Bose polarons at finite temperature and strong coupling

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Outline

- Quantum mixtures
- Impurities in an ideal Fermi sea (“Fermi polarons”)
- Impurities in a weakly-interacting Bose gas (“Bose polarons”)
  - Zero-temperature physics
  - New features appearing at non-zero temperature

Collaborators

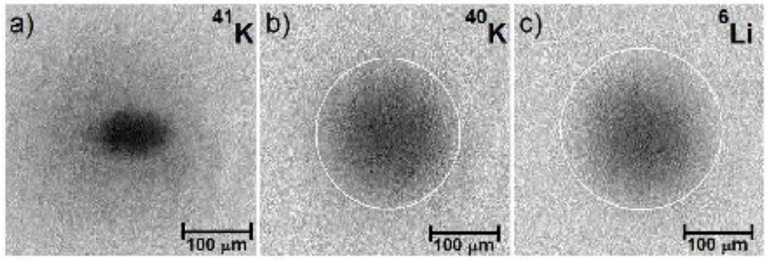
Nils Guenther

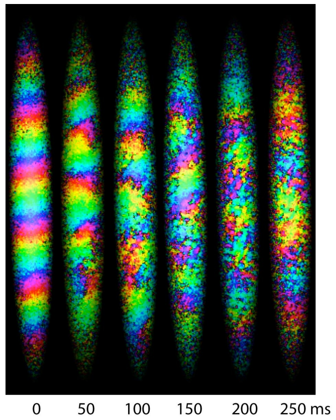
Maciej Lewenstein

Georg M. Bruun

Quantum Mixtures in CondMat

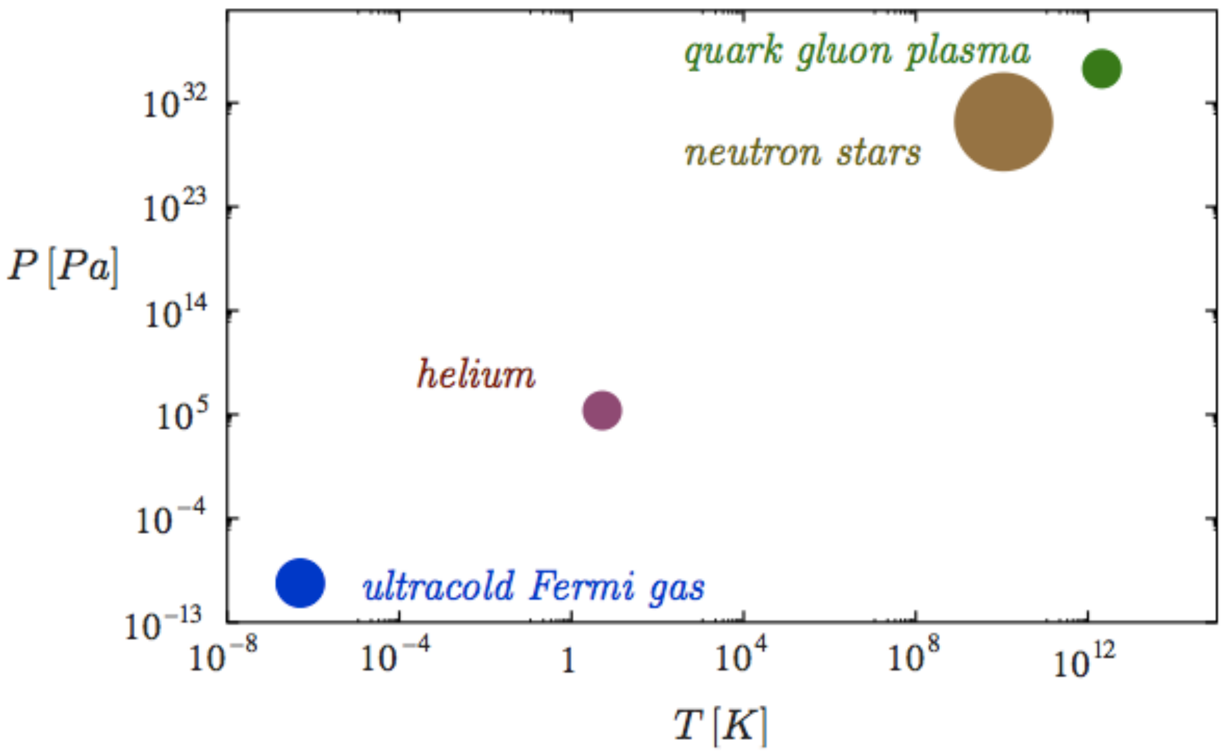
- ^{3}He-^{4}He
- ultracold gaseous mixtures:
  - FF (BEC-BCS crossover) [Zwerger, Lecture Notes in Phys.]
  - B+FF superfluids (coherent/damped dynamics) ENS-Paris
  - BB mixtures (ultradilute quantum liquid droplets) Stuttgart, Innsbruck, Barcelona
  - spinor gases, SU(N) invariant systems Kyoto, Florence, Munich, …
- quantum magnets, quantum Hall systems, spin-liquids
- quark-gluon plasma
- neutron stars





Very different microscopically, but
∃ common ***emergent*** *and* ***universal*** *many-body descriptions*.

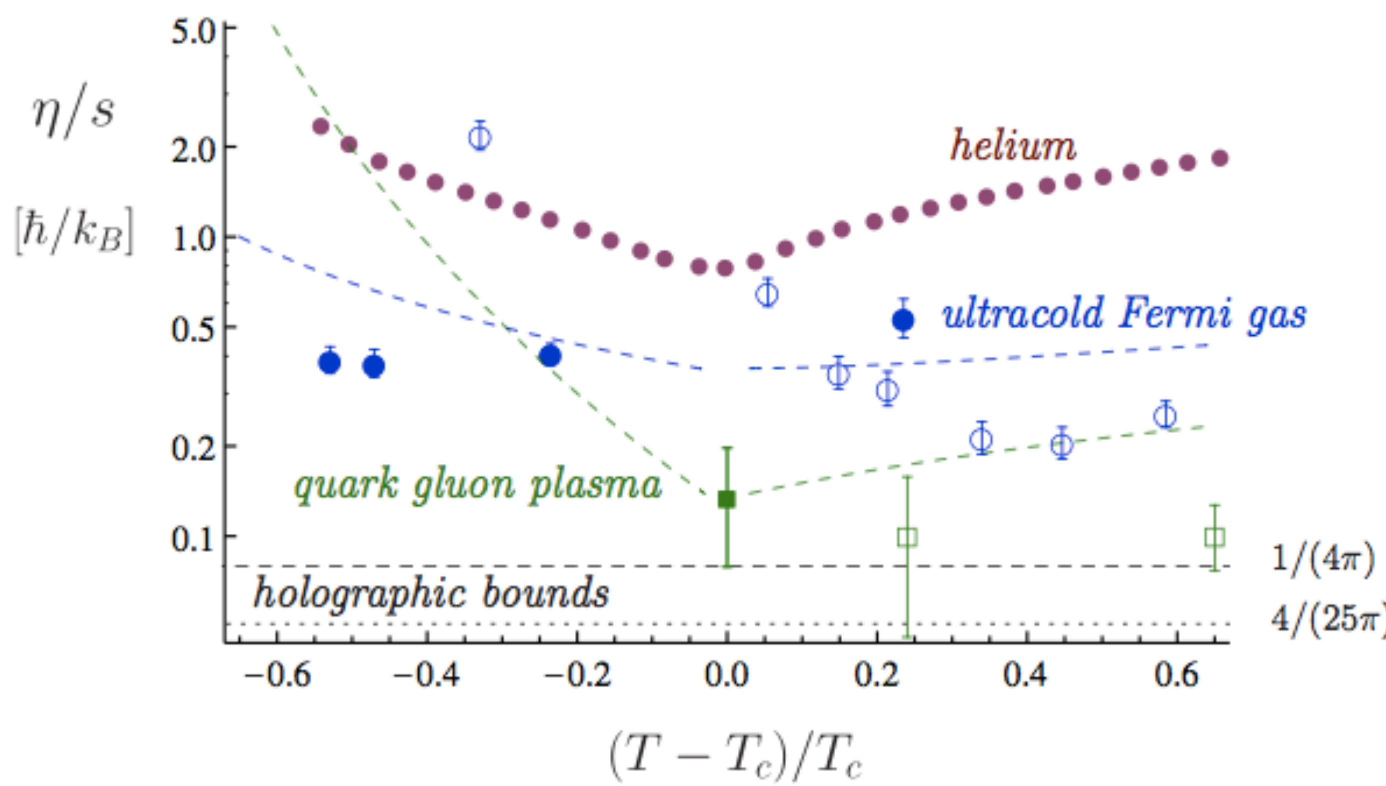
Universality in Quantum Mixtures



20 orders of magnitude difference in temperature

but similar transport properties!

e.g.,
shear viscosity/entropy density:



[Adams *et al.*, NJP 2012]

Many-body systems

A GUIDE TO FEYNMAN DIAGRAMS

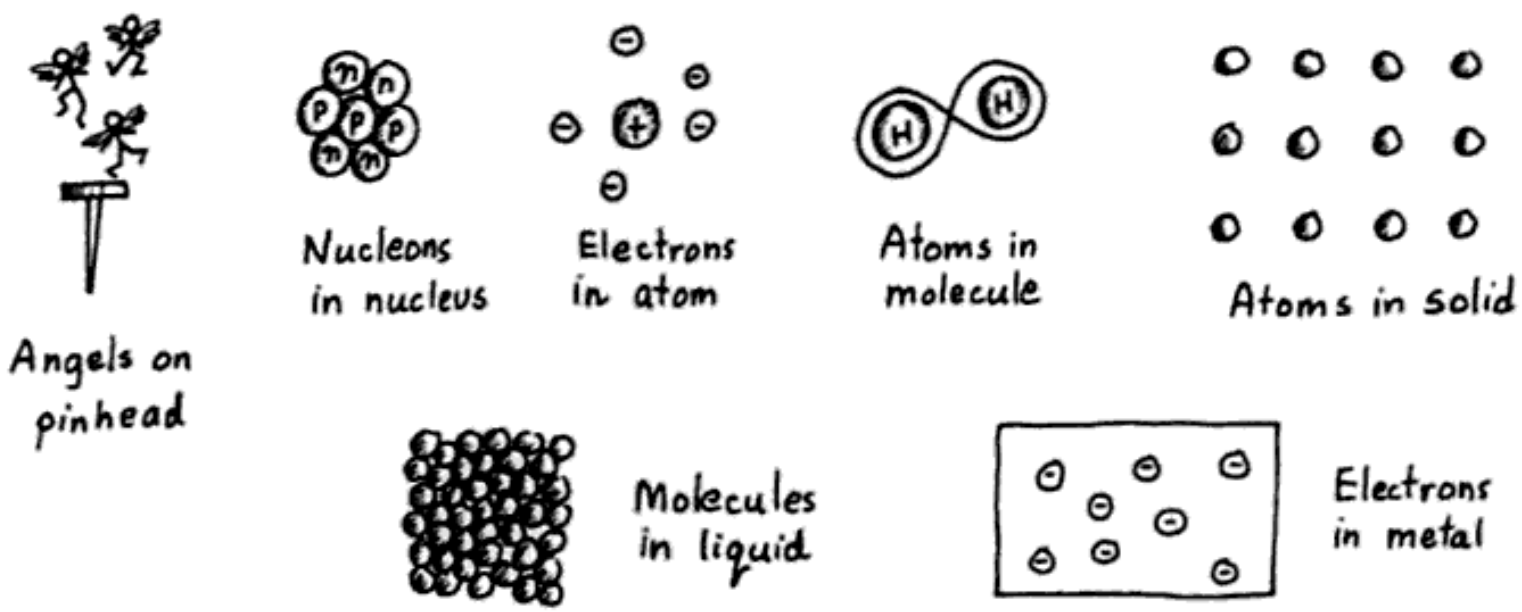
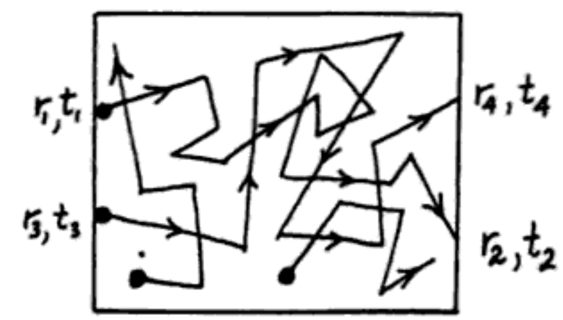


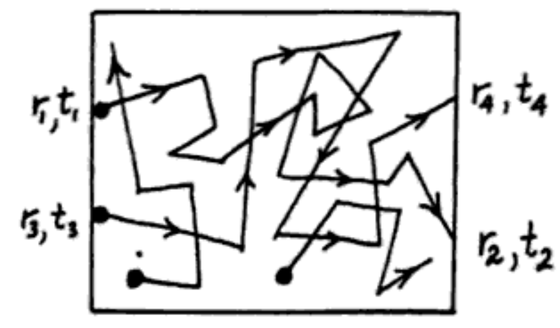
Fig. 0.1 *Some Many-body Systems*



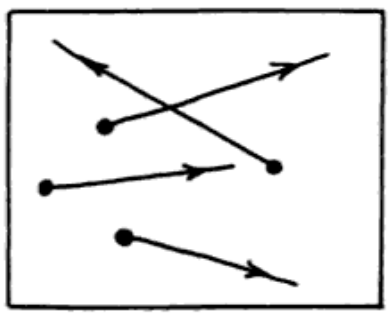
(from Richard Mattuck's book)

Quasi-Particles

No chance of studying real particles



Landau:
of importance are the collective excitations,
which generally behave as quasi-particles!



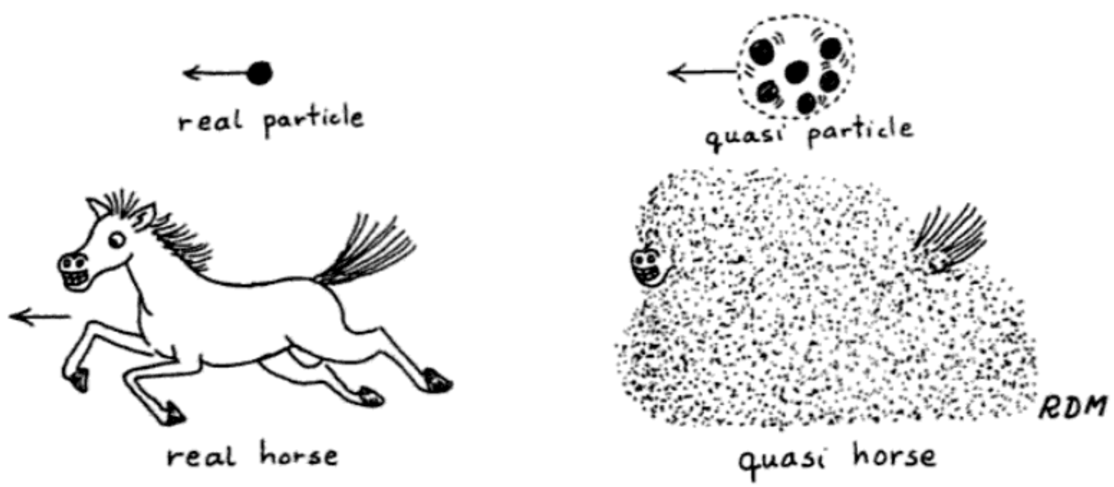


Fig. 0.4 *Quasi Particle Concept*

a QP is a “free” particle with:

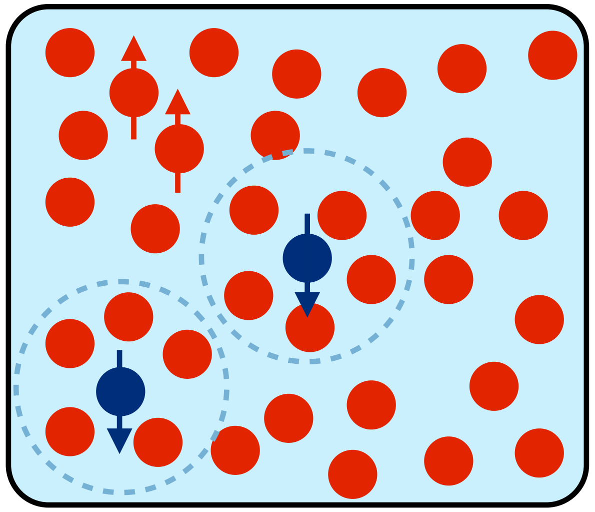
@ q. numbers (charge, spin, ...)
@ renormalized mass
@ chemical potential
@ shielded interactions
@ lifetime

Ultracold atoms

- chemical composition
- interaction strength
- temperature

- periodic potentials
- physical dimension
- atom-light coupling
- exotic interactions
  (x-wave, spin-orbit)
- dynamics
- disorder
- periodic driving
  (shaken optical lattices)

Imbalanced Fermi gases



Two-component Fermi gas with $N_\uparrow \gg N_\downarrow$:
a strongly-interacting system,
or an ensemble of weakly-interacting quasi-particles
(a *Fermi liquid*)

$$E = \frac{3}{5}\epsilon_F N_\uparrow \left[1 + \frac{m}{m^*}\left(\frac{N_\downarrow}{N_\uparrow}\right)^{5/3} \right] + N_\downarrow E_p + \ldots,$$

kinetic energy
of the Fermi sea

kinetic energy
of the polarons
(m* is their effective mass)

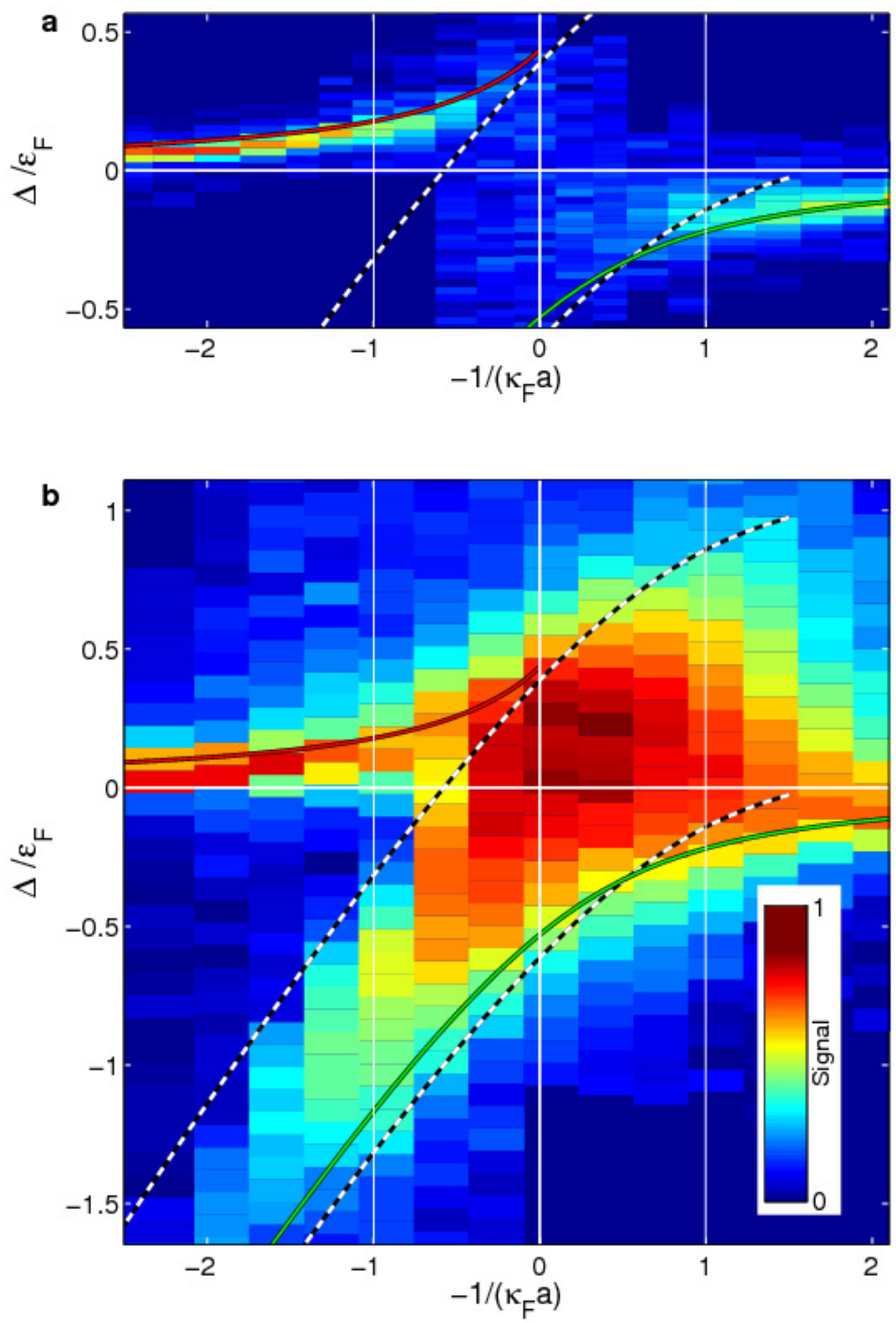
chemical potential (energy)
of one polaron

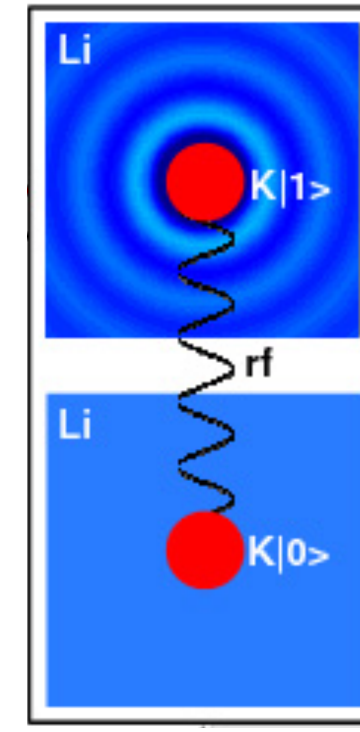
Spectrum of Fermi polarons

low power RF:

high power RF:

high power is needed to couple to the MH continuum, due to a small FC overlap





repulsive pol.

attractive pol.

molecule+hole continuum

experiments: MIT (2009), ENS-Paris (2009), Innsbruck (2012), Cambridge (2012), Innsbruck (2016), LENS (2017)

theory: Chevy, Recati, Combescot, Zwerger, Enss, Schmidt, Bruun, Pethick, Zhai, Levinsen, Parish, Castin, …

review: PM, Zaccanti and Bruun, Rep. Prog. Phys. (2014)

Repulsive polarons

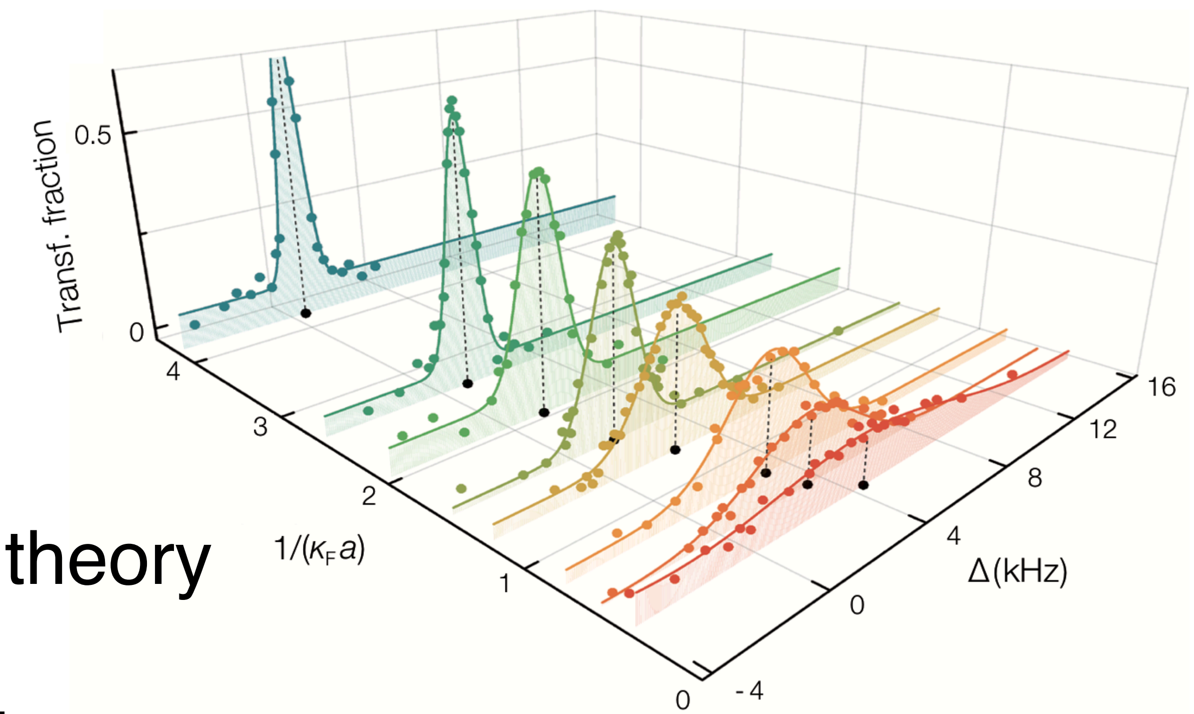
- most general case
  (equal masses, broad resonance)

- ∃ meta-stable quasiparticle at E>0

- long-lived, even close to unitarity

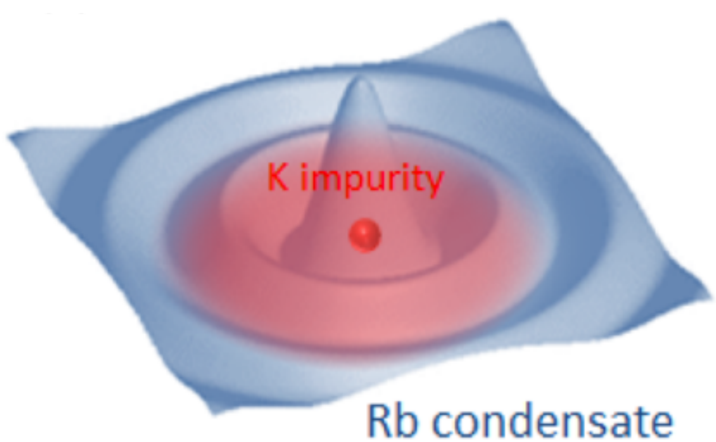
- measures of E, m_{eff} and Z
  in very good agreement with simple theory

- polaron-polaron interactions negligible

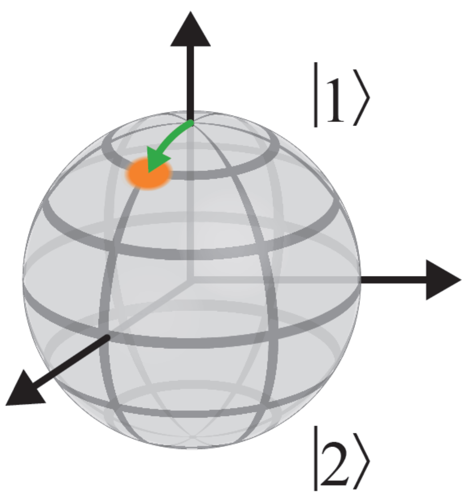


[Scazza, Valtolina, PM, Recati *et al.*, PRL 2017]

Impurities in a Bose gas



JILA: Hu, …, Cornelll and Jin, PRL (2016)

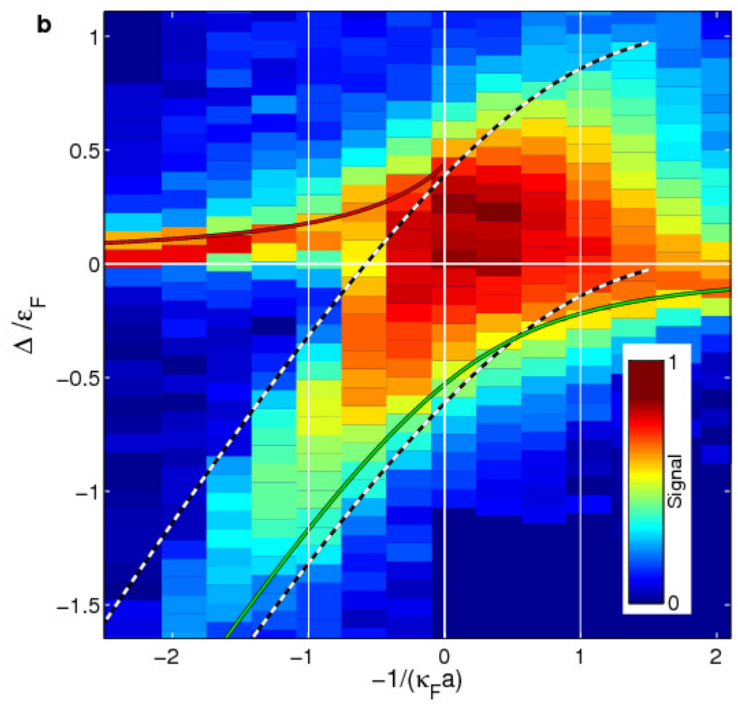


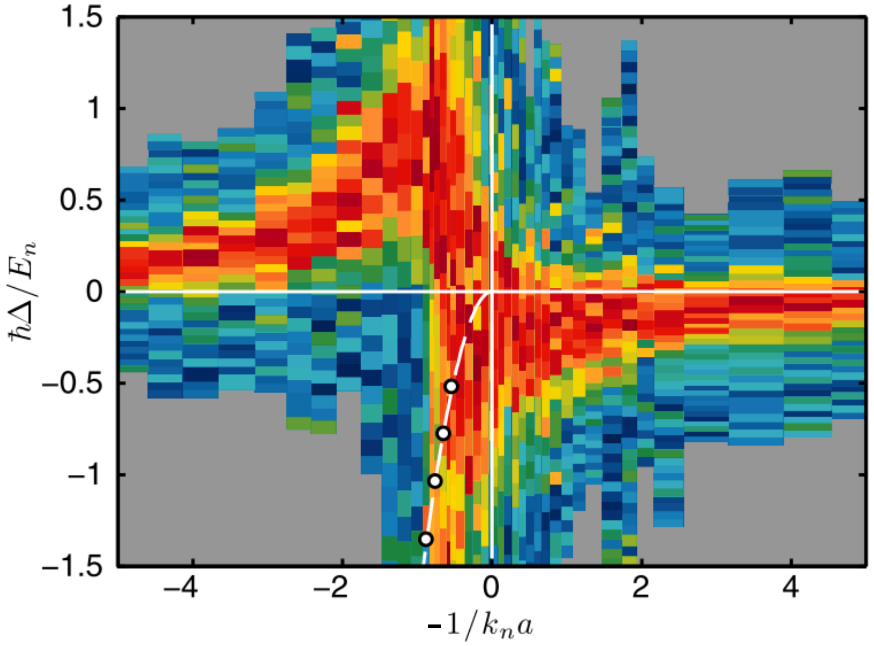
weak RF pulse + quick decoherence:
a few l2> impurities in a bath of l1> atoms

Aarhus: Jørgensen, …, Bruun and Arlt, PRL (2016)

T=0 theory: Rath, Schmidt, Das Sarma, Bruun, Levinsen, Parish, Giorgini, …

Fermi vs. Bose





	non-interacting Fermi sea	weakly-interacting Bose gas ($k_N a_B \ll 1$)
Temperature	smooth crossover from degenerate to classical	BEC phase transition at T_c
Impurity ground state	polaron/molecule transition	smooth crossover
Three-body physics	negligible	important role
Stability	rather stable mixture	rapid three-body losses

Definition of the problem

units: $k_n = (6\pi^2 n)^{1/3}$
$E_n = k_n^2/2m_B$

- Bath treated with Bogoliubov theory

» critical temperature: $T_c = \frac{2\pi}{m_B}\left(\frac{n}{\zeta(\frac{3}{2})}\right)^{2/3} \approx 0.436 E_n$

» condensate density: $n_0 = n[1-(T/T_c)^{3/2}]$

» bath chemical potential: $\mu_B = \mathcal{T}_B n_0$

» bath vacuum scattering matrix: $\mathcal{T}_B = 4\pi a_B/m_B$

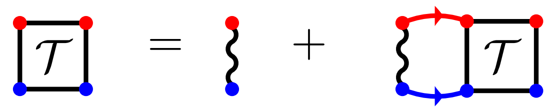
» dispersion of the excitations: $E_{\mathbf{k}} = \sqrt{\epsilon_{\mathbf{k}}^B(\epsilon_{\mathbf{k}}^B + 2\mu_B)}$

» free bosons: $\epsilon_{\mathbf{k}}^B = k^2/2m_B$

- Impurity-bath coupling: **finite temperature Green's functions (non-perturbative!)**
- Polaron energy: $\omega_{\mathbf{p}} = \epsilon_{\mathbf{p}} + \mathrm{Re}[\Sigma(\mathbf{p},\omega_{\mathbf{p}})]$
- Polaron residue: $Z_{\mathbf{p}} = \frac{1}{1-\partial_\omega \mathrm{Re}[\Sigma(\mathbf{p},\omega)]|_{\omega_{\mathbf{p}}}}$

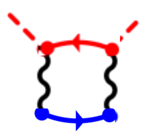
Diagrammatic scheme

$$\text{Impurity Green's function: } \mathcal{G}(\mathbf{p}, i\omega_j) = \frac{1}{\mathcal{G}_0(\mathbf{p}, i\omega_j)^{-1} - \Sigma(\mathbf{p}, i\omega_j)}$$



$$\text{Ladder T-matrix: } \mathcal{T}(\mathbf{p}, i\omega_j)^{-1} = \mathcal{T}_v^{-1} - \Pi(\mathbf{p}, i\omega_j)$$

T>0: important diagram missing in ladder approx:



T=0 ladder: Rath and Schmidt, PRA 2013

Perturbation theory at T>0: Levinsen, Parish, Christensen, Arlt, and Bruun, arXiv:1708.09172

Extended T>0 diagrammatic scheme: Guenther, PM, Lewenstein and Bruun, arXiv:1708.08861

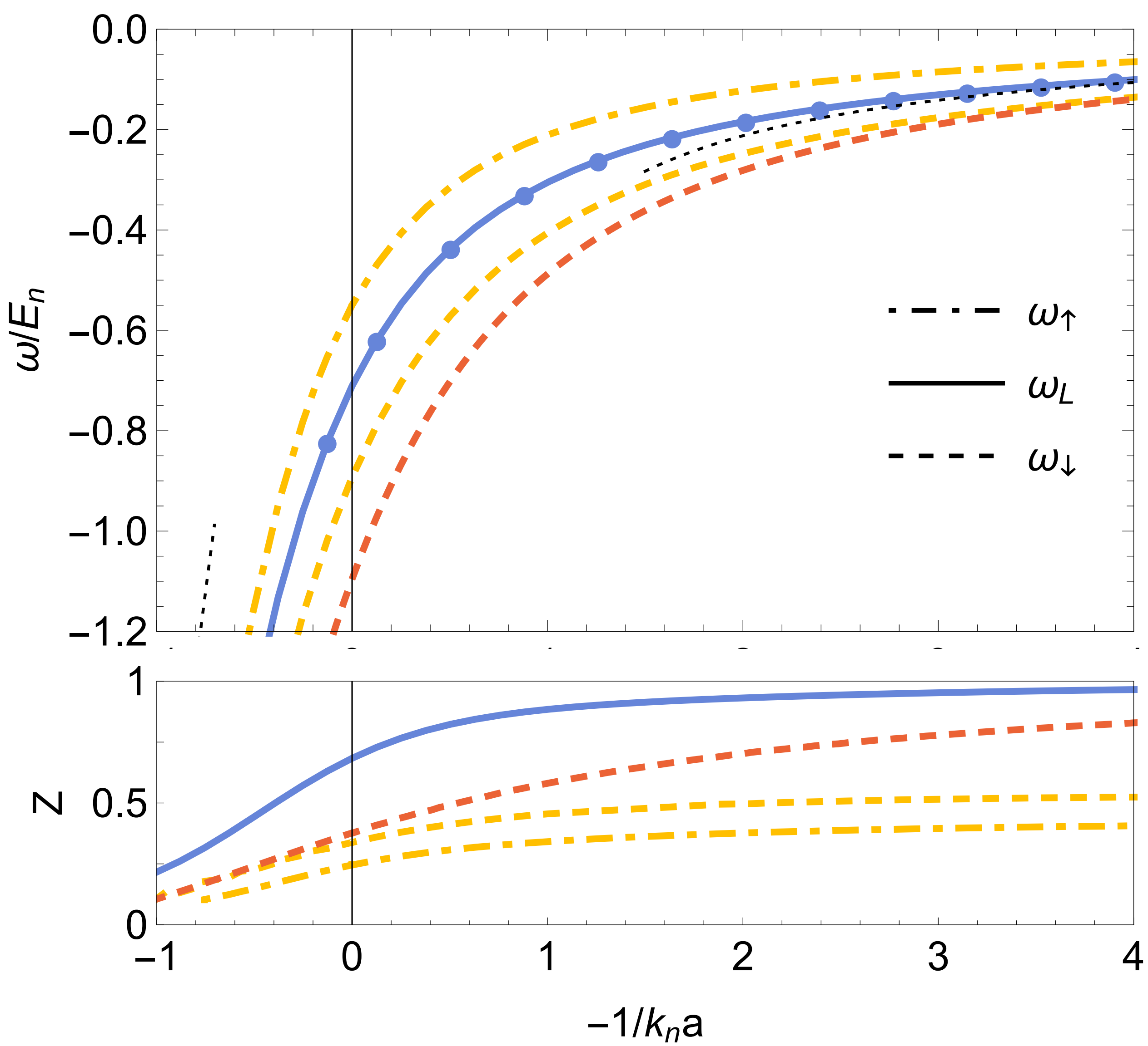
Varying coupling strength

Aarhus: $k_n a_B = 0.01$

$T\!=\!0$

$T\!=\!0.5T_c$

$T\!=\!T_c$



dots: T=0 ladder theory by Rath and Schmidt, PRA 2013

Guenther, PM, Lewenstein, and Bruun, arXiv:1708.08861

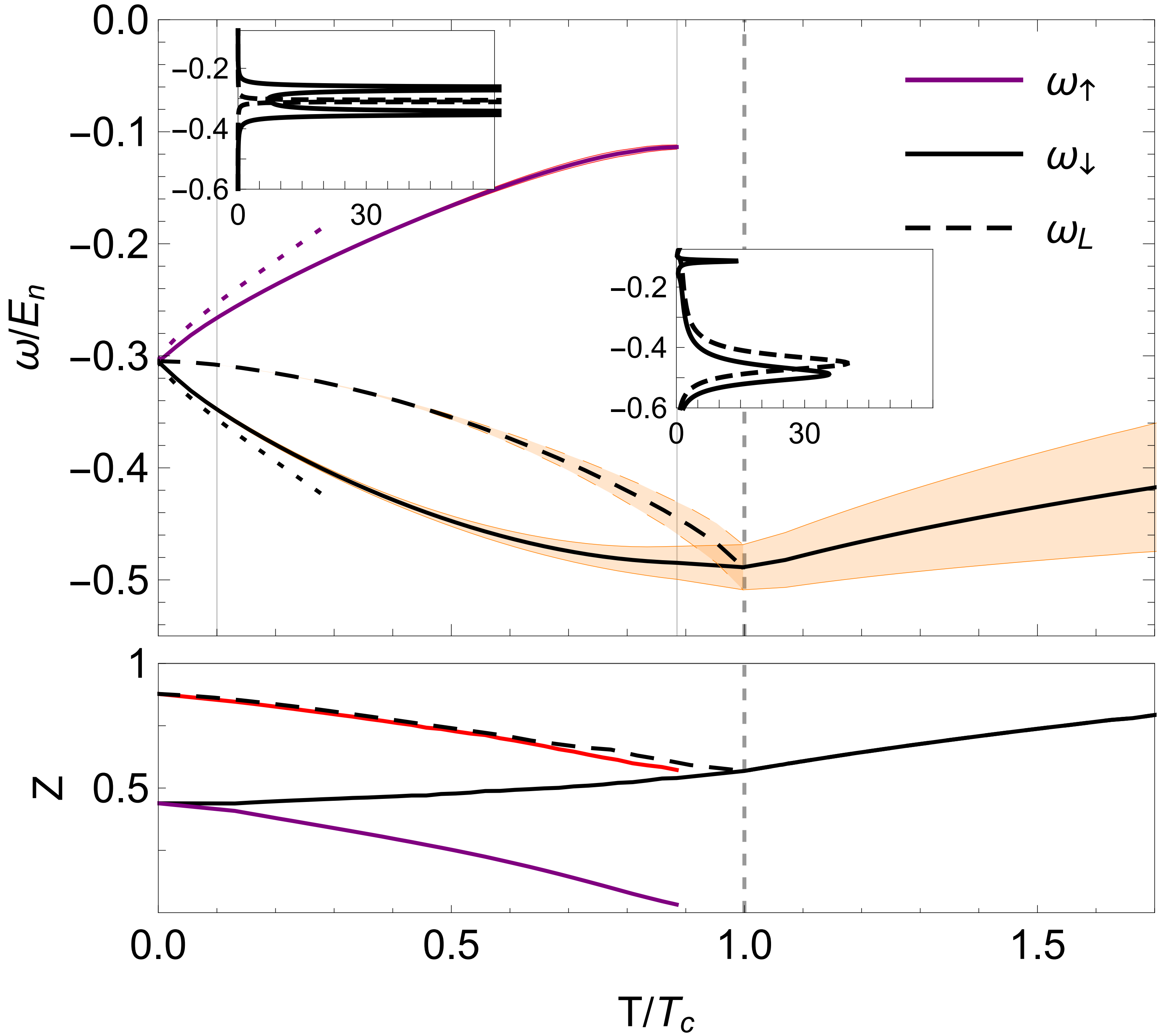
Varying temperature

Weak attraction

$(k_n a = -1)$

Energy:

Residue:



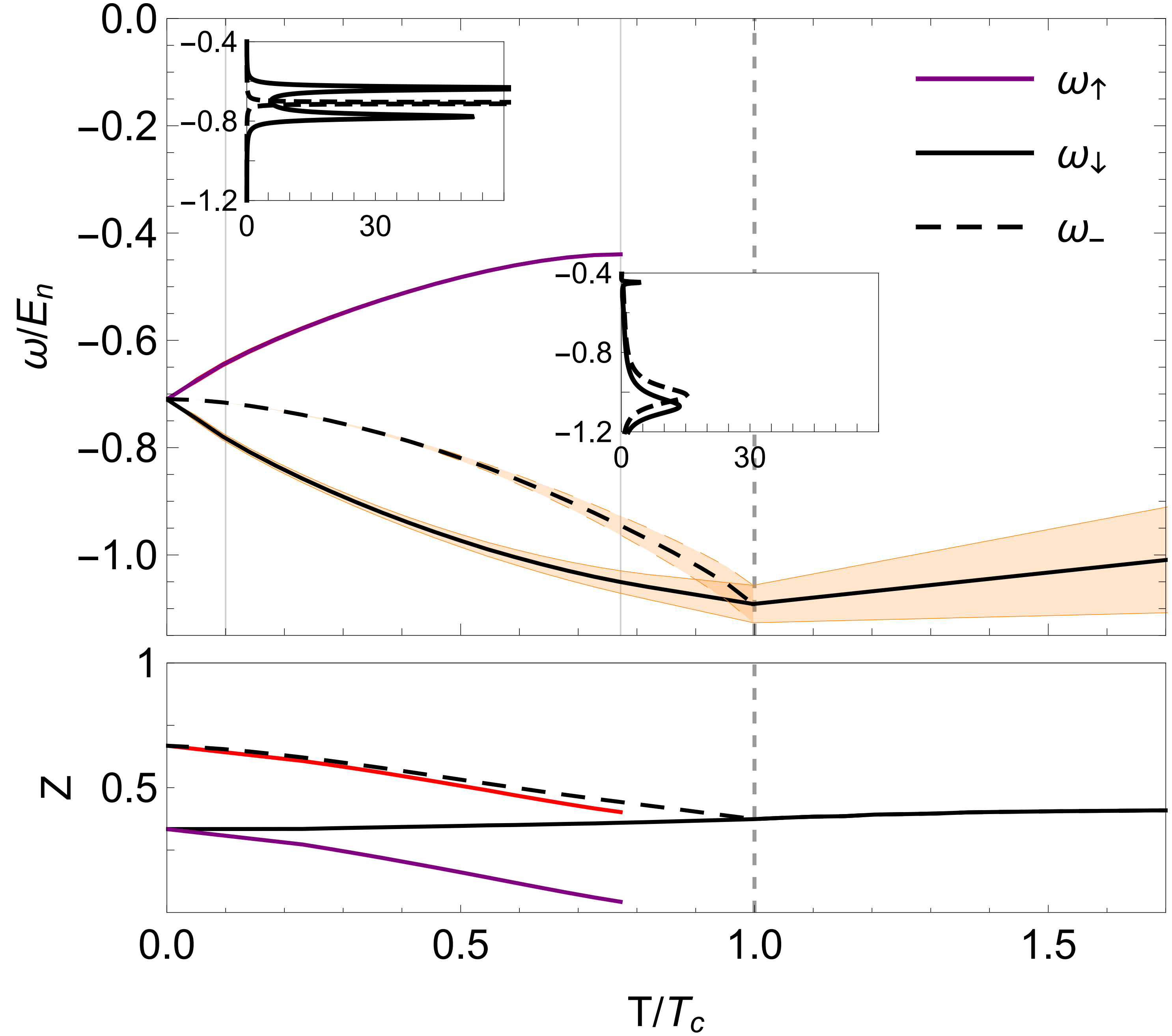
Guenther, PM, Lewenstein, and Bruun, arXiv:1708.08861

Varying temperature

Strong attraction (unitarity)

Energy:

Residue:



Guenther, PM, Lewenstein, and Bruun, arXiv:1708.08861

Understanding fragmentation

$$\omega_0 = \mathrm{Re}[\Sigma(\mathbf{p}=0,\omega_0)]$$

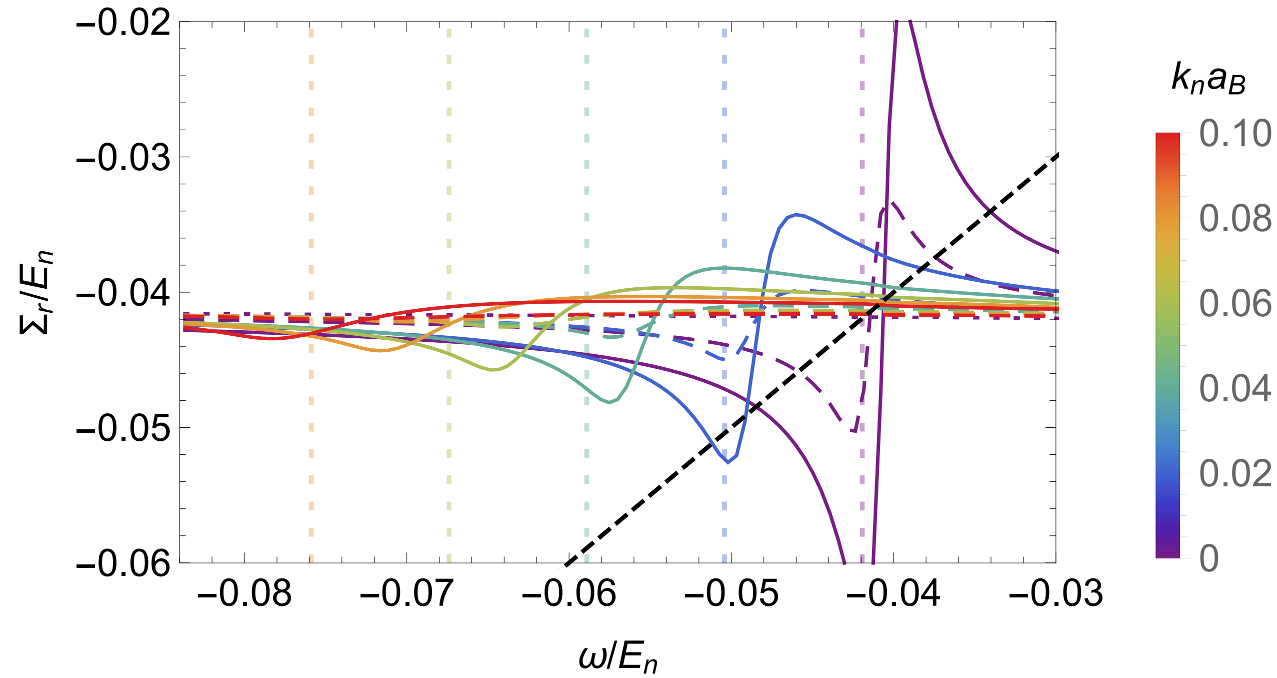
Weak coupling,

low temperature behavior of $\mathrm{Re}(\Sigma)$:

$$(k_n a = -0.1)$$

dashed: $T = 0.05T_c$

solid: $T = 0.1T_c$

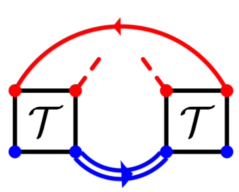


$$\Sigma_1(\omega) \approx \int \frac{d^3k}{(2\pi)^3} \frac{f_{\mathbf{k}}}{\boxed{\mathcal{T}_v^{-1} - \Pi(\mathbf{k},\omega+E_{\mathbf{k}}) - \frac{n_0}{\omega+E_{\mathbf{k}}-\epsilon_{\mathbf{k}}}}}$$

on-shell for: $\omega + E_{\mathbf{k}} = \epsilon_{\mathbf{k}} + \Sigma_0(\mathbf{k},\omega+E_{\mathbf{k}})$

$$\approx \frac{\omega + n_0\mathcal{T}_B}{\omega - n_0(\mathcal{T}_v - \mathcal{T}_B)} n_{\mathrm{ex}}\mathcal{T}_v$$

non-condensed fraction



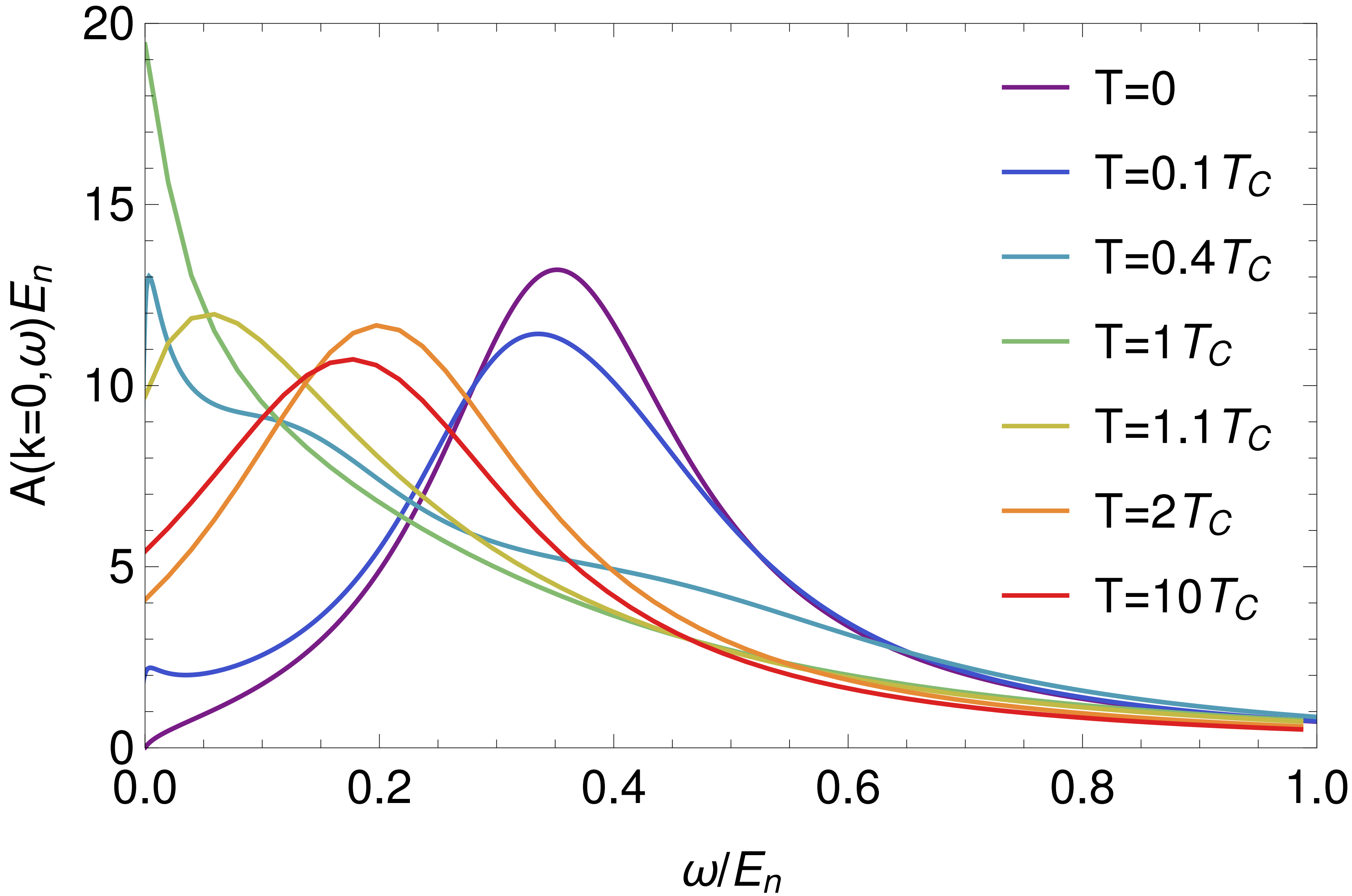
$\lvert a\rvert \gtrsim a_B$: equal splitting	$\lvert a\rvert \lesssim a_B$: single polaron
$\omega_{\uparrow,\downarrow} \simeq \omega_0[1 \pm (Z_0 n_{\mathrm{ex}}/n_0)^{1/2}]$	$\omega_{\uparrow} \simeq n\mathcal{T}_v$
$Z_{\uparrow,\downarrow} \simeq Z_L/2$	in accord with perturbation theory [Levinsen et al., arXiv:1708.09172]

Repulsive polarons

Weak repulsion

$(k_n a = 1)$

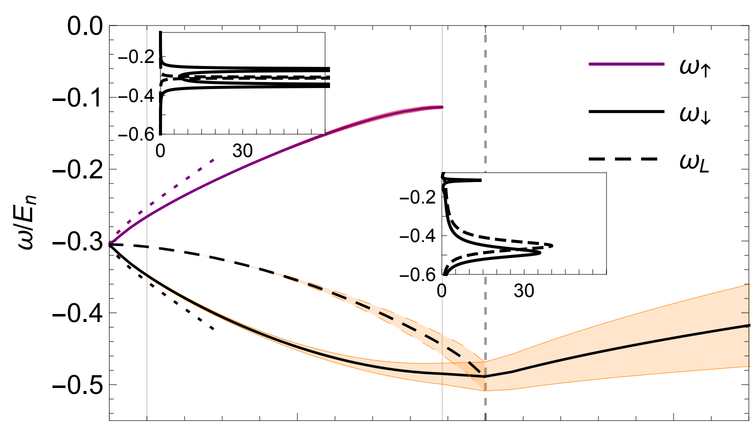
Spectral function:



Guenther, PM, Lewenstein, and Bruun, arXiv:1708.08861

Conclusions

- Bose polarons greatly differ from Fermi ones
- No polaron/molecule transition
- Fundamental role played by the BEC, and the associated large low-energy density of states
- Non-perturbative treatment is crucial
- The T=0 attractive polaron fragments into two quasiparticles at T>0
- The upper of the two negative energy excitations disappears at T_c
- The ground state quasiparticle remains well-defined across T_c



Thank you!