Effects of interactions on Bose-Einstein condensation

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Experiment
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Theory w/
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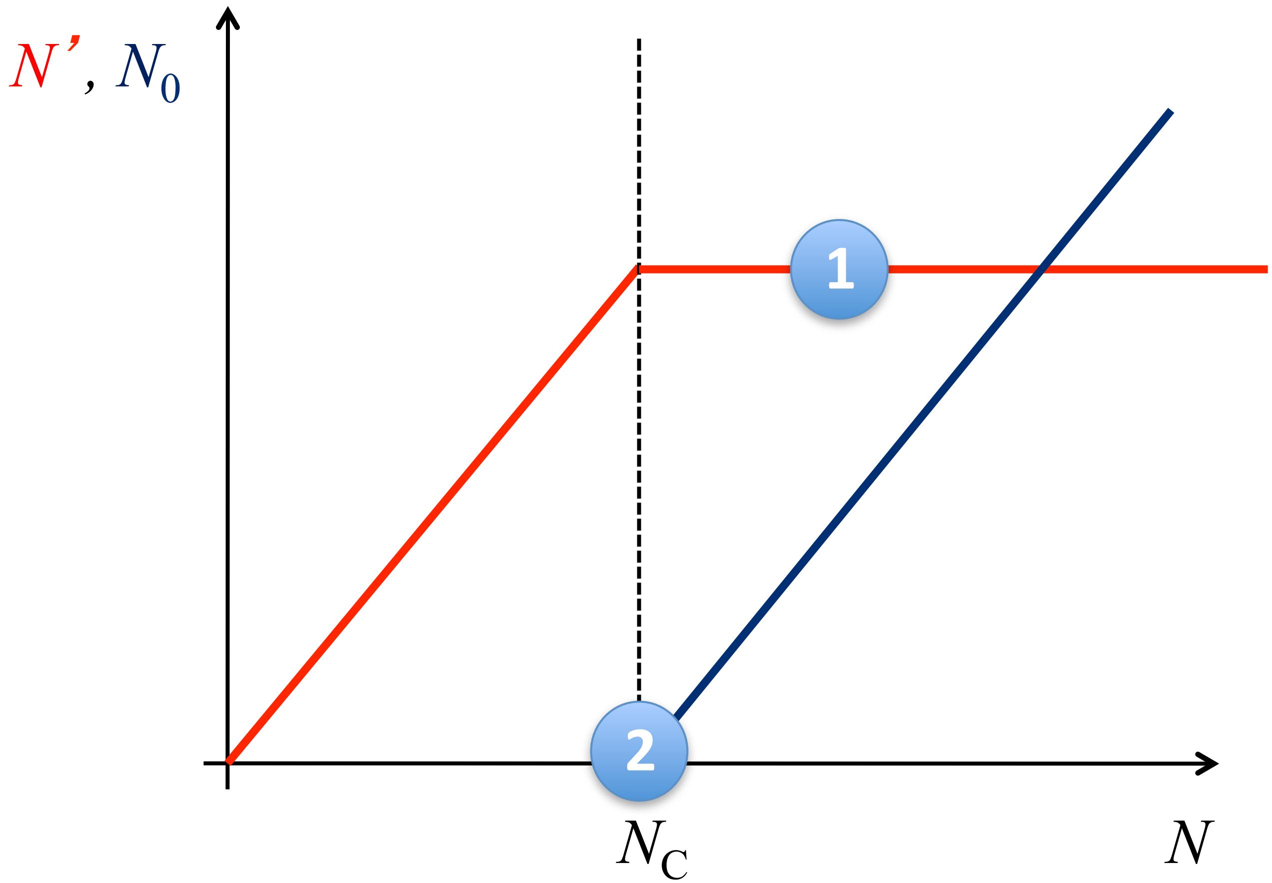
EPSRC
Engineering and Physical Sciences Research Council

Basic (Einstein's) picture of BEC

3D, ideal gas, constant *T*, vary *N*:

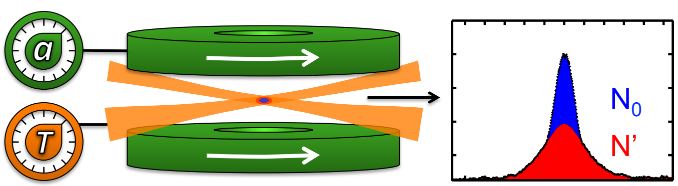


3 Non-equilibrium effects

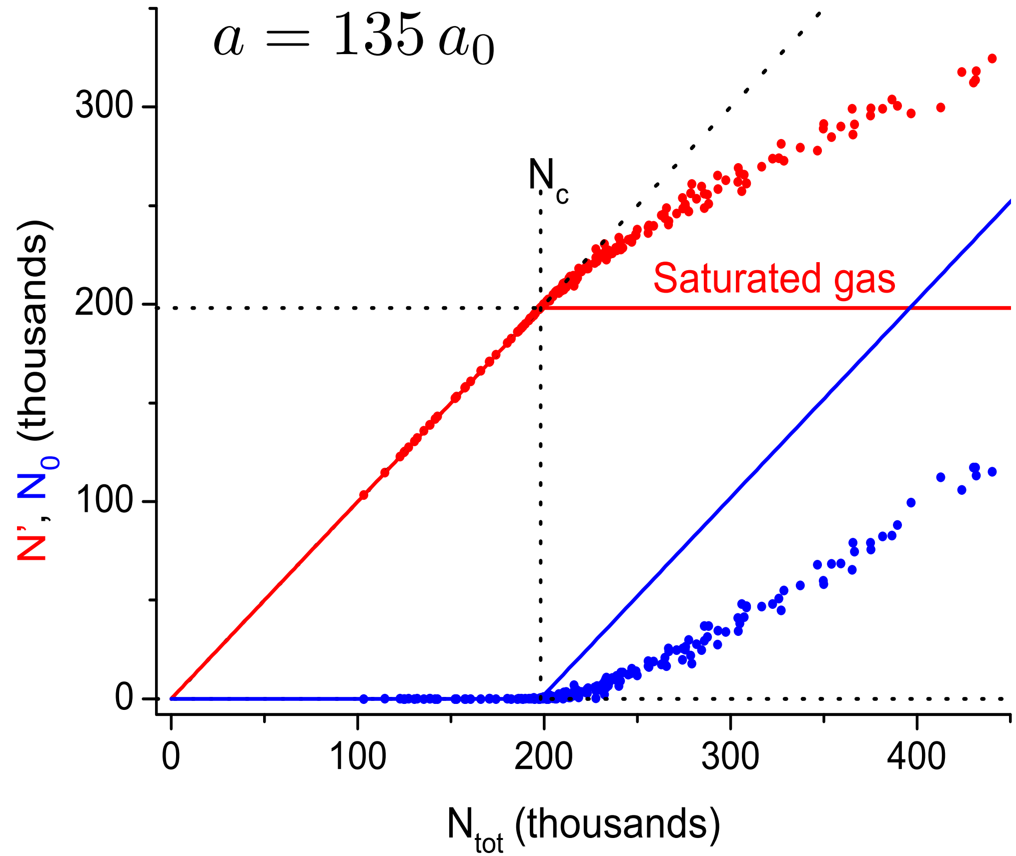
1

Saturation?

Not even close…

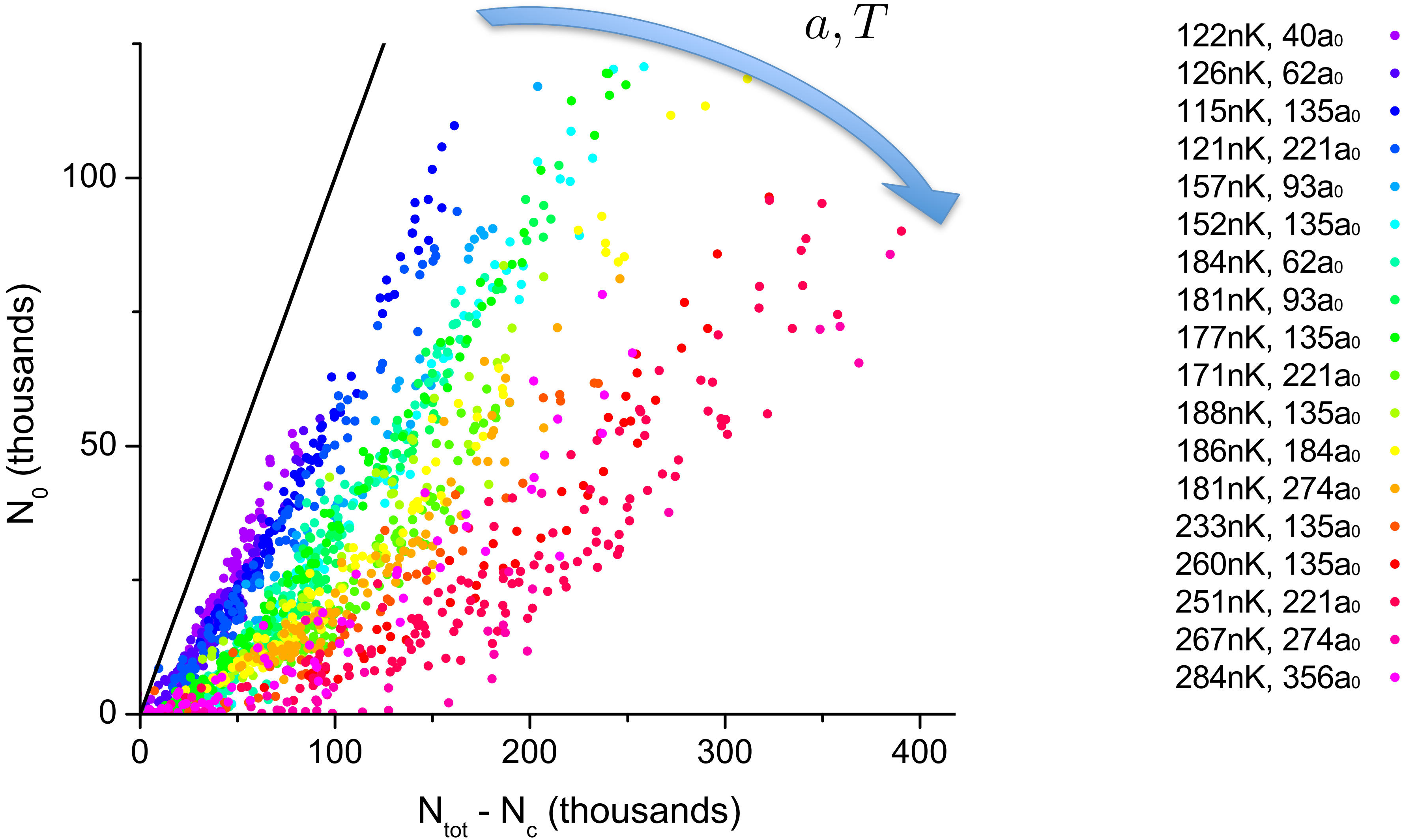


^{39}K, broad Feshbach at 402 G



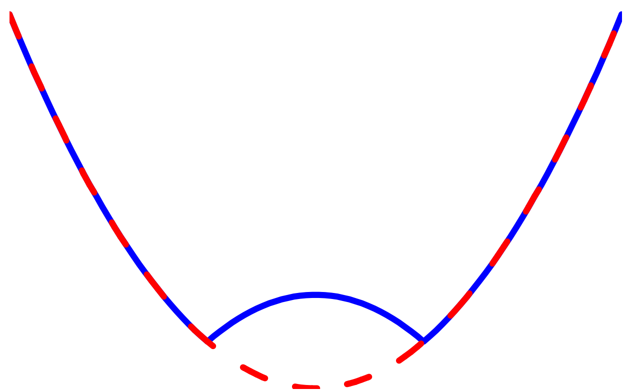
N. Tammuz *et al.*, PRL 2011

Dependence on interactions and temperature



Simplest theory

Hartree-Fock, thermal atoms interact only w/ the denser BEC, feel a Mexican hat potential



$$\frac{N'}{N_c} \approx 1 + 1.37\,\frac{\mu_0}{k_B T}$$

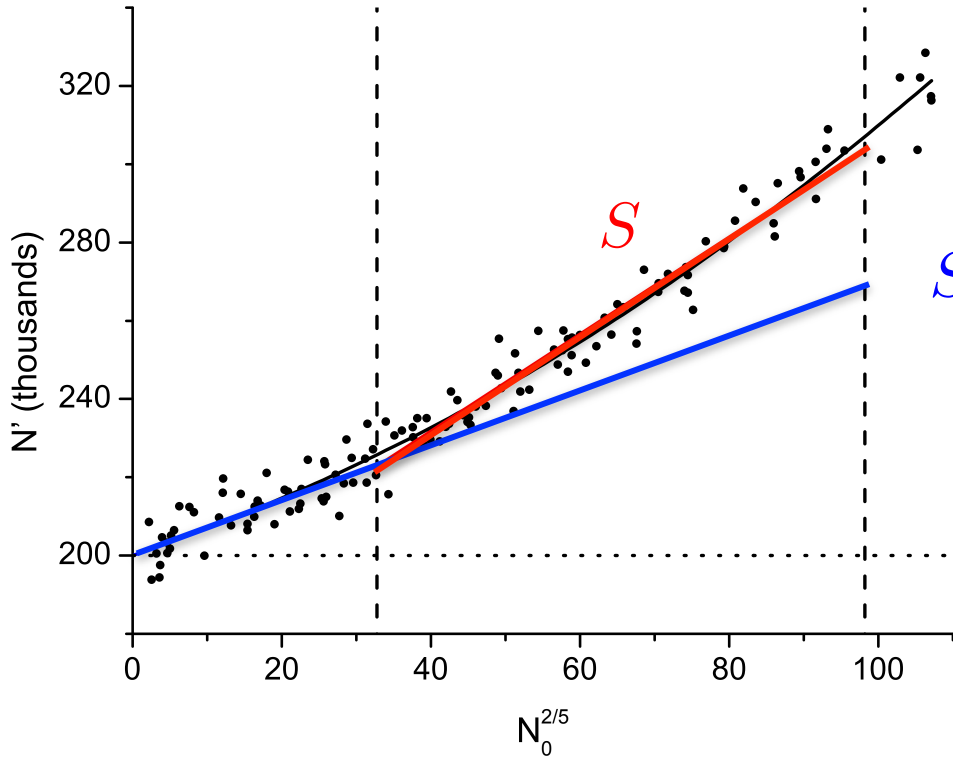
Following Stringari et al. cca 1996

$$\mu_0 \propto (N_0 a)^{2/5}$$

Non-saturation slope:

$$S_{\mathrm{HF}} = \frac{dN'}{dN_0^{2/5}} = 1.37\,X \qquad X = \xi a^{2/5} T^2$$

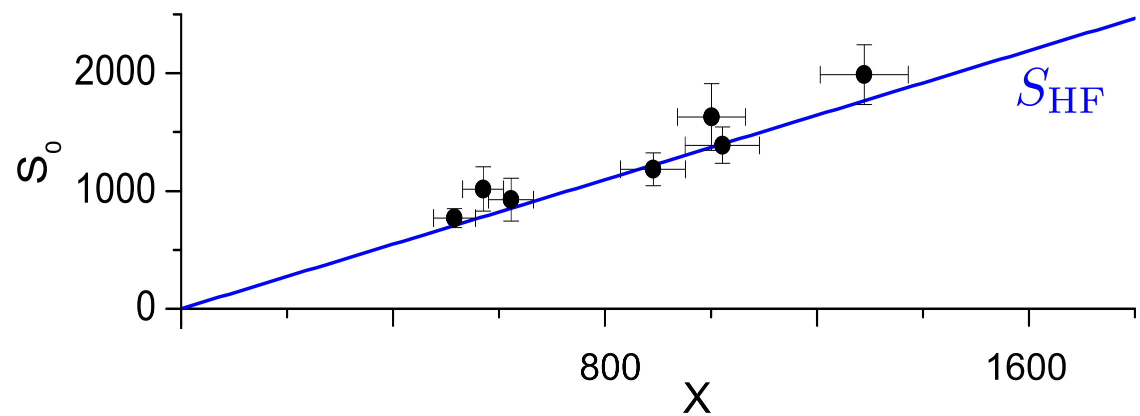
Comparison with experiments



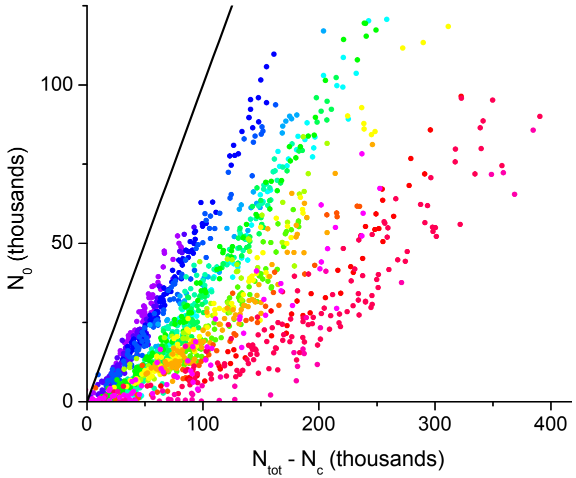
$$S_0 = S_{\mathrm{HF}} = 1.37\,X$$

vary a, T

$$X \propto a^{2/5} T^2$$

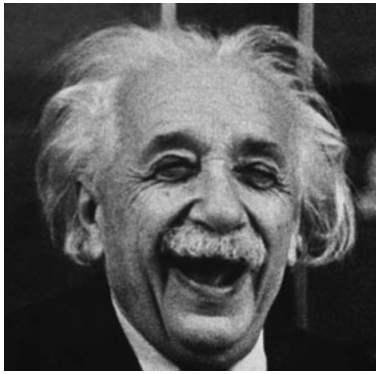


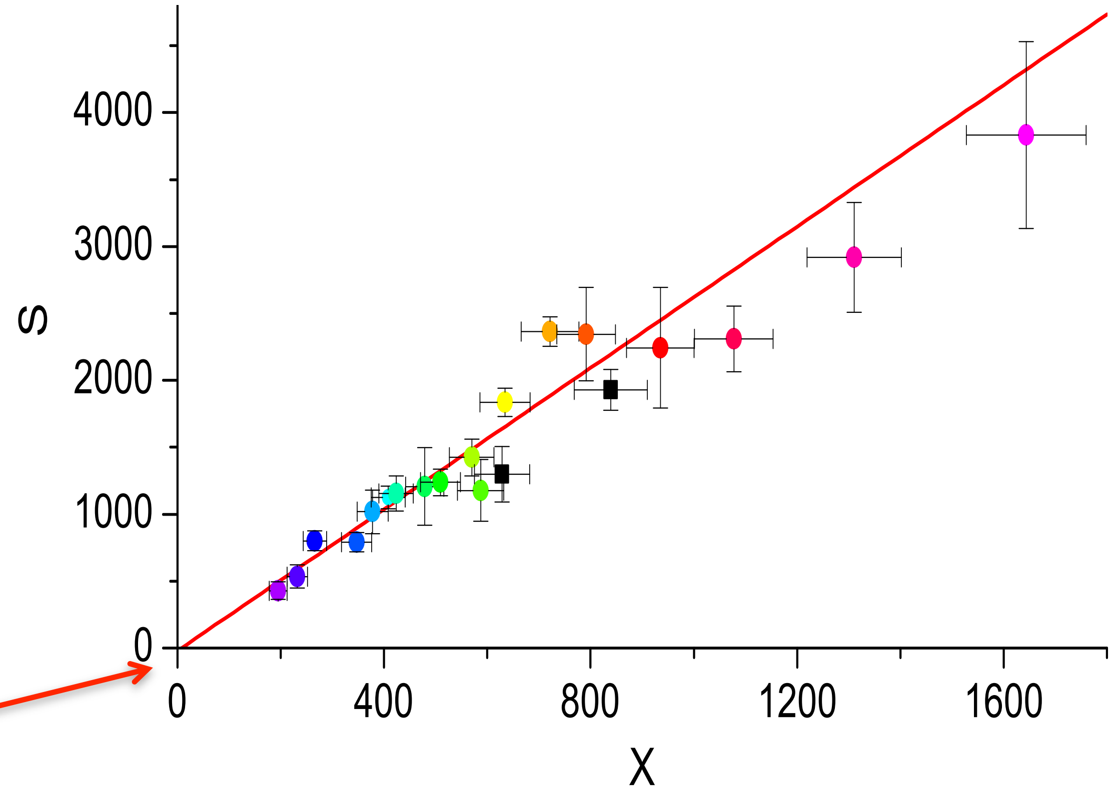
Saturation in the non-interacting limit



all ^{39}K data
+ some ^{87}Rb

$$X \propto a^{2/5} T^2$$





$$S(0) = -20 \pm 100 \qquad dS/dX = 2.6(3)$$

2

Critical point of a dilute Bose gas

Discussed since Lee & Yang 1957…

- Ideal gas: $n\lambda_0^3 = \zeta(3/2) \approx 2.612$

- Uniform system: $$\frac{\Delta T_c}{T_c^0} \approx +1.8\frac{a}{\lambda_0} + \ldots$$

Stoof et al., Baym et al., Prokof' ev & Svistunov, Arnold & Moore...

beyond-MF effect!

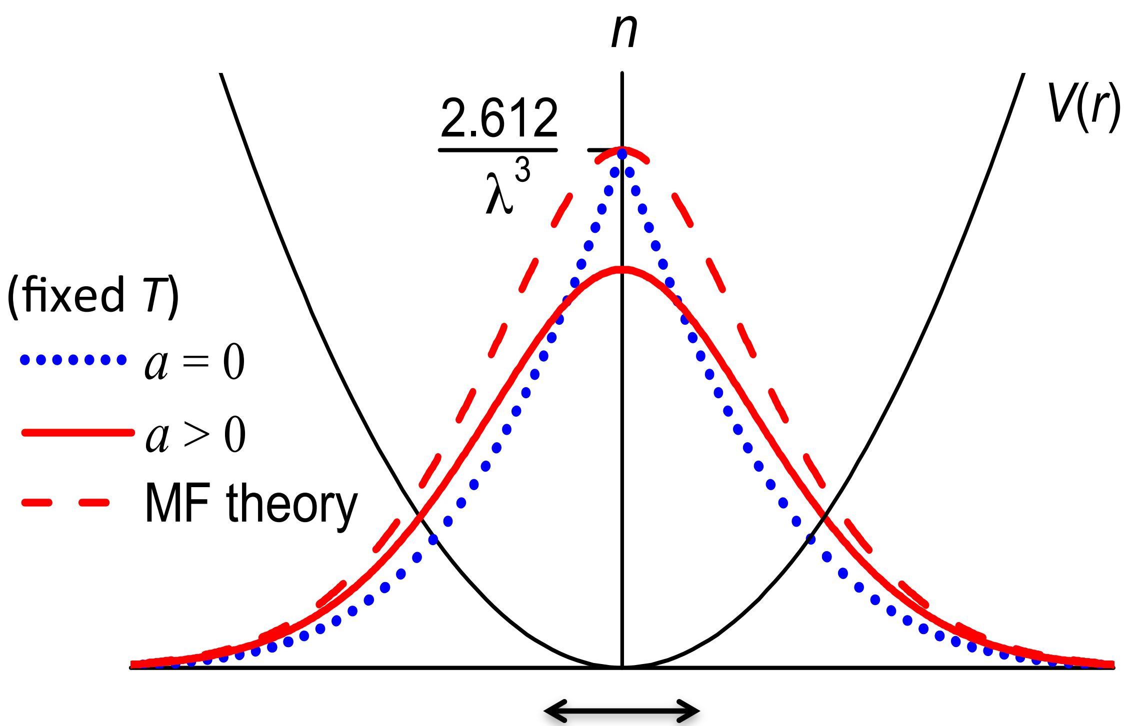
- Harmonic trap: $$\frac{\Delta T_c}{T_c^0} \approx -3.426\frac{a}{\lambda_0} + \ldots$$

Stringari et al.

MF! beyond-MF

Two competing effects in a trapped gas

at the critical point…

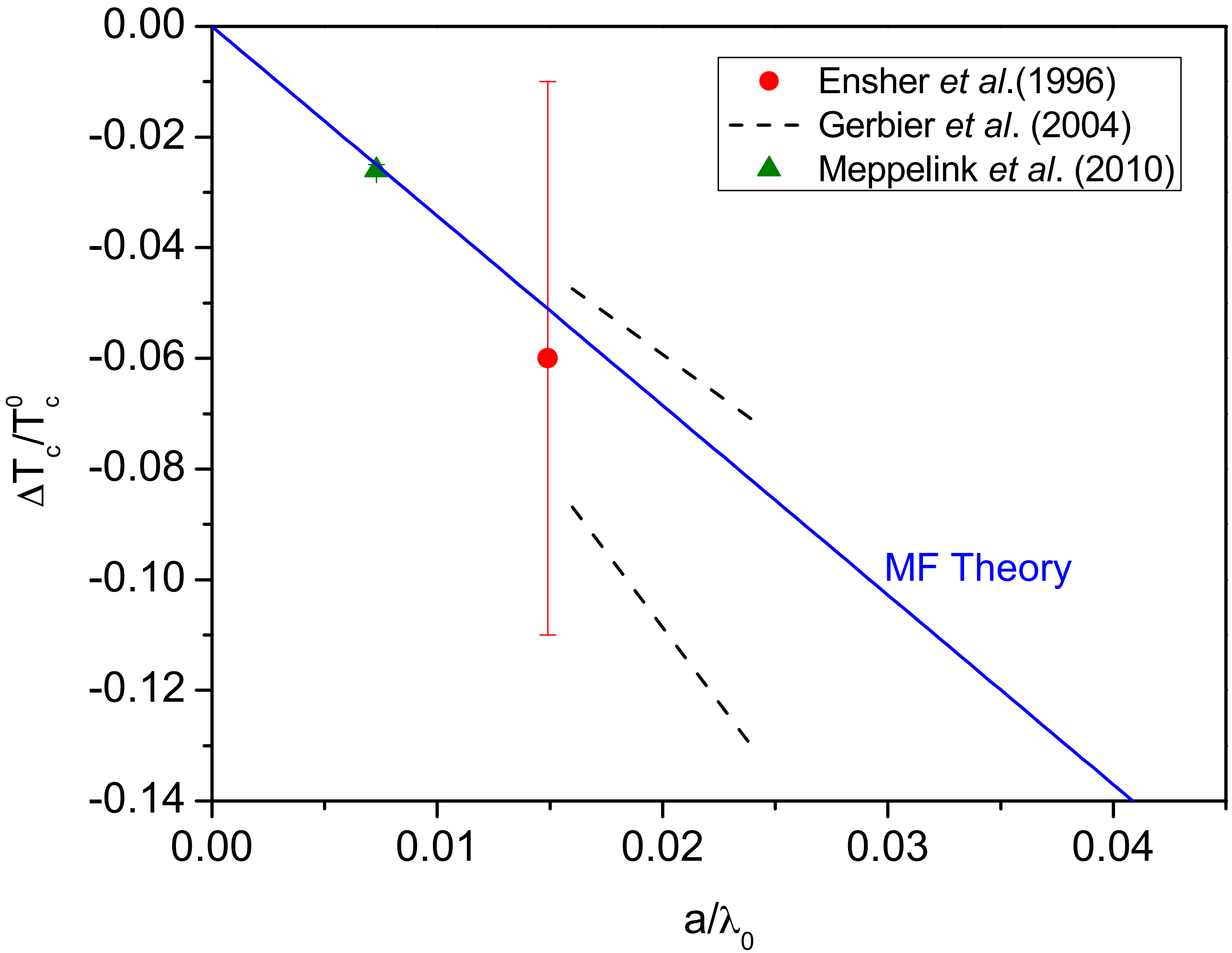


critical region: $r_c \sim a/\lambda_0$

MF exact
to 1st order

$$\frac{\Delta T_c}{T_c^0} = -3.426\frac{a}{\lambda_0} + \ldots$$

Previous T_C measurements



all consistent with MF

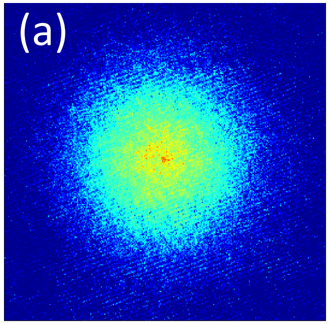
^{39}K Feshbach in our experiments

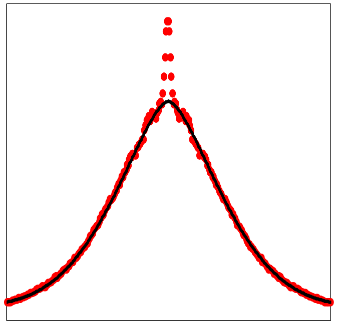
What we do differently…

1. Zoom-in on the critical point (precision)

interactions off during TOF,
detect very small condensates

$N_0/N \approx 0.14\%$





2. Differential measurements (accuracy)

Usually: <u>measure</u> $T_c(N, \omega, a)$ [or $N_c(T, \omega, a)$]

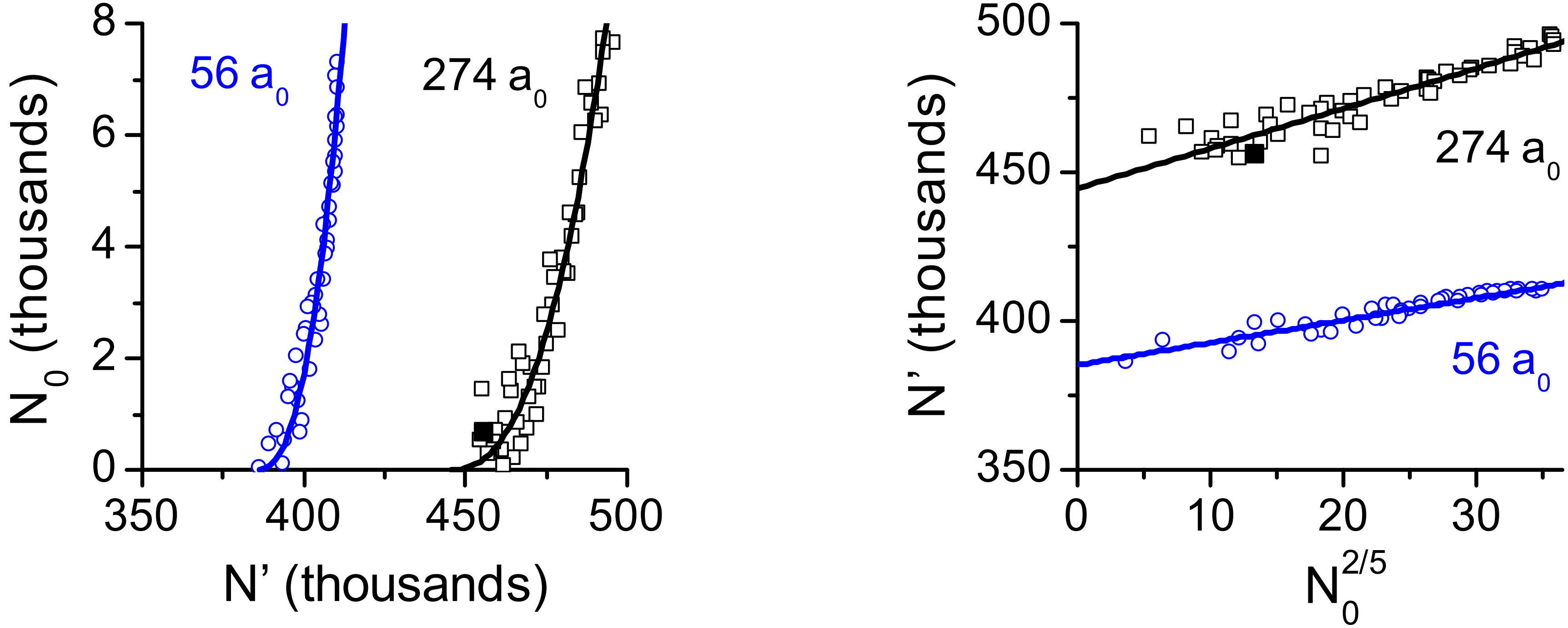
<u>calculate</u> $T_c(N, \omega, a = 0)$

Our work: <u>measure both</u> $T_c(N, \omega, a)$ and $T_c(N, \omega, \mathrm{small}\ a)$

(need thermal equilibrium)

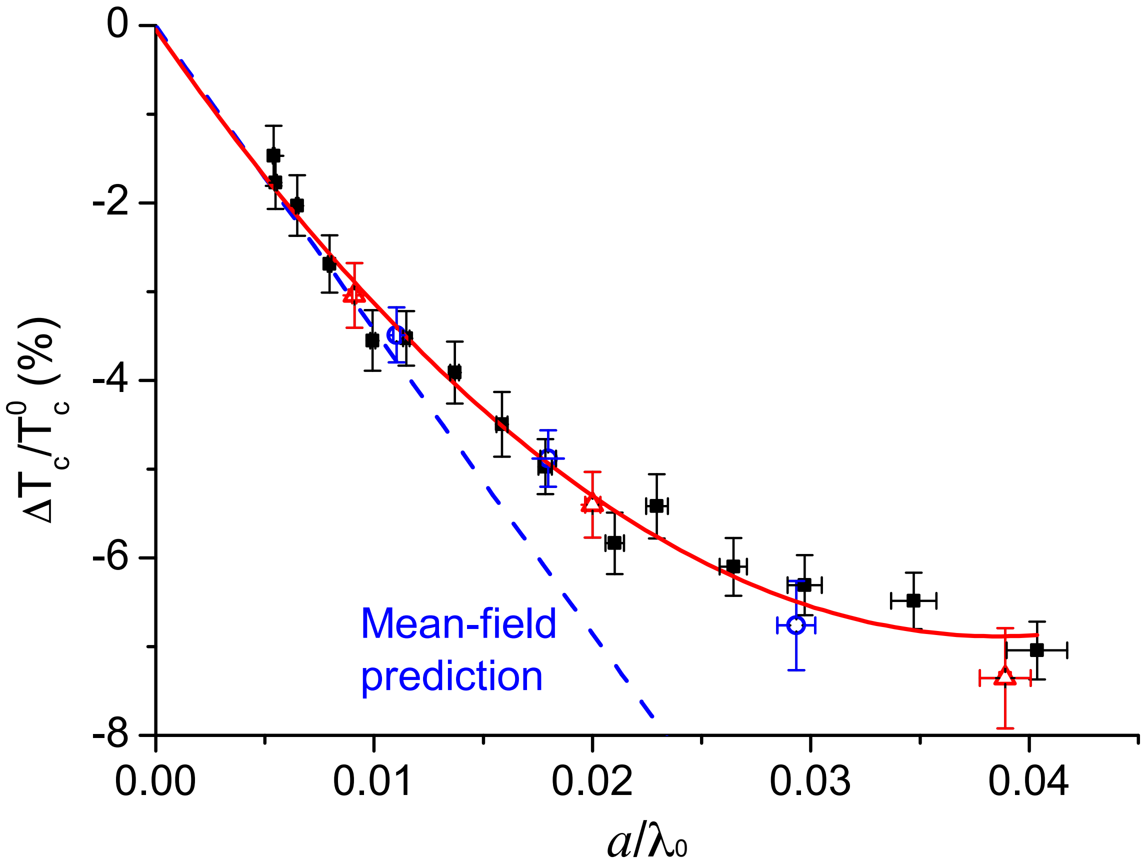
(Differential) critical point

Same T, ω , different a :



Beyond-MF T_C shift

R.P. Smith *et al.*, PRL 2011



different symbols:
$N = 2, 4, 8 \times 10^5$

$$\frac{\Delta T_c}{T_c^0} = -3.426\frac{a}{\lambda_0}$$

$$\frac{\Delta T_c}{T_c^0} = -3.5(3)\frac{a}{\lambda_0} + 46(5)\left(\frac{a}{\lambda_0}\right)^2$$

small print: neglect logarithmic corrections

3

(Non-)Equilibrium?

What does it take? $\gamma_{\rm el}\tau > \cancel{3}\quad 5$ $\qquad t_{\rm hold} > \tau > 1/\omega$

Not the whole story if we have constant dissipation…

relevant τ depends on the measurement precision

$$0.01\ N_c \quad \to \tau = 0.01/\gamma_{\rm loss}$$

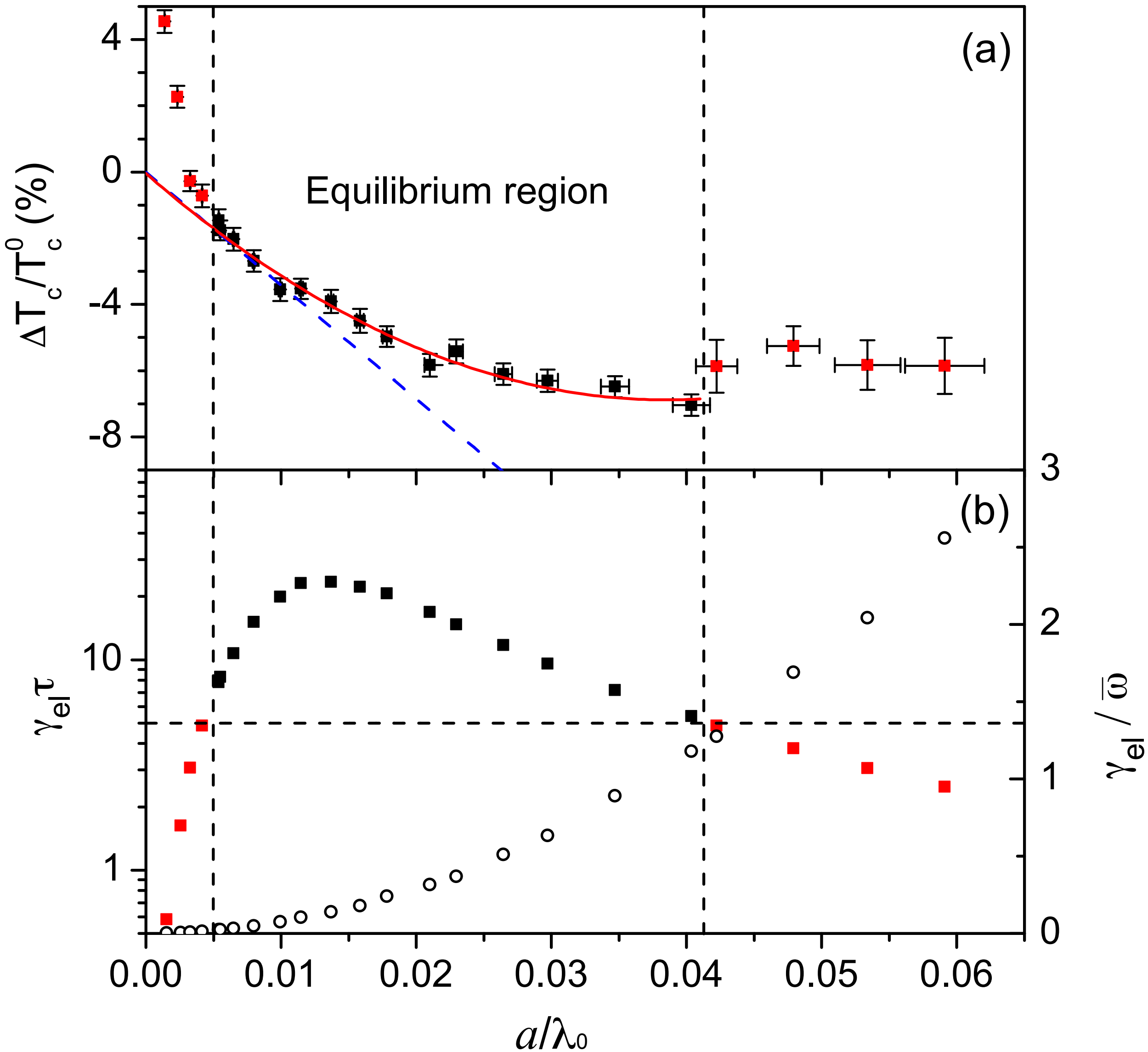
Two kinds of non-equilibrium:

1. "transient" – could reach equilibrium, but $t_{\rm hold}$ too short
2. "intrinsic" – thermalization slower than dissipation:

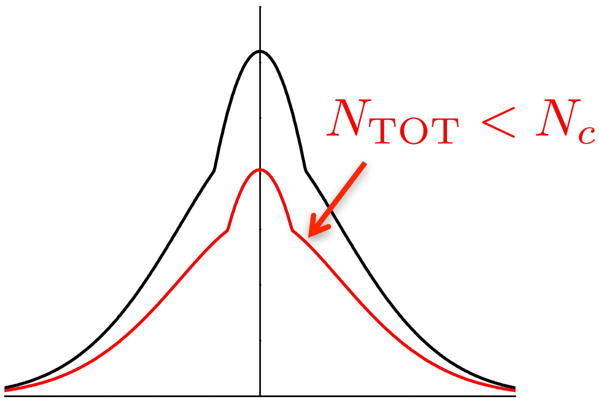
$$t_{\rm hold} > \tau > 1/\omega \ ✓ \qquad \gamma_{\rm el} t_{\rm hold} > 5 \ ✓$$

$$\text{but}\ \ \gamma_{\rm el}\tau < 5 \ ✗$$

Non-equilibrium effects



“super-heated” BECs in both extremes



R.P. Smith *et al.*, PRL 2011

4

new stuff...

Uniform vs. harmonic (again)

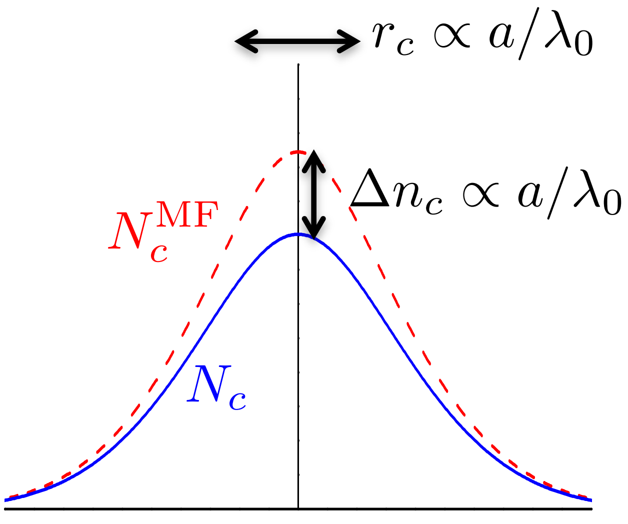
(subtract the trivial MF part)

Uniform system:

$$\frac{\Delta T_c}{T_c^0} = c\frac{a}{\lambda_0}$$

$$\Delta n_c \propto \frac{a}{\lambda_0}$$

Harmonic trap:



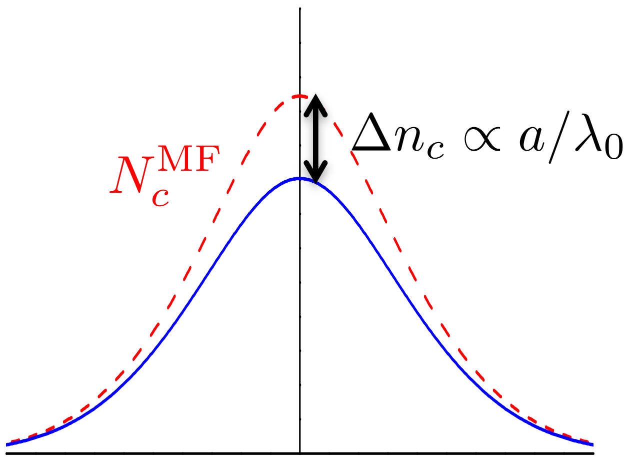
$$\mu_c^{\mathrm{MF}} - \mu_c \propto \left(\frac{a}{\lambda_0}\right)^2 \longleftrightarrow N_c^{\mathrm{MF}} - N_c \propto (a/\lambda_0)^2$$

$$\text{not } \; a/\lambda_0 \; \text{ or } \; (a/\lambda_0)^4$$

T_c shift in the harmonic trap dominated by the density shift *outside* the critical region

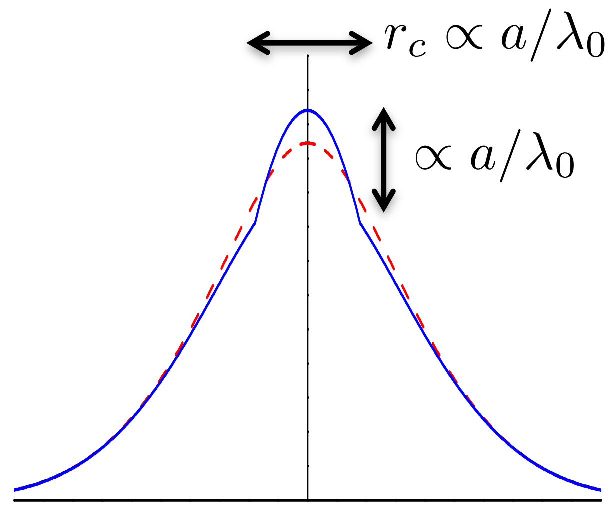
Condensed fraction induced by critical correlations

$$N = N_c < N_c^{\mathrm{MF}}$$



$$N_c^{\mathrm{MF}} - N_c \propto (a/\lambda_0)^2$$

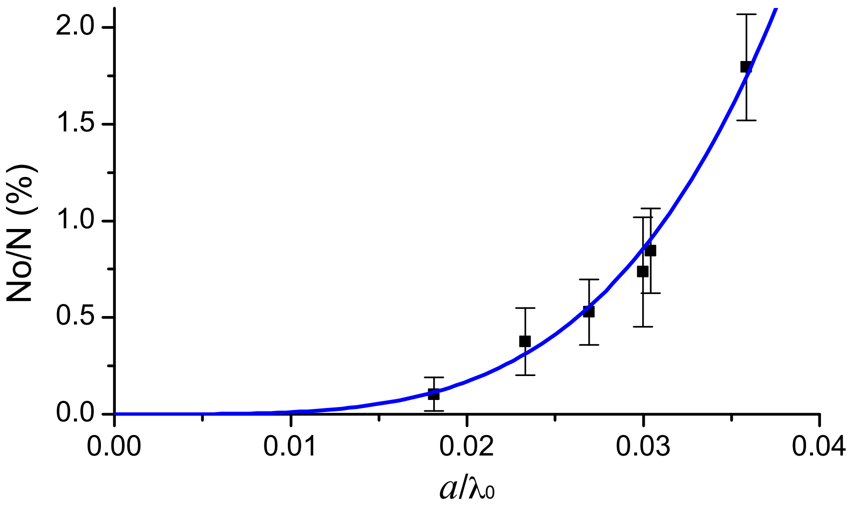
$$N = N_c^{\mathrm{MF}} > N_c$$

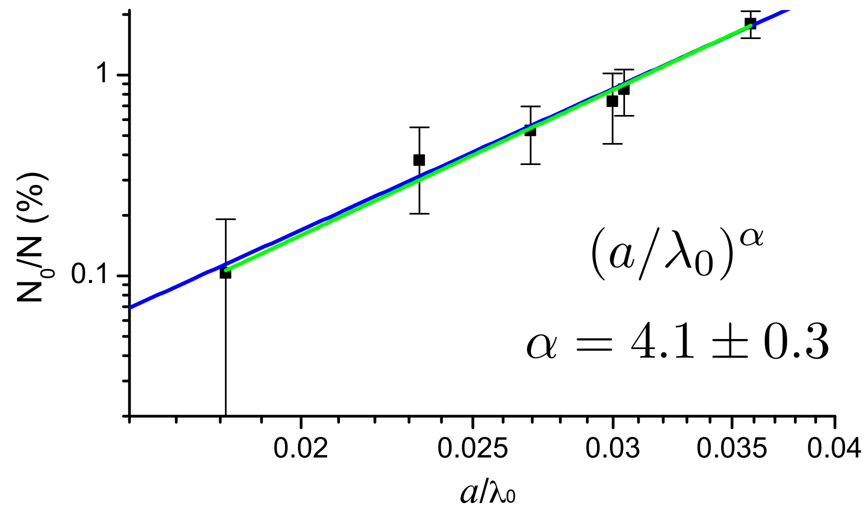


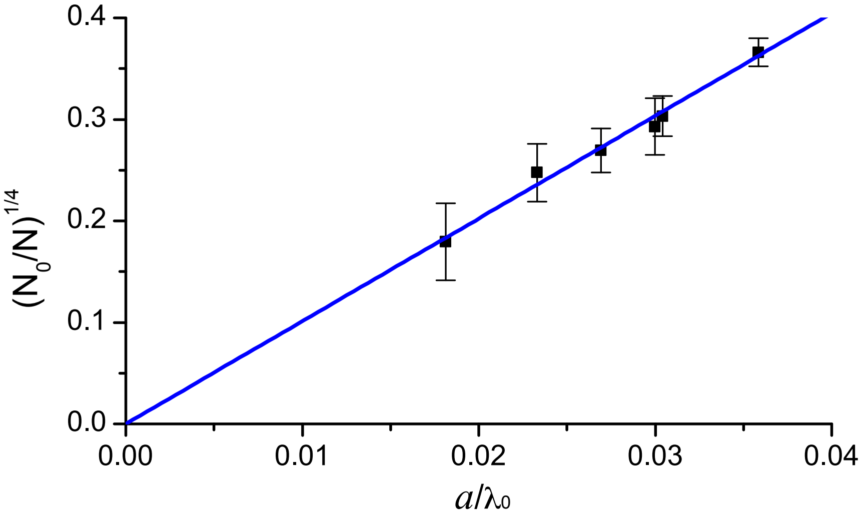
$$\boxed{\begin{array}{c}\text{iff } n_c^{\mathrm{MF}} - n_c \propto a/\lambda_0\,, \\ f_0 = N_0/N \propto (a/\lambda_0)^4\end{array}}$$

Baym & Holzmann
Prokof'ev & Svistunov

Preliminary data…



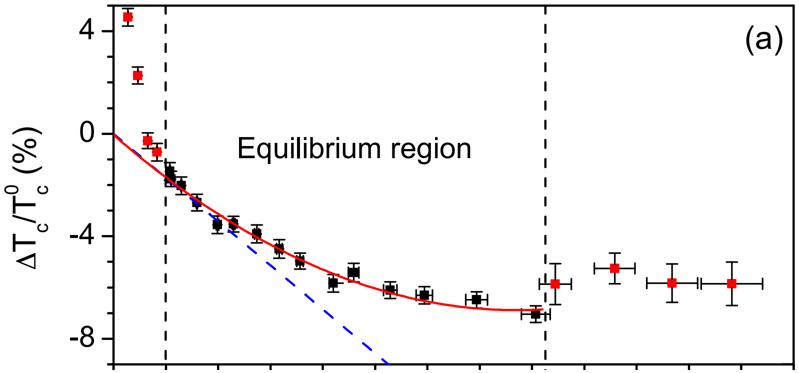




$$(N_0/N)^{1/4} \approx 10\, a/\lambda_0$$

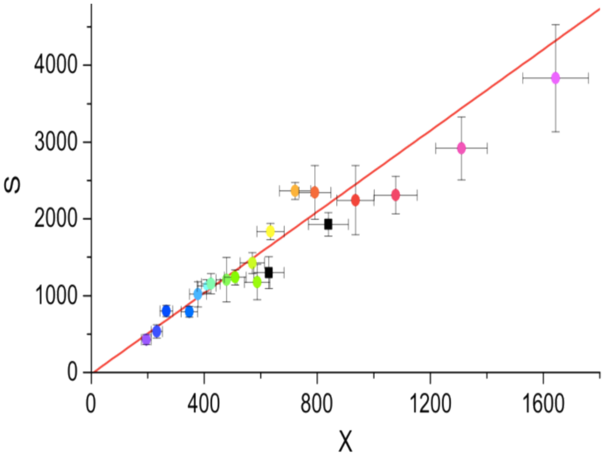
Can be compared with uniform system MC + LDA…
(Prokof' ev & Svistunov)

Summary



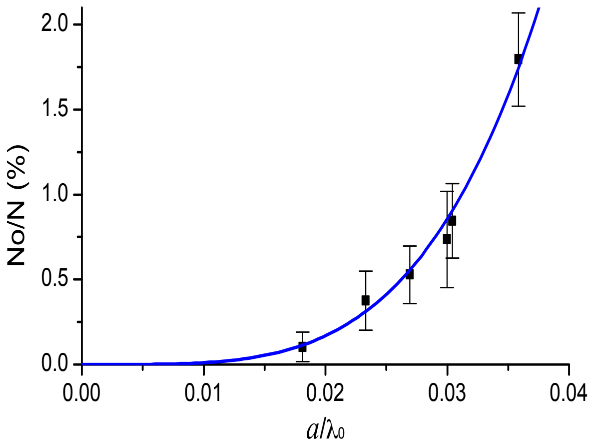
critical point
beyond-MF
&
non-equilibrium

R.P. Smith *et al.*, PRL 2011



thermal
MF?

N. Tammuz *et al.*, PRL 2011



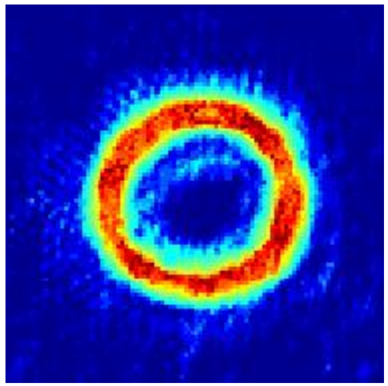
condensed
beyond-MF

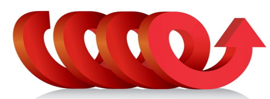
5

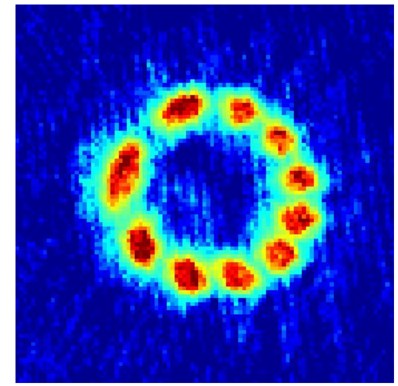
Sneak preview - Superfluidity in ring geometry…

Laguerre-Gauss
trapping beam
w/ various
L values

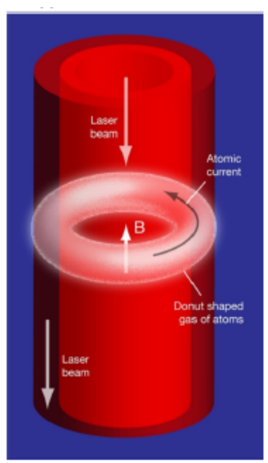
L = 1 @ NIST







q=10 vortex
interferometrically detected



azimuthal vector potentials,
superfluid density

N.R. Cooper & ZH, PRL 2010
S.T. John, ZH & N.R. Cooper, PRA 2011

THE END