FORTH

Atomtronic Matterwave Guides

CRETANMATTERWAVES

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FOMO2021
15/07/2021

FET FUTURE & EMERGING TECHNOLOGIES scheme
NanoLace
Marie Curie-Excellence MatterWaves

FET FUTURE & EMERGING TECHNOLOGIES scheme
MatterWave
Marie Curie-Excellence MatterWaves

ΕΣΠΑ 2014-2020 ανάπτυξη - εργασία - αλληλεγγύη

esa
ESA-OBST1
ESA-OBST2

AtomQT
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

CRETANMATTERWAVES

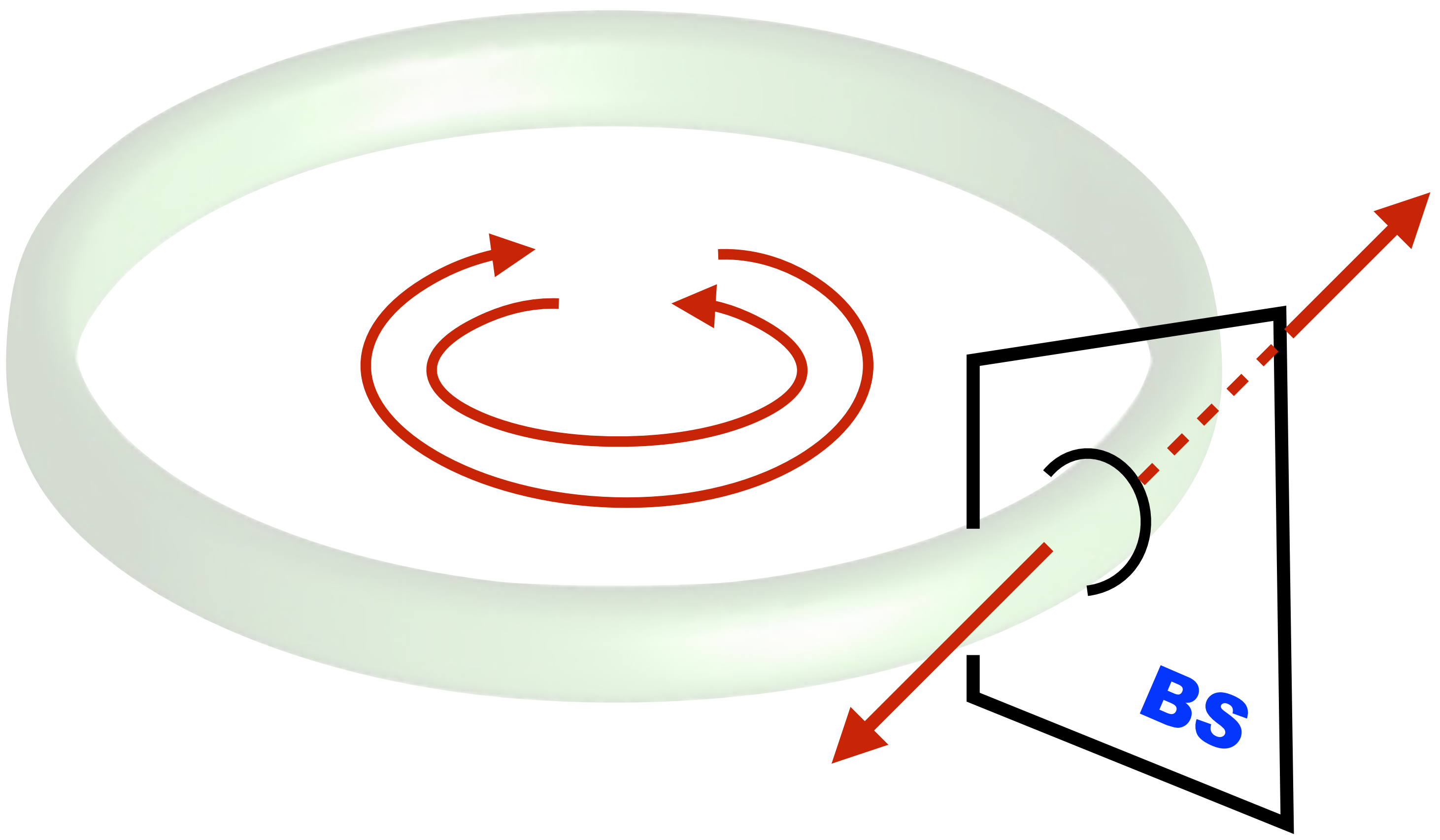
IESL-FORTH

Matter-Wave Interferometry, an example

A Sagnac Gyroscope:

$$\Delta\phi = \frac{4\pi}{\lambda v}\Omega A$$

$$\frac{\Delta\phi_{\mathrm{atom}}}{\Delta\phi_{\mathrm{light}}} = \frac{\lambda_{\mathrm{light}}\, c_0}{h/m} = 5\mathrm{x}10^{10}$$



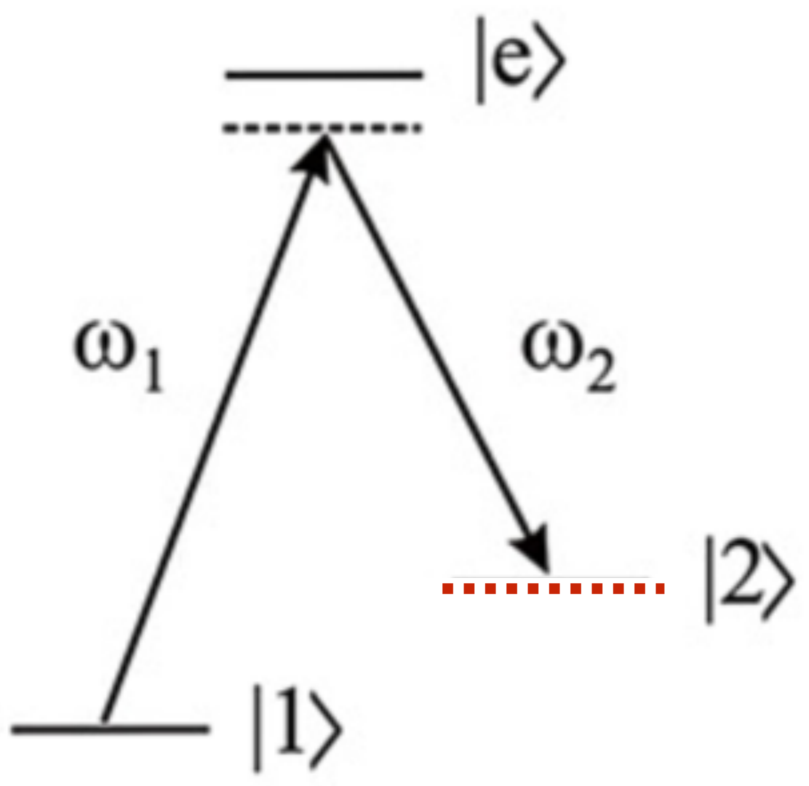
Plus

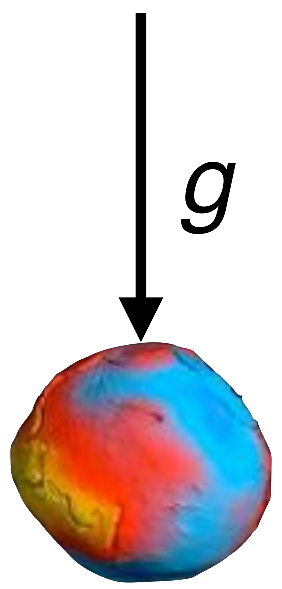
+ Internal States
+ Gravitation (waves)
+ Atom-Atom Interaction
  => Heisenberg Limited Detection

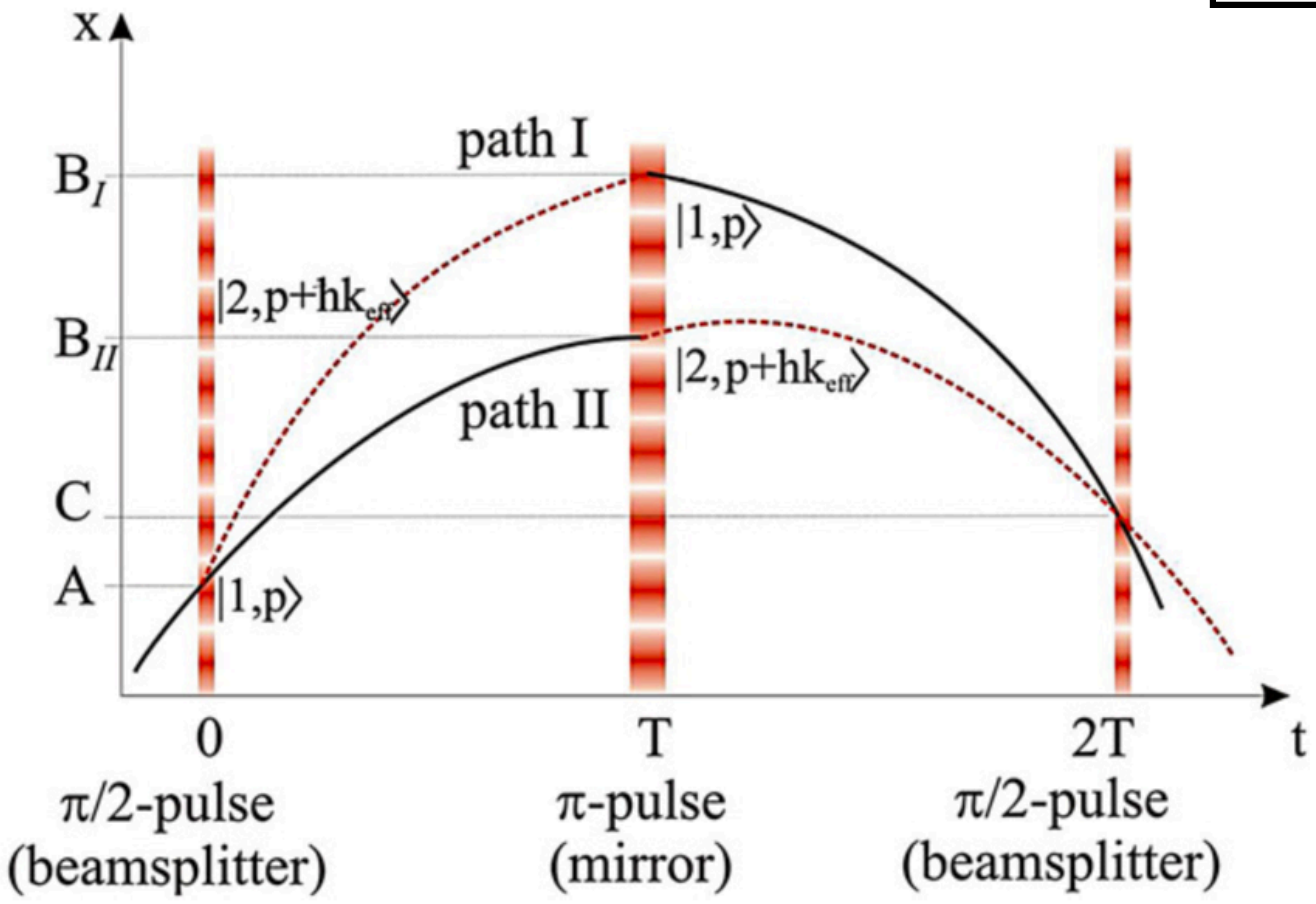
Savas Dimopoulos et al. *Physics Letters B* **678:1** 37--40 (2009)

Matter-Wave Interferometry, an example

Stimulated Raman Transition





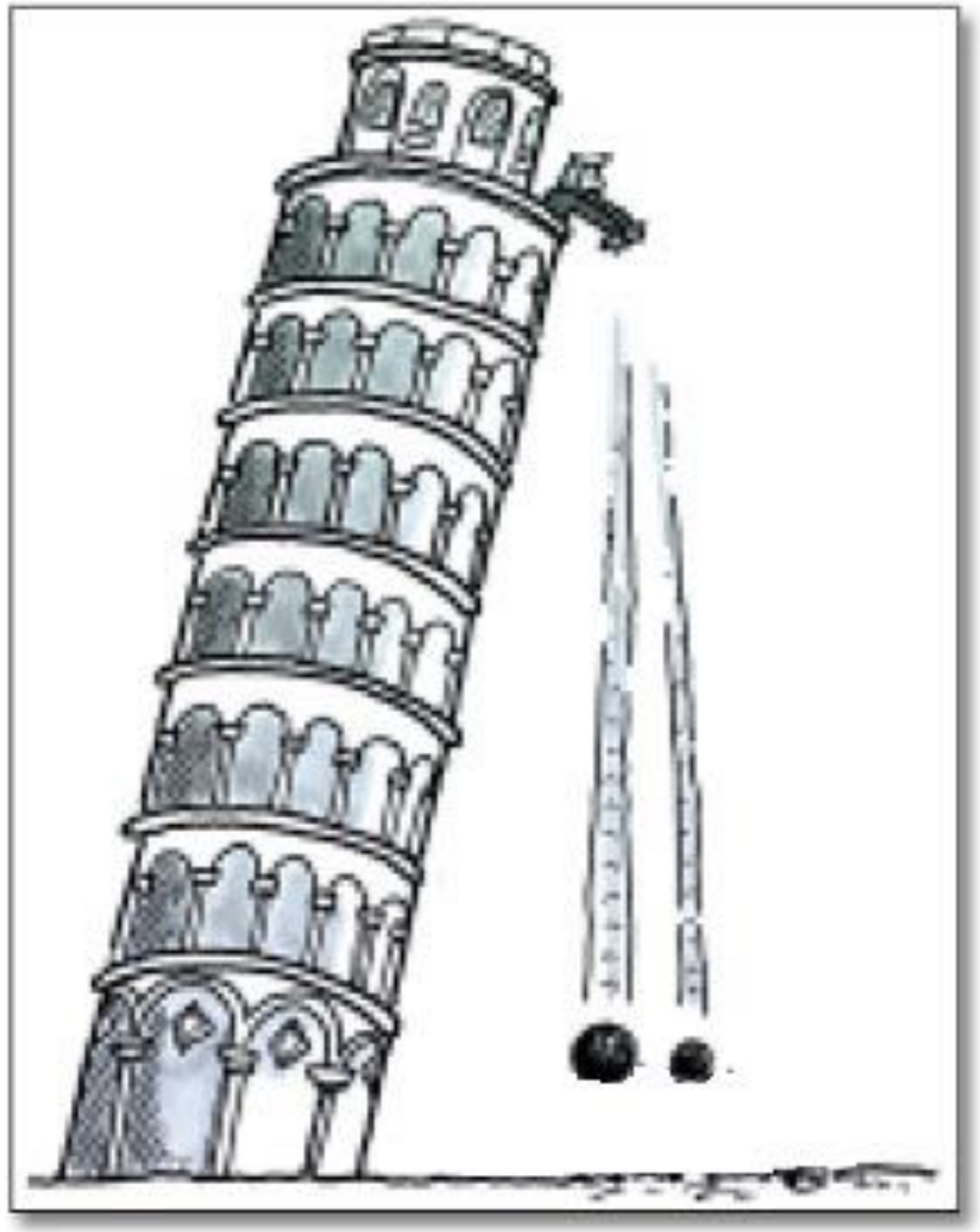


Phase of Interferometer

$$\Delta\phi_g = -k_{\text{eff}}\, g T^2$$

M de Angelis et al. *Precision gravimetry with atomic sensors*
Measurement Science and Technology **20 2** 022001 (2008)
DOI:/10.1088/0957-0233/20/2/022001

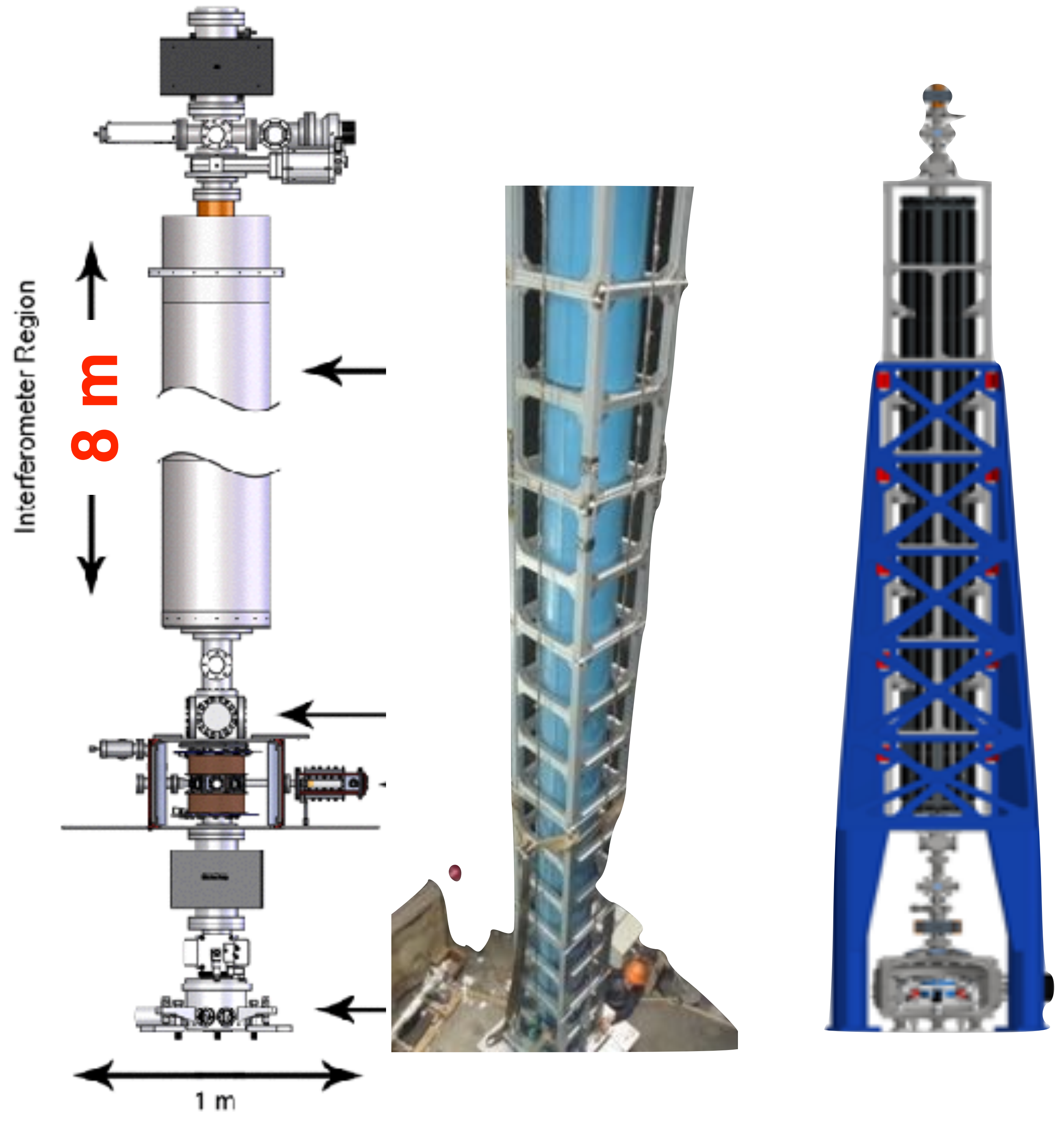
Motivation



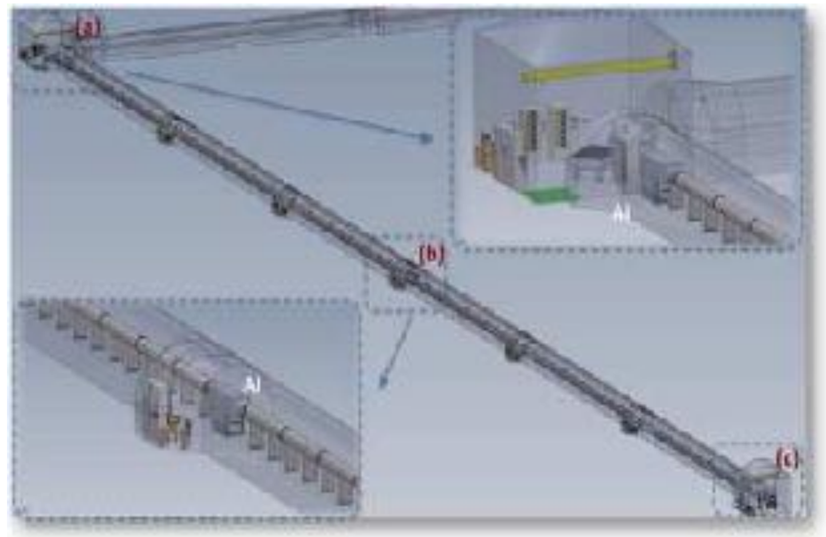
https://www.youtube.com/watch?v=-4_rceVPVSY

Matter-Wave Interferometry: t^2

Large Tubes



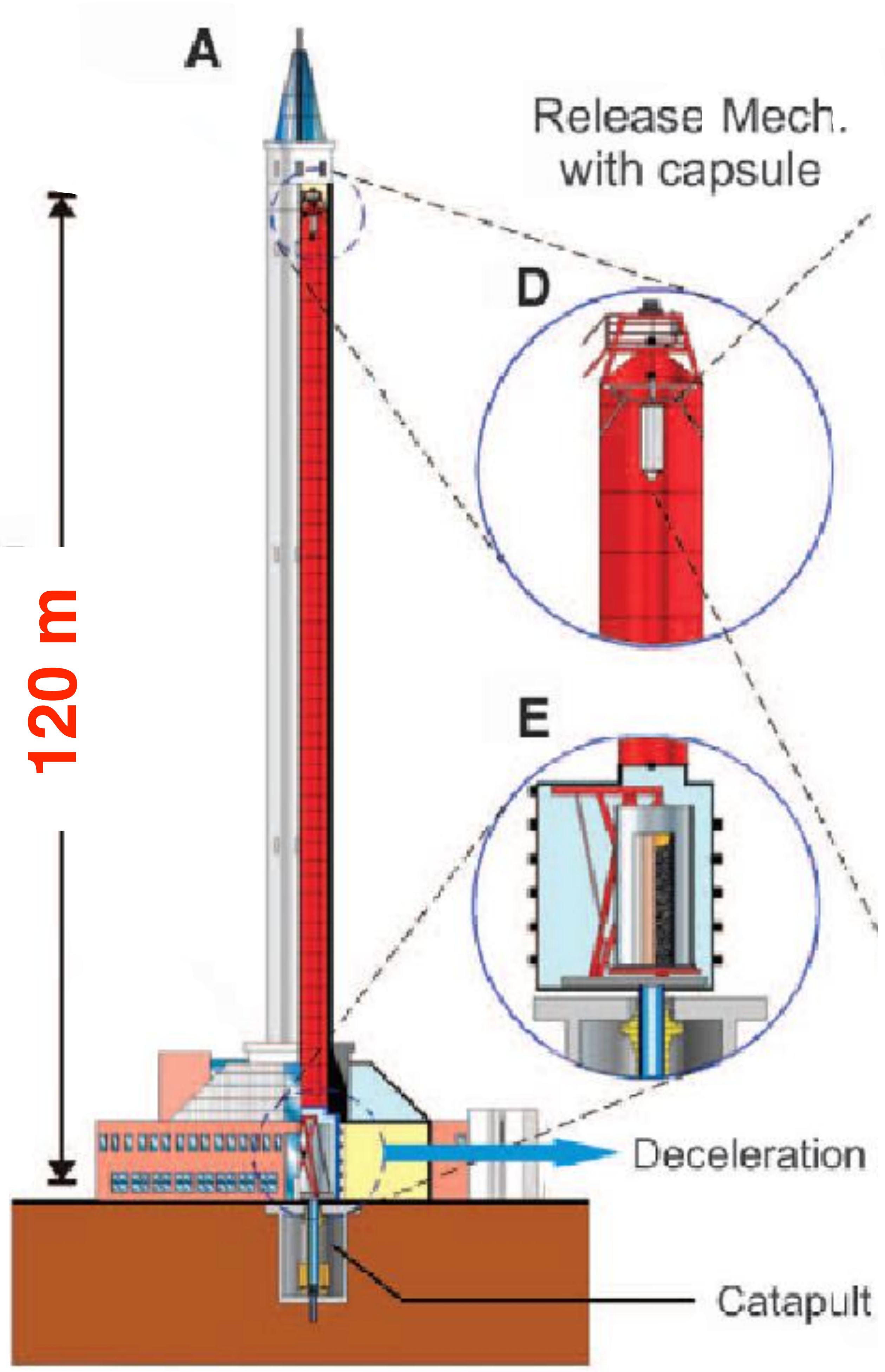
Stanford / Wuhan / Hannover



ELGAR

Free Fall

ZARM
drop Tower



Space

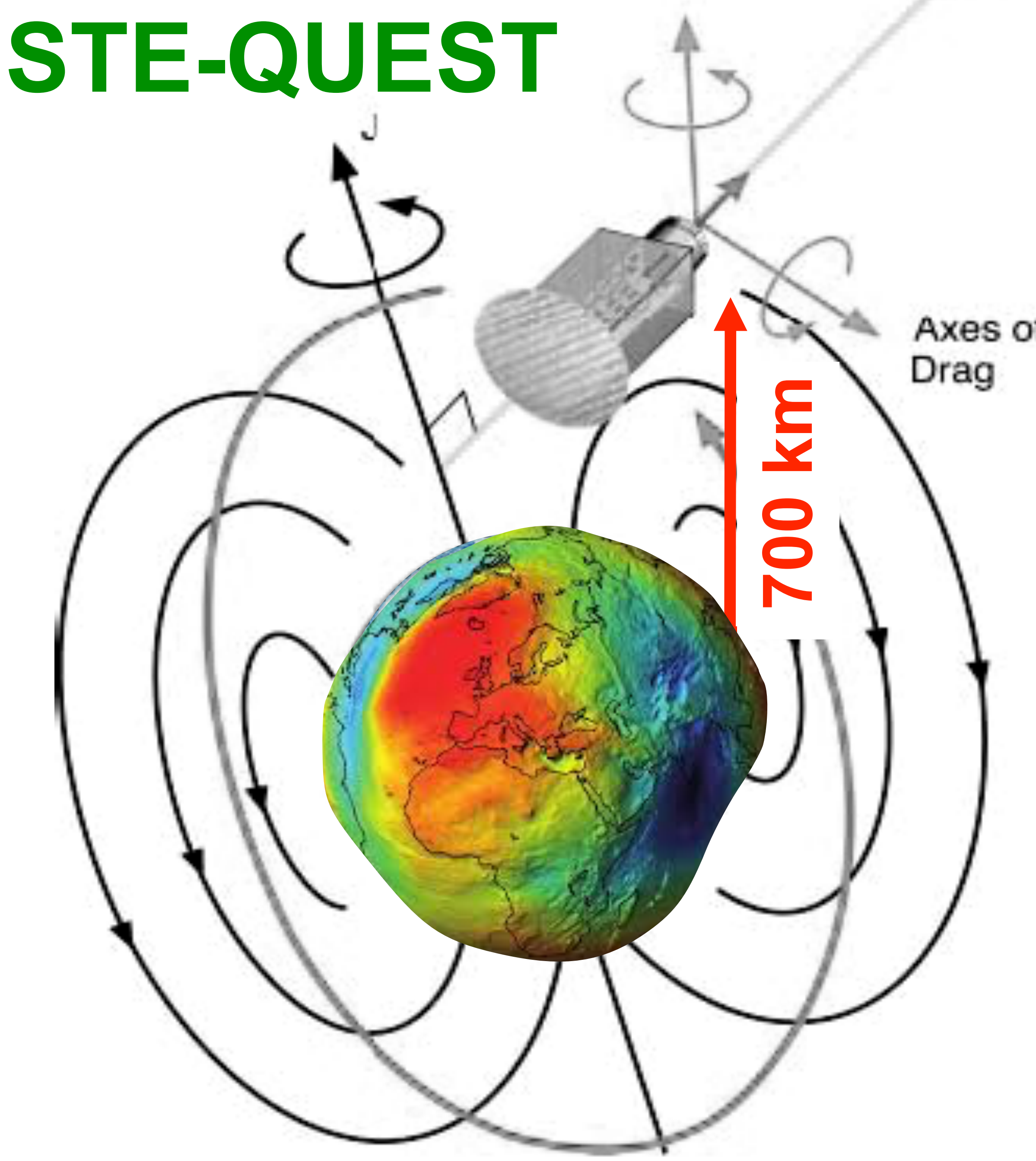
SAGE

AEDGE

STE-QUEST

NASA
CAL

ESA
C-COOL

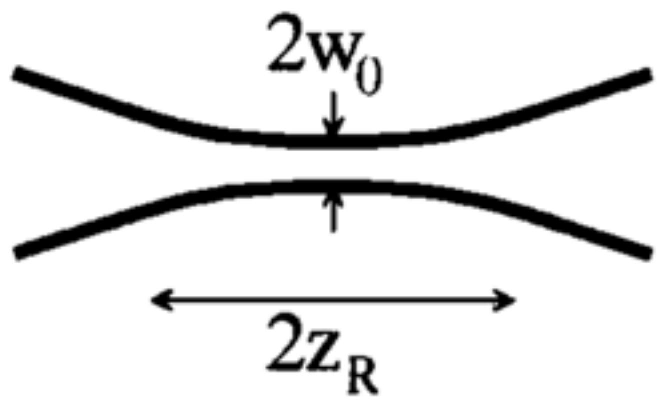


Parabolic Flights

Atomtronic Matterwave guides

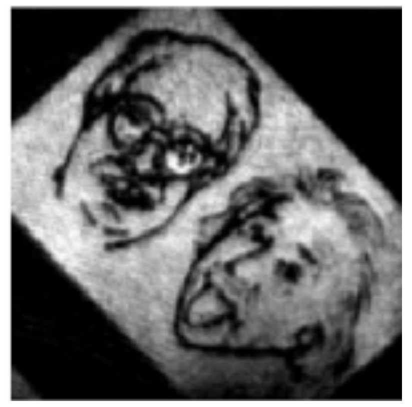

Kufstein
MERIDIAN

Atomtronic Time Scales



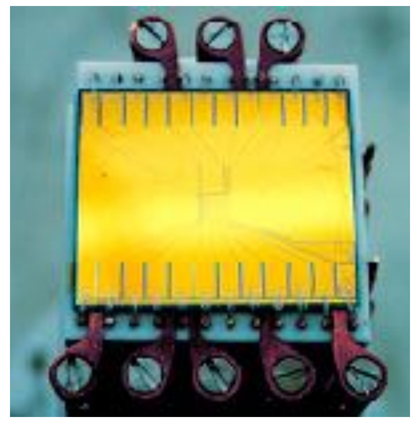
Experiment
Repetition

10^{-1}



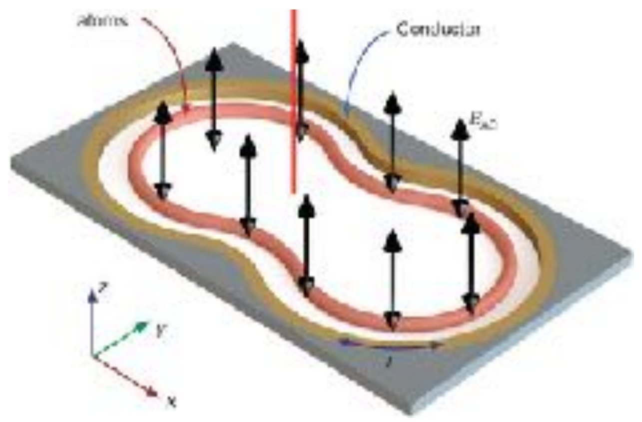
Quasi DC
Manipulation

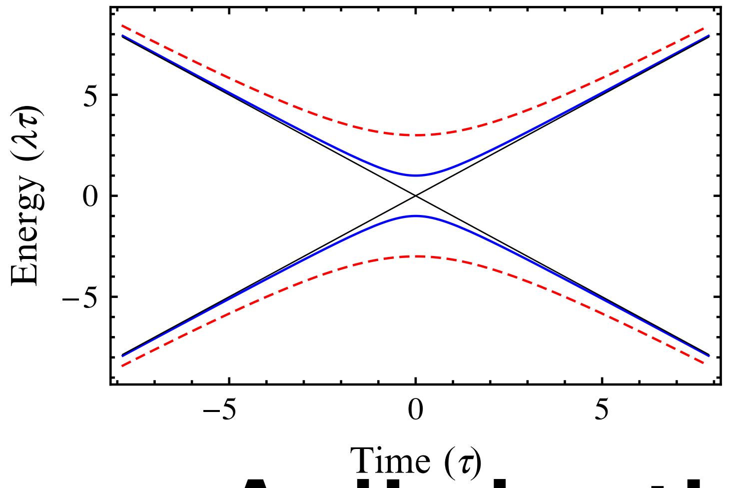
10^{0}



Time
Averaging

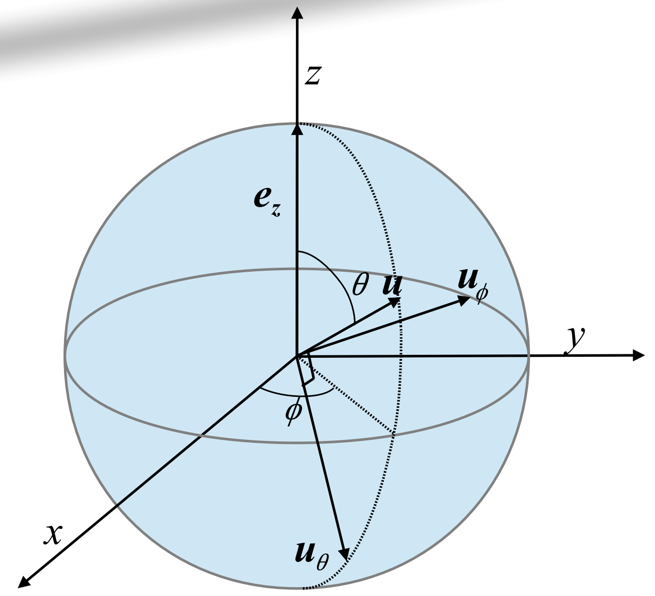
10^{3}





Adiabatic
(RF-Dressing)

10^{6}



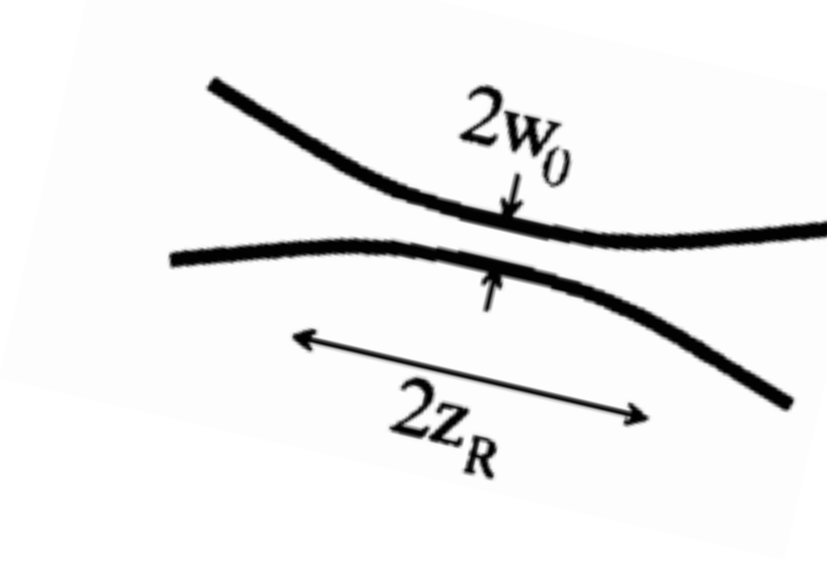
Hyperfine
Transitions

10^{10}

Trapping &
Detection

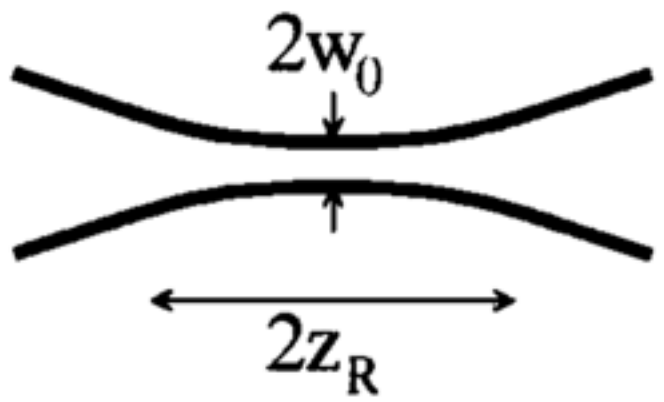
10^{14}

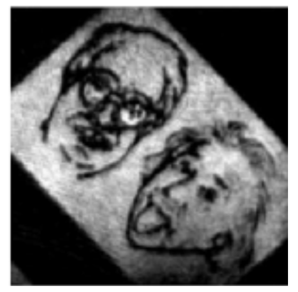
Frequency [Hz]

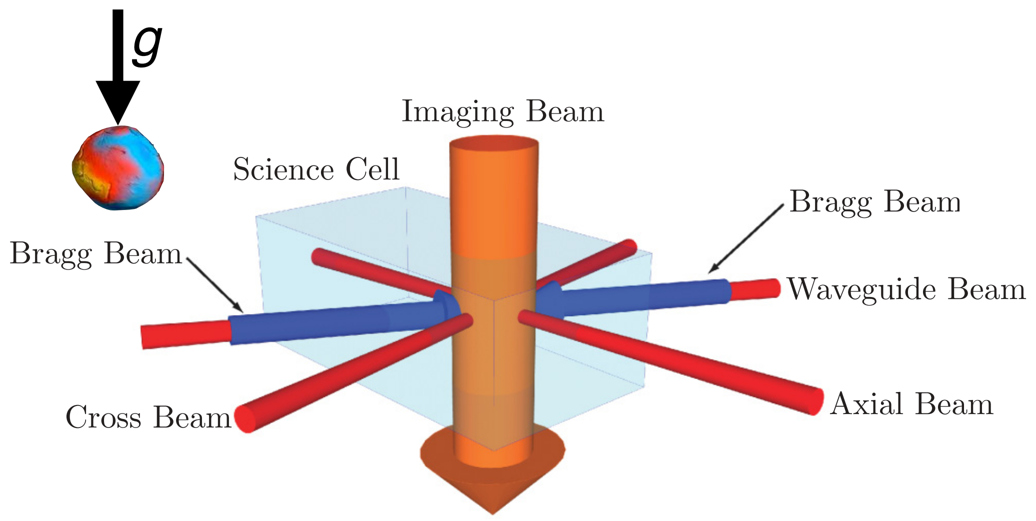


Types of MW-Guides

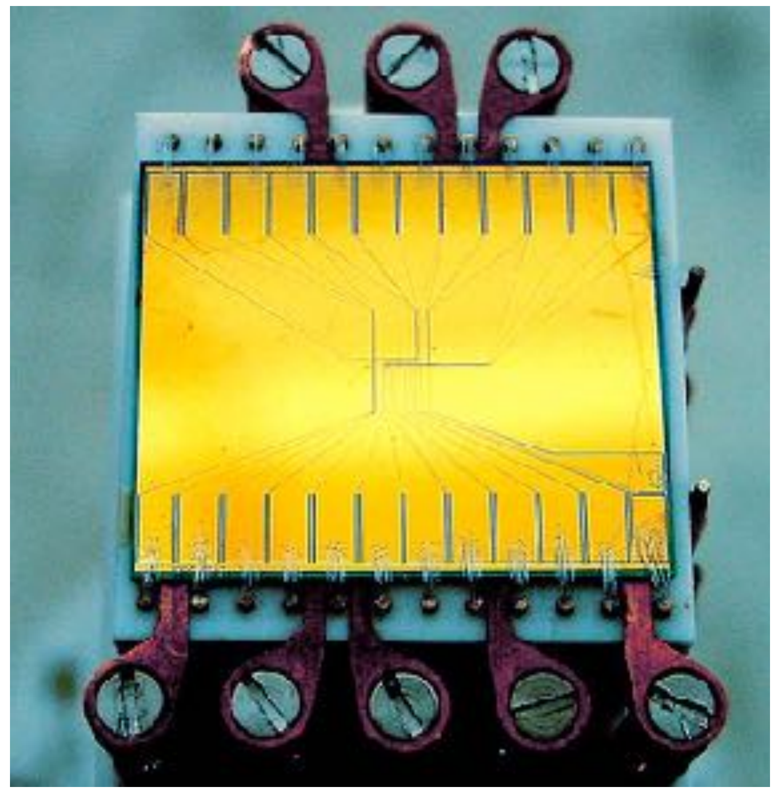
Light-Based

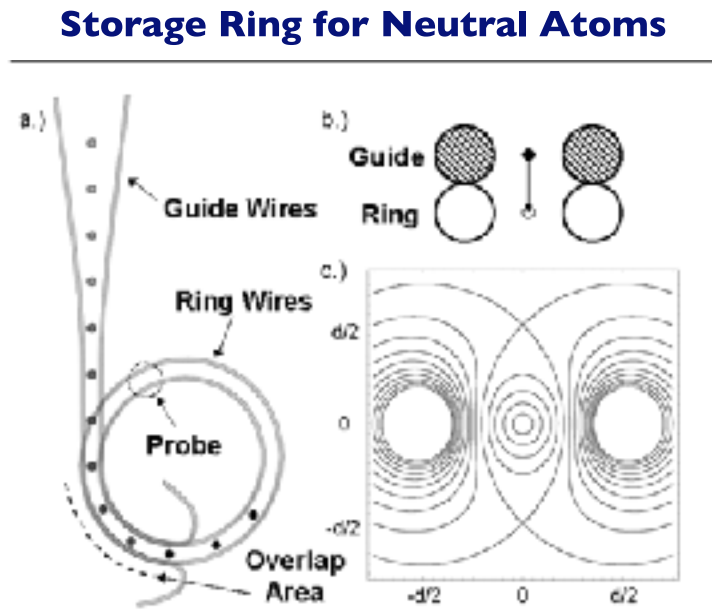




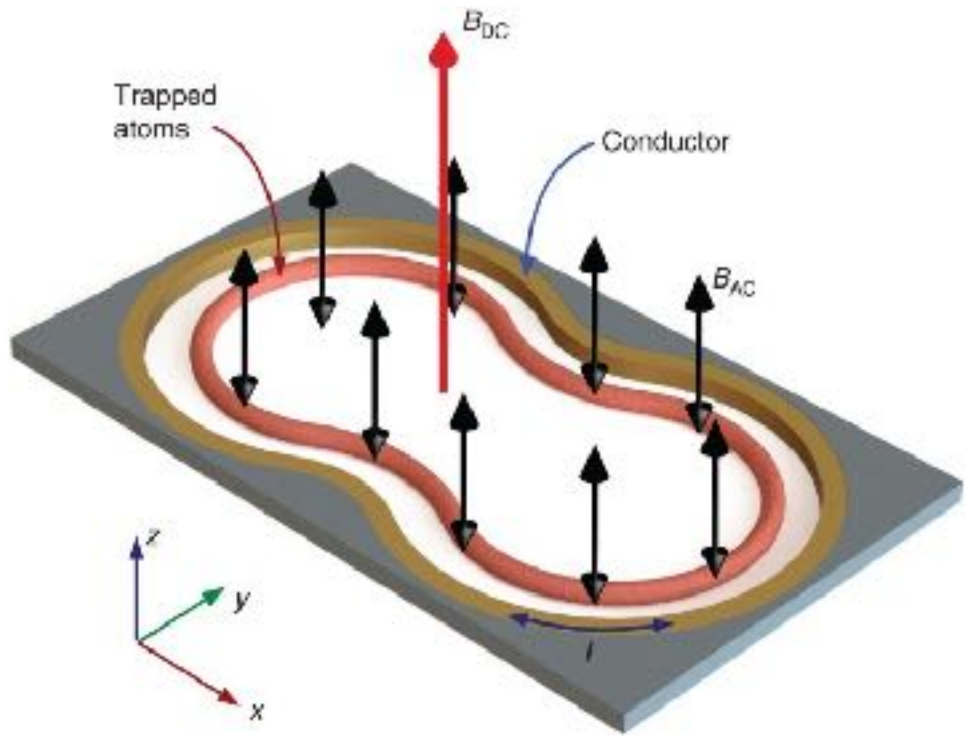


DC-Magnetic

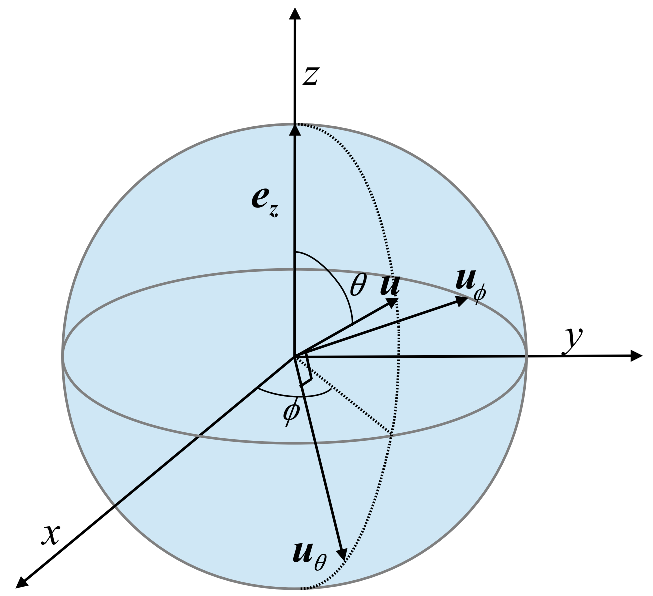


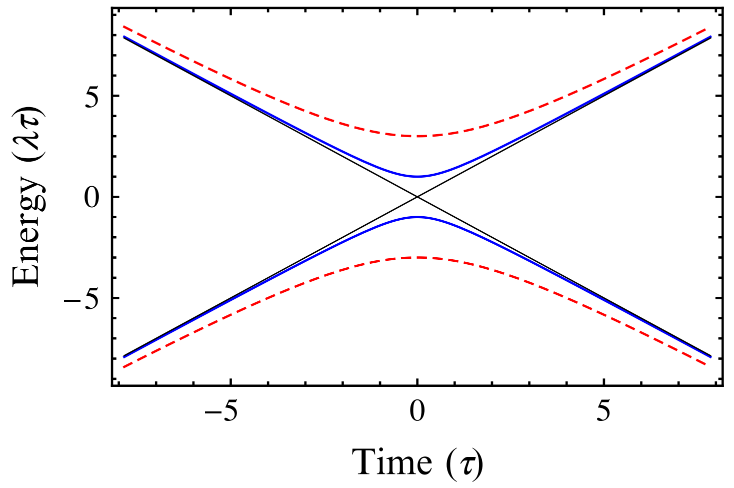


AC-Magnetic



Dressed



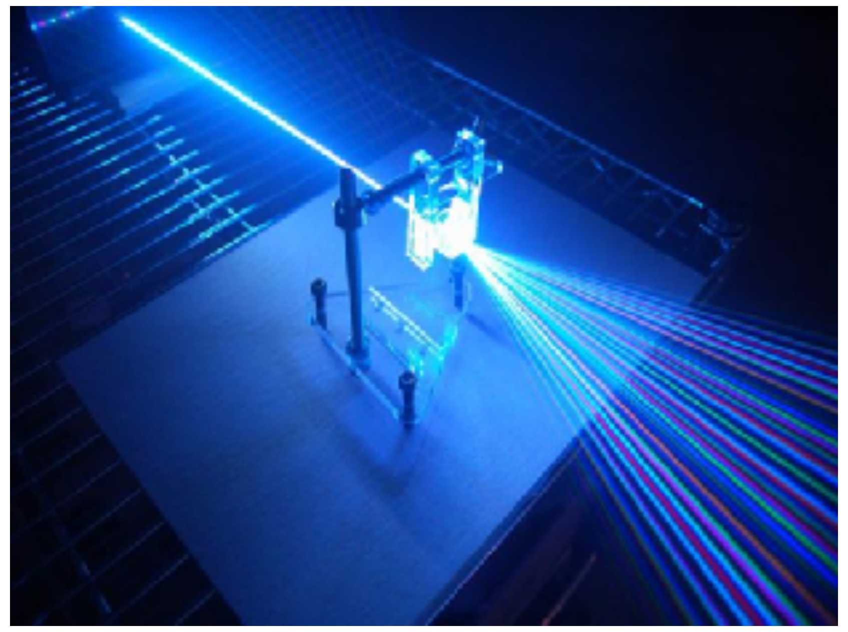


G. D. McDonald et al.
Optically guided linear Mach-Zehnder atom interferometer
Physical Review A **87:1** 013632 (2013)
DOI:/10.1103/PhysRevA.87.013632

J. A. Sauer, M. D. Barrett, and M. S. Chapman
Storage Ring for Neutral Atoms
Physical Review Letters **87:27** 270401 (2001)
DOI:/10.1103/PhysRevLett.87.270401

German A. Sinuco-Leon et al.
Inductively guided circuits for ultracold dressed atoms
Nature Communications **5:1** (2014)
DOI:/10.1038/ncomms6289

Hélène Perrin and Barry M. Garraway
Trapping Atoms With Radio Frequency Adiabatic Potentials
Advances In Atomic, Molecular, and Optical Physics (2017)
DOI:/10.1016/bs.aamop.2017.03.002 -



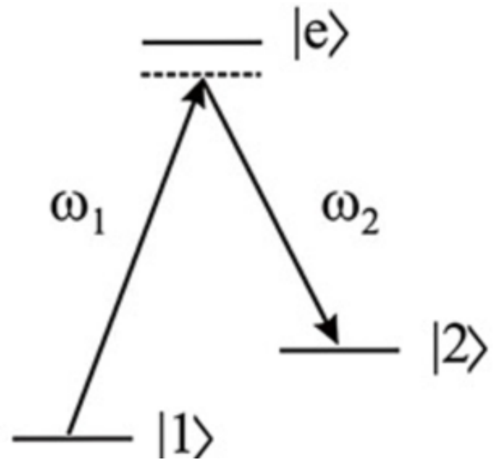
Optical Grating

Types of Beam Splitters

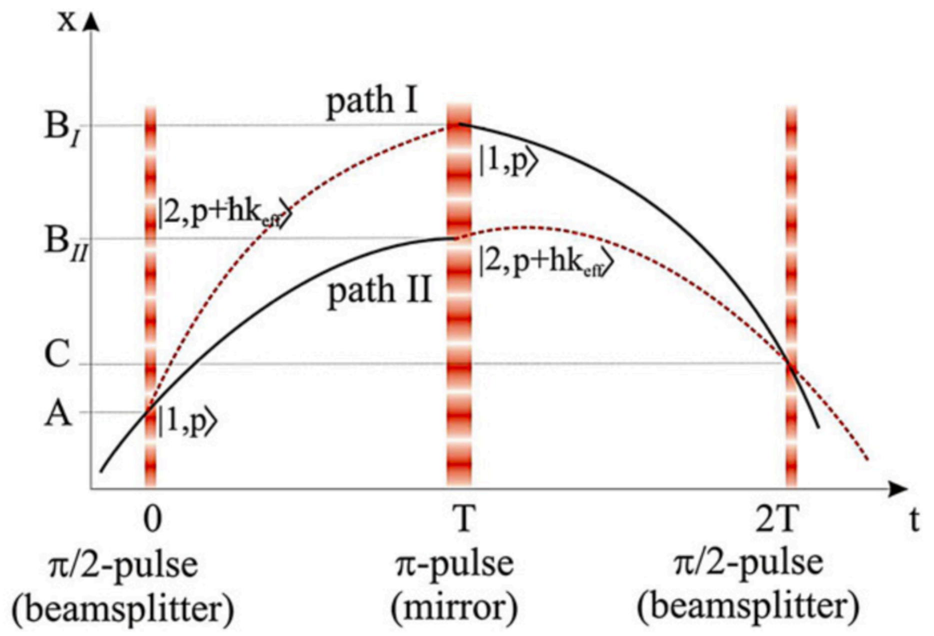
AOM

Internal State Changing

Raman Scattering

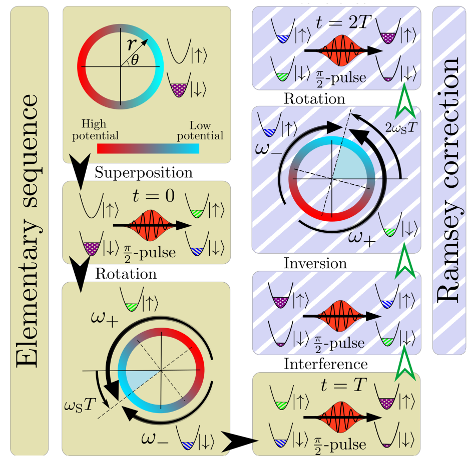


Raman Scattering



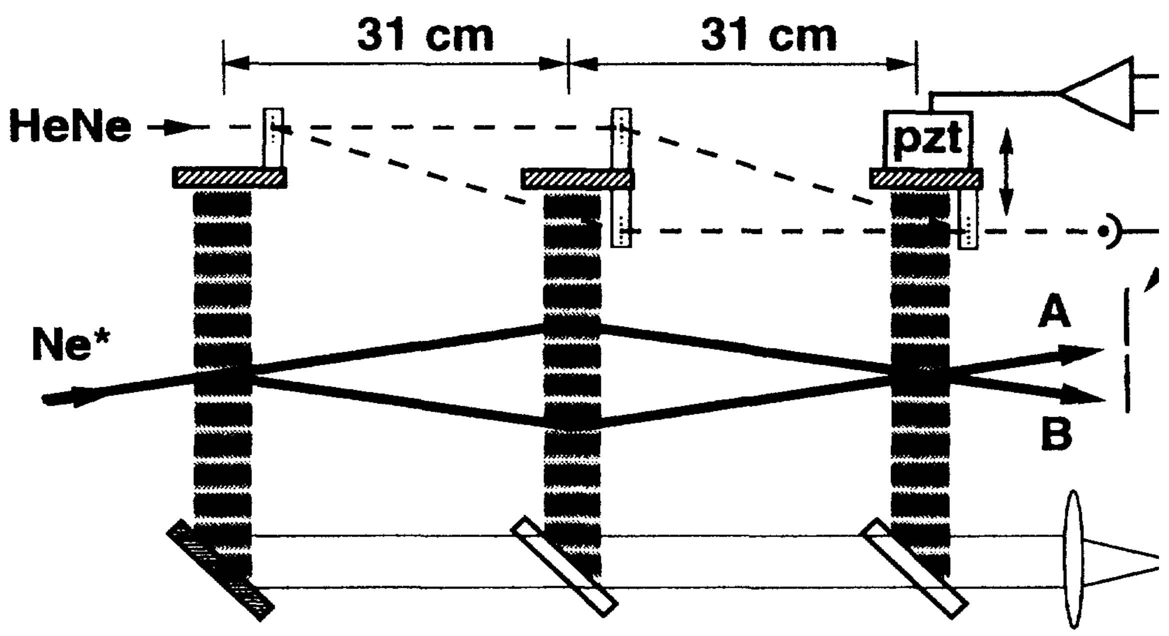
M de Angelis et al. *Precision gravimetry with atomic sensors* Measurement Science and Technology **20 2** 022001 (2008) DOI:/10.1088/0957-0233/20/2/022001

Microwave Transitions



R. Stevenson et al.
Sagnac Interferometry with a Single Atomic Clock
Physical Review Letters **115:** 163001 (2015)
DOI:/10.1103/PhysRevLett.115.163001

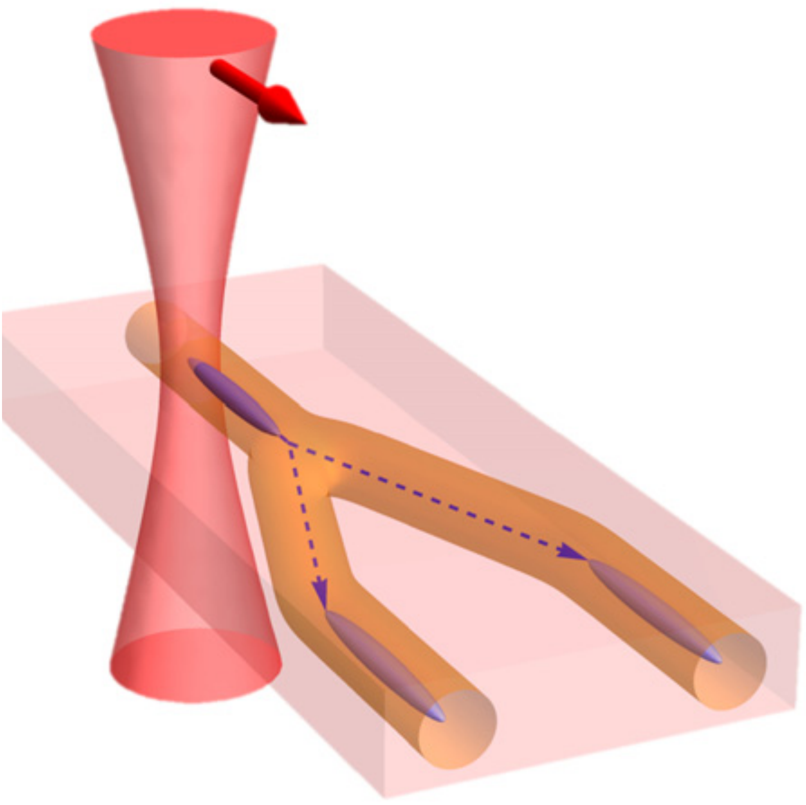
External State Changing



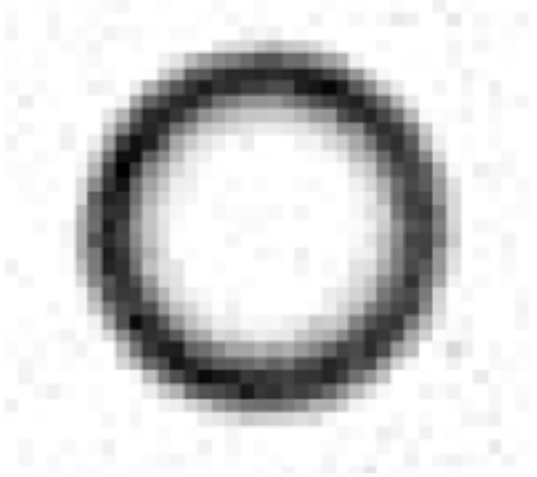
Bragg Scattering

D. M. Giltner, R. W. Mcgowan, and S. A. Lee
Atom Interferometer Based on Bragg Scattering From Standing Light Waves
Physical Review Letters **75:14** 2638-2641 (1995)
DOI:/10.1103/PhysRevLett.75.2638

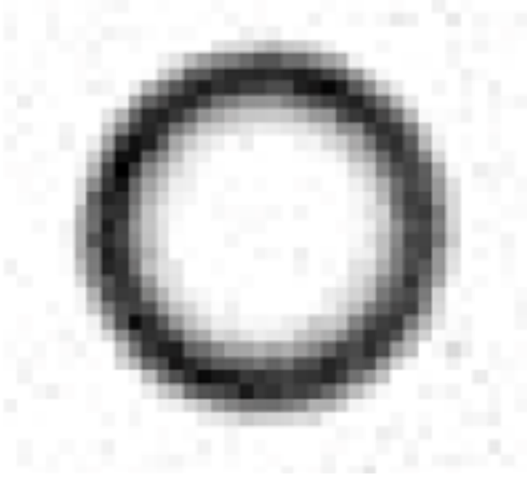
Physical Splitting of confinement

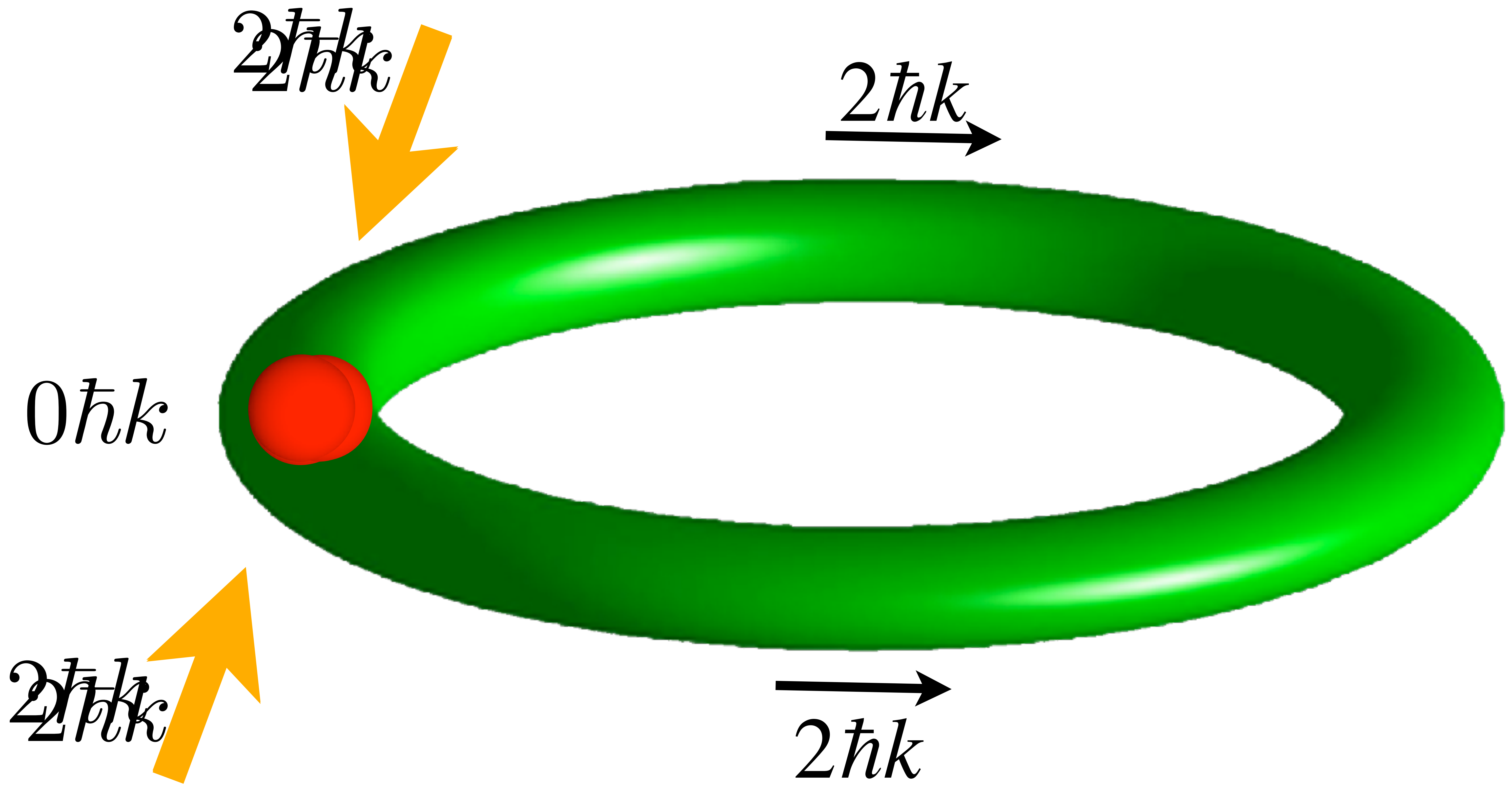


C. Ryu and M. G. Boshier
Integrated coherent matter wave circuits
New Journal of Physics **17:9** (2015)
DOI:/10.1088/1367-2630/17/9/092002



Sagnac Interferometer

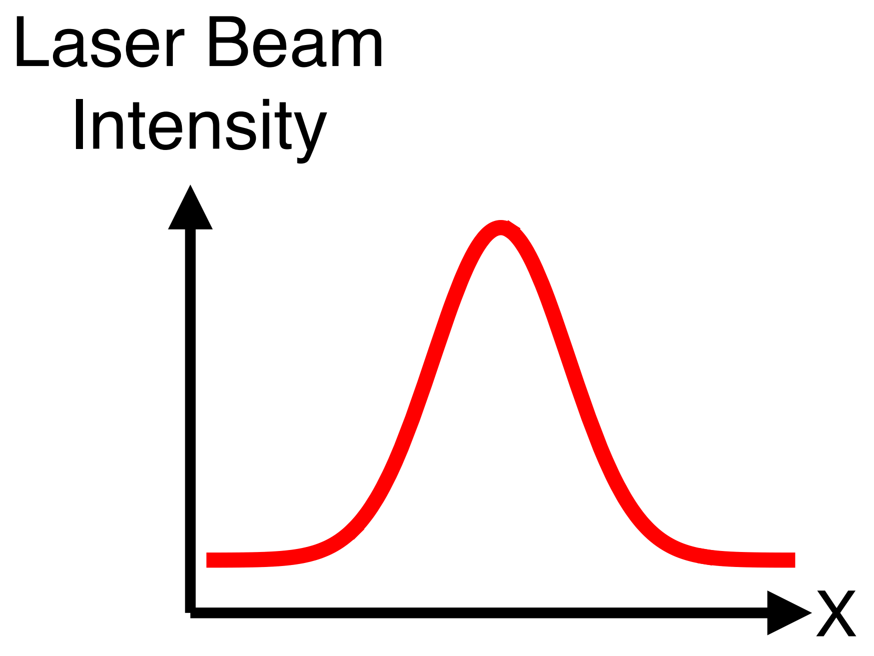




Light-Based MW-Guides

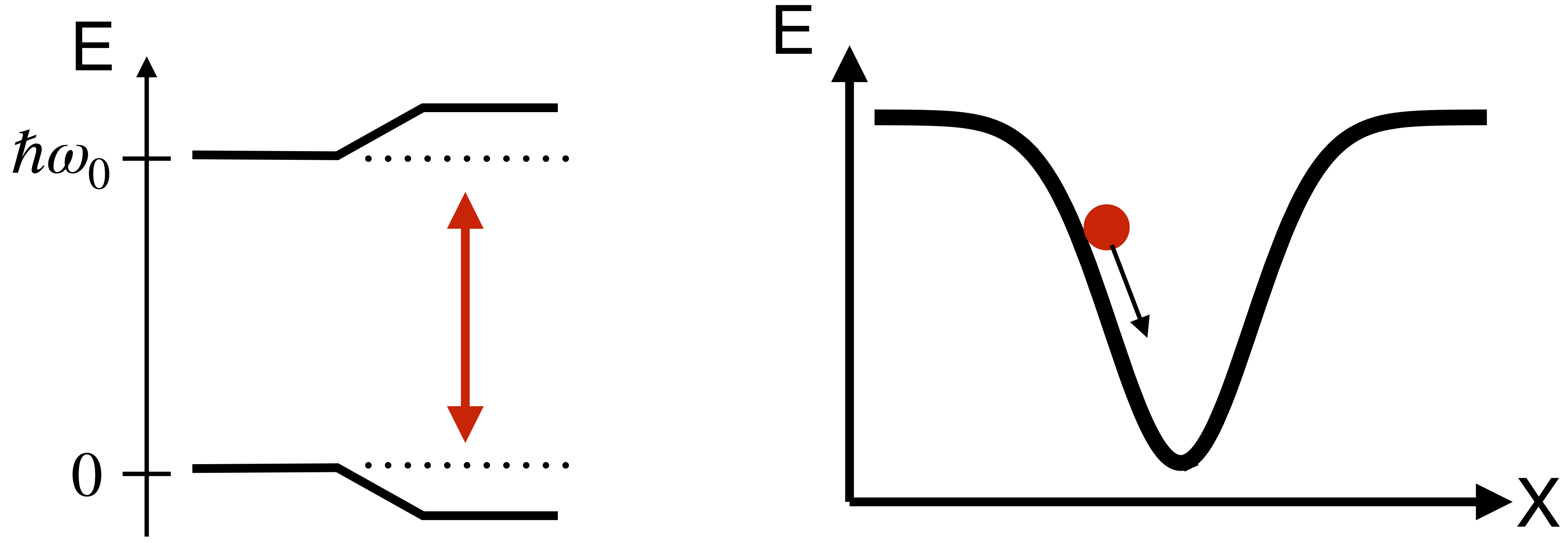
$$U(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(\mathbf{r})$$

where $\Delta = \omega - \omega_0$ is the detuning, Γ is the natural decay rate of the population of the excited state, and $I(\mathbf{r})$ is the position-dependent laser intensity. This dipole force can be attractive ($\Delta < 0$ or "red-detuned") or repulsive ($\Delta > 0$ or "blue-detuned")



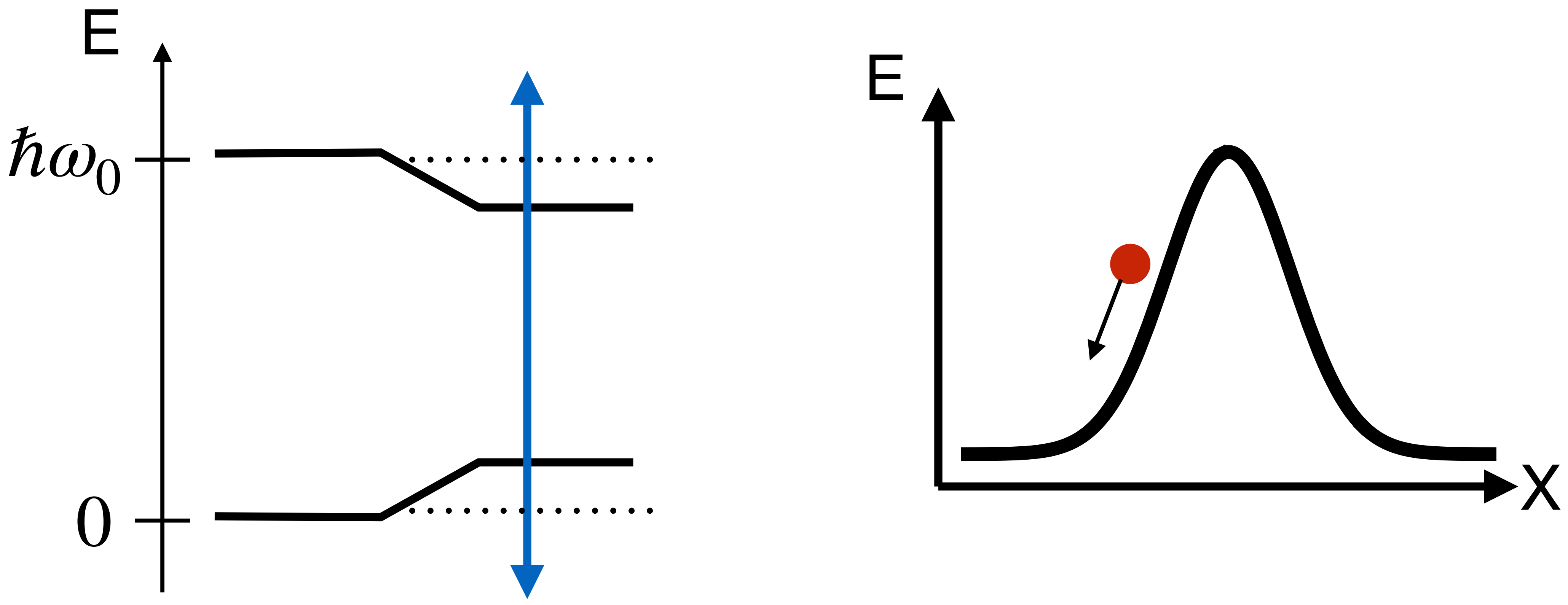
Red Detuned

$(\omega < \omega_0)$



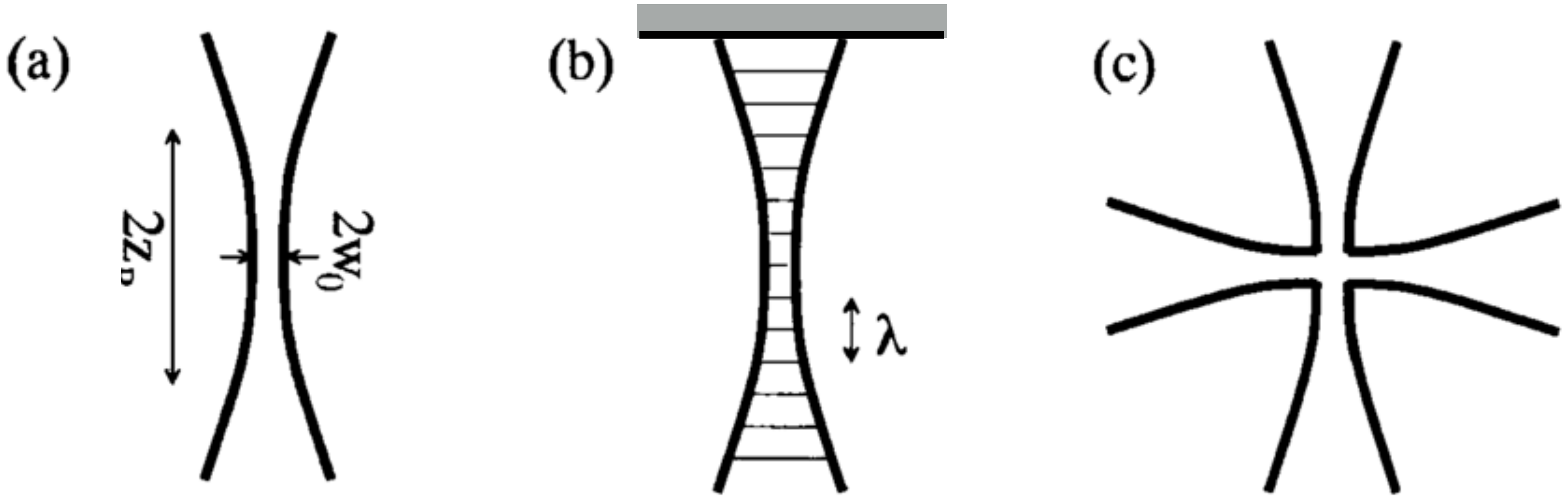
Blue Detuned

$(\omega > \omega_0)$

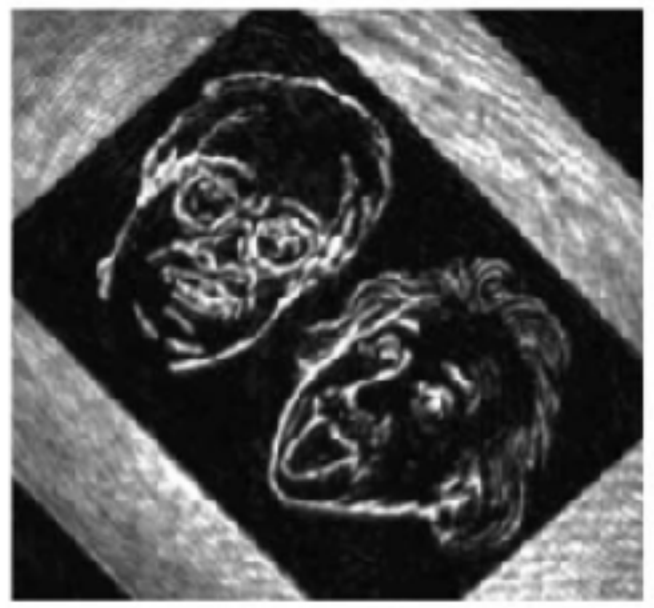


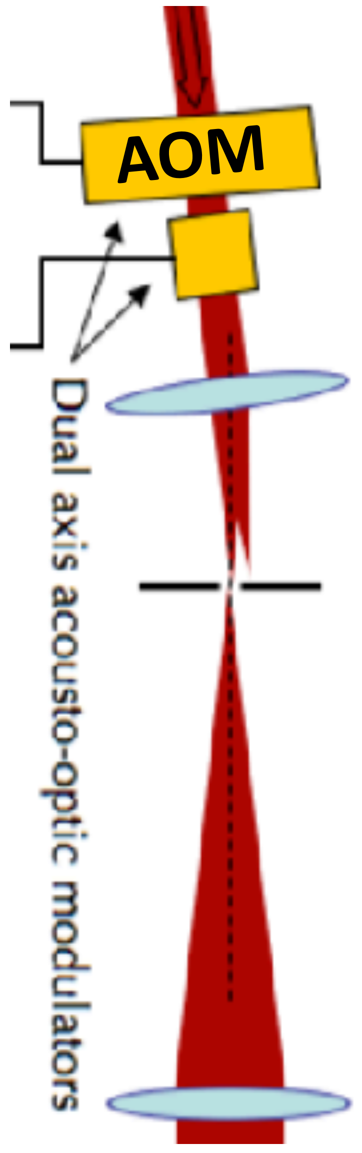
Light-Based MW-Guides

Light:



digital-micro-mirror device





Atoms:

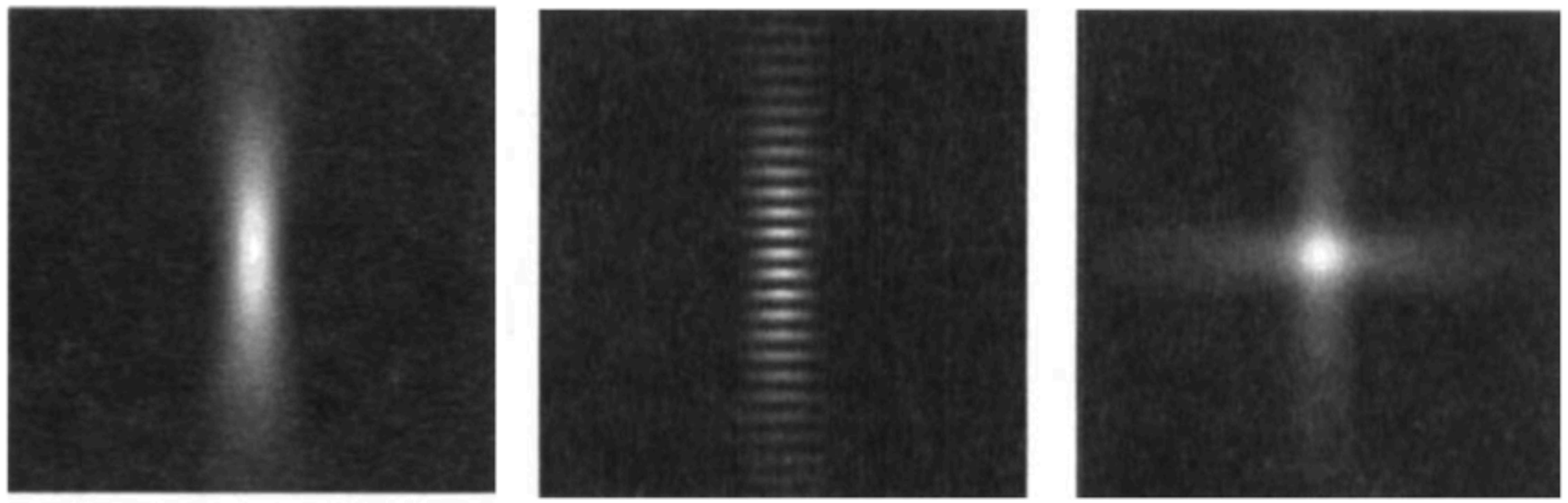
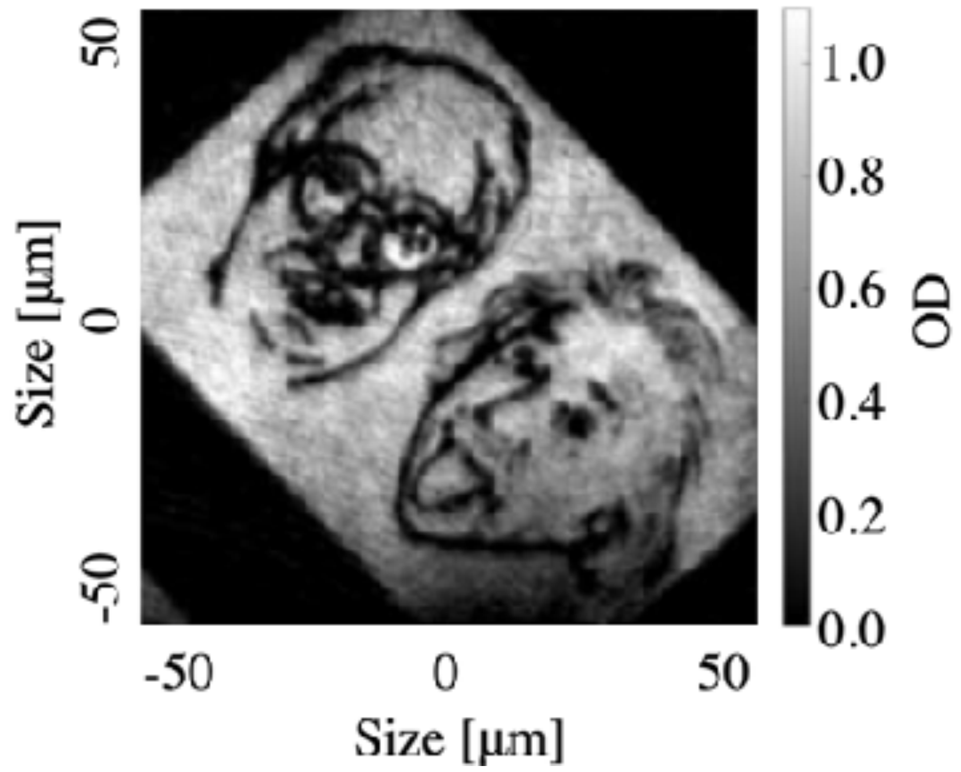
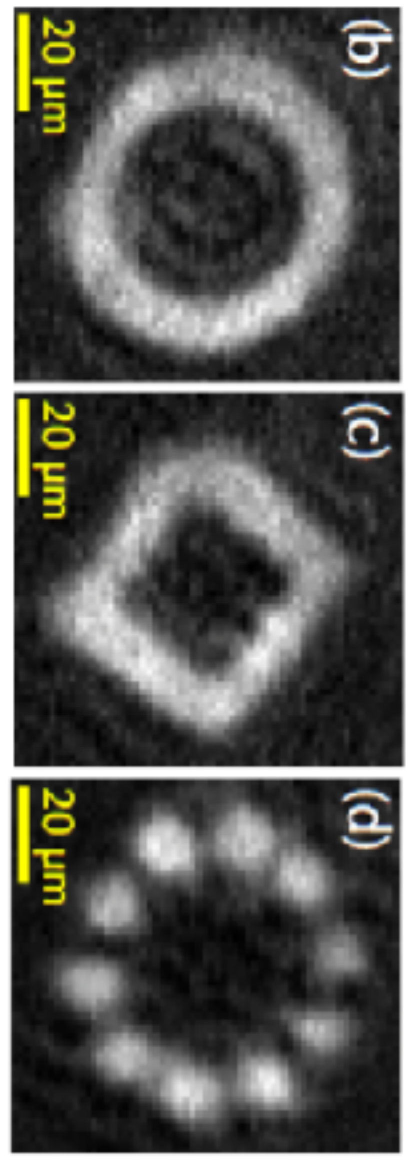


FIG. 5. Beam configurations used for red-detuned far off-resonance traps. Shown below are the corresponding calculated intensity distributions. (a) Horizontal focused-beam trap. (b) Vertical standing-wave trap. (c) Crossed-beam trap. The waist w_0 and the Rayleigh length z_R are indicated.





G. Gauthier et al.
Direct imaging of a digital-micromirror device for configurable microscopic optical potentials
Optica **3:10** 1136 (2016)
DOI:/10.1364/OPTICA.3.001136

Rudolf Grimm, Matthias Weidemüller, and Yurii B. Ovchinnikov
Optical Dipole Traps for Neutral Atoms
Advances In Atomic, Molecular, and Optical Physics **:** 95--170 (2000)
DOI:/10.1016/S1049-250X(08)60186-X

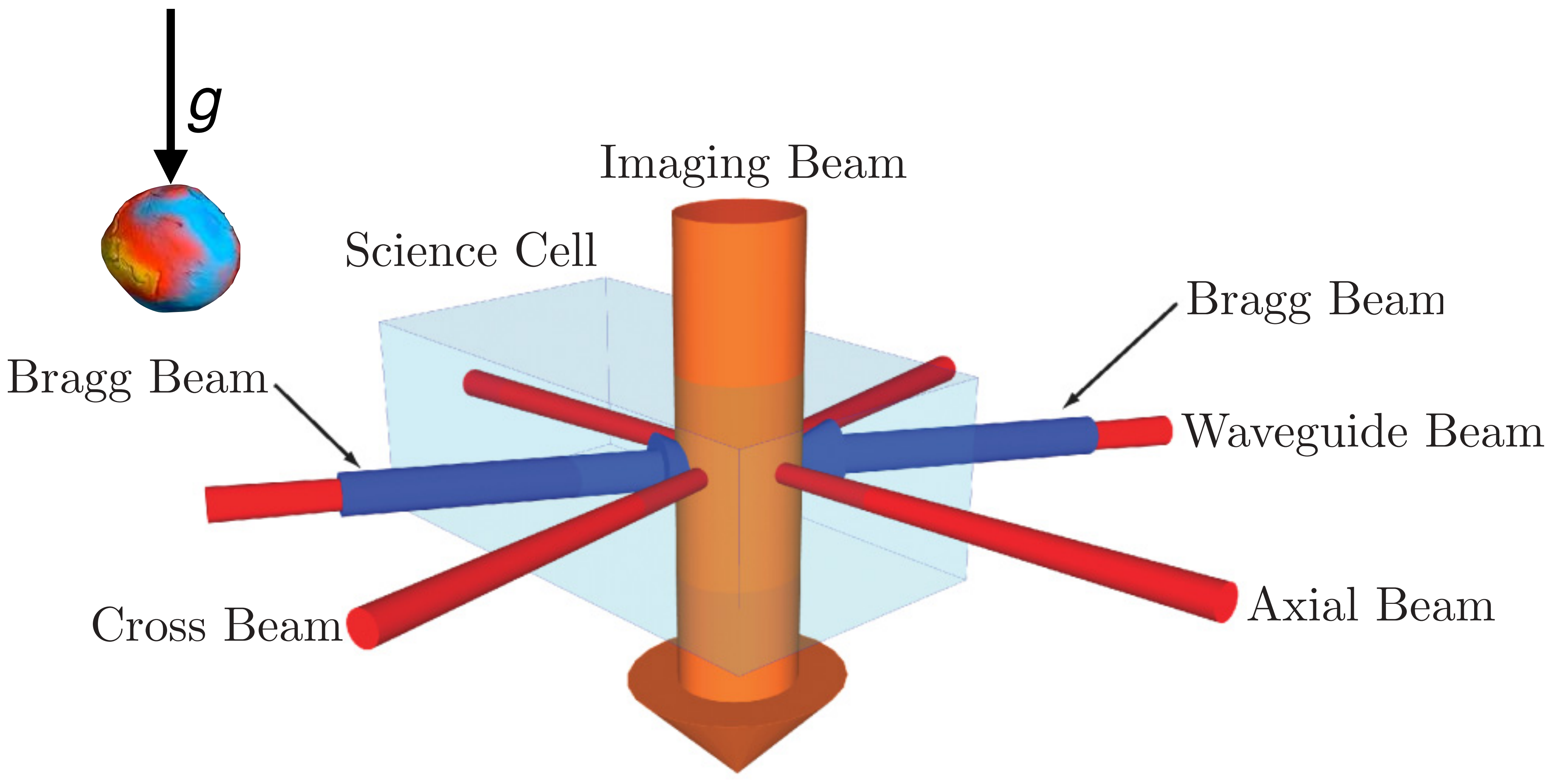
K. Henderson et al.
Experimental demonstration of painting arbitrary and dynamic potentials for BECs
New Journal of Physics **11:** 043030 (2009)
DOI:/10.1088/1367-2630/11/4/043030

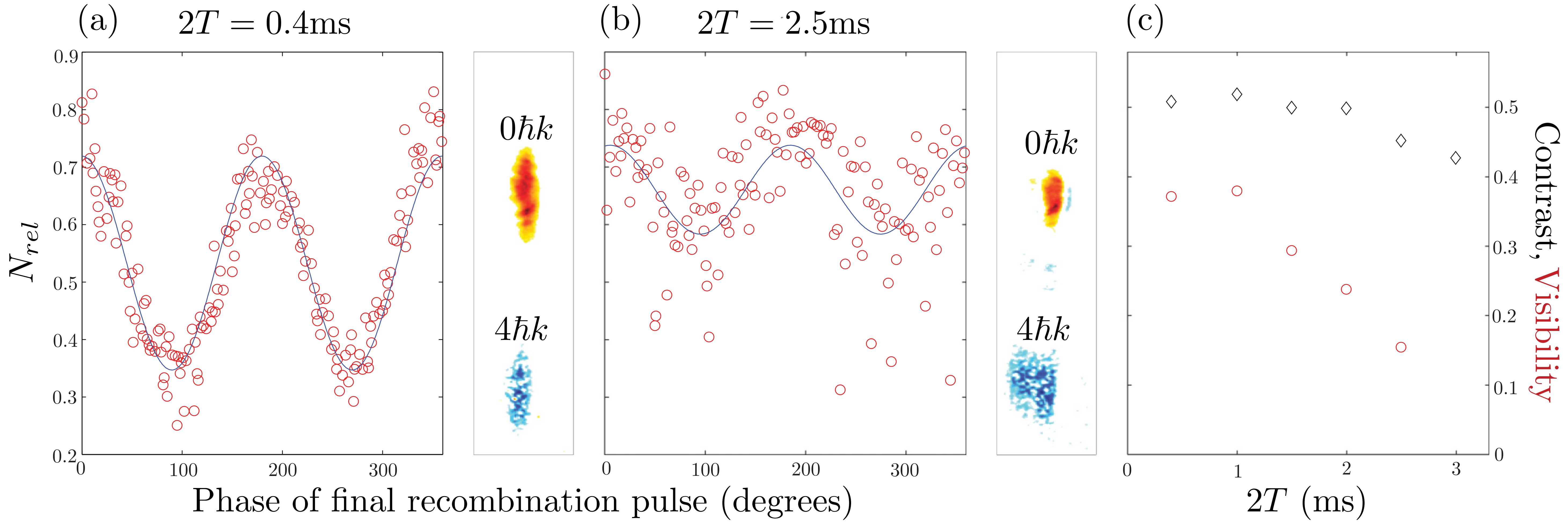
Light-Based MW-Guides

Interferometers based on Gaussian beams

$\Delta a = 7 \times 10^{-4} m/s^2$ @ 2T = 2.5 ms over 136 runs

$$2 \times 1.25\,\text{ms} \times 6\hbar k/m = 88\,\mu\text{m}$$





G. D. McDonald et al.

Optically guided linear Mach-Zehnder atom interferometer

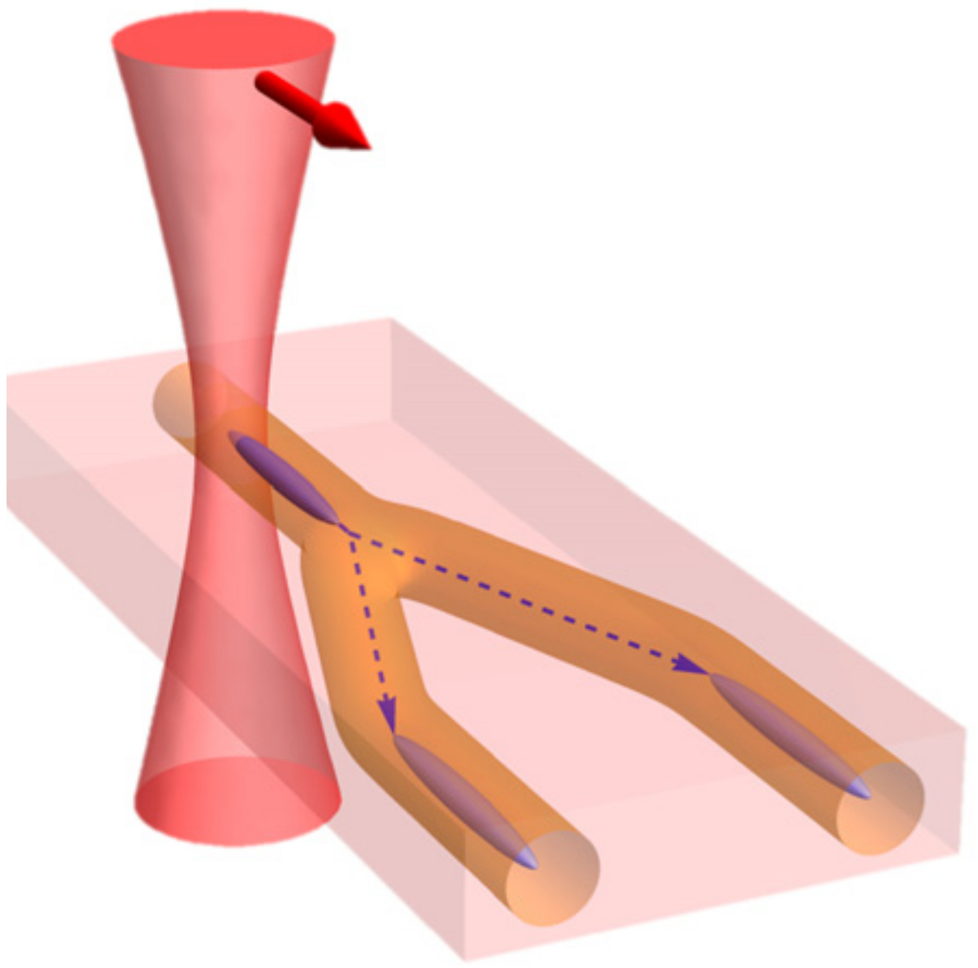
Physical Review A **87:1** 013632 (2013)
DOI:/10.1103/PhysRevA.87.013632

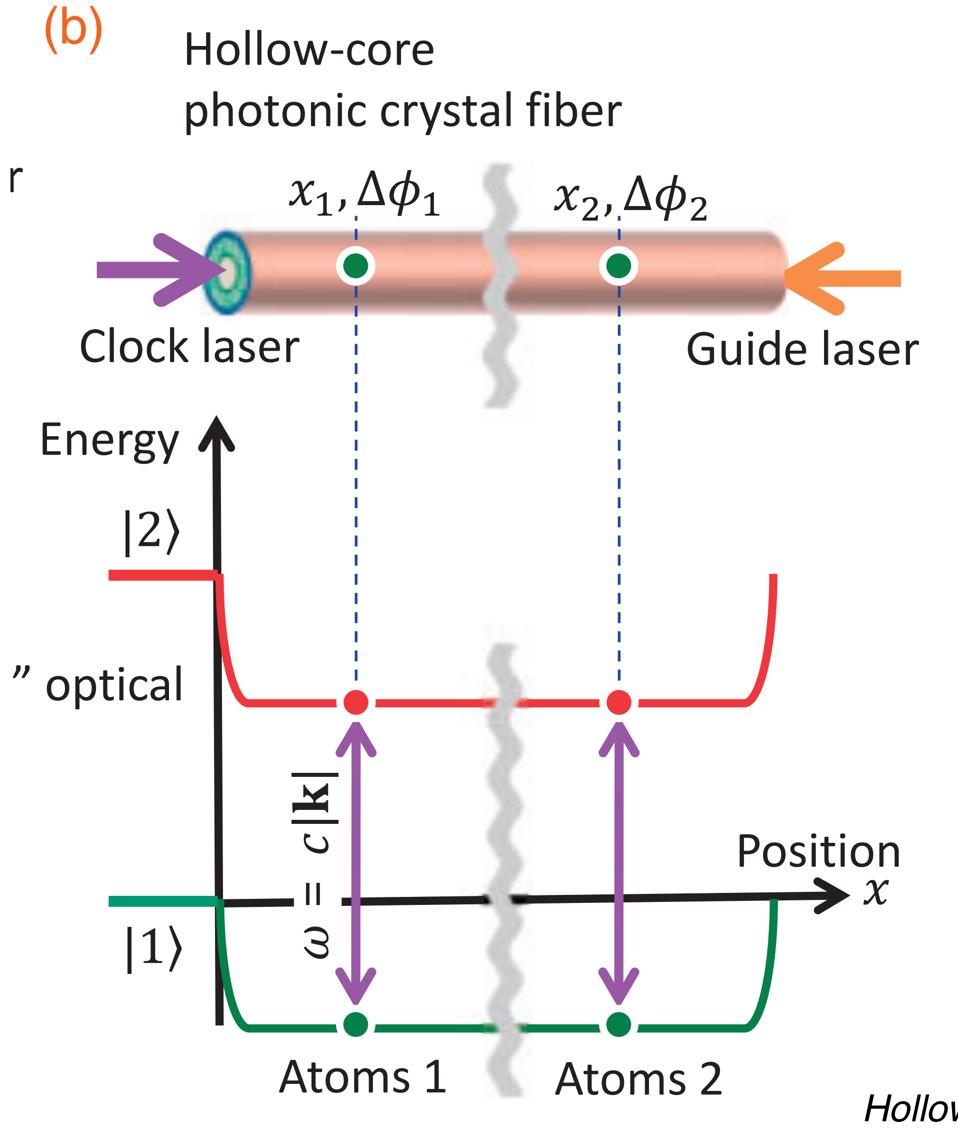
Best free-space results: ~ few x 10^{-7} m·s^{-2}/Hz$^{1/2}$

Near Future: Sagnac Interferometer using dipole guides (Boshier Group)

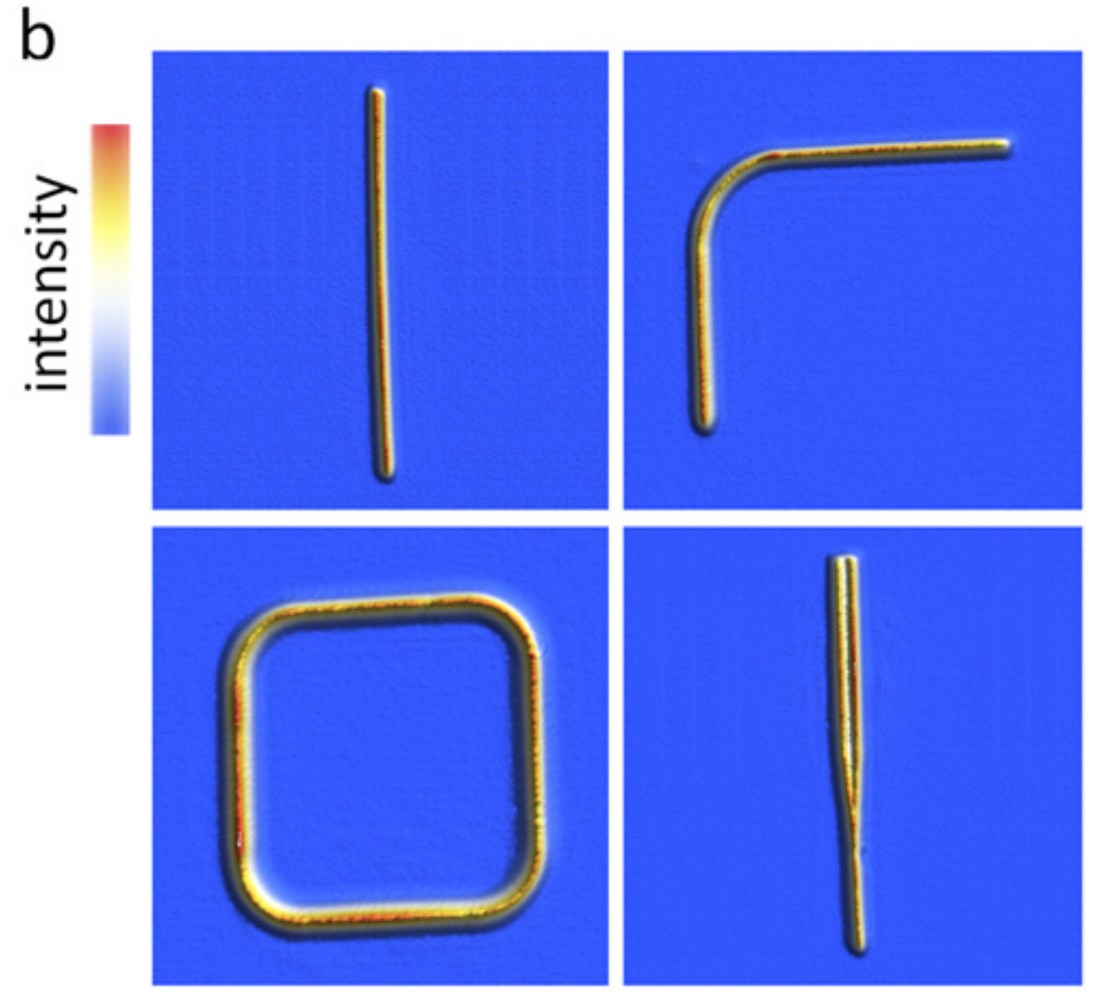
Light-Based MW-Guides

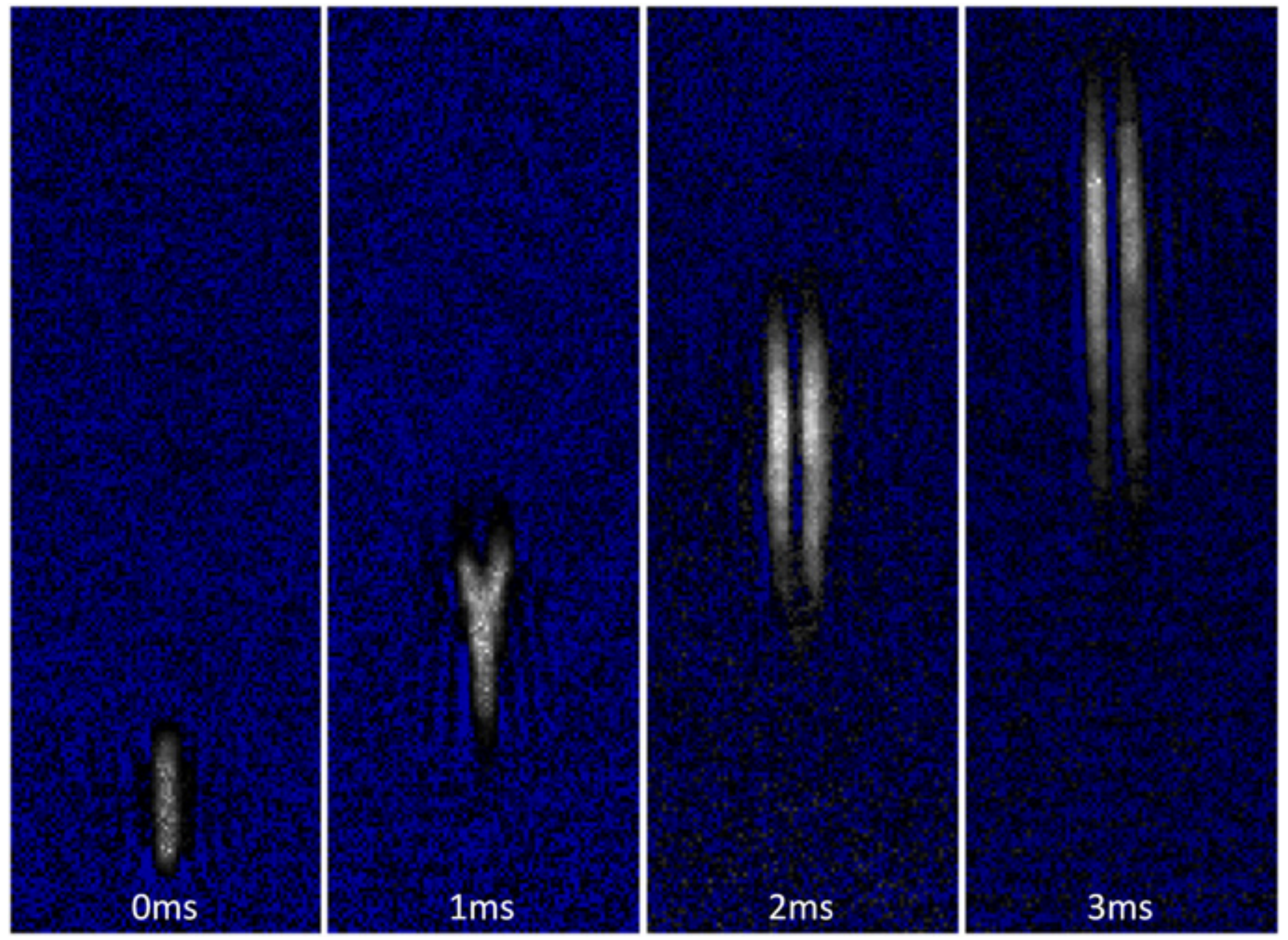
Interferometers based on Painted Potentials





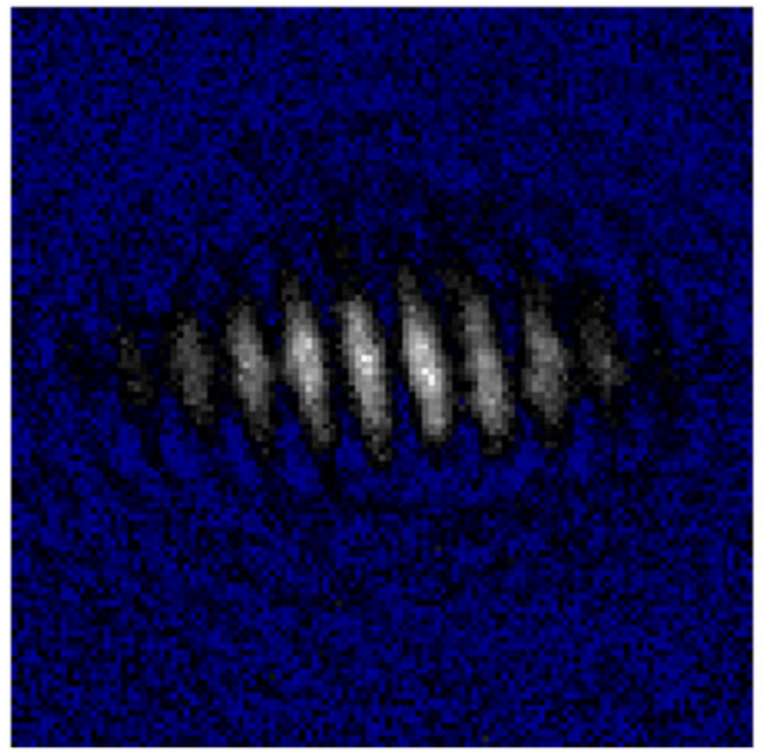
R. G. Dall et al.
Hollow fibre guides for metastable helium atoms
Comptes Rendus De L'Academie Des Sciences Serie IV **2:4** 595--603 (2001)
DOI:/10.1016/S1296-2147(01)01190-8





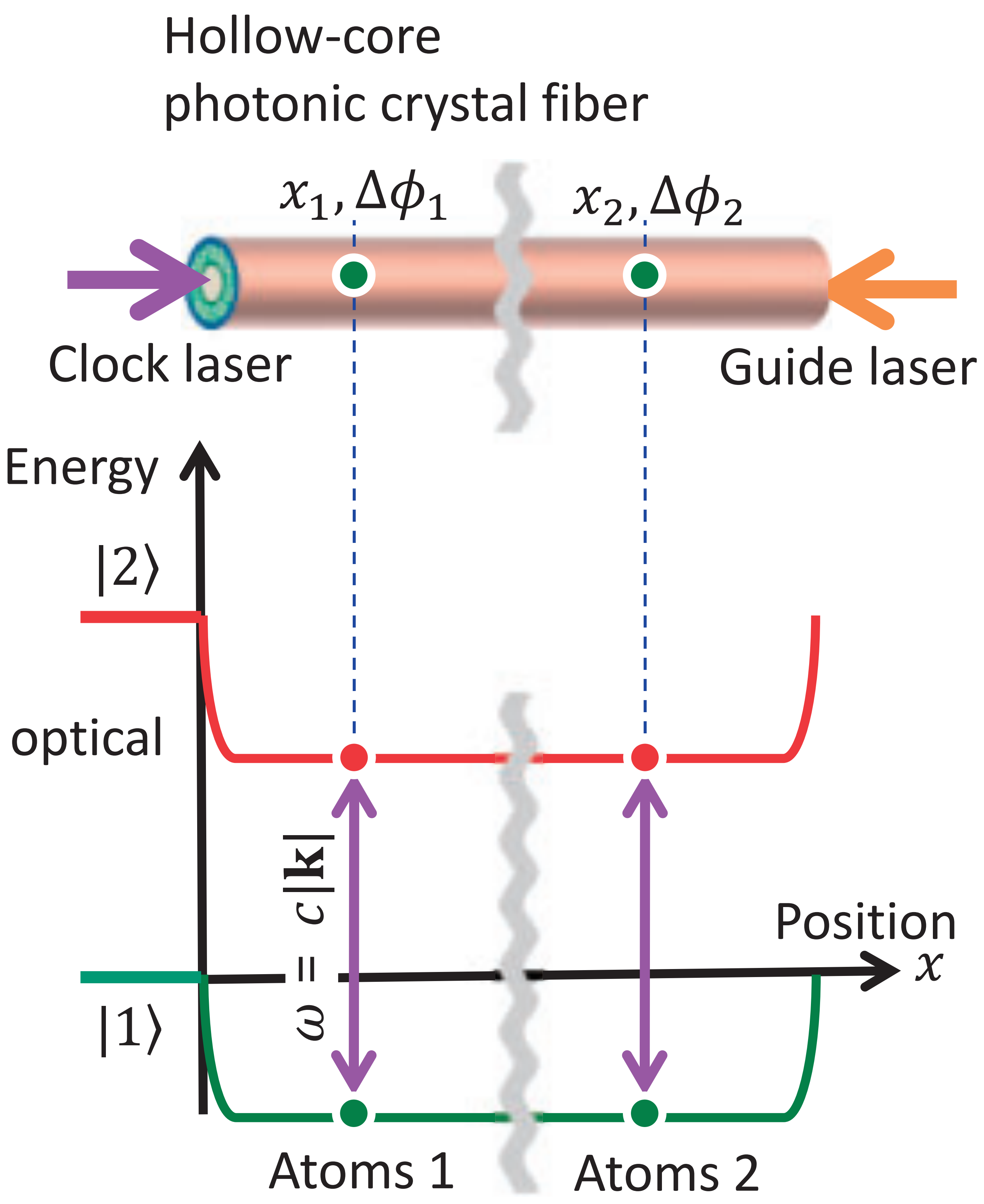
C. Ryu and M. G. Boshier
Integrated coherent matter wave circuits
New Journal of Physics **17:9** (2015)
DOI:/10.1088/1367-2630/17/9/092002

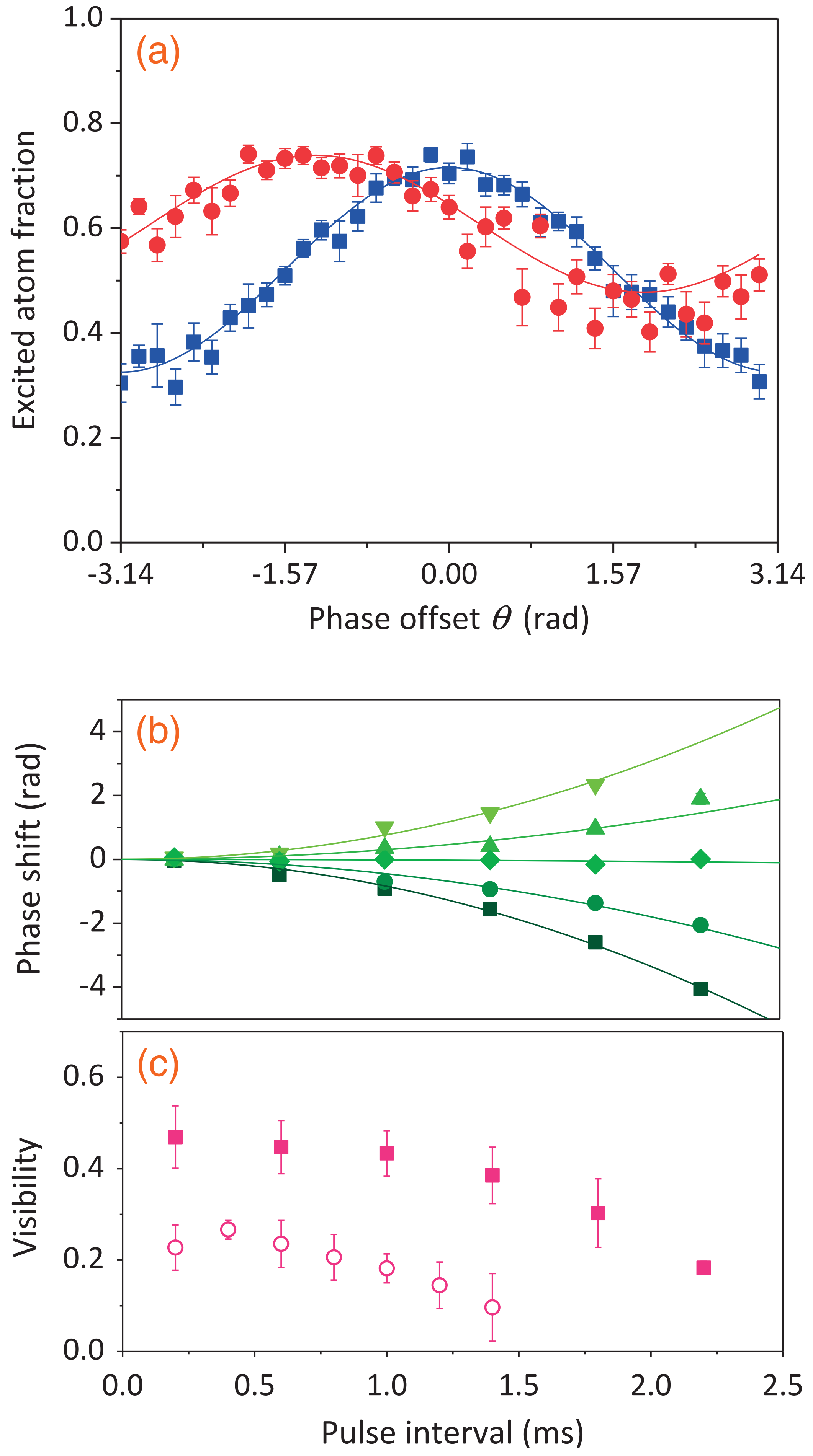
Expansion



Light-Based MW-Guides

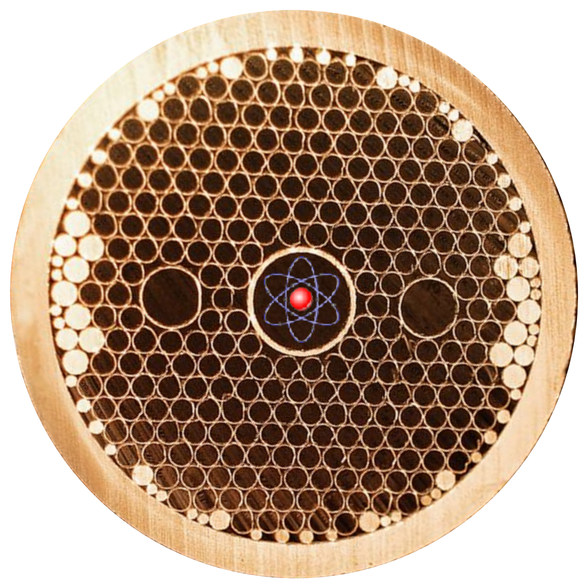
Interferometers based on Hollow Core Fibers

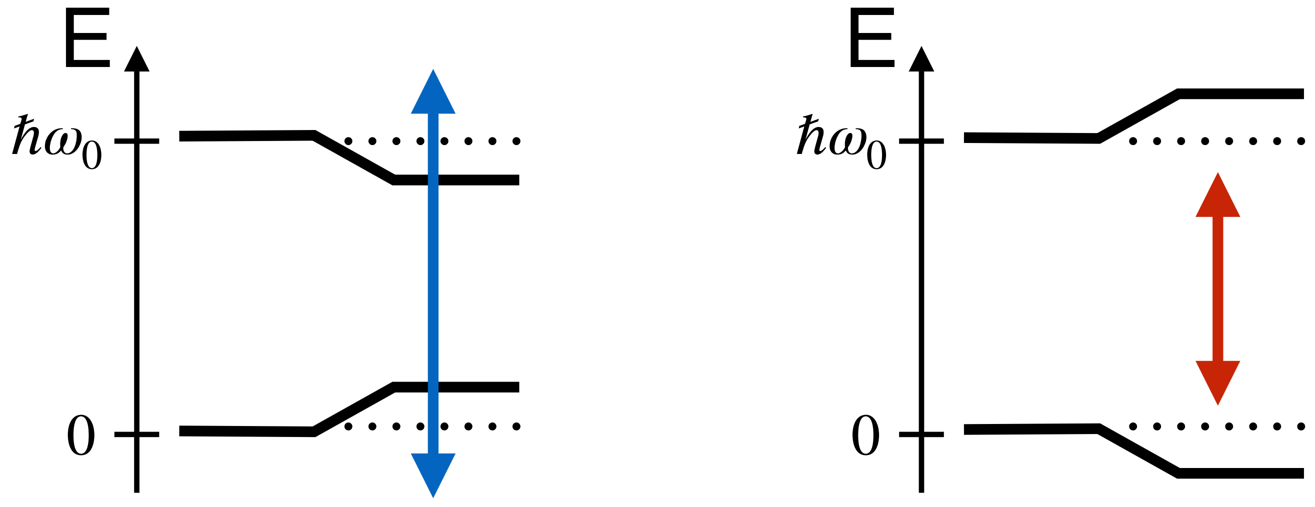




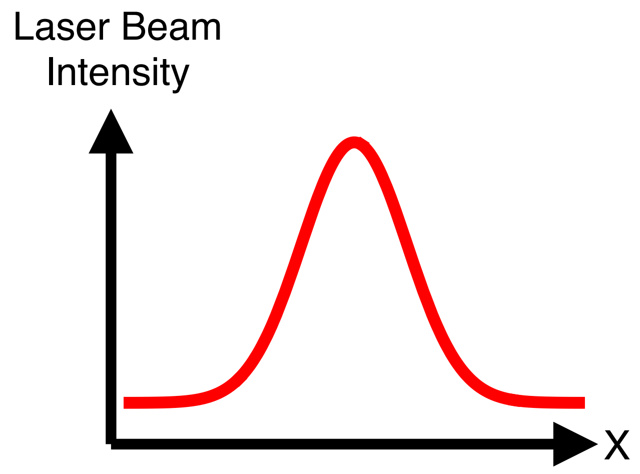
Tomoya Akatsuka, Tadahiro Takahashi, and Hidetoshi Katori
Optically guided atom interferometer tuned to magic wavelength
Applied Physics Express **10:11** 112501 (2017)
DOI:/10.7567/apex.10.112501

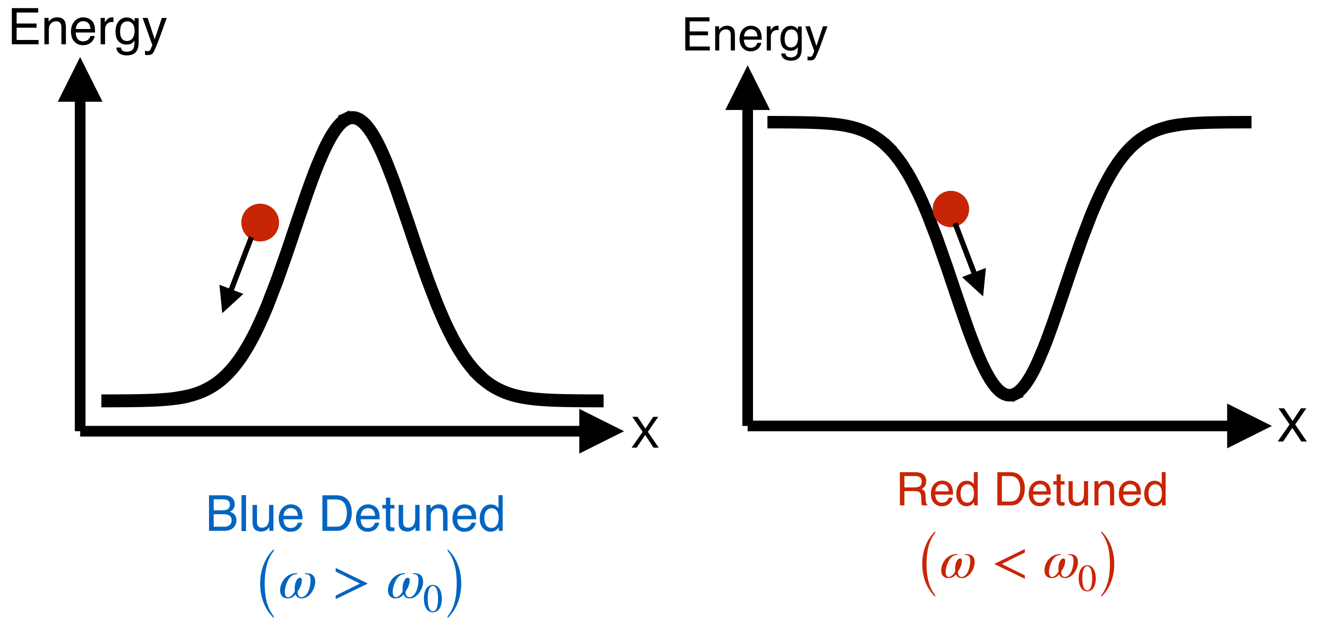
Light-Based MW-Guides

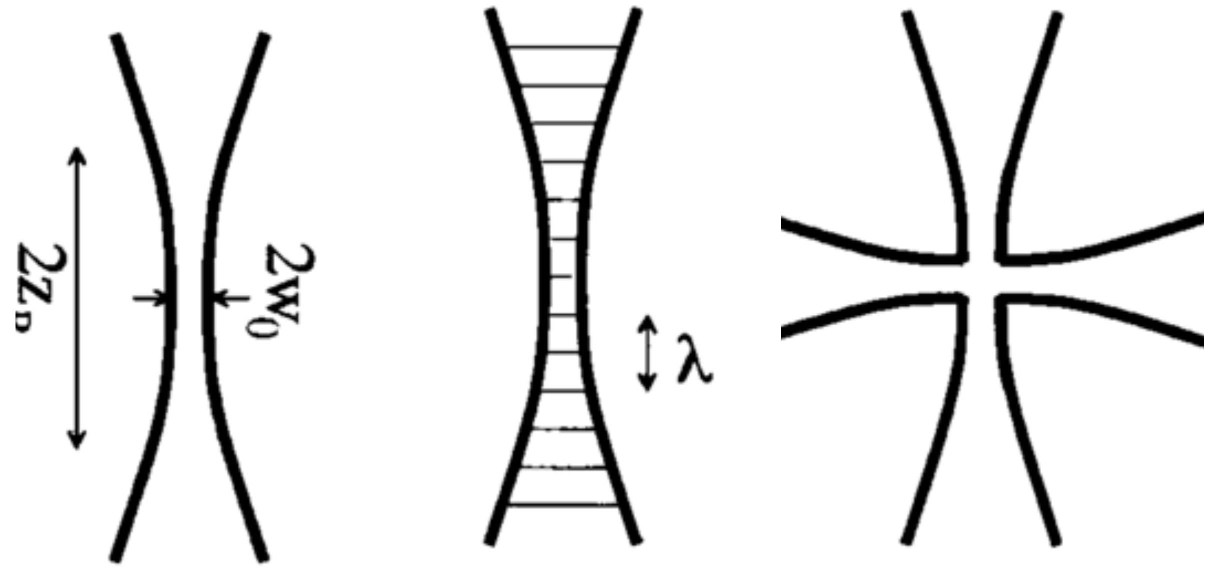


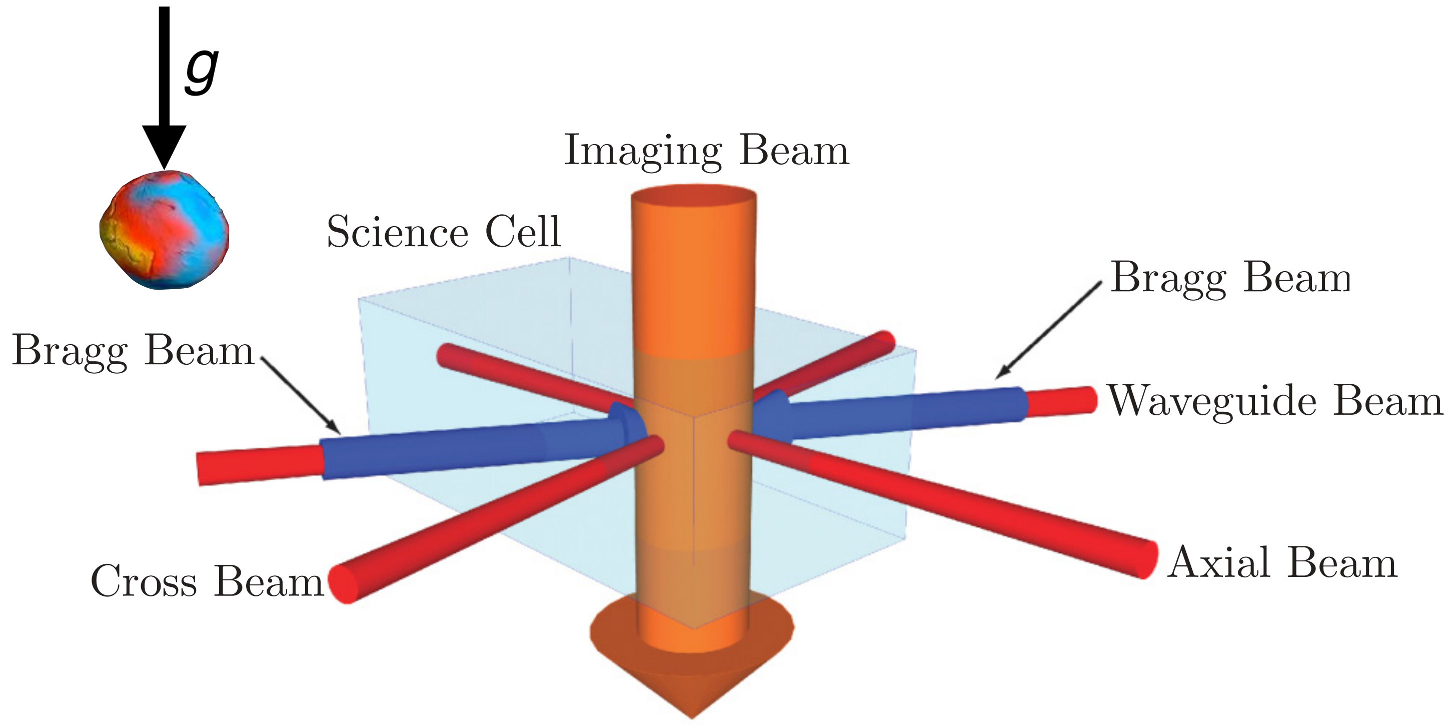


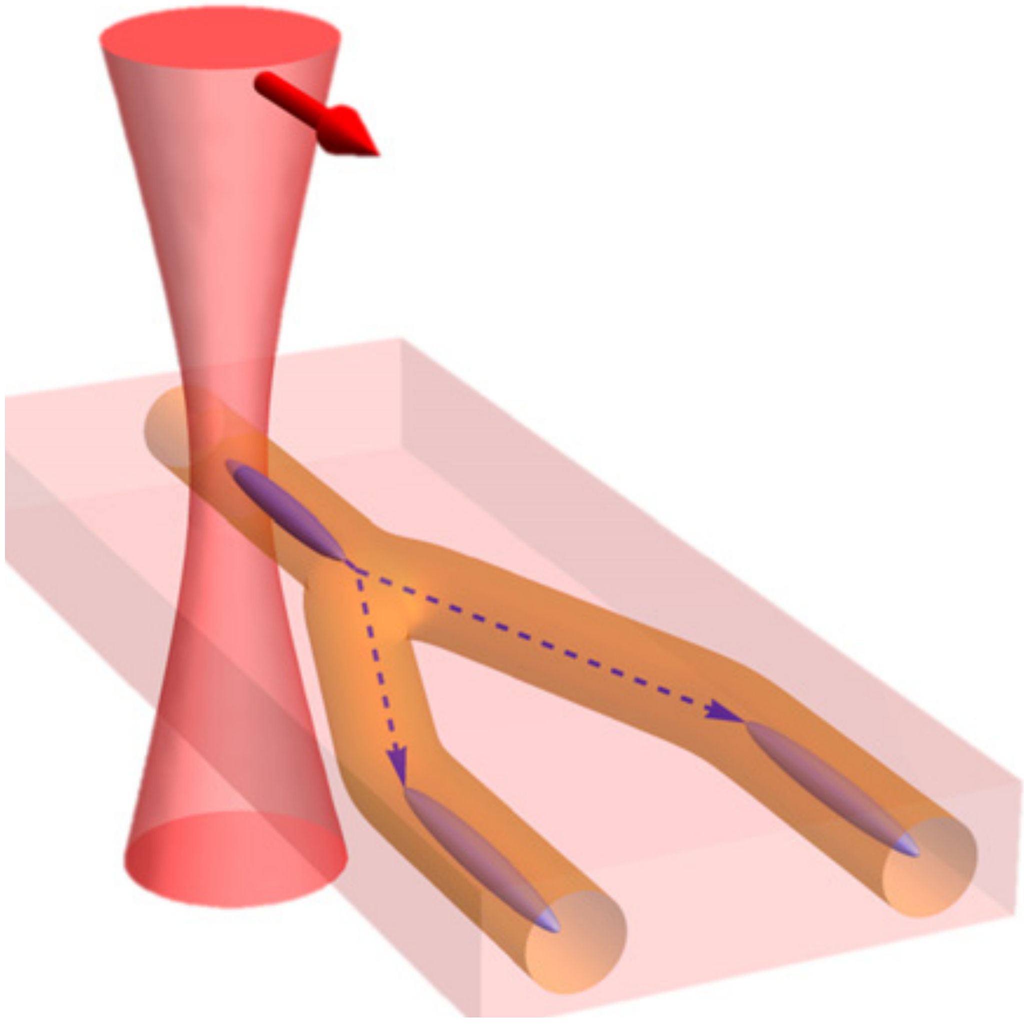
$$U(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(\mathbf{r})$$

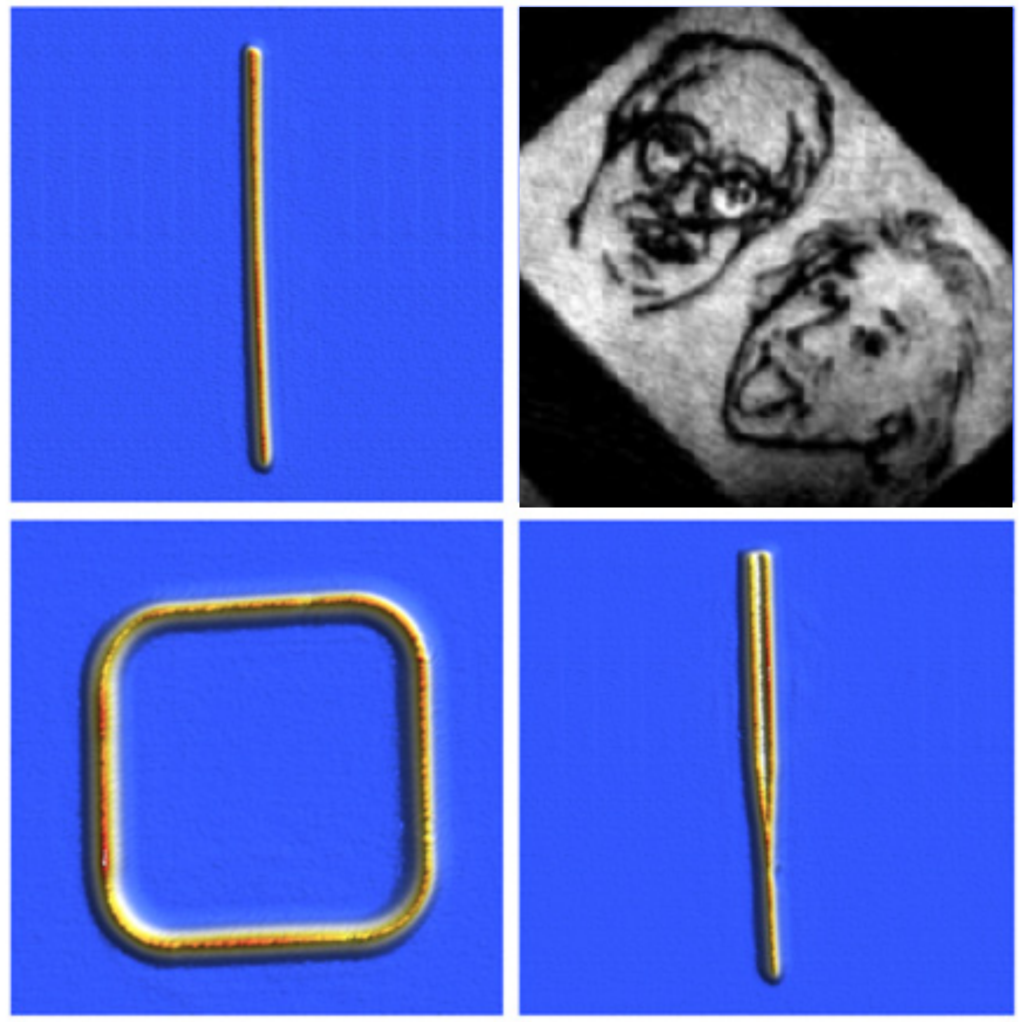


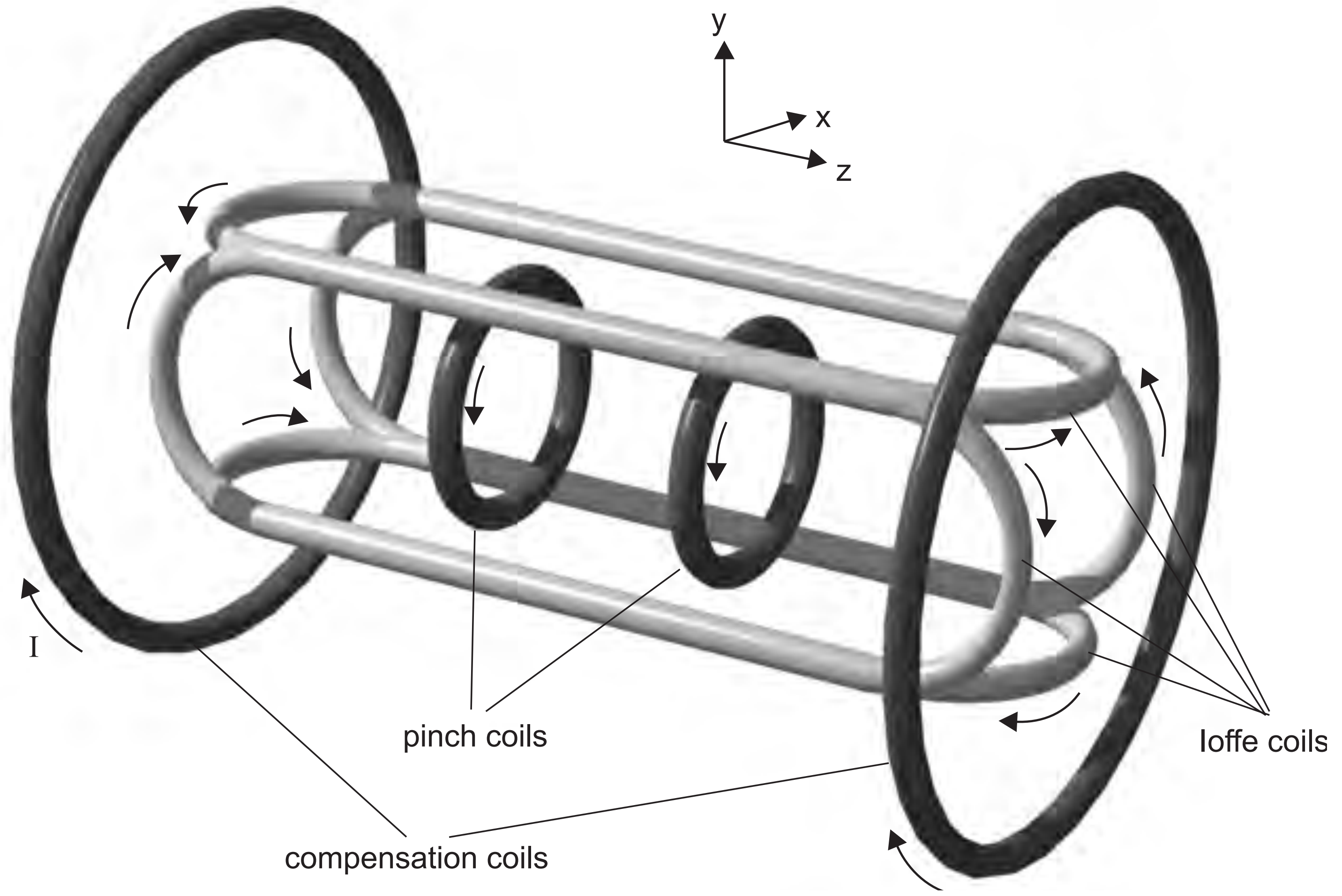




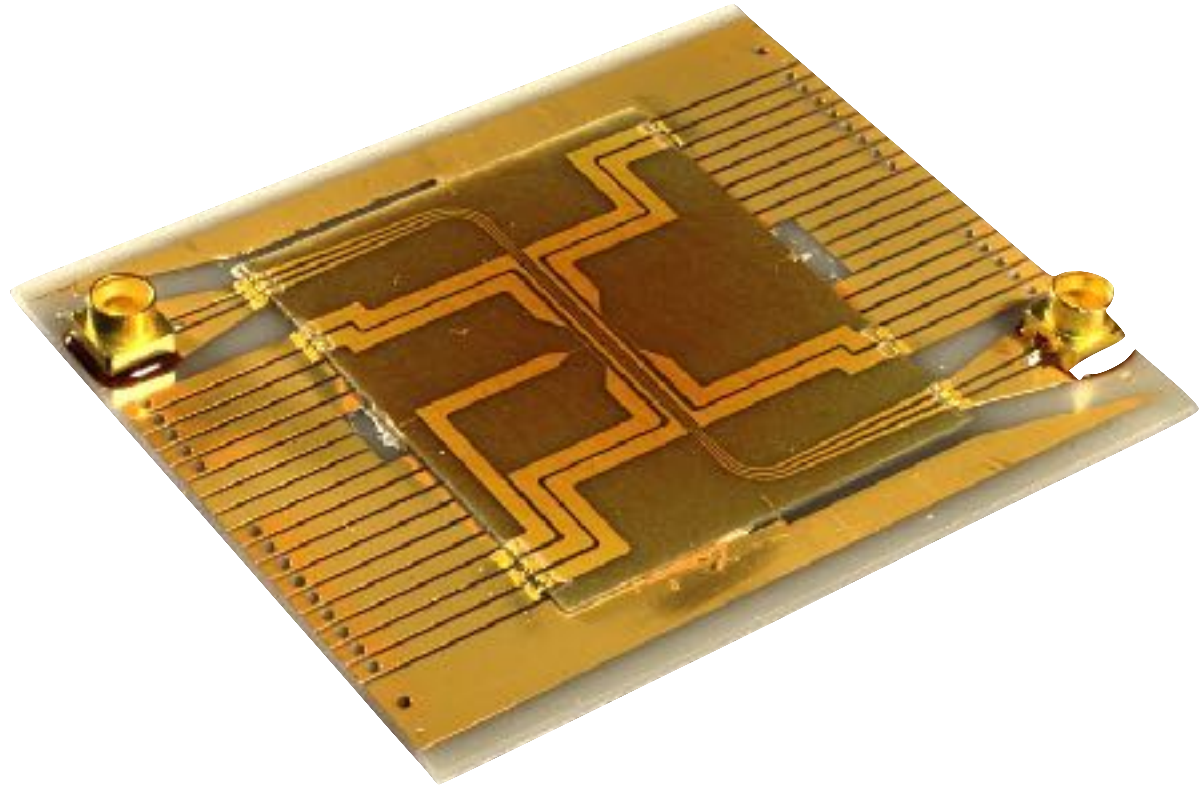








Magnetic Taps



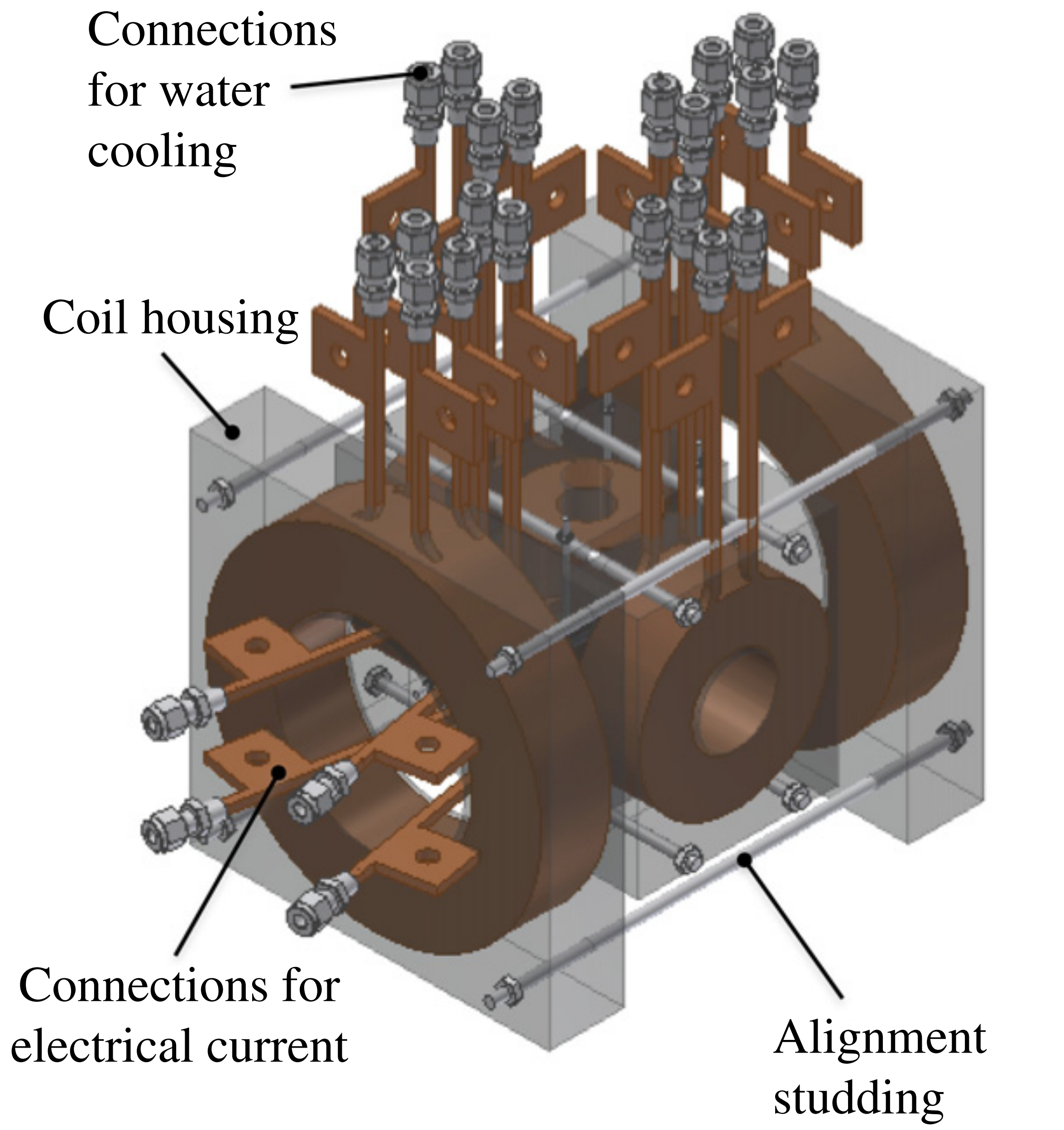
Magnetic Potentials

$$V = -\mu \cdot \mathbf{B} = m_F g_F \mu_B \left| \mathbf{B} \right|$$

Ioffe Pritchard Trap

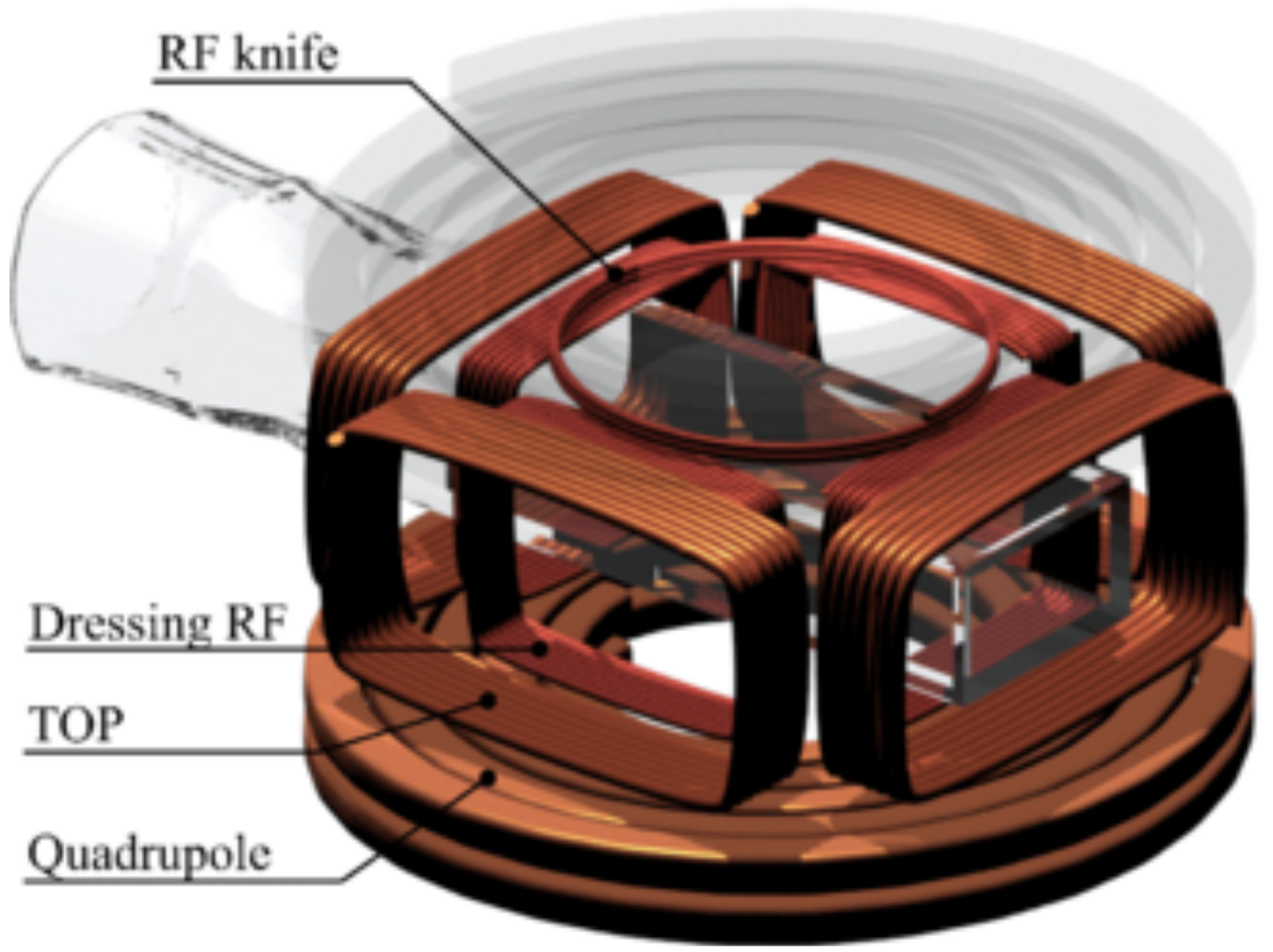
$$\mathbf{B}_{\mathrm{IP}} = \alpha \left(x\, \hat{\boldsymbol{e}}_{\mathrm{x}} - y\, \hat{\mathbf{e}}_{\mathrm{y}} \right) + \left(B_0 + \frac{1}{2} \beta\, z^2 \right) \hat{\mathbf{e}}_{\mathrm{z}}$$

$$\omega_\rho = \sqrt{\frac{m_F g_F \mu_B}{m} \left(\frac{\alpha^2}{B_0} - \frac{\beta}{2} \right)} \qquad \omega_z = \sqrt{\frac{m_F g_F \mu_B}{m} \beta}$$

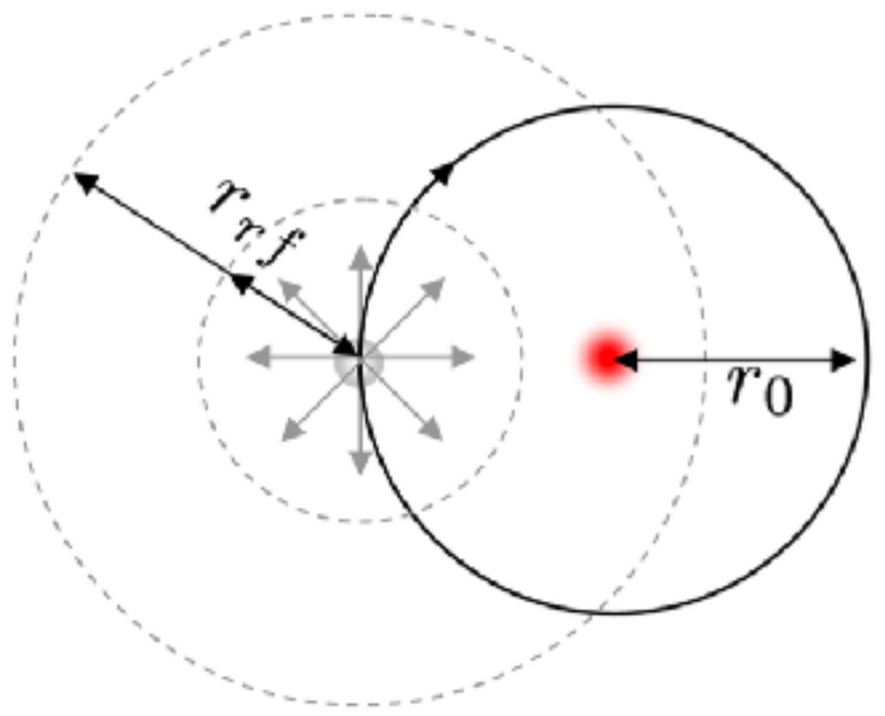


Yu. T. Baiborodov et al.
An adiabatic trap with combined magnetic field
Soviet Atomic Energy **14:5** 459--461 (1964)
DOI:/10.1007/BF01121888

David E. Pritchard
Cooling Neutral Atoms in a Magnetic Trap for Precision Spectroscopy
Physical Review Letters **51:15** 1336-1339 (1983)
DOI:/10.1103/PhysRevLett.51.1336



Magnetic Taps



Magnetic Potentials

$$V = -\mu \cdot \mathbf{B} = m_F g_F \mu_B \left|\mathbf{B}\right|$$

Time Orbiting Potential (TOP) Trap

$$\vec{B}_{TOP} = \vec{B}_Q + \vec{B}_{mod}$$

$$\vec{B}_Q = \alpha \begin{pmatrix} x \\ y \\ 2z \end{pmatrix}$$

$$\vec{B}_m(t) = B_m \begin{pmatrix} \sin t \\ \cos t \\ 0 \end{pmatrix}$$

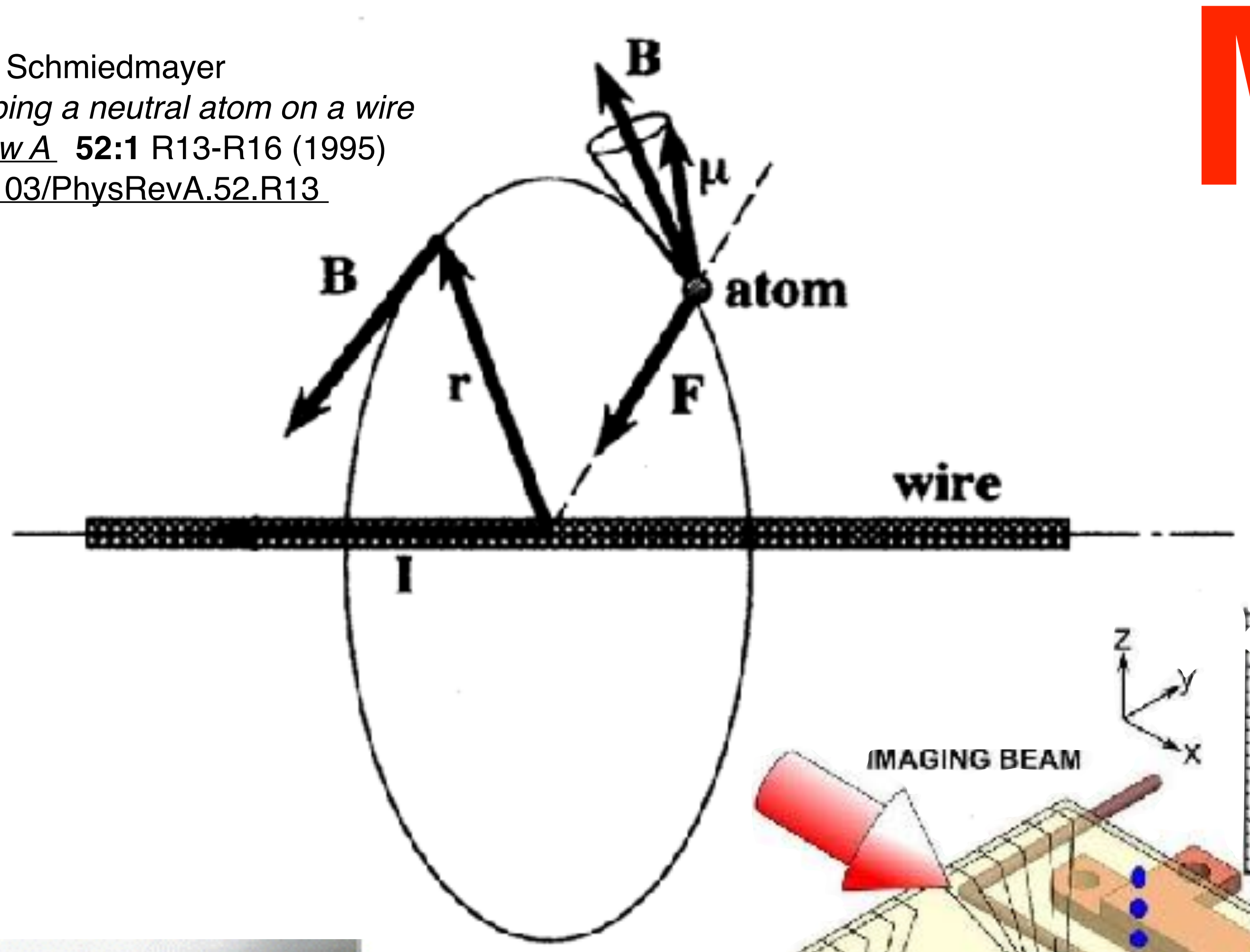
$$\omega_\rho = \sqrt{\frac{m_F g_F \mu_B}{m} \frac{\alpha^2}{B_m}} \qquad \omega_z = \sqrt{8}\, \omega_\rho$$

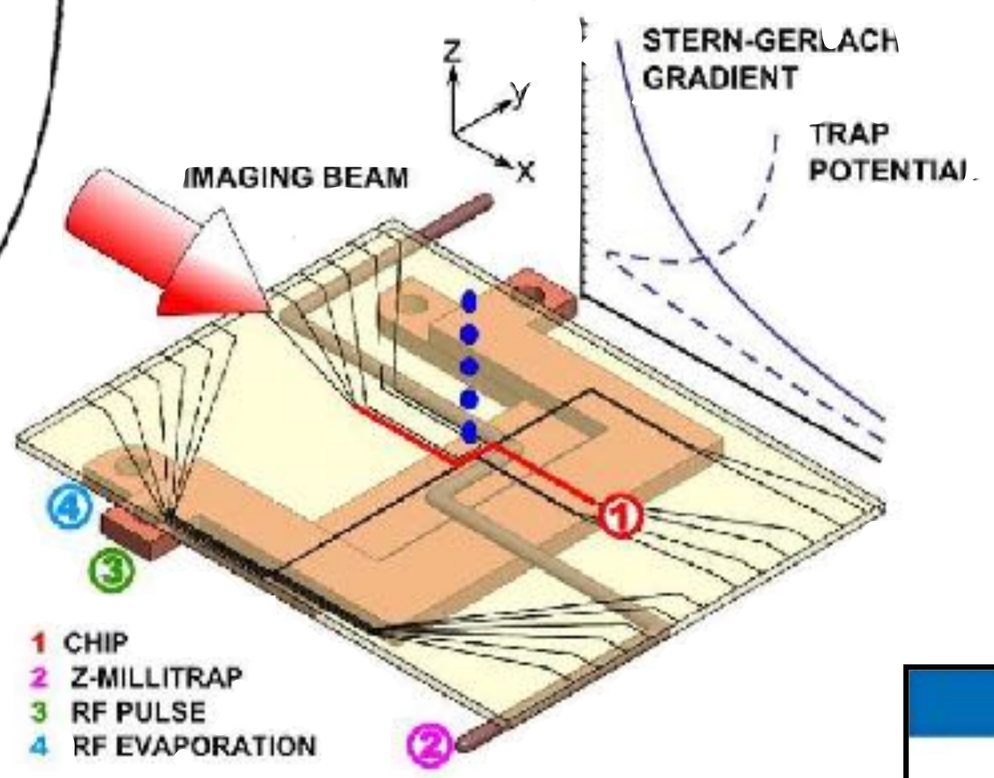
W. Petrich et al.
Stable, Tightly Confining Magnetic Trap for Evaporative Cooling of Neutral Atoms
Physical Review Letters **74:17** 3352-3355 (1995)
DOI:/10.1103/PhysRevLett.74.3352

Magnetic Traps

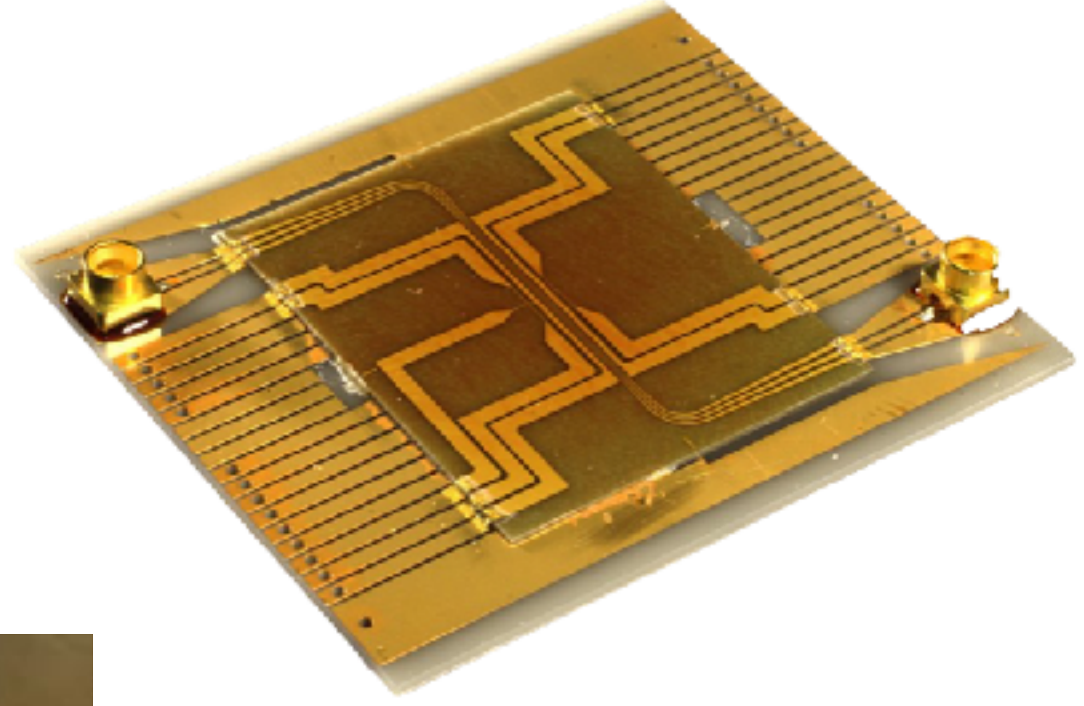
Atom Chips

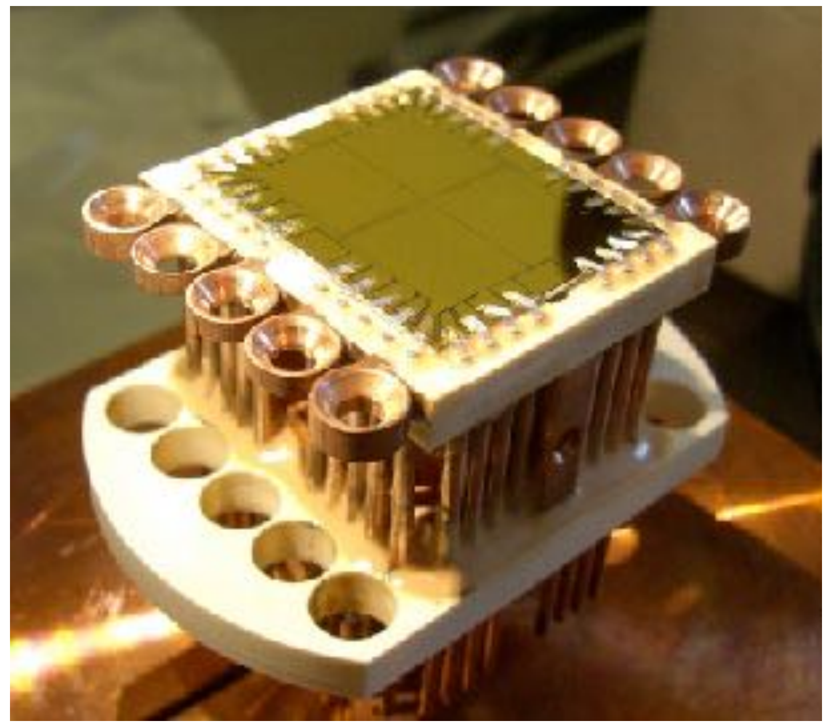
Jörg Schmiedmayer
Guiding and trapping a neutral atom on a wire
Physical Review A **52:1** R13-R16 (1995)
DOI:/10.1103/PhysRevA.52.R13

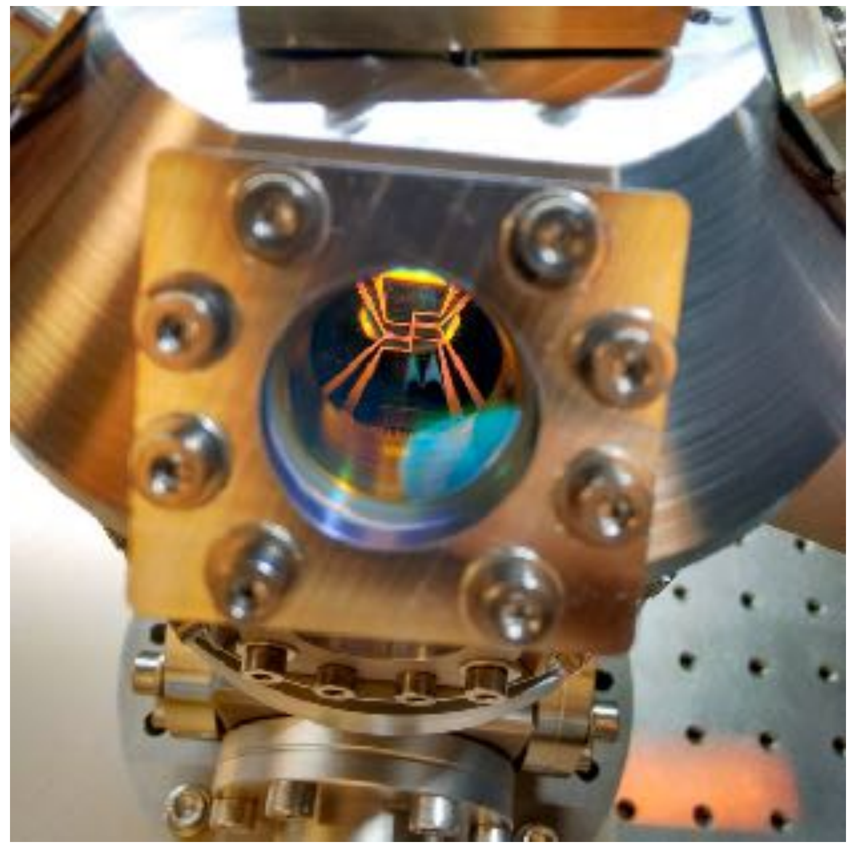


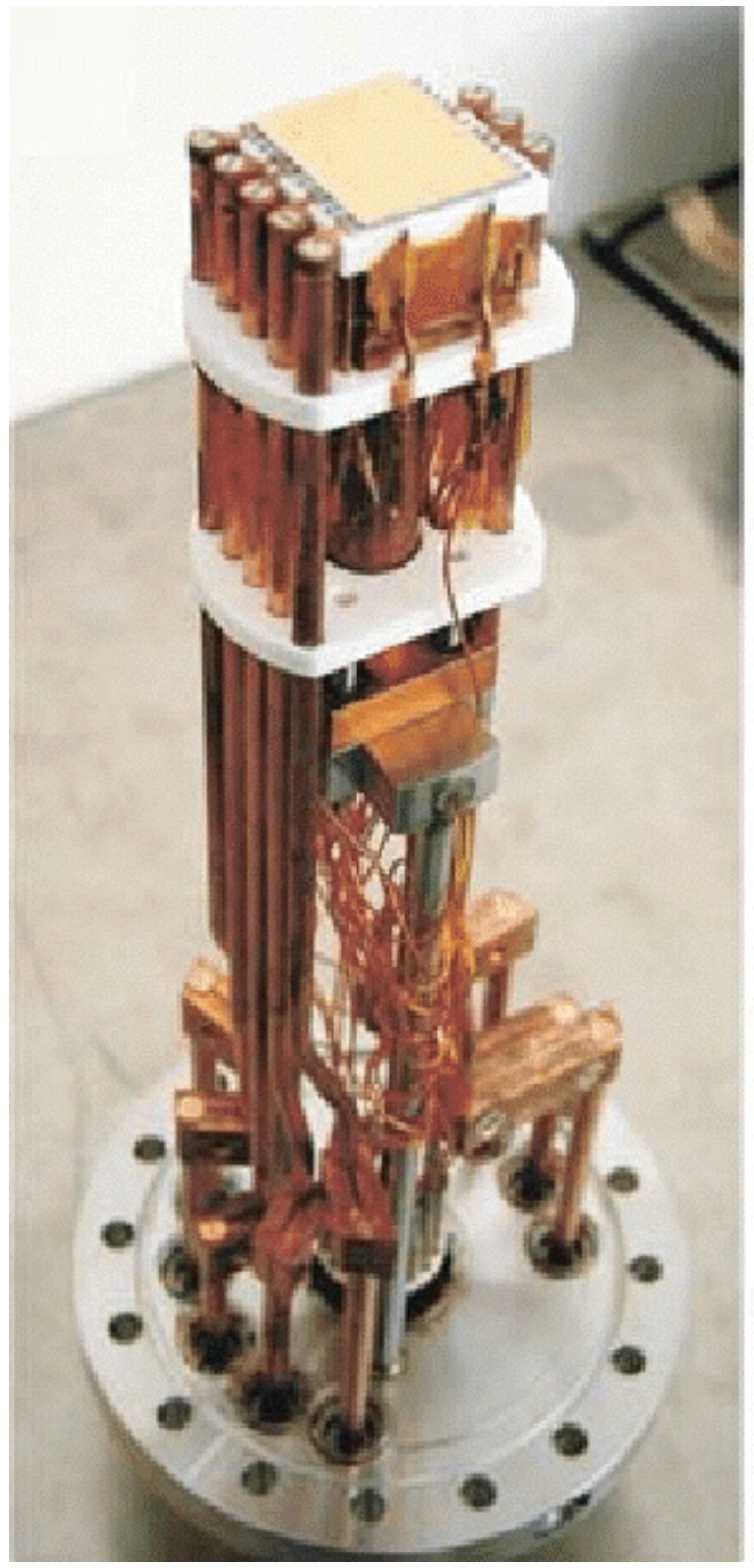


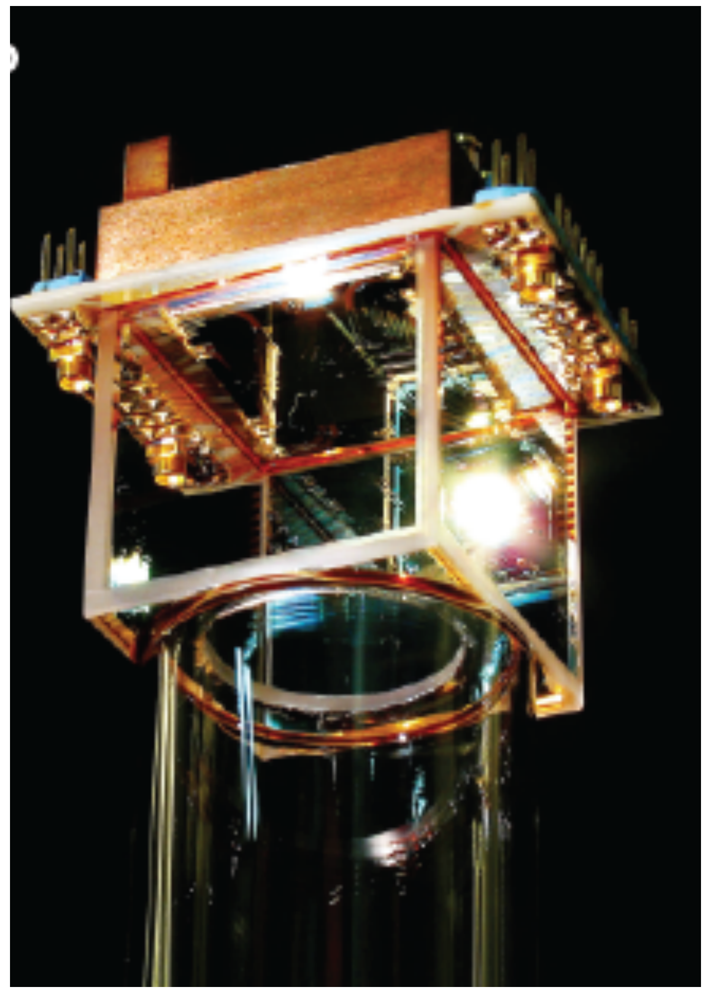
arXiv:1111.4321 [physics.atom-ph]

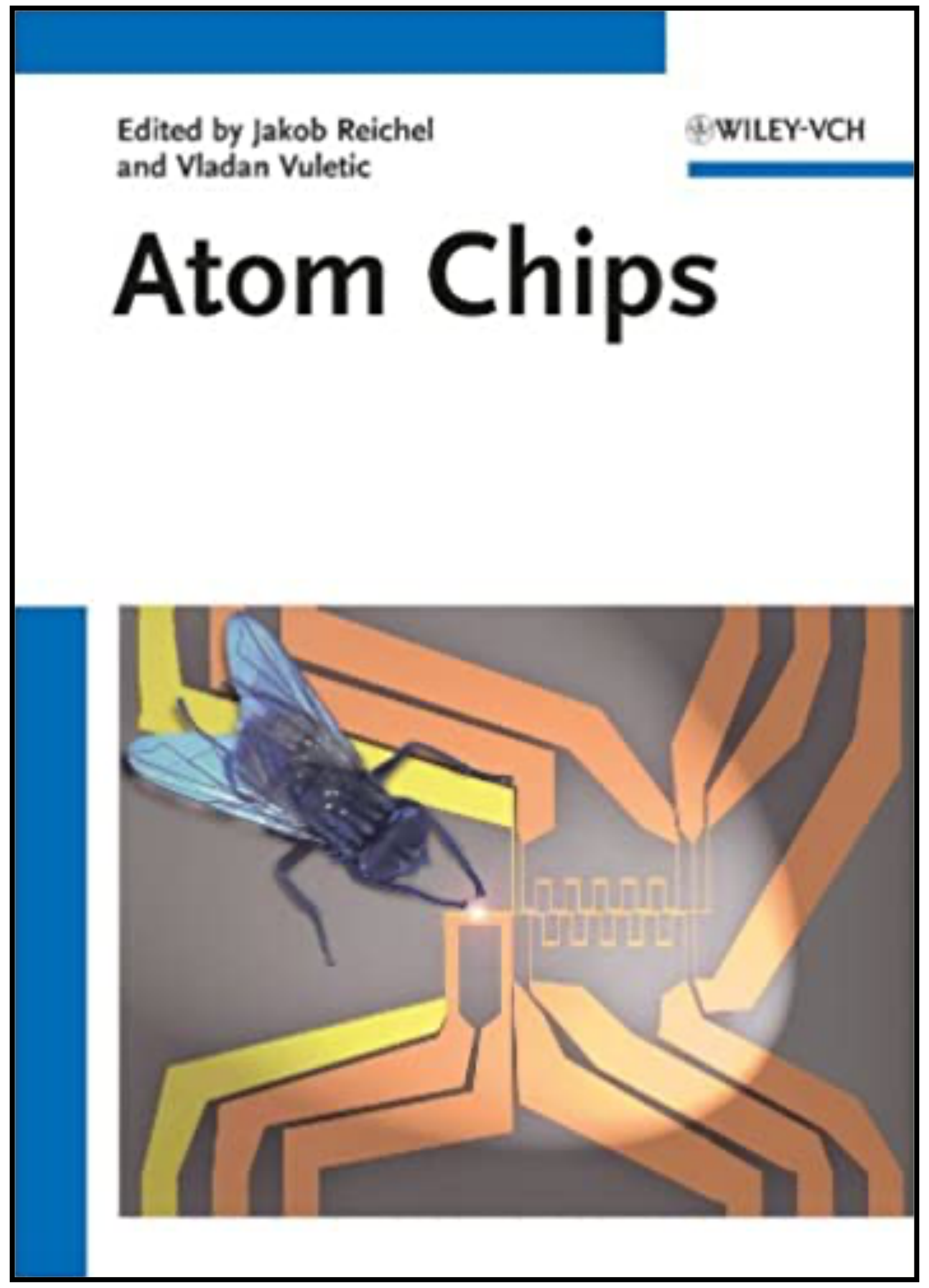


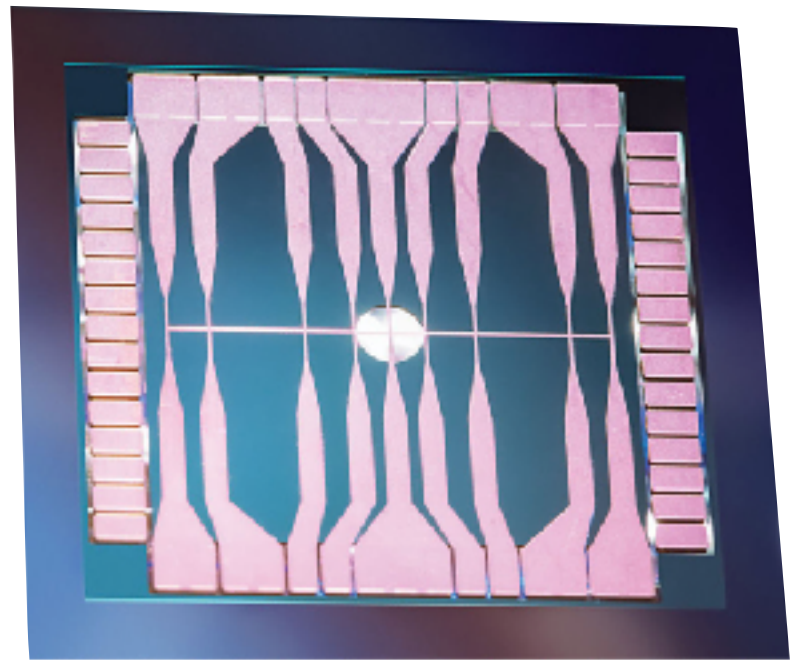












Y. J. Wang et al.
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Physical Review Letters **94:** 090405 (2005)
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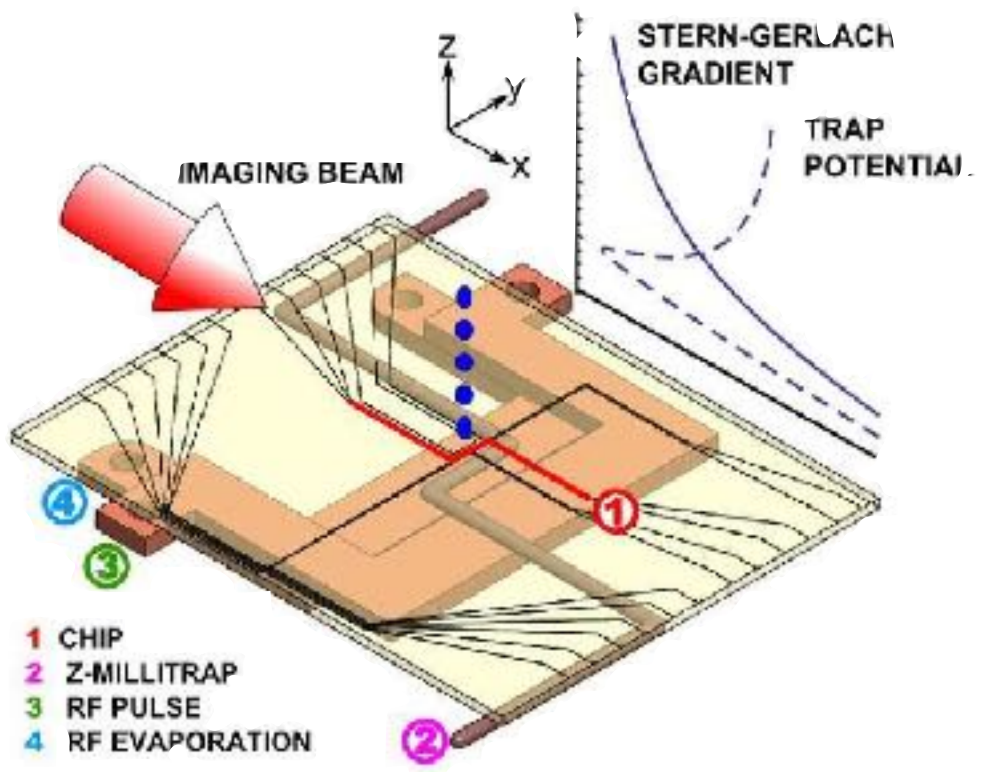
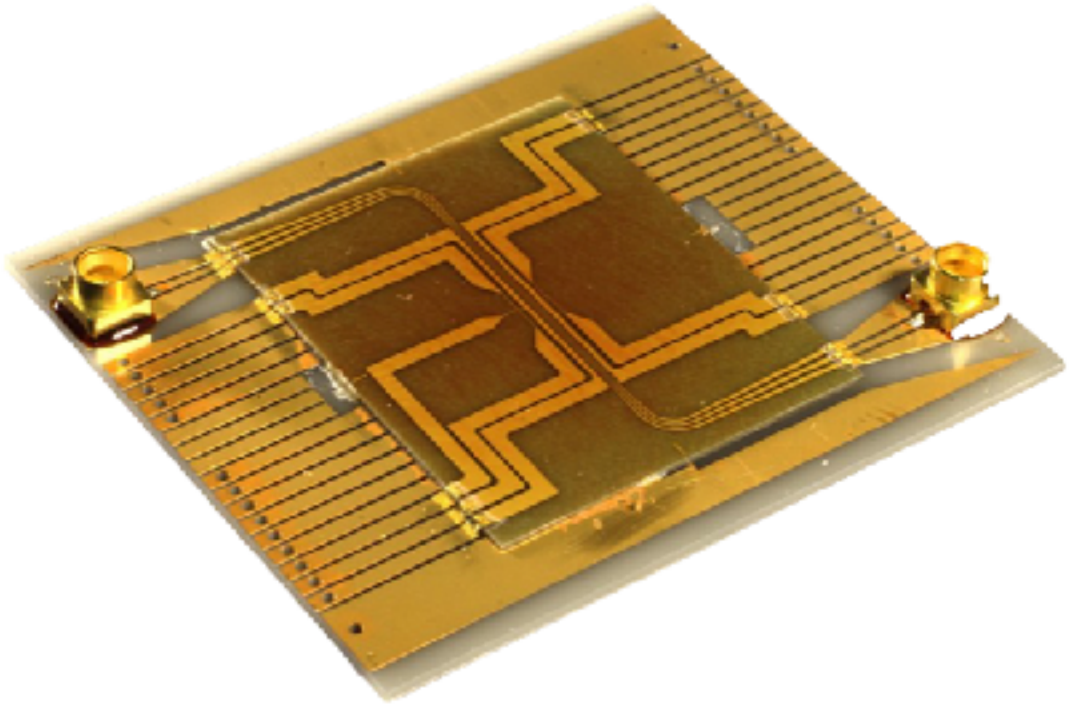


arXiv:1111.4321 [physics.atom-ph]

Magnetic Traps

Atom Chips

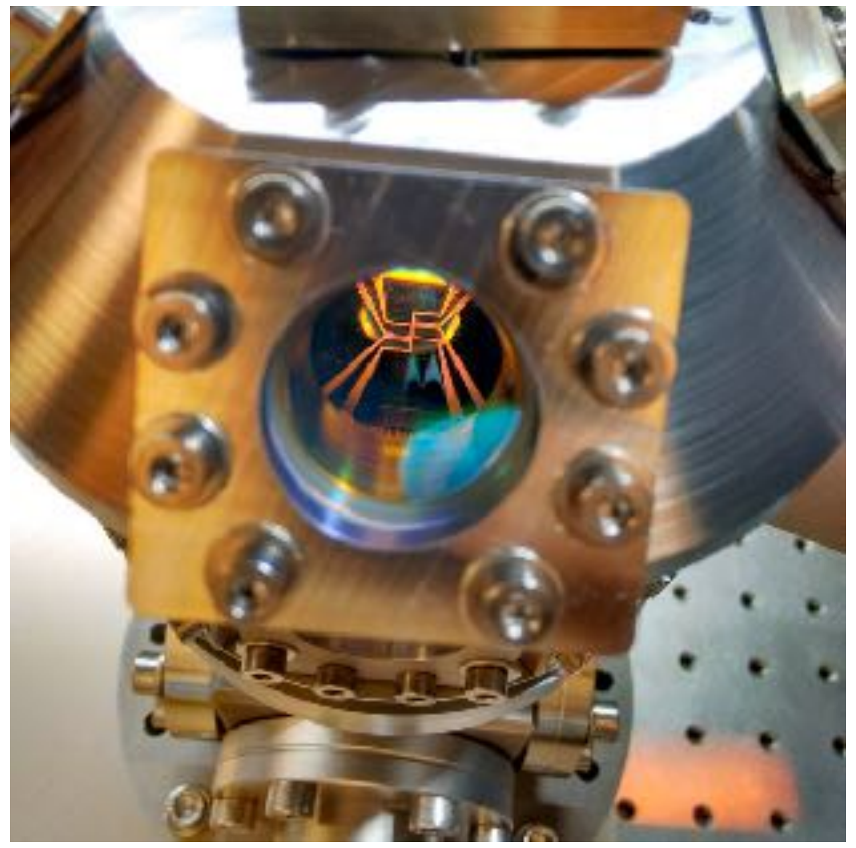


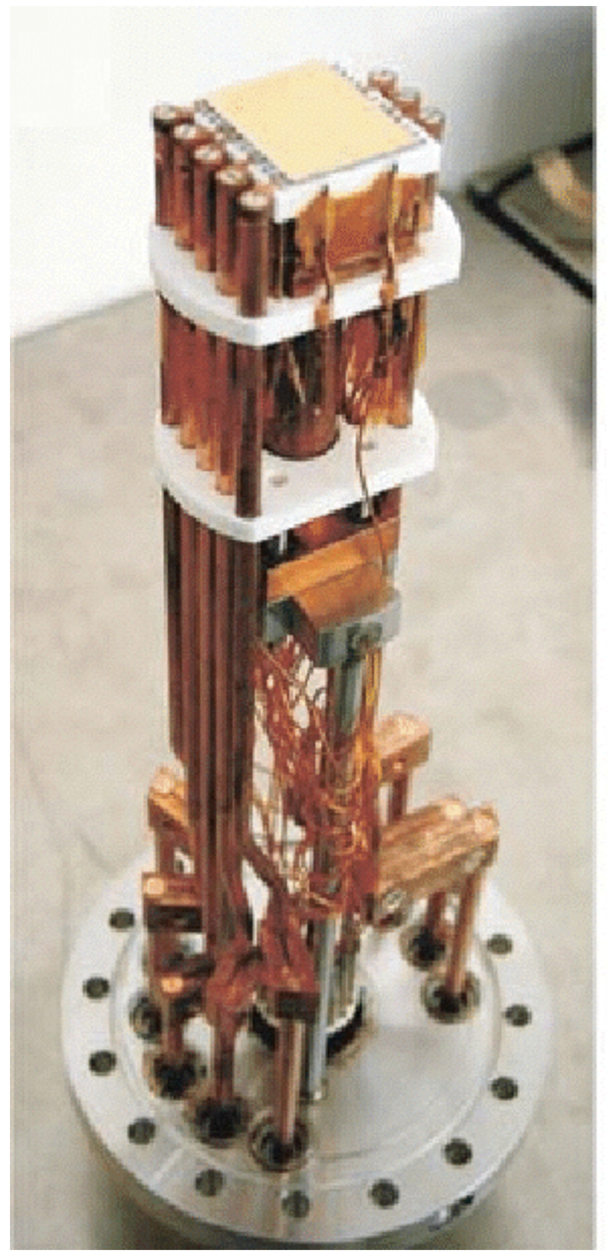
Interferometers

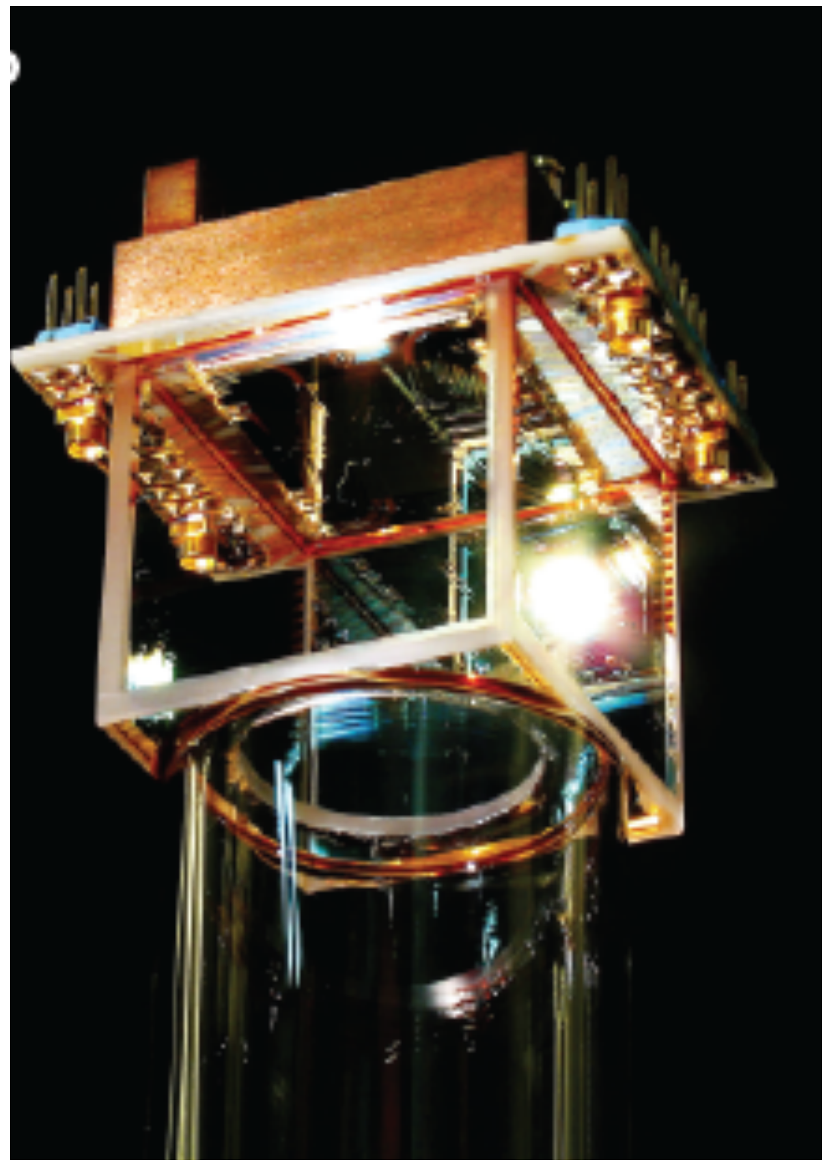
- Acceleration
- Gravity
- Rotation
- Tilt

Versatile Potentials for

- Fundamental Physics
- Thermodynamics
- Mesoscopic systems
- Superfluidity

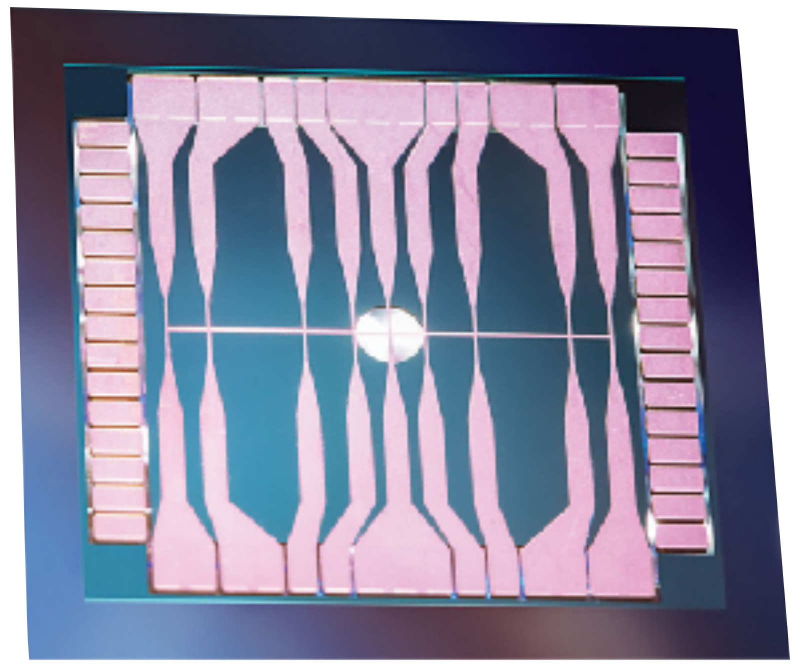






Atom Sources

- Space
- Mobile applications



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Magnetic Waveguides

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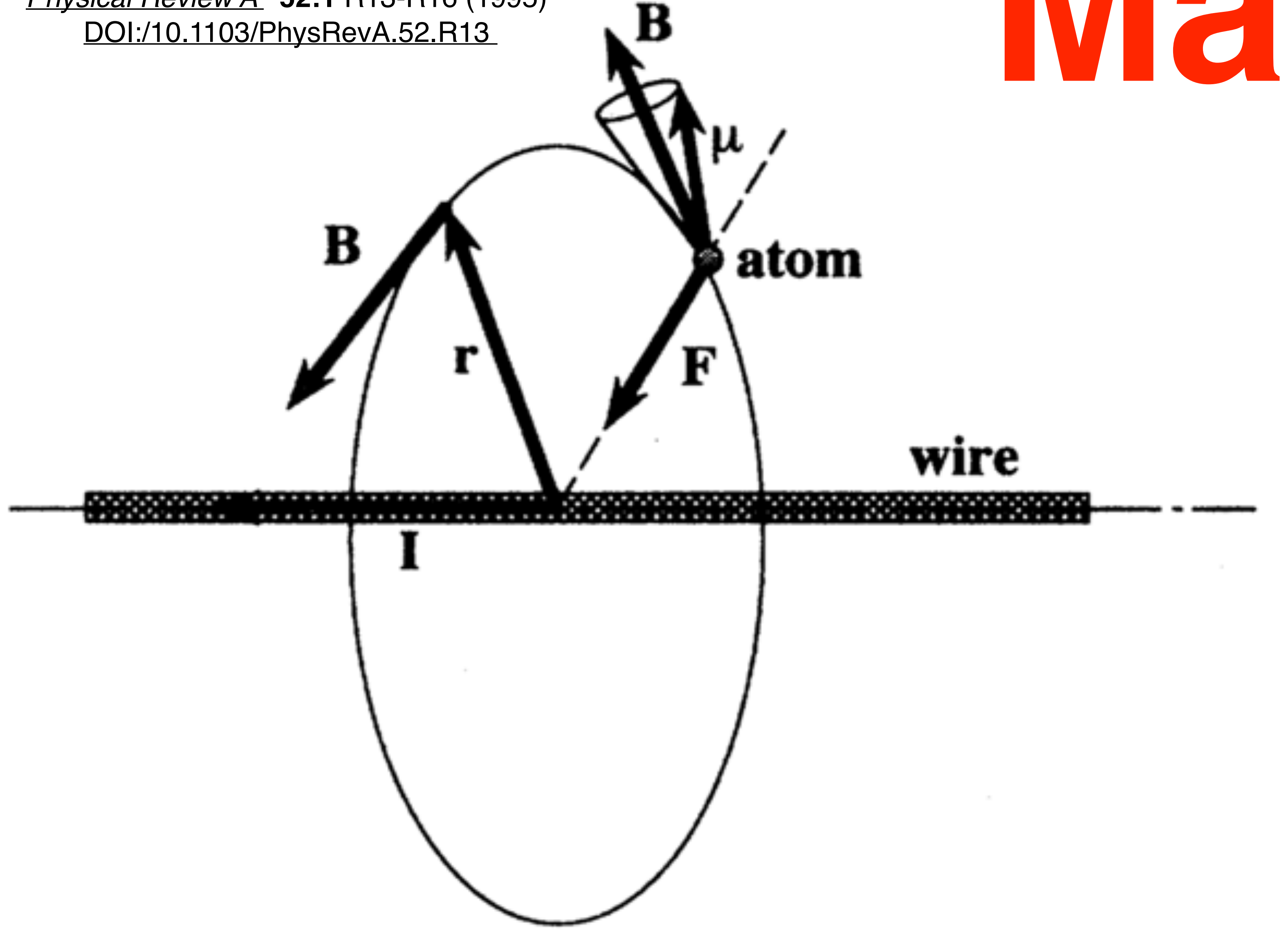
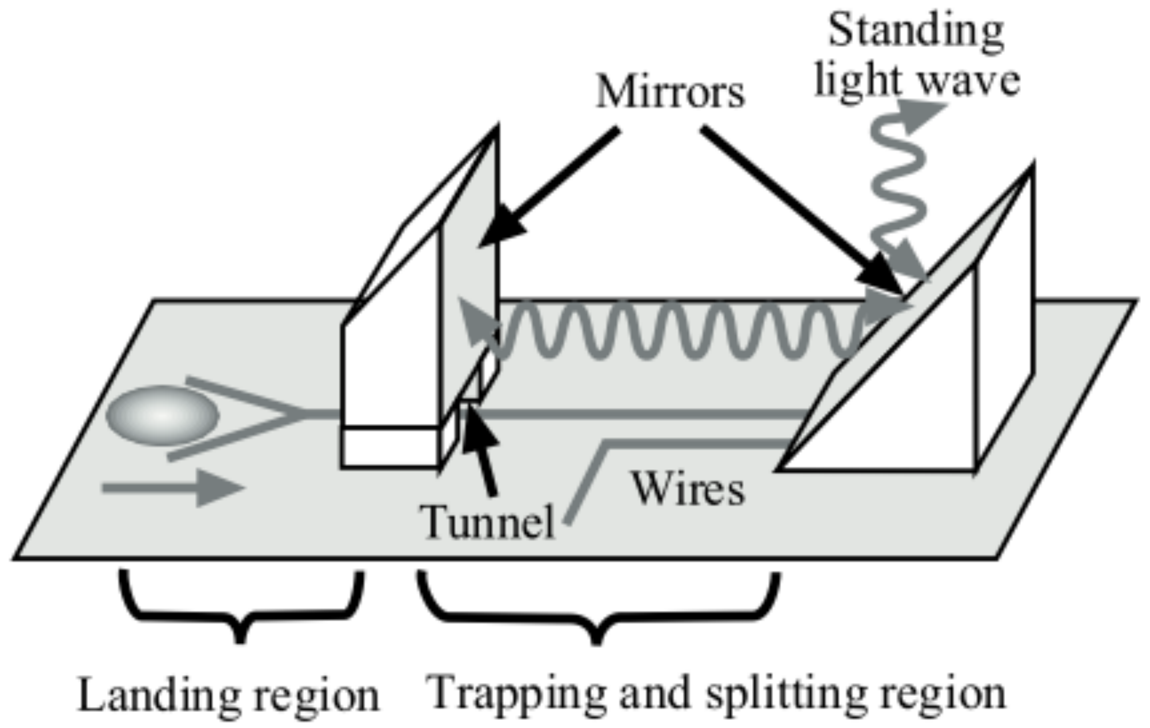


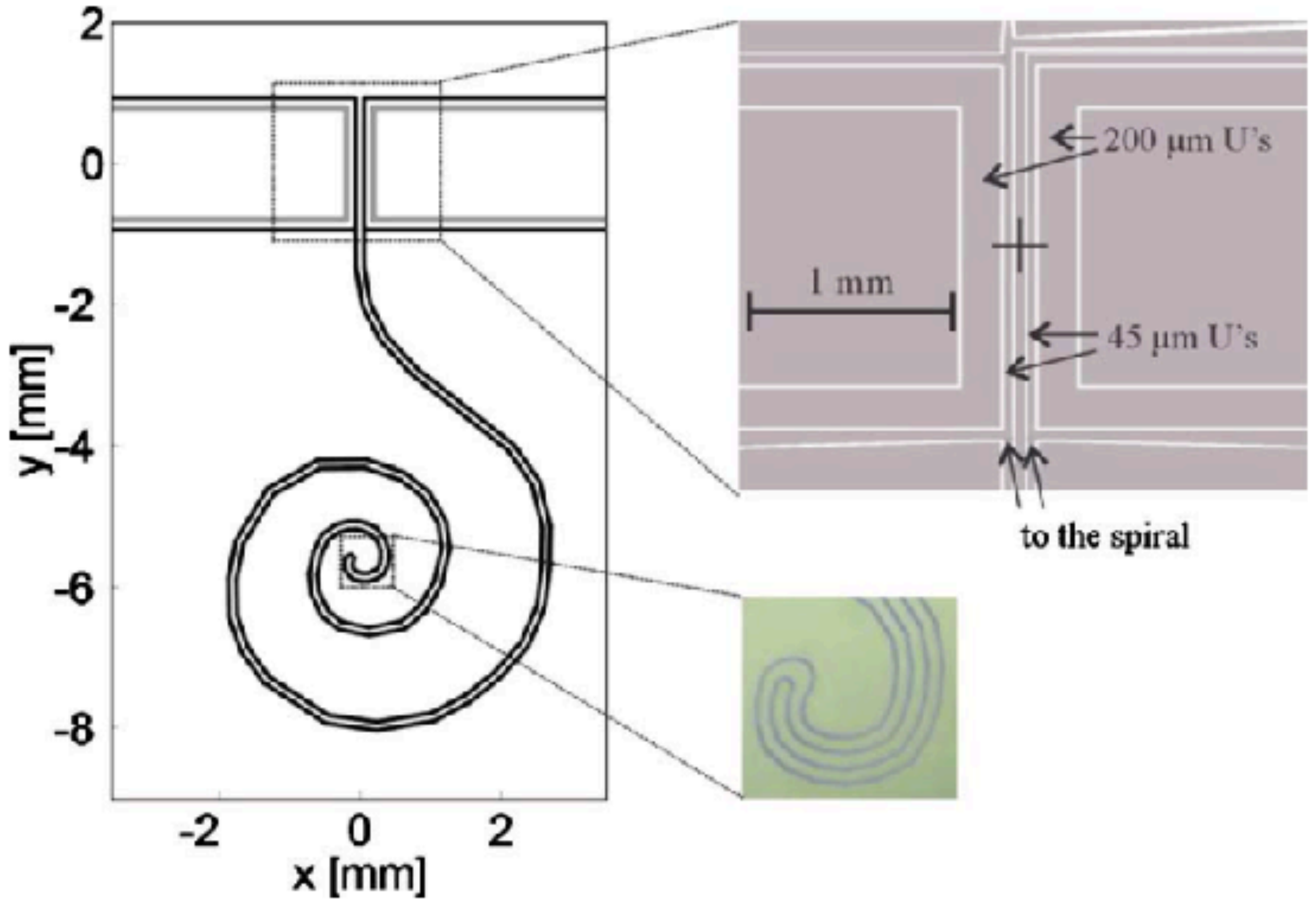
Magnetic Potentials

$$V = -\mu \cdot \mathbf{B} = m_F g_F \mu_B \left| \mathbf{B} \right|$$

Chip-based Interferometer

120μm separation of wave packages





K. Brugger et al.
Two-wire guides and traps with vertical bias fields on atom chips
Physical Review A **72:2** (2005)
DOI:/10.1103/physreva.72.023607

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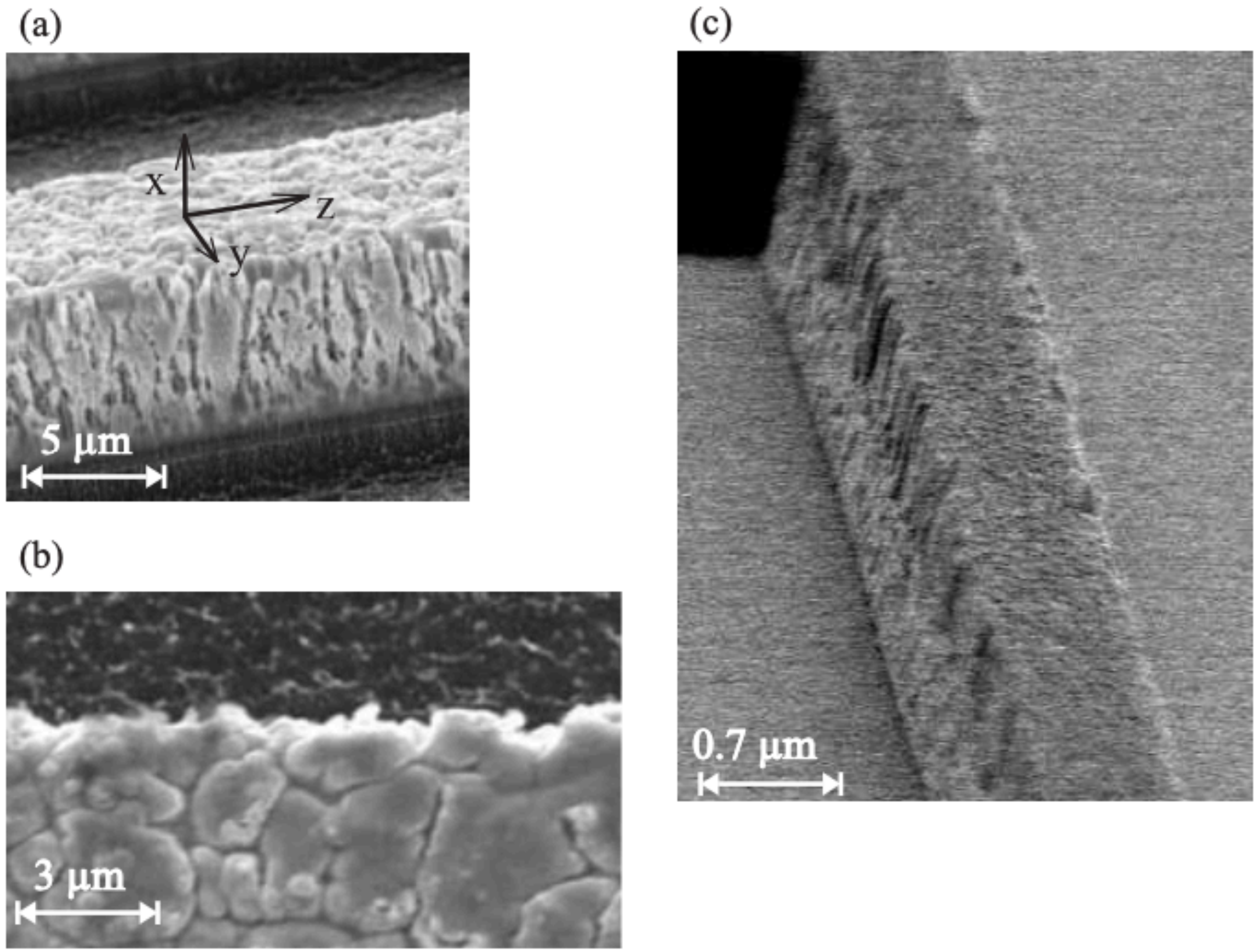
Magnetic Waveguides

Corrugations



T. Schumm et al.
Atom chips in the real world: the effects of wire corrugation
The European Physical Journal D **32:2** 171--180 (2005)

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However, the modulation of the B-Field drops exponentially with the distance:

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Journal of Physics B **37:2** L15 (2004)
DOI:/10.1088/0953-4075/37/2/L01

10 min Break

Magnetic Traps

Atom Chips

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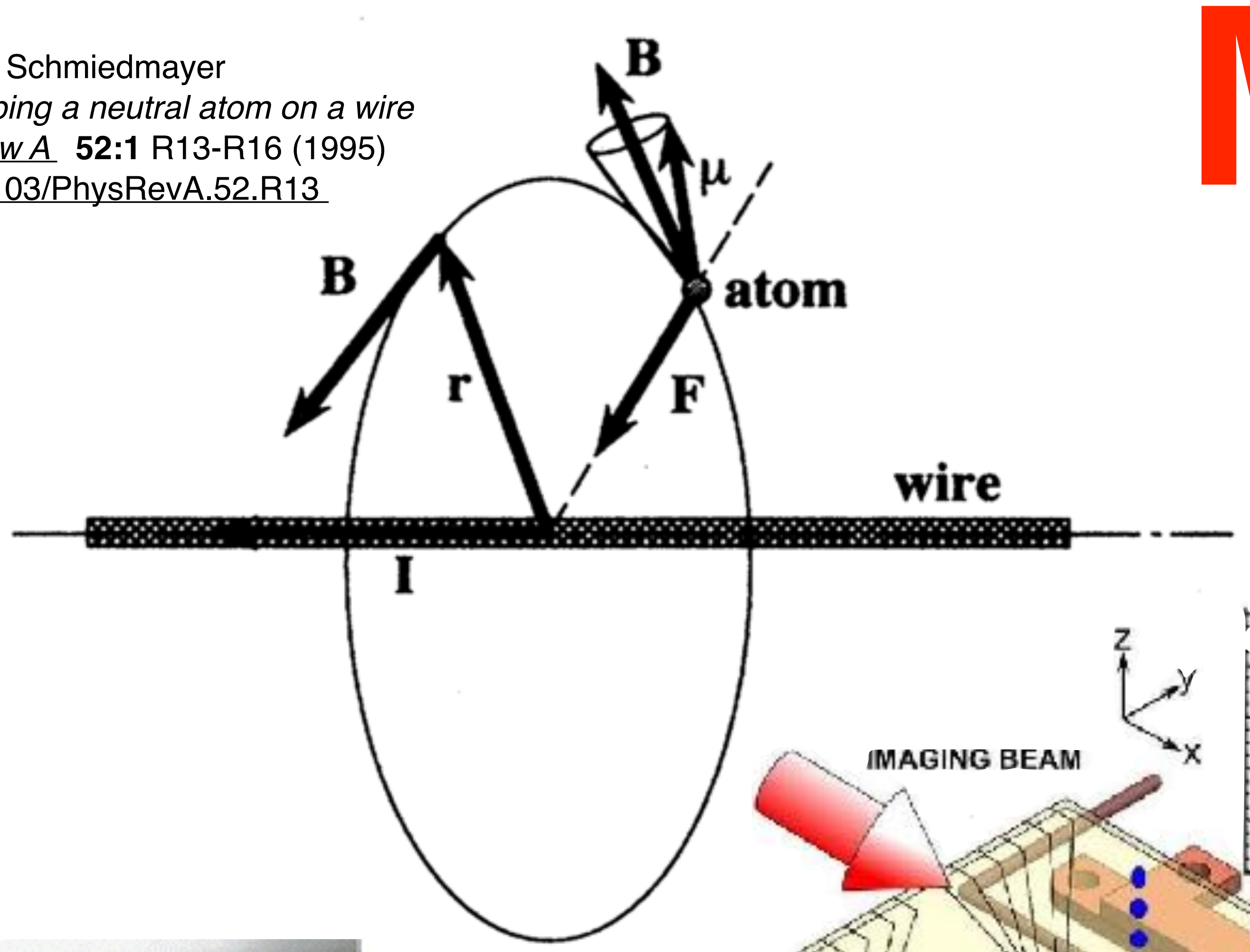
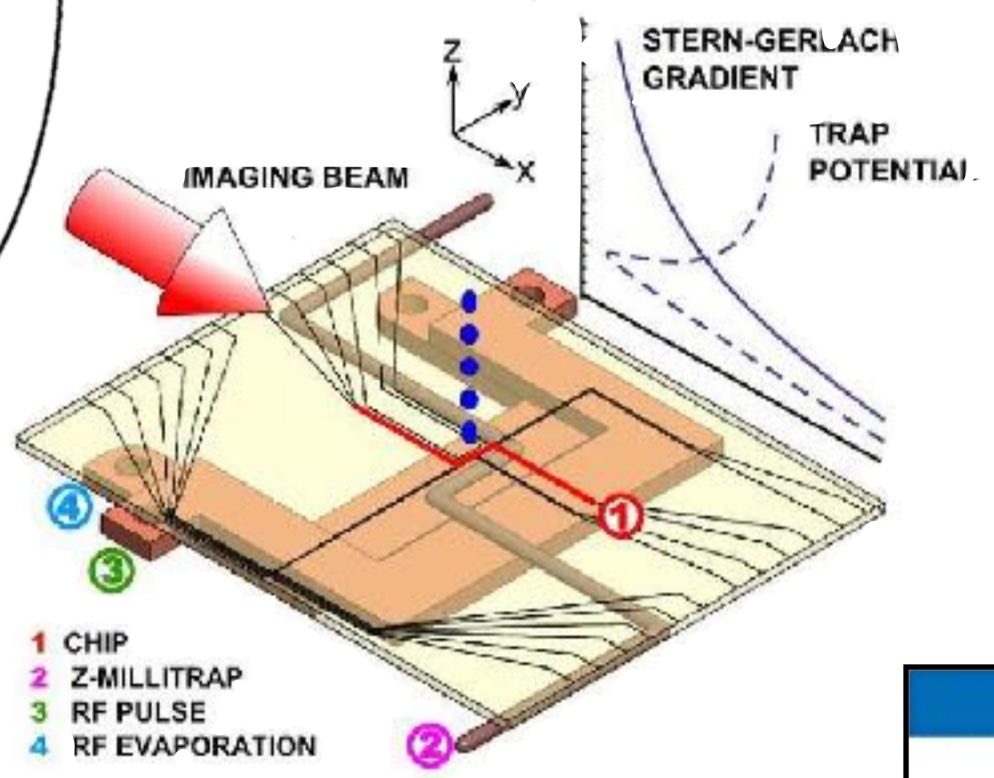
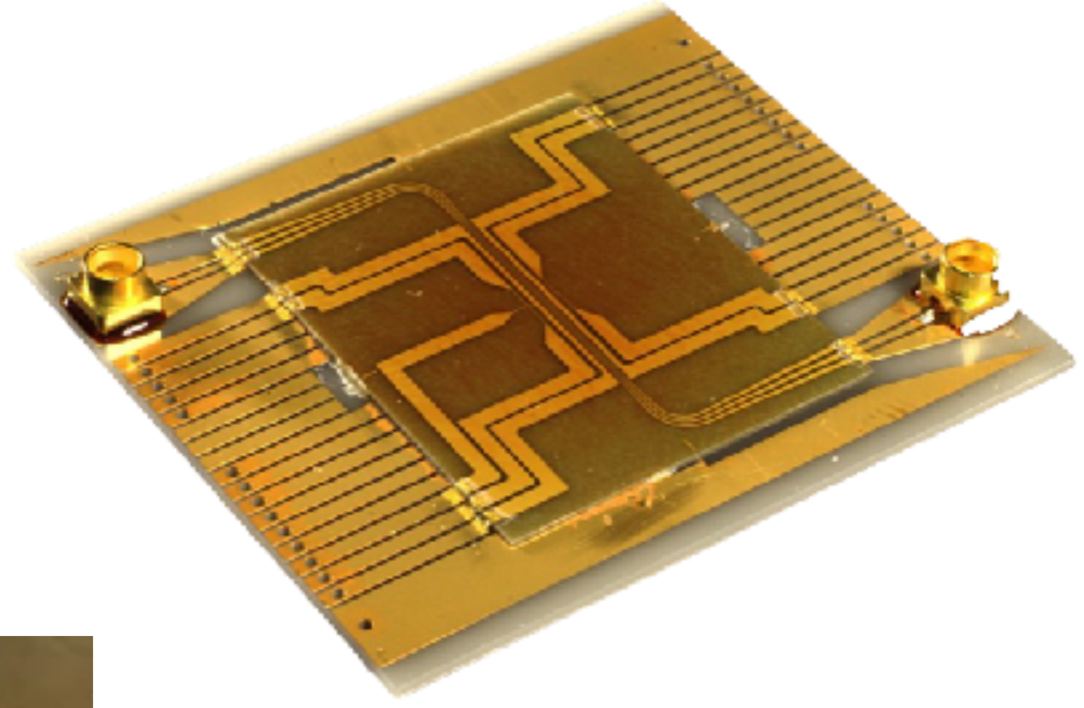
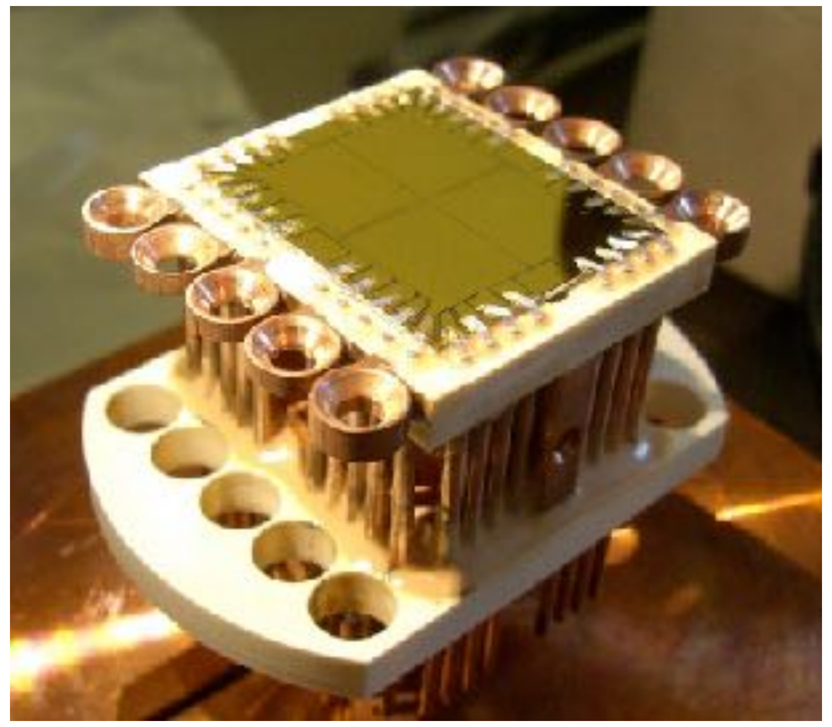
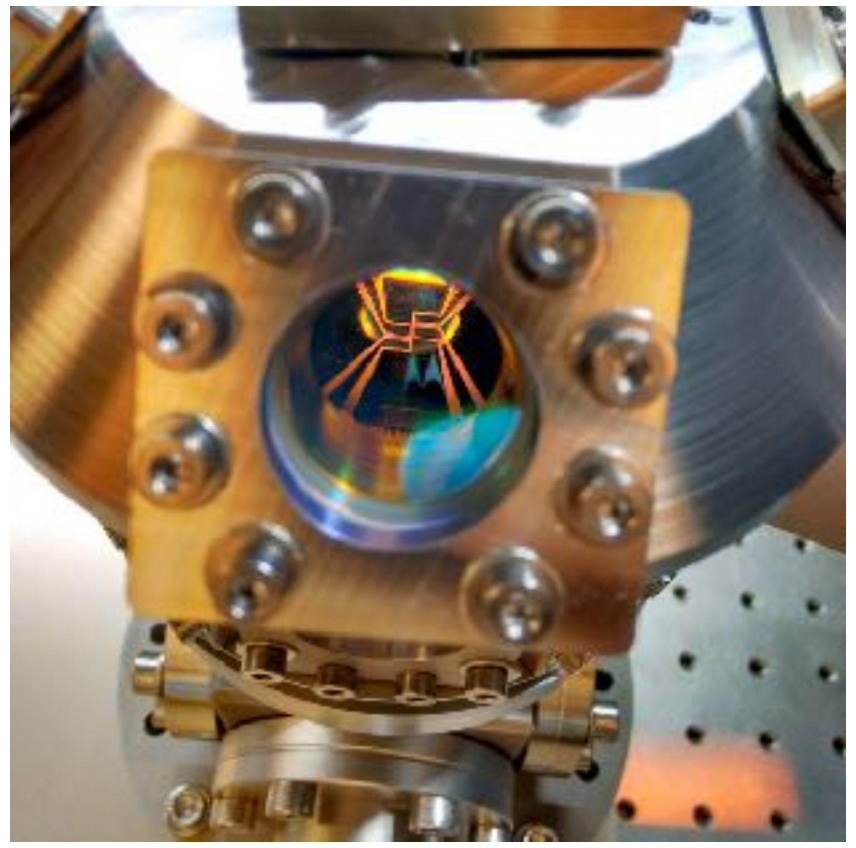


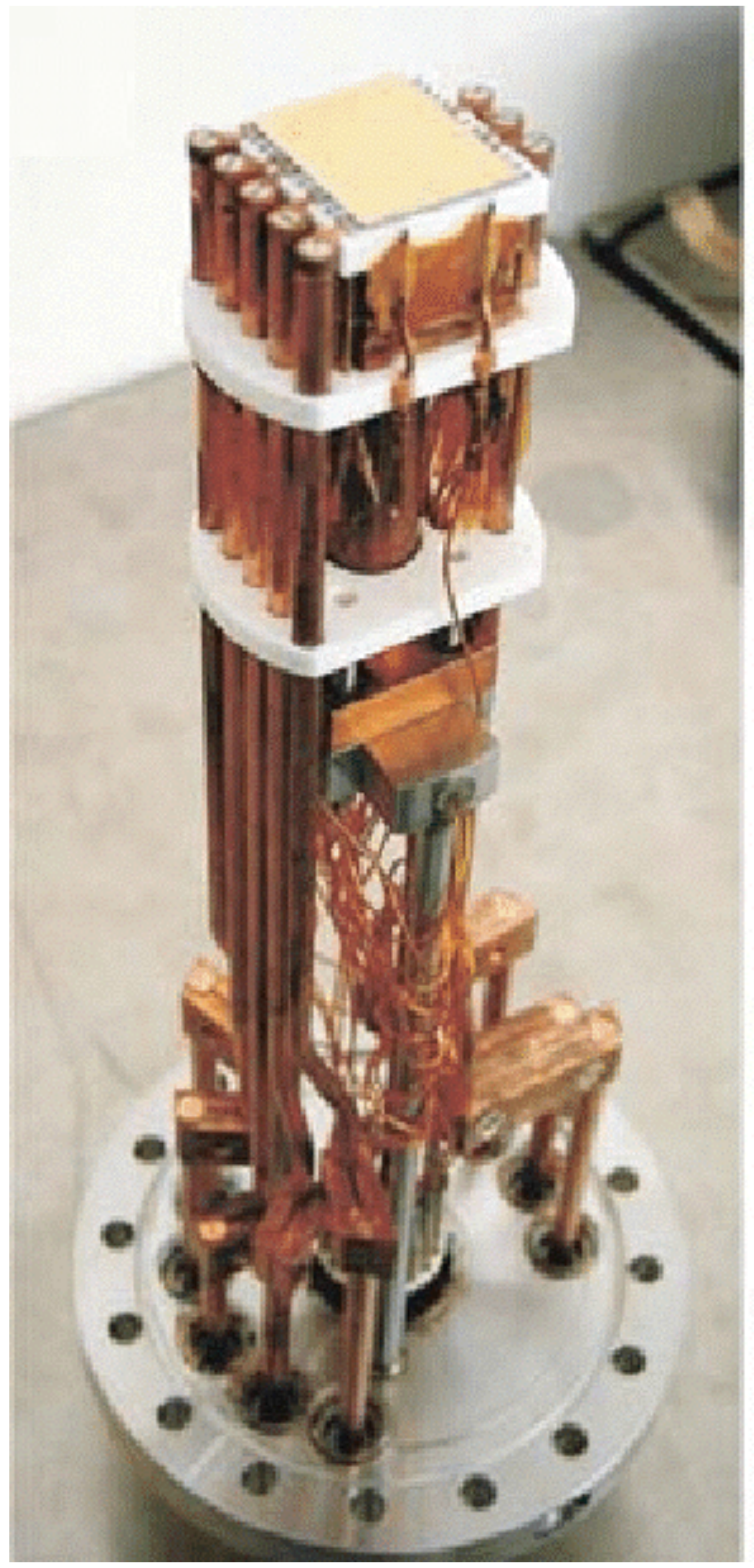


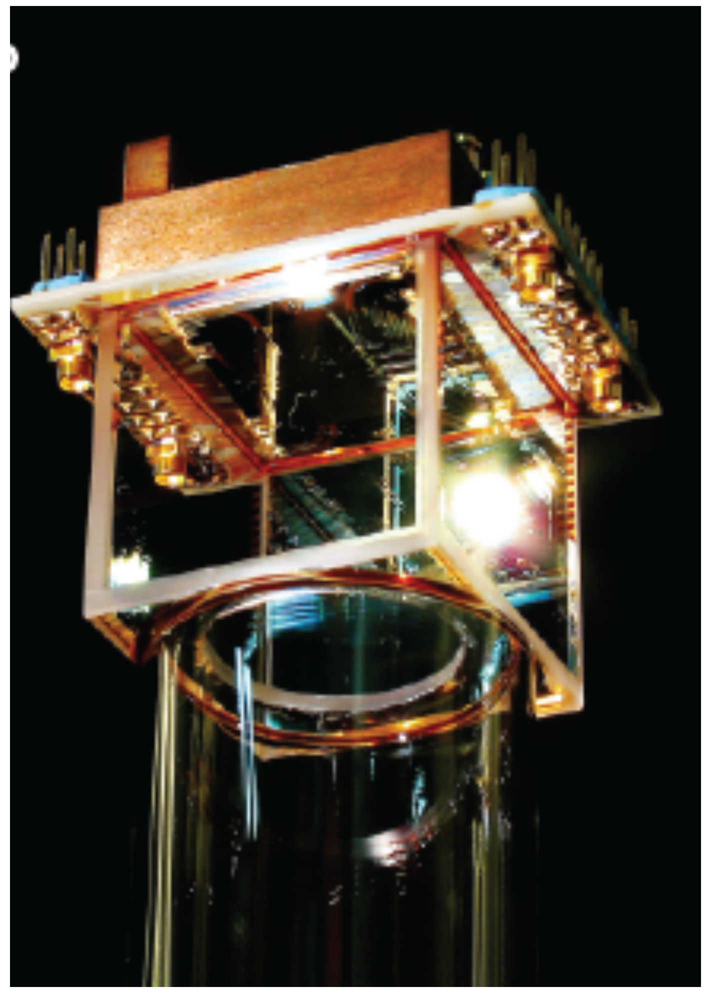
arXiv:1111.4321 [physics.atom-ph]

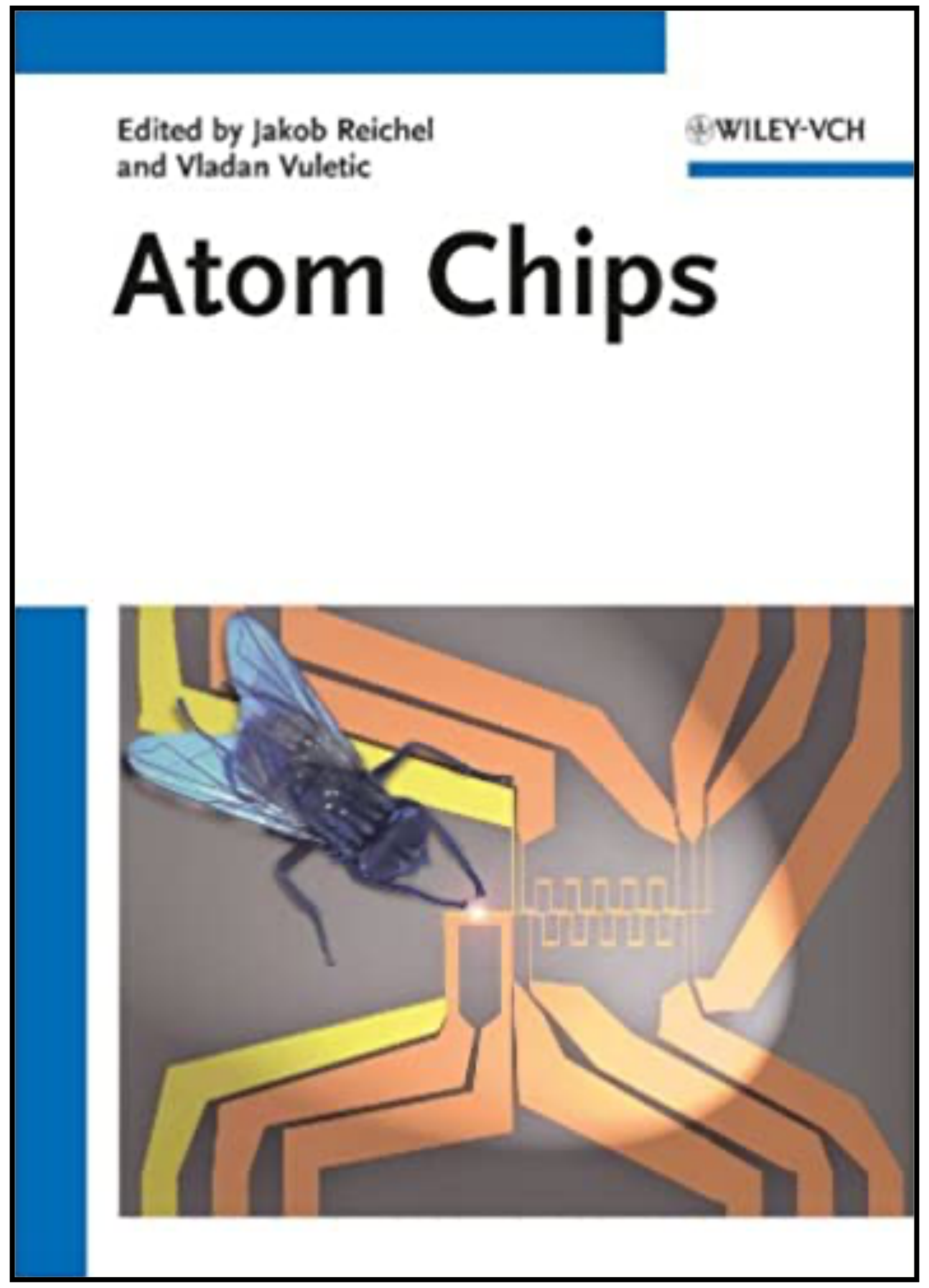


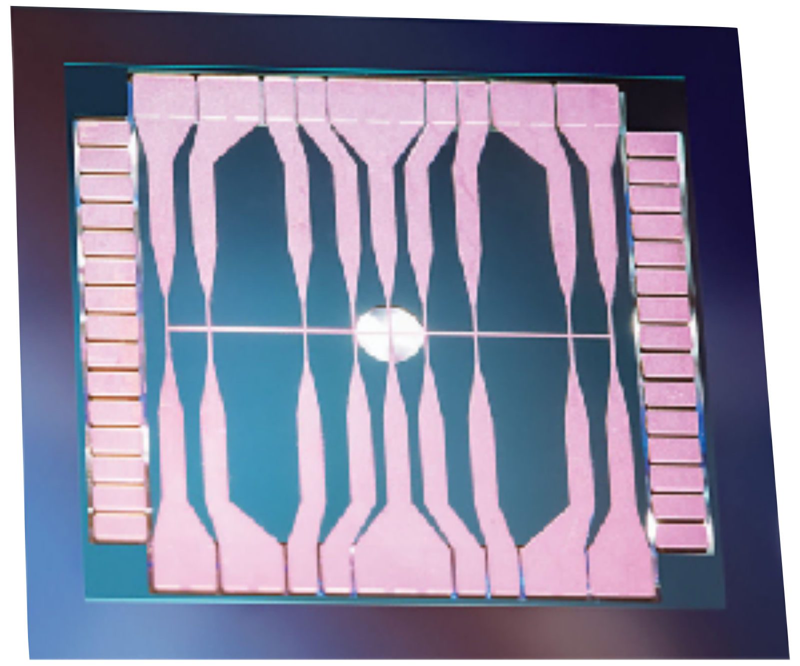












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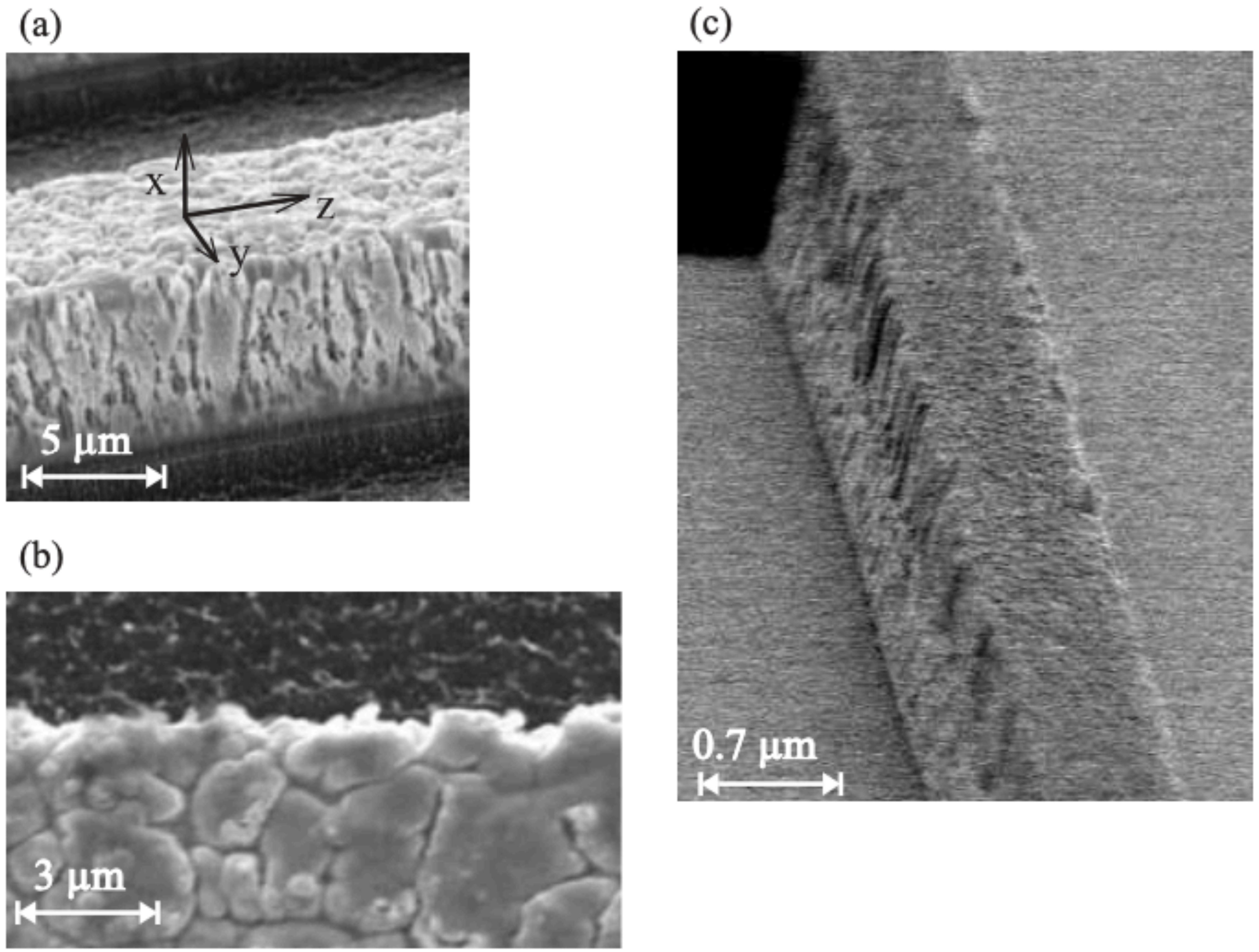
Magnetic Waveguides

Corrugations



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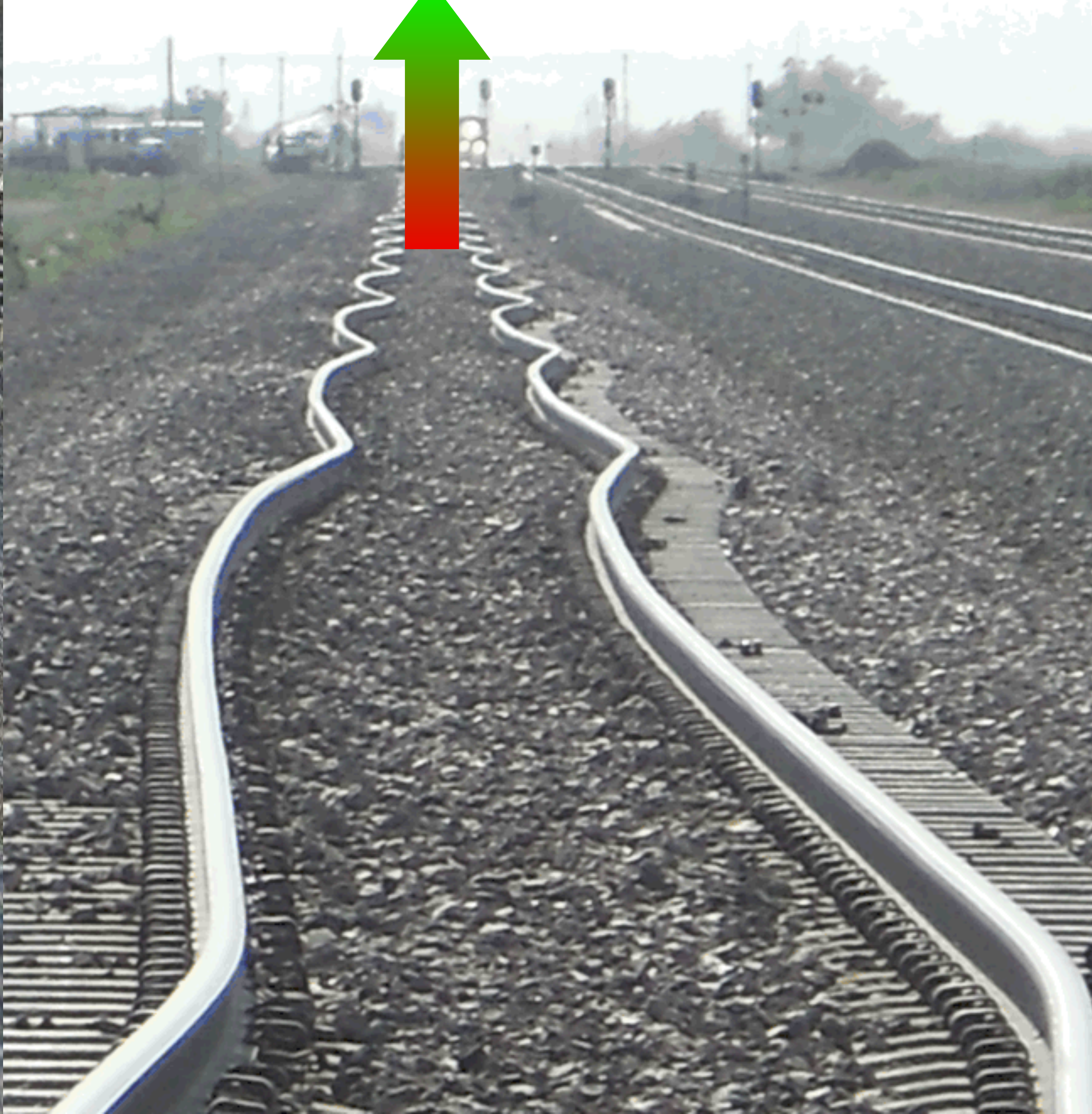
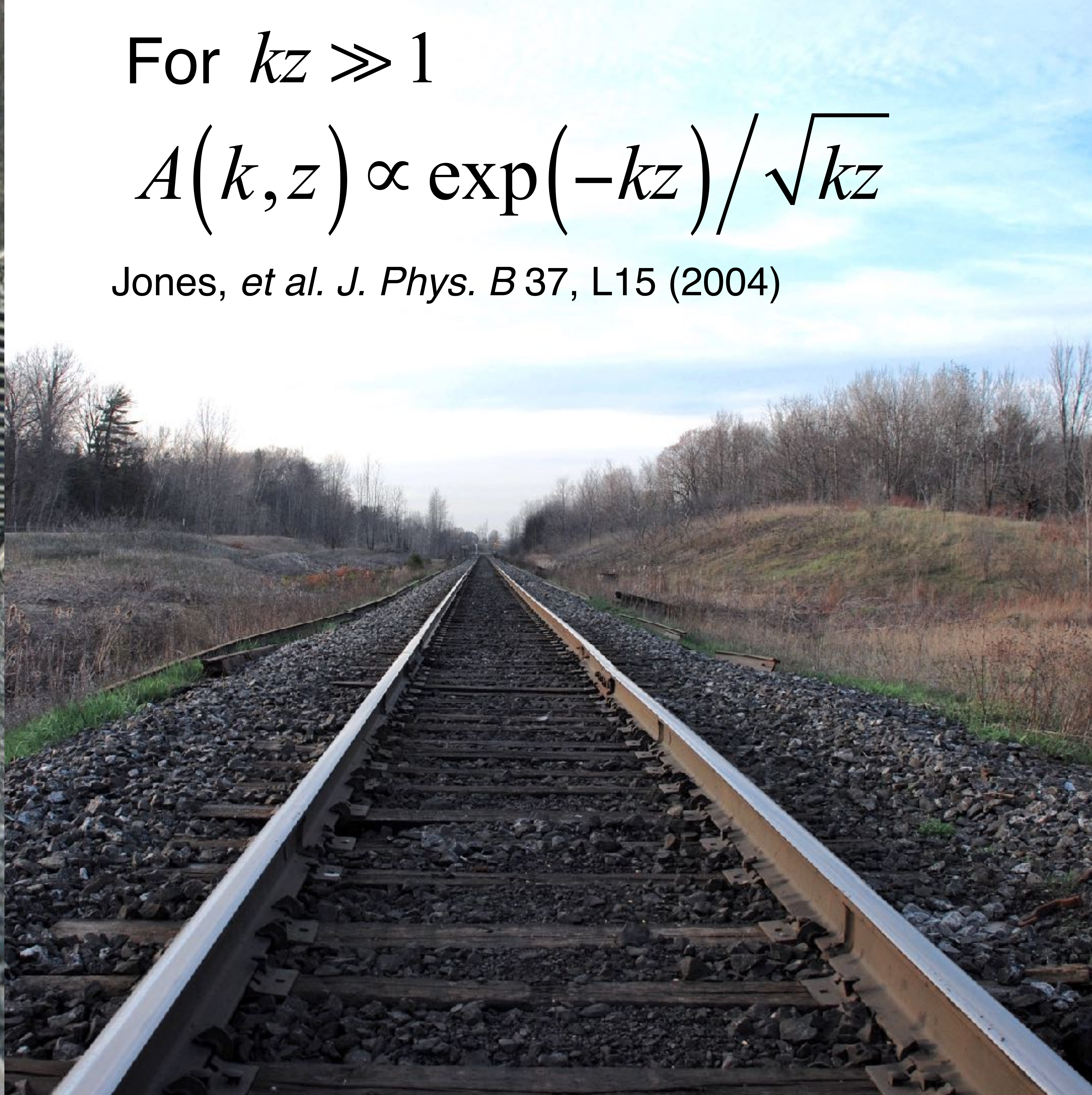
MERIDIAN
ET 315

$$A\left(k,z\right)\propto\exp\left(-kz\right)/\sqrt{kz}$$





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Jones, *et al. J. Phys. B* 37, L15 (2004)

For $kz \gg 1$

$$A(k,z) \propto \exp(-kz)/\sqrt{kz}$$

Jones, *et al. J. Phys. B* 37, L15 (2004)

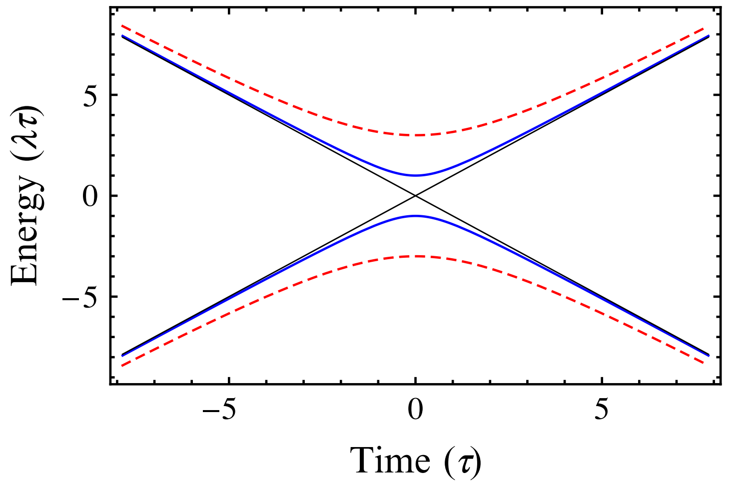
$$\text{For } kz = \frac{2\pi}{0.5\,\text{mm}} \times 50\,\text{mm} \simeq 630$$

$$A(k,z) \propto \exp(-kz)/\sqrt{kz} \approx 10^{-275}$$

Atomtronic Time Scales

Trapping & Detection

10^{14}

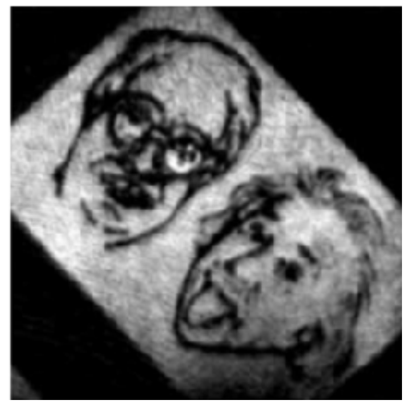


Adiabatic (RF-Dressing)

10^{6}

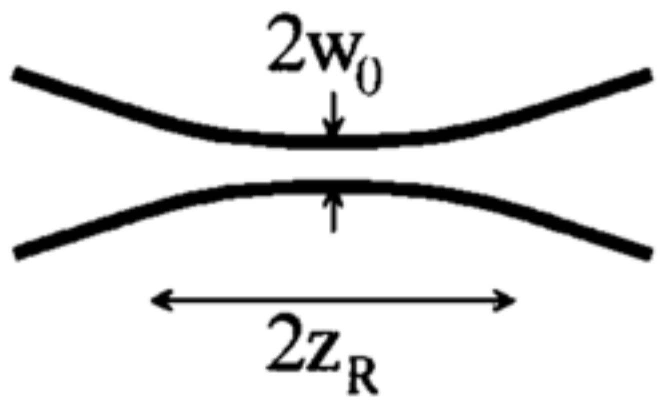
Hyperfine Transitions

10^{10}



Time Averaging

10^{3}



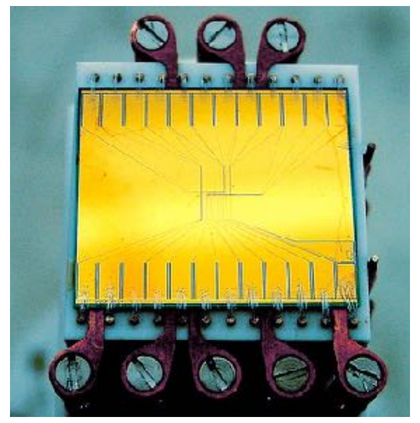
Quasi DC Manipulation

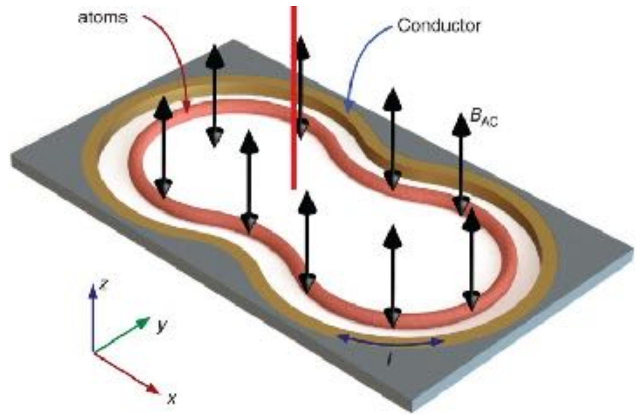
10^{0}

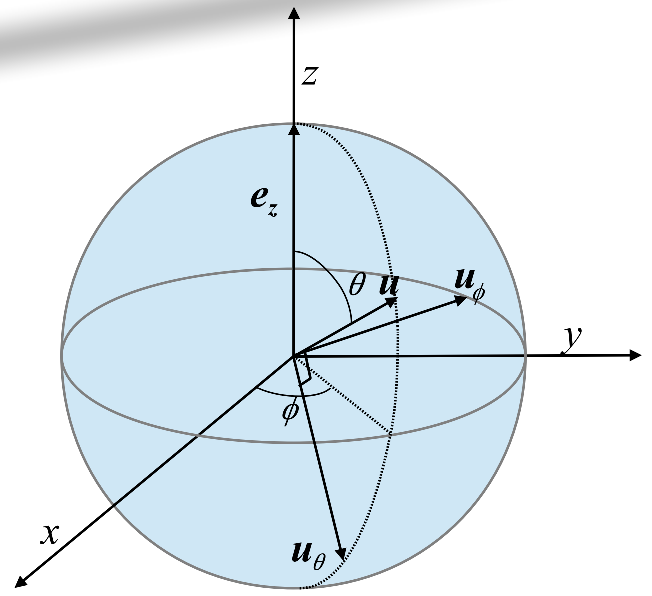
Experiment Repetition

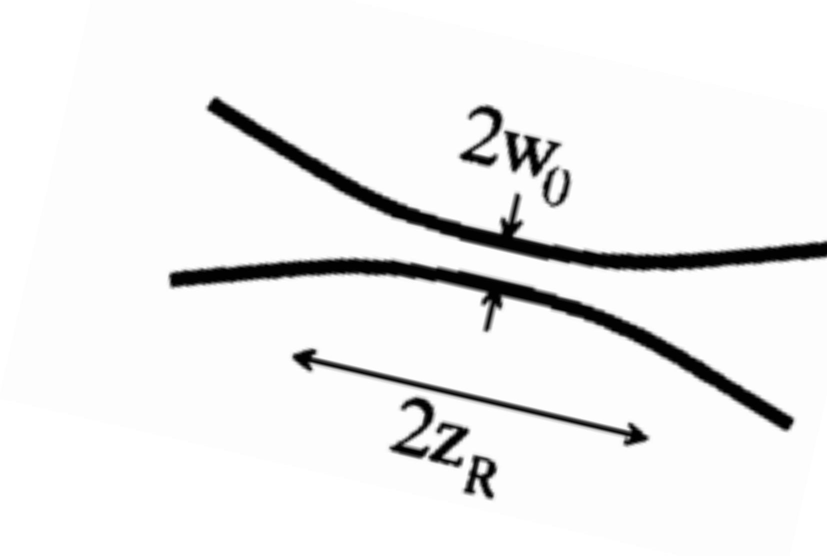
10^{-1}

Frequency [Hz]

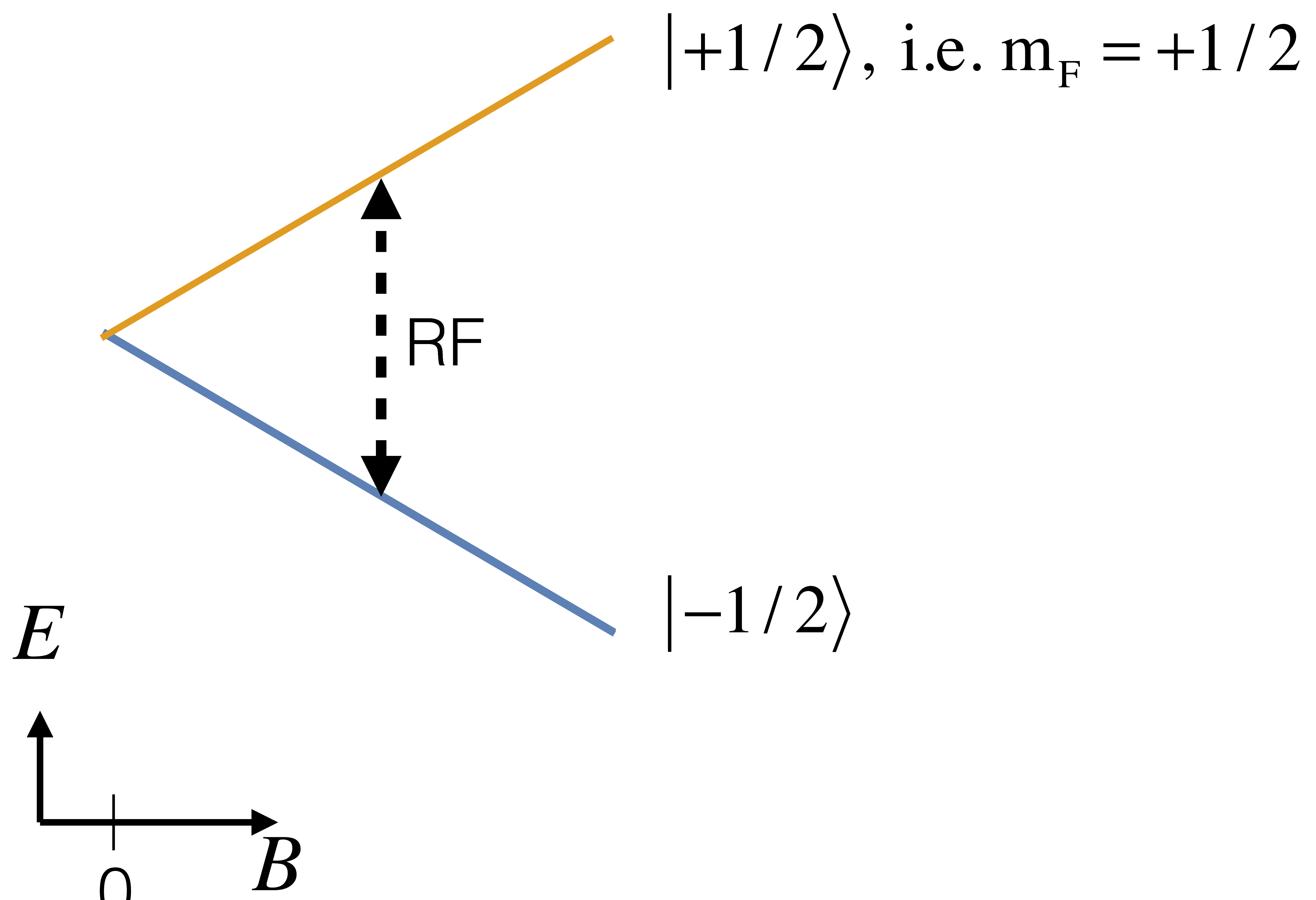




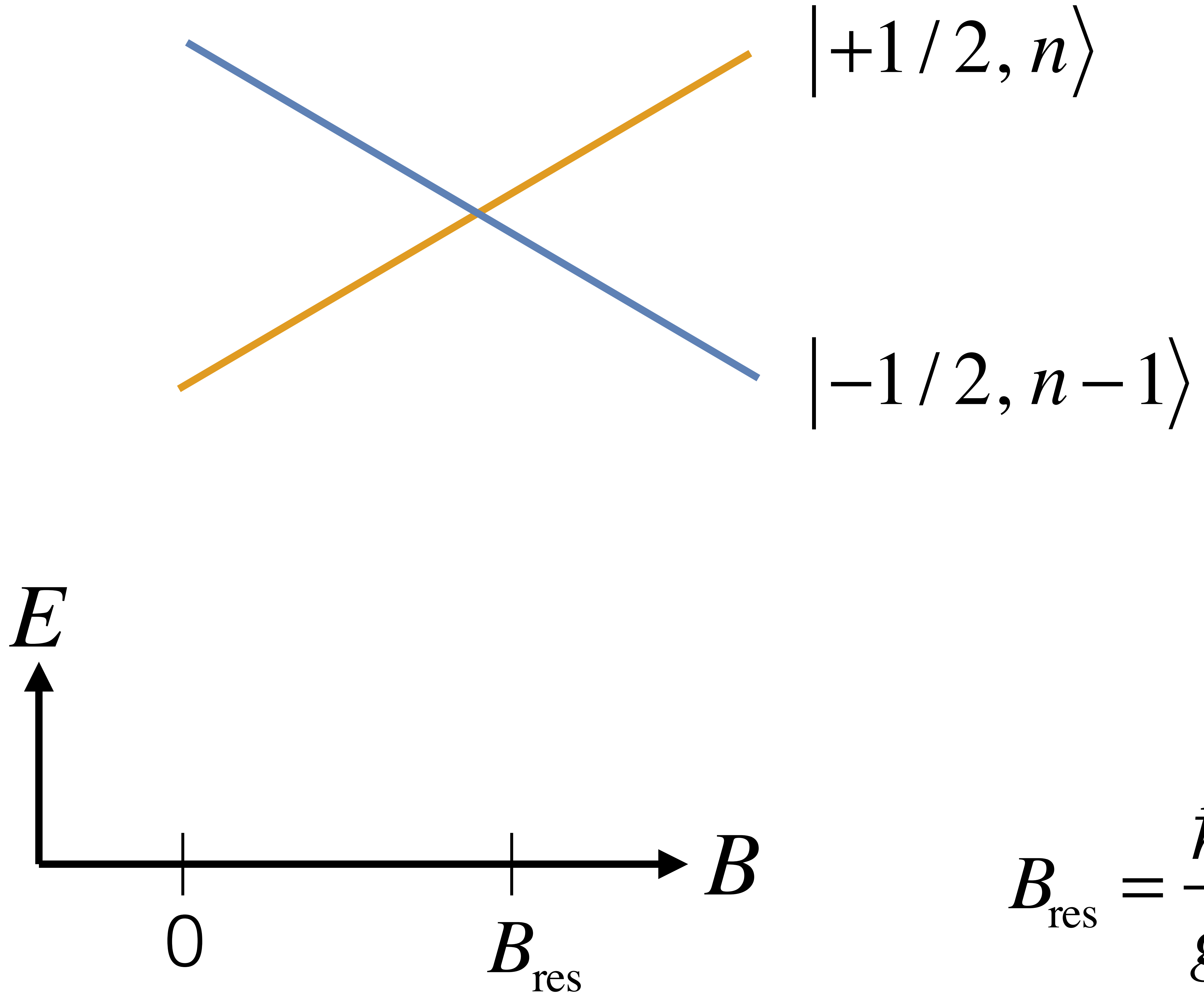




Dressed Potentials

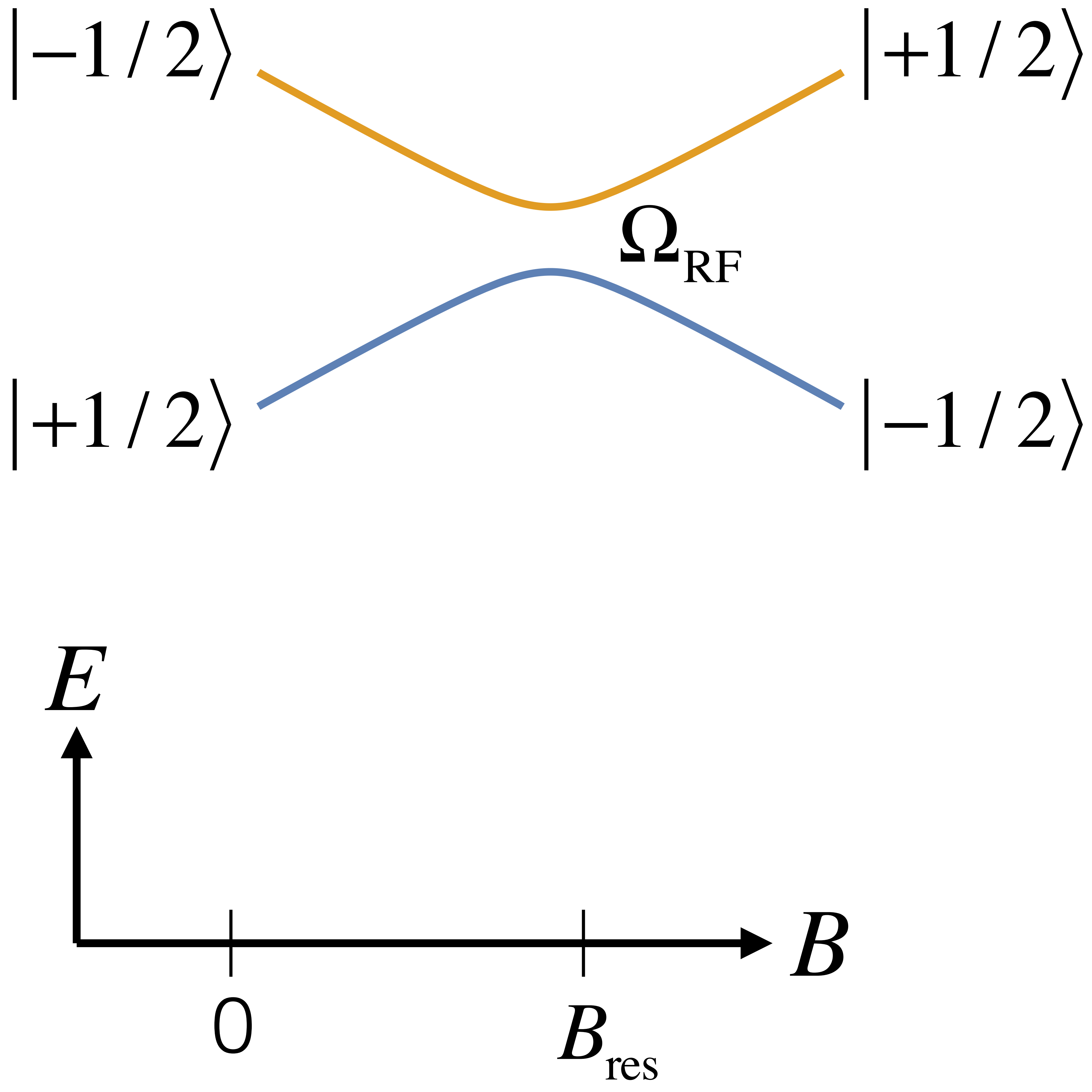


Dressed Potentials



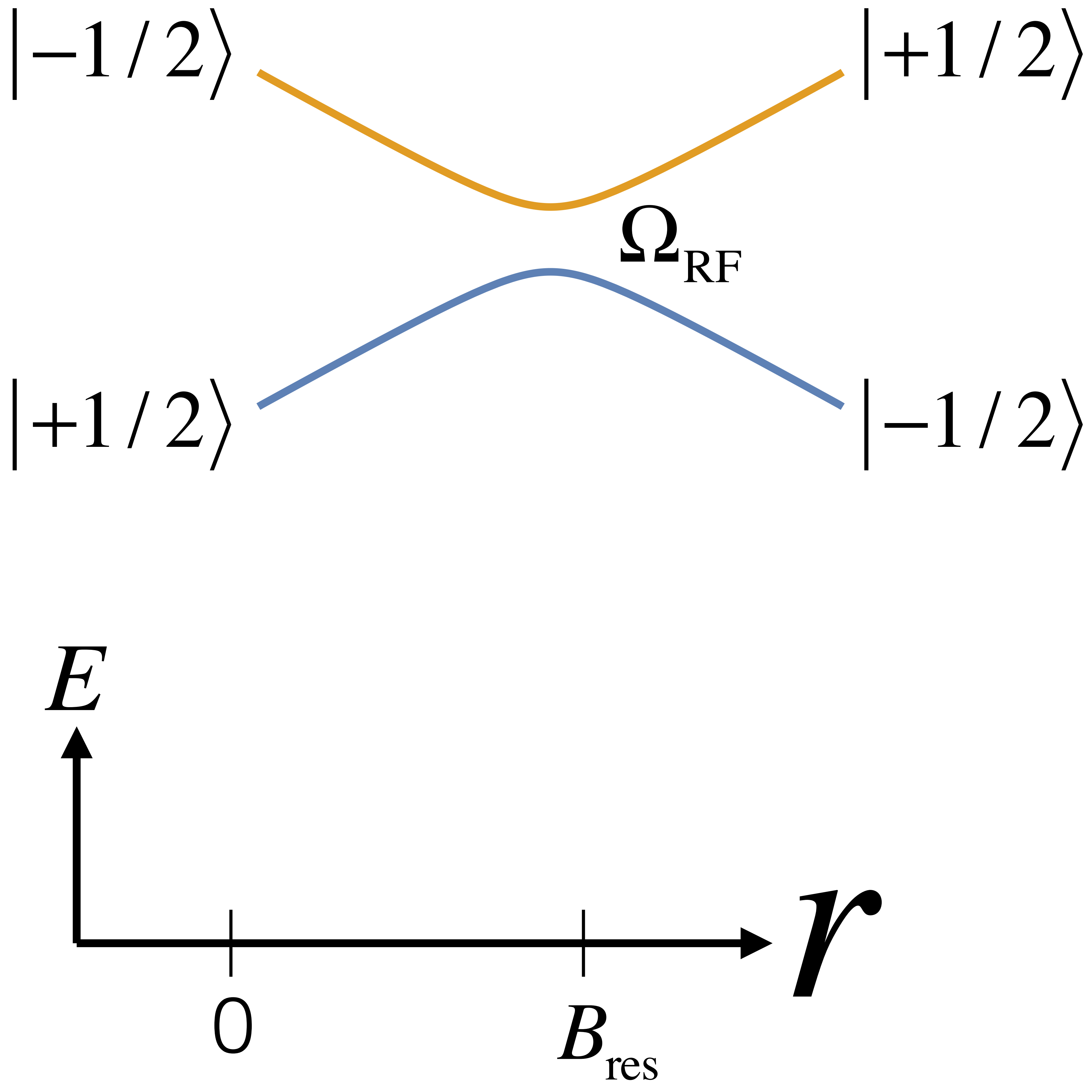
$$B_{\text{res}} = \frac{\hbar\omega_{\text{rf}}}{g_{\text{f}}\,\mu_{\text{B}}}$$

Dressed Potentials



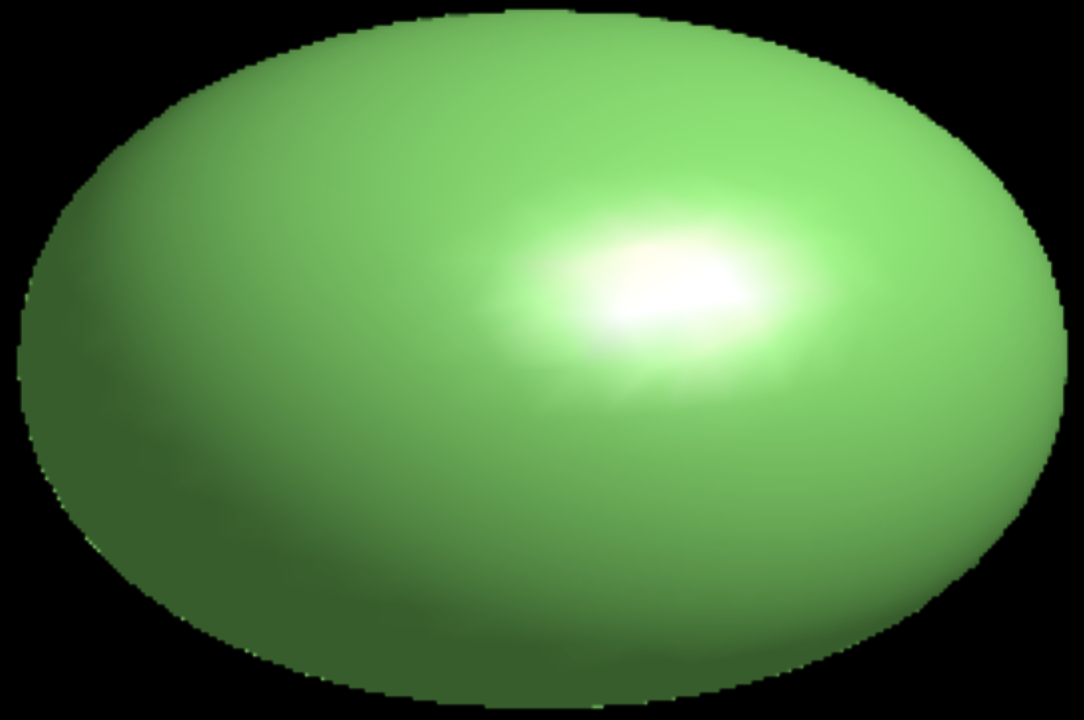
$$B_{\mathrm{res}} = \frac{\hbar \omega_{\mathrm{rf}}}{g_{\mathrm{f}} \mu_{\mathrm{B}}}$$

Dressed Potentials in a Quadrupole

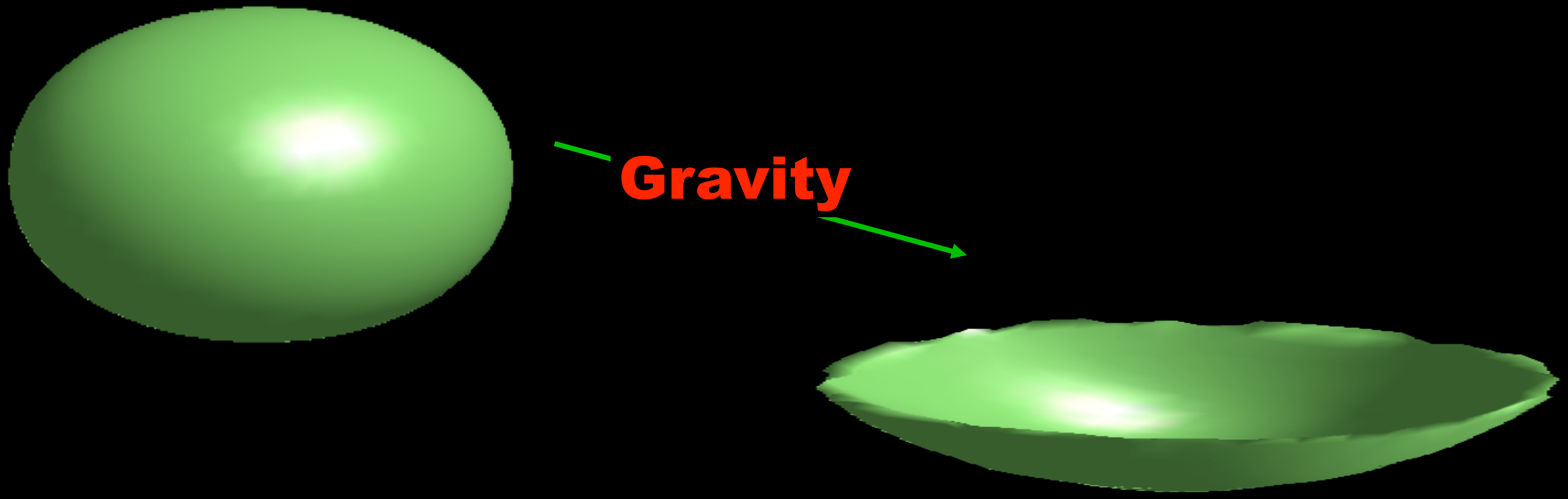


$$B_{res} = \frac{\hbar\omega_{rf}}{g_f \mu_B}$$

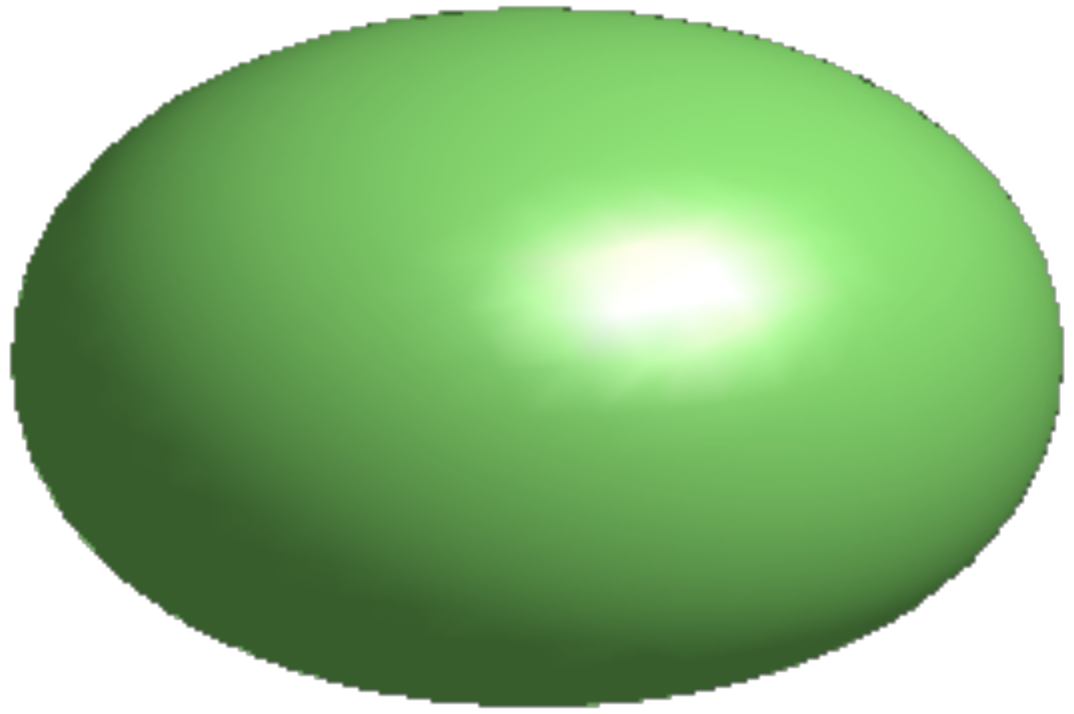
Adiabatic Potentials



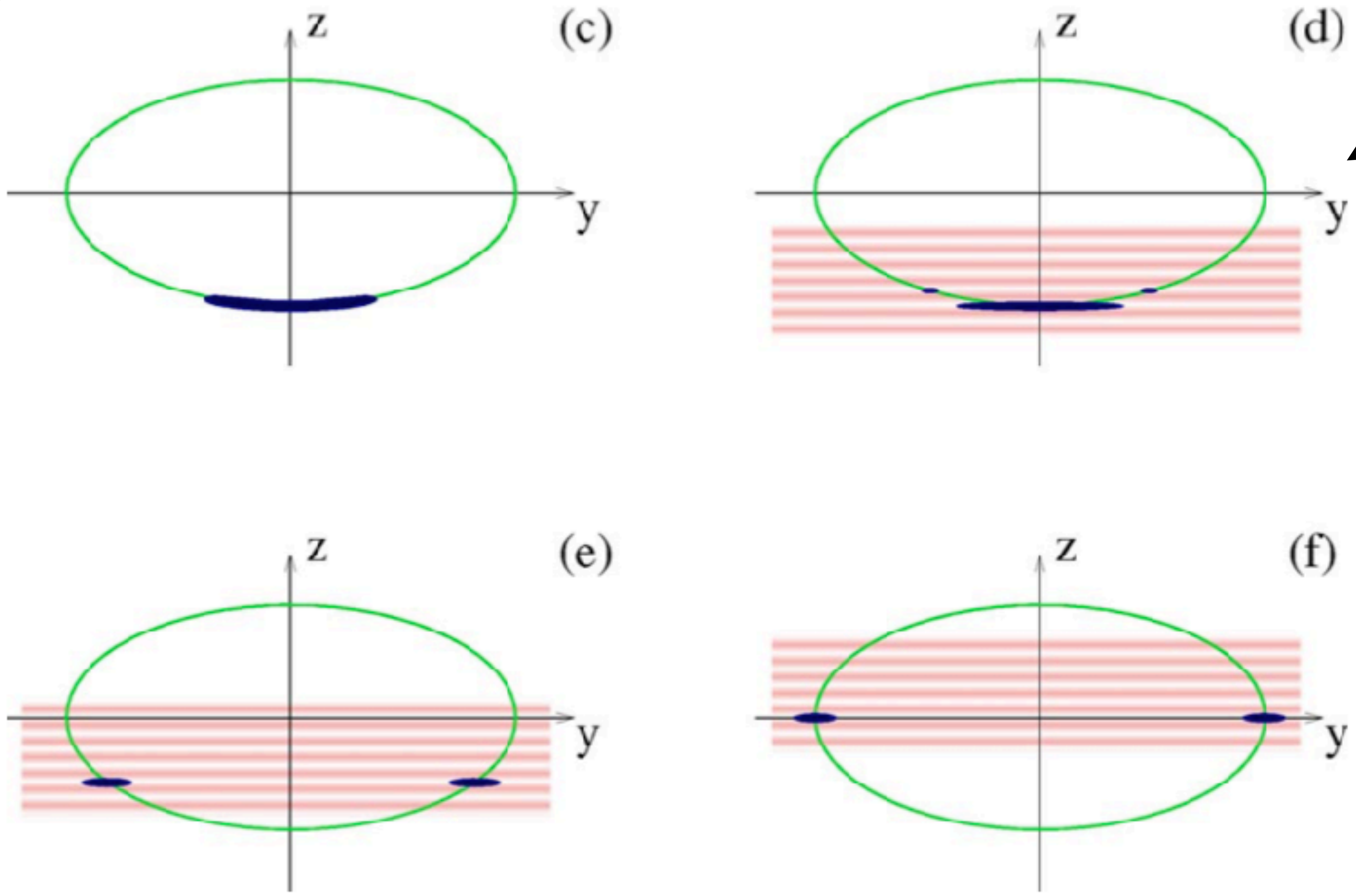
Adiabatic Potentials



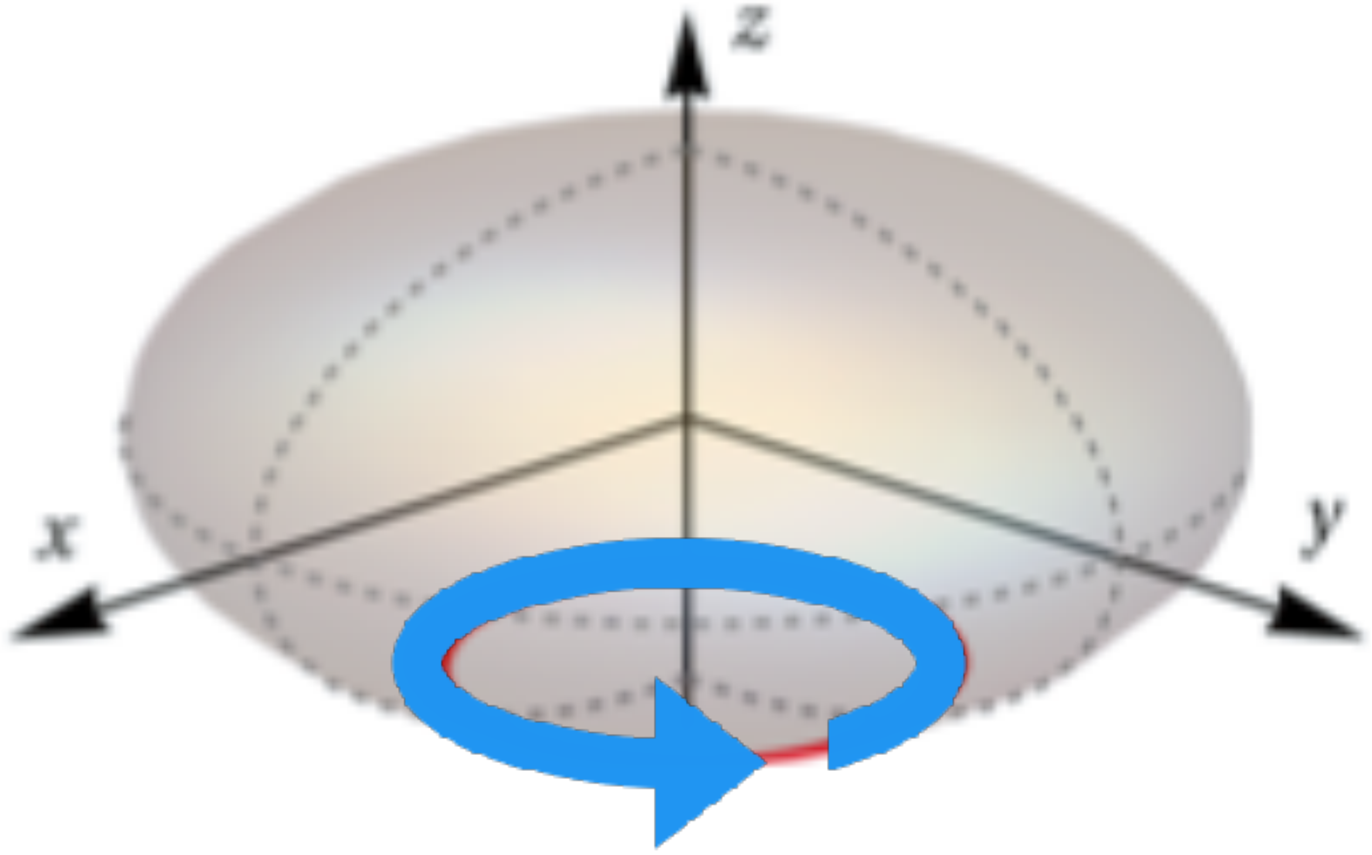
Adiabatic Potentials



Light sheets

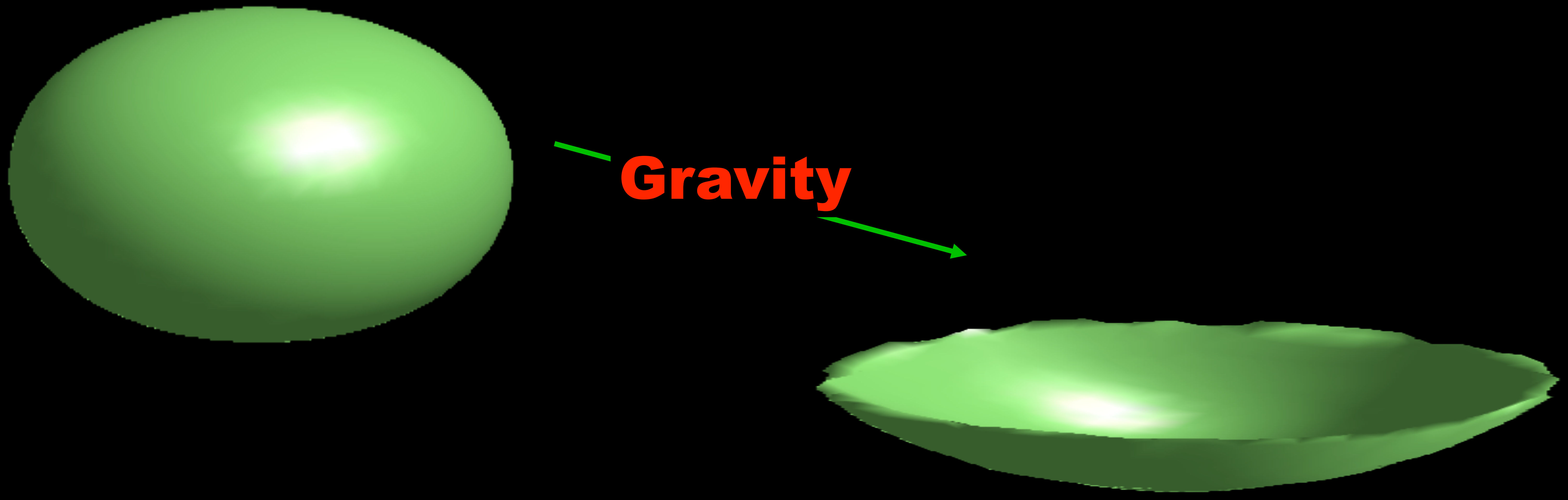


O. Morizot et al.
Ring trap for ultracold atoms
Physical Review A **74:2** 023617 (2006)



Yuanyuan Guo et al.
Supersonic Rotation of a Superfluid: A Long-Lived Dynamical Ring
Physical Review Letters **124:2** (2020)

Adiabatic Potentials

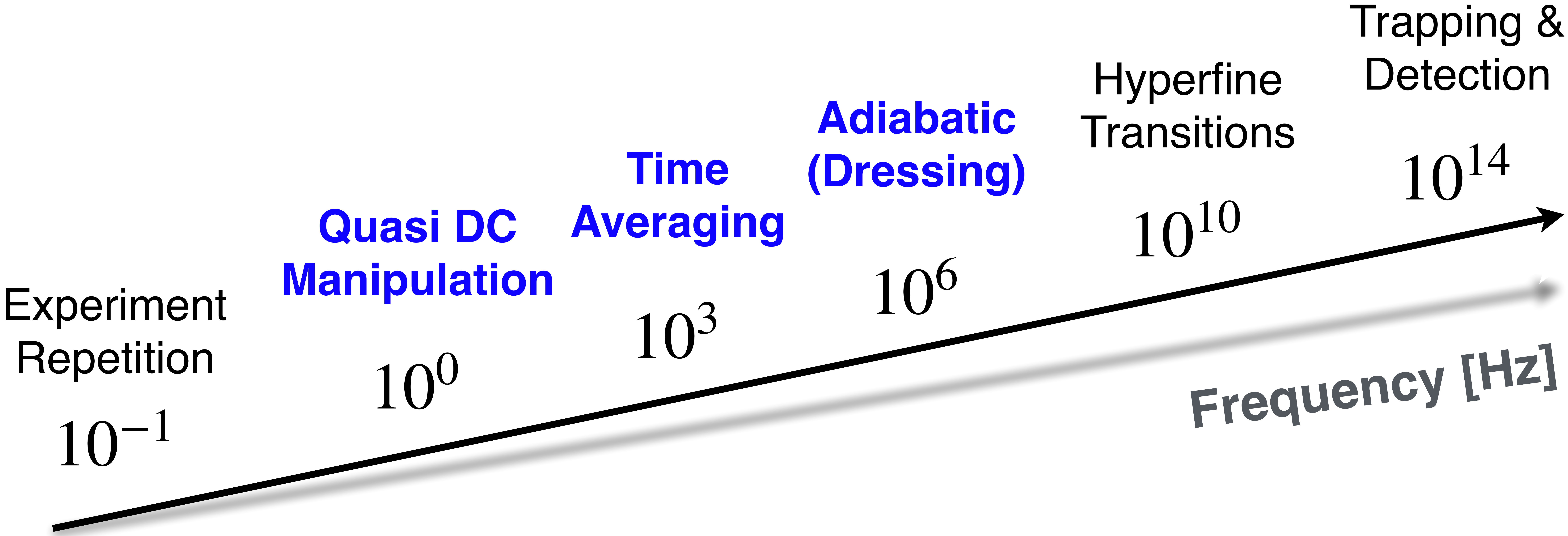


Time averaged Adiabatic Averaged Potentials (TAAP)

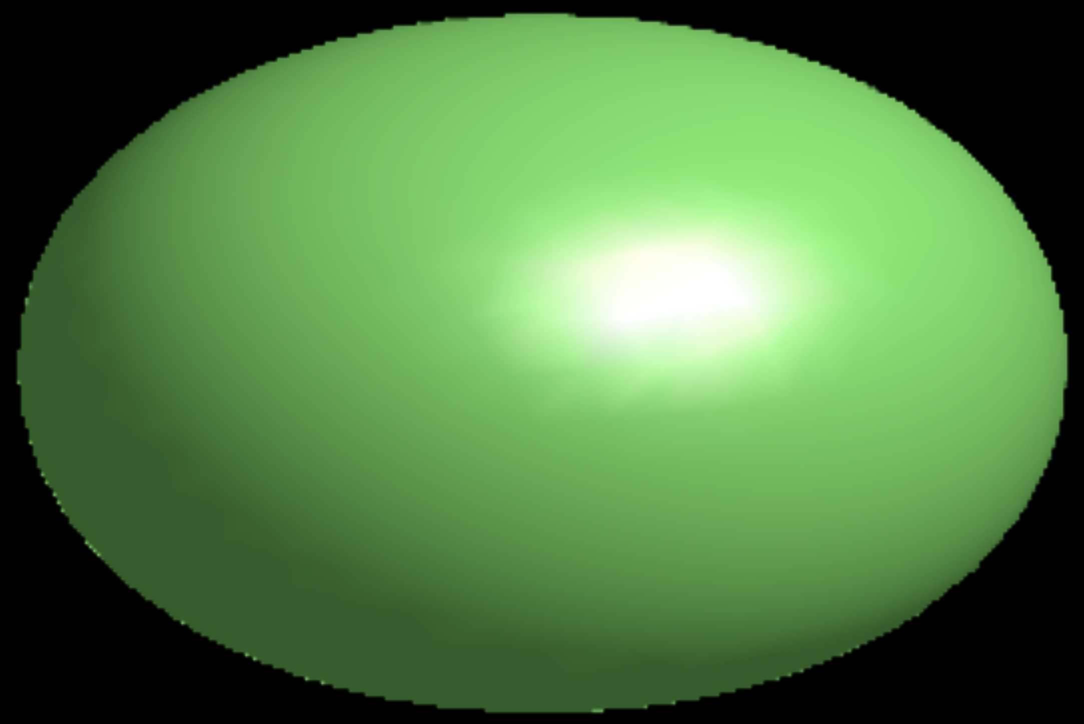
ω_{Trap} ω_{Larmor}

Quasi Static	Time-Averaging	Adiabatic Potentials
~ DC	Audio	RF

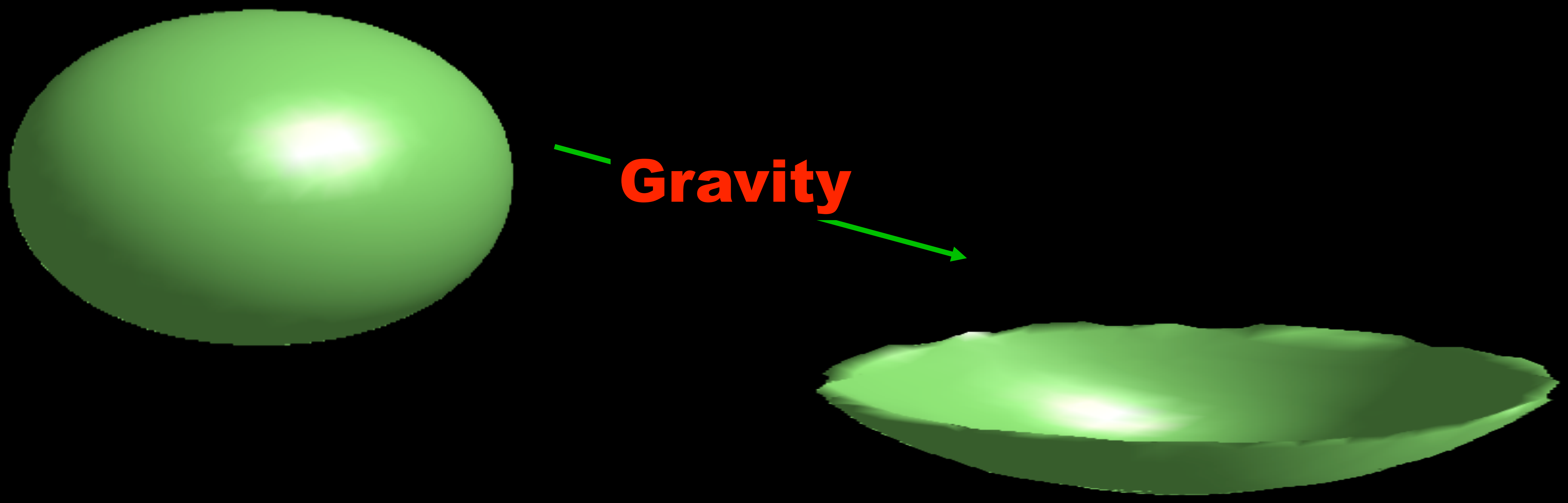
Atomtronic Time Scales



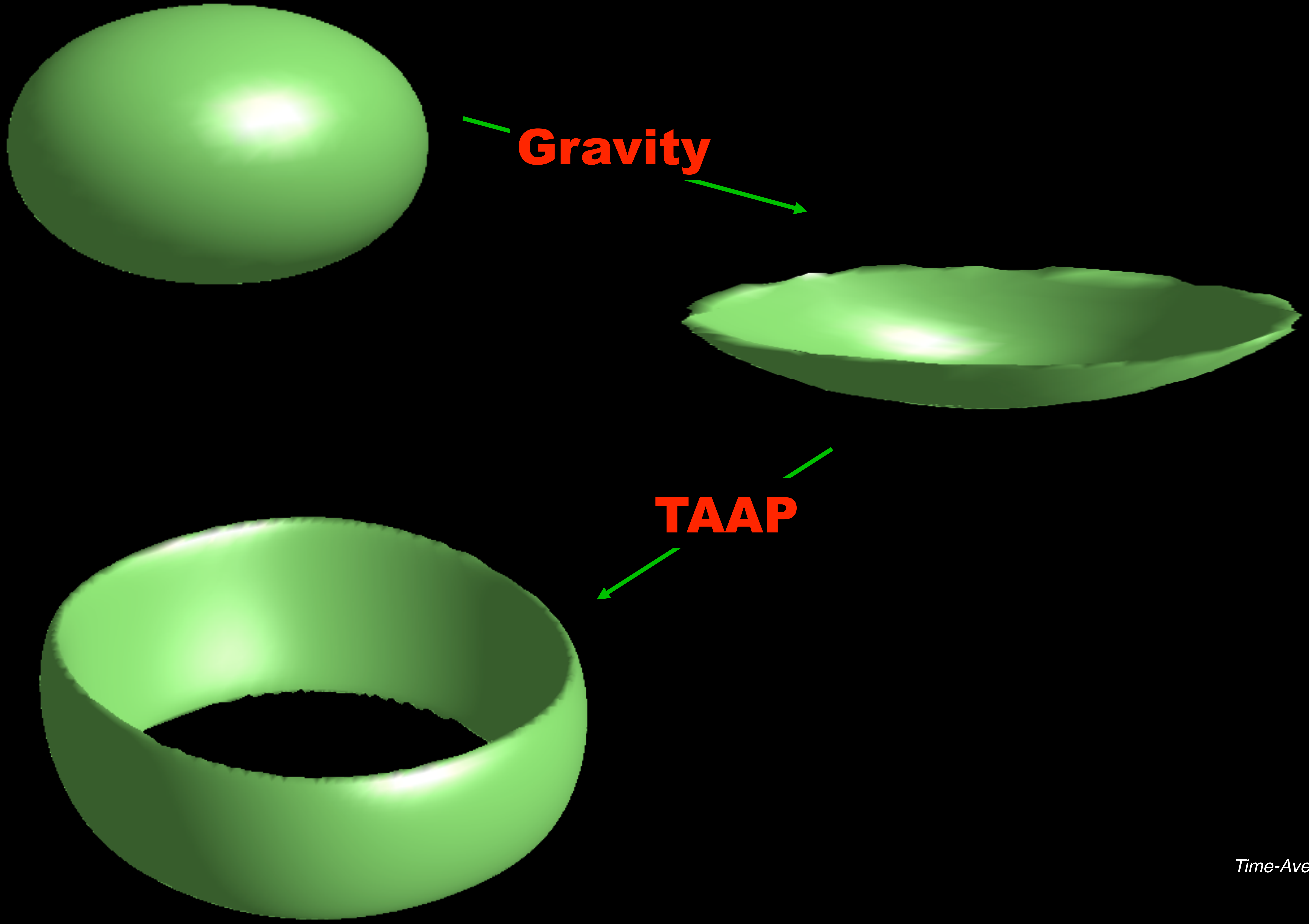
Adiabatic Potentials



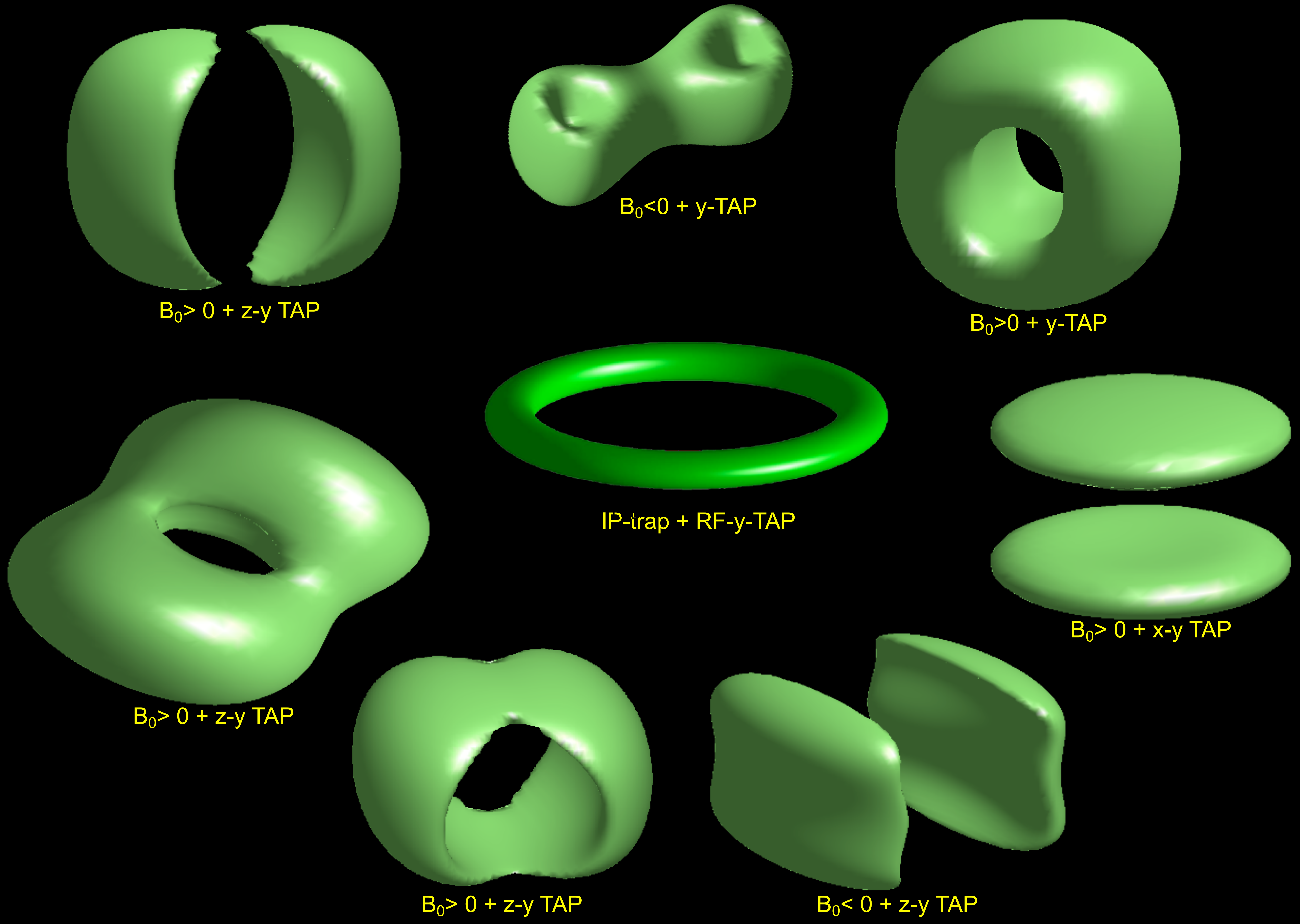
Adiabatic Potentials



Time-Averaged Adiabatic Potentials (TAAP)



I. Lesanovsky and Wolf von Klitzing
Time-Averaged Adiabatic Potentials: Versatile Matter-Wave Guides and Atom Traps
Physical Review Letters **99:8** 083001 (2007)
DOI:/10.1103/PhysRevLett.99.083001



(1 μK iso-potential surfaces in a TAAP trap)

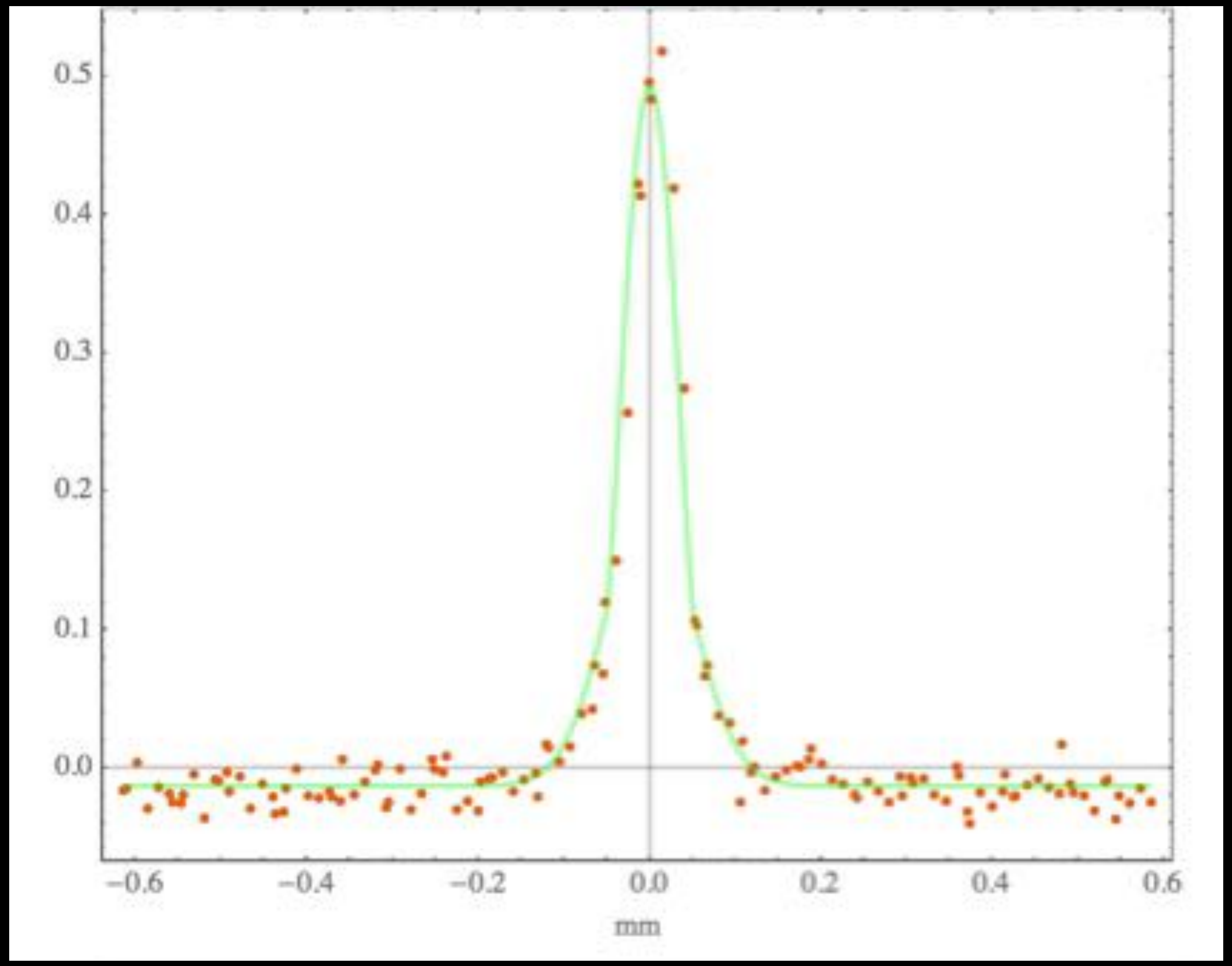
PRL **99:8** 083001 (2007)

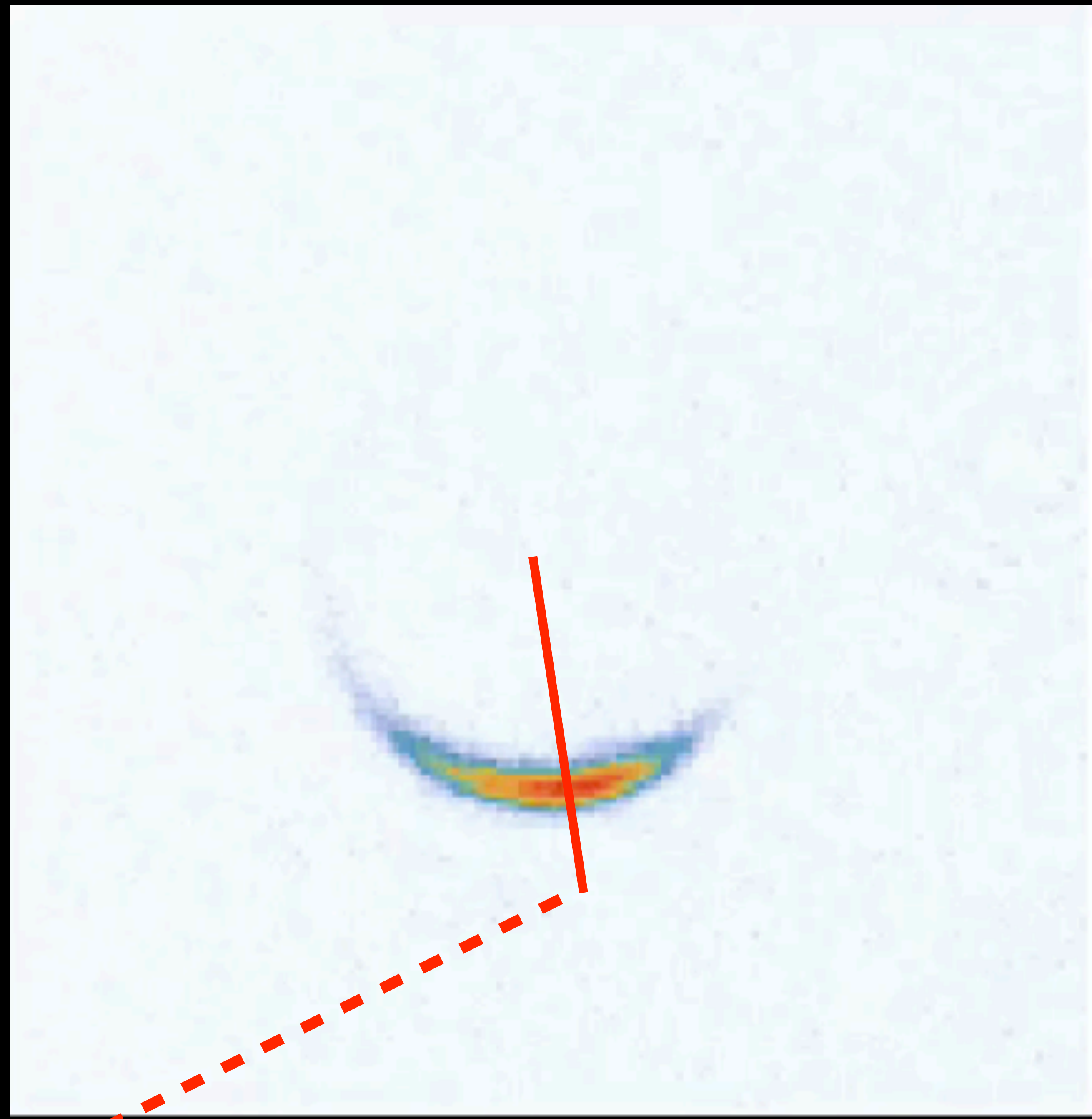
BEC in a Ring

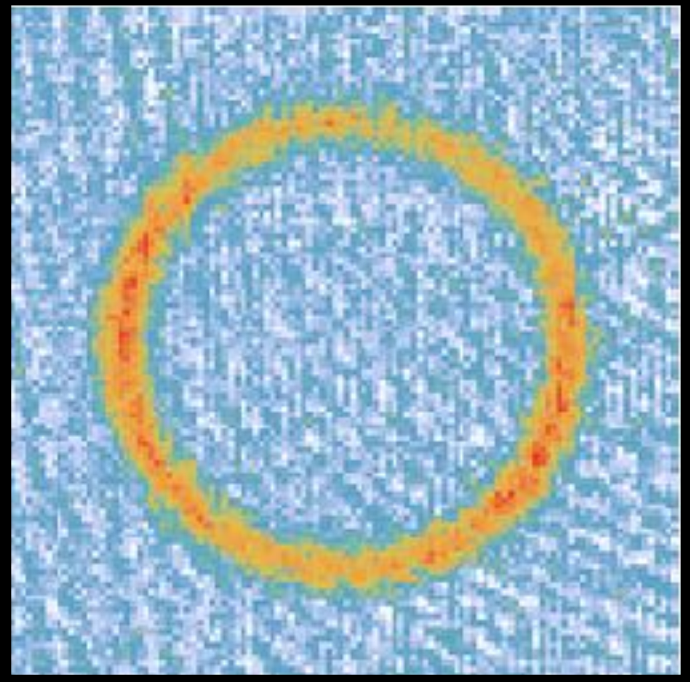
N=300k, T=3-30 nK Ø=1-2 mm

BEC in a Ring

1) MOT
2) Quadrupole-Trap
3) BEC in Dipole Trap
4) **BEC in Ring**

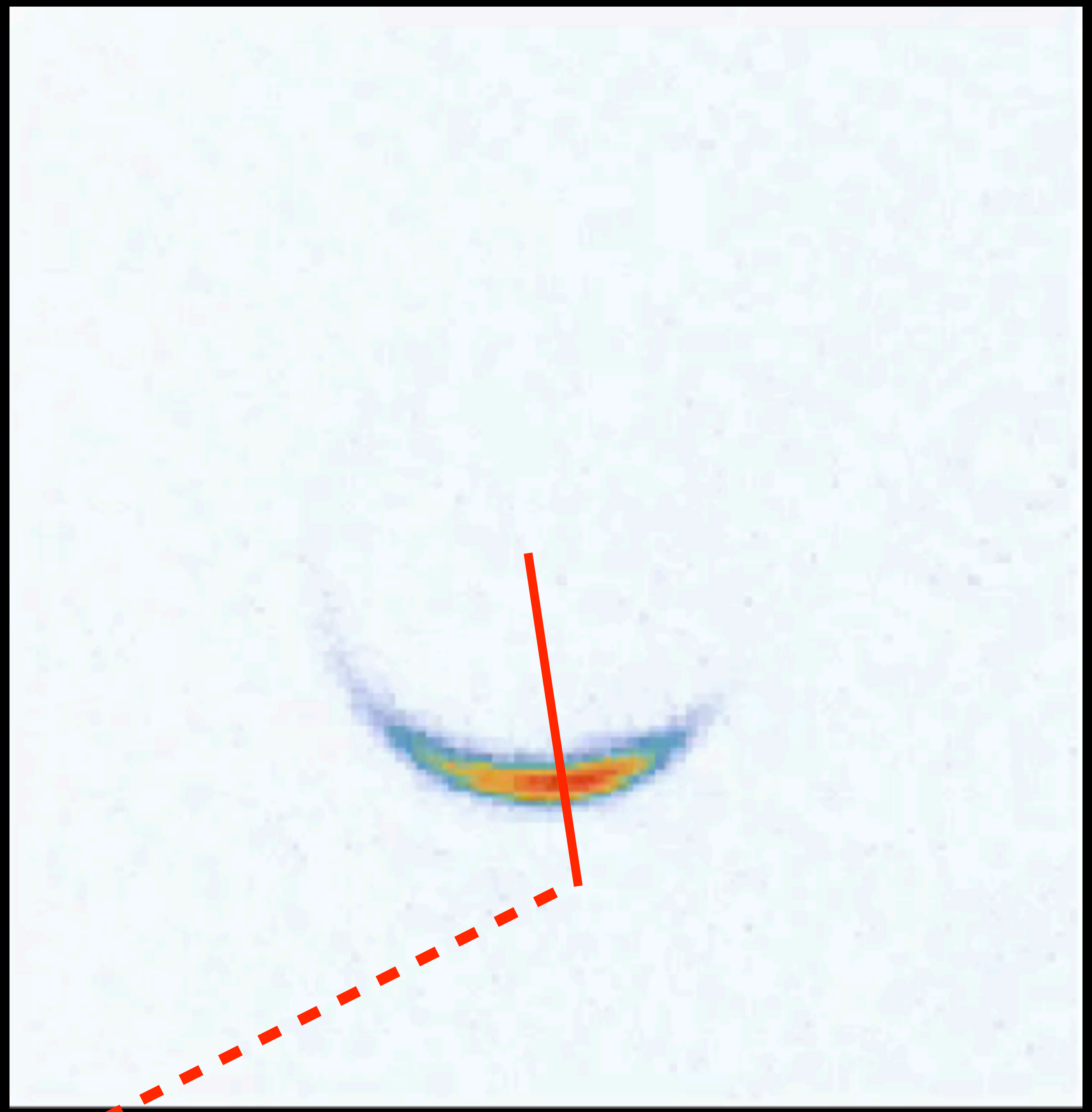


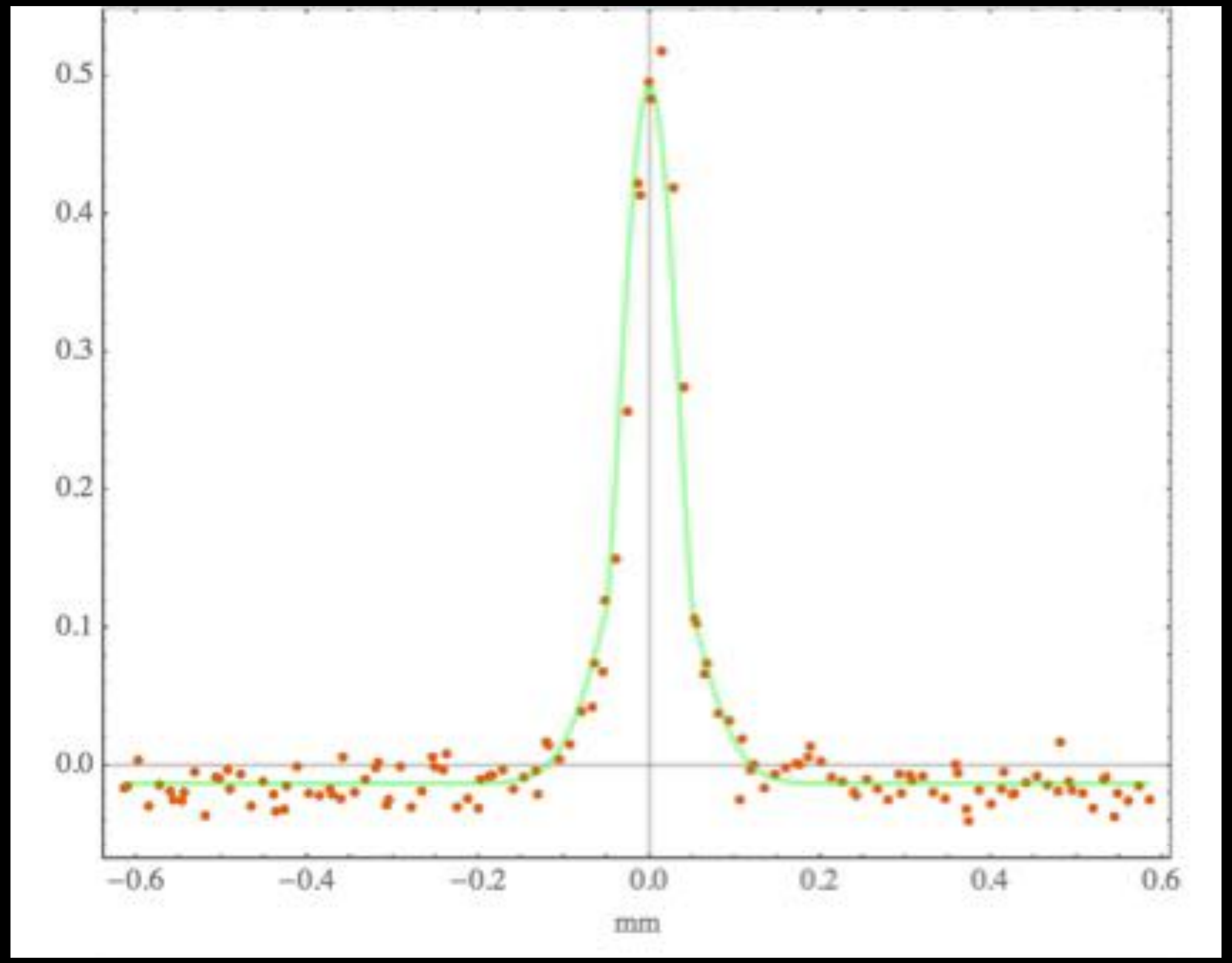




BEC in a Ring

1) MOT
2) Quadrupole-Trap
3) BEC in Dipole Trap
4) BEC in Ring
5) **Accelerate**





Bang-Bang Scheme of Optimal Control Theory

Chen et al. Phys. Rev. A **84,** 43415 (2011).

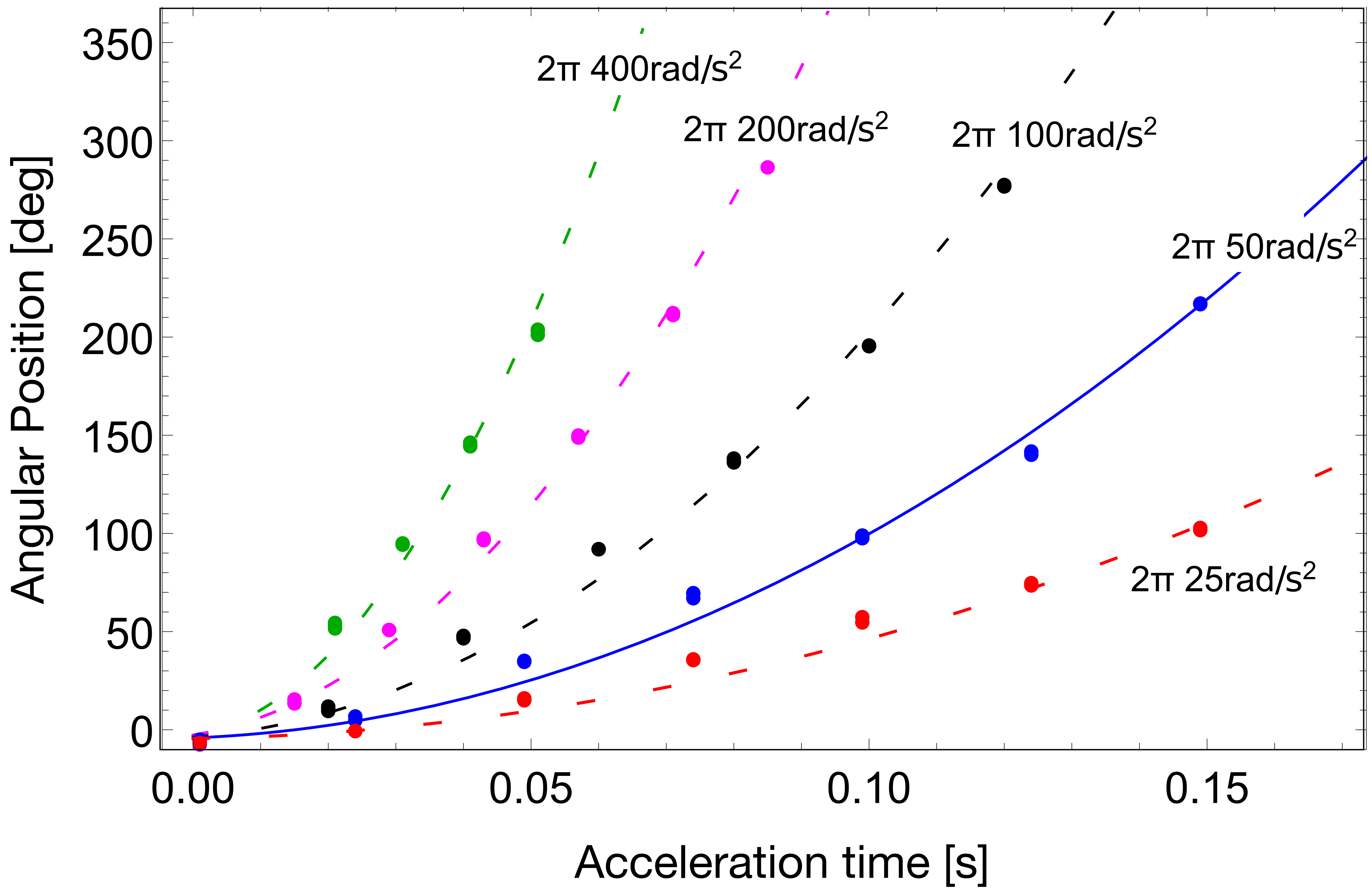
Ring Accelerator

Ring Accelerator

Acceleration of BECs in TAAP rings

using the bang-bang scheme of optimal control theory

Chen et al. Phys. Rev. A **84,** 43415 (2011).



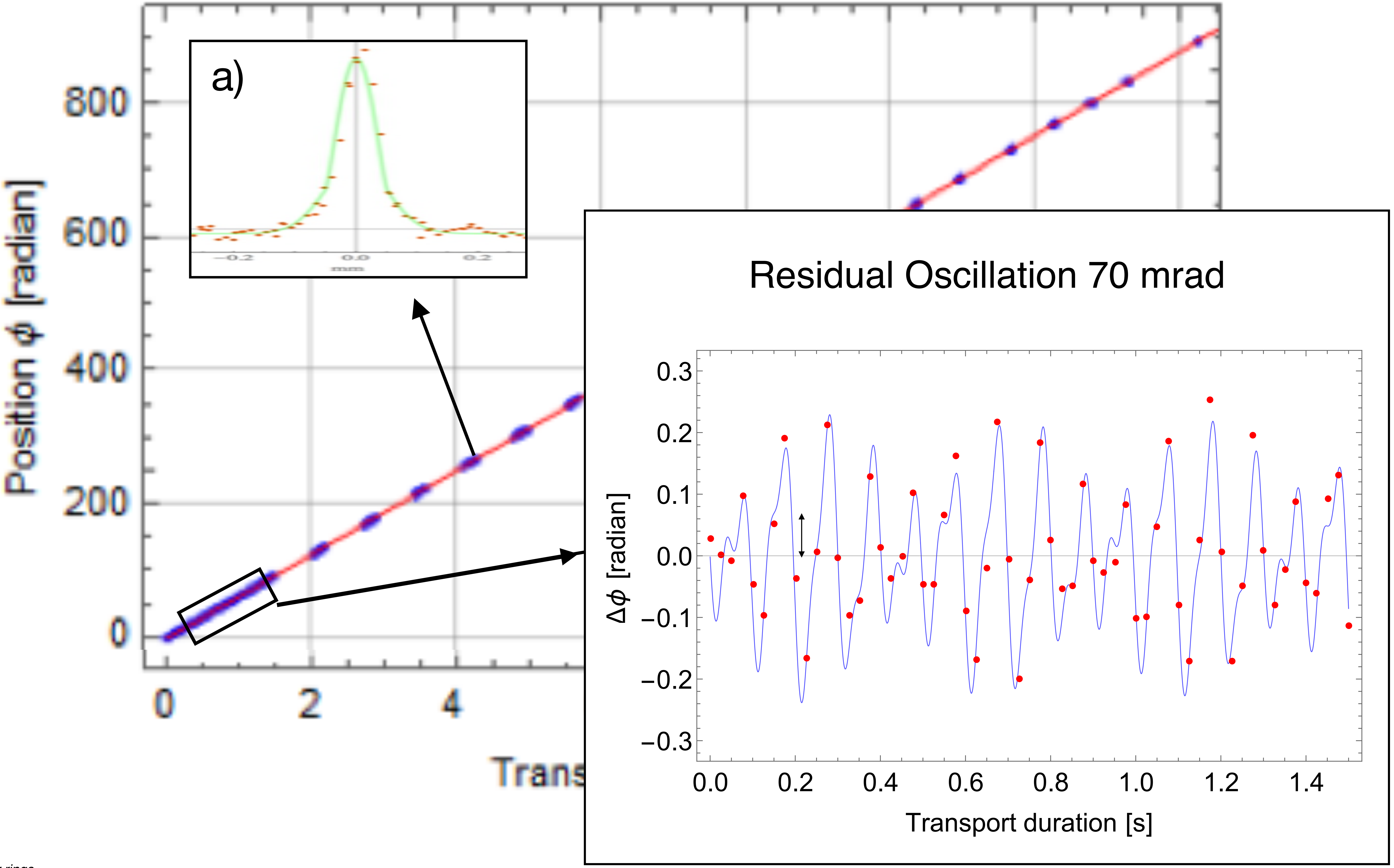
Saurabh Pandey et al.

Hypersonic Bose--Einstein condensates in accelerator rings

Nature **570:7760** 205--209 (2019)

DOI:/10.1038/s41586-019-1273-5

BEC in an accelerator ring



Saurabh Pandey et al.

Hypersonic Bose--Einstein condensates in accelerator rings

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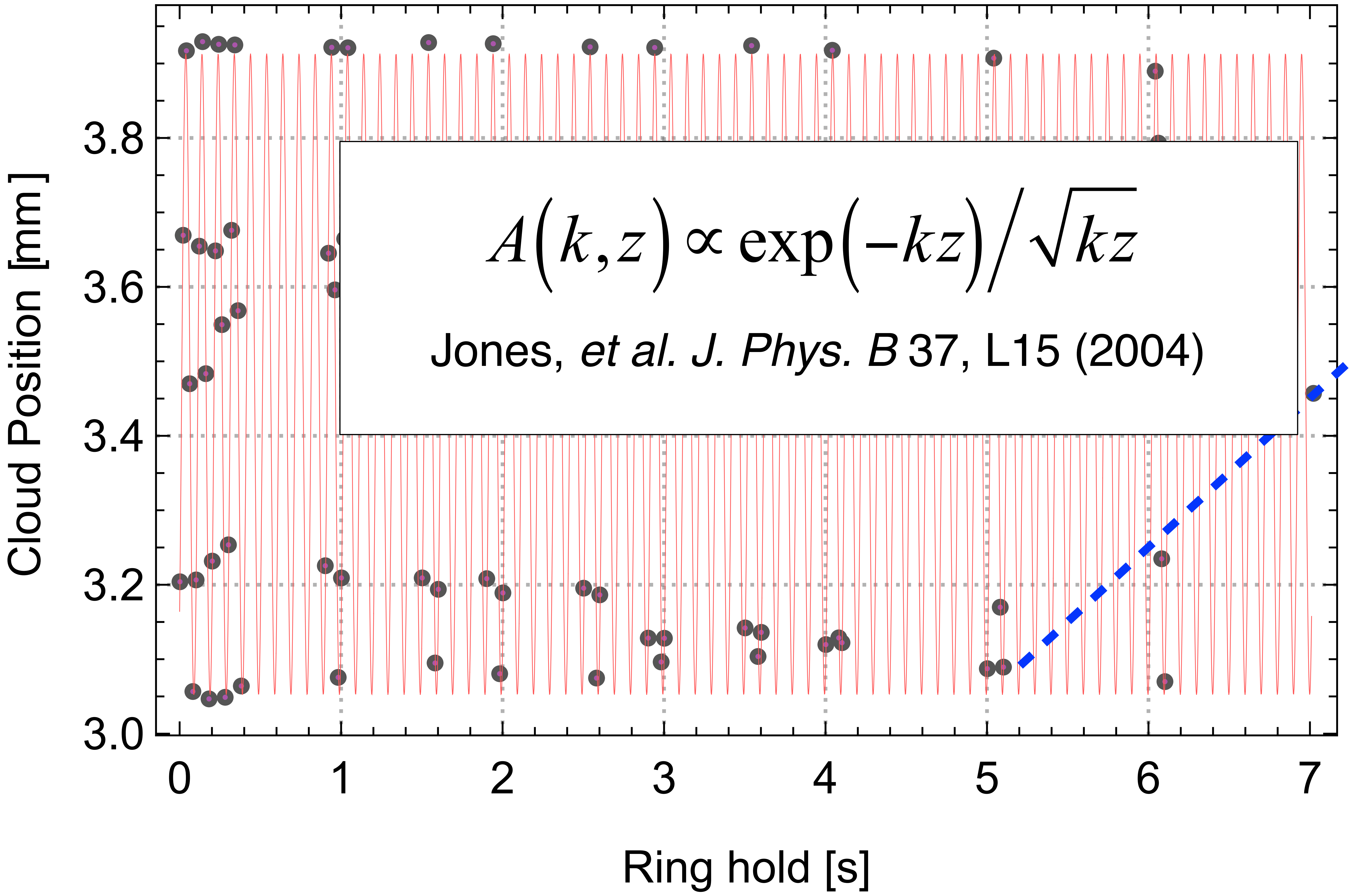
DOI:/10.1038/s41586-019-1273-5

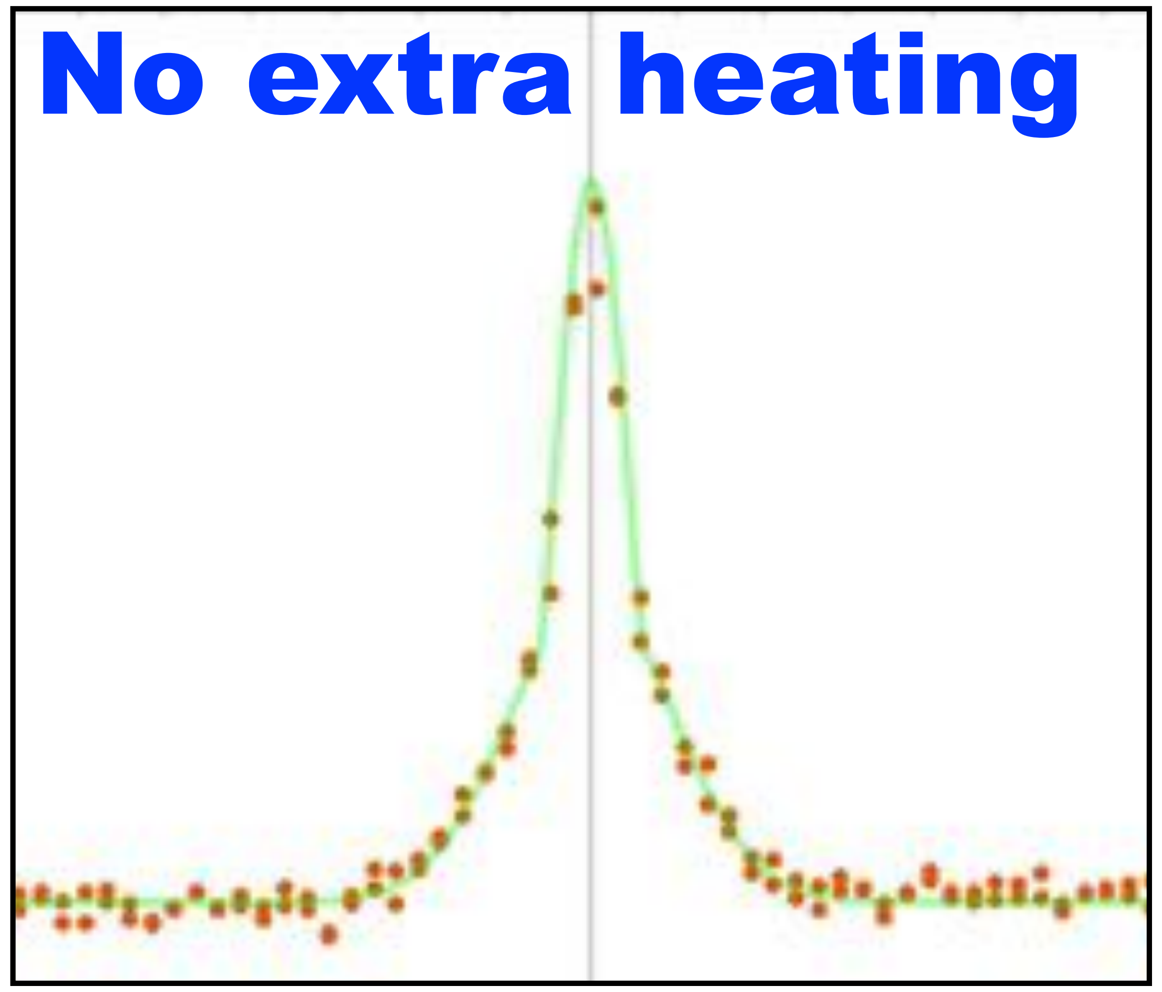
BEC in a waveguide @ 30 mm/s



$$A(k,z) \propto \exp(-kz)/\sqrt{kz}$$

Jones, *et al. J. Phys. B* 37, L15 (2004)

S. Pandey et al. *Nature* **570** 205--209 (2019)



T = 113 nK

Superfluid critical velocity:

$$v_c = \sqrt{\mu/m}$$
$$= 1.8 \text{ mm/s}$$

v = Mach 17

=> perfectly smooth wave guides

$$kz = \frac{2\pi}{0.5\,\text{mm}} \times 50\,\text{mm} \simeq 630$$

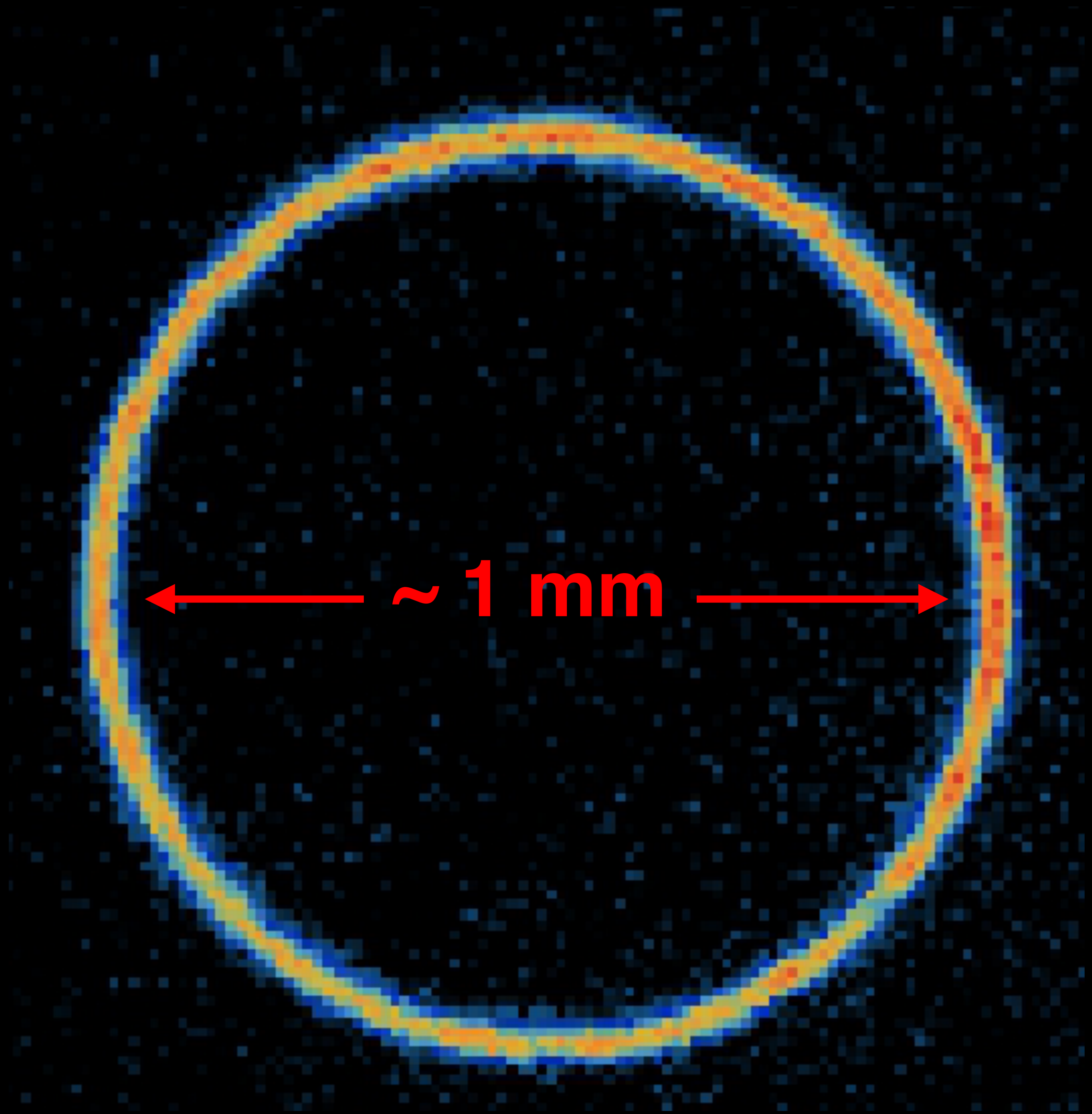
$$A(k,z) \propto \exp(-kz)/\sqrt{kz} \approx 10^{-275}$$

Jones, *et al. J. Phys. B* 37, L15 (2004)

Expansion of a rotating BEC in the ring

Matterwave Guide/Ring

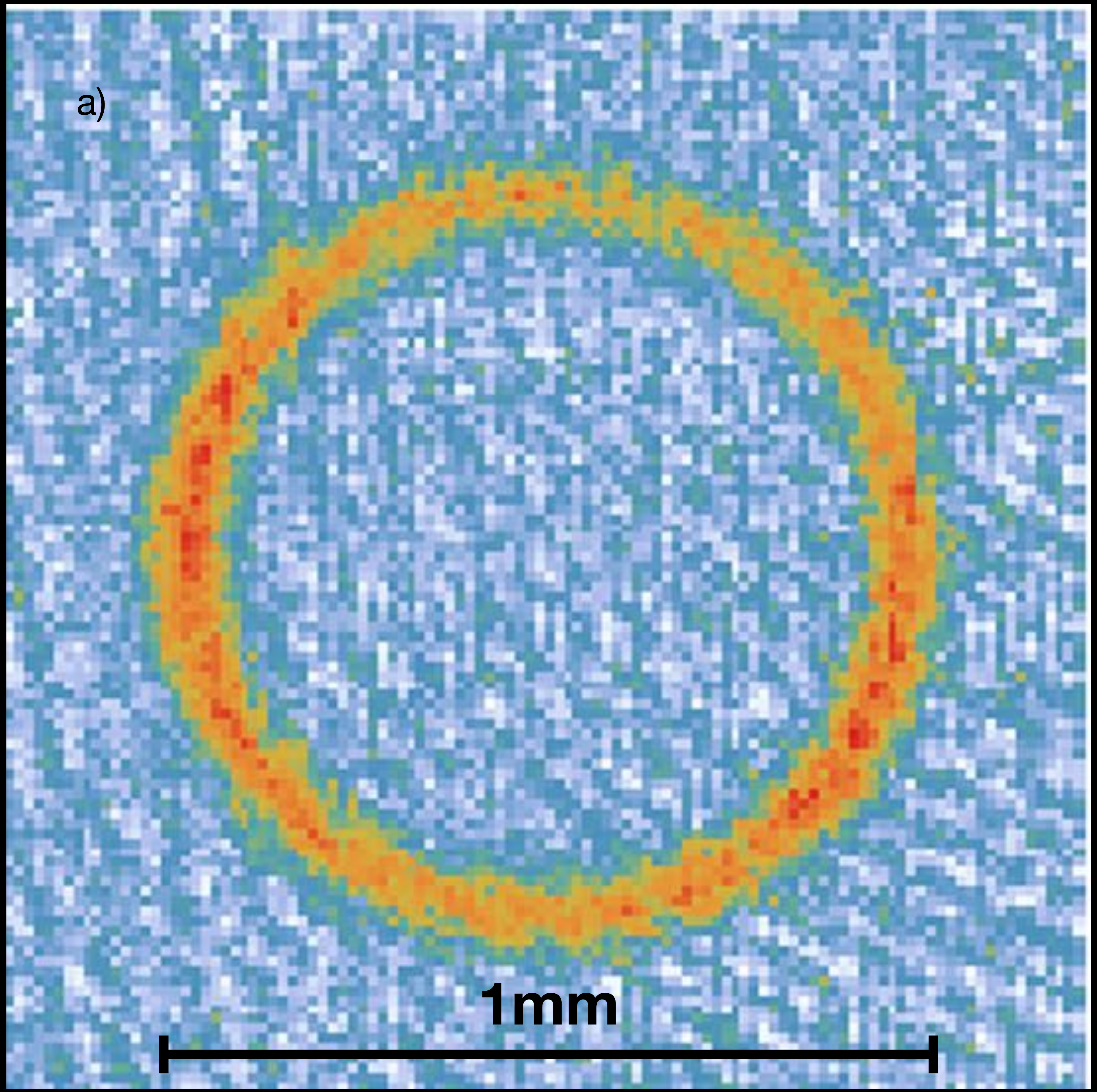
80 000 atoms with 40 000 $\hbar$ / atom



Effective Flatness of the waveguide:

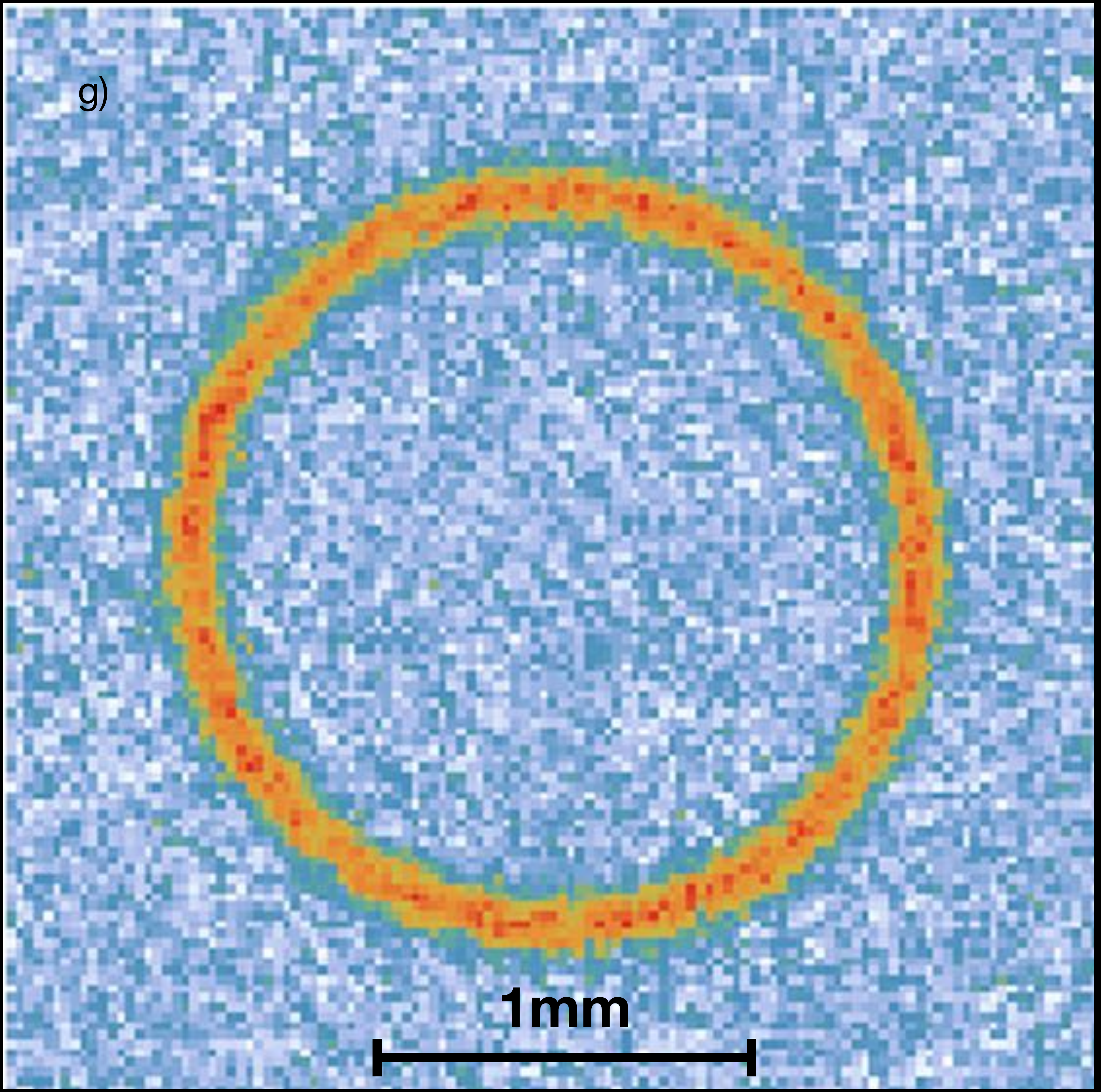
189 pK = 2 nm height difference

Static vs Supersonic atoms



Flatness < 250 nK

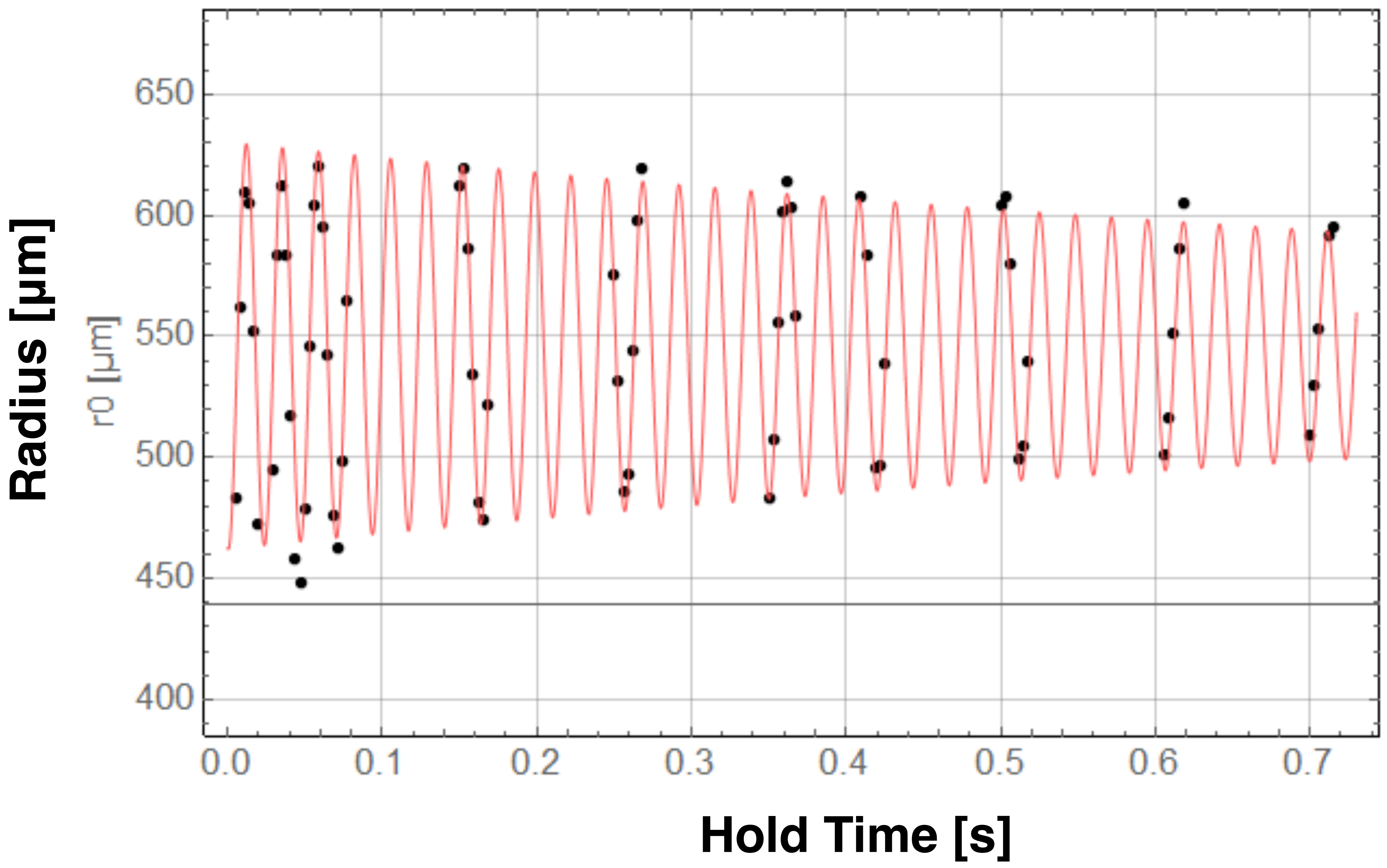
Static

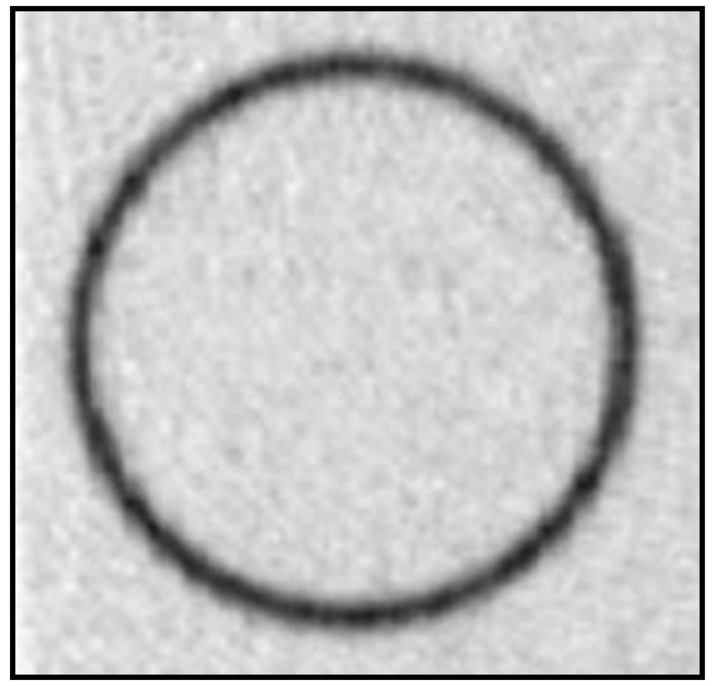


Flatness < 189 pK

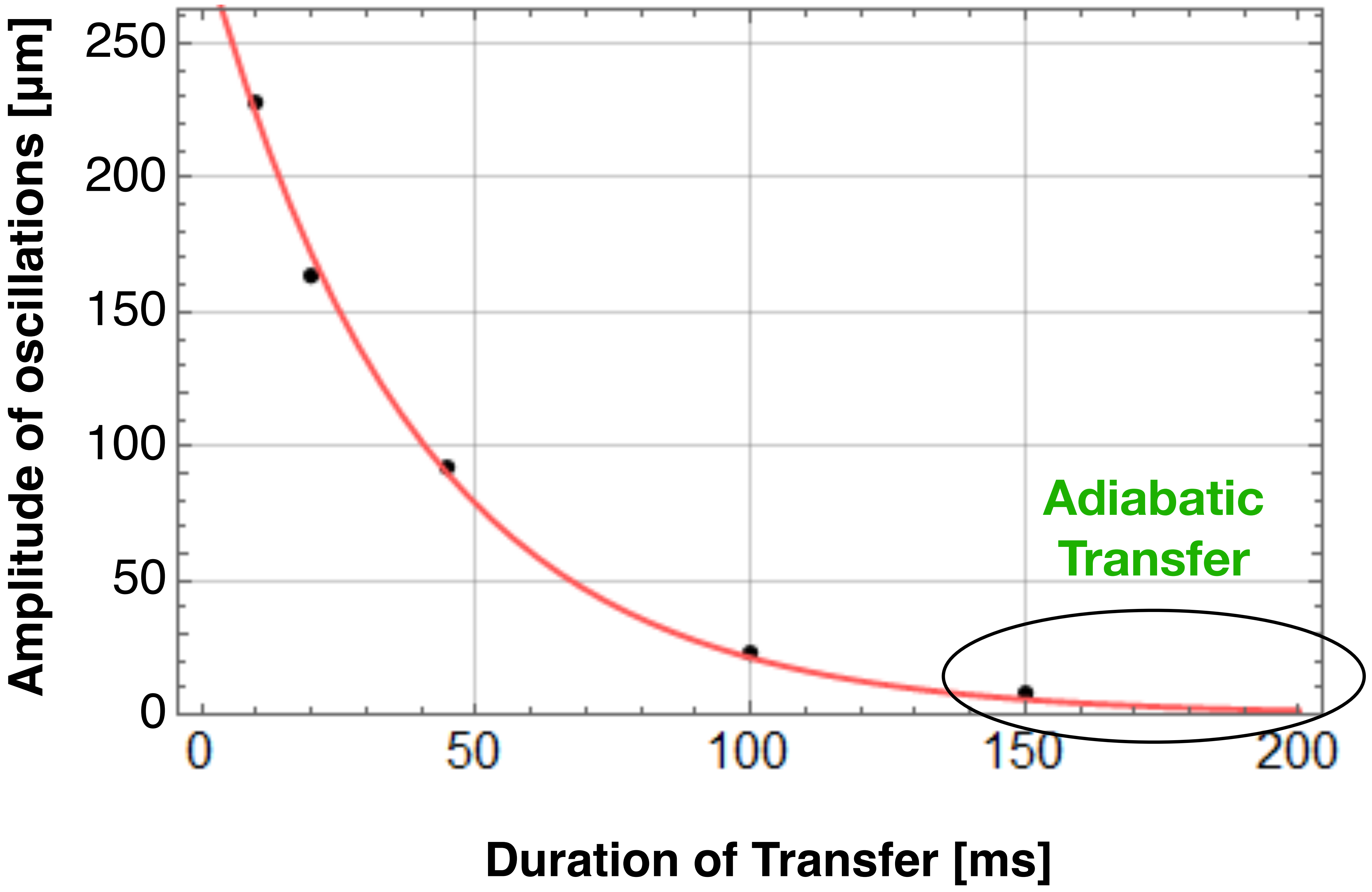
Supersonic

Rotating BECs in a Shell Trap

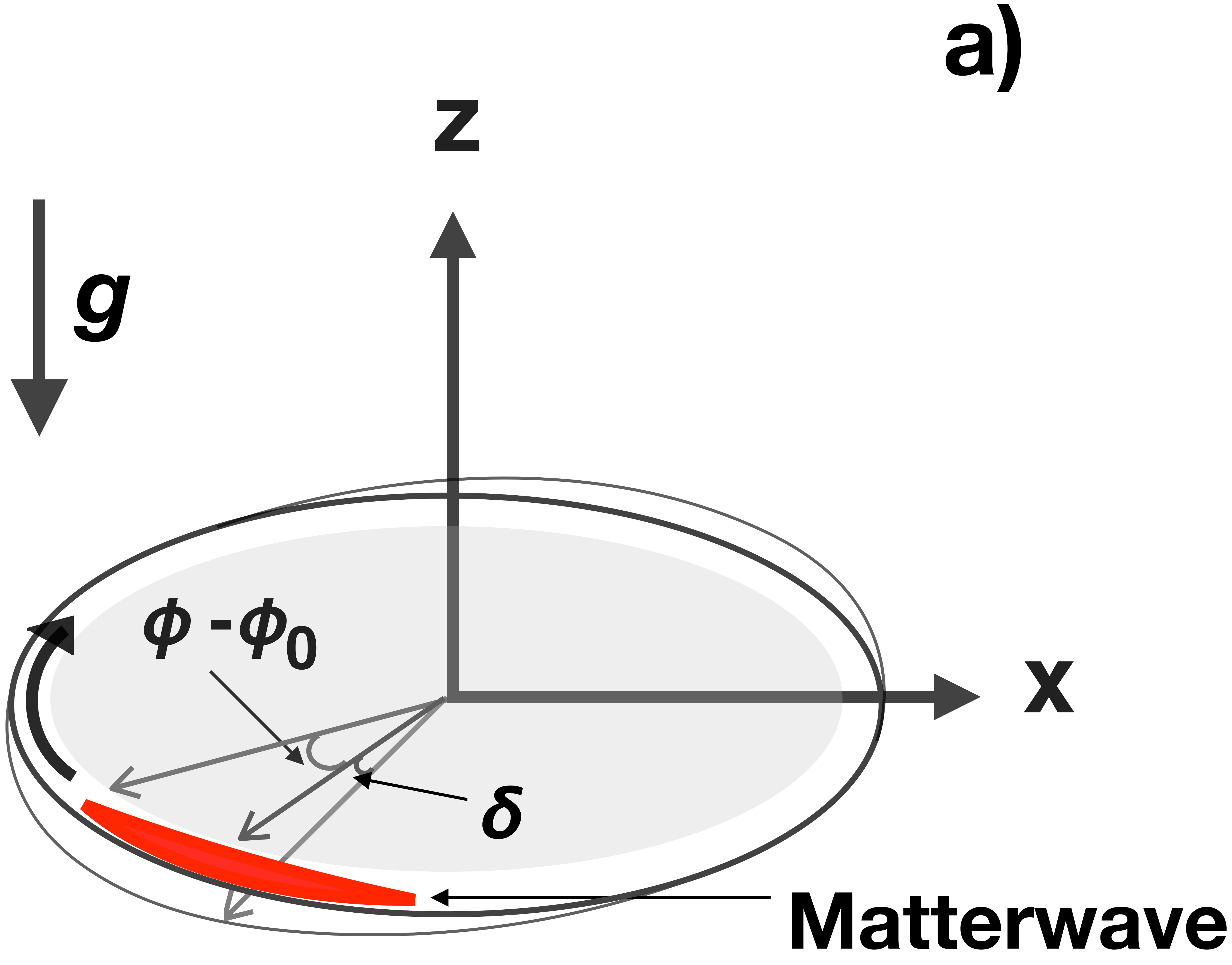


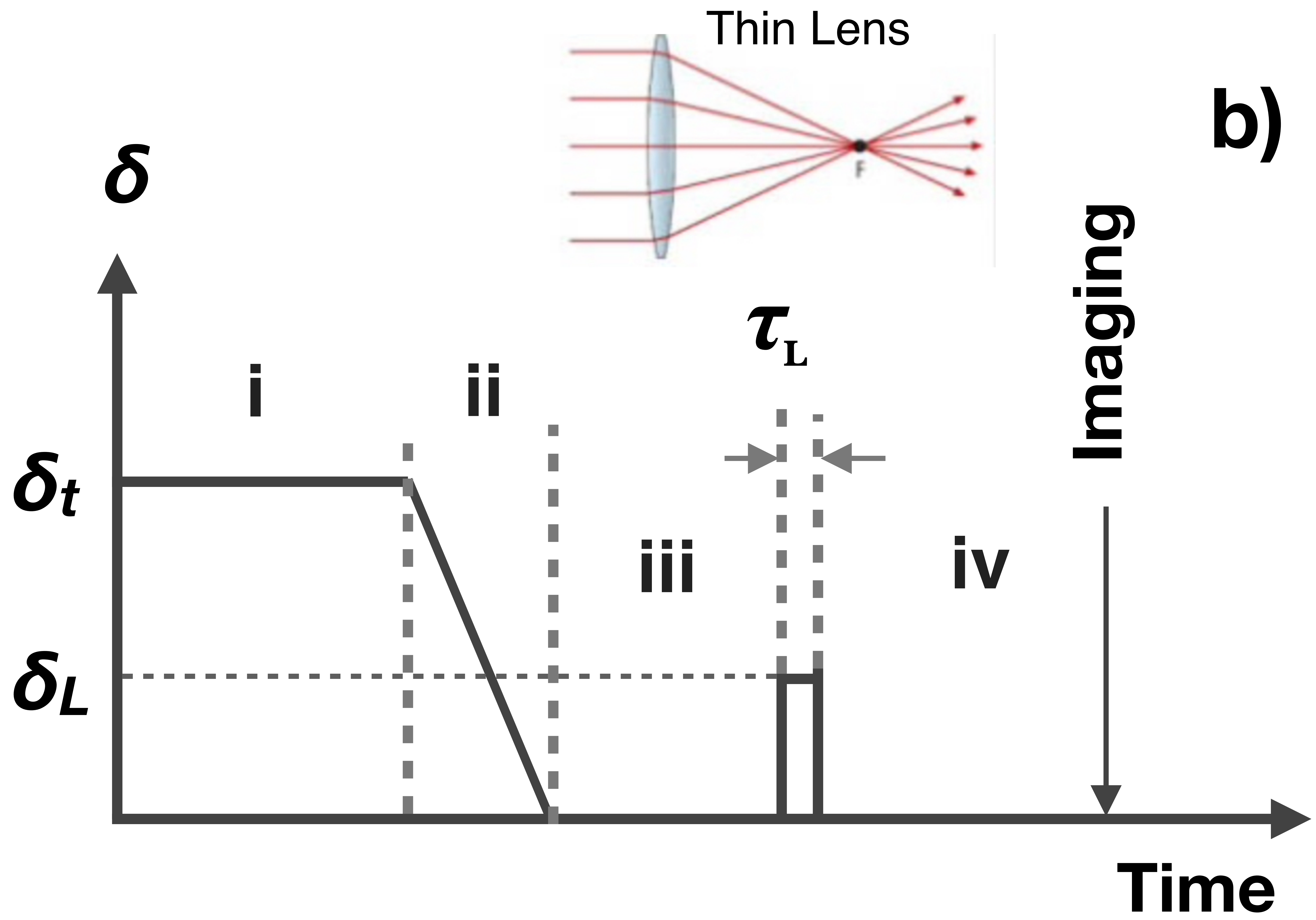


BECs in a shell
@ 50 nK

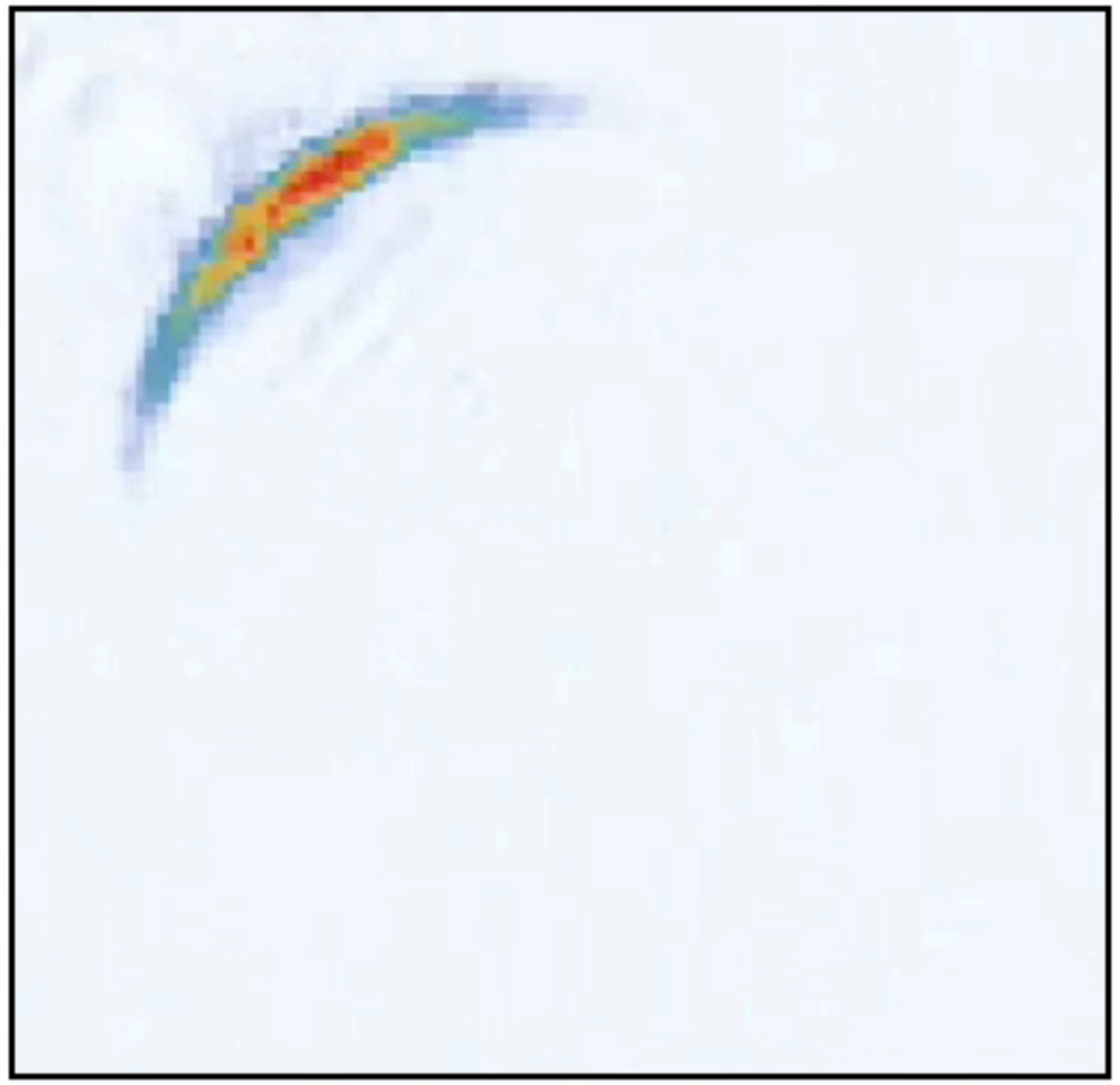


Matterwave Optics: Lenses

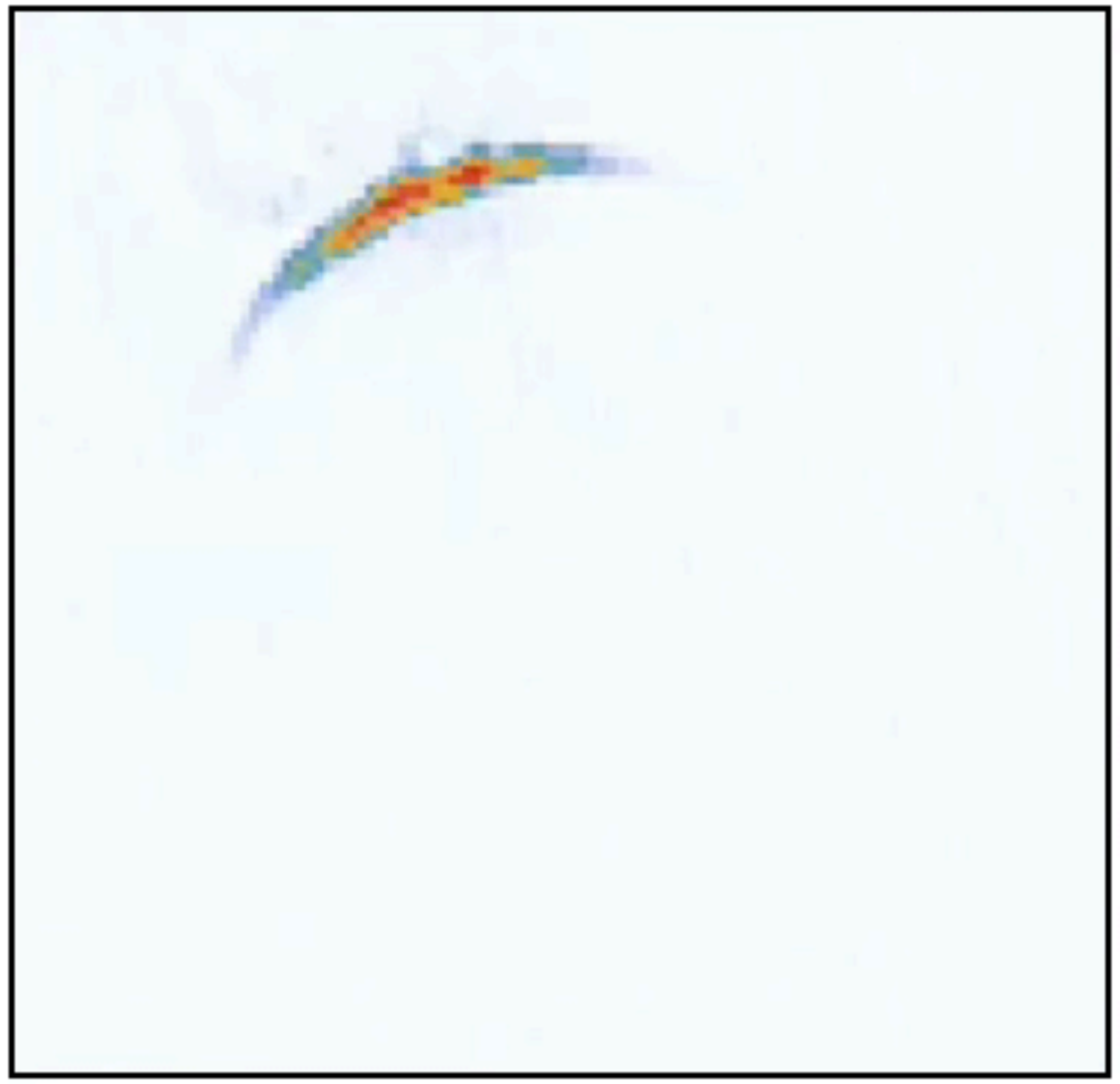




Optimal Control
Atom-Optics

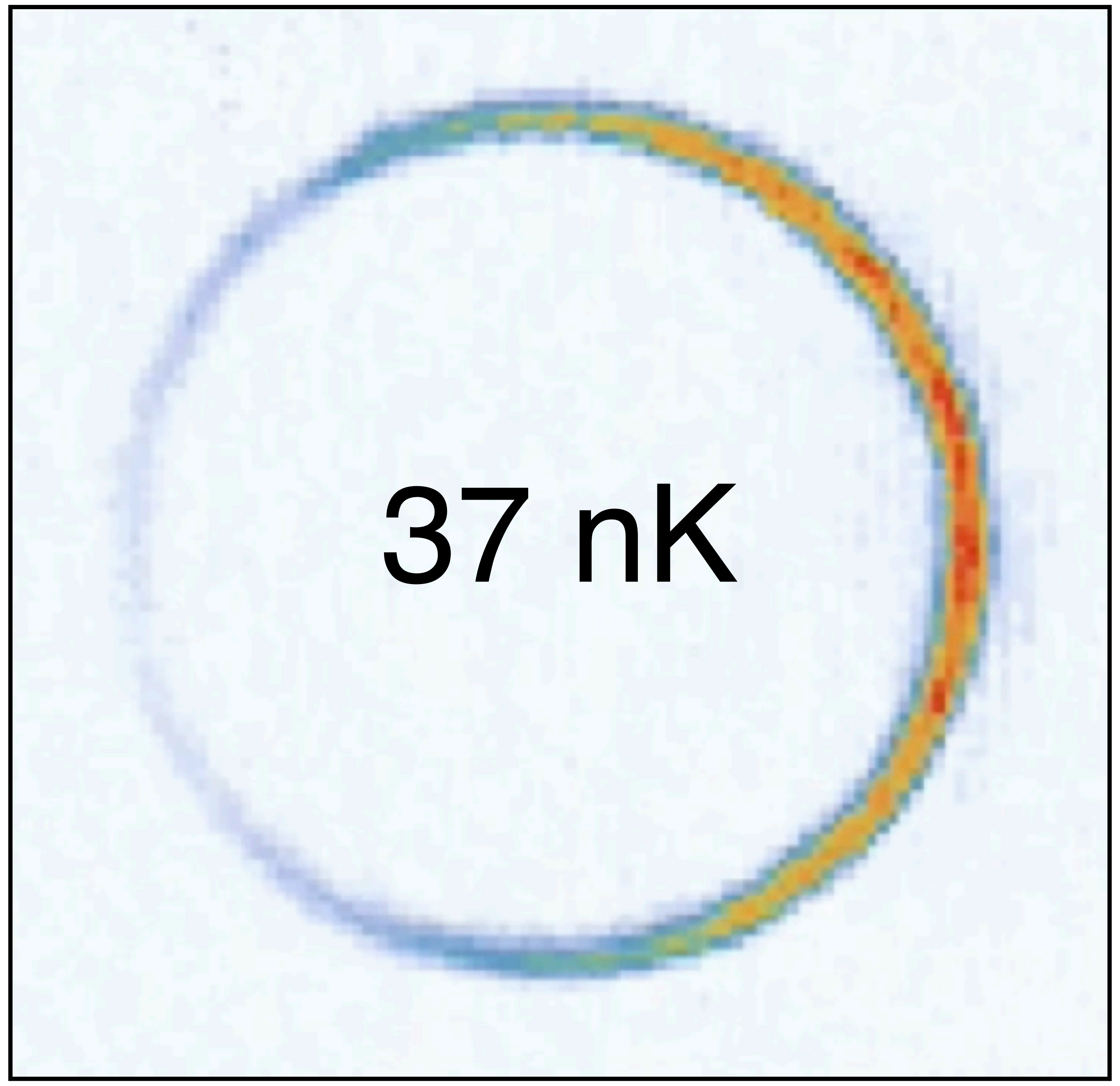


Free expansion

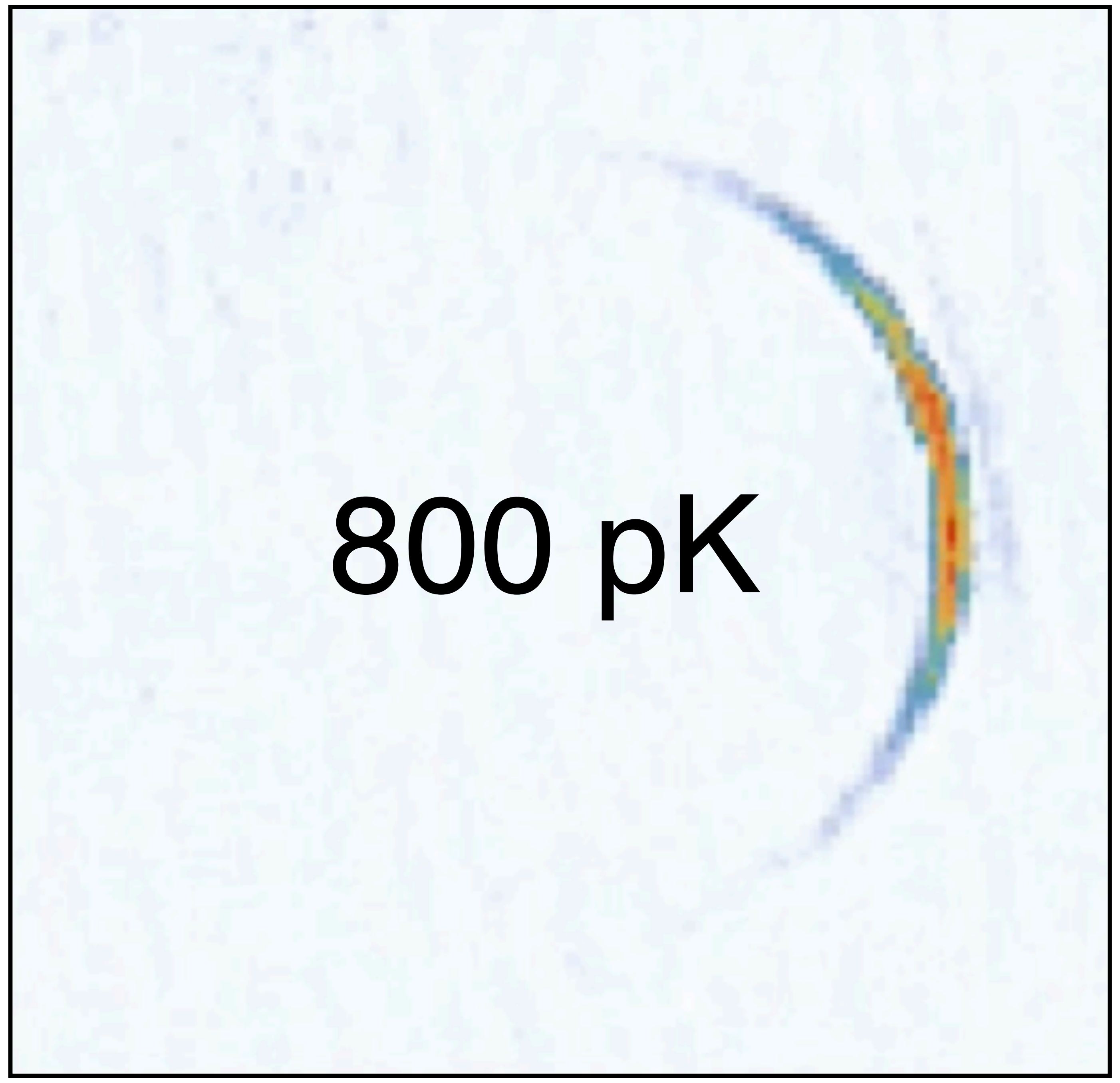


Delta Kick

Optimal Control
Atom-Optics



Free expansion



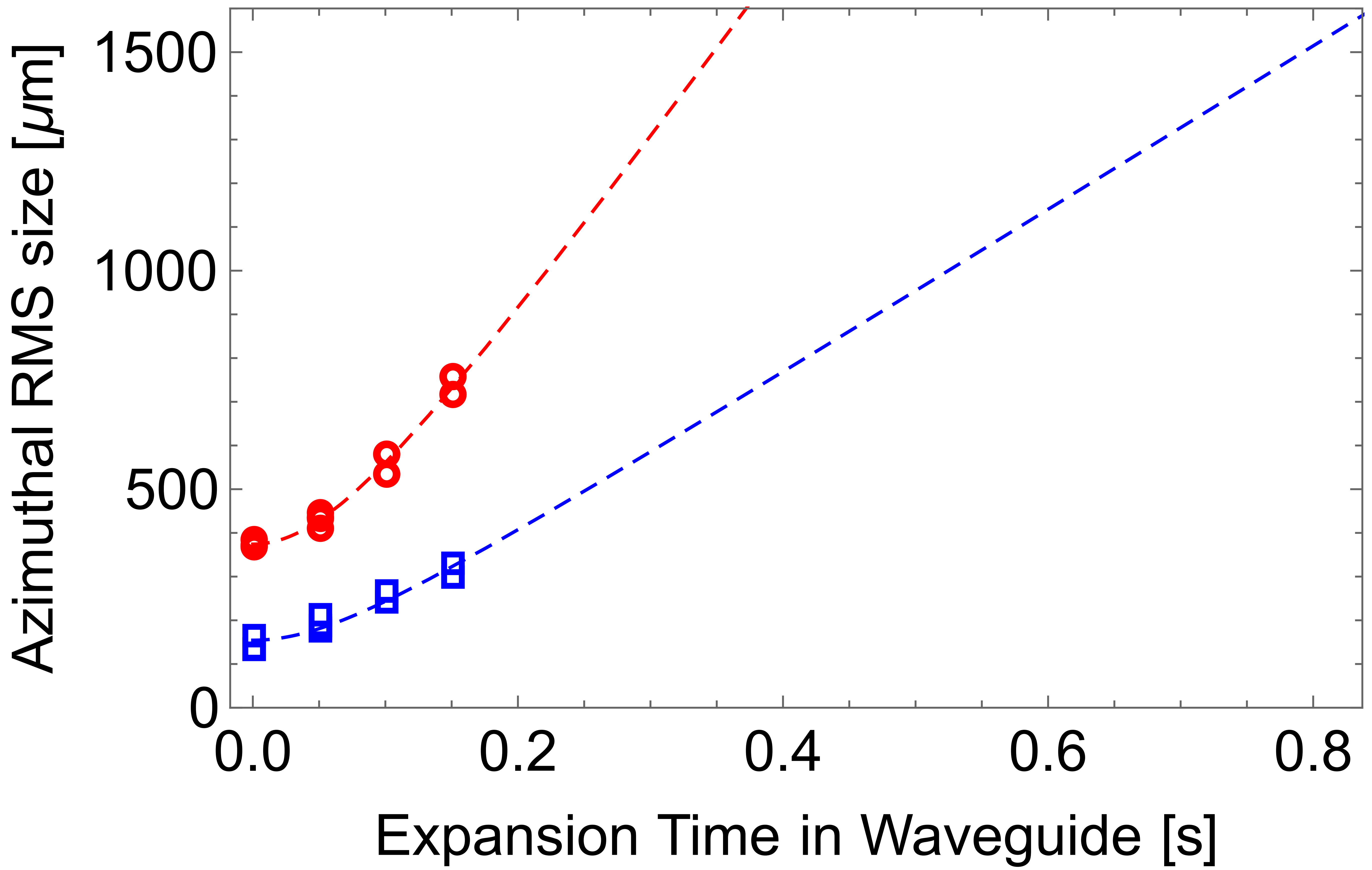
Delta Kick

Average Kinetic Energy
E_{kin} / k_B [nK]
120
100
80
60
40
20
0
0
20
40
60
80
100
Strength of Lens (tilt angle δ) [mra
Azimuthal size [μm]
900
600
300
0
0.
0.1
0.2
Waveguide expansion
0 ms
20 ms
40 ms
60 ms
80 ms
100 ms
130 µm
450 µm

Expansion in the Ring

Thermal (Free expansion)
$T_{kin} = 183^{+21}_{-20}$ nK_{rms}

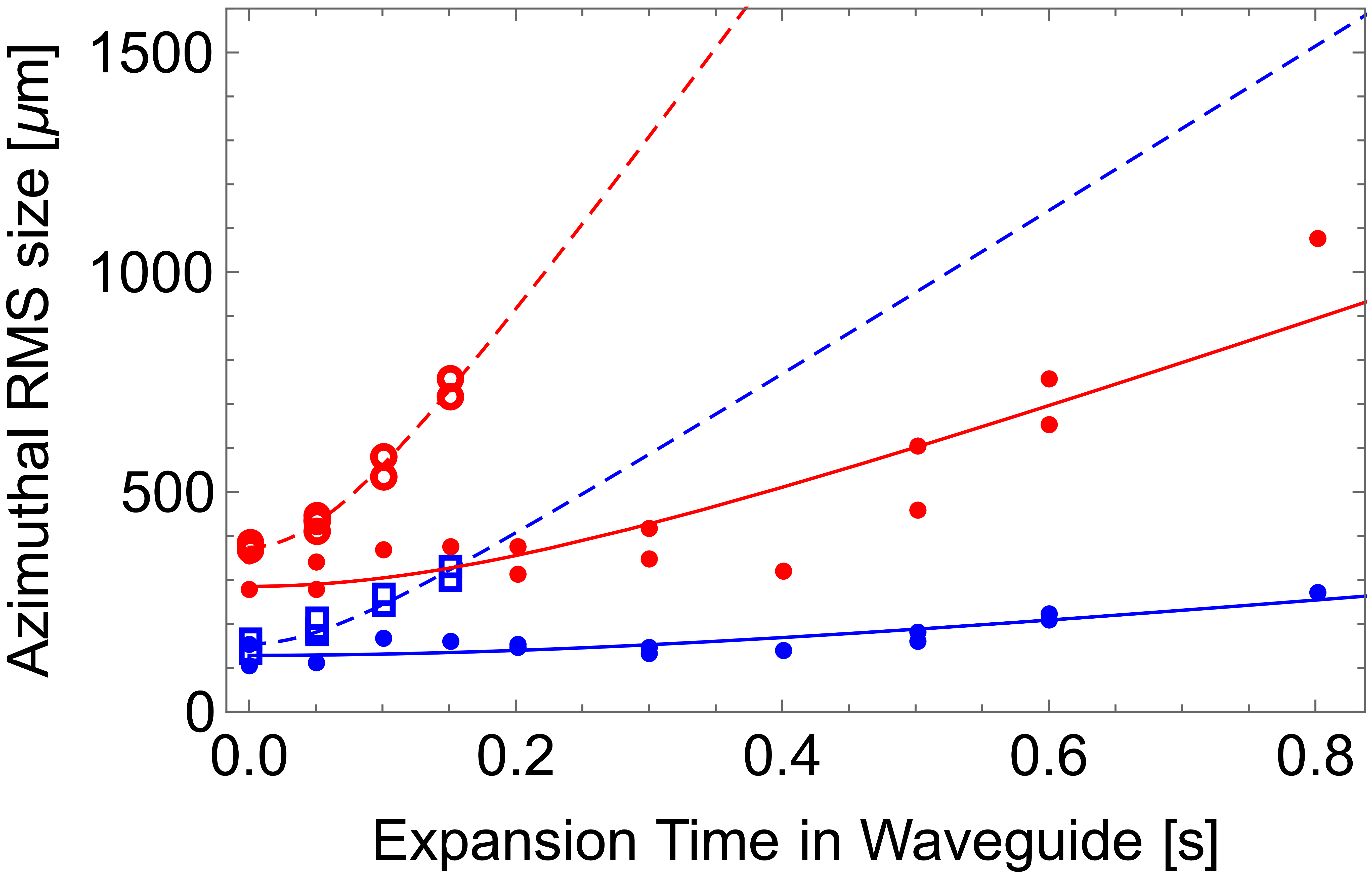
BEC (Free expansion)
$T_{kin} = 37^{+10}_{-9}$ nK_{rms}



Expansion in the Ring

Thermal (Free expansion)
$T_{kin} = 183^{+21}_{-20}\ nK_{rms}$

BEC (Free expansion)
$T_{kin} = 37^{+10}_{-9}\ nK_{rms}$

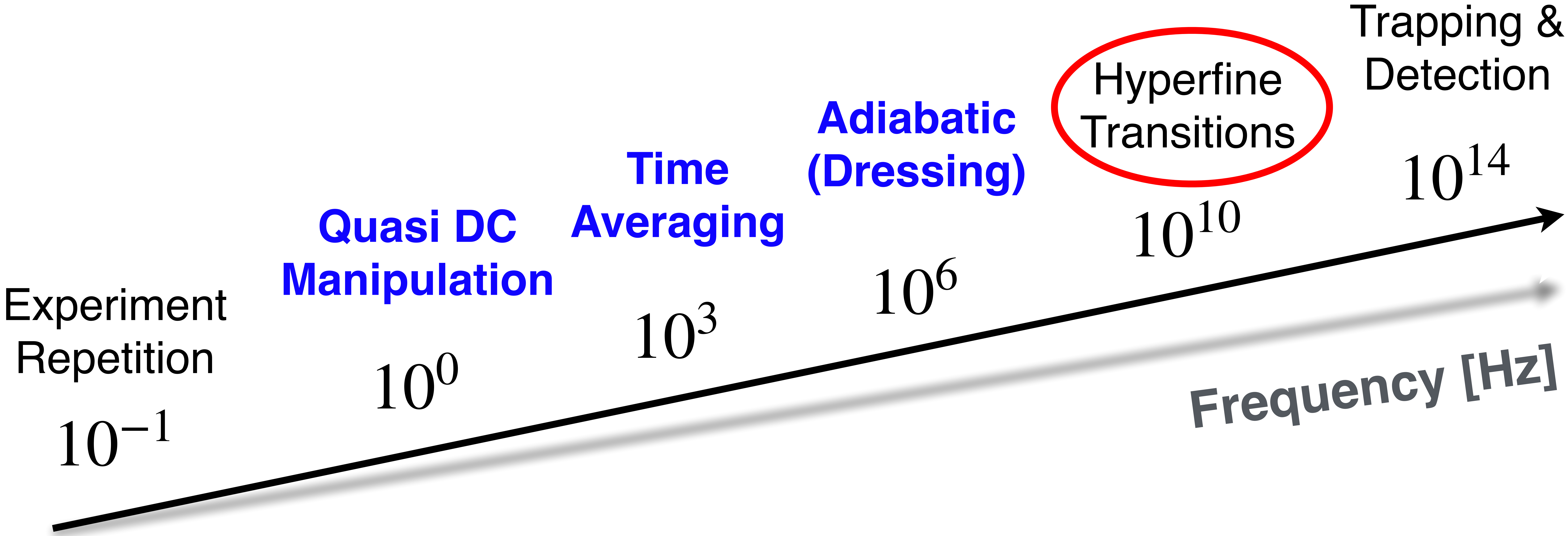


Thermal (Delta–Kick Cooled)
$T_{kin} = 12^{+4}_{-4}\ nK_{rms}$

BEC (Delta–Kick Cooled)
$T_{kin} = 0.8^{+0.3}_{-0.3}\ nK_{rms}$

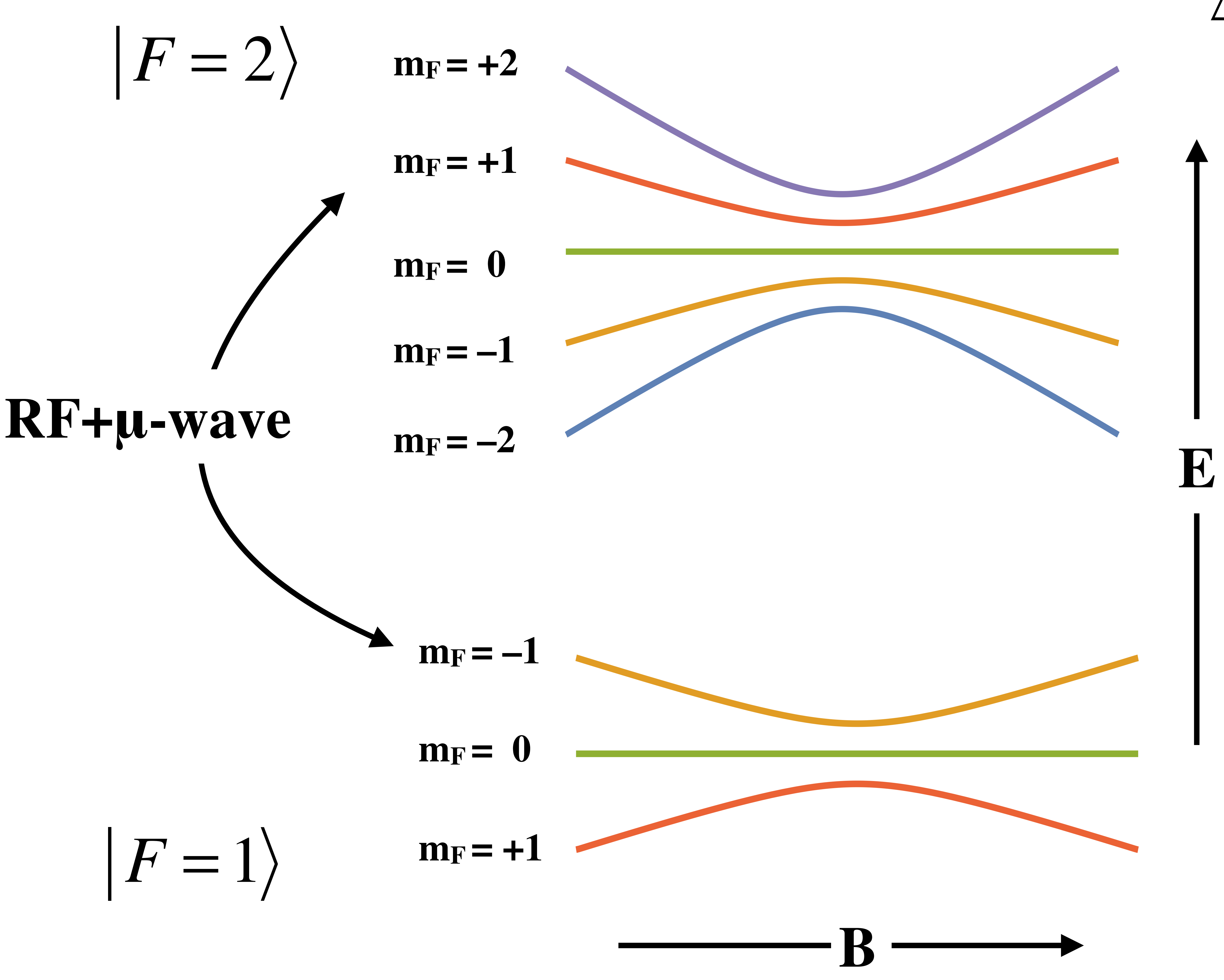
46 x lower

Atomtronic Time Scales



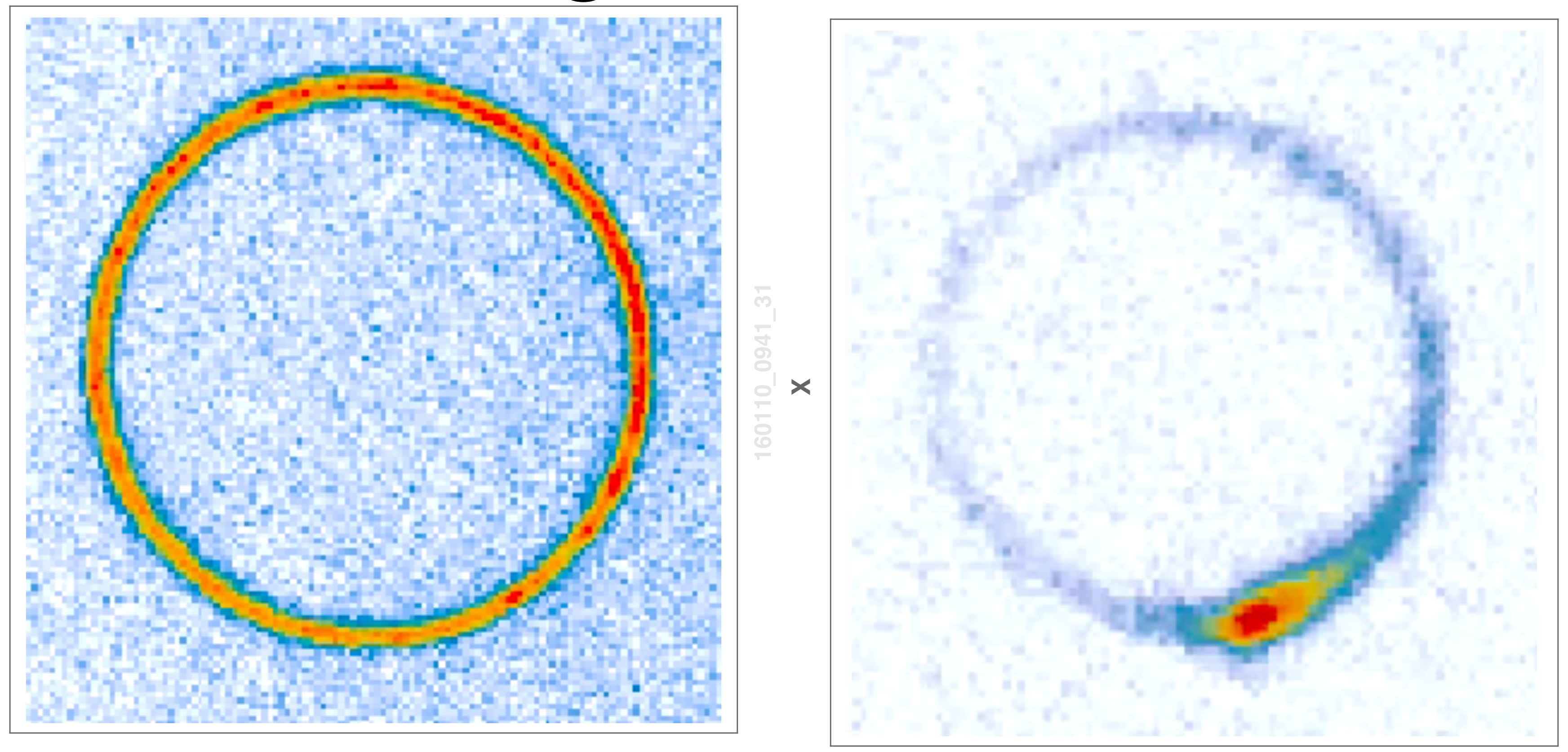
Coupling Hyperfine States with Microwaves

$$\Delta E_B \approx (-1)^F m_F g_F \mu_B B$$

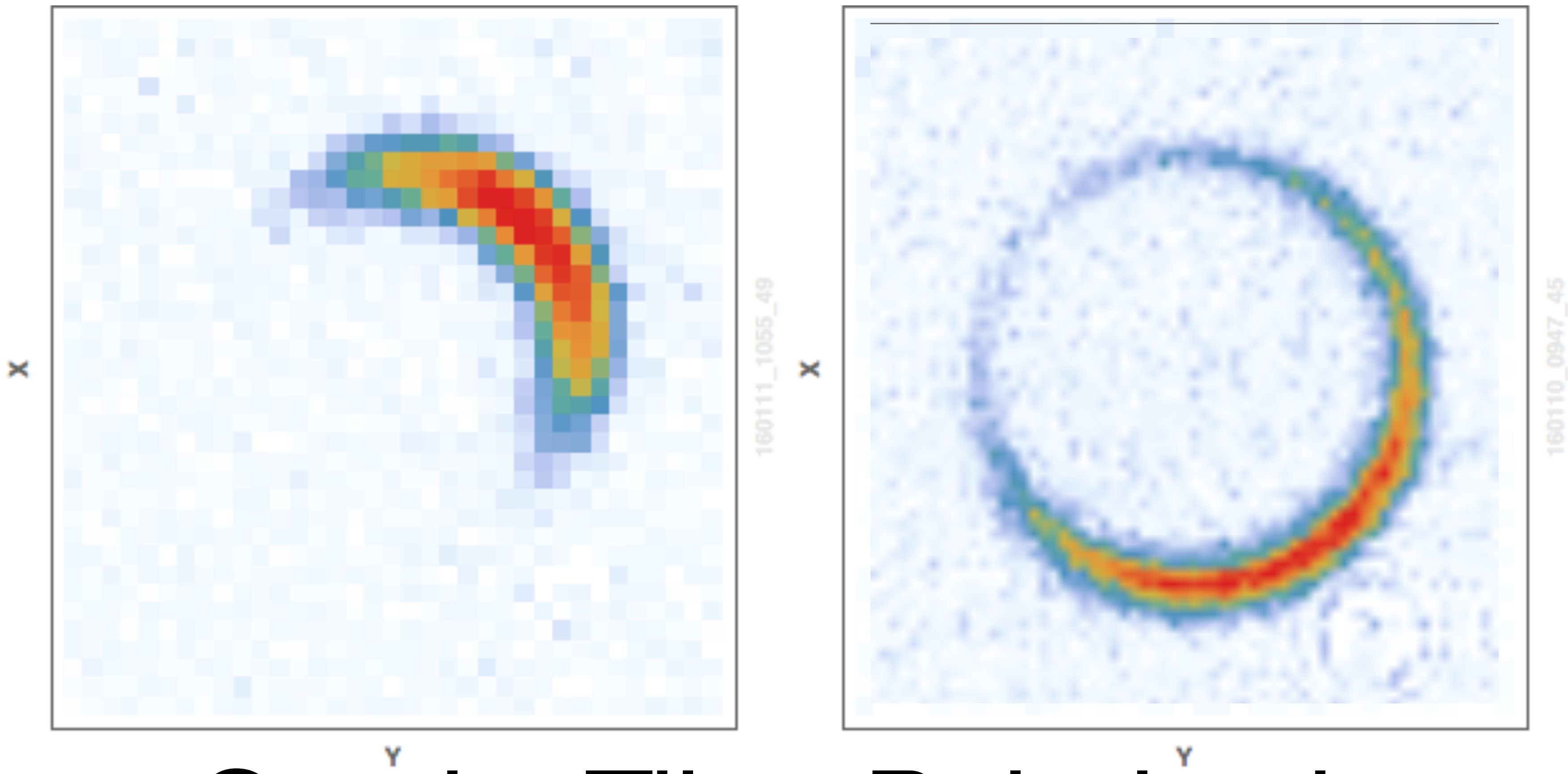


Independent
State-Dependent Buckets

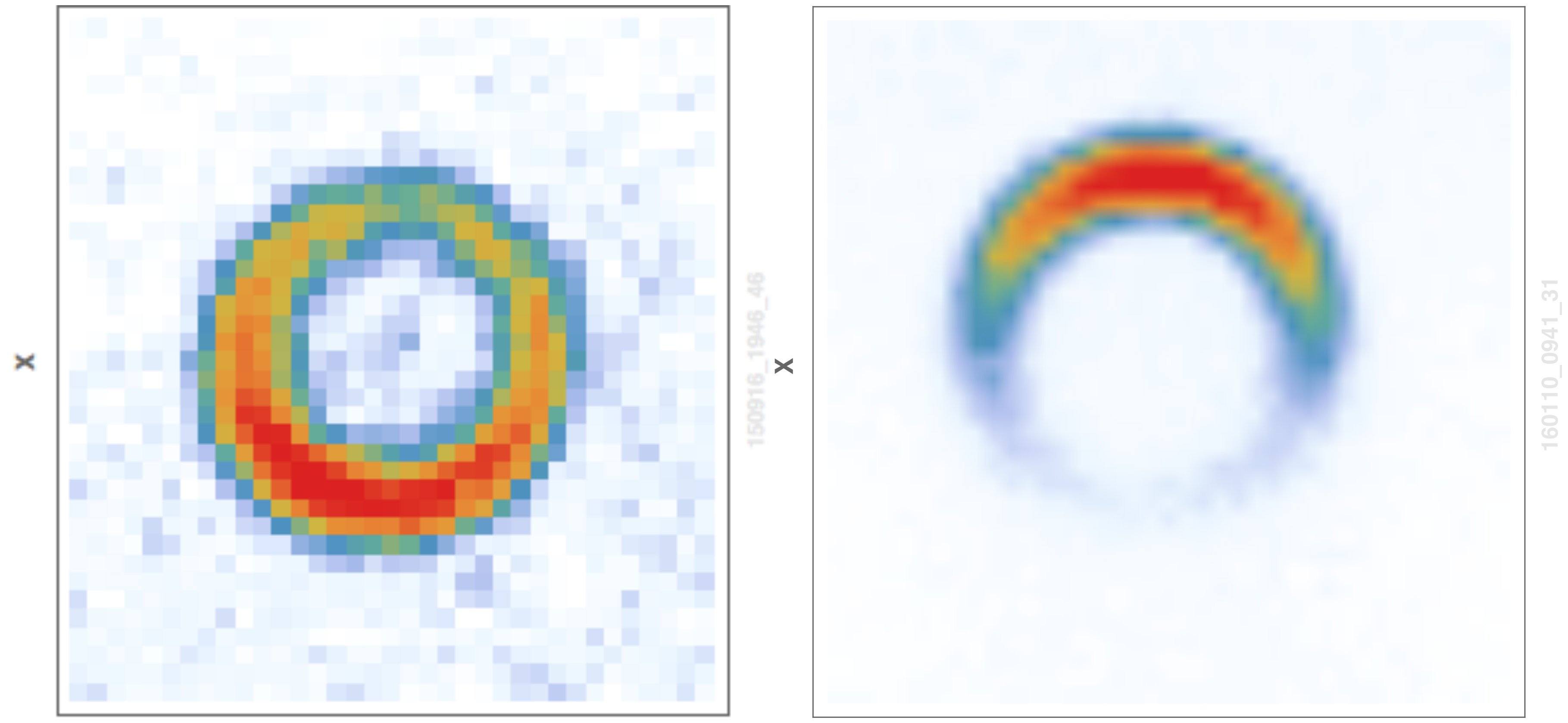
Flat Ring | Waveguide



Gravity Tilt

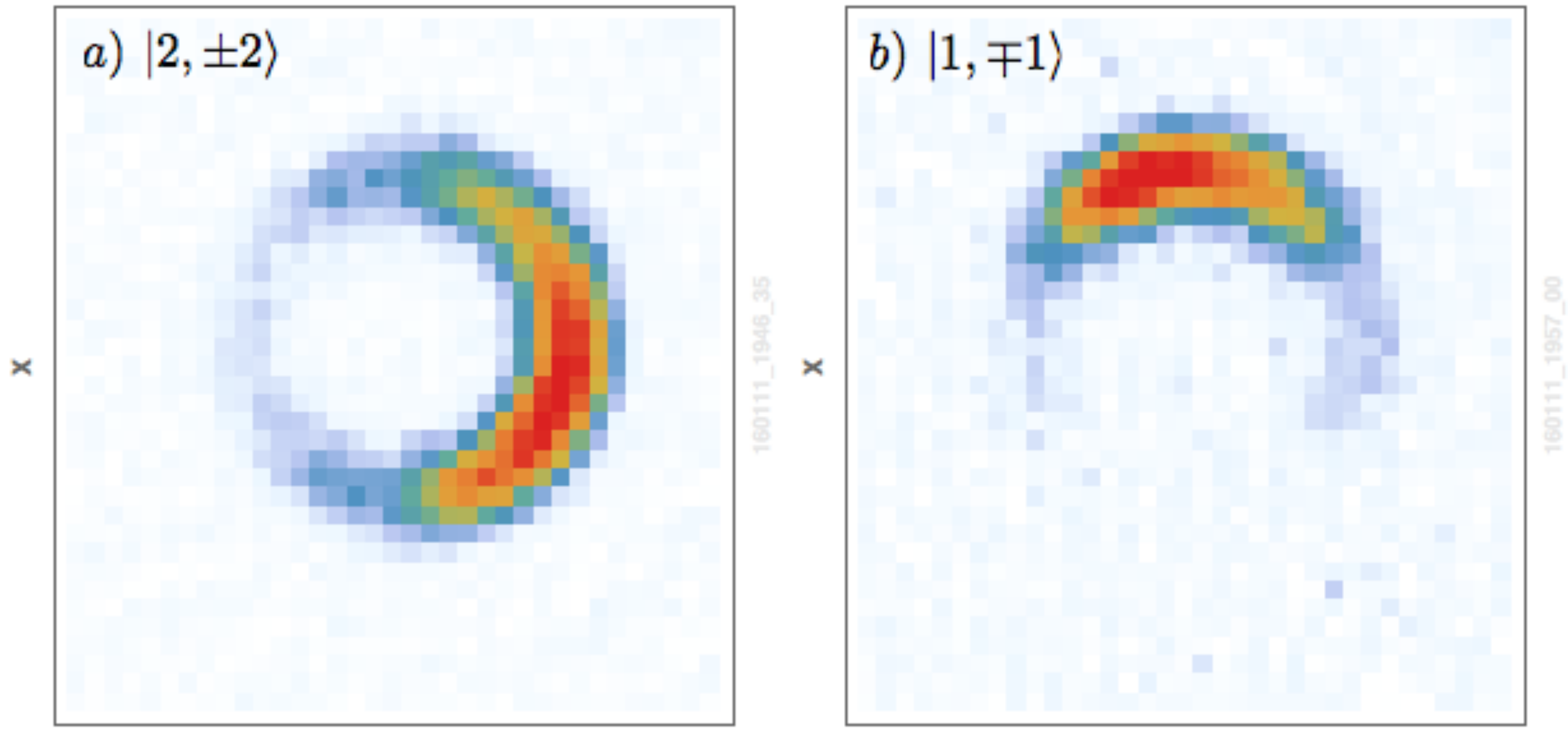


Polarization



$$\left|F=1, m_F=-1\right\rangle \qquad \left|F=2, m_F=+1\right\rangle$$

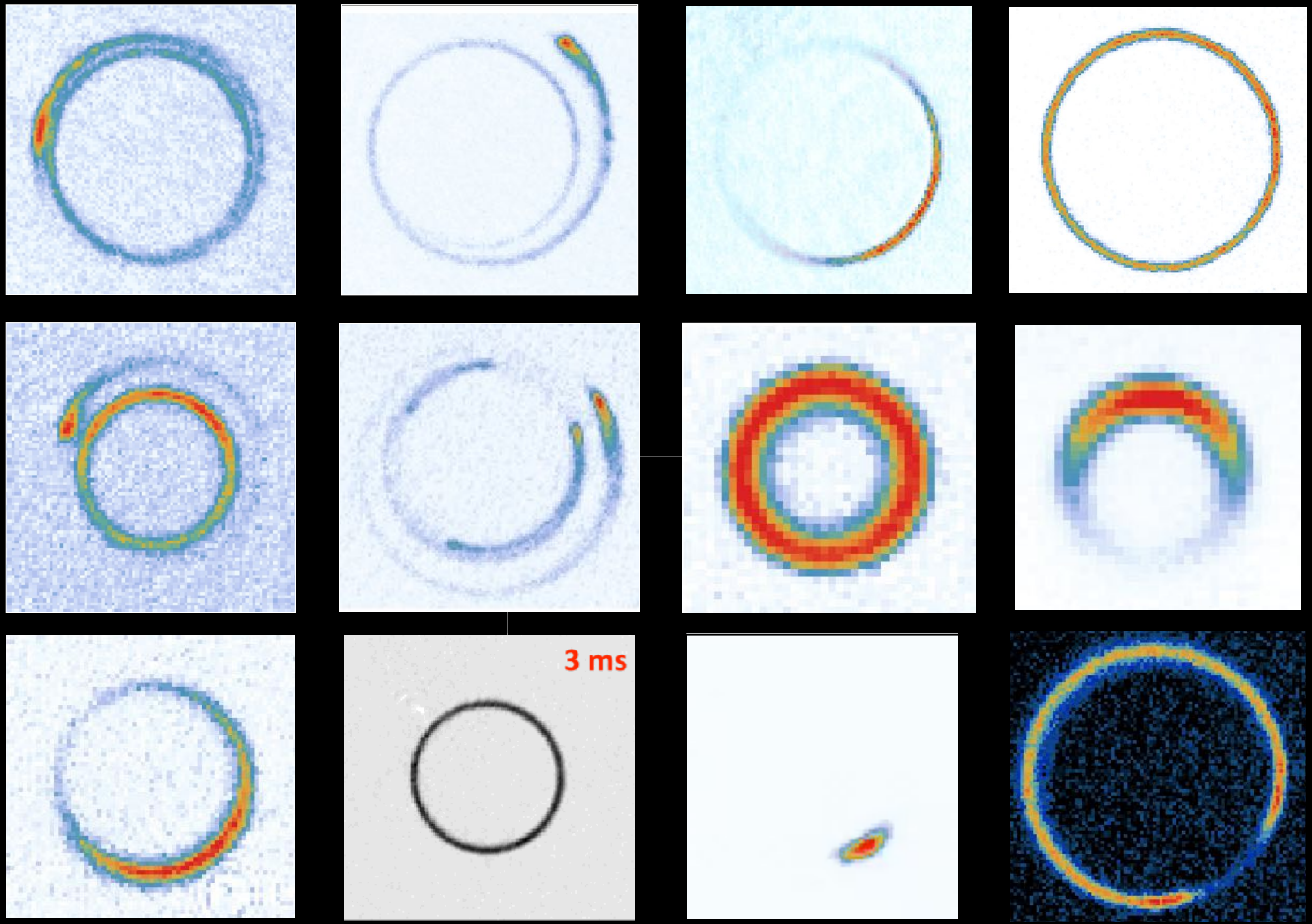
Gravity Tilt + Polarization



$$\left|F=1, m_F=-1\right\rangle \qquad \left|F=2, m_F=+1\right\rangle$$

P Navez et al. *New Journal of Physics* **18:7** 075014 (2016)

Atomtronic Ring Physics



Pandey et al @ Nature 2019