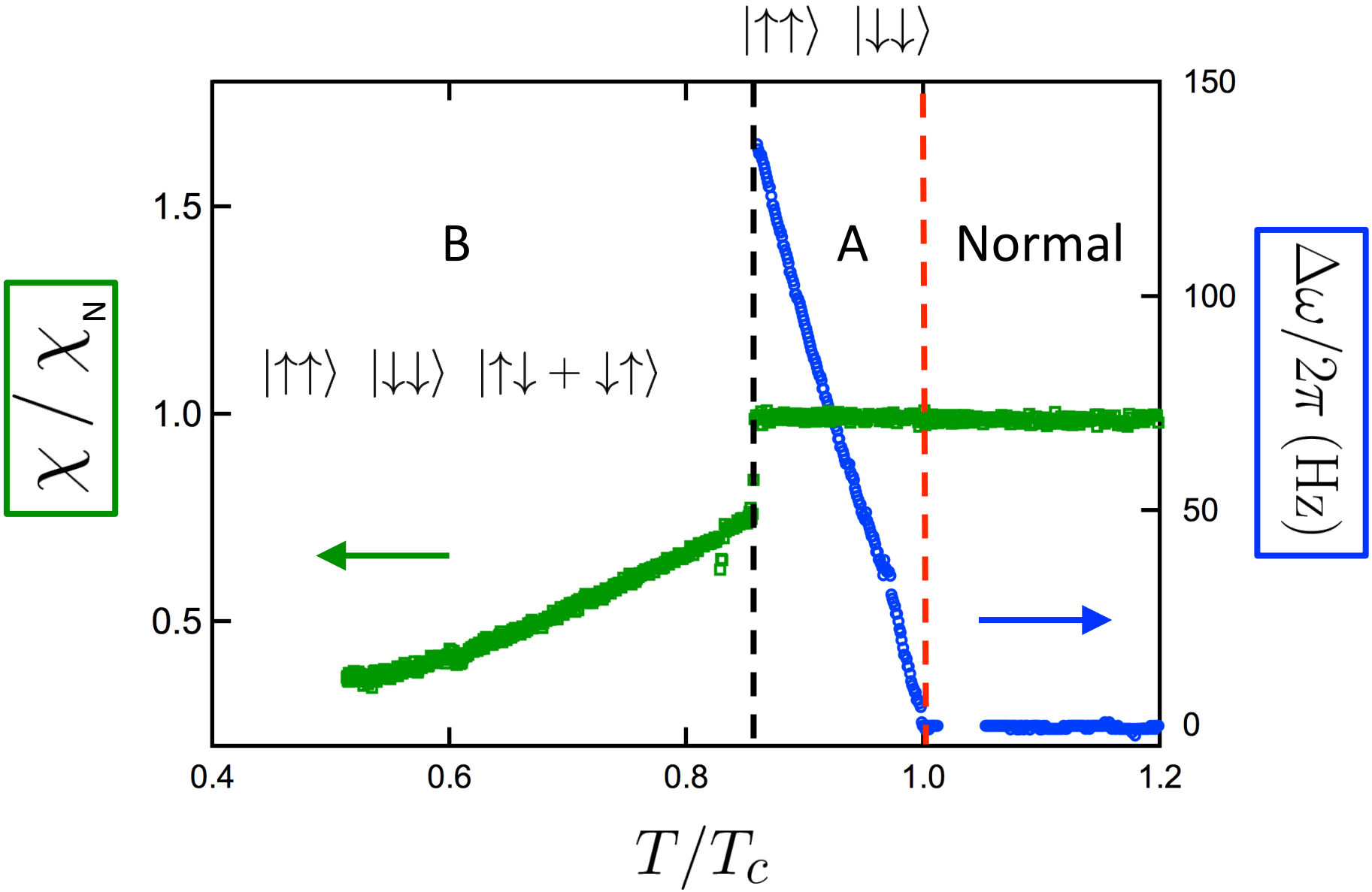
(P, T, β)

$$\boxed{\chi = \frac{\partial M}{\partial B}}$$

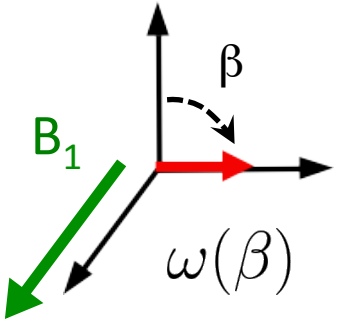
$$|\uparrow\uparrow\rangle \quad |\downarrow\downarrow\rangle \quad |\uparrow\downarrow + \downarrow\uparrow\rangle$$

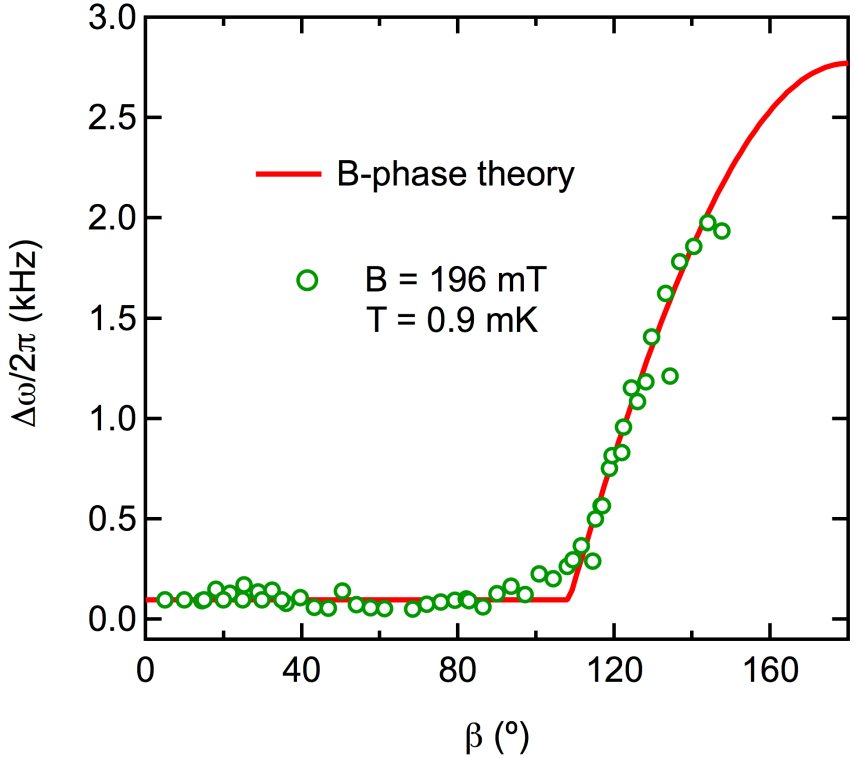


NMR **isotropic** aerogel



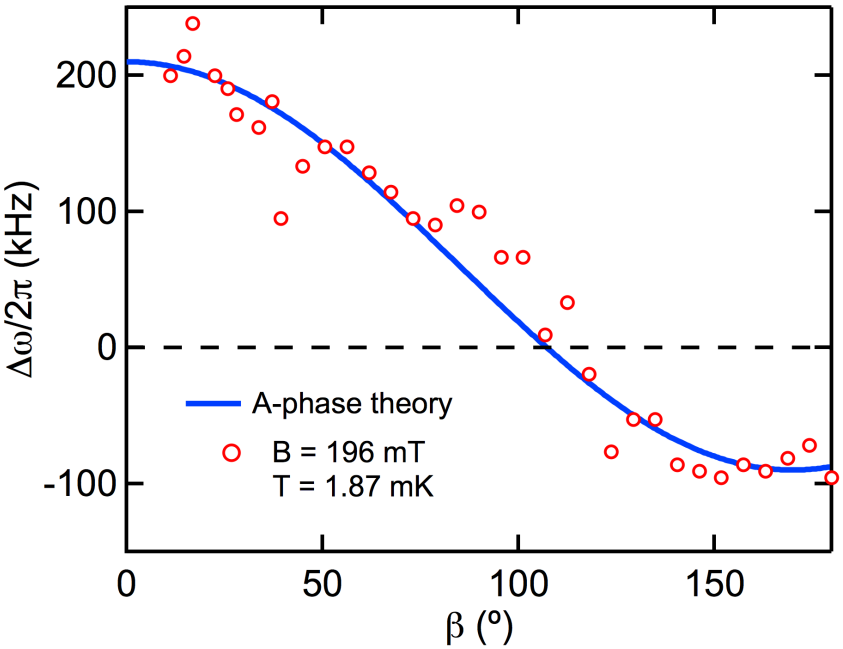
β-dependence: **isotropic** aerogel





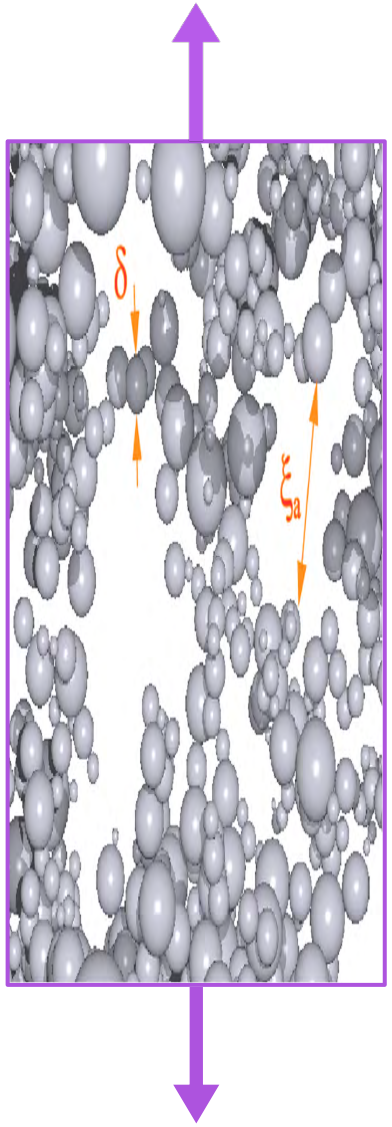
$$\Delta\omega = -\frac{4}{15}\frac{\Omega_B^2}{\omega_L}(1 + 4\cos\beta)$$

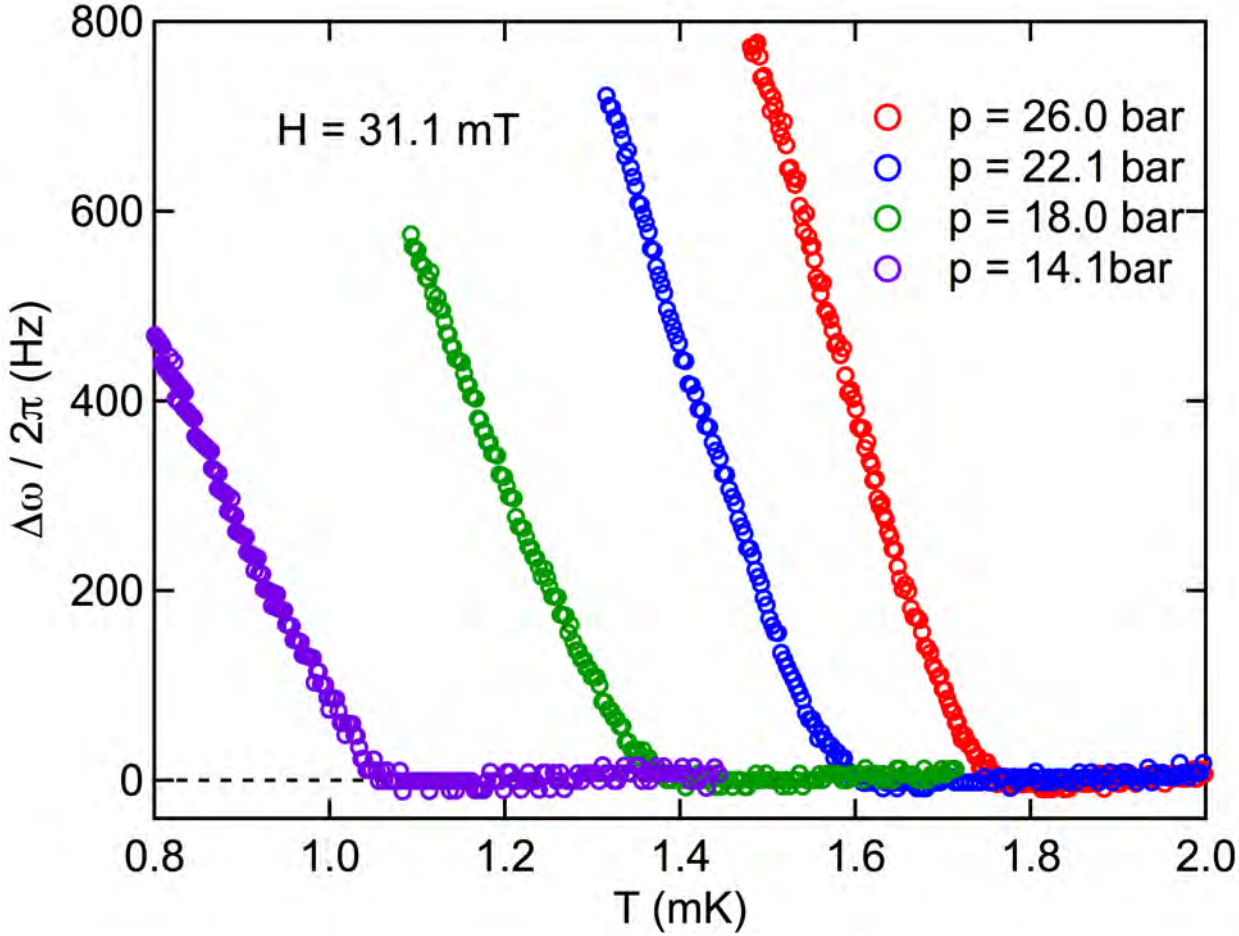
Pollanen *et al.*, PRL **107**, 195301 (2011)



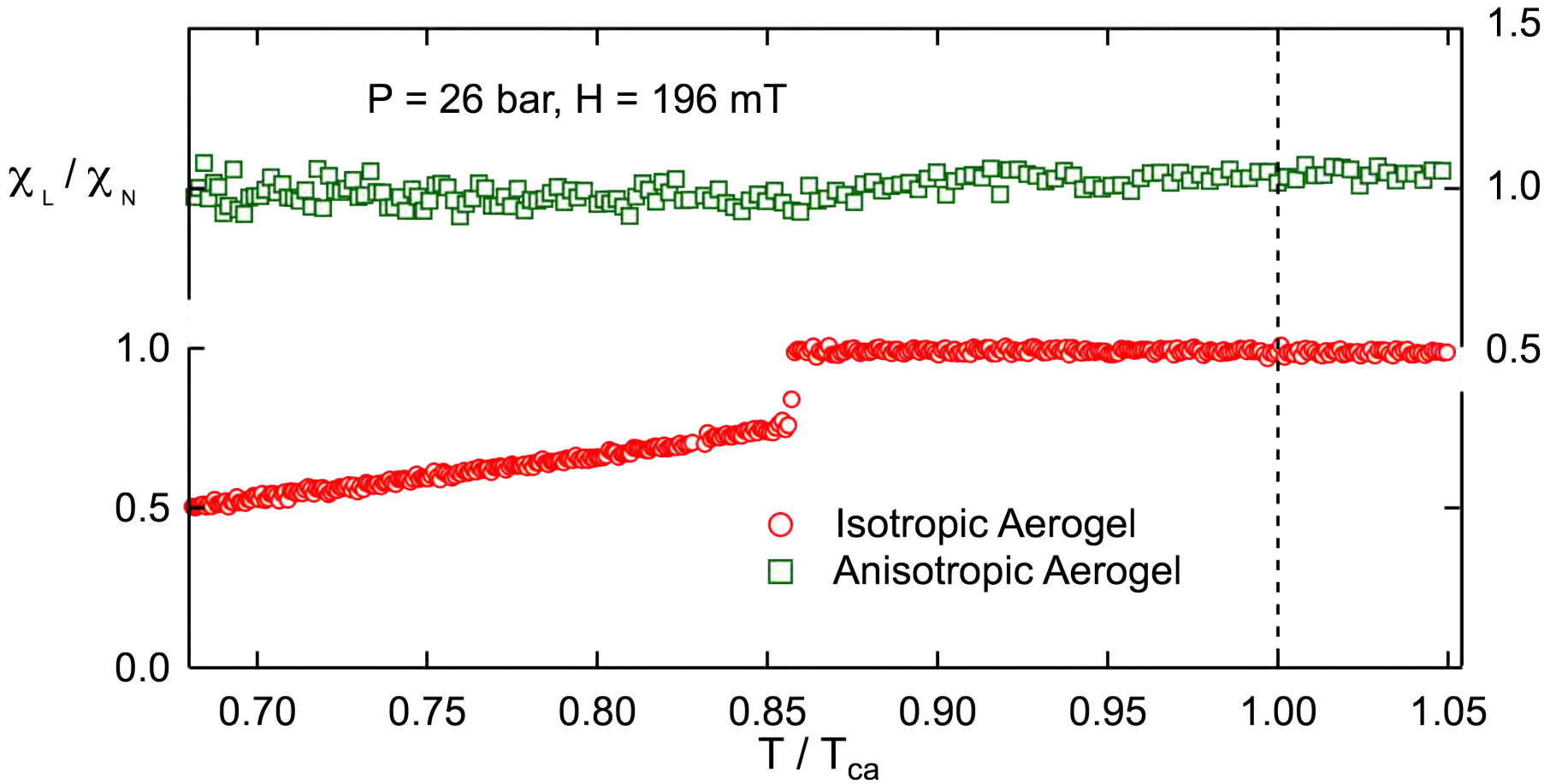
$$\Delta\omega = \frac{1}{4}\frac{\Omega_A^2}{2\omega_L}(3\cos\beta + 1)$$

Anisotropic aerogel: frequency shift



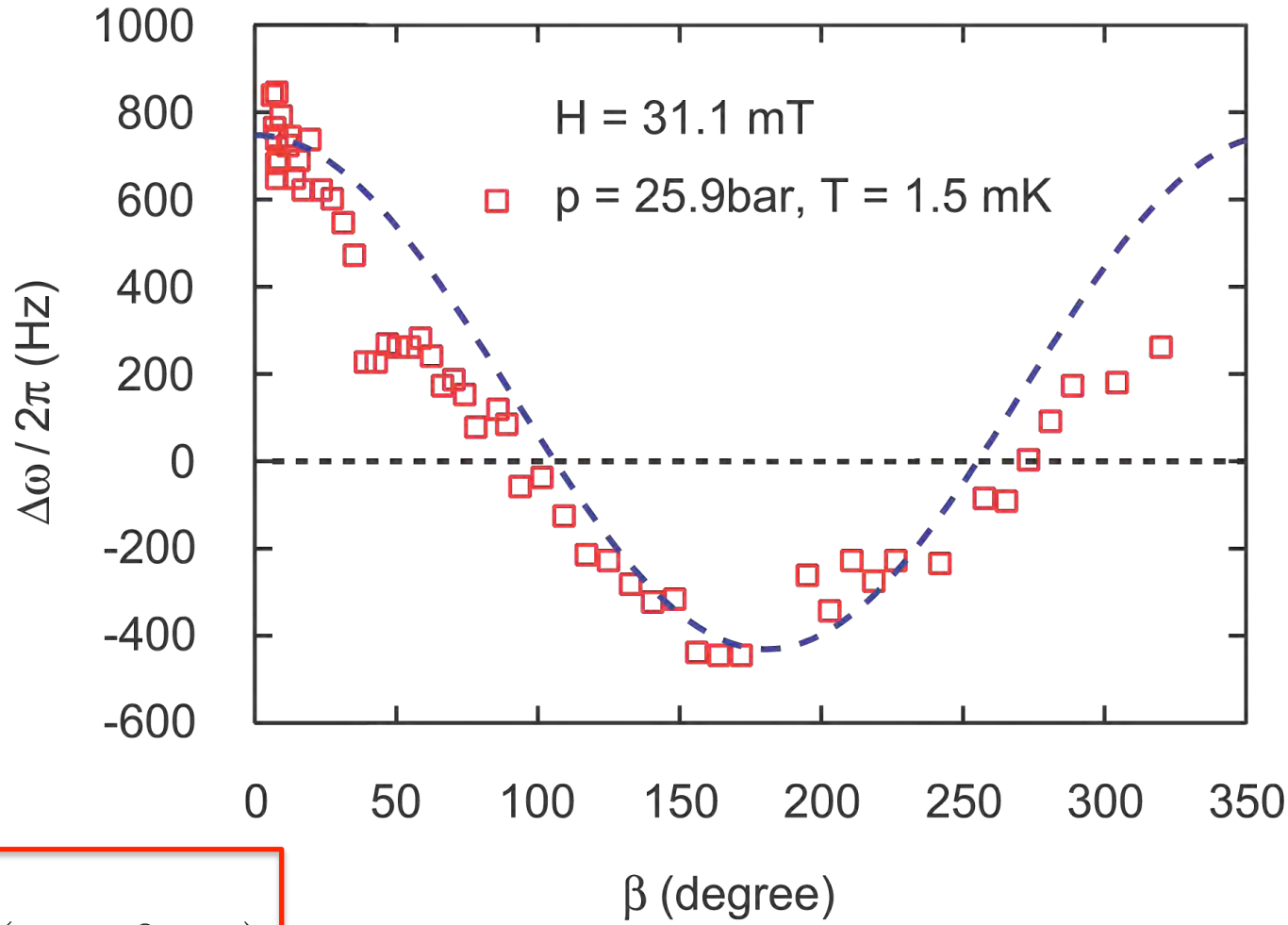


Anisotropic aerogel: susceptibility



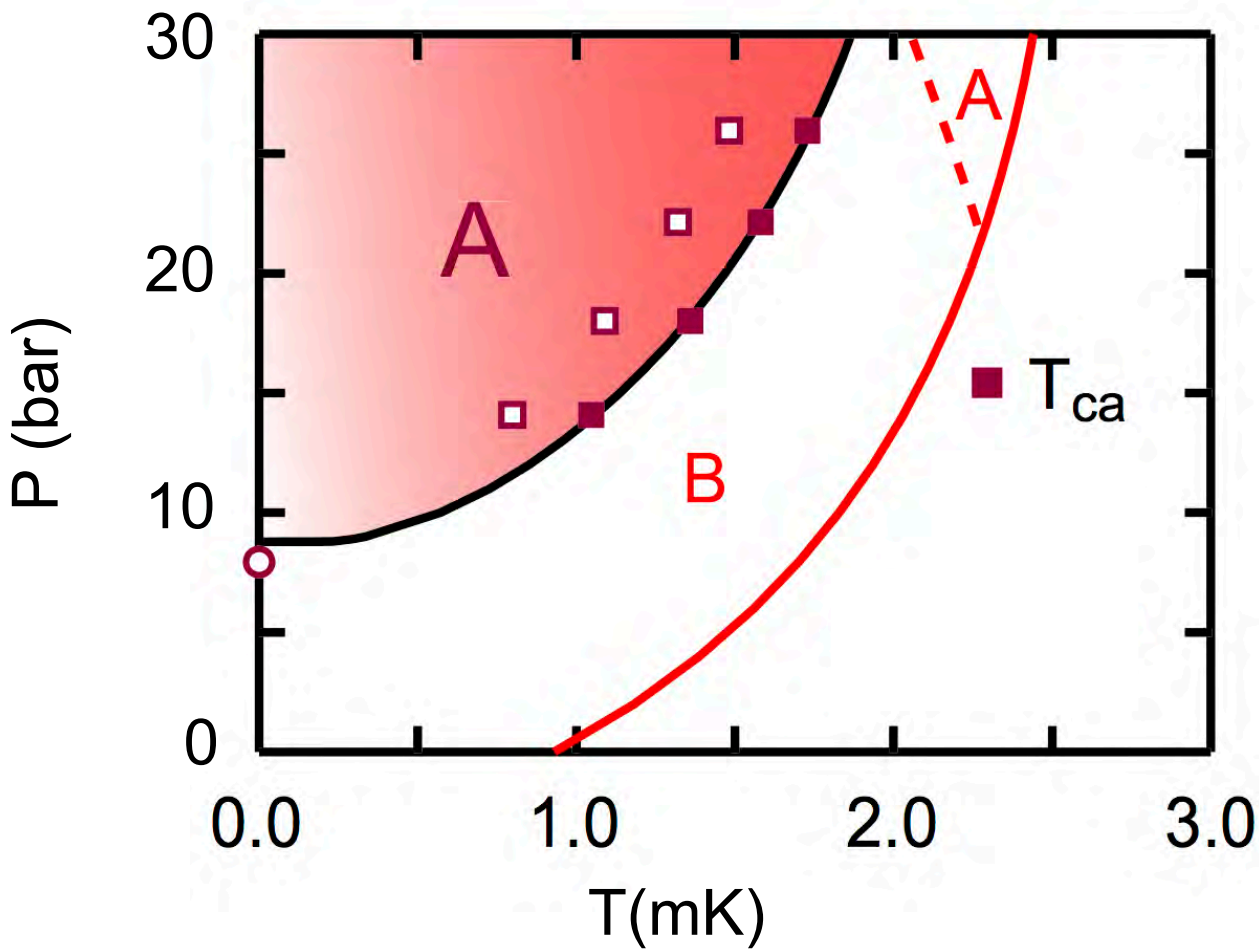
$|\uparrow\uparrow\rangle \quad |\downarrow\downarrow\rangle$

Anisotropic aerogel: frequency shifts



$$\Delta\omega = \frac{1}{4}\frac{\Omega_A^2}{2\omega_L}\left(3\cos\beta + 1\right)$$

Anisotropic superfluidity



Chiral A-phase stabilized in our **anisotropic** aerogel

Pollanen *et al.*, Nature Physics **8**, 317 (2012)

Outline

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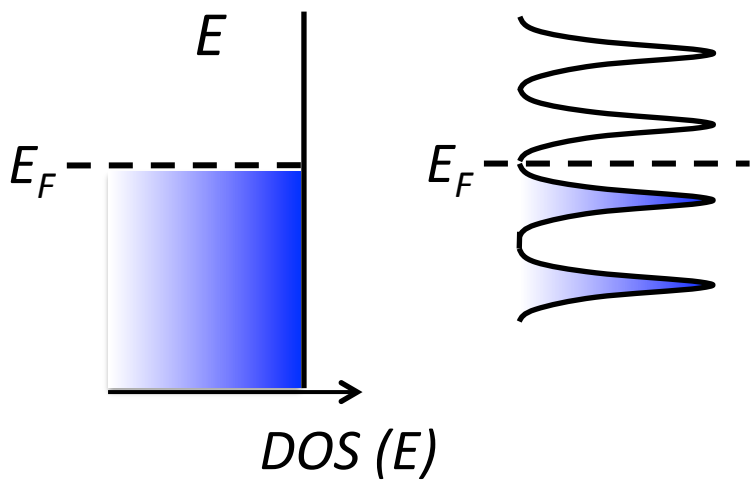
Electrons on helium + nano-scale devices & topological states of matter

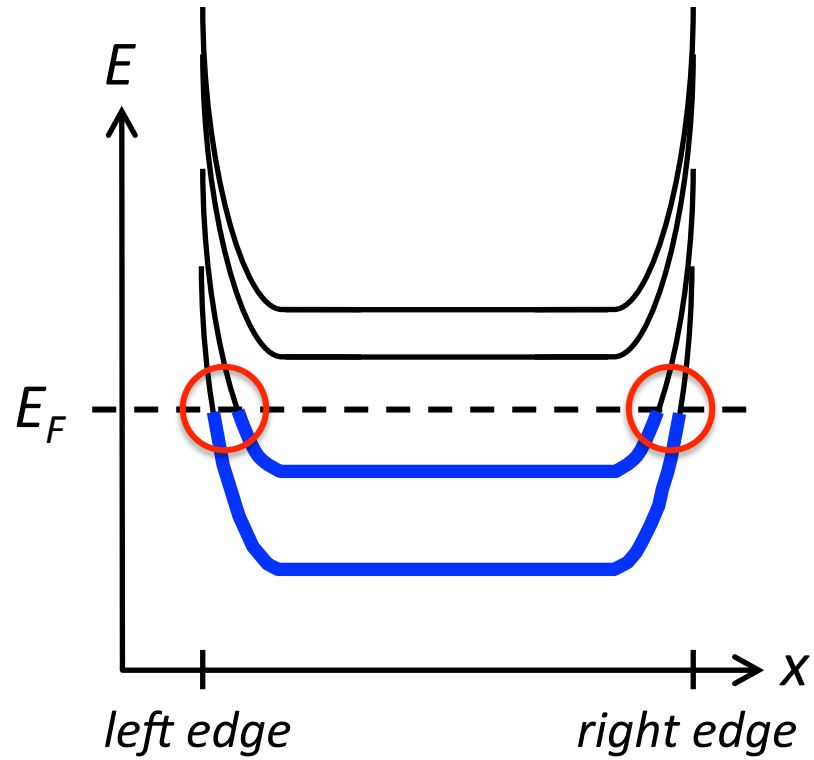
2-D electrons in a B-field at T=0

$$E_F = \frac{\hbar^2 \pi n}{m^*}$$



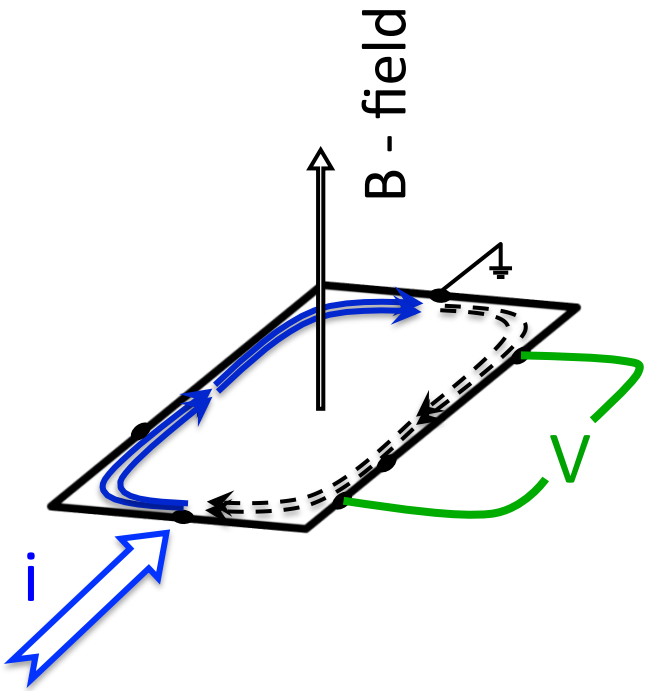
$B = 0 \longrightarrow B > 0$

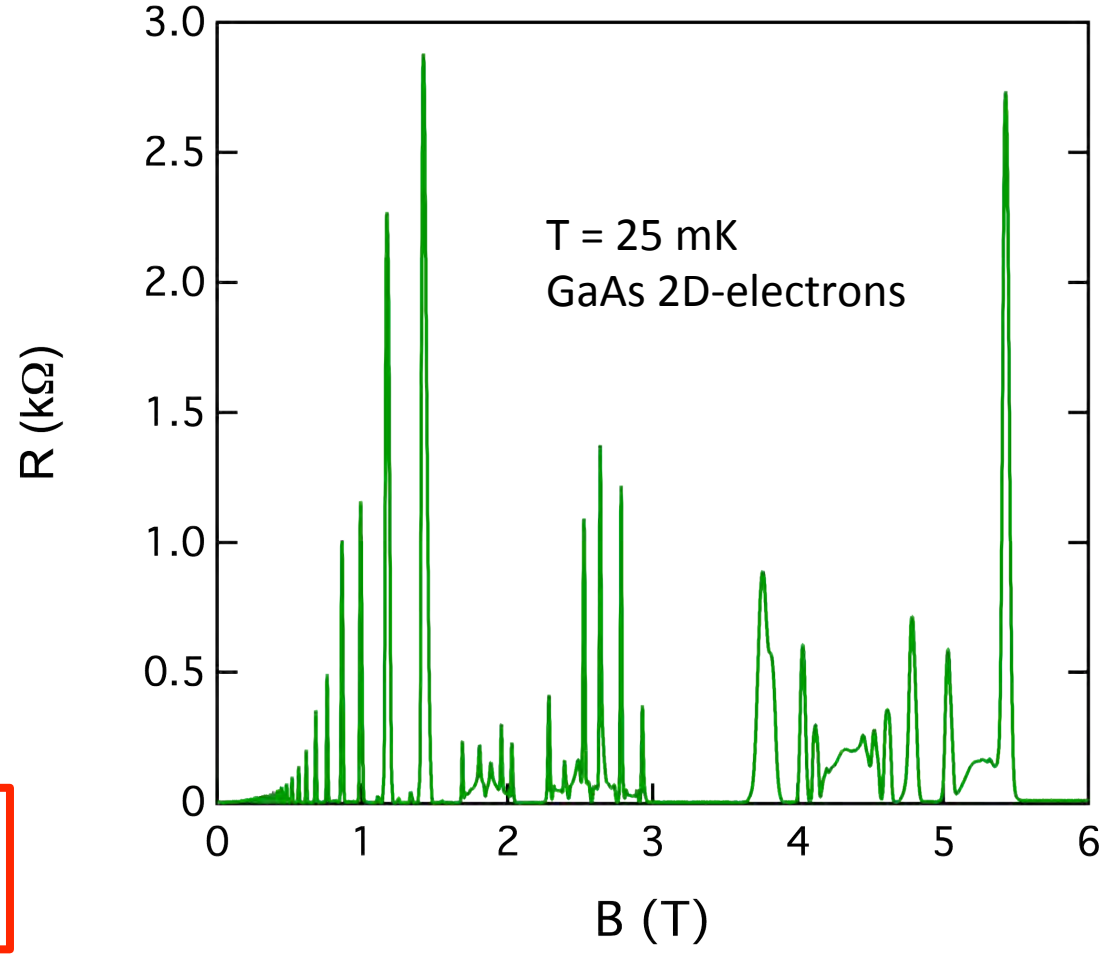
$$E_N = \hbar\omega_c \left(N + \frac{1}{2} \right)$$



Edge = **dissipationless**

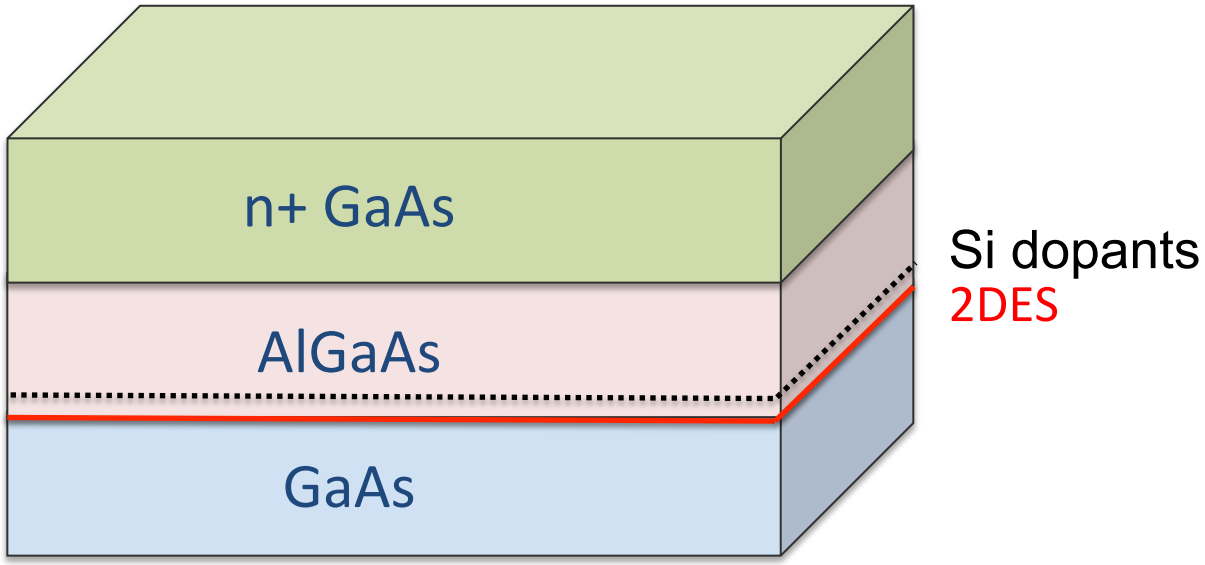
Beyond single particle physics





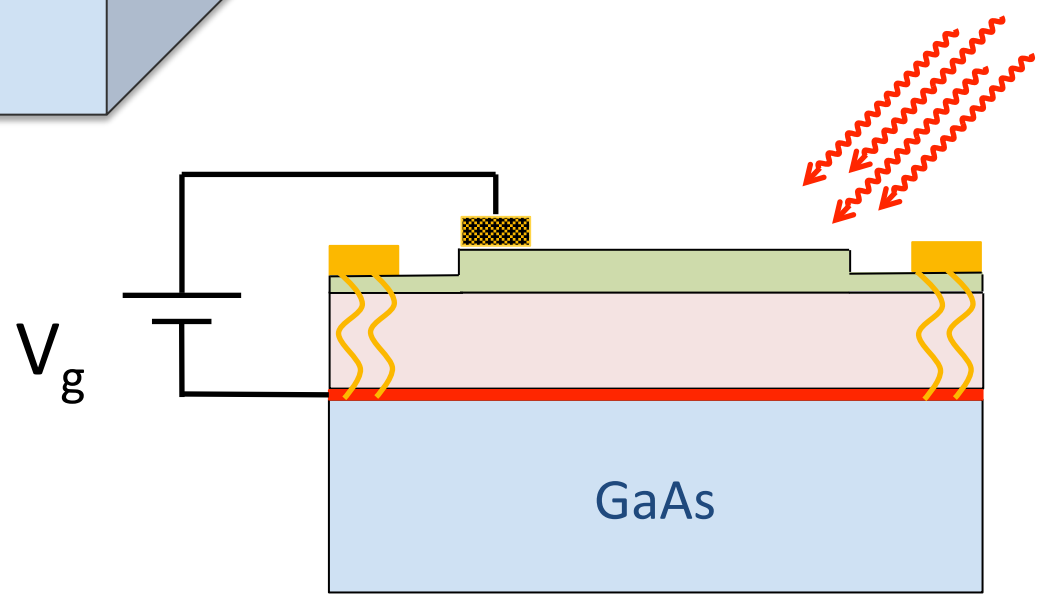
Can we **control** interactions ?

Transparent variable density device

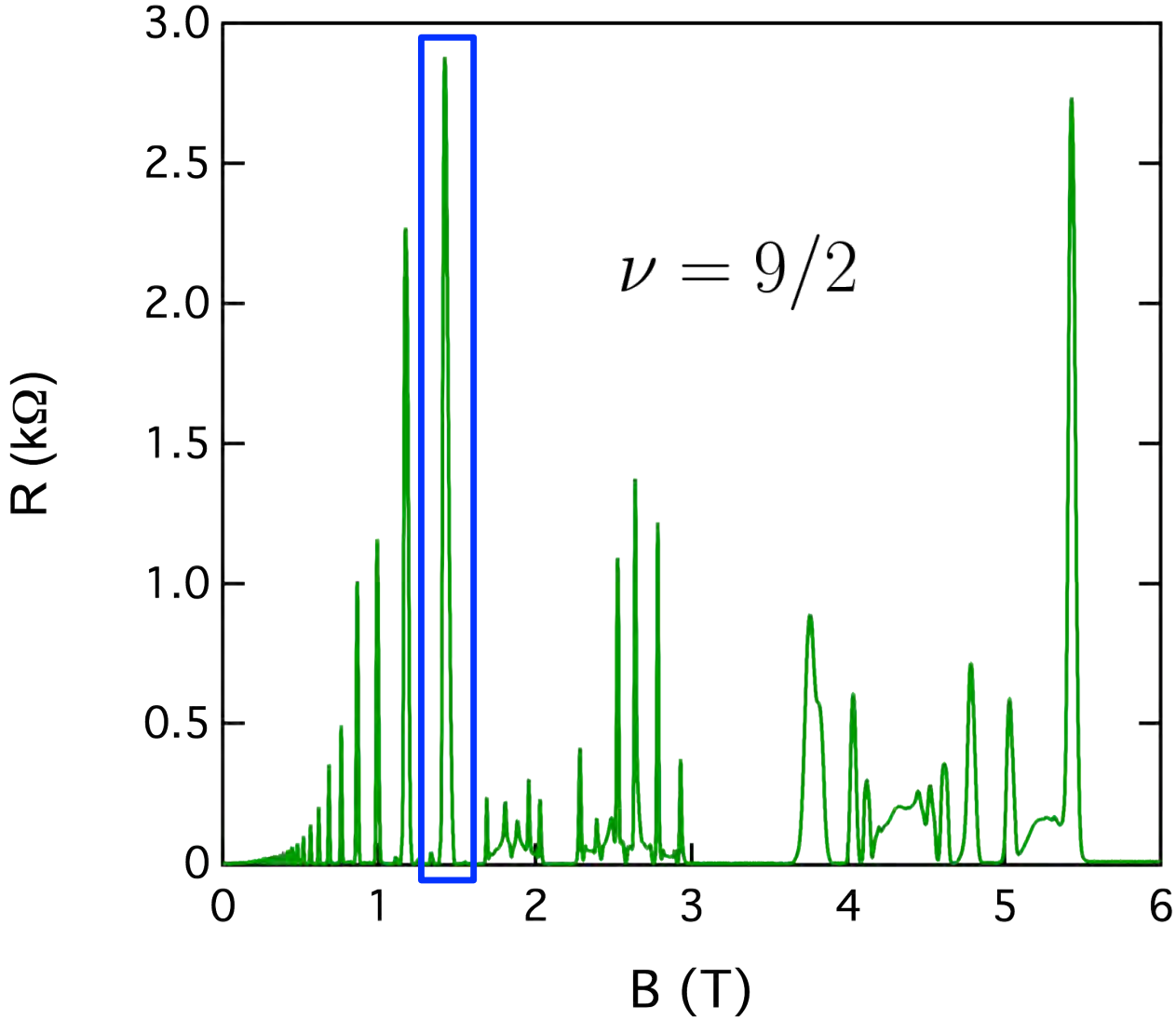


$$C = \frac{\varepsilon A}{d}$$

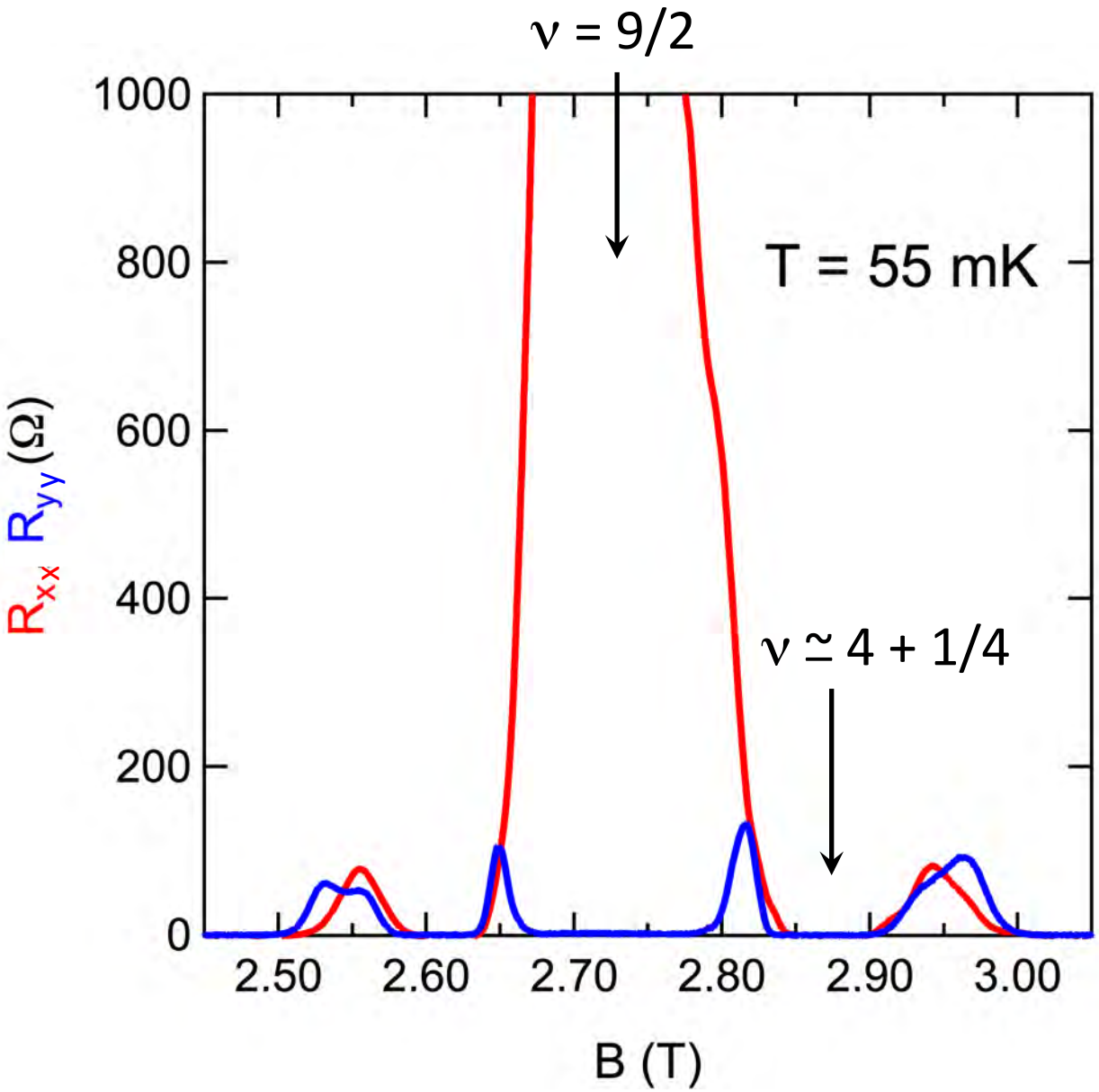
$$\frac{dn}{dV_g} = \frac{\varepsilon}{d}$$

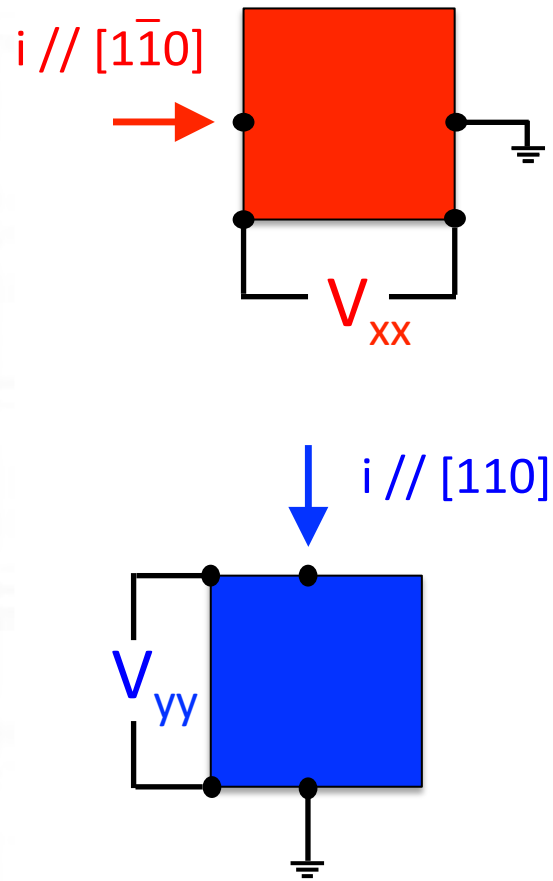


Collective states near ½ filling of N = 2



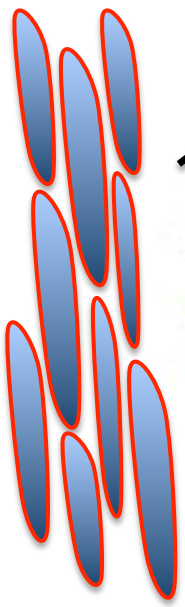
Transport signatures

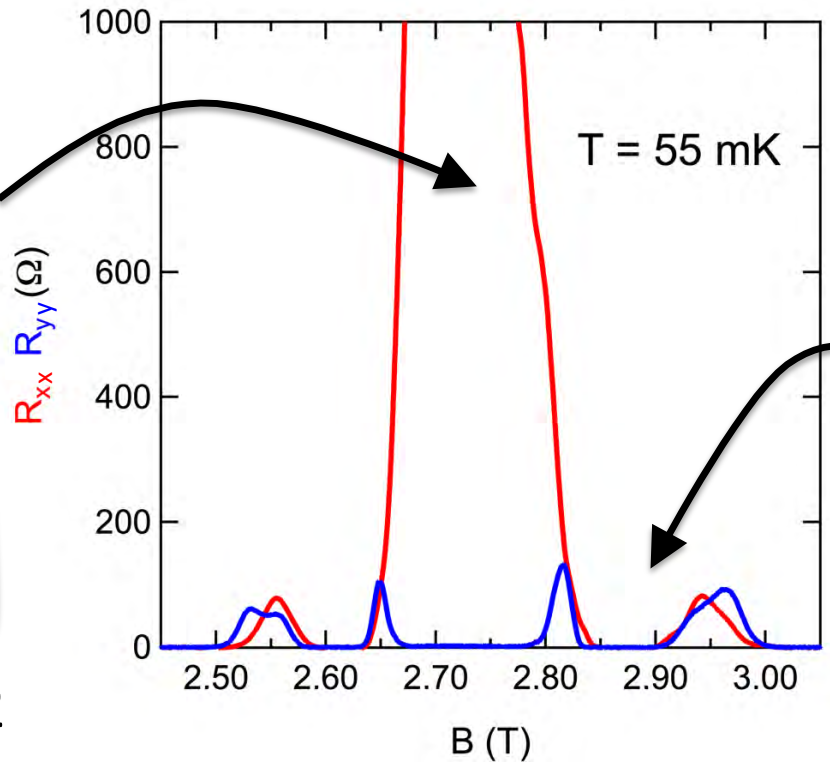




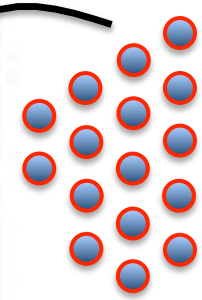
Lilly *et al.* 1999
Du *et al*. 1999

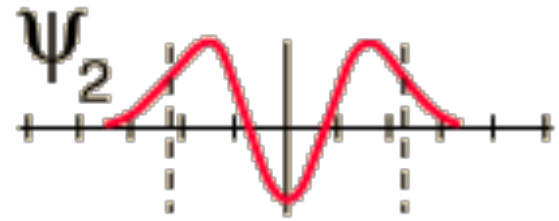
Collective electron states: N = 2





Koulakov, Fogler & Shklovskii 1996
Moessner & Chalker 1997
Fradkin & Kivelson 1999





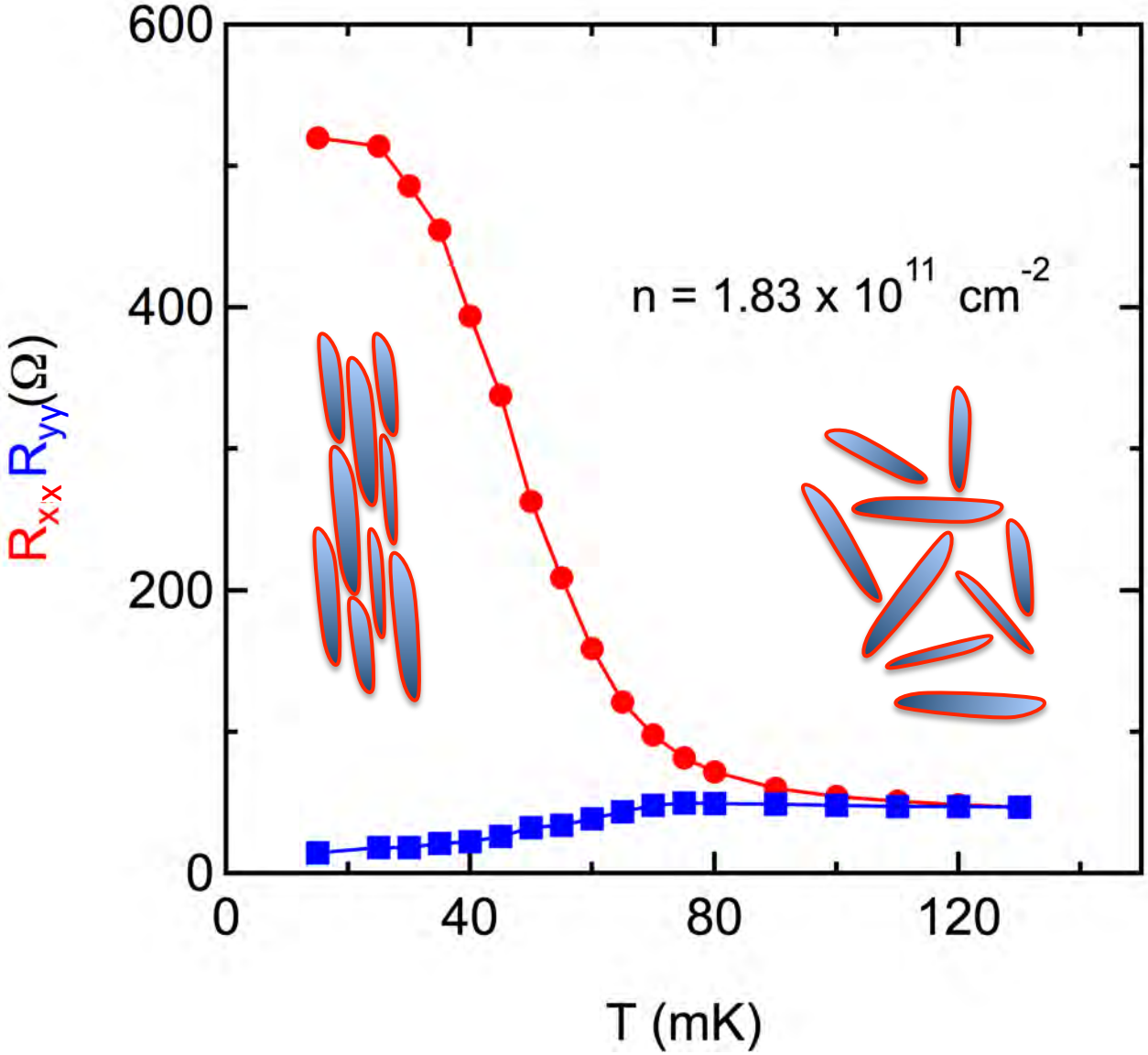
$\nu = 9/2$

$$\lambda \sim R_c = \sqrt{\frac{\hbar(2N+1)}{eB}}$$

- Nodes → reduce <u>short range</u> Coulomb repulsion
- Exchange → attractive
- <u>Long range Coulomb</u> unaffected by <u>nodes</u>

Pollanen *et al.*, arXiv:1506.08482 (2015)

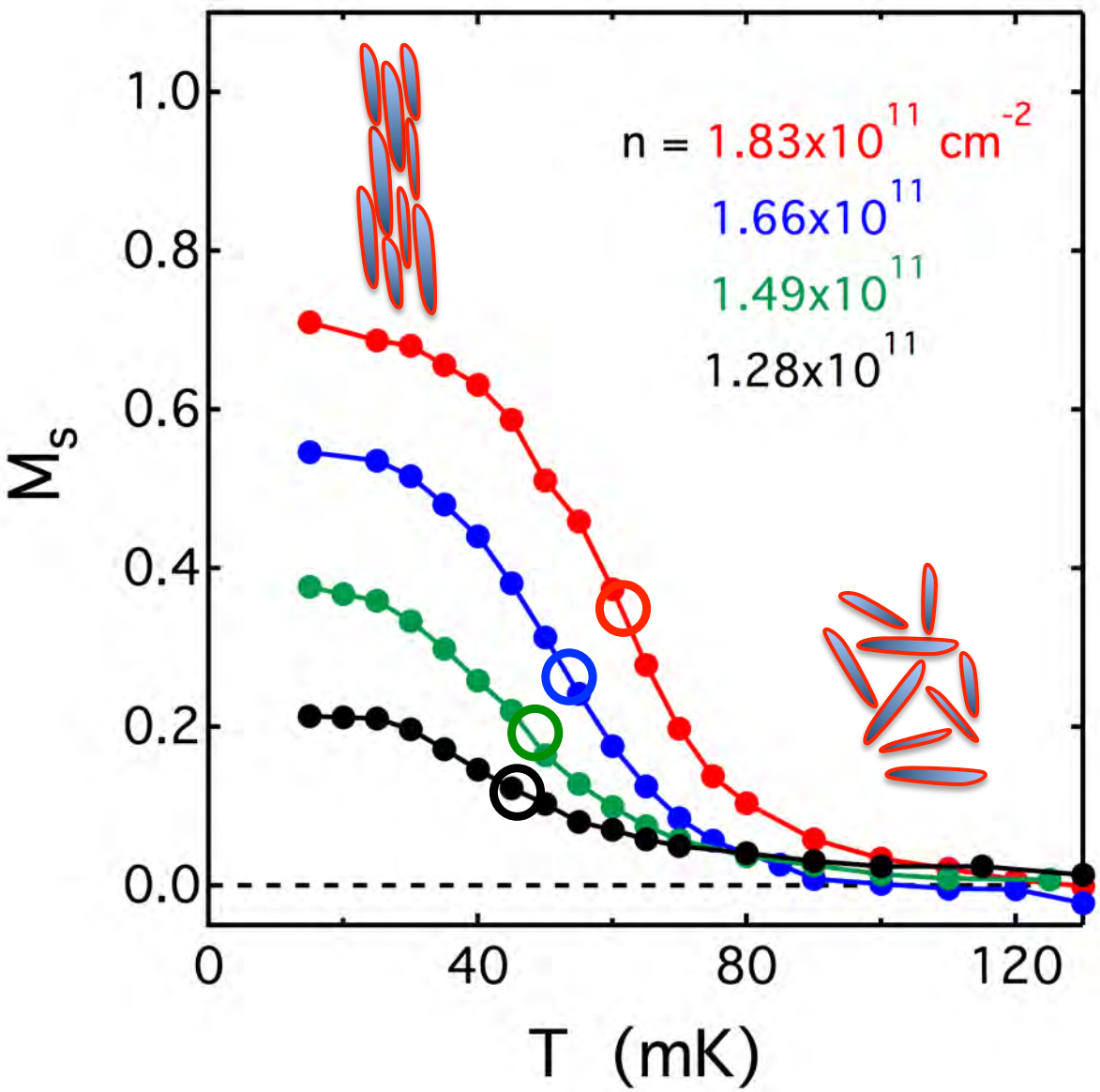
T-dependence: ν = 9/2



Evidence for *local* nematic order at high T

Cooper *et al.* 2002

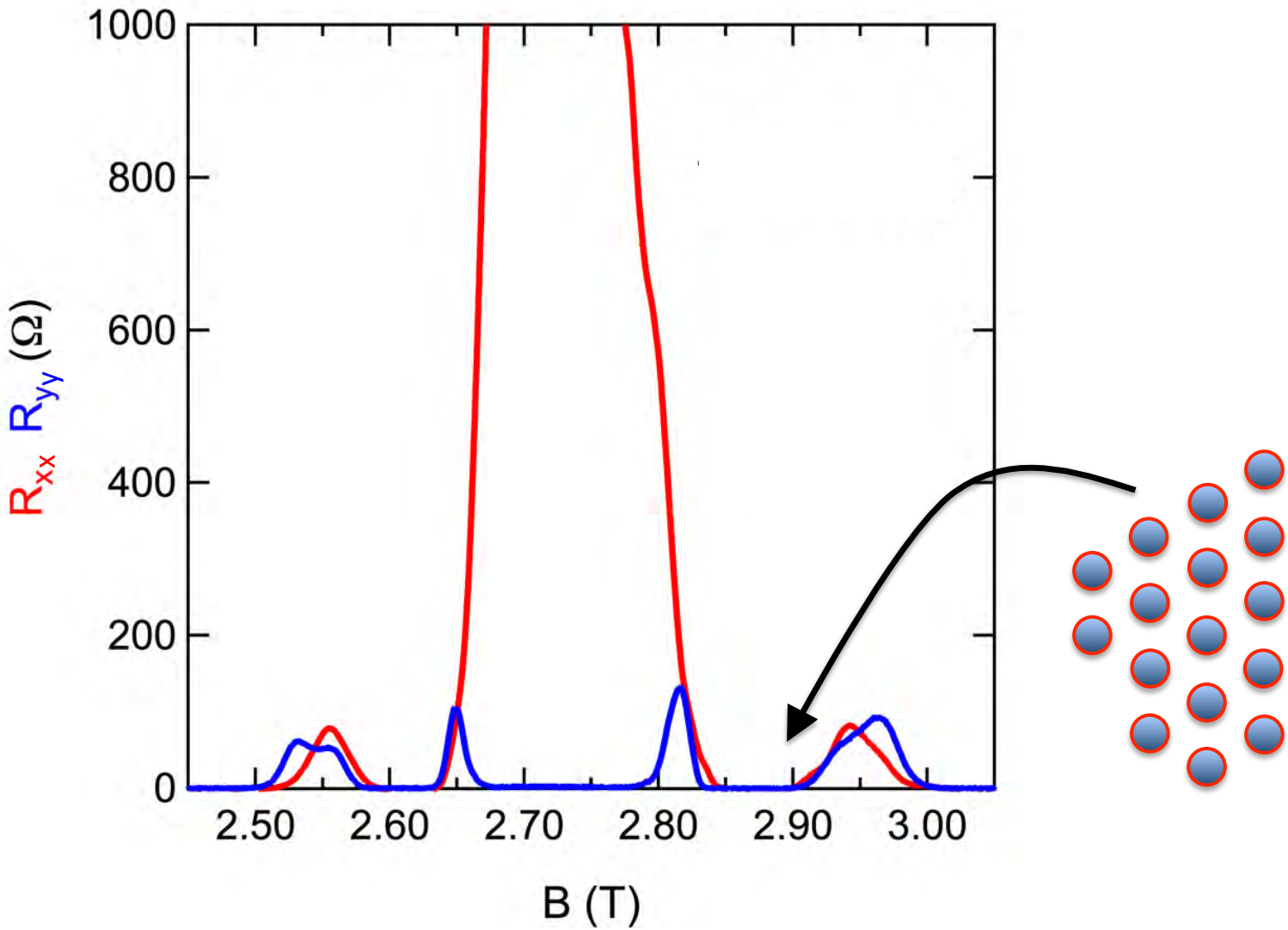
Density dependent nematic order



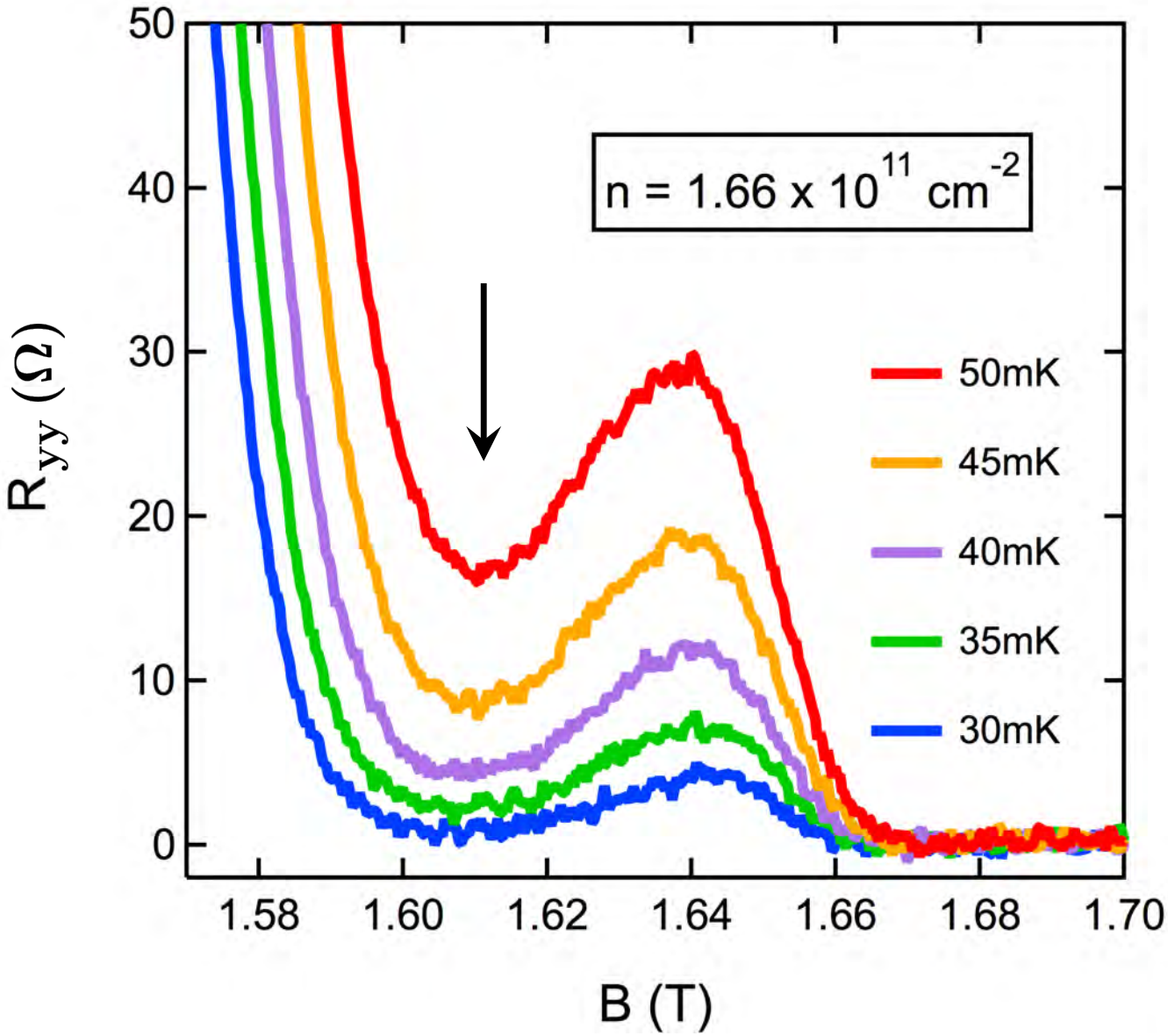
$$M_s = \frac{\rho_{xx} - \rho_{yy}}{\rho_{xx} + \rho_{yy}}$$

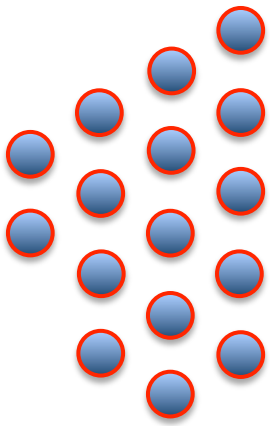
Simon 1999
Fradkin & Kivelson 1999

Insulating phase at $\nu \simeq 4 + 1/4$

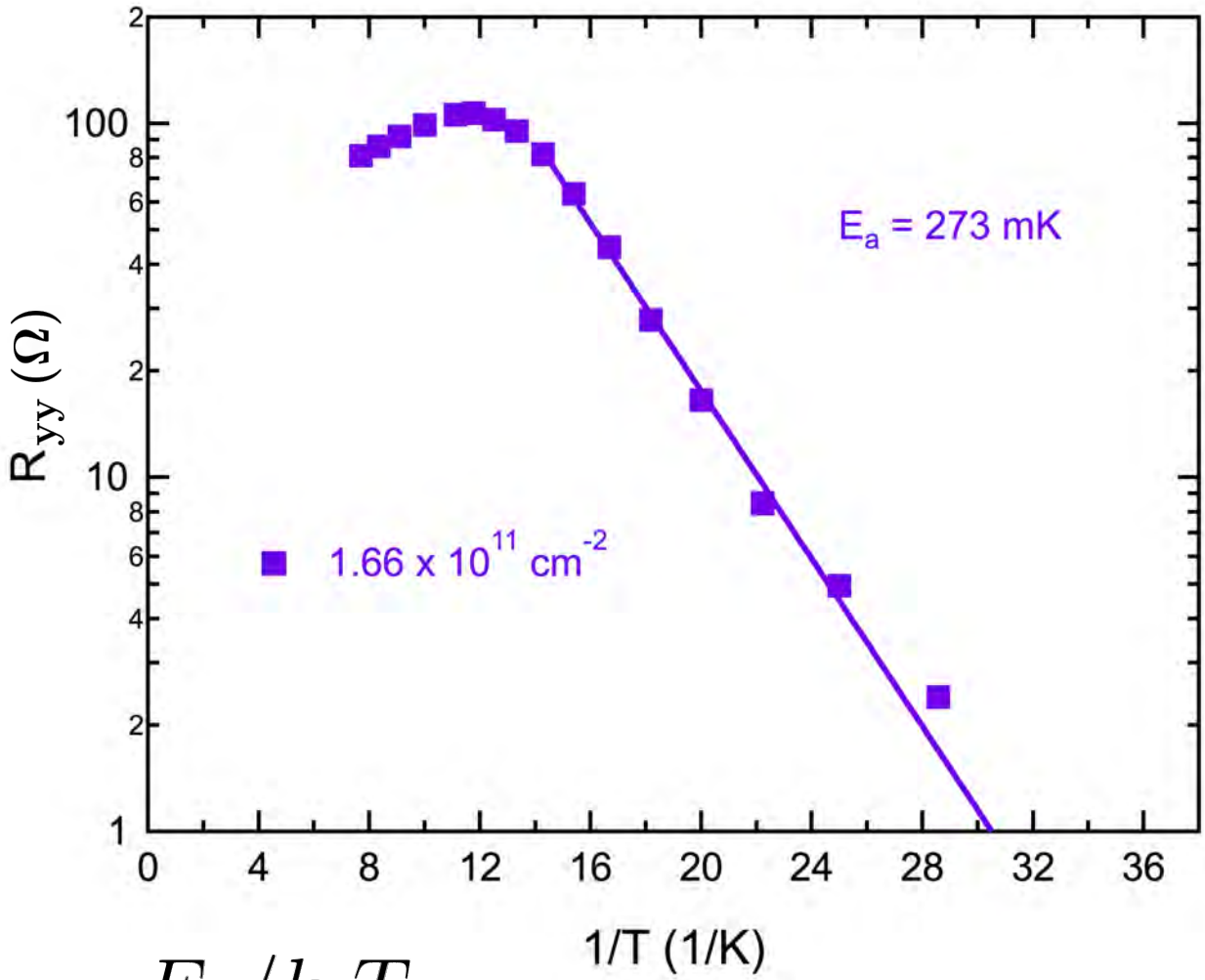


Fixed density, T-dependence



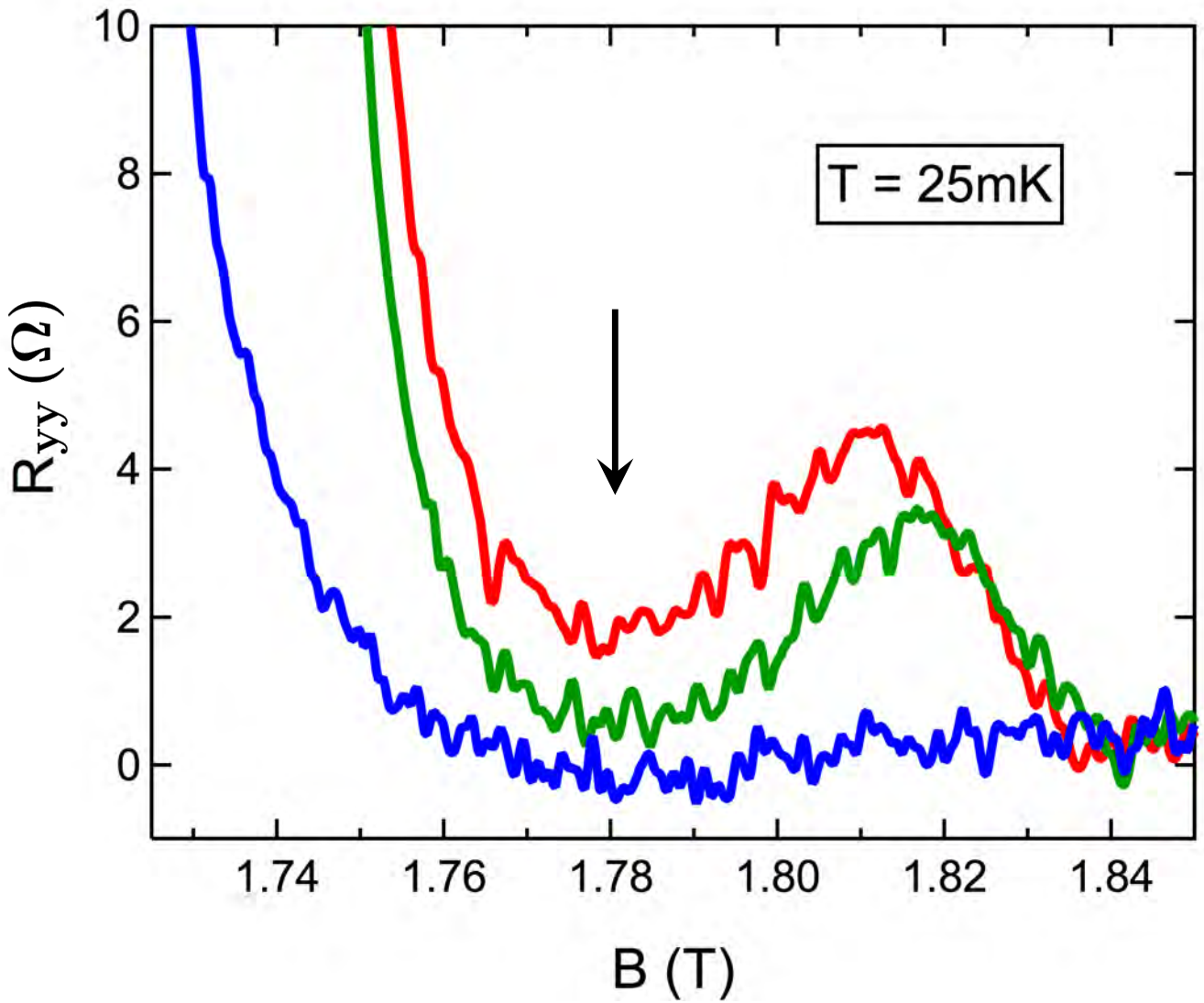


Thermally activated conduction



$$R_{yy} = R_o\, e^{-E_a/k_b T}$$

Fixed T, n-dependence

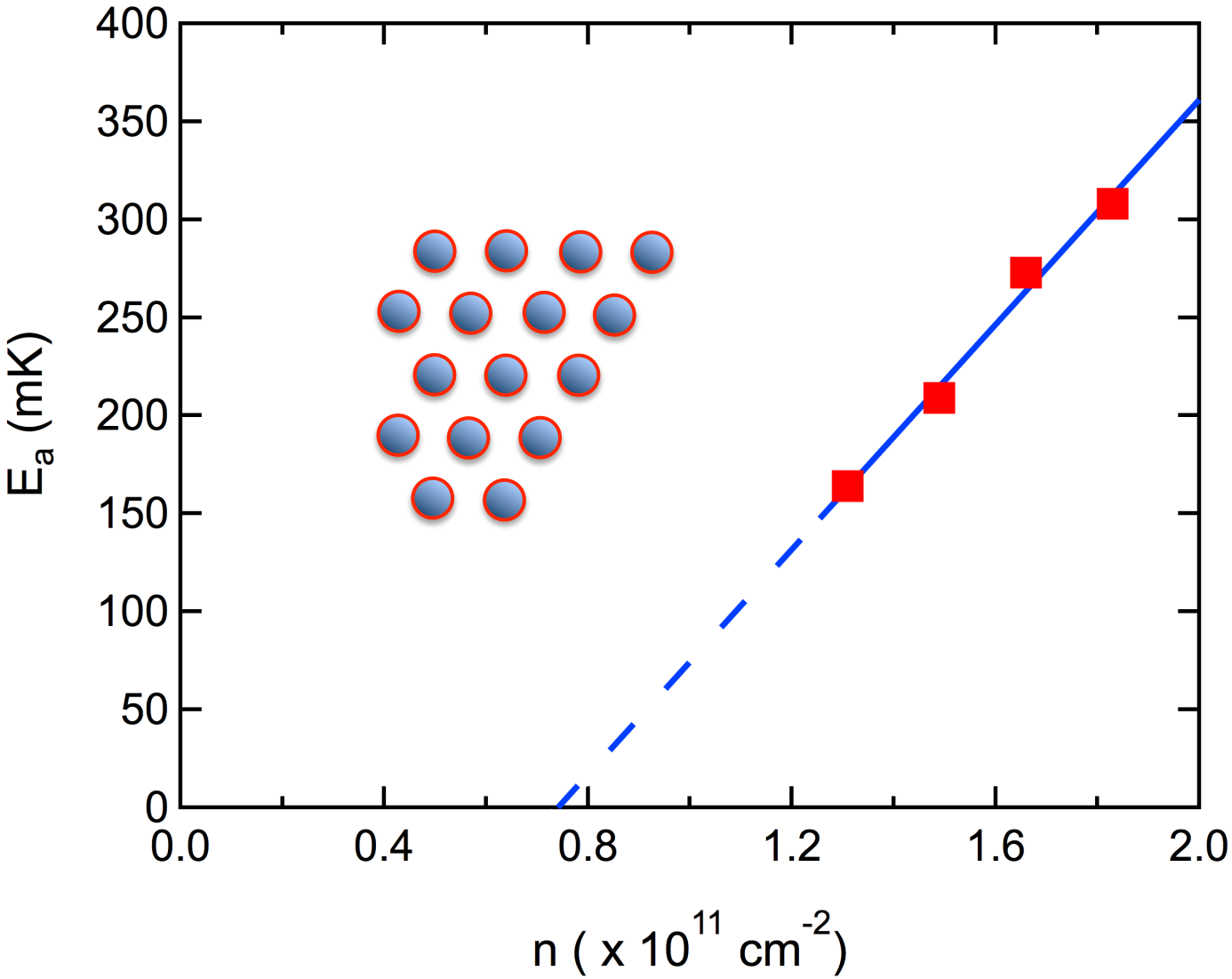


1.43 x 10^{11} cm^{-2}

1.63 x 10^{11} cm^{-2}

1.83 x 10^{11} cm^{-2}

Energy gap versus n



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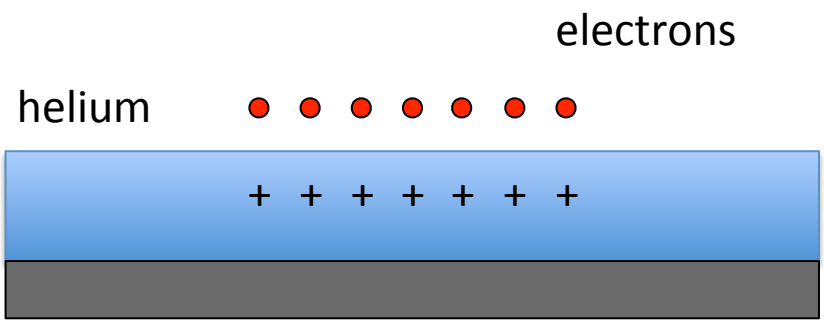
Electrons on helium + nano-scale devices & topological states of matter

Electrons on helium (eoH)



Quantum computing proposals:

Platzman & Dykman Science **284**, 1967 (1999)

Lyon PRA **74**, 052338 (2006)

Schuster *et al*. PRL **105**, 040503 (2010)

Quantum simulation (spin models):

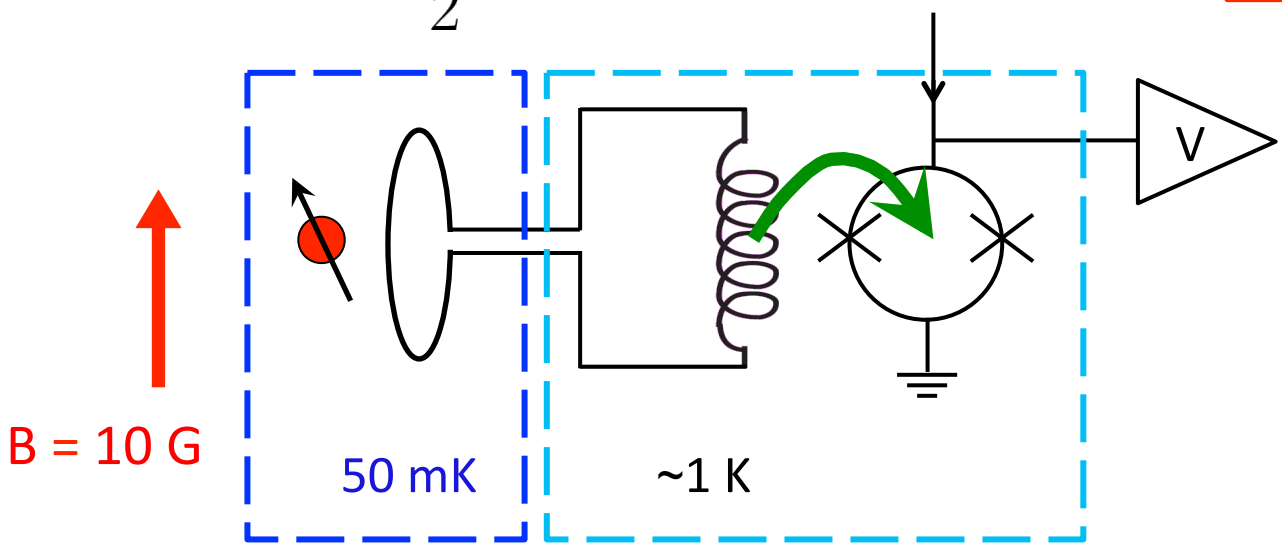
Mostame & Schützhold PRL **101**, 220501 (2008)

- Ultra clean 2-D electrons: $\mu > 10^8\,\mathrm{cm}^2/\mathrm{Vs}$
- Long *predicted* spin coherence $> 100\,\mathrm{sec}$
- Controllable density (interactions) $n = 10^8 - 10^{12}\,\mathrm{cm}^{-2}$
- Reduced screening = strong interactions

Spin resonance of eoH

$$S = \frac{1}{2}$$

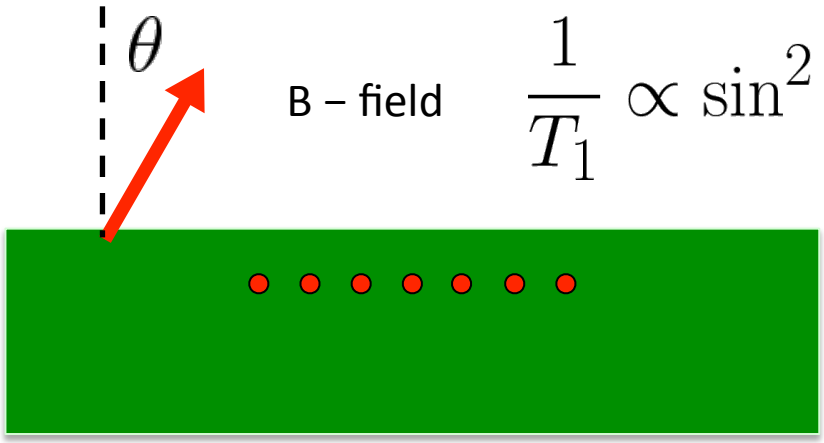
NO ESR on 2-D eoH



SQUID Magnetometer

- Extremely sensitive: ~ femto-Tesla
- Spin dynamics of strongly interacting 2-D electrons!

Majorana detection with eoH

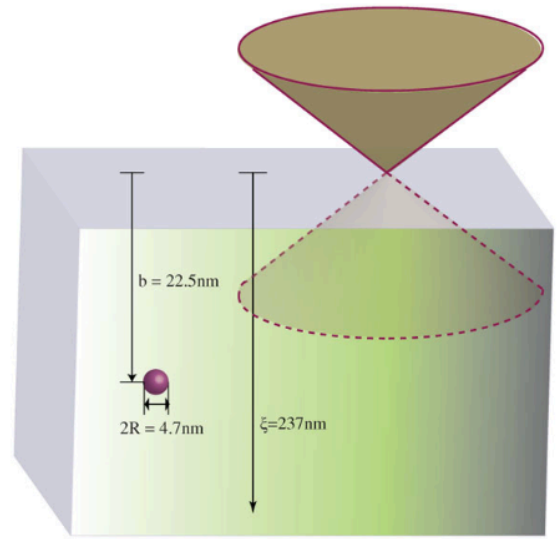


B – field

$$\frac{1}{T_1} \propto \sin^2(\theta)$$

Chung & Zhang PRL **103**, 235301 (2009)

Superfluid ^{3}He-B



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

NMR (SQUID-based) on ^{3}He nucleus:

Silaev PRB **84**, 144508 (2011)

Mourik *et al*. Science **336**, 1003 (2012)

The end

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Prof. Jim Eisenstein

Chandni U
Erik Henriksen (WashU)
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Debaleena Nandi
Sarah Brandsen
Bill Chickering

<u>Northwestern University</u>

Profs. Bill Halperin
Jim Sauls

John P. Davis (Alberta)
Hyoungsoon Choi (KAIST)
Leo Li (Columbia)
Charles Collett (Amherst College)
Bill Gannon (Brookhaven)
Andrew Zimmerman
Andy Mounce (LANL)
Bo Chen (UCF)
Sutirtha Mukhopadhyay

Sam Blinstein
Kent Shirer (UC Davis)
Andrew Fang

<u>Princeton</u>

Loren Pfeiffer
Ken West
Kirk Baldwin

<u>MSU</u>

Mark Dykman

<u>Cornell</u>

Prof. Jeevak Parpia

Nik Zhelev
Andrew Fefferman
Rob Bennett
Eric Smith

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