Superconducting Symmetries of Topological-Superconductor Candidate, Strontium Ruthenate

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A.-M. S. Tremblay

https://arxiv.org/abs/1808.02527

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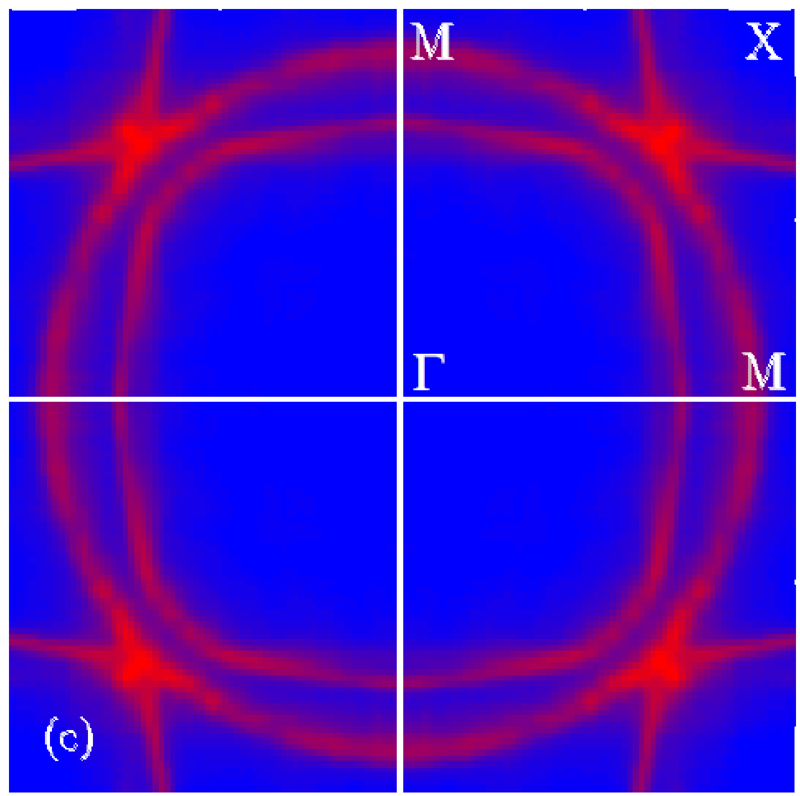
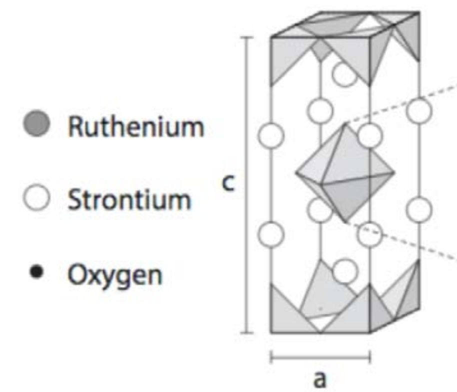


Sr_2RuO_4 cleaved at 180 K

T= 10 K hν=28 eV

Damascelli, A. et al. Phys. Rev. Lett. 85, 5194–5197 (2000).

A solid state analog of ^3He ?



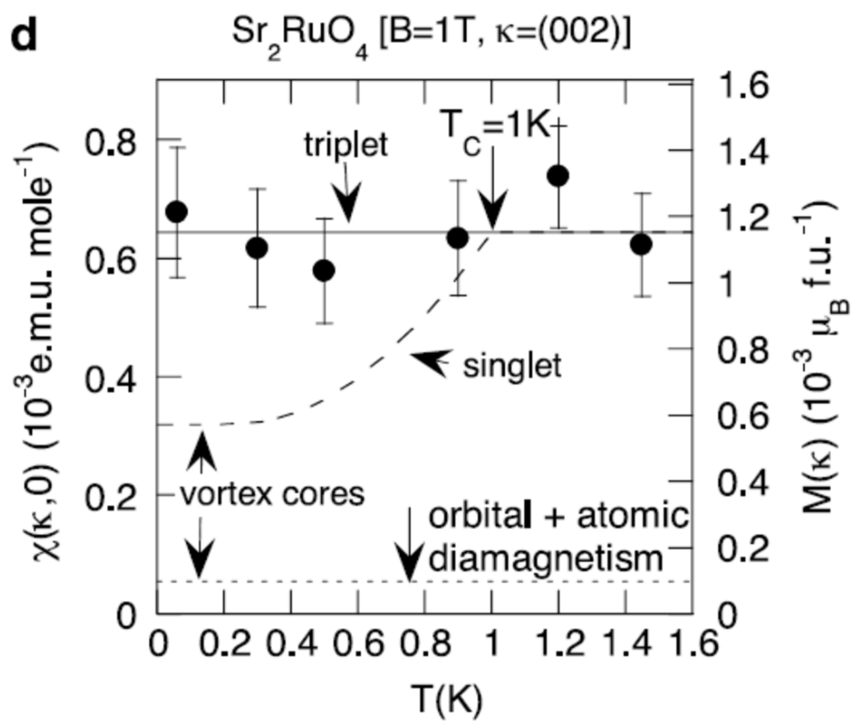
- -> 1994 superconductivity: HTSC structure without Cu
- -> $p_x + ip_y$ order parameter symmetry
  (Rice, T. & Sigrist, M. J. Phys.-Cond. Mat **7**, L643–L648 (1995).)
- -> Unconventional SC in Fermi liquids
- -> Majorana edge modes (Topological quantum computation)

- Outline

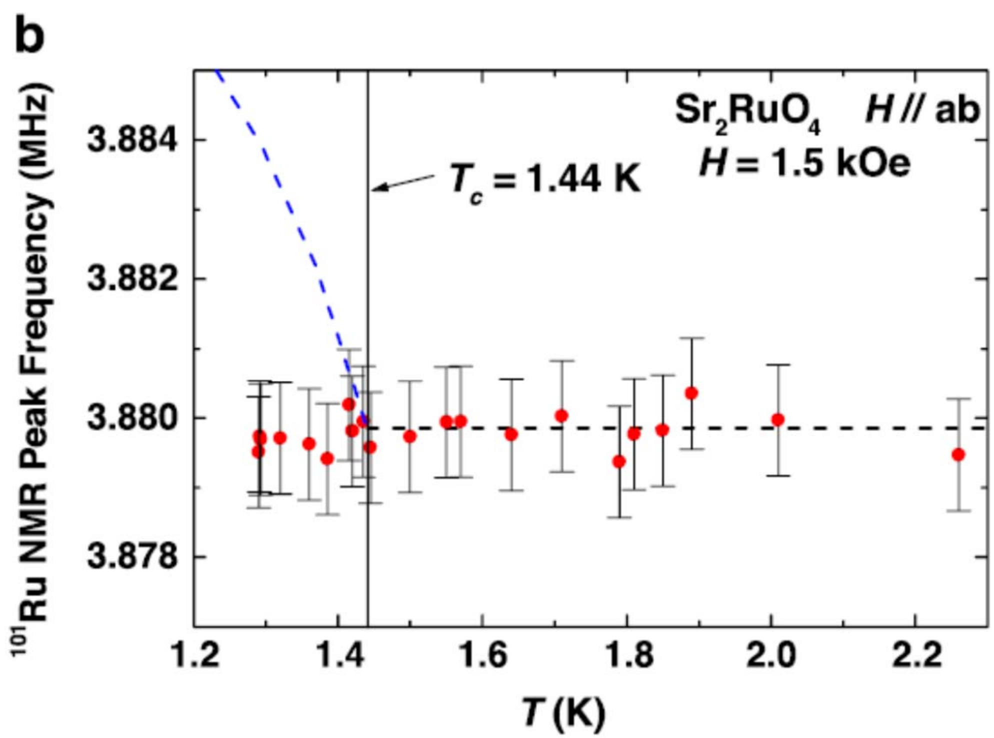
  Experiments
  Our results
  How we got them
  Theory vs experiment
  Conclusion

A confusing experimental situation

1) Spin triplet?

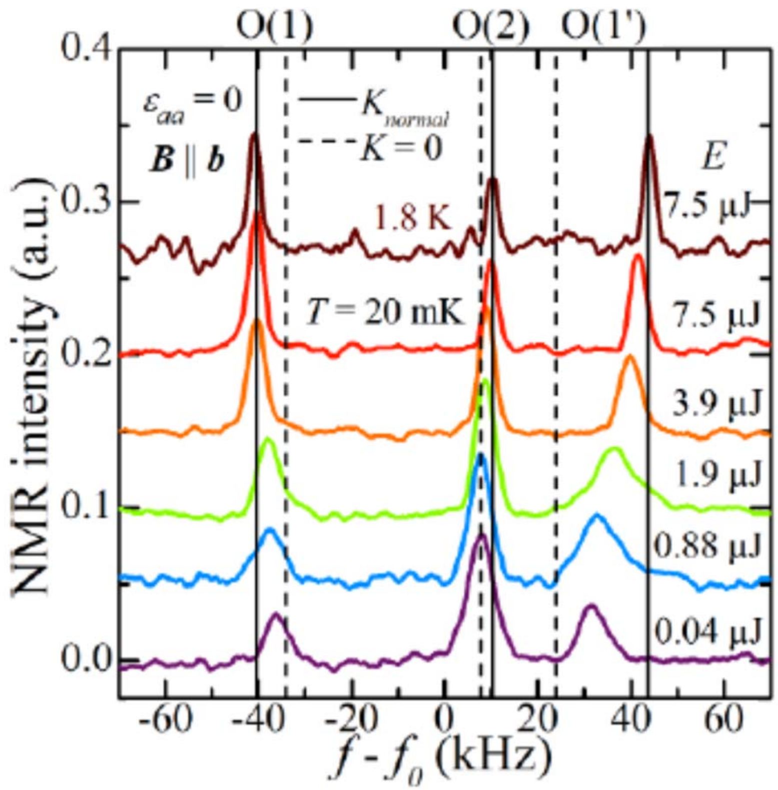


Duffy, J. A. et al. Polarized-neutron scattering
Phys. Rev. Lett. **85**, 5412–5415 (2000).



Murakawa, H. et al.
J. Phys. Soc. Jpn. **76**, 024716 (2007).

Not quite… No Knight shift was effect of heating



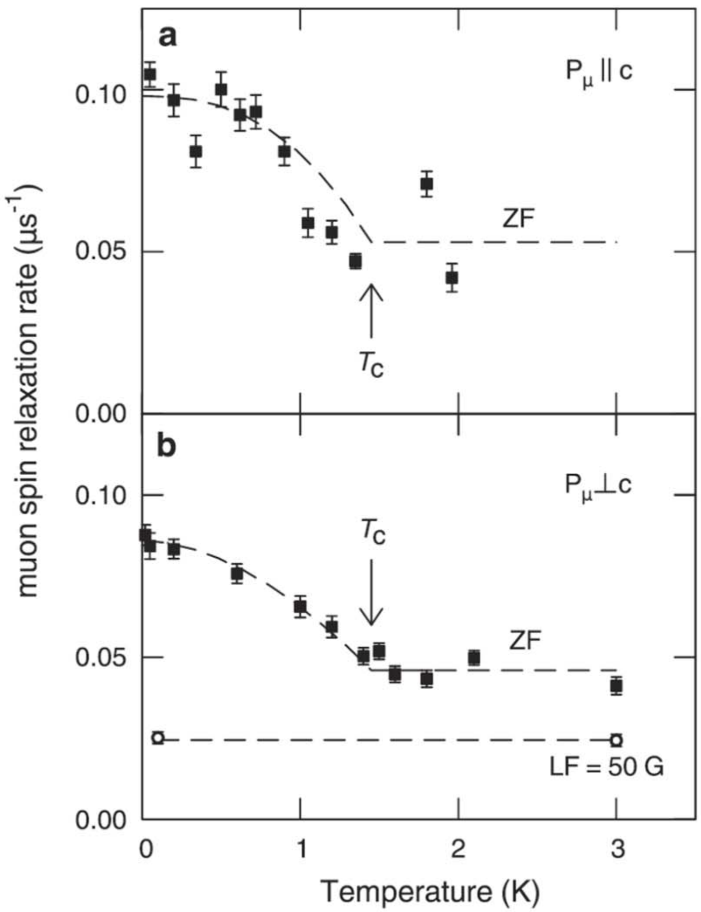
Pustogow *et al.*, arXiv:1904.00047 (2019)

But, phase sensitive tunneling experiments:

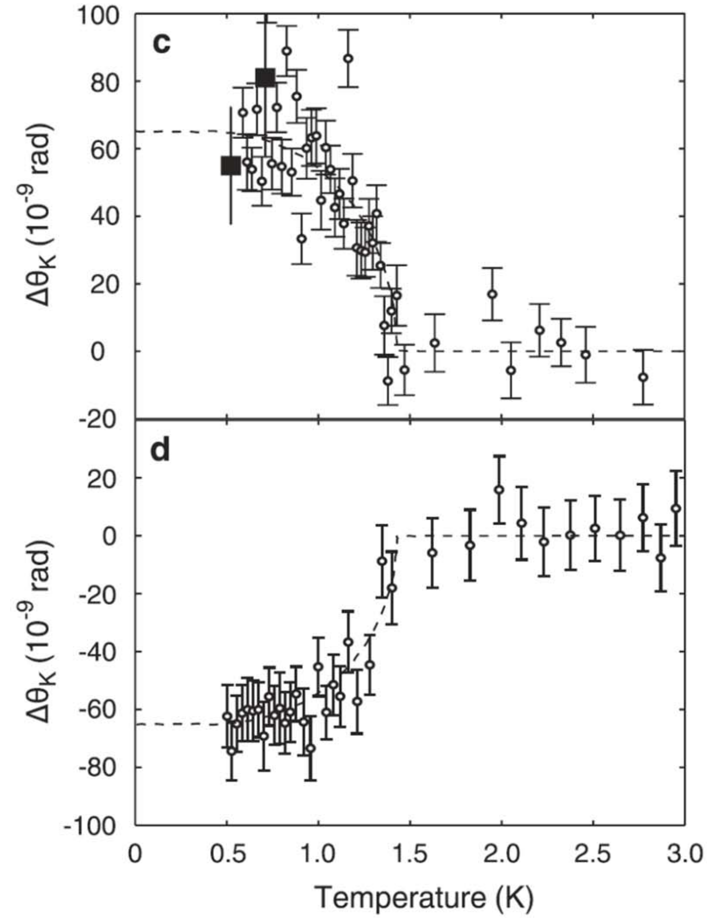
Odd under inversion

Review:
Y. Liu, QZ Mao
Physica C 514 (2015) 339–353

2) Time-reversal symmetry breaking (examples)

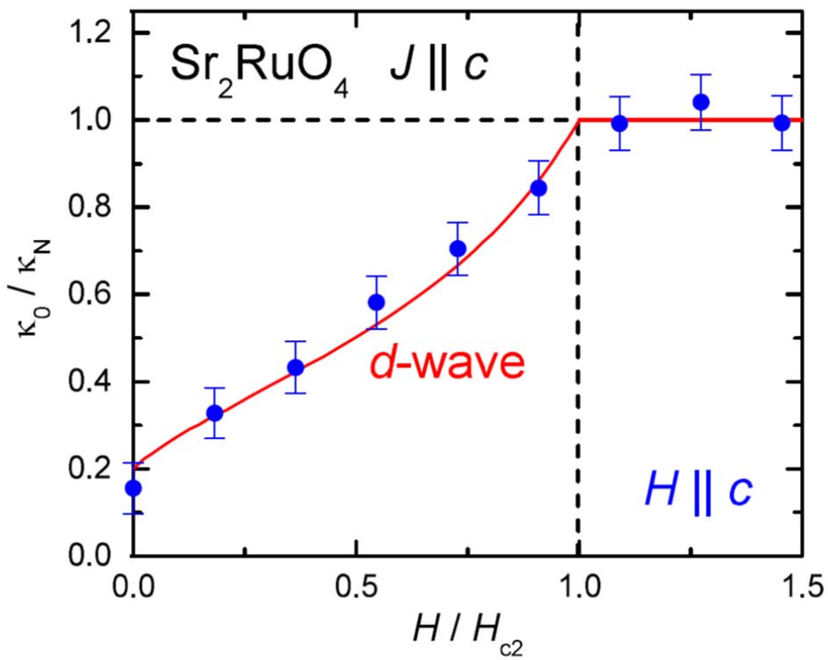


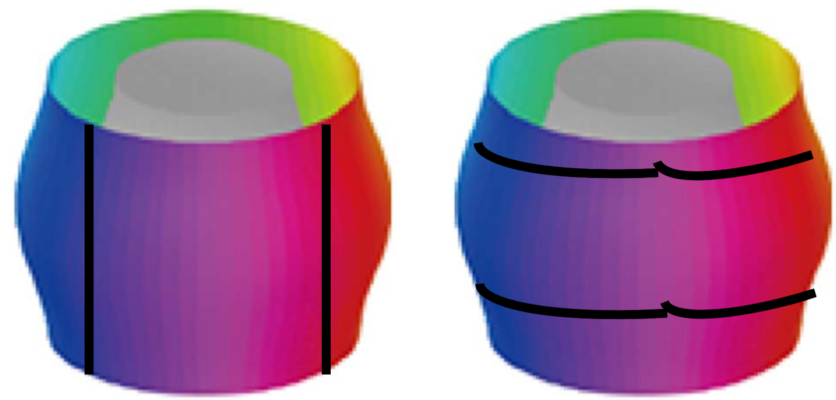
Luke, G. M. et al.
Nature 394, 558–561 (1998).



Xia, J., Maeno, Y., et al.
Phys. Rev. Lett. 97, 167002 (2006).

3) There are nodes, (C_V, κ, v_s) but where are they?





Vertical line nodes

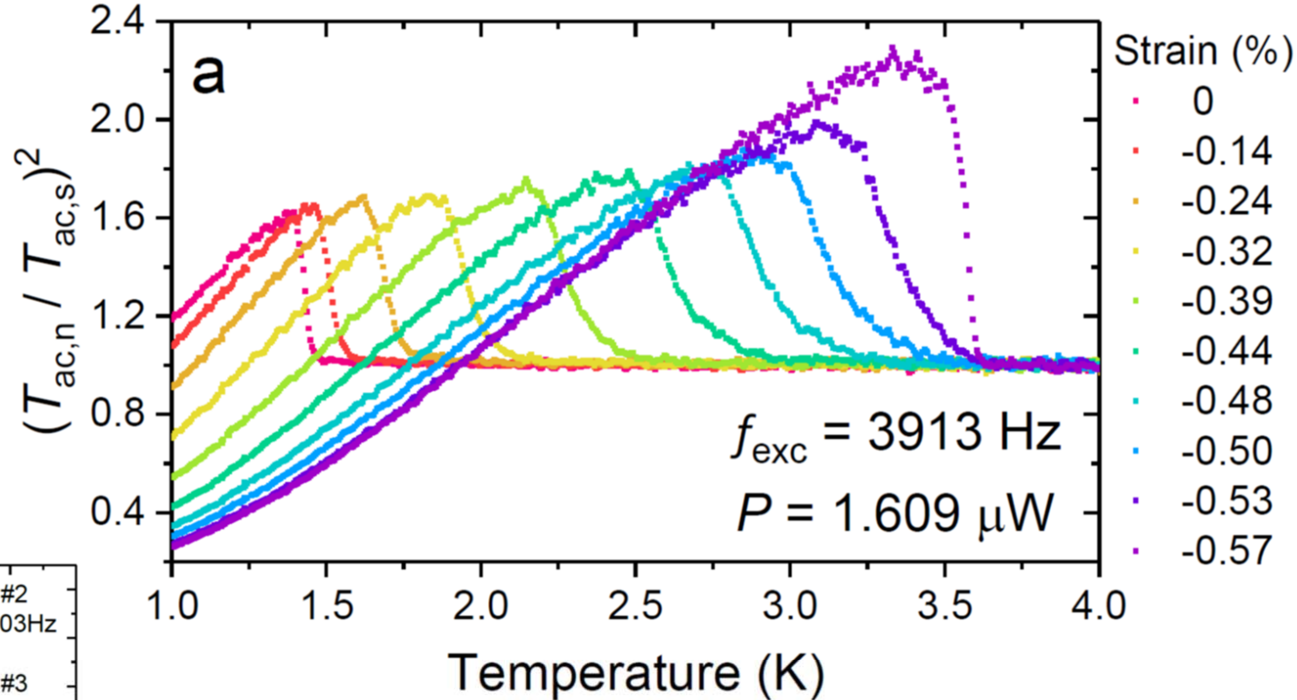
Horizontal line nodes ($C_V(H,\theta)$)

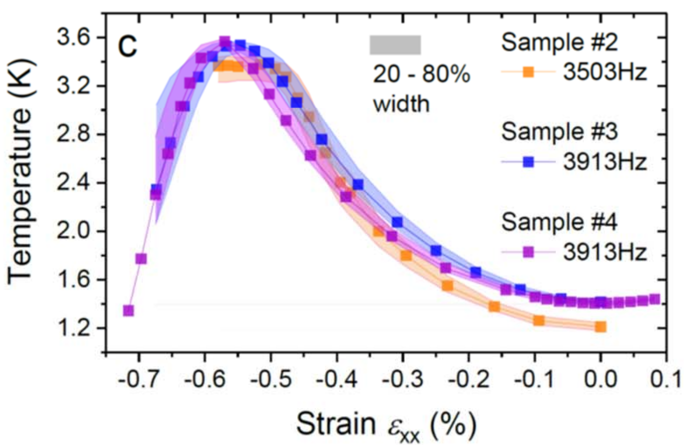
$\lim_{T\to 0} \frac{\kappa}{T}$

E. Hassinger, *et al.*
Phys. Rev. X 7, 011032 (2017)

S. Kittaka et al.
J. Phys. Soc. Jpn, **87**, 093703 (2018)

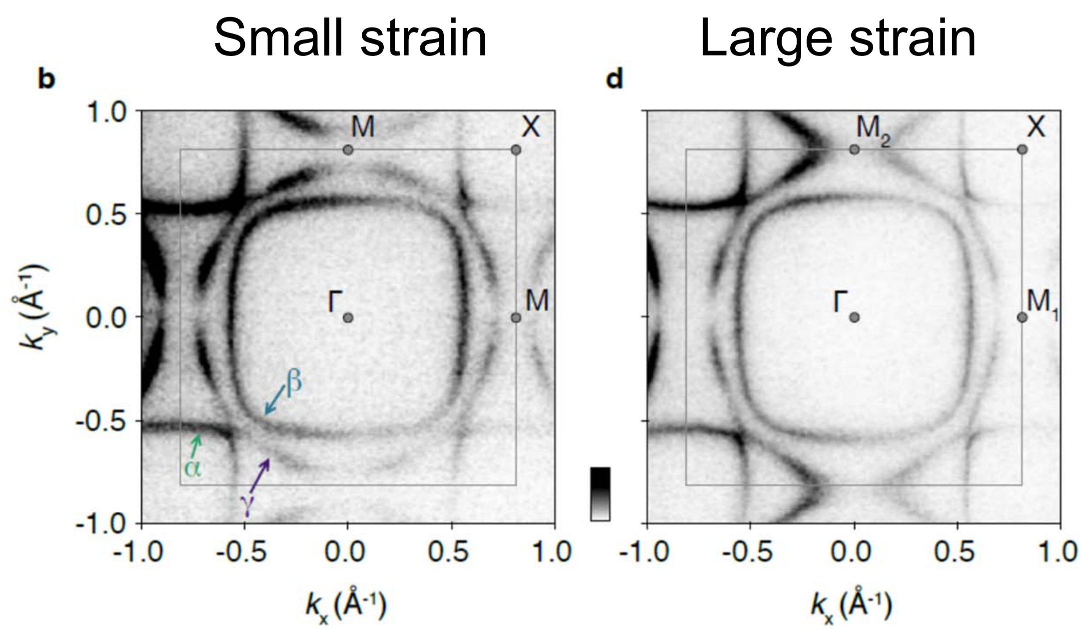
4) Effect of uniaxial pressure on specific heat: single transition



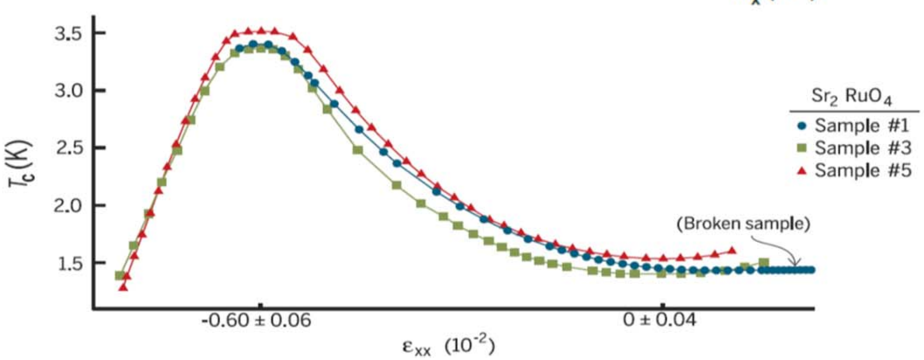


Y.-S. Li et al. ArXiv:1906.07597.pdf

Detailed information under uniaxial pressure



Sunko et al.
arXiv:1903.09581



Steppke, A. et al.
Science **355**, eaaf9398 (2017).

A first principle approach
Spin and charge-fluctuation mediated superconductivity

Leading instabilities

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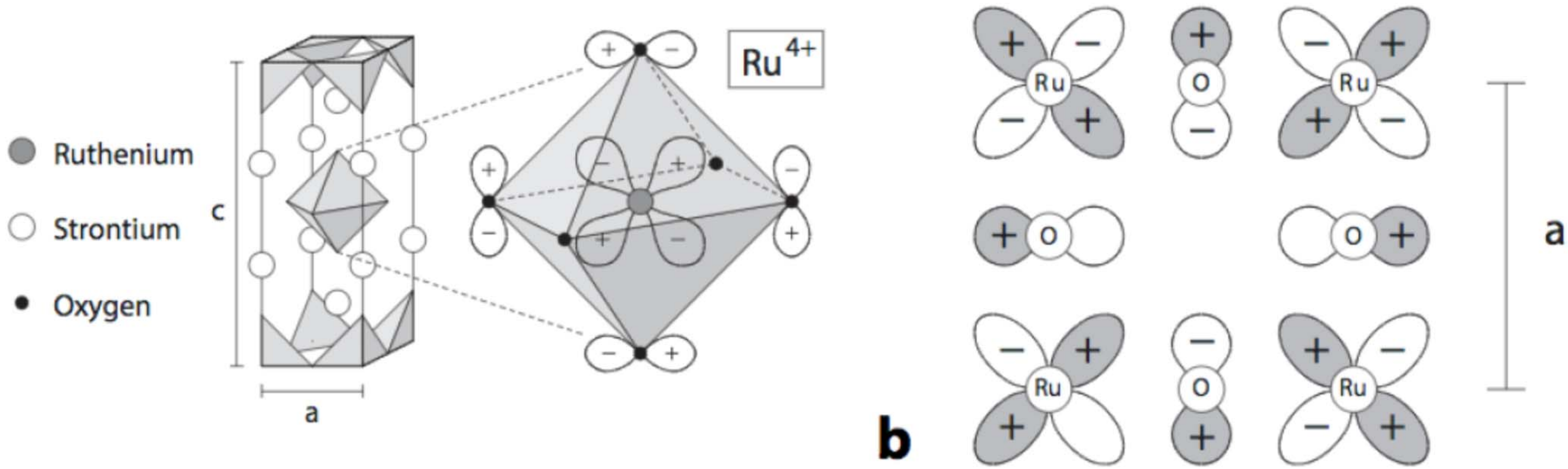
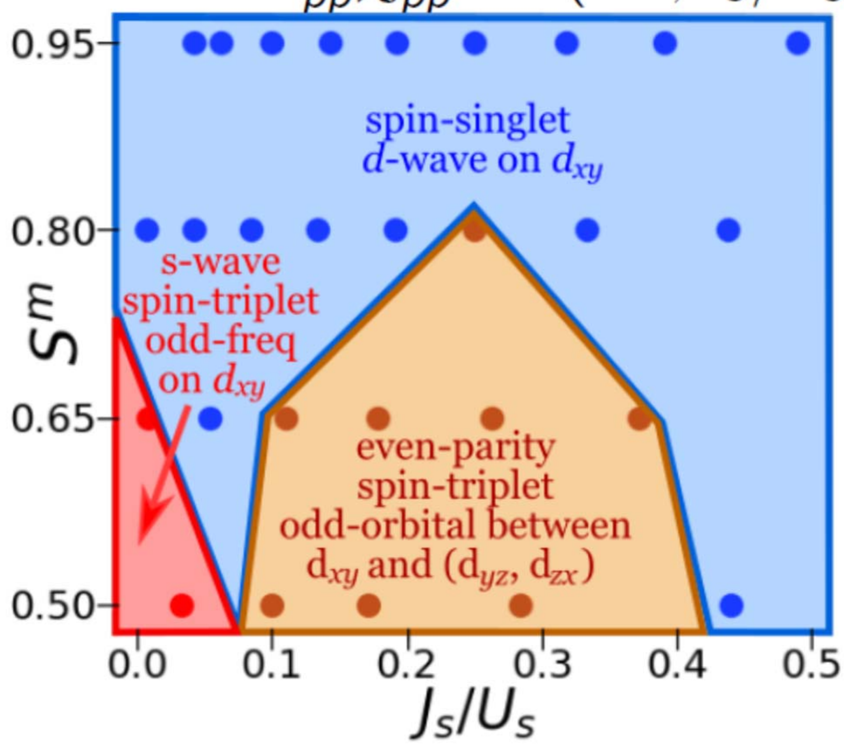


Bergemann *et al.*, Adv. Phys. **52**, 639 (2003)

Leading instabilities (without SOC)

$S^m, J_s/U_s$

$$\lambda^\nu \Delta^\nu = -\Gamma^{irr}_{pp}\chi^0_{pp}\Delta^\nu \; (S^m, J_s/U_s)$$

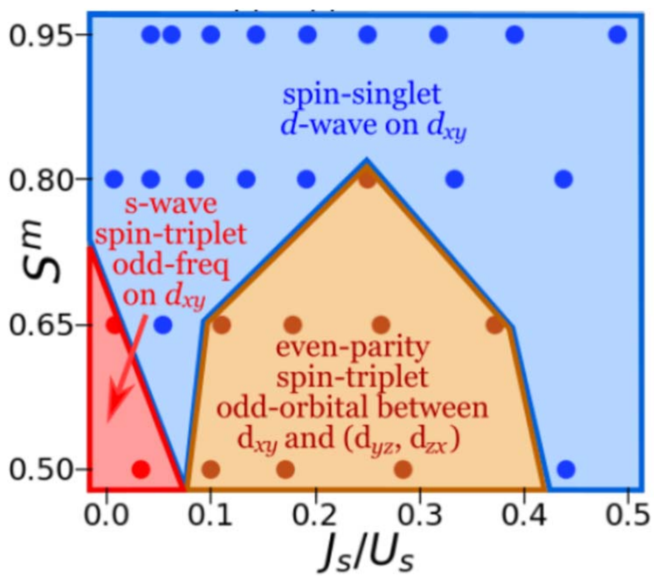


Superconducting order parameter symmetry

$$\langle c_{\mathbf{k}\sigma\ell}(i\omega_n)c_{-\mathbf{k}\sigma'\ell'}(-i\omega_n)\rangle$$

| $\hat{S}$ | $\hat{P}$ | $\hat{O}$ | $\hat{T}$

Leading instabilities



	$\hat{S}$	$\hat{P}$	$\hat{O}$	$\hat{T}$
p_x, p_y	+	-	+	+
$d_{x^2-y^2}$	-	+	+	+
odd-orb.	+	+	-	+
odd-freq	+	+	+	-

Possible symmetries:

- Gap function symmetry: $\mathbf{\Delta}(1,2) = -\mathbf{\Delta}(2,1)$ with $1 \equiv \mathbf{r}_1, t_1, \sigma_1, l_1$
- Fourier-Matsubara transform

With decoupled quantum numbers:

- $[\hat{S}\mathbf{\Delta}]^{\sigma_1\sigma_2} = \pm[\mathbf{\Delta}]^{\sigma_2\sigma_1}$
- $\hat{P}\mathbf{\Delta}_{(\mathbf{k},i\omega_m)} = \pm\mathbf{\Delta}_{(-\mathbf{k},i\omega_m)}$

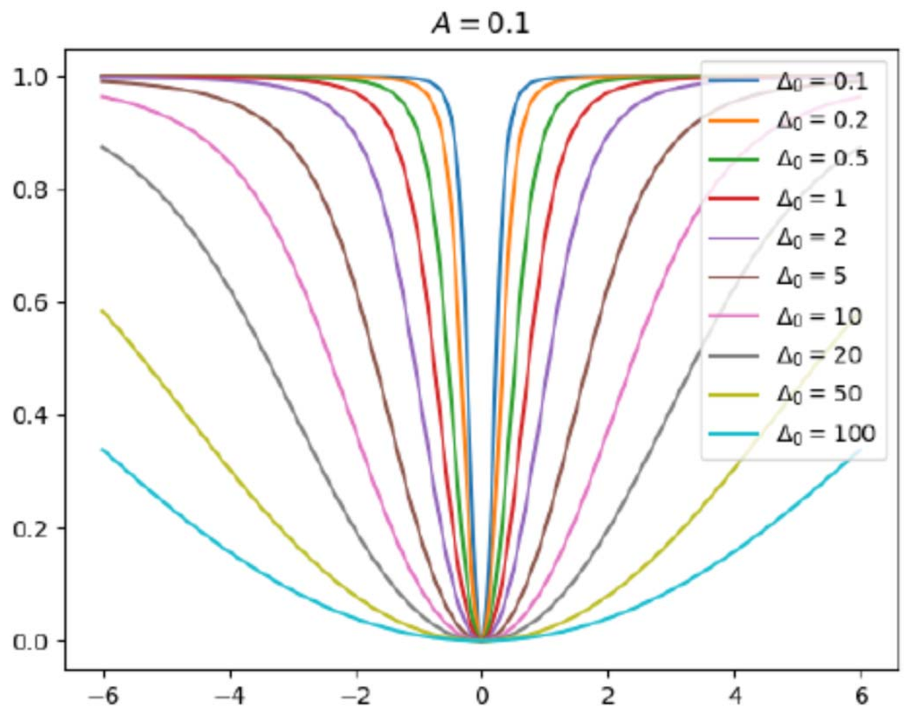
but also possible:

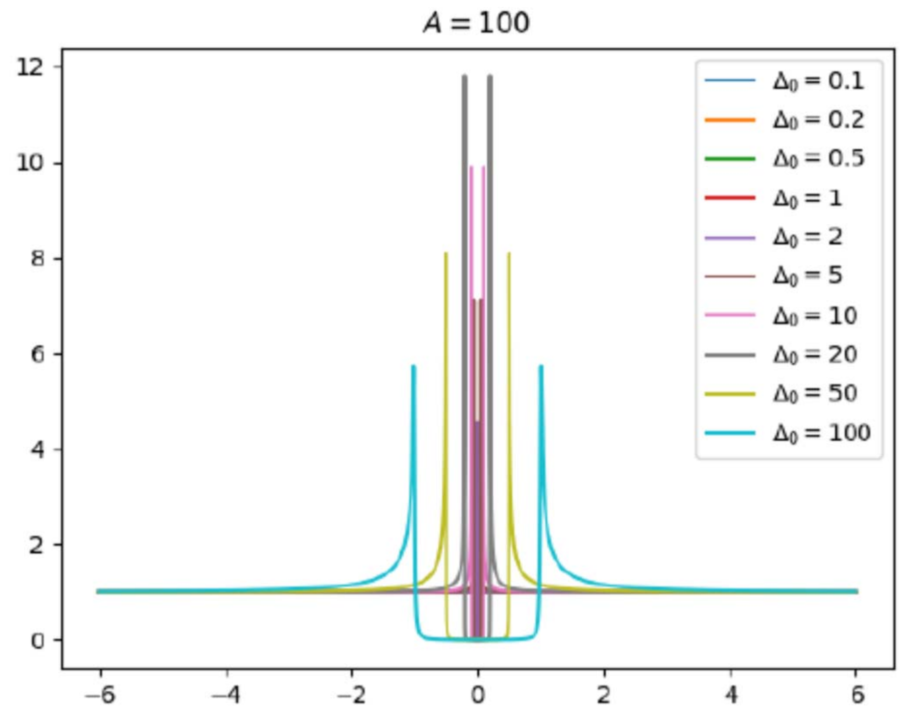
- $[\hat{O}\mathbf{\Delta}]_{l_1 l_2} = \pm[\mathbf{\Delta}]_{l_2 l_1}$
- $\hat{T}\mathbf{\Delta}_{(\mathbf{k},i\omega_m)} = \pm\mathbf{\Delta}_{(\mathbf{k},-i\omega_m)}$

$$\Rightarrow \hat{S}\hat{P}\hat{O}\hat{T}\mathbf{\Delta}(1,2) = -\mathbf{\Delta}(1,2)$$

Odd-frequency s-wave

$$\Delta_{\uparrow\uparrow}(i\omega_n) = -i\Delta_0 \frac{\mathrm{sng}(\omega_n)}{A + |\omega_n|}$$





A first principle approach: Spin and charge-fluctuation mediated superconductivity

Some details

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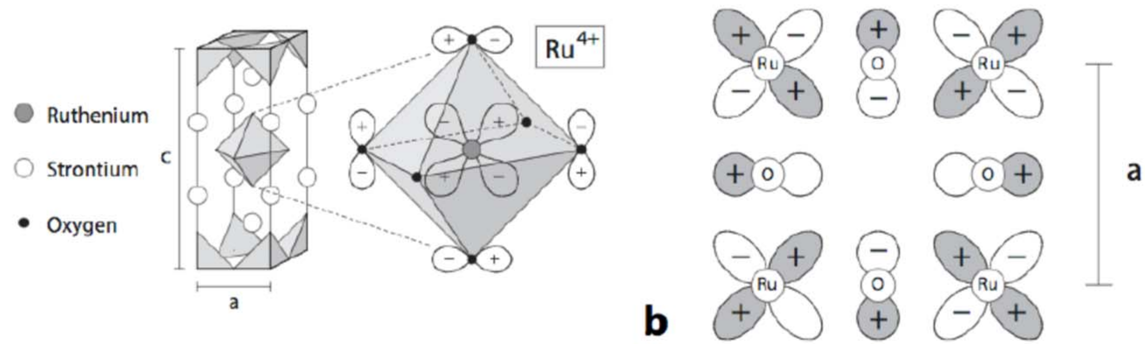
Correlated electronic structure

Normal State:

- Quasi 2D: Ru-O planes
- Partially occupied Ru $4d_{t_{2g}}$
- Multiband Correlated Fermi liquid

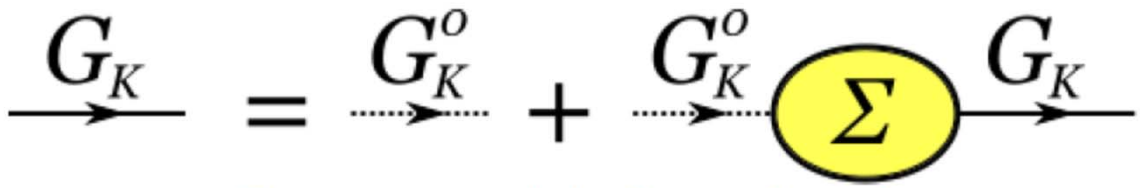


Bergemann *et al.*, Adv. Phys. **52**, 639 (2003)

http://abinit.org

LDA+DMFT

$U = 2.4eV$, $J = 0.4eV$



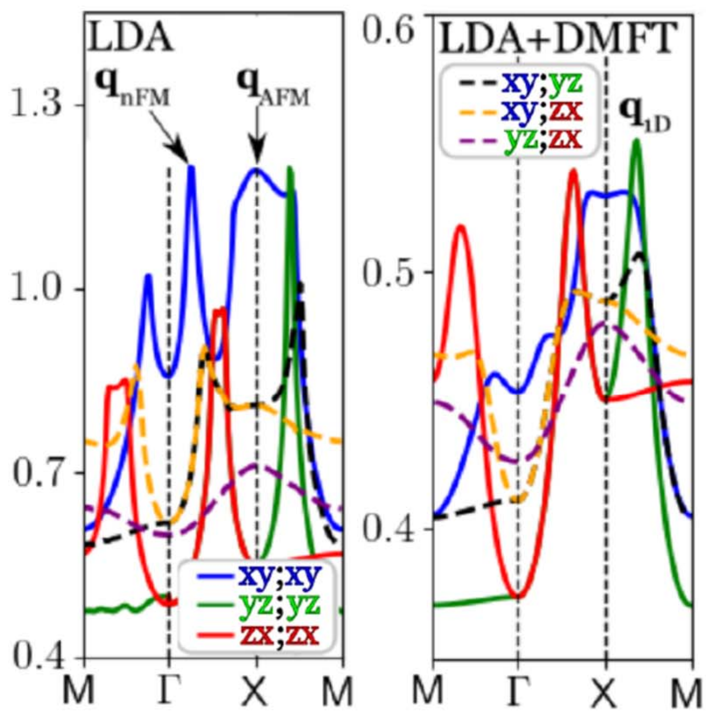
- $\boldsymbol{G}_K$: one-particle Green function
- $K \equiv (\mathbf{k}, i\omega_n)$
- $\Sigma(i\omega_n)$: Local self-energy

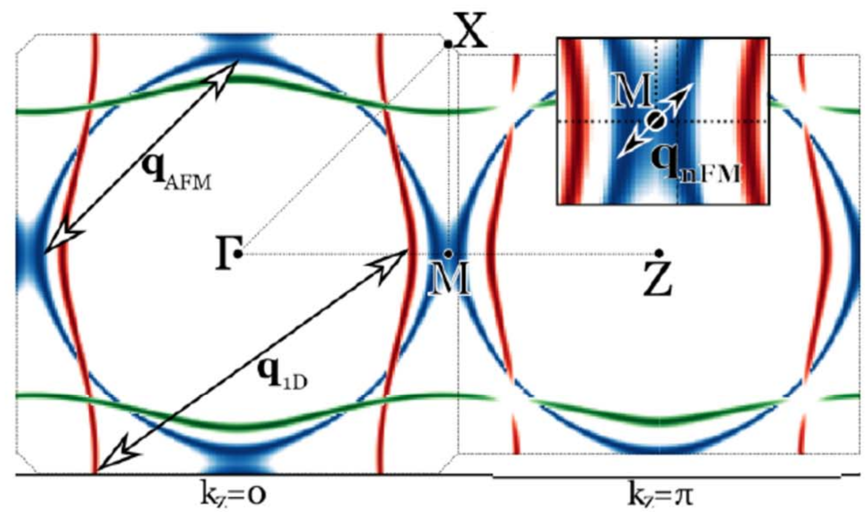
Particle-particle irreducible vertex (no SOC)

Superconductivity

$[\Gamma^{irr}_{pp}]_{Kl_1l_2;K'l_3l_4}$: **irreducible pairing vertex**

- Exchange of dressed particle-hole (ph) excitations (Spin- and Charge-fluctuations)
- Bare ph excitations characterized by bare susceptibility $\chi^0_{ph} \propto \boldsymbol{G}_{Kl_1l_3}\boldsymbol{G}_{Kl_4l_2}$





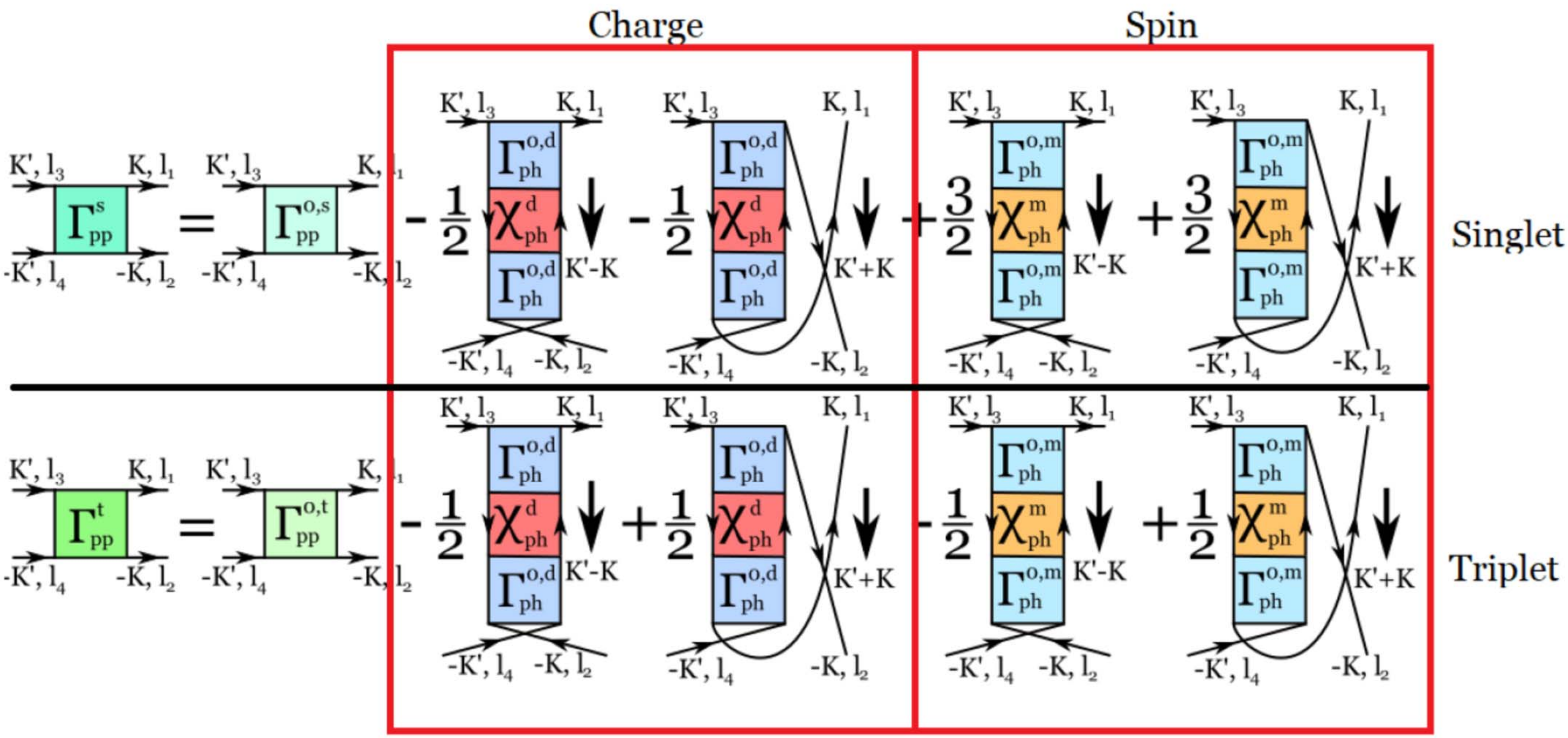
Important nesting vectors:

- ~~$\mathbf{q}_{nFM}$~~
- $\mathbf{q}_{AFM}$
- $\mathbf{q}_{1D}$

Normal state Eliashberg equations

(Meng et al. for Sr_2IrO_4, PRL **113**, 177003 (2014))

$$\lambda^{\nu}\Delta^{\nu} = -\Gamma^{irr}_{pp}\chi^{0}_{pp}\Delta^{\nu}$$



A last look at theory vs experiment

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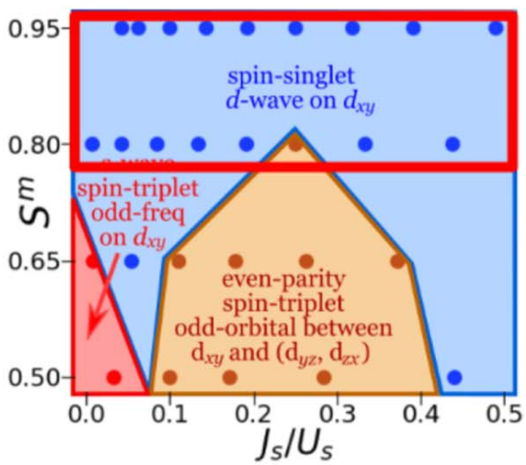
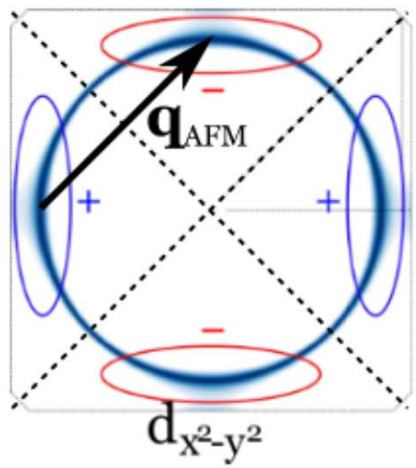
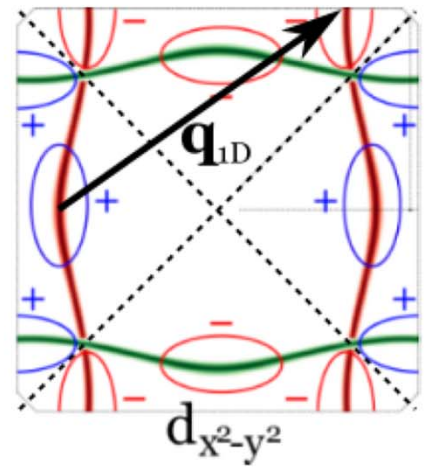
Spin-singlet d-wave



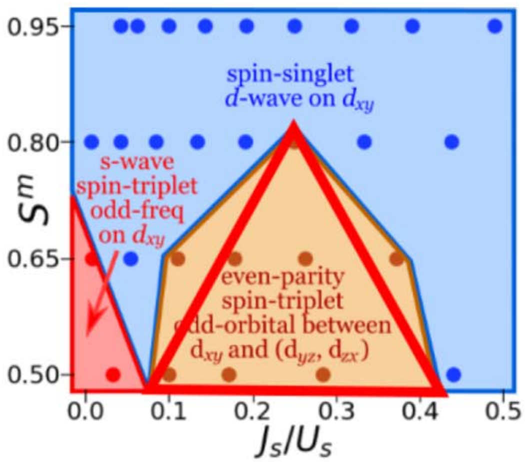




- **Large** S^m: Singlet favored, **repulsive**
- Nesting vector $\mathbf{q}_{\text{AFM}}$ on d_{xy} favors $d_{x^2-y^2}$
- Nesting vector $\mathbf{q}_{\text{1D}}$ on $d_{yz,zx}$ favors $d_{x^2-y^2}$

Spin-triplet	X
TRSB	X
Nodes	✓
No degeneracy	✓

Spin-triplet Odd-orbital *s*-wave



Inter-orbital pairing:
- Cooper pairs with electrons **on different orbitals**

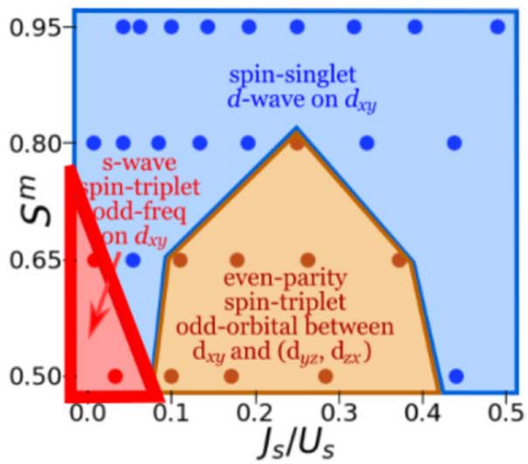
Odd-orbital (odd-o):
- $[\hat{O}\mathbf{\Delta}]_{l_1 l_2} = -[\mathbf{\Delta}]_{l_1 l_2}$

Two momentum-independent **degenerate states**:
- $s_1 \rightarrow [\mathbf{\Delta}]_{xy;yz}$ and $s_2 \rightarrow [\mathbf{\Delta}]_{xy;zx}$
- Possible **chiral** state: $s_1 + is_2$

- **Smaller** S^m: More room for triplet
- **Large** inter-orbital components of χ^0_{pp}
- **Optimal** odd-orbital pairing around $\boxed{\frac{J_s}{U_s} \sim \frac{1}{4}}$

Spin-triplet	✓
TRSB	✓
Nodes	?
No degeneracy	X

Spin-triplet Odd-frequency (Odd-ω) s-wave



- **Strong retardation effects** allows same-site pairing at different times
- **Smaller** S^m: More room for triplet
- **Smaller** J_s/U_s: Larger charge-fluctuations

- Odd-ω correlations **essential for Kerr effects**
  Komendová and Black-Schaffer, PRL **119**, 087001 (2017)
- **Gapless** but renormalization of quasiparticle spectrum
  Abrahams *et al.*, PRB **52**, 1271 (1995)
- Definitive experiment would be **ARPES** below T_C

Spin-triplet	✓
TRSB	✓
Nodes	✓
No degeneracy	✓

Conclusion

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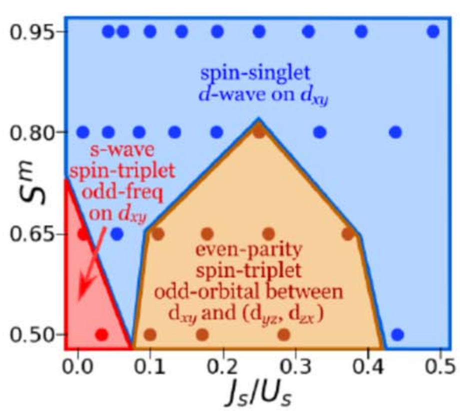
Conclusion

- Superconducting symmetry of Sr_2CuO_4 is an important question
- Spin and charge fluctuation mediated superconductivity obtained from correlated electronic structure
- Frequency-dependent symmetries found
- SOC and strain in further studies



	$p_x \pm ip_y$	d-wave	odd-o	odd-ω
Spin-triplet	✓	X	✓	✓
TRSB	✓	X	✓	✓
Nodes	✓	✓	?	✓
No degeneracy	X	✓	X	✓

We find exotic possibilities arXiv:1808.02527

Acknowledgments

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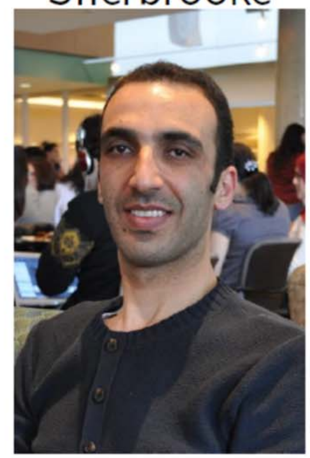
Sherbrooke



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Thank you!

Merci

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