Spontaneously broken time-reversal symmetry in d-wave superconductors

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Chalmers University of Technology, Göteborg, Sweden

M. Håkansson et al, Nature Physics 11 755 (2015)
P. Holmvall et al submitted (arXiv:1706:06165) and in manuscript

Vetenskapsrådet Knut och Alice Wallenbergs Stiftelse MC2 Microtechnology and Nanoscience

Mesoscopic unconventional superconductivity ?

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- mesoscopic ☞ system size comparable to typical length scales, λ_F , ξ
- unconventional superconductivity is fragile to:
  - ✳ impurities and disorder
  - ✳ surface scattering

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☞ other competing states/orders may be made visible….

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typical length scales e.g. YBCO:

$L \gtrsim \xi \gtrsim 1/k_F$

$1/k_F = 0.3$ nm

$\xi = 2$ nm

$L = 100$ nm

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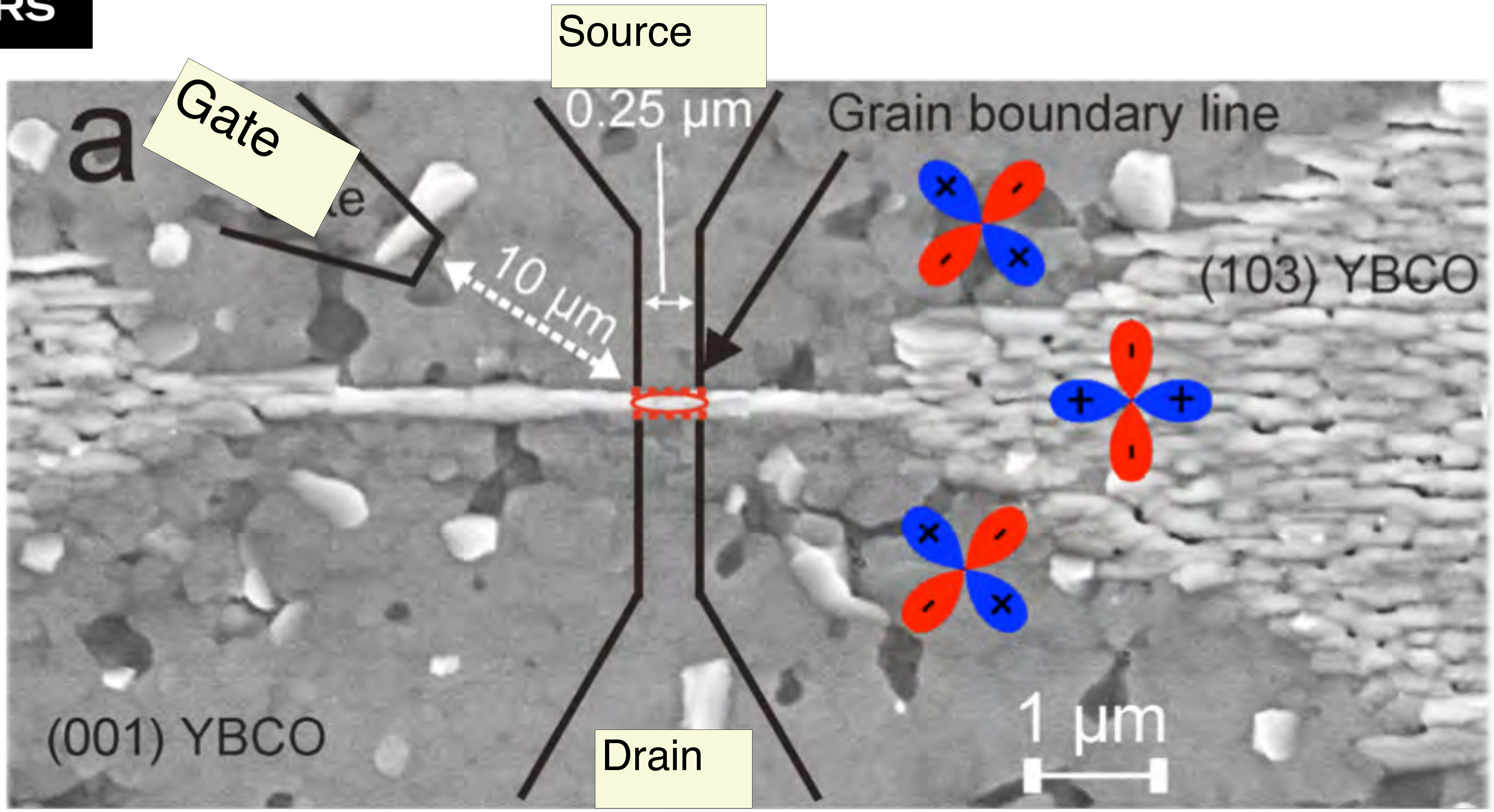
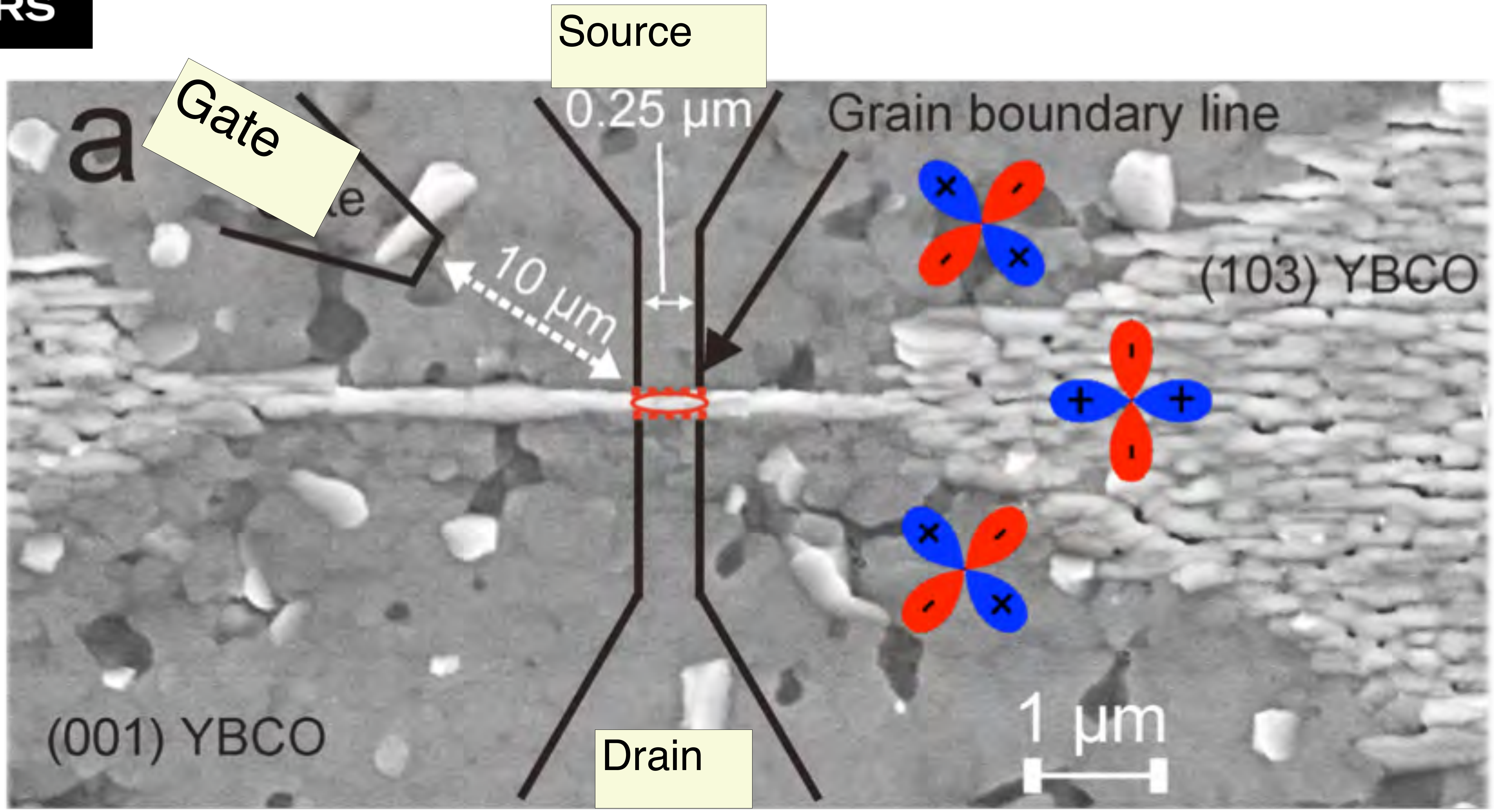


study current (I_{sd}) vs. source-drain voltage (V_{sd})
as a function of gate charge (n_g=V_gC_g) -> charging effects, single-electron-ics
at low T (≲20 mK) varying an applied magnetic field



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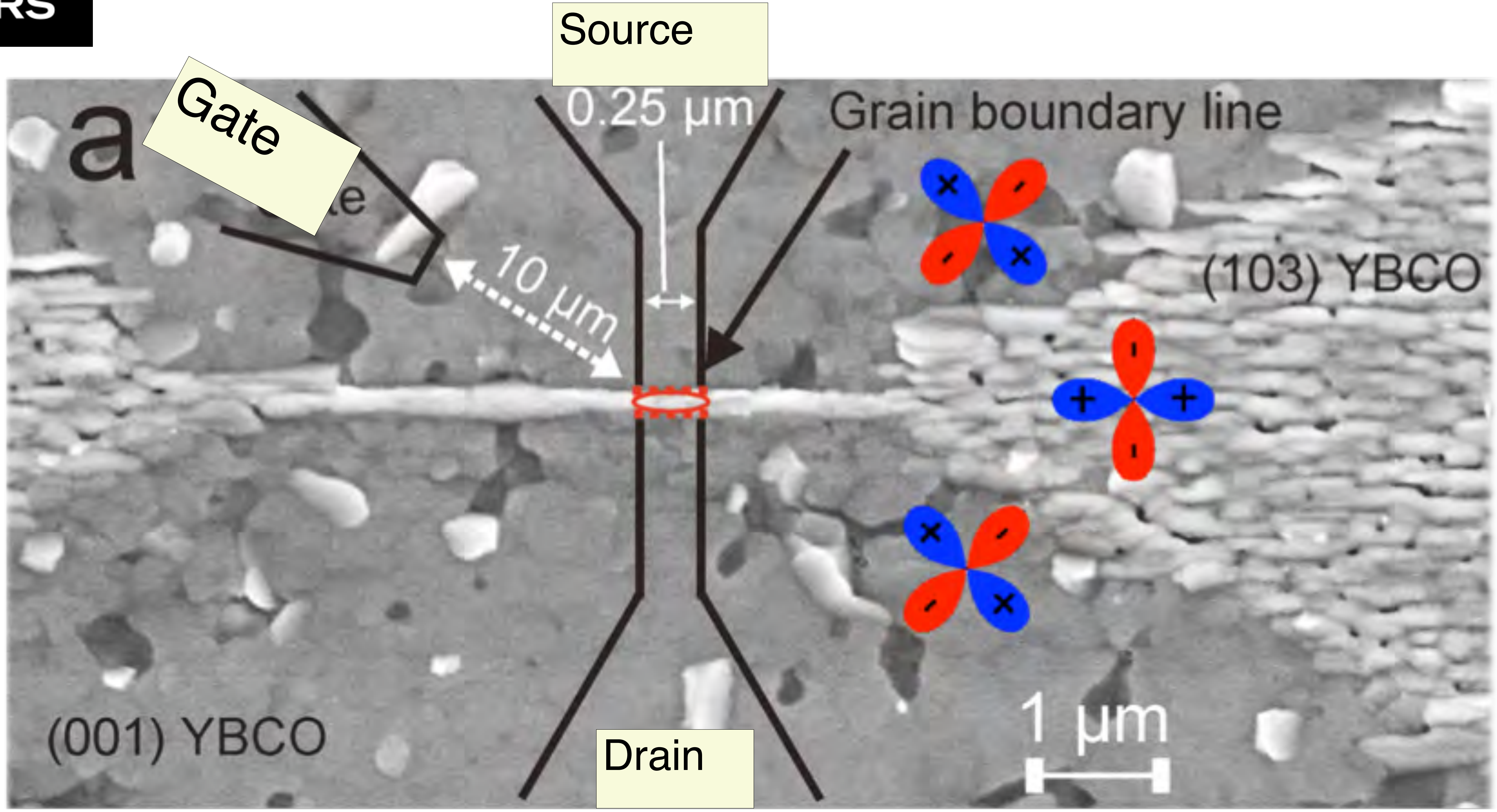
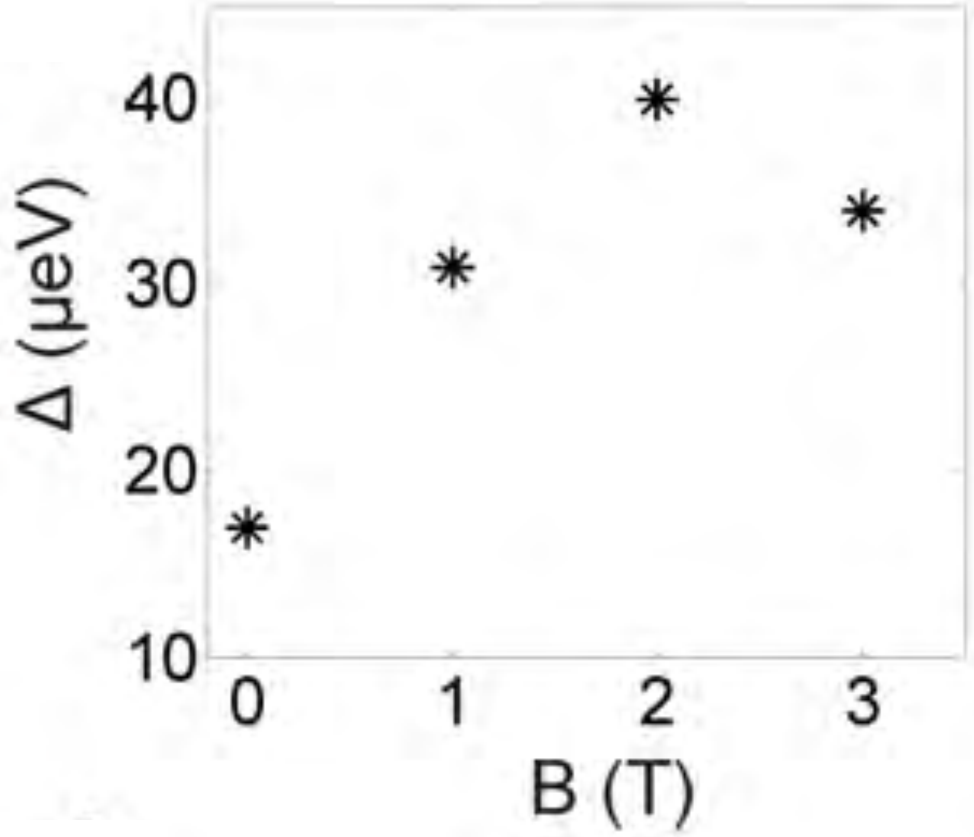
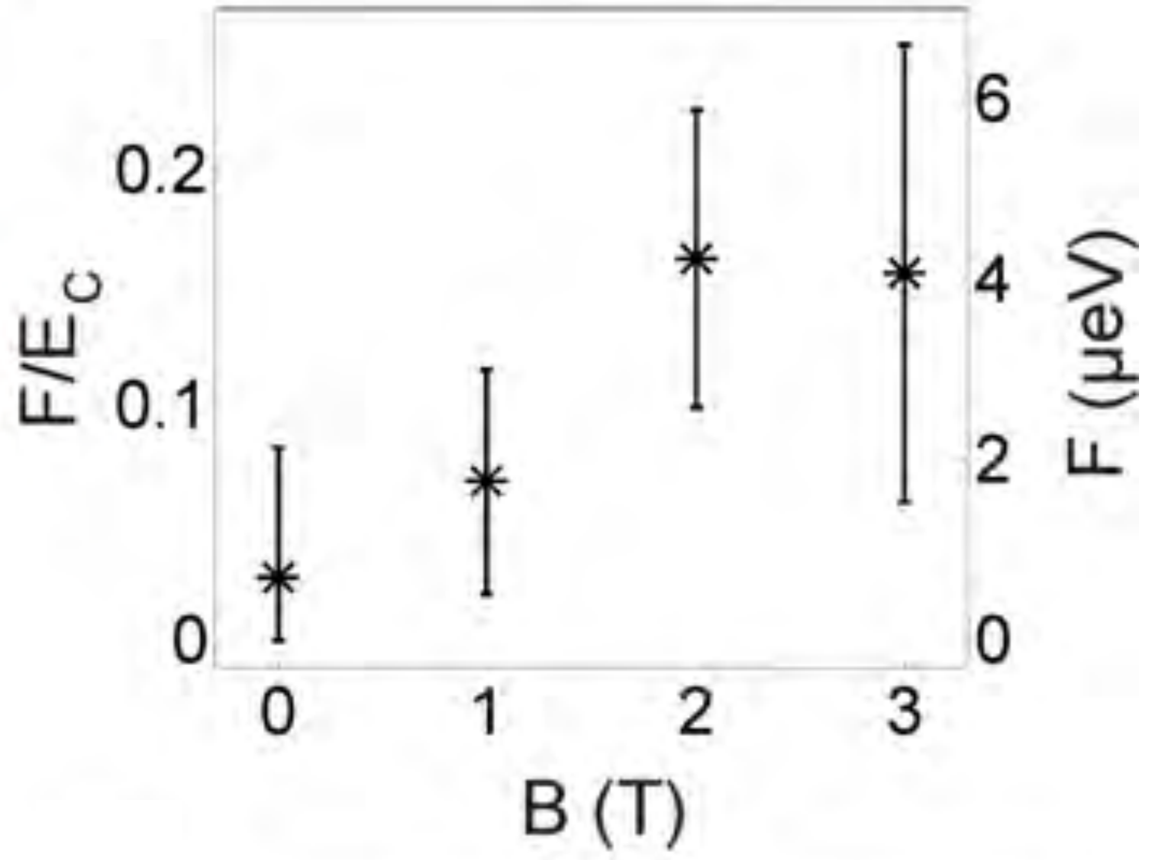
<u>I_{sd}(V_{sd}) depends on the gate charge n_G:</u>
- ☞ an "odd/even in e" parity effect is seen
- ☞ this parity effect increases with applied B.







B (T)	T_{eff} (mK)	d (µeV)
0	73	0.5
1	105	0.3
2	120	0.3
3	140	0.9

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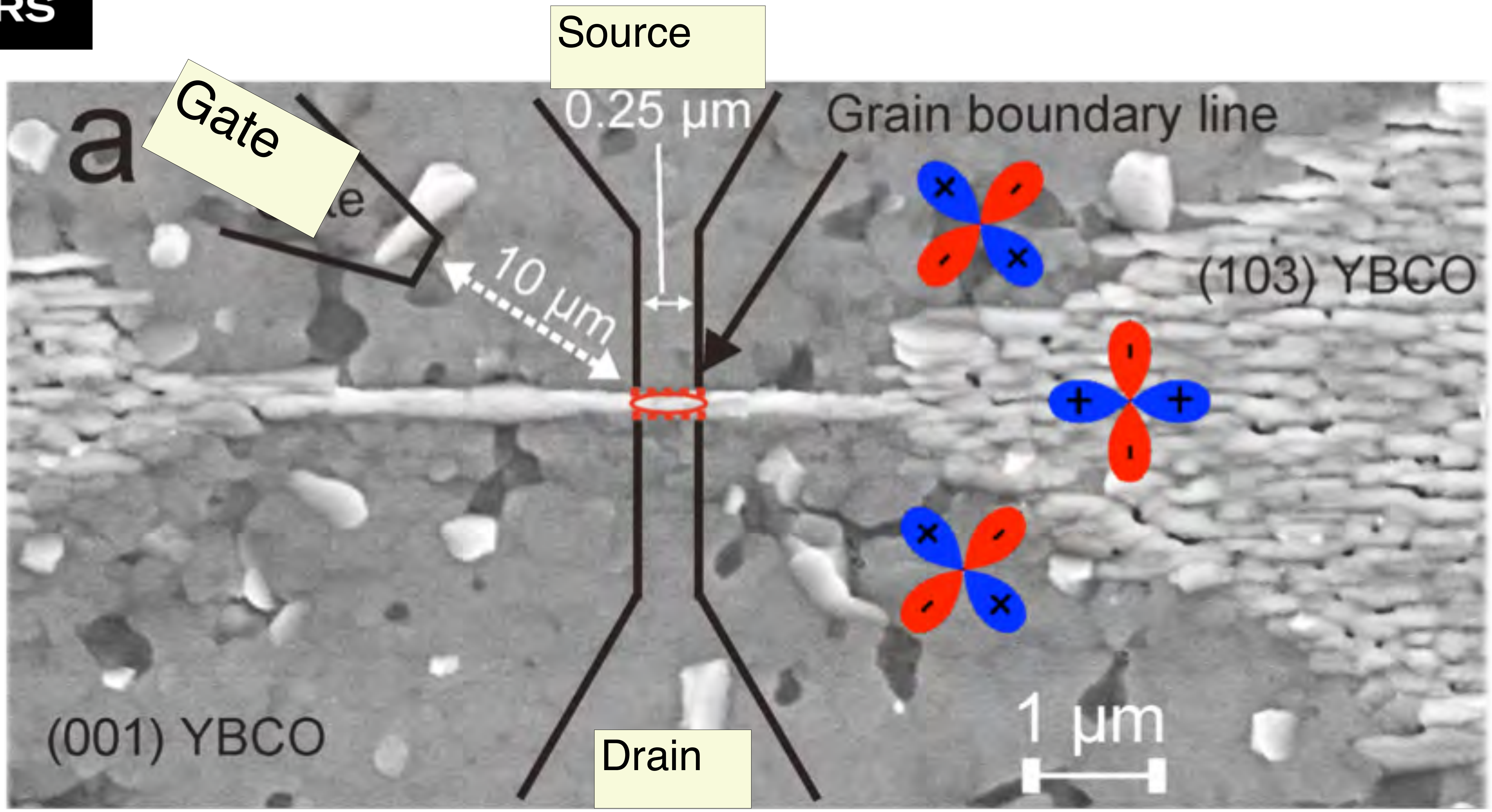

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nature nanotechnology LETTERS
PUBLISHED ONLINE: 9 DECEMBER 2012 | DOI: 10.1038/NNANO.2012.214

Fully gapped superconductivity in a nanometre-size $YBa_2Cu_3O_{7-\delta}$ island enhanced by a magnetic field

D. Gustafsson[1], D. Golubev[2], M. Fogelström[1], T. Claeson[1], S. Kubatkin[1], T. Bauch[1] and F. Lombardi[1]*

D. Gustafsson PhD-work in F. Lombardis group at Chalmers

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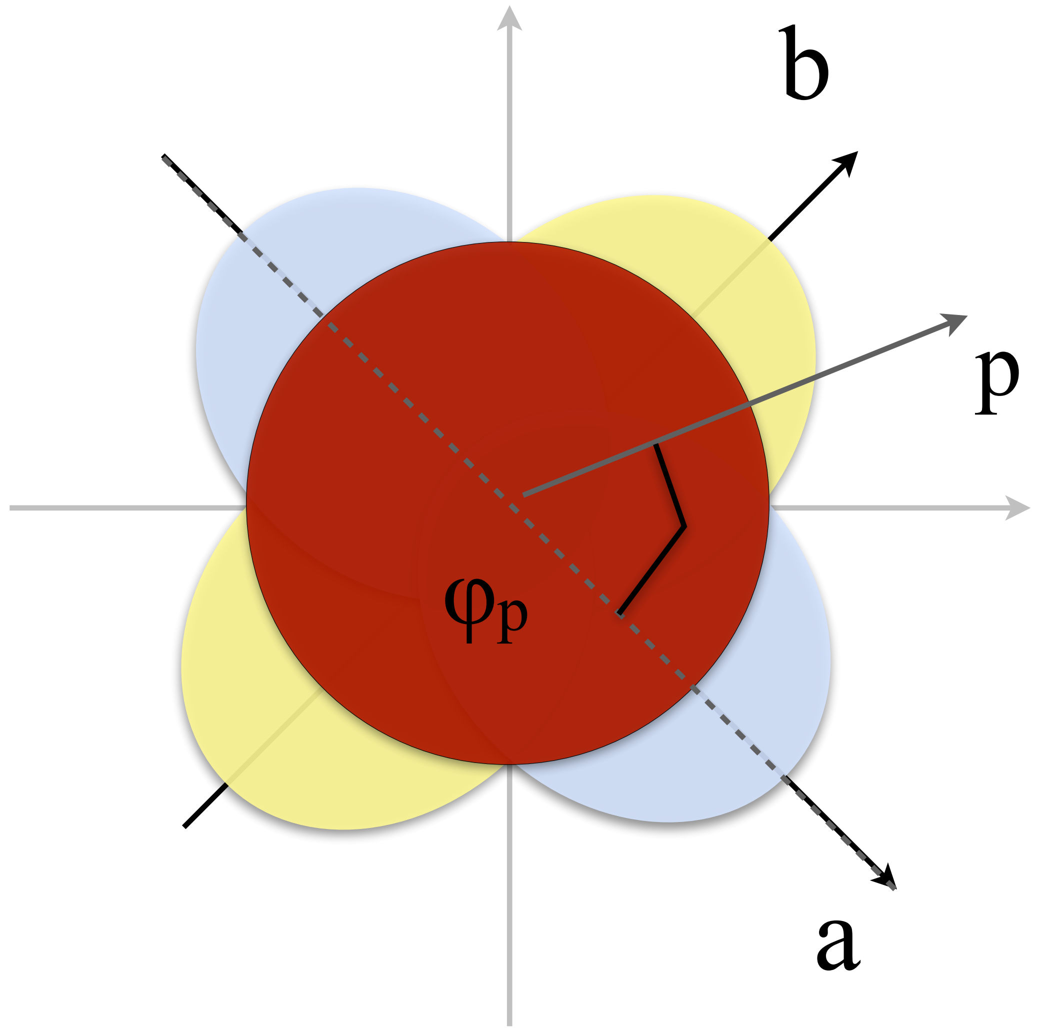
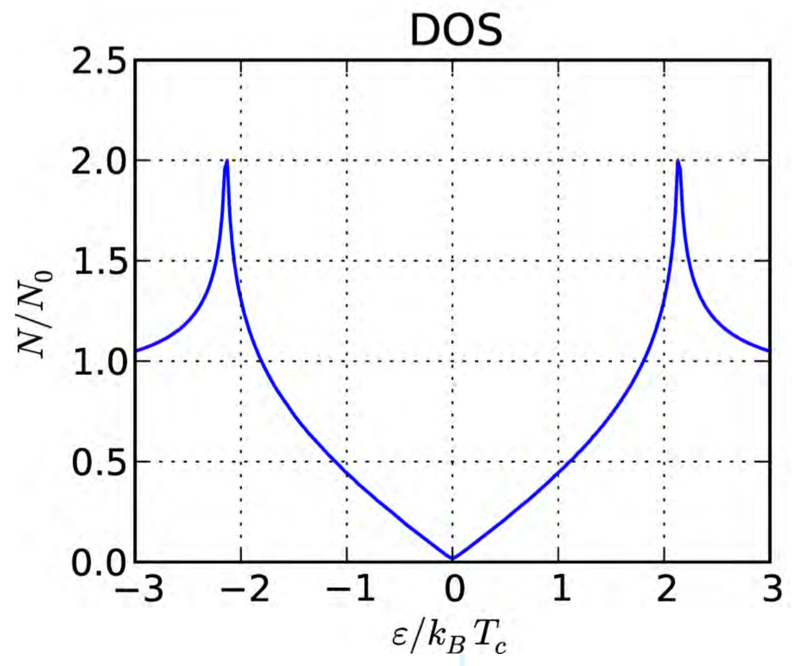
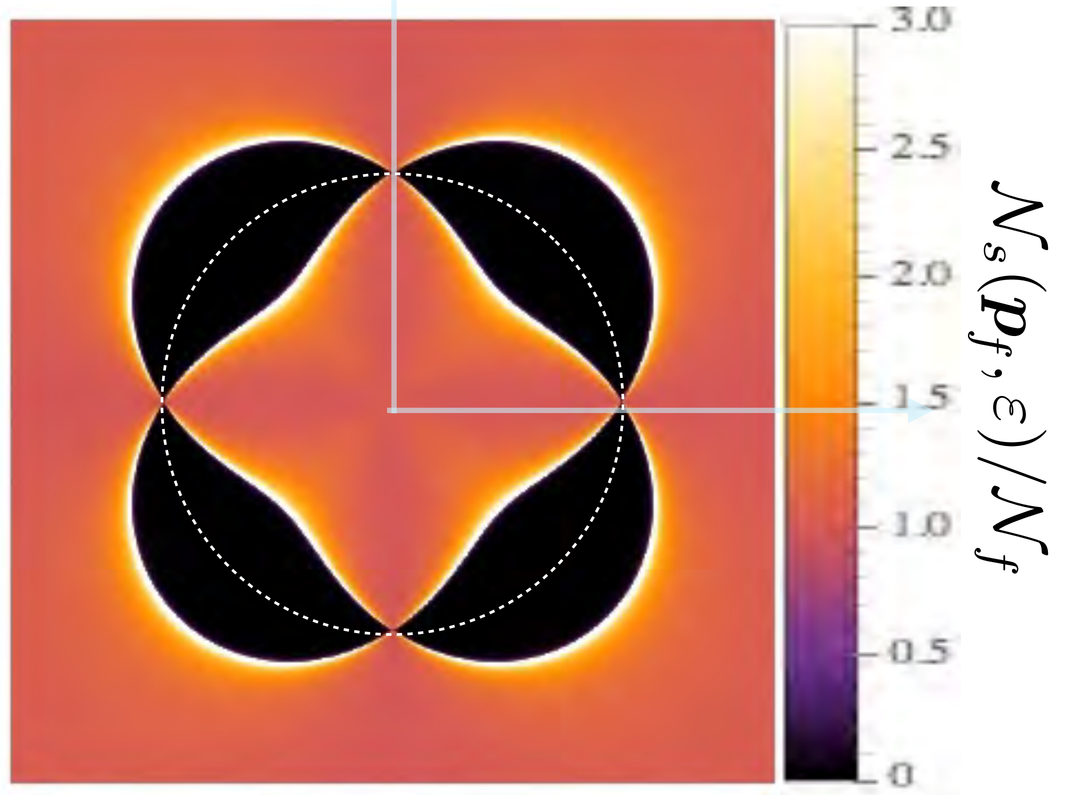
A d-wave superconductor $\Delta(p_F) \approx \Delta_0 \cos(2\varphi_p)$







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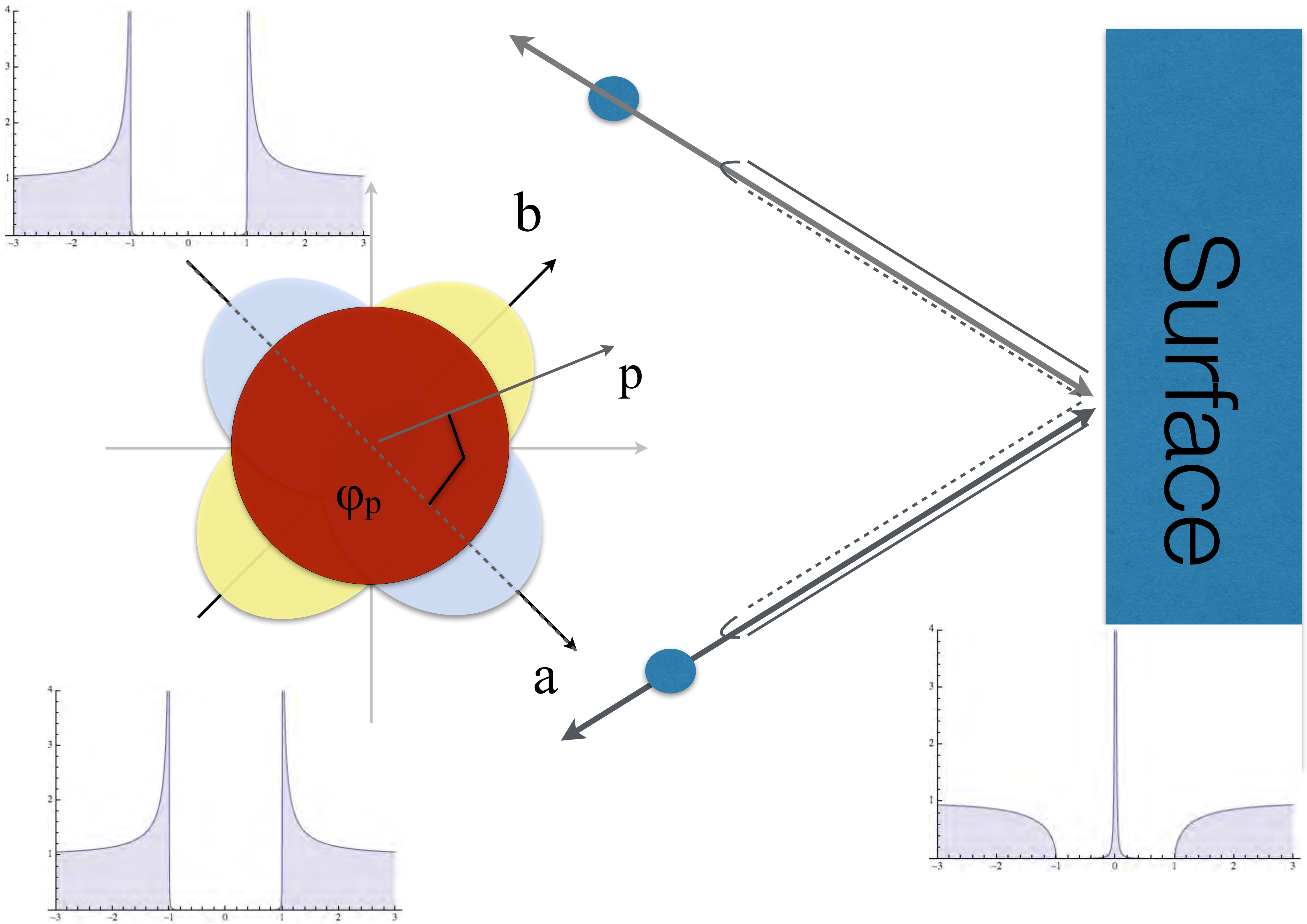

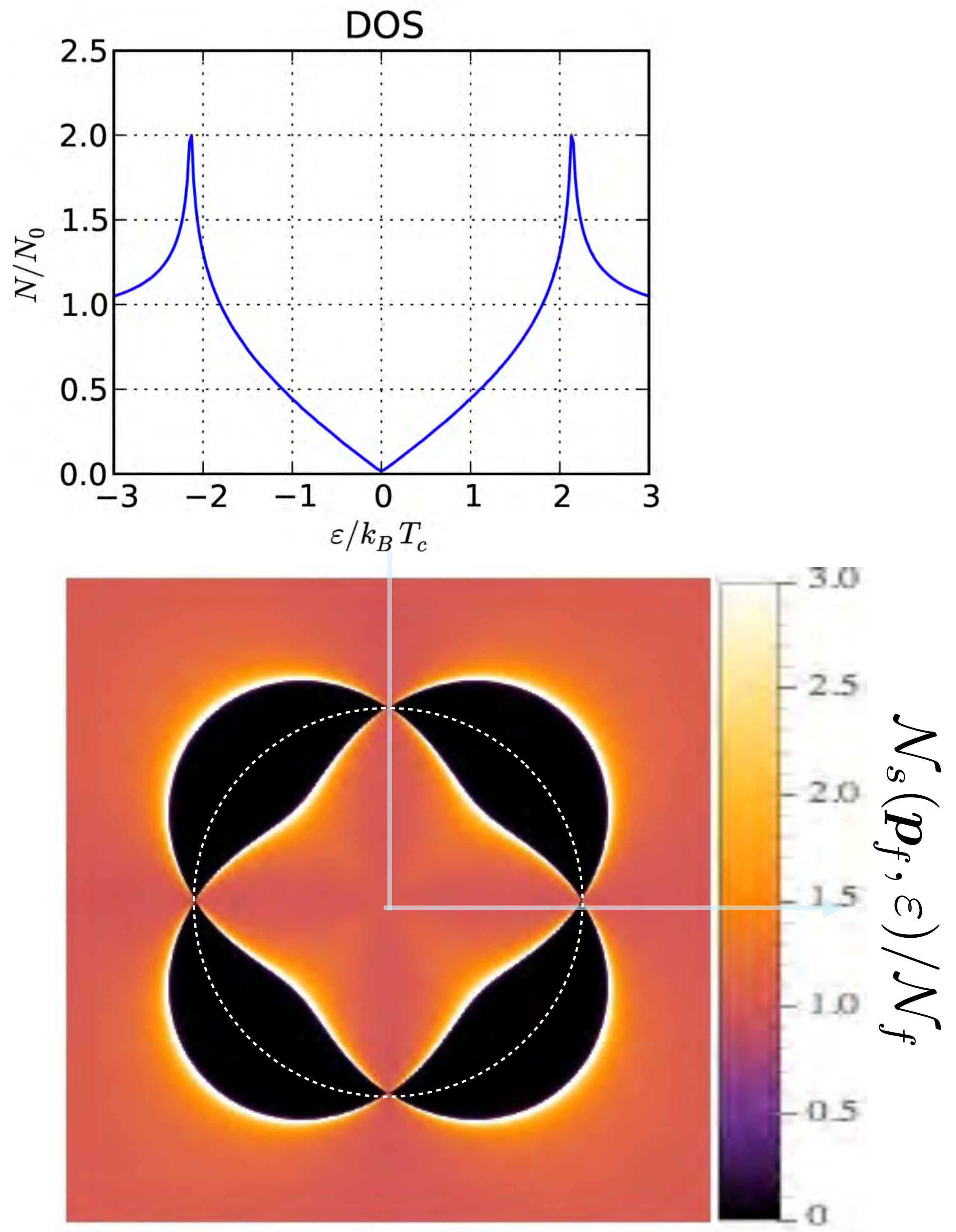

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spatial dependence of N(**p**,ε)

$$N(\mathbf{p}_f, x; \epsilon) = \text{Im}\left(\frac{\tilde{\varepsilon}^R}{D^R} - \frac{|\Delta(\mathbf{p}_f)|^2}{\tilde{\varepsilon}^R D^R} e^{-2D^R x/|\mathbf{v}_f\cdot\hat{\mathbf{x}}|}\right)$$

$$D^R = \sqrt{|\Delta(\mathbf{p}_f)|^2 - \tilde{\varepsilon}^R(\mathbf{p}_f,\epsilon)^2}$$

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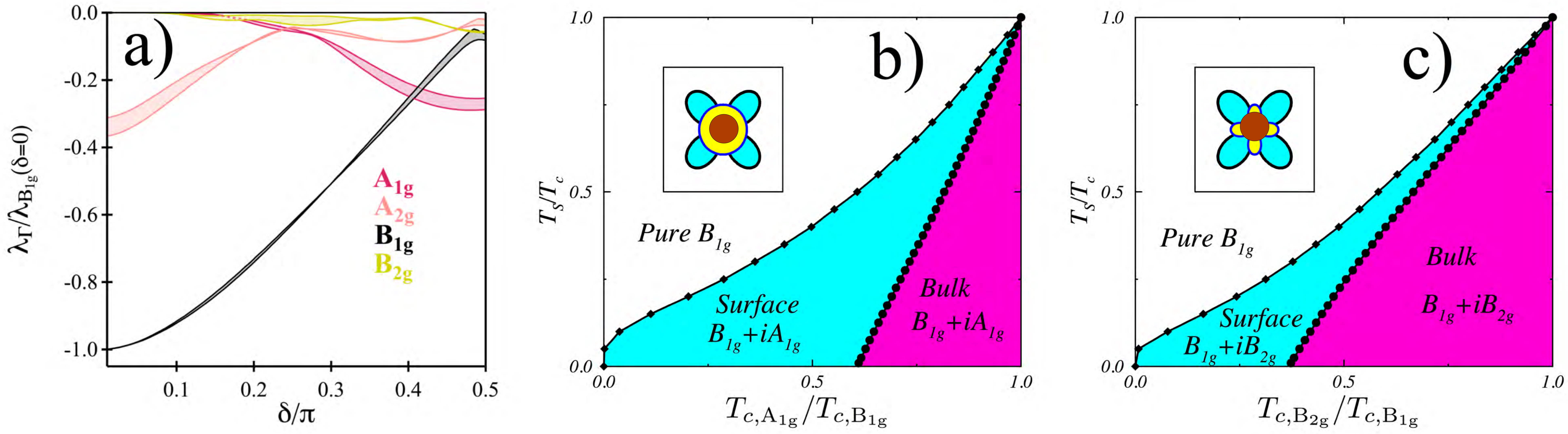
J. Phys. Chem Solids Vol 59, No. 10–12, pp. 2040–2044, 1998

ANDREEV BOUND STATES, SURFACES AND SUBDOMINANT PAIRING IN HIGH T_c SUPERCONDUCTORS

D. RAINER[a,*], H. BURKHARDT[a], M. FOGELSTRÖM[b] and J. A. SAULS[b]
[a]Physikalisches Institut, Universität Bayreuth, D-95440 Bayreuth, Germany
[b]Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA

Possible low-T transition to a fully gaped superconducting state



Superconducting instabilities at at [110]-surfaces in d-wave SC:s

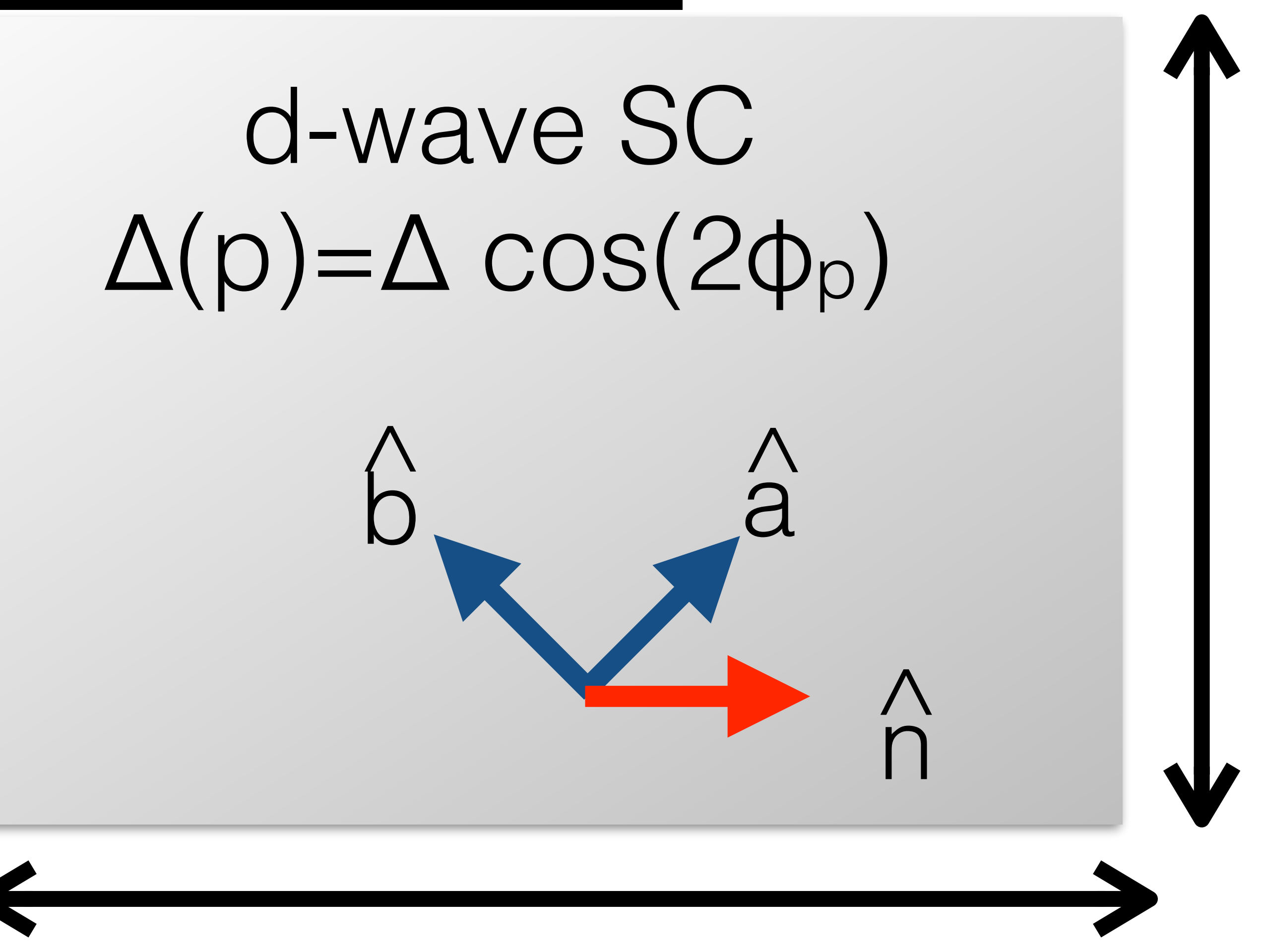
Fractional Vortices as Evidence of Time-Reversal Symmetry Breaking in High-Temperature Superconductors, M Sigrist, D. B. Bailey, and R. B. Laughlin, PRL 74, (1995)
Coexistence of Different Symmetry Order Parameters near a Surface in d-Wave Superconductors, M Matsumoto and H. Shiba, J. Phys. Soc. Jpn. (1995)
Thermodynamics of ad-wave superconductor near a surface, L. J. Buchholtz, M. Palumbo, D. Rainer, and J. A. Sauls, J. Low Temp Phys. 101 (1995)
Tunneling into Current-Carrying Surface States of High-T_c Superconductors, M Fogelström, D. Rainer, and J. A. Sauls, PRL 79, (1997)
Magnetic Induction of $d_{x^2-y^2}+id_{xy}$ Order in High-Tc Superconductors, R B Laughlin, PRL 80, (1998)
Spontaneous time reversal and parity breaking in a $d_{x^2-y^2}$-wave superconductor with magnetic impurities, A. V. Balatsky, PRL 80, (1998)
(and many more)
……….

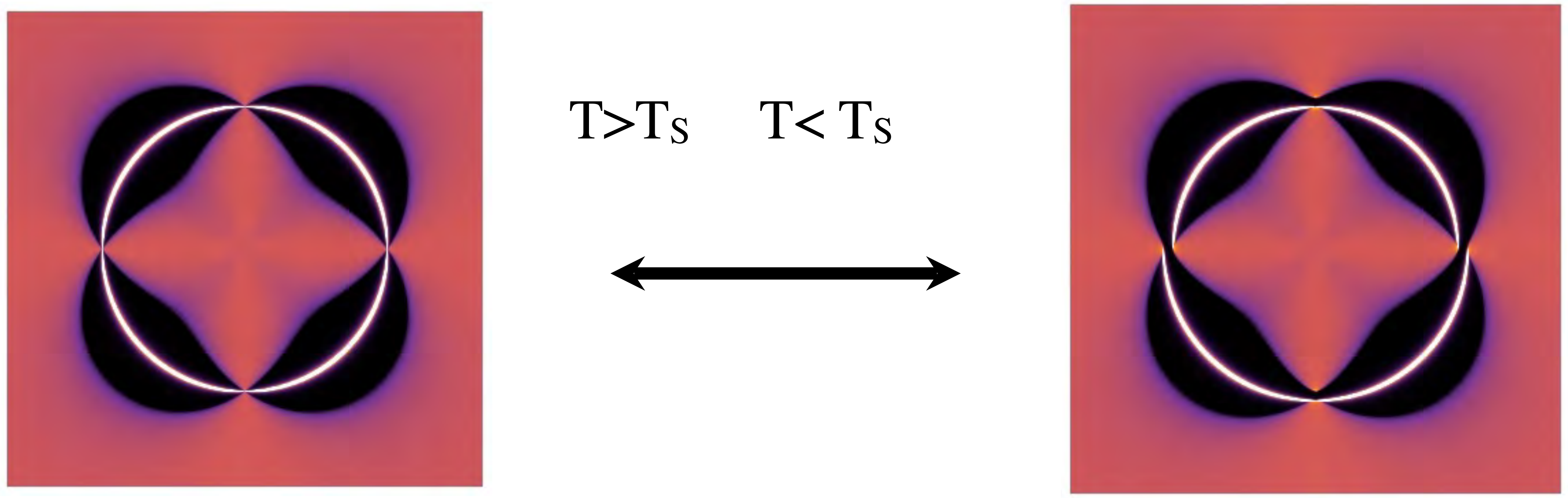
Magnetic or spin-density wave instabilities at [110]-surfaces

Instabilities at [110] surfaces of $d_{x^2-y^2}$ superconductors, C. Honerkamp, K. Wakabayashi and M. Sigrist, Europhys. Lett., 50 (2000)
Edge Ferromagnetism from Majorana Flat Bands: Application to Split Tunneling-Conductance Peaks in High-Tc Cuprate Superconductors, A.C. Potter & P.A. Lee, PRL 112 (2014)
……….

Other types of instabilities at [110]-surfaces ??

A $d_{x^2-y^2}$+is state in a nanoscaled YBCO grain





Tight-binding BdG calculation

Quasi-classical calculation

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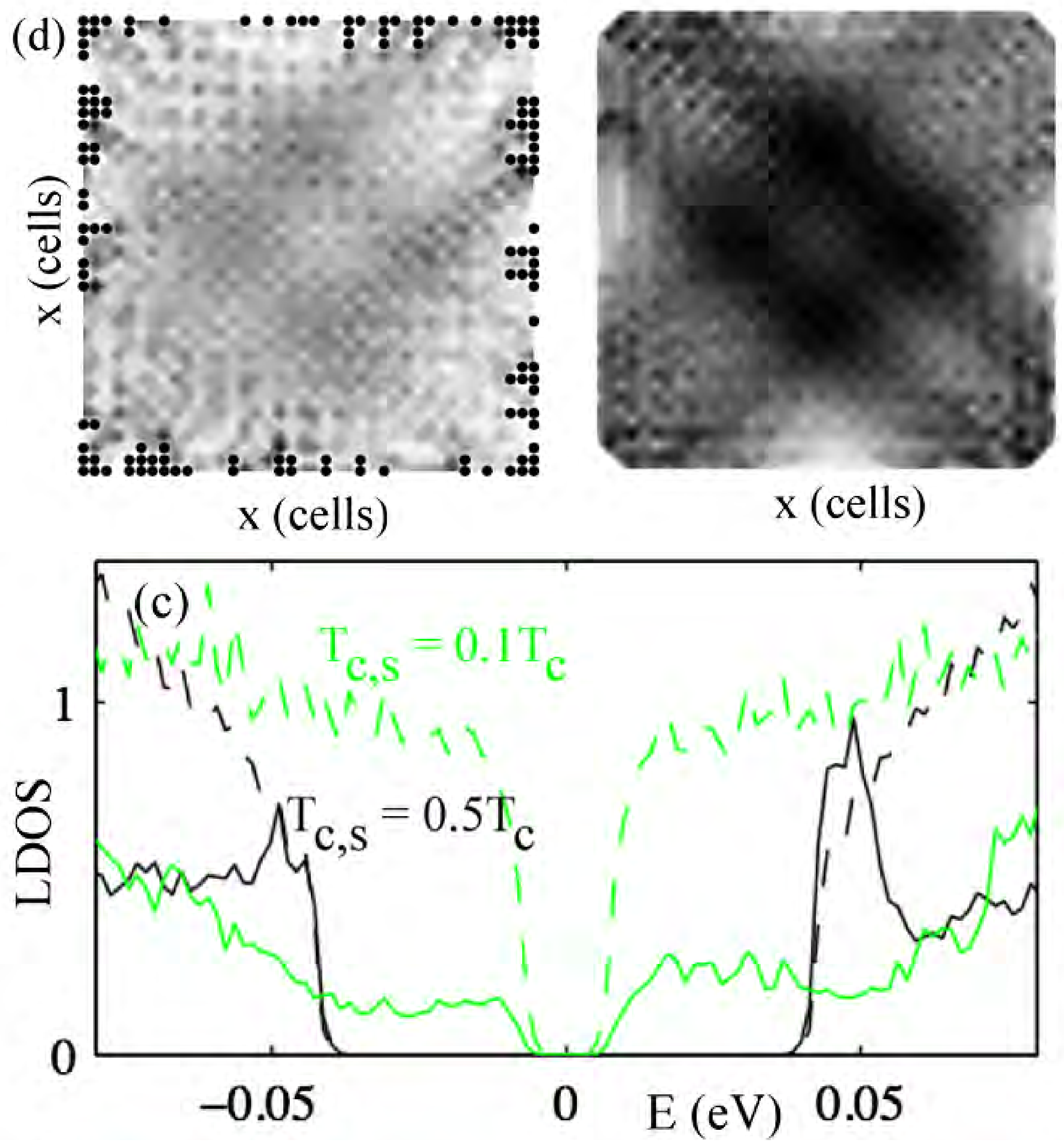

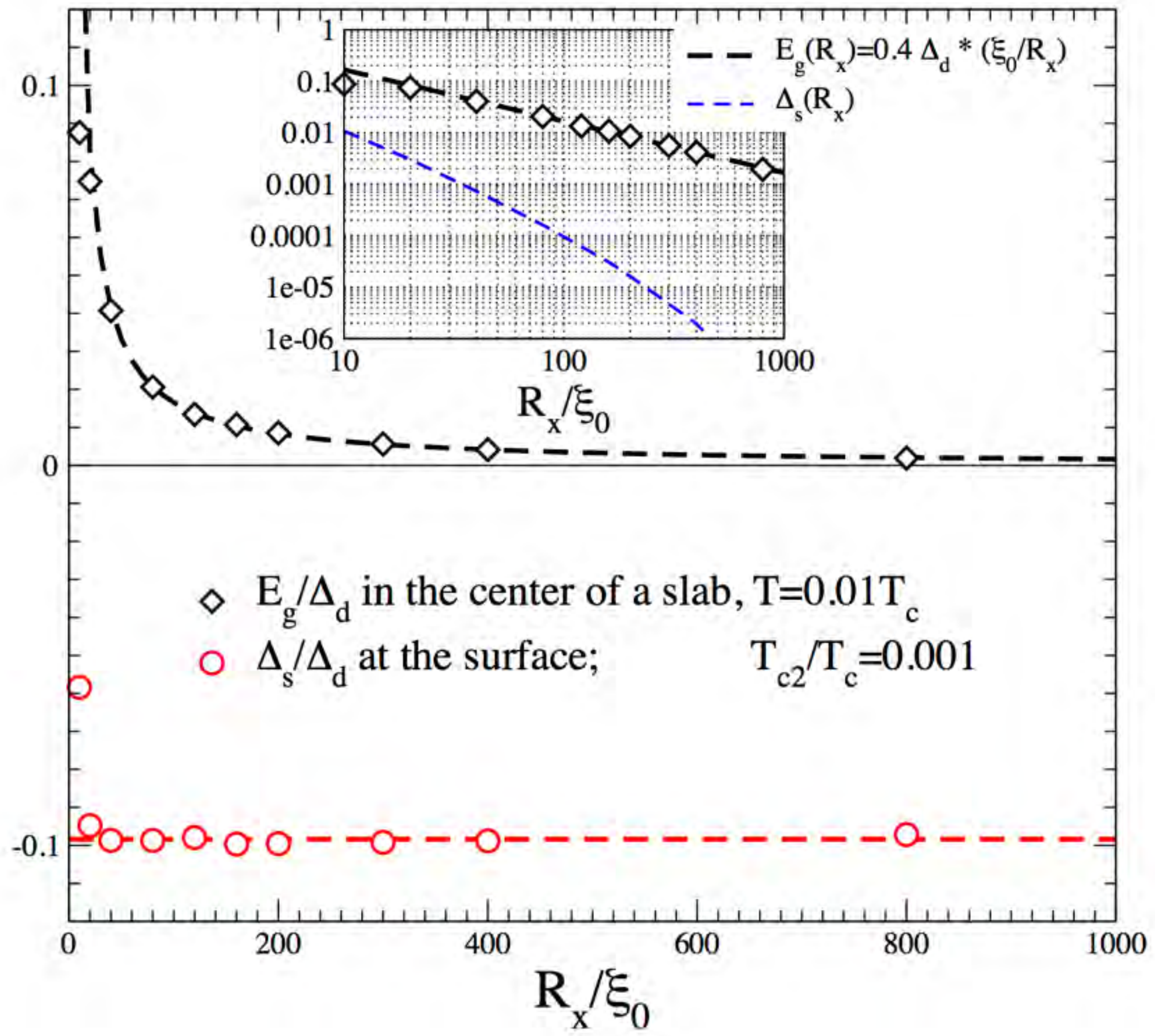

The spectral gap: E_g ~1/R, R is the slab width

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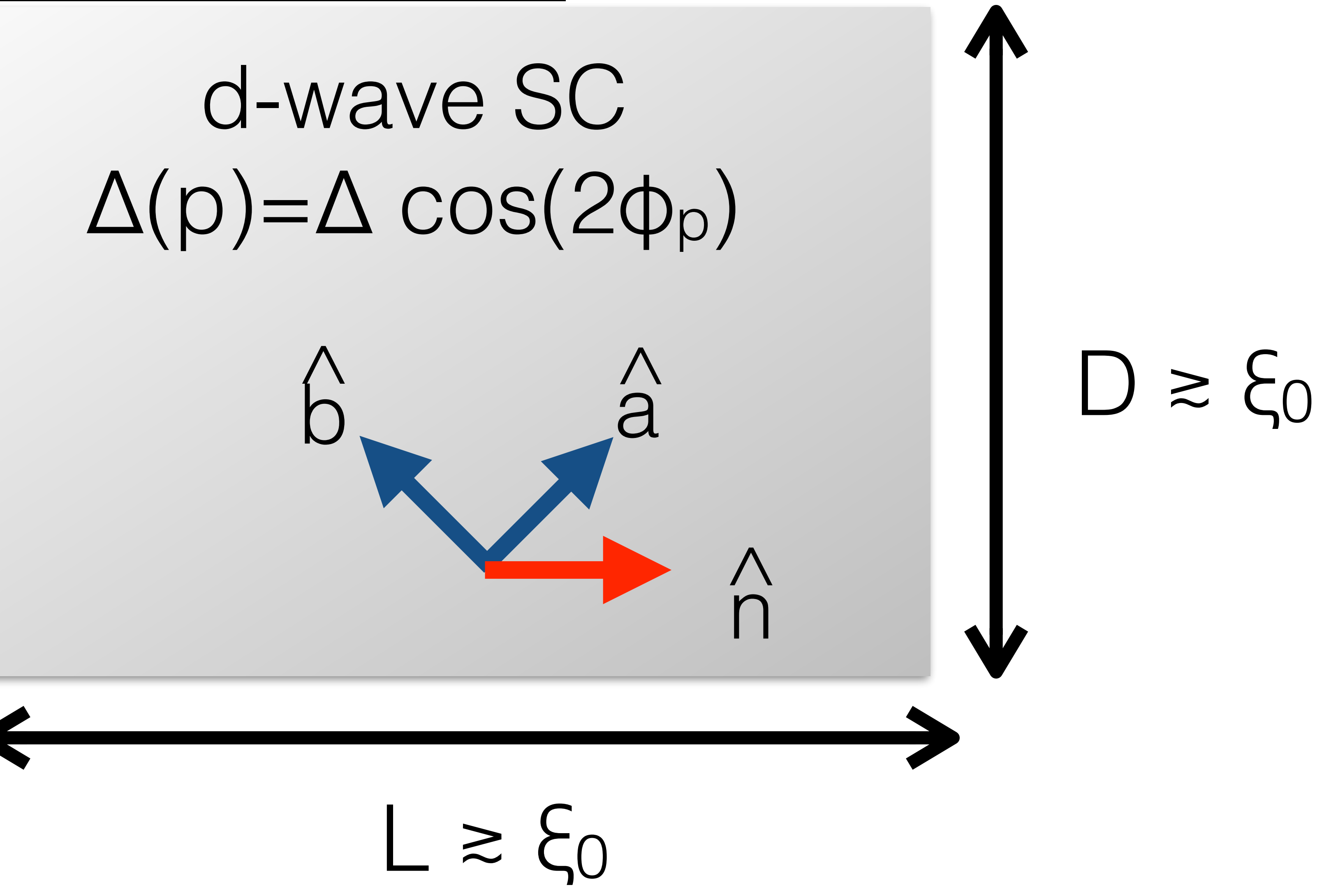

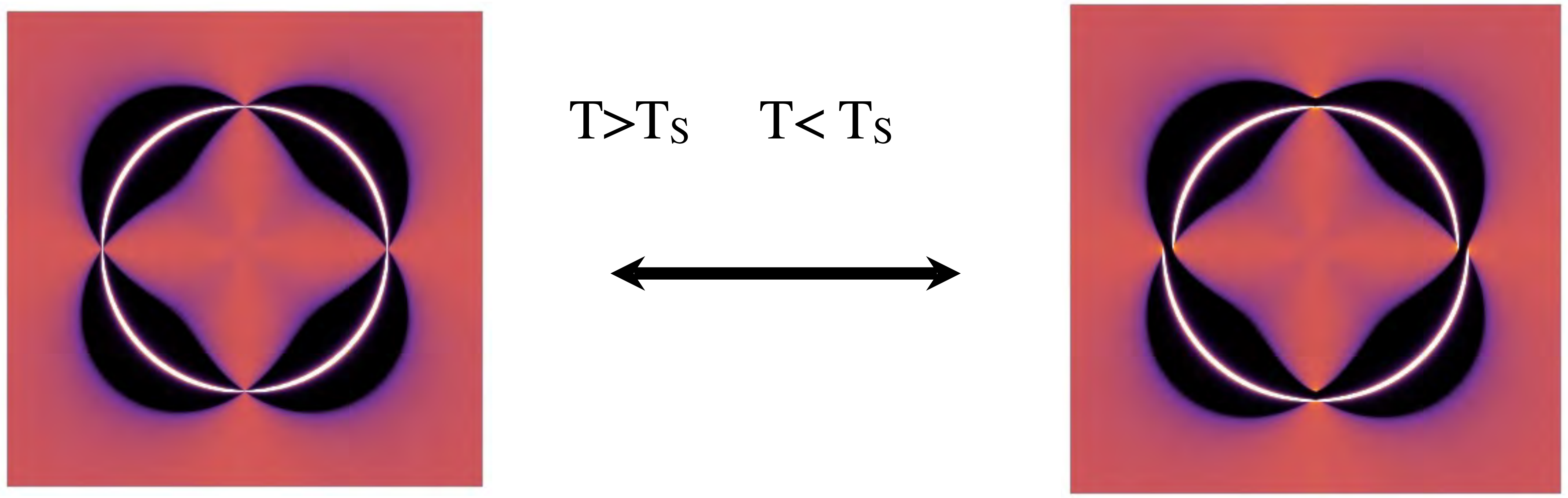

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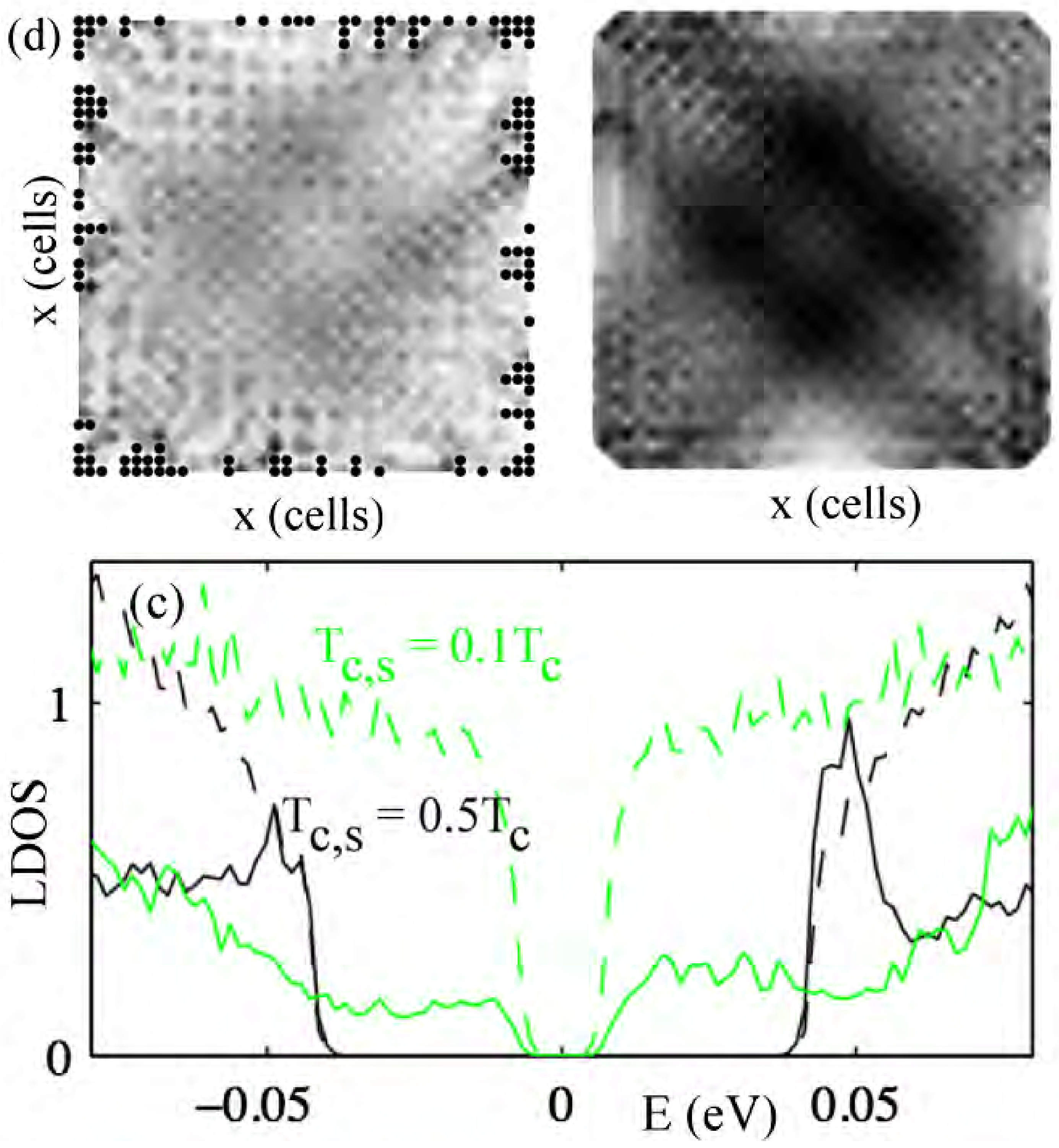

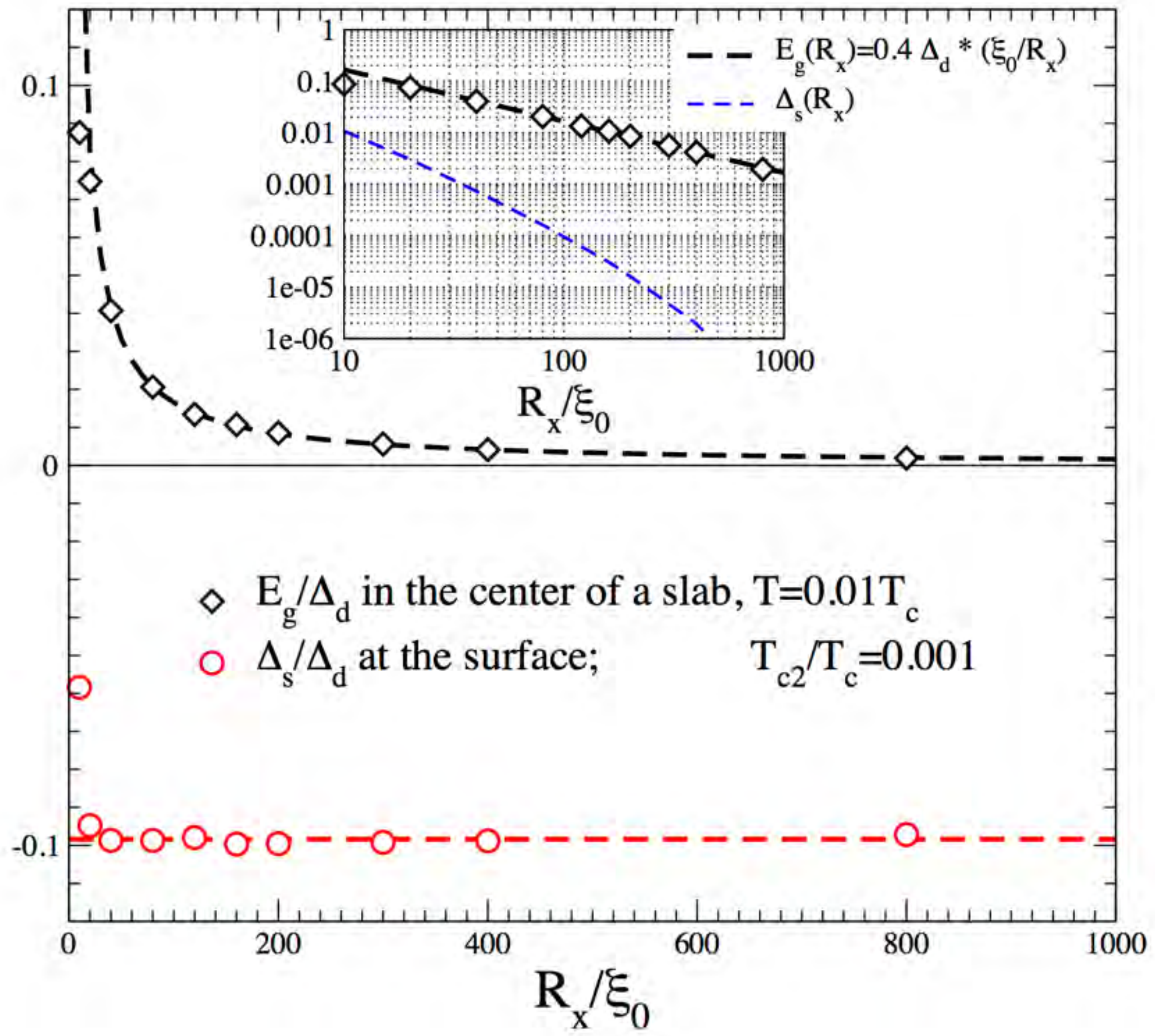

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PRL 110, 197001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Model Evidence of a Superconducting State with a Full Energy Gap in Small Cuprate Islands

Annica M. Black-Schaffer,[1] Dmitri S. Golubev,[2] Thilo Bauch,[3] Floriana Lombardi,[3] and Mikael Fogelström[3]
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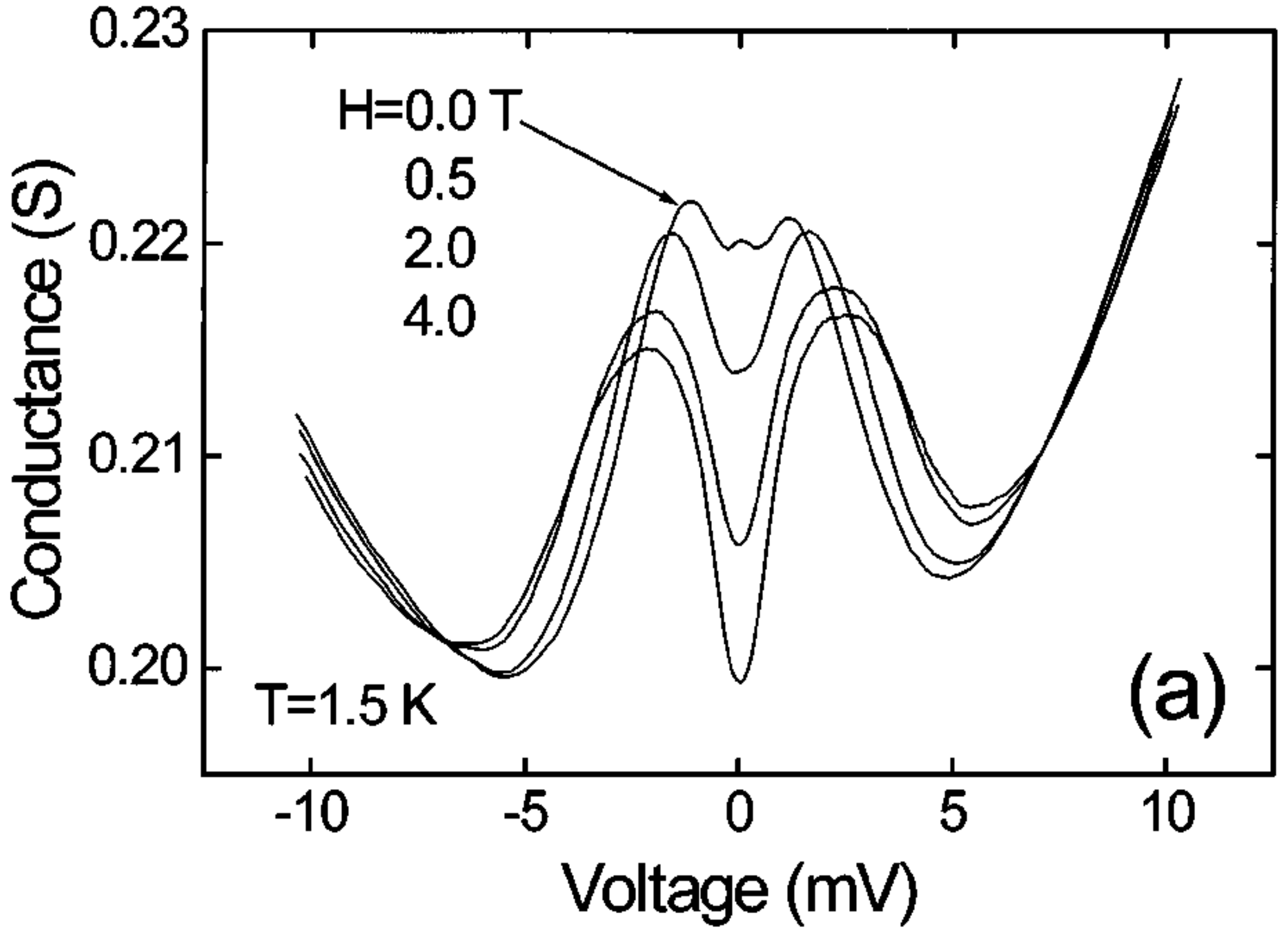
[2]Institute of Nanotechnology, Karlsruhe Institute of Technology (KIT), Herman-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[3]Department of Microtechnology and Nanoscience, Chalmers University of Technology, S-412 96 Göteborg, Sweden
(Received 22 December 2012; published 7 May 2013)

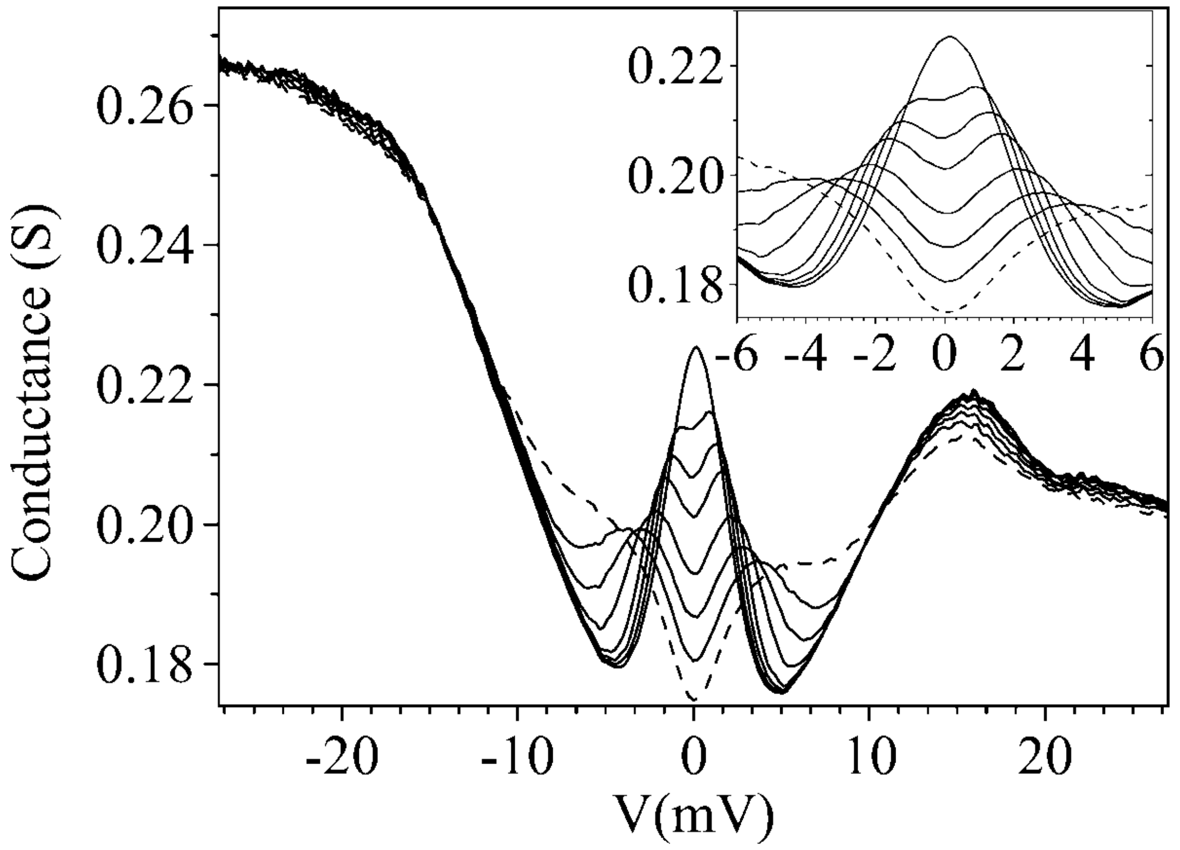
Existing experimental evidence of $\mathcal{T}$-symmetry breaking state

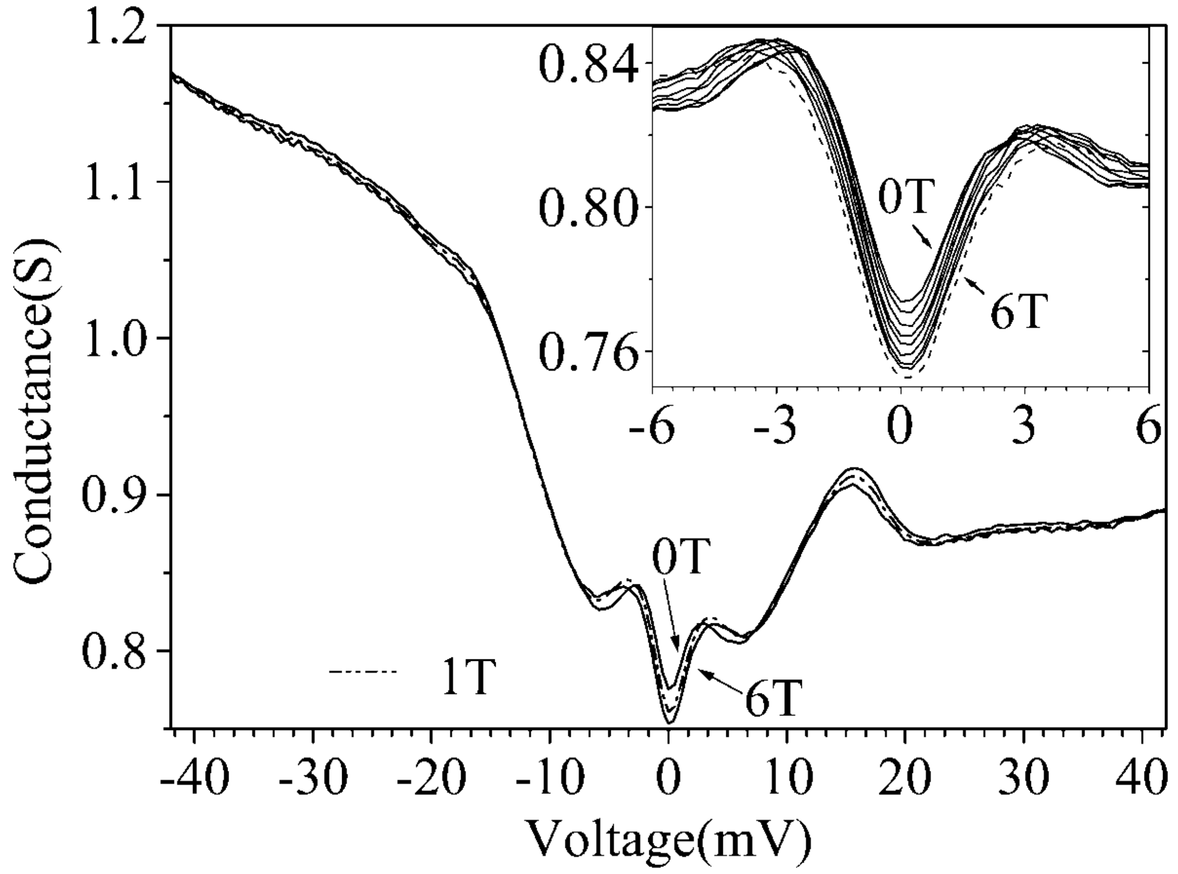


VOLUME 79, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JULY 1997

Observation of Surface-Induced Broken Time-Reversal Symmetry in $YBa_2Cu_3O_7$ Tunnel Junctions

M. Covington,* M. Aprili, E. Paraoanu, and L. H. Greene
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
F. Xu, J. Zhu, and C. A. Mirkin
Department of Chemistry, Northwestern University, Evanston, Illinois 60208
(Received 6 March 1997)

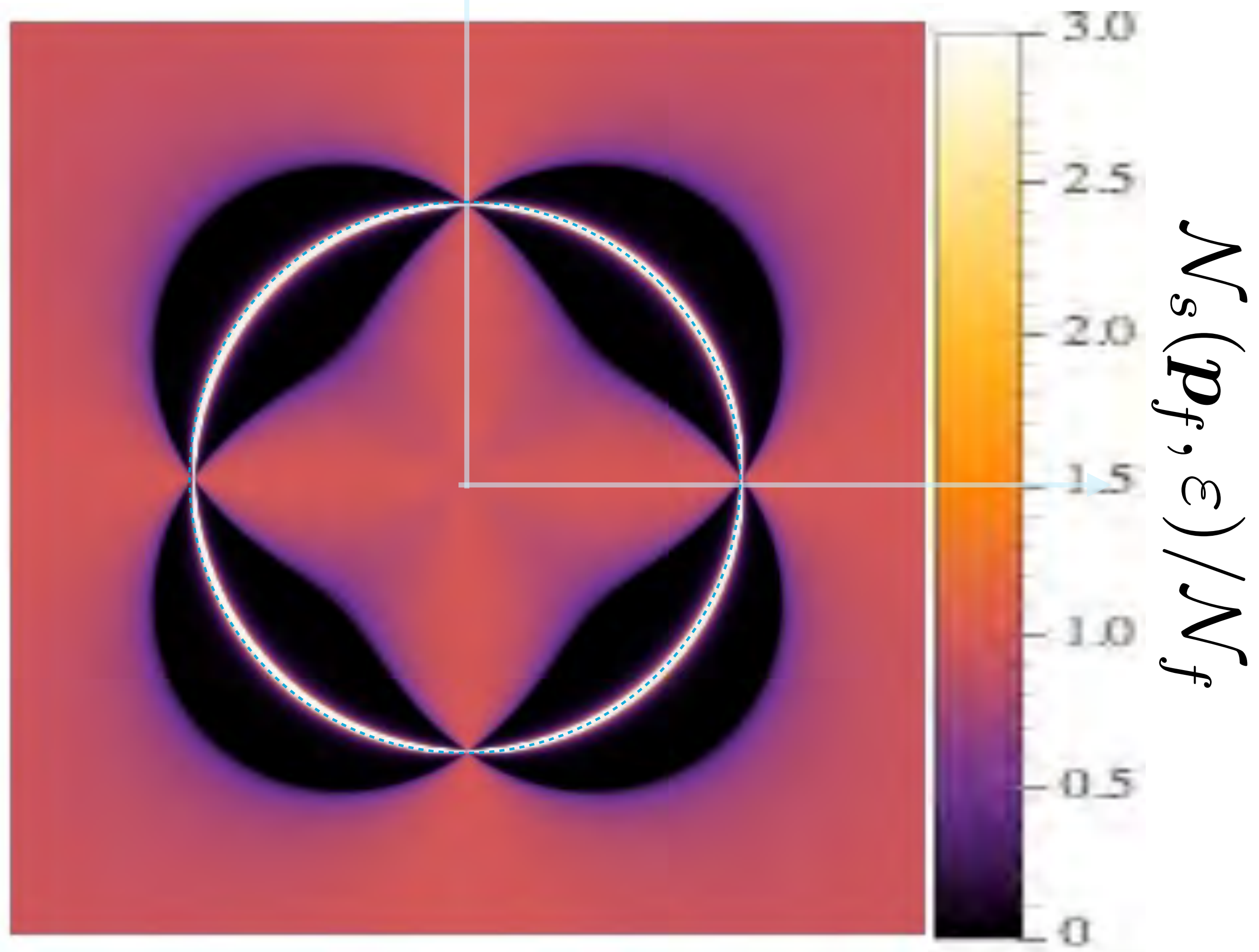




VOLUME 87, NUMBER 17 PHYSICAL REVIEW LETTERS 22 OCTOBER 2001

Doping and Magnetic Field Dependence of In-Plane Tunneling into $YBa_2Cu_3O_{7-x}$: Possible Evidence for the Existence of a Quantum Critical Point

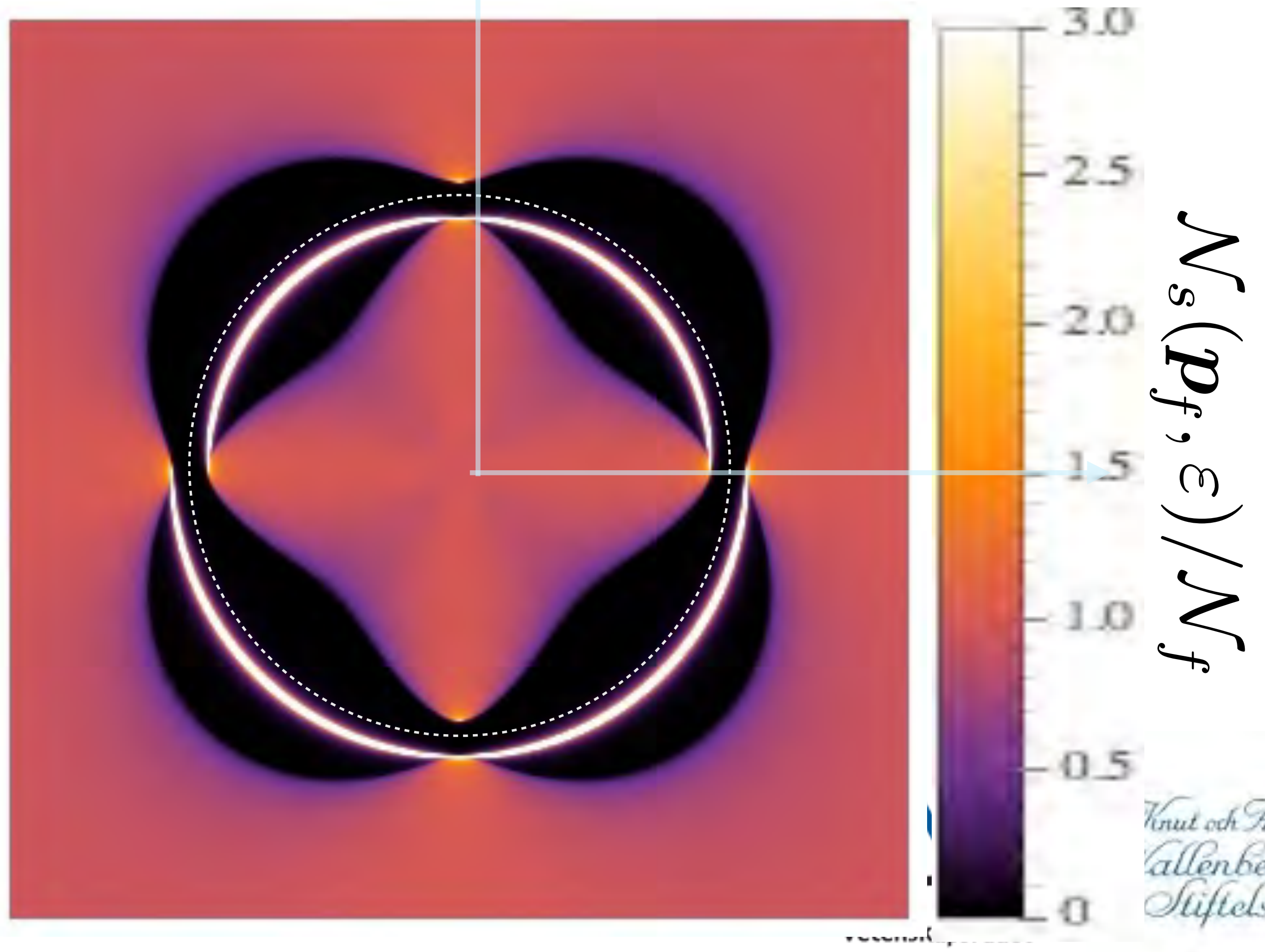
Y. Dagan and G. Deutscher
School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, 69978 Tel Aviv, Israel
(Received 2 August 2000; published 8 October 2001)



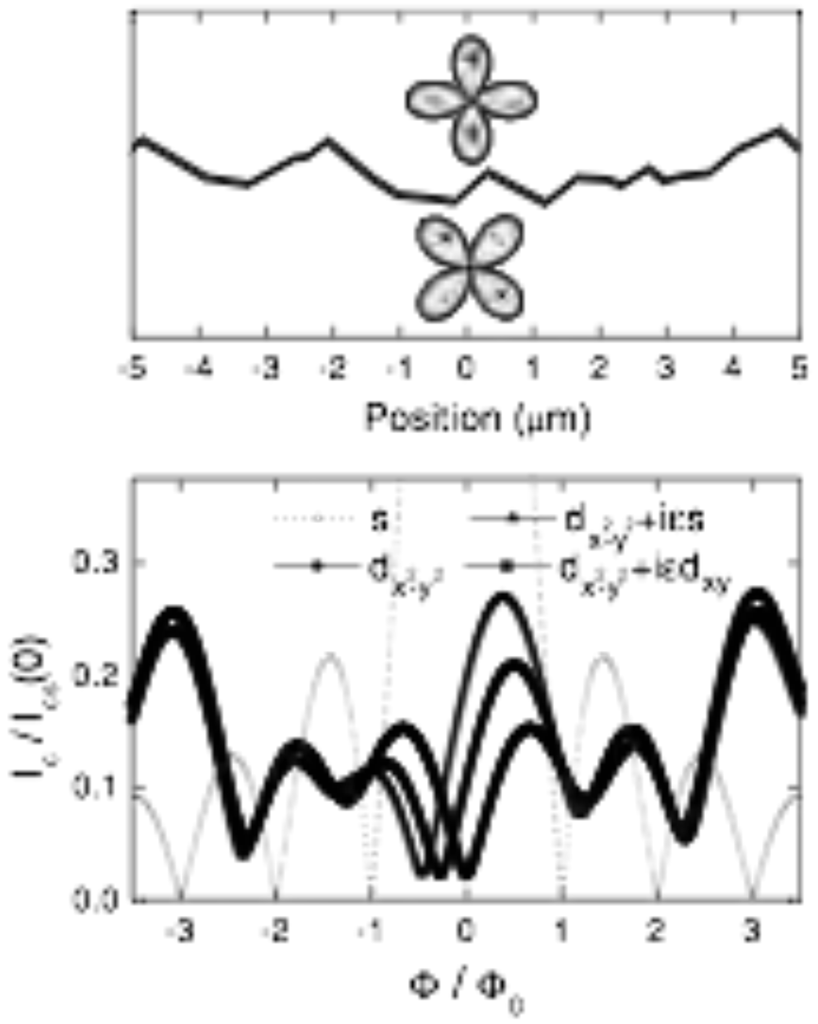
T>T$_S$ T< T$_S$

↔

$d_{x^2-y^2}+i\,s$



severe restrictions on a $\mathcal{T}$-symmetry breaking state

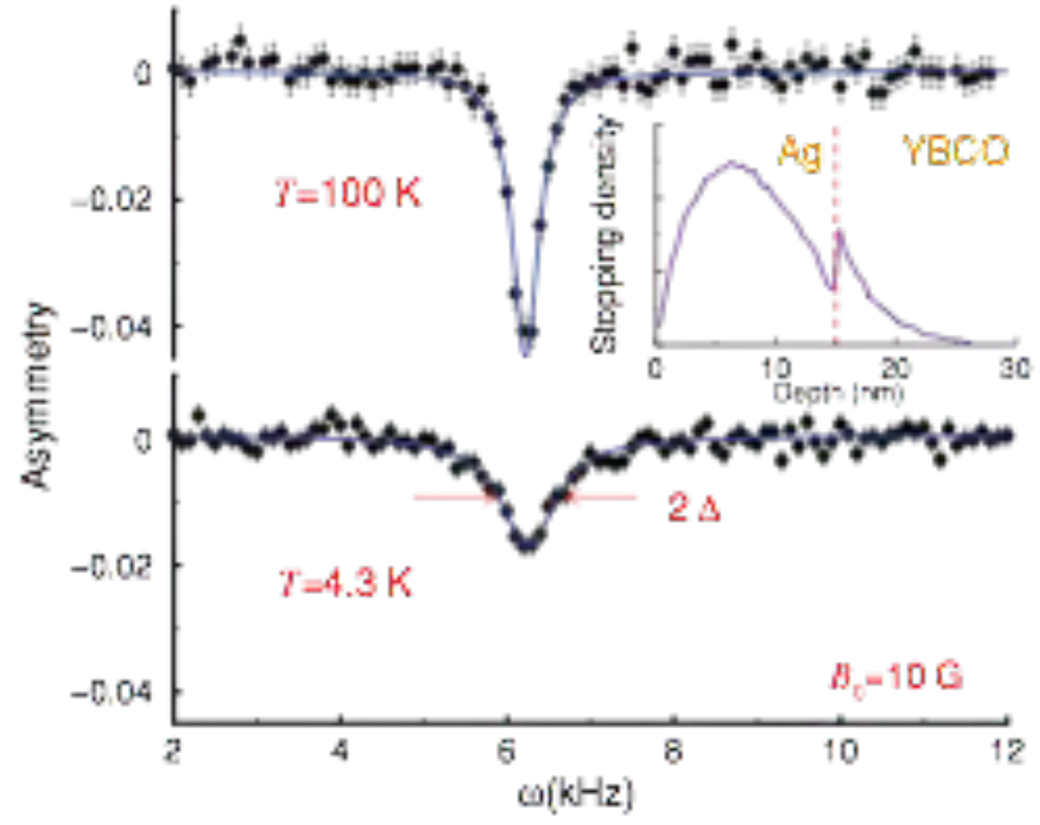


subdominant Δ
less than 1% of
dominant one

VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

Experimental Test for Subdominant Superconducting Phases with Complex Order Parameters in Cuprate Grain Boundary Junctions

W. K. Neils and D. J. Van Harlingen
Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801
(Received 20 May 2001; published 9 January 2002)



spontaneous field due to a $Δ_{sub}$
less than 0.2G

PHYSICAL REVIEW B 83, 054504 (2011)

Search for broken time-reversal symmetry near the surface of superconducting $YBa_2Cu_3O_{7-\delta}$ films using β-detected nuclear magnetic resonance

H. Saadaoui,[1,*] G. D. Morris,[2] Z. Salman,[3,*] Q. Song,[1] K. H. Chow,[4] M. D. Hossain,[1] C. D. P. Levy,[2] T. J. Parolin,[5] M. R. Pearson,[2] M. Smadella,[1] D. Wang,[1] L. H. Greene,[6] P. J. Hentges,[6] R. F. Kiefl,[1,2,7] and W. A. MacFarlane[5]
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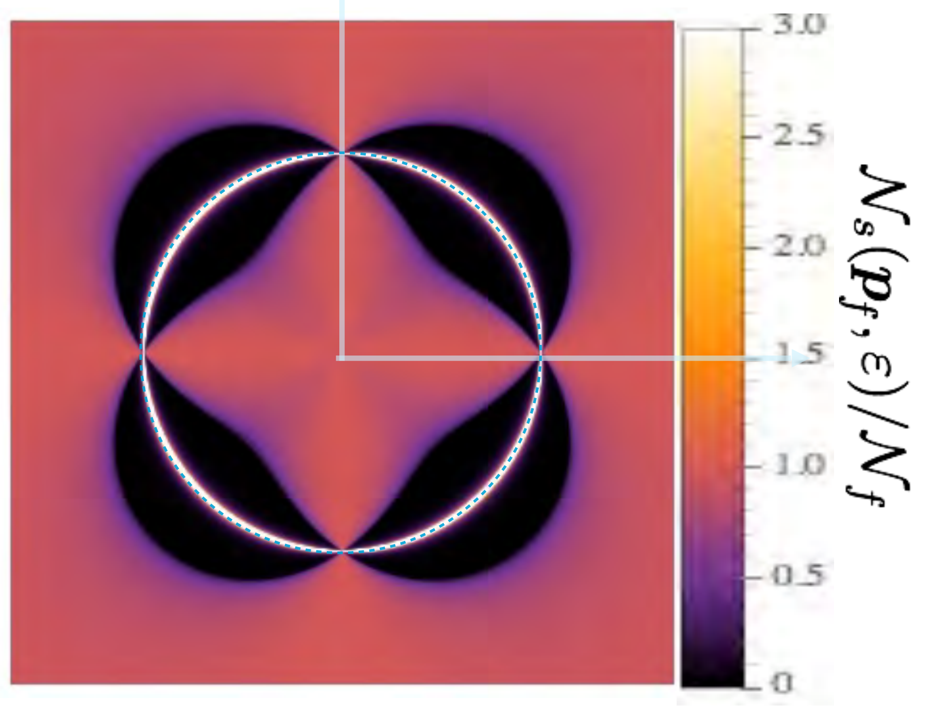
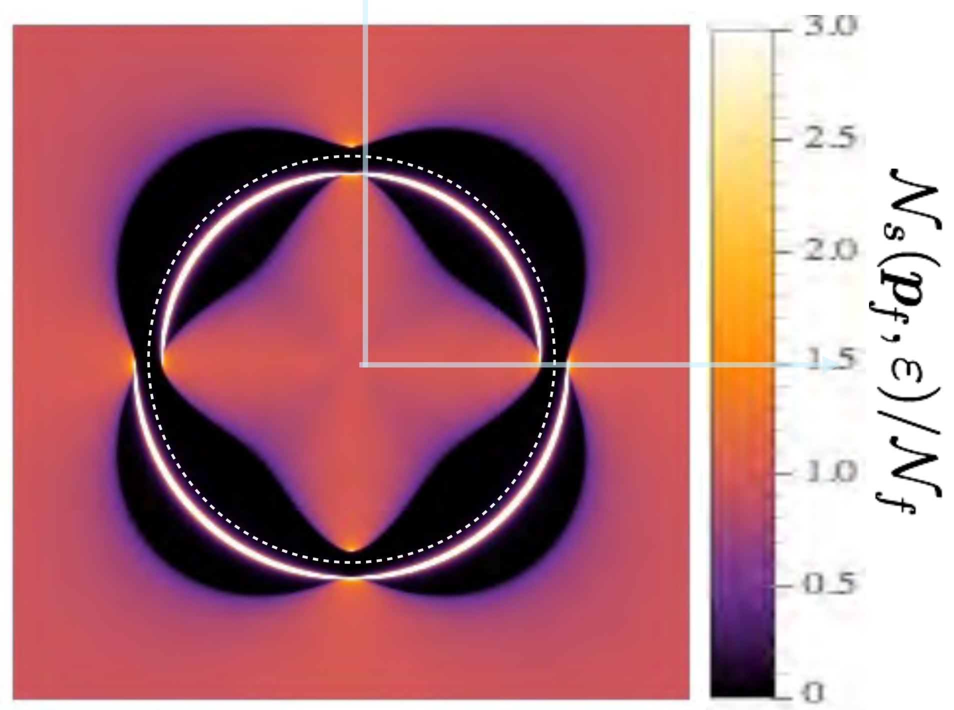
[2]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[3]*Clarendon Laboratory, Department of Physics, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom*
[4]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2G7*
[5]*Chemistry Department, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[6]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[7]*Canadian Institute for Advanced Research, Toronto, Ontario, Canada M5G 1Z8*
(Received 23 December 2010; published 9 February 2011)



T>T_S ⟷ T< T_S

$d_{x^2-y^2}$+i s



CHALMERS

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Chalmers University of Technology, Göteborg, Sweden


A theoretical excursion……

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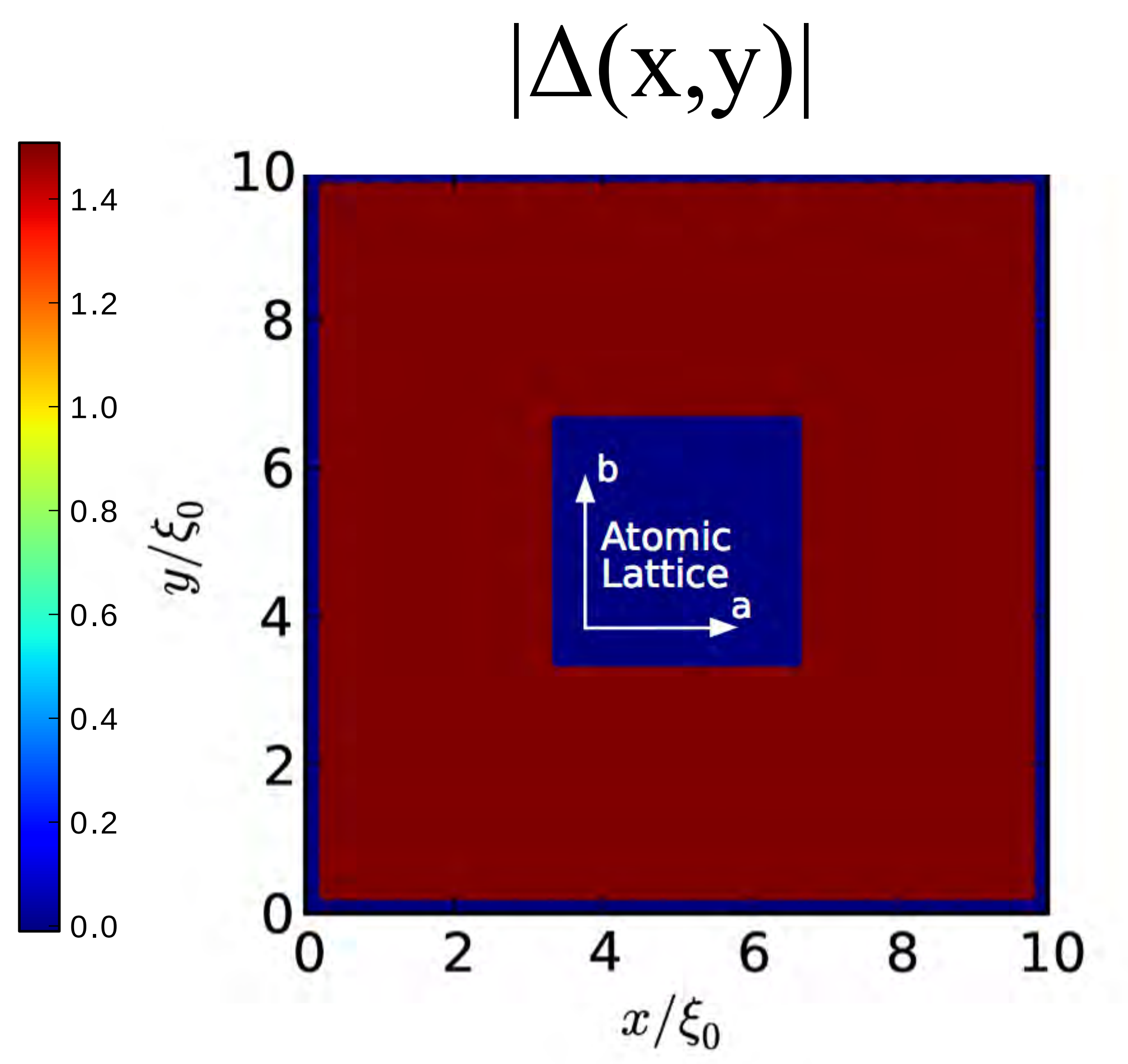
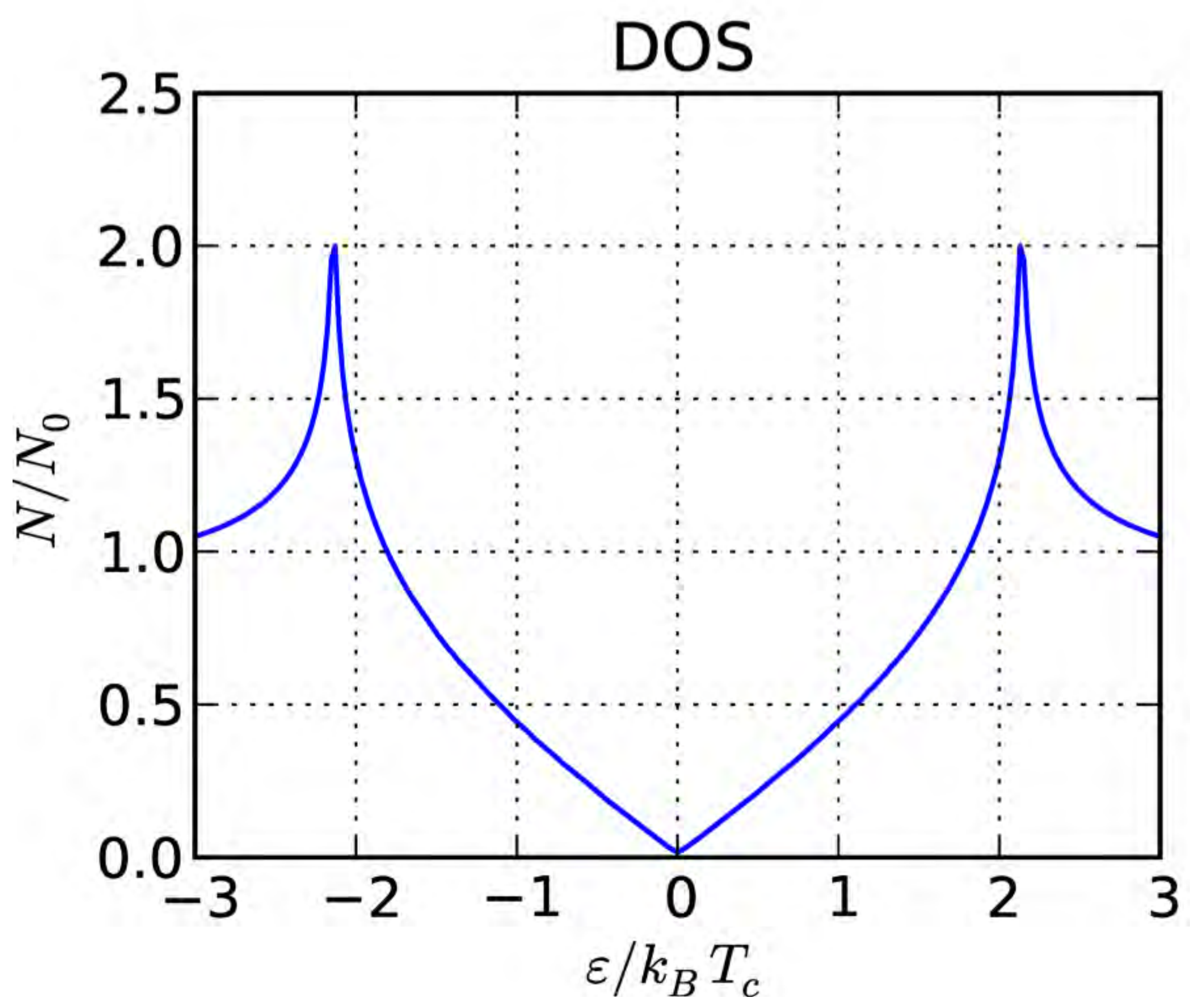
Theoretical study of a d-wave SC mesoscopic grain





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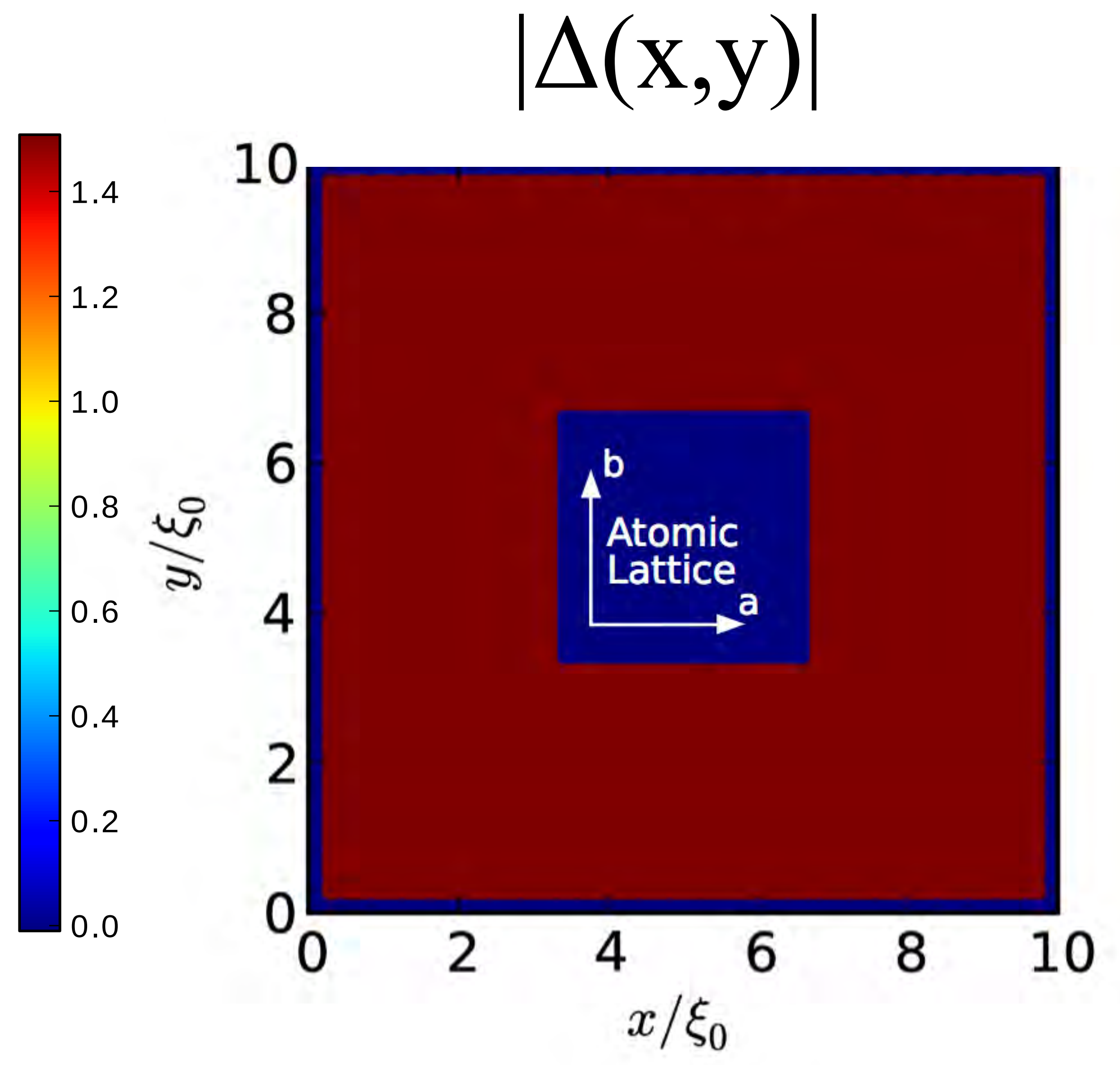
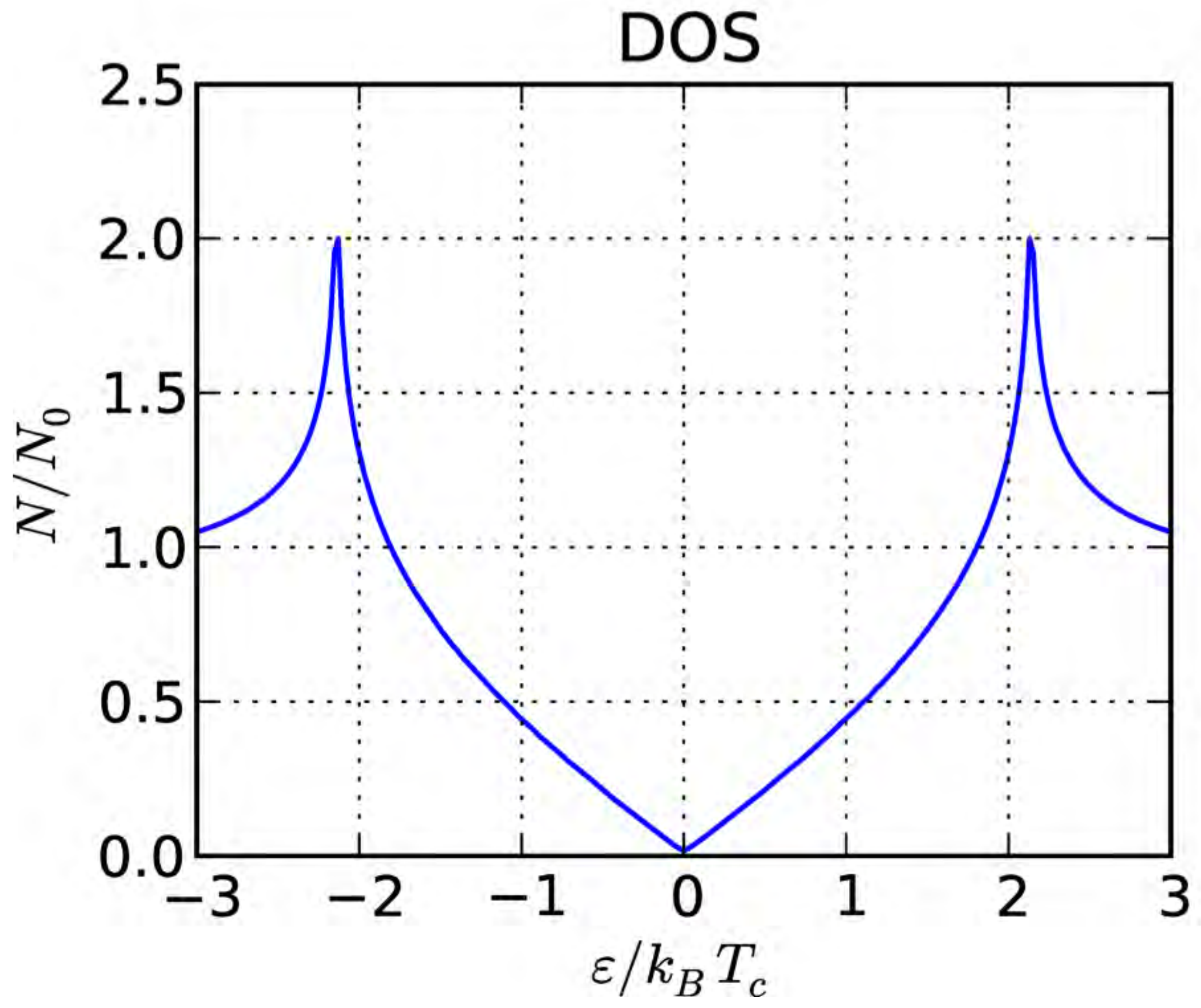




Quasiclassical study

Order parameter field Δ(x,y)
-pure d-wave SC ~ Δ cos(2ϕ)

Total density of states:

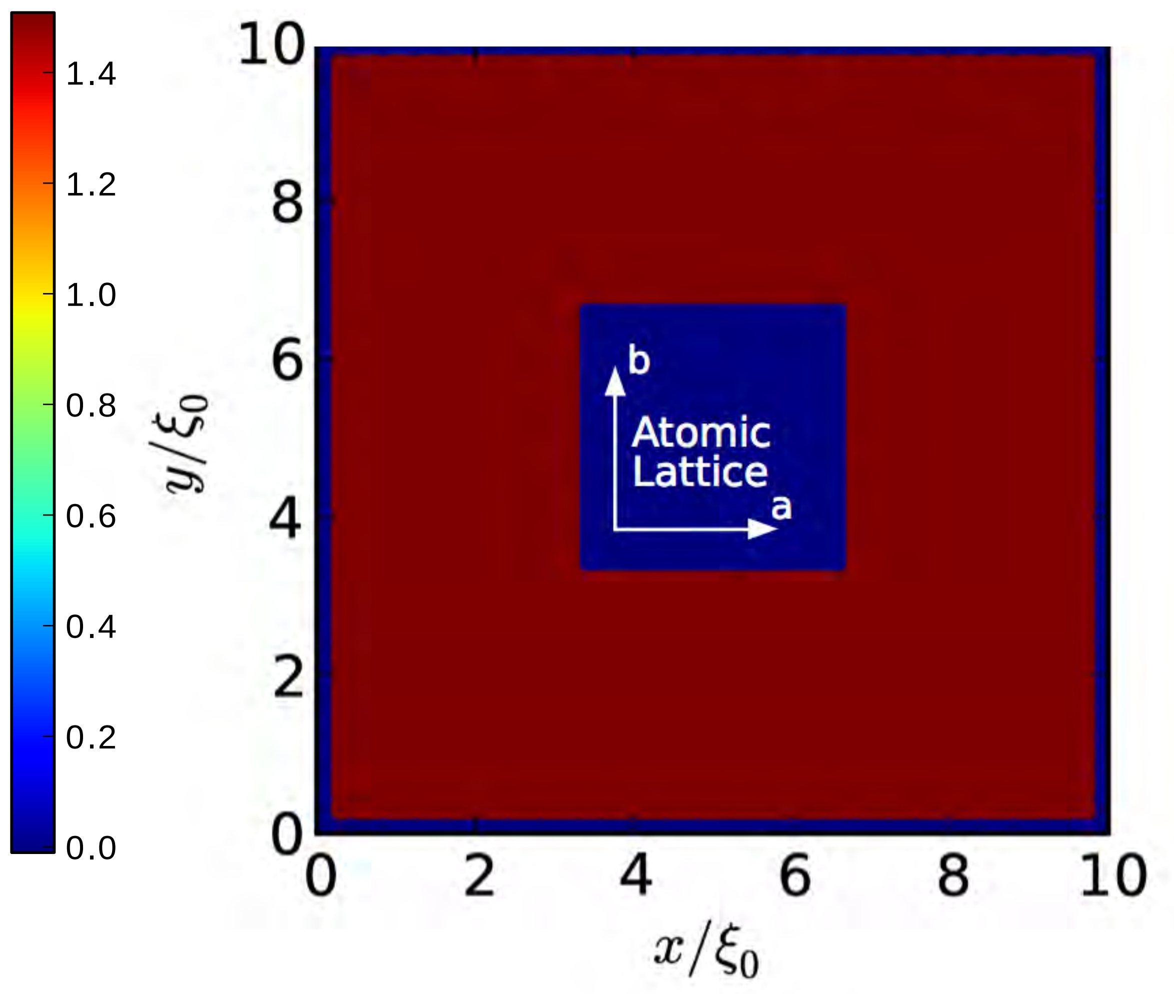
$$N(\varepsilon)=\int dR \ \langle N(R,p;\varepsilon)\rangle$$

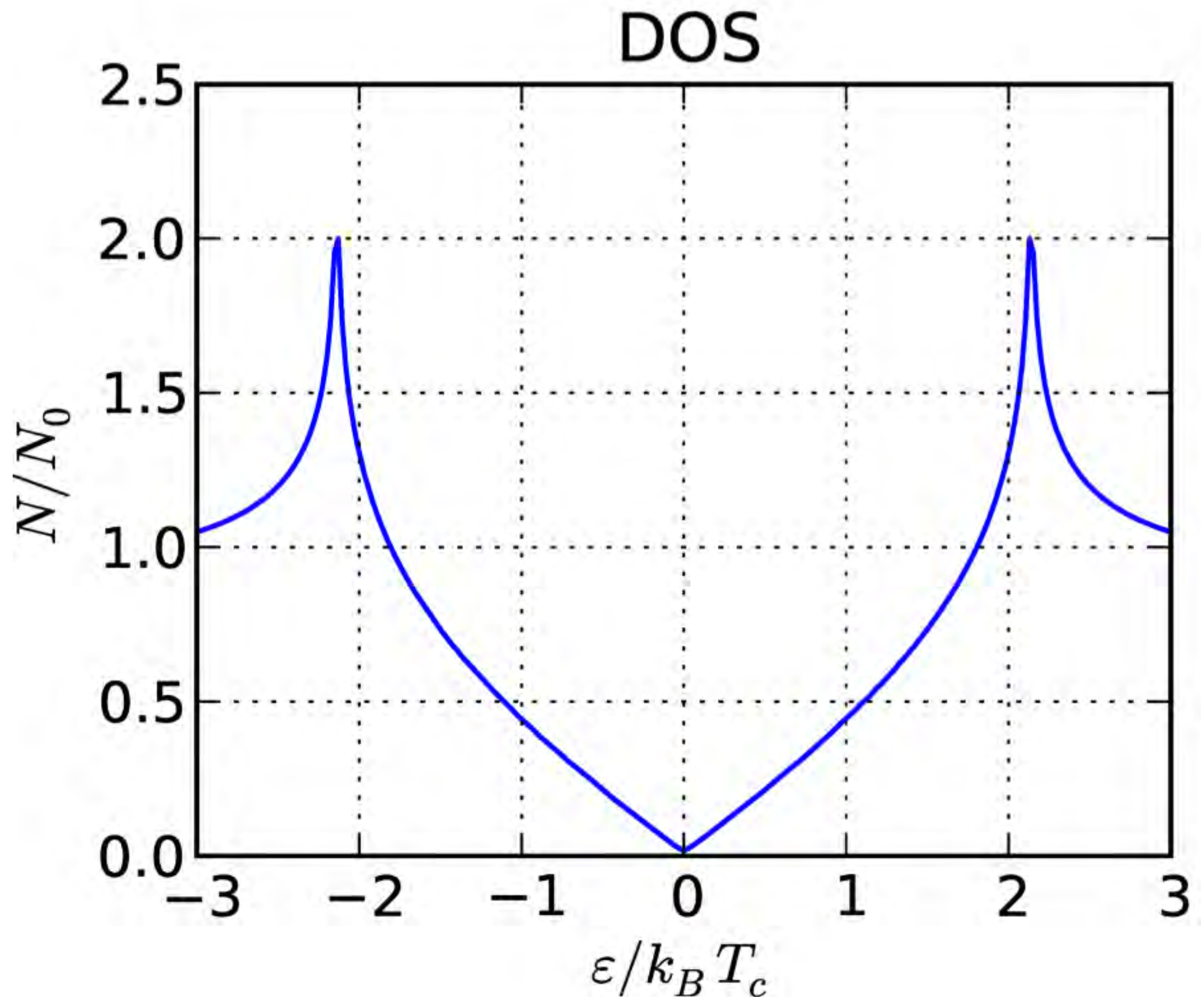
with

$$N(R,p;\varepsilon)=-\mathrm{Im}[g^R(R,p;\varepsilon)]$$

Theoretical study of a d-wave SC mesoscopic grain

$|\Delta(x,y)|$





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Total density of states:

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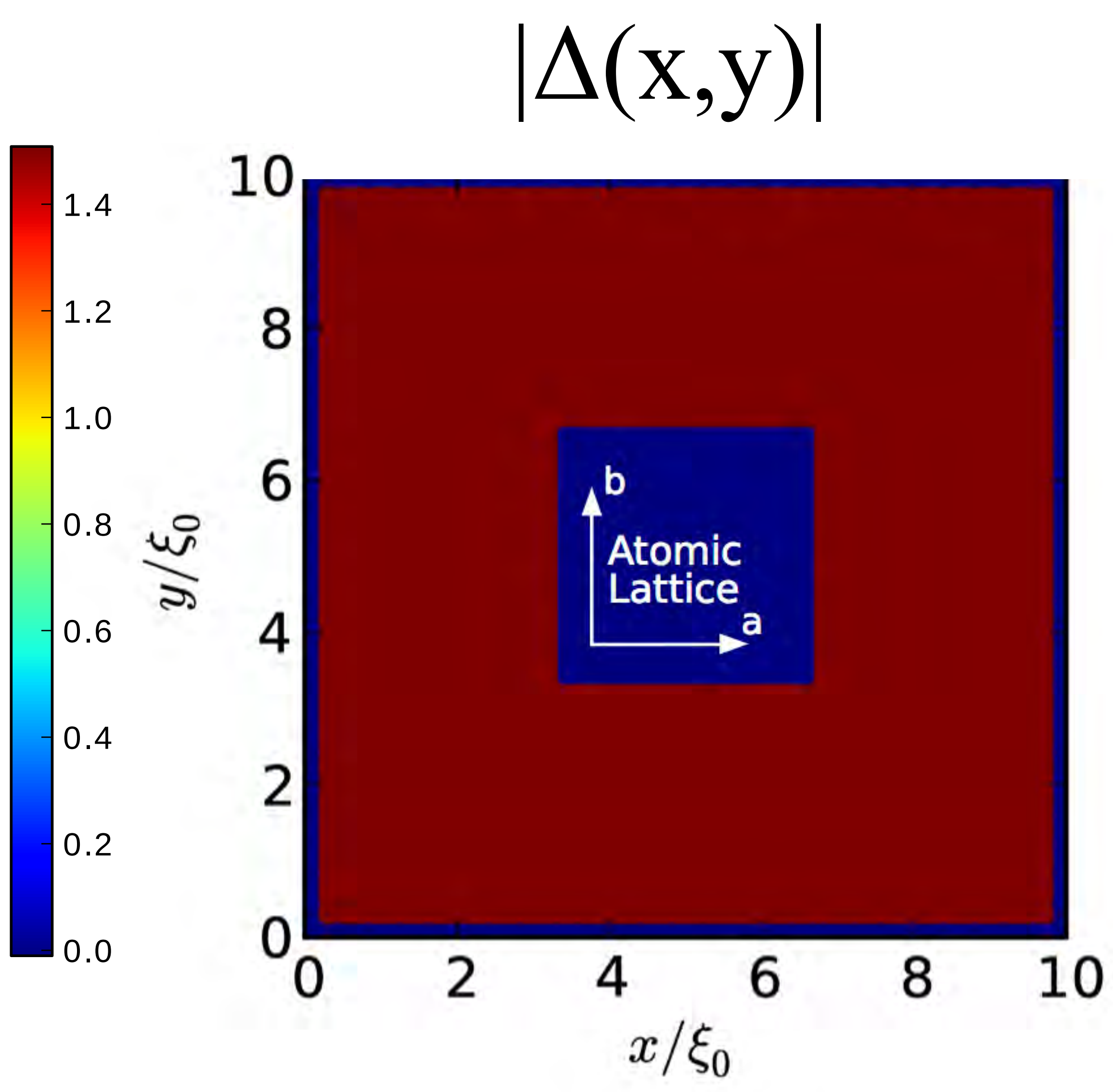
with
$N(R,p;\varepsilon)=-\mathrm{Im}[g^R(R,p;\varepsilon)]$

Introduce pair-breaking surfaces

Theoretical study of a d-wave SC mesoscopic grain



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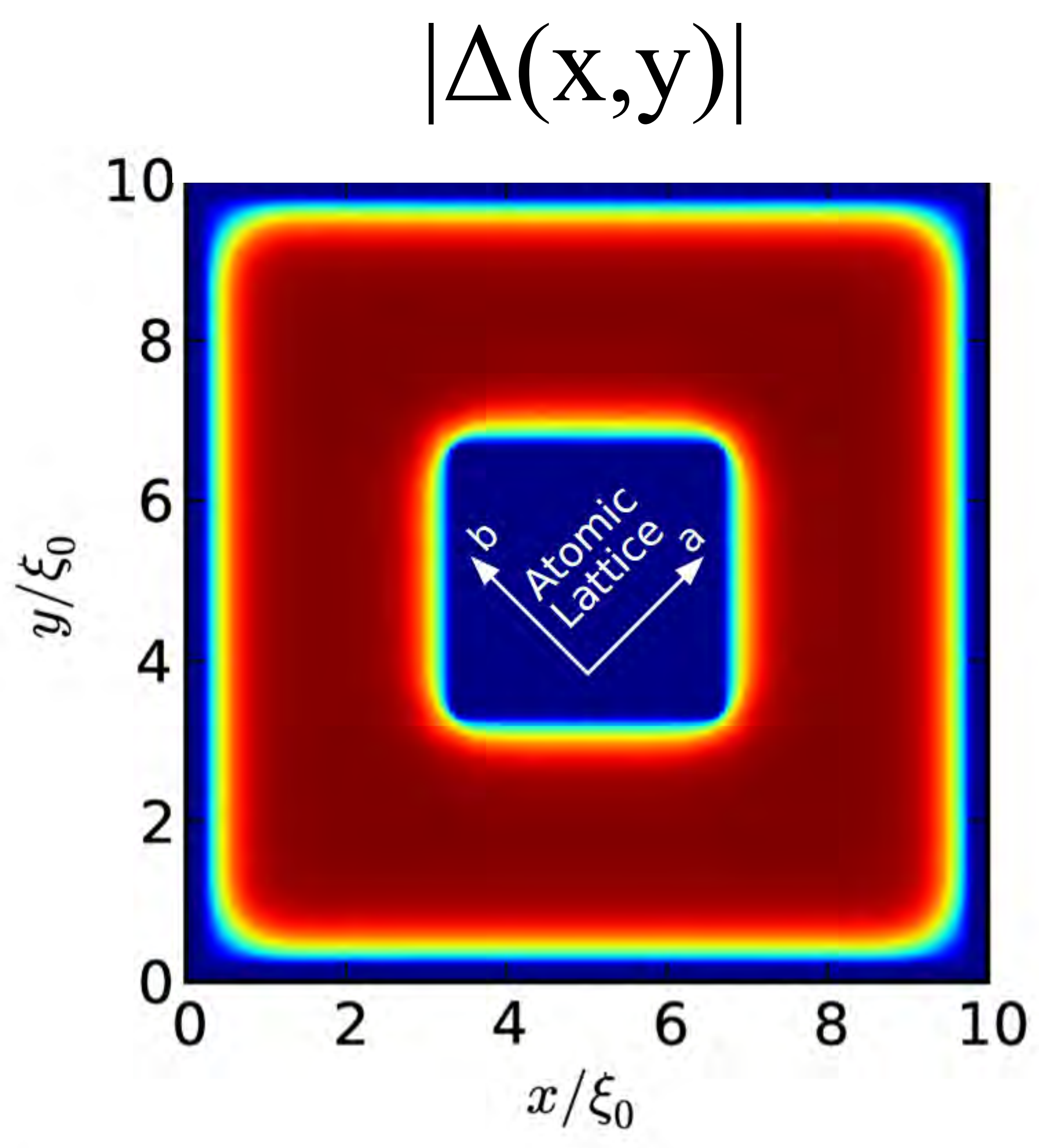
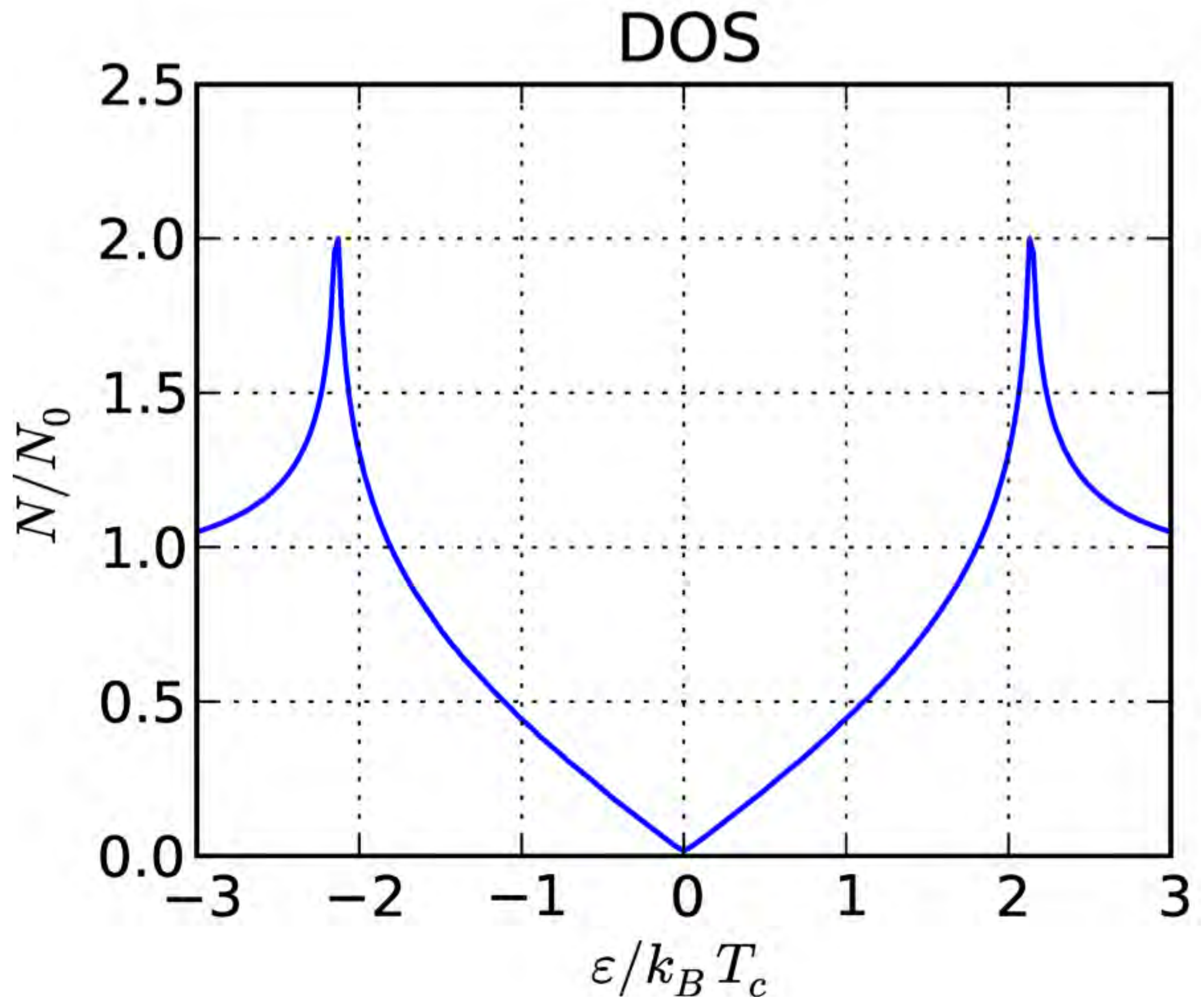
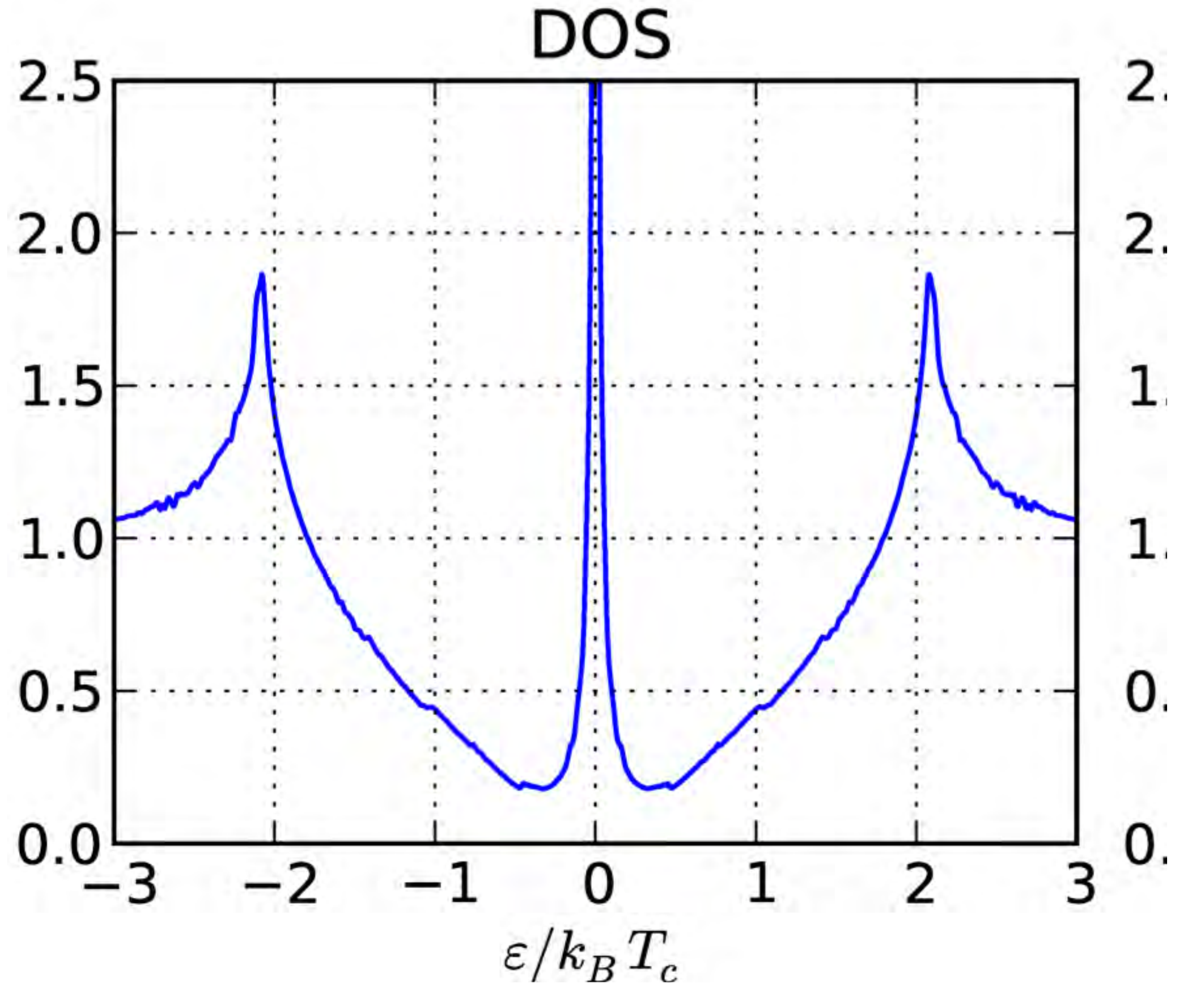




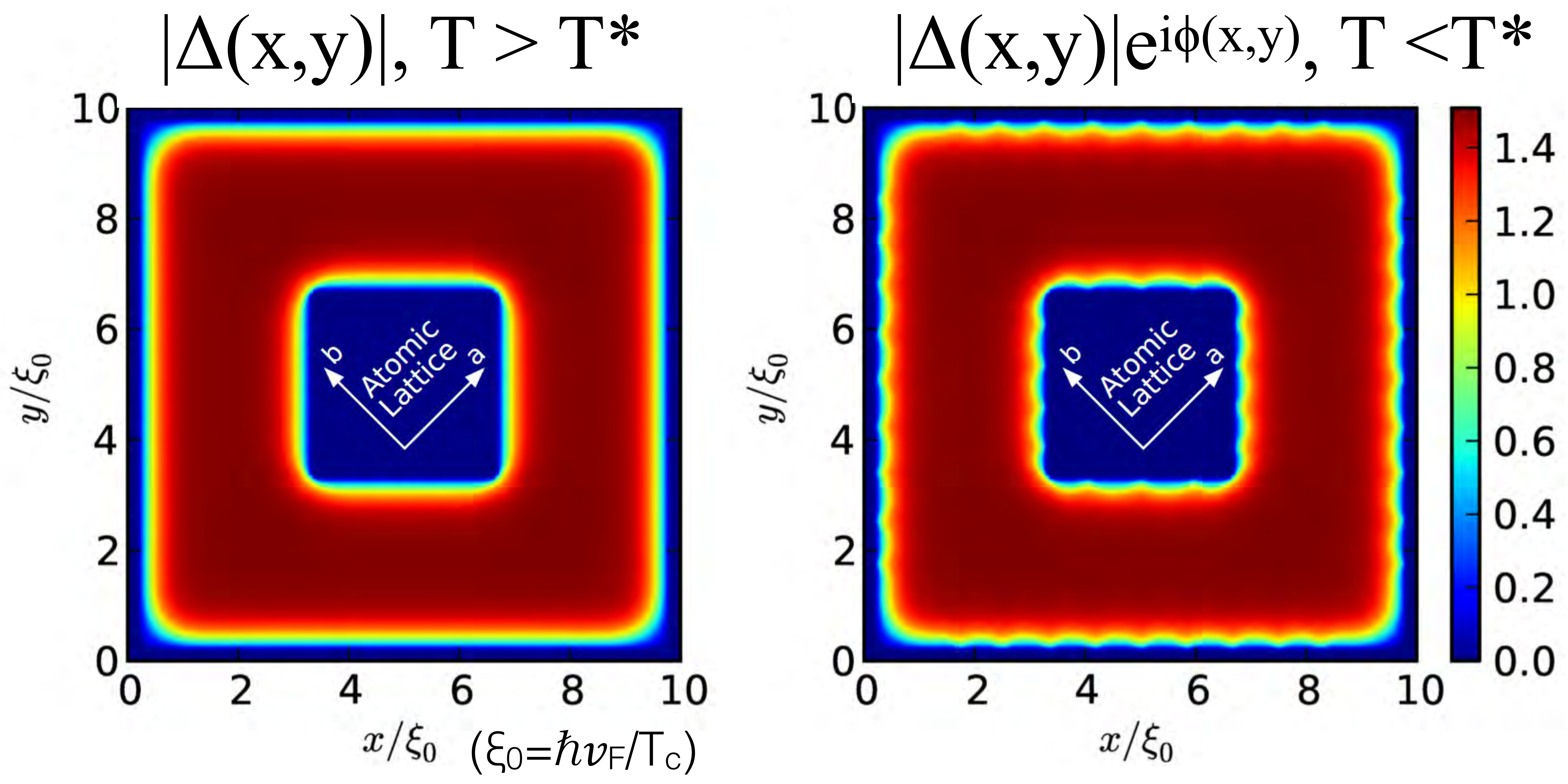
Total density of states:

N(ε)=∫dR ⟨N(R,p;ε)⟩
with
N(R,p;ε)=-Im[g^R(R,p;ε)]



Introduce pair-breaking surfaces

The d-wave SC grain undergoes a change of state at T=T*



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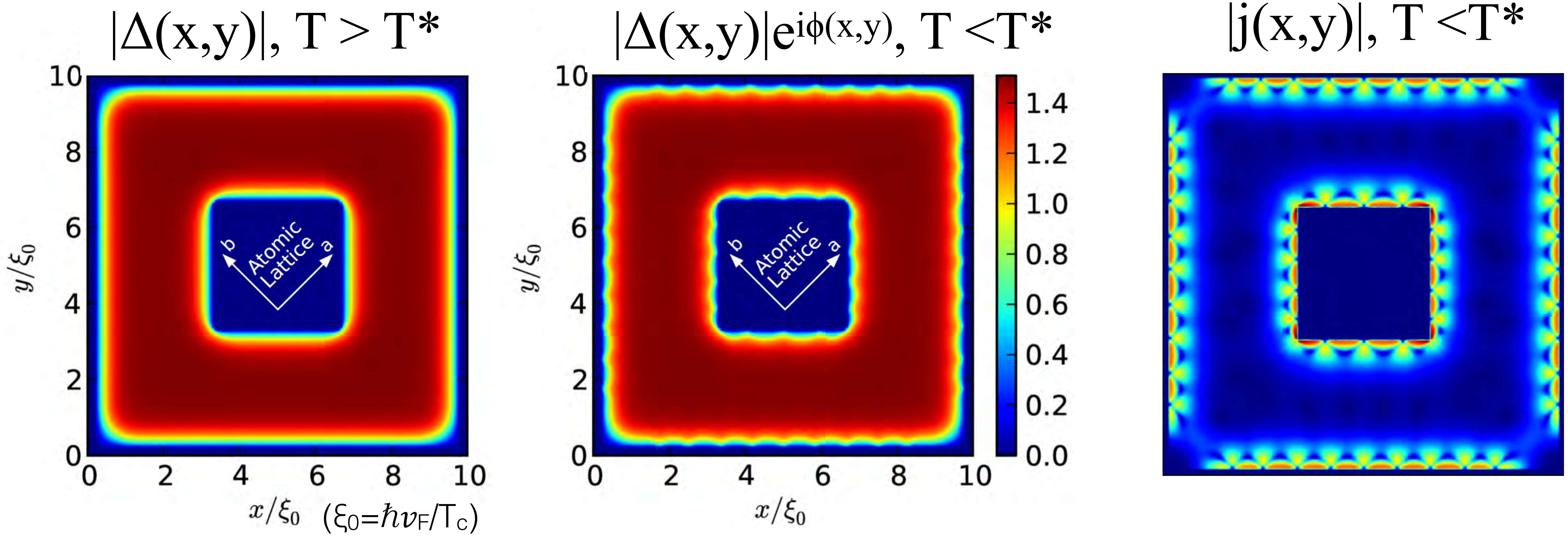
MC2 Microtechnology and Nanoscience

The d-wave SC grain undergoes a change of state at T=T*



local phase gradients in the OP gives a finite superfluid momentum

$$\mathbf{p}_s(\mathbf{R}) = \frac{\hbar}{2}\nabla\phi(\mathbf{R})$$

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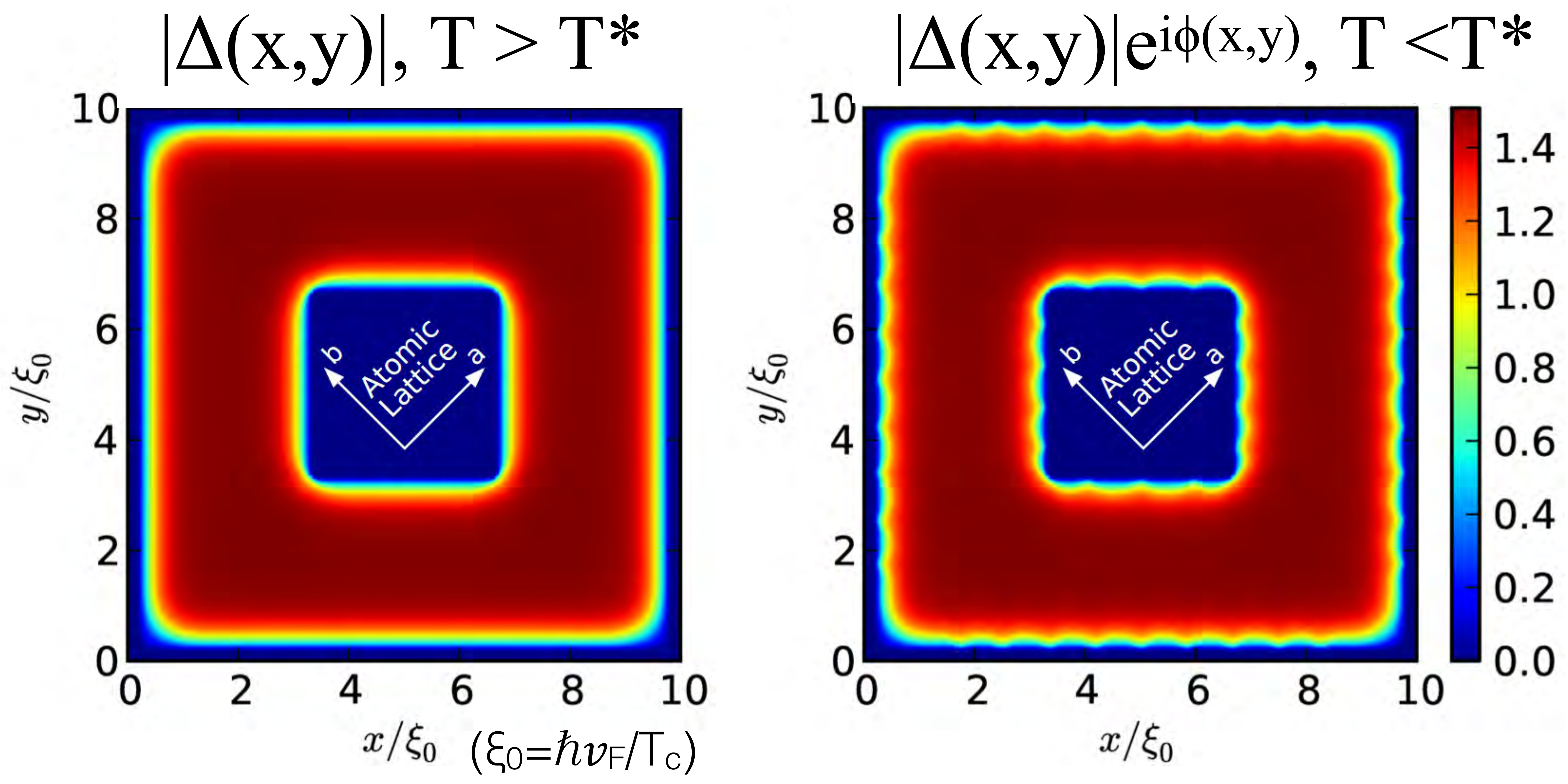

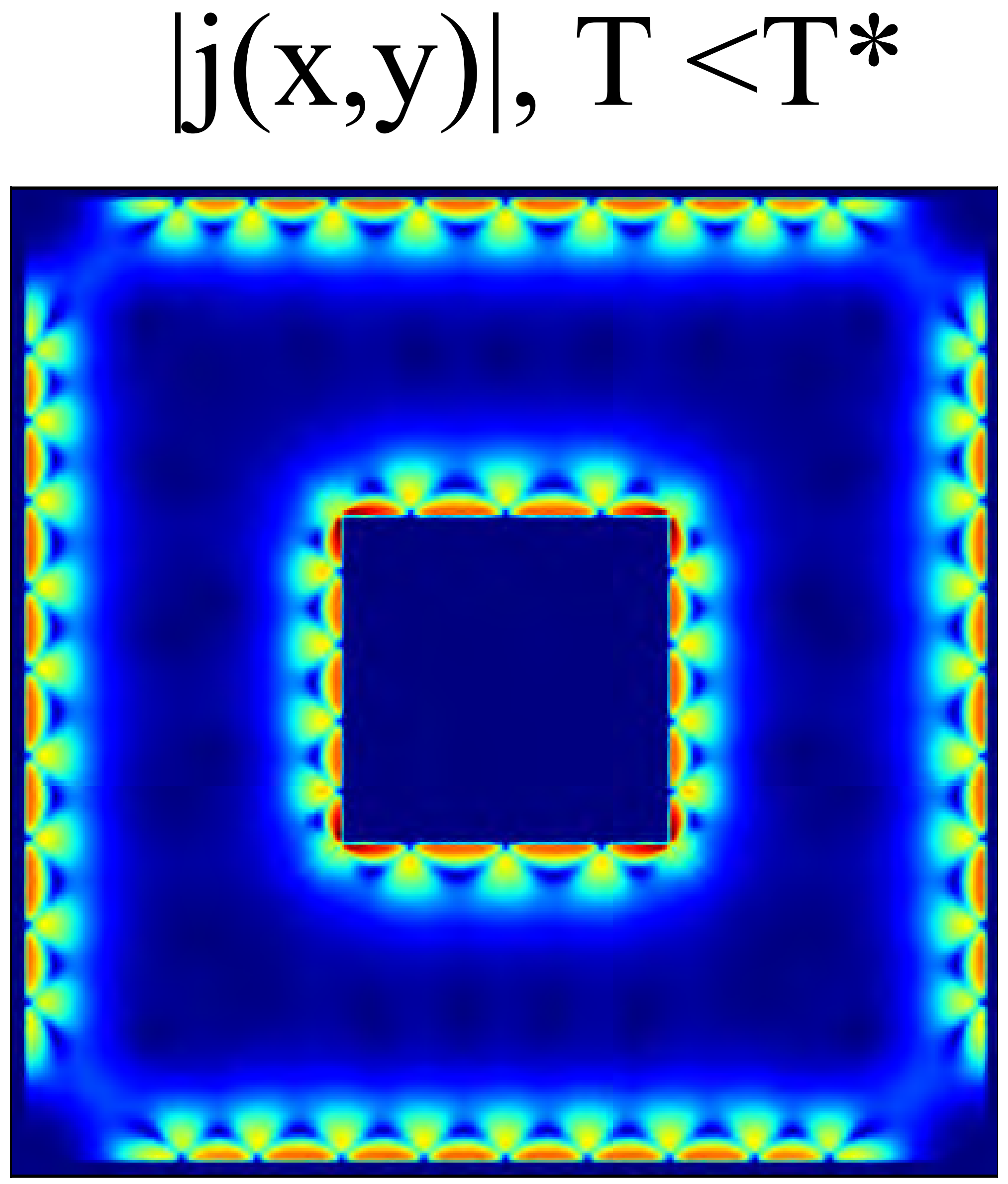

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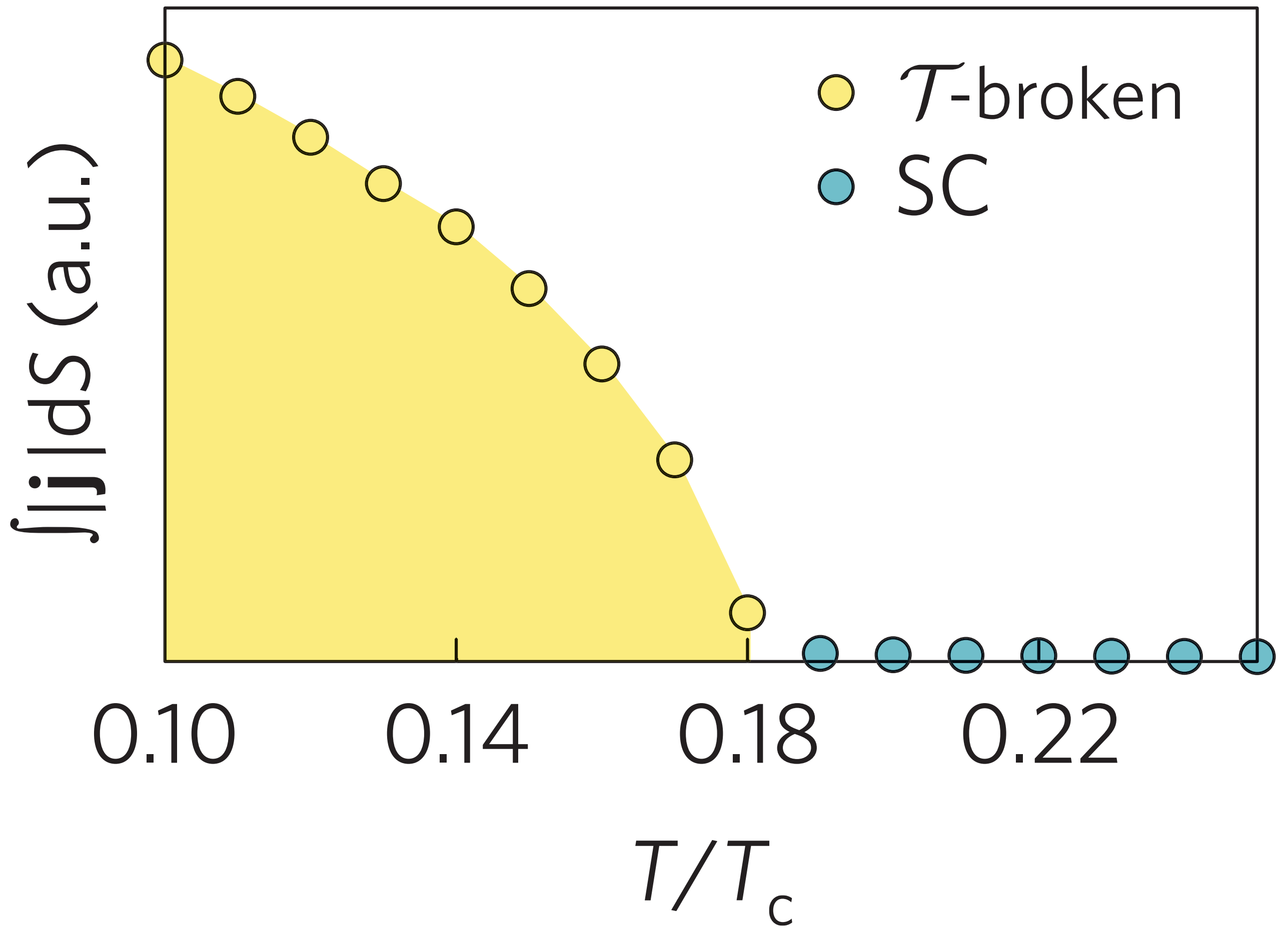

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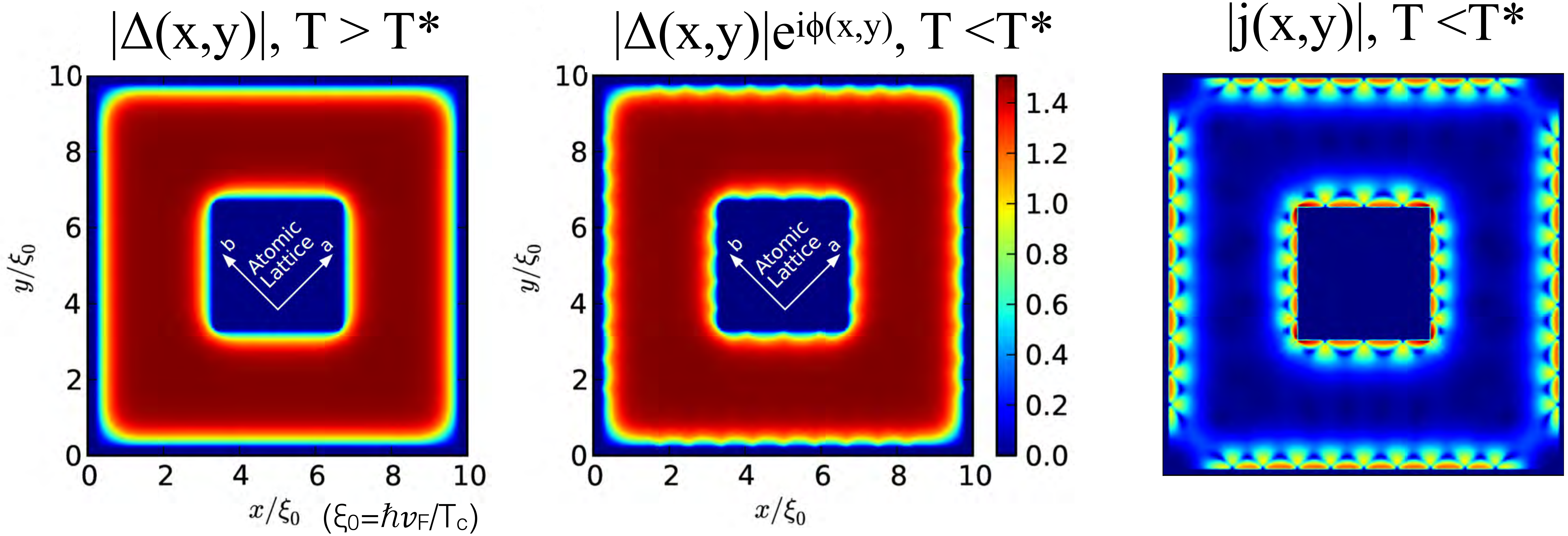

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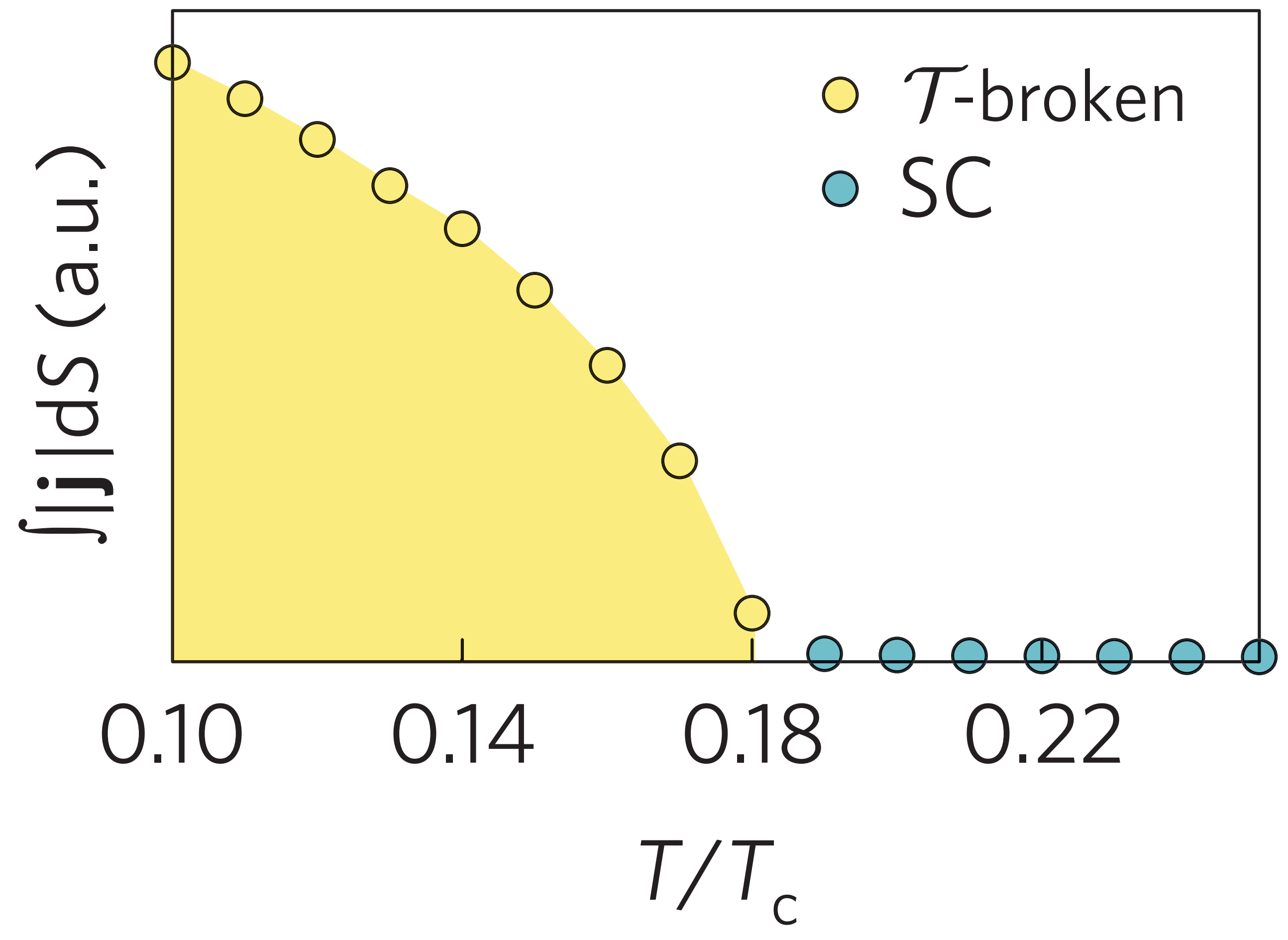

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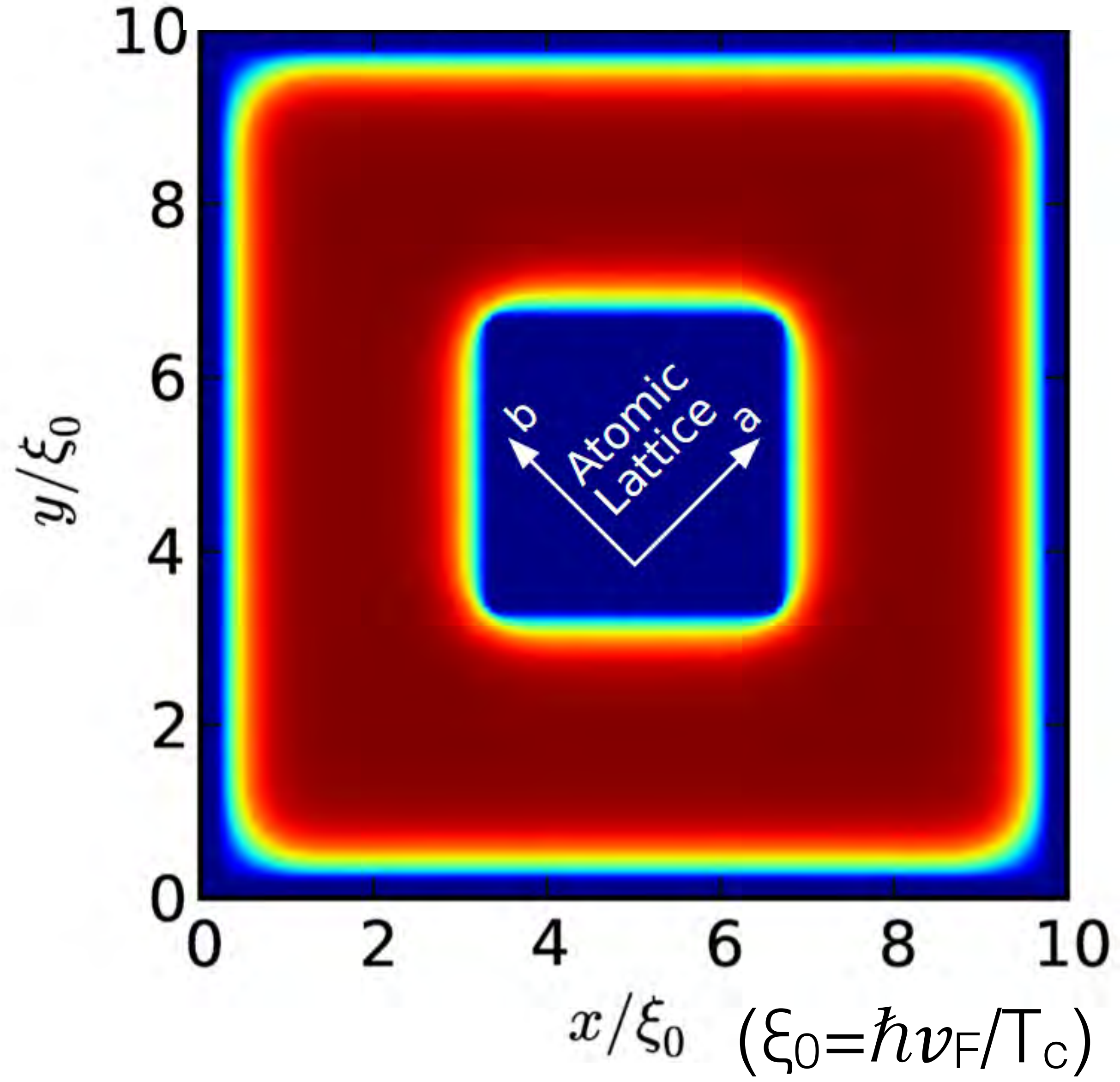
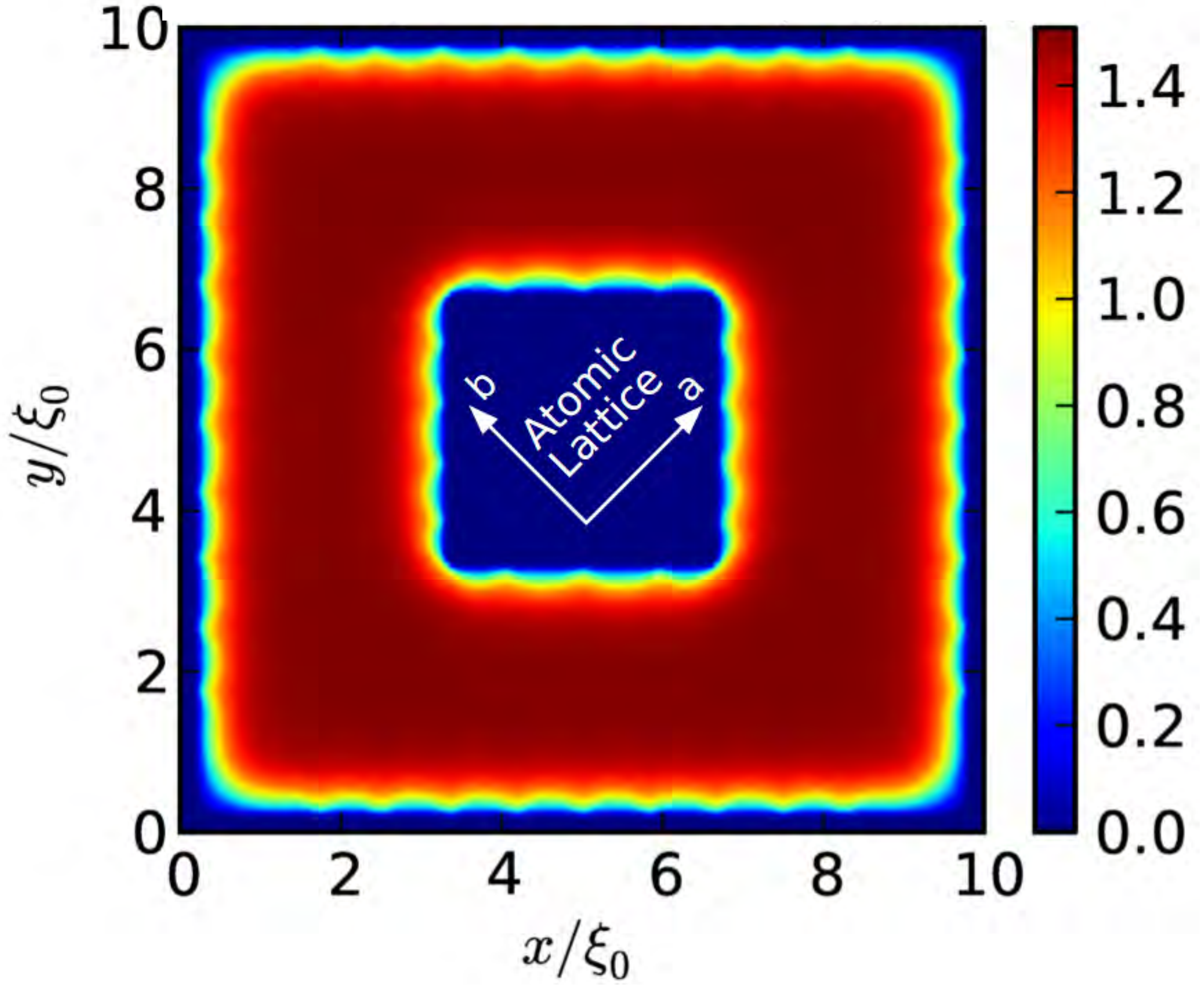


$|\Delta(x,y)|e^{i\phi(x,y)}$, T <T*



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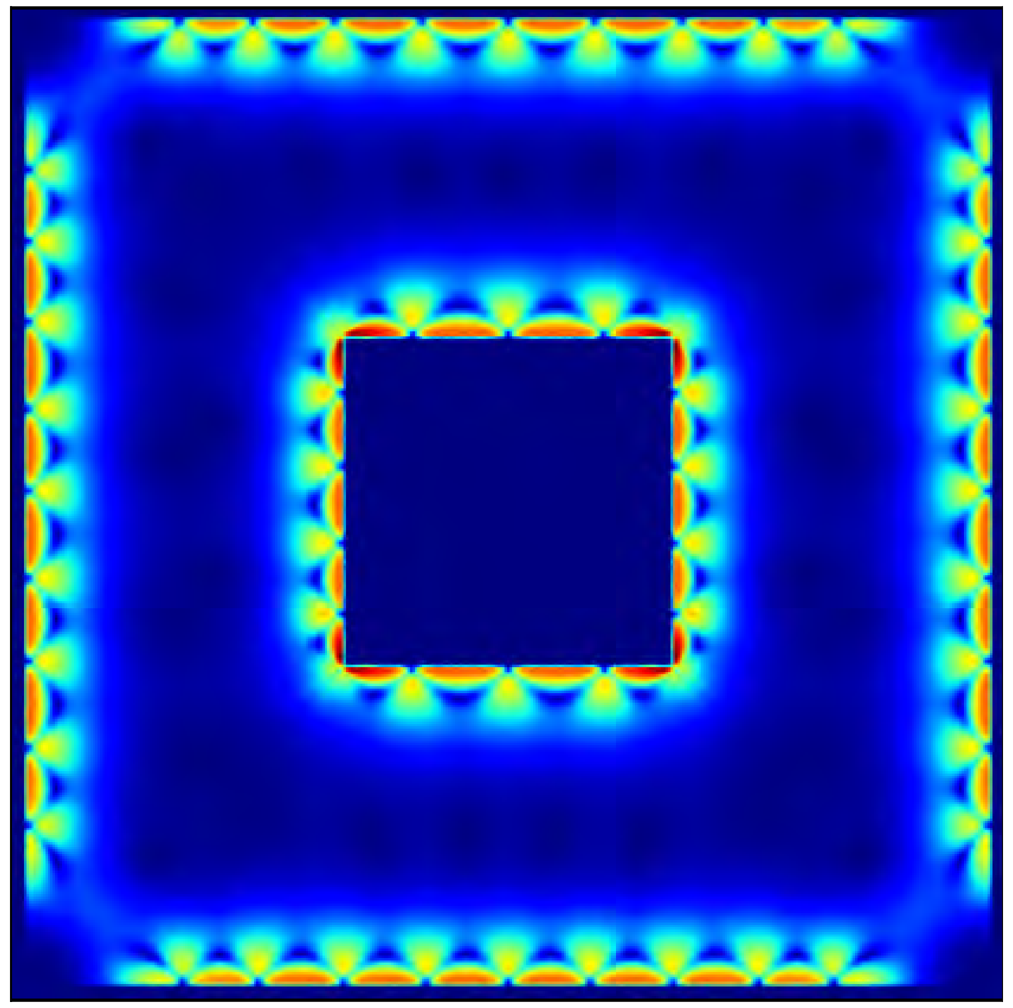

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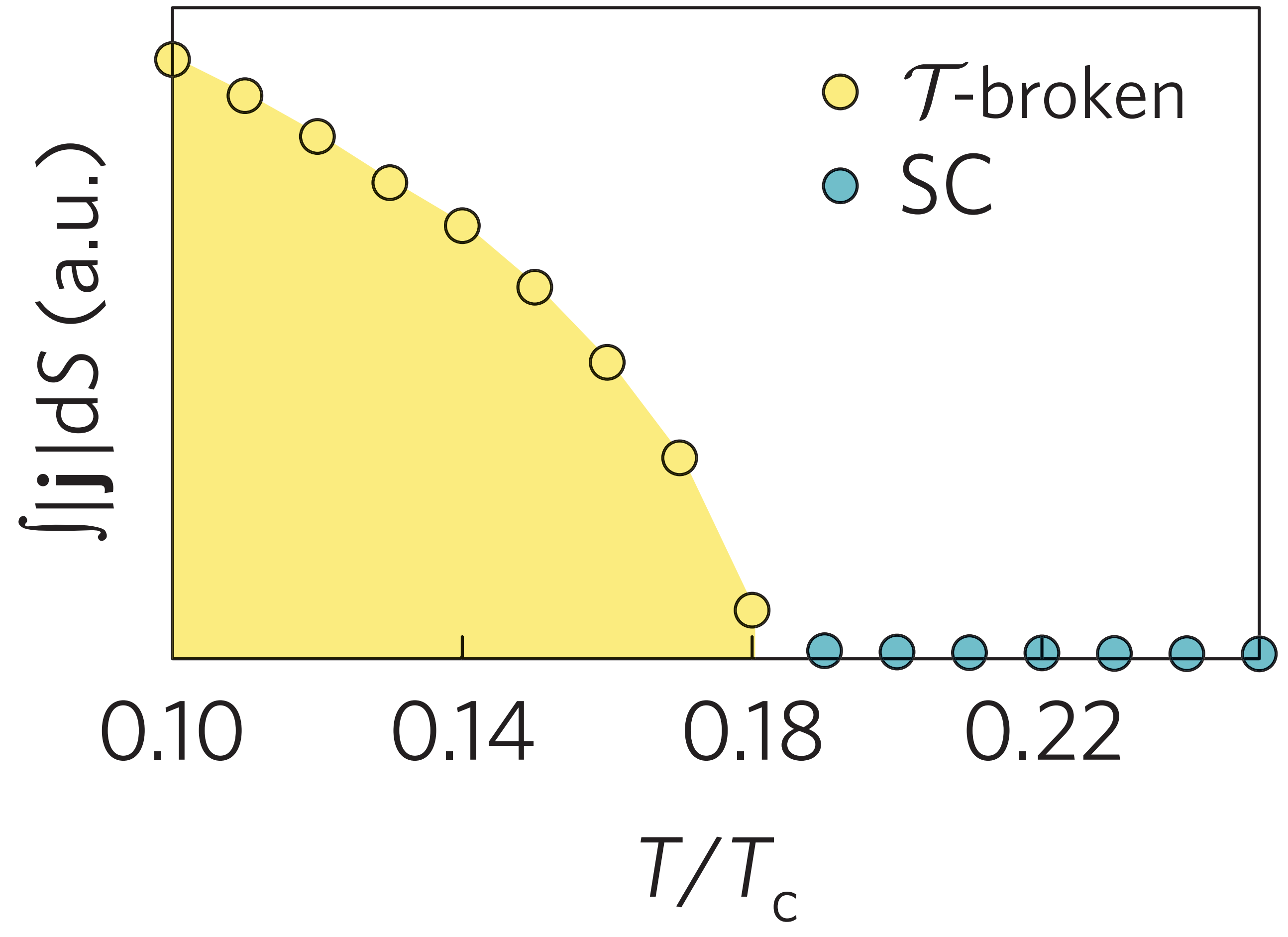
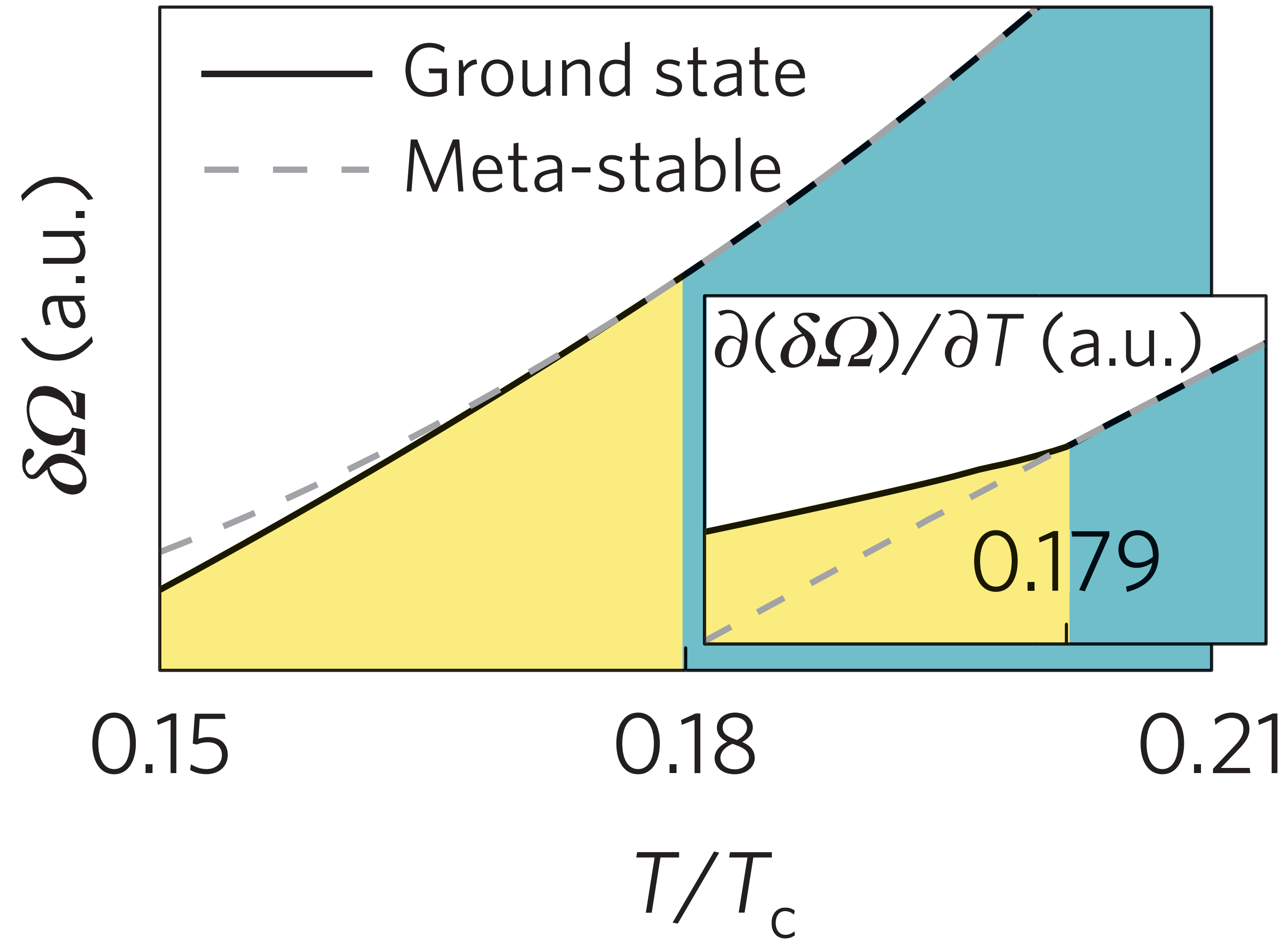
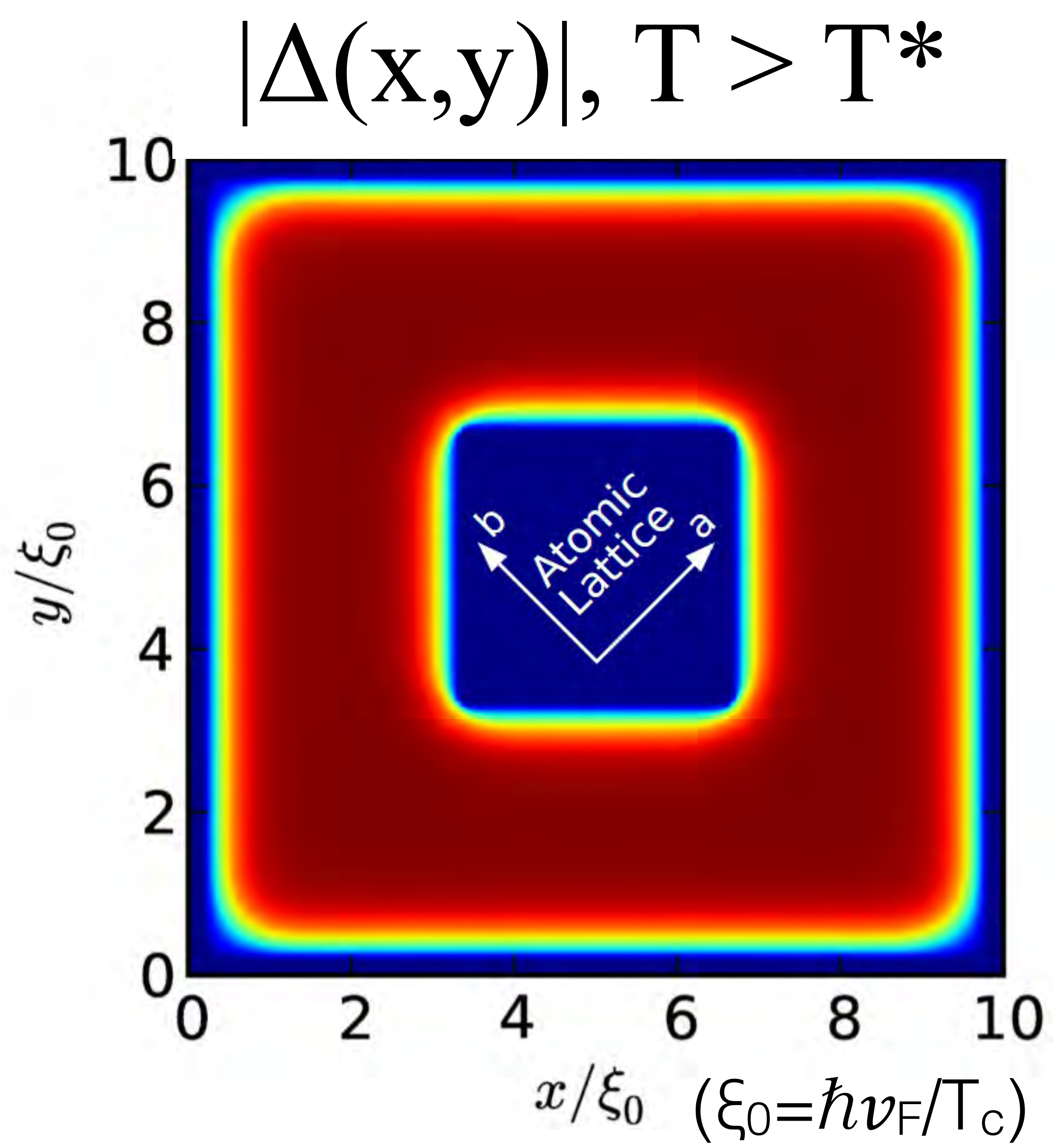
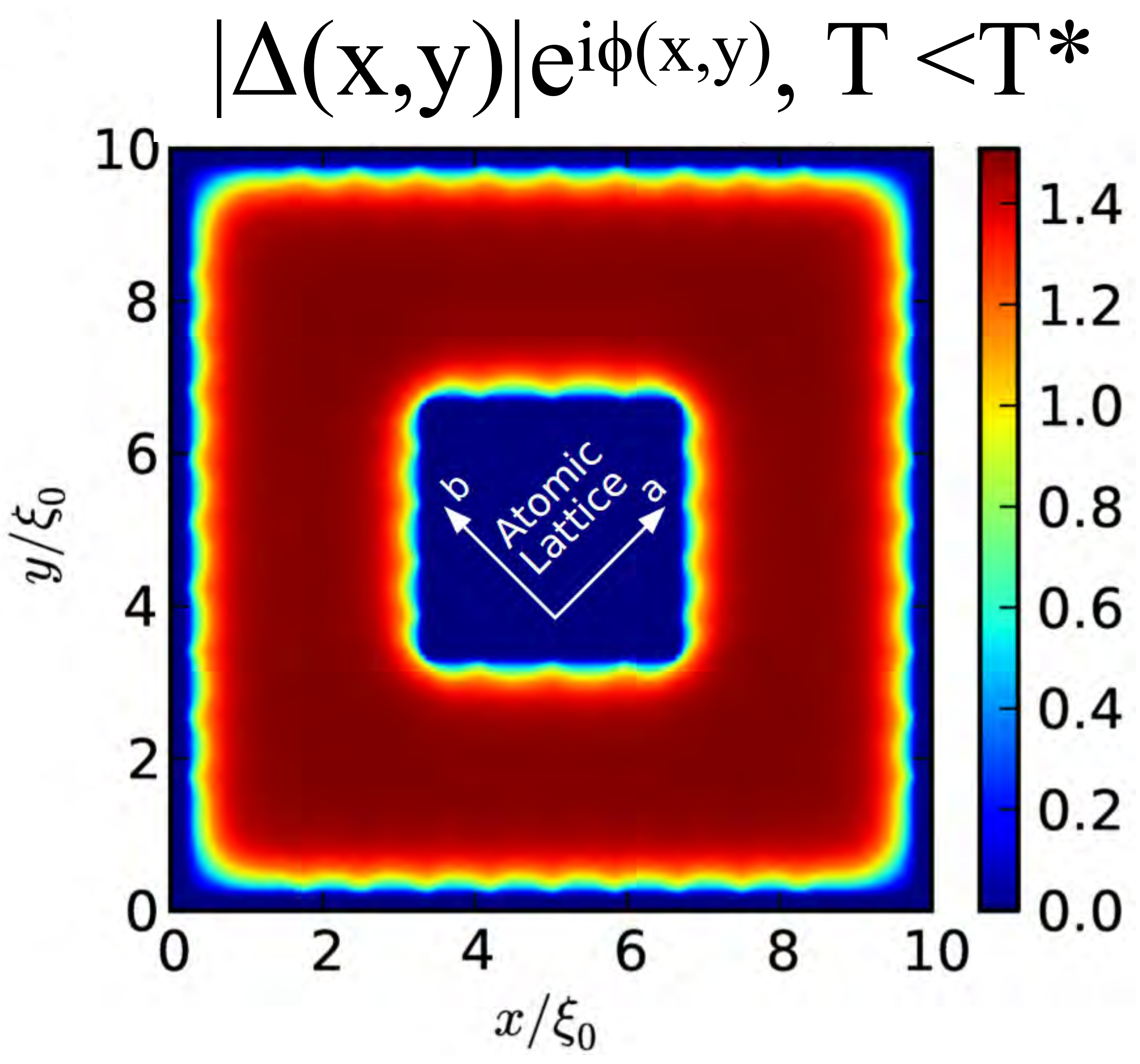


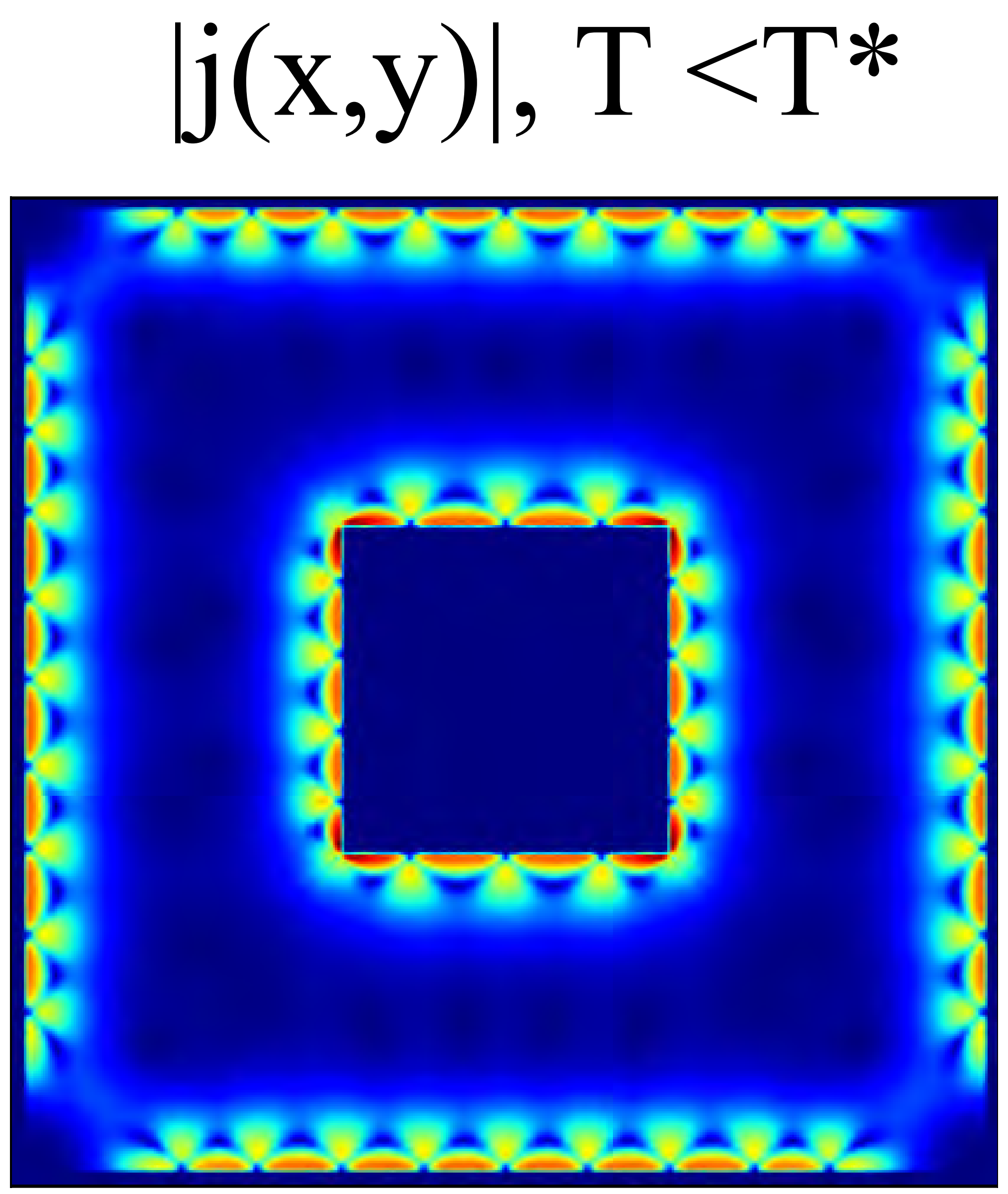


Free energy vs T

The d-wave SC grain undergoes a change of state at T=T*







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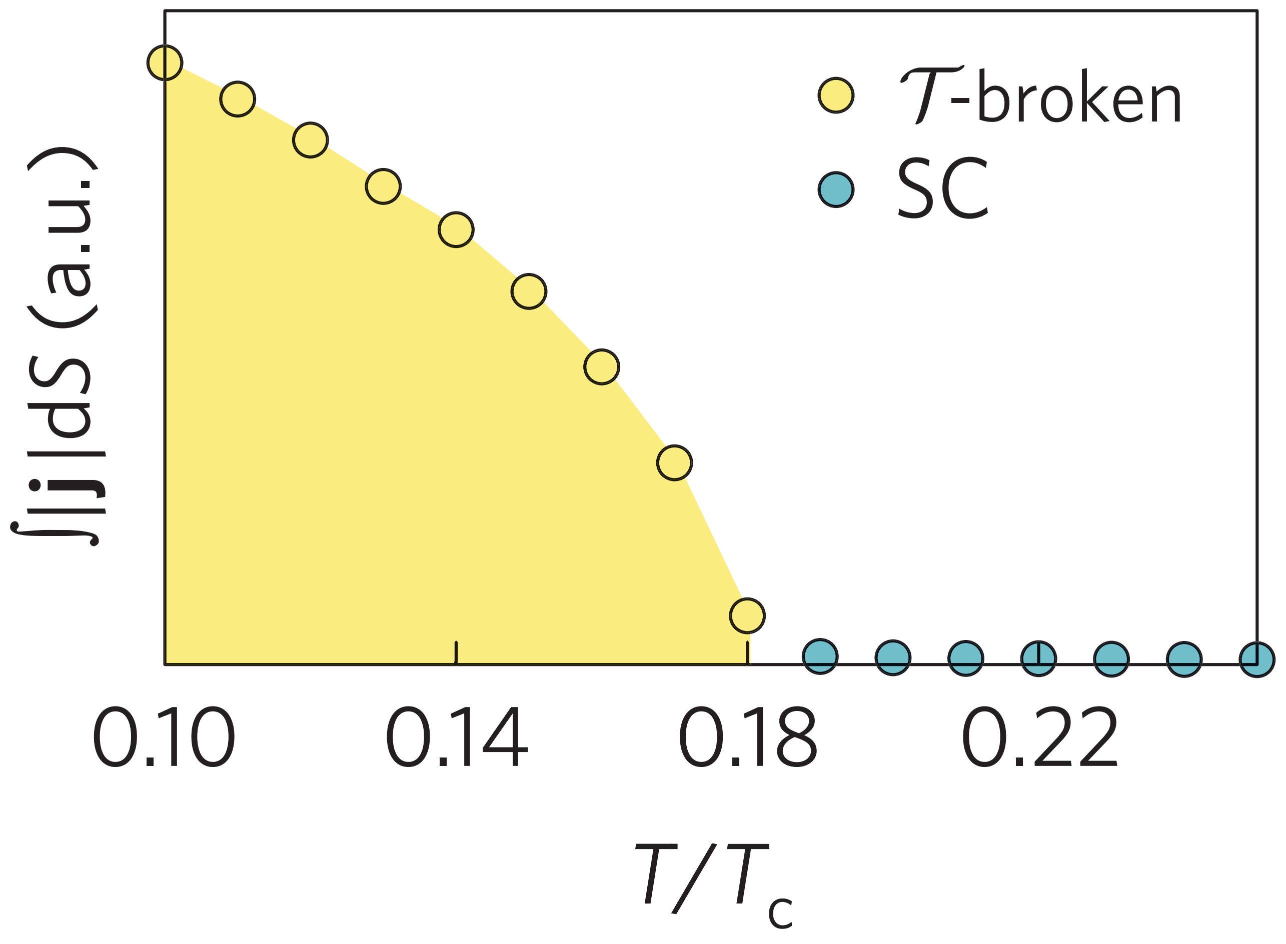

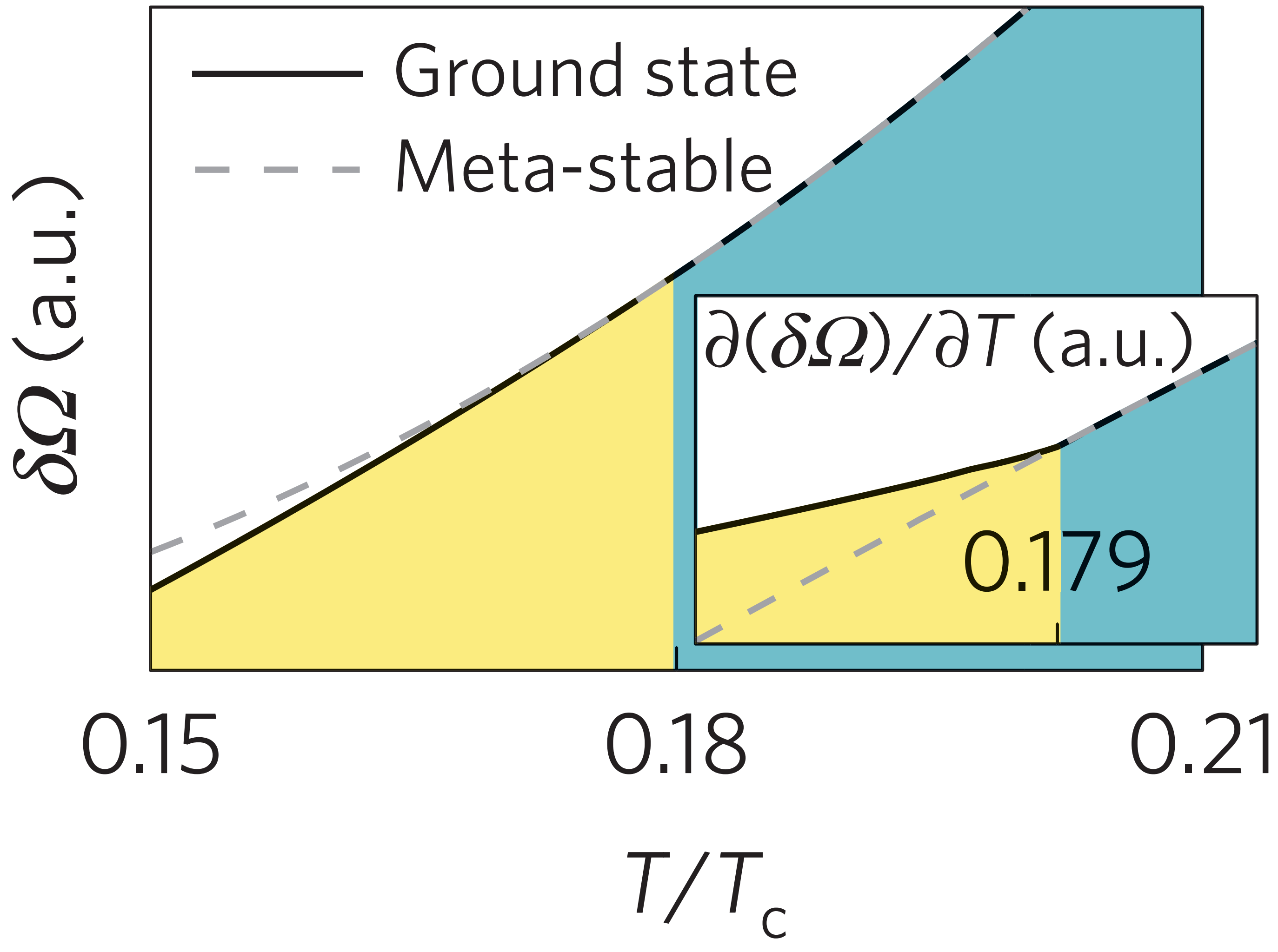

Free energy vs T

The transition in to the T-broken state is a second-order phase transition at $T^*=0.18T_c$

Mikael Fogelström, Applied Quantum Physics Laboratory

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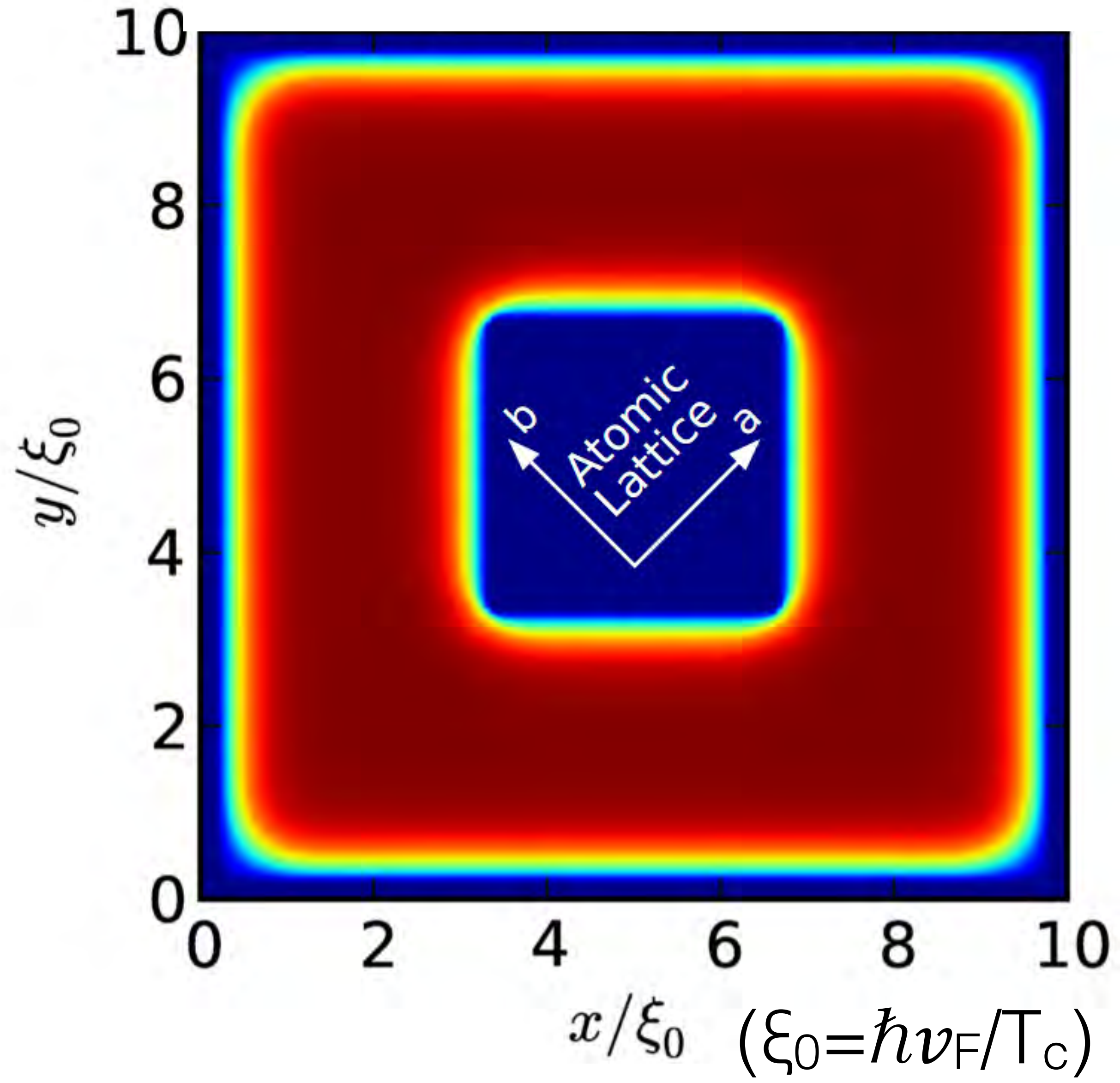

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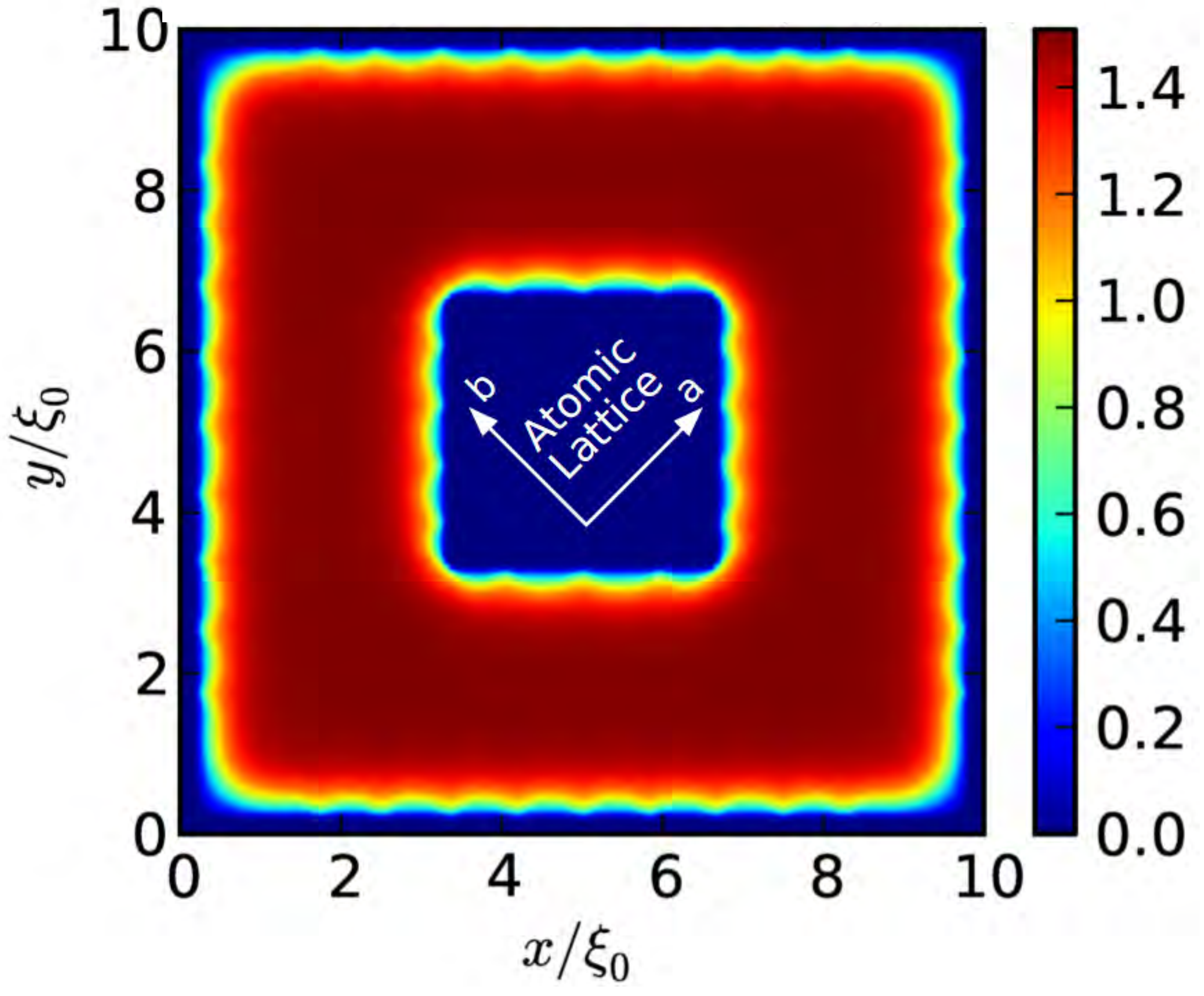

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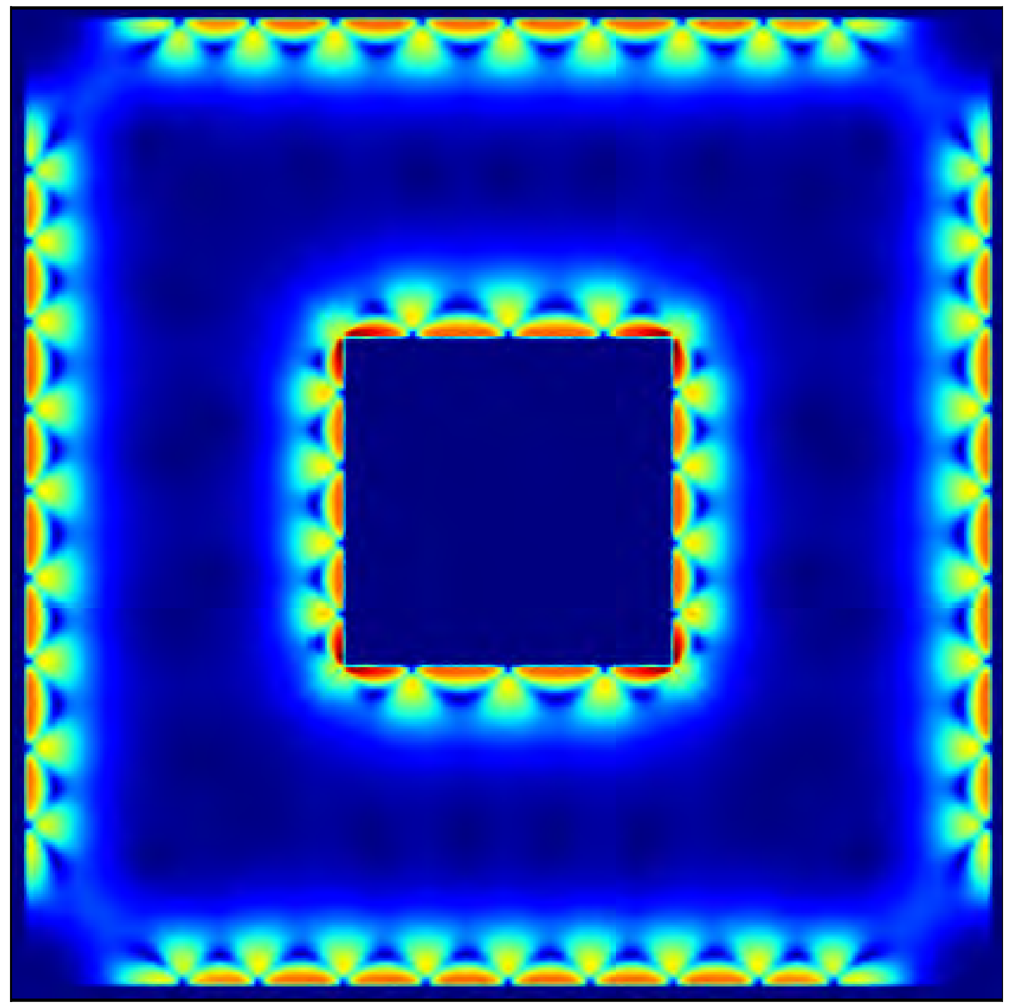

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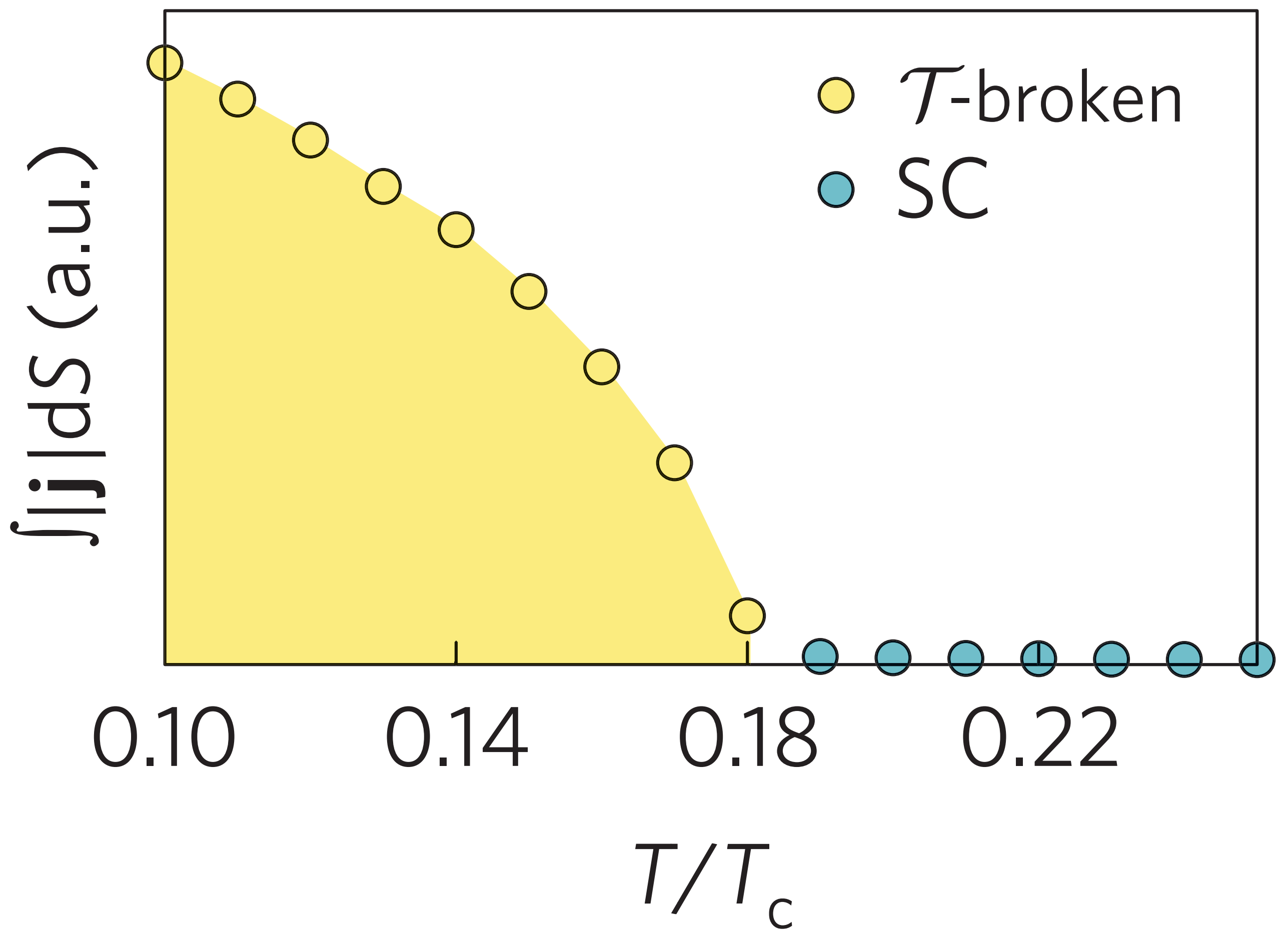

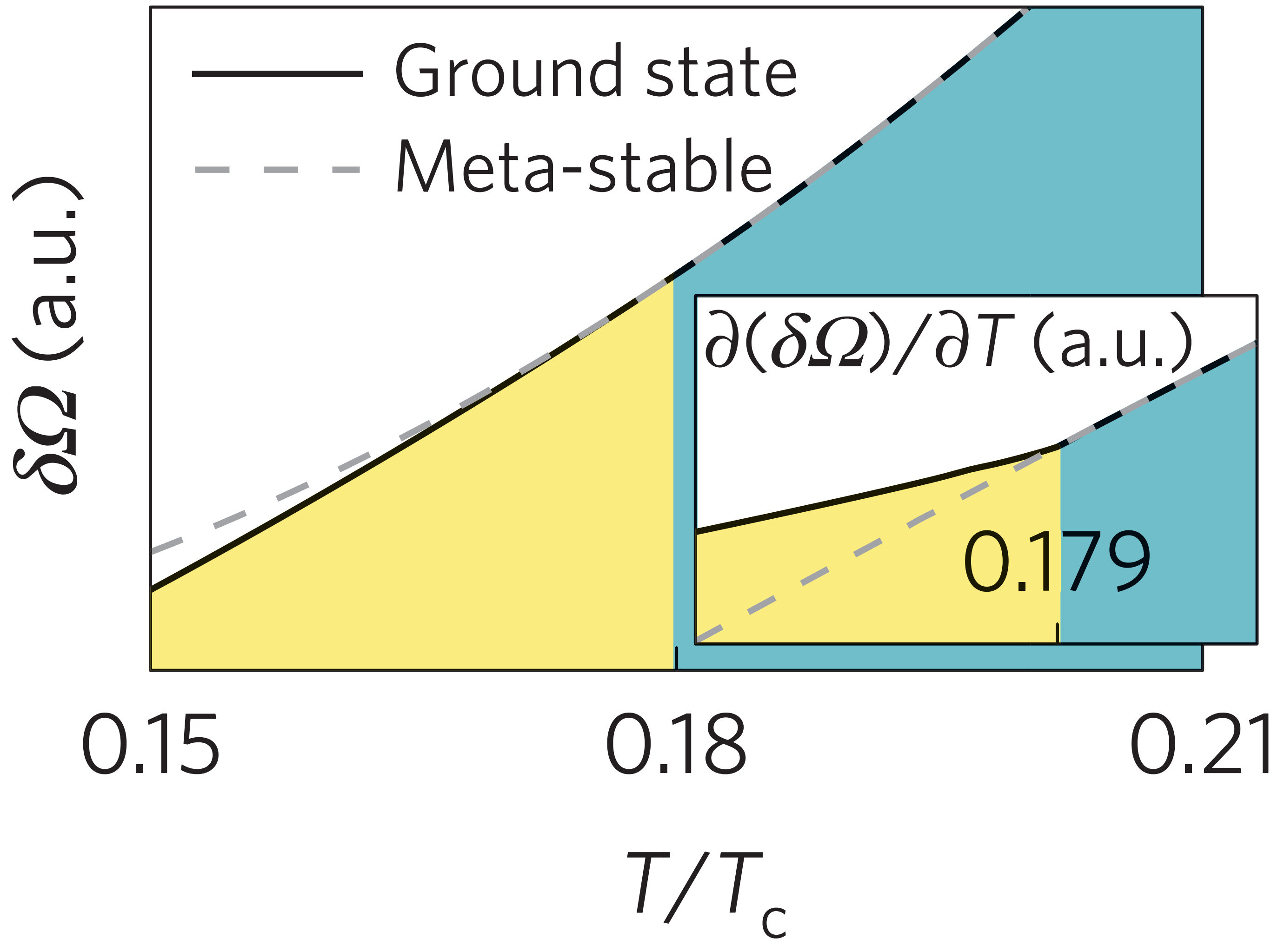

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The transition in to the T-broken state is a second-order phase transition at $T^*=0.18T_c$

<u>This in a pure d-wave SC</u>

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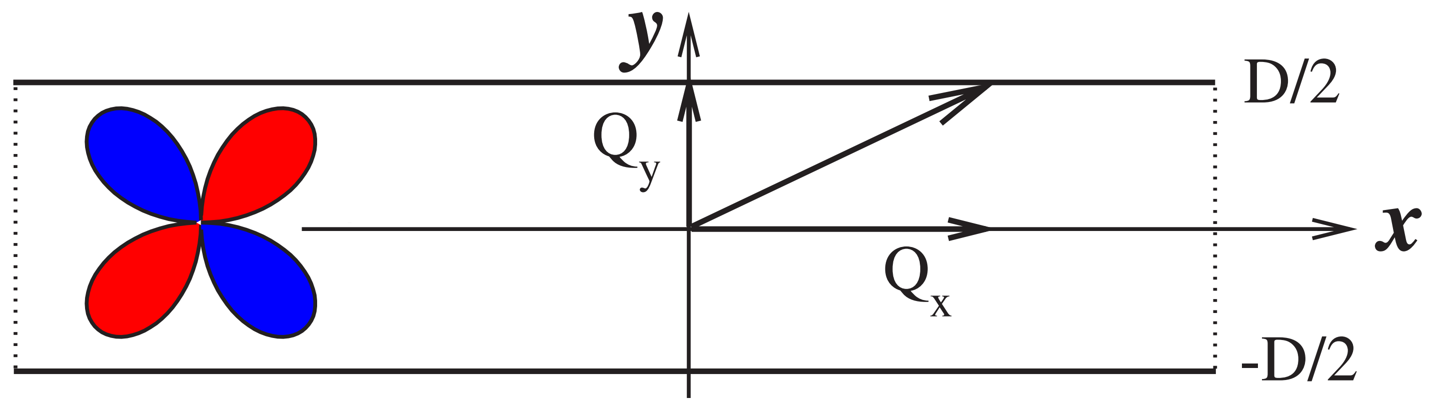
PRL **102,** 177001 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

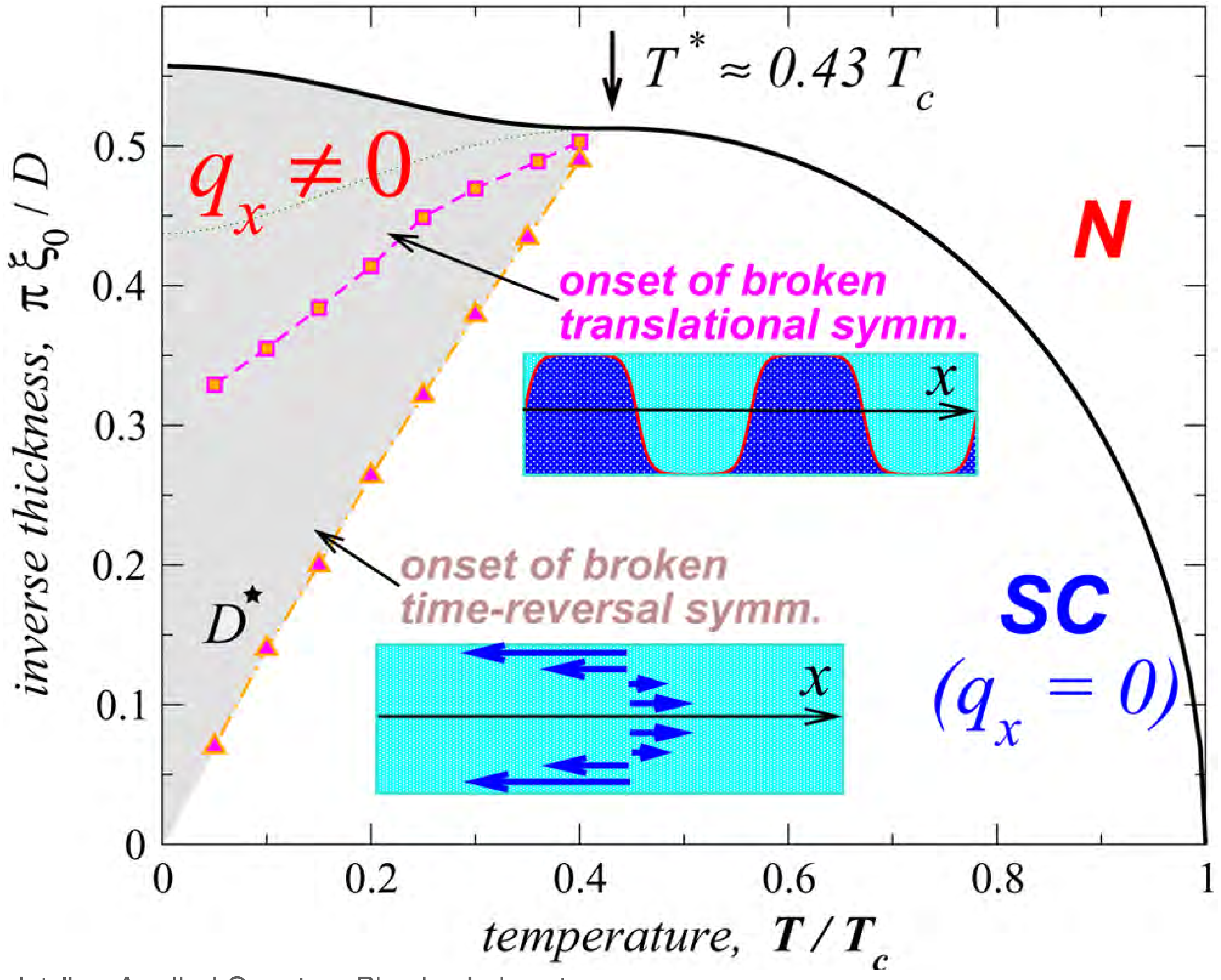
Broken Translational and Time-Reversal Symmetry in Unconventional Superconducting Films

A. B. Vorontsov*

Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, 70803, USA

(Received 28 April 2008; published 27 April 2009)





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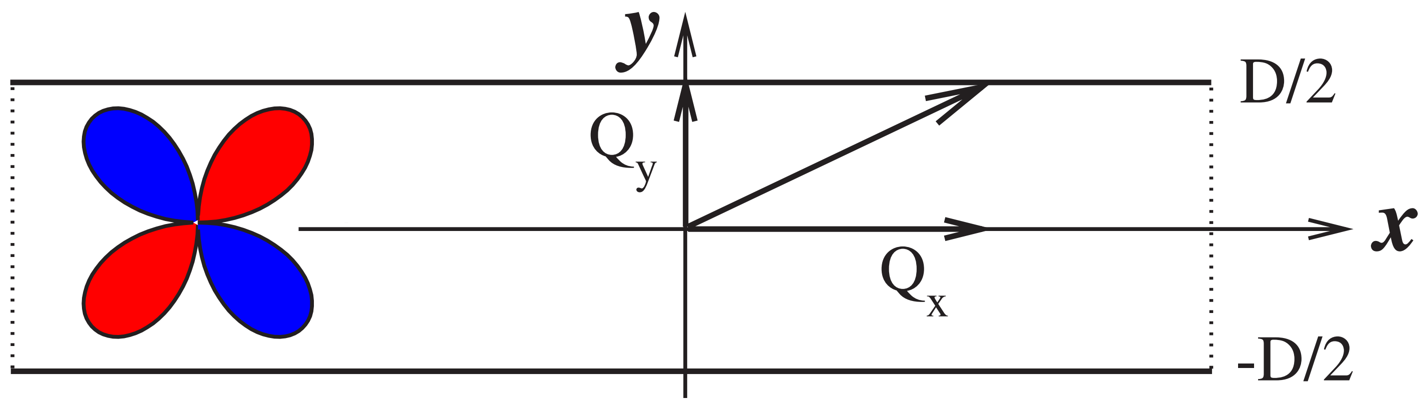

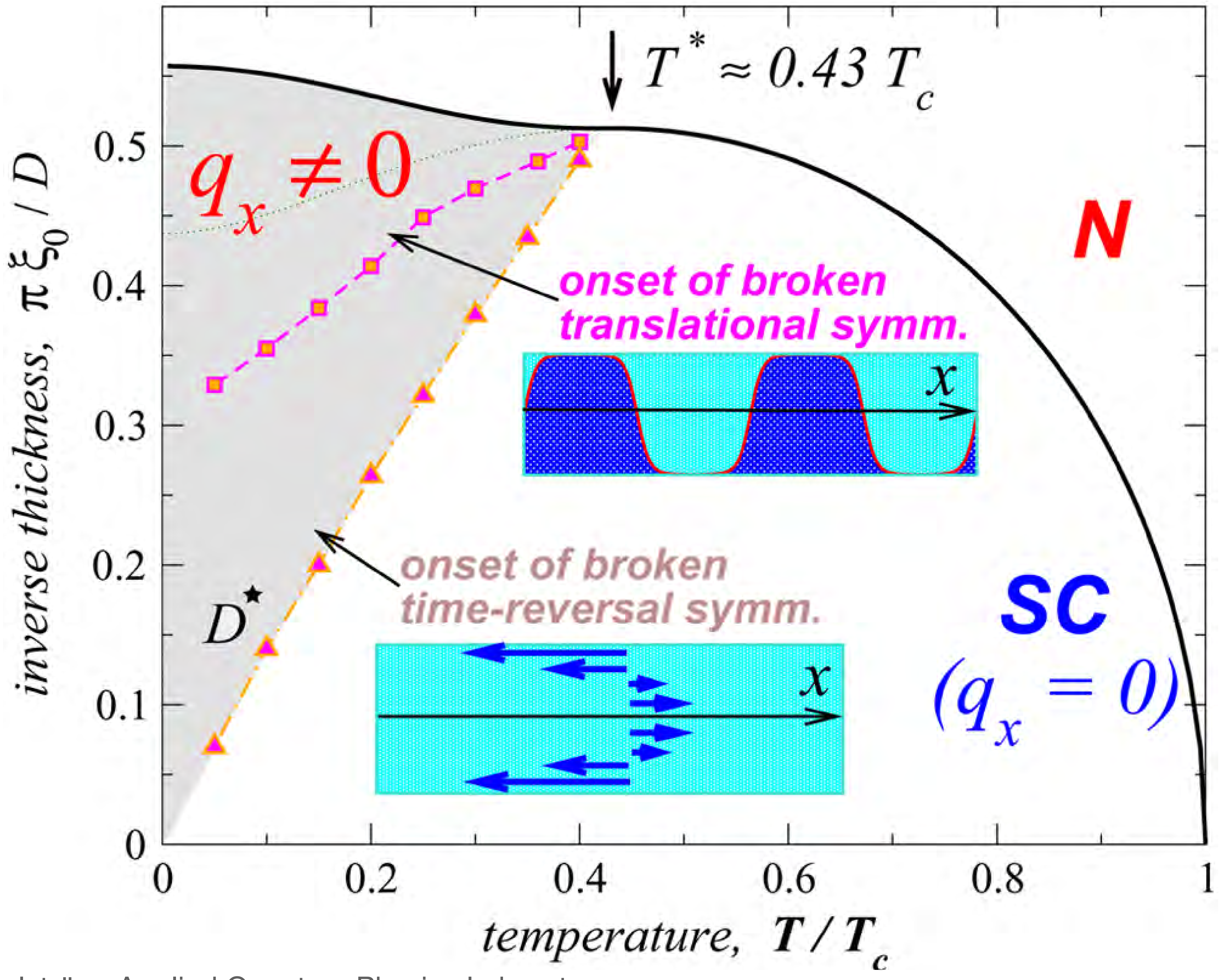

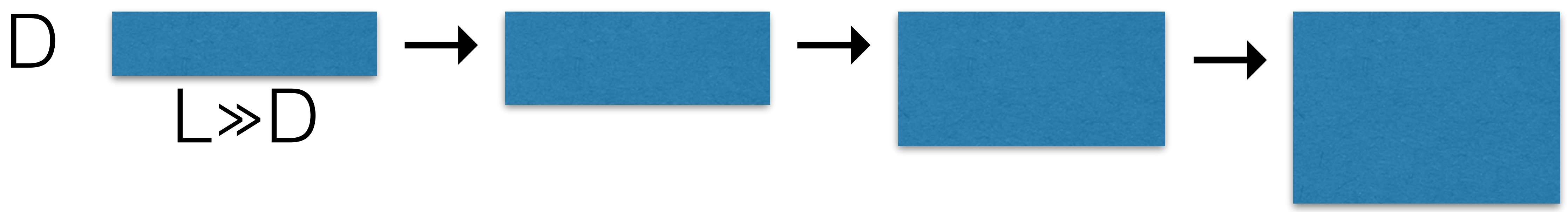

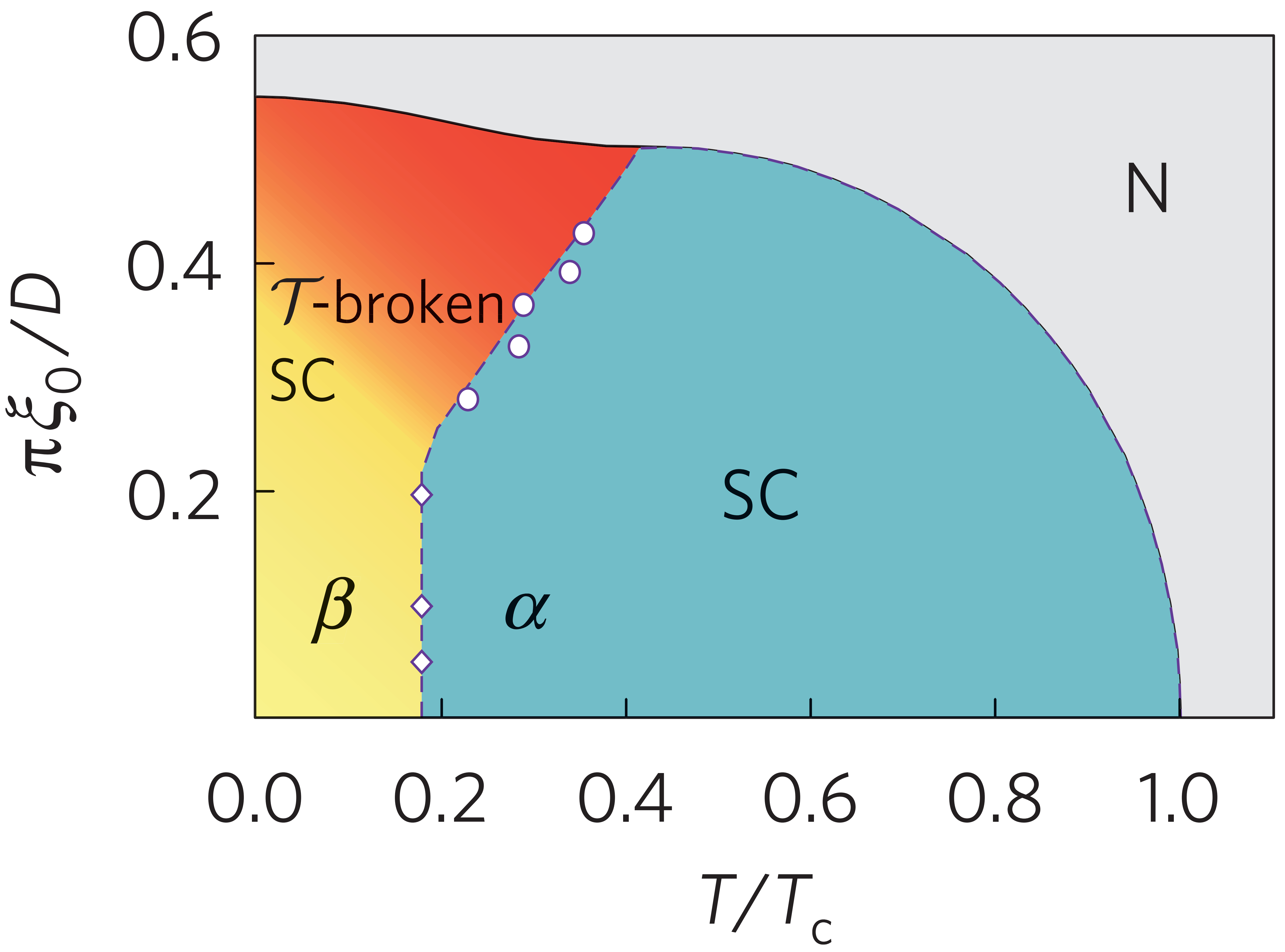

The transition in to the T-broken state becomes <u>independent</u> of size for $D \gtrsim 4\pi\xi_0$

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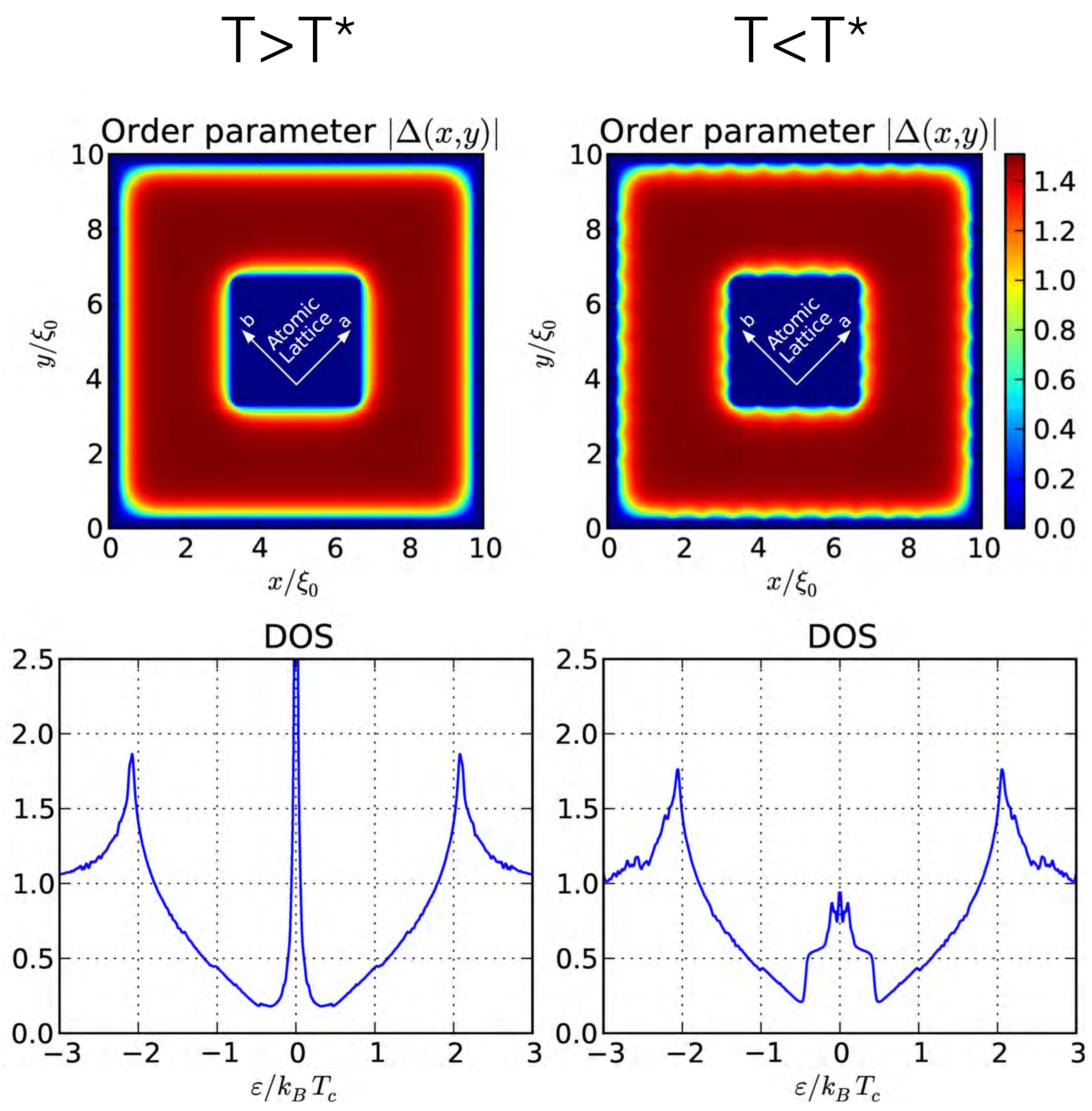
T-breaking is driven by a rearrangement of the qp-spectrum



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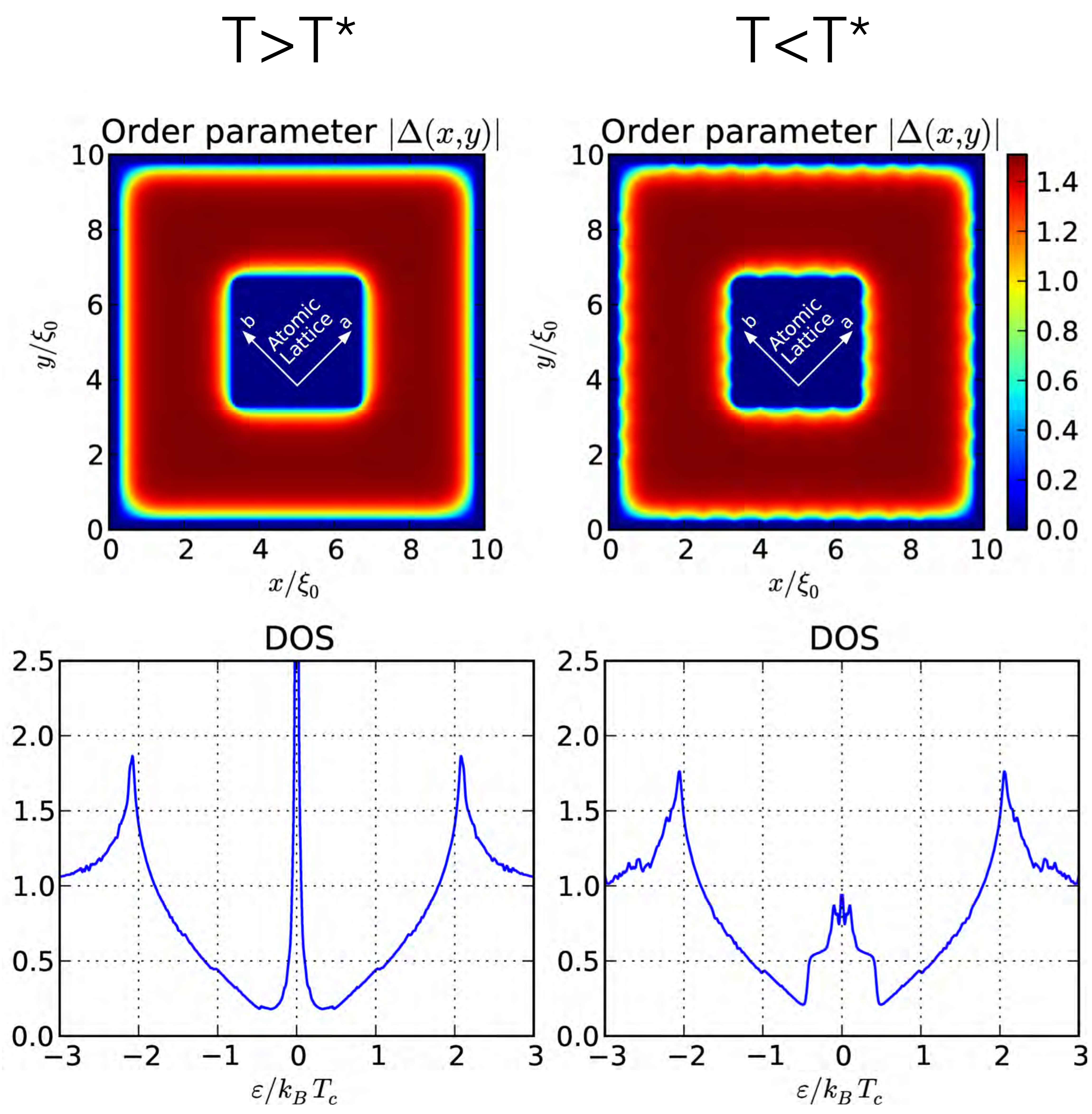
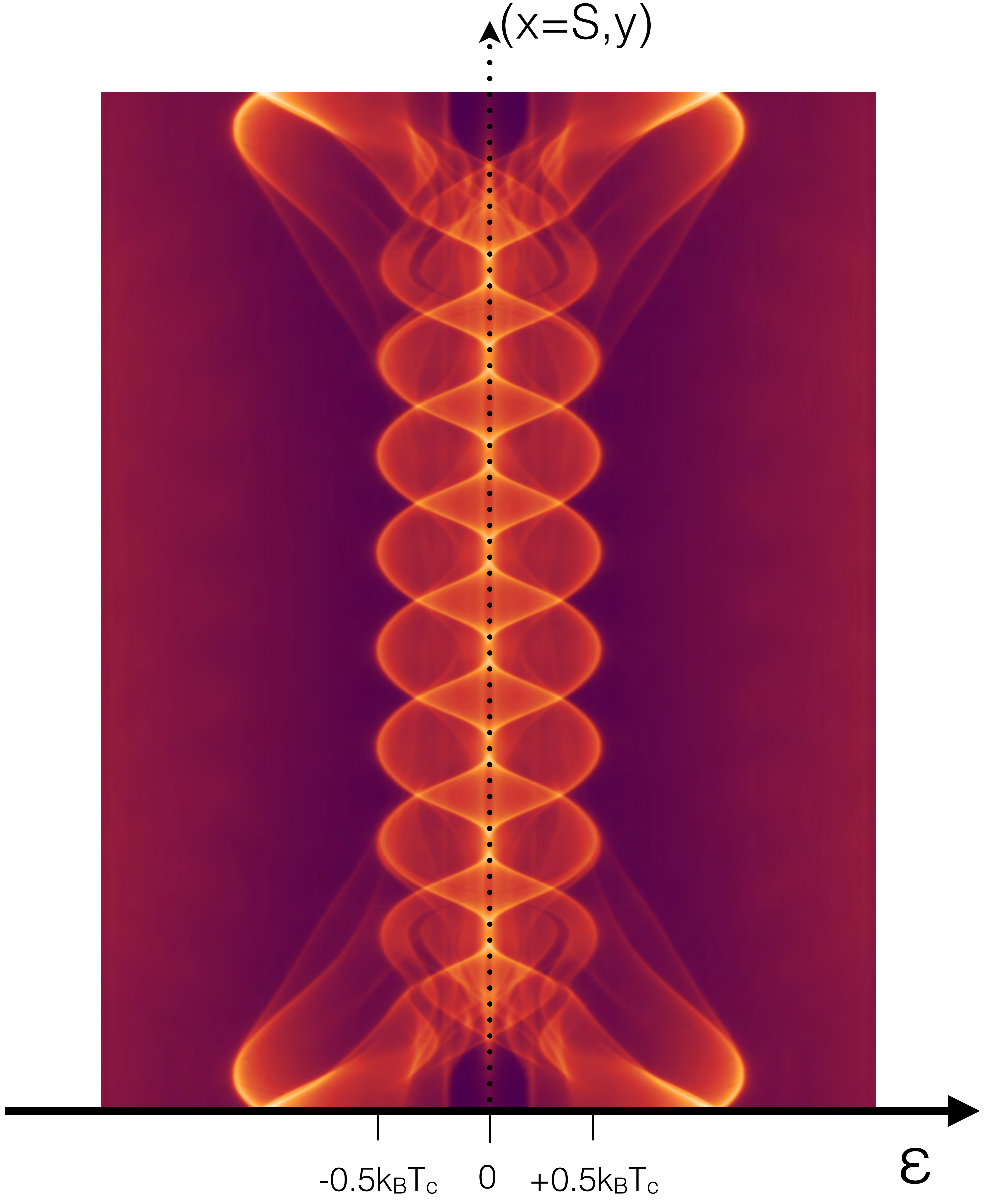
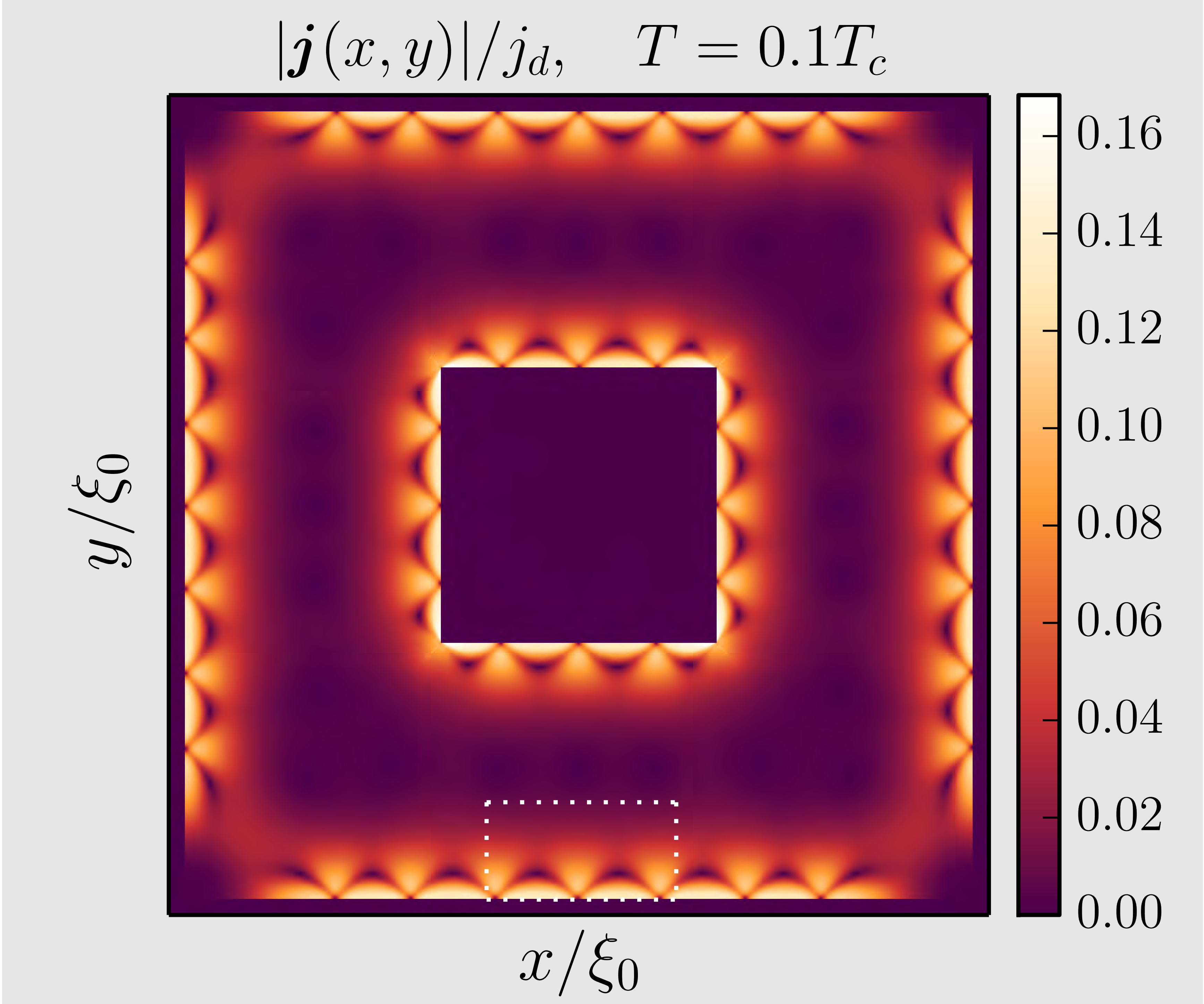




Rearrangement of the qp-spectrum give local currents



Here $j_{\rm d} = 2\pi e N_{\rm f} k_{\rm B} T_{\rm c}$
is the de-pairing current density
The currents come from the local
Doppler shift of the spectra

$$\mathbf{v}_F \cdot \mathbf{p}_s(\mathbf{R})$$

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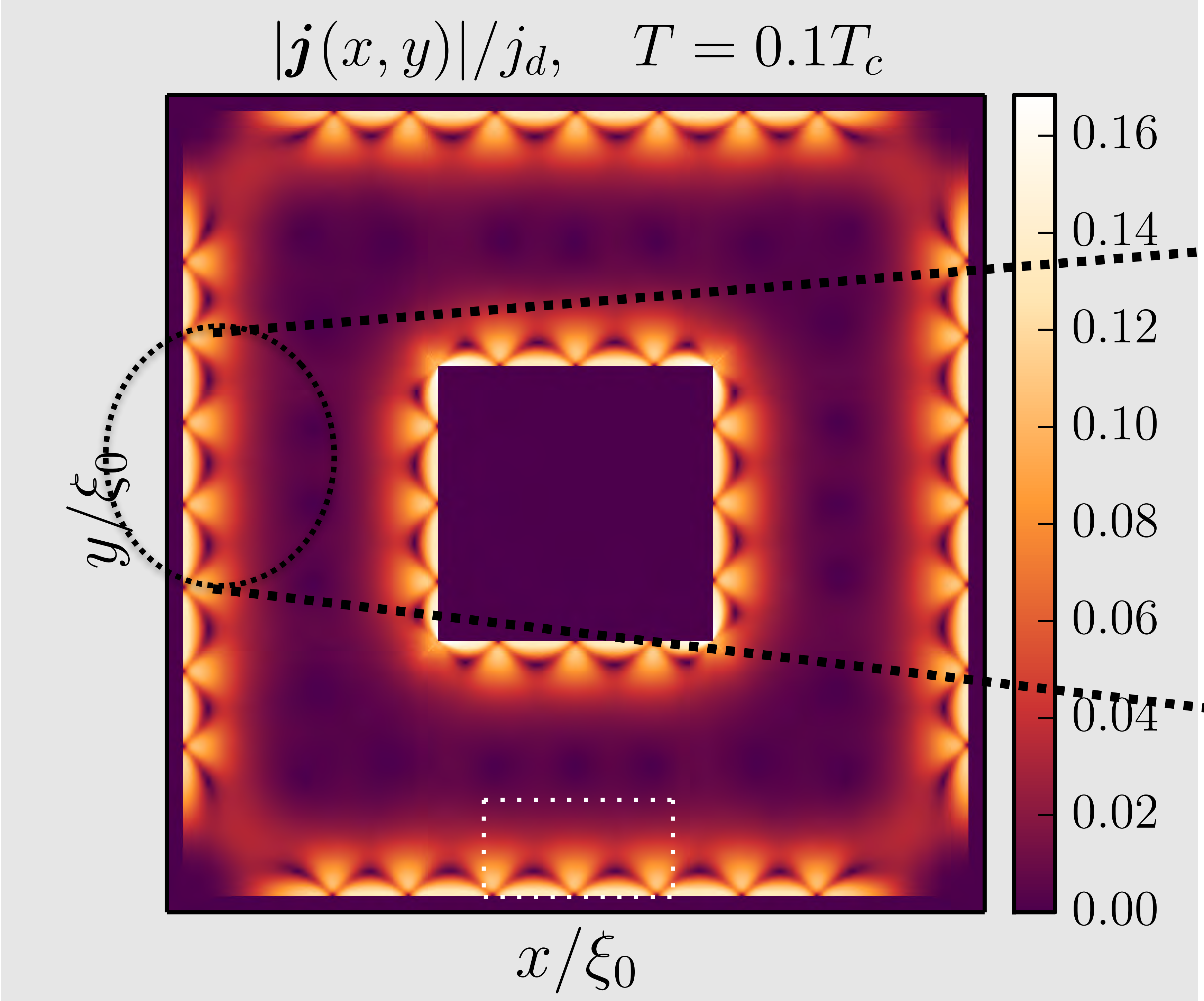

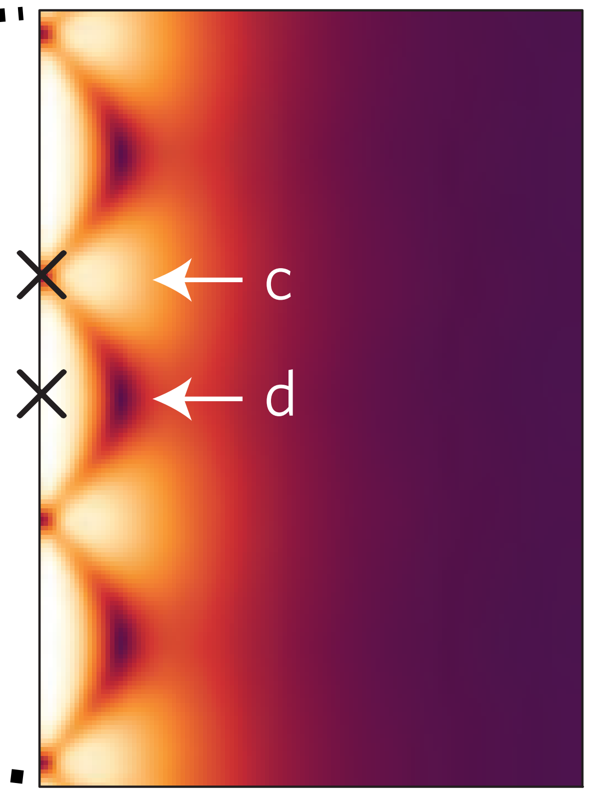

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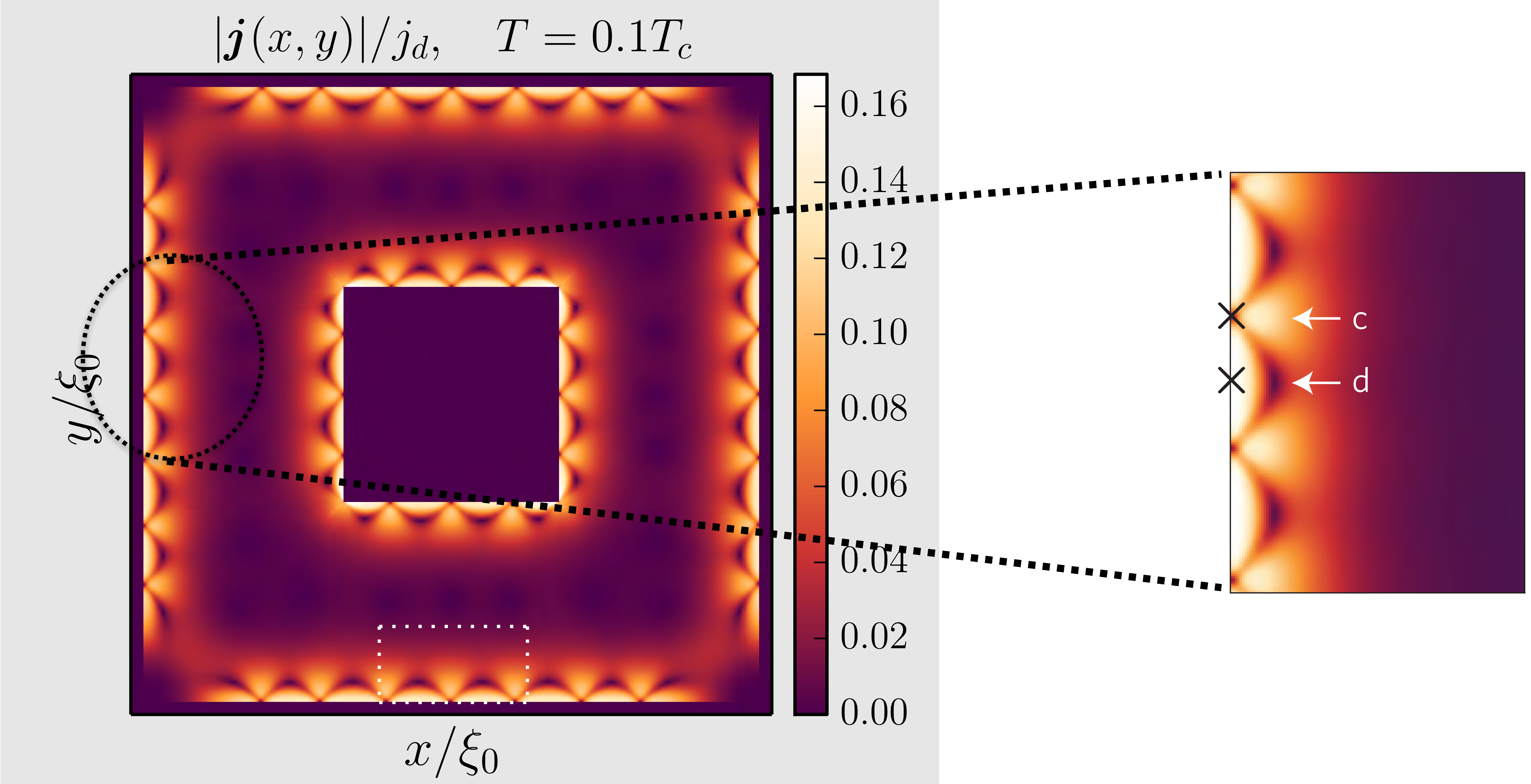
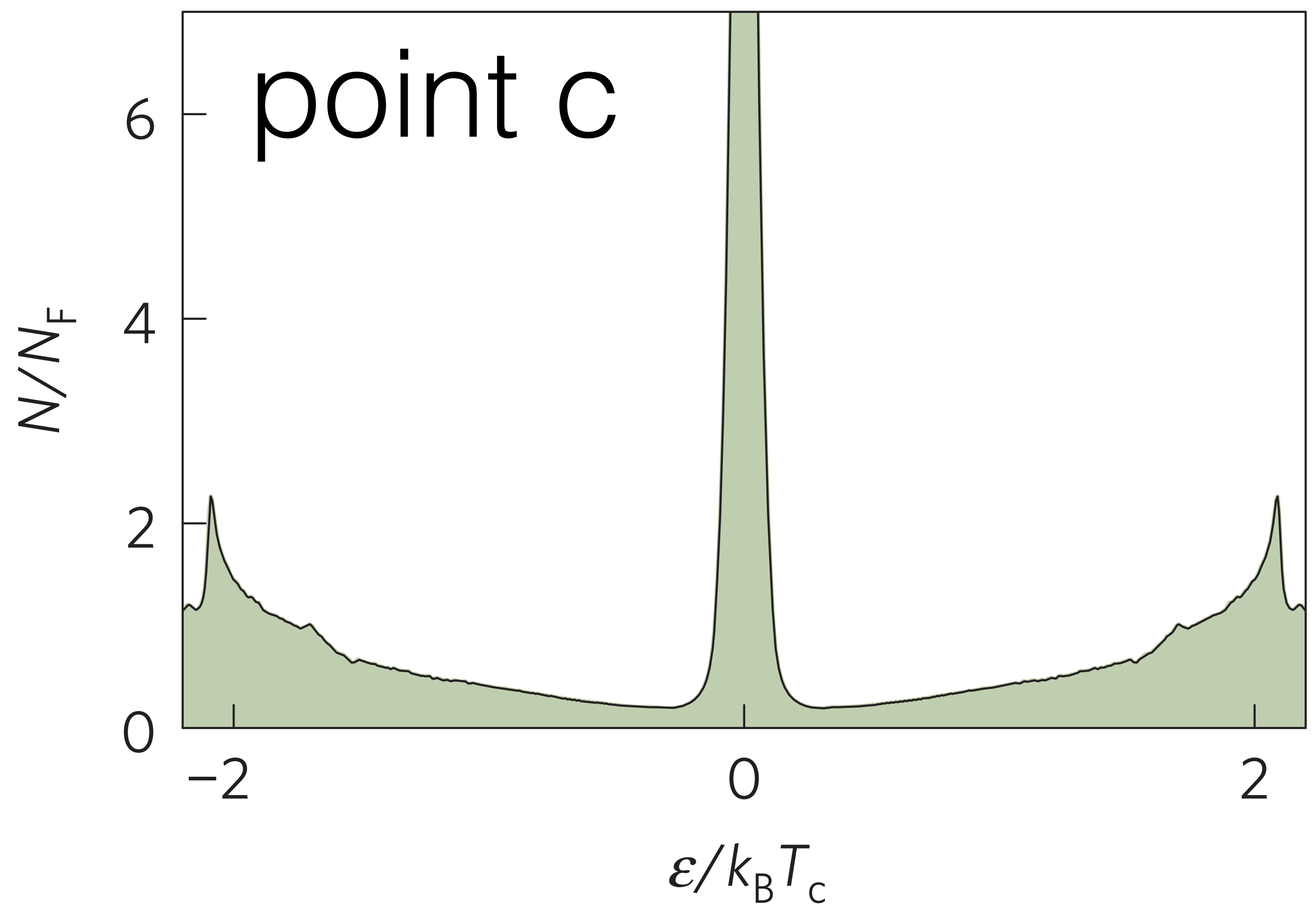


current node



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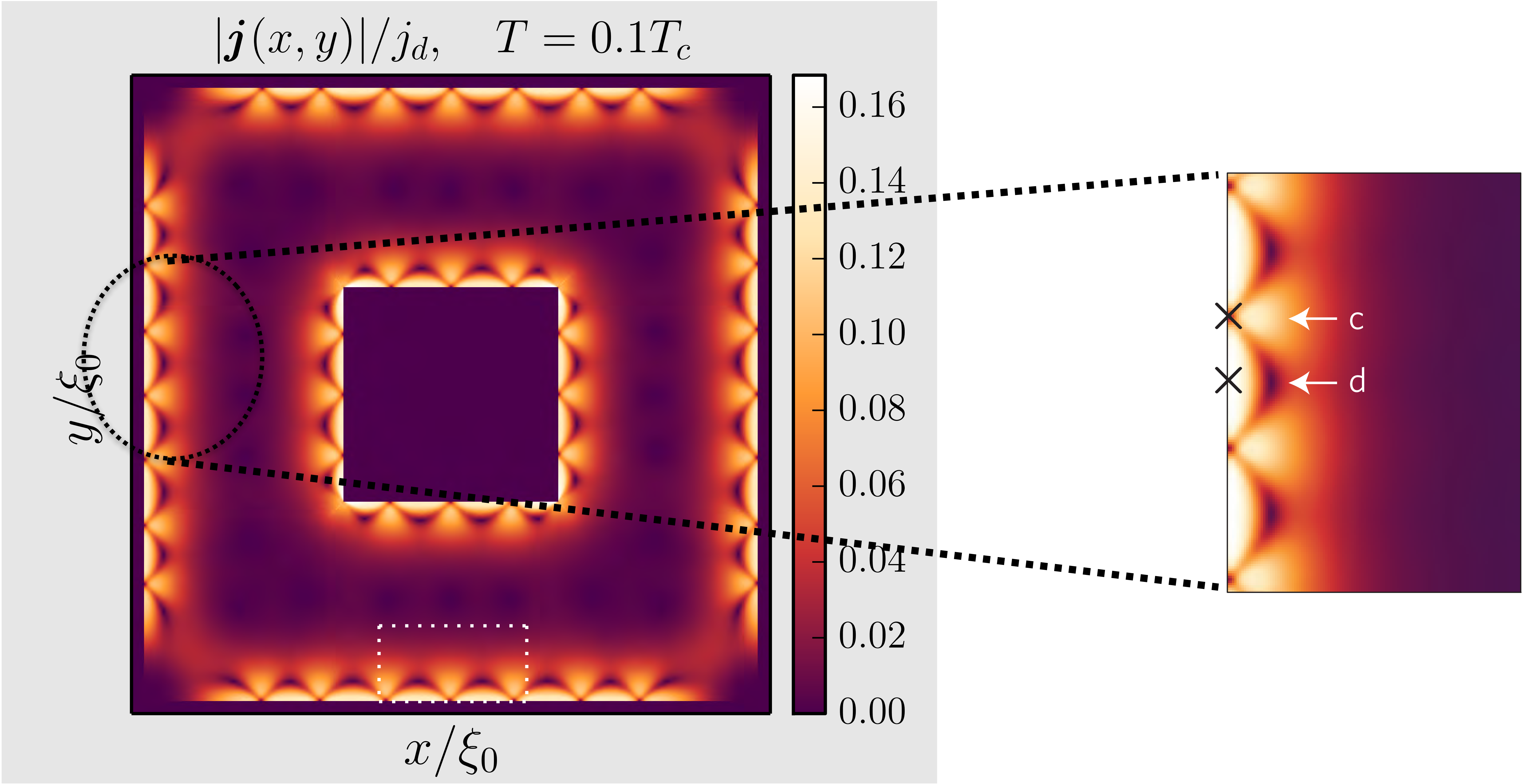

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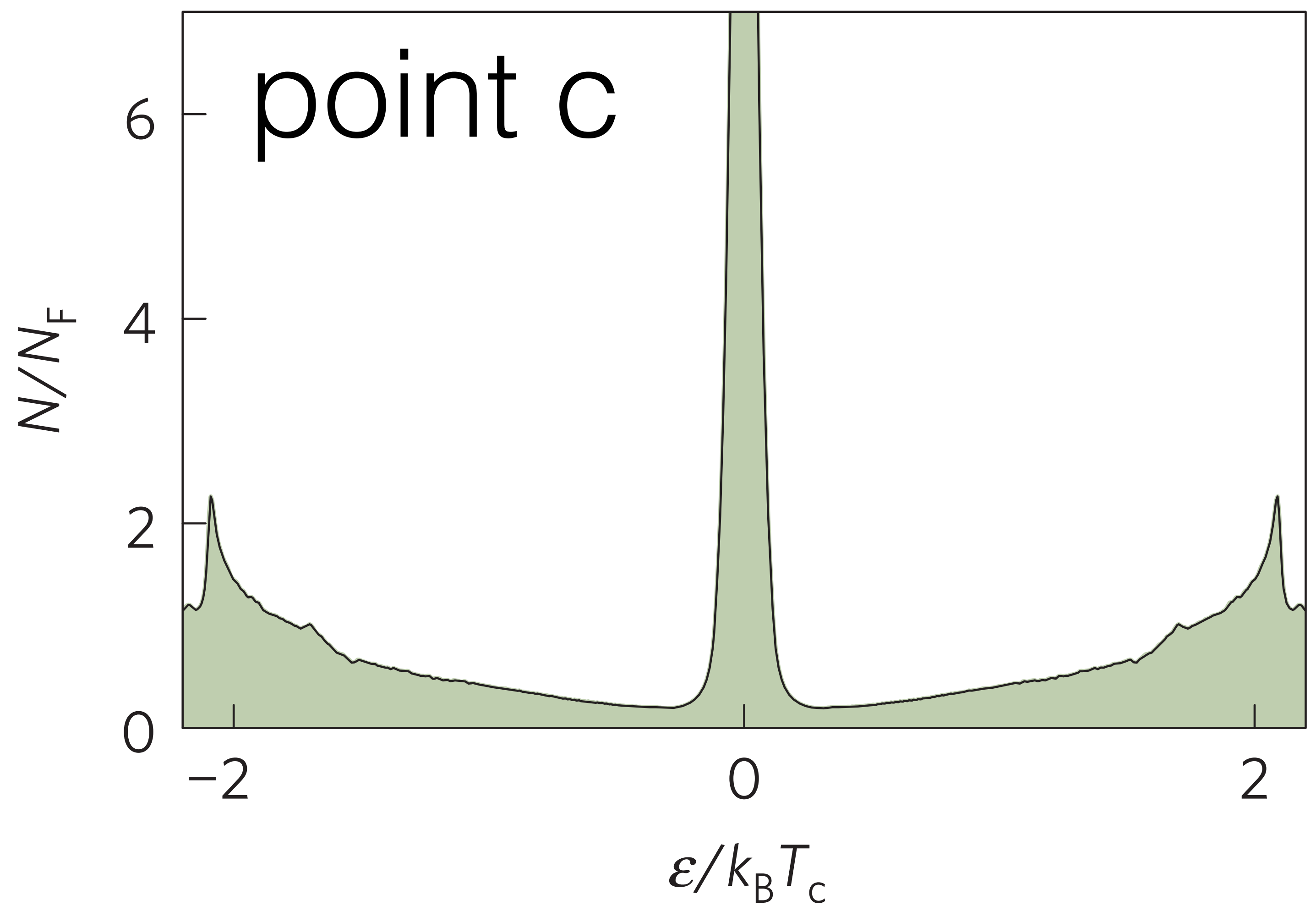
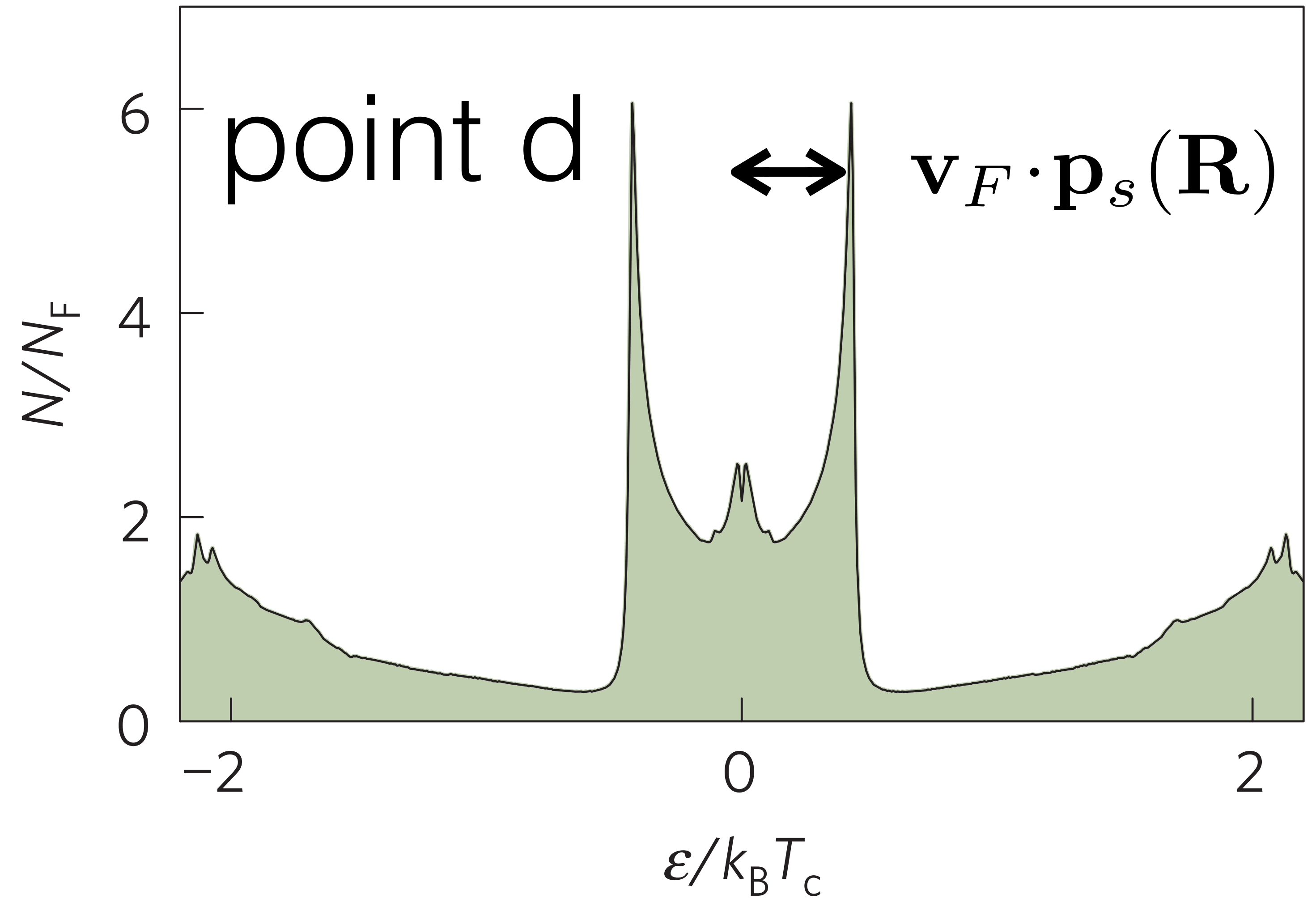


current maxima



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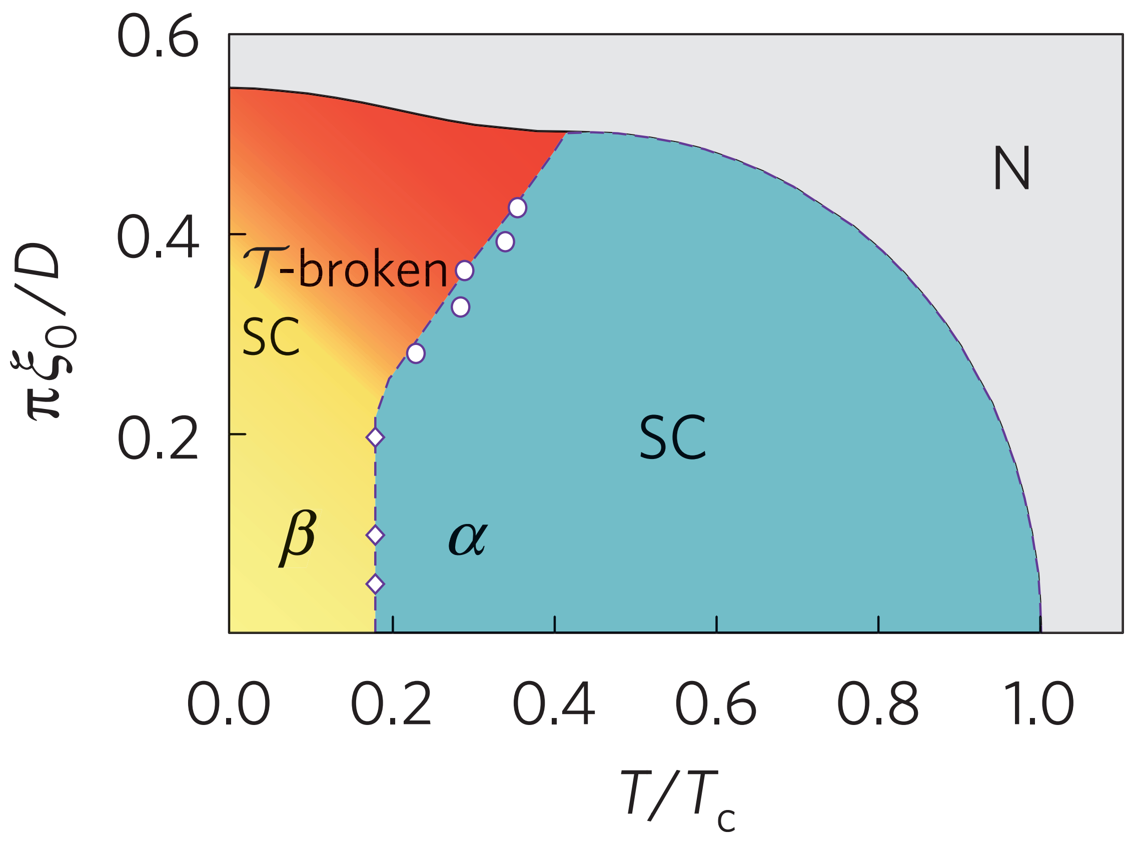

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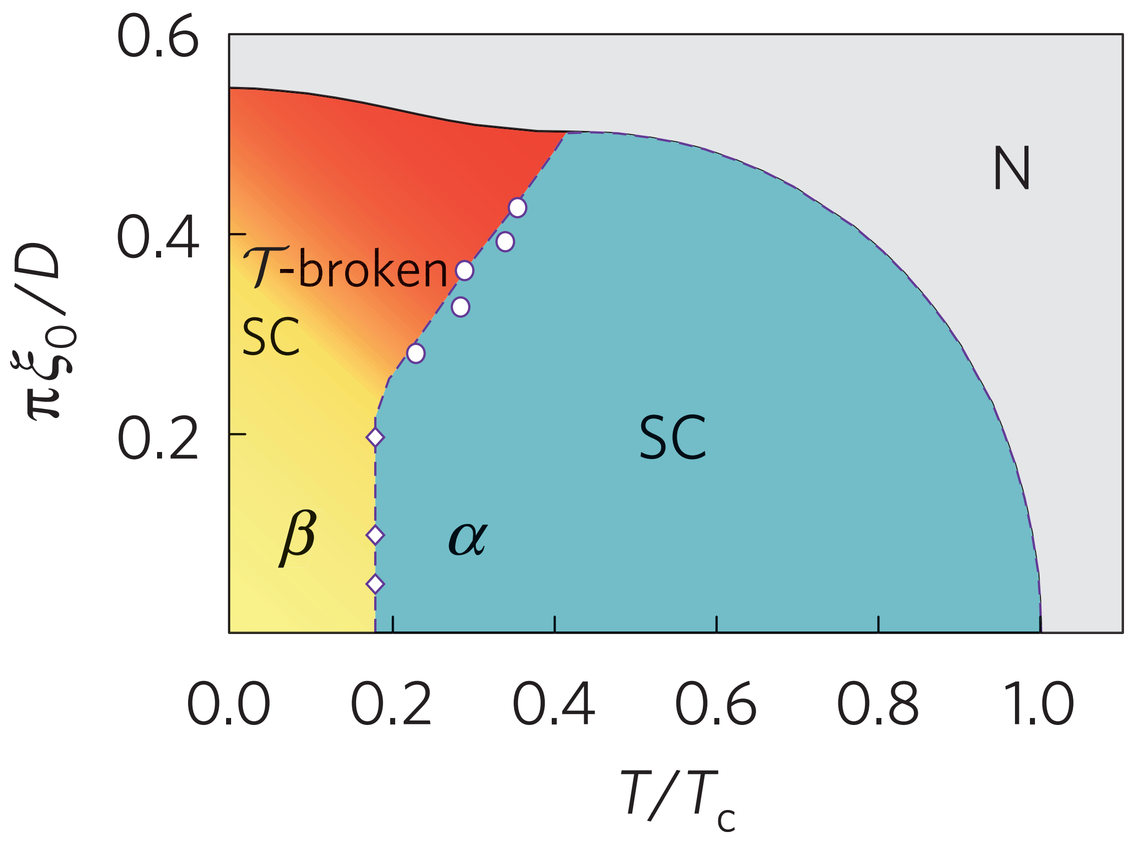
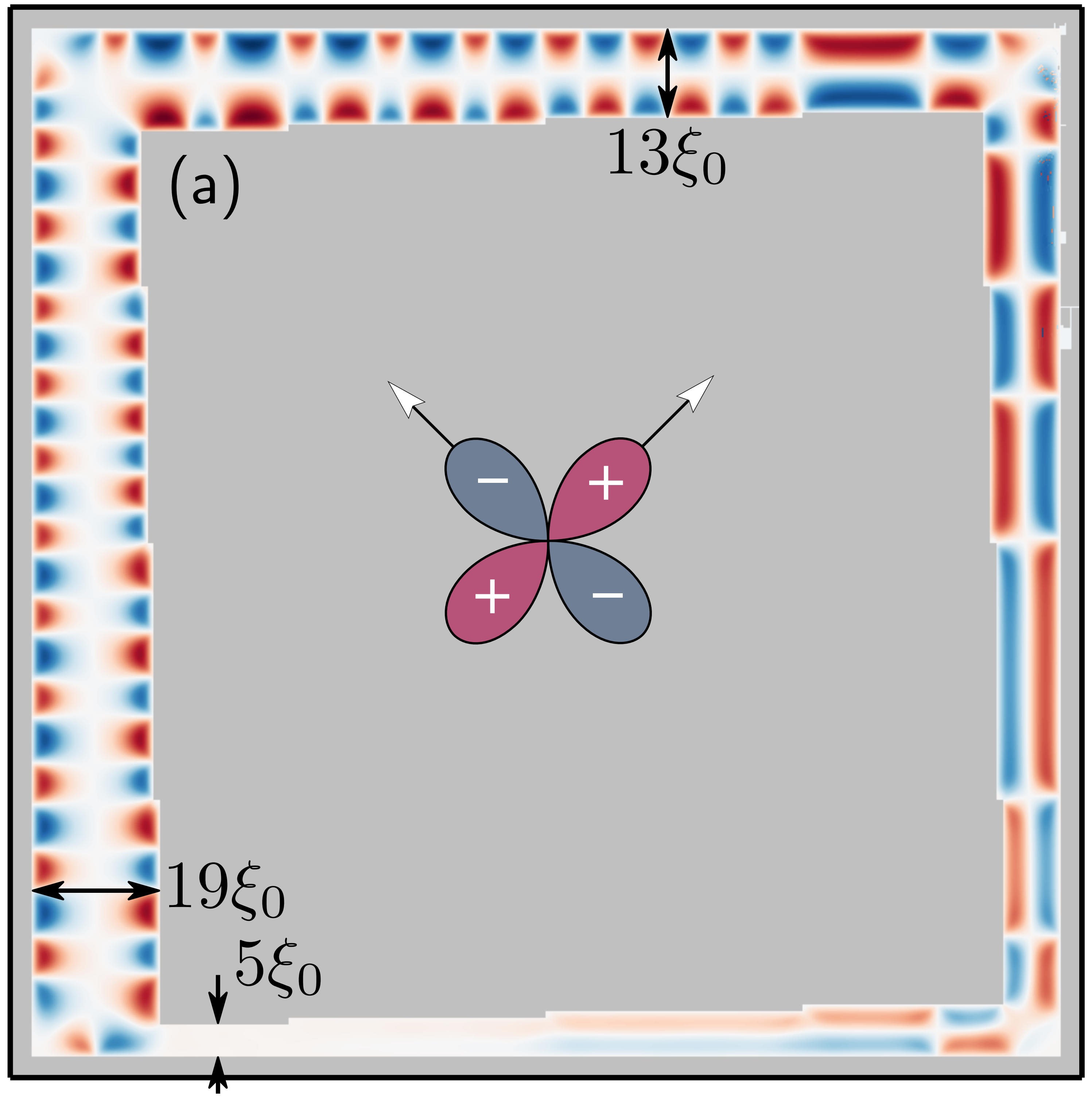
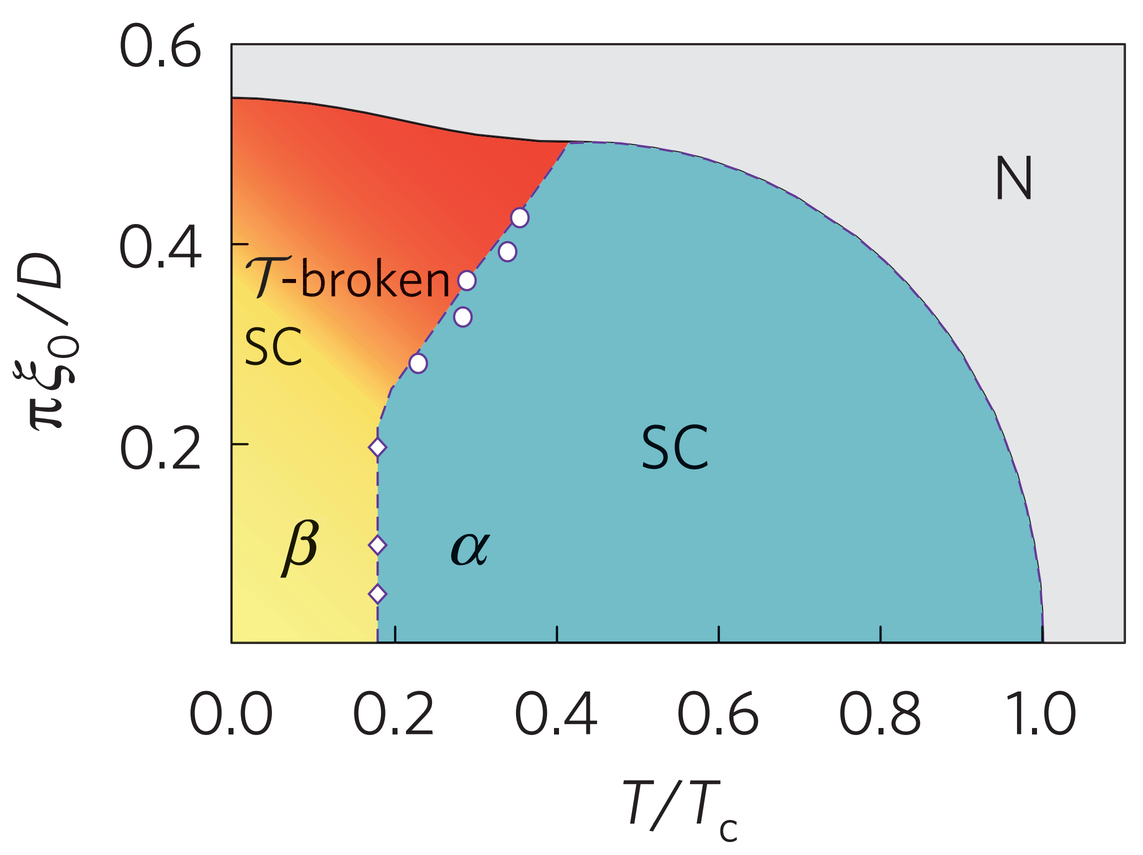
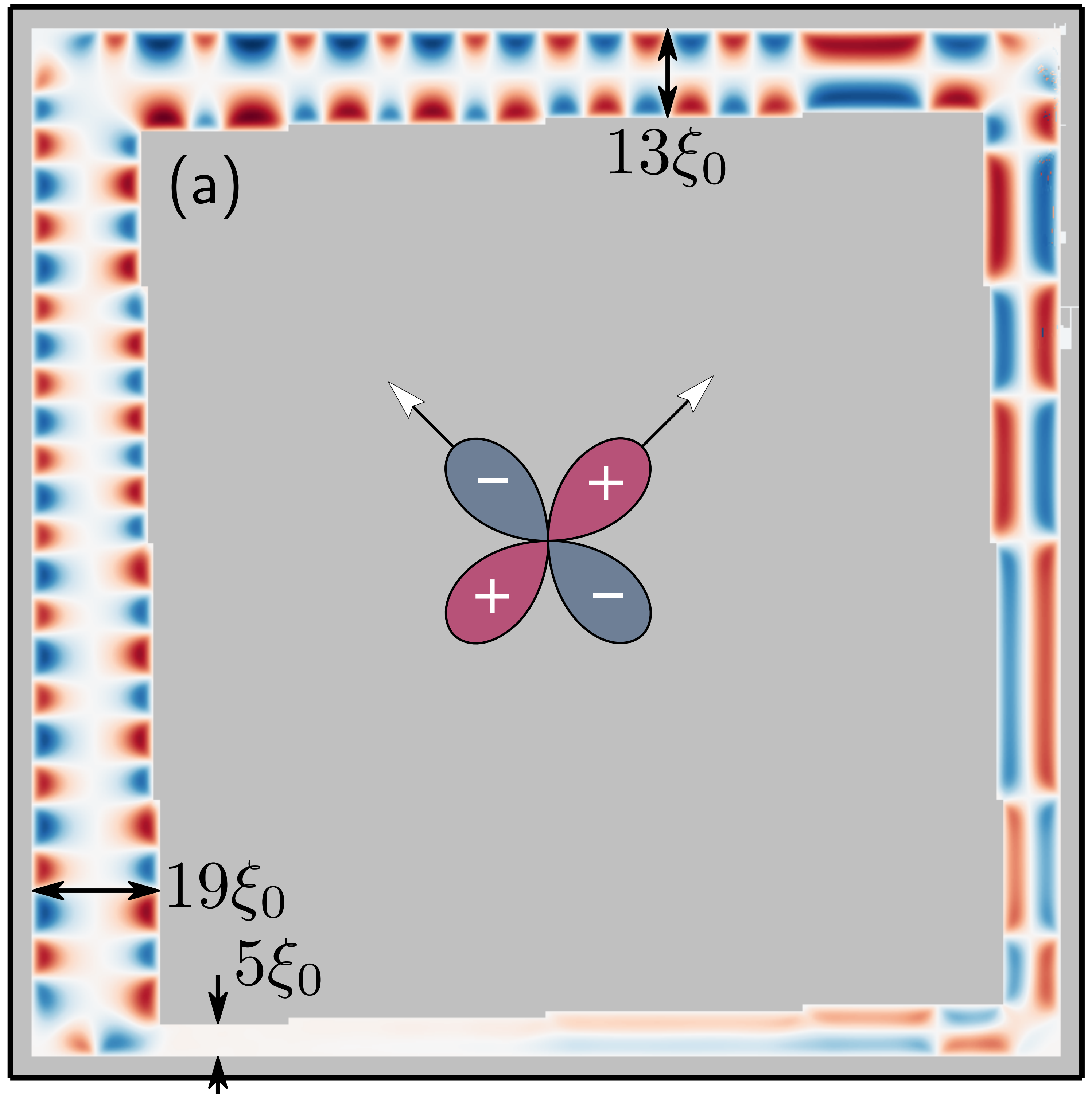
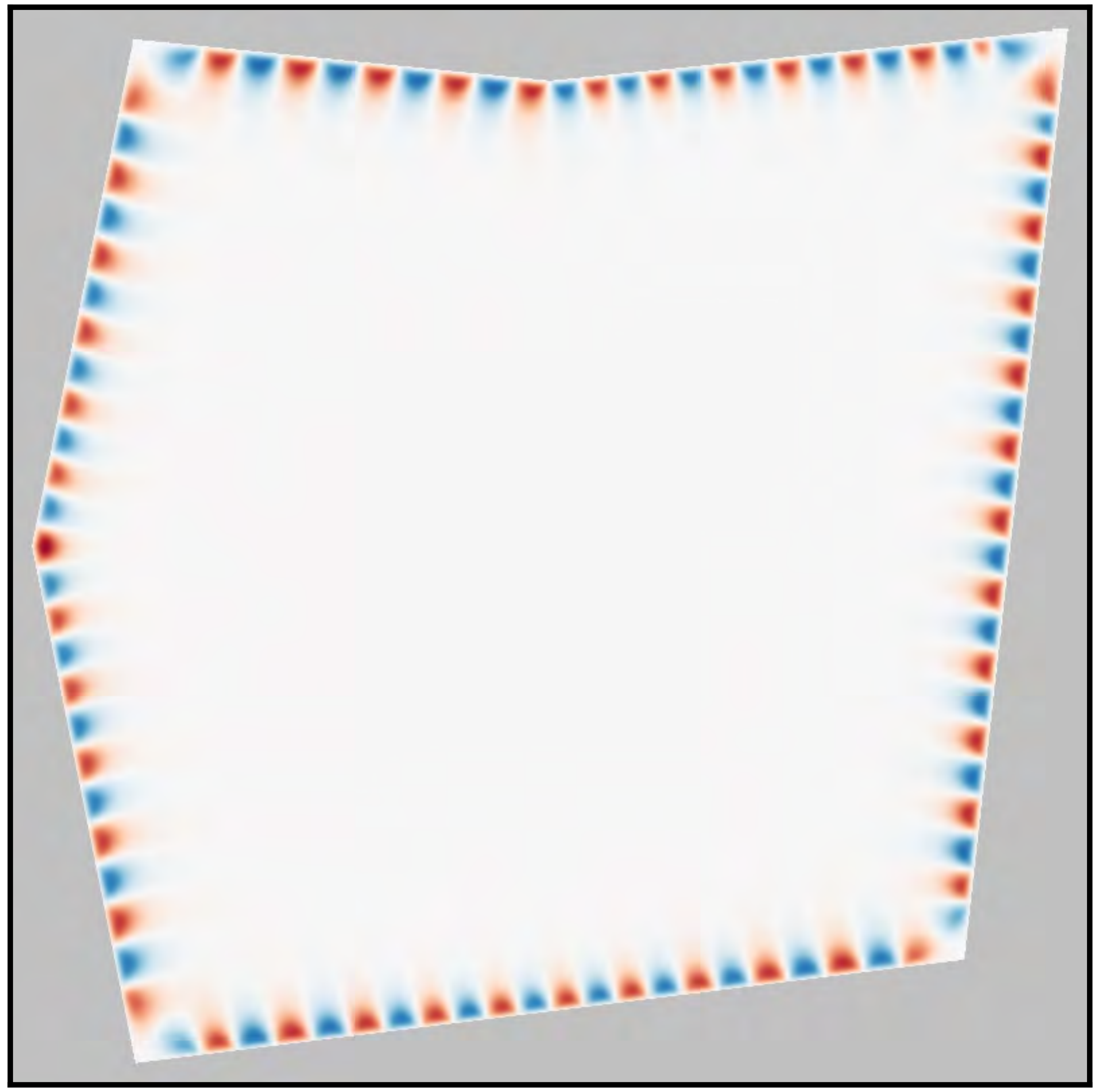
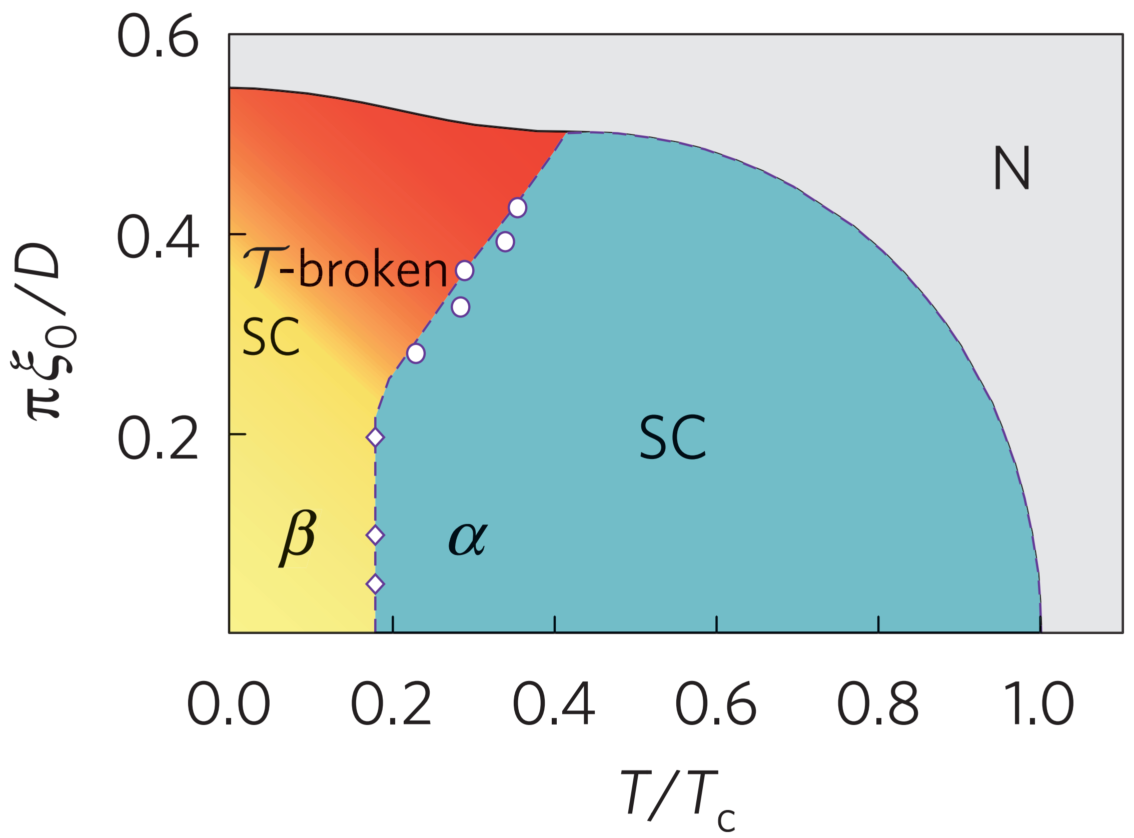

0.6
0.4
0.2
πξ0/D
0.0
0.2
0.4
0.6
0.8
1.0
T/Tc
N
T-broken
SC
SC
β
α


(a)
13ξ0
19ξ0
5ξ0
−
+
+
−

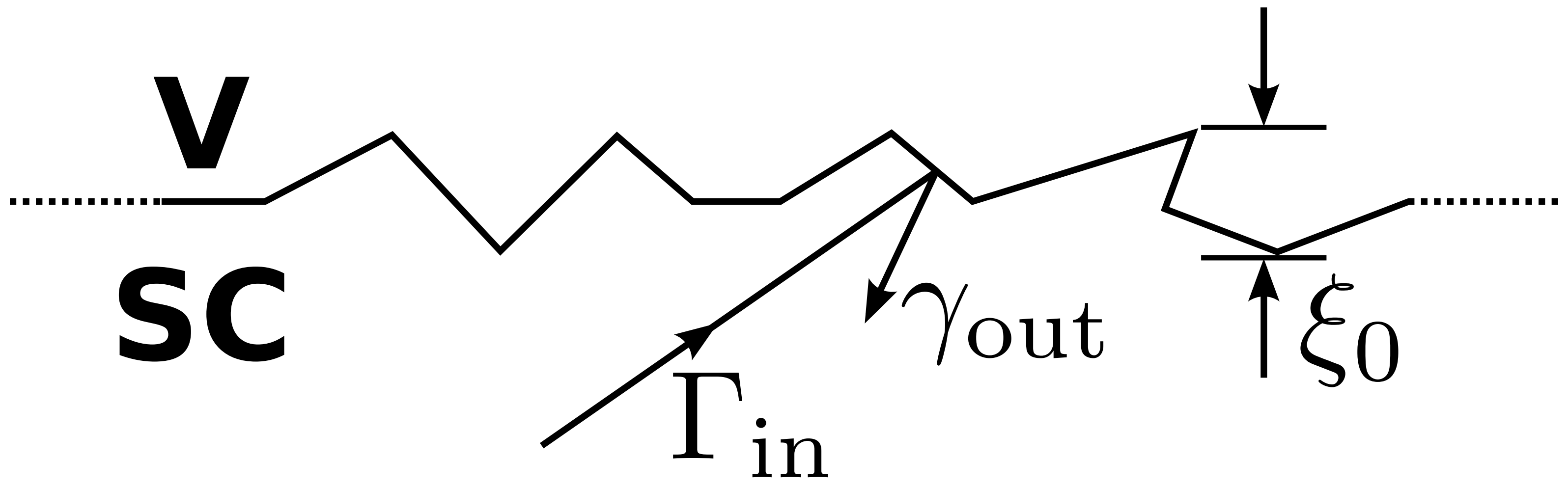

0.6
0.4
0.2
$\pi\xi_0/D$
N
$\mathcal{T}$-broken
SC
SC
β
α
0.0
0.2
0.4
0.6
0.8
1.0
T/T_c

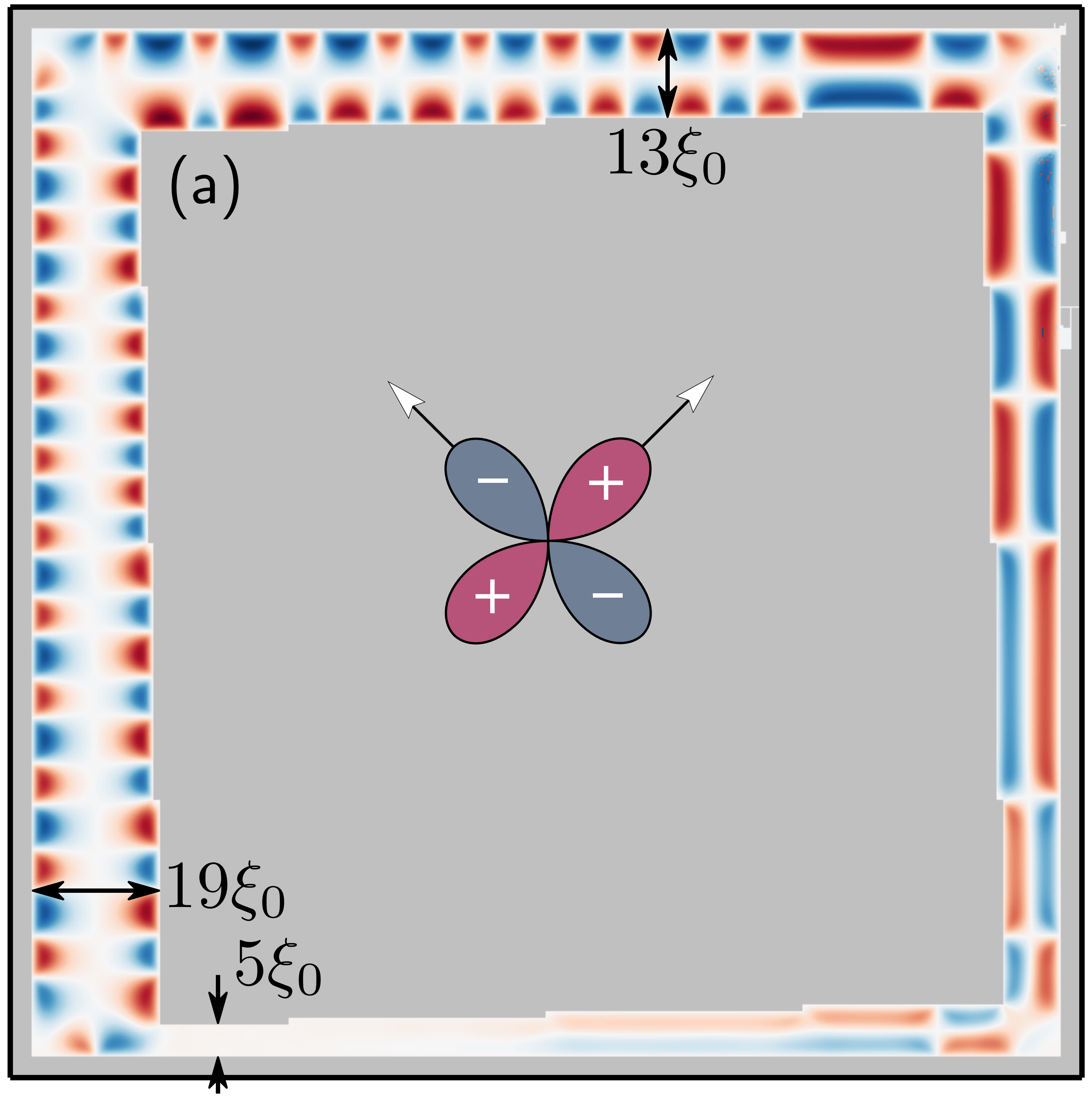

(a)
$13\xi_0$
$19\xi_0$
$5\xi_0$
−
+
+
−

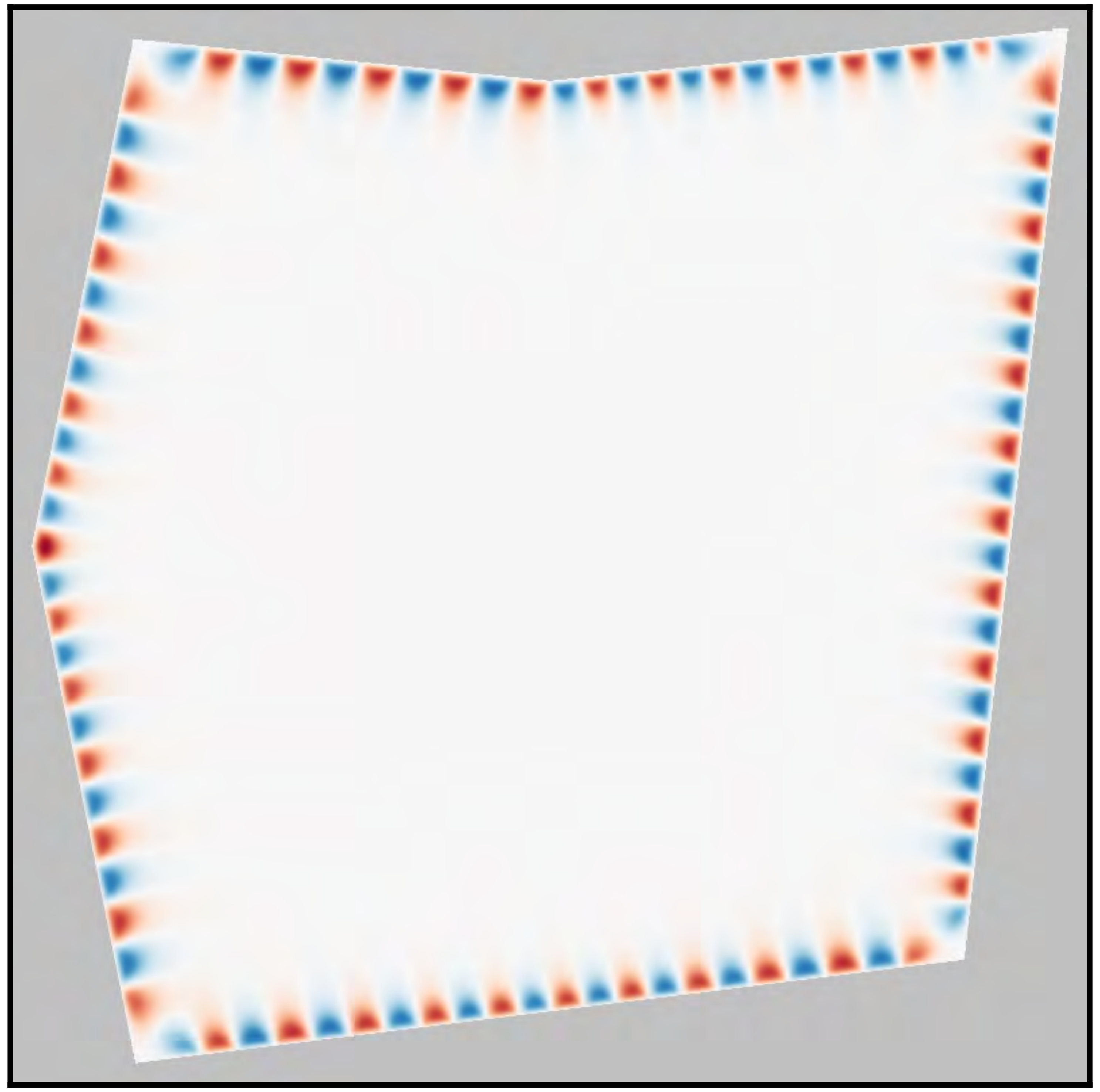


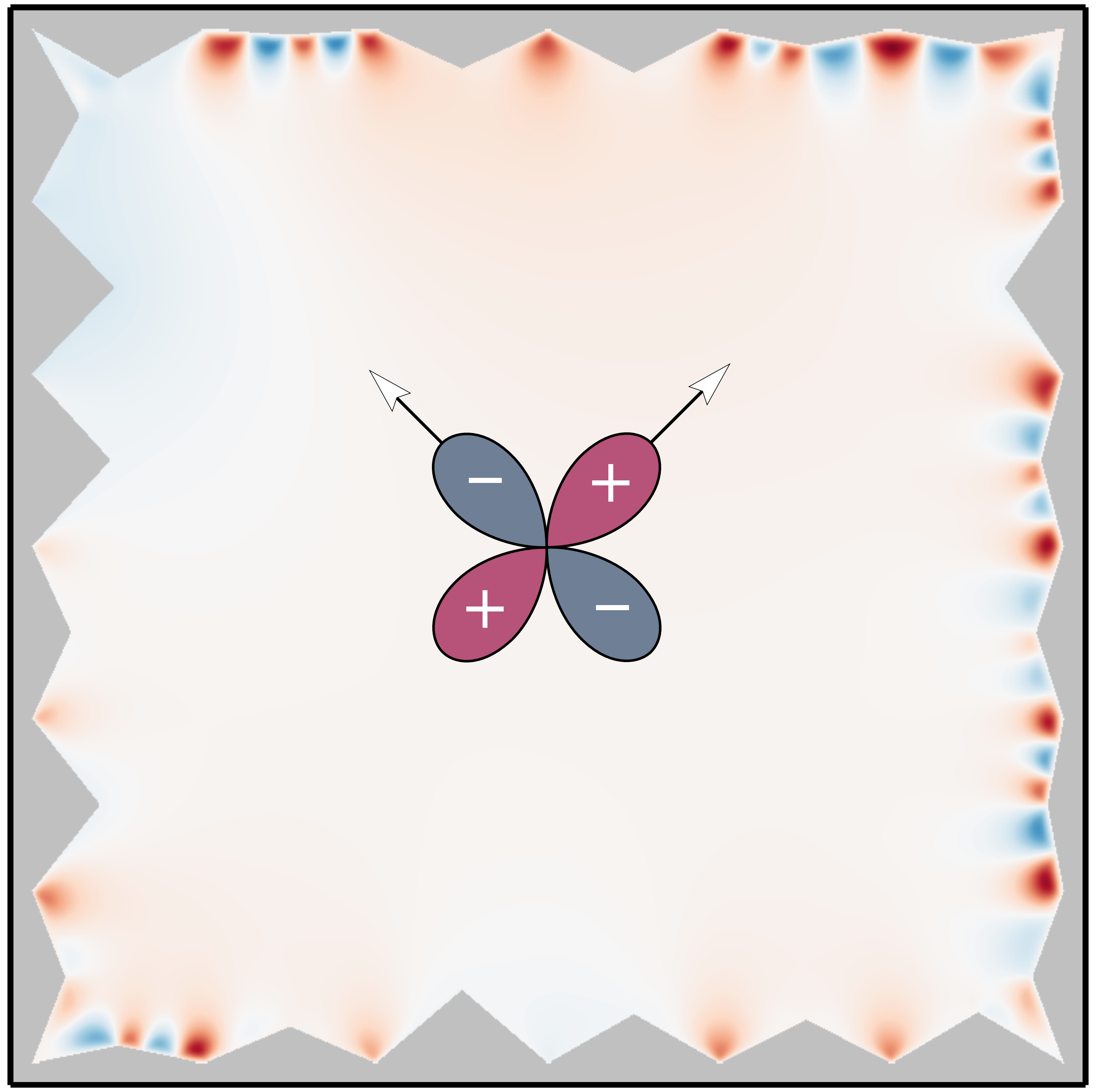


Surface roughness









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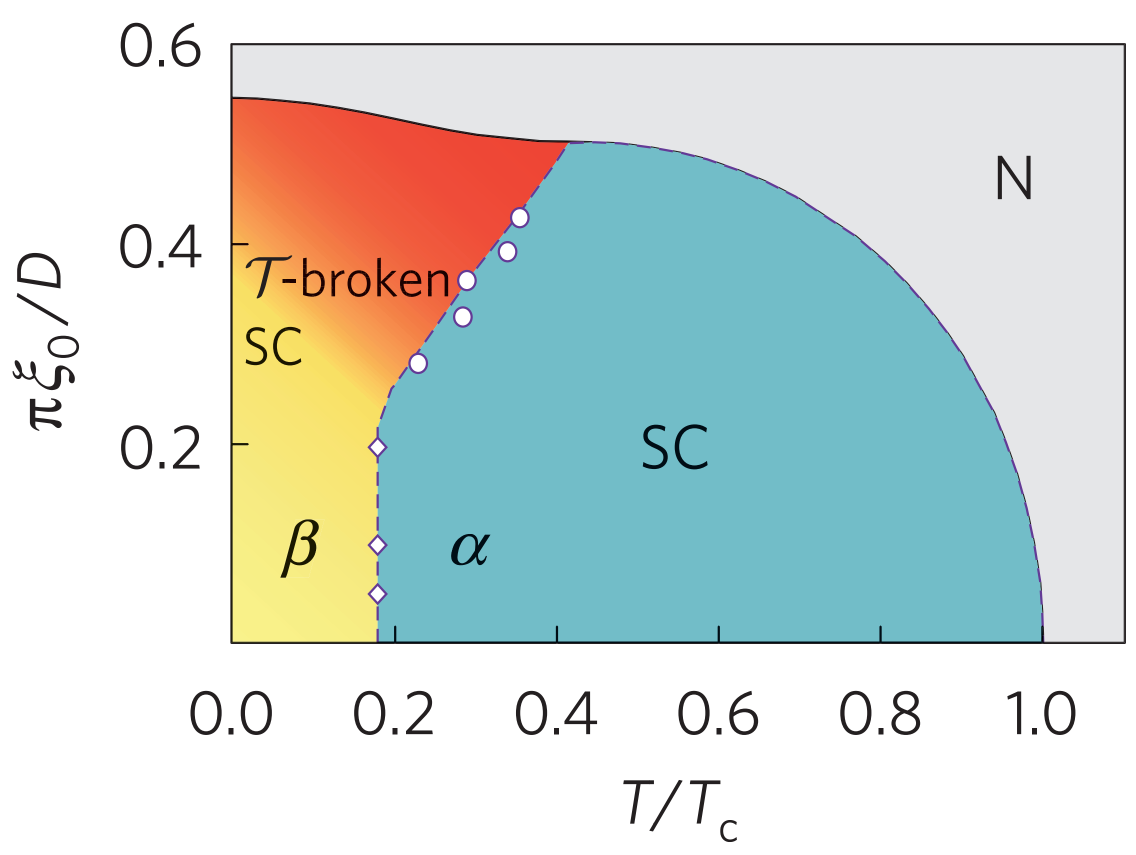

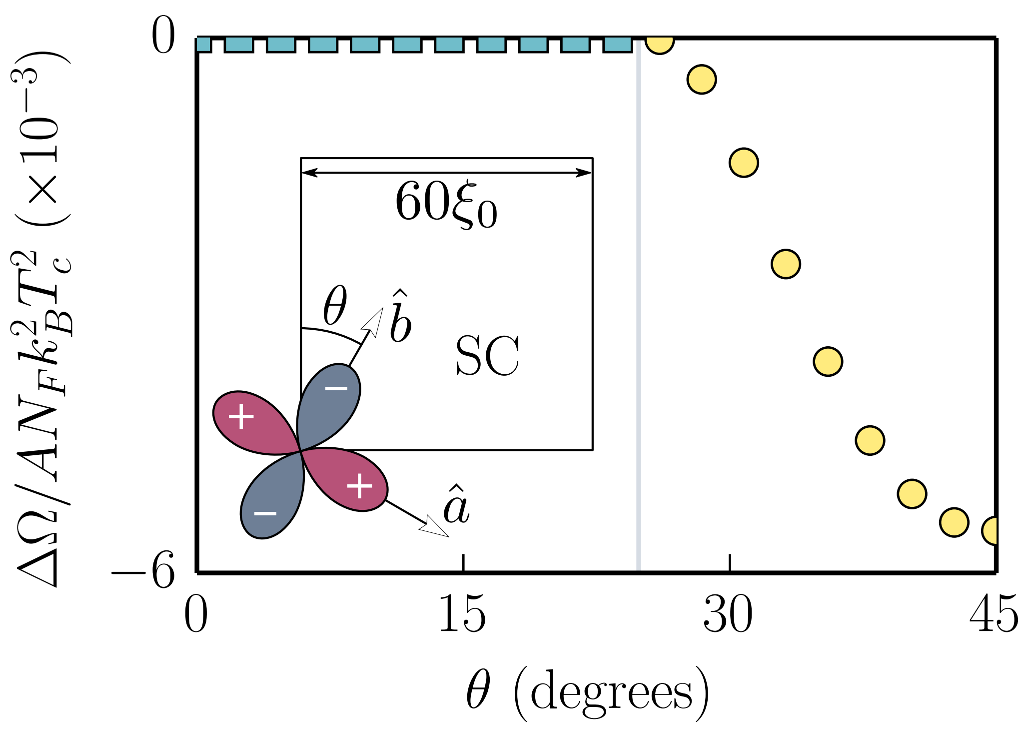

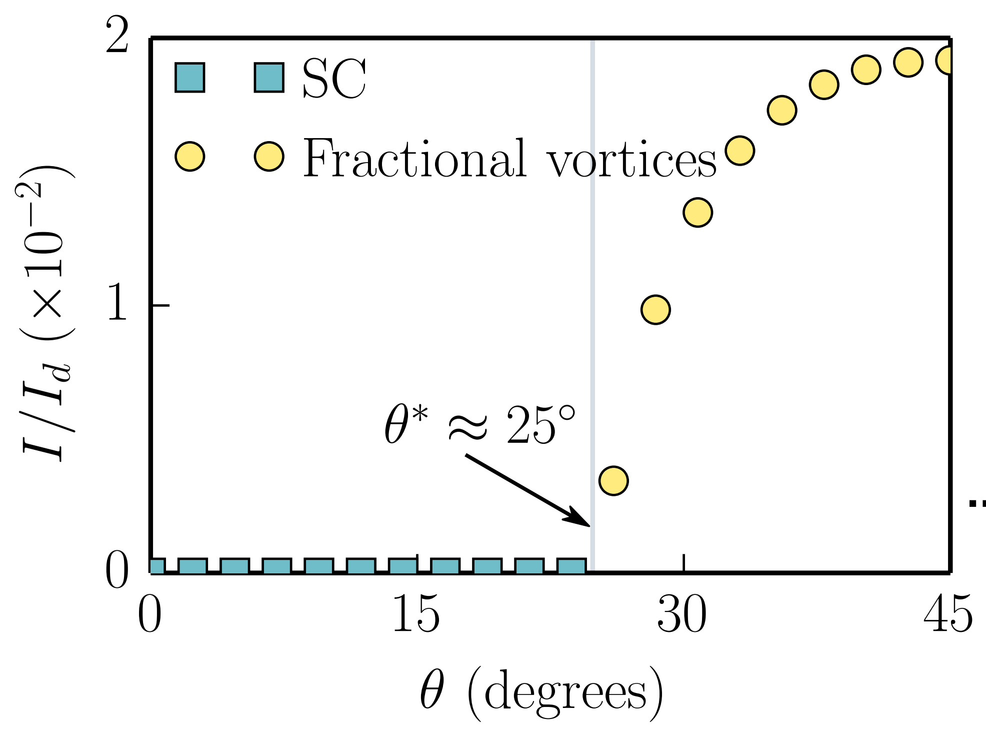

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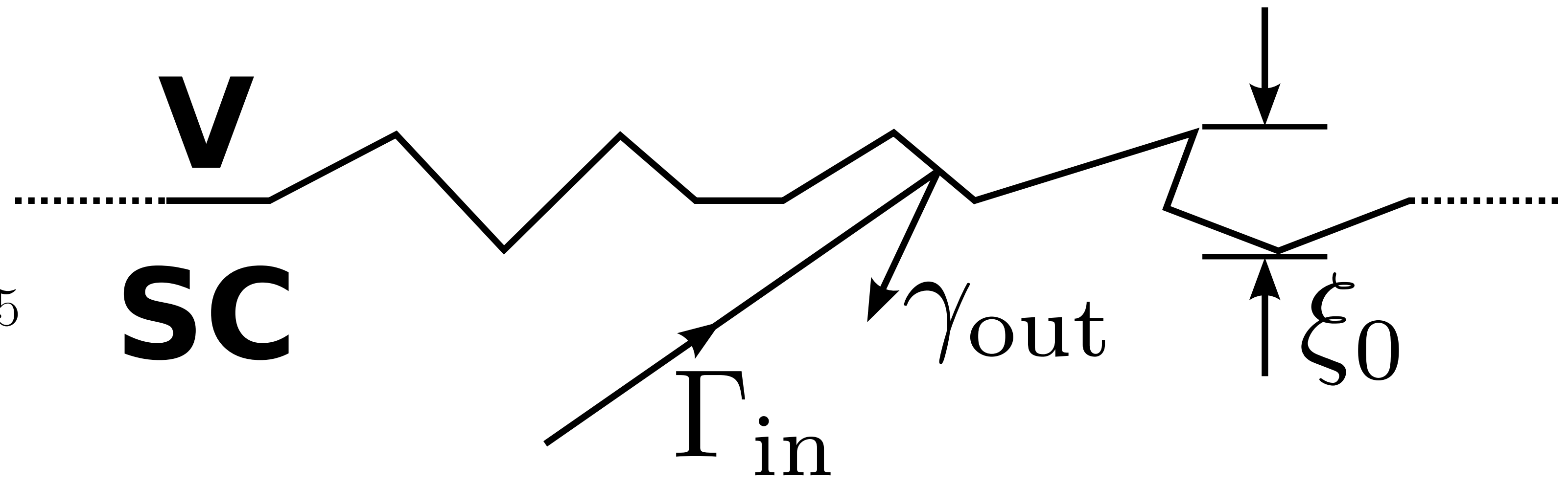

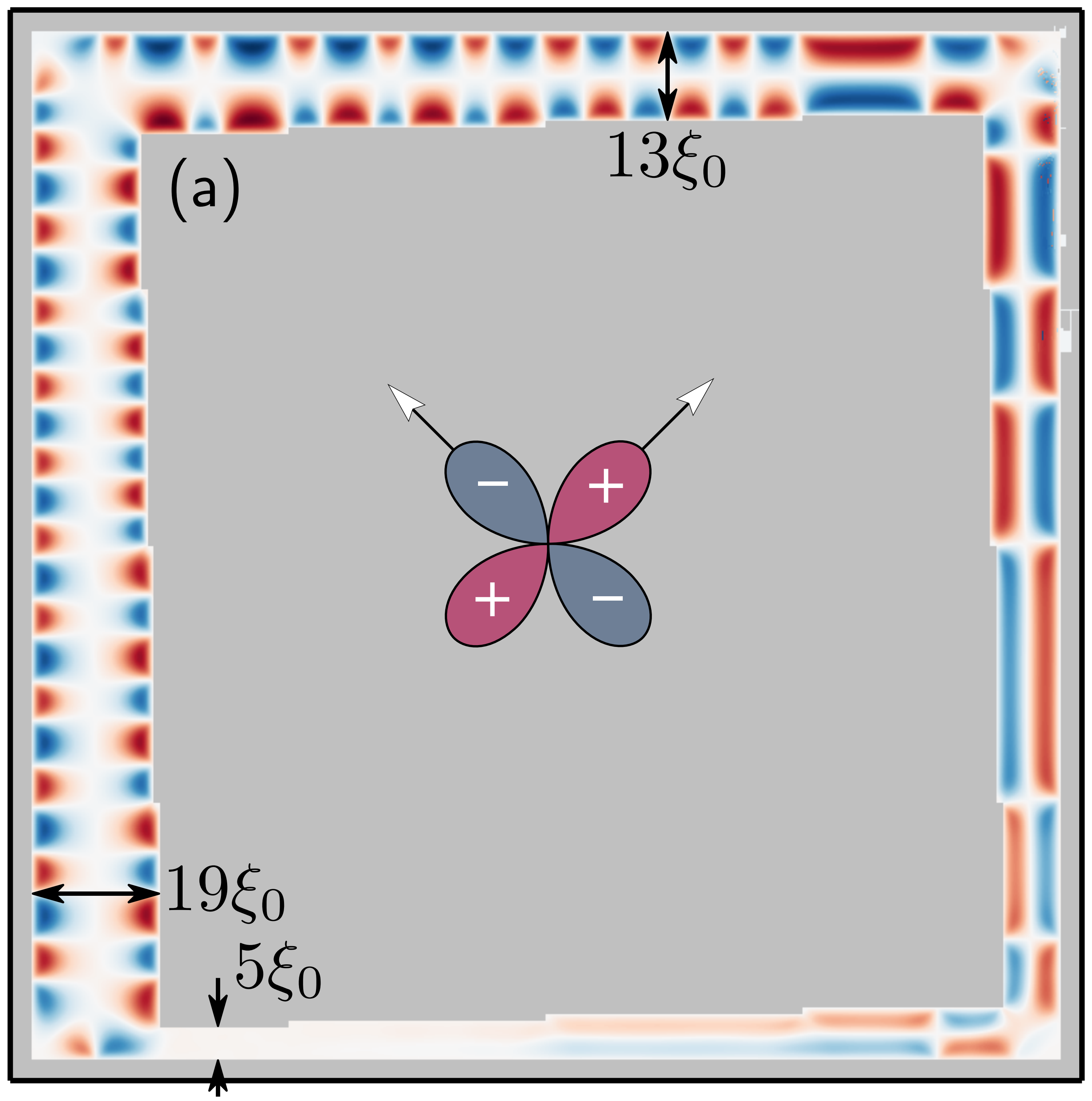

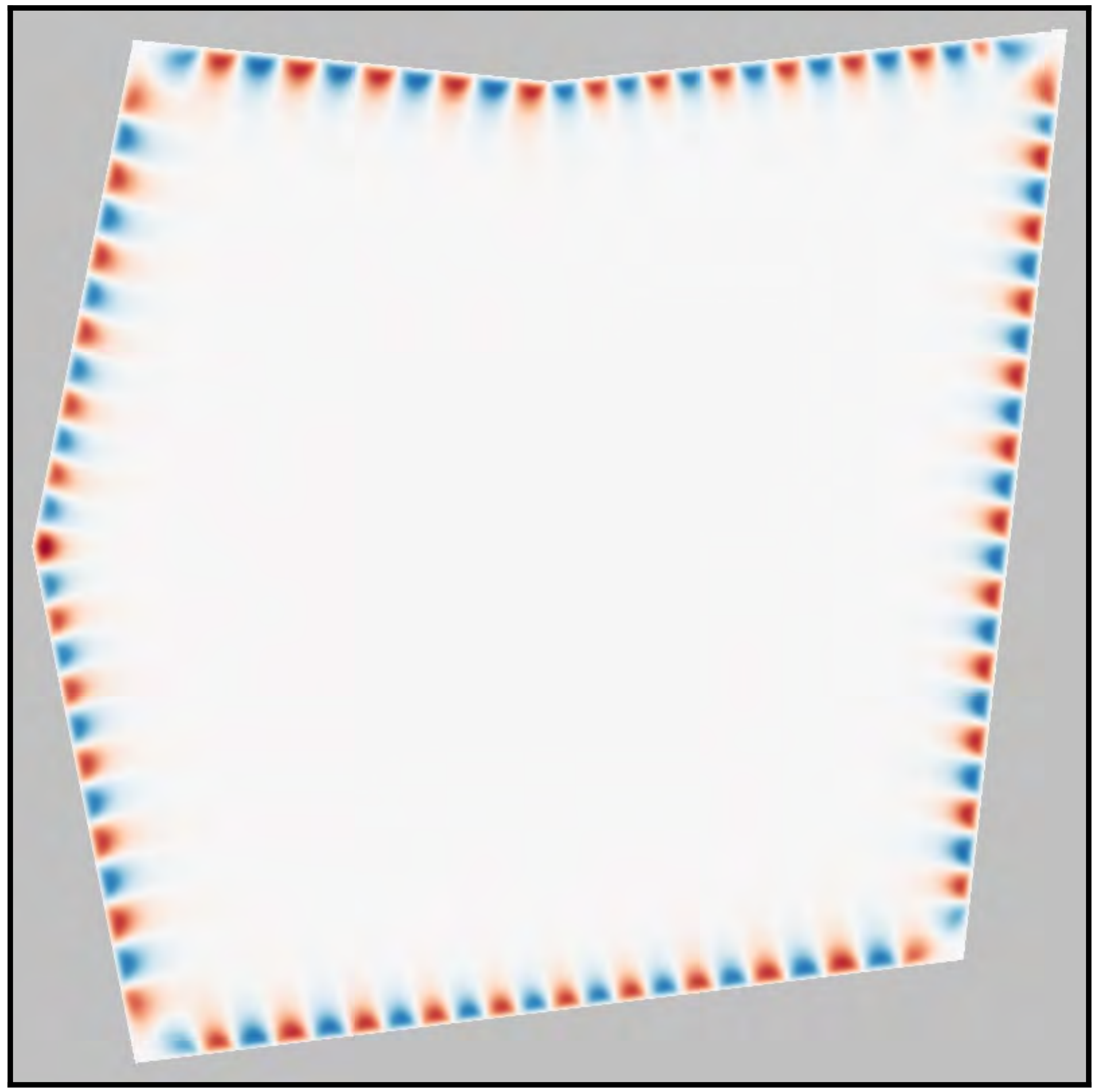

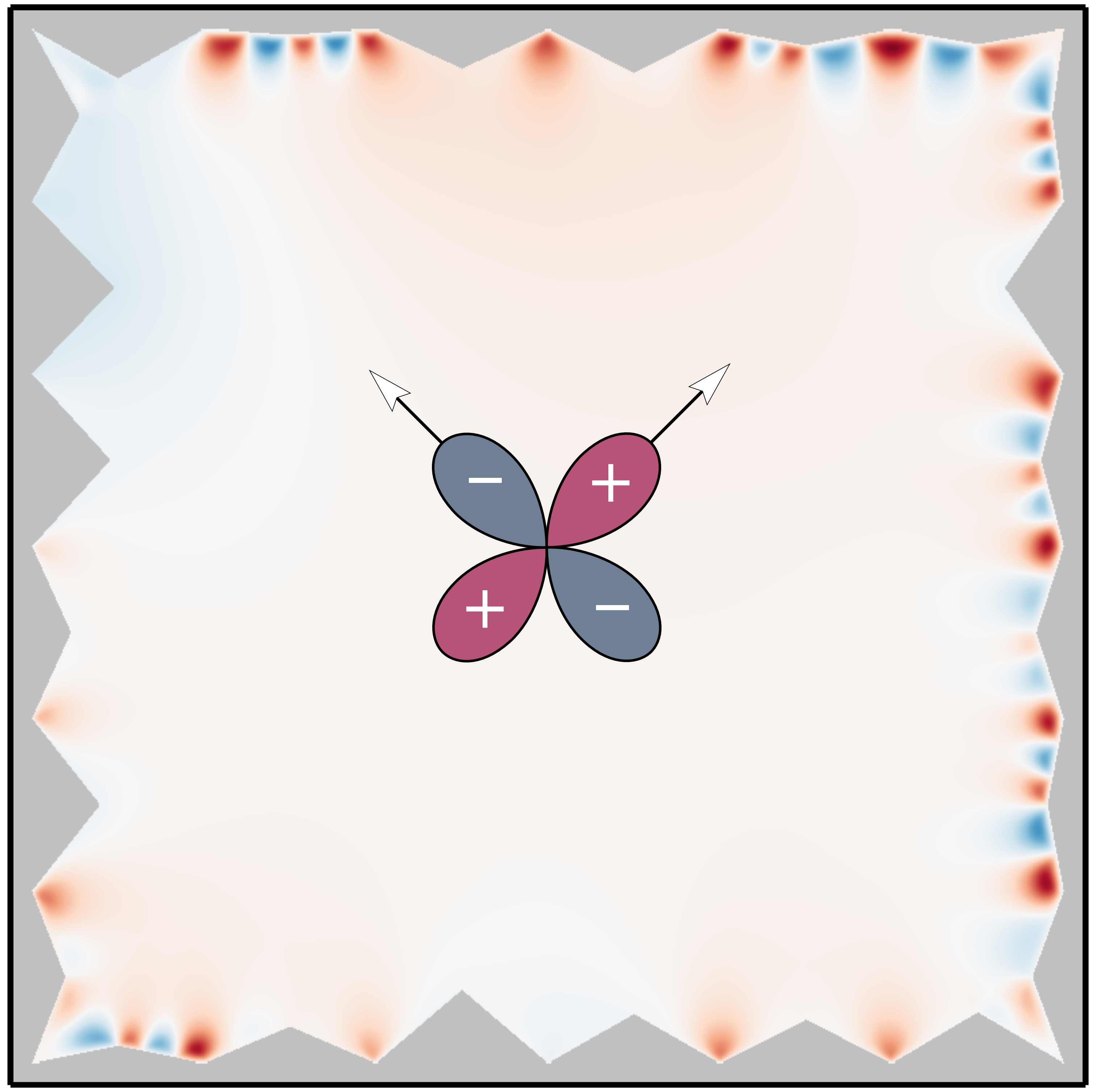

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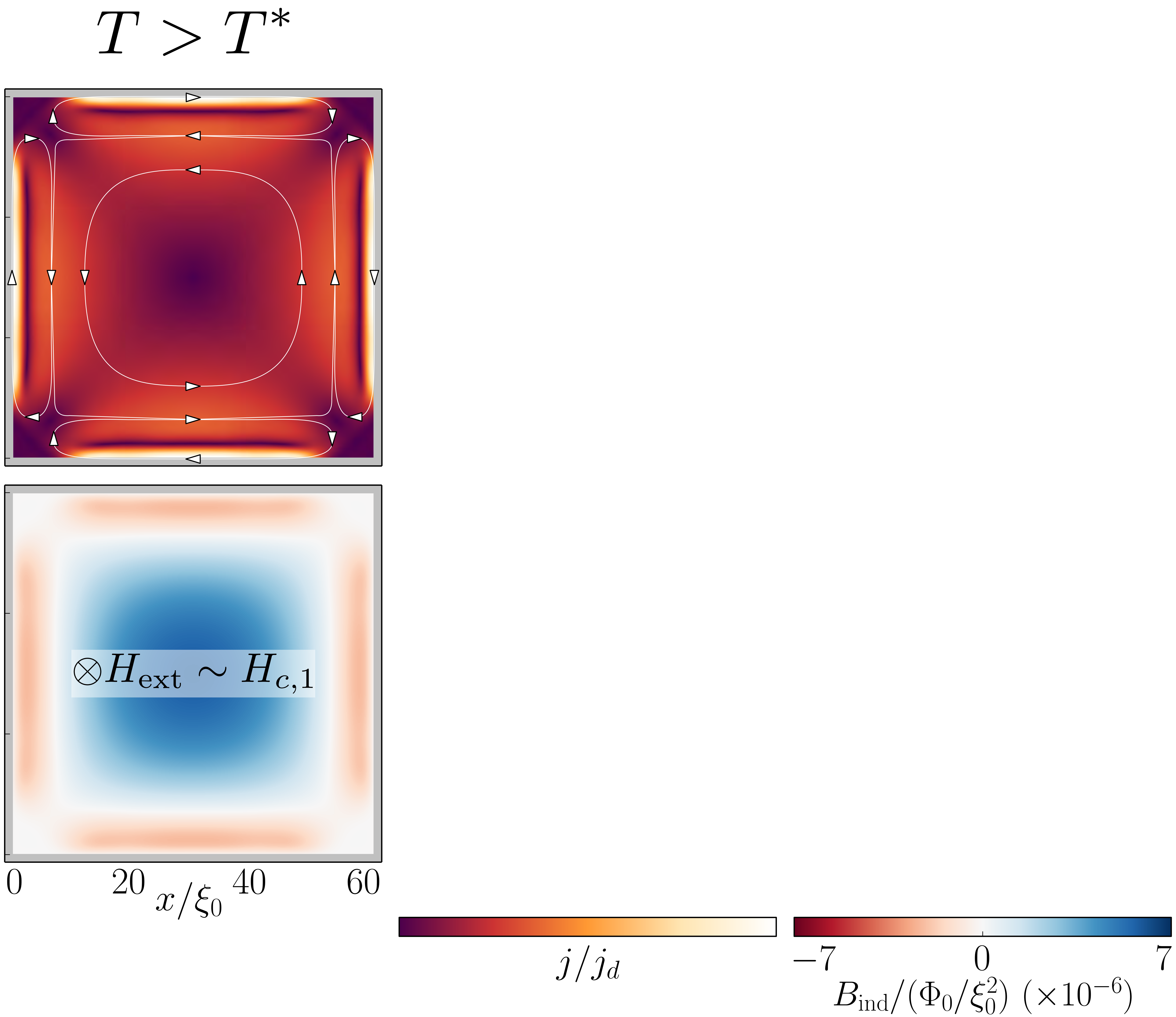
Adding an eternal magnetic field ~$H_{c,g}$



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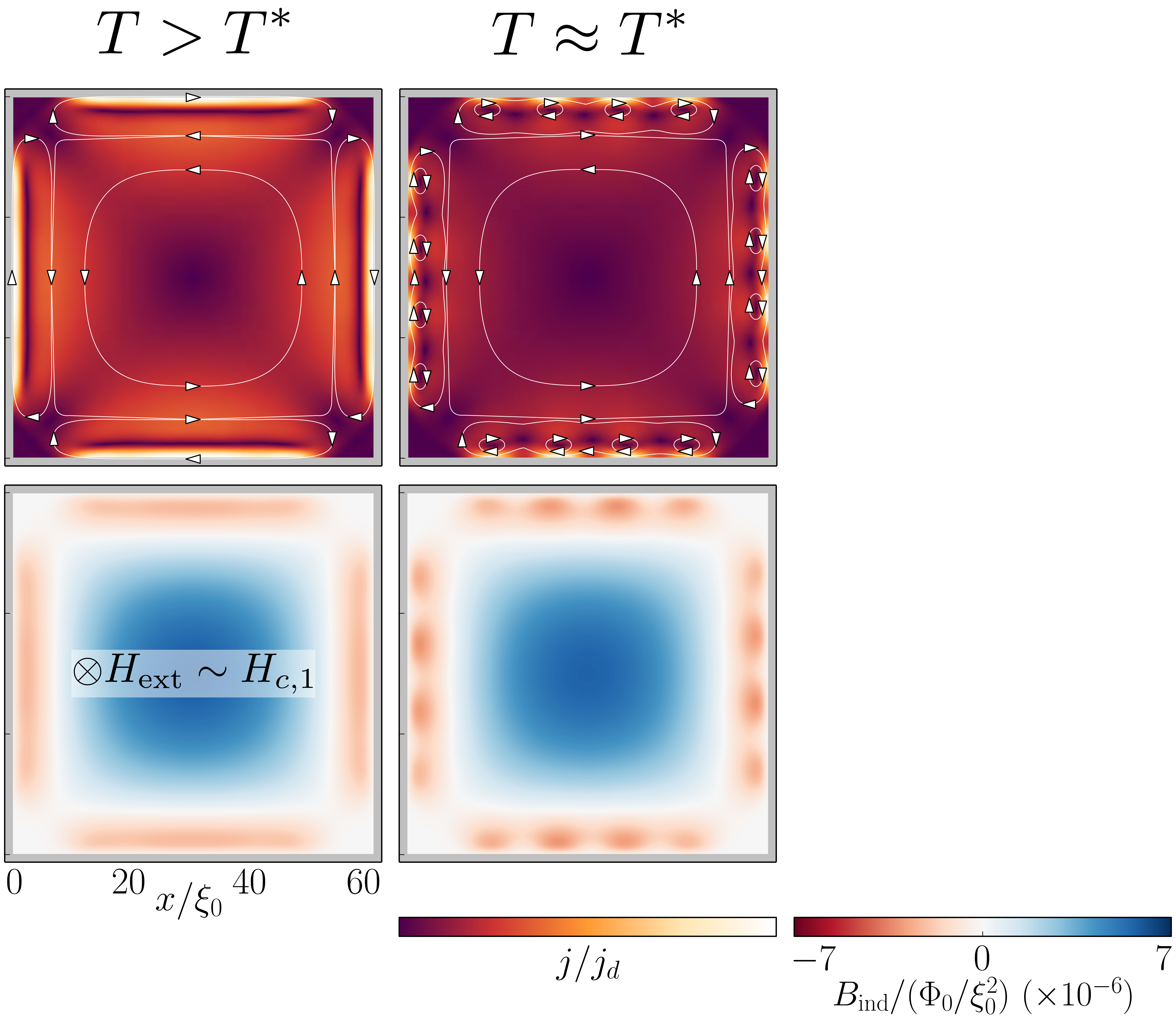

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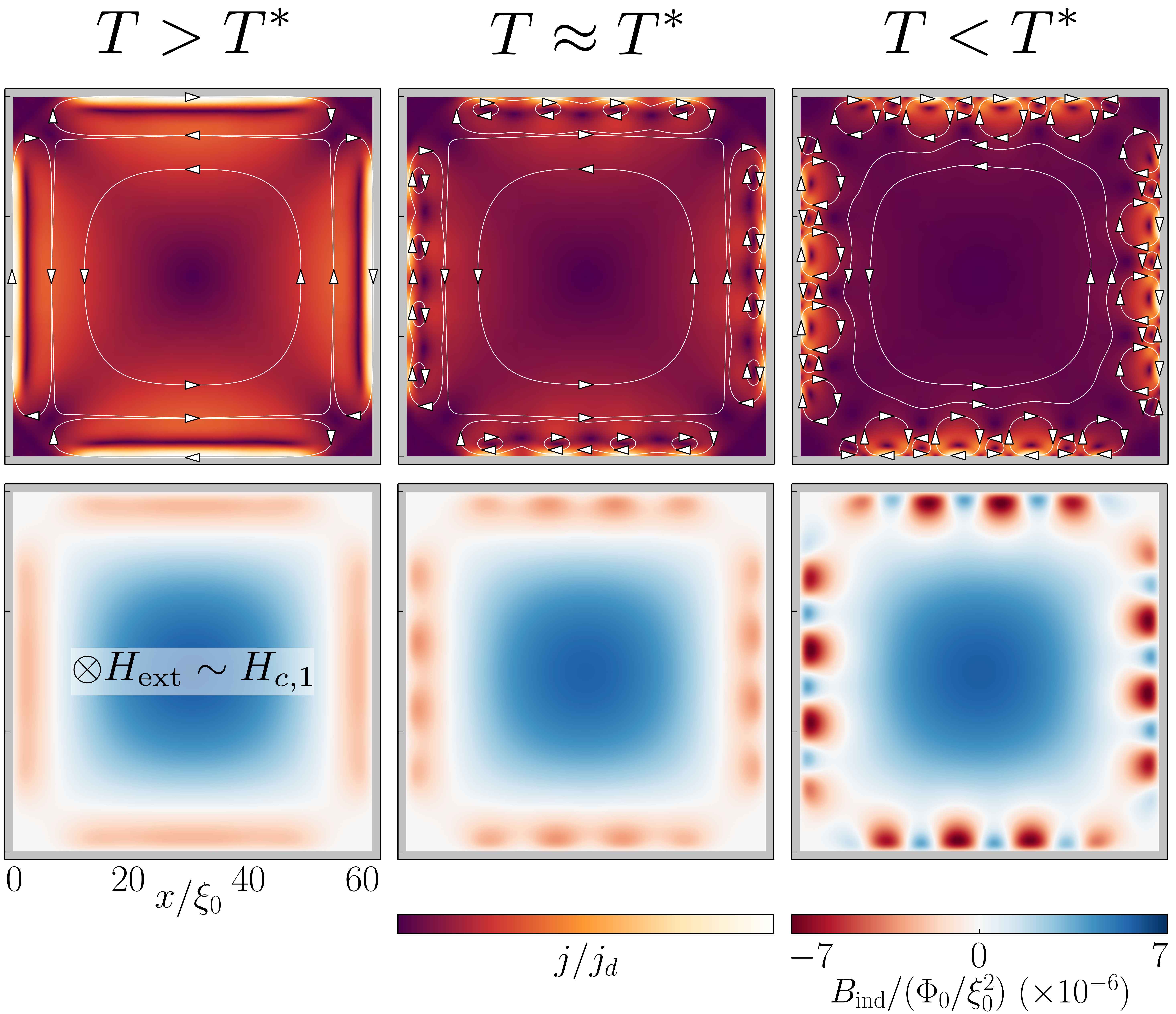
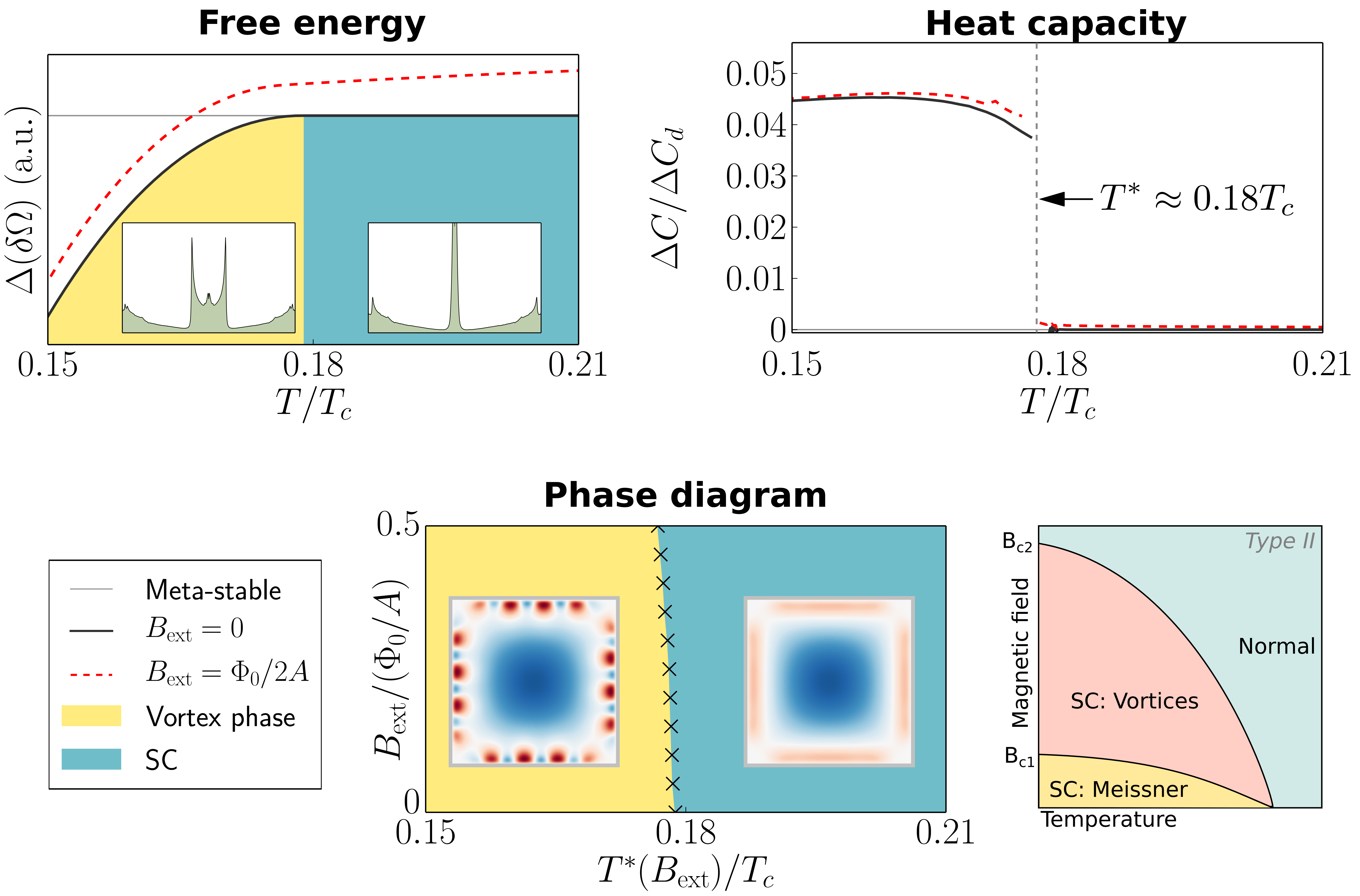


Thermodynamics in an external field (λ≫ξ)



Mikael Fogelström, Applied Quantum Physics Laboratory

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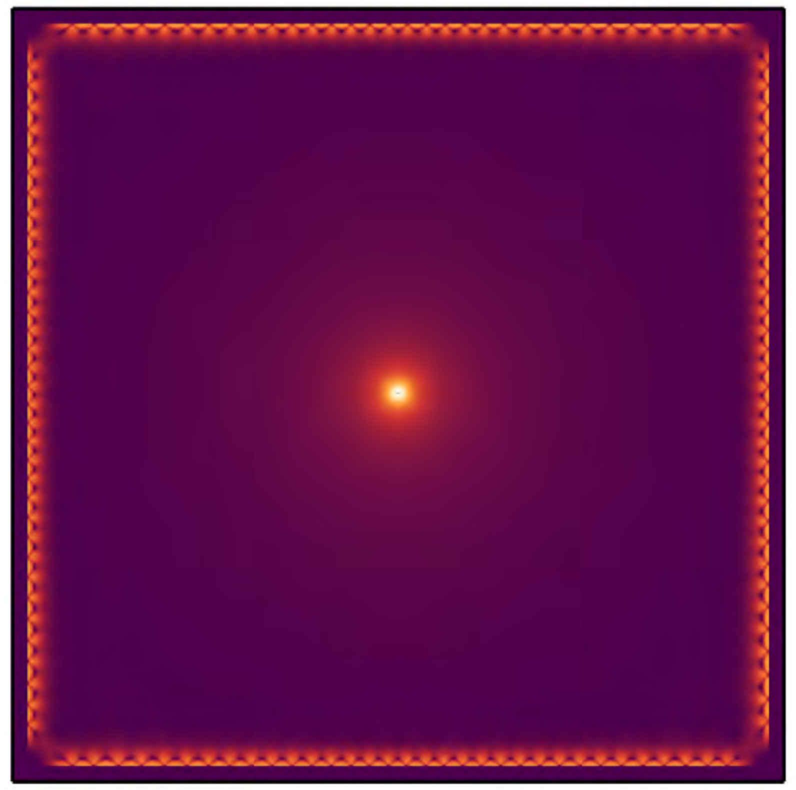
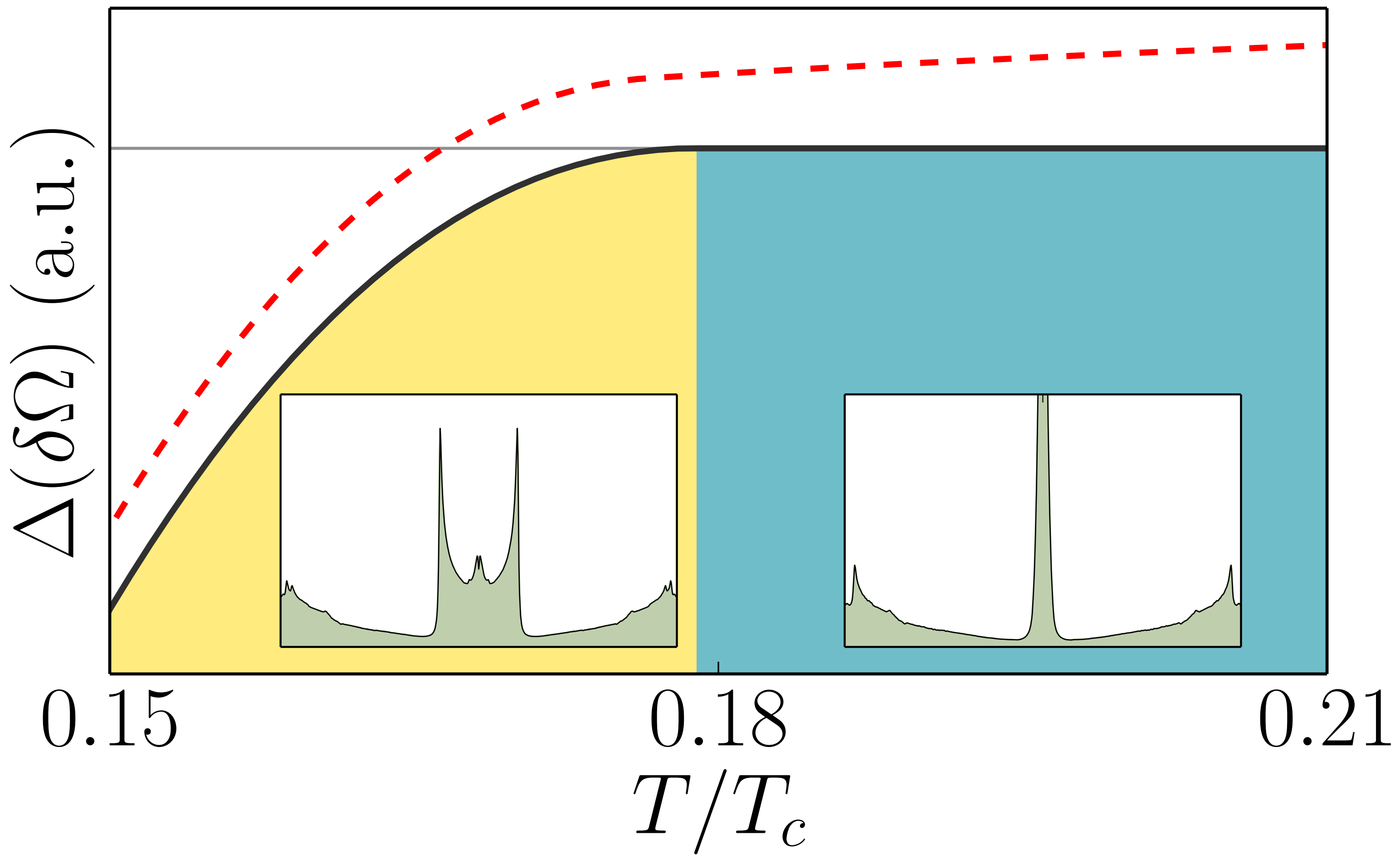
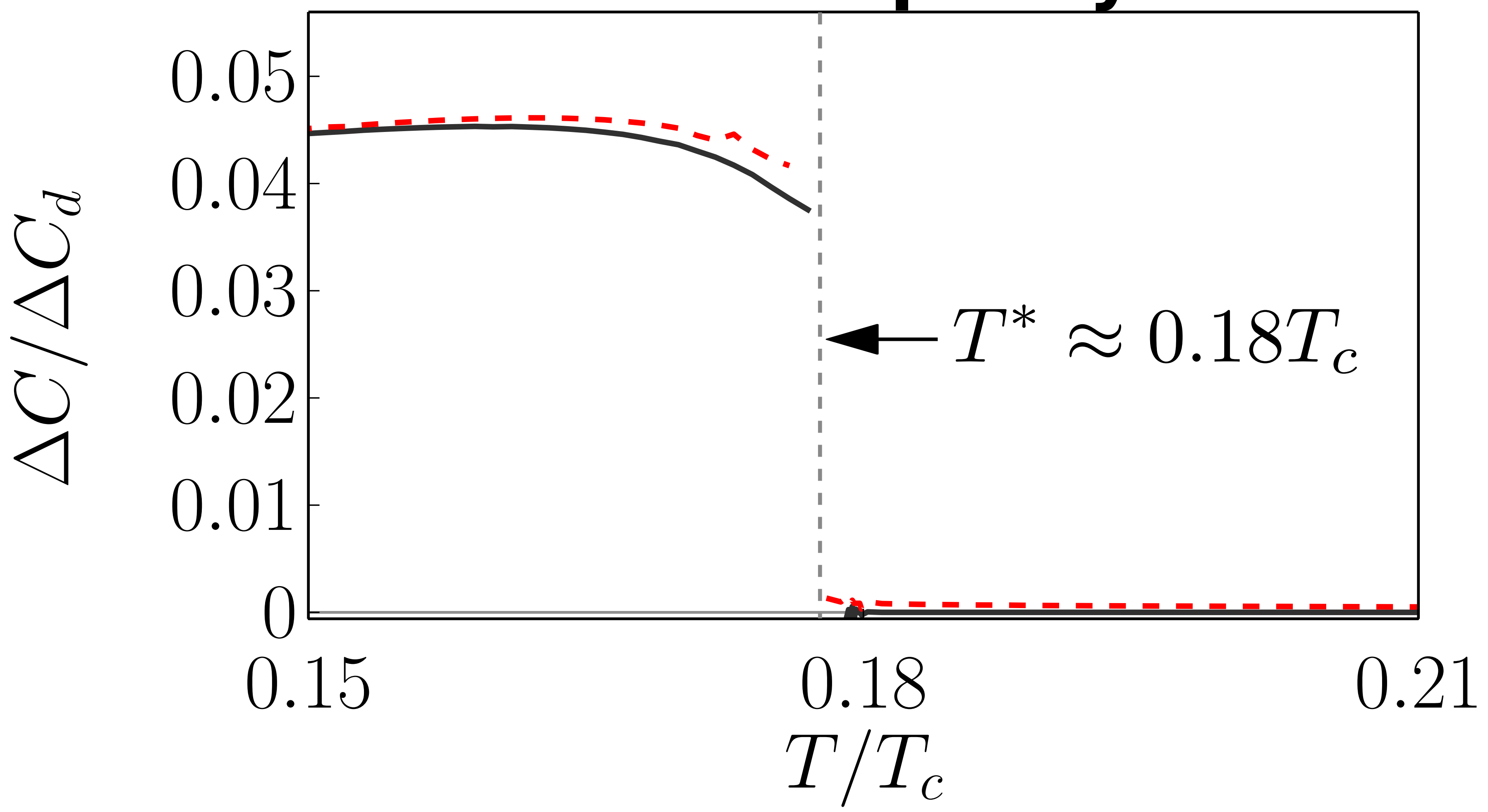


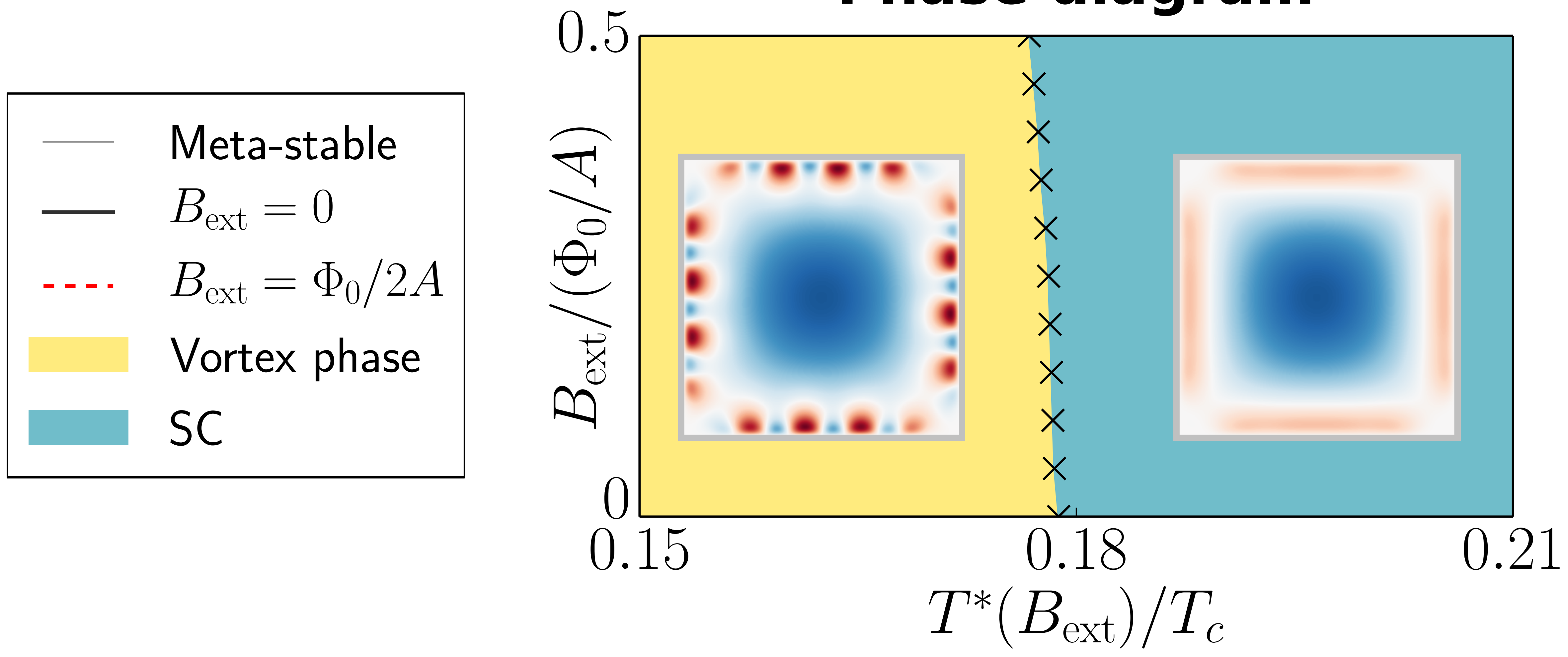
Free energy

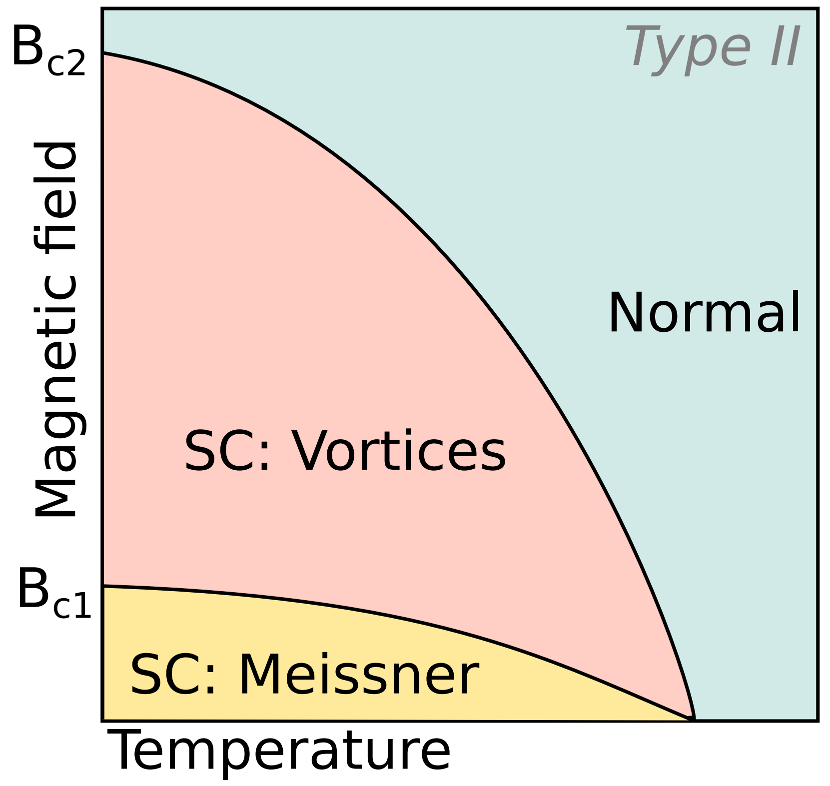


Heat capacity

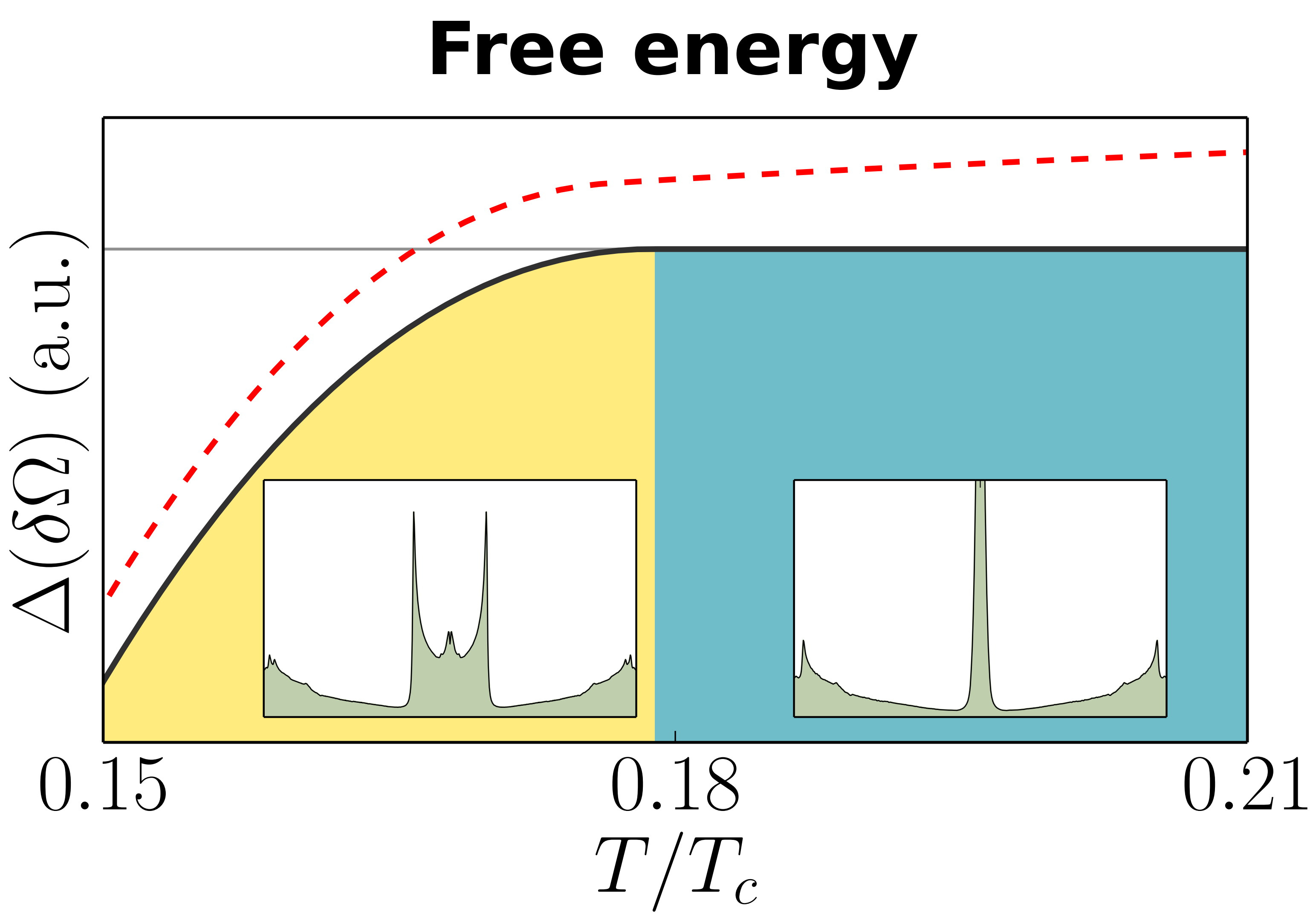


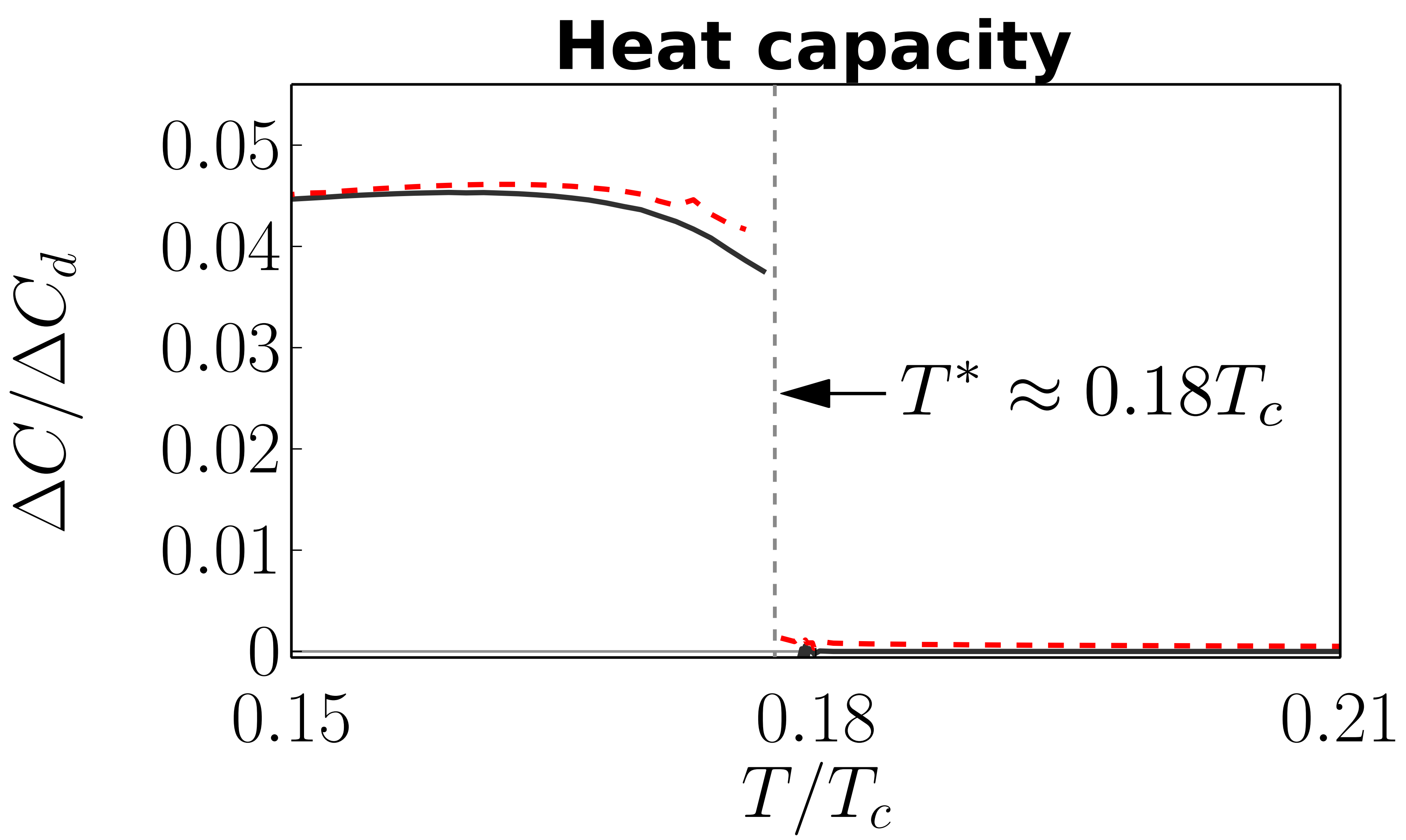
Phase diagram

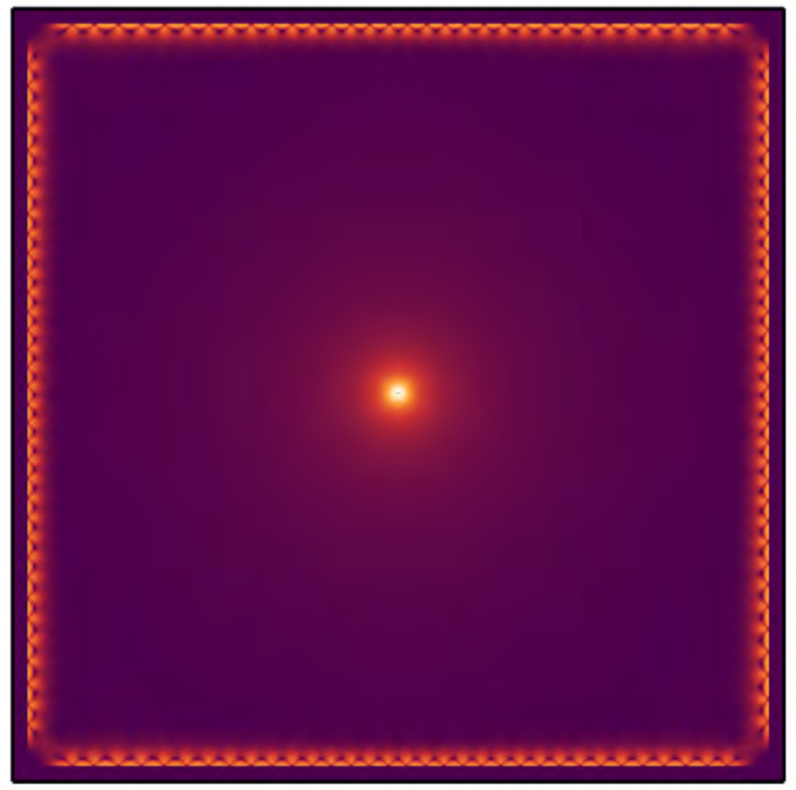


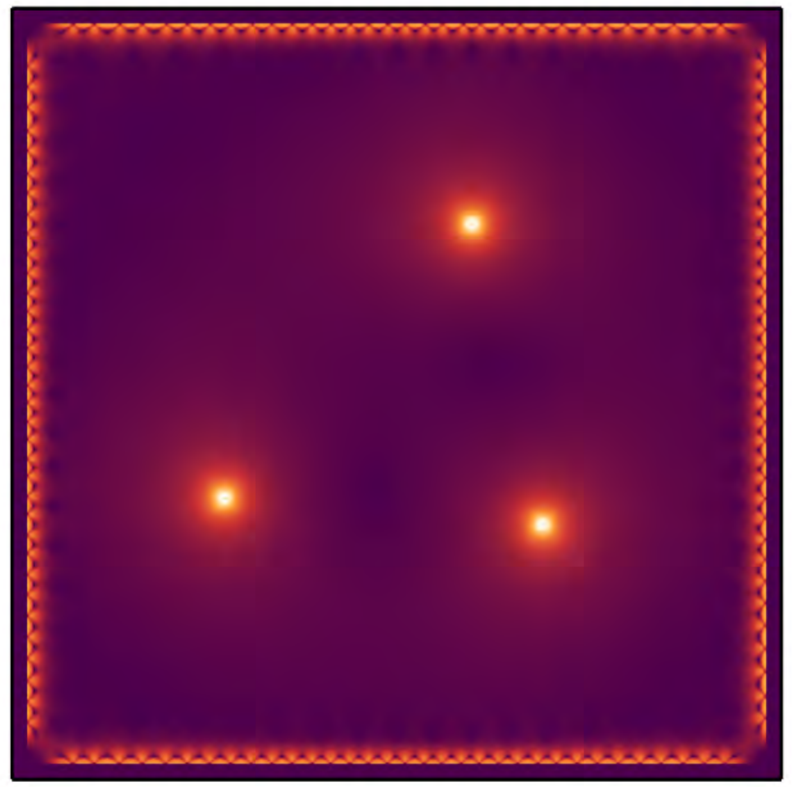


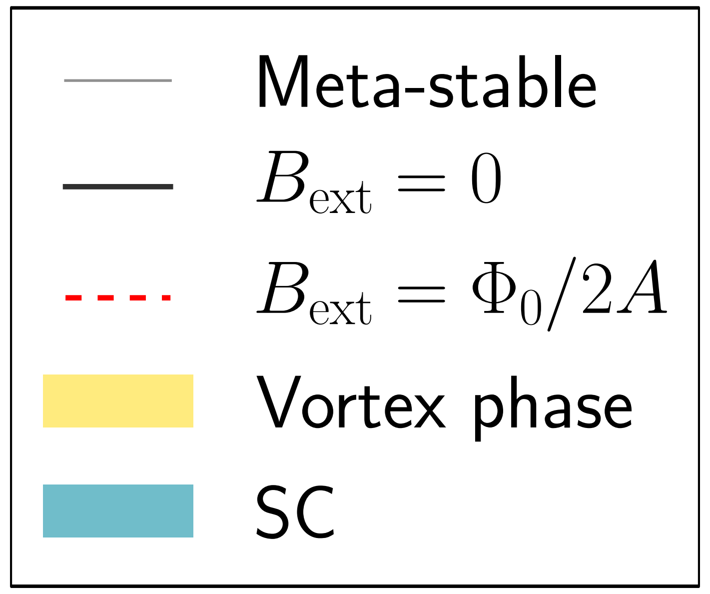
Thermodynamics in an external field (λ≫ξ)

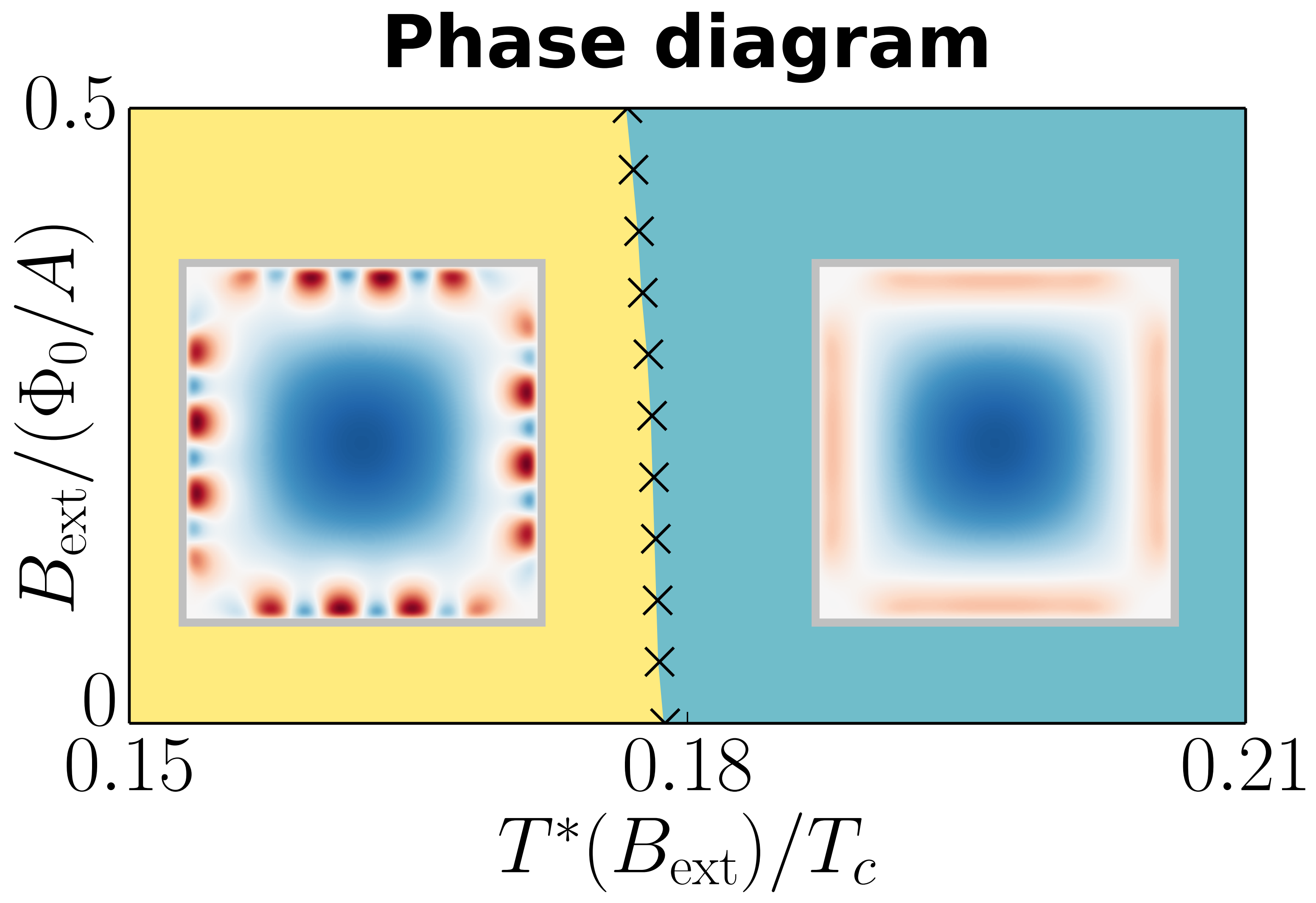


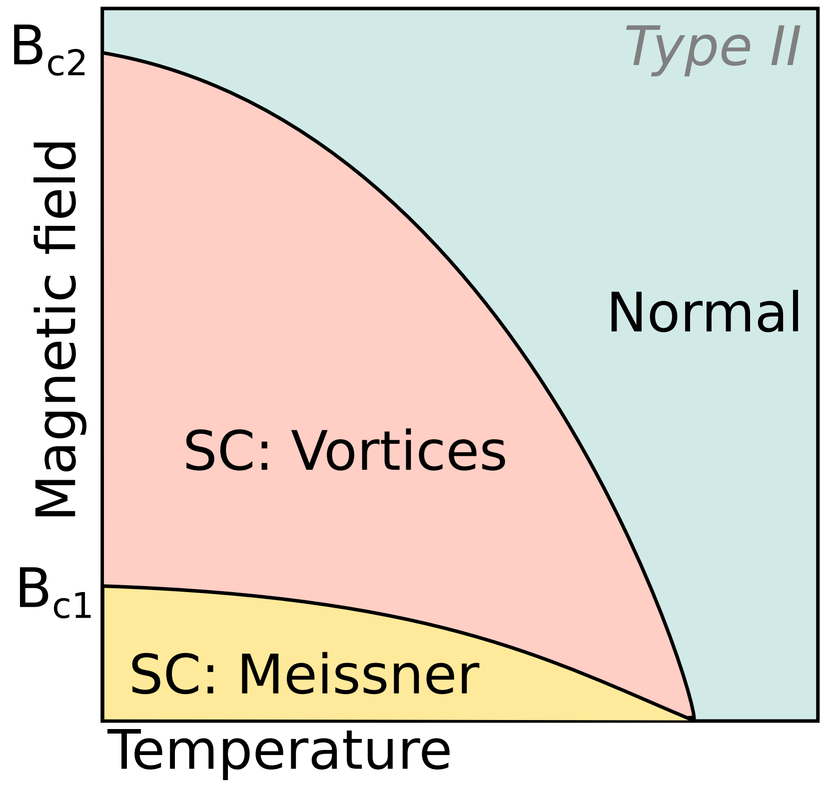




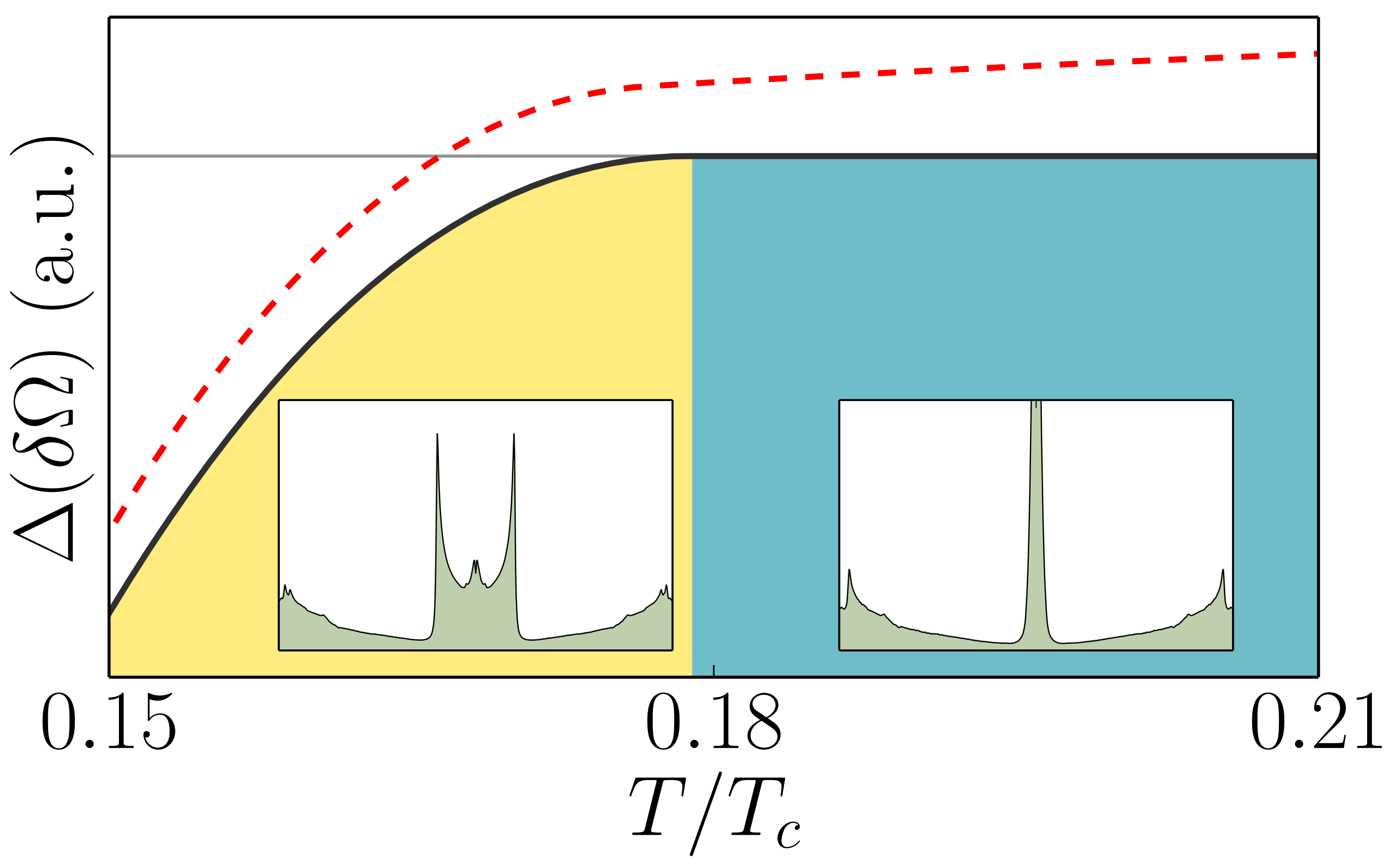


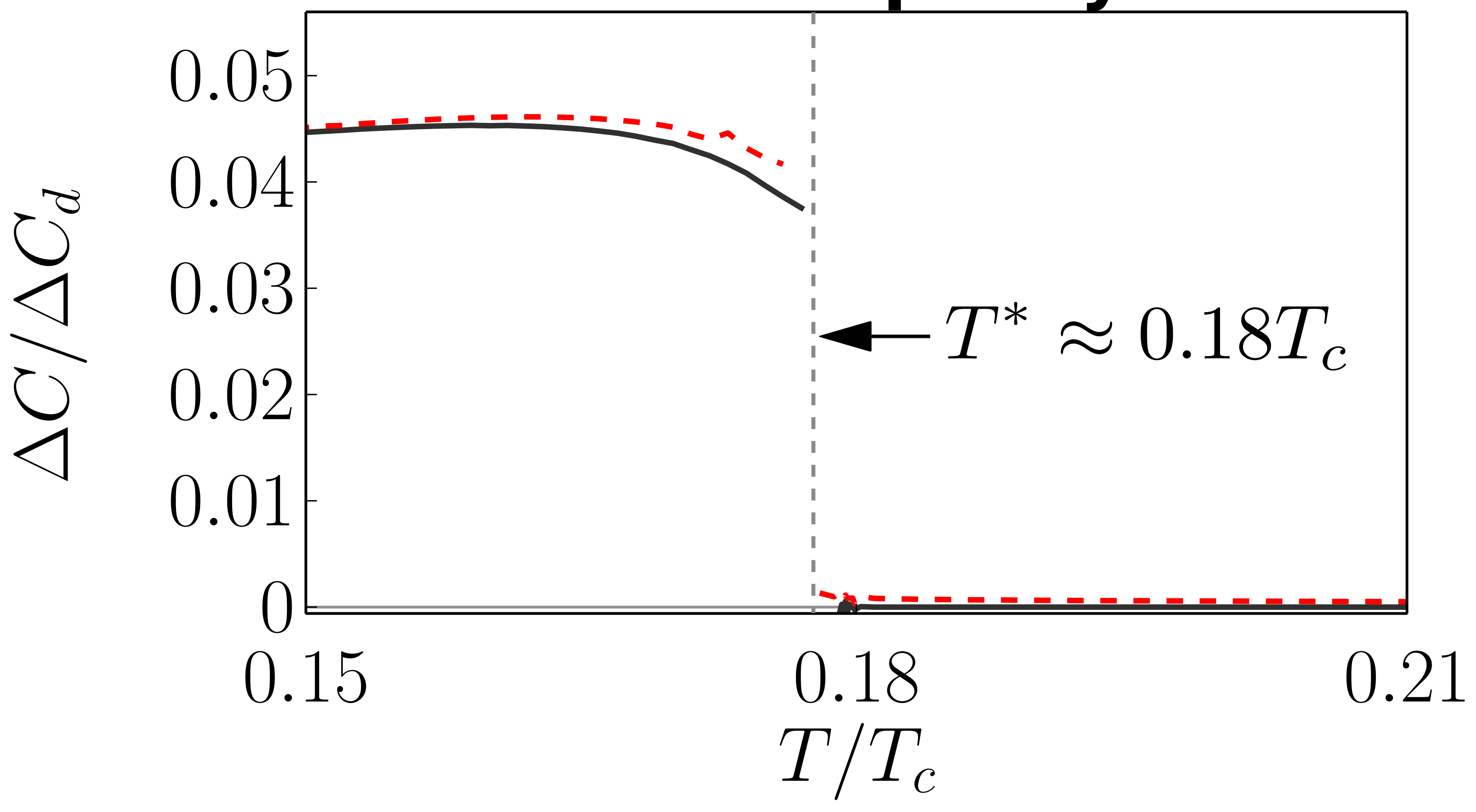


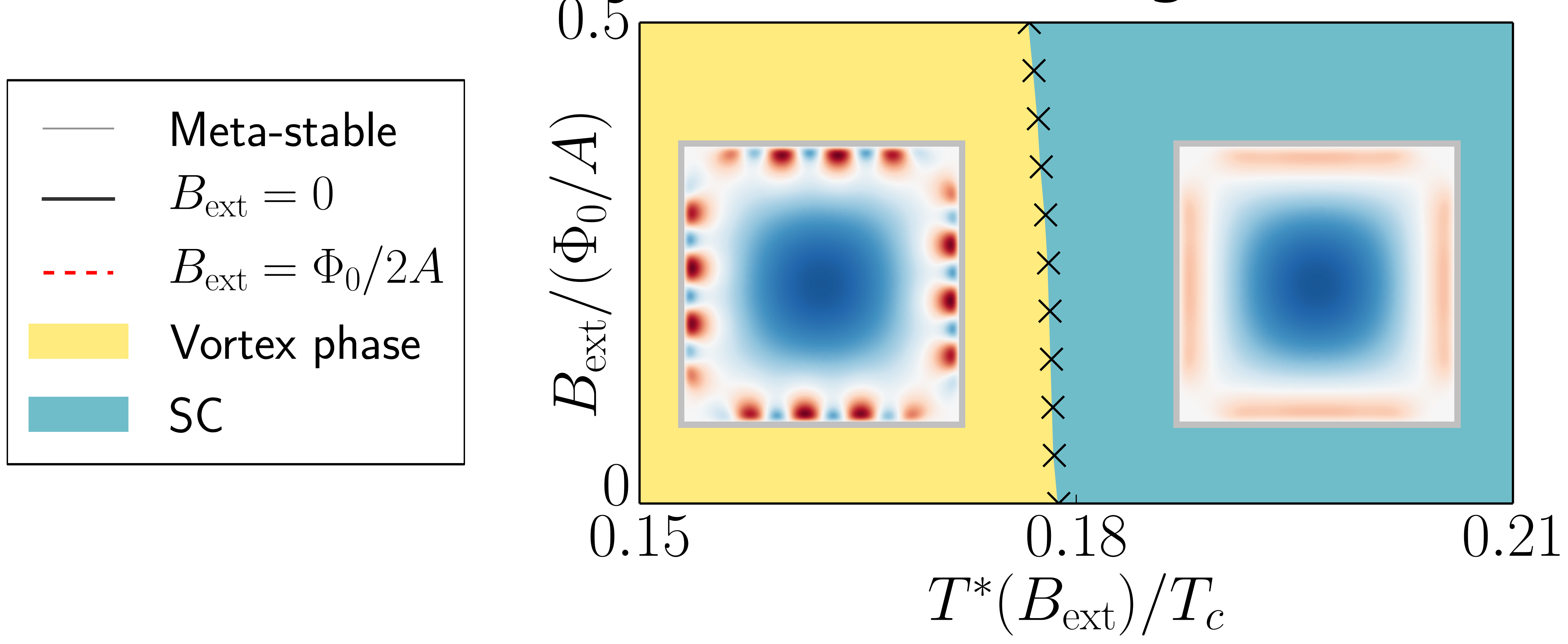


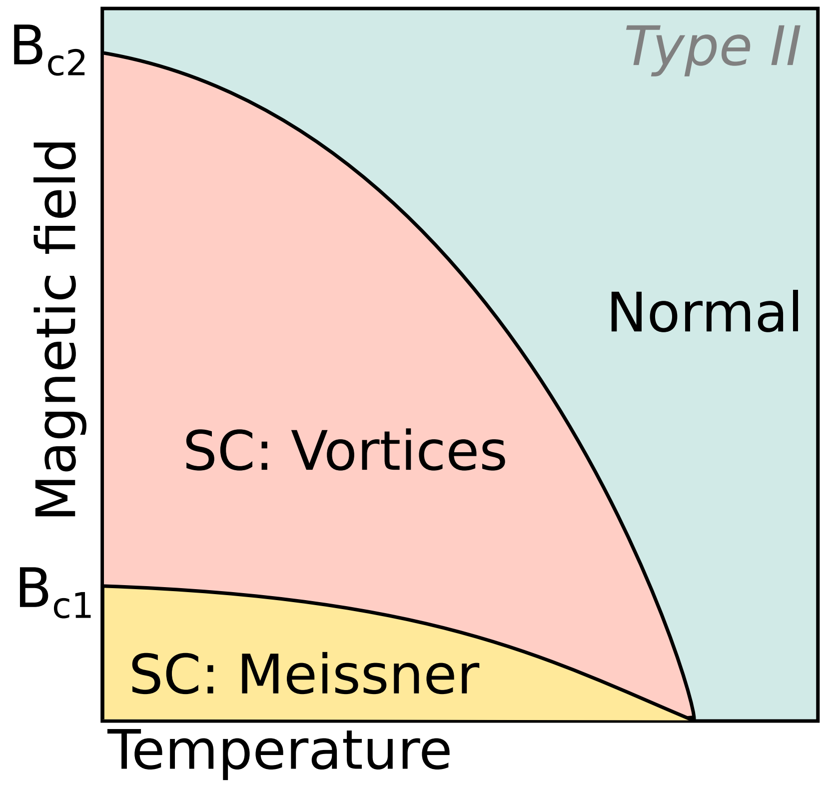


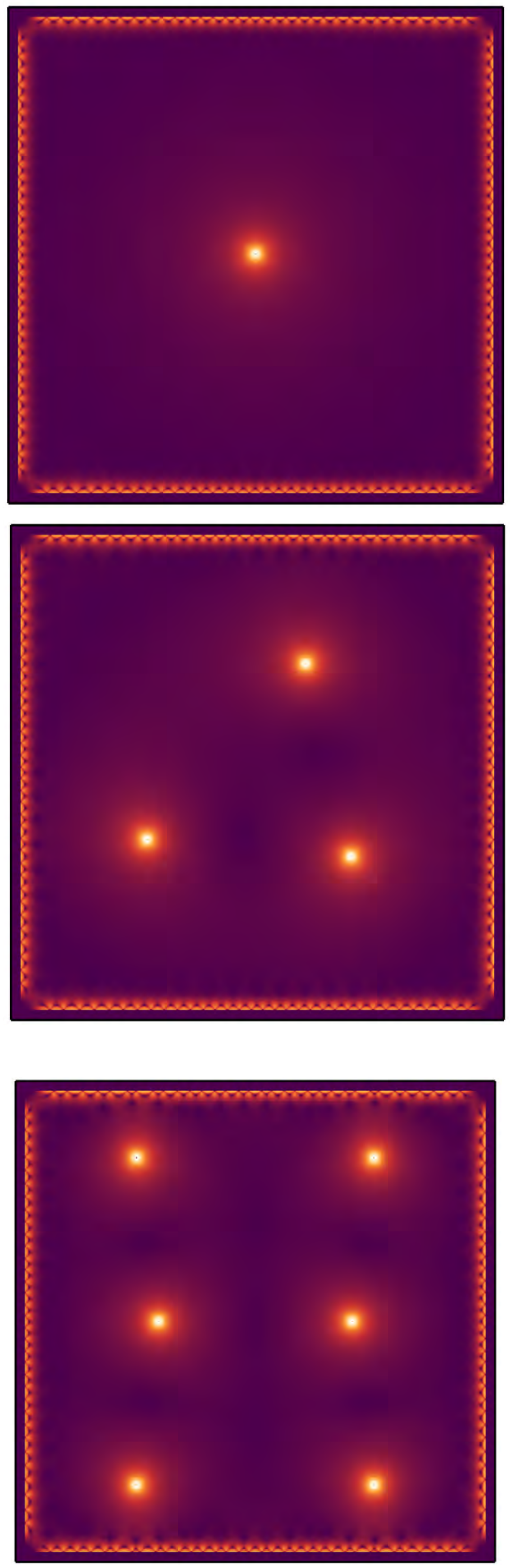
Thermodynamics in an external field (λ≫ξ)











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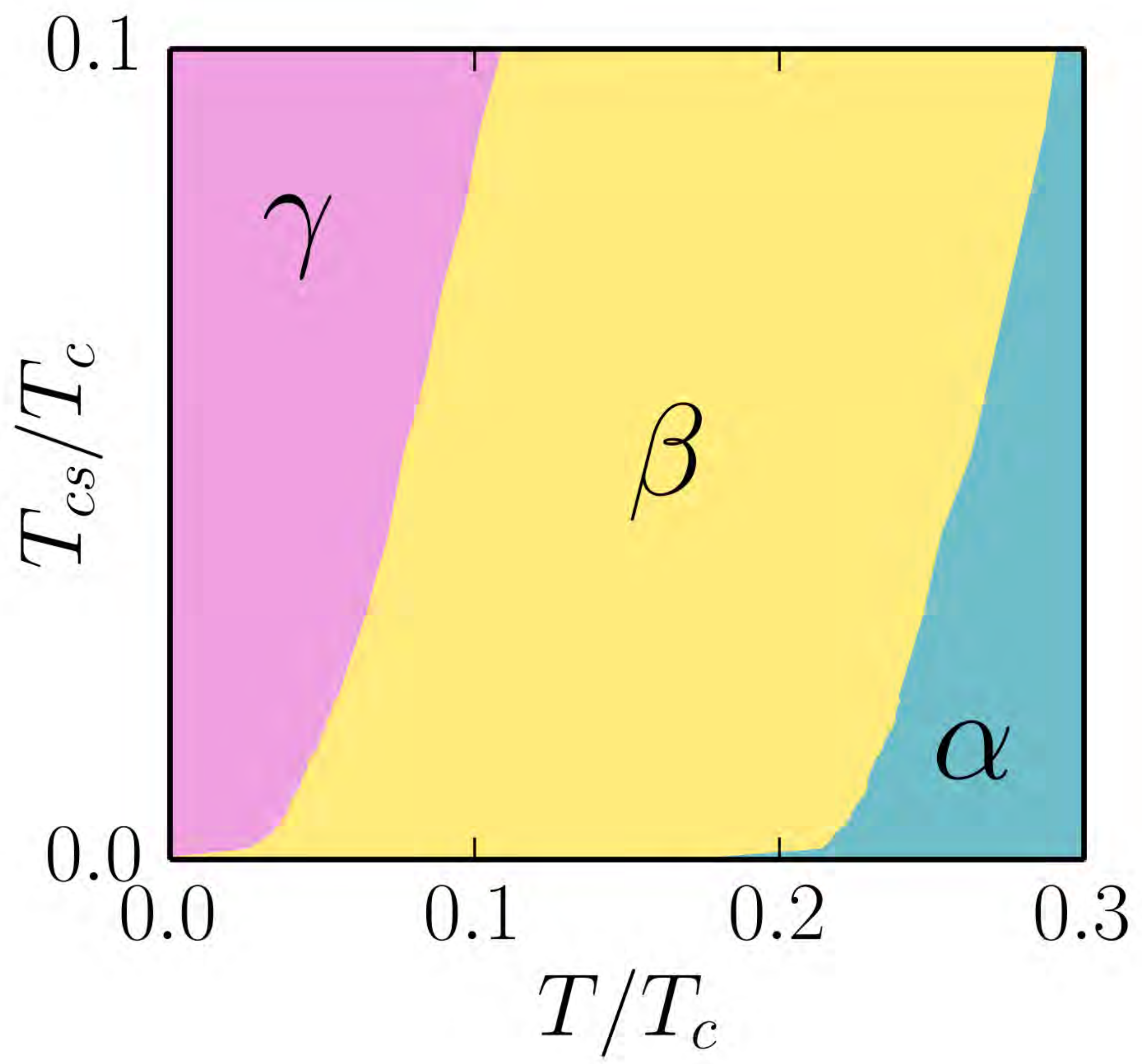
Adding a sub-dominant s-wave pairing channel



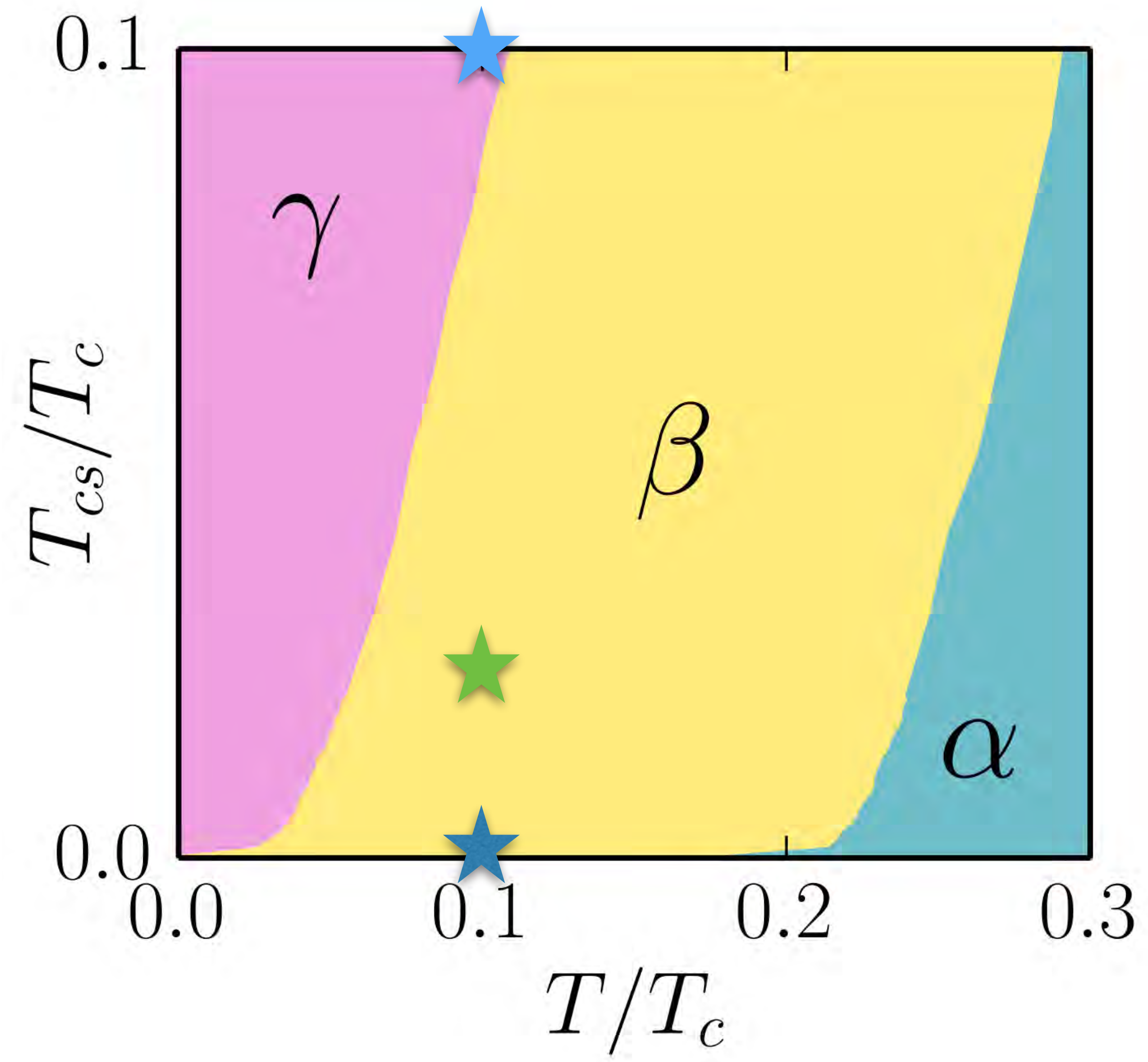
<u>phase-diagram with s-wave pairing channel</u>

α - plain d-wave SC

β - T-broken SC with fractional vortices

γ - T-broken SC d+is

Adding a sub-dominant s-wave pairing channel



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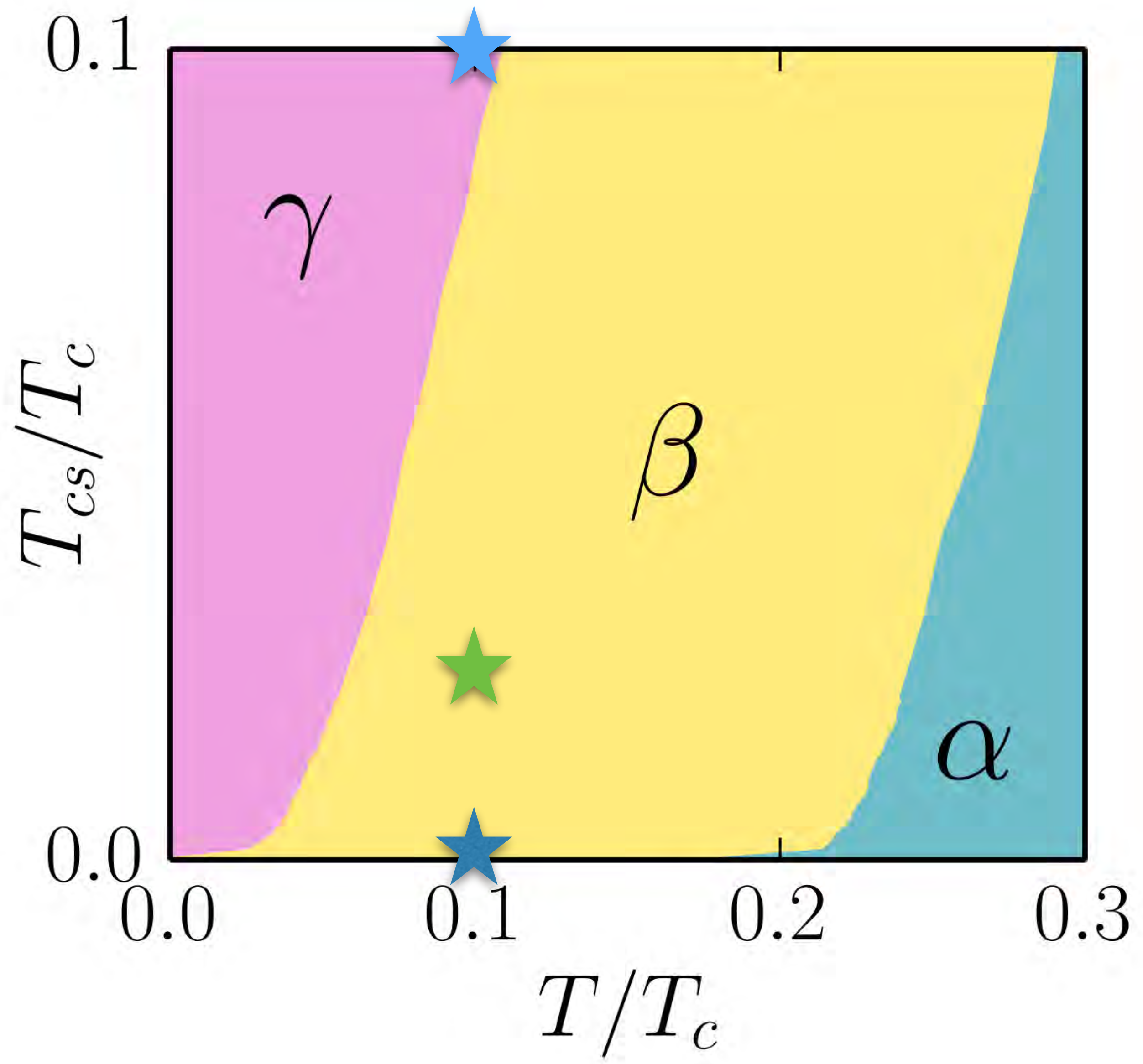

phase-diagram with s-wave pairing channel

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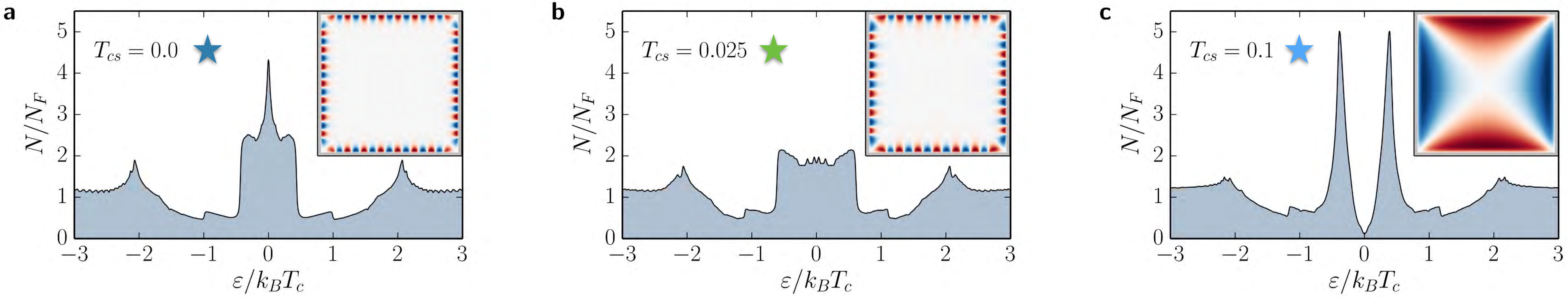

T-broken d-wave
weak B-field

weak d+is wave
weak B-field

strong d+is wave
large B-field

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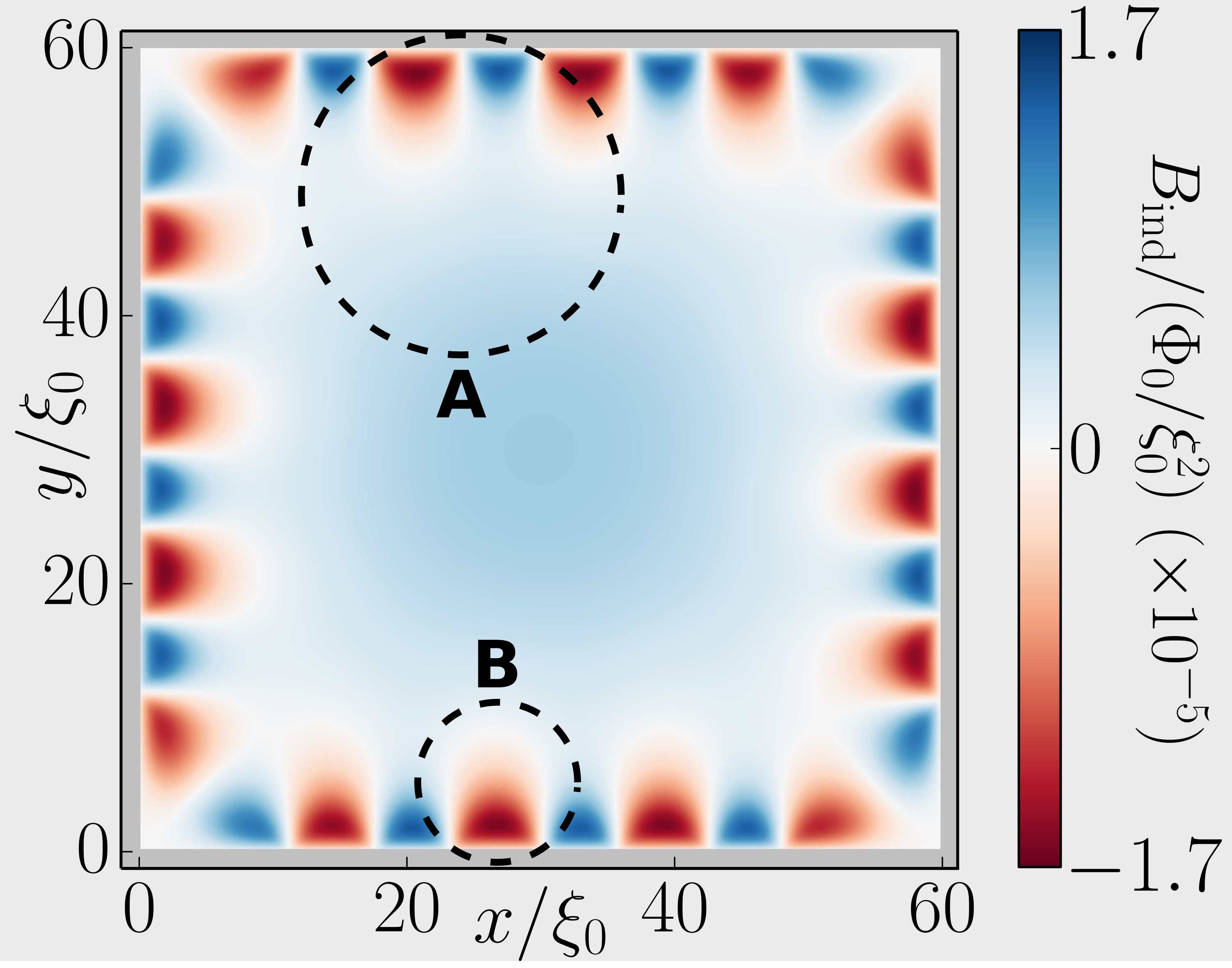
Direct observation: Nano-SQUIDS

magnetic field *(YBCO: 9 mT)*

$$B = \frac{1.7\mu\Phi_0}{\xi_0^2} = \frac{35\ \mathrm{mT}}{(\xi_0/\mathrm{nm})^2}$$



typical area

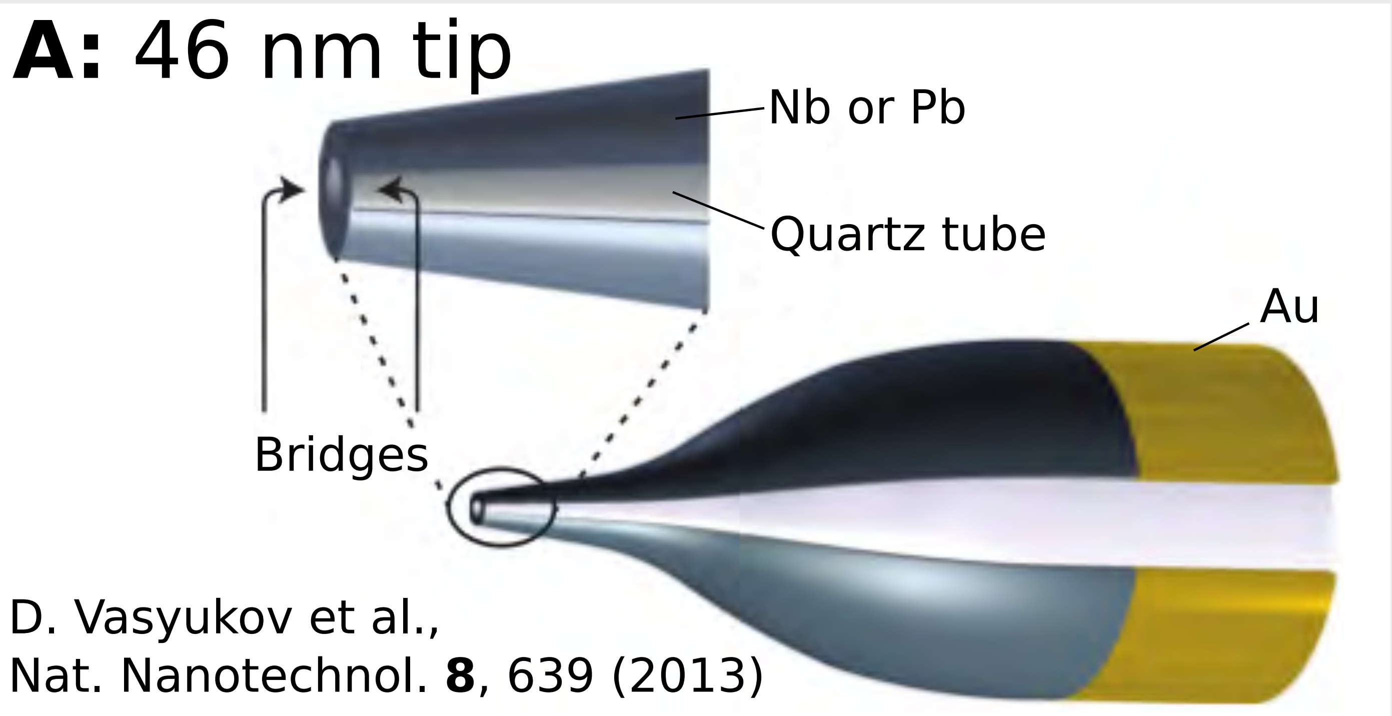
$A = (5\xi_0)^2$

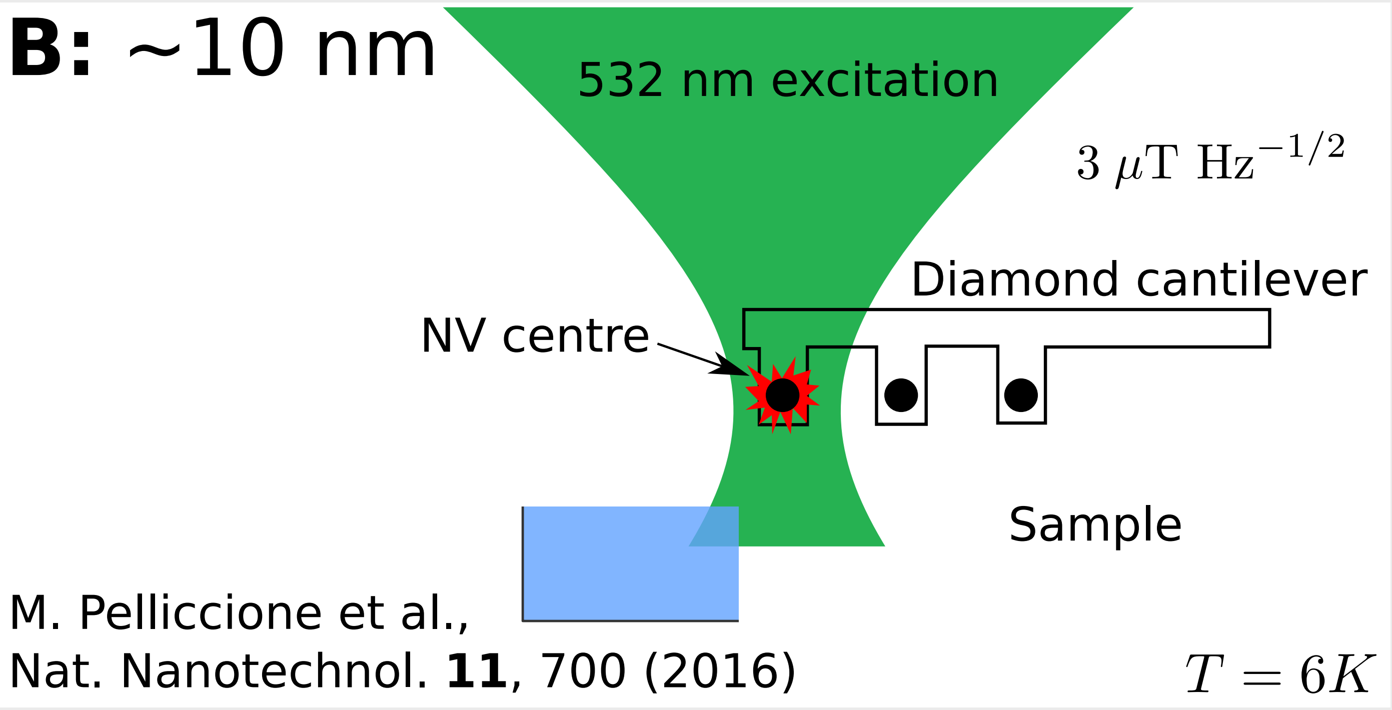
(YBCO: 10x10 nm)

Temperatures:

$0.15 - 0.21 T_c$

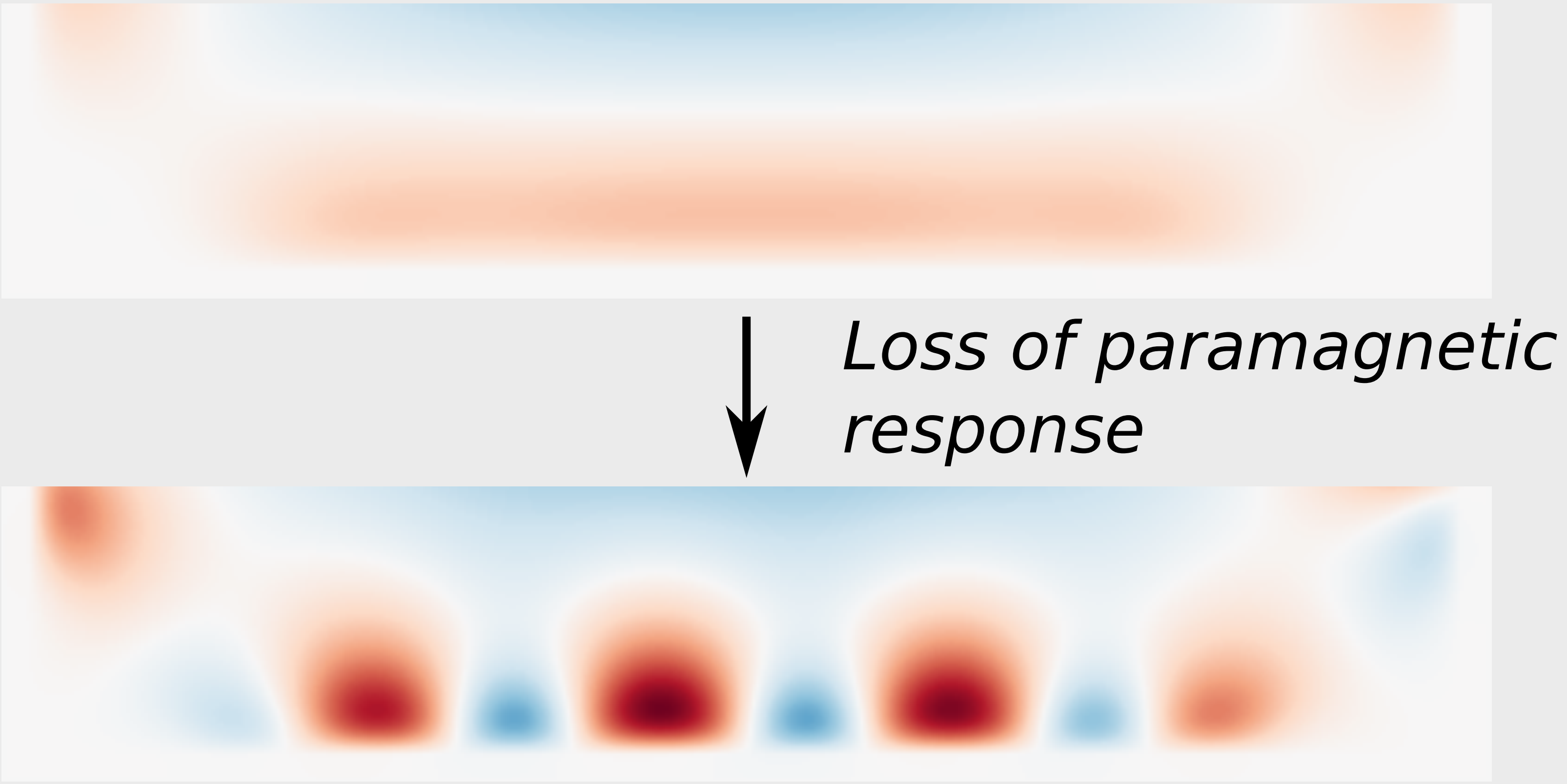
(YBCO: 12-17 K)



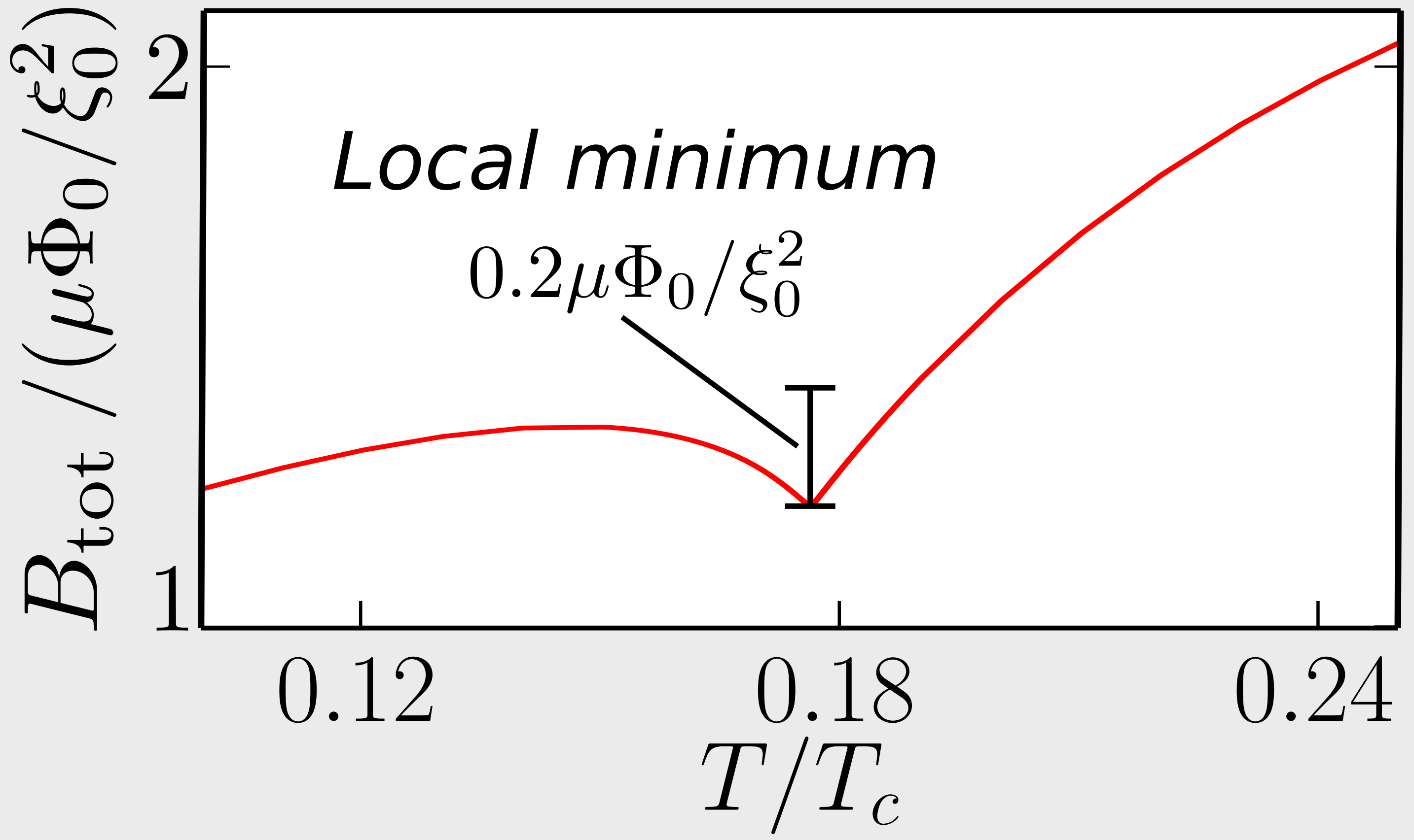


Indirect observation

λ-measurement:



B_{tot}-measurement:



Conclusions

The experimental consequences of our findings are as follows:

A. Finding evidence of a T-symmetry breaking state does not necessarily imply a multicomponent superconducting order-parameter

B. A hallmark of a d-wave superconductor is a conductance peak at zero bias and this peak should narrow as temperature is decreased. This is not seen experimentally, instead the conductance peak width saturates at~10-20% of the full gap scale, a width consistent with the modifications of the local spectrum of quasiparticles caused by the T-breaking state we find. It might well be that the phase we describe has been repeatedly seen in NIS-tunnelling experiments

C. The magnetic trace of an inhomogeneous, T-symmetry broken state, can only be detected if the experimental probe can resolve a magnetic flux variation on length scales ~10 nm (for YBCO). State-of-the-art nano-SQUIDS may do that. Also, measurement of the total magnetisation should show a non-monotonous temperature dependence at small fields

M. Håkansson et al, Nature Physics 11 755 (2015)
P. Holmvall et al submitted (arXiv:1706:06165) and in manuscript