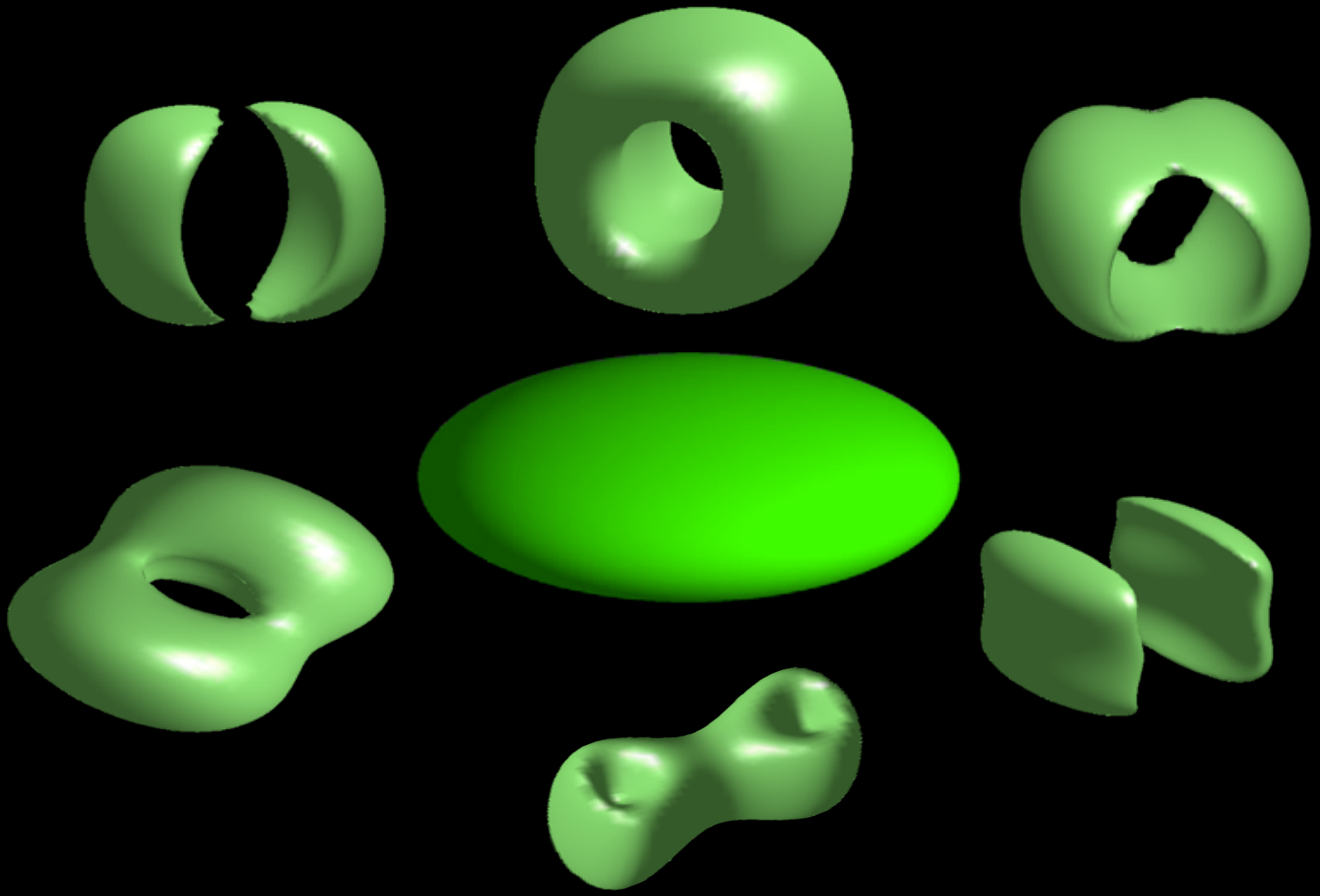
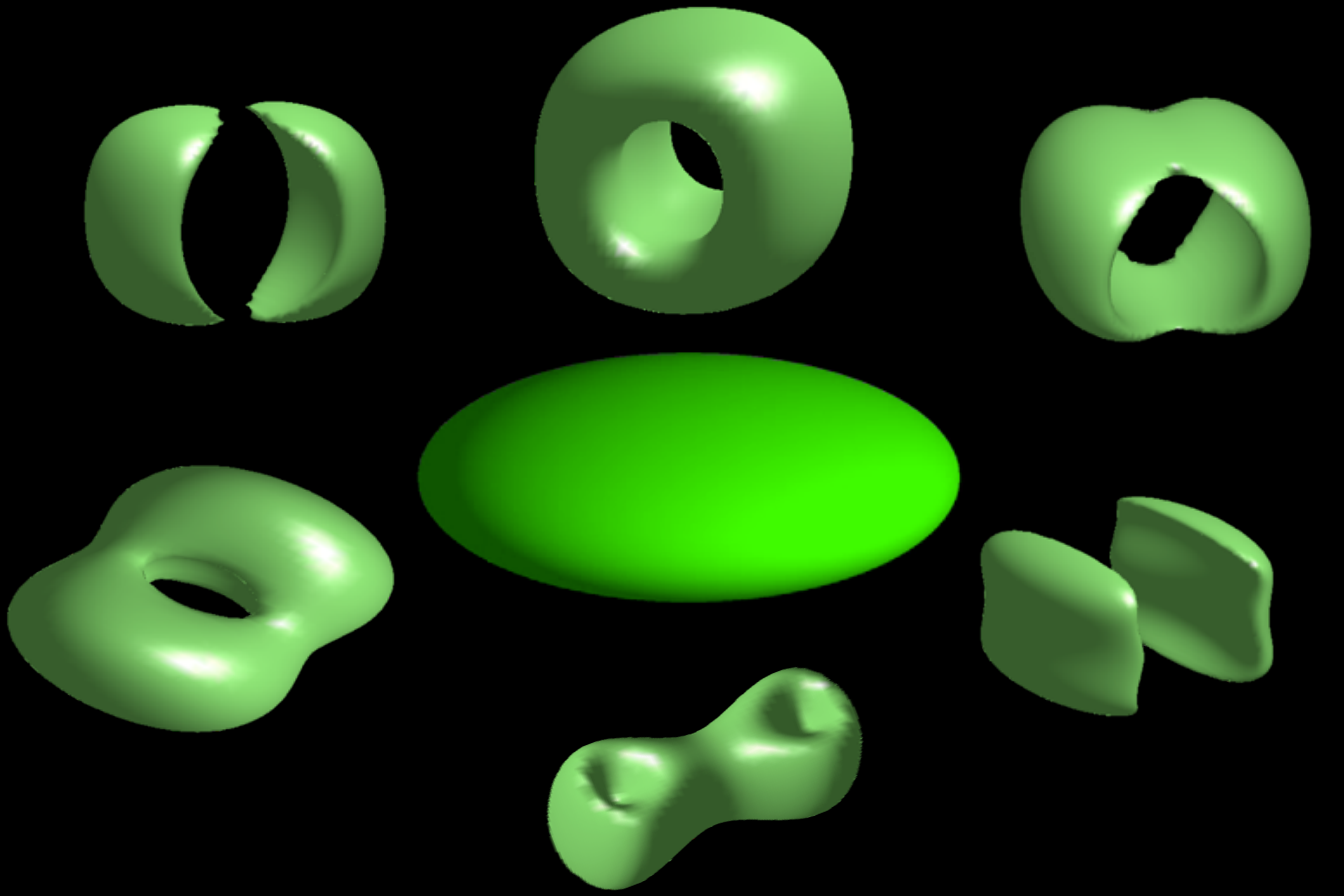
Time averaged adiabatic Potentials (TAAP)



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

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

Time averaged adiabatic Potentials (TAAP)



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

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

Cretan Matter-Waves Group

FORTH
IESL

Guided MatterWave Interferometers

Wolf von Klitzing

Benasque
06.05.2015

Outline

- Interferometry — Why? How?
- Time-Averaged Adiabatic Potentials (TAAP)
- Bucket Atomtronics
- Atom Lasers

Matter-Wave Interferometry
Why???

Sensitivity (Sagnac)

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

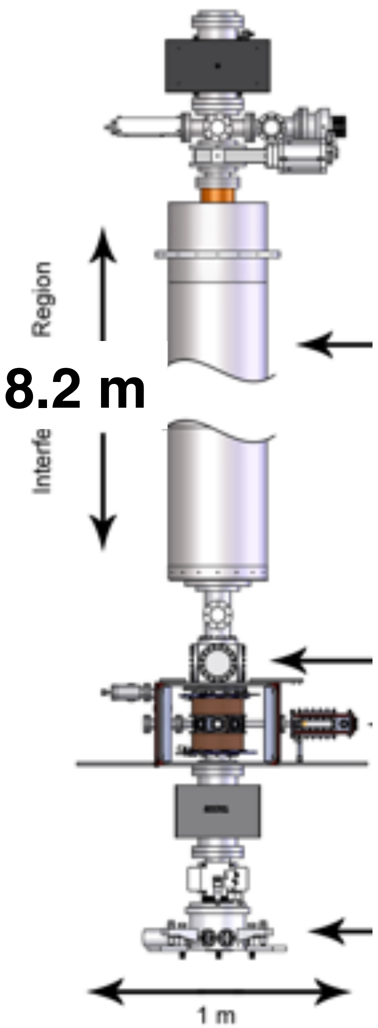
$$\frac{\Delta\phi_{\mathrm{atom}}}{\Delta\phi_{\mathrm{light}}} = \frac{\lambda_{\mathrm{light}}\, c_0}{h/m} = 5\mathrm{x}10^{10}$$

Plus

+ Internal States
+ Gravitation
+ Atom-Atom Interaction
  - Heisenberg Limited Detection

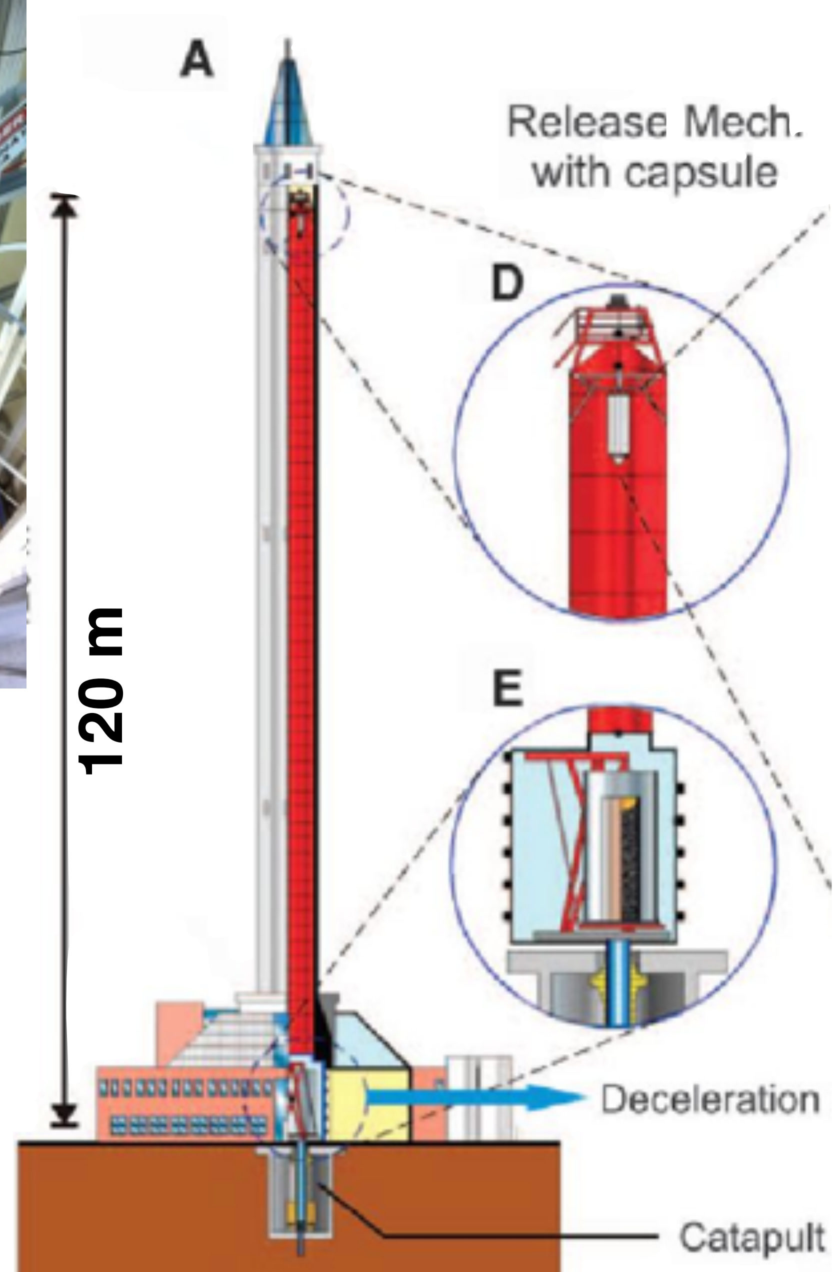
Matter-Wave Interferometers

Free Space

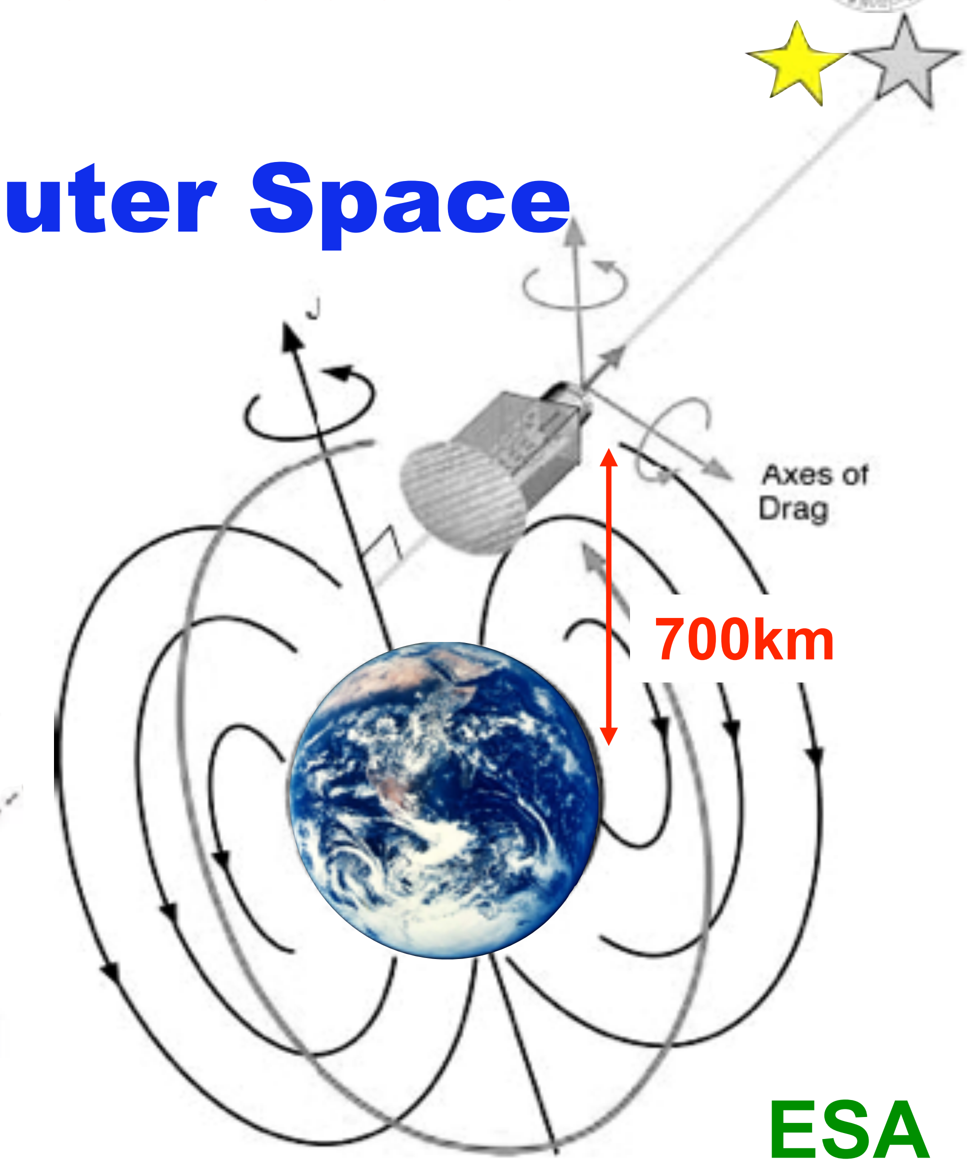


Stanford

ZARM
drop Tower



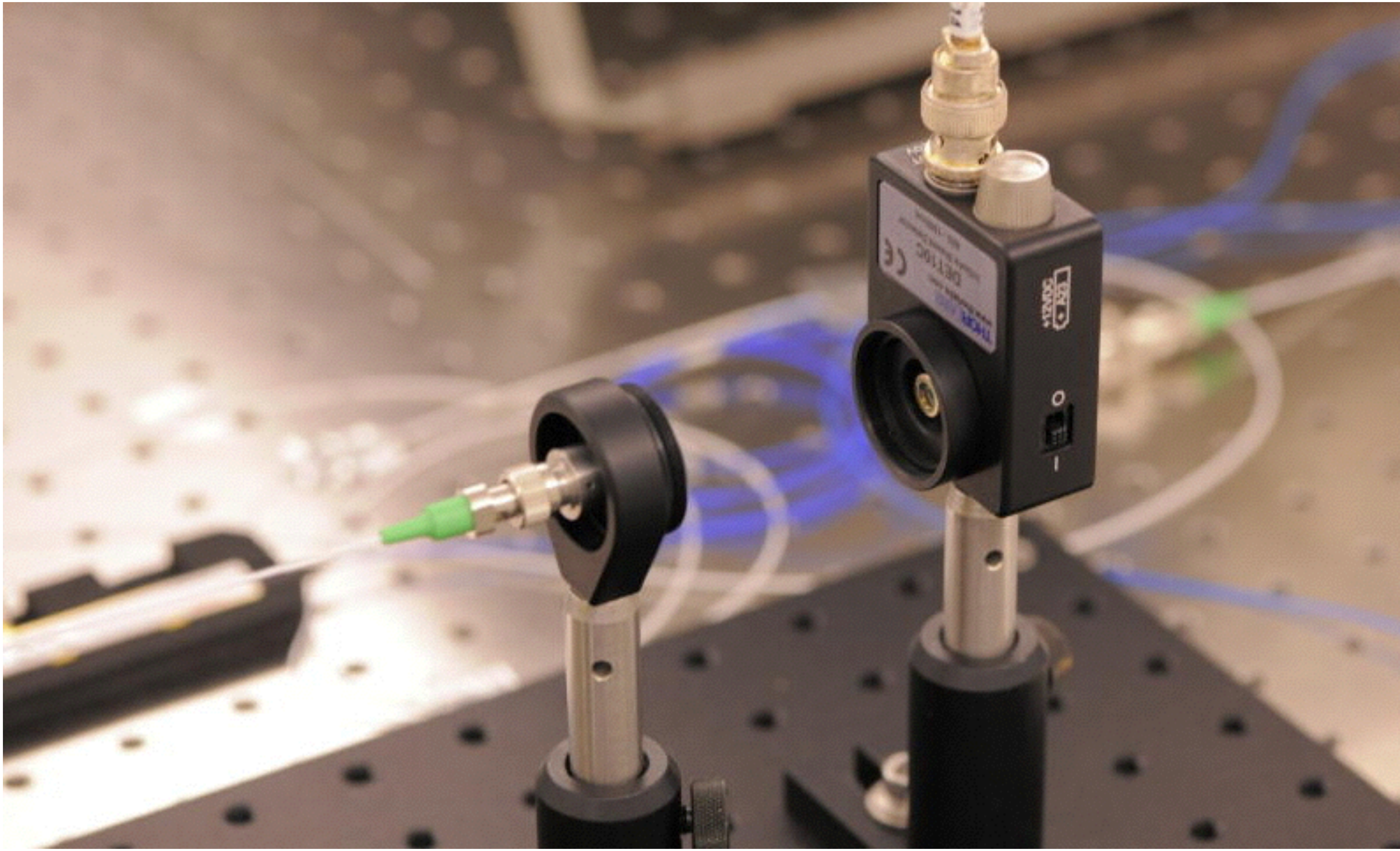
Outer Space



ESA
STE-QUEST

Preparation time:
~10 years

Repetition rate:
~23 μHz

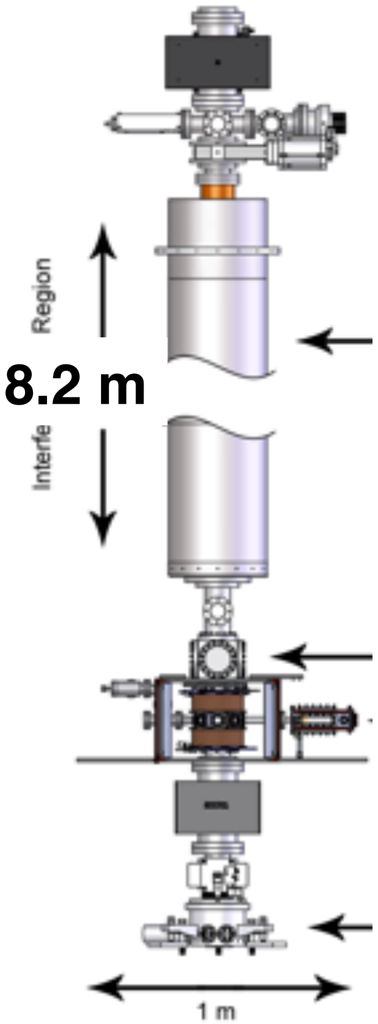


Shown here is the Goddard-designed breadboard laser system critical to advancing atom-optics instruments. The device will be tested in the Stanford University drop tower. Credit: NASA/Pat Izzo

http://www.sciencedaily.com/releases/2012/10/121018185947.htm

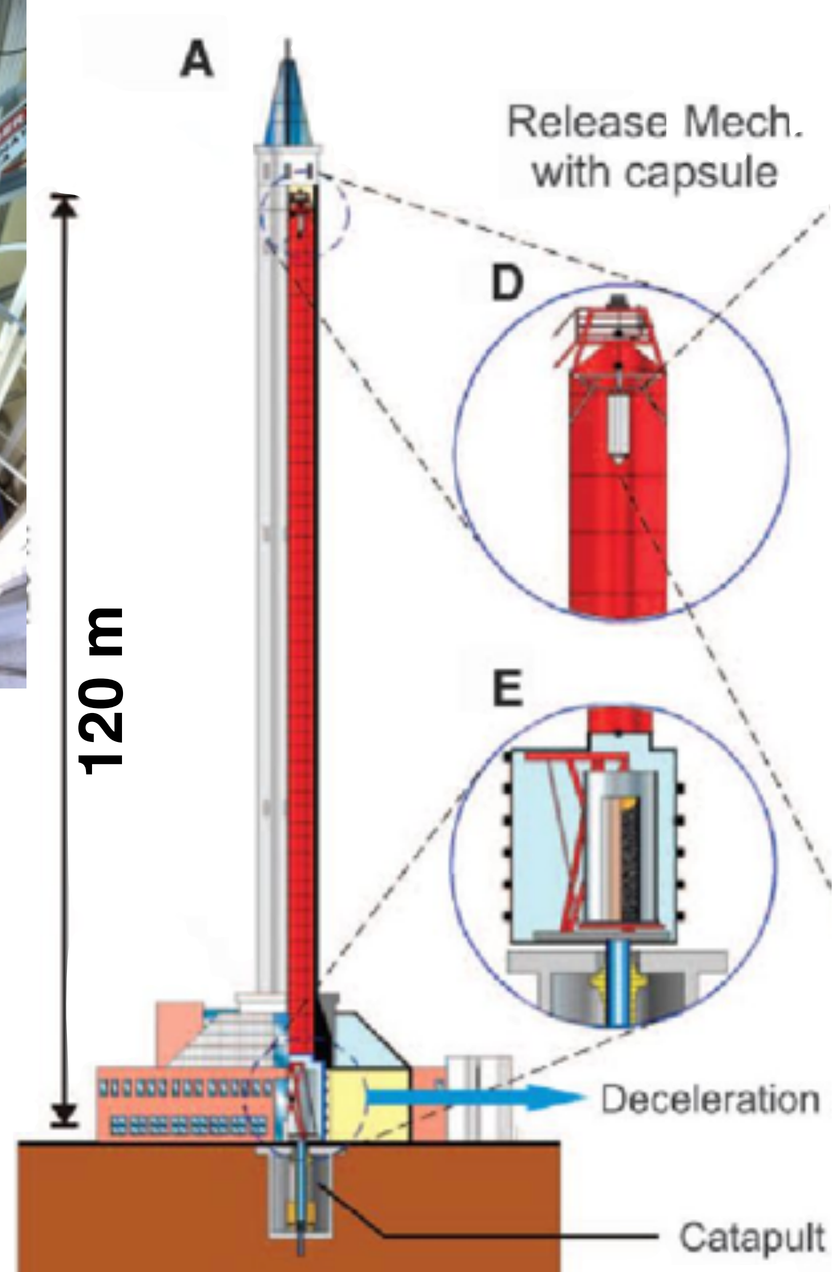
Matter-Wave Interferometers

Free Space

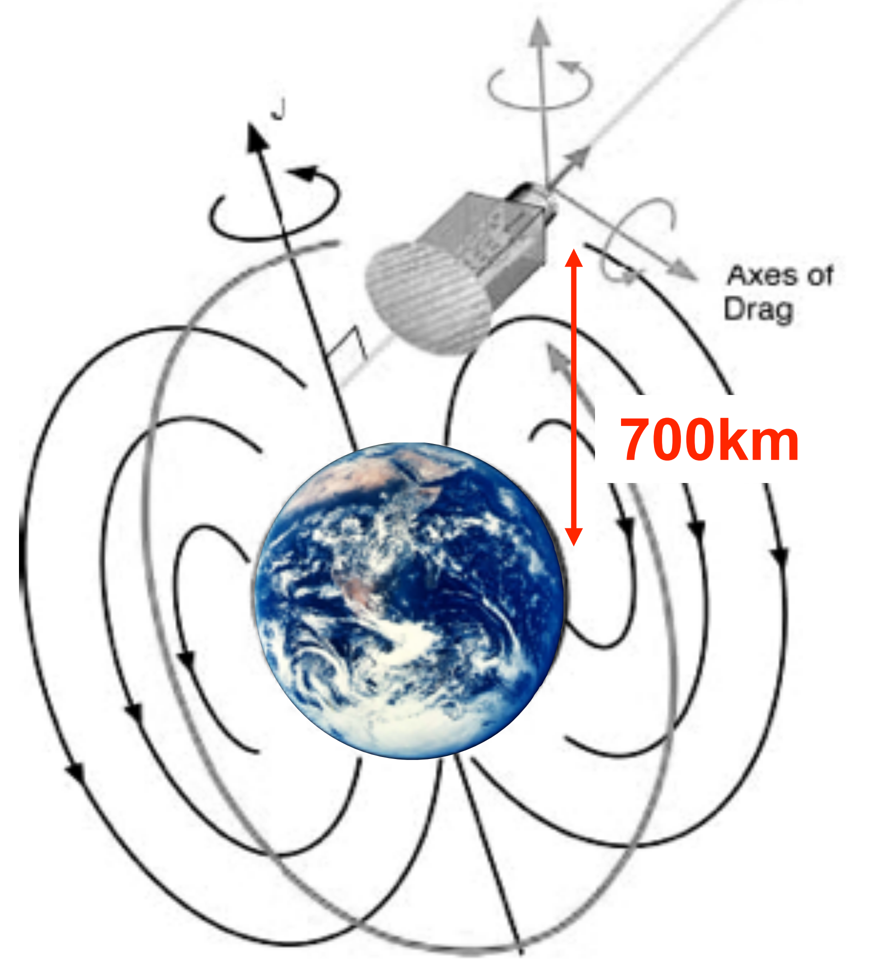


Stanford

ZARM drop Tower



Outer Space

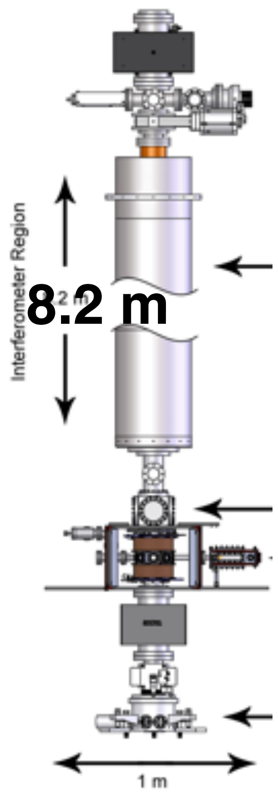


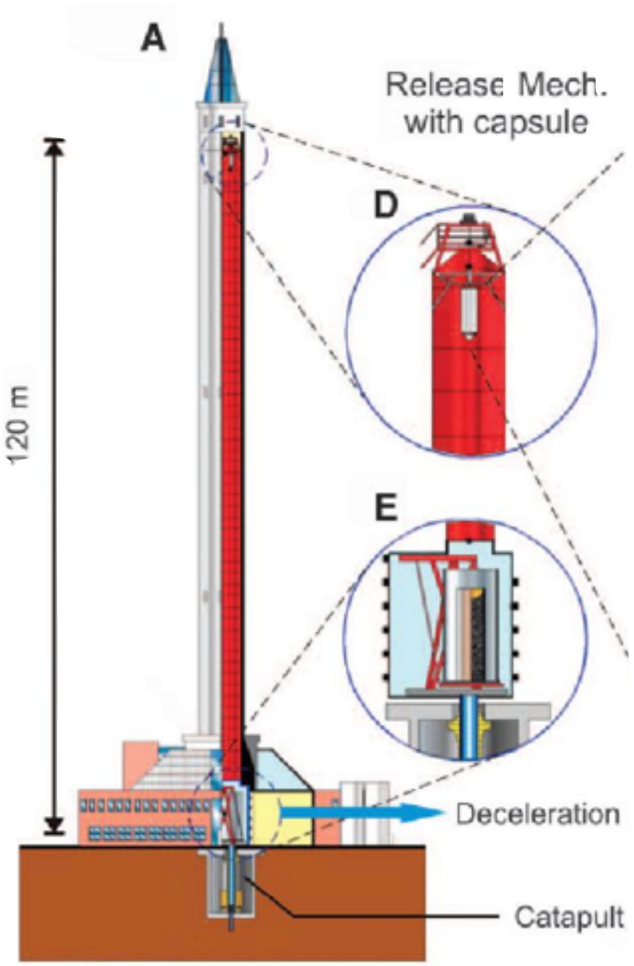
Preparation time: ~10 years

Repetition rate: ~23 μHz

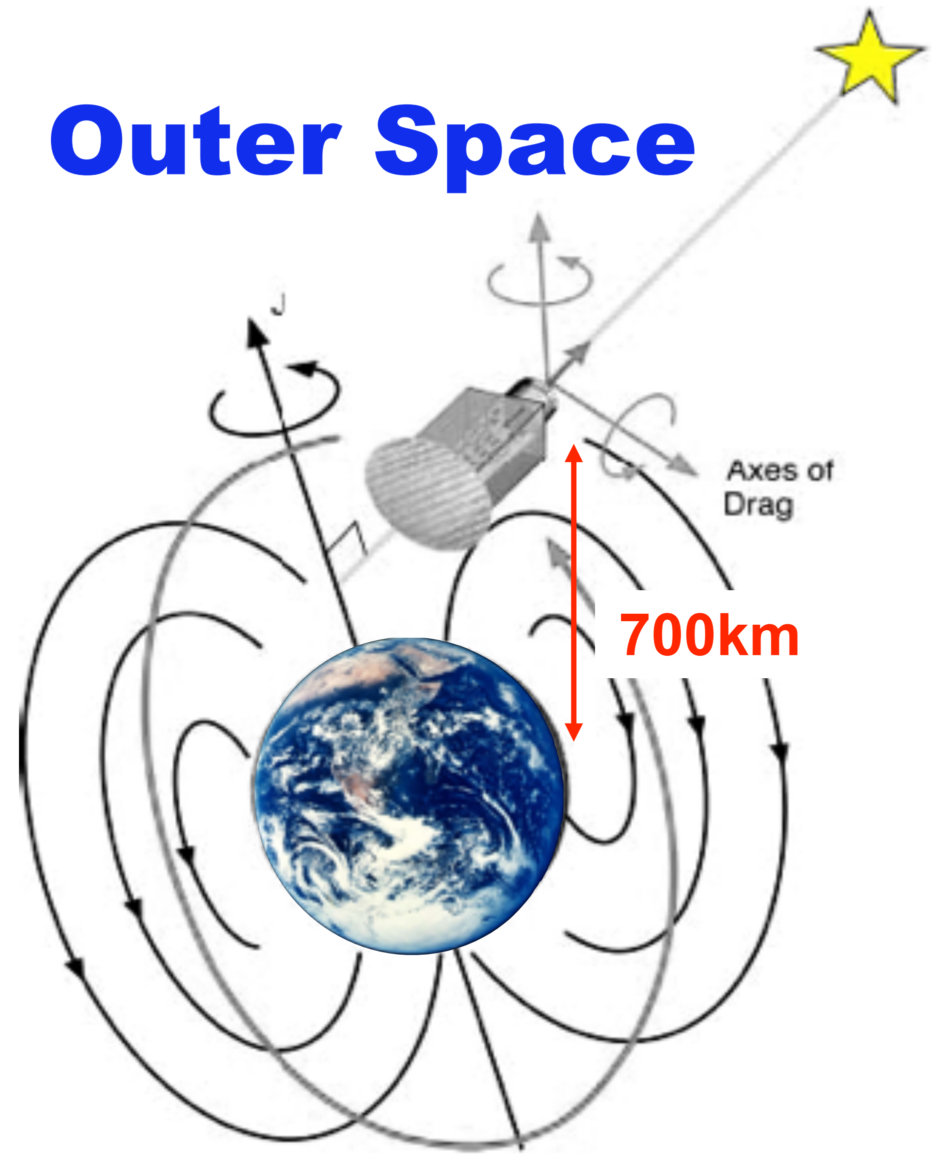
Matter-Wave Interferometers

Free Space

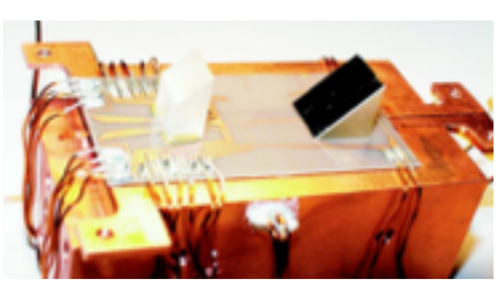




Outer Space

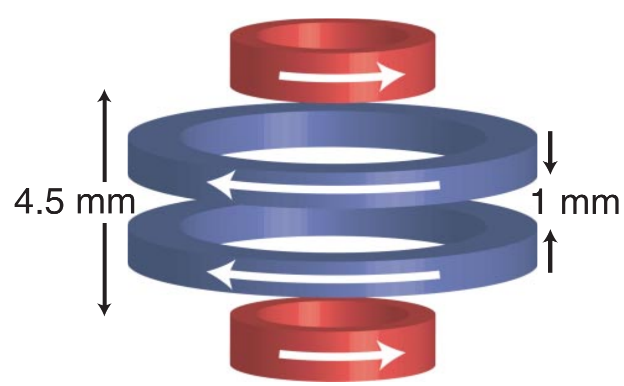


Guided: Atomtronics

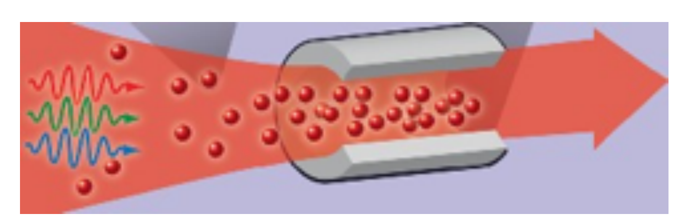


← 2cm →

← 5 µm - 2 cm →



← 1-3 mm →



← cm →

Why Guiding is BAD

- Interactions
  - With the environment
  - With with guide
  - With other atoms
- Two Examples
  - The rotating bucket
  - Chemical Potential…

$$\mu = \frac{\hbar\,\omega_{\text{ho}}}{2}\left(\frac{15Na}{a_{\text{ho}}}\right)^{2/5}$$

Thomas Fermi BEC with

1000 atoms / 1kHz radial / 40 aspect ratio => 0.1s

Why Guiding is GOOD

- Interactions
  - With the environment
  - With with guide
  - With other atoms
- Two Examples
  - The rotating bucket
  - Chemical Potential…

More Time

$$\mu = \frac{\hbar\,\omega_{\rm ho}}{2}\left(\frac{15Na}{a_{\rm ho}}\right)^{2/5}$$

Squeezing

Thomas Fermi BEC with

1000 atoms / 1kHz radial / 40 aspect ratio => 0.1s

Miniaturisation!

Matter-Wave Guides

Atomtronics Circuits

- **Bend - Closed Loop**
- **Smooth / Coherent**
- **Dynamically Controllable**

Matter-Wave Guides

Boshier Criteria of Atomtronics

- **L**oop
- **S**mooth
- **D**ynamic

Matter-Wave Guides

Boshier Criteria of Atomtronics

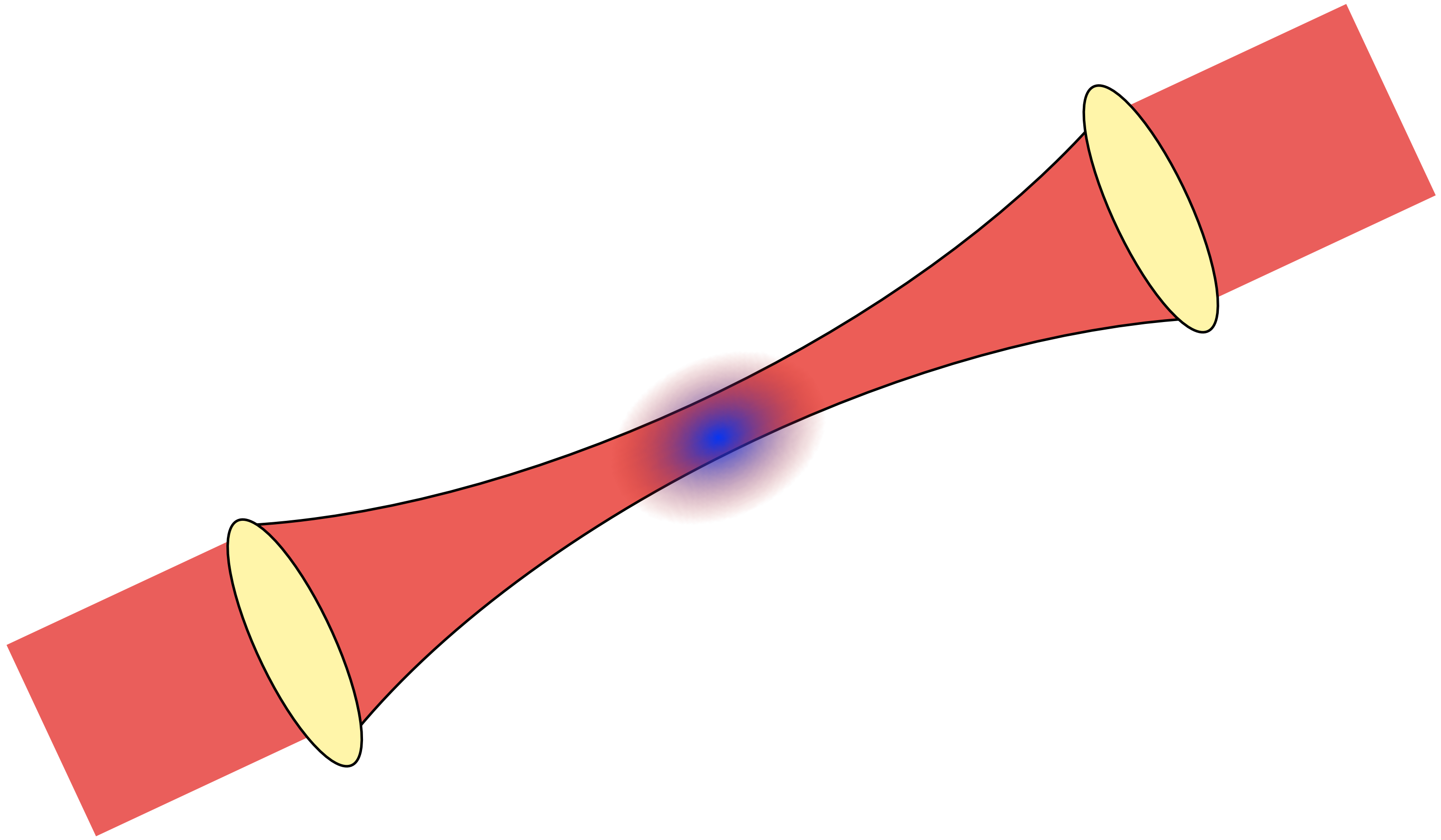
- **L**oop
- **S**mooth
- **D**ynamic

- **Dipole Traps & Guides**
- **Magnetic Fields**

Boshier, Benasque 2015

Dipole Guides

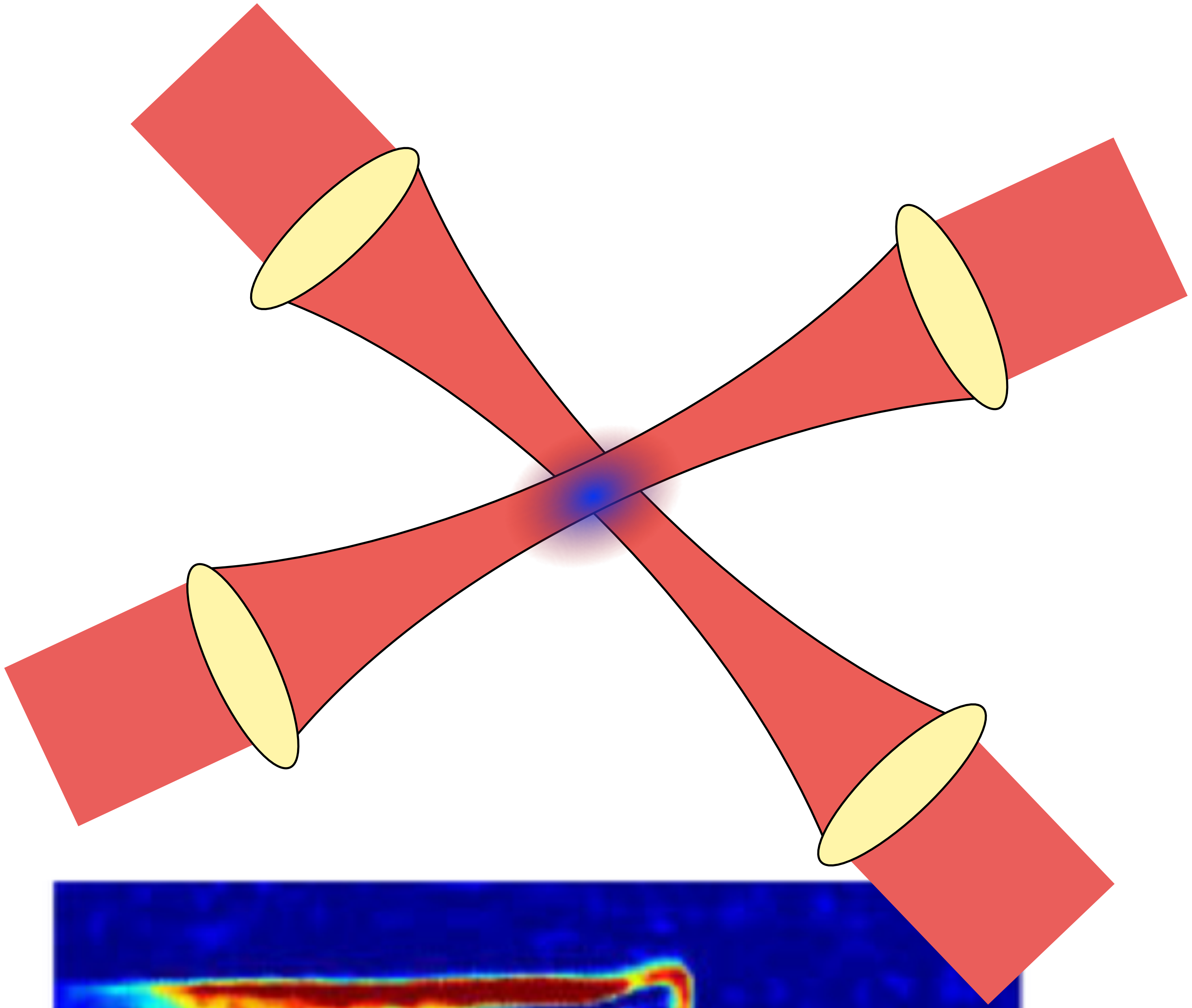
- Free space beams
- Lattices
- Paintings
- Fibres

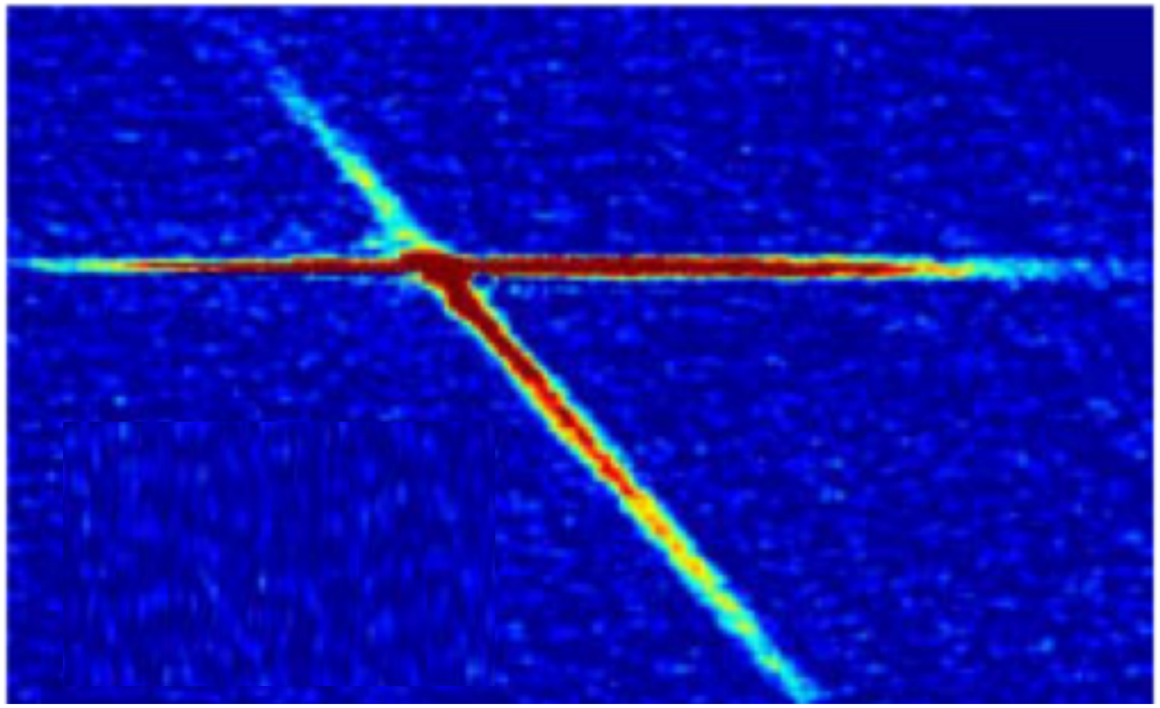


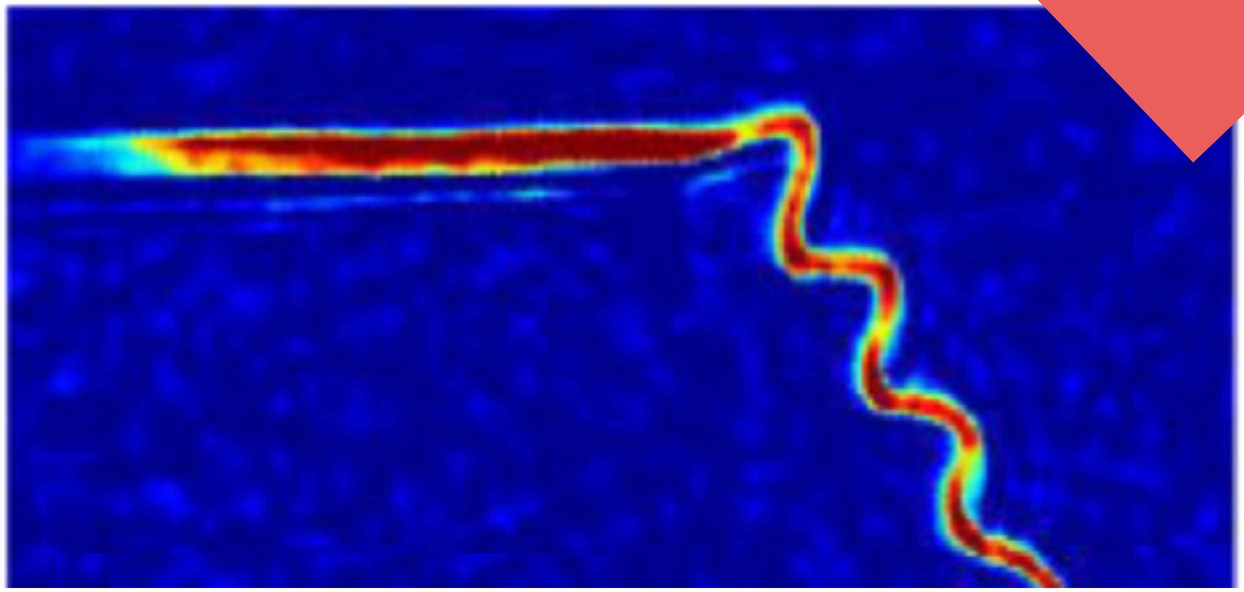
$$U_{\text{dipole}} \simeq \frac{\hbar\Omega^2}{4\delta} \equiv \frac{\hbar\Gamma}{8}\frac{\Gamma}{\delta}\frac{I}{I_{\text{sat}}}\,.$$

Dipole Guides: Beam Splitters

- Free space beams
- Lattices
- Paintings
- Fibres

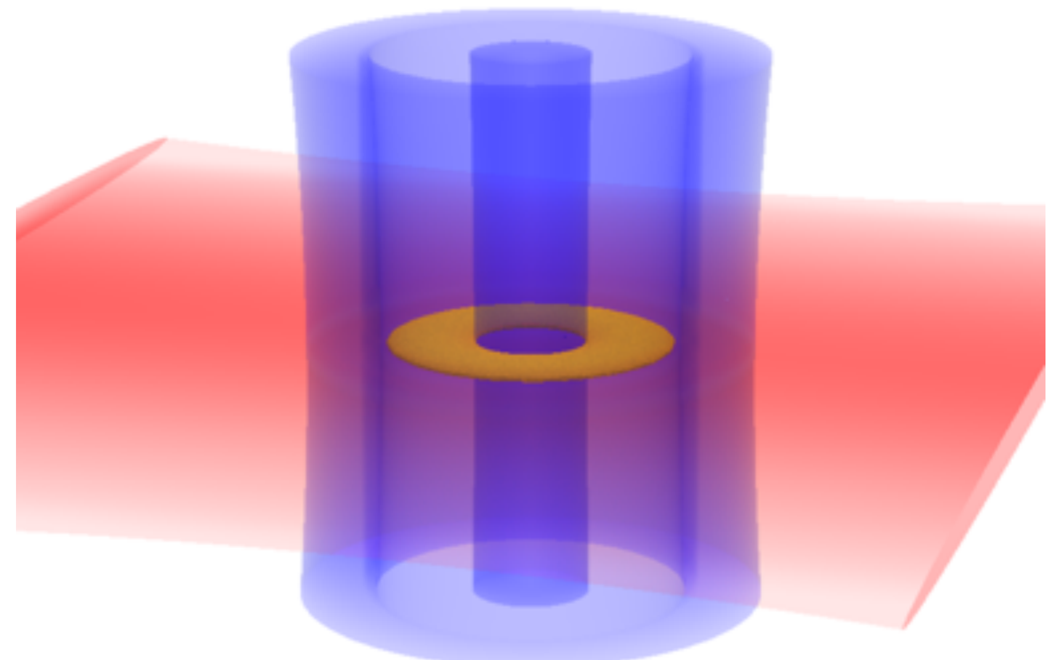


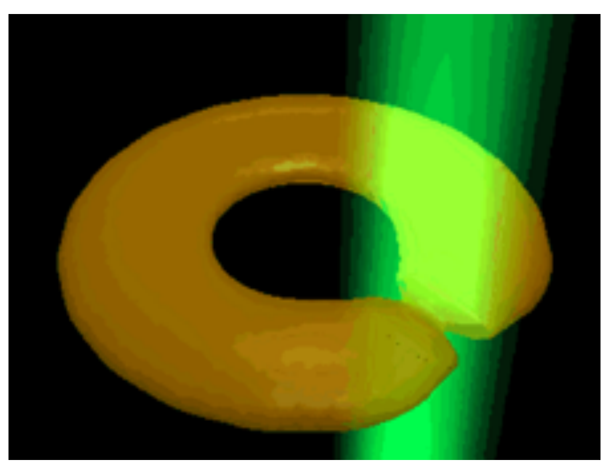




Dipole: Rings

- Free space beams
- Lattices
- Paintings
- Fibres

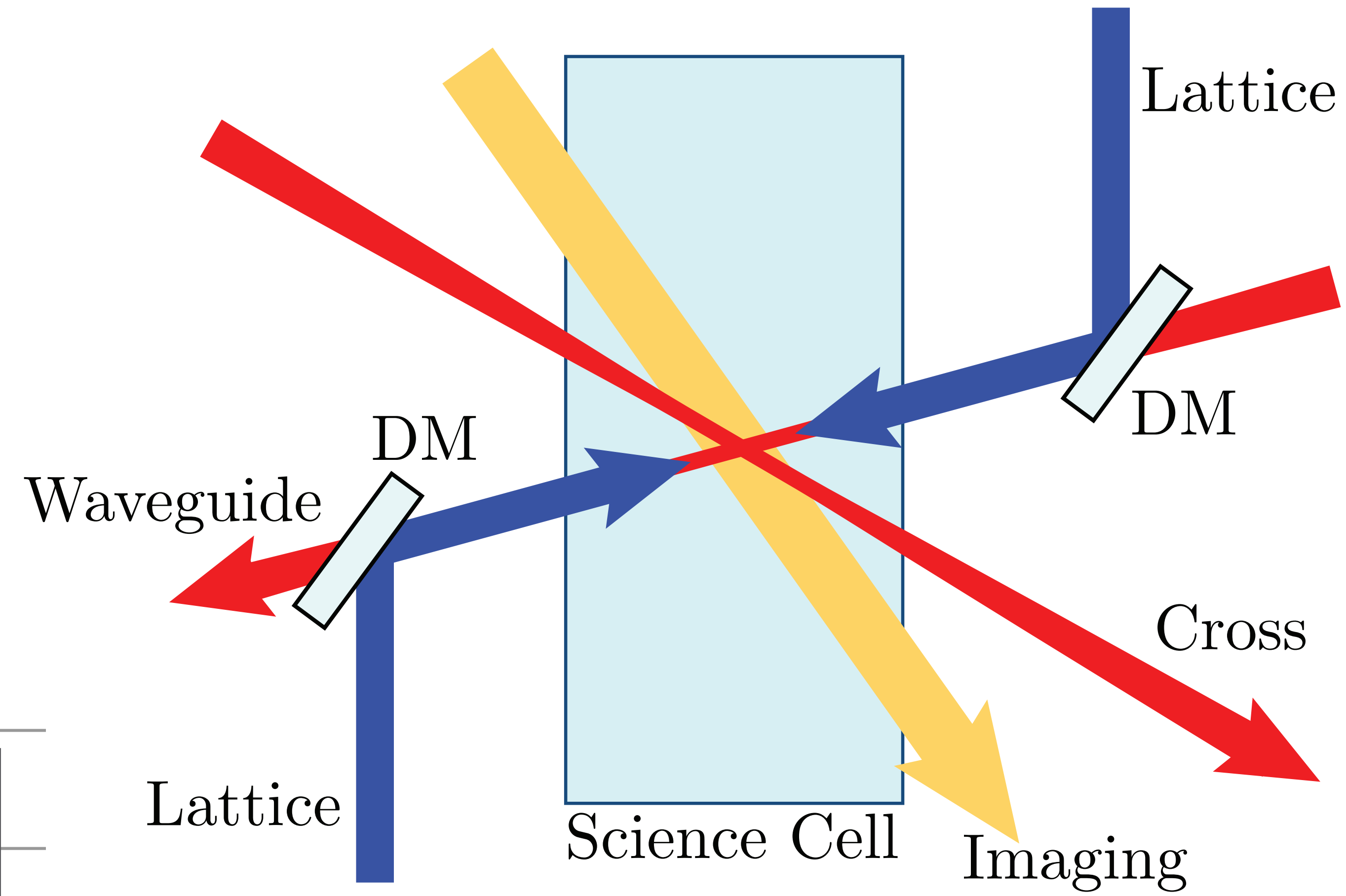


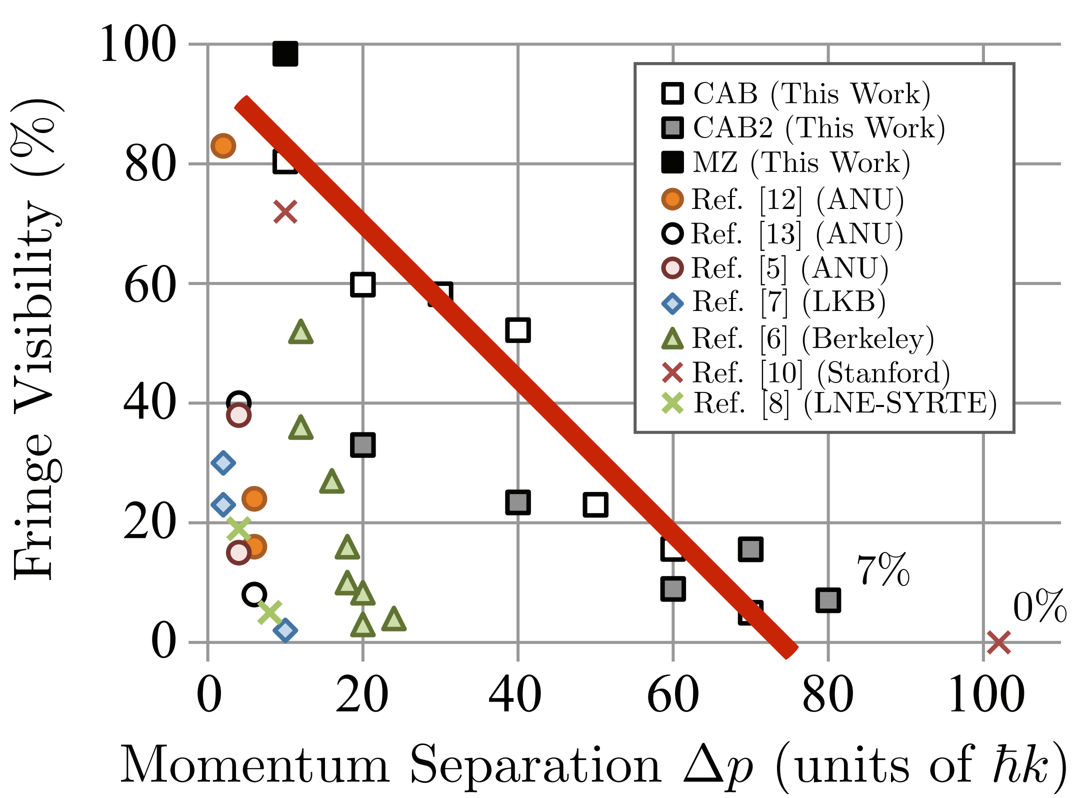


Experimental demonstration of ***painting*** arbitrary and dynamic potentials for Bose-Einstein condensates
K. Henderson et al. N.J.Phys **11**: 043030 (2009)

Dipole Guides: Beam Splitters

- Free space beams
- Lattices
- Paintings
- Fibres





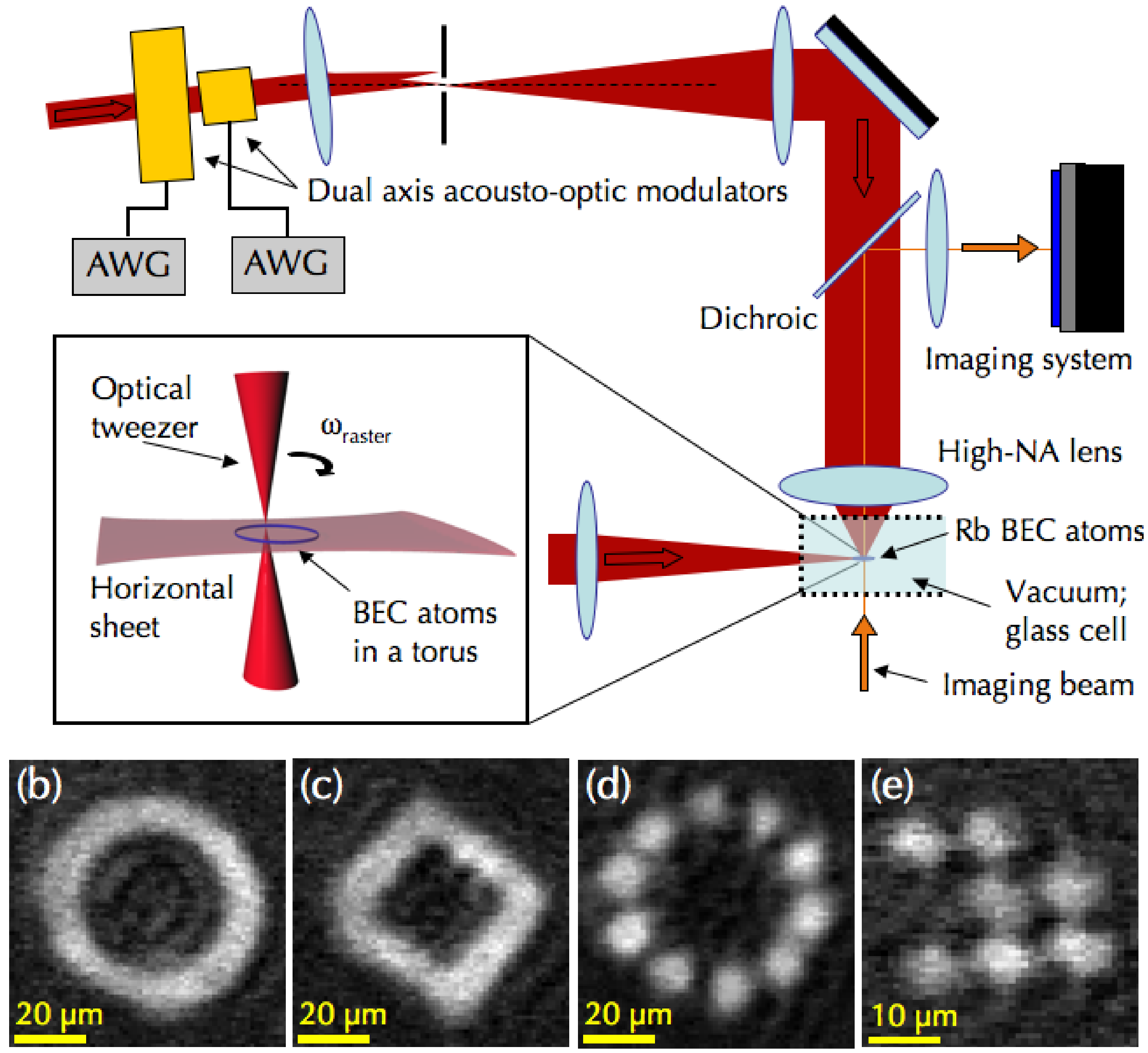
$80\hbar k$

Beam-Splitter by Bloch Oscillations

G D McDonald et al. PHYSICAL REVIEW A **88:5** 053620 (2013)

Dipole: Paintings

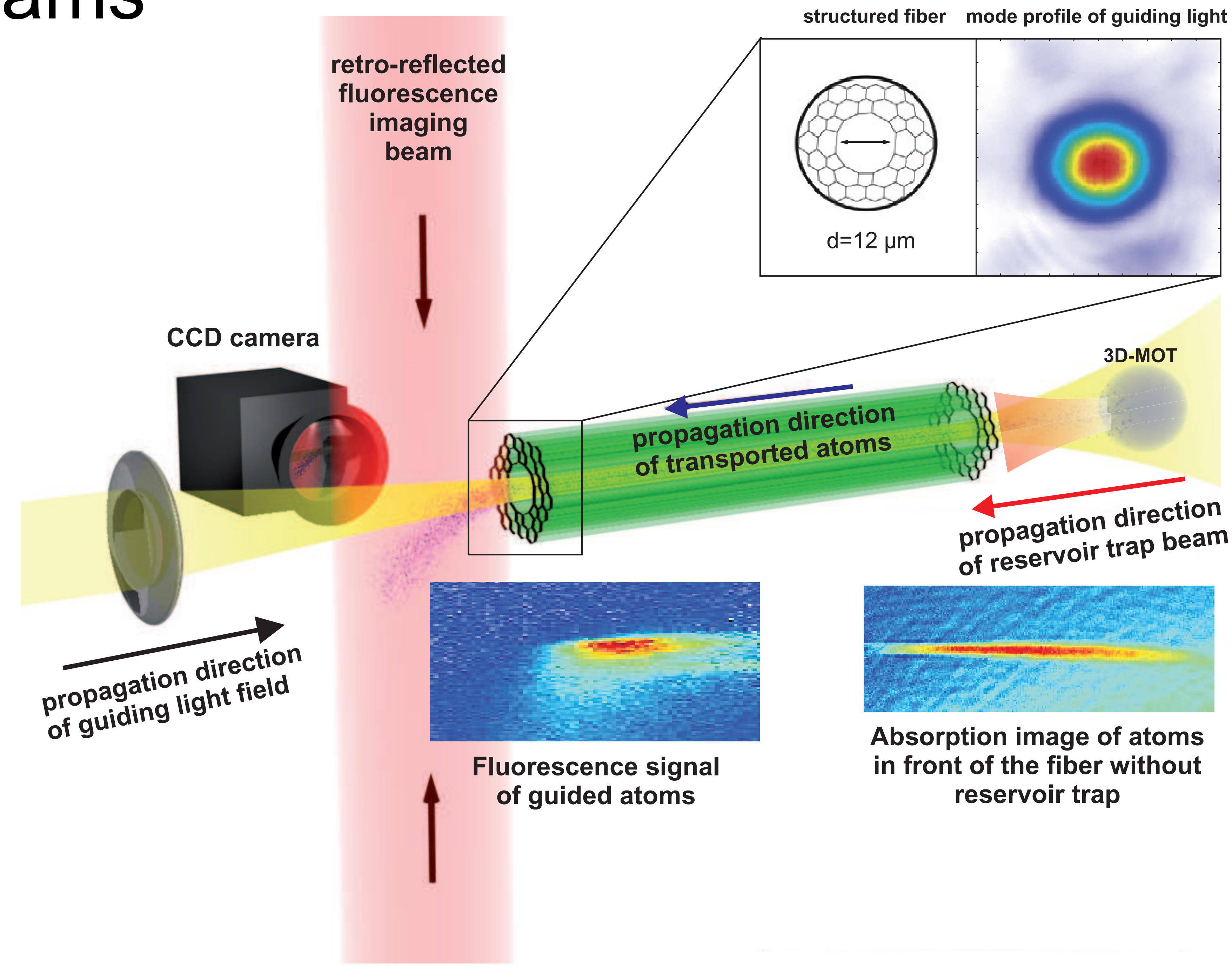
- Free space beams
- Lattices
- Paintings
- Fibres



Experimental demonstration of ***painting*** arbitrary and dynamic potentials for Bose-Einstein condensates
K. Henderson et al. N.J.Phys **11**: 043030 (2009)

Dipole Guides: Optical Fibres

- Free space beams
- Lattices
- Paintings
- Fibres



S. Vorrath, S. A. Möller, P. Windpassinger, K. Bongs, and K. Sengstock New Journal of Physics **12:12** 123015 (2010)

Dipole
Matter-Wave Guides

- **Dipole Traps**

LSD - Guides

LSD - Lattices

LSD - Paintings

LSD - Fibres

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
- **Dynamic**

Magnetic Matter-Wave Guides

- **Magnetic Fields**
  - IP-Trap
  - Atomic chips
  - Mini-traps
  - Adiabatic

Boshier Criteria of Atomtronics

- **Loop**
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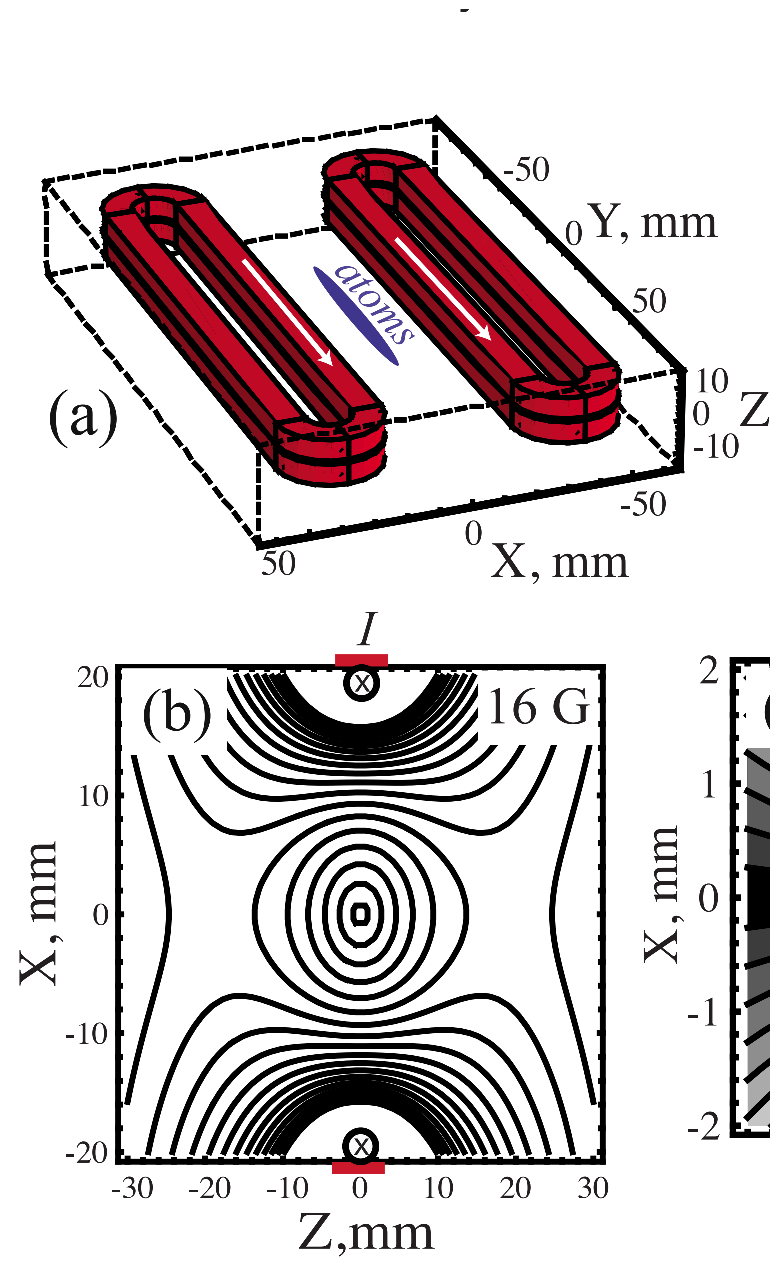
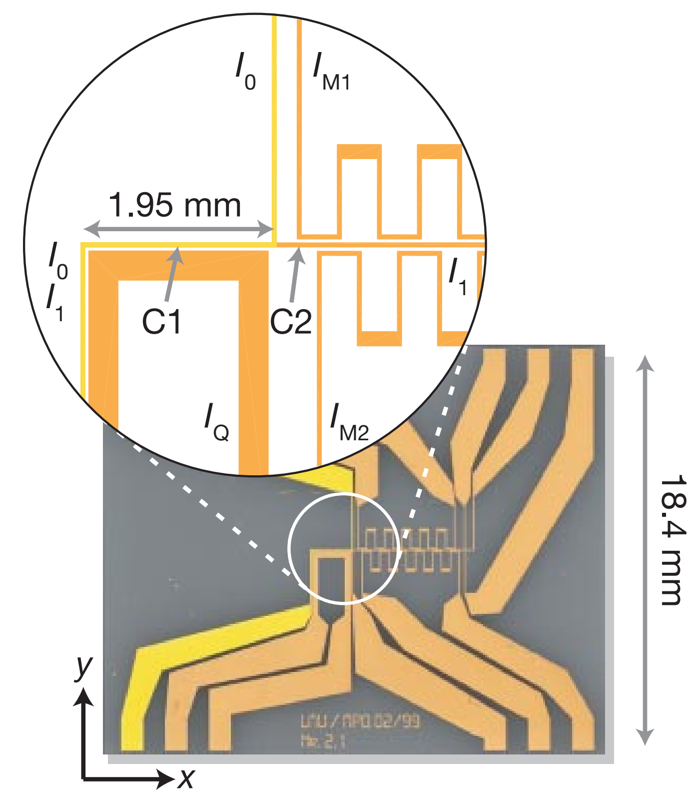
- **Dynamic**

Magnetic Guides

- **Magnetic Fields**
  - IP-Trap
  - Atomic chips
  - Mini-traps
  - TAAPs





Alexey Tonyushkin and Mara Prentiss Journal of Applied Physics **108**:9 094904 (2010)

Magnetic Guides

- **Magnetic Fields**
  - IP-Trap
  - Atomic chips

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
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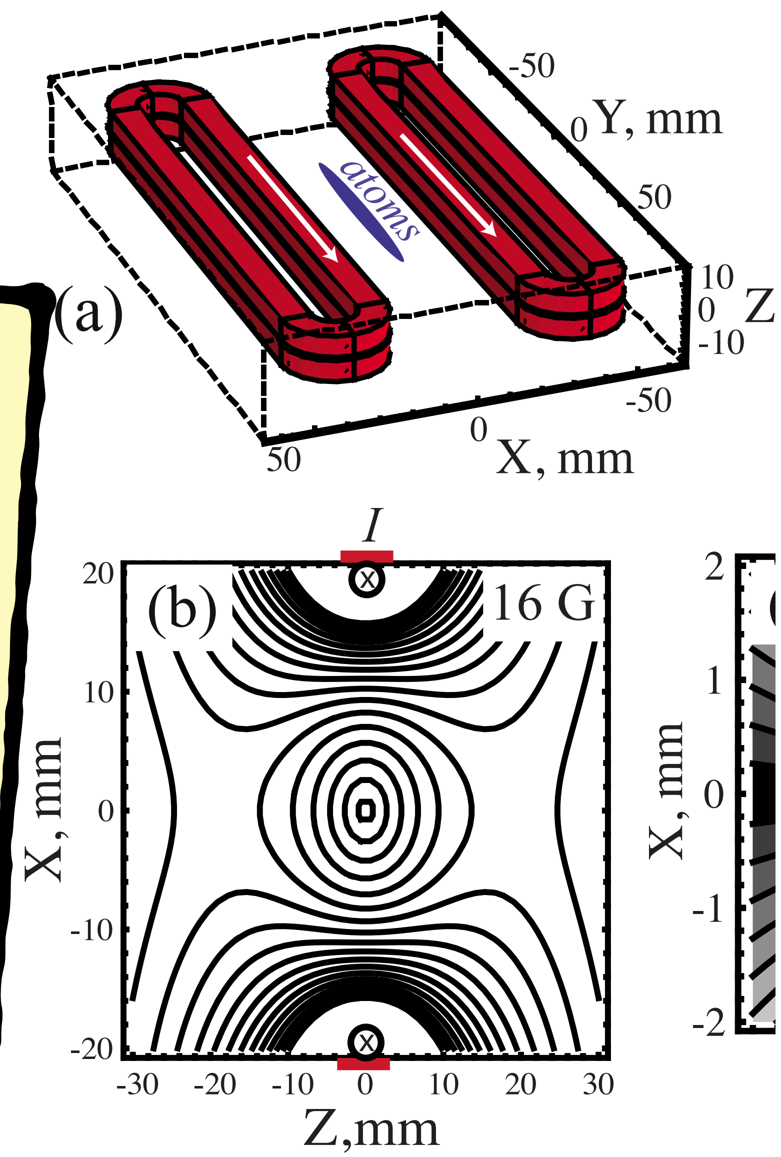
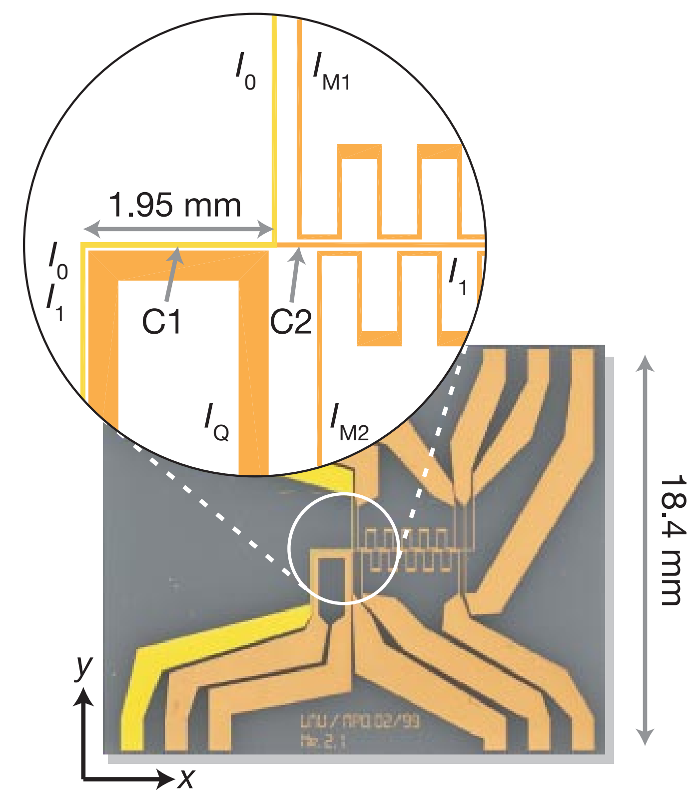
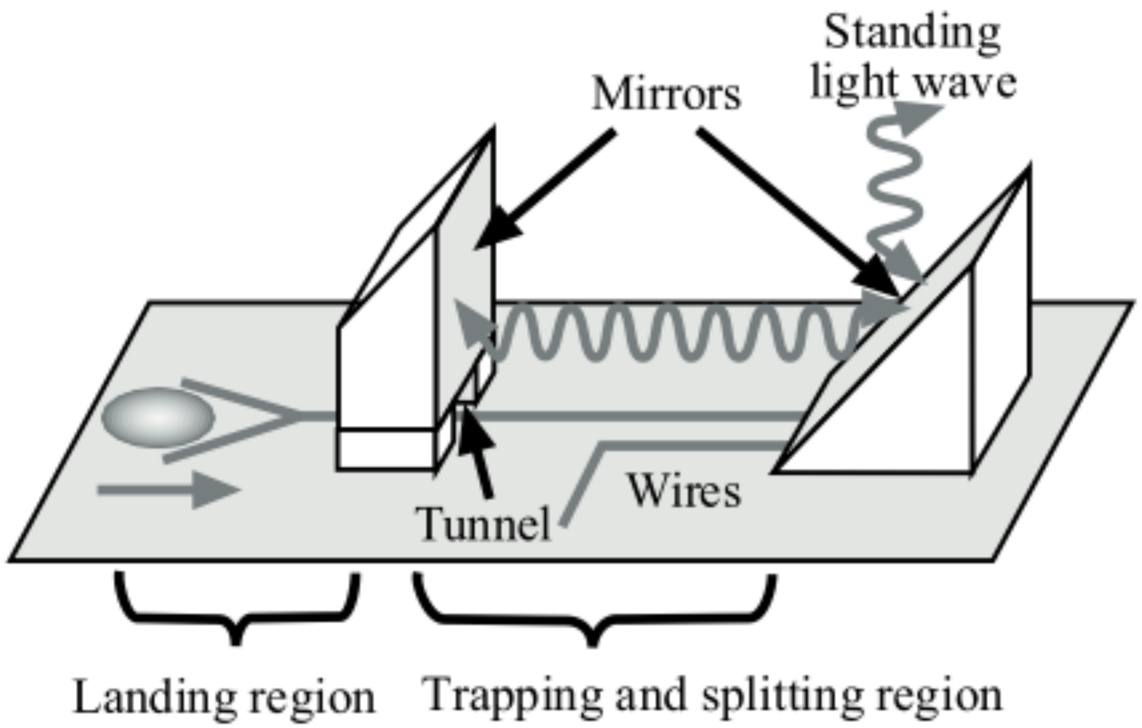
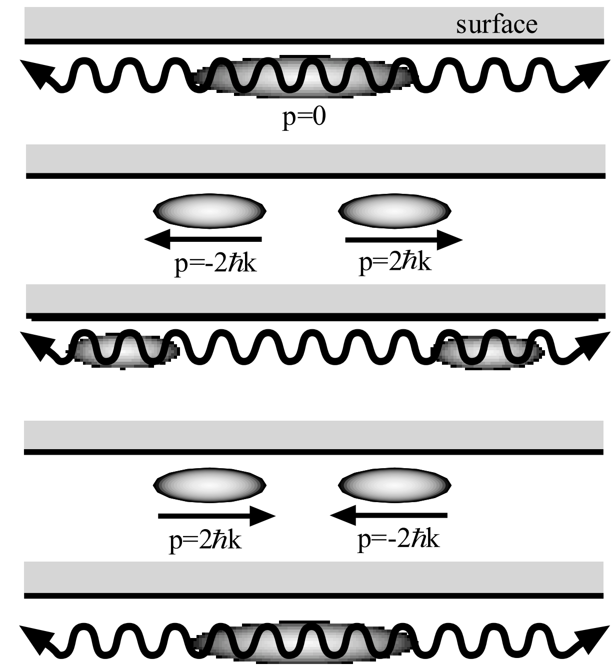


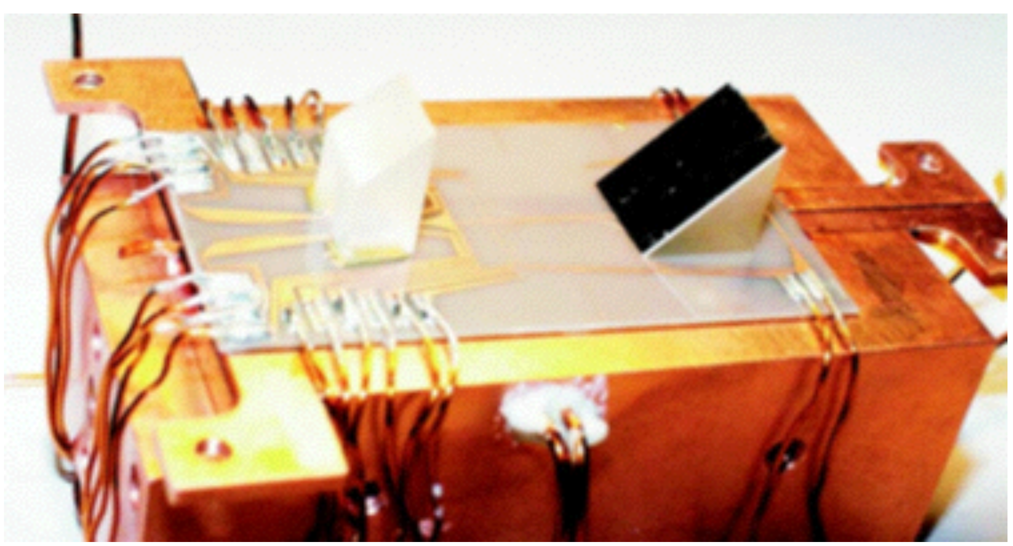


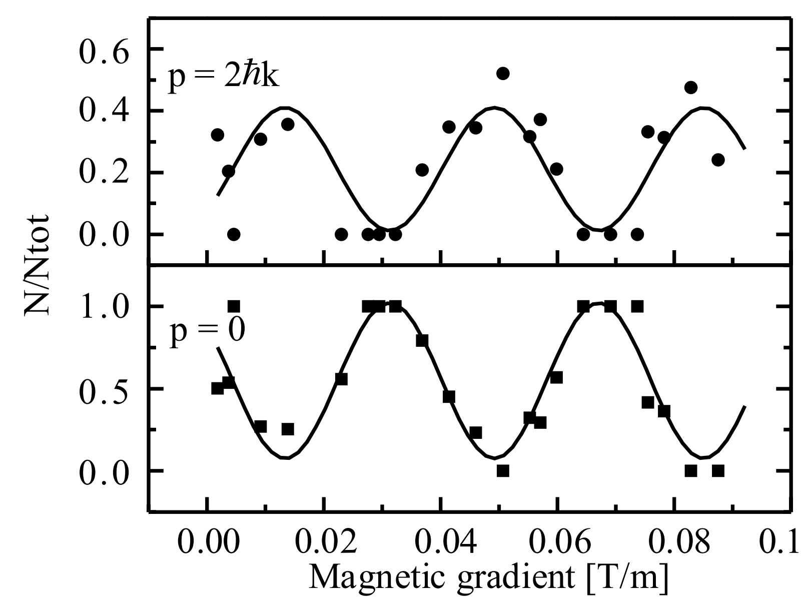
Alexey Tonyushkin and Mara Prentiss Journal of Applied Physics **108**:9 094904 (2010)

Micro Chips







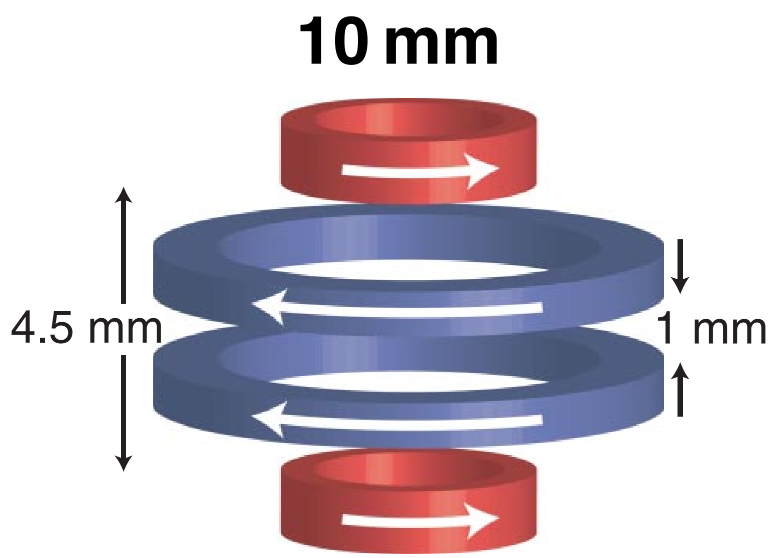


Atom Michelson interferometer on a chip using a Bose-Einstein condensate

Physical Review Letters 94 090405 (2005)

Y. J. Wang, D. Z. Anderson, V. M. Bright, E. A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R. A. Saravanan, S. R. Segal, and S. J. Wu

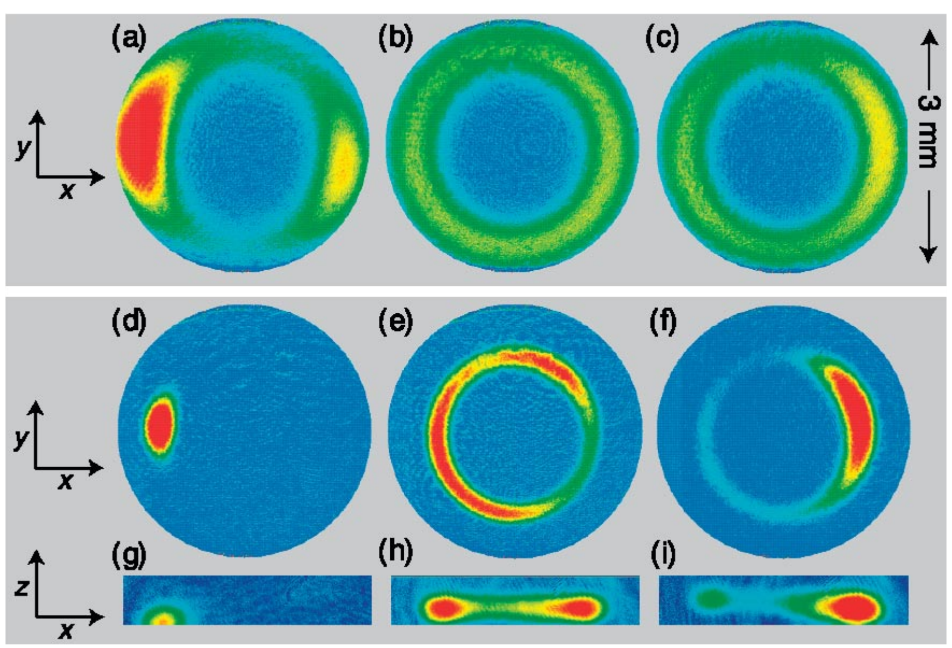
Magnetic Ring Traps

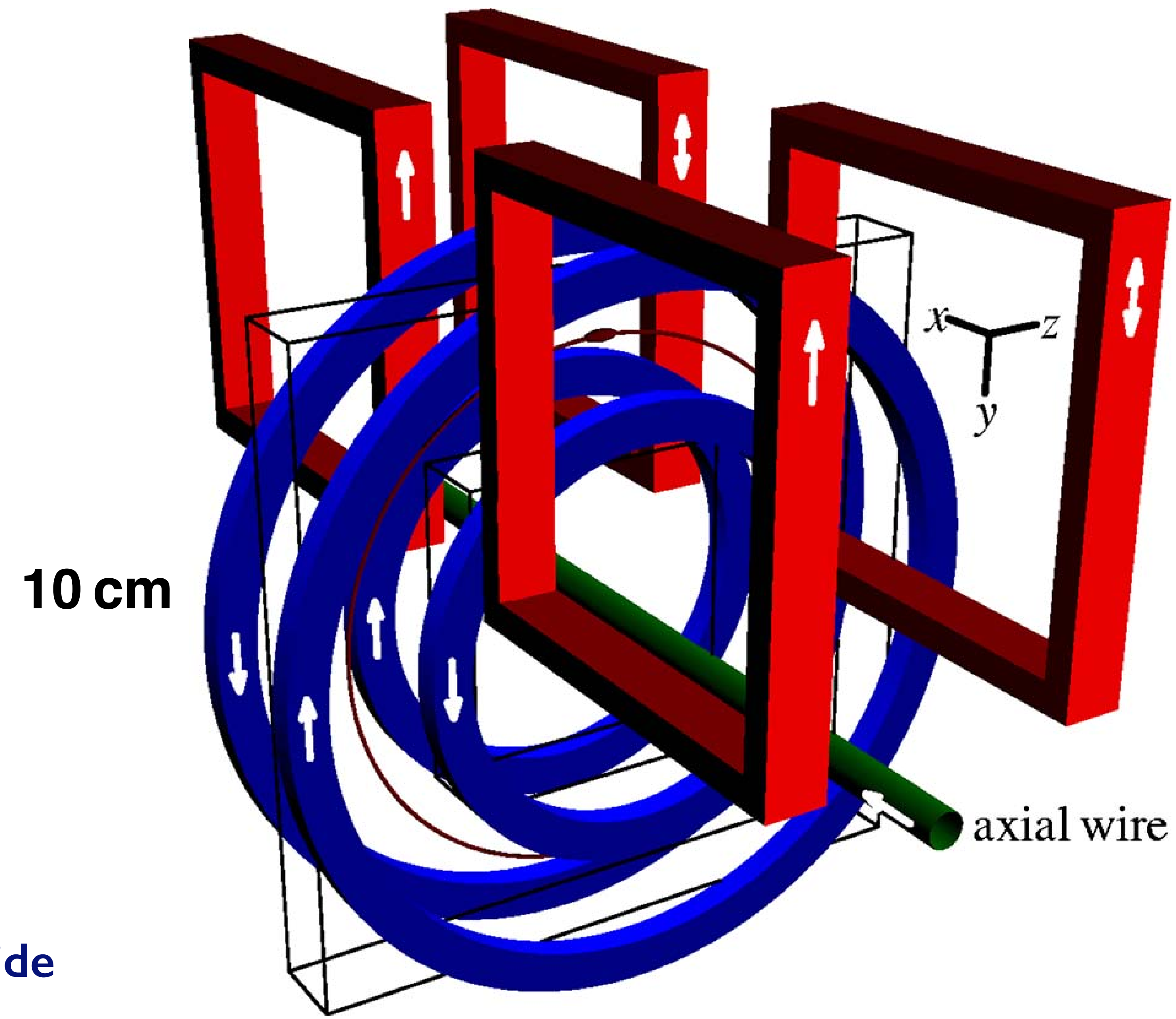


Large magnetic storage ring for Bose-Einstein condensates

Physical Review A ***73*** *41606 (2006)*

A. Arnold, C. Garvie, and E. Riis

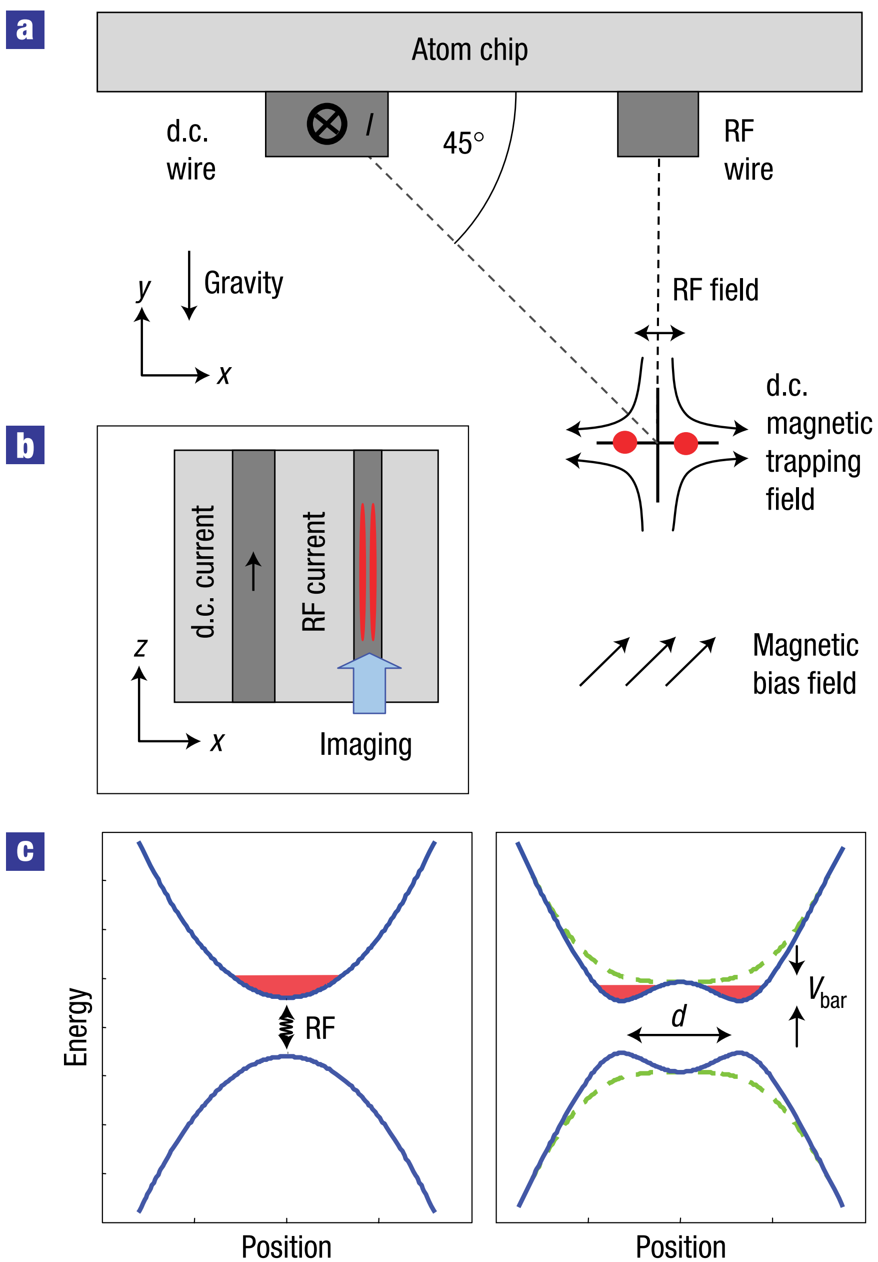


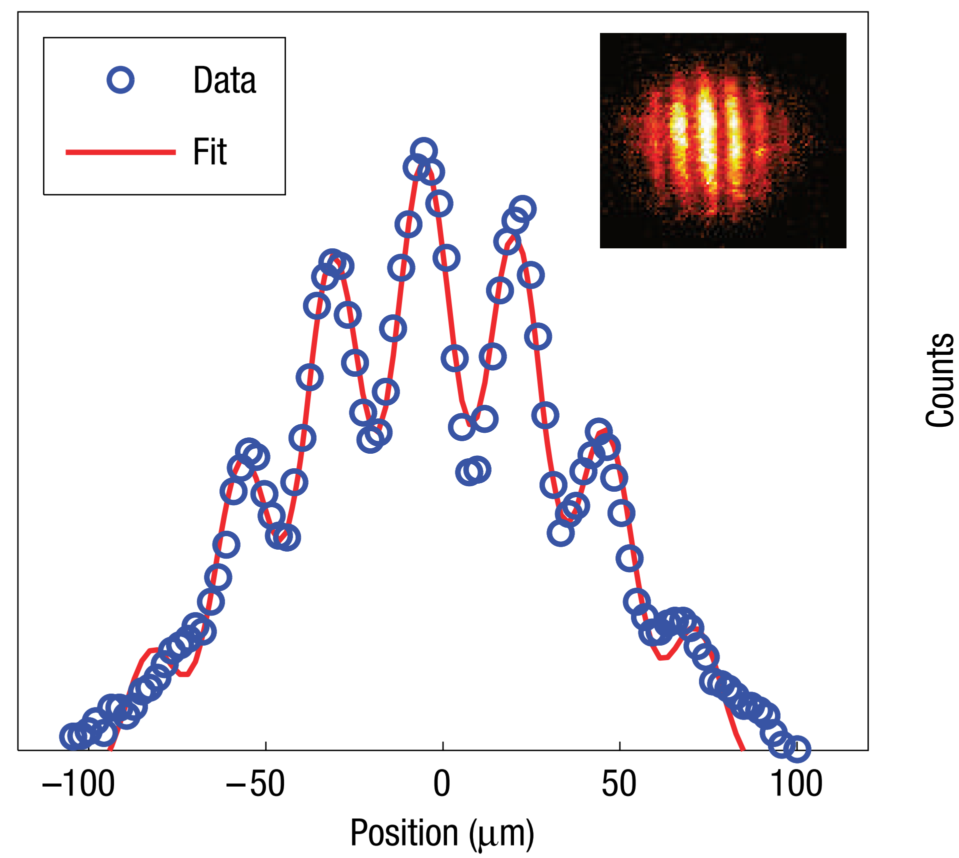


Bose-Einstein condensation in a circular waveguide

Physical Review Letters ***95*** *143201 (2005)*

S. Gupta, K. W. Murch, K. L. Moore, T. P. Purdy, and D. M. Stamper-Kurn





Matter-wave interferometry in a double well on an atom chip

Nature Physics ***1*** *57-62 (2005)*

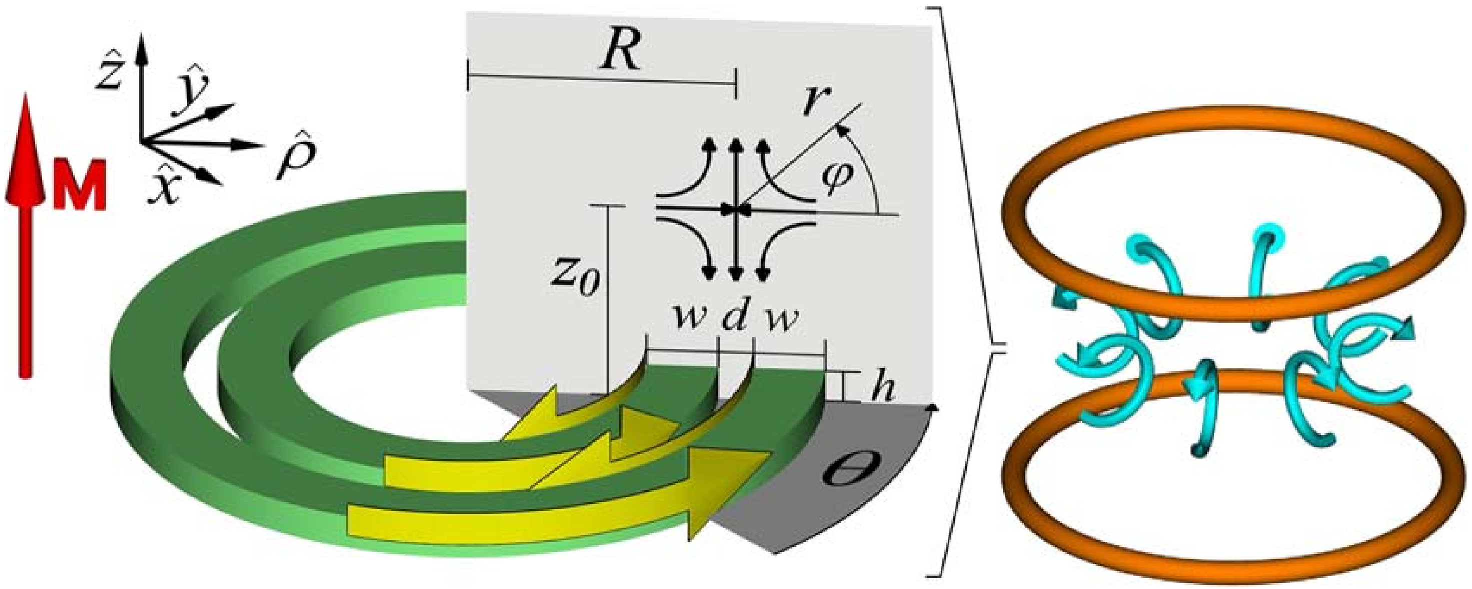
T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Kruger

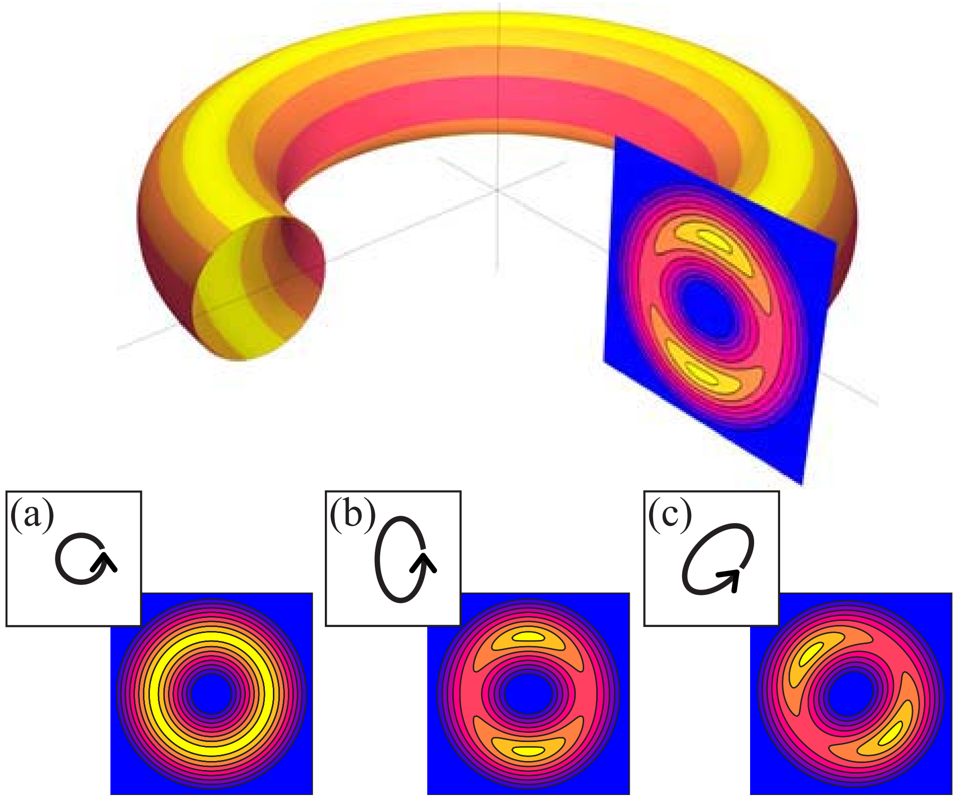
Two-Dimensional Atom Trapping in Field-Induced Adiabatic Potentials

Physical Review Letters ***86*** *1195-1198 (2001)*

O. Zobay and B. M. Garraway

Dressed Ring Traps

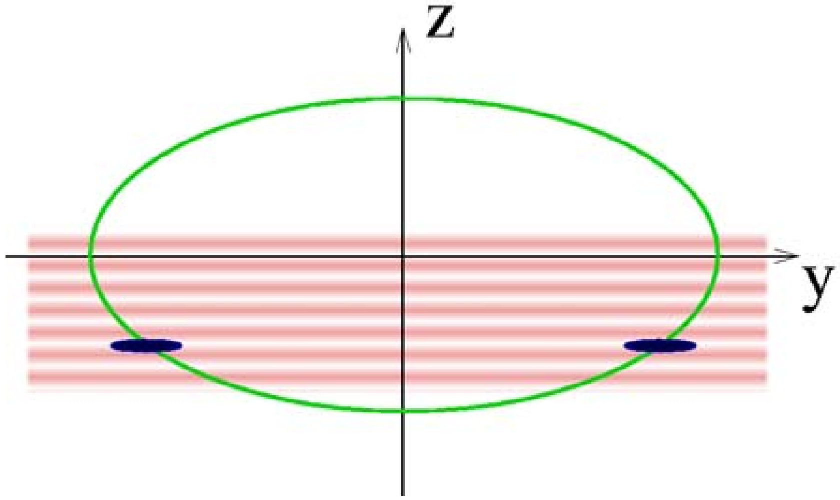




Dynamically controlled toroidal and ring-shaped magnetic traps

Physical Review A ***75*** *063406 (2007)*

T. Fernholz, R. Gerritsma, P. Krüger, and R. J. C. Spreeuw



Ring trap for ultracold atoms

Physical Review A ***74*** *023617 (2006)*

O. Morizot, Y. Colombe, V. Lorent, H. Perrin, and B. M. Garraway

Matter-Wave Guides

- **Magnetic Fields**
  - IP-Trap
  - Atomic chips
  - Mini-traps
  - Adiabatic

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
- **Dynamic**

Matter-Wave Guides

- **Magnetic Fields**

  LSD - IP-Trap

  LSD - Atomic chips

  LSD - Mini-traps

  LSD - Adiabatic (**LSD**)

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
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Matter-Wave Guides

- **Magnetic Fields**

LSD - IP-Trap

LSD - Atomic chips

LSD - Mini-traps

LSD - Adiabatic (**LSD**)

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
- **Dynamic**

- **Dipole Traps**

LSD - Guides

LSD - Lattices

LSD - Paintings

LSD - Fibres

Dipole+Magnetic
(Helene Perrin) LSD

Matter-Wave Guides

- **Magnetic Fields**

  LSD - IP-Trap

  LSD - Atomic chips

  LSD - Mini-traps

  LSD - Adiabatic (LSD)

  LSD - TAAPs

Boshier Criteria of Atomtronics

- **Loop**
- **Smooth**
- **Dynamic**

- **Dipole Traps**

  LSD - Guides

  LSD - Lattices

  LSD - Paintings

  LSD - Fibres

Time-Averaged Adiabatic Potentials

Dipole+Magnetic (Helene Perrin) LSD

Time-Scales of Magnetically Trapped Atoms

ω_{TRAP} ω_{LARMOR}

Quasi DC | Time-Averaging | Adiabatic Potentials

Increasing Frequency →

Cretan Matter-Waves Group

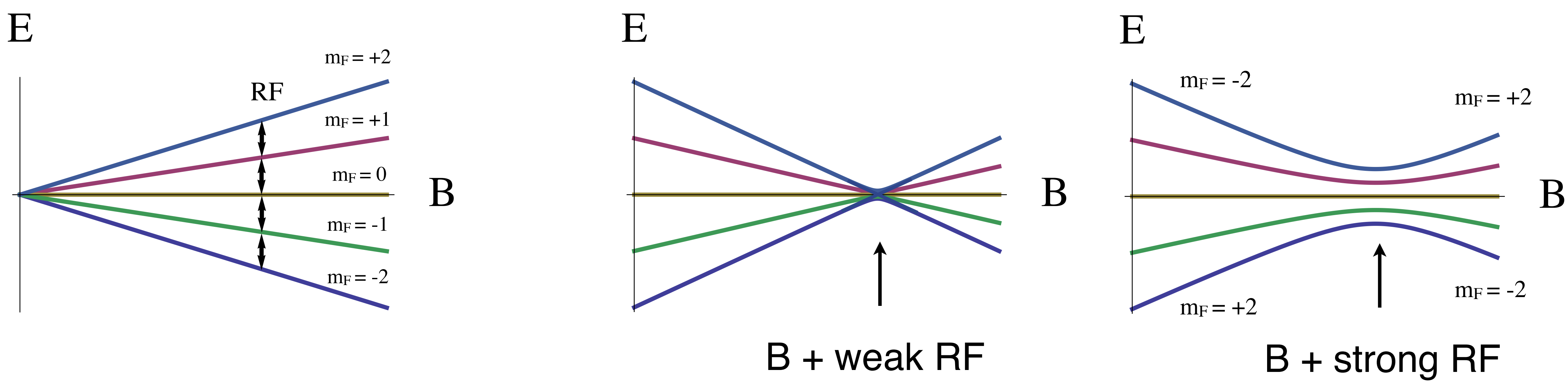
Magnetic Trapping + RF

FORTH
IESL

$E(B)$

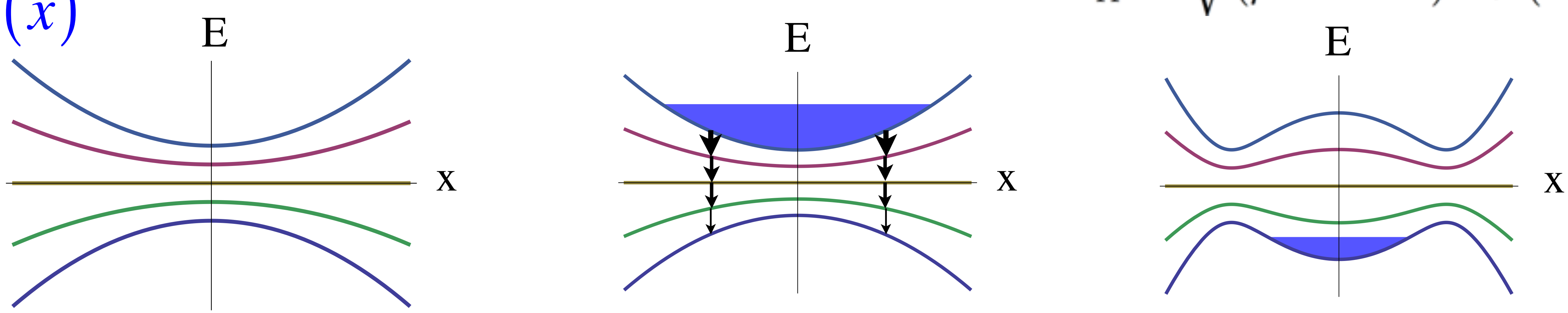
Weak Coupling
(Spin flips)

Strong Coupling
(Adiabatic Potentials)



$$U_{\rm rf} = \sqrt{(\mu B - h\nu)^2 + (h\,\Omega)^2}$$

$E(x)$



O. Zobay, B. M. Garraway Phys. Rev. Lett. **86-7**, 1195-1198 (2001)
Y. Colombe, et al. *Europhys. Lett.* **467**, 593-599 (2004)

Cretan Matter Waves

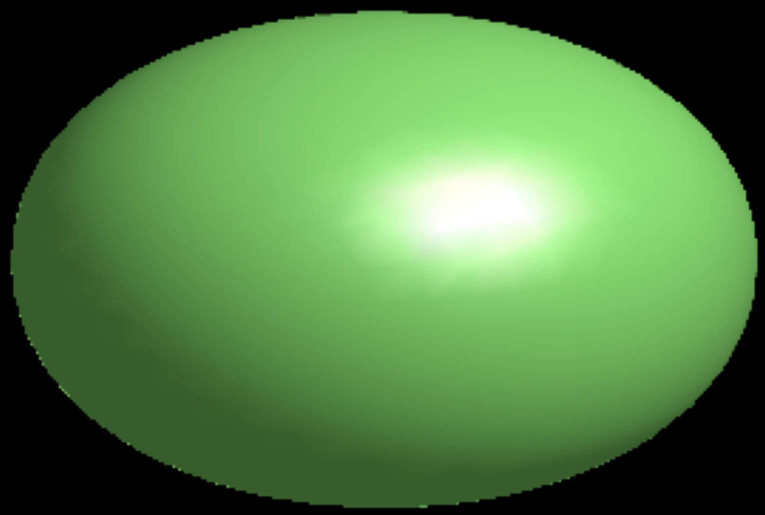
Time-Scales of Magnetically Trapped Atoms

ω_{TRAP}		ω_{LARMOR}	
Quasi DC	Time-Averaging		Adiabatic Potentials

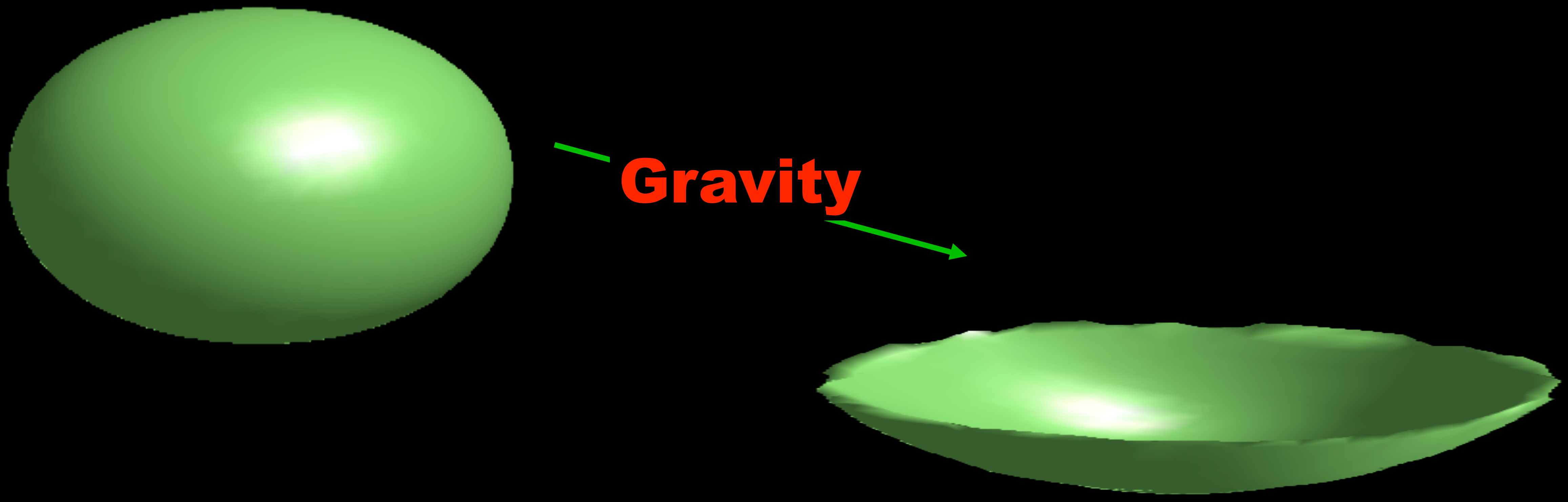
Increasing Frequency →

$$V_{\pm}^{eff}(\mathbf{r}) = \frac{\omega_m}{2\pi}\int_0^{2\pi/\omega_m} dt\, V_{\pm}(\mathbf{r},t) = \frac{\omega_m}{2\pi}\int_0^{2\pi/\omega_m} dt\, \hbar\sqrt{\left(\Omega_L(\mathbf{r},t)-\omega(t)\right)^2 + \Omega_{\pm}^2(\mathbf{r},t)}$$

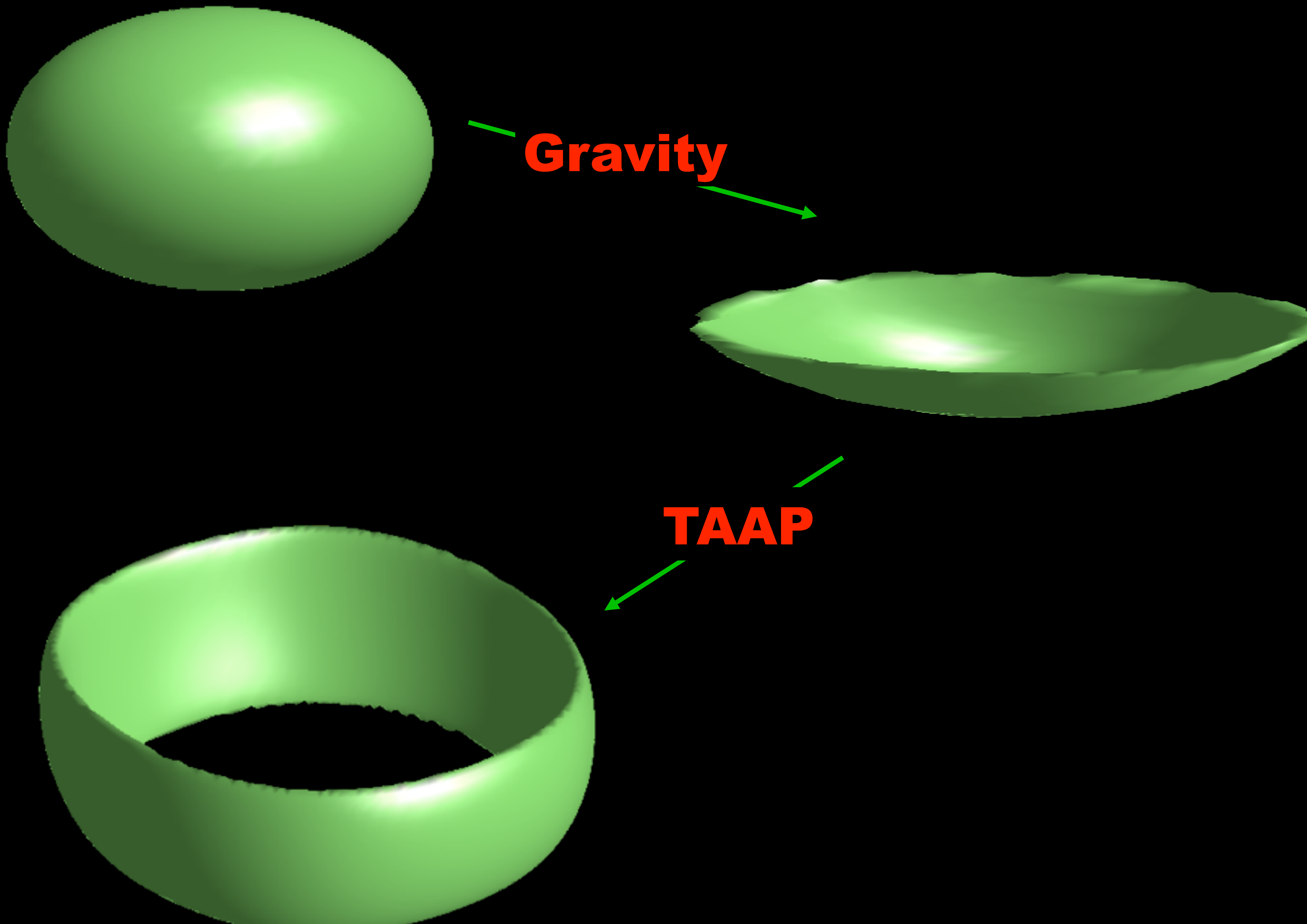
Adiabatic Potentials



Adiabatic Potentials



Time-Averaged Adiabatic Potentials (TAAP)

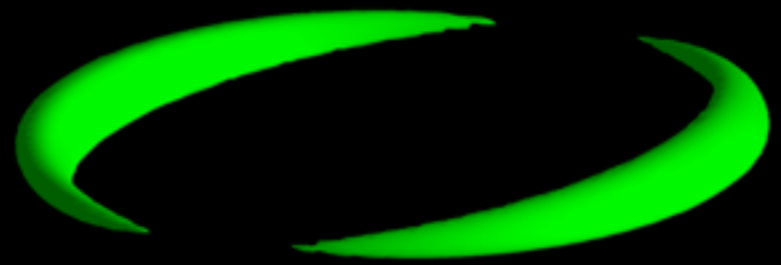


IP-trap + RF-y-TAP

Smooth

Radius 10 µm - 2 cm

Transverse confinement > 1000 Hz

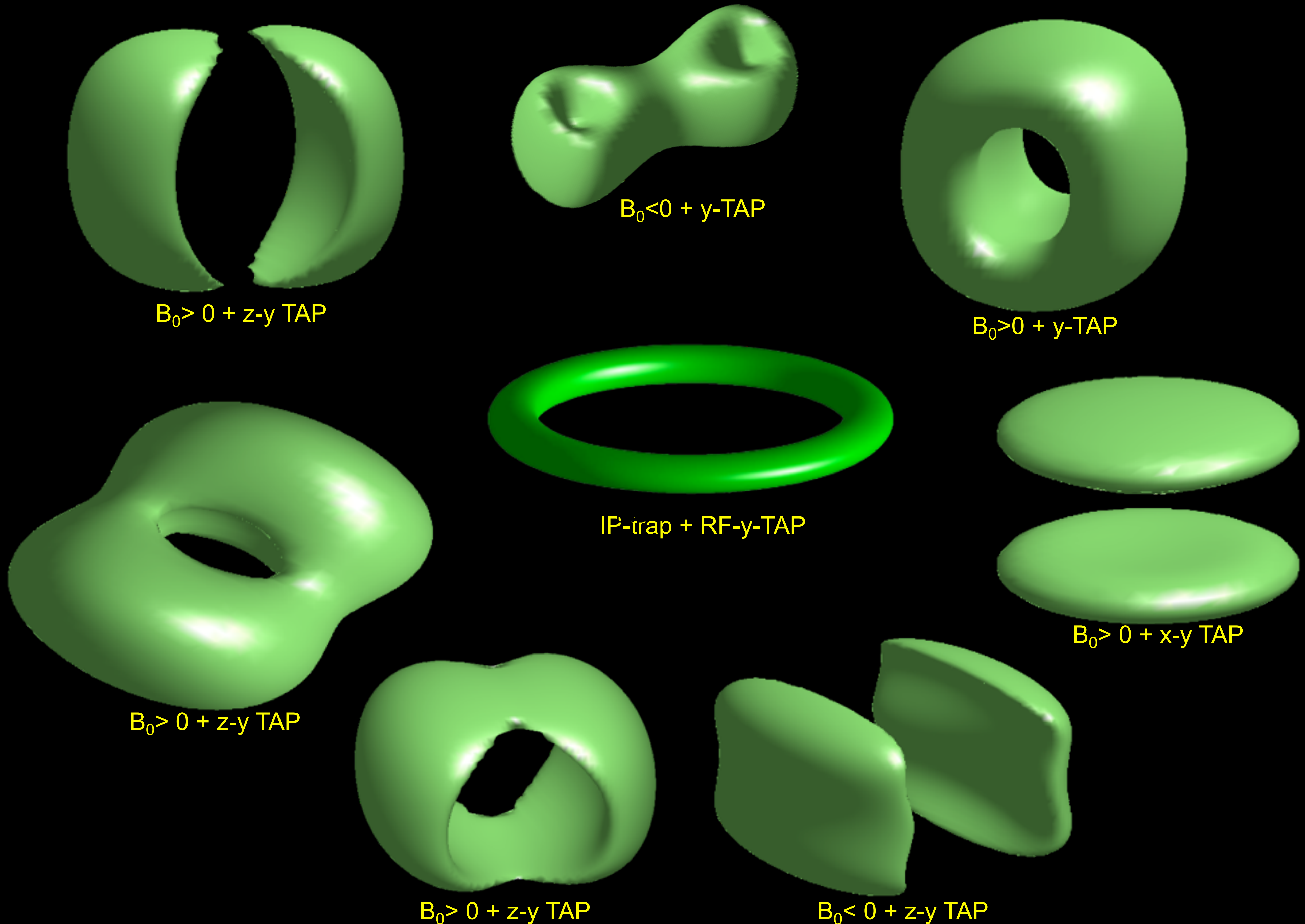


IP-trap + RF-y-TAP

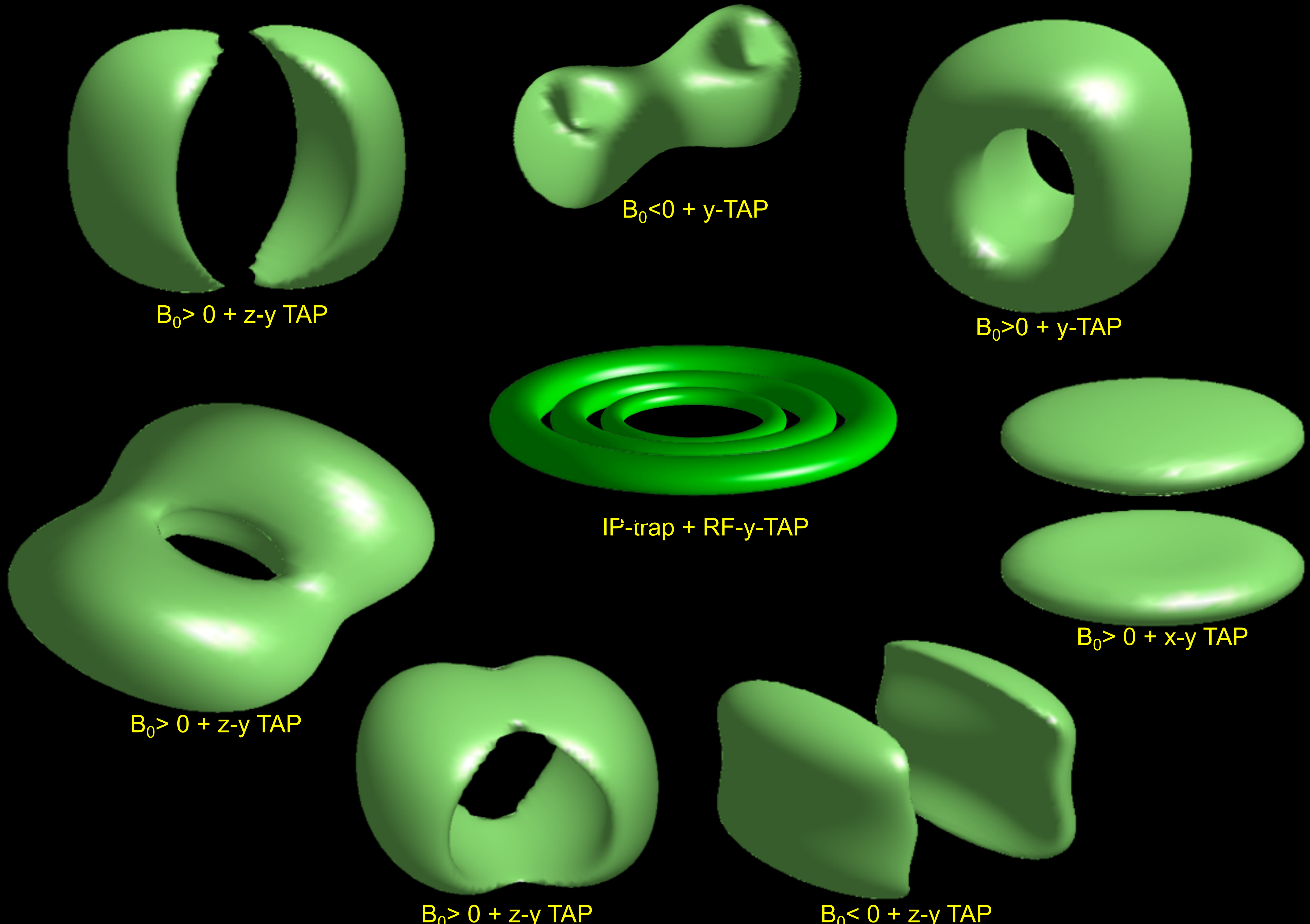
Smooth

Radius 10 µm - 2 cm

Transverse confinement > 1000 Hz



(1 μK iso-potential surfaces in a TAAP trap)
PRL **99:8** 083001 (2007)



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

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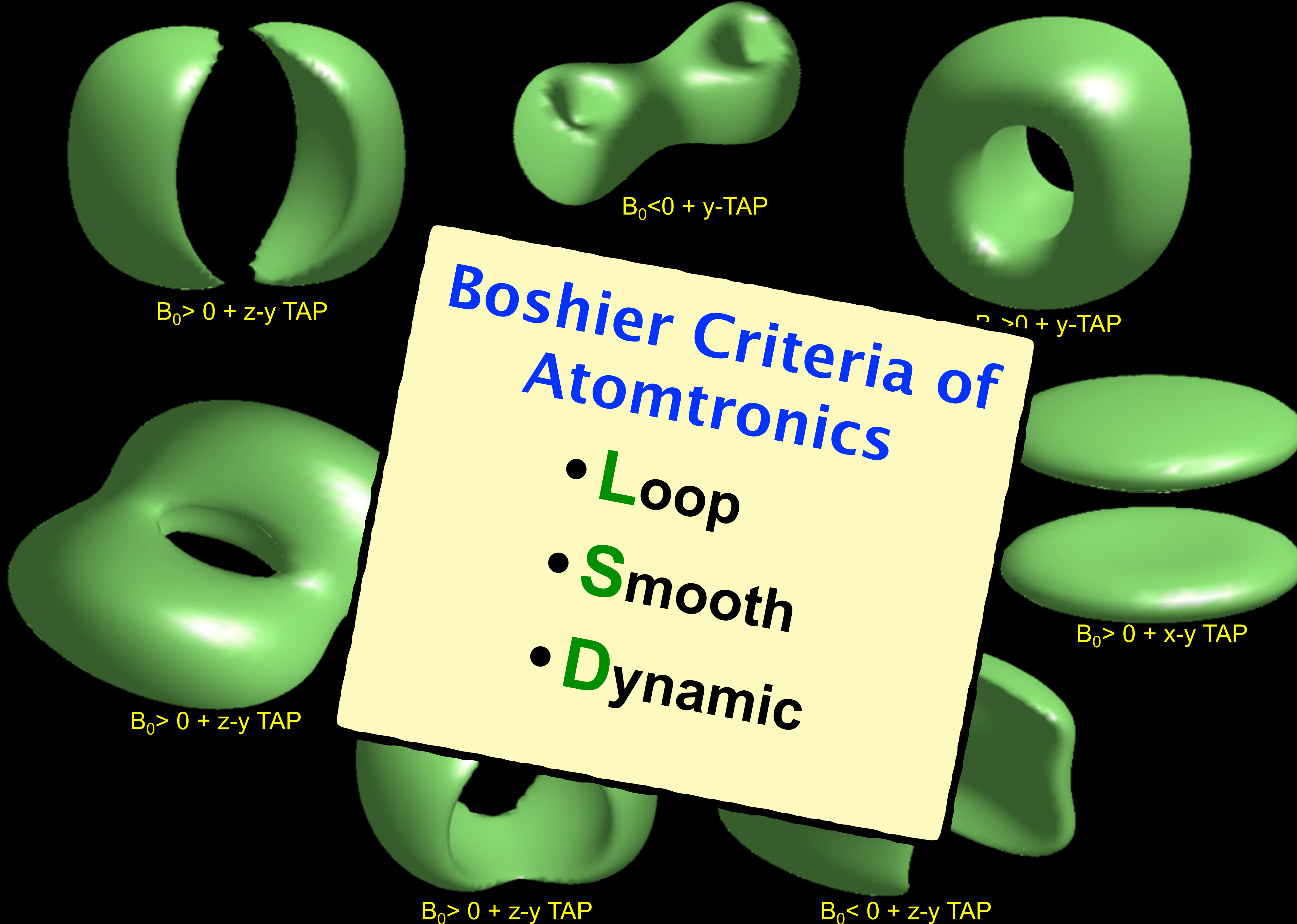
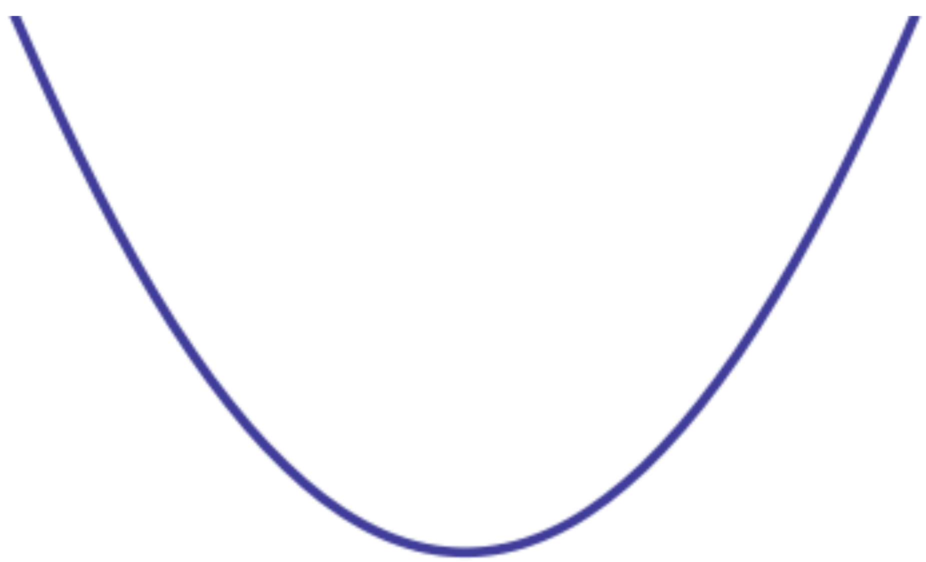


(1 µK iso-potential surfaces in a TAAP trap)

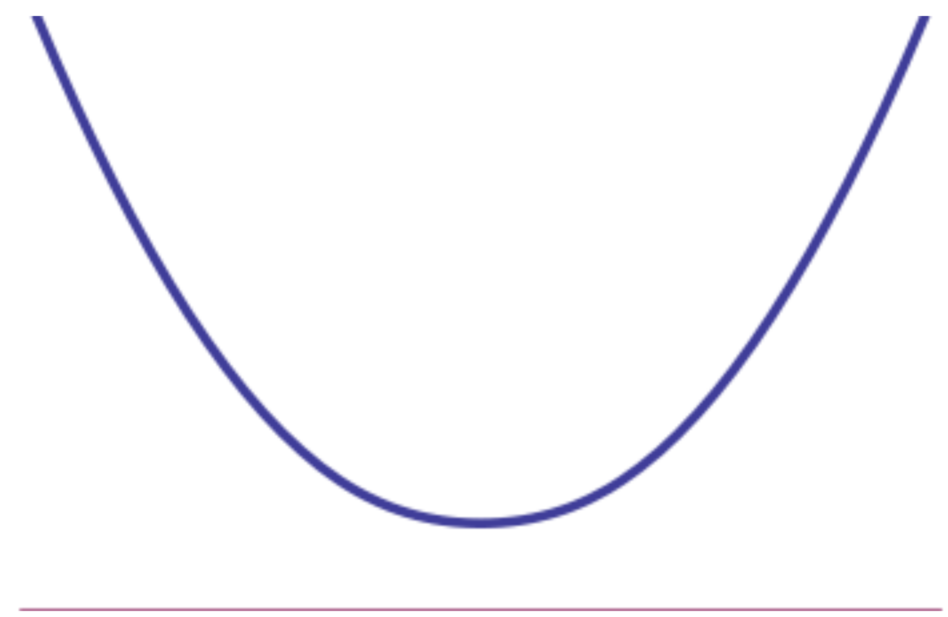
PRL **99:8** 083001 (2007)

Adiabatic Potentials

$$V_{\pm}^{eff}(\mathbf{r}) = \frac{\omega_m}{2\pi}\int_0^{2\pi/\omega_m} dt\, V_{\pm}(\mathbf{r},t) = \frac{\omega_m}{2\pi}\int_0^{2\pi/\omega_m} dt\, \hbar\sqrt{\left(\Omega_L(\mathbf{r},t)-\omega(t)\right)^2 + \Omega_{\pm}^2(\mathbf{r},t)}$$



RF-evaporation



AP-Loading

Zobay, and Garraway, PRL **86** 1195 (2001)

Adiabatic Potentials Loading

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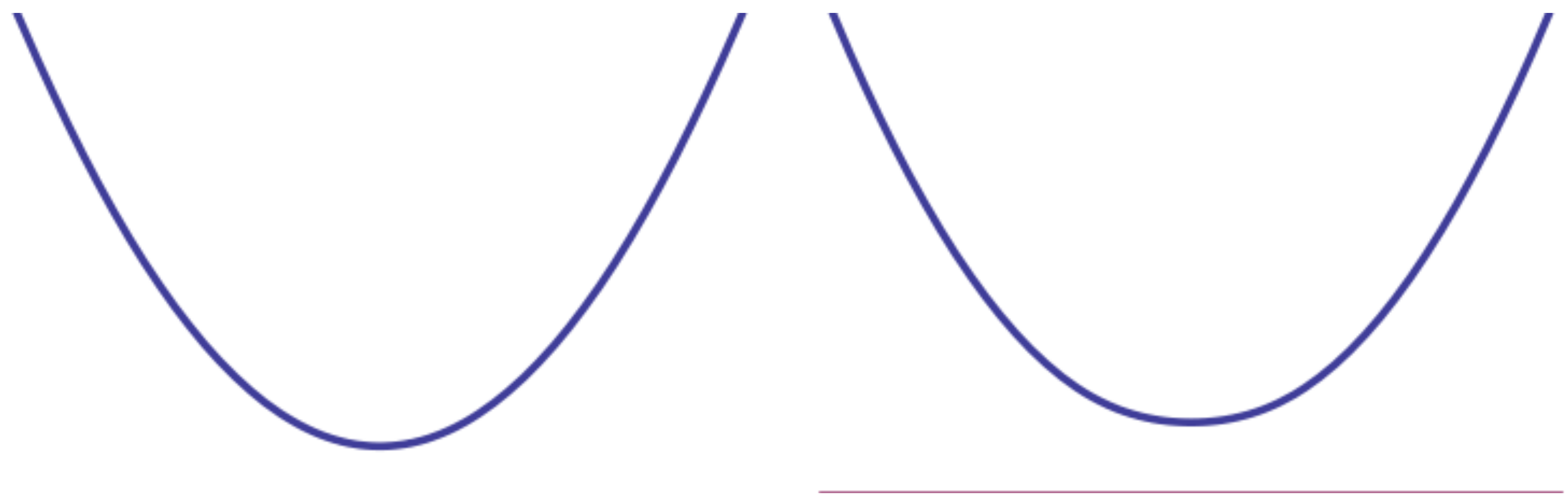

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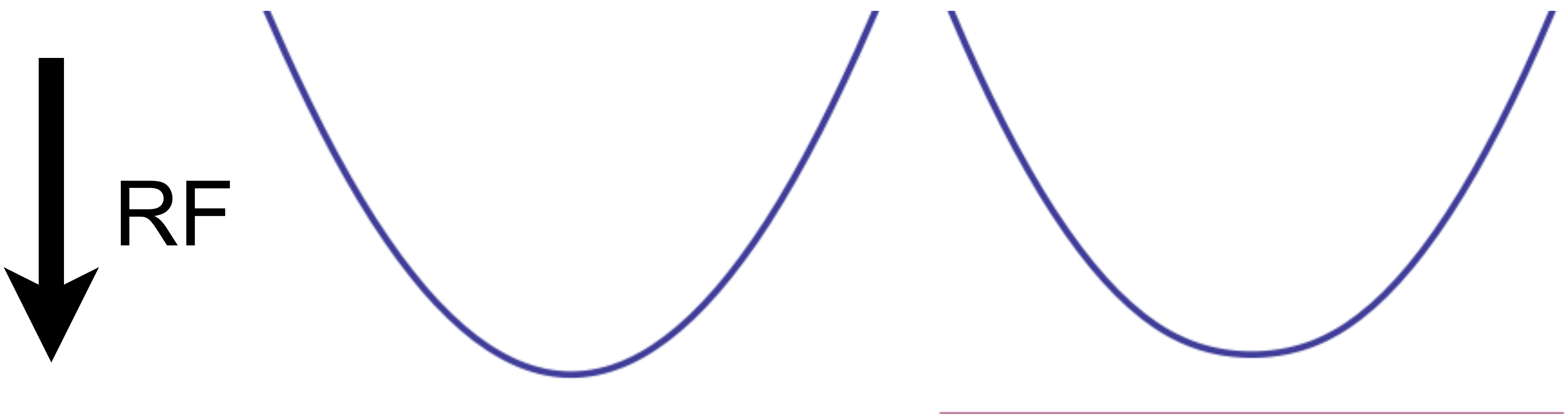

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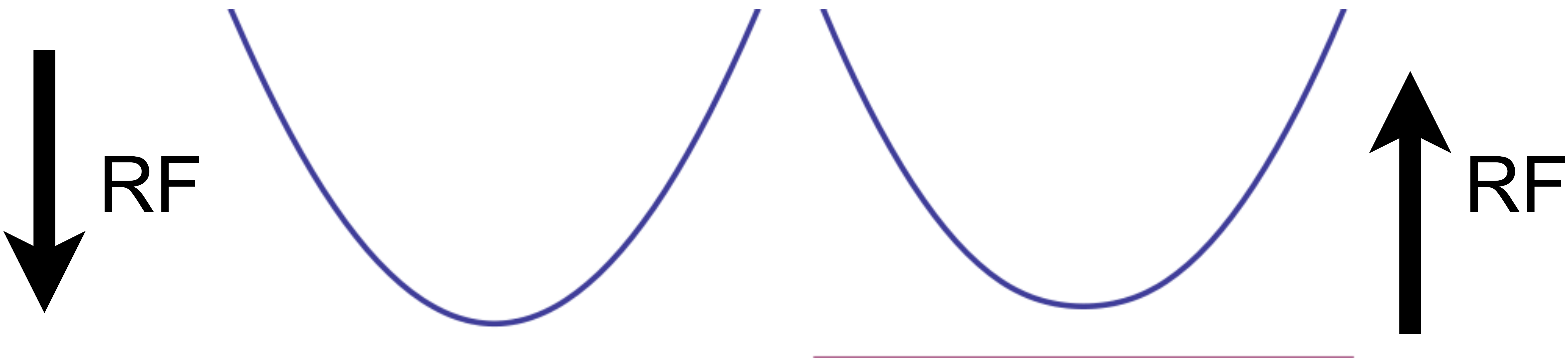


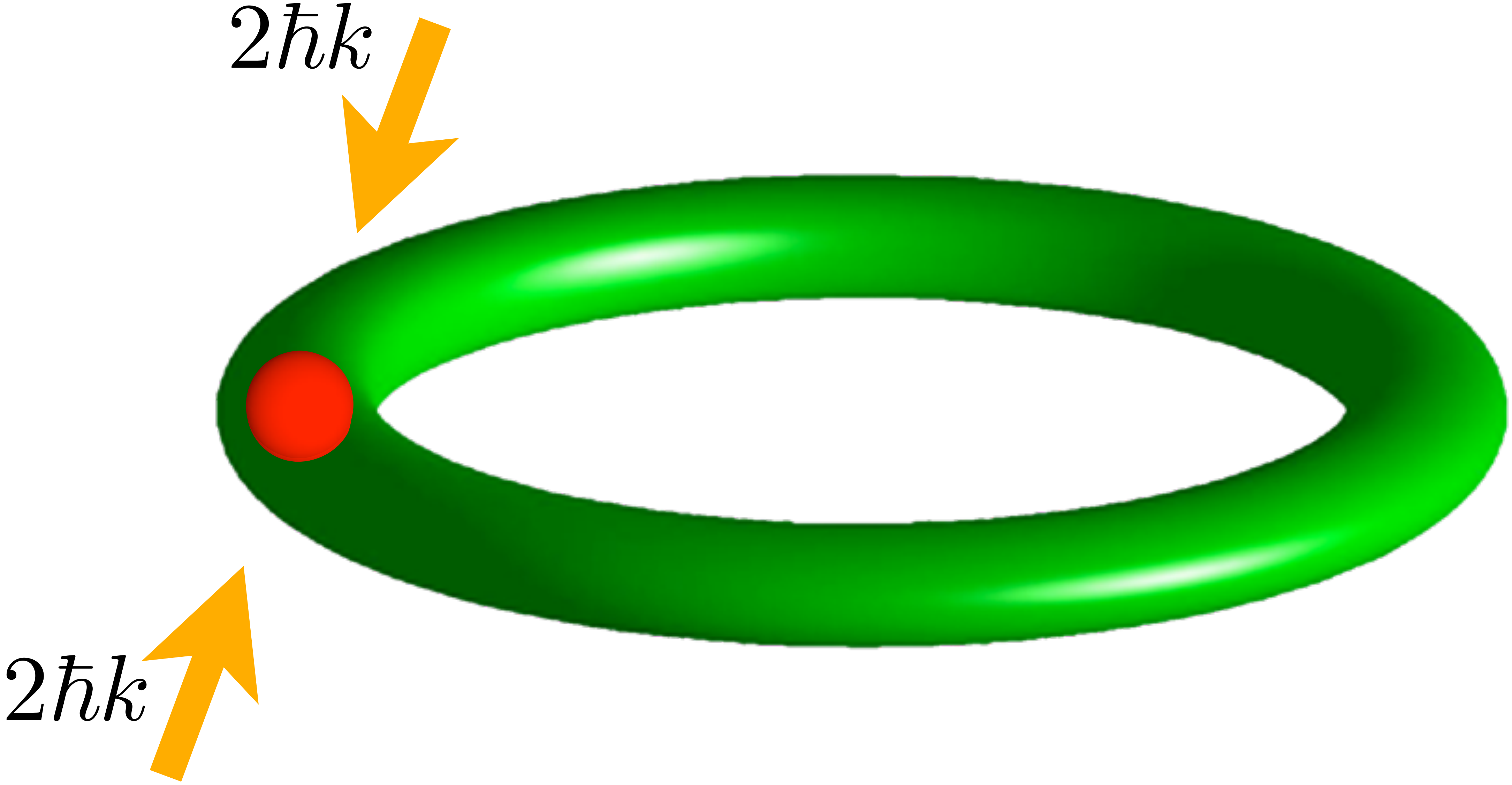
RF-evaporation AP-Loading

Zobay, and Garraway, PRL **86** 1195 (2001)

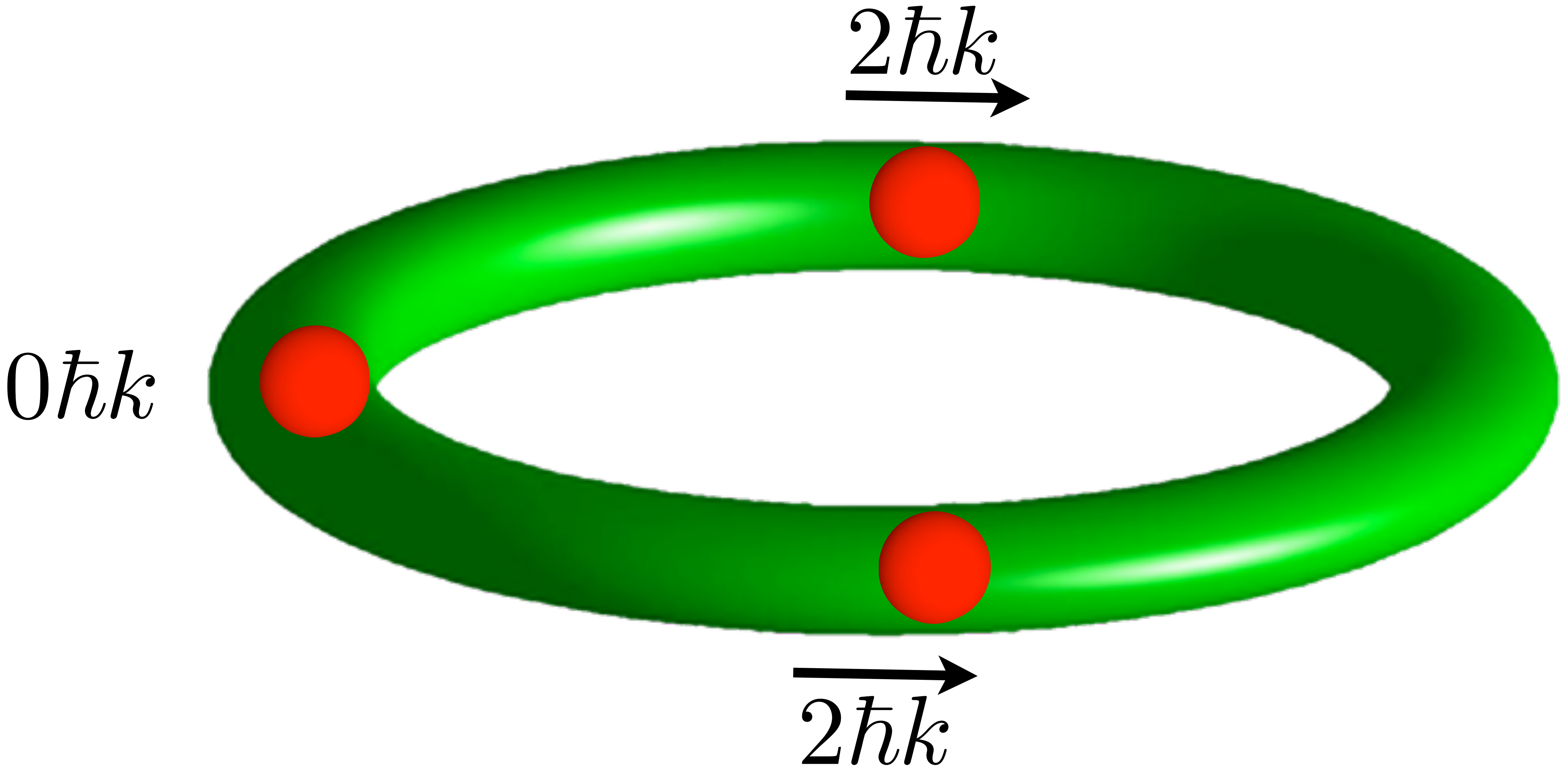
Sagnac Interferometer

Sagnac Interferometer

Sagnac Interferometer



Sagnac Interferometer



Outline

- Interferometry — Why? How?
- Time-Averaged Adiabatic Potentials (TAAP)
- Bucket Atomtronics
- Atom Lasers

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- Interferometry — Why? How?
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How about a bucket?

What if we were to carry two buckets in opposite directions in a circle?

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

Around-the-World Atomic Clocks: Observed Relativistic Time Gains

Science 177 166-168 and 168-170 (1972)

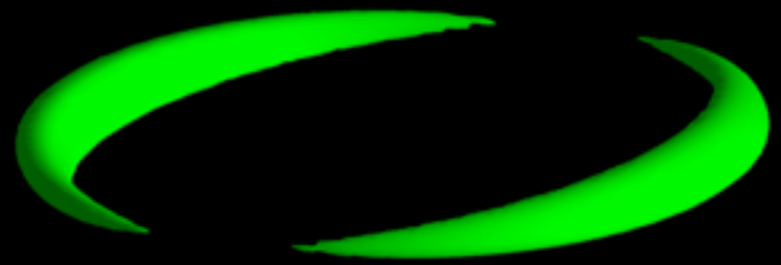
J. C. Hafele and R. E. Keating

IP-trap + RF-y-TAP

Smooth

Radius 10 μm - 2 cm

Transverse confinement > 1000 Hz



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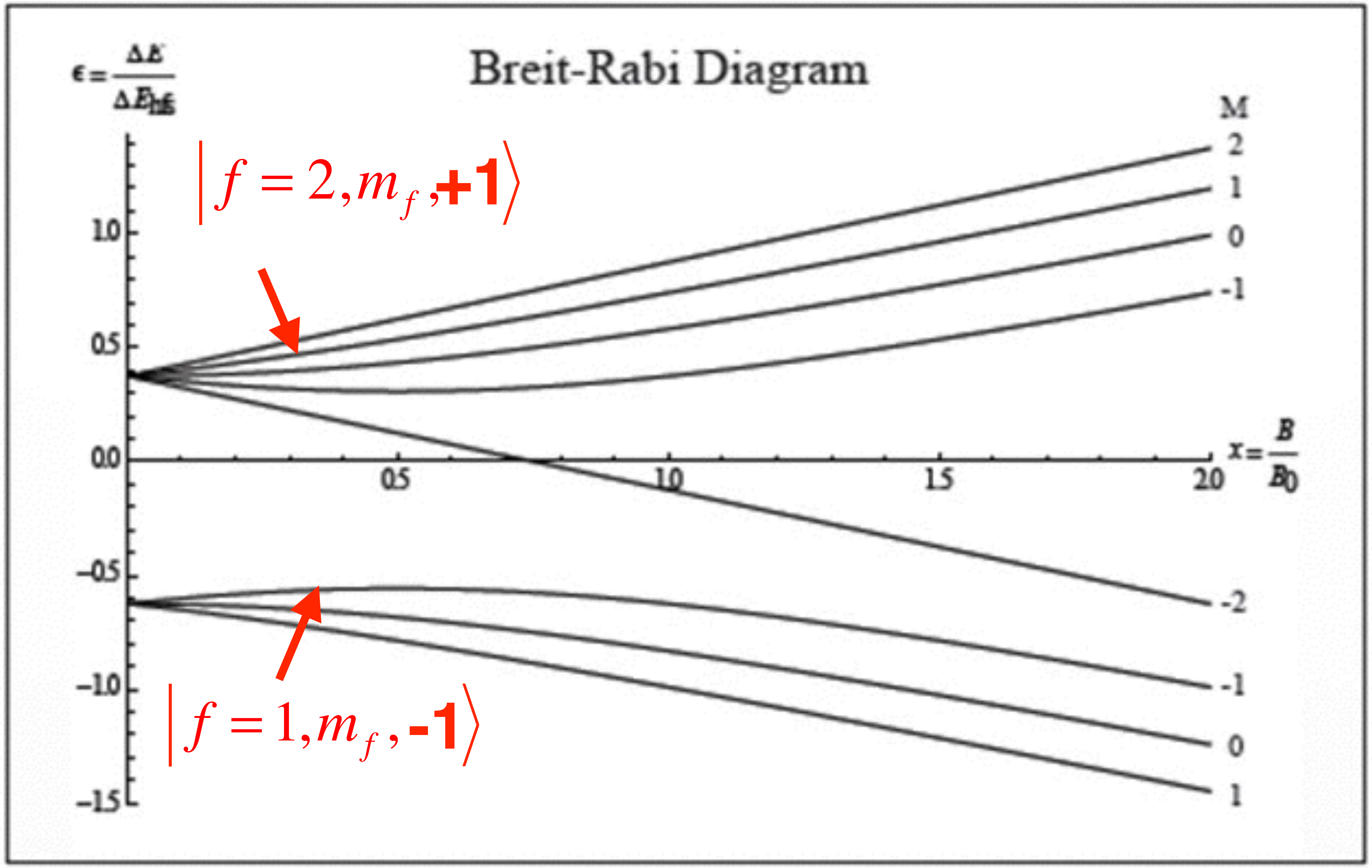
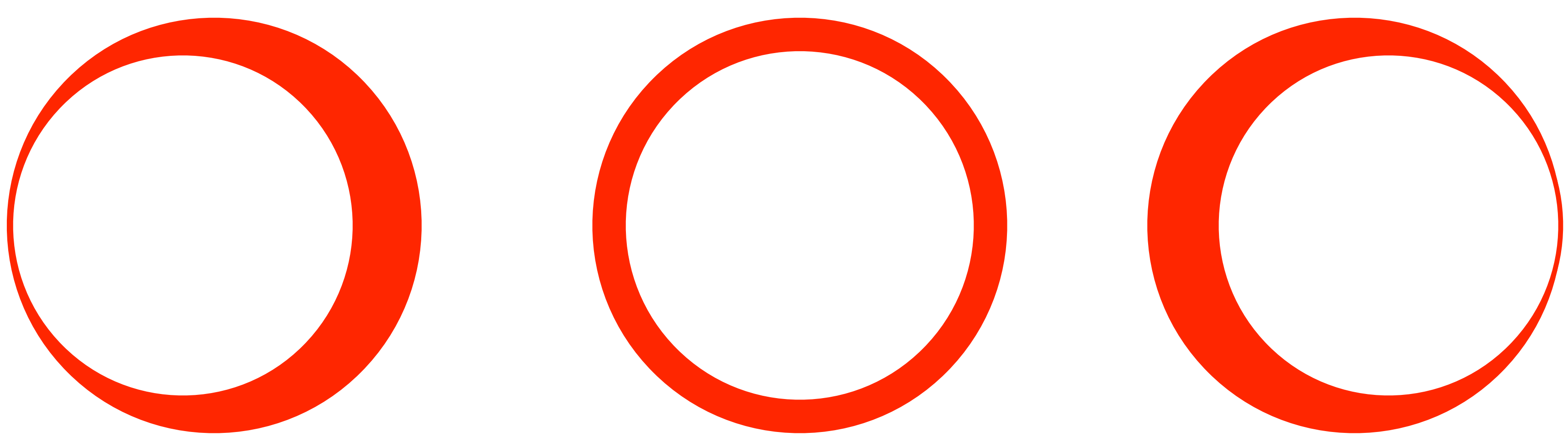


F=1 $\sigma^{(-)}$
F=2 $\sigma^{(+)}$

π

F=1 $\sigma^{(+)}$
F=2 $\sigma^{(-)}$



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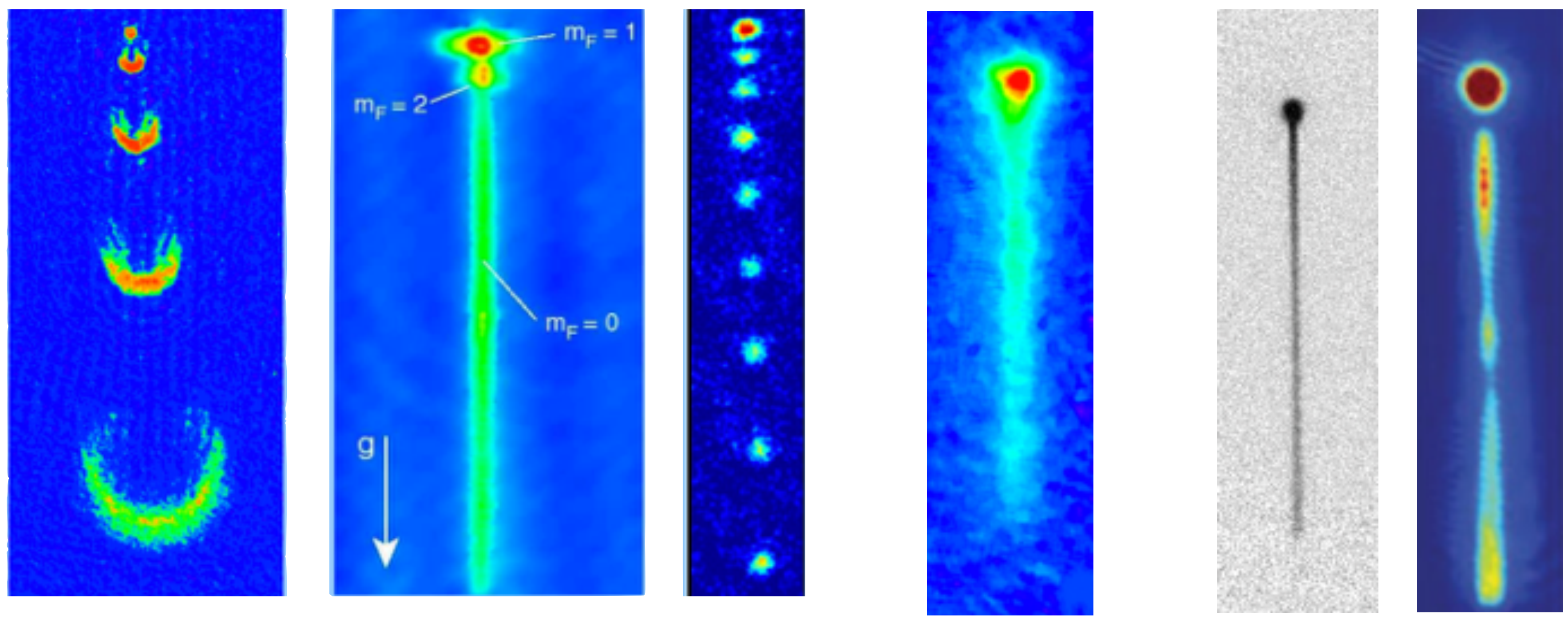
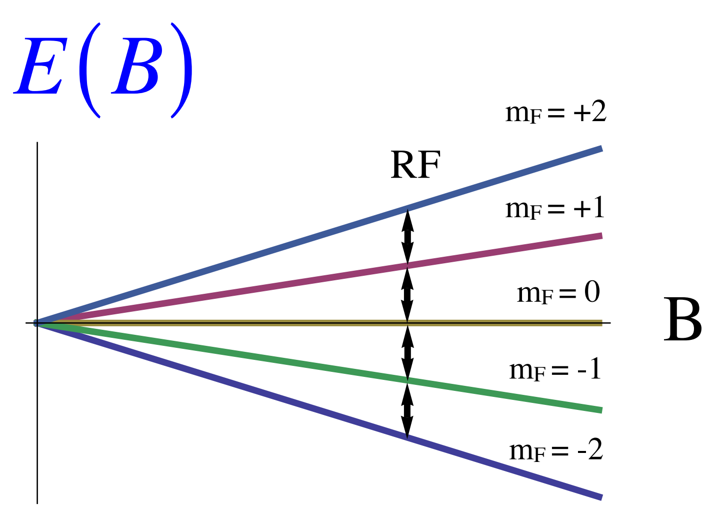
Cretan Matter-Waves Group

Atom Laser Outcouplers for Magnetic Traps

Weak

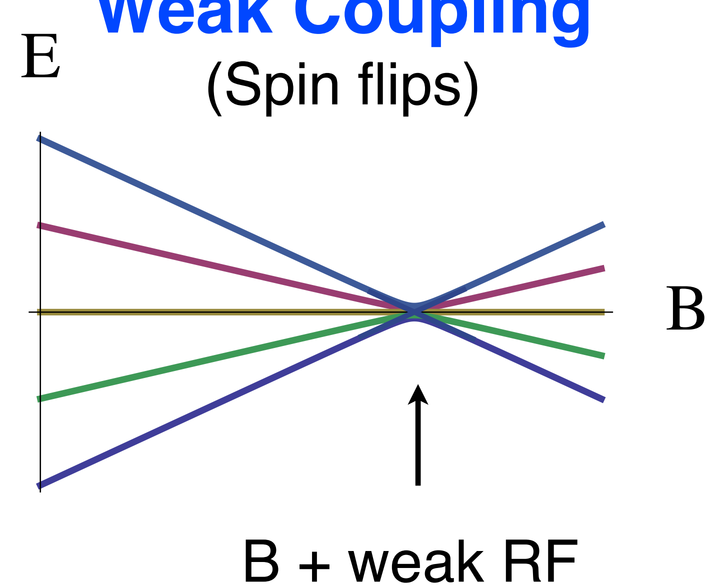


MIT 1997 | Munich 1999 | Yale 1998 | NIST 1999 | ETH 2005 | Australia 2010



Weak Coupling

(Spin flips)

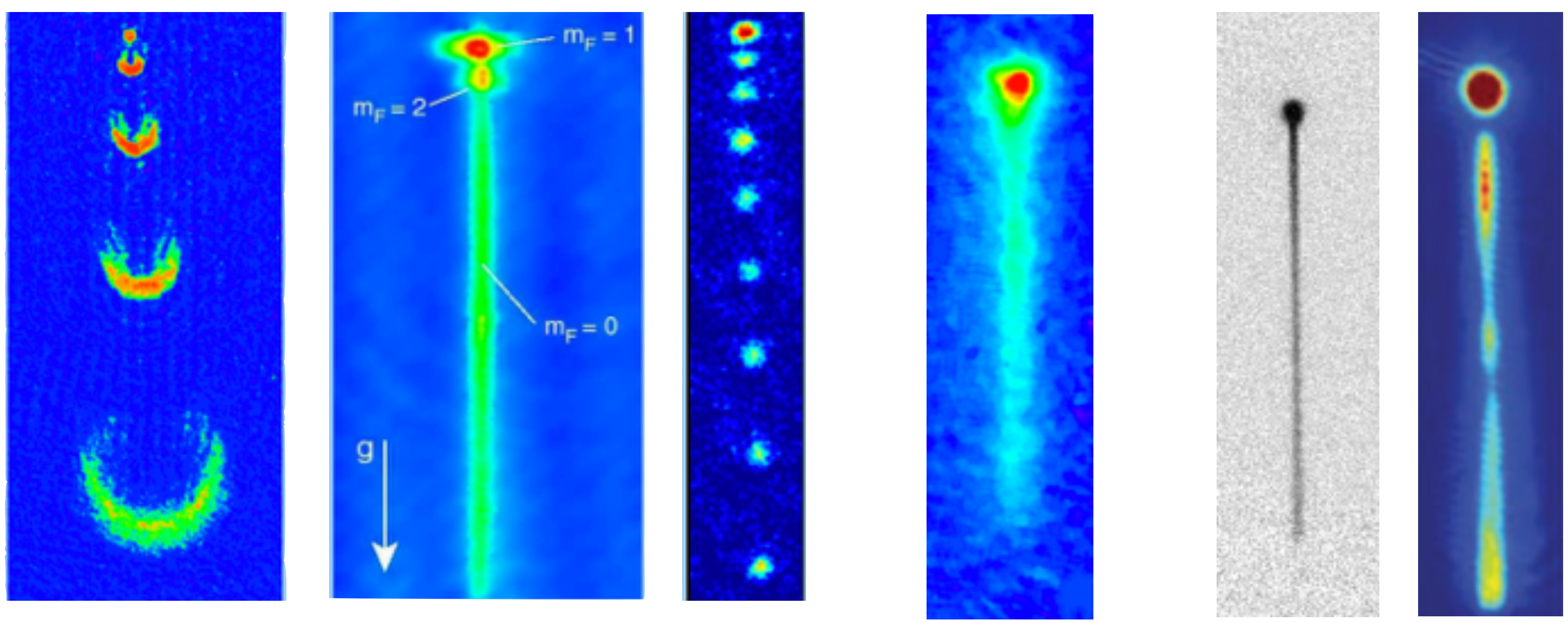


Cretan Matter Waves

Cretan Matter-Waves Group

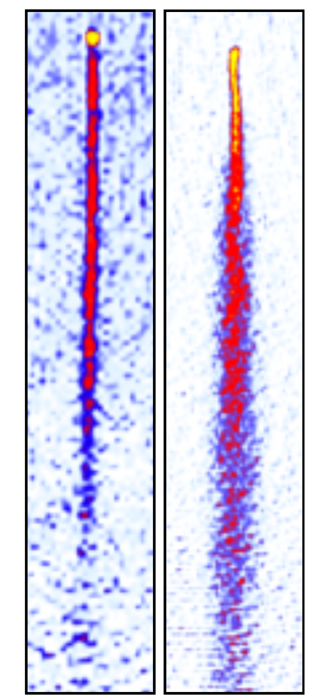
Atom Laser Outcouplers

Weak

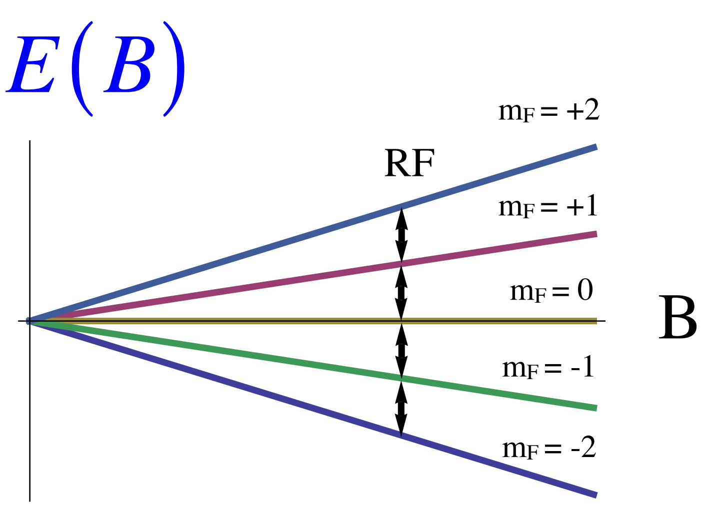


MIT 1997 | Munich 1999 | Yale 1998 | NIST 1999 | ETH 2005 | Australia 2010

Strong



IESL 2012



Weak Coupling

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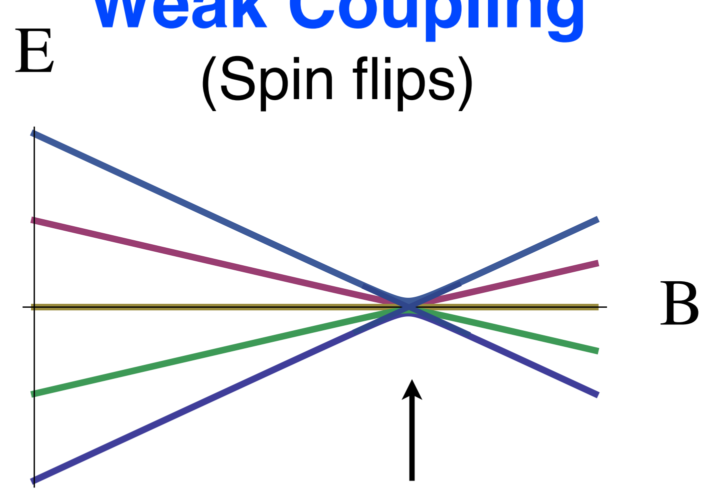
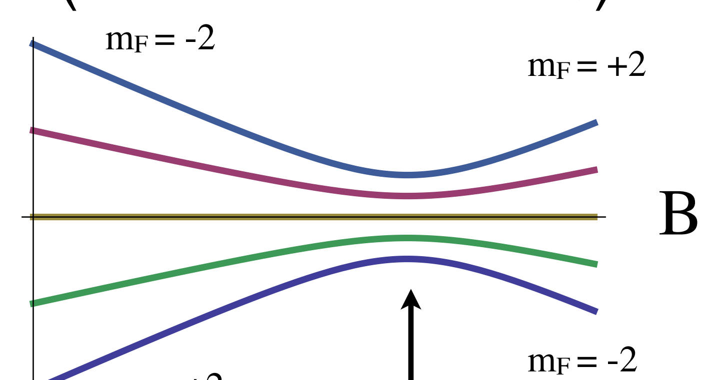


B + weak RF

Strong Coupling

(Adiabatic Potentials)

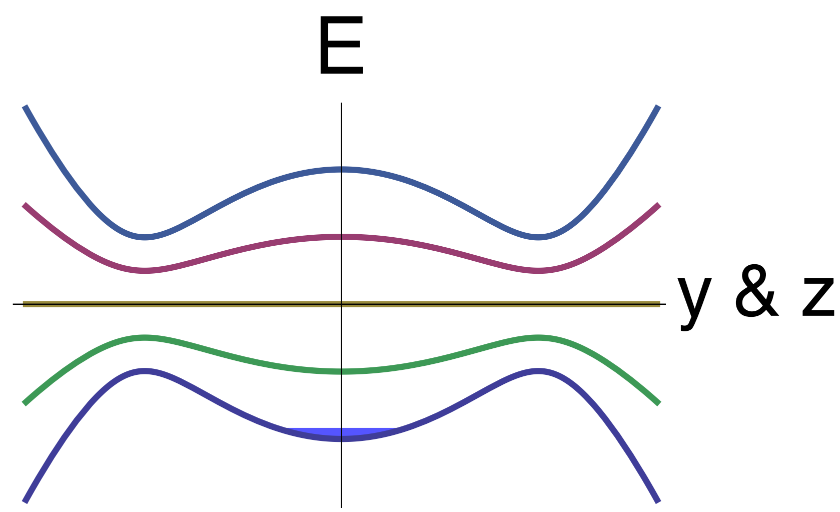


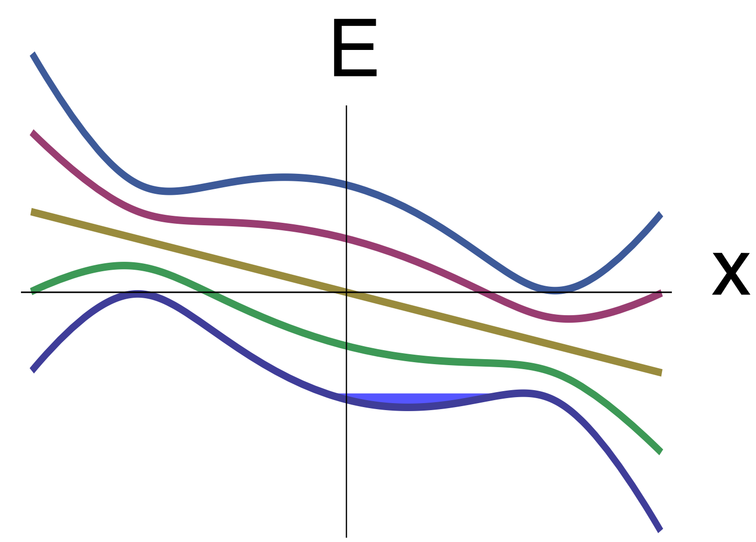
B + strong RF

Cretan Matter-Waves Group

Atom Lasers from Magnetic Traps

FORTH
IESL

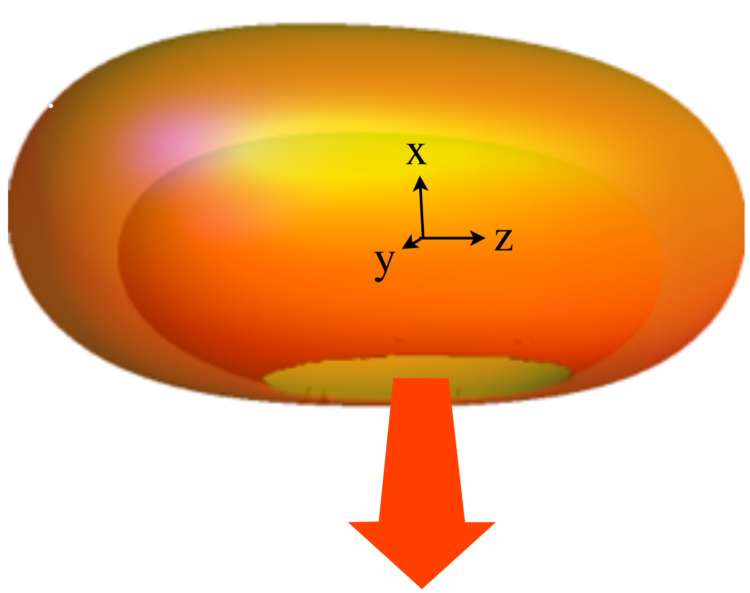




Adiabatic Potentials
(Strong RF)

$$V(\mathbf{r}) = m_F \hbar \sqrt{\left(\Omega_L - \omega_{rf}\right)^2 + \Omega_{rf}^2} + M g_e x$$

Isopotential surface



- Arbitrary Outcoupling rates
- All atoms are transferred from $m_F = +2$ directly to $m_F = -2$
- Outcoupling occurs from a single point below the condensate
- Atoms are accelerated by gravity *and* field gradient **(1cm ⇒ Λ_{dB}=1nm)**

Cretan Matter-Waves Group

Atom Laser Genesis

FORTH
IESL

MOT — >10^{10} atoms, 120 μK

Magnetic Trap — 2×10^9 atoms, 150 μK, 10x12 Hz

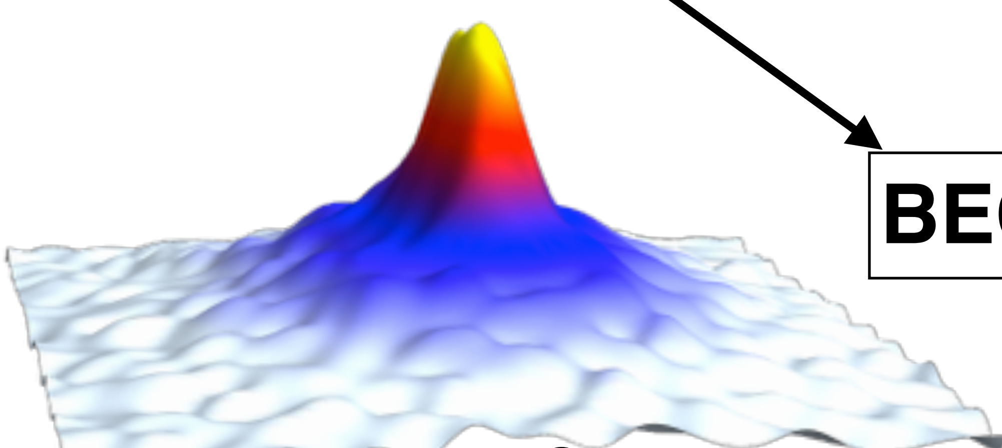
Compression — 2×10^8 atoms, 1mK, 17x793 Hz

Evaporation — RF Ramp: 50 MHz – 560 kHz; RF Ramp speed: ~ 5 MHz/s

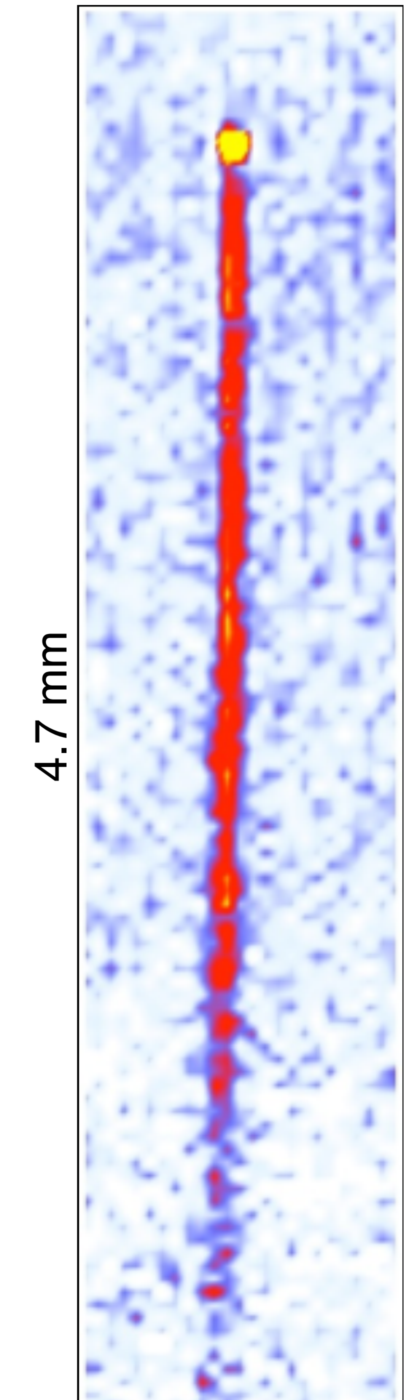
BEC — 30–200 $\times 10^3$ atoms

Atom Laser

Imaging



BEC



Cretan Matter-Waves Group

Analysis in Slices

FORTH
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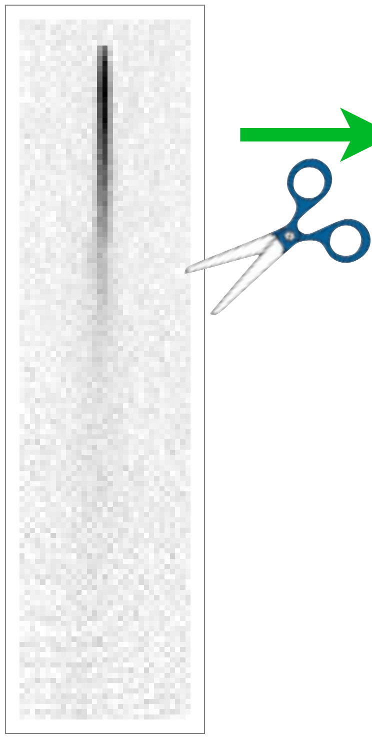
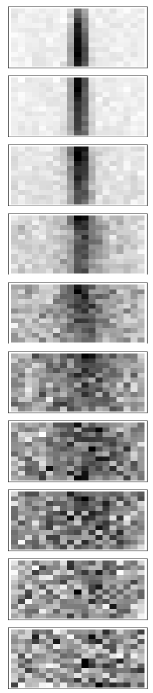
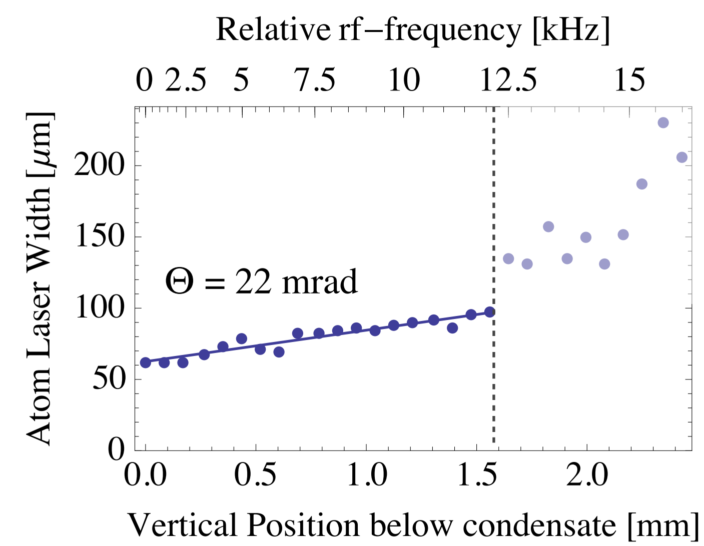


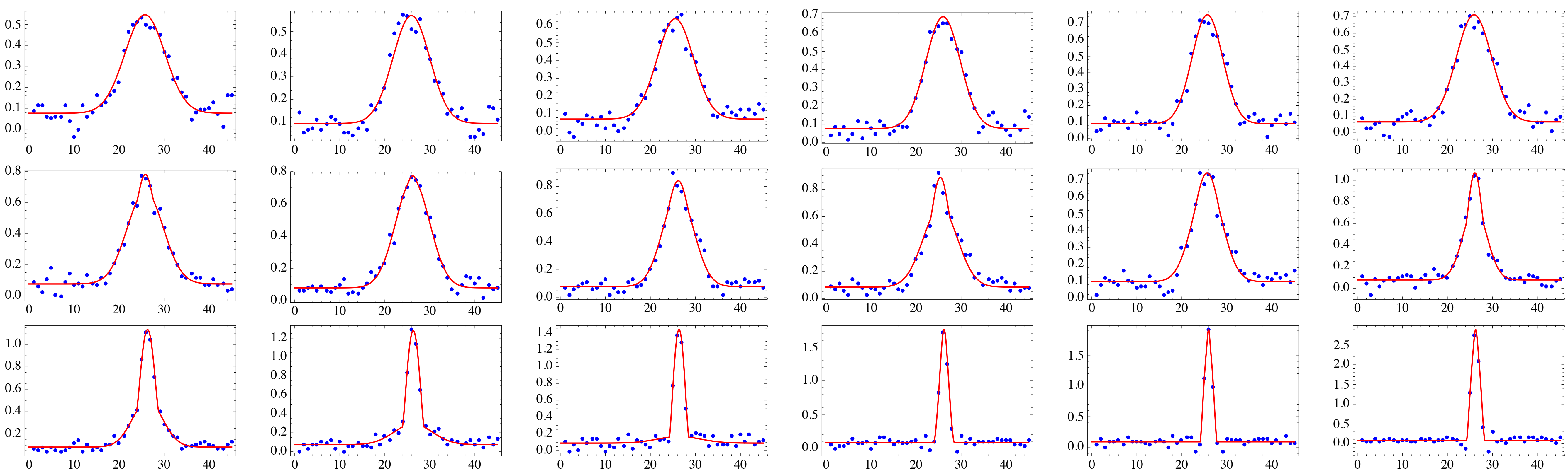


Integrate

Fit

$$f = a + b\,e^{-\left(\frac{x-x_0}{\Delta x_t}\right)^2} + c\,\mathrm{Re}\left[\left(1-\frac{x-x_0}{\Delta x_k}\right)^{3/2}\right]$$





Cretan Matter-Waves Group

3 Atom Lasers

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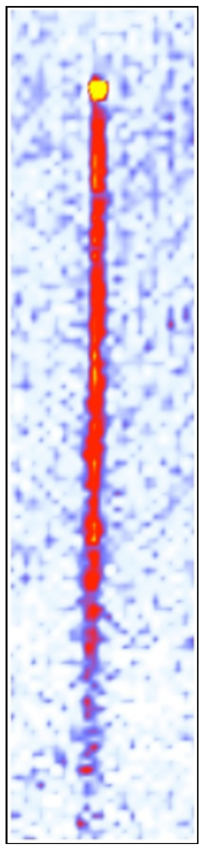
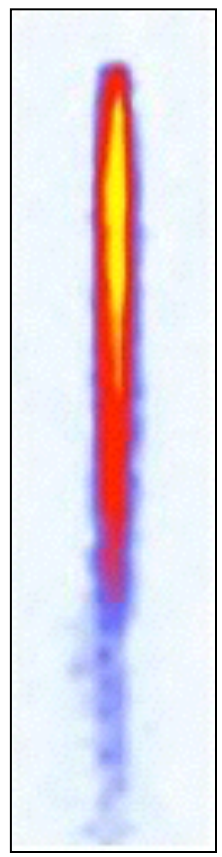
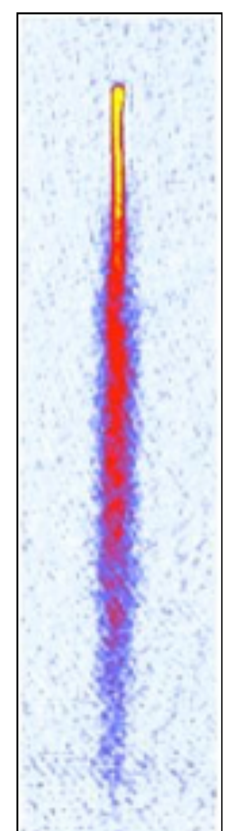
IESL



Pure



High Flux



Ultra-Cold Thermal

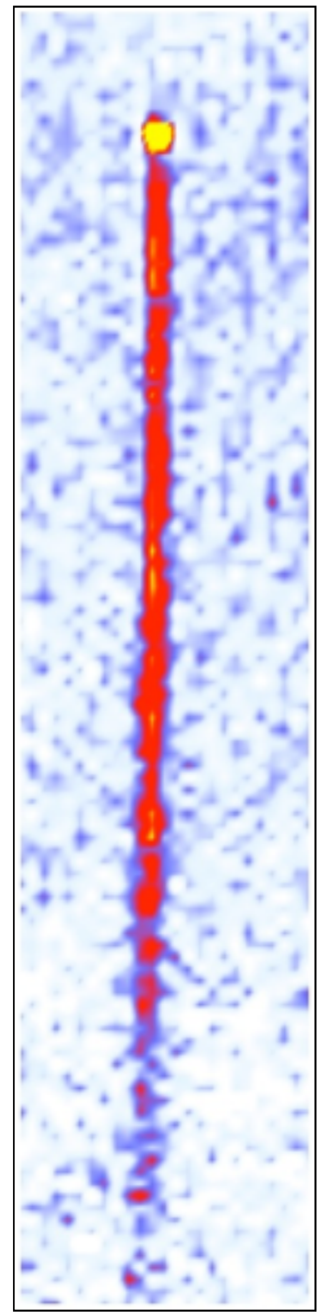
Cretan Matter-Waves Group

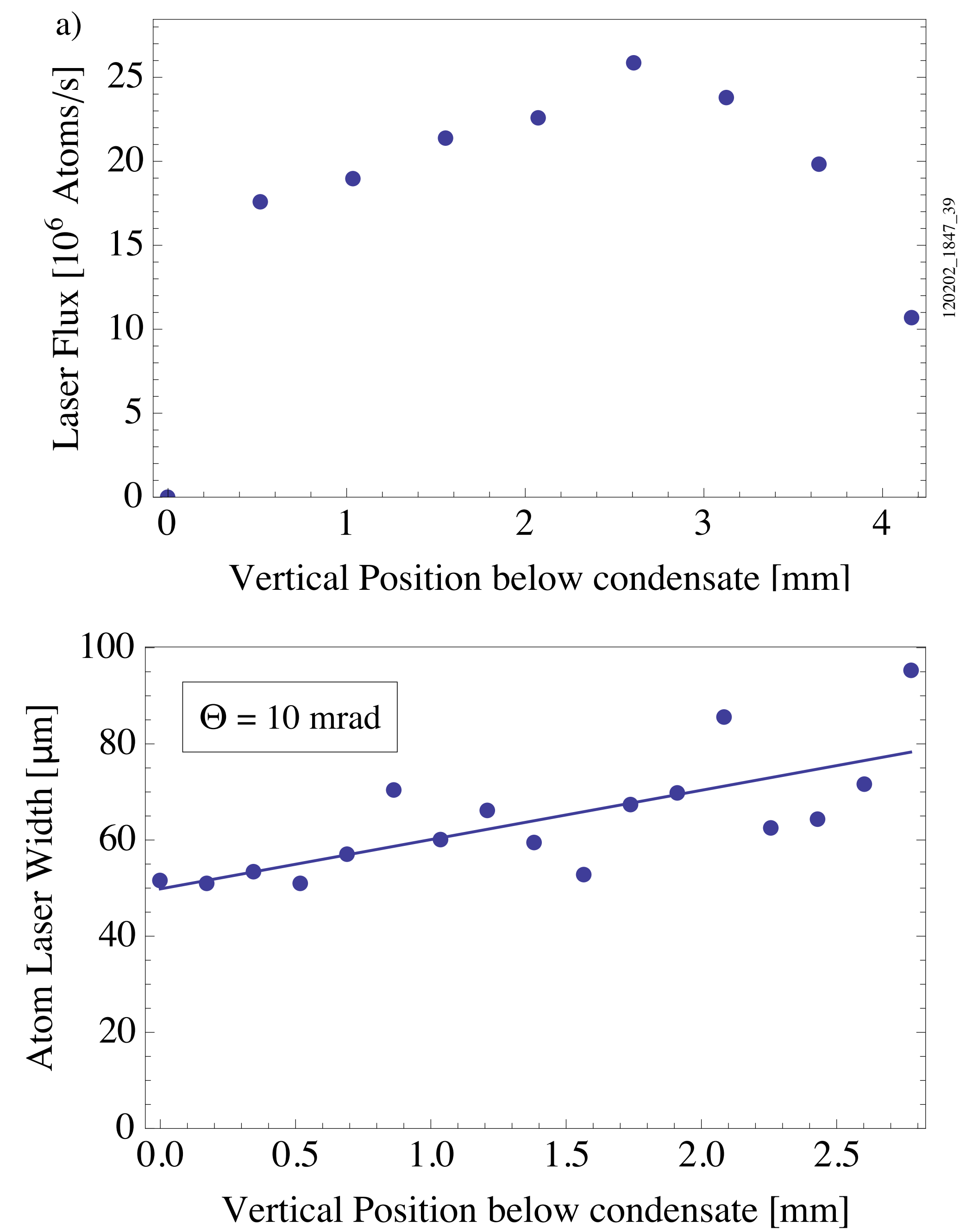
A Pure Atom Laser

FORTH
IESL

Ramping the rf-frequency slowly

4.7 mm





Cretan Matter Waves

Cretan Matter-Waves Group

A High-Flux Atom Laser

FORTH
IESL

Ramping the rf-frequency fast

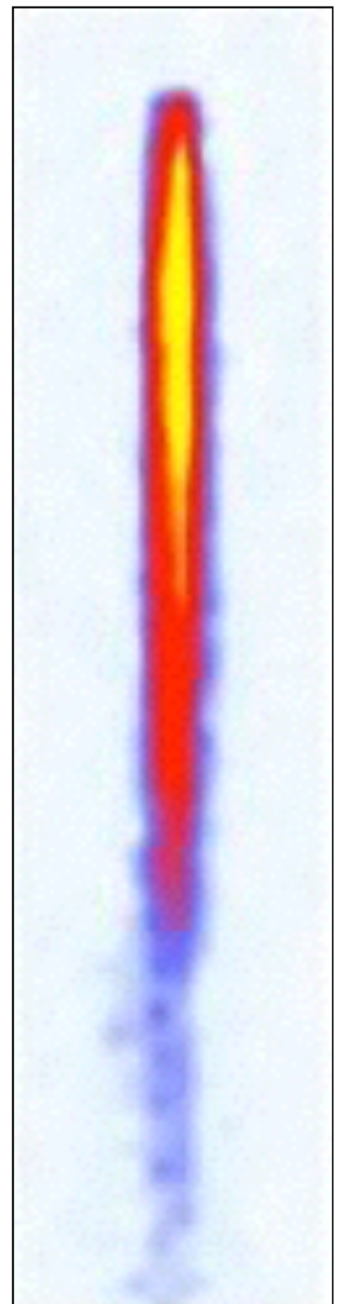
Flux:
= 8×10^{7} atoms s^{-1}

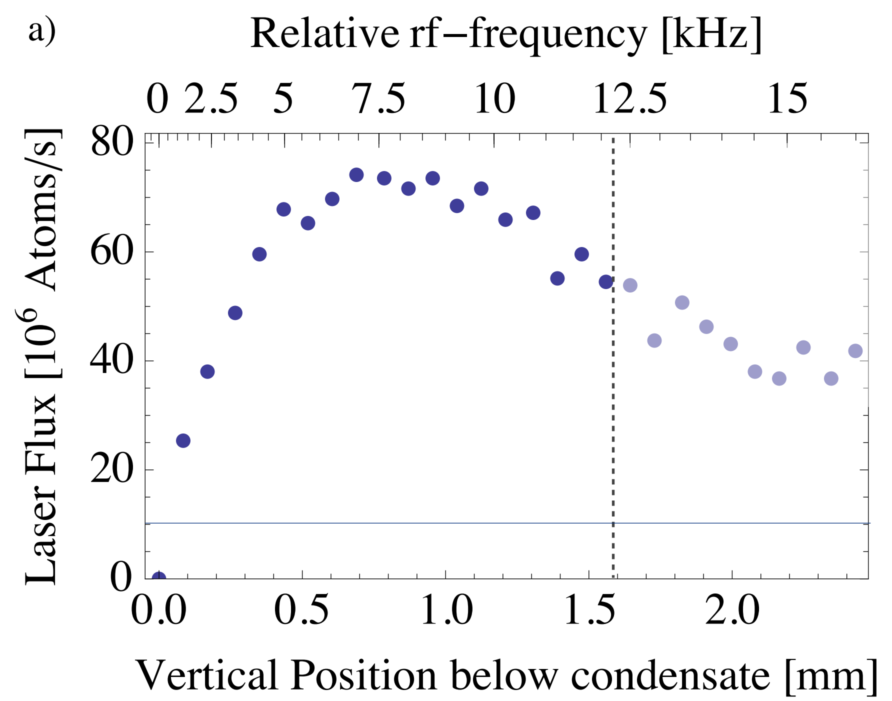
Brightness:

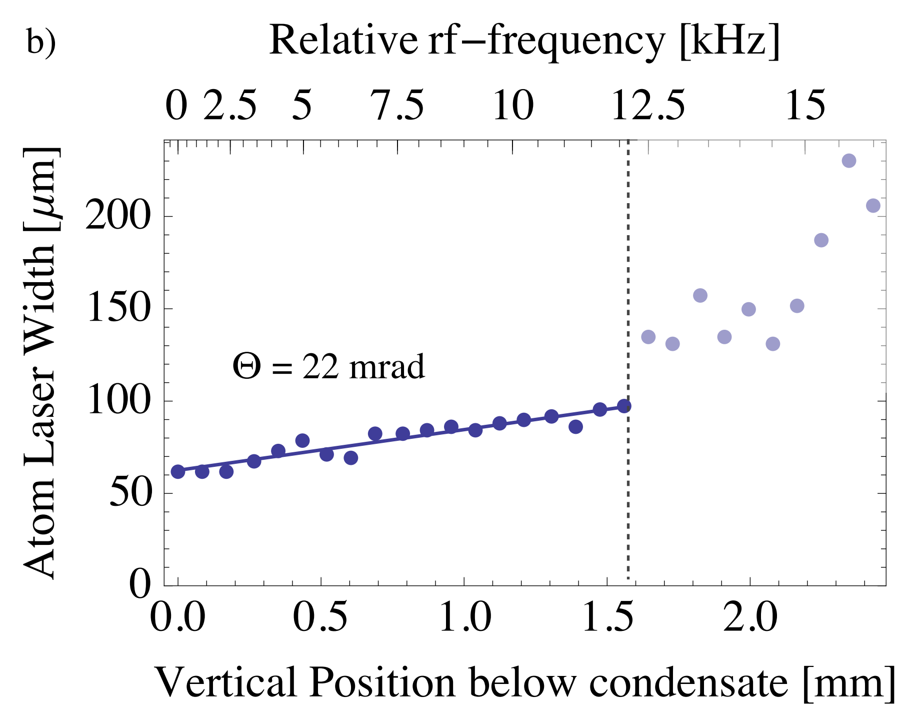
$$= N\left(\Delta t\, A \Delta v_x\, \Delta v_z \Delta v_z\right)^{-1}$$

$\approx 10^{28}$ atoms $s^{2}\, m^{-5}$

2.5 mm







Cretan Matter-Waves Group

A High-Flux Atom Laser

FORTH
IESL

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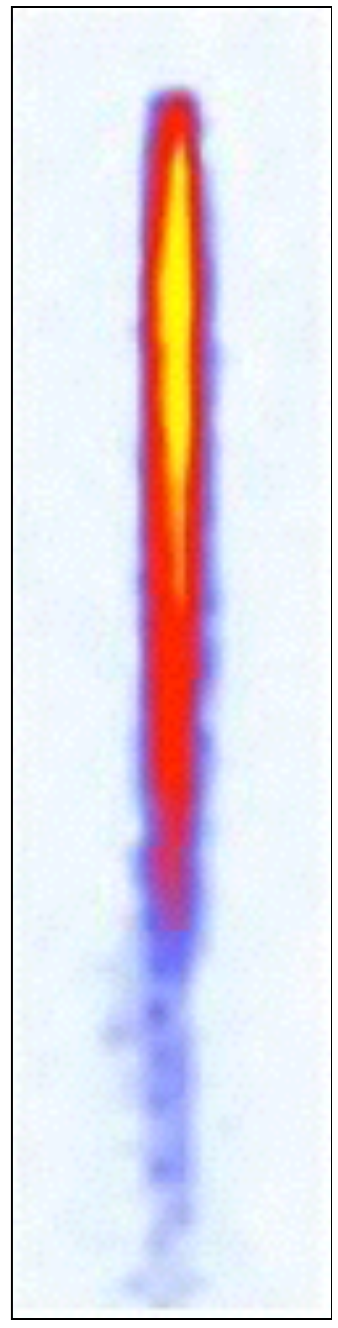
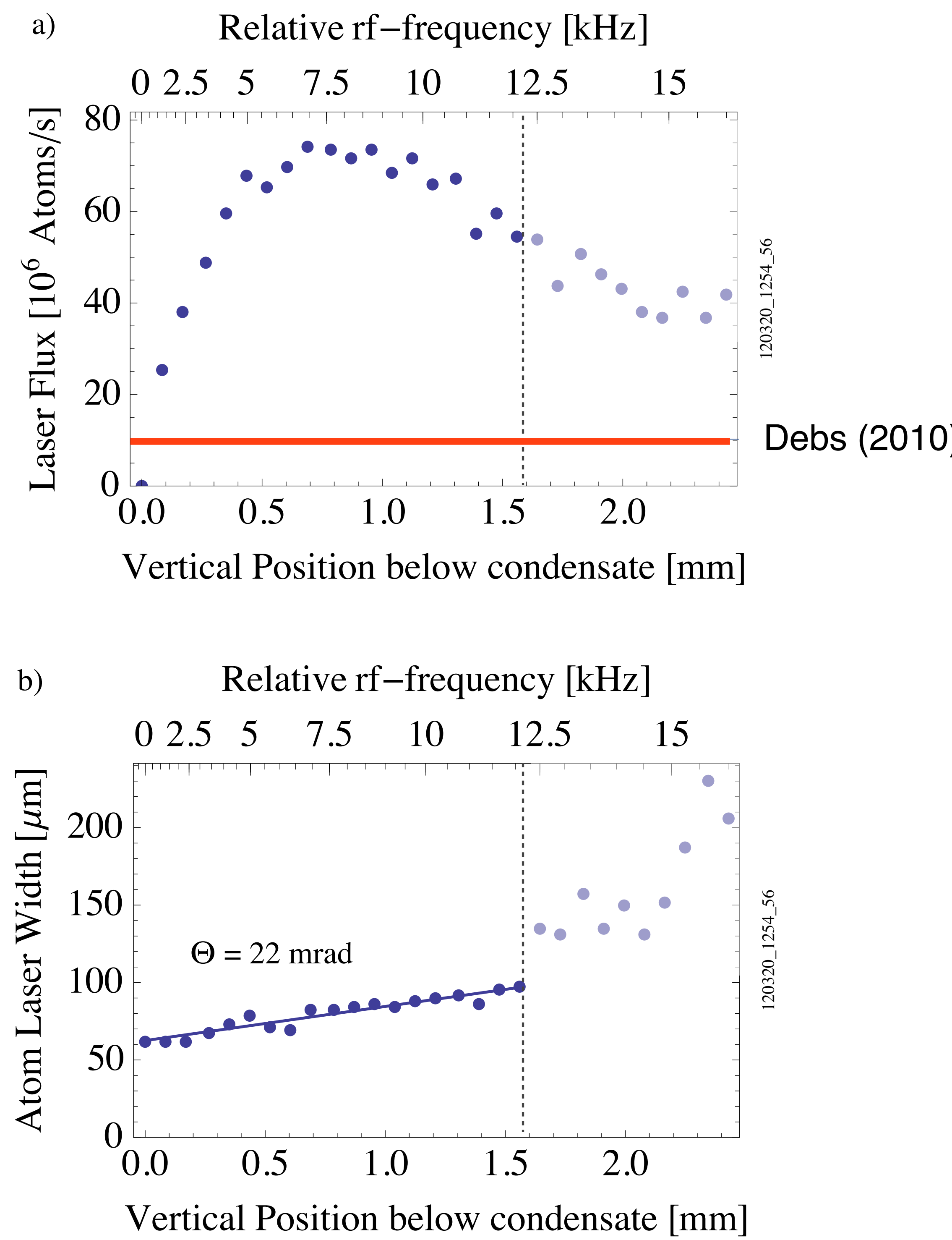




J. E. Debs et al.
Phys. Rev. A **81:2** 013618 (2010)

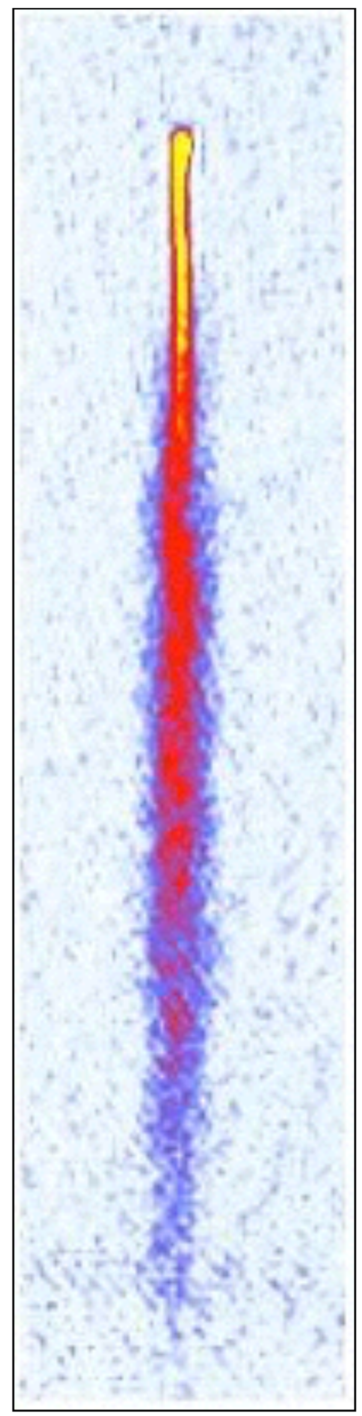
Cretan Matter-Waves Group

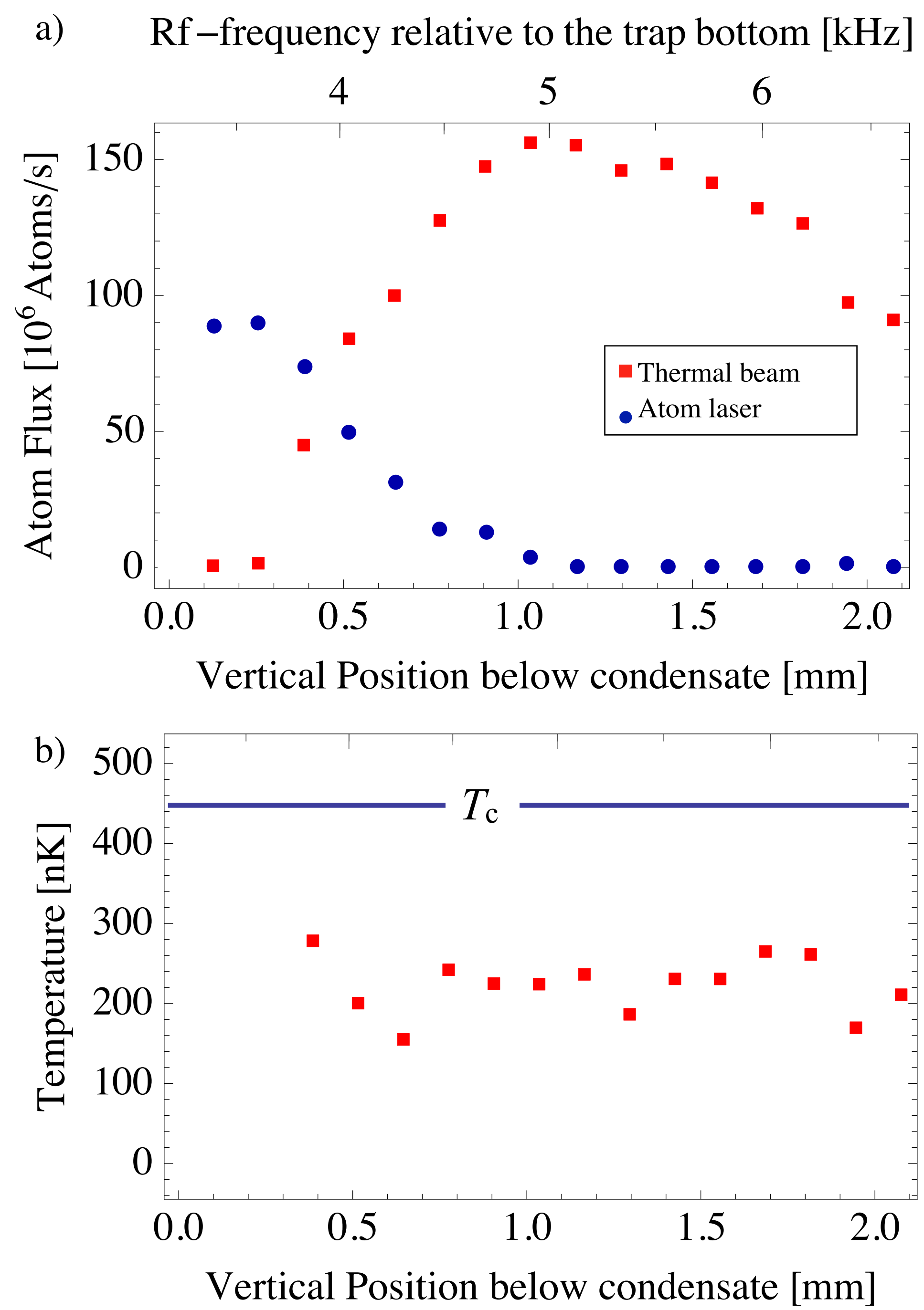
Ultra-Cold Thermal Atom Beam

FORTH
IESL

Smaller, Colder atom cloud

200 nK Atom Beam



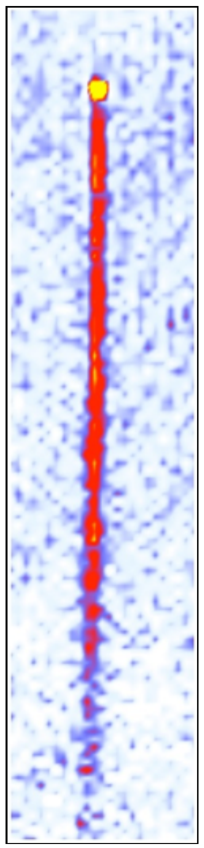


Cretan Matter Waves

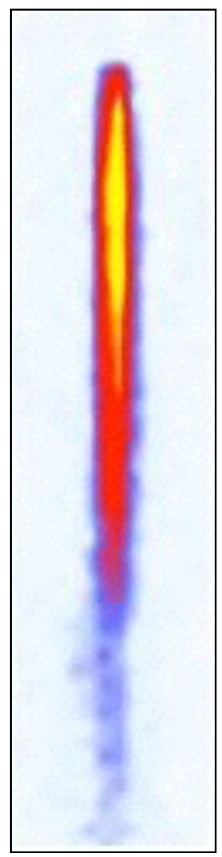
Cretan Matter-Waves Group

3 Atom Lasers

FORTH
IESL

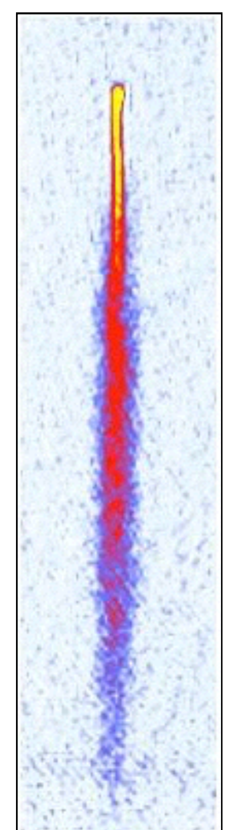


A pure atom laser



A high-flux atom laser

(10^8 atoms/s = 7 x ...)



Ultra-Cold Thermal

(200 nK = 1/100 x ...)

Cretan Matter Waves

Conclusions

- TAAPs are **LSD**
- Bucket Atomtronics
- Atom Lasers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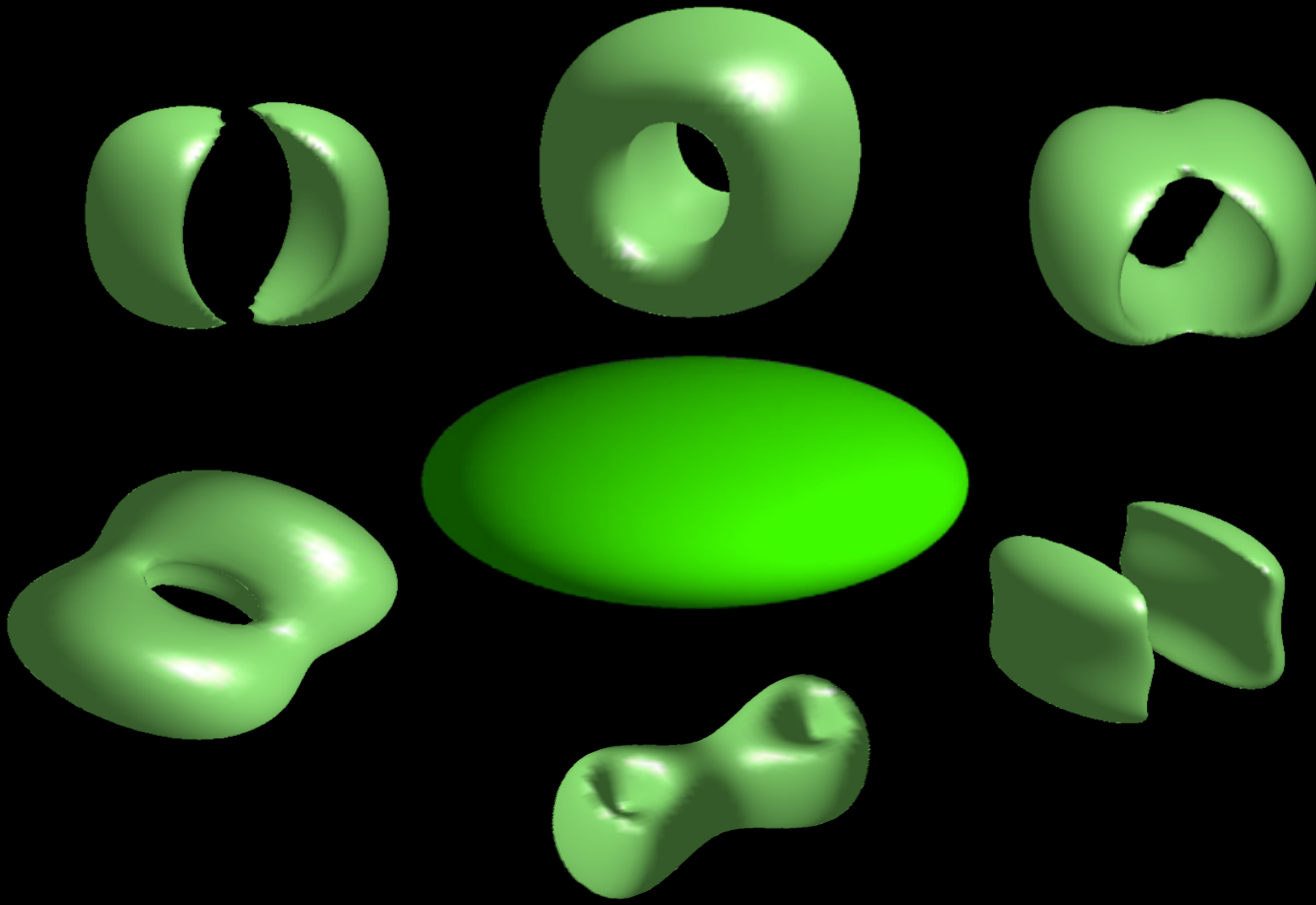
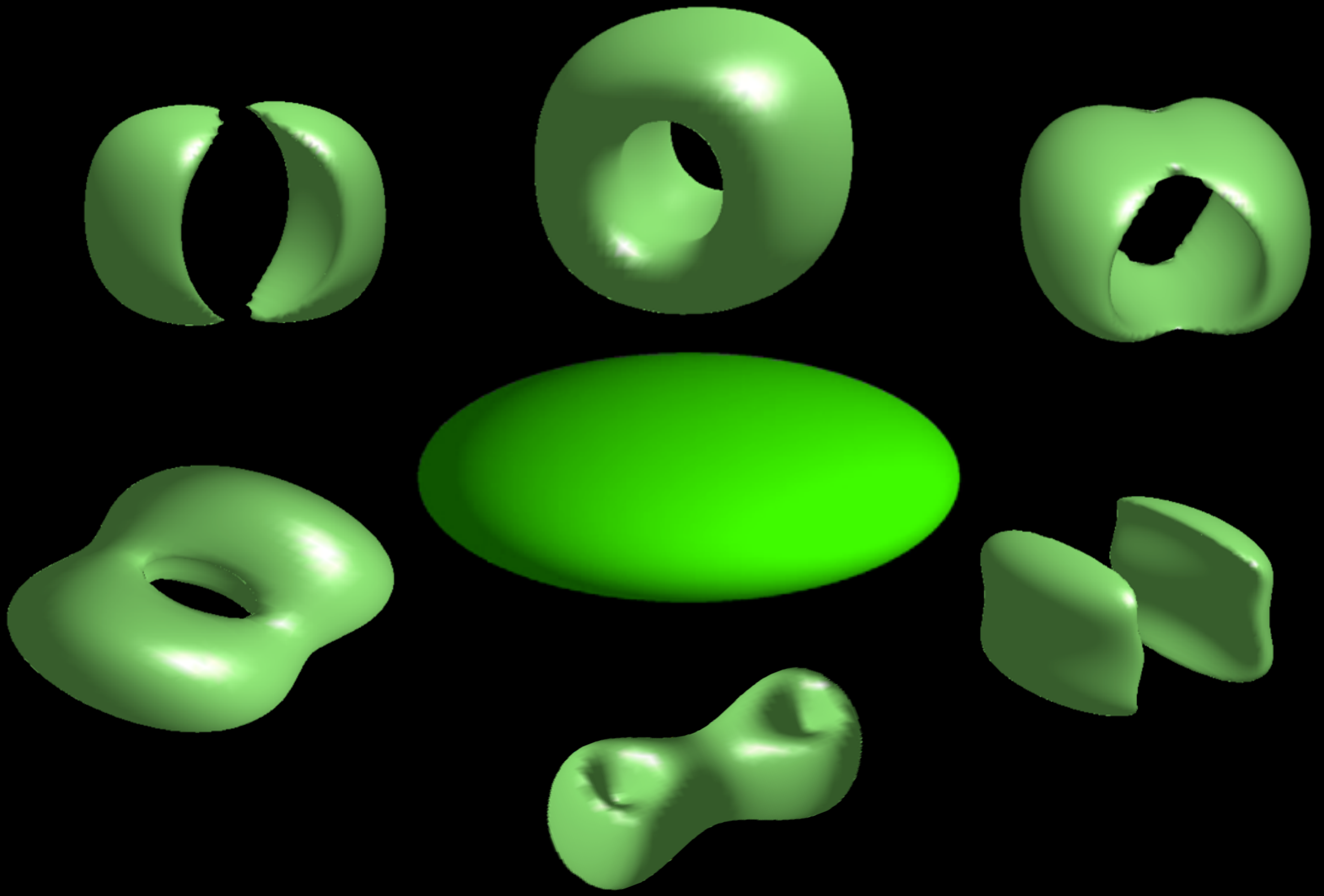
Time averaged adiabatic Potentials (TAAP)



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

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

Time averaged adiabatic Potentials (TAAP)



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

TMP

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The Cretan MatterWaves Group
You?
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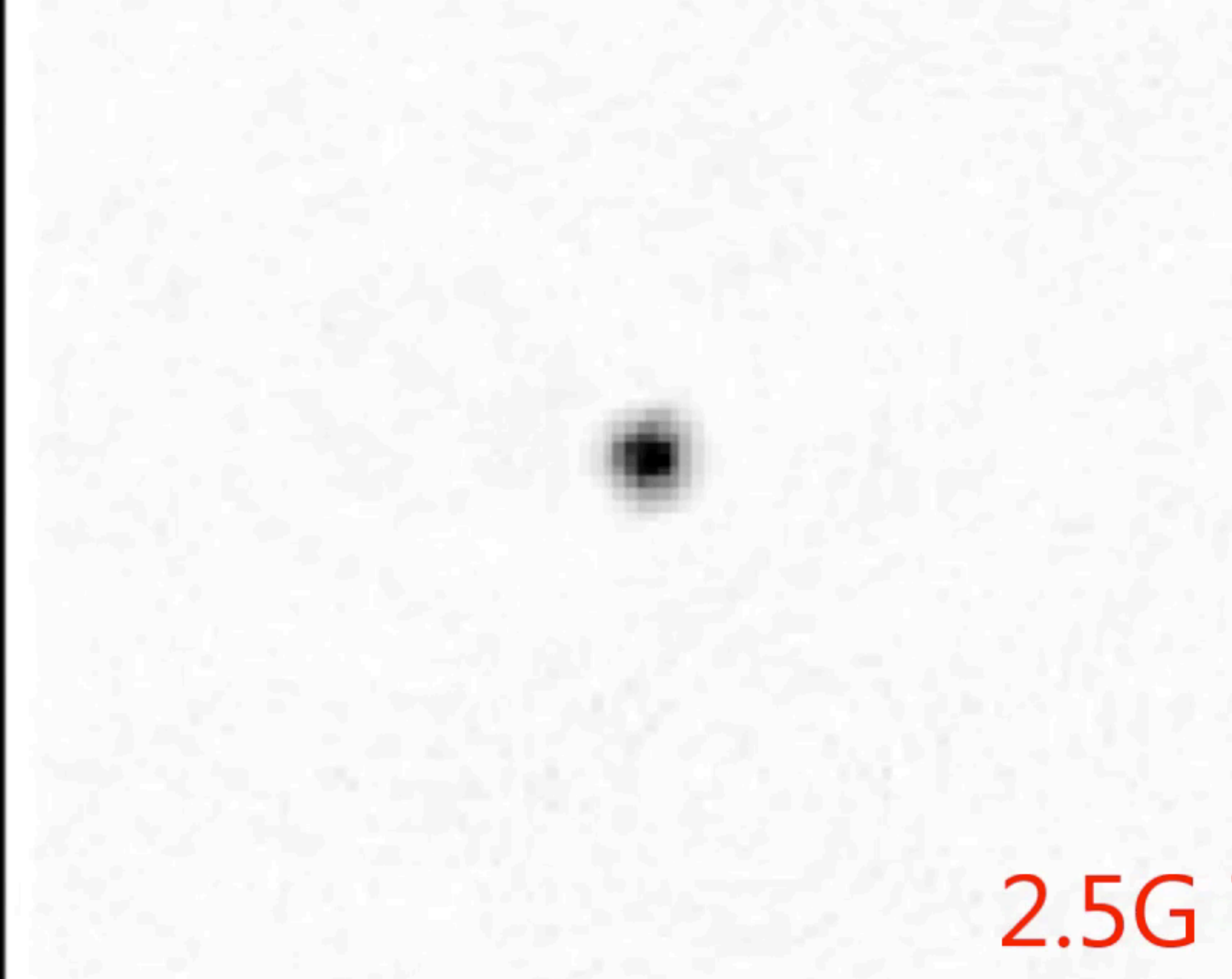
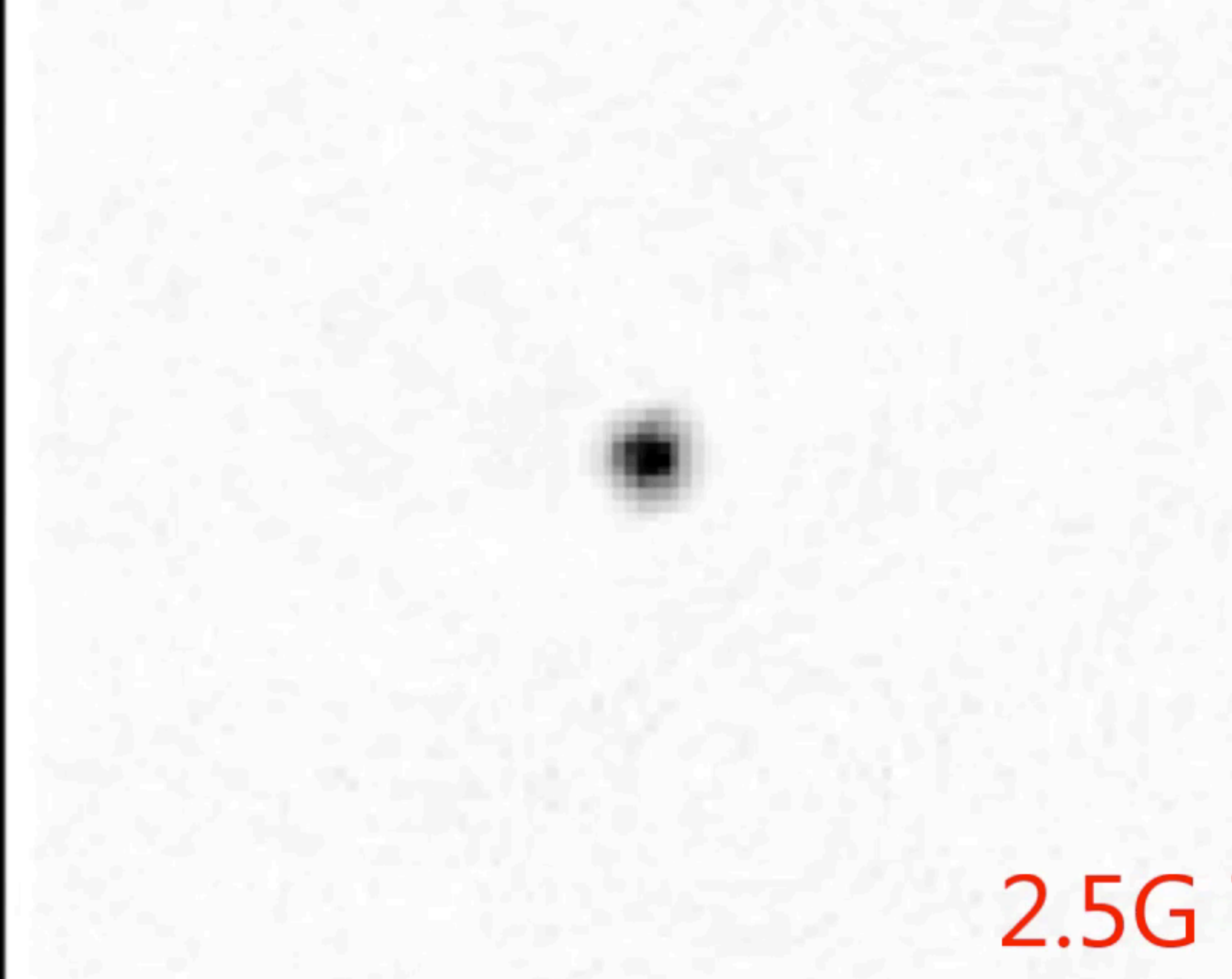

2.5G


2.5G

Boshier Criteria for Atomtronics Circuits

- Smooth / Coherent
- Stable
- Controllable
- Closed Loop

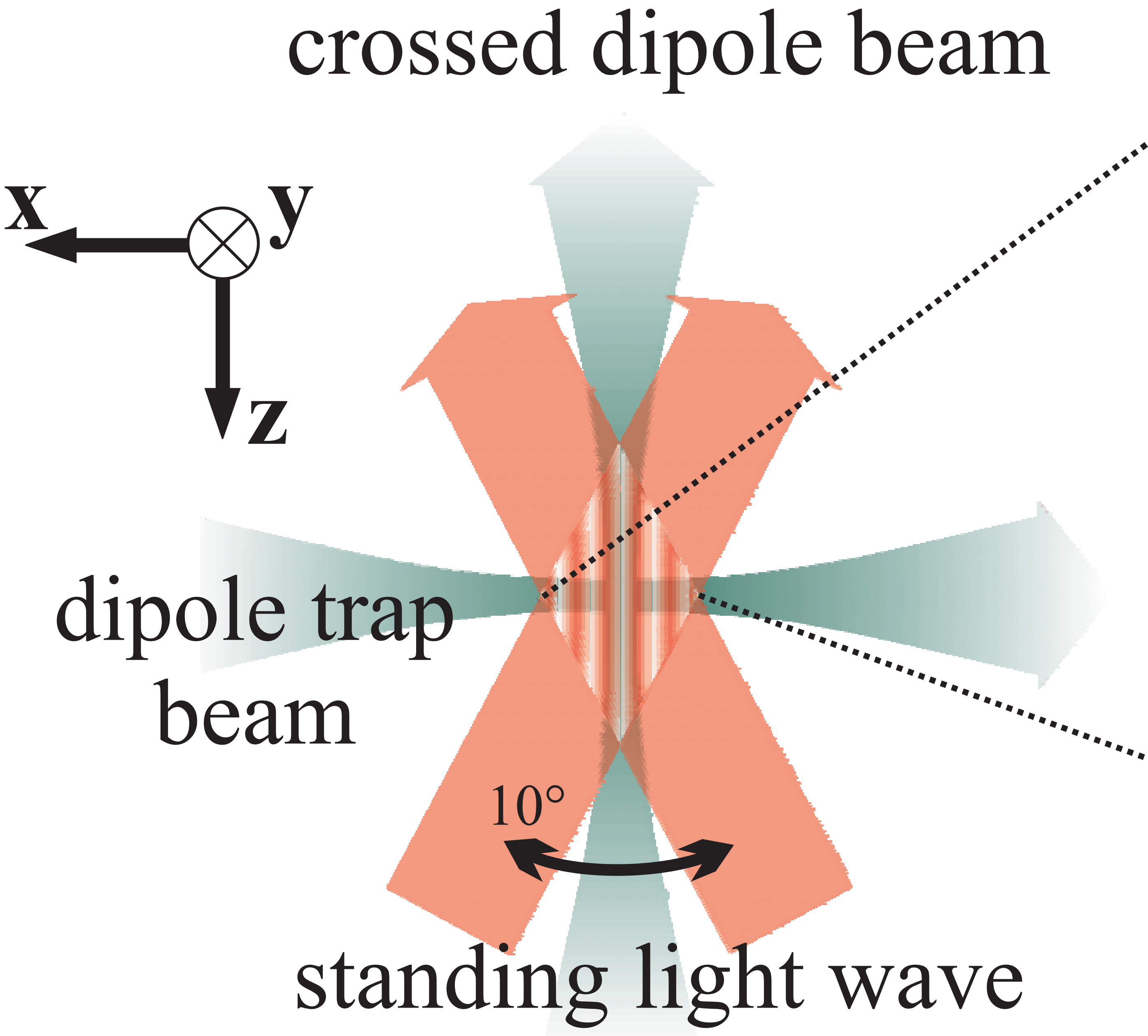
Matter-Wave Guides

- **Smooth**
- **Stable**
- **Controllable**
- **Closed Loop**

- **Dipole Traps & Guides**
  - Free space beams
  - Lattices
  - Fibres
- **Magnetic Fields**

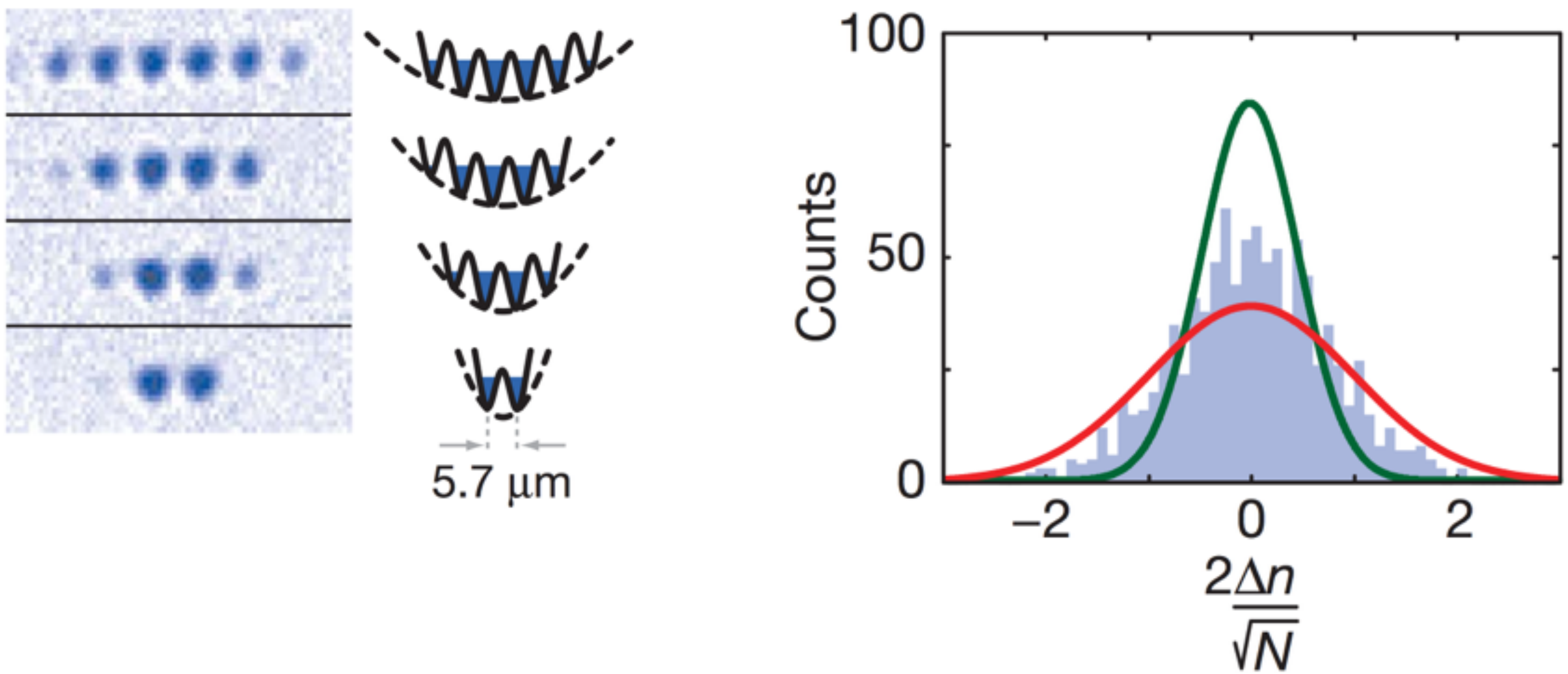
Dipole Guides

- **Dipole Traps**
  - Free space beams
  - Lattices
  - Fibres



R. Gati and M. Oberthaler
Journal of Physics B **40:10** 61 (2007)

Squeezing by Splitting a BEC



Squeezing and entanglement in a Bose-Einstein condensate.
J. Estève et al. Nature **455:7217** 1216--1219 (2008)

Boshier Criteria of Atomtronics

- Loop
- Smooth
- Dynamic

Cretan Matter-Waves Group

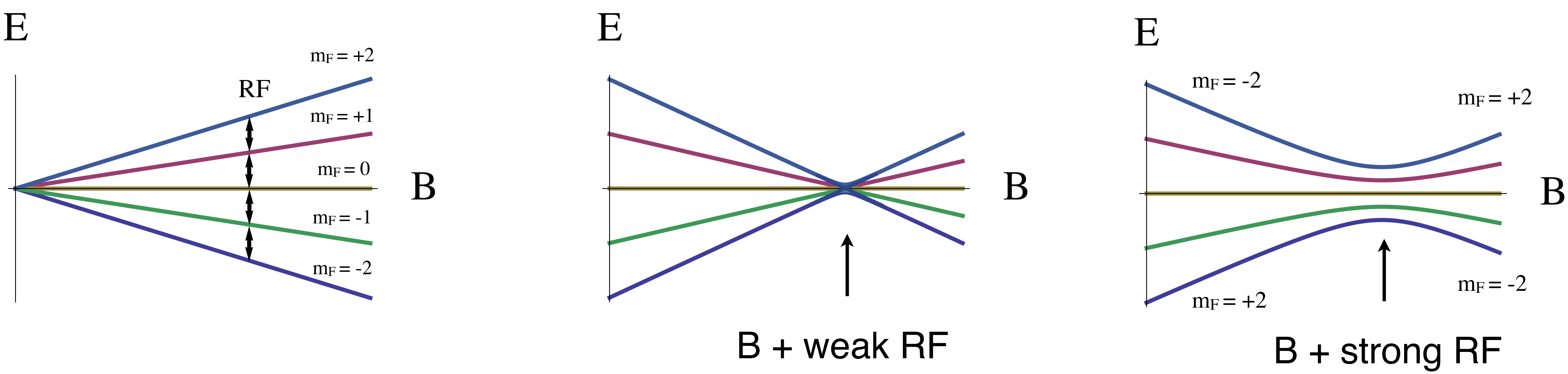
Magnetic Trapping + RF

FORTH
IESL

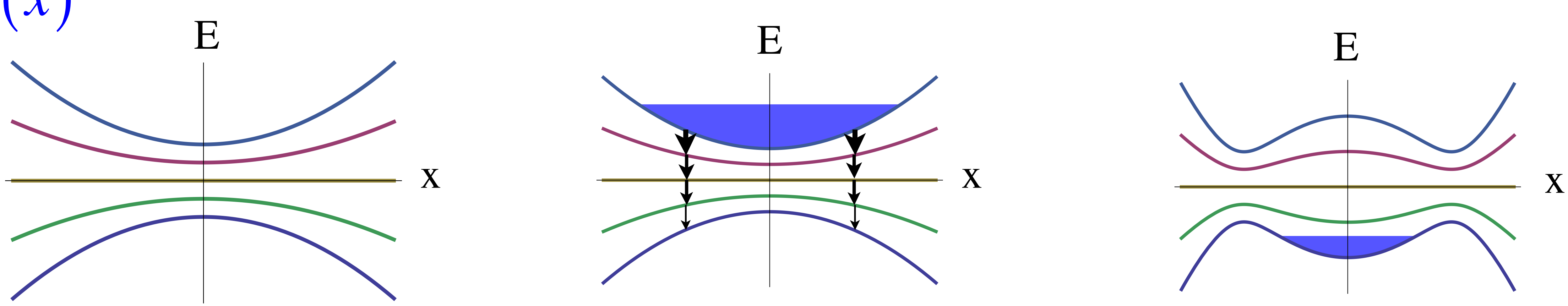
$E(B)$

Weak Coupling
(Spin flips)

Strong Coupling
(Adiabatic Potentials)



$E(x)$



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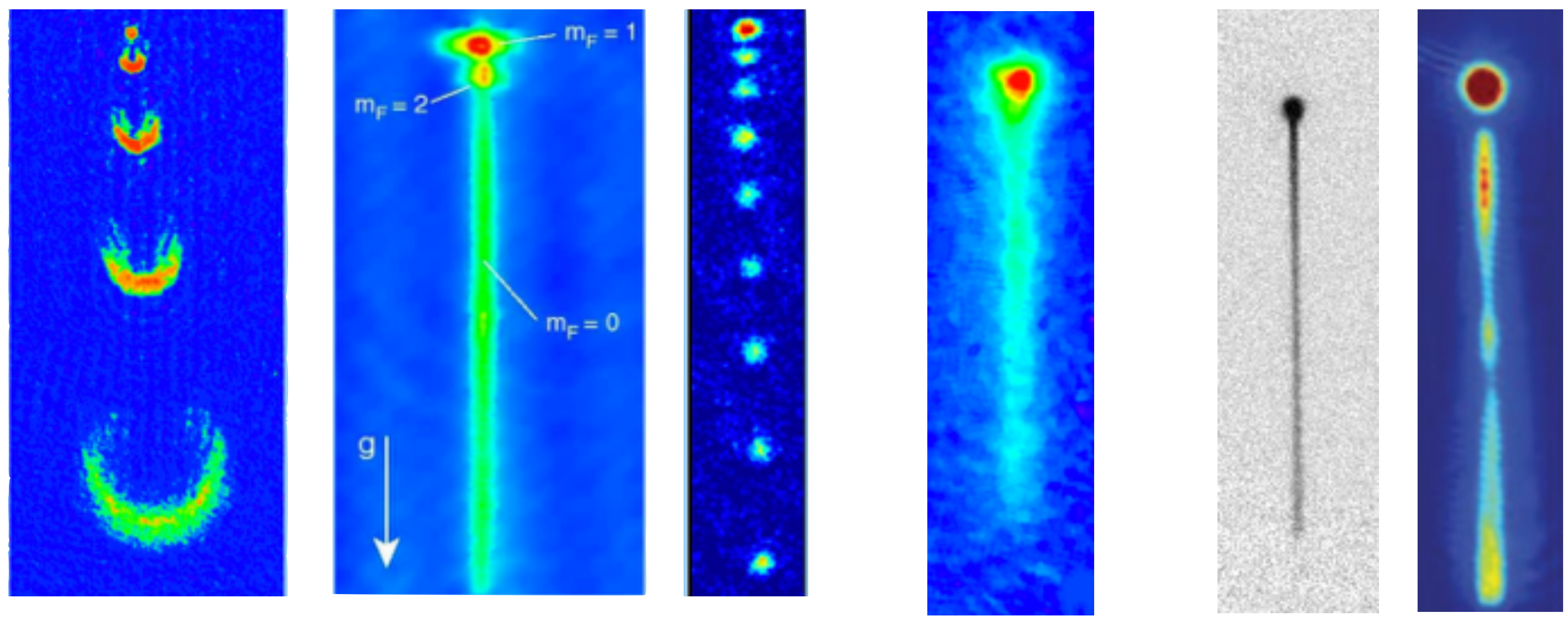
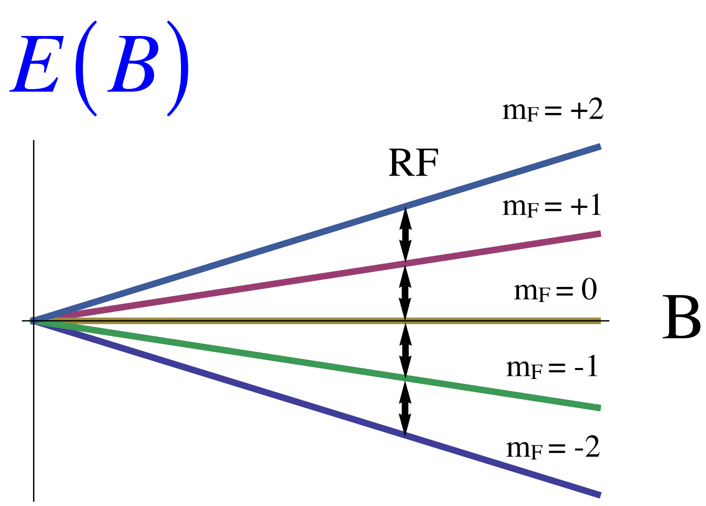
Cretan Matter-Waves Group

Atom Laser Outcouplers for Magnetic Traps

Weak



MIT 1997 | Munich 1999 | Yale 1998 | NIST 1999 | ETH 2005 | Australia 2010



Weak Coupling

(Spin flips)