Nematic boson in an iron-based superconductor

Ukratop Workshop
December 4-5, 2018

Christian Hess
Institute for Solid State Research
IFW Dresden

Leibniz Institute
for Solid State and
Materials Research
Dresden

Member of the
Leibniz Association

Acknowledgement

Quantum Matter: Transport and Tunneling

SPP1458

Deutsche Forschungsgemeinschaft DFG

erc
European Research Council
Established by the European Commission

STM experiments

Pranab K. Nag
Jose Guevara
Zhixiang Sun
Sven Hoffmann

Theory

Steffen Sykora

Crystals

R. Kappenberger, S. Wurmehl

Acknowledgement

Quantum Matter: Transport and Tunnel

PHYSICAL REVIEW B 98, 201107(R) (2018)

Rapid Communications

Anomalous Nernst effect and field-induced Lifshitz transition in the Weyl semimetals TaP and TaAs

F. Caglieris,[1] C. Wuttke,[1] S. Sykora,[1] V. Süss,[2] C. Shekhar,[2] C. Felser,[2] B. Büchner,[1,3,4] and C. Hess[1,4]

Leibniz Institute for Solid State and Materials Research Dresden

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STM

Pranab

Jose Gue

F. Caglieris, Lixiang Sun, Sven Hoffmann

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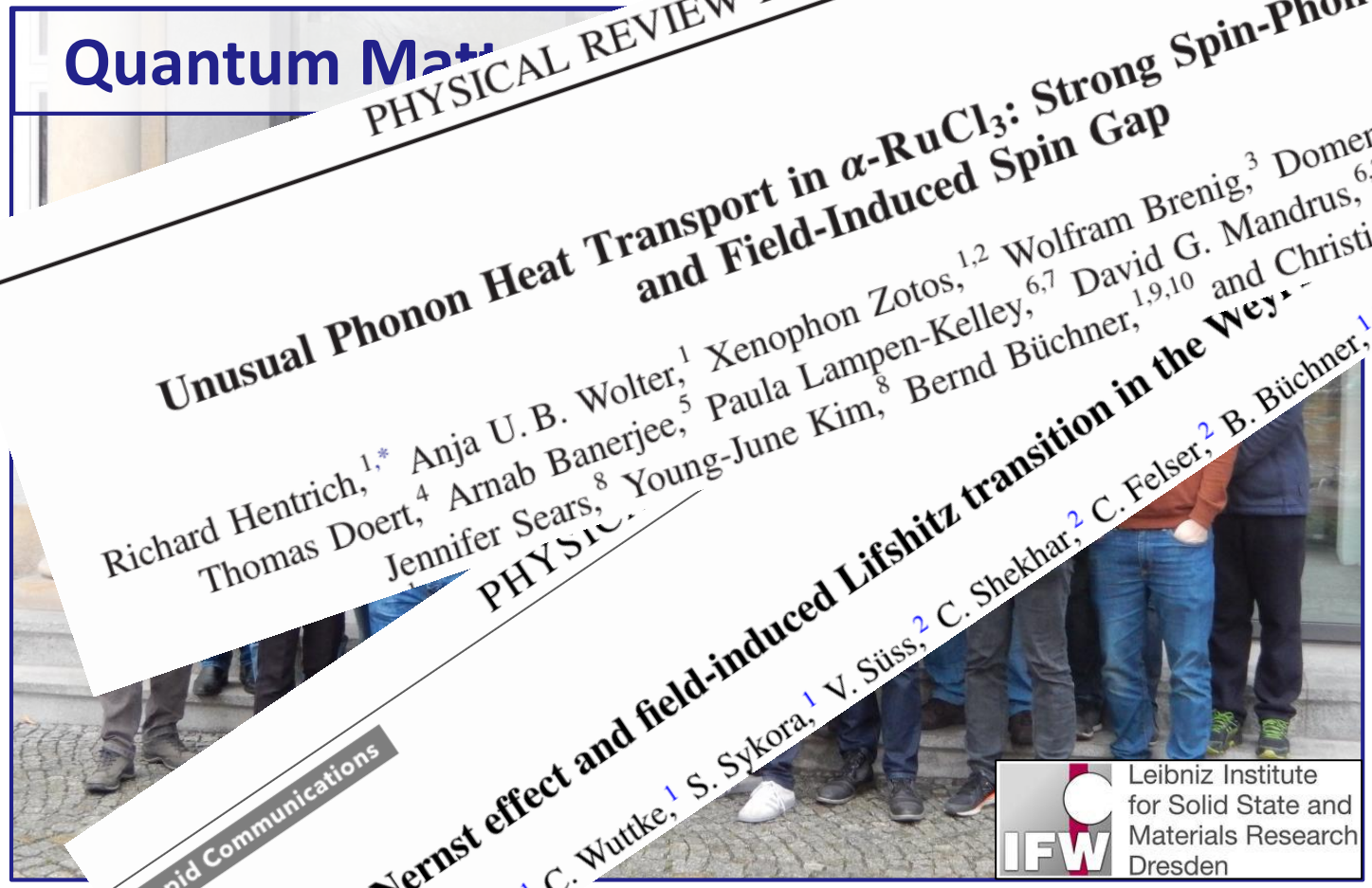
Acknowledge

Quantum Mat



PHYSICAL REVIEW LETTERS 120, 117204 (2018)

Unusual Phonon Heat Transport in α-$RuCl_3$: Strong Spin-Phonon Scattering and Field-Induced Spin Gap

Richard Hentrich,[1,*] Anja U. B. Wolter,[1] Xenophon Zotos,[1,2] Wolfram Brenig,[3] Domenic Nowak,[4] Anna Isaeva,[4] Thomas Doert,[4] Arnab Banerjee,[5] Paula Lampen-Kelley,[6,7] David G. Mandrus,[6,7] Stephen E. Nagler,[5] Jennifer Sears,[8] Young-June Kim,[8] Bernd Büchner,[1,9,10] and Christian Hess[1,10,†]

PHYSIC

Anomalous Nernst effect and field-induced Lifshitz transition in the Wey

F. Caglieris,[1] C. Wuttke,[1] S. Sykora,[1] V. Süss,[2] C. Shekhar,[2] C. Felser,[2] B. Büchner,[1,3,4] and C. Hess

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Outline

Warm-up

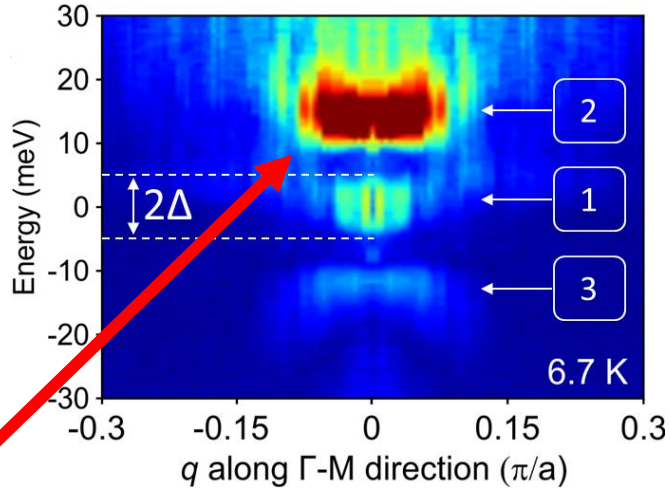
Scanning tunneling microscopy and spectroscopy

Superconductivity

Probing electron-boson coupling in LiFeAs

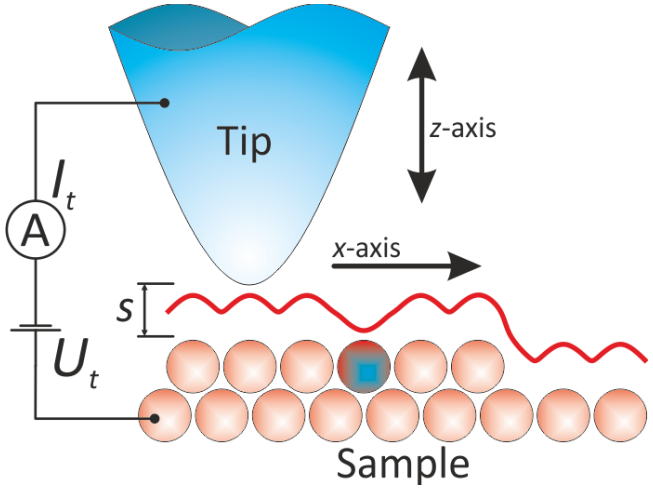
Local spectroscopy

Friedel oscillations



Signature of electron-boson coupling

Scanning Tunneling Microscopy (STM)



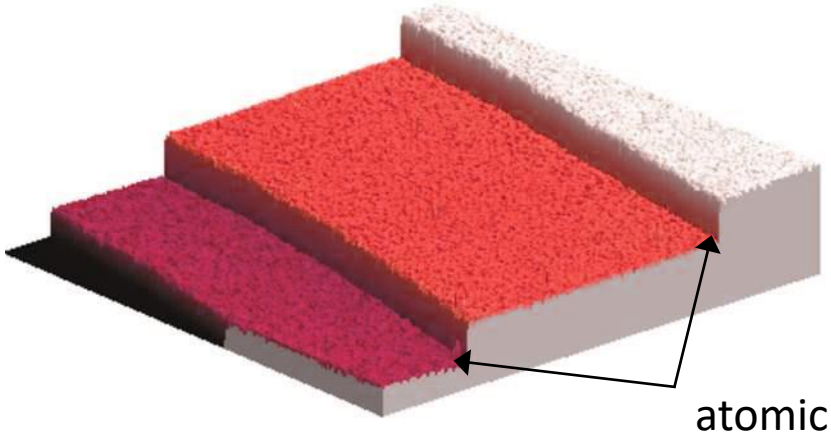
$T \approx 0$

$$I_t \propto e^{-2\kappa s} \int_0^{eU_t} \rho_s(\epsilon)\, d\epsilon$$

distance

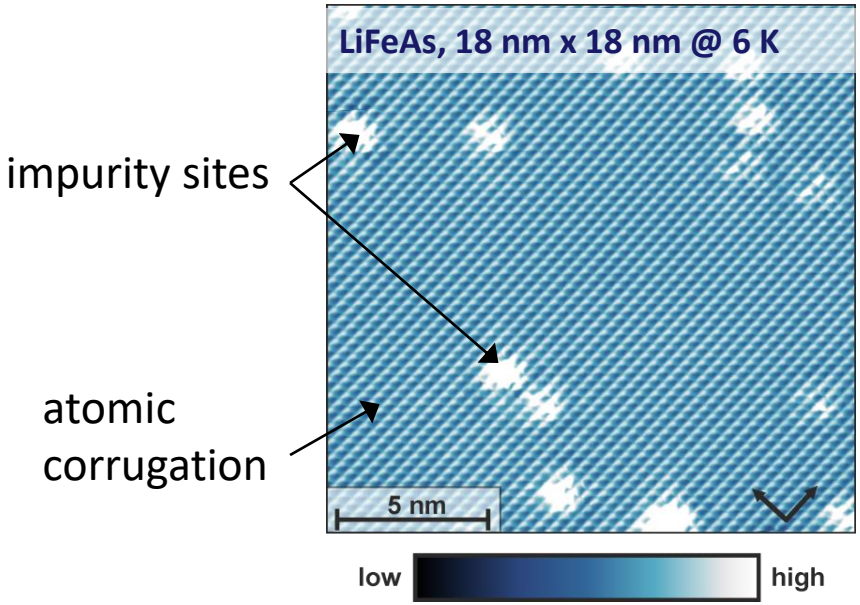
local density of states (LDOS)

➡ Topographic surface data



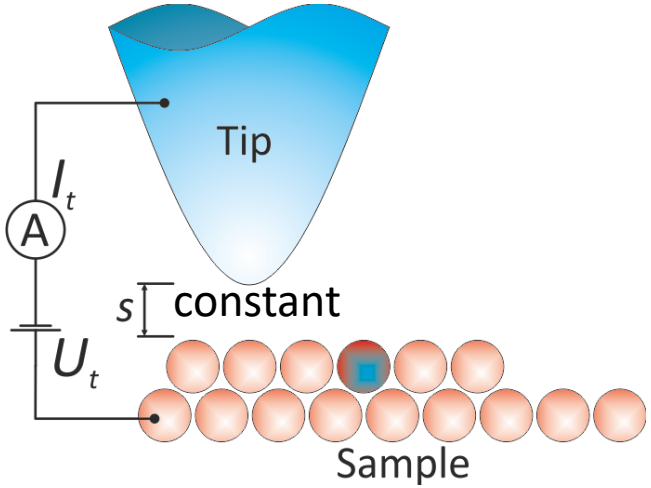
W(110), 200 nm x 200 nm

Danny Baumann, PhD thesis, IFW Dresden



Hänke, Hess et al., PRL 2012

Scanning Tunneling Spectroscopy (STS)



$T \approx 0$

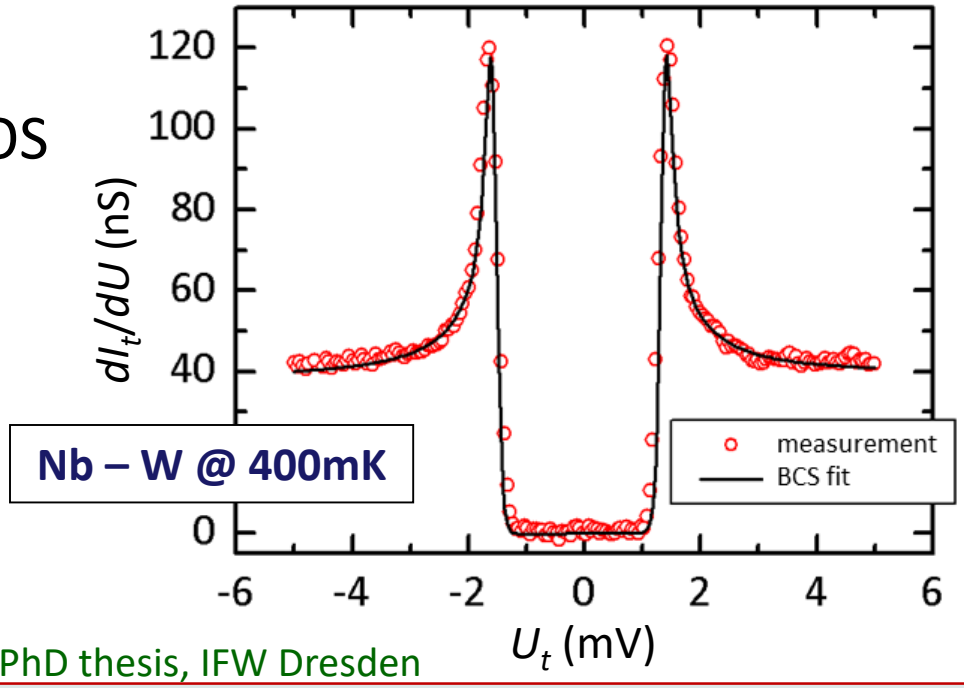
$$I_t \propto e^{-2\kappa s} \int_0^{eU_t} \rho_s(\epsilon)\, d\epsilon$$

distance

local density of states (LDOS)

➡ direct measurement of LDOS

$$\frac{dI_t}{dU}(U_t) \propto \rho_s(eU_t)$$

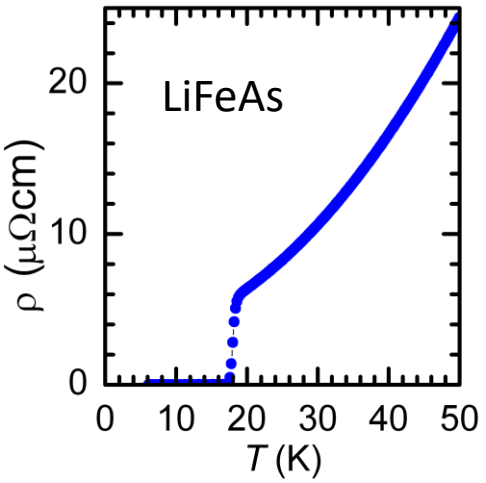


Danny Baumann, PhD thesis, IFW Dresden

Superconductivity: short introduction

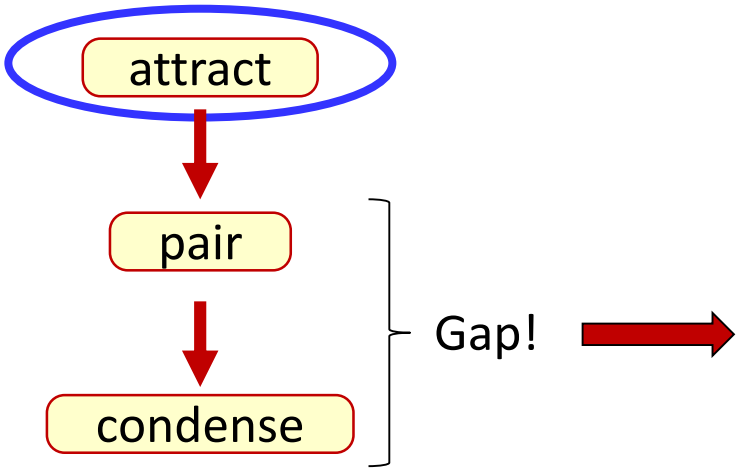
Macroscopic quantum state

- Zero resistivity[1]
- Meißner effect[2]

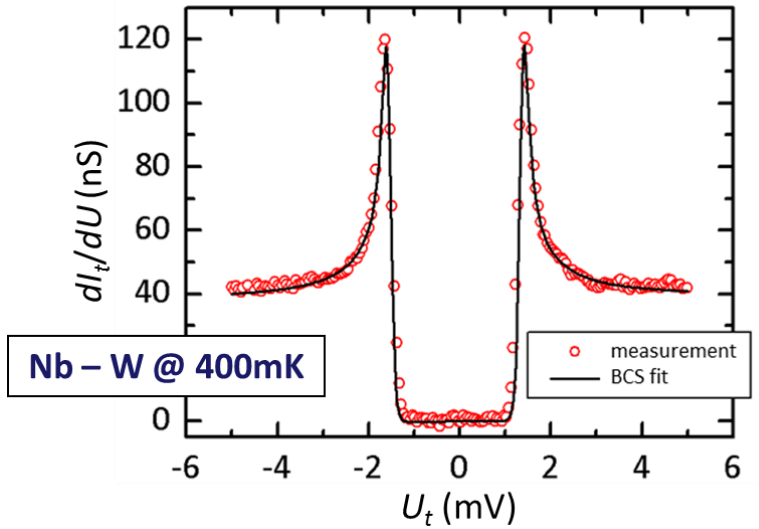


Microscopic BCS-theory[3]

Electrons



Tunneling spectroscopy!



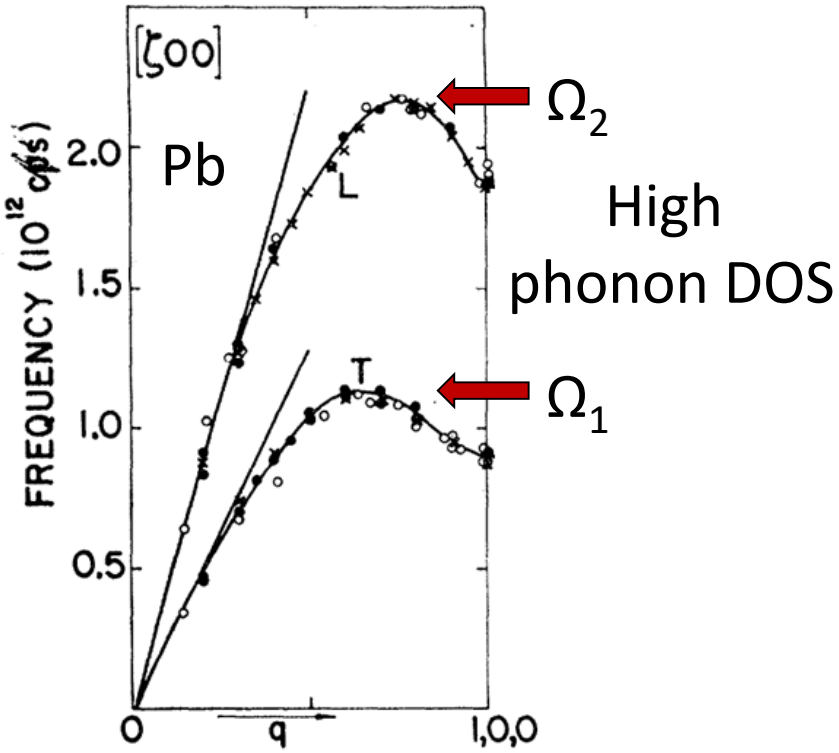
[1]Kamerlingh-Onnes, Comm. Leiden **120b** (1911)

[2]Meißner & Ochsenfeld, Naturwissenschaften **21**, 787 (1933)

[3]Bardeen, Cooper, Schrieffer, Phys. Rev. **108**, 1175 (1957)

Conventional: electron-phonon interaction

Phonons



High phonon DOS

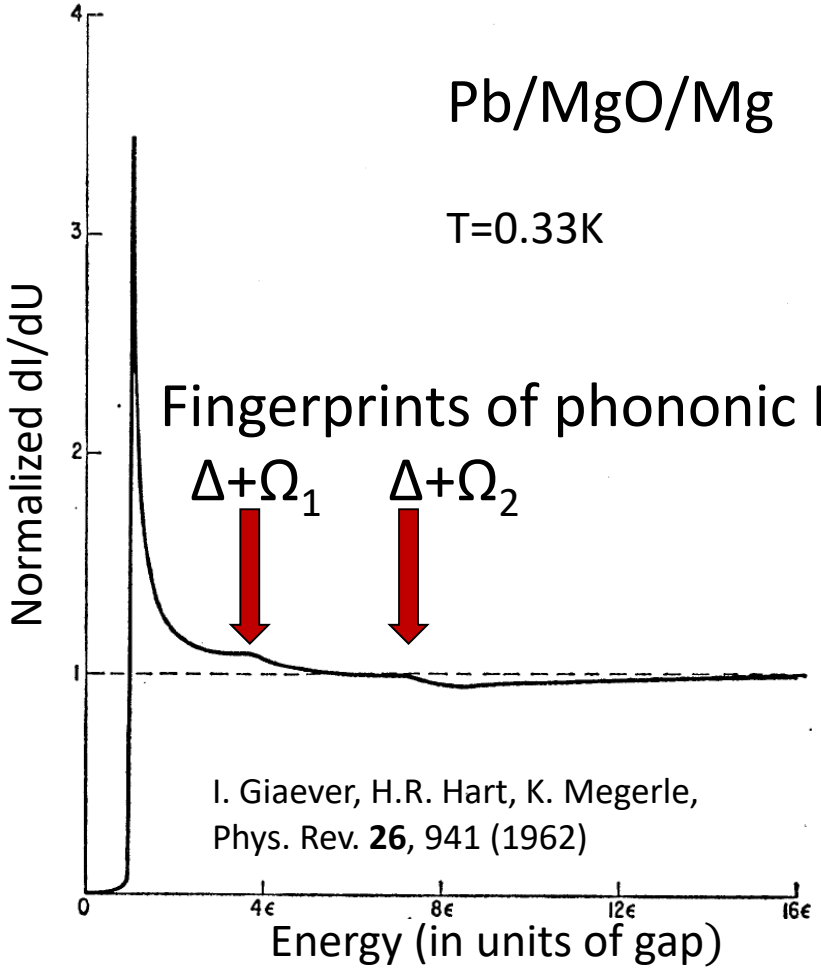
B.N. Brockhouse et al., Phys. Rev. **128**, 1099 (1962)

Electron-phonon coupling

↓

Renormalization of electronic states

Tunneling spectroscopy



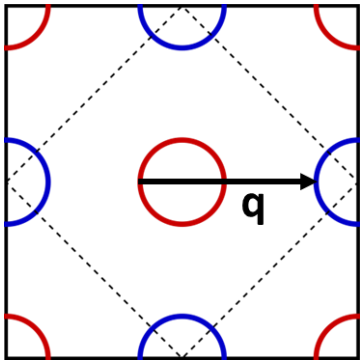
I. Giaever, H.R. Hart, K. Megerle, Phys. Rev. **26**, 941 (1962)

Theory: Rowell, et al., PRL **10**, 334 (1963)
Schrieffer et al., PRL **10**, 336 (1963); PR **148**, 263 (1966)
Scalapino et al., PR **148**, 263 (1966)

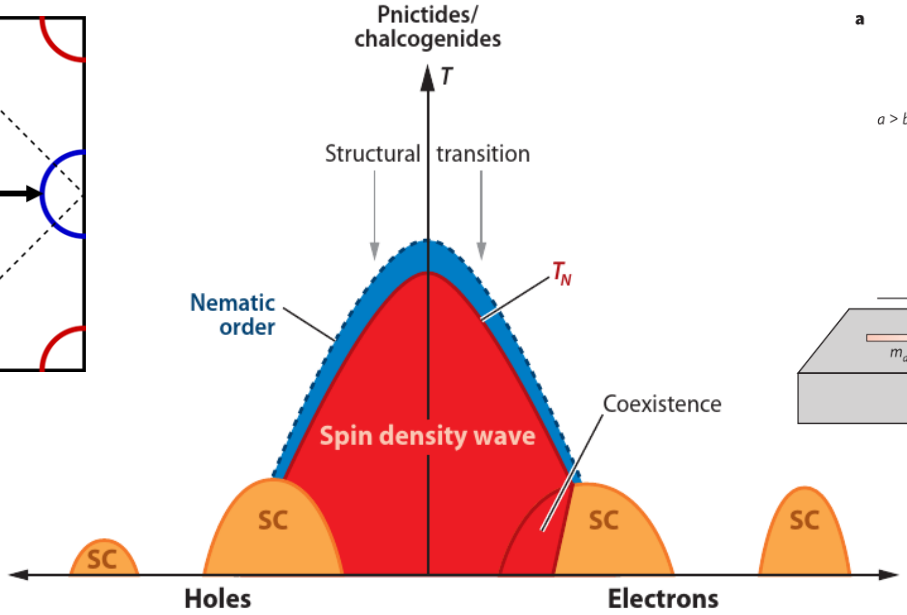
Unconventional: electron-electron interaction

e.g. in iron-based superconductors

Spin fluctuations…

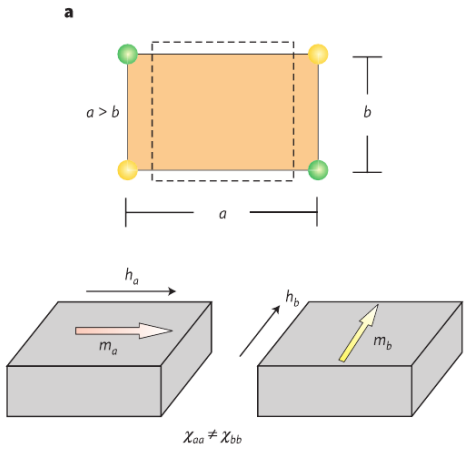


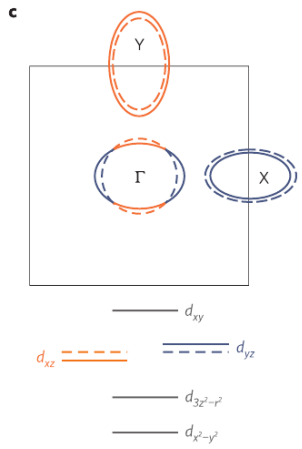
Peak in
$\chi_{mag}(\mathbf{q},\omega)$
at $\mathbf{q}=(\pi,0)$



A. Chubukov, 2012

Orbital fluctuations…





Fernandes, Chubukov, Schmalian
Nat. Phys. **10**, 97 (2014)

Idea: Fermi surface nesting and spin fluctuations drive superconductivity

I. Mazin, Phys. Rev. Lett. **101**, 057003 (2008)

Idea: Orbital (nematic fluctuations) drive superconductivity

Kontani & Onari, Phys. Rev. Lett. **104**, 1547001 (2010)

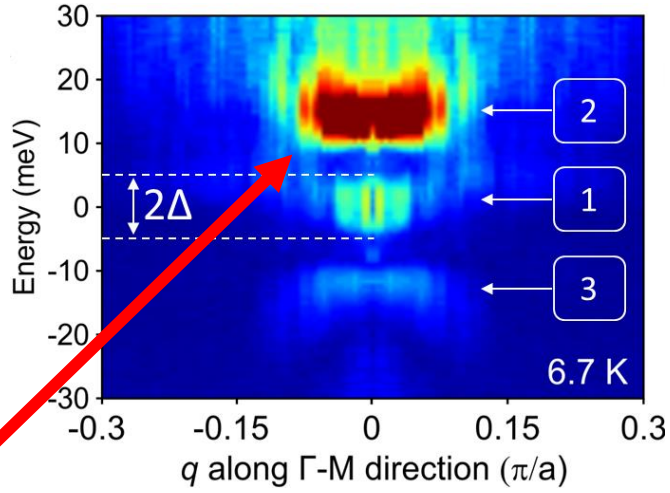
Outline

Warm-up

- Scanning tunneling microscopy and spectroscopy
- Superconductivity

Probing electron-boson coupling in LiFeAs

- Local spectroscopy
- Friedel oscillations

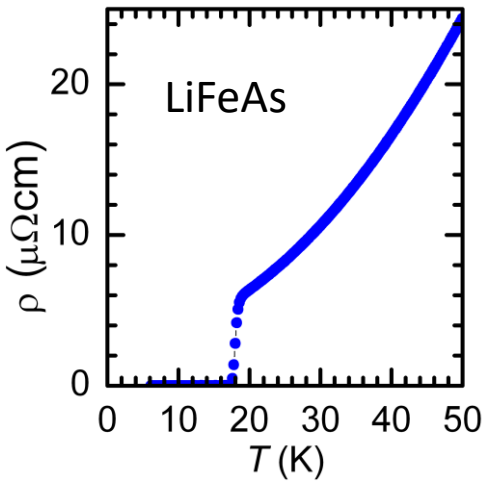


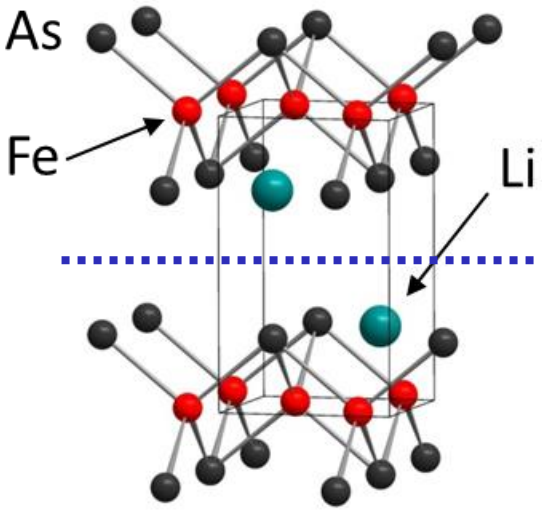
Signature of electron-boson coupling

Explore possible pairing bosons by STM/STS

LiFeAs

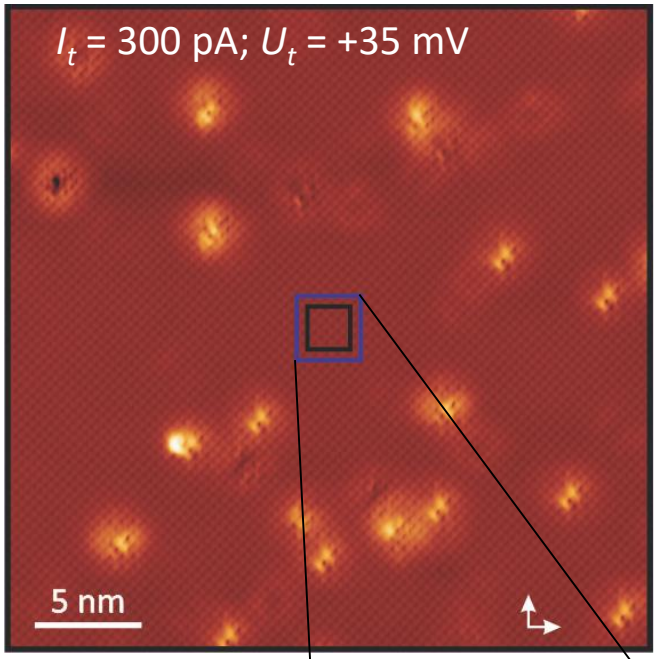
- Iron-pnictide superconductor
  - ➡ unconventional
- T_c ~ 17 K
- Stoichiometric superconductor
- “perfect” surfaces
- No magnetic order
- No nematic order





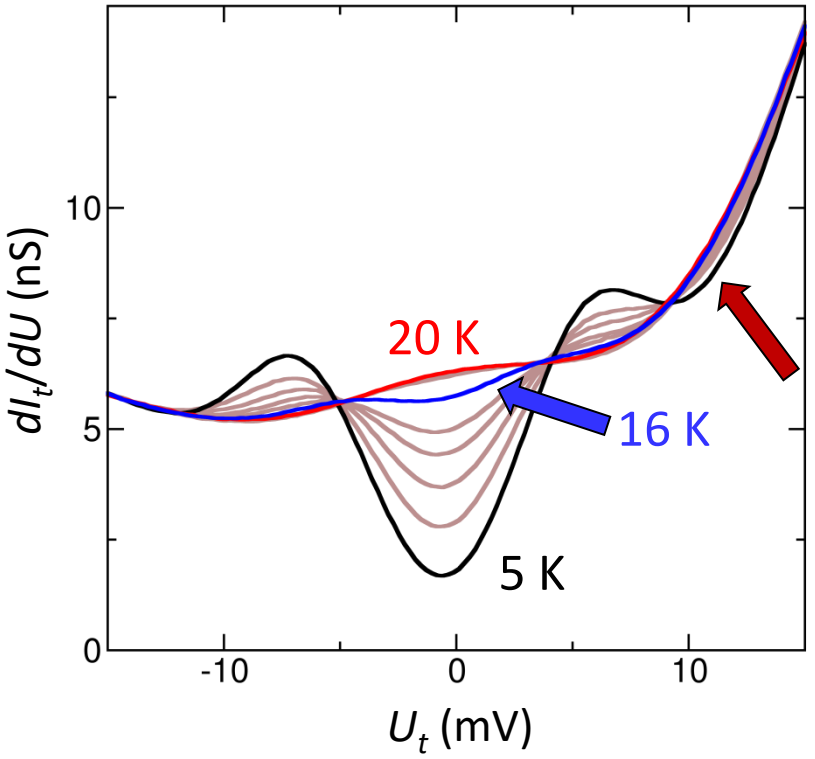
Temperature dependent STS on LiFeAs

Topography @ 5 K



clean area

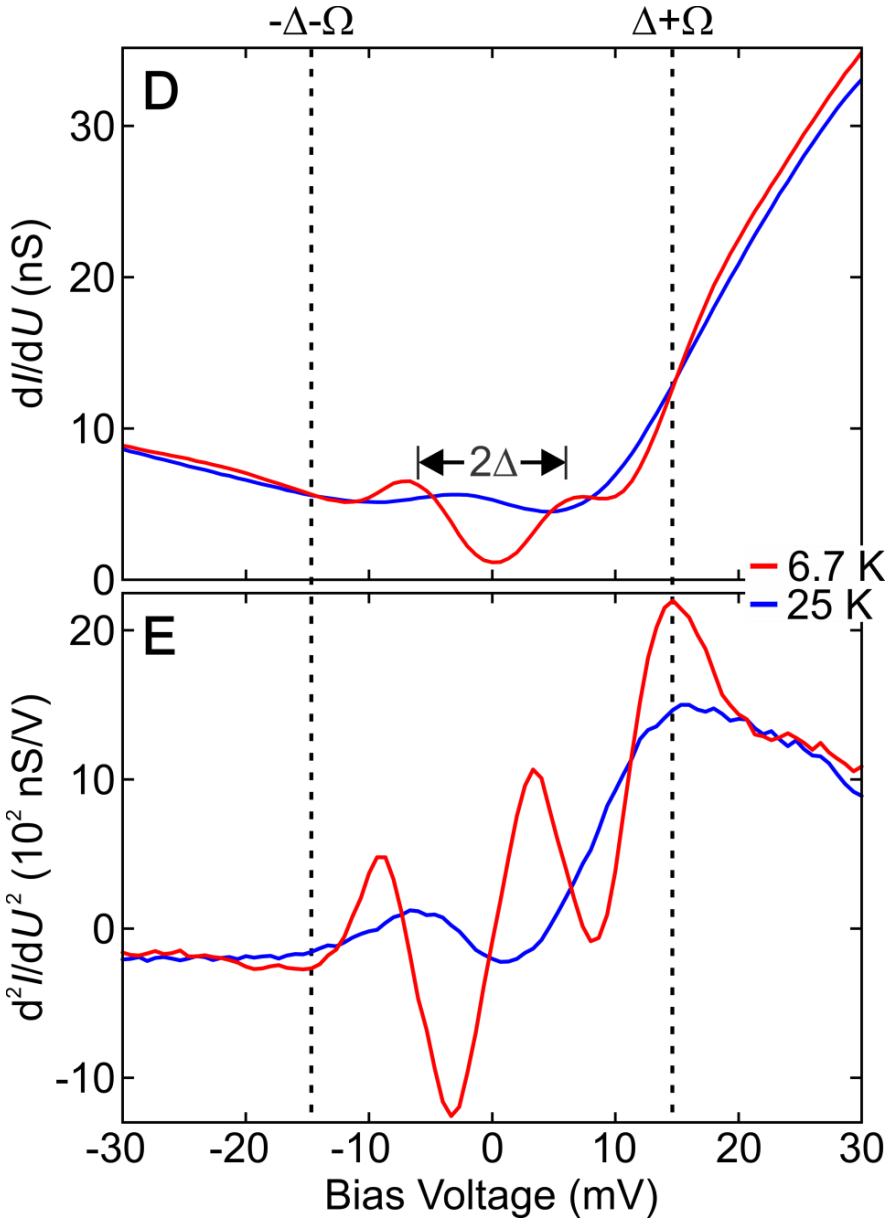
Spectroscopy



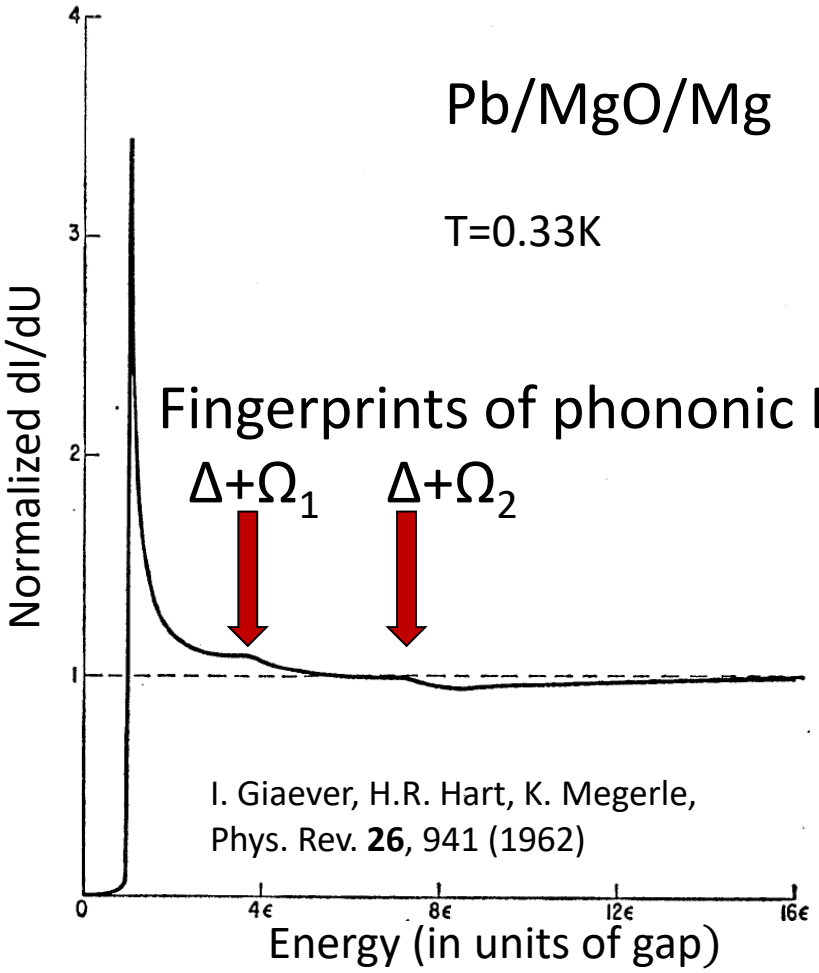
- Superconducting gap Δ ~ 6meV
- $T_c \approx 16$ K
- High-energy depletion
  ➡ signature of boson!

Nag, Hess et al., Scientific Reports 2016

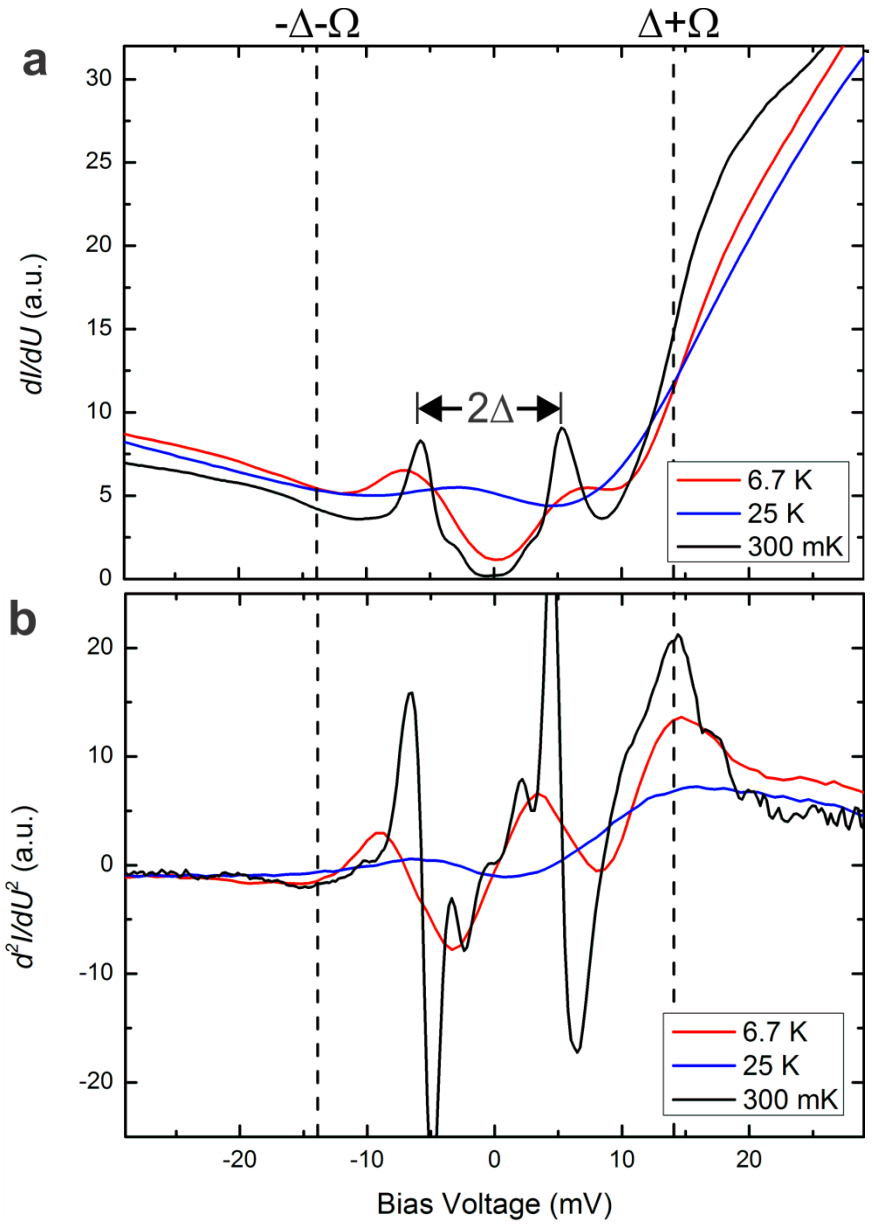
Bosonic mode signature



Reminder:



Bosonic mode signature



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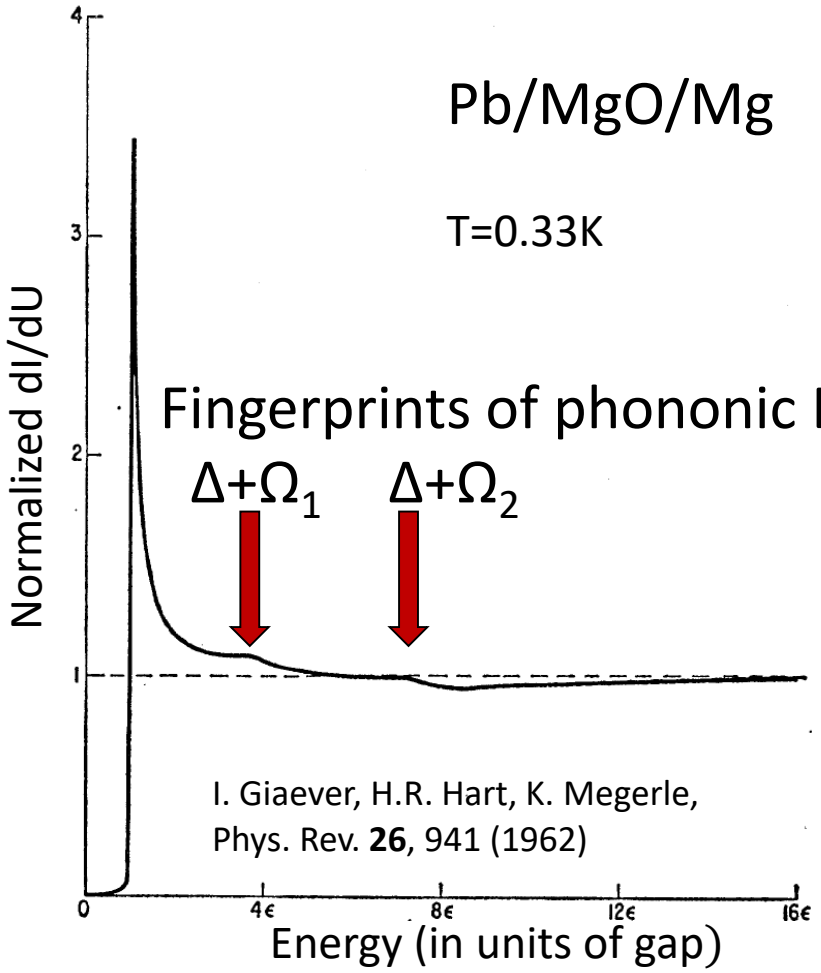
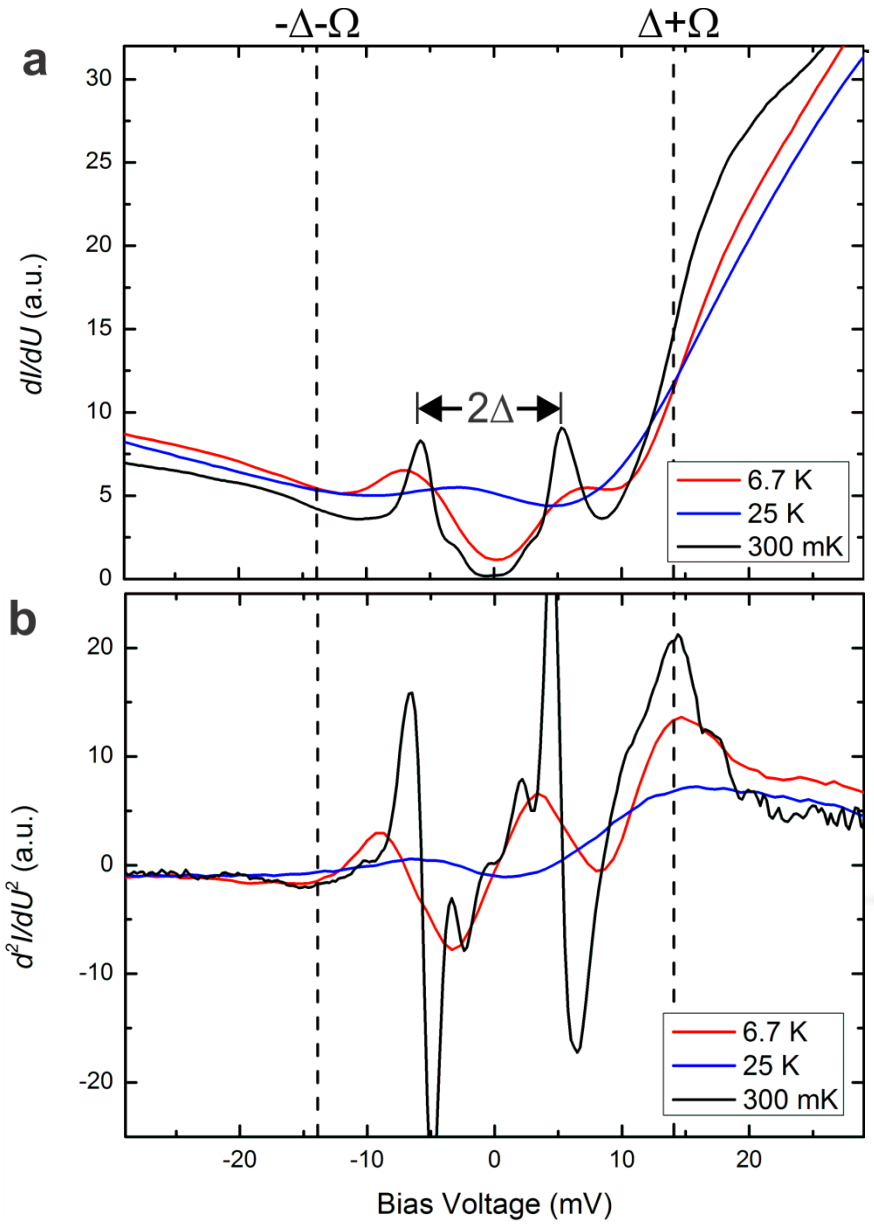


Bosonic mode signature



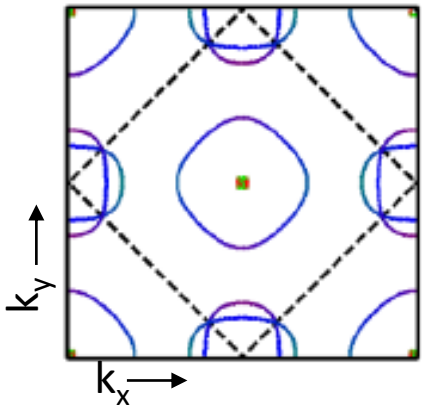
$\Delta+\Omega \approx 14$ meV

$\Delta \approx 6$meV → **$\Omega \approx 8$ meV**

Phonon?

Spin fluctuation?

Which parts of the FS?



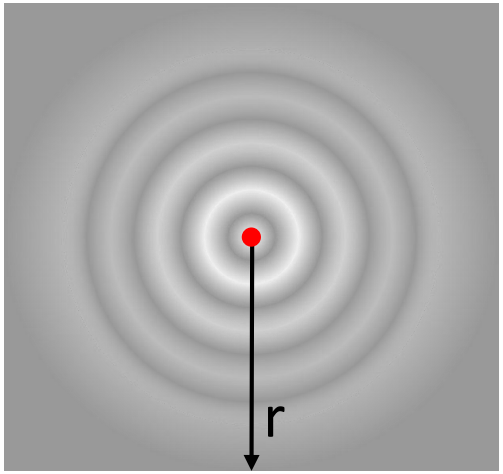
Band structure data:
Wang et al., PRB 2013

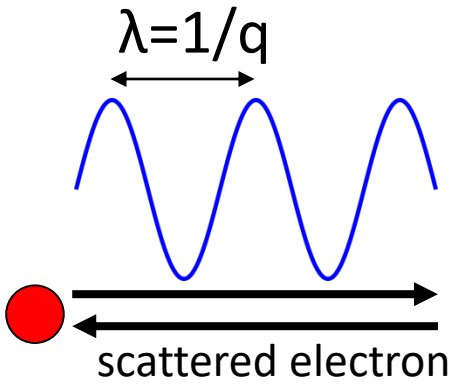
…add momentum sensitivity!

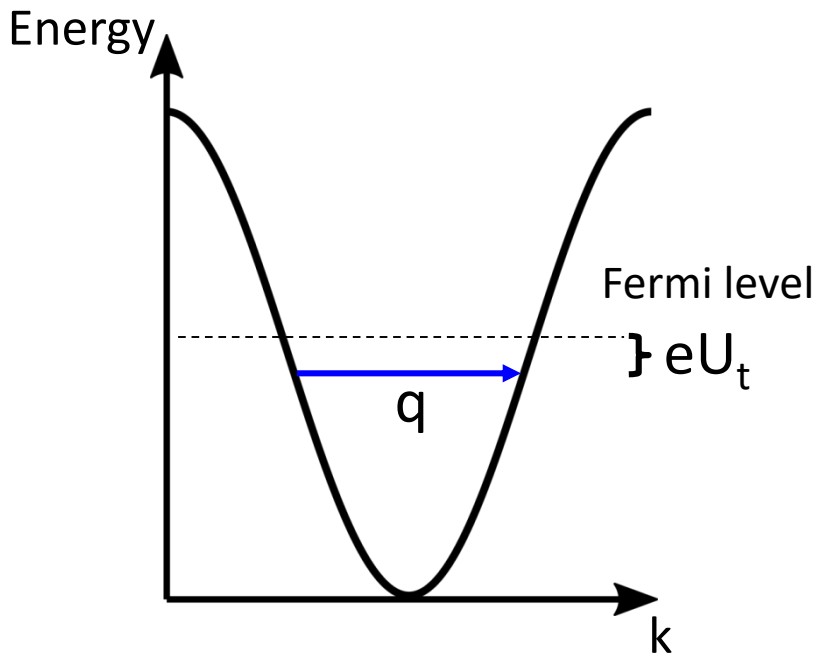
Friedel oscillations

Quasiparticle scattering off defects → Friedel oscillations

impurity in a metal

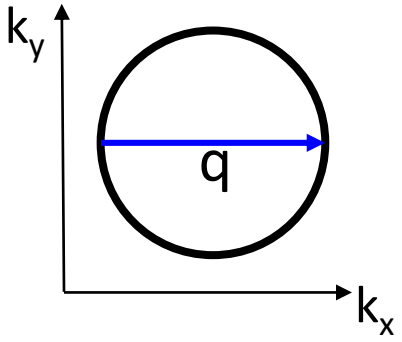






$\Delta LDOS \sim \cos^2(rq)$

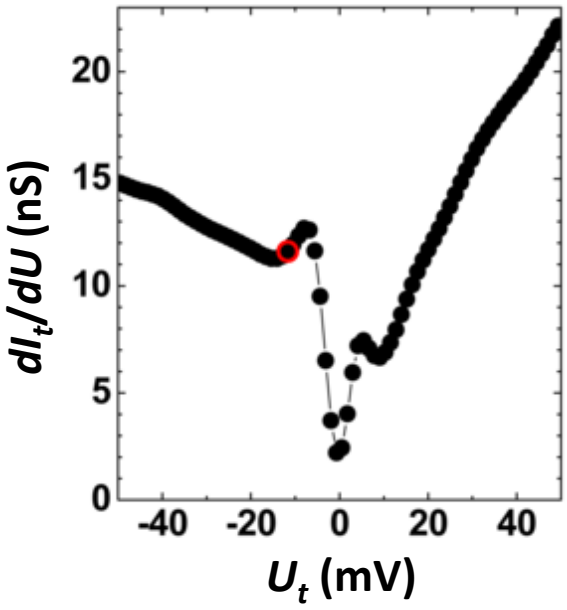
Accessible by STM/STS



➡ probe band structure and scattering processes!

Friedel oscillations in LiFeAs

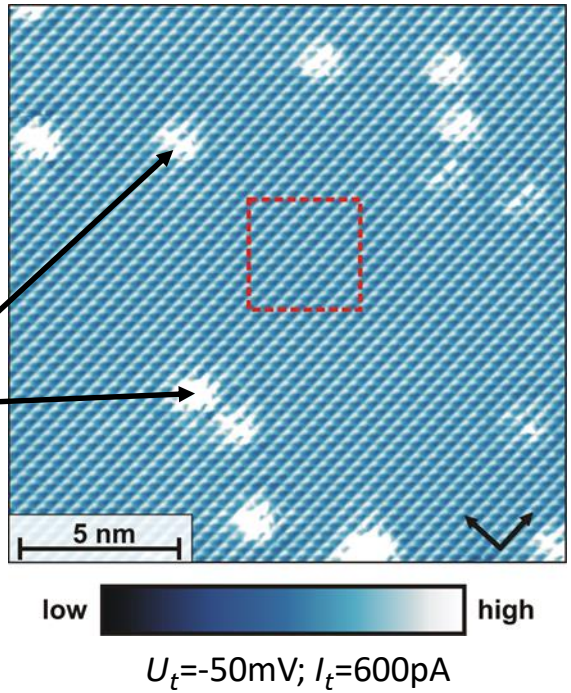
dI_t/dU@6K



measured at each tip position

Impurity sites causing Friedel oscillations

Topography@6K

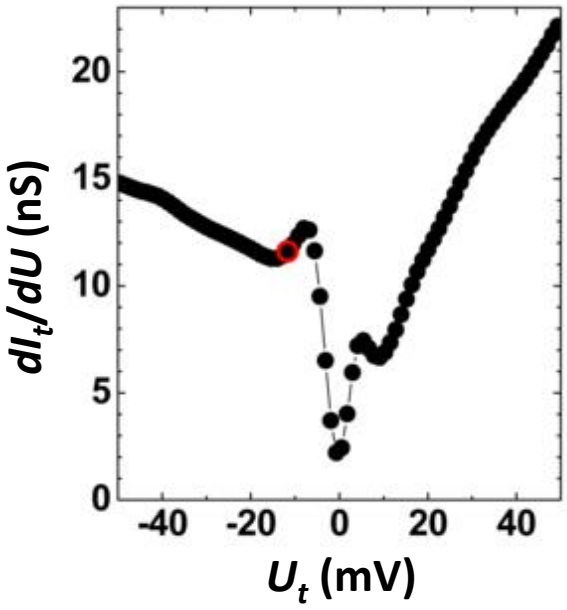


U_t=-50mV; I_t=600pA

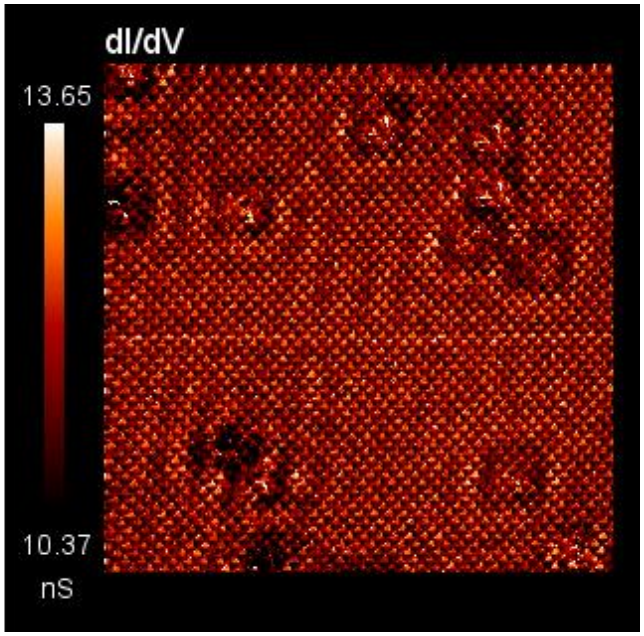
Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

Friedel oscillations in LiFeAs

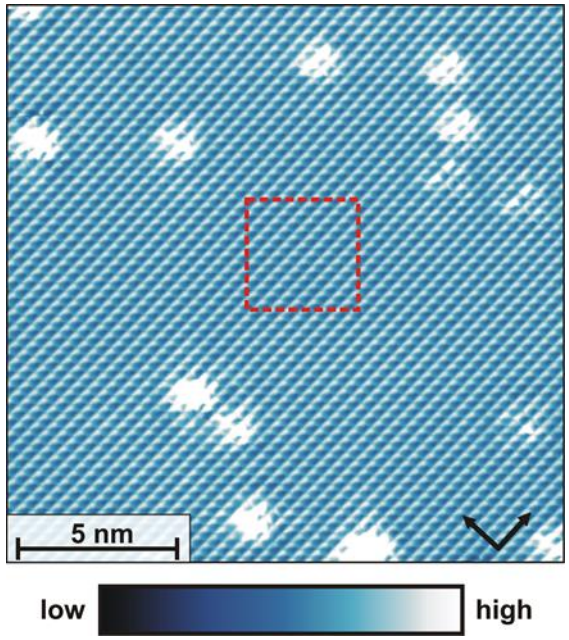
dI_t/dU@6K



dI_t/dU map @ -12 mV



Topography@6K



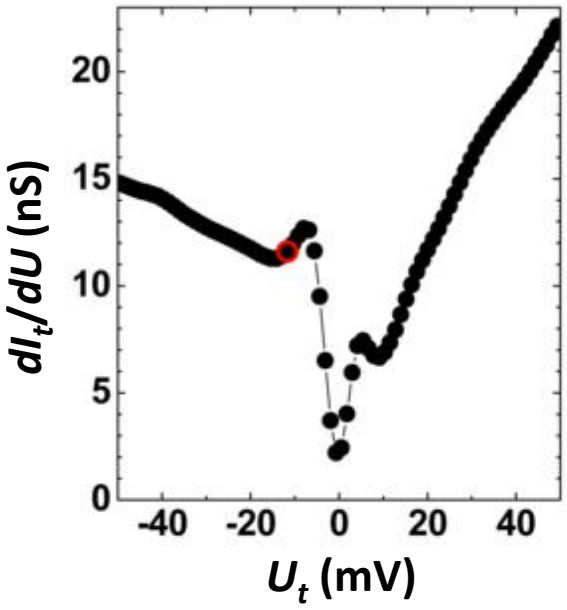
U_t=-50mV; I_t=600pA

„Quasiparticle Interference (QPI)“

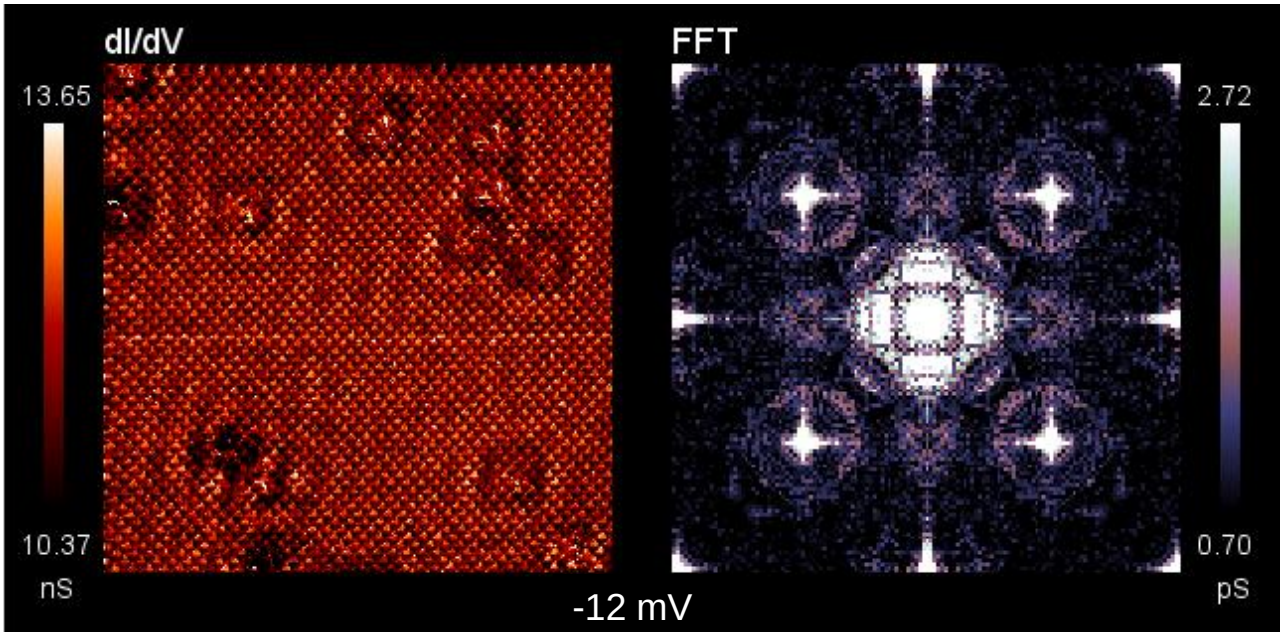
Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

Friedel oscillations in LiFeAs

dI_t/dU@6K



dI_t/dU map @ -12 mV



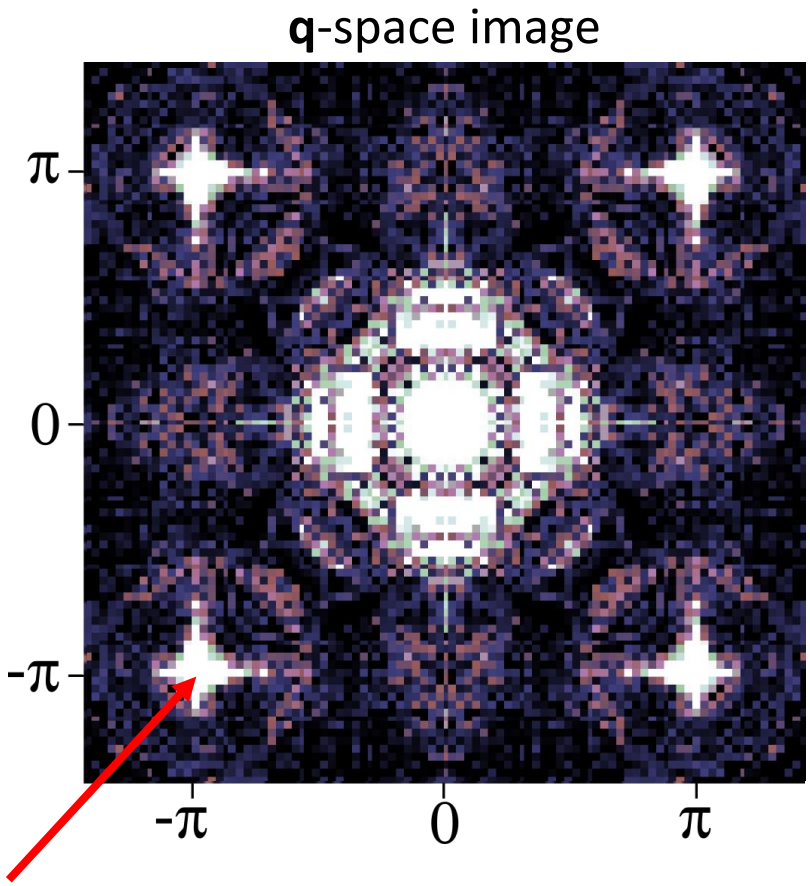
Fourier transform

Scattering vector map!

„Quasiparticle Interference (QPI)“

Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

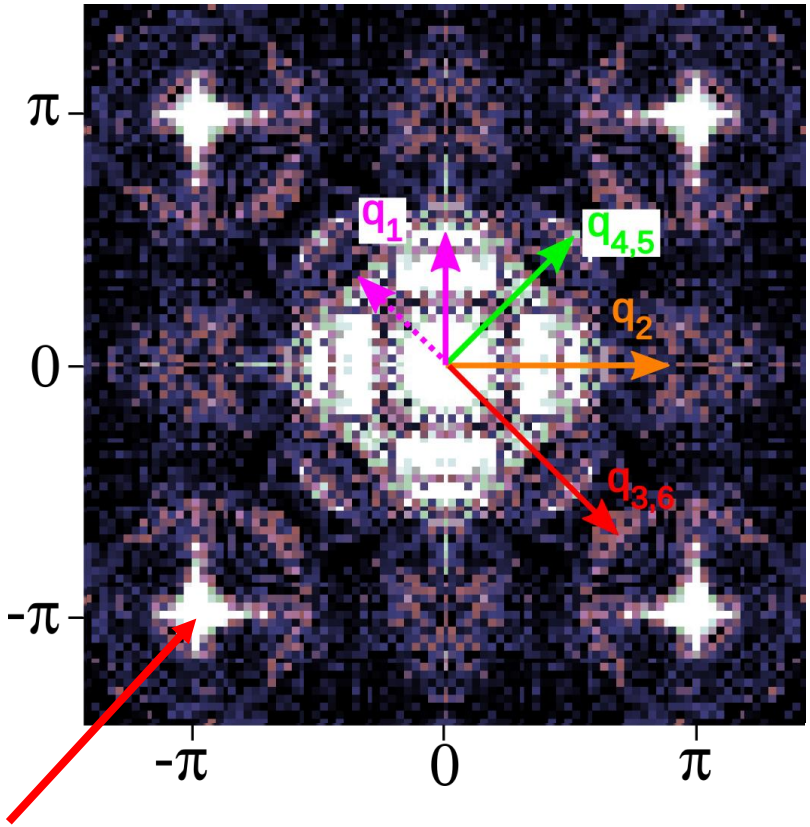
Friedel oscillations in LiFeAs



Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

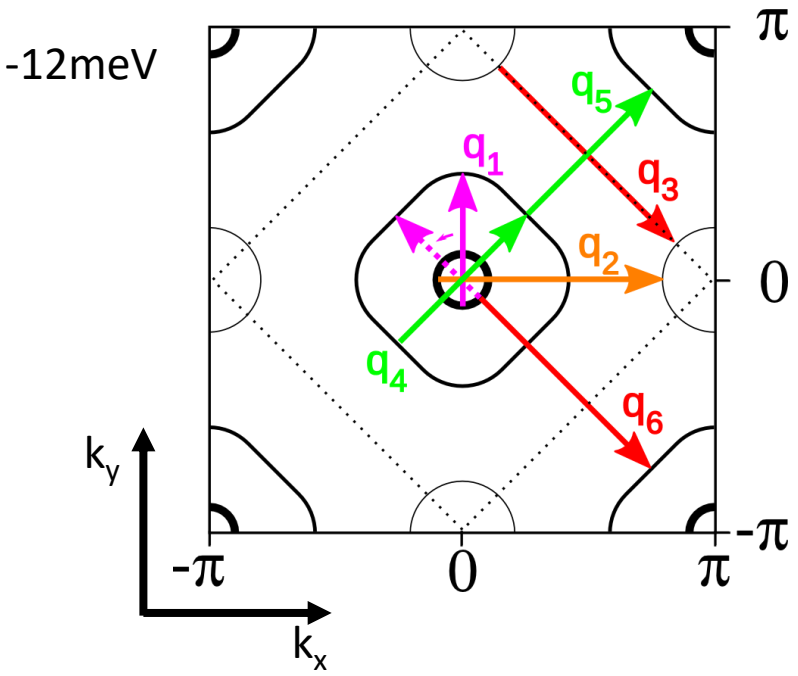
Friedel oscillations in LiFeAs

q-space image



Reciprocal atomic lattice

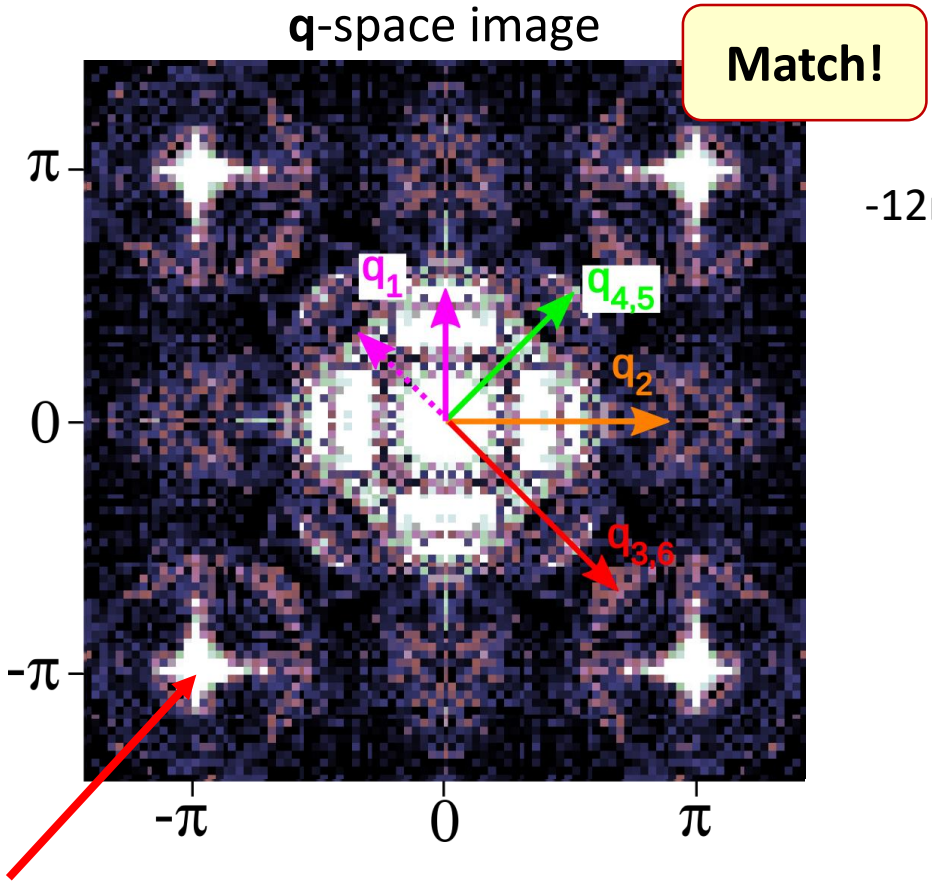
ARPES band structure

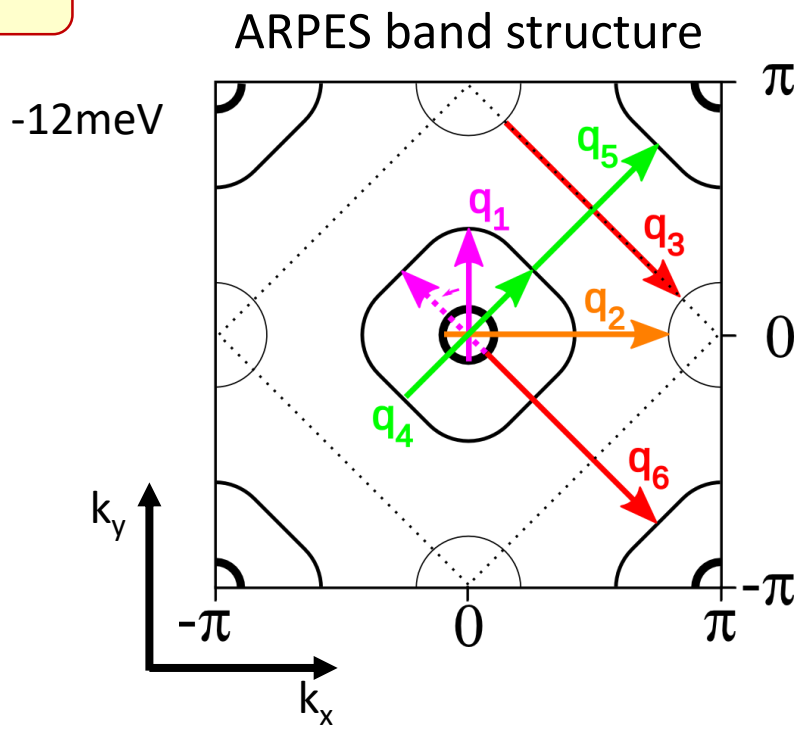


Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

ARPES-Data: S. Borisenko et al., PRL **105**, 067002 (2010)

Friedel oscillations in LiFeAs



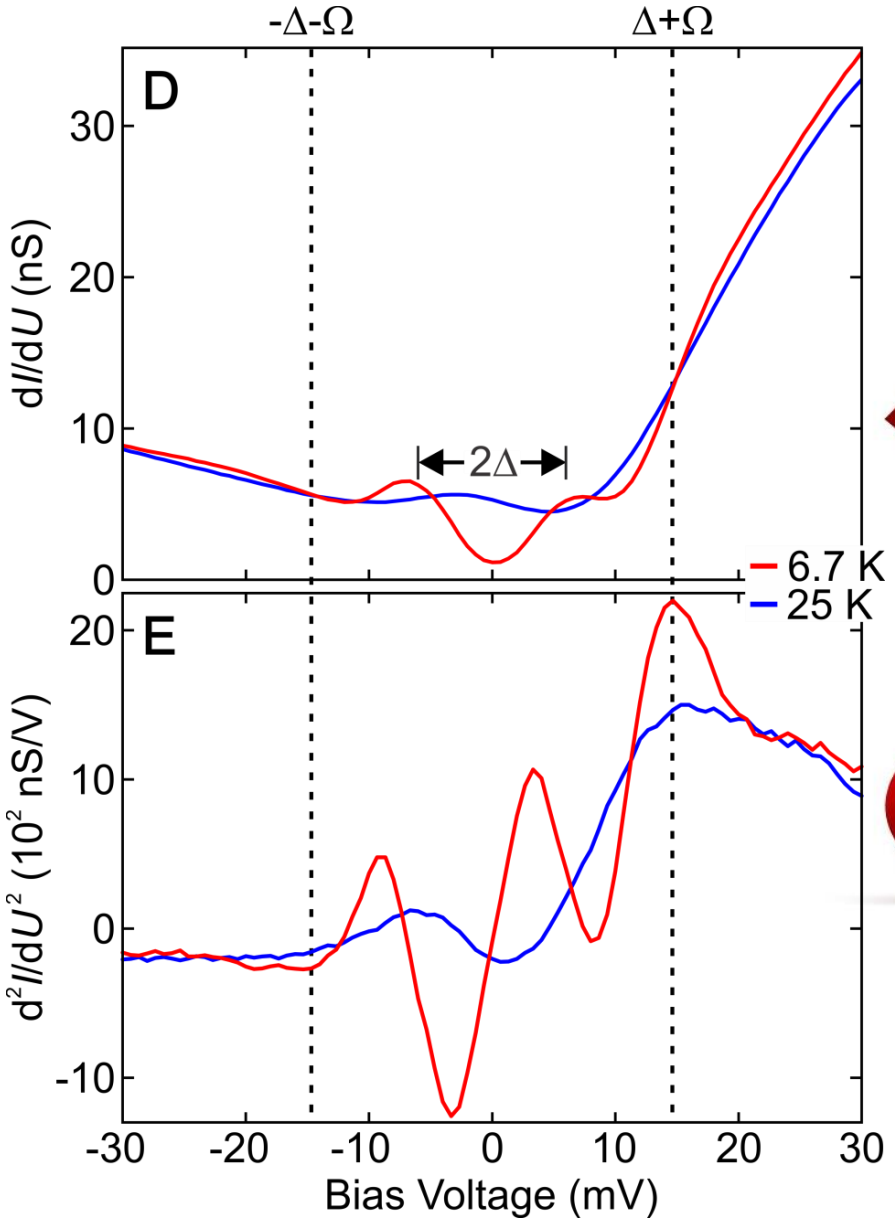


See also:
Allan et al., Science **336**, 563 (2012)
Chi et al., PRB **89**, 104522 (2014)

Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

ARPES-Data: S. Borisenko et al., PRL **105**, 067002 (2010)

Bosonic mode signature



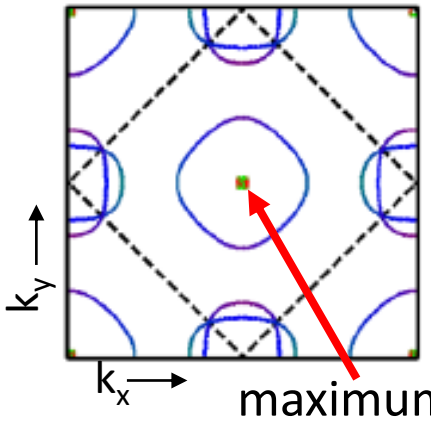
$\Delta+\Omega \approx 14$ meV

$\Delta \approx 6$meV → **$\Omega \approx 8$ meV**

Phonon?

Spin fluctuation?

Which parts of the FS?

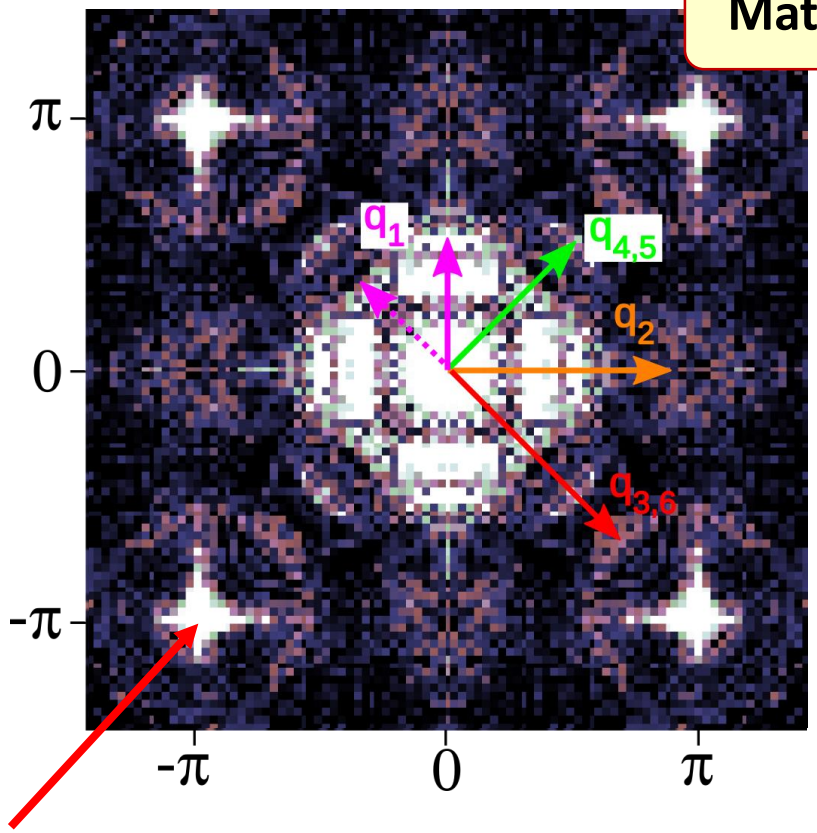


Band structure data:
Wang et al., PRB 2013

…add momentum sensitivity!

Friedel oscillations in LiFeAs

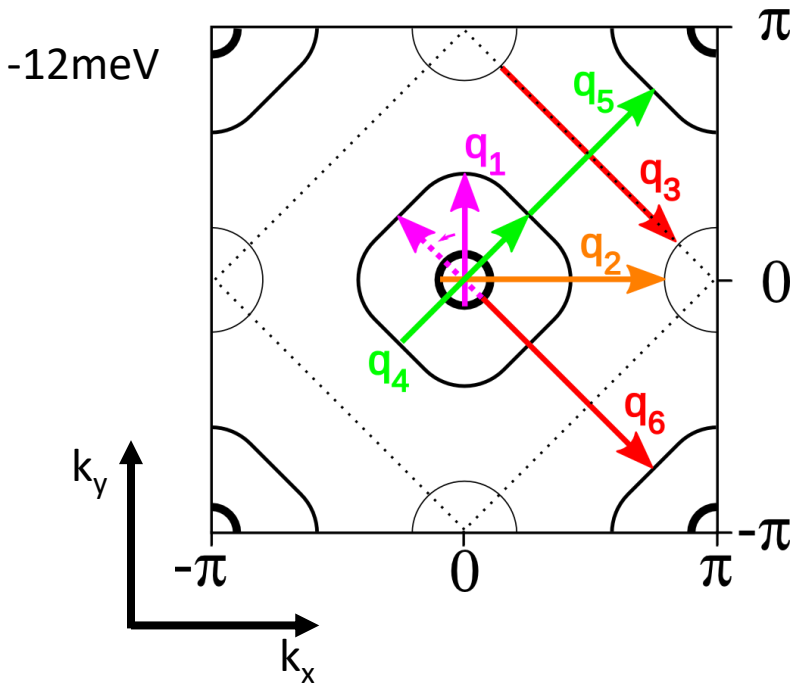
q-space image



Reciprocal atomic lattice

Match!

ARPES band structure



Required:

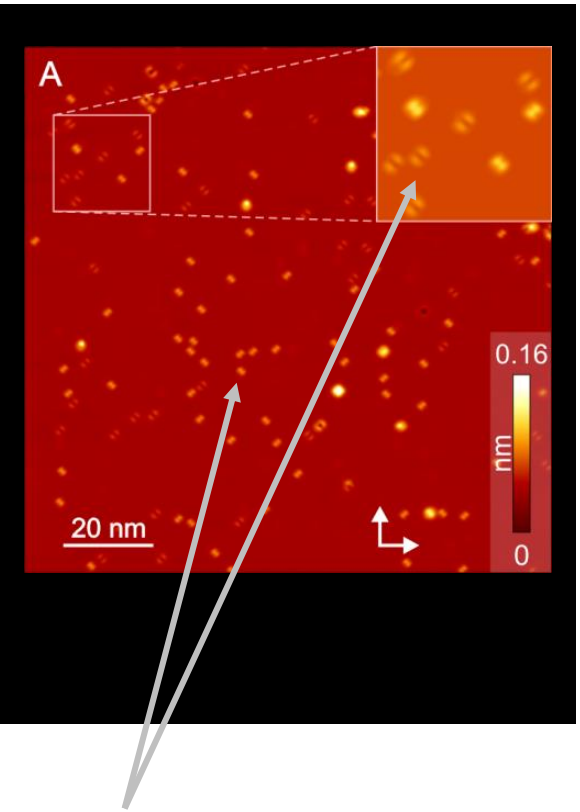
Higher resolution at $q<q_1$

➡ new measurement

Hänke, Hess et al., PRL 2012; Hess et al., PRL 2013

Friedel oscillations with high q resolution

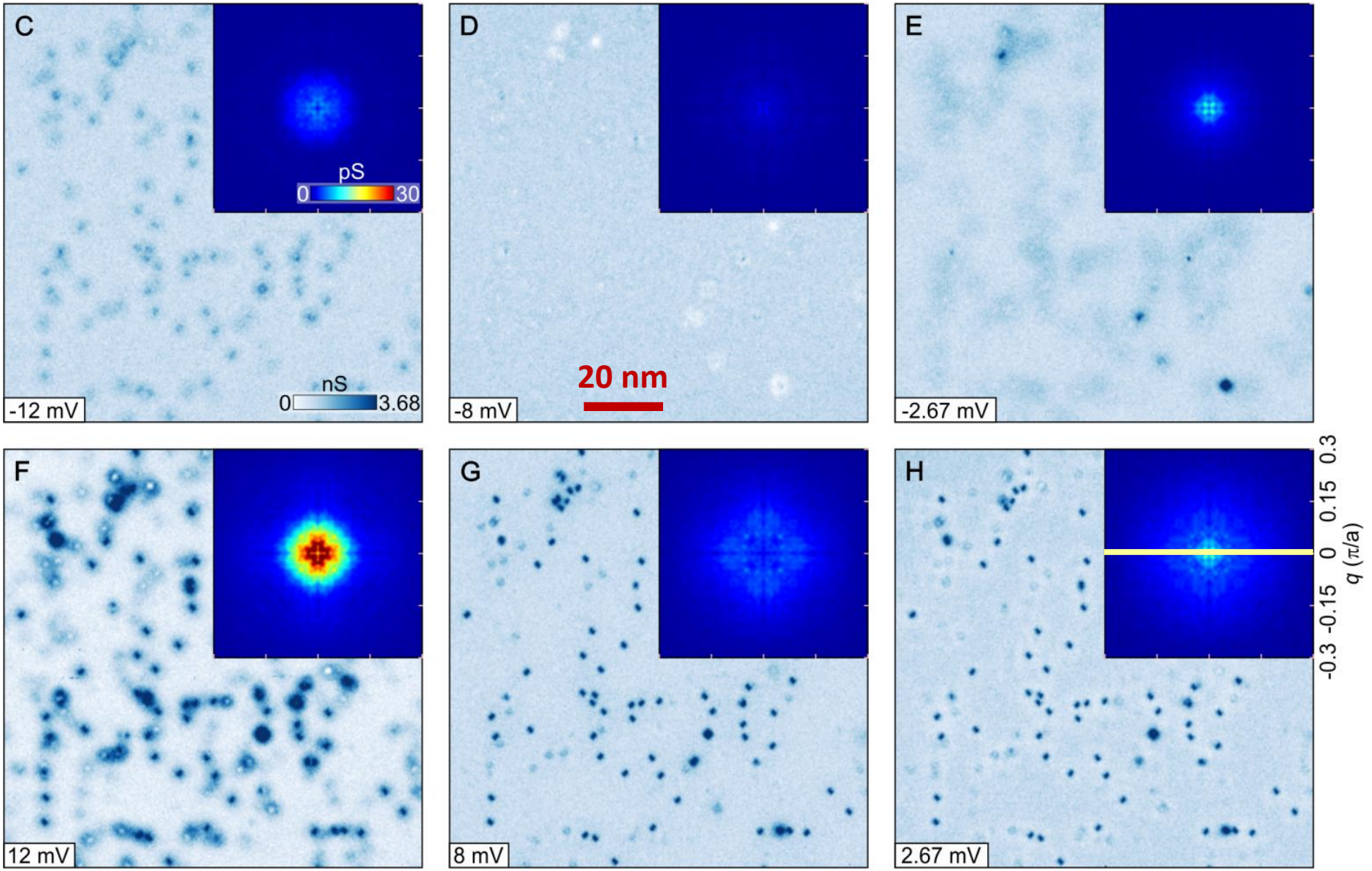
Topography @ 6.7 K



Iron defects

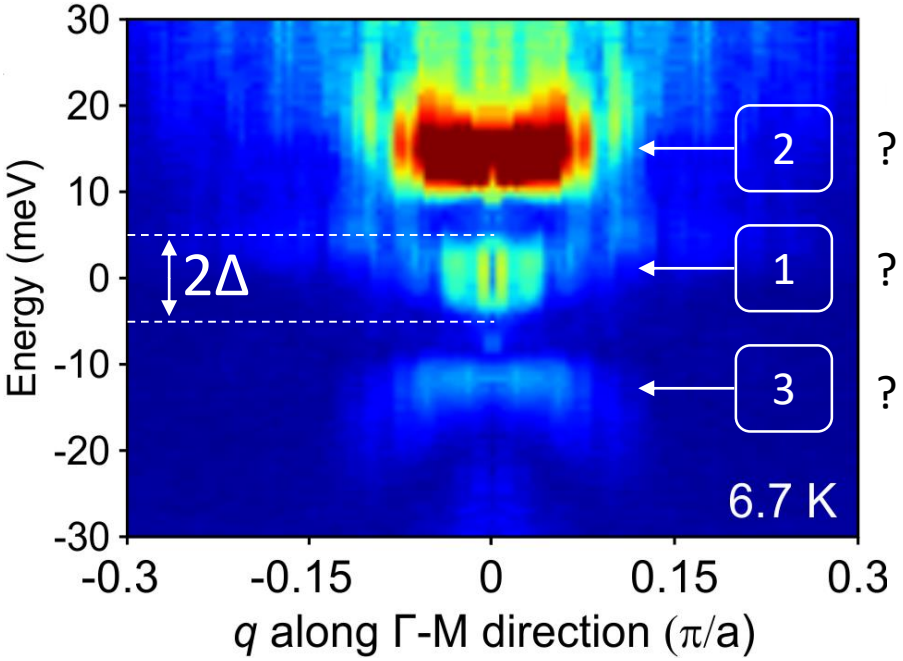
Schlegel, Hess et al., PSSB 2017; Grothe et al., PRB 2012

Energy dependence



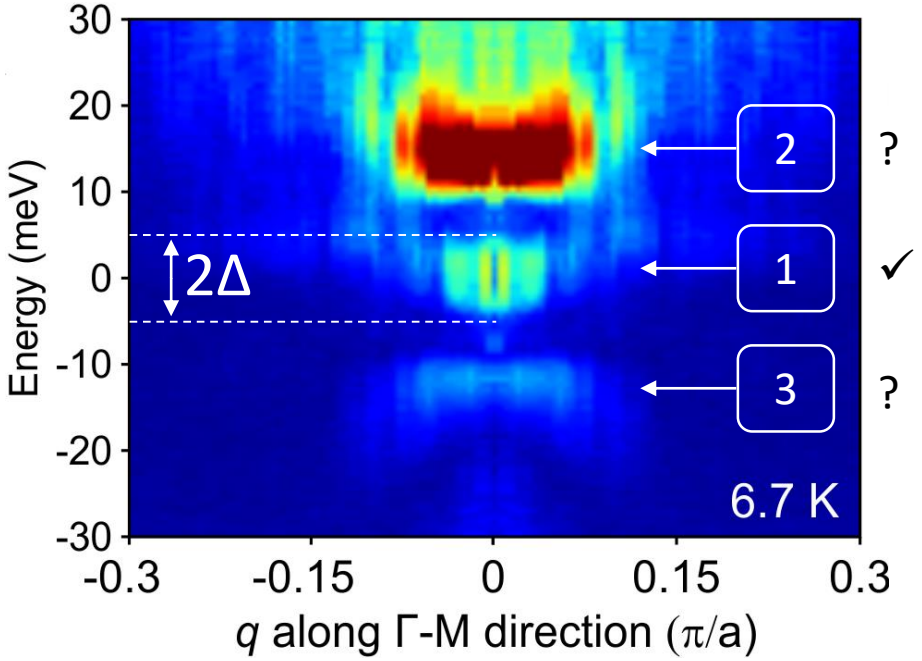
Energy-momentum dependence

T = 6.7 K



Energy-momentum dependence

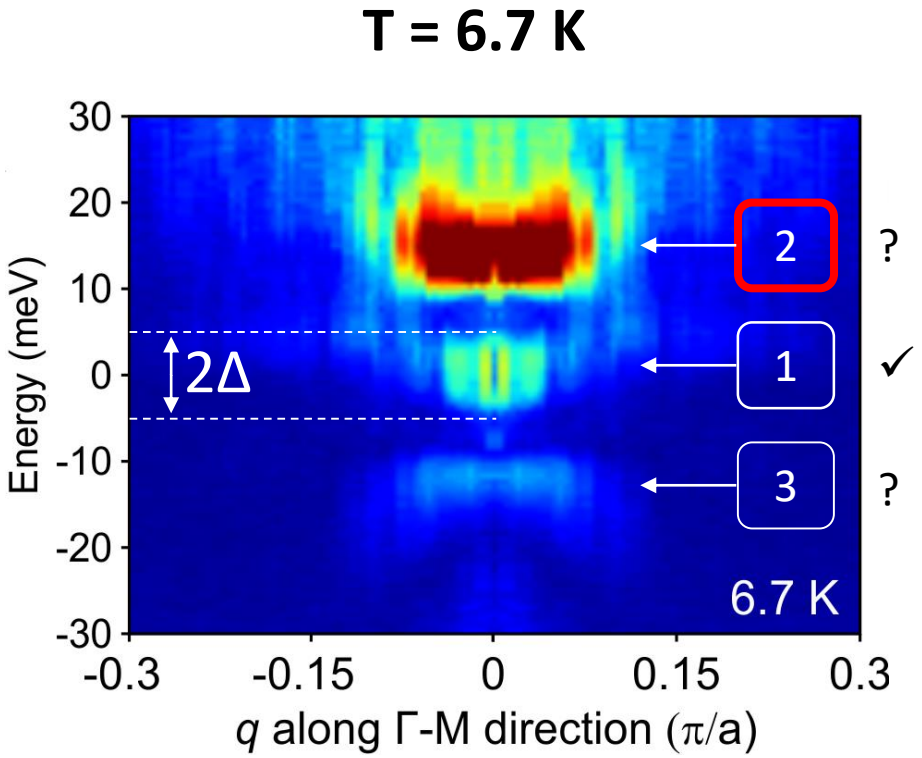
T = 6.7 K

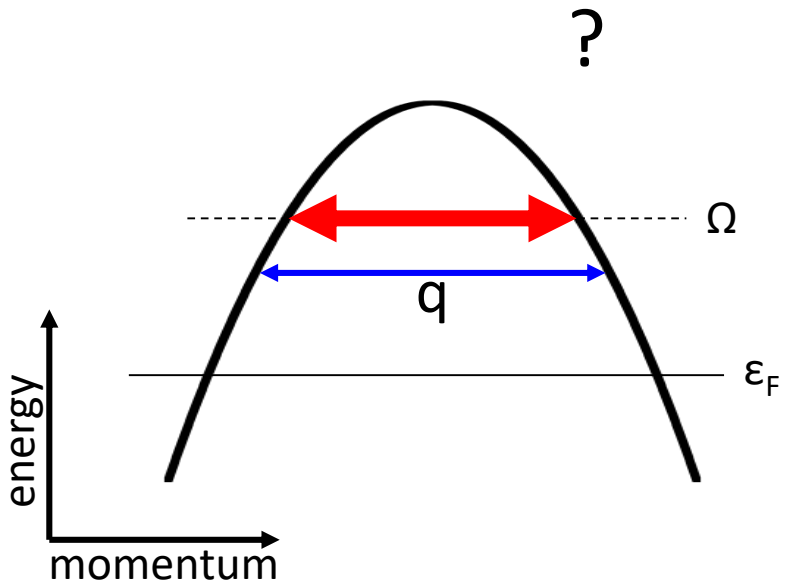


1 Impurity bound states[1]

[1]Schlegel, Hess et al., Phys. Stat. Sol. B 2017

Boson-assisted scattering?





1 Impurity bound states[1]

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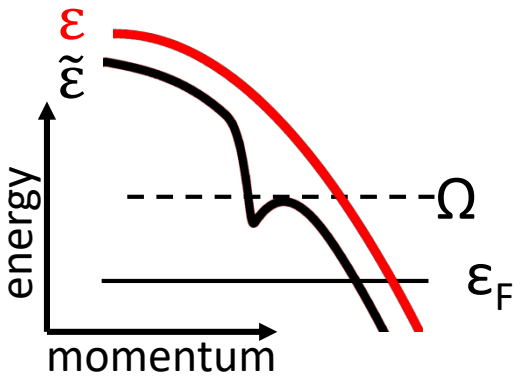
Boson-assisted scattering

Electron-boson coupling

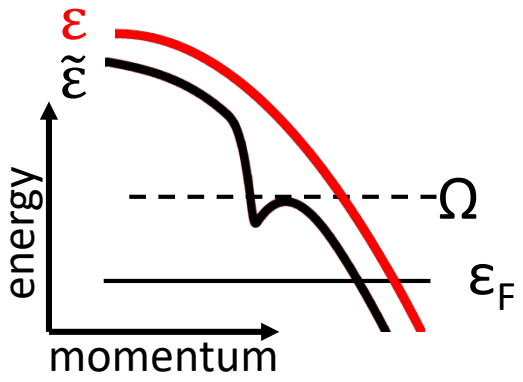


Well established: Band energy renormalization

$\varepsilon \rightarrow \tilde{\varepsilon}$

Boson-assisted scattering

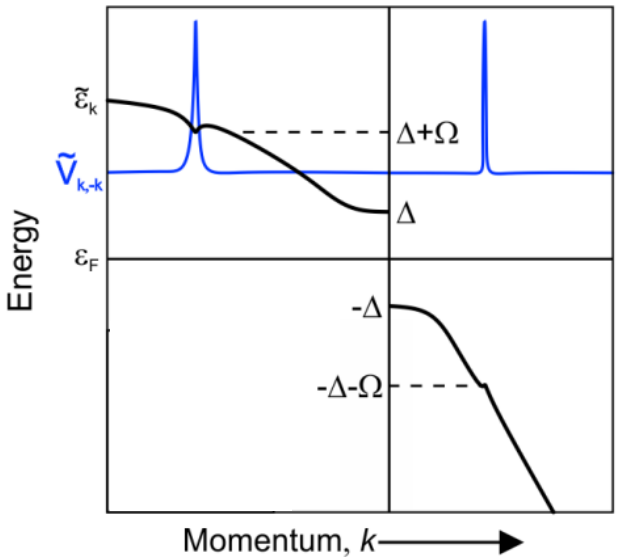
Electron-boson coupling



Well established: Band energy renormalization

$\varepsilon \rightarrow \tilde{\varepsilon}$

Here: consider electron **scattering** (Friedel Oscillation)

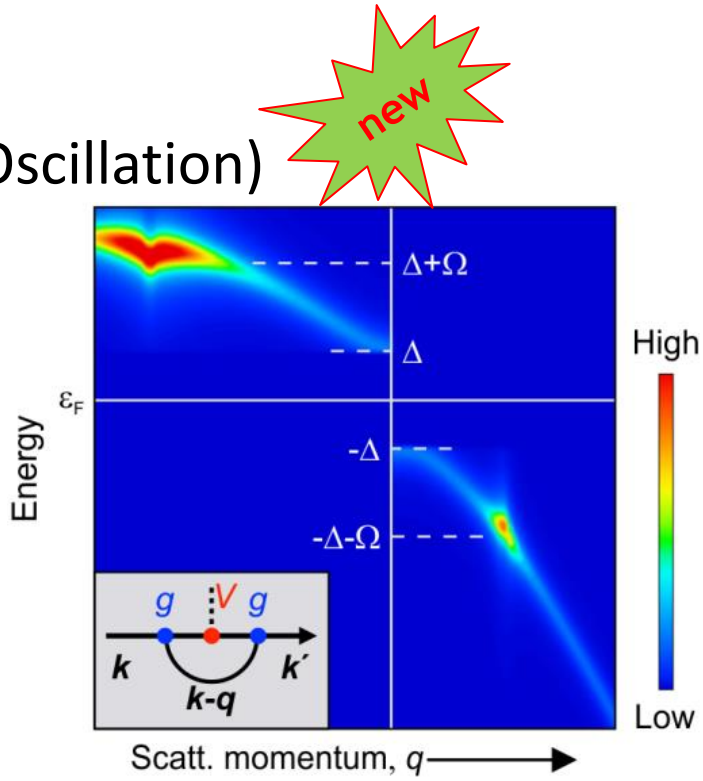


Scattering potential

$V \rightarrow \tilde{V}$

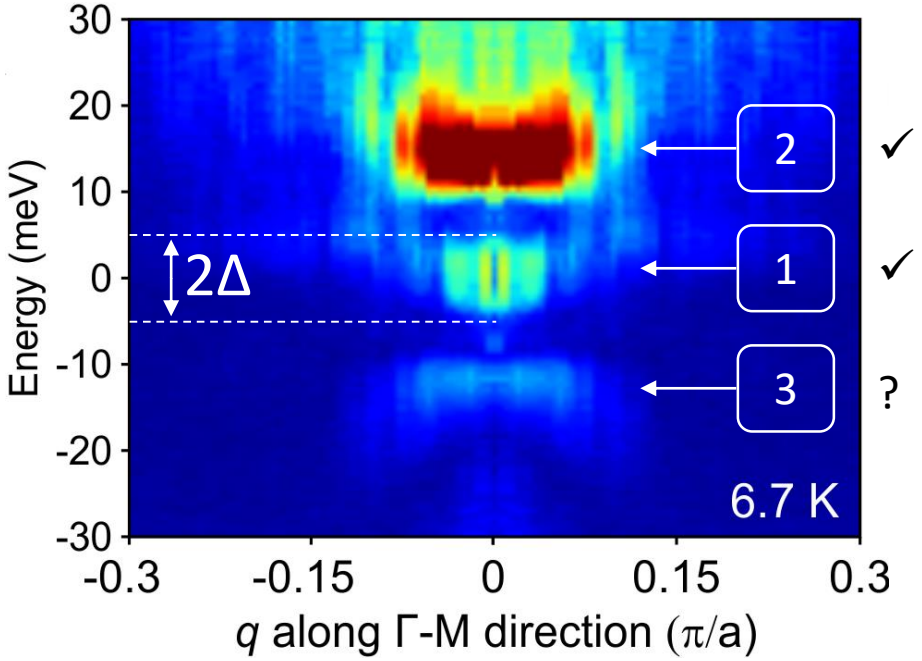
Resonant enhancement!

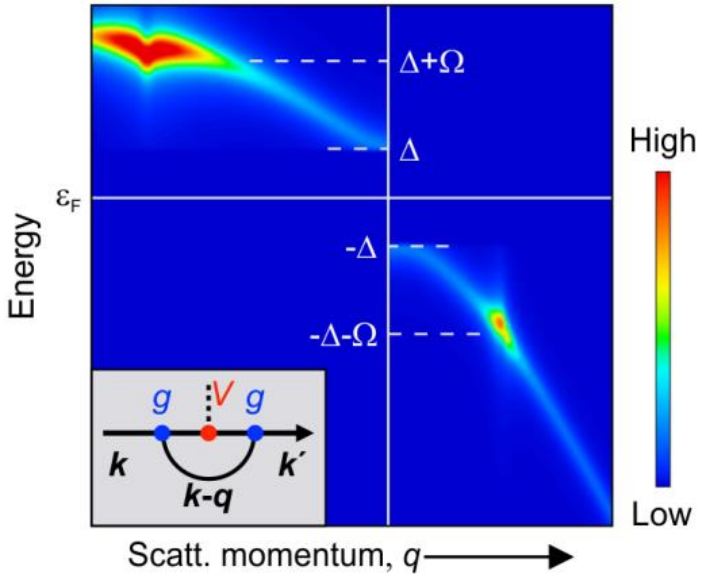
Theory: Steffen Sykora



Resonantly enhanced Friedel oscillations

Superconducting State – 6.7 K



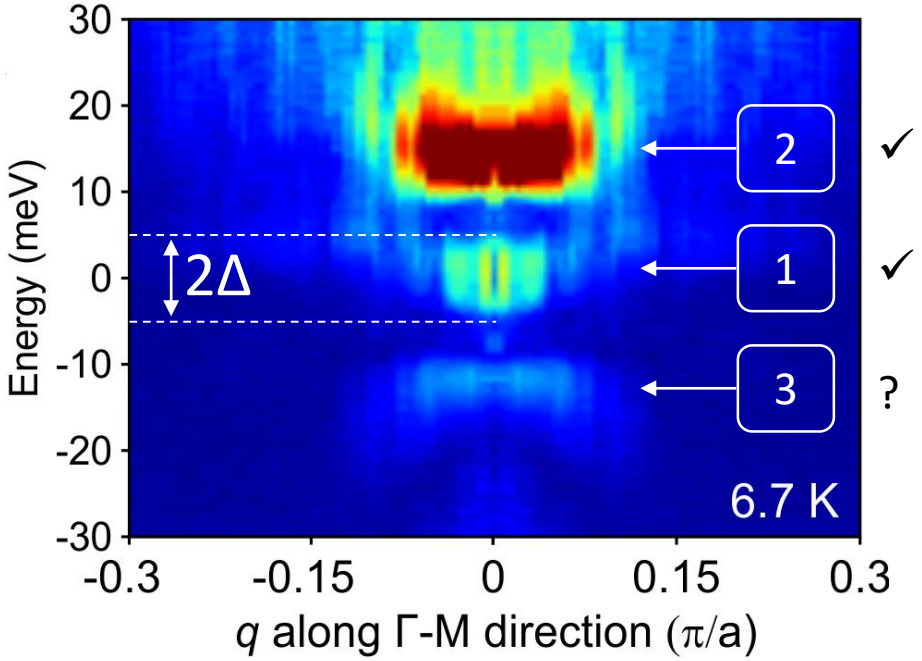


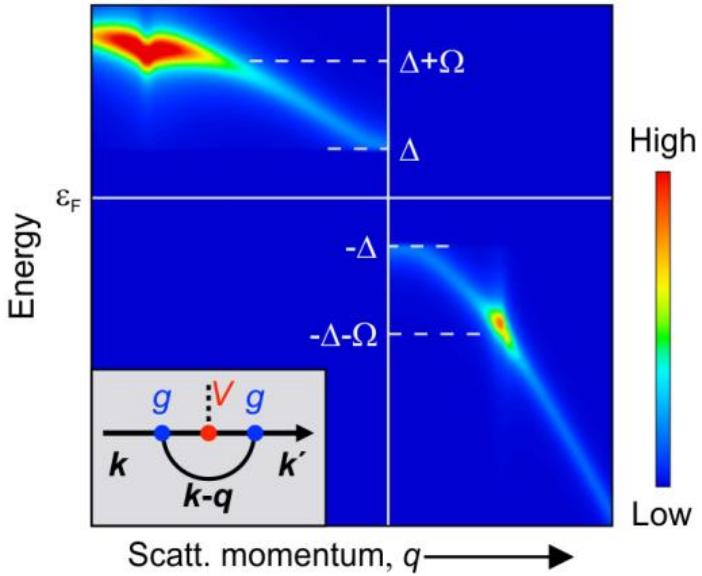
1 Impurity bound states

2 Resonant peak → **Boson** at Δ+Ω ≈ 14 meV, **q** ≈ **0**

Check: signature at negative energies?

Superconducting State – 6.7 K



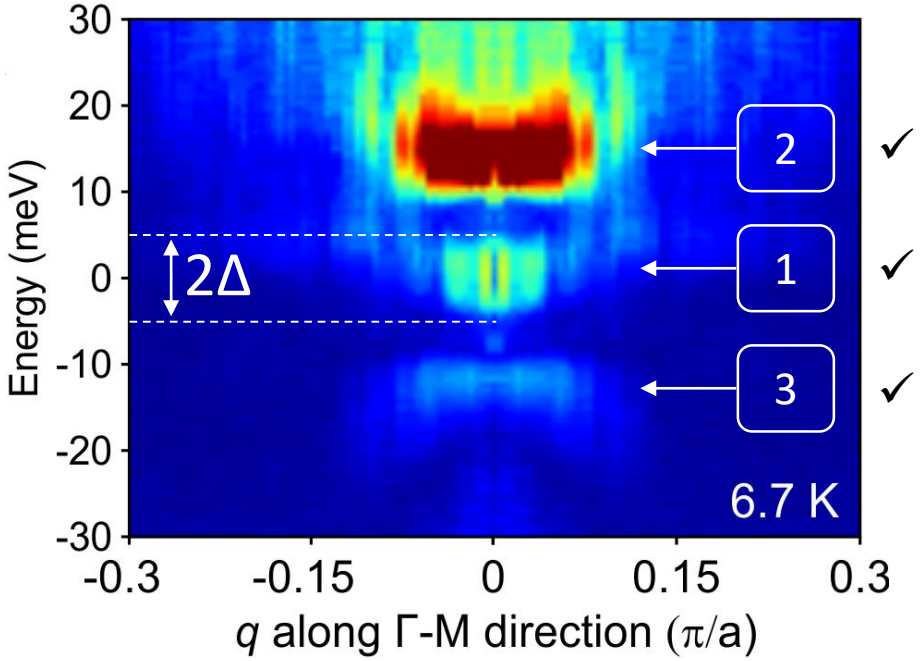


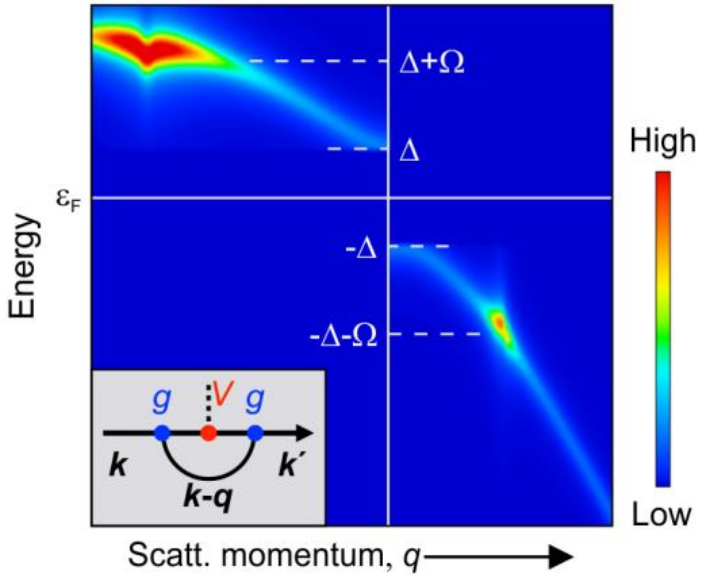
1	Impurity bound states
2	Resonant peak → **Boson** at Δ+Ω ≈ 14 meV, **q** ≈ **0**

Prediction: Signature at -Δ-Ω

Check: signature at negative energies?

Superconducting State – 6.7 K

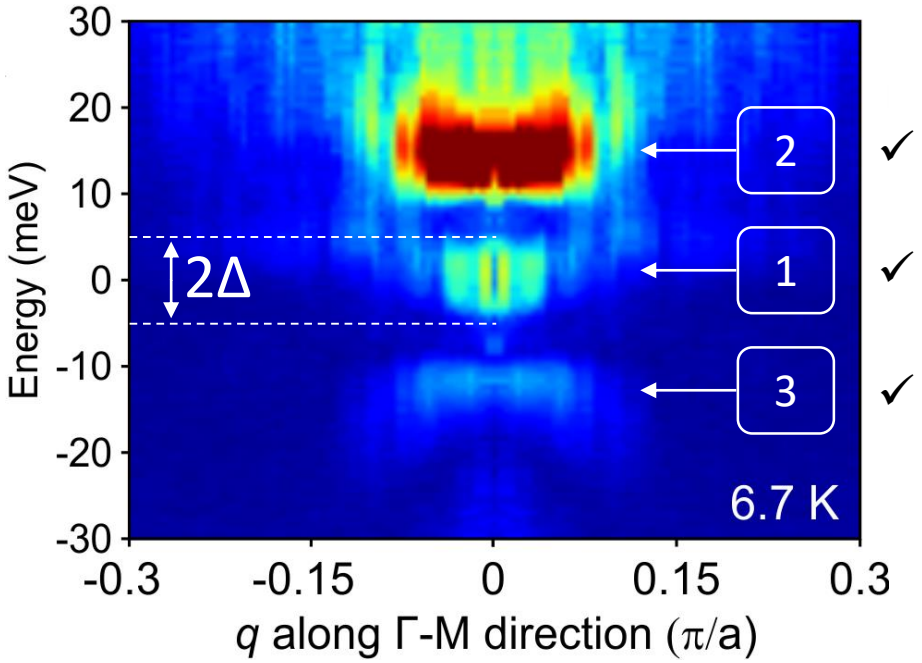




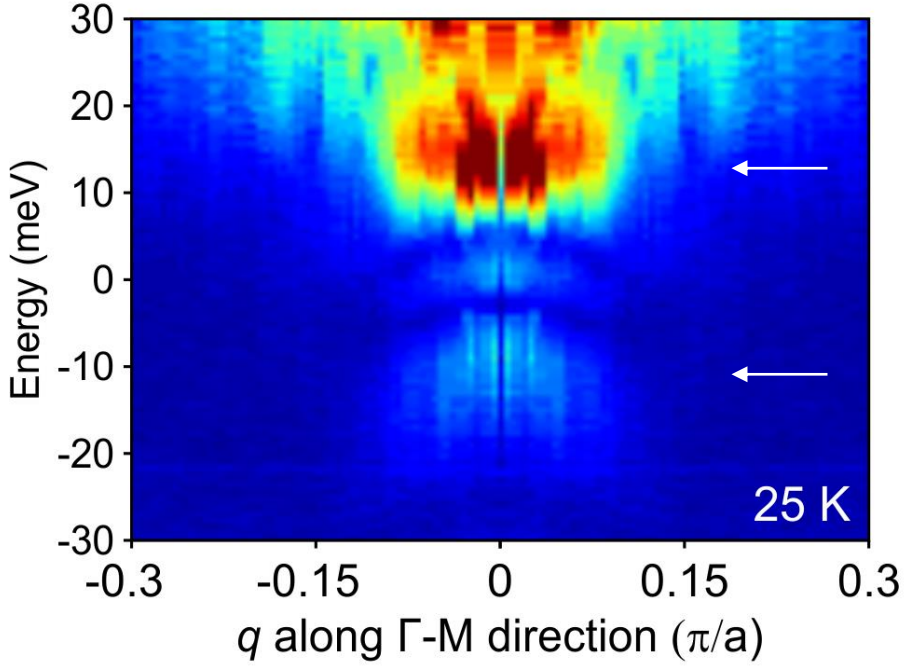
1	Impurity bound states
2	Resonant peak → **Boson** at Δ+Ω ≈ 14 meV, **q** ≈ **0**
3	Resonant peak → **Boson** at -Δ-Ω ≈ -14 meV, **q** ≈ **0**

Superconducting vs. Normal State

Superconducting State – 6.7 K



Normal State – 25 K

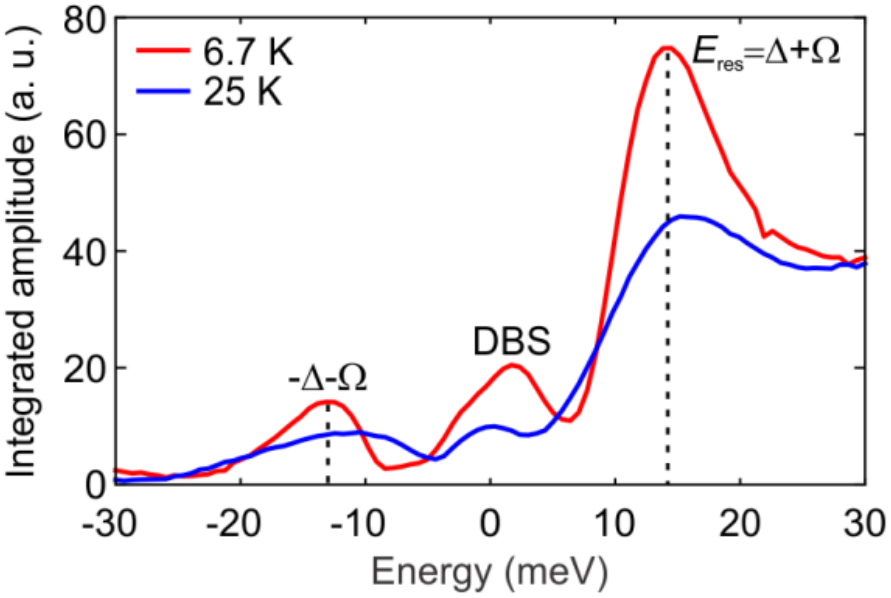


Resonance at ~14 meV persists! *

* Spin orbit split bands (λ~10meV) yield similar shift in normal state as Δ in SC state

Friedel oscillations vs. dI/dU

Integration for q<0.1π/a



$\Delta+\Omega \approx 14$ meV

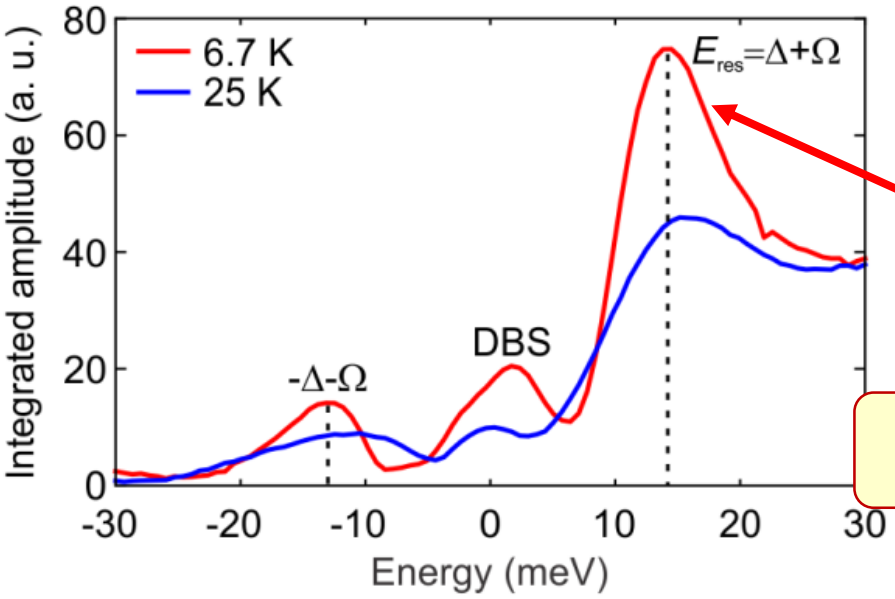
$\Delta \approx 6$meV

$\Omega \approx 8$ meV

Check tunneling spectra…

Friedel oscillations vs. dI/dU

Integration for q<0.1π/a

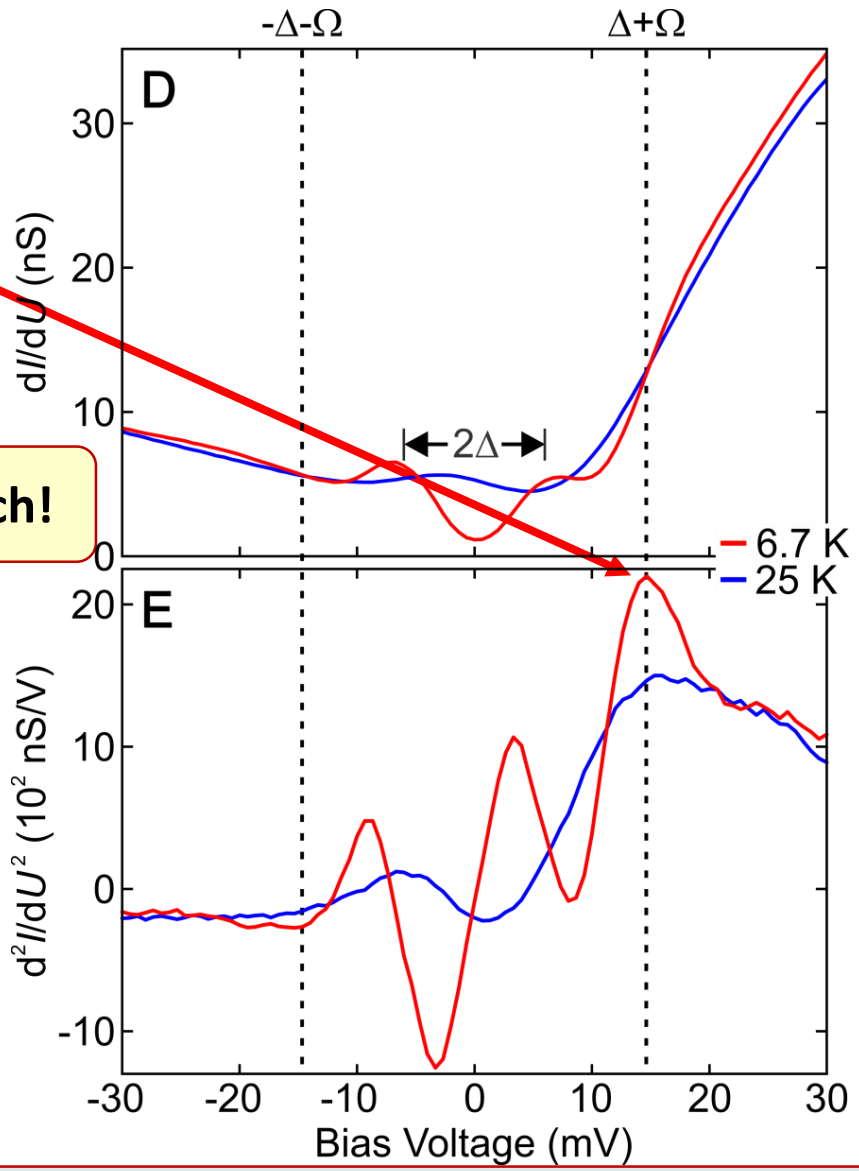


Δ+Ω ≈ 14 meV

Δ≈6meV **Ω ≈ 8 meV**

Check tunneling spectra…

dI/dU away from impurities



Match!

Conclusions

Electron-boson coupling ⟶ Enhanced Friedel oscillations

New probe: **energy and momentum** of renormalized states

Conclusions

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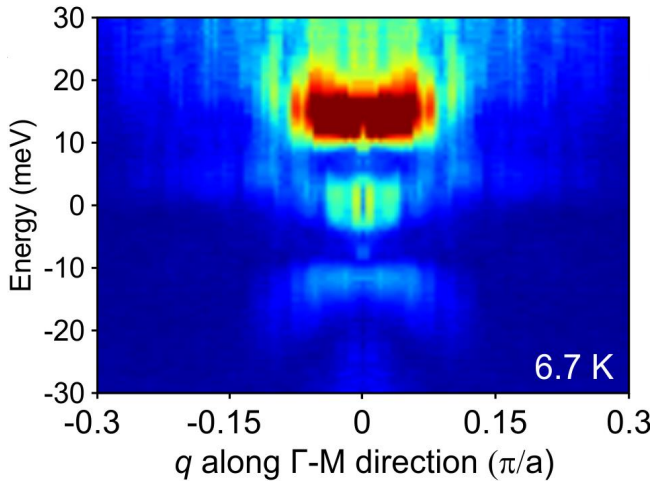
New probe: **energy and momentum** of renormalized states

Here: LiFeAs

Ω≈8 meV, q≈0

New constraints for pairing models



AF spin fluctuations

Mazin, PRL 2008
Wang et al., PRB 2013
Ahn et al., PRB 2014
Yin, Nat. Phys. 2014

Orbital (nematic) fluct.

Kontani & Onari, PRL 2010
Saito et al., PRB 2014, PRB 2015

Small-q spin fluct.

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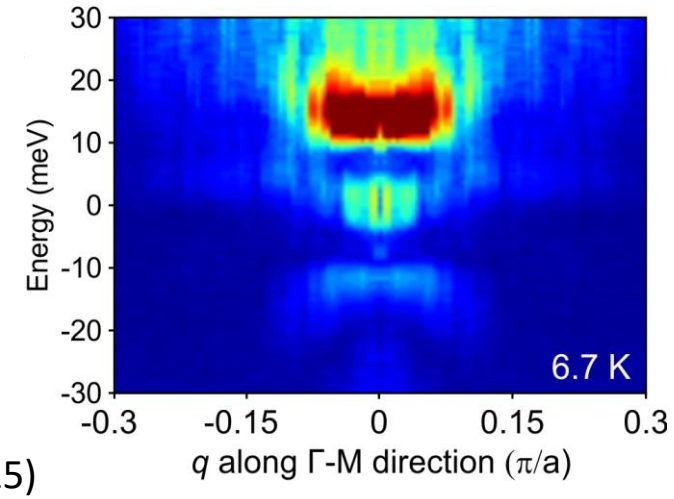

*Optical Spec.: Hwang et al., J. Phys. Cond. Mat. 27, 055701 (2015)

AF spin fluctuations	Orbital (nematic) fluct.	Small-q spin fluct.
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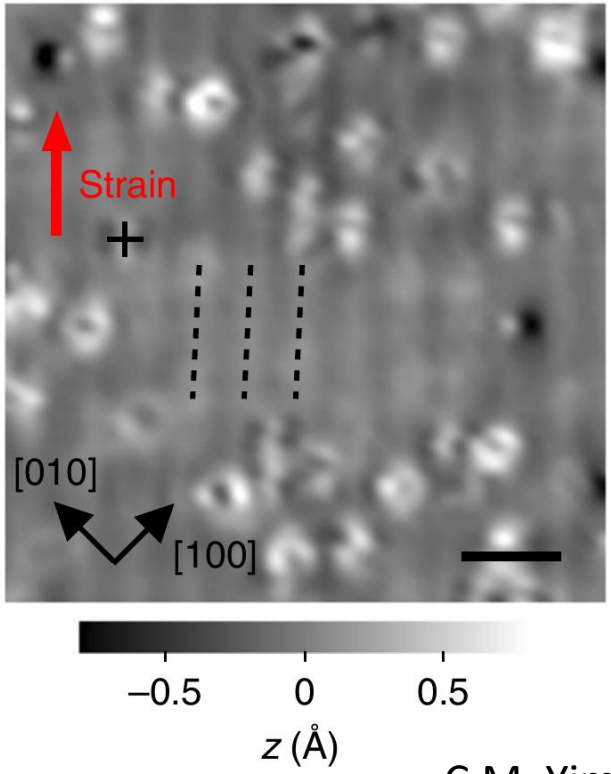
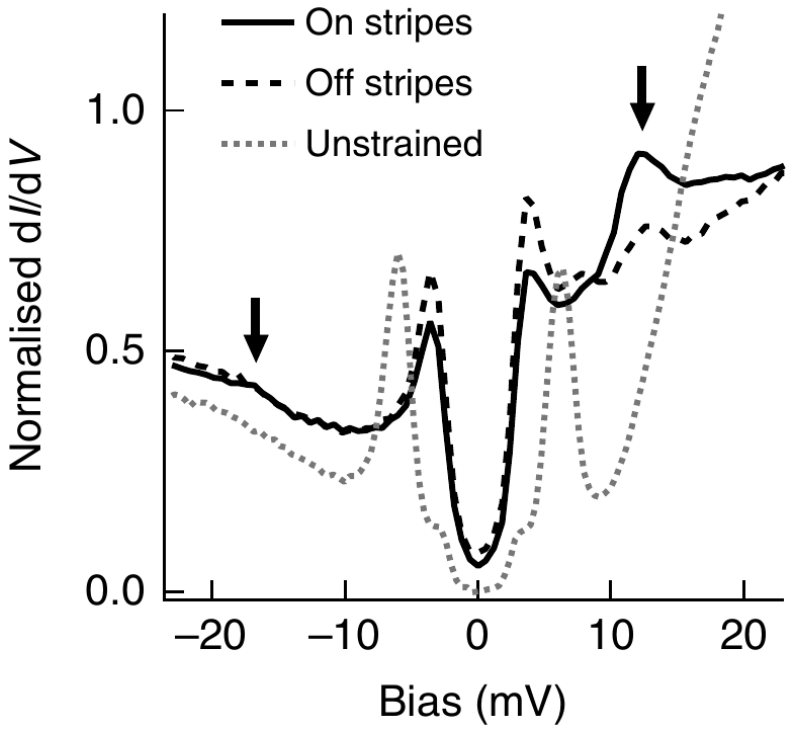
Strained LiFeAs

Topography



Spectroscopy



C.M. Yim et al., Nat. Comm. 9, 2602 (2018)

- Suppressed leading gap Δ
- Global appearance of resonance peak
- Stripe order

Conclusions

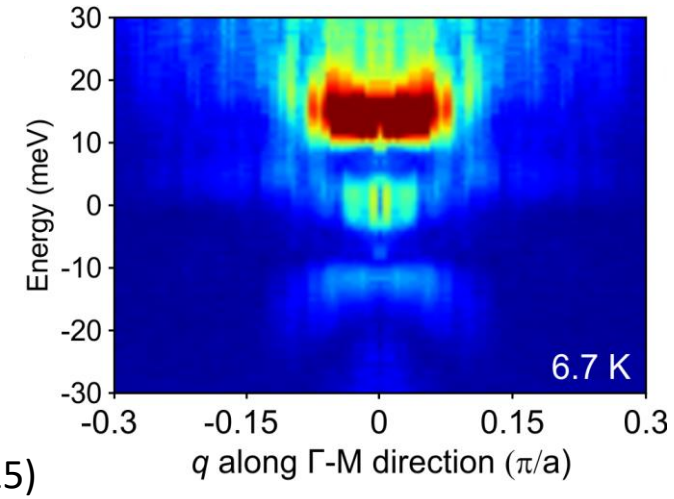
Electron-boson coupling ⟶ Enhanced Friedel oscillations

New probe: **energy and momentum** of renormalized states

Here: LiFeAs

Ω≈8 meV, q≈0 *

New constraints for pairing models



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