Ultracold atomic bubbles in orbital microgravity

progress and prospects aboard ISS with NASA CAL

Nathan Lundblad
Bates College

DQ-mat workshop
April 6, 2022

- Our work: toward a shell / bubble-geometry Bose-Einstein condensate

"BEC on the surface of a sphere"

$$n(\mathbf{r}) \longleftarrow U(\mathbf{r}), k_b T, N$$

Open questions

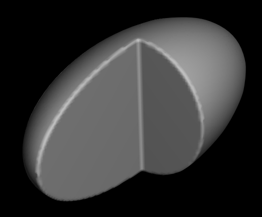
- ***vortex behavior on curved surface***
- ***3D/2D crossover effects (BKT?)***
- ***dilute-gas limits***

Physics playground

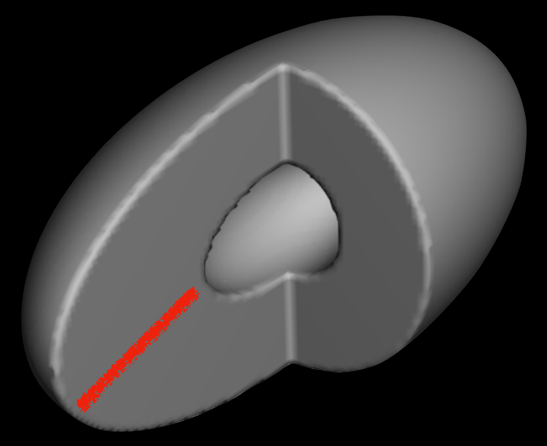
- *'inflation' dynamics*
- *collective modes*
- *self-interference behavior*

'Engineering'

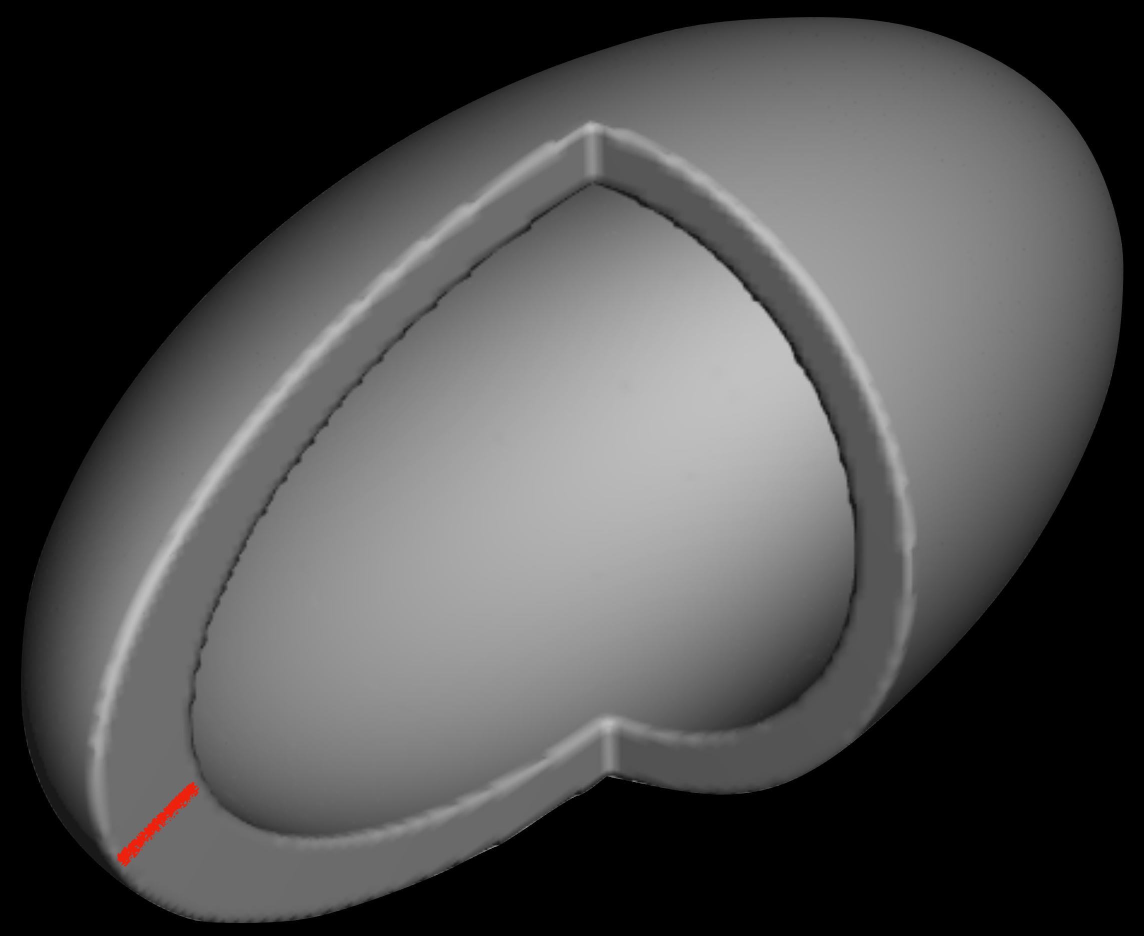
- *rf dressing physics*
- *adiabatic cooling*



'typical' ultracold gas / BEC

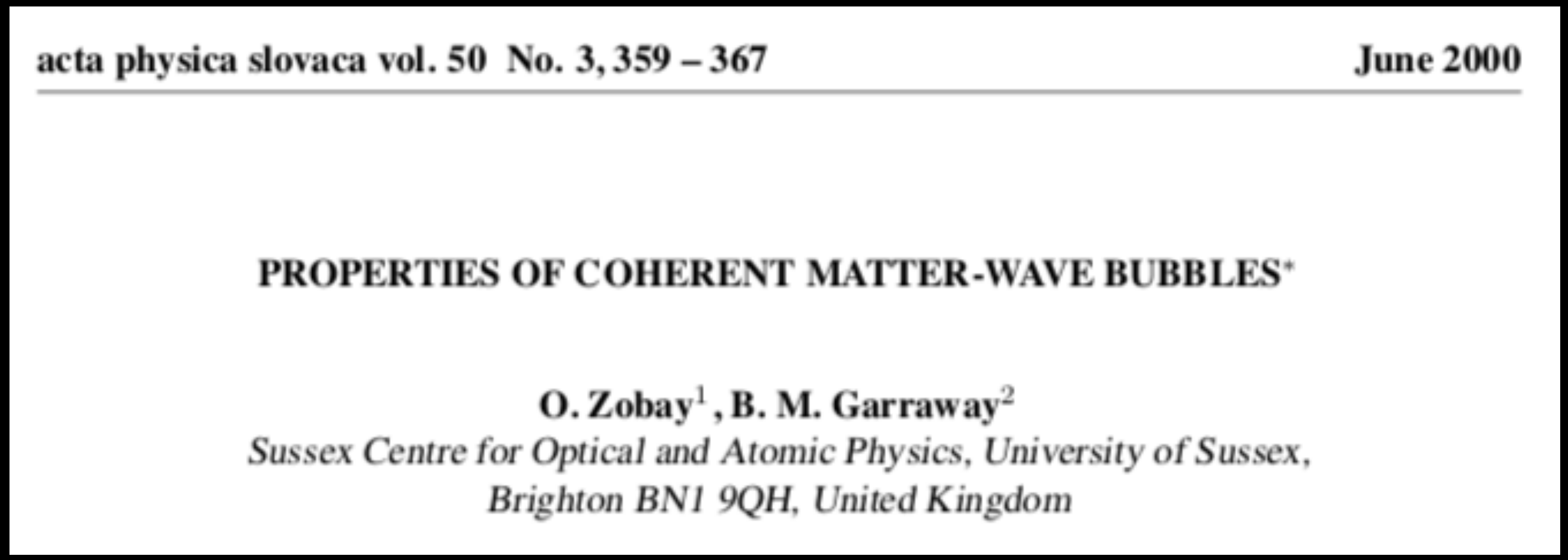


'thick shell'



'thin shell'

original idea:



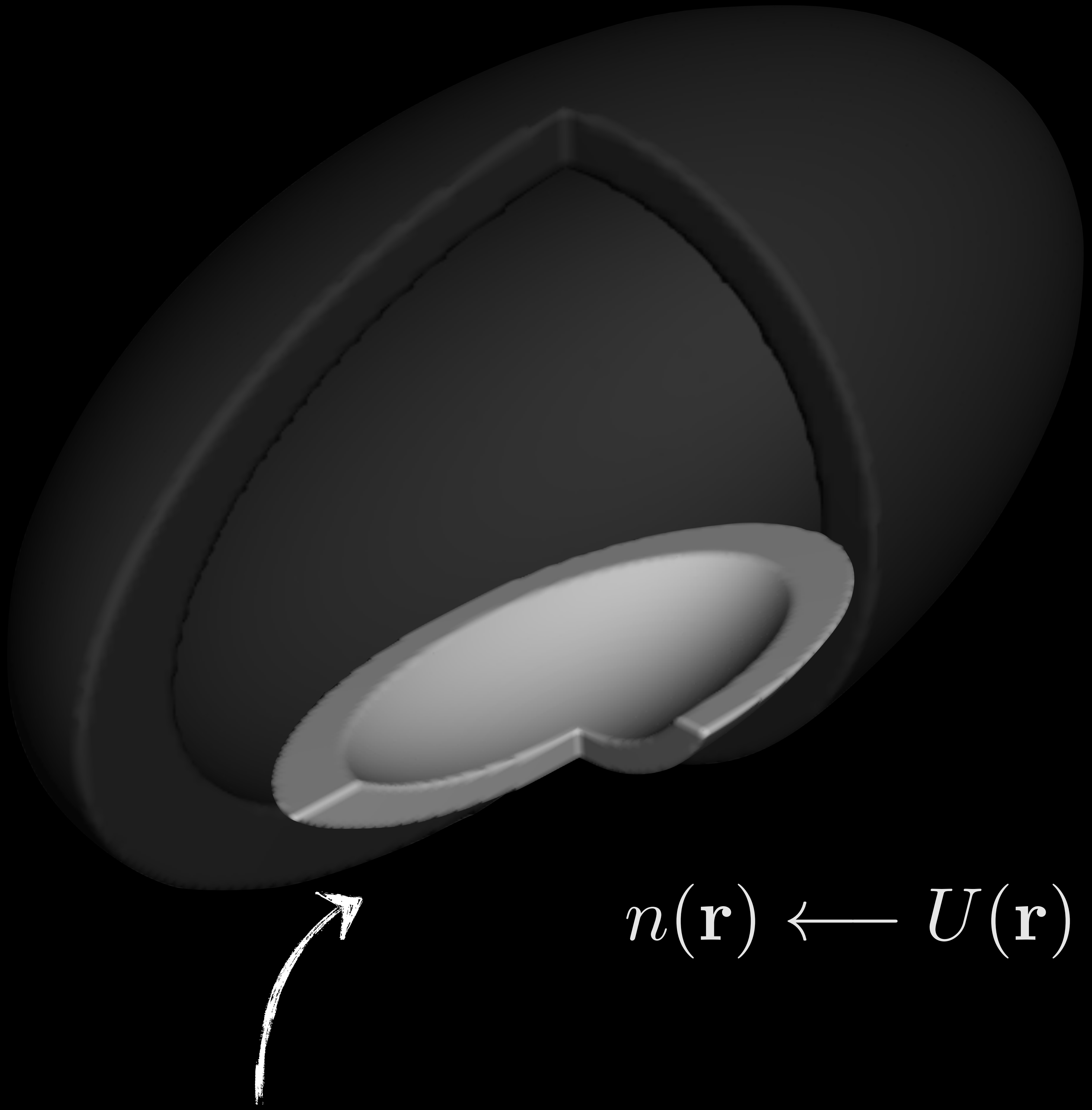
acta physica slovaca vol. 50 No. 3, 359 – 367 June 2000

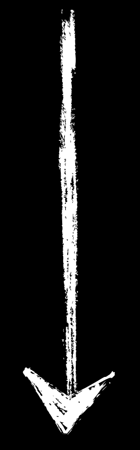
PROPERTIES OF COHERENT MATTER-WAVE BUBBLES*

O. Zobay[1], B. M. Garraway[2]
Sussex Centre for Optical and Atomic Physics, University of Sussex, Brighton BN1 9QH, United Kingdom

Also as: Zobay, O. & Garraway, B. M. *Two-dimensional atom trapping in field-induced adiabatic potentials*. PRL **86**, 1195 (2001).

➢ **But: tricky to do in the presence of gravity.**





$$n(\mathbf{r}) \longleftarrow U(\mathbf{r}) + mgz, k_bT, N$$

(‘contact lens’ trap, observed, and still potentially useful)

How to operate without mgz constraints?

➢ Cancel gravity with external means

➢ **DC magnetic (Zeeman gradients)**: not possible given that shell construction inherently relies on superpositions of spin states with different magnetic moments

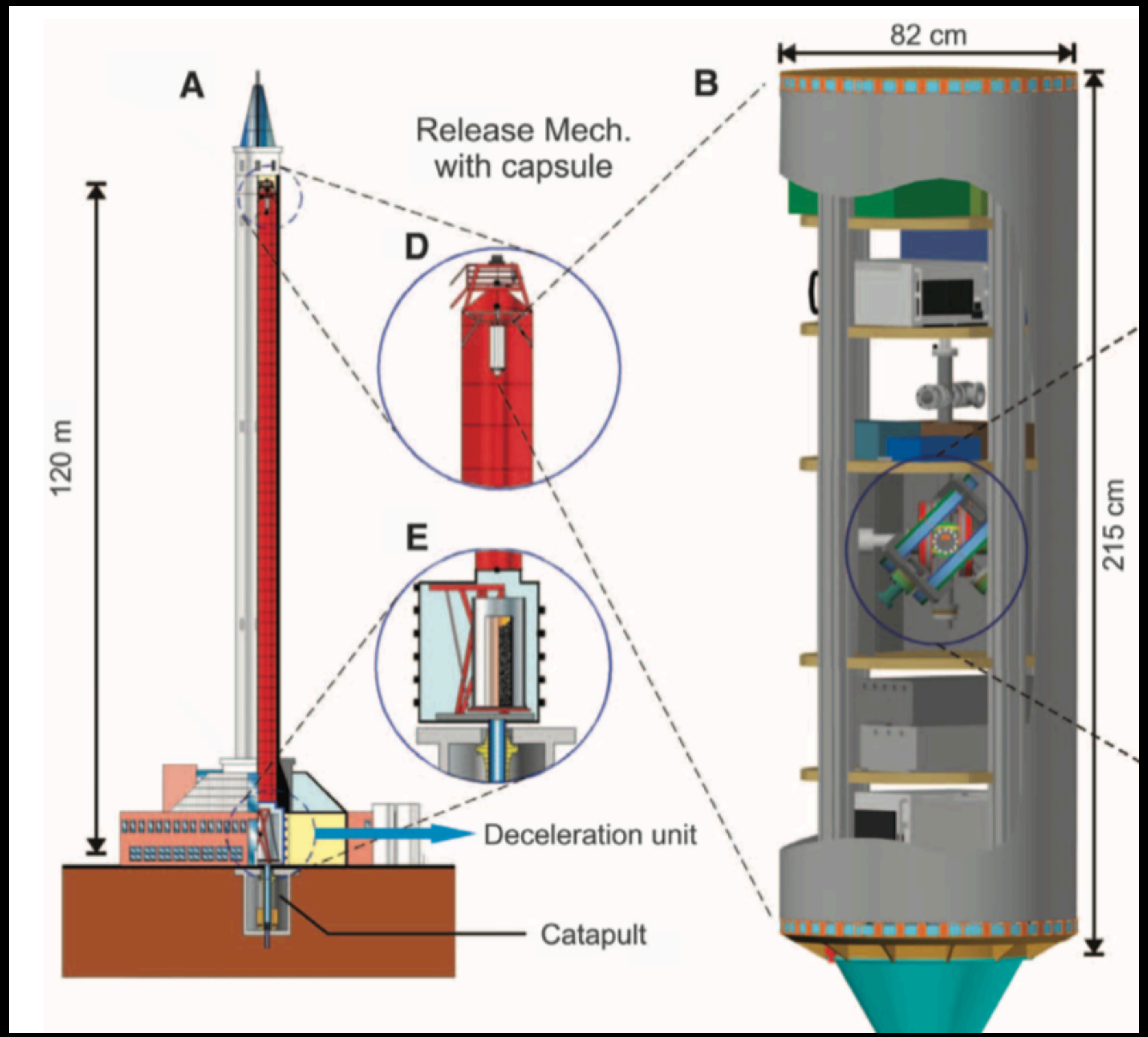
➢ **AC Electric (Stark gradients)**: theoretically doable, but *very* tricky: levitation laser power, uniformity, stability reqs HIGH

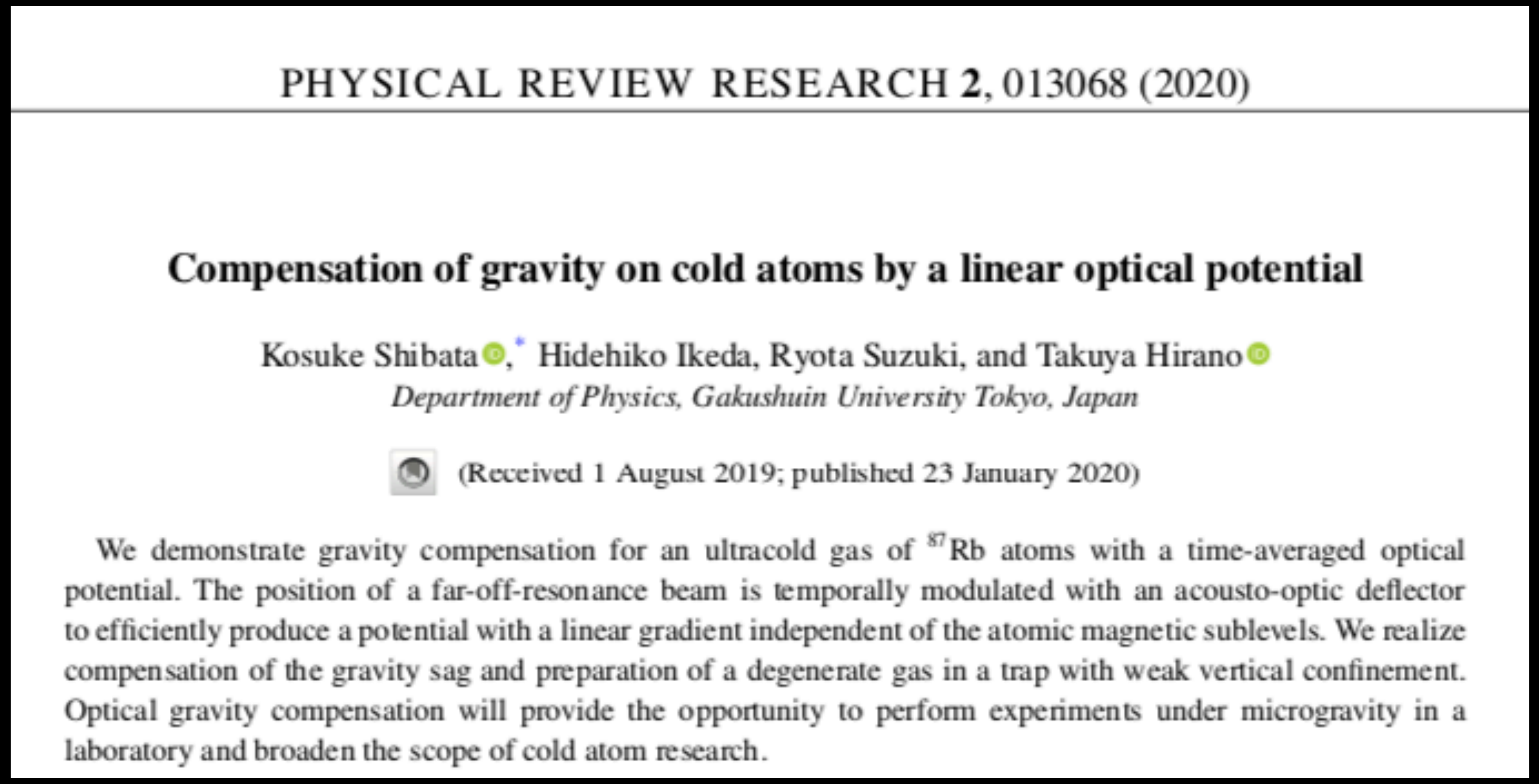
➢ **AC magnetic (Rabi gradients)**: intriguing possibilities!

➢ Drop (and catch) your cold-atom machine

➢ d**rop-tower (Bremen)**

Van Zoest, T. et al. *Bose-Einstein Condensation in Microgravity*. Science **328**, 1540–1543 (2010).



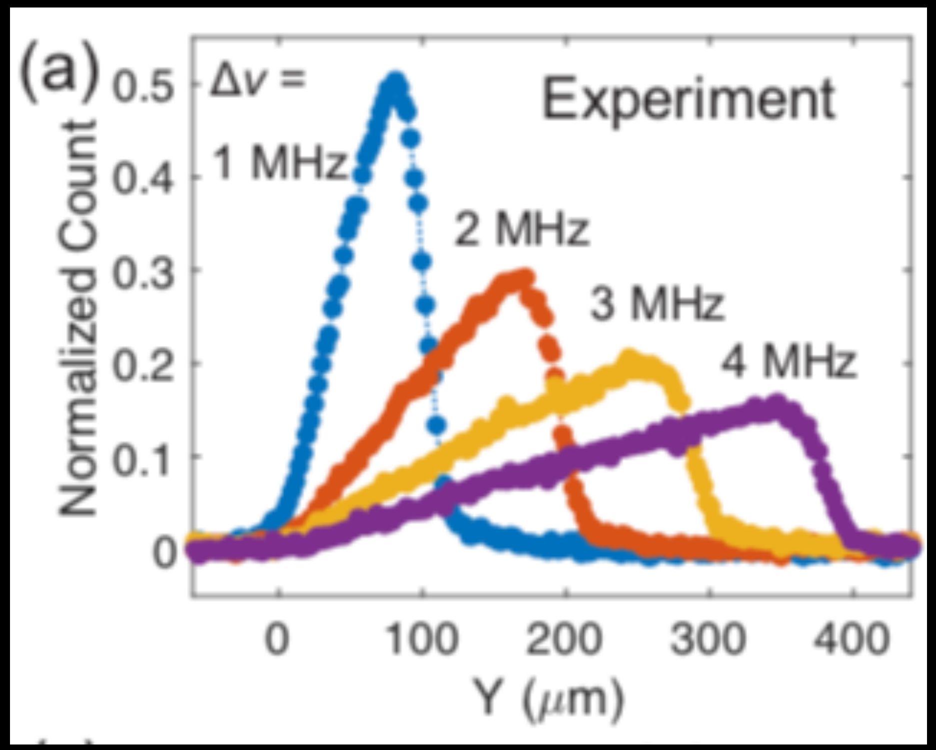

PHYSICAL REVIEW RESEARCH **2**, 013068 (2020)

Compensation of gravity on cold atoms by a linear optical potential

Kosuke Shibata,* Hidehiko Ikeda, Ryota Suzuki, and Takuya Hirano
Department of Physics, Gakushuin University Tokyo, Japan

(Received 1 August 2019; published 23 January 2020)

We demonstrate gravity compensation for an ultracold gas of ^{87}Rb atoms with a time-averaged optical potential. The position of a far-off-resonance beam is temporally modulated with an acousto-optic deflector to efficiently produce a potential with a linear gradient independent of the atomic magnetic sublevels. We realize compensation of the gravity sag and preparation of a degenerate gas in a trap with weak vertical confinement. Optical gravity compensation will provide the opportunity to perform experiments under microgravity in a laboratory and broaden the scope of cold atom research.



- NASA CAL: remotely operated BEC machine in (extended, orbital) microgravity (delivered to ISS May 2018)

- A multi-user remote facility for the study of ultracold gases
  - ISS has been in LEO for > 15 years
  - Orbiting every 90 min, (8 km per sec)
  - Equipped with 8 **EXPRESS** racks (EXpedite the PRocessing of Experiments to the Space Station)

What does the CAL facility offer Earth's experimenters as a user facility?

- Possibility of very weak traps and very low temperatures
- Very long time-of-flight expansion / free interrogation time
- **Elimination** of trap-potential tilt $\mathbf{m_{Rb}g = k_B\ 100\ nK/\mu m}$
- Remote operation permits 'user facility' data approach
- More, considering upgrades!

Jan. 30, 2020

Astronaut Christina Koch works on the Cold Atom Lab

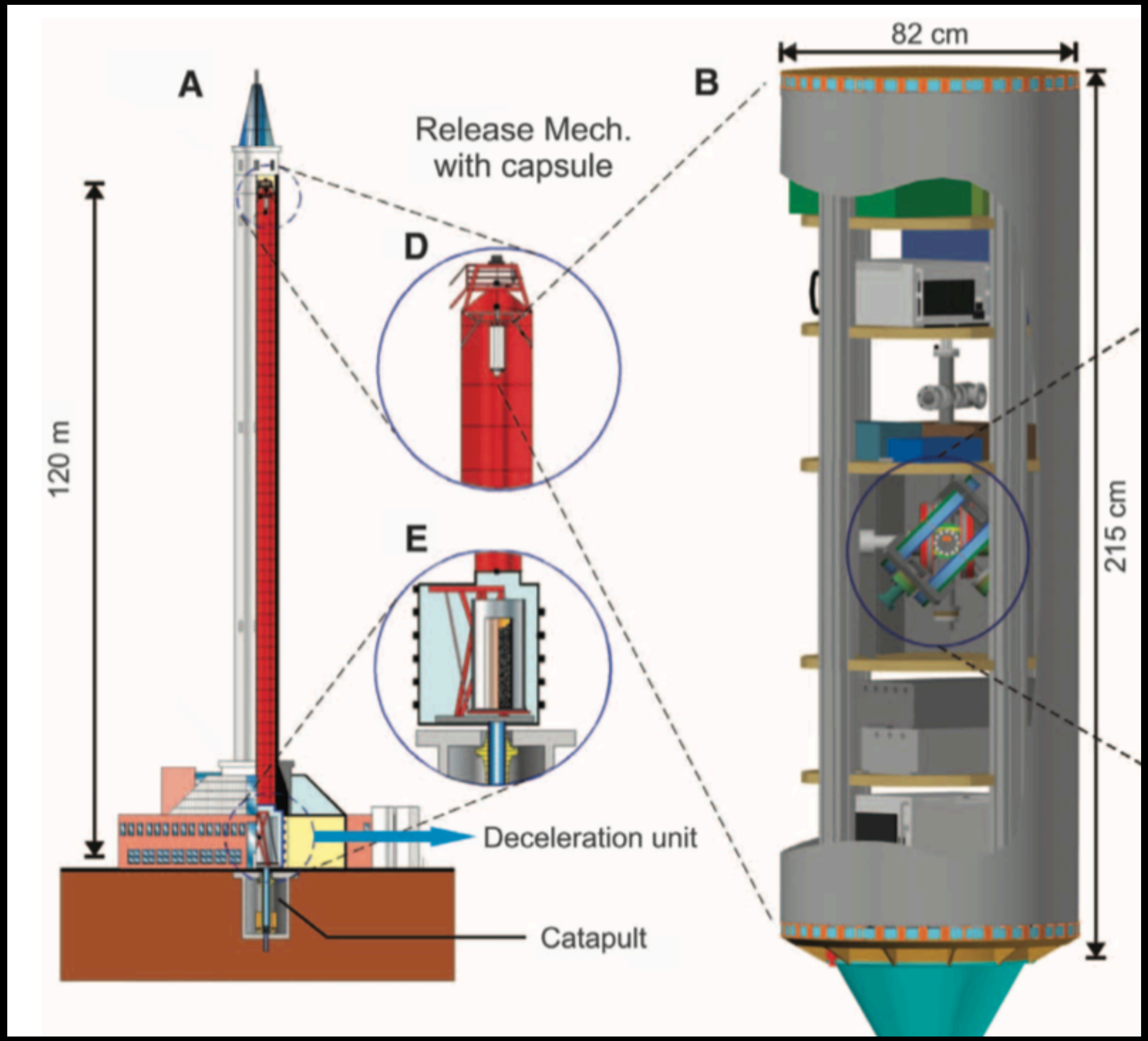
iss061e145487 (Jan. 28, 2020) --- NASA astronaut and Expedition 61 Flight Engineer Christina Koch works on the Cold Atom Lab (CAL) swapping and cleaning hardware inside the quantum research device. The CAL enables research into the quantum effects of gases chilled to nearly absolute zero, which is colder than the average temperature of the universe.

https://www.nasa.gov/image-feature/astronaut-christina-koch-works-on-the-cold-atom-lab

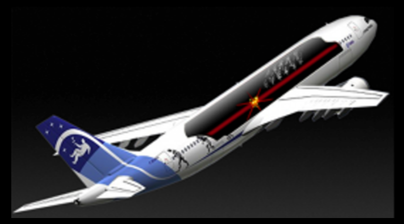
How to operate without mgz constraints?

➢ Drop (and catch) your trapped-BEC machine

Van Zoest, T. et al. *Bose-Einstein Condensation in Microgravity*. Science **328**, 1540–1543 (2010).



➢ ~~“vomit comet”~~ ballistic aircraft approach



I.C.E.
Atom Interferometry in Microgravity

Received 12 Jun 2016 | Accepted 1 Nov 2016 | Published 12 Dec 2016 DOI: 10.1038/ncomms13786

Dual matter-wave inertial sensors in weightlessness

Brynle Barrett[1], Laura Antoni-Micollier[1], Laure Chichet[1], Baptiste Battelier[1], Thomas Lévèq & Philippe Bouyer[1]

➢ machine throw-and-catch

PHYSICAL REVIEW LETTERS **123**, 240402 (2019)

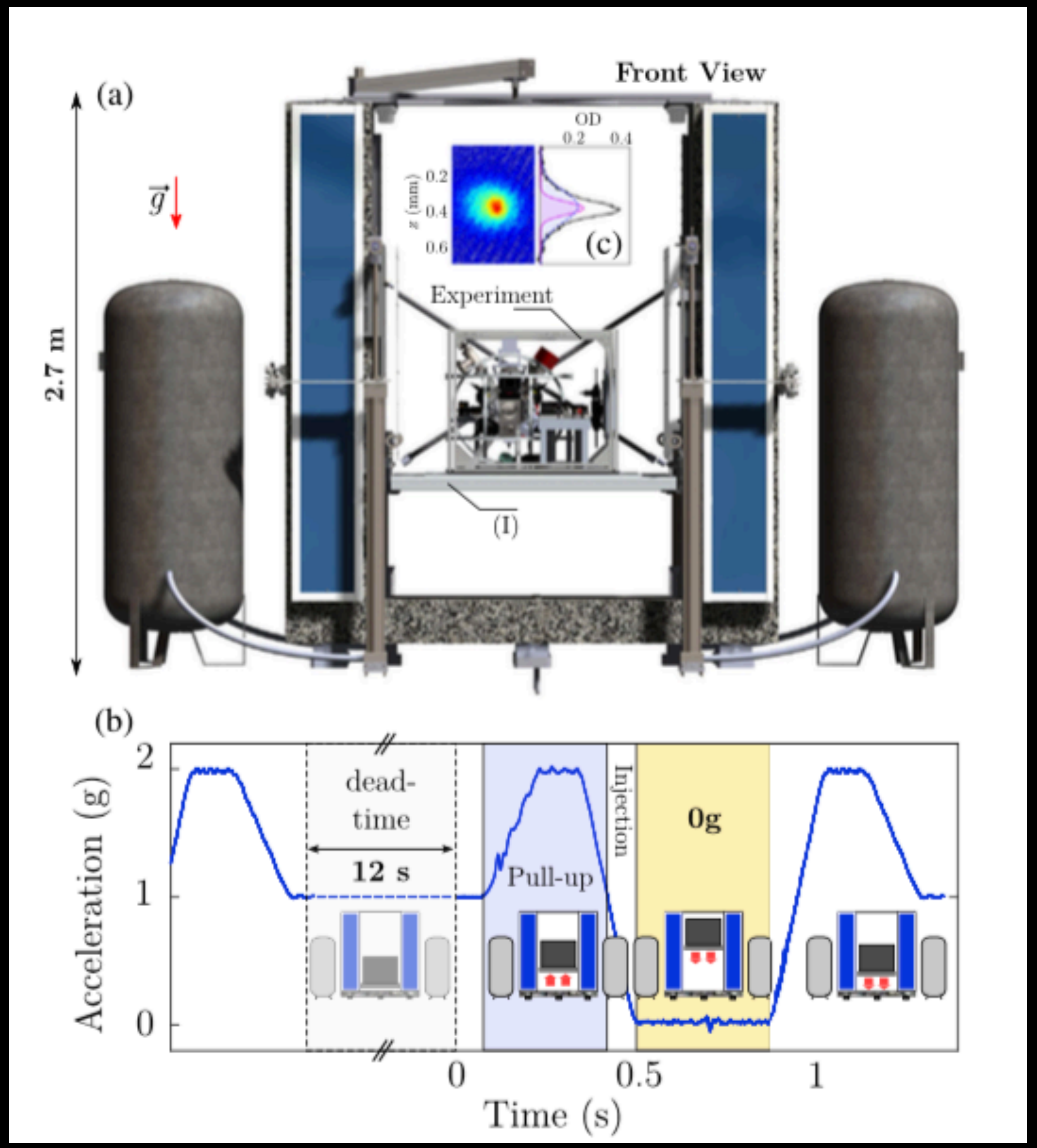
All-Optical Bose-Einstein Condensates in Microgravity

G. Condon, M. Rabault, B. Barrett, L. Chichet, R. Arguel, H. Eneriz-Imaz, D. Naik, A. Bertoldi, B. Battelier, and P. Bouyer
LP2N, Laboratoire Photonique, Numérique et Nanosciences, Université Bordeaux–IOGS–CNRS:UMR 5298, 1 rue François Mitterrand, 33400 Talence, France

A. Landragin
LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, 61 avenue de l'Observatoire, 75014 Paris, France

(Received 24 June 2019; published 13 December 2019)

We report on the all-optical production of Bose-Einstein condensates in microgravity using a combination of grey molasses cooling, light-shift engineering and optical trapping in a painted potential. Forced evaporative cooling in a 3-m high Einstein elevator results in 4×10^4 condensed atoms every 13.5 s, with a temperature as low as 35 nK. In this system, the atomic cloud can expand in weightlessness for up to 400 ms, paving the way for atom interferometry experiments with extended interrogation times and studies of ultracold matter physics at low energies on ground or in Space.



How to operate without mgz constraints?

➢ Launch your trapped-BEC machine in a sounding rocket

Becker, D. et al. *Space-borne Bose–Einstein condensation for precision interferometry*. Nature **562**, 391–395 (2018).

Lachmann, M.D., Ahlers, H., Becker, D. et al. Ultracold atom interferometry in space. Nat Commun 12, 1317 (2021).

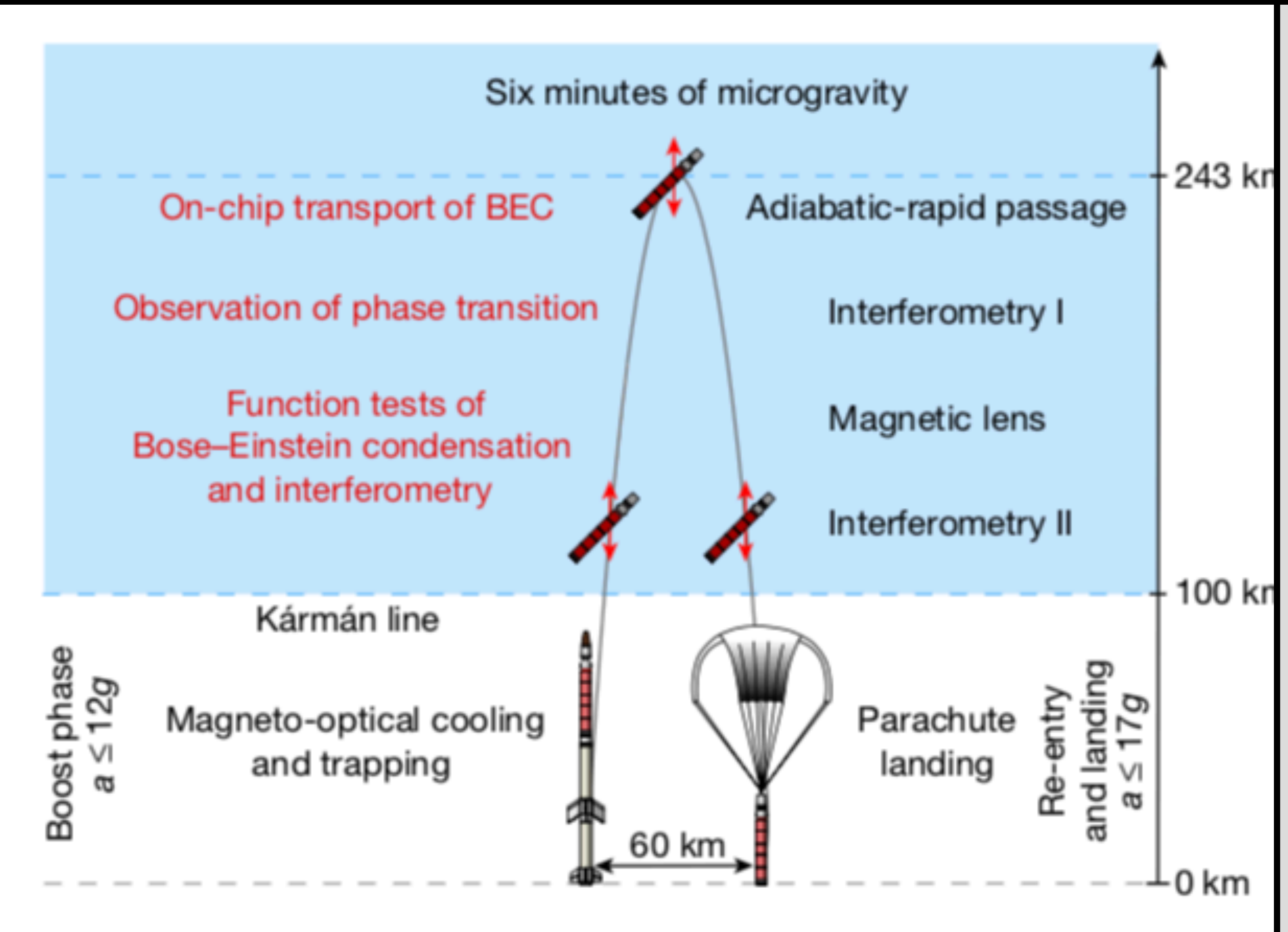


Fig. 2 | Schedule for the MAIUS-1 sounding-rocket mission. During the boost phase (bottom left) and the 6 min of space flight (blue-shaded region), 110 atom-optics experiments were performed. Those discussed

MAIUS 1 – First Bose-Einstein condensate generated in space

or:

➢ Put your BEC machine in perpetual freefall.

➢ **How?**

➢ Ask NASA & JPL!

- Our work: toward a shell / bubble-geometry Bose-Einstein condensate
  - CAL / ISS facility-user collaboration
  - ~5 user groups overall currently

BATES ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN SMITH COLLEGE JPL UMASS AMHERST

- How to actually make a shell potential (and use it in microgravity?)

- An old friend used in a new(ish) way: **rf coupling** of Zeeman-split spin states!

2013: "if CAL existed, what could you do with it?"

2015: Science Concept Review (SCR)

2018: launch and establishment of operation

2019-20: "SM2" first data campaign

2021-22: "SM3" second data campaign

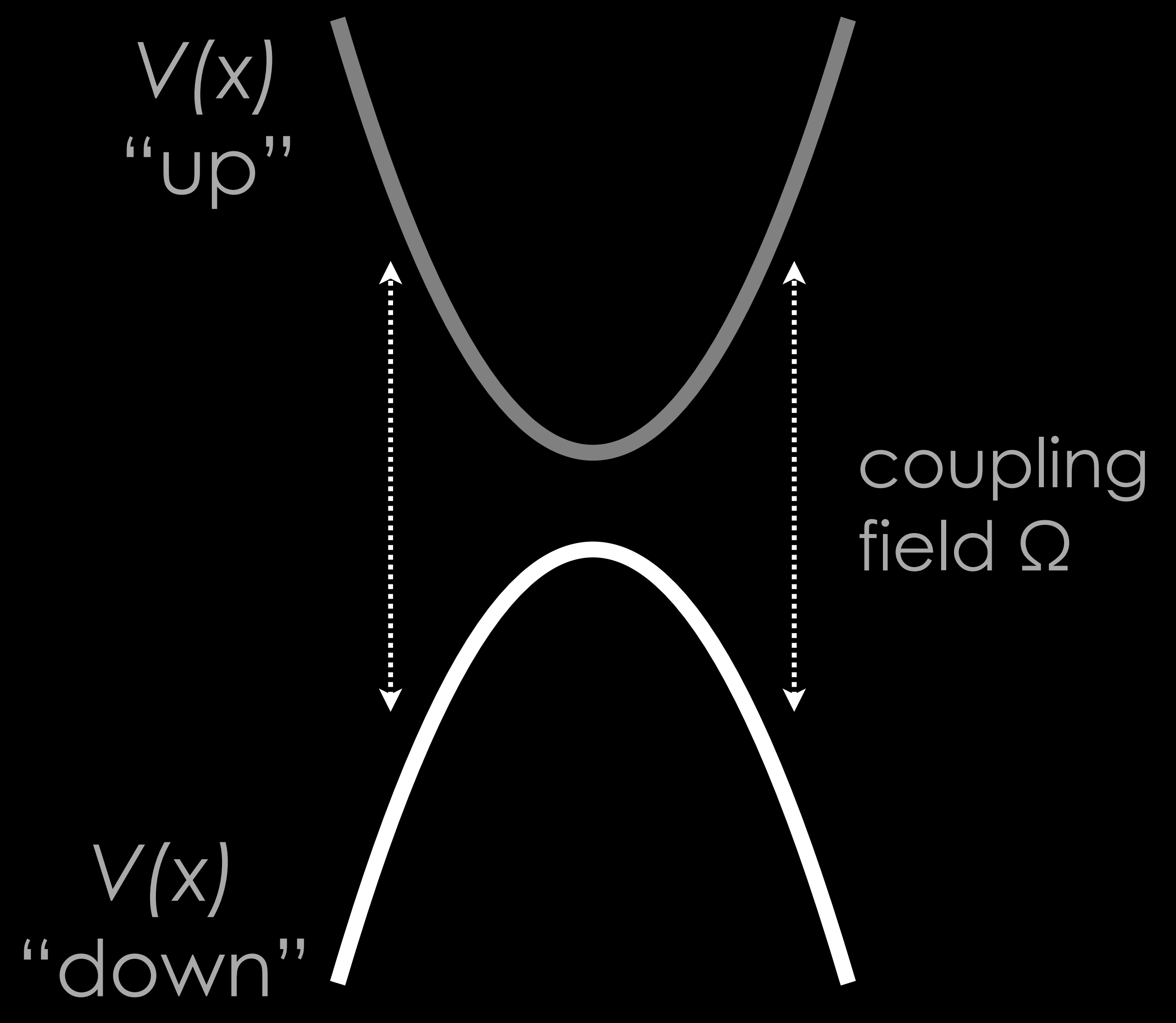
ARTICLE OPEN

Shell potentials for microgravity Bose–Einstein condensates

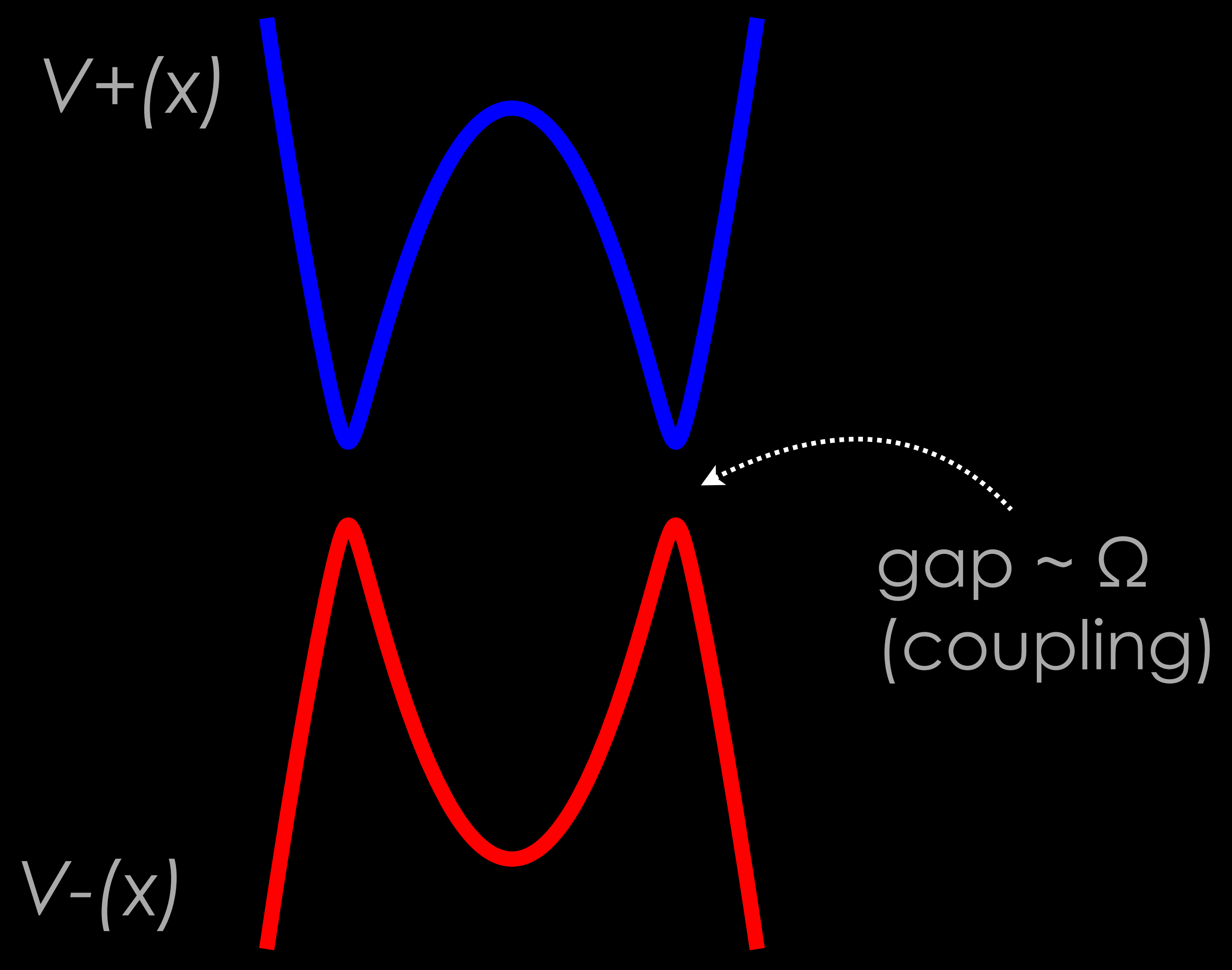
N. Lundblad[1*], R. A. Carollo[1], C. Lannert[2,3], M. J. Gold[1], X. Jiang[1], D. Paseltiner[1], N. Sergay[1] and D. C. Aveline[4]

Lundblad, N. et al. *Shell potentials for microgravity Bose–Einstein condensates*. npj Microgravity **5**, 1–6 (2019).

“bare” potentials

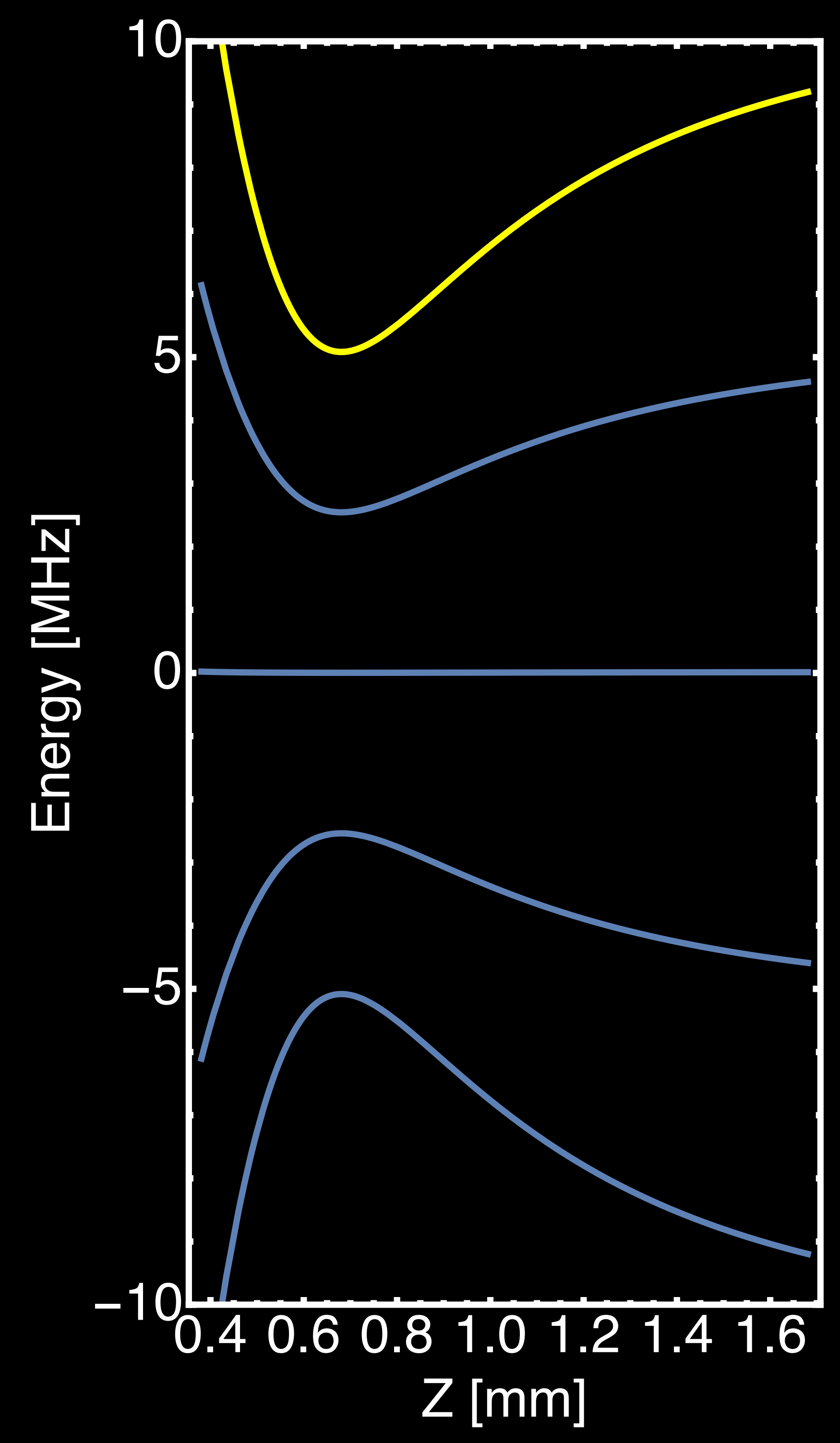


“dressed” potentials

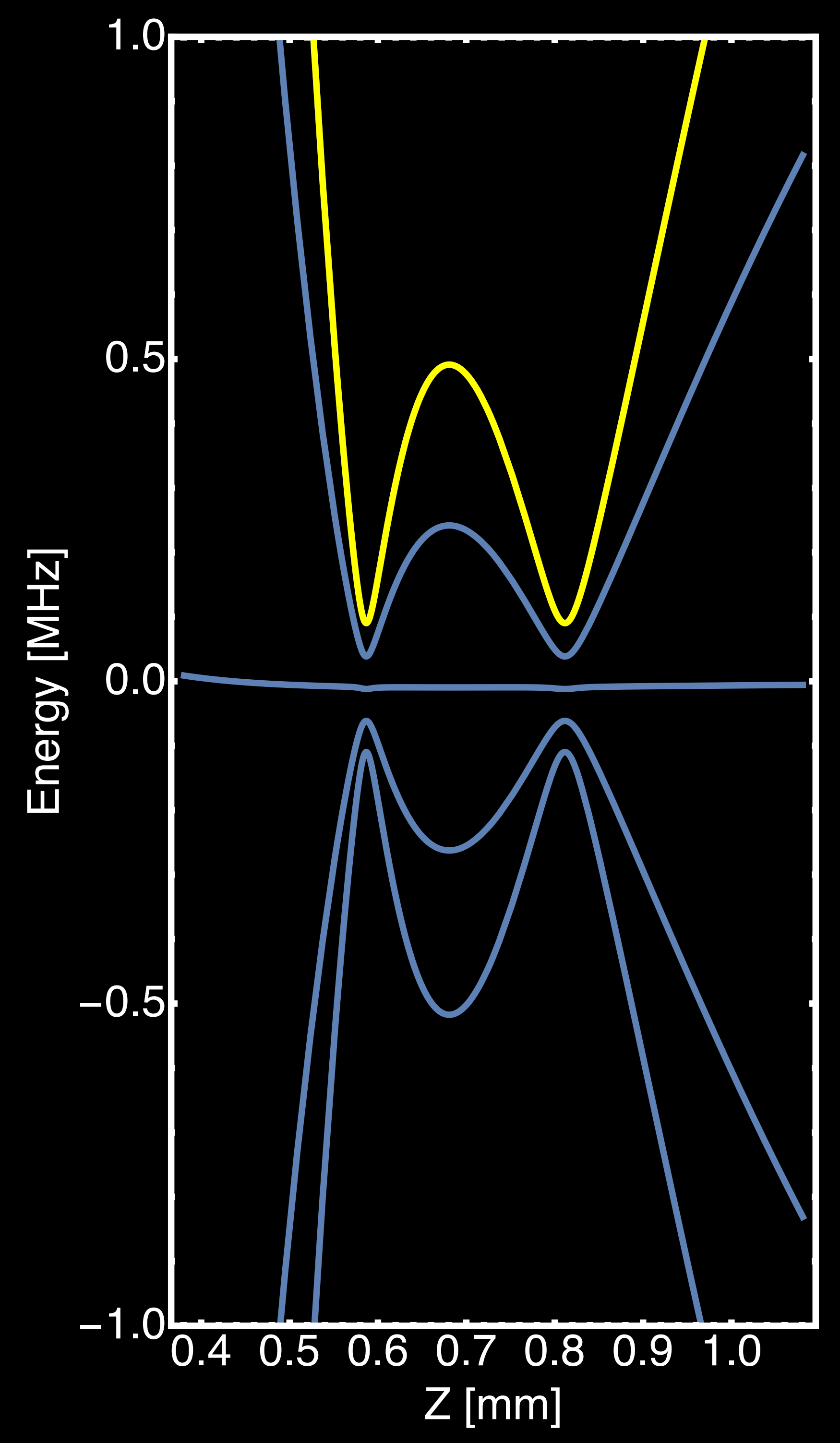


- ➢ **Lower** adiabatic potential familiar from evaporative cooling
- ➢ Typical intuition : **spatially-dependent superposition of bare-basis spins**
  - ➢ “an rf rapid passage whose completeness depends where you are”
  - ➢ Assumes strong enough coupling to avoid Landau-Zener nonadiabaticity
- ➢ **Upper** potential useful for new trap structures

“bare” potentials



dressed potentials



Real life: 5 states, not 2:

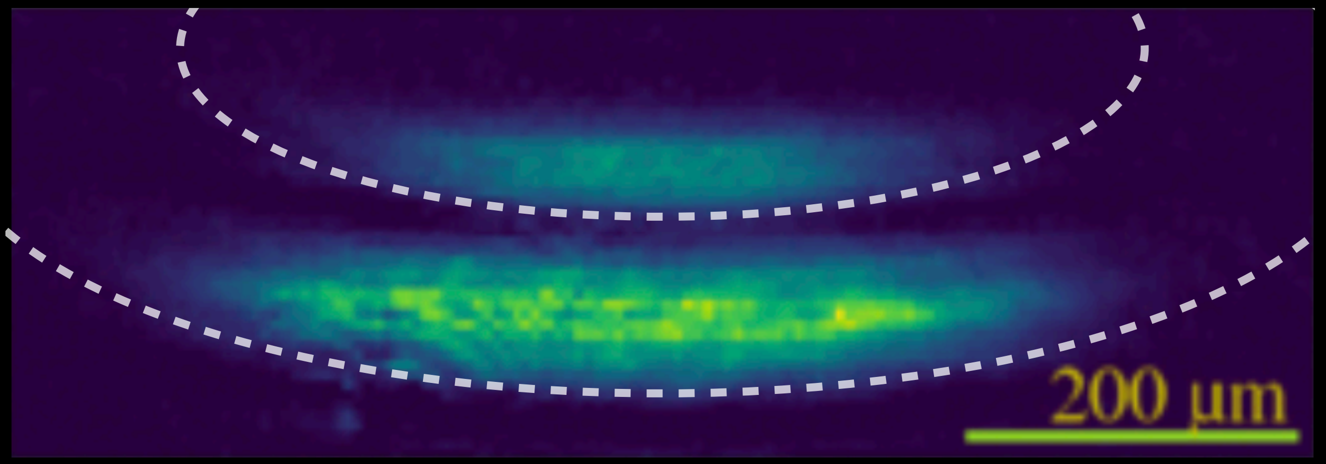
Rb-87 F=2 ground state, rotating-frame + RWA Hamiltonian:

$$\mathcal{H} = \begin{pmatrix} 2\omega & \Omega/2 & 0 & 0 & 0 \\ \Omega/2 & \omega & \frac{\sqrt{3}}{2}\Omega/2 & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2}\Omega/2 & 0 & \frac{\sqrt{3}}{2}\Omega/2 & 0 \\ 0 & 0 & \frac{\sqrt{3}}{2}\Omega/2 & -\omega & \Omega/2 \\ 0 & 0 & 0 & \Omega/2 & -2\omega \end{pmatrix} + \mathcal{H}_{\text{Zeeman}}(\mathbf{r})$$

Why microgravity?

➢ **$m_{Rb}g = k_B$ 100 nK/μm tilt**: depending on radius, BEC won't be shell, but "bowl"

Foot group (Oxford)



Bentine….Foot, J. Phys. B ***50*** *094002 (2017)*

Harte….Foot, PRA ***97*** *013616 (2018)*

von Klitzing group (Crete)

PHYSICAL REVIEW A **100**, 053416 (2019)

Microwave spectroscopy of radio-frequency-dressed ^{87}Rb

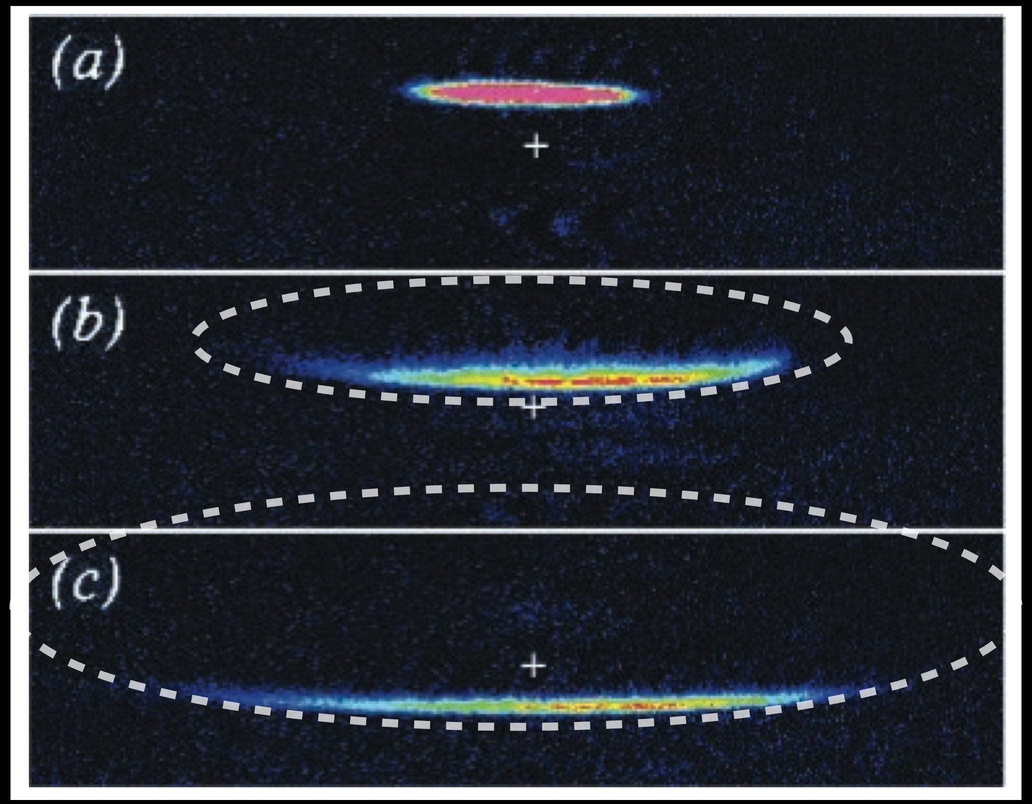
G. A. Sinuco-Leon* and B. M. Garraway
Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

H. Mas,* S. Pandey, G. Vasilakis, V. Bolpasi, and W. von Klitzing
Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, Heraklion 70013, Greece

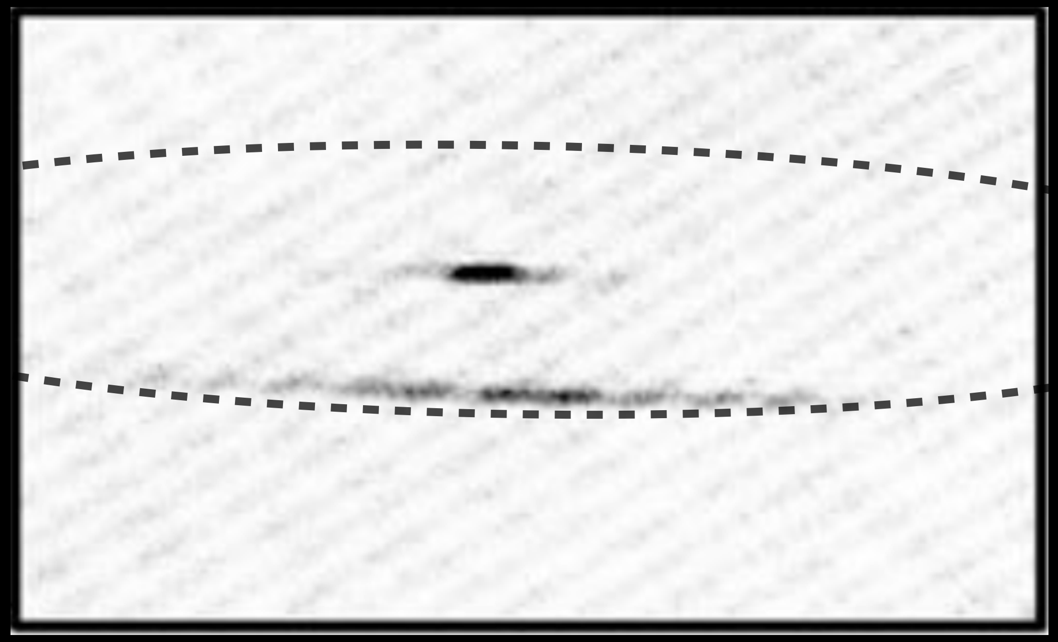
B. Foxon,† S. Jammi,† K. Poulios, and T. Fernholz
School of Physics & Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

(Received 28 April 2019; revised manuscript received 25 July 2019; published 22 November 2019)

Perrin group (Paris)



Colombe….Perrin, Europhys. Lett. ***67*** *593 (2004)*



White….DeMarco, PRA ***74*** *023616 (2006)*

Demarco group (UIUC)

A two-dimensional quantum gas in a magnetic trap

K Merloti, R Dubessy, L Longchambon, A Perrin, P-E Pottie[1], V Lorent and H Perrin[2]

Laboratoire de Physique des Lasers, CNRS, Université Paris 13, Sorbonne Paris Cité, 99 Avenue Jean-Baptiste Clément, F-93430 Villetaneuse, France
E-mail: helene.perrin@univ-paris13.fr

New Journal of Physics **15** (2013) 033007 (15pp)
Received 22 November 2012
Published 6 March 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/3/033007

Abstract. We present the first experimental realization of a two-dimensional quantum gas in a purely magnetic trap dressed by a radio frequency field in the presence of gravity. The resulting potential is extremely smooth and very close to harmonic in the two-dimensional plane of confinement. We fully characterize the trap and demonstrate the confinement of a quantum gas to two dimensions. The trap geometry can be modified to a large extent, in particular in a dynamical way. Taking advantage of this possibility, we study the monopole and the quadrupole modes of a two-dimensional Bose gas.

PHYSICAL REVIEW A **74**, 023616 (2006)

Bose-Einstein condensates in rf-dressed adiabatic potentials

M. White, H. Gao, M. Pasienski, and B. DeMarco
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
(Received 9 June 2006; published 21 August 2006)

Bose-Einstein condensates of ^{87}Rb atoms are transferred into radio-frequency induced adiabatic potentials and the properties of the corresponding dressed states are explored. We report on measurements of the spin composition of dressed condensates. We also show that adiabatic potentials can be used to trap atom gases in novel geometries, including suspending a cigar-shaped cloud above a curved sheet of atoms.

DOI: 10.1103/PhysRevA.74.023616 PACS number(s): 03.75.Hh, 03.75.Mn, 32.60.+i

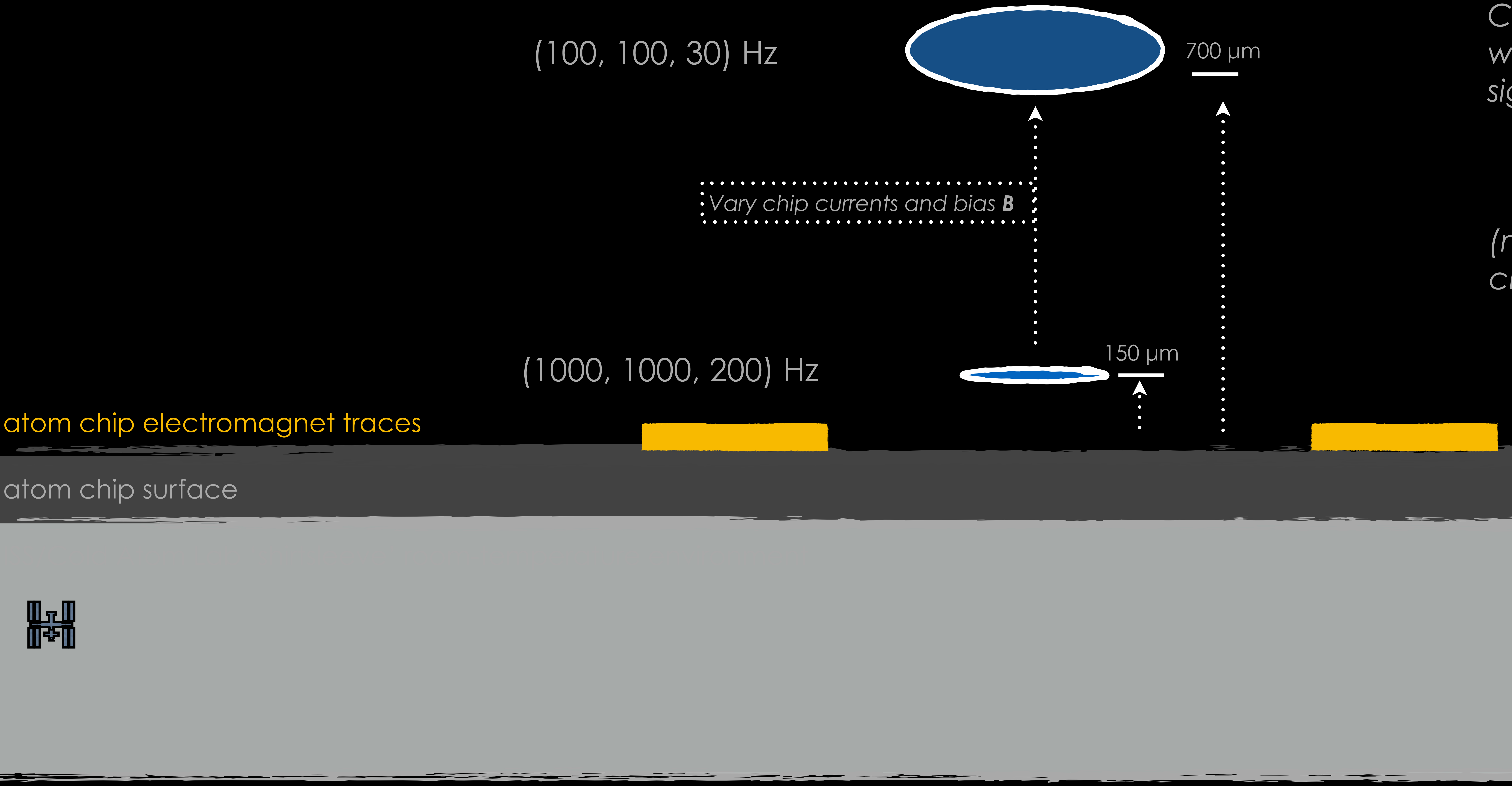
Campbell (JQI)

A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab

S. Eckel,[1] A. Kumar,[1] T. Jacobson,[2] I. B. Spielman,[1] and G. K. Campbell[1,*]
[1]*Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, Gaithersburg, Maryland 20899, USA*

1) make a BEC

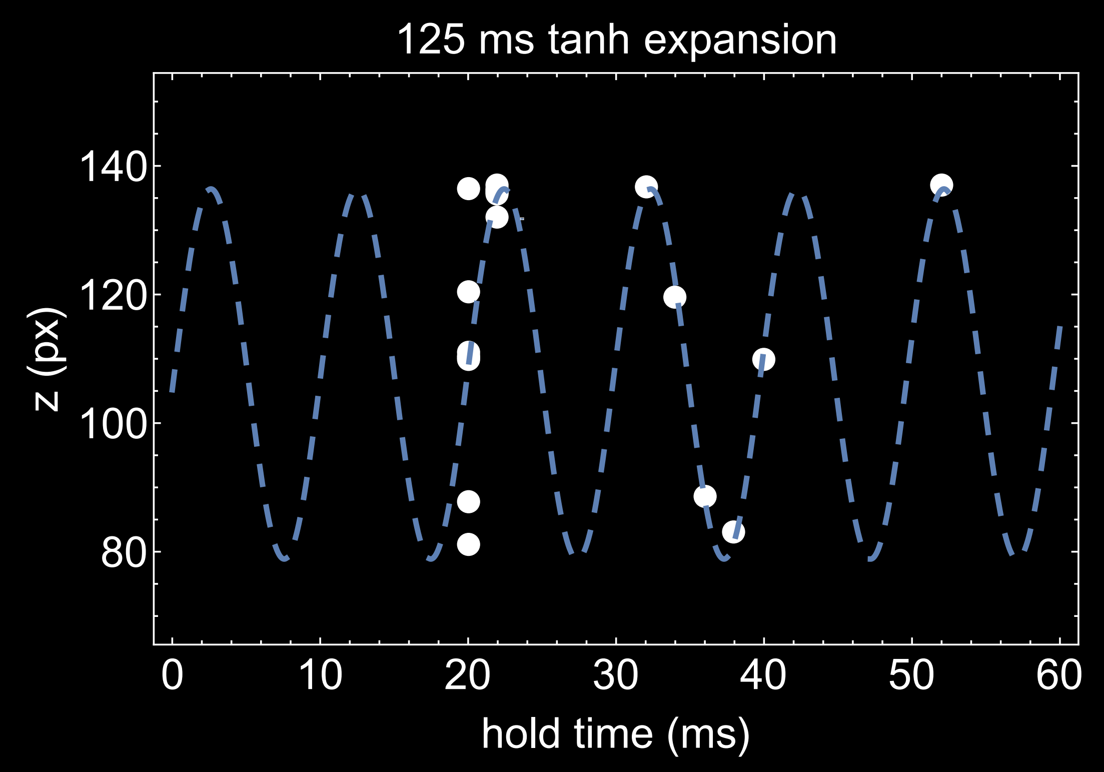
2) get to preferred starting geometry



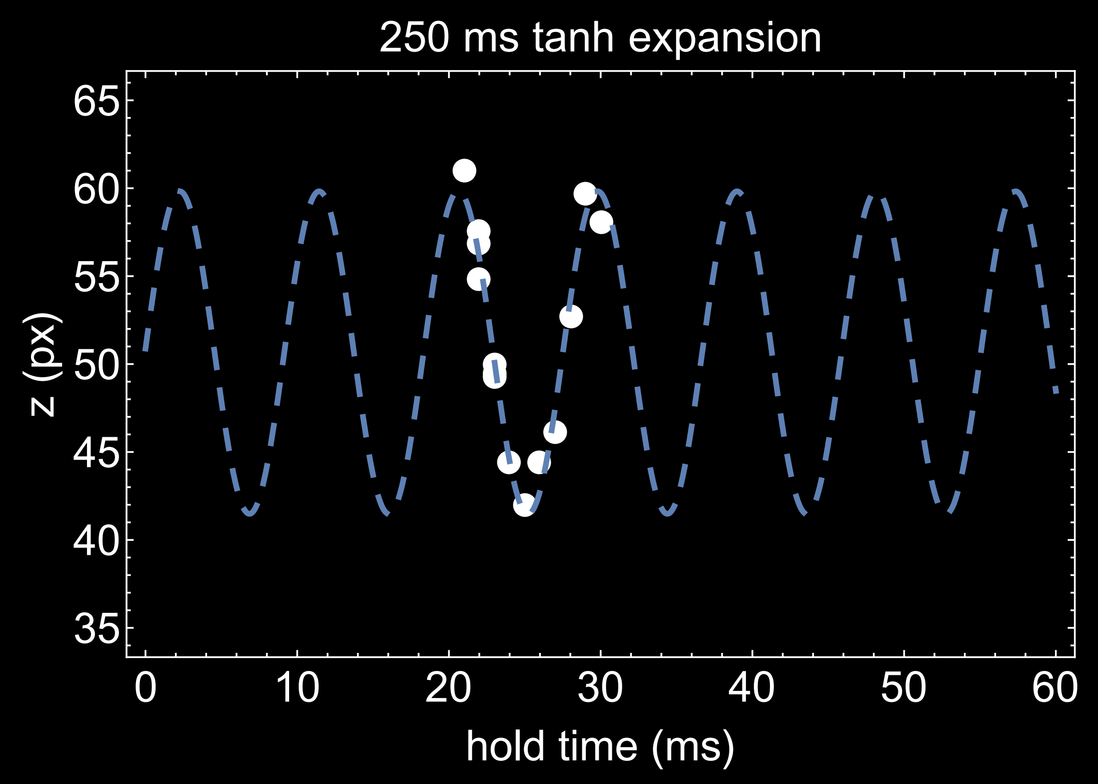
Can we move and decompress without exciting the system significantly?

(non-spherical aspect ratio + tightness is a challenge of the atom-chip geometry)

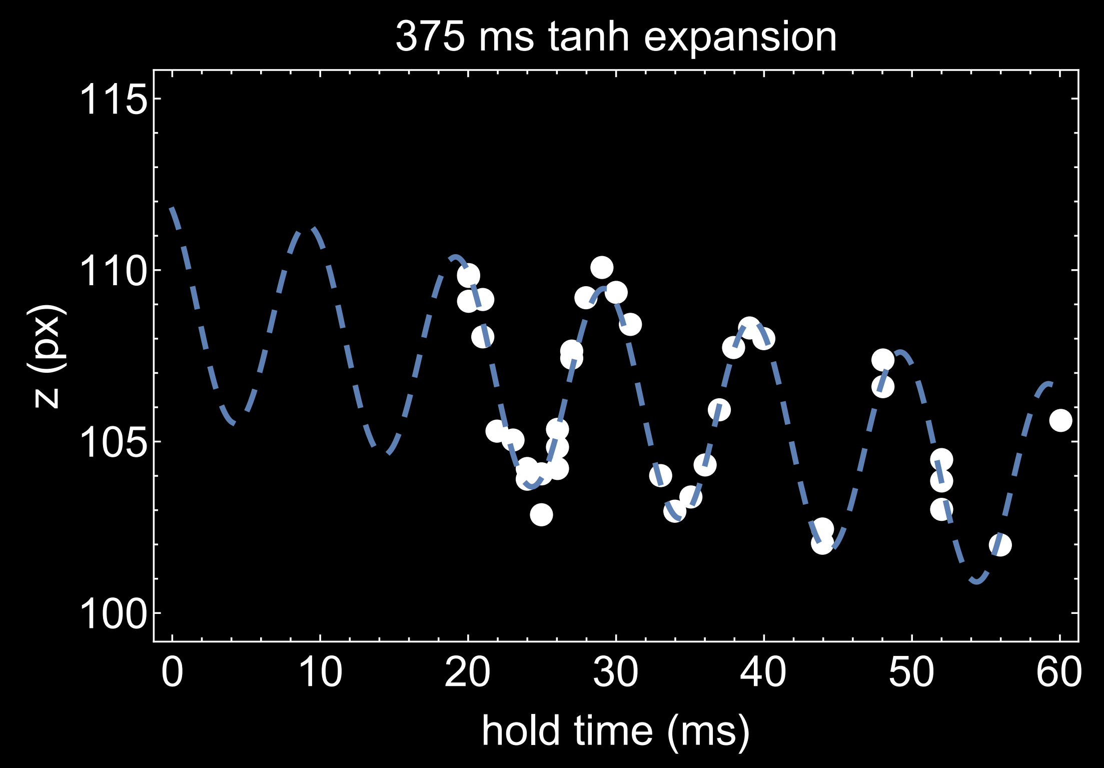
‘Sloshing’ in expanded trap (starting point of shell studies)



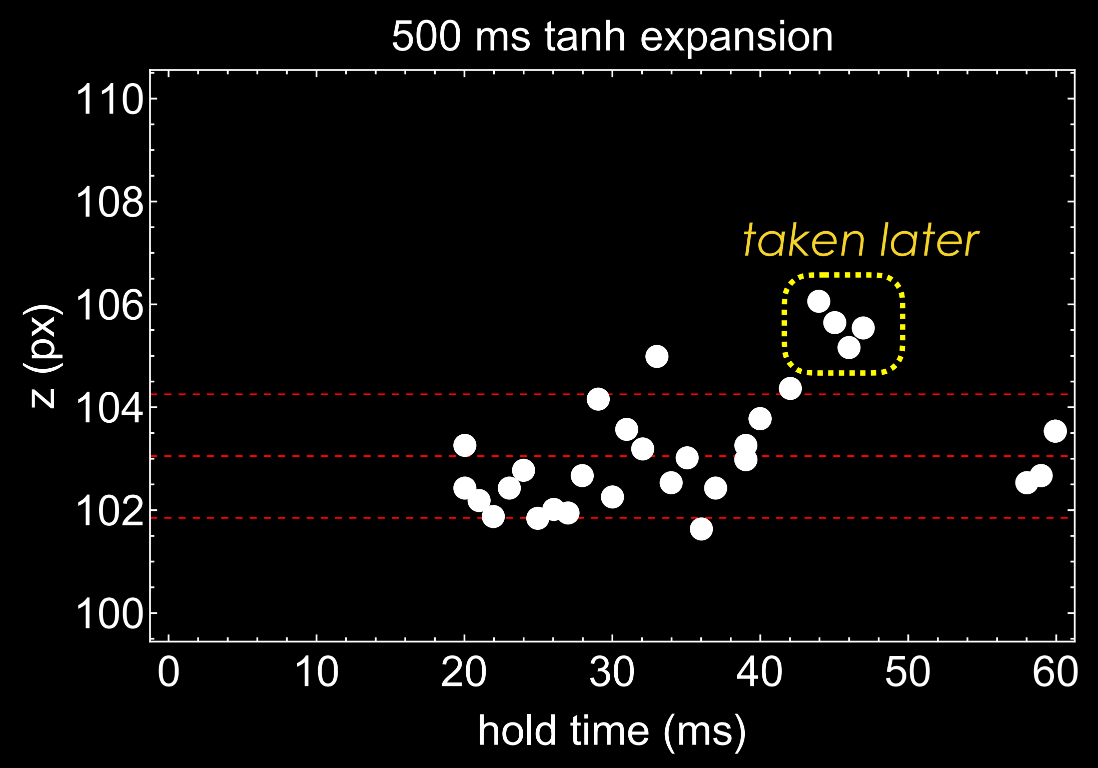
101(3) Hz; 130 um amplitude



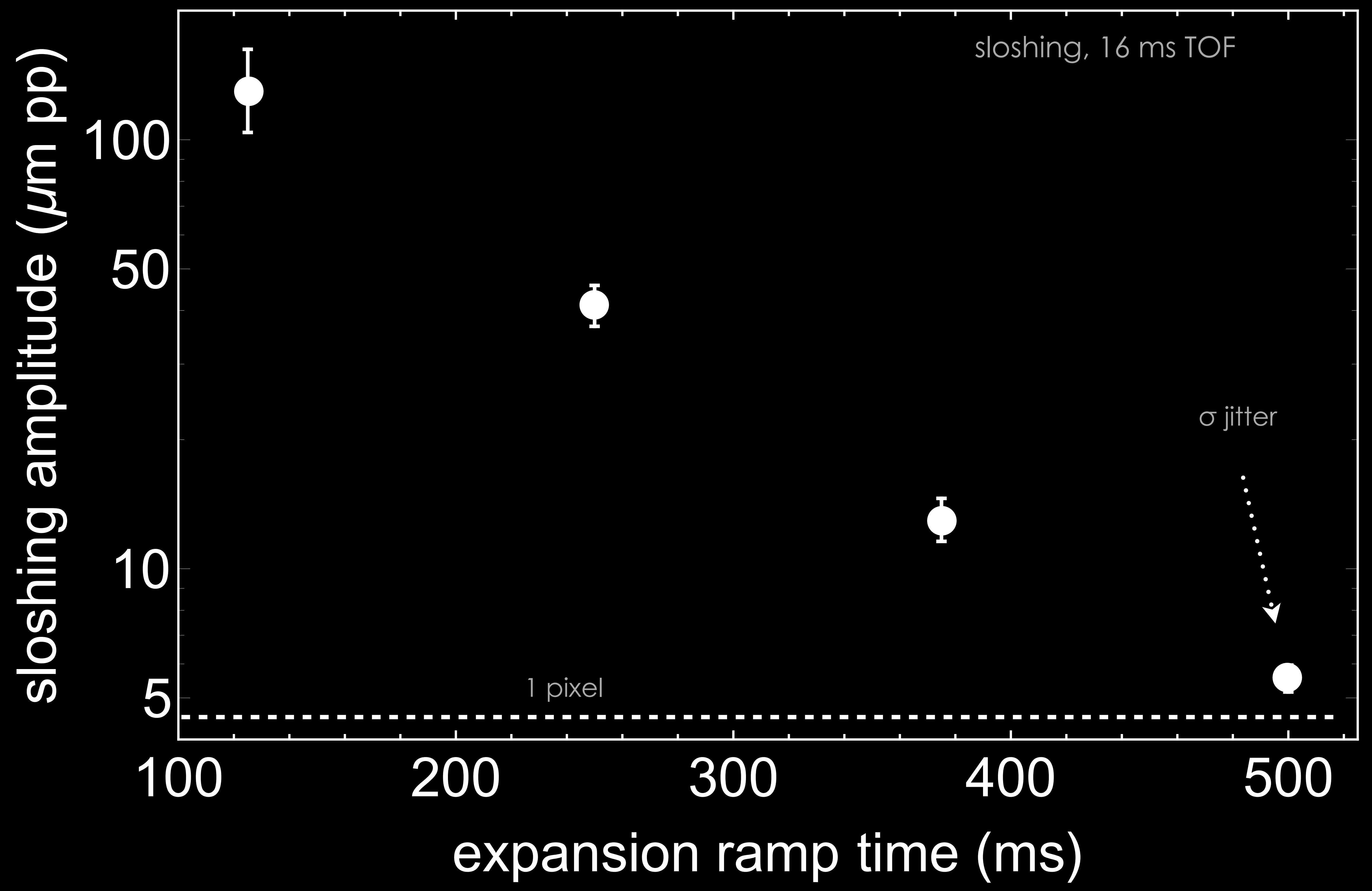
108(6) Hz; 41 um amplitude



100(1) Hz; 13 um amplitude



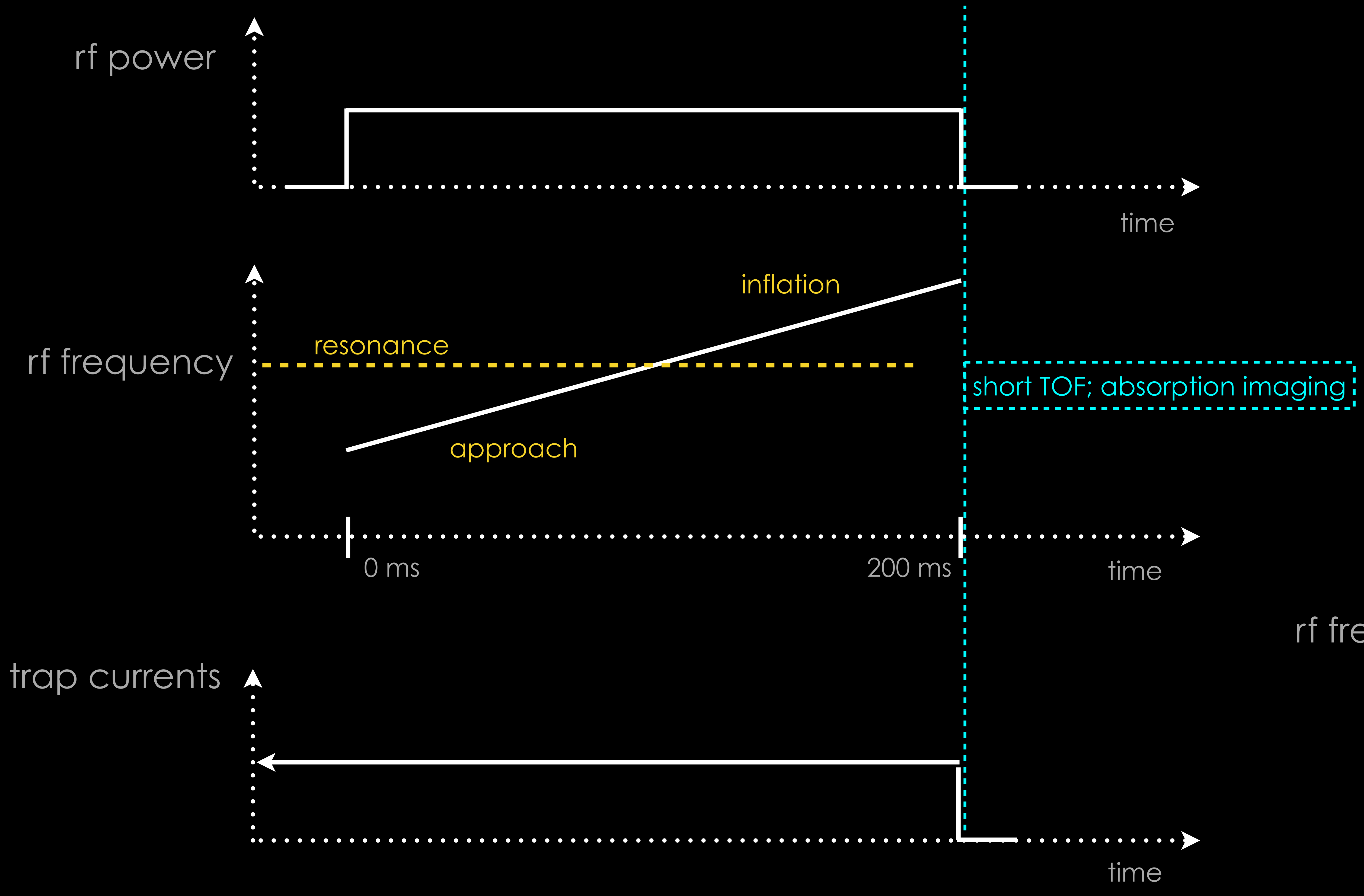
model: 101(2) Hz



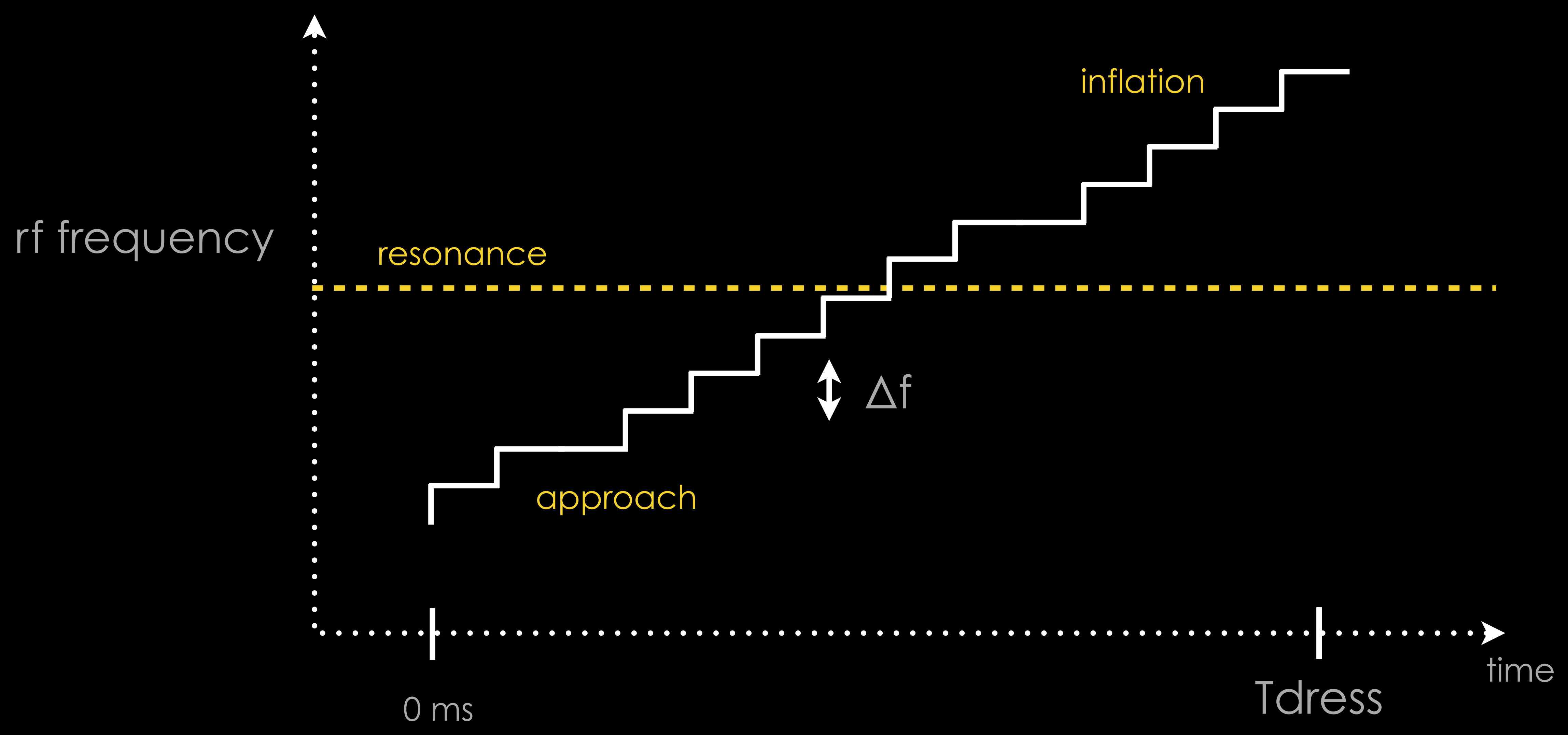
Extrapolated motion given 16 ms TOF from a ~100 Hz trap:

$\Delta z_{pp} \lesssim 1\ \mu m$ (But some heating too)

dressing/inflation process



realistic dressing / inflation process



1) need Δf to be << Rabi to not miss resonance (like rapid passage)

2) avoid heating: small Δf, large Tdress (open questions!)

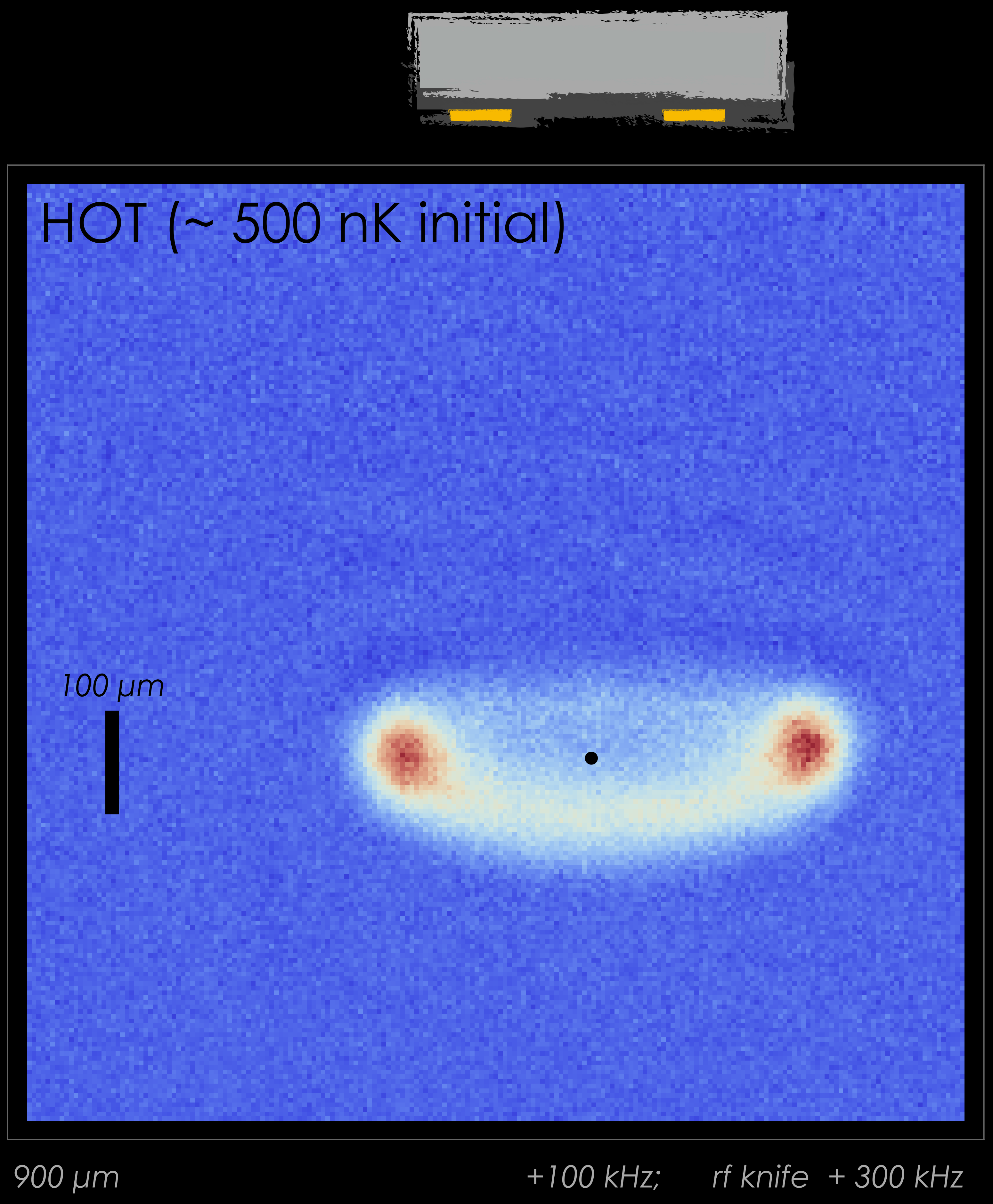
3) need to start many Rabi below resonance

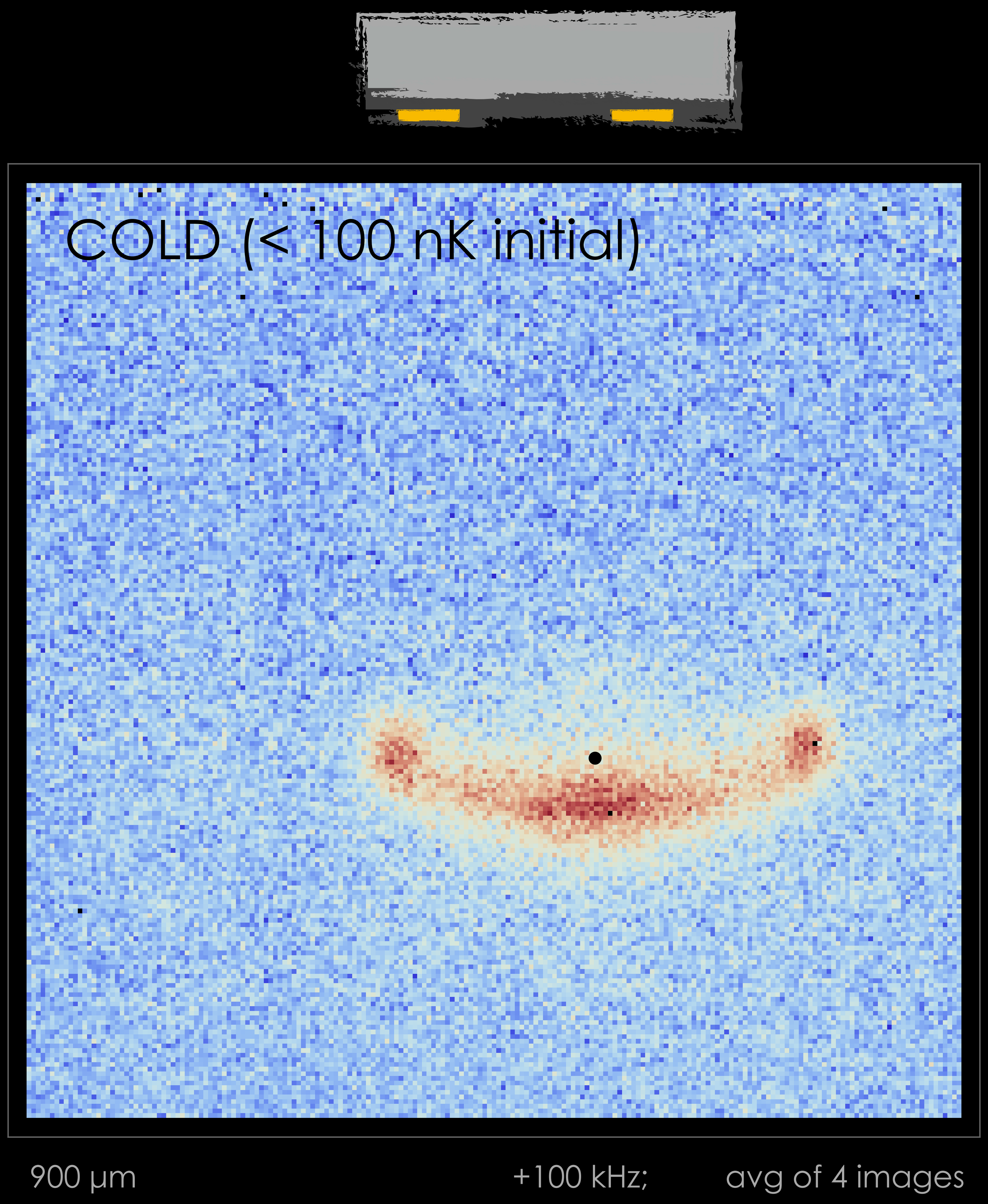
Inflate **large bubbles** to build intuition (2019-20)

(Small bubbles blurred by imaging resolution)

$k_b T / mg \sim 1 - 5\ \mu m$

(impossible on earth)





Q: How can we interpret these structures?

A: Look to our model for guidance as to size, shape, temperature, potential BEC fraction chip layout | currents & fields | Biot-Savart

↓

Zeeman shifts | dressing physics

↓

dressed potentials

- aspect ratio, anharmonicity
- bias B inhomogeneity
- coupling rf inhomogeneity

Schroedinger ground state

Gross-Pitaevskii ground state

Thomas-Fermi ground state

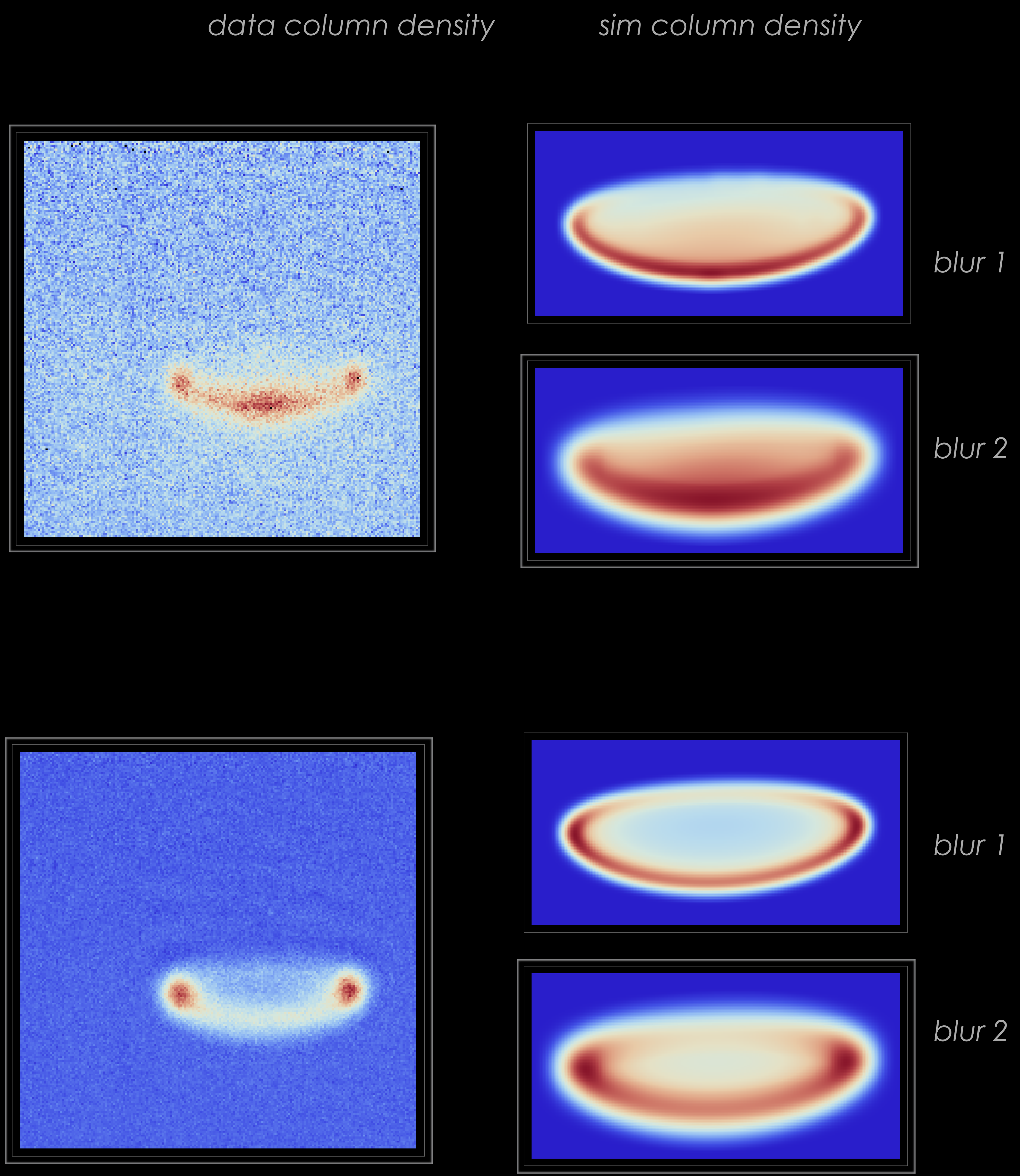
thermal density distribution

FOCUS ON THESE LARGE STRUCTURES DESPITE INHOMOGENEITY

initial T	bubble T (calc)
90 nK	20 nK

partially condensed

initial T	bubble T (calc)
450 nK	160 nK



➢ Realistic model of the CAL absorption imaging system for ~0.5 mm scale clouds is crucial to understanding these images in detail chip layout | currents & fields | Biot-Savart

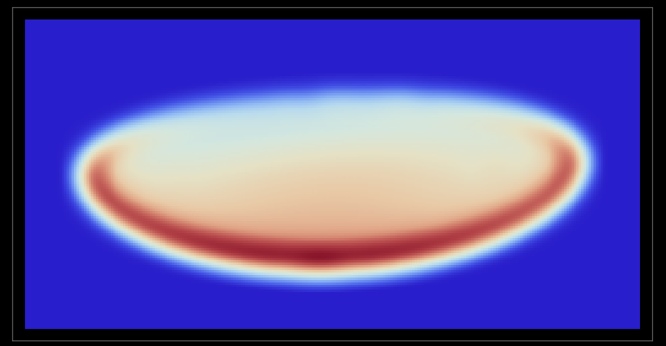
Zeeman shifts | dressing physics

dressed potentials

FOCUS ON THESE LARGE STRUCTURES
DESPITE INHOMOGENEITY

data column density

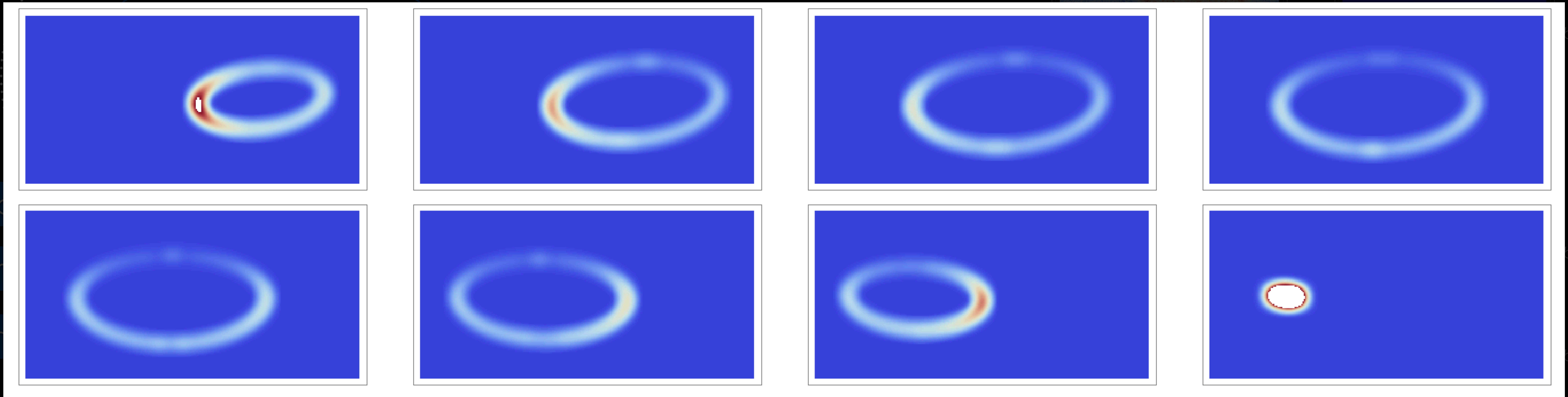
model column density



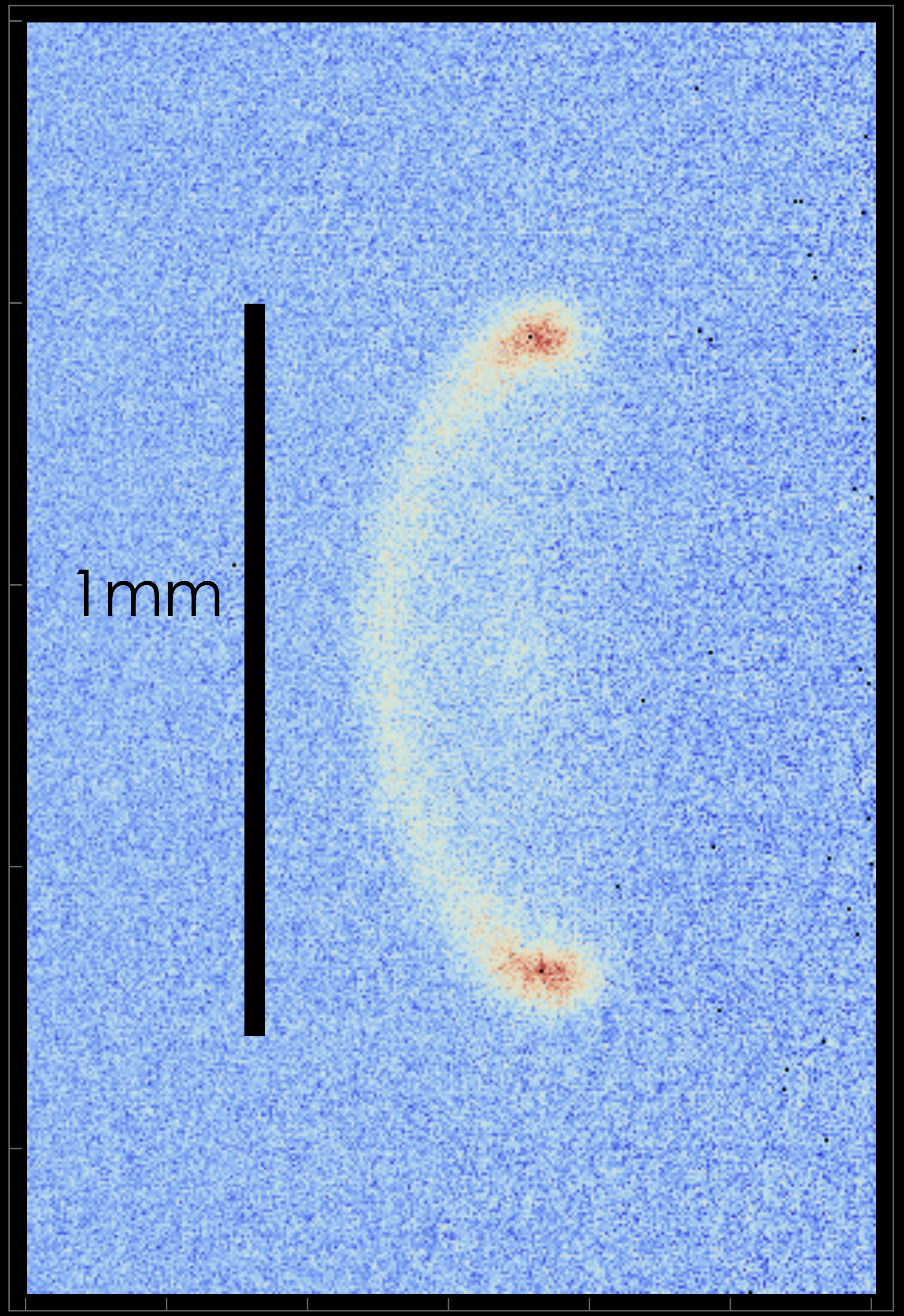
blur 1

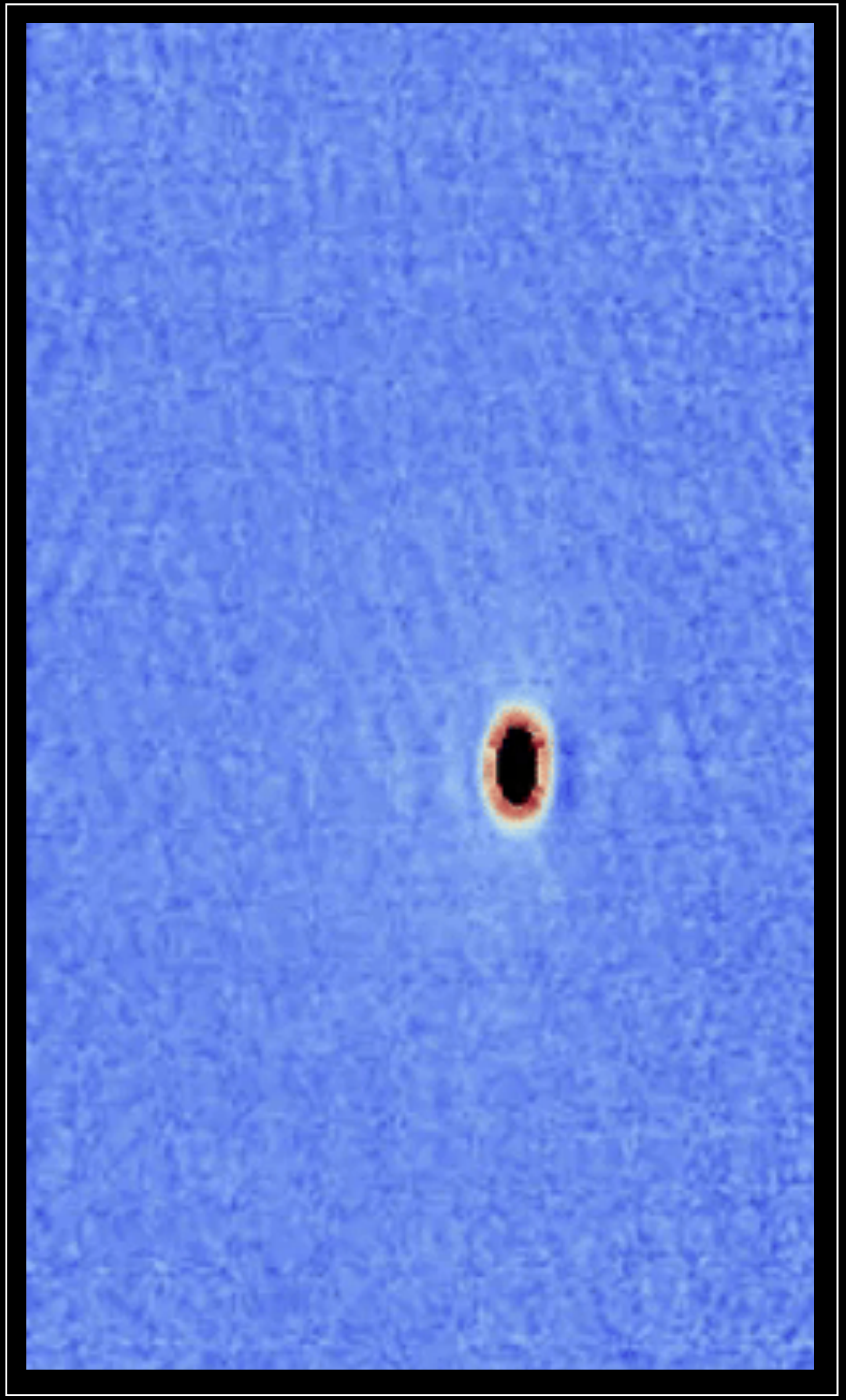
90 nK ········➤ 20 nK

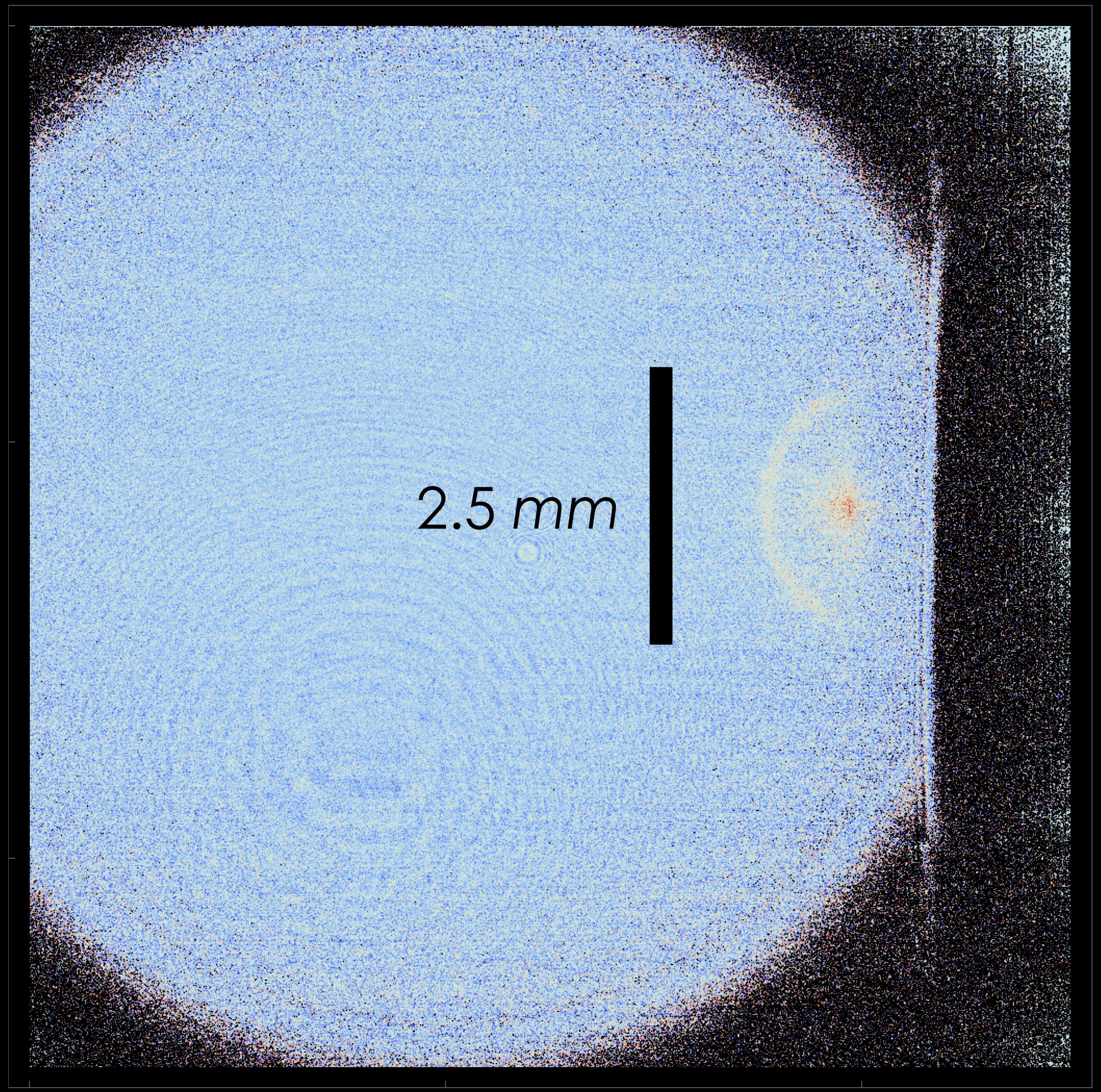
TAKE SLICES IN MODEL TO CONFIRM 'SHELLNESS'



imaging system for ~0.5 mm scale clouds is
crucial to understanding these images in detail


1mm

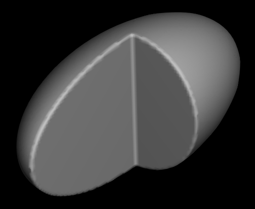


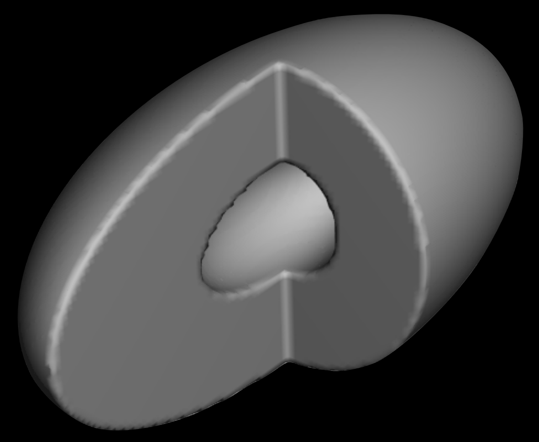

2.5 mm

Thermodynamics of shell potentials

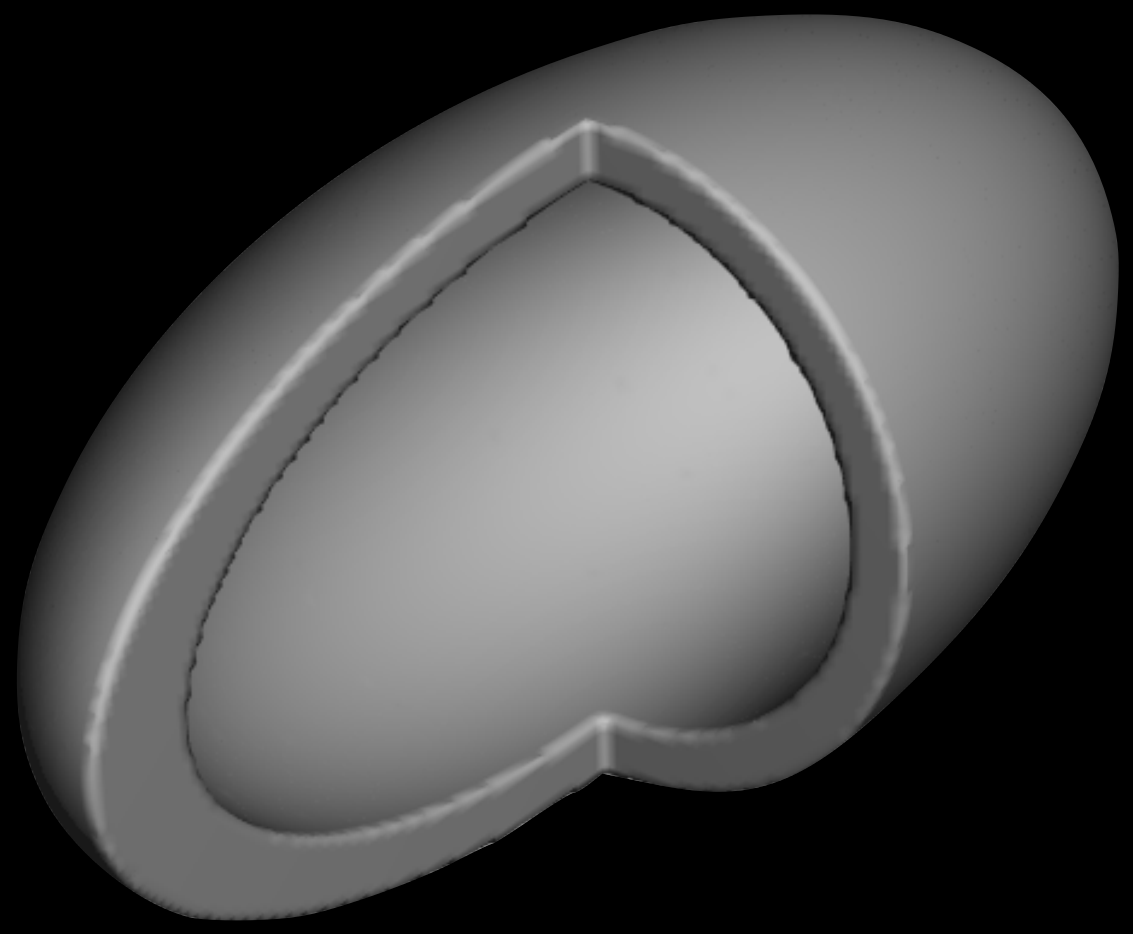
collab: Vishveshwara group : Brendan Rhyno (UIUC)

Initial entropy S_0, T, Tc, PSD, N_0/N





Final entropy S_0, T, Tc, PSD, N_0/N



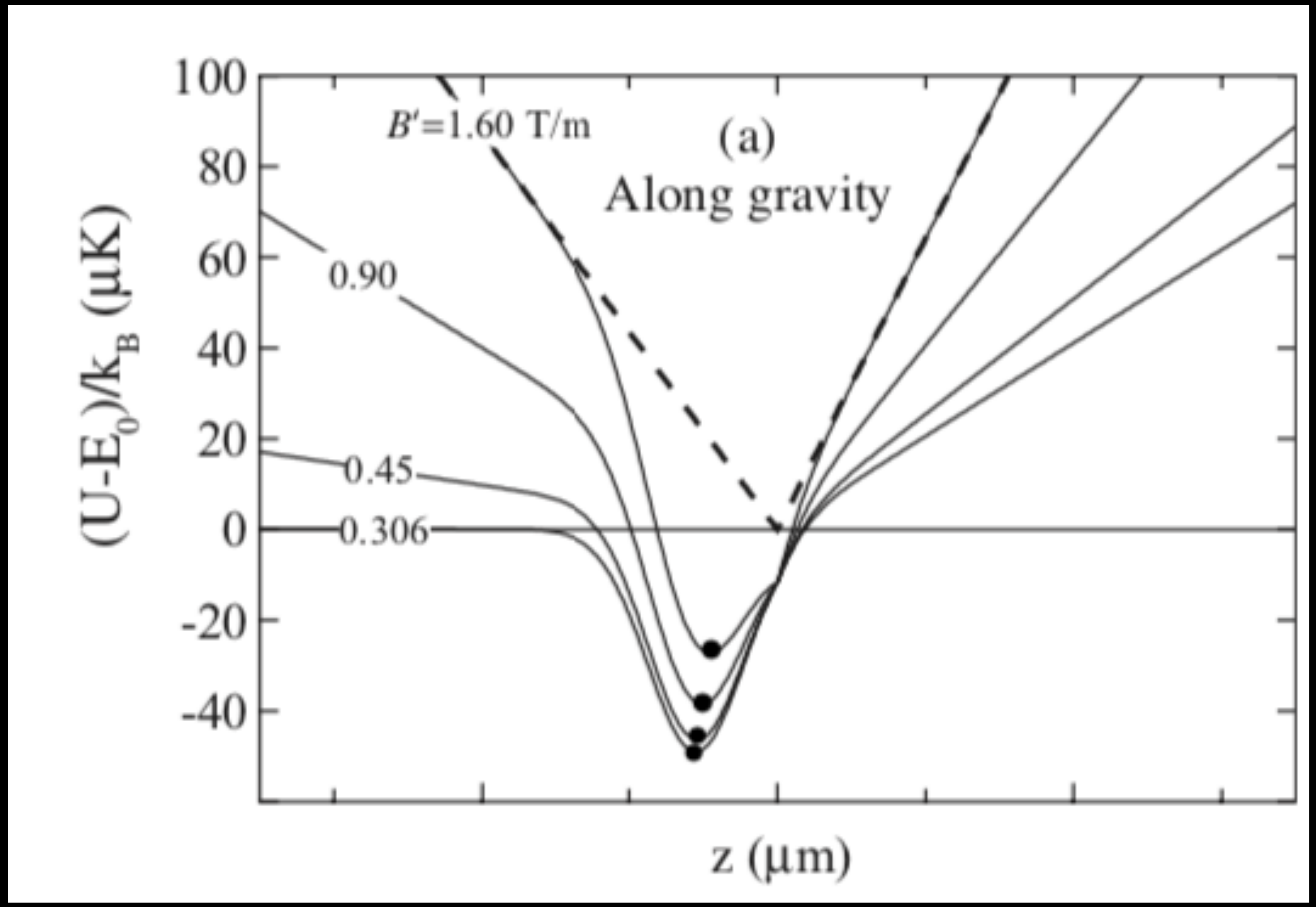
adiabatic* trap deformation

squeezing ***into*** *shell surface, but spreading* ***out*** *over surface as well*

Thermodynamics of shell potentials

collab: Vishveshara group; PhD student Brendan Rhyno (UIUC)

- Net effect during inflation: T drops, but Tc drops **faster**!
  - **LOSS** of PSD despite nominal adiabaticity



PHYSICAL REVIEW A **79**, 063631 (2009)

Rapid production of ^{87}Rb Bose-Einstein condensates in a combined magnetic and optical potential

Y.-J. Lin, A. R. Perry, R. L. Compton, I. B. Spielman,* and J. V. Porto†
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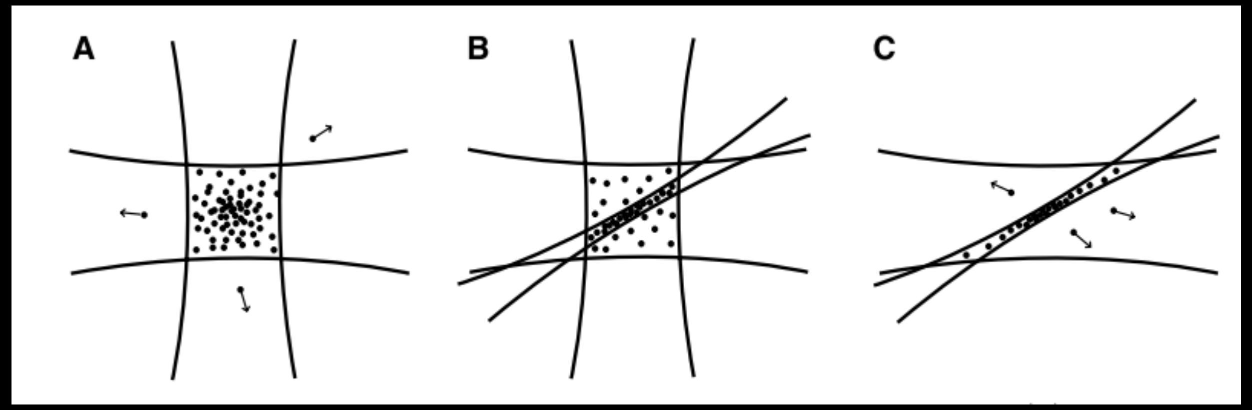
(Received 2 April 2009; published 29 June 2009)

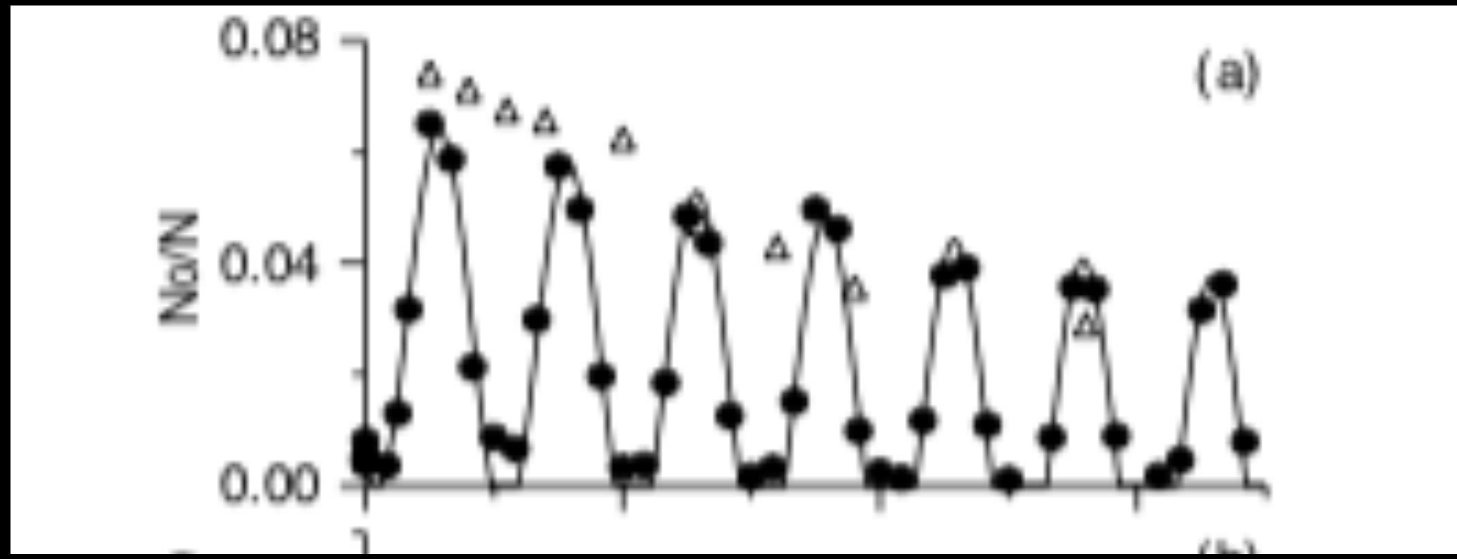


Bose-Einstein Condensation of Cesium

Tino Weber, Jens Herbig, Michael Mark, Hanns-Christoph Nägerl, Rudolf Grimm

Bose-Einstein condensation of cesium atoms is achieved by evaporative cooling using optical trapping techniques. The ability to tune the interactions between the ultracold atoms by an external magnetic field is crucial to obtain the condensate and offers intriguing features for potential applications. We explore various regimes of condensate self-interaction (attractive, repulsive, and null interaction strength) and demonstrate properties of imploding, exploding, a non-interacting quantum matter.

- others: **GAINS** of PSD with adiabatic deformation



Reversible Formation of a Bose-Einstein Condensate

D. M. Stamper-Kurn, H.-J. Miesner, A. P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle
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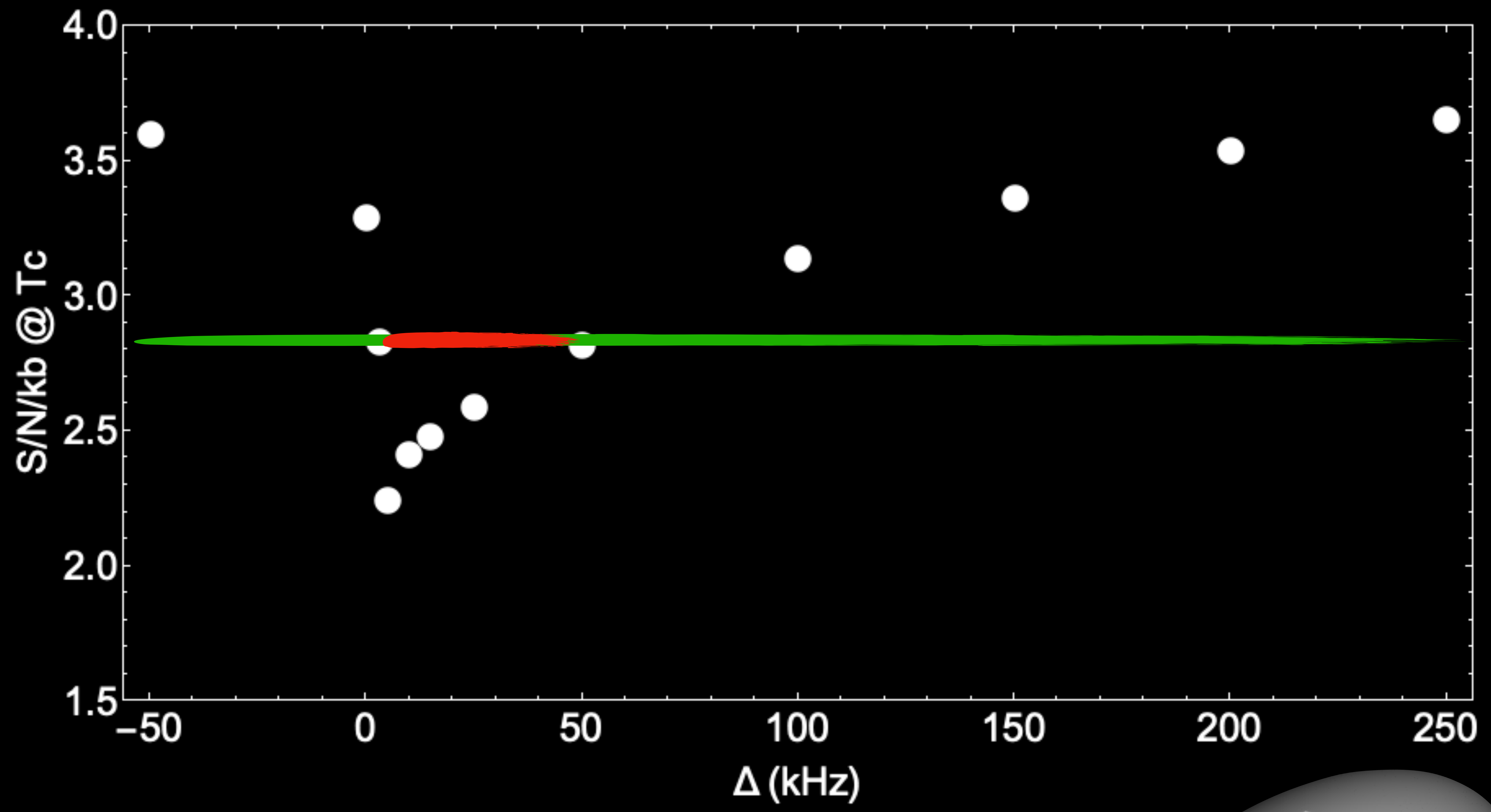
(Received 1 May 1998)

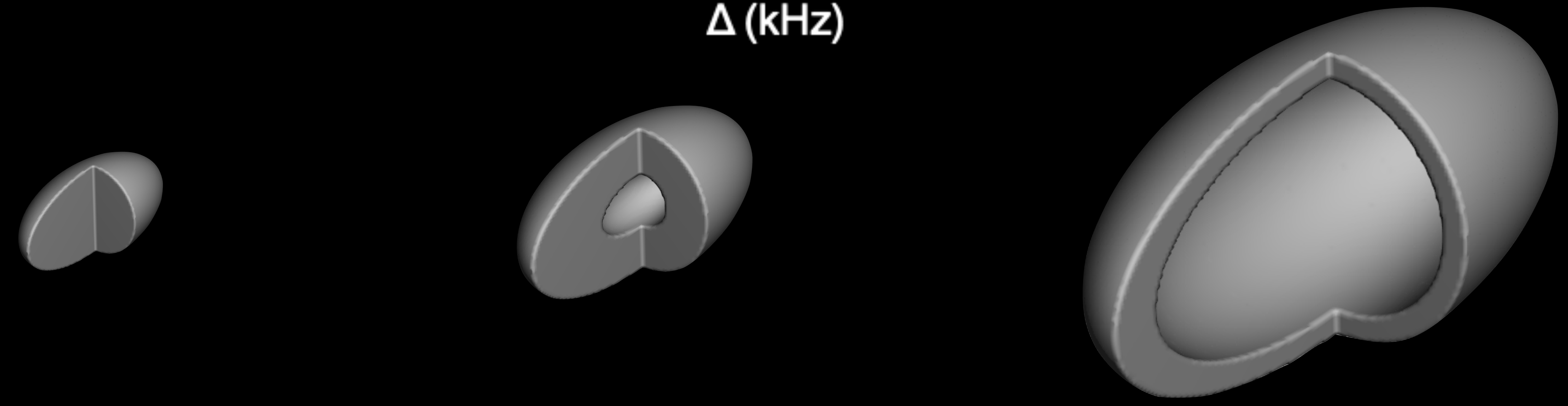
We present a method of adiabatically changing the local phase-space density of an ultracold gas using a combination of magnetic and optical forces. Applying this method, we observe phase-space density increases in a gas of sodium atoms by as much as 50-fold. The transition to Bose-Einstein condensation was crossed reversibly, attaining condensate fractions of up to 30%. Measurements of the condensate fraction reveal its reduction due to interactions. [S0031-9007(98)07066-5]

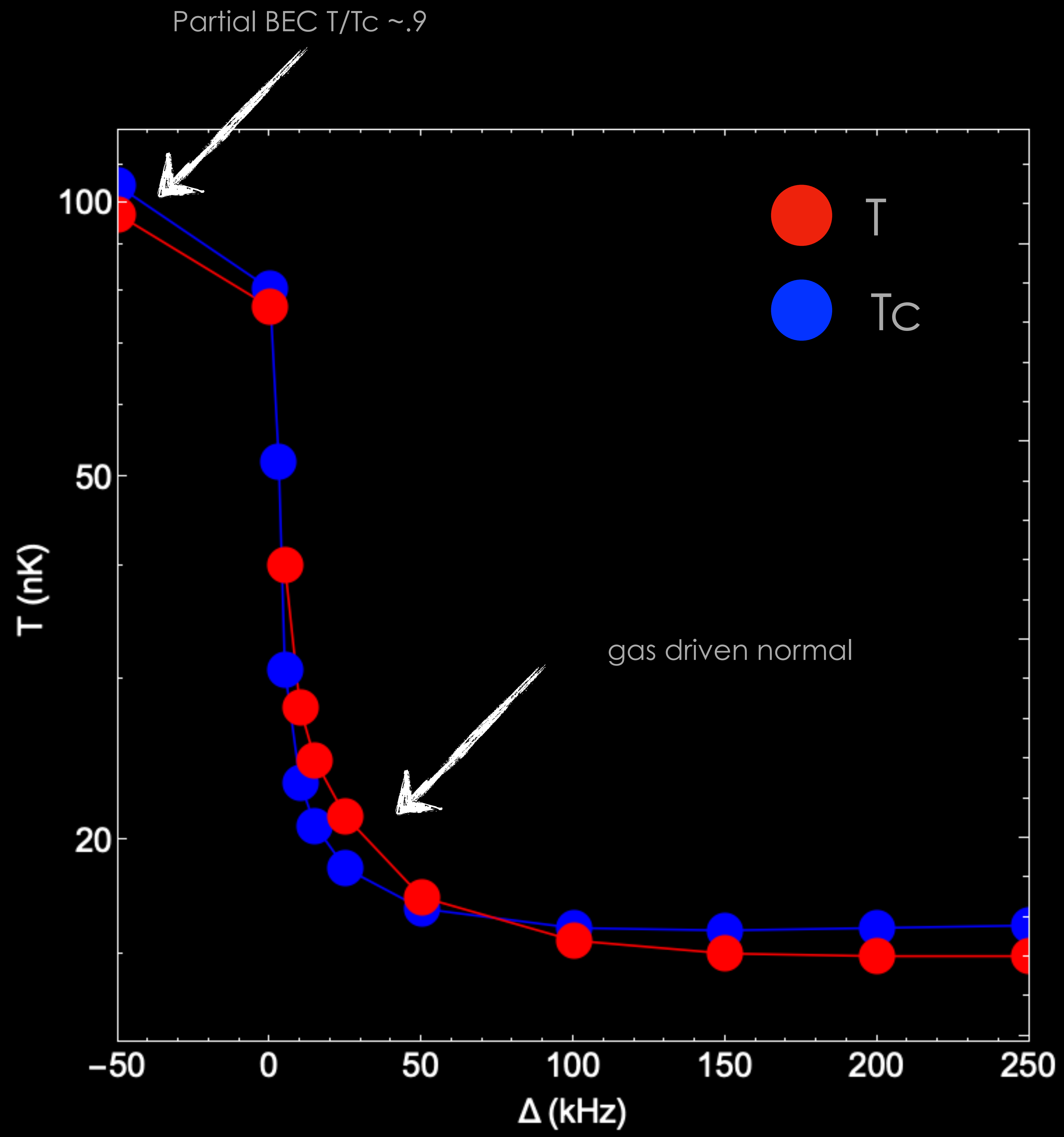
Thermodynamics of shell potentials (PRA **104**, 063310 2021)

collab: Vishveshara group (UIUC) : Brendan Rhyno et al.

(Numeric) entropy at Tc, N = 40,000



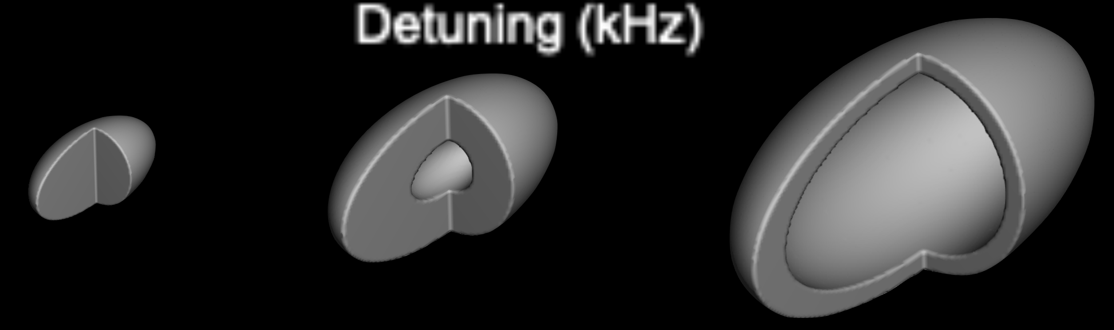




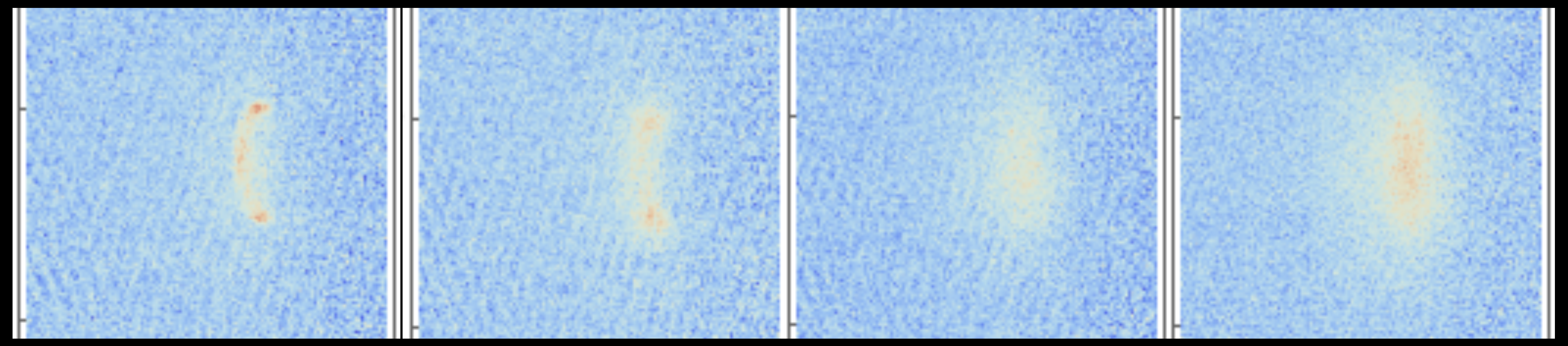
Calculations of shell thermodynamics

collab: Vishveshwara group : Brendan Rhyno (UIUC)

Thermometry: snap off rf & chip trap; expand into TOF; **measure temperature** from expansion history



Time-of-flight (TOF) expansion of “+100” kHz shell, 100 nK starting temp, 60(20) nK final



2 ms 16 ms 32 ms 48 ms

- Nonadiabaticity?
- Bad thermometry at large detunings?
- …Why not both?

where we're at: arXiv:2108.05880, *Observation of ultracold atomic bubbles in orbital microgravity* (in press, ***Nature***)

- ➢ Structures distinctly unlike terrestrial equivalents
- ➢ good model / intuition for observed patterns
  - ➢ What's next with 'SM3' upgrade (2021-onward)?
    - ➢ better condensate fraction
    - ➢ expected better inhom. (new rf loop, new chip)
    - ➢ figure out shell adiabaticity & track down condensation signature
  - ➢ The future: bigger ideas, things to explore given successful initial work… and maybe on BECCAL too?
    - ➢ **microwave dressing (Sussex collab)**; secondary cooling? spectroscopy? microwave shells?
    - ➢ 2D-3D crossover (thick/thin shell) signs?
    - ➢ **Vortex dynamics** on curved surface and on unbounded simply-connected surface (possibly more interesting on ellipsoidal shell- nonconstant curvature)
    - ➢ Bragg spectroscopy???

growing theory base

Vortex-antivortex physics in shell-shaped Bose-Einstein condensates

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Quantum Bubbles in Microgravity

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Bose–Einstein condensation on curved manifolds

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Static and dynamic properties of shell-shaped condensates

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Bose-Einstein Condensation on the Surface of a Sphere

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Physics of hollow Bose-Einstein condensates

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- *Joe Murphree (postdoc, soon to be ColdQuanta)*
- *Ryan Carollo (former postdoc, now Senior Physicist at SwitchgearHP)*
- *Tom Jarvis (former postdoc, now faculty @ EKU)*

NOW HIRING!

- *Michal Cwik '20 (now Physical Sciences Inc.)*
- *Max Gold '19 (now UIUC Physics)*
- *Xiaole (Alex) Jiang '21 (now CUNY Physics)*

*(and **many** other summer/thesis students)*

BECCAL project (launching ~2024)

Deutsches Zentrum für Luft- und Raumfahrt

Courtney Lannert

Smitha Vishveshwara

- Karmela Padavic (grad student)
- Brendan Rhyno (grad student)

David Aveline

CAL Science Module Lead

CAL Co-Investigator

Robert J. Thompson (Project Scientist)
Kamal Oudrhiri (Project Manager)
Ethan Elliott, Jim Kohel, Jason Williams, many others on CAL project team

$$$ acknowledgment: NASA CAL via JPL RSA
(NASA Fundamental Physics, was in HEOMD/SLPS — now in SMD/BPS


Canada