

# **Ultracold atoms for quantum devices and quantum simulations**

**A. Trombettoni  
(Università di Trieste)**

**Three Minutes seminars, 19 November 2021**

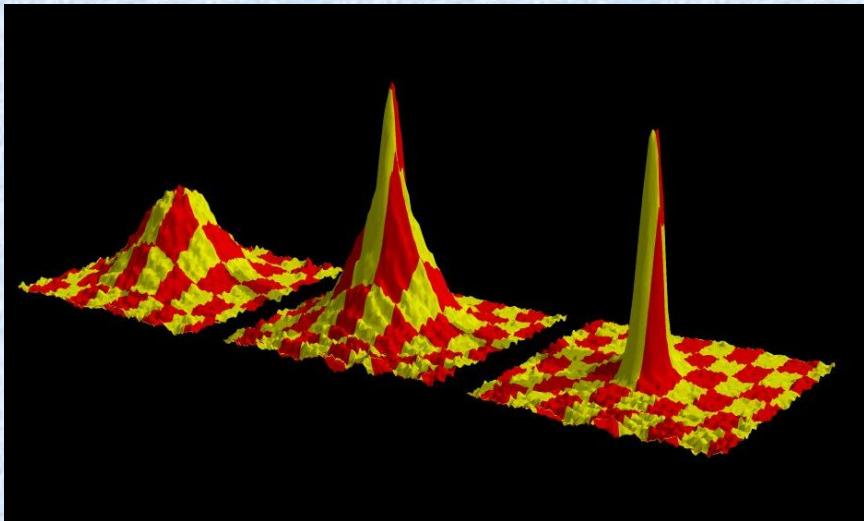
# The ultracold family: Bosons & Fermions

1 1A																					
1 H Hydrogen 1.01	2 2A																				
2 2 Li Lithium 6.94	3 Be Beryllium 9.01																				
3 11 Na Sodium 22.99	4 12 Mg Magnesium 24.31	5 3B	6 4B	7 5B	8 6B	9 7B	10 8B	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A	He Helium 4.00					
4 19 K Potassium 39.10	5 20 Ca Calcium 40.08	6 21 Sc Scandium 44.96	7 22 Ti Titanium 47.87	8 23 V Vanadium 50.94	9 24 Cr Chromium 52.00	10 25 Mn Manganese 54.94	11 26 Fe Iron 55.85	12 27 Co Cobalt 58.93	13 28 Ni Nickel 58.69	14 29 Cu Copper 63.55	15 30 Zn Zinc 65.39	16 31 Ga Gallium 69.72	17 32 Ge Germanium 72.61	18 33 As Arsenic 74.92	19 34 Se Selenium 78.96	20 35 Br Bromine 79.90	21 36 Kr Krypton 83.80				
5 37 Rb Rubidium 85.47	6 38 Sr Strontium 87.62	7 39 Y Yttrium 88.91	8 40 Zr Zirconium 91.22	9 41 Nb Niobium 92.91	10 42 Mo Molybdenum 95.94	11 43 Tc Technetium (98)	12 44 Ru Ruthenium 101.07	13 45 Rh Rhodium 102.91	14 46 Pd Palladium 106.42	15 47 Ag Silver 107.87	16 48 Cd Cadmium 112.41	17 49 In Indium 114.82	18 50 Sn Tin 118.71	19 51 Sb Antimony 121.76	20 52 Te Tellurium 127.60	21 53 I Iodine 126.90	22 54 Xe Xenon 131.29				
6 55 Cs Cesium (132.04)	7 56 Ba Barium 137.33	8 57 La Lanthanum 138.91	9 72 Hf Hafnium 178.49	10 73 Ta Tantalum 180.95	11 74 W Tungsten 183.84	12 75 Re Rhenium 186.21	13 76 Os Osmium 190.23	14 77 Ir Iridium 192.22	15 78 Pt Platinum 195.08	16 79 Au Gold 196.97	17 80 Hg Mercury 200.59	18 81 Tl Thallium 204.38	19 82 Pb Lead 207.2	20 83 Bi Bismuth 208.98	21 84 Po Polonium (209)	22 85 At Astatine (210)	23 86 Rn Radon (222)				
7 87 Fr Francium (223)	8 88 Ra Radium (226)	9 89 Ac Actinium (227)	10 104 Rf Rutherfordium (261)	11 105 Db Dubnium (262)	12 106 Sg Seaborgium (266)	13 107 Bh Bohrium (264)	14 108 Hs Hassium (269)	15 109 Mt Meitnerium (268)													
* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.																					
58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97								
90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)								

Typical values:

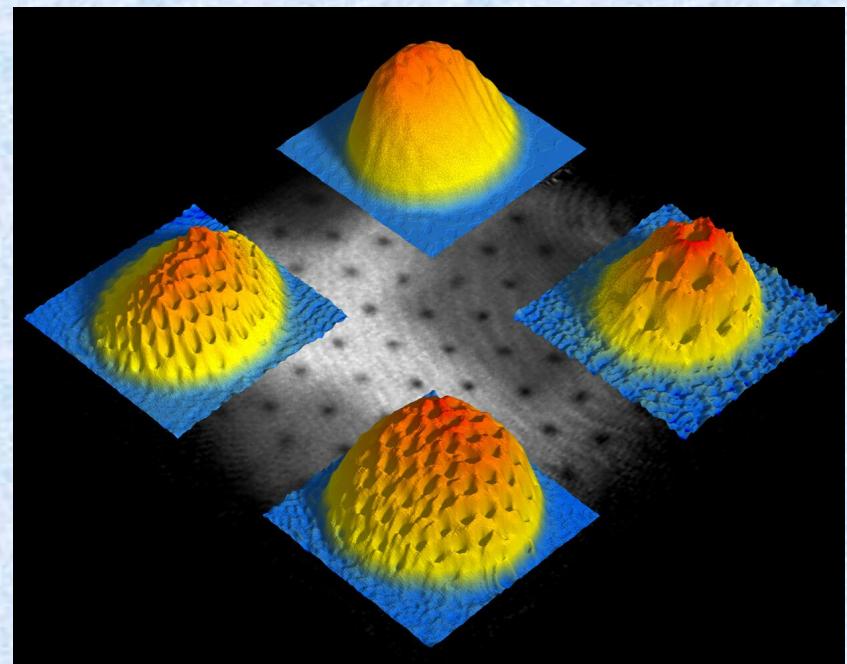
$\left\{ \begin{array}{l} \text{numbers: } 10^3 - 10^6 \text{ atoms} \\ \text{temperatures: } 10 - 100 \text{ nanoKelvin} \\ \text{sizes: } 1 - 50 \text{ micrometers} \end{array} \right.$

# Trapped Ultracold Atoms: Bosons



**Bose-Einstein condensation  
(at temperature  $\sim 100\text{nK}$ )**

**Vortices & Superfluidity**

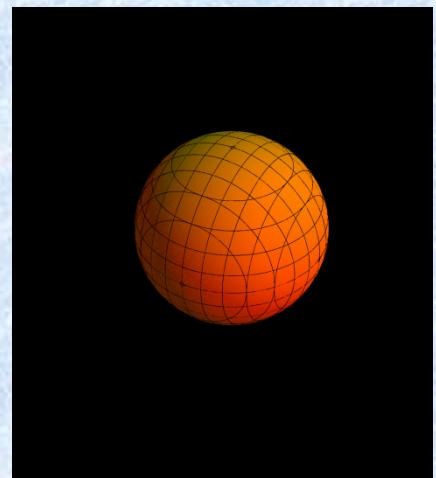


# Geometry

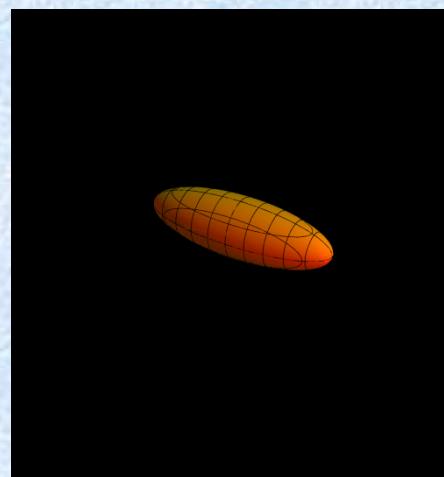
E.g. with a magnetic harmonic potential:

$$V(x, y, z) = \frac{1}{2} m (\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2)$$

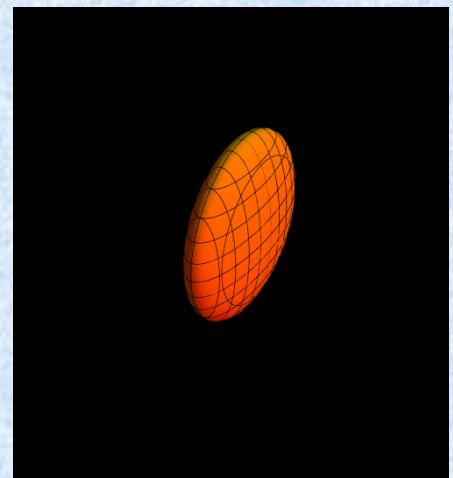
$$\omega_x = \omega_y = \omega_z$$



$$\omega_x \ll \omega_y = \omega_z$$



$$\omega_x \gg \omega_y = \omega_z$$



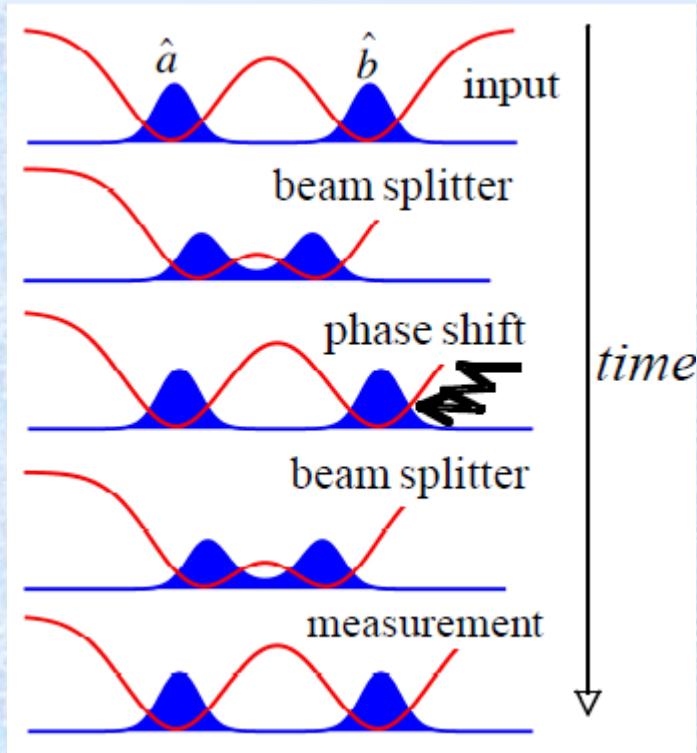
# Main available “ingredients”

- **Bosons and/or Fermions**
- **Geometry (1D / 2D)**
- **Long-range interactions**
- **Add disorder**
- **Simulate a magnetic field through a rotation or with optical tools**
- **Time-dependence (and to a certain extent space-dependence) of the parameters of the Hamiltonian**
- **Explicit tuning of the interactions via Feshbach resonances**
- **Optical lattices**

# Outline

- **Introduction on ultracold atoms**
- **Ultracold atoms for quantum devices**
- **Ultracold atoms for quantum simulations**

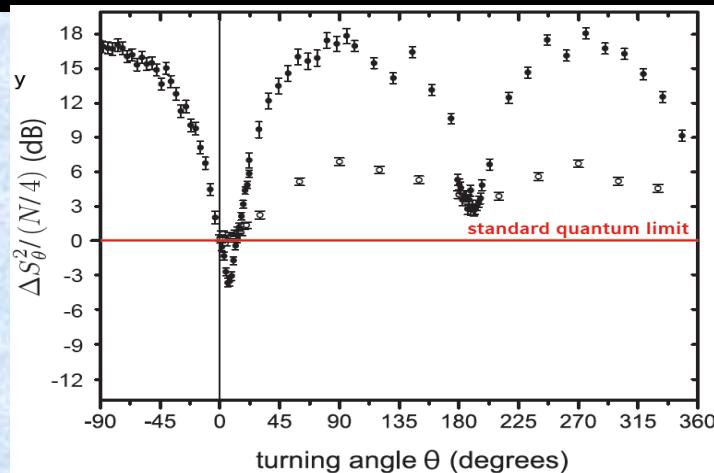
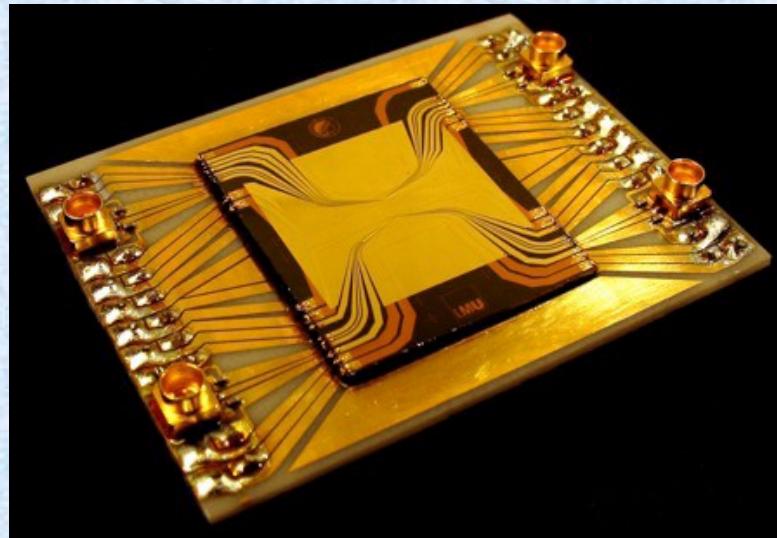
# Quantum interferometers with ultracold atoms



$$H = E_C(t) \hat{S}_z^2 - K(t) \hat{S}_x + \Delta E(t) \hat{S}_z$$

$$\hat{S}_x = \frac{1}{2} (a^\dagger b + b^\dagger a)$$

$$\hat{S}_z = \frac{1}{2} (a^\dagger a - b^\dagger b)$$



Riedel et al. & Gross et al. [Nature, 2010]

# Outline

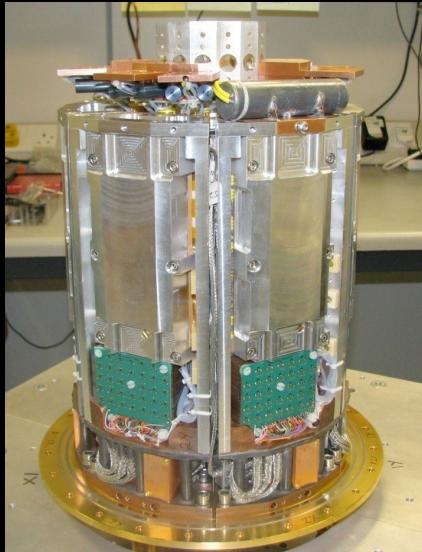
- **Introduction on ultracold atoms**
- **Ultracold atoms for quantum devices**
- **Ultracold atoms for quantum simulations**

# **Ultracold atoms as quantum simulators of:**

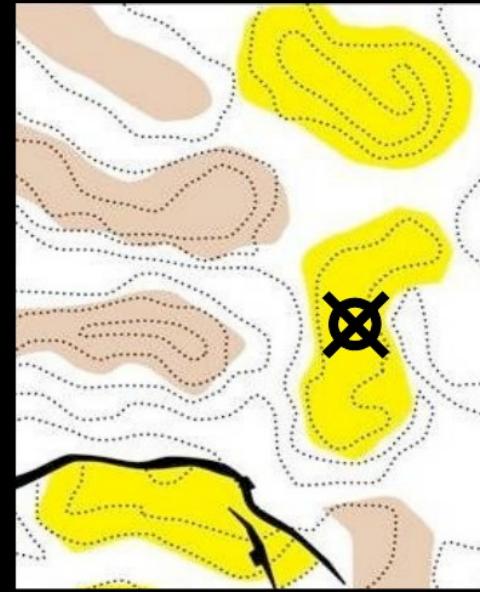
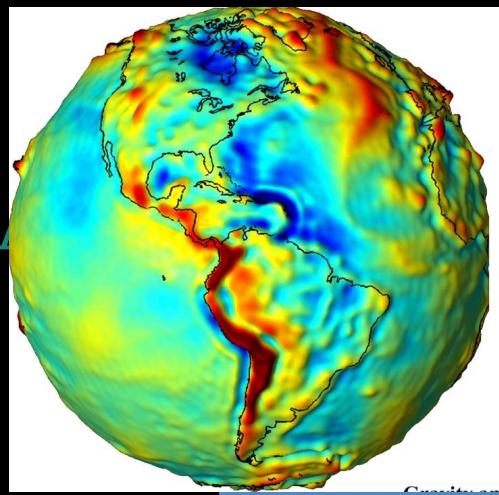
- **Interacting lattice systems**
- **Disordered models**
- **Analogue models of gravity**
- **Relativistic field theories**
- **Low-dimensional & integrable systems**
- **Quantum Hall physics**

# Thank you!

[atrombettone@units.it](mailto:atrombettone@units.it)



an example

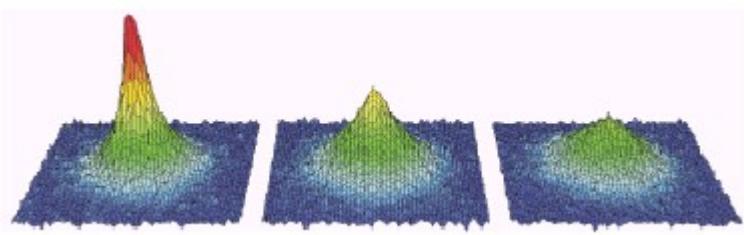


Gabon

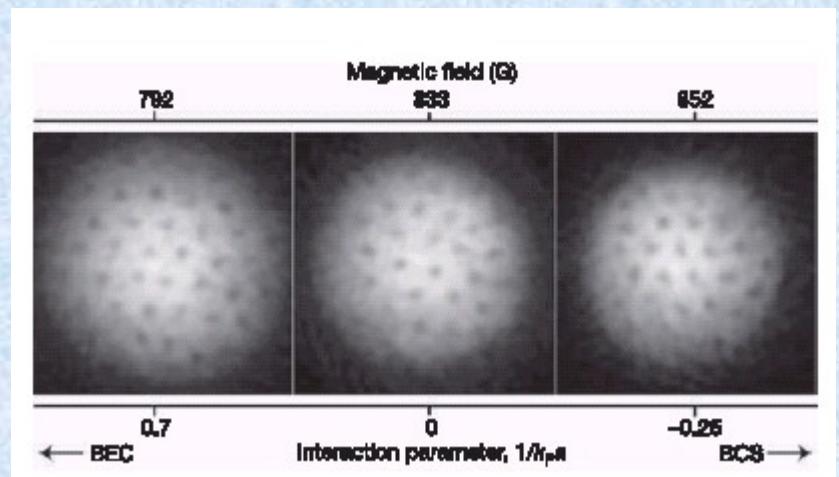
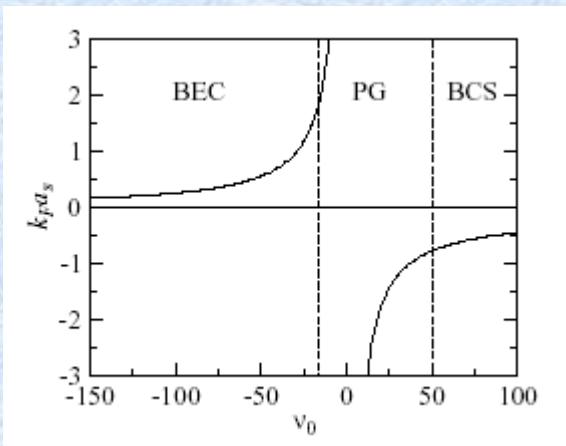


Images used with the kind  
permission of ARKeX

# Trapped Ultracold Atoms: Fermions



With attractive interactions...

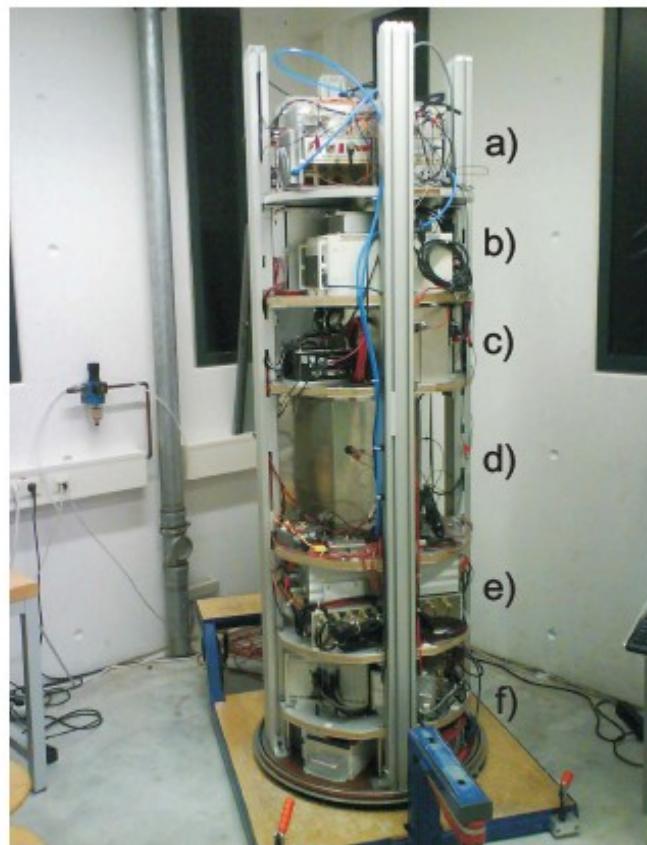


Vortices

# Quantum technology

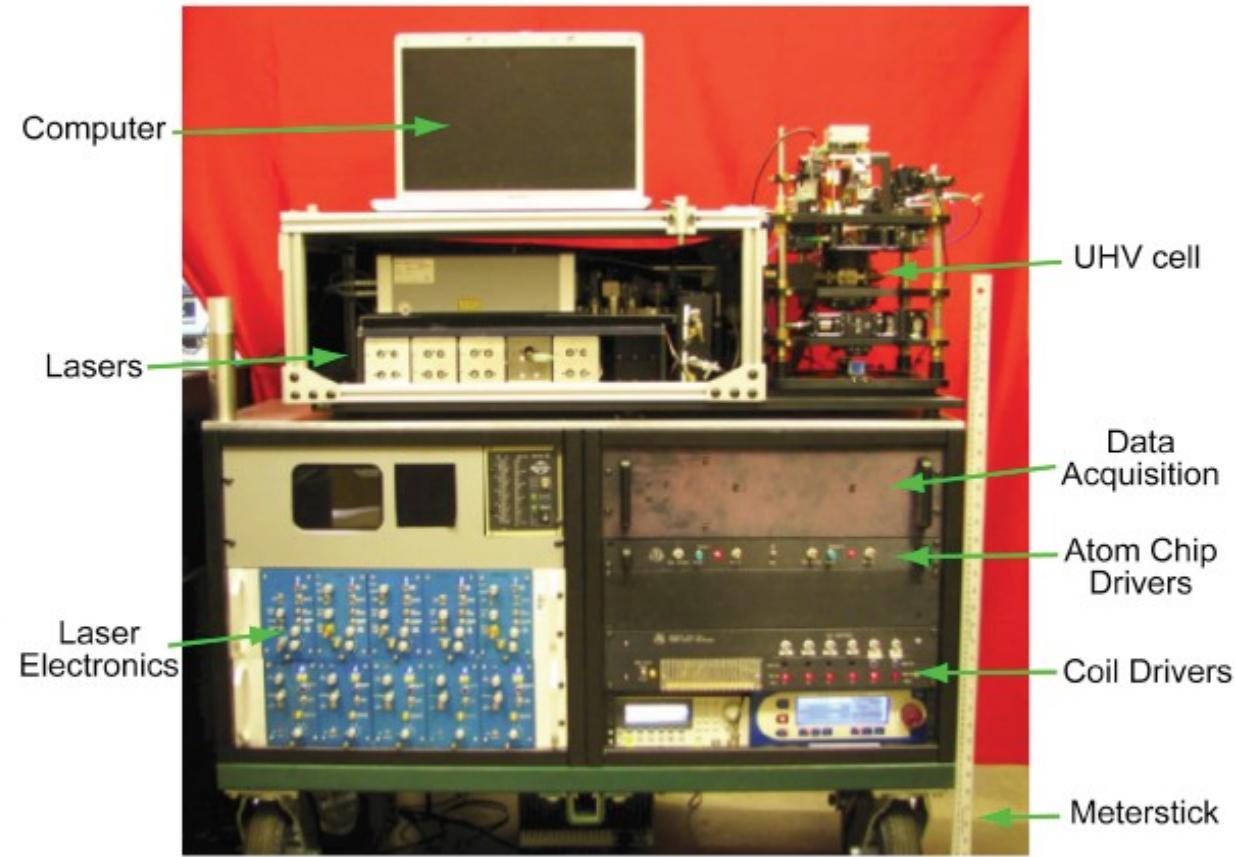
## QUANTUS project

A. Vogel et al.,  
Appl. Phys. B 84, 663 (2006).



## D. Anderson's group, Boulder

D. M. Farkas et al., arXiv:0912.0533 (2009).



Key components  
commercially available:



ColdQuanta

[www.coldquanta.com](http://www.coldquanta.com)