



AT MIT

# Dynamics and energetics of fermionic impurities in a BEC



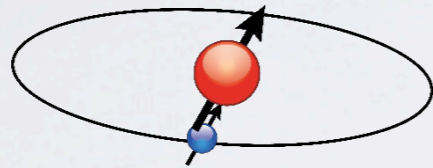
Z. Z. Yan, Y. Ni, CR, M. Zwierlein  
Science 368 (2020)

Carsten Robens  
— Zwierlein Group —

September 2021

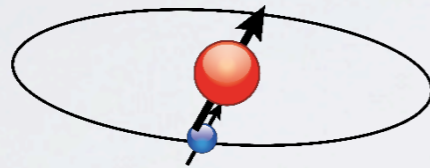
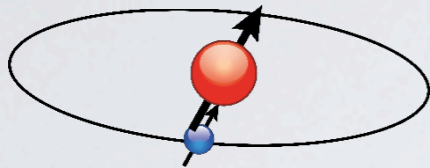
Dynamics and local control of impurities in complex quantum environments

# The success of quasiparticles



$$H(t) |\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

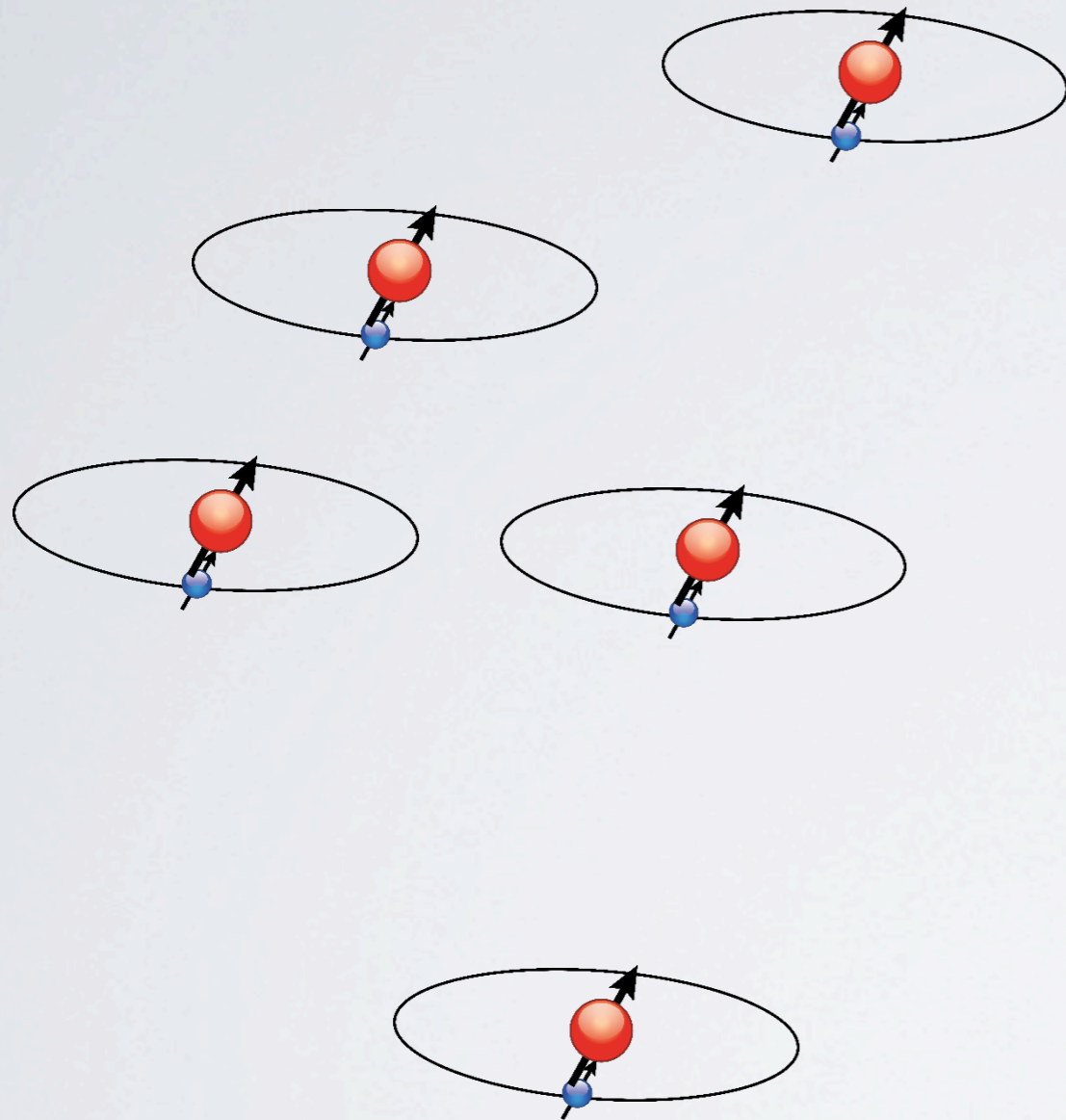
# The success of quasiparticles



$$H(t) |\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$



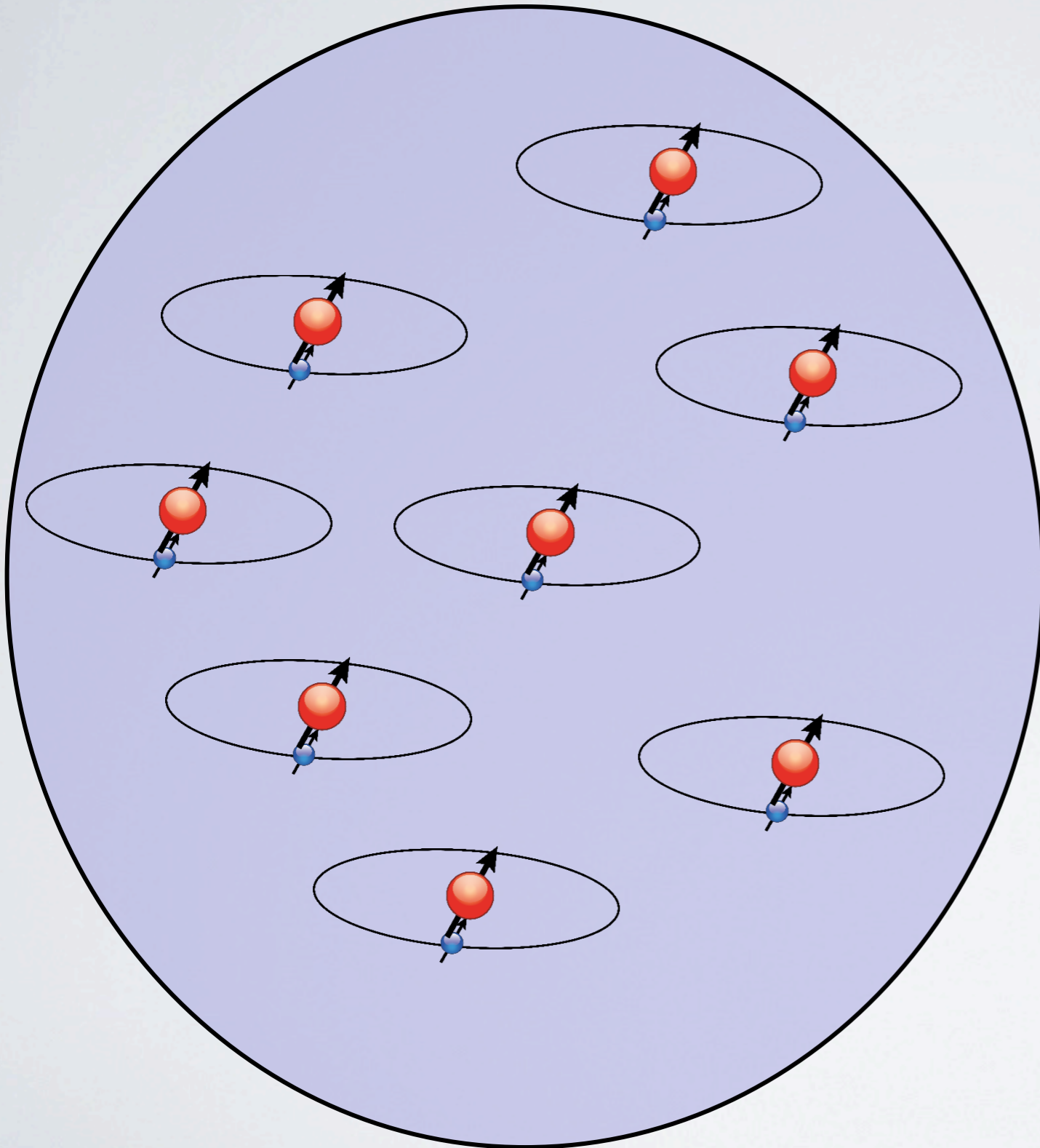
# The success of quasiparticles



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# The success of quasiparticles

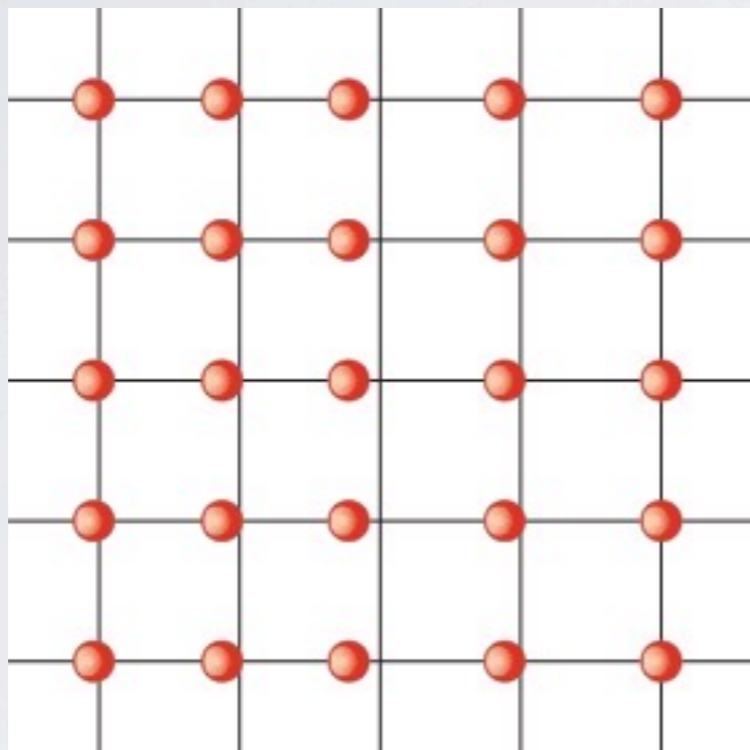
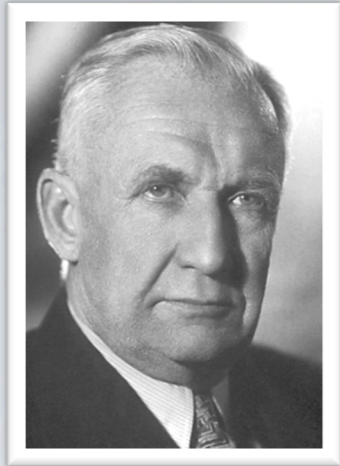


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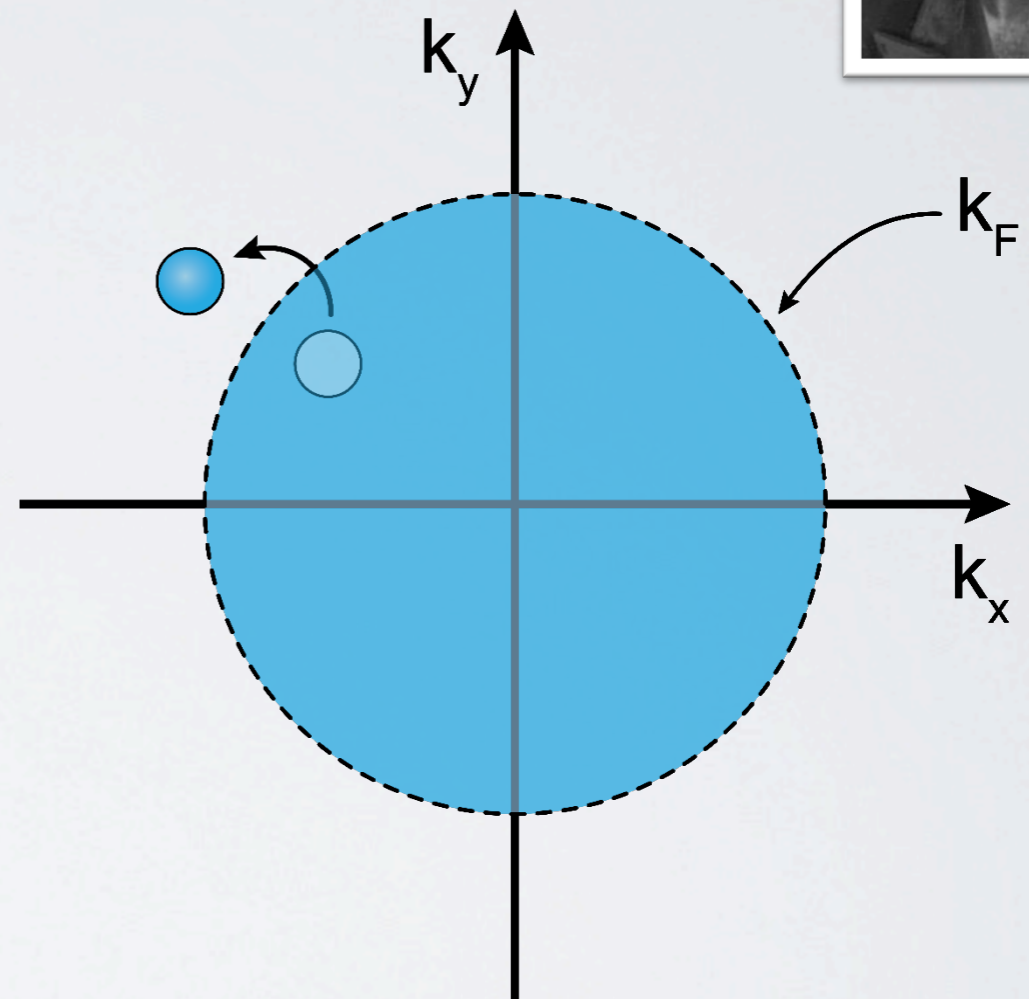
“The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe”

Anderson, “More is Different” (1972)

# Quasiparticles: examples



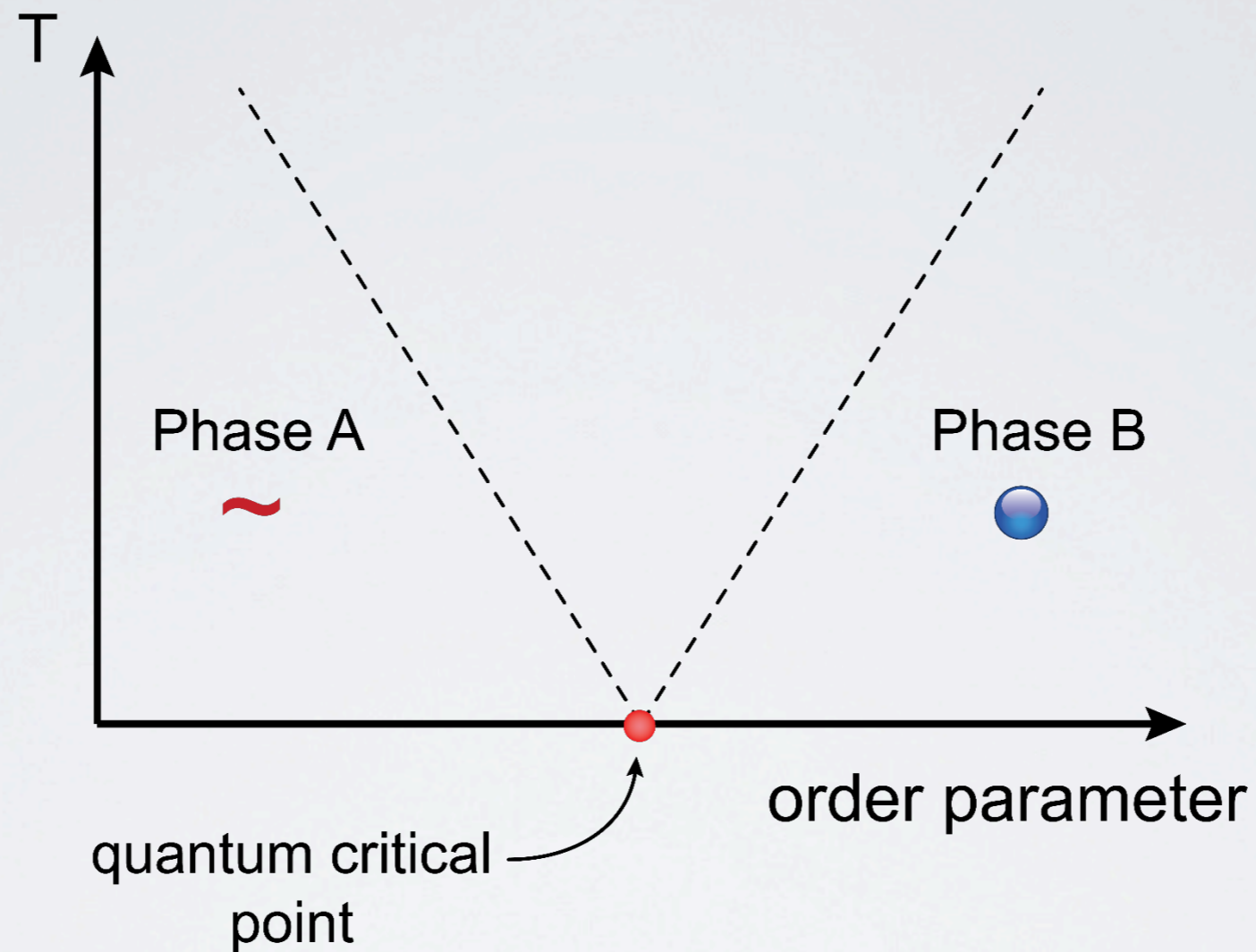
Phonon  
Igor Y. Tamm (1932)



Fermi liquid theory  
Lev Landau (1956)

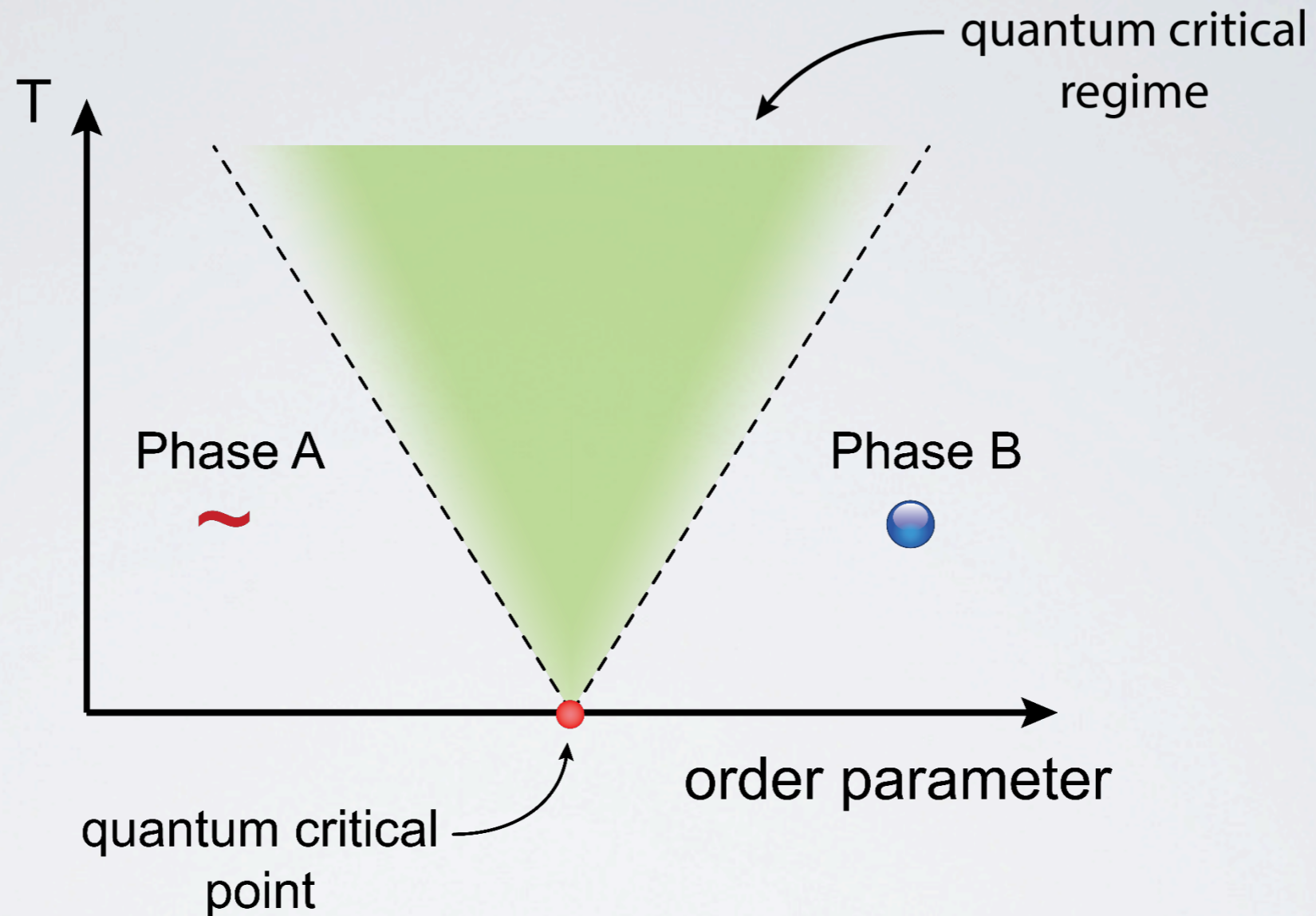


# Quasiparticles and quantum phase transitions





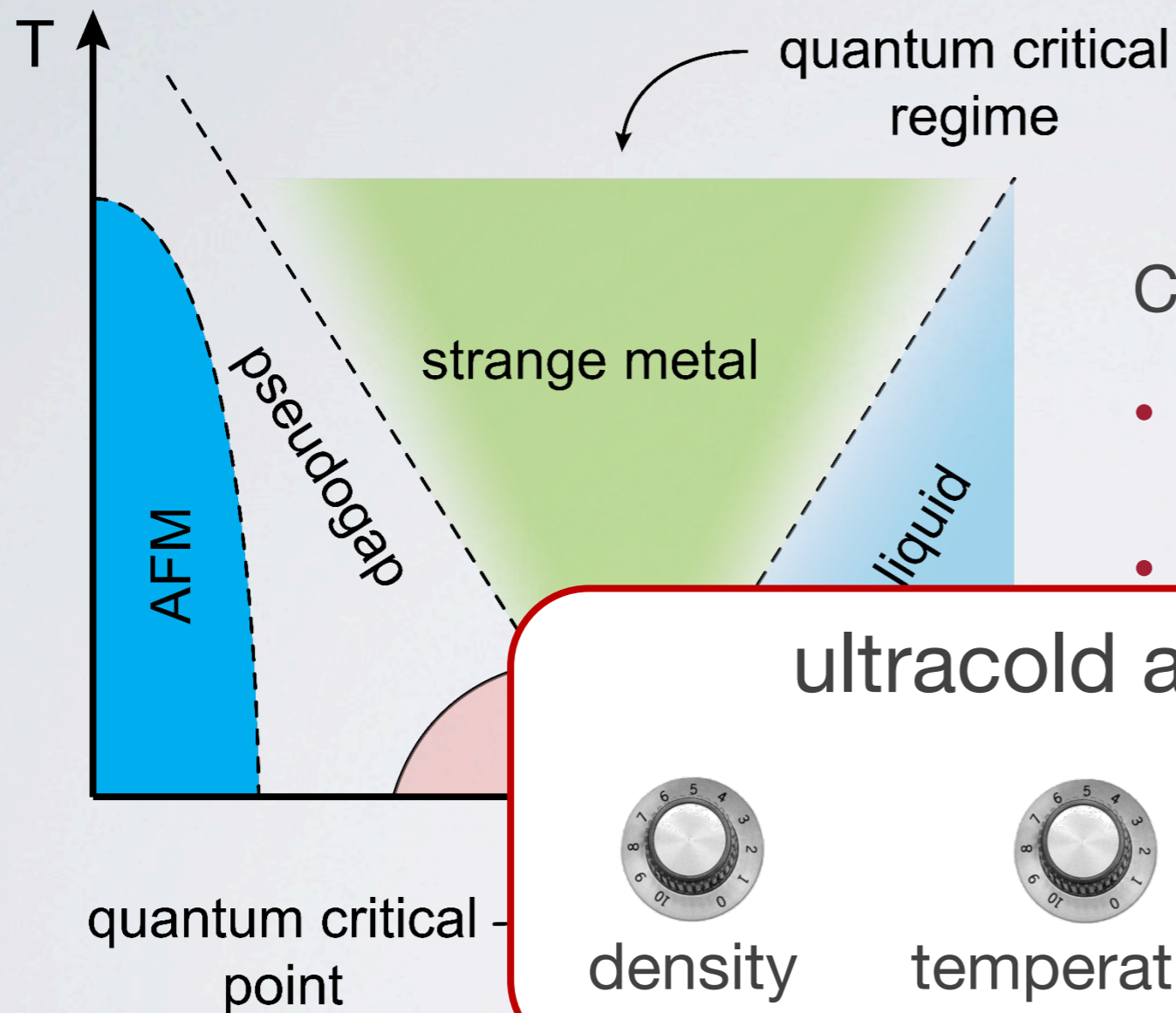
# The fate of quasiparticles at quantum criticality



Key characteristics:

- Thermal equilibrium time  $\tau_{\text{eq}}^{-1} \sim T$   
(independent of microscopic details)

# Cuprate superconductors



Characteristics:

- resistivity  $\rho \sim \frac{k_B T}{\hbar}$
- mean free path  $<$  lattice spacing (Ioffe-Regel limit)

ultracold atoms



density



temperature



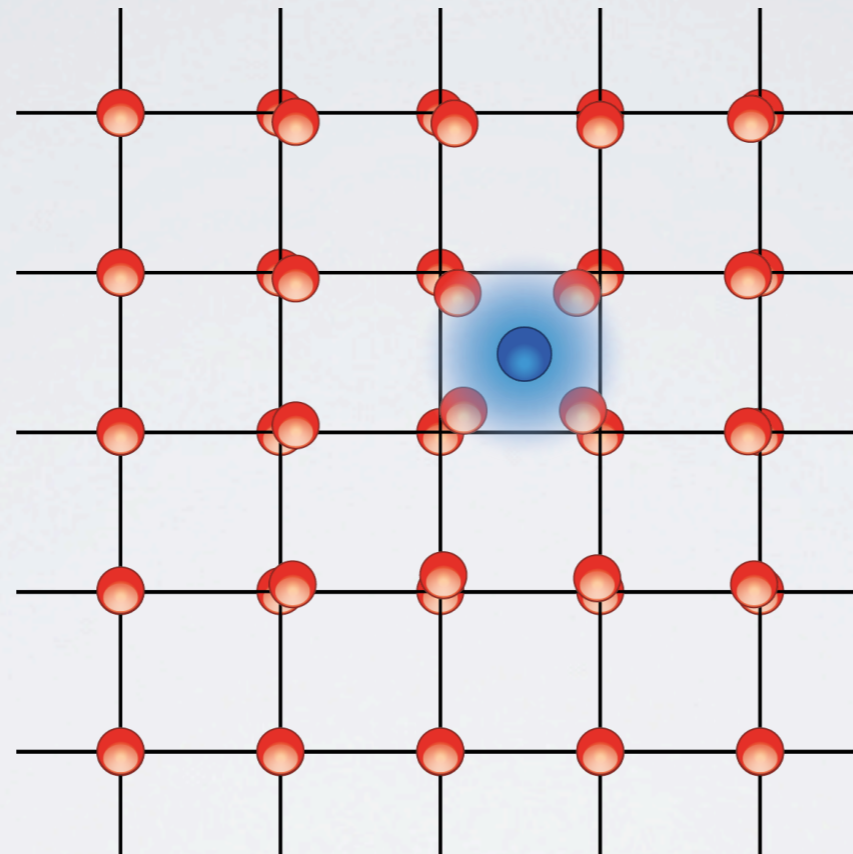
interactions

breakdown





# The Bose polaron



Landau, Phys. Z. Sowjetunion 3, 644 (1933)

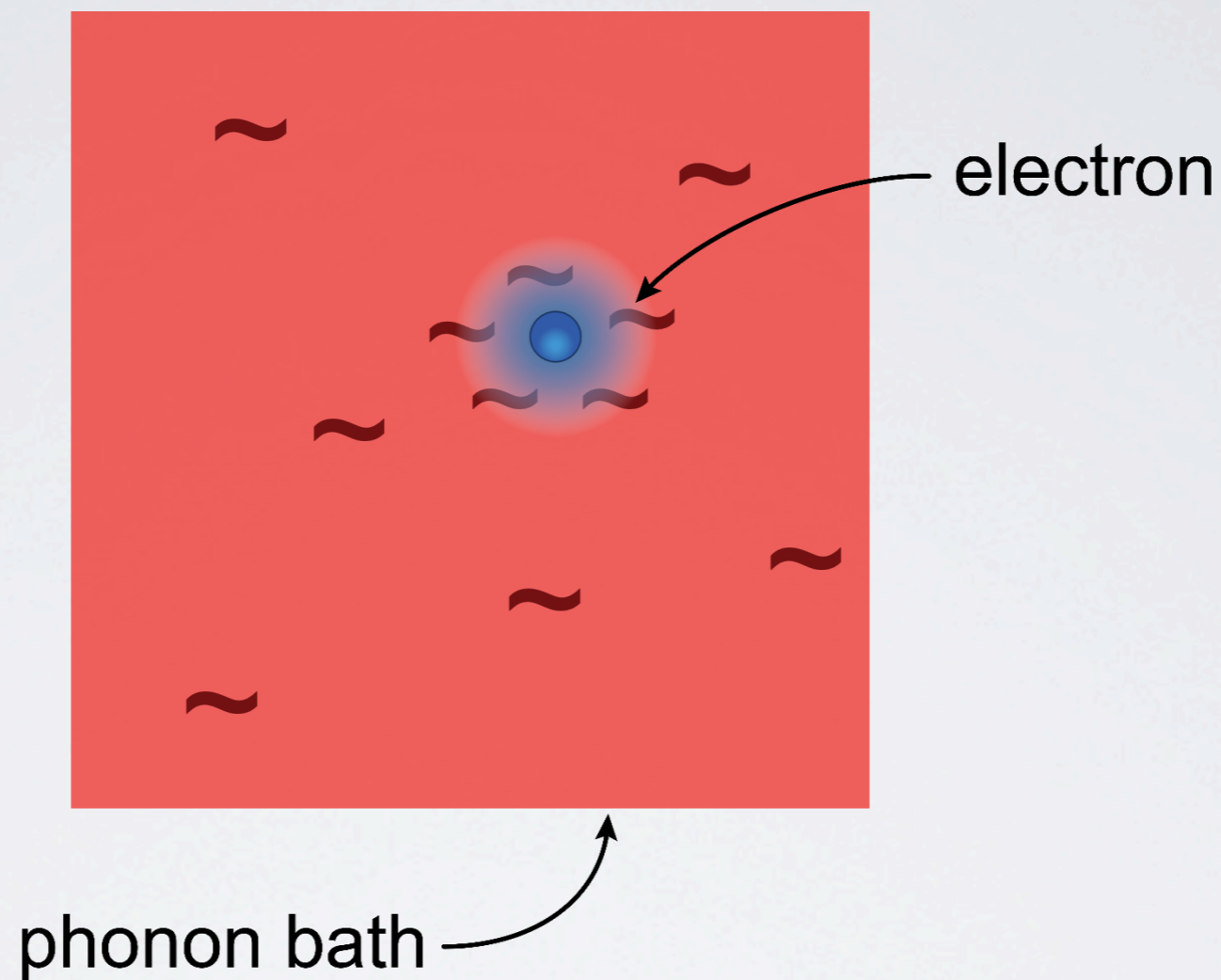
Pekar, Zh. Eksp. Teor. Fiz. 16, 335 (1946)

Landau & Pekar, Zh. Eksp. Teor. Fiz. 18, 419 (1948)





# The Bose polaron



Landau, Phys. Z. Sowjetunion 3, 644 (1933)

Pekar, Zh. Eksp. Teor. Fiz. 16, 335 (1946)

Landau & Pekar, Zh. Eksp. Teor. Fiz. 18, 419 (1948)

# The Bose polaron

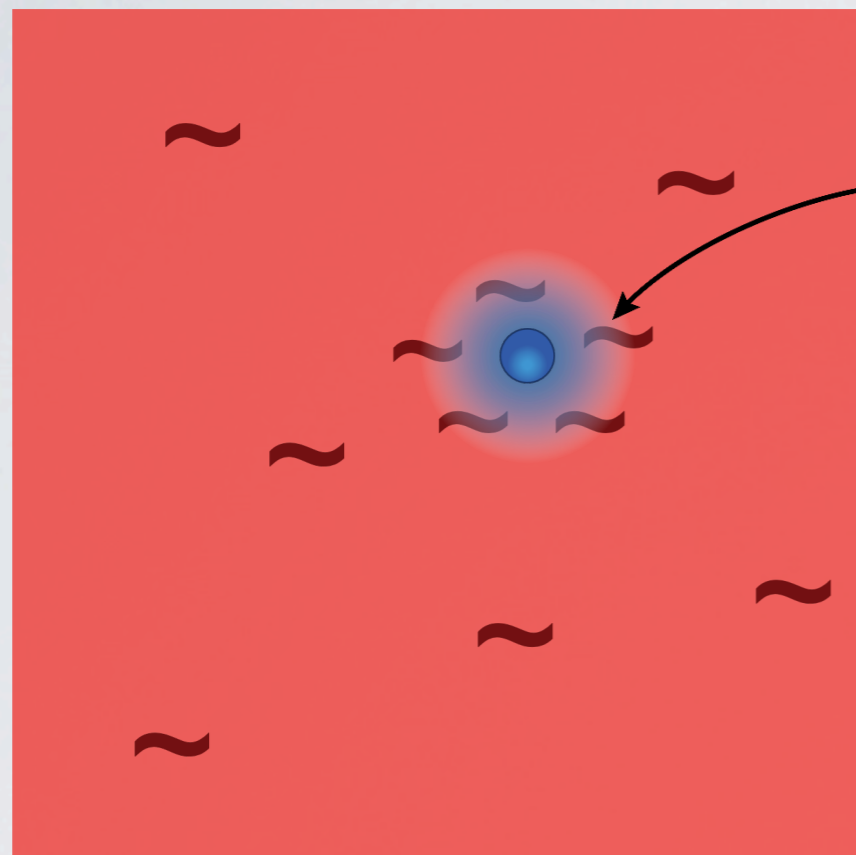


electron

- Colossal magnetoresistance
- $^3\text{He}$  impurities in liquid  $^4\text{He}$
- Organic field-effect transistors
- ...

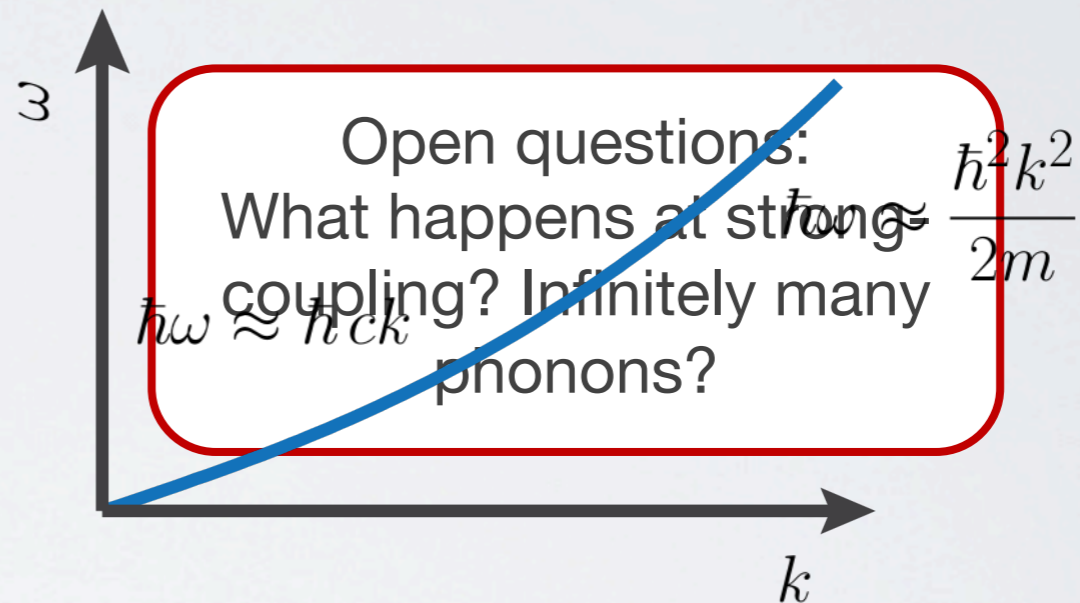
phonon bath

# The Bose polaron in ultracold atoms



BEC

atomic impurity



Early proposals:

- F. Cucchietti et al., PRL 96, 210401 (2006)
- R. Kalas et al., PRA 73, 043608 (2006)
- J. Tempere et al., PRB 80, 184504 (2009)

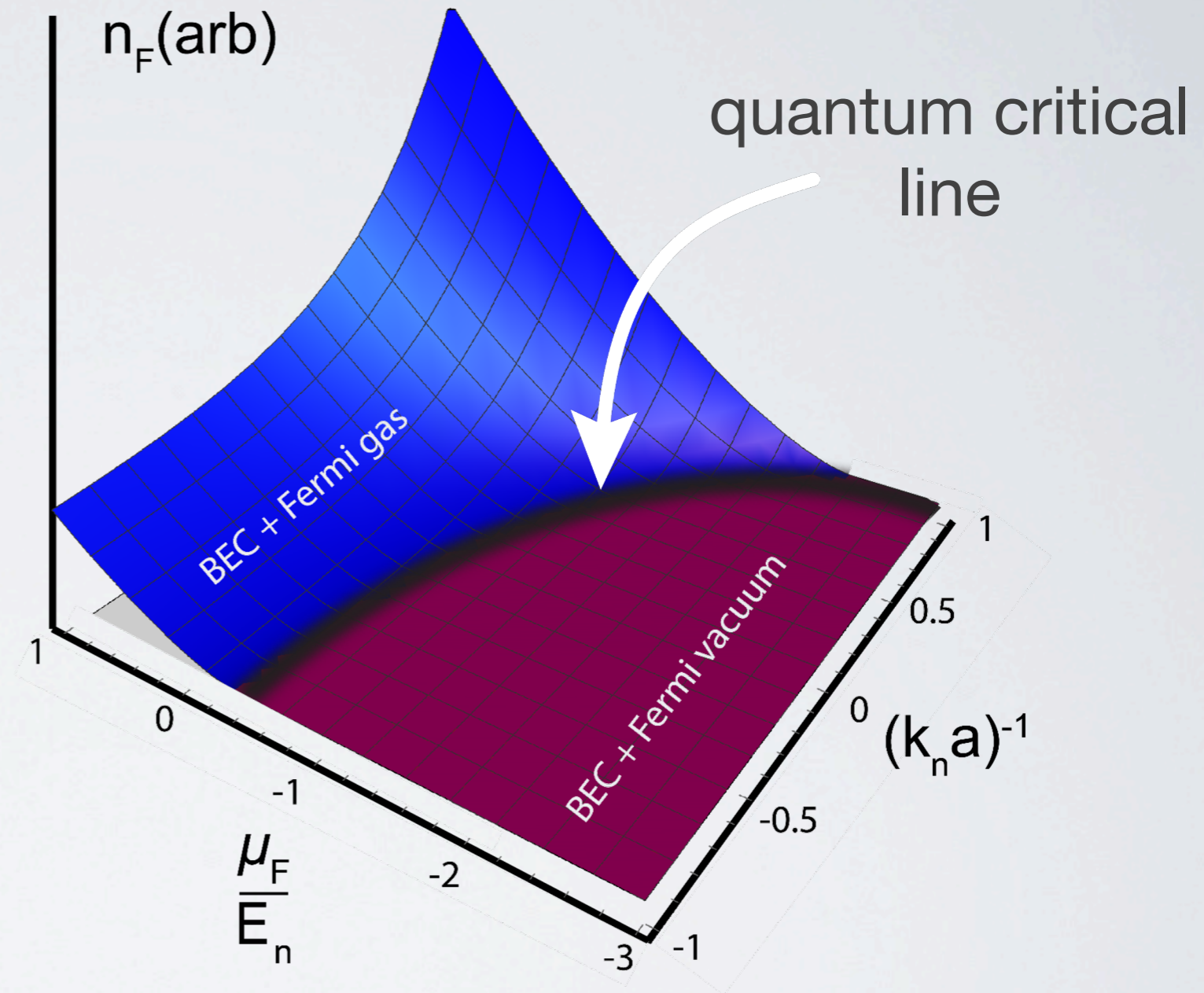
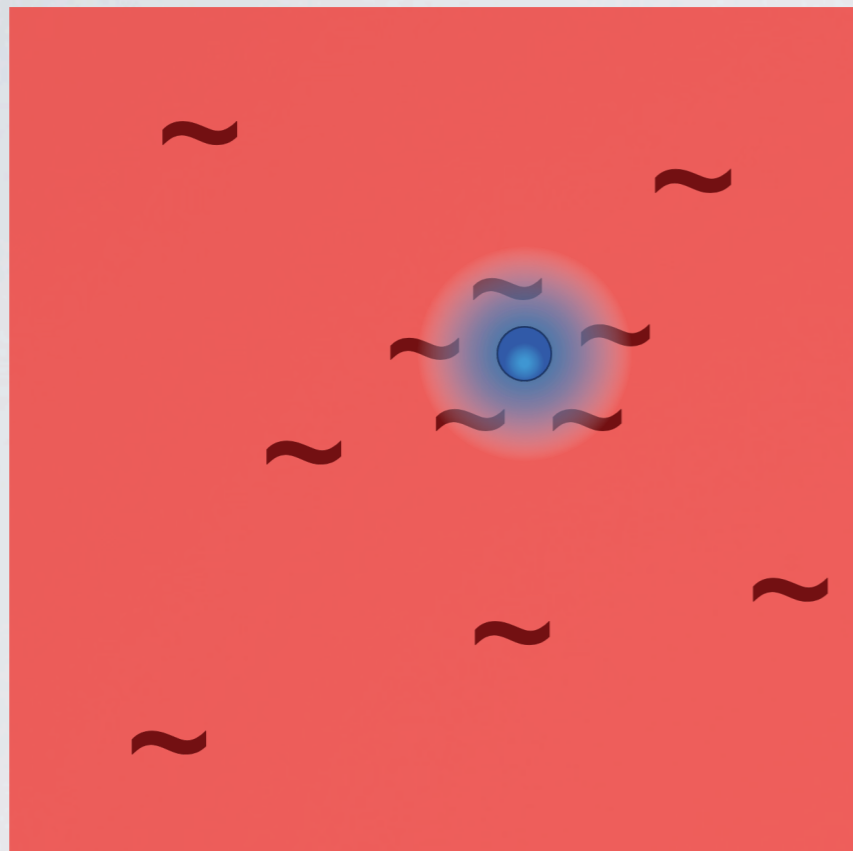
Bose polaron continuum of excited states:

- C. Wu et al., PRL 109, 08301 (2012) MIT
- M. Hu et al., PRL 117, 055301 (2016) JILA
- N. Jørgensen et al., PRL 117, 055302 (2016) Aarhus



# Quantum criticality in ultracold Bose-Fermi mixtures

~~$\mu_B$~~     $\mu_F$     ~~$g_{BB}$~~     $g_{BF}$     ~~$\frac{m_F}{m_B}$~~



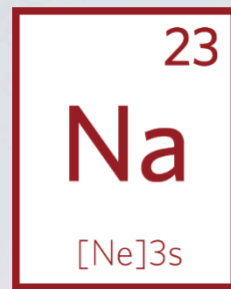
Z. Z. Yan, Y. Ni, CR, M. Zwierlein, Science 368 (2020)

S. Sachdev, Quantum Phase Transitions, (2011)

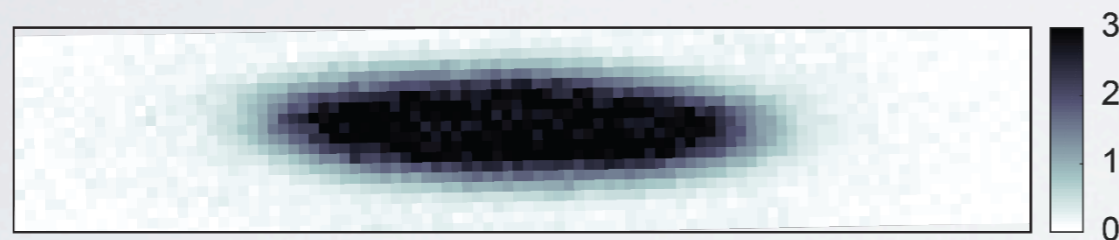
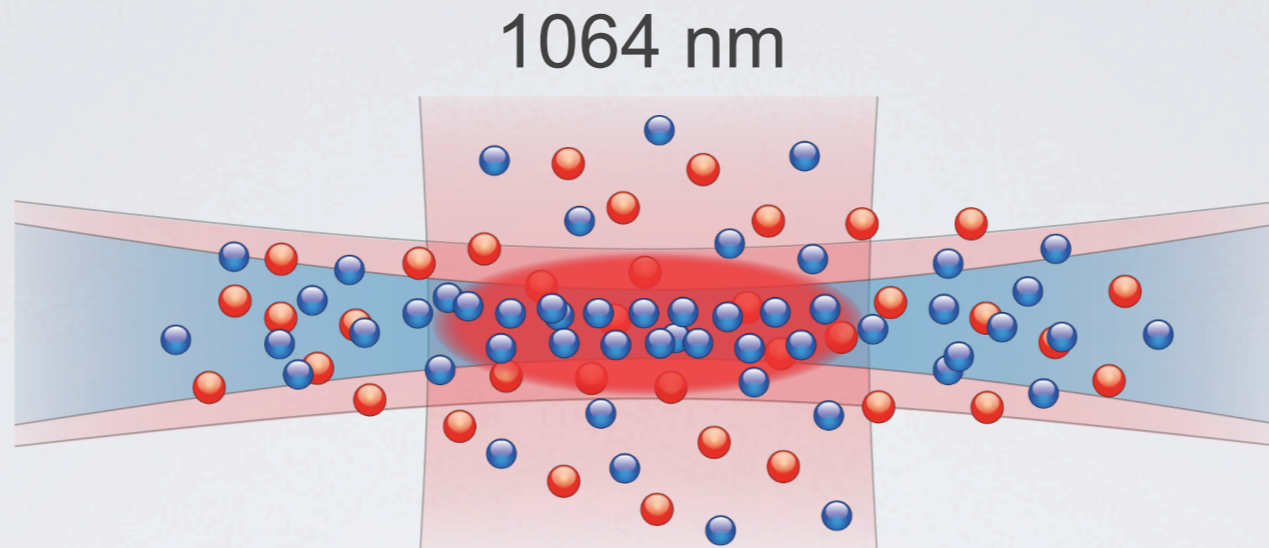
D. Ludwig et.al., PRA 84, 033629 (2011)

T. Enss, PRA 86, 013616 (2012)

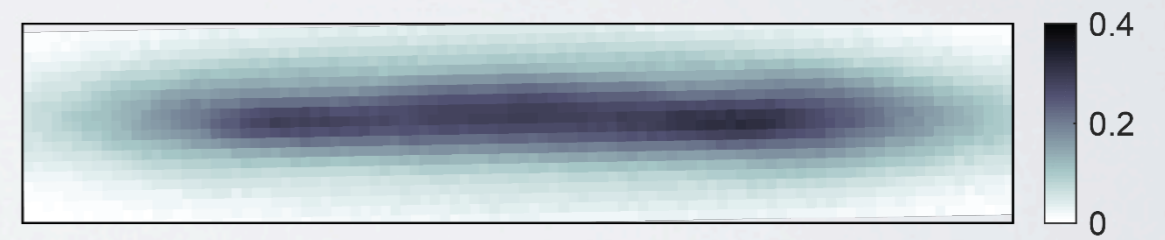
# Creating strongly-coupled Bose polarons with $^{23}\text{Na}^{40}\text{K}$



775 nm



$$n_{\text{Na}} = 6 \cdot 10^{13} \text{ cm}^{-3}$$

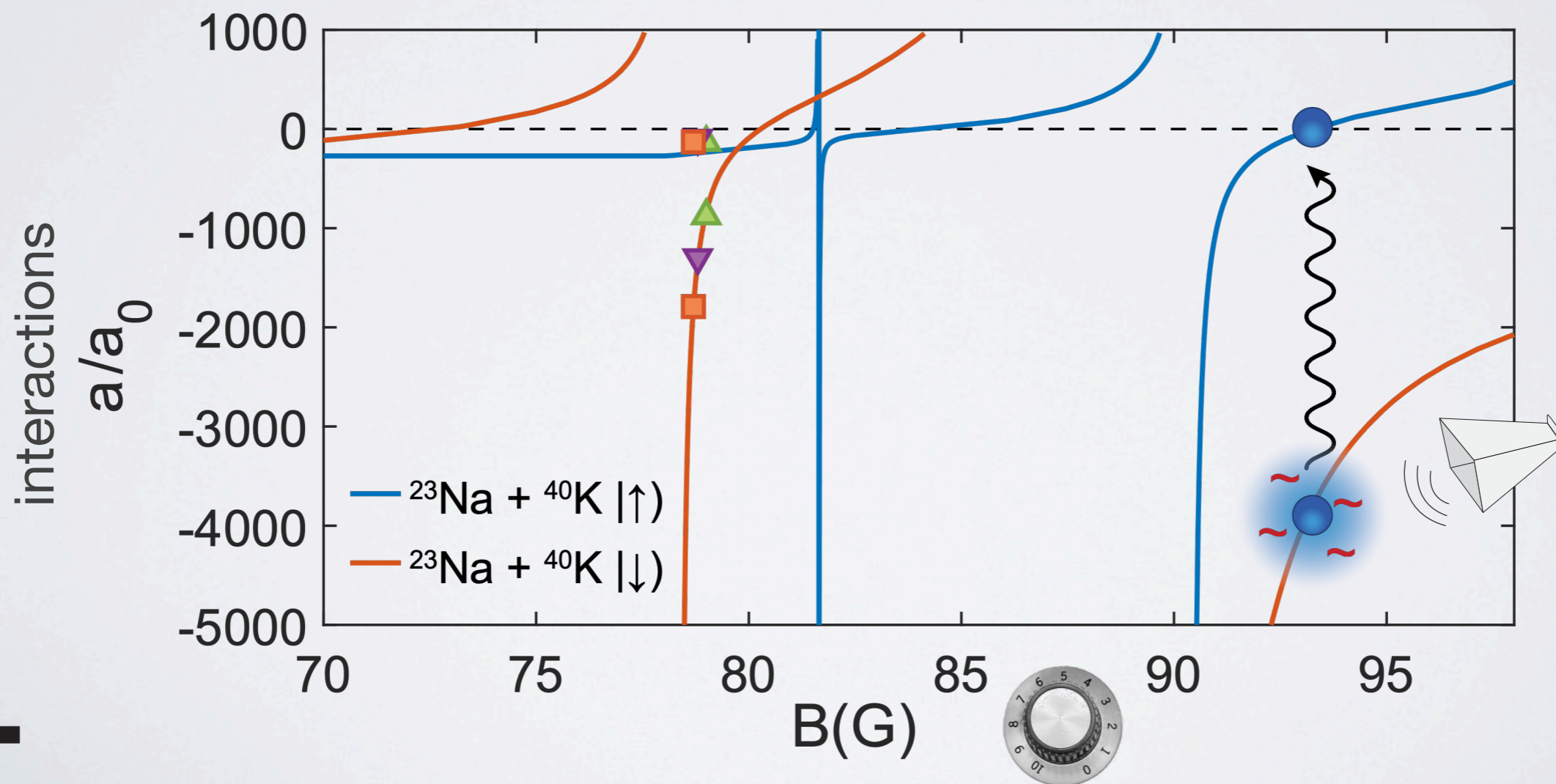
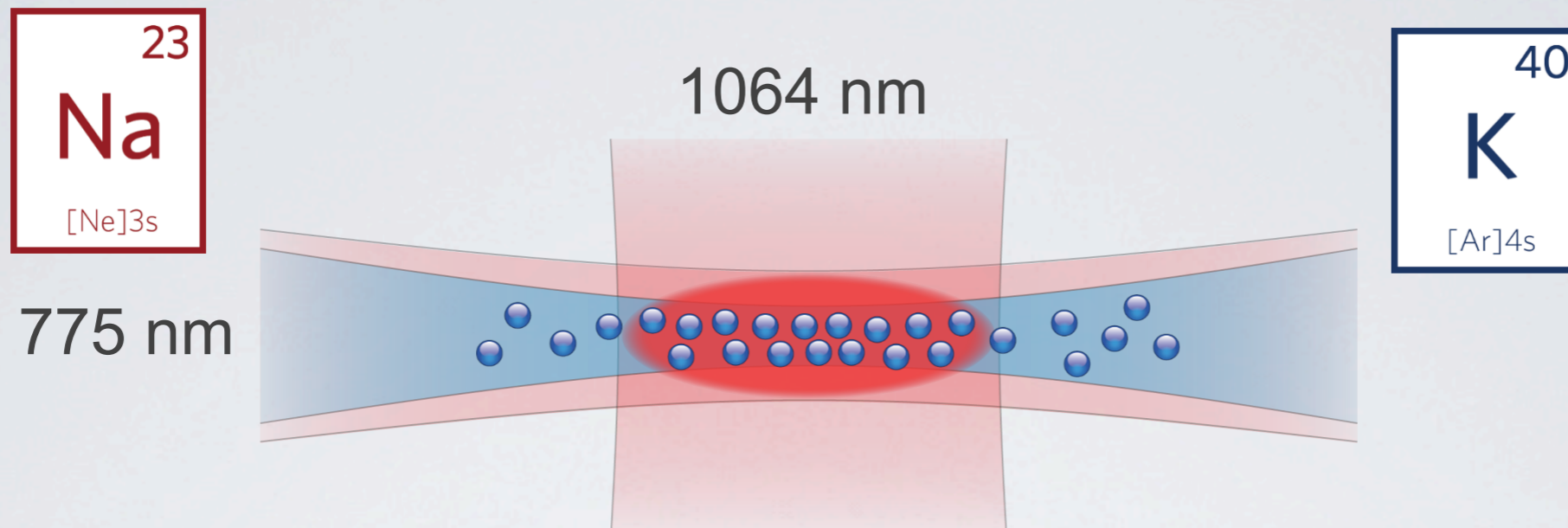


$$n_{\text{K}} = 2 \cdot 10^{11} \text{ cm}^{-3}$$

Impurity  
concentration  
 $n_{\text{K}} / n_{\text{Na}} = 0.3\%$



# Ejection spectroscopy on Bose polarons



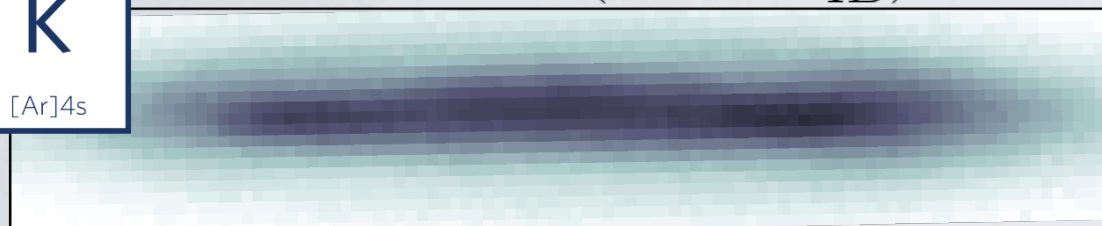


# Bose polaron ejection spectroscopy

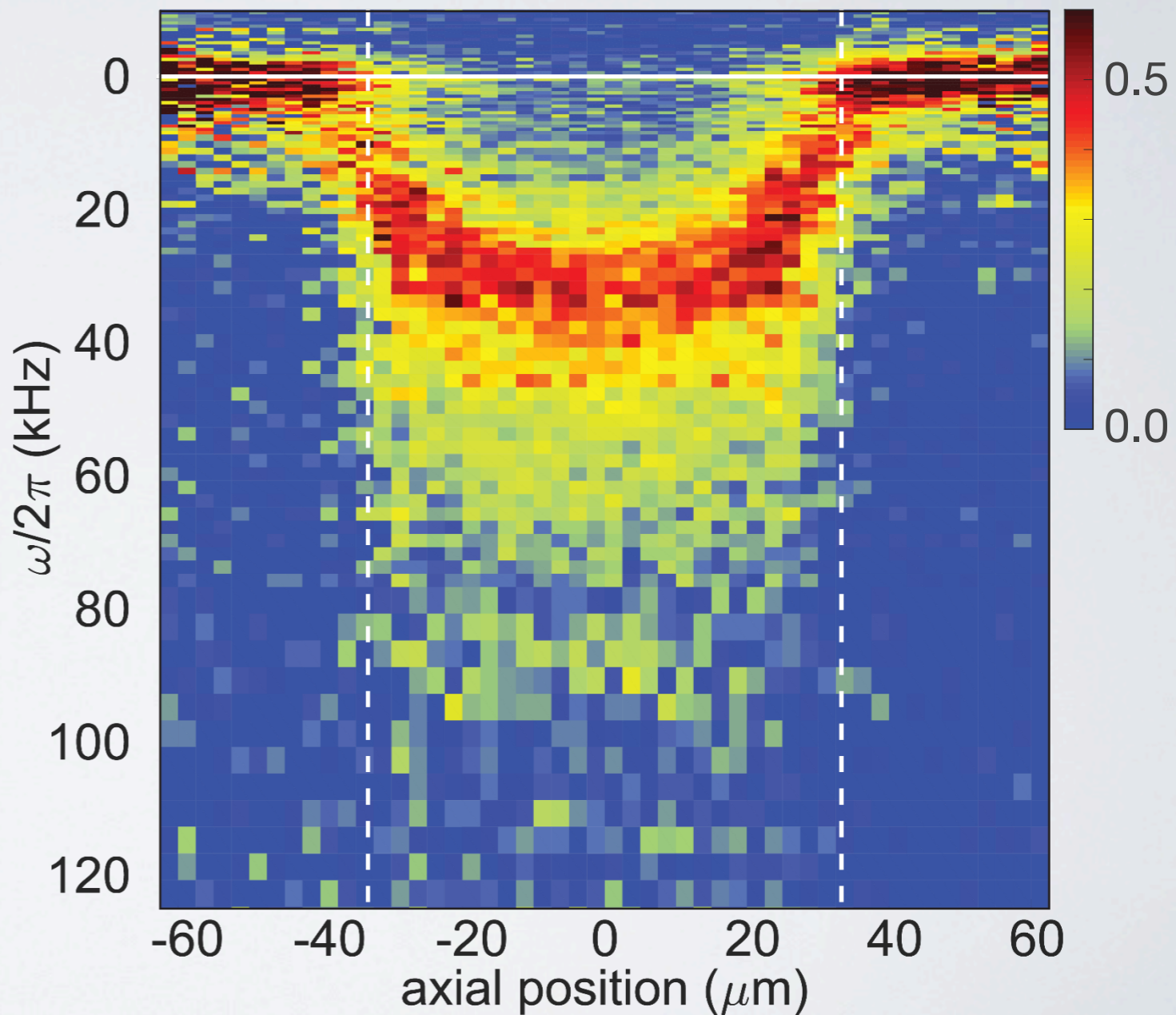
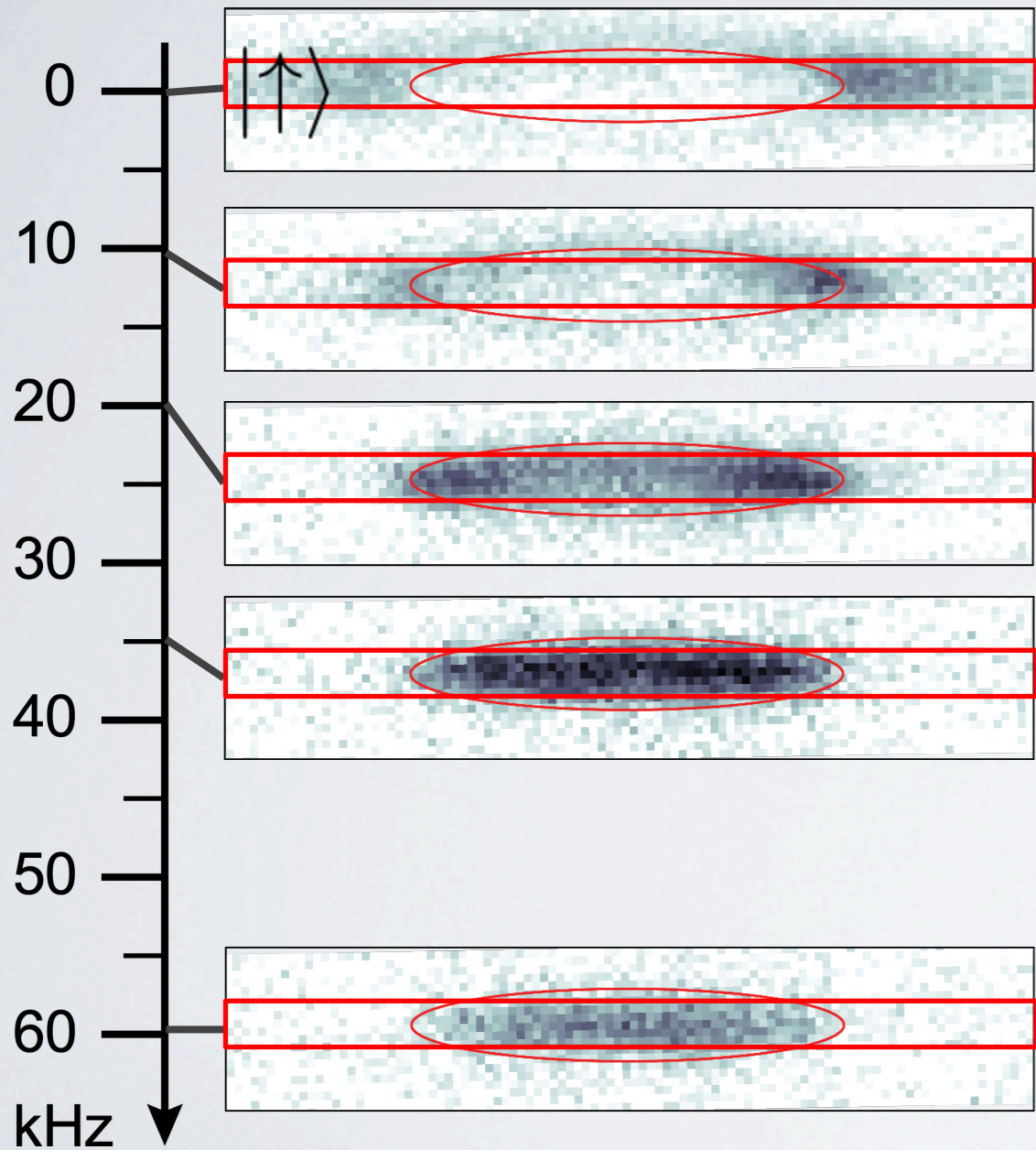
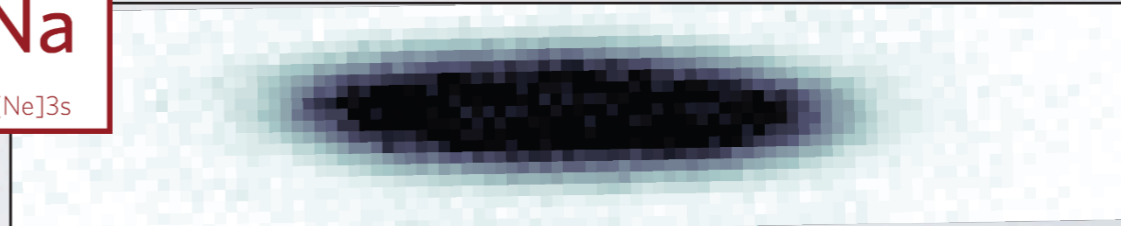
$$(k_n^{\text{peak}} a_{\text{IB}})^{-1} = -0.3$$

40  
**K**  
[Ar]4s

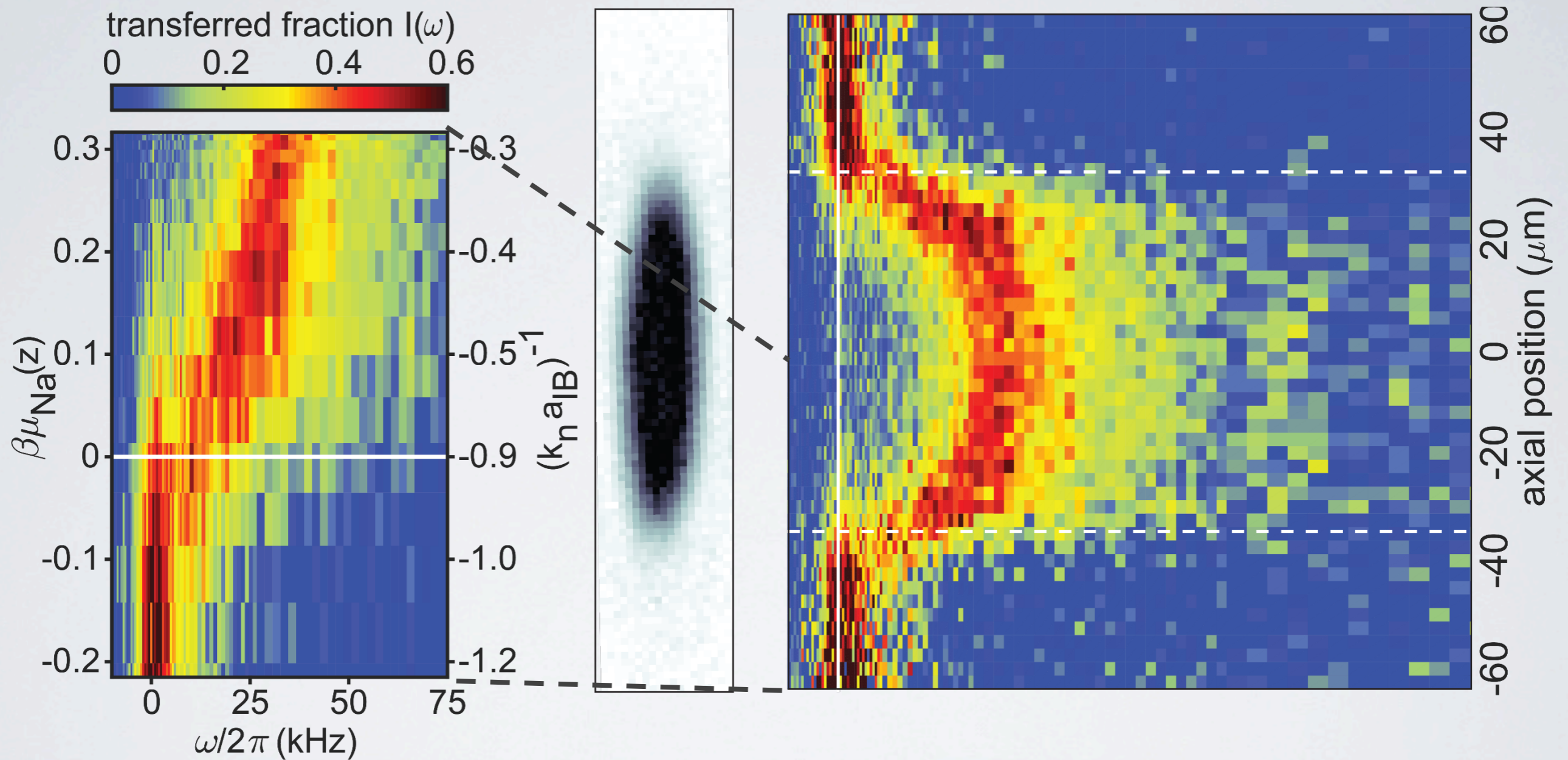
$|\downarrow\rangle$



23  
**Na**  
[Ne]3s



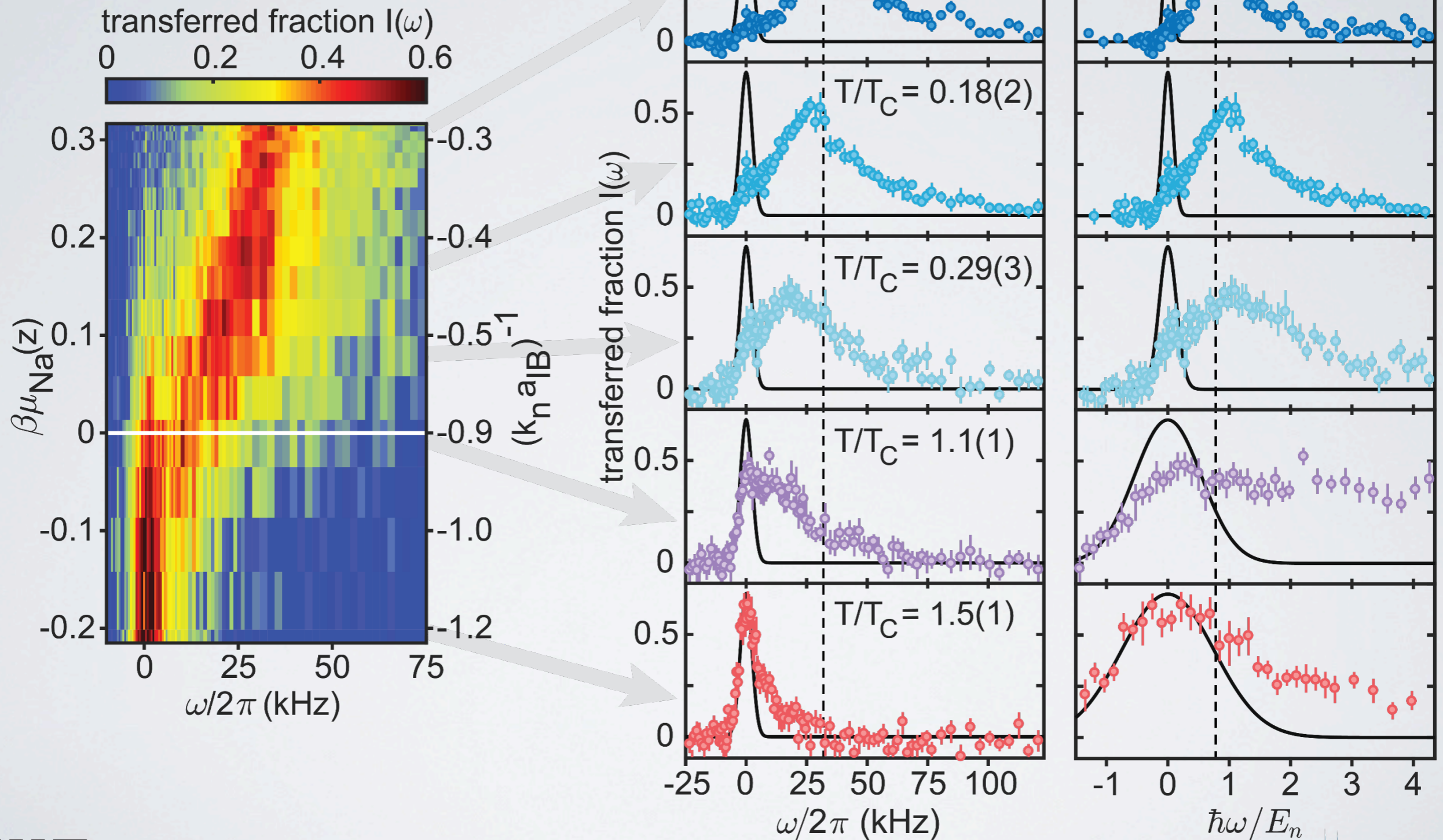
# Polaron spectra in local density approximation (LDA)





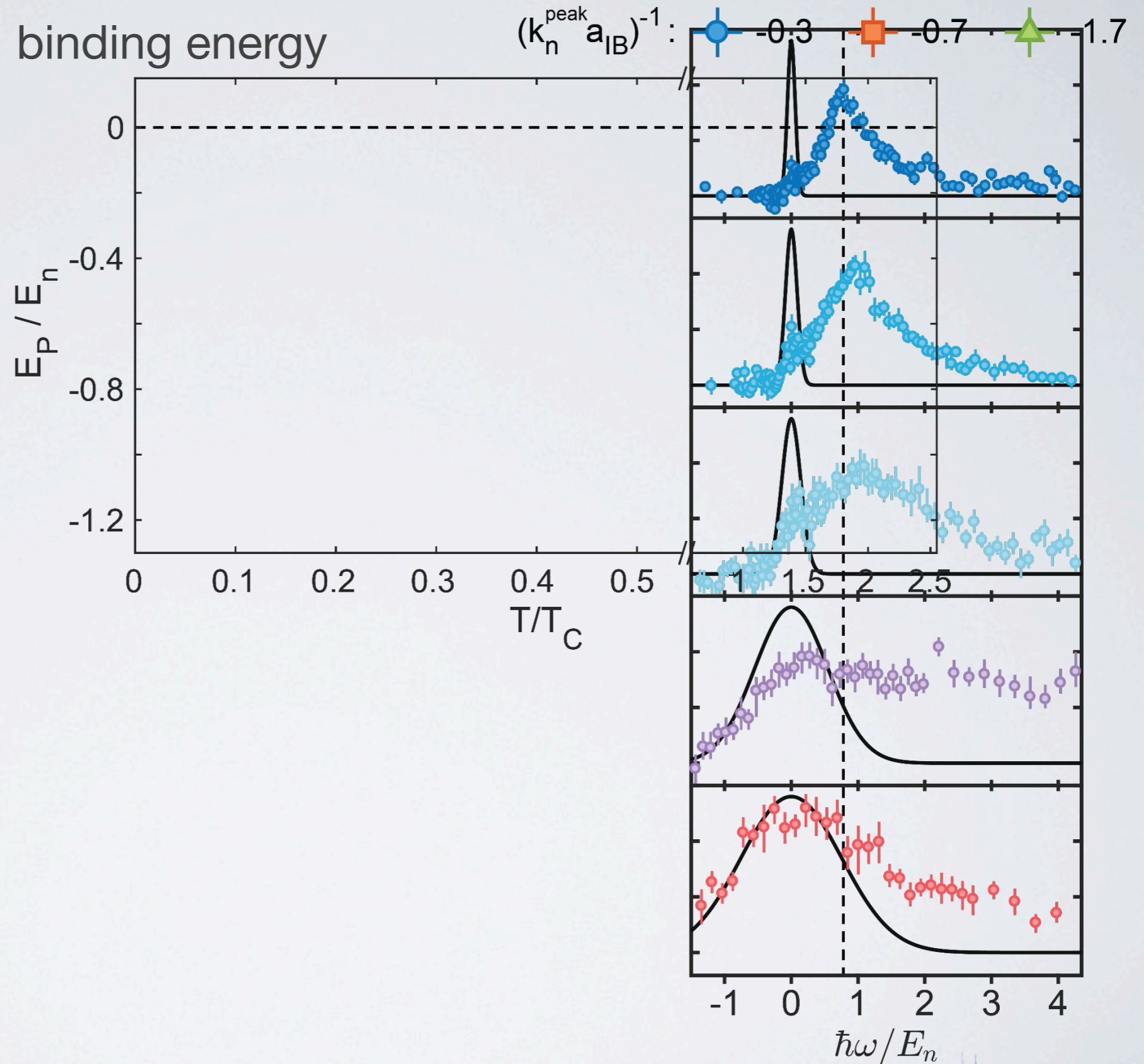
# Polaron spectra in LDA

$$E_n = \frac{\hbar^2 k_n^2}{4m_r} \sim n_{\text{Na}}^{2/3}$$

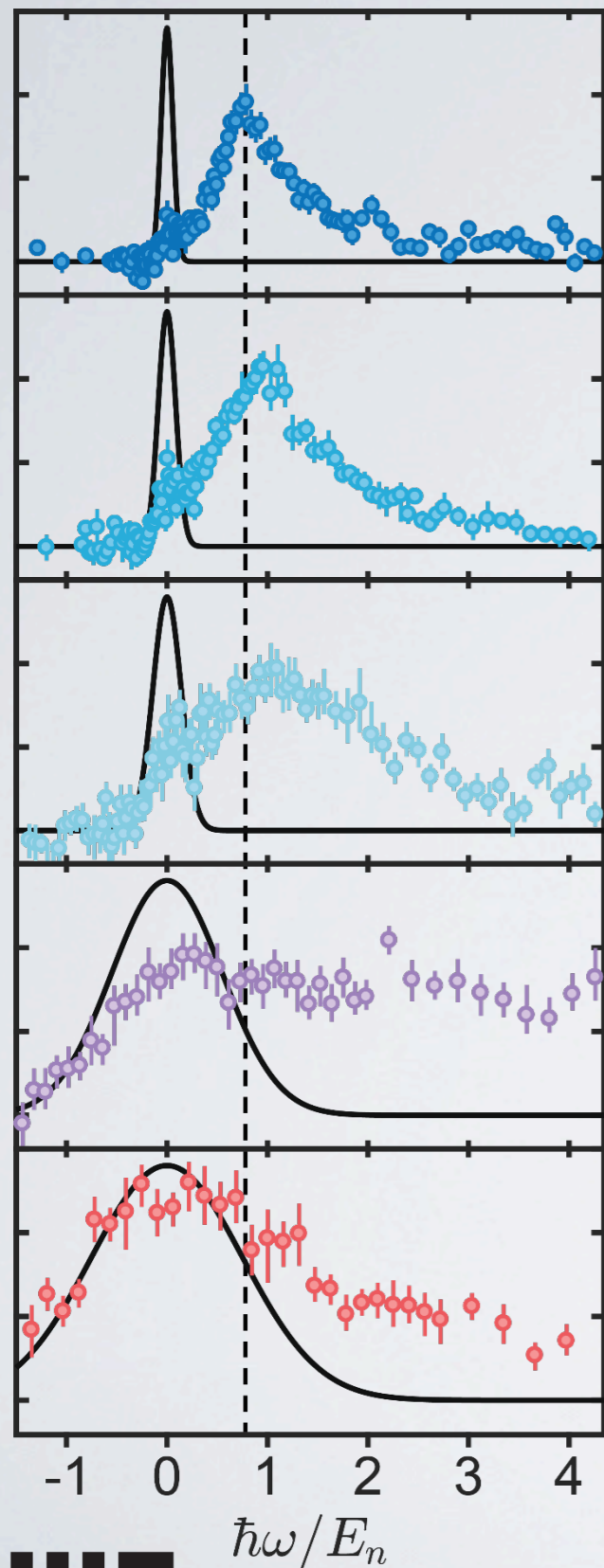




# Polaron spectra in LDA

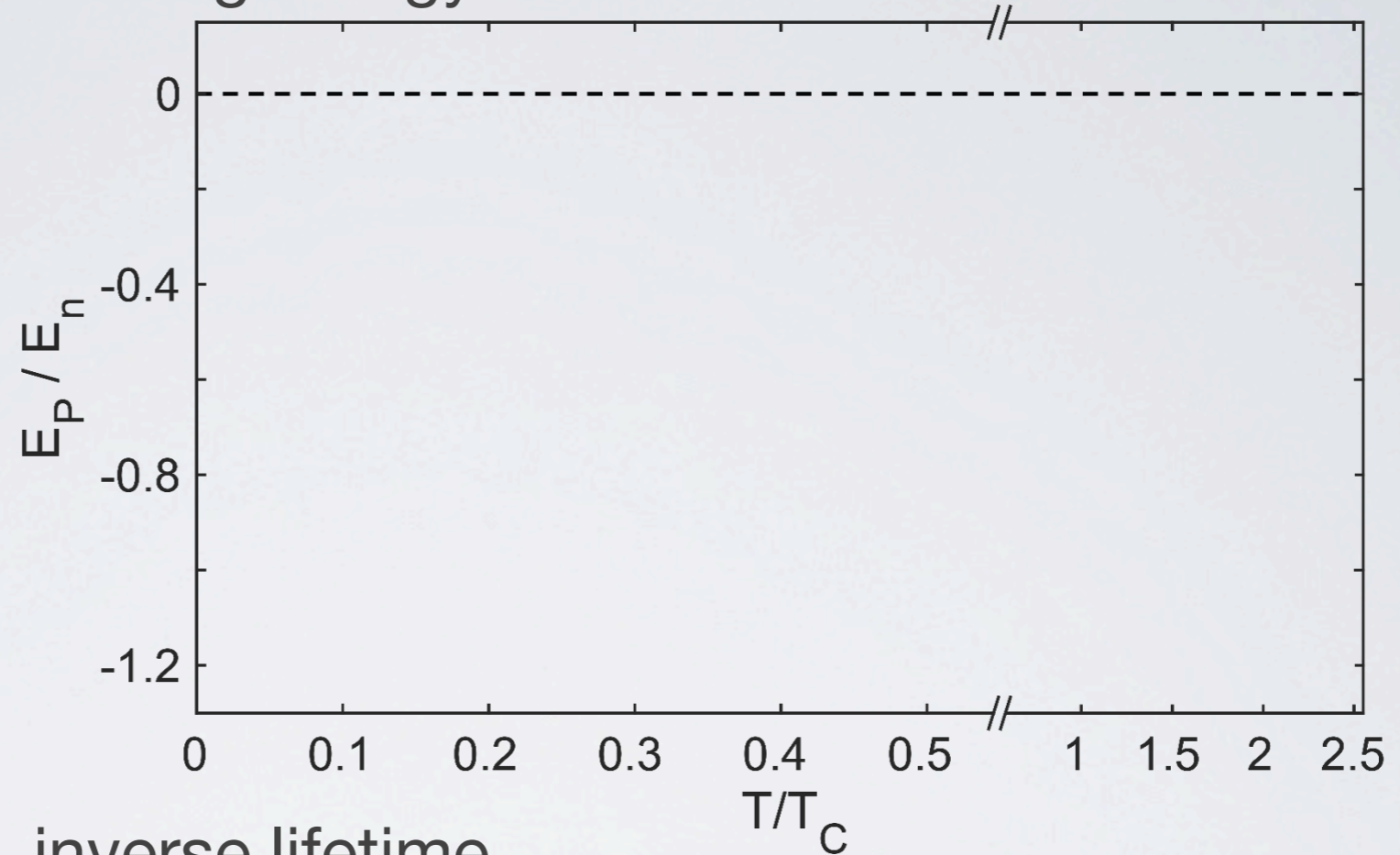


# Polaron spectra in LDA

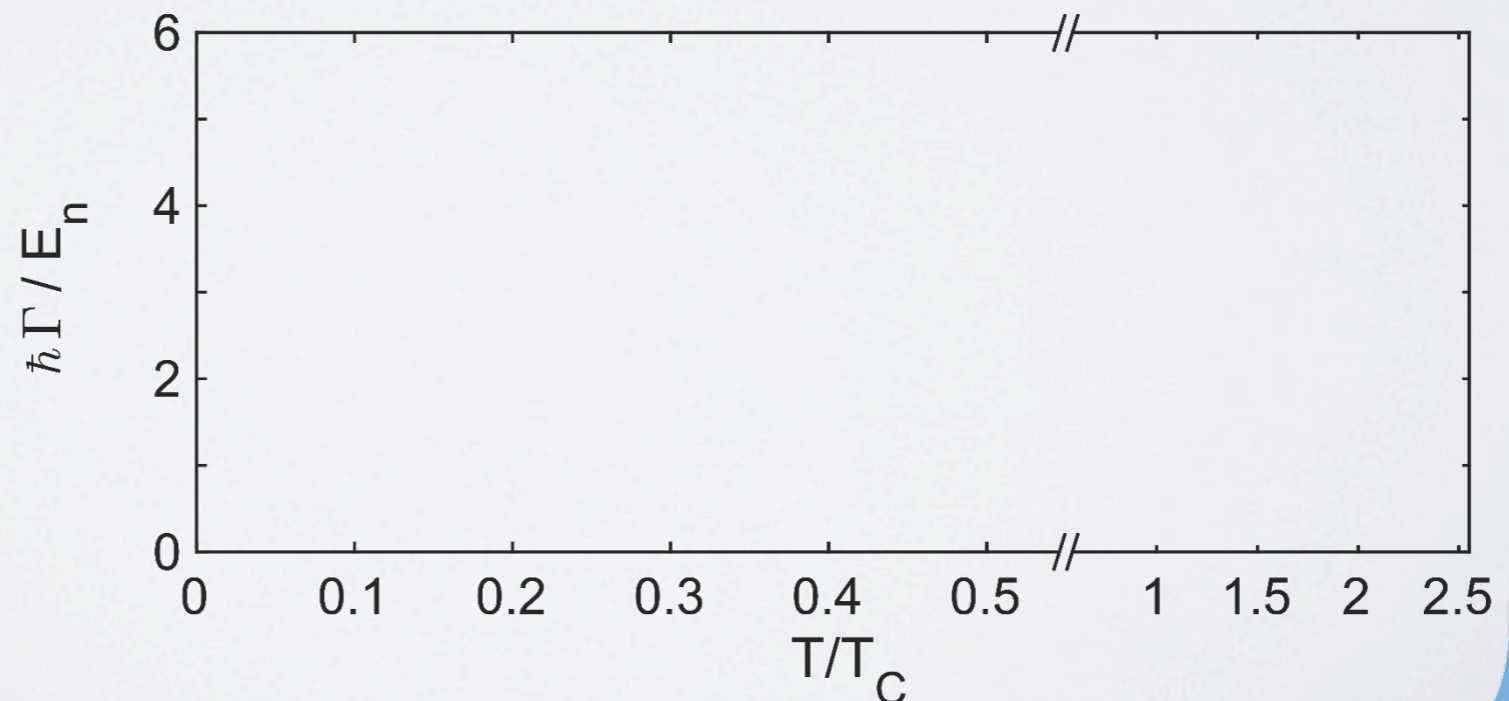


binding energy

$(k_n^{\text{peak}} a_{\text{IB}})^{-1}$ : ● -0.3 ■ -0.7 ▲ -1.7

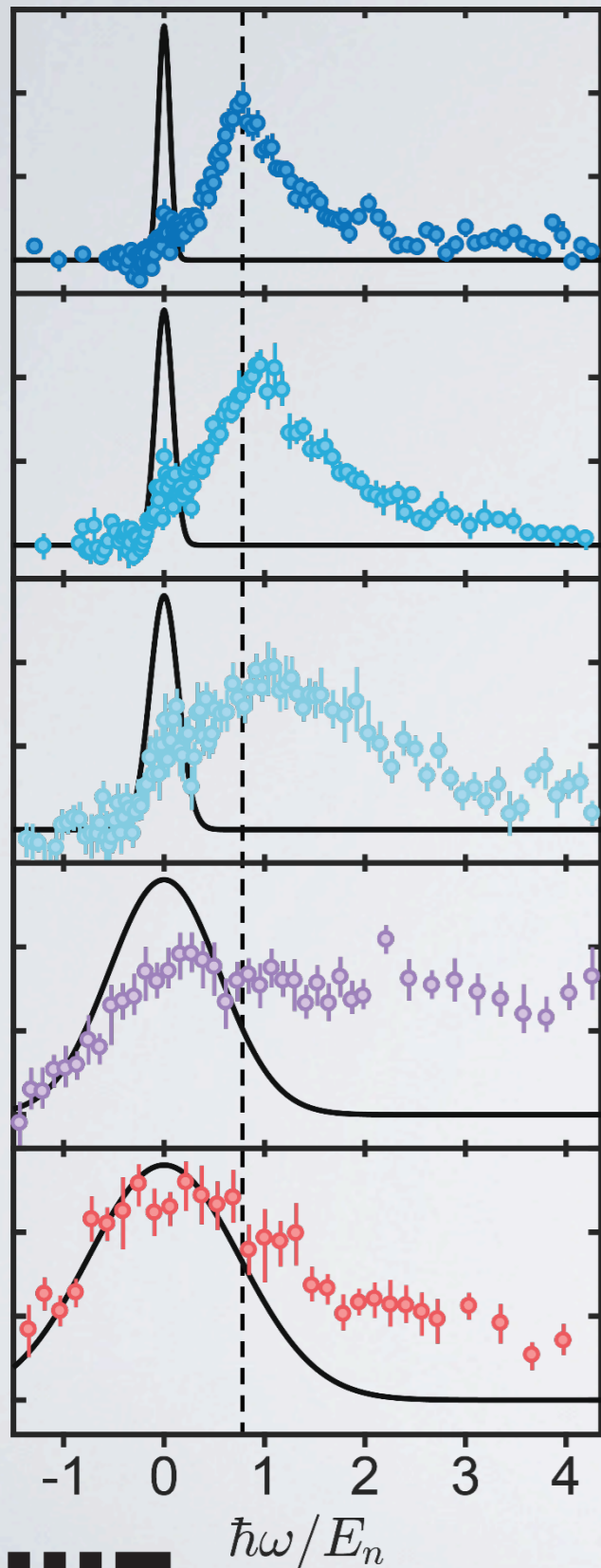


inverse lifetime



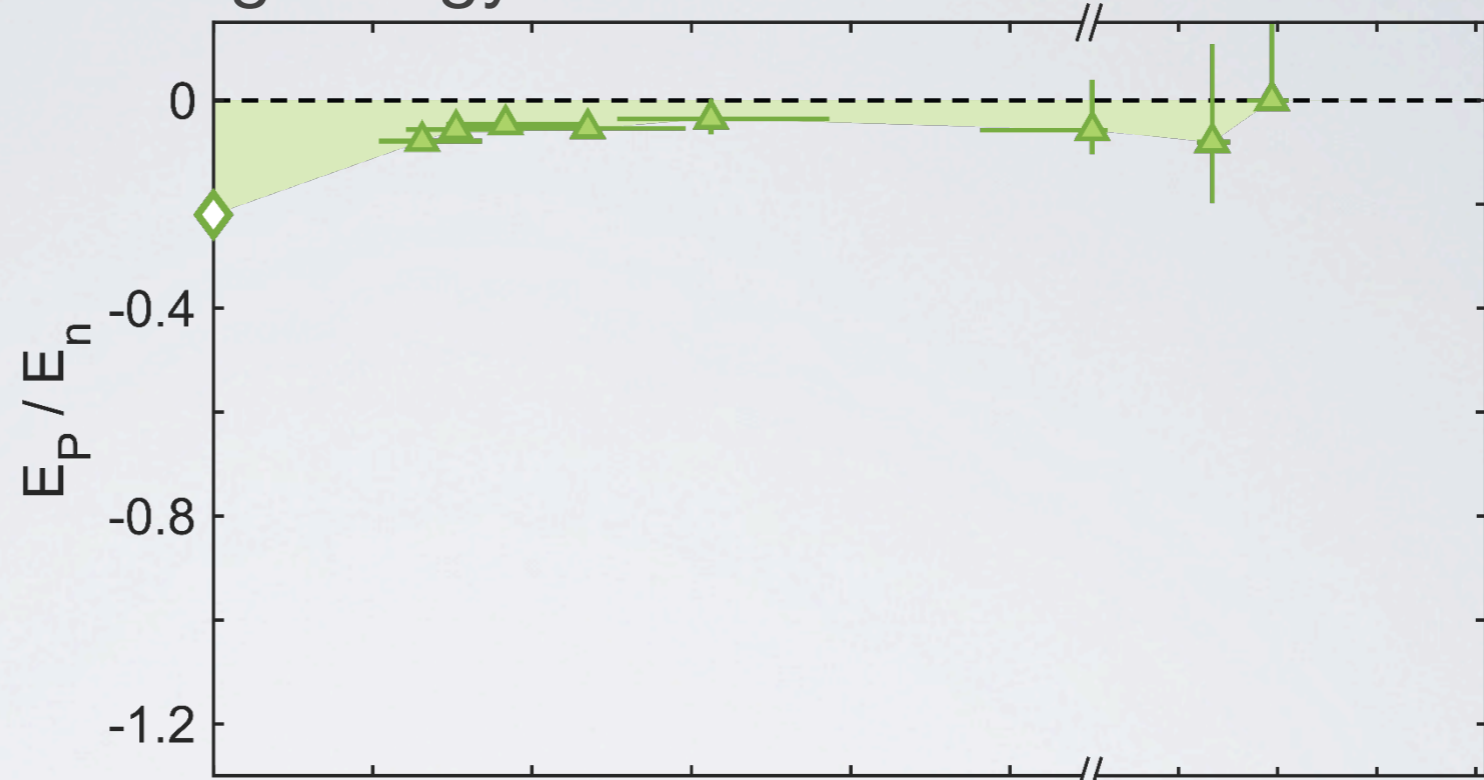


# The Bose polaron near quantum criticality

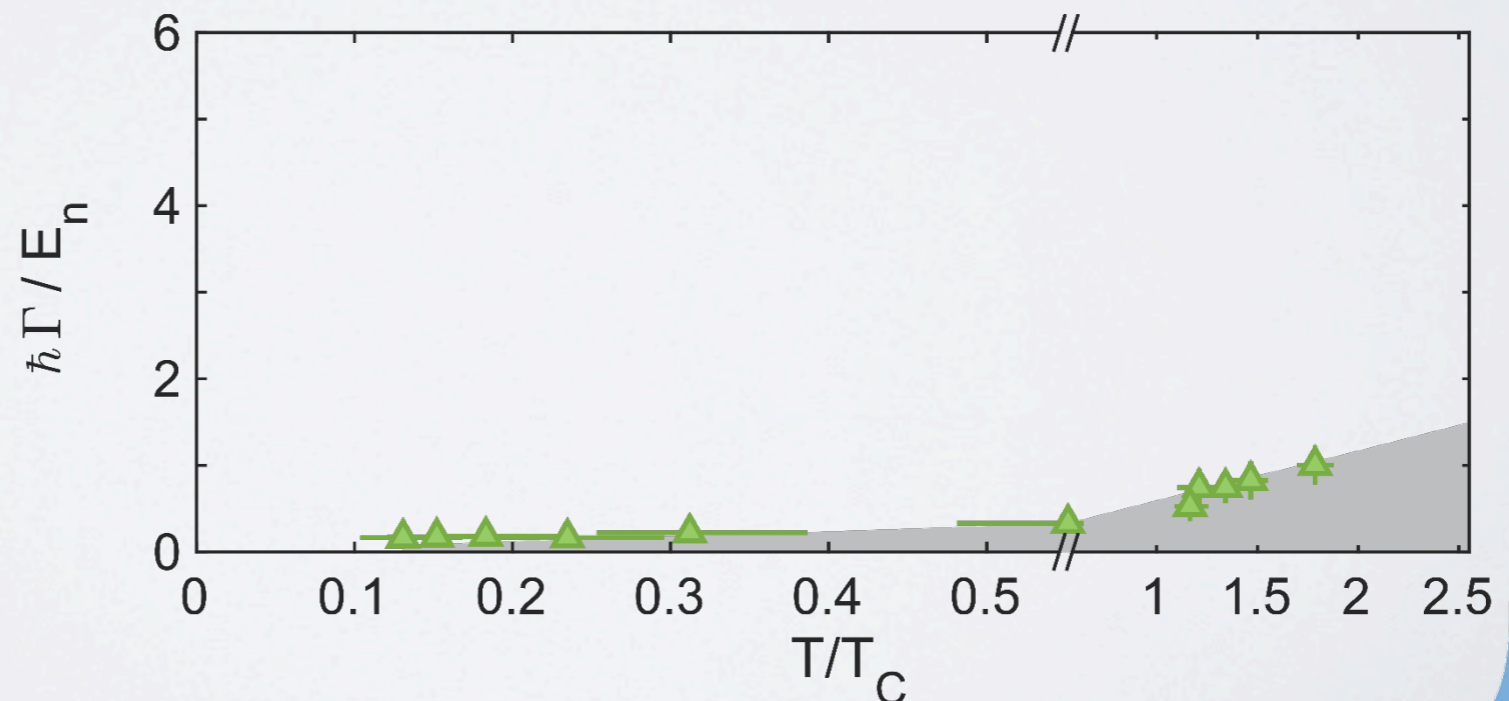


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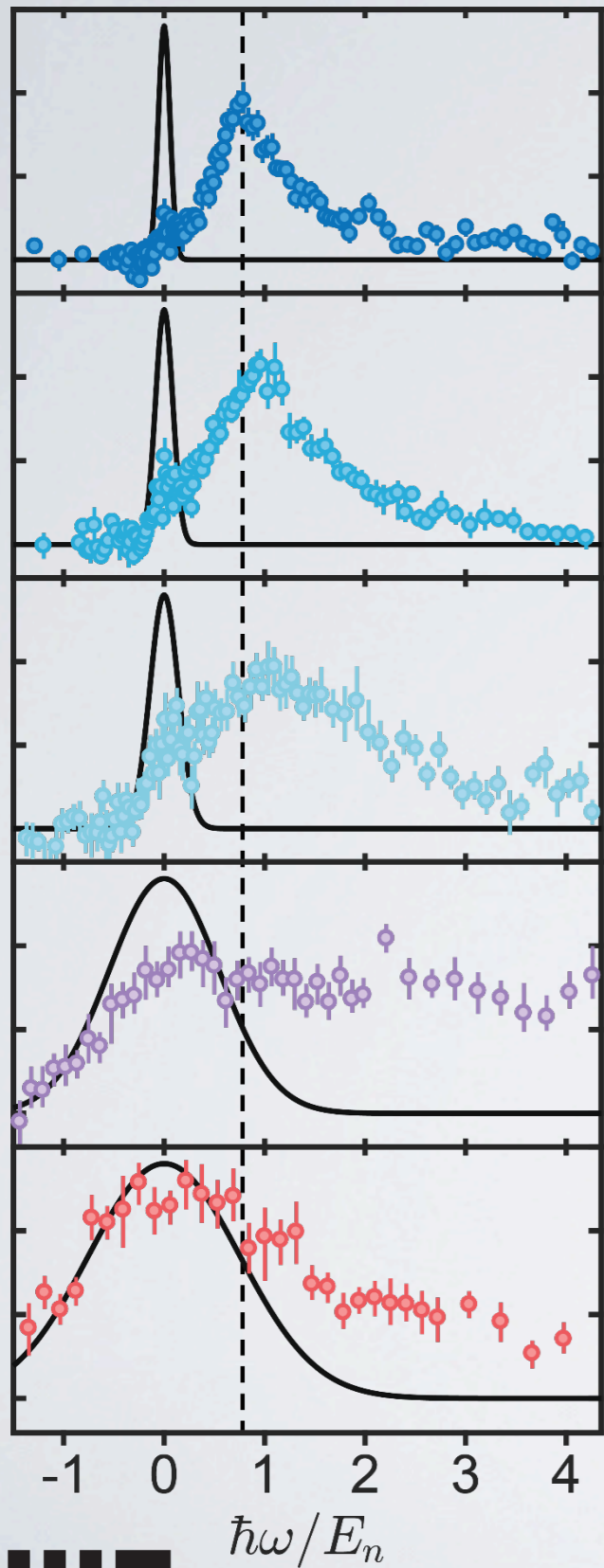


inverse lifetime



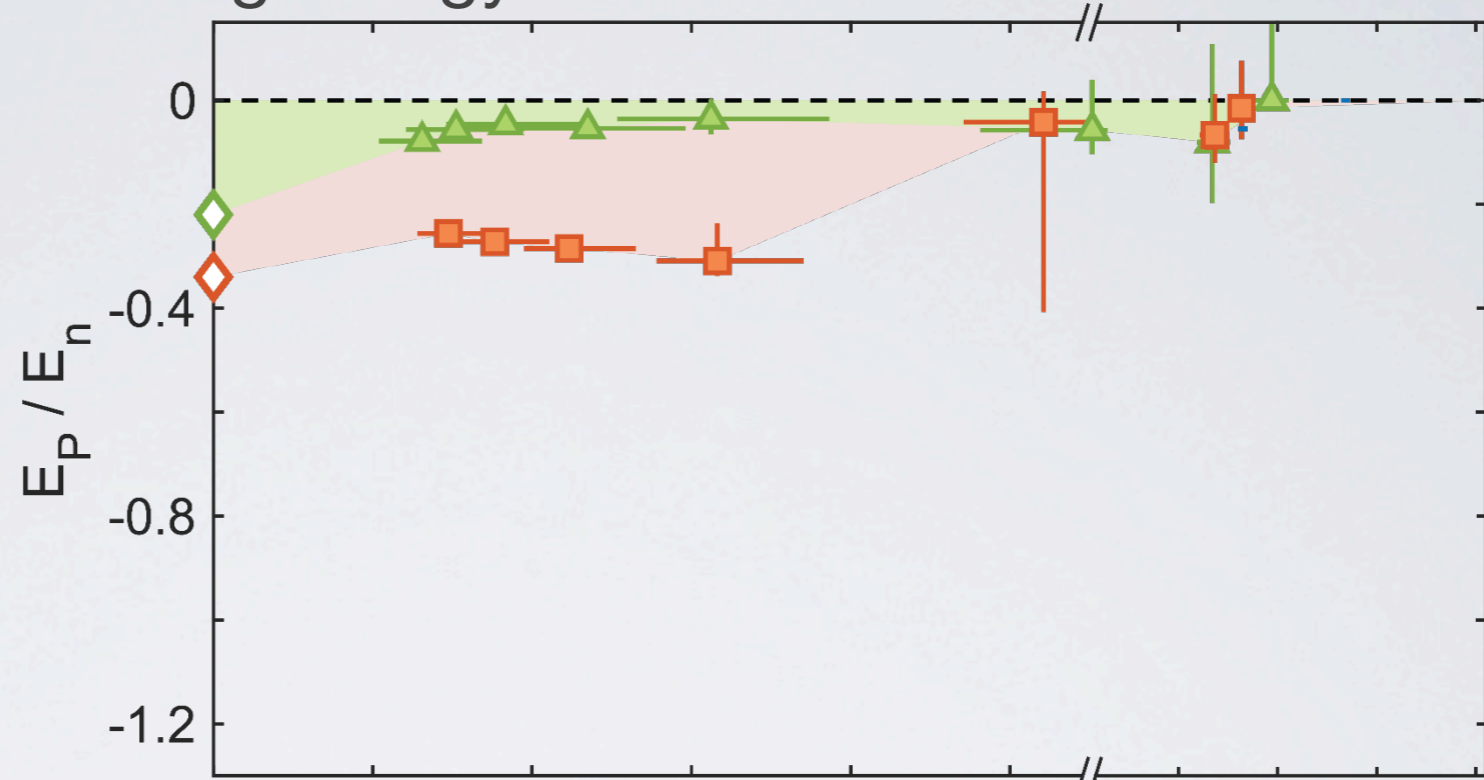


# The Bose polaron near quantum criticality

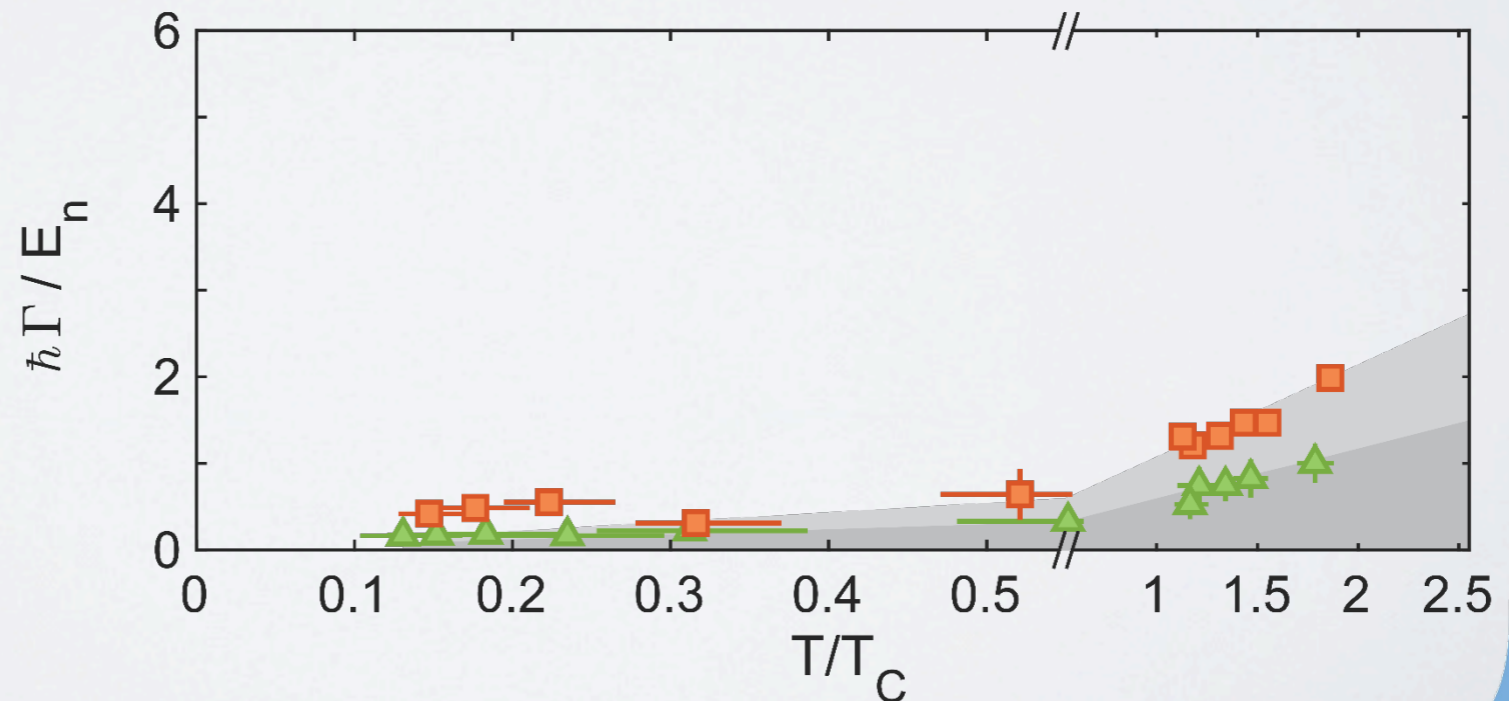


binding energy

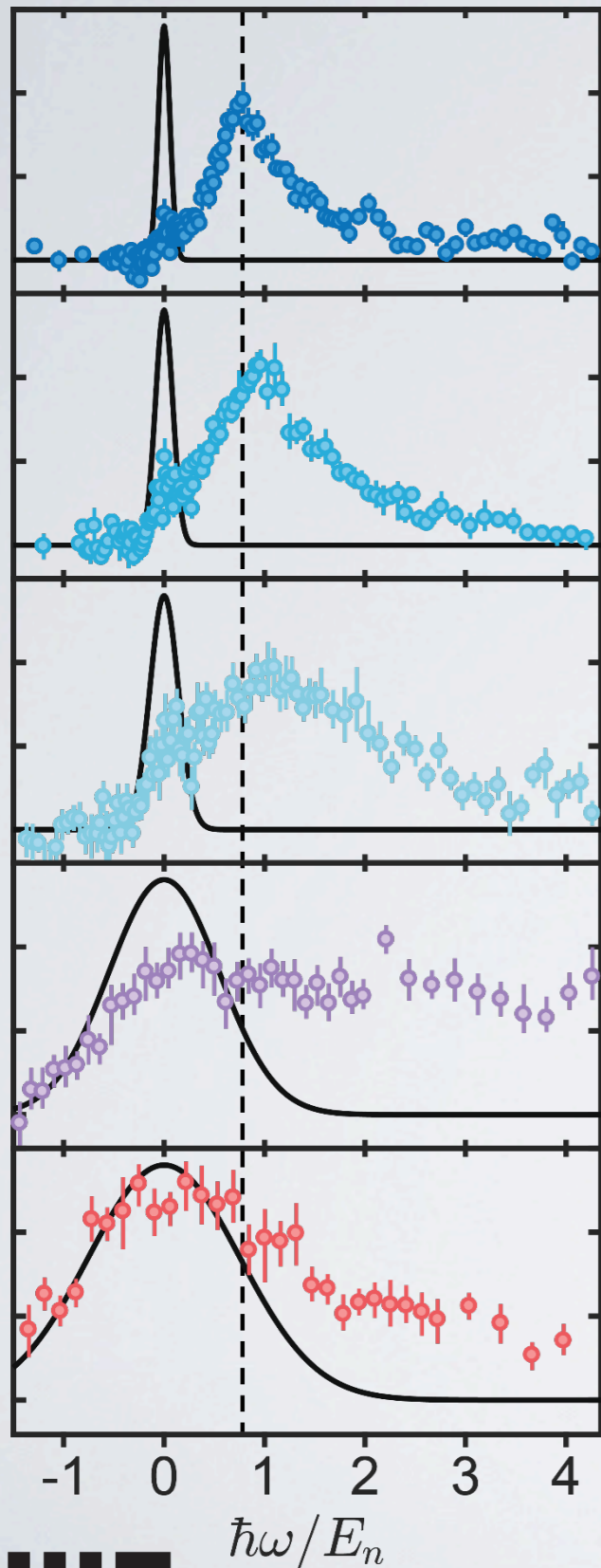
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inverse lifetime

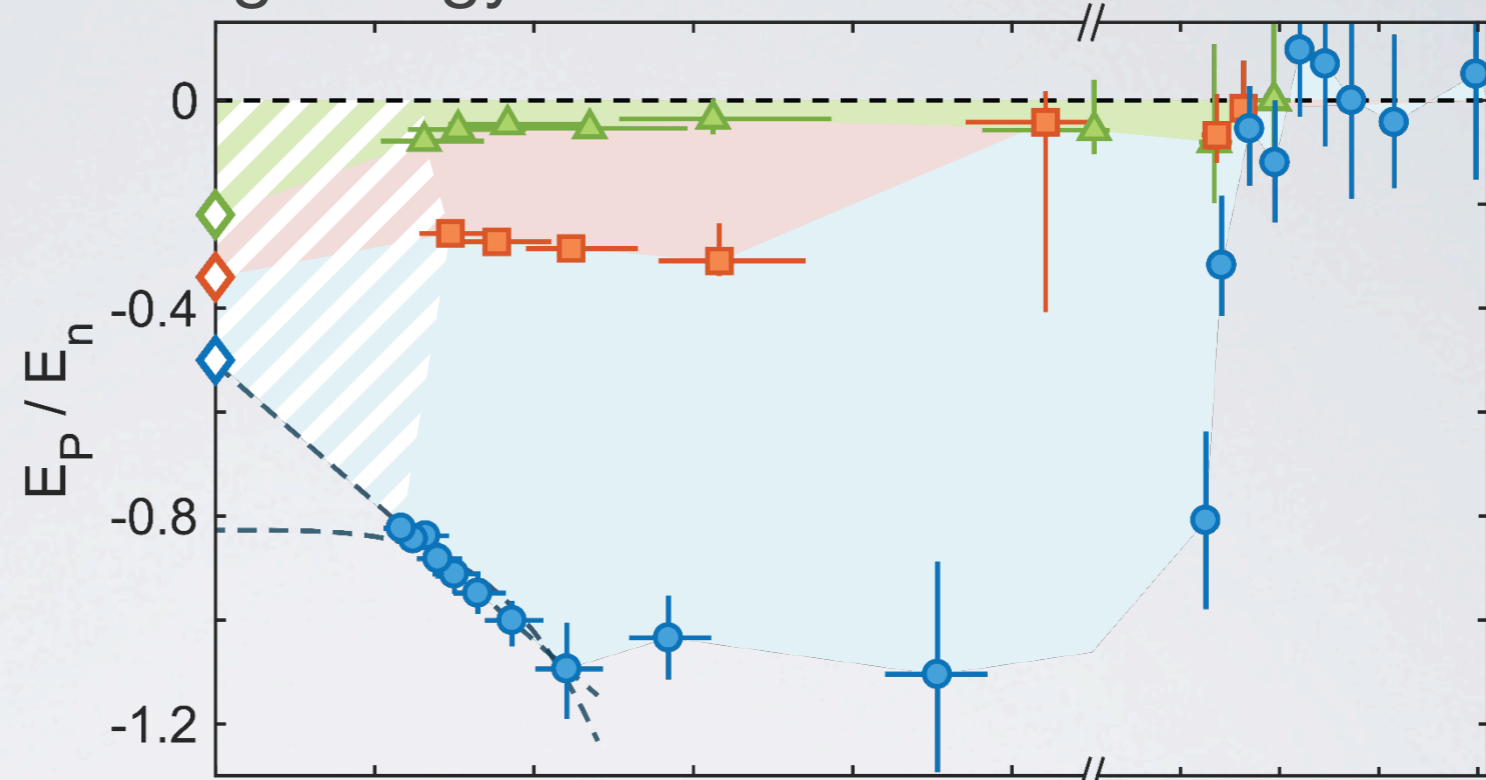


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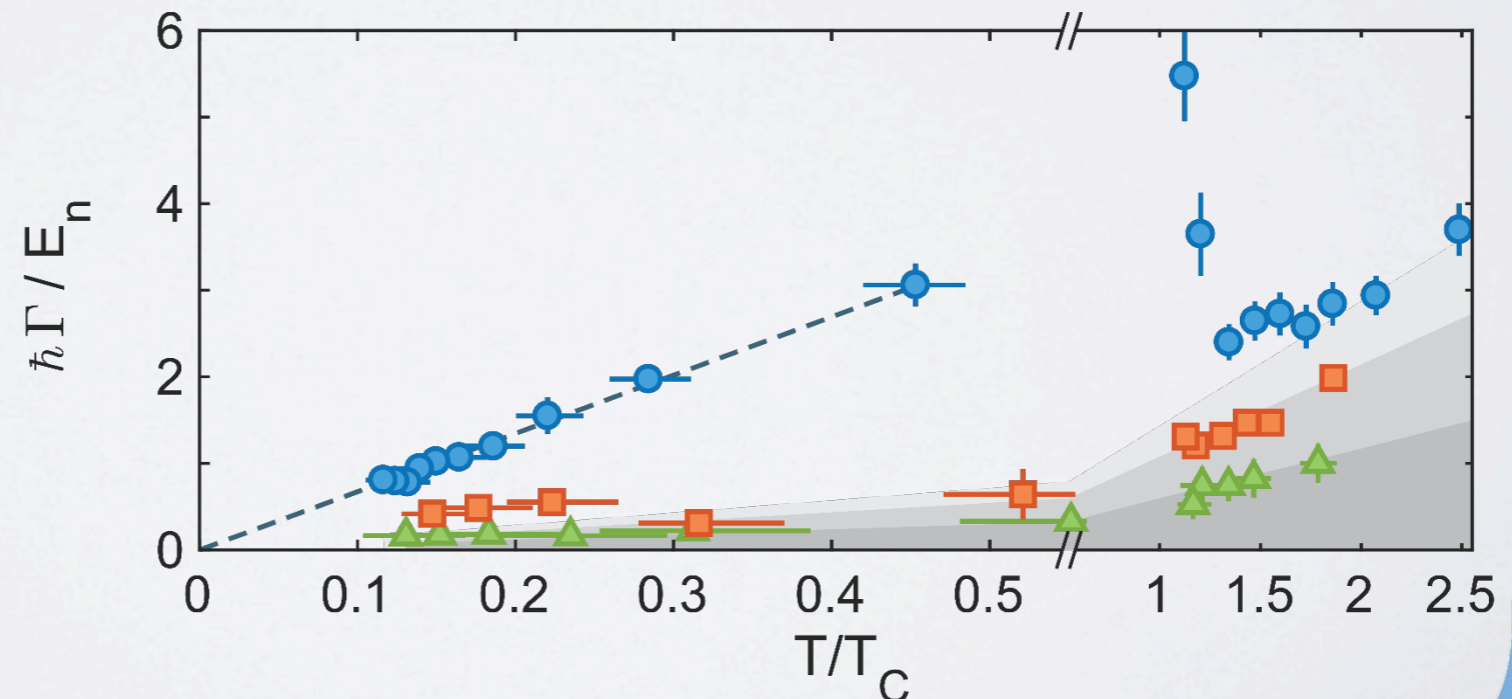


binding energy

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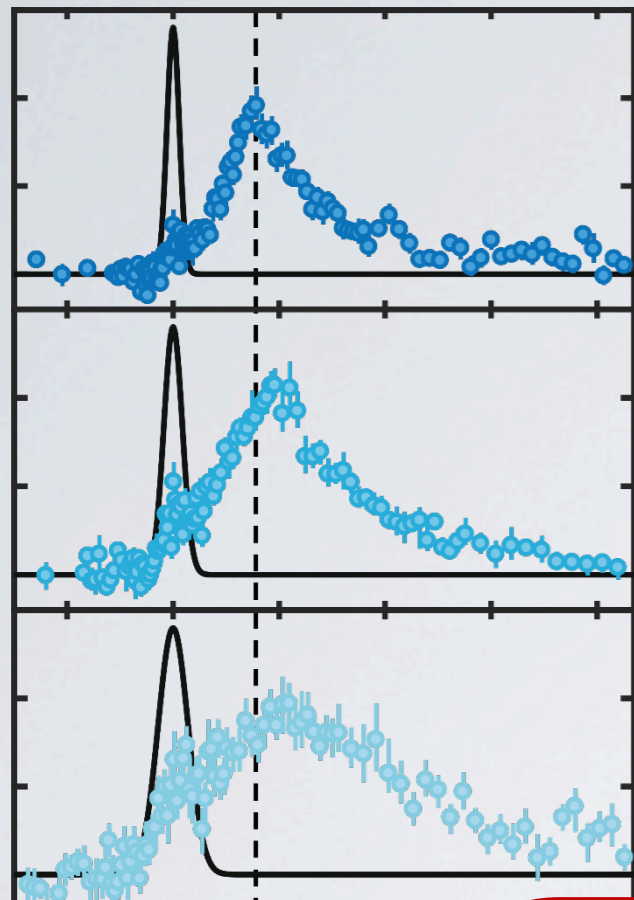


inverse lifetime



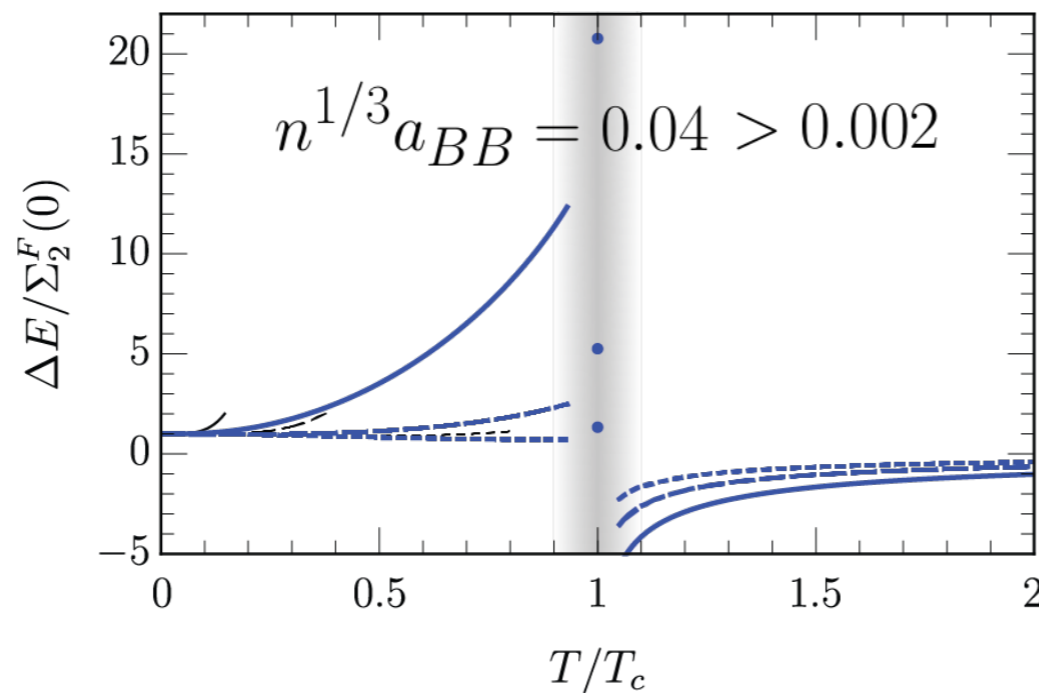
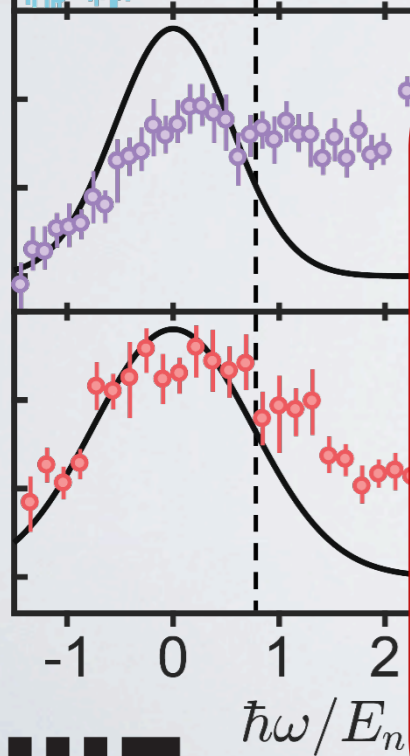
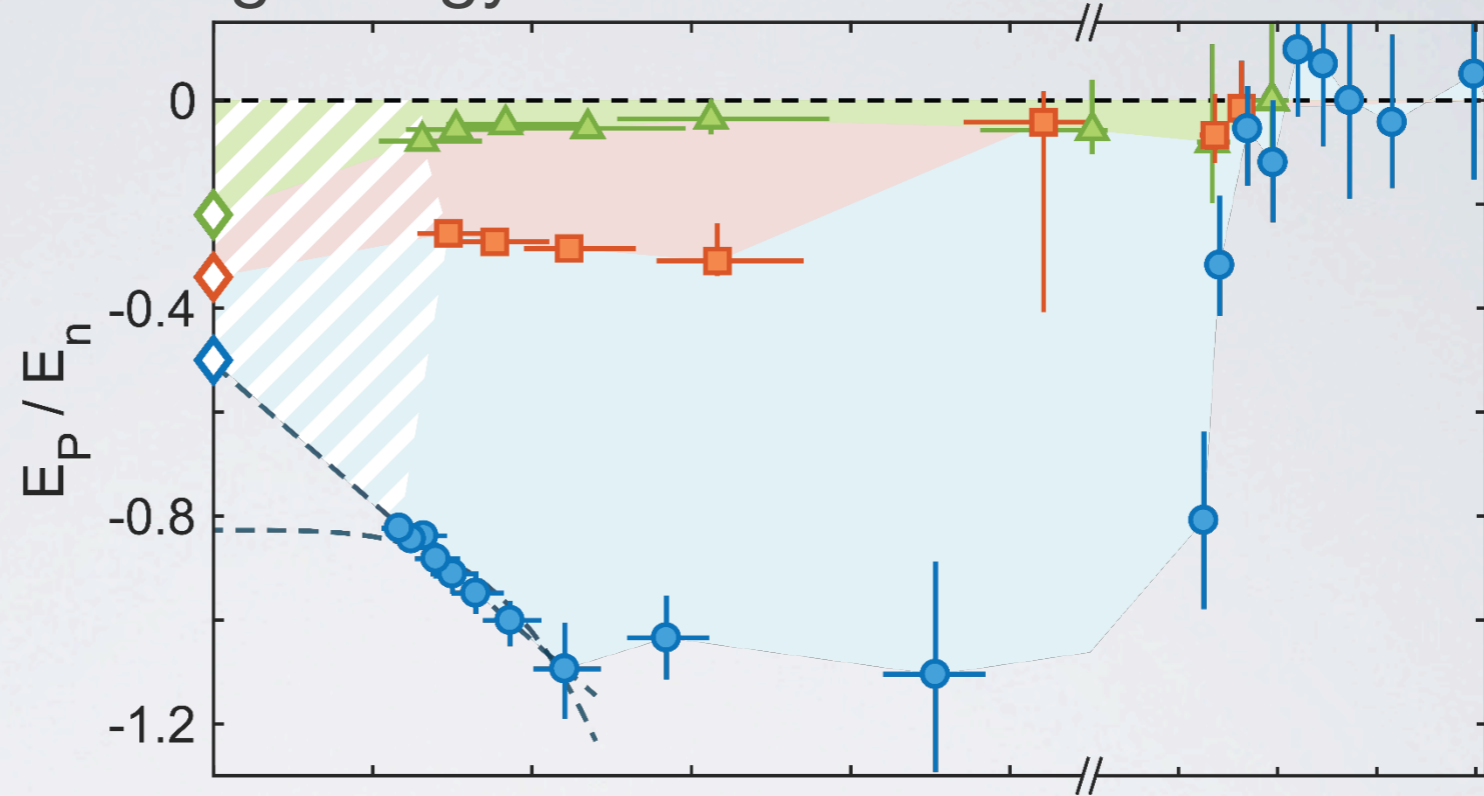


# The Bose polaron near quantum criticality

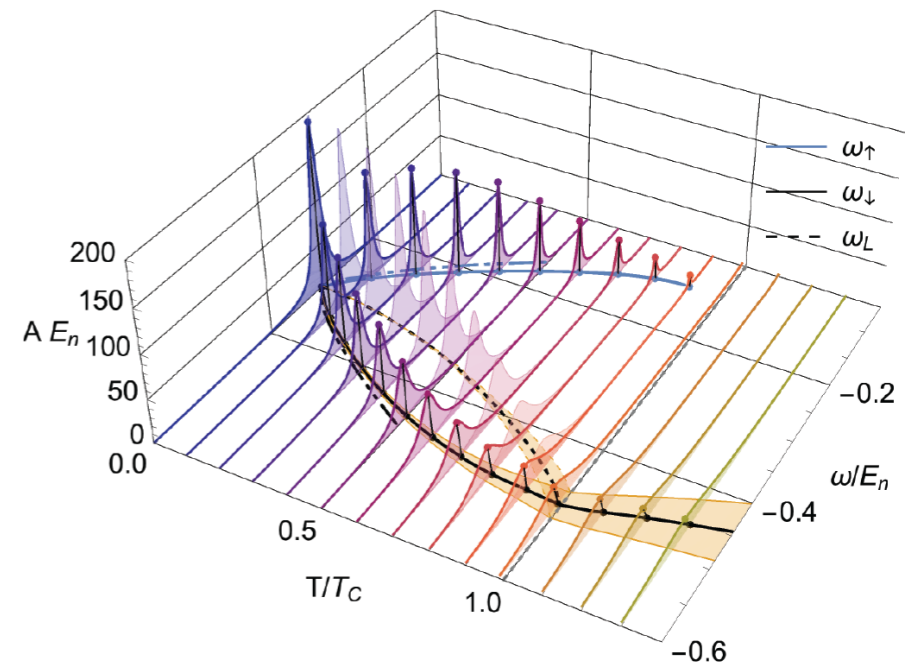


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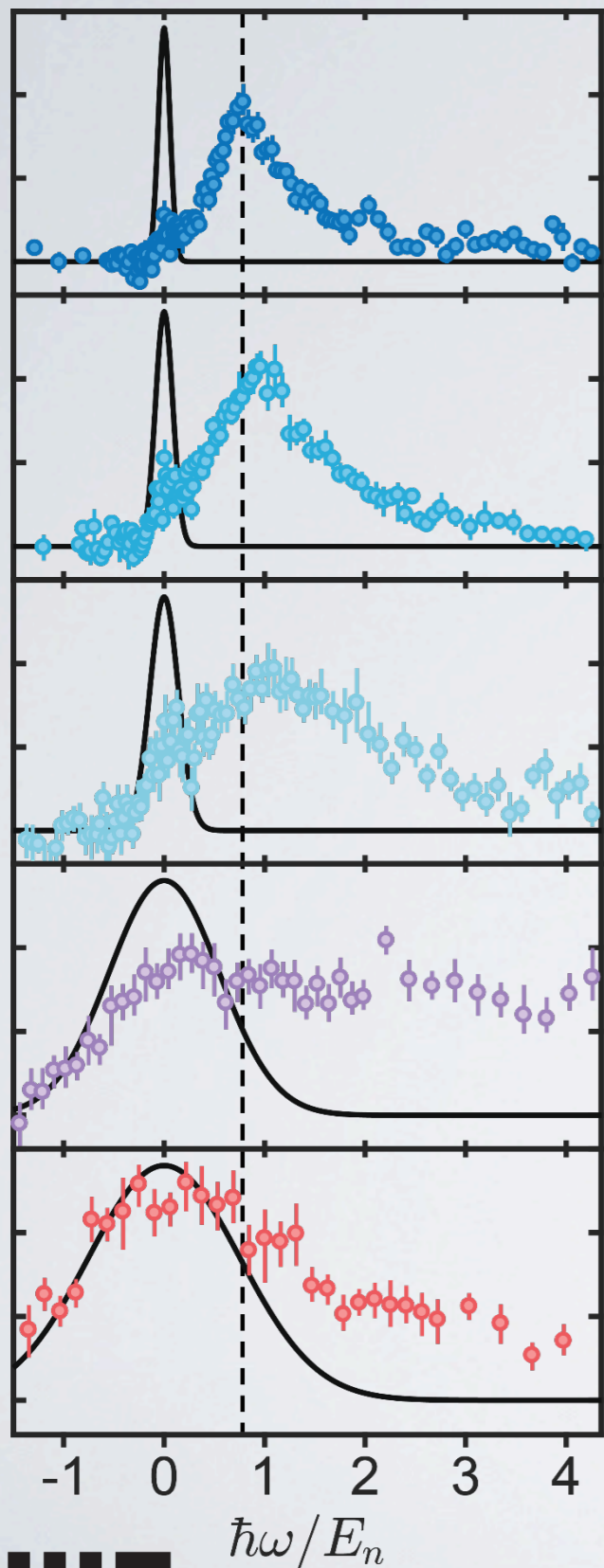
J. Levinsen *et al.*, PRA (2017)



N. Guenther *et al.*, PRL (2018)

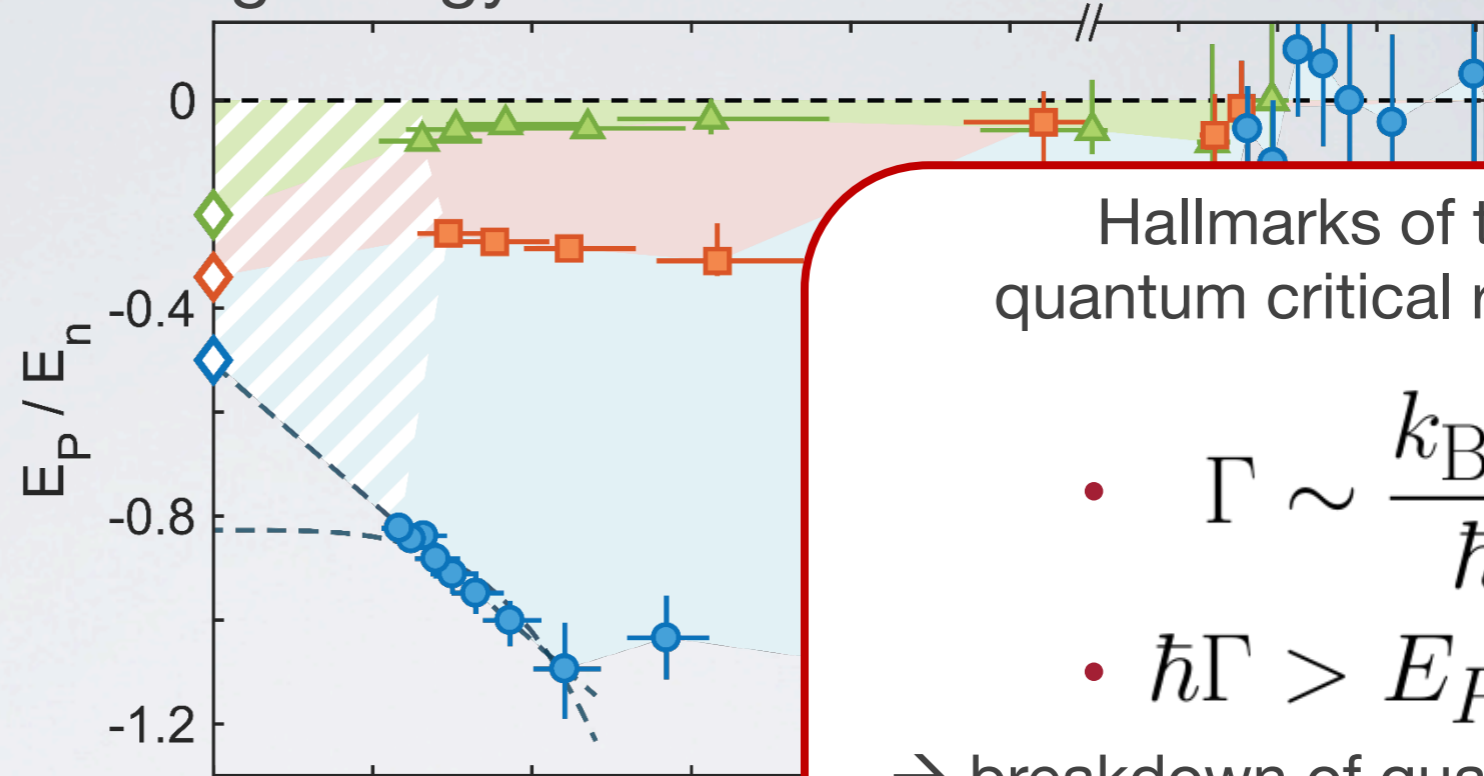


# The Bose polaron near quantum criticality



binding energy

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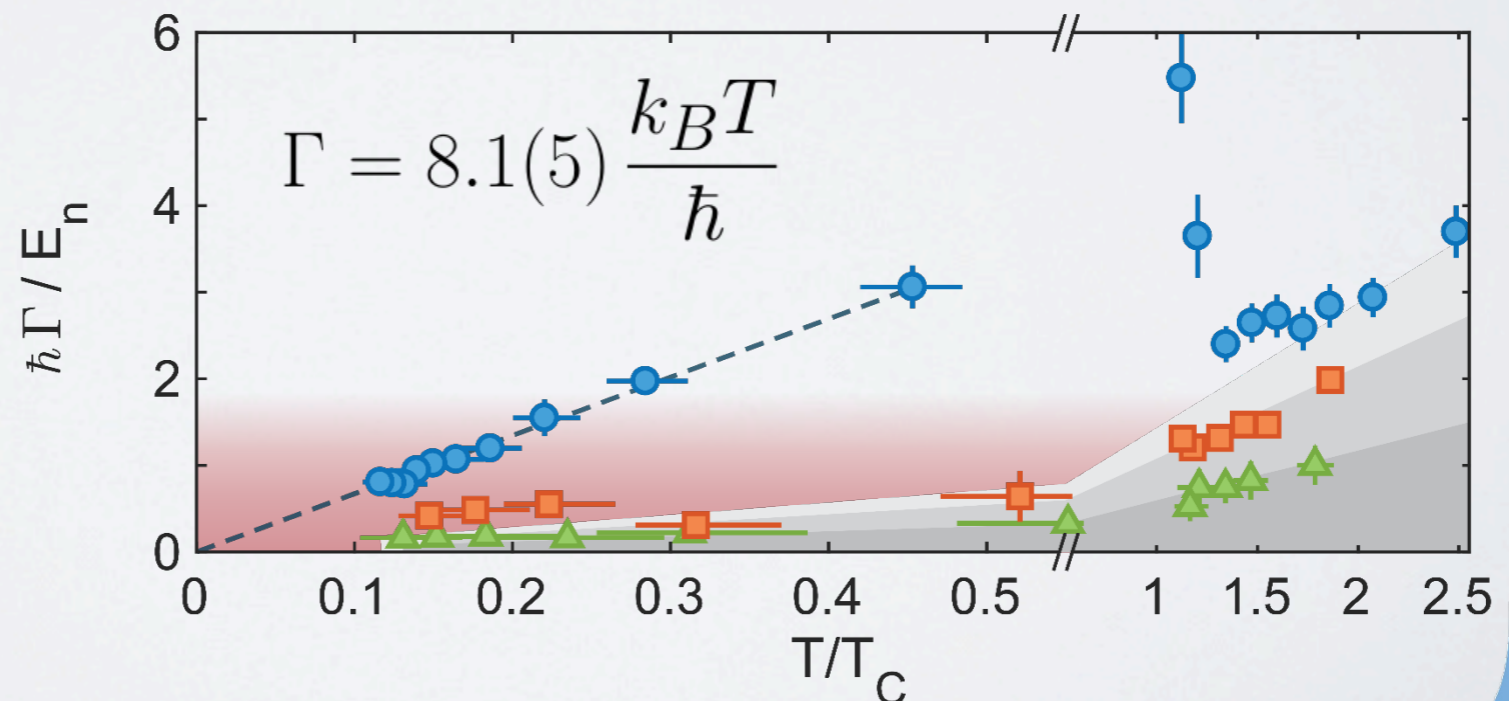
Hallmarks of the quantum critical regime

- $\Gamma \sim \frac{k_B T}{\hbar}$

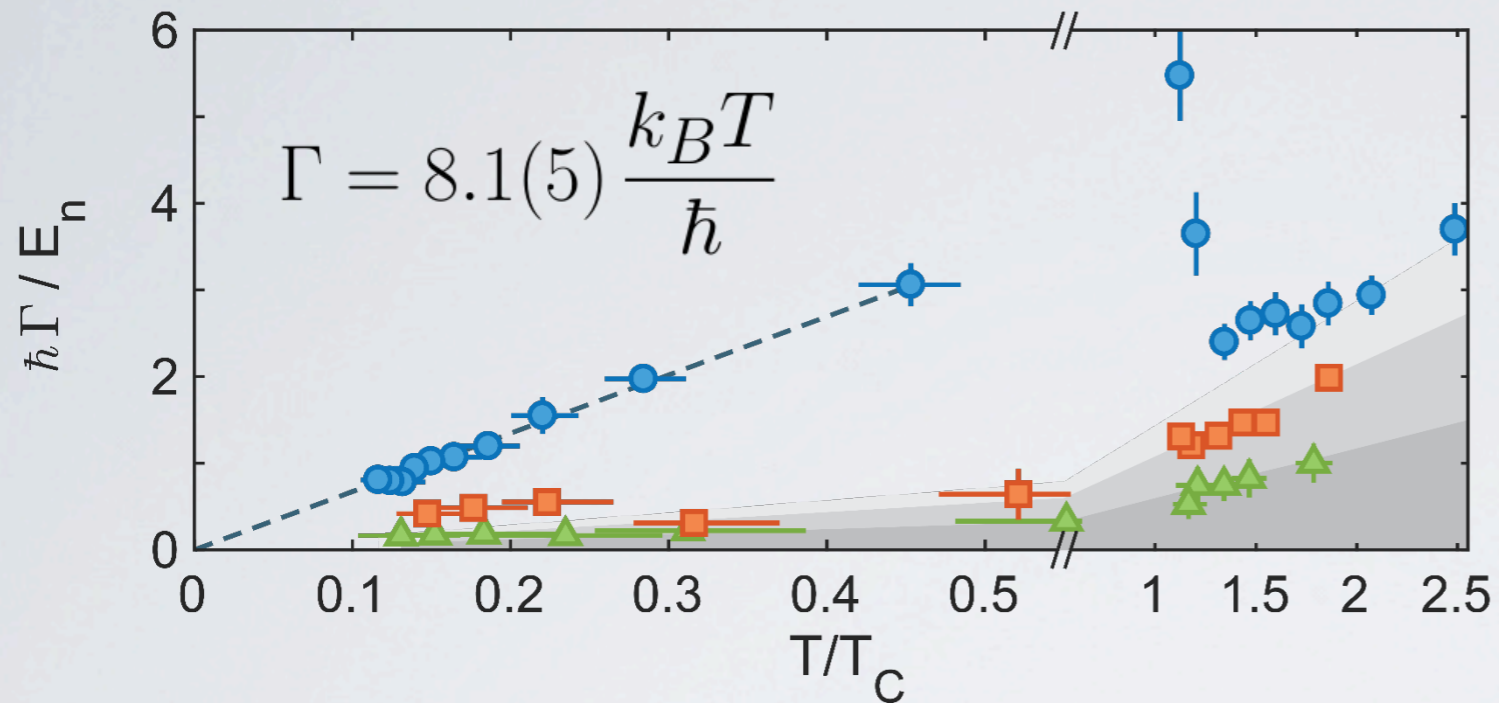
- $\hbar\Gamma > E_p$

→ breakdown of quasiparticle

inverse lifetime



# The Bose polaron near quantum criticality



Simple estimate of the Bose polaron's decay rate:

- BEC dresses the impurity
- Polaron scatters with thermally excited Bosons

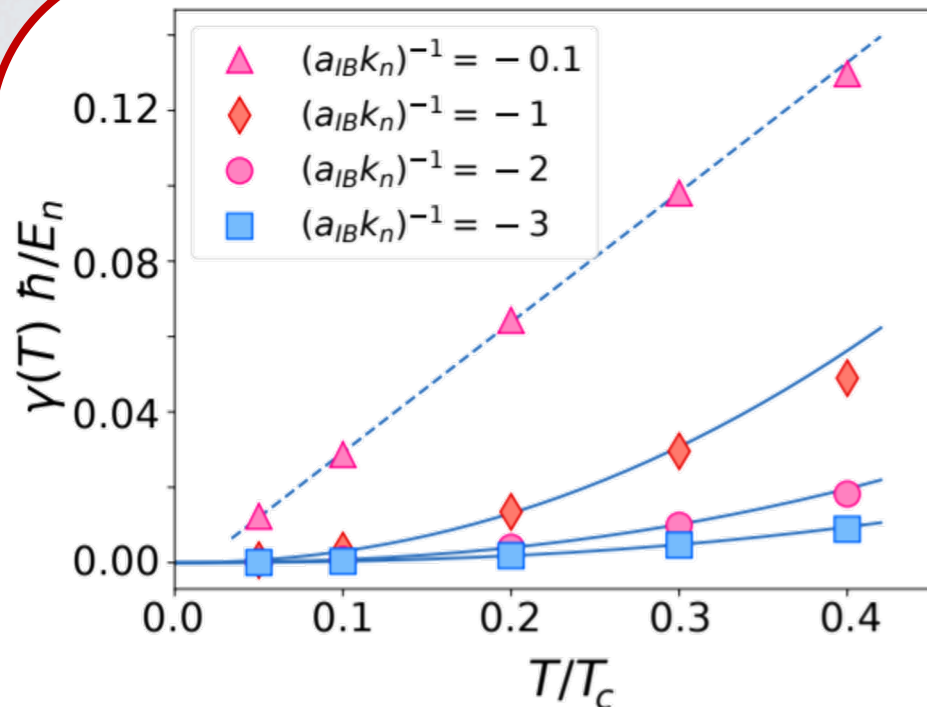
$$\Gamma = n_{\text{th}} \sigma v_{\text{rel}}$$

$$\sim \frac{1}{\lambda^3} \lambda^2 \sqrt{\frac{k_B T}{m}}$$

$$\sim \frac{k_B T}{\hbar}$$

De-Broglie wavelength:

$$\lambda \sim \frac{1}{\sqrt{T}}$$

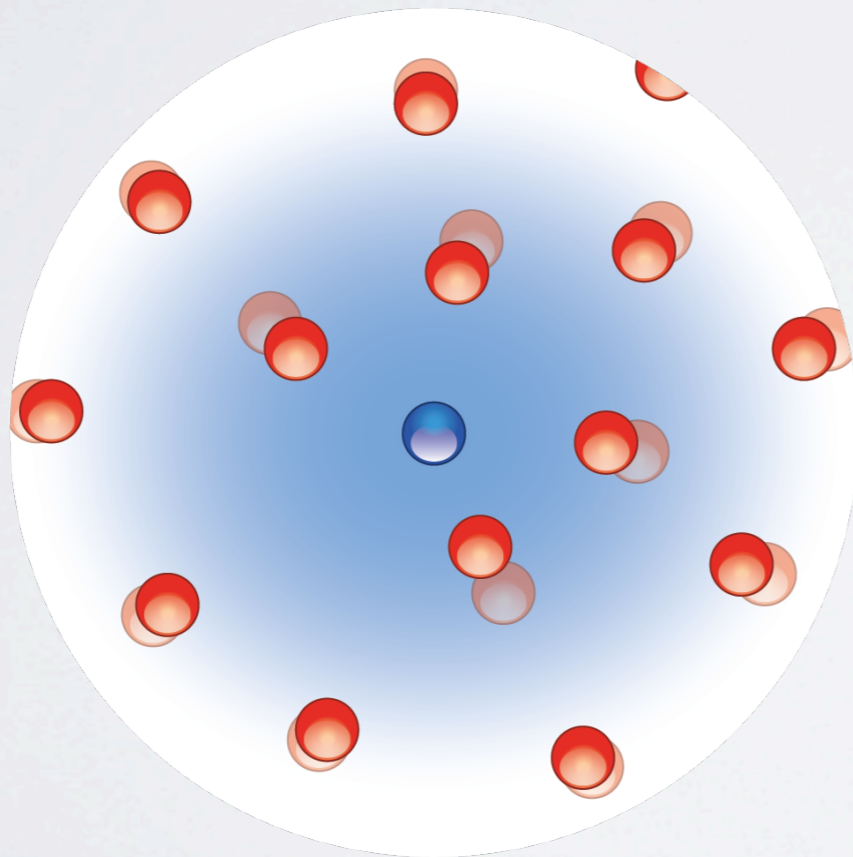
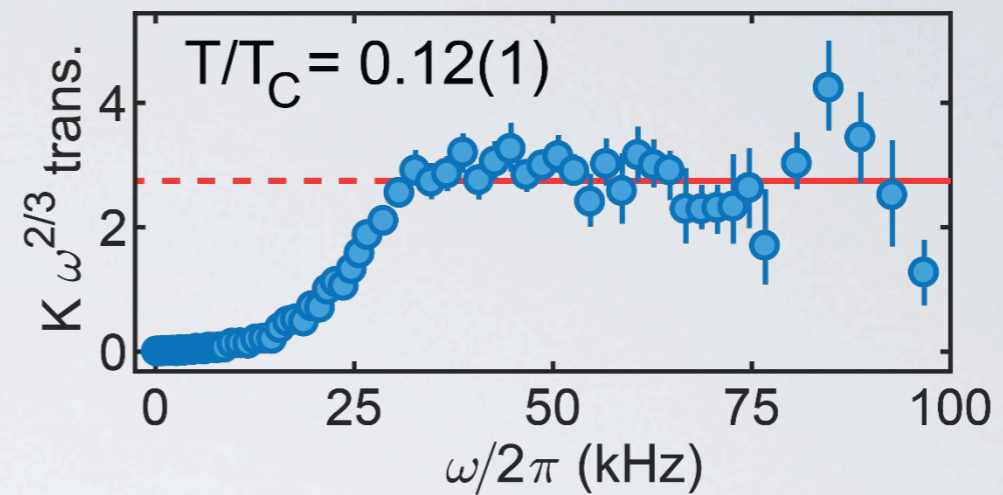
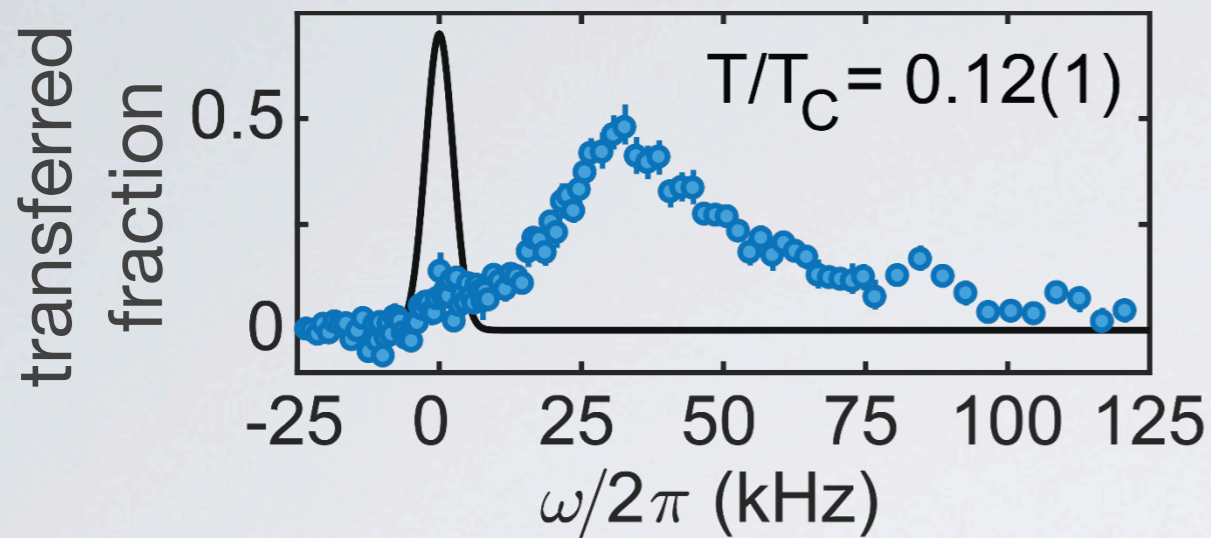


D. Dzsojtjan,  
R. Schmidt,  
M. Fleischhauer.  
arXiv:1909.12856

“Close to unitary interactions a linear temperature dependence is found (dashed), linked to quantum critical behavior [1]”



# Short-range correlations - The Bose polaron's contact

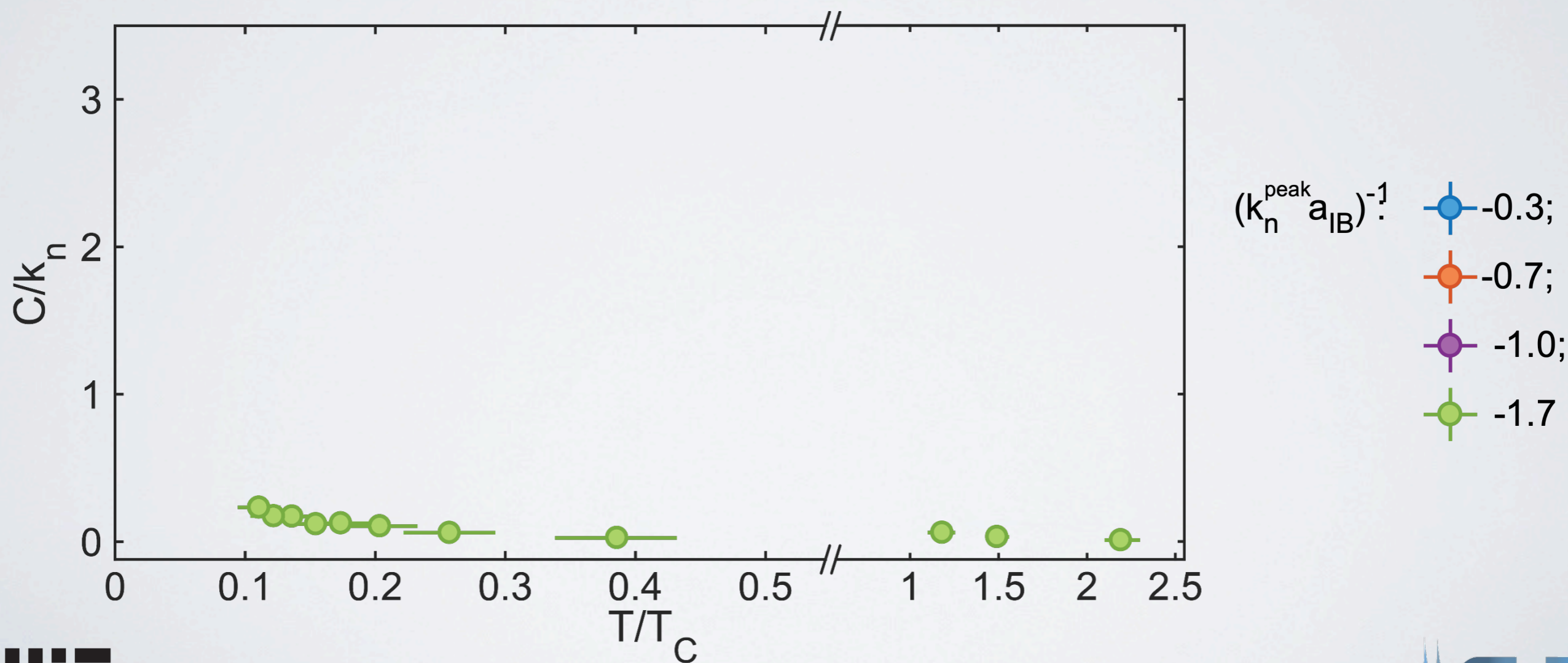
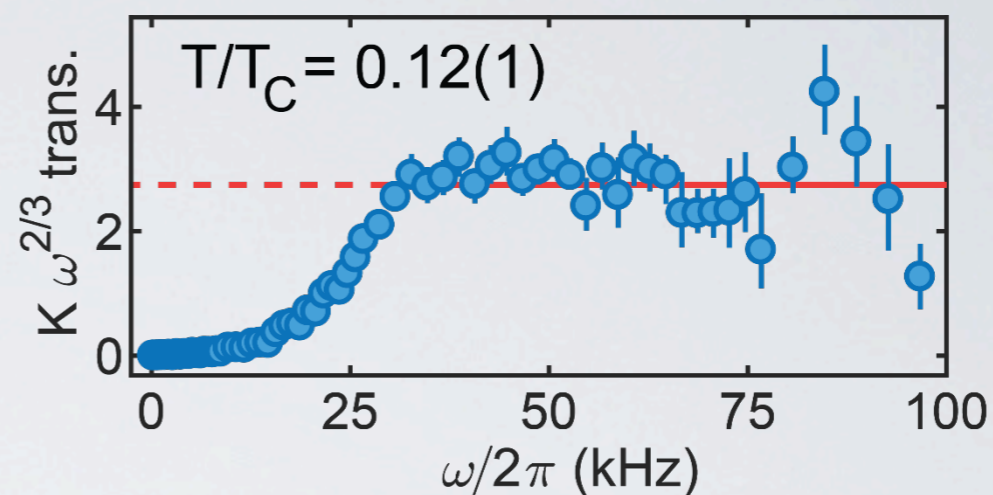
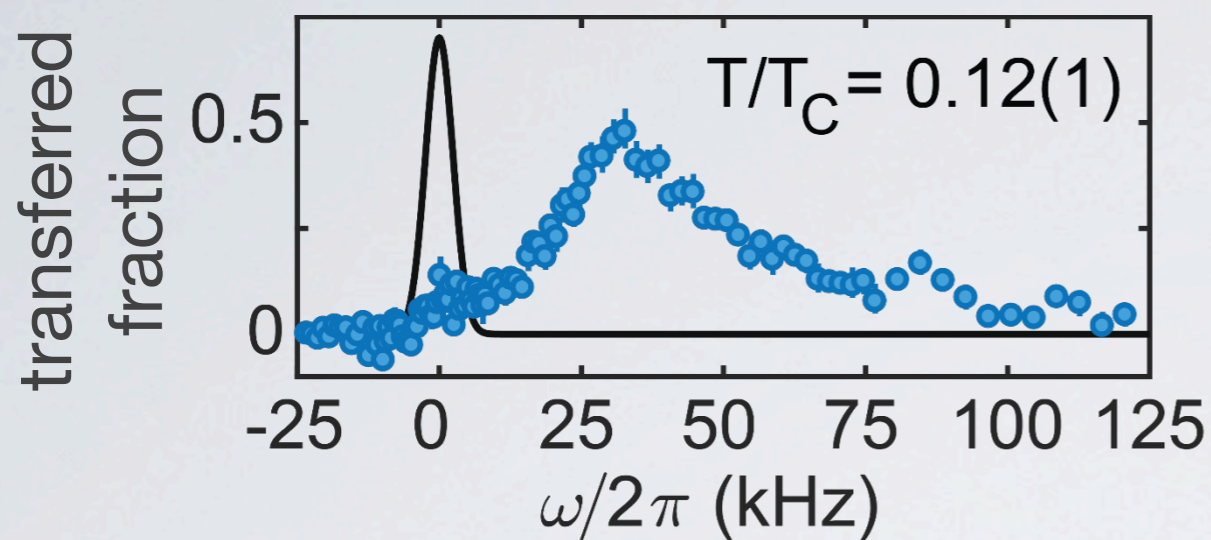


$$C = \frac{4\pi m}{\hbar^2} \frac{\partial E}{\partial(a^{-1})} \Big|_{S,N,V}$$

$$I(\omega) \xrightarrow{\omega \rightarrow \infty} \frac{\Omega_p \sigma}{8\sqrt{\pi}} \sqrt{\frac{\hbar}{2\mu}} \frac{C}{\omega^{3/2}}$$

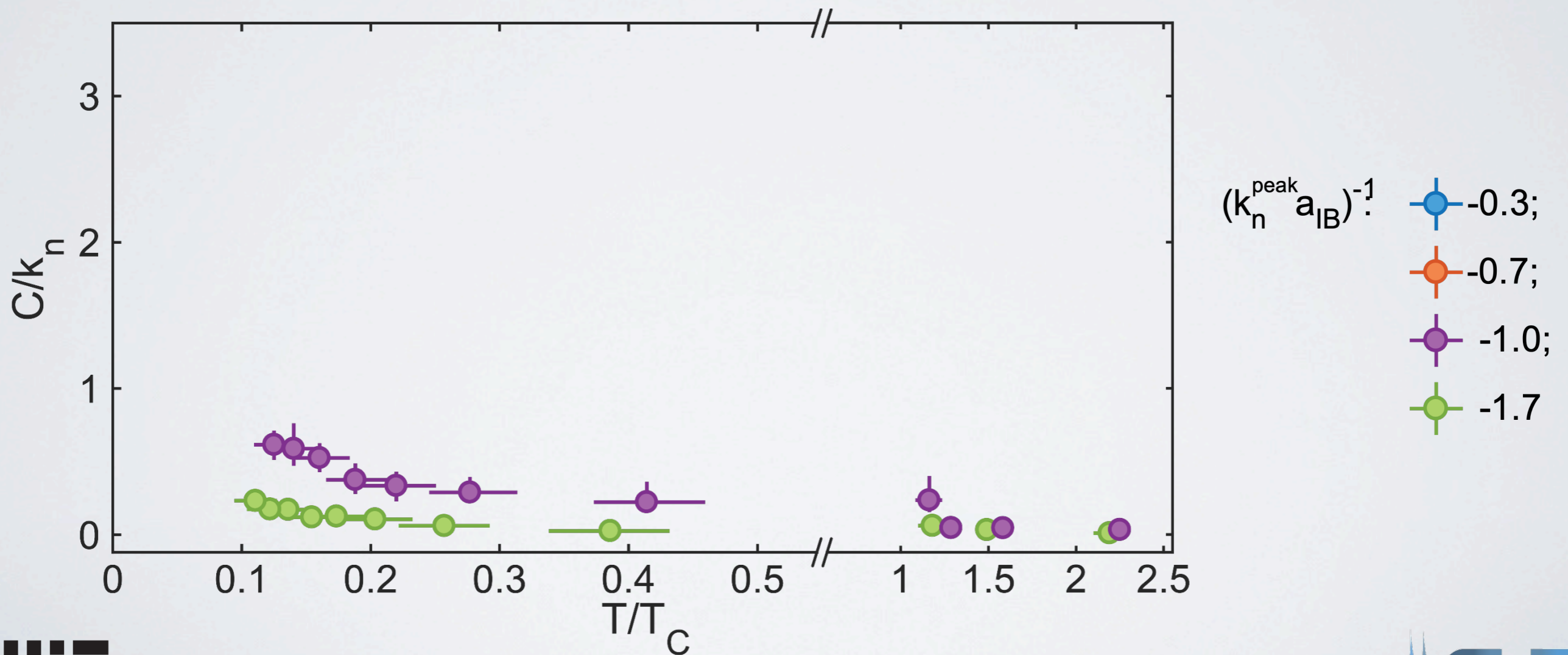
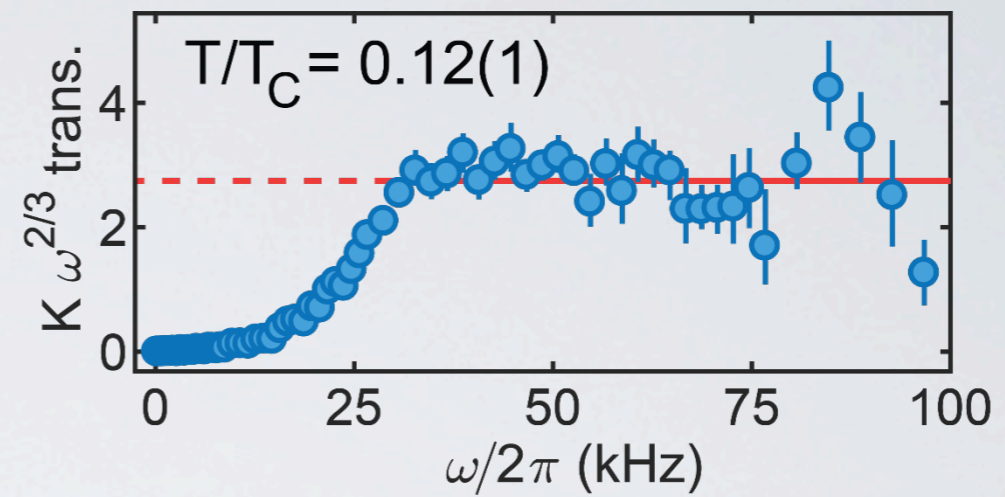
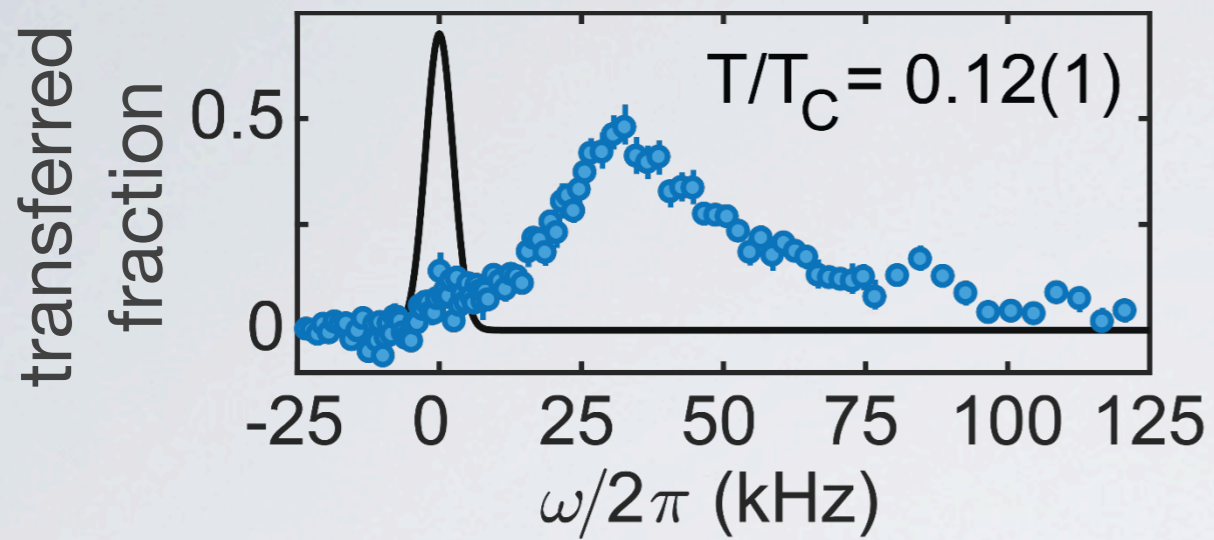
S. Tan, *Annals of Physics* (2008)  
E. Braaten, arXiv:1008.2922 (2010)

# Short-range correlations - The Bose polaron's contact

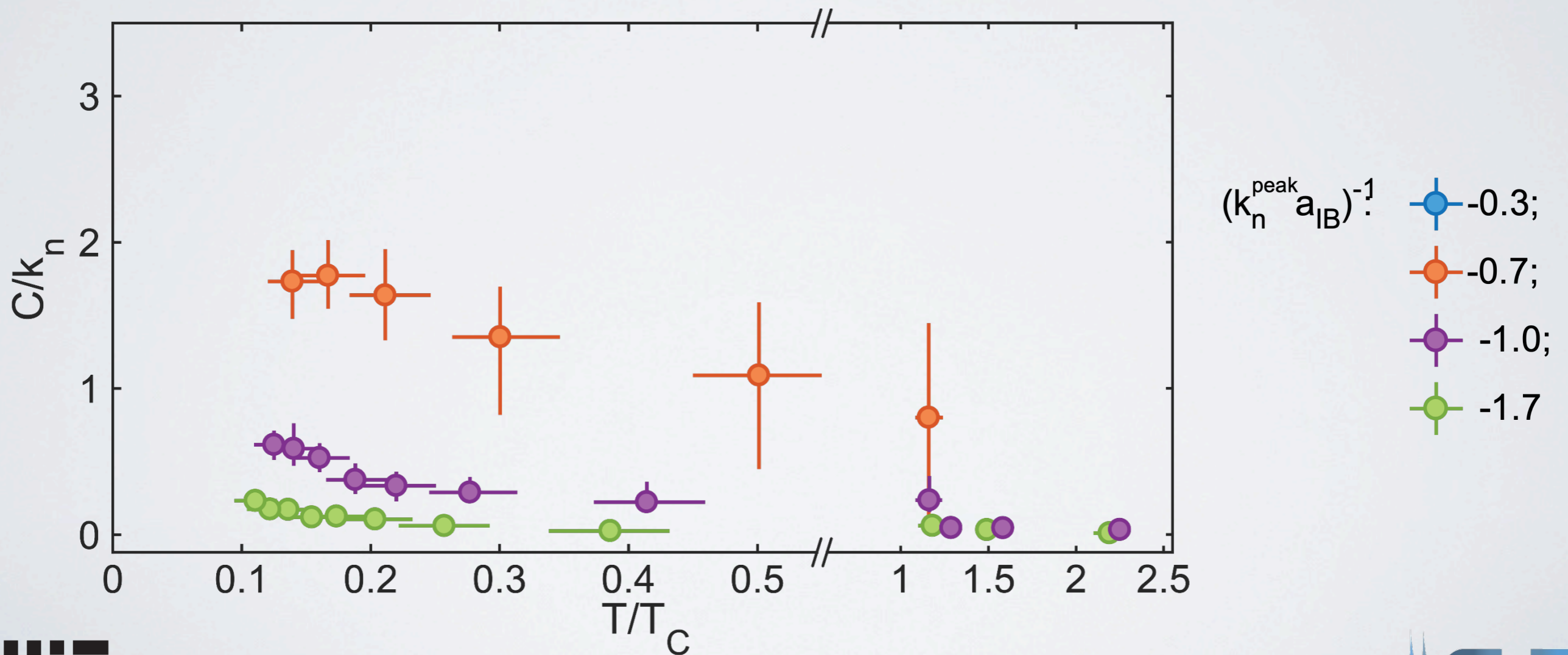
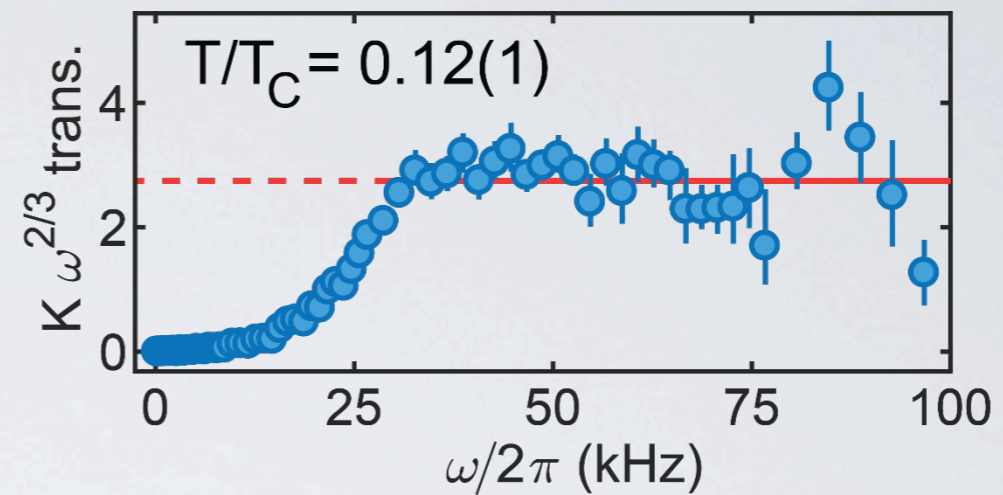
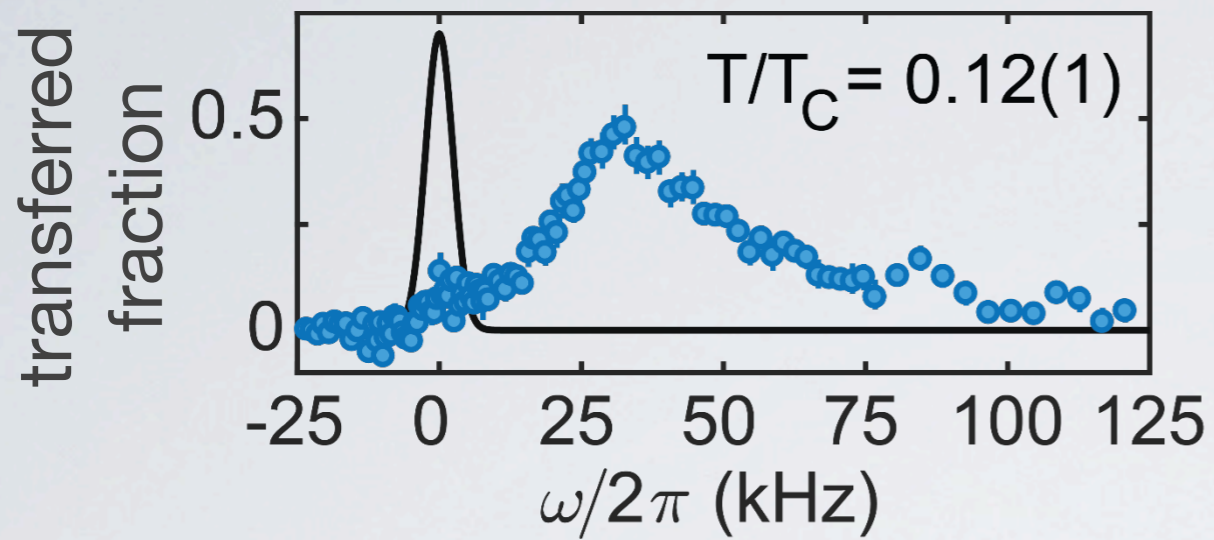




# Short-range correlations - The Bose polaron's contact

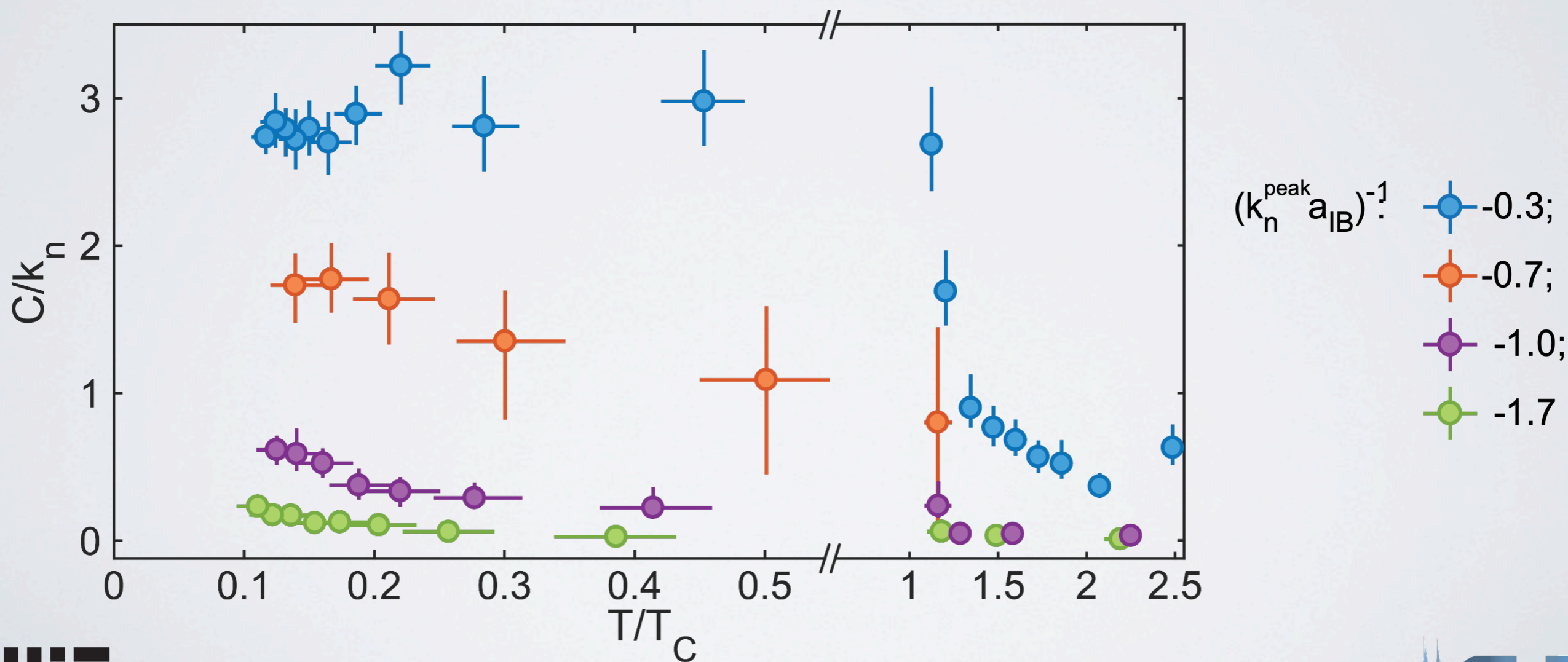
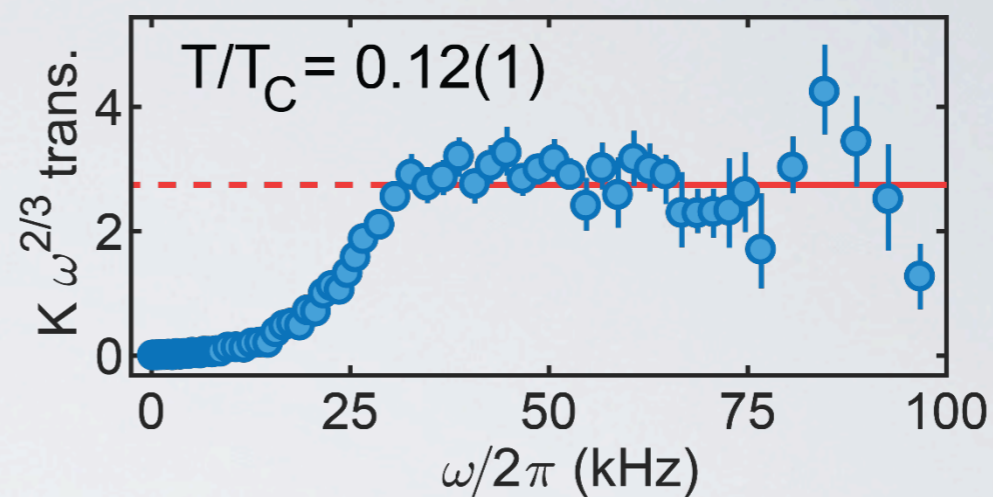
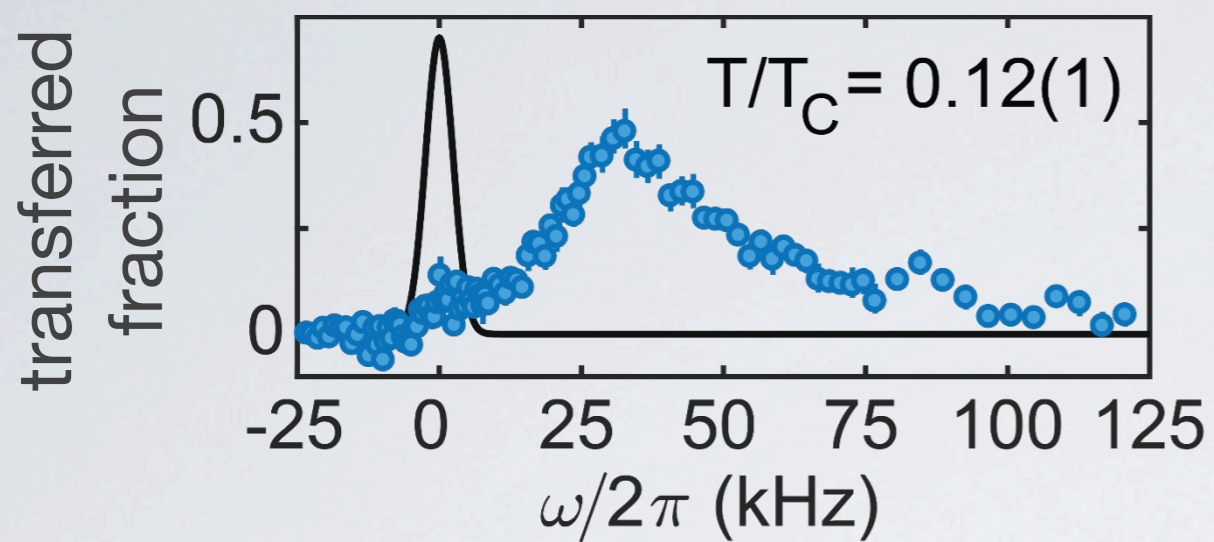


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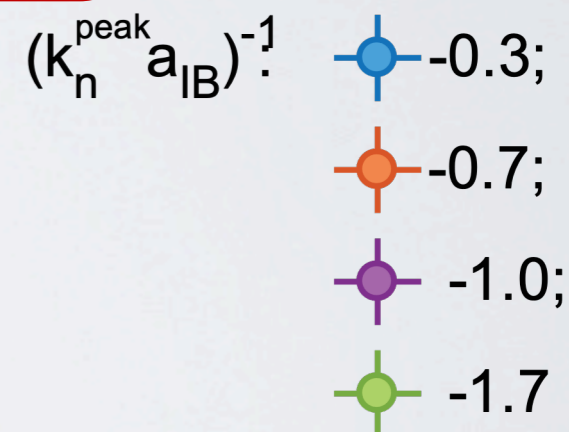
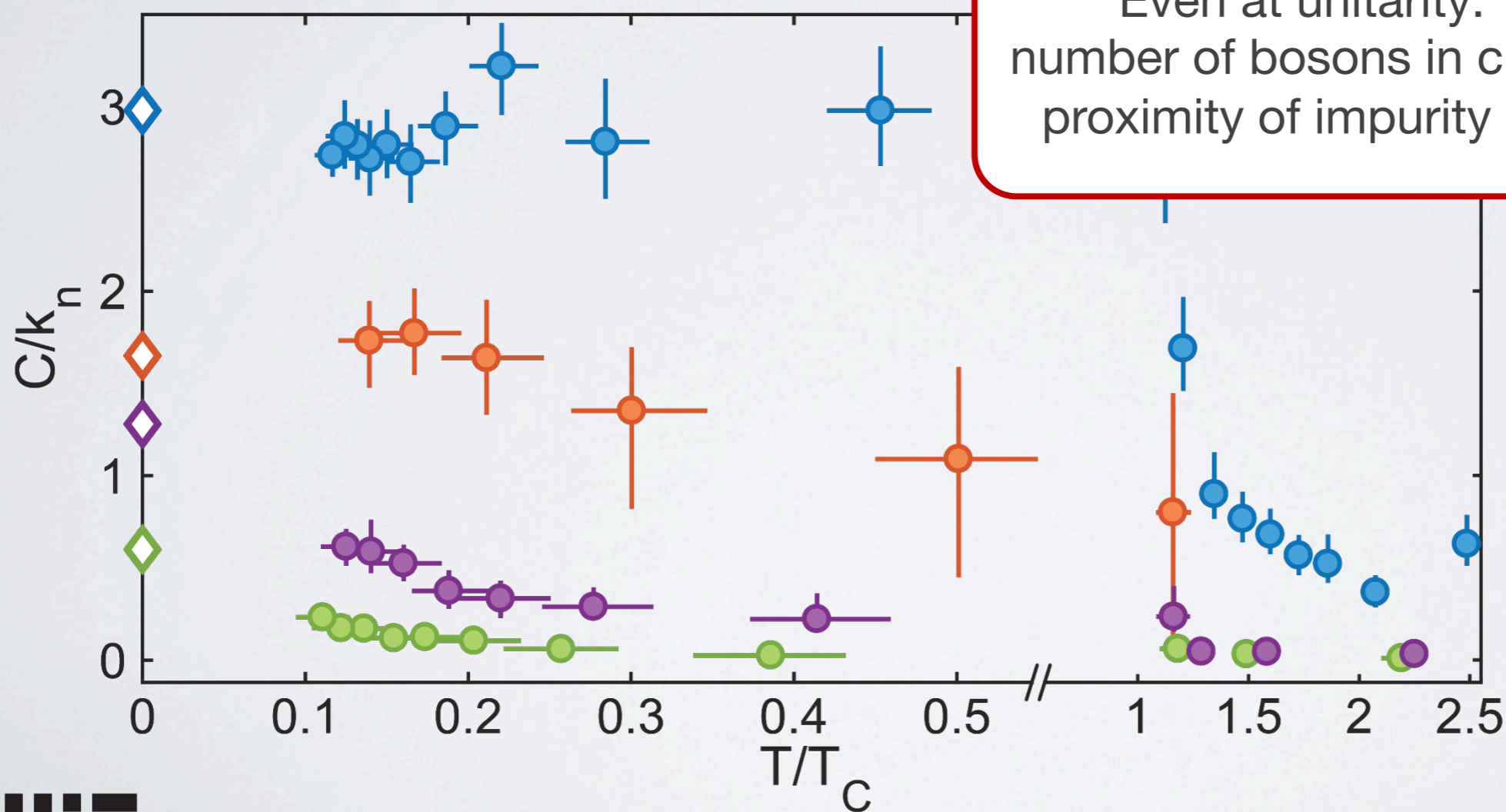
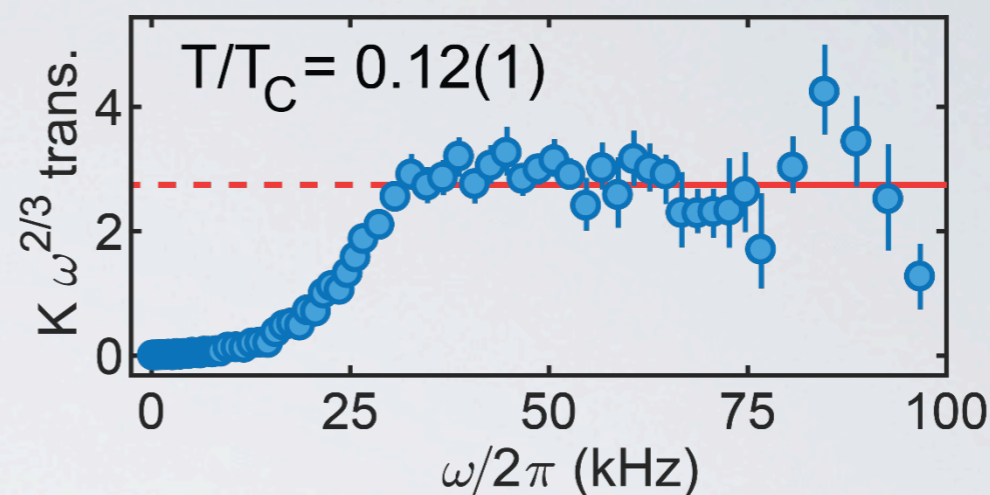
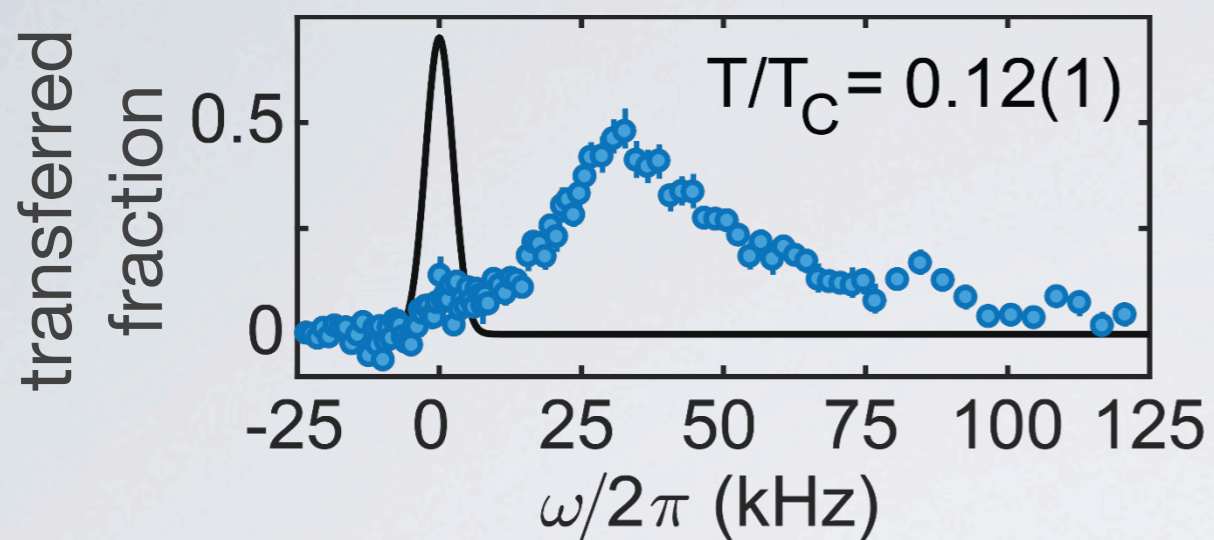




# Short-range correlations - The Bose polaron's contact

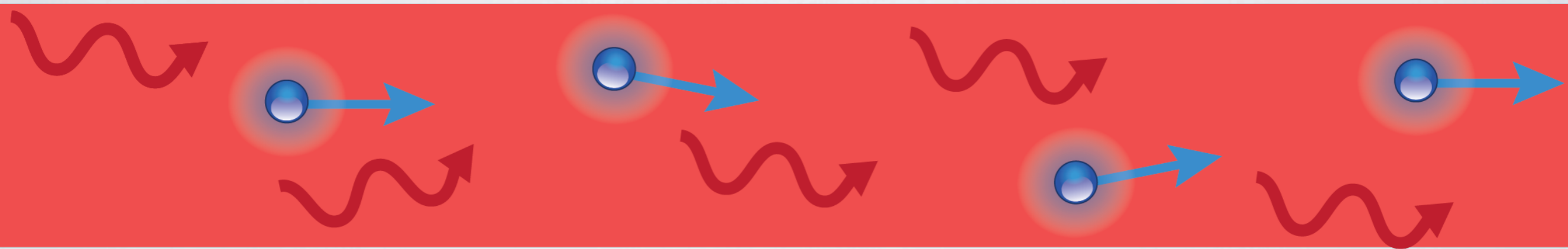


# Short-range correlations - The Bose polaron's contact





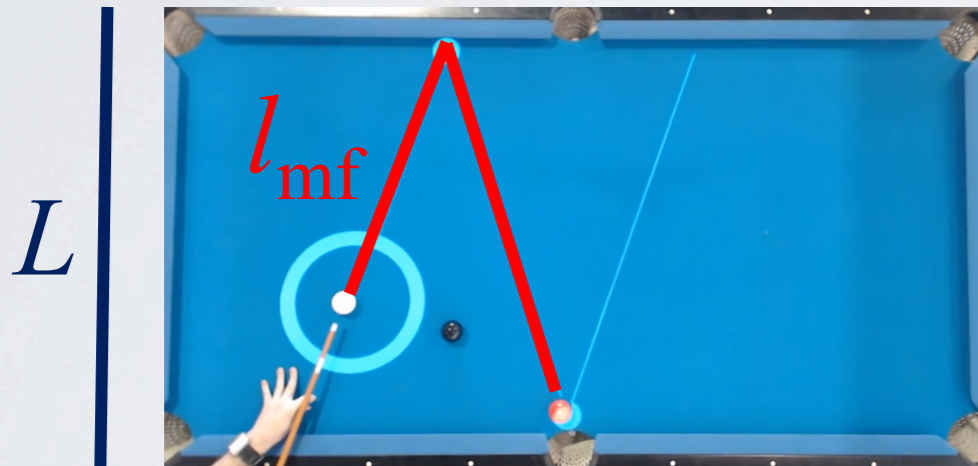
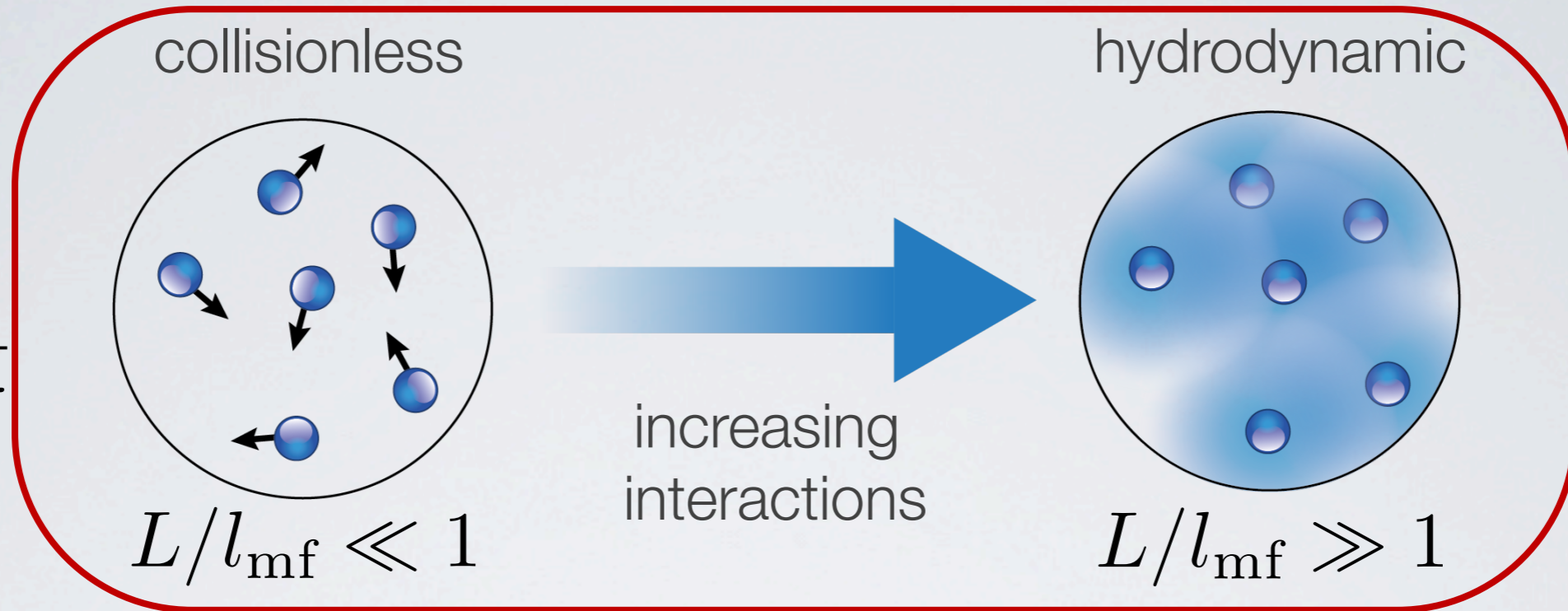
# Dissipationless flow in a Bose-Fermi mixture



Z. Z. Yan, Y. Ni, A. Chuang,  
CR, M. Zwierlein (in preparation)

# Collective modes in many-body systems

$$l_{mf} = \frac{1}{n \sigma}$$



- Classical billiard balls
- Ideal gasses (e.g. ultracold spin polarized fermions)



- Classical fluids (e.g. water)
- Bose Einstein condensates (superfluid hydrodynamics)
- 2D electron fluids in ultraclean materials\*

\* A. Berdyugin, et.al., Science 364 (2019)  
 D. Bandurin et al, Science 351 (2016)  
 P. Moll, et.al., Science 351 (2016)

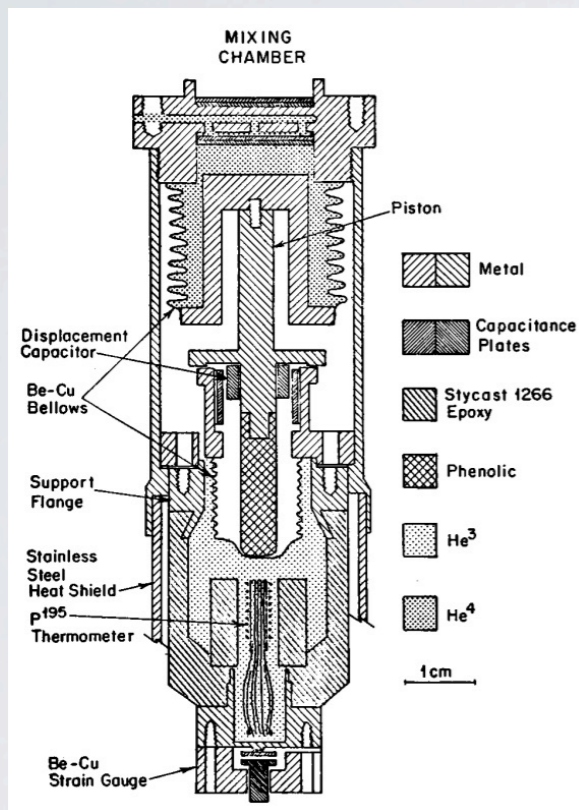
J. Sulpizio, et.al., Nature 576 (2019)  
 J. Crossno, et.al., Science 351 (2016)



# Previous studies of Bose-Fermi quantum fluids

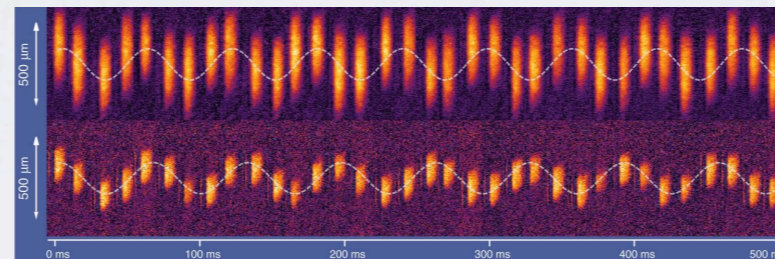
Mixtures of  $^3\text{He}$  &  $^4\text{He}$

Ultracold atomic Bose-Fermi mixtures



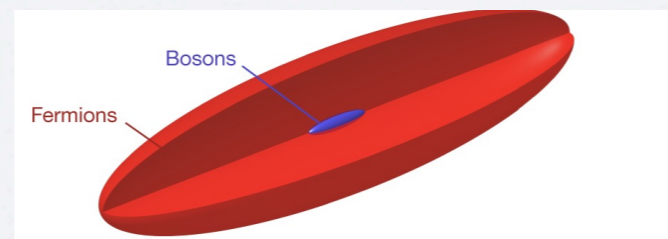
David M. Lee Rev. Mod. Phys. **69**, 645

- coupled Bose-Fermi superfluids: see e.g. LKB ENS, U. Washington, USTC



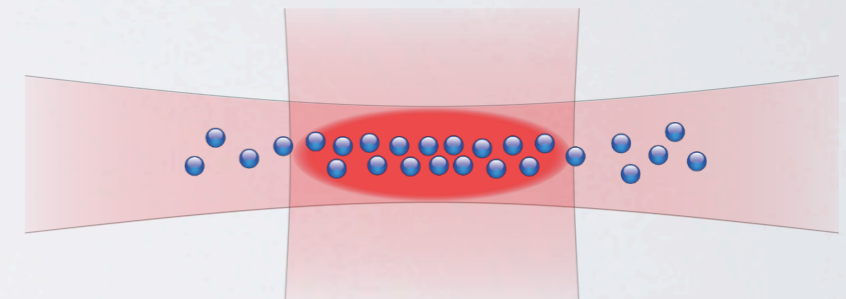
I. Ferrier-Barbut, et al, Science 29 Aug 2014, Vol. 345, Issue 6200, pp. 1035-1038

- Small BEC in large Fermi cloud: see e.g. Innsbruck, LENS, UChicago



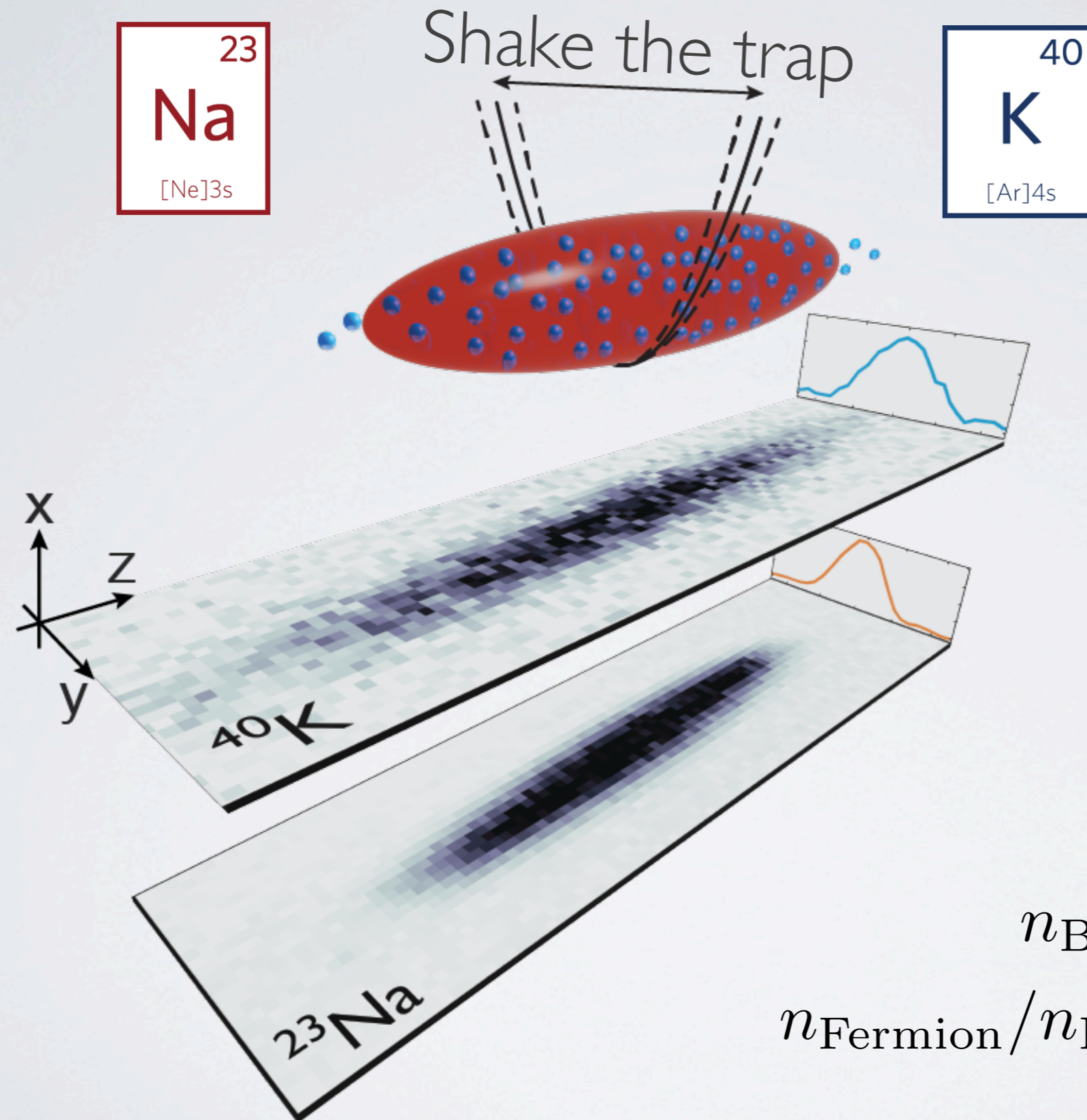
B. J. DeSalvo, et al, Nature volume 568, pages61–64 (2019)

This work:  
Bose polarons  
impurities in a BEC





# Creating a strongly interacting Bose-Fermi mixture



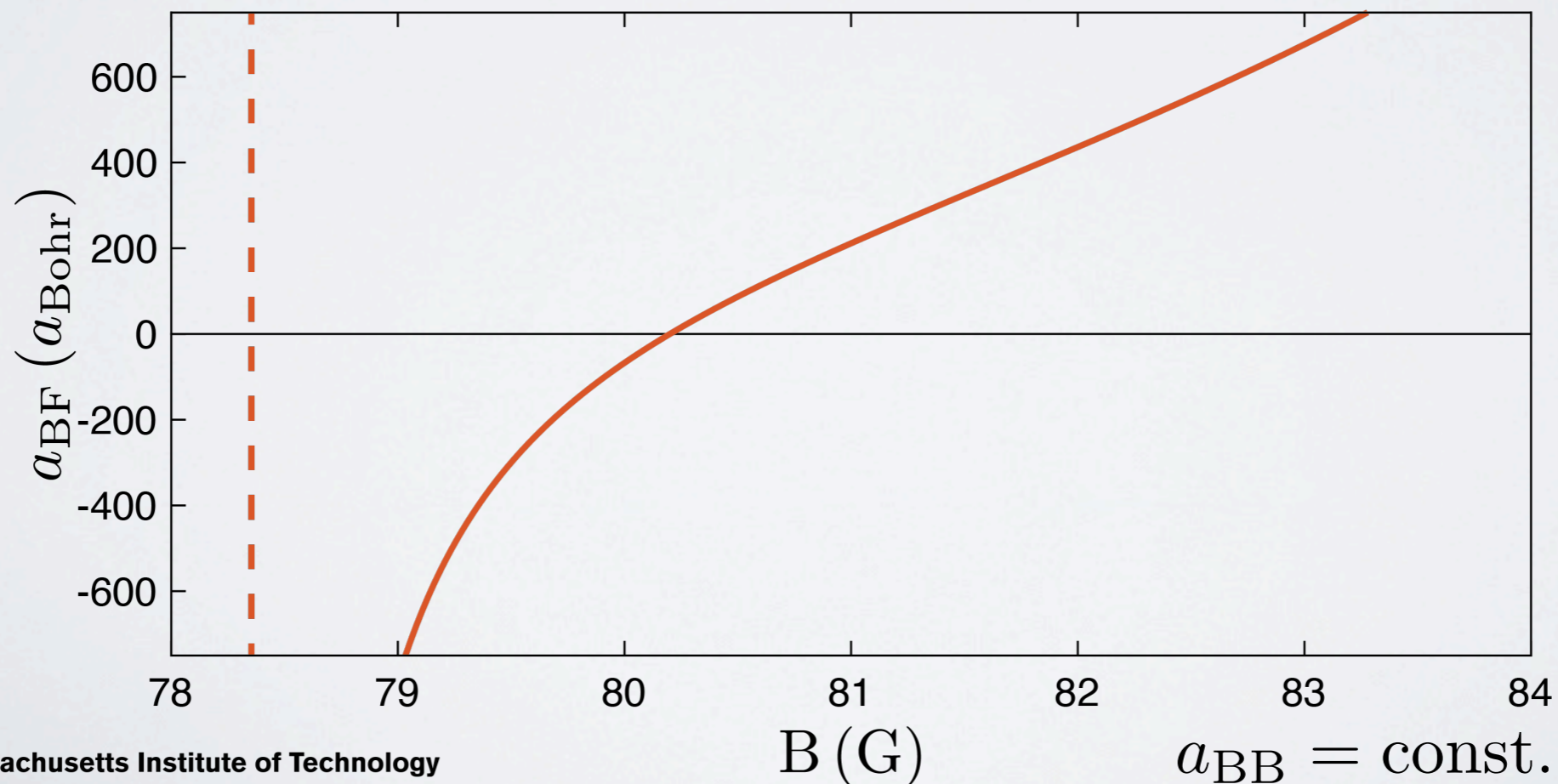
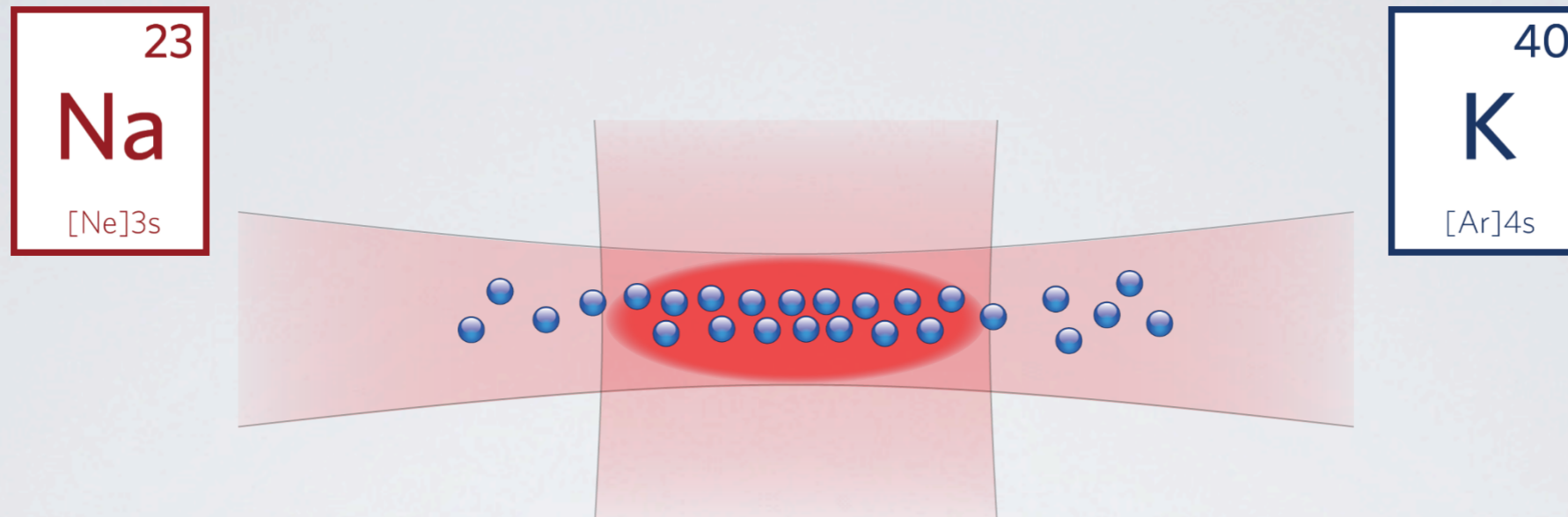
$$T = 100 \text{ nK}$$

$$n_{\text{Bosons}} = 10^{14} \text{ cm}^{-3}$$

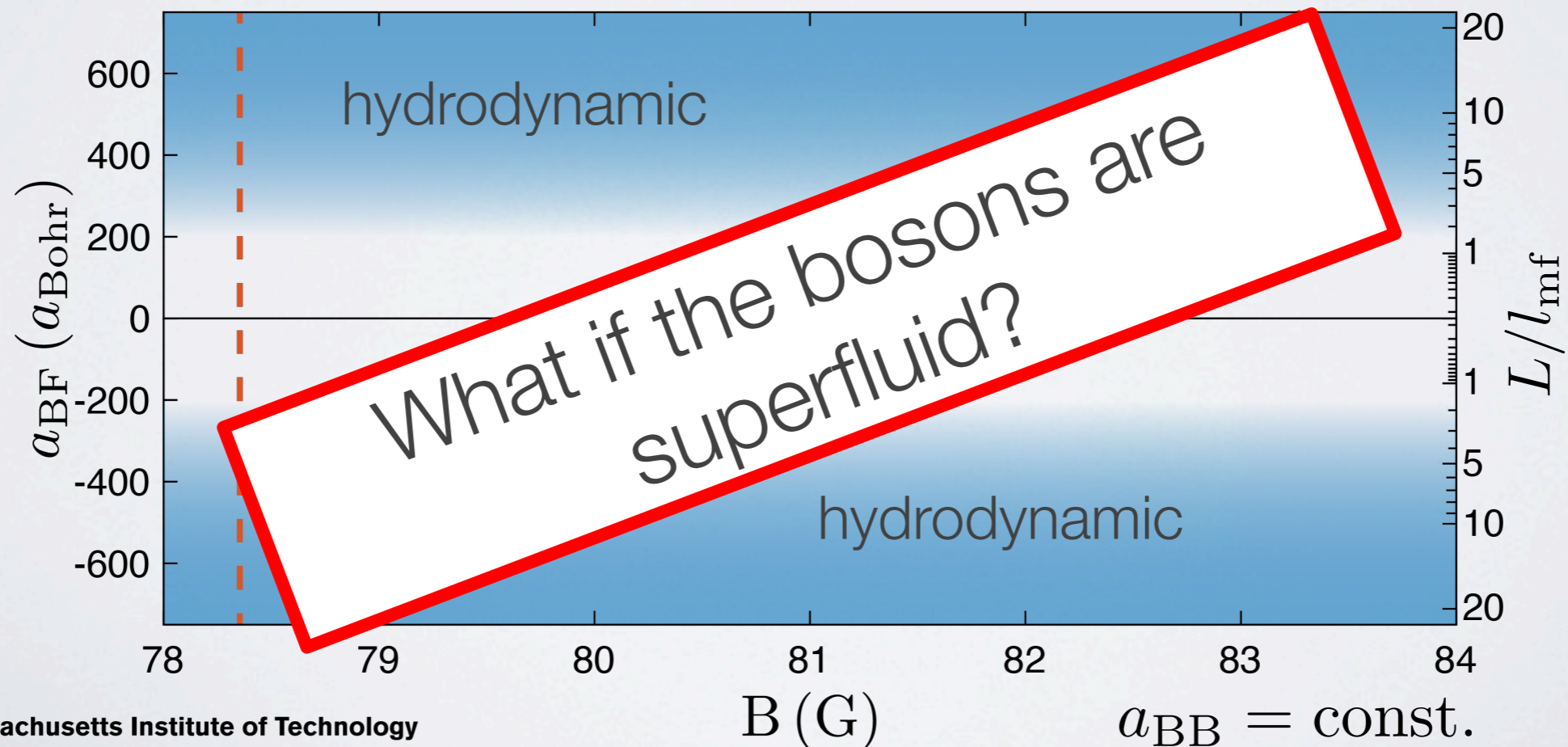
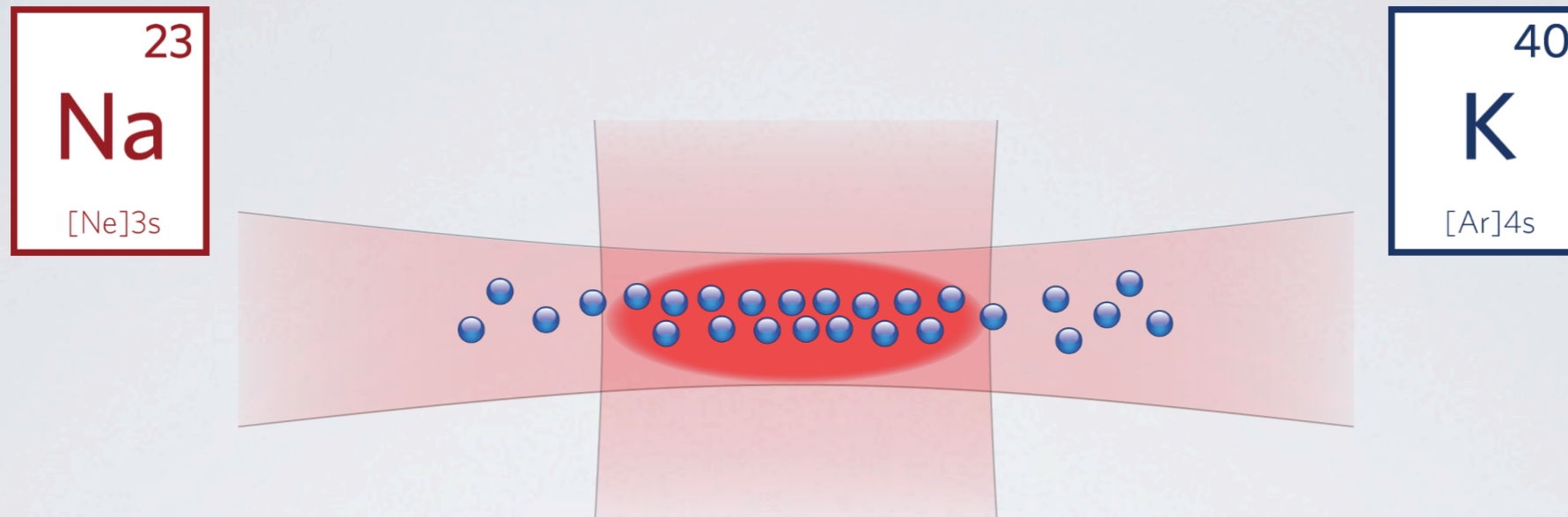
$$n_{\text{Fermion}}/n_{\text{Boson}} \approx 0.01$$



# Creating a strongly interacting Bose-Fermi mixture

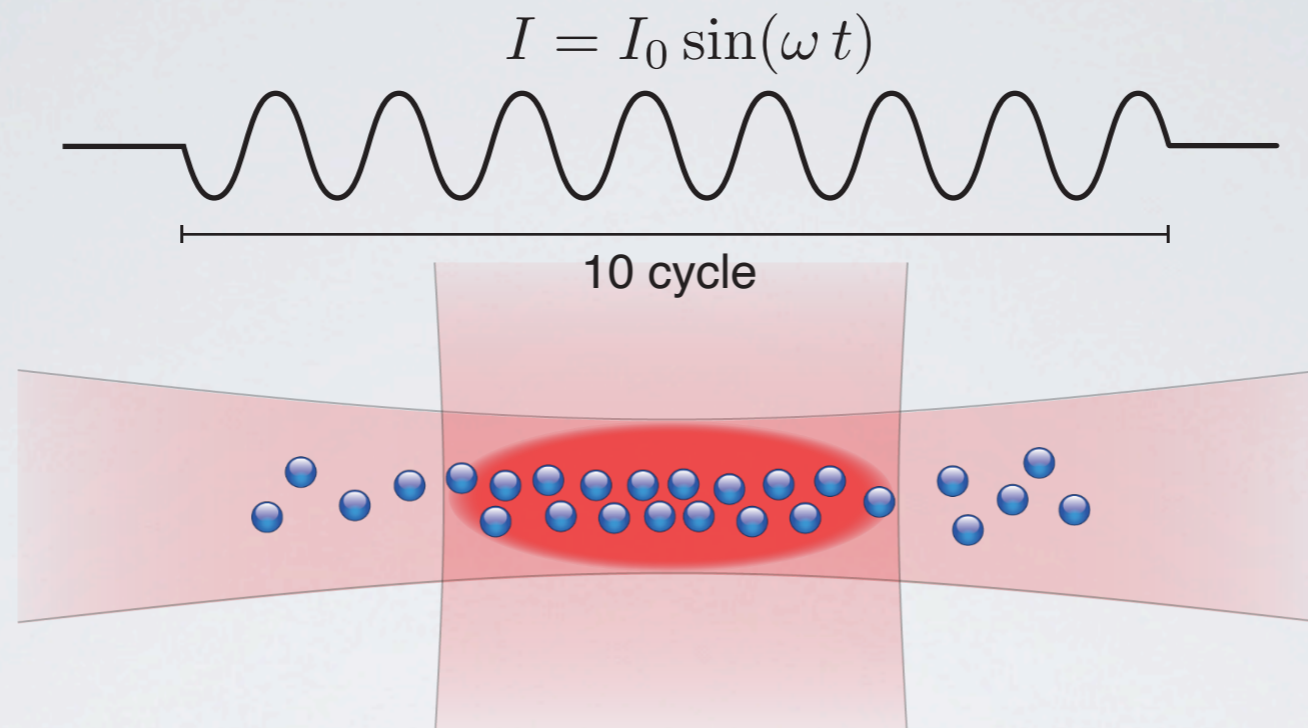


# Creating a strongly interacting Bose-Fermi mixture

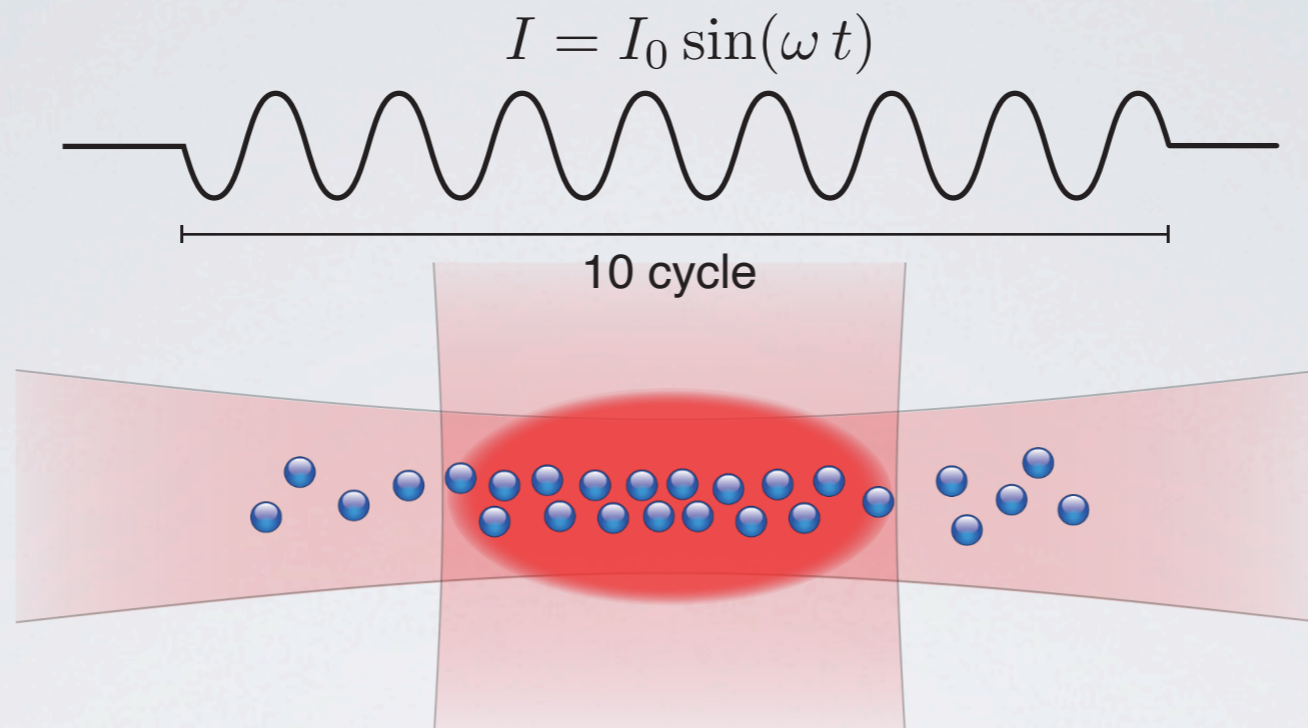




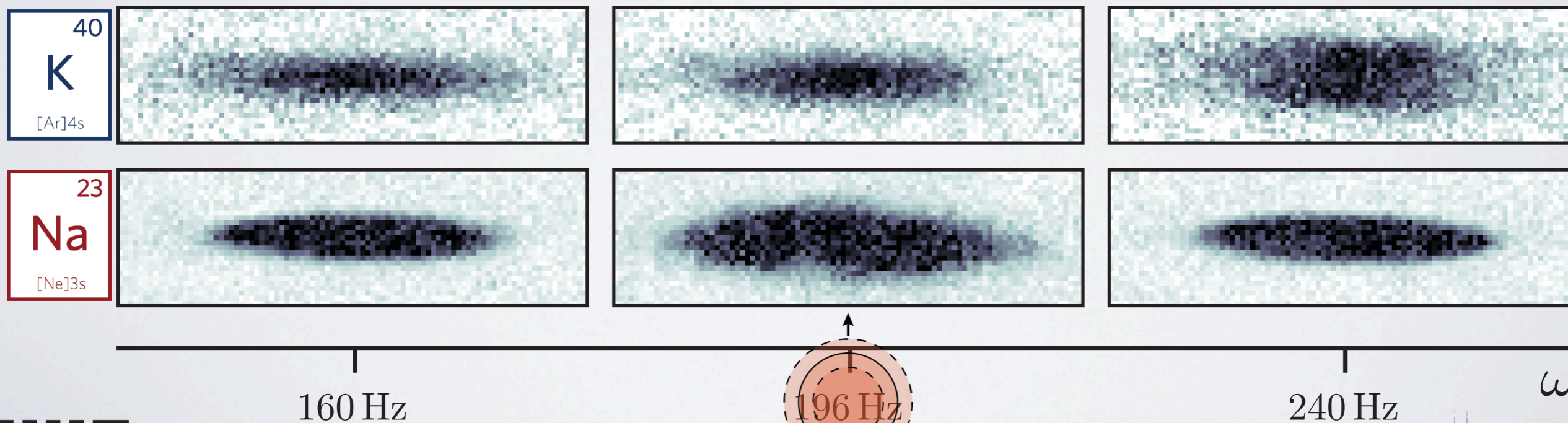
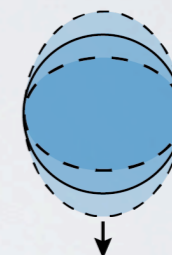
# Probing collective excitations spectroscopically



# Probing collective excitations spectroscopically

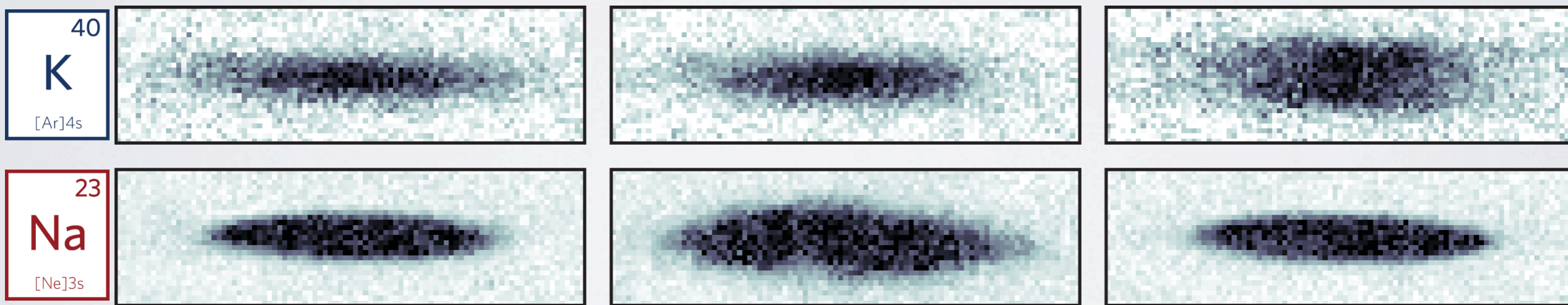
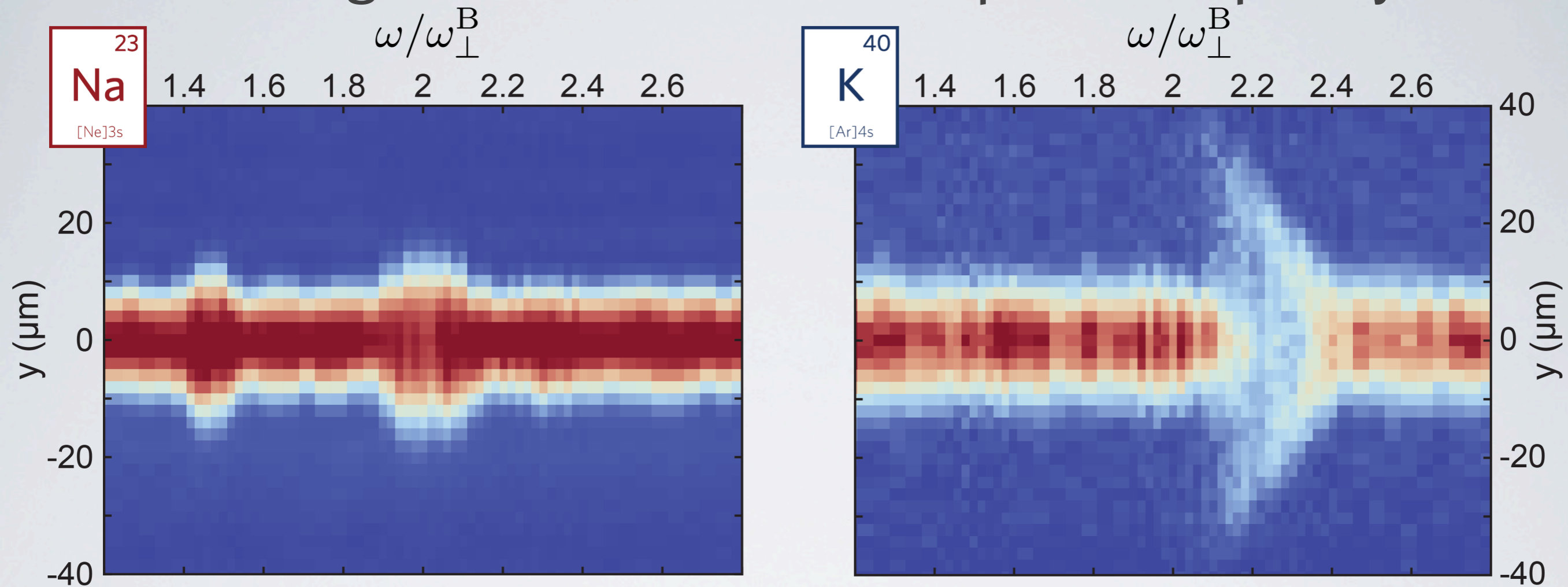


$a_{BF} \approx 0$





# Probing collective excitations spectroscopically



160 Hz

196 Hz

240 Hz

$\omega$

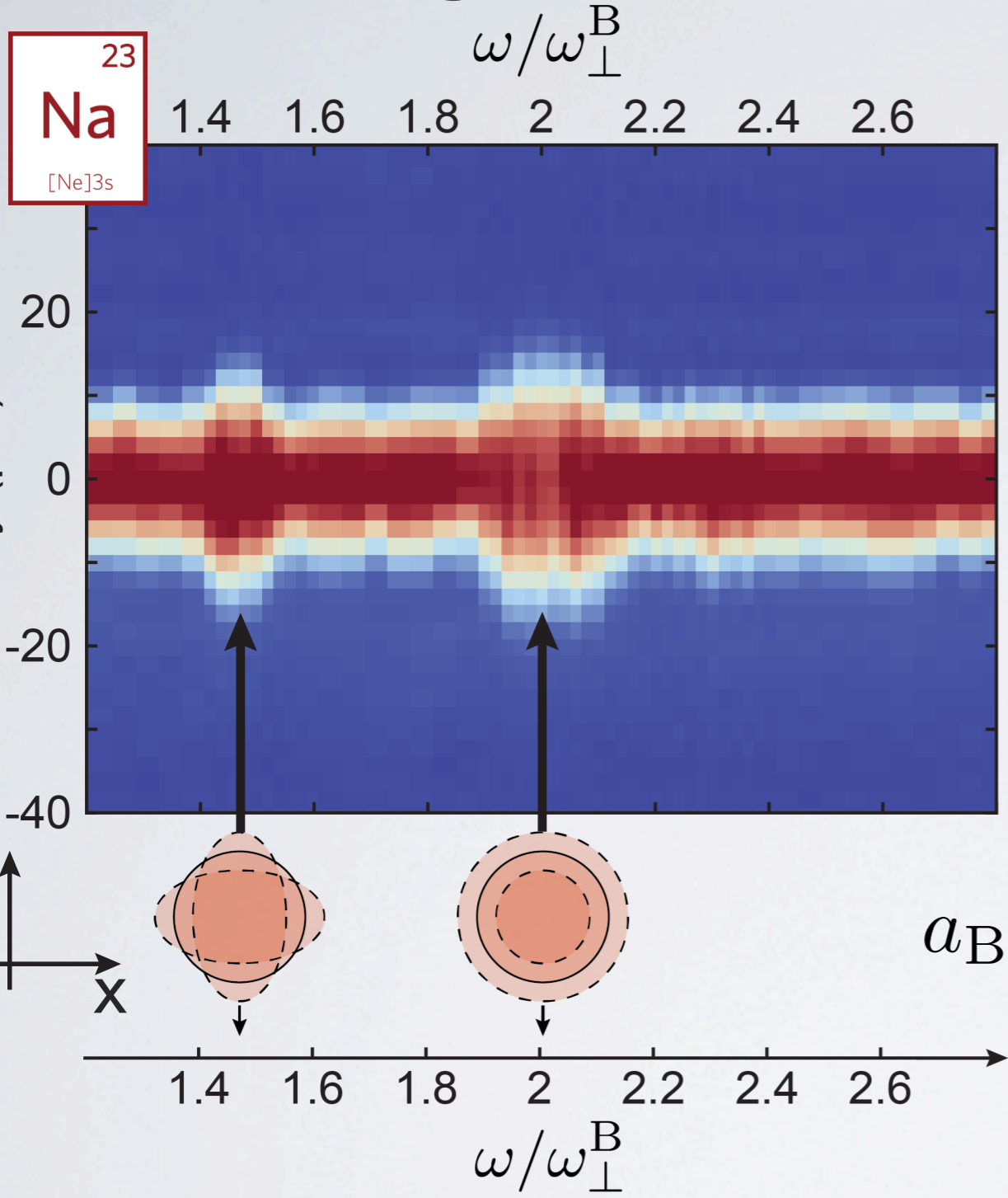
$$a_{BF} \approx 0$$



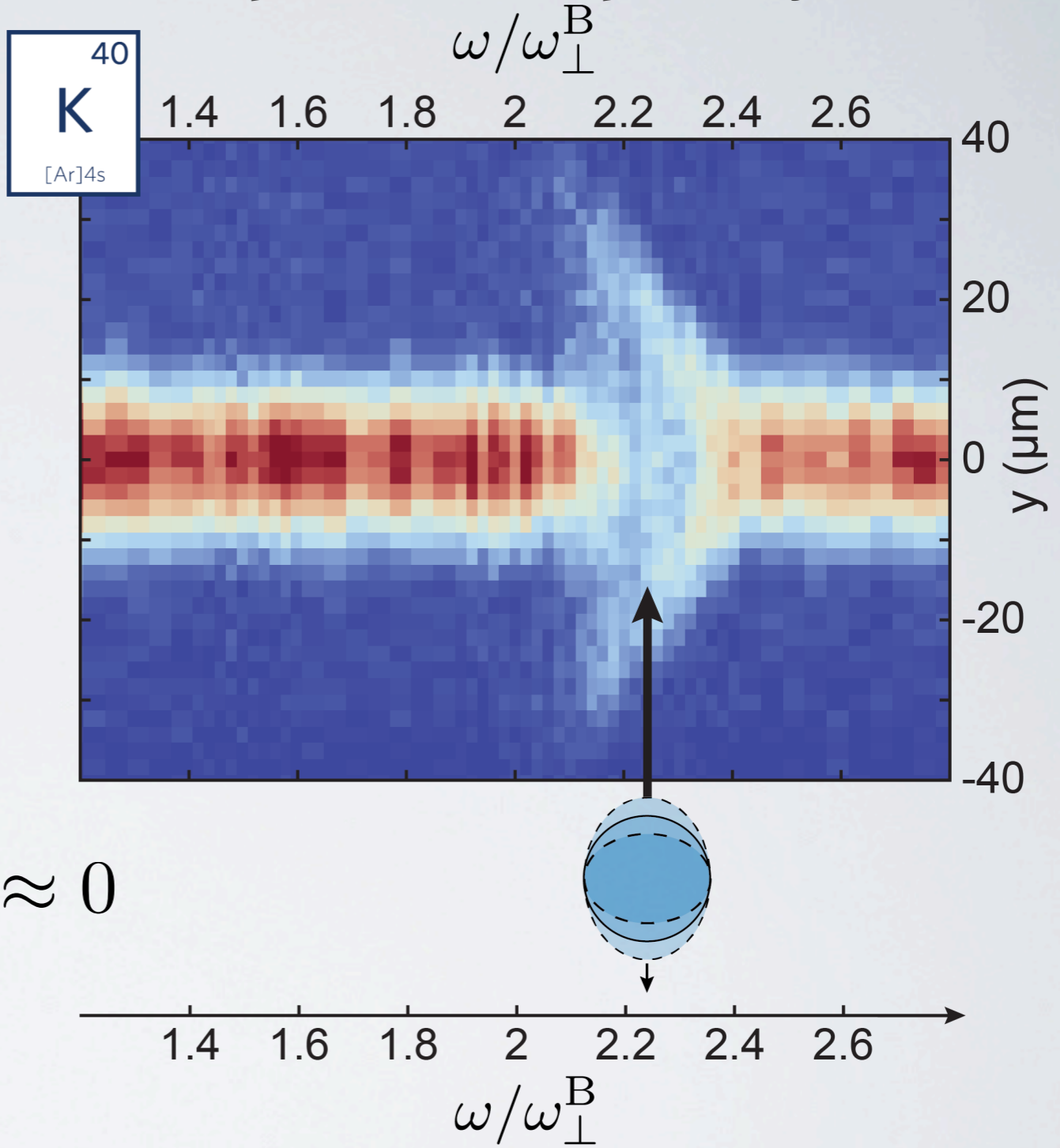
Massachusetts Institute of Technology



# Probing collective excitations spectroscopically



BEC  
(hydrodynamic superfluid)



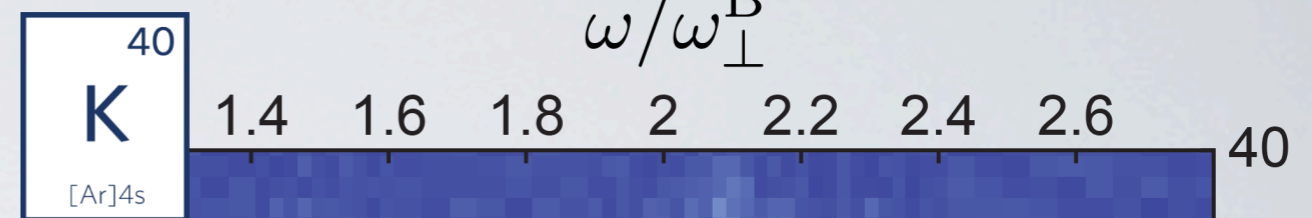
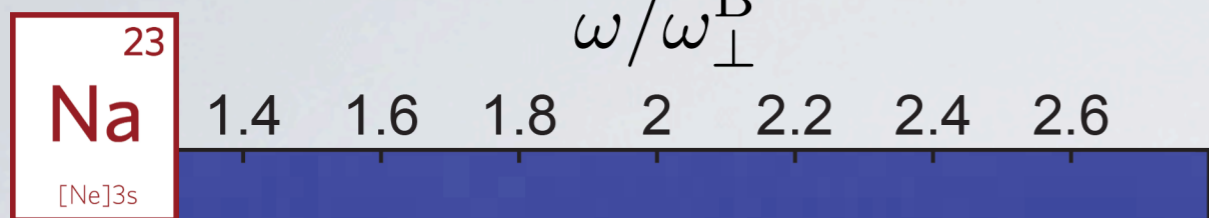
dilute fermions  
(collisionless gas)

$a_{BF} \approx 0$

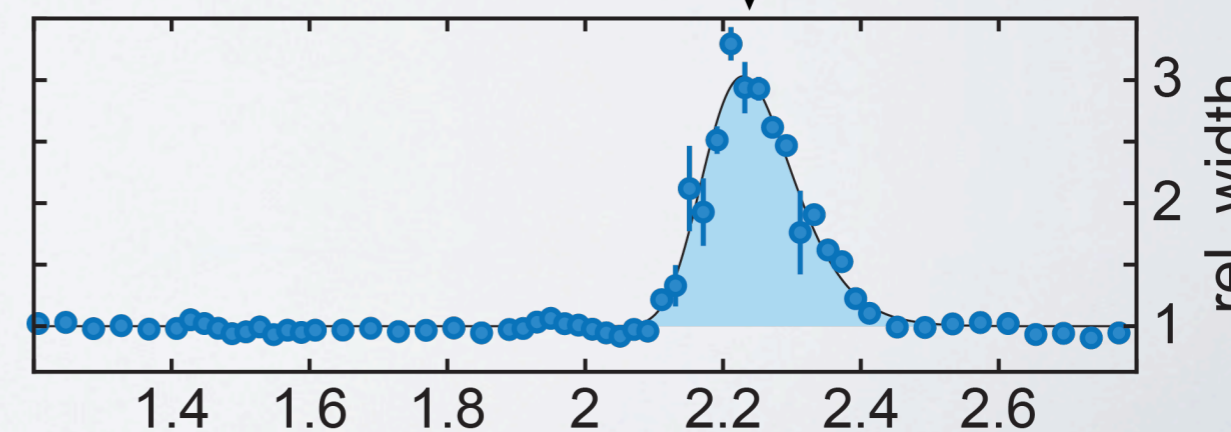
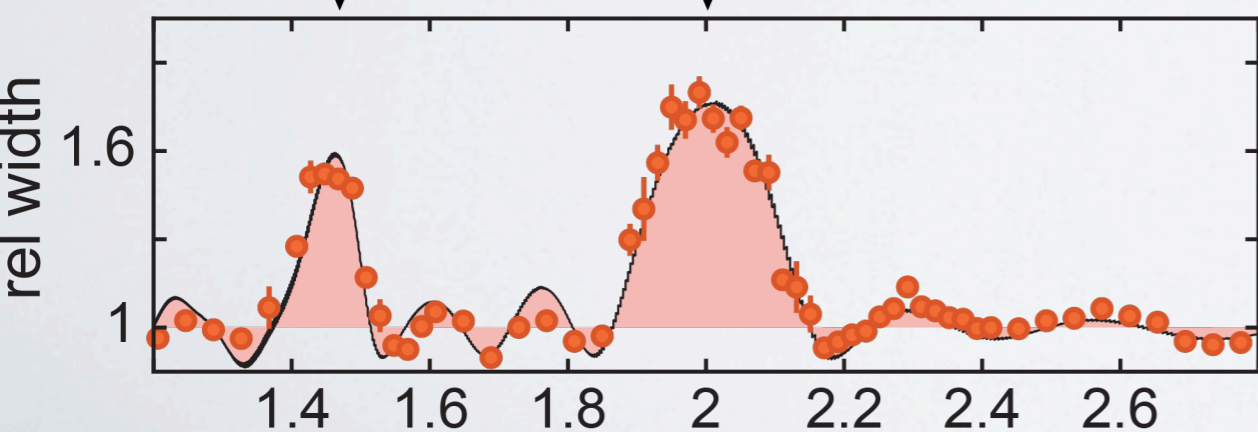
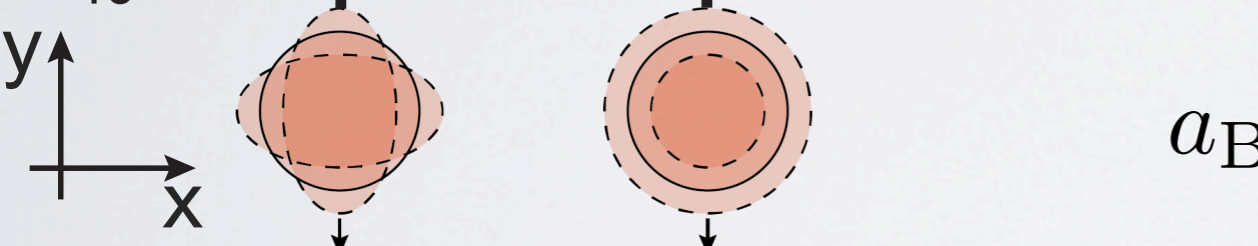
$\omega_{\perp}^B = \sqrt{\omega_x^B \omega_y^B}$



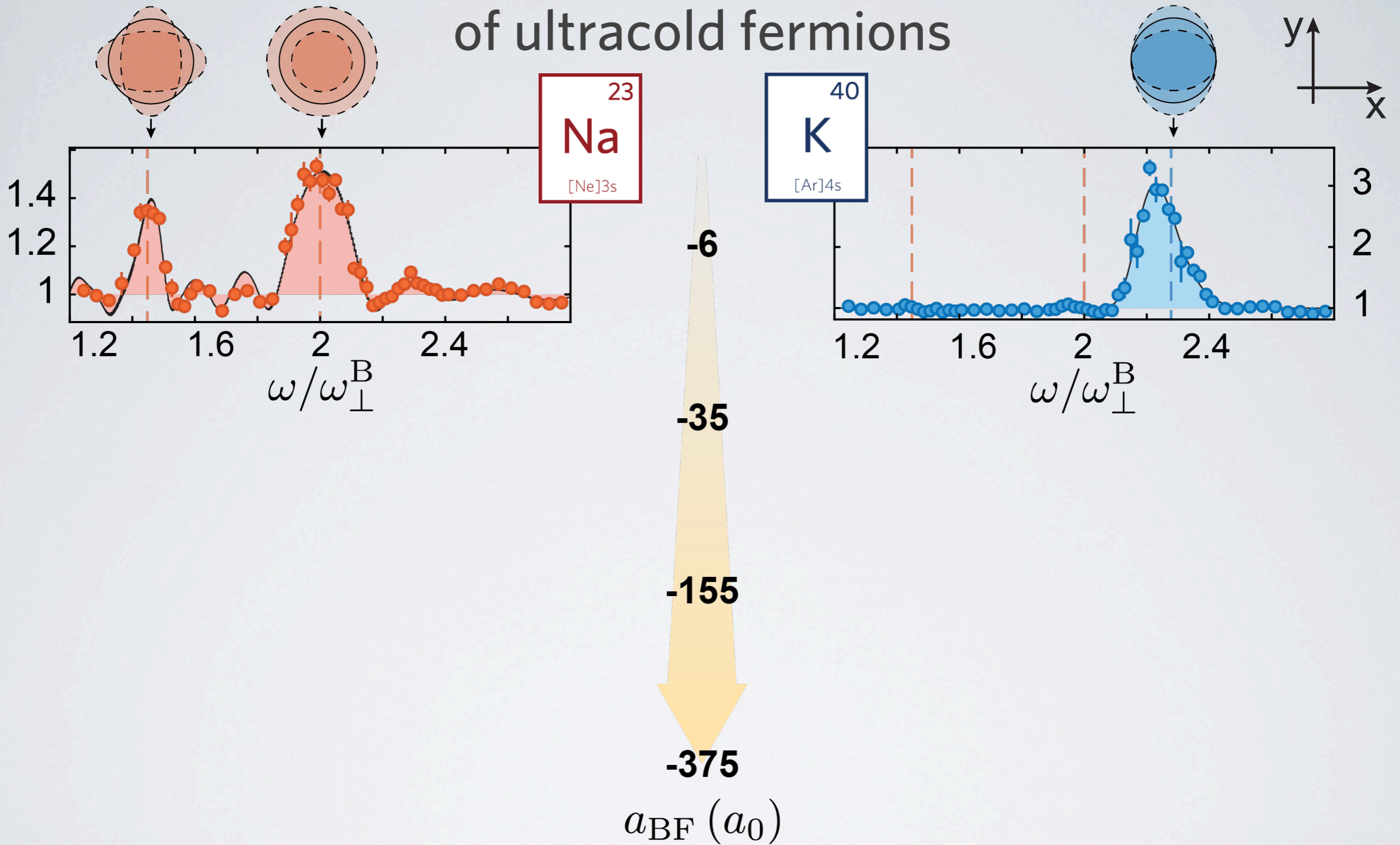
# Probing collective excitations spectroscopically



$a_{\text{BF}} \approx 0$

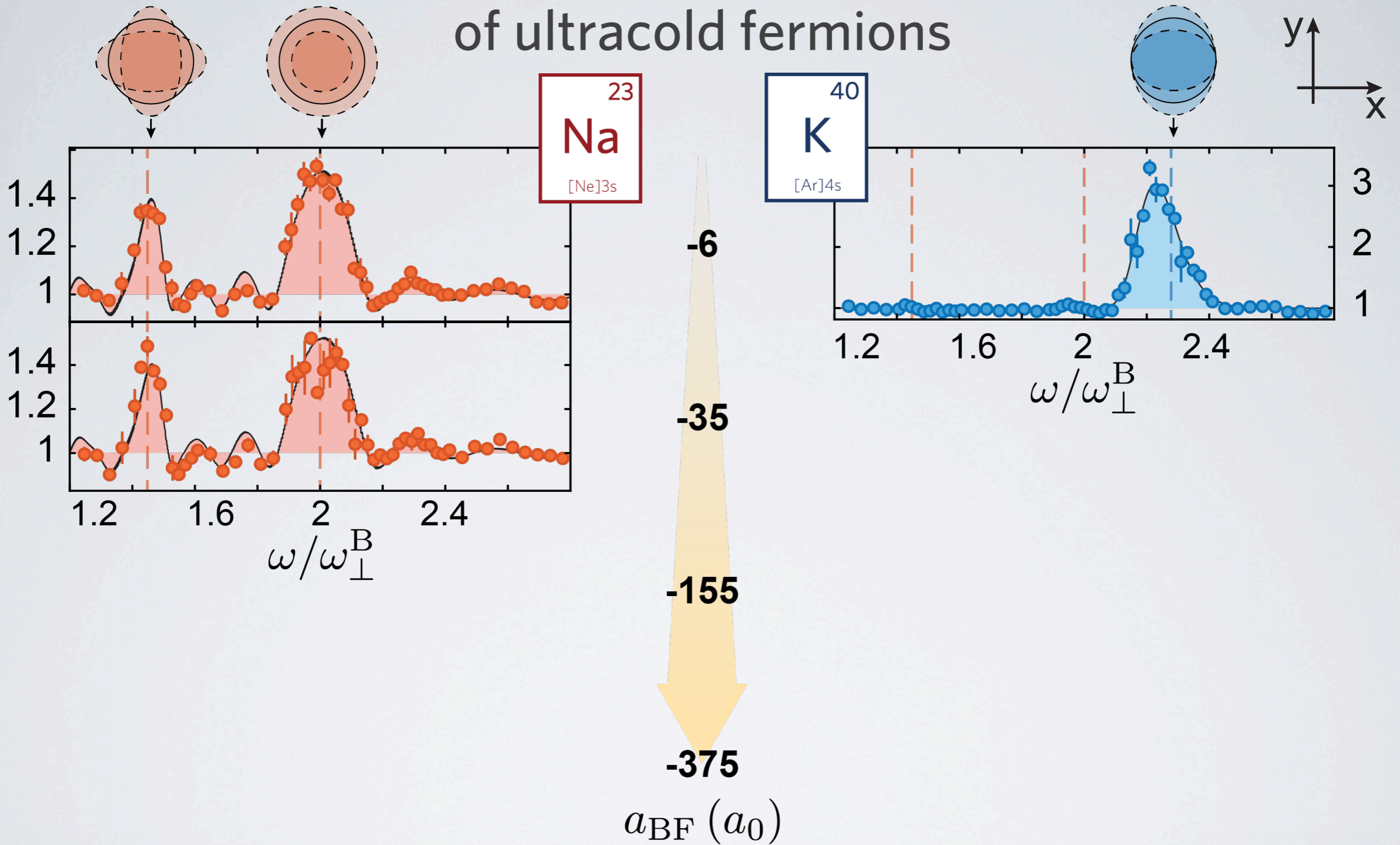


# Collisionless to hydrodynamic transition of ultracold fermions

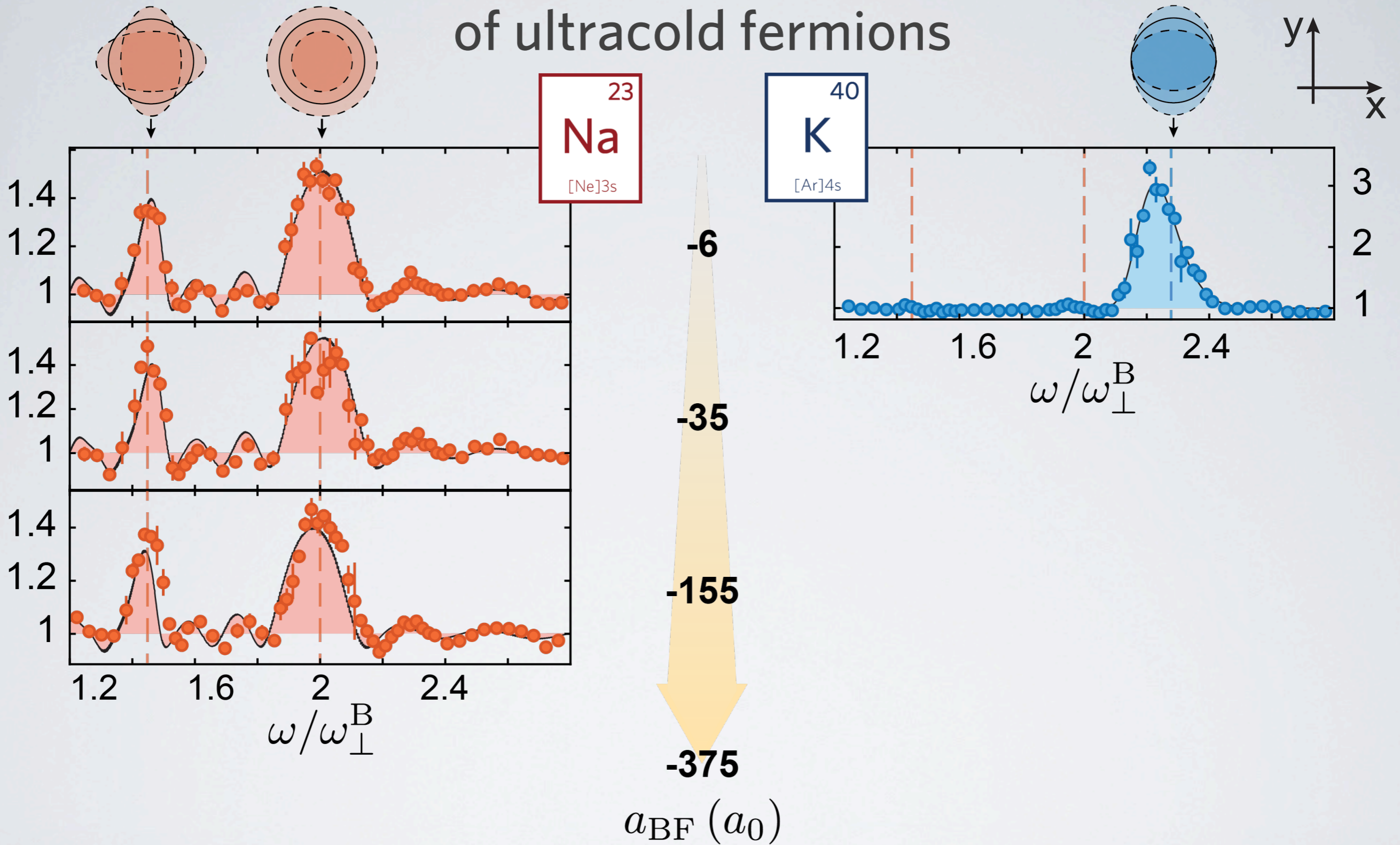




# Collisionless to hydrodynamic transition of ultracold fermions

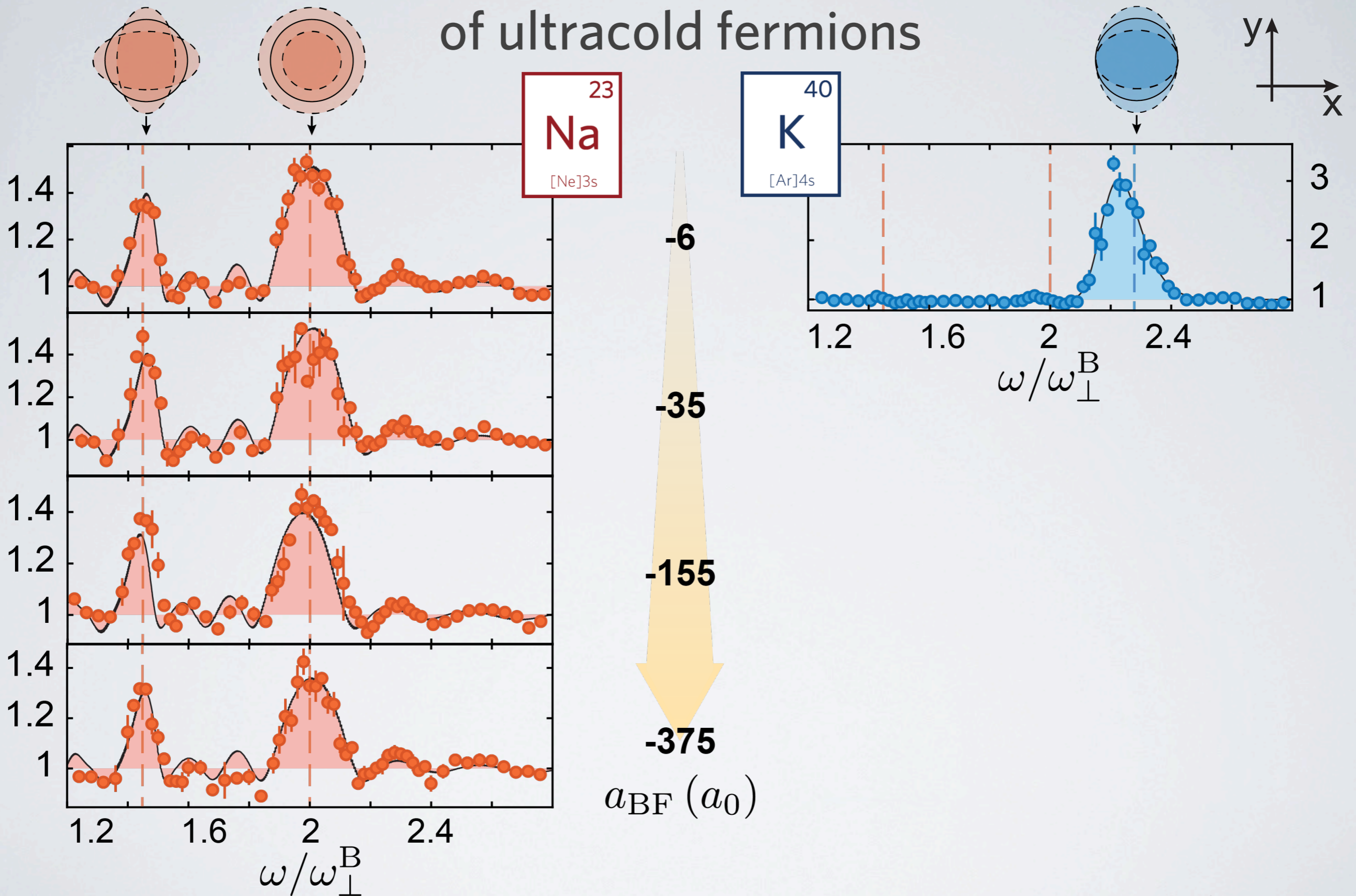


# Collisionless to hydrodynamic transition of ultracold fermions

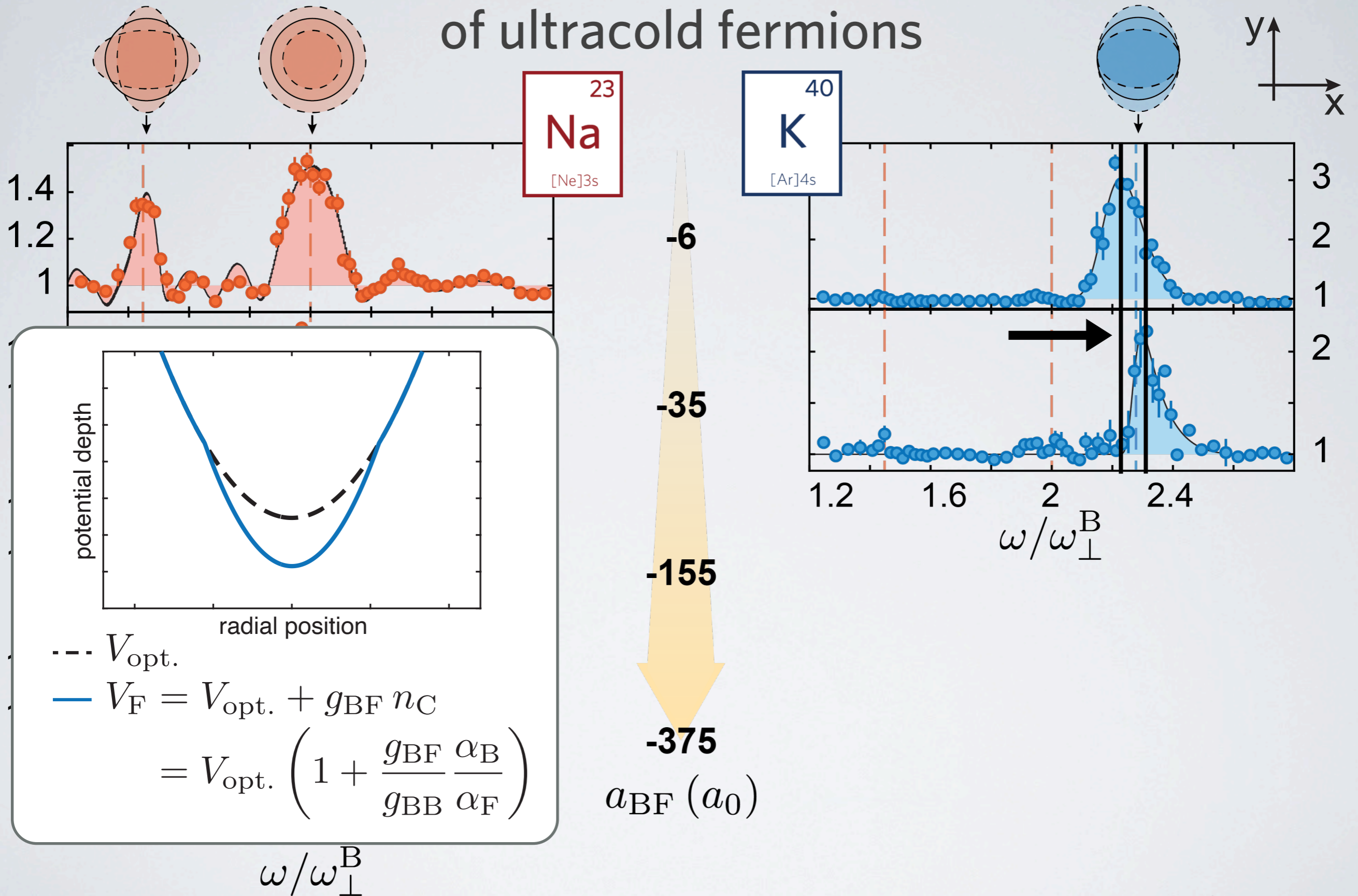




# Collisionless to hydrodynamic transition of ultracold fermions

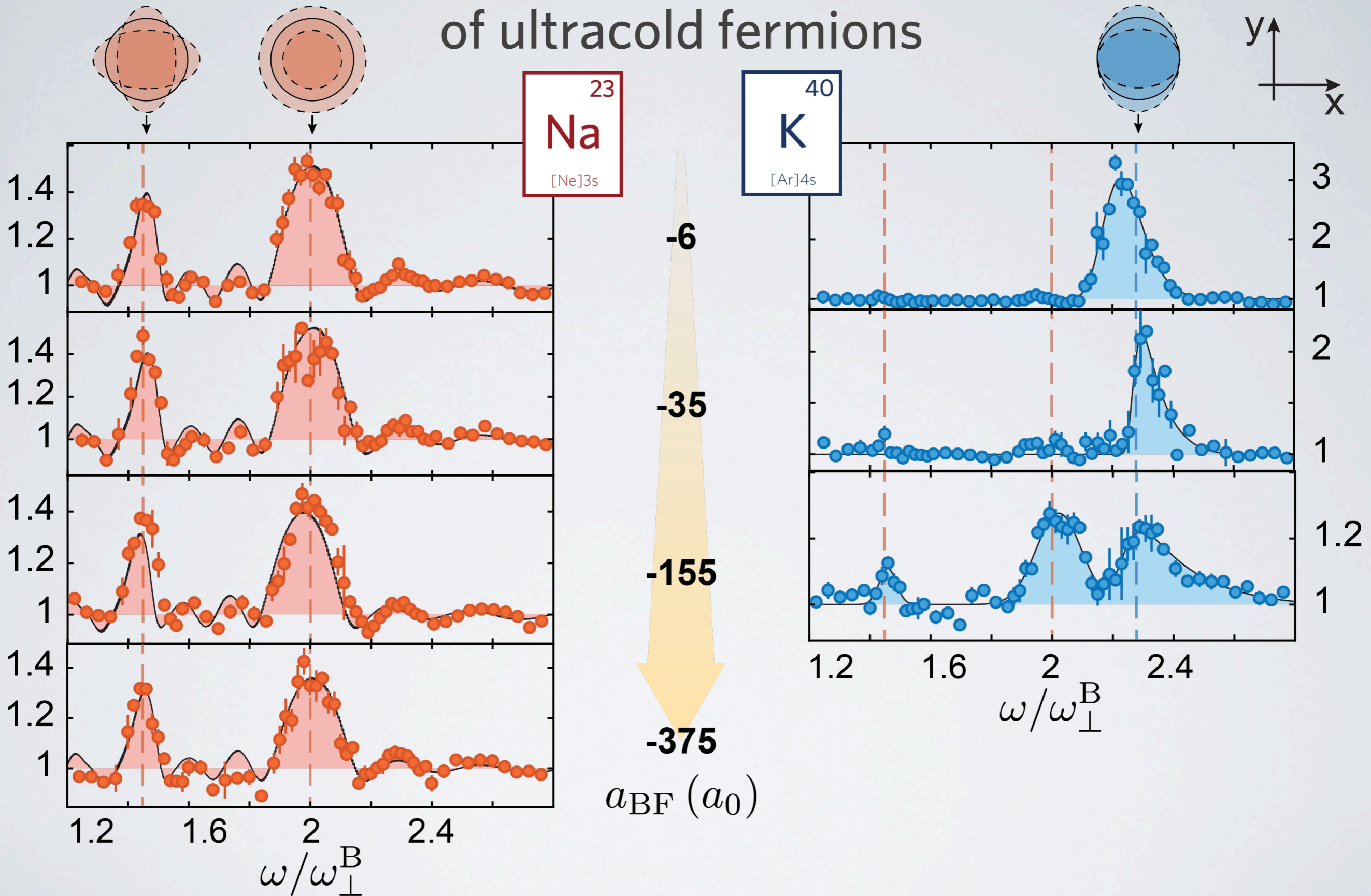


# Collisionless to hydrodynamic transition of ultracold fermions

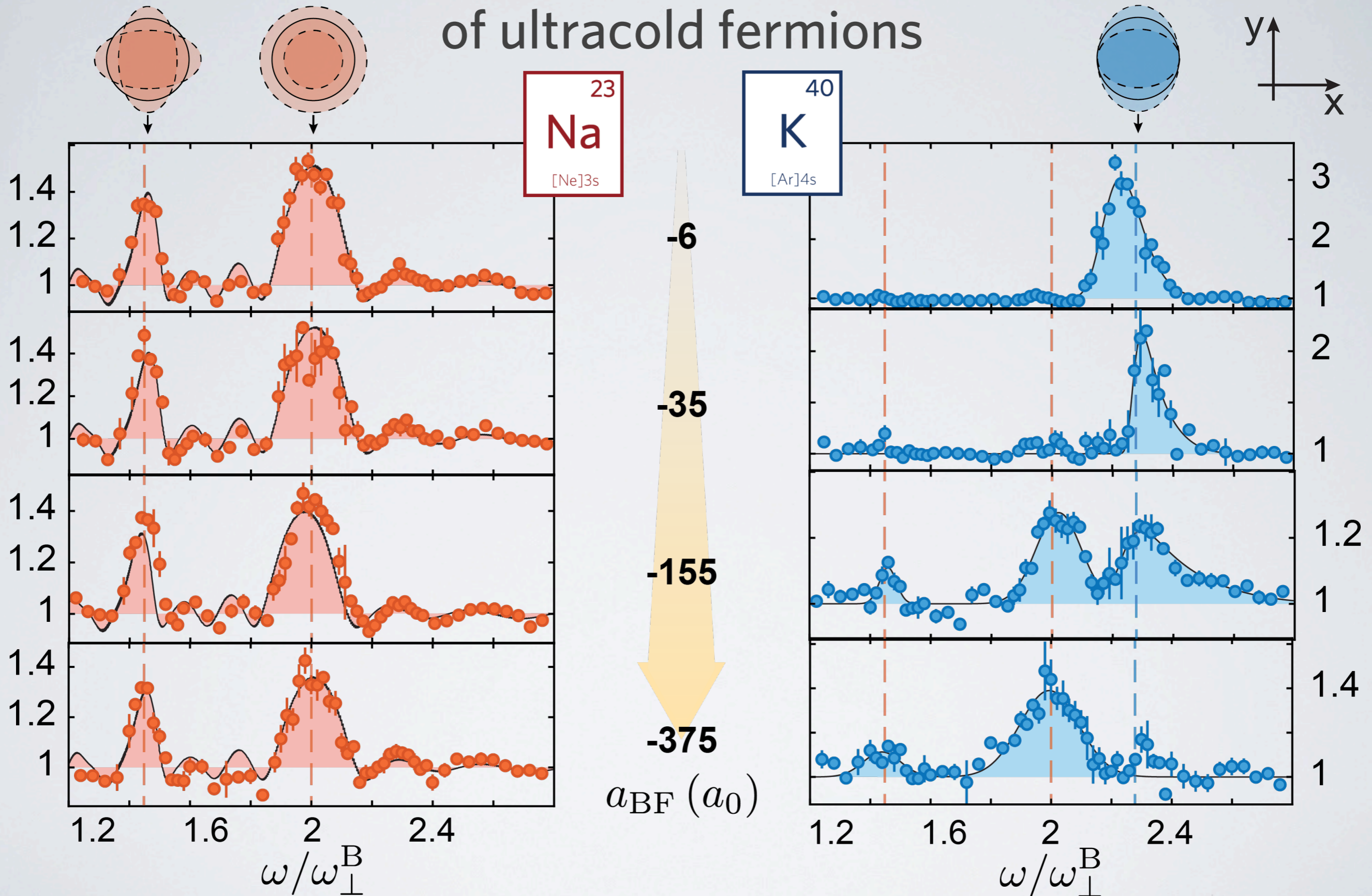




# Collisionless to hydrodynamic transition of ultracold fermions

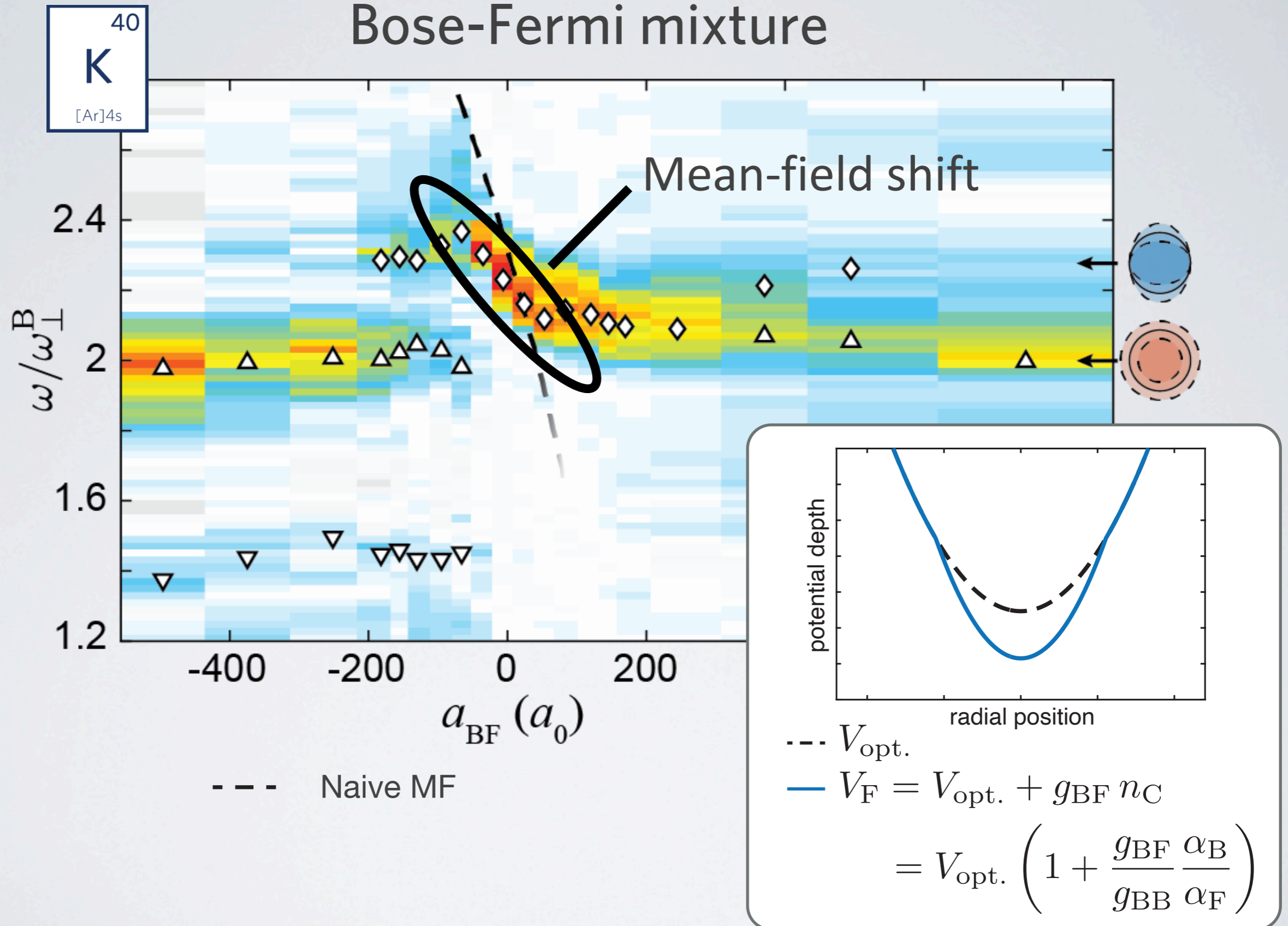


# Collisionless to hydrodynamic transition of ultracold fermions

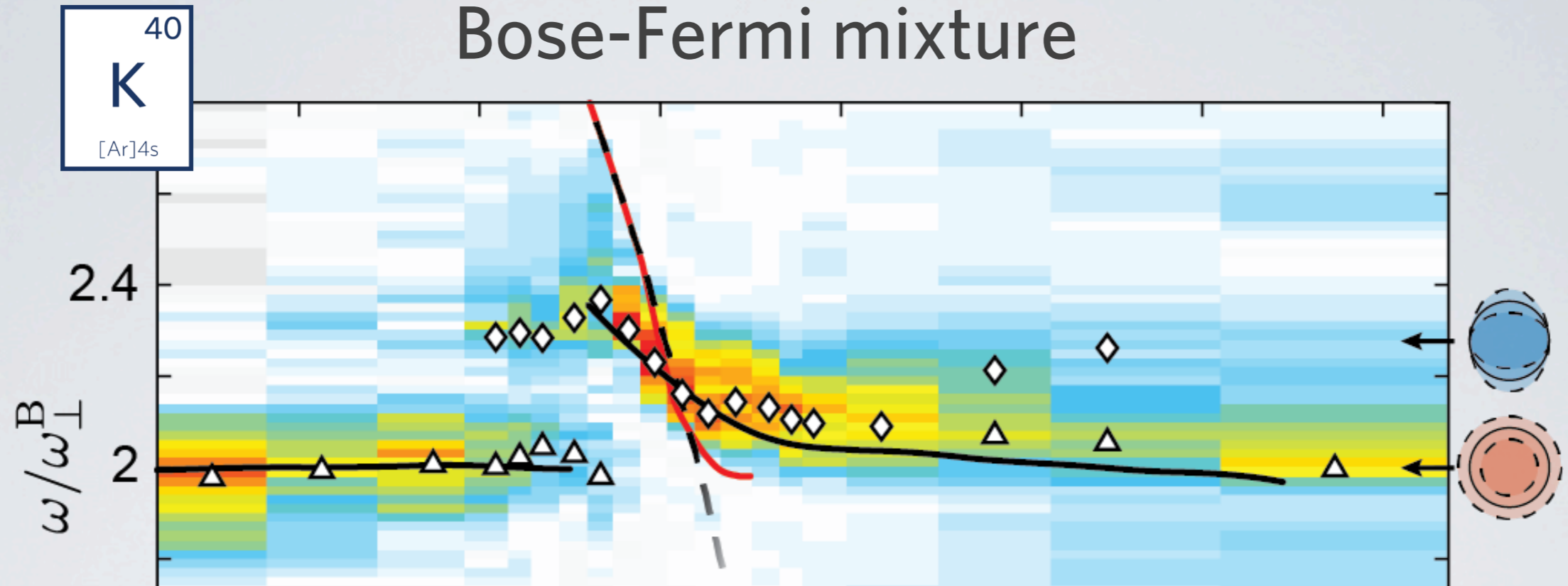




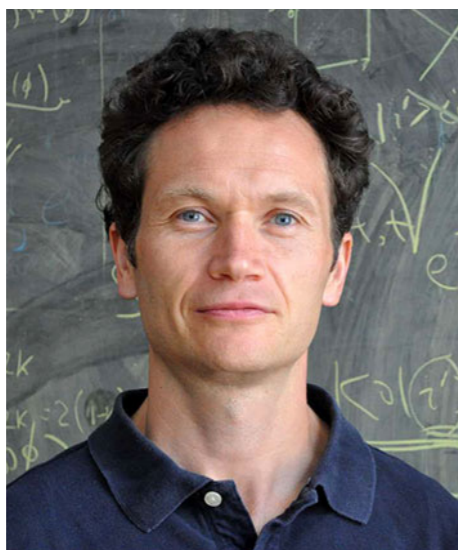
# Dissipationless flow in a Bose-Fermi mixture



# Dissipationless flow in a Bose-Fermi mixture



Work in progress: solving finite temperature Boltzmann-Vlasov equation for Bose-Fermi mixture



Eugene Demler



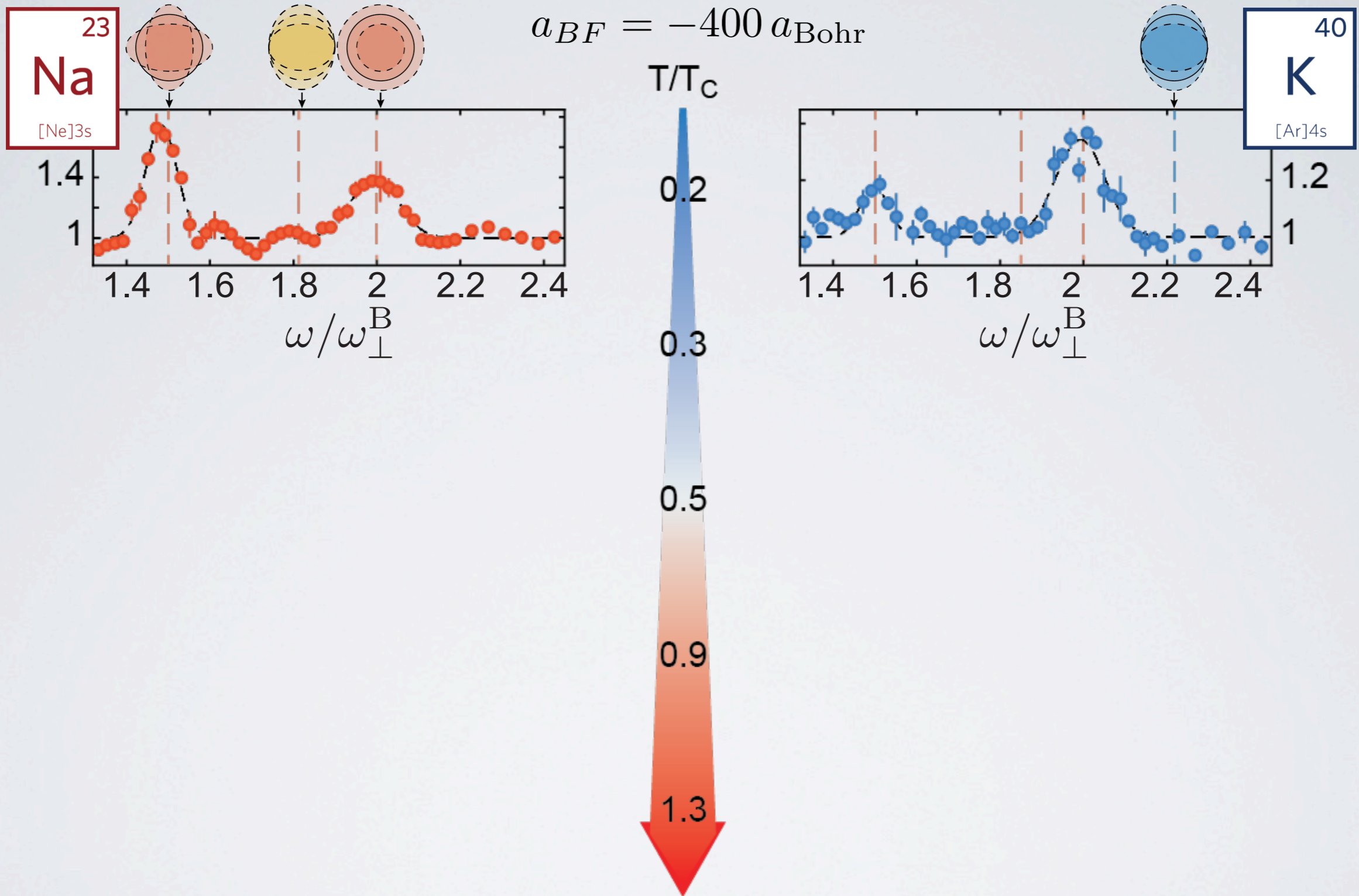
Kushal Seetharam



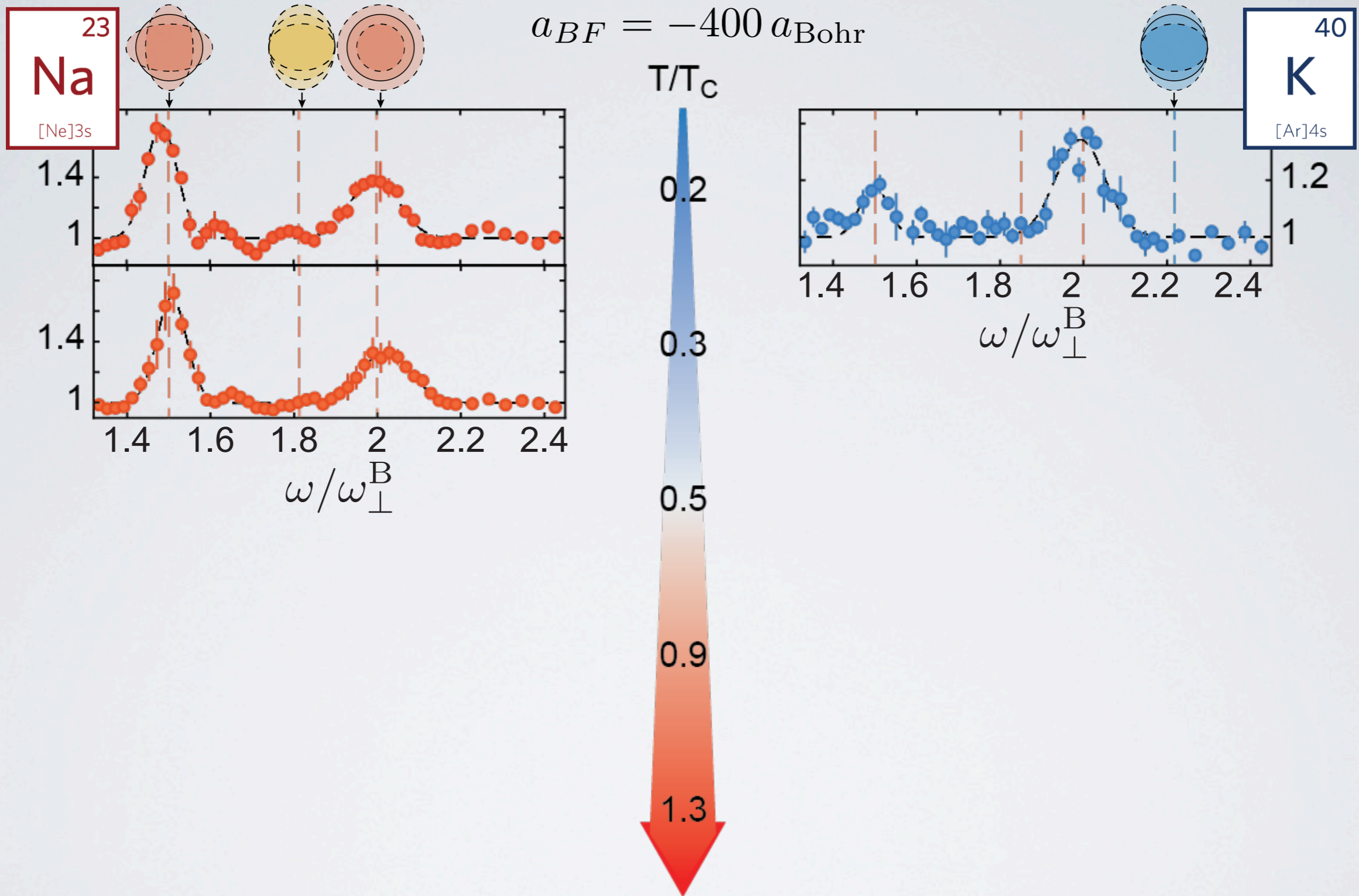
Pavel Dolgirev



# Collisionless to hydrodynamic transition

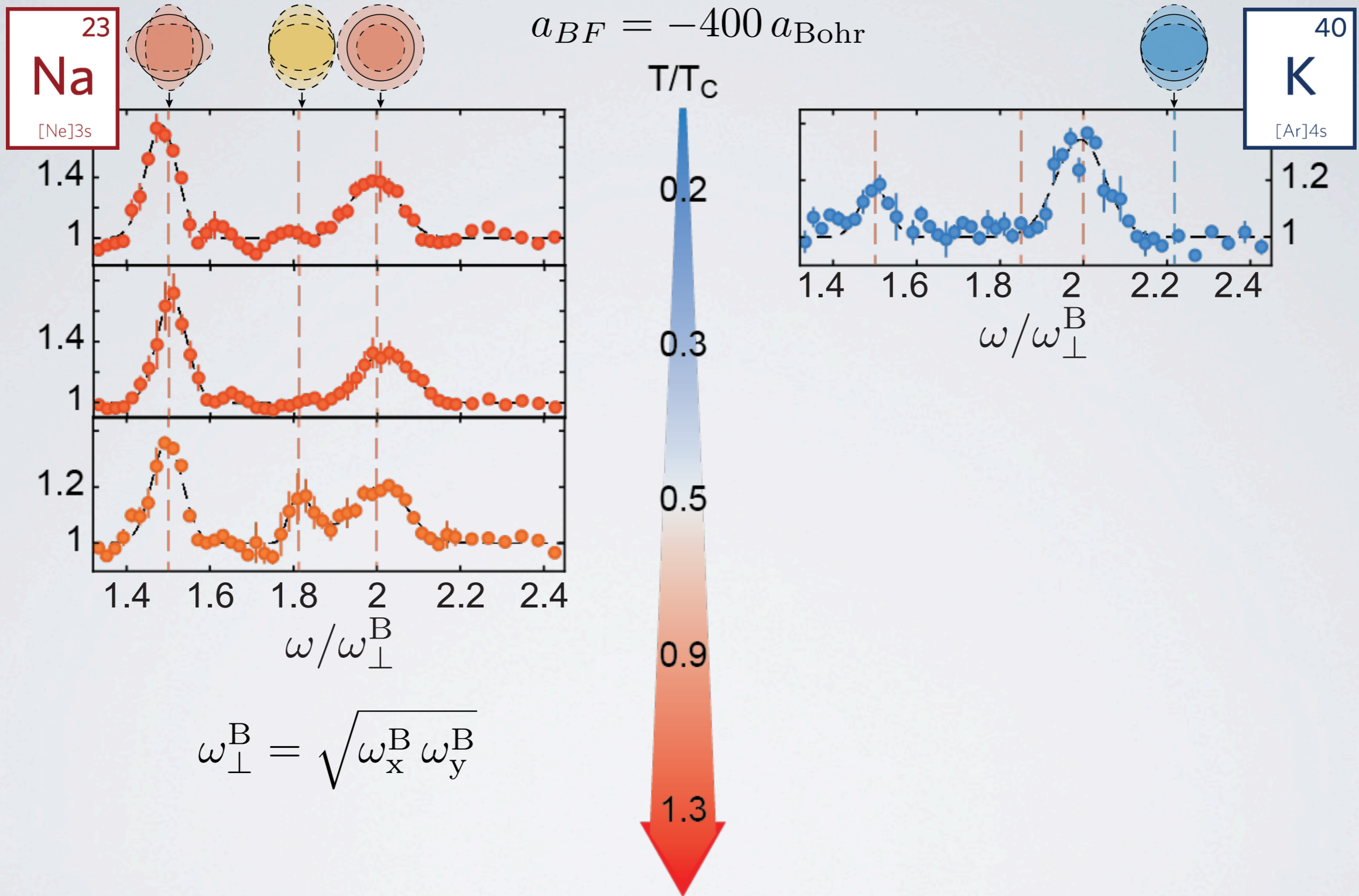


# Collisionless to hydrodynamic transition

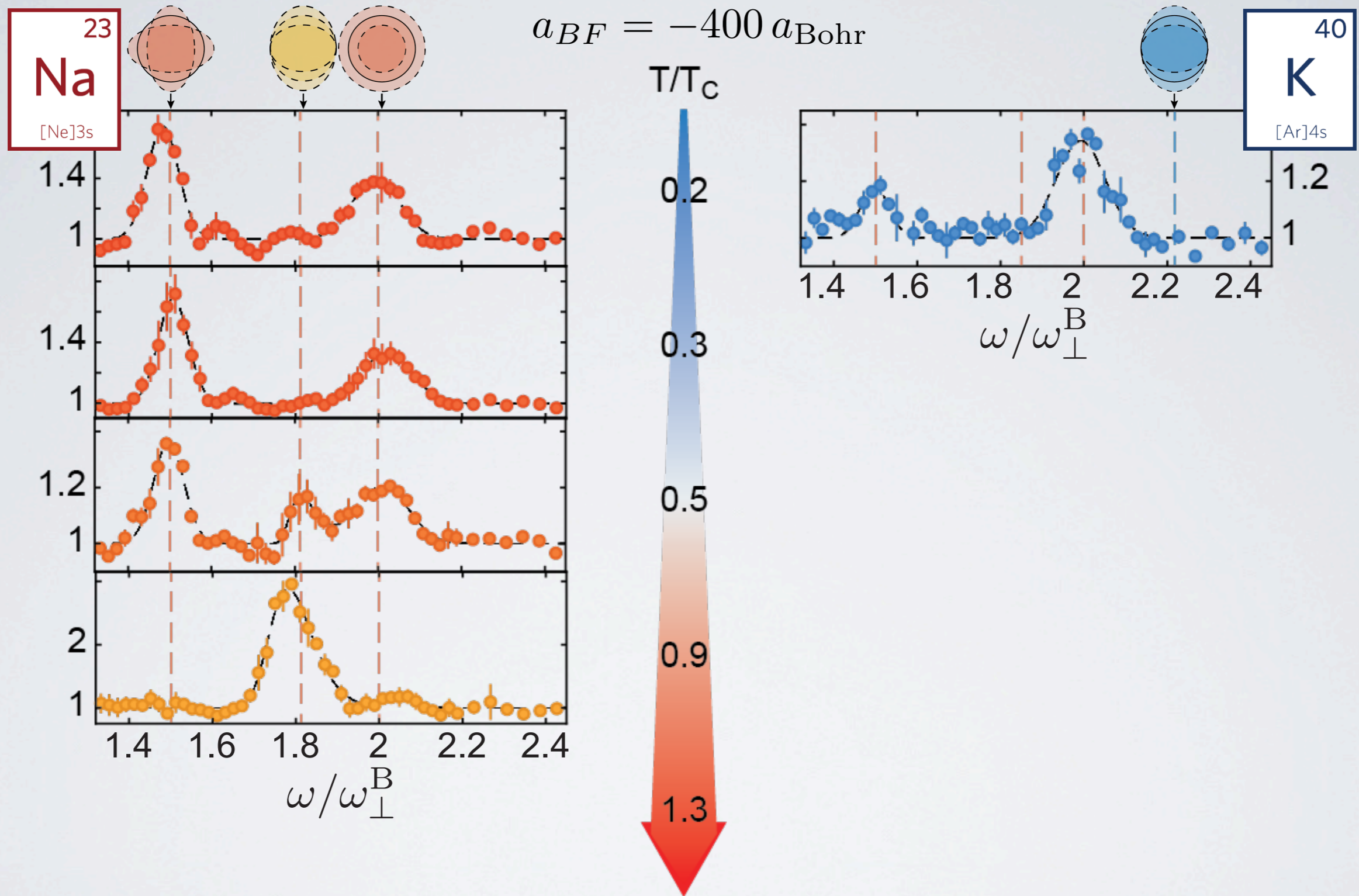




# Collisionless to hydrodynamic transition

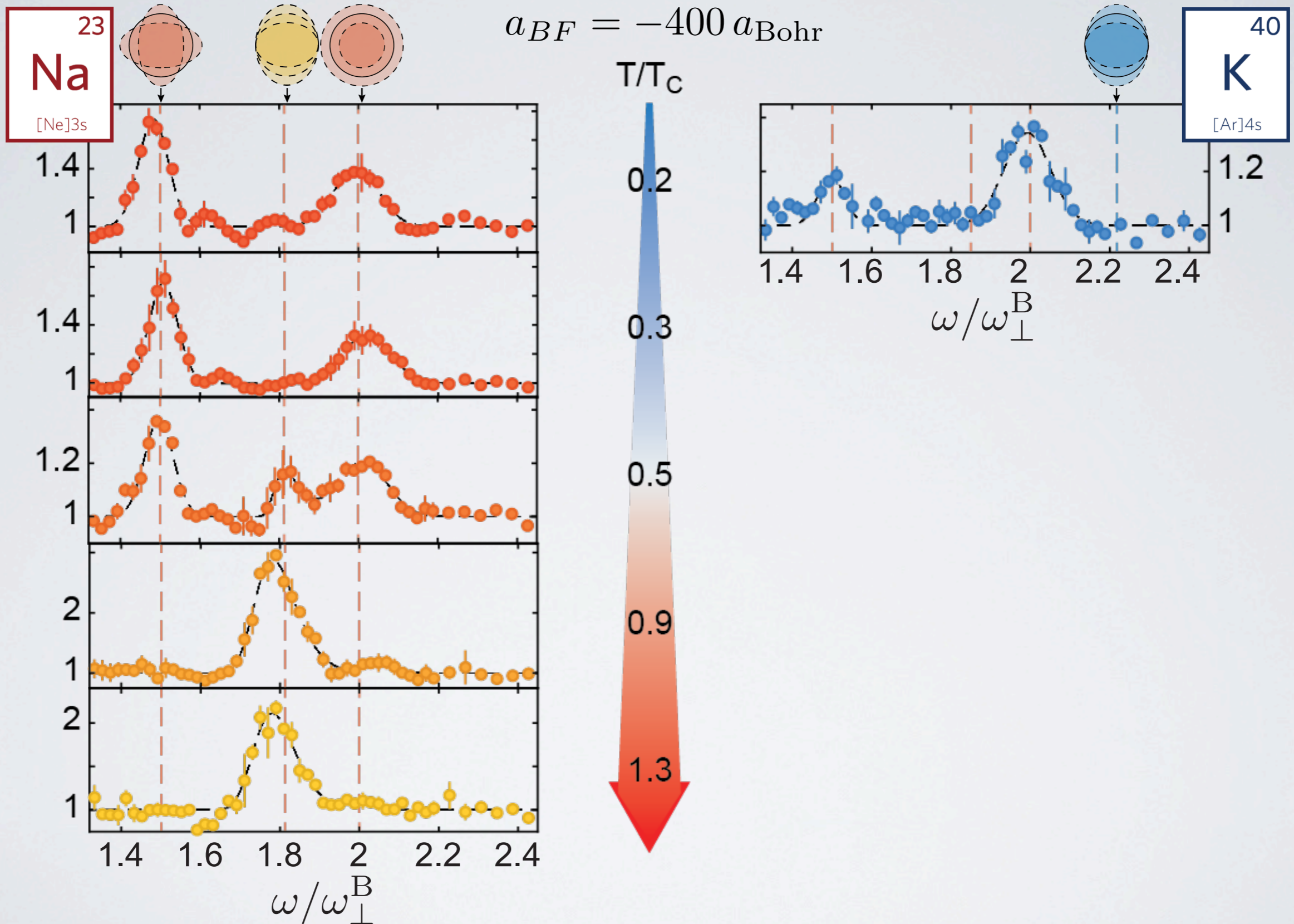


# Collisionless to hydrodynamic transition

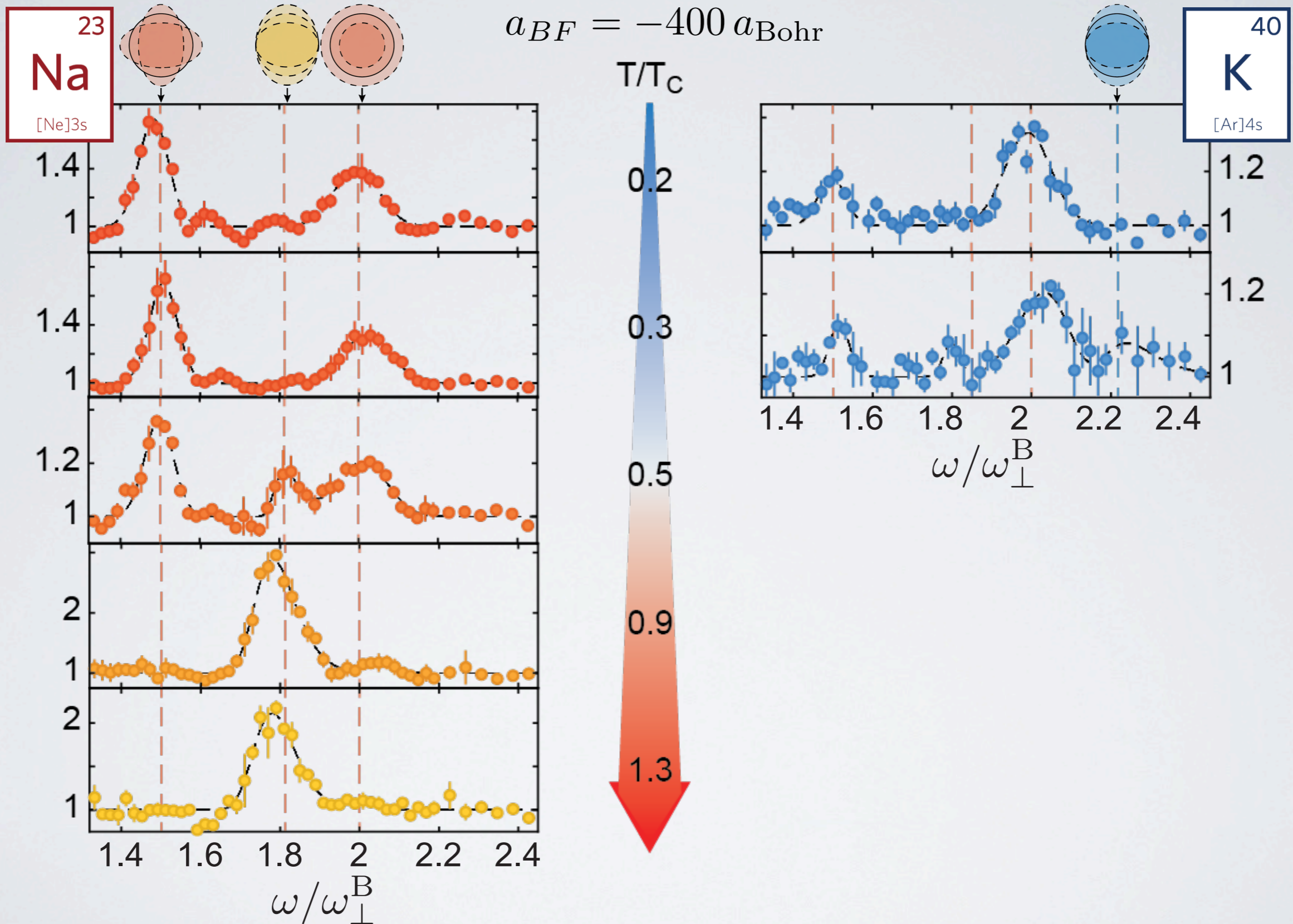




# Collisionless to hydrodynamic transition

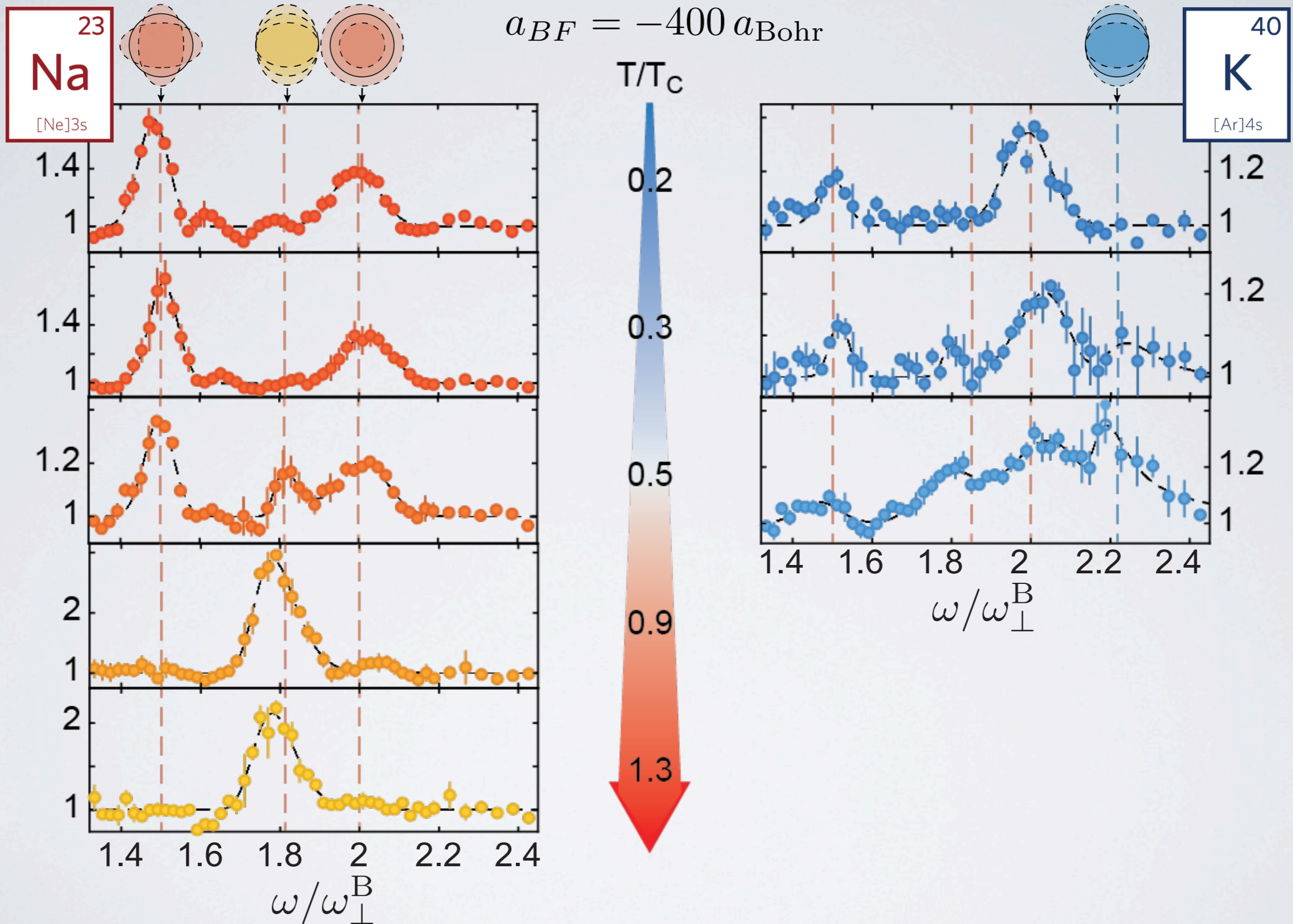


# Collisionless to hydrodynamic transition

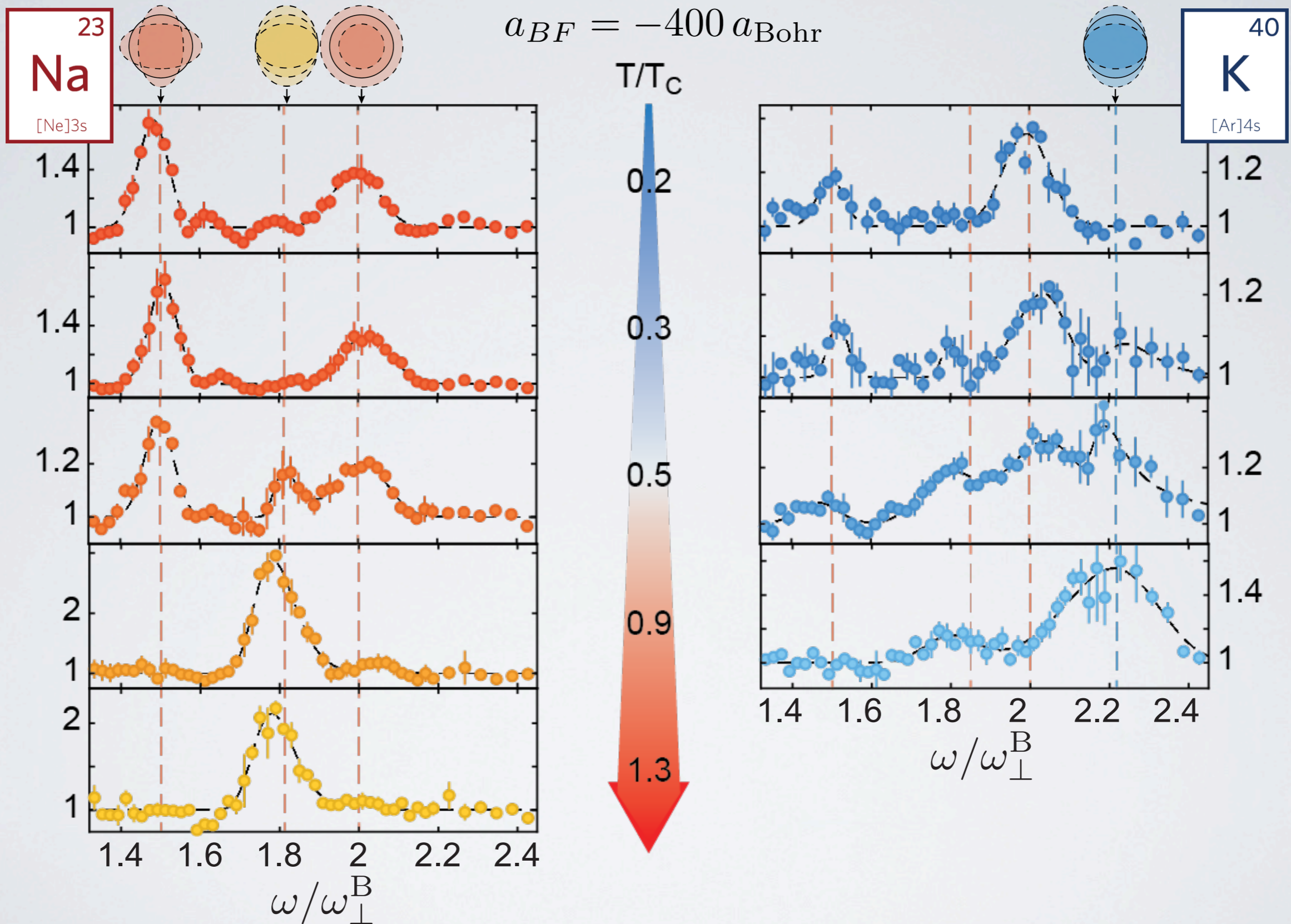




# Collisionless to hydrodynamic transition

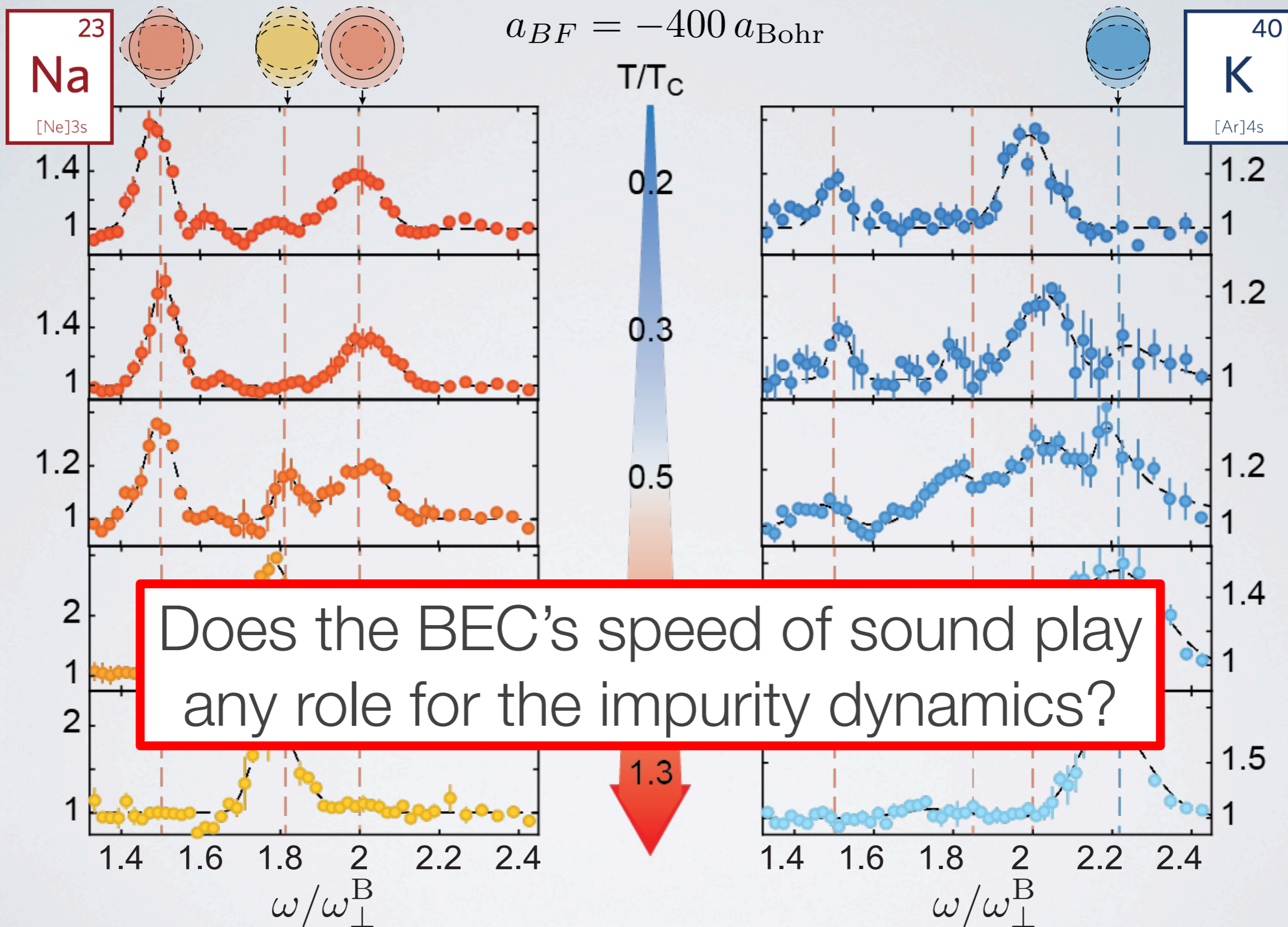


# Collisionless to hydrodynamic transition

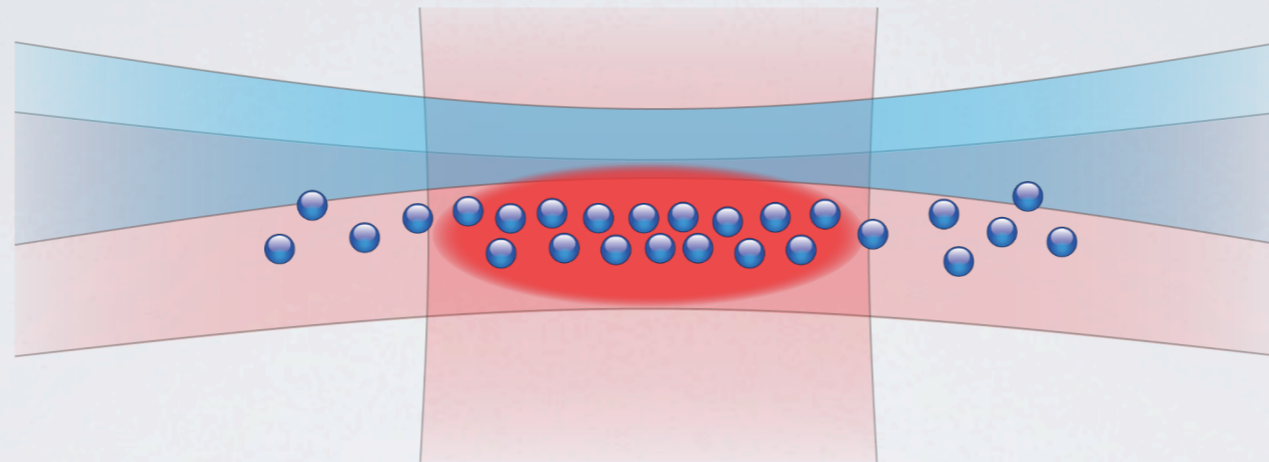
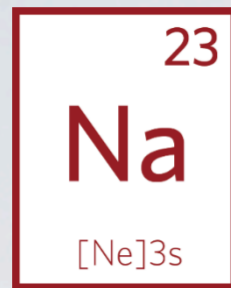




# Collisionless to hydrodynamic transition

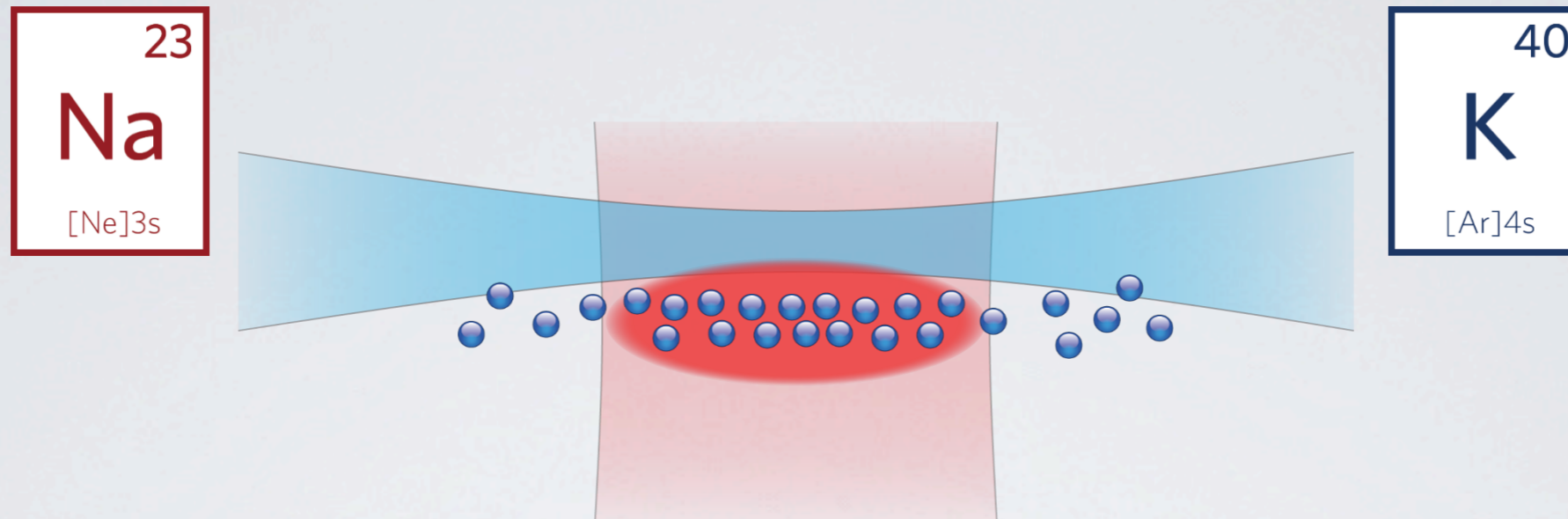


# Dipole oscillations in a Bose-Fermi mixture

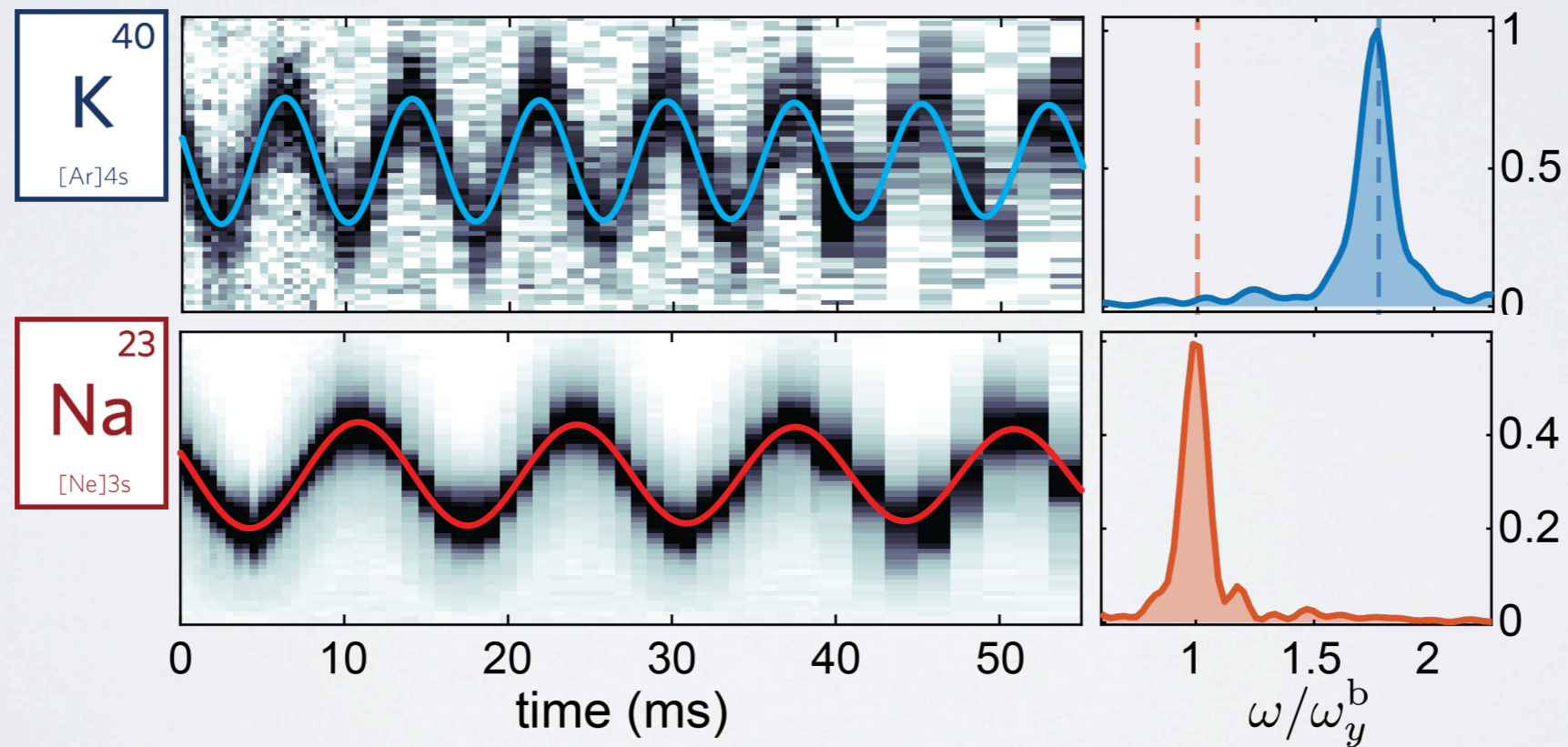




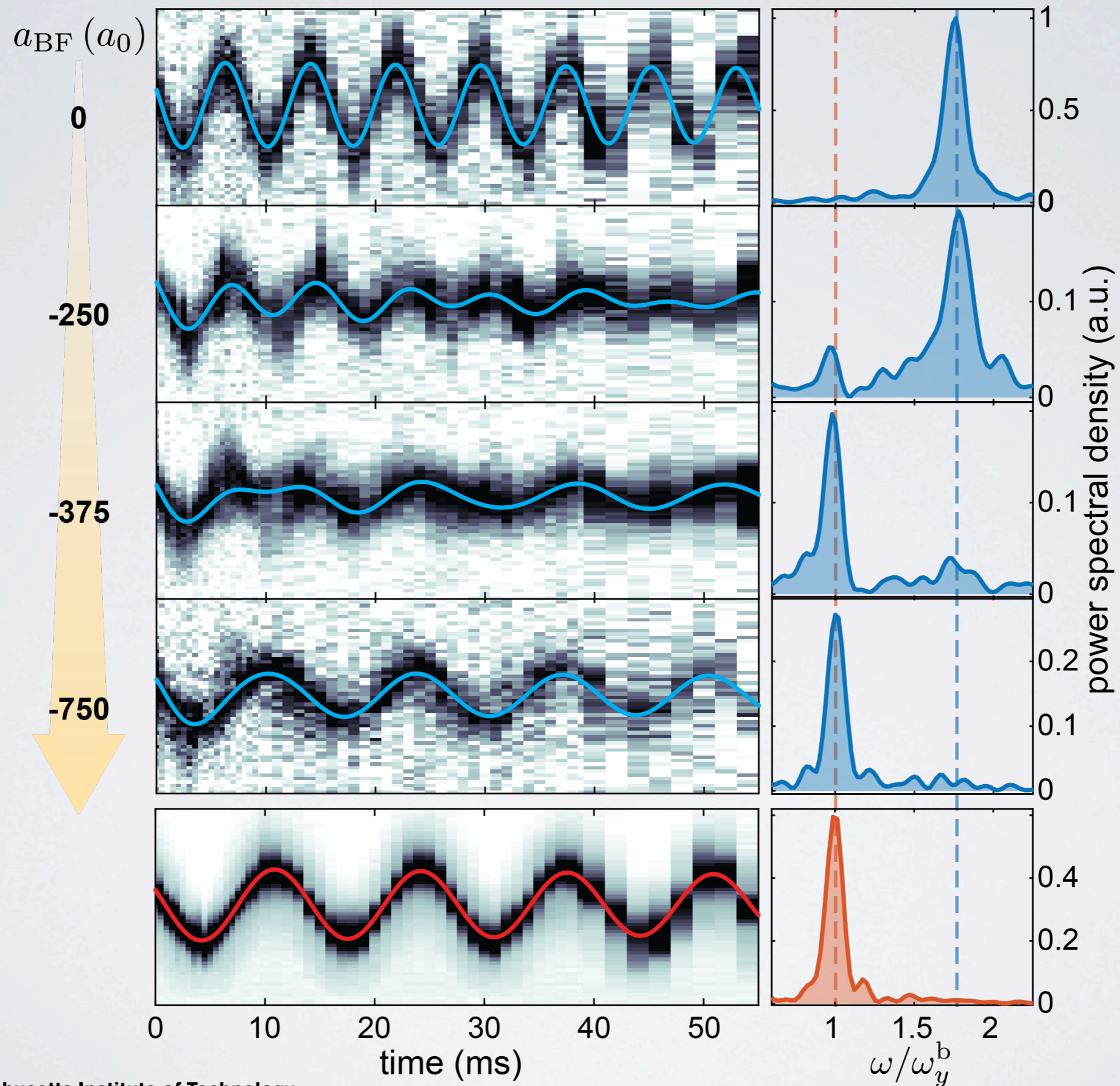
# Dipole oscillations in a Bose-Fermi mixture



$$a_{BF} \approx 0$$

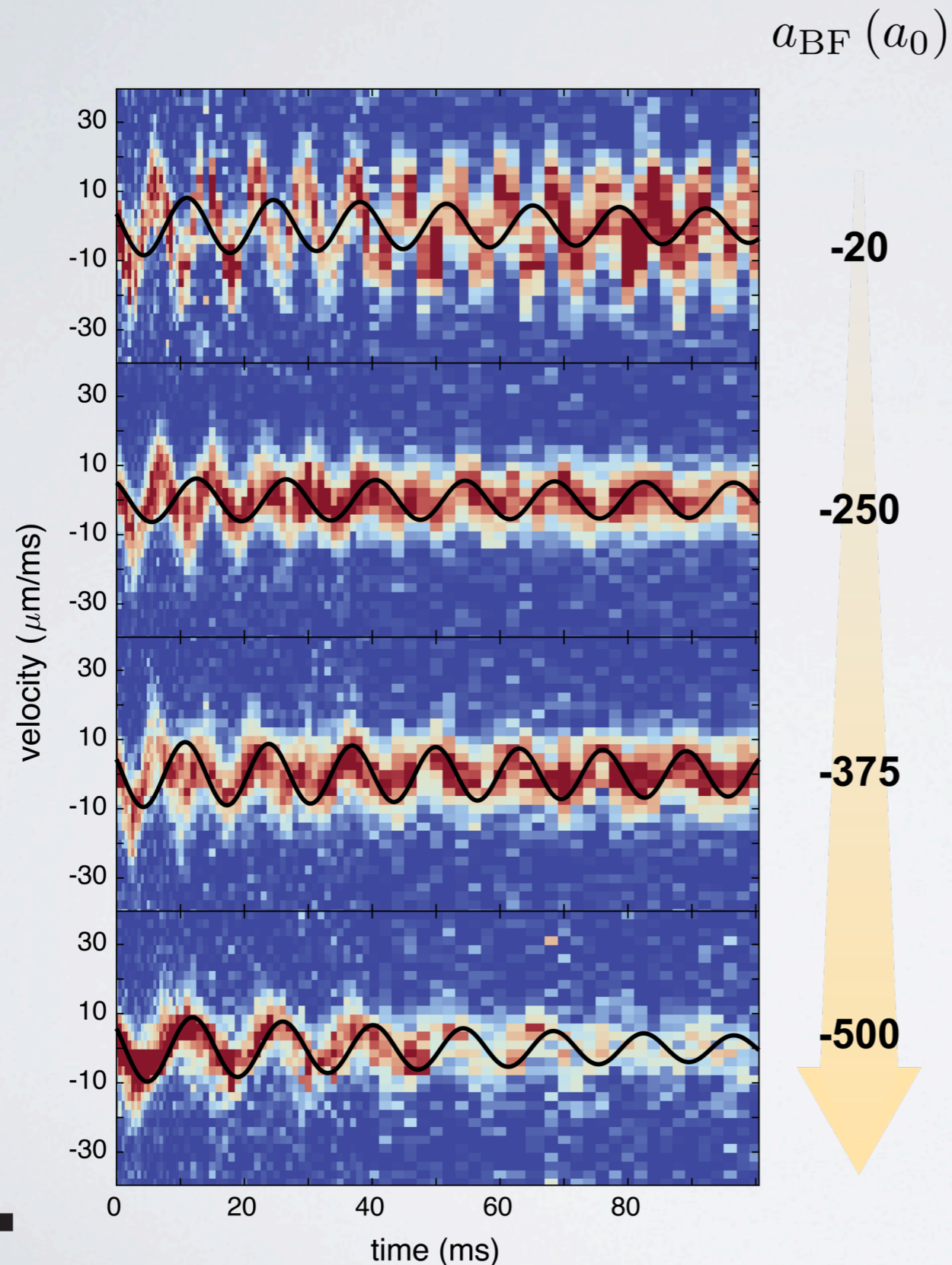


# Dipole oscillations in a Bose-Fermi mixture

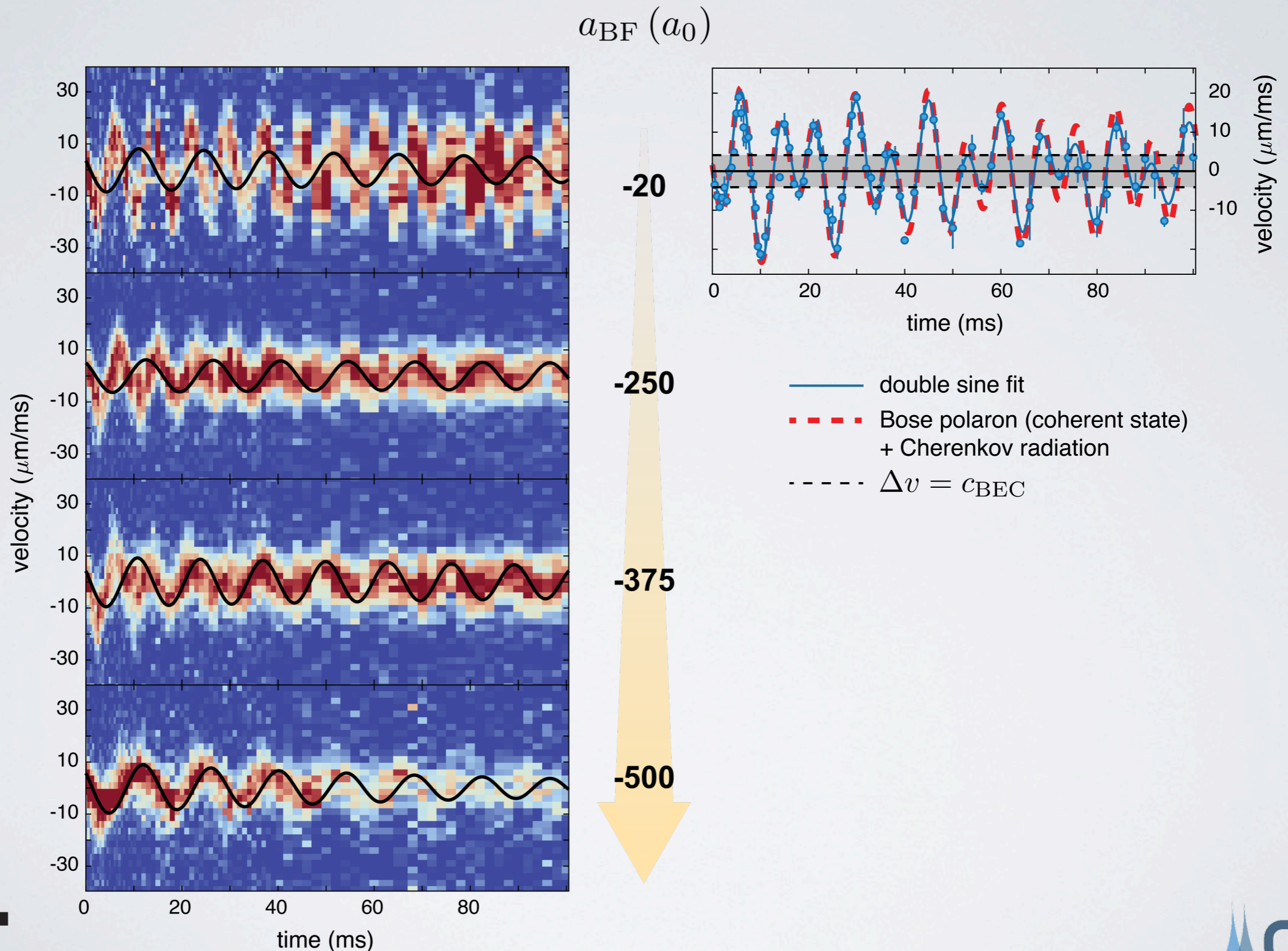




# The devil physics lies in the details!



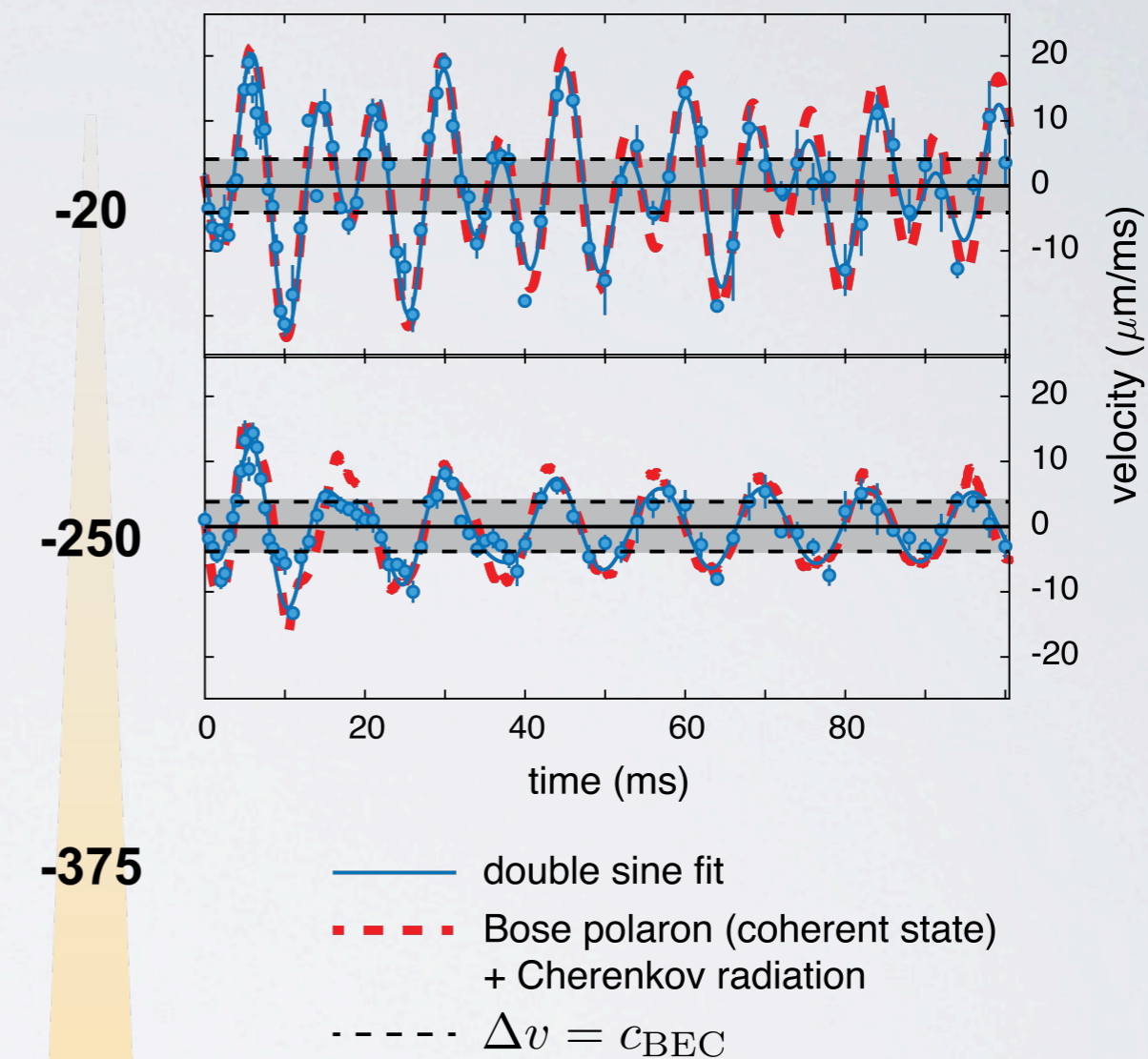
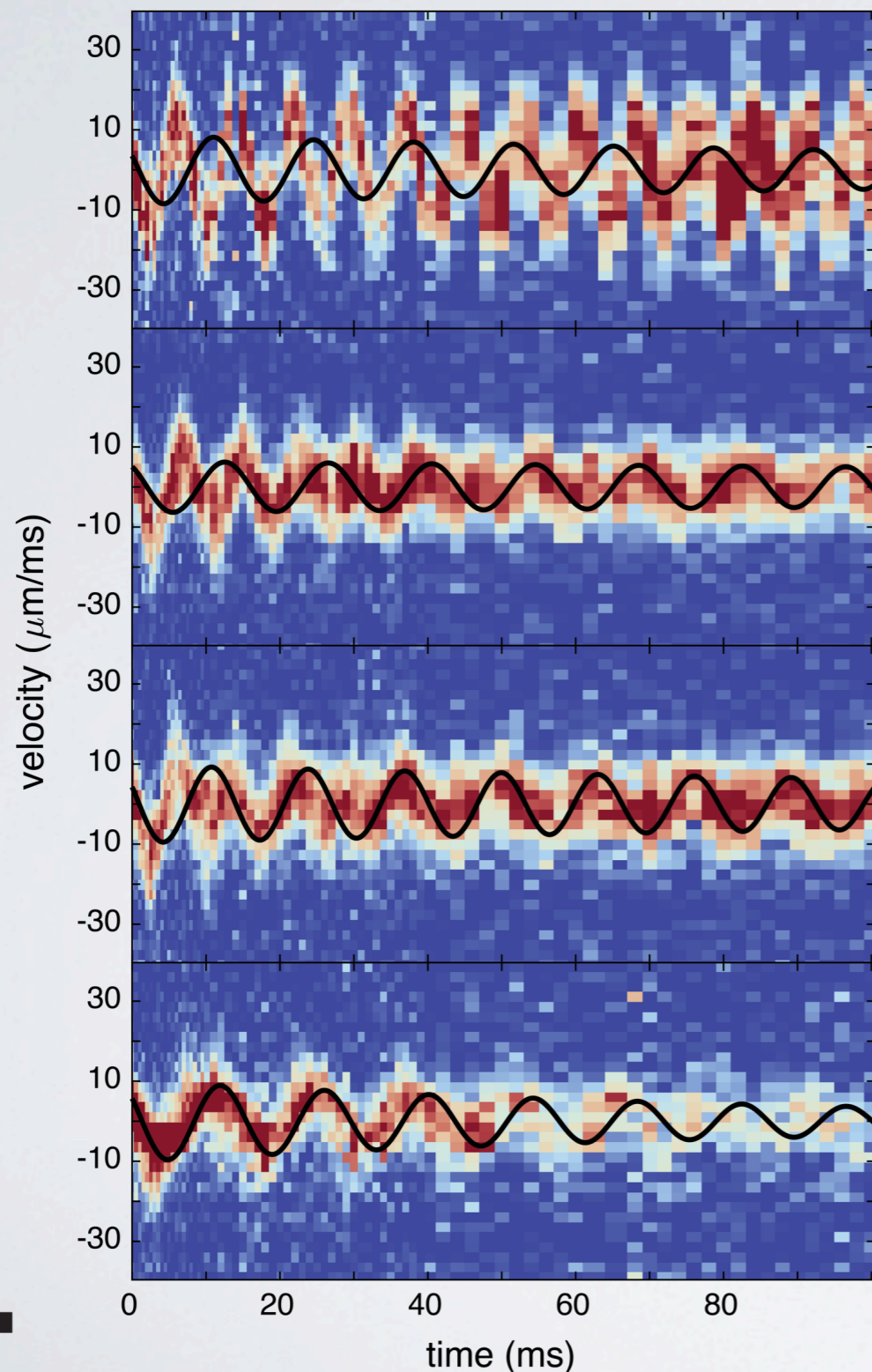
# The devil physics lies in the details!





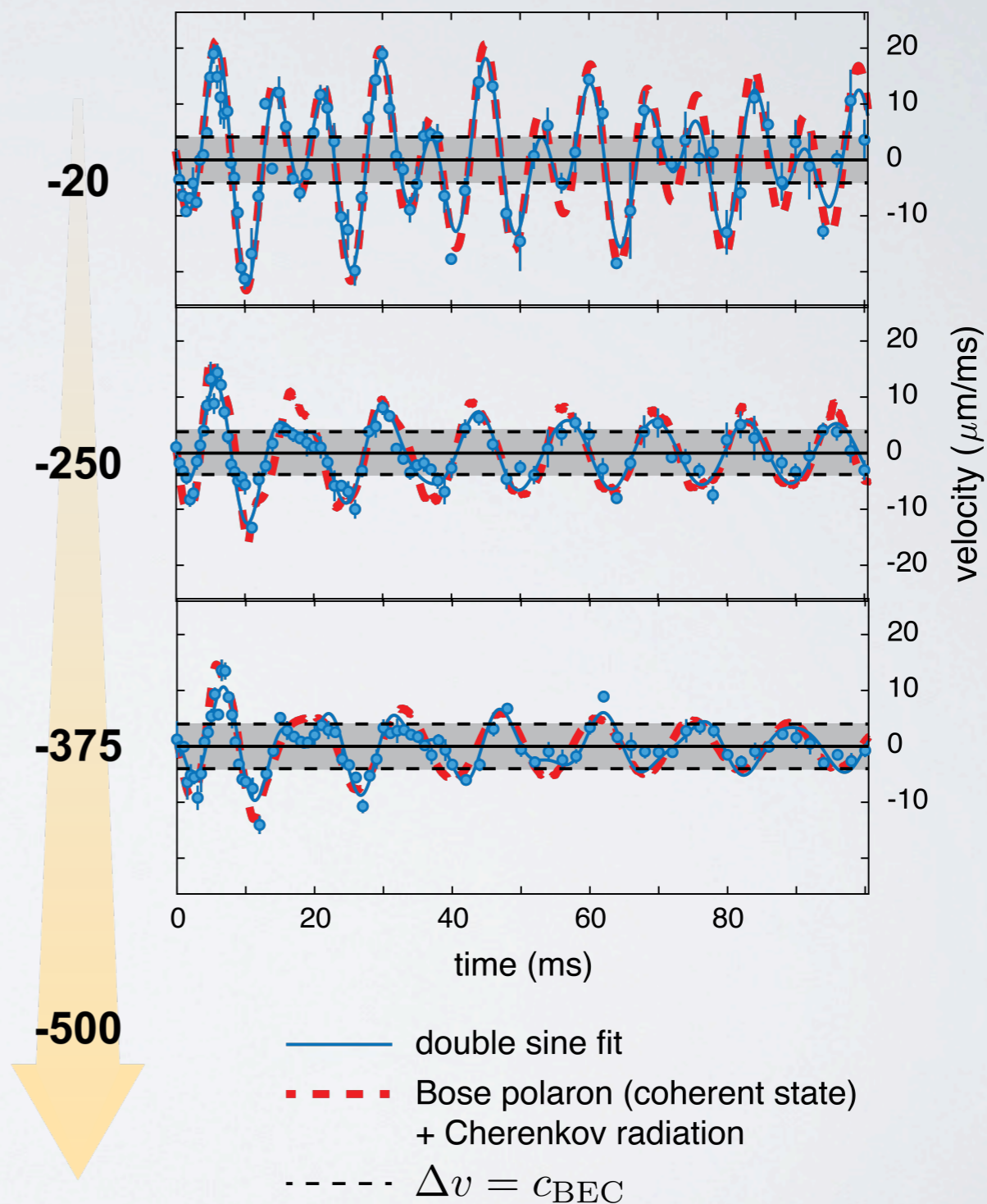
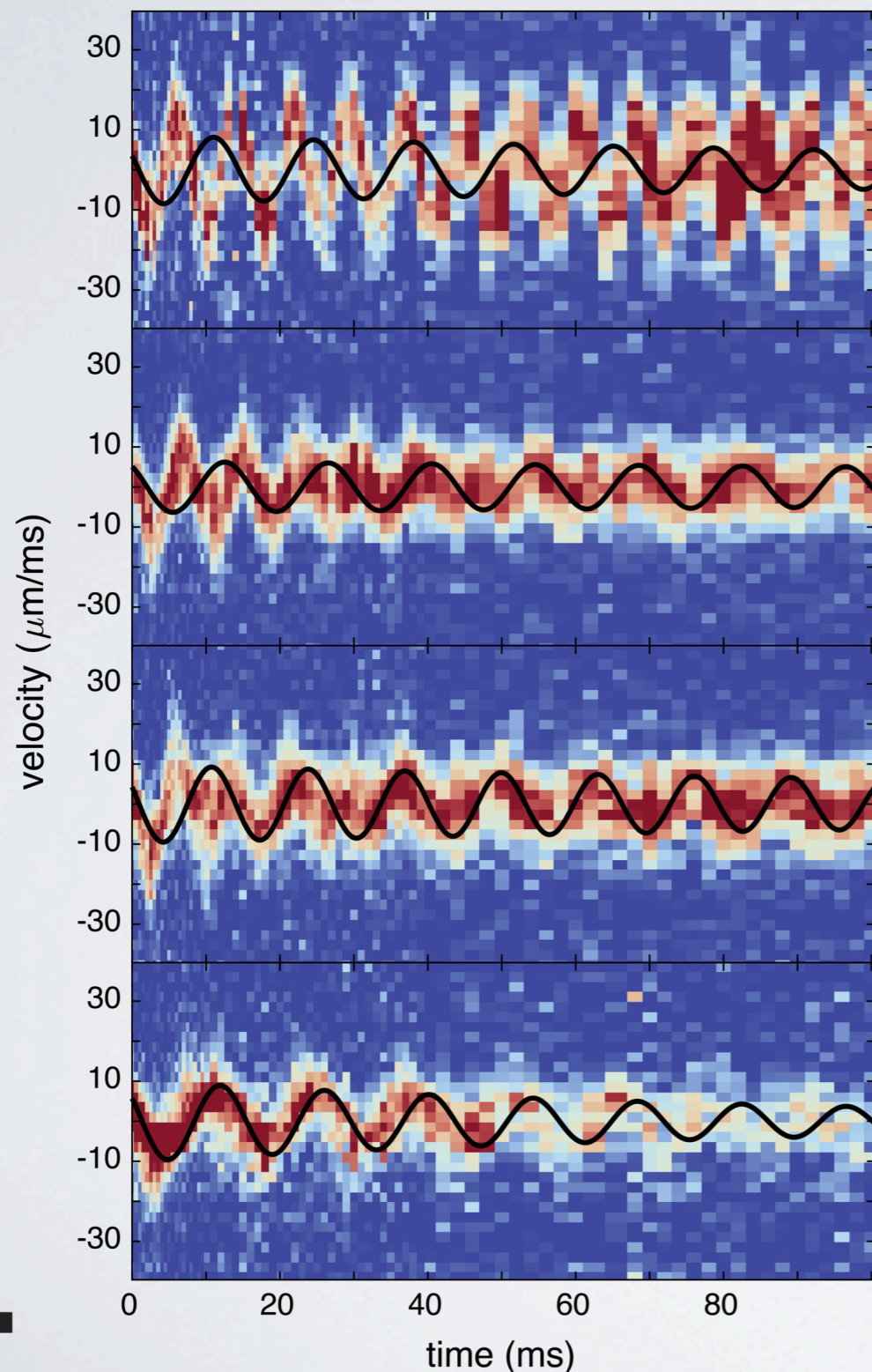
# The devil physics lies in the details!

$a_{\text{BF}} (a_0)$



# The devil physics lies in the details!

$a_{\text{BF}} (a_0)$



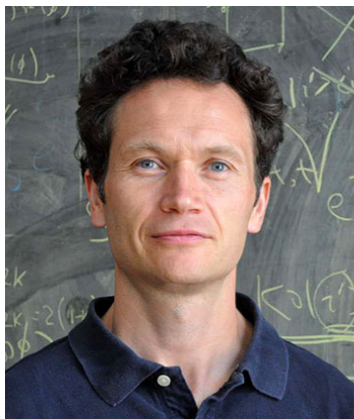
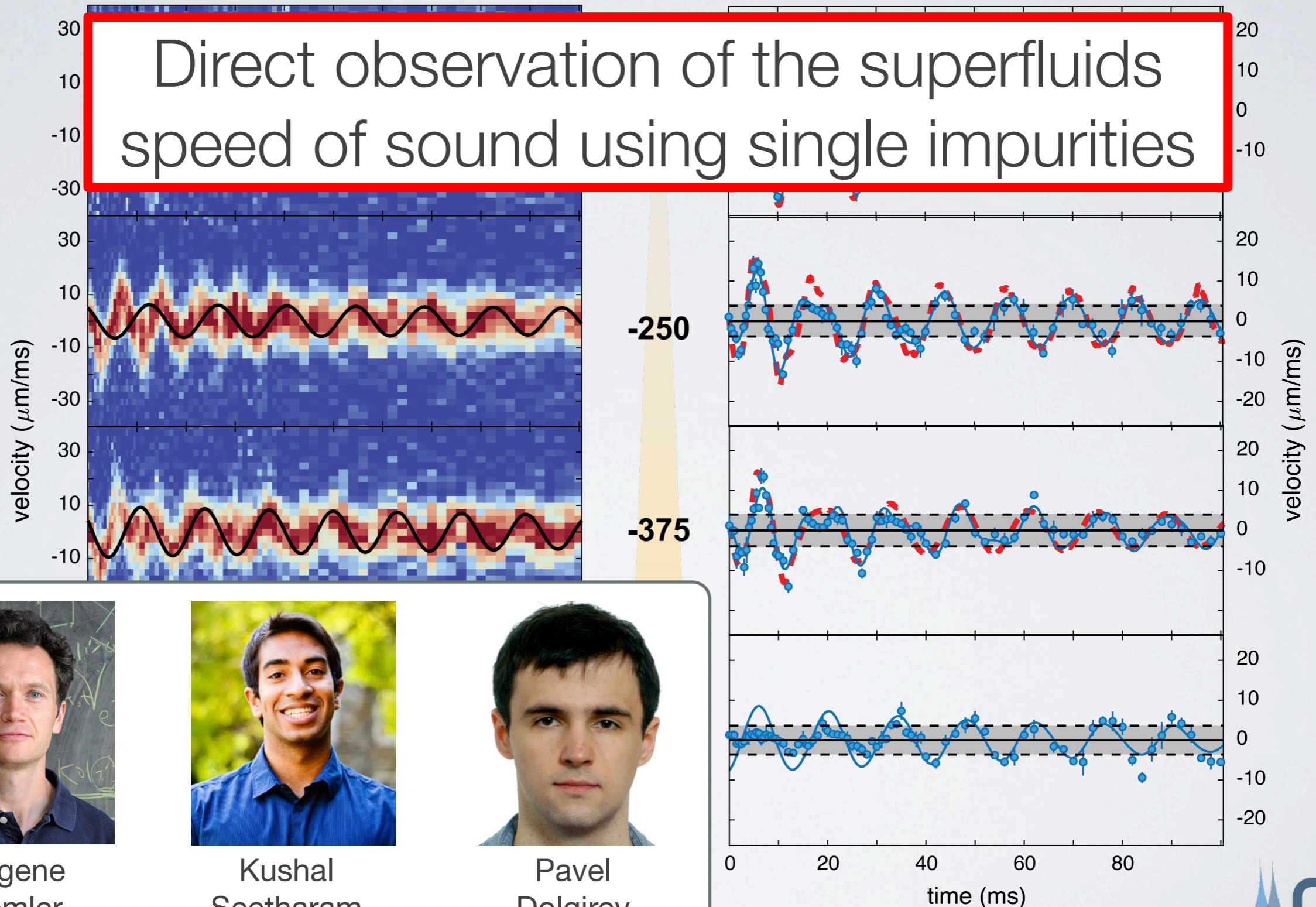


# The devil physics lies in the details!

- double sine fit
- - - Bose polaron (coherent state) + Cherenkov radiation
- - -  $\Delta v = c_{\text{BEC}}$

$a_{\text{BF}} (a_0)$

Direct observation of the superfluids speed of sound using single impurities



Eugene Demler



Kushal Seetharam



Pavel Dolgirev



# The Fermi1 team behind the work:



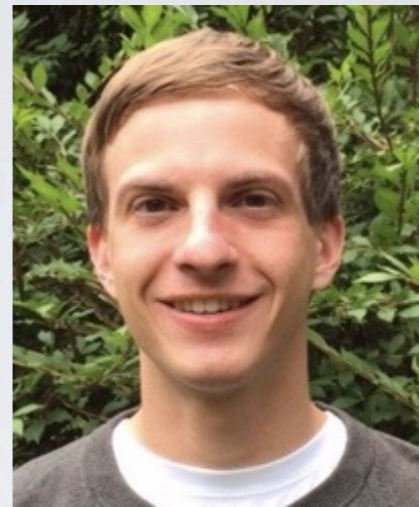
Zoe  
Yan



Yiqi  
Ni



Alex  
Chuang



Eric  
Wolf



Martin  
Zwierlein

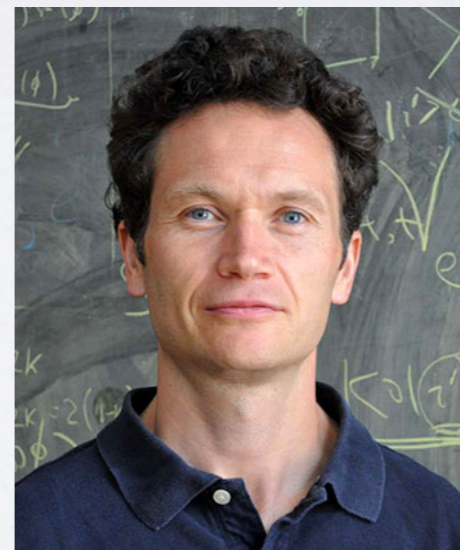
## Theory collaborators



Kushal  
Seetharam



Pavel  
Dolgirev

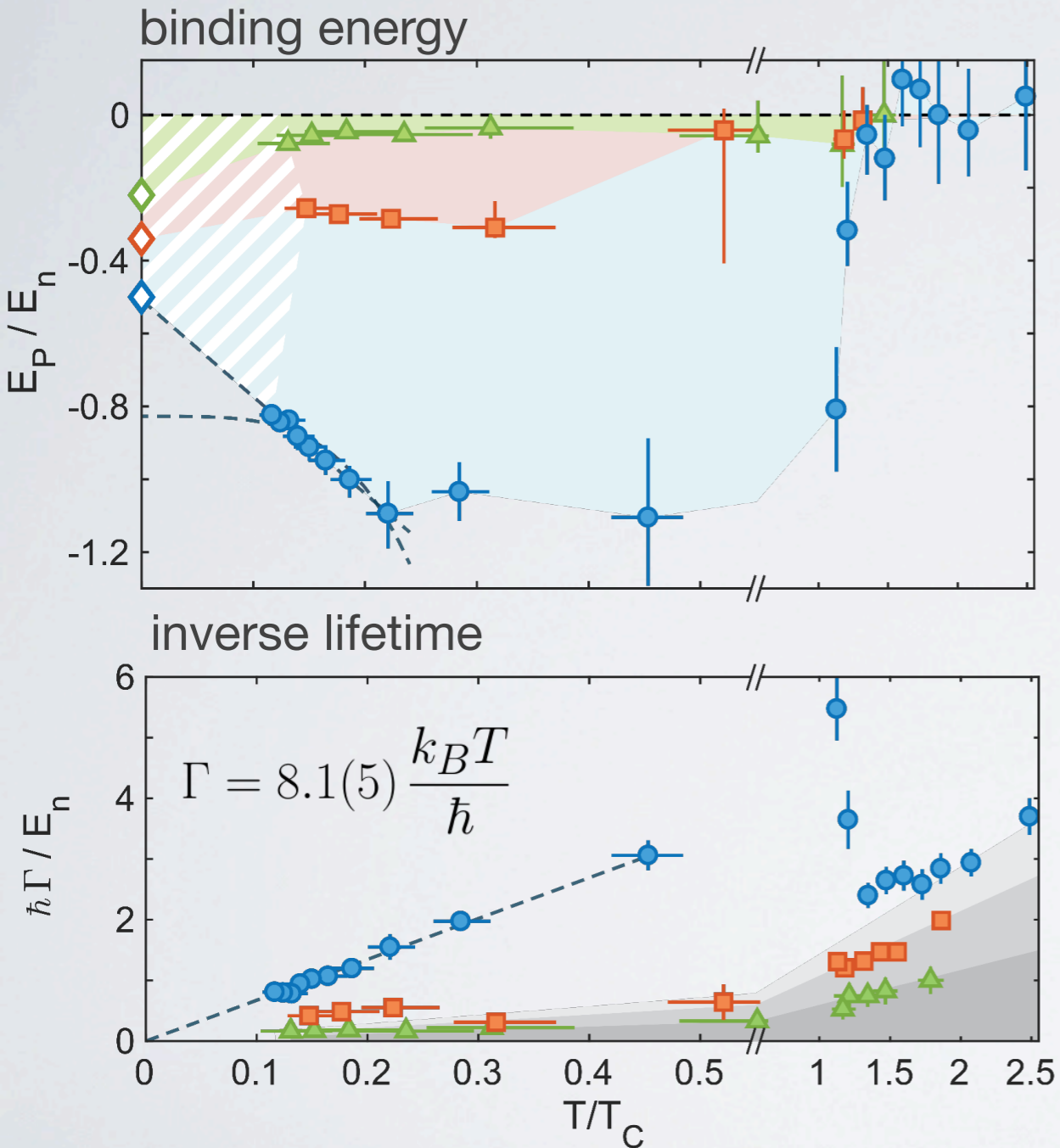


Eugene  
Demler

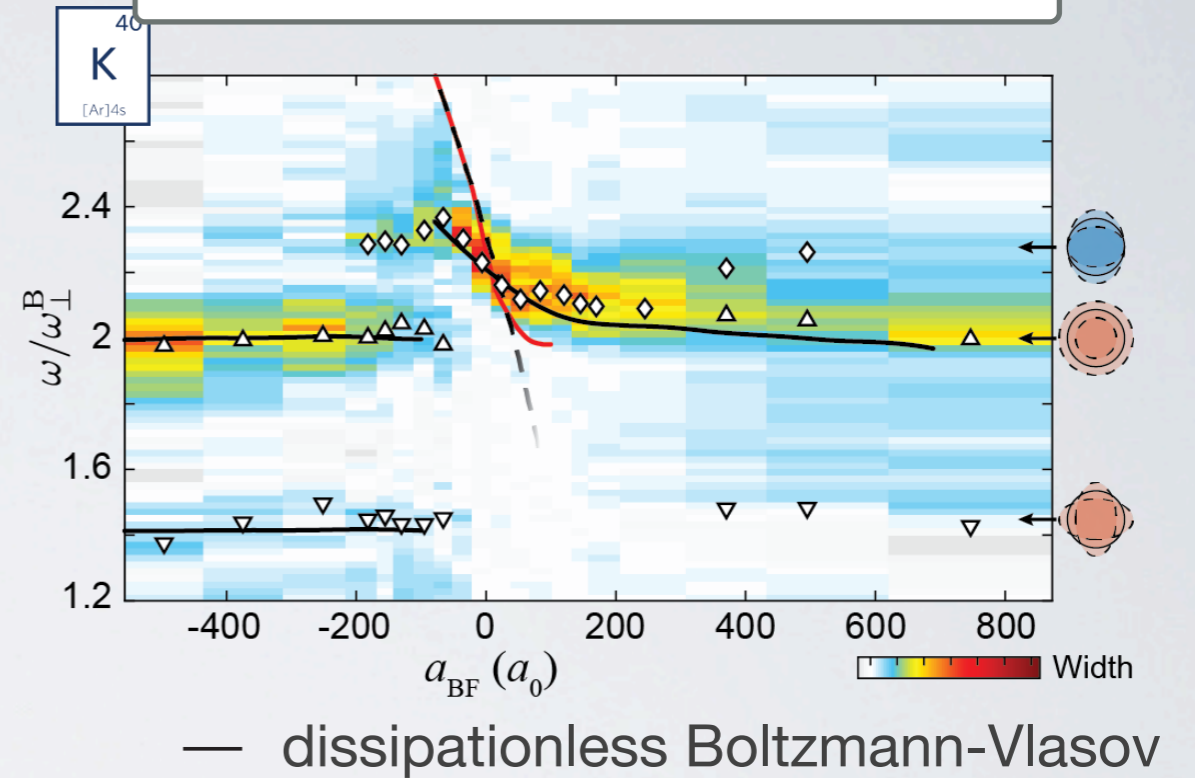


# Summary

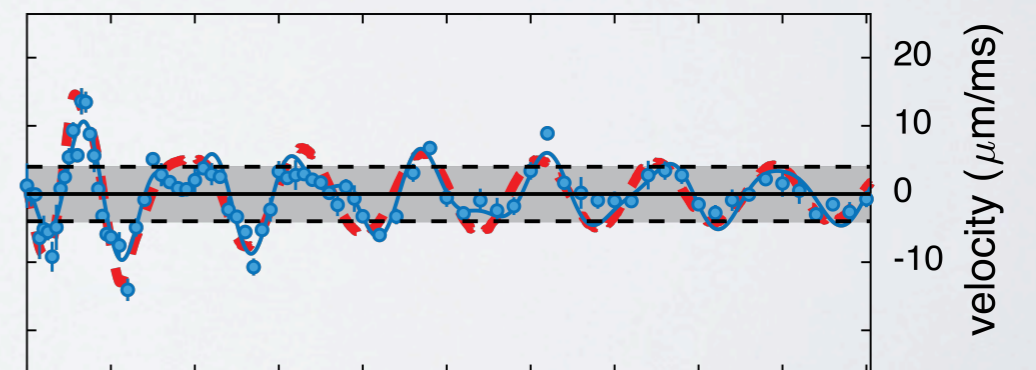
## Bose polarons near quantum criticality



## Dissipationless flow in a Bose-Fermi mixture



## Bose polarons emitting Cherenkov radiation



- double sine fit
- - - Bose polaron (coherent state) + Cherenkov radiation
- - -  $\Delta v = c_{\text{BEC}}$