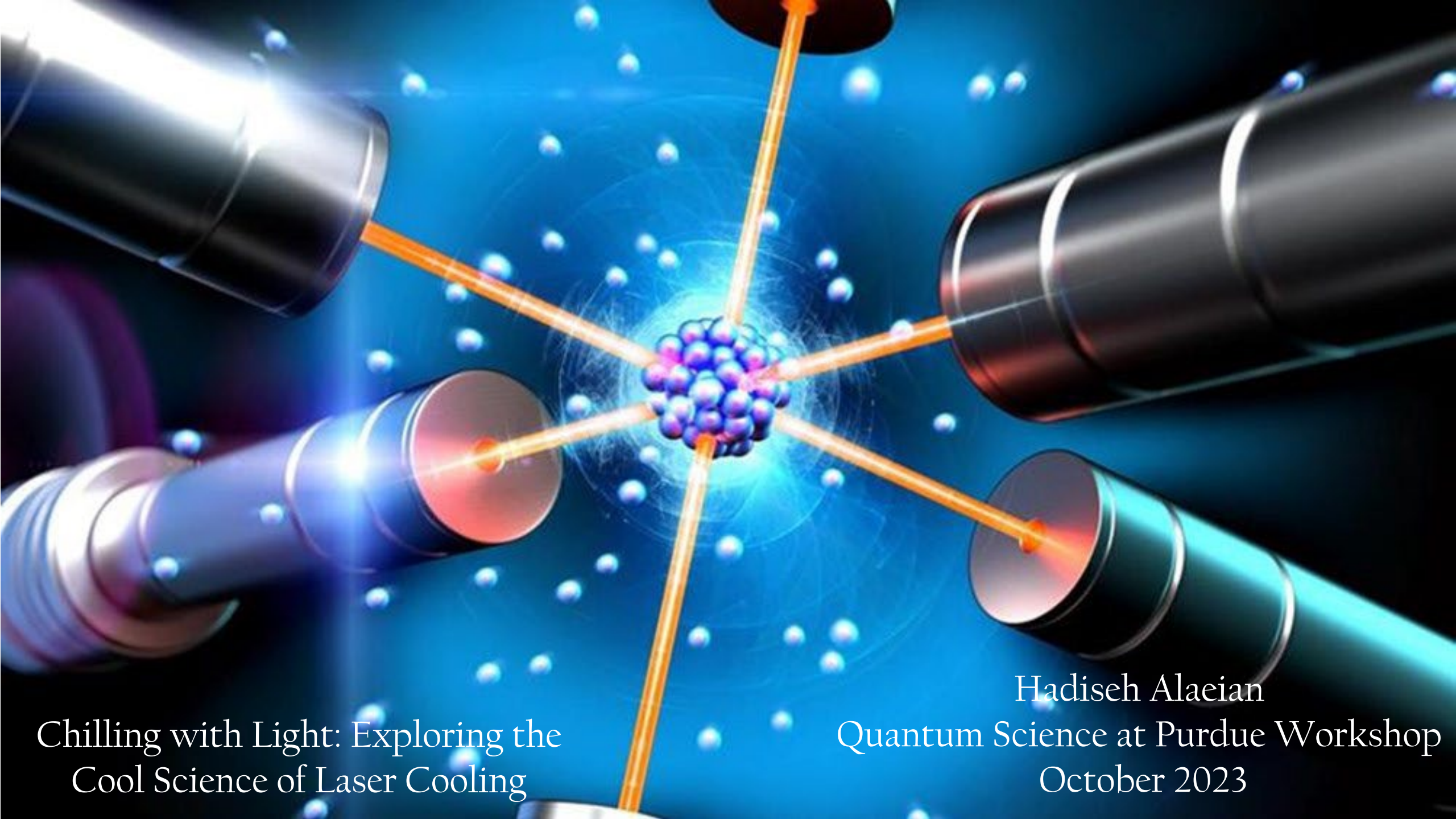


Chilling with Light: Exploring the Cool Science of Laser Cooling

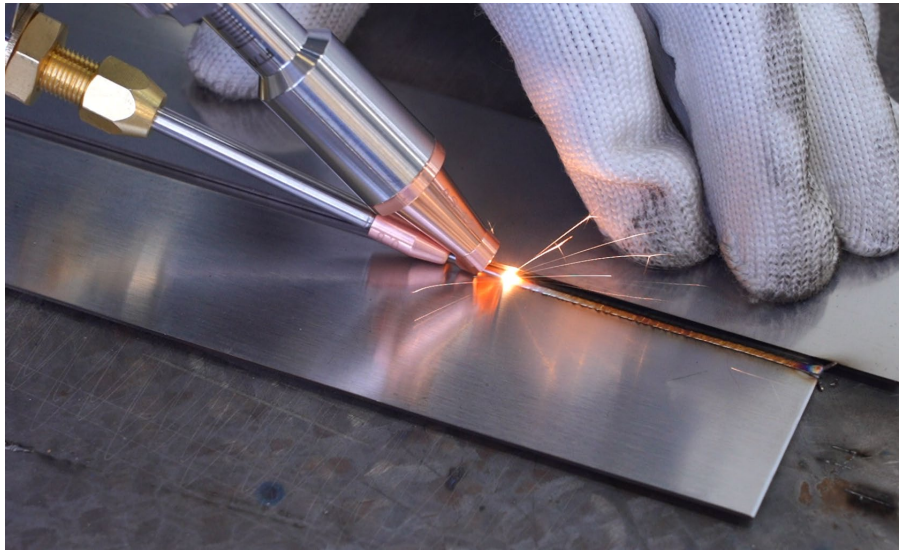
Hadiseh Alaeian

Quantum Science at Purdue Workshop

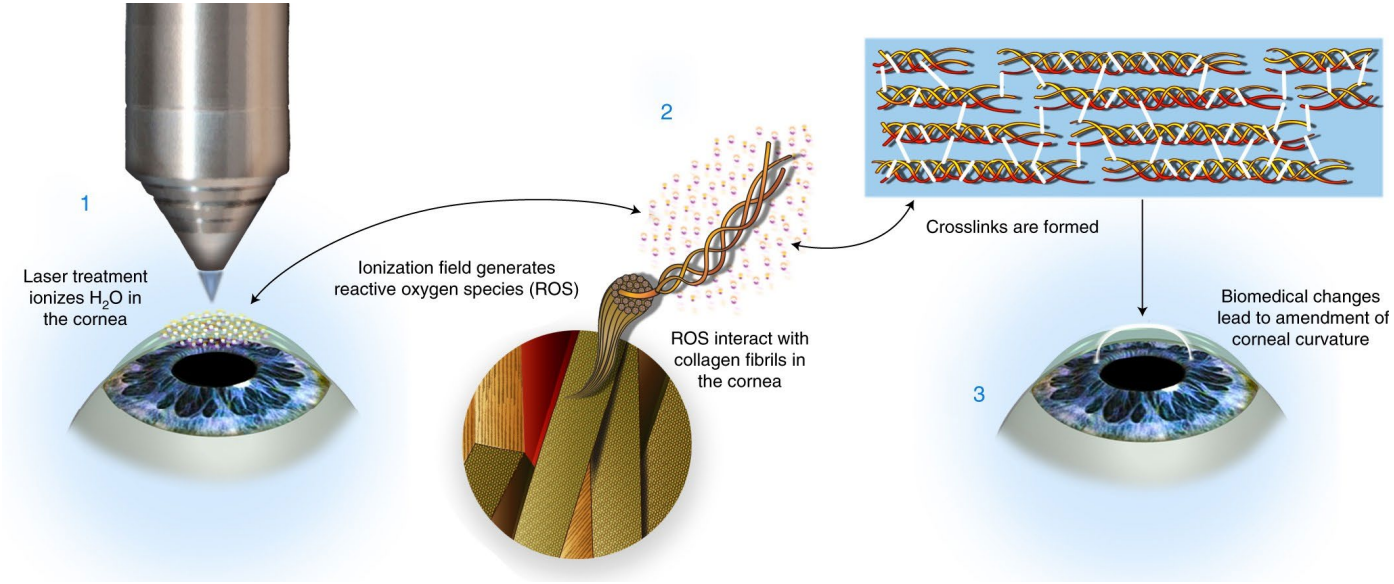
October 2023

Things to Do with Lasers

Laser welding/cutting



Laser surgery

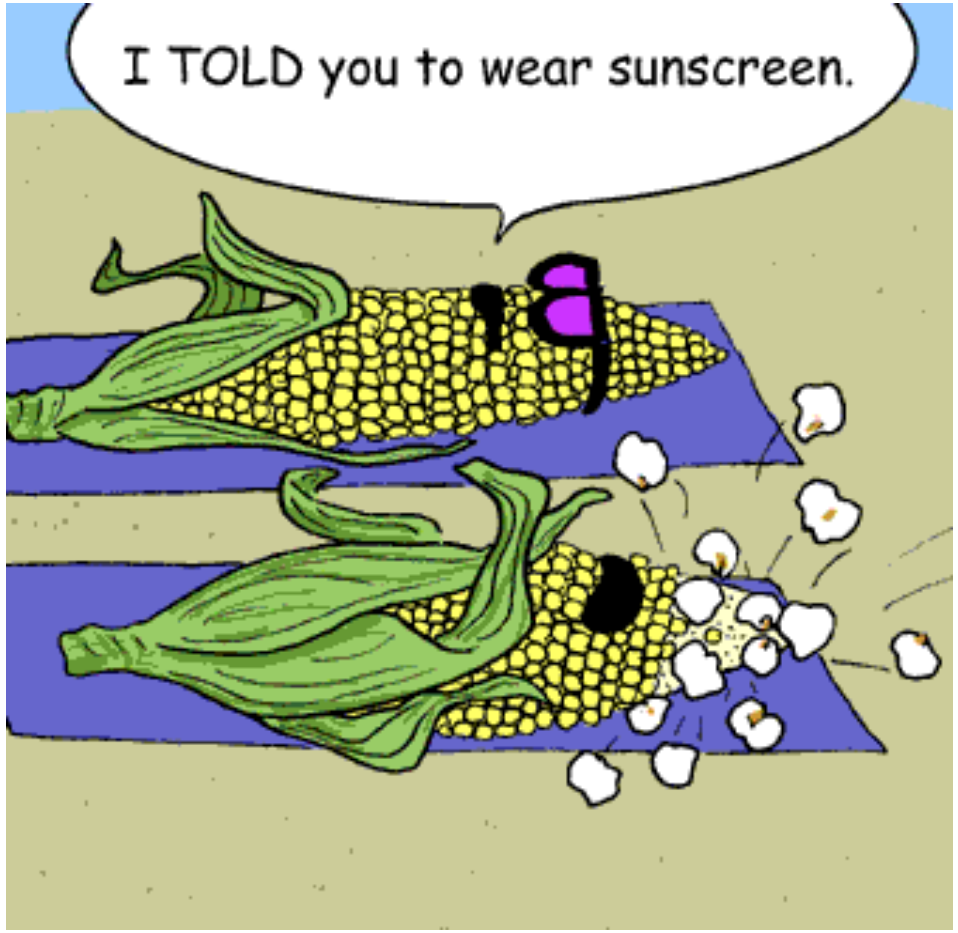


2018

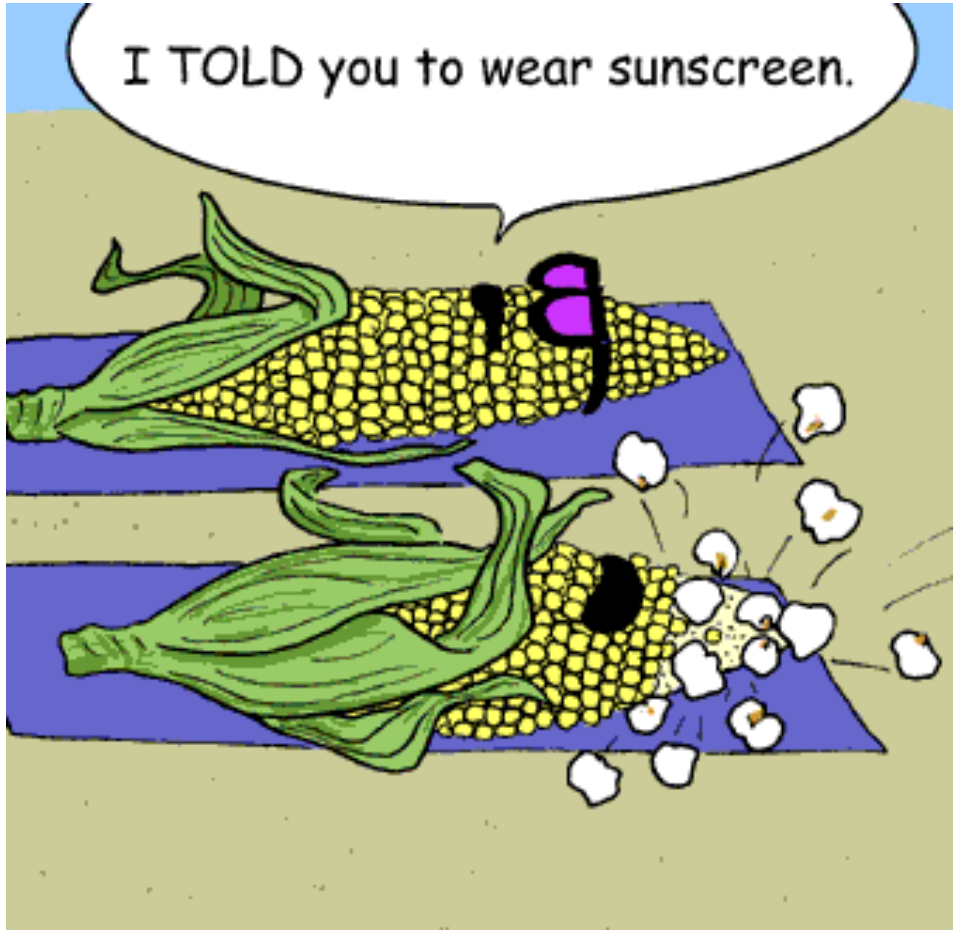
2023

Imaging with *fast* lasers

Heating with Laser



Cooling with Laser?!




WHY iT MATTERS ?


LASER
STOP
LASER

Let's Catch an Atom

- How fast does an atom move? $\frac{1}{2}mv^2 = \frac{3}{2}k_BT$
- Rubidium velocity at room temperature $v \approx 300\ m/s$

Ferrari S90: 95 m/s

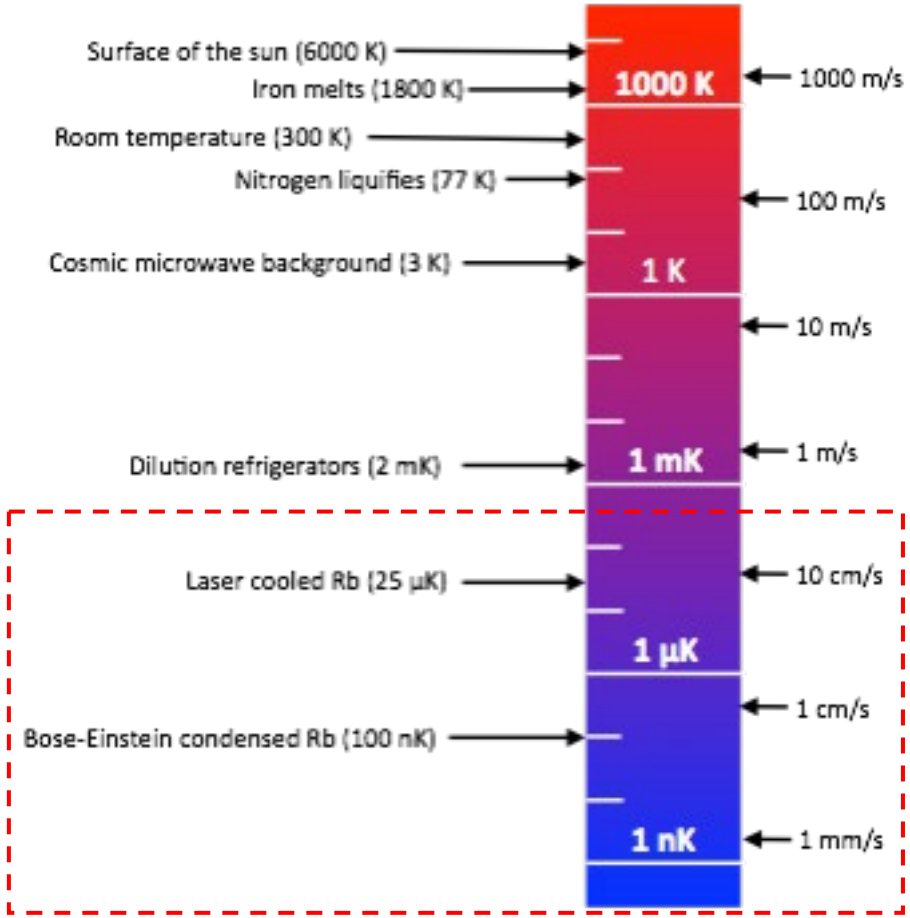
Tesla S: 117 m/s

Buggatti Chiron: 136 m/s

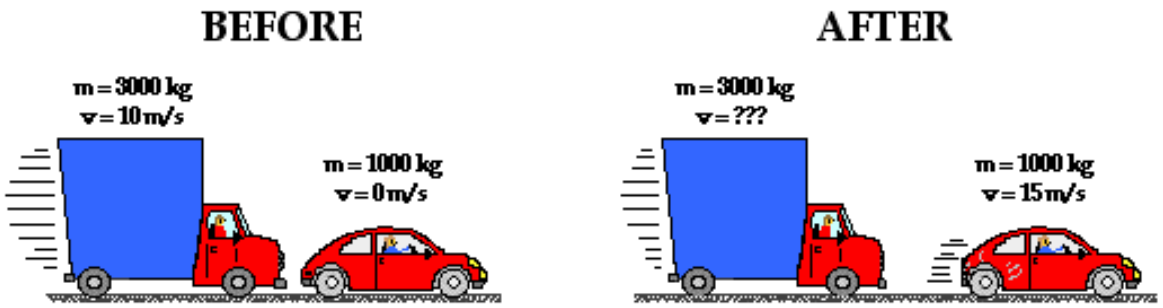
Let's **Not** Catch a *Thermal* Atom

- How fast does an atom move? $\frac{1}{2}mv^2 = \frac{3}{2}k_B T$
- Rubidium velocity at room temperature $v \approx 300\ m/s$

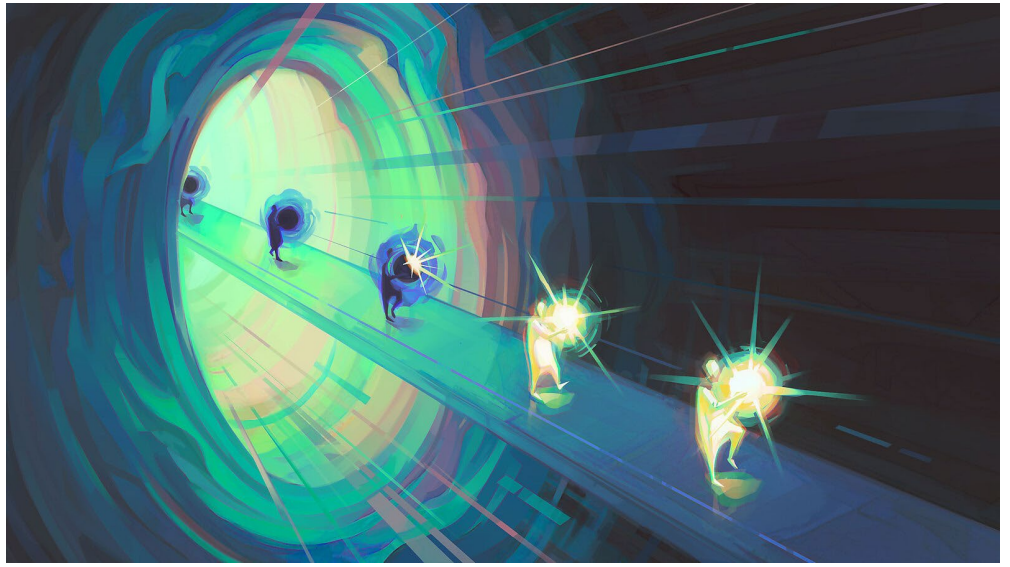
As fast as a supersonic plane!!

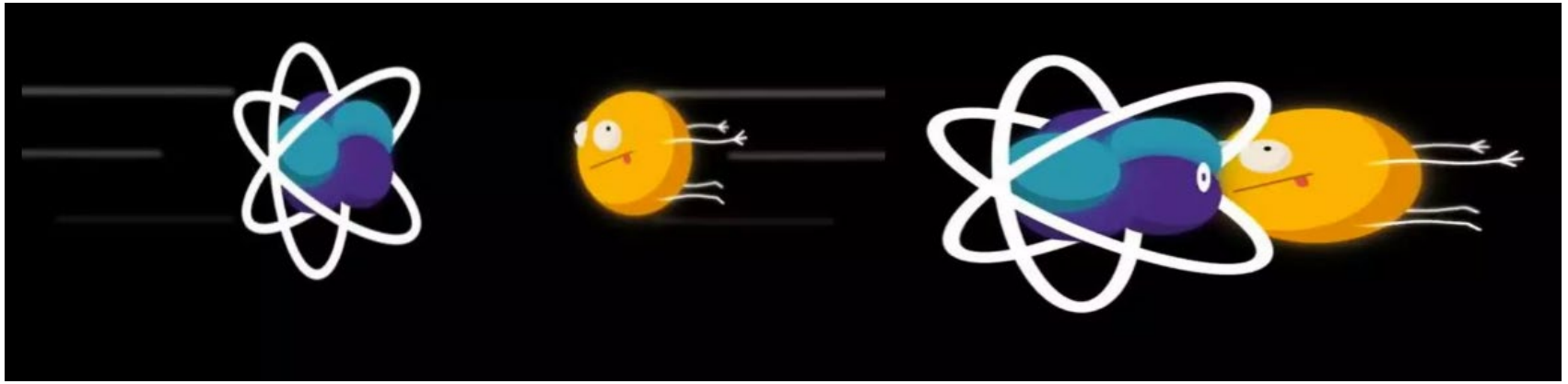


Slowing-Down Through Collision



Energy $E = h\nu$ Momentum $p = \hbar k$





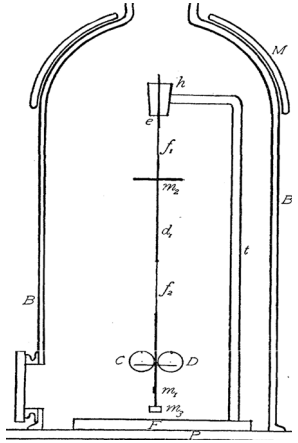
Mechanical Effects of Light in a Glance

Kepler (1600)

Crookes (1875)

Failed attempt due to the residual gas pressure

Lebedev & Hull (1901)



Successful observation of *radiation pressure*

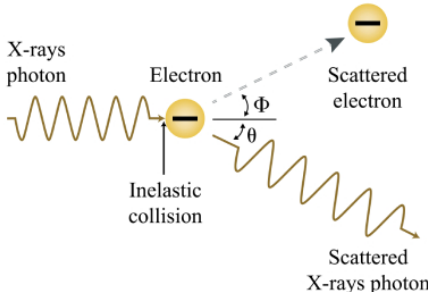
Einstein (1901)

Birth of the *photon*

1922

Compton (1920)

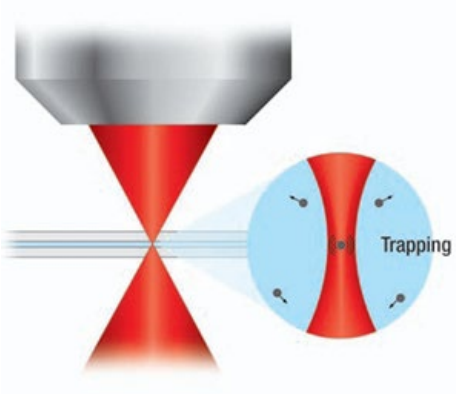
Frisch (1933)



Colliding with *Photons*

1927

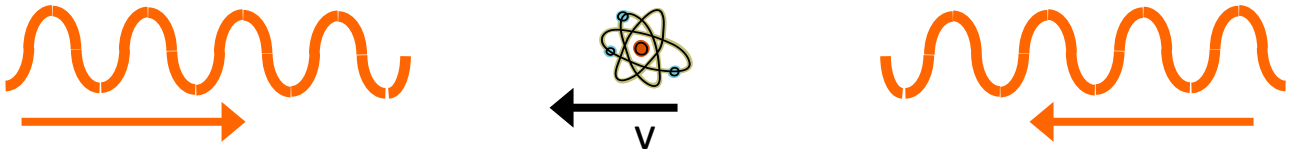
Ashkin (1970)

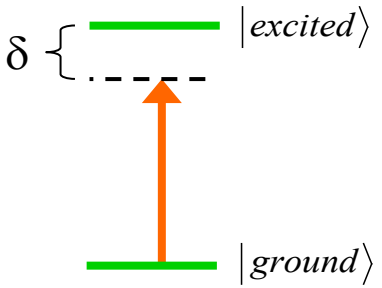


2018

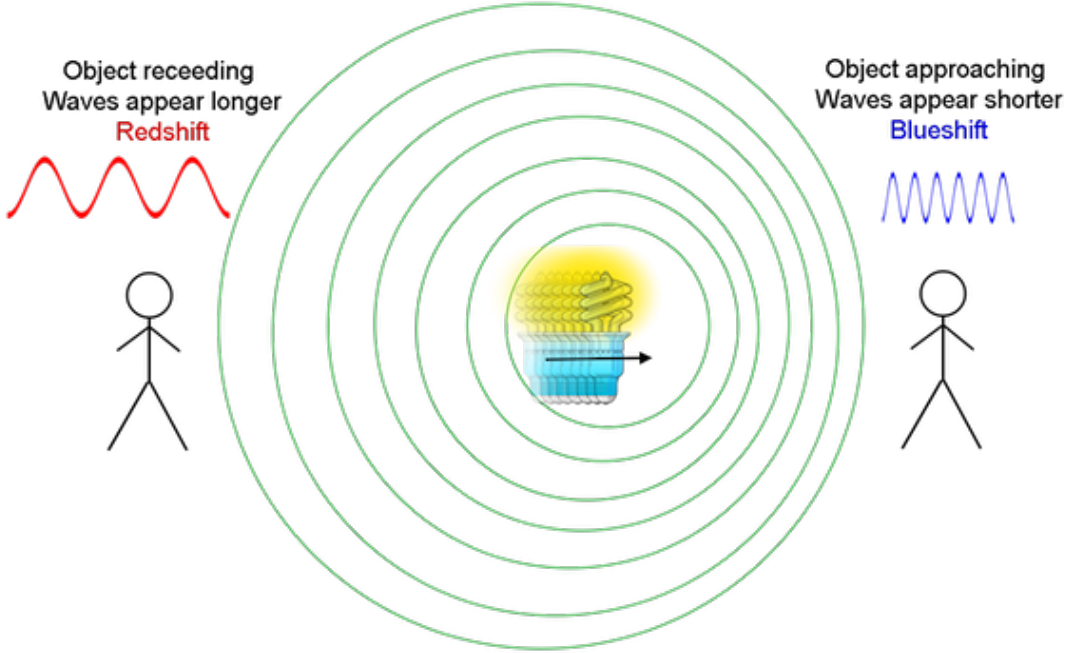
& then the fun began...

Doppler Cooling

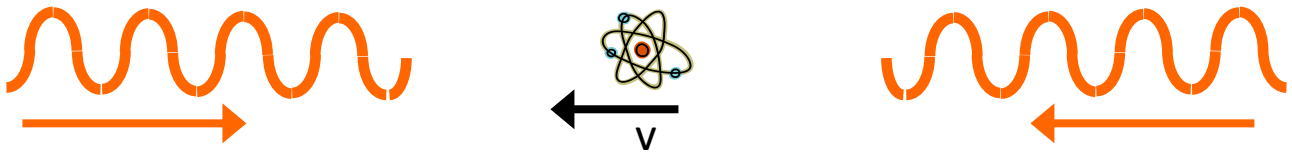


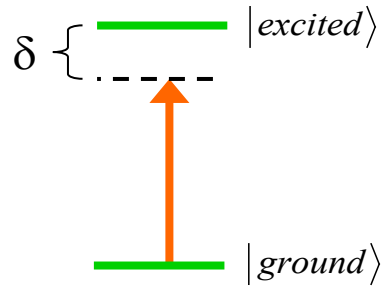


- A classical particle with get a kick always.
- Atoms are not easy going & do care about the color of photons.
- Counter-propagating photons get absorbed. Remember the *Doppler* effect?!

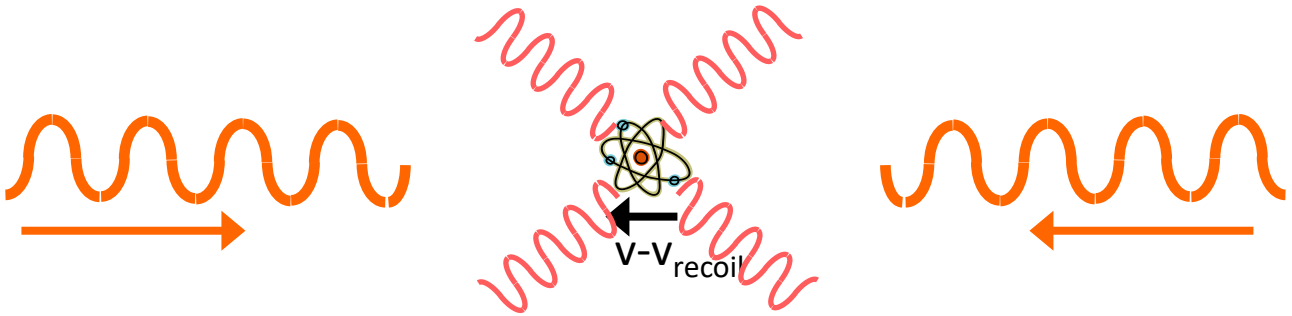


Doppler Cooling



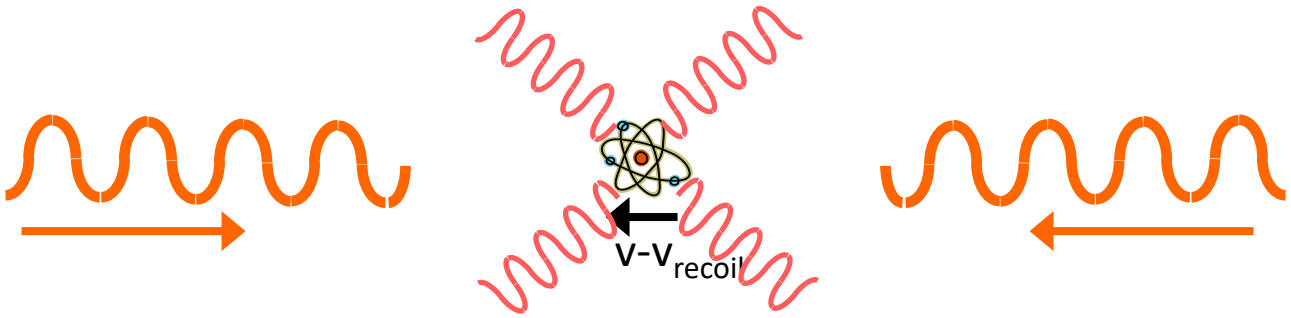


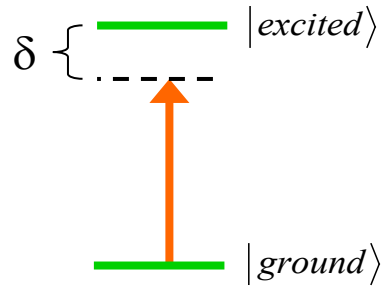
$$\delta' = \delta + \vec{k}.\vec{v}$$



- Atom velocity get reduced by $\frac{\hbar k}{m} \sim 6 \times mm/s$
- Repeat the process 10M/s

Doppler Cooling





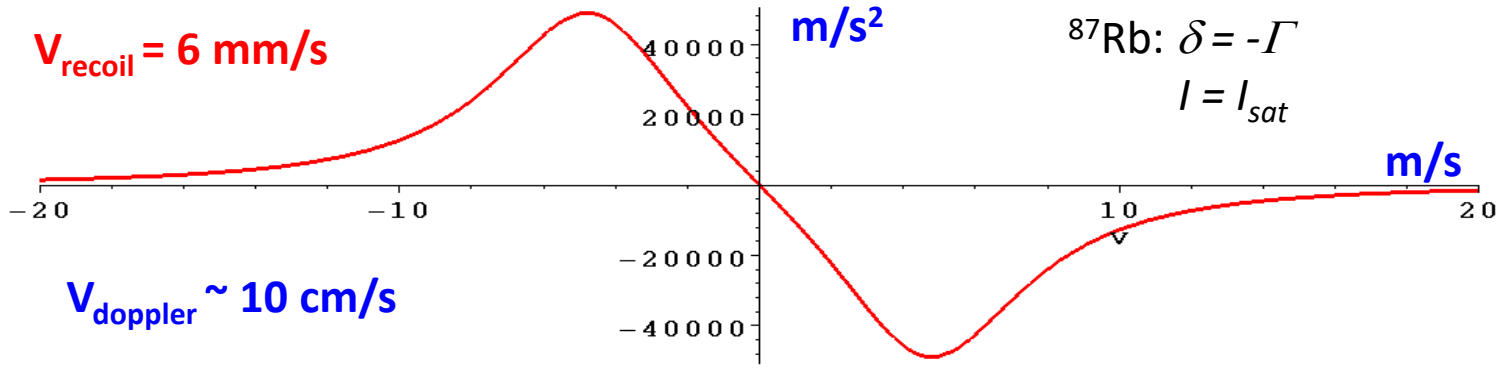
$F = -\alpha v$

Effective decelerating force

Friction coefficient

V_{recoil} = 6 mm/s

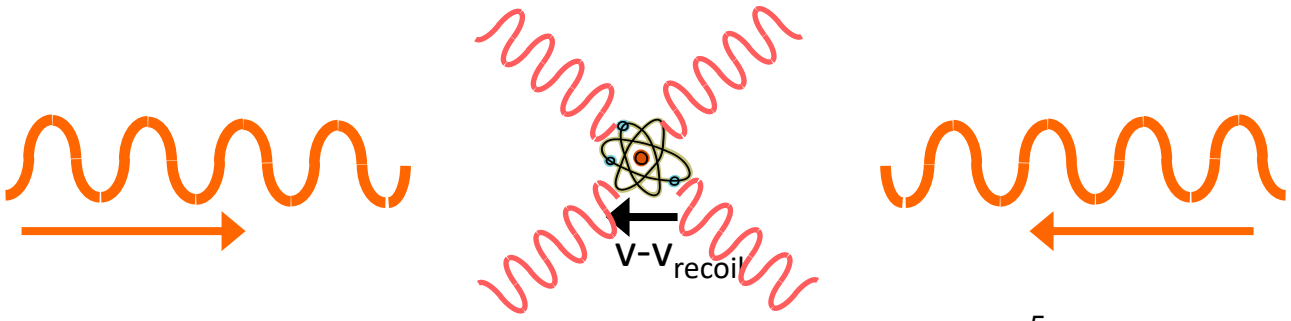
$V_{doppler}$ ~ 10 cm/s

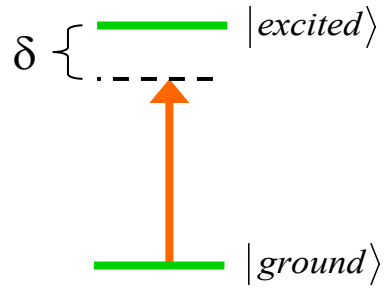


^{87}Rb: $\delta = -\Gamma$

$I = I_{sat}$

Doppler Cooling



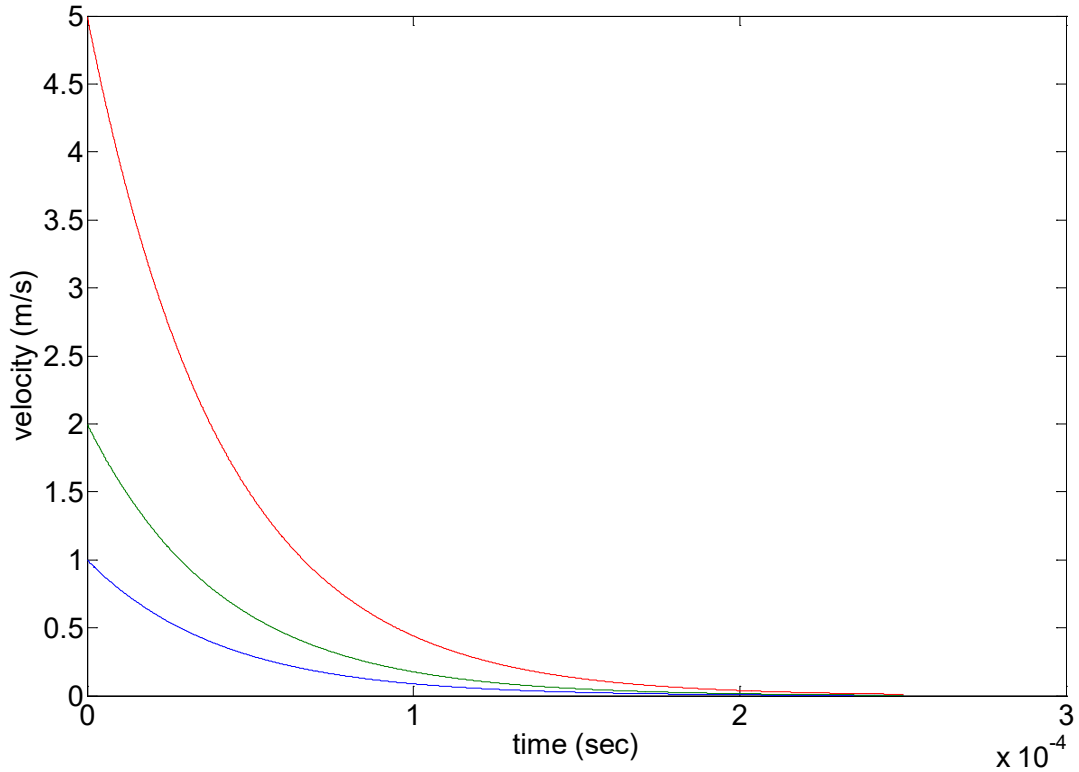


$$F = -\alpha v$$

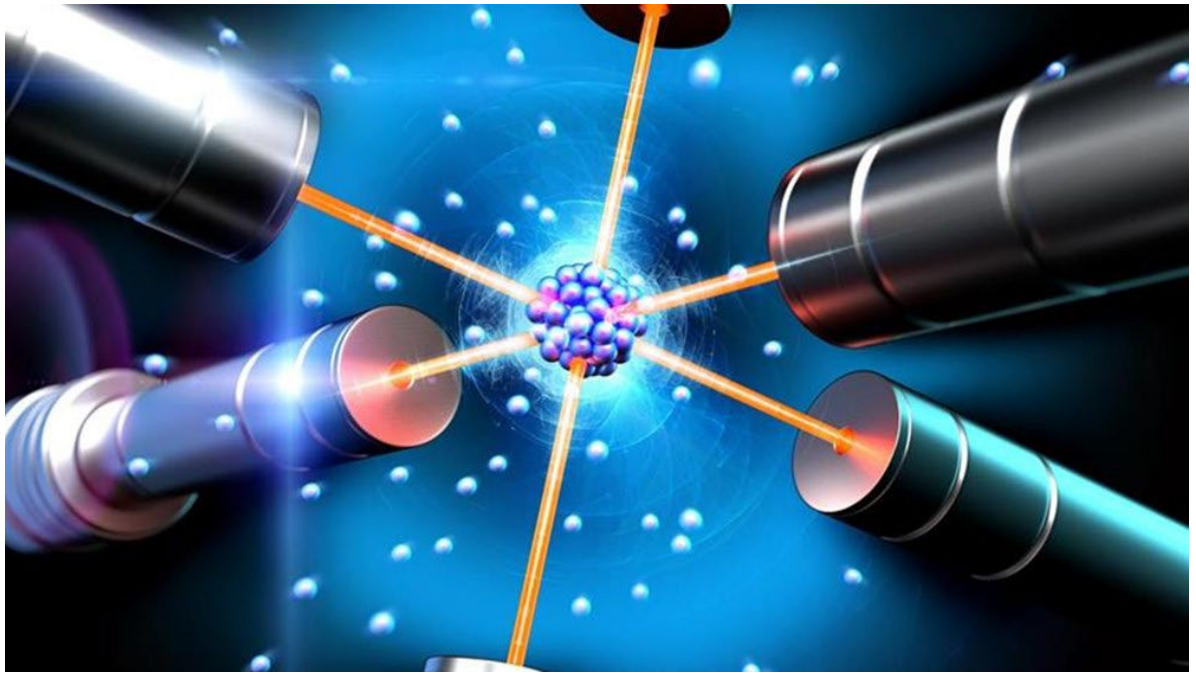
Effective decelerating force

Friction coefficient

$T \approx 200\ \mu K$



Optical Molasses

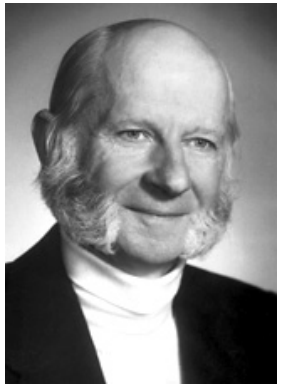


proposal in 1975 for atoms

1981

2005

proposal in 1975 for ions



1989

2012

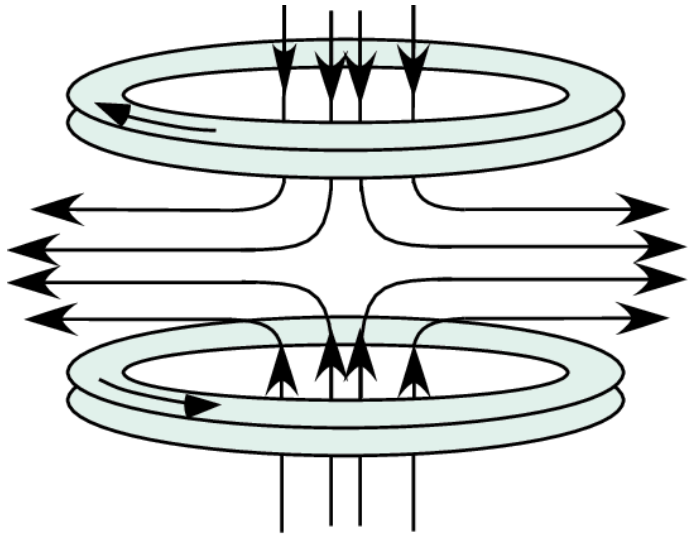
cooling & trapping of atoms

1997

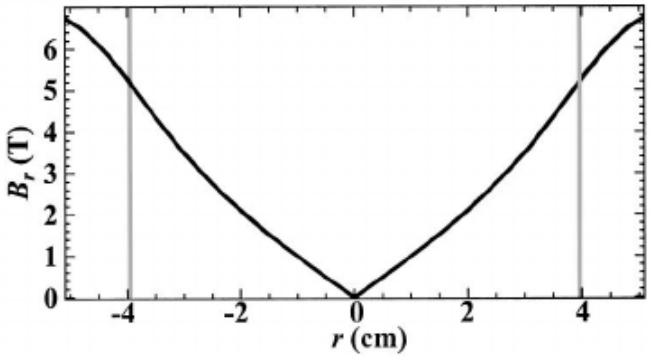
Let's Catch a *Cold* Atom

- Laser cooling can slow-down the atoms.
- Atoms are still all over the place and not confined.
- Let's trap the slow atoms using a position-dependent force

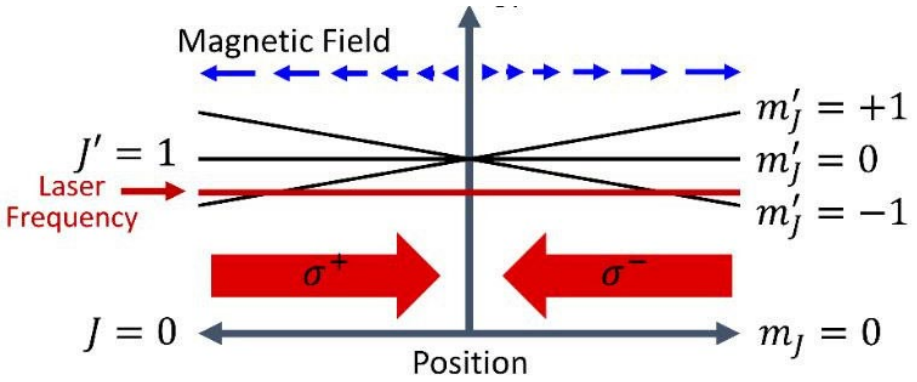
Anti-Helmholtz coil



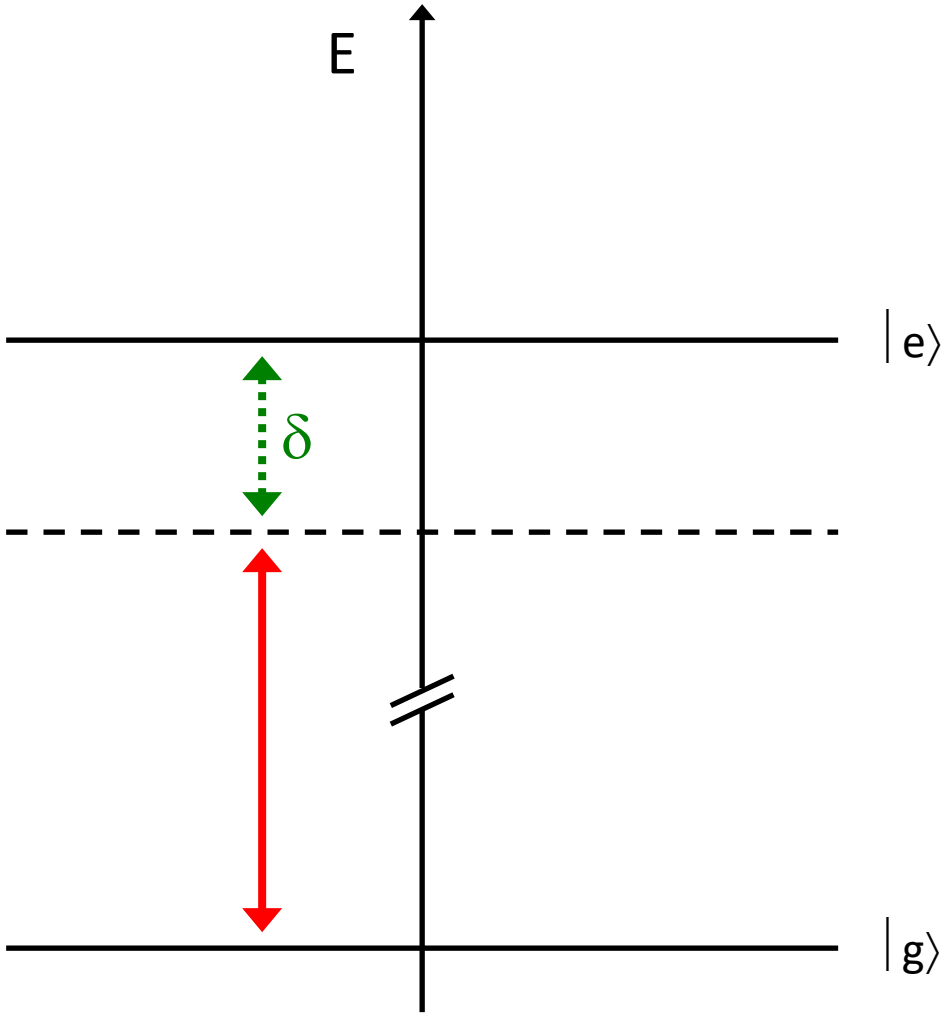
Magnetic field vs. position



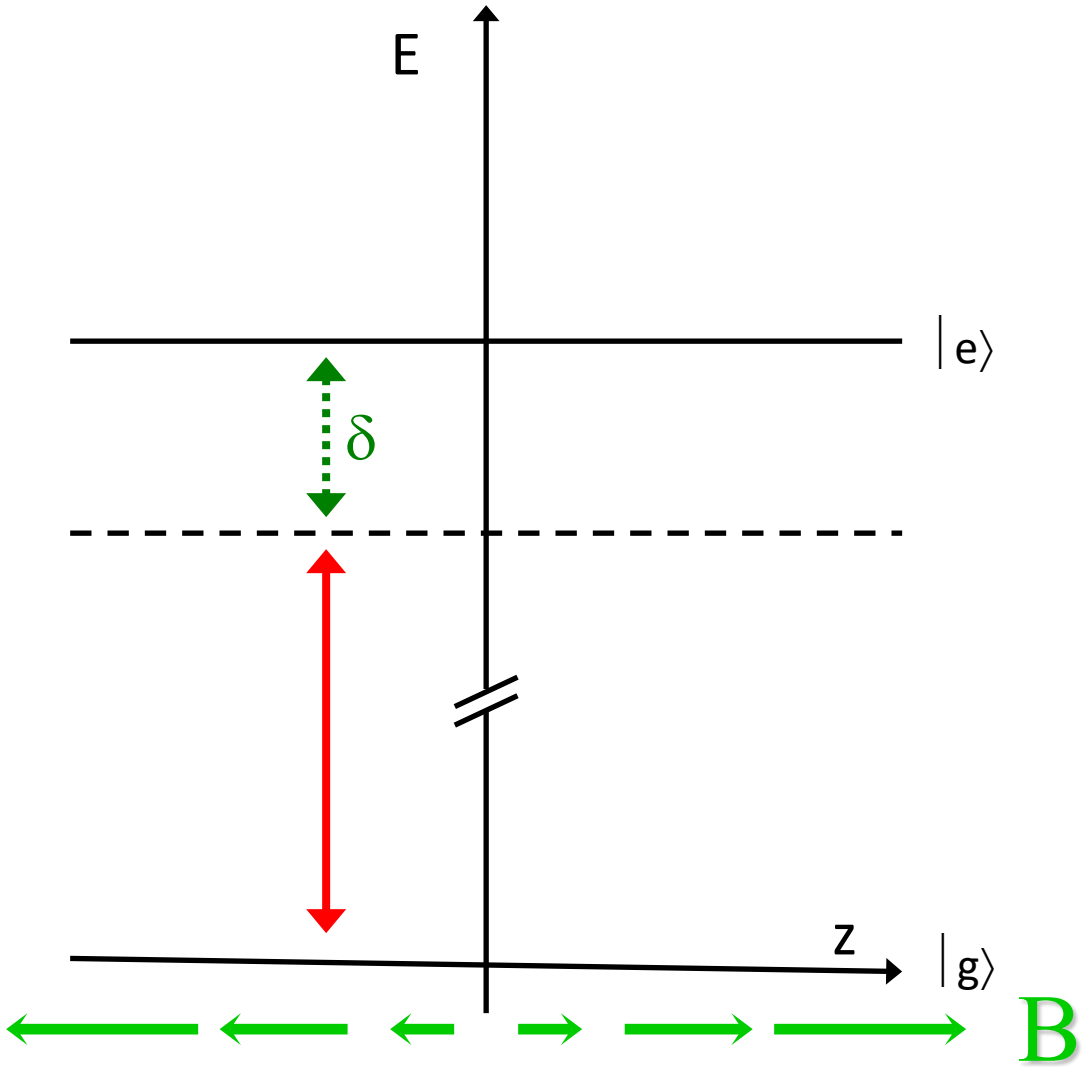
Zeeman-splitting vs. position



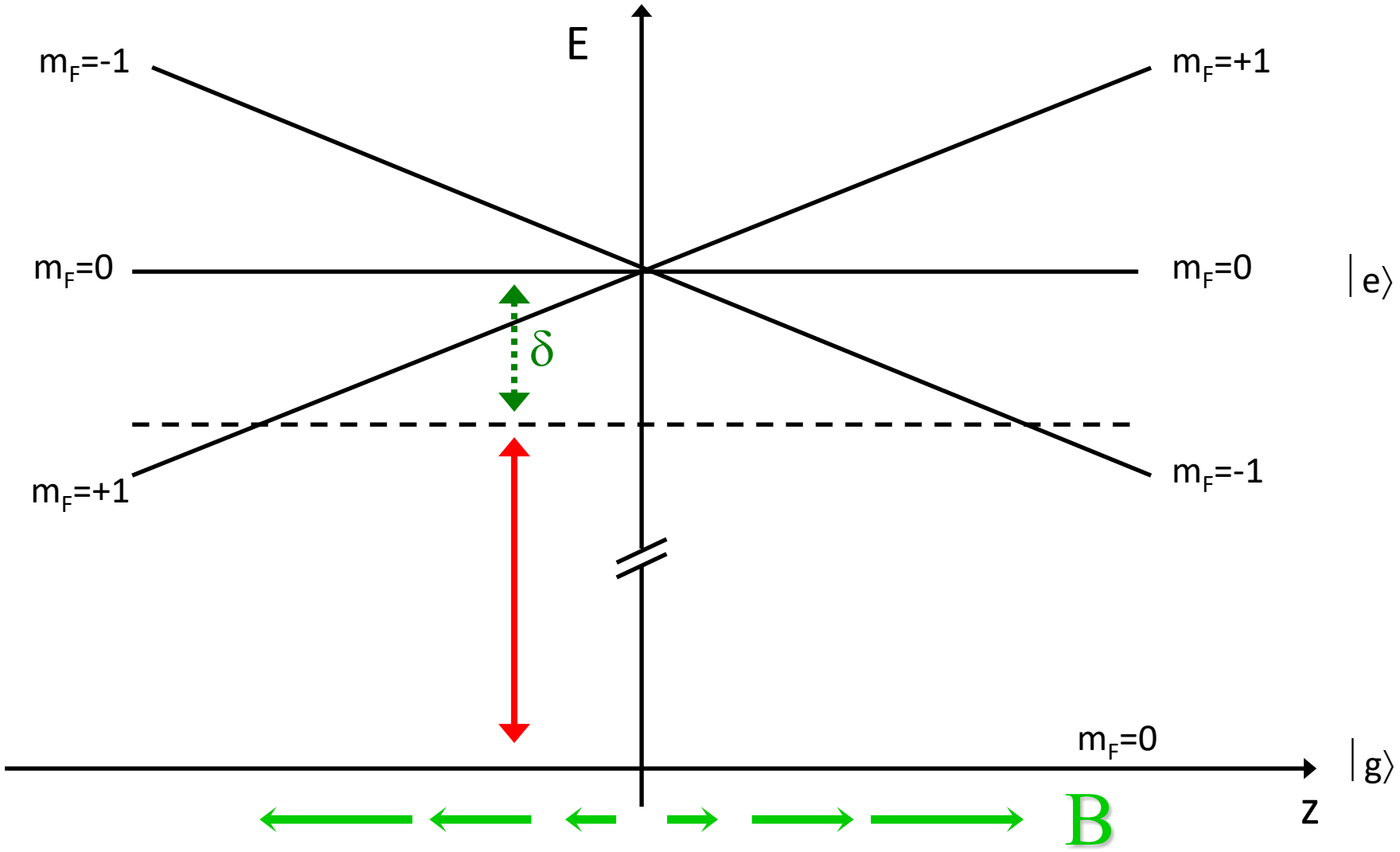
Magneto-Optical Trap



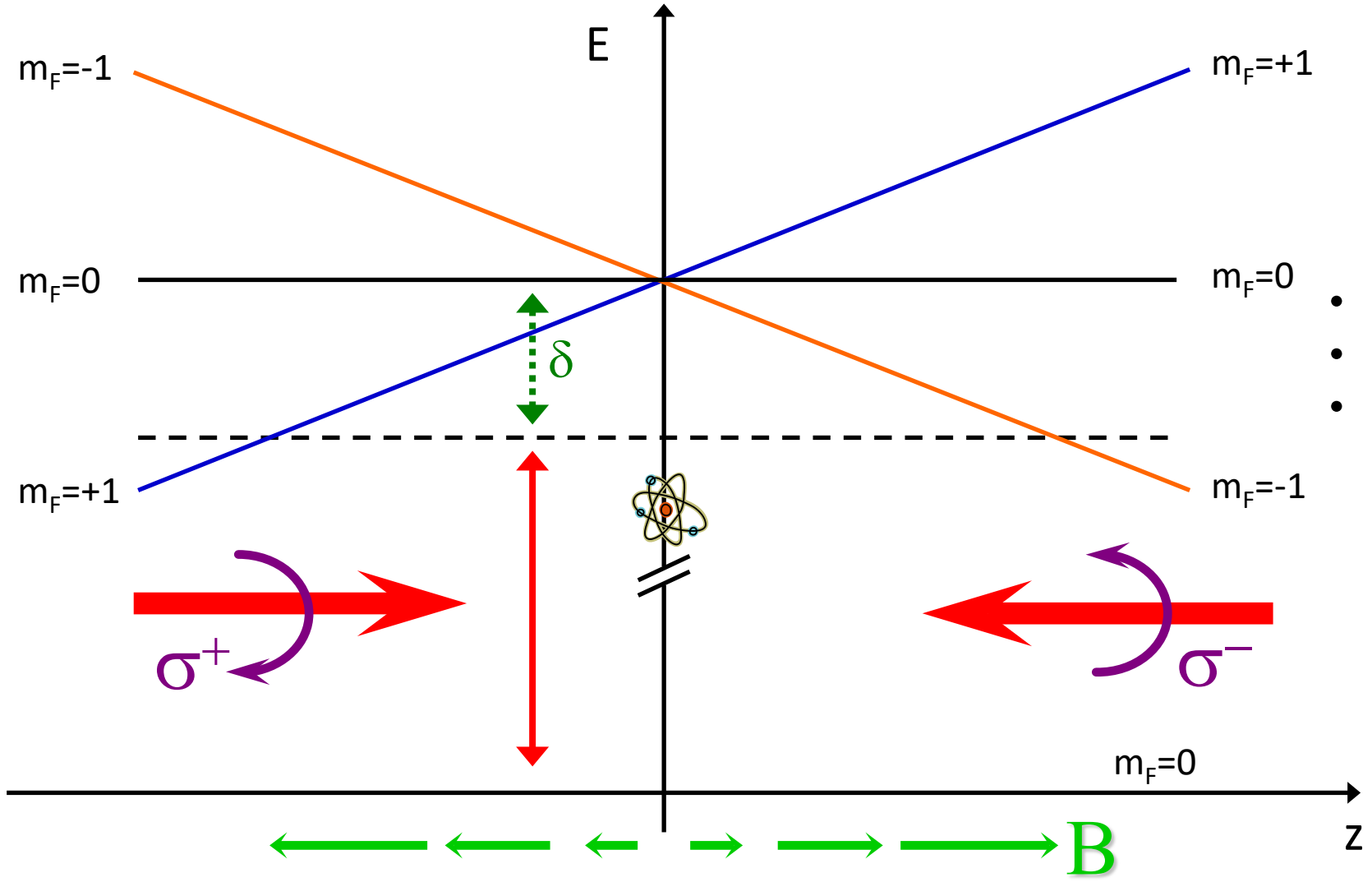
Magneto-Optical Trap



Magneto-Optical Trap

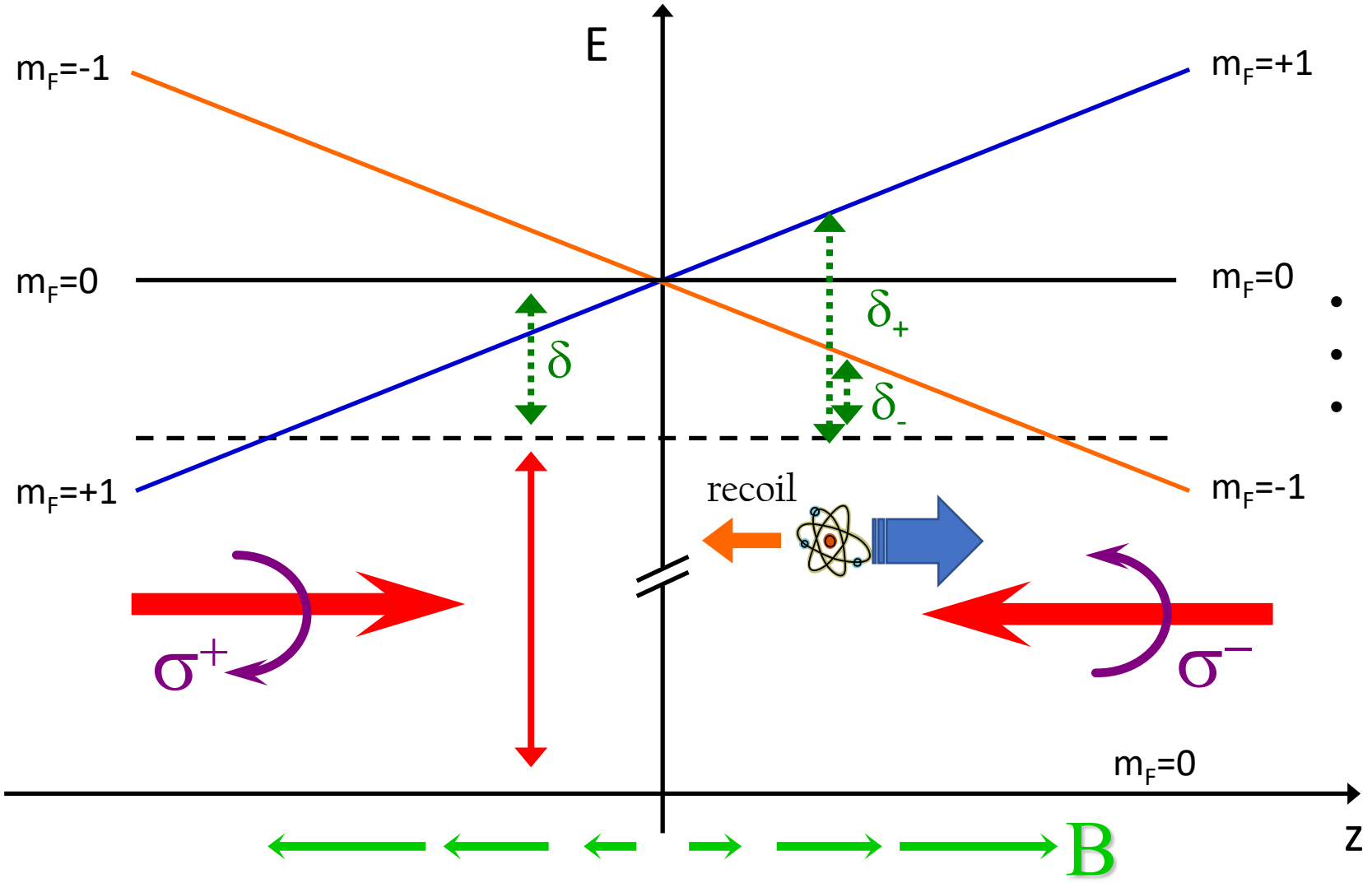


Magneto-Optical Trap: Slow Atom at z = 0



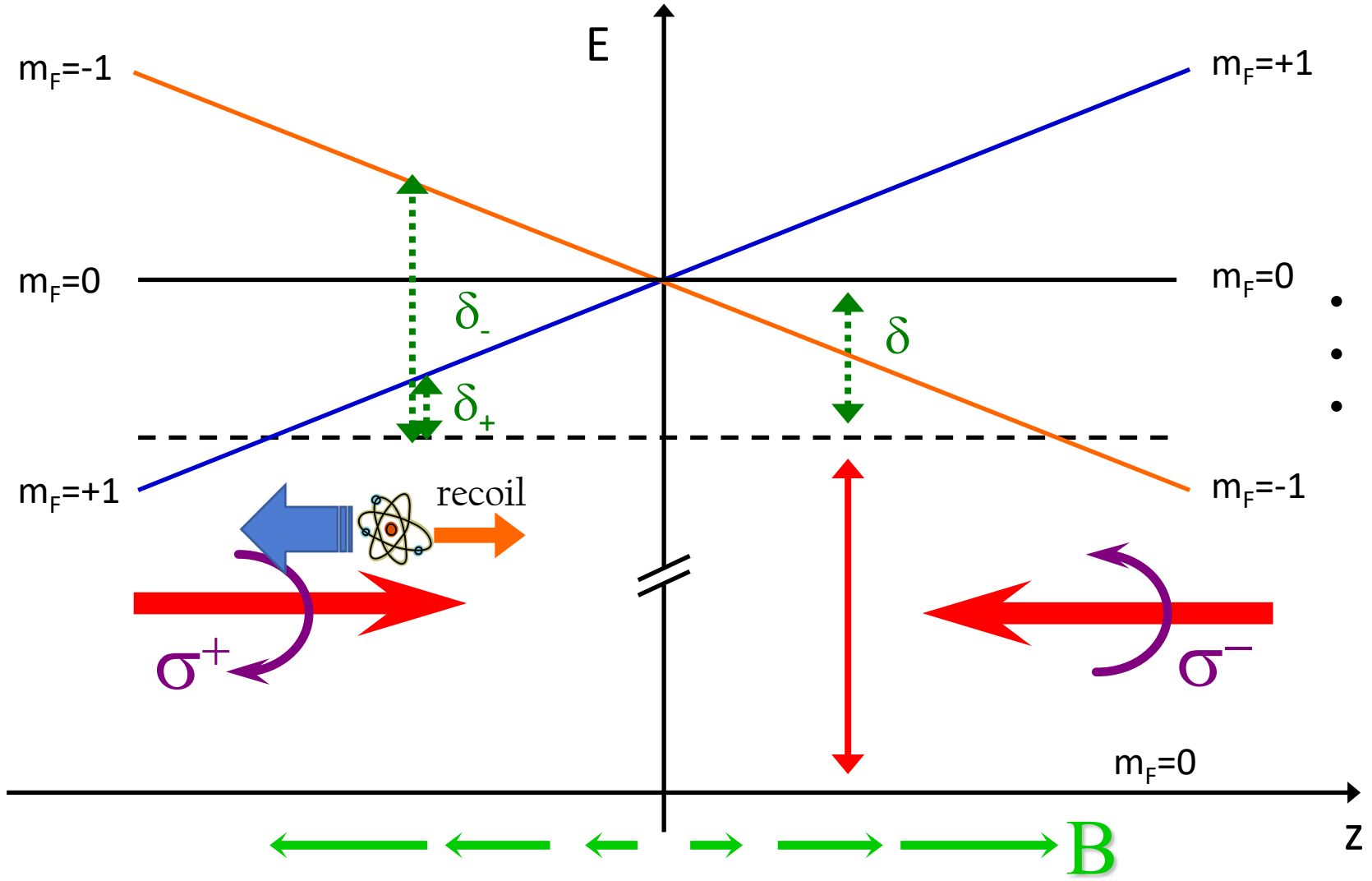
- Atom is far-detuned from both lasers.
- Scattering is the least.
- Slowest atoms pile up here.

Magneto-Optical Trap: Right-Moving Atom



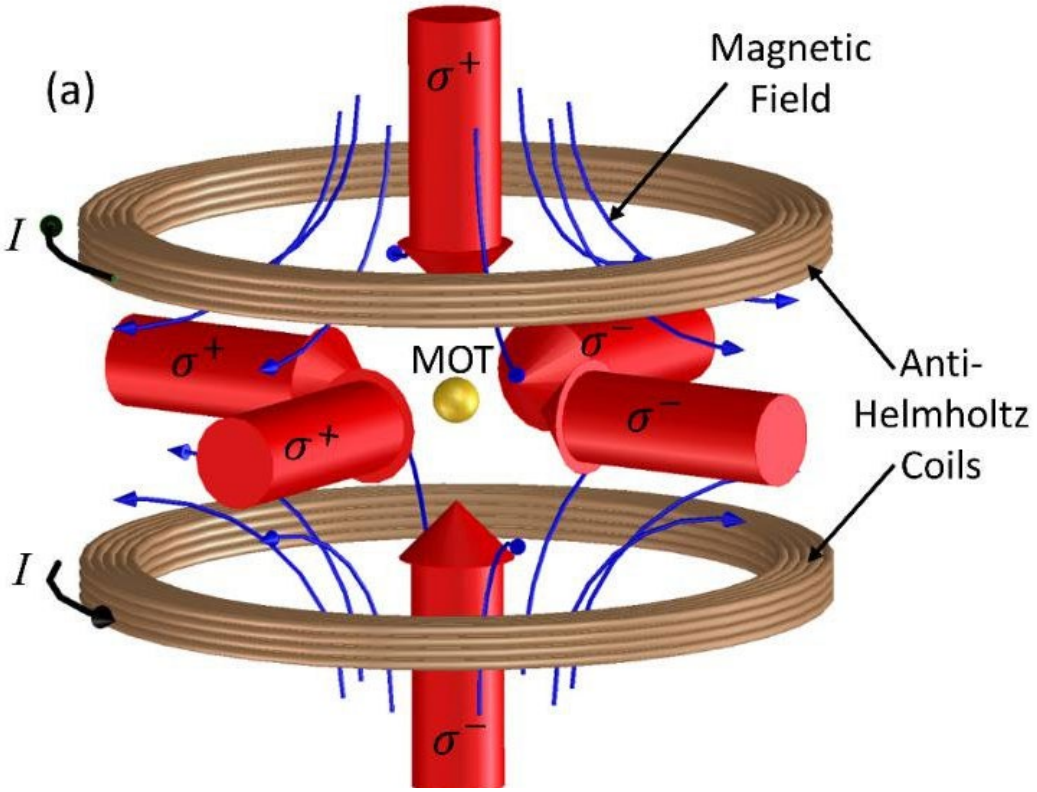
- Detuning from σ^- laser is small.
- σ^- laser gets absorbed.
- Atom get a kick to left.

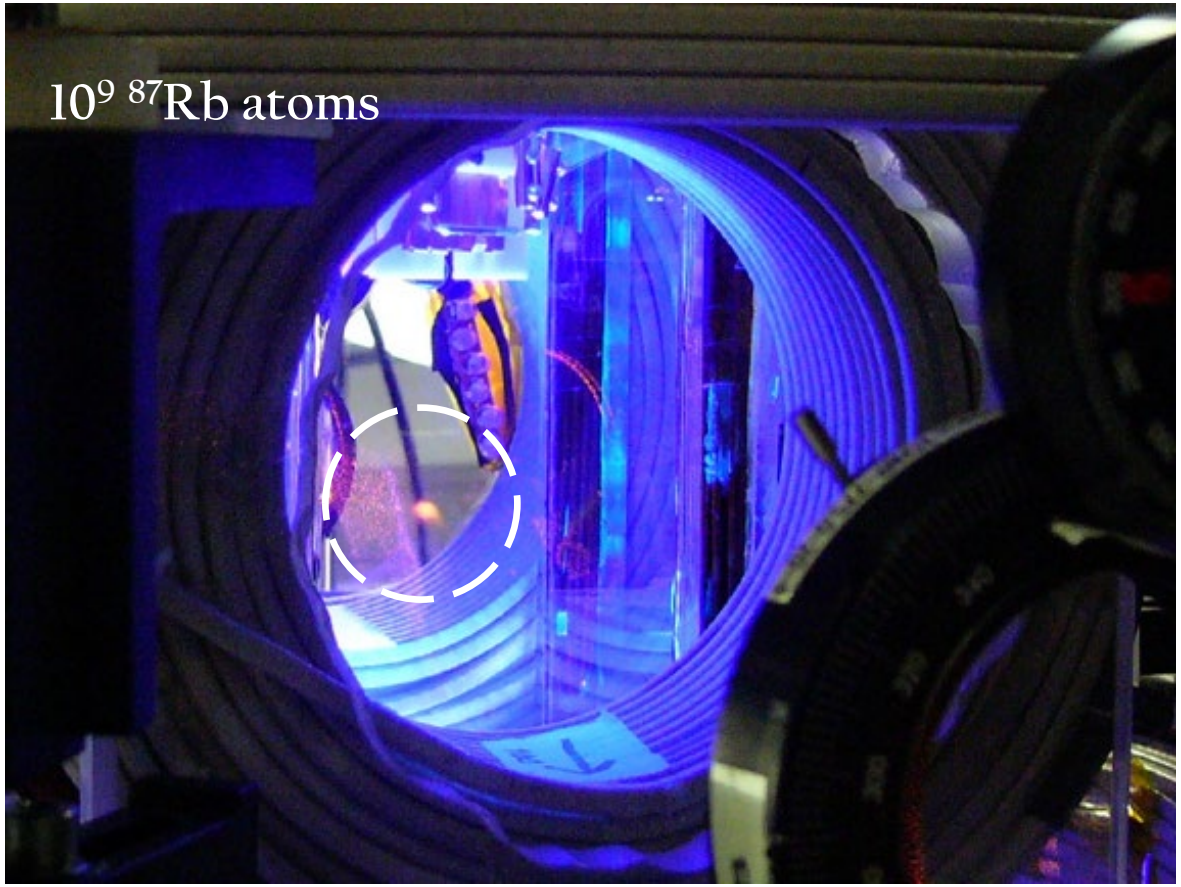
Magneto-Optical Trap: Left-Moving Atom



- Detuning from σ^+ laser is small.
- σ^+ laser gets absorbed.
- Atom get a kick to right.

Magneto-Optical Trap





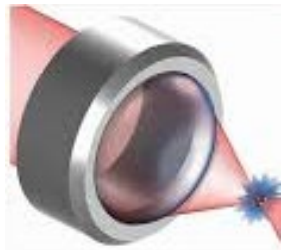
- Atoms away from the center experience a stronger damping.

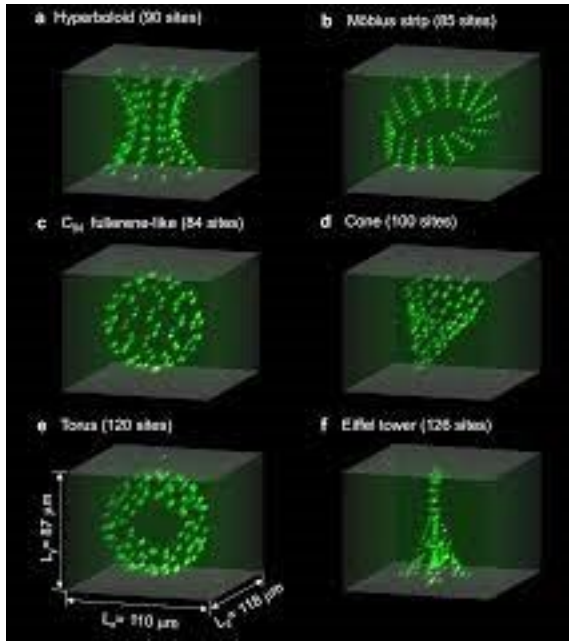
$$F = -\alpha v - \beta z$$

$$T \approx 20\ \mu K$$

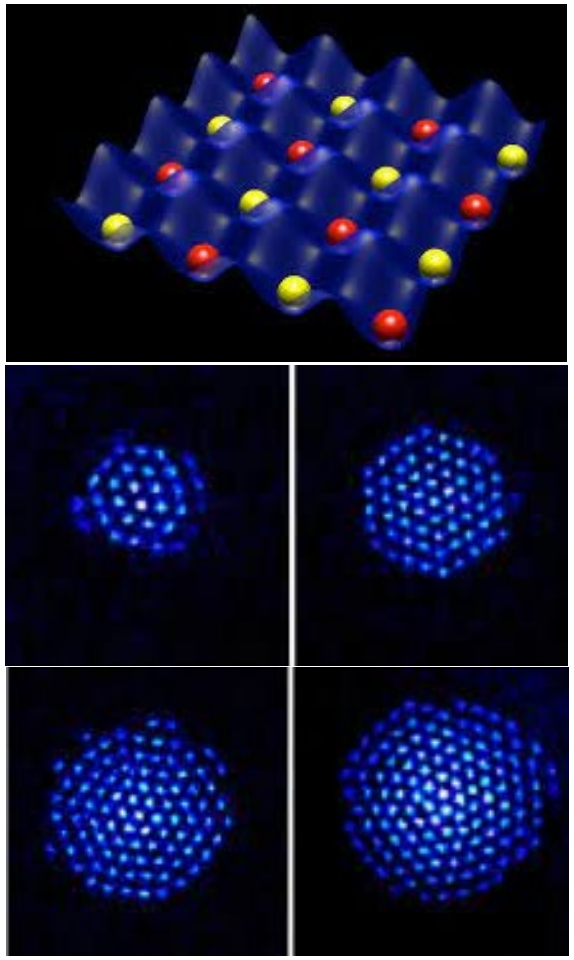
Applications

Optical Tweezer
One atom at a time

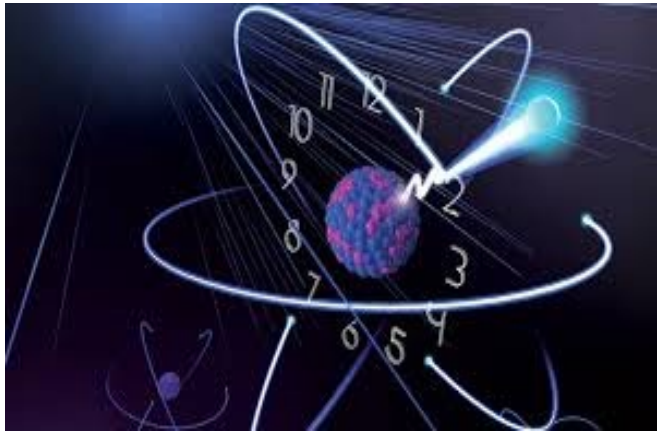




Bottom-up Quantum
simulation



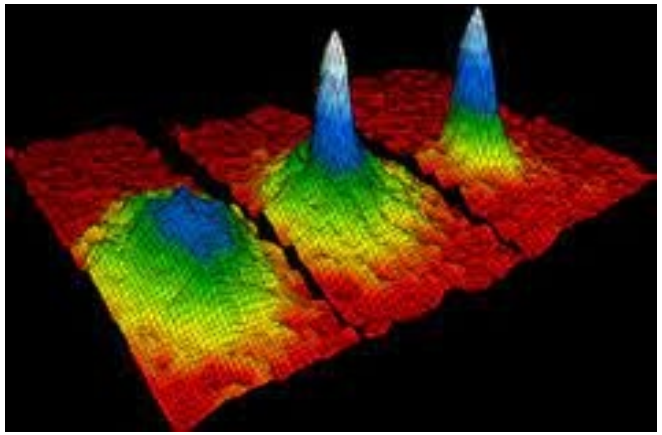
Atomic Clocks
with error of 1 ns in 10
million years



GPS
Space navigation

Bose-Einstein
Condensation

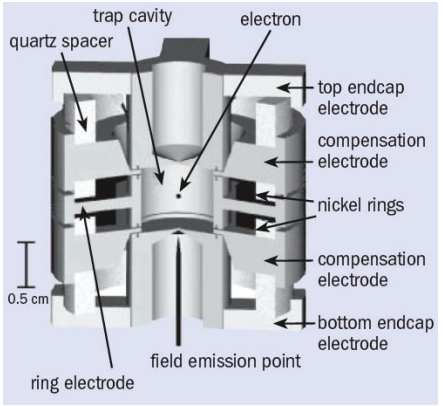
2001



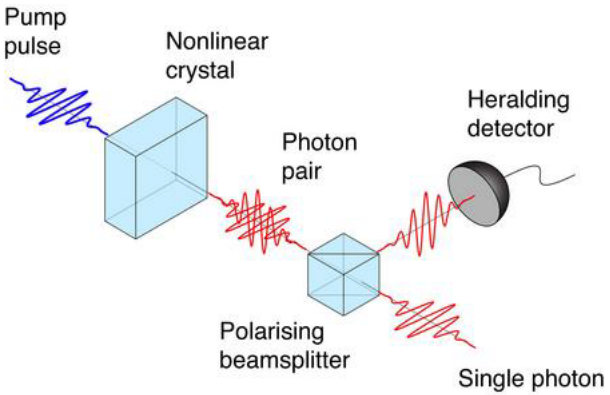
A large Quantum object

Today's Quantum Toolkit

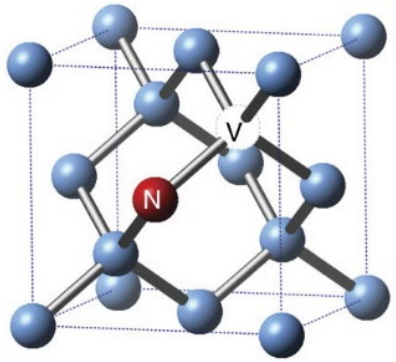
Trapped Electrons



Photons

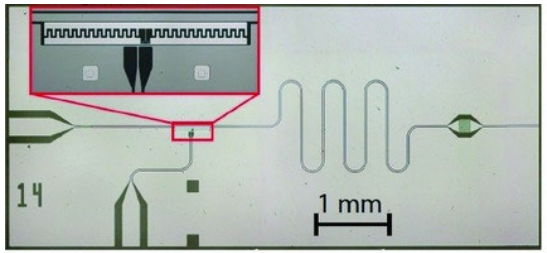


Vacancy centers



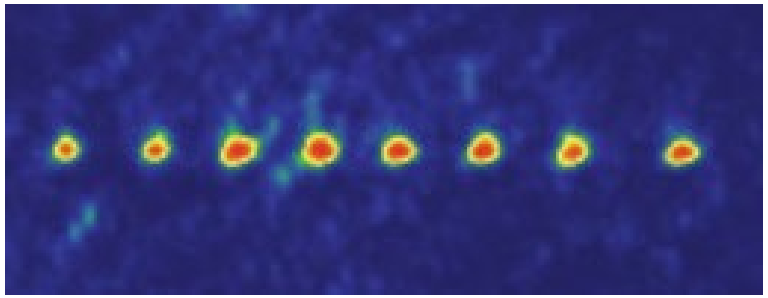
Quantum dots

Superconducting circuit



2023

Ultracold Atoms & ions



Let's Raise Ichthyosauria in the Zoo!

"... we never experiment with just one electron or atom of (small) molecule. We are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo..."