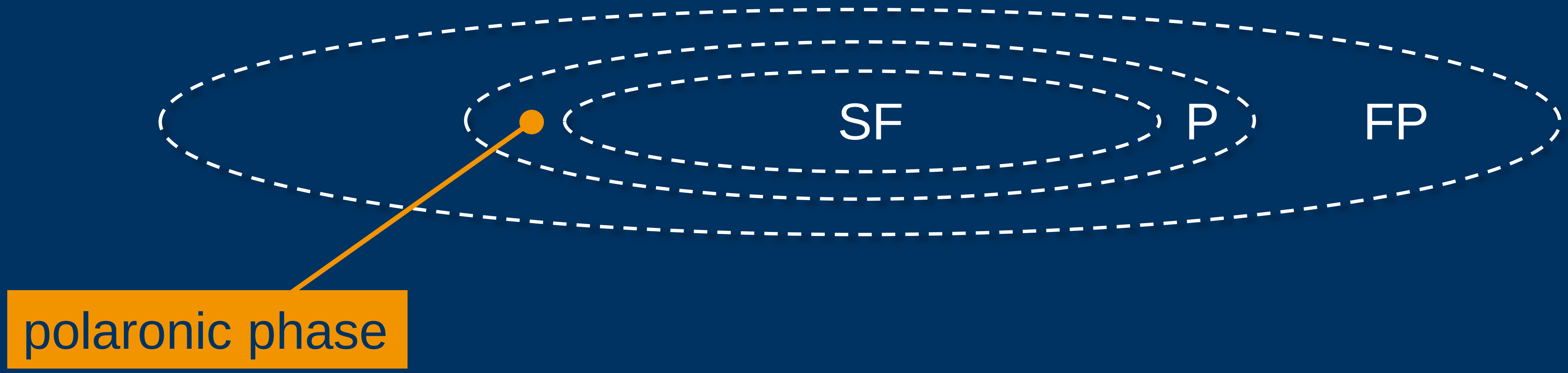
Quantum Mixtures with Ultracold Atoms, Varenna, 18-23 July 2022

Rudolf Grimm

Experiments with quantum mixtures II: Fermi polarons

Austrian Acad. of Sciences
IQI
universität innsbruck
Inst. of Experimental Physics

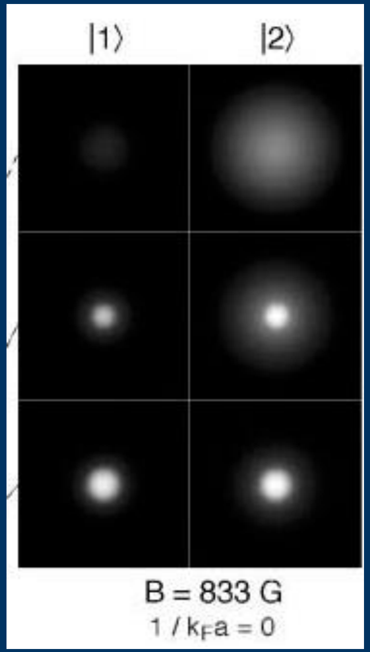
population-imbalanced, resonant Fermi gas in a harmonic trap



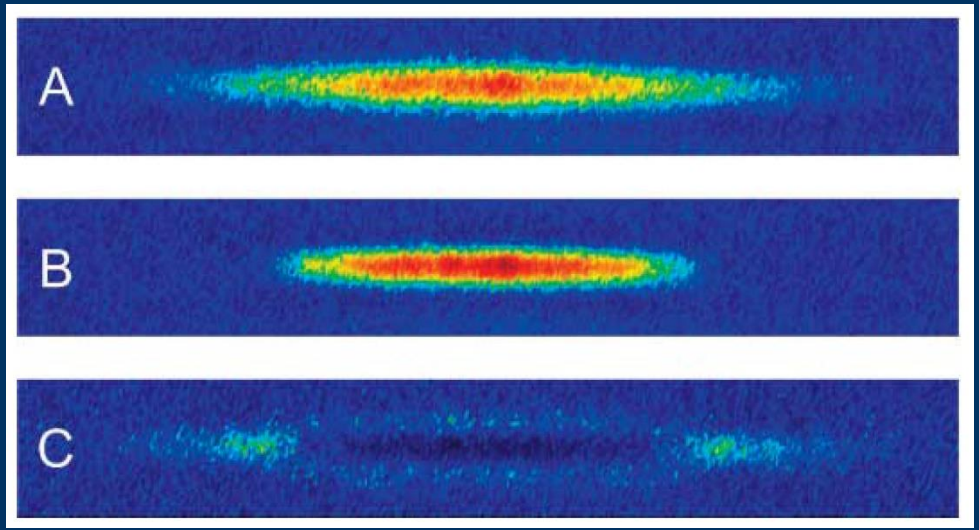
early experimental work on
phase separation

Ketterle group at MIT
Zwierlein et al., Science 311, 492 (2006)

Hulet group at Rice
Partridge et al., Science 311, 503 (2006)

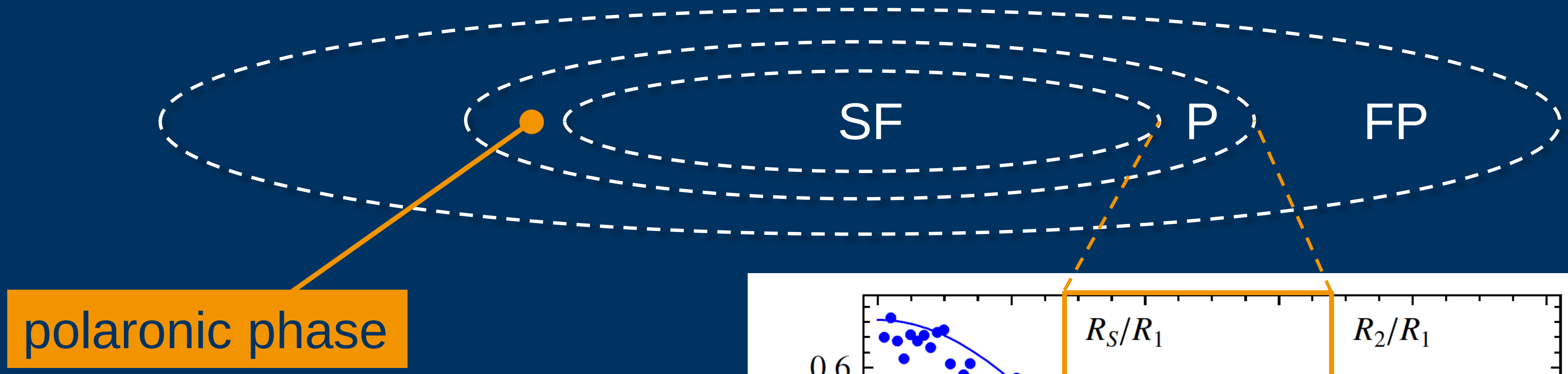


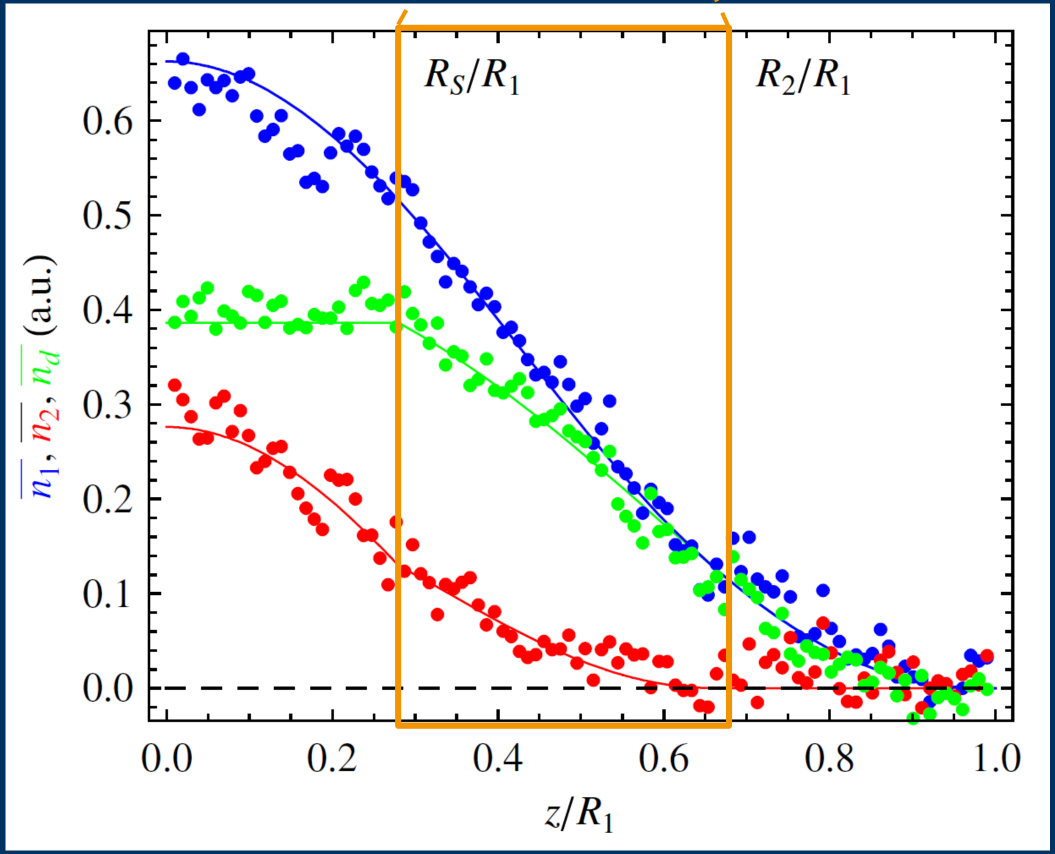
MIT



Rice

population-imbalanced, resonant Fermi gas in a harmonic trap





ENS Paris

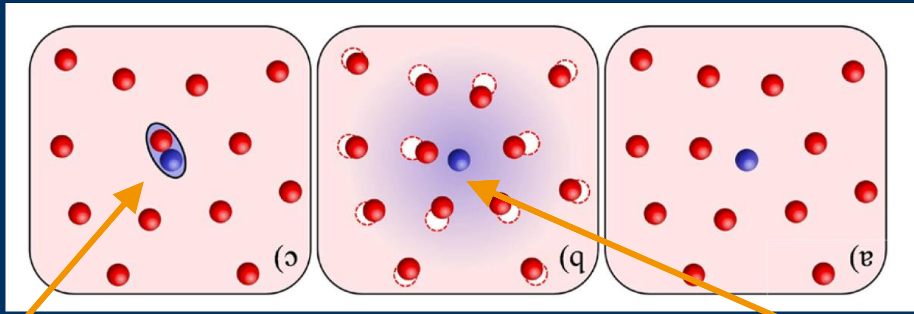
S. Nascimbène et al., PRL 103, 170402 (2009)

effective mass measured by collective oscillations

polaron spectroscopy

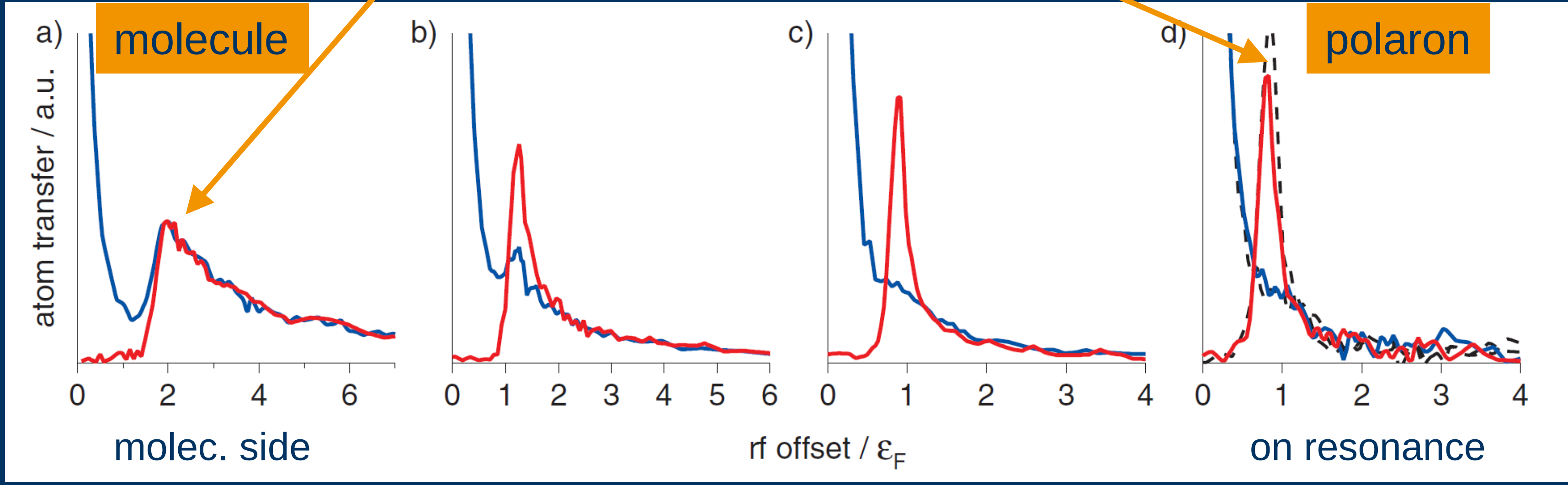
Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms

André Schirotzek, Cheng-Hsun Wu, Ariel Sommer, and Martin W. Zwierlein
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 17 February 2009; revised manuscript received 9 April 2009; published 8 June 2009)



A. Schirotzek et al.,
PRL 102, 230402 (2009)

radio-freq.
“ejection”
spectroscopy



Li-K team

poster on Tue


Isabella Fritsche


Cosetta Baroni


Erich Dobler

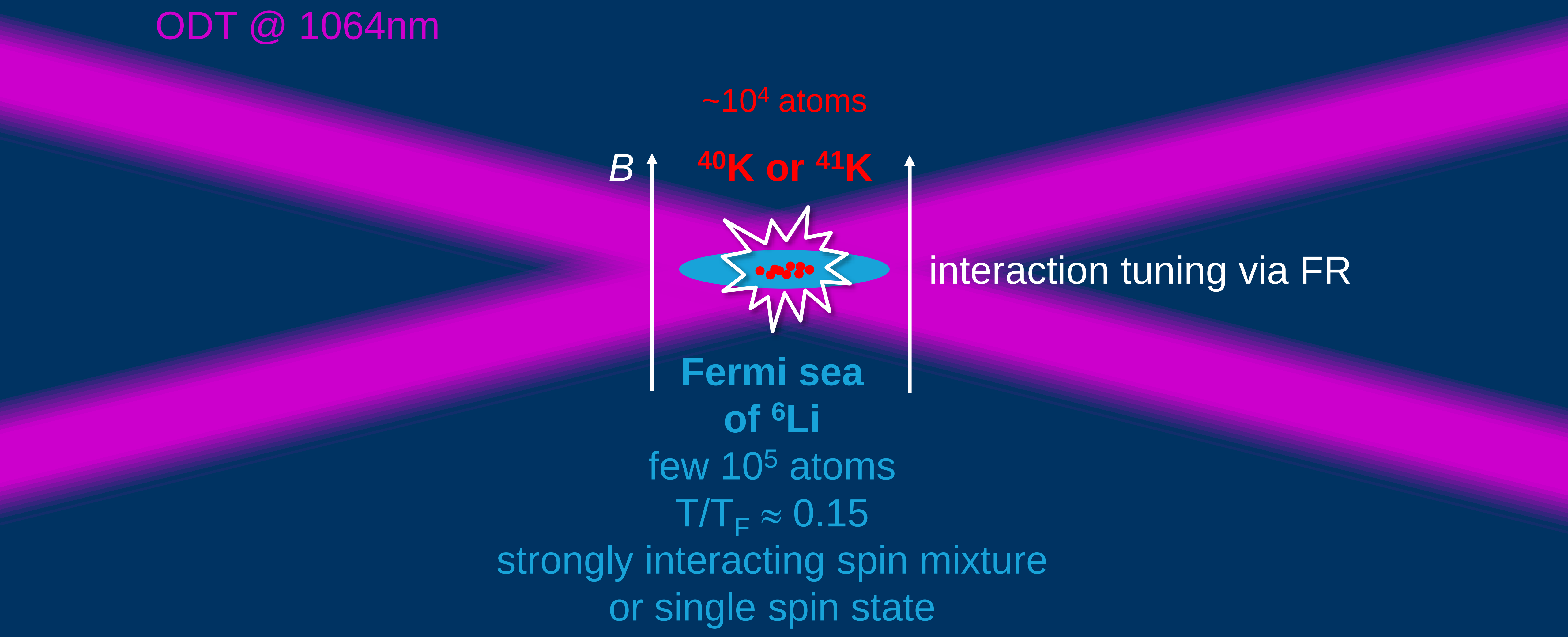

Adrian König


Bo Huang

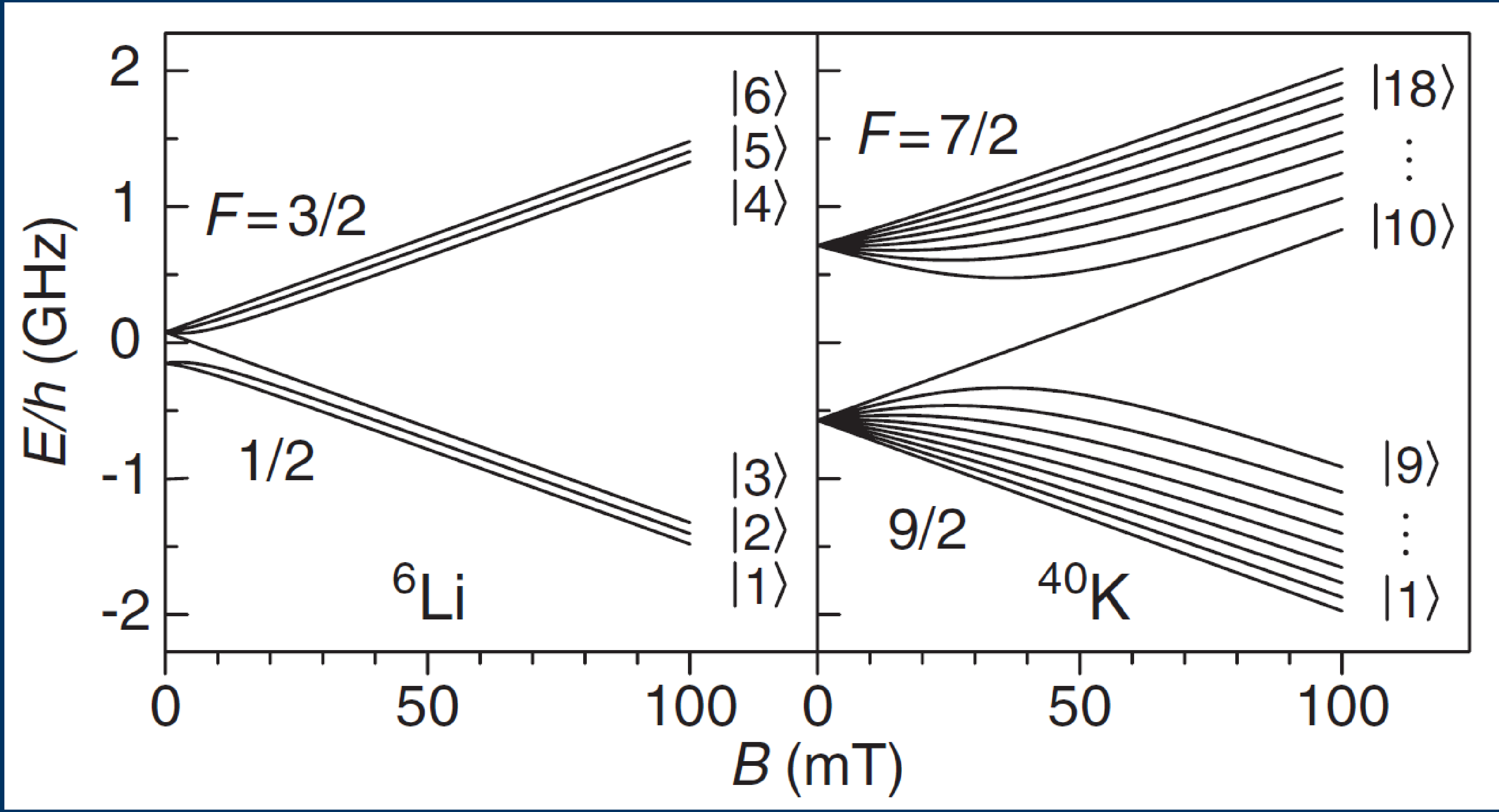

Emil Kirilov


RG

typical experimental situation



spin states

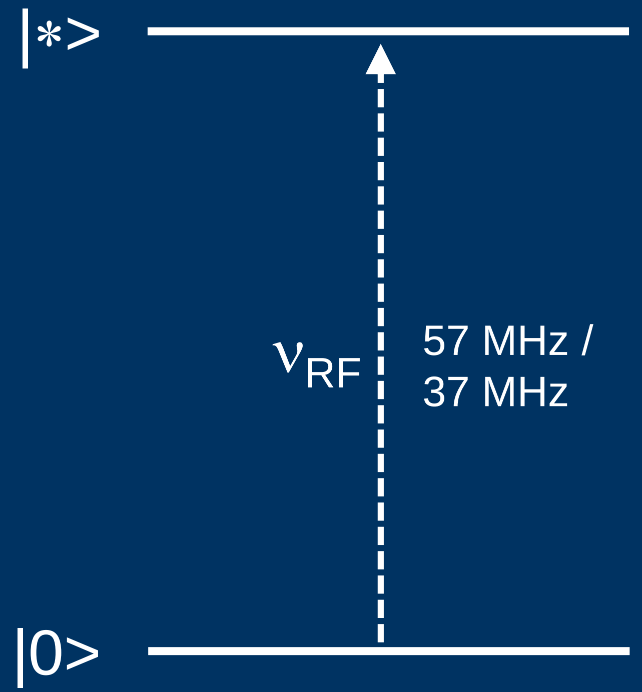


E/h (GHz)
2
1
0
-1
-2
F=3/2
1/2
|6⟩
|5⟩
|4⟩
|3⟩
|2⟩
|1⟩
6Li
F=7/2
9/2
|18⟩
⋮
|10⟩
|9⟩
⋮
|1⟩
40K
0
50
100
0
50
100
B (mT)

radio-frequency “injection” spectroscopy

impurity
spin states

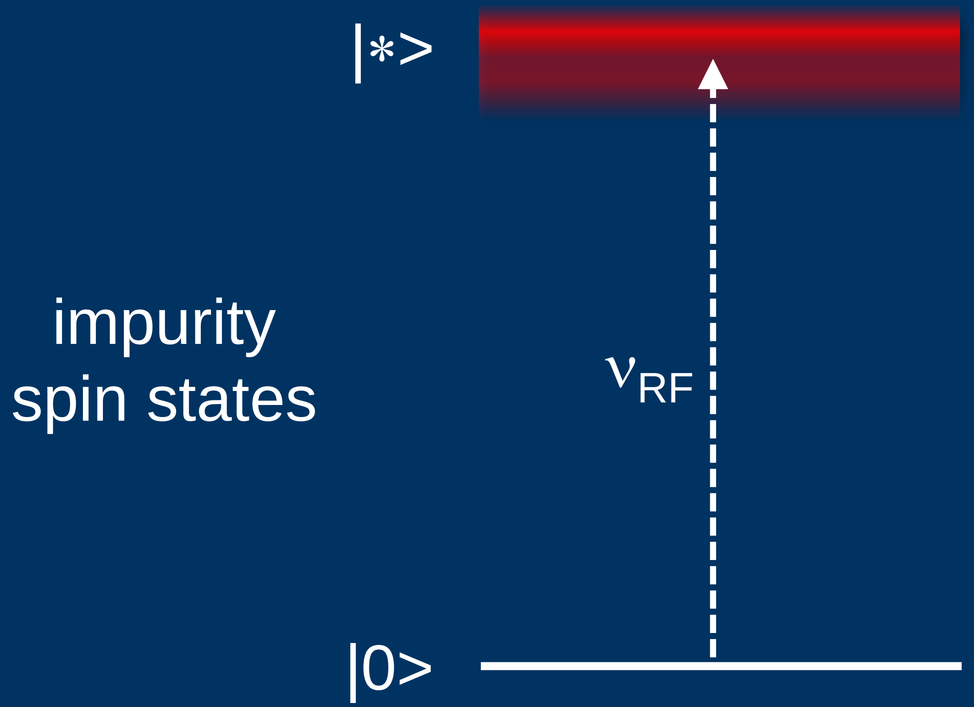
tunable interaction
with ^{6}Li medium



weakly interacting
with ^{6}Li medium
(preparation)

	^{41}K bosons	^{40}K fermions
Feshbach resonances (~1G wide, very similar)	335.1 G	154.7 G
|*>	$F = 1$, $m_F = 1$	$F = 9/2$, $m_F = -5/2$
|0>	$F=1$, $m_F = 0$	$F = 9/2$, $m_F = -7/2$

radio-frequency “injection” spectroscopy



spectral function

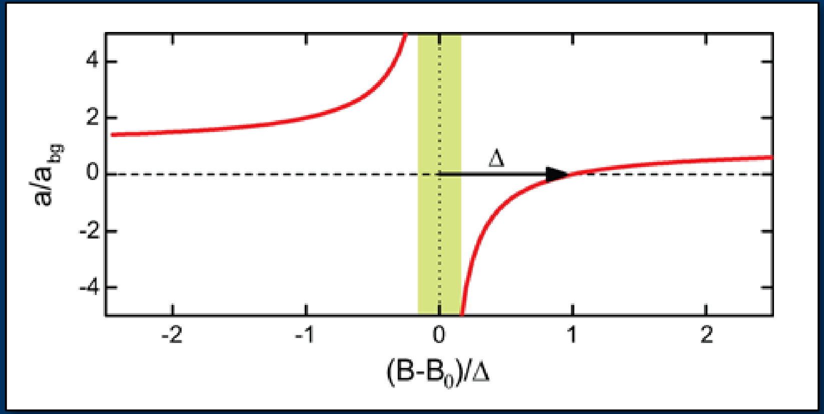
probed by RF transfer

“injection” spectroscopy

details on RF pulses:

- π-pulses w/o ^{6}Li medium
- 1-ms Blackman pulses (no side lobes)
- spectral resolution ~700 Hz (~4% E_F)

interaction parameter



dimensionless

$$X \equiv -\frac{1}{k_F a}$$

Fermi wave number
(interparticle distance)$^{-1}$

$$E_F = \frac{(\hbar k_F)^2}{2m}$$

s-wave
scattering length

tunable via
Feshbach resonance

typically $1/k_F \approx 4000\, a_0$

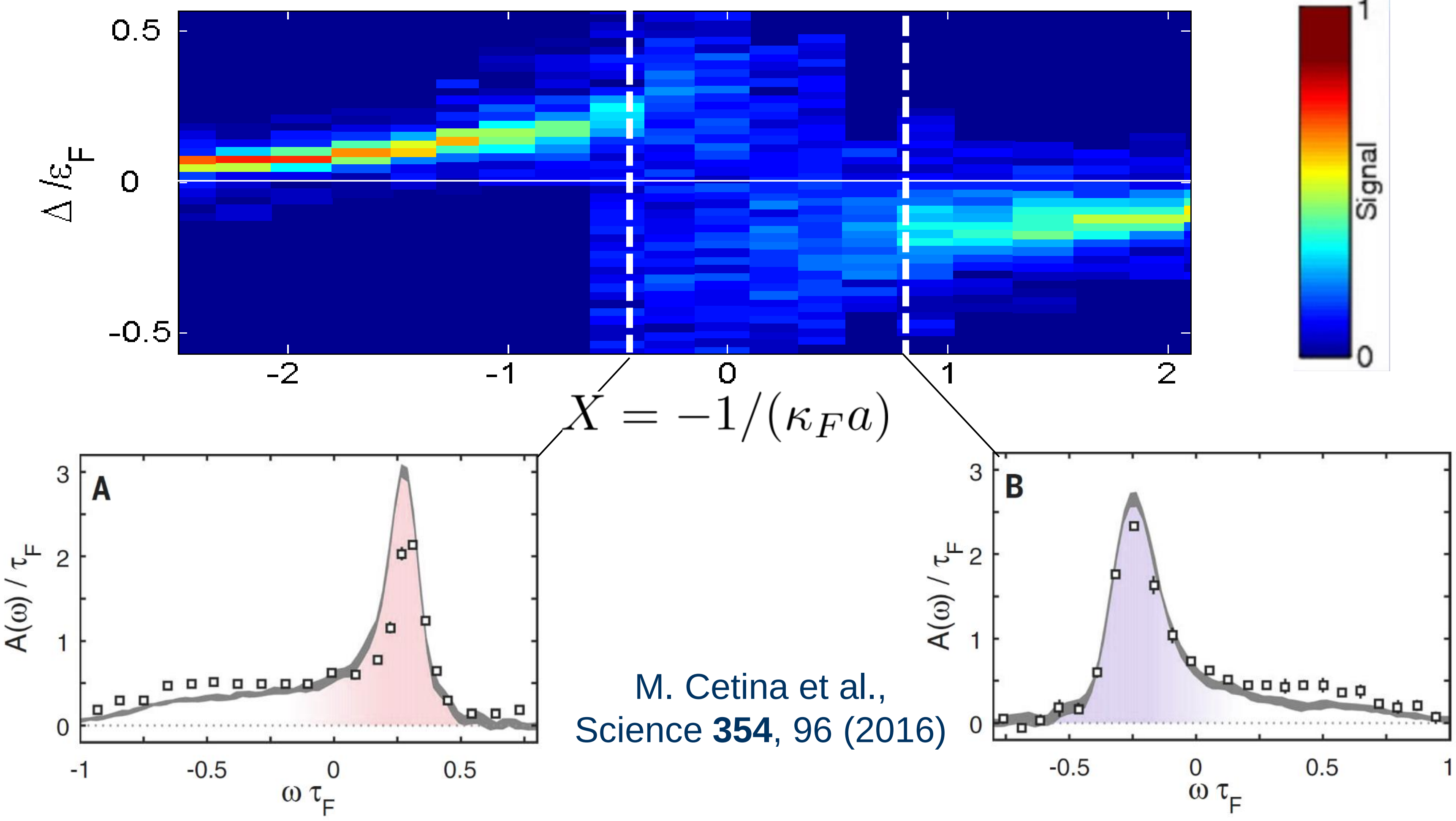
strongly interacting regime ($|X| \leq 1$)
just ±13mG wide,
experimentally very challenging

spectral response

^{40}K

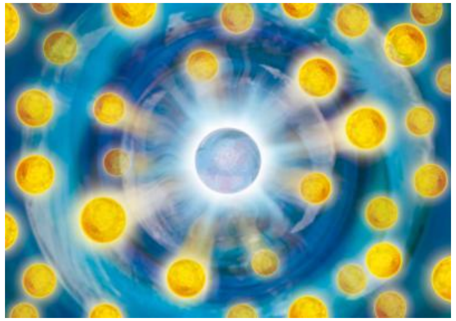
C. Kohstall, M. Zaccanti et al.,
Nature **485**, 615 (2012)

population
transfer
|0> → |∗>

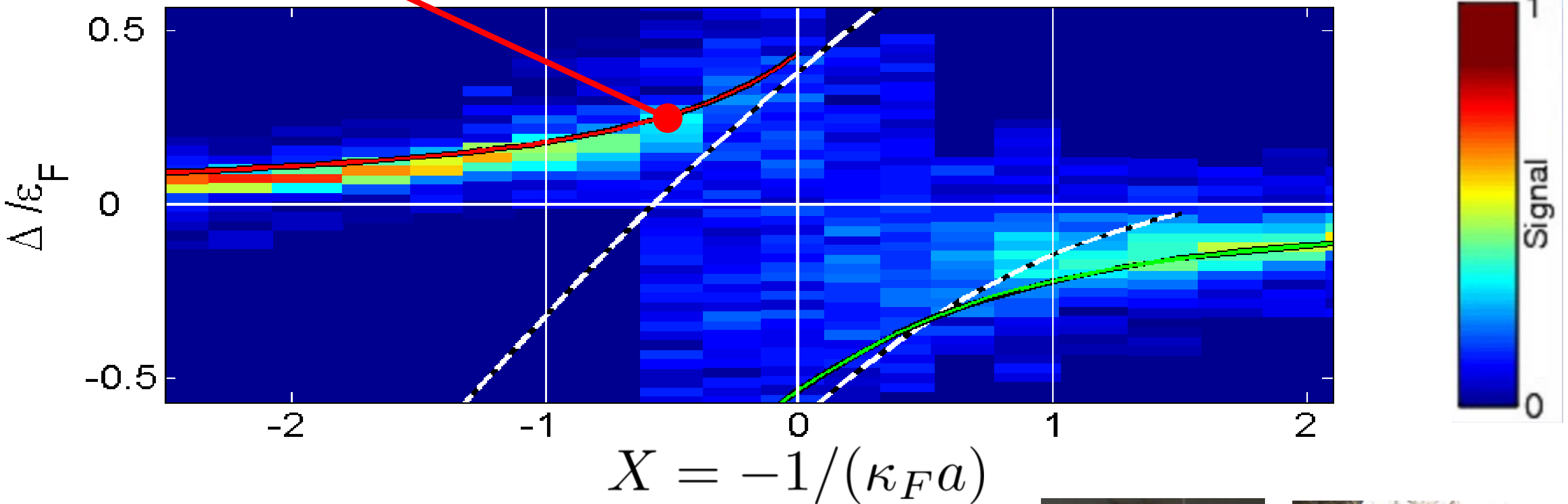


M. Cetina et al.,
Science **354**, 96 (2016)

spectral response



"repulsive polaron"
lifetime ms



theory: T-matrix approach
single particle-hole excitations

Pietro Massignan
ICFO, Spain

Georg Bruun
U Aarhus, Denmark

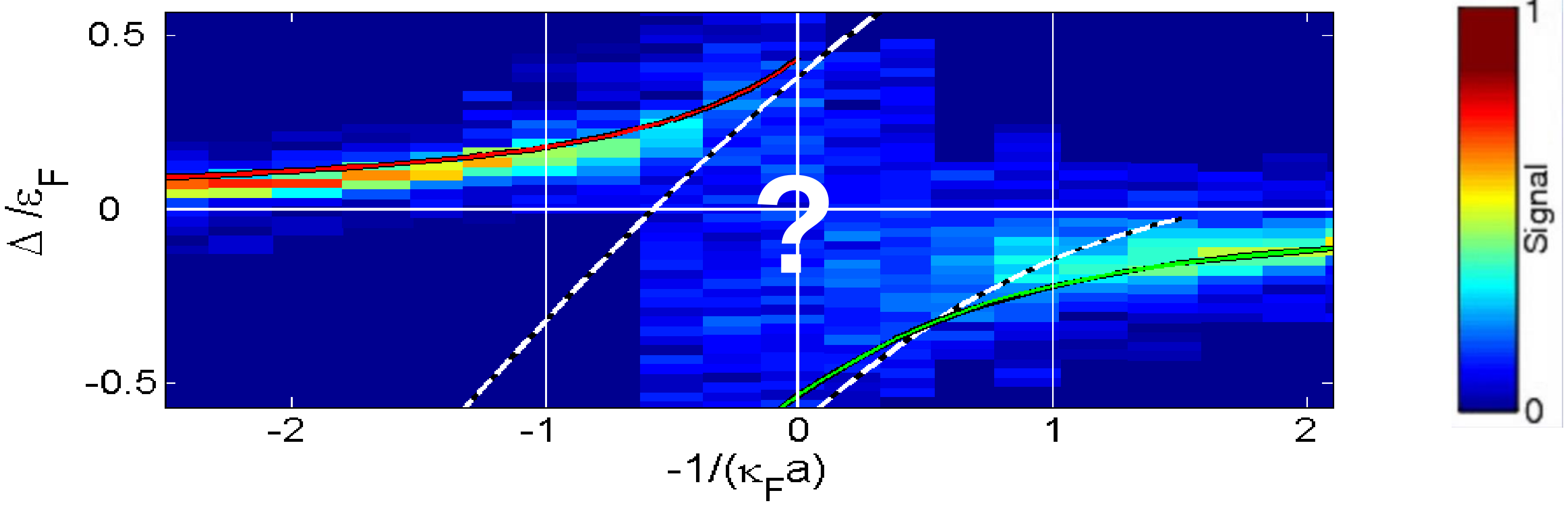
C. Kohstall et al., Nature **485**, 615 (2012)

^{40}K

spectral response

1 ms rf pulse (π w/o interaction)

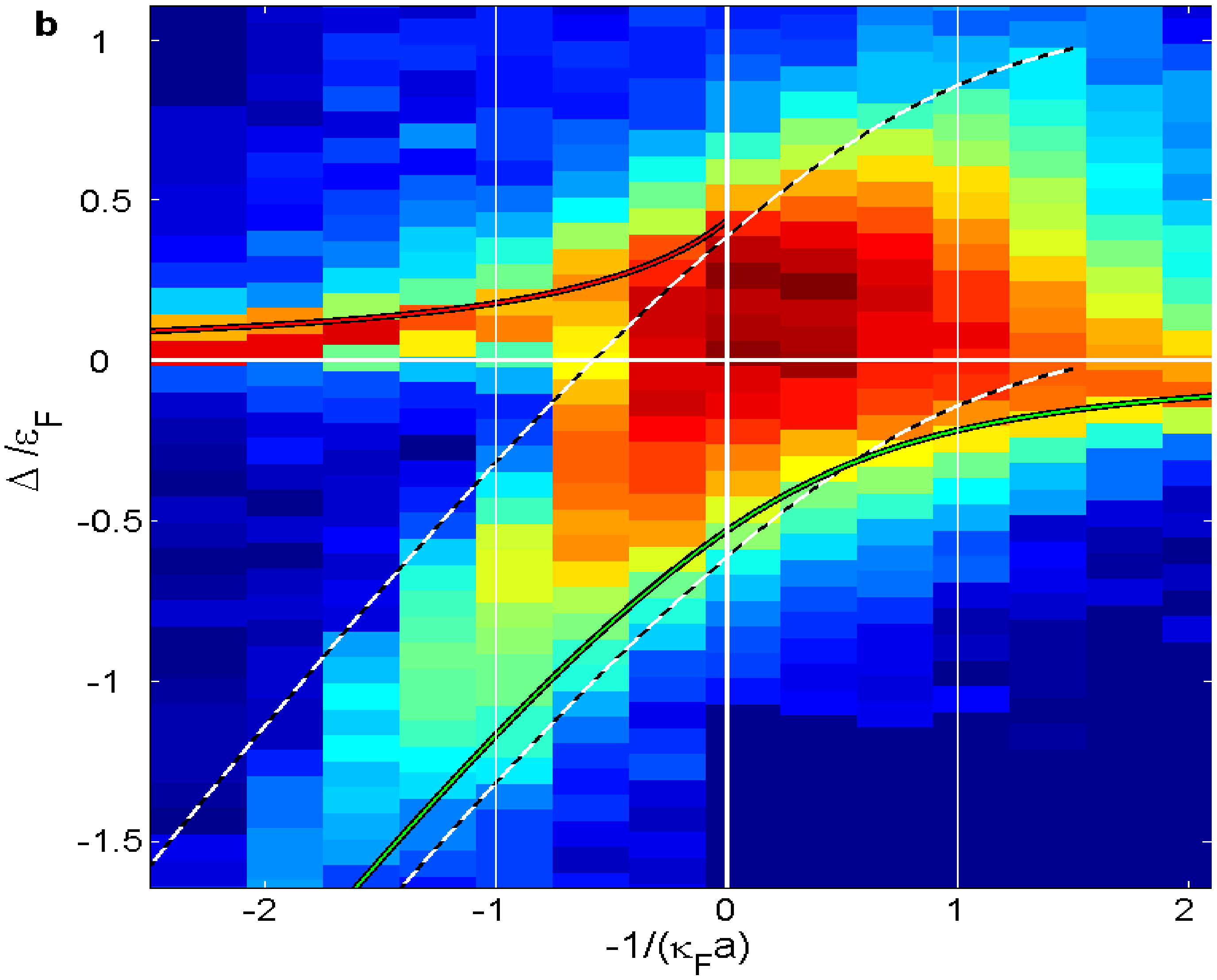
population transfer
|0> $\rightarrow$ |*>



C. Kohstall et al., Nature **485**, 615 (2012)

^{40}K

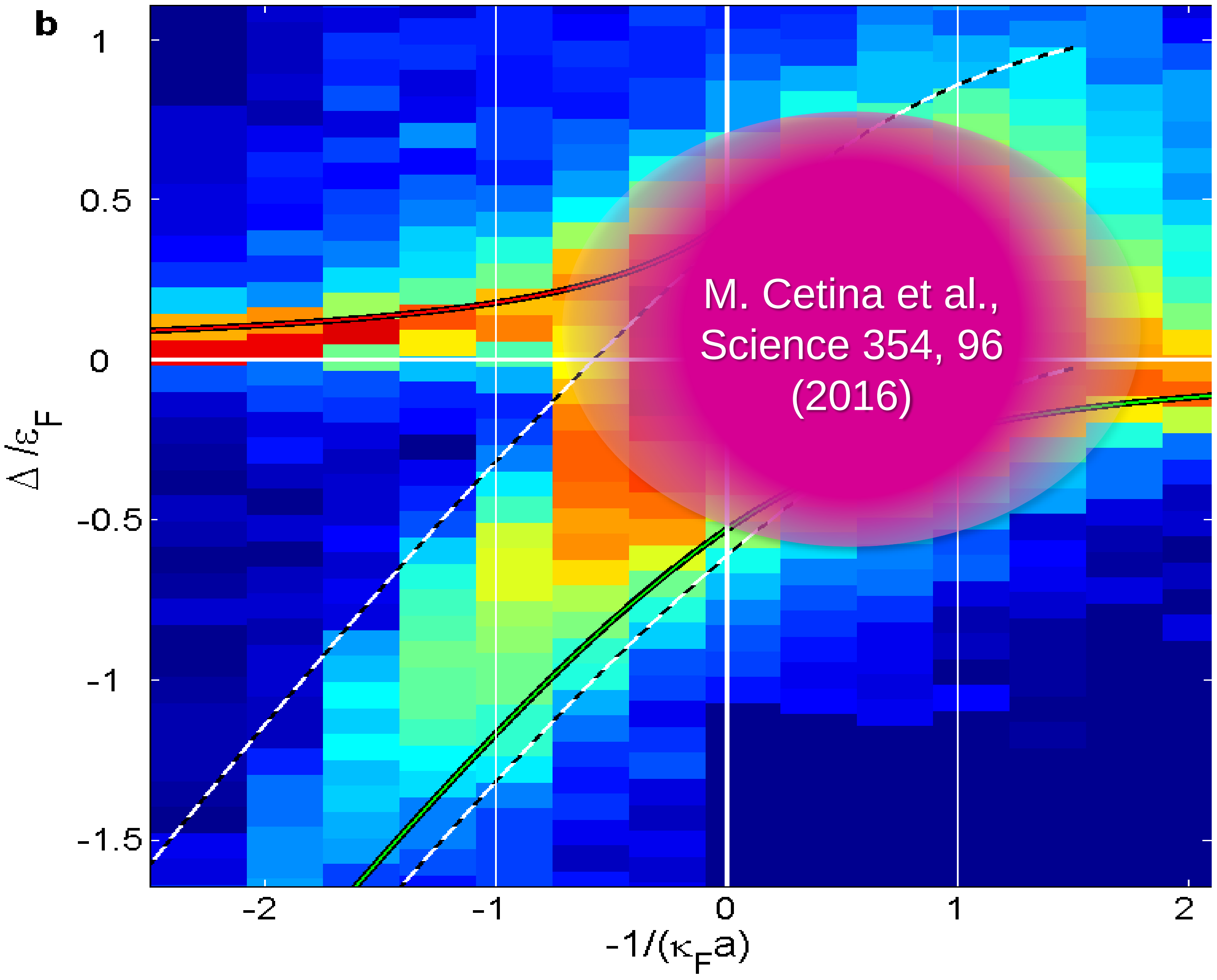
spectral response (strong rf)



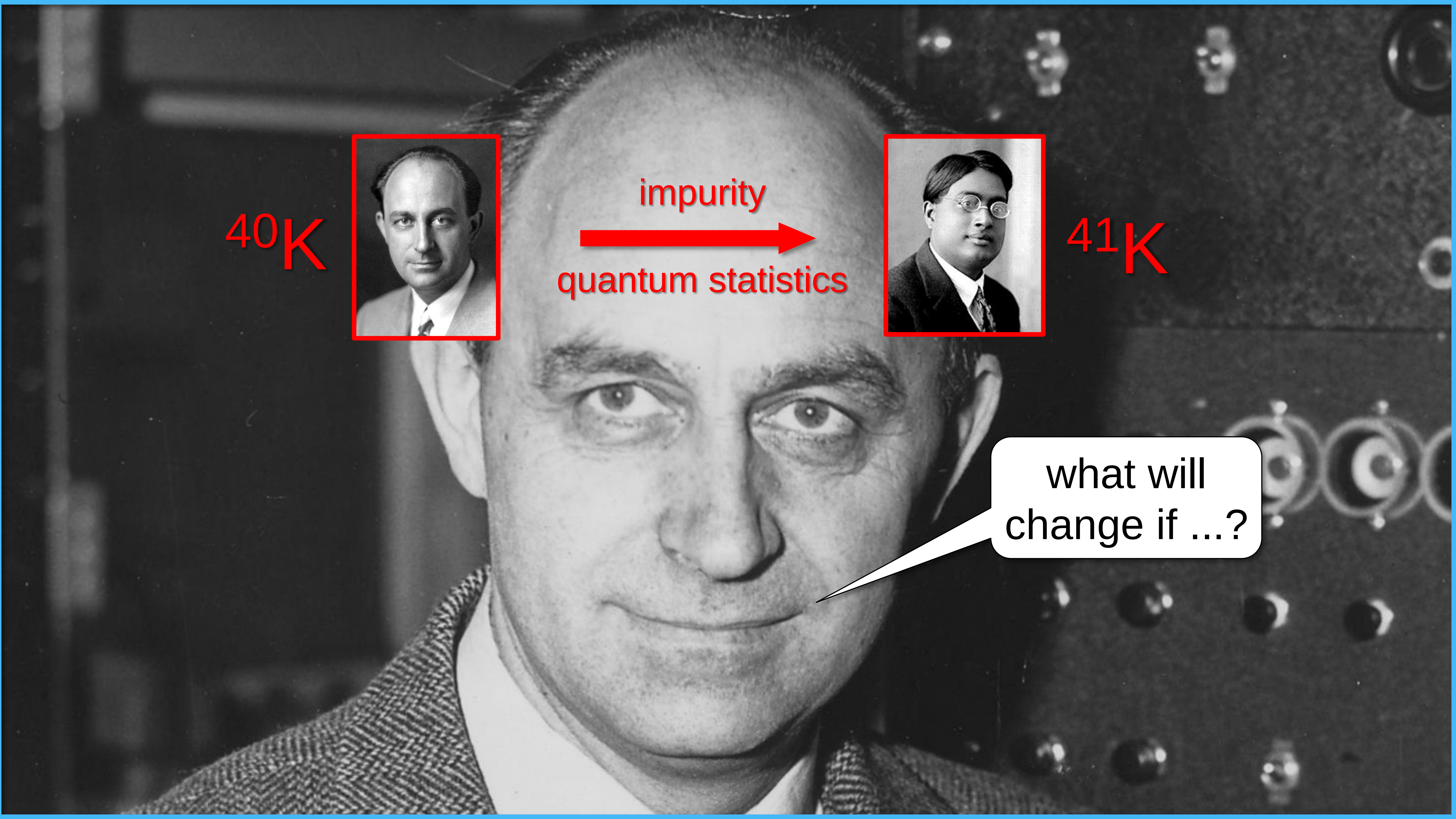
C. Kohstall et al., Nature **485**, 615 (2012)

^{40}K

spectral response (strong rf)

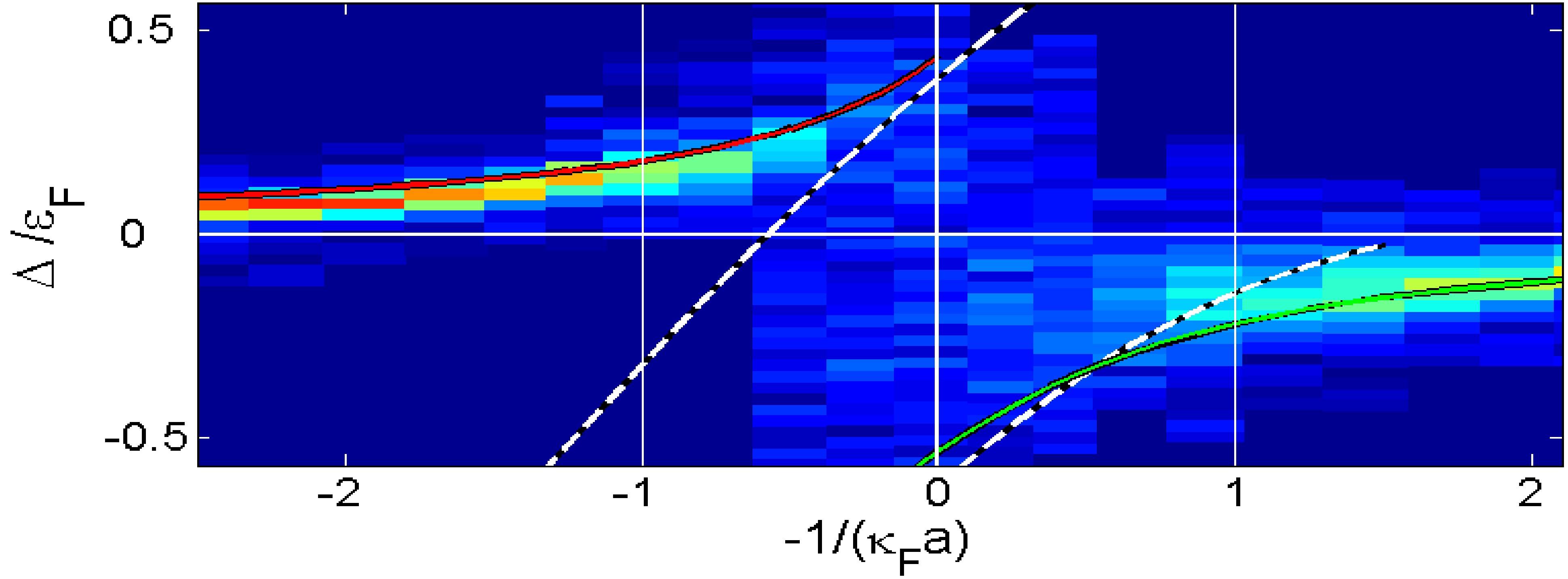


C. Kohstall et al.,
Nature **485**, 615 (2012)



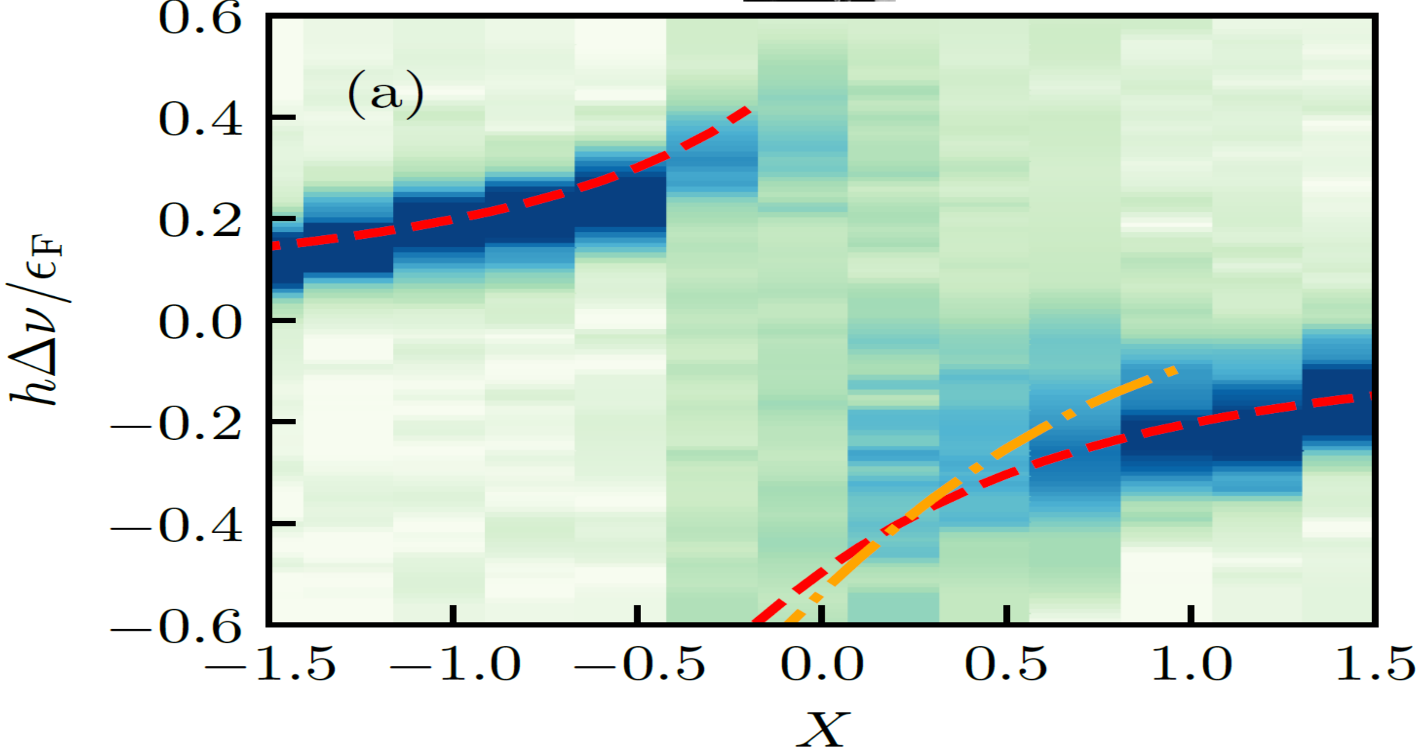
^{40}K
impurity
quantum statistics
^{41}K
what will change if ...?

direct comparison

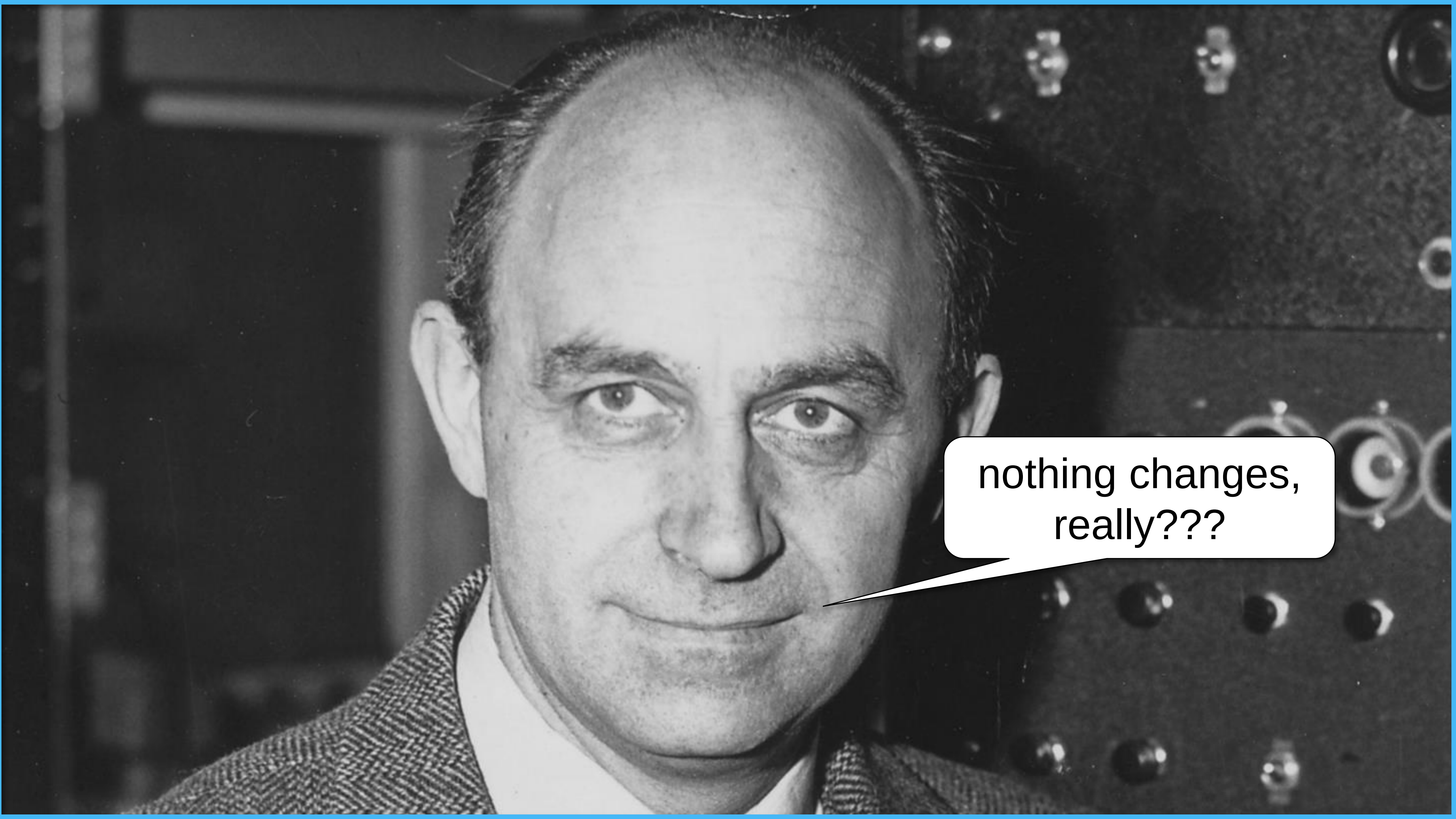


C. Kohstall et al., Nature **485**, 615 (2012)

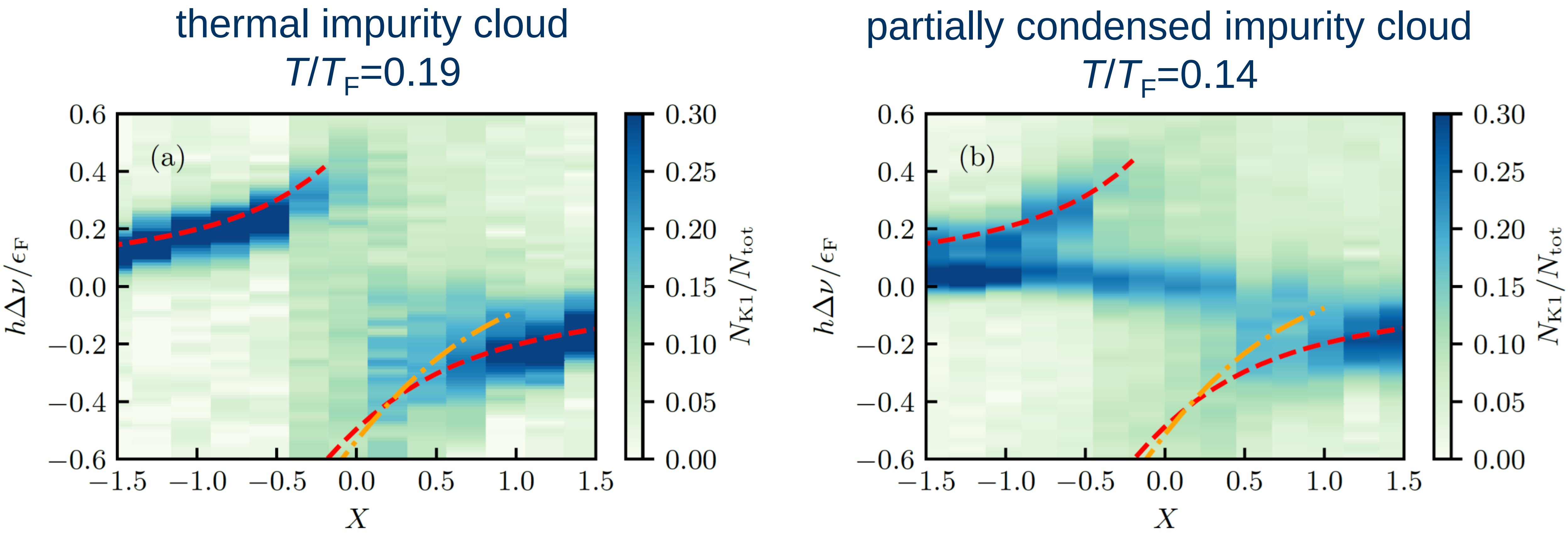
direct comparison



I. Fritsche et al., Phys. Rev. A **103**, 053314 (2021)


nothing changes,
really???

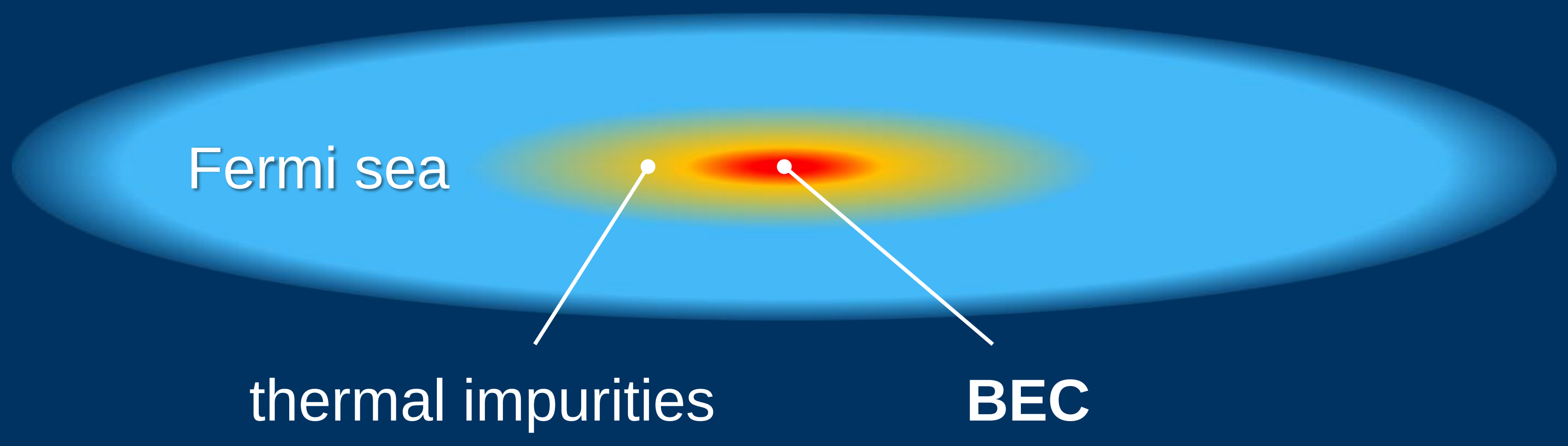
spectral response of bosonic ^{41}K impurities



Fritsche et al., PRA **103**, 053314 (2021)

new branch emerges in the spectrum:
BEC with much less energy shift

regions in the trap

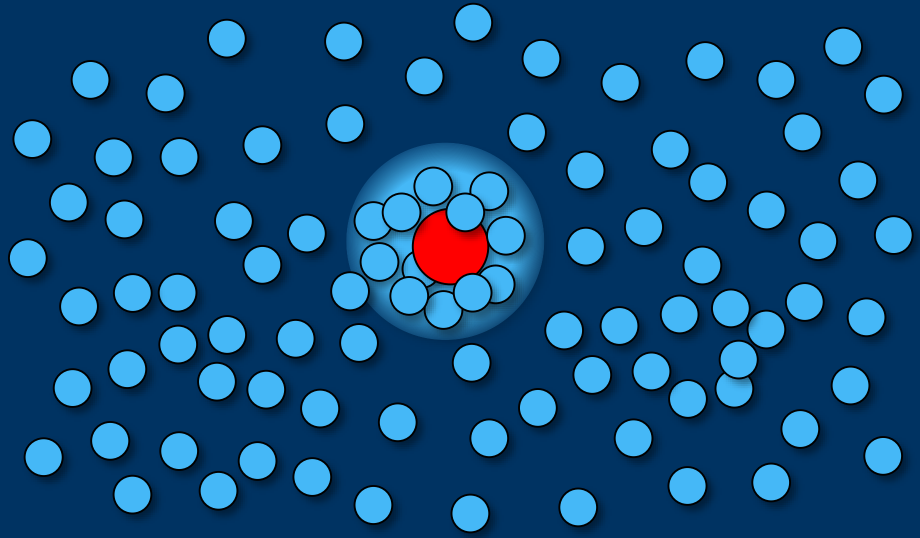


system has no time to phase separate or to collapse!

on **phase separation** of BEC in Fermi gas at repulsive interaction

- static behavior (reduced overlap), Lous et al., PRL **120**, 243403 (2018)
- dynamics (collective oscillations), Huang et al., PRA **99**, 041602(R) (2019)

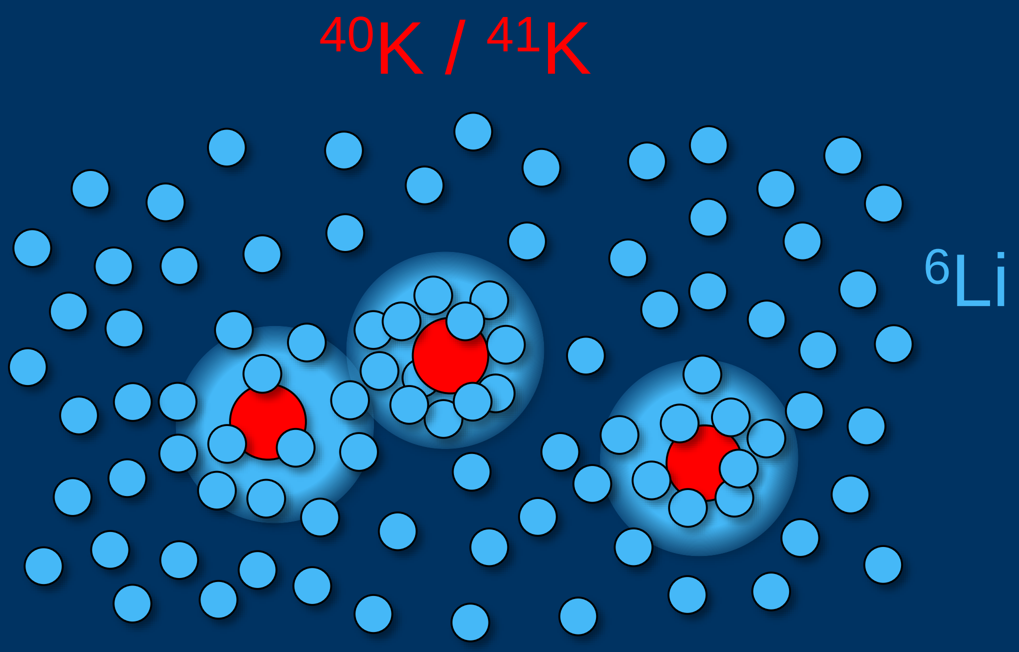
nota bene



everything discussed so far (except of BEC):
<u>single-impurity limit</u>

though experiments have typical concentration of 20%:
single-impurity picture rather robust, interaction effects rather small?

interactions between Fermi polarons?



- basic mechanisms of interaction?
- attraction or repulsion?
- role of impurity quantum statistics?
- role of molecule formation?

prediction from Fermi-liquid theory

interaction energy per particle

$$\Delta E_{\text{int}}/E_F = \mp\frac{2}{3}(\Delta N)^2\mathcal{C}$$

Yu and Pethick,
PRA 85, 063616 (2012)
(perturbative approach)

attractive for bosons
repulsive for fermions

number of atoms
in dressing cloud
(no difference between
attractive and repulsive case)

impurity
concentration

???

mediated interaction not always attractive
why does impurity quantum statistics matter here?
relation to other impurity interaction scenarios?

prediction from Fermi-liquid theory

interaction energy
per particle

$$\Delta E_{\text{int}}/E_F = \mp\frac{2}{3}(\Delta N)^2 \mathcal{C}$$

Yu and Pethick,
PRA 85, 063616 (2012)
(perturbative approach)

attractive for bosons
repulsive for fermions

number of atoms
in dressing cloud
(no difference between
attractive and repulsive case)

impurity
concentration

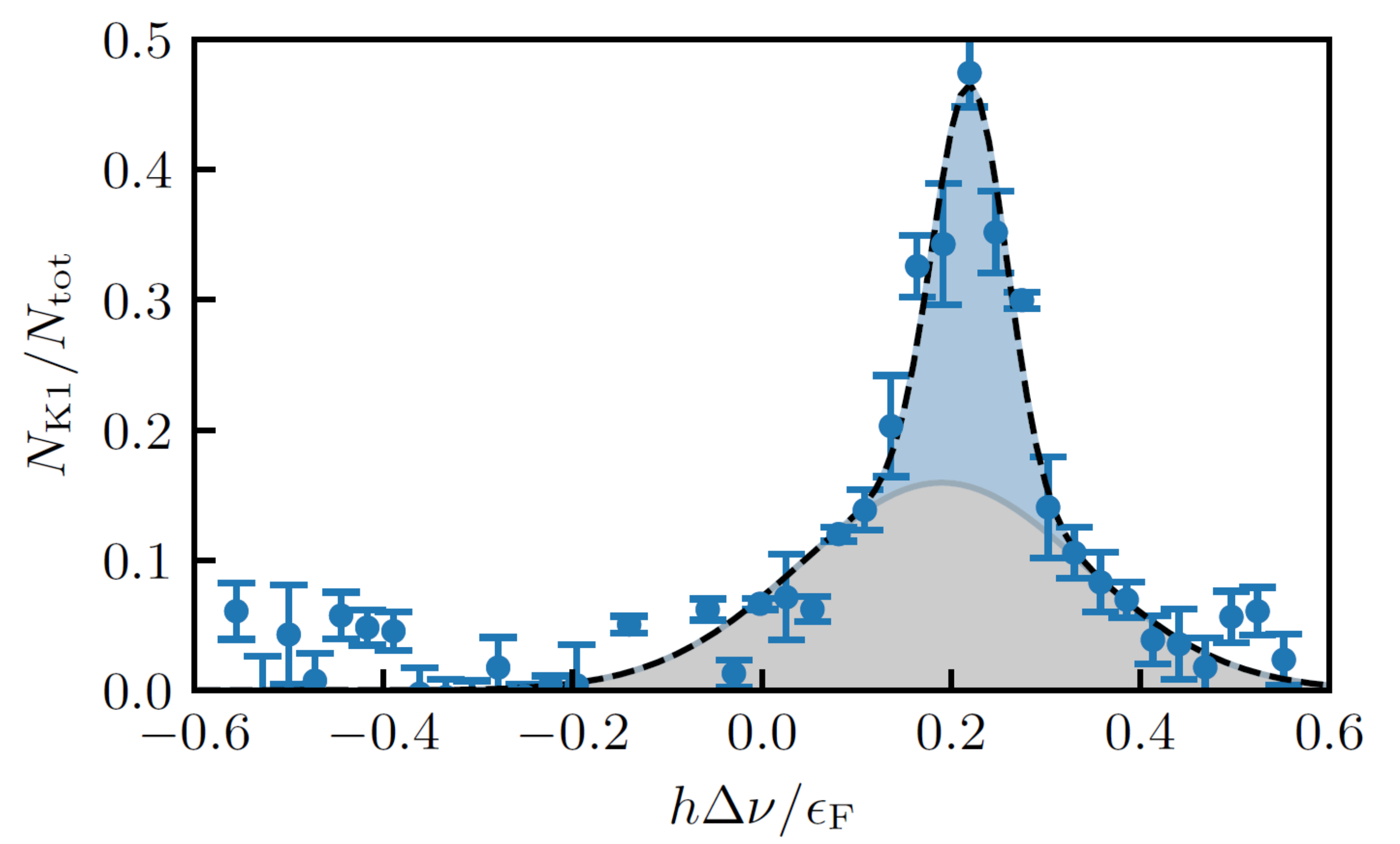
⇨ for our spectroscopy
method

$$S = \mp\frac{1}{3}(\Delta N)^2$$

factor ½ owing to gradual
increase of *C* during rf pulse

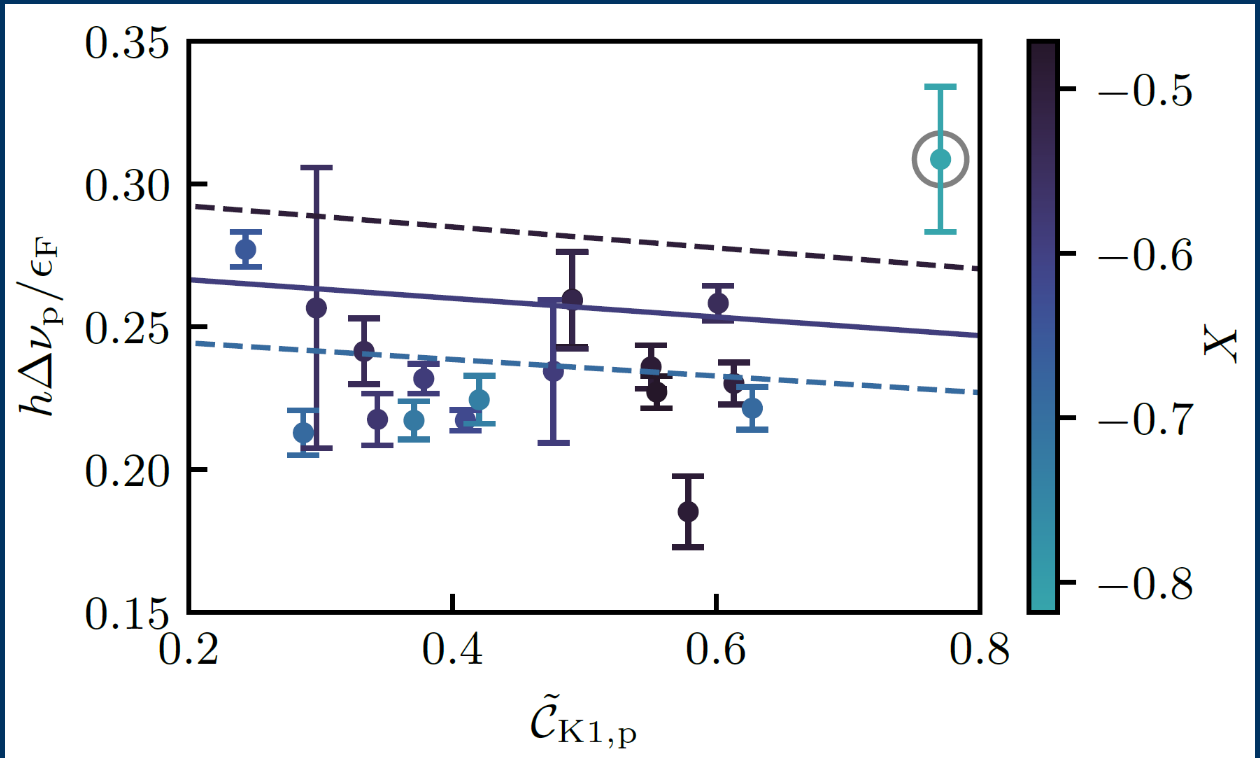
rf spectrum

how does the polaron peak shift
with varying impurity concentration?



thermal impurities: polaron peak shift?

Fermi-liquid theory
(perturbative approach):
Yu and Pethick,
PRA 85, 063616 (2012)



polaron concentration

$X \approx -0.6$

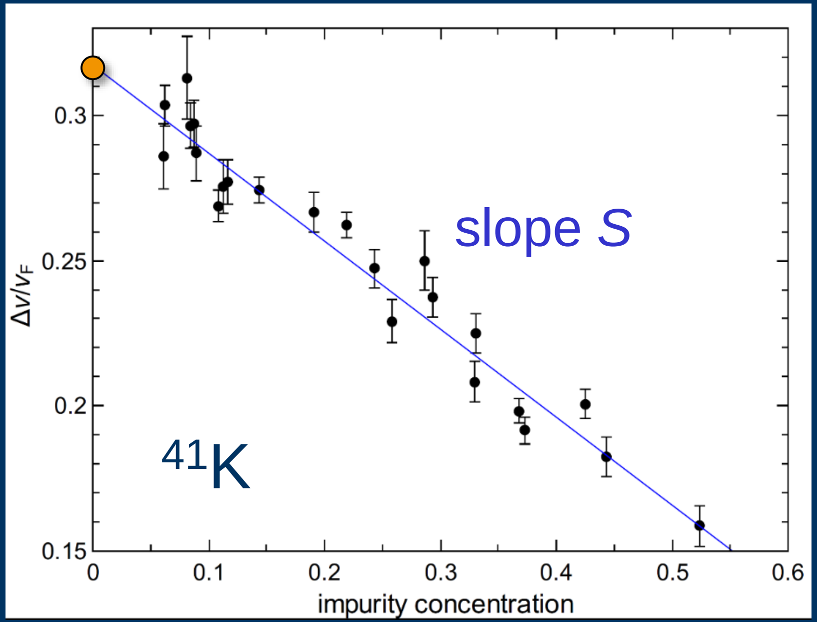
Fritsche et al.,
PRA **103**, 053314 (2021)

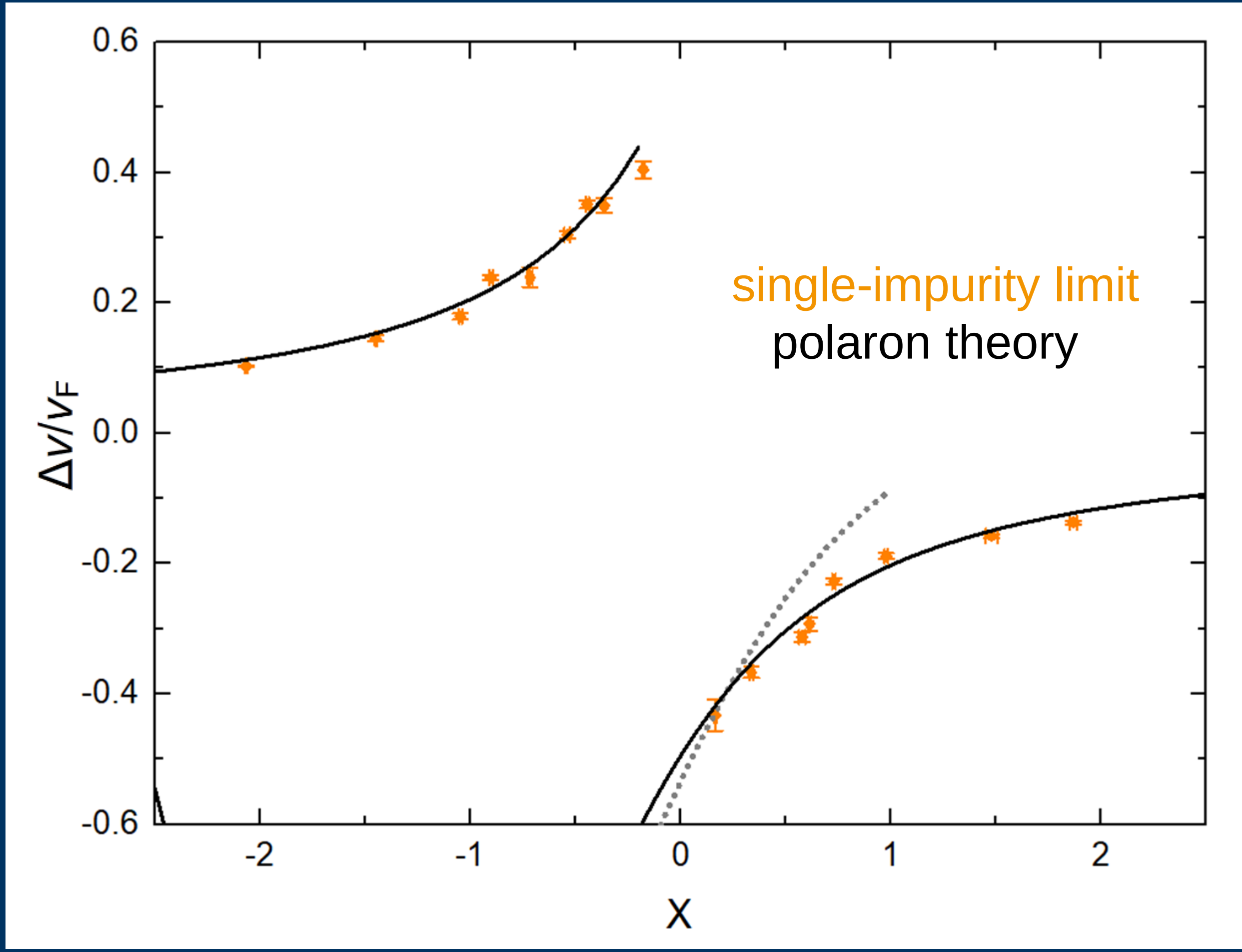
indications of a density-dependent shift,
but (expt. issues) fluctuations of *X* and *T* too large

new measurements (running since spring 2021)

concentration dependence at X = -0.6

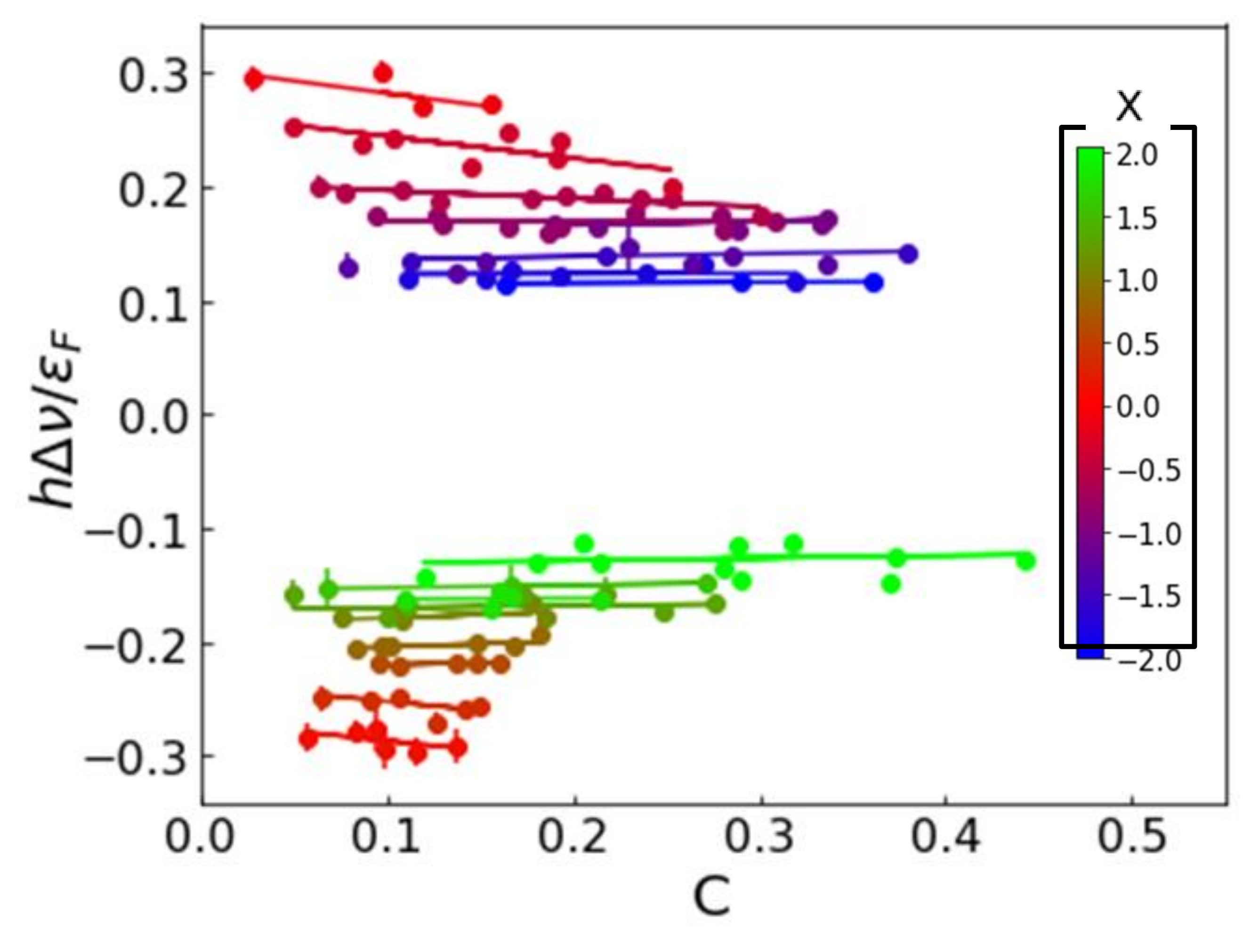
energy shift vs. X





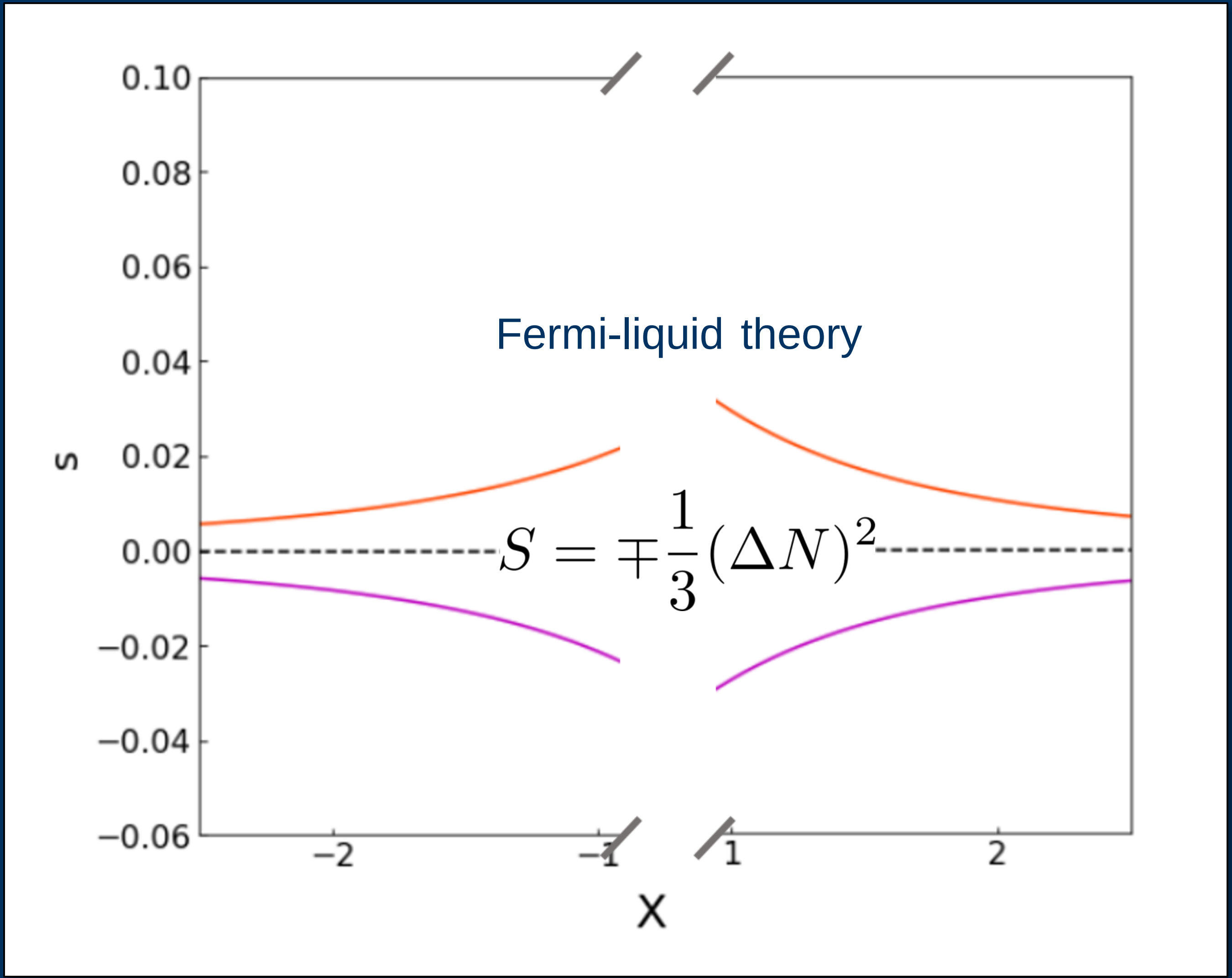
C. Baroni et al, in progress

many, many measurements



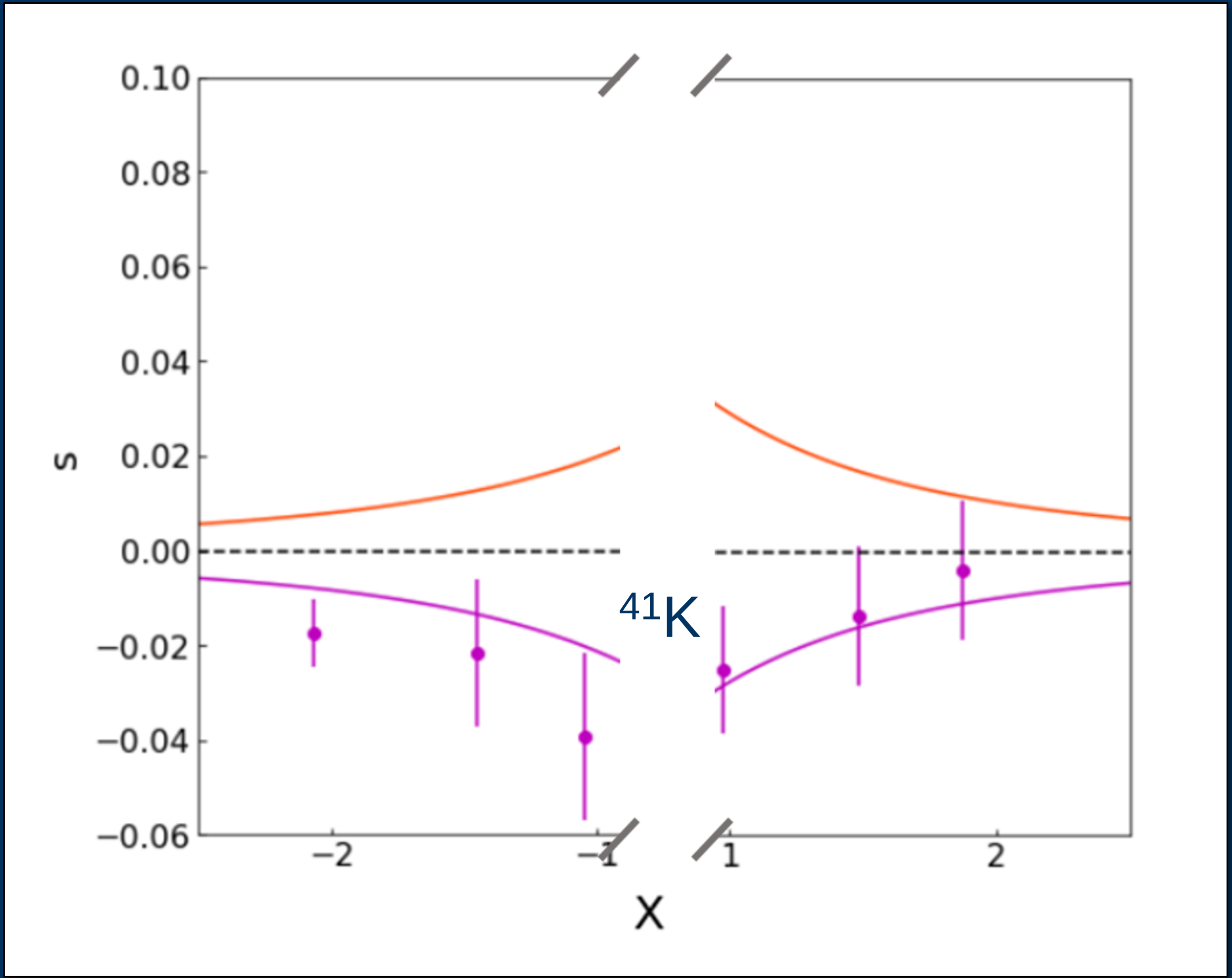
C. Baroni et al, in progress

mediated interactions



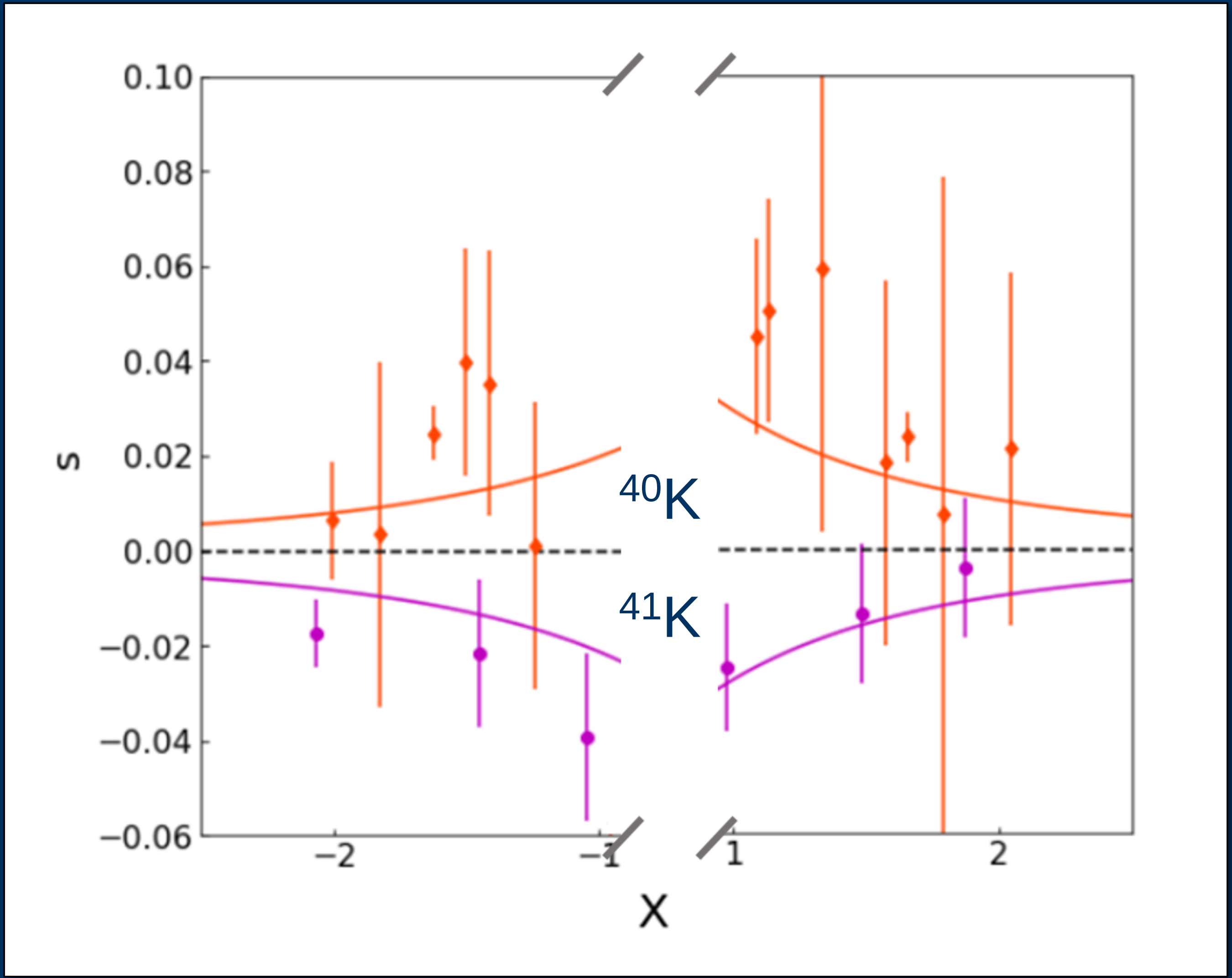
C. Baroni et al, in progress

mediated interactions



C. Baroni et al, in progress

mediated interactions

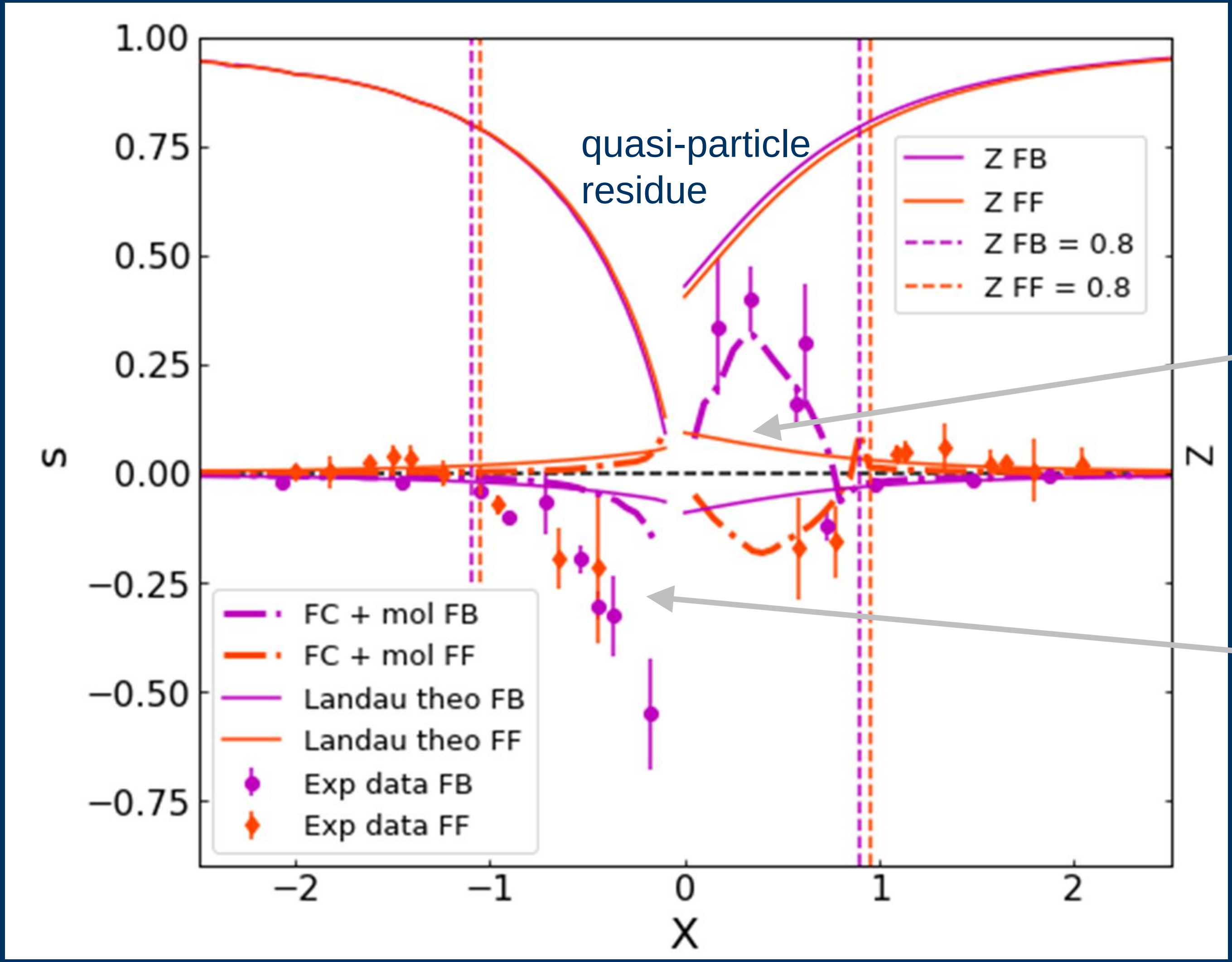


C. Baroni et al, in progress

density dependence in strongly interacting regime

work in progress

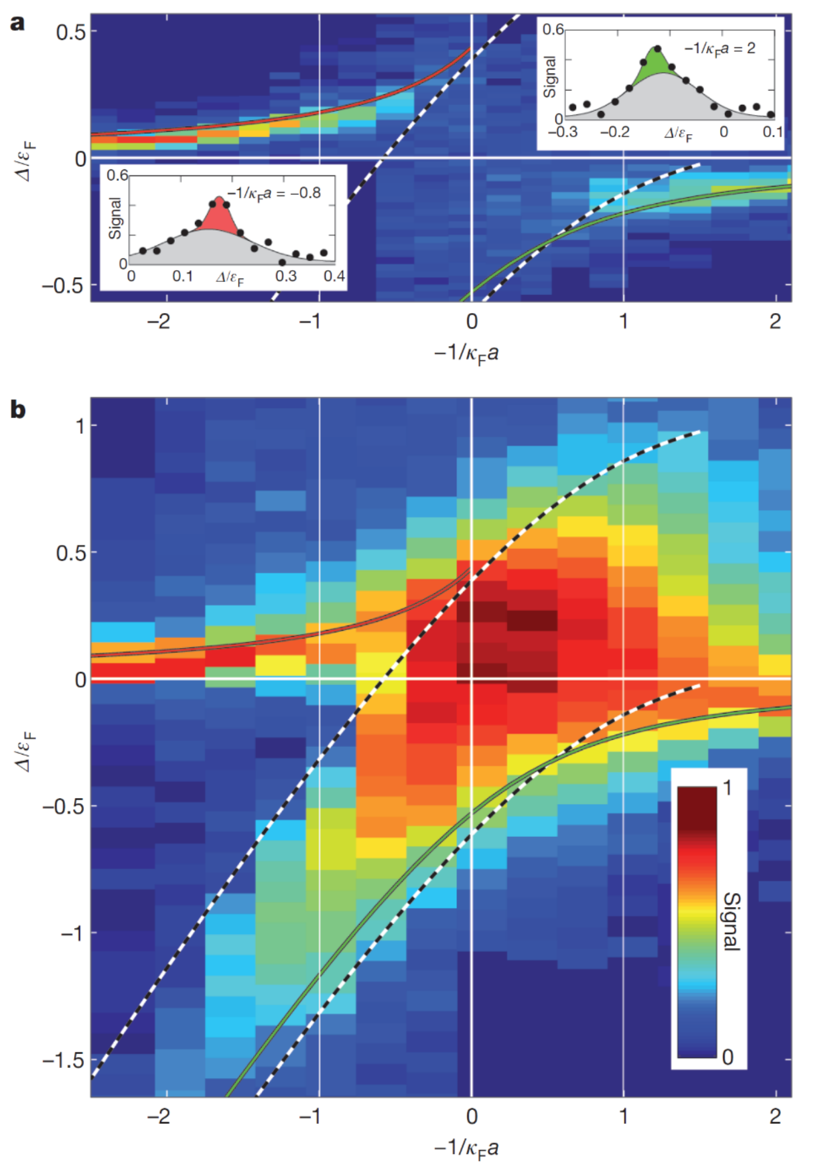
theory:
M. Bastarrachea-Magnani
G. Bruun
P. Massignan



polaron-molecule interactions?

breakdown of polaron description??

back to the single-impurity limit



other ways to probe the system?

frequency domain

→ time domain

Meera's second lecture

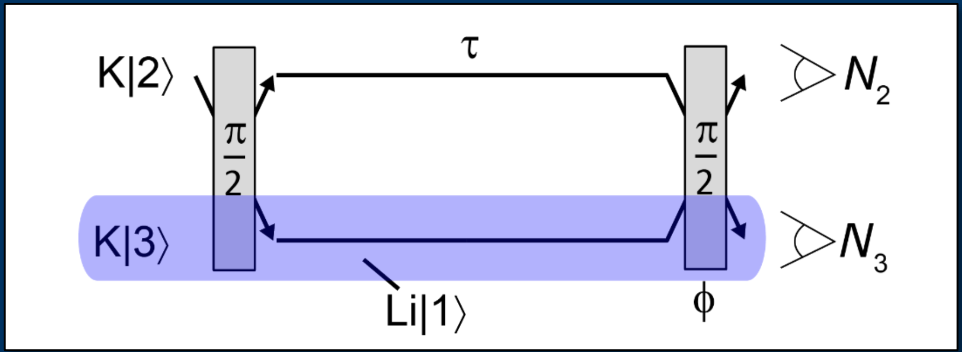
idea for time-domain impurity spectroscopy

PHYSICAL REVIEW X **2**, 041020 (2012)

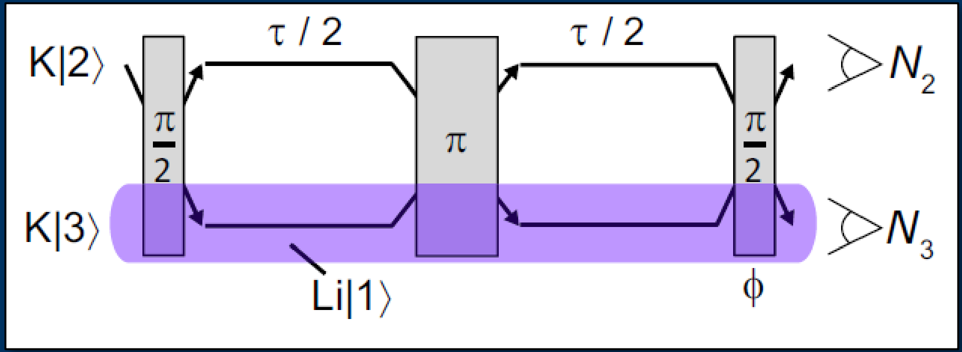
Time-Dependent Impurity in Ultracold Fermions: Orthogonality Catastrophe and Beyond

Michael Knap,[1,2] Aditya Shashi,[3] Yusuke Nishida,[4] Adilet Imambekov,[3] Dmitry A. Abanin,[2] and Eugene Demler[2]
[1]*Institute of Theoretical and Computational Physics, Graz University of Technology, 8010 Graz, Austria*
[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[3]*Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA*
[4]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
(Received 2 July 2012; published 27 December 2012)

Ramsey scheme

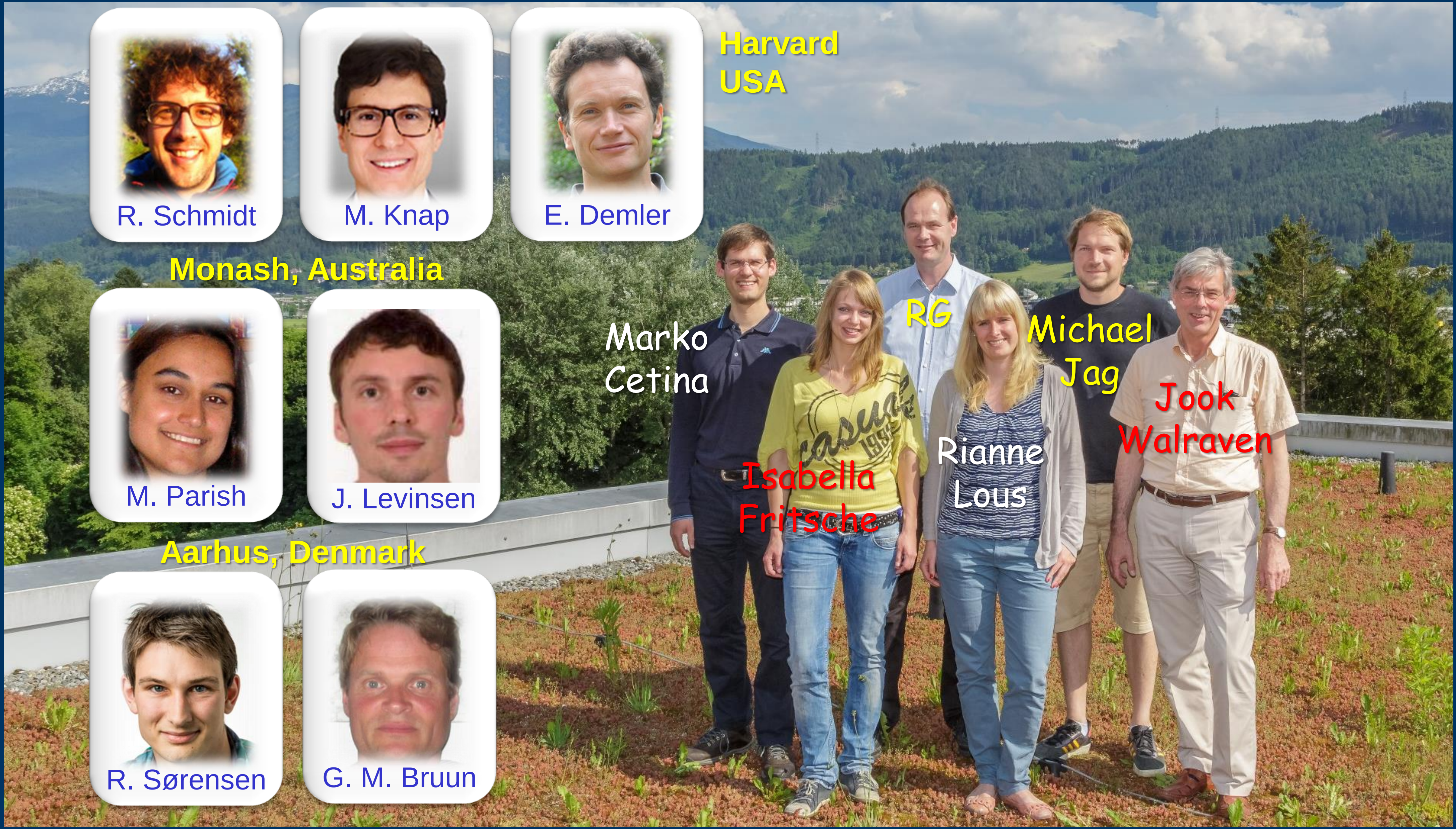


spin echo scheme

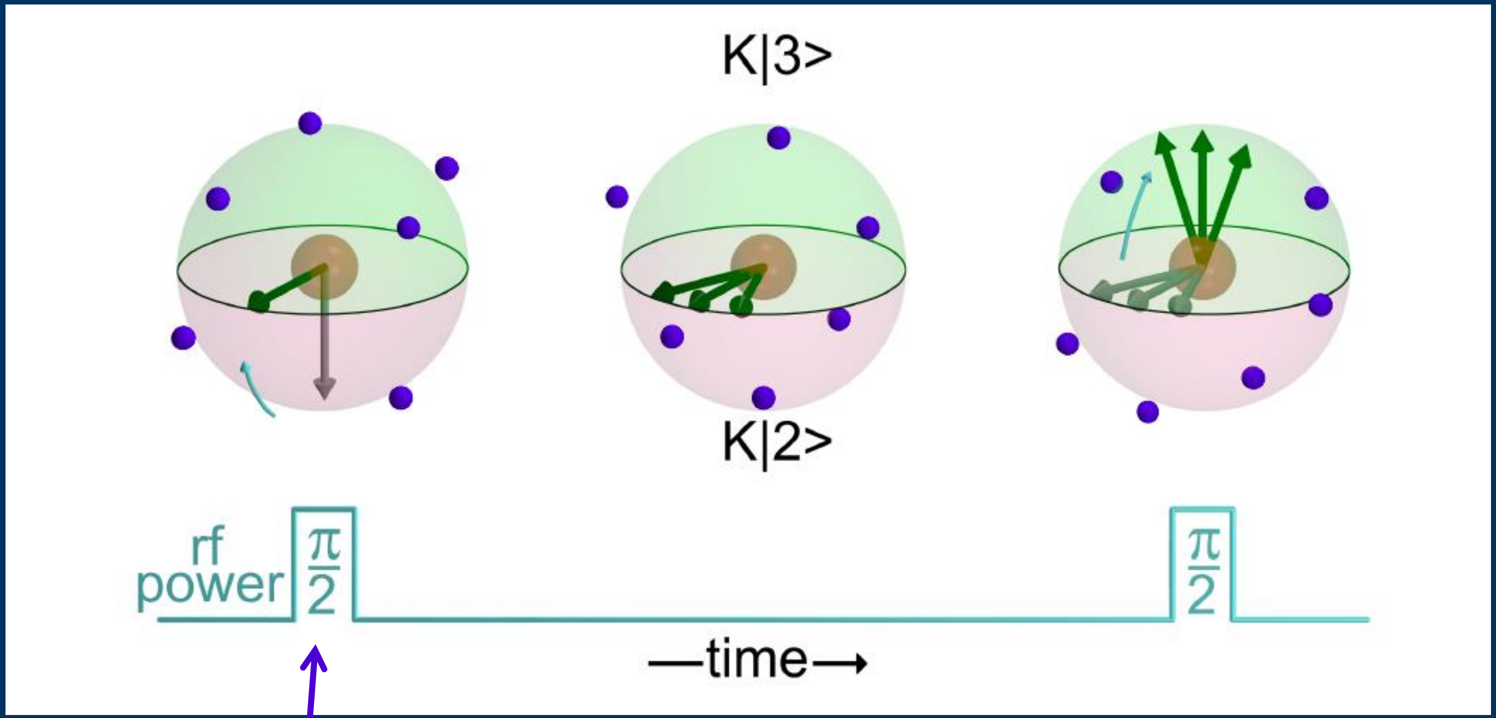


atom interferometer
(with non-interacting state as phase reference)

Innsbruck team (2015/6) + theory collaborators

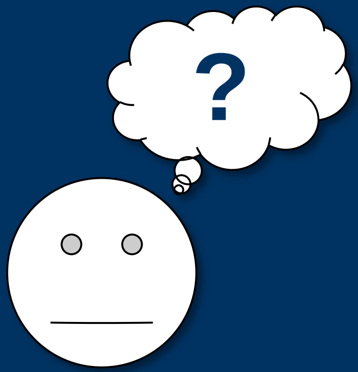


Ramsey interferometer

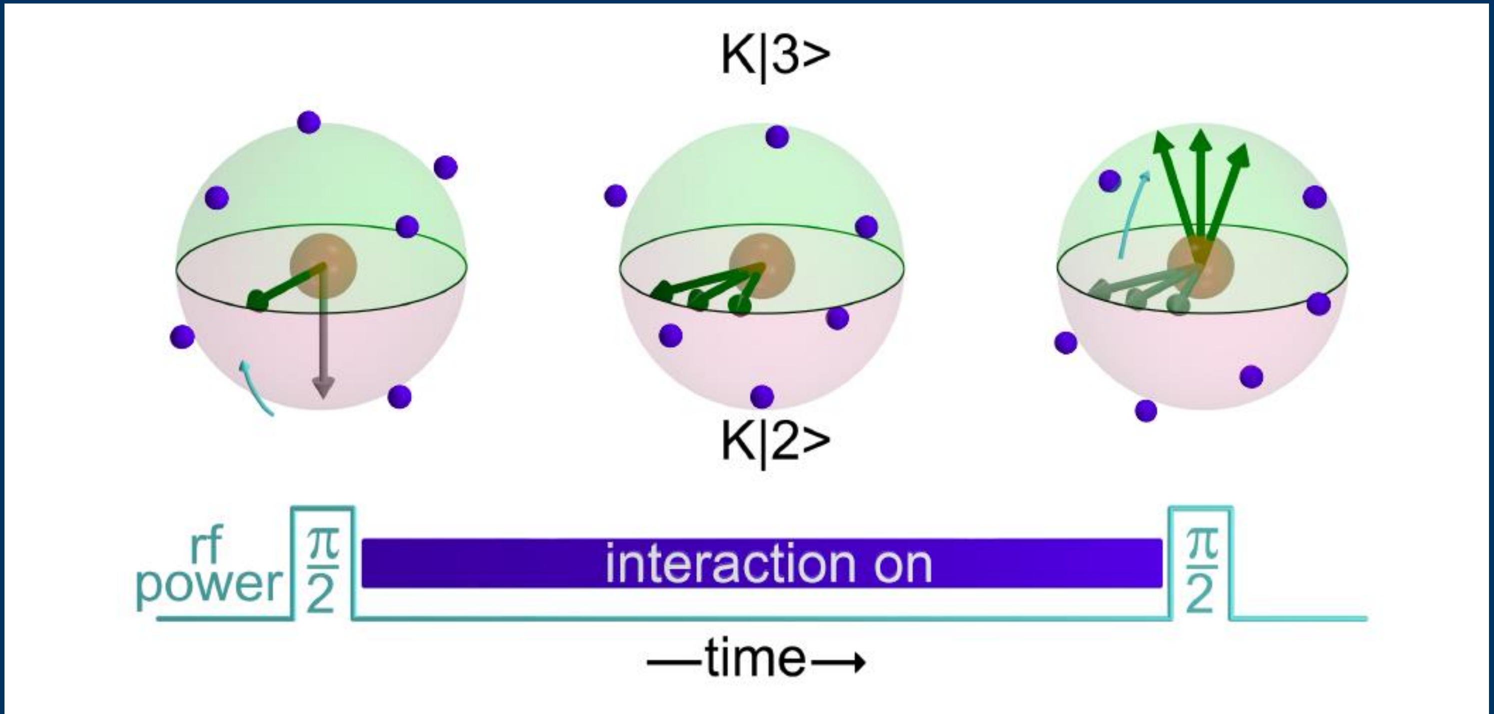


10μs
(not shorter!)

but $\tau_F = 2.9\mu s$



Ramsey interferometer

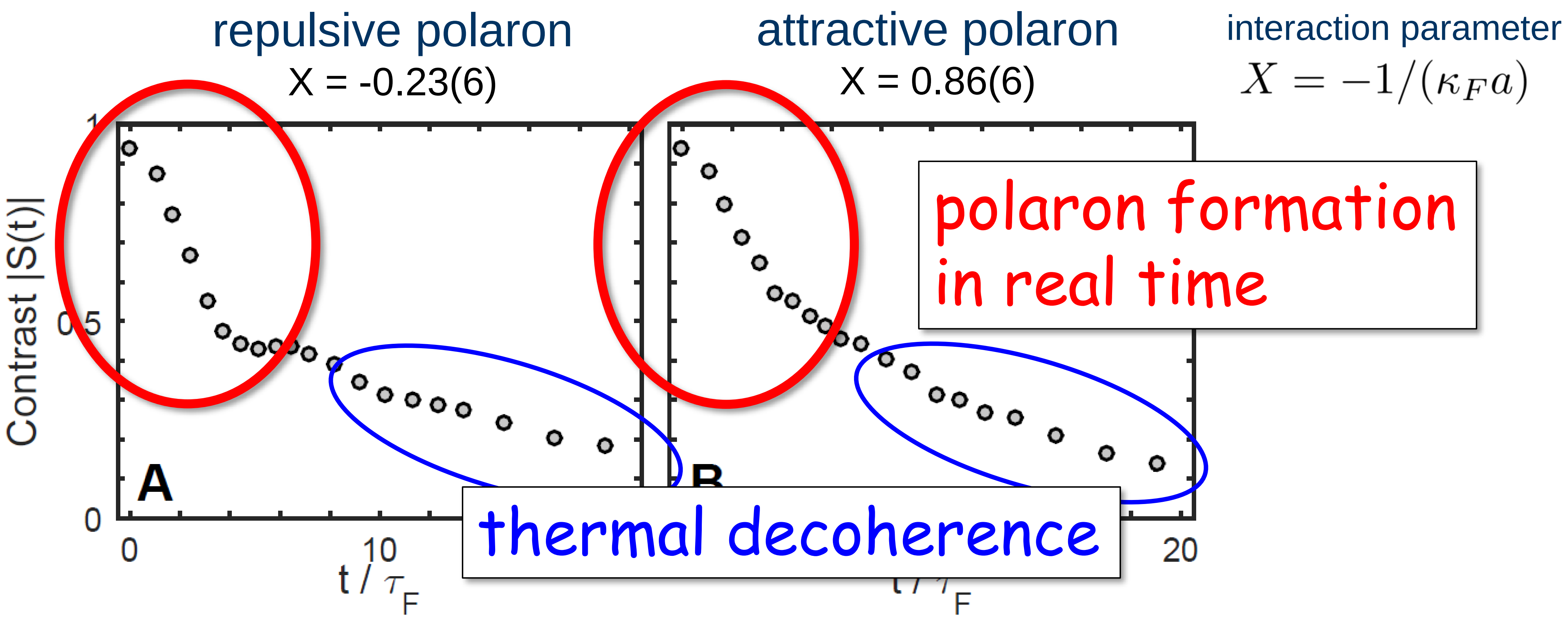


drive π/2 pulses under weakly interacting conditions

turn on strong interaction only between pulses

use light shift of Feshbach resonance

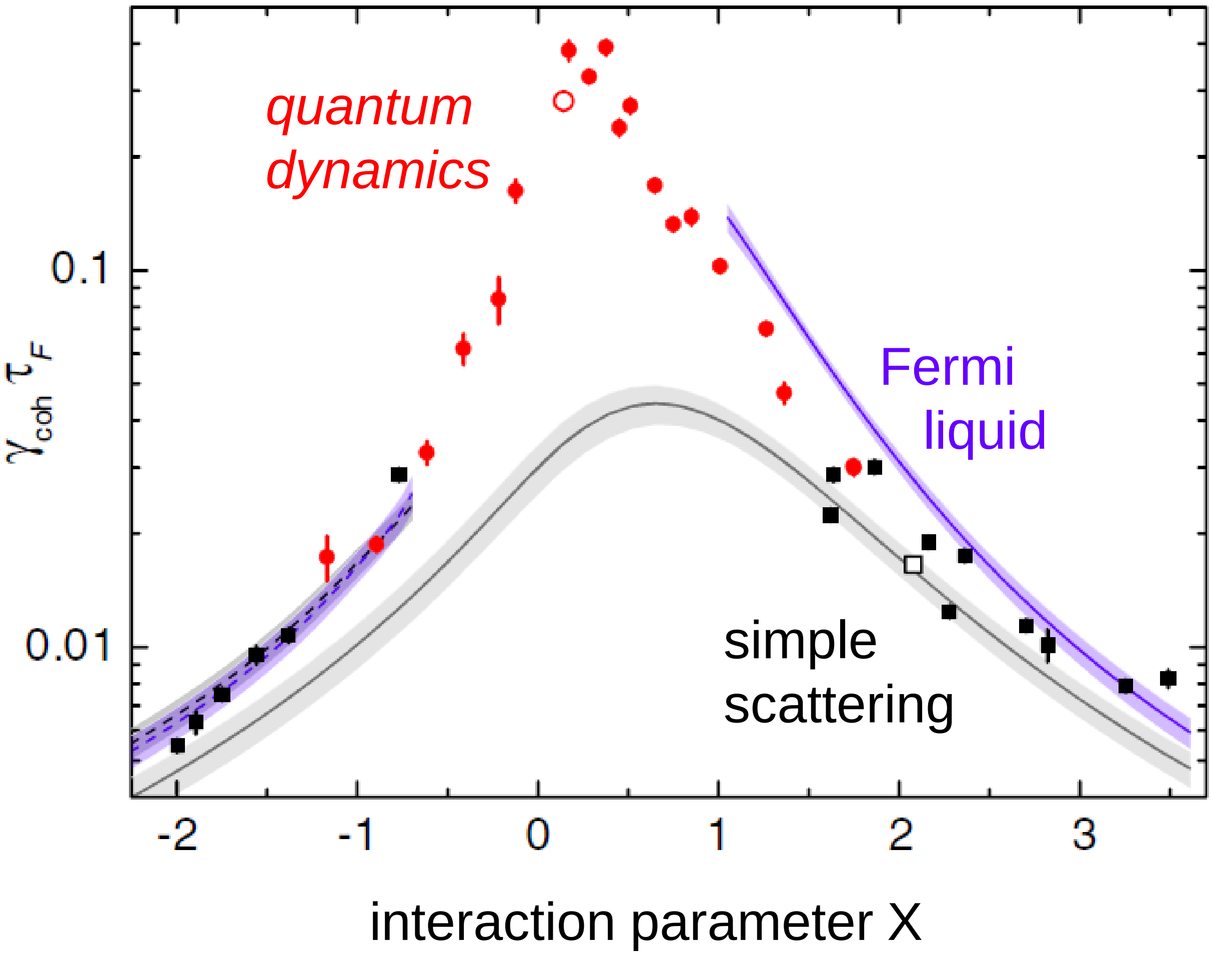
experimental results



thermal decoherence

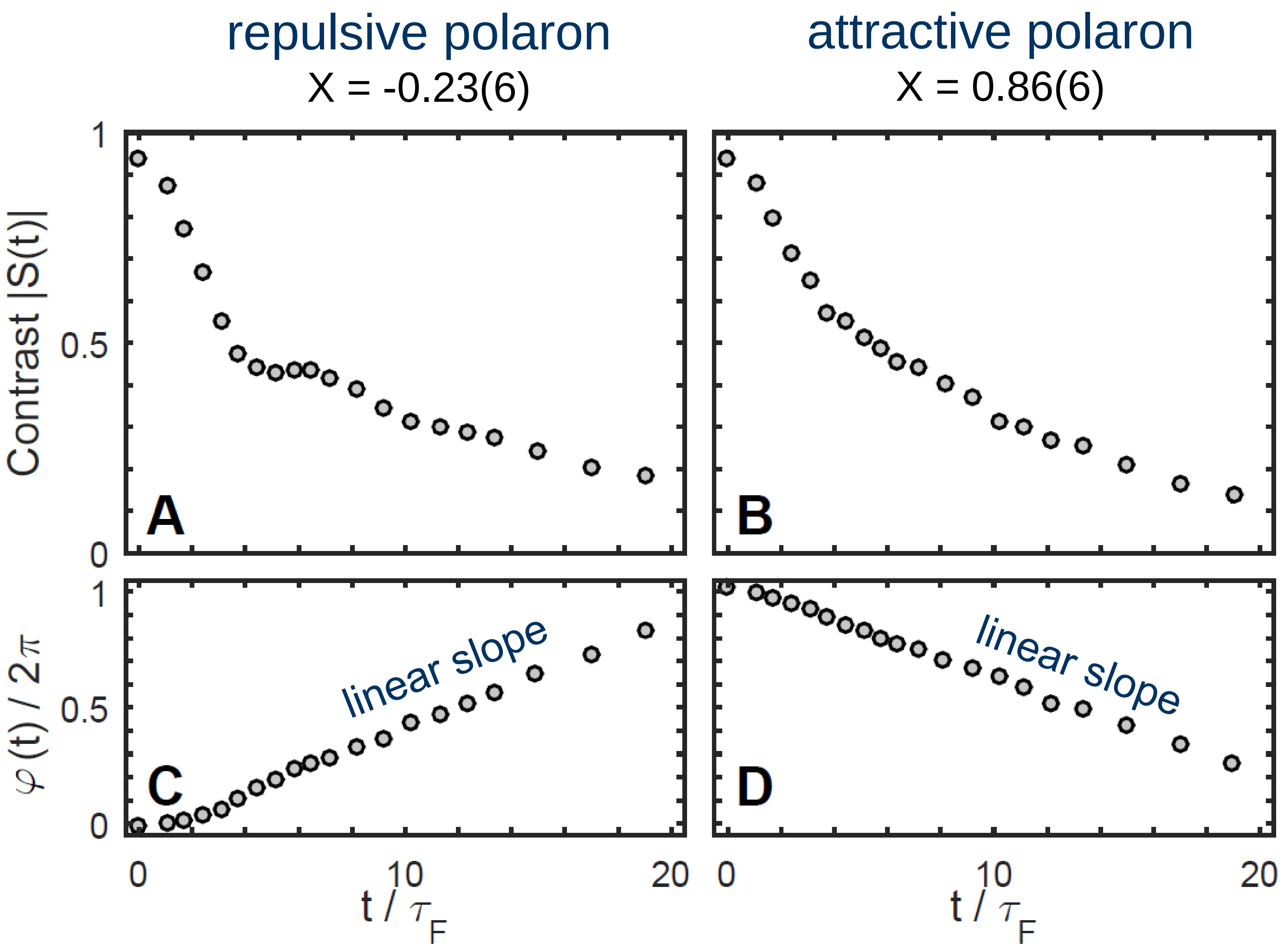
theory

Aarhus, DK



Cetina et al.,
PRL 115,135302
(2015)

experimental results



two theoretical approaches

TBM – Truncated Basis Method
time-dependent version of Chevy ansatz

single particle-hole excitations
(no multiple excitations)

details see Phys. Rev. B 94, 184303 (2016)

including finite-T: PRL 122, 205301 (2019)


M. Parish


J. Levinsen

Monash, Australia

FDA – Functional Determinant Approach
exact solution of dynamical many-body problem

assumes fixed impurity ($M/m \to \infty$)

details see Rep. Prog. Phys. 81, 024401 (2018)

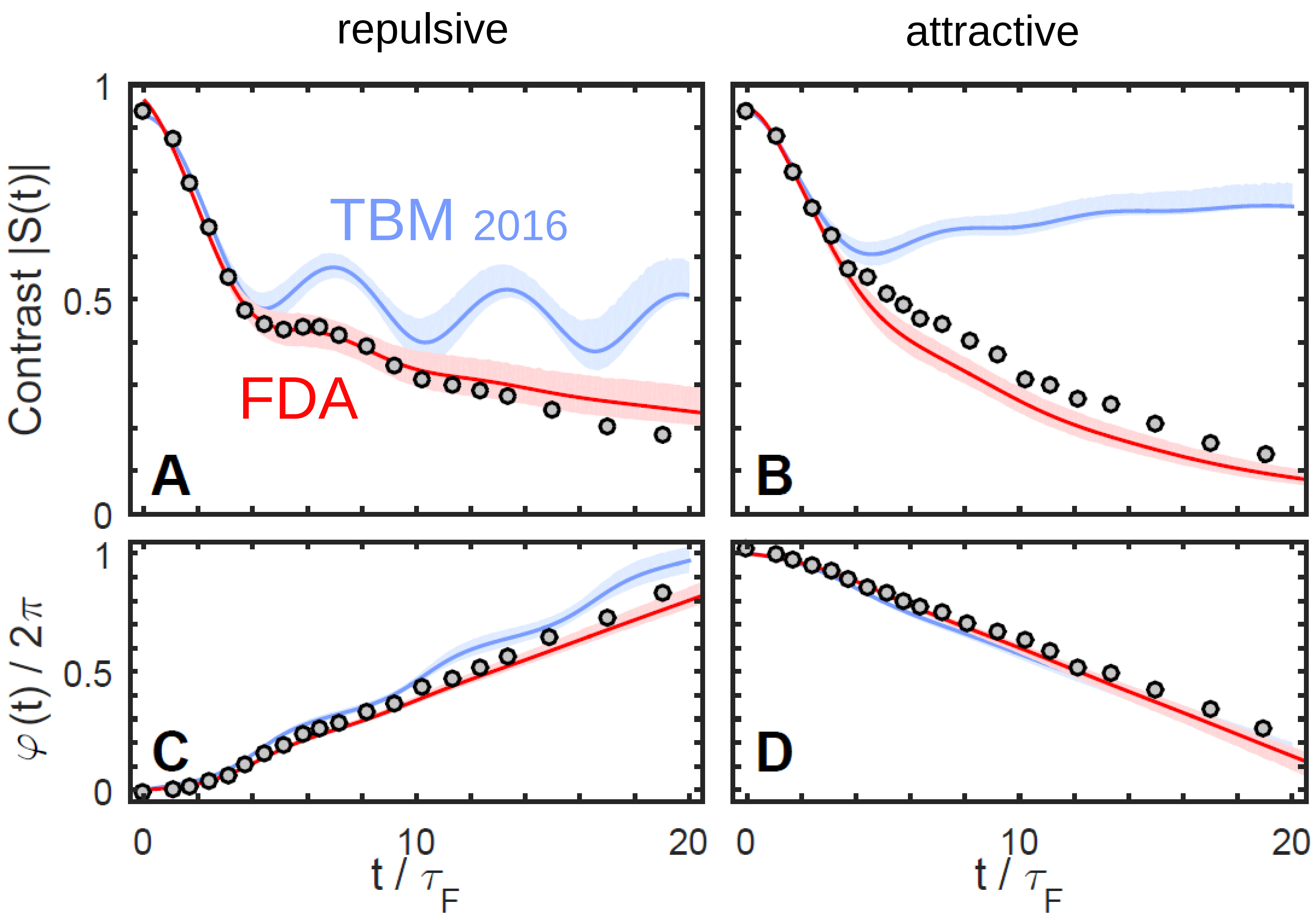
Harvard, USA


R. Schmidt

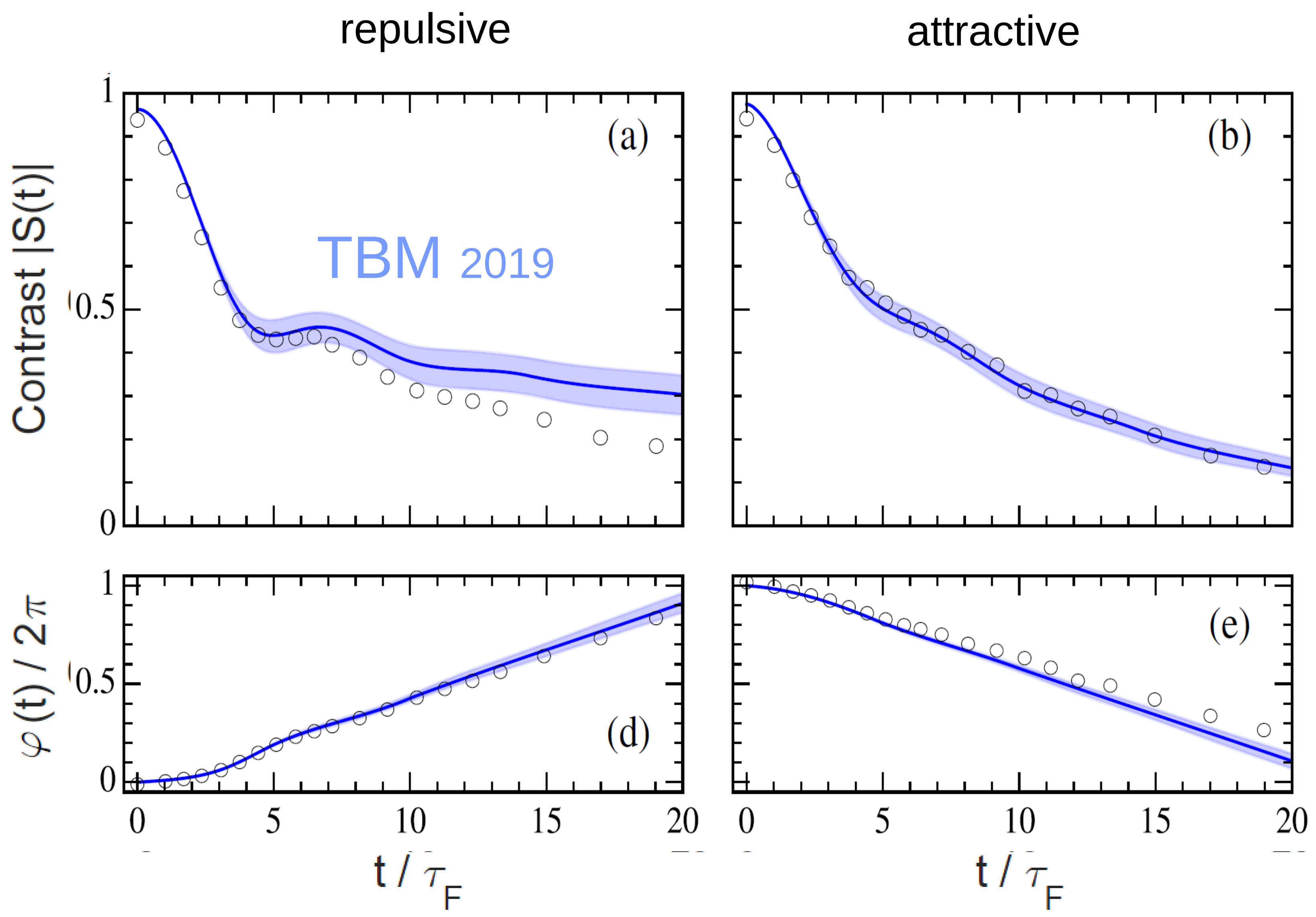

M. Knap


E. Demler

theory vs. experiment



theory vs. experiment



two theoretical approaches

TBM – Truncated Basis Method
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single particle-hole excitations
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including finite-T: PRL 122, 205301 (2019)

we are not (yet) there, where these approximations break down!

FDA – Functional Determinant Approach
exact solution of dynamical many-body problem

assumes fixed impurity ($M/m \to \infty$)

details see Rep. Prog. Phys. 81, 024401 (2018)

orthogonality catastrophe

VOLUME 18, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1967

INFRARED CATASTROPHE IN FERMI GASES WITH LOCAL SCATTERING POTENTIALS

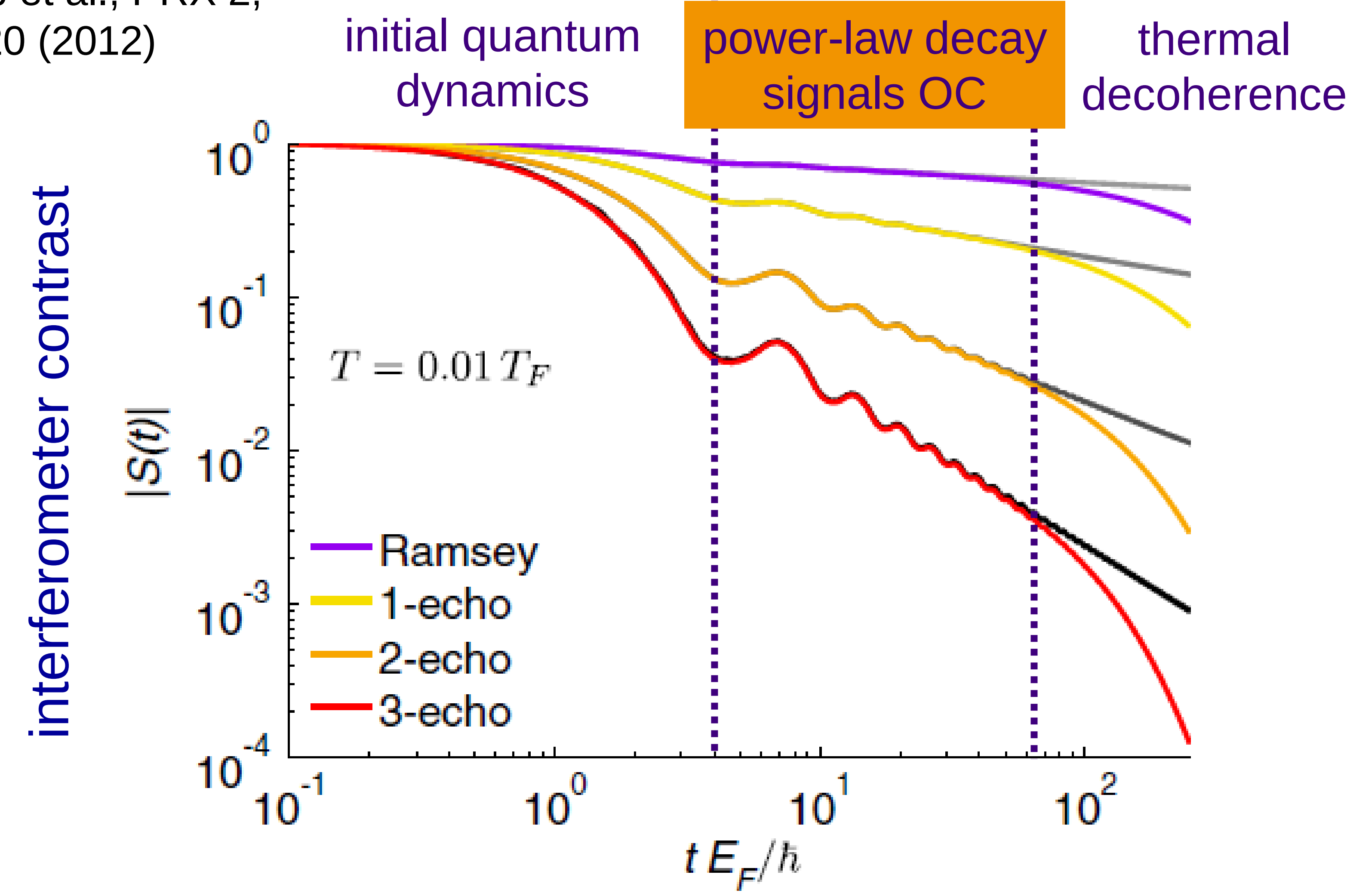
P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 27 March 1967)

We prove that the ground state of a system of N fermions is orthogonal to the ground state in the presence of a finite range scattering potential, as $N \rightarrow \infty$. This implies that the response to application of such a potential involves only emission of excitations into the continuum, and that certain processes in Fermi gases may be blocked by orthogonality in a low-T, low-energy limit.

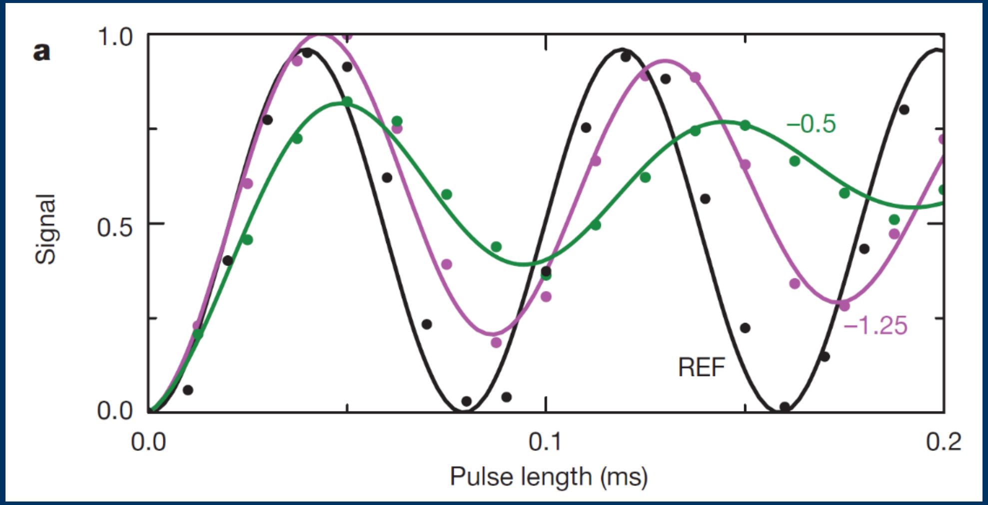
http://www.princeton.edu/physics/people/display_person.xml?netid=pwa

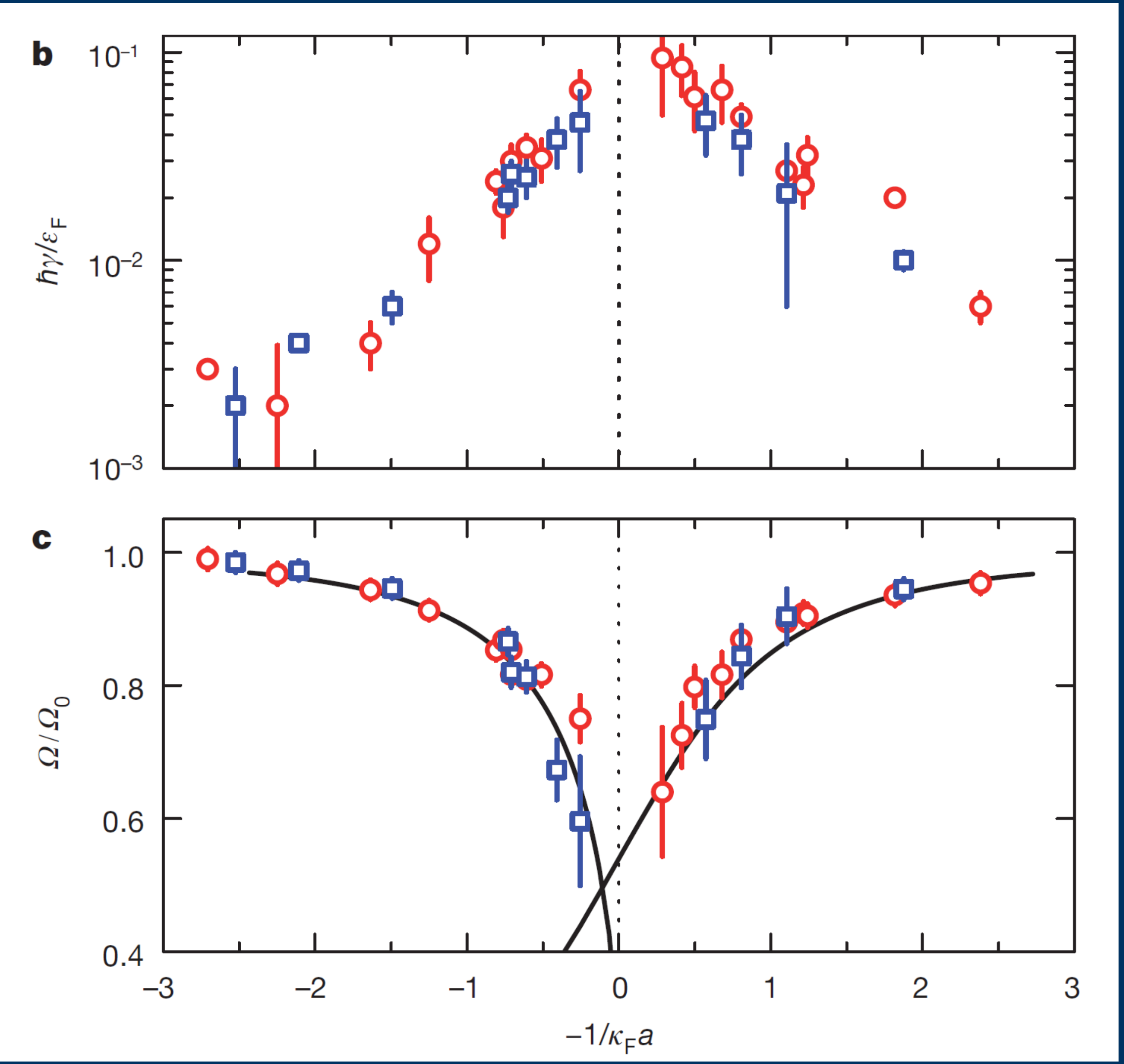
Anderson‘s orthogonality catastrophe observable ?

Knap et al., PRX 2, 04020 (2012)



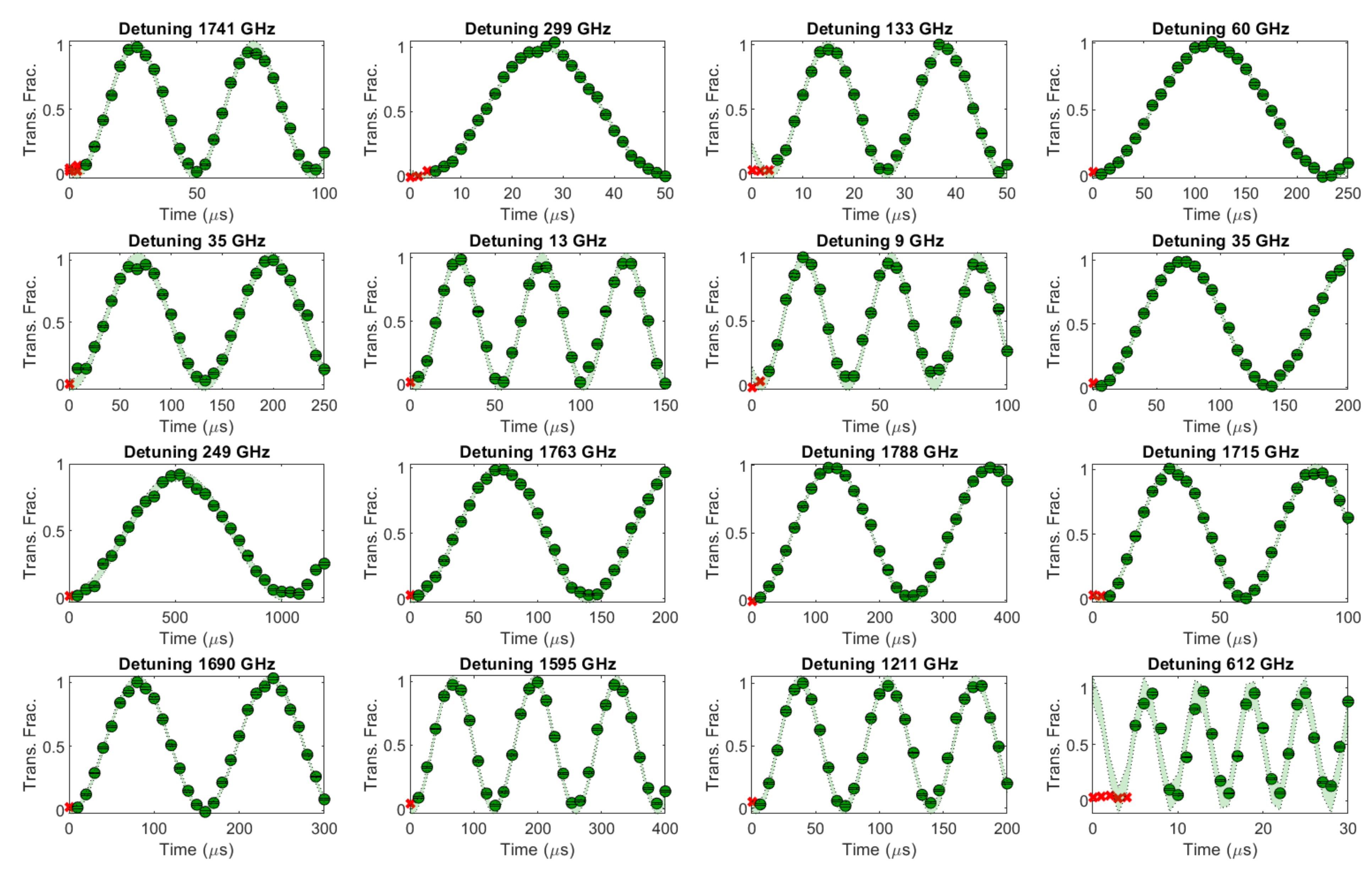
powerful tool: Rabi oscillations



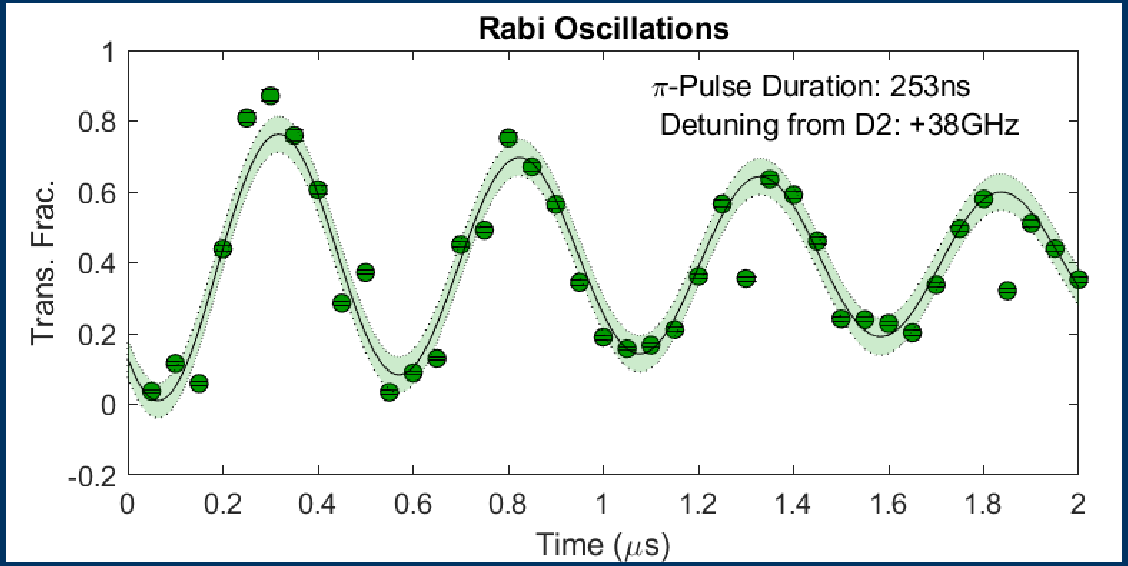


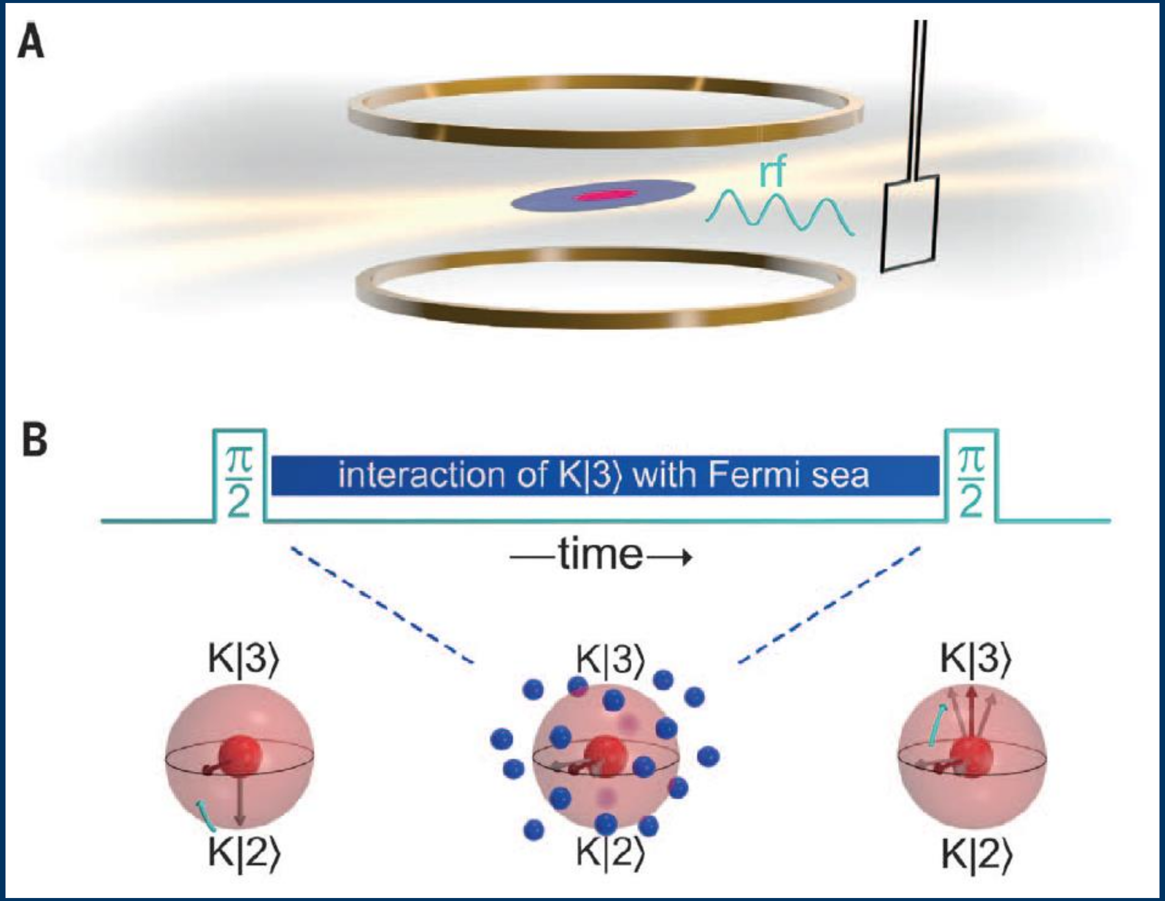
C. Kohstall, M. Zaccanti et al., Nature **485**, 615 (2012)

Raman pulses and Rabi oscillations



"ultrafast" pi-pulses





pi-pulse duration 250 ns

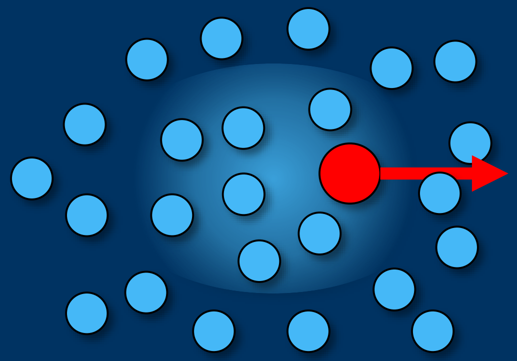
<<

Fermi time $E_F/\hbar \approx 5$ μs

Cetina et al., Science 354, 96 (2016)

polarons in motion

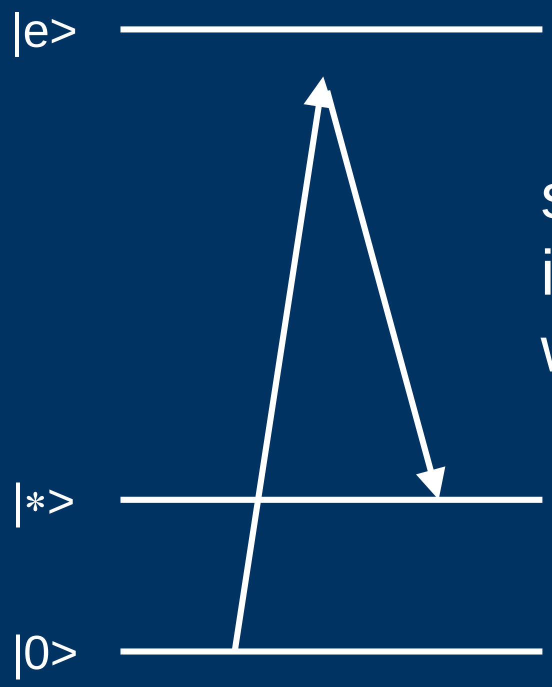
breakdown
of the quasiparticle ?



Fermi speed

$$E_F \approx k_B \times 700\ \mathrm{nK}$$

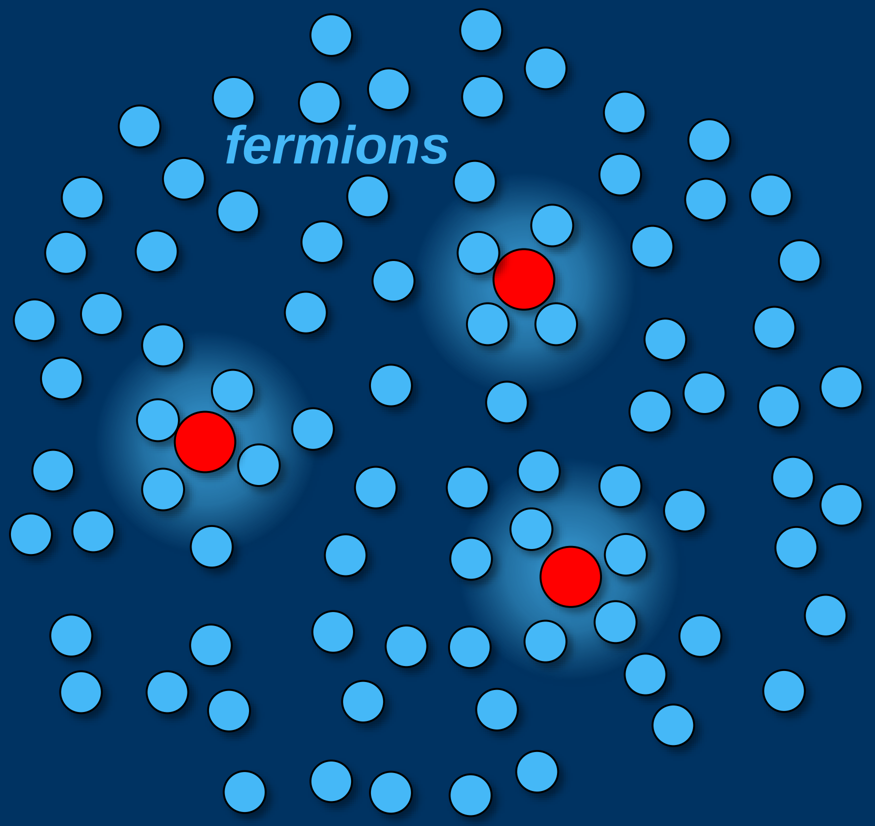
$$v_F = \sqrt{2E_F/m} \approx \mathbf{44\ mm/s}$$



suggested tool:
injection spectroscopy
with Raman pulses

$$\frac{2\hbar k}{m} \approx \mathbf{26}\,\frac{\mathbf{mm}}{\mathbf{s}} \approx \frac{v_F}{2}$$

Fermi polaron conclusion



- static quasiparticle properties
- stability and lifetime
- formation dynamics

done

- impurity quantum statistics
- impurity-impurity interactions
- motional effects

in progress

- few-body effects
- light impurities in heavy medium

open