Synchronization of Higgs Oscillations in Long-Range Interacting Superconductors

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Experimental relevance of long-range interactions

Skyrmion stabilization due to dipolar interactions

Nat. Mater. **14**, 478 (2015)
Nat. Commun. **8**, 1 (2017)
Nat. Commun. **11**, 1 (2020)

Tunable long-range spin interactions in trapped ion chains

Science **340**, 583 (2013)
Nature **511**, 198 (2014)
Nature **511**, 202 (2014)
Rev. Mod. Phys. **93**, 025001 (2021)

Long-range interactions in cold atoms using atomic dipolar interactions or van der Waals interactions between Rydberg states

Rev. Mod. Phys. **82**, 2313 (2010)
Nature **534**, 667 (2016)
Science **357**, 995 (2017)

Superconductivity + long-range Interactions

Long-range pairing in heterostructures (possible Majorana modes)

Phys. Rev. Lett. **120**, 017001 (2018)

Science **346**, 602 (2014)

Phys. Rev. B **88**, 165111 (2013)

Long-range SC in THz nanoplasmonic cavities

Phys. Rev. Lett. **125**, 053602 (2020)

Phys. Rev. Lett. **126**, 173601 (2021)

Phys. Rev. Lett. **127**, 177002 (2021)

Nat. Comm. **12**, 5901 (2021)

Phonon mediated long-range pairing

Science **373**, 1235 (2021)

Phys. Rev. Lett. **127**, 197003 (2021)

Generalized BCS equation for long-range interactions

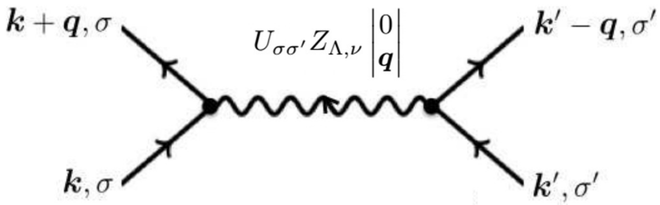
- Starting from tight-binding Hamiltonian with on-site + long-range interactions

$$H = H_0 + H_{\text{int}} \qquad H_{\text{int}} = \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\boldsymbol{x},\boldsymbol{y}\in\Lambda} c^\dagger_{\sigma,\boldsymbol{x}} c^\dagger_{\sigma',\boldsymbol{x}-\boldsymbol{y}} V_{\sigma\sigma'}(\boldsymbol{y}) c_{\sigma',\boldsymbol{x}-\boldsymbol{y}} c_{\sigma,\boldsymbol{x}}$$

$$V_{\sigma\sigma'}(\boldsymbol{0}) = -C_{\sigma\sigma'} \leq 0 \qquad V_{\sigma\sigma'}(\boldsymbol{y}) = -U_{\sigma\sigma'}\frac{1}{|\boldsymbol{y}|^\nu} \leq 0$$

- Fourier transformation naturally leads to a representation in terms of Epstein zeta function:

$$H_{\text{int}} = -\frac{V_\Lambda}{2}\sum_{\sigma,\sigma'}\int_{E^*}\int_{E^*}\fint_{E^*}\left(C_{\sigma\sigma'} + U_{\sigma\sigma'} Z_{\Lambda,\nu}\begin{vmatrix}0\\ \boldsymbol{q}\end{vmatrix}\right) c^\dagger_\sigma(\boldsymbol{k}+\boldsymbol{q}) c^\dagger_{\sigma'}(\boldsymbol{k}'-\boldsymbol{q}) c_{\sigma'}(\boldsymbol{k}') c_\sigma(\boldsymbol{k})\,\mathrm{d}\boldsymbol{q}\,\mathrm{d}\boldsymbol{k}\,\mathrm{d}\boldsymbol{k}'$$



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Generalized BCS equation for long-range interactions

- Mean-field leads to standard BCS form of the Hamiltonian

$$H_{\text{int}} = -\frac{1}{2}\sum_{\sigma,\sigma'}\int_{E^*} \left(\Delta_{\sigma\sigma'}(\boldsymbol{k})c_\sigma^\dagger(\boldsymbol{k})c_{\sigma'}^\dagger(-\boldsymbol{k}) + \text{h.c.}\right)\mathrm{d}\boldsymbol{k}$$

$$\Delta_{\sigma\sigma'}(\boldsymbol{k}) = V_\Lambda \fint_{E^*} \left(C_{\sigma\sigma'} + U_{\sigma\sigma'} Z_{\Lambda,\nu}\left|\begin{matrix}0\\ \boldsymbol{q}\end{matrix}\right|\right)\alpha_{\sigma\sigma'}(\boldsymbol{k}-\boldsymbol{q})\,\mathrm{d}\boldsymbol{q}$$

with

$$\alpha_{\sigma\sigma'}(\boldsymbol{k}) = \int_{E^*}\langle c_{\sigma'}(\boldsymbol{k}')c_\sigma(\boldsymbol{k})\rangle\,\mathrm{d}\boldsymbol{k}'$$

- Singularity of Epstein zeta at **q**=0 corresponds to long-range tail of interaction
- Requires Singular Euler Maclaurin Expansion (SEM) for evaluation

$$Z_{\Lambda,\nu}\left|\begin{matrix}0\\ \boldsymbol{q}\end{matrix}\right| = \frac{\hat{s}_\nu(\boldsymbol{q})}{V_\Lambda} + Z_{\Lambda,\nu}^{\text{reg}}\left|\begin{matrix}0\\ \boldsymbol{q}\end{matrix}\right|$$

w/ continuum FT of interaction:

$$\hat{s}(\boldsymbol{y}) = \pi^{\nu-d/2}\frac{\Gamma((d-\nu)/2)}{\Gamma(\nu/2)}|\boldsymbol{y}|^{\nu-d}$$

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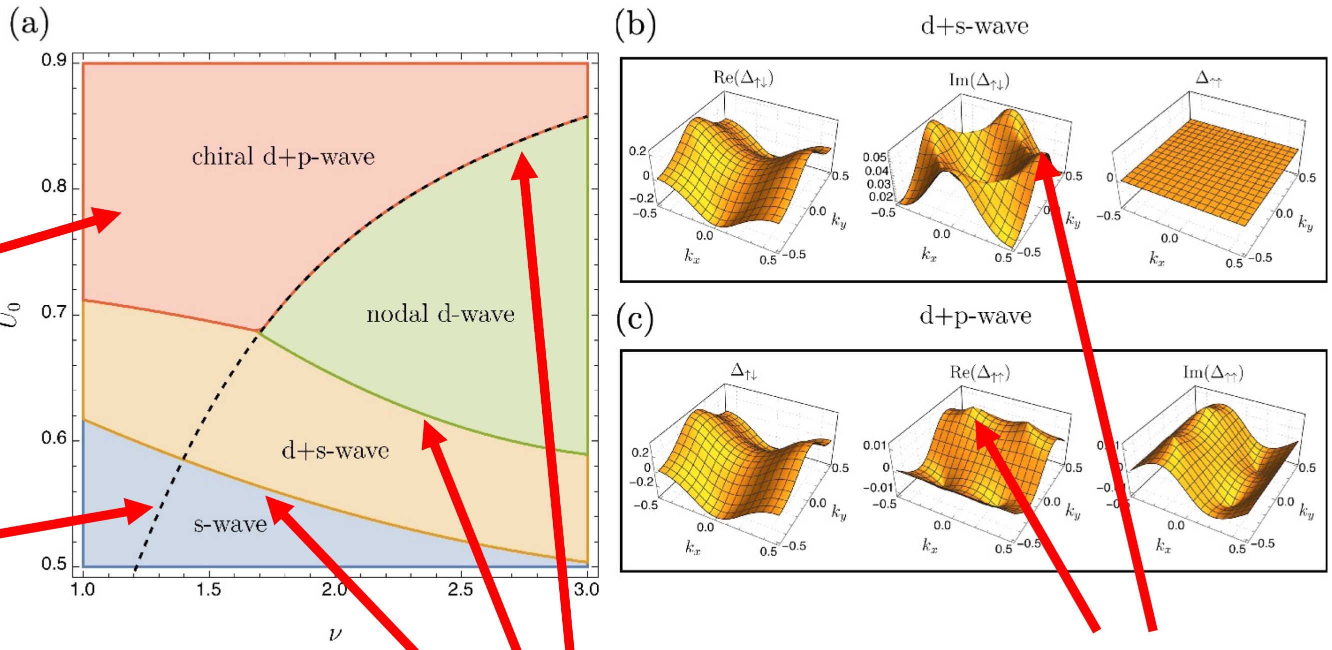
Solutions in 2D

- Phase diagram for square lattice, nearest-neighbour hopping, half-filling, C_0 = 0.75



Non-trivial topological phase

C_0 = 0 phase boundary

Continuous phase transitions

Cusp at Fermi surface

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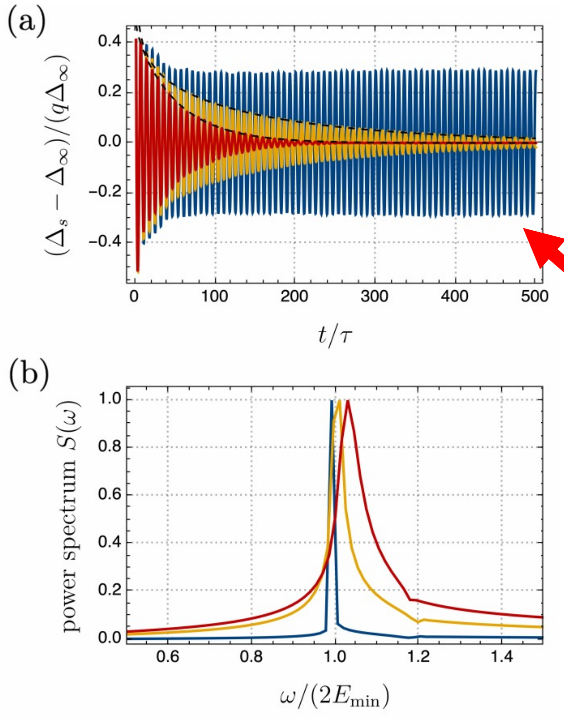
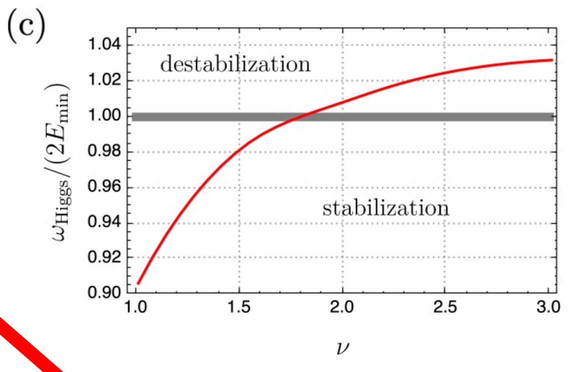
Higgs mode tunability by long range interactions

- Starting in s-wave phase, small quenches $C_0 \to (1-q)C_0$, $U_0 \to (1-q)U_0$ w/ $q = 10^{-2}$





Higgs mode stabilization or destabilization possible due to quasiparticle scattering

Higgs mode damping and frequency depends on interaction exponent

Schwarz, L., Fauseweh, B., Tsuji, N. *et al.* Classification and characterization of nonequilibrium Higgs modes in unconventional superconductors. *Nat Commun* **11**, 287 (2020). https://doi.org/10.1038/s41467-019-13763-5

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Higgs mode synchronization in mixed phases

- Higgs oscillations after in quench in topological p+d phase
- Two component oscillations
  (red = d-wave), (black = p-wave)

d-wave component decays quickly

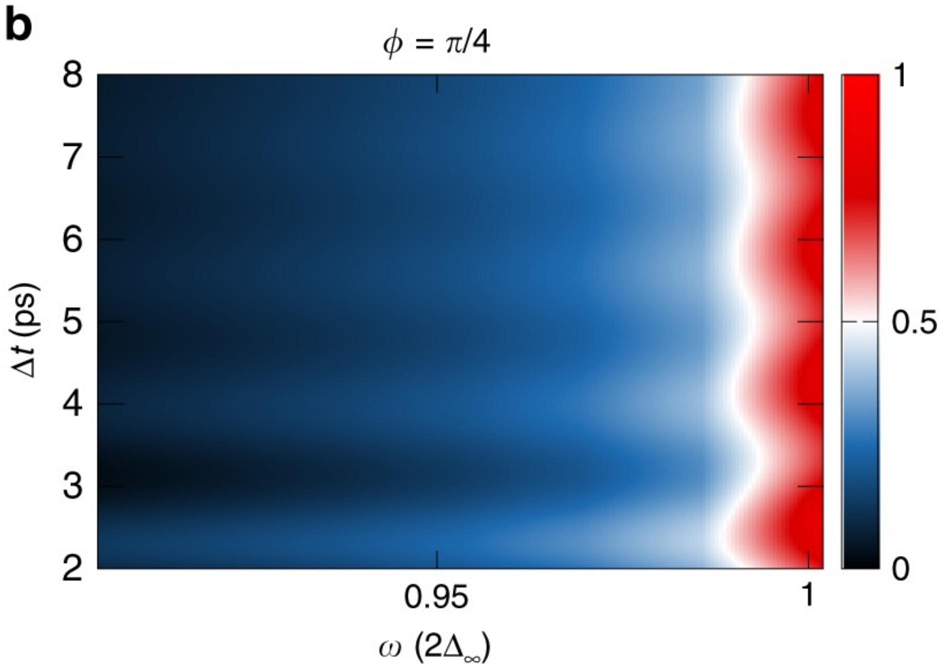
p-wave shows stable oscillations

After decay: d-wave and p-wave synchronize

Buchheit, Kessler, Fauseweh, tba

Higgs mode in optical conductivity

- Higgs oscillations visible in pump-probe spectroscopy
- So far: s-wave and d-wave superconductors
- Proposal: Measure Higgs synchronization through time resolved optical conductivity



https://doi.org/10.1103/PhysRevB.101.180507
https://doi.org/10.1103/PhysRevB.101.224510
https://doi.org/10.1103/PhysRevB.102.165128
https://doi.org/10.1103/PhysRevB.103.224305

Schwarz, L., Fauseweh, B., Tsuji, N. *et al.* Classification and characterization of nonequilibrium Higgs modes in unconventional superconductors. *Nat Commun* **11**, 287 (2020). https://doi.org/10.1038/s41467-019-13763-5

Thank you!