Evolution of the Pseudogap in Strongly Interacting Fermi Gases

Erich Mueller
Cornell University

Sourish Basu
Stefan Baur
Dan Goldbaum
Kaden Hazzard

Kathy Levin
Henk Stoof
Mohit Randeria
Cheng Chin
Francesco Fumarola
Tin-Lun Ho
Kyle Shen
Martin Zwierlein
Wolfgang Ketterle

Nandini Trivedi
Henk Stoof
Paivi Torma
Giancarlo Strinati
Wilhelm Zwerger
Christian Schunck

$$ -- NSF, Darpa OLE

If you get bored...

- Submit a symposium for the 2009 DAMOP meeting (Charlottesville, Virginia, May 19-23, 2009) --

  http://meetings.aps.org/aps_invited/Invited/LoginForm.cfm?MT=DAMOP09&UNIT=DAMOP

  Deadline: next Monday

- Apply to attend workshop at Aspen Center for physics:
  Quantum Simulation/Computation with Cold Atoms and Molecules (May 24-June 14 2009)

  http://www.aspenphys.org/

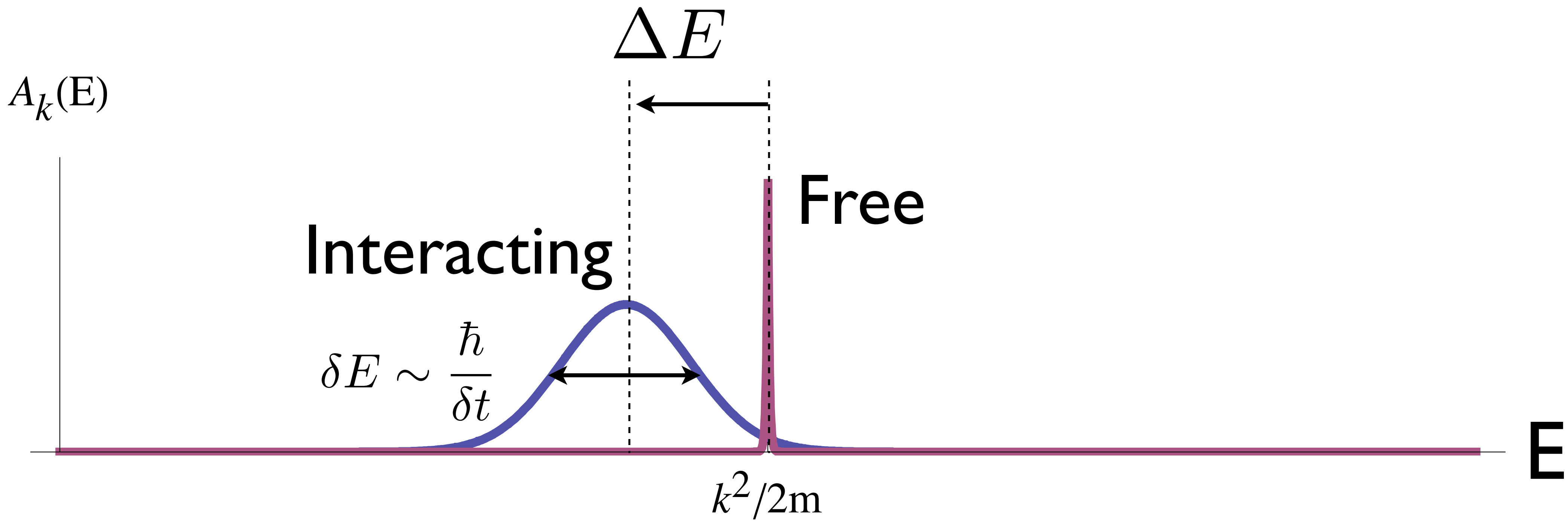
  Deadline: Jan 31, 2009

Outline

- Background
  - Spectral Densities
    - Gaps and Pseudogaps
- Pseudogap in Polarized gases
- RF Spectroscopy
- What modes drive superfluidity?

Spectral Density

If I add a particle with momentum k, what energy does it have?

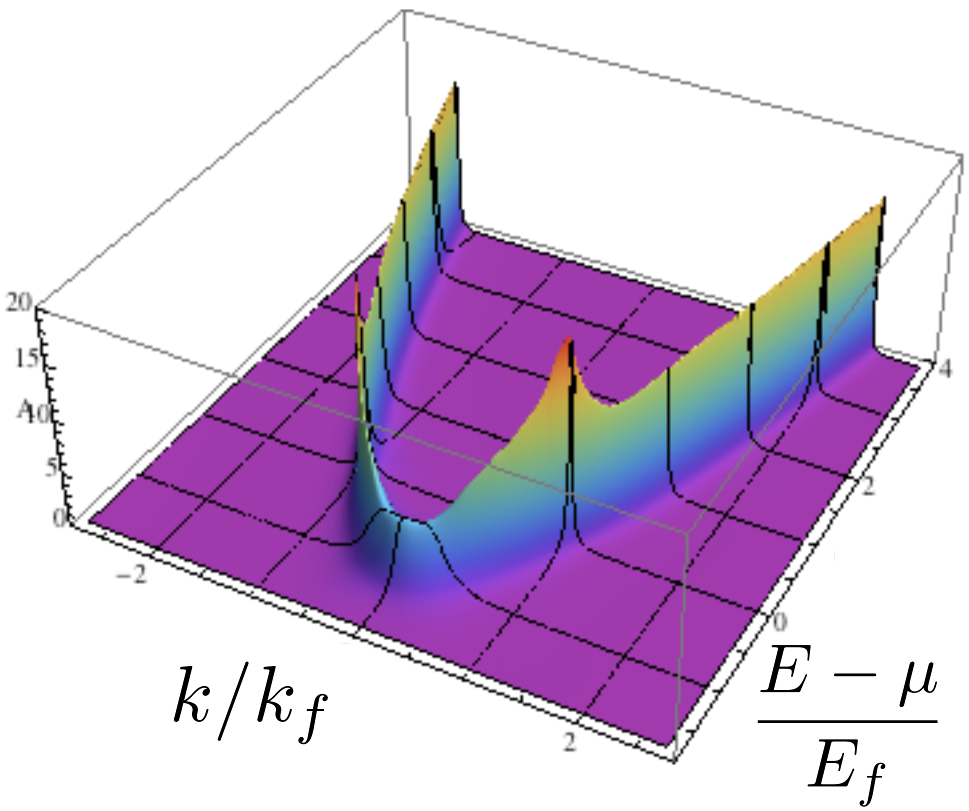


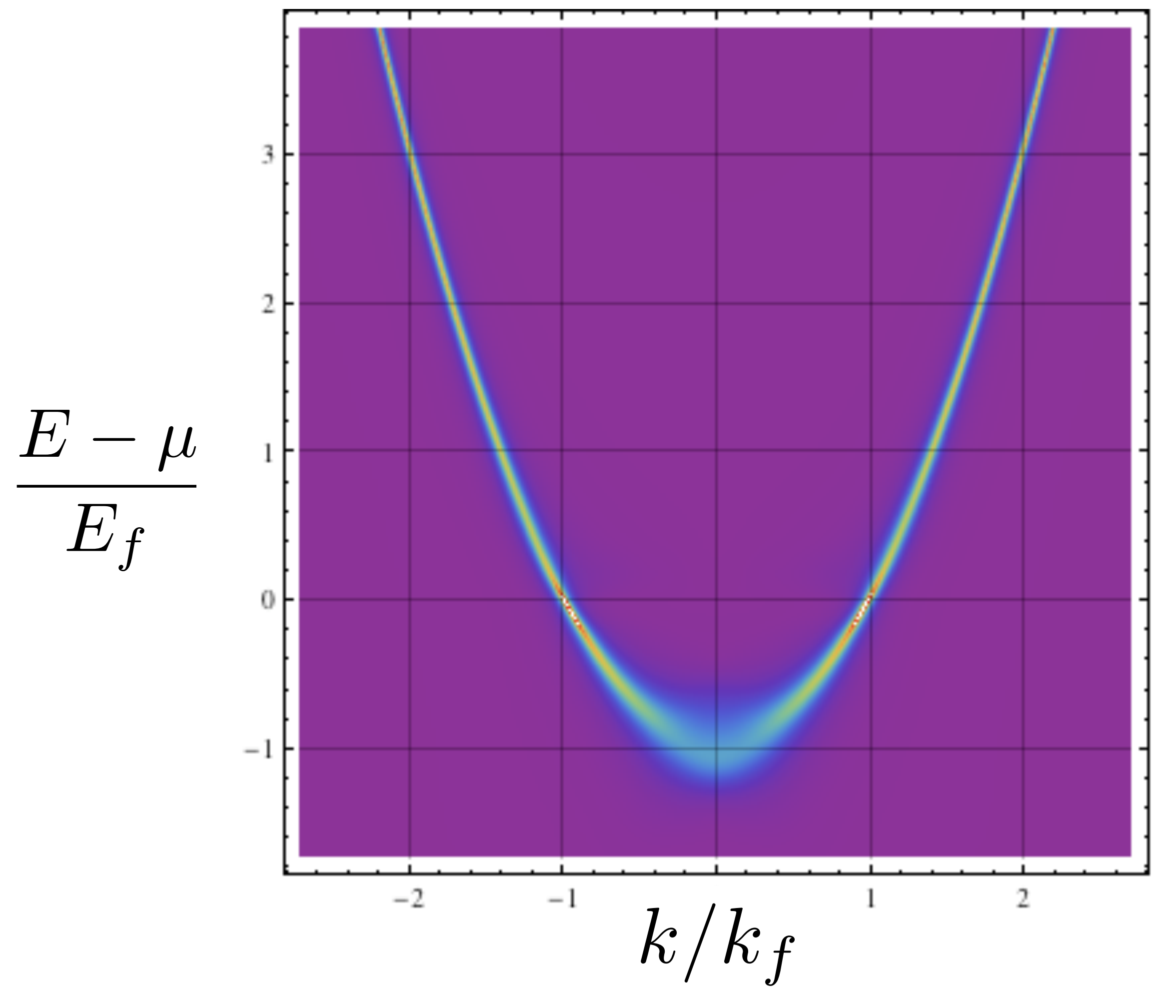
Shift: ΔE average potential seen by atoms

Broadening: $\delta E \sim \frac{\hbar}{\delta t}$ Heisenberg

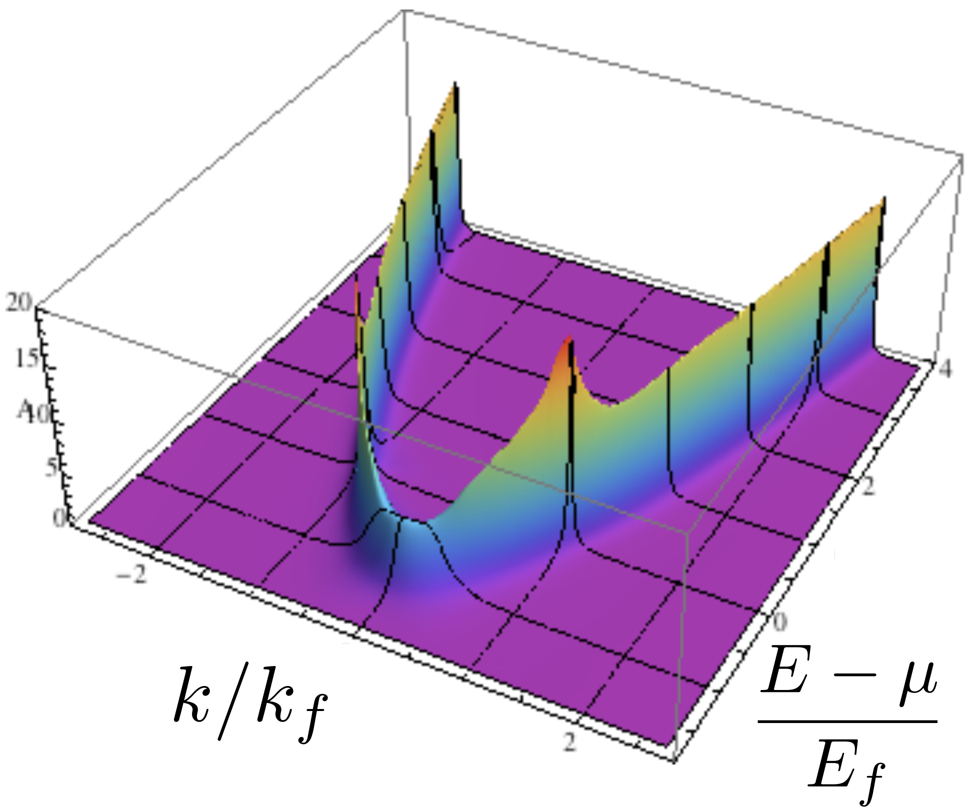
Analogy: shine light through a cavity filled with atoms
Cavity mode shifted and broadened

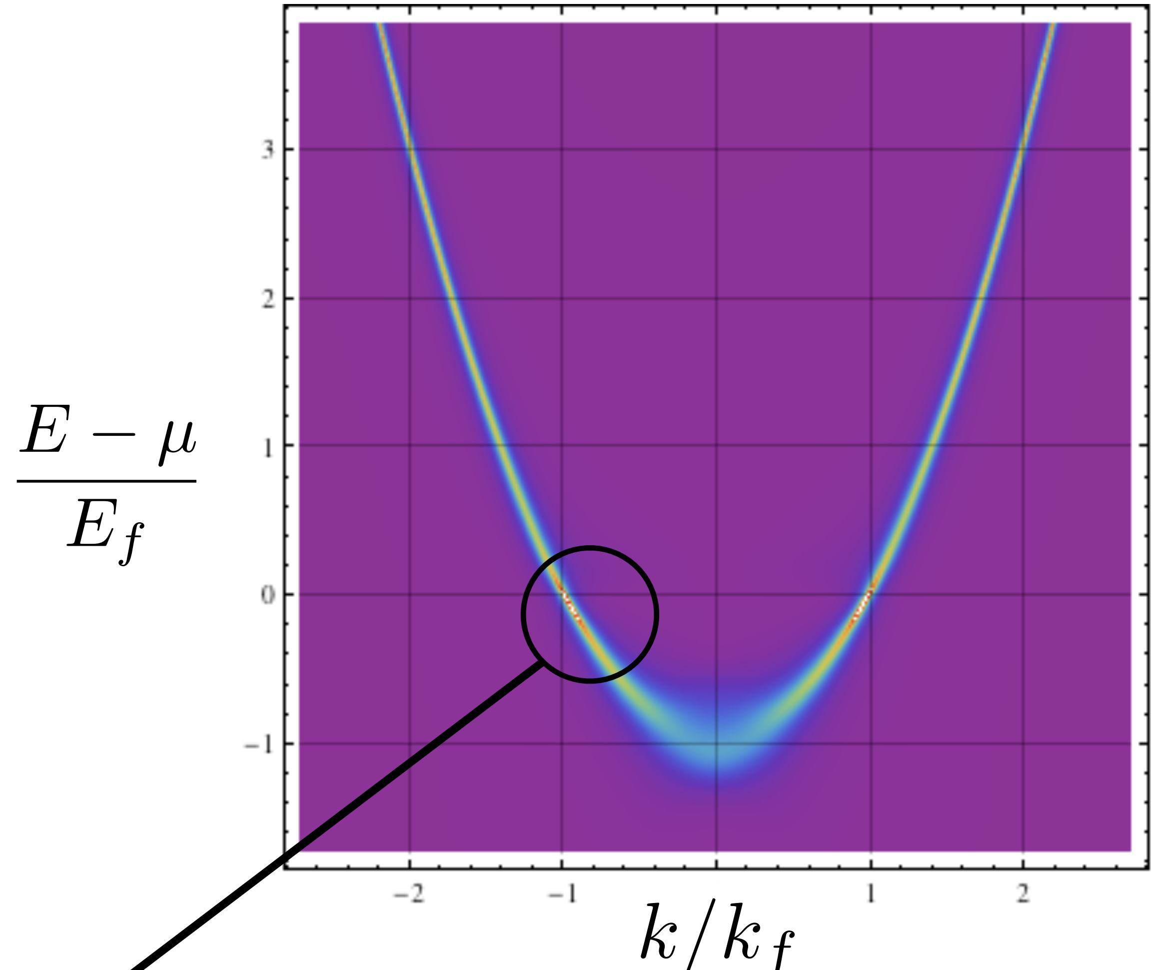
Dispersion





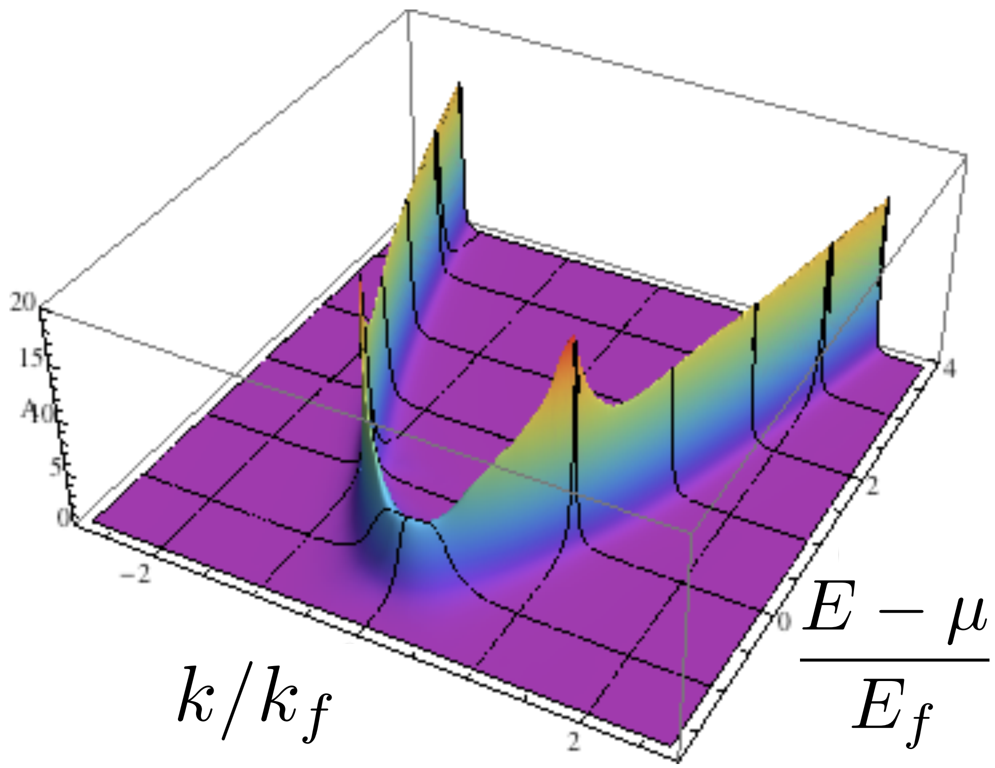
Dispersion

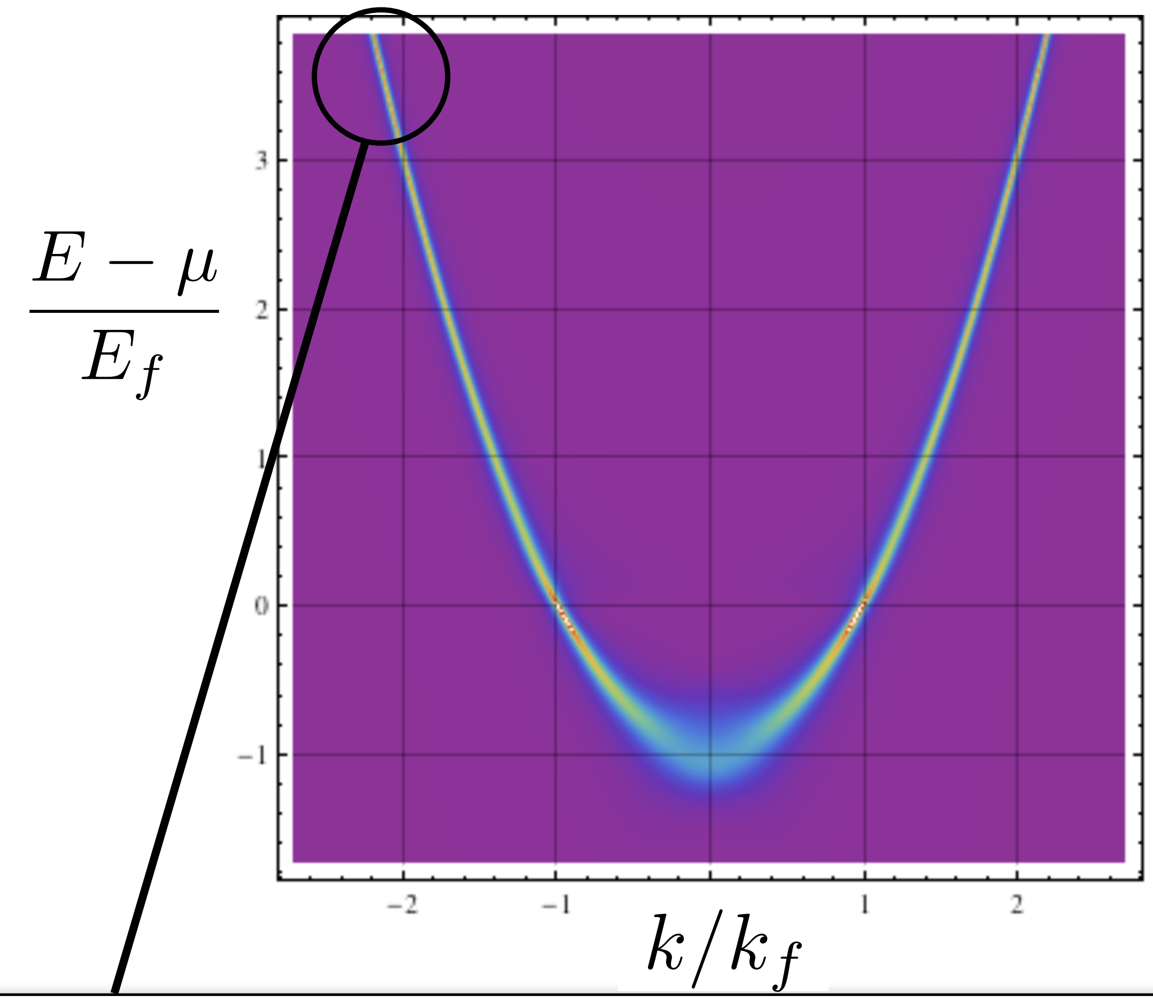




Zero (low) T:
Atoms at Fermi surface have nowhere to scatter
Spectral density has delta-function peak
"Fermi Liquid"

Dispersion





High energies:
Scattering cross-sections become small

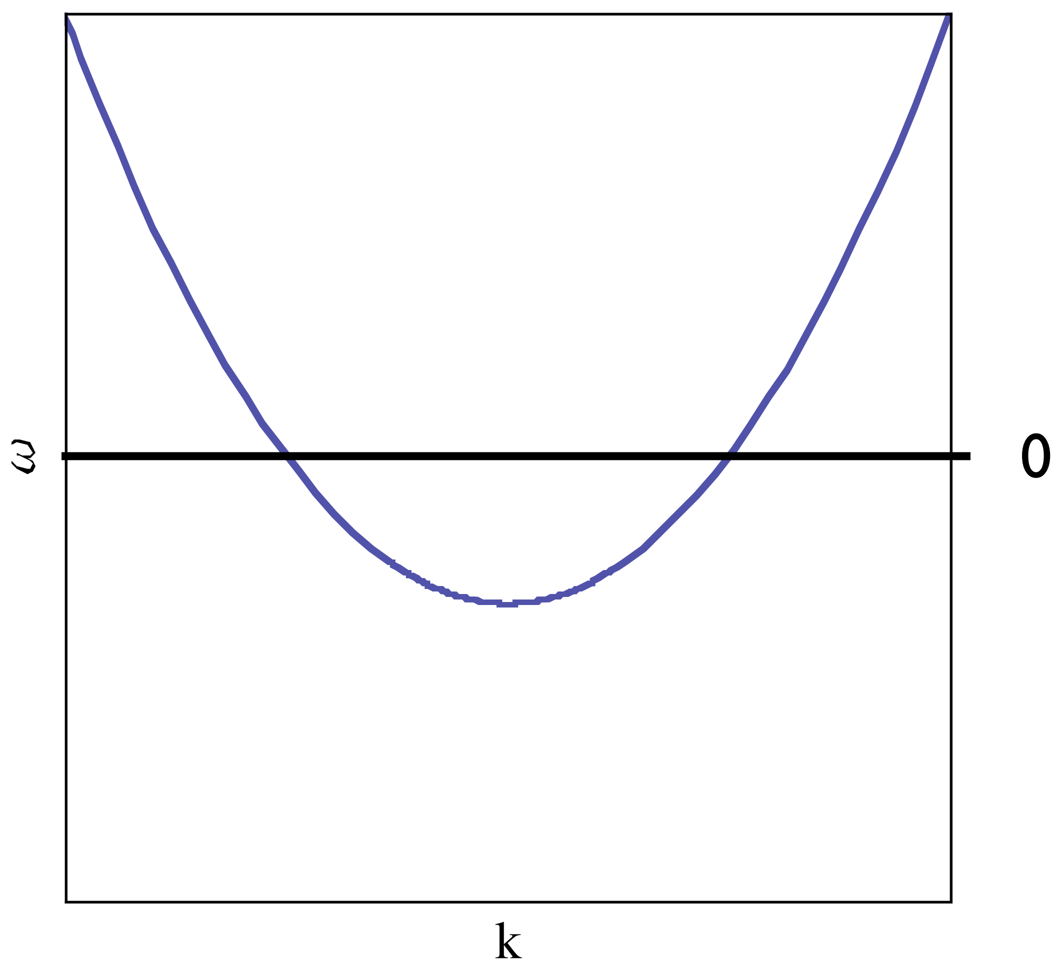
Now on: $\hbar = 1$ $E \leftrightarrow \omega$

Pairing

Two ways to add particle:

Simply add the particle

$$\omega = \frac{k^2}{2m} - \mu$$



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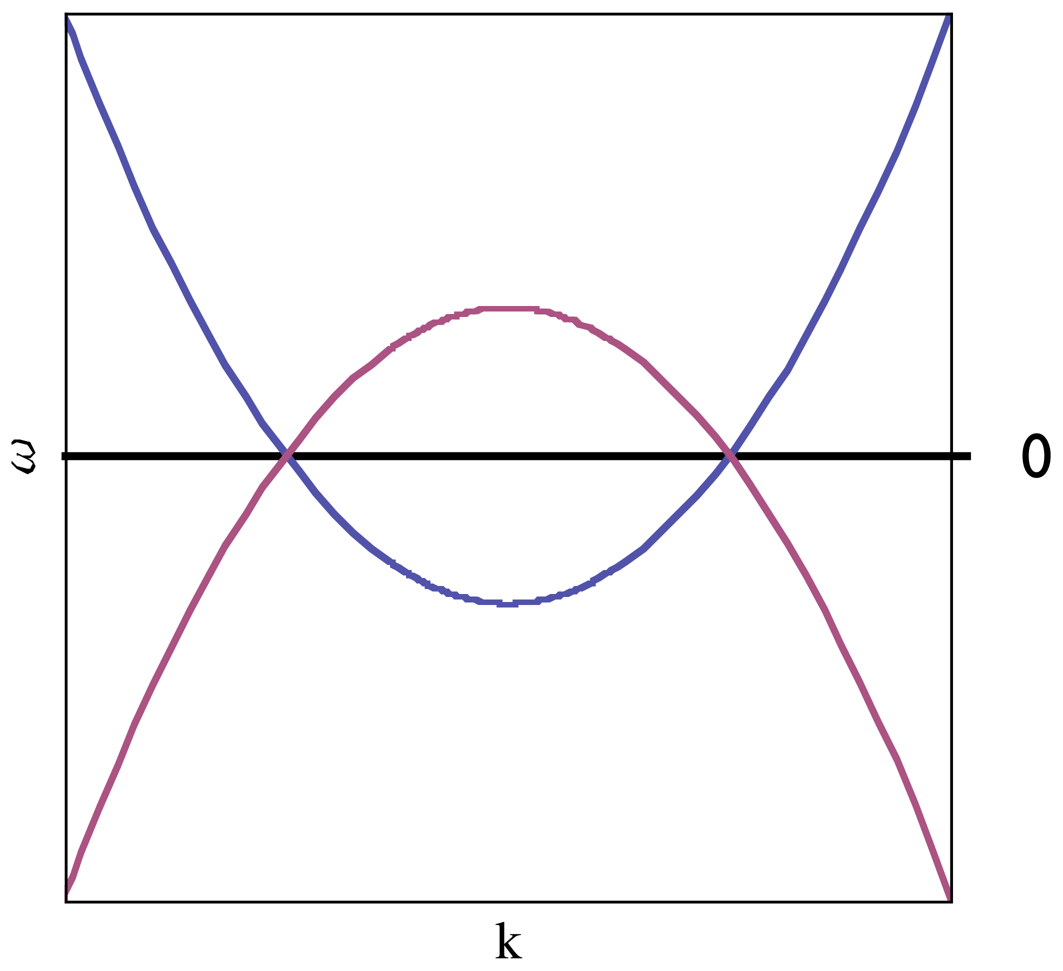


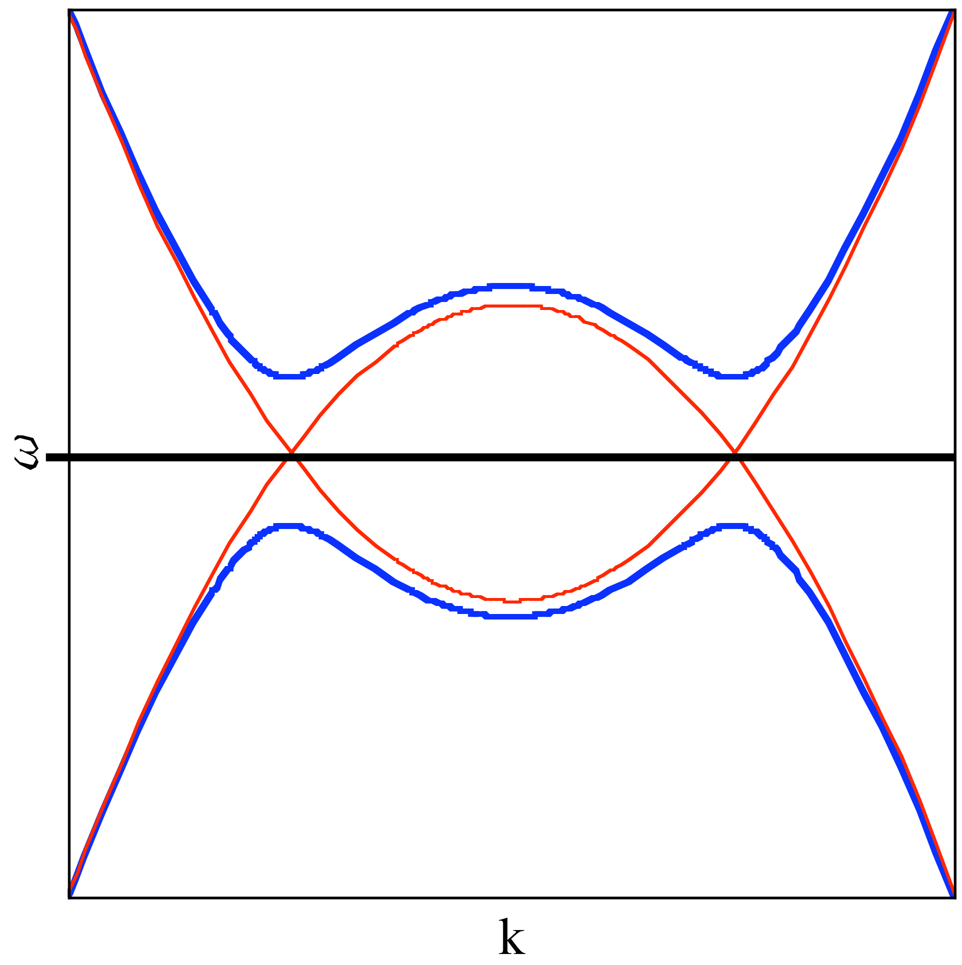
Add pair + remove a particle

$$E = E_f - E_i = (E_b - \mu_b) - (k^2/2m - \mu)$$

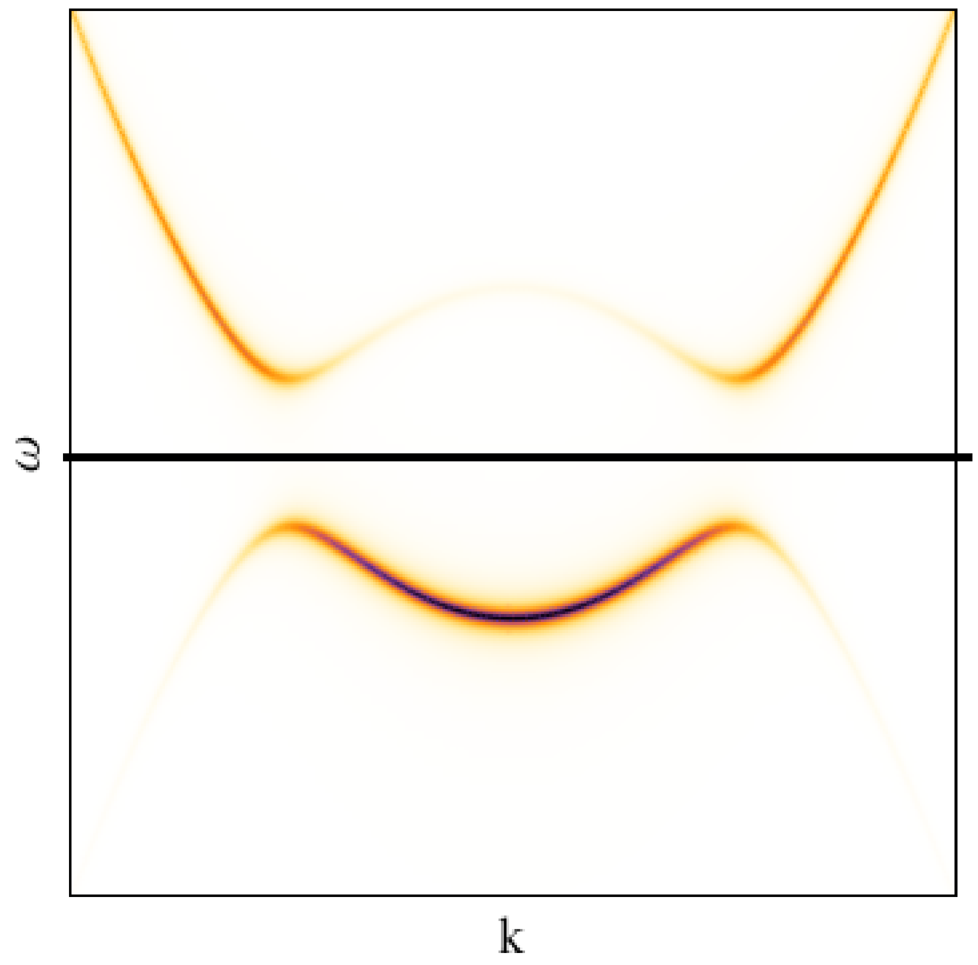
$$= \mu - k^2/2m$$

(condensate)

Pairing

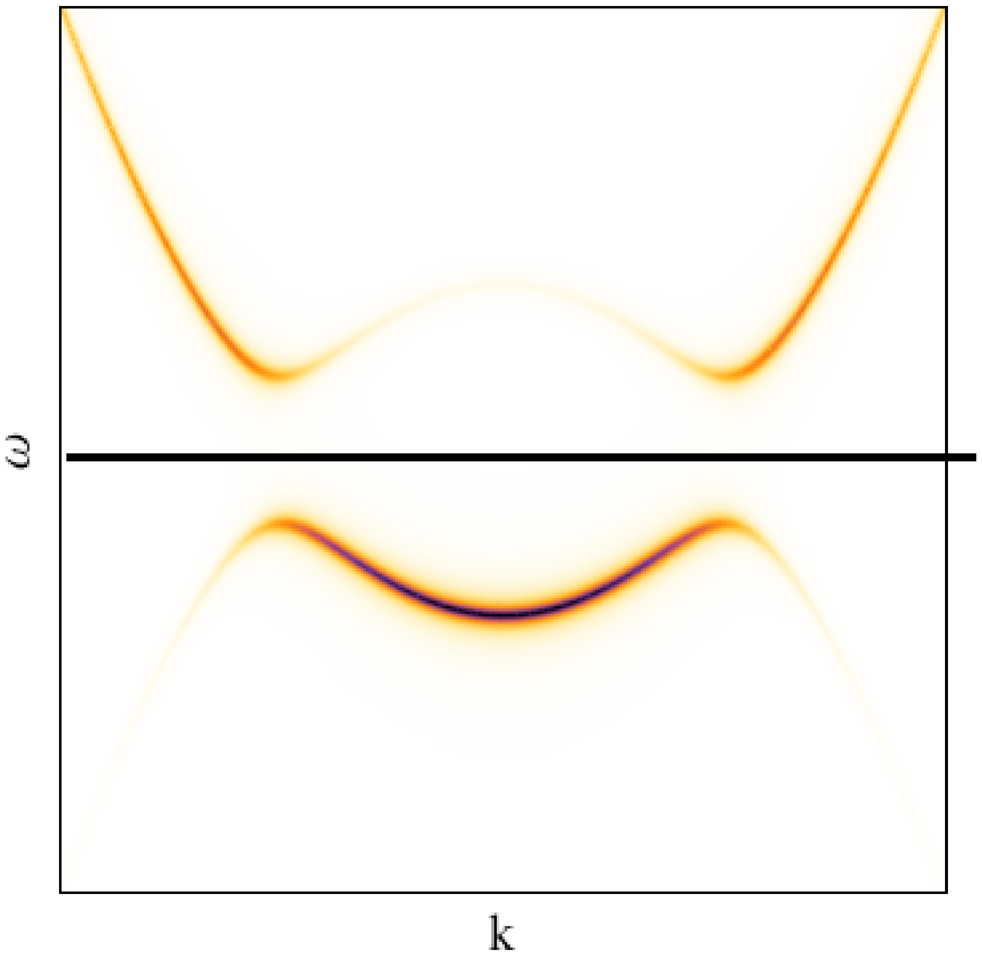


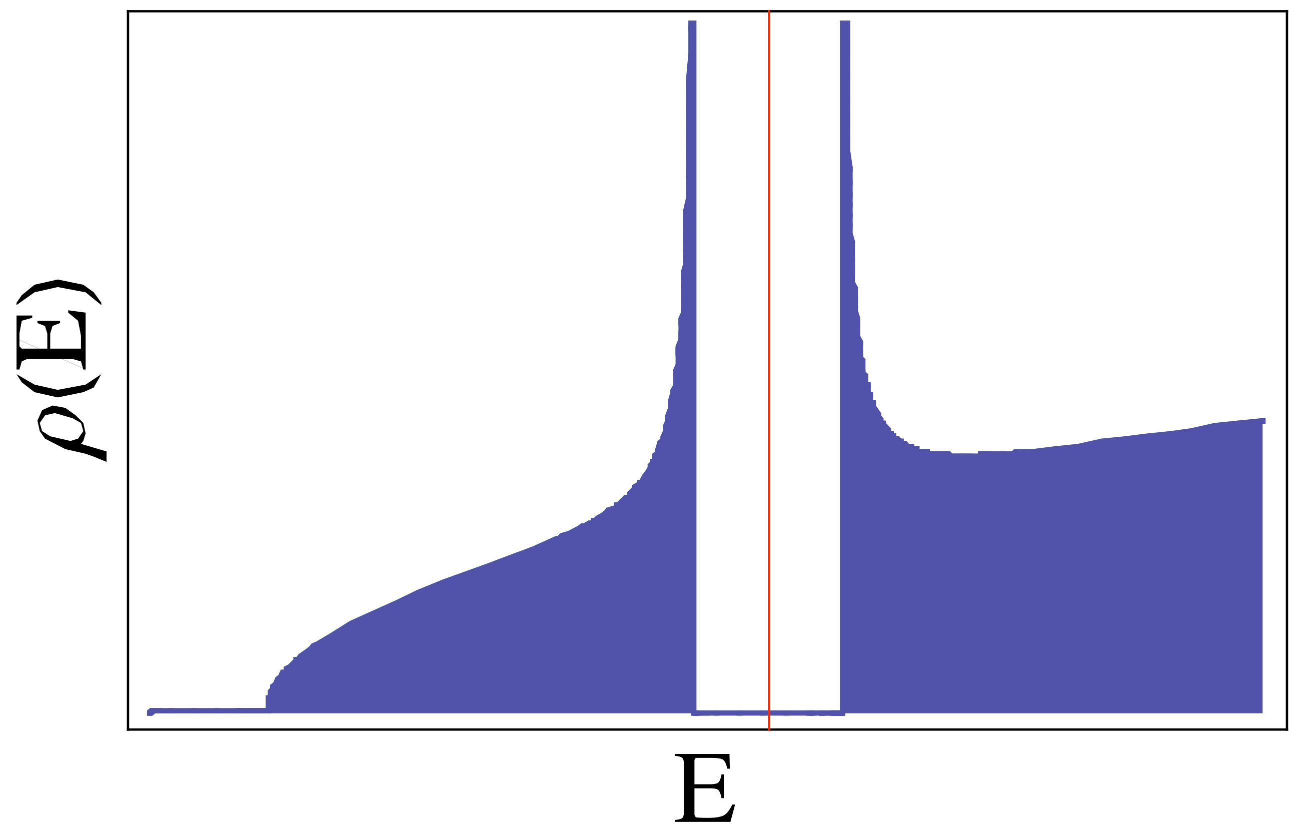
States Hybridize



Weight states with overlap with free-particles (coherence factors)

Spectral Gap





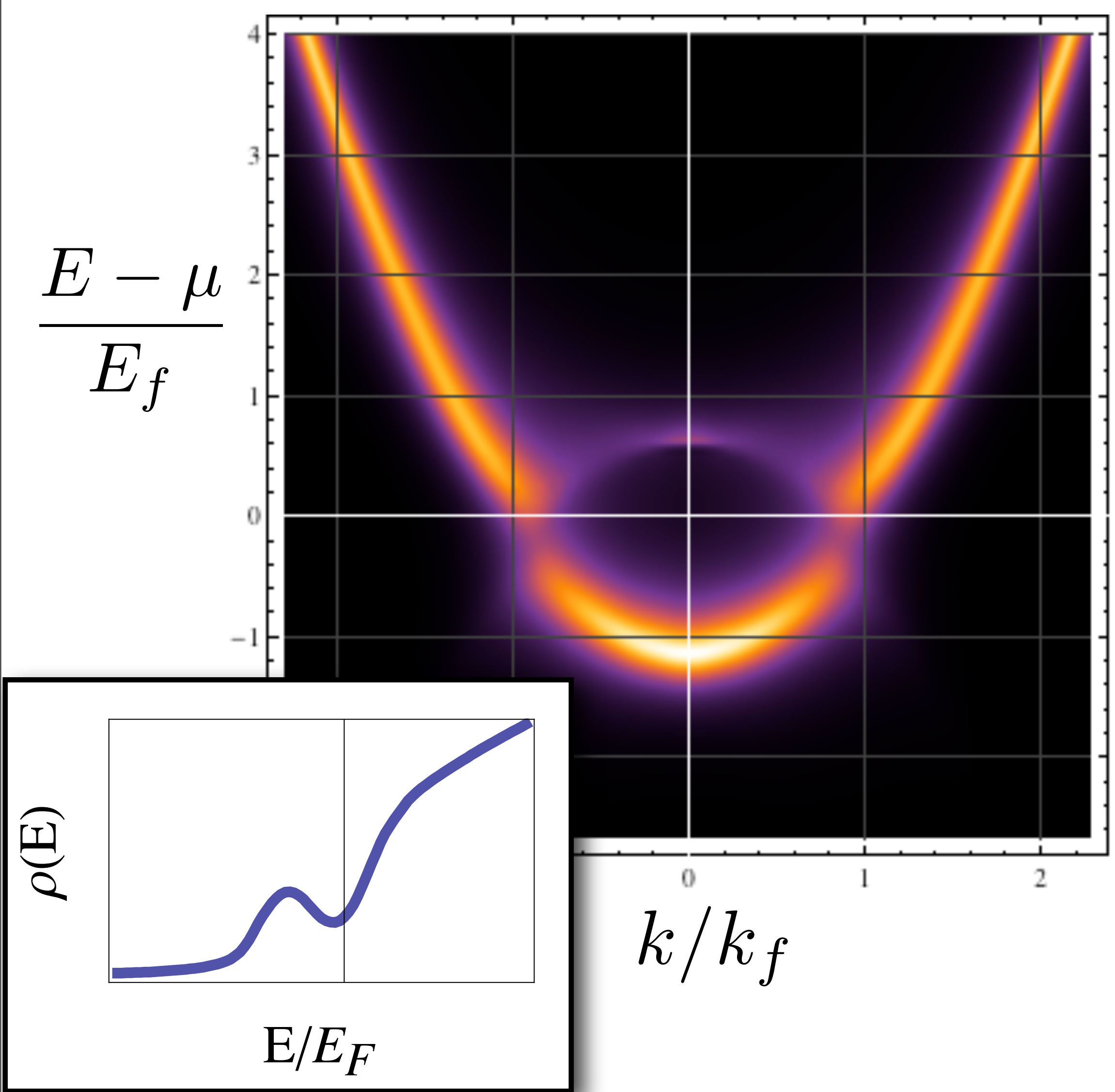
Other systems with gaps:
Semiconductors/insulator, Charge/Spin Density Waves,

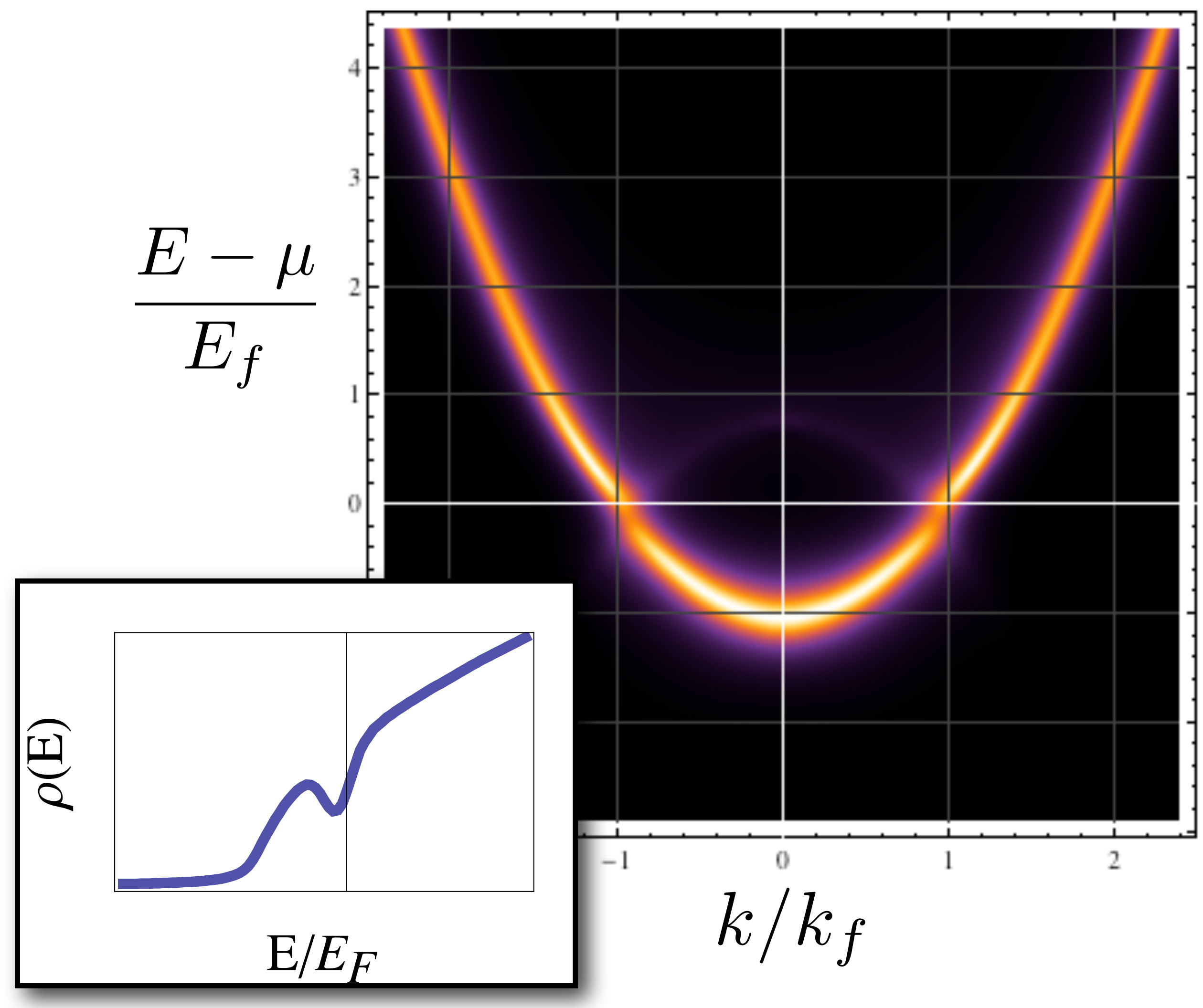
Above Tc

$$\frac{1}{k_f a} = -0.2$$

Normal State

$$\frac{1}{k_f a} = -0.6$$

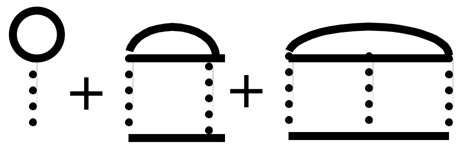




(Using NSR -- qualitatively generic)

Physics: non-condensed pairs in normal state

Minimal model

$\Sigma =$  +... (no self-consistency)

ie. fully treat 2-body problem

many-body effects only enter through Pauli principle

$$A_\downarrow(\omega,k) = \mathrm{Im}\ \Big(\omega - \epsilon_k^\downarrow - \Sigma_\downarrow(\omega,k)\Big)^{-1}$$

$$\Sigma_\downarrow(\omega,k) = \int dz\, \Gamma_\downarrow(z,k)/(2\pi(\omega-z))$$

$$\Gamma_\downarrow(\omega,k) = \int \frac{dq}{(2\pi)^3} \Lambda(\omega+\epsilon_q^\uparrow, k+q)[f_q^\uparrow + g(\omega+\epsilon_q^\uparrow)]$$

$$\Lambda(\omega,k) = 2\mathrm{Im}T(\omega,k)$$

$$T(\omega,k) = (4\pi\hbar^2/m)/(a^{-1}+\Theta(\omega,k))$$

$$\Theta(\omega,k) = \int \frac{dz}{2\pi(\omega-z)} \int \frac{d^3q}{(2\pi)^3} \left[\frac{1-f_{k/2+q}^\uparrow - f_{k/2-q}^\downarrow}{\omega - \epsilon_{k/2+q}^\uparrow - \epsilon_{k/2-q}^\downarrow} - \frac{m}{k^2}\right]$$

Formally derive:
Gaussian fluctuations about normal state

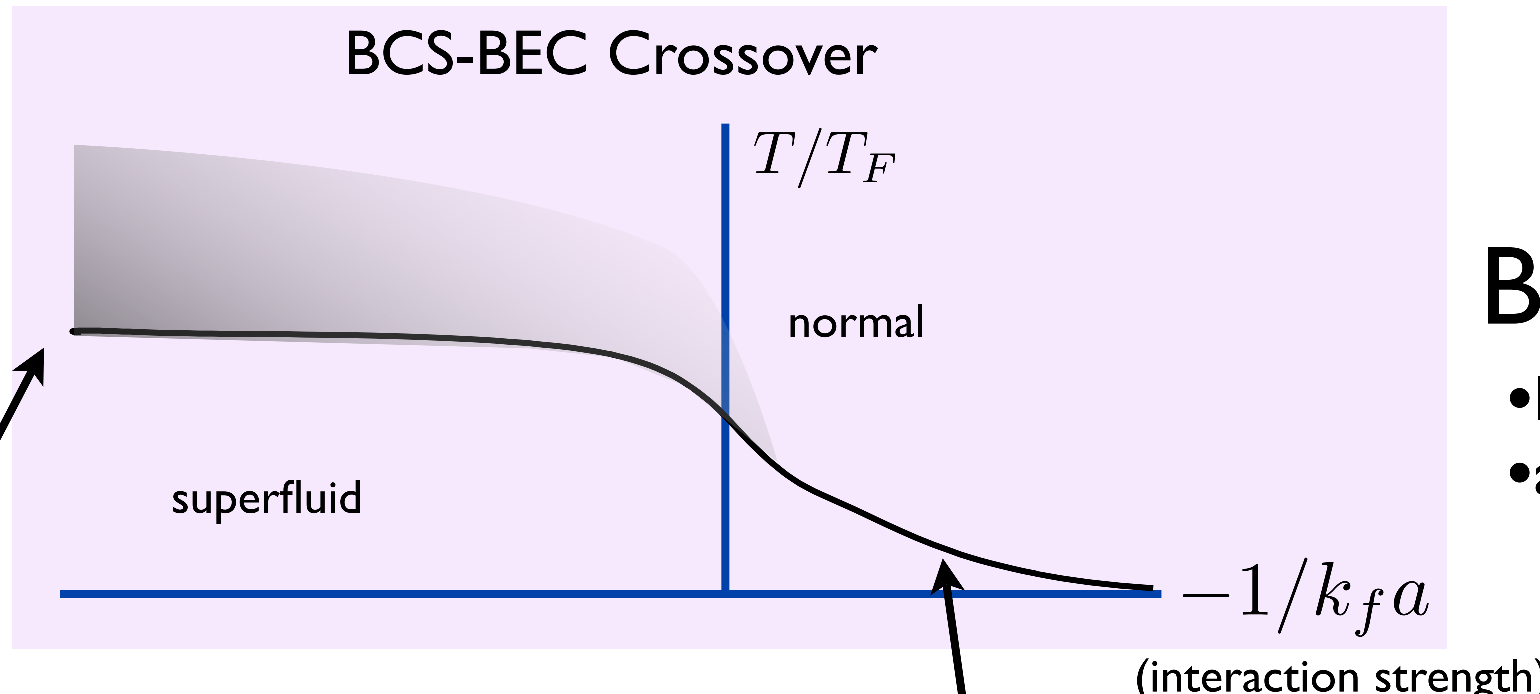
Includes “Hartree”

Reduces problem to a set of integrals

Pseudogap

- Idea: pairing is not limited to superfluid phase

BEC
- small pairs
- form at high temperature

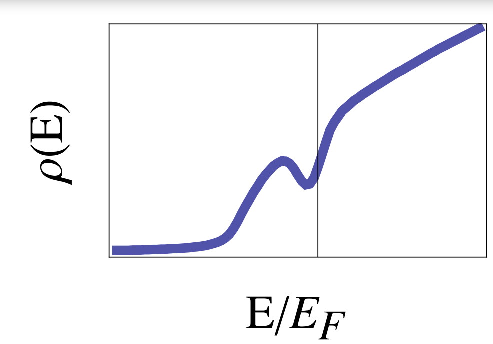


BCS
- large pairs
- appear at transition

Bose-Einstein Condensation of a gas of pairs

Bardeen-Cooper-Schreifer instability of the Fermi surface

Uncondensed pairs: gap-like feature



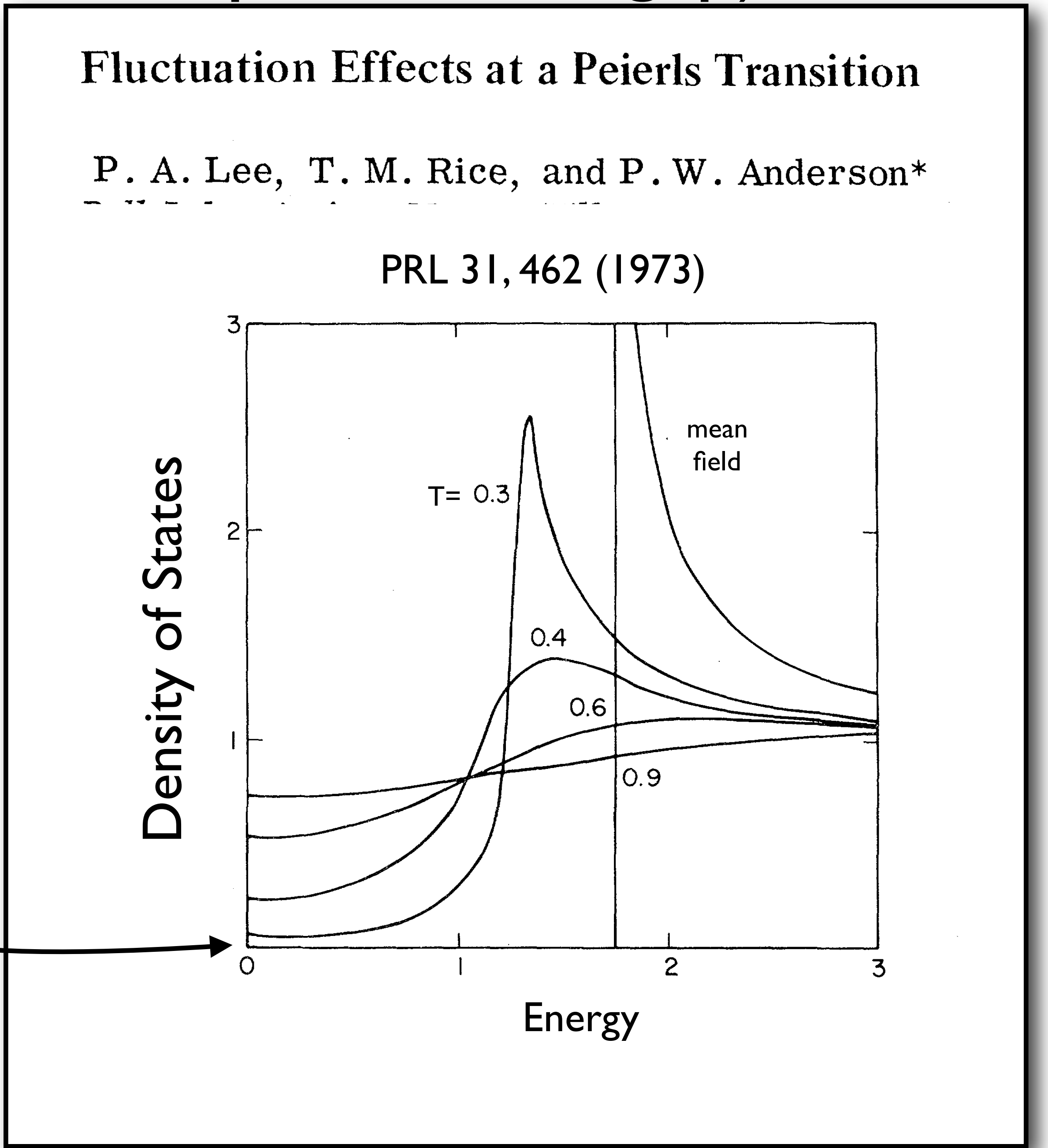
History

Charge Density Wave:

(density wave + interactions = periodic potential = gap)

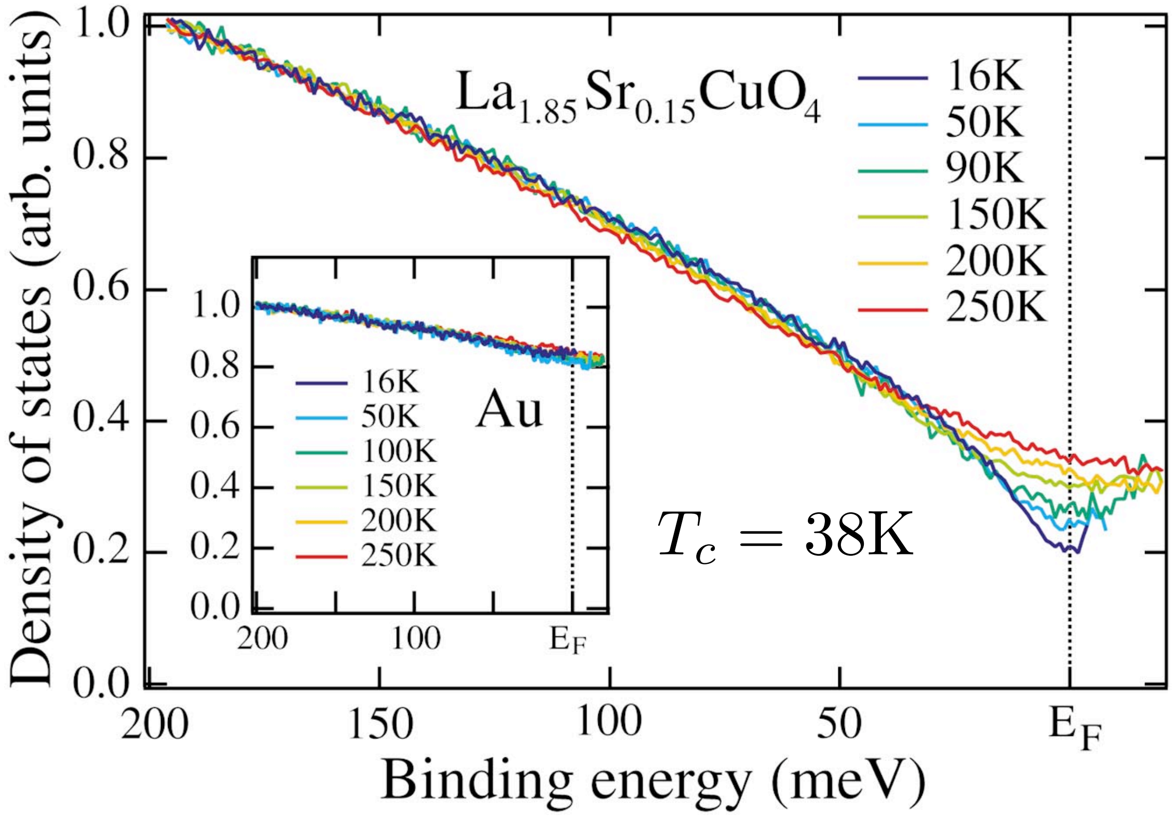
Adding fluctuations: suppresses T_c

Vestiges of gap remain (pseudogap)

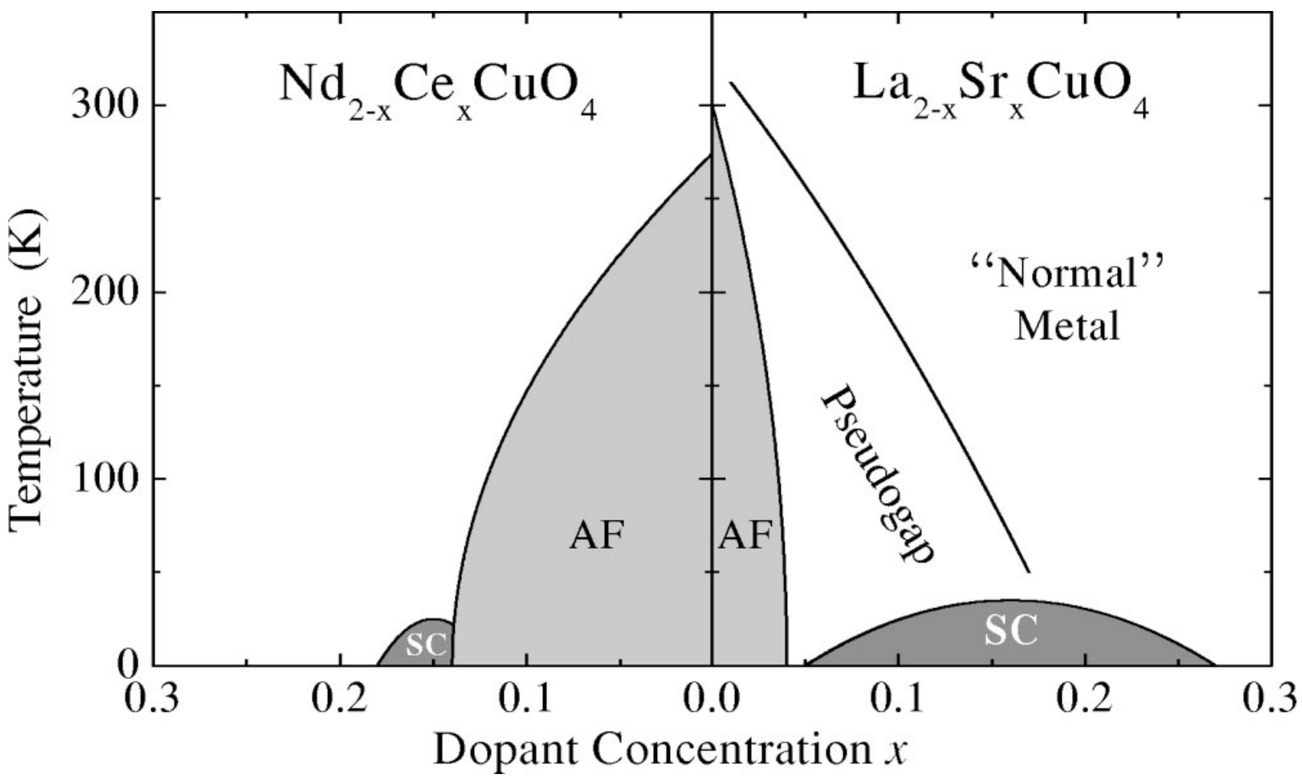


Qualitatively: Same phenomenon

High Temperature Superconductors:



Sato, T., L. T. Yokoya, Y. Naitoh, T. Takahashi, K. Yamada, and Y. Endoh, 1999, Phys. Rev. Lett. **83**, 2254.



Damascelli, Hussain, Shen,
Rev. Mod. Phys. 75, 473 (2003)

Also: spin susceptibility, Nernst effect,...

May not have anything to do with superconductivity

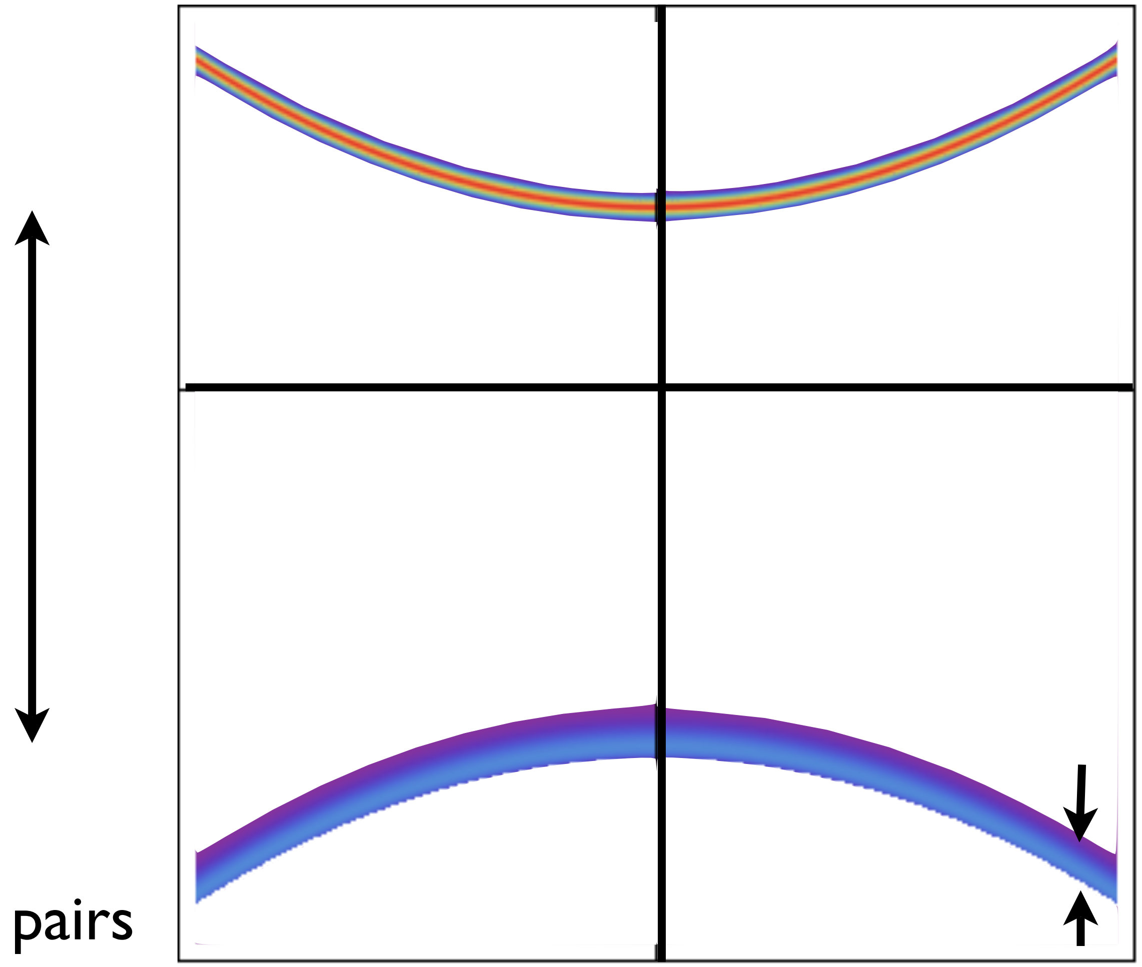
Extreme BEC limit

Fermion chemical potential: $\mu < 0$

ie. all atoms are paired

Pair binding energy: $E_B \gg k_b T$

Spectrum in normal state has two branches:



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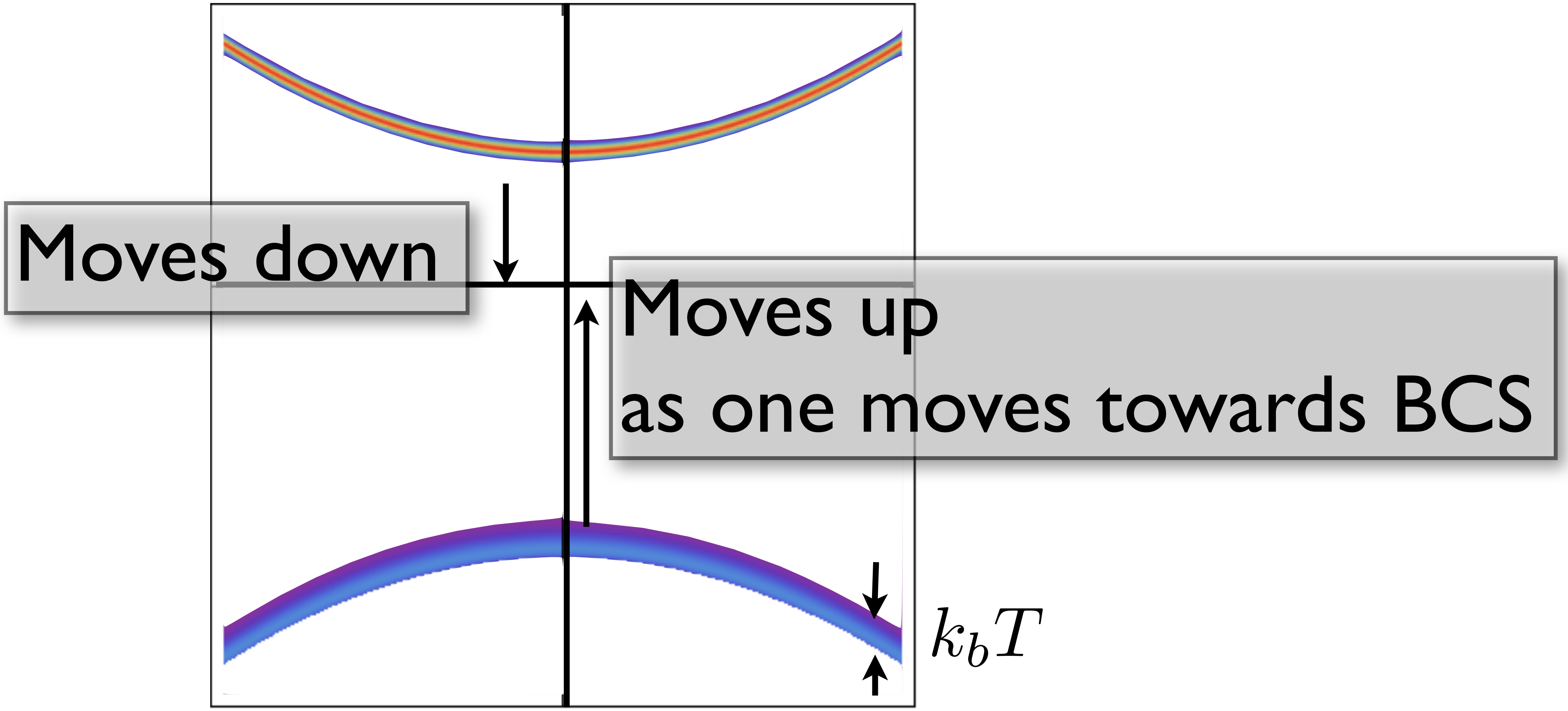
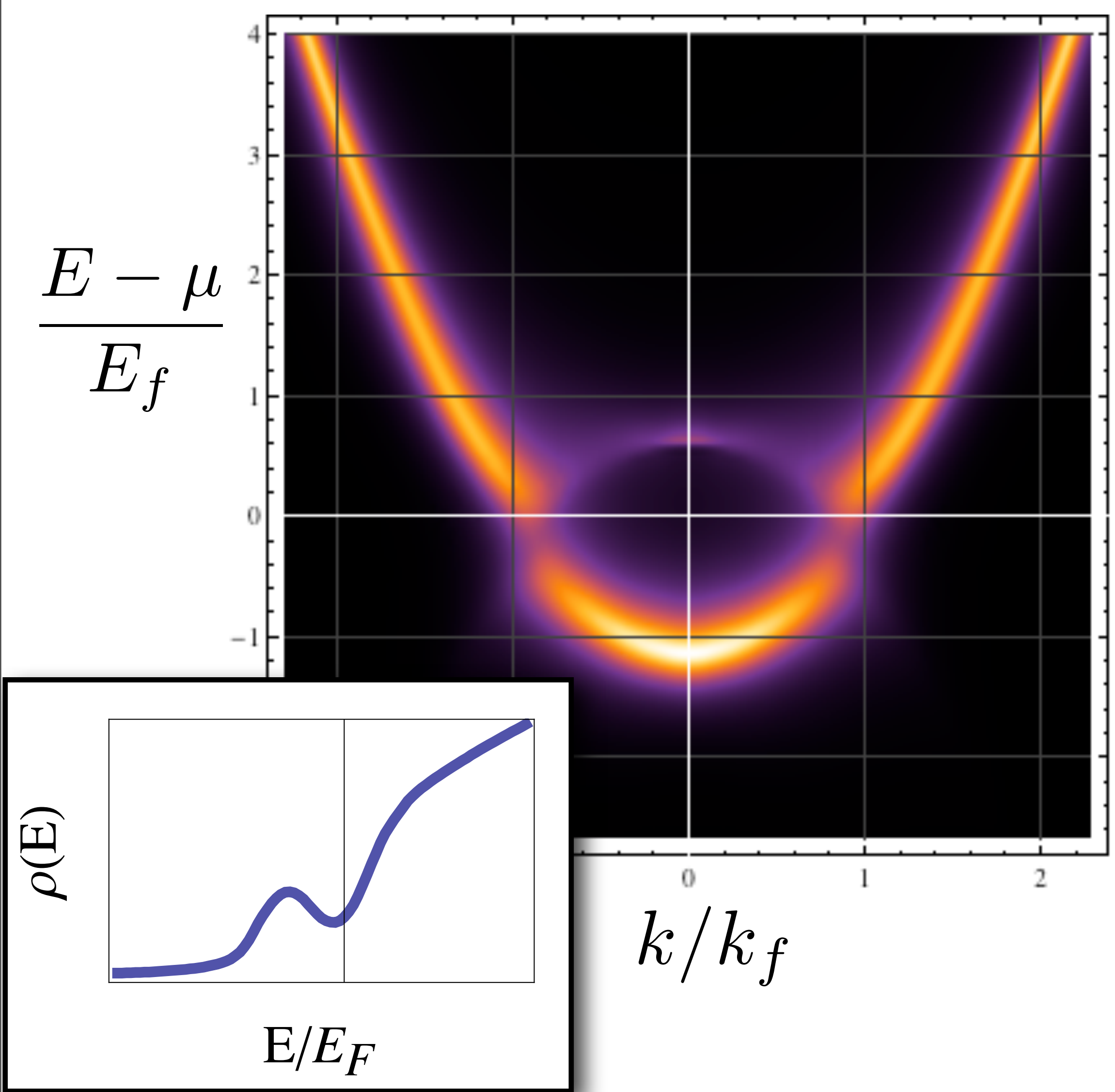


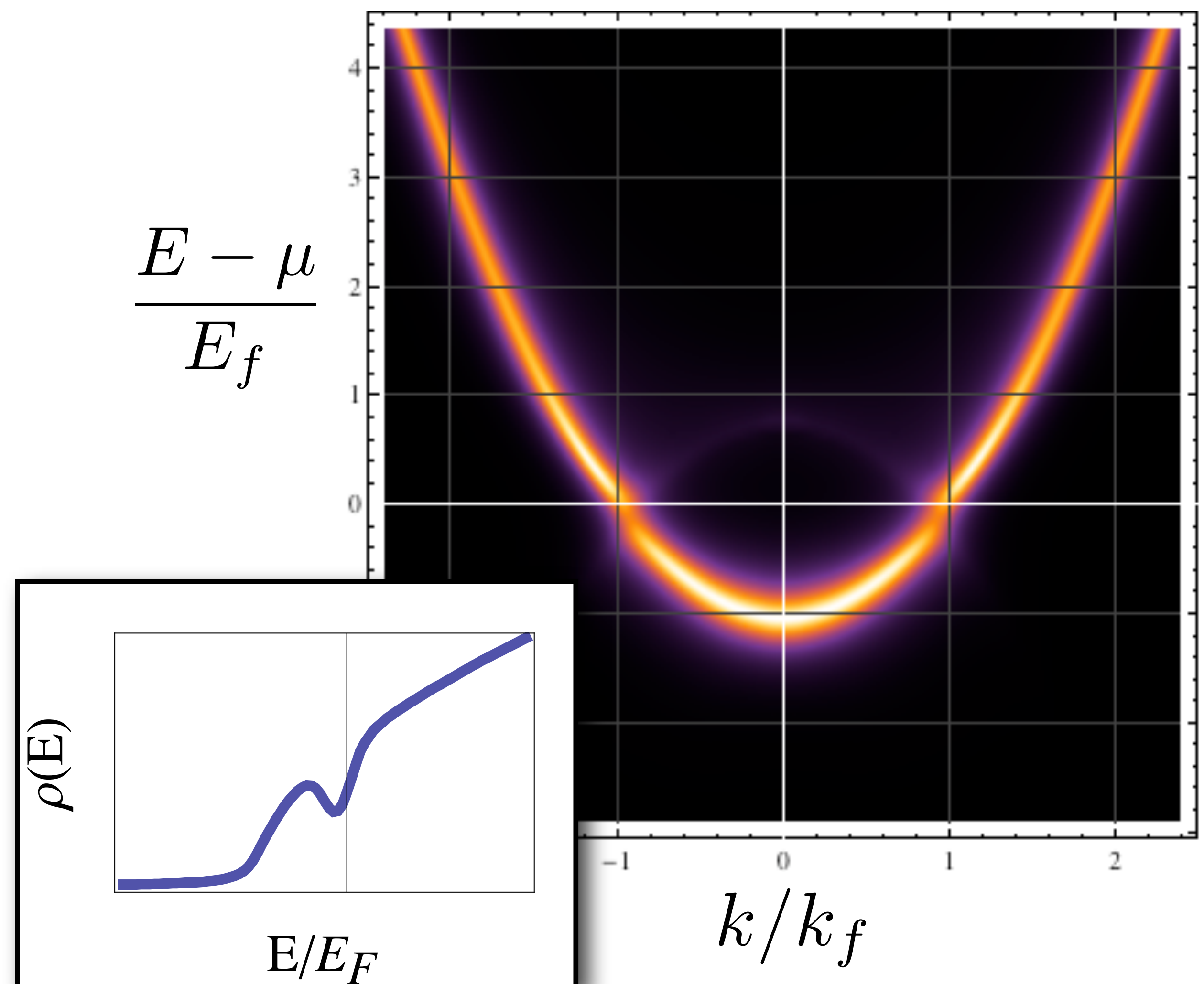
After bands cross

Normal State

$$\frac{1}{k_f a} = -0.2$$



$$\frac{1}{k_f a} = -0.6$$



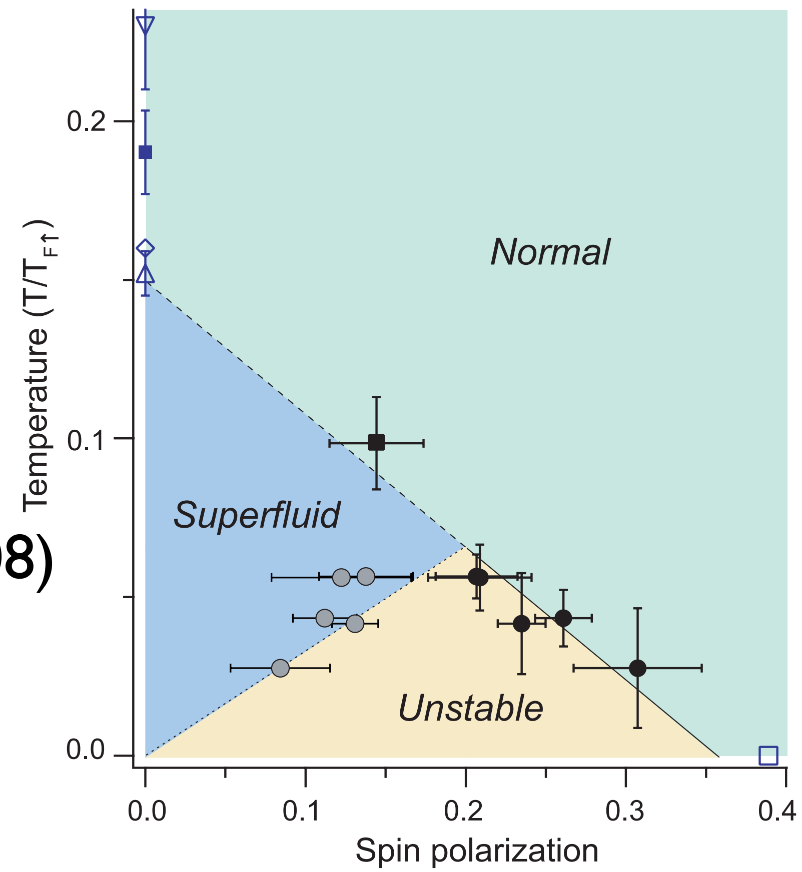
Physics: pairs in normal state give two excitation branches

Polarized Gases

Motivations:

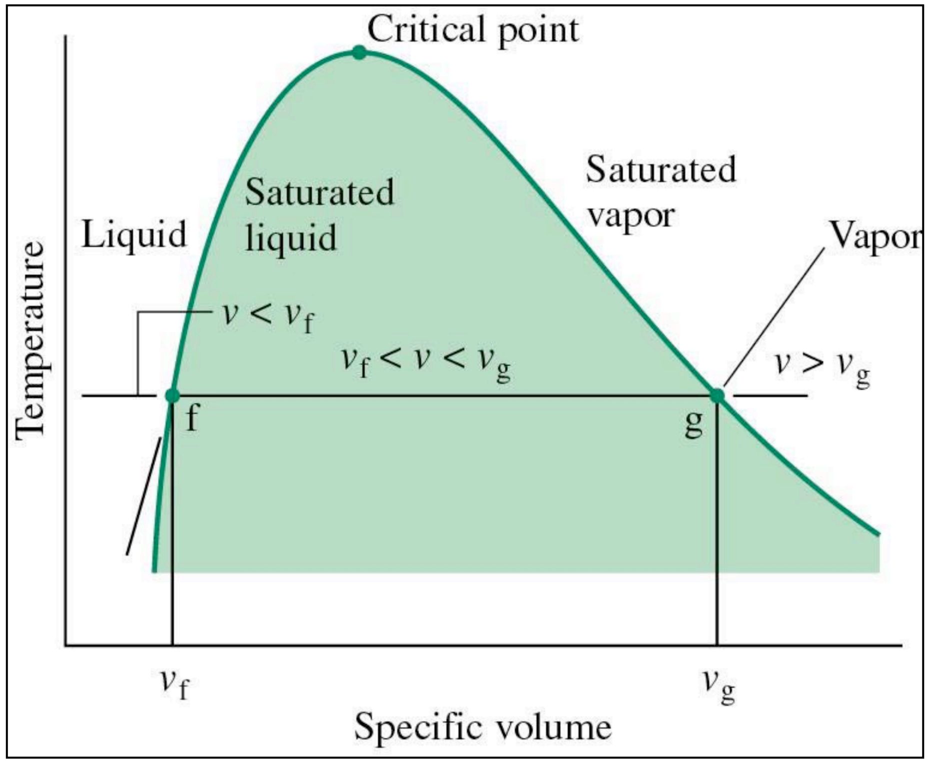
- Investigate Low Temperature Normal State
- FFLO
- Interplay between Superconductivity and Magnetism

Experimental Phase Diagram (Unitarity)

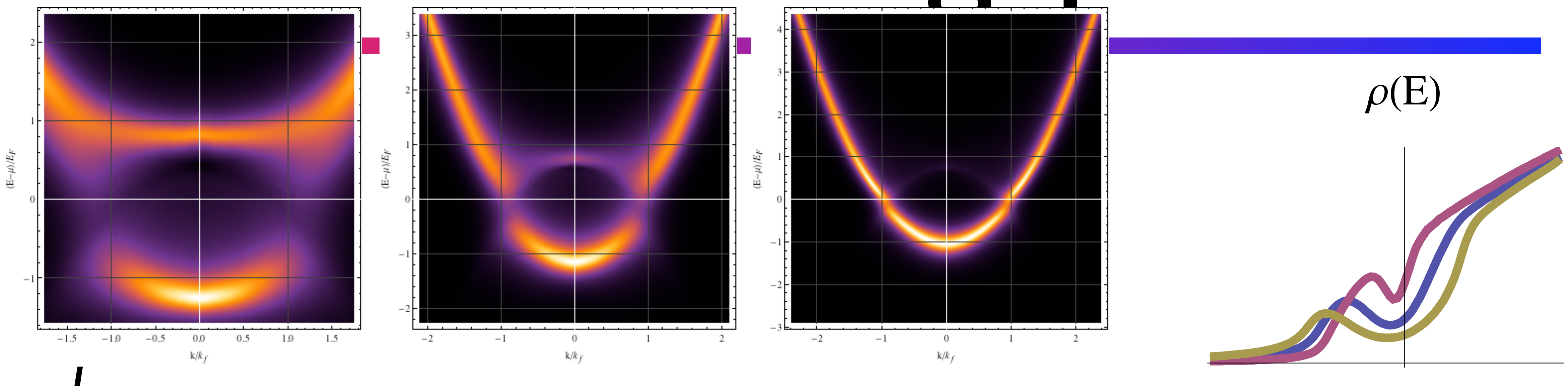


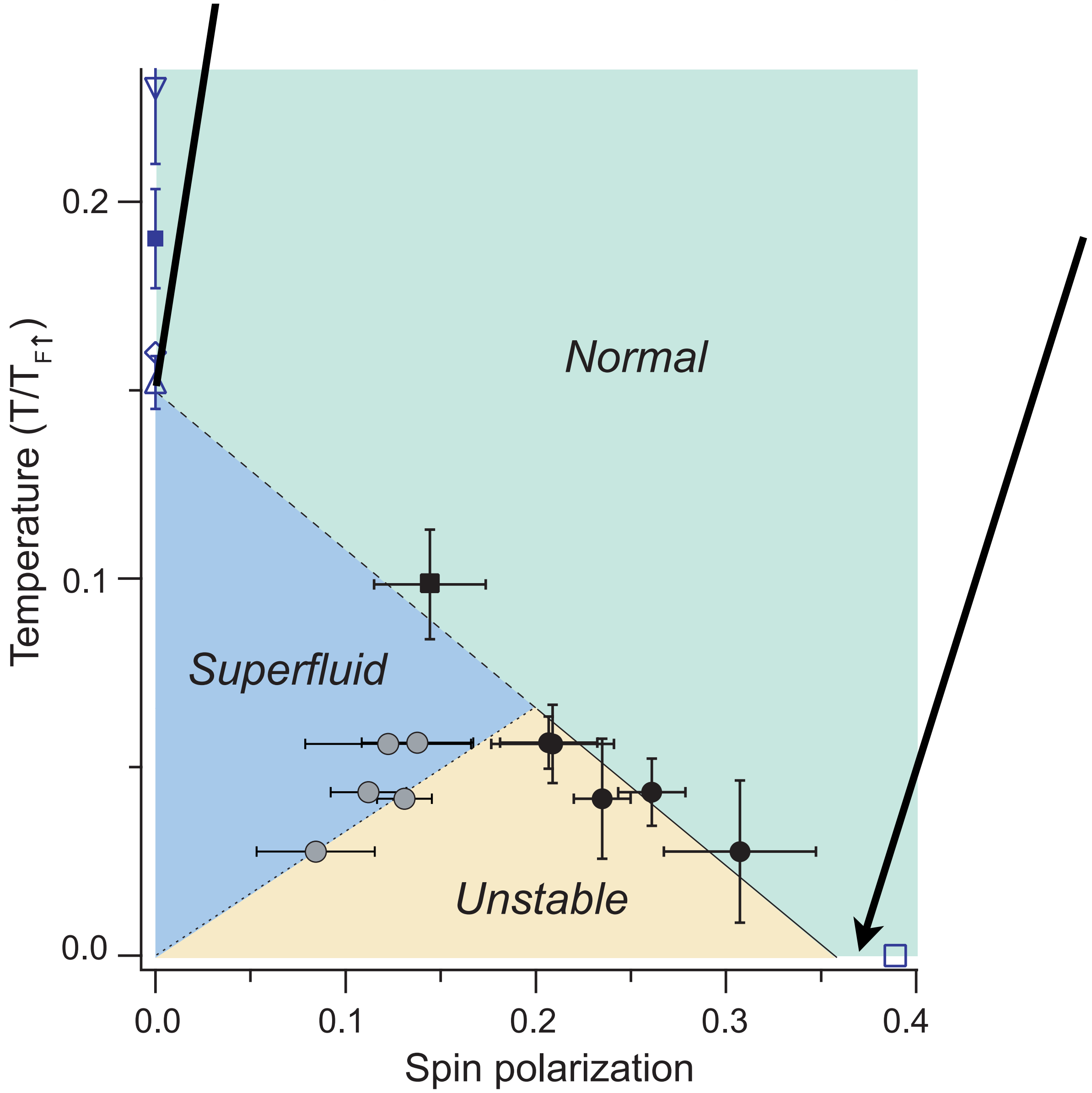
Shin, Schunck, Schirotzek, Ketterle, Nature, 451, 689 (2008)

cf.



Pseudogap





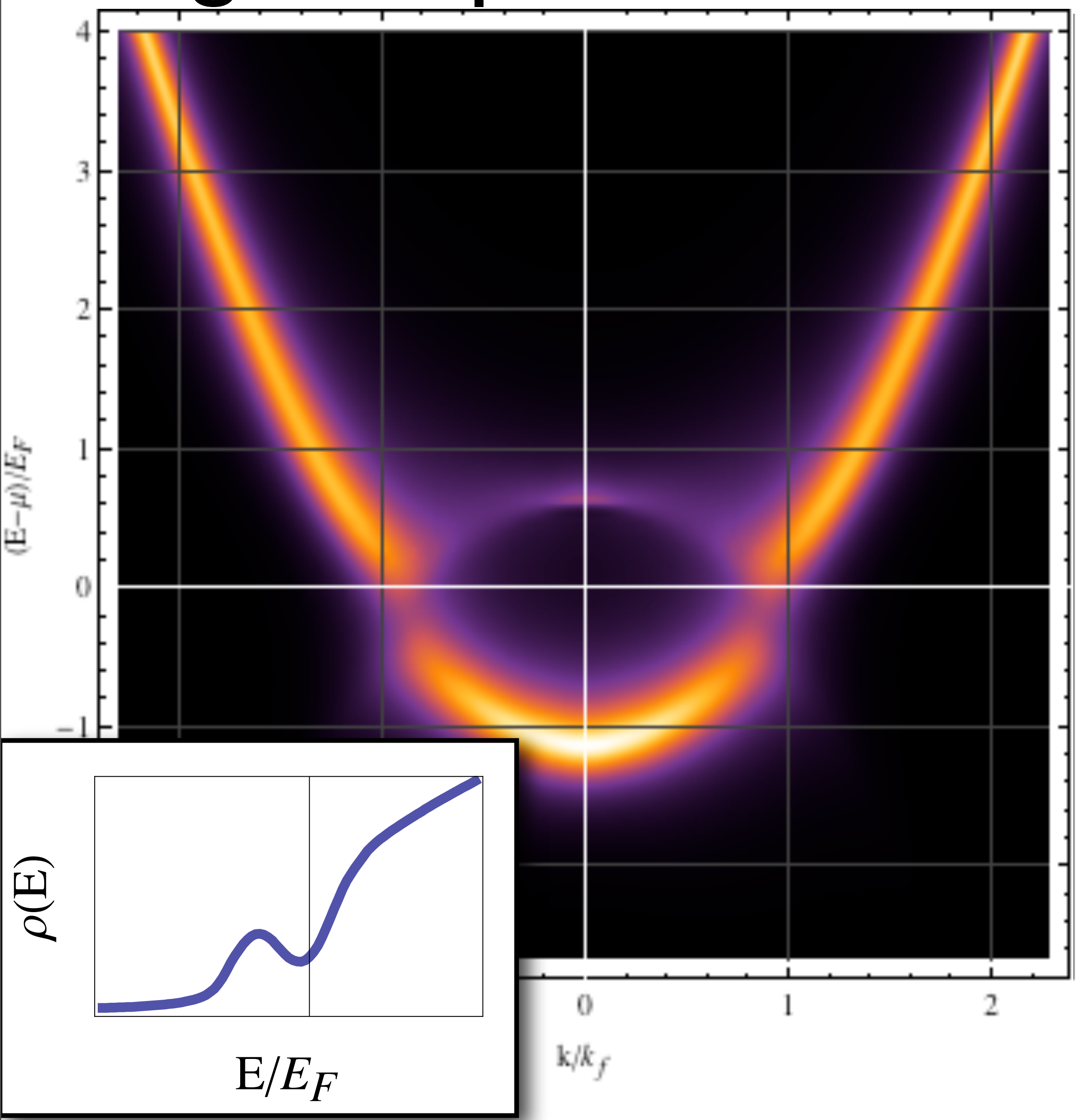
No condensed Bosons (normal)
No non-condensed Bosons (T=0)

What happens to pseudogap?

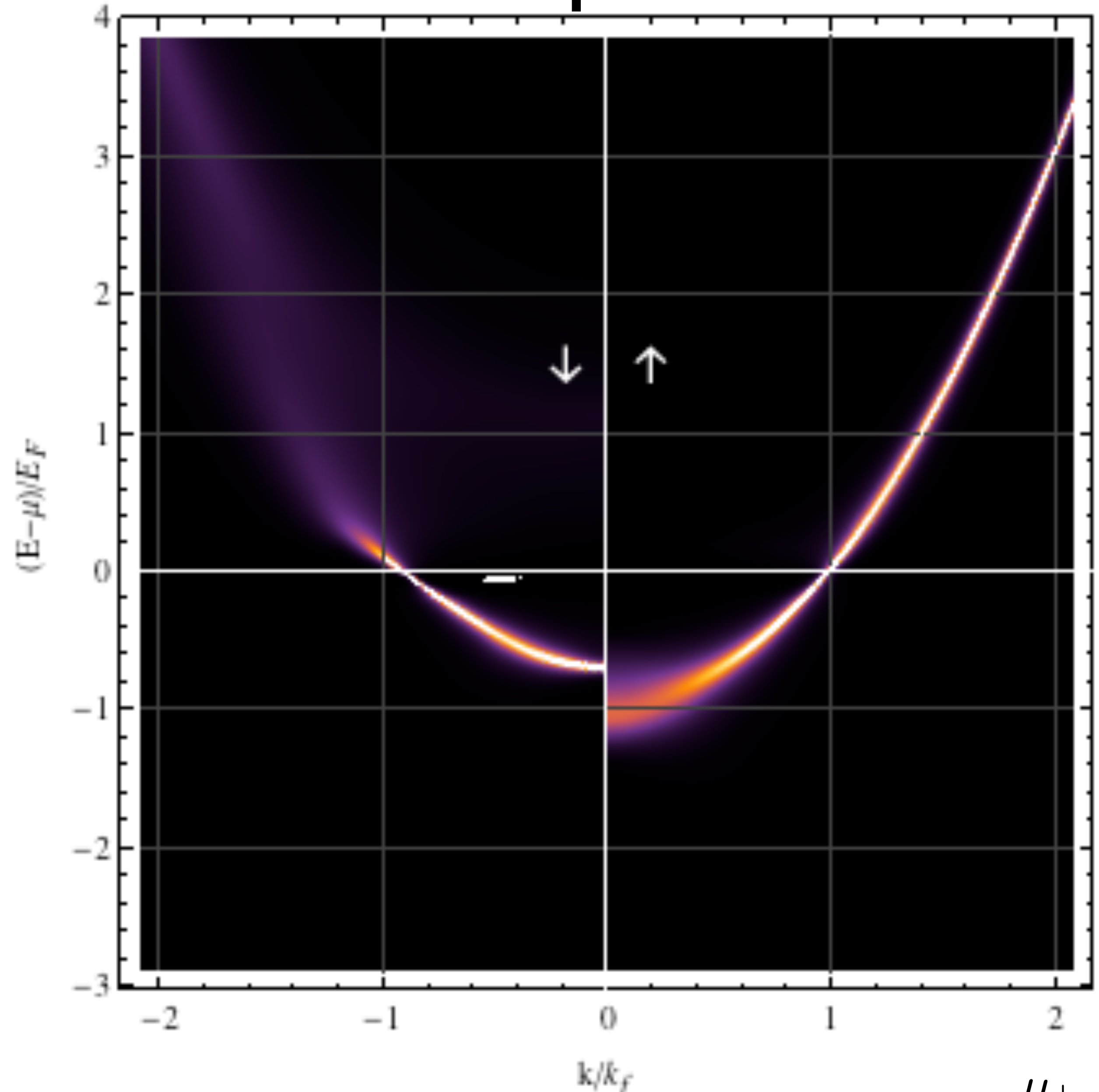
Parameters: Temp, Polarization, Interactions

Basic Result

Unpolarized
High temperature



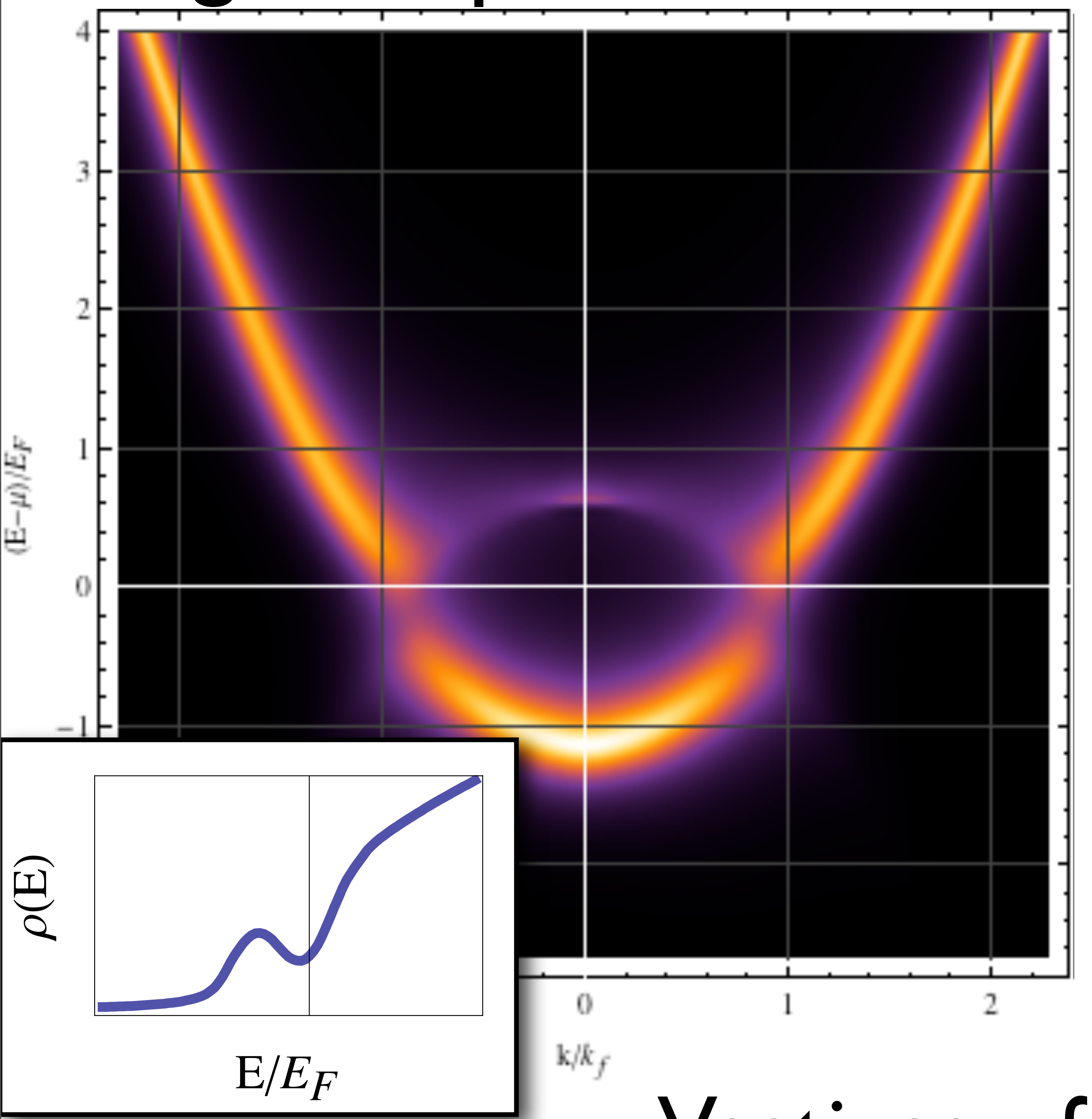
Polarized
Low temperature



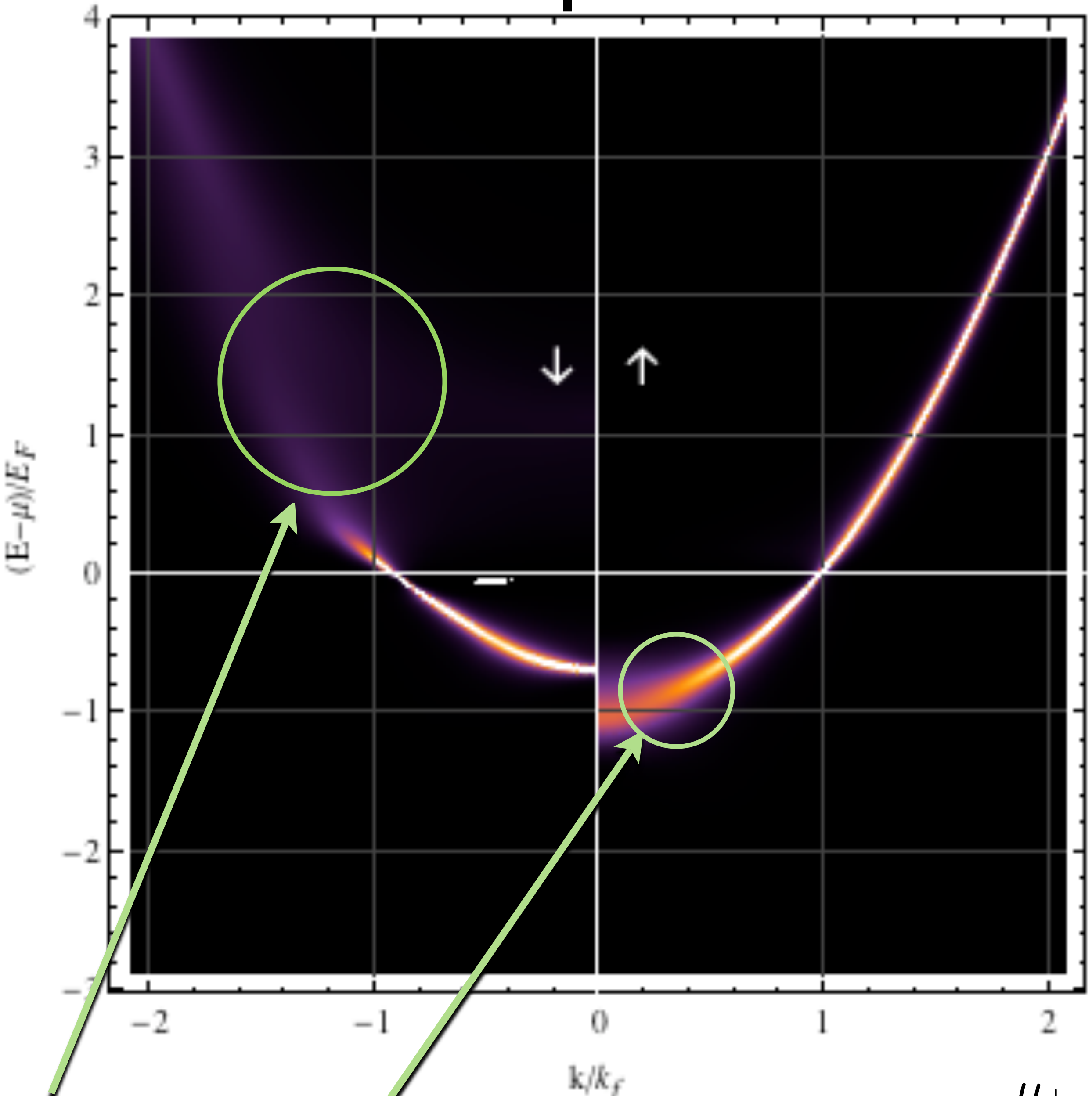
$$\frac{\mu_\downarrow}{\mu_\uparrow} = 0.2$$

Basic Result

Unpolarized
High temperature



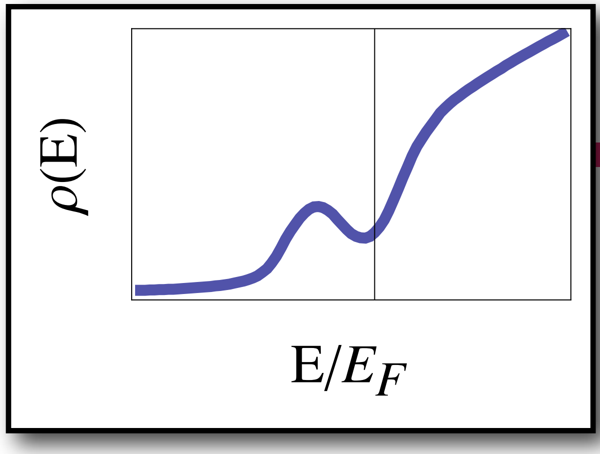
Polarized
Low temperature

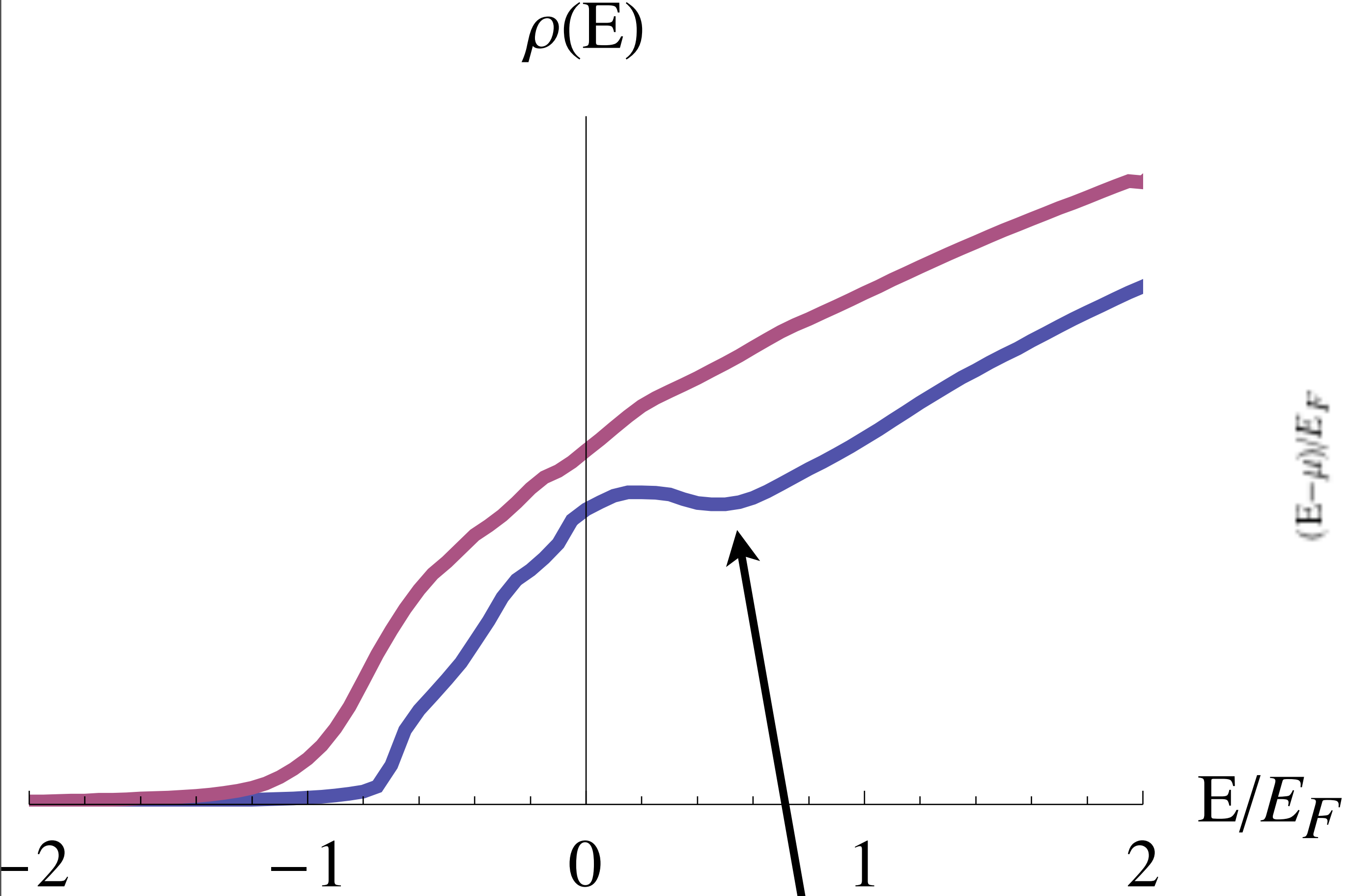


Vestiges of Pseudogap

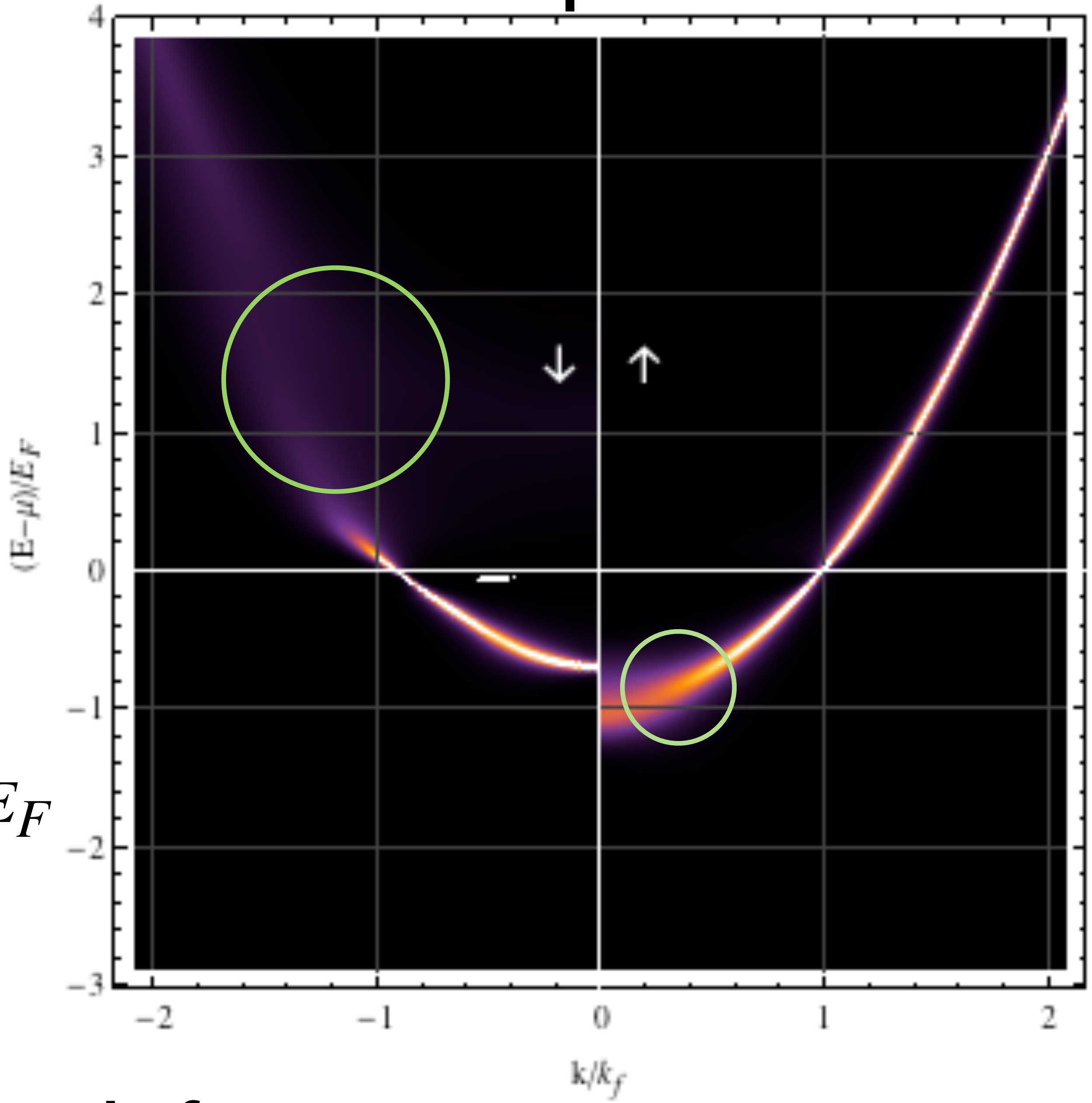
$$\frac{\mu_\downarrow}{\mu_\uparrow} = 0.2$$

Basic Result



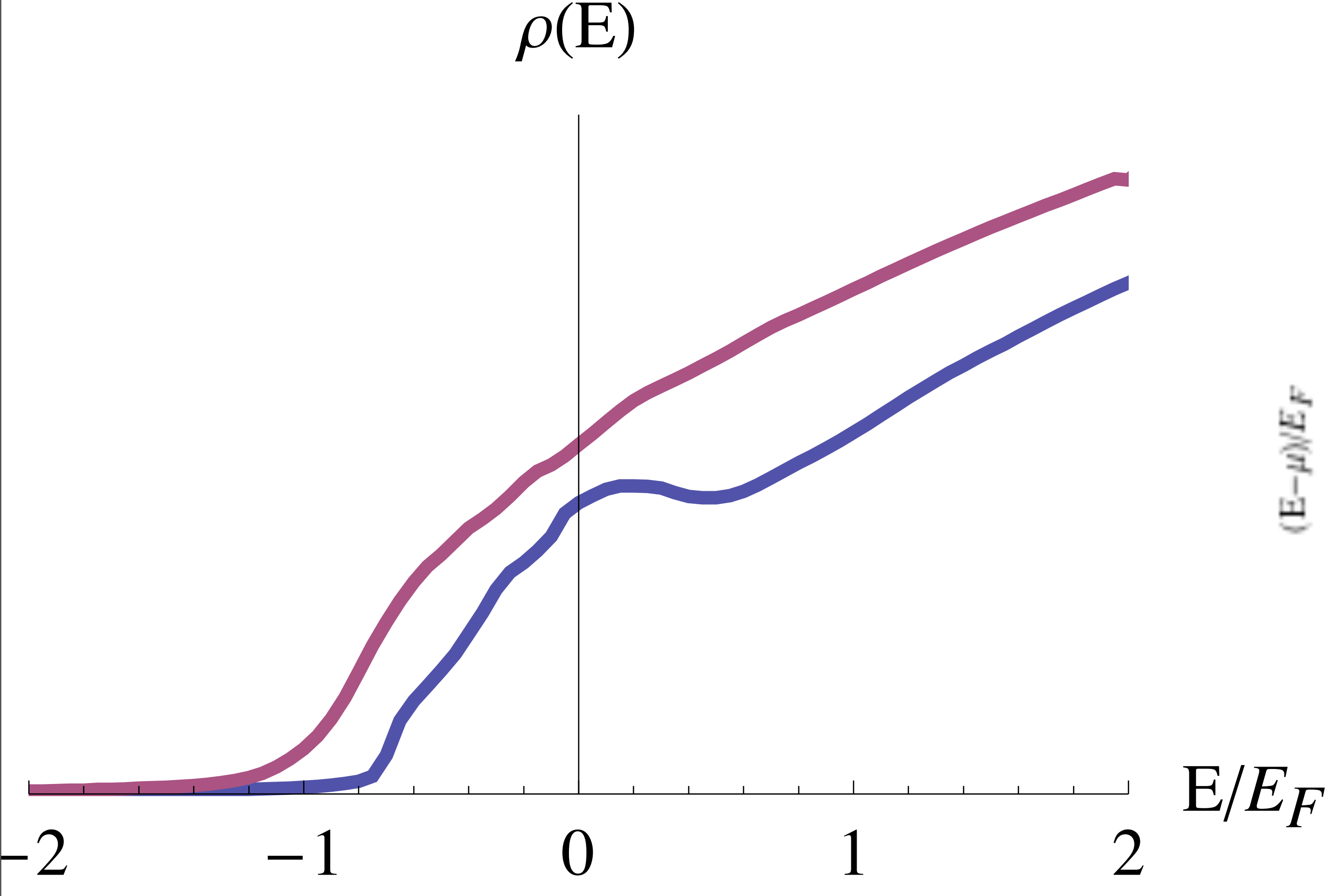


Polarized
Low temperature

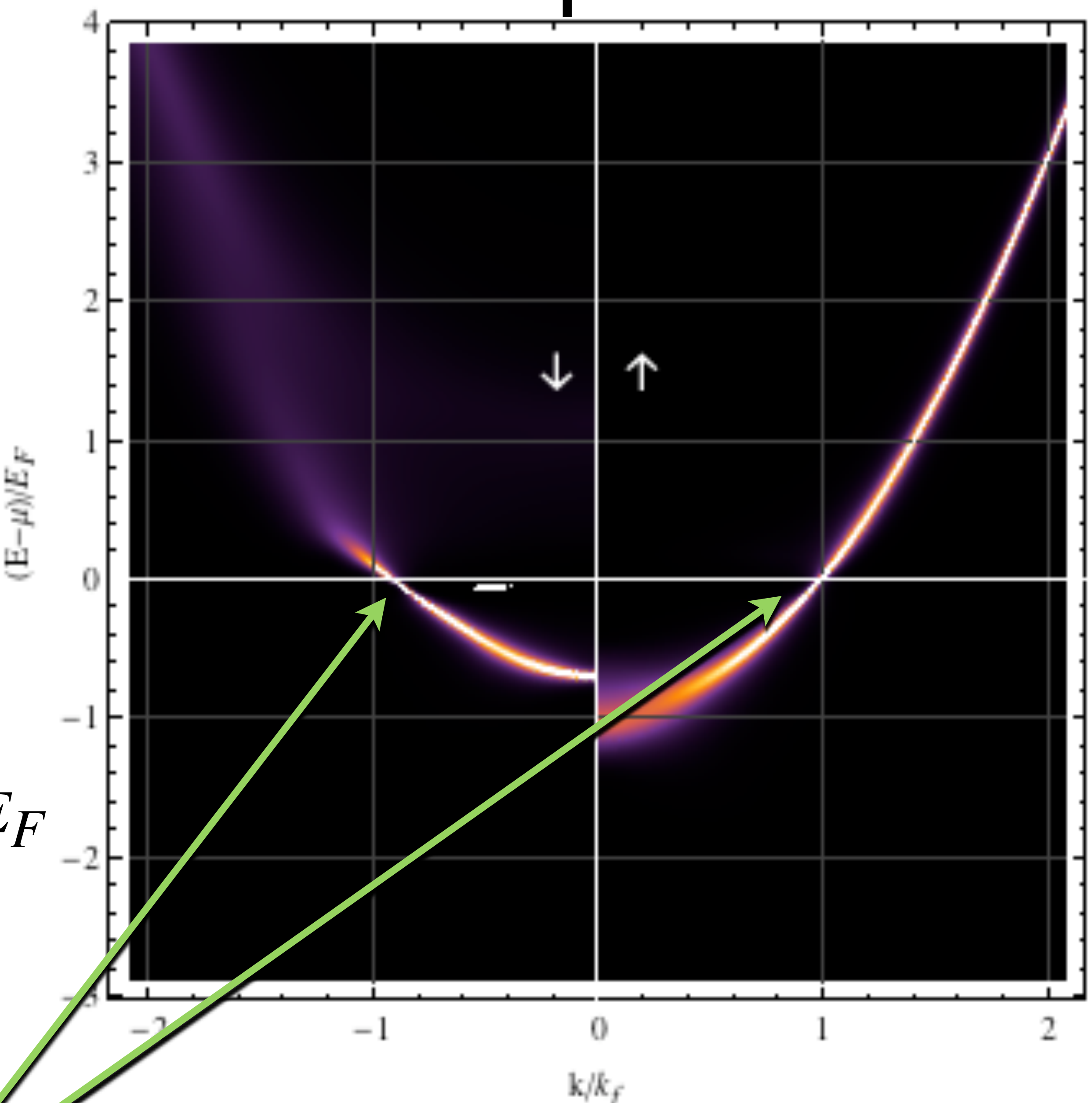


Pseudogap shifts

Basic Result

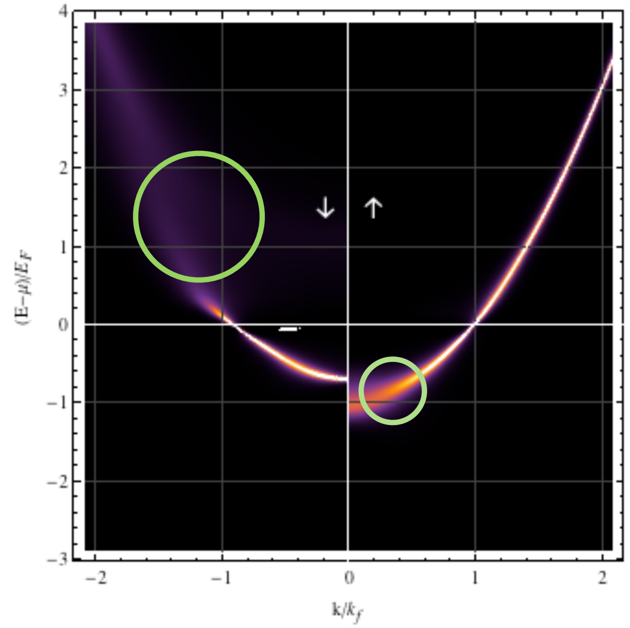


Polarized
Low temperature



Fermi Liquid

Basic Idea



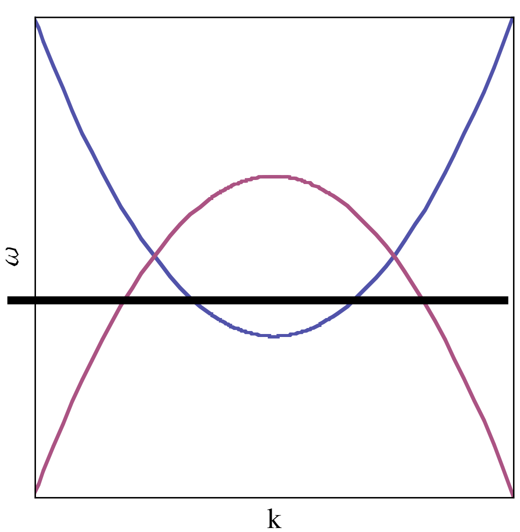
Minority Species

method 1: add particle

$$\omega = \frac{k^2}{2m} - \mu_\downarrow$$

method 2: add pair + hole

$$\omega = (\cancel{E_b - \mu_b}) - (\frac{k^2}{2m} - \mu_\uparrow)$$



gap (pseudogap)
lifted above
Fermi surface

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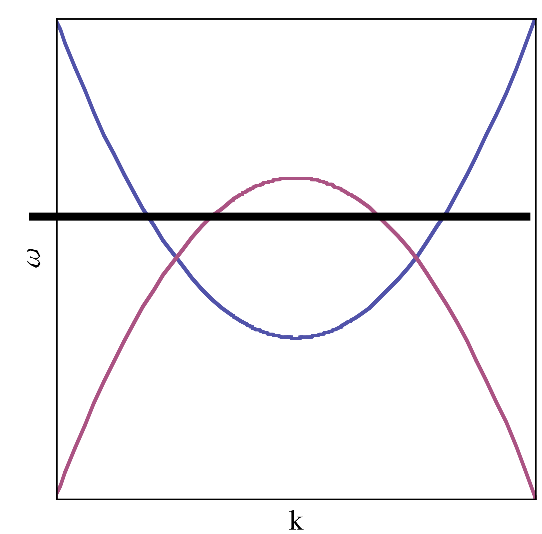
method 2: add pair + hole

$$\omega = (\cancel{E_b - \mu_b}) - (\frac{k^2}{2m} - \mu_\downarrow)$$

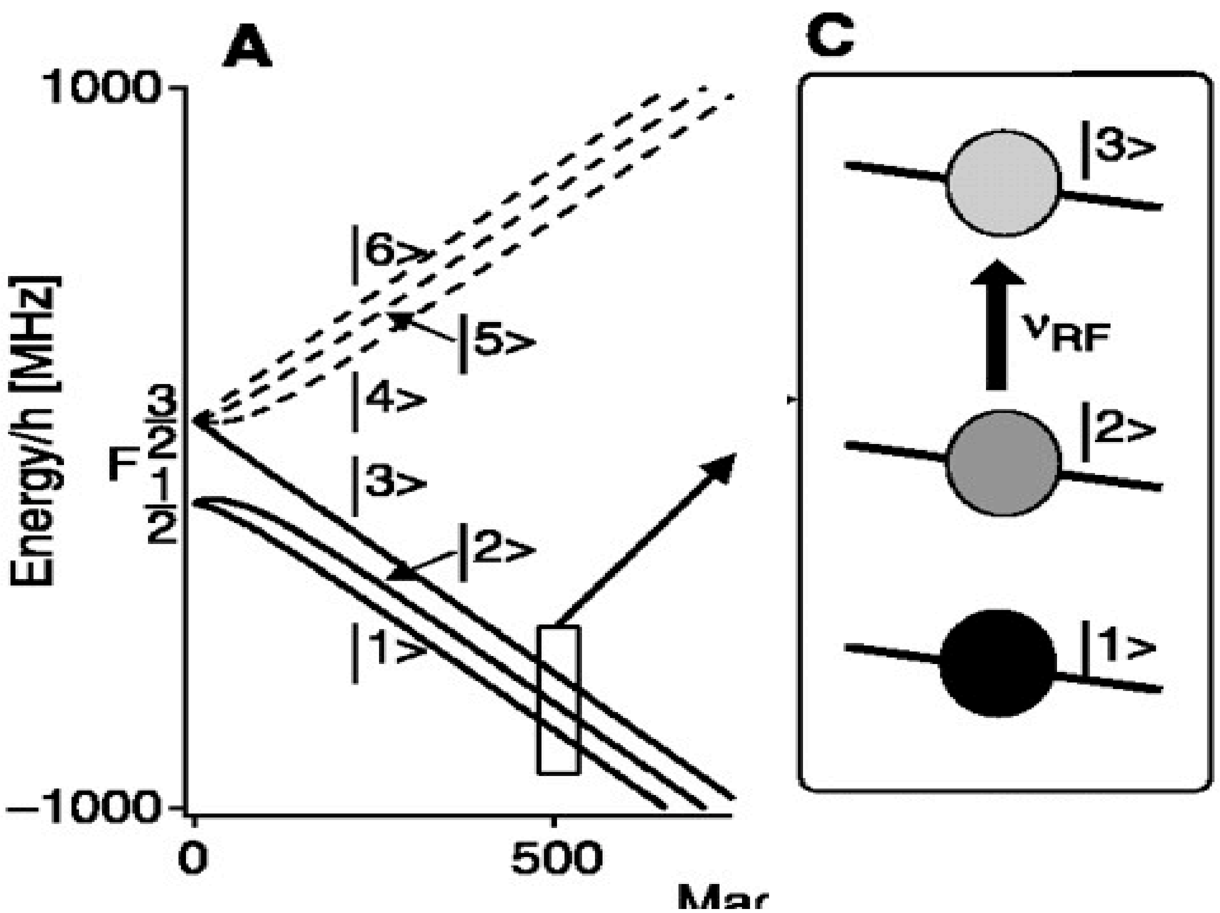
gap (pseudogap)
pushed below
Fermi surface



cf. “breached pairs” -- Liu

Detection

RF Spectroscopy:



S. Gupta, Z. Hadzibabic, M.W. Zwierlein, C.A. Stan, K. Dieckmann, C.H. Schunck, E.G.M. van Kempen, B.J. Verhaar, W. Ketterle, Science, 300, 1723 (2003)

Assuming:

- no atoms in 3
- no interactions with 3

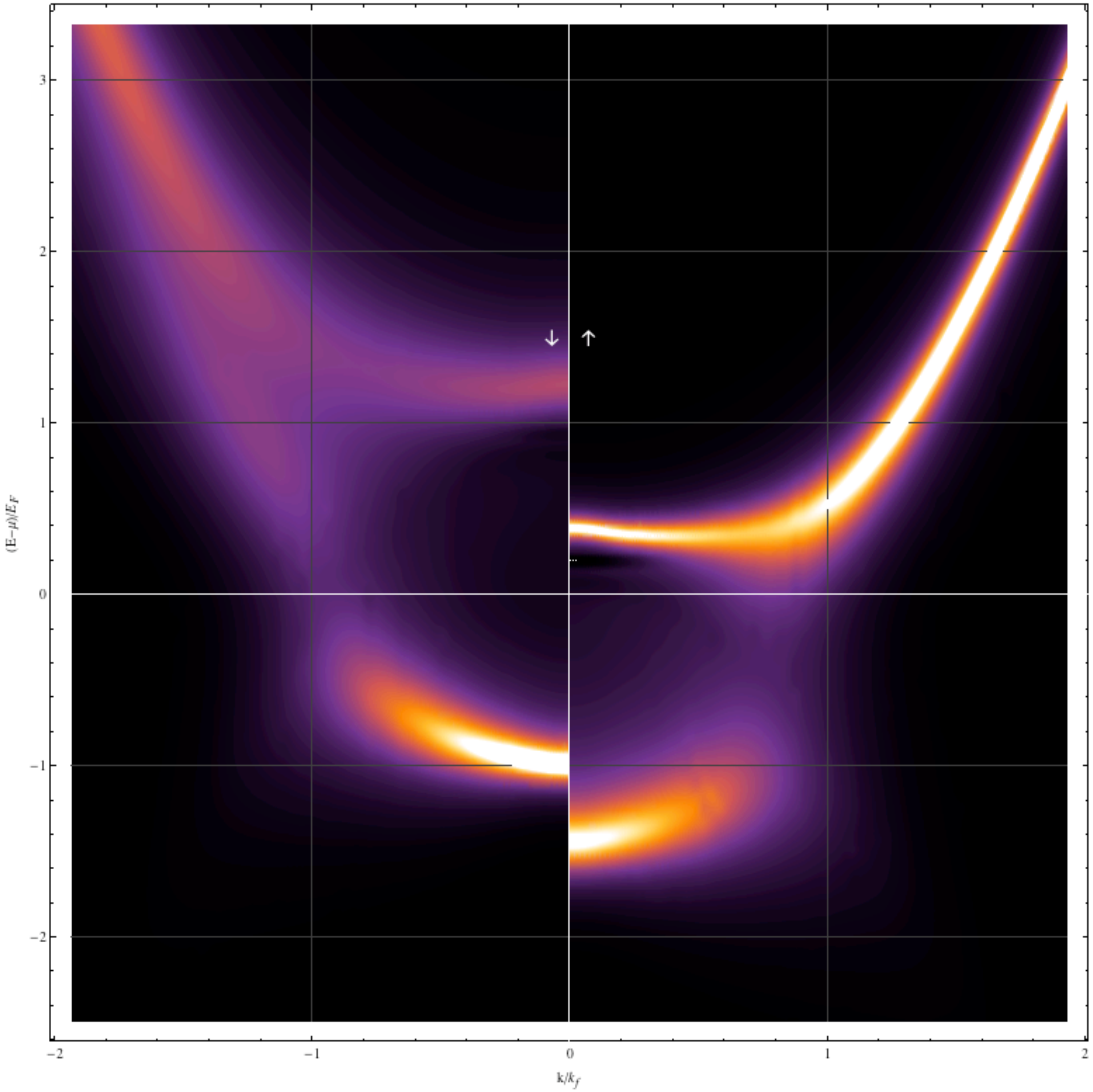
Transition rate maps spectrum

$$I(\omega) \propto \int d^3k\, G_a^<(k, \omega - \epsilon_k^{(b)})$$

(transfer from a to b)

(Problem 1: non-interacting assumption is bad)
(Problem 2: inhomogeneous broadening)

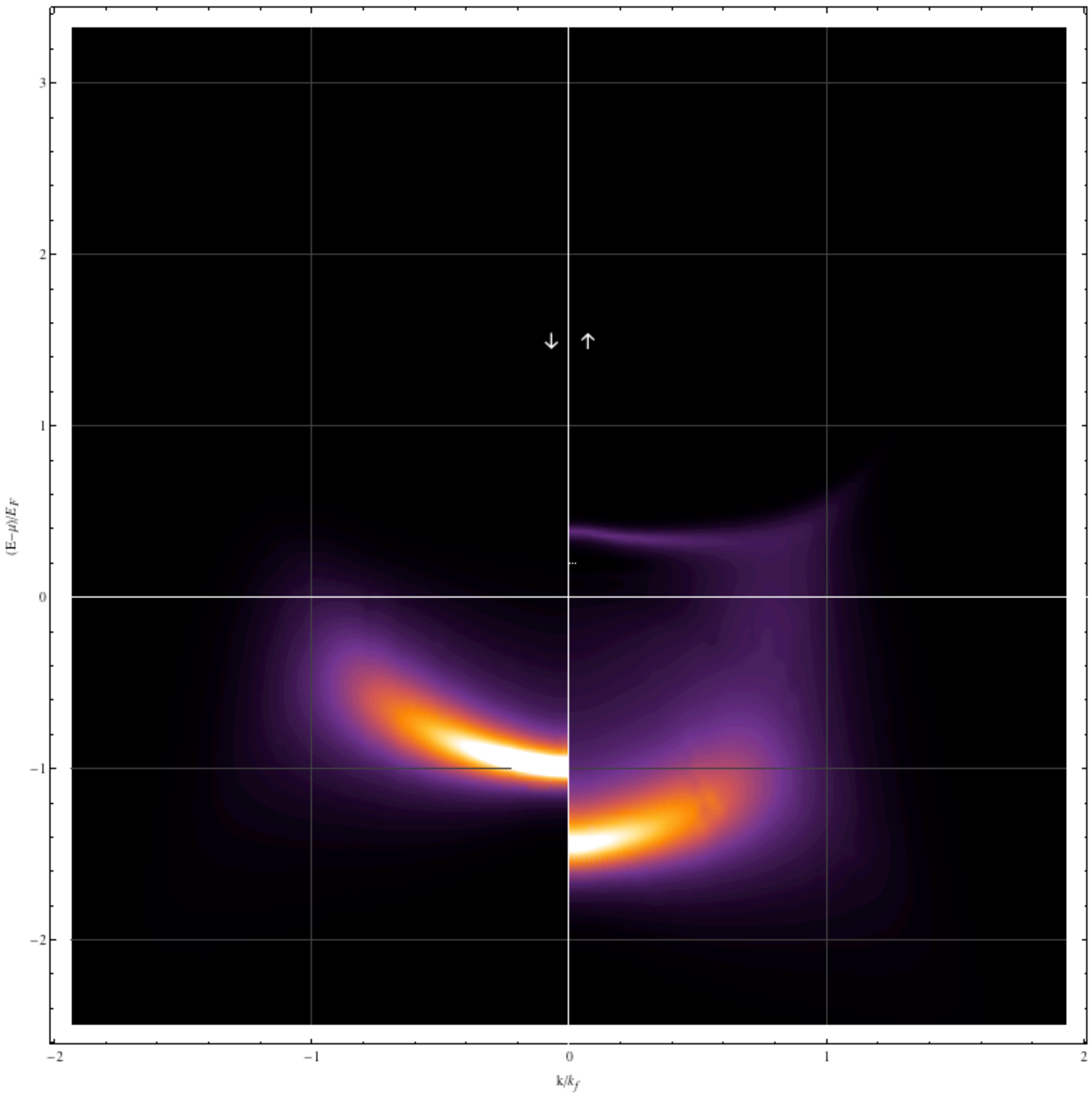
Graphical argument



1: Spectral Density

$$I(\omega) \propto \int d^3k\, G_a^{<}(k, \omega - \epsilon_k^{(b)})$$

Graphical argument

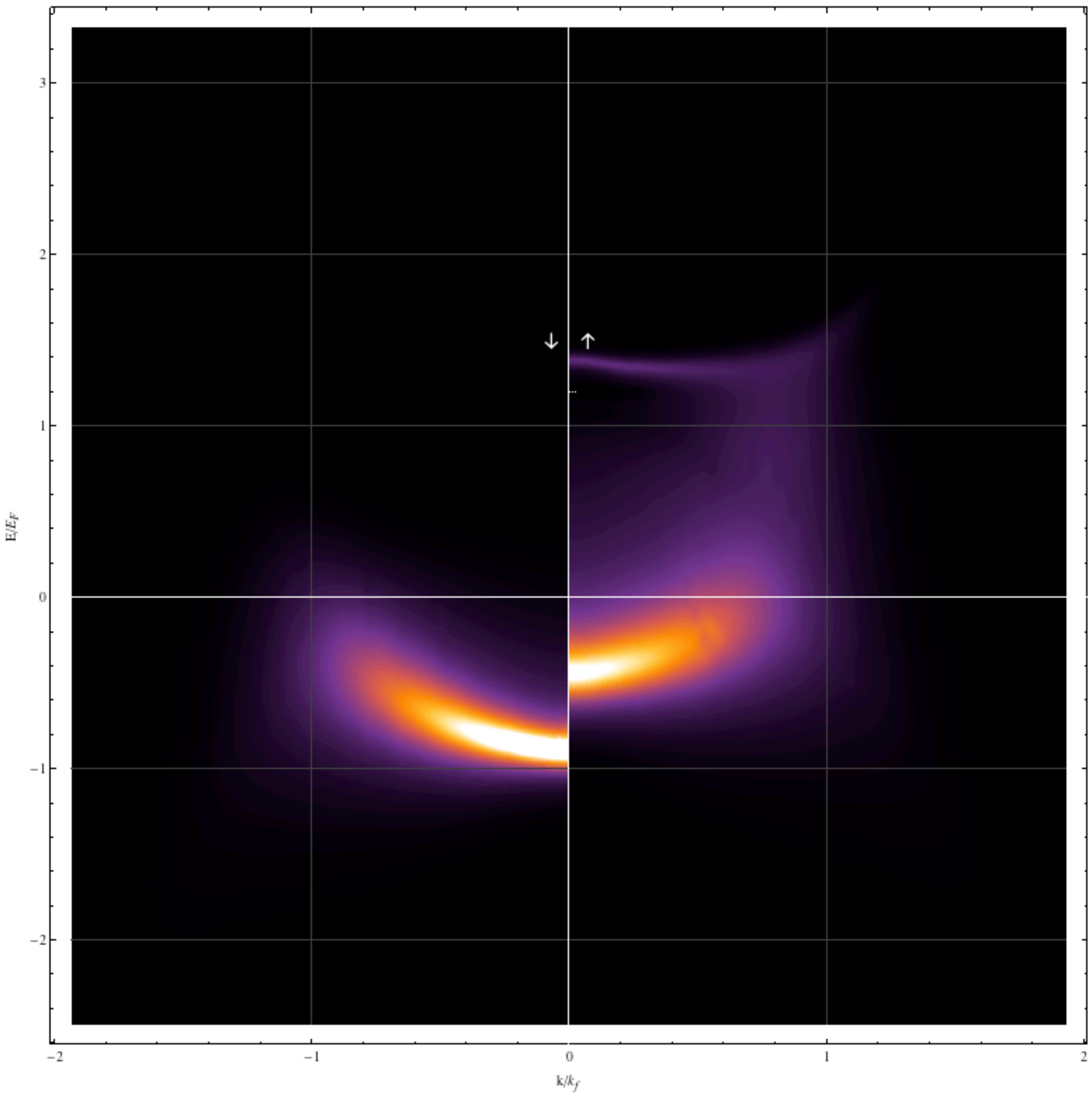


1: Spectral Density

2: Fermi function

$$I(\omega) \propto \int d^3k\, G_a^<(k, \omega - \epsilon_k^{(b)})$$

Graphical argument



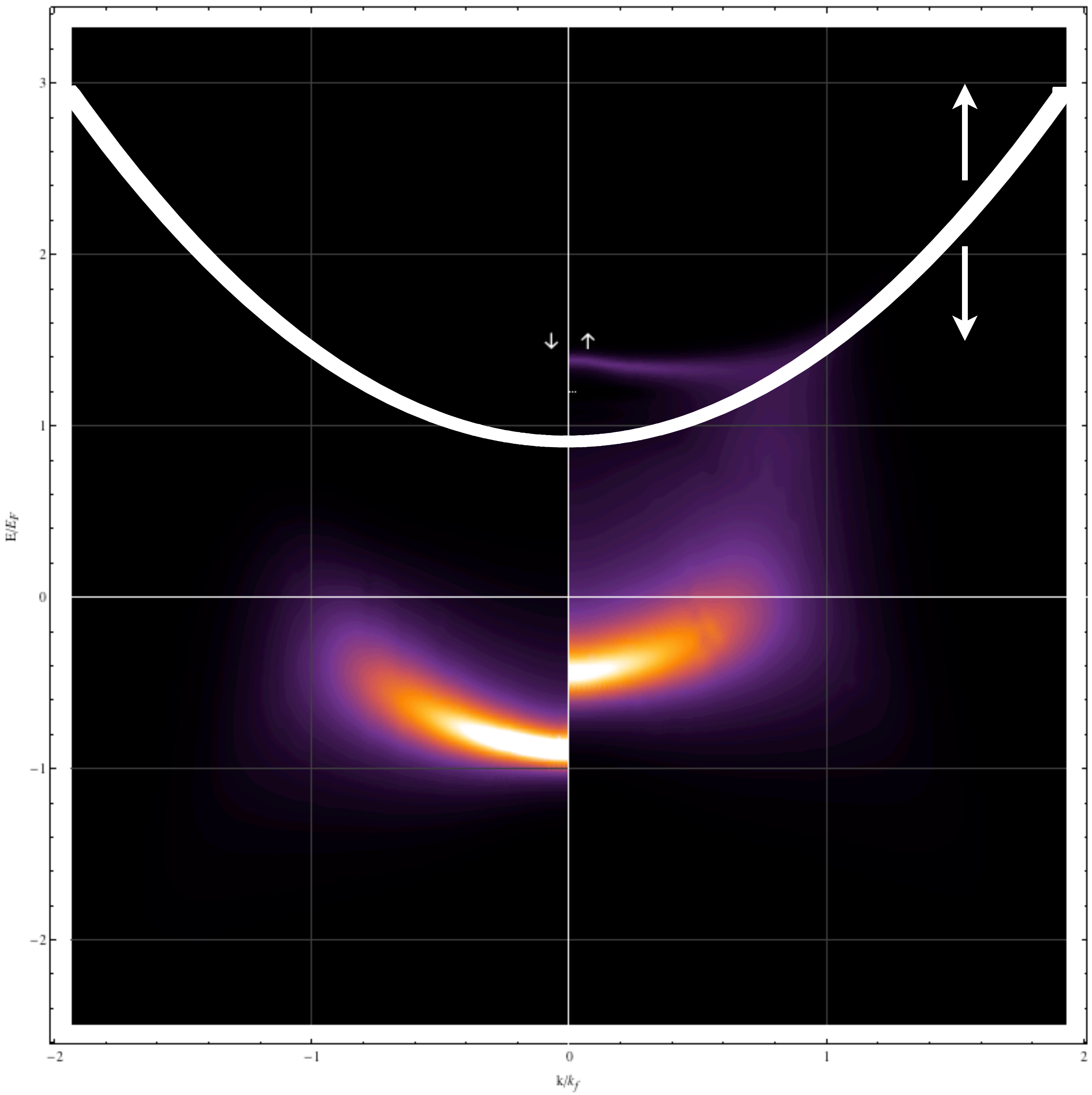
1: Spectral Density

2: Fermi function

3: Shift axes (remove μ from Hamiltonian)

$$I(\omega) \propto \int d^3k\, G_a^<(k, \omega - \epsilon_k^{(b)})$$

Graphical argument



1: Spectral Density

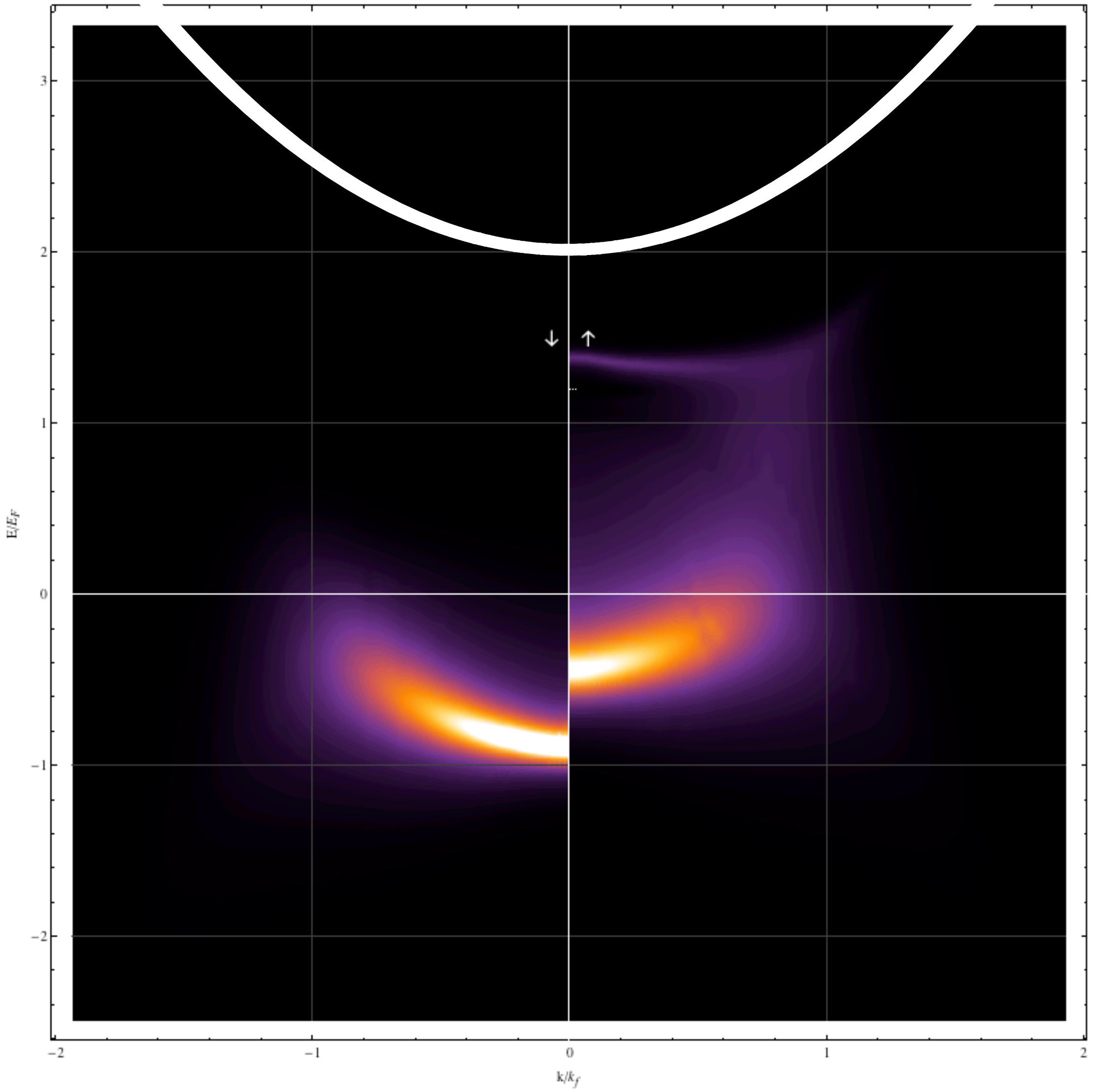
2: Fermi function

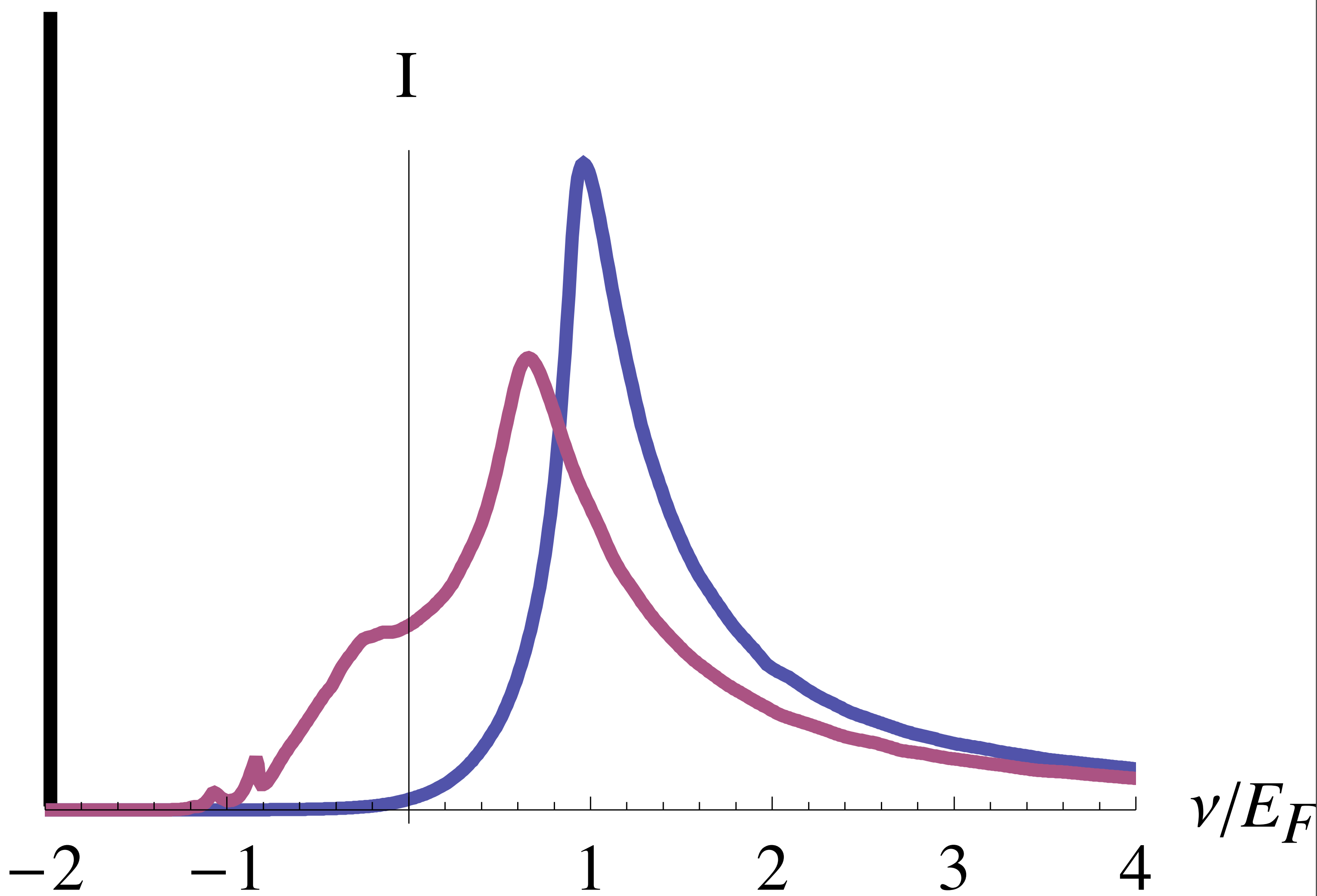
3: Shift axes (remove μ from Hamiltonian)

4: Fermi's Golden Rule

$$I(\omega) \propto \int d^3k\, G_a^{<}(k, \omega - \epsilon_k^{(b)})$$

Graphical argument

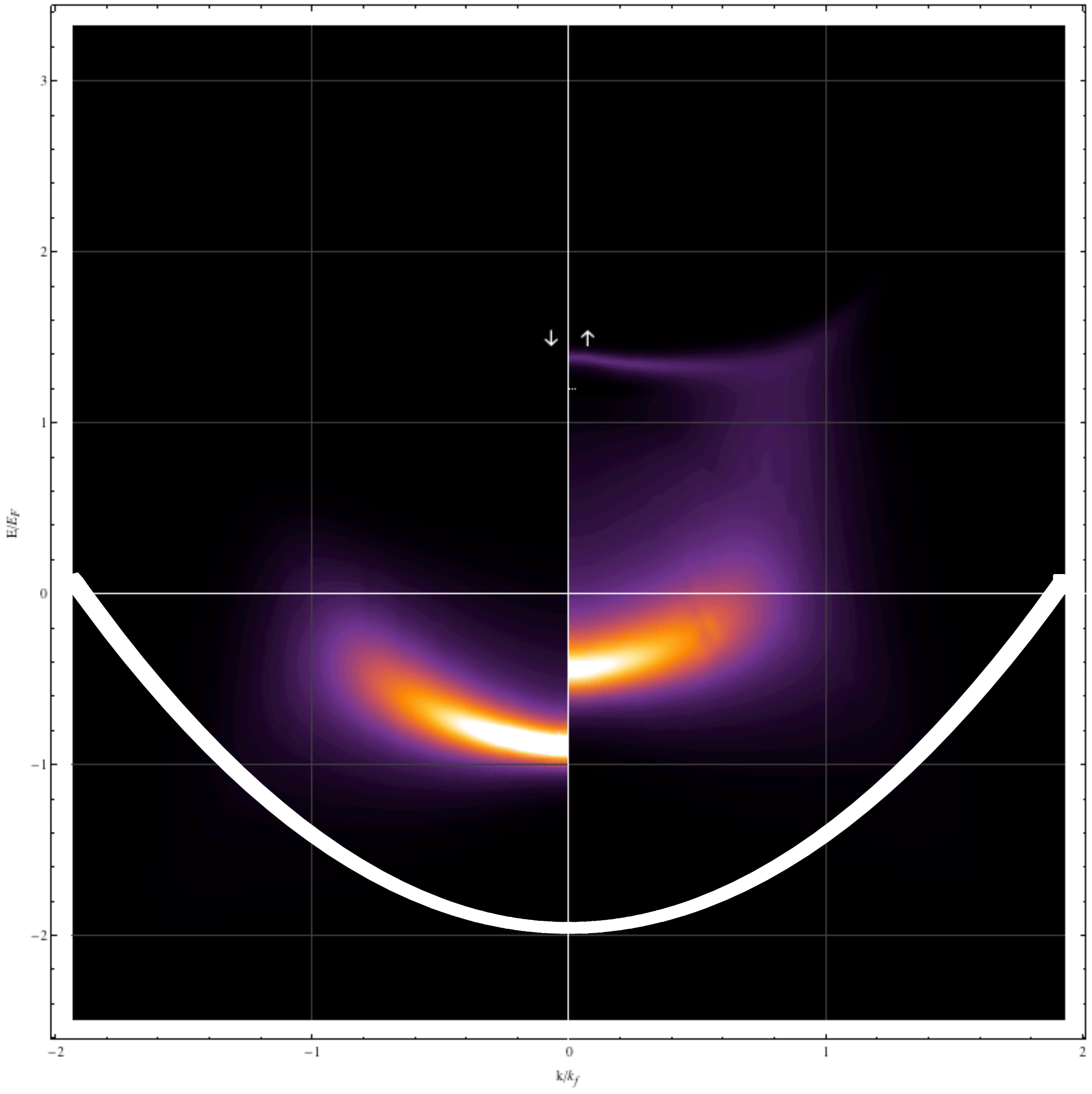


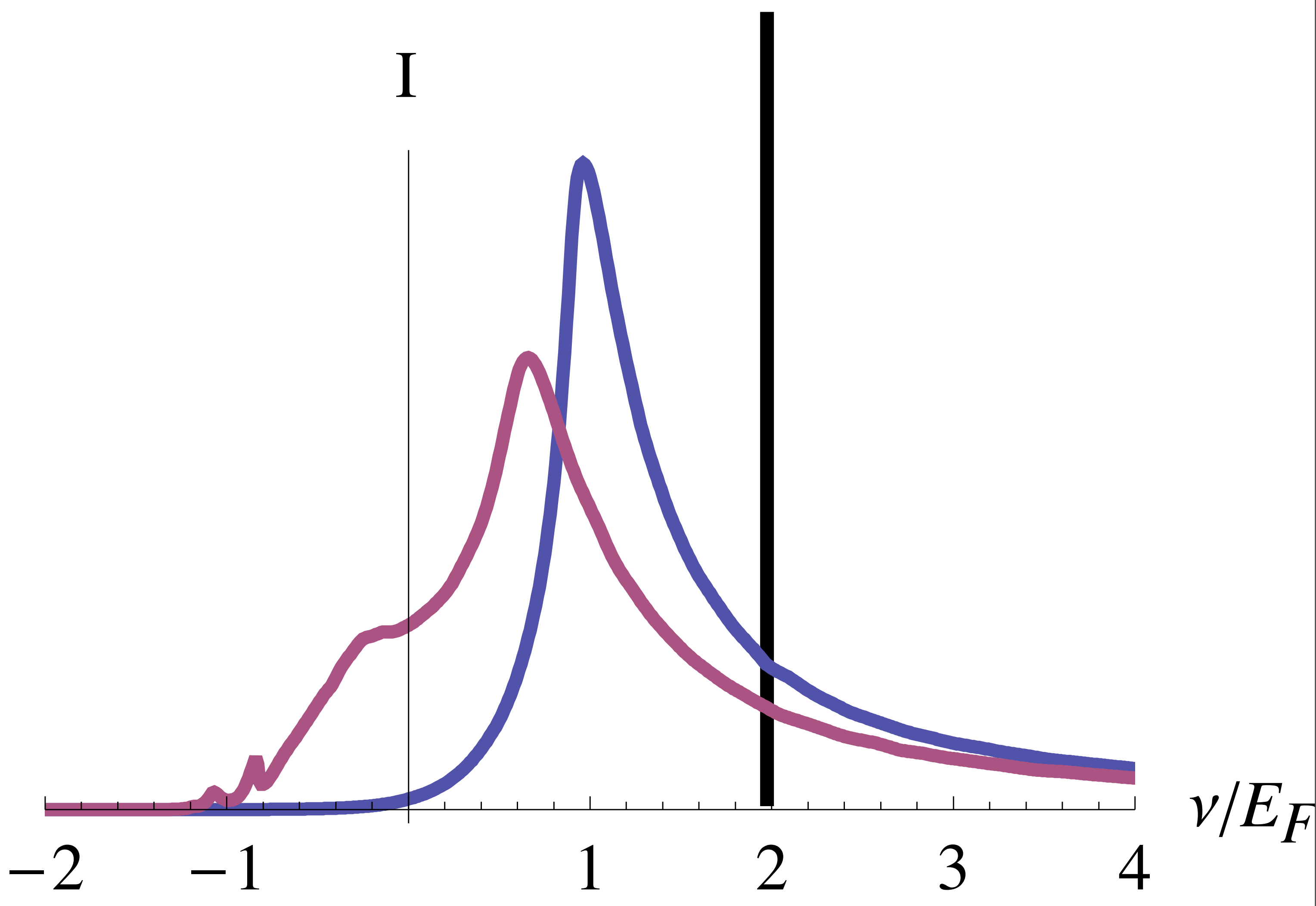


Most prominent features:
deep in Fermi sea

$$I(\omega) \propto \int d^3k\, G_a^<(k, \omega - \epsilon_k^{(b)})$$

Graphical argument





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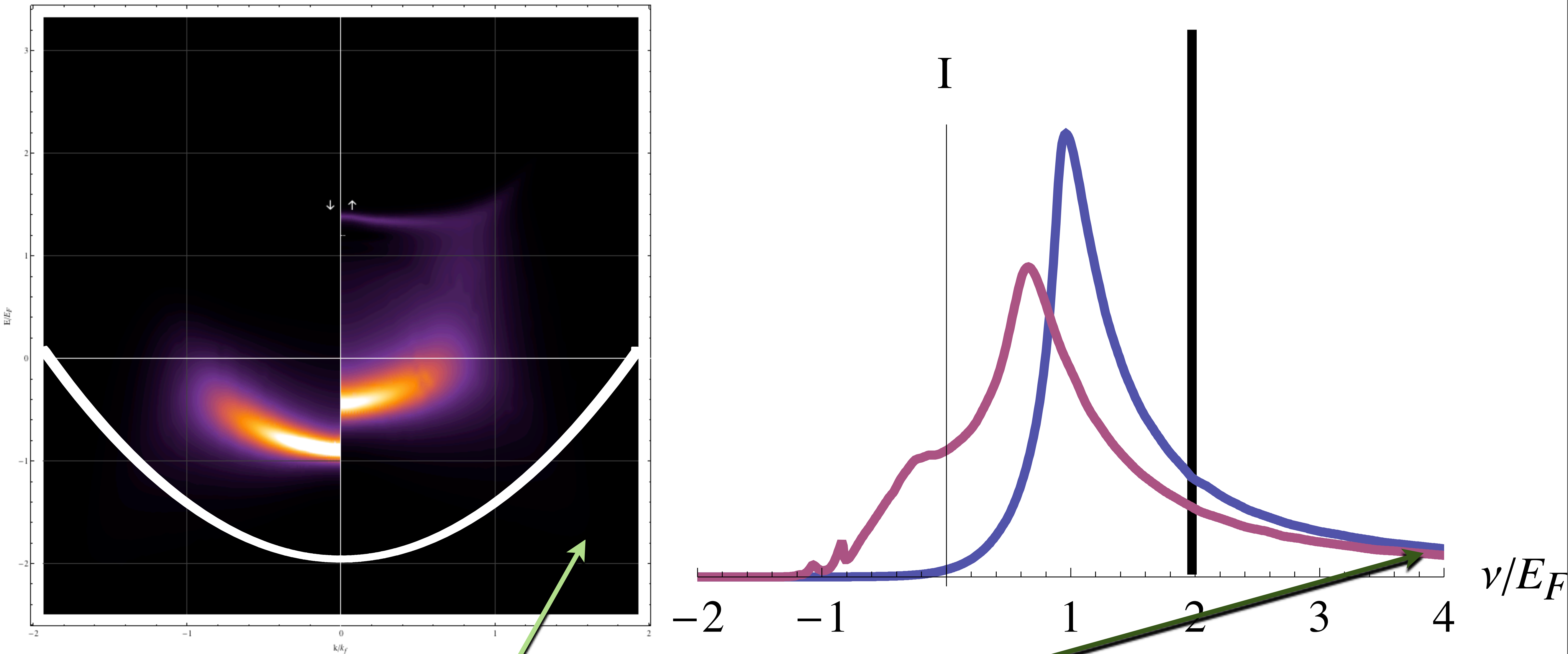
Graphical argument



Diffuse weight

$$I(\omega) \propto \int d^3k \, G_a^<(k, \omega - \epsilon_k^{(b)})$$

Direct measurement

Momentum Resolution:

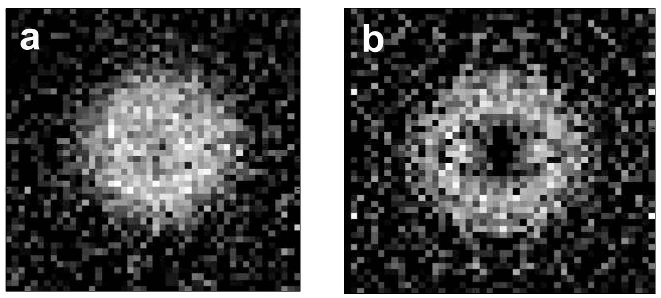
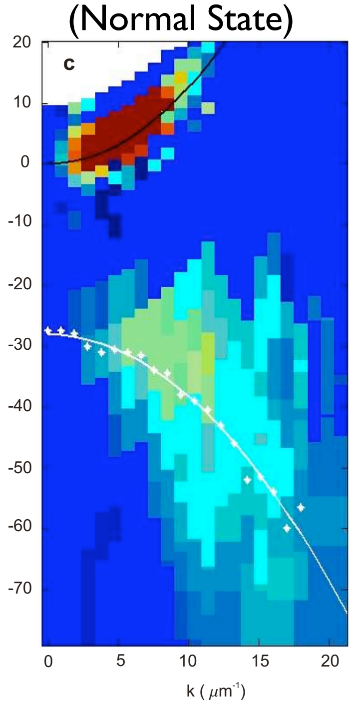
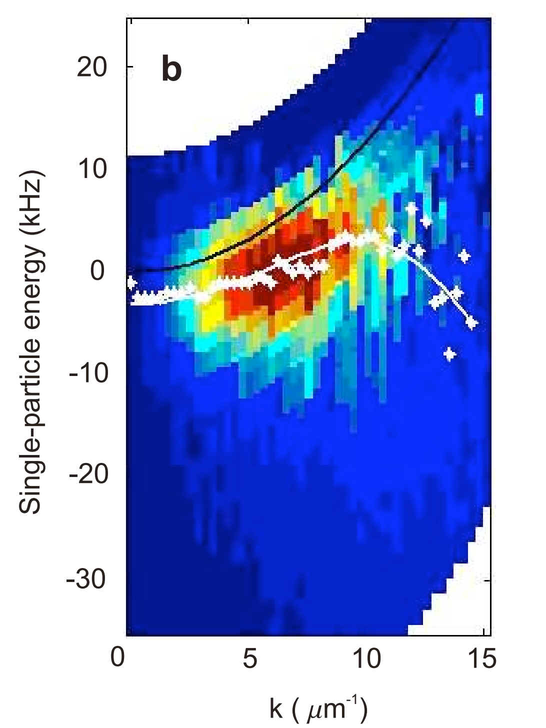


Image transfered atoms after time of flight

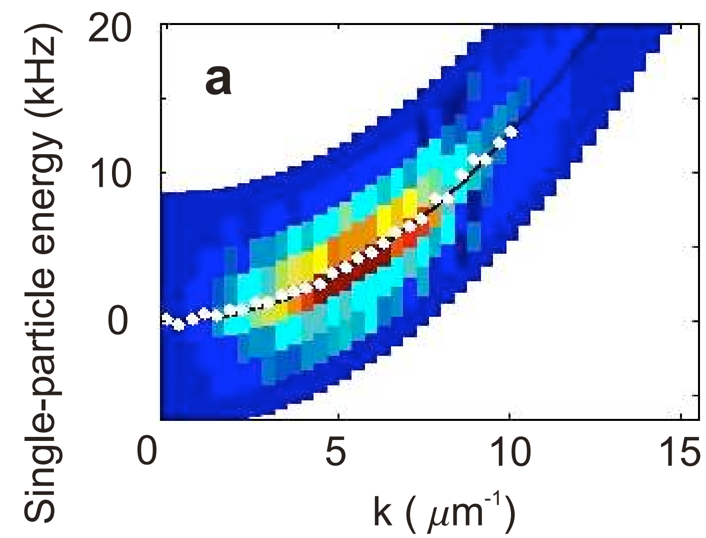
Stewart, Gaebler, and Jin, Nature 454, 744 (2008)

BEC
(Normal State)





BCS
(Normal State)



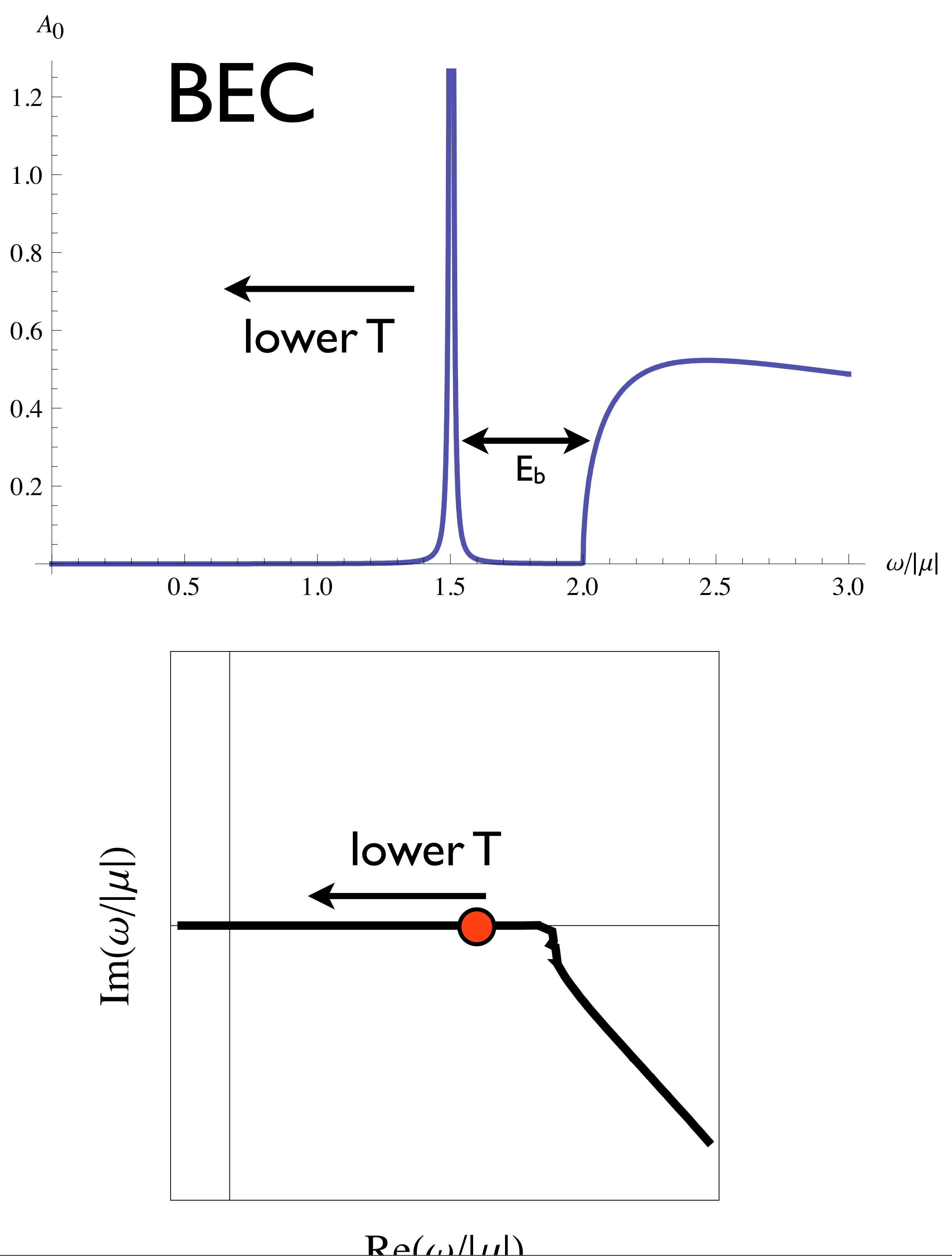
Pair spectra

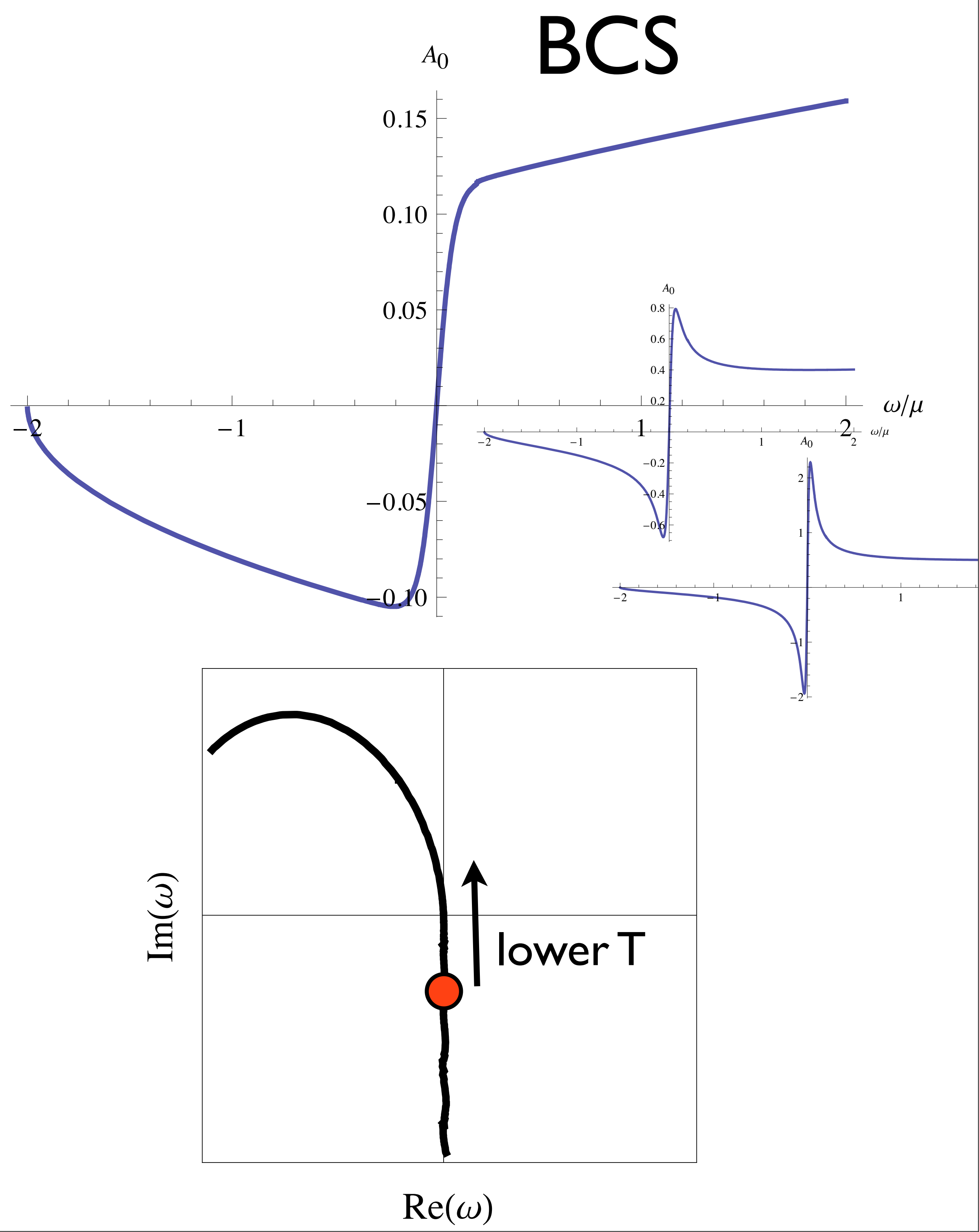
- Question: what modes go unstable at the superfluid transition?

2 particle spectral density:
add 2 particles with total momentum k, what are allowed energies?

Pair susceptibility diverges at transition

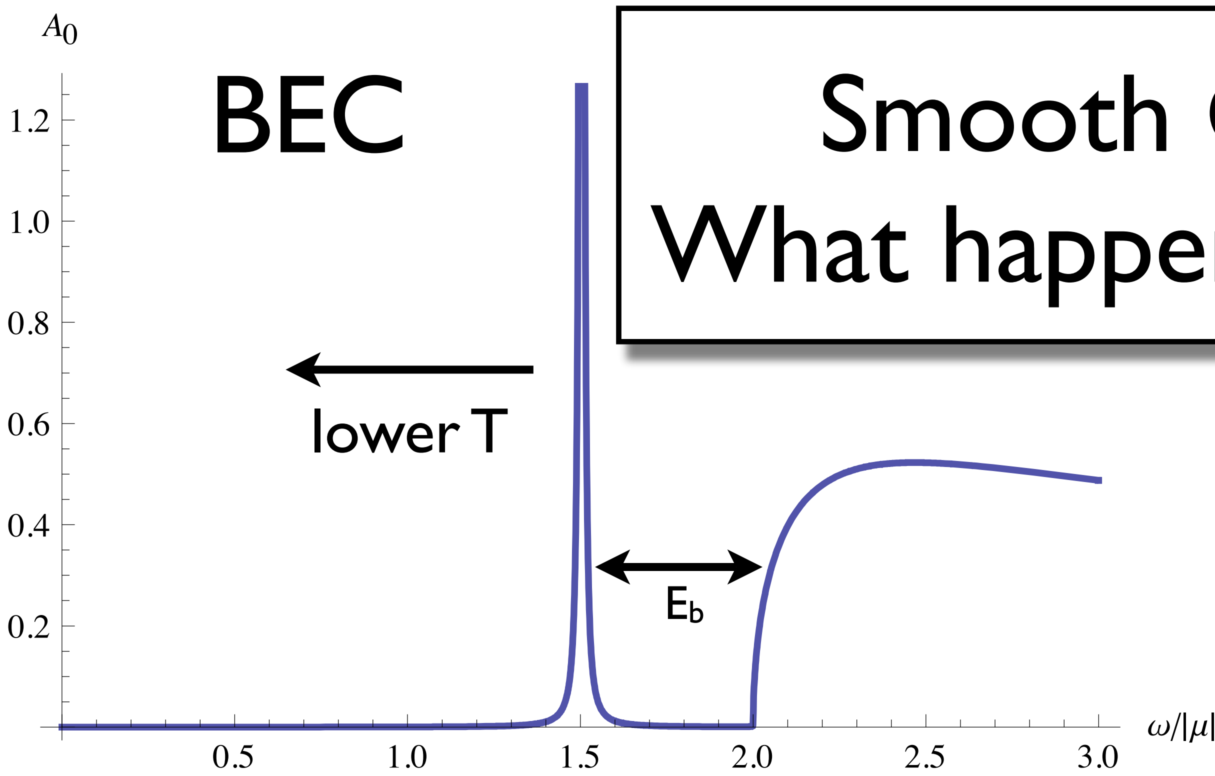
Modes that drive transition

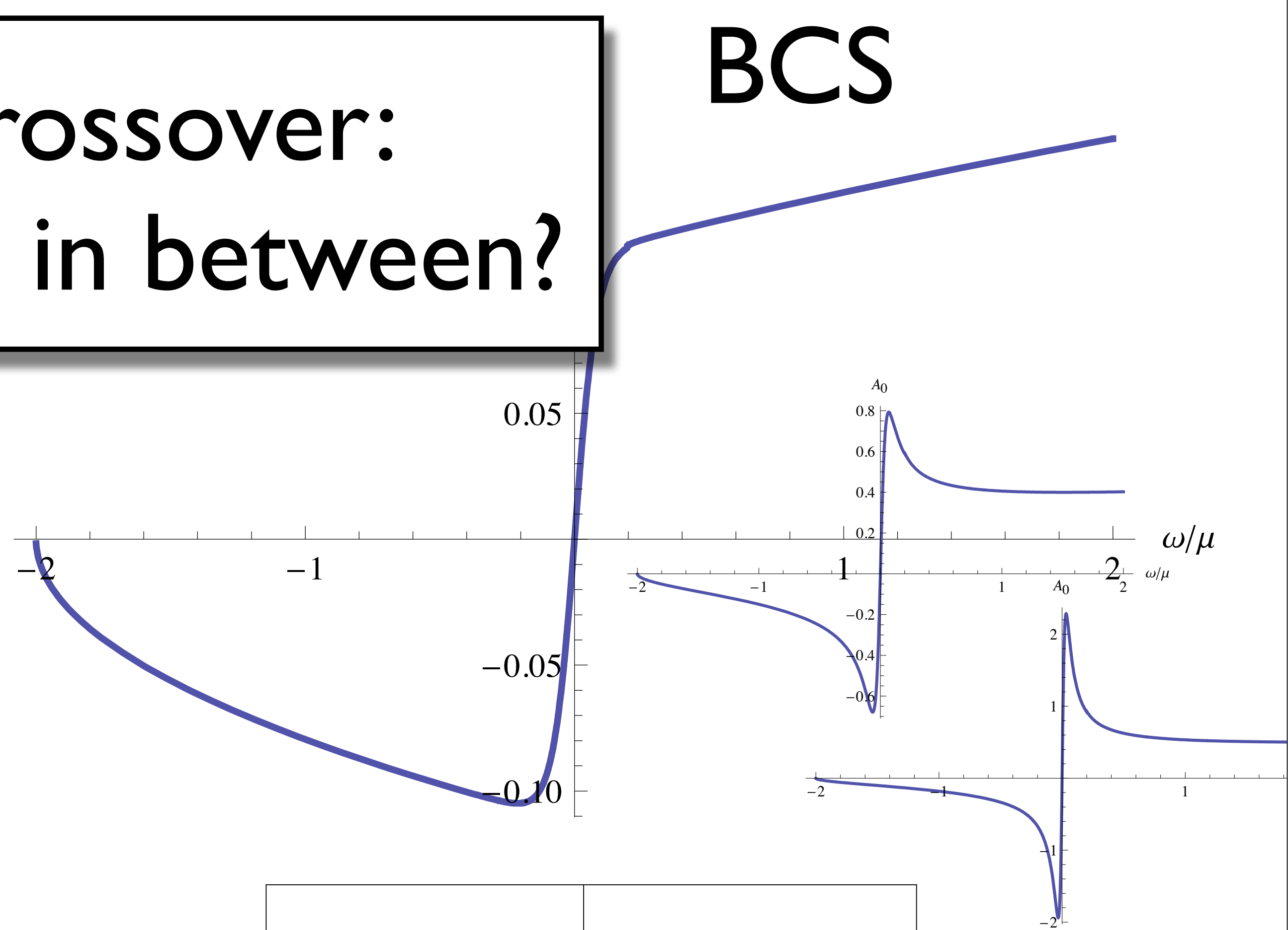


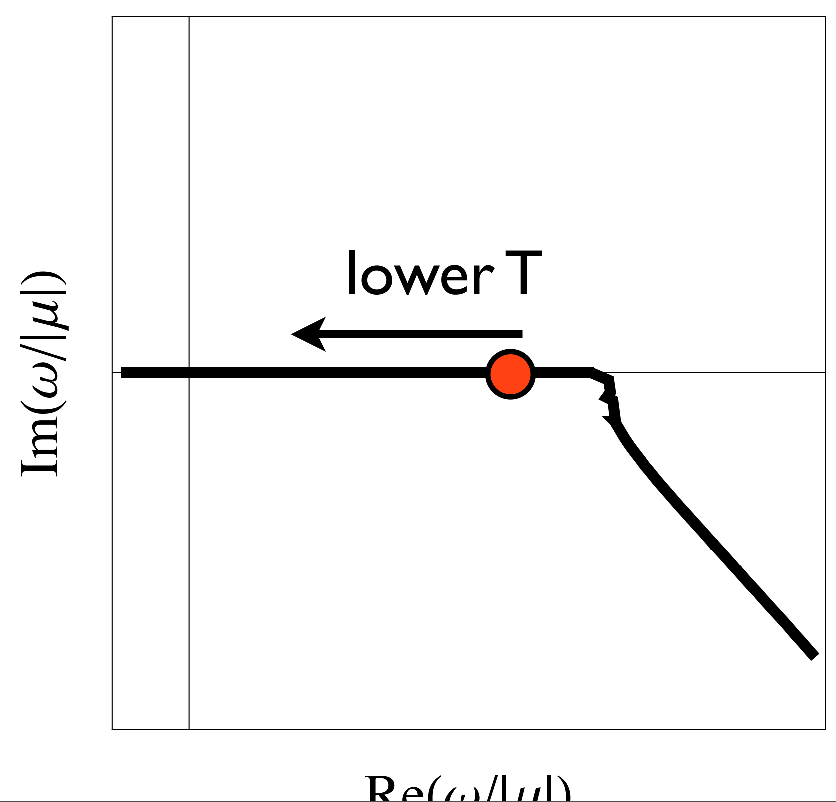


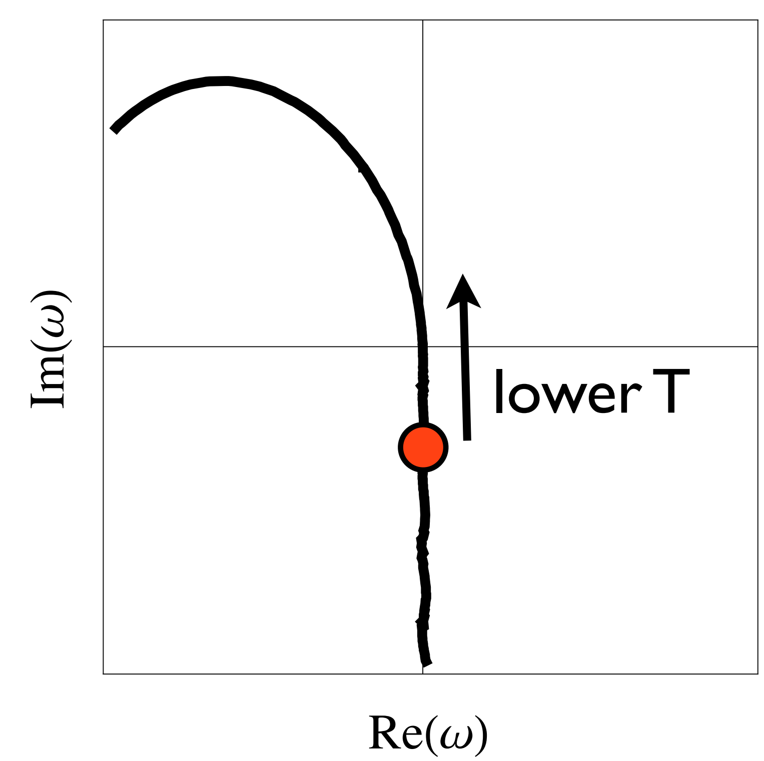
Modes that drive transition

Smooth Crossover:
What happens in between?

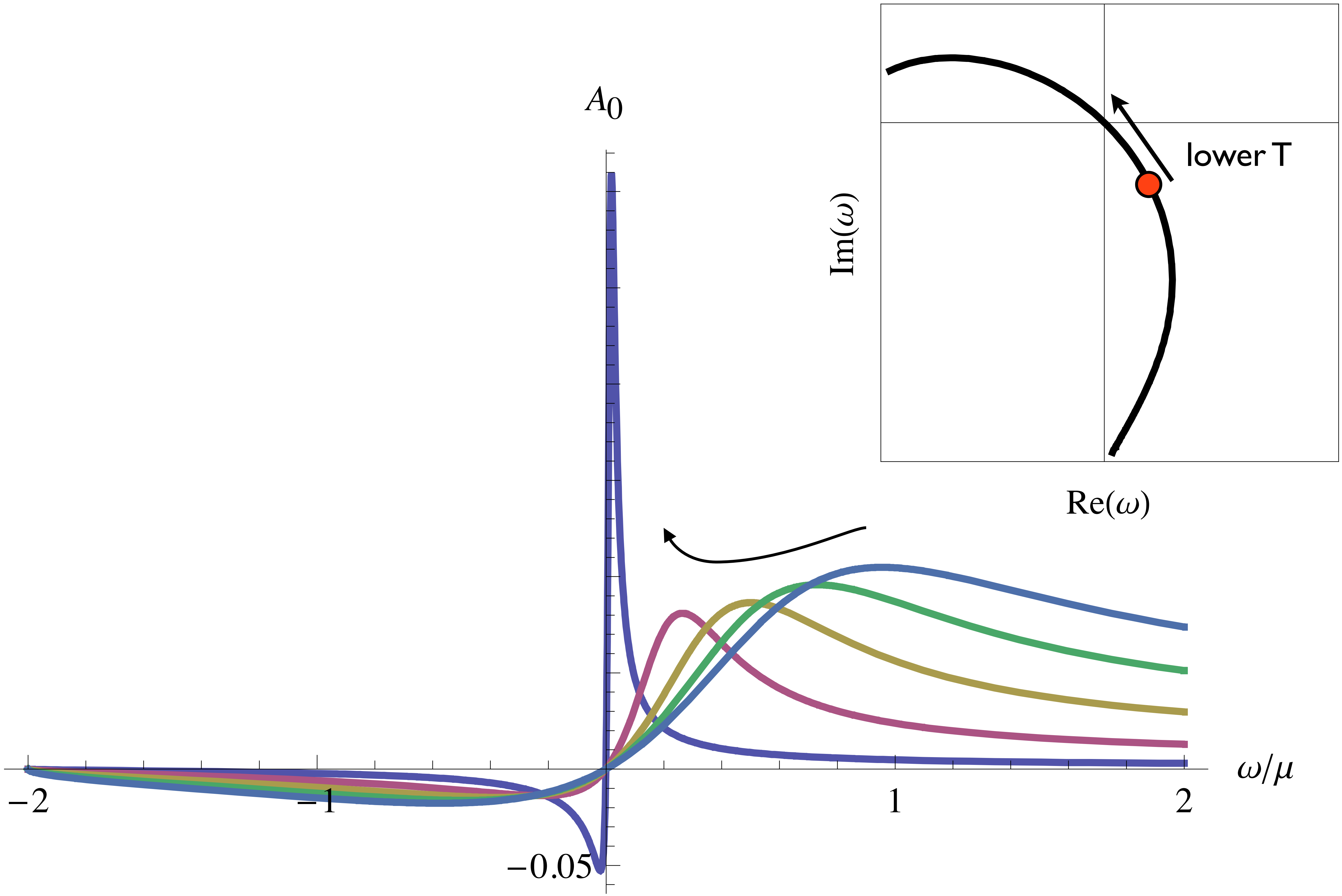




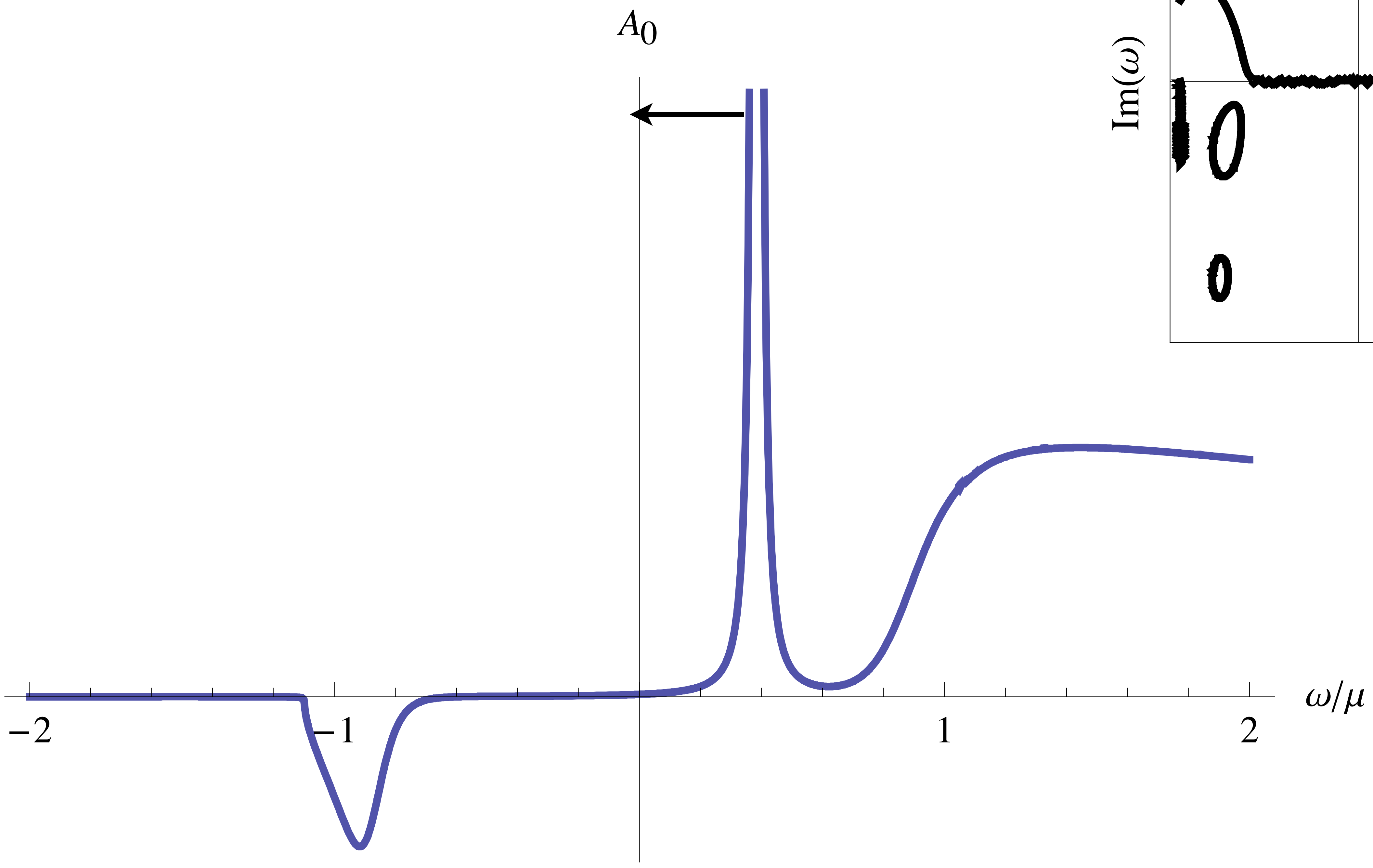


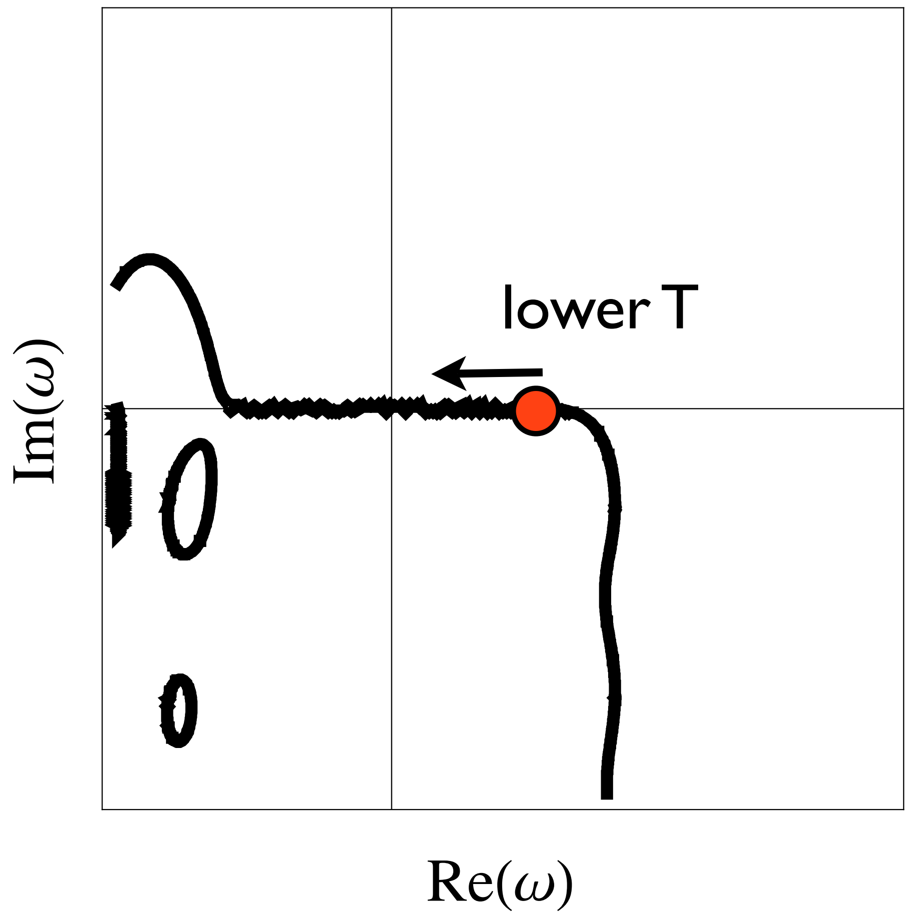


Crossover

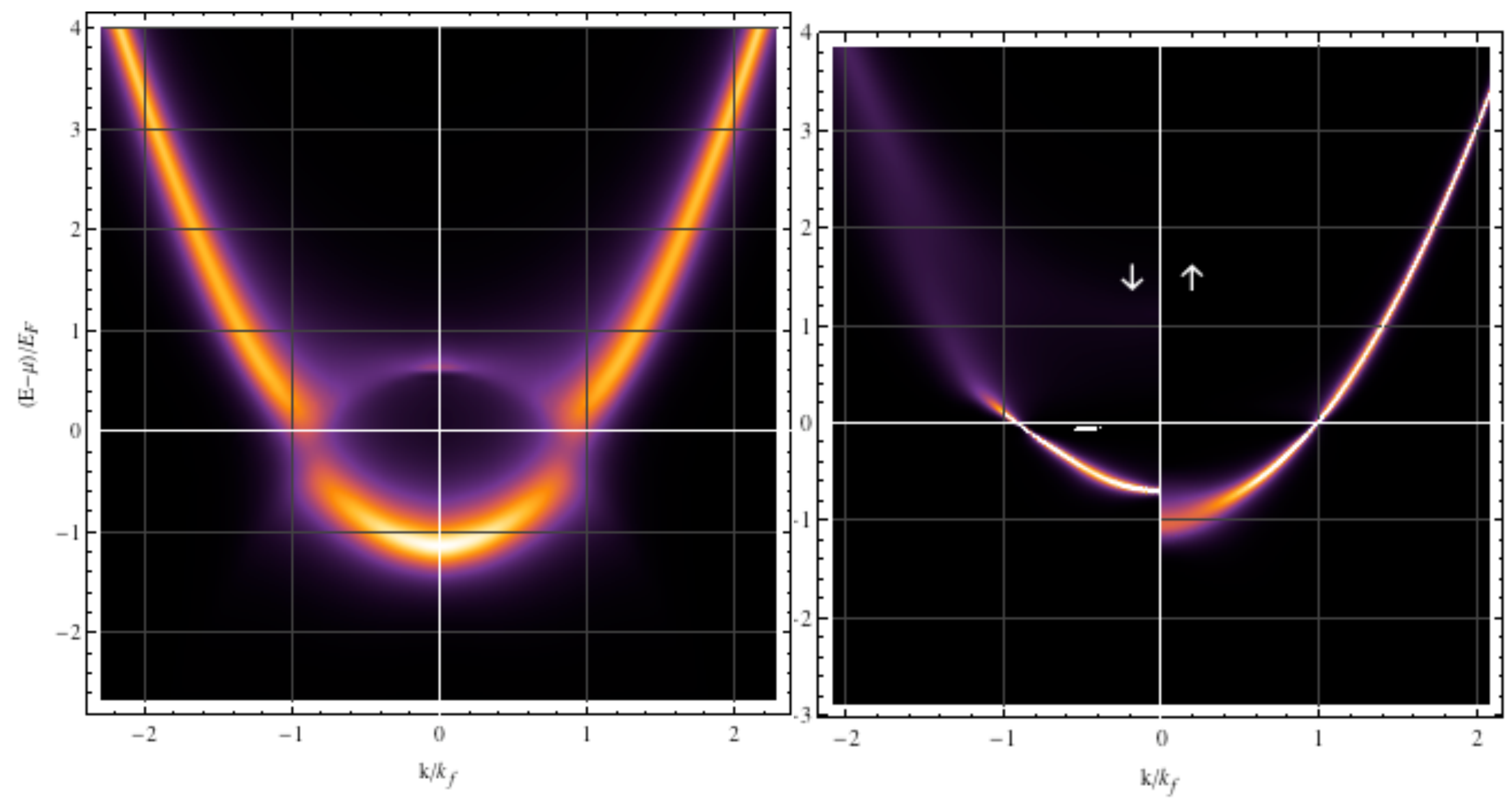


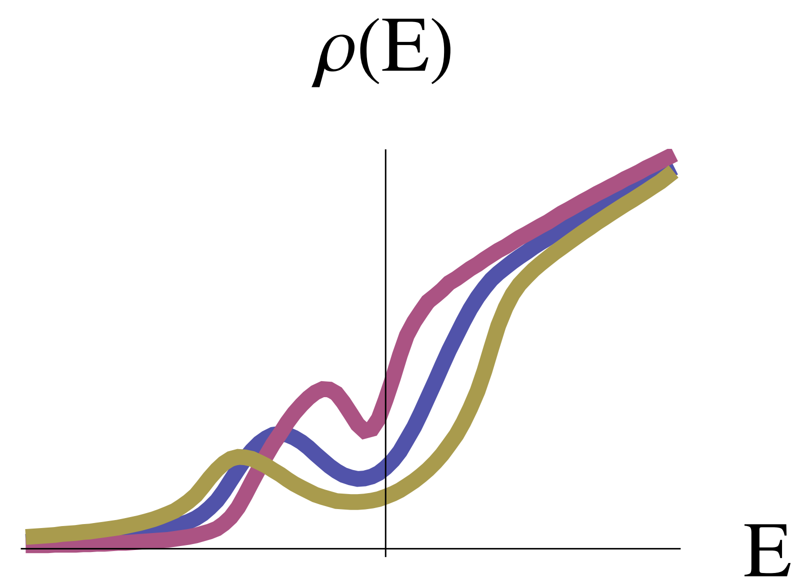
Polarized

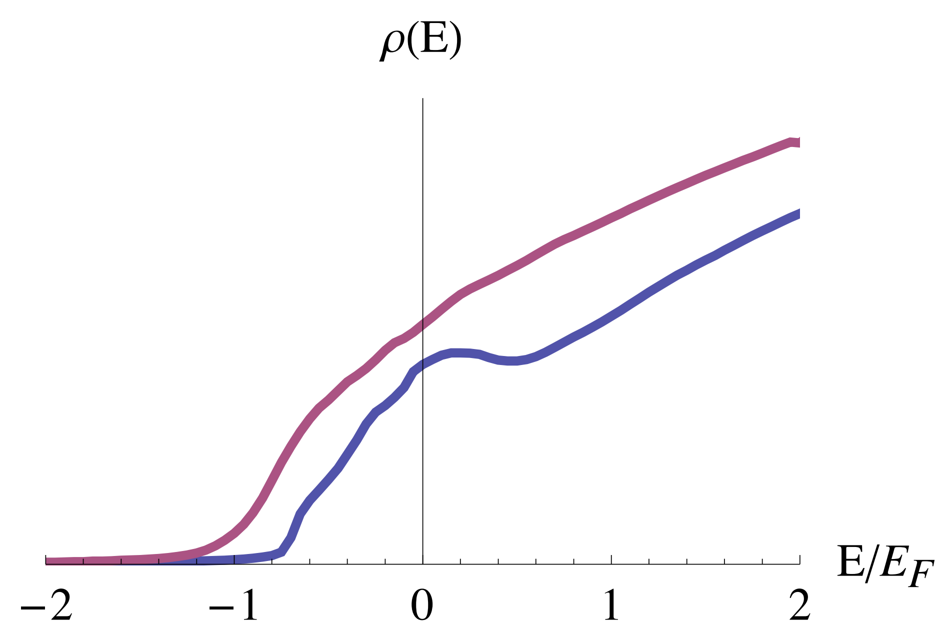




Summary

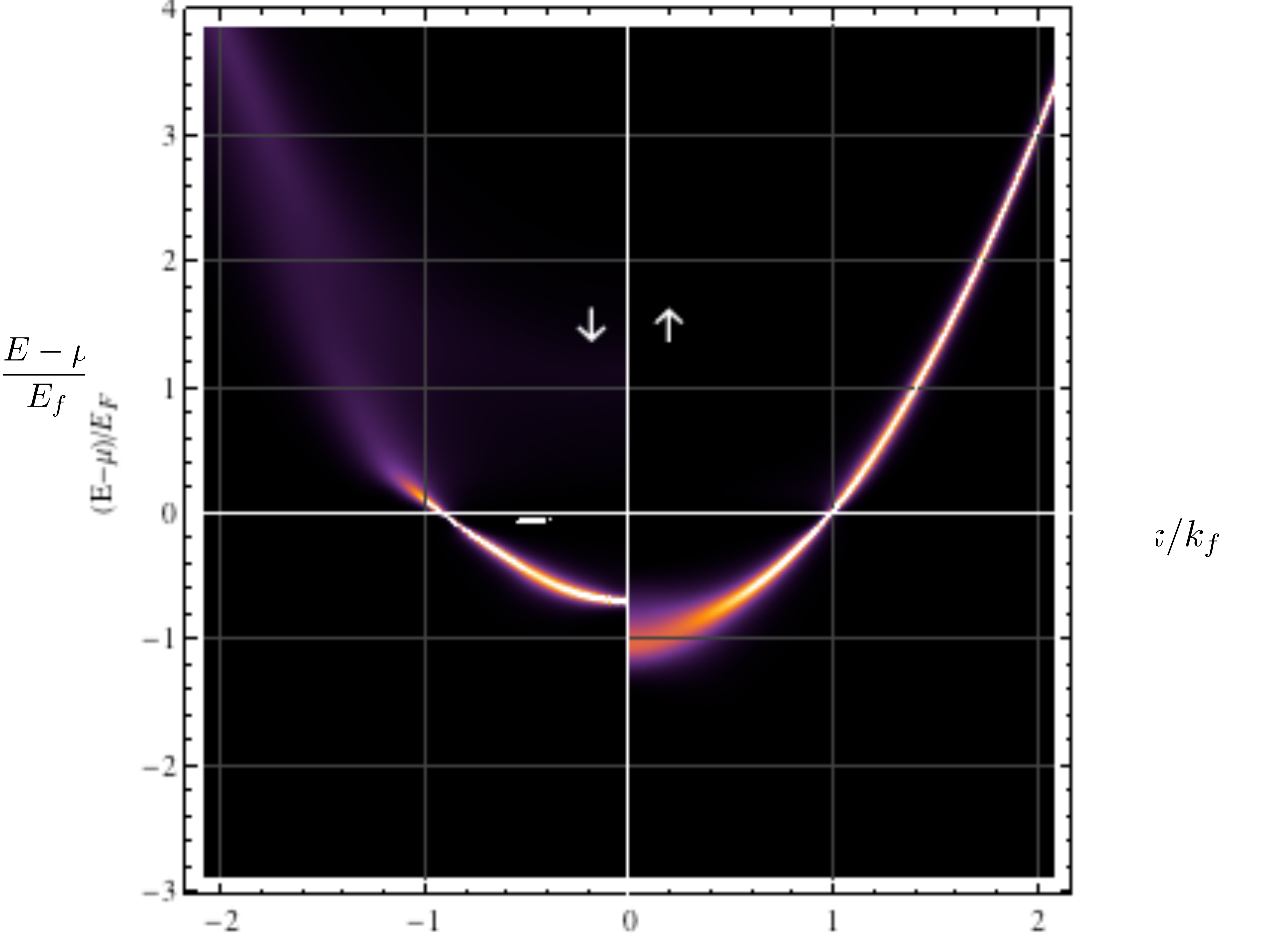






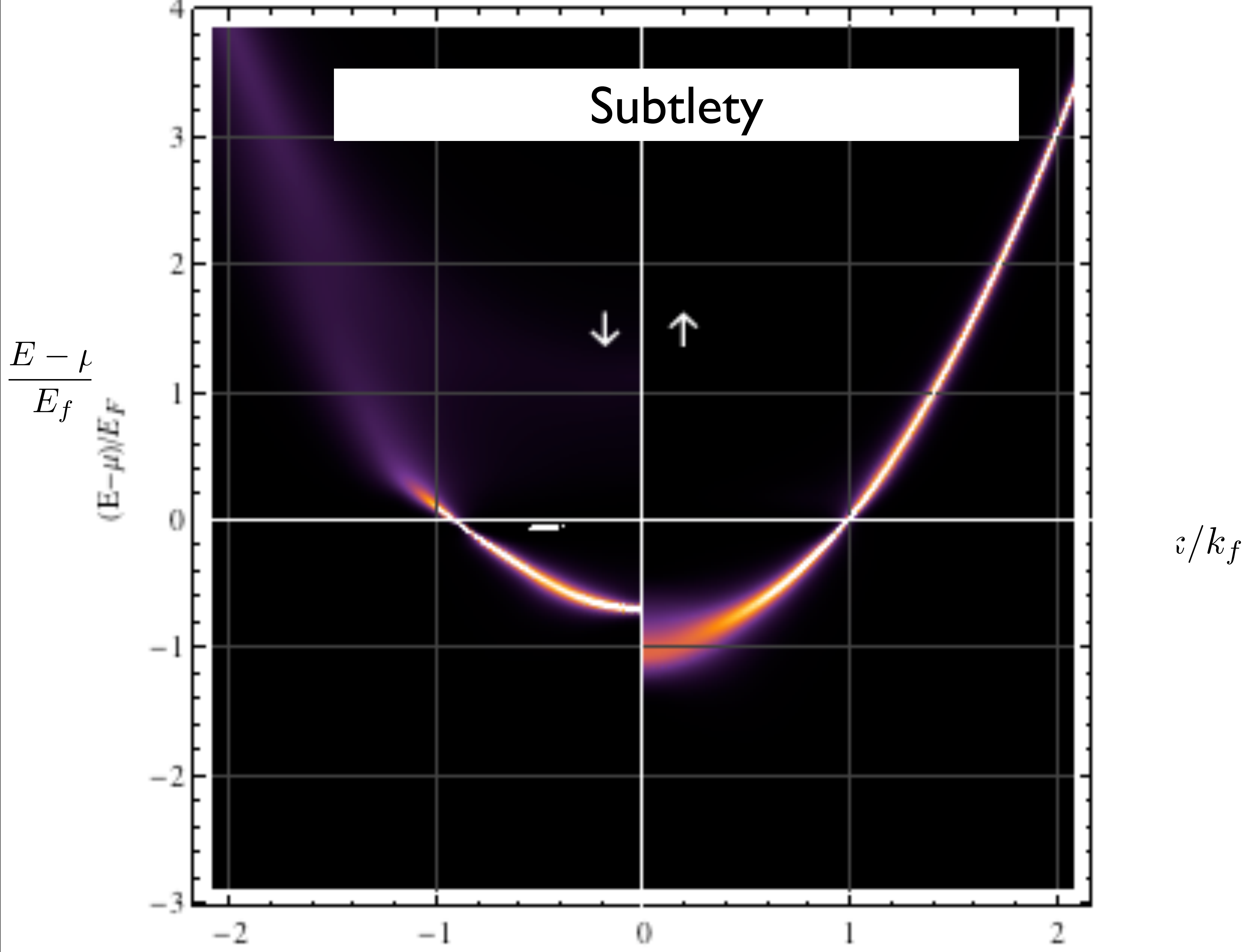
Pseudogap in Normal state
(from normal pairs)

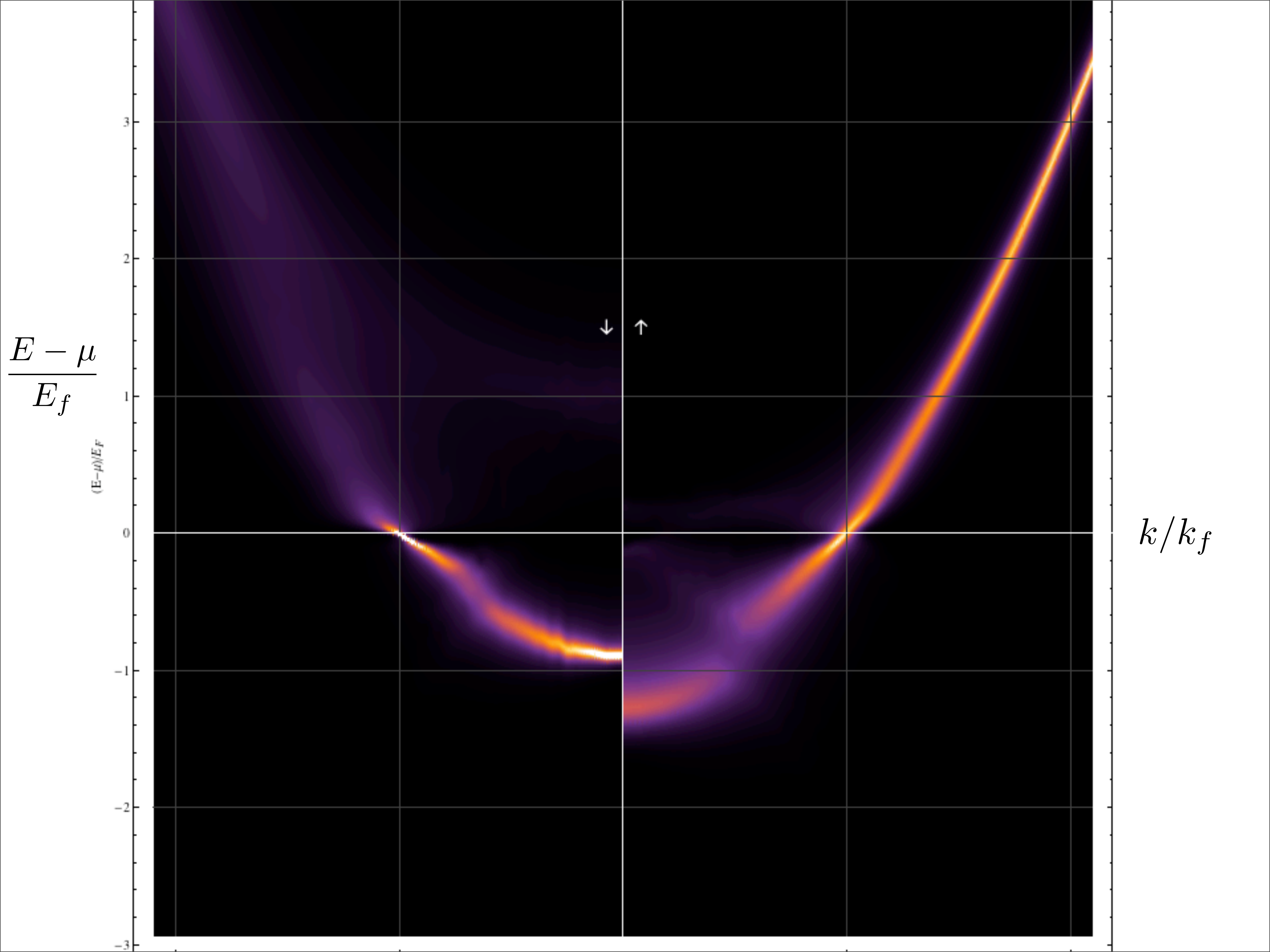
Moves away from Fermi energy at low T



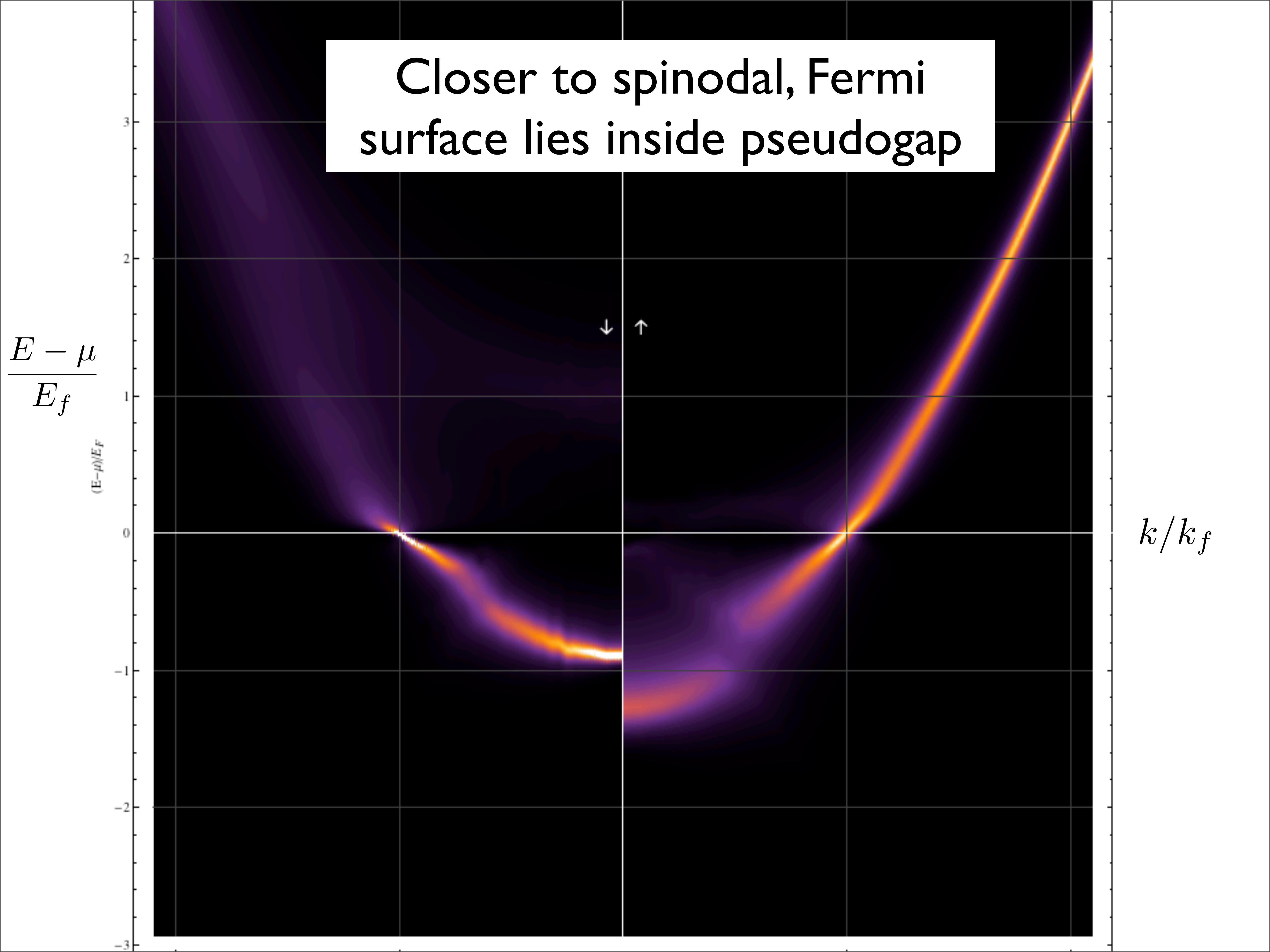
$\frac{E-\mu}{E_f}$
(E−μ)/E_F
$\imath/k_f$
↓
↑
4
3
2
1
0
−1
−2
−3
−2
−1
0
1
2

Subtlety



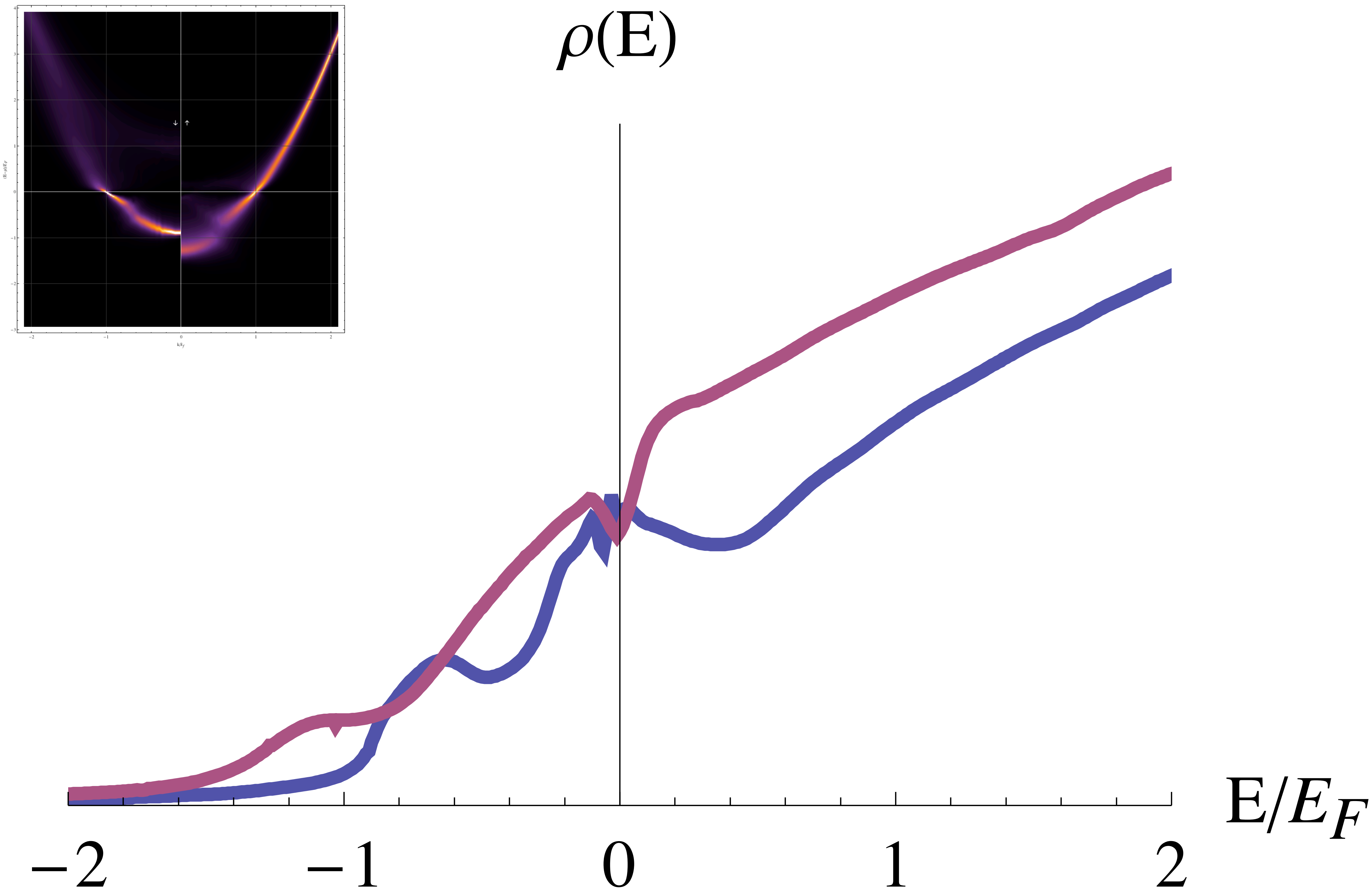


$\frac{E-\mu}{E_f}$
k/k_f
(E−μ)/E_F
↓ ↑
3
2
1
0
−1
−2
−3



Closer to spinodal, Fermi surface lies inside pseudogap
$\frac{E-\mu}{E_f}$
k/k_f
(E−μ)/E_F
3
2
1
0
−1
−2
−3
↓ ↑

“Midgap” sharpening



High polarization limit

(Chevy, Combescot, Zwierlein,...)

One downspin wavefunction

$$|\Psi\rangle = \Bigg[\phi_0 a_\downarrow^\dagger(0) + \sum_{kq} \phi_{kq} a_\downarrow^\dagger(q) a_\uparrow^\dagger(k) a_\uparrow(k+q)$$

$$+ \sum_{kqpl} \phi_{kqplm} a_\downarrow^\dagger(q) a_\uparrow^\dagger(k) a_\uparrow^\dagger(p) a_\uparrow(l) a_\uparrow(k+q+p-l)$$

$$+ \cdots \Bigg] |\mathrm{FS}_\uparrow\rangle$$

Language

"Preformed Pairs" ⟷ "Order Parameter Fluctuations"

Pair condensate

$\langle \psi_\uparrow \psi_\downarrow \rangle$ ⟷ Δ

Non-condensed pairs

$\langle \psi_\downarrow^\dagger \psi_\uparrow^\dagger \psi_\uparrow \psi_\downarrow \rangle$ ⟷ $(\delta\Delta)^2$