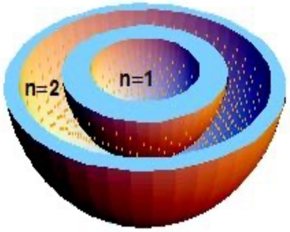
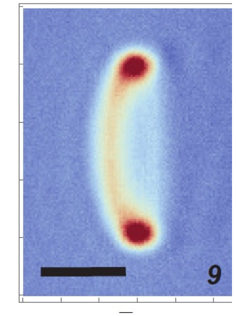
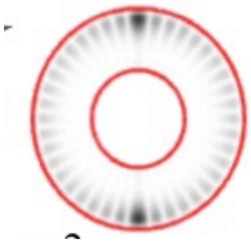
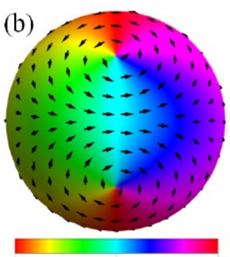




Condensate Bubbles: Co-existence, Collective Modes, Cooling and more



Smitha Vishveshwara
Dept. of Physics, University of Illinois at Urbana-Champaign



In Collaboration with

Groups of *C. Lannert, N. Lundblad*, JPL

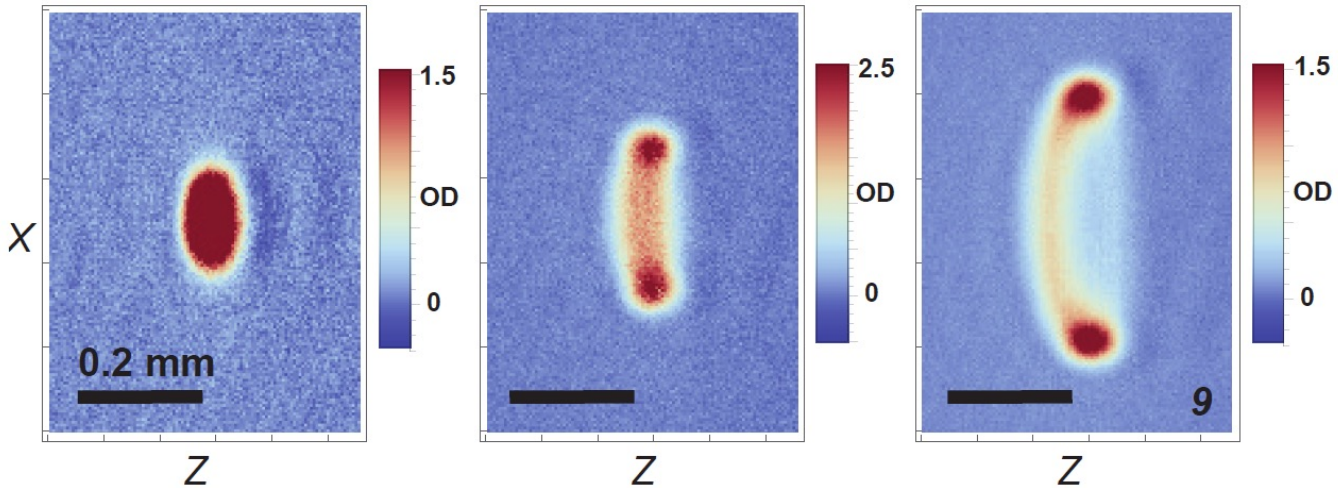
K. Sun, K. Padavic, B. Rhyno,

D. Aveline, R. Barankov, B. DeMarco, R. Carollo,

J. Murphee, T.C. Wei, F. Yang

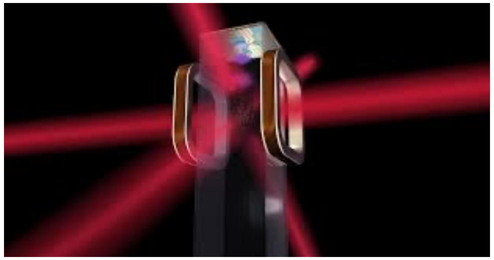
Ap7, 2022; Workshop, Prospects of Quantum Bubble Physics, Leibniz Univ.

Observation and Thermodynamics of Quantum Bubbles in Space



Lundblad Group+JPL
CAL, ISS
arXiv2108:05880
Accepted to Nature

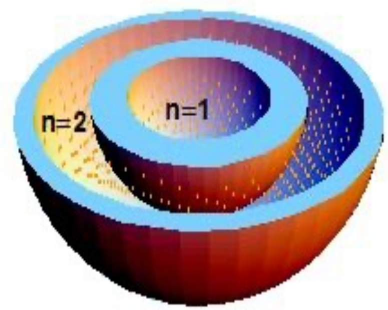
Theoretical Input (Rhyno)
along with Lannert Group

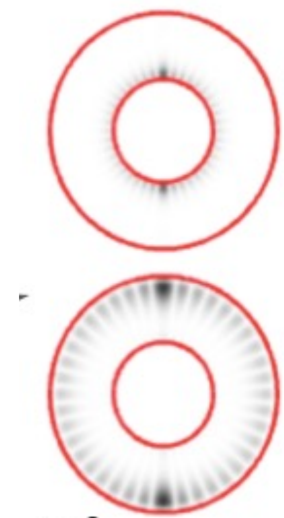


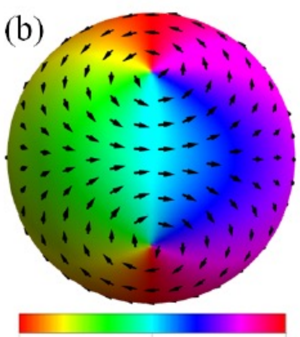
Talks by Lundblad; Garroway, Salasnich, von Klitzing, and Williams

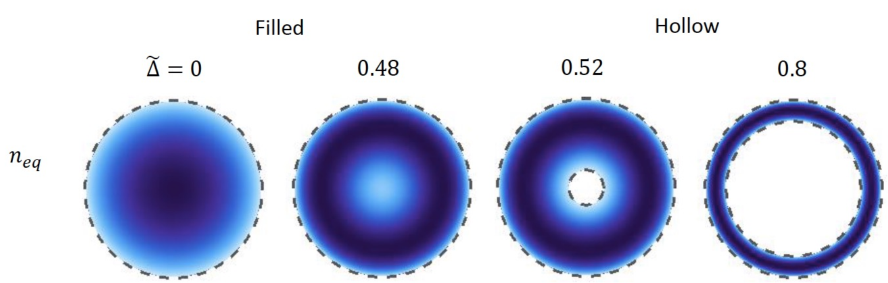
In what follows

- Condensate shells in different contexts
- Superfluid-Mott systems—realization, collective modes
- Shell expansion
- Connecting with CAL Experiments
- Collective modes contd.
- Vortices
- Thermometry



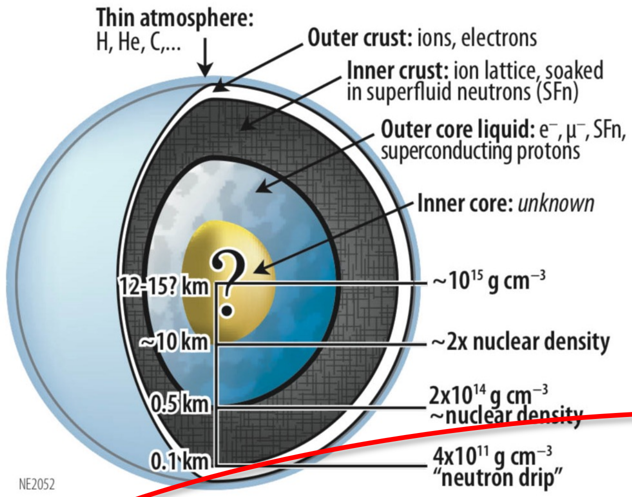




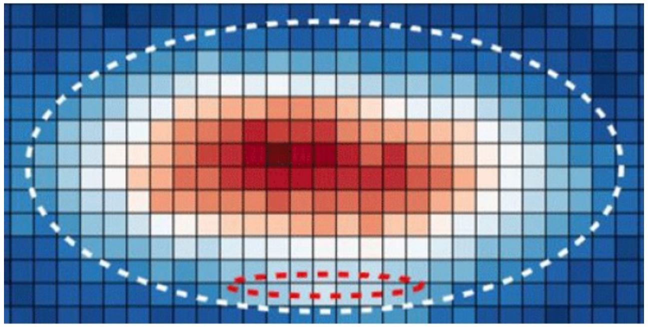


Condensate bubbles in different settings

Stellar Bodies

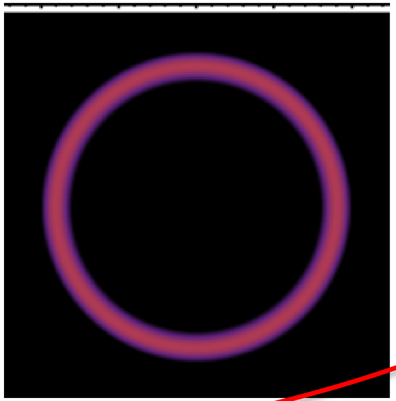


Gas Mixtures

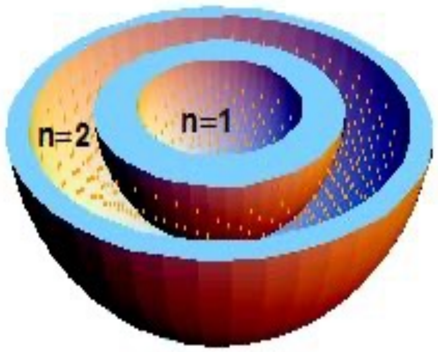


Bose-Fermi: Chin Lab; Bosons—Talk by Meister

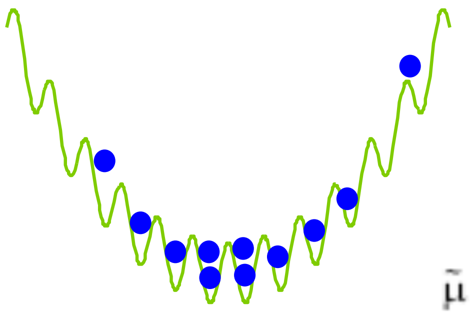
Free Space



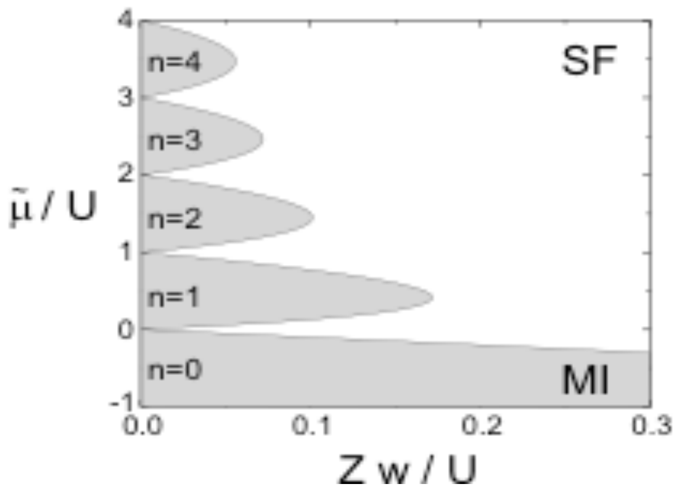
Optical Lattice

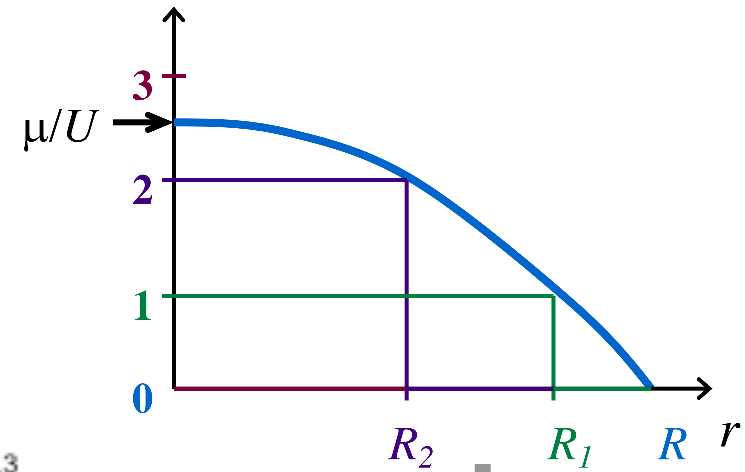


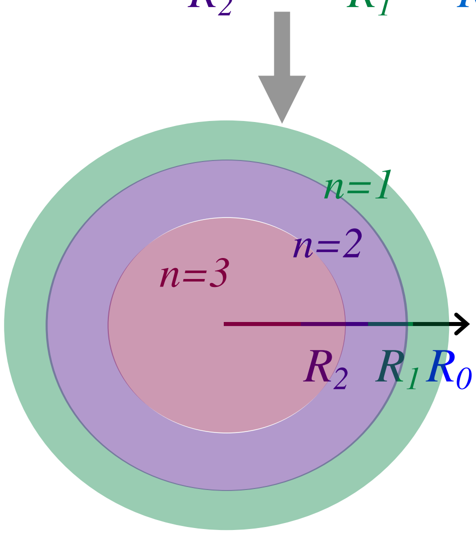
Optical Lattices---Coexistence—Mott Insulator Shells



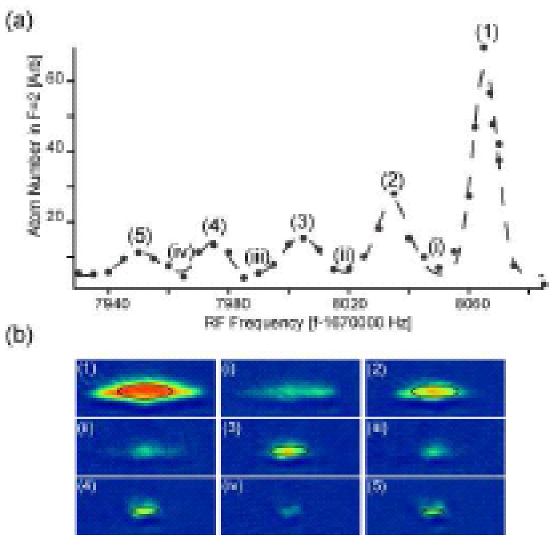
Optical Lattice+ Harmonic Trap







Low tunneling: Mott Shells

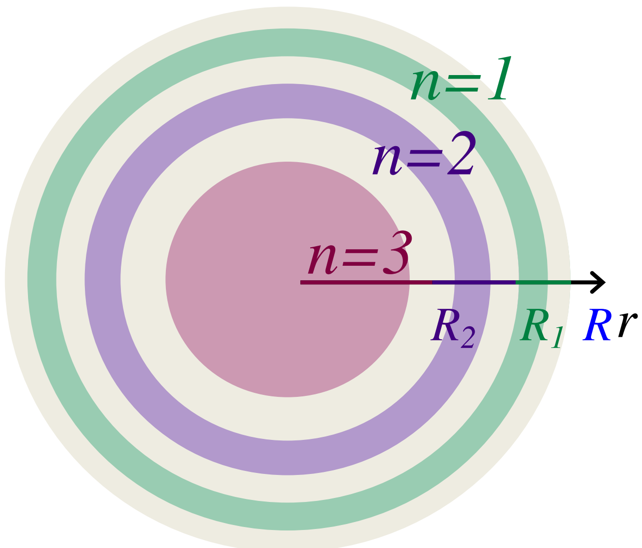


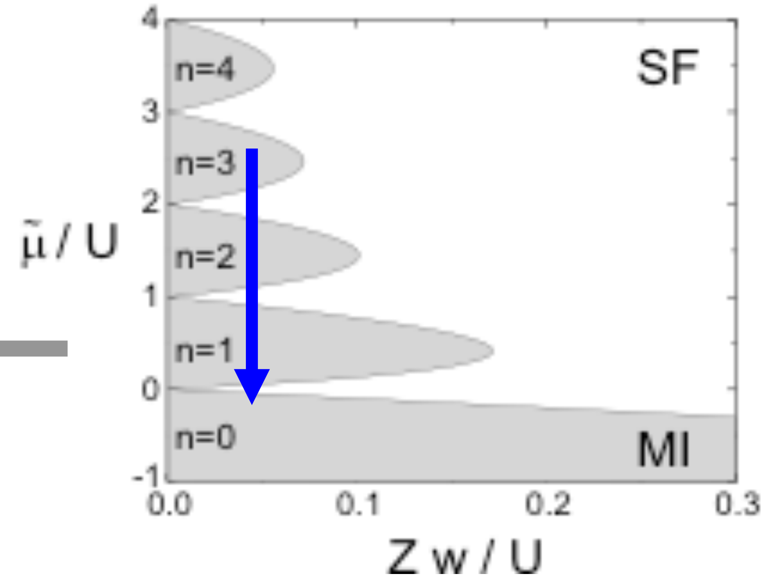
Spectroscopy

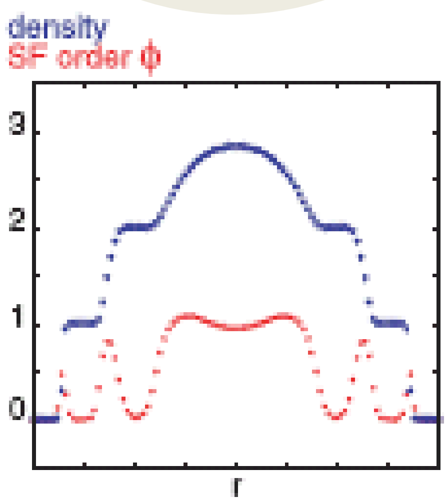
G. G. Bartoumi et al PRL (1990) D. Jaksch et al,, PRL (1998) ;
De Marco, C. Lannert, SV, T.C. Wei, PRA (2005);

E.g. Campbell et al., Science 2006; Foelling et al., PRL 2006

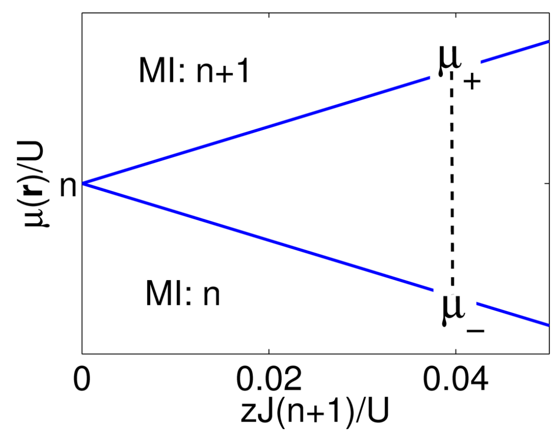
Number fluctuations –
The "wedding cake" scenario







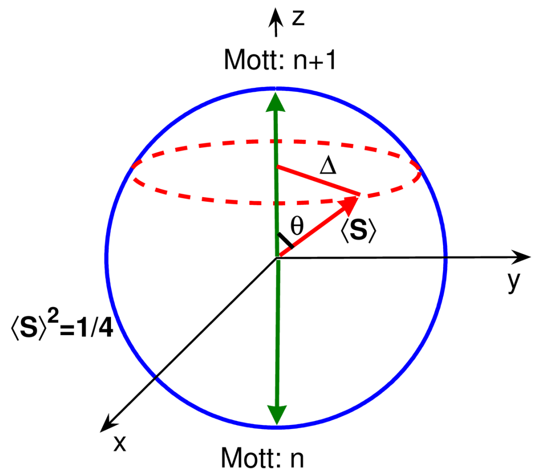
In between layers



E.g. D. S. Rokhsar and B. G. Kotliar, Phys. Rev. B (1991); C. Bruder, R. Fazio, and G. Schon, Phys. Rev. B (1993)

Condensate layer---Collective Modes

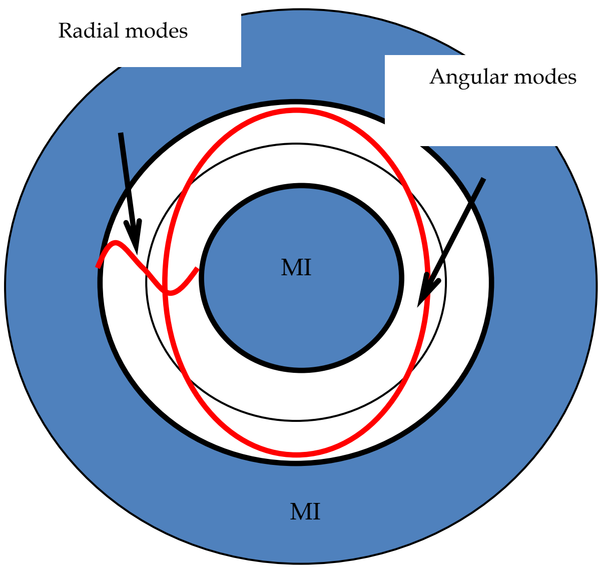
Pseudospin description



Density distortions

$$\partial_t^2\,\delta\rho = 4z\,(J(n+1)\ell)^2\,\nabla\left[\Delta_0^2\,\nabla\delta\rho\right]$$

$$\Delta_0(\mathbf{r}) = (1/2)\sin\theta(\mathbf{r})$$



Collective Modes

Radial modes: $\Omega_r = 2\sqrt{6}J(n+1)\ell/\delta R_n$

Angular modes: $\Omega_s = \sqrt{3}J(n+1)\ell/R_n$

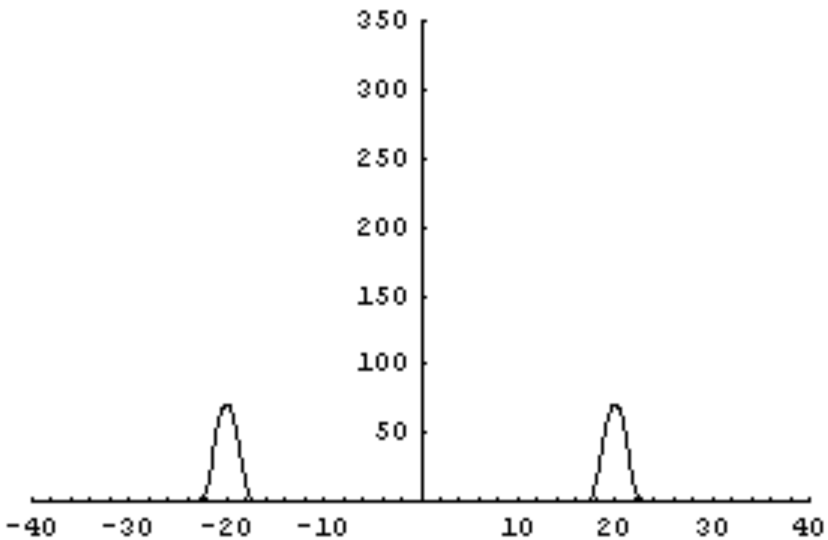
Can probe in spectroscopy

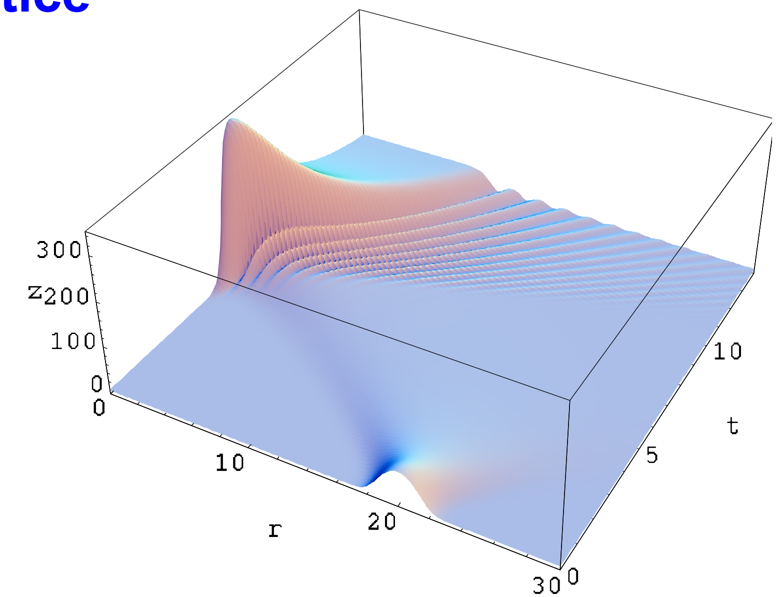
Effective dimensionality of condensate : tunable, determined by Ω_r and Ω_s

R. Barankov, C. Lannert, S.V., PRA (2007); K. Sun, C. Lannert, S.V. (2009)

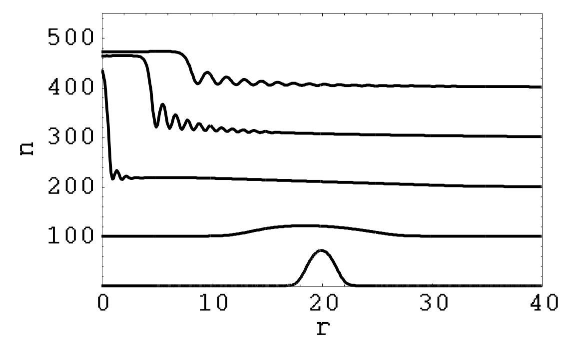
Free space—3D shell expansion

Simulations in the absence of a lattice





Features:
Mass accumulation, self-interference

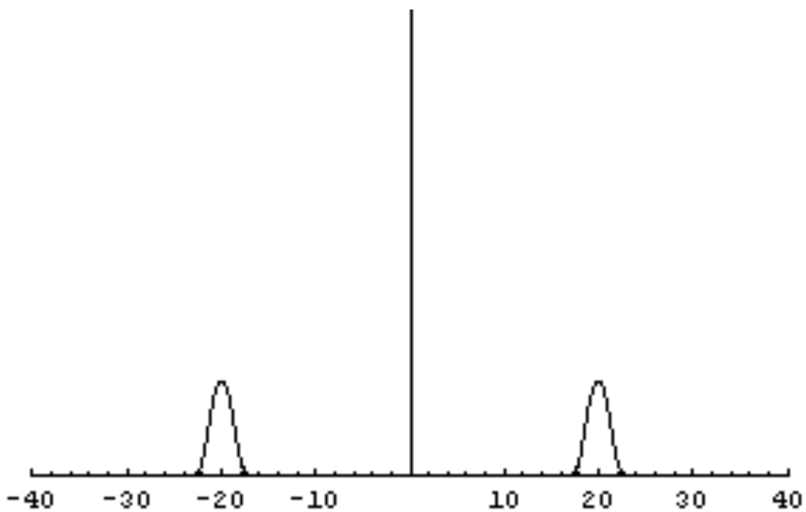


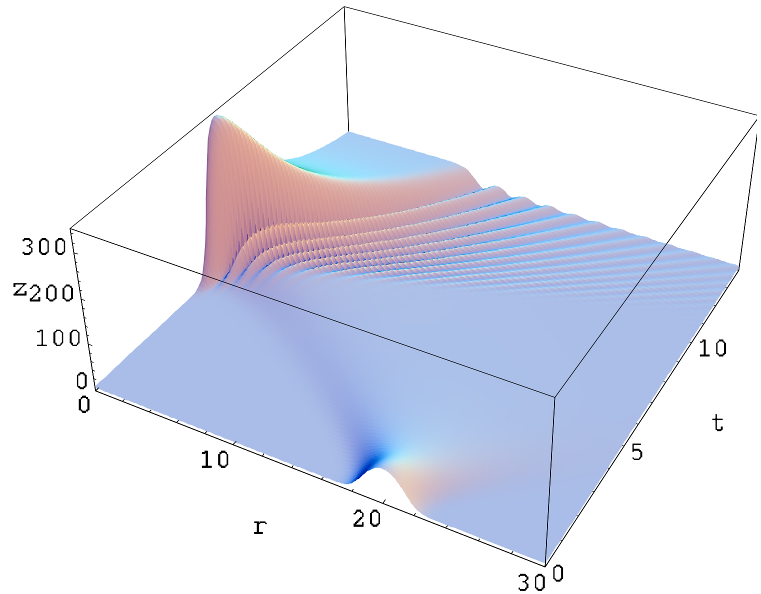
C. Lannert, S.V. and T. C. Wei, PRA (2007)

Related: Tononi, F. Cinti and L. Salasnich, PRL (2020)

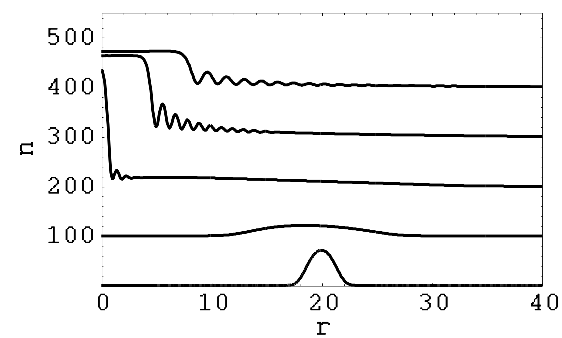
Free space—3D shell expansion

Simulations in the absence of a lattice



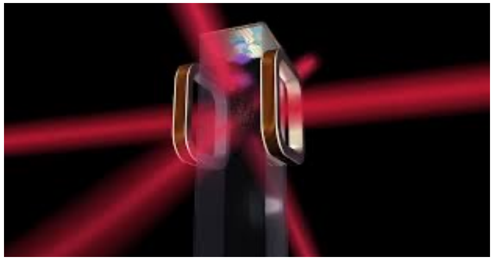


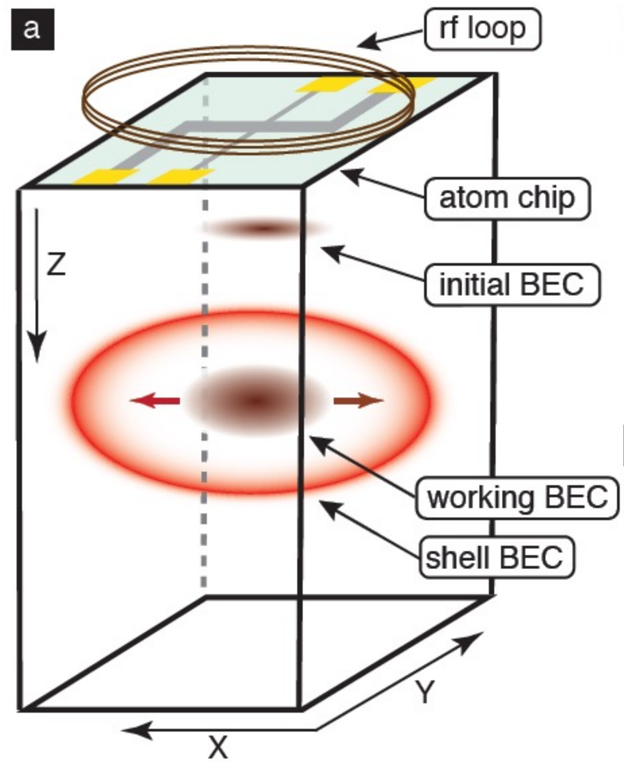
Features:
Mass accumulation, self-interference



C. Lannert, S.V. and T. C. Wei, PRA (2007)

Bubbles in Space





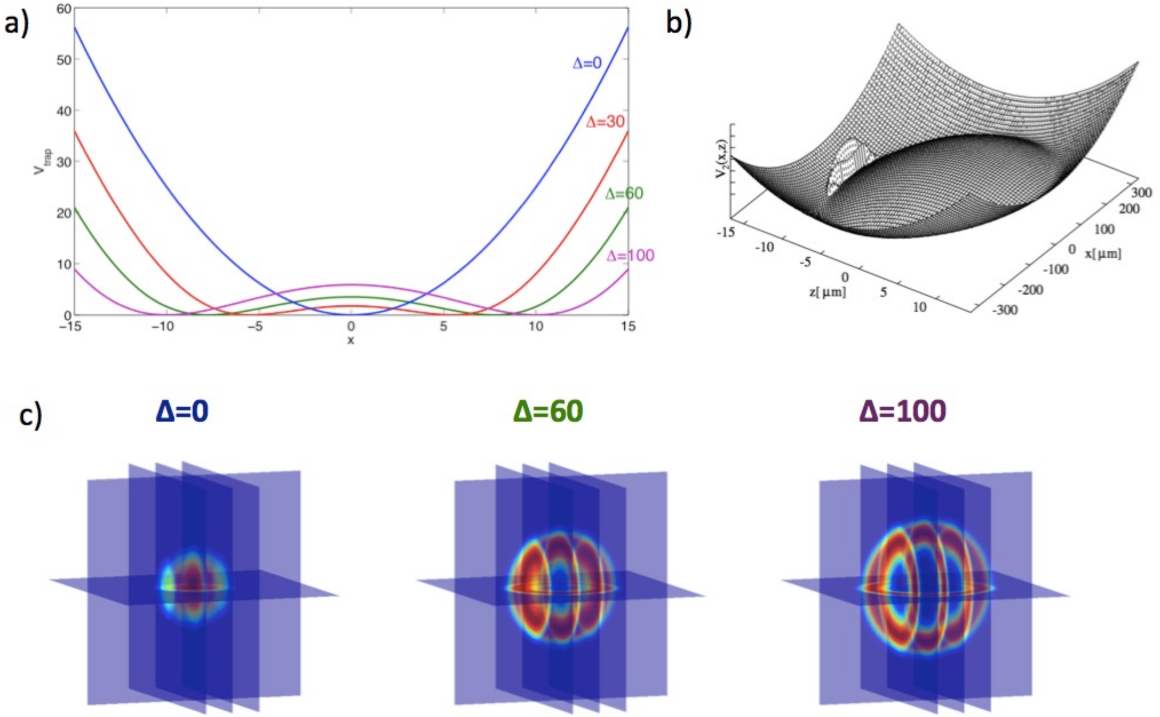
Lundblad et al, NPJ Microgravity (2019)

SPACE & PHYSICS

Ultracold Quantum Collisions Have Been Achieved in Space for the First Time

K. Padavic, Scientific American, March 2021

Condensates in Bubble Traps

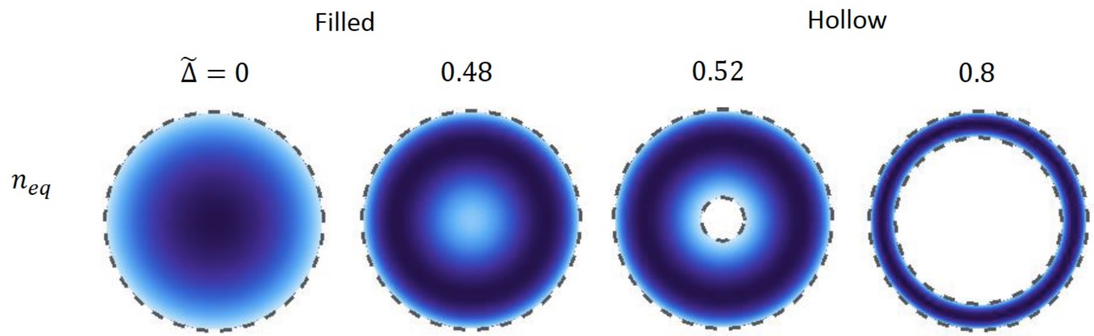


$$V_{\mathrm{bubble}}(\mathbf{r}) = m\omega_0^2 S_l^2 \sqrt{(r^2-\Delta)^2/4+\Omega^2}$$

O. Zobay, B.M. Garraway, Phys. Rev. A, (2004); *K. Merloti et al, New J. Phys. (2013);*

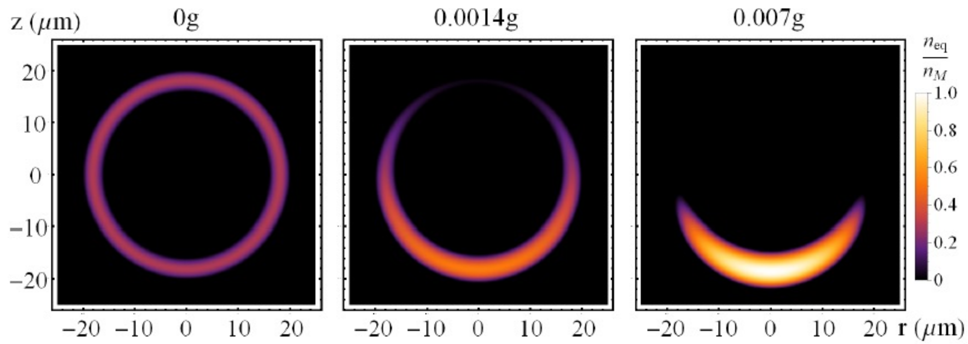
Talk by Garroway

Condensates in Bubble Traps



Filled to Hollow

Gravity

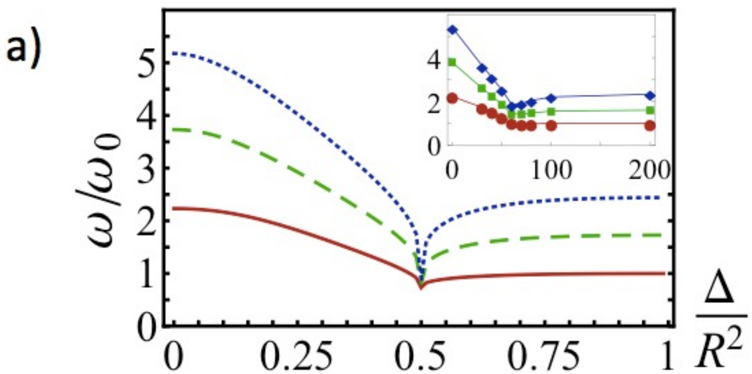


$$V_{\text{bubble}}(\mathbf{r}) = m\omega_0^2 S_l^2 \sqrt{(r^2 - \Delta)^2/4 + \Omega^2}$$

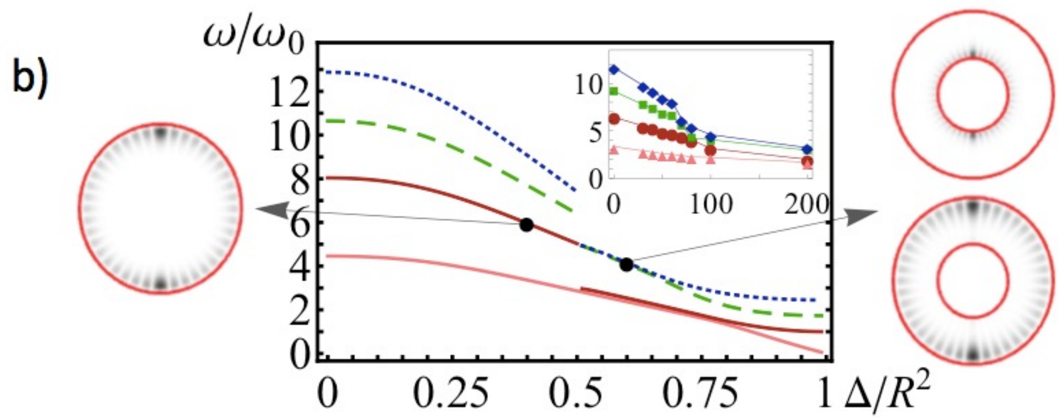
K. Padavic et al, EPL (2017); K. Sun et al, PRA (2018)

Collective modes and hollowing

Radial Modes (l=0)



Surface Modes (large l)



Hollowing-out topological transition:

- Dip in spherically symmetric modes
- Jump in surface mode frequencies

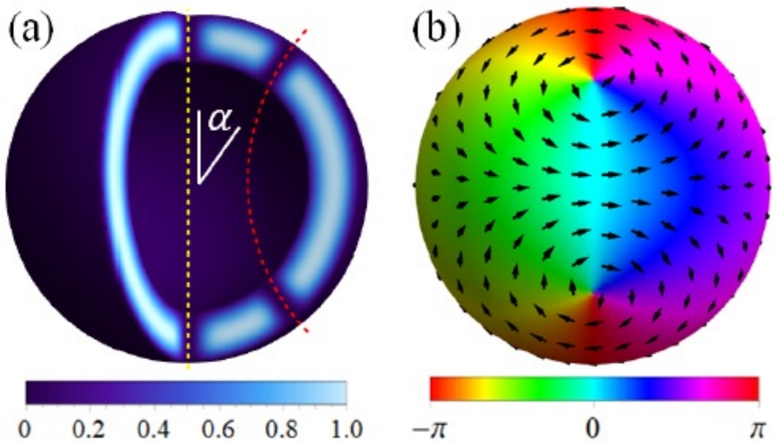
$$-m\omega^2\delta n = U_0(\nabla n_{\rm eq}\cdot\nabla\delta n + n_{\rm eq}\nabla^2\delta n)$$

$$V_{\rm bubble}(\mathbf{r}) = m\omega_0^2 S_l^2\sqrt{(r^2-\Delta)^2/4+\Omega^2}$$

K. Padavic et al, EPL (2017); K. Sun et al, PRA (2018)

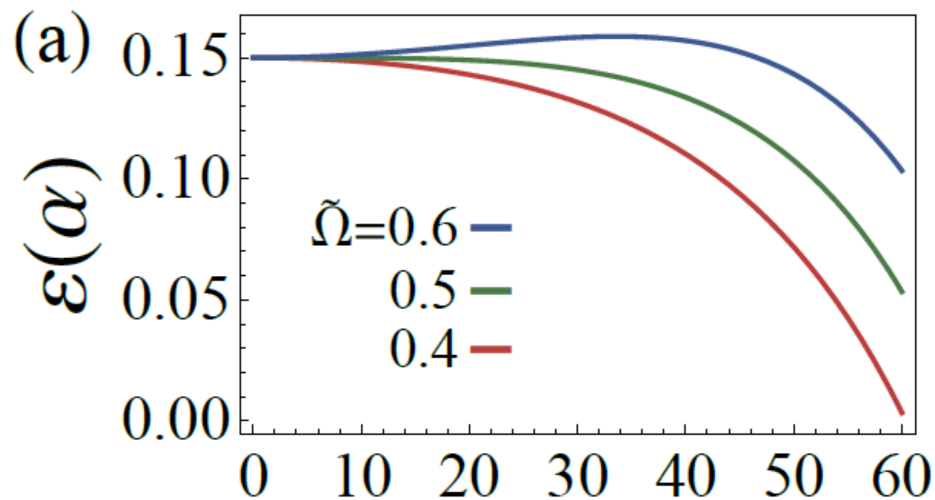
Wolf et al, arxiv2110.15247
Relevant talk by Meister

Vortex-Antivortex structure



Simplest
Topologically allowed structure

Energy (dimensionless) as a function
Of vortex line angle
Shows critical angle for stabilization
(2D Limit shown here; 3D systematically studied)



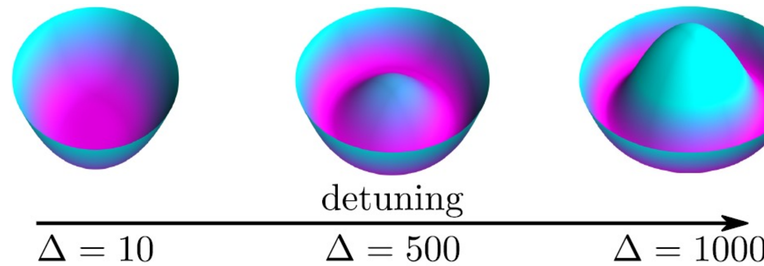
Fetter, RMP (2009)
Zhang et al, Phys Rev. Fluids (2018)

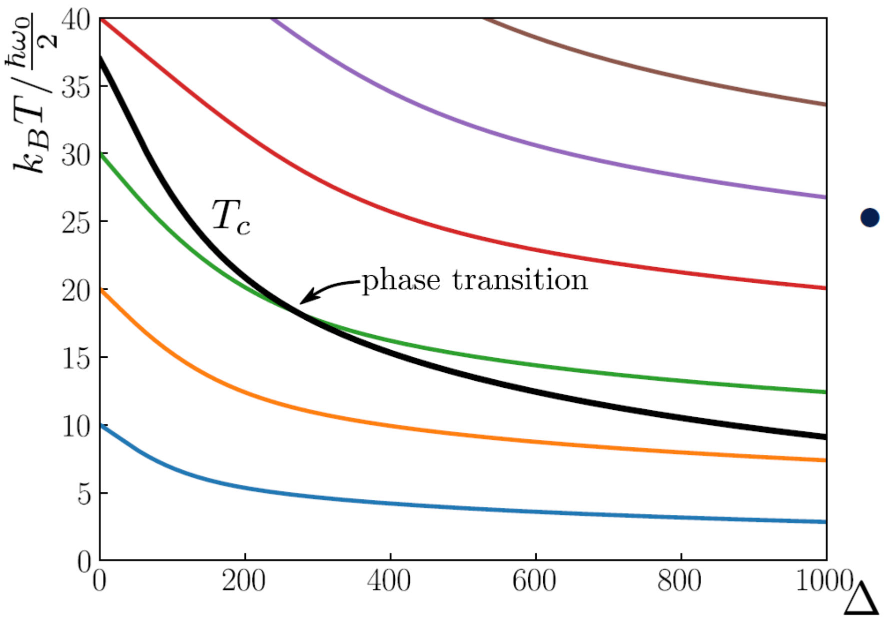
K. Padavic et al, PRA (2020)

Relevant talks by White, Massignan and Dubessy

Thermometry

$$V_{\text{bubble}}(\vec{x}) \propto \sqrt{[|\vec{x}|^2 - \Delta]^2 + (2\Omega)^2}$$





- BEC critical temperature:

$$N = \sum_{\alpha \neq 0} \frac{1}{e^{(\varepsilon_\alpha - \varepsilon_0)/k_B T_c} - 1}$$

- Temperature as system inflates into a bubble adiabatically:

$$N(T, \mu) = \sum_\alpha f_\alpha$$

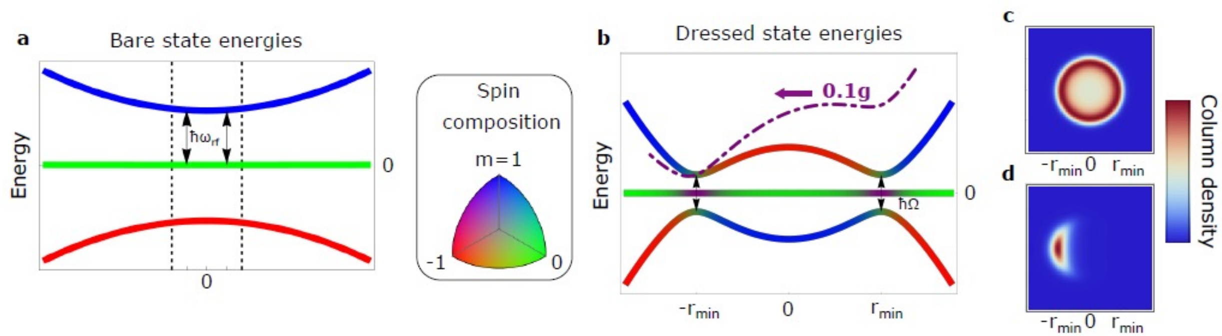
$$S(T, \mu) = k_B \sum_\alpha [(1 + f_\alpha)\ln(1 + f_\alpha) - f_\alpha \ln f_\alpha]$$

where $f_\alpha = 1/(e^{\beta(\varepsilon_\alpha - \mu)} - 1)$.

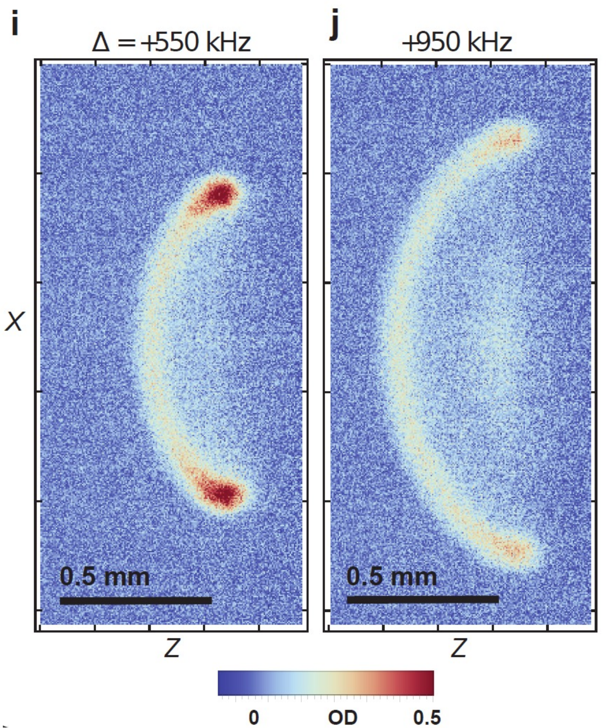
B. Rhyno et al, PRA (2021)

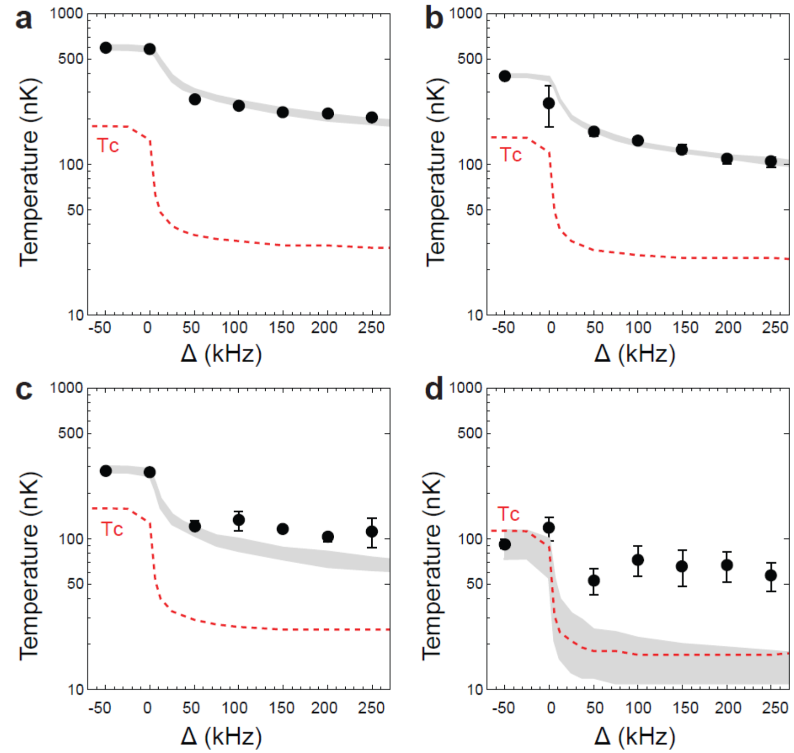
Related: Tononi and Salasnich, PRL (2019) ; Talk by Salasnich

CAL Bubble Experiment and Thermometry



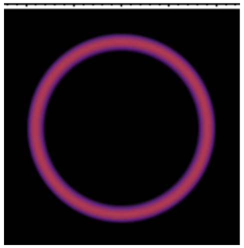
- Extreme inflation to mm-scale sizes ($T_i \approx 1\mu K$)



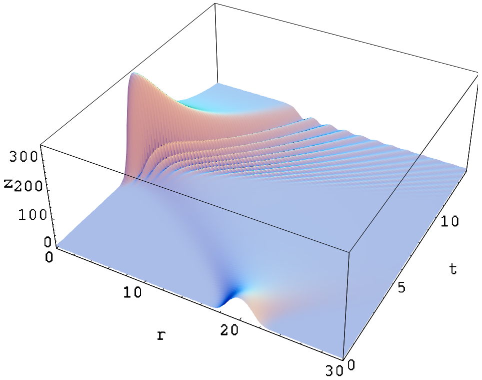


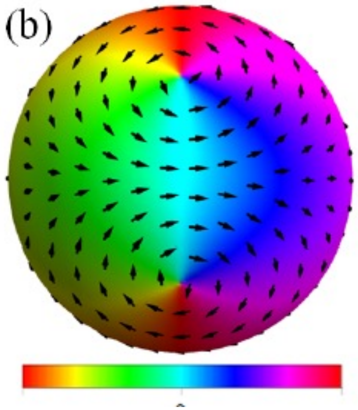
R. Carrollo et al, Accepted to Nature

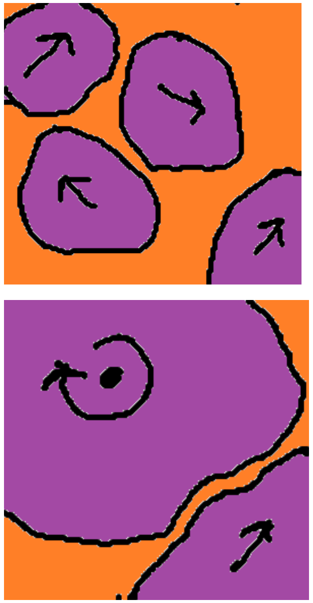
Future Directions

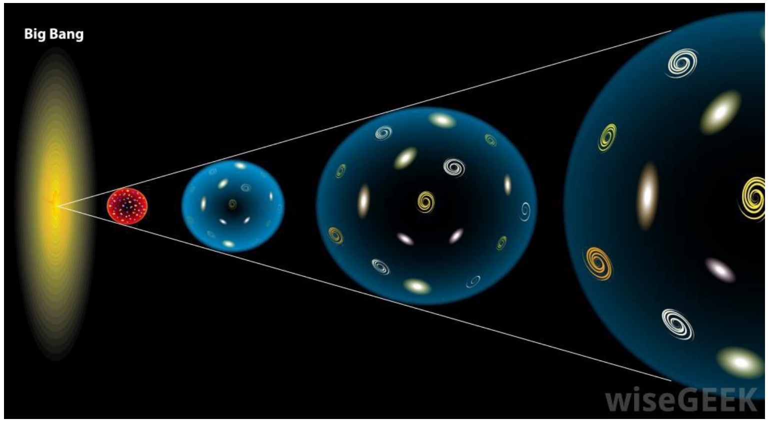


- Realistic traps and further thermometry
- Testing collective modes and expansion predictions
- BKT physics and vortex dynamics
- Coherent states and lowest Landau levels
- Non-equilibrium and Kibble-Zurek physics
- Expanding Universe









Many thanks to

Courtney Lannert and group
Smith College

Nathan Lundblad and group
Bates College

David Aveline and colleagues
JPL

Kuei Sun
UT Dallas

Karmela Padavic
Bard HSEC

Brendan Rhyno
UIUC

Roman Barankov, Ryan Carollo, Brian DeMarco, Ethan Elliot, Joseph Murphee, Robert Thompson, Tzu-Chieh Wei, Jason Williams, Frances Yang,

And to you all!!

In Conclusion:

- Condensate shells in different contexts
- Superfluid-Mott systems—realization, collective modes
- Shell expansion
- Connecting with CAL Experiments
- Bubble trap collective modes
- Vortices
- Thermometry