Pairing by nematic fluctuations in doped FeSe

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PRB 111, 094125 (2025)
arXiv:2605.05433 (2026)

Elastically Driven Phases and Dynamics in Quantum Materials, SPICE, Sept. 1, 2026

The story will be about

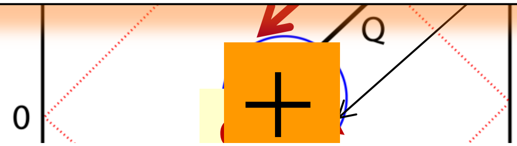
superconductivity

due to electron-electron interaction near the onset of a nematic order in doped FeSe

The most discussed scenario of electronic pairing in correlated electron systems is spin fluctuation mechanism

Workhorse for SC in Fe-based materials from 2008

One needs strong (π,π) spin fluctuations to enhance pair hopping



ket g_2 (pair hopping)

Mazin et al, ….

otliar, Nature 601, 35-44 (2022)

Both inter

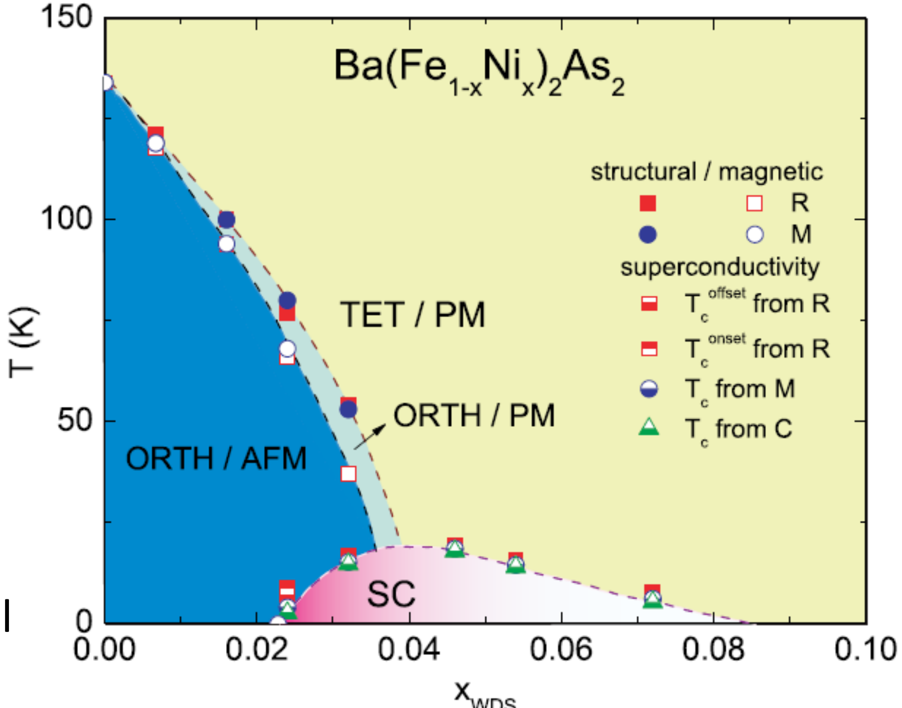
exceeds i

hopping g_2

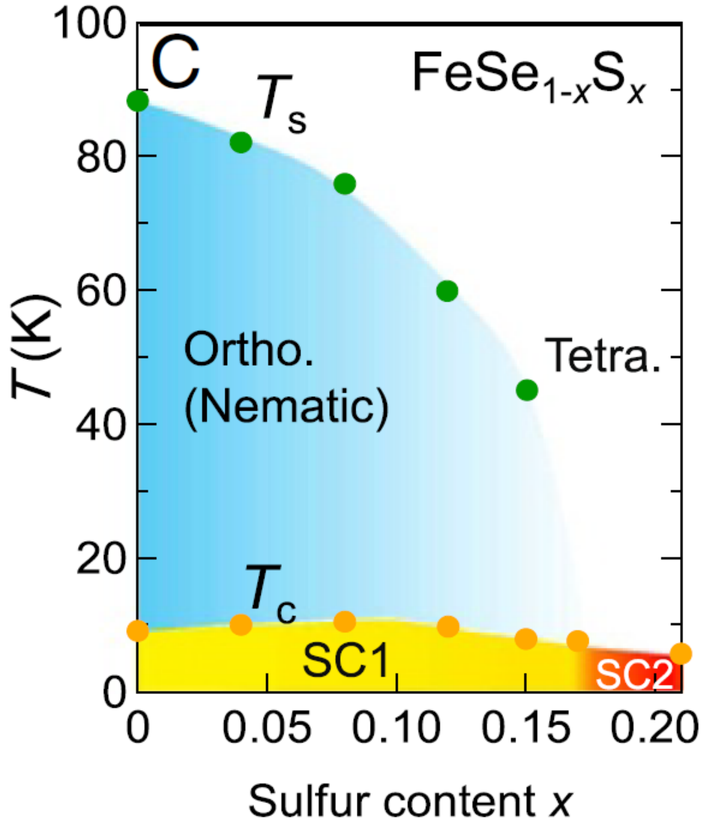
y emerges

n.

Canfield et al



Iron chalcogenide: S and Te-doped FeSe
$FeSe_{1-x}S_x$ and $FeSe_{1-x}Te_x$

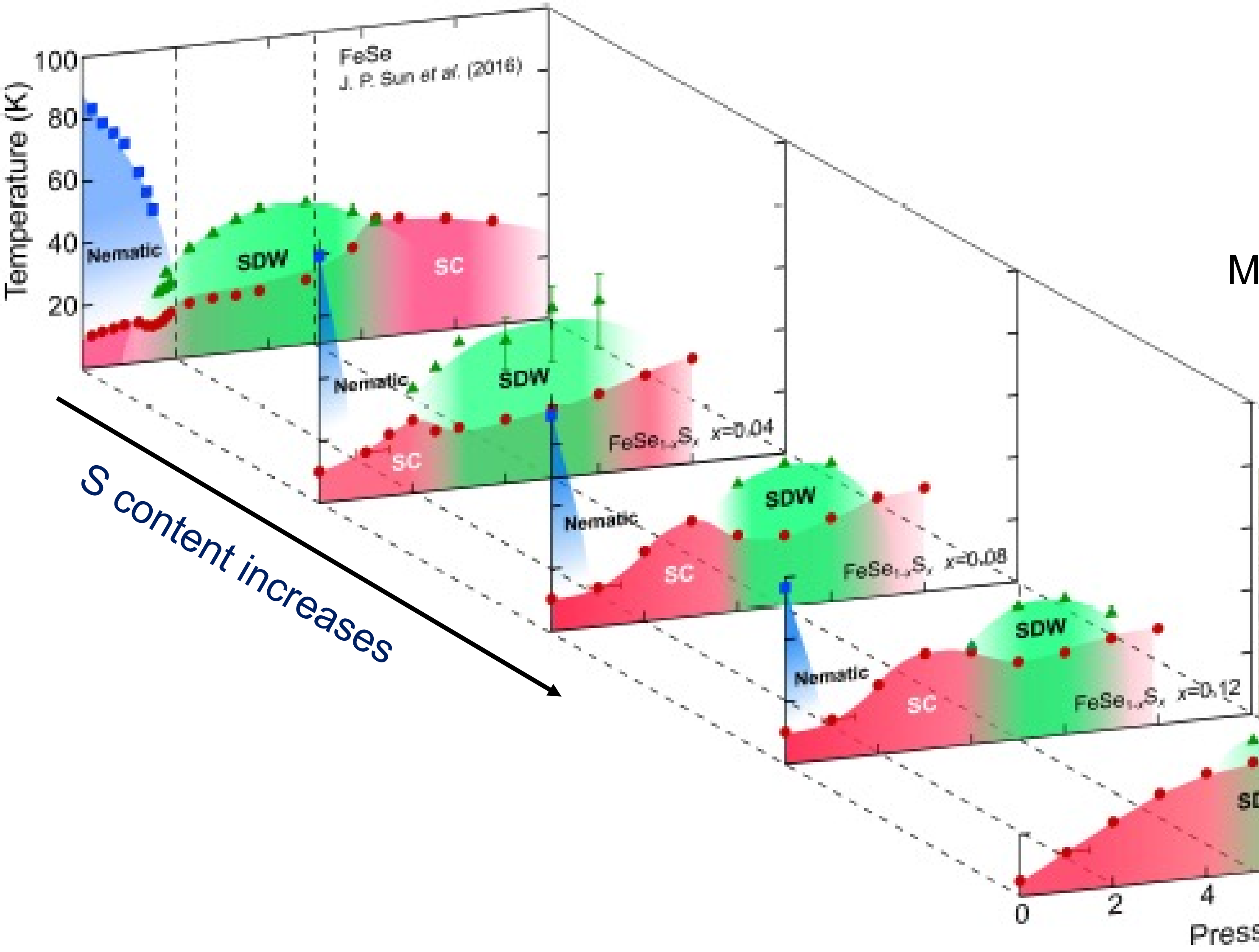


A. Coldea et al, T. Shibauchi et al…

- Pure FeSe develops a nematic order at T_n=85K, SC at 9K
- Upon doping by S, T_n decreases and vanishes at around x_c=0.18
- At a critical x_c, superconducting Tc is finite
- No SDW at ambient pressure

$FeSe_{1-x}S_x$: magnetic fluctuations are reasonably strong at x=0, but are much weaker at x =0.18, where nematic order ends

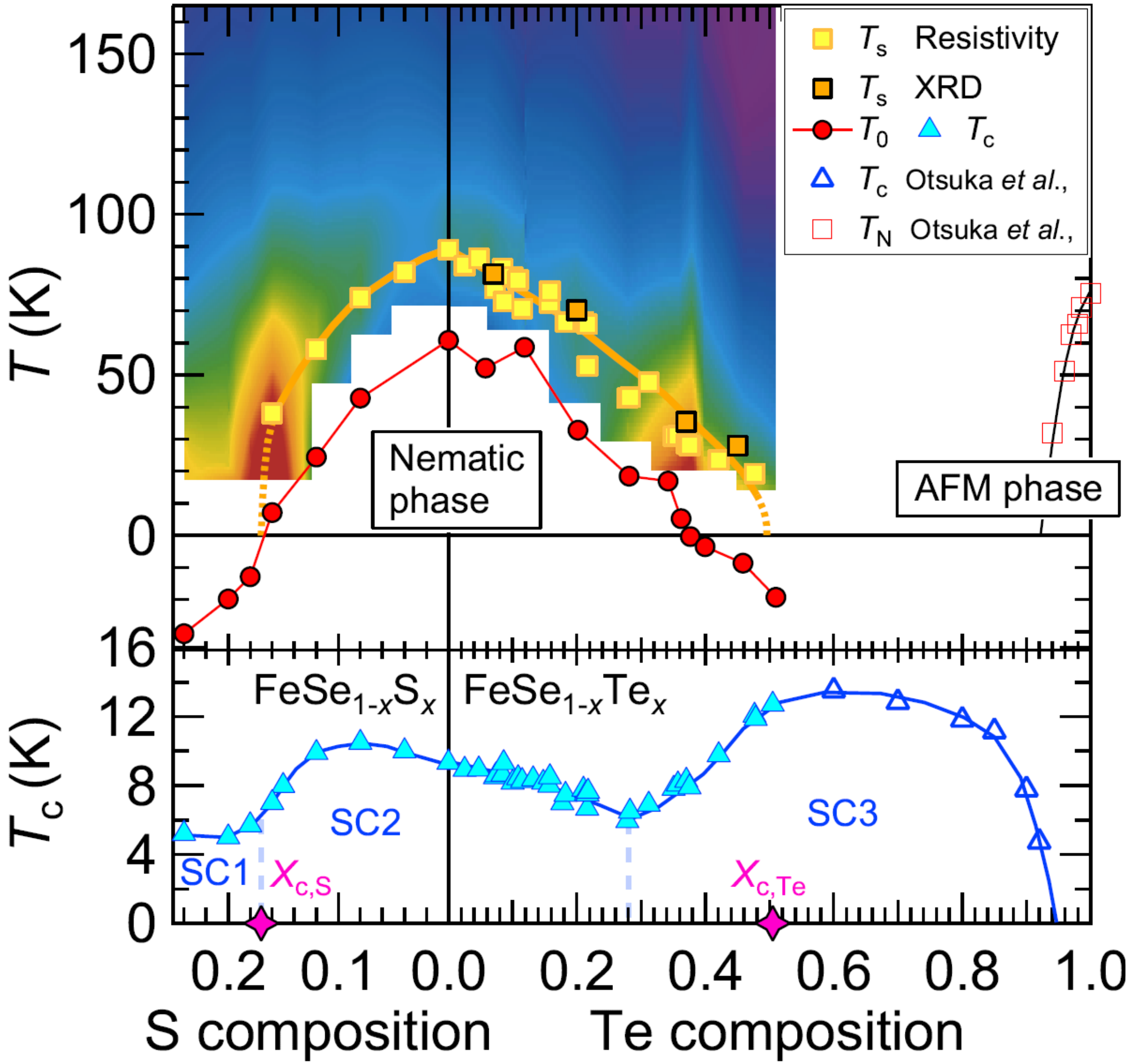
Spin fluctuations



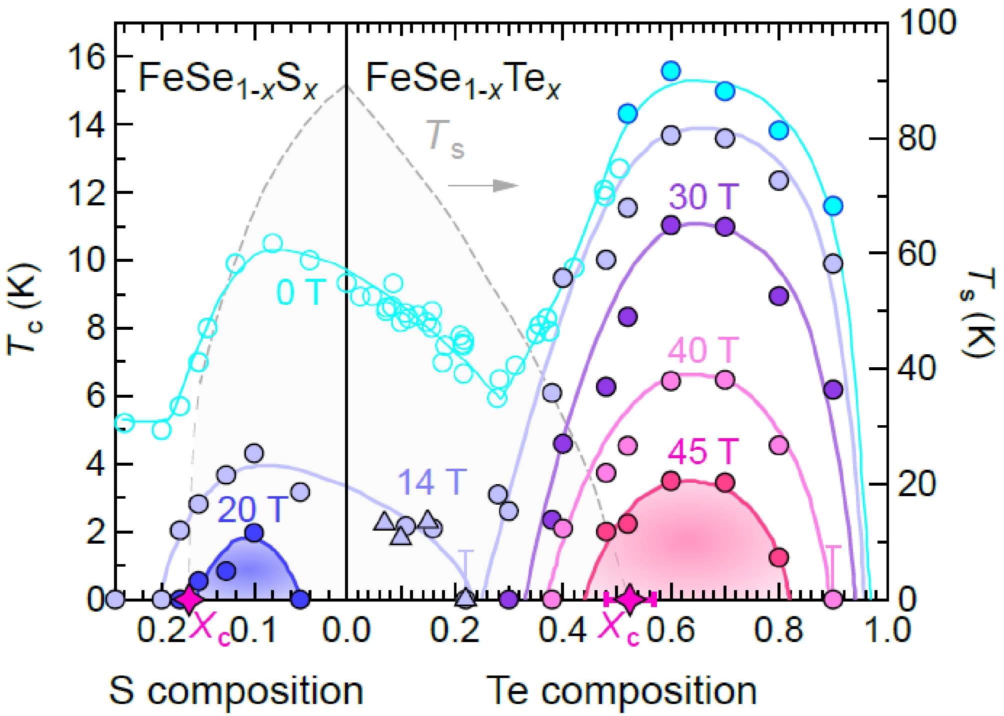
Matsuura et al

Spin fluctuations

FeSeS and FeSeTe

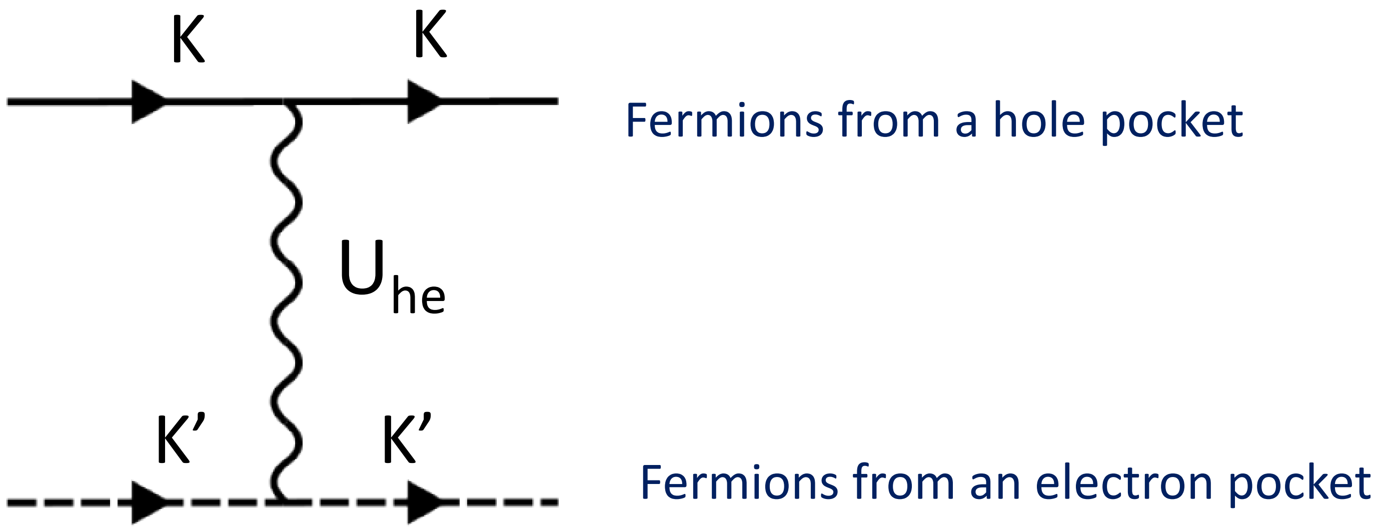


Nematic fluctuations



K. Ishida et al, 2022

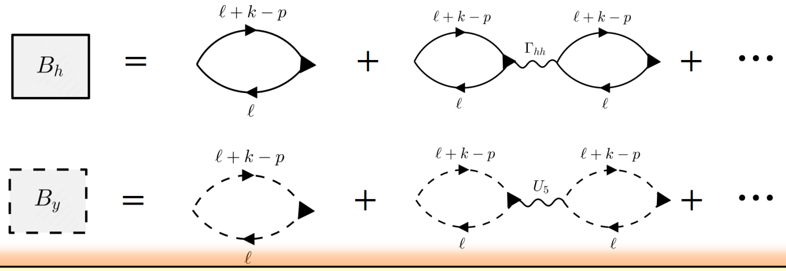
The interaction that gives rise to a d-wave nematic order and to SC, mediated by nematic fluctuations, is inter-pocket density-density repulsion



- This interaction is with zero momentum transfer and the total momentum near (π,π).

Theory kitchen

Pairing interaction
within a given pocket



Inter-pocket density-density interaction U_{he} gives rise to:

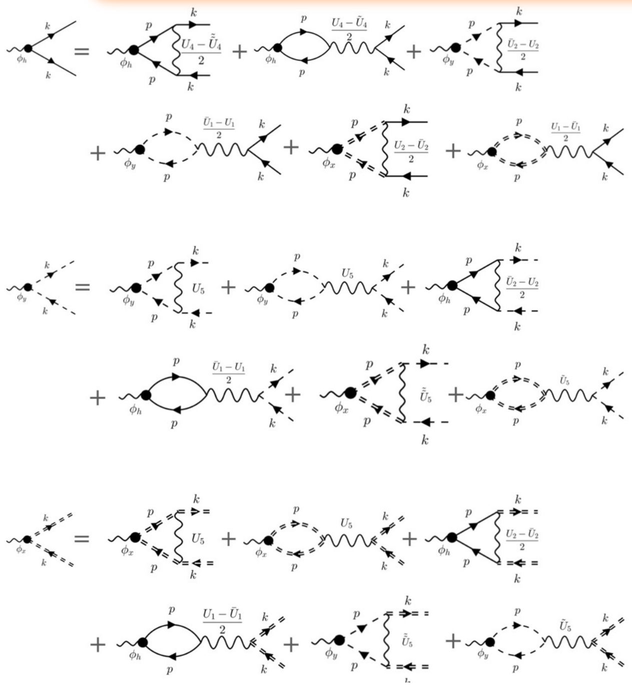
(i) d-wave nematic order changing sign between hole and electron pockets,

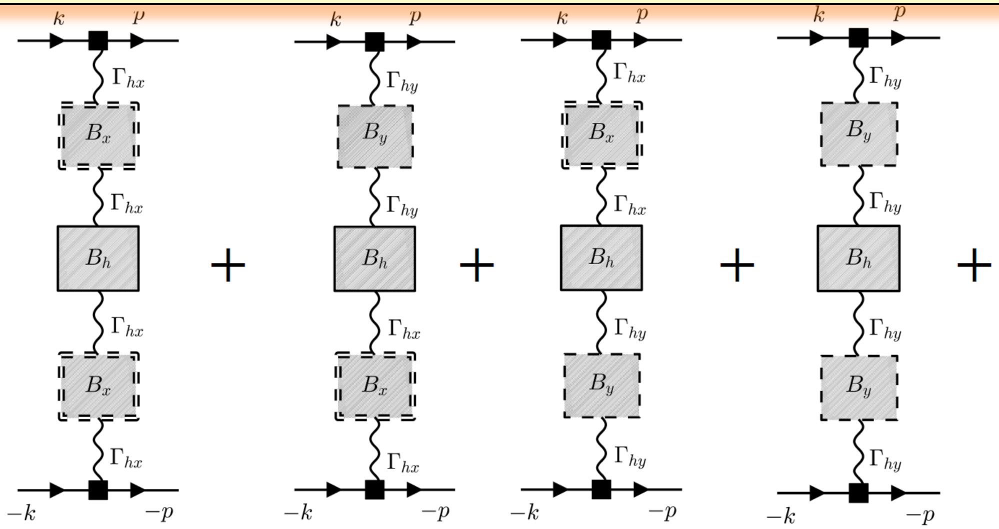
and

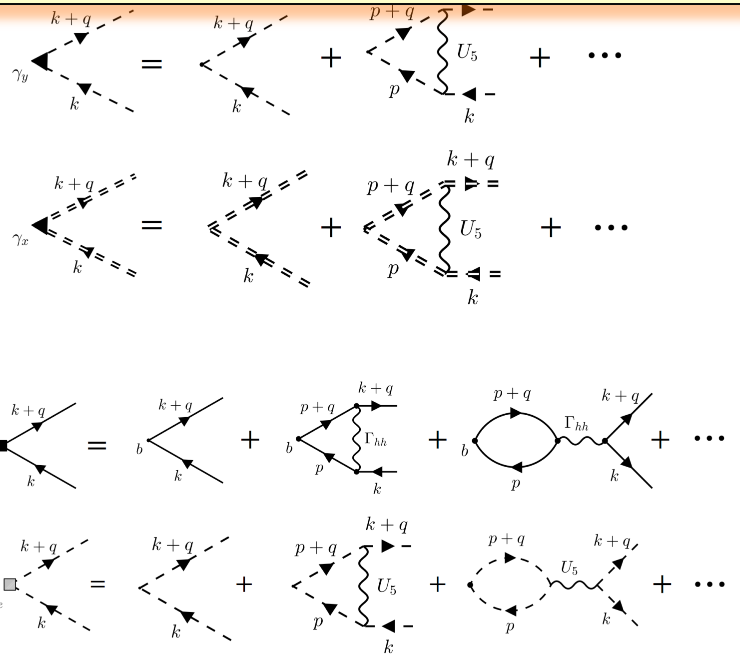
(ii) attractive pairing interaction, proportional to the d-wave χ_{nem}

Ner

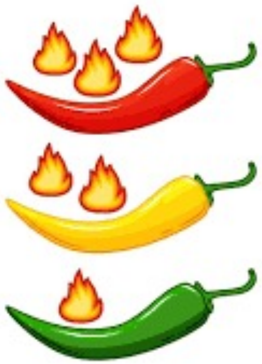
(d-v

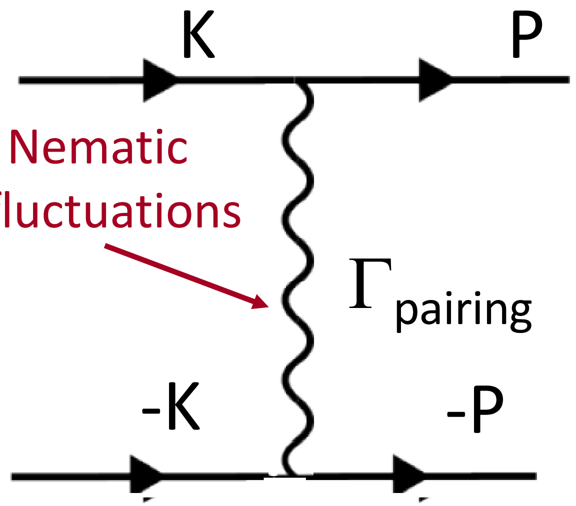






The spicy part





Pairing by soft nematic fluctuations has been analyzed phenomenologically by several groups

Schattner, Lederer, Kivelson, Berg, Kontani, Onari, Schmalian, Garst, Fernandes, Klein, A.C.....

Phenomenological theories emphasized that the pairing interaction between fermions on the Fermi surface, specified by angles θ_k (for K) and θ_p (for P), is a function of $\theta_k - \theta_p$.

Different pairing channels (s,p,d...) are almost degenerate

Microscopic calculation: the attractive interaction, induced by U_{ph}, knows about the orbital content of low-energy excitations on the hole pocket (dxz and dyz)

Interaction is dressed by coherence factors of the transformation from orbitals to bands

$$\boxed{\Gamma(\theta_k, \theta_p) = \Gamma(\theta_k - \theta_p, \theta_k + \theta_p) = -\underbrace{\cos^2(\theta_k + \theta_p)}_{\text{from coherent factors}} f(\theta_k - \theta_p)}$$

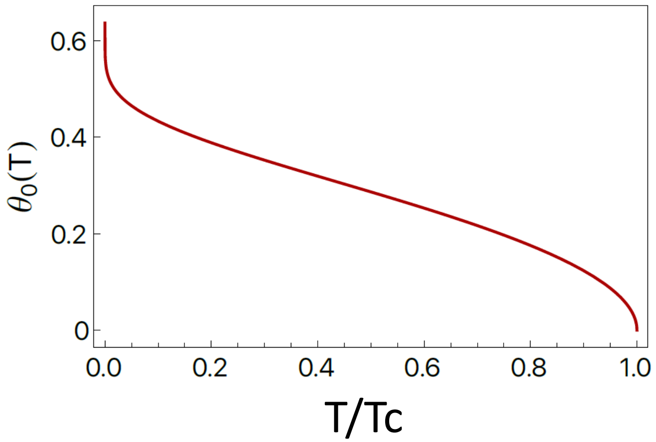
Near a nematic QCP, relevant transferred momenta are small (a nematic order has Q=0), and the pairing interaction effectively becomes

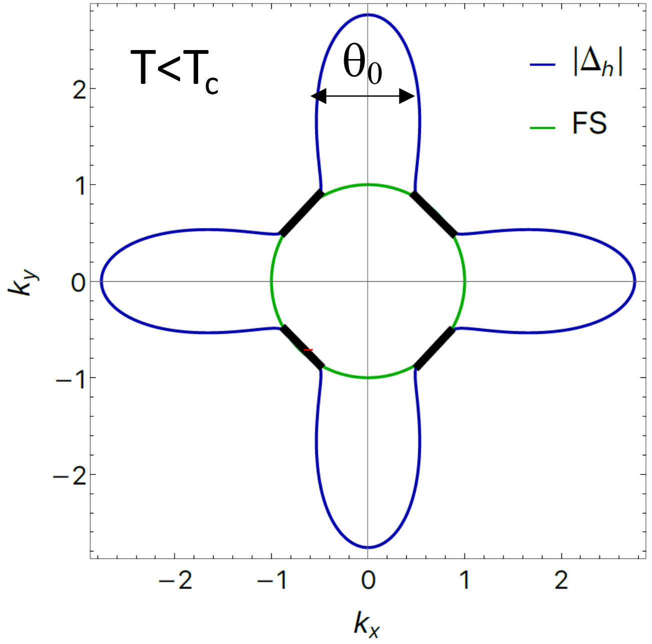
$$\Gamma(\theta_k,\theta_p) \approx \Gamma(\theta_k) = \underbrace{-g\cos^2(2\theta_k)}_{\text{from coherent factors}}\,\delta(\theta_k-\theta_p)$$

Interaction strength depends on the direction of momentum along the hole Fermi surface

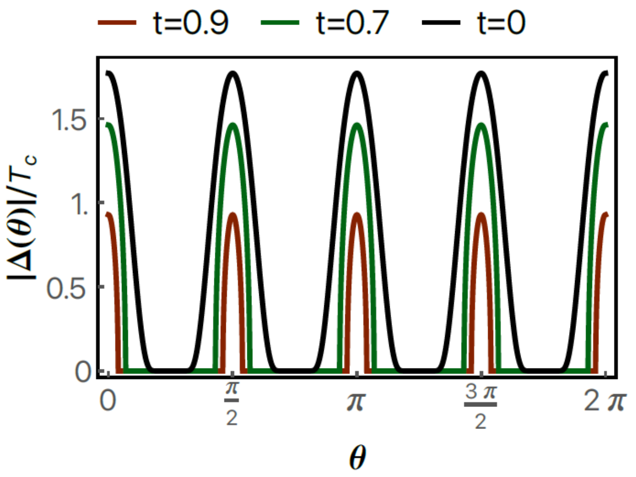
SC gap opens at Tc only at k= 0, $\pi/2$…, and extends along the FS as T decreases

gap edges merge at T=0





t = T/T_c

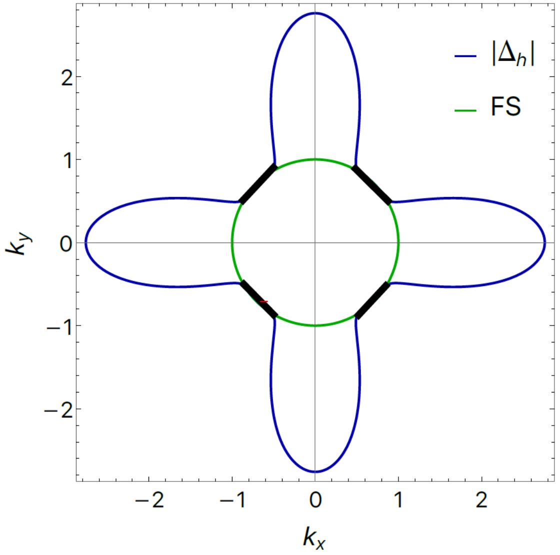


Experiment

Can experiments distinguish between nematic and spin fluctuation scenarios?

Spin fluctuation and nematic pairing mechanisms yield qualitatively different gap anisotropy

Nematic scenario: a highly anisotropic gap function, with deep minima at 45^0 with respect to x and y directions in 1Fe unit cell

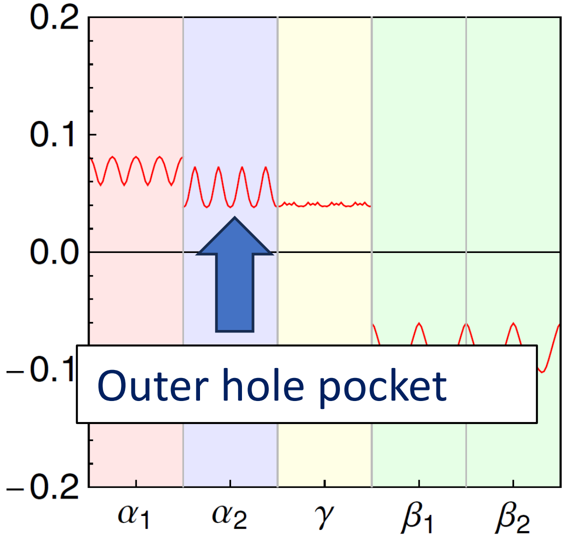


c > 0, gap minima along diagonals

Rotation of the gap min/max by 45°

$\Delta = a + c \cos(4\Theta)$

Magnetic scenario: gap minima along x and y directions in 1Fe unit cell



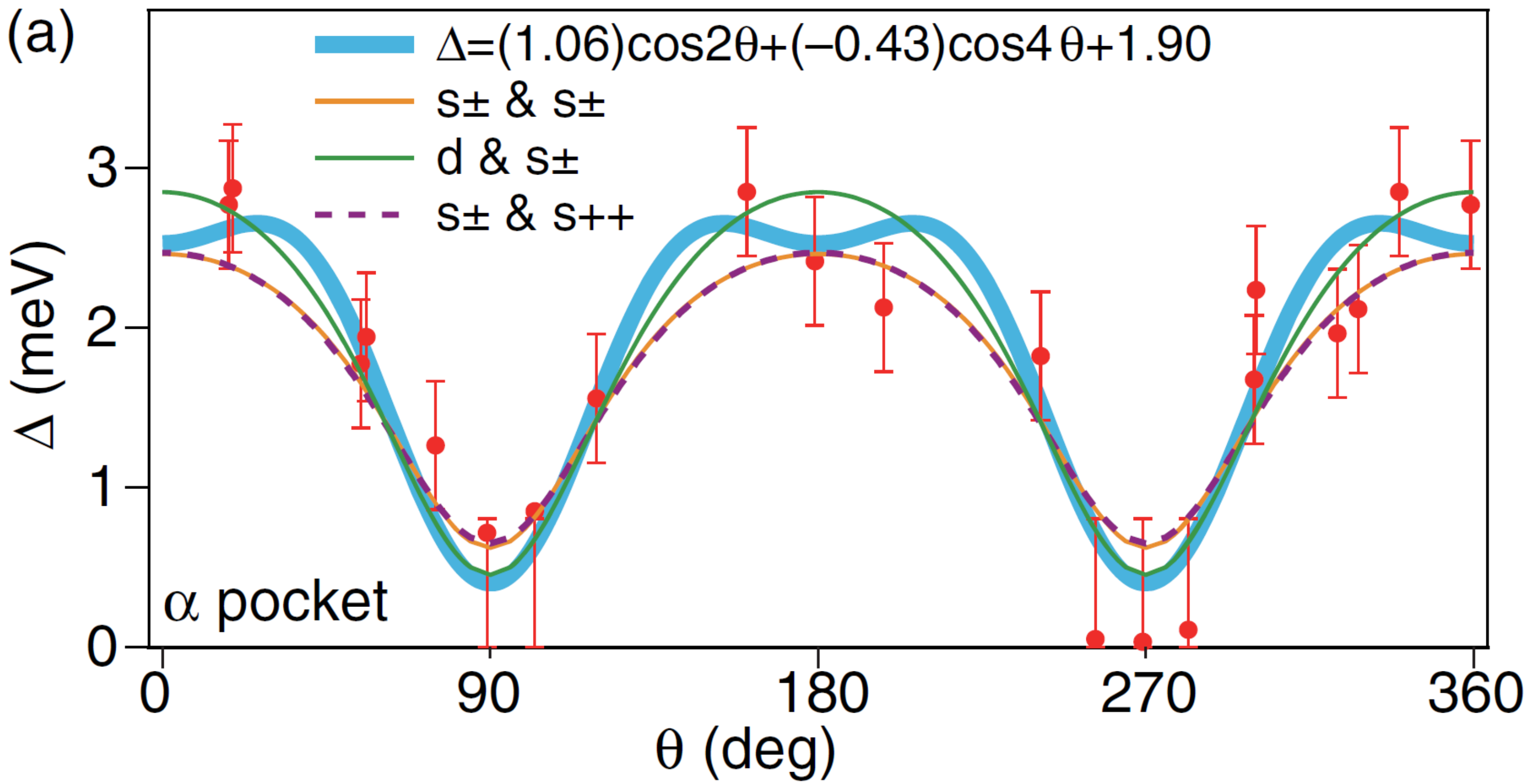
Graser et al

c <0, gap minima along x and y

Gap anisotropy in the nematic state of $FeSe_{1-x}S_x$

$\Delta = a + b \cos(2\Theta) + c \cos(4\Theta)$

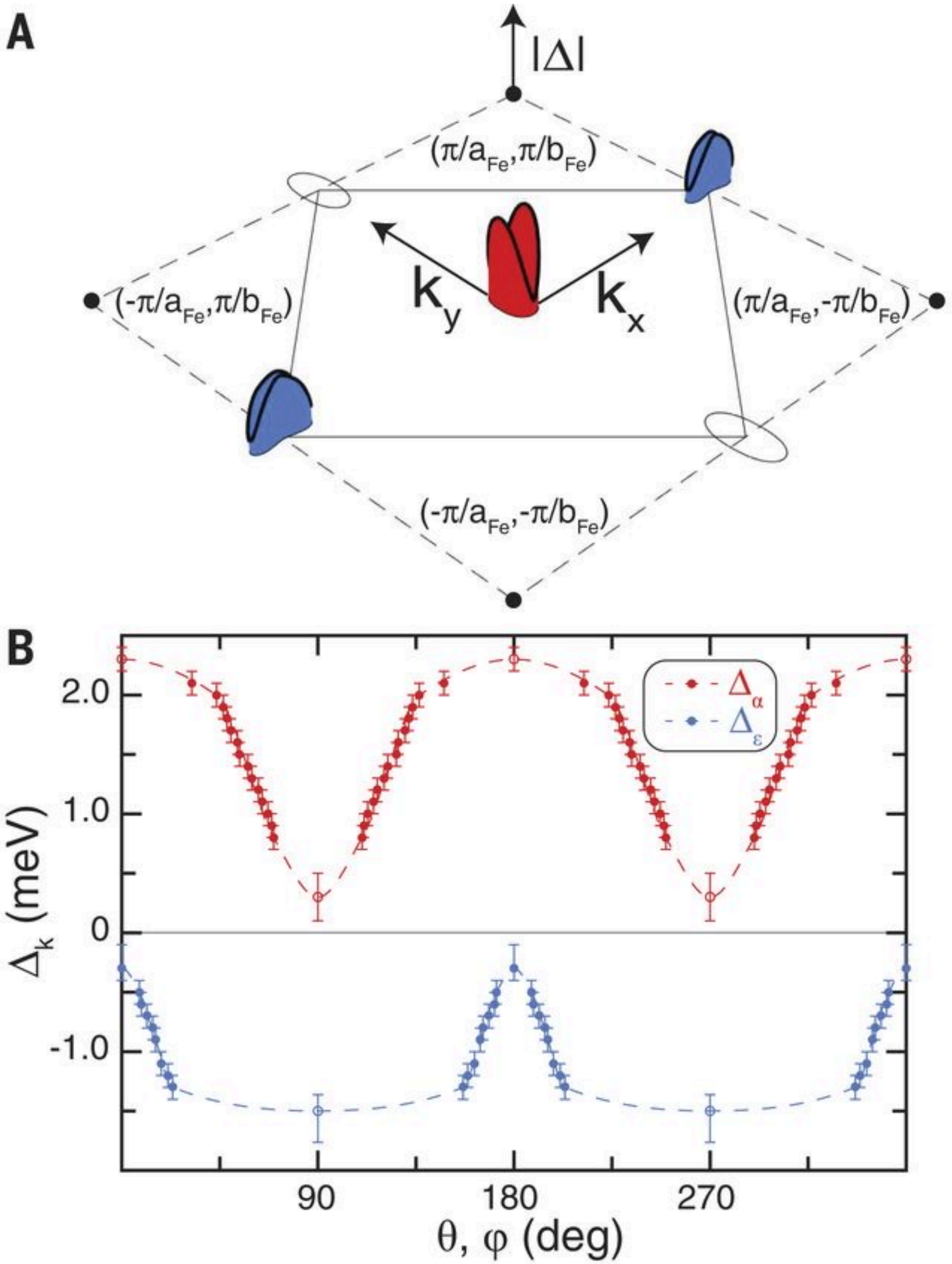
$FeSe_{0.93}S_{0.07}$



D. Feng et al

Similar results:
X. J. Zhou et al

c is negative, spin fluctuations in the driver's seat



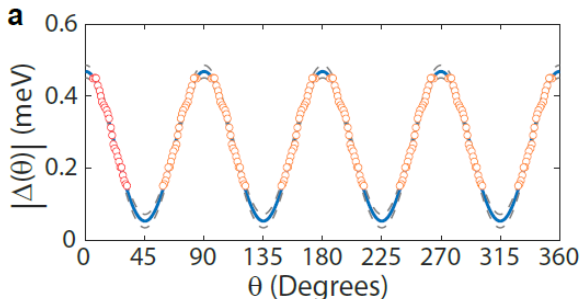
STM

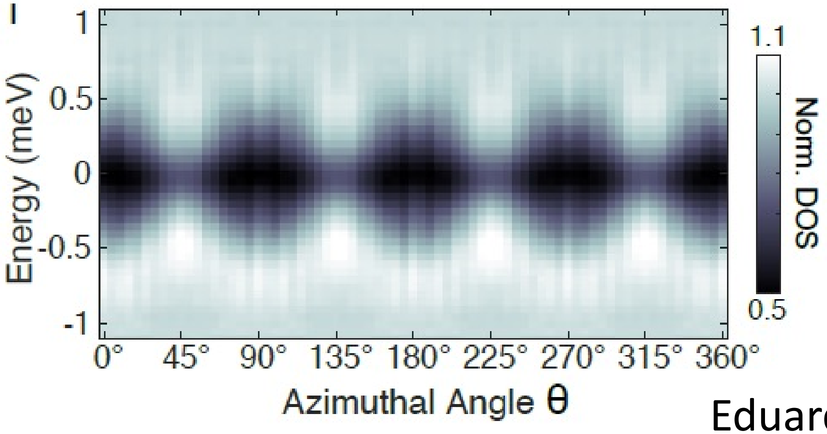
Sprau et al

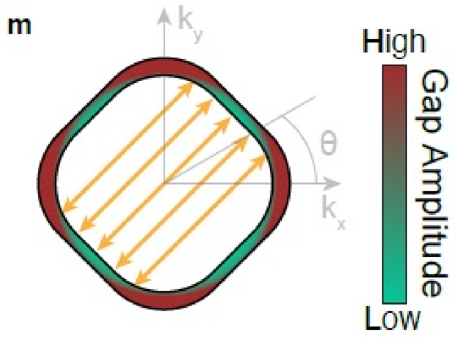
The same conclusion

Gap anisotropy in the tetragonal state (x =0.19)

Gap anisotropy in $FeSe_{0.81}S_{0.19}$ from QPI



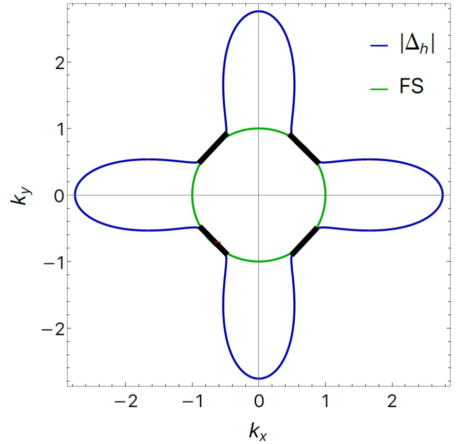


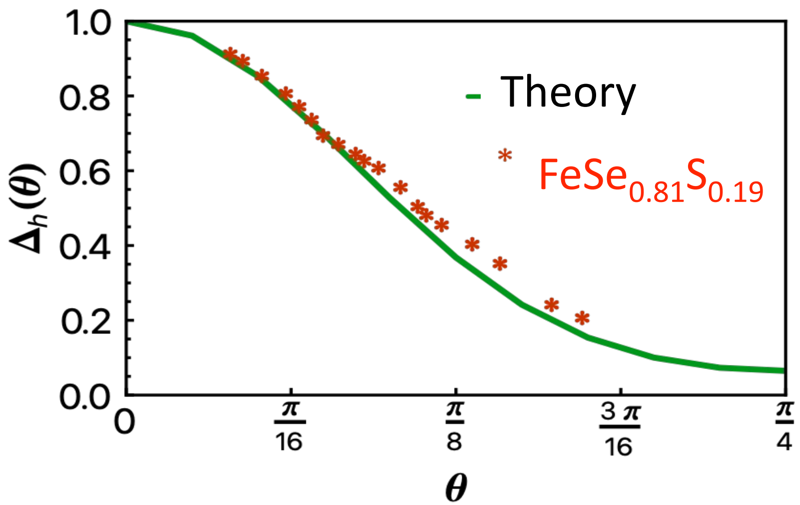


Eduardo H da Silva Neto, R. Fernandes….

Δ = a + c cos(4Θ)

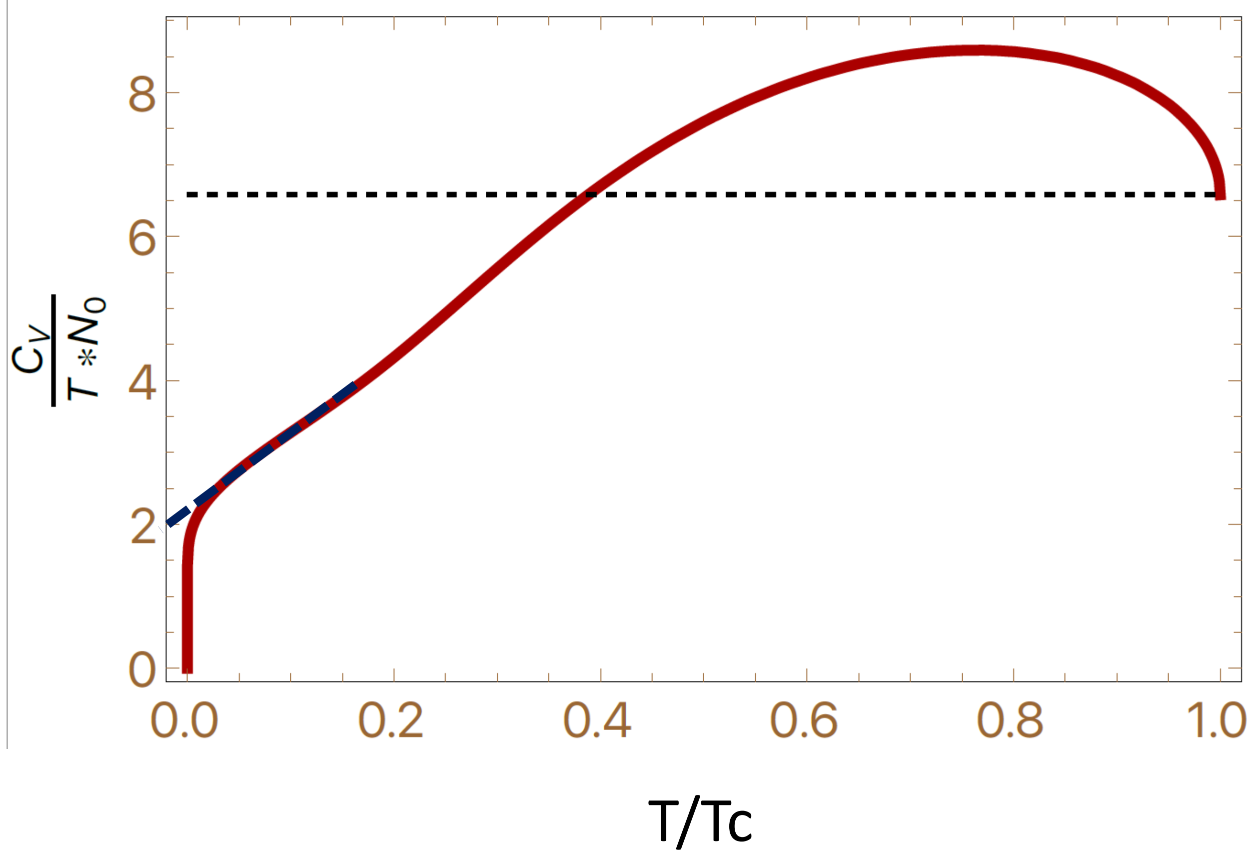
c is positive





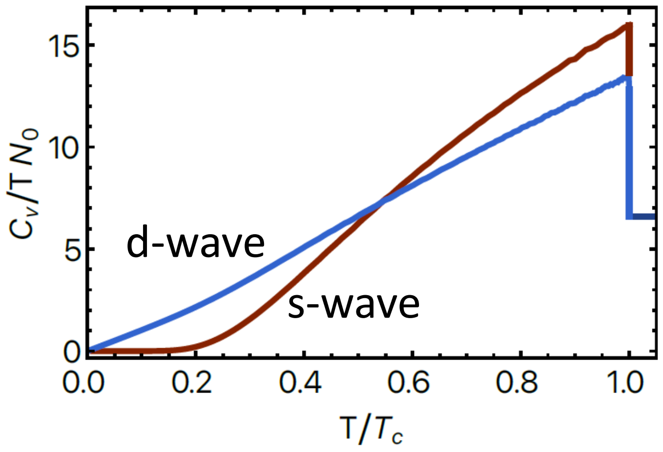
Other observables:

Specific heat: very different from BCS



- no jump at $T_{c,}$ $C_V(T)$ ~$(T_c\text{-}T)^{1/2}$
- max near 0.8 Tc
- "almost" finite C_v at T->0

BCS



Specific heat

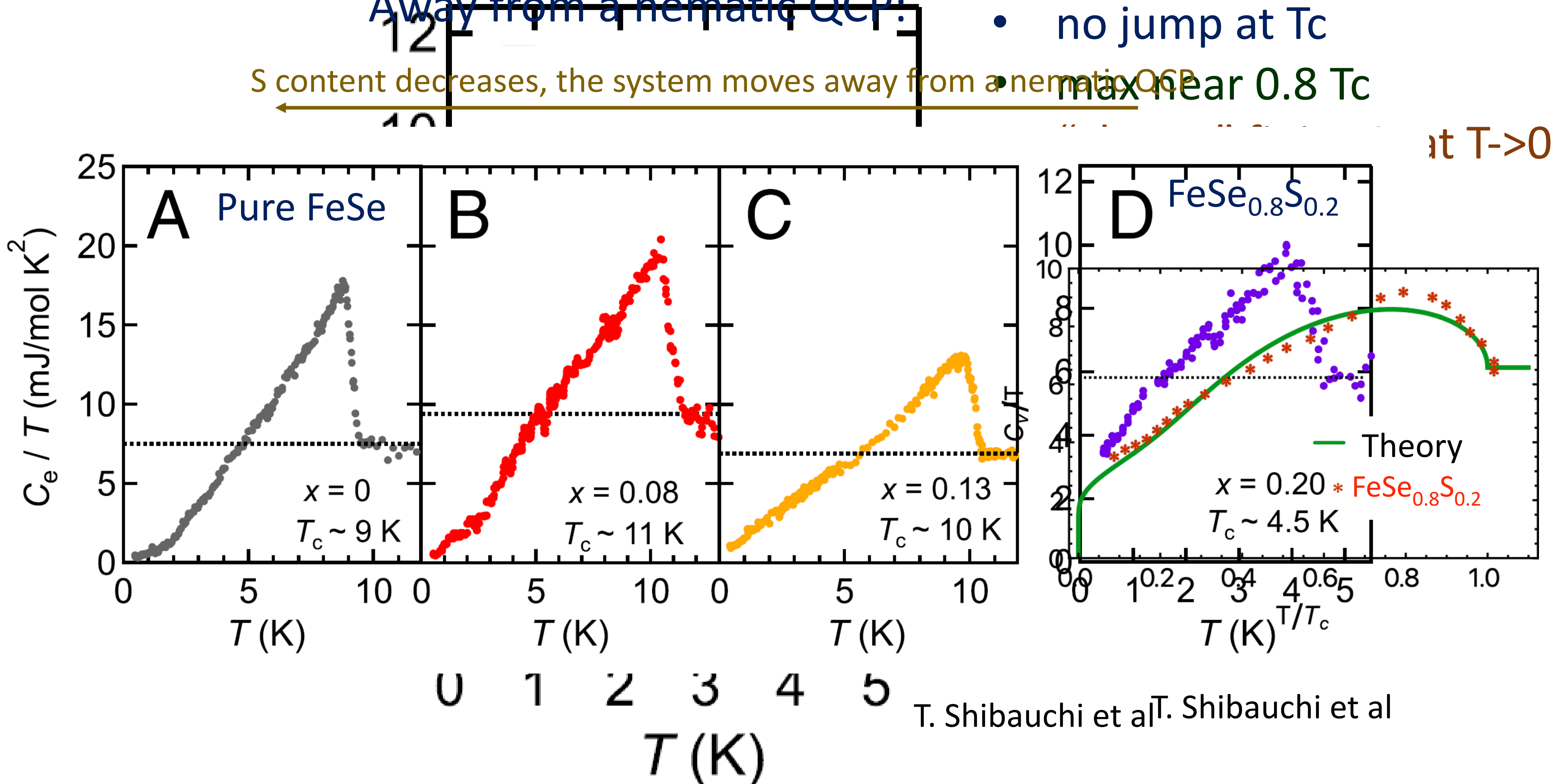
$FeSe_{0.8}S_{0.2}$

Away from a nematic QCP:

- no jump at Tc
- max near 0.8 Tc

at T->0

S content decreases, the system moves away from a nematic QCP

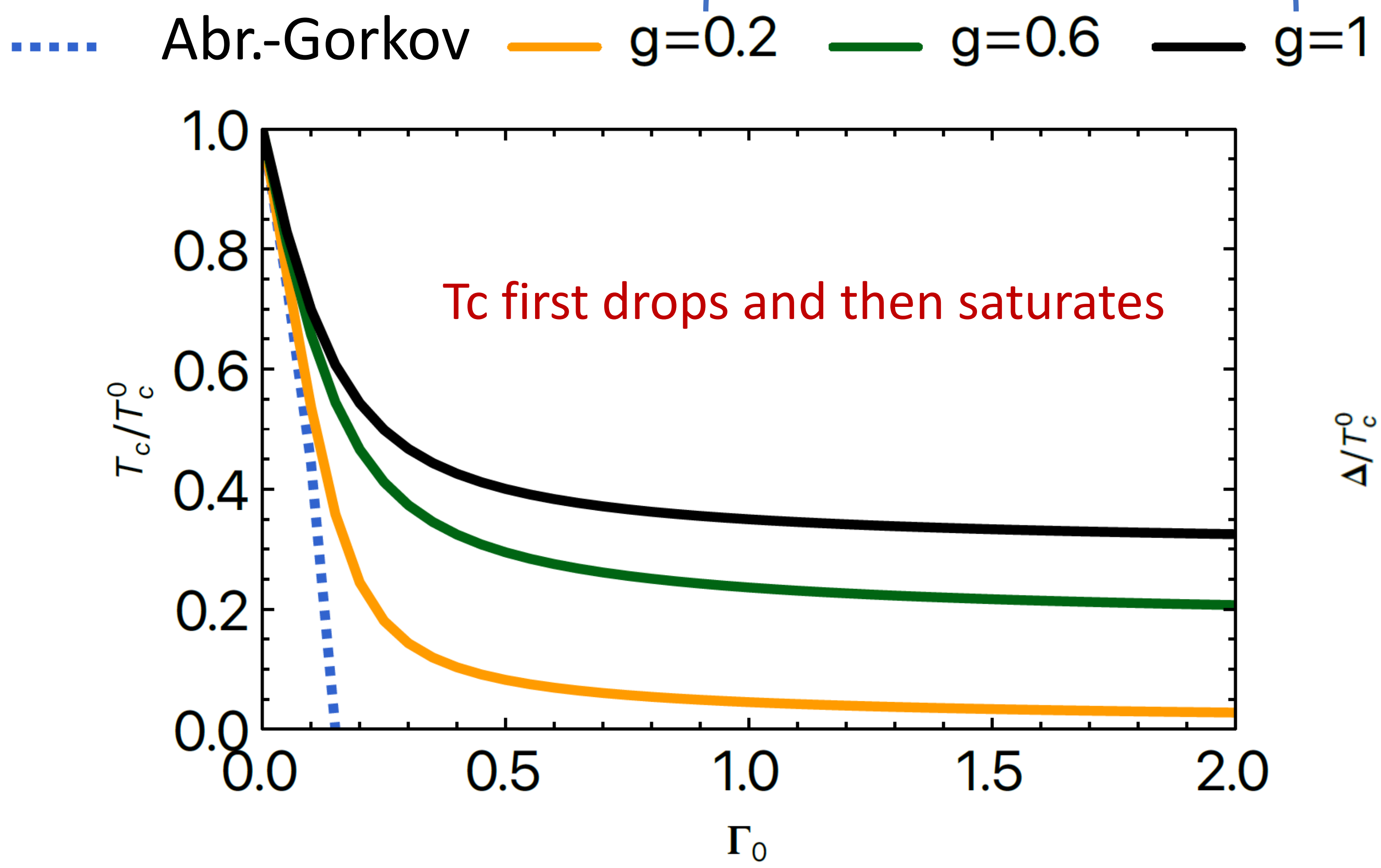


T. Shibauchi et al

T. Shibauchi et al

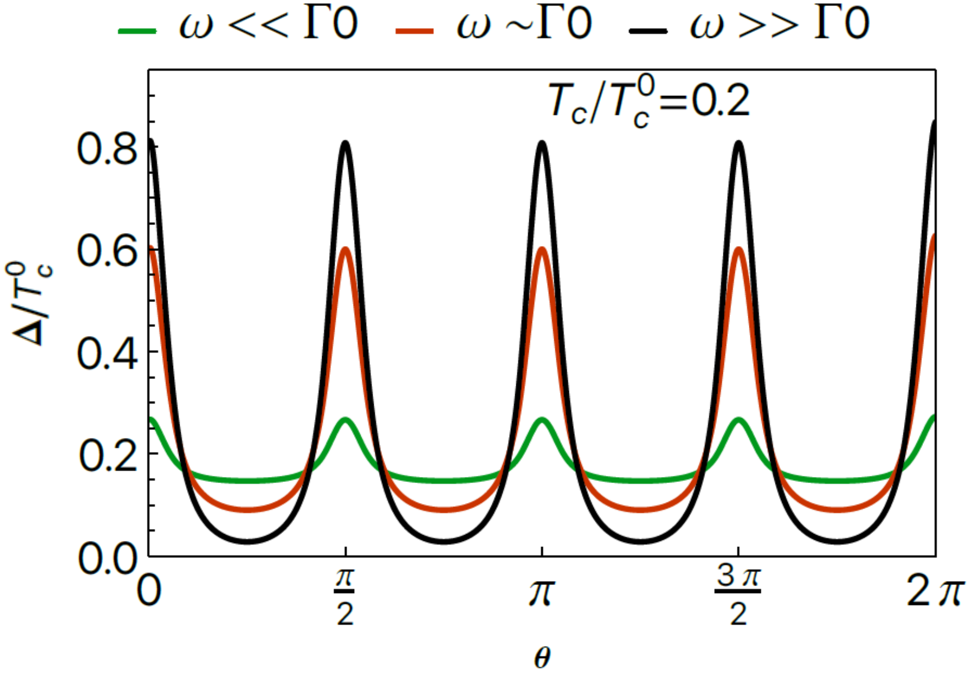
Tc variation with impurity scattering rate

Different couplings



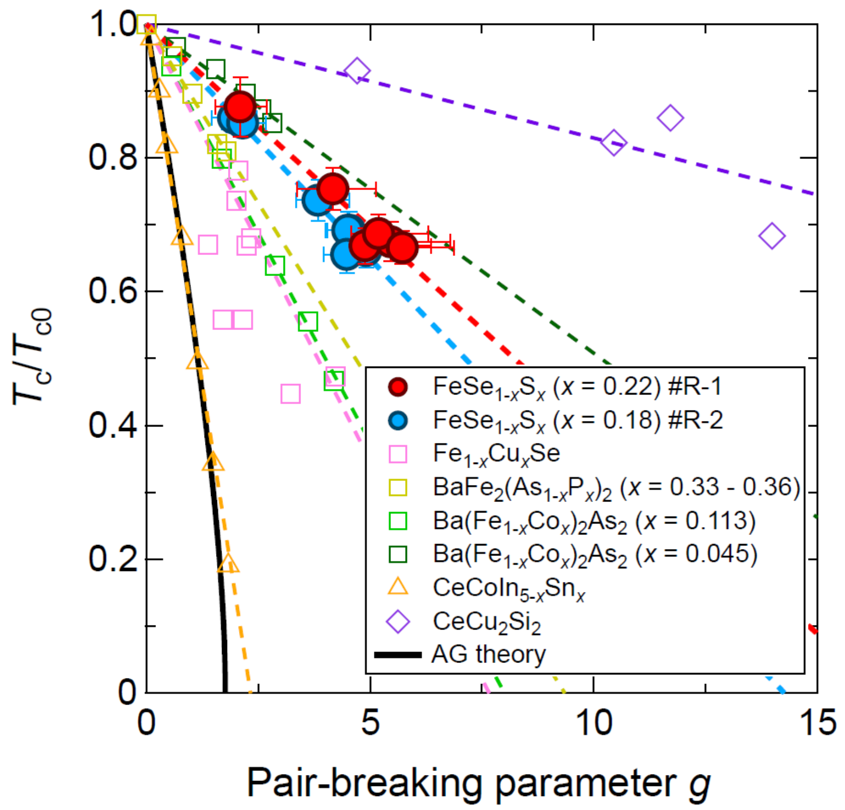
As impurity scattering increases, gap anisotropy gets weaker

Gap function $\Delta(\theta,\omega)$



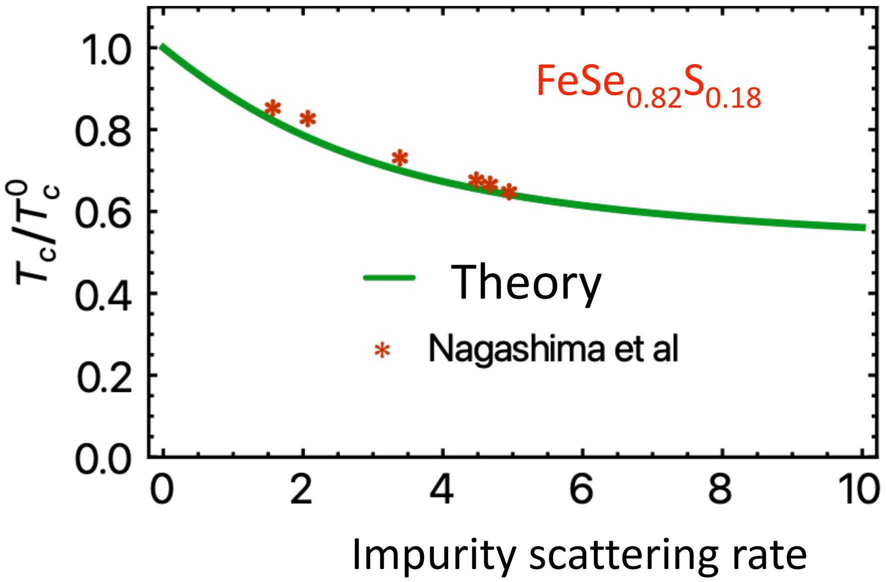
Tc variation with impurity scattering

Experiment

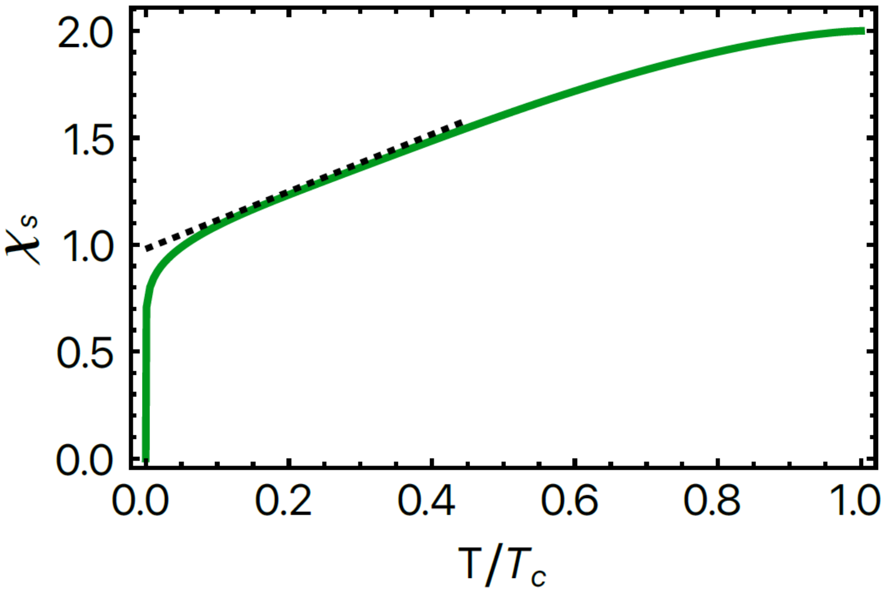


T. Nagashima et al (Shibauchi group)

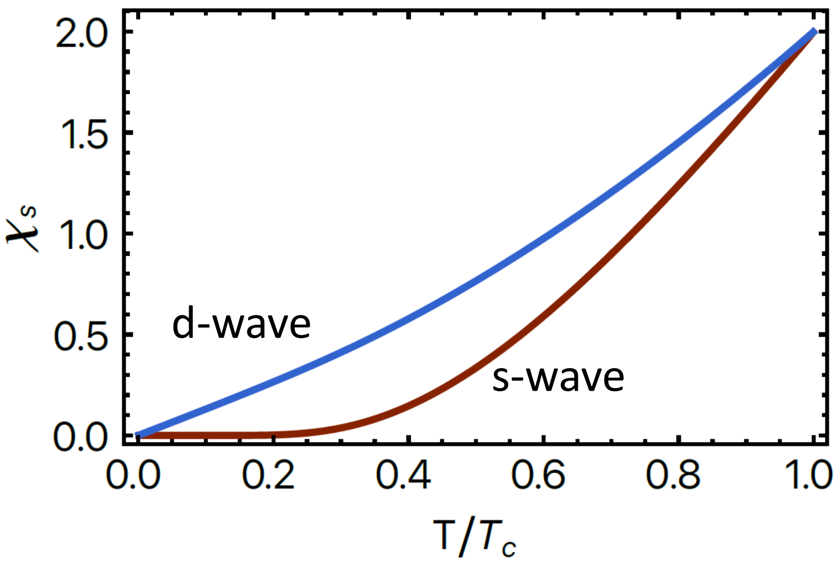
Theory



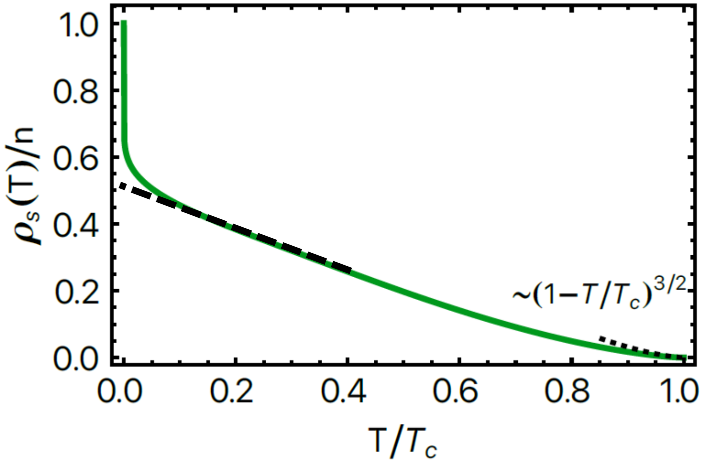
Spin susceptibility



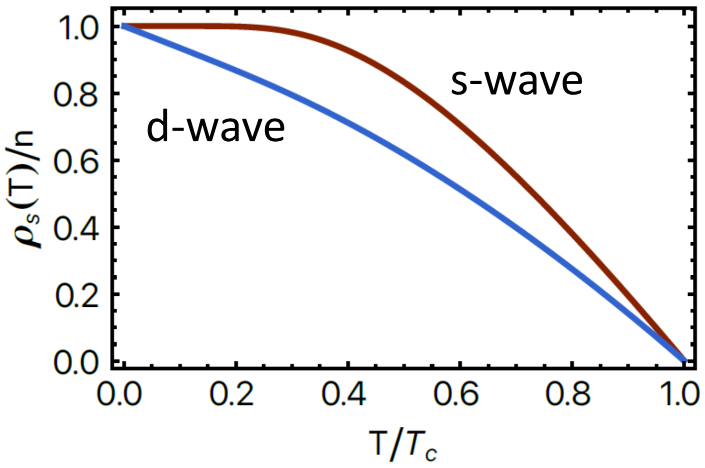
BCS



Superfluid stiffness

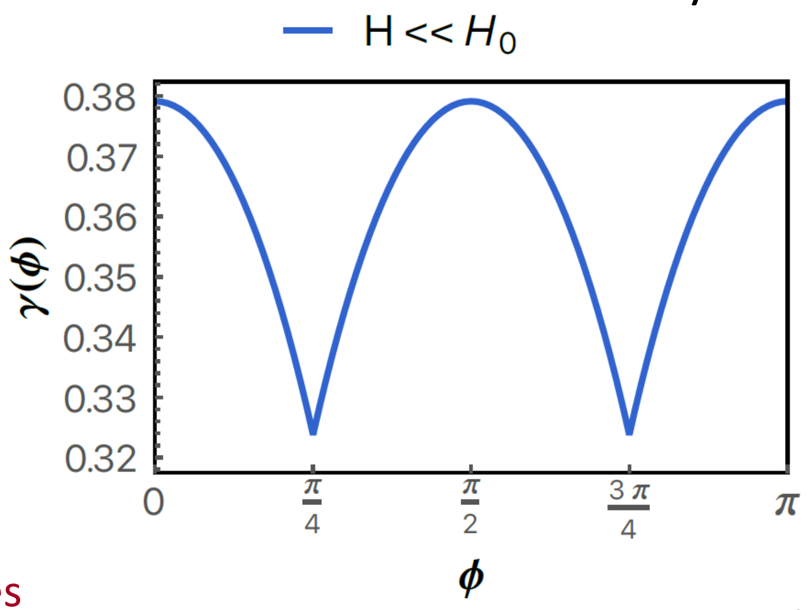


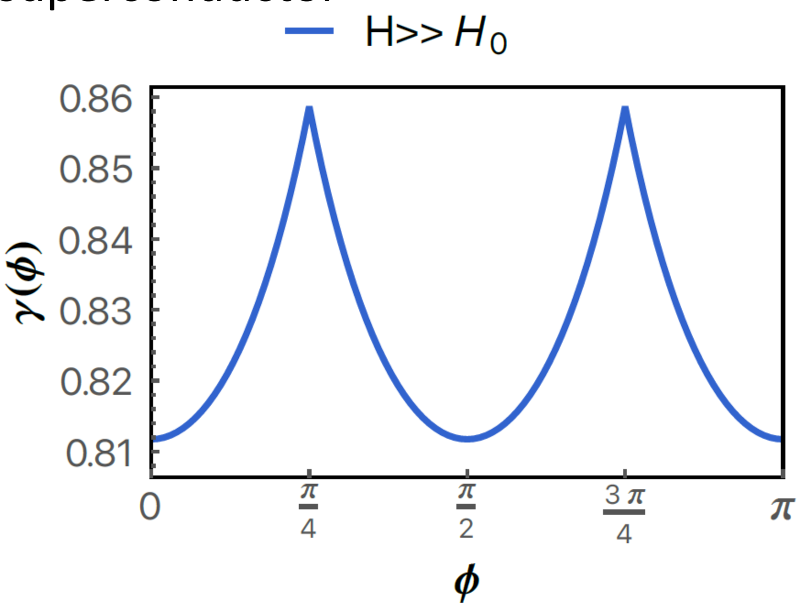
BCS



Dependence of the specific heat coefficient on the angular variation of an applied field

Ordinary d--wave superconductor

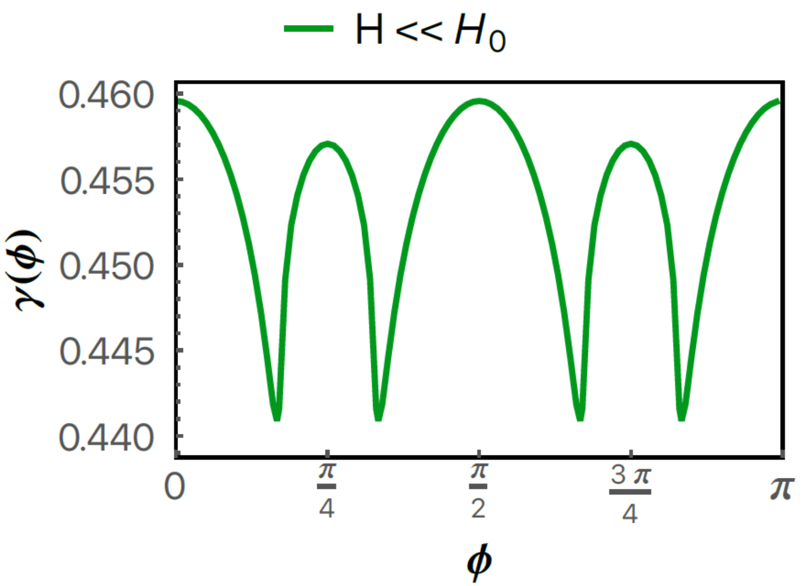


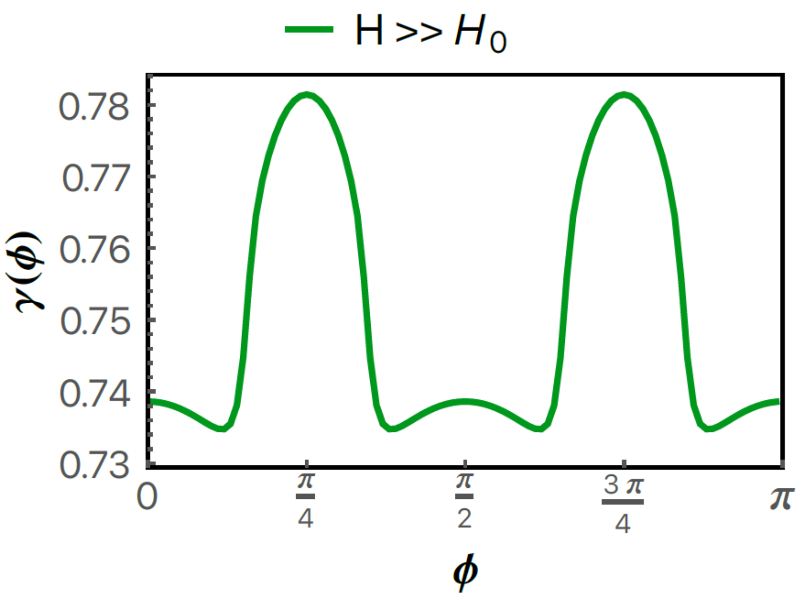


Vekher & Vorontsov
Eremin and A.C.

In both cases,
the gap vanishes
along the diagonal

Our case: SC mediated by nematic fluctuations



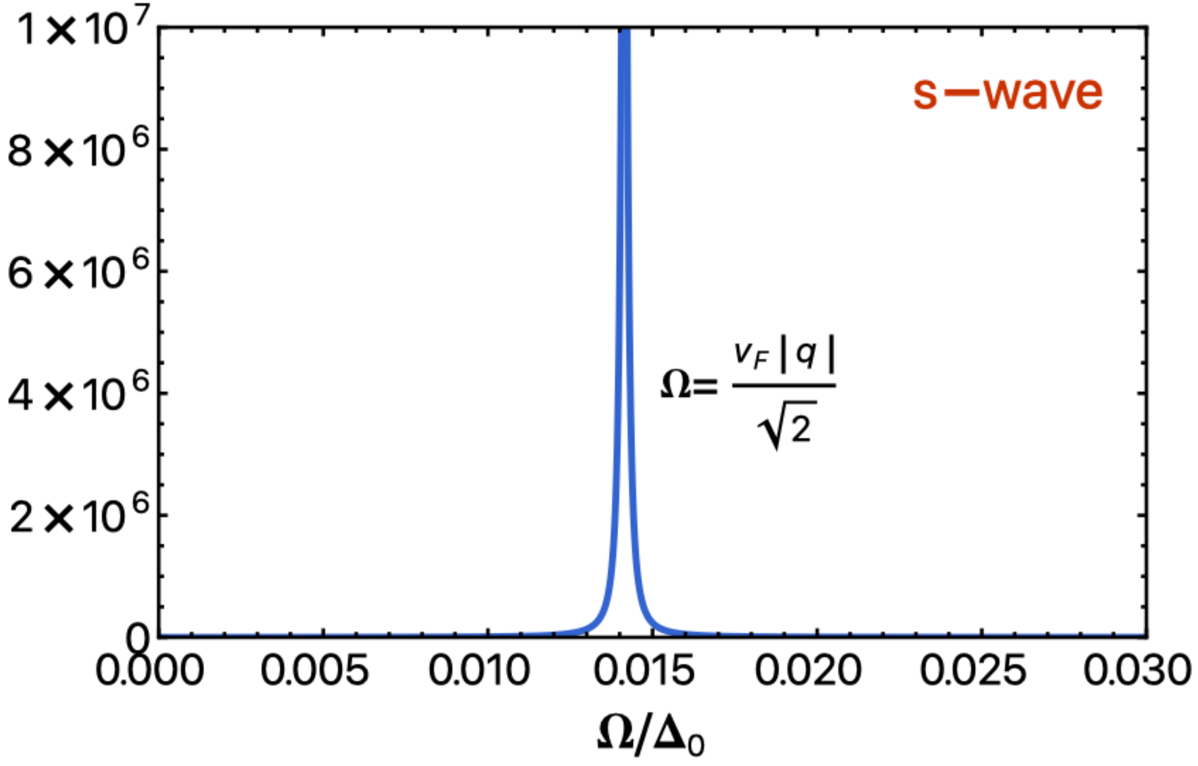


Collective modes:

Transverse pair susceptibility at various momenta (phase fluctuations), no Coulomb.

Our case: two damped modes at $\Omega = v_F\, q \cos\theta_q$ and $\Omega = v_F\, q \sin\theta_q$

BCS s-wave: a single undamped mode at $\Omega = v_F|\mathbf{q}|/\sqrt{2}$

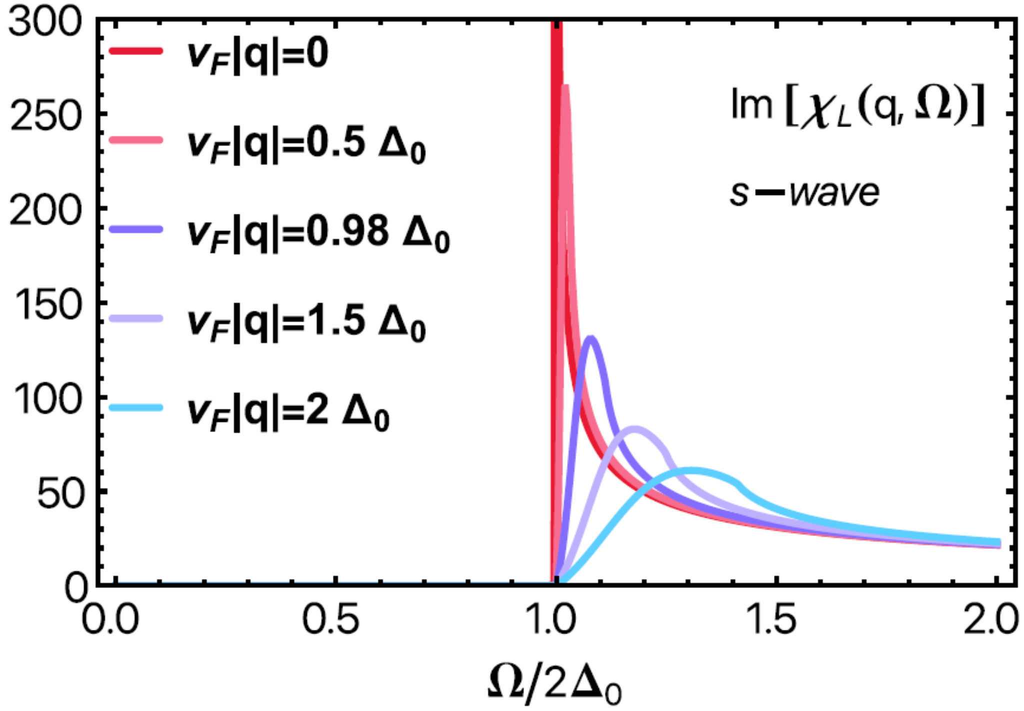


The structure of the transverse pair susceptibility $\chi(q,\Omega)$ depends on the direction of the momentum q

Longitudinal pair susceptibility at various momenta (longitudinal gap fluctuations)

Our case – strongly anisotropic s-wave gap

S-wave BCS superconductor



Conclusions

Superconductivity in doped FeSe near a nematic QCP can be mediated by nematic fluctuations

- At a nematic QCP, the pairing interaction is attractive, but local in k-space: the strength of attraction depends on the position on the Fermi surface
- As the consequence, the gap opens up at Tc only at certain points, and extends along the FS as T decreases.

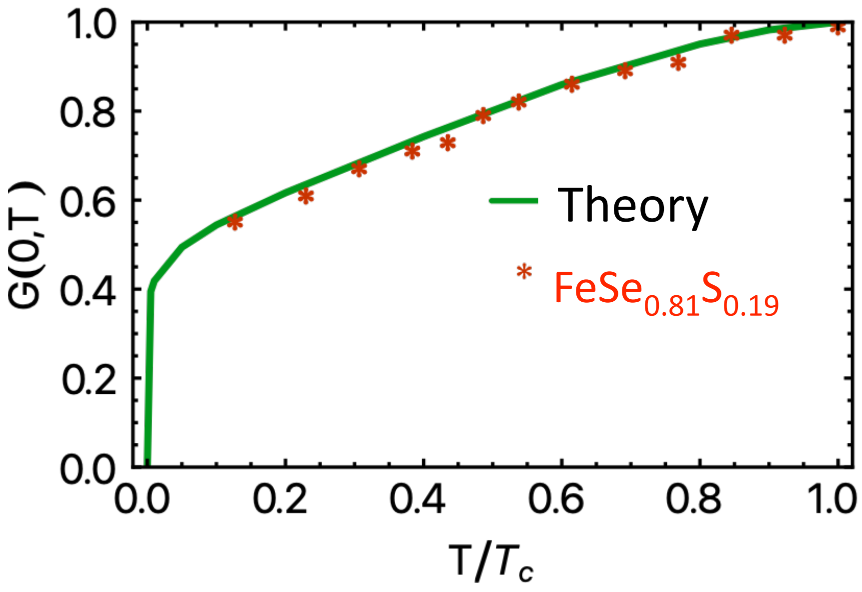
Features:

- Strong gap anisotropy on the hole pocket (near-nodes of the gap)
- Non-BCS behavior of the specific heat
- Impurity scattering lifts the gap in the nodal regions and reduces Tc,
- Phase and longitudinal collective excitations are not like in a BCS SC

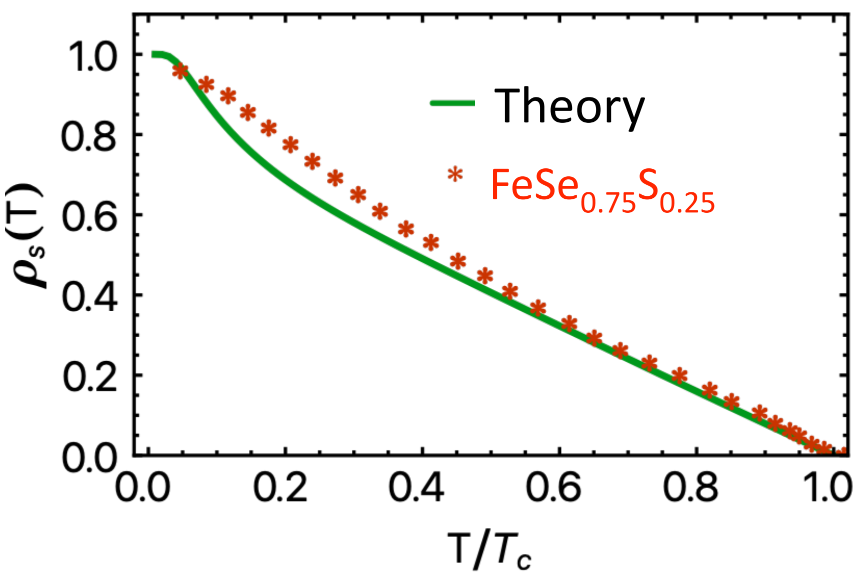
This talk

THANK YOU

Zero-bias tunneling density

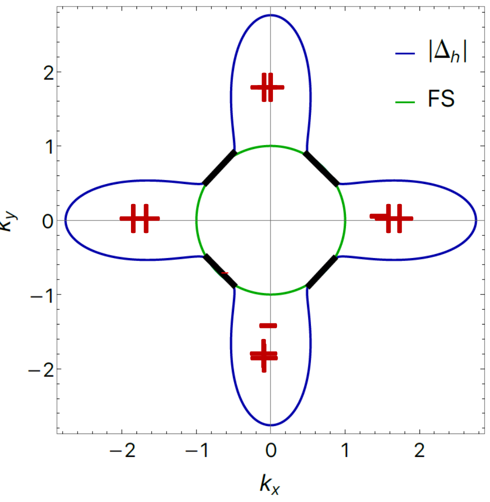


Superfluid stiffness



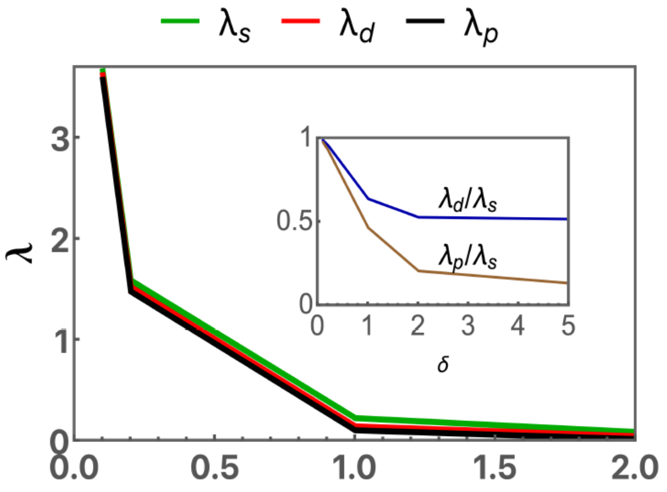
Experimental data:
Sato et al, Nagashima et al, Nag et al,….

Pairing symmetry

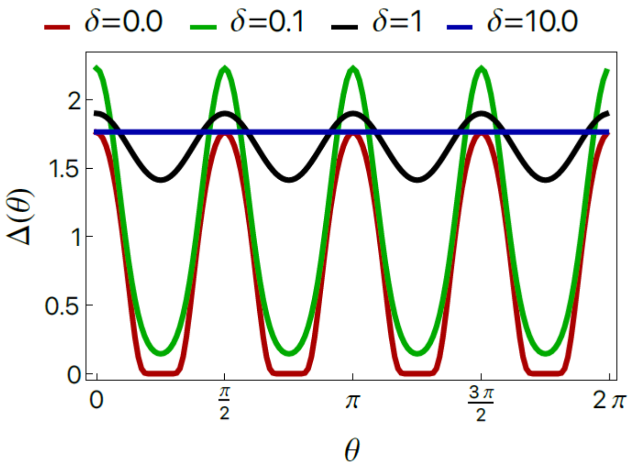


- At a nematic QCP, s-wave, d-wave, p-wave gaps are all degenerate
- Away from a QCP, or due to extra interactions, one of these states wins.

  In the model of only nematic fluctuations, this is s-wave



δ – distance to a QCP



The gap is highly anisotropic, with hot and cold regions