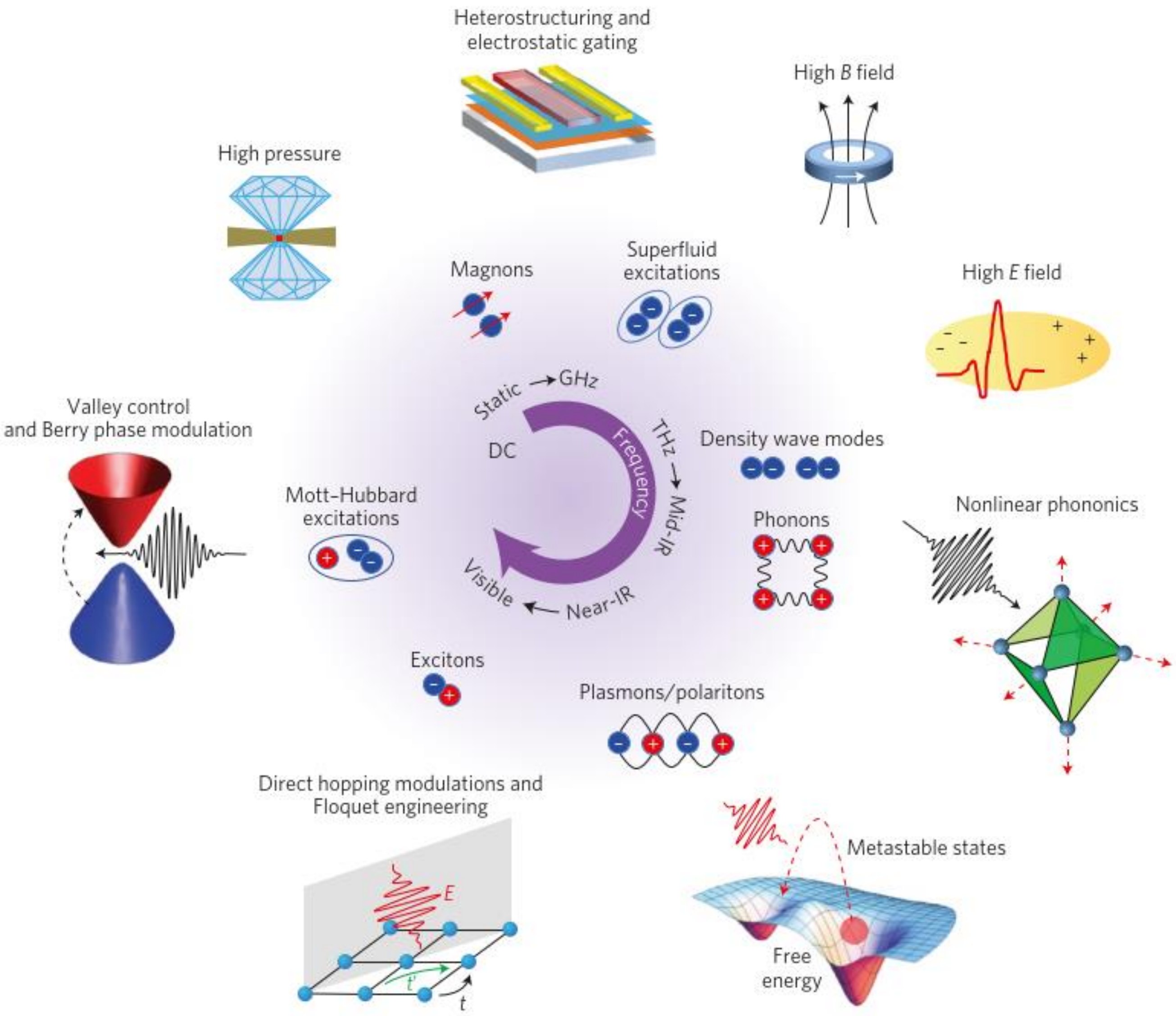
Multiple optical gaps and lasing in 2D Ising superconductors

Mikhail Silaev (Tampere University, Finland)

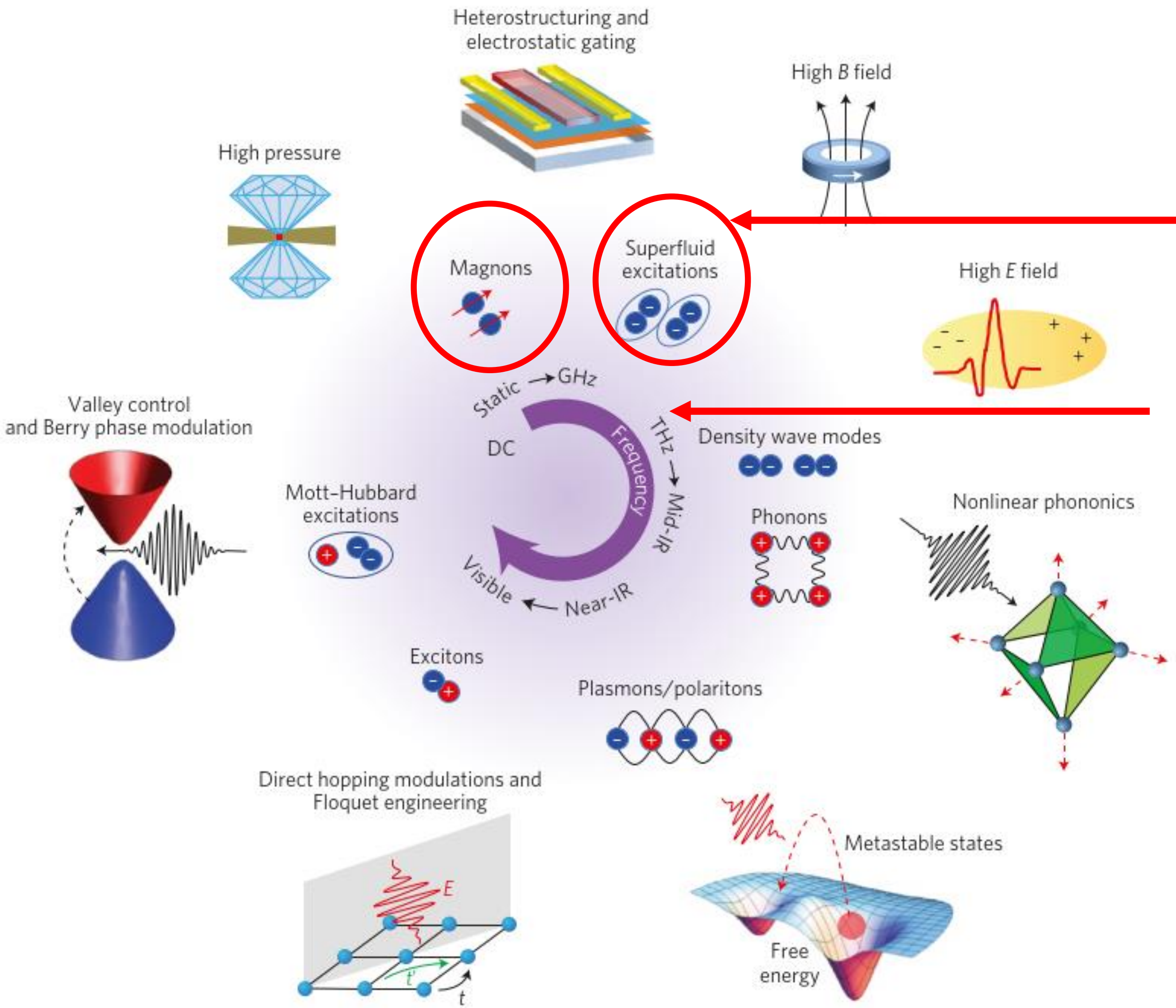
PRB 99, 224511 (2019)
arXiv:2111.03623

Properties on demand in quantum materials



Basov, Averitt & Hsieh, Nat. Mat. 16, 1077 (2017)

Properties on demand in quantum materials



Quantum technologies, spintronics

THz: High-speed communication, imaging, etc

Basov, Averitt & Hsieh, Nat. Mat. 16, 1077 (2017)

Properties on demand in quantum materials

In typical superconductors (Nb) $T_c = 10\ K \rightarrow \Delta \approx 0.5\ THz$

Outline:

Interaction of THz light with superconductors can

- Excite collective modes
- Probe unconventional pairing in Ising SC

Interaction of superconductors with light

IR conductivity of superconductors

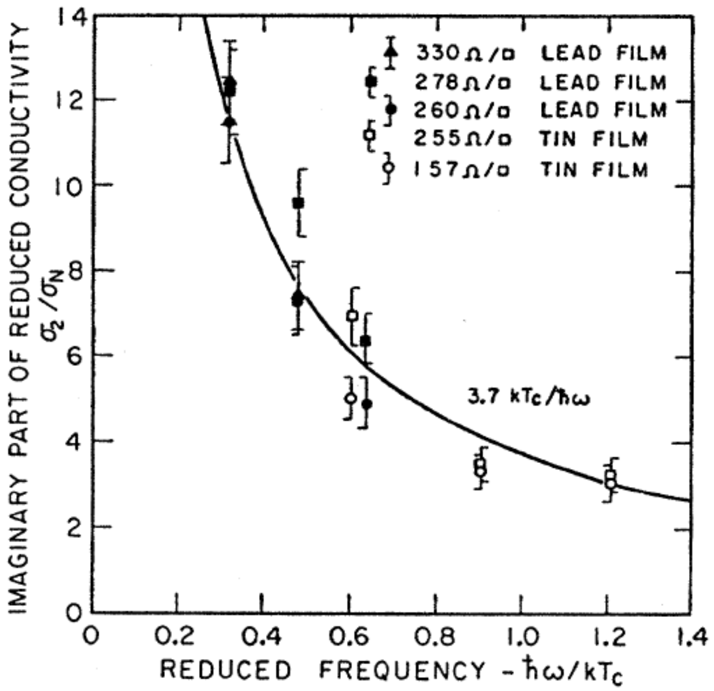
PHYSICAL REVIEW VOLUME 108, NUMBER 2 OCTOBER 15, 1957

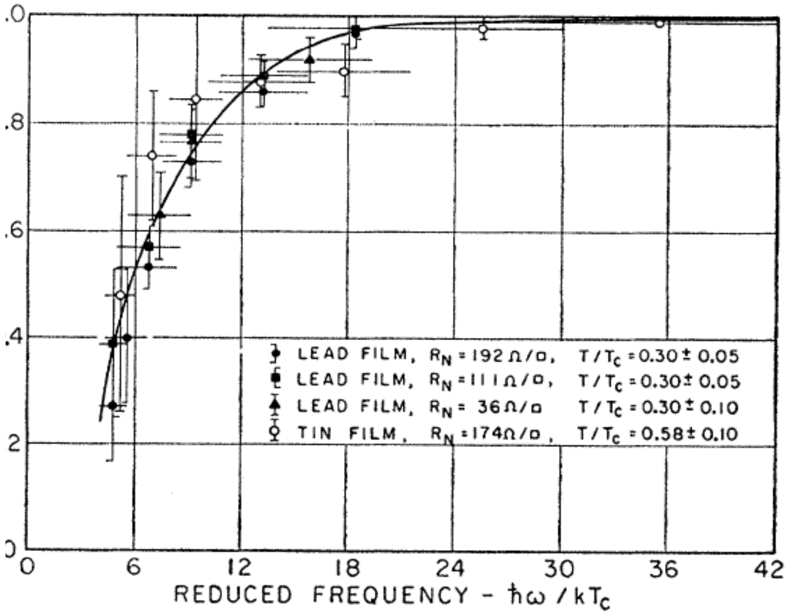
Conductivity of Superconducting Films for Photon Energies between 0.3 and $40kT_c$*

R. E. GLOVER, III,† *University of California, Berkeley, California and University of North Carolina, Chapel Hill, North Carolina*

AND

M. TINKHAM, *University of California, Berkeley, California*





6. Frequency dependence of σ_1/σ_N for several lead and tin films in the superconducting state.

T_c= 7 K

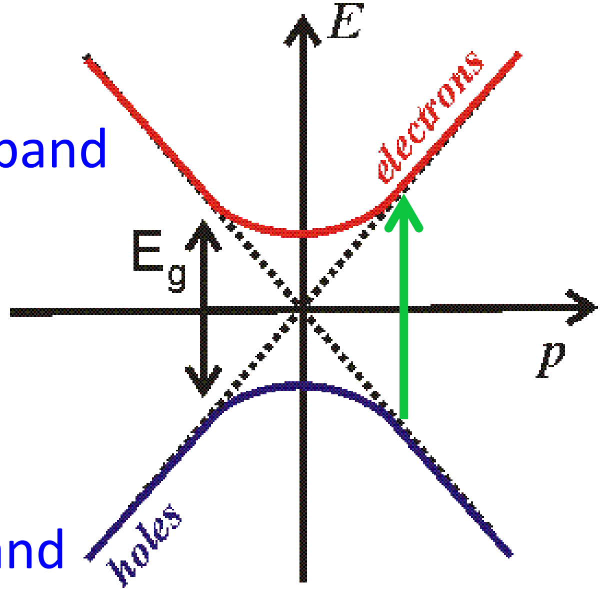
ω= 0.04 -6 THz

Absorption mechanism

$$\hat{H}_{BdG}\Psi = E\Psi$$

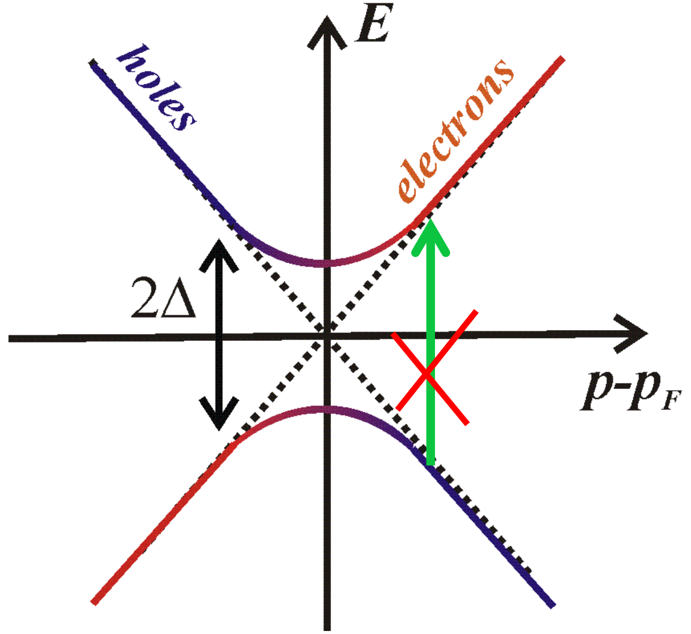
Band insulators

Conduction band



Valence band

Superconductors



Electron-hole symmetry prohibits vertical transitions.

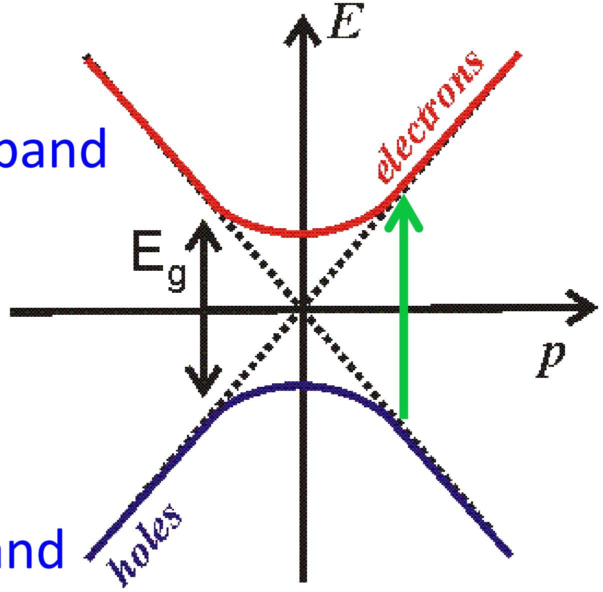
$$\hat{V}_A = \boldsymbol{pA}$$

$$\langle\Psi(E)|\hat{V}_A|\Psi(-E)\rangle = (\boldsymbol{pA})\langle\Psi(E)|\Psi(-E)\rangle = 0$$

Absorption mechanism

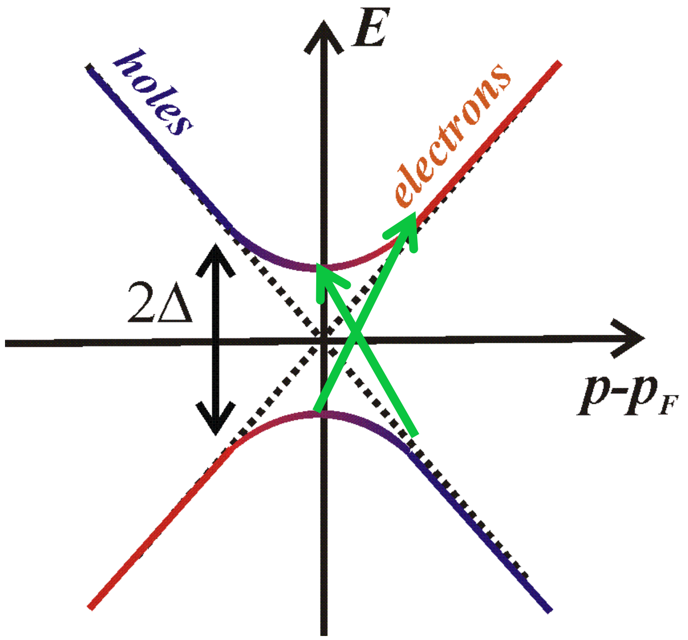
Band insulators

Conduction band



Valence band

Superconductors



Electron-hole symmetry prohibits vertical transitions.

We need impurity scattering

8

Theory of the Anomalous Skin Effect in Normal and Superconducting Metals*

D. C. MATTIS† AND J. BARDEEN
Department of Physics, University of Illinois, Urbana, Illinois
(Received February 24, 1958)

Impurity scattering is introduced phenomenologically into the electron density matrix

$$\rho_\epsilon(R)=\frac{\sin kR}{kR}e^{-R/2l}.$$

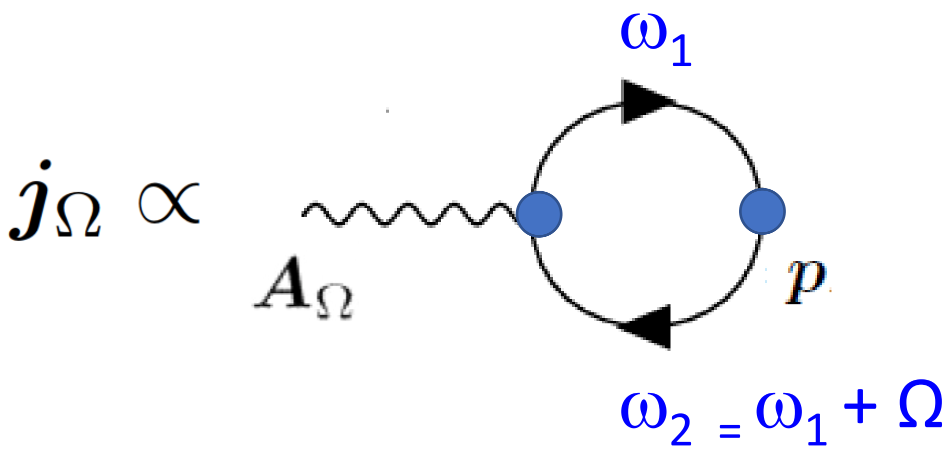
$$\mathbf{j}(\mathbf{r},t)=\sum_\omega \frac{e^2N(0)v_0}{2\pi^2\hbar c}\int\frac{\mathbf{R}[\mathbf{R}\cdot\mathbf{A}_\omega(r')]I(\omega,R,T)e^{-R/l}dr'}{R^4}$$

"Dirty" limit $l \ll \xi$:

Re (σ)

$$\frac{\sigma_1}{\sigma_N}=\frac{2}{\hbar\omega}\int_{\epsilon_0}^{\infty}[f(E)-f(E+\hbar\omega)]g(E)dE+\frac{1}{\hbar\omega}\int_{\epsilon_0-\hbar\omega}^{-\epsilon_0}[1-2f(E+\hbar\omega)]g(E)dE,$$

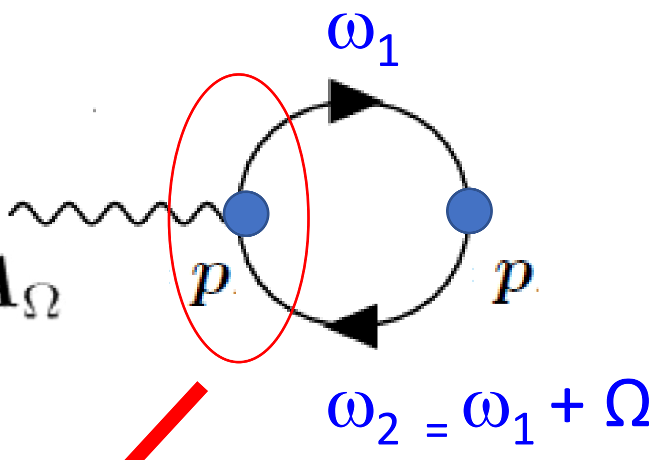
Quasiclassical Green's function approach



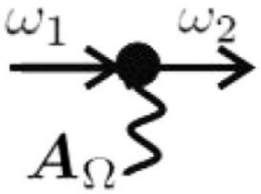
Abrikosov, Gor'kov, Dzyaloshinskiy, *Methods of Quantum Fields Theory in Statistical Physics*

Quasiclassical Green's function approach

$j_\Omega \propto$



$\hat{G}_A(12) =$



$$\hat{g}_A = \nu \int dp \hat{G}_A$$

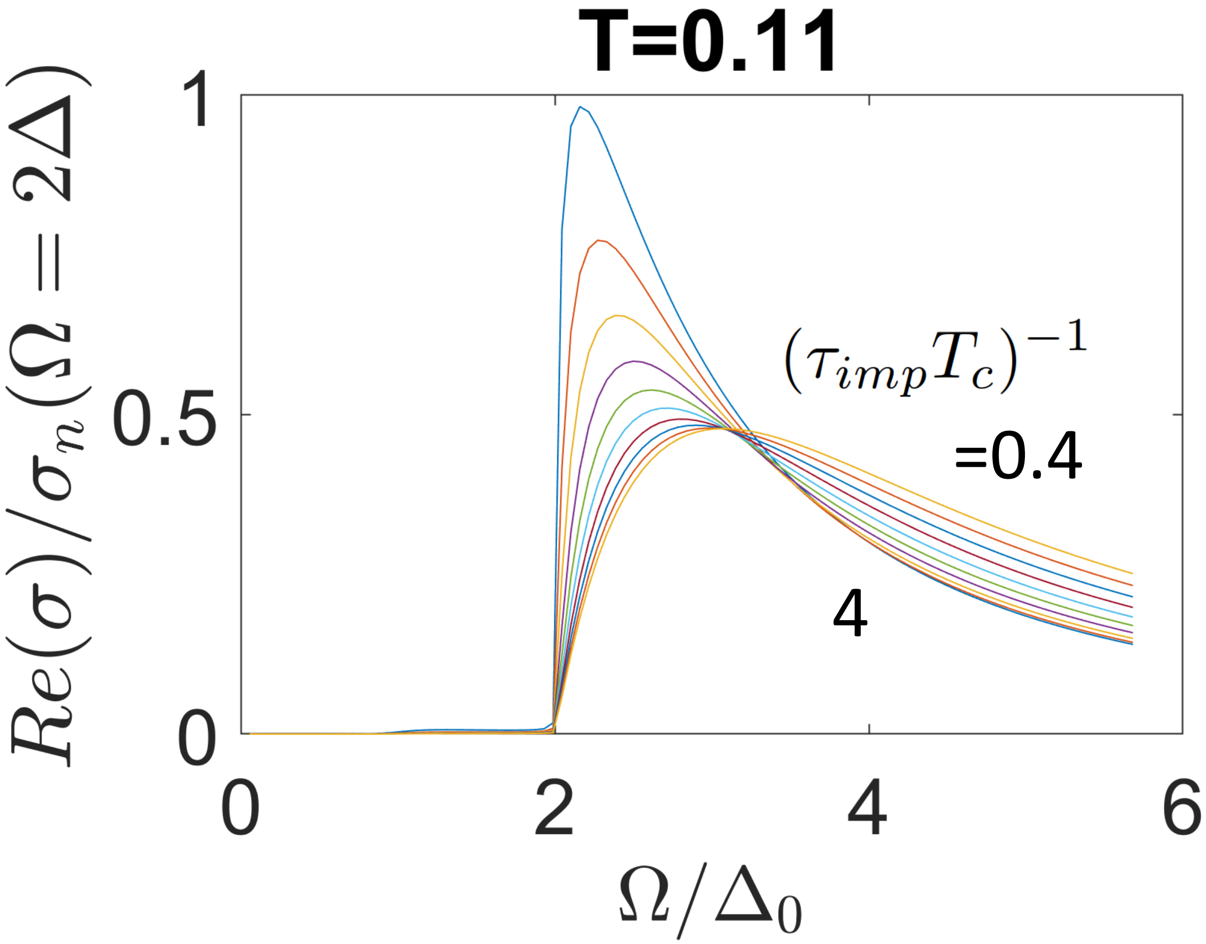
$$\frac{ie}{c} v_F [\hat{\tau}_3 \boldsymbol{A}, \hat{g}]_t = -i\{\hat{\tau}_3 \partial_t, \hat{g}\}_t + i[\hat{\tau}_3 \hat{\Delta}, \hat{g}]_t + \frac{1}{2\tau_{imp}}[\langle \hat{g} \rangle \circ, \hat{g}]_t$$

G. Eilenberger, Z. Phys. 214, 195 (1968)

Quasiclassical Green's function approach

$$\frac{\sigma(\Omega)}{\sigma_n} = \frac{T}{\Omega}\sum_{\omega_1}\frac{(\omega_1\omega_2 - \Delta^2)\tau_{imp}}{s_1 s_2(s_1 + s_2 + \tau_{imp}^{-1})} \qquad \omega_2 = \omega_1 + \Omega$$

analytic continuation
to real frequencies



Zimmerman et al,
Physica C 183 (1991) 99-104

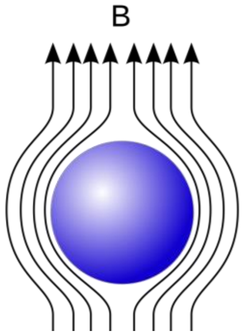
Non-linear optics in superconductors

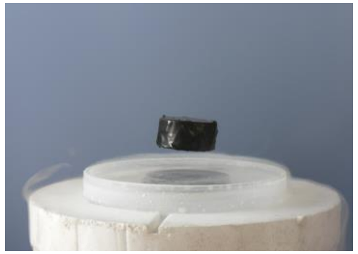
Light-induced Higgs mode

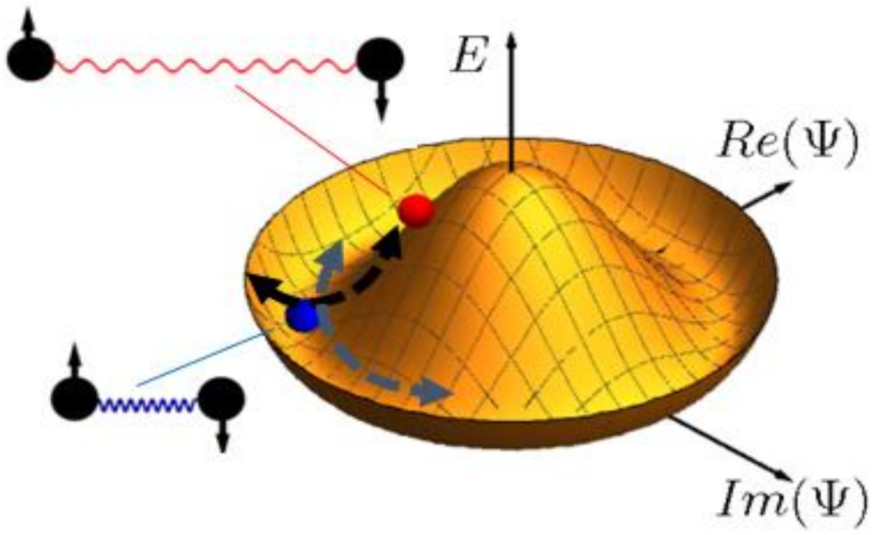
Higgs field

High-energy: scalar field providing the gauge symmetry breaking mass of electroweak W and Z bosons, electrons and other particles (Higgs, PRL 1964)

Superconductors: Meissner effect

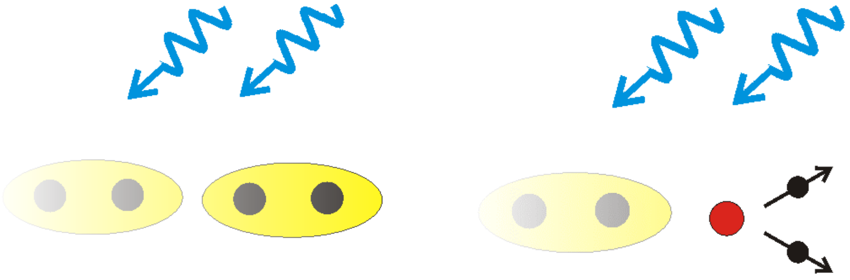


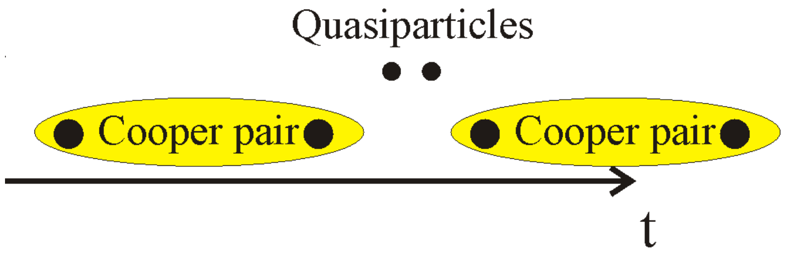




Higgs mode / boson: Oscillations of the order parameter Higgs field amplitude

Way to observe HM: Excitation of usual superconductor with light- nonlinear optics.





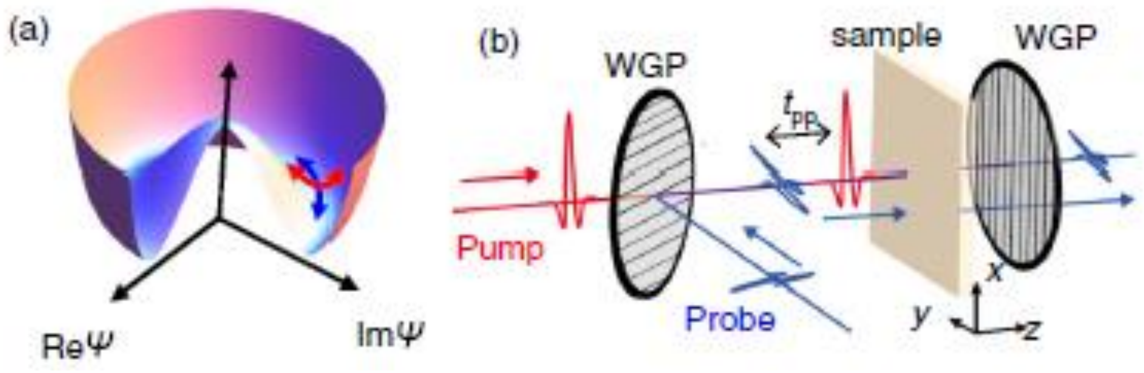
Light-induced Higgs mode

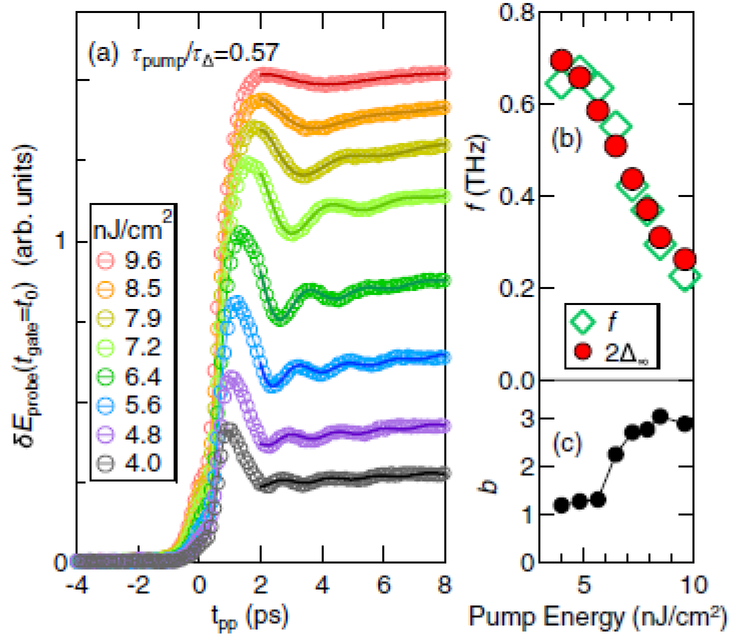
NbTiN Tc=15K,
Δ0=0.75 THz

THz pump-probe spectroscopy
of Higgs mode

THz pumps Ω=1.75 THz < 2Δ(0)

Matsunada et al PRL 111, 057002 (2013)





$$\tilde{\Delta}(t) \propto \frac{e^{2i\Delta_0 t}}{\sqrt{\Delta_0 t}}$$

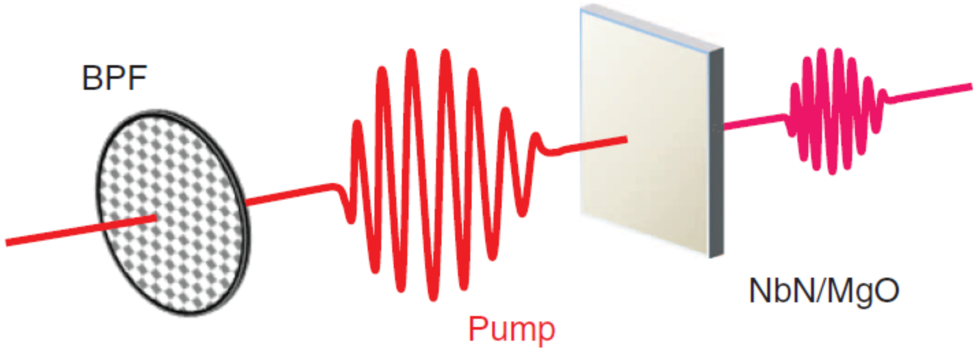
Volkov, Kogan, JETP 38, 1018 (1974)].

Light-induced Higgs mode

NbN Tc=15K,
Δ0=0.75 THz

Resonant 3rd harmonic generation in transmission spectroscopy

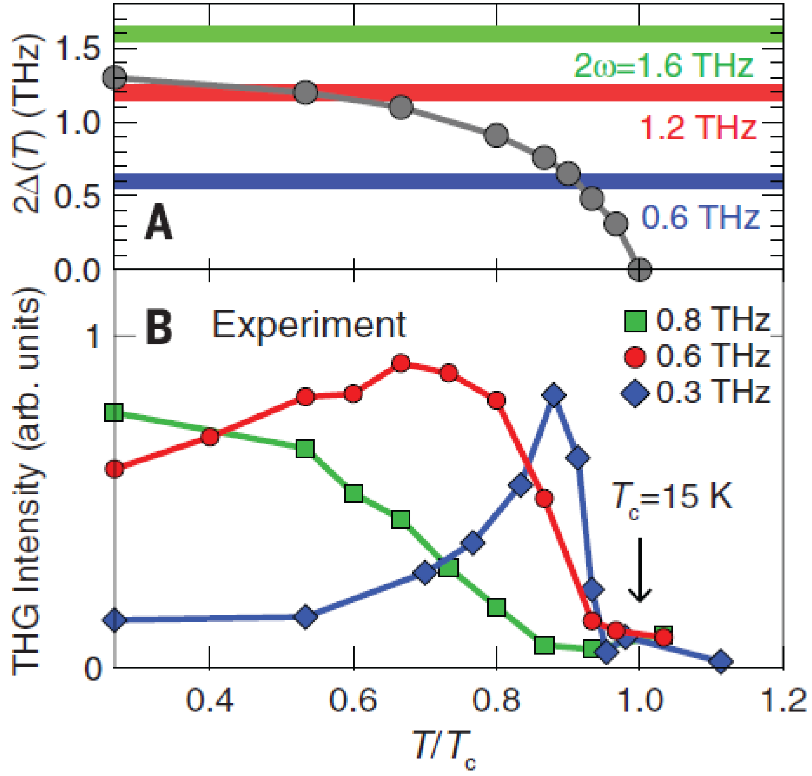
Matsunaga, et al, Science 345, 1145 (2014).



$$A(t) = A_\Omega e^{i\Omega t}$$

$$\Delta_{2\Omega} \propto A_\Omega^2$$

$$j_H(3\Omega) \propto A_\Omega \Delta_{2\Omega}$$

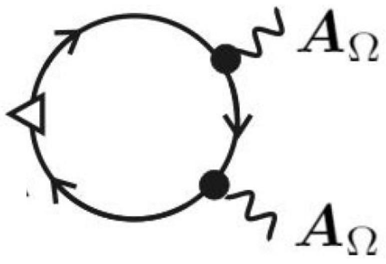


Resonant behavior of 3rd harmonic Ω=Δ(T)

Mechanism of THG and Higgs mode excitation by light

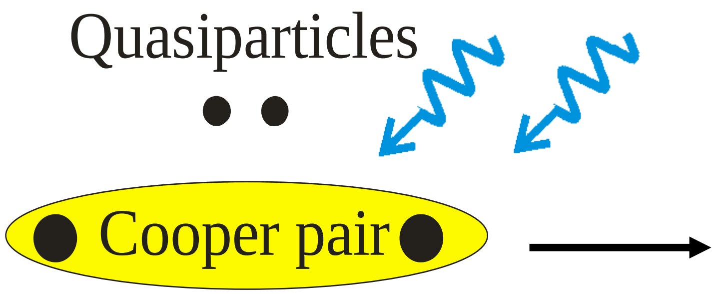
Clean limit: no coupling

$\Delta_{2\Omega}$ =



=0

This can be interpreted as a Galilean invariance:

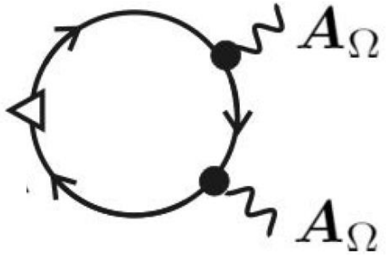


$$\boldsymbol{V}(t) = \frac{e\boldsymbol{A}(t)}{mc}$$

Mechanism of THG and Higgs mode excitation by light

Clean limit: no coupling

$\Delta_{2\Omega}$ =



=0

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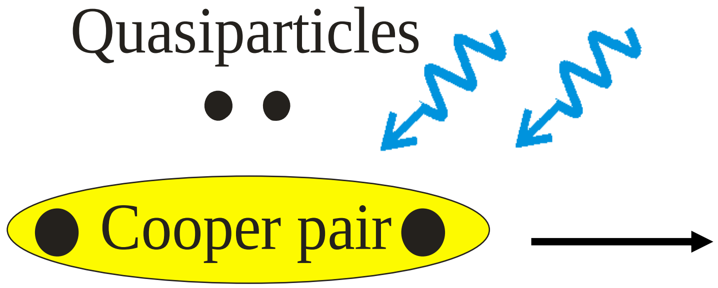
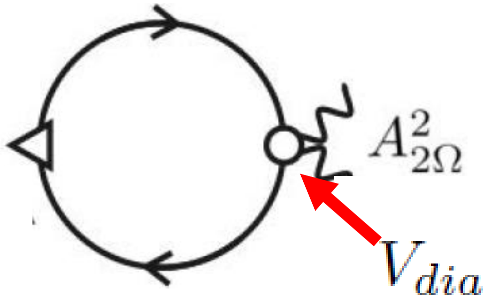


$$\boldsymbol{V}(t) = \frac{e\boldsymbol{A}(t)}{mc}$$

Correlation-based mechanisms

Tsuji, Aoki, PRB 92, 064508 (2012)

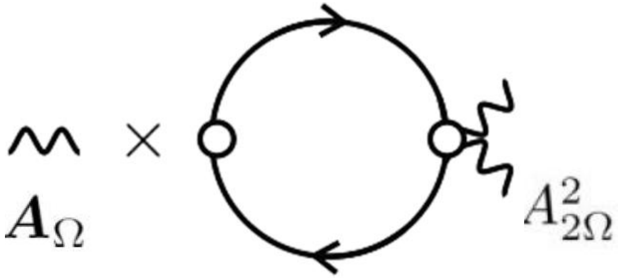
$\Delta_{2\Omega}$ =



$$V_{dia} = \hat{\tau}_3 \frac{\boldsymbol{A}^2}{2m}$$

Cea, Castellani, Benfatto, PRB, 93, 180507 (2016)

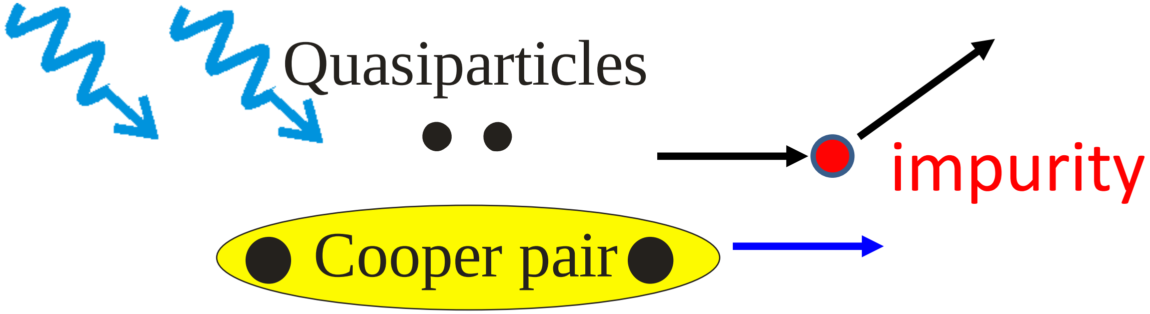
$j^{(d)}_{AAA} =$

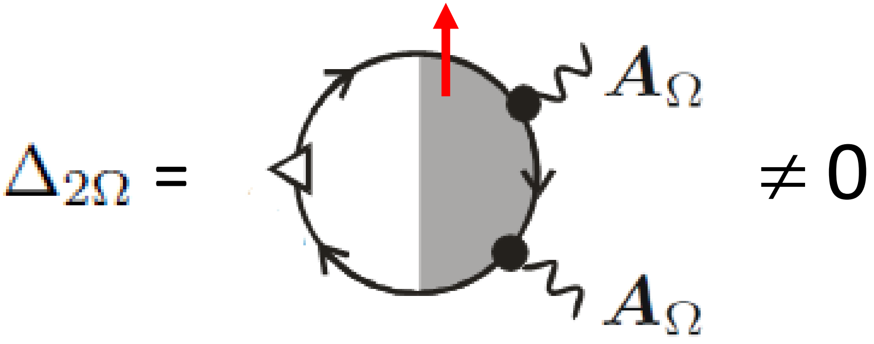


Mechanism of Higgs mode excitation by light

Let's break Galilean invariance

Impurity ladder





PHYSICAL REVIEW B **99**, 224511 (2019)

Editors' Suggestion

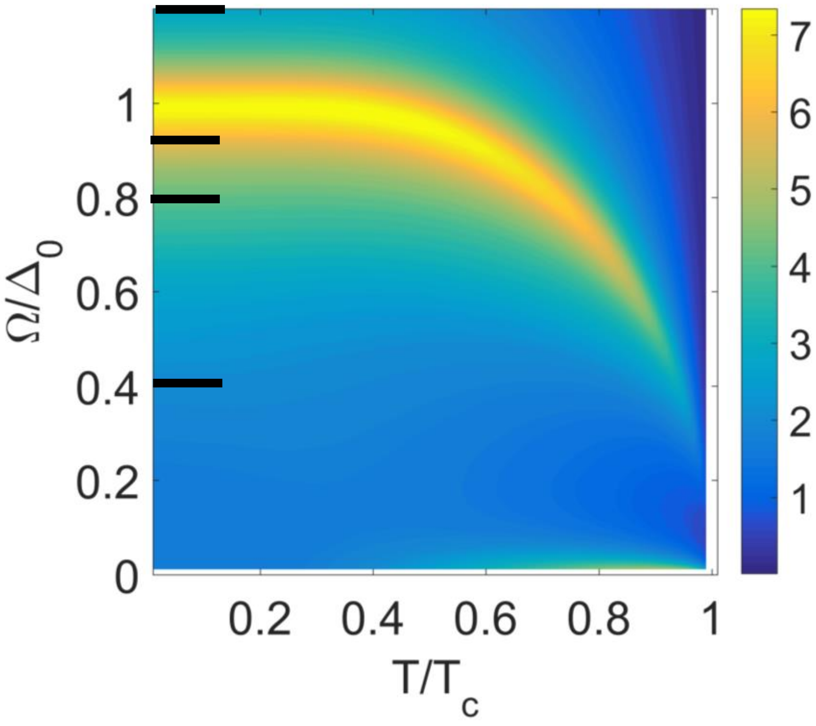
Nonlinear electromagnetic response and Higgs-mode excitation in BCS superconductors with impurities

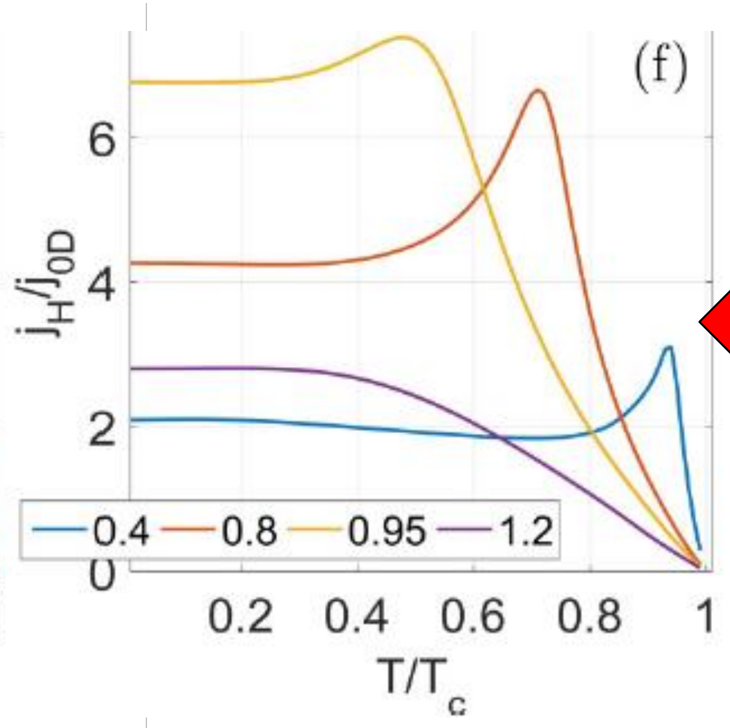
Mikhail Silaev

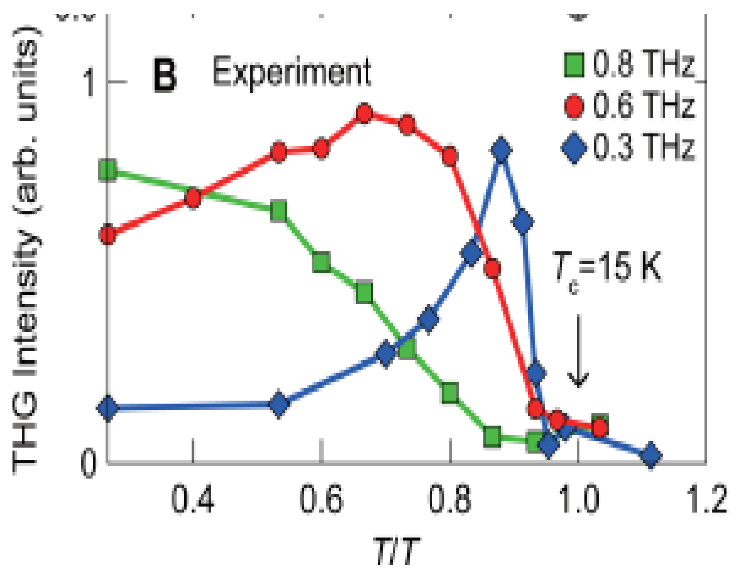
Department of Physics and Nanoscience Center, University of Jyväskylä, P.O. Box 35 (YFL), FI-40014 University of Jyväskylä, Finland

Mechanism of Higgs mode excitation by light

Third harmonic current





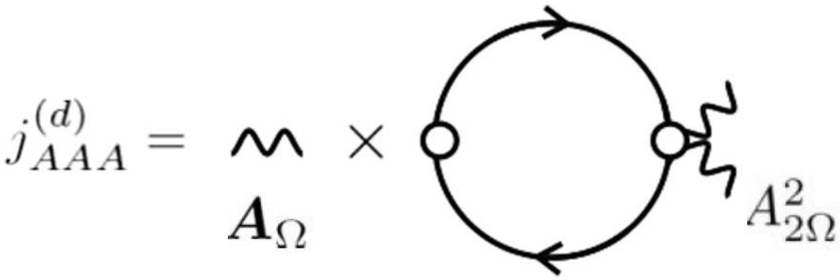


Matsunaga, et al,
Science 345, 1145 (14).

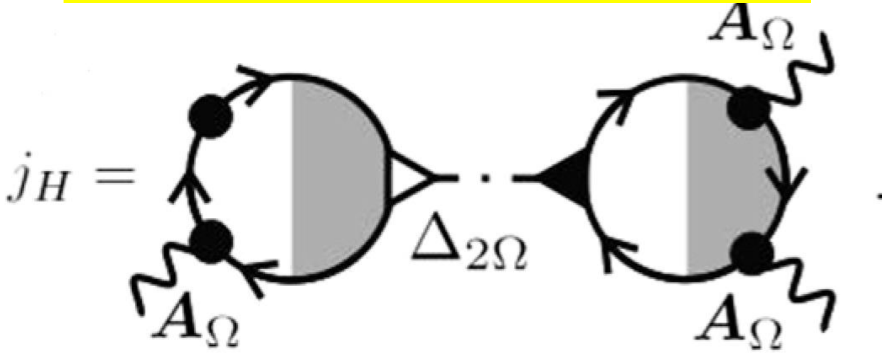
Silaev, PRB 99, 224511 (19)

Correlation effects masked by disorder

Correlations- induced



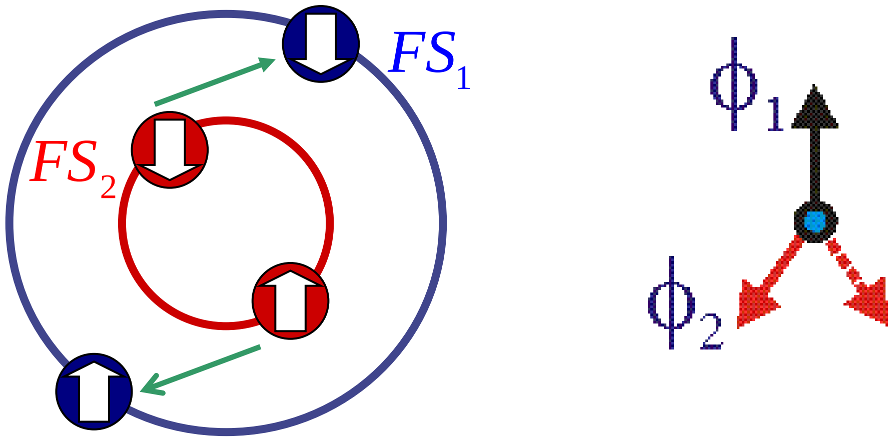
Disorder- induced



$$\boxed{\tau_{\text{imp}} T_c > 10^{-3} \left(\frac{E_F}{T_c} \right)^2}$$

Other collective modes

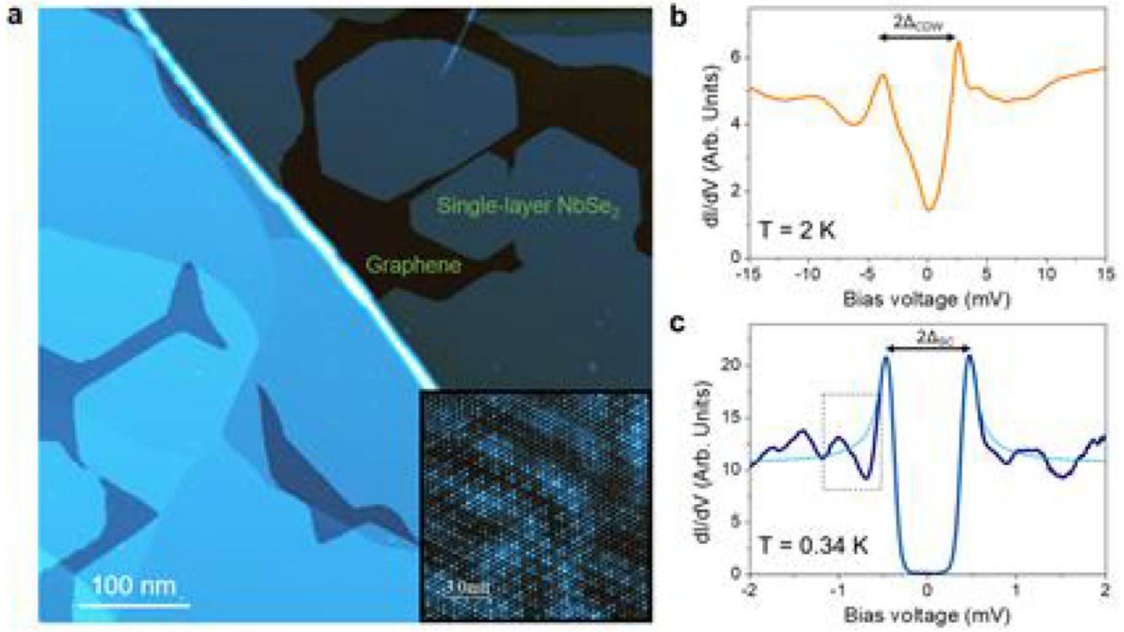
Leggett mode:



Interband tunneling produces phase excitation – the Leggett mode

Leggett, PTP (1966);

Collective Modes in Single-layer $NbSe_2$

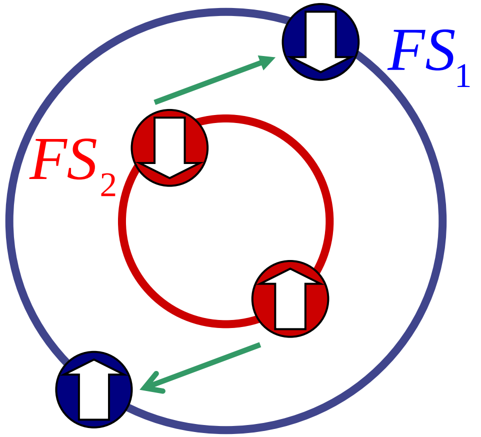


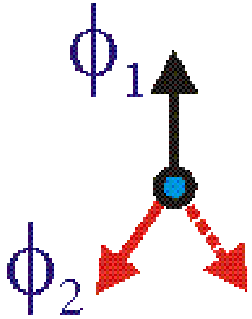
Wan W. et al. Advanced Materials (2022)

Other collective modes

Leggett mode in MgB_2

Leggett mode:

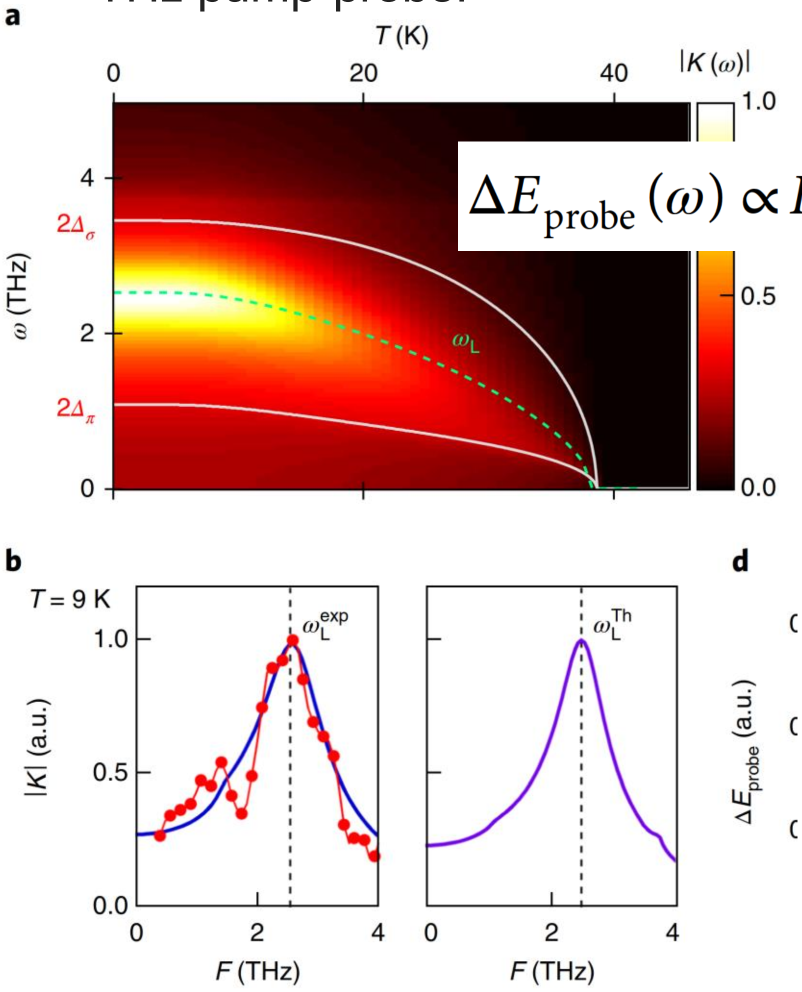




Interband tunneling produces phase excitation – the Leggett mode

Leggett, PTP (1966);

THz pump-probe:



$$\Delta E_{\mathrm{probe}}(\omega) \propto K(\omega)\bar{A}^{2}_{\mathrm{pump}}(\omega)$$

Giorgianni, et al Nat. Phys. 15, 341 (2019)

Correlations: spontaneous decay of collective modes

Decay of Higgs boson

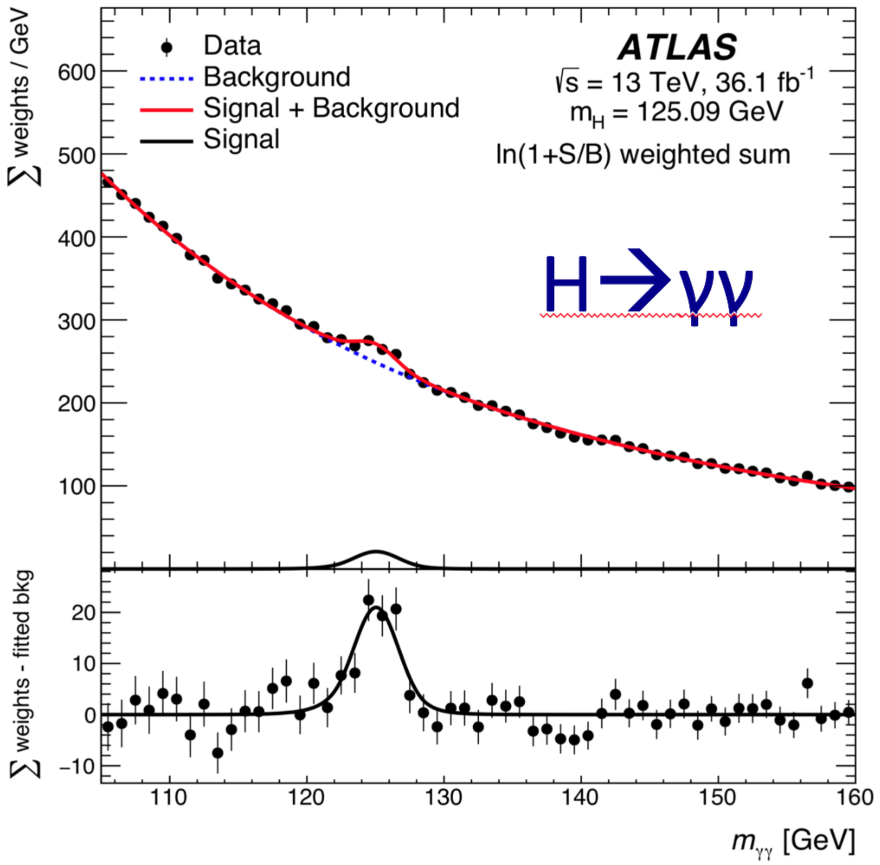
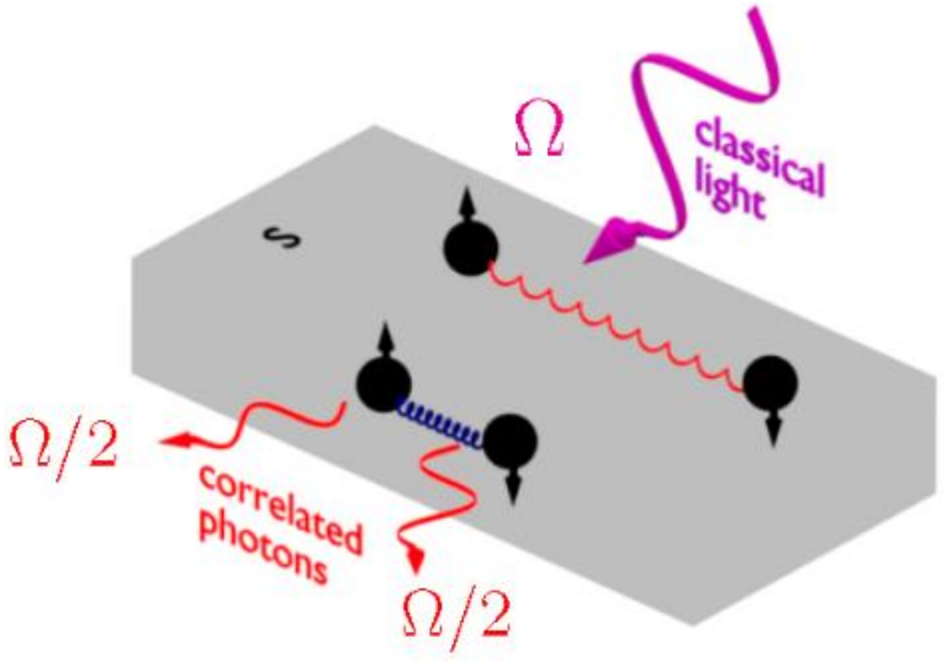


Figure from
https://msneubauer.github.io/projects/4_project/

Decay of superconducting Higgs mode



Main message:

Because of disorder light is directly coupled to the collective modes in superconductors

Stimulated superconductivity

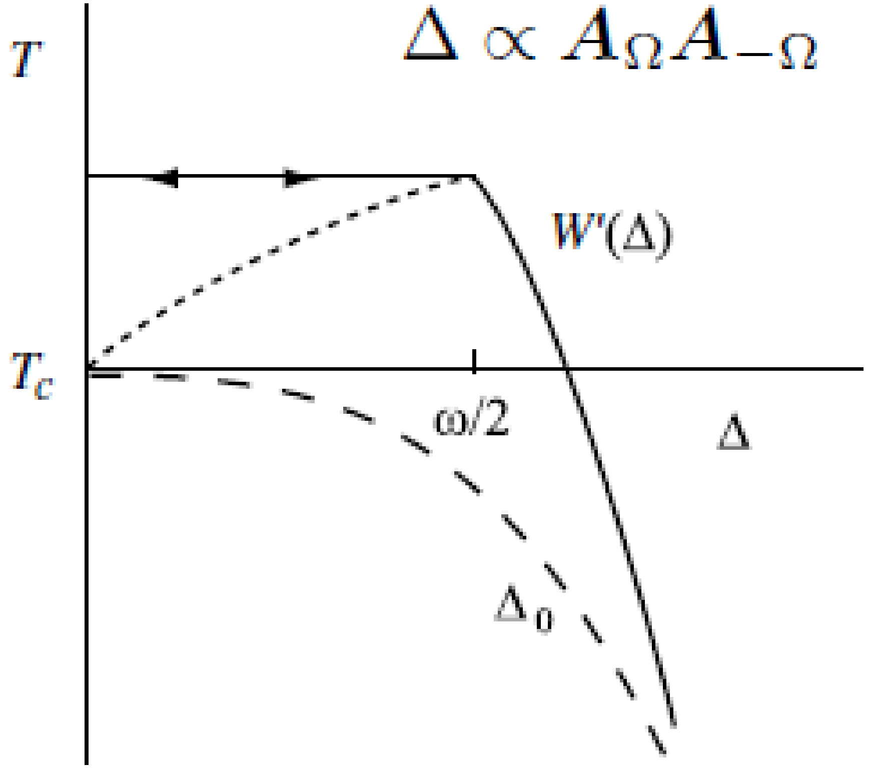
Stationary corrections to order parameter:

Theory:

Eliashberg, JETP Lett. **11**, 114 (1970)]

$$\boldsymbol{A}(t) = \boldsymbol{A}_{\Omega} e^{i\Omega t} + \boldsymbol{A}_{-\Omega} e^{-i\Omega t}$$

$$\tilde{\Delta} \propto \boldsymbol{A}_{\Omega} \boldsymbol{A}_{-\Omega}$$



Experiment:

Gap enhancement

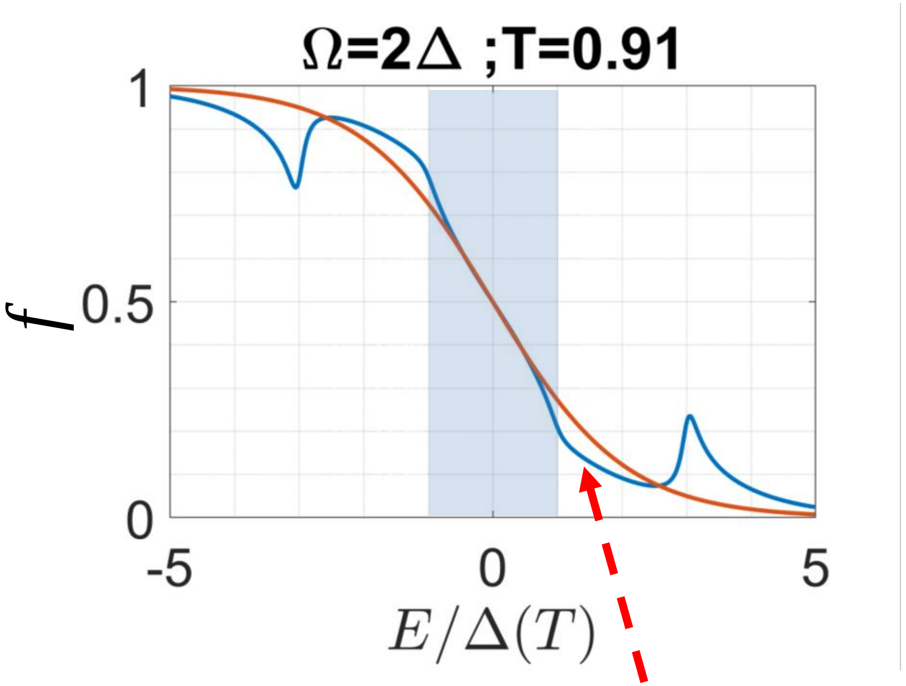
Kommers and Clarke, PRL, 38, 1091 (1977)

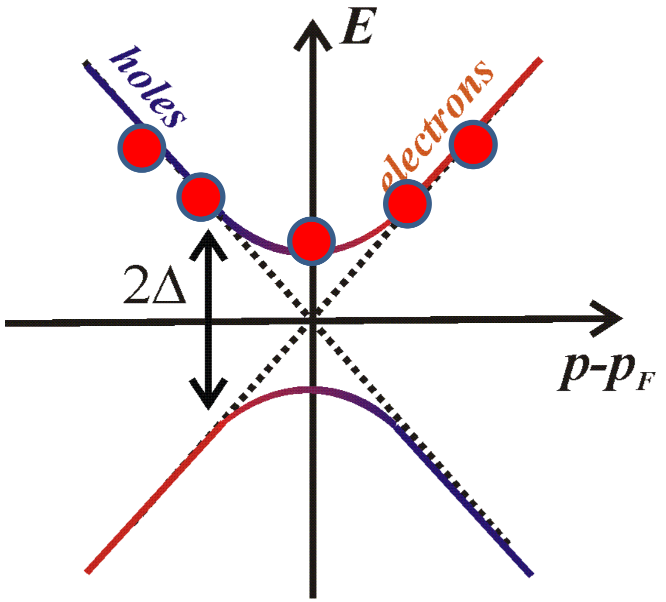
I_c enhancement

Dayem and Wiegand, Phys. Rev. **155**, 419 (1967).
Wyatt, et al., PRL **16**, 1166 (1966).
Klapwijk, Van Den Bergh,. Mooij, JLTP 26, 385 (1977).

Stimulated superconductivity

Correction to the quasiparticle distribution function:

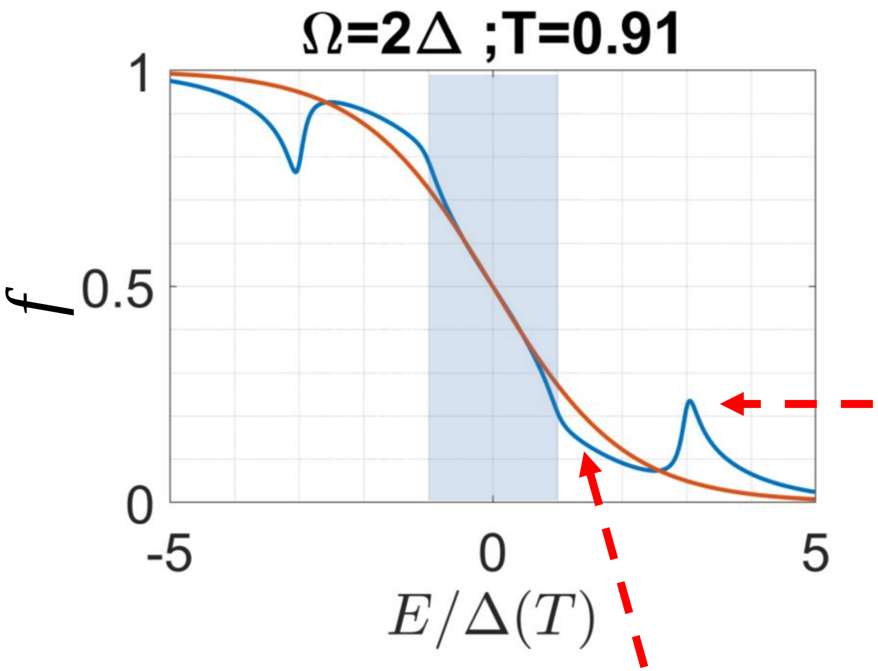


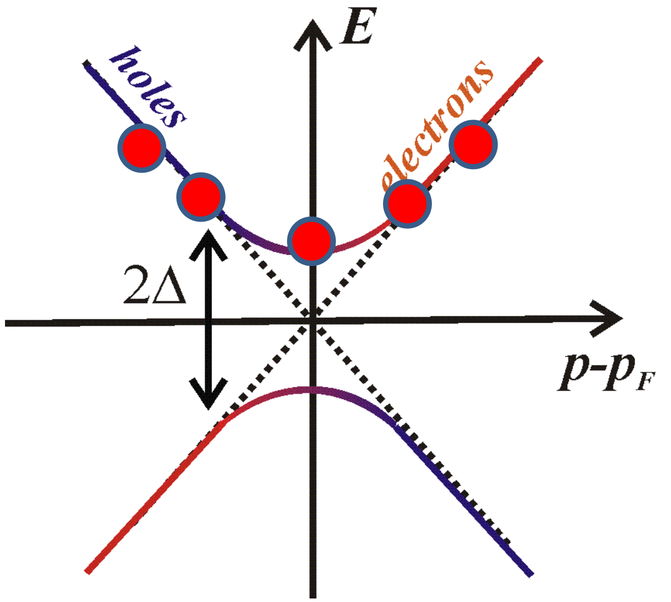


Effective cooling
→ Superconductivity enhancement

Stimulated superconductivity

Correction to the quasiparticle distribution function:





Population inverse

→ Laser effect σ< 0 ?

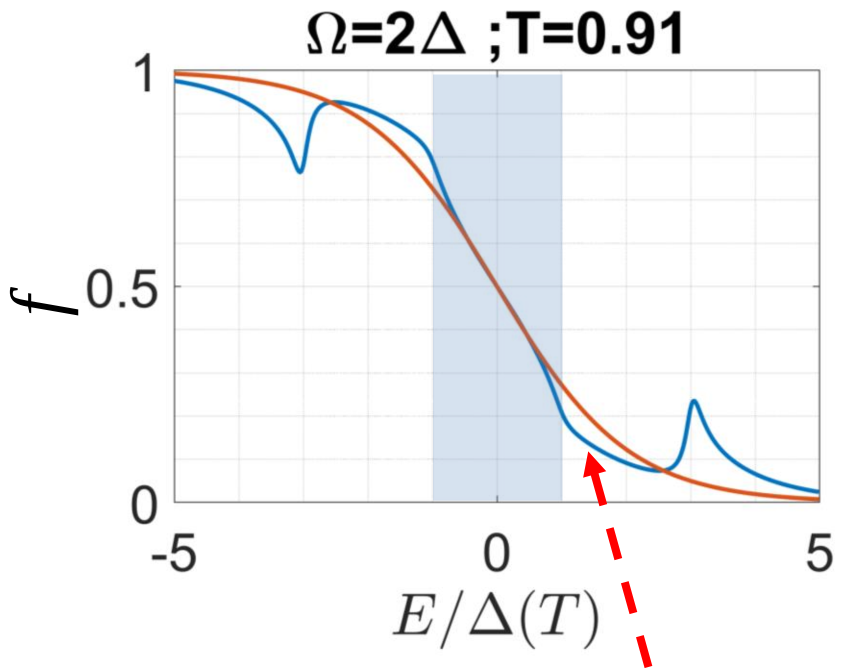
$$\frac{\sigma(\omega)}{\sigma_n} = \frac{2}{\omega}\int_{\Delta}^{\infty}\left(1+\frac{\Delta^2}{\varepsilon(\varepsilon+\omega)}\right)N(\varepsilon)N(\varepsilon+\omega)[f(\varepsilon)-f(\varepsilon+\omega)]$$

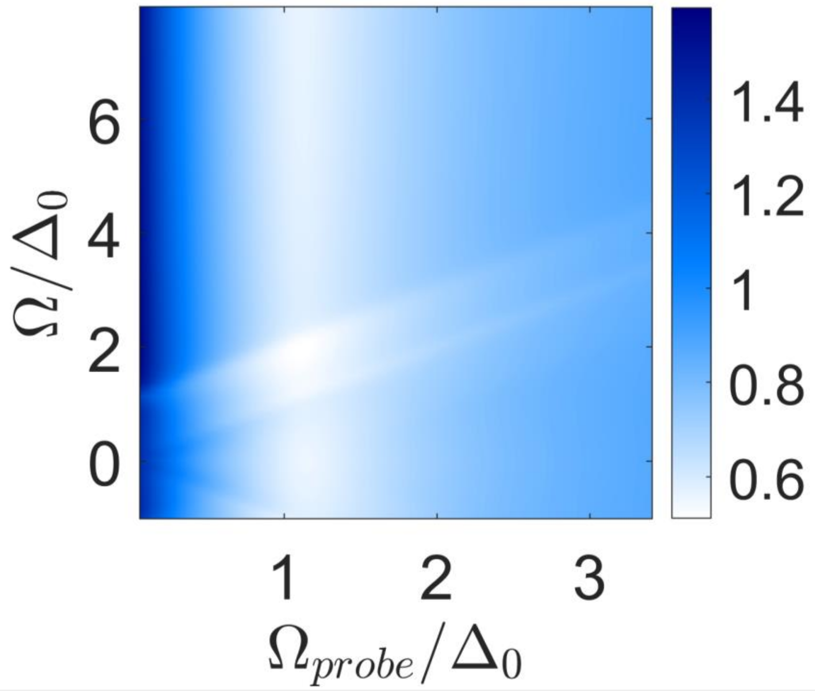
Effective cooling

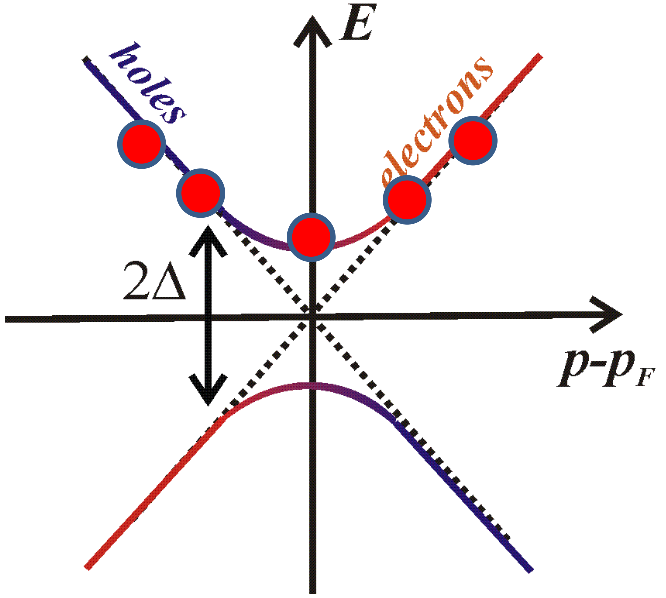
→ Superconductivity enhancement

Stimulated superconductivity

Correction to the quasiparticle distribution function:





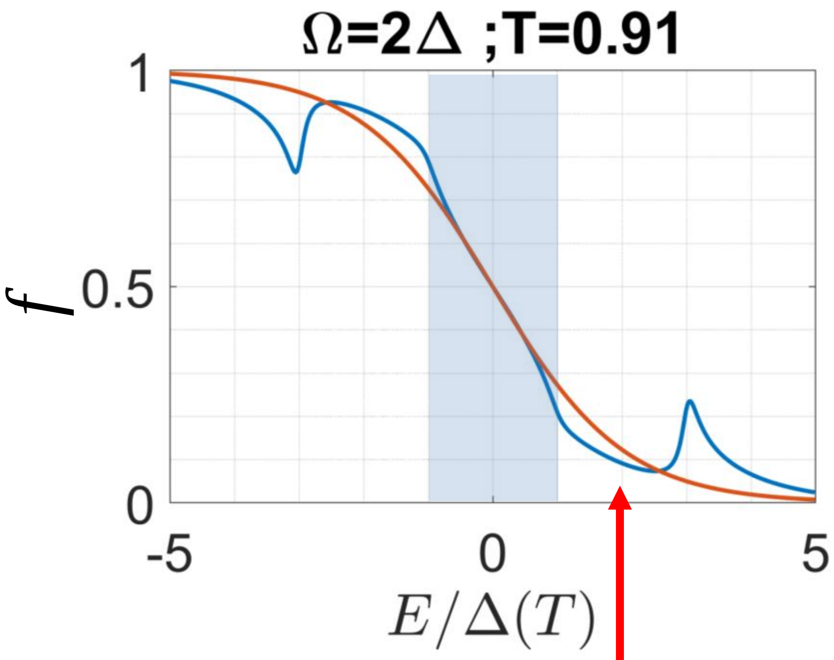


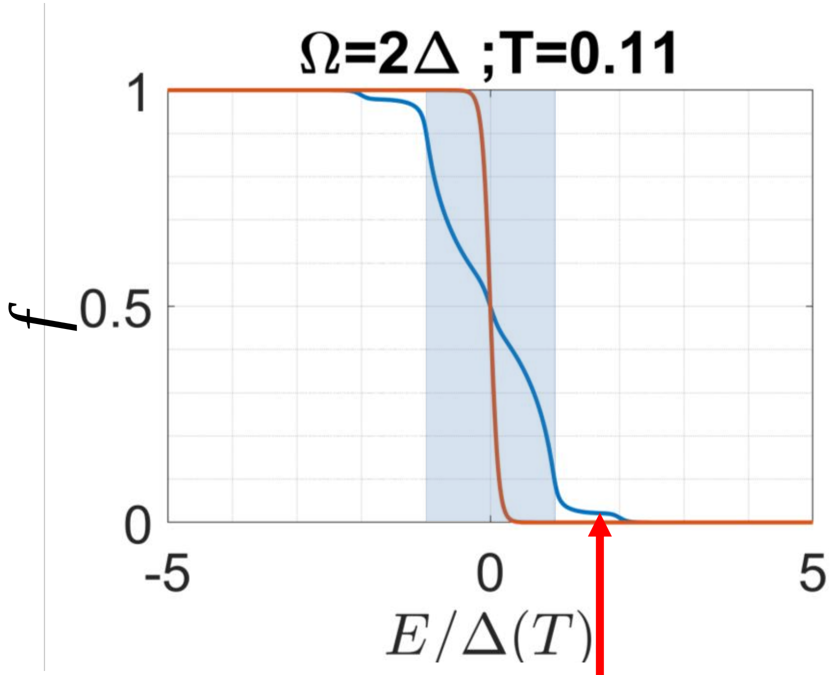
Effective cooling

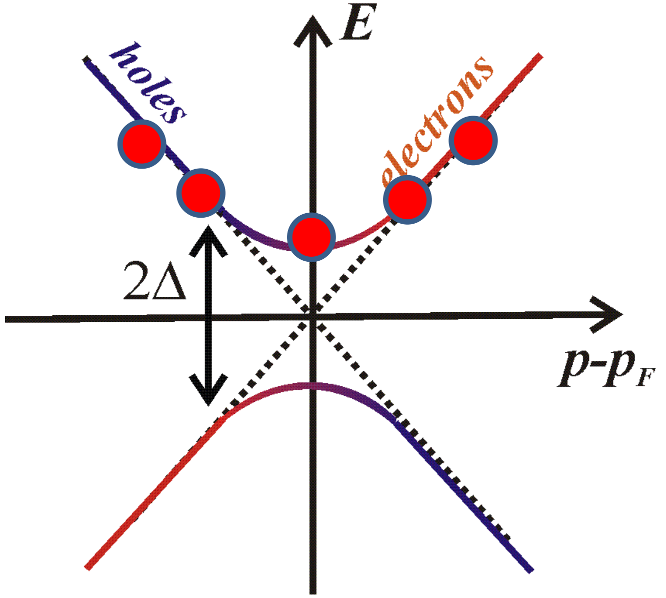
→ Superconductivity enhancement

Stimulated superconductivity

Correction to the quasiparticle distribution function:





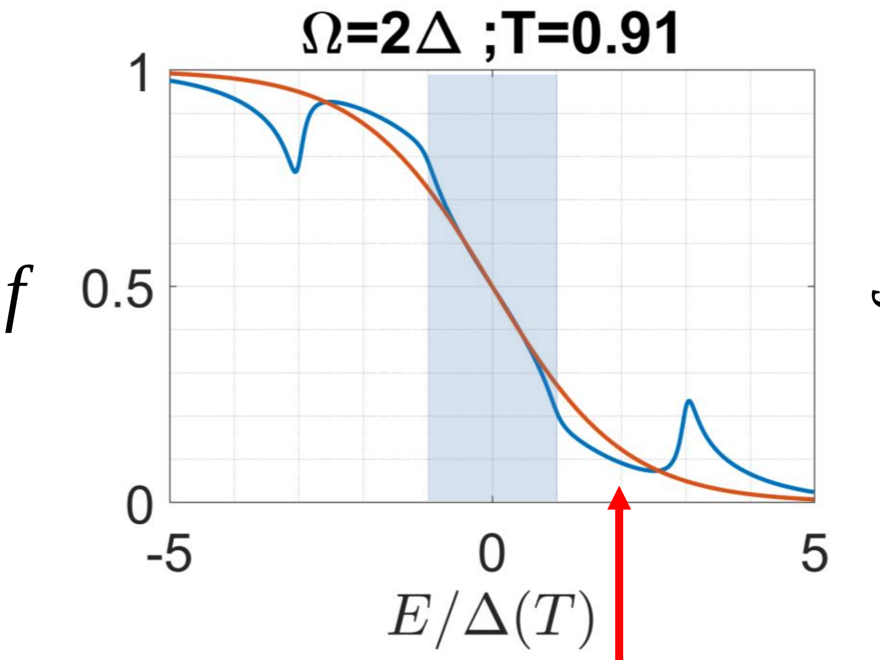


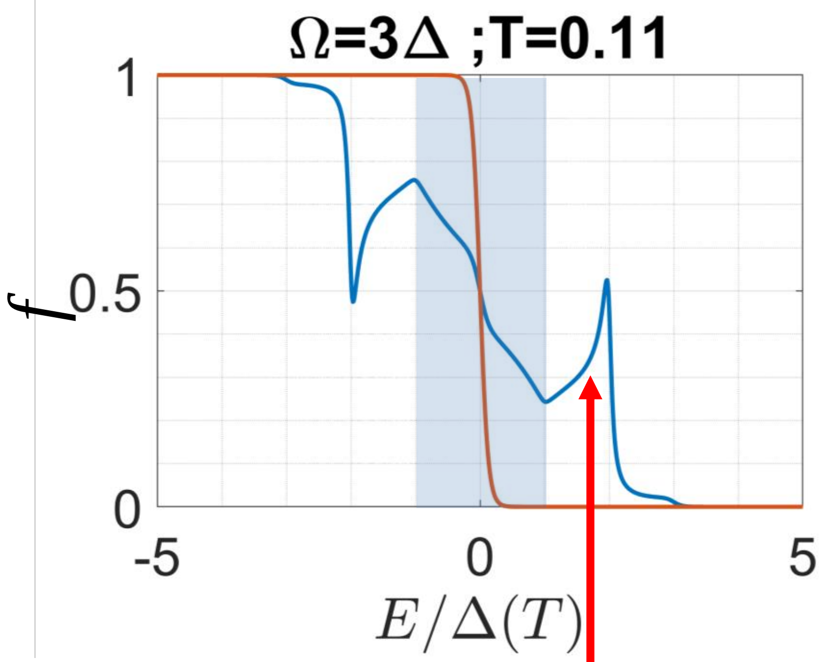
Effective cooling
→ Superconductivity enhancement

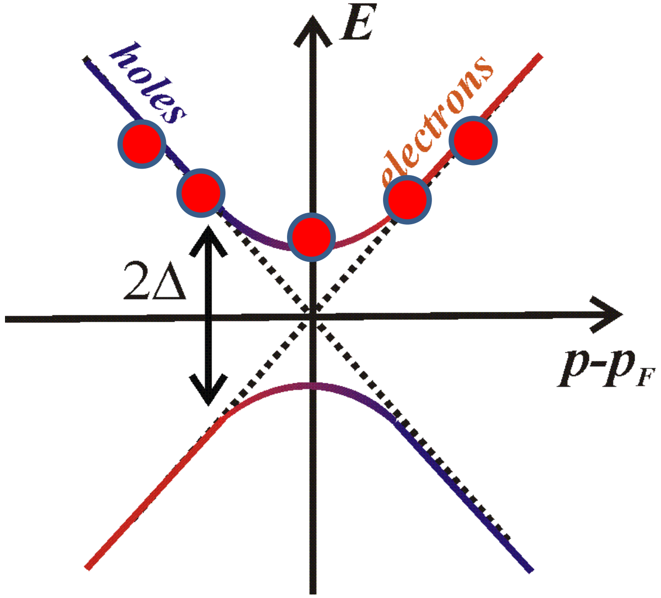
Effective heating

Stimulated superconductivity

Correction to the quasiparticle distribution function:





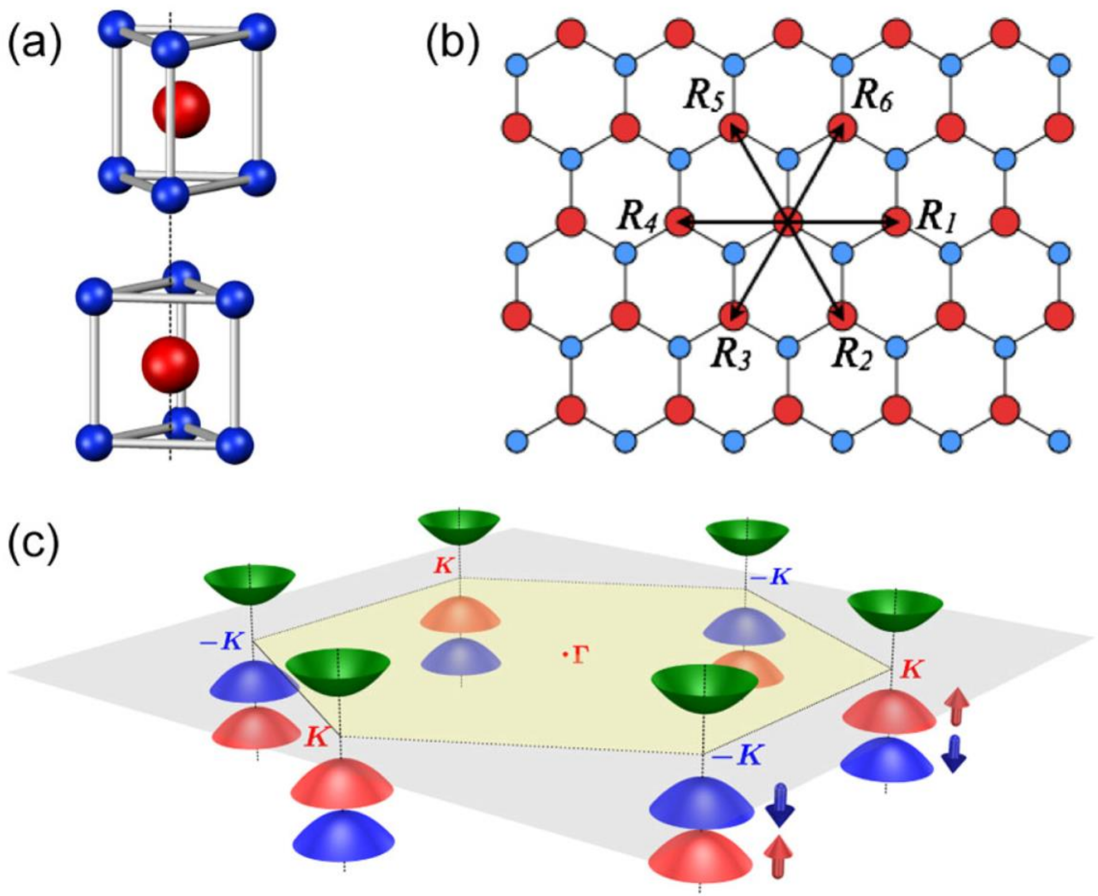


Effective cooling
→ Superconductivity enhancement

Population inversion→
lasing effect ?

Opical properties of Ising superconductors

Introduction to Ising SC in Transition Metal-Dichalcogenides



transition-metal dichalcogenides (TMD)

MoS_2, $NbSe_2$, WS_2, WSe_2, $MoTe_2$

Inversion symmetry breaking in single layer
+ Spin-orbit coupling
→ spin –valley locking

Ising SOC
→ Opposite Zeeman fields in K/-K points

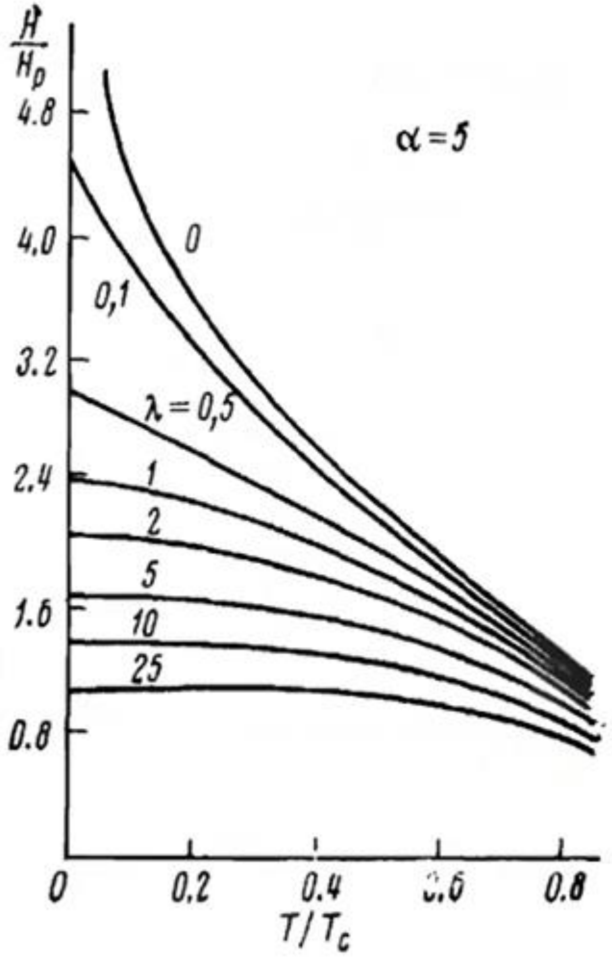
$H_{so} = s\ \beta\sigma_z$ with $s = \pm 1$ for K/-K

D. Xiao, *et al.*, Coupled Spin and Valley Physics in Monolayers MoS2 and other group-VI dichalcogenides, PRL (2012).

Evidence of Ising SC : enhanced critical field

In usual superconductors there is Pauli critical field given by Chandrasekhar-Clogston limit

$$H_p = \frac{\Delta}{\sqrt{2}\mu_B}$$



Superconductivity in crystals without symmetry centers

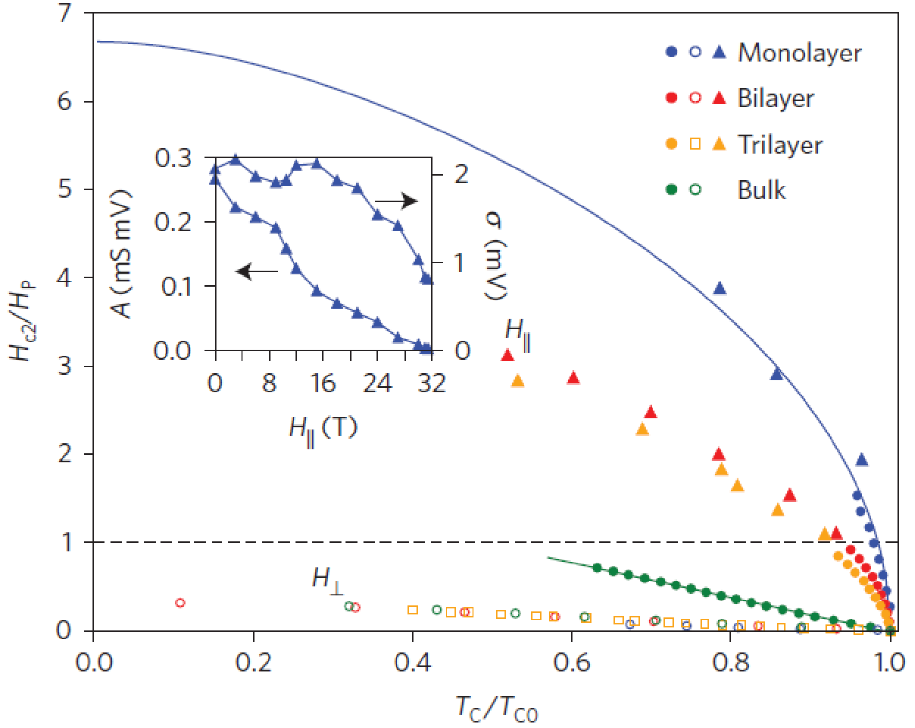
Belaevskii, Guseinov, Rusinov, JETP, 44, 1243 (1976)

λ: impurity scattering rate
α: SOC strength

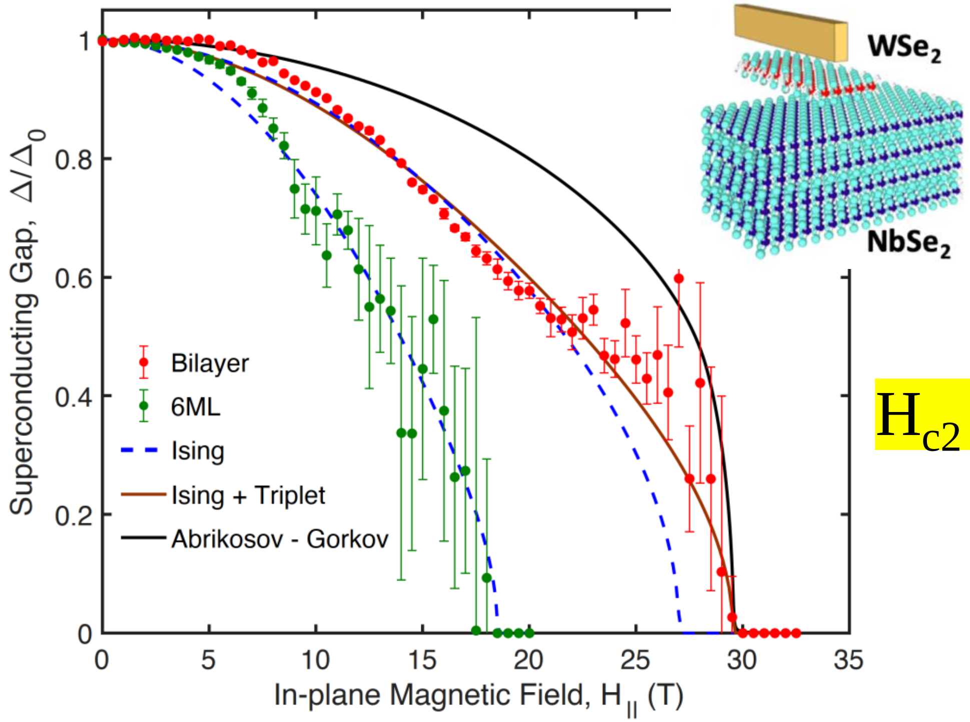
H_c strongly exceeds H_P

Evidence of Ising SC : enhanced critical field

Ising pairing in superconducting NbSe2 atomic layers, Xi, et al., Nat. Phys. (2016)



Tunnelling spectroscopy of superconducting $NbSe_2$, Kuzmanović, et al arXiv:2104.00328

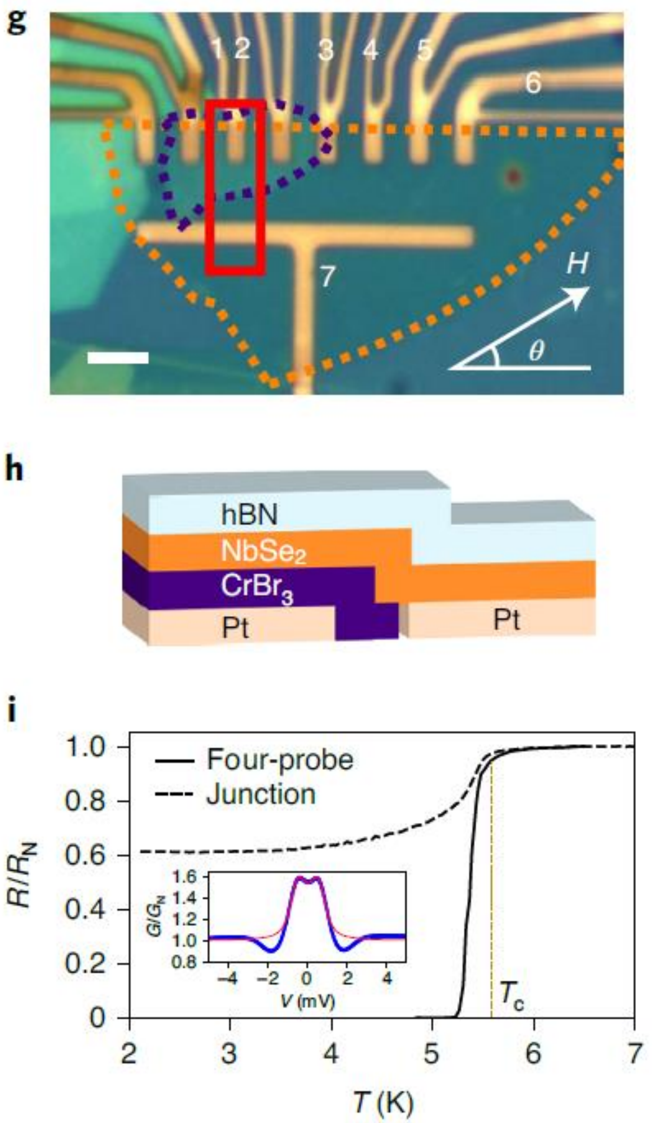


$H_{c2} > 30$ T

See also:

Luo, et al, Evidence for two-dimensional Ising SC in gated MoS2, Science (2015)
Saito, et al, SC protected by spin-valley locking in ion-gated MoS2, Nat.Phys. (2016)
Lu, et al, Full SC dome of strong Ising protection in gated monolayer WS2, PNAS (2018)
Sohn, , et al, An unusual continuous paramagnetic-limited SC phase transition in 2D NbSe2, Nat. Mat. (2019)
Li, , et al, Printable 2D SC monolayers, Nat. Mat. (2020)

Ising superconductivity + ferromagnetism



nature physics

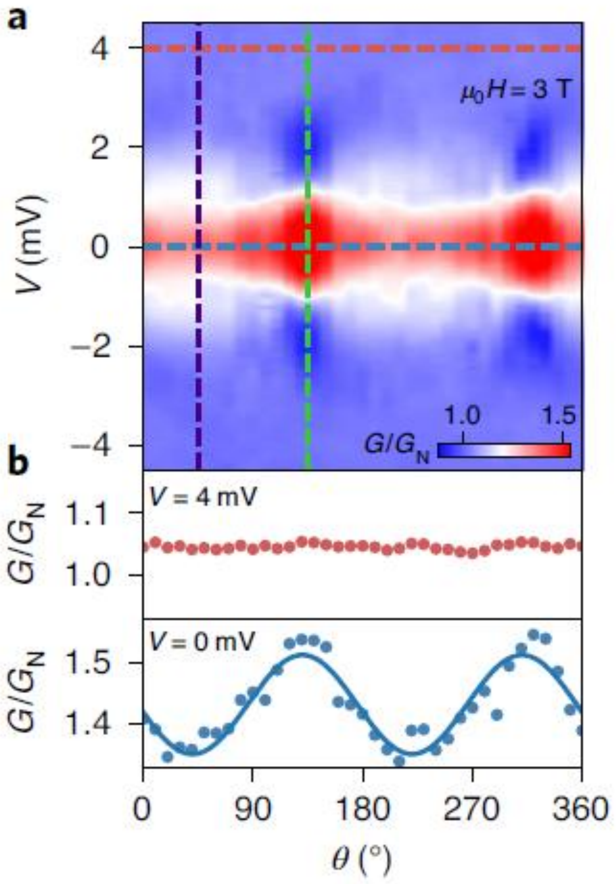
ARTICLES

https://doi.org/10.1038/s41567-021-01219-x

Check for updates

Two-fold symmetric superconductivity in few-layer $NbSe_2$

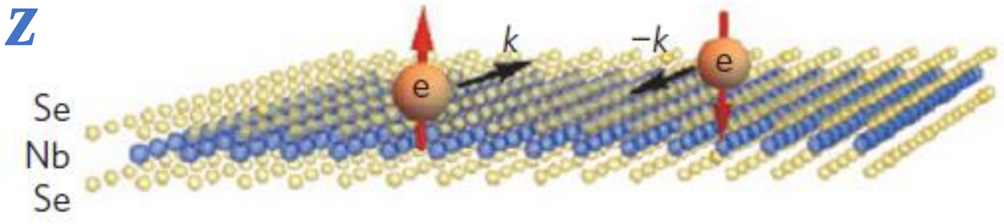
Alex Hamill[1,8], Brett Heischmidt[1,8], Egon Sohn[2,3,8], Daniel Shaffer[1], Kan-Ting Tsai[1], Xi Zhang[1], Xiaoxiang Xi[4], Alexey Suslov[5], Helmuth Berger[6], László Forró[6], Fiona J. Burnell[1], Jie Shan[3,7], Kin Fai Mak[3,7], Rafael M. Fernandes[1], Ke Wang[1]✉ and Vlad S. Pribiag[1]✉



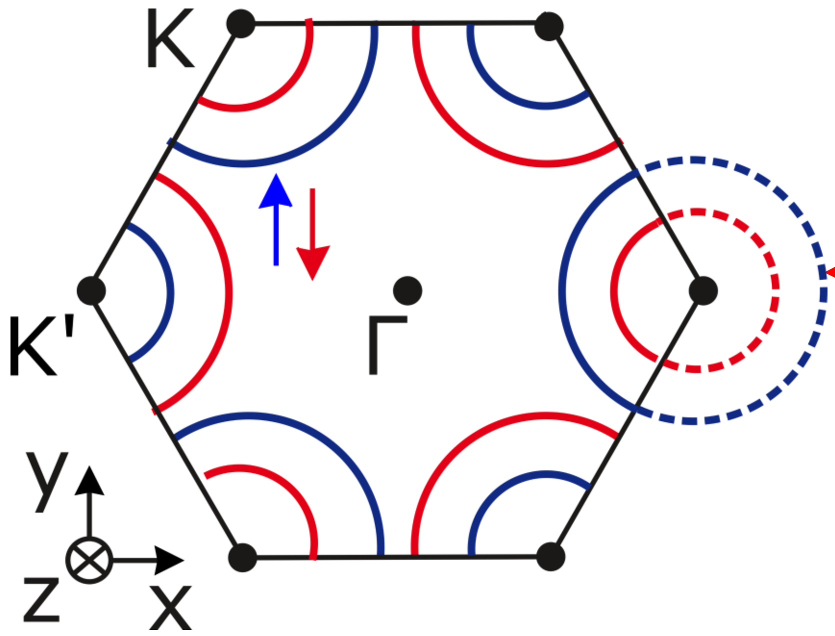
Modulation of local conductance by the direction of H is the signature of magnetic proximity

Model of Ising SC

$\boldsymbol{H}_{\mathrm{SO}} = \beta\, \boldsymbol{z}$



$\boldsymbol{B}$



BdG Hamiltonian in each electron pocket

$$\hat{H}_{BdG} = \begin{pmatrix} \xi_p + s\beta\sigma_z + h\sigma_x & \Delta \\ \Delta & -\xi_p - s\beta\sigma_z + h\sigma_x \end{pmatrix}$$

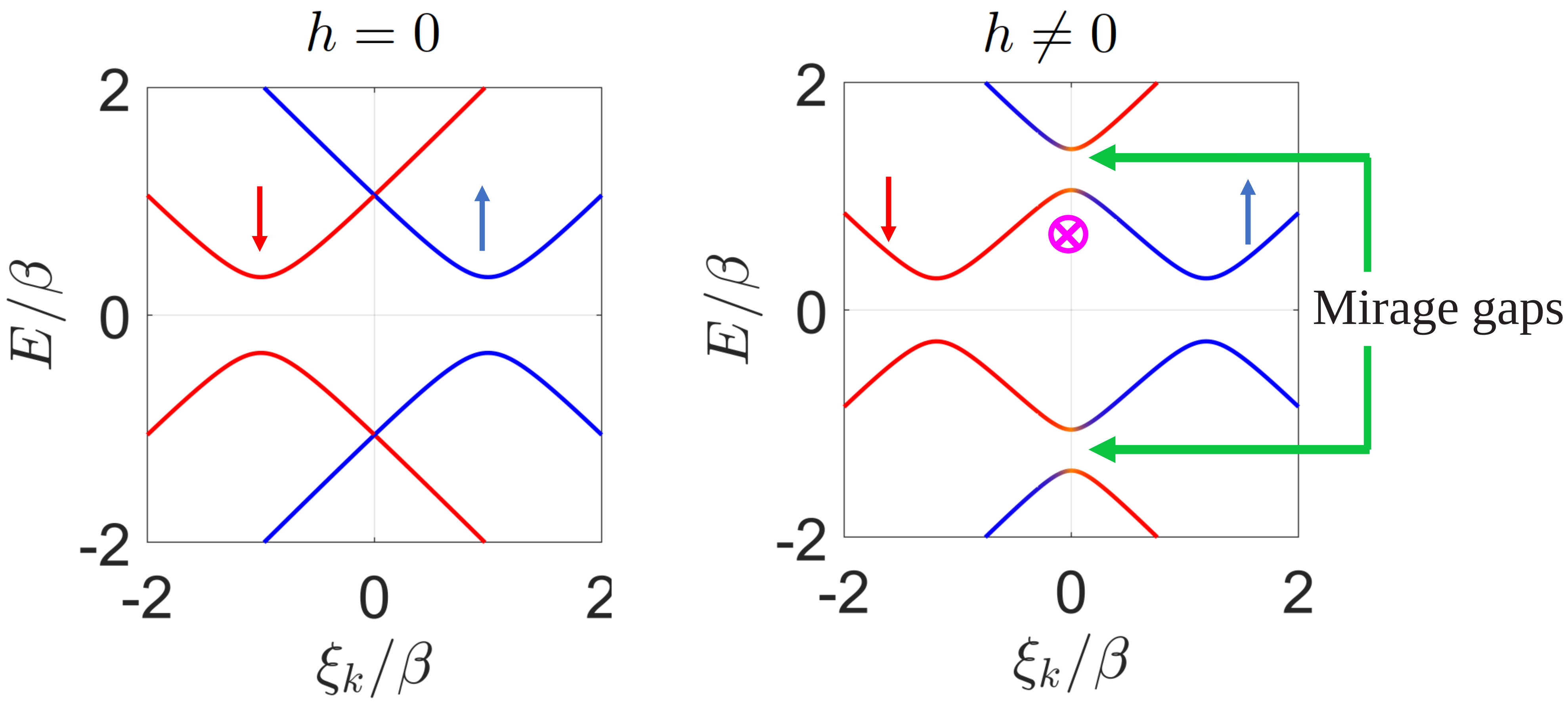
external field $h=\mu_B B$

SOC

s= ± 1 valley index

"Mirage" superconducting gap

$$E_{\pm}(k) = \sqrt{E_{bdg}^2 + \beta^2 + h^2 \pm 2\sqrt{h^2 E_{bdg}^2 + \xi_k^2 \beta^2}} \qquad E_{bdg} = \sqrt{\xi_k^2 + \Delta^2}$$

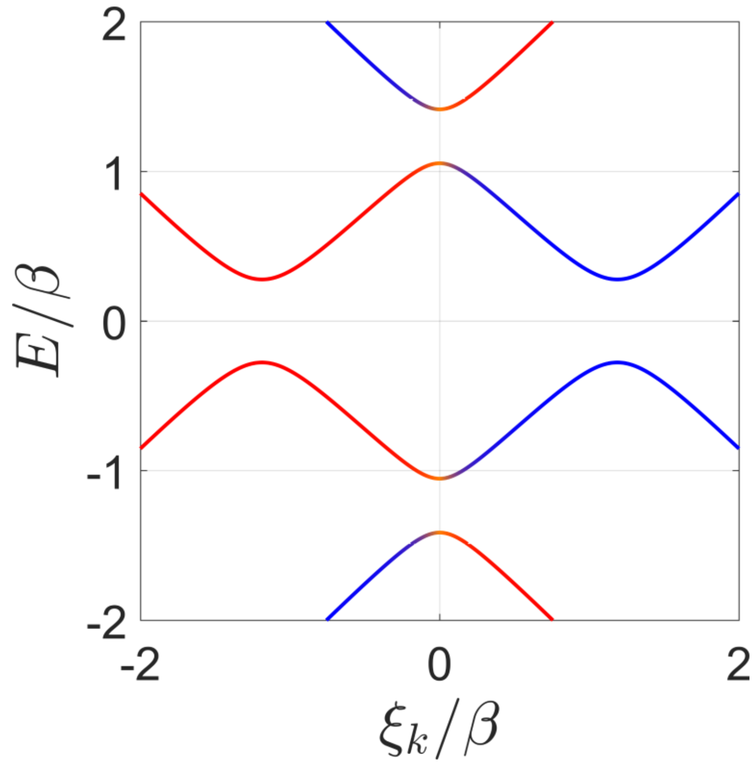


Tang , Bruder, Belzig, PRL 126, 237001 (2021)

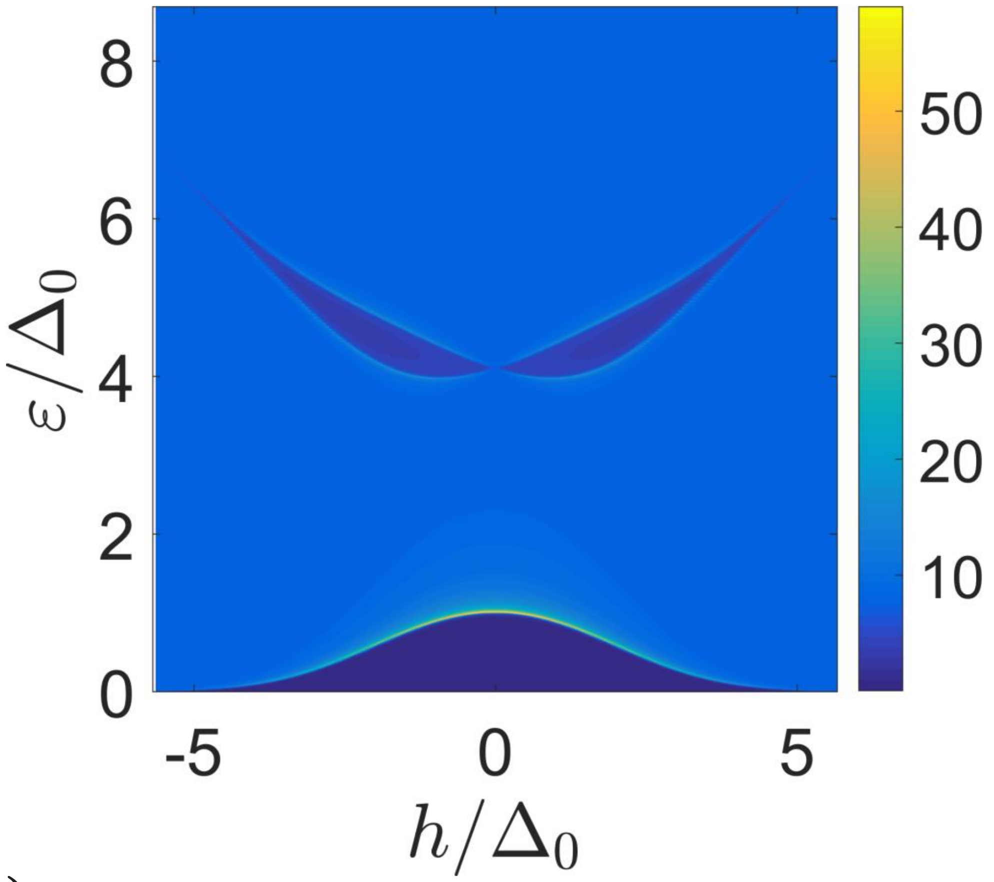
“Mirage” superconducting gap

$$E_{\pm}(k) = \sqrt{E_{bdg}^2 + \beta^2 + h^2 \pm 2\sqrt{h^2 E_{bdg}^2 + \xi_k^2 \beta^2}}$$

$$h \neq 0$$

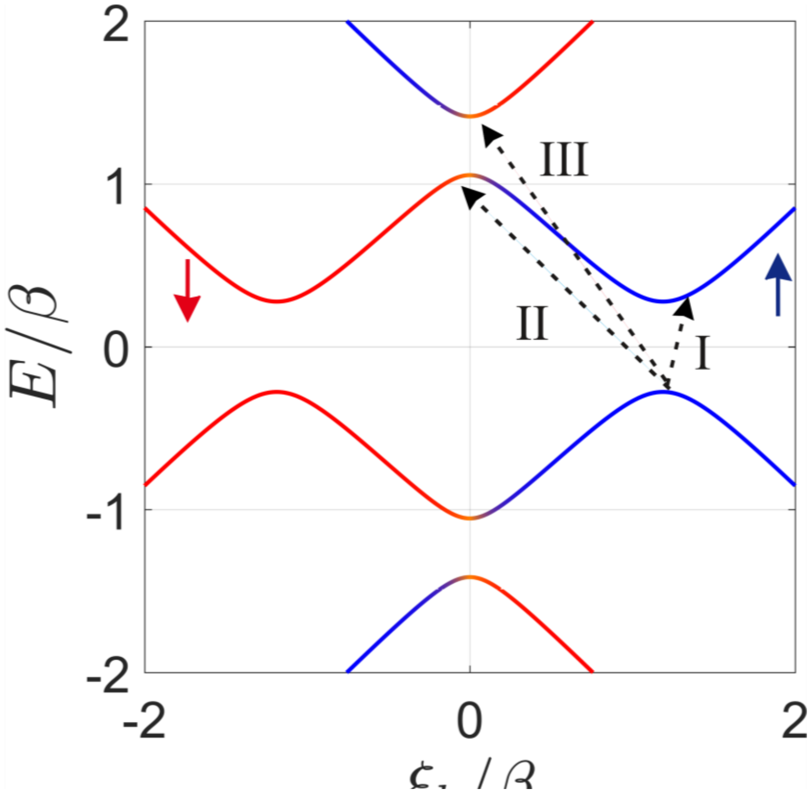


Density of states



Tang , Bruder, Belzig, PRL 126, 237001 (2021)

Optical probes of finite-energy pairing



Optical Gaps visible in conductivity and Raman scattering

$$\Omega_I = 2\Delta_{ord}$$
$$\Omega_{II} = \Delta_{ord} + \Delta_-$$
$$\Omega_{II} = \Delta_{ord} + \Delta_+$$

$$\Delta_{ord} = \Delta\sqrt{1 - h^2/\beta^2}$$
$$\Delta_\pm = \sqrt{(h \pm \Delta)^2 + \beta^2}$$

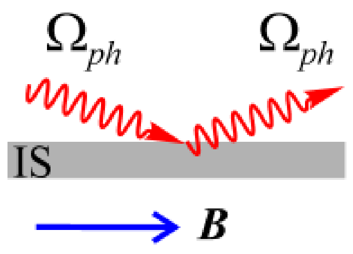
Tc ≈ 6.5 K
β ≈ 70 -140 K

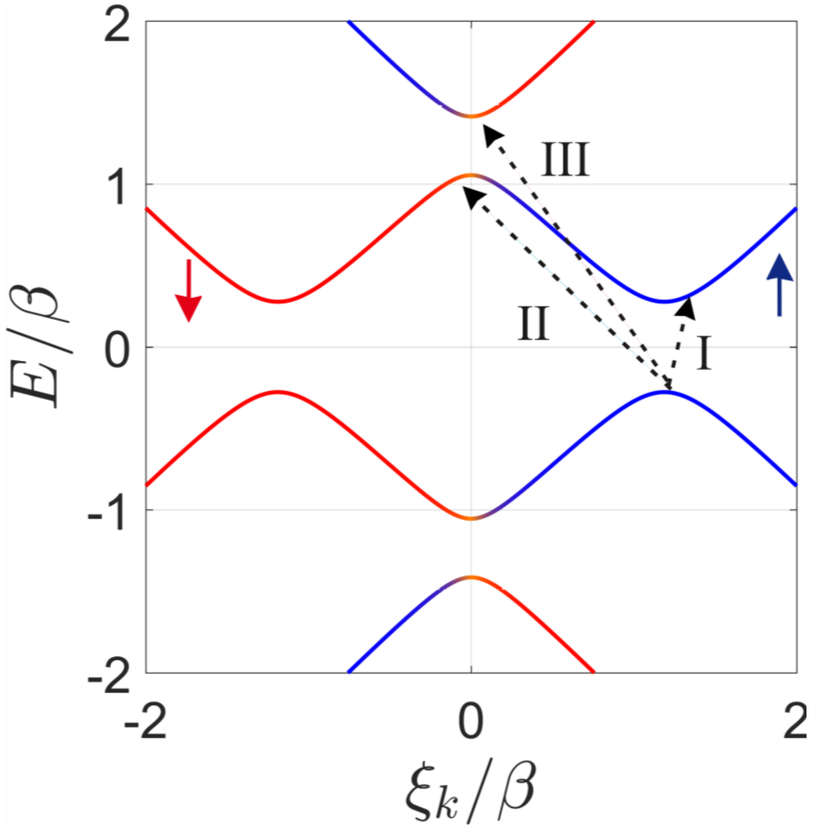
Ω_I, $\Omega_{II} \approx 1.5$ THz

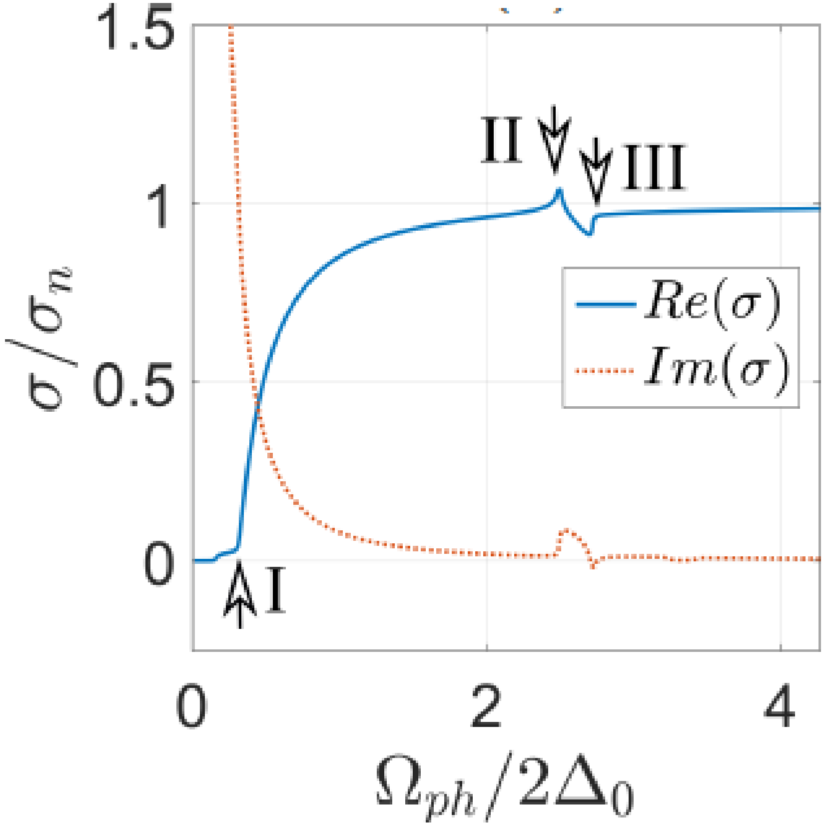
Luo, et al, Evidence for 2D Ising SC in gated MoS2, Science (2015)

Optical conductivity

Quasiclassical calculation,
dirty limit, β=4$\Delta_{0,}$ Δ_0 =1.76 T_{c0}

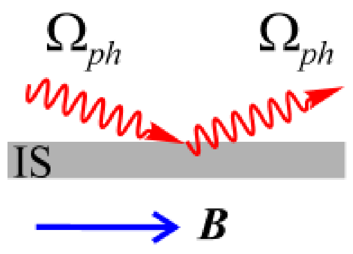


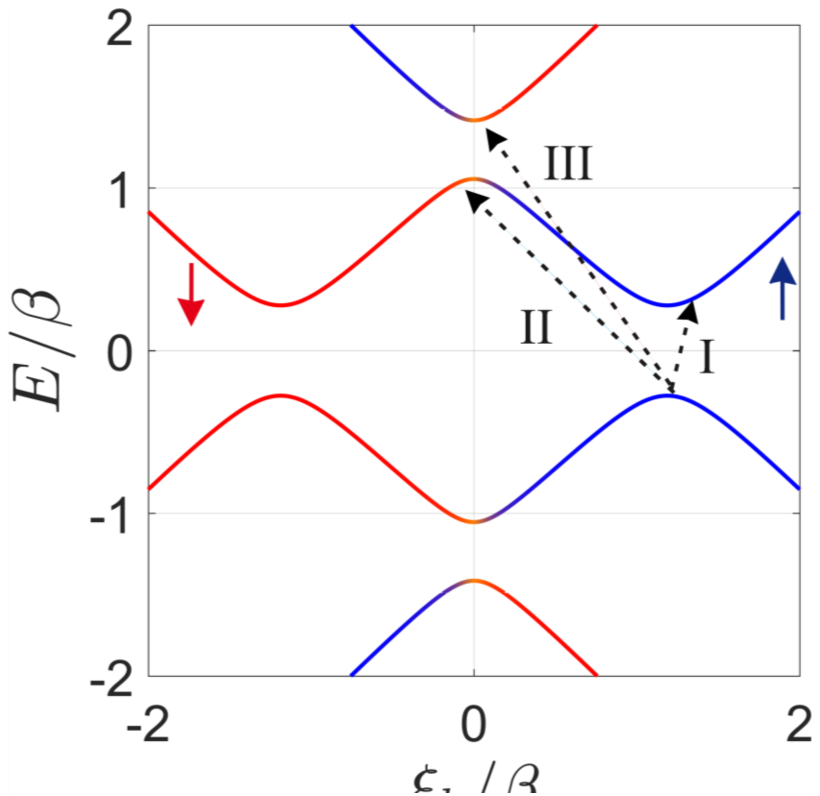


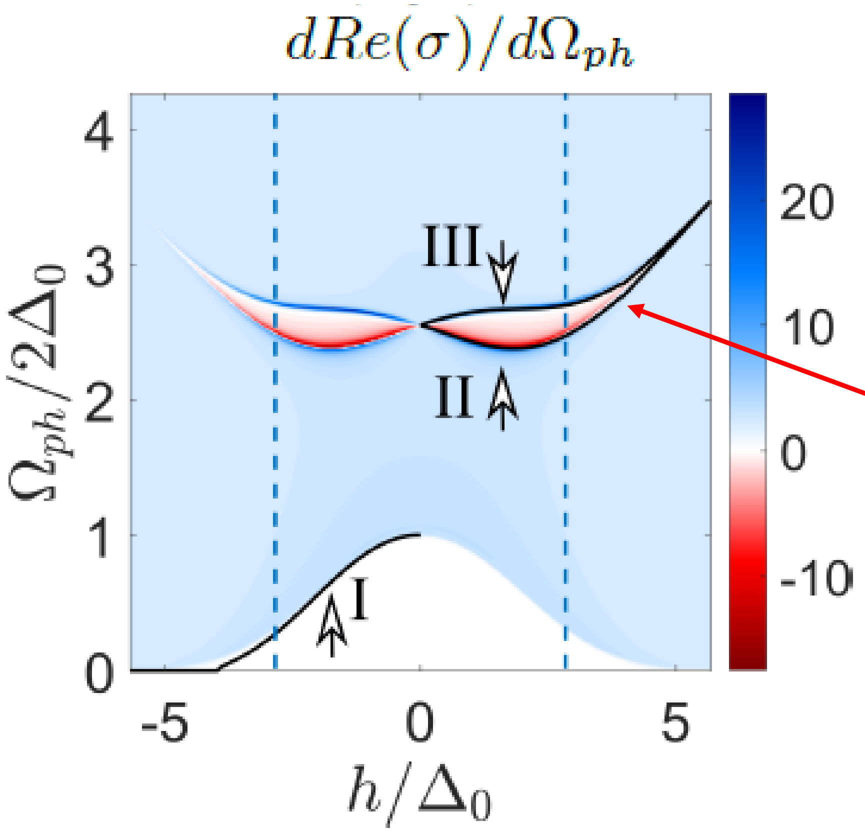


Optical conductivity

Quasiclassical calculation, dirty limit, $\beta=4\Delta_0$, $\Delta_0=1.76\ T_{c0}$







$$\Omega_I = 2\Delta_{ord}$$

$$\Omega_{II} = \Delta_{ord} + \Delta_-$$

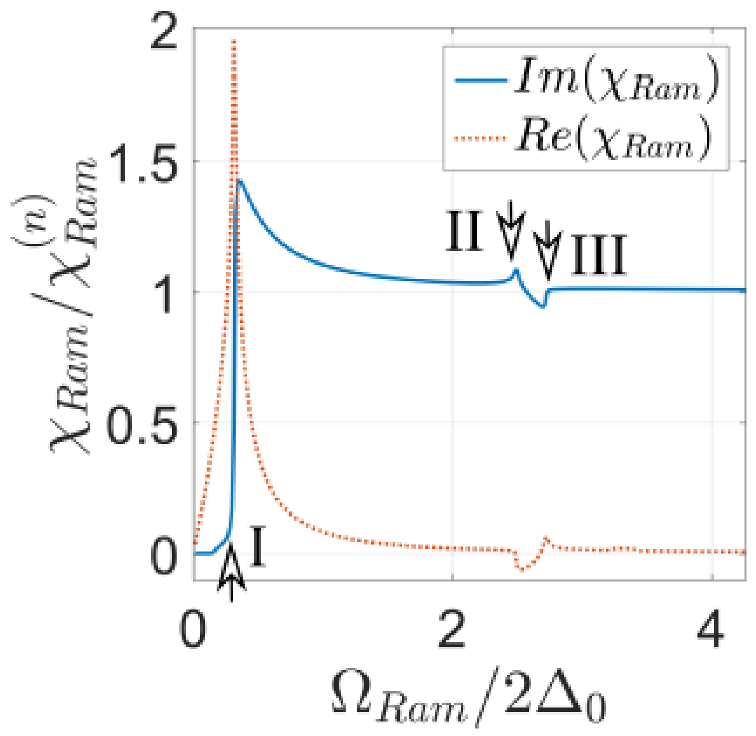
$$\Omega_{II} = \Delta_{ord} + \Delta_+$$

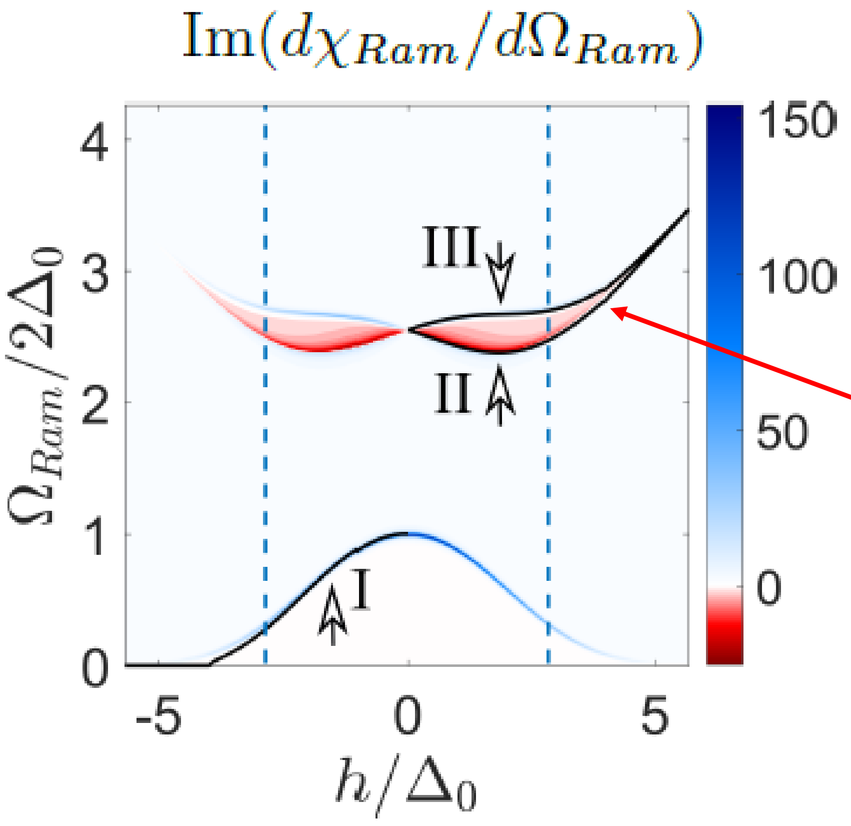
$$\Delta_{ord} = \Delta\sqrt{1 - h^2/\beta^2}$$

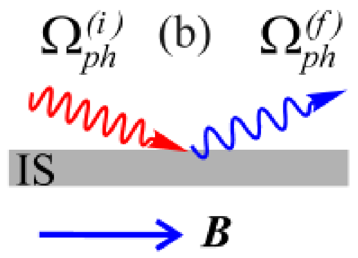
$$\Delta_\pm = \sqrt{(h \pm \Delta)^2 + \beta^2}$$

Raman scattering

Dirty limit, $\beta=4\Delta_0$, $\Delta_0=1.76\,T_{c0}$







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$$\Omega_{II} = \Delta_{ord} + \Delta_-$$

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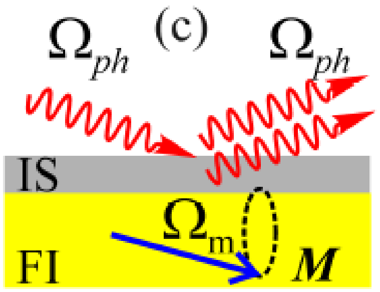
$$\Delta_{ord} = \Delta\sqrt{1 - h^2/\beta^2}$$

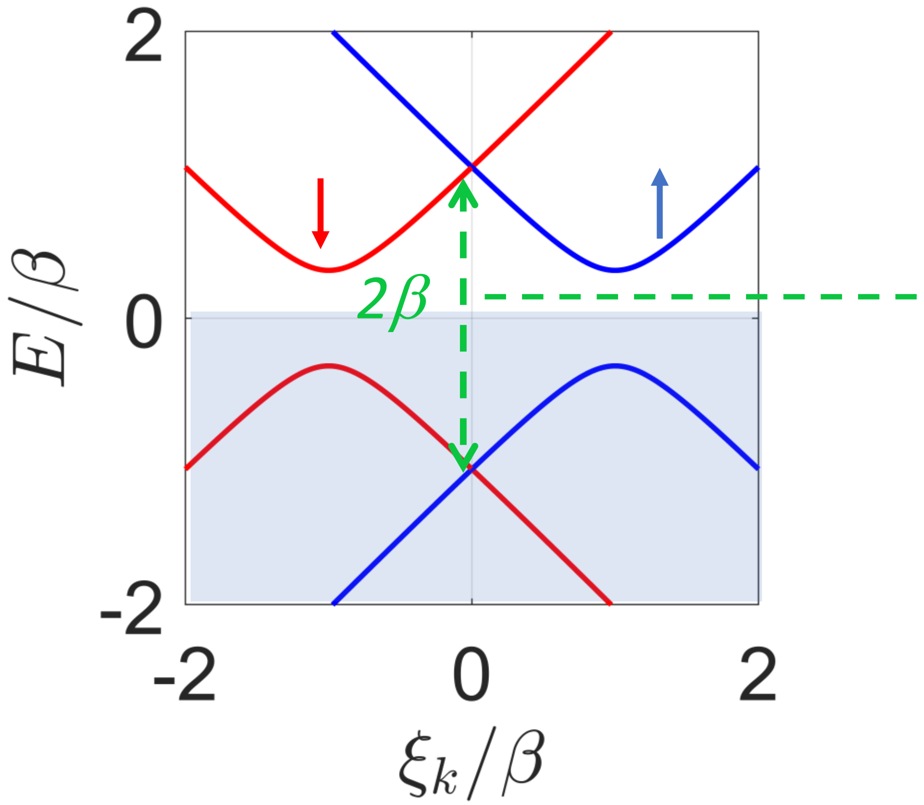
$$\Delta_\pm = \sqrt{(h \pm \Delta)^2 + \beta^2}$$

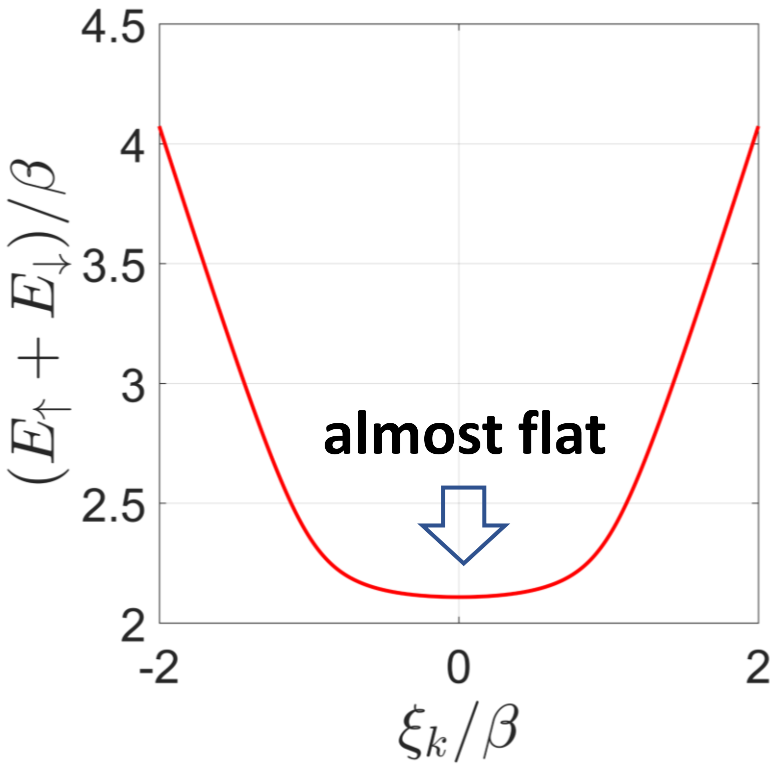
Technical details: arXiv:2111.03623

Direct spin- flip transitions

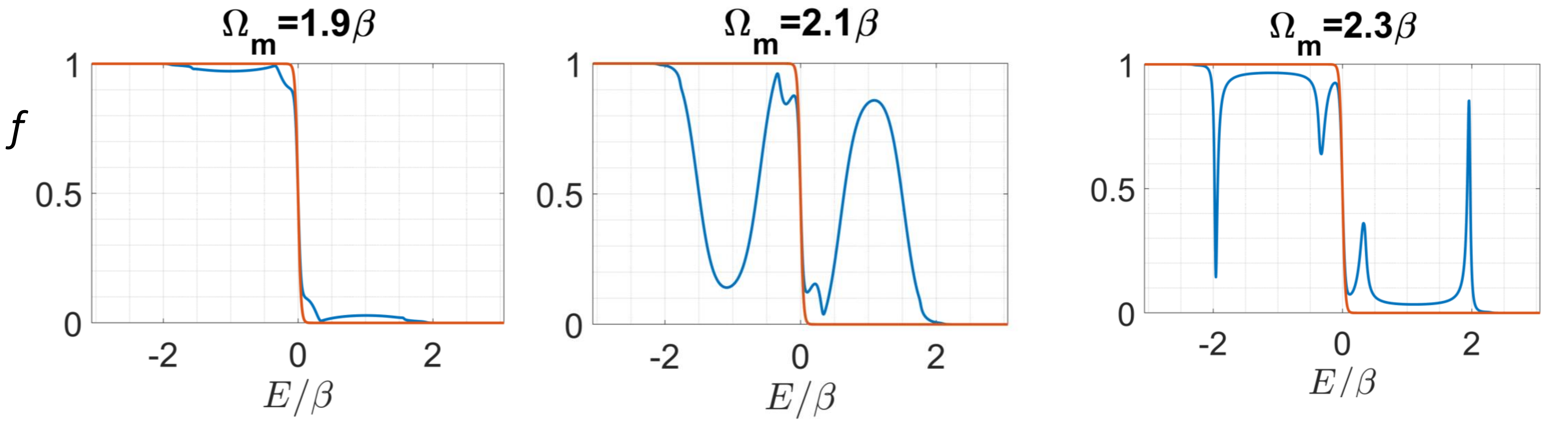


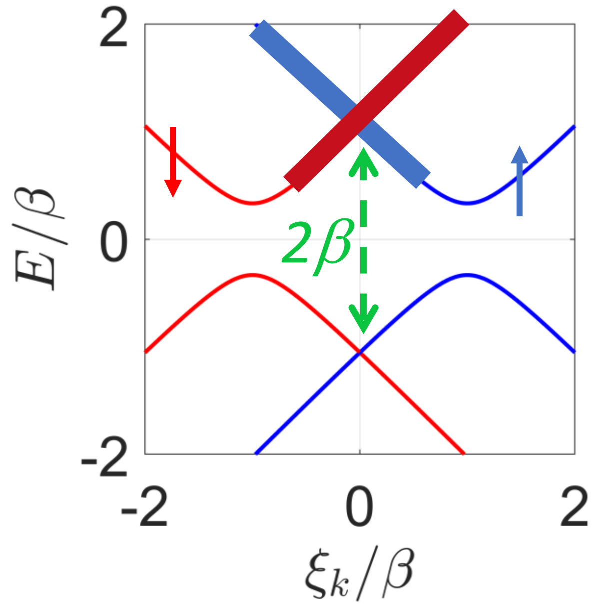
$$\boldsymbol{h} = h_m \cos(\Omega_m t)\boldsymbol{x}$$





Non-equilibrium distribution function

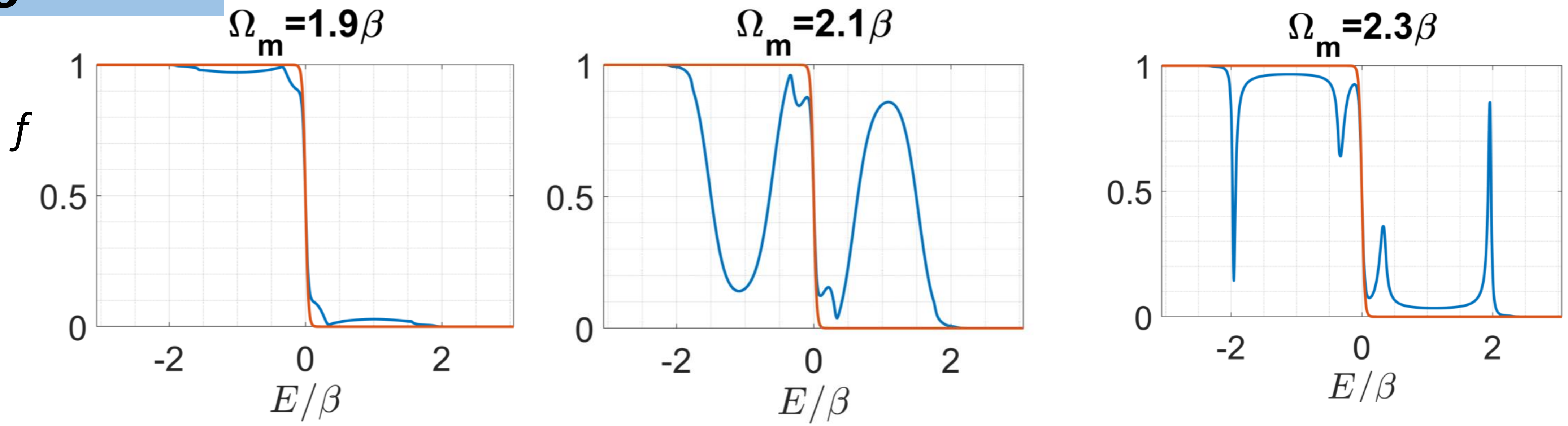




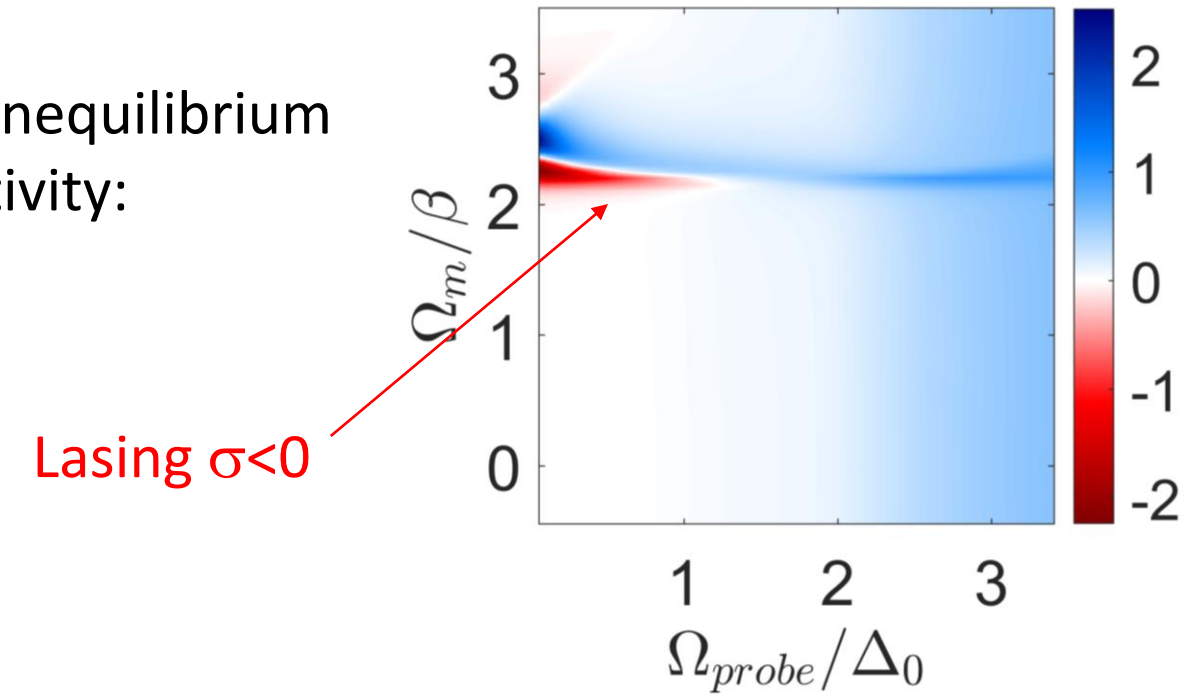
$$\boldsymbol{h} = h_m \cos(\Omega_m t)\boldsymbol{x}$$

Γ=0.1T_c; h_m=0.3T_c ; T=0.2 Tc

Lasing effect



Total nonequilibrium conductivity:



$$\boldsymbol{h} = h_m \cos(\Omega_m t)\boldsymbol{x}$$

Γ=0.1T_c; h_m=0.3T_c ; T=0.2 Tc

Conclusions

- THz spectroscopy and Raman response can be used to detect Ising superconductivity
- Lasing effect is possible in Ising superconductors

Thank you for your attention!