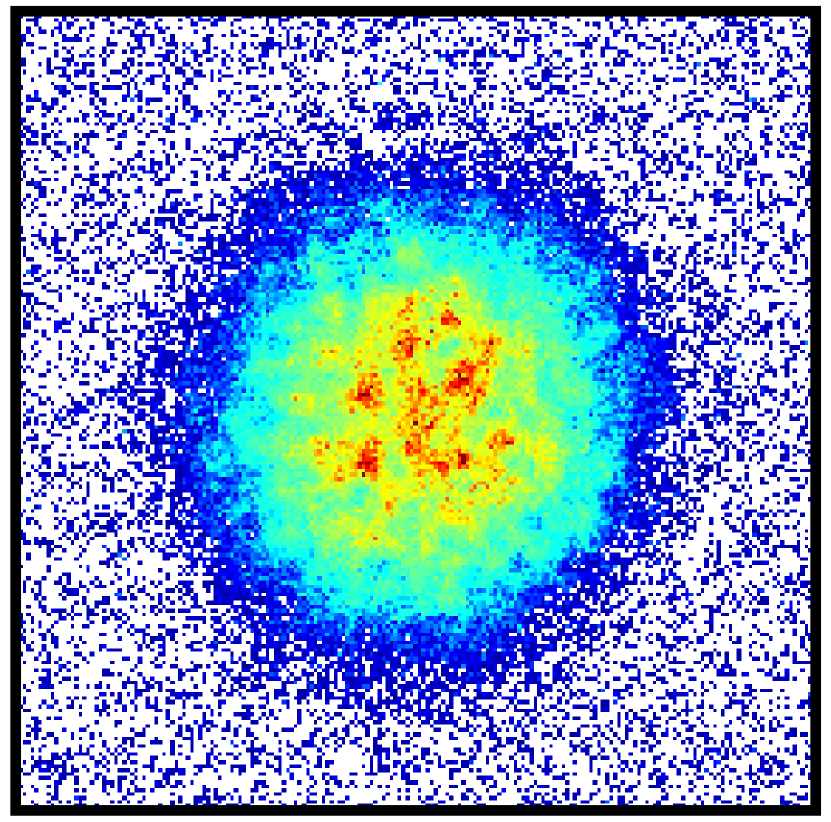
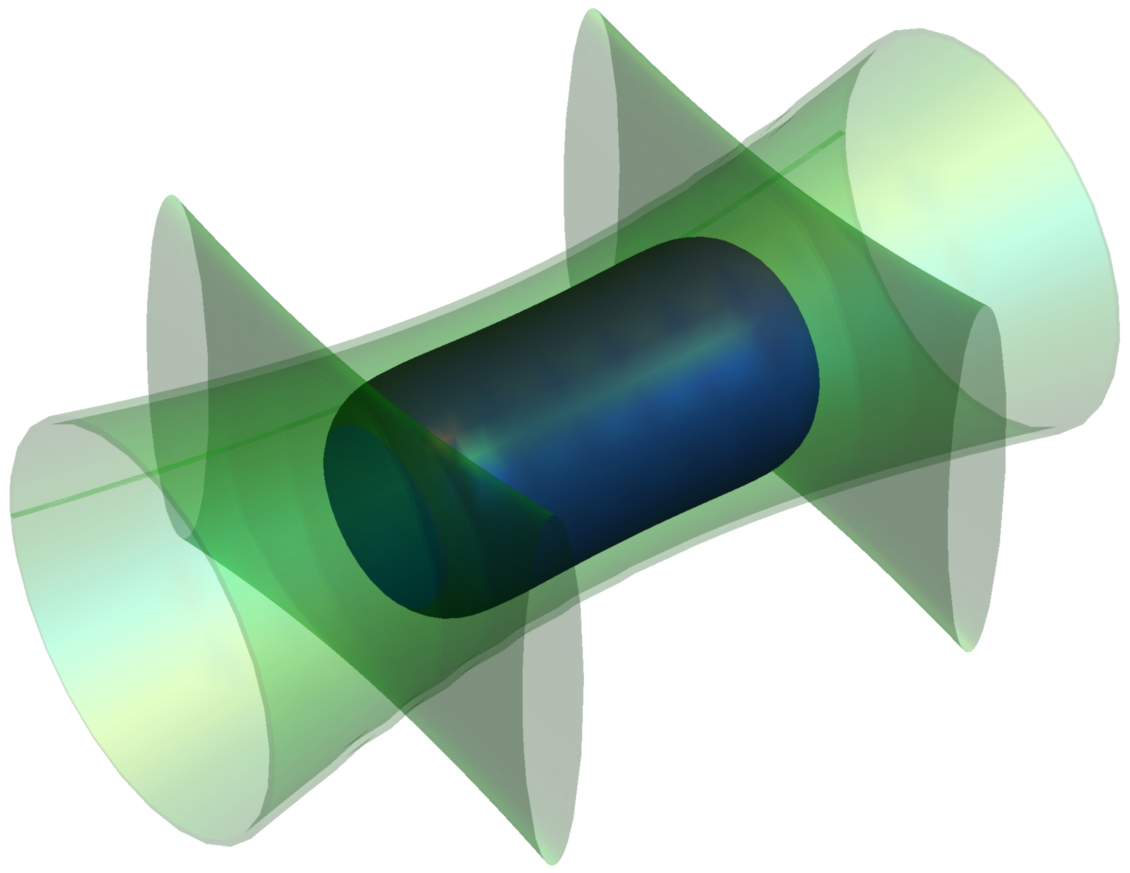
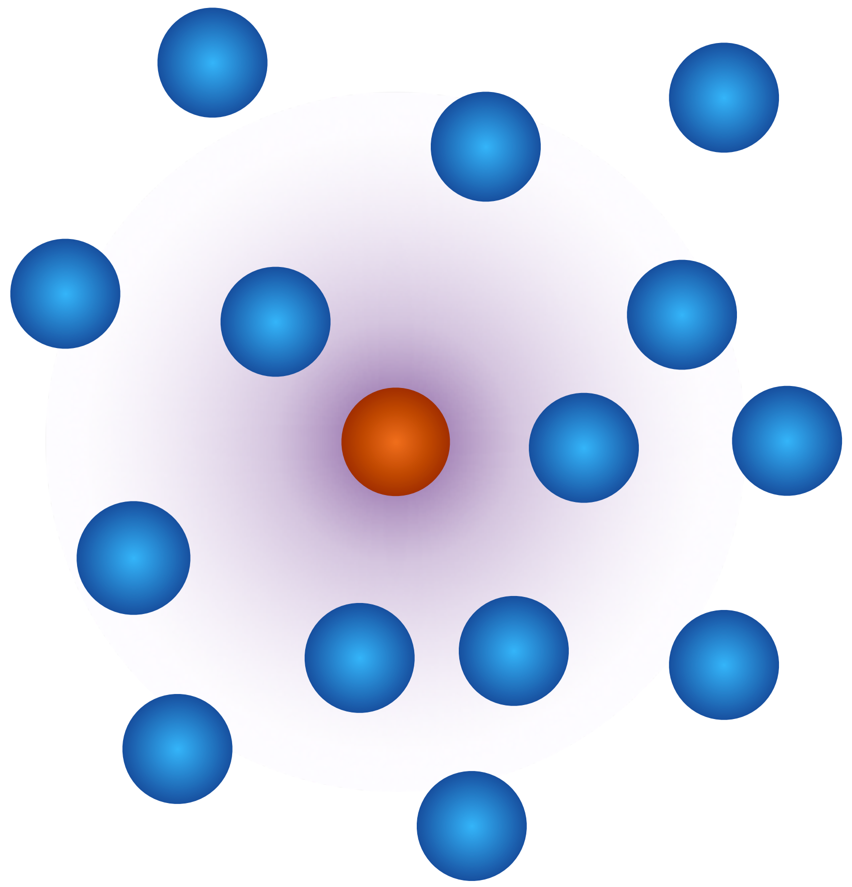
One- and many-body physics with box-trapped Bose gases

far-from-equilibrium dynamics





Bose polarons



Christoph Eigen

UNIVERSITY OF CAMBRIDGE

ECT Workshop, Trento

The physics of strongly interacting matter

April 25th, 2024

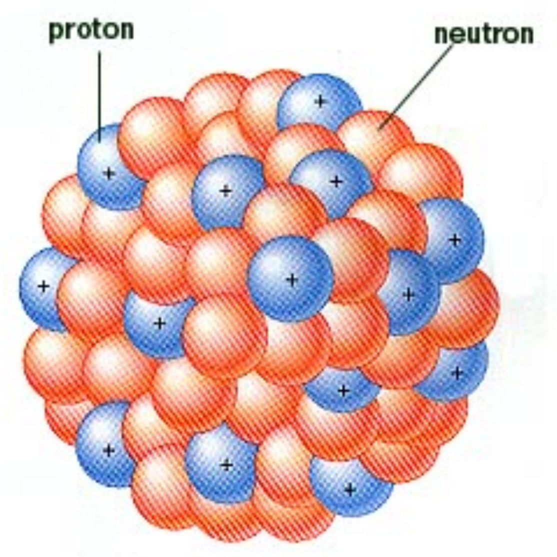
Introduction

systems far from equilibrium

many interacting components

in the quantum realm…

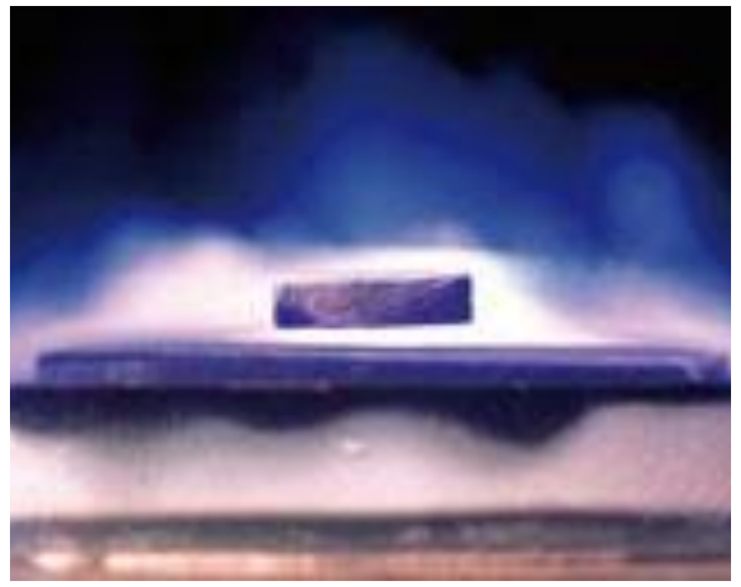
nuclear physics



small

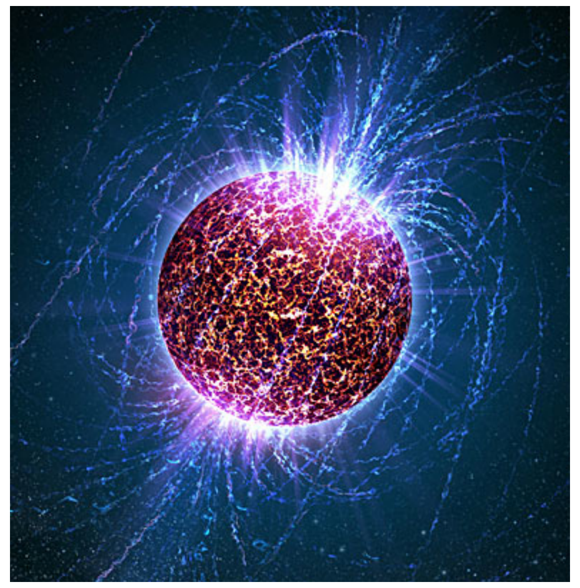
superfluid helium

high T_c superconductors



just plain hard

neutron stars



far

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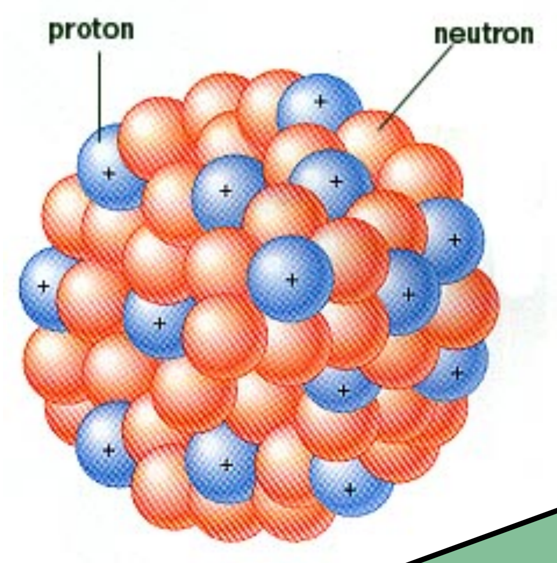
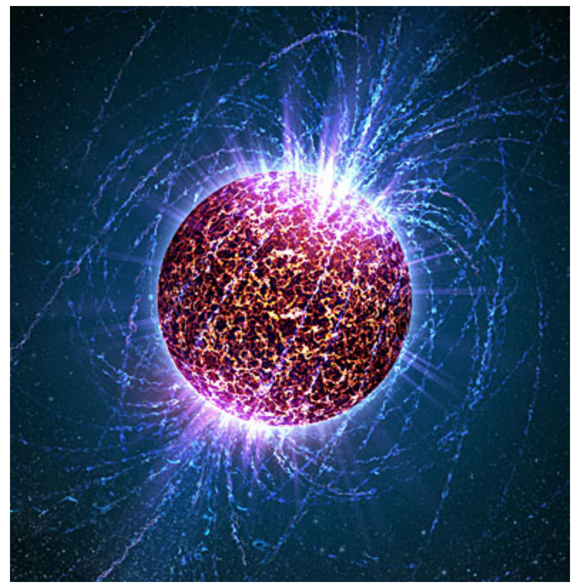




Quantum simulation!

sm

just plain hard

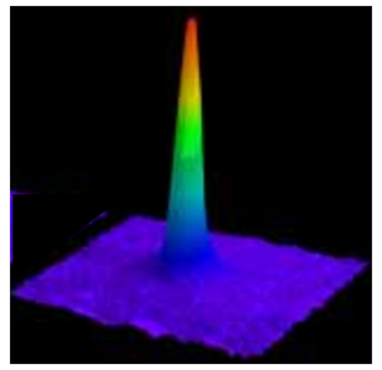
far

Why ultracold atoms?

Why ultracold atoms?

temperature scale (logarithmic)

ultracold atom experiments

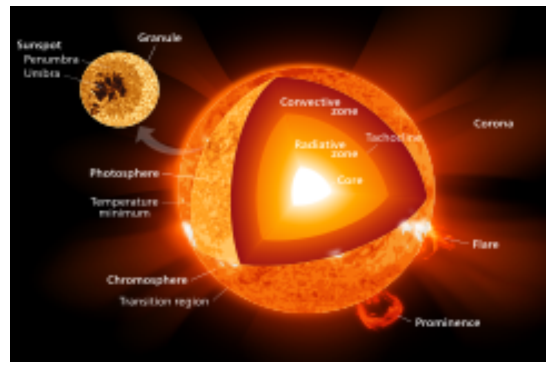


dilution refrigerator

outer space

warm place on earth

sun's center



10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} T (K)

atoms move at

~ 1 mm/s

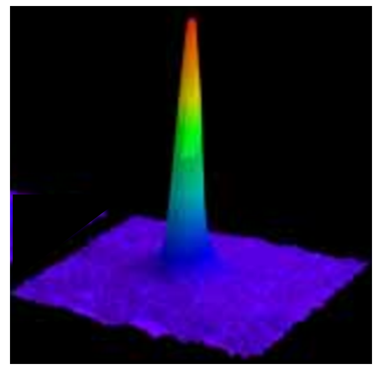
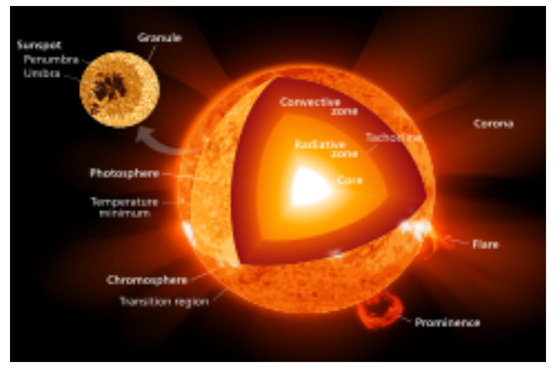
~ 100 m/s

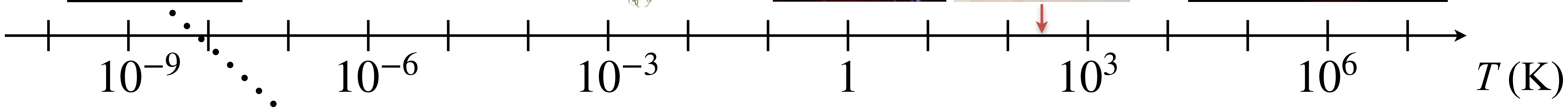
~ 100 km/s

Cambridge to Trento in ~10 s

Why ultracold atoms?

temperature scale (logarithmic)

ultracold atom experiments	dilution refrigerator	outer space	warm place on earth	sun's center
				



atoms move at

~ 1 mm/s

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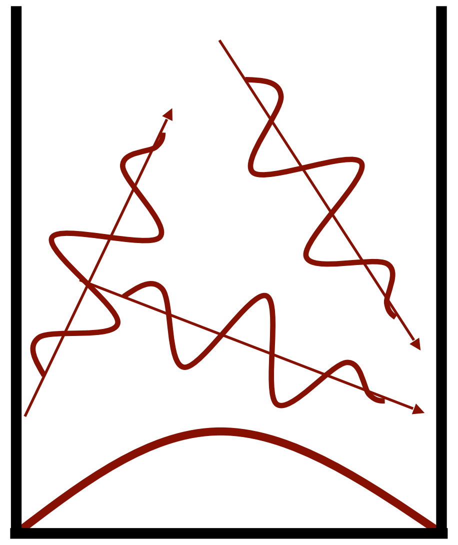
coherent macroscopic quantum objects
(Bose-Einstein condensate / degenerate Fermi gases)

real-time dynamics | highly controllable



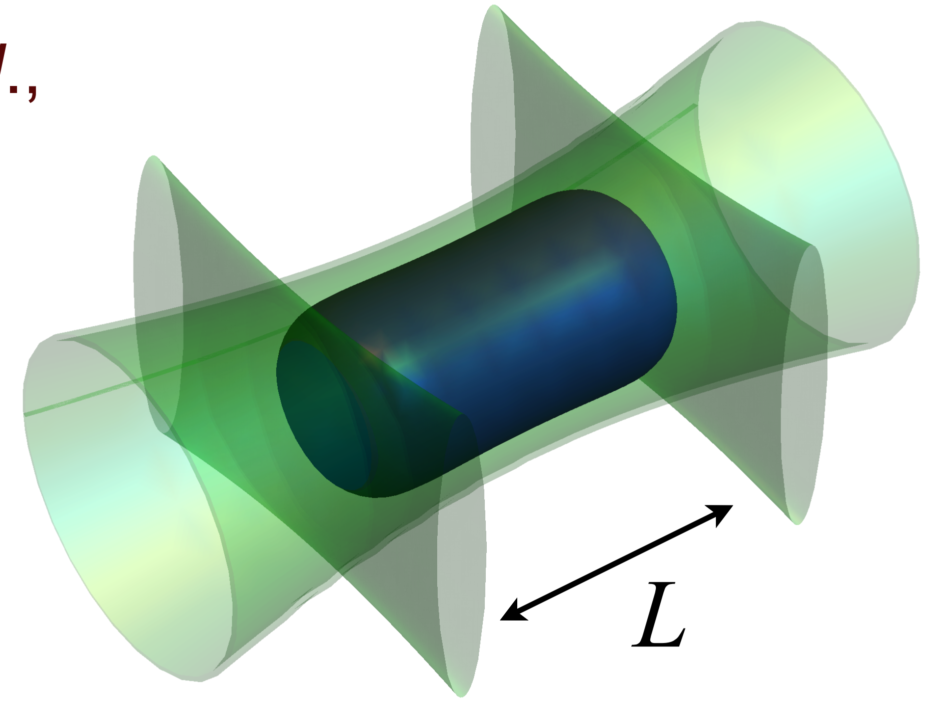
macroscopic quantum system

Christoph Eigen

Experimental platform

ultracold ^{39}K
Bose gas in a box

review: N. Navon *et al.*, Nat. Phys. **17**, 1334 (2021)



optical box

A. L. Gaunt *et al.*, PRL **110**, 200406 (2013)

C. Eigen *et al.*, PRX **6**, 041058 (2016)

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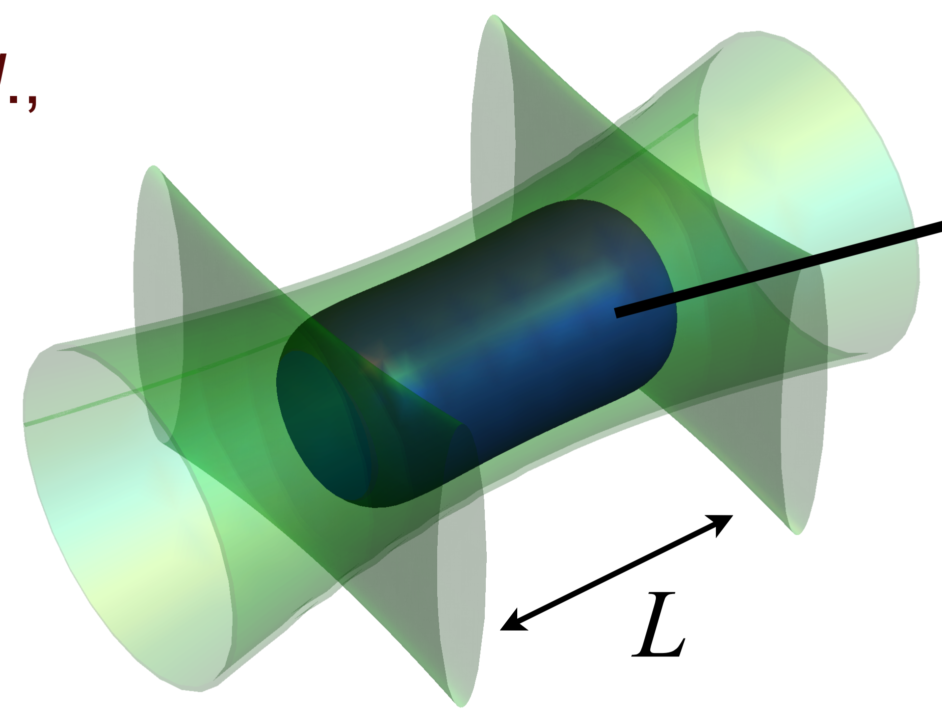

optical box
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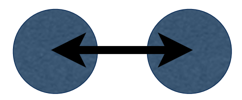
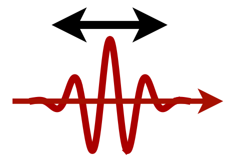
three relevant length scales

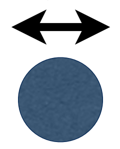
interparticle spacing — $n^{-1/3}$



thermal wavelength — $\lambda \propto 1/\sqrt{T}$



s-wave scattering length — a



small print:
the 3-body length scale R_0 (set by Efimov physics) is another potentially relevant length scale, as well as the finite box size L

Experimental platform

ultracold ^{39}K
Bose gas in a box

tuneable *s*-wave interactions using
Feshbach resonances
rich landscapes in ^{39}K

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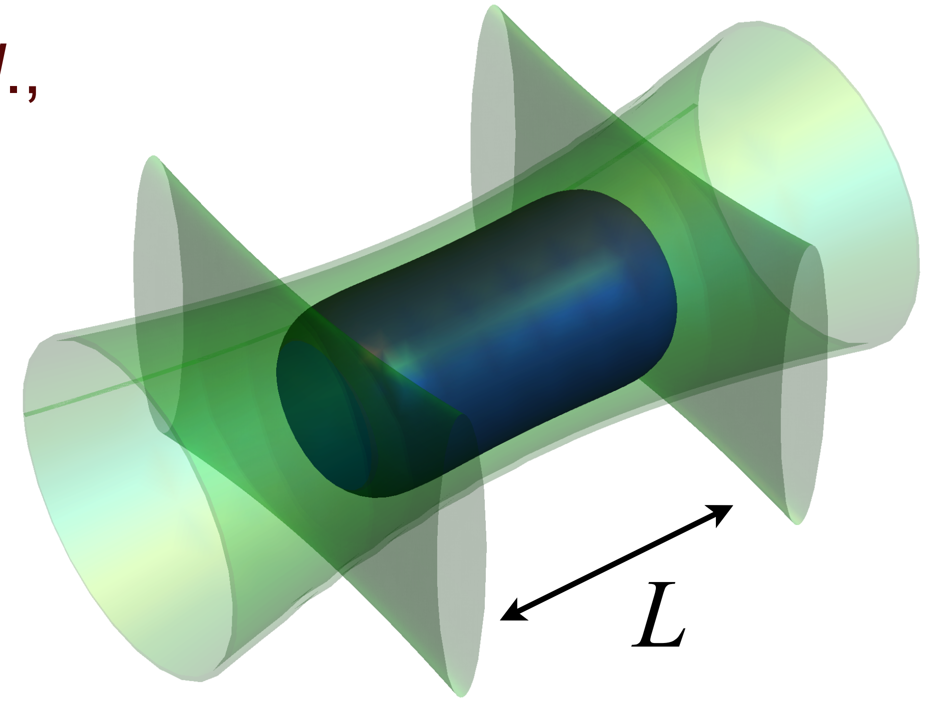

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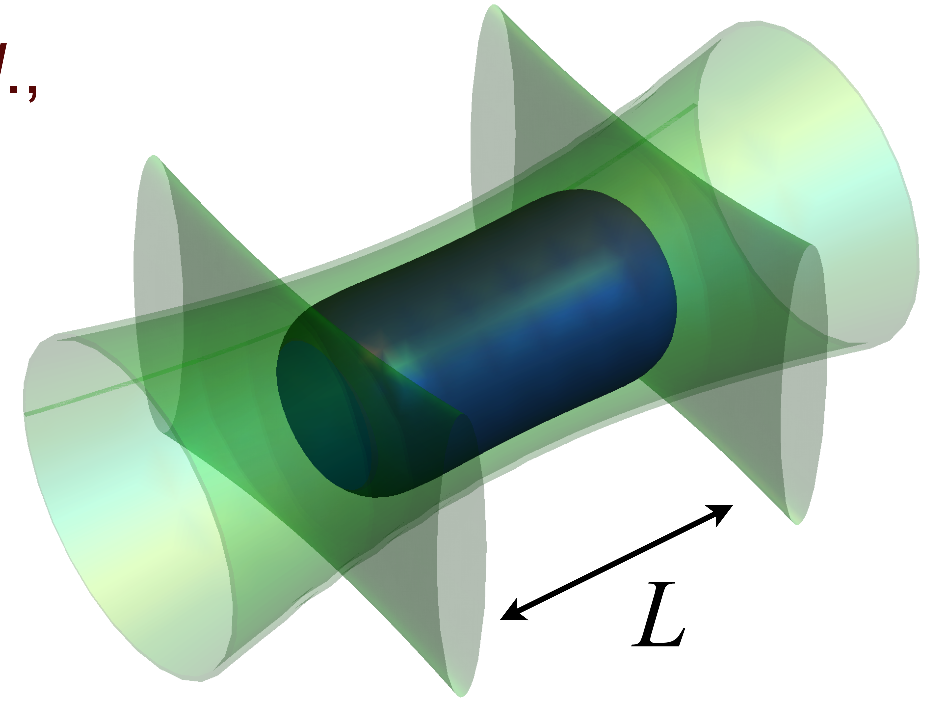

optical box

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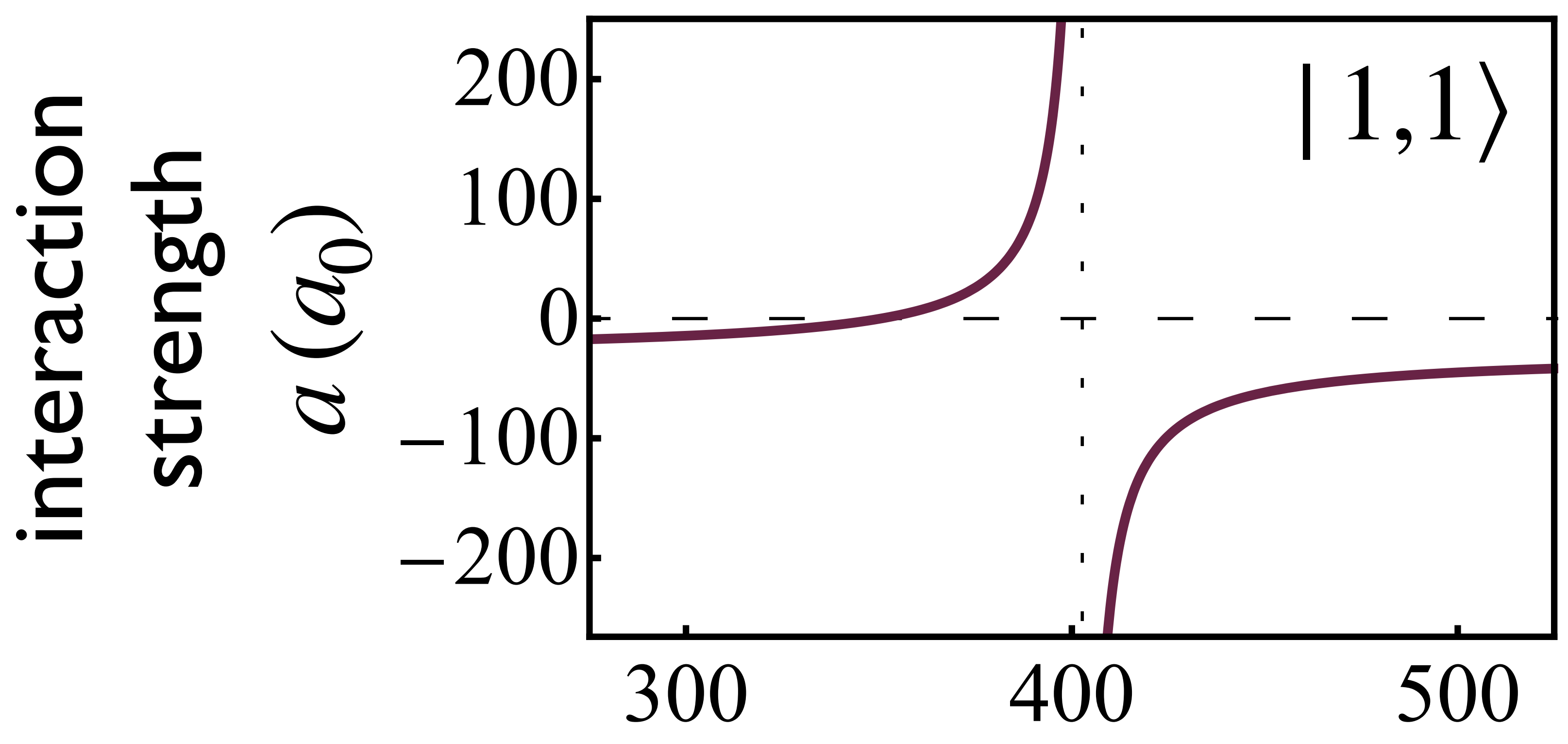
C. Eigen *et al.*, PRX **6**, 041058 (2016)

tuneable s-wave interactions using Feshbach resonances

for any single resonance, full control!



unitary regime (at B_{res}) $a \to \infty$

can also turn off interactions! ($a = 0$)

many-body

is one good resonance enough?

Experimental platform

ultracold ^{39}K
Bose gas in a box

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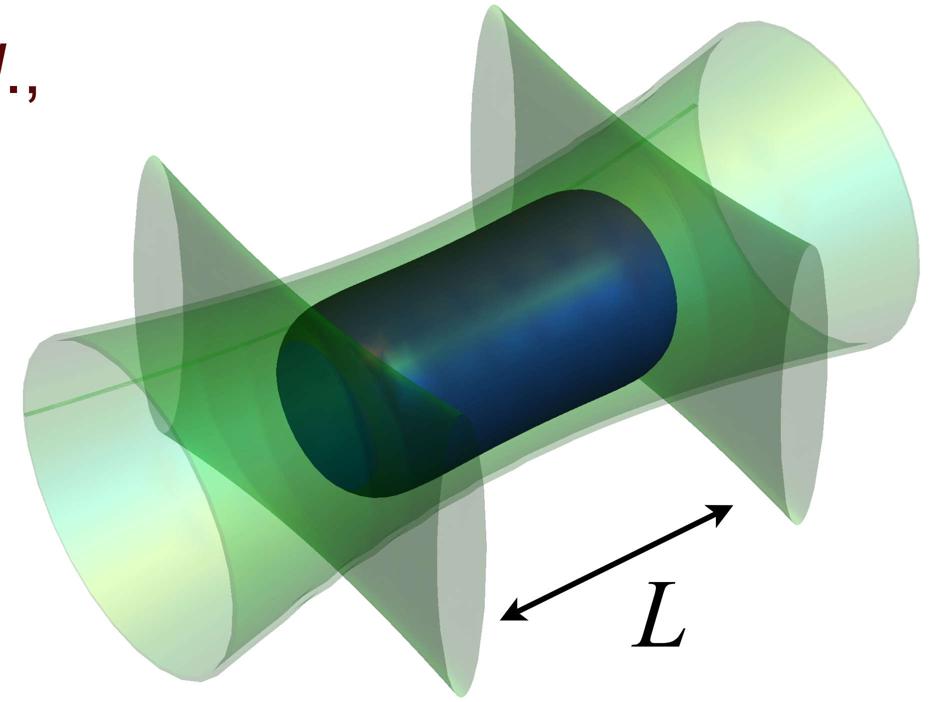

optical box
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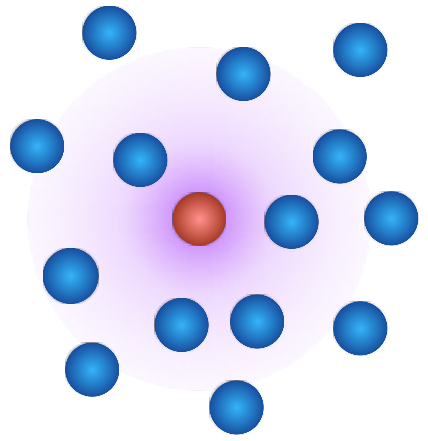
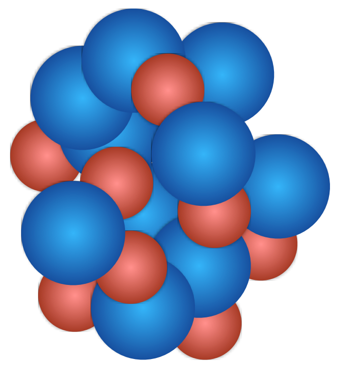
many-body

- ✦ spin-state-based interaction switches
  a_{11}, a_{22}
- ✦ quantum mixtures
  a_{11}, a_{22}, a_{12}



polarons



droplets

✦…

atom matters!
(not just m…)

Experimental platform

ultracold ^{39}K
Bose gas in a box

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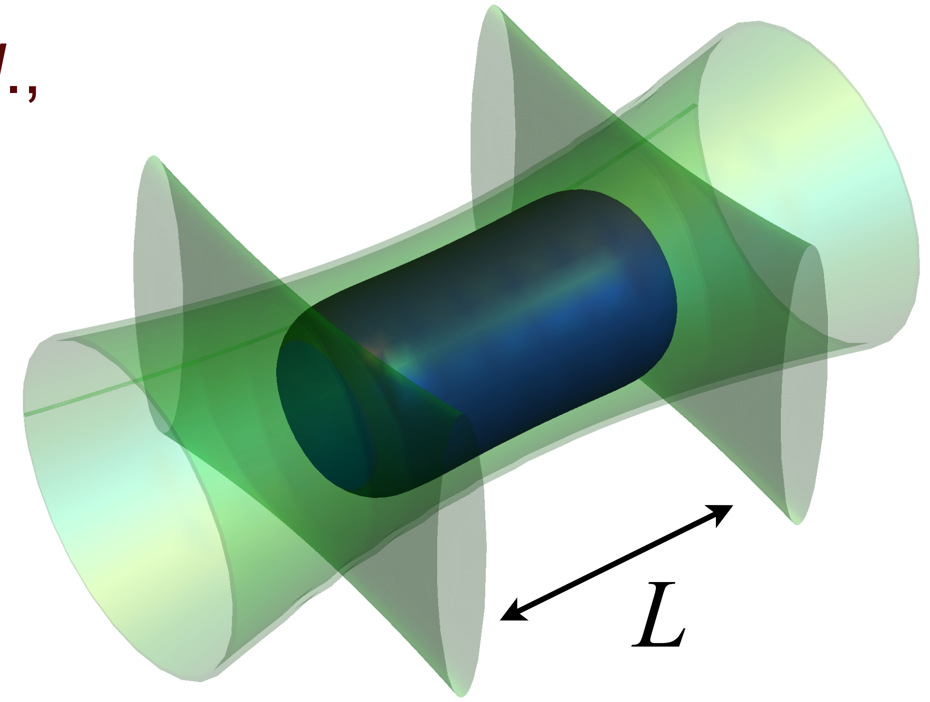

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tuneable s-wave interactions using Feshbach resonances

rich landscapes in ^{39}K

many-body

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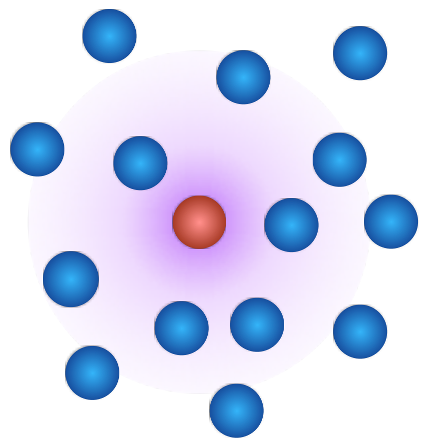
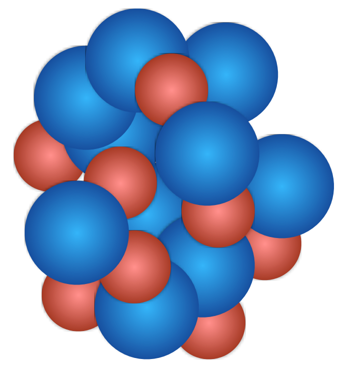


polarons

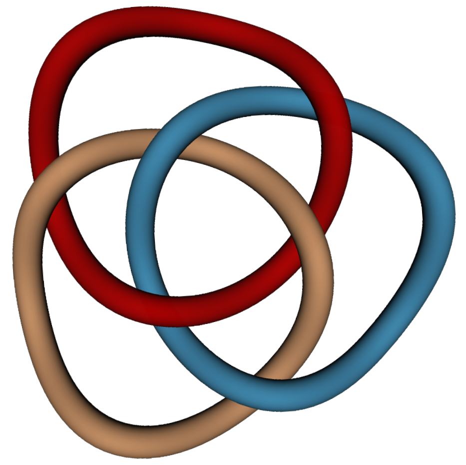


droplets

- …

few-body

- Efimov physics

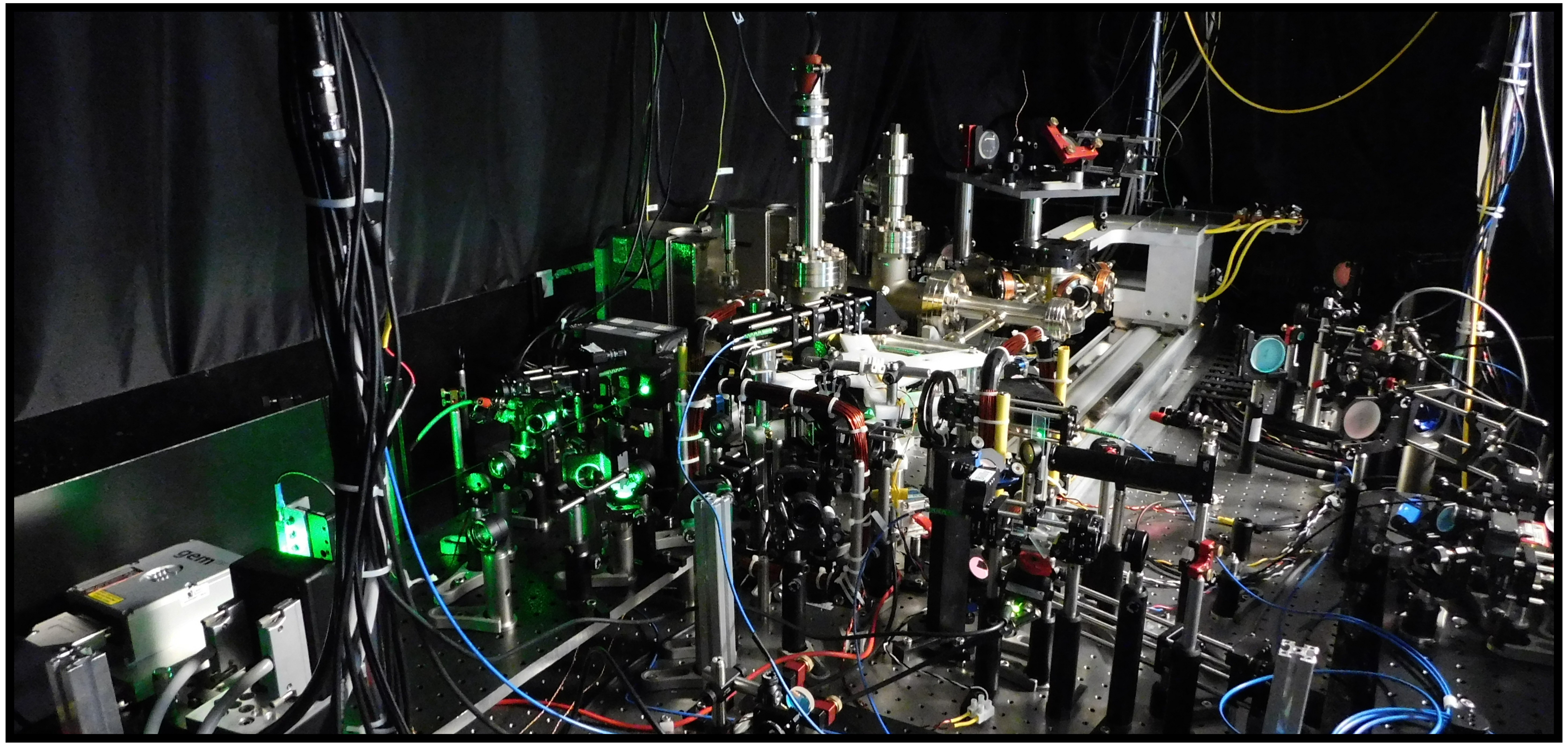


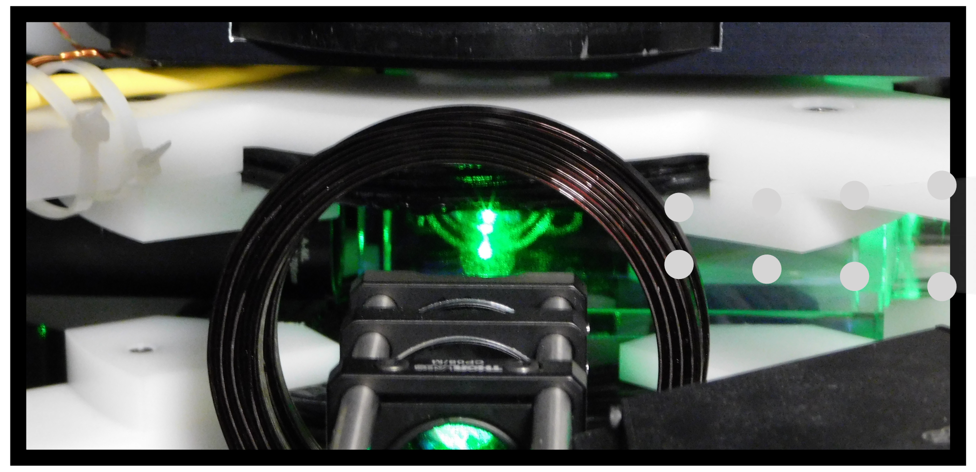
Efimov trimers
quantum mechanical analogue of Borromean rings

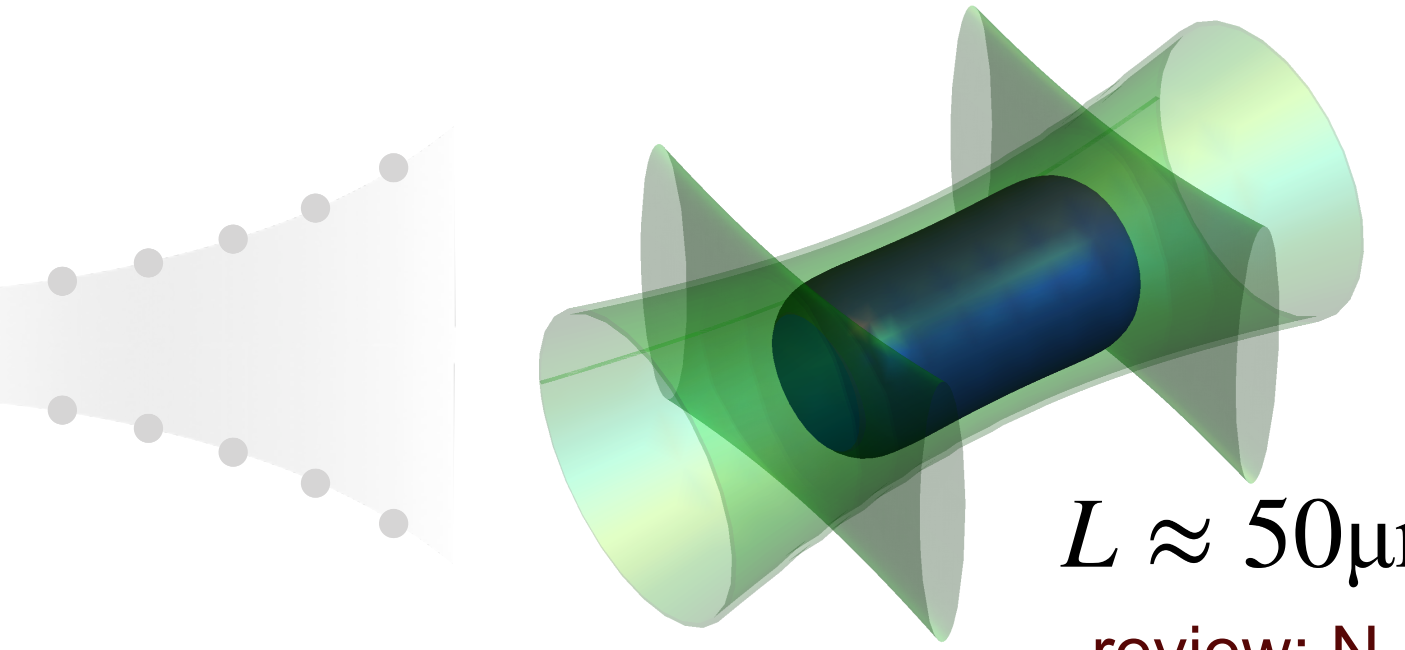
How does it look in practice?

How does it look in practice?

How does it look in practice?







review: N. Navon *et al.*, Nat. Phys. **17**, 1334 (2021)

Talk outline

1. Subdiffusive dynamic scaling in a driven disordered Bose gas

G. Martirosyan et al. PRL **132**, 113401 (2024)

Y. Zhang et al. C. R. Phys. **24** [online first] (2023)

2. Bose polarons in box

J. Etrych et al. arXiv:2402.14816 (2024)

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2. Bose polarons in box

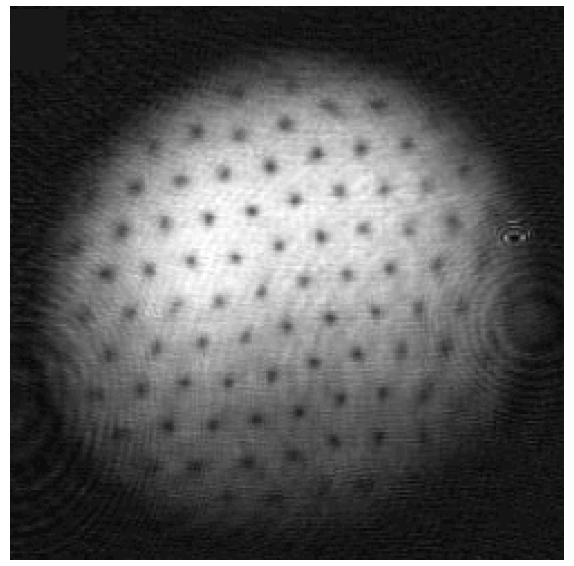
J. Etrych et al. arXiv:2402.14816 (2024)

Matter-wave fluid dynamics

Nonlinear Schrödinger equation with cubic nonlinearity (Gross-Pitaevskii Equation)

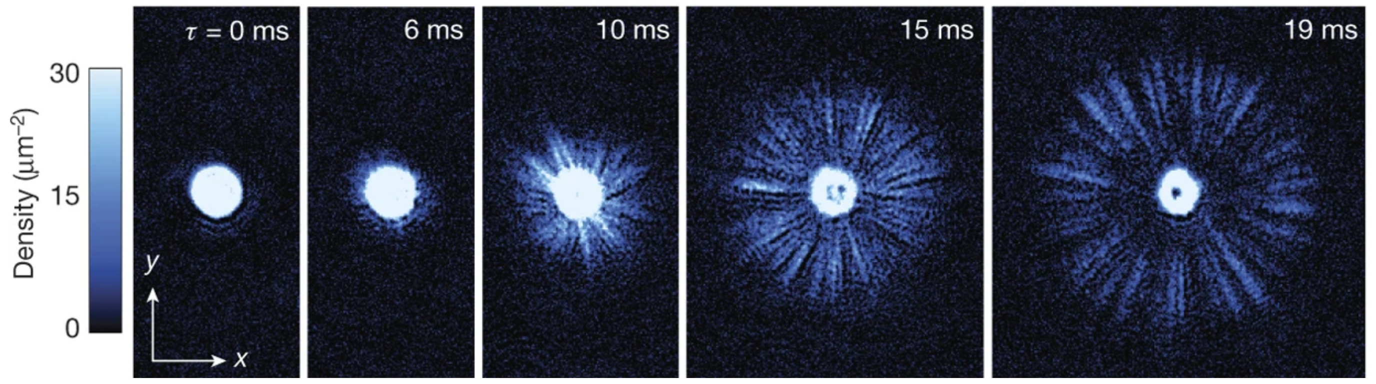
$$i\hbar\frac{\partial\Psi(\mathbf{r},t)}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}) + g|\Psi(\mathbf{r},t)|^2\right)\Psi(\mathbf{r},t)$$

Abrikosov lattices



J. R. Abo-Shaeer *et al.*, Science **292**, 476 (2001)

Bose fireworks



L. W. Clark *et al.*, Nature **551**, 356 (2017)

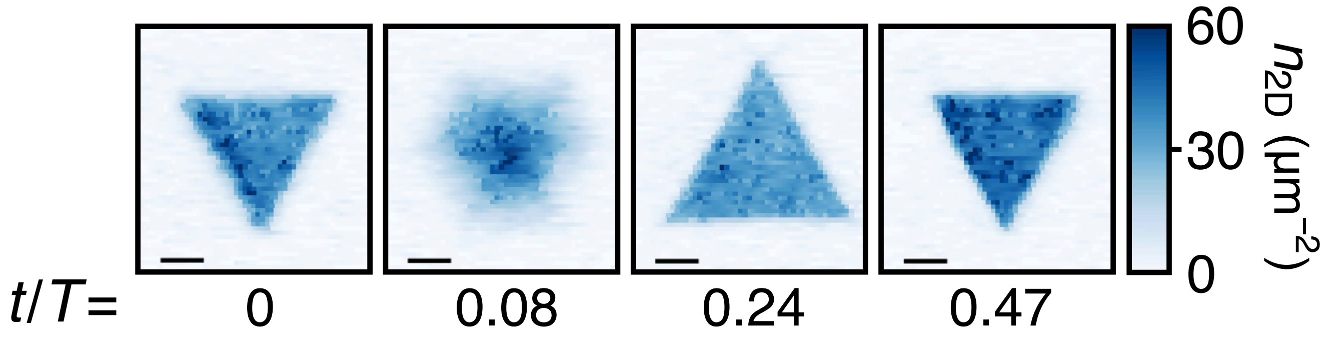
transport

solitons

turbulence

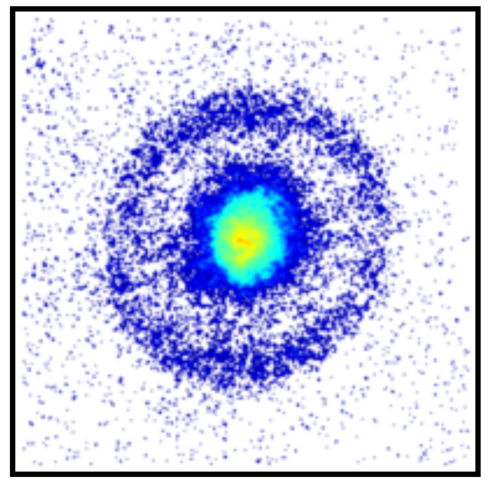
cf. classical fluid dynamics

Breathers



R. Saint-Jalm *et al.*, PRX **9**, 021035 (2019)

Wave collapse



Shaken, not stirred

ultracold ^{39}K
Bose gas in a box

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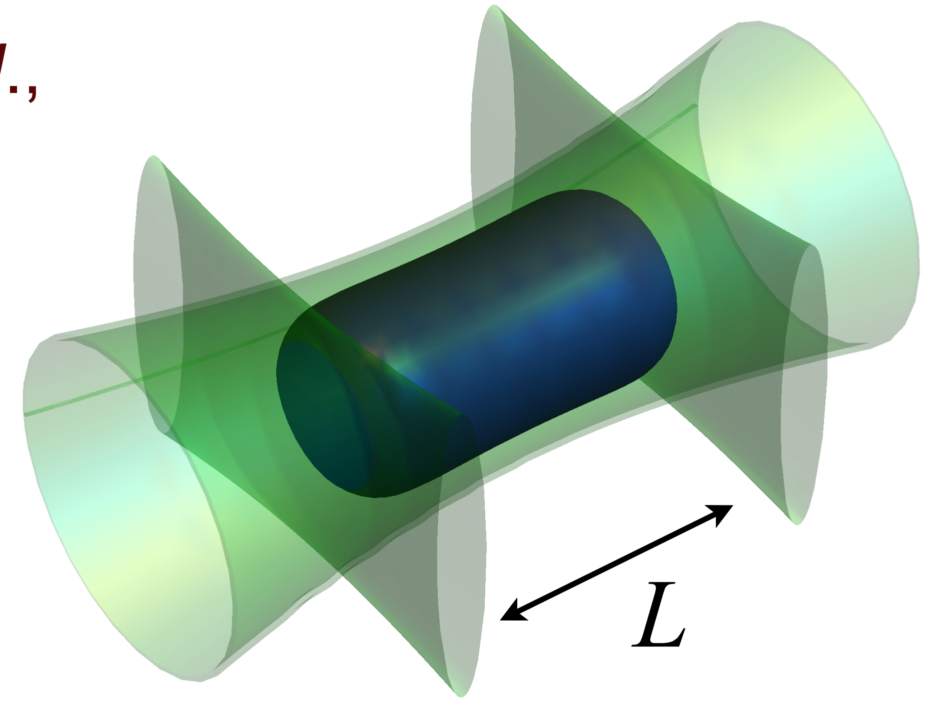
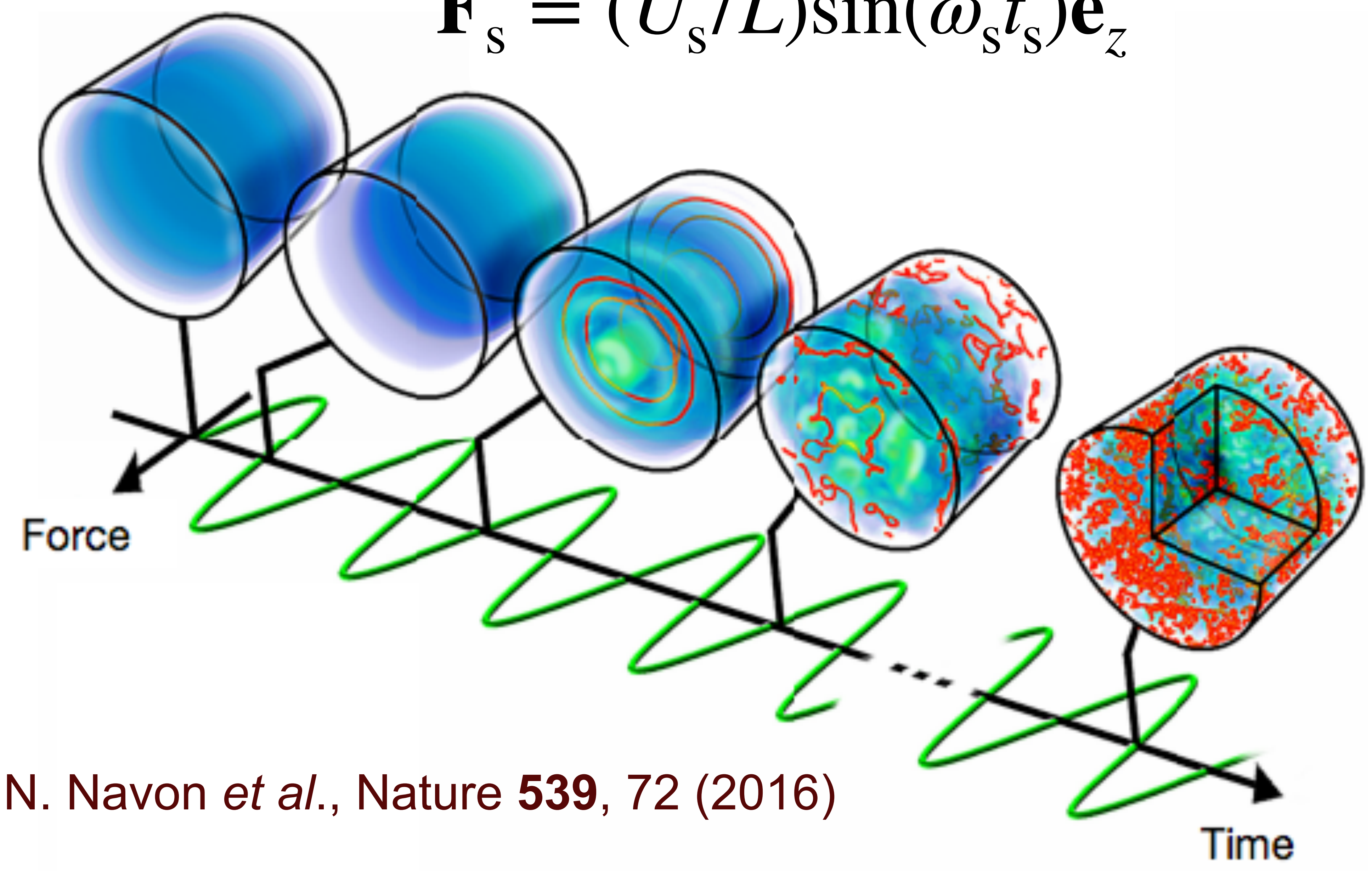


optical box

A. L. Gaunt *et al.*, PRL **110**, 200406 (2013)
C. Eigen *et al.*, PRX **6**, 041058 (2016)

excite the system by oscillating spatially uniform force

$$\mathbf{F}_\mathrm{s} = (U_\mathrm{s}/L)\sin(\omega_\mathrm{s} t_\mathrm{s})\hat{\mathbf{e}}_z$$

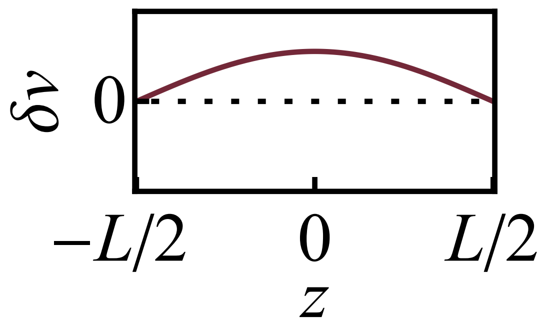


N. Navon *et al.*, Nature **539**, 72 (2016)

Shaken interacting homogeneous Bose gases

also at nonzero *T*
In 2D: P. Christodoulou *et al.*, Nature **594**, 191 (2021)
In 3D: T. A. Hilker *et al.*, PRL **128**, 223601 (2022)

Bogoliubov sound waves



single-particle excitations → sound waves
S. Garratt *et al.*, PRA **99**, 021601(R) (2019)

excitation amplitude, U_s ($\times\ t_s$)

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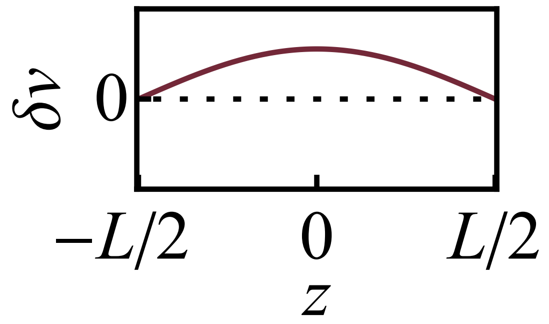

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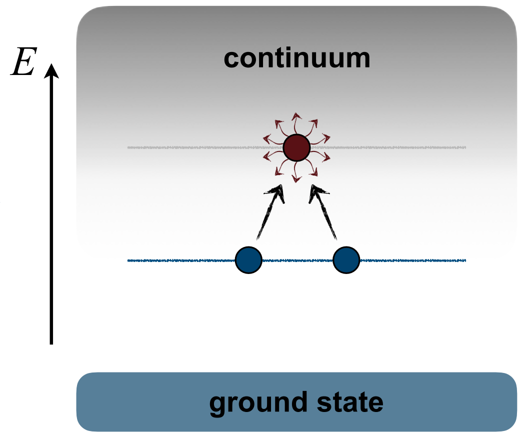
Route to turbulence

first-step: many-body decay



theory collab. W. Zheng, N. R. Cooper

J. Zhang *et al.*, PRL **126**, 060402 (2021)

also in 2D
M. Gałka *et al.*, PRL **129,** 190402 (2022)

excitation amplitude, U_s $(\times\, t_s)$

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also at nonzero T
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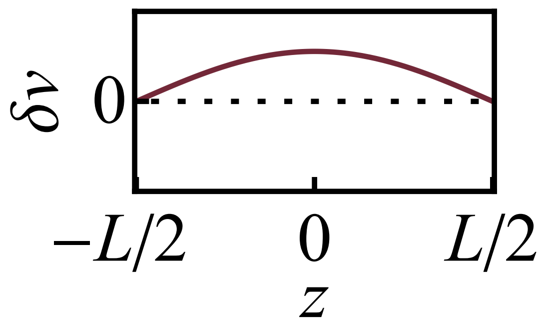
energy grows linearly with t_s!

Bogoliubov sound waves



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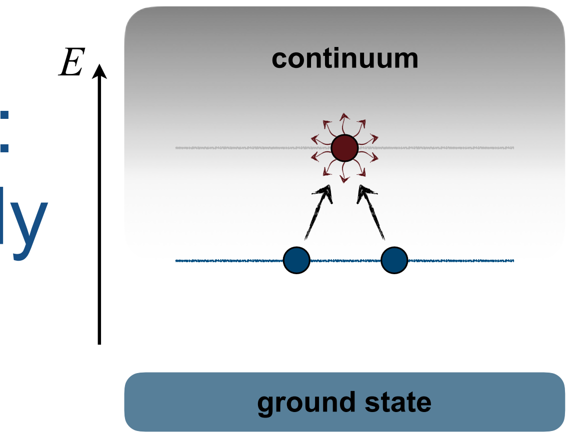

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also in 2D
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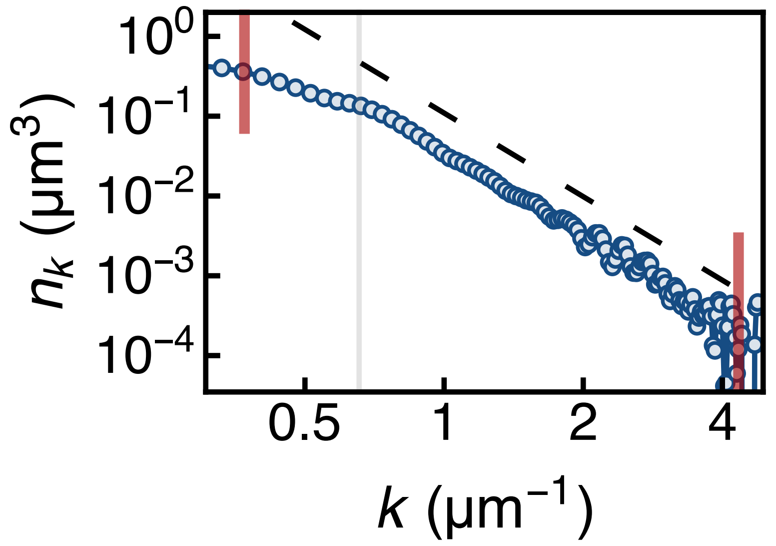
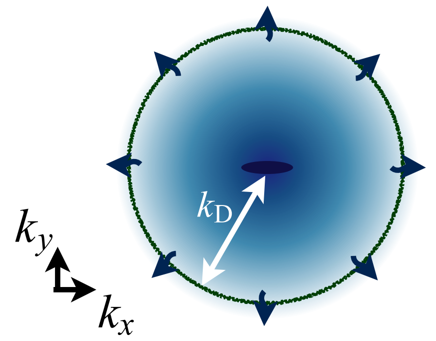
Wave Turbulence





$n_k = n_0\, k^{-\gamma},\ \gamma \approx 3.4$

N. Navon *et al.*, Nature **539**, 72 (2016)
N. Navon *et al.*, Science **366**, 382 (2019)
L. H. Dogra *et al.*, Nature **620**, 521 (2023)

excitation amplitude, U_s $(\times\ t_s)$

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also at nonzero T
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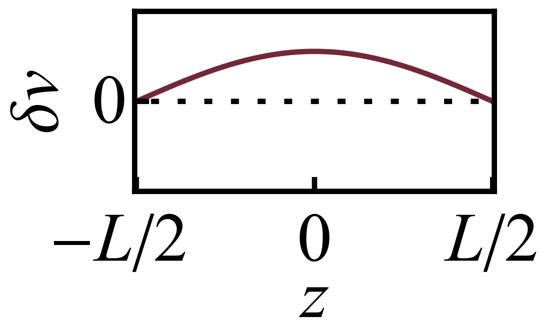
energy grows linearly with t_s!

Bogoliubov sound waves



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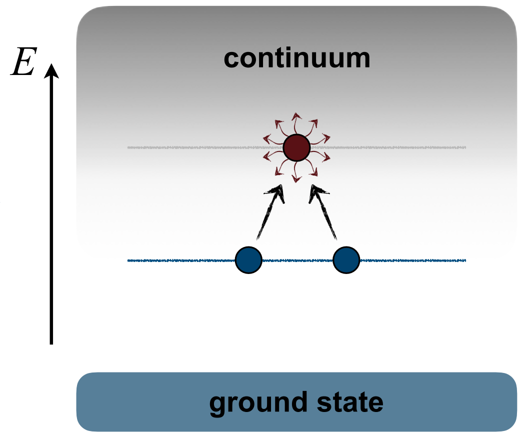
Route to turbulence

first-step: many-body decay



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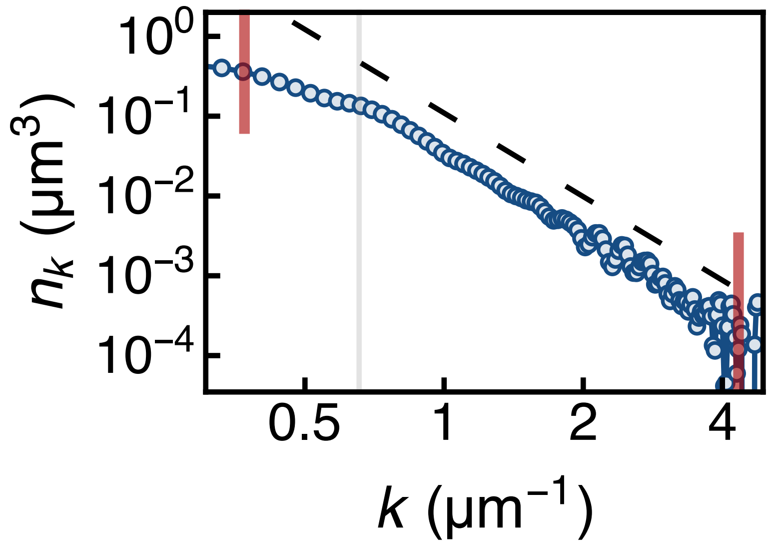
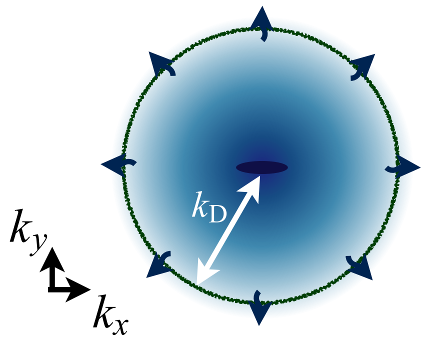
Wave Turbulence





$$n_k = n_0 k^{-\gamma}, \ \gamma \approx 3.4$$

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N. Navon *et al.*, Science **366**, 382 (2019)
L. H. Dogra *et al.*, Nature **620**, 521 (2023)

excitation amplitude, $U_s \ (\times \ t_s)$

What happens in the absence of interactions?

Particle in a box

can turn off interactions!

^{39}K in $|1,1\rangle$ at the $B = 350.4(1)\mathrm{G}$
zero crossing ($a \to 0$)

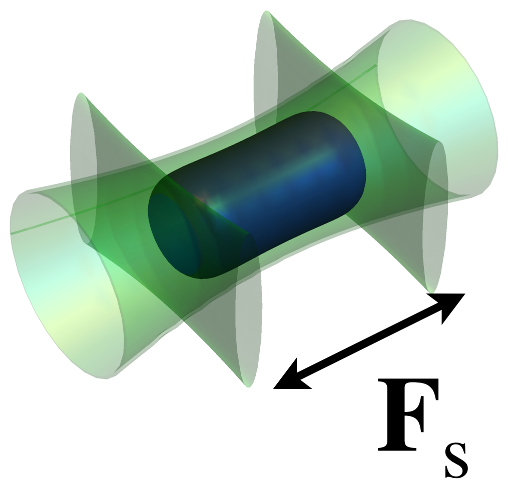
cylindrical box ($L \approx 50\mu\mathrm{m}$ and $R \approx 15\mu\mathrm{m}$)

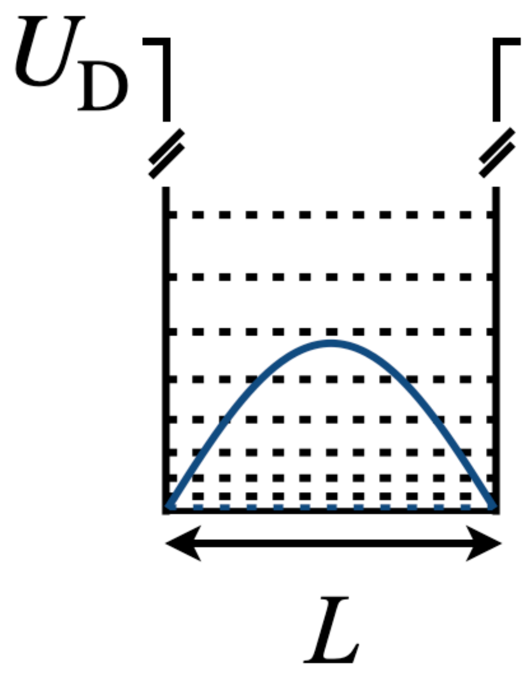
Driven particle in a box

can turn off interactions!

^{39}K in $|1,1\rangle$ at the $B = 350.4(1)$G zero crossing ($a \to 0$)

cylindrical box ($L \approx 50\mu$m and $R \approx 15\mu$m)





$$\mathbf{F}_\mathrm{s} = (U_\mathrm{s}/L)\cos(\omega_\mathrm{s} t_\mathrm{s})\hat{\mathbf{e}}_z$$

lowest-lying axial excitation

$$\omega_K = (\varepsilon_1 - \varepsilon_0)/\hbar = \frac{3\hbar}{2m}\left(\frac{\pi}{L}\right)^2 = 2\pi \times 2\mathrm{Hz}$$

weak kick → Rabi oscillations

extremely low ~100pK energy scale!

dynamics described by Schrödinger equation:

$$i\hbar\frac{\partial}{\partial t}\varphi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r},t)\right]\varphi(\mathbf{r},t)$$

Driven particle in a box

can turn off interactions!

^{39}K in $|1{,}1\rangle$ at the $B = 350.4(1)\mathrm{G}$ zero crossing ($a \to 0$)

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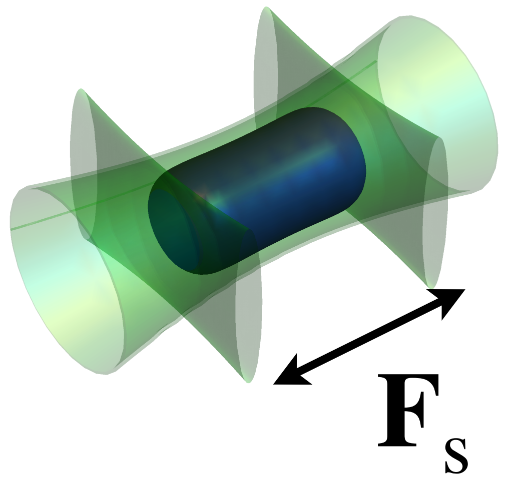

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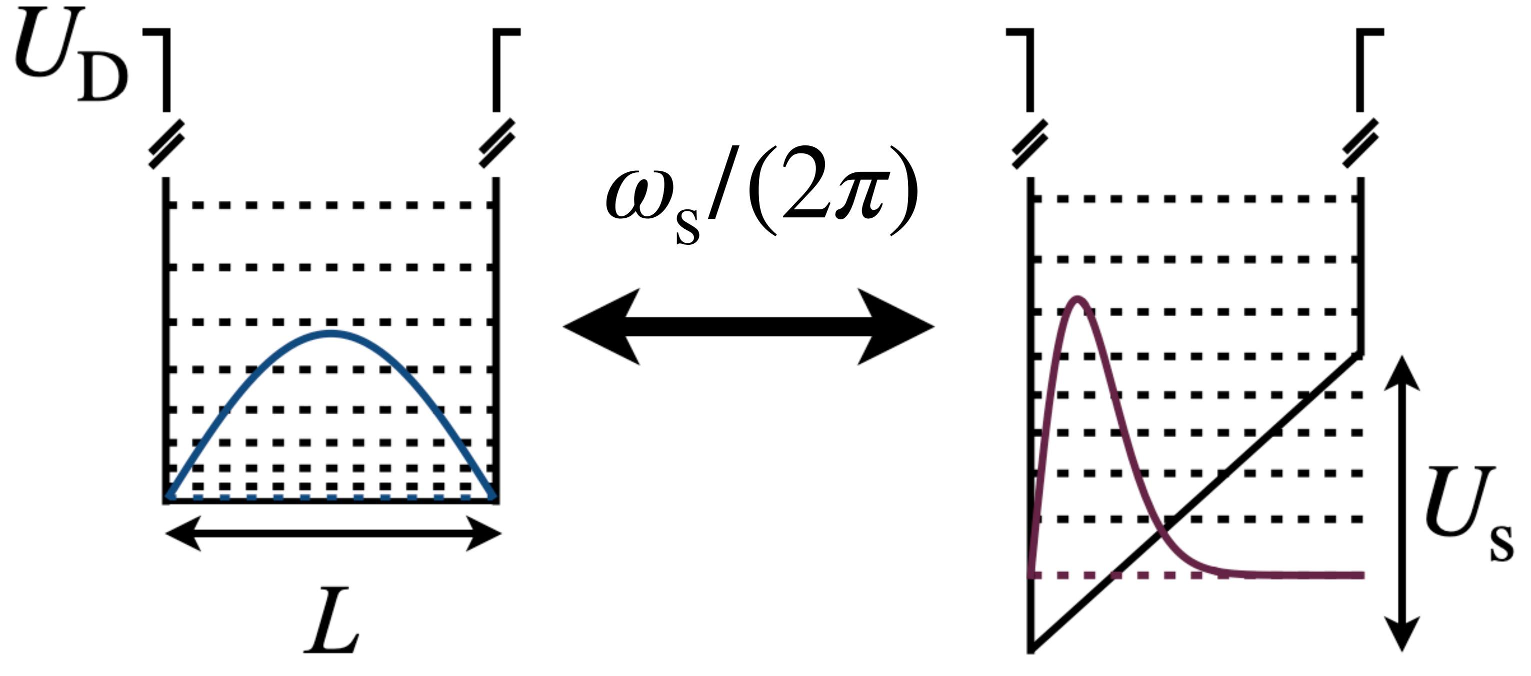
weak kick → Rabi oscillations

extremely low ~100pK energy scale!

more violent excitation?



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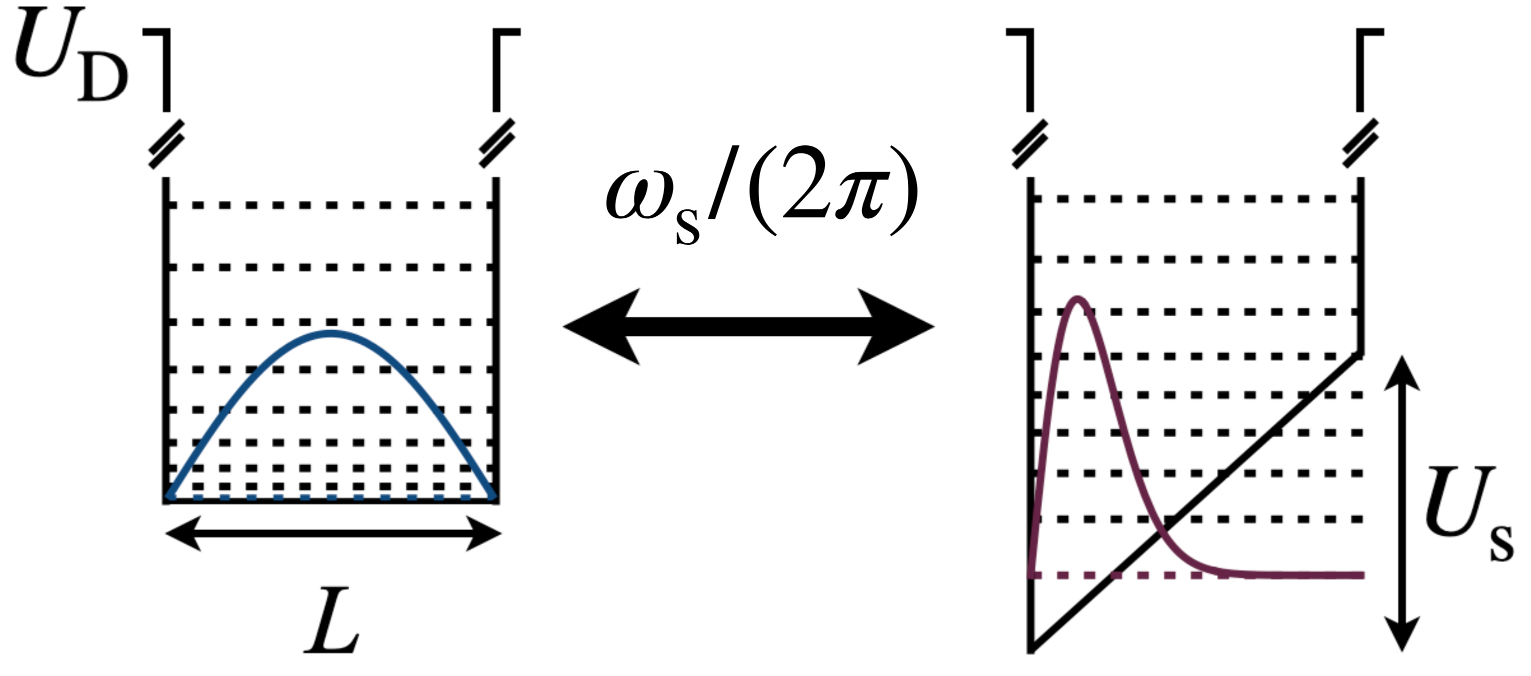
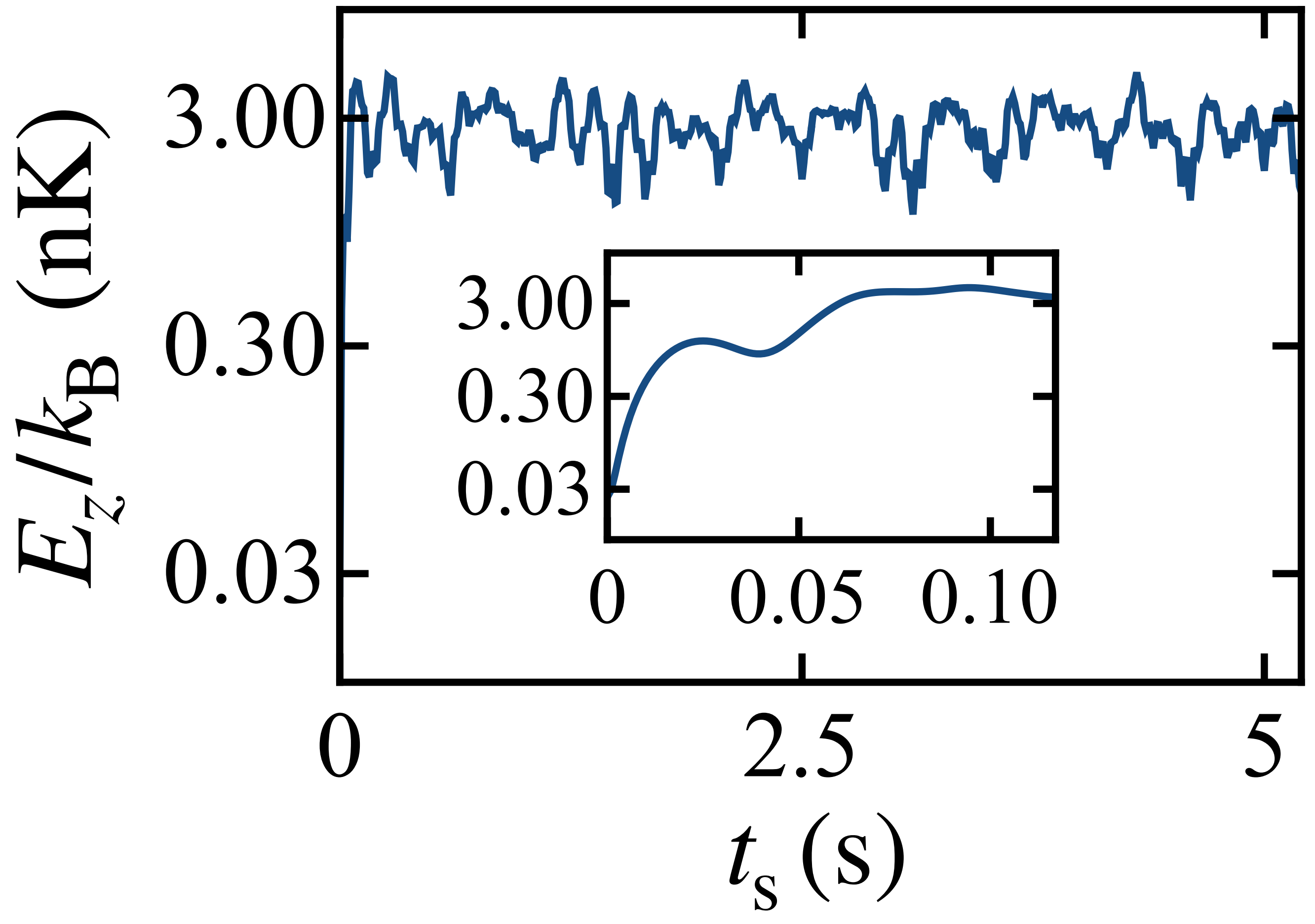
Driven particle in a box

violent excitation



energy fluctuates
but average saturates!



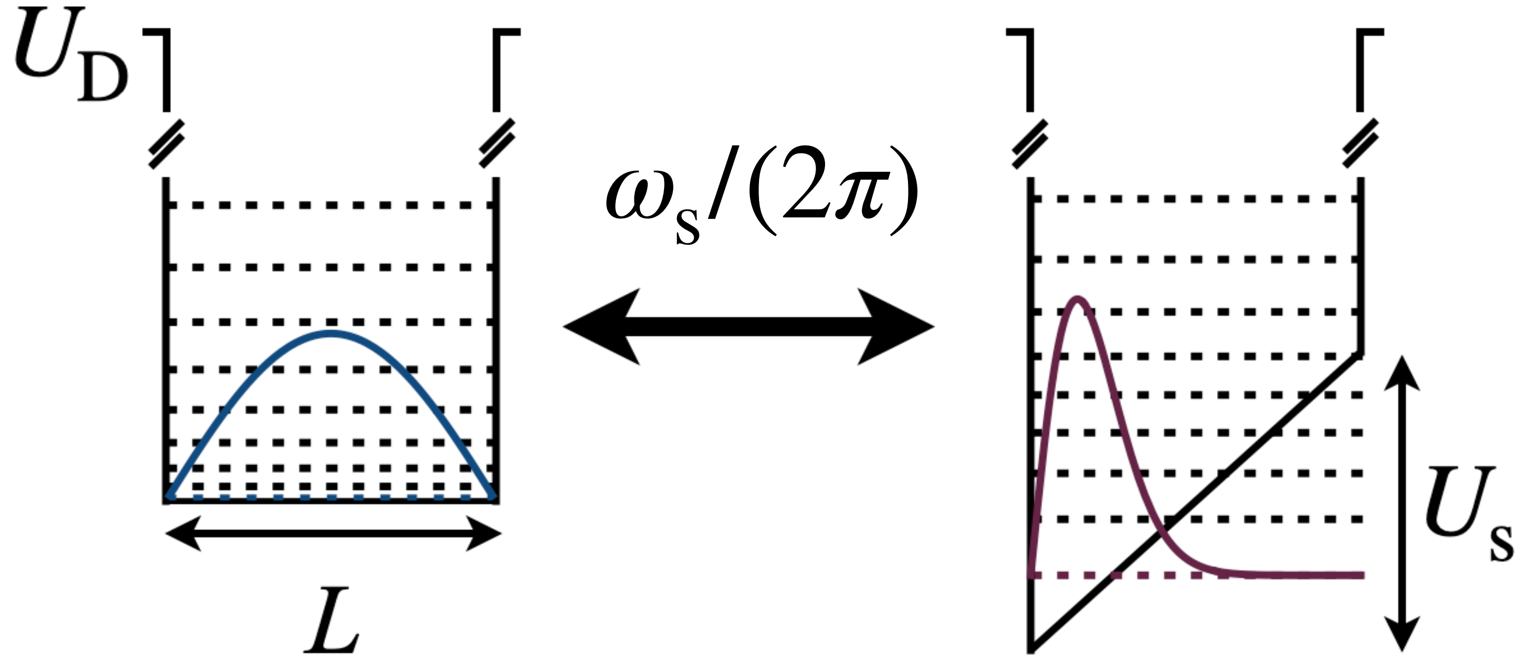
$\omega_s/(2\pi) = 10\,\text{Hz}$

$L = 50\,\mu\text{m}$

$U_s/k_B = 10.5\,\text{nK}$

Driven particle in a box

violent excitation



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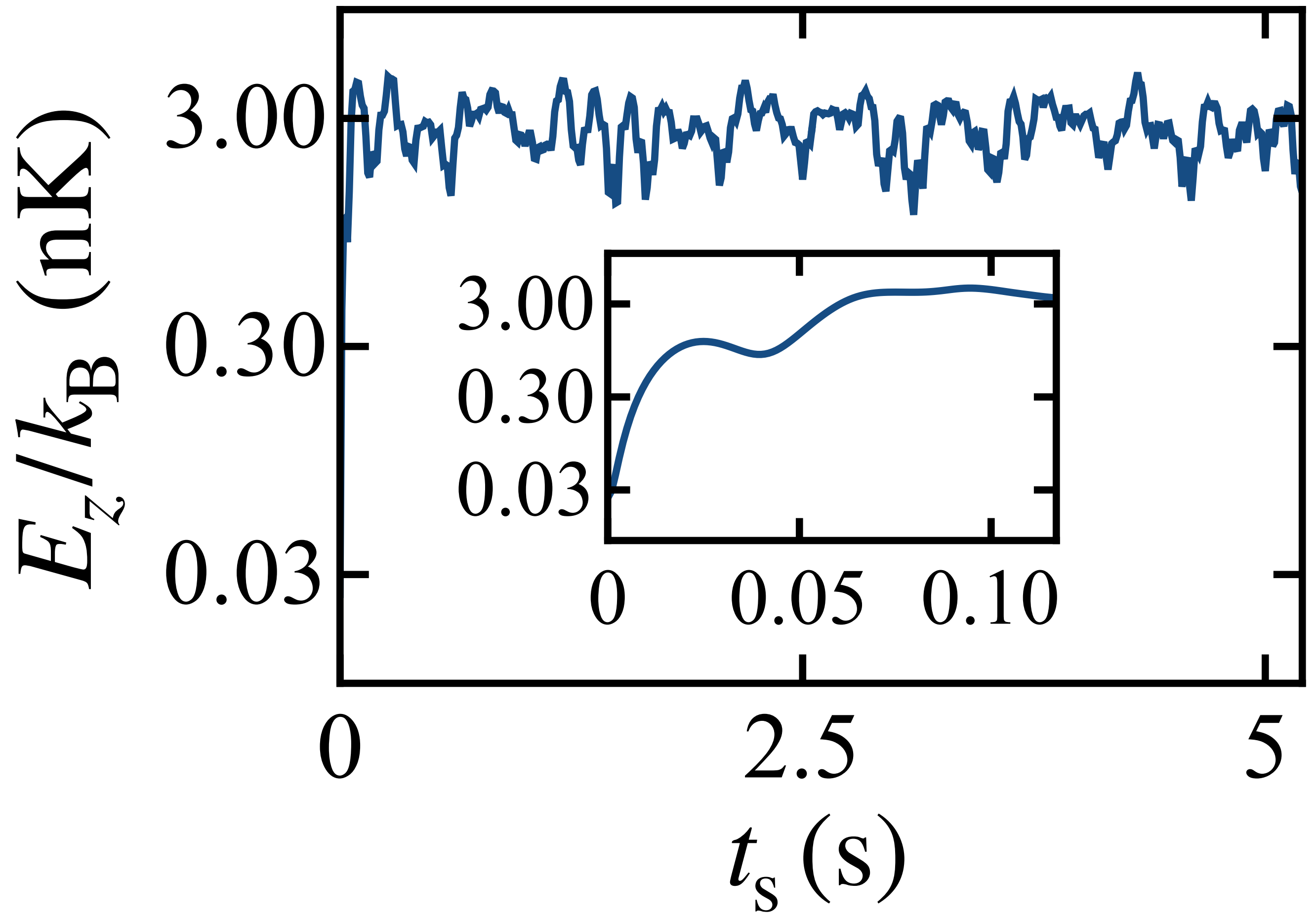

$\omega_s/(2\pi) = 10\,\text{Hz}$

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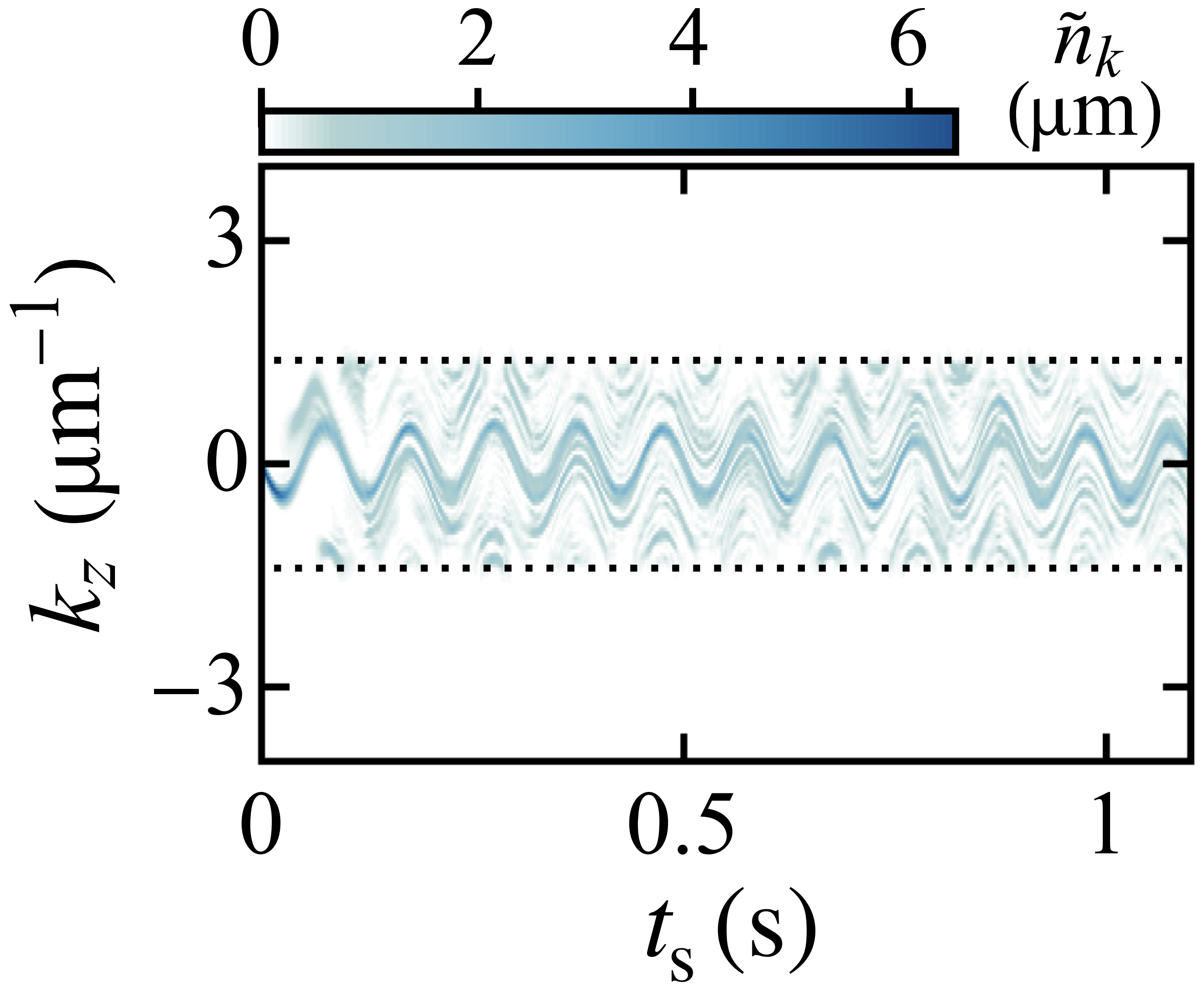
momentum
distribution
spreads up to k_c

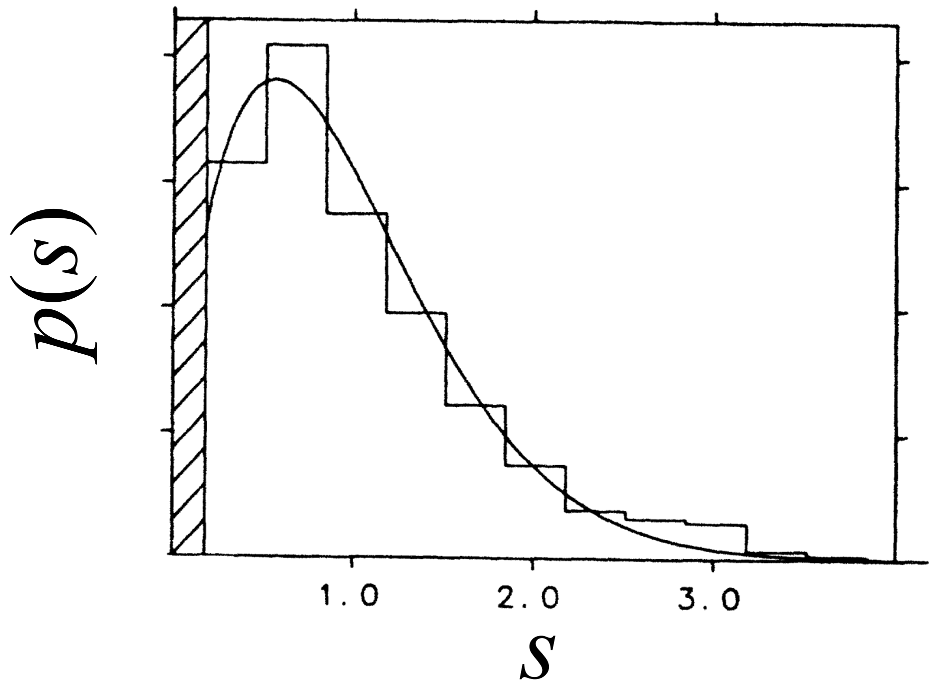


Driven particle in a box

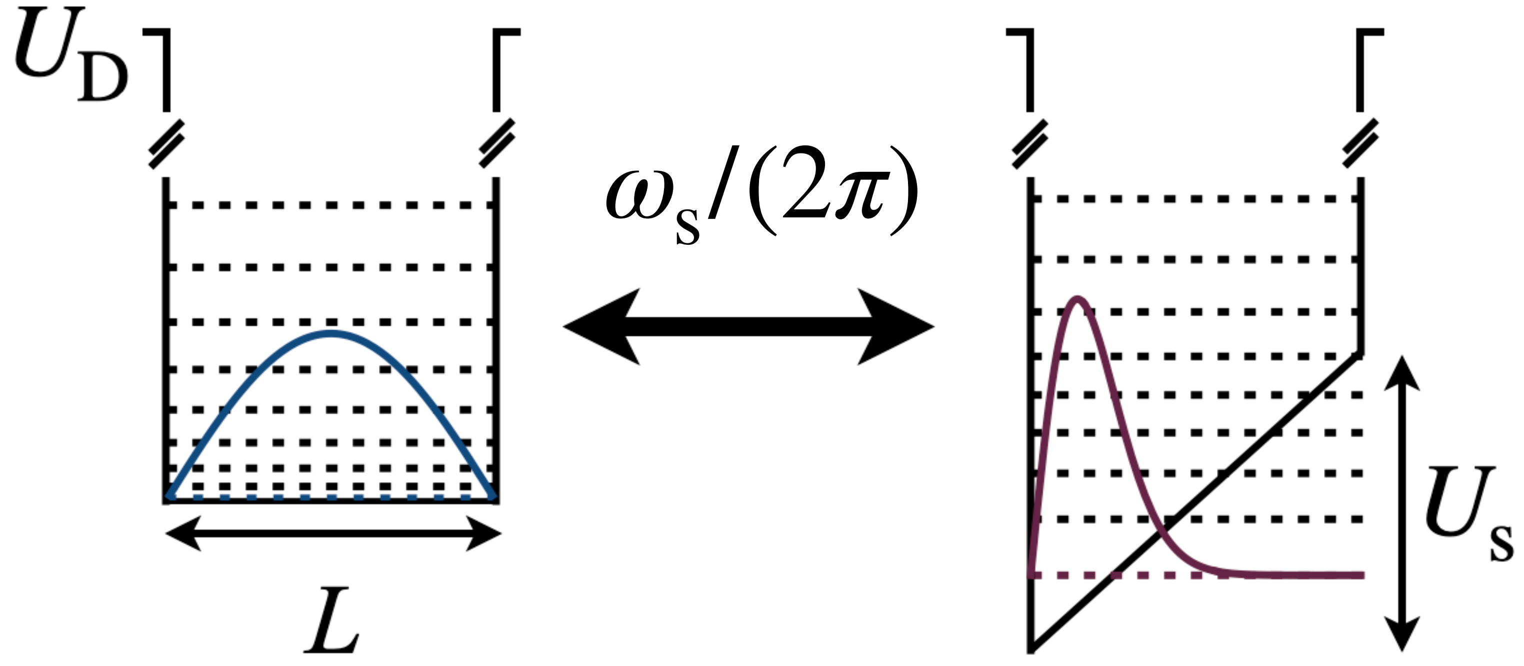
signatures of chaos

In Floquet basis
energy level statistics show
Wigner-Dyson distribution

W. A. Lin & L. E. Reichl, Physica D **19**, 145 (1986)
L. E. Reichl & W. A. Lin, PRA **33**, 3598 (1986)
W. A. Lin & L. E. Reichl, PRA **37**, 3972 (1988)



violent excitation



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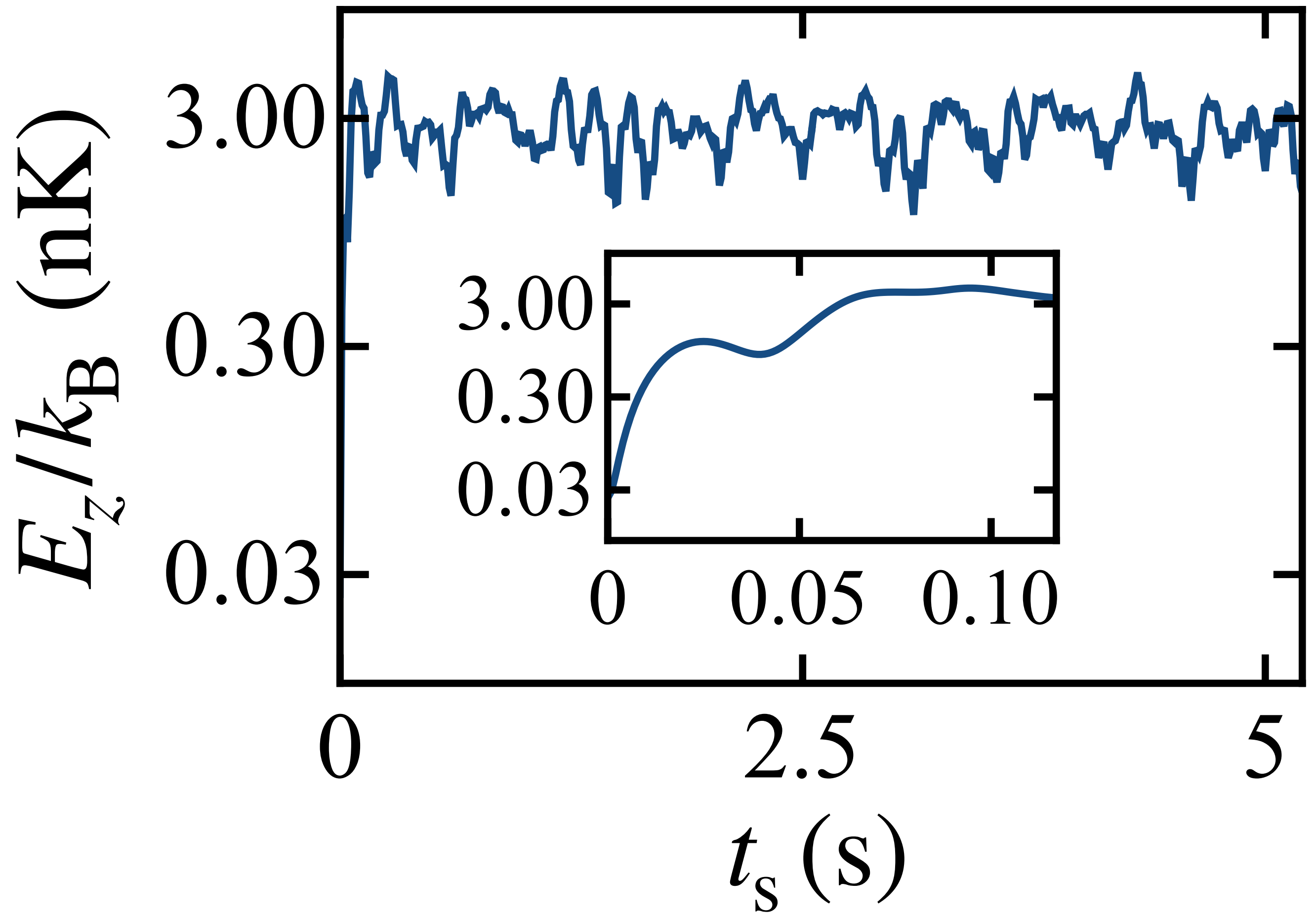

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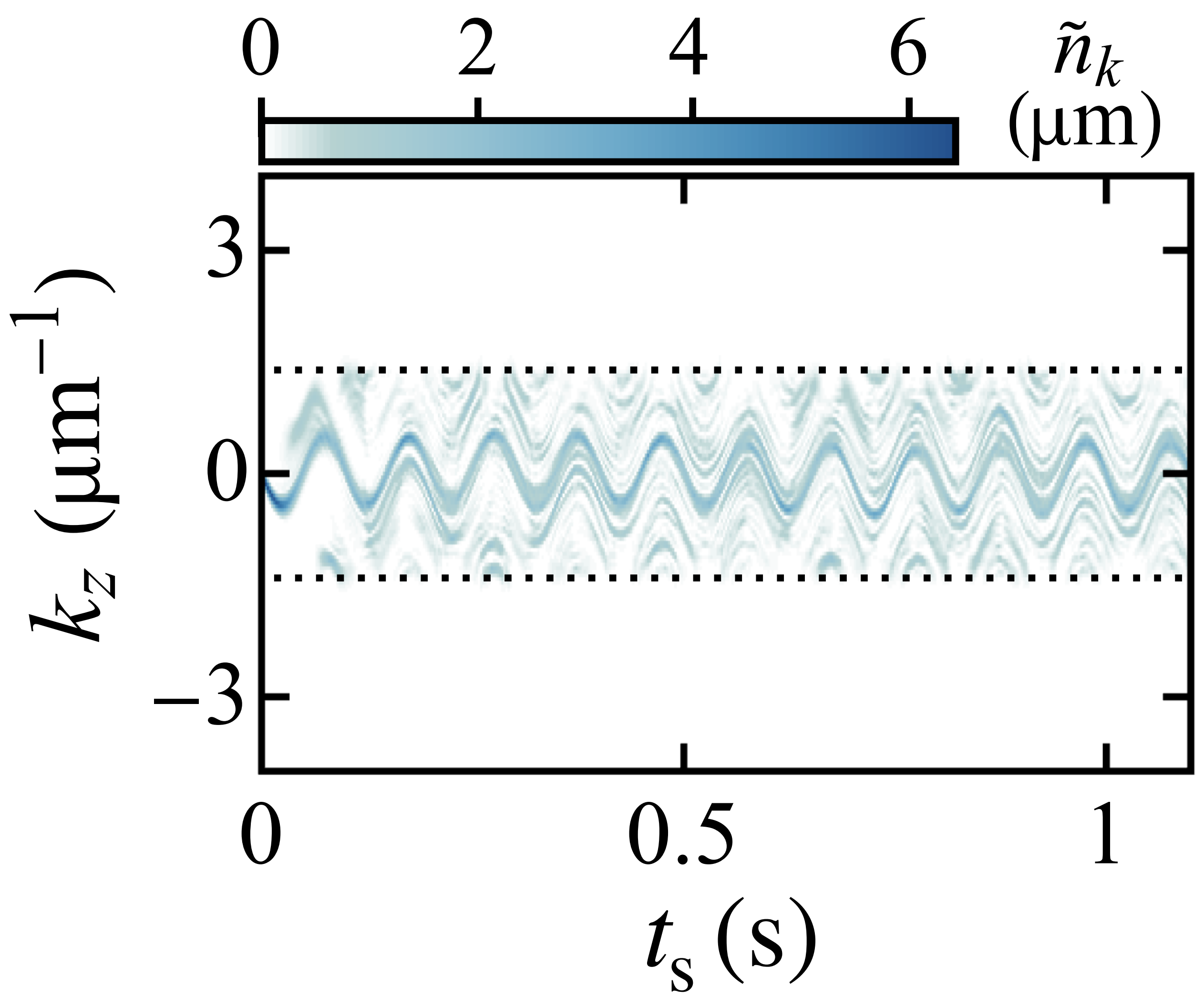
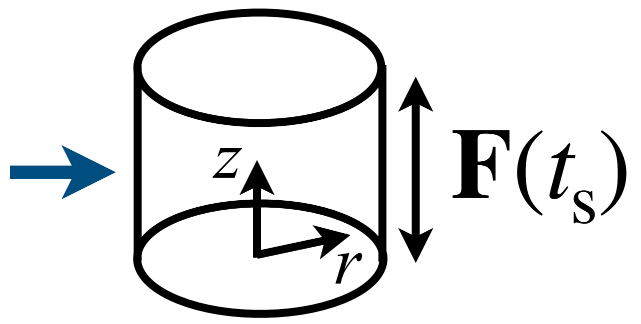
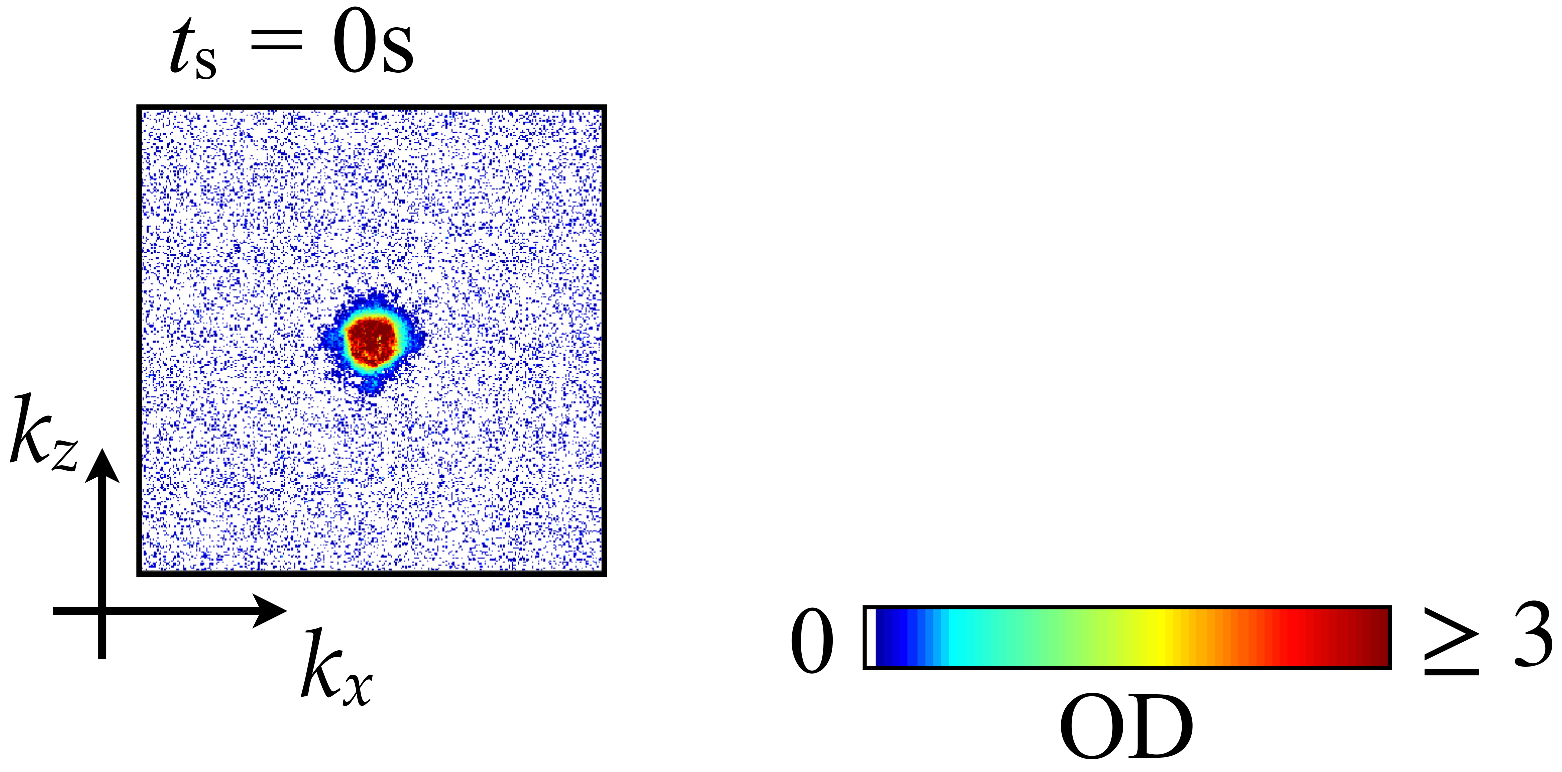


Shaking up a noninteracting 3D Bose gas

$$\mathbf{F}_s = (U_s/L)\cos(\omega_s t_s)\hat{\mathbf{e}}_z$$

absorption image





50 ms
ToF

protocol

prepare BEC at $a \approx 0$ in
trap of depth $U_D/k_B \approx 90\mathrm{nK}$

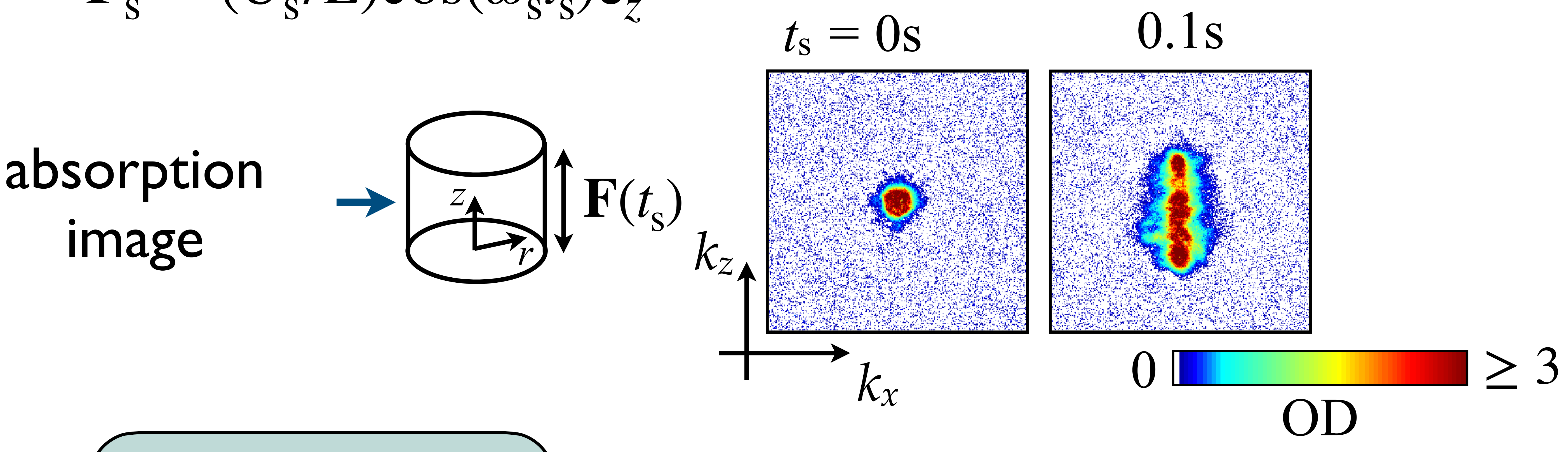
violently shake axially
$(U_s/k_B = 10.5\,\mathrm{nK}, \omega_s/(2\pi) = 10\,\mathrm{Hz})$

$(\hbar\omega_z \ll U_s \ll U_D)$

Shaking up a noninteracting 3D Bose gas

$\mathbf{F}_\mathrm{s} = (U_\mathrm{s}/L)\cos(\omega_\mathrm{s} t_\mathrm{s})\hat{\mathbf{e}}_z$

violent drive



50 ms
ToF

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$(\hbar\omega_z \ll U_\mathrm{s} \ll U_\mathrm{D})$

✦ rapid excitation of axial modes

G. Martirosyan *et al.*, PRL **132**, 113401 (2024)

Shaking up a noninteracting 3D Bose gas

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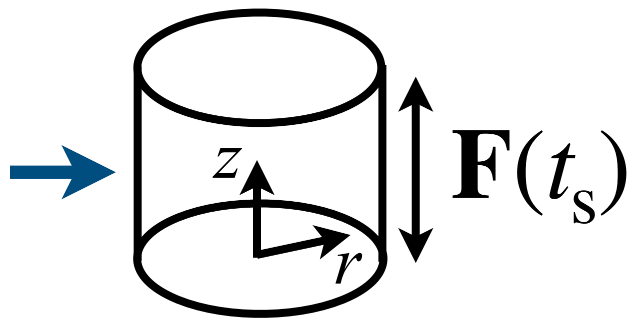
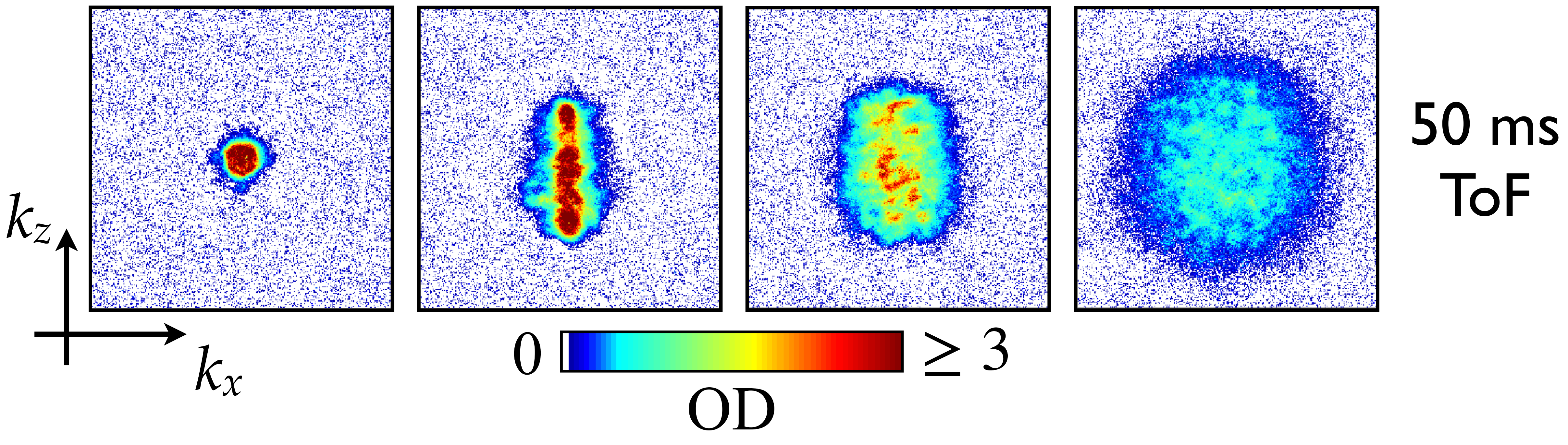
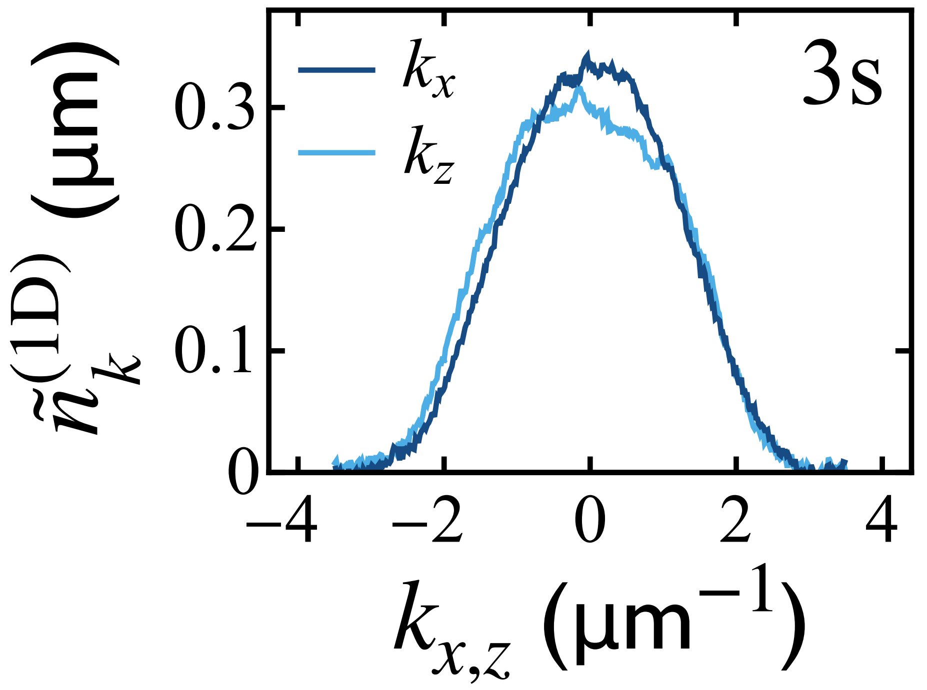


violent drive + weak disorder



nearly isotropic!



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violently shake axially
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$(\hbar\omega_z \ll U_\mathrm{s} \ll U_\mathrm{D})$

- ✦ rapid excitation of axial modes
- ✦ energy gradually leaks into radial modes!
- ✦ center-of-mass (CoM) motion persists (reaches steady-state)

G. Martirosyan *et al.*, PRL **132**, 113401 (2024)

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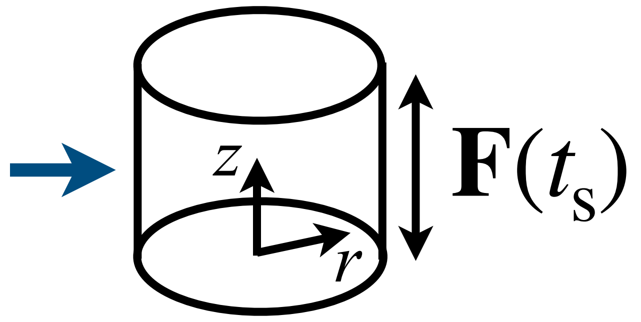
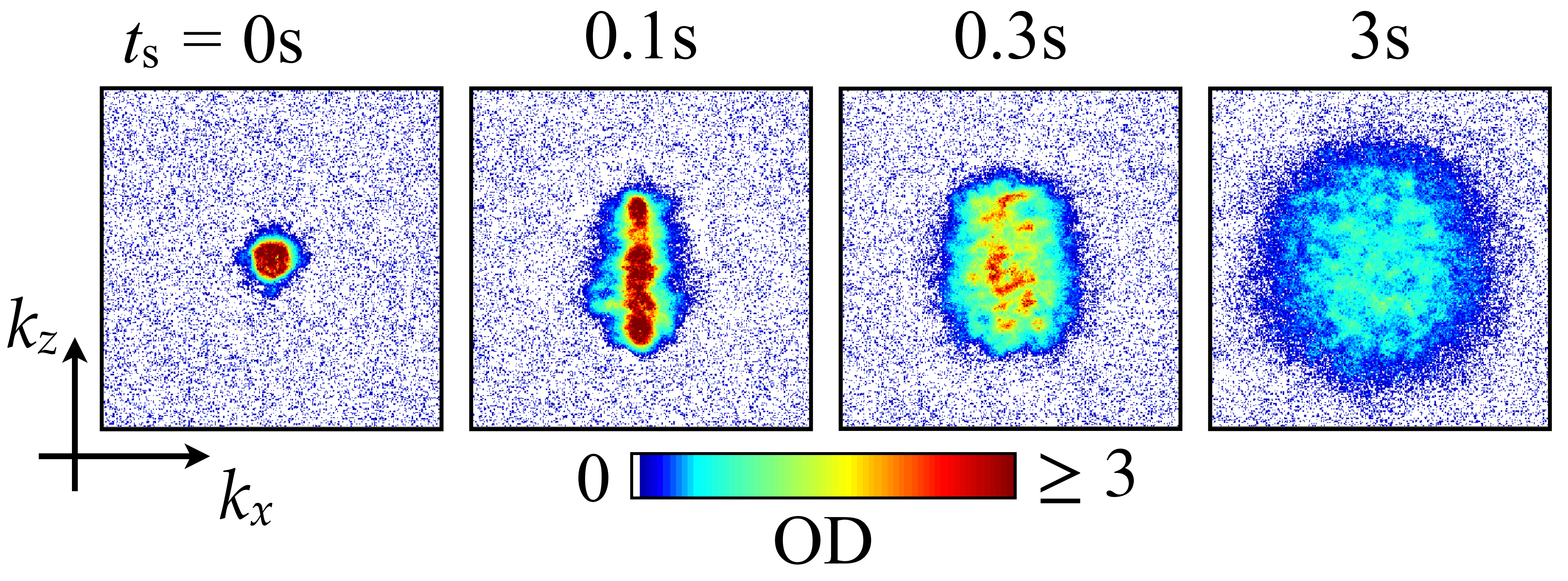
absorption image

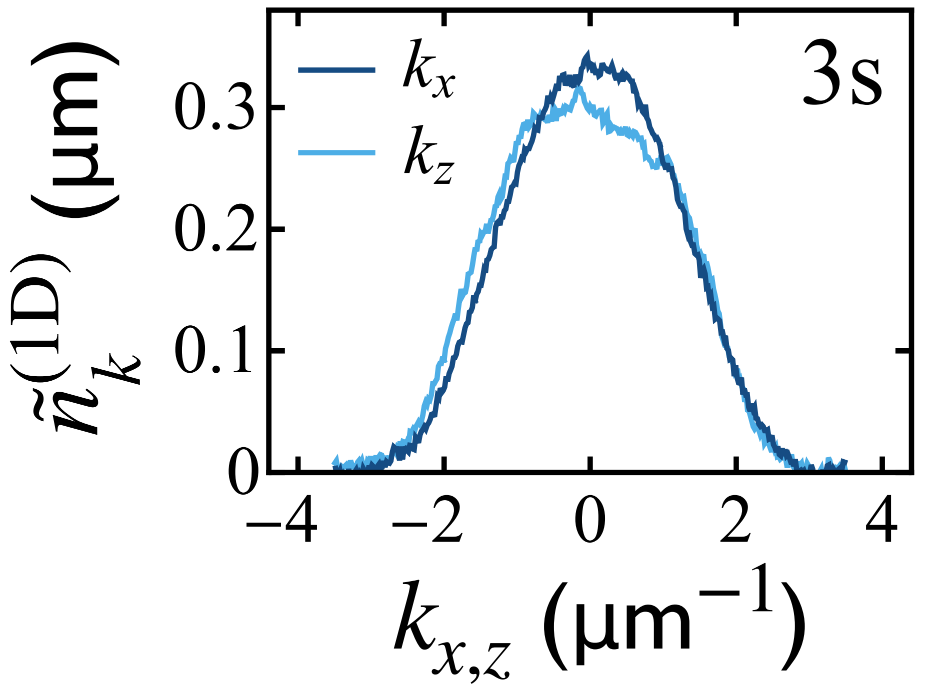


violent drive + weak disorder



50 ms ToF

nearly isotropic!



protocol

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$(U_s/k_B = 10.5\,\text{nK}, \omega_s/(2\pi) = 10\,\text{Hz})$

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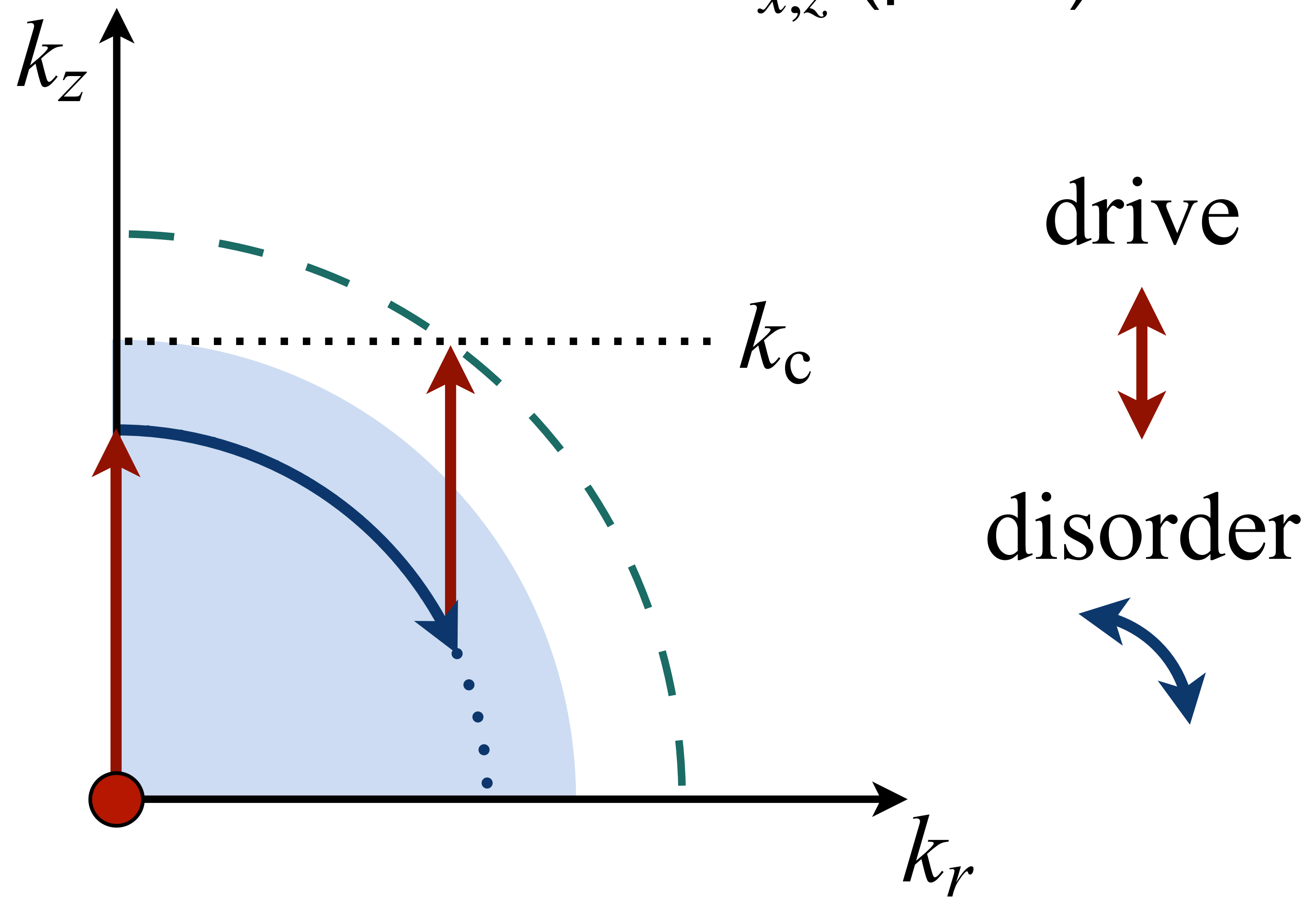

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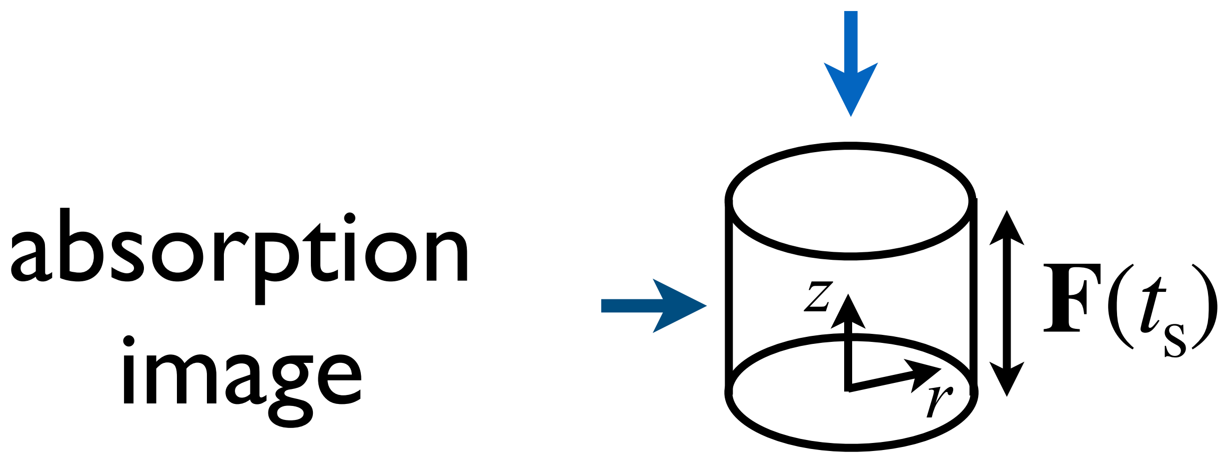

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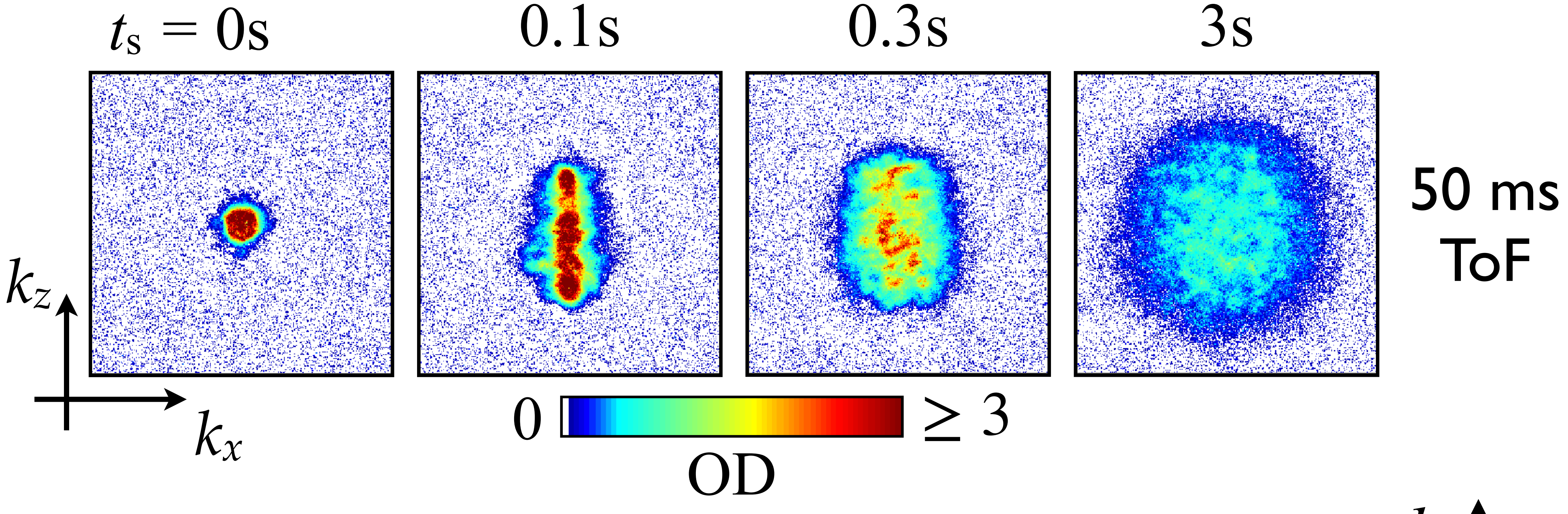
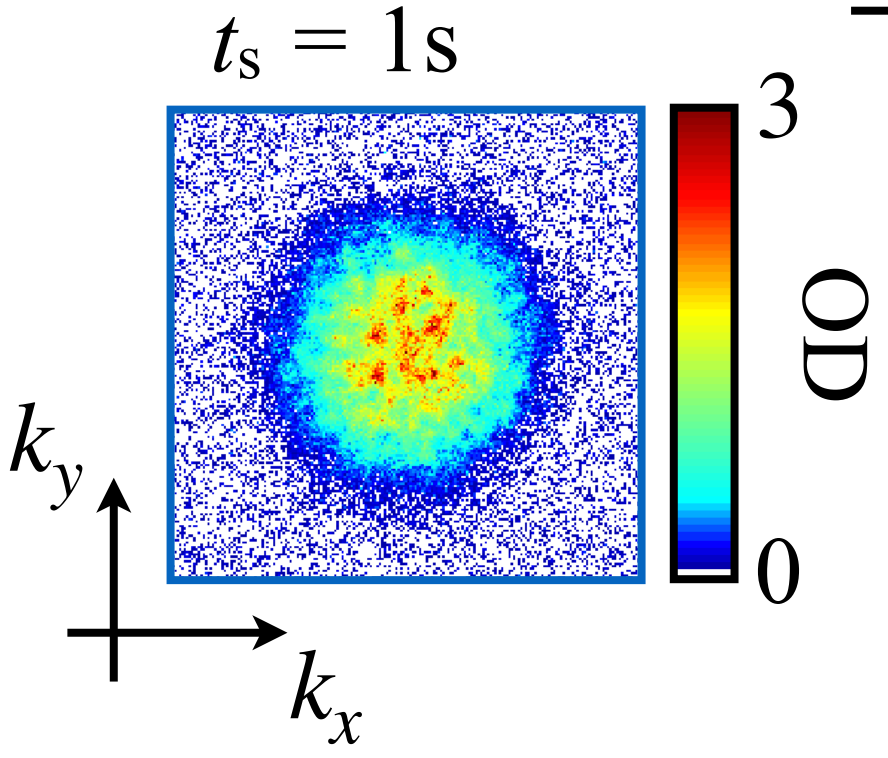
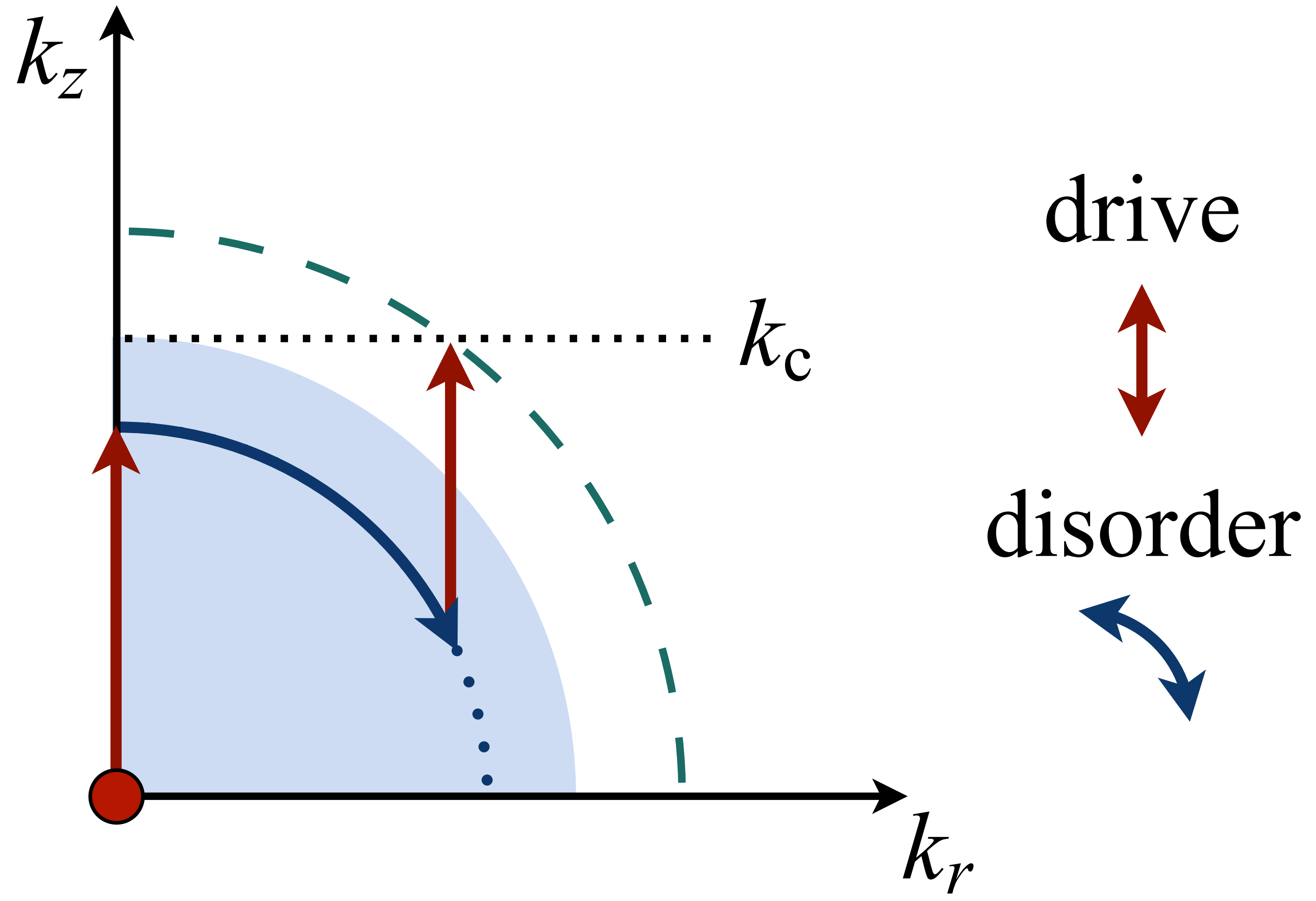




look down tube to isolate spreading dynamics

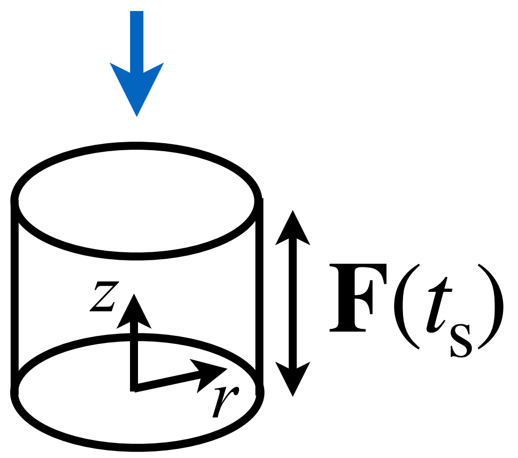


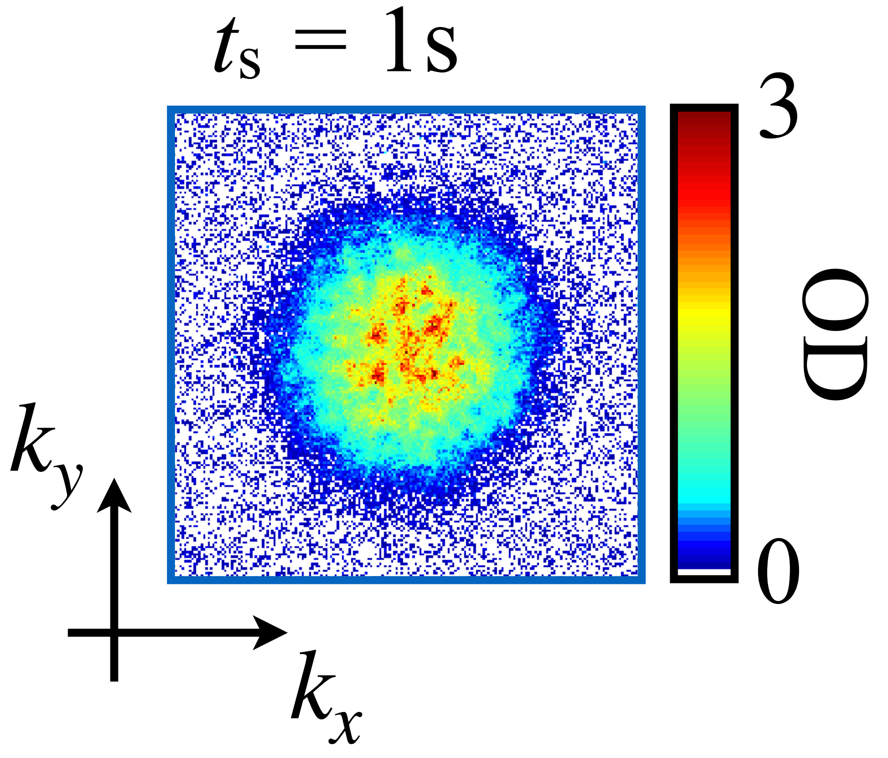
G. Martirosyan *et al.*, PRL **132**, 113401 (2024)

New far-from-equilibrium state?

highly nonthermal distribution!

$\mathbf{F}_s = (U_s/L)\cos(\omega_s t_s)\hat{\mathbf{e}}_z$



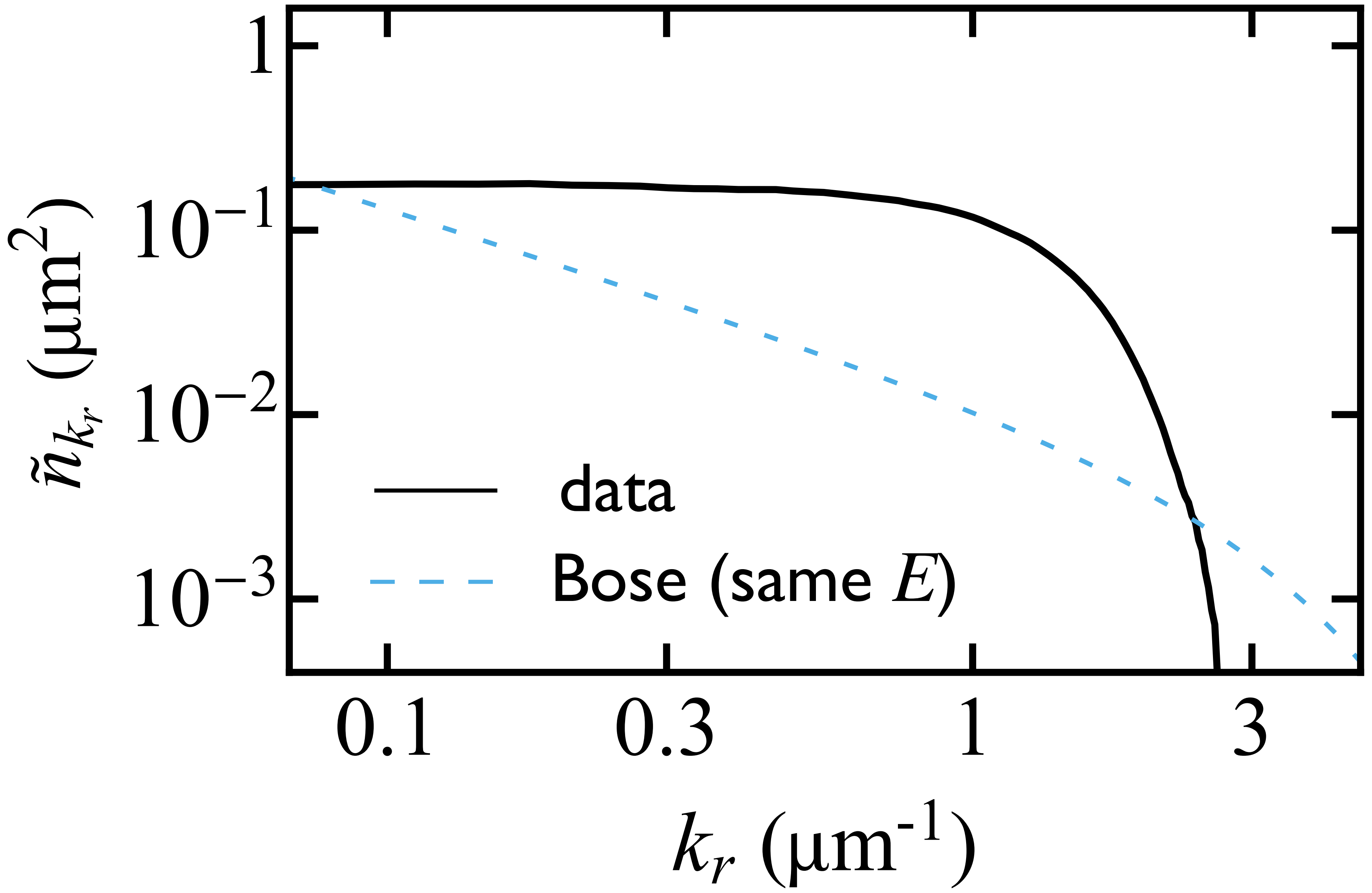


$N = 3.3(1) \times 10^5$

$T_c \approx 180\,\text{nK}$

$E/k_B \approx 13\,\text{nK}$

$a = 0$



$$\int 2\pi k_r \tilde{n}_{k_r} \mathrm{d}k_r = 1$$

very low energy,
no BEC!

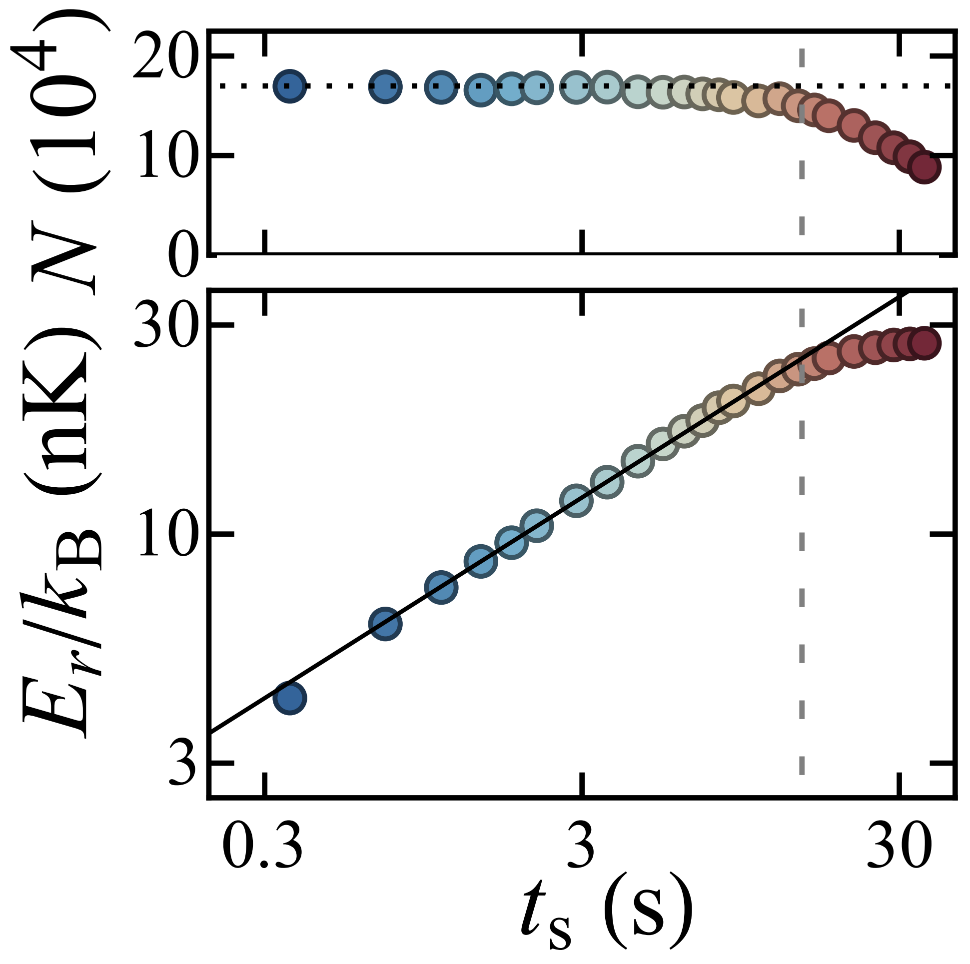
If allowed to equilibrate,
condensed fraction
$\approx 75\,\%$

Subdiffusive dynamic scaling

in the dynamics of a noninteracting Bose gas driven far from equilibrium

$U_D/k_B \approx 90\text{nK}, U_s/k_B = 7.0\,\text{nK}, \ \omega_s/(2\pi) = 10\,\text{Hz}$

$E_r \propto t_s^\eta\,,\ \eta = 0.46(2)$



✦ power-law energy growth

✦ E saturates when loss occurs

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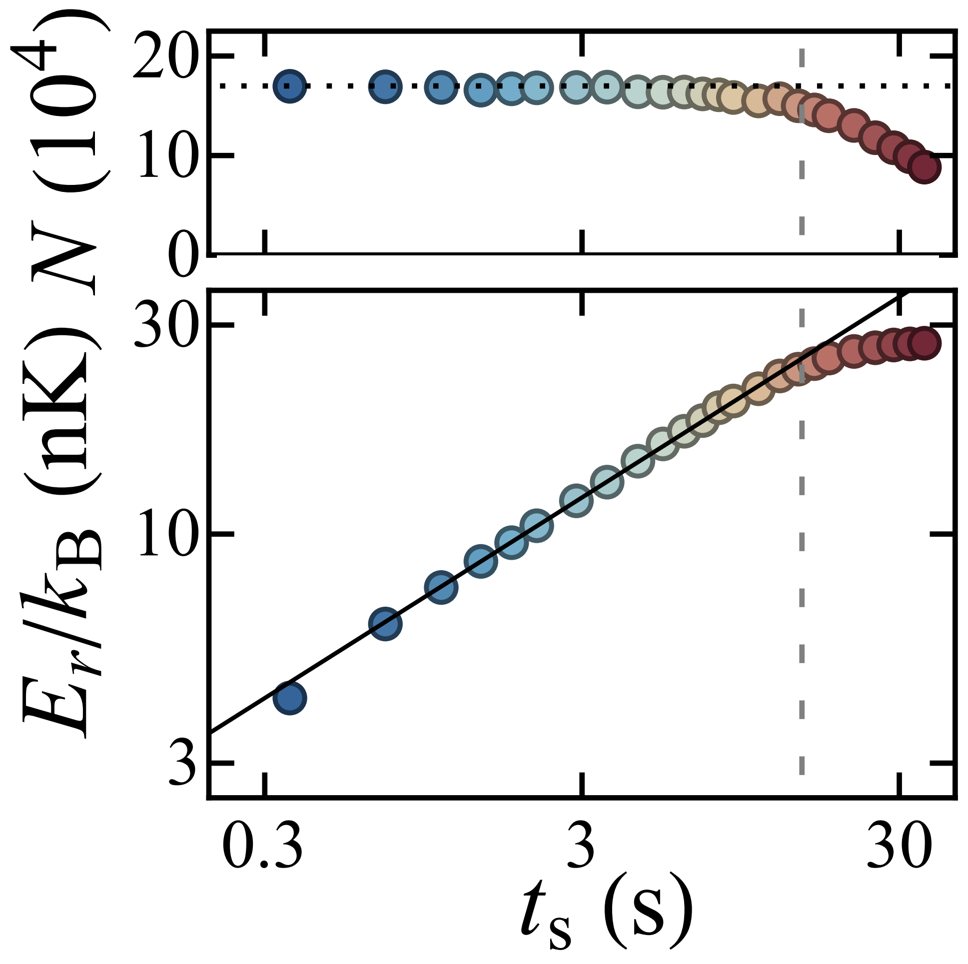
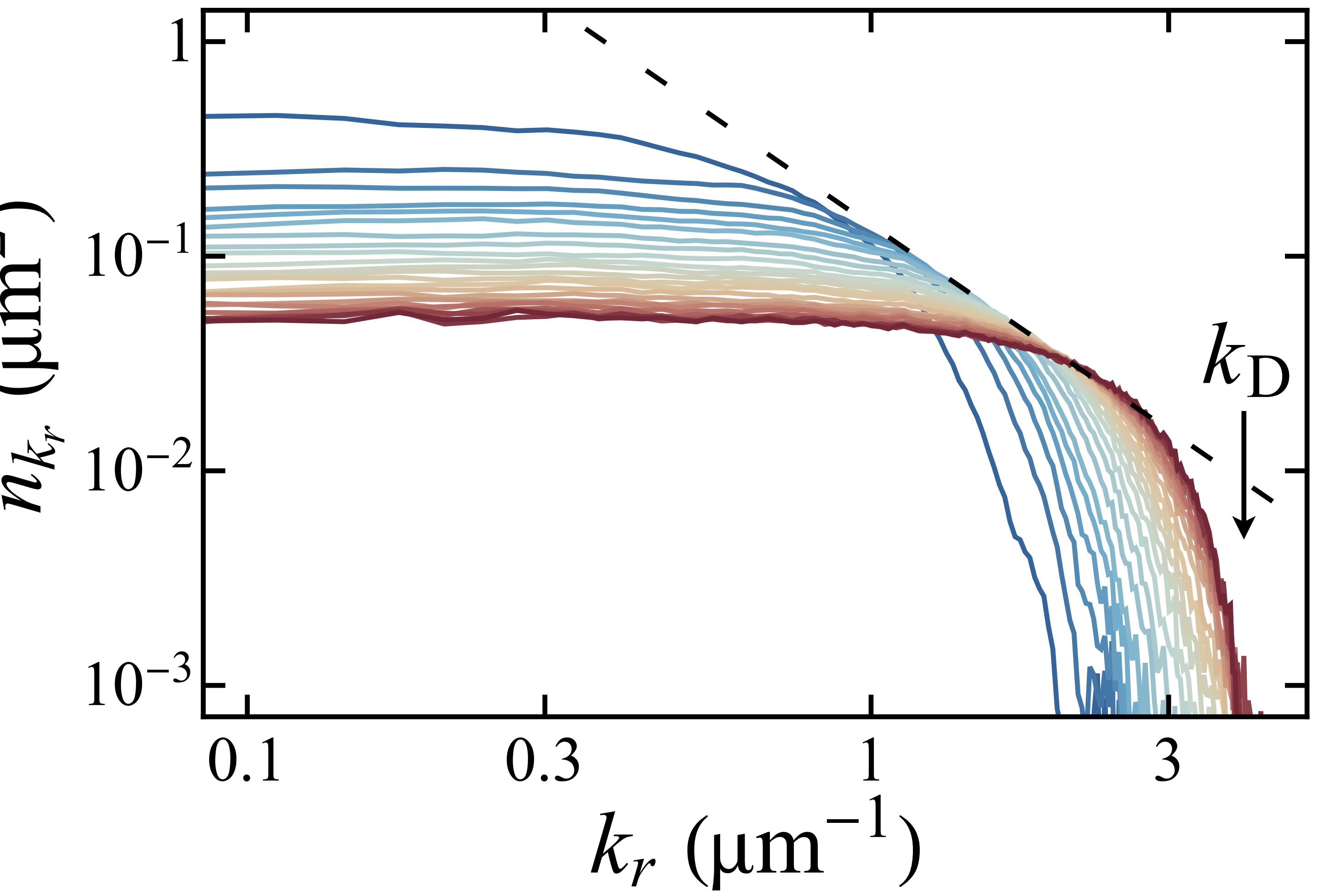


$\int 2\pi k \tilde{n}_k \mathrm{d}k = 1$



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dynamic scaling?

Subdiffusive dynamic scaling

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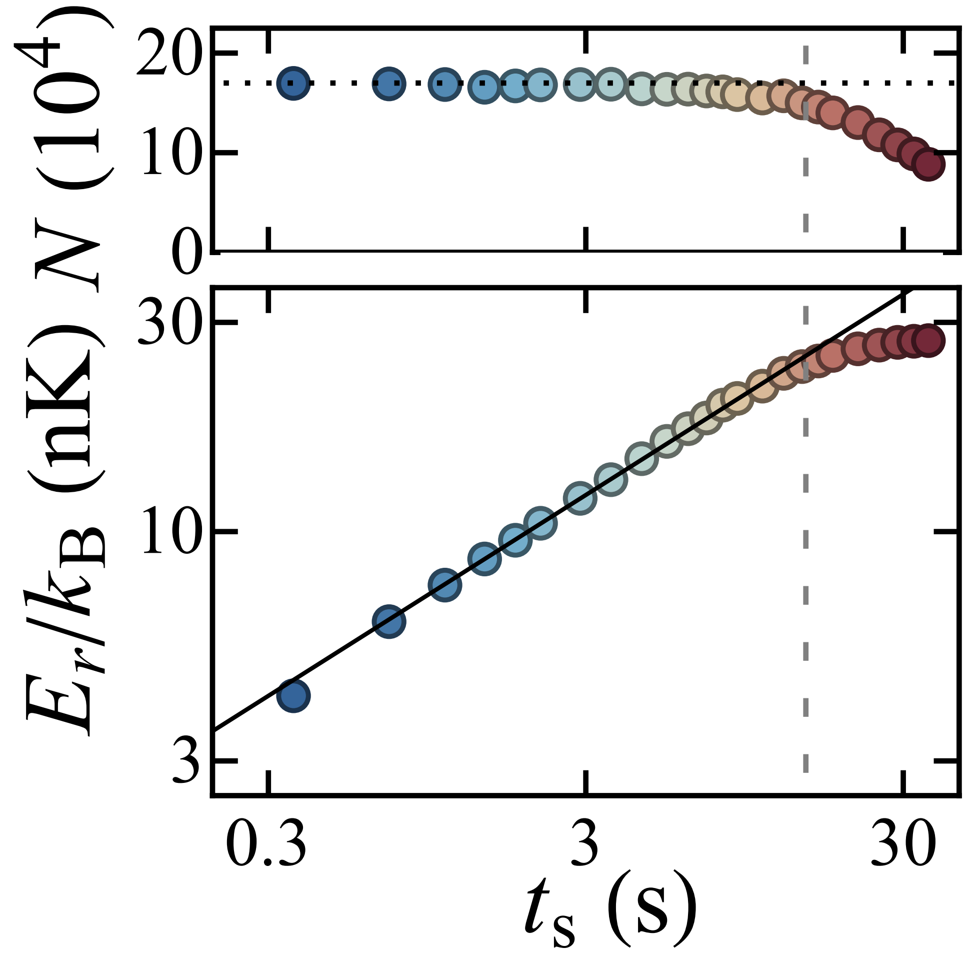

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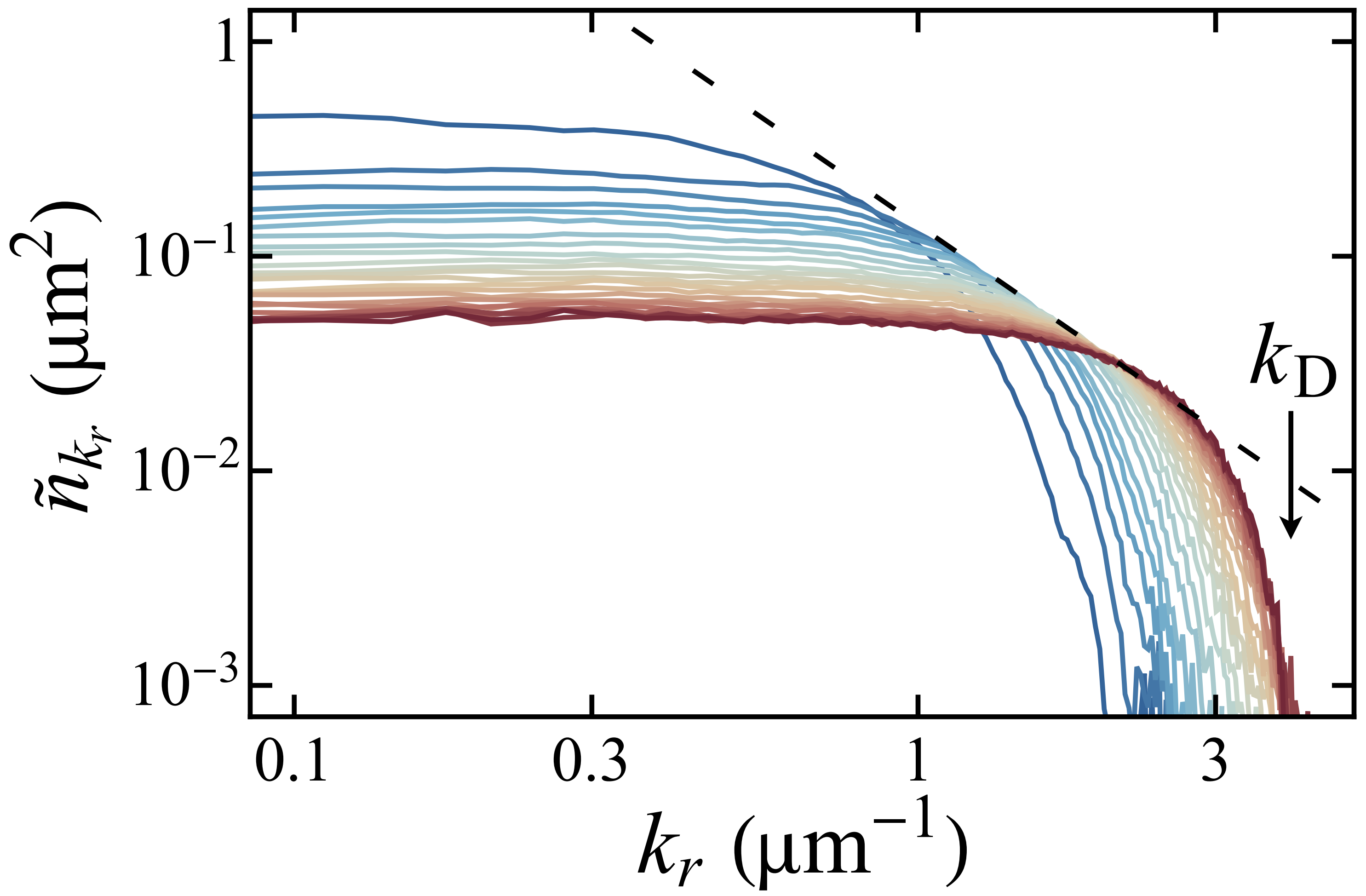

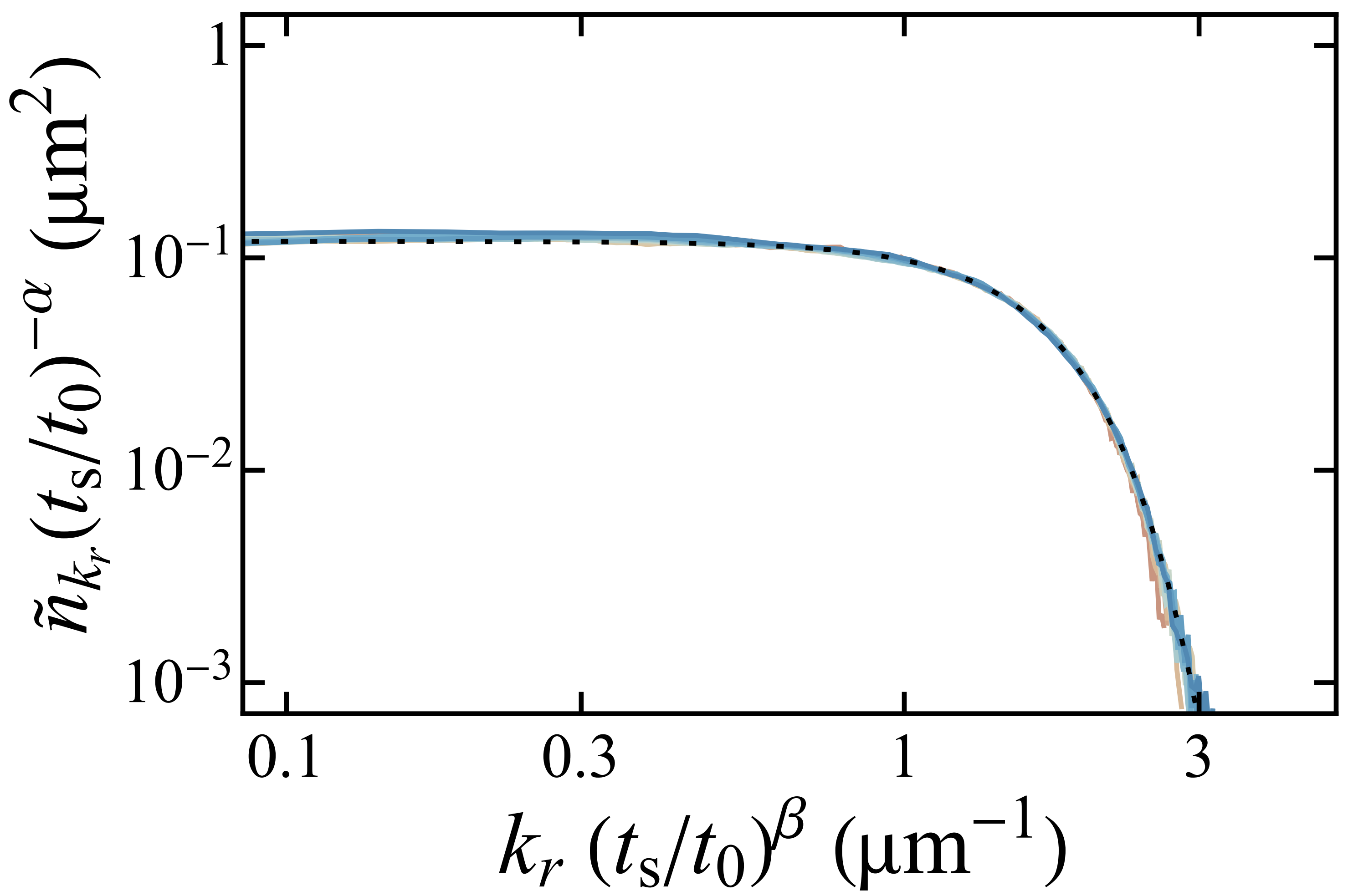

particle-conserving UV transport with

$\alpha = -0.45(2)$

$\beta = -0.23(1)$

$t_s \in \{1.1 - 14.4\}\text{s}$

$t_0 = 3\text{s}$

- ✦ power-law energy growth
- ✦ E saturates when loss occurs

dynamic scaling? $\tilde{n}_{k_r}(k_r, t_s) = \tilde{t}^{\alpha}\tilde{n}_{k_r}(\tilde{t}^{\beta}k_r, t_0)$

$\tilde{t} = t_s/t_0$

Subdiffusive dynamic scaling

in the dynamics of a noninteracting Bose gas driven far from equilibrium

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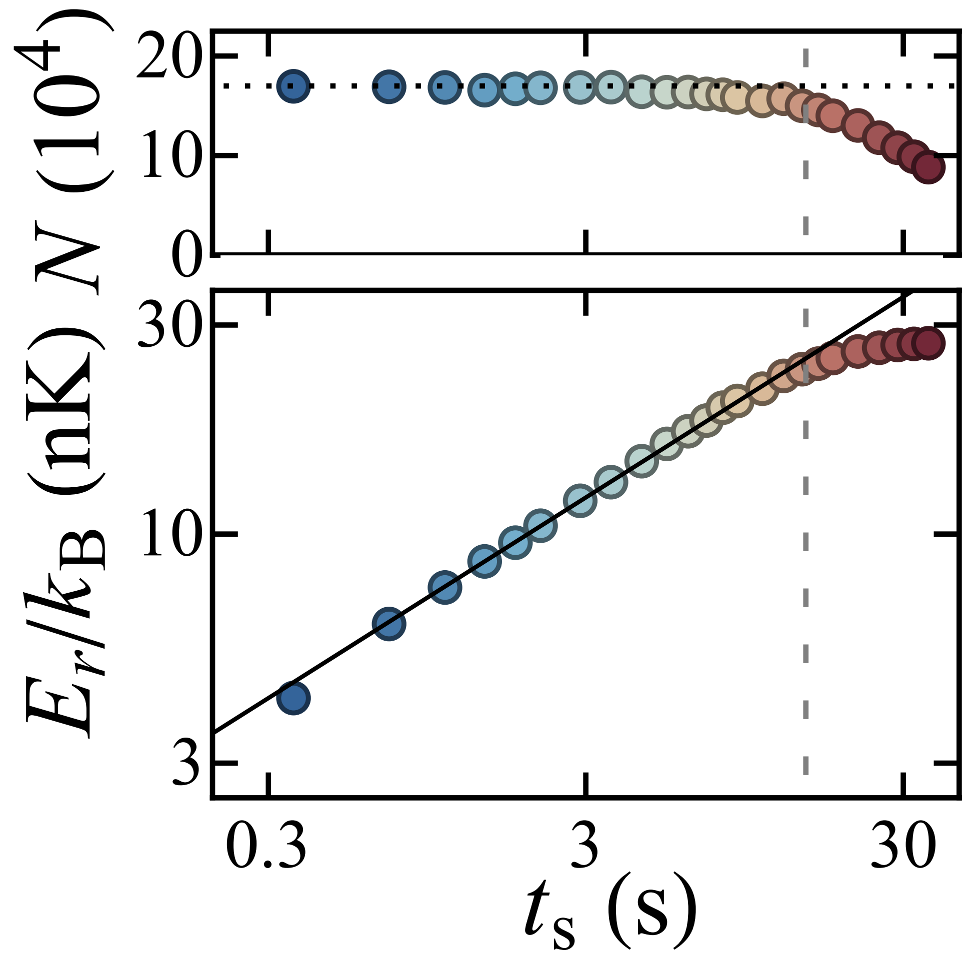

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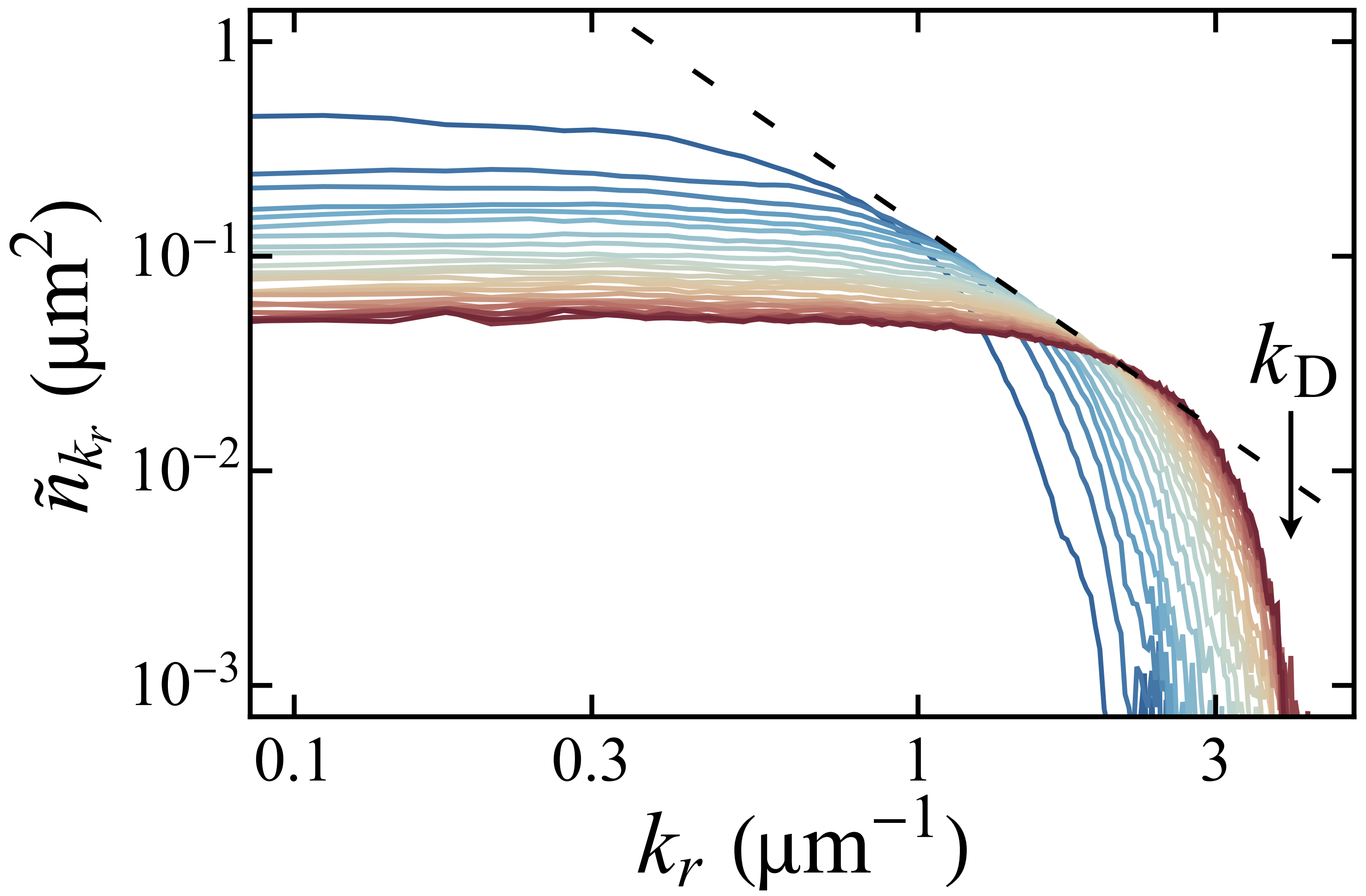

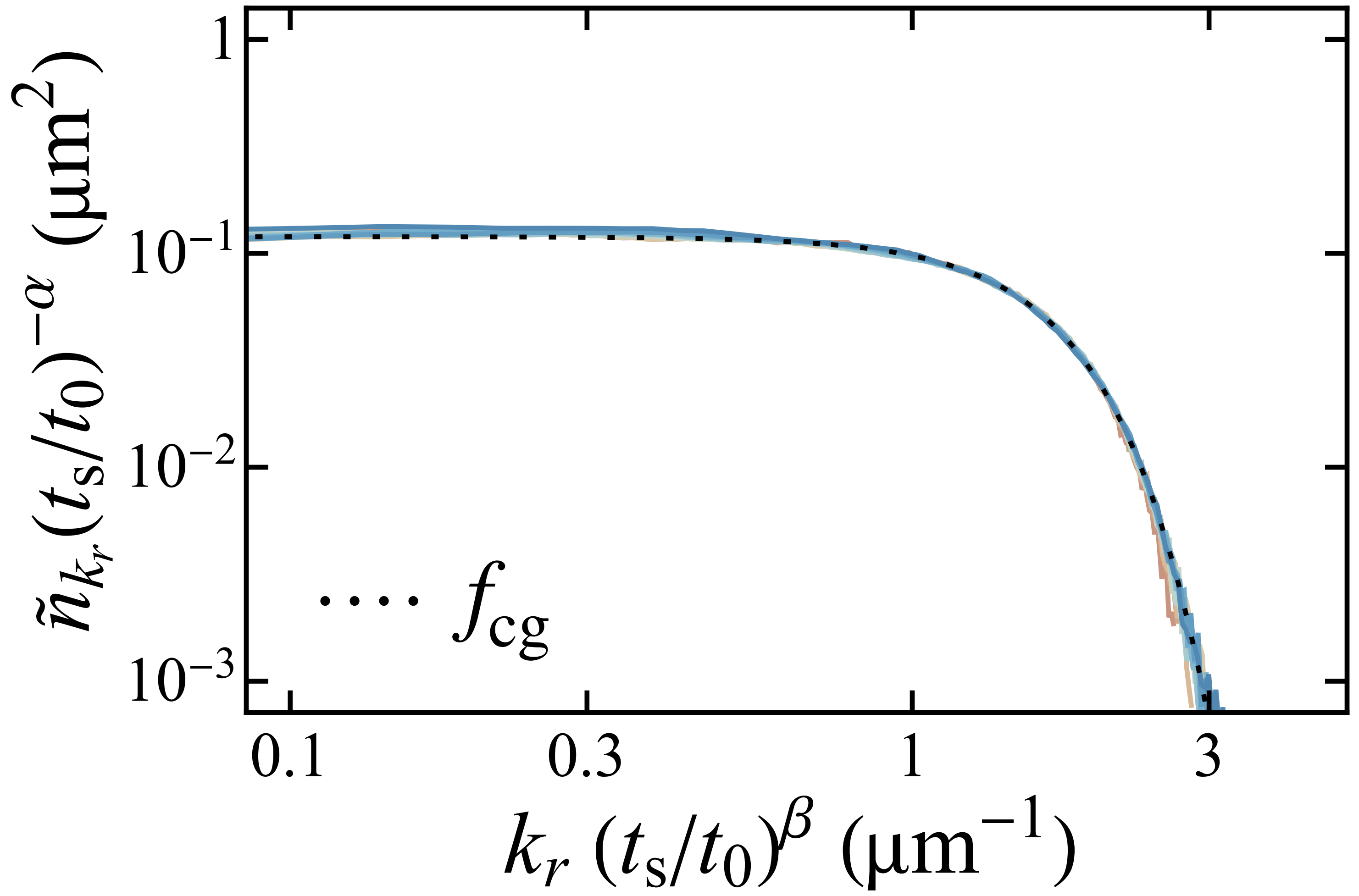

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$$\tilde{t} = t_s/t_0$$

scaling function

$f_{cg} = A_0 \exp[-(k/k_0)^{\kappa}]$,

with $\kappa = 3.0(2)$

Subdiffusive dynamic scaling

behavior reproduced with Schrödinger equation simulations with speckle disorder

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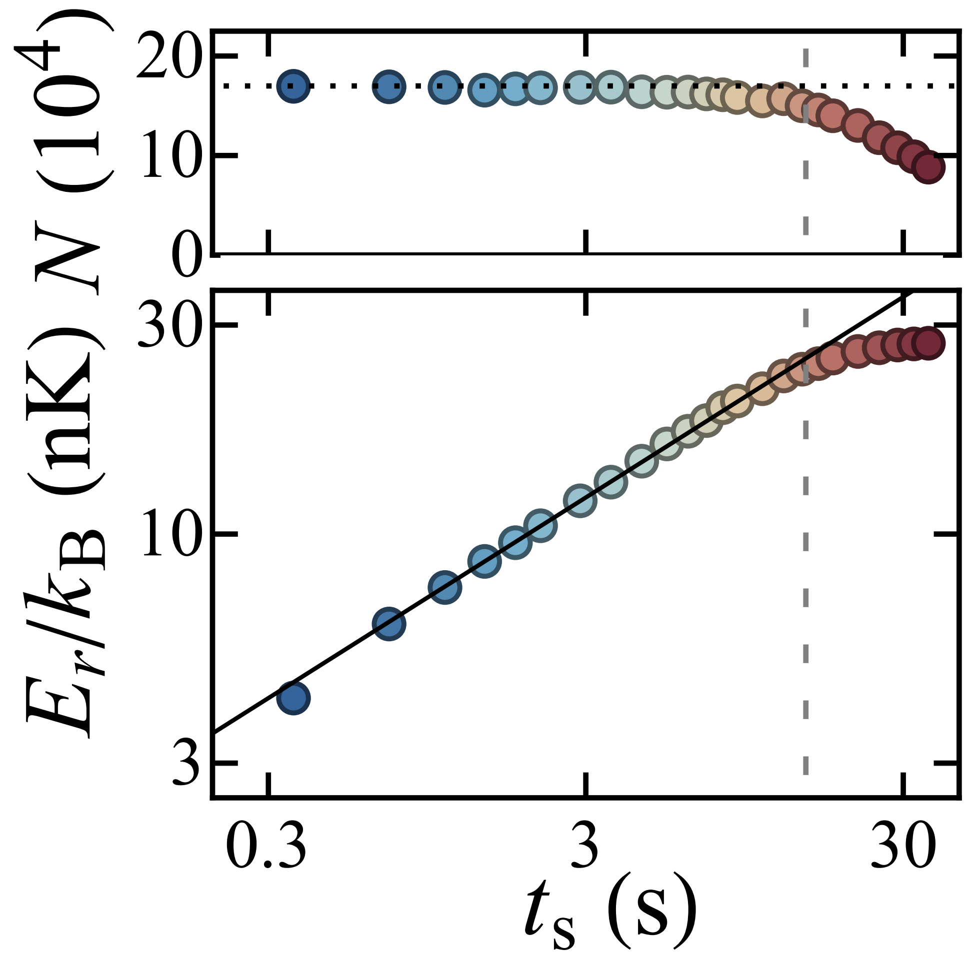

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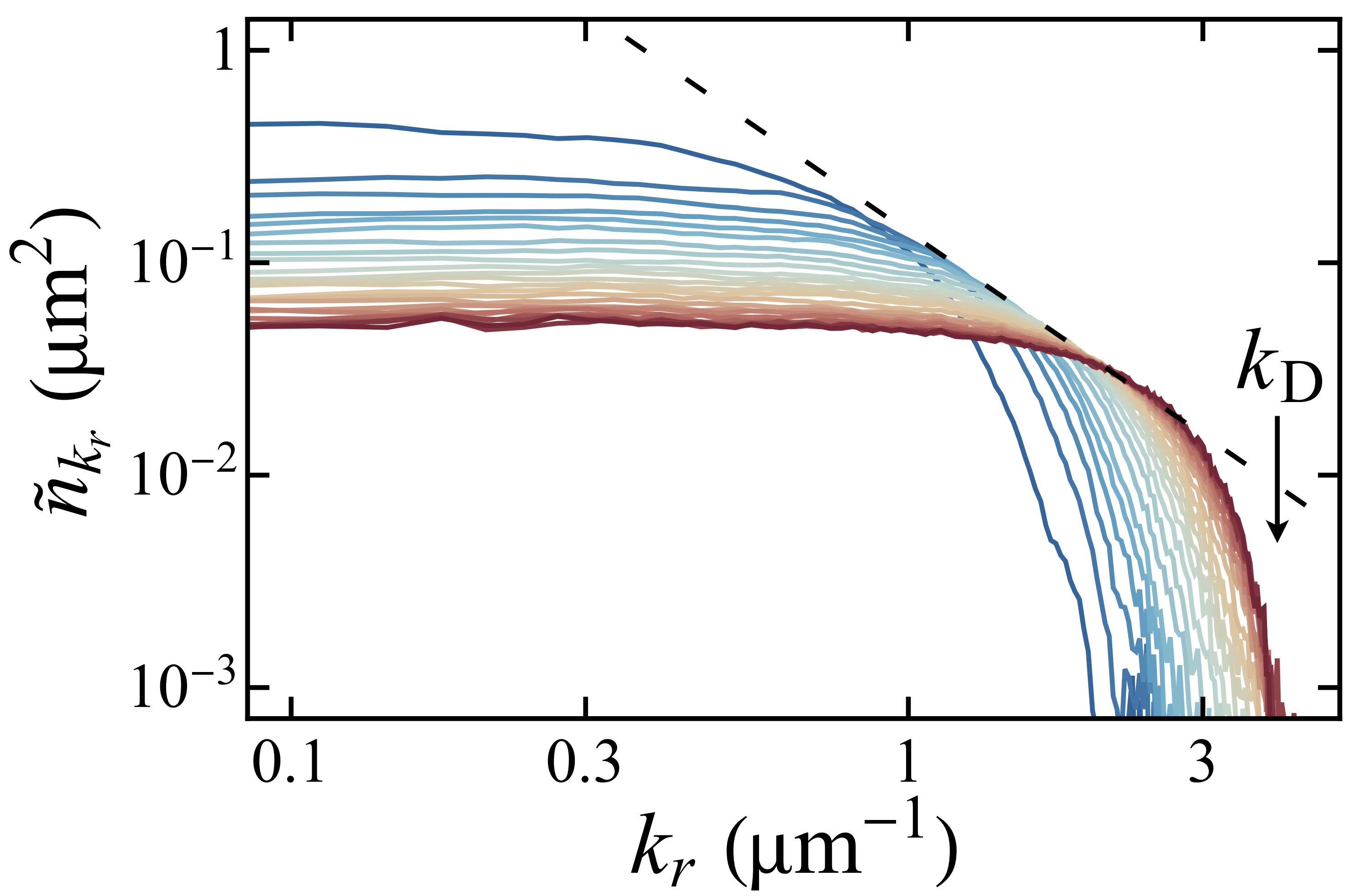

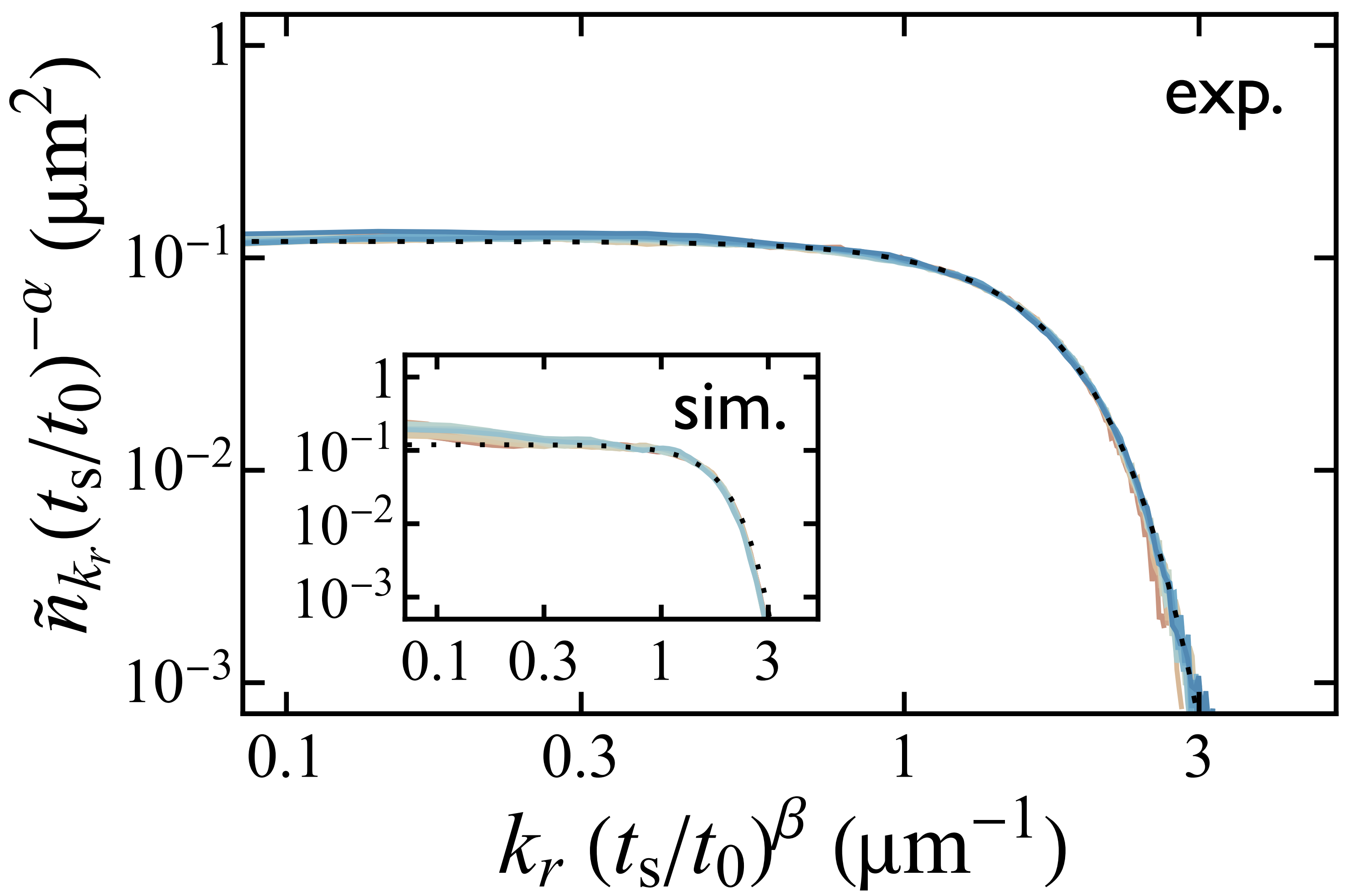

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G. Martirosyan *et al.*, PRL **132**, 113401 (2024)

Robustness of dynamic scaling

in the dynamics of a noninteracting box-trapped Bose gas driven far from equilibrium

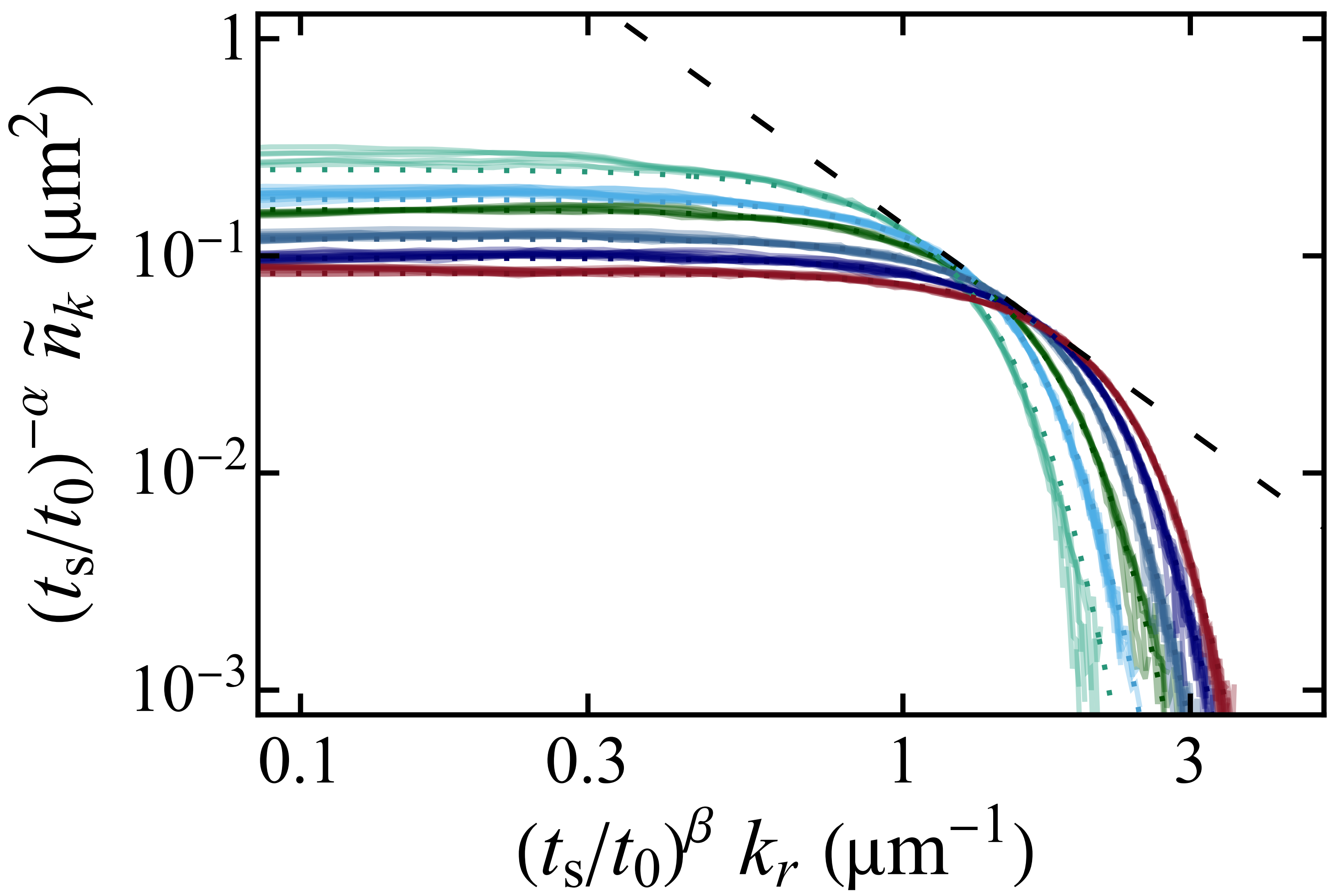
vary disorder ($\Gamma_d \propto U_D^2$) and drive (U_s)

	Γ_d (s^{-1})	U_s/k_B (nK)	$\omega_s/(2\pi)$ (Hz)	t_s (s)	κ	$-\alpha$	$-\beta$
—	2.5	3.5	10	{5.0-10}	2.7	0.51	0.26
—	2.5	10.5	10	{1.5-4.0}	2.7	0.47	0.25
—	8.0	3.5	10	{2.0-25}	2.9	0.47	0.24
—	8.0	7.0	10	{1.1-14}	3.0	0.45	0.23
—	8.0	10.5	10	{0.96-9.6}	2.9	0.45	0.23
—	15.0	10.5	10	{0.6-4.5}	3.0	0.47	0.24

fixed $t_0 = 3\,\mathrm{s}$

calibrate disorder potential to be $\sim 2\,\%$ of U_D

collapsed curves



faster for larger U_s and Γ_d

robust behavior consistent with

$\alpha = -0.48(4)$

$\beta = -0.24(2)$

$\kappa = 2.9(2)$

Robustness of dynamic scaling

in the dynamics of a noninteracting box-trapped Bose gas driven far from equilibrium

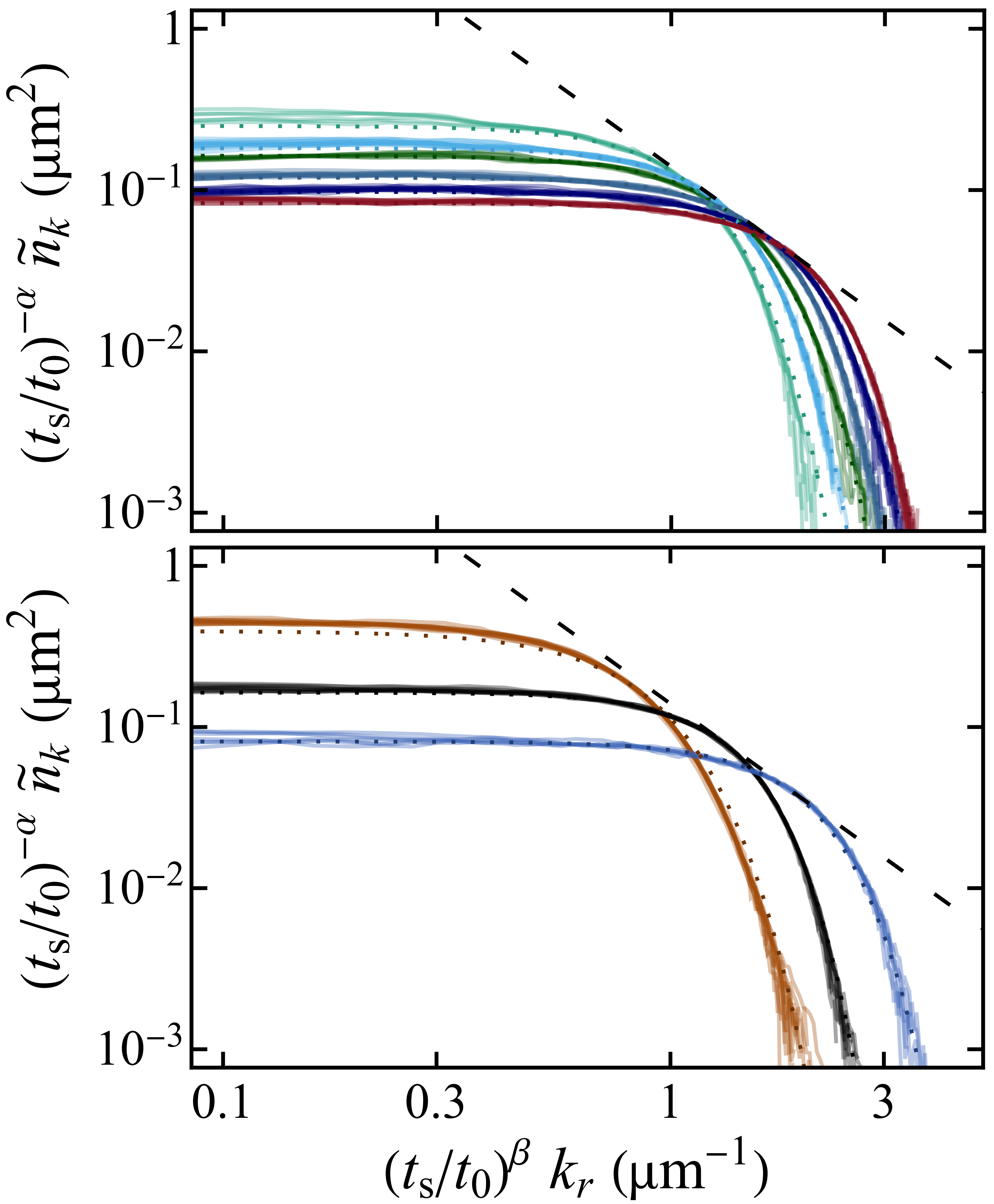
vary disorder ($\Gamma_d \propto U_D^2$) and drive (U_s) and $\omega_s/(2\pi)$

	Γ_d (s^{-1})	U_s/k_B (nK)	$\omega_s/(2\pi)$ (Hz)	t_s (s)	κ	$-\alpha$	$-\beta$
—	2.5	3.5	10	{5.0-10}	2.7	0.51	0.26
—	2.5	10.5	10	{1.5-4.0}	2.7	0.47	0.25
—	8.0	3.5	10	{2.0-25}	2.9	0.47	0.24
—	8.0	7.0	10	{1.1-14}	3.0	0.45	0.23
—	8.0	10.5	10	{0.96-9.6}	2.9	0.45	0.23
—	15.0	10.5	10	{0.6-4.5}	3.0	0.47	0.24
—	8.0	10.5	2	{2.0-15}	2.2	0.58	0.30
—	8.0	10.5	5	{1.6-8.0}	2.9	0.47	0.24
—	8.0	10.5	15	{1.0-2.5}	2.8	0.48	0.26

fixed $t_0 = 3\,s$

calibrate disorder potential to be $\sim 2\,\%$ of U_D

collapsed curves



faster for larger U_s and Γ_d

robust behavior consistent with

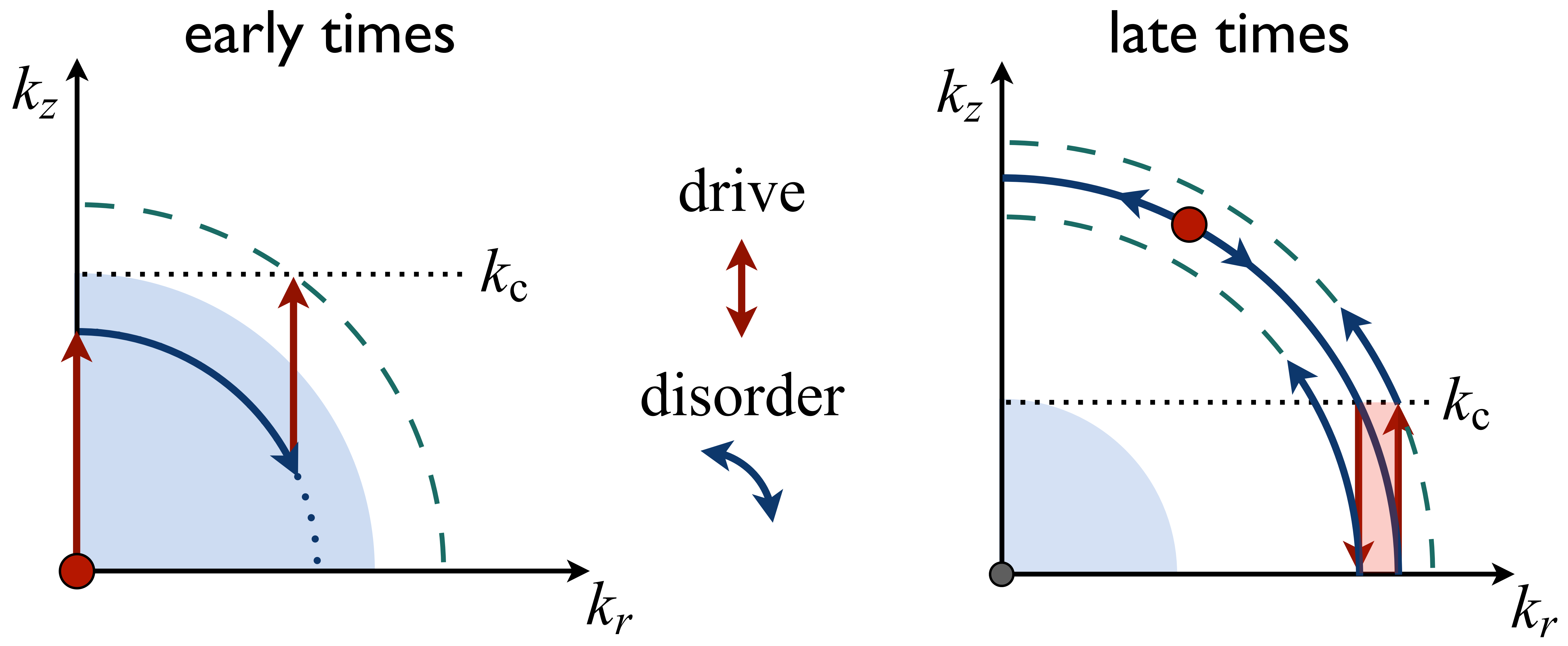
$\alpha = -0.48(4)$

$\beta = -0.24(2)$

$\kappa = 2.9(2)$

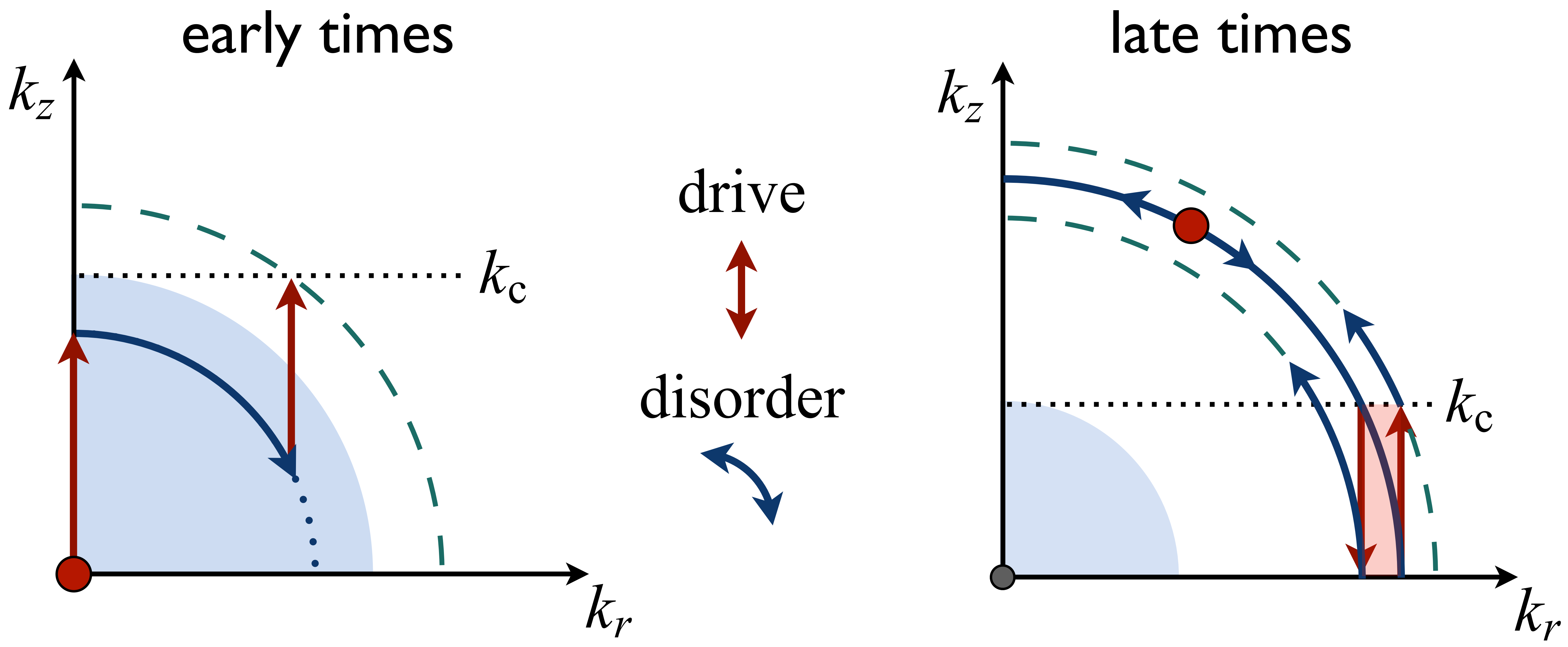
also not fine-tuned in frequency

Semi-classical model



Semi-classical model

random walk in energy-space



$$\frac{\mathrm{d}}{\mathrm{d}t}\langle E^2\rangle = rE_\mathrm{c}^2$$

step size:

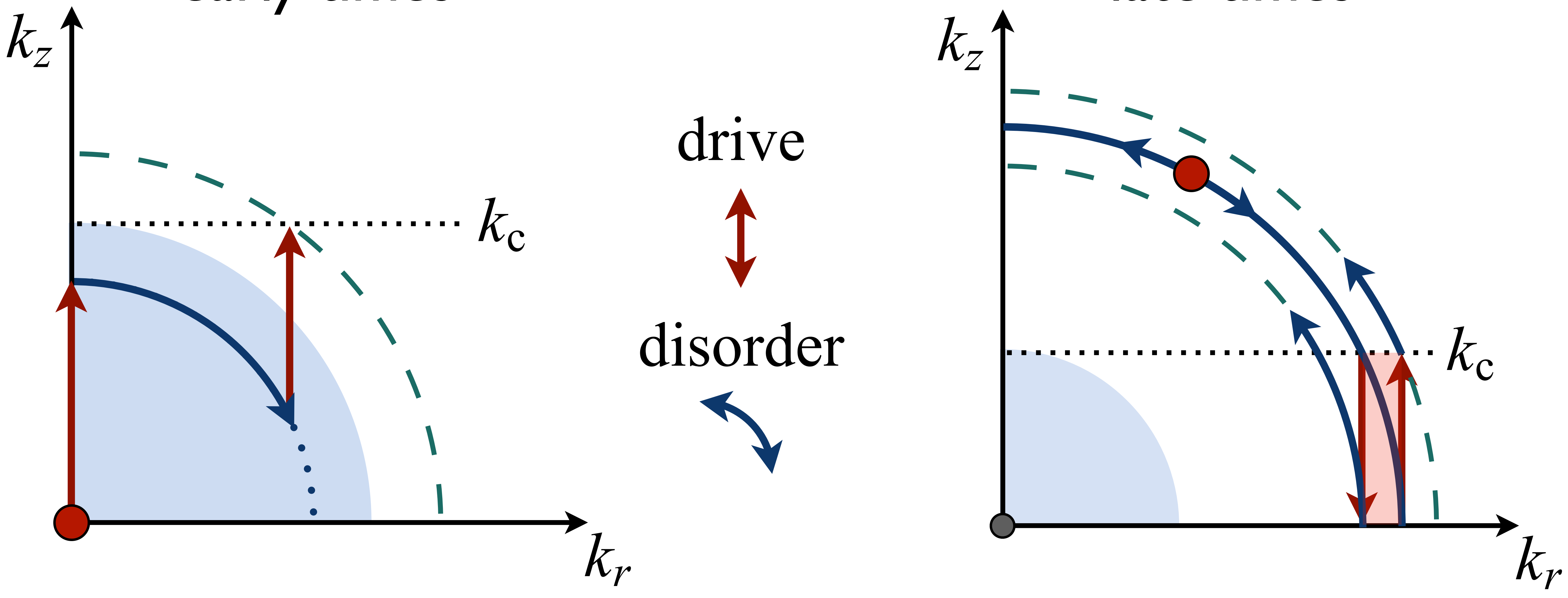
$$E_\mathrm{c} = \hbar^2 k_\mathrm{c}^2/(2m)$$

Semi-classical model

random walk in energy-space

early times

late times



$$\frac{\mathrm{d}}{\mathrm{d}t}\langle E^2 \rangle = r E_c^2$$

step size:
$E_c = \hbar^2 k_c^2/(2m)$

weak disorder limit:
$E \propto t^\eta$, with $\eta = 1/2$

$n_k \propto \exp[-(k/k_0)^{\kappa_{3D}}]$,
with $\kappa_{3D} = 4$

$\kappa_{3D} = 4$
corresponds to
$\kappa \approx 3$

Gaussian in energy-space!

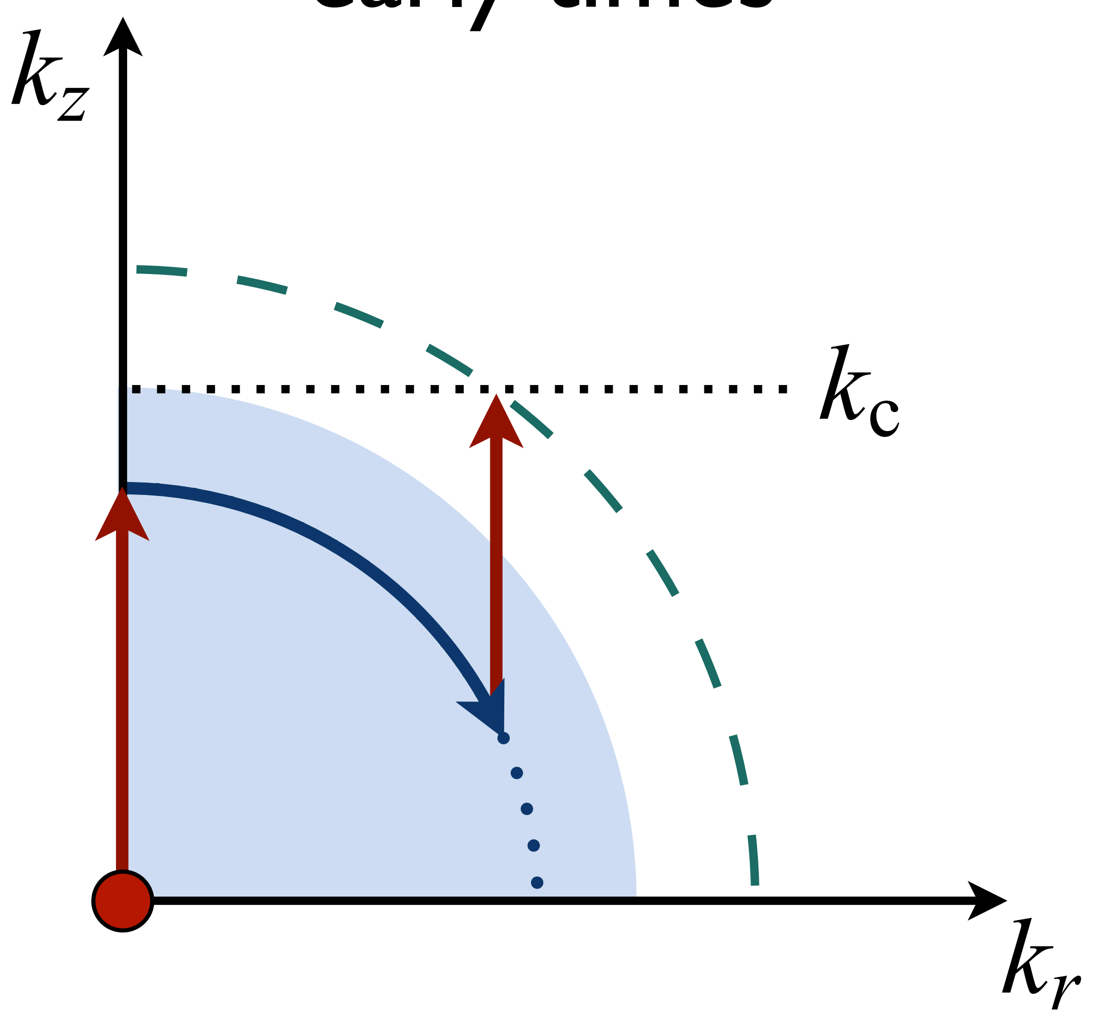
$n_k \propto \exp[-(E/E_0)^2]$

reflecting boundary at $E = 0$, so E grows!

Semi-classical model

random walk in energy-space

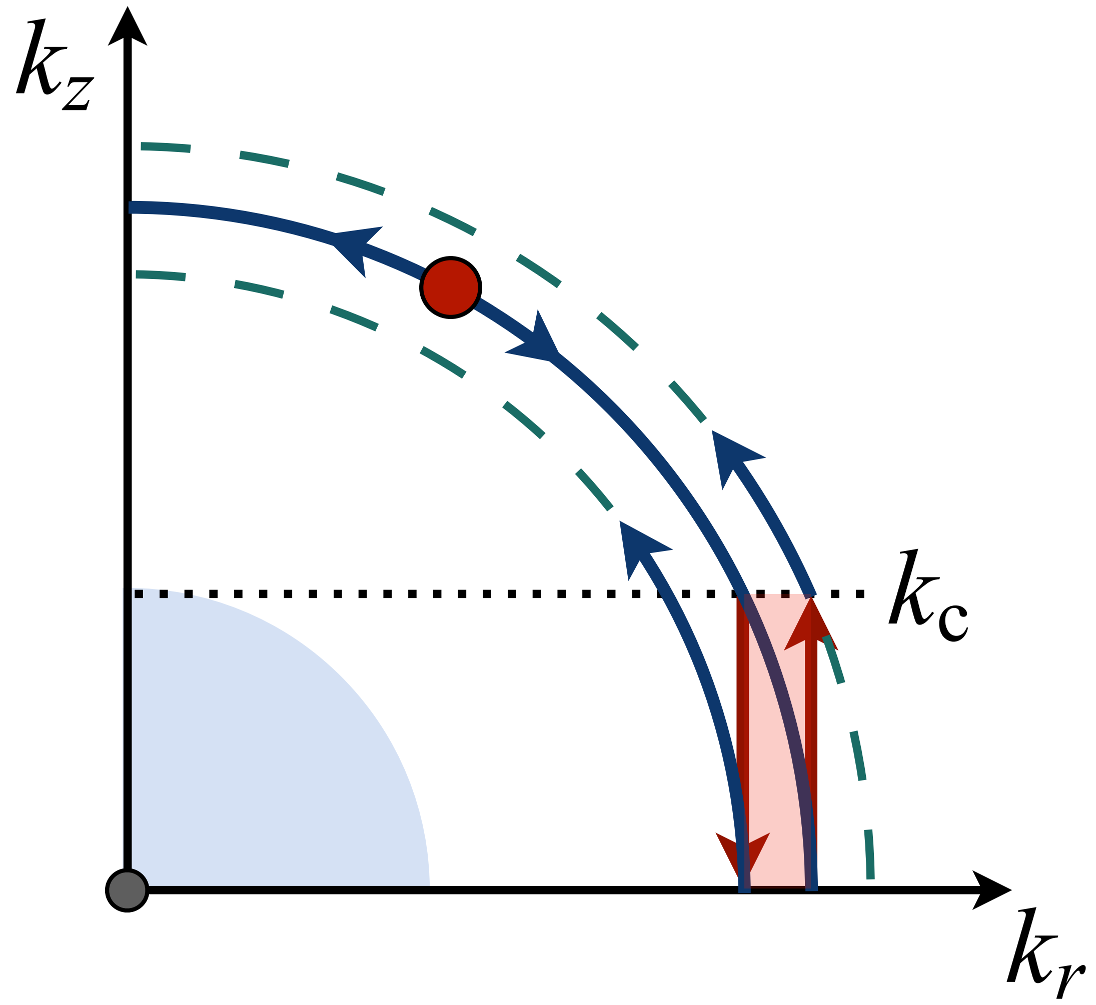
early times



drive

disorder

late times



$$\frac{\mathrm{d}}{\mathrm{d}t}\langle E^2 \rangle = rE_c^2$$

step size:

$$E_c = \hbar^2 k_c^2/(2m)$$

in general:

$E \propto t^\eta$, with

$\eta \in \{0.5 - 0.4\}$

$n_k \propto \exp[-(k/k_0)^{\kappa_{3D}}]$

with $\kappa_{3D} \in \{4 - 5\}$

$\kappa_{3D} = 4$

corresponds to

$\kappa \approx 3$

drift-diffusion equation

$$\frac{\partial P}{\partial t} = \frac{4sfk_cE_c^2}{45}\frac{\partial}{\partial E}\left[\frac{1}{sk+f}\left(\frac{\partial P}{\partial E} - \frac{P}{2E}\right)\right]$$

Y. Zhang *et al.*, C. R. Phys. **24** [online first] (2023)

Crossover to wave-turbulent behavior

what happens in the presence of weak interactions?

✦ excite cloud
$(U_s/k_B \approx 7.0\,\text{nK}, \omega_s/(2\pi) = 10\,\text{Hz}, t_s = 1\,\text{s})$

✦ vary initial interaction strength a

a (a_0)
0
5
20
50
100

Crossover to wave-turbulent behavior

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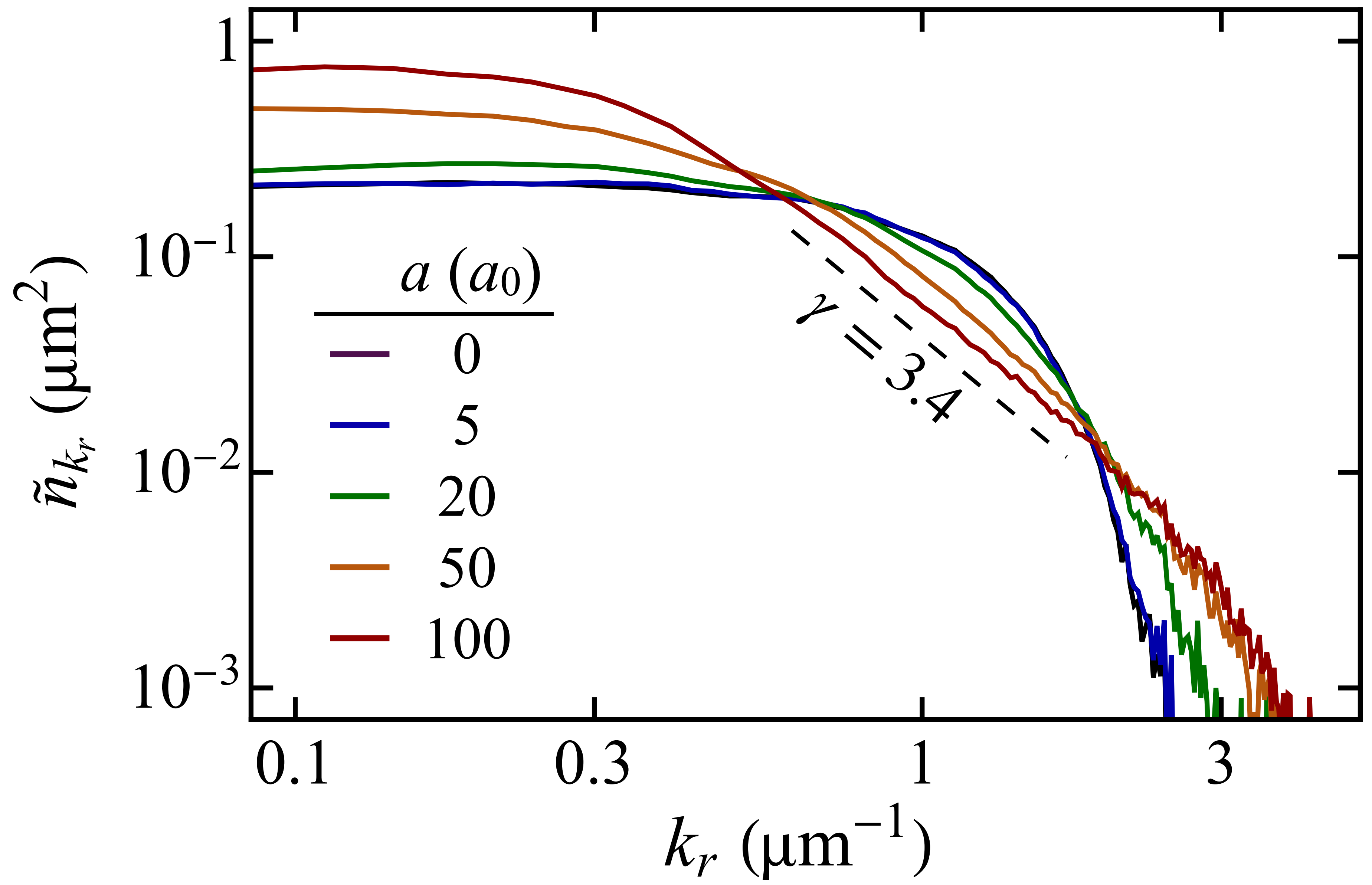

for weak-wave turbulence

$$f_p = n_0\, k^{-\gamma+1}$$

N. Navon *et al*., Nature **539**, 72 (2016)
N. Navon *et al*., Science **366**, 382 (2019)
L. H. Dogra *et al*., Nature **620**, 521 (2023)

Crossover to wave-turbulent behavior

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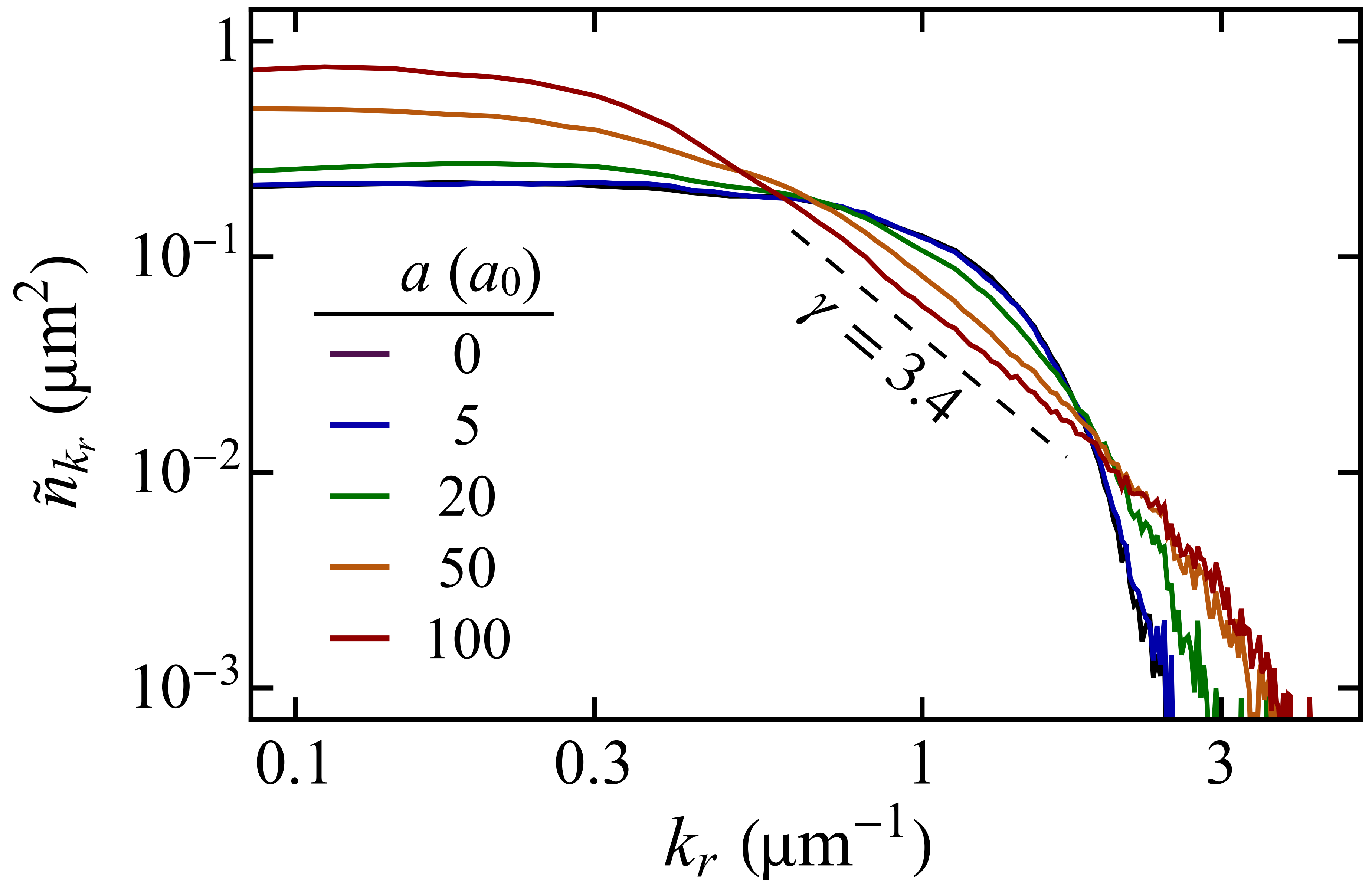


✦ fit with

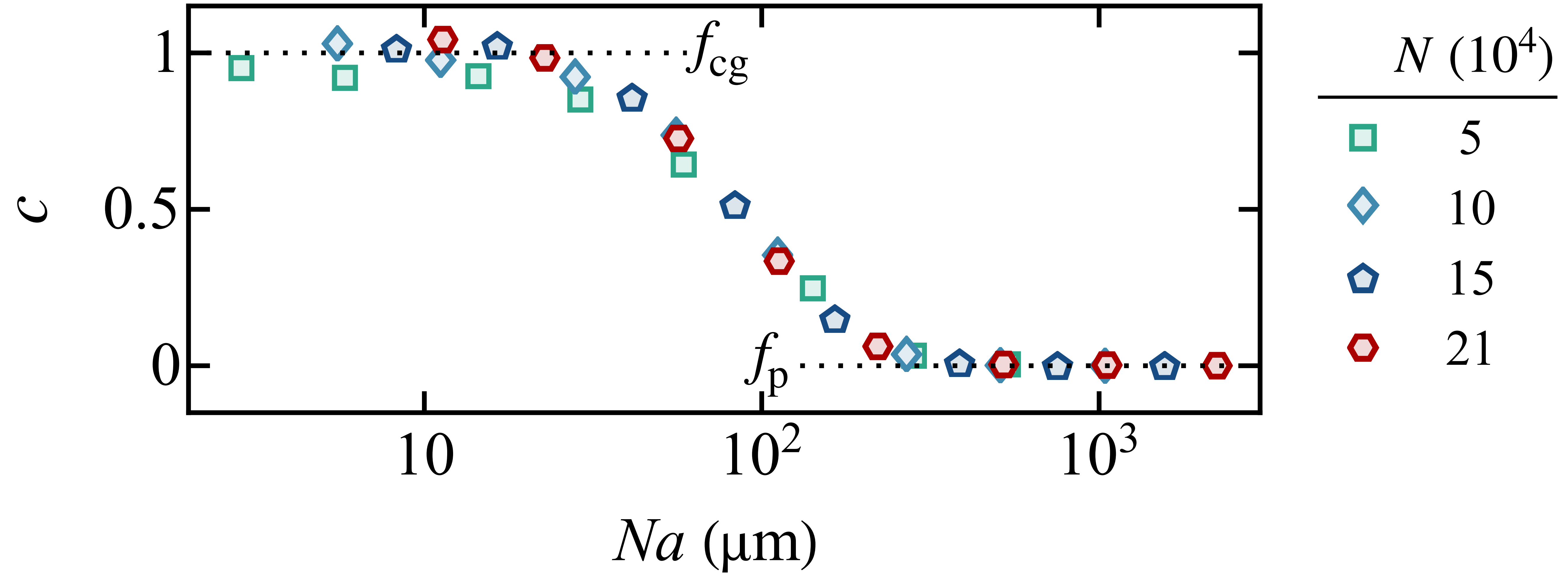
$$c f_{cg} + (1-c) f_p$$

$$f_{cg} = A_0 \exp[-(k/k_0)^\kappa]$$

$$f_p = n_0 k^{-\gamma+1}$$

free n_0, c

fix $\kappa = 2.7, \gamma = 3.4,$
$k_0 = 1.1\mu\mathrm{m}^{-1}, A_0(k_0)$

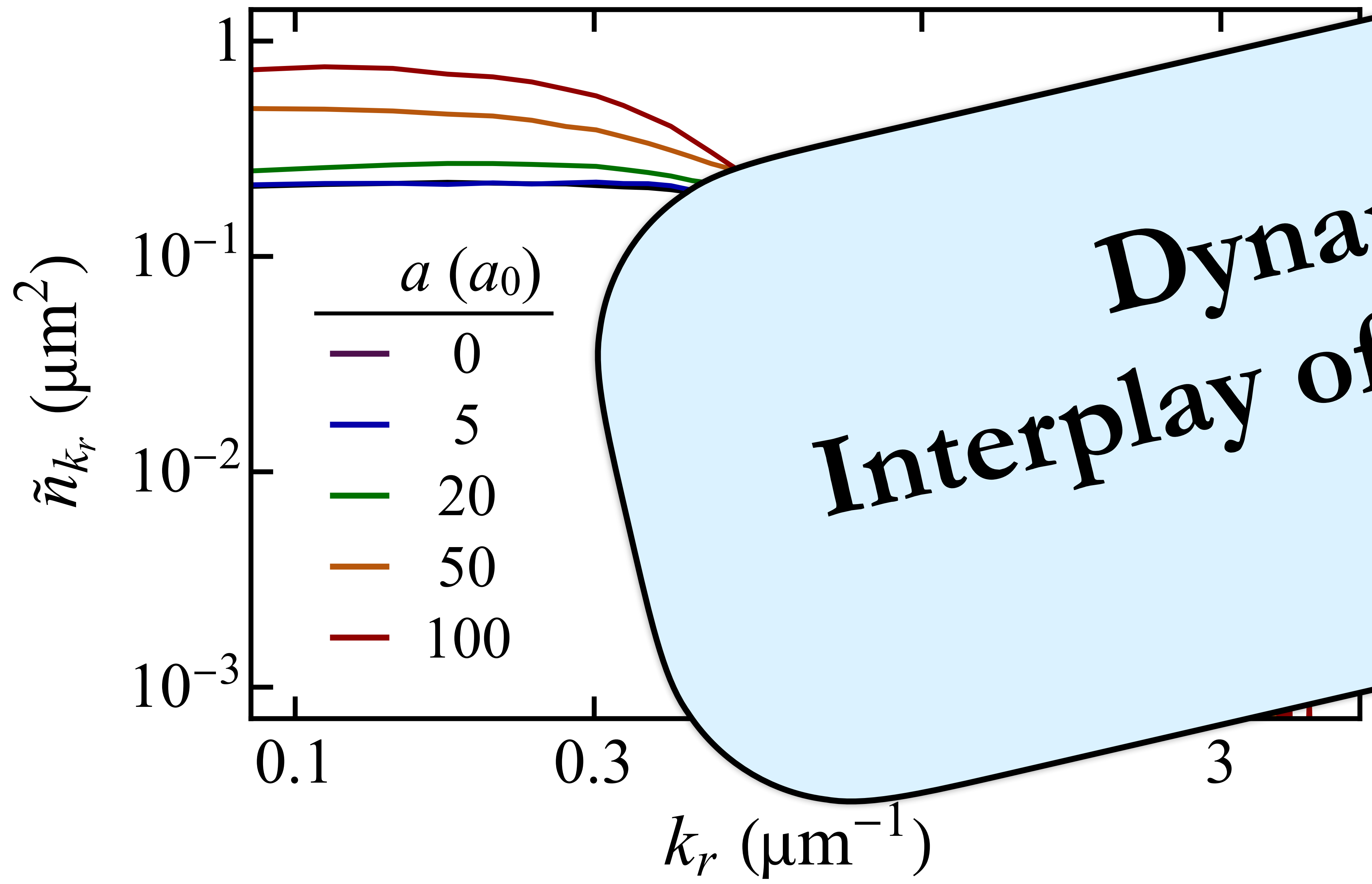


Crossover to wave-turbulent behavior

what happens in the presence of weak interactions?

✦ excite cloud
$(U_s/k_B \approx 7.0\,\mathrm{nK}, \omega_s/(2\pi) = 10\,\mathrm{Hz}, t_s = 1\,\mathrm{s})$

✦ vary initial interaction strength a

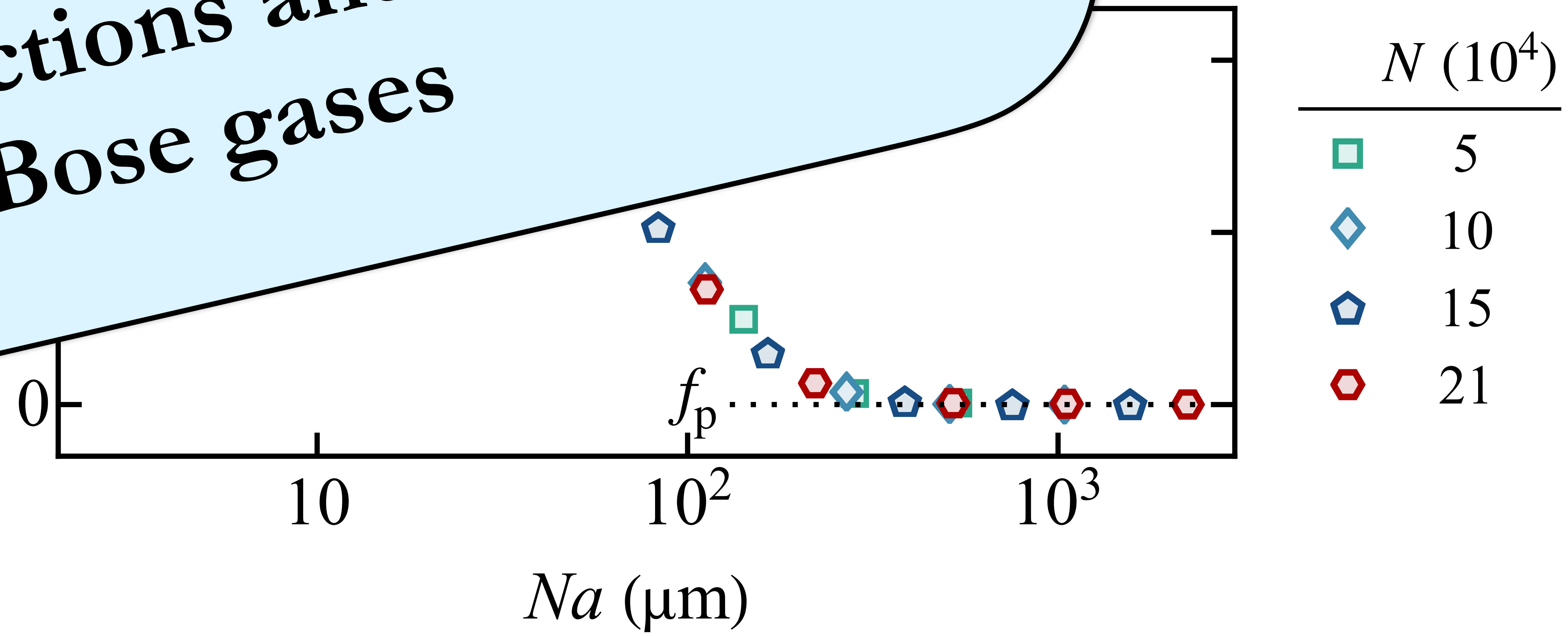


✦ fit with

$cf_{cg} + (1 - \ldots)$ free n_0, c

$= 2.7, \gamma = 3.4,$

$1\,\mu\mathrm{m}^{-1}, A_0(k_0)$



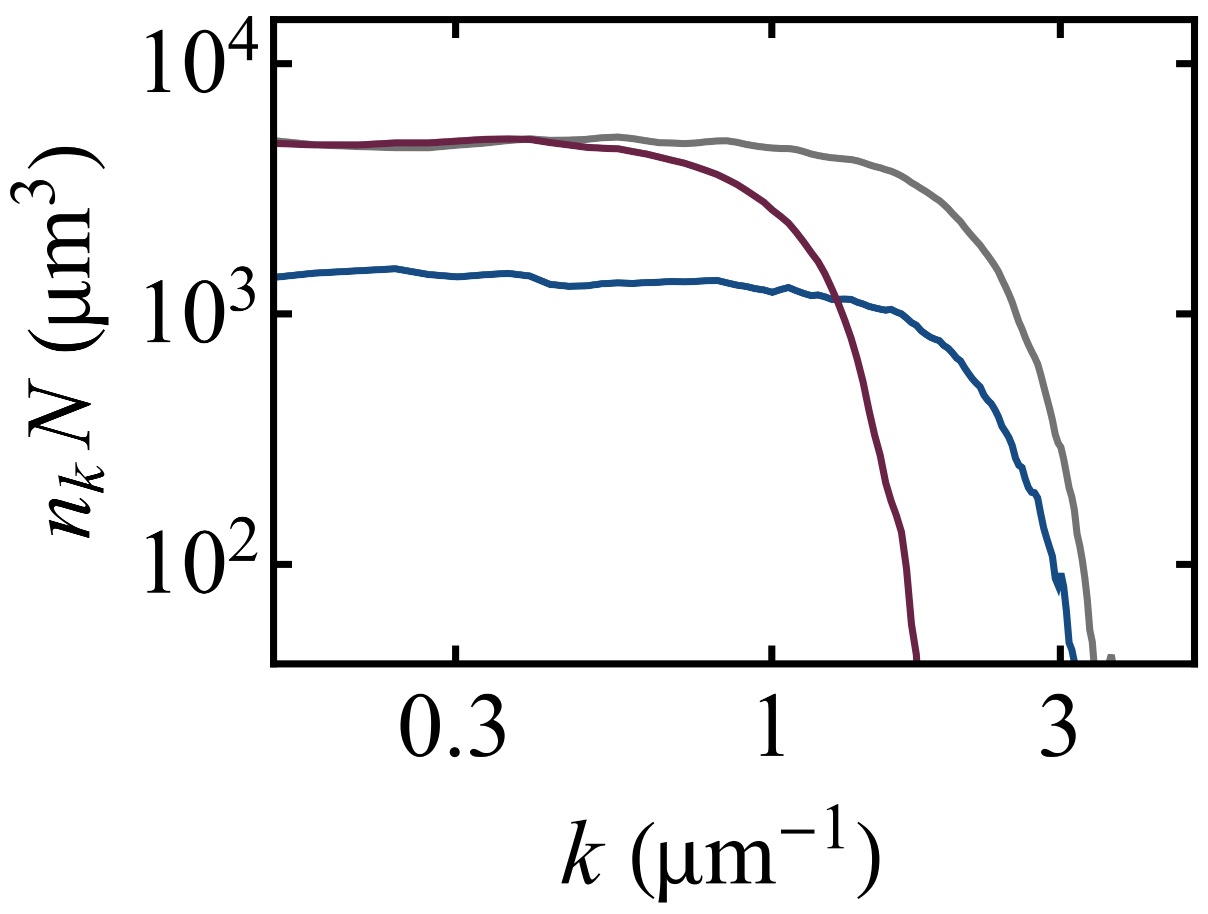
Dynamical phase diagram?
Interplay of interactions and disorder in driven Bose gases

G. Martirosyan *et al.*, PRL **132**, 113401 (2024)

Exploit far-from-equilibrium state?

coarsening dynamics

far-from-equilibrium
state engineering



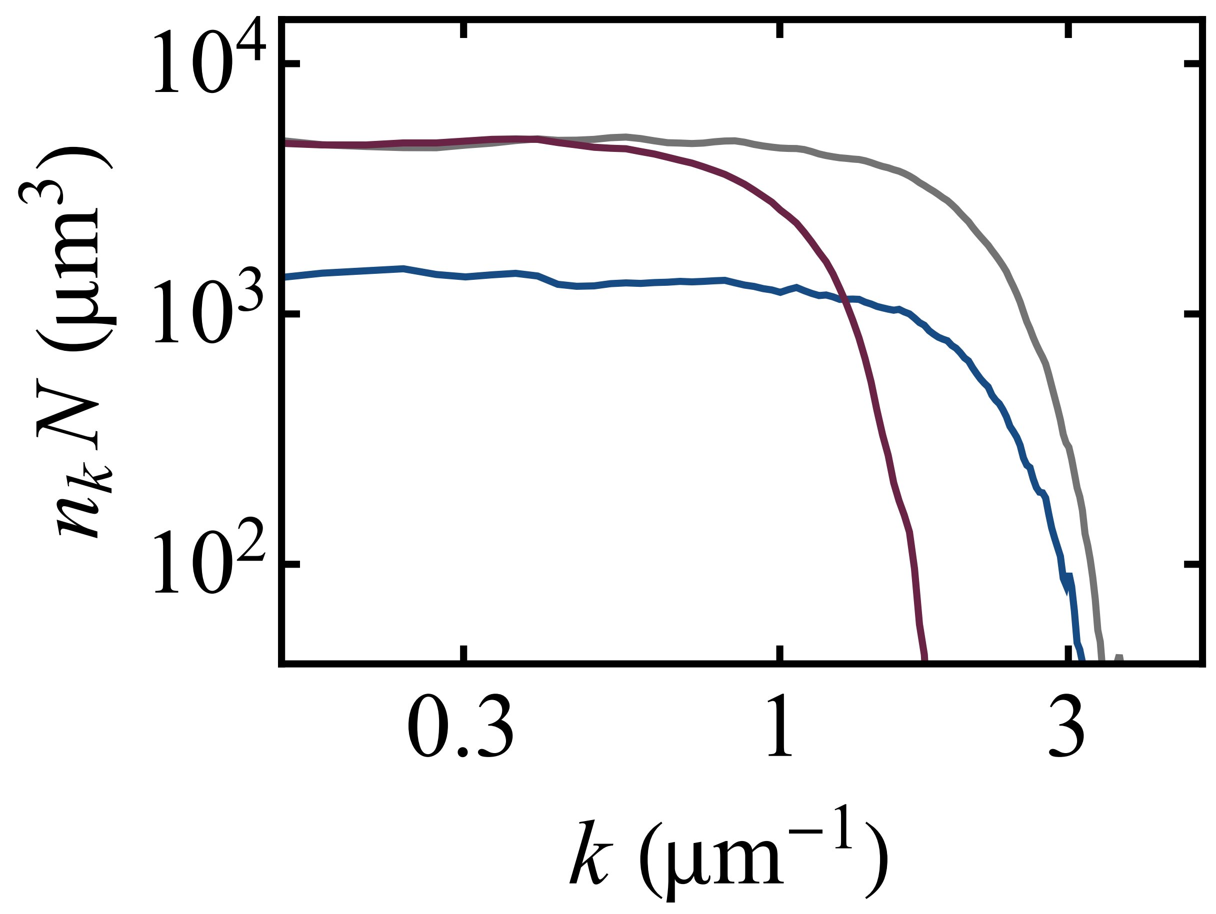
very useful!

can vary initial $N, E, k_{\mathrm{D}}, \cdots$

Exploit far-from-equilibrium state?

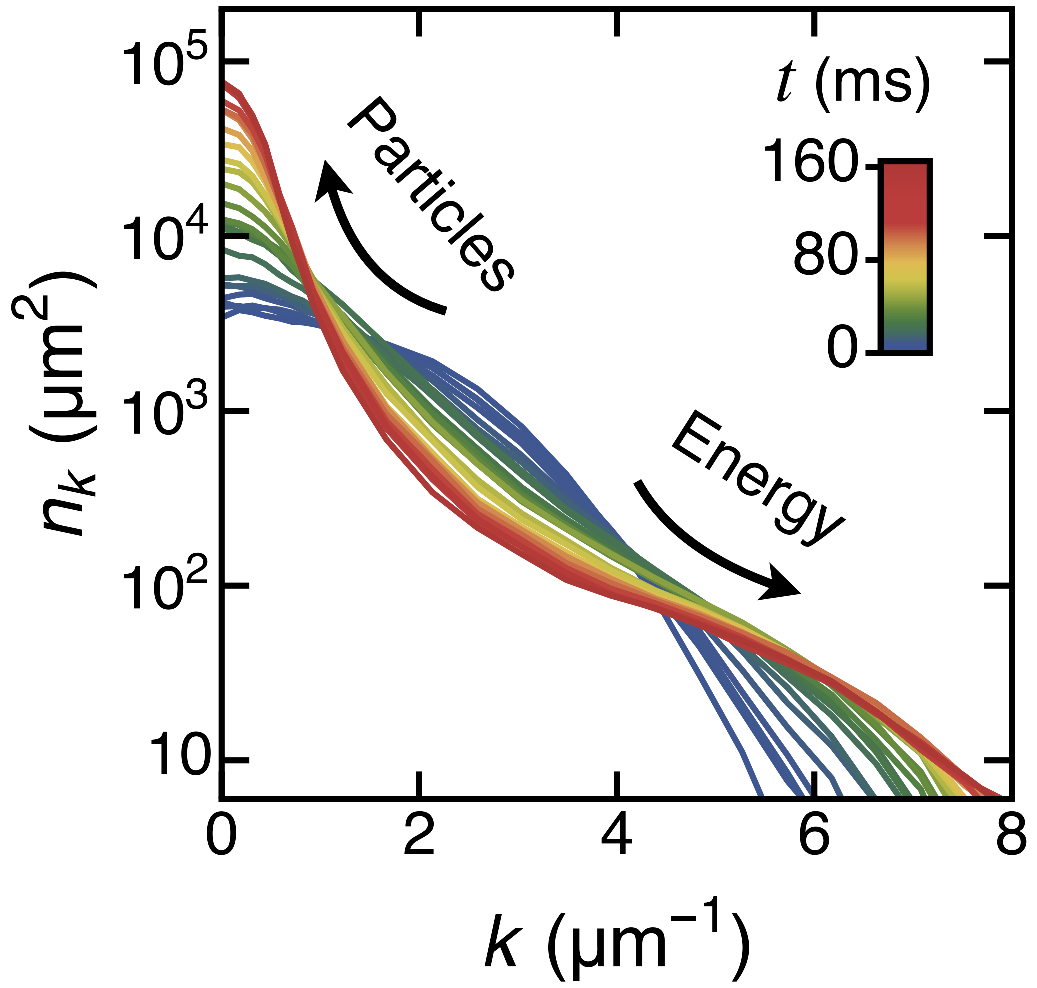
coarsening dynamics

far-from-equilibrium
state engineering



can vary initial $N, E, k_{\mathrm{D}}, \cdots$

also in 2D,
used to study coarsening



bidirectional transport

see also

M. Prüfer *et al.*, Nature **563**, 217 (2018)
S. Erne *et al.*, Nature **563**, 225 (2018)
J. A. P. Glidden *et al.*, Nat. Phys. **17**, 457 (2021)
S. Huh *et al.*, Nat. Phys. **20**, 402 (2024)

Exploit far-from-equilibrium state?

coarsening dynamics

far-from-equilibrium
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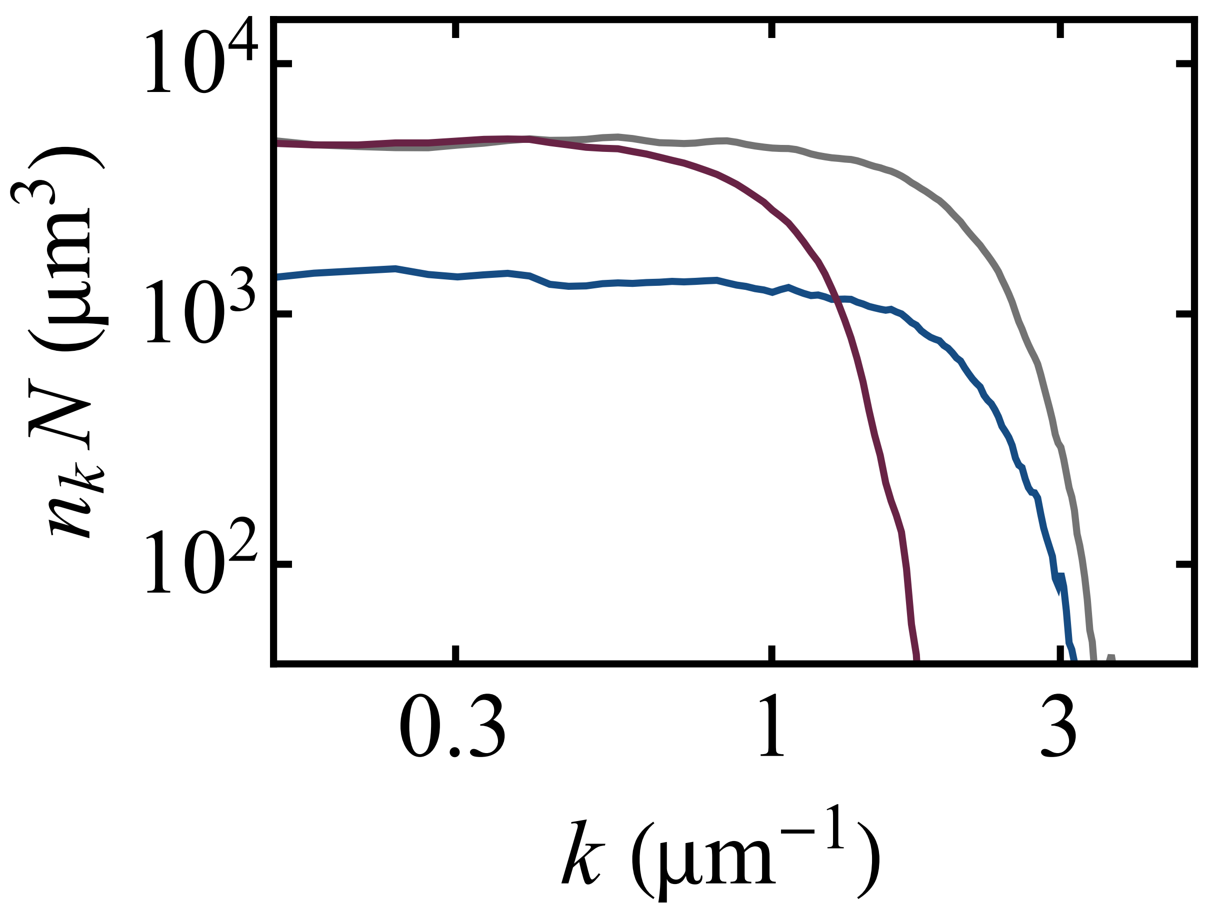
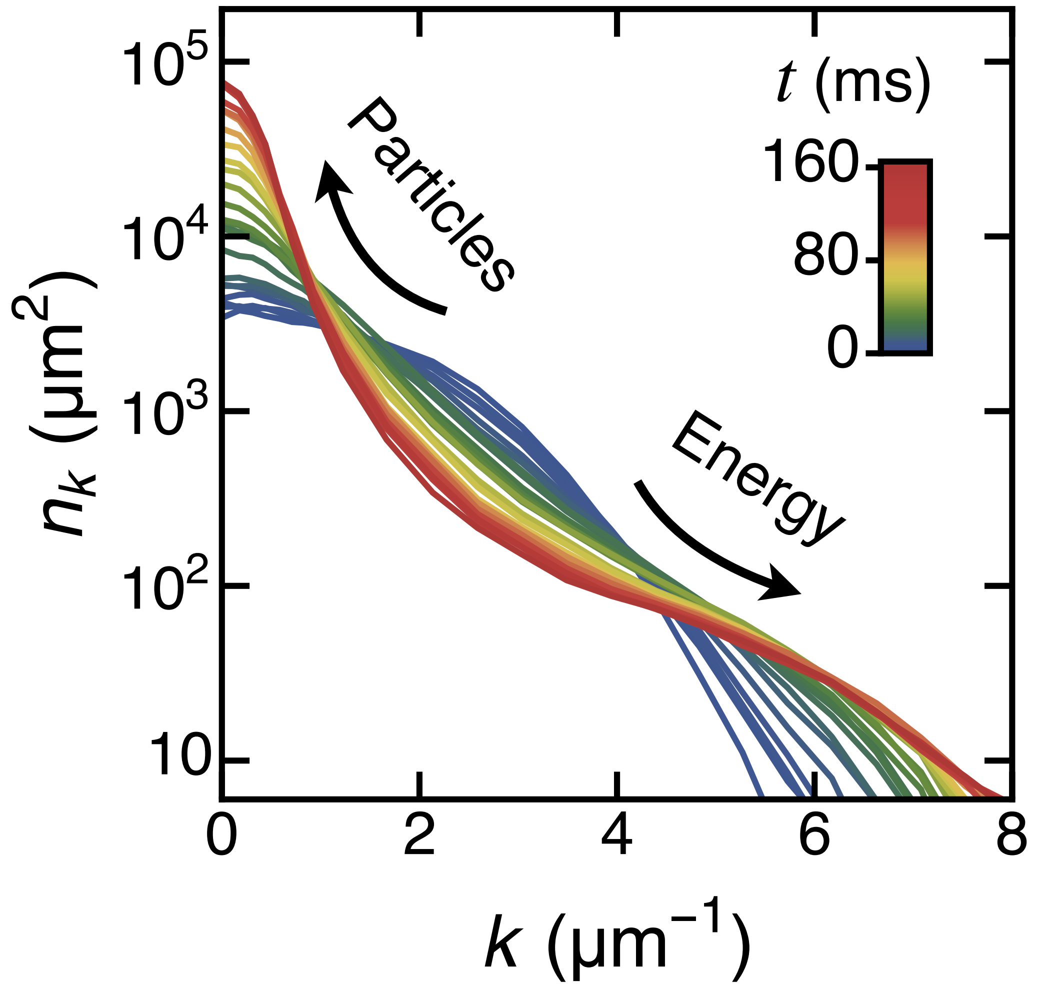


can vary initial $N, E, k_\mathrm{D}, \cdots$

relaxation studies
in 3D ongoing

also in 2D,
used to study coarsening



bidirectional transport

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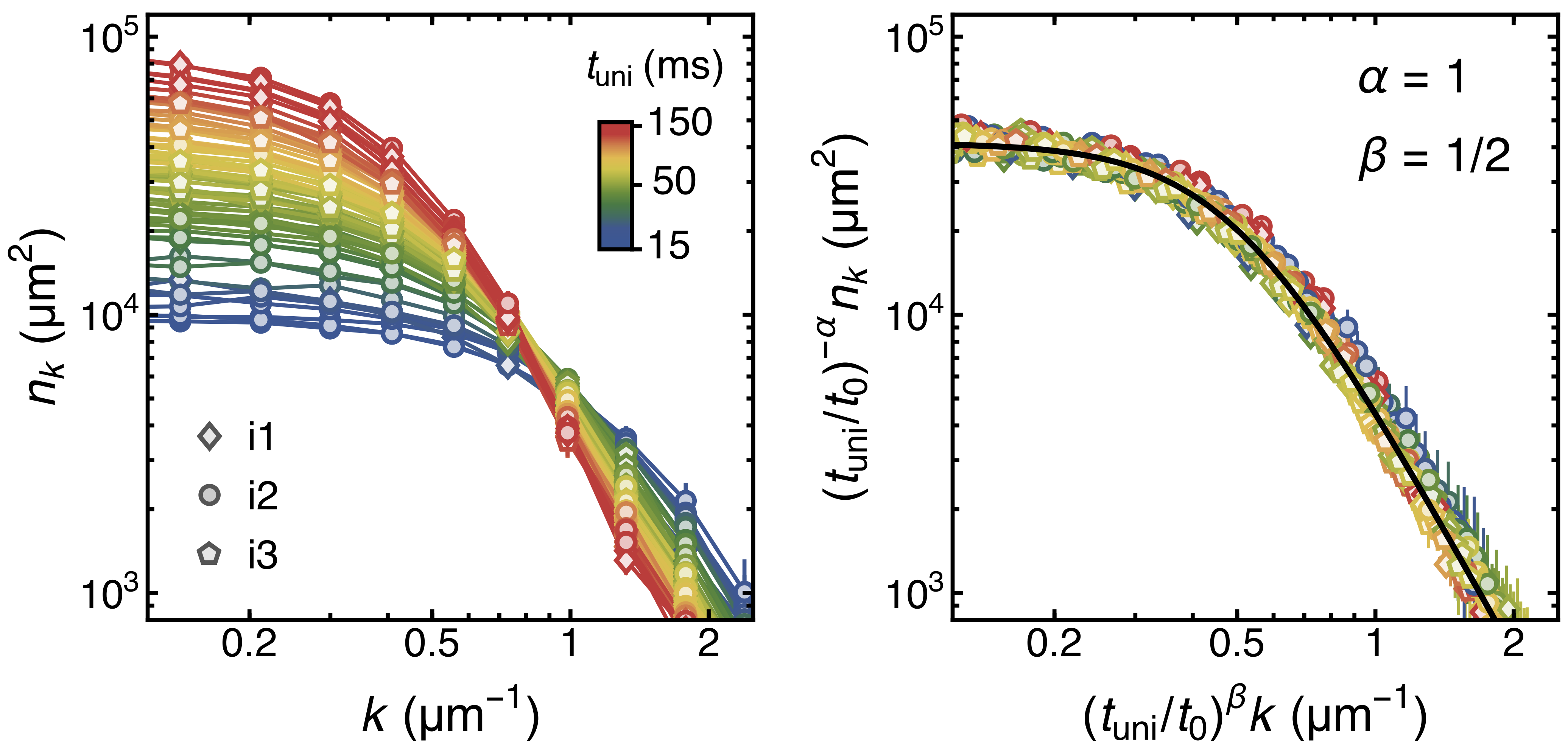
J. A. P. Glidden *et al.*, Nat. Phys. **17**, 457 (2021)
S. Huh *et al.*, Nat. Phys. **20**, 402 (2024)

account for prescaling, get t_uni



M. Gazo *et al.*, arXiv:2312.09248

agreement with analytical
field-theory NTFP predictions

Talk outline

1. Subdiffusive dynamic scaling in a driven disordered Bose gas

G. Martirosyan et al. PRL **132**, 113401 (2024)

Y. Zhang et al. C. R. Phys. **24** [online first] (2023)

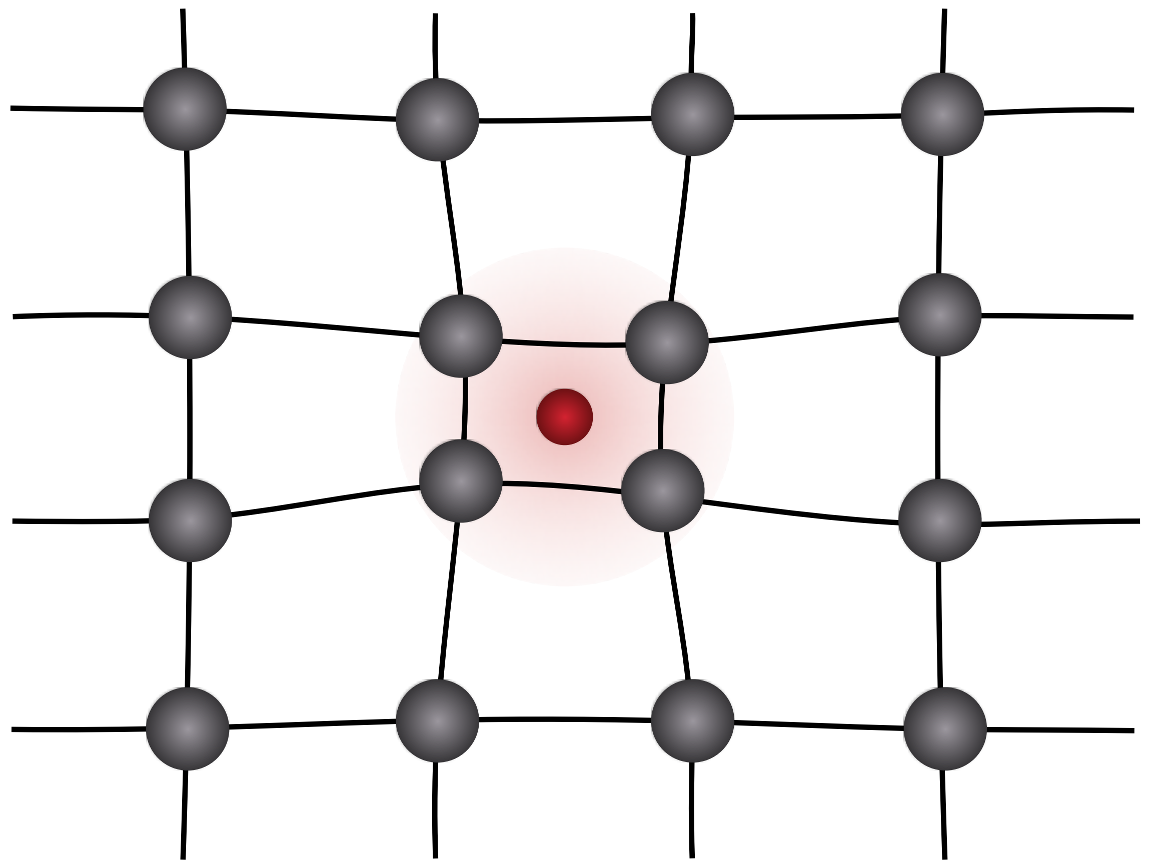
2. Bose polarons in box

J. Etrych et al. arXiv:2402.14816 (2024)

Impurities in a quantum bath

fundamental problem in physics

historically: Landau, Pekar, …



generic!
quantum system + environment

Fröhlich Hamiltonian, simple
mean-field theories…

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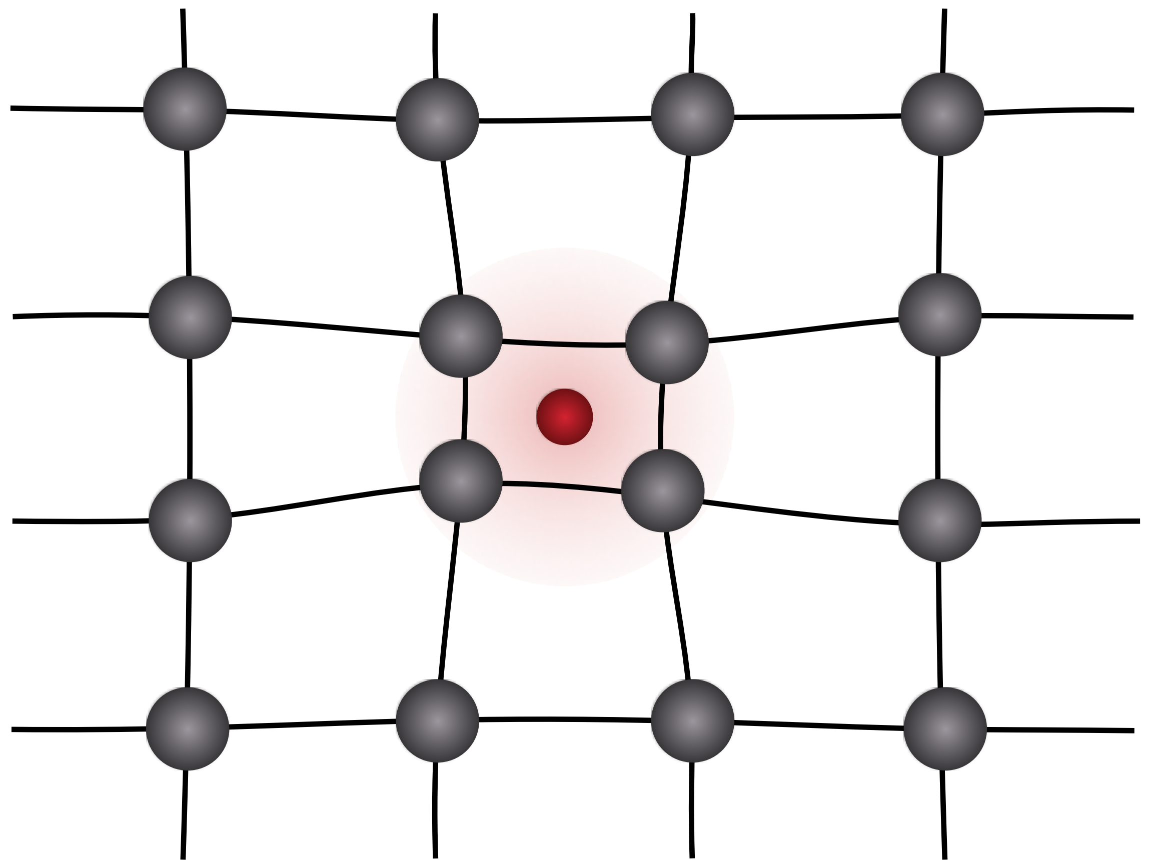


widespread concept relevant in many materials!

e.g. Kondo effect, colossal magnetoresistance

relevant for hybrid quantum simulation platforms: e.g. coolants, …

generic!
quantum system + environment

Fröhlich Hamiltonian, simple mean-field theories…

Impurities in a quantum bath

fundamental problem in physics

Fermi polaron

impurities immersed
in a Fermi gas

Some highlights:

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

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

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

Koschorreck *et al.*, Nature **485**, 619 (2012)

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

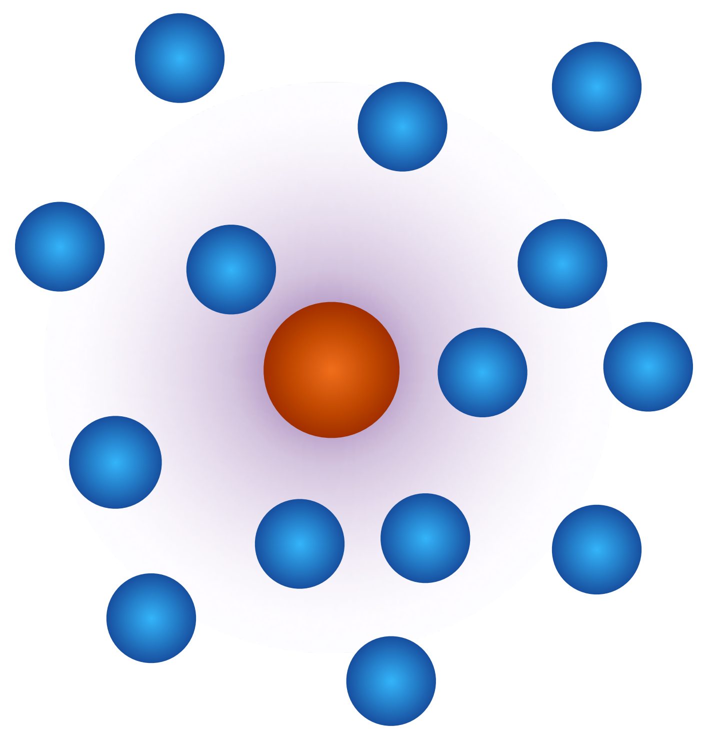
Scazza *et al.*, PRL **118**, 083602 (2017)

Ness *et al.*, PRX **10**, 041019 (2020)

Baroni *et al.*, Nat. Phys **20**, 68 (2024)

Vivanco *et al.*, arXiv:2308.05746

in ultracold atoms



Paris, Innsbruck, MIT, Cambridge,
JILA, Aarhus,…

Other related systems:
Rydberg impurities, monolayer
semiconductors, lattice polarons, etc…

Bose polaron

impurities immersed
in a BEC

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Kohstall *et* … 12)

Koscho… (2012)

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pretty good
understanding by now

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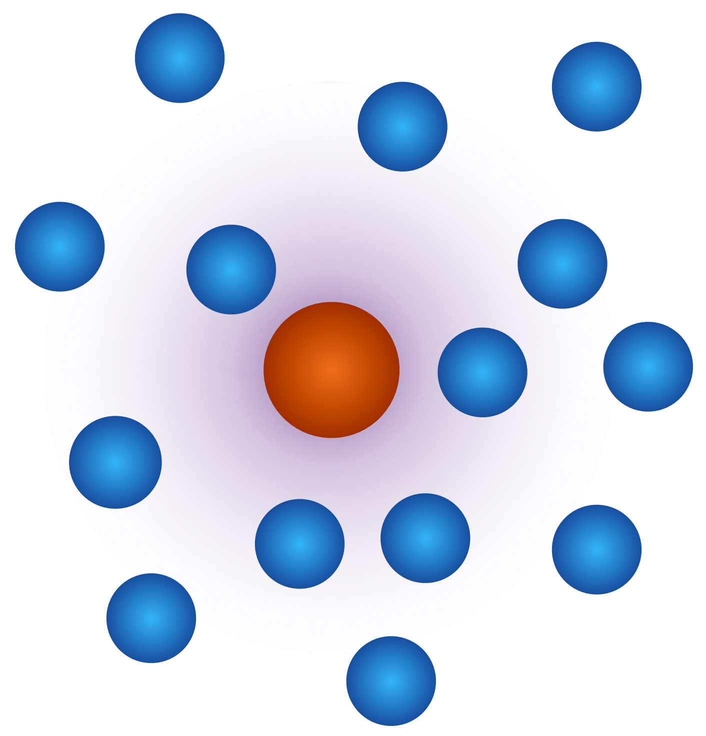

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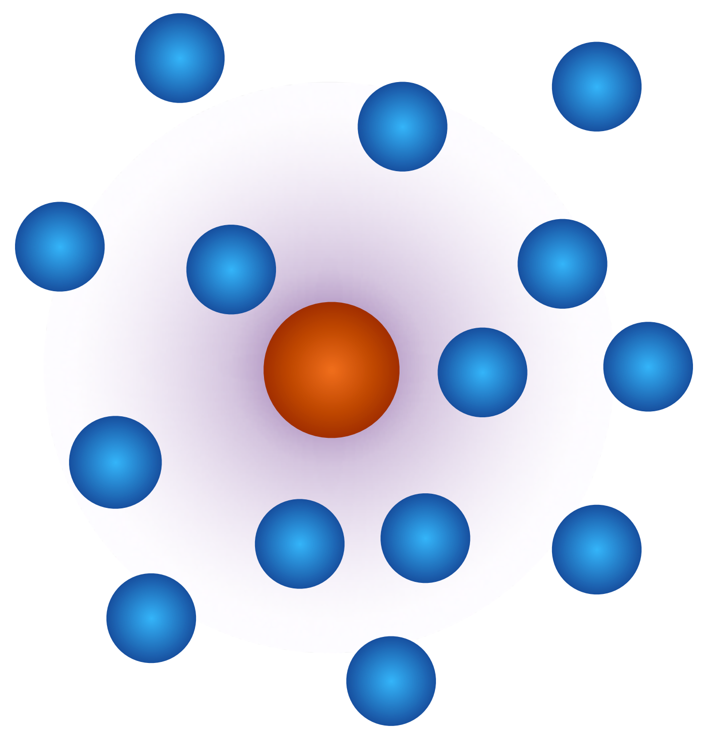

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Some highlights:

Hu *et al.*, PRL **117**, 055301 (2016)

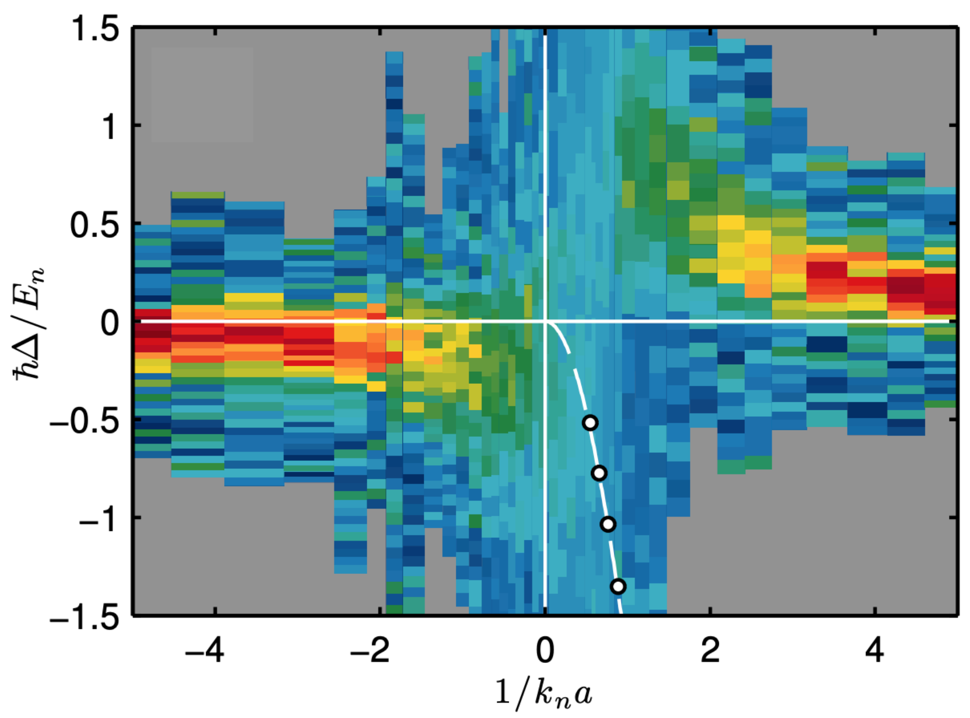
Jørgensen *et al.*, PRL **117**, 055302 (2016)

Yan *et al.*, Science **368**, 190 (2020)

Skou *et al.*, Nat. Phys. **17**, 731 (2021)

Cayla *et al.*, PRL **130**, 153401 (2023)

from Jørgensen *et al.*, PRL **117**, 055302 (2016)



injection spectrum

Impurities in a quantum bath

fundamental problem in physics

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Baroni *et al.*, Nat. Phys **20**, 68 (2024)

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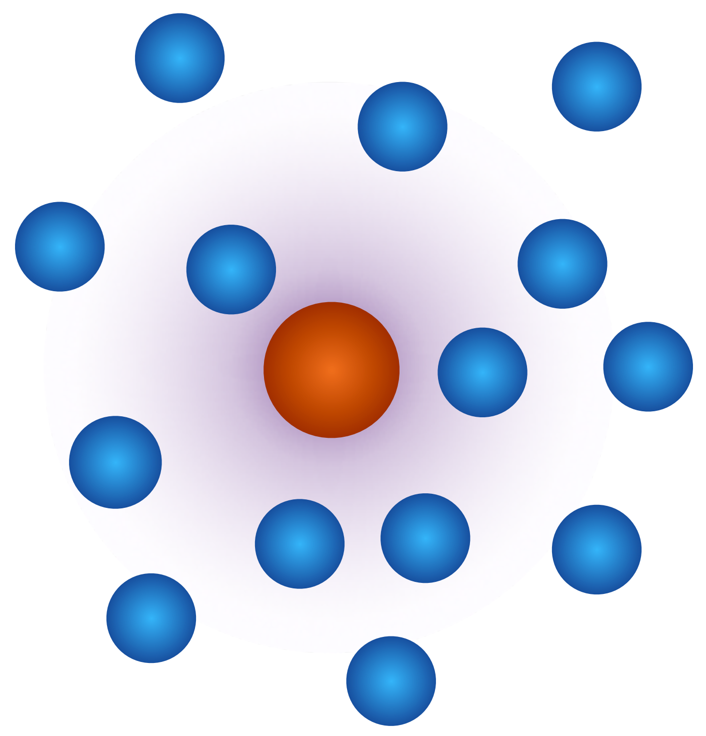

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Rydberg impurities, monolayer
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Bose polaron

impurities immersed
in a BEC

many rich theories…

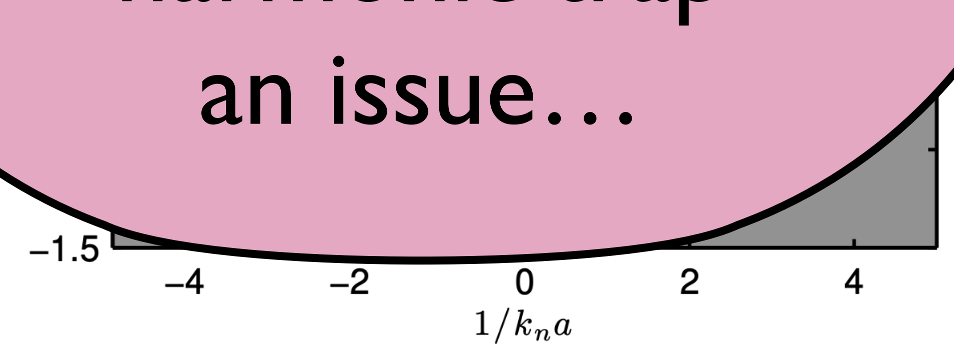
Tempere, Bruun, Massignan, Enss,
Schmidt, Demler, Grusdt, Gurarie,
Giorgini, Parish, Levinsen,
Lewenstein, Devreese, Naidon,
Schmelcher, Busch, …

some aspects understood,
but questions remain…

harmonic trap
an issue…

…6)

from Jørgen…
et al., PRL **1**…
055302 (2016…



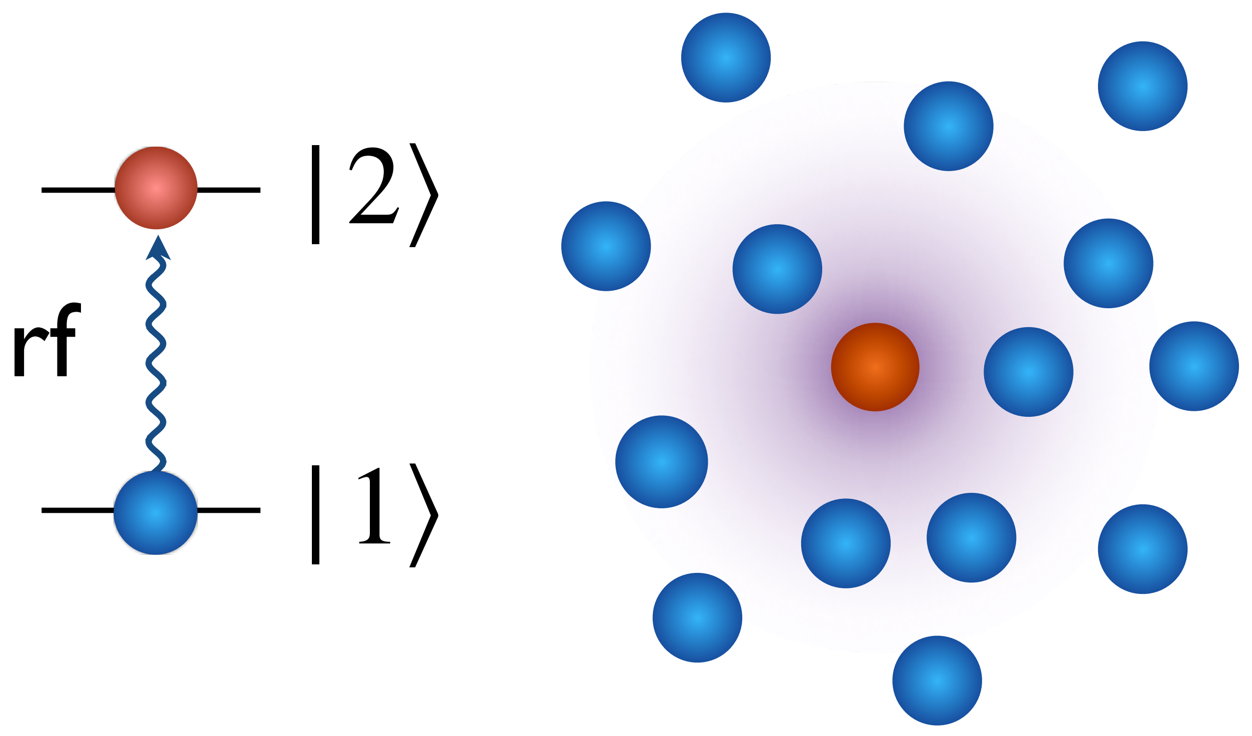
injection spectrum

Christoph Eigen

Trento, April 2024

Bose polarons in a homogeneous BEC

another spin state
mobile equal-mass impurities



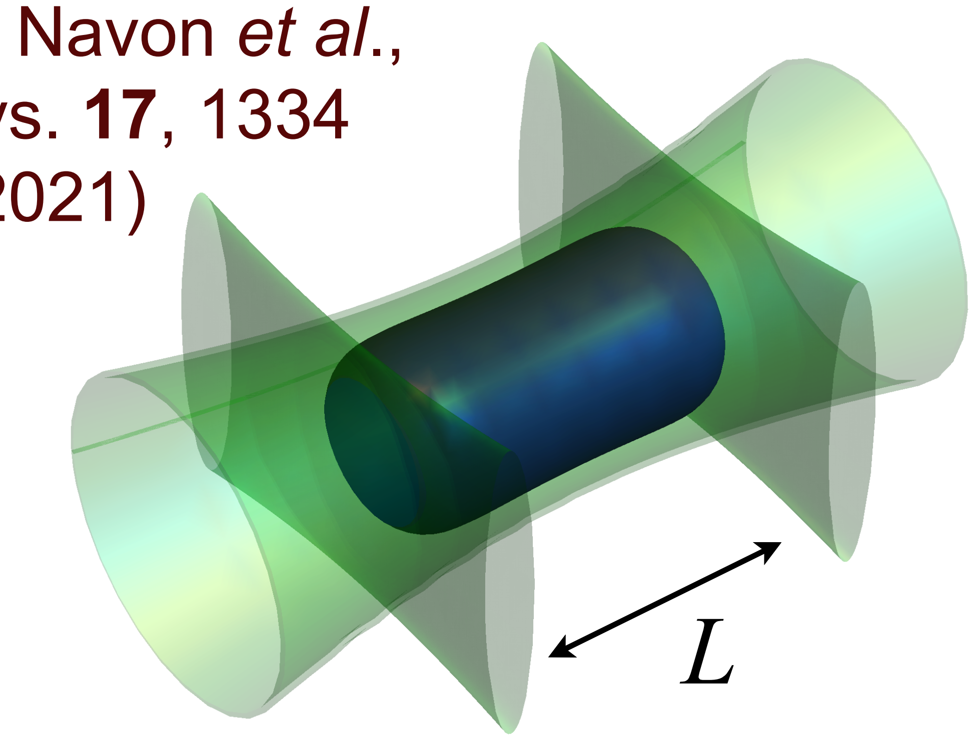
rich Feshbach resonance landscape
for tuning intra- and inter-state
interactions…

3 interactions strengths
a, a_B, a_I

Bose polarons in a homogeneous BEC

ultracold ^{39}K
Bose gas in a box

review: N. Navon *et al.*, Nat. Phys. **17**, 1334 (2021)

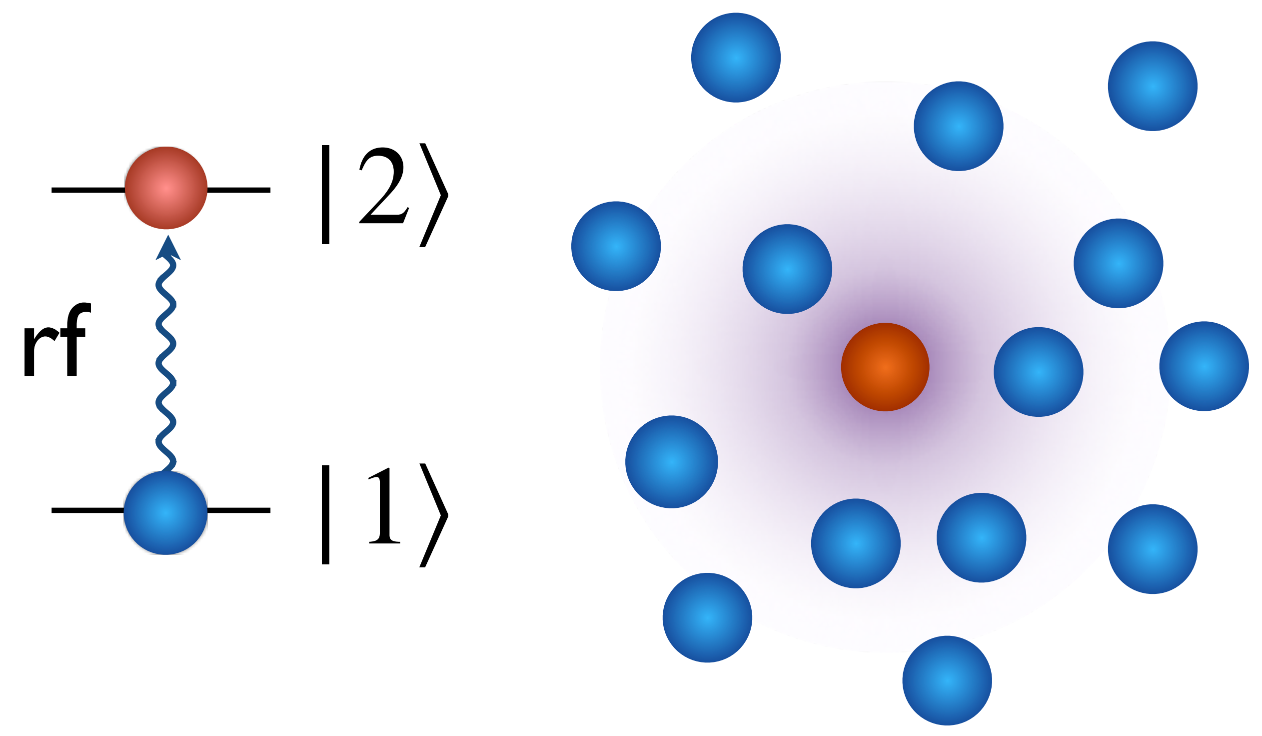


optical box
A. L. Gaunt *et al.*, PRL **110**, 200406 (2013)
C. Eigen *et al.*, PRX **6**, 041058 (2016)

homogeneous density n

momentum: $k_n = (6\pi^2 n)^{1/3}$
energy: $E_n = \hbar^2 k_n^2/(2m)$
time: $t_n = \hbar/E_n$

another spin state
mobile equal-mass impurities



rich Feshbach resonance landscape for tuning intra- and inter-state interactions…

3 interactions strengths
a, a_B, a_I

levitate two spin states against gravity?

Pinpointing Feshbach resonances in ^{39}K

recent precision measurements of few-body physics!

Intrastate

$\|F, m_F\rangle$	B_{res} (G)	$a_{bg}\Delta$ (a_0 G)	B_{zero} (G)	$\mu(\mu_B)$
$\|1,1\rangle$	25.91(6)	-	-	−0.605
$\|1,1\rangle$	402.74(1)	1530(20)	350.4(1)[a]	−0.961
$\|1,1\rangle$	752.3(1)[b]	-	-	−0.987
$\|1,0\rangle$	58.97(12)	-	-	−0.337
$\|1,0\rangle$	65.57(23)	-	-	−0.370
$\|1,0\rangle$	472.33(1)	2040(20)	393.2(2)	−0.945
$\|1,0\rangle$	491.17(7)	140(30)	490.1(2)	−0.949
$\|1,-1\rangle$	33.5820(14)[c]	−1073[c]	/	0.324
$\|1,-1\rangle$	162.36(2)	760(20)	/	−0.489
$\|1,-1\rangle$	561.14(2)	1660(20)	504.9(2)	−0.959

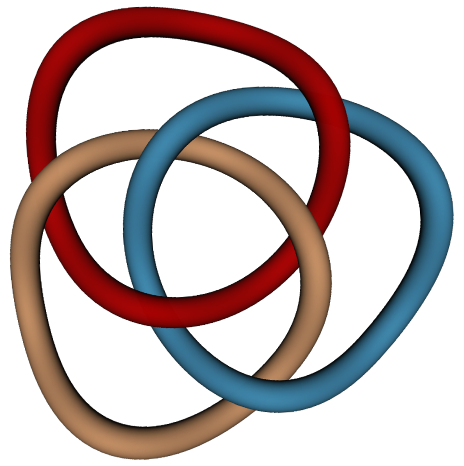
a) Fattori *et al.*, PRL **101**, 190405 (2008) b) D'Errico *et al.*, NJP **9**, 223 (2007)
c) Chapurin *et al.*, PRL **123**, 233402 (2019)

Interstate

$\|F, m_F\rangle_1 + \|F, m_F\rangle_2$	B_{res} (G)	$a_{bg}\Delta$ (a_0 G)	$\mu_1(\mu_B)$	$\mu_2(\mu_B)$
$\|1,1\rangle + \|1,0\rangle$	25.81(6)	-	−0.605	−0.155
$\|1,1\rangle + \|1,0\rangle$	39.81(6)	-	−0.651	−0.235
$\|1,1\rangle + \|1,0\rangle$	445.42(3)	1110(40)	−0.967	−0.939
$\|1,1\rangle + \|1,-1\rangle$	77.6(4)	-	−0.747	0.034
$\|1,1\rangle + \|1,-1\rangle$	501.6(3)	-	−0.973	−0.948
$\|1,0\rangle + \|1,-1\rangle$	113.76(1)[d]	715(7)[d]	−0.569	−0.215
$\|1,0\rangle + \|1,-1\rangle$	526.16(3)	970(50)	−0.956	−0.953

d) Tanzi *et al.*, PRA **98**, 062712 (2018) - used for previous ^{39}K polarons

also explored Efimov universalities



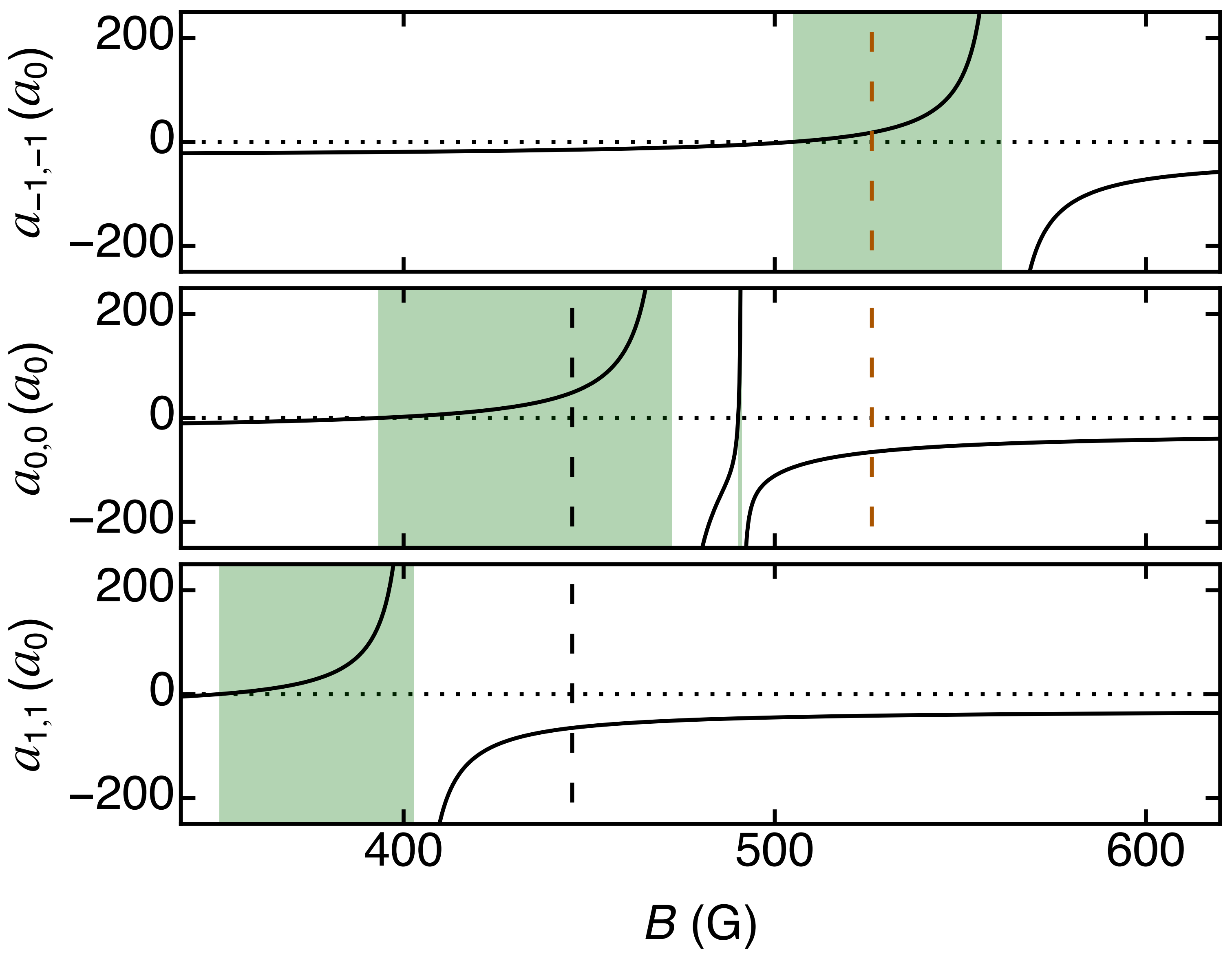
s-wave interaction strength

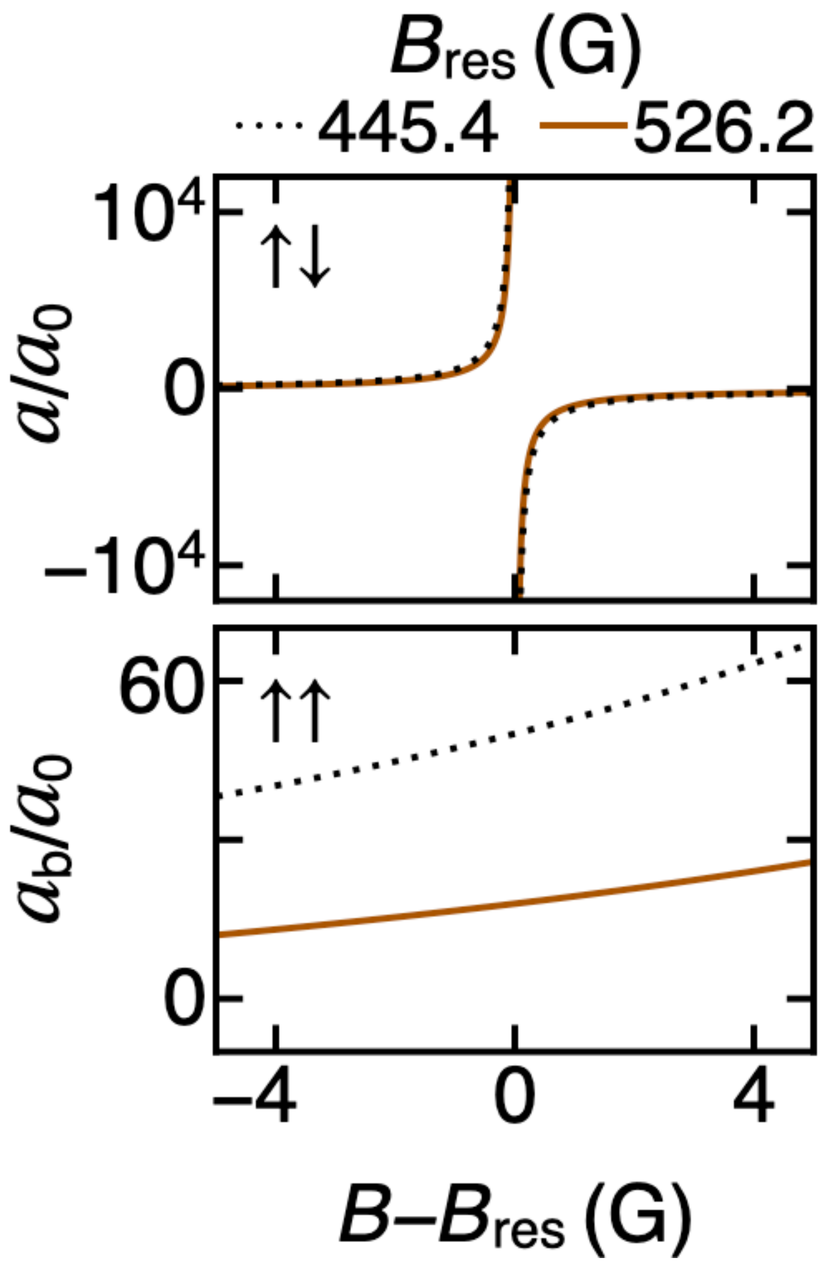
$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_{res}}\right)$$

J. Etrych et al., PRR **5**, 013174 (2023)

Pinpointing Feshbach resonances in ^{39}K

recent precision measurements of few-body physics!

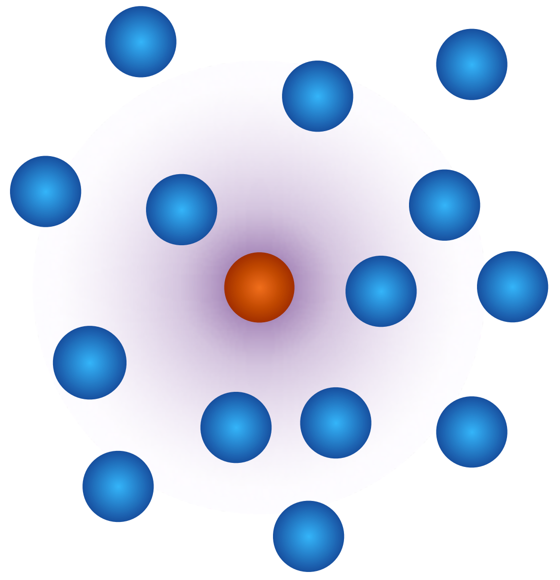


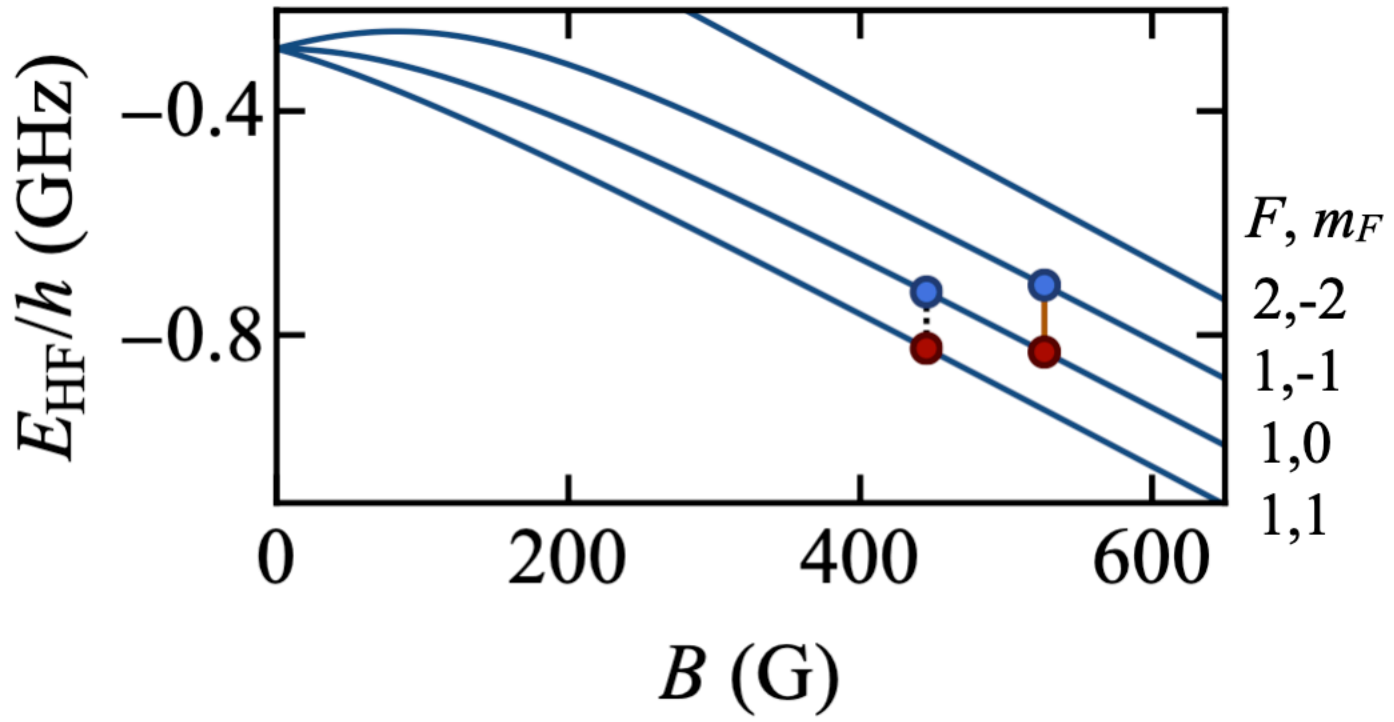


Interstate

$\lvert F,m_F\rangle_1+\lvert F,m_F\rangle_2$	B_{res} (G)	$a_{bg}\Delta$ (a_0 G)	$\mu_1(\mu_B)$	$\mu_2(\mu_B)$
$\lvert 1,1\rangle+\lvert 1,0\rangle$	25.81(6)	-	−0.605	−0.155
$\lvert 1,1\rangle+\lvert 1,0\rangle$	39.81(6)	-	−0.651	−0.235
$\lvert 1,1\rangle+\lvert 1,0\rangle$	445.42(3)	1110(40)	−0.967	−0.939
$\lvert 1,1\rangle+\lvert 1,-1\rangle$	77.6(4)	-	−0.747	0.034
$\lvert 1,1\rangle+\lvert 1,-1\rangle$	501.6(3)	-	−0.973	−0.948
$\lvert 1,0\rangle+\lvert 1,-1\rangle$	113.76(1)[d]	715(7)[d]	−0.569	−0.215
$\lvert 1,0\rangle+\lvert 1,-1\rangle$	526.16(3)	970(50)	−0.956	−0.953

d) Tanzi *et al.*, PRA **98**, 062712 (2018) - used for previous ^{39}K polarons

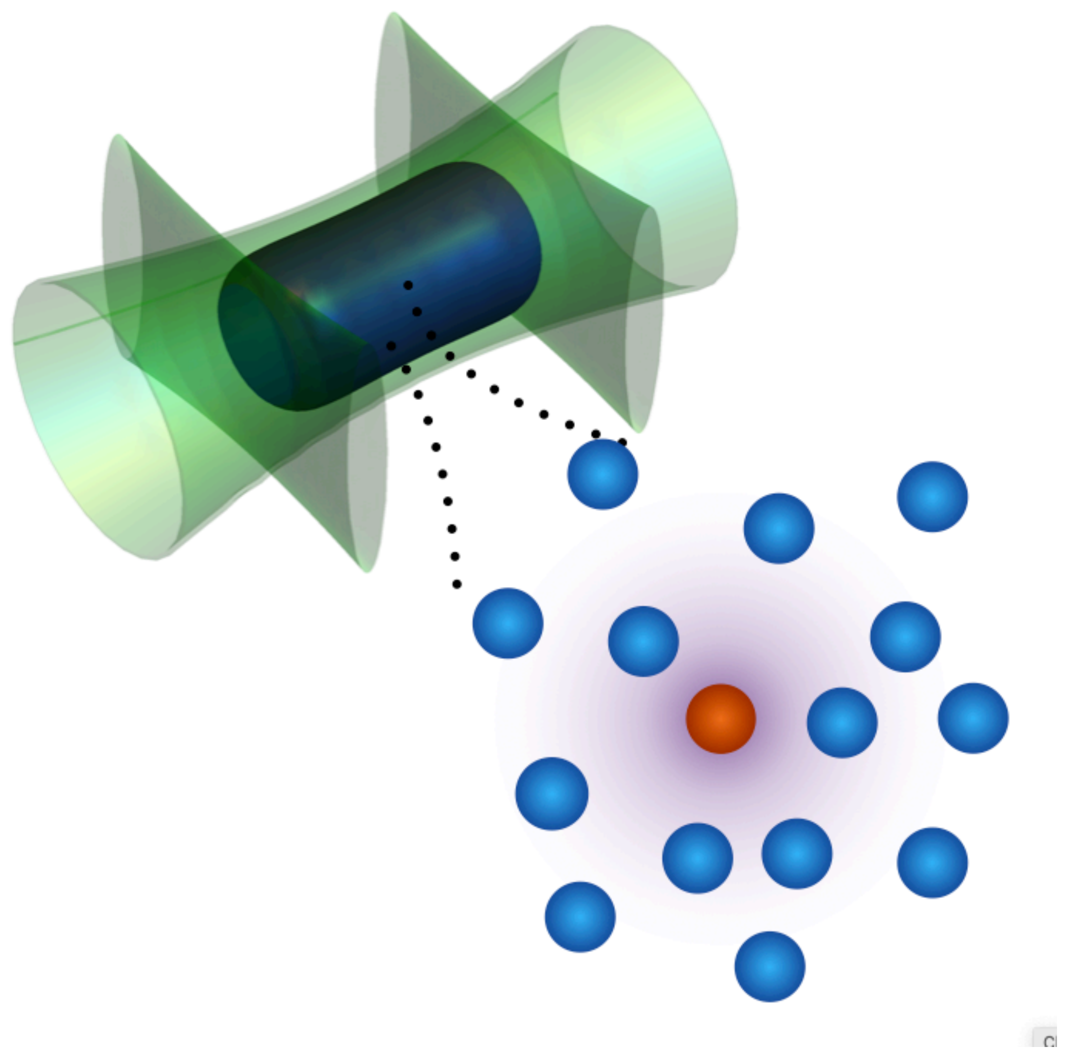




homogeneous Bose mixtures?

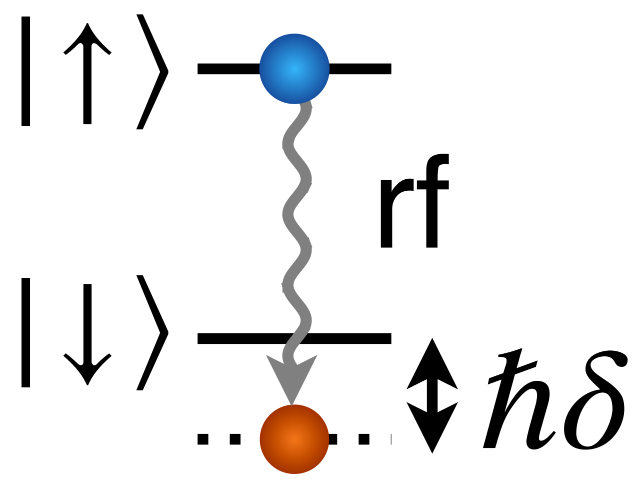
445.42(3)G	526.16(3)G
$a_B \approx 50a_0$ $a_I \approx -65a_0$	$a_B \approx 18a_0$ $a_I \approx -64a_0$
moments differ by 3%	moments differ by 0.3%

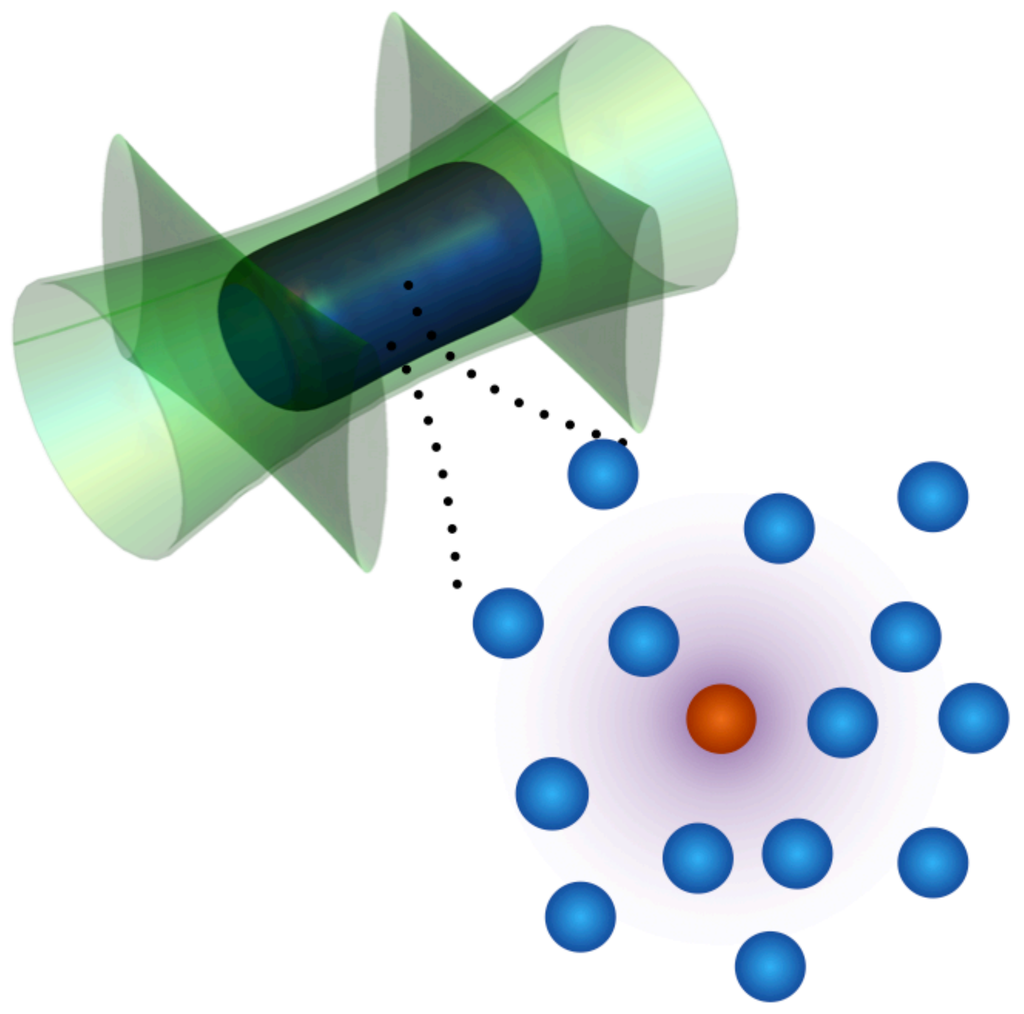
Experimental probes



Experimental probes

Injection (indirect) spectroscopy





Hu *et al.*, PRL **117**, 055301 (2016)
Jørgensen *et al.*, PRL **117**, 055302 (2016)

weak, long pulses:
access to spectral function $A(\omega)$

measure fractional atom loss $\Delta N/N$
following a quench to B_{res} and hold time

$$I(\omega) = \frac{t_{\mathrm{rf}}}{2\pi} \int_{-\infty}^{\infty} A(\omega') \, \mathrm{sinc}\left[\frac{(\omega-\omega')\, t_{\mathrm{rf}}}{2}\right]^2 \mathrm{d}\omega'$$

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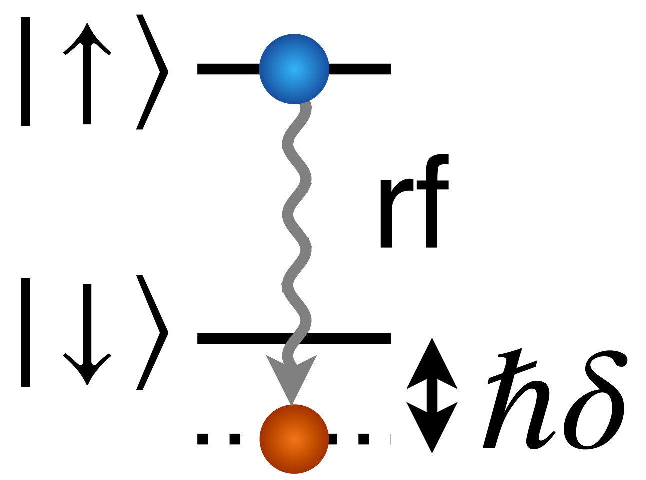

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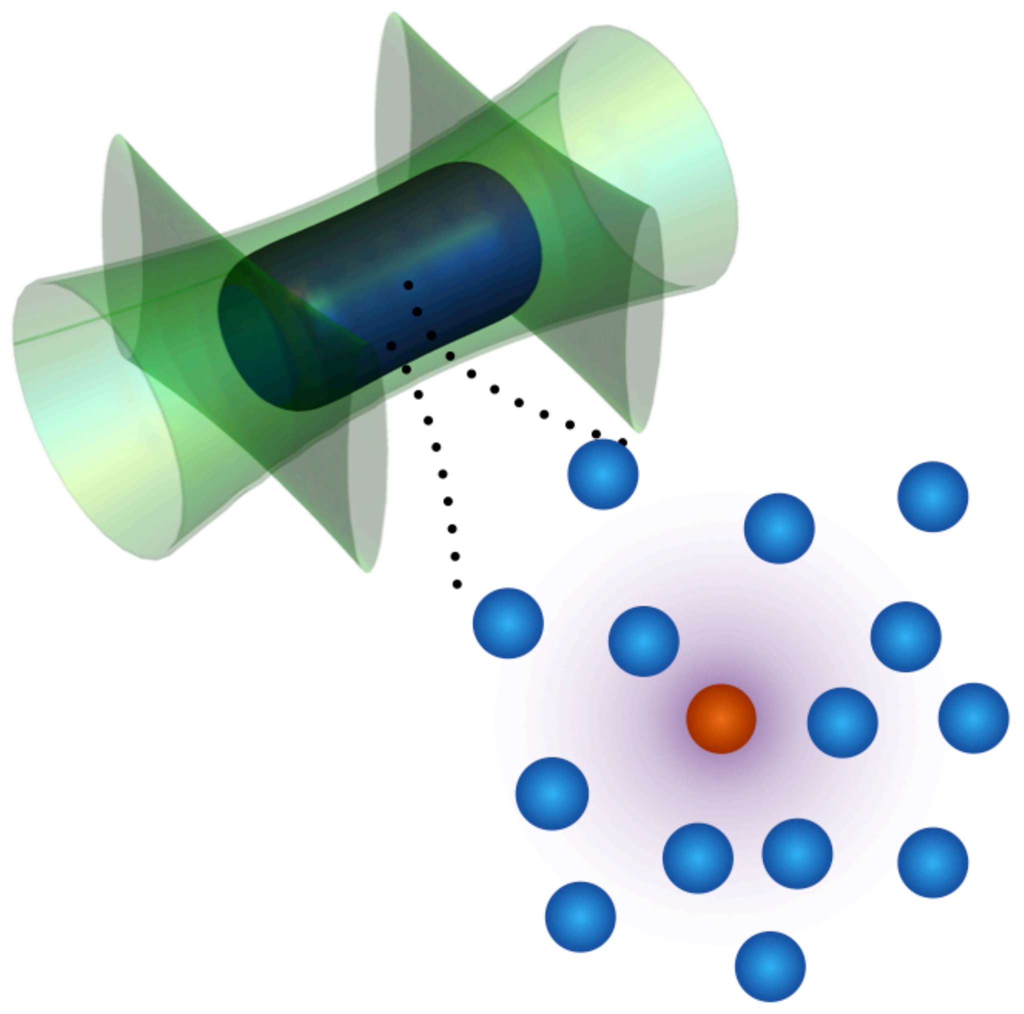
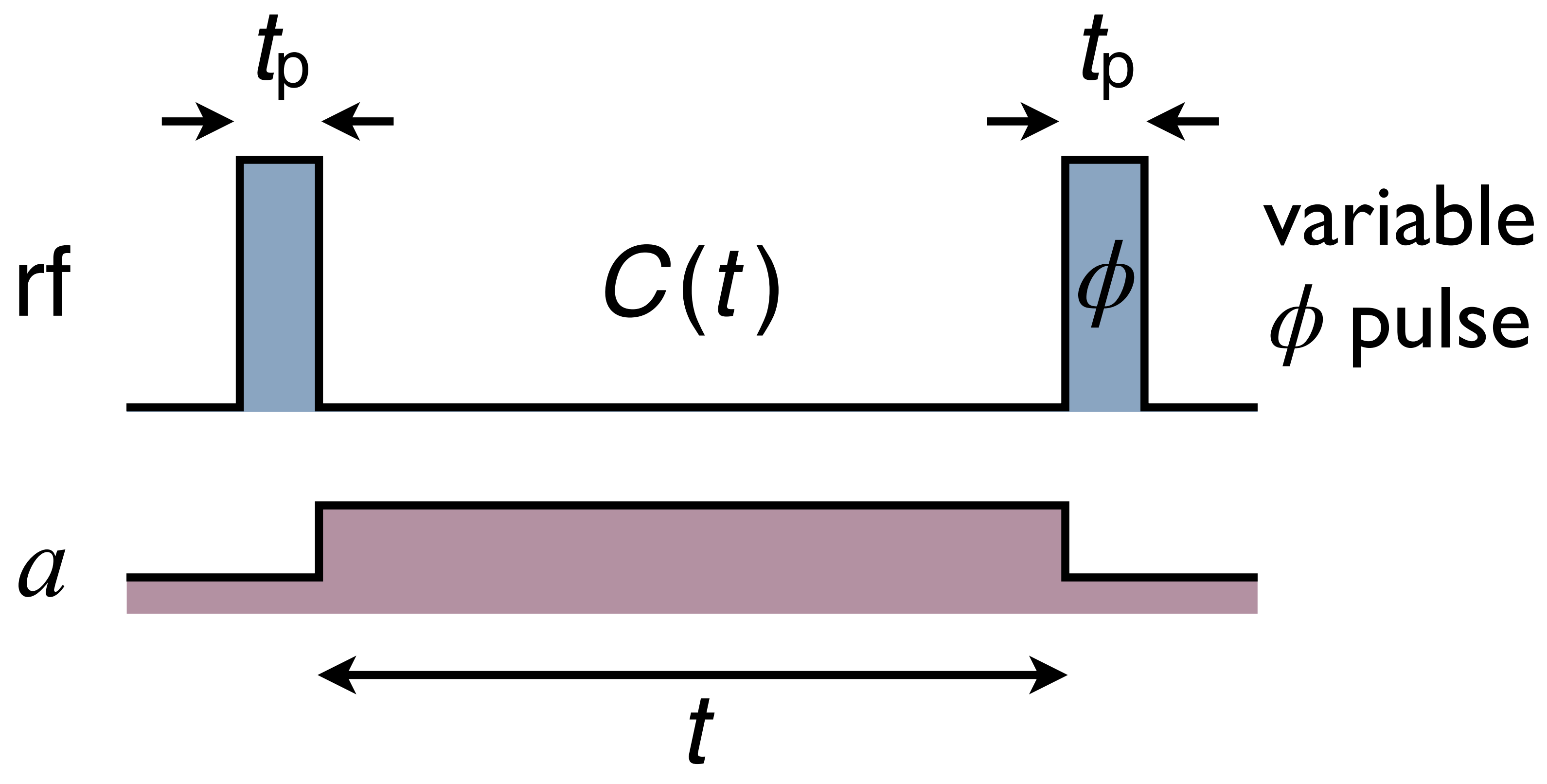


Ramsey-type many-body interferometry



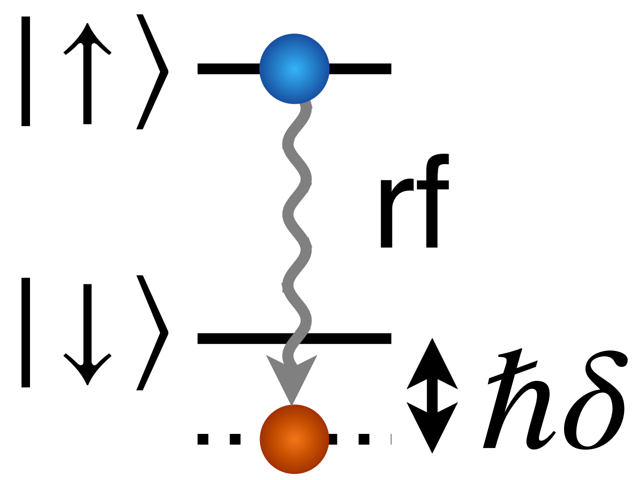
following Cetina et al. Science **354**, 96 (2016)
see also Skou et al. Nat. Phys. **17**, 731 (2021)

probes coherence $C(t) = \langle \psi(t) | \psi(0) \rangle$

$$A(\omega) = \frac{1}{\pi}\,\mathrm{Re}\left[\int_0^{\infty} C(t)\,e^{-i\omega t}\,\mathrm{d}t\right]$$

Experimental probes

Injection (indirect) spectroscopy

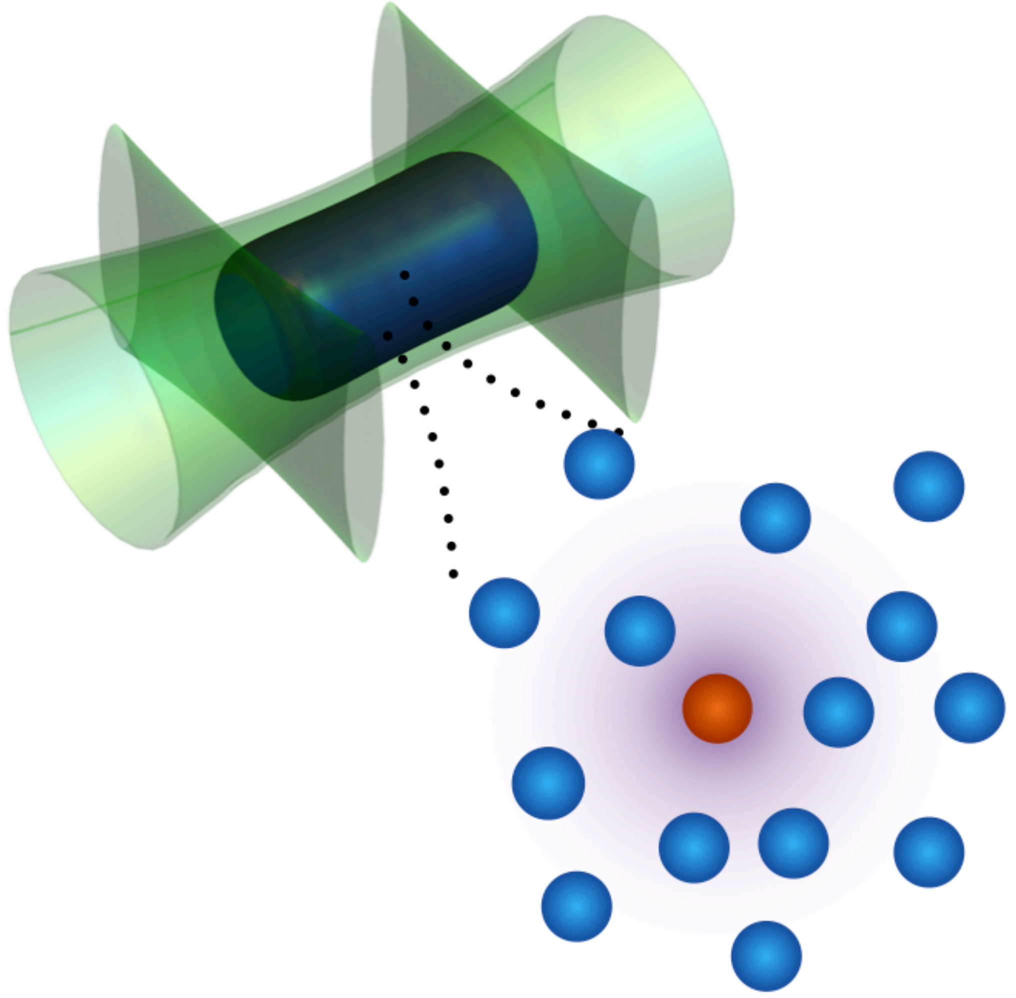


Hu *et al.*, PRL **117**, 055301 (2016)
Jørgensen *et al.*, PRL **117**, 055302 (2016)

weak, long pulses:
access to spectral function $A(\omega)$

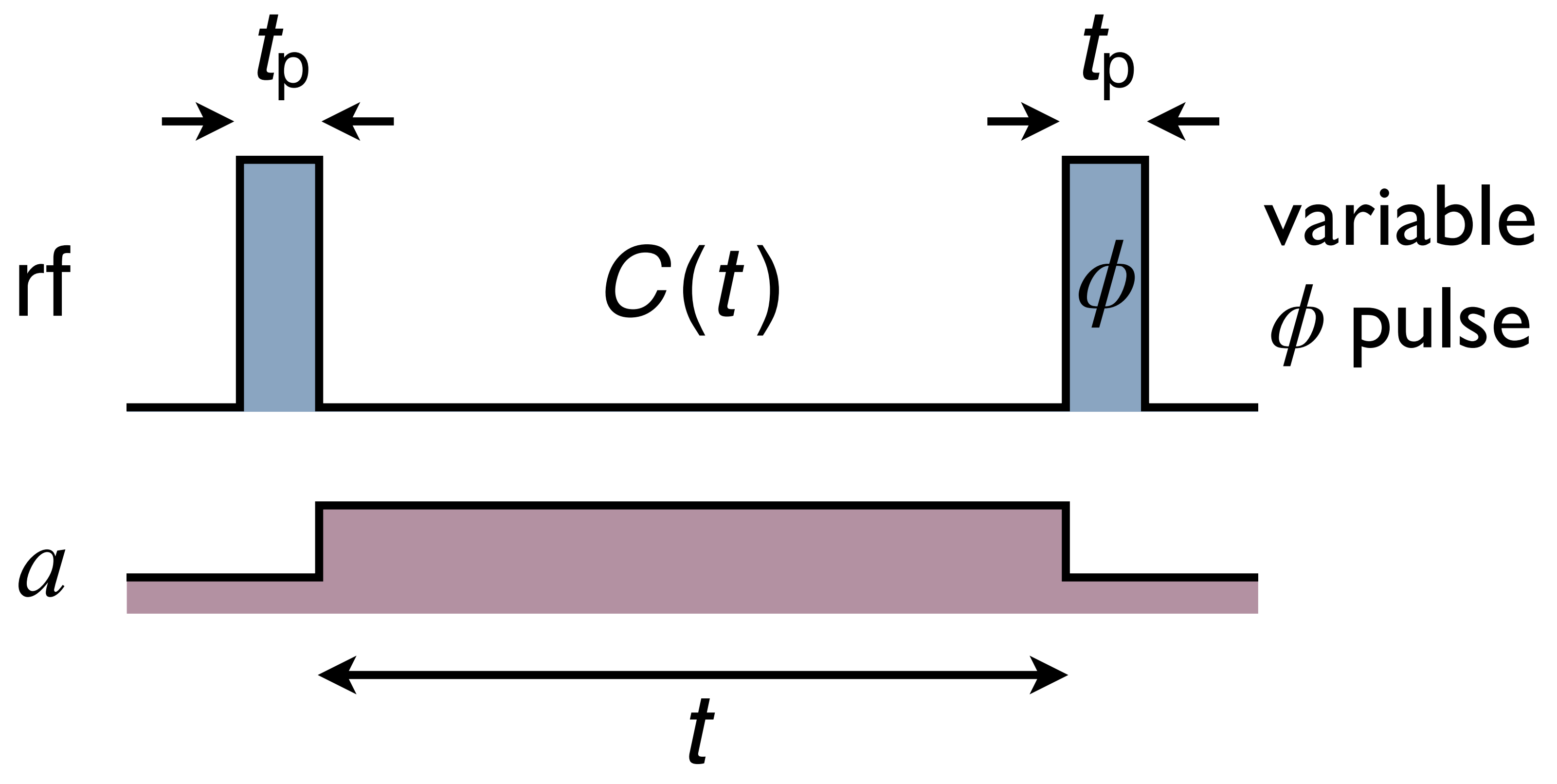
measure fractional atom loss $\Delta N/N$
following a quench to $B_{\rm res}$ and hold time

$$I(\omega) = \frac{t_{\rm rf}}{2\pi}\int_{-\infty}^{\infty} A(\omega')\,{\rm sinc}\left[\frac{(\omega-\omega')\,t_{\rm rf}}{2}\right]^2 {\rm d}\omega'$$



response of system following a spin/ interaction quench

Ramsey-type many-body interferometry



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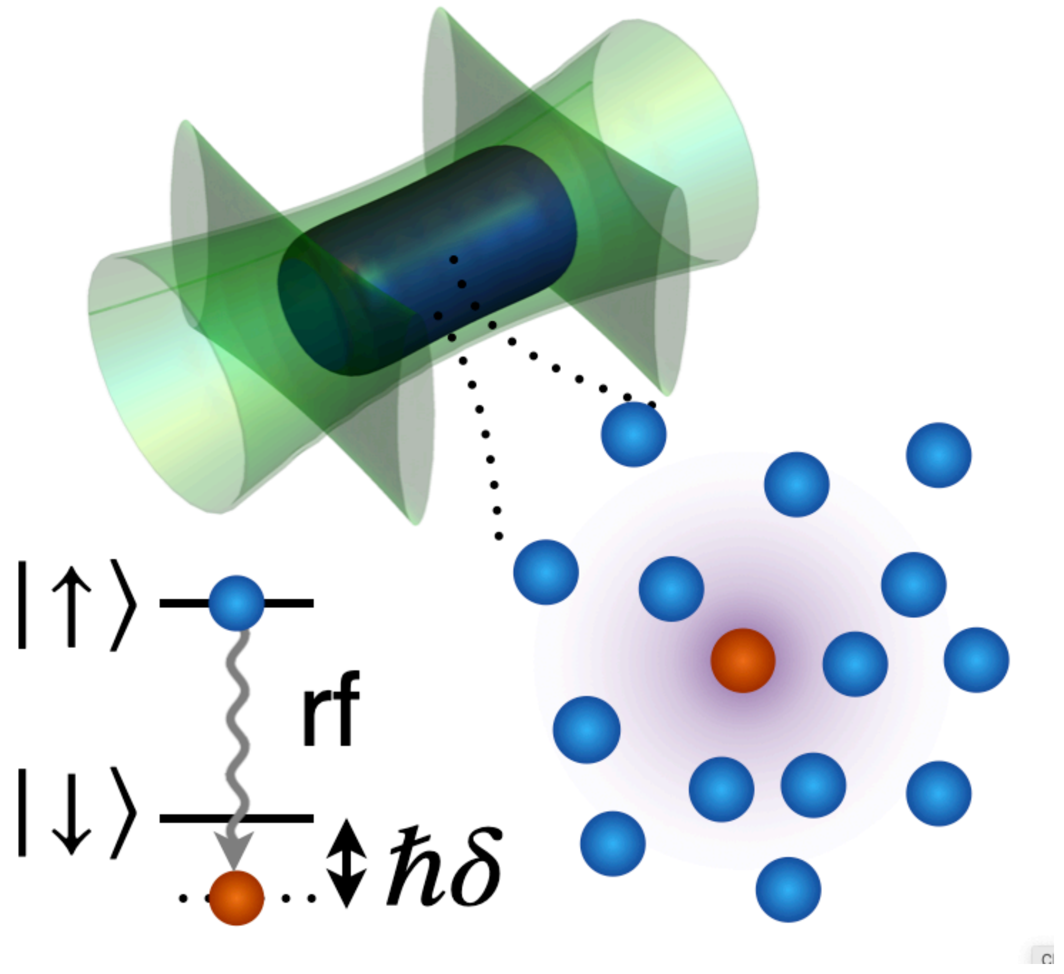
methods to access equilibrium properties:
ejection spectroscopy, effective mass,…

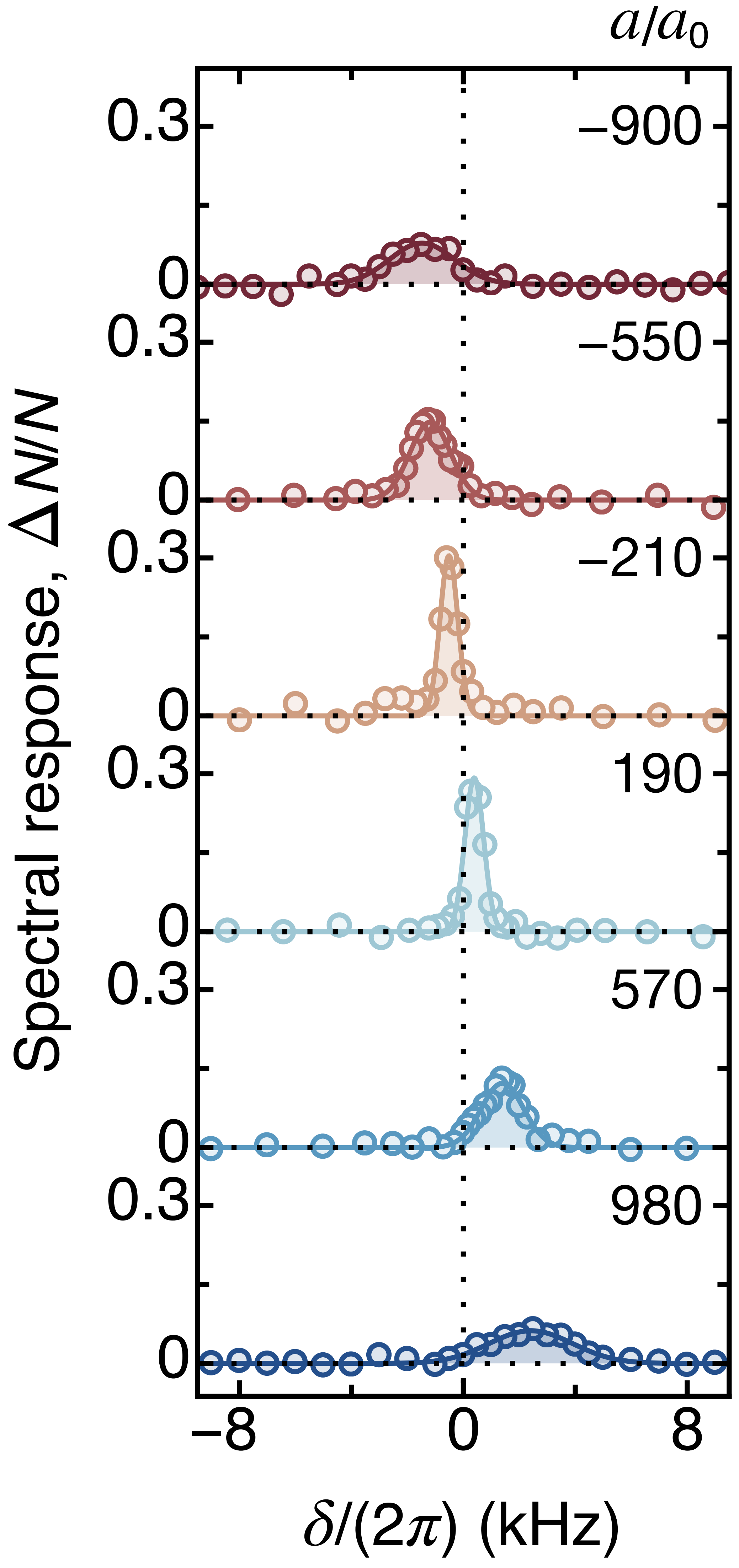
Weakly interacting regime



$|\uparrow\rangle = |1,\text{-}1\rangle,\ |\downarrow\rangle = |1,0\rangle$

$B_{\text{res}} = 526.2\,\text{G}$

narrow!
little technical broadening
(1600 μs pulse,
$< 10\,\%$ transfer)

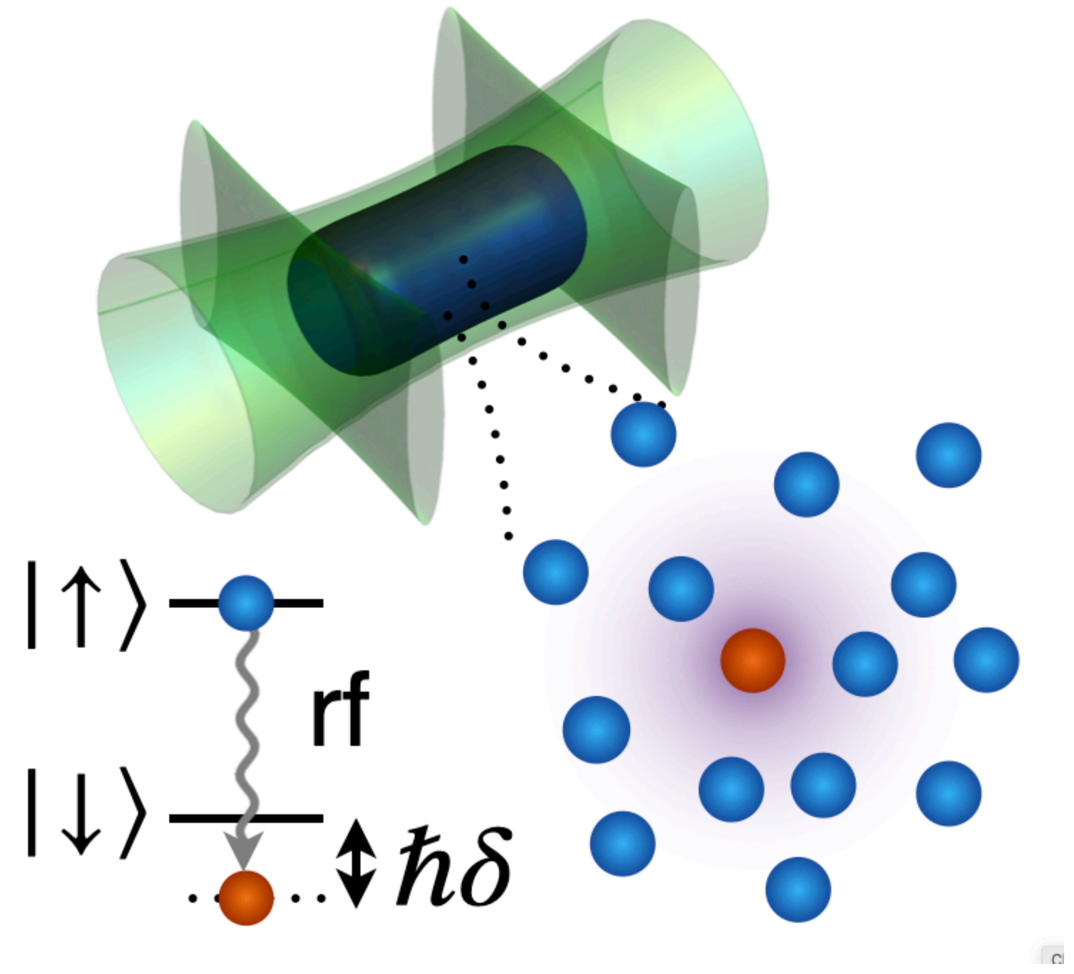


in the weakly interacting limit:

$$E_{\text{p}} = 4\pi\hbar^2 an/m = gn$$

J. Etrych *et al.*, arXiv:2402.14816 (2024)

Weakly interacting regime



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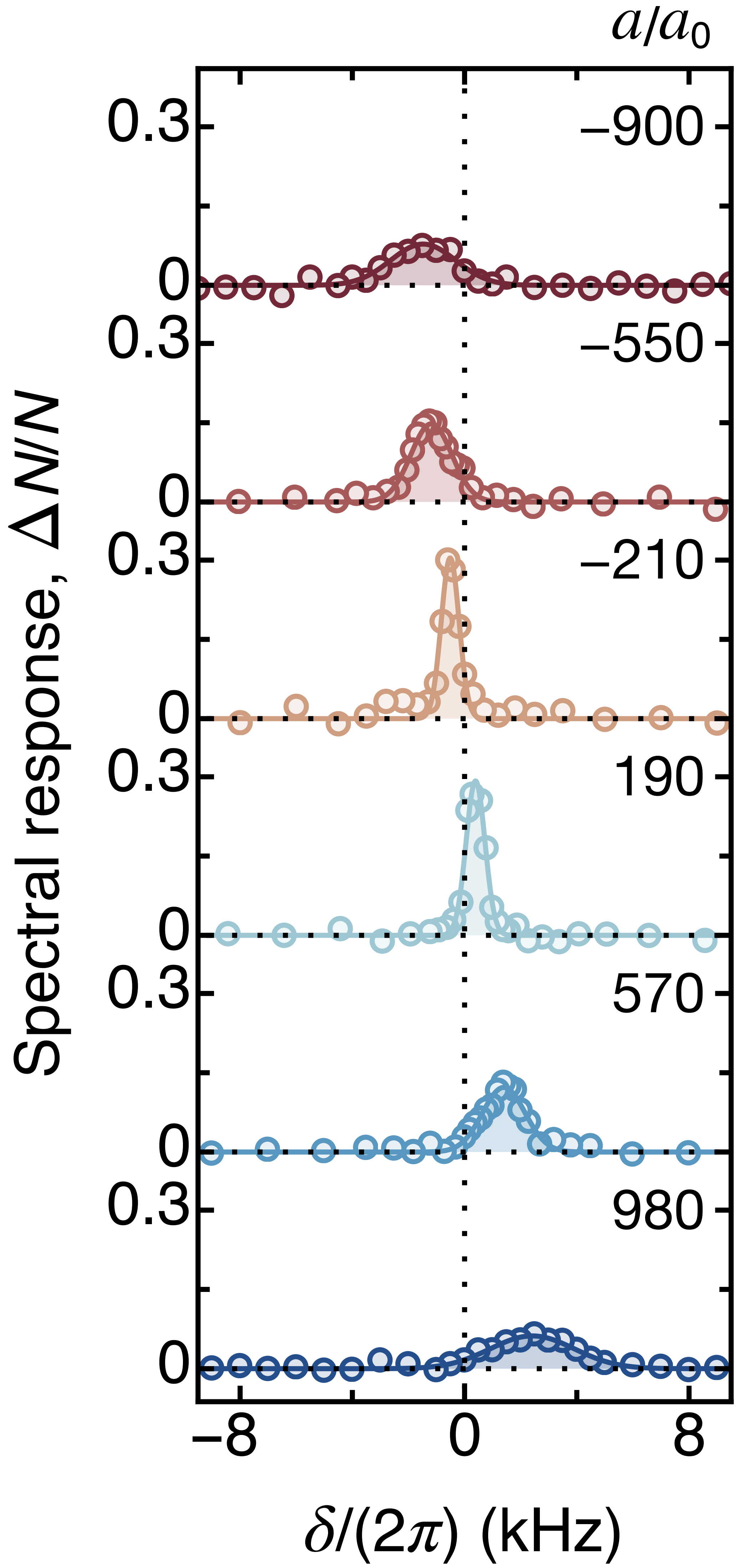

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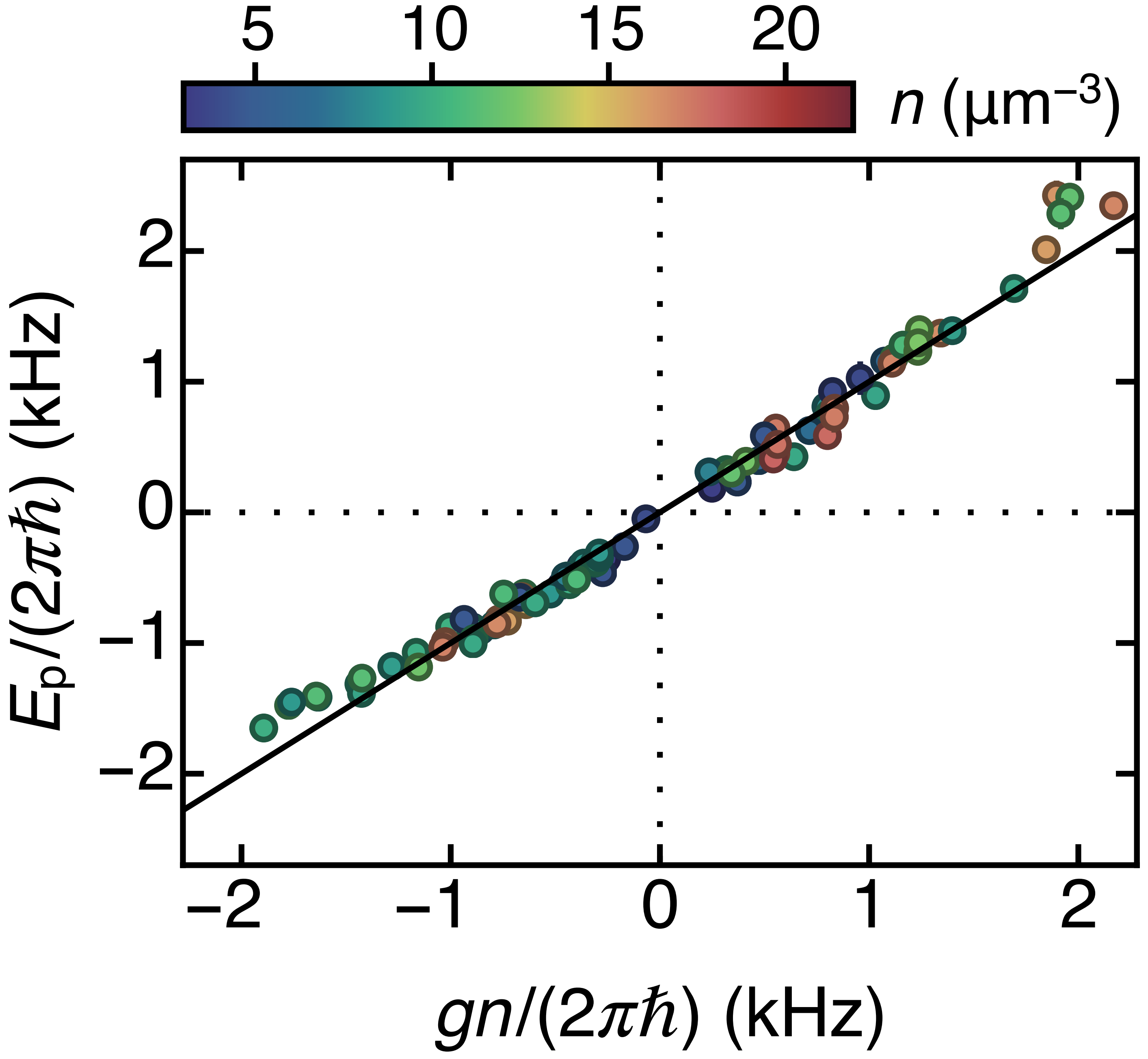
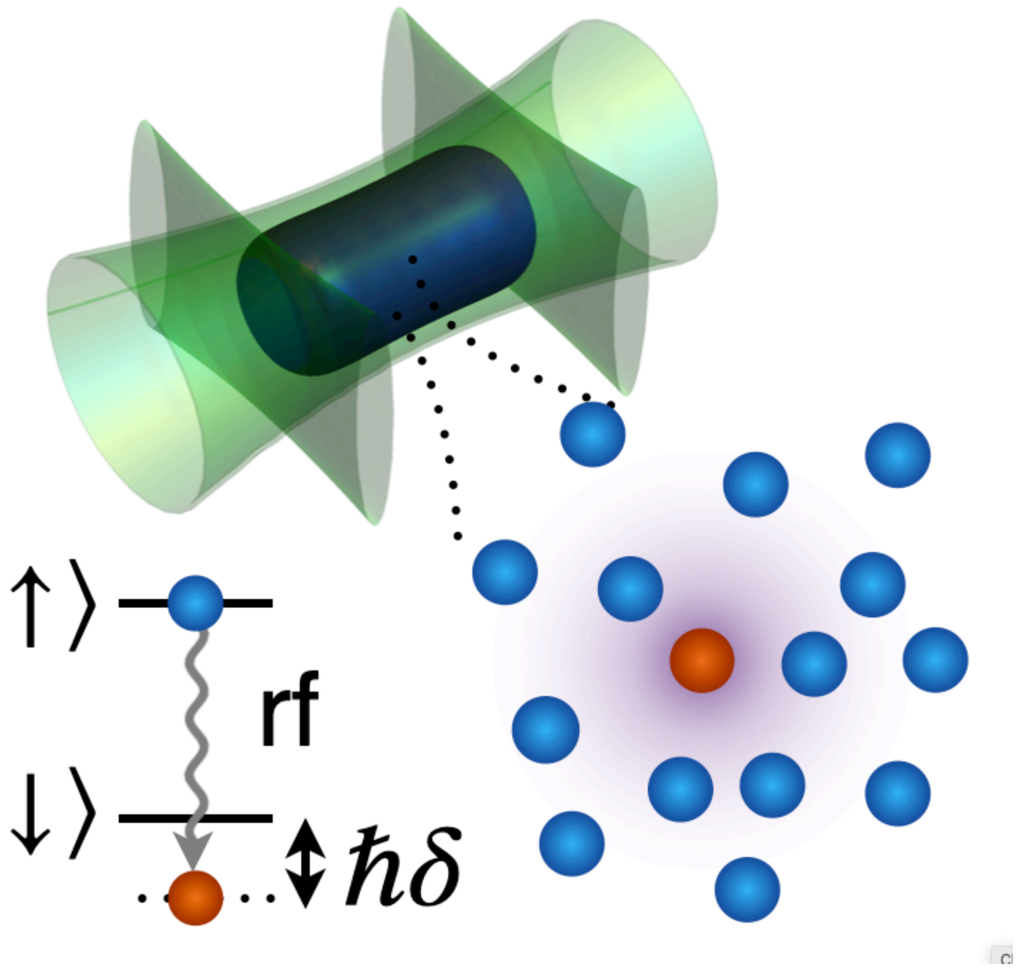
density calibration



Weakly interacting regime



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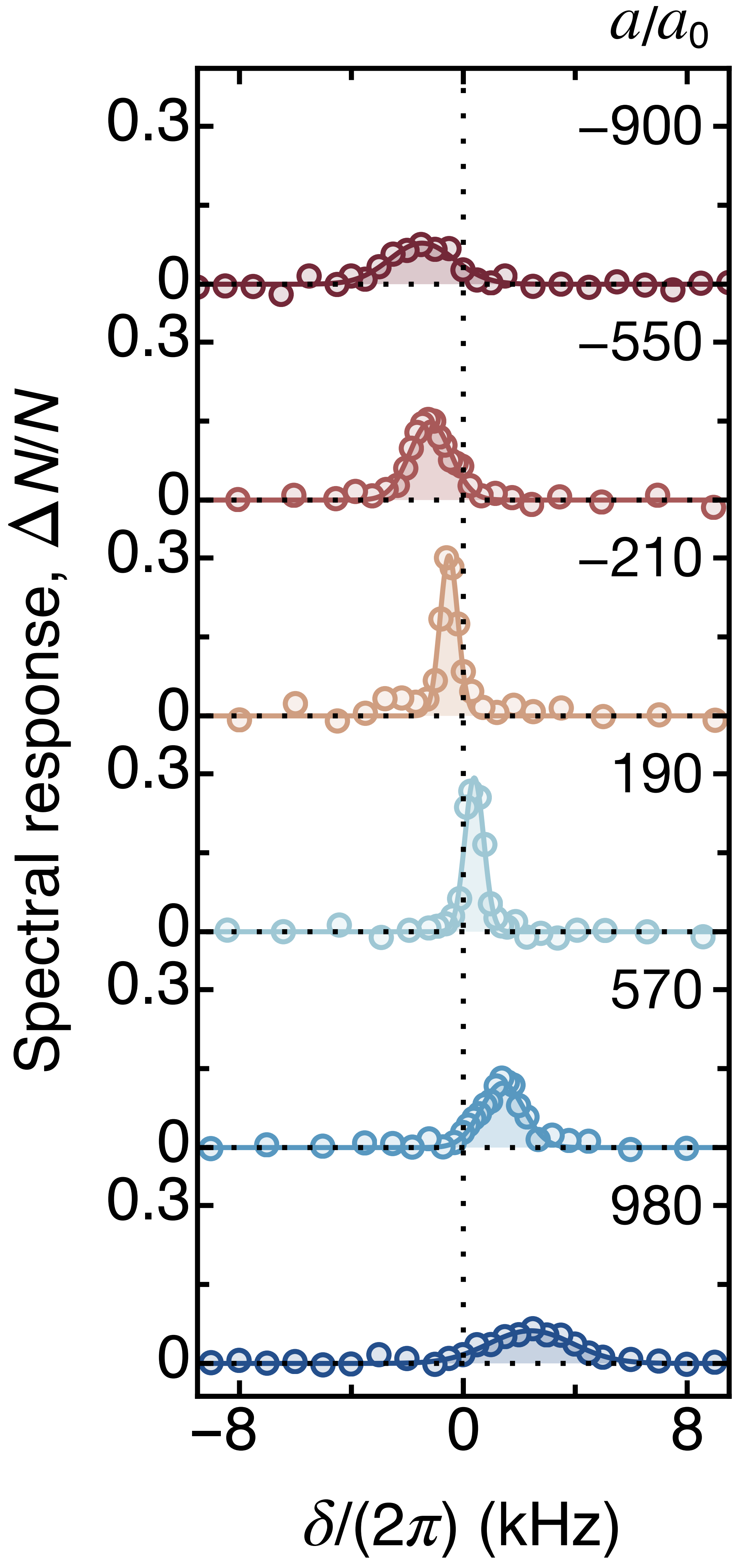
little technical broadening ($1600\ \mu s$ pulse, $< 10\,\%$ transfer)



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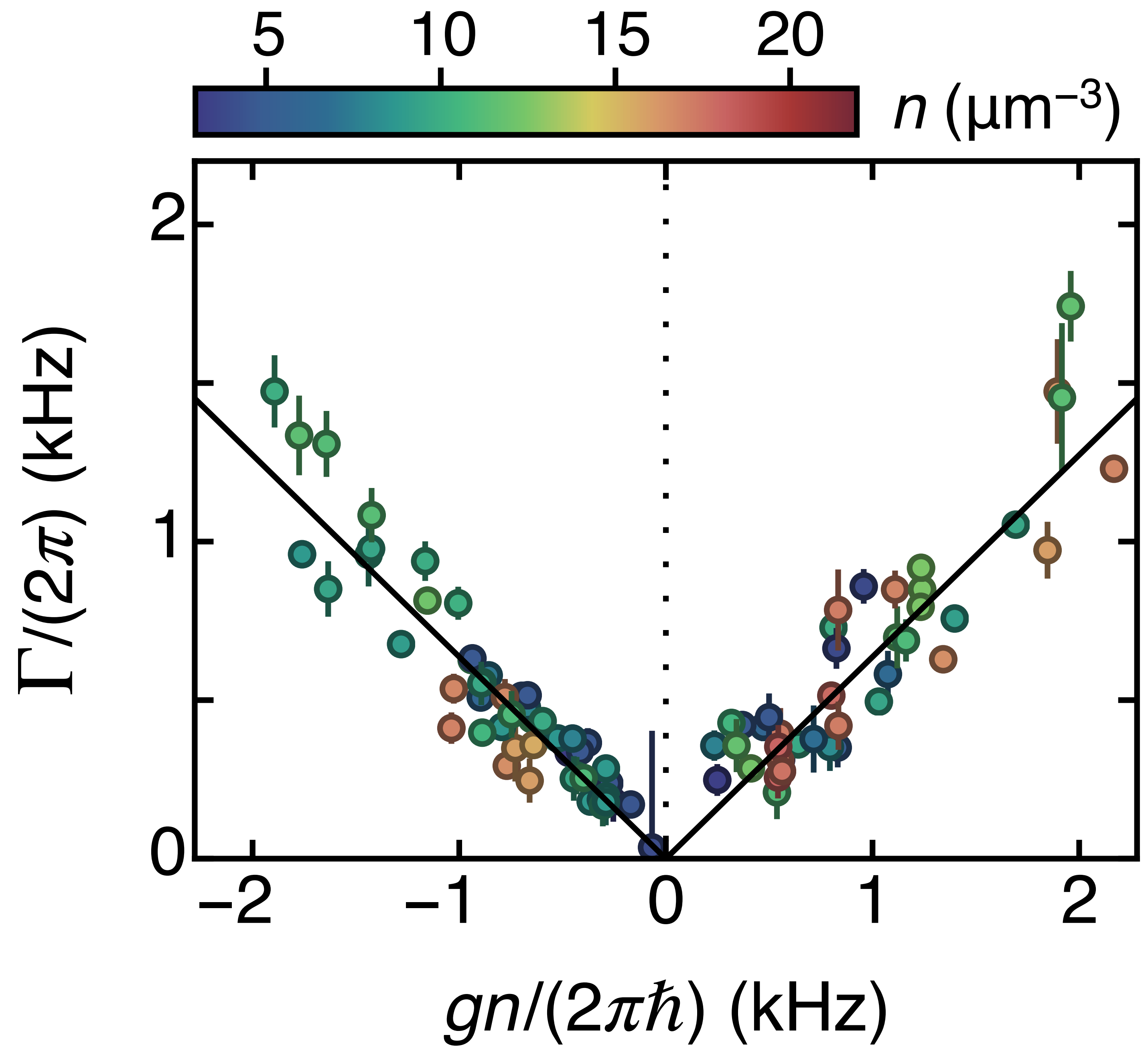
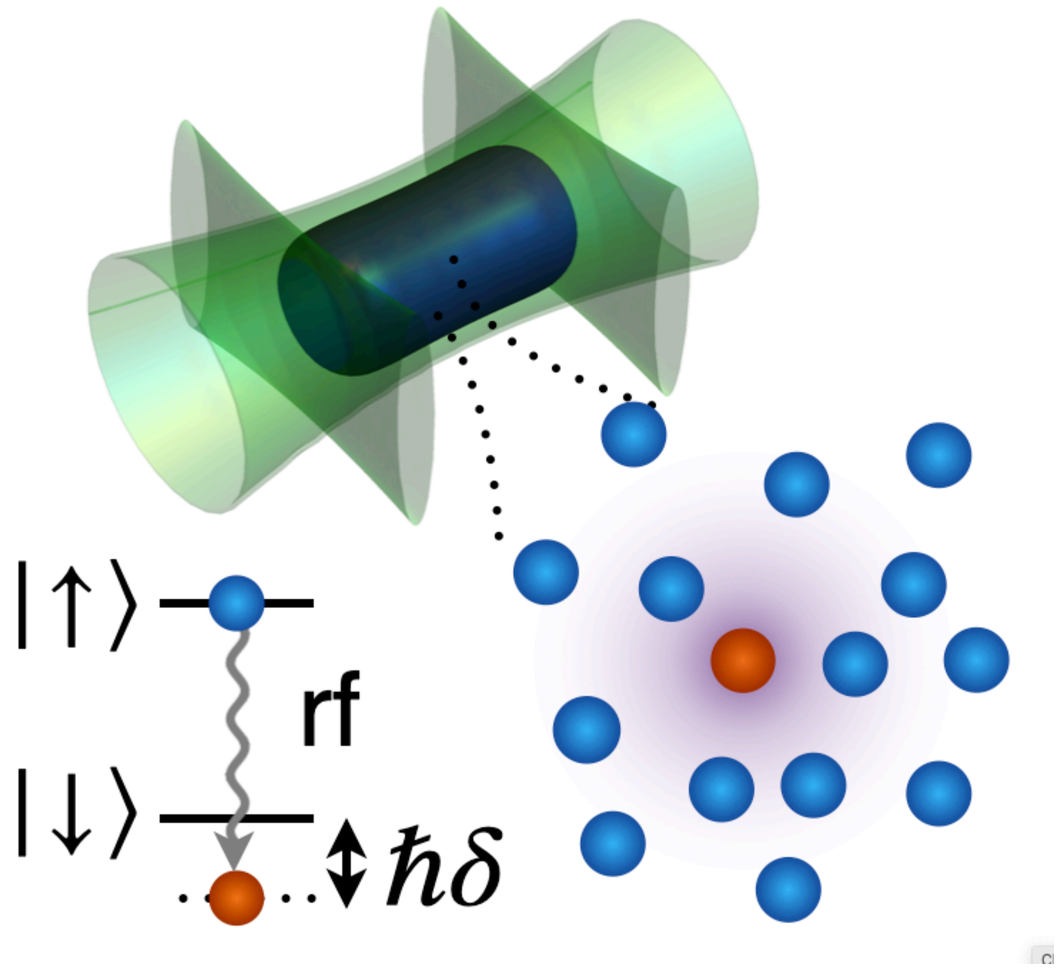
unexpected width



Weakly interacting regime



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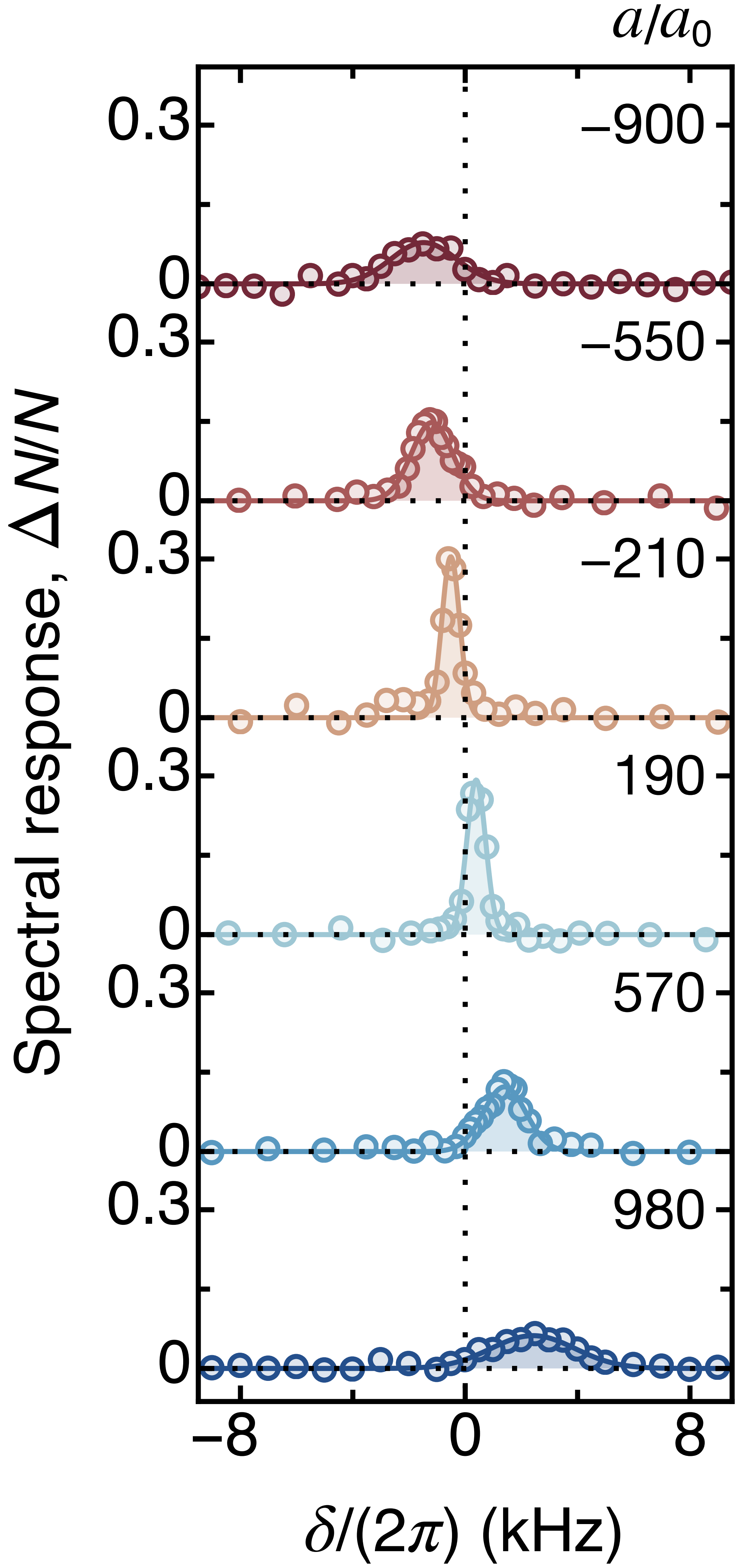


in the weakly interacting limit:

$$E_{\mathrm{p}} = 4\pi\hbar^2 an/m = gn$$

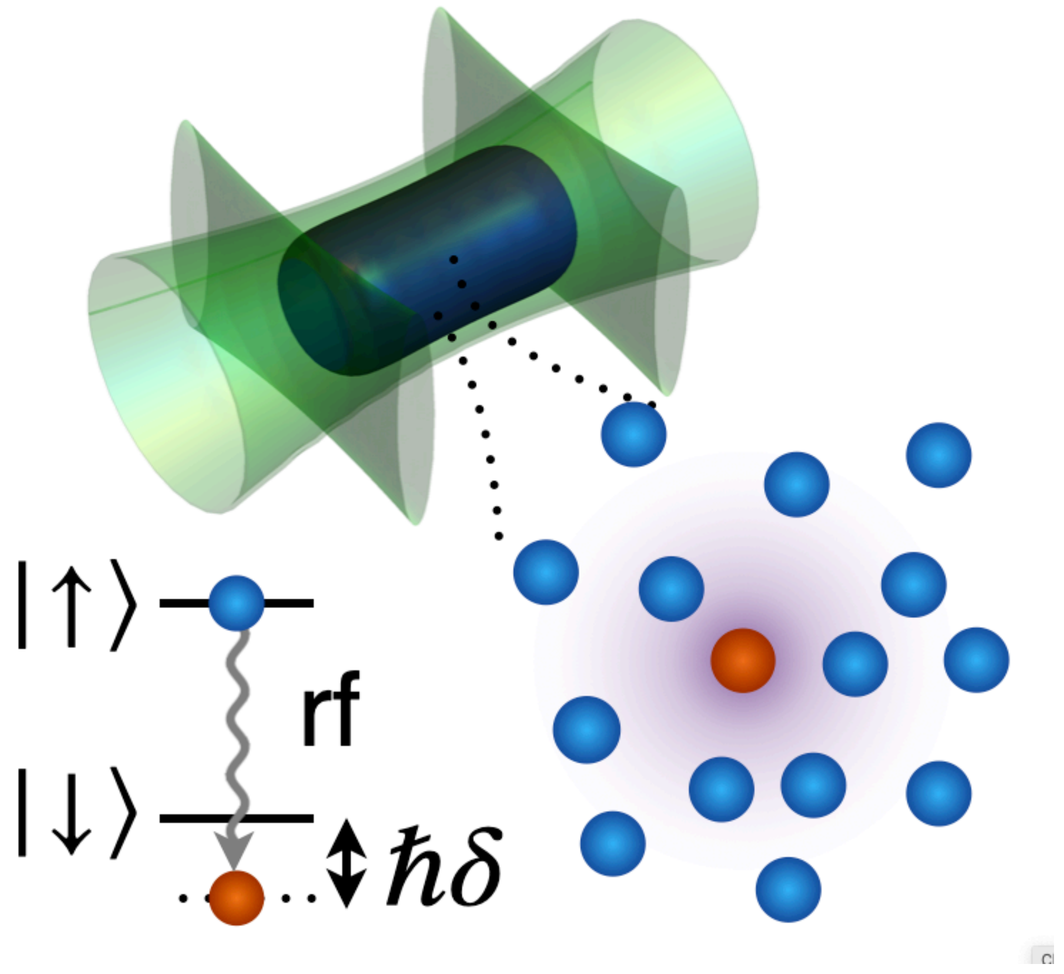
unexpected width

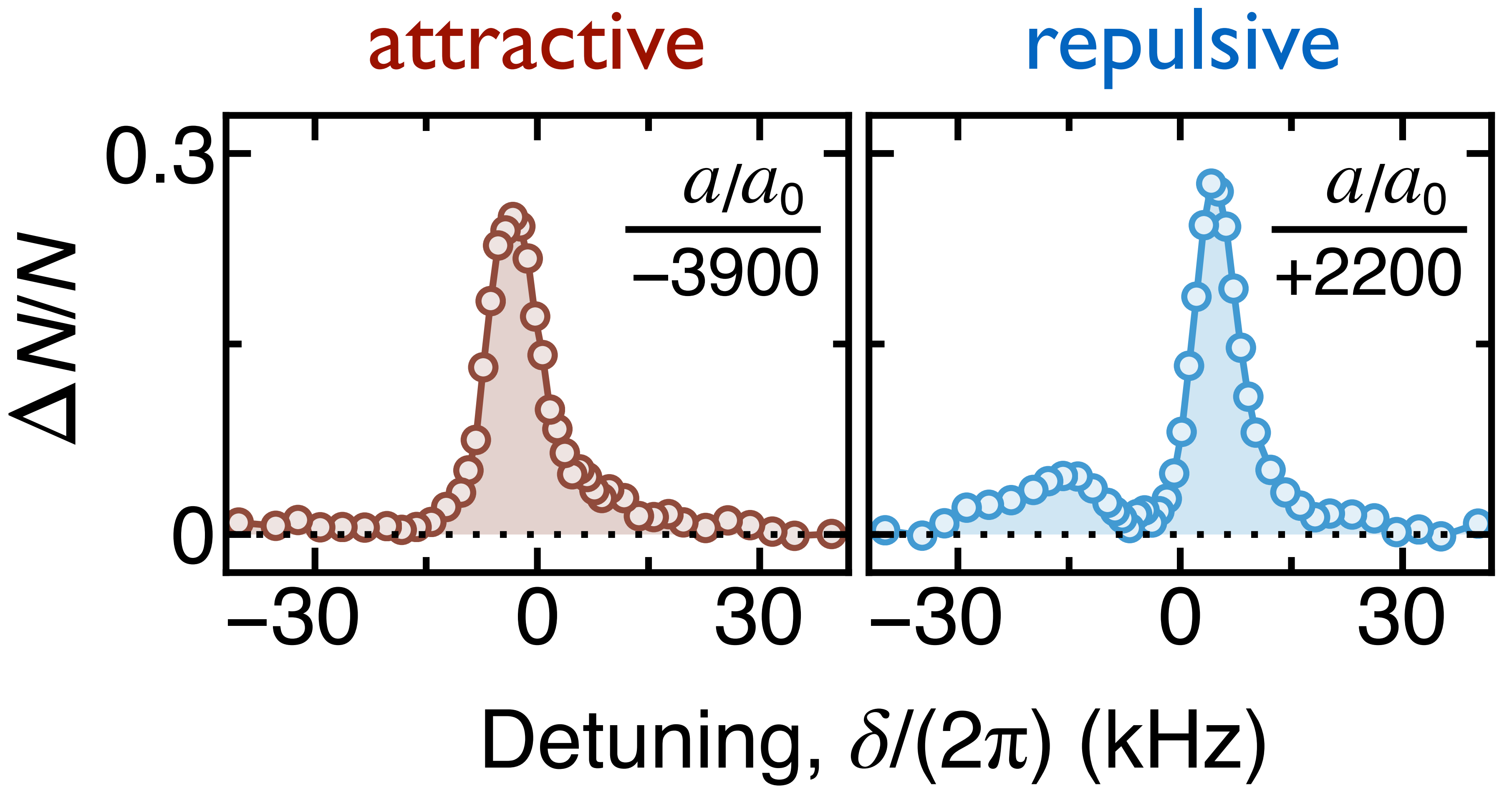
broadening due to dynamics of impurities

$$i\hbar\frac{d\psi}{dt} = -\frac{\hbar^2}{2m}\nabla^2\psi + g_{\mathrm{i}}|\psi|^2\psi + gn_{\mathrm{bath}}(\mathbf{r})\psi$$

dynamical finite-size effect,
quench physics!

Bose polaron injection spectrum





asymmetric bimodal

$|\uparrow\rangle = |1,\text{-}1\rangle,\ |\downarrow\rangle = |1,0\rangle$

$B_{\text{res}} = 526.2\,\text{G}$

fixed $n \approx 12\,\mu\text{m}^{-3}$

$k_n = (6\pi^2 n)^{1/3} \approx 9\,\mu\text{m}^{-1}$

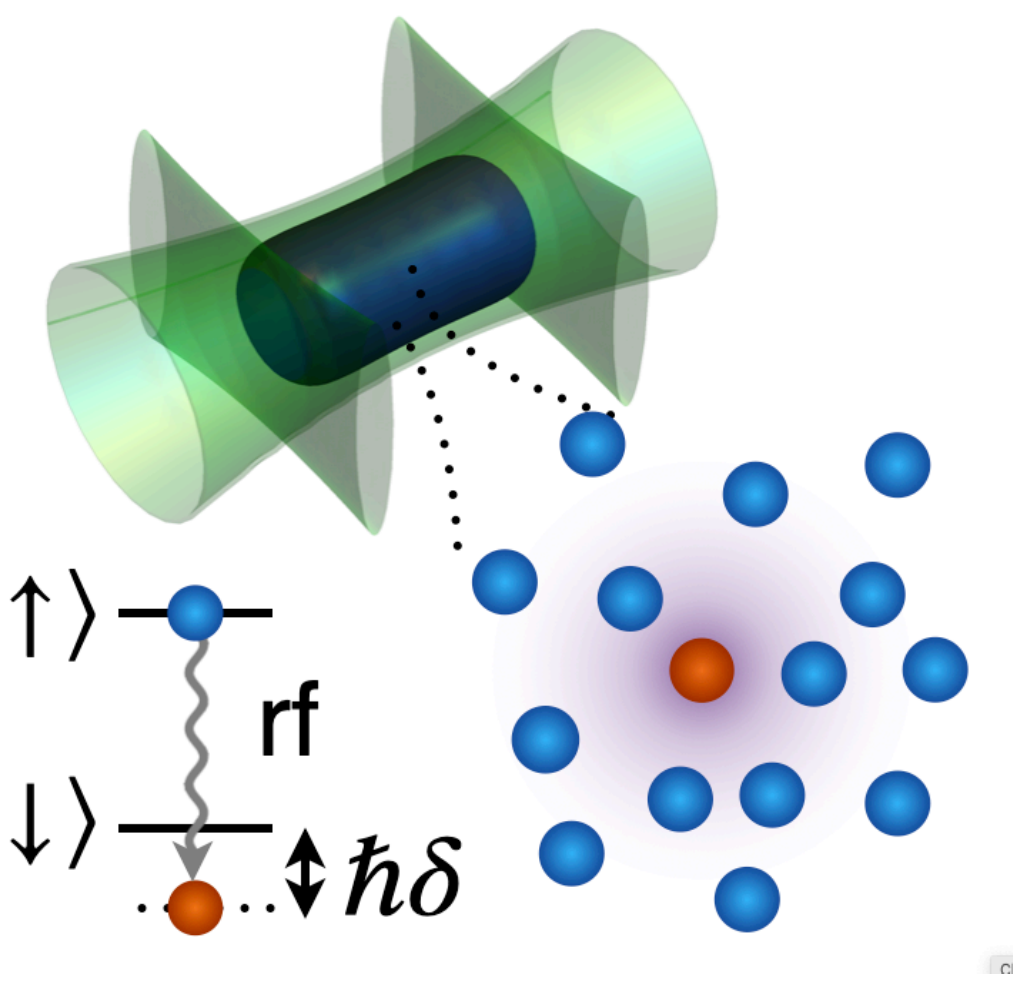
$E_n = \hbar^2 k_n^2/(2m) \approx 10\,\text{kHz}$

$200\,\mu\text{s}$ sq rf pulse

$\Omega/(2\pi) = 0.6\,\text{kHz}$

J. Etrych *et al.*, arXiv:2402.14816 (2024)

Bose polaron injection spectrum



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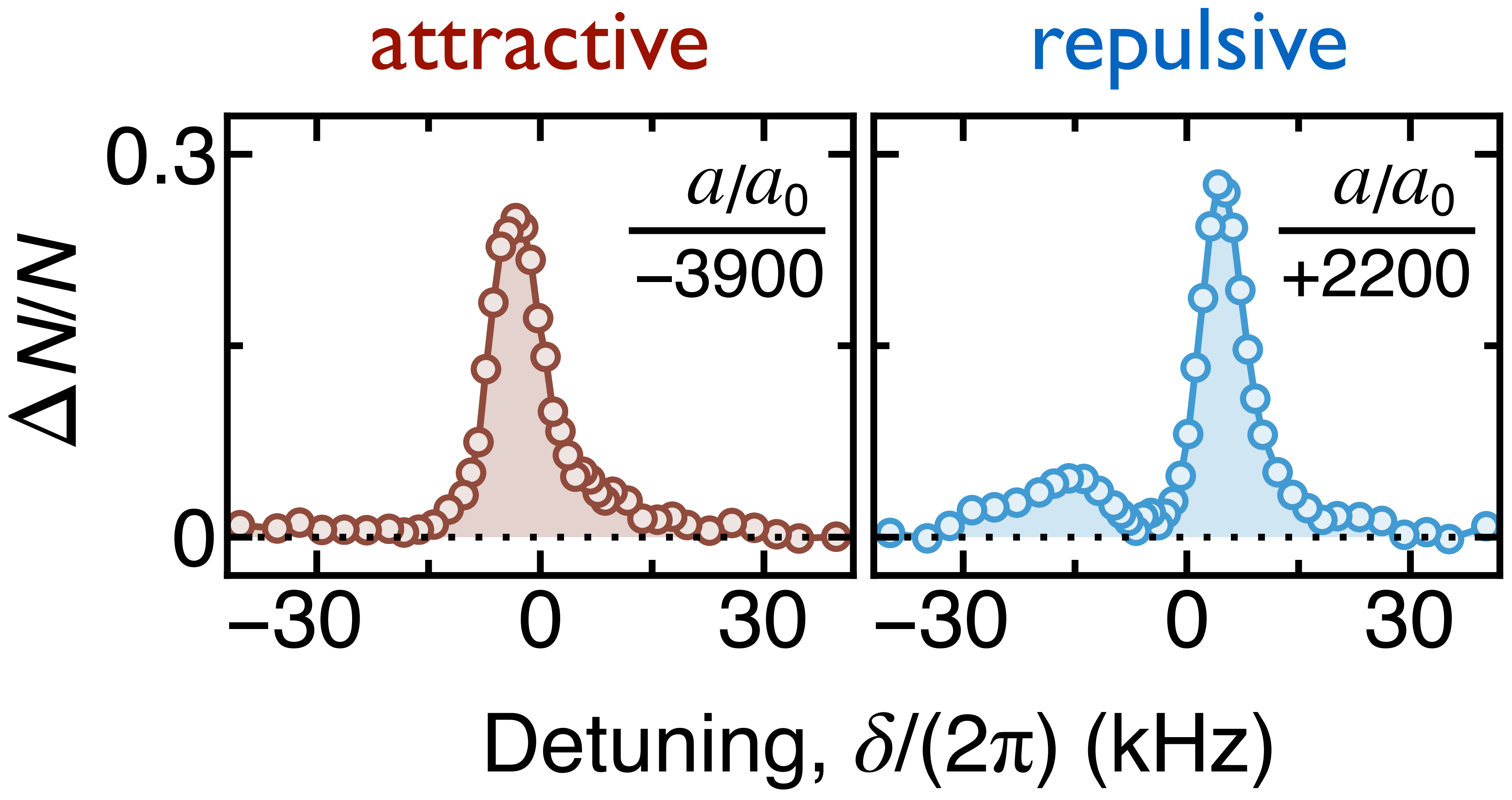
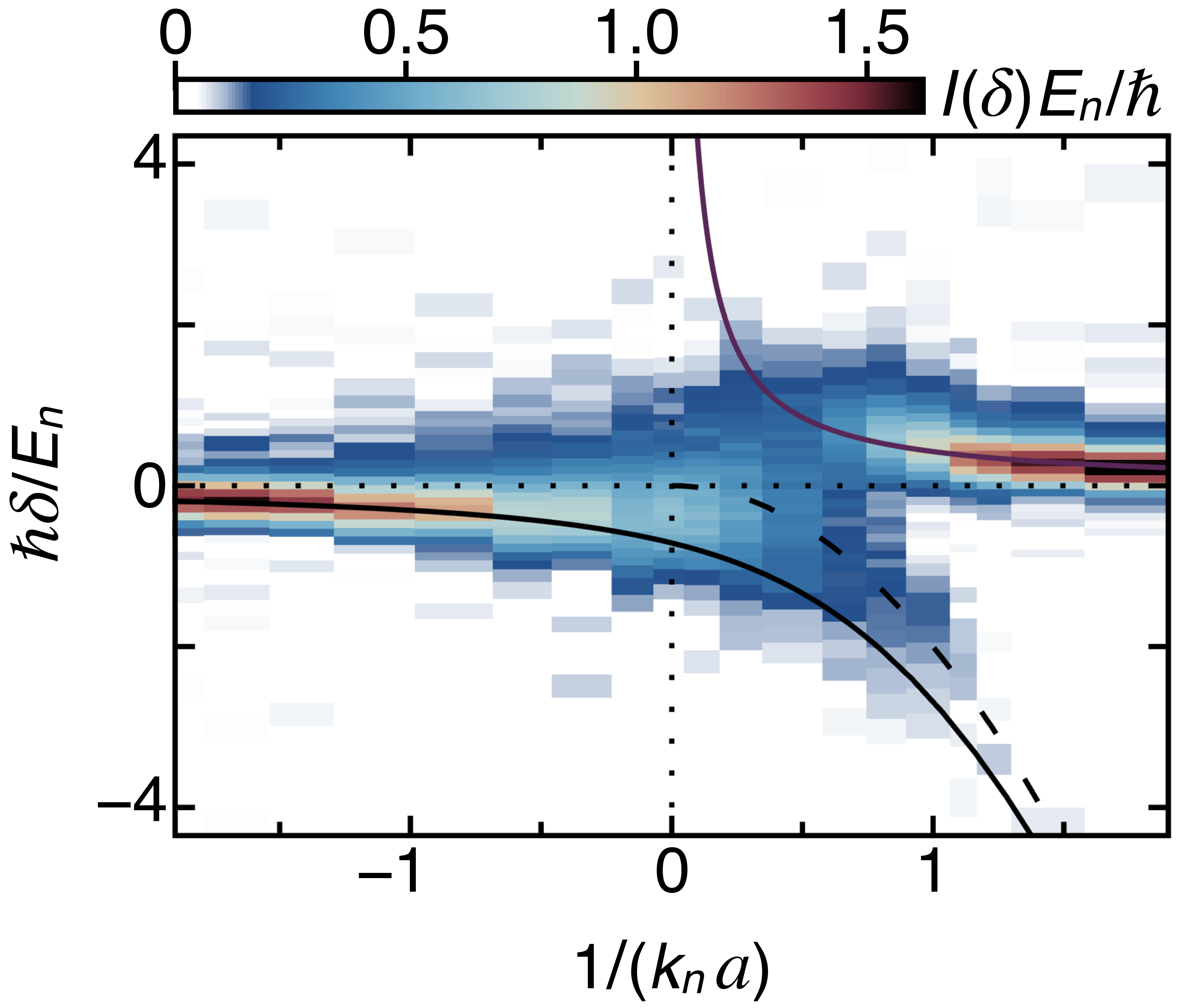
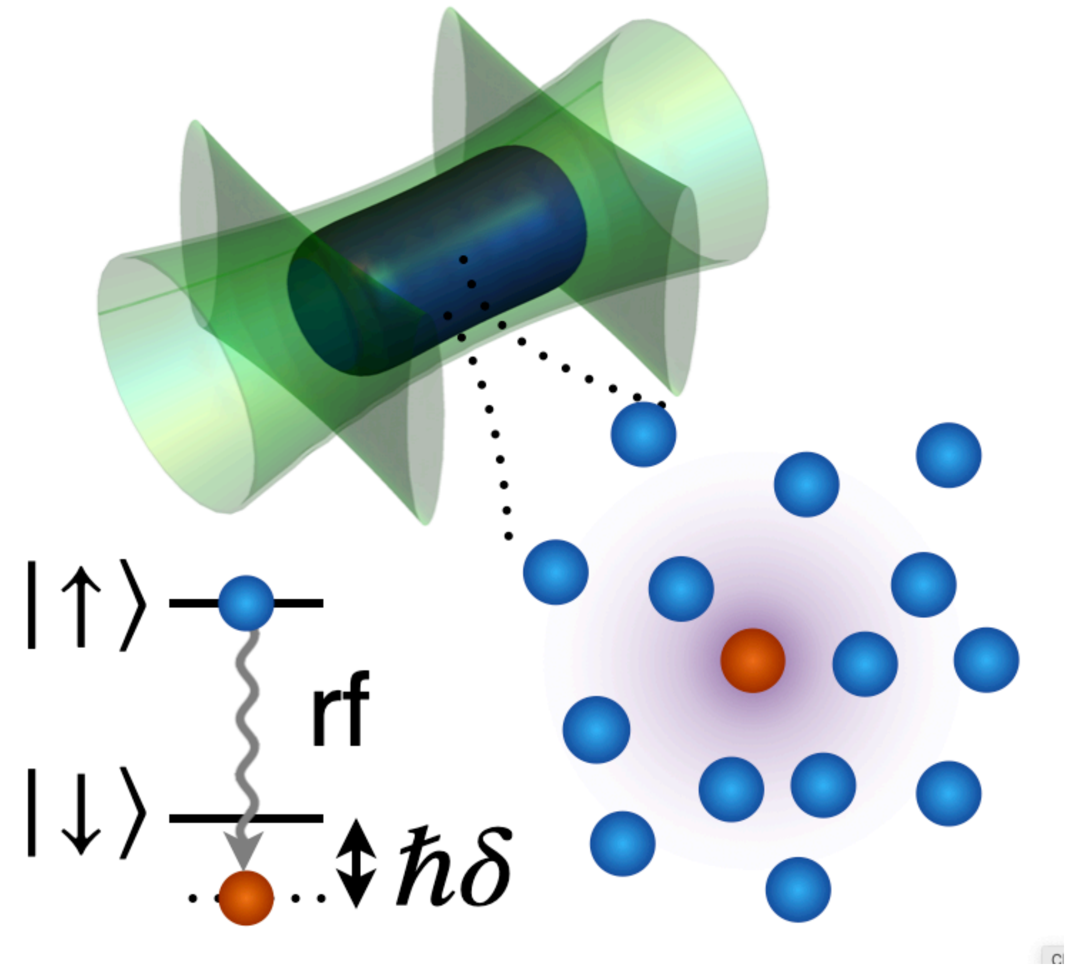




Injection spectrum
$I(\delta) \propto \Delta N/N$

Bose polaron injection spectrum



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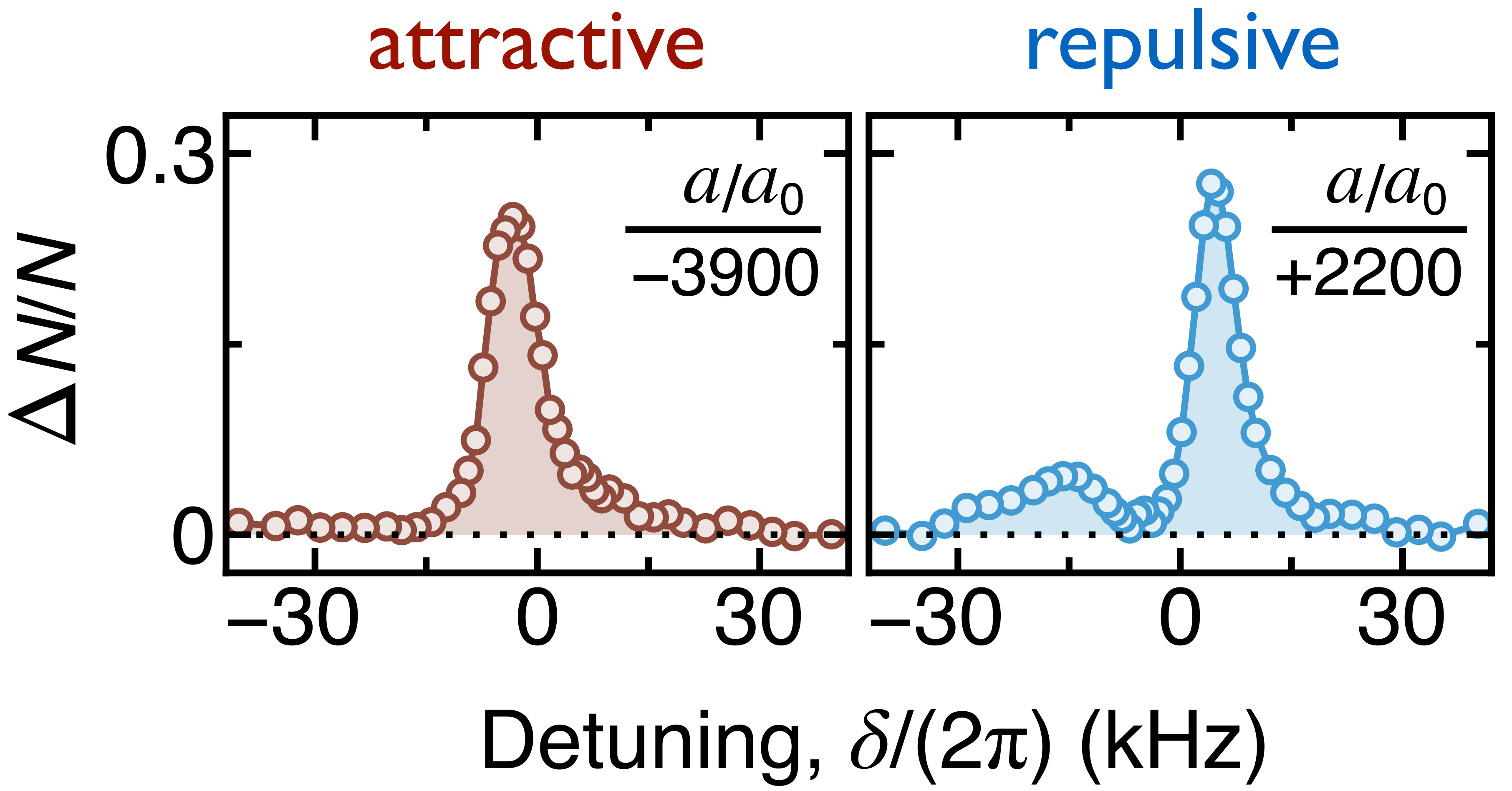
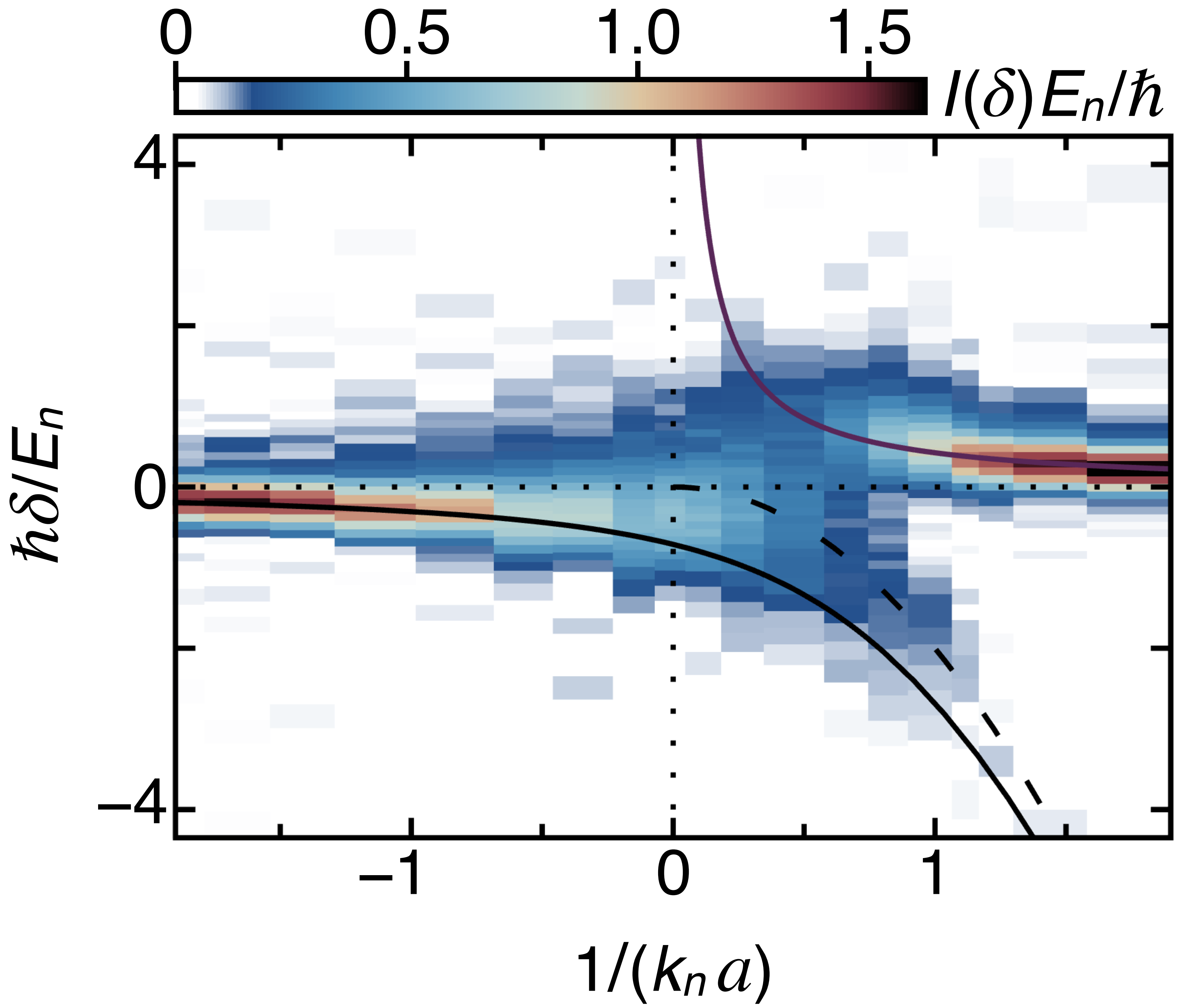




simple theories
(no free parameters!)

- - - Feshbach dimer

mean-field

single-phonon ansatz/
T-matrix

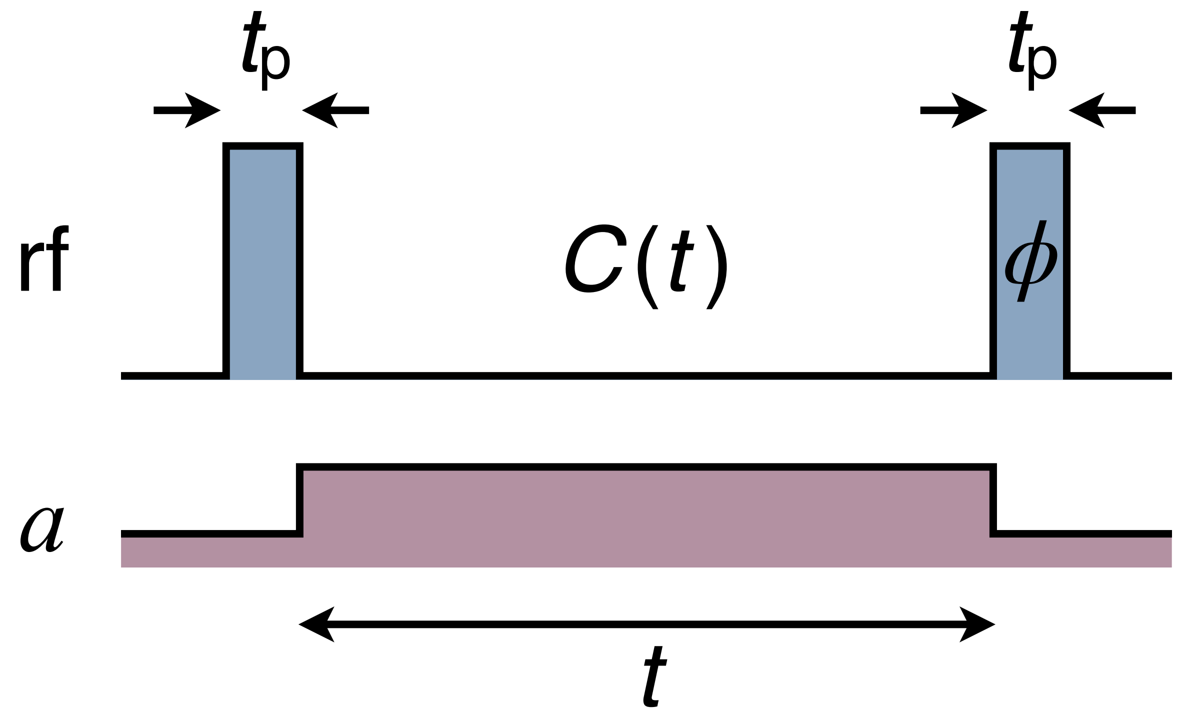
Rath *et al.*, PRA **88**, 053632 (2013)

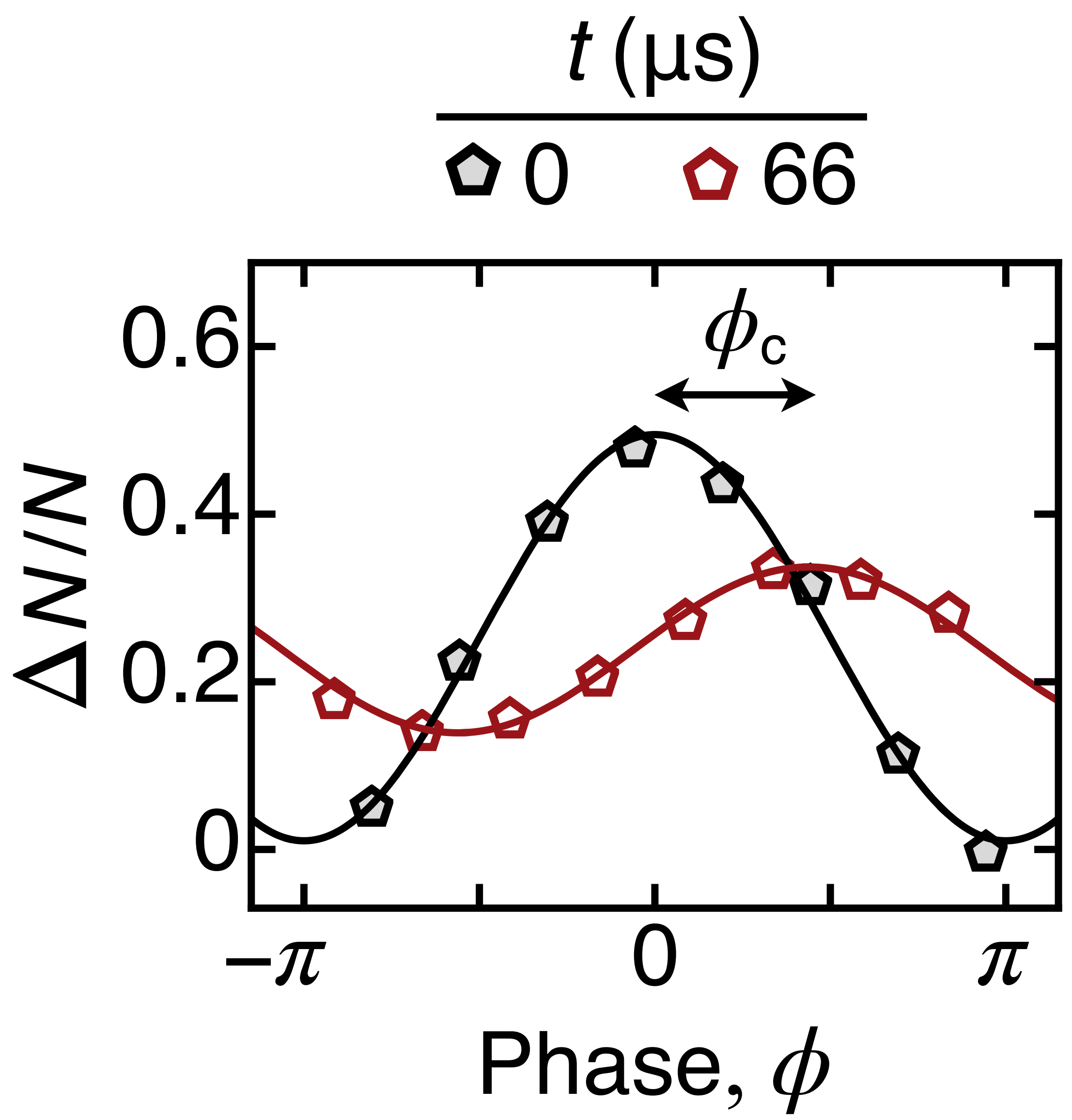
modern theories:
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

Real-time dynamics

Ramsey-like many-body interferometry

coherence function
$C(t) = |C(t)|\exp[i\varphi_c(t)]$





defined so that
$C(0) = 1$

J. Etrych *et al.*, arXiv:2402.14816 (2024)

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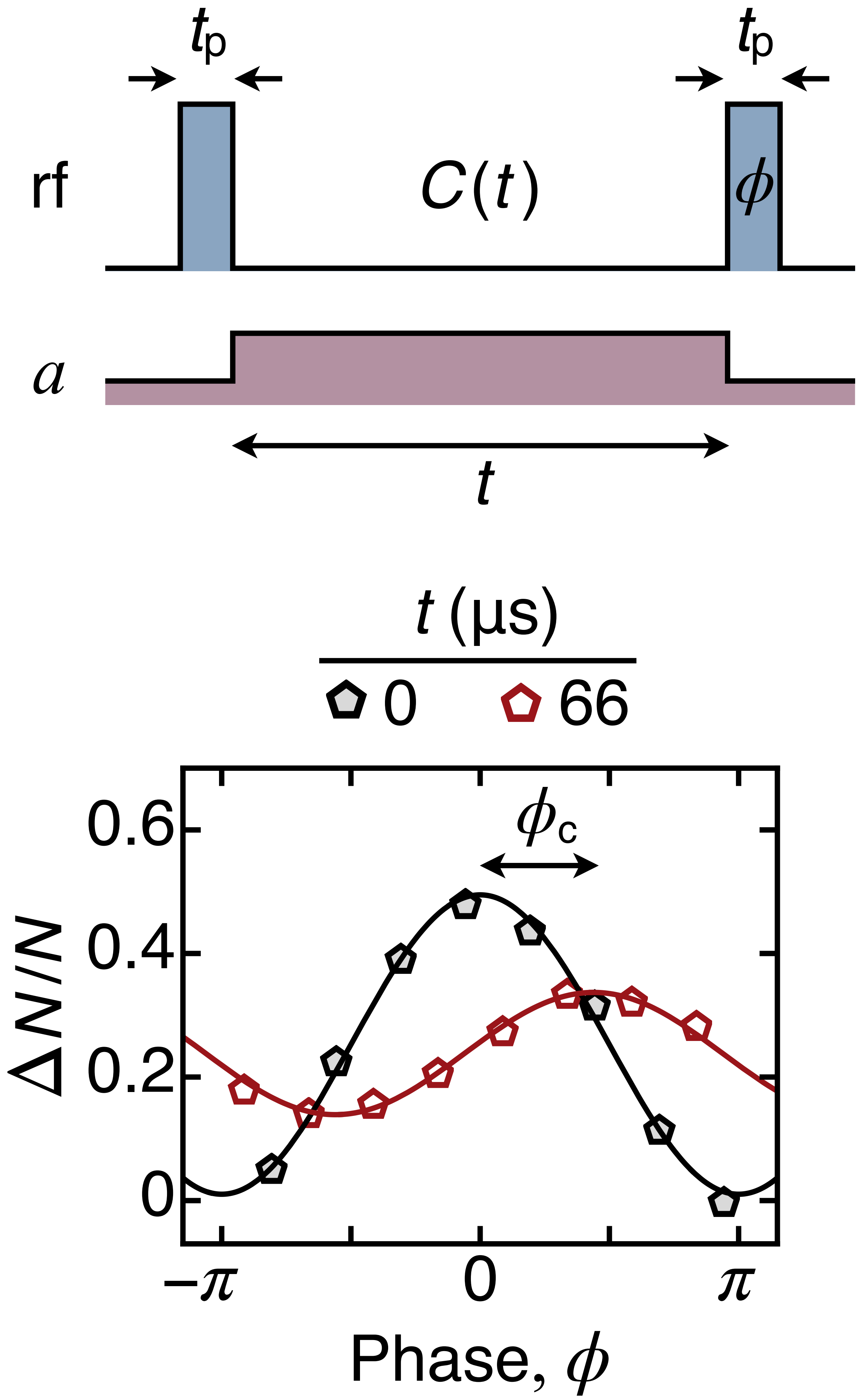
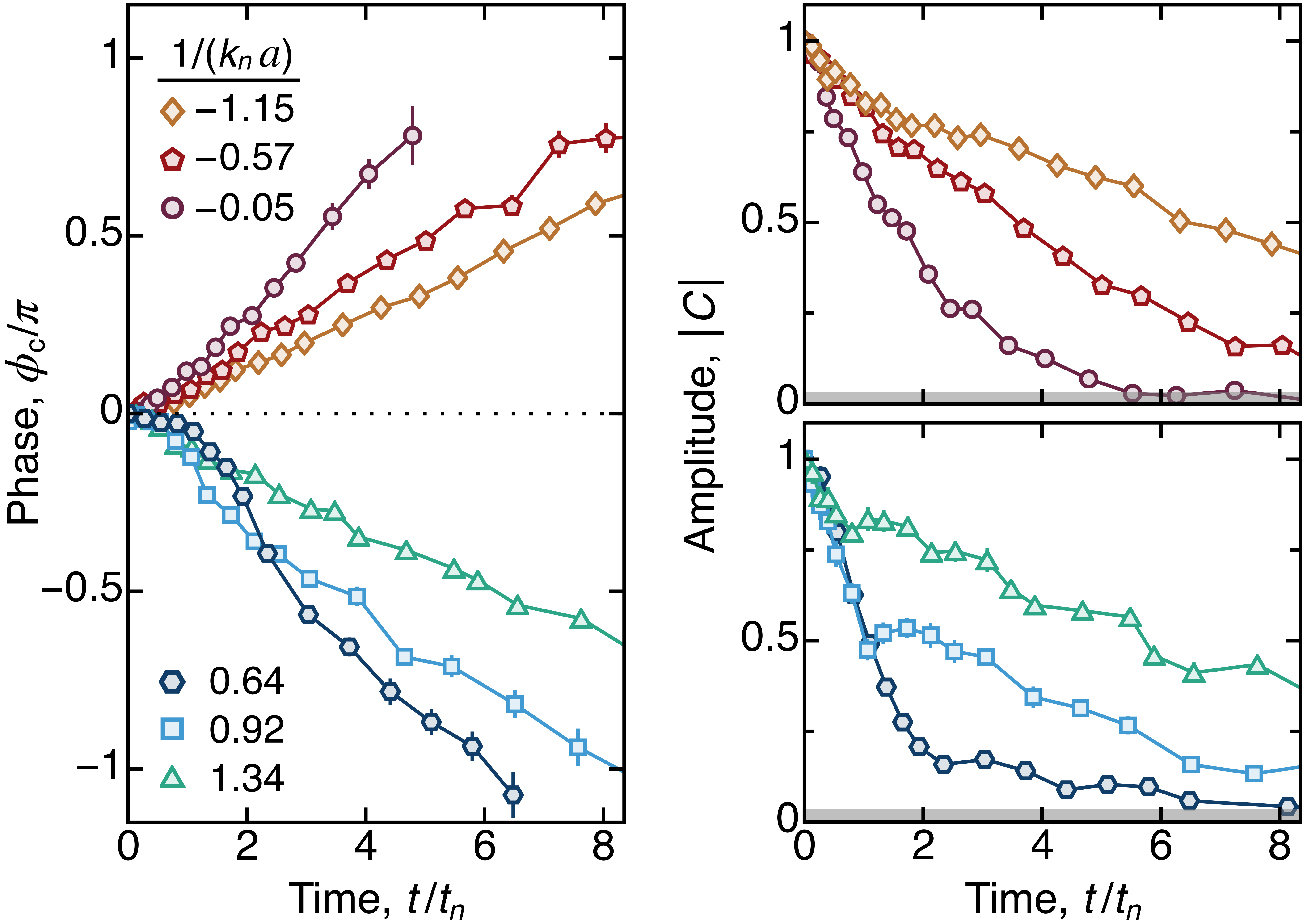


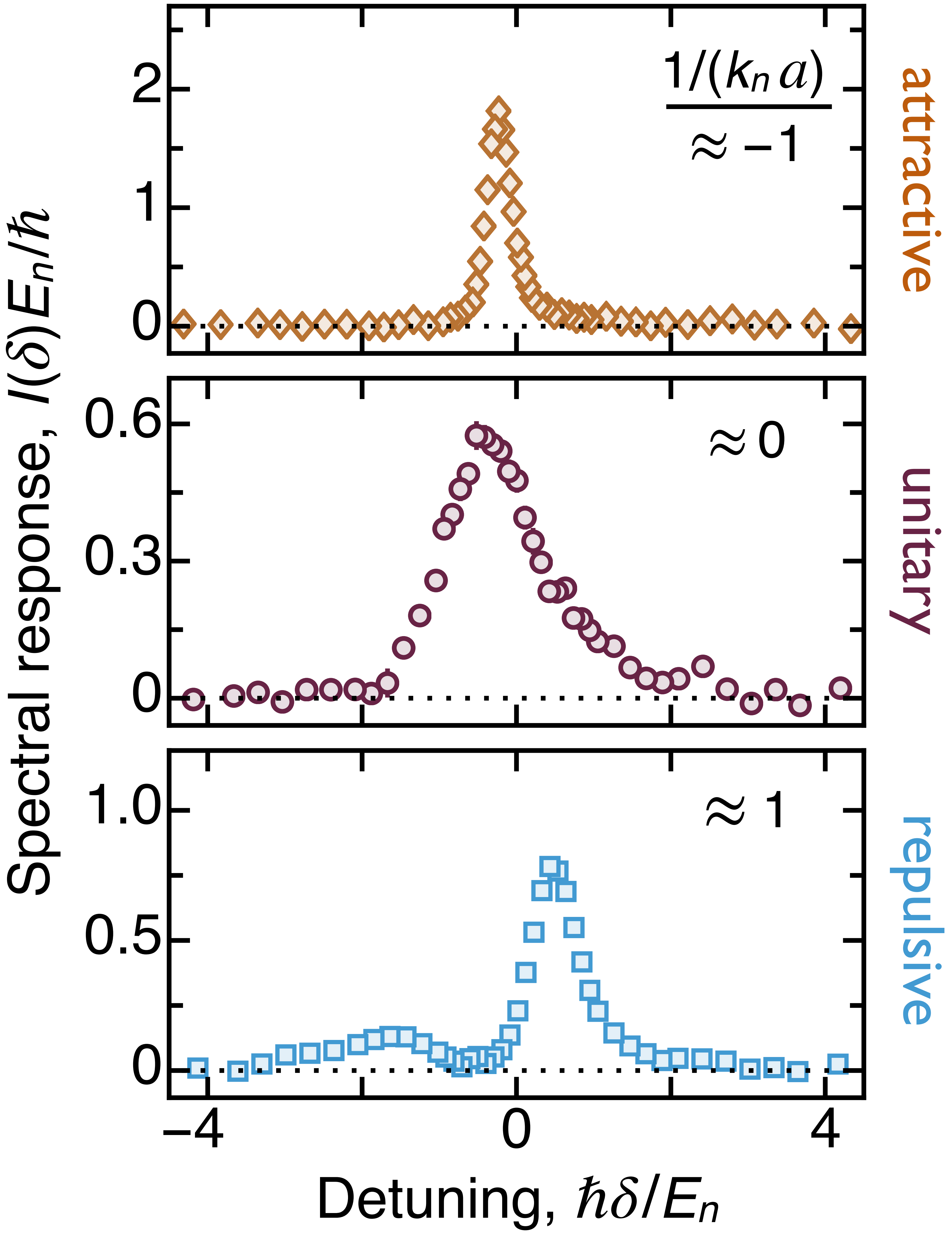


dynamics faster for larger $|a|$

rich dynamics (beats)

Comparison of spectroscopy & interferometry

symbols
spectroscopy data



J. Etrych *et al.*, arXiv:2402.14816 (2024)

Comparison of spectroscopy & interferometry

symbols
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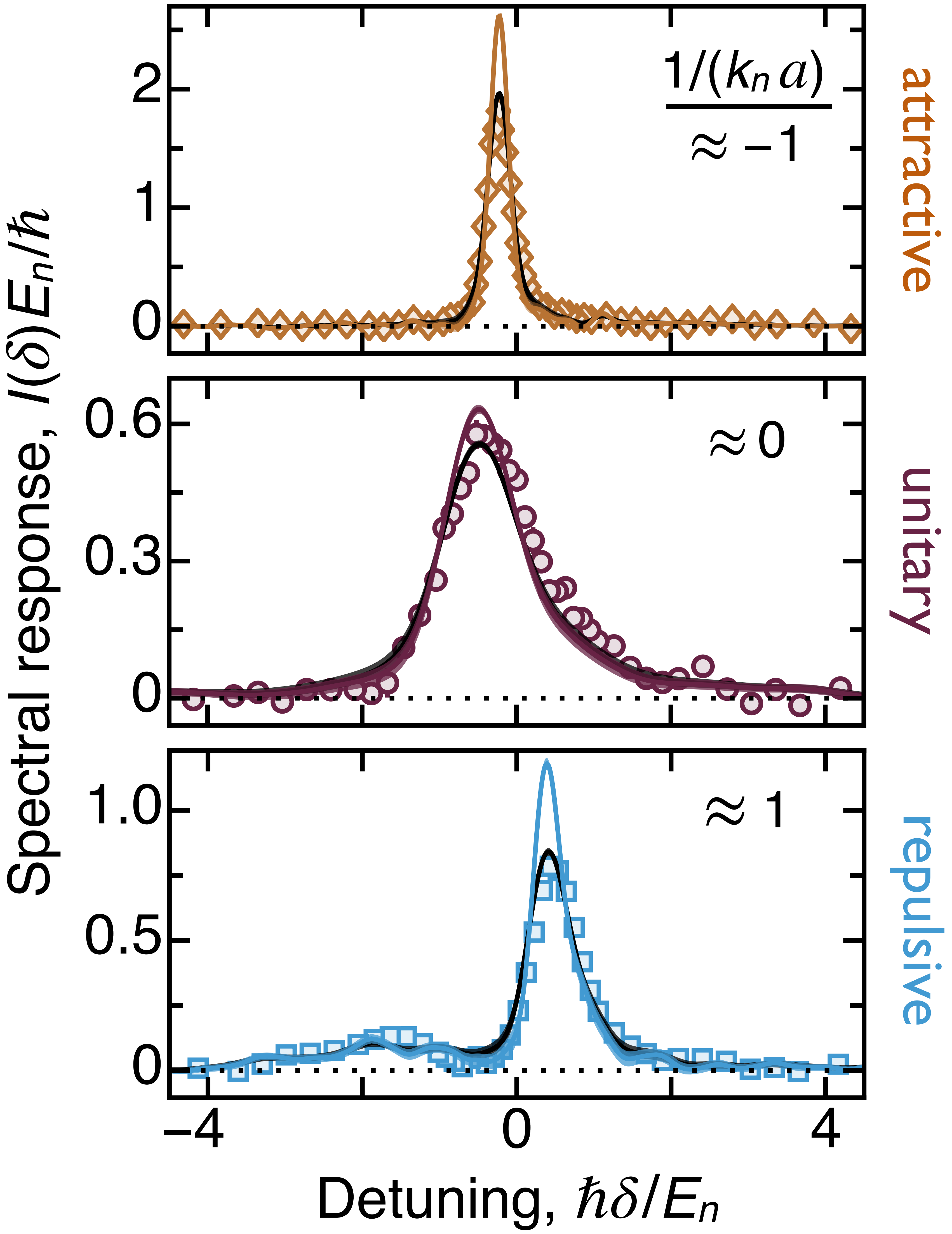
Fourier transform of $C(t)$

accounting for Fourier broadening of spectra



J. Etrych *et al.*, arXiv:2402.14816 (2024)

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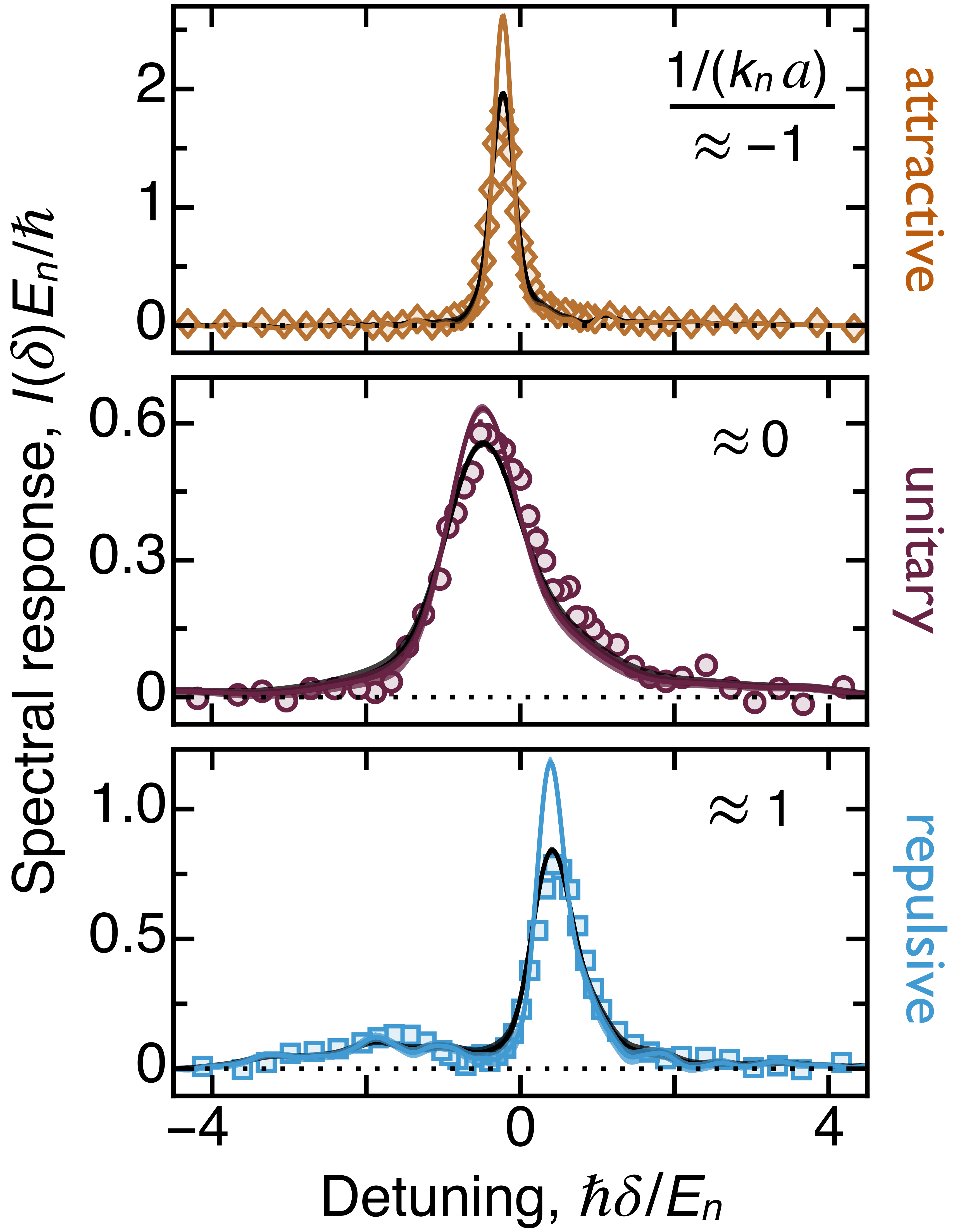
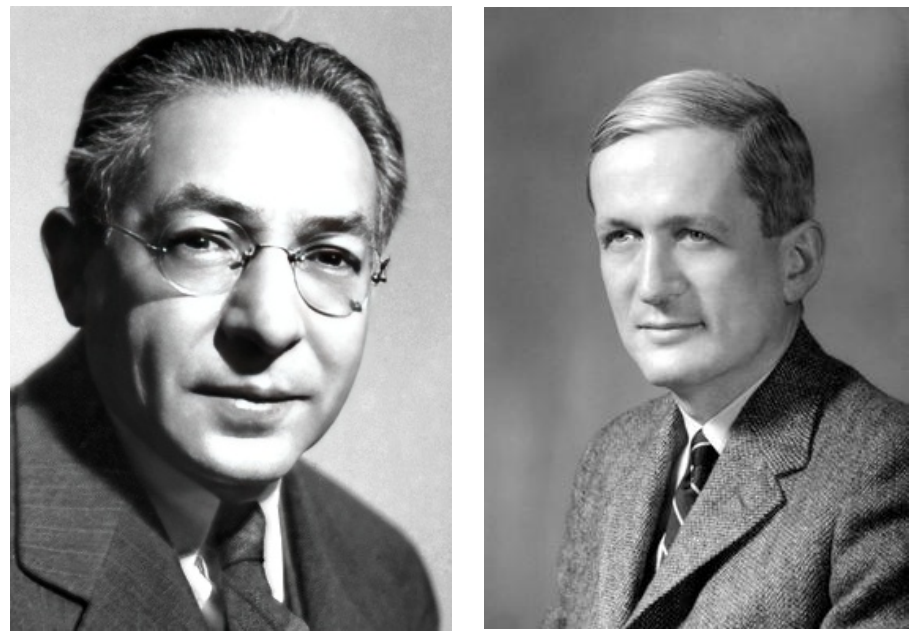


Rabi and Ramsey
would be happy :)



How universal are the dynamics?

Naively, physics set by:

- ✦ dimensionless interaction parameter $1/(k_n a)$
- ✦ energy scale E_n

density-set units

$$k_n = (6\pi^2 n)^{1/3} \qquad E_n = \hbar^2 k_n^2/(2m)$$

$$t_n = \hbar/E_n$$

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For Bosons, other scales thought to weakly enter:

e.g. bath properties a_b, Efimov physics? …

some examples:
J. Levinsen *et al*. PRL **115**, 125302 (2015)
L. A. Pena Ardila *et al*. PRA **92**, 033612 (2015)
Y. E. Shchadilova *et al*. PRL **117**, 113002 (2016)
F. Grusdt *et al*. PRA **96**, 013607 (2017)
S. M. Yoshida *et al*., PRX **8**, 011024 (2018)
M. Drescher *et al*. PRR **2**, 032011 (2020)
P. Massignan *et al*. PRL **126**, 123403 (2021)
A. Christianen *et al*. PRA **105**, 053302 (2022)
A. Christianen *et al. SciPost Phys.* **16**, 067 (2024)

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A. Christianen *et al. SciPost Phys.* **16**, 067 (2024)

Start at unitarity ($a \to \infty$), so it drops out and can just vary n

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Aside: Universality in the Unitary Bose Gas

universality in single-component bulk unitary Bose gases

P. Makotyn *et al.*, Nat. Phys. **10**, 116 (2014)
C. E. Klauss *et al.*, PRL **119**, 143301 (2017)
CE *et al.*, PRL **119**, 250404 (2017)
CE *et al.*, Nature **563**, 221 (2018)

Naively, physics set by:

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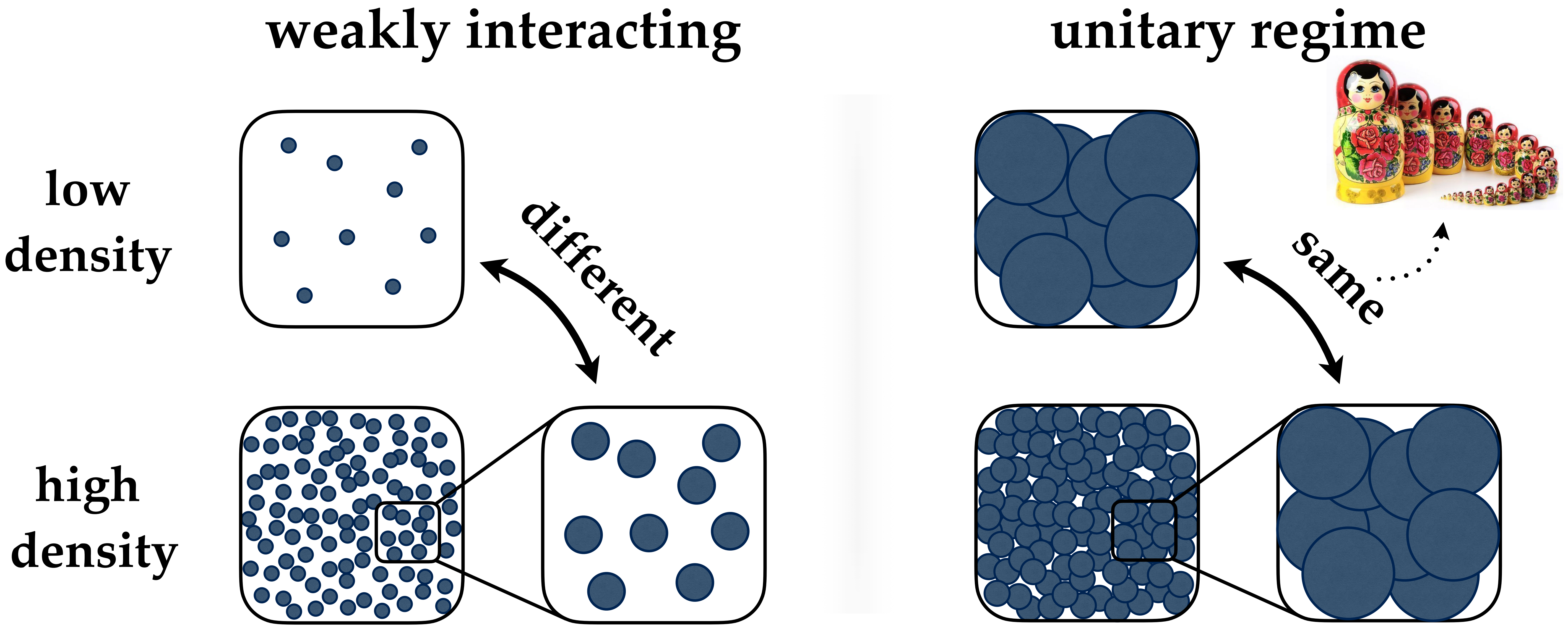

density-set units

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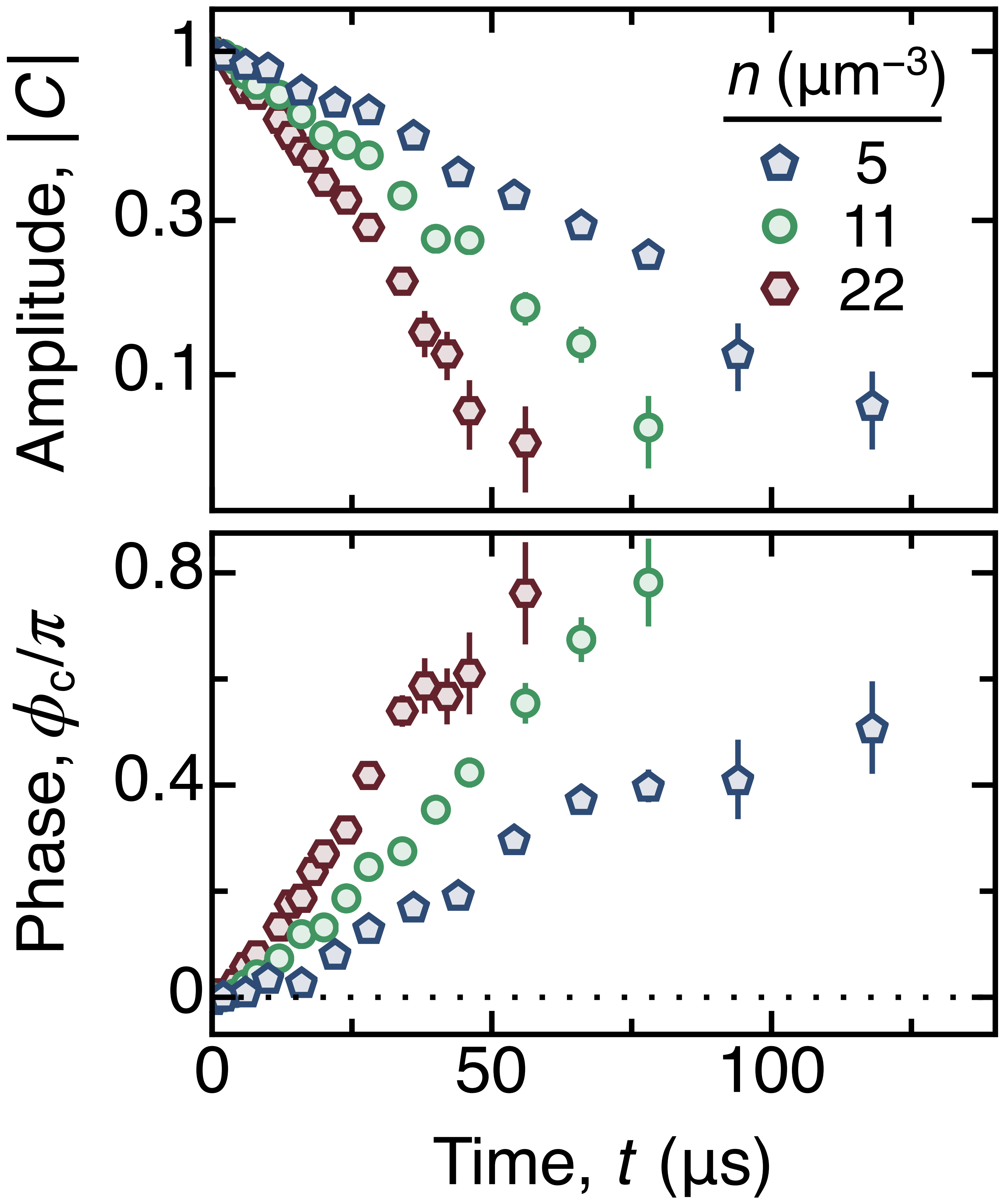
Universal dynamics at unitarity?

coherence function, $C(t) = |C(t)| \exp[i\varphi_c(t)]$



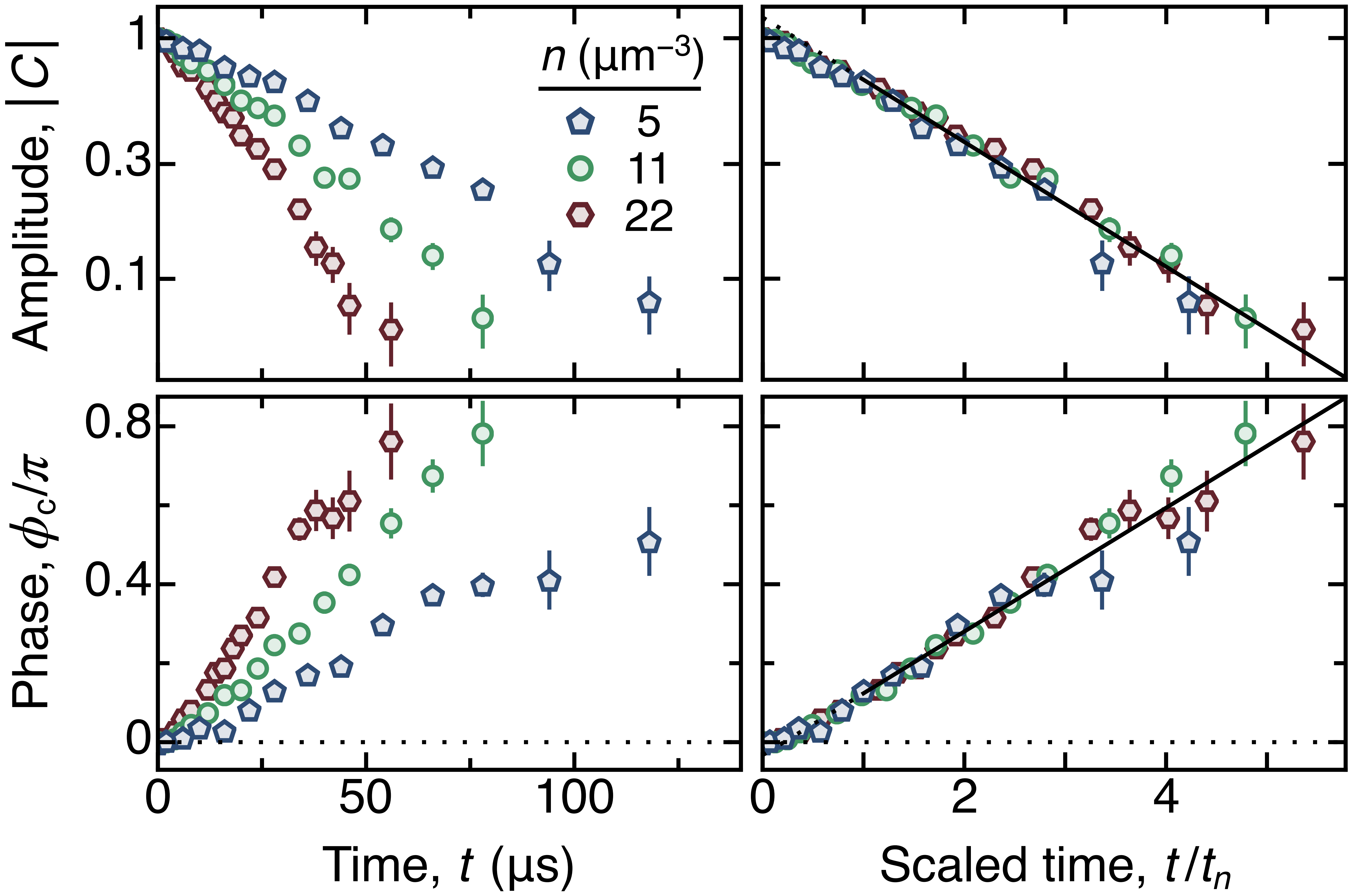
Start at unitarity ($a \to \infty$), so it drops out and can just vary n

✦ dynamics faster for larger n

Universal dynamics at unitarity

universal quantum dynamics!

coherence function, $C(t) = |C(t)| \exp[i\varphi_c(t)]$



J. Etrych *et al.*, arXiv:2402.14816 (2024)

Universal dynamics at unitarity

universal quantum dynamics!

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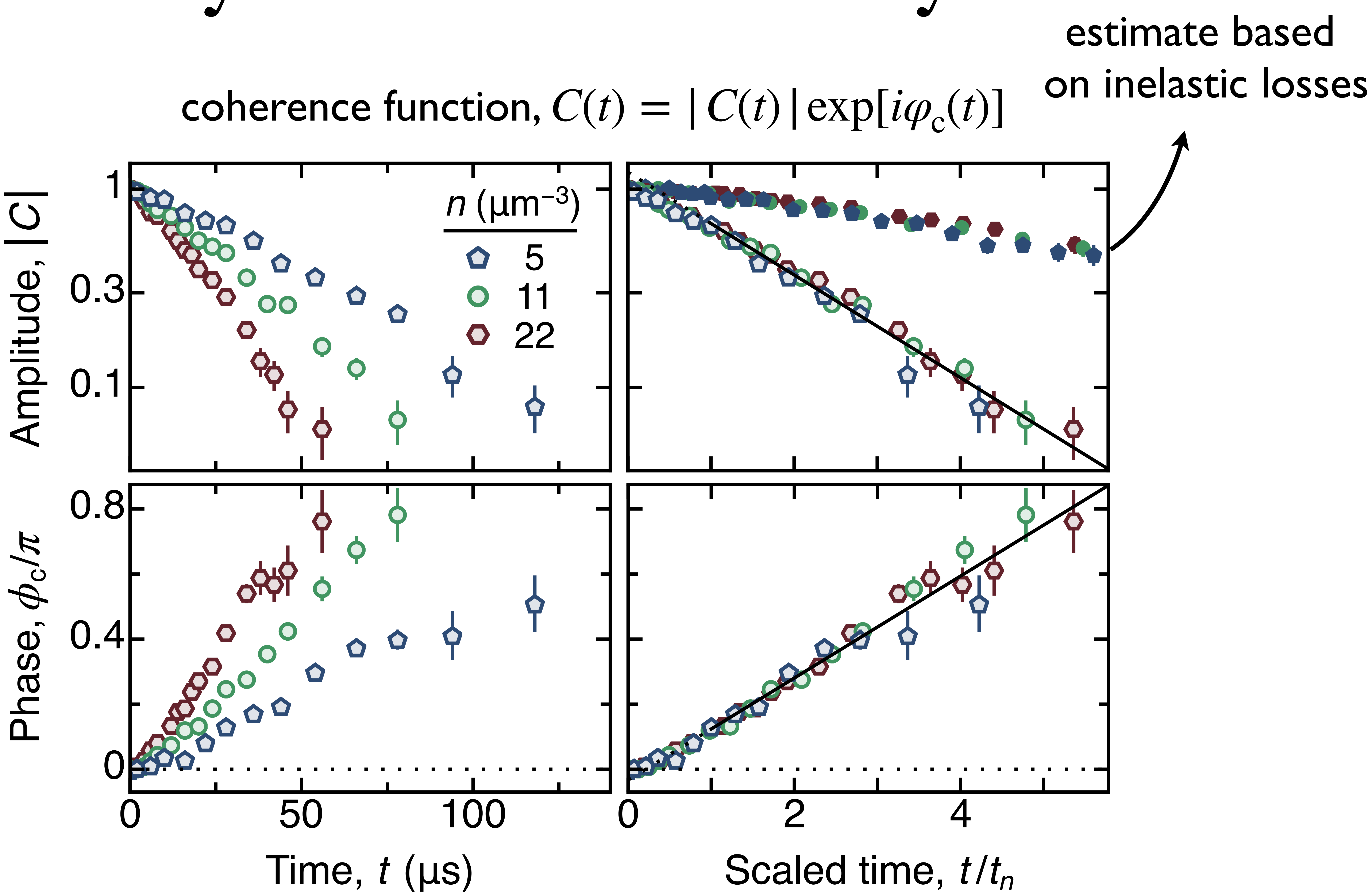
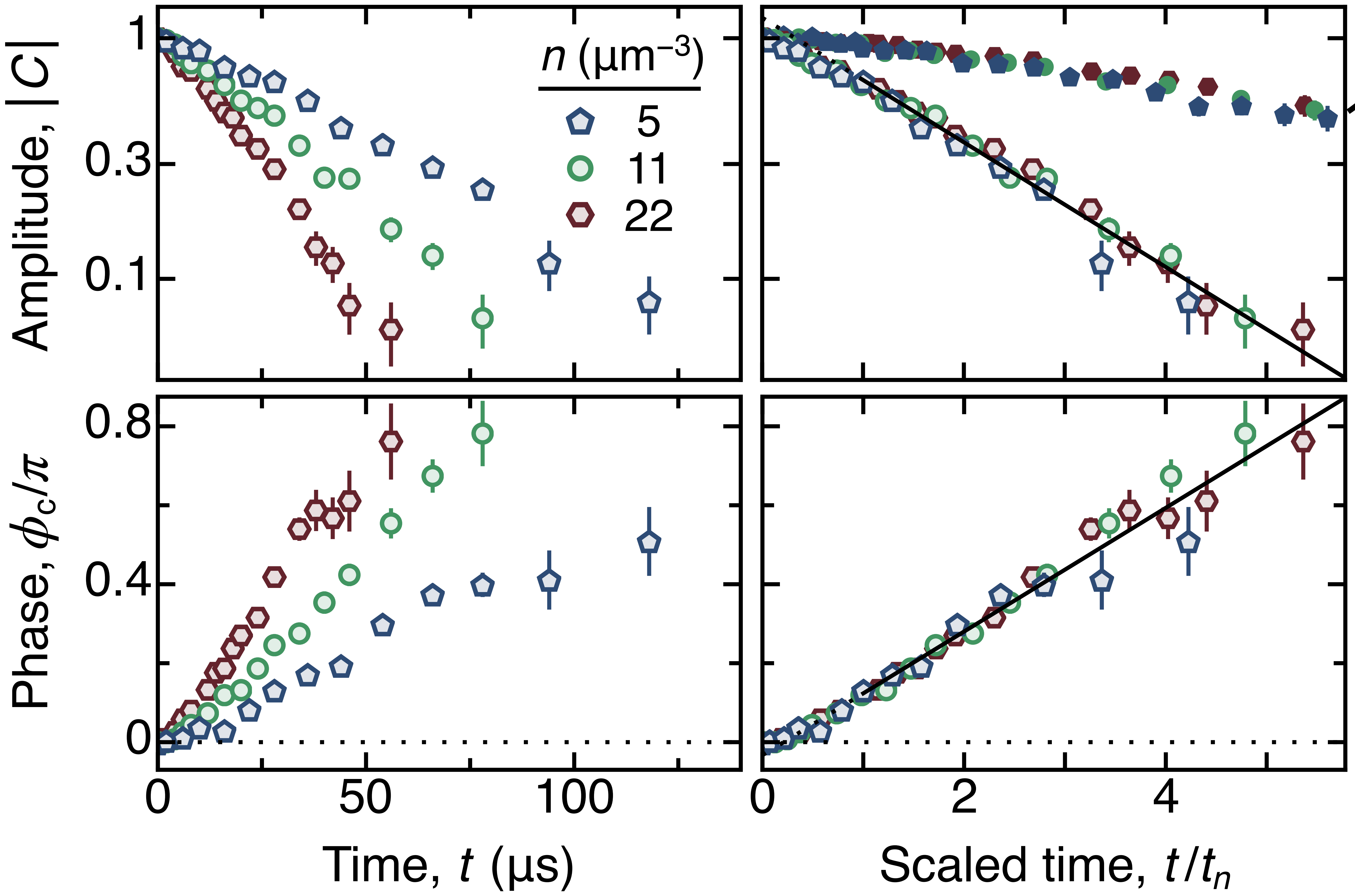


J. Etrych *et al.*, arXiv:2402.14816 (2024)

Universal dynamics at unitarity

estimate based on inelastic losses

coherence function, $C(t) = |C(t)|\exp[i\varphi_c(t)]$



universal quantum dynamics!

quasiparticles?

✦ phase winds linearly w/ slope $0.49(4)/t_n$

Universal dynamics at unitarity

universal quantum dynamics!

~~**quasiparticles?**~~

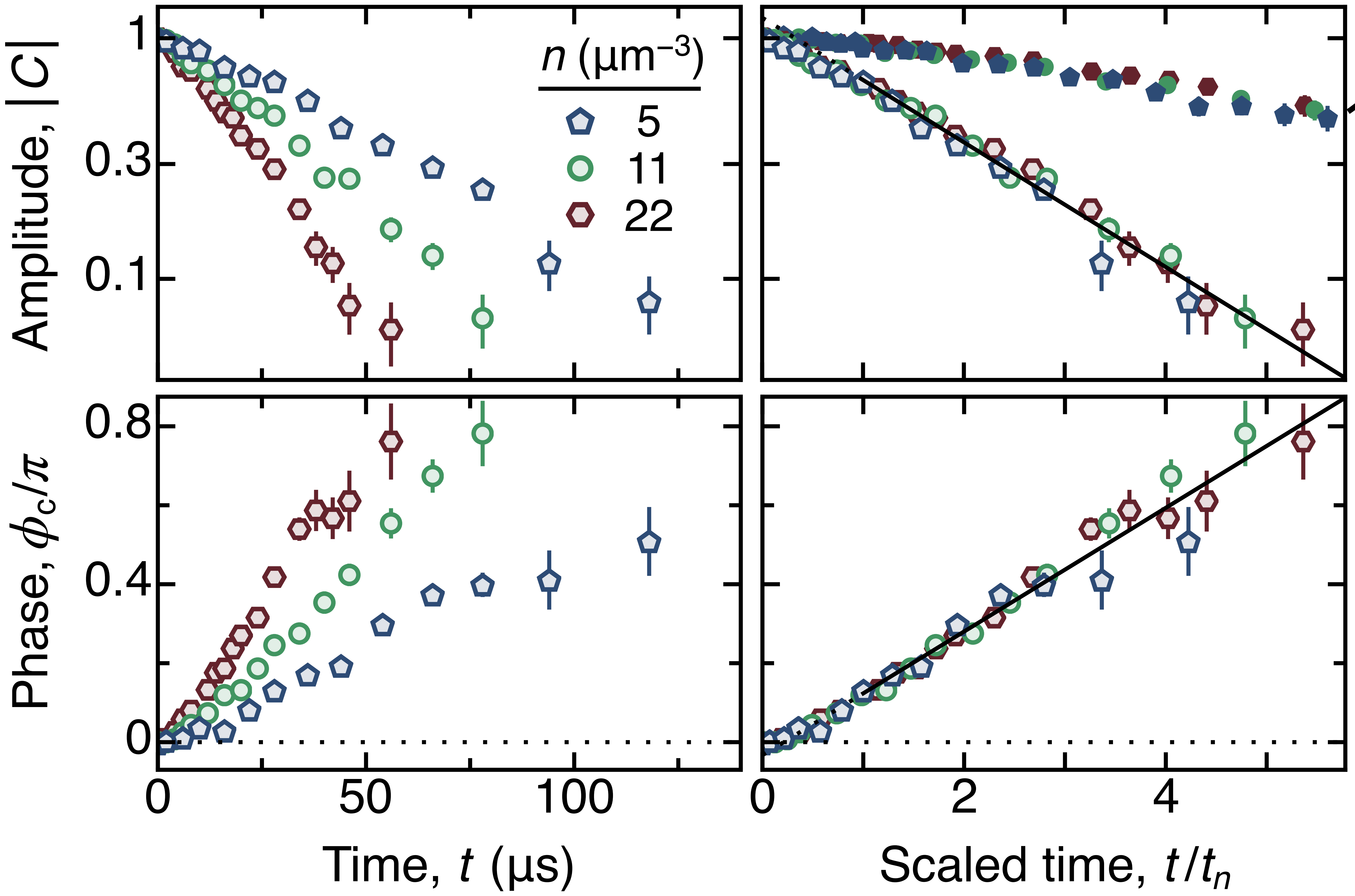
✦ phase winds linearly w/ slope $0.49(4)/t_n$

BUT

✦ decoherence approx. exponential w/ inverse lifetime $0.60(8)/t_n$

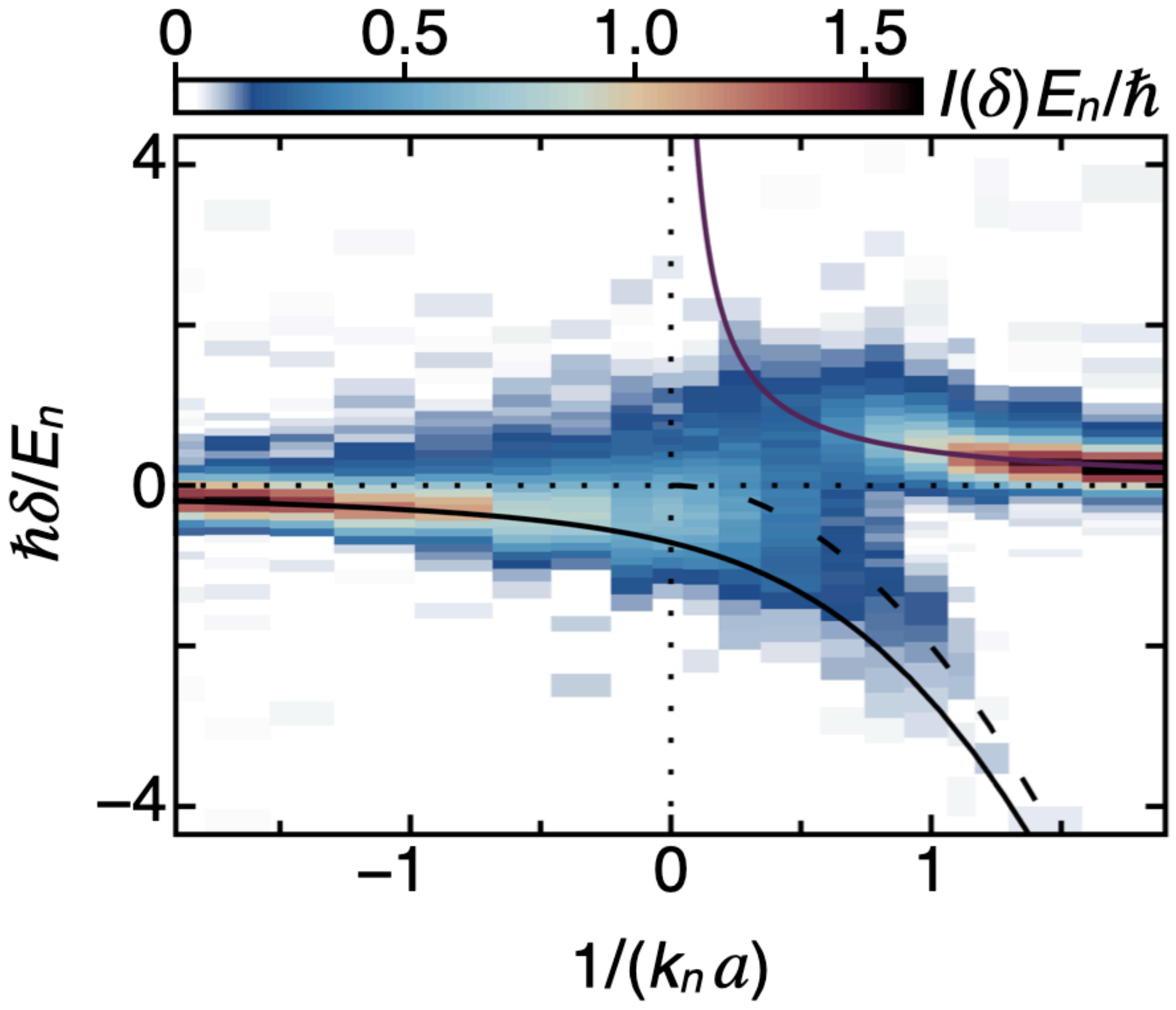
coherence function, $C(t) = |C(t)| \exp[i\varphi_c(t)]$

estimate based on inelastic losses



Universality of the Bose polaron spectrum?

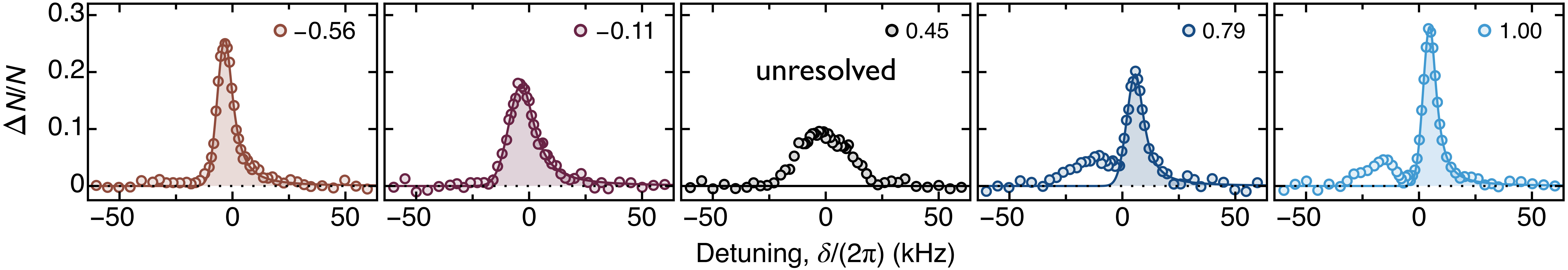
spectroscopy to amass data with different
n, a, a_b



Analyzing the injection spectra

characteristic spectra across the resonance

heuristic fits to polaron features to extract peak position E_p and half width $\hbar\Gamma$



small print: we always correct Γ for Fourier broadening using $\Gamma = (\Gamma_e^2 - \Gamma_{rf}^2)^{1/2}$

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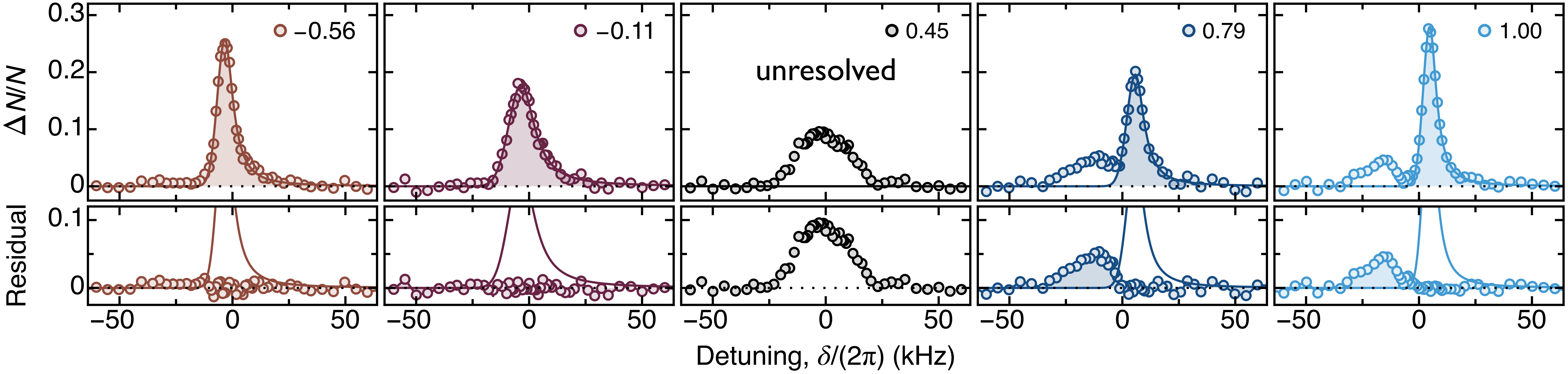


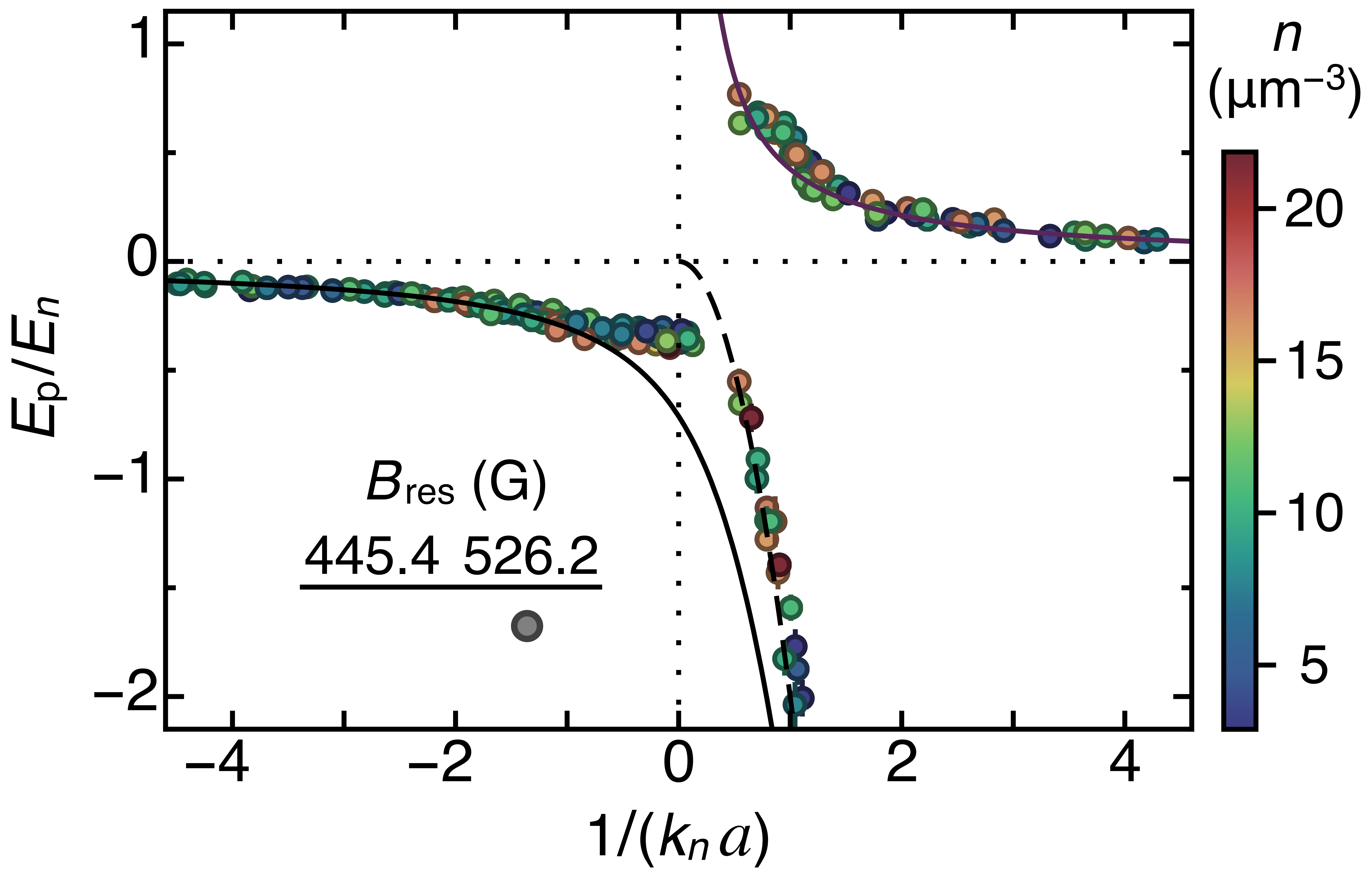
residual isolates second branch for $a > 0$, extract E_p and $\hbar\Gamma$

small print: we always correct Γ for Fourier broadening using $\Gamma = (\Gamma_\mathrm{e}^2 - \Gamma_\mathrm{rf}^2)^{1/2}$

Universality of Bose polaron spectrum

vary n

peak position E_p



same simple theory lines as before!

J. Etrych *et al.*, arXiv:2402.14816 (2024)

Universality of Bose polaron spectrum

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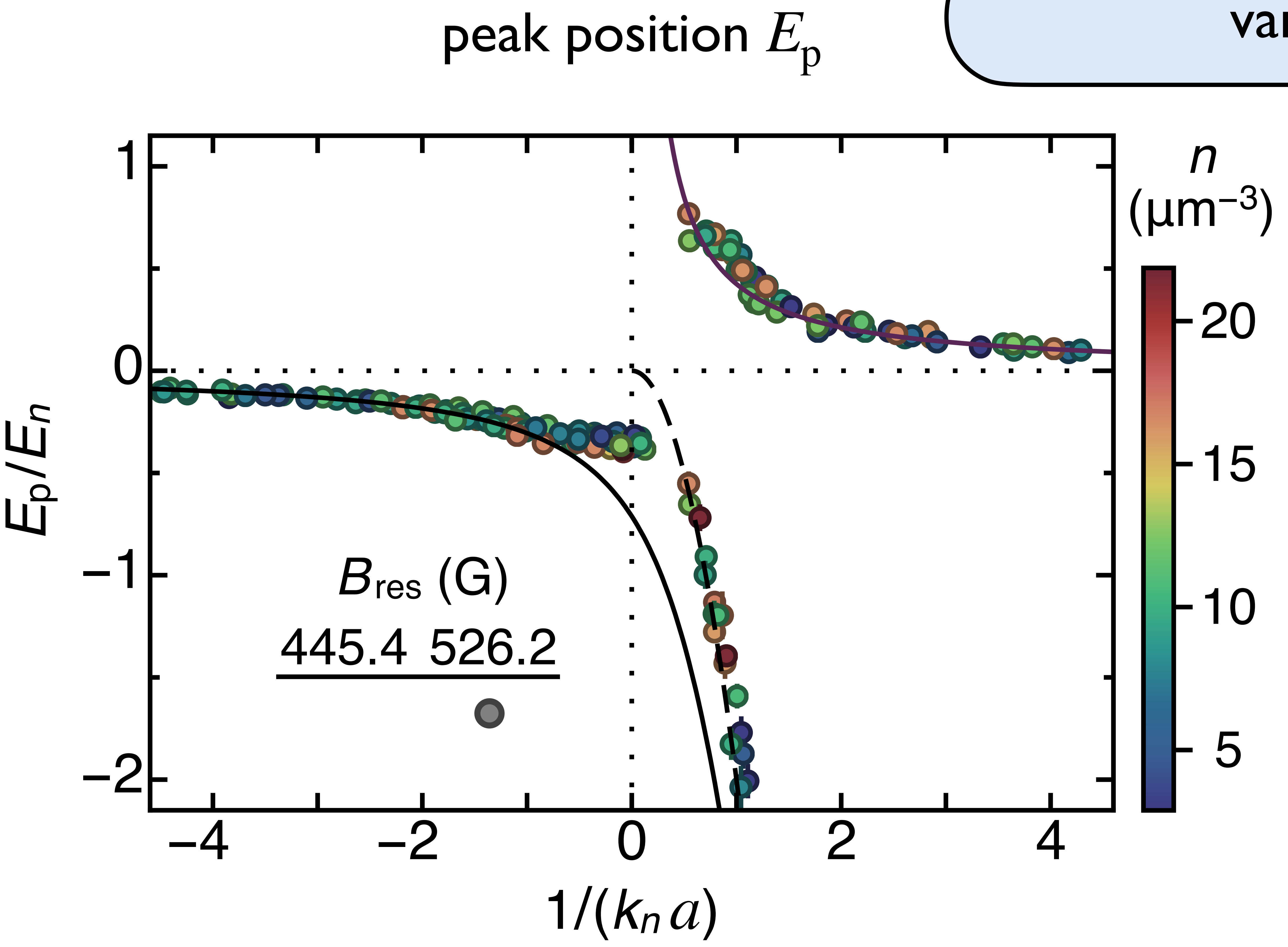
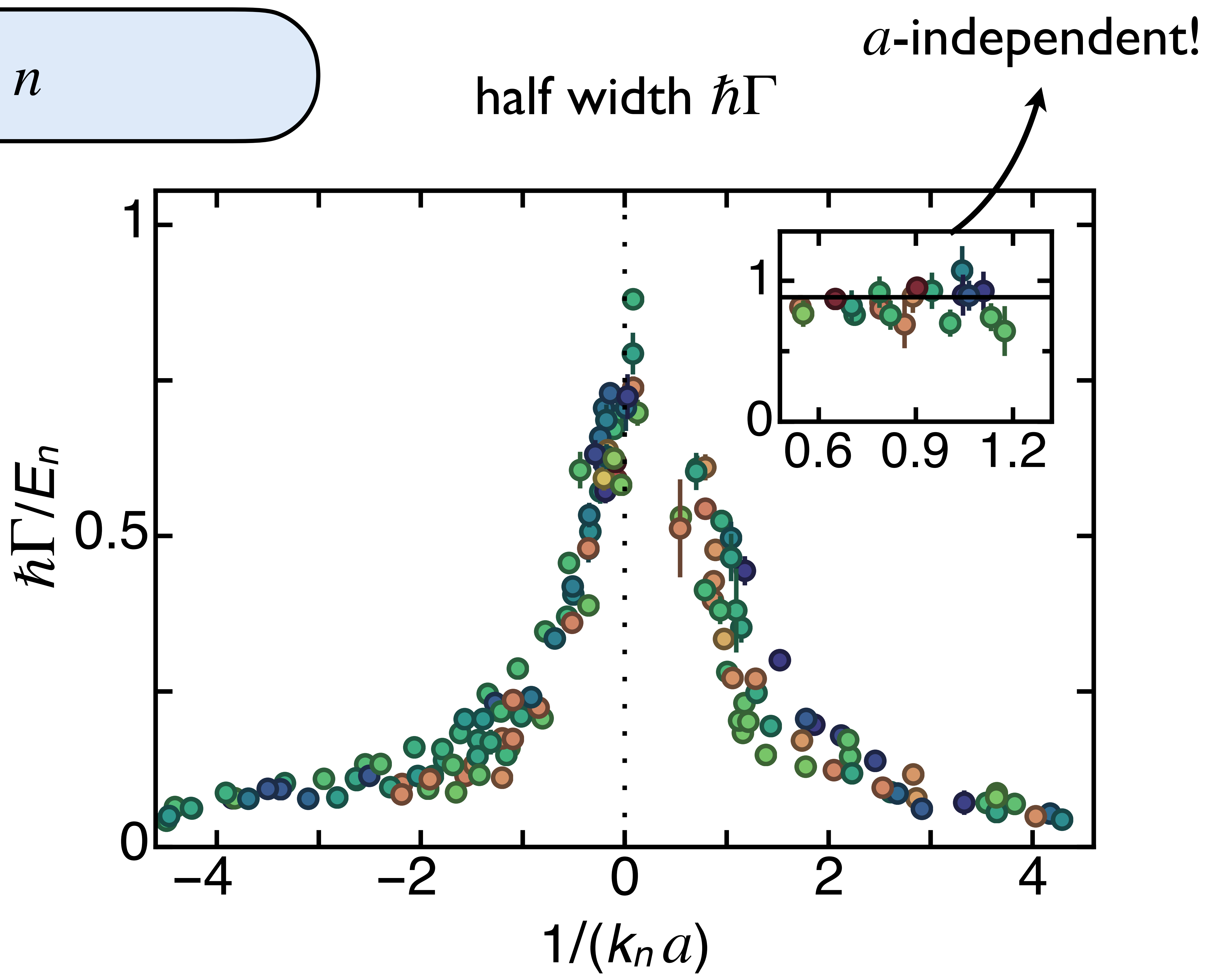


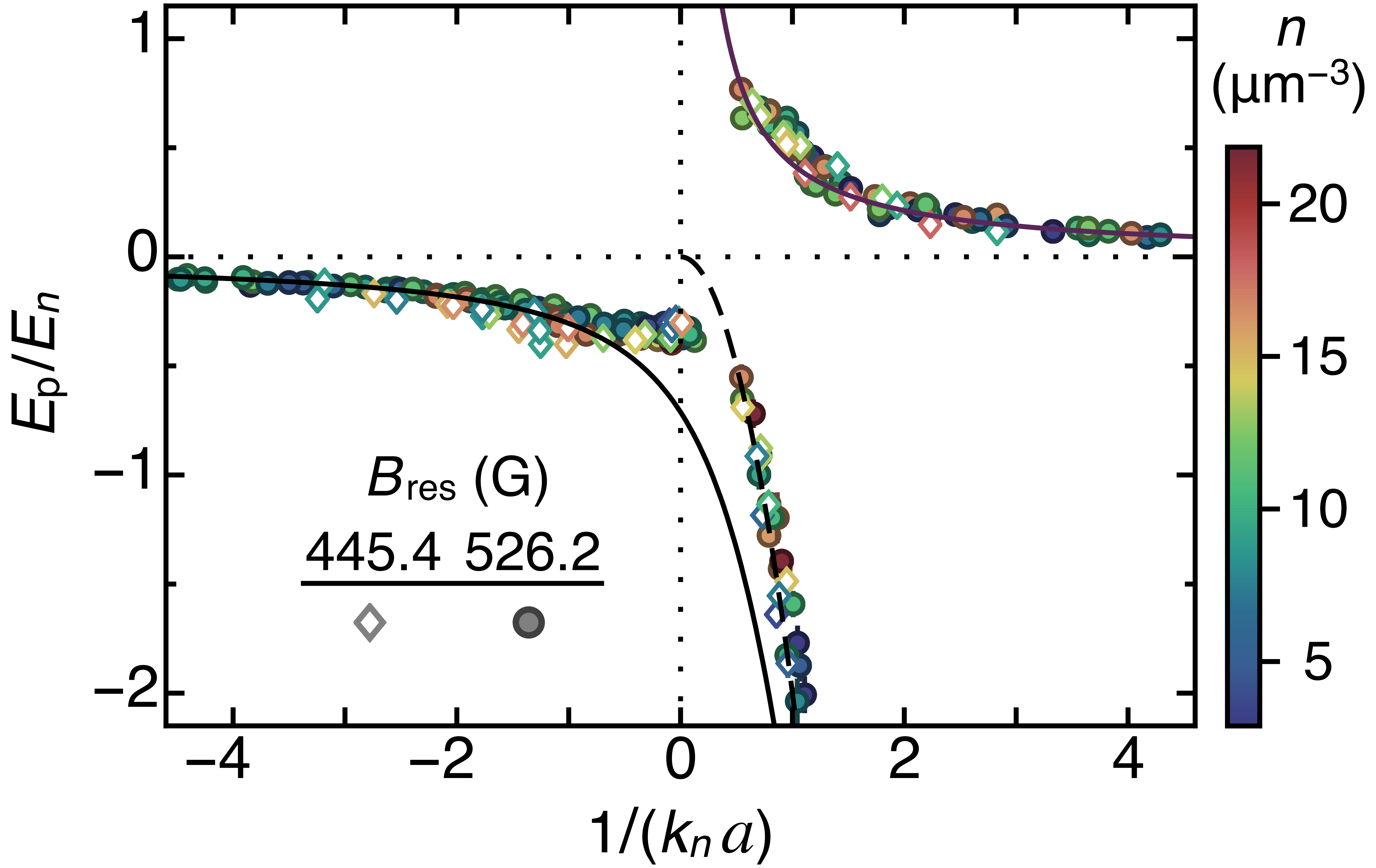


same simple theory lines as before!

Universality of Bose polaron spectrum

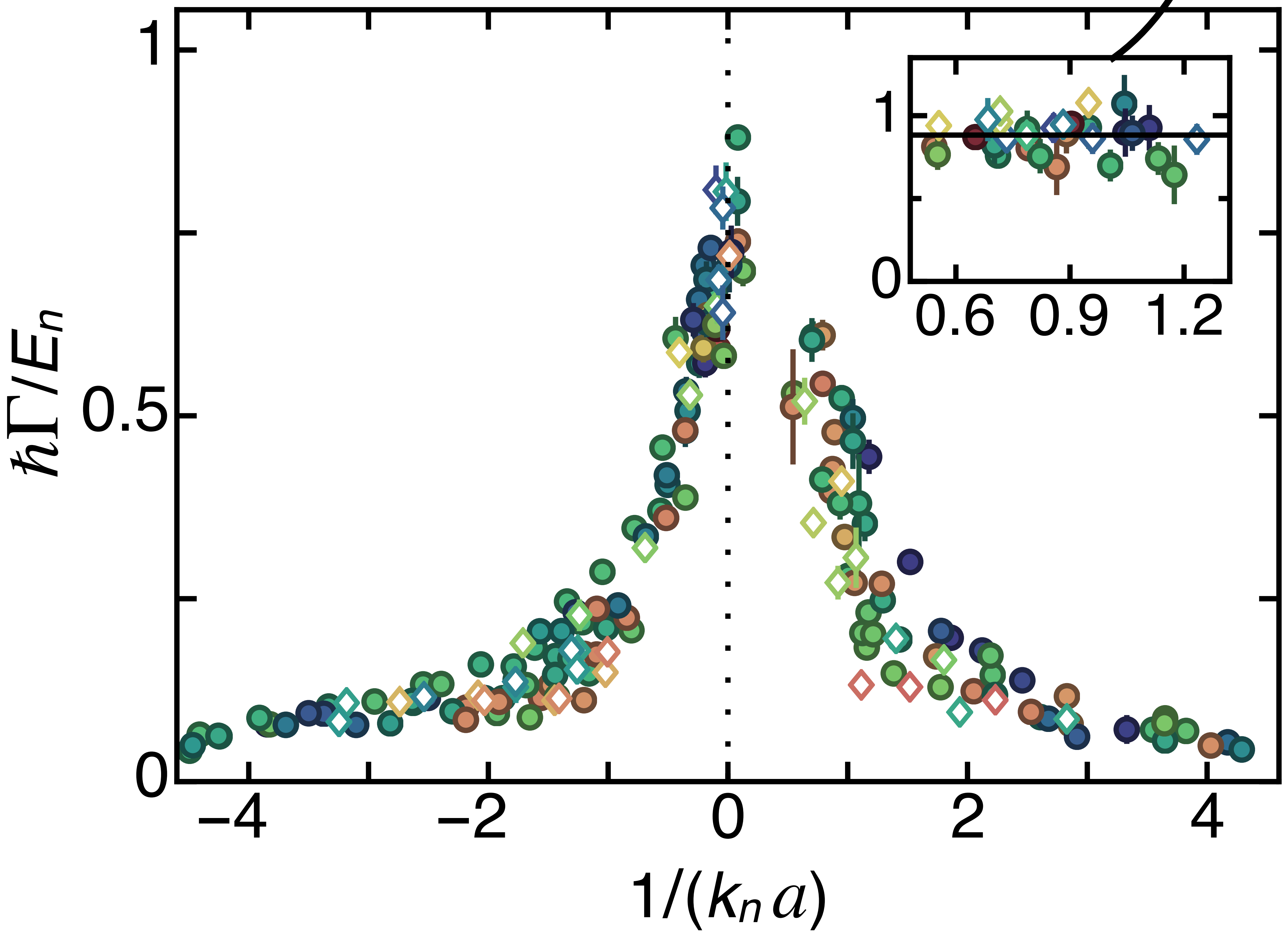
vary n and a_b

peak position E_p



half width $\hbar\Gamma$

a-independent!



E_p/E_n and $\hbar\Gamma/E_n$
universal functions of $1/(k_n a)$

Christoph Eigen

J. Etrych *et al.*, arXiv:2402.14816 (2024)

Trento, April 2024

Universality of Bose polaron spectrum

vary n and a_b

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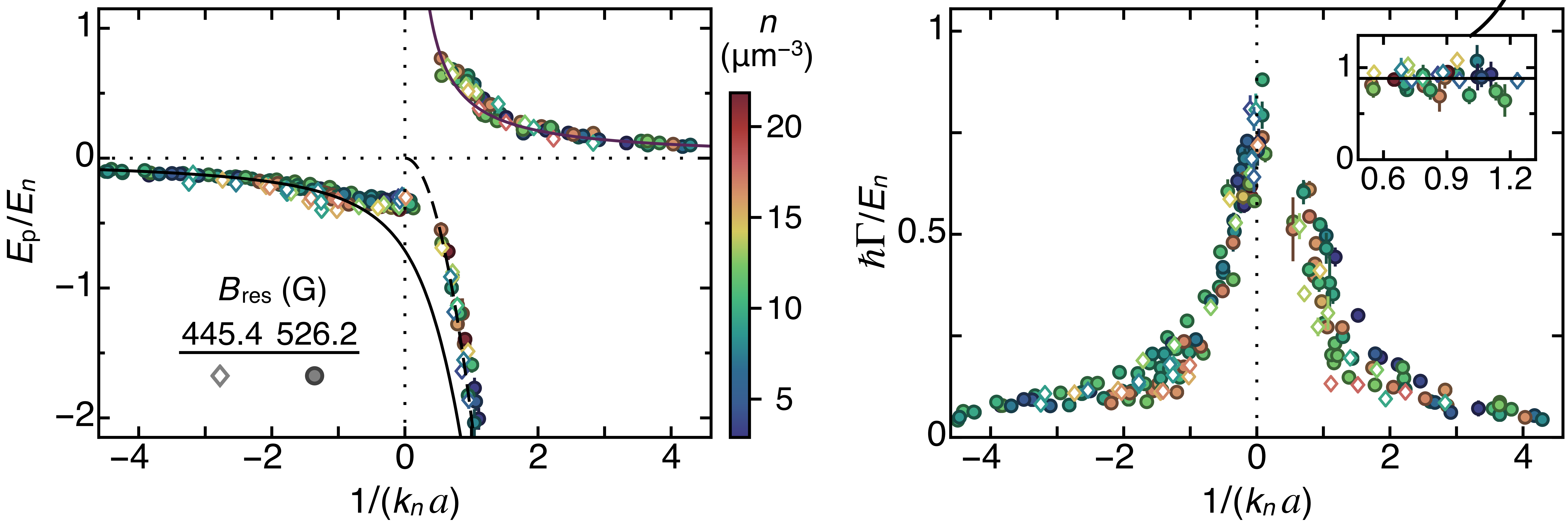


next: look at ratio $\hbar\Gamma/E_p$

Christoph Eigen

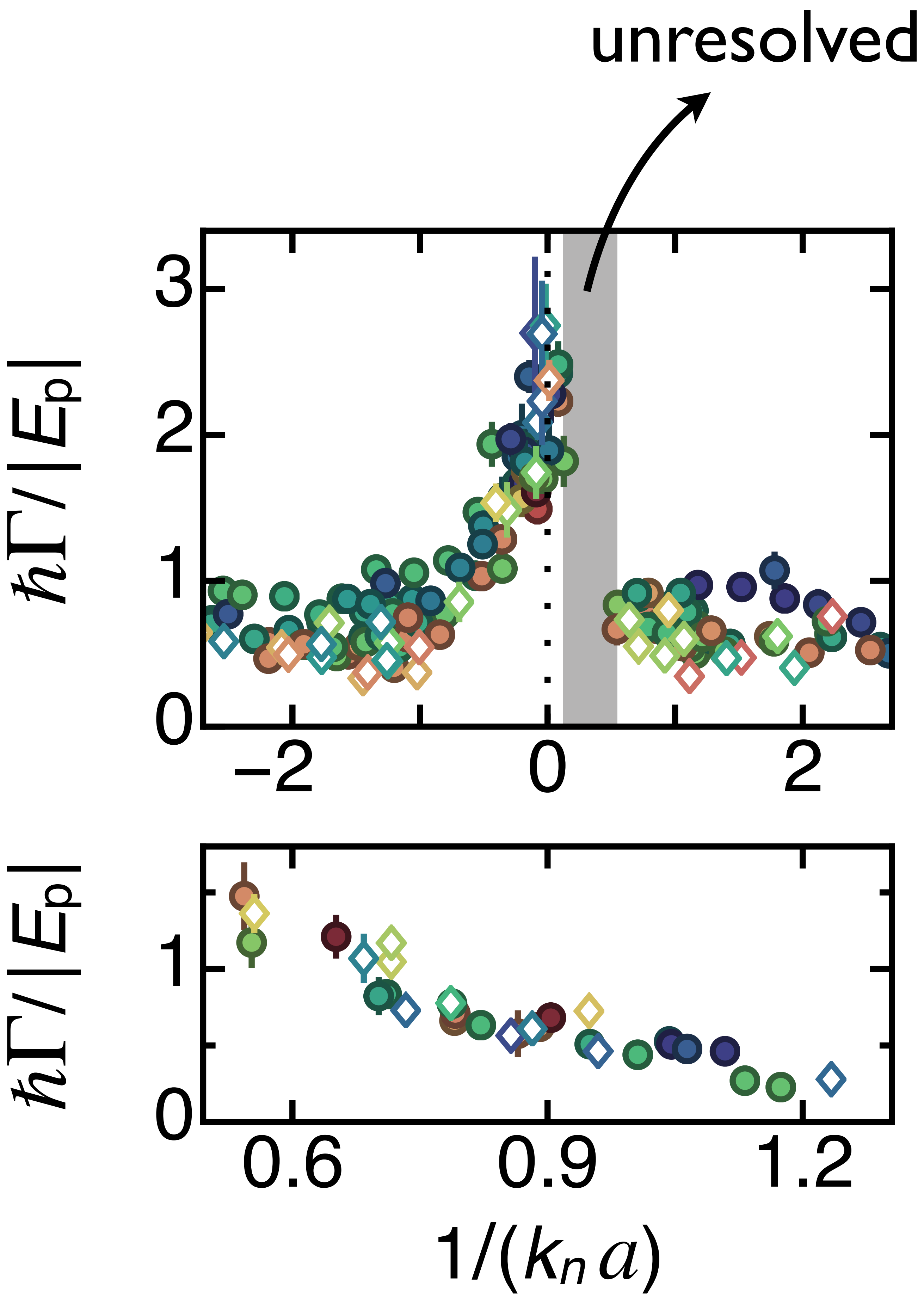
J. Etrych *et al.*, arXiv:2402.14816 (2024)

Trento, April 2024

Breakdown of quasiparticle picture near unitarity

polarons branches

molecular branch

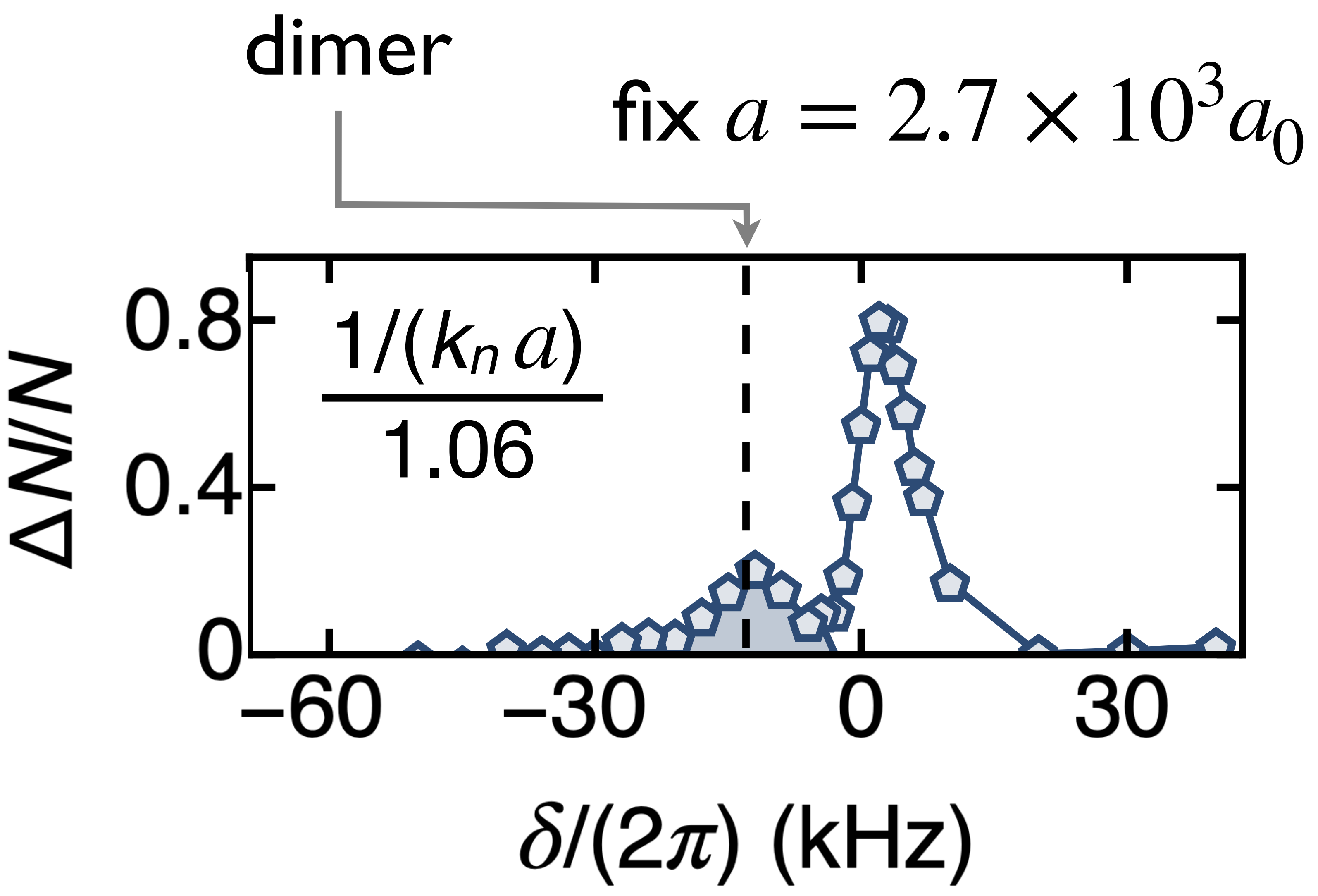


✦ for $1/(k_n a) \gtrsim 1$, ratio $\hbar\Gamma/E_\mathrm{p} \approx$ constant

✦ near B_res $1/(k_n a) \lesssim 1$, width exceeds energy!

quasiparticles no longer well defined near B_res!

Strongly repulsive regime

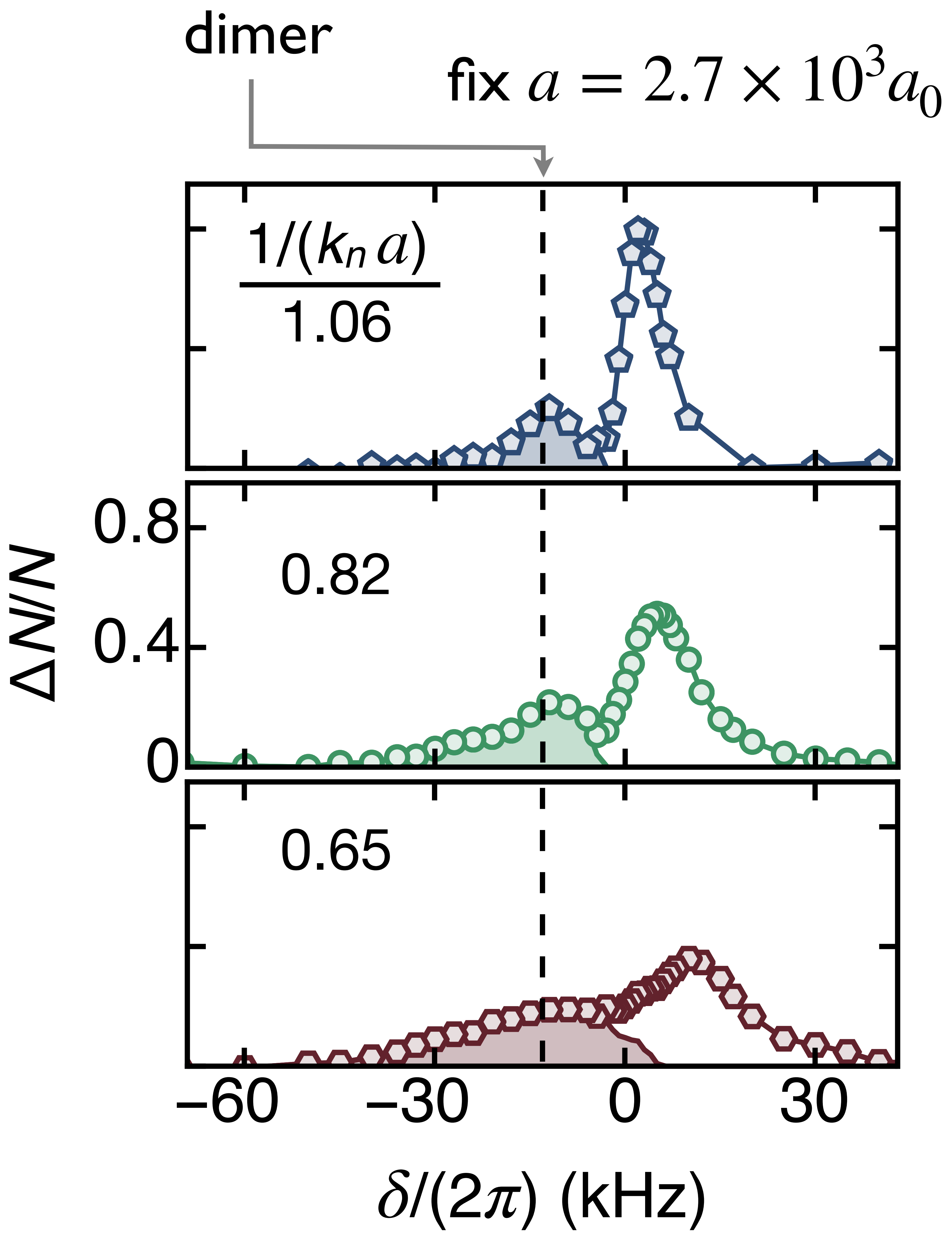


nature of dimer-like peak?

$E_d = -\hbar^2/(ma^2) = -13\,\text{kHz}$

vary density

Strongly repulsive regime



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both peaks broaden…

molecular branch shows a many-body character!

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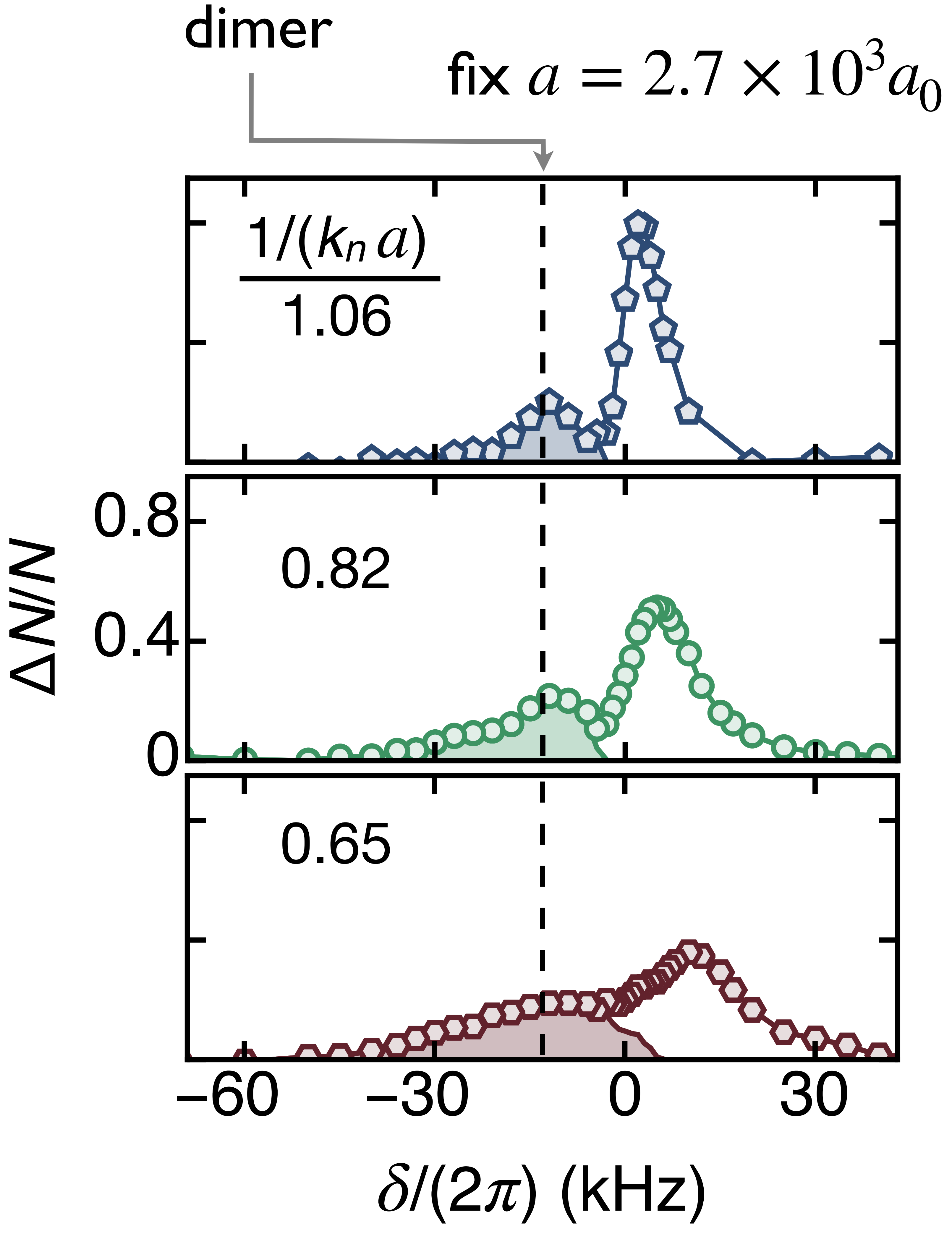

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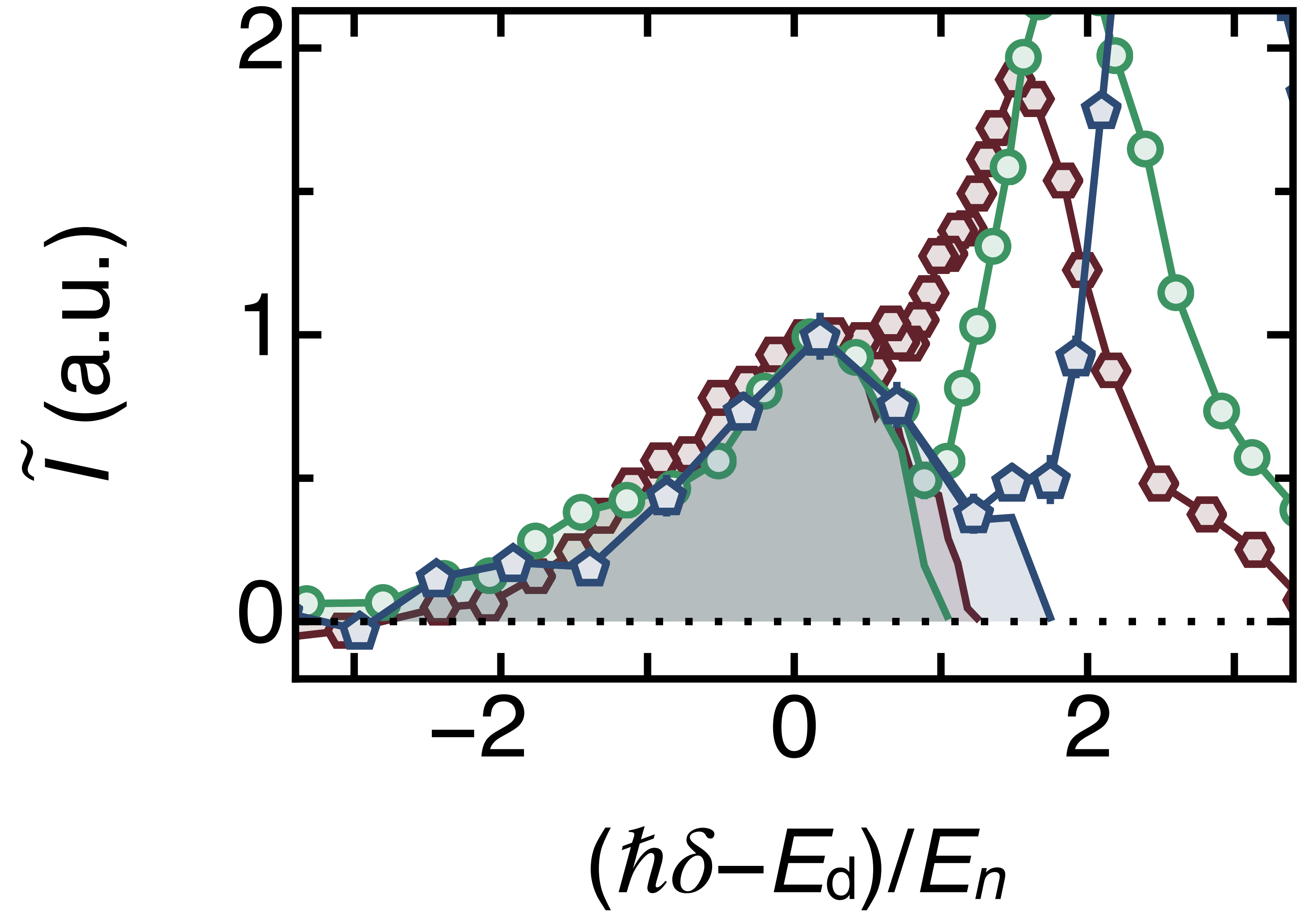
spectroscopy

scale x axis and normalize heights

universal shape



Differential interferometry

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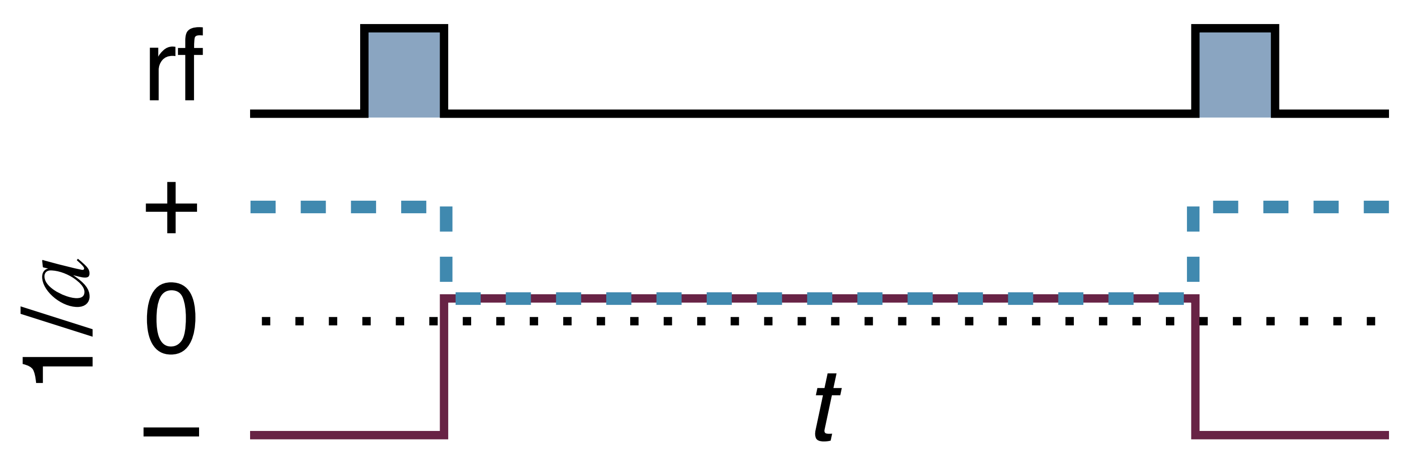
$1/(k_n a) \approx 0.6$

differential interferometry



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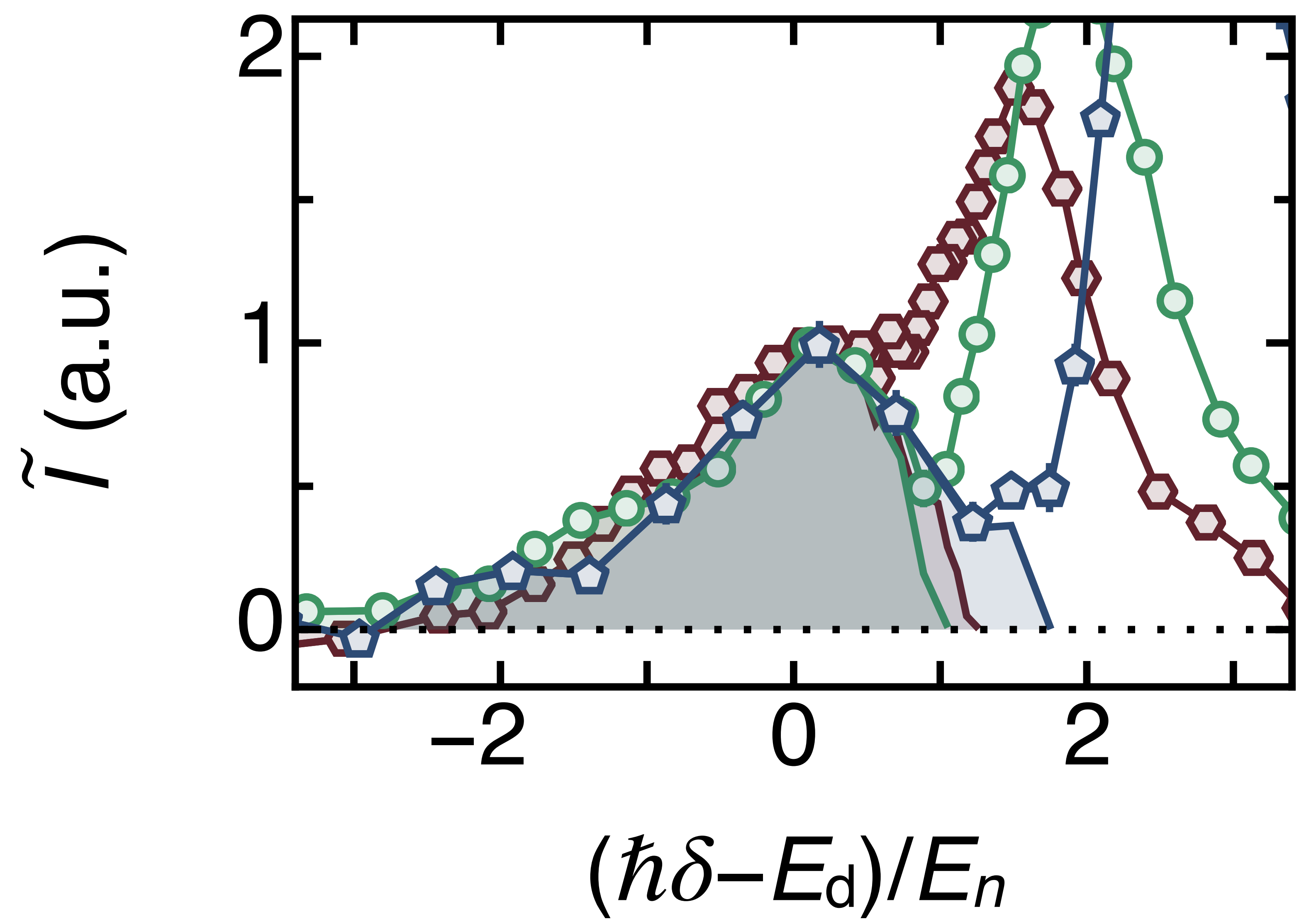

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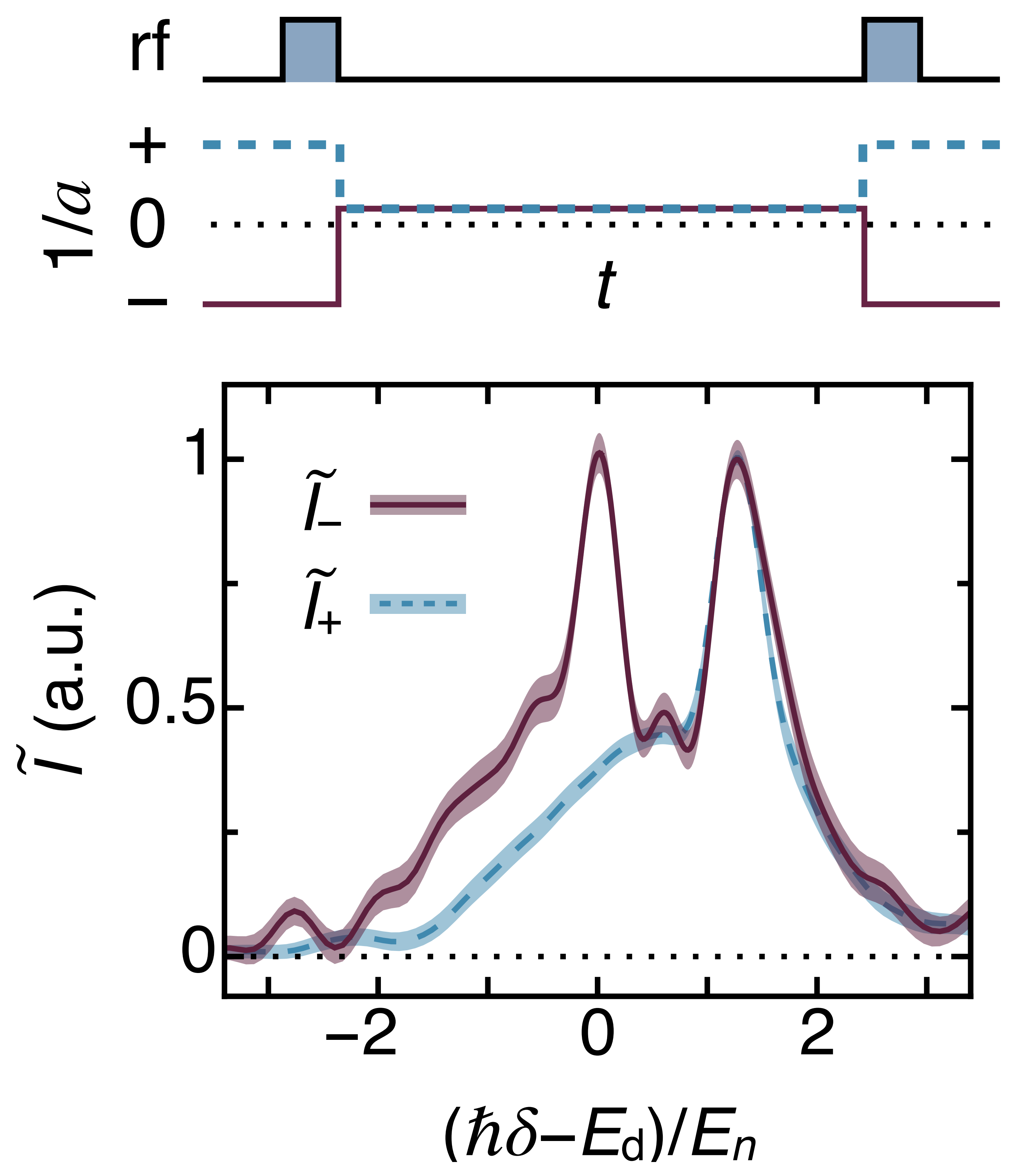

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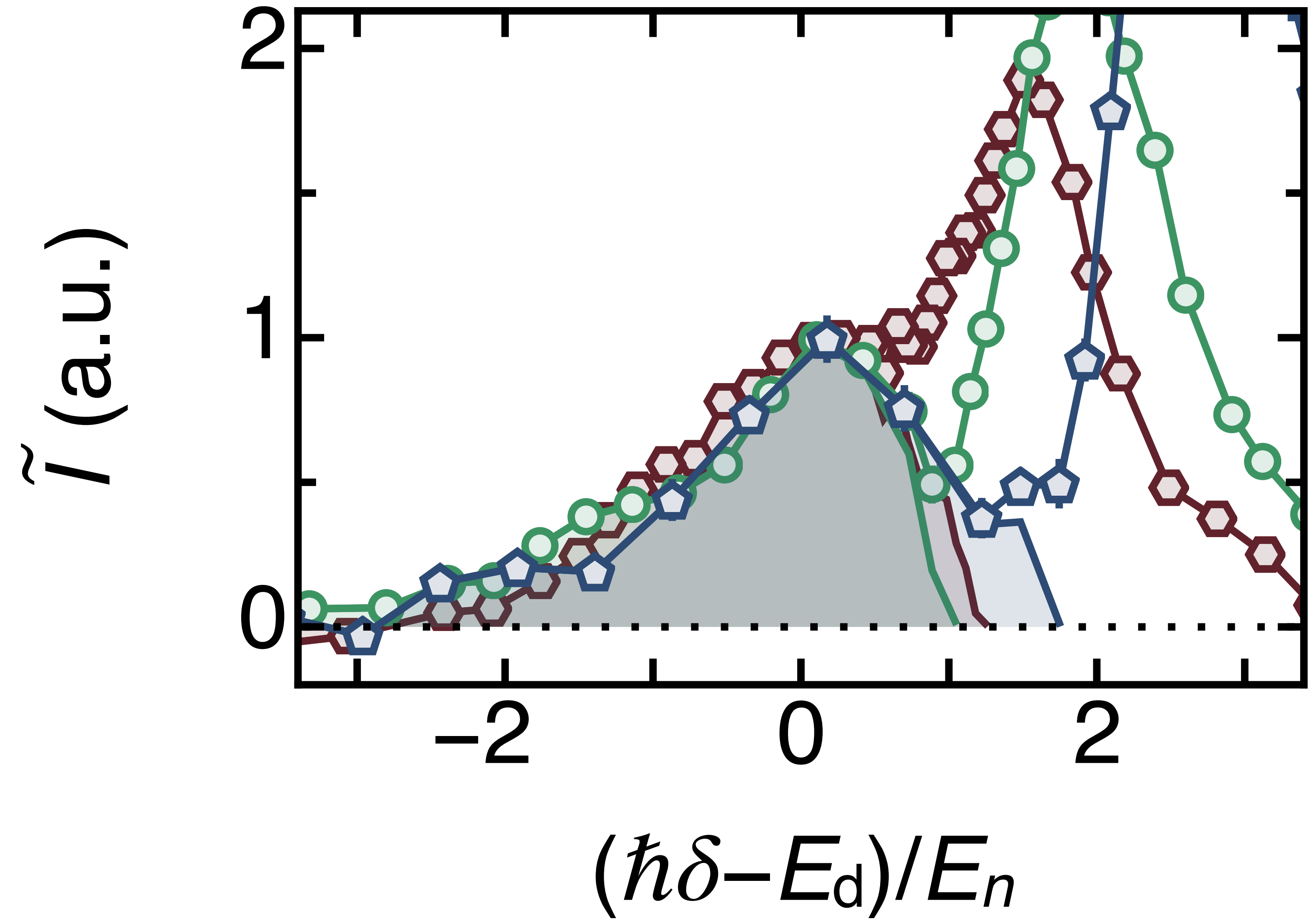

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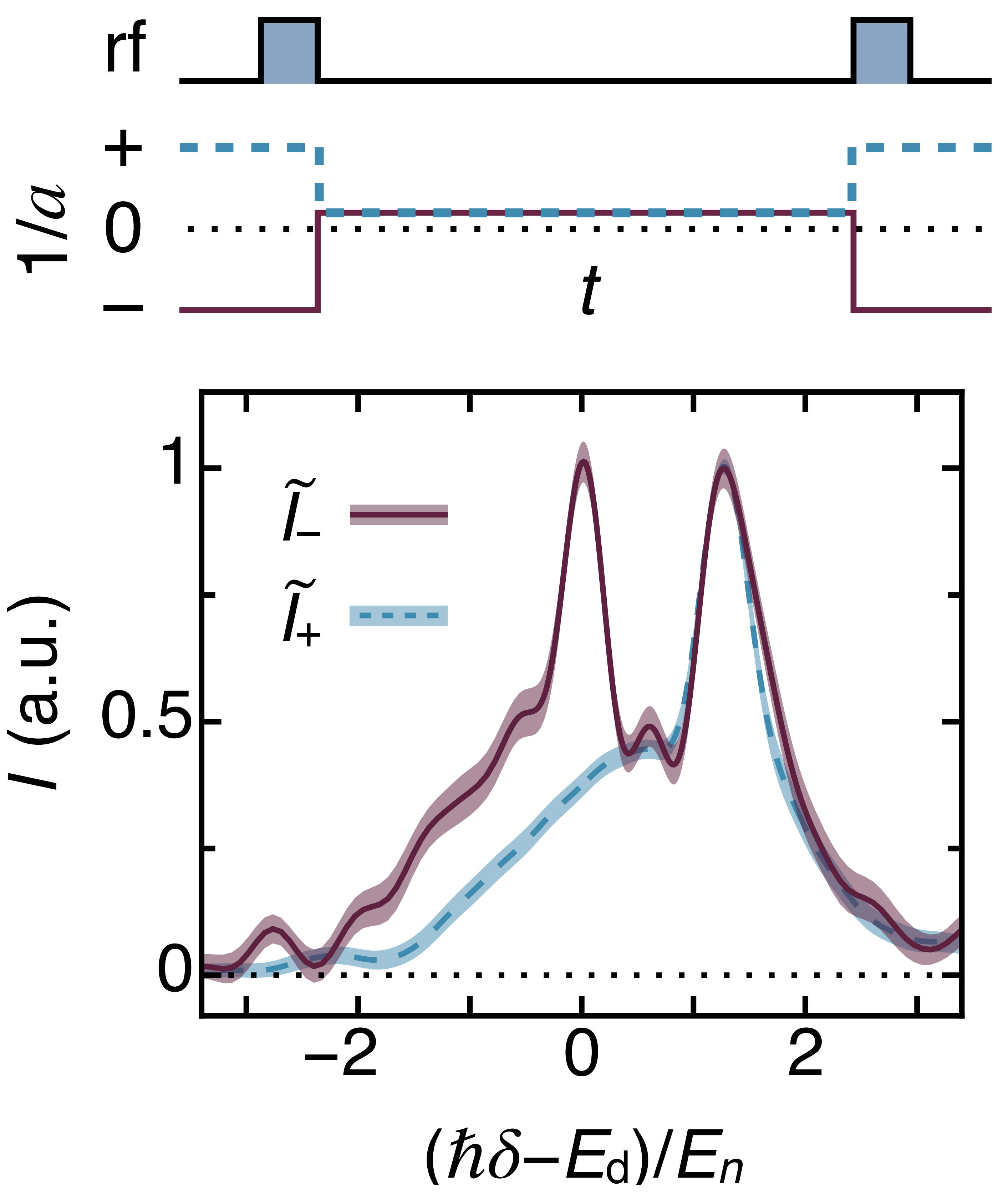

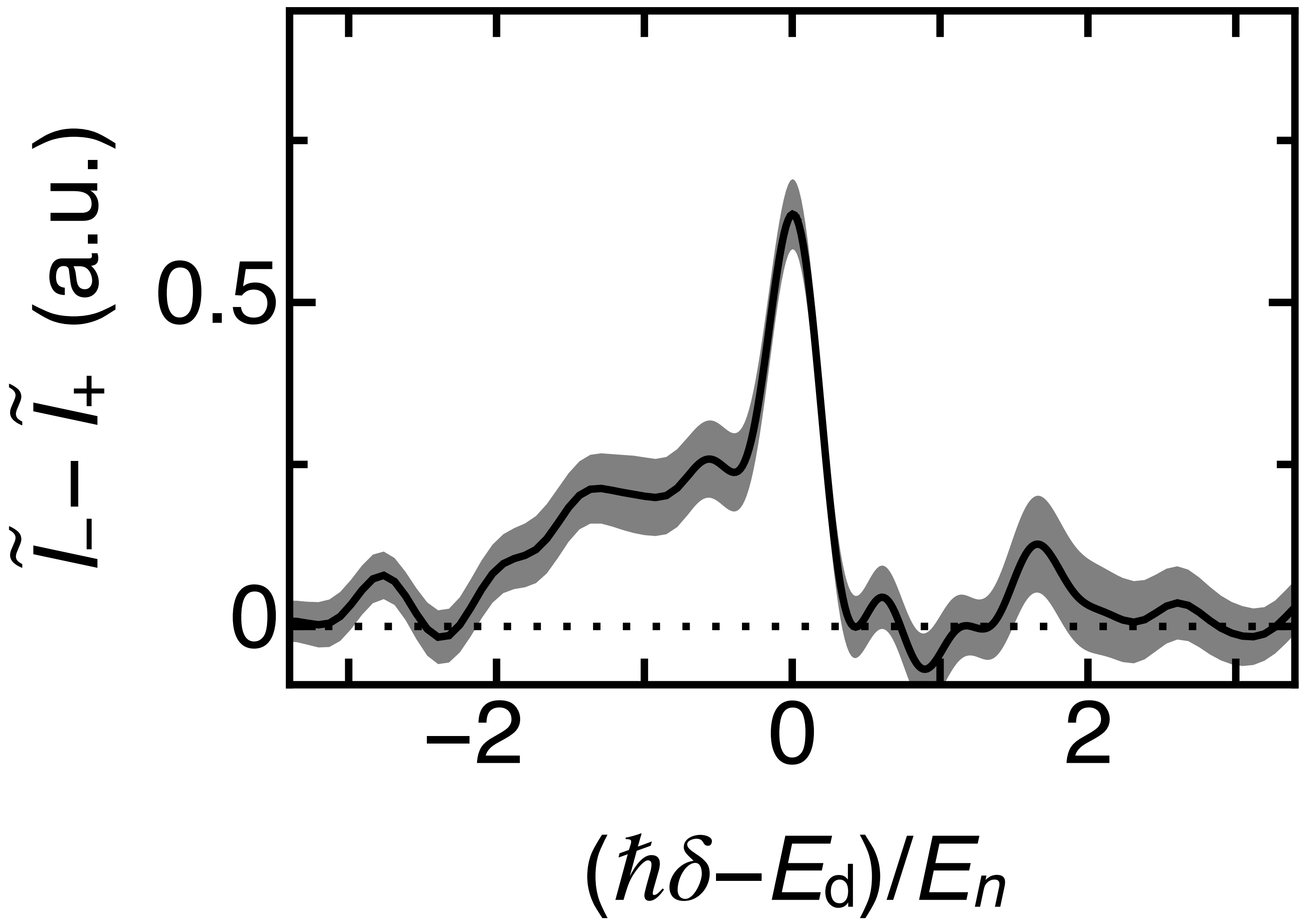

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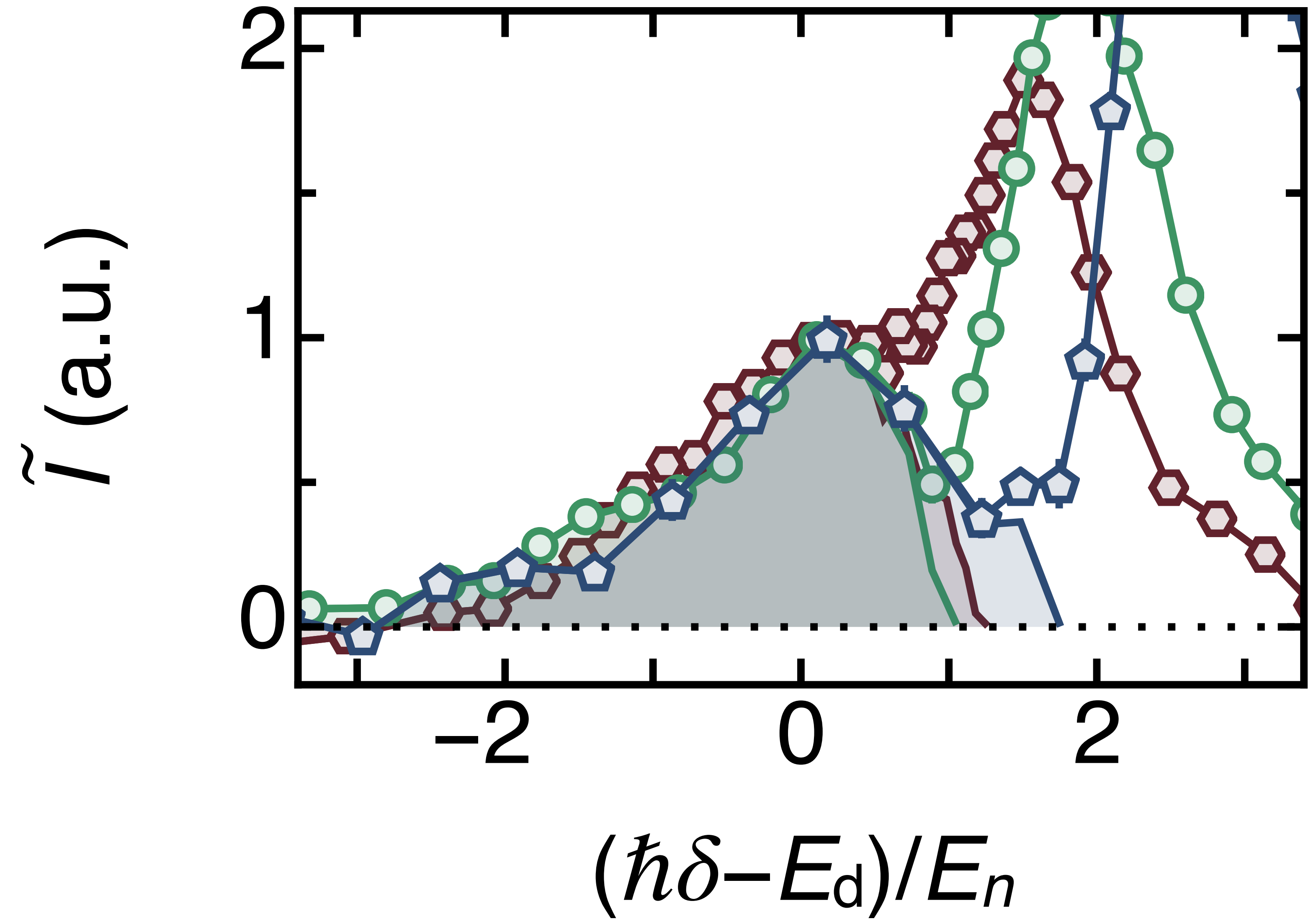

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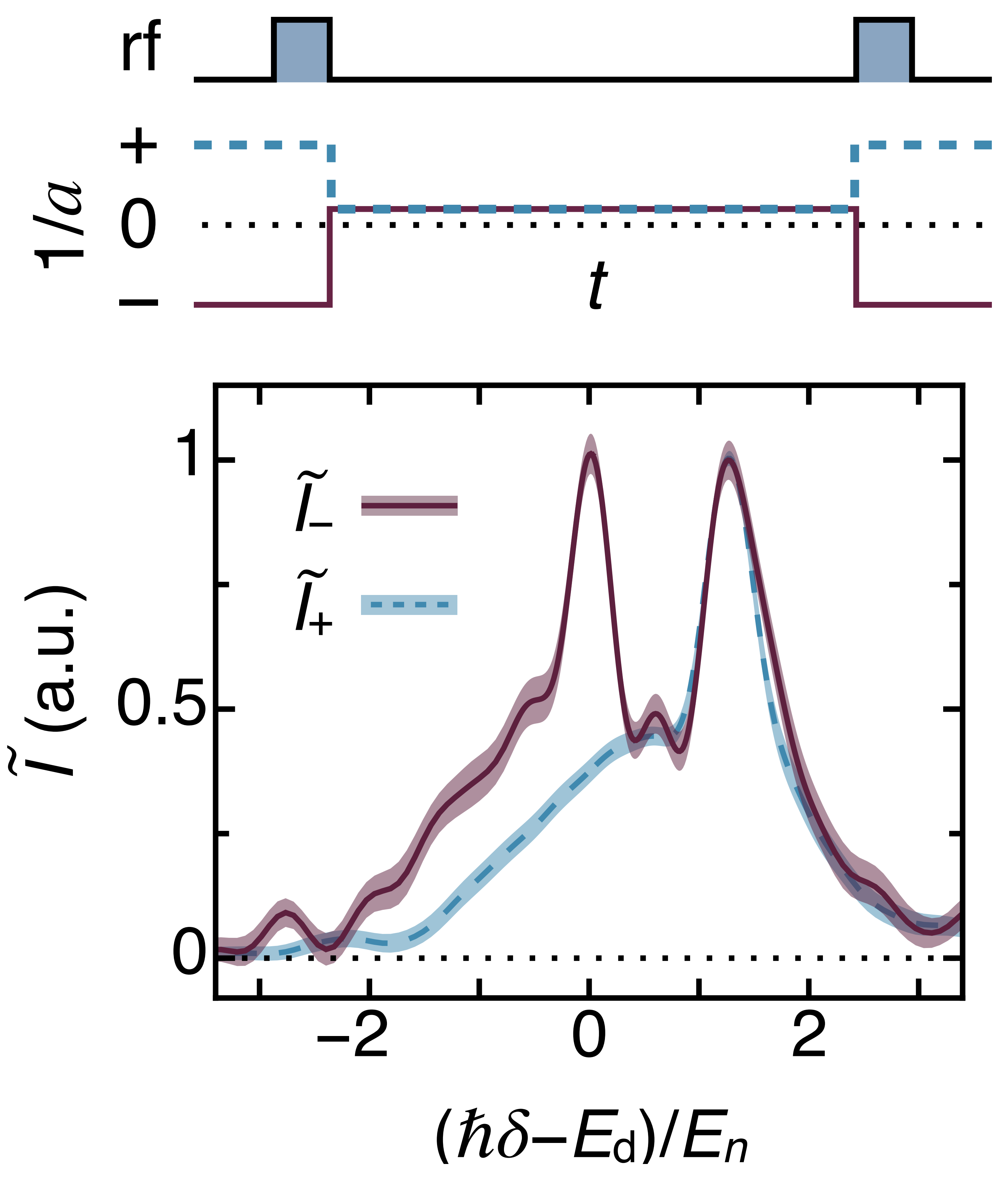
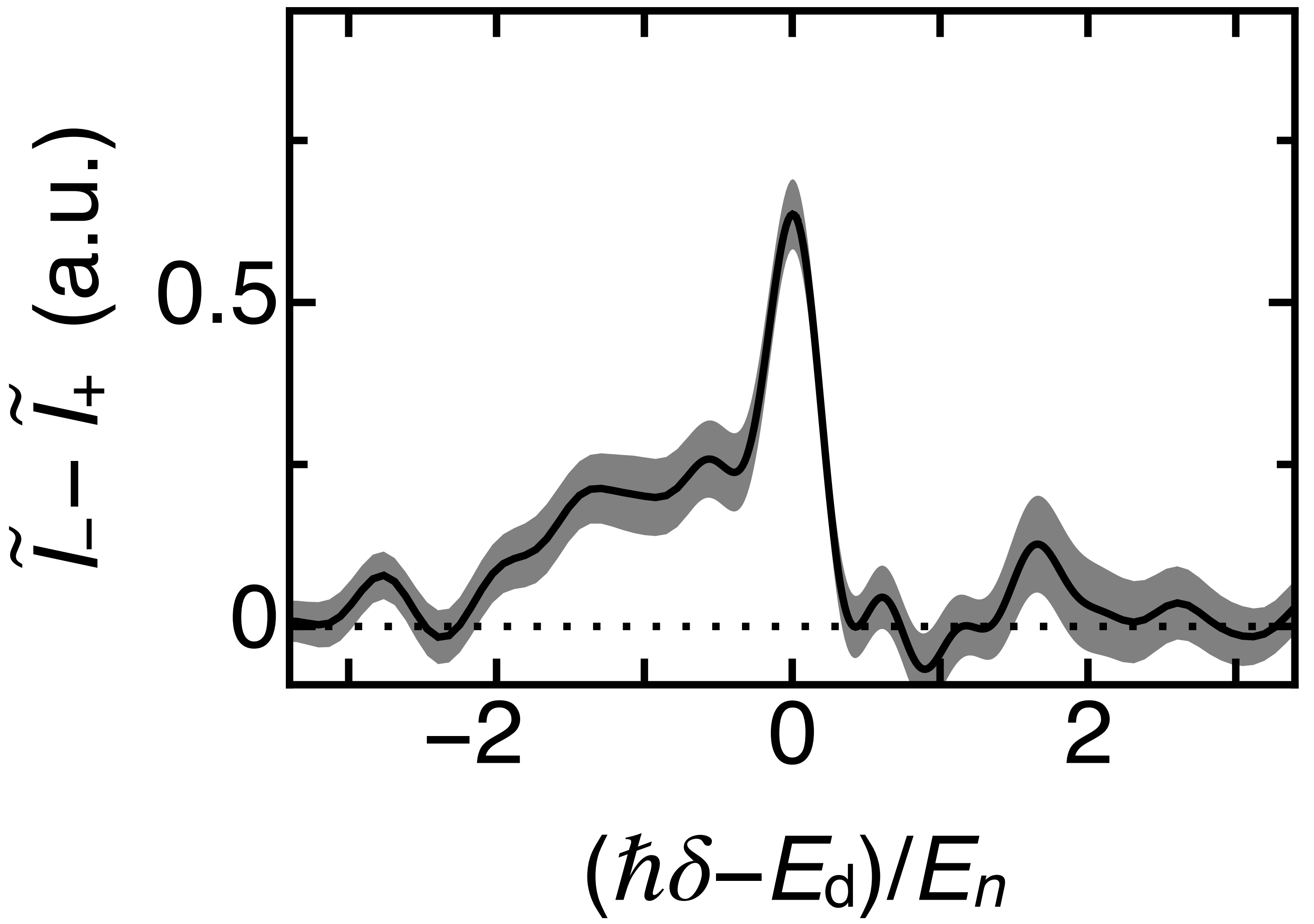


many-body state(s) with attractive-polaron character (with energy $\approx E_n$ below E_d)



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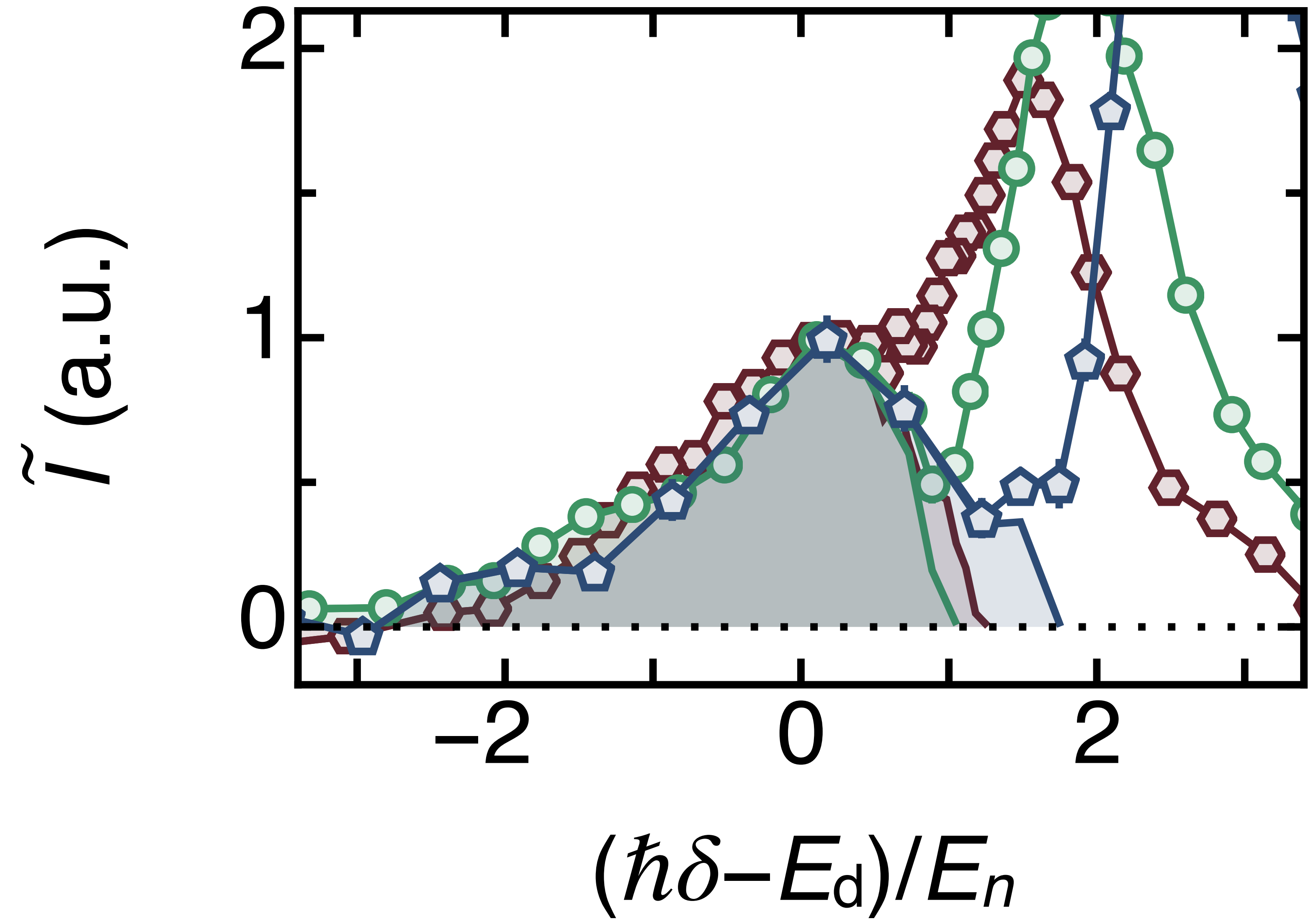
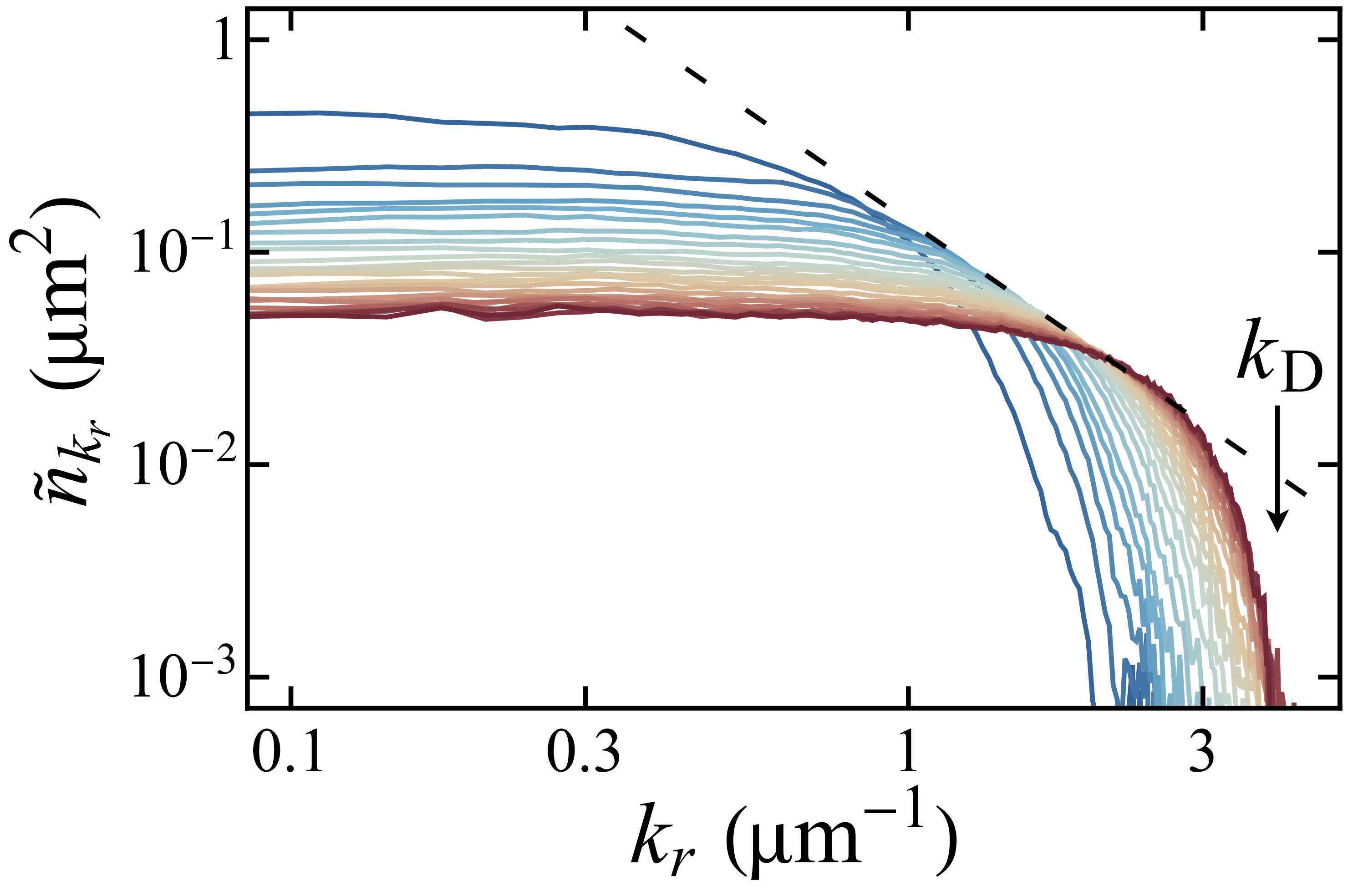


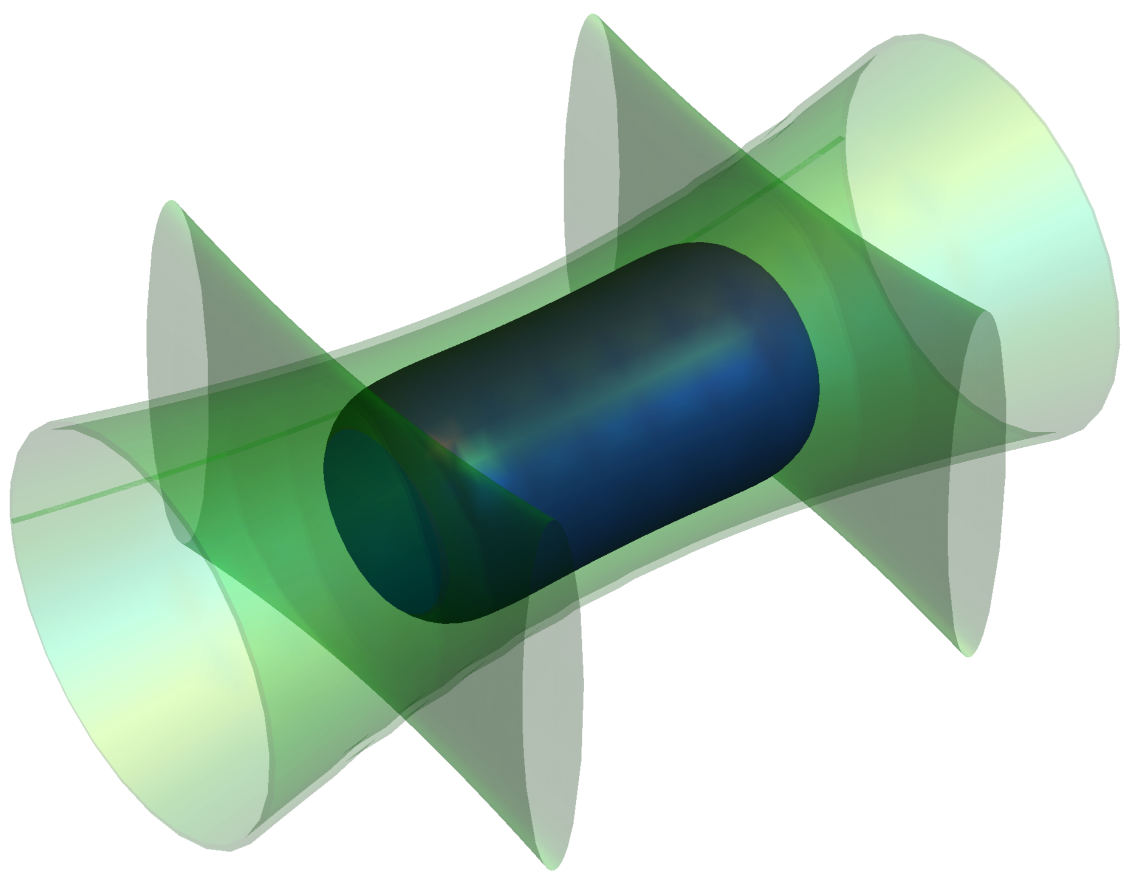
J. Etrych *et al.*, arXiv:2402.14816 (2024)

Conclusion & Outlook

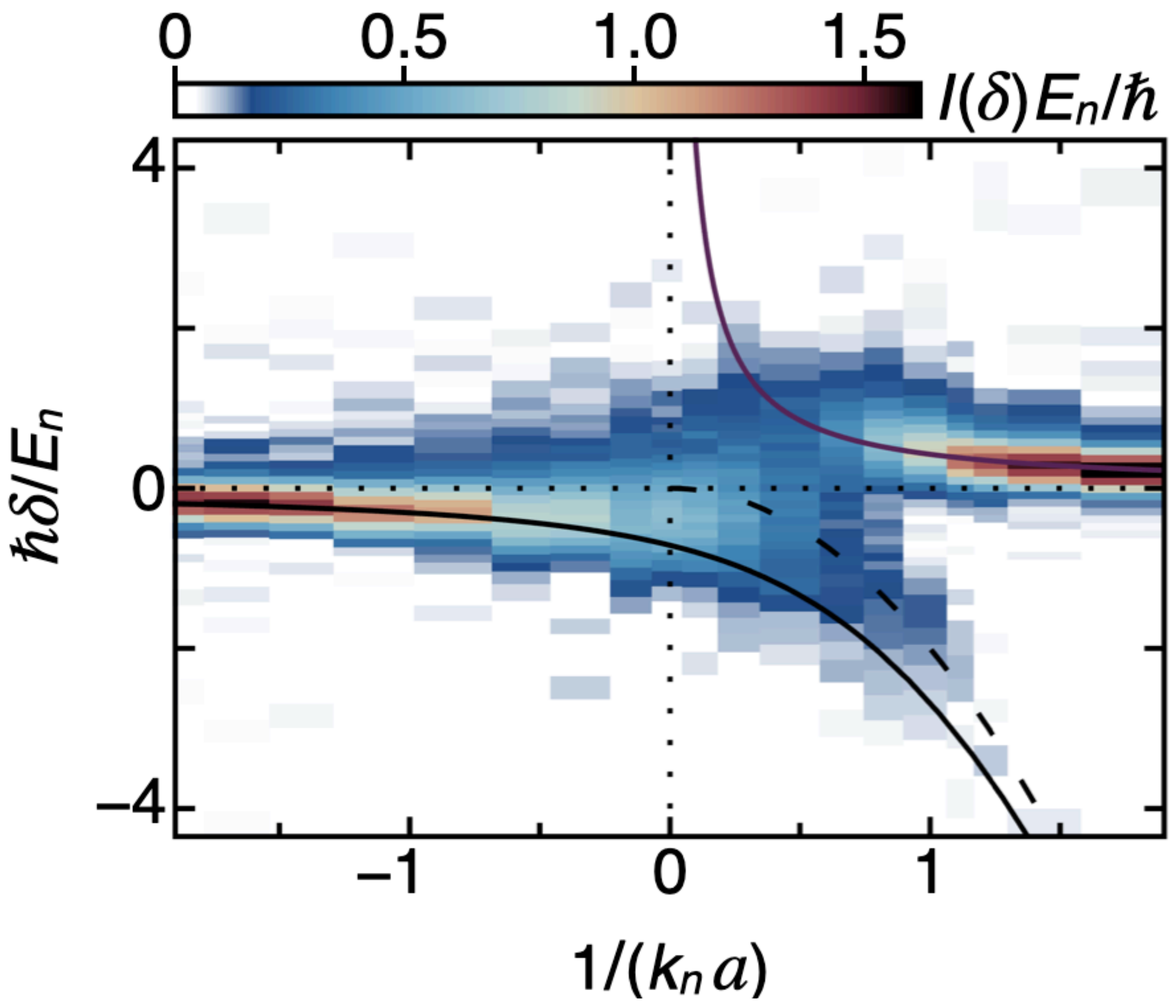
Energy-space random walk



- ✦ dynamic phase diagram?
- ✦ stronger disorder (localization)
- ✦ useful far-from-eq. state!



Bose polarons



- ✦ bipolarons?
- ✦ effective mass?
- ✦ fate of polarons at finite temperature

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Seb Morris

Simon Fischer

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QSimFP

UKRI
Science and Technology Facilities Council

EPSRC
Engineering and Physical Sciences Research Council

DesOEQ

Christoph Eigen

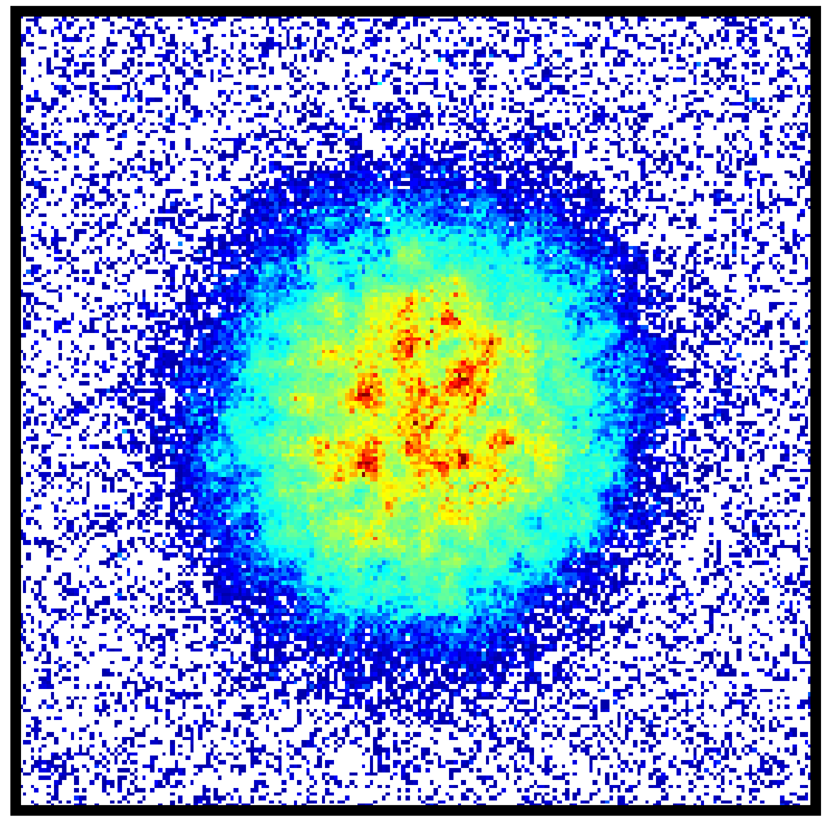
UNIVERSITY OF CAMBRIDGE

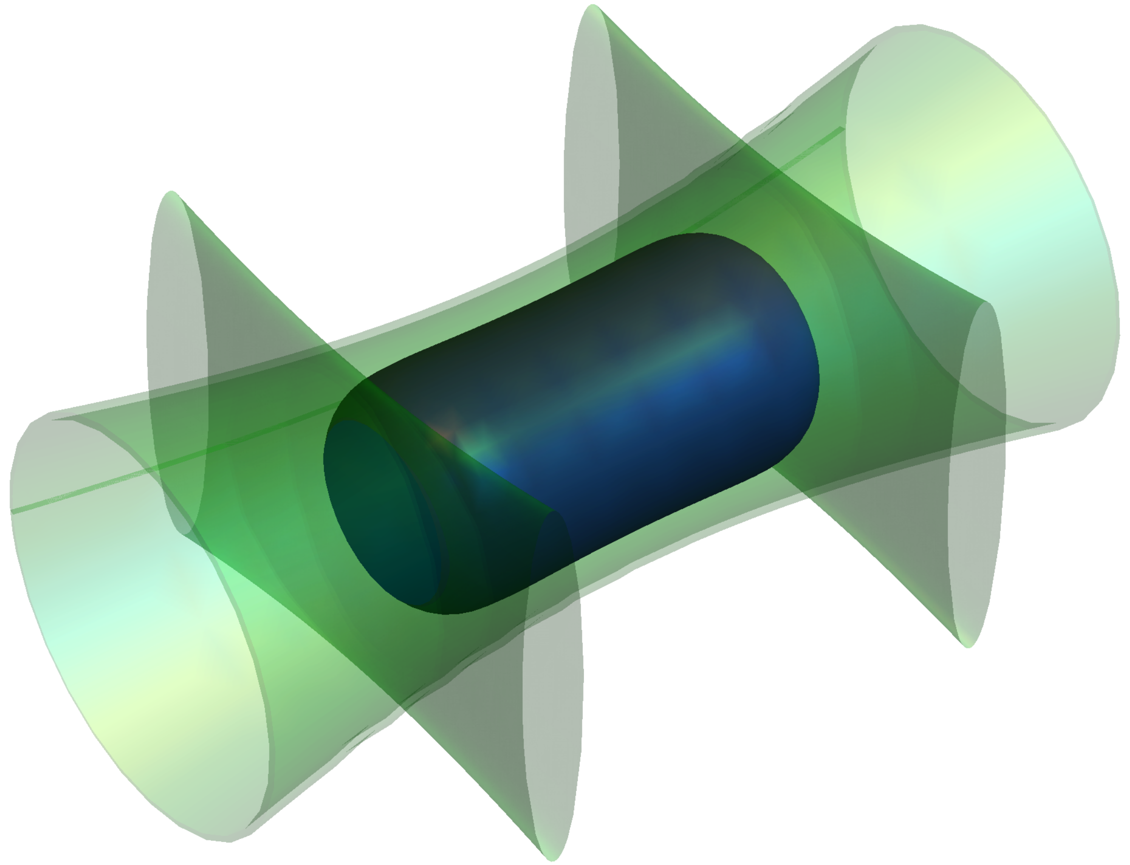
ECT Workshop, Trento

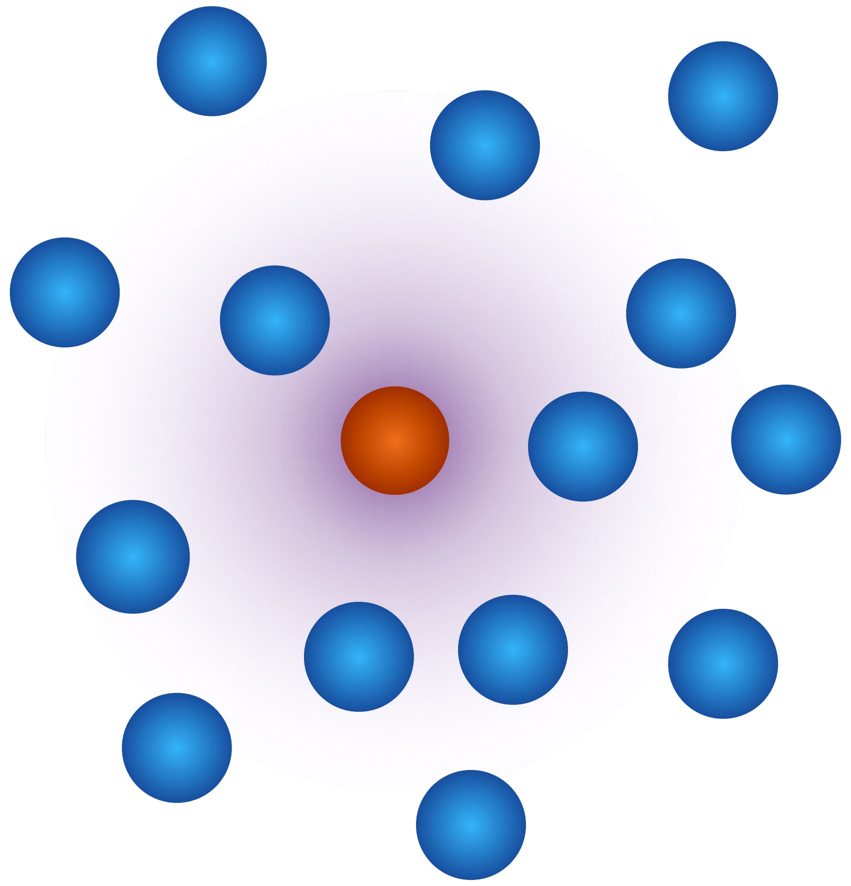
The physics of strongly interacting matter

April 25th, 2024

Thank you!







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