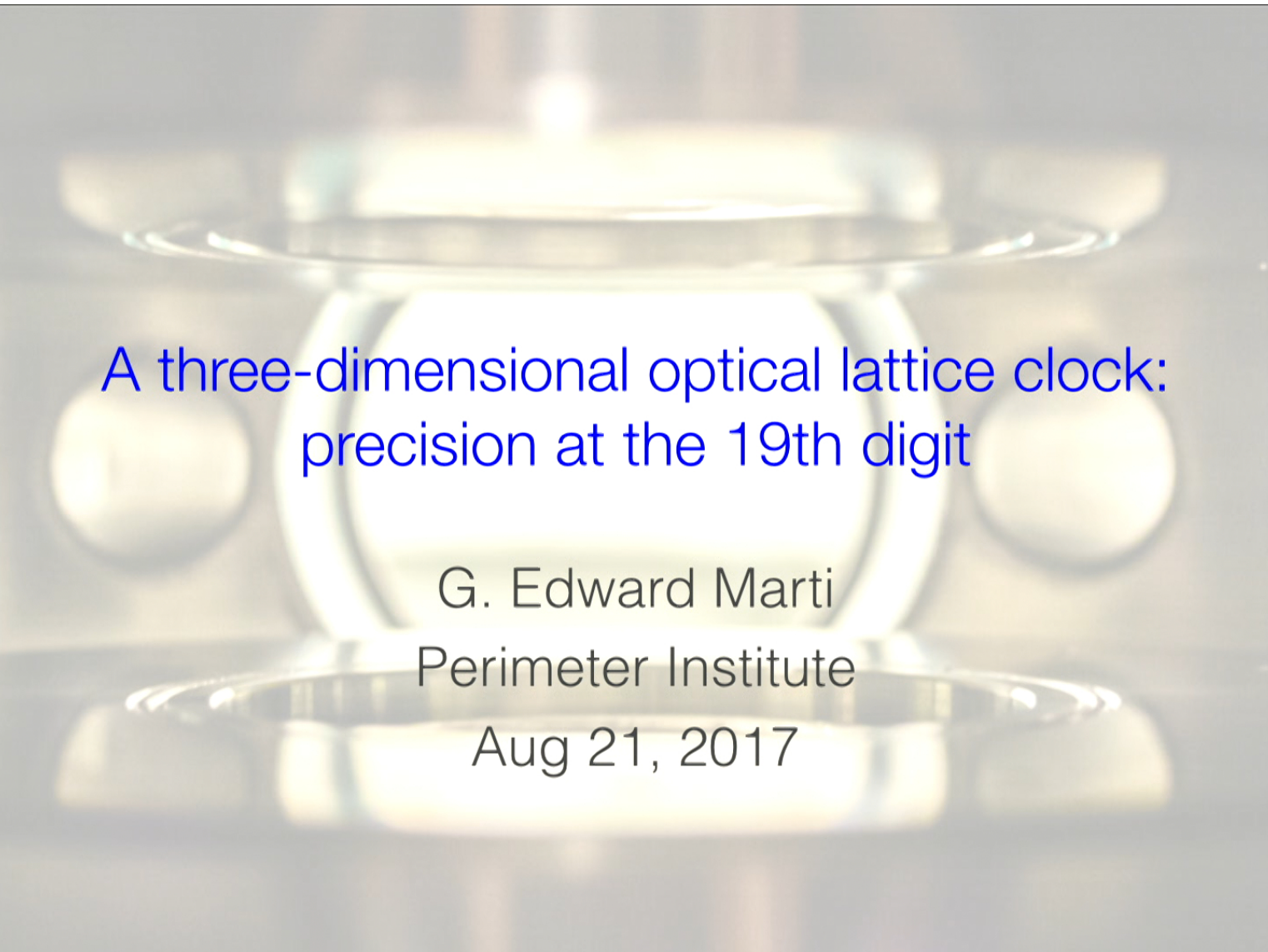


Title: A three-dimensional optical lattice clock: precision at the 19th digit

Date: Aug 21, 2017 11:00 AM

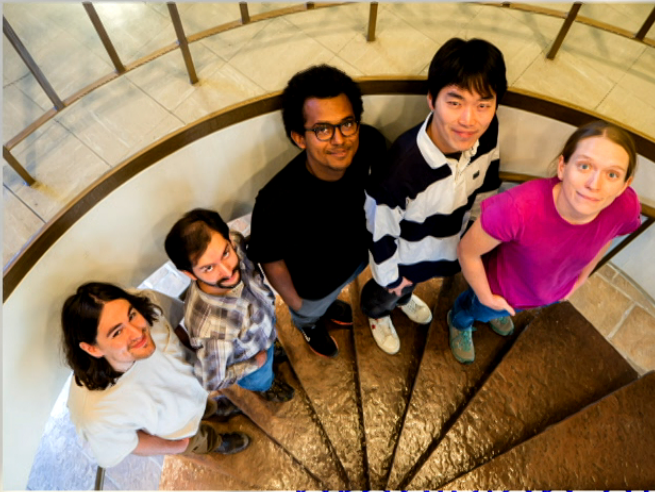
URL: <http://pirsa.org/17080019>

Abstract:



A three-dimensional optical lattice clock:  
precision at the 19th digit

G. Edward Marti  
Perimeter Institute  
Aug 21, 2017

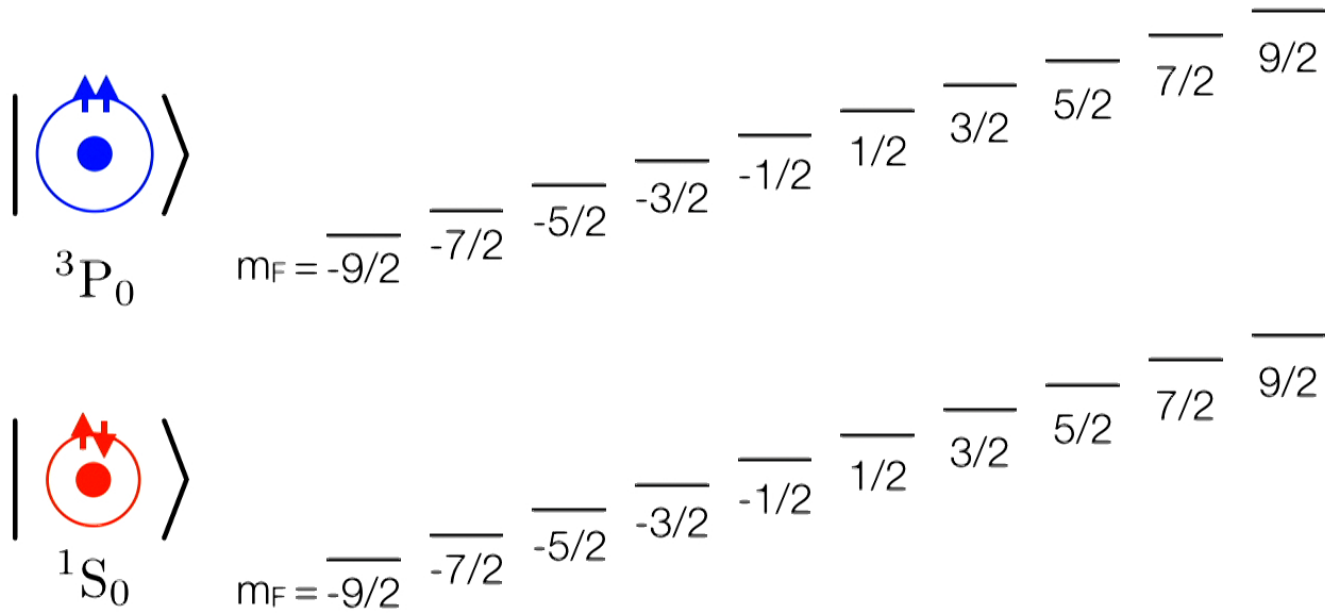


al optical lattice clock:  
precision at the 19th digit

G. Edward Marti  
Perimeter Institute  
Aug 21, 2017



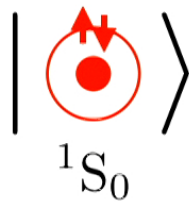
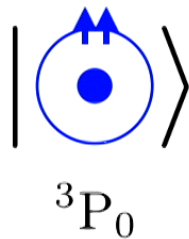
# Quantum resources: fermionic $^{87}\text{Sr}$



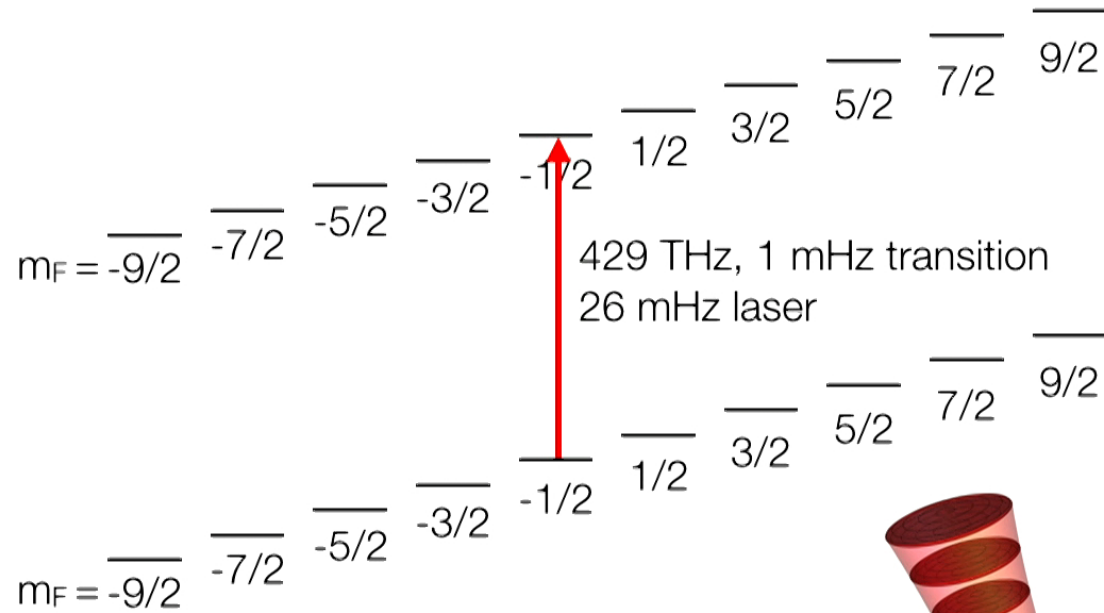
electronic state

nuclear spin state

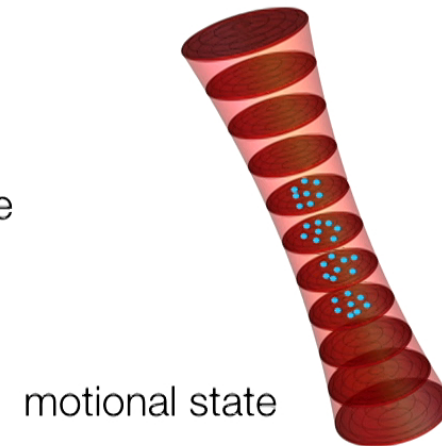
# Quantum resources: fermionic $^{87}\text{Sr}$



electronic state

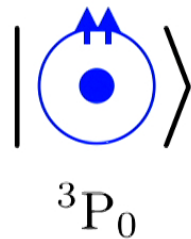


nuclear spin state

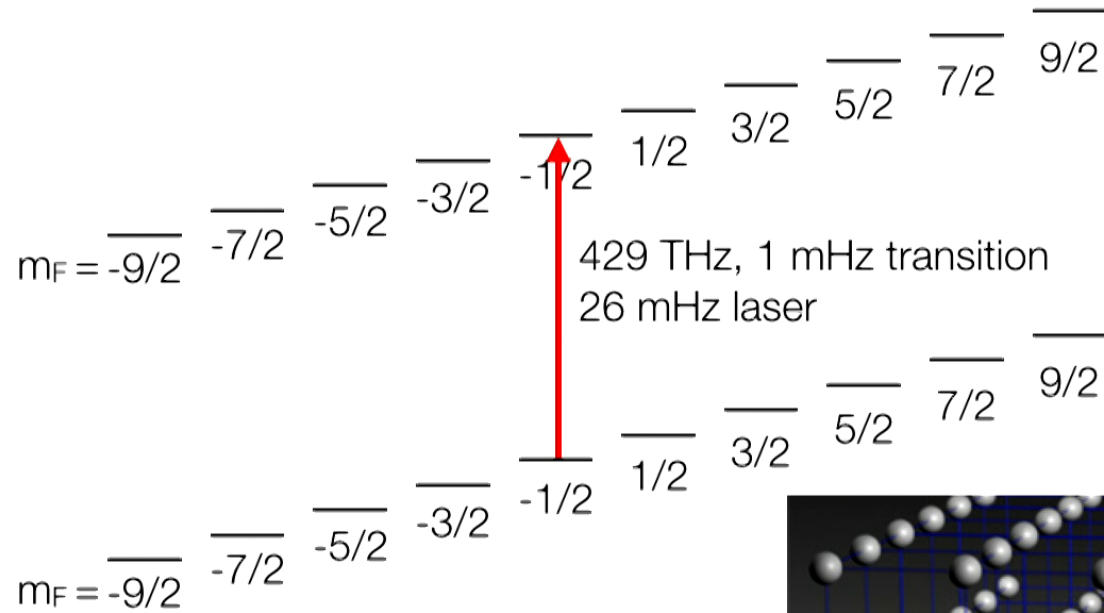


motional state

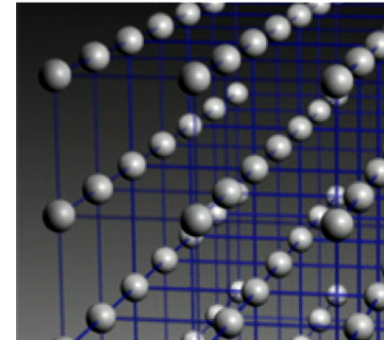
# Quantum resources: fermionic $^{87}\text{Sr}$



electronic state

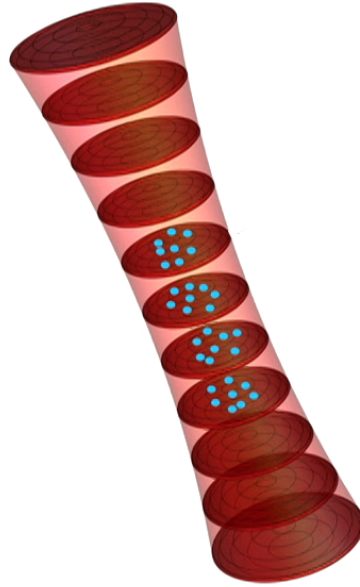


nuclear spin state



motional state

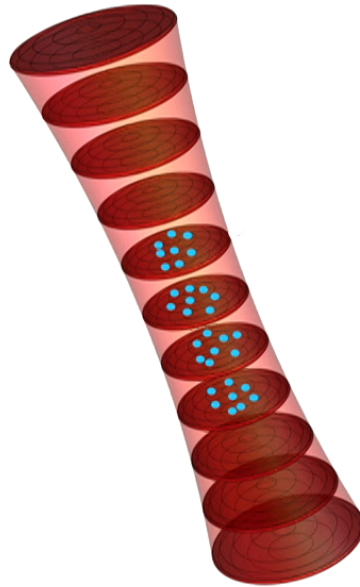
# Why clocks?





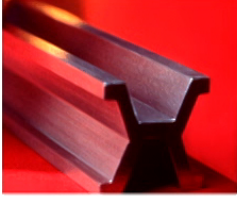
# Why clocks?

Standards

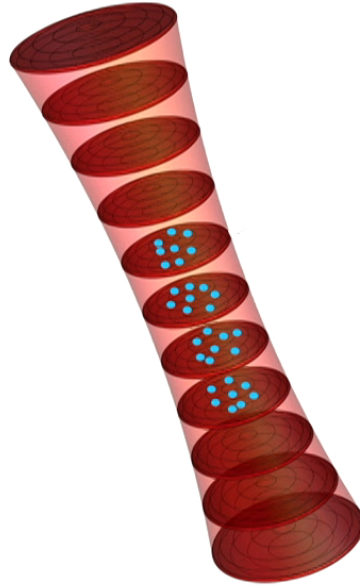
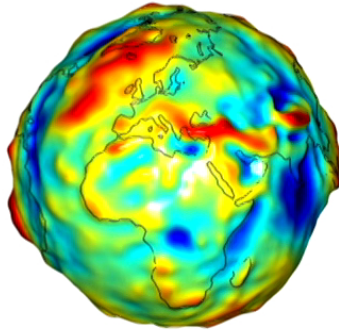


# Why clocks?

Standards

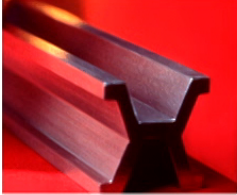


Applied science

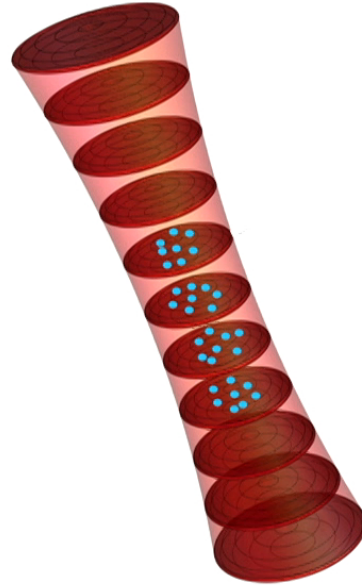
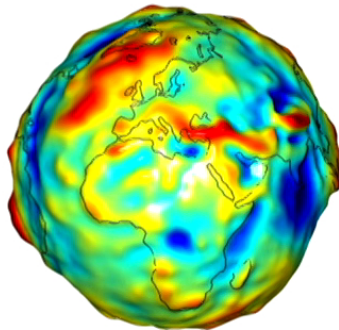


# Why clocks?

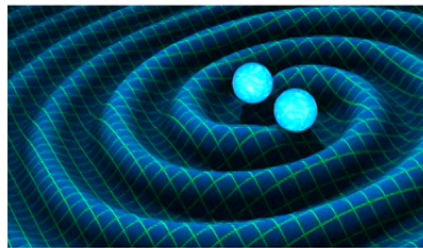
Standards



Applied science

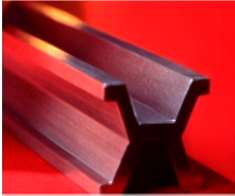


Astrophysics & cosmology

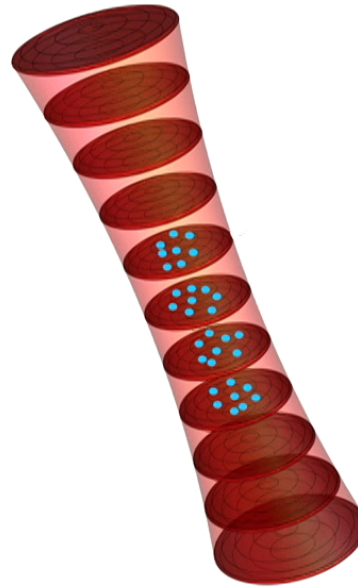
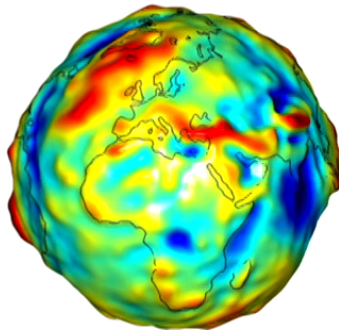


# Why clocks?

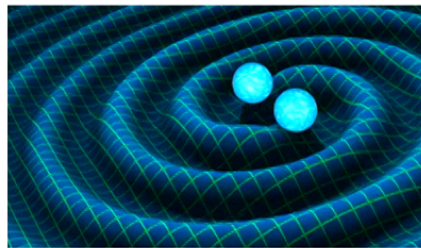
Standards



Applied science



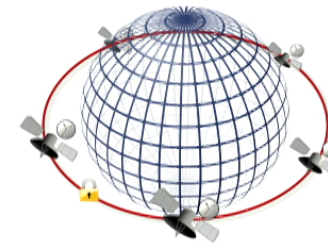
Astrophysics & cosmology



Fundamental physics

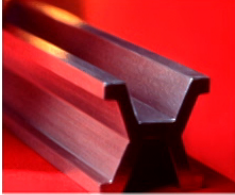


Quantum Information

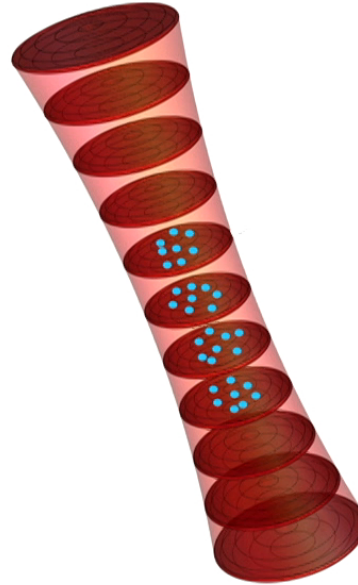
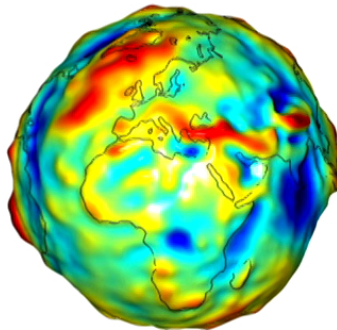


# Why clocks?

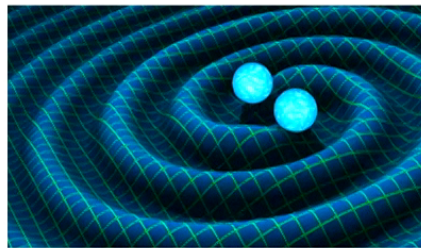
Standards



Applied science



Astrophysics & cosmology



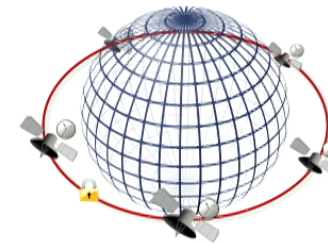
Many-body physics



Fundamental physics



Quantum Information



# Introduction to clocks

***Fundamental physics in a post-accelerator era***

Many-body physics



Fundamental physics



# Introduction to clocks

## ***Fundamental physics in a post-accelerator era***

- ▶ Outstanding problems
  - Dark matter, dark energy
  - Matter/antimatter asymmetry
  - Hierarchy problem
  - ...
- ▶ Outstanding puzzles
  - muonic g-2
  - proton charge radius
  - need more!

Many-body physics



Fundamental physics



# Introduction to clocks

## ***Fundamental physics in a post-accelerator era***

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Many-body physics



Fundamental physics





# Introduction to clocks

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  - proton charge radius
  - need more!
- ▶ Sensitivity to new physics scales with clock accuracy

***What does the 19th digit (and beyond) of an optical frequency tell us about dark matter or other particles beyond the Standard Model?***

Many-body physics



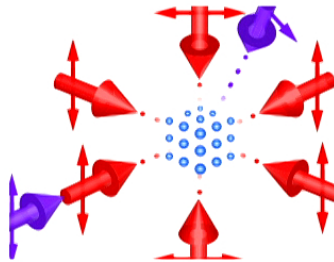
Fundamental physics



# Outline

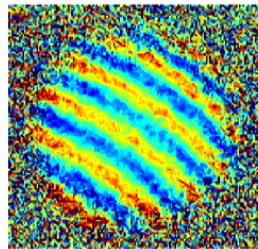


## Optical lattice clocks



## 3D lattice clock

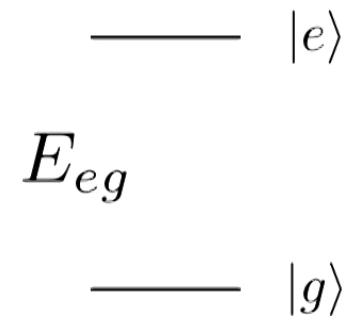
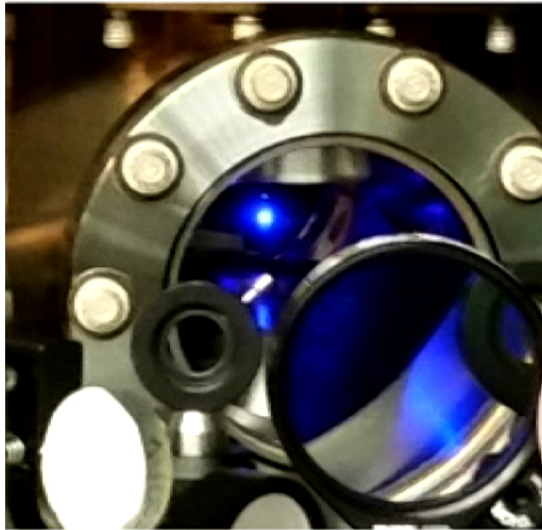
Record Q-factor



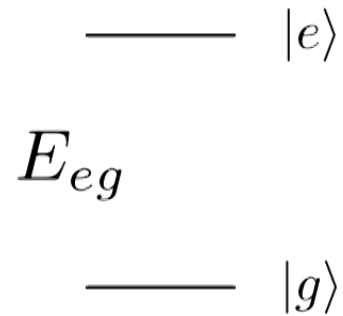
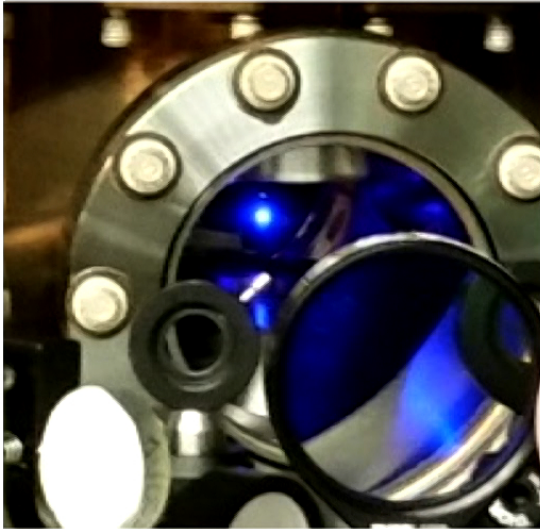
## Atom-atom coherence

Record synchronous stability

# Introduction to clocks

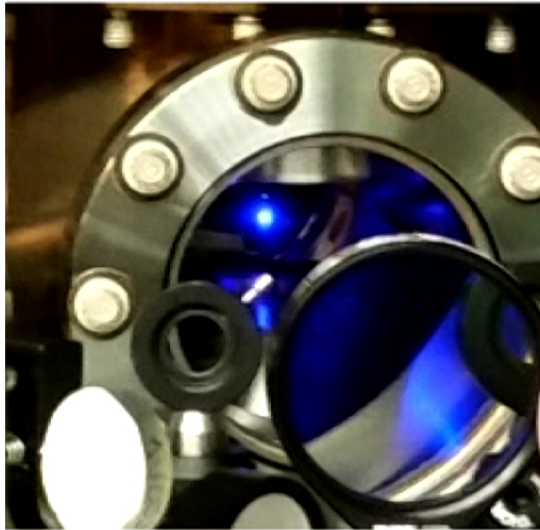


## Introduction to clocks



- ▶ Choose states sensitive to things we care about
- ▶ Control sensitivity to things we don't care about (**accuracy**)
- ▶ Use lots of atoms (**precision**) but not too many (**accuracy**)

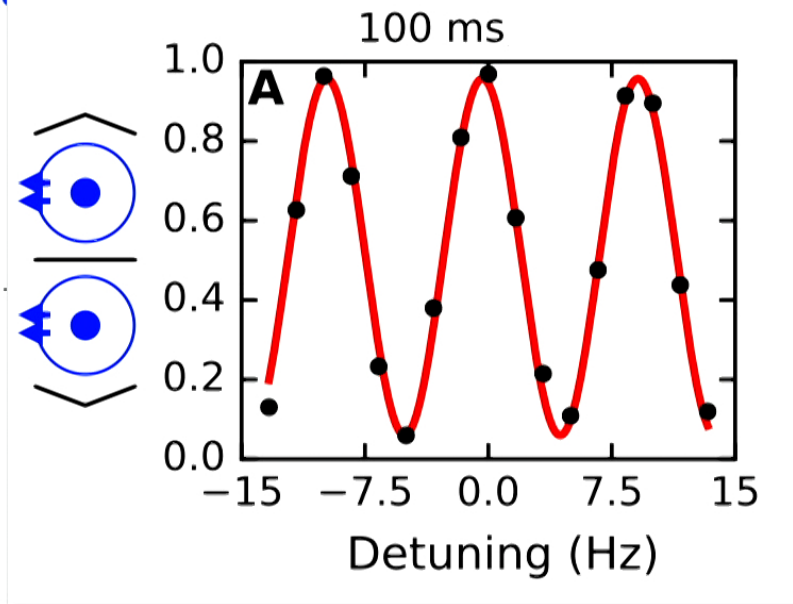
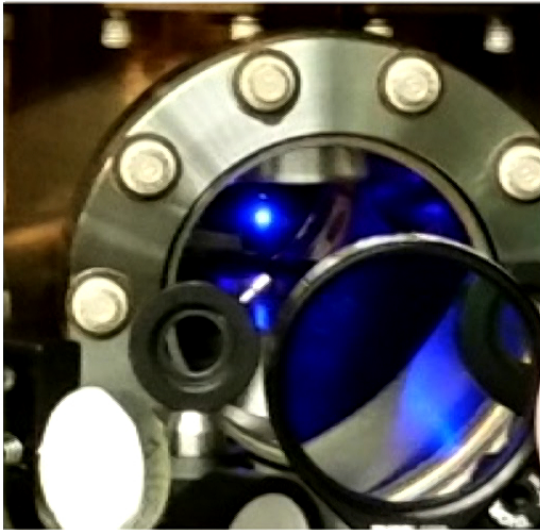
# Introduction to clocks



$$\begin{aligned} & \text{---} \left| \begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} \right\rangle \\ E_{eg} & \quad 429,228,004,229,873.1(1) \text{ Hz} \\ & \text{---} \left| \begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} \right\rangle \\ & \left| \begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} \right\rangle + e^{-iE_{eg} t/\hbar} \left| \begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} \right\rangle \end{aligned}$$

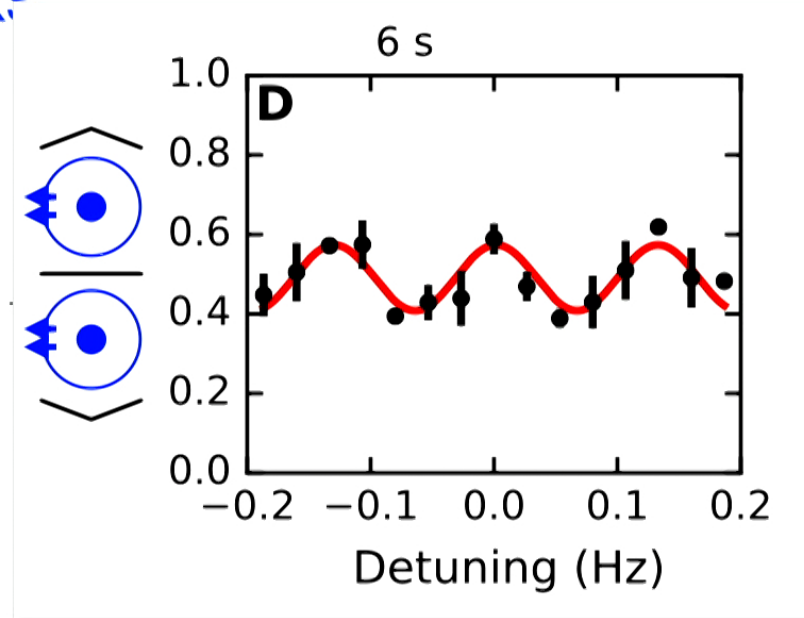
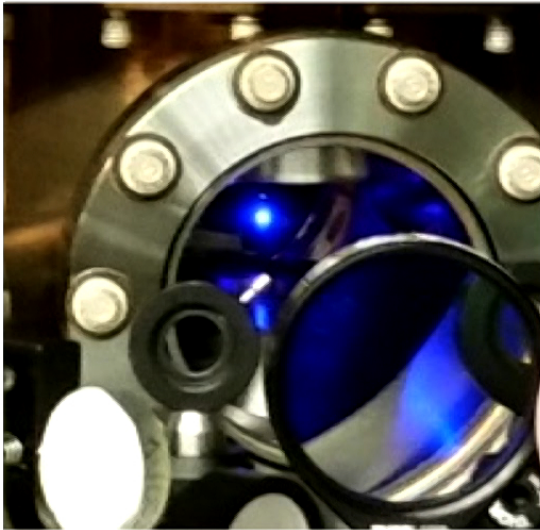
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## Introduction to clocks



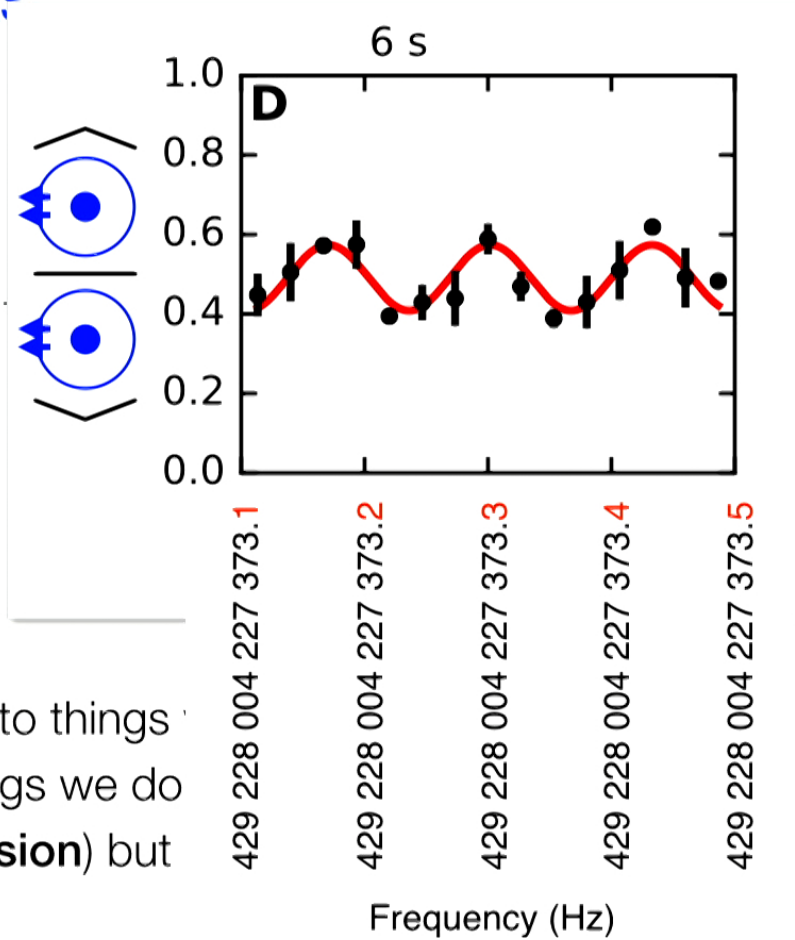
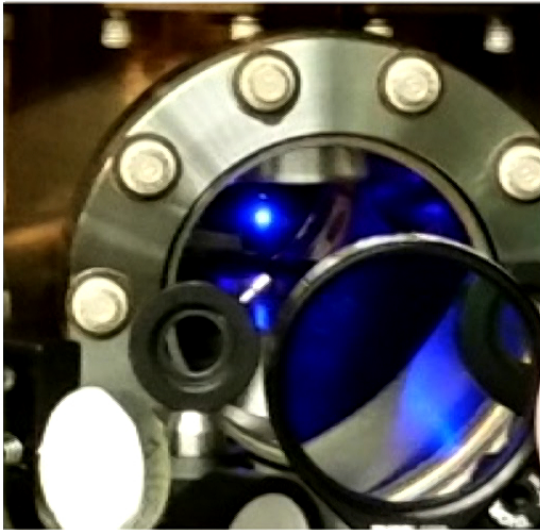
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## Introduction to clocks



- ▶ Choose states sensitive to things we care about
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# Introduction to clocks

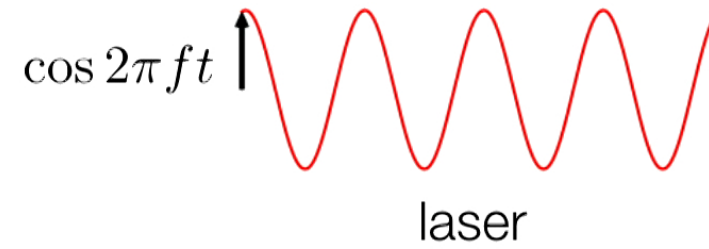


- ▶ Choose states sensitive to things
- ▶ Control sensitivity to things we do
- ▶ Use lots of atoms (**precision**) but

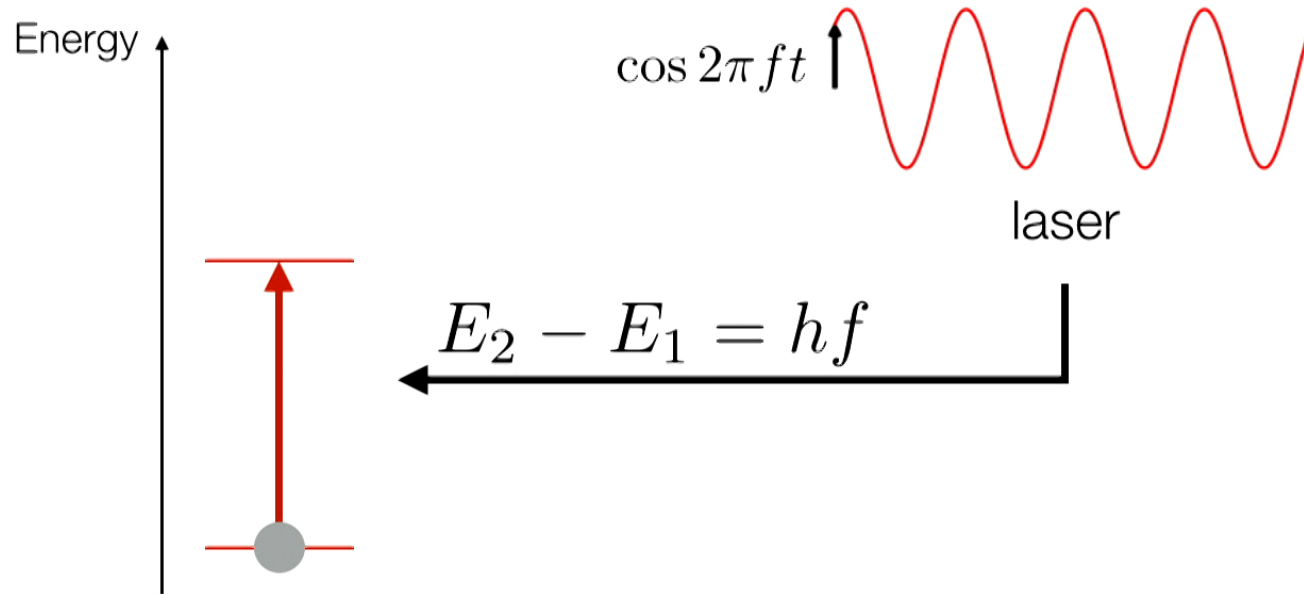


# Making a clock

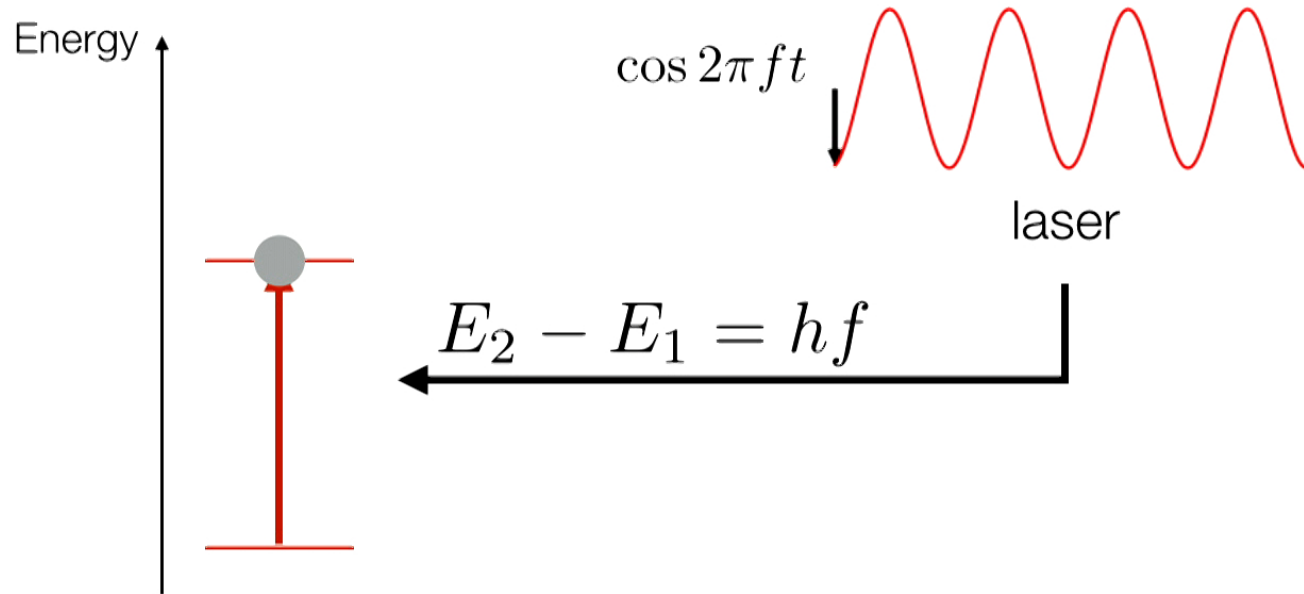
Energy



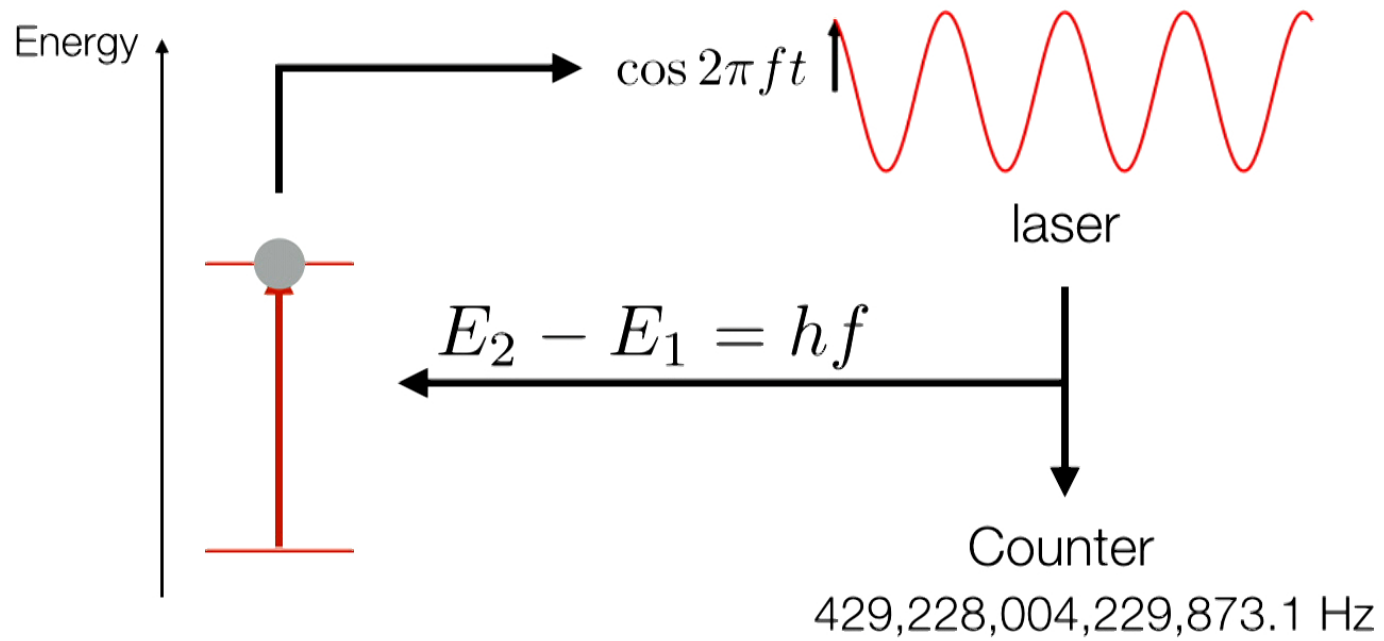
# Making a clock



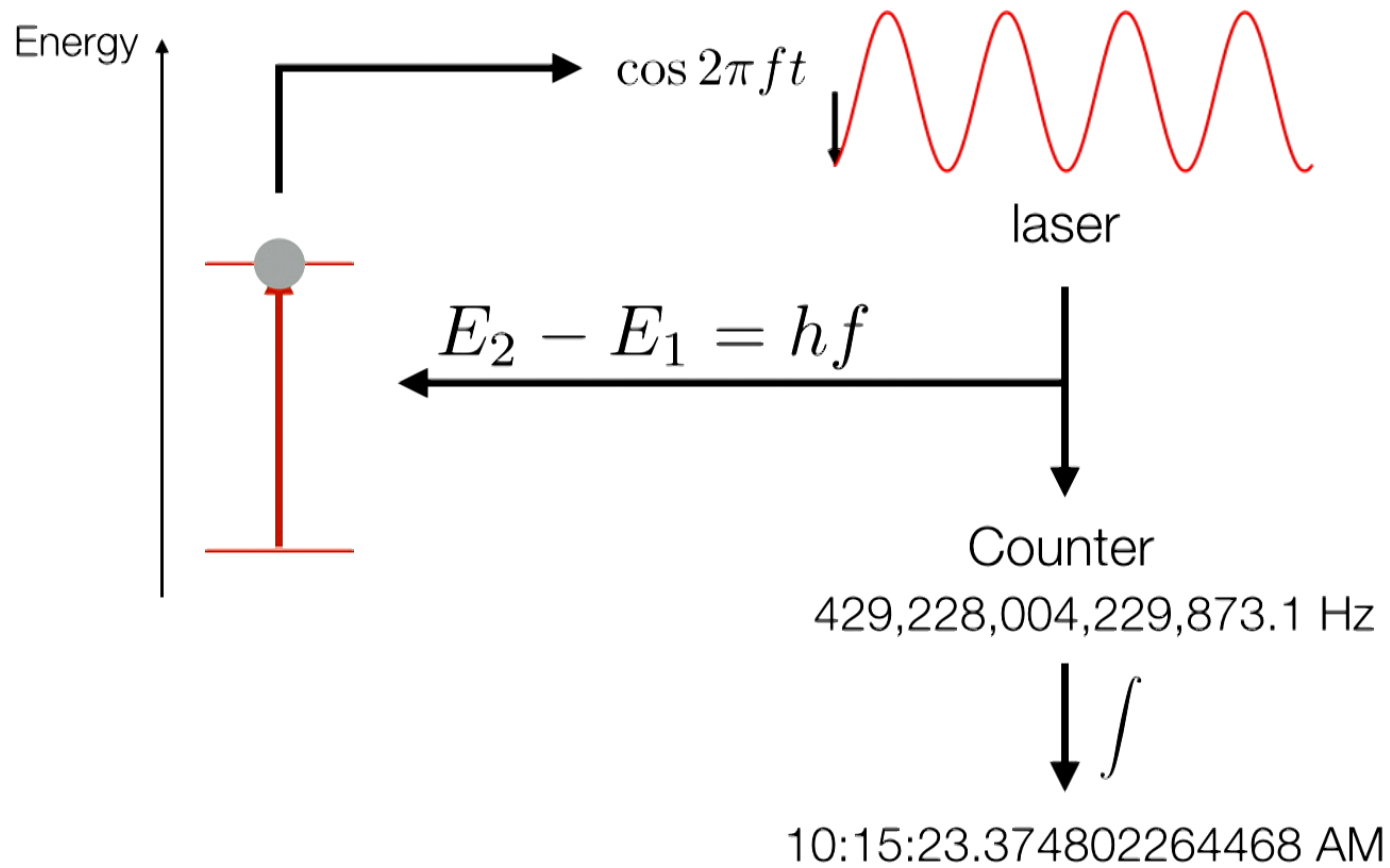
# Making a clock



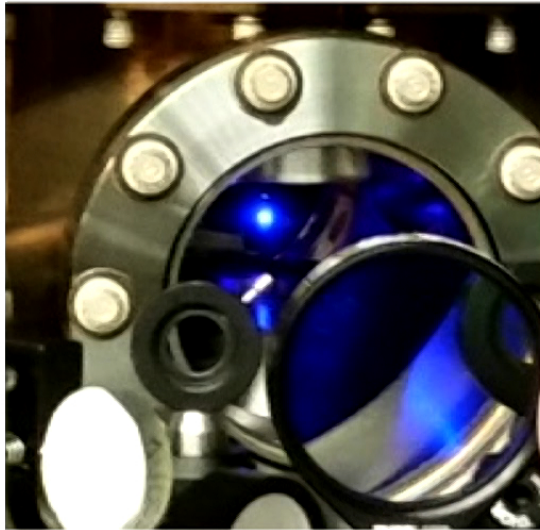
## Making a clock



# Making a clock



# Introduction to clocks



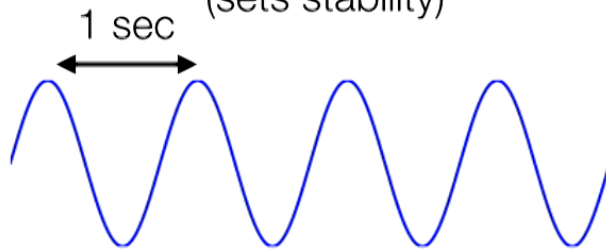
$$\begin{aligned} & \text{---} \left| \begin{array}{c} \uparrow \\ \uparrow \\ \bullet \\ \circ \end{array} \right\rangle \\ E_{eg} & 429,228,004,229,873.1(1) \text{ Hz} \\ & \text{---} \left| \begin{array}{c} \downarrow \\ \downarrow \\ \bullet \\ \circ \end{array} \right\rangle \\ \sin(E_{eg}t/\hbar) & \left| \begin{array}{c} \downarrow \\ \downarrow \\ \bullet \\ \circ \end{array} \right\rangle + \cos(E_{eg}t/\hbar) \left| \begin{array}{c} \uparrow \\ \uparrow \\ \bullet \\ \circ \end{array} \right\rangle \end{aligned}$$

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# Making a clock



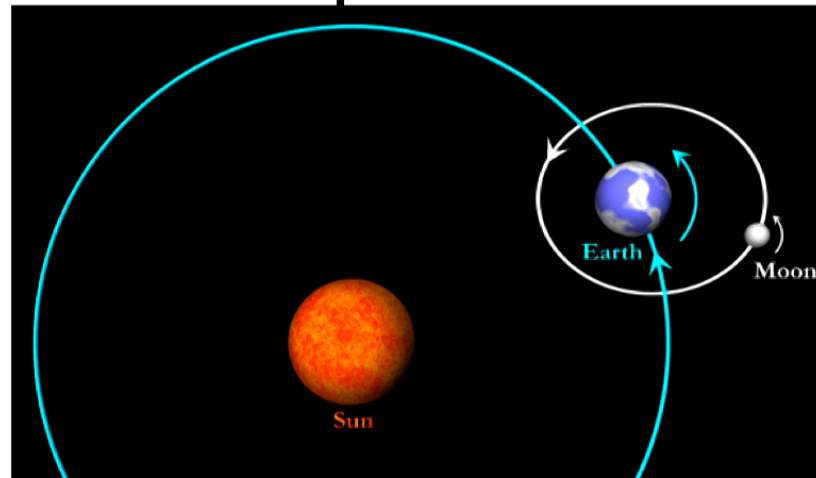
Local oscillator  
(sets stability)



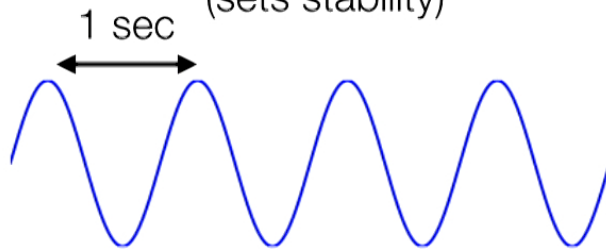
# Making a clock



Local oscillator  
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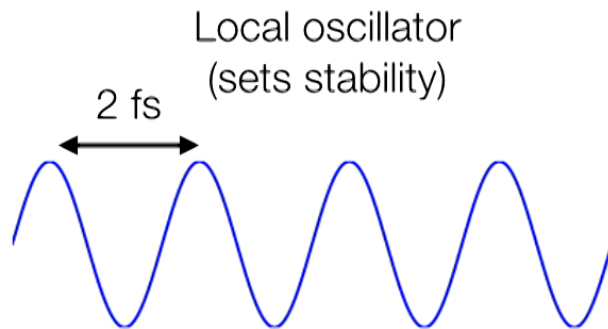


Frequency standard  
(sets accuracy)



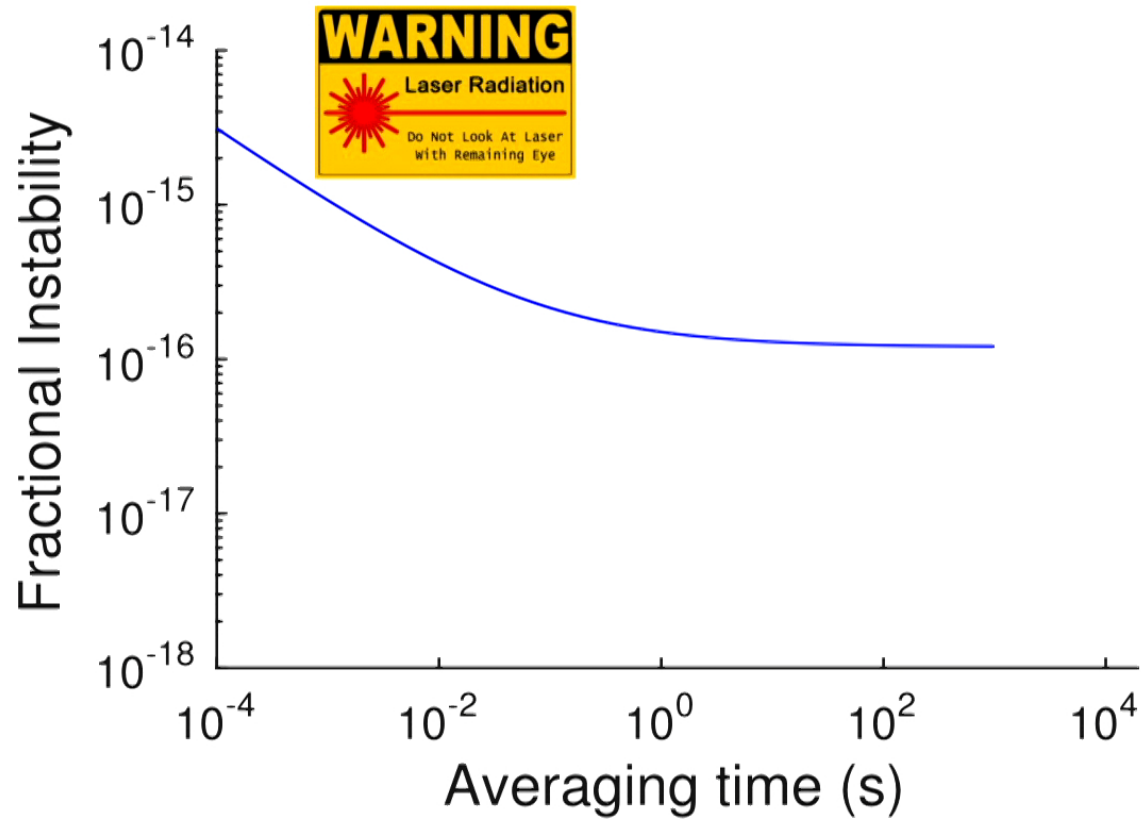


# Making a clock



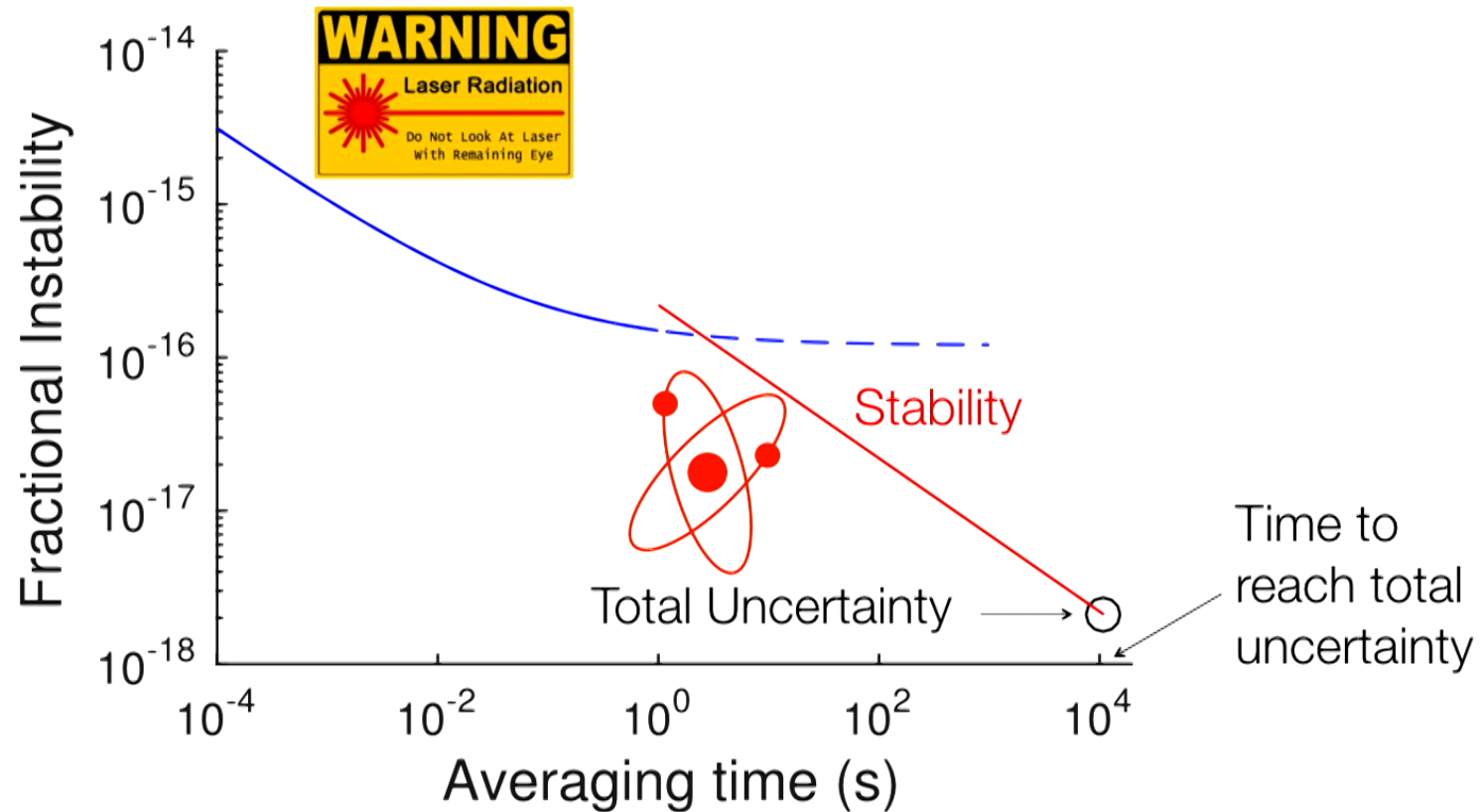
Frequency standard  
(sets accuracy)

# Atoms + Laser



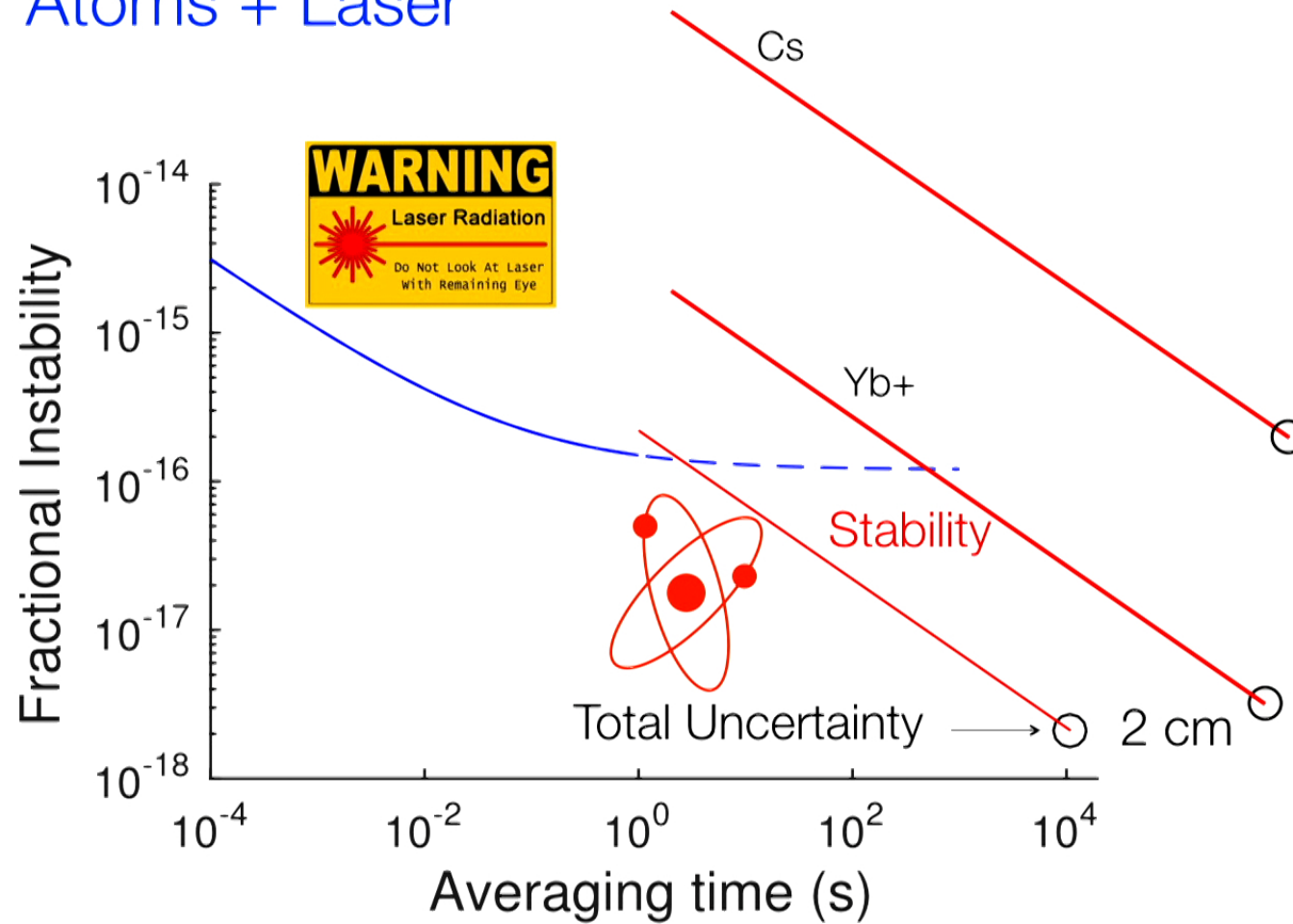
Nicholson, Campbell, Hutson, **Marti**, Bloom, McNally, Zhang, Barrett, Safronova, Strouse, Tew, and Ye, *Nat. Comm.* **6**, 6896 (2015)

# Atoms + Laser



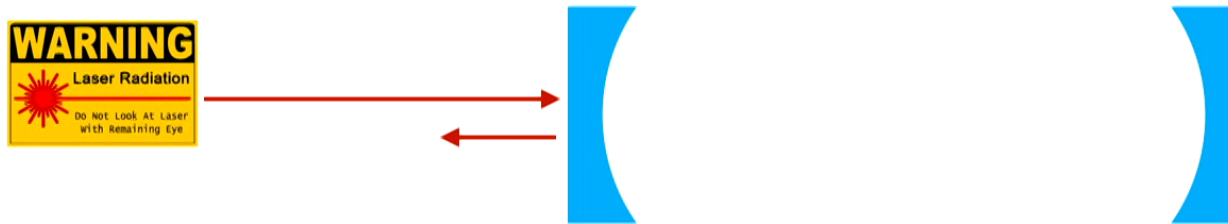
Nicholson, Campbell, Hutson, **Marti**, Bloom, McNally, Zhang, Barrett, Safronova, Strouse, Tew, and Ye, *Nat. Comm.* **6**, 6896 (2015)

# Atoms + Laser



Nicholson, Campbell, Hutson, **Marti**, Bloom, McNally, Zhang, Barrett, Safronova, Strouse, Tew, and Ye, *Nat. Comm.* **6**, 6896 (2015)

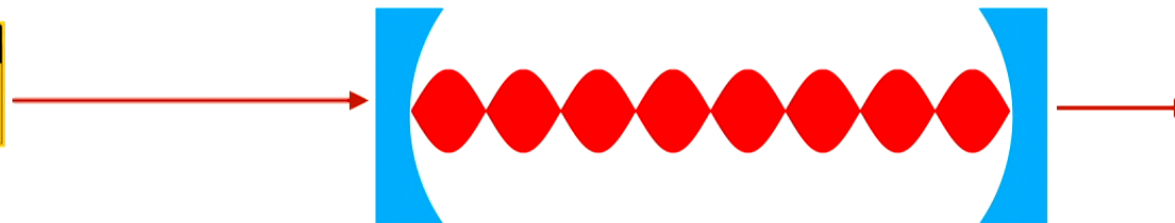
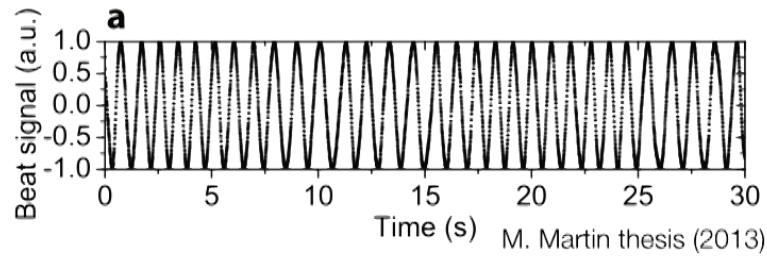
# Making a clock: lasers



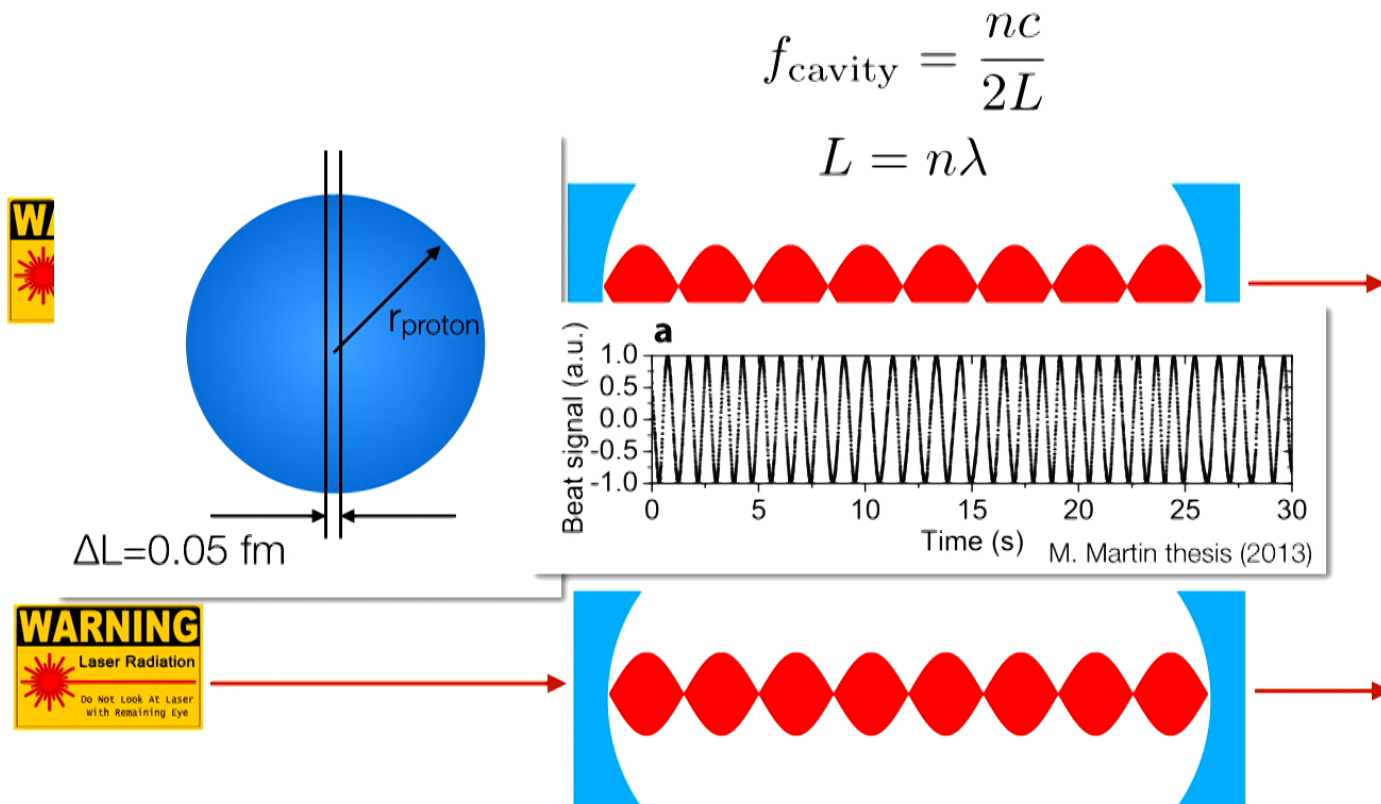
# Making a clock: lasers

$$f_{\text{cavity}} = \frac{nc}{2L}$$

$$L = n\lambda$$

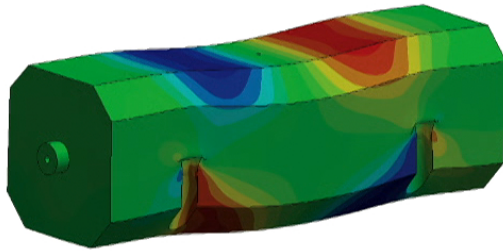


# Making a clock: lasers



## Making a clock: lasers

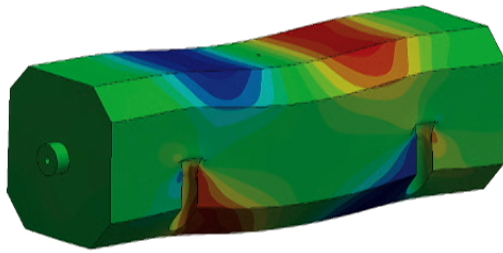
Acceleration sensitivity



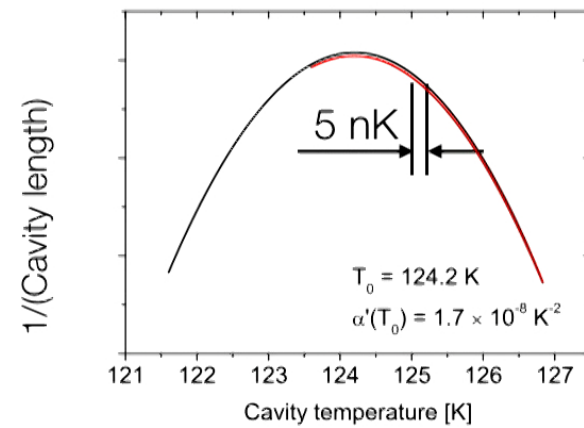


# Making a clock: lasers

Acceleration sensitivity

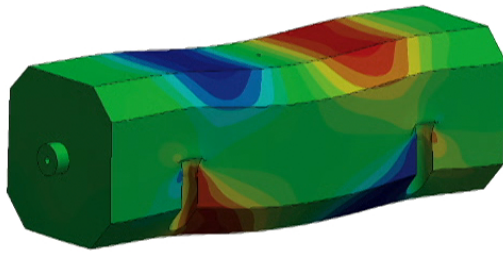


Temperature sensitivity

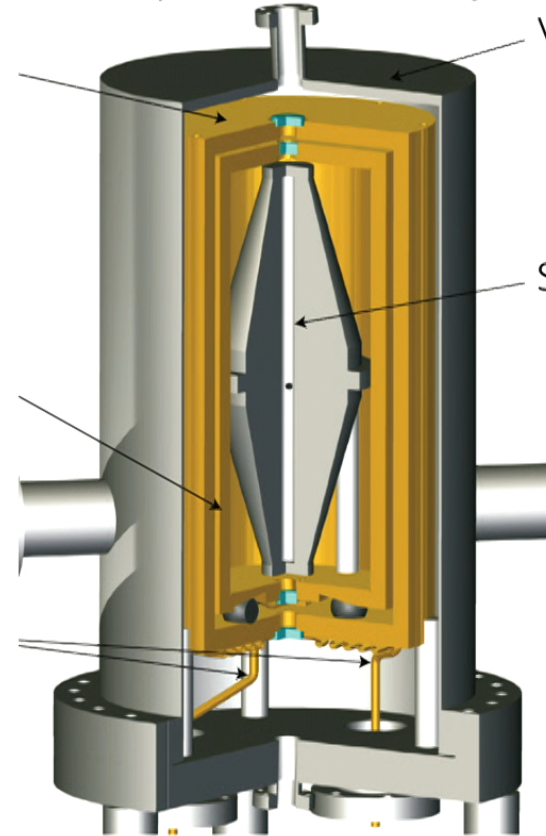


# Making a clock: lasers

Acceleration sensitivity

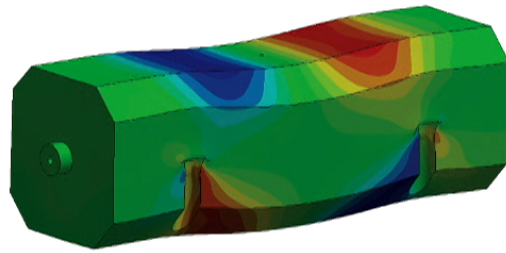


Temperature sensitivity

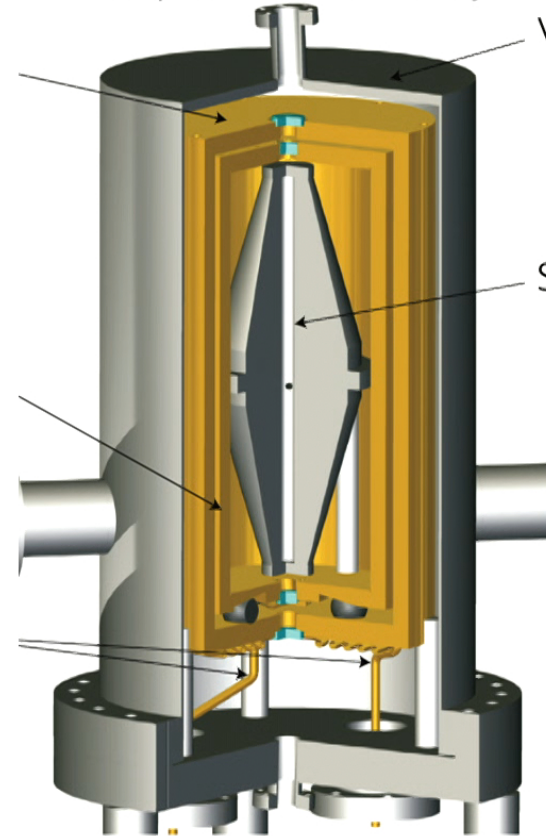


# Making a clock: lasers

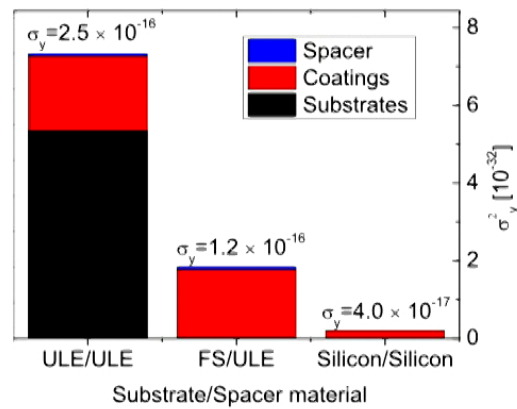
Acceleration sensitivity



Temperature sensitivity

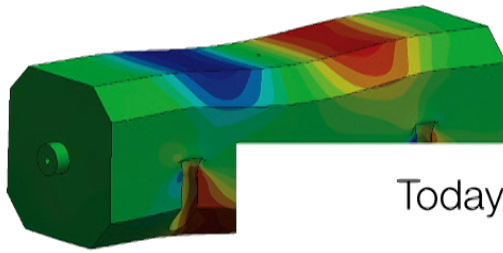


Brownian noise



# Making a clock: lasers

Acceleration sensitivity



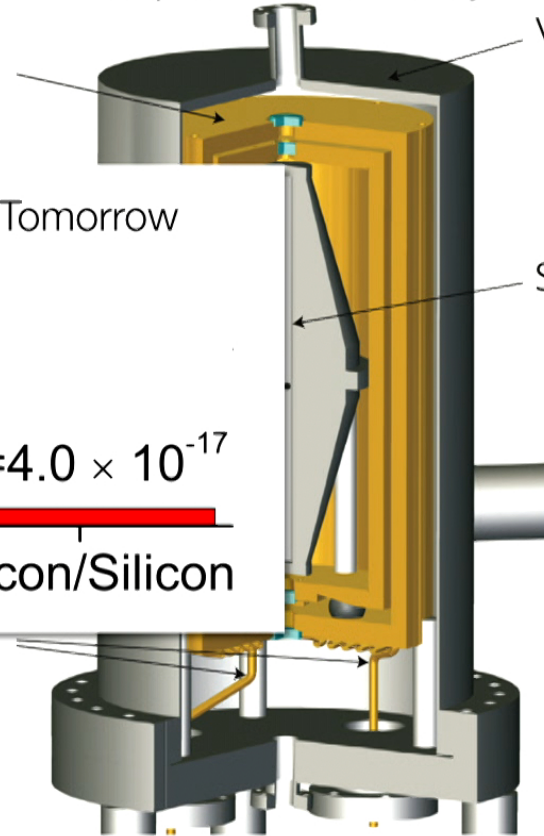
Today

$$\sigma_y = 1.2 \times 10^{-16}$$



FS/ULE

Temperature sensitivity

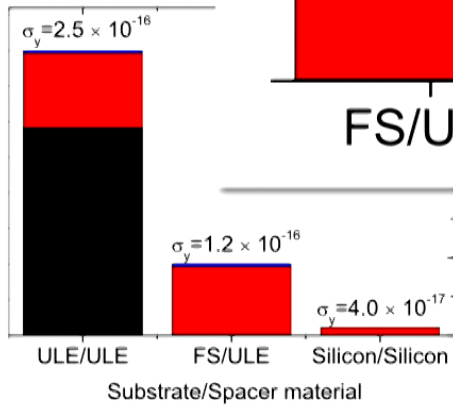


Tomorrow

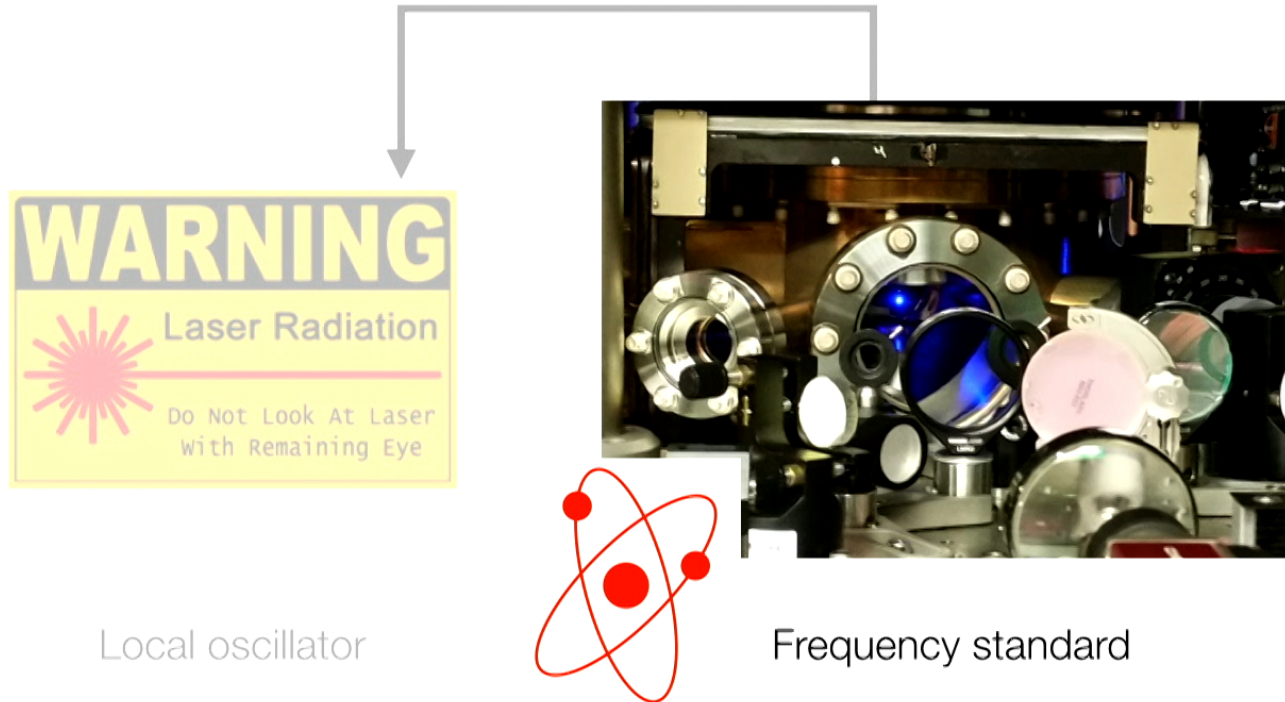
$$\sigma_y = 4.0 \times 10^{-17}$$

Silicon/Silicon

Browni

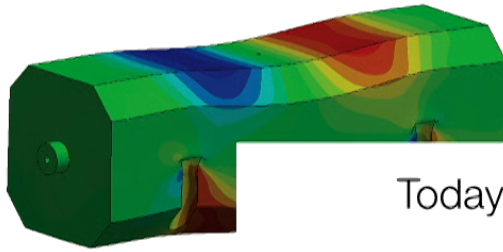


# Making a clock: atoms



# Making a clock: lasers

Acceleration sensitivity



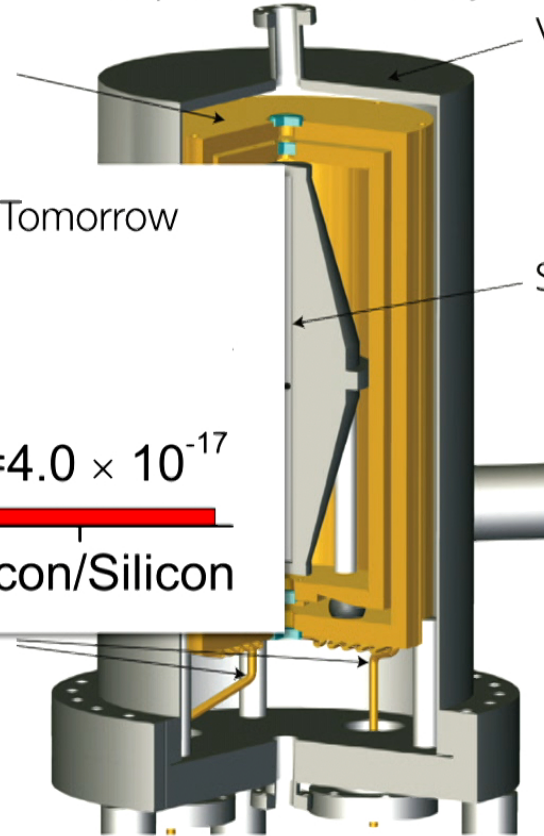
Today

$$\sigma_y = 1.2 \times 10^{-16}$$



FS/ULE

Temperature sensitivity

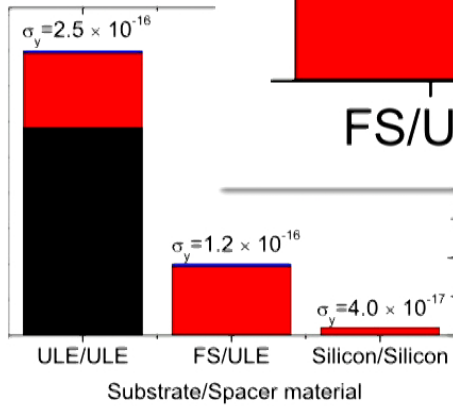


Tomorrow

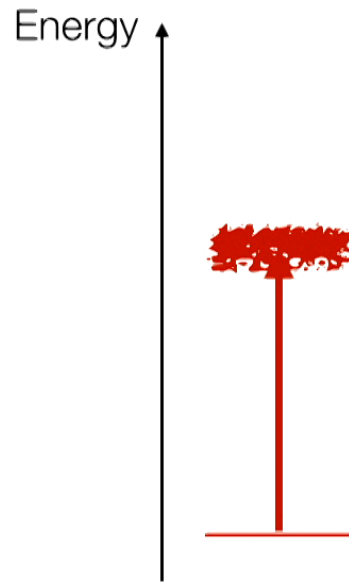
$$\sigma_y = 4.0 \times 10^{-17}$$

Silicon/Silicon

Browni



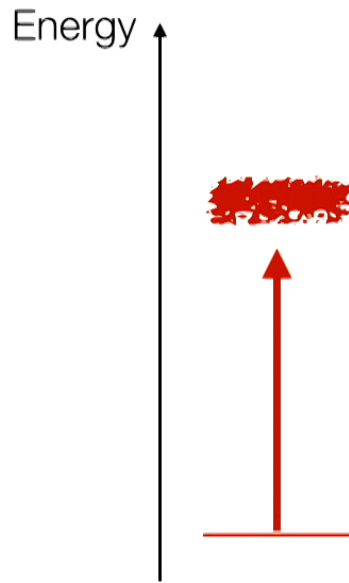
# Making a clock: atoms



▶ **Stability:** Blurring the energy

- Atomic motion
- Interactions between atoms
- Energy-time uncertainty
- Laser noise
- Quantum noise

# Making a clock: atoms



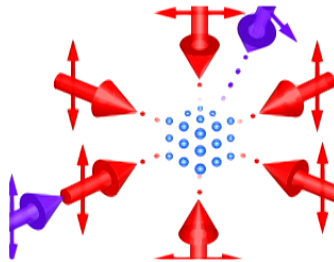
- ▶ **Stability:** Blurring the energy
  - Atomic motion
  - Interactions between atoms
  - Energy-time uncertainty
  - Laser noise
  - Quantum noise
- ▶ **Accuracy:** Shifting the energy
  - Magnetic and electric fields
  - Blackbody radiation
  - Interacting atoms



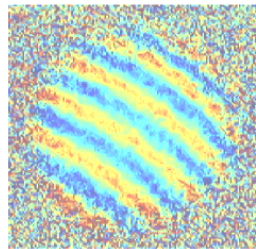
# Outline



**Optical lattice clocks**



**3D lattice clock**  
Record Q-factor



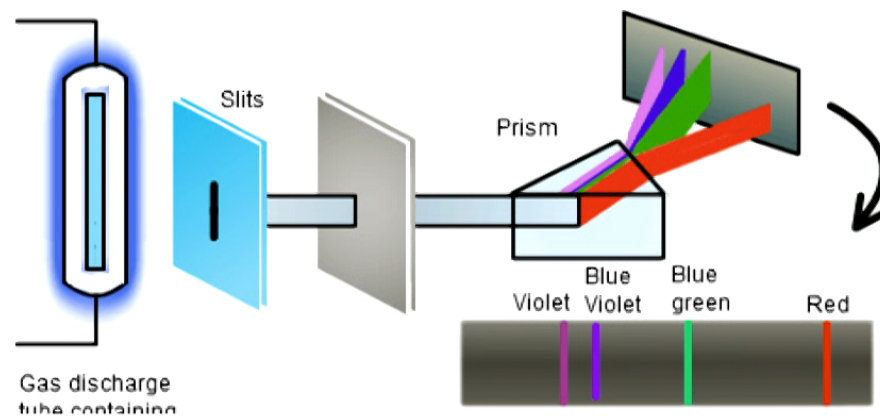
**Atom-atom coherence**  
Record synchronous stability

## Reaching 0.2 Hz linewidths with a 3D clock

429 228 004 229 783.130 Hz

# Reaching 0.1 Hz linewidths

429 228 004 229 783.130 Hz



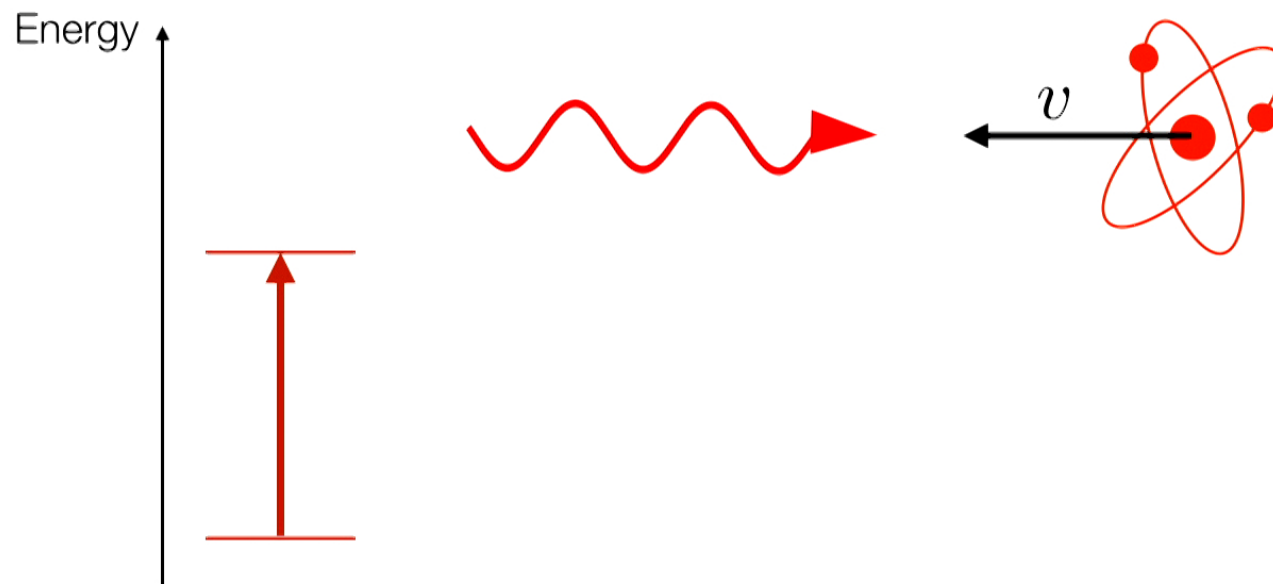
<http://chemistry.tutorvista.com/inorganic-chemistry/spectral-lines.html>

# Reaching 0.1 Hz linewidths

Linewidth

300 K

429 228 004 229 783.130 Hz



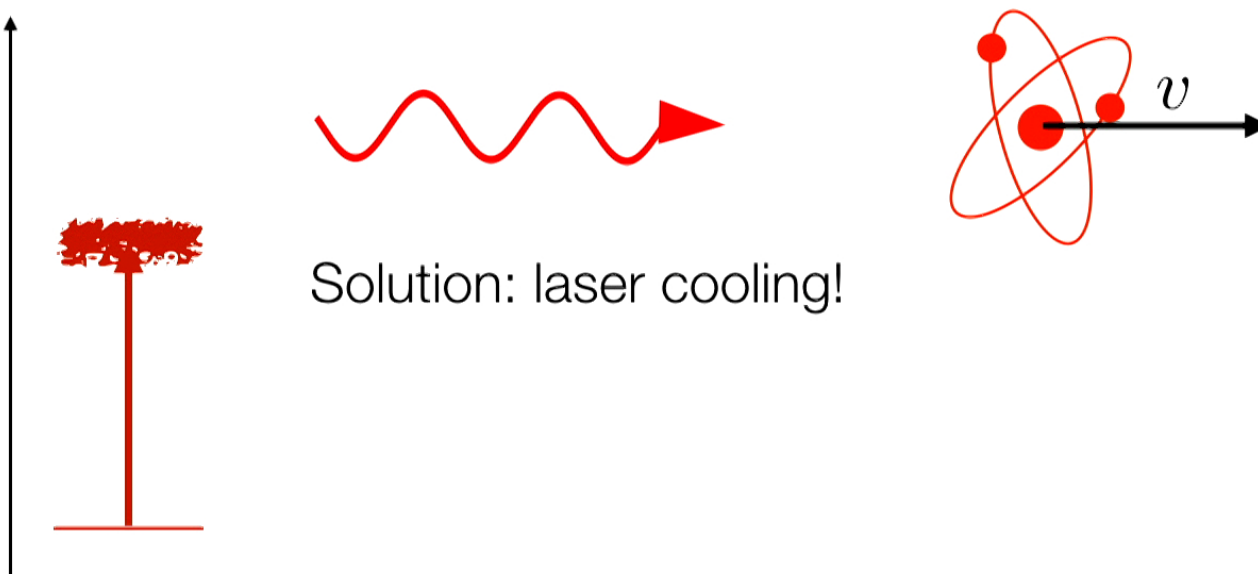
# Reaching 0.1 Hz linewidths

Linewidth



429 228 004 229 783.130 Hz

Energy



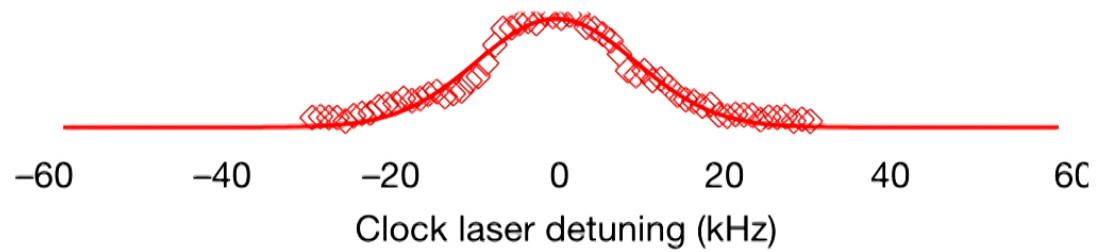
# Resolving motion

Linewidth

1  $\mu$ K



429 228 004 229 783.130 Hz

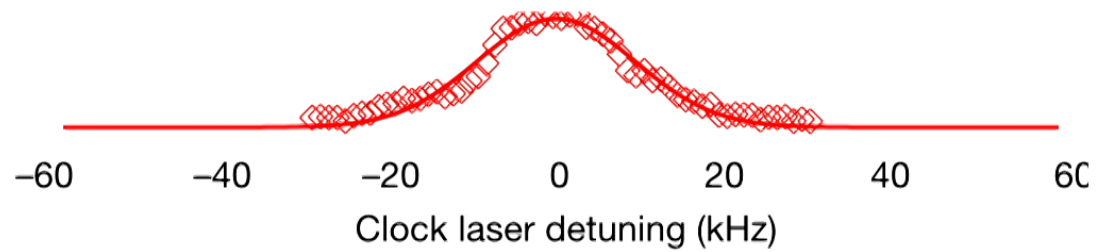


# Resolving motion

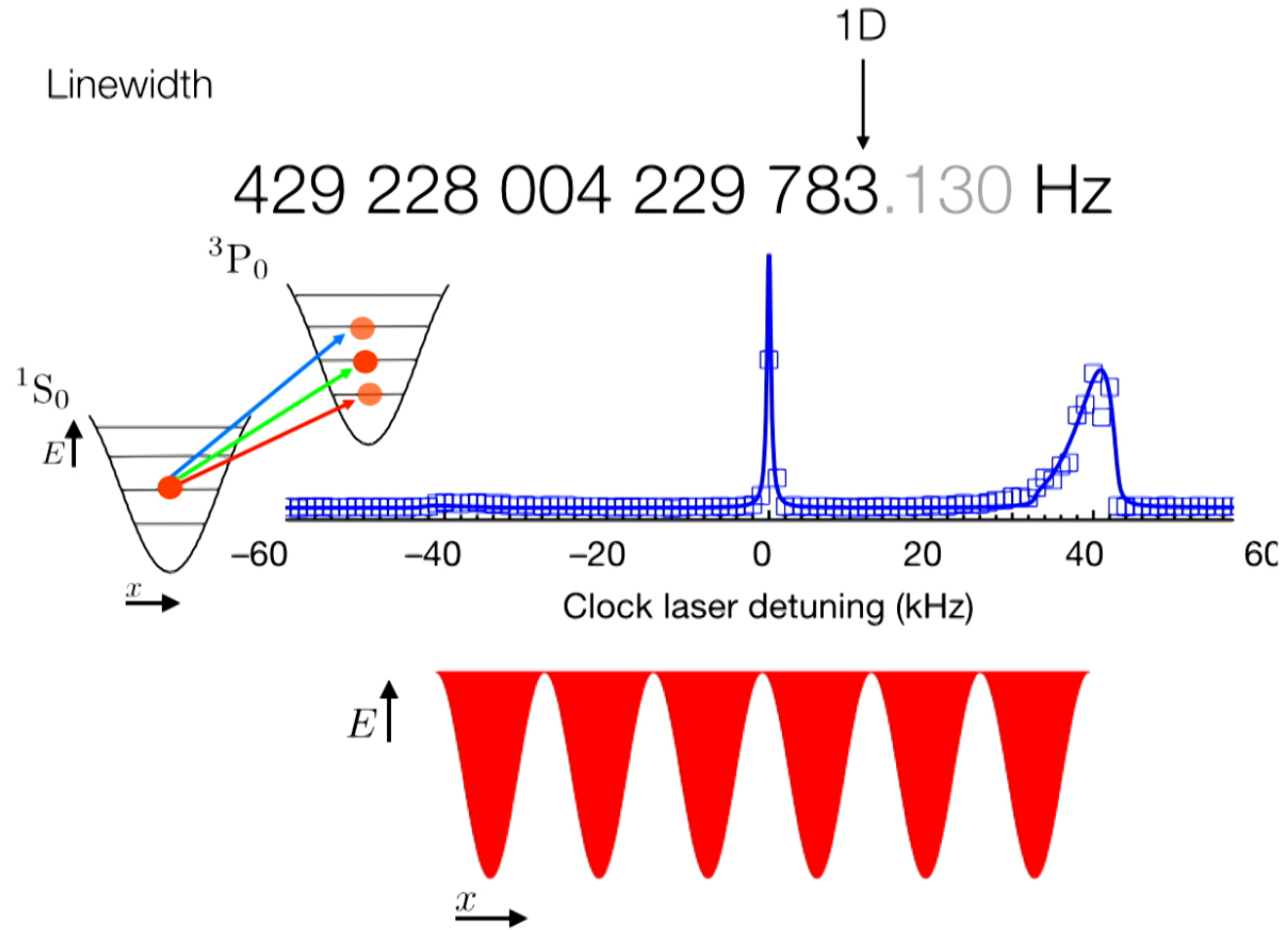
Linewidth

$1 \mu\text{K}$

429 228 004 229 783.130 Hz



# Resolving motion

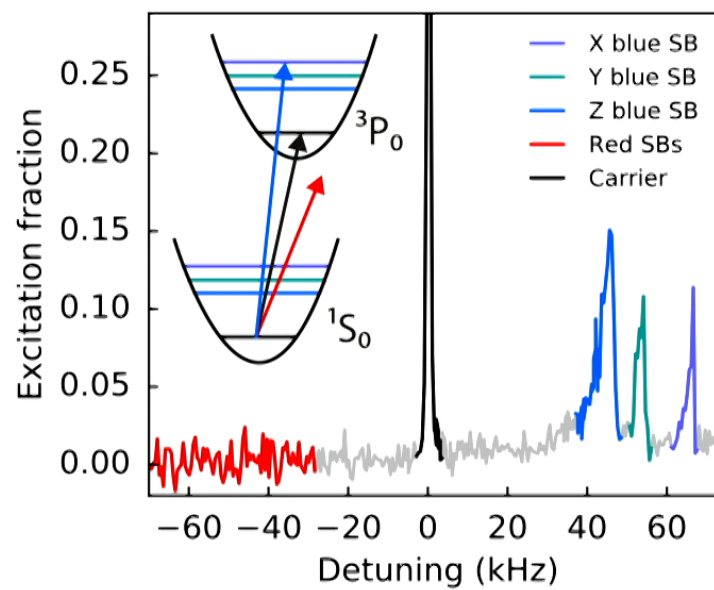
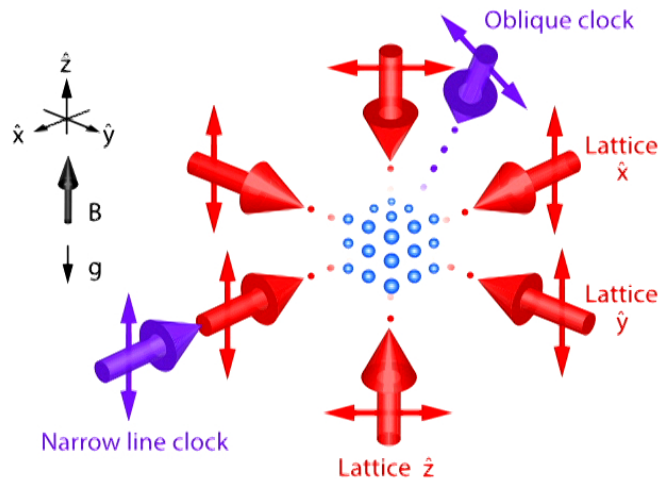




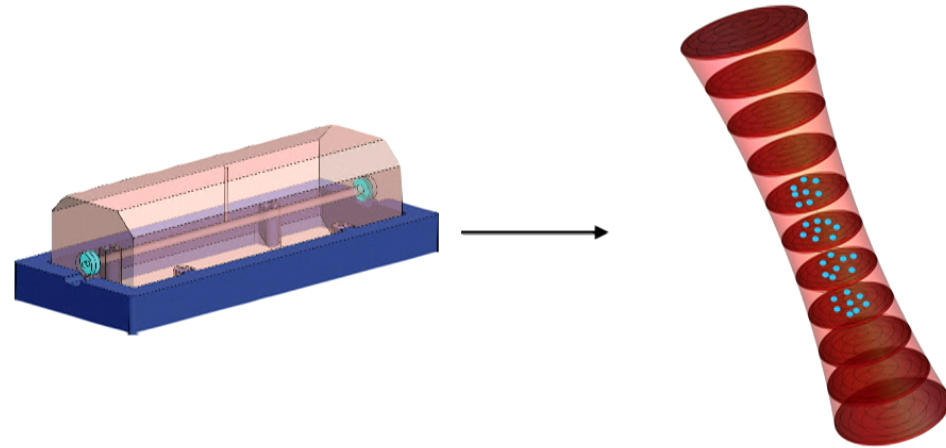
# Resolving motion

Linewidth

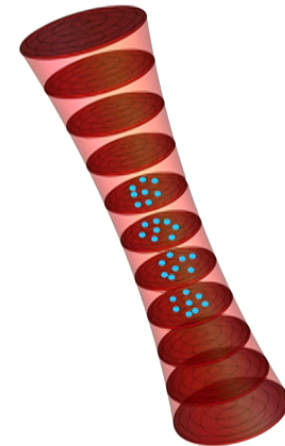
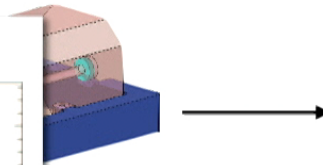
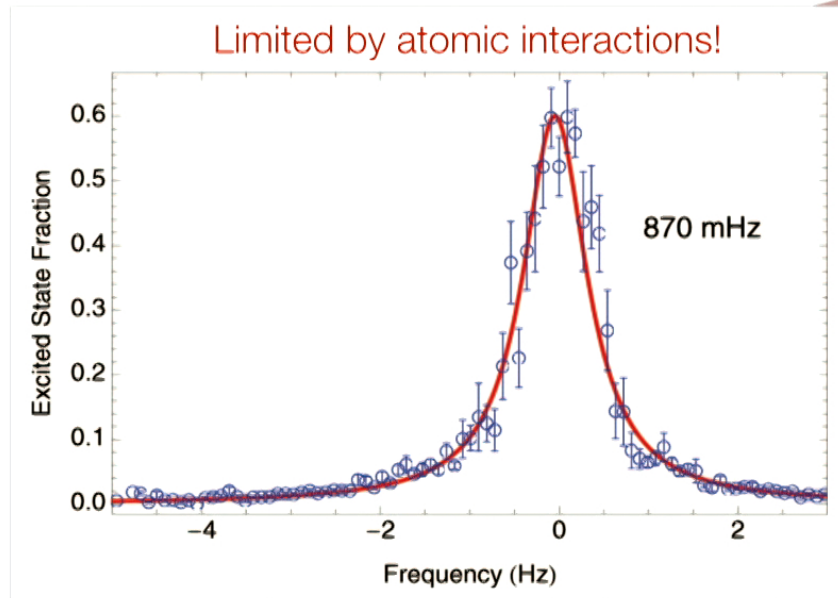
1D  
↓  
429 228 004 229 783.130 Hz



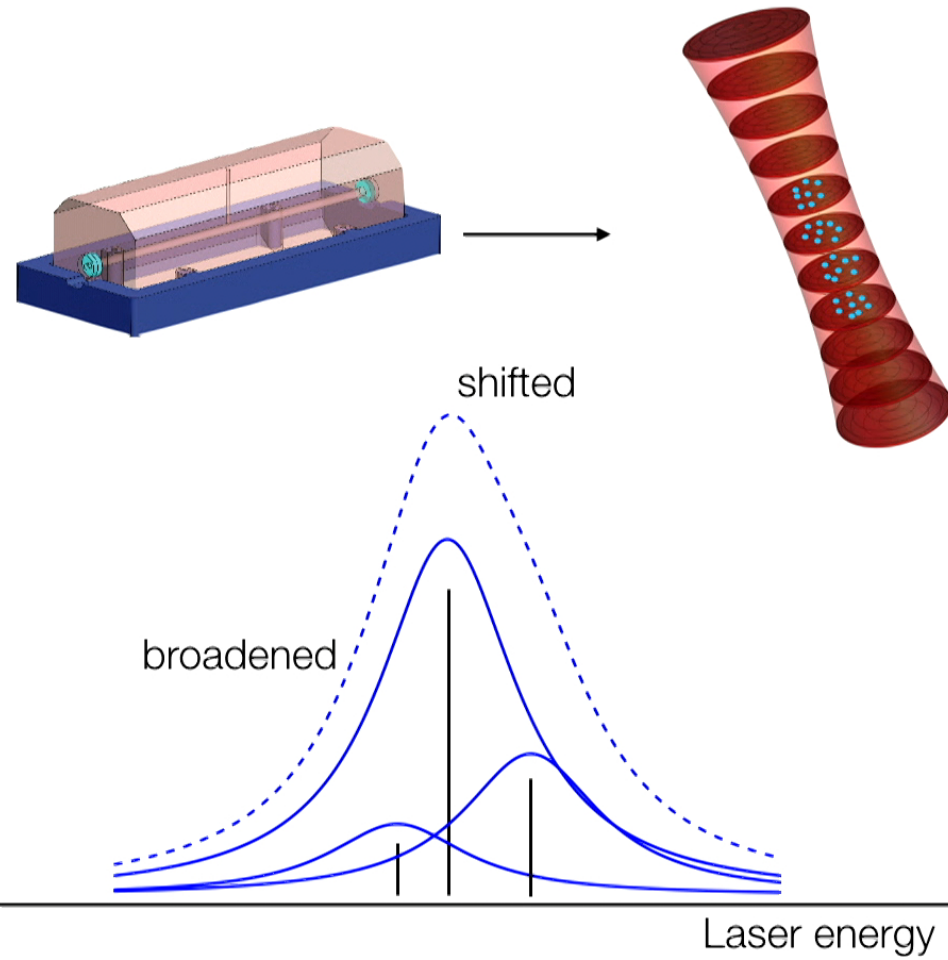
# Resolving interactions: 1D to 3D lattices



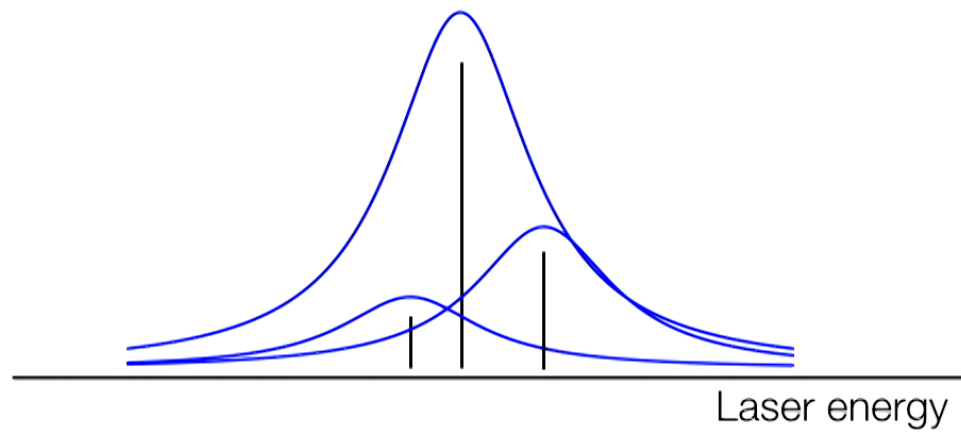
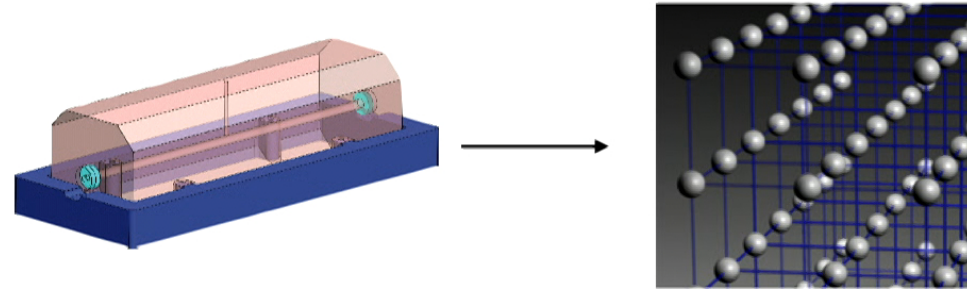
# Resolving interactions: 1D to 3D lattices



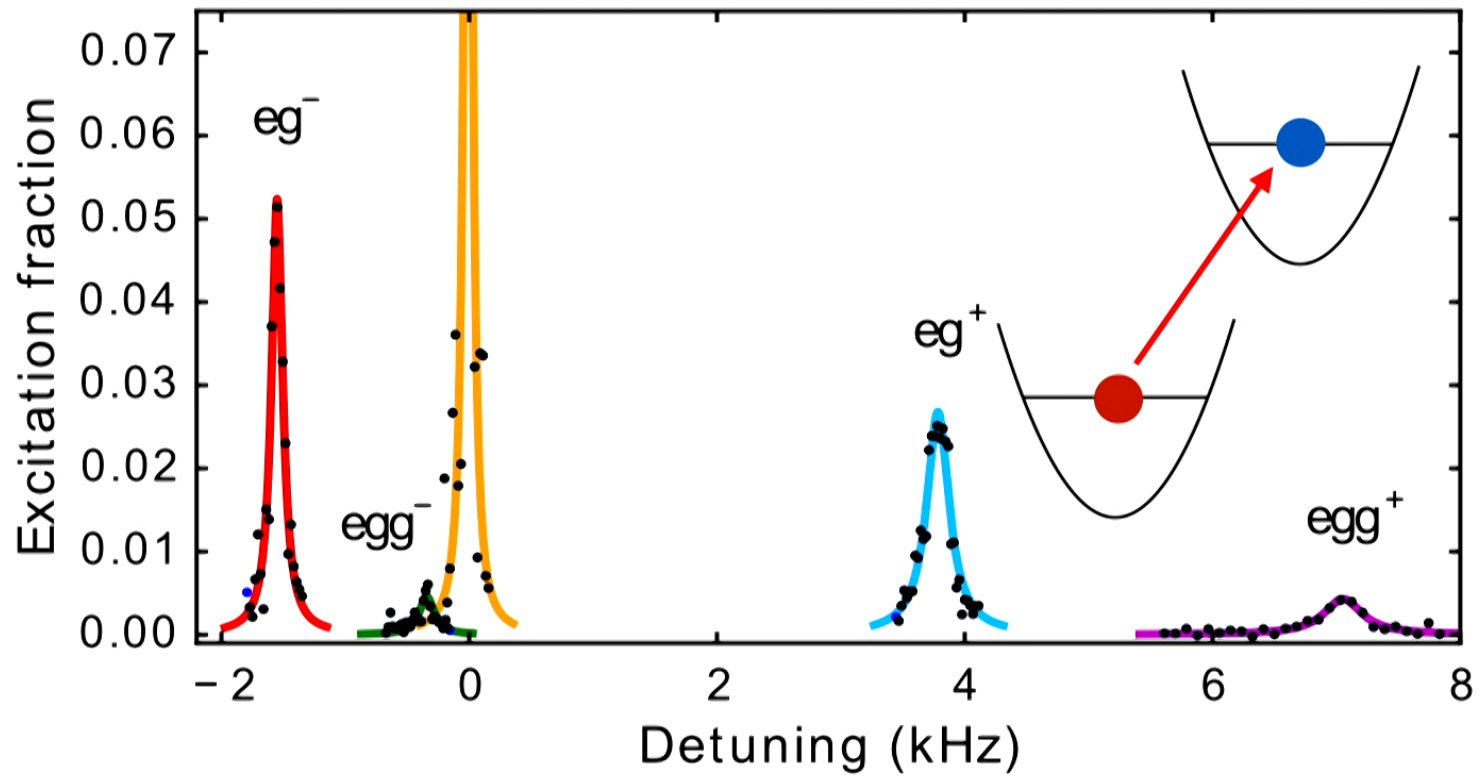
# Resolving interactions: 1D to 3D lattices



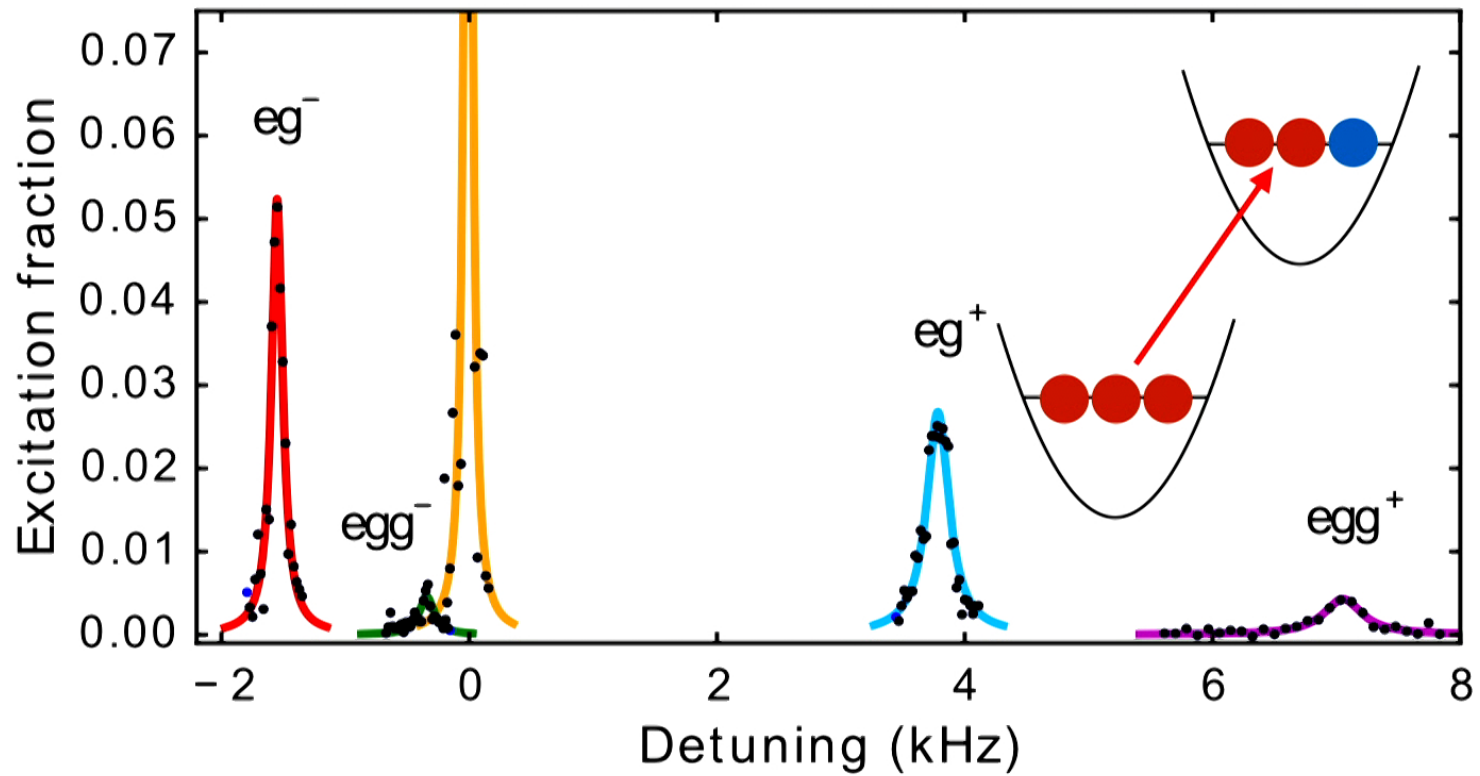
# Resolving interactions: 1D to 3D lattices



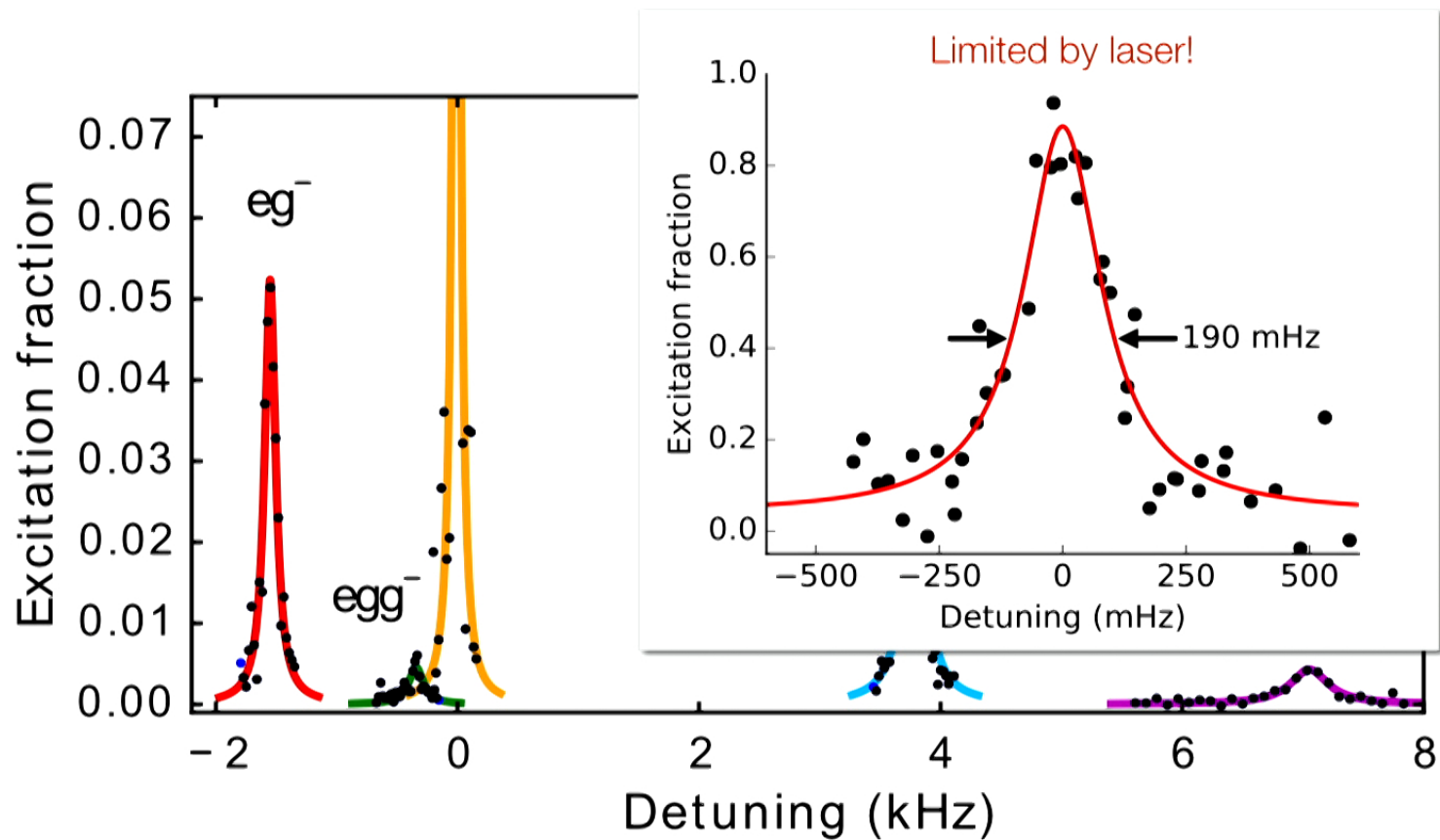
# Resolving interactions: 3D lattices



# Resolving interactions: 3D lattices

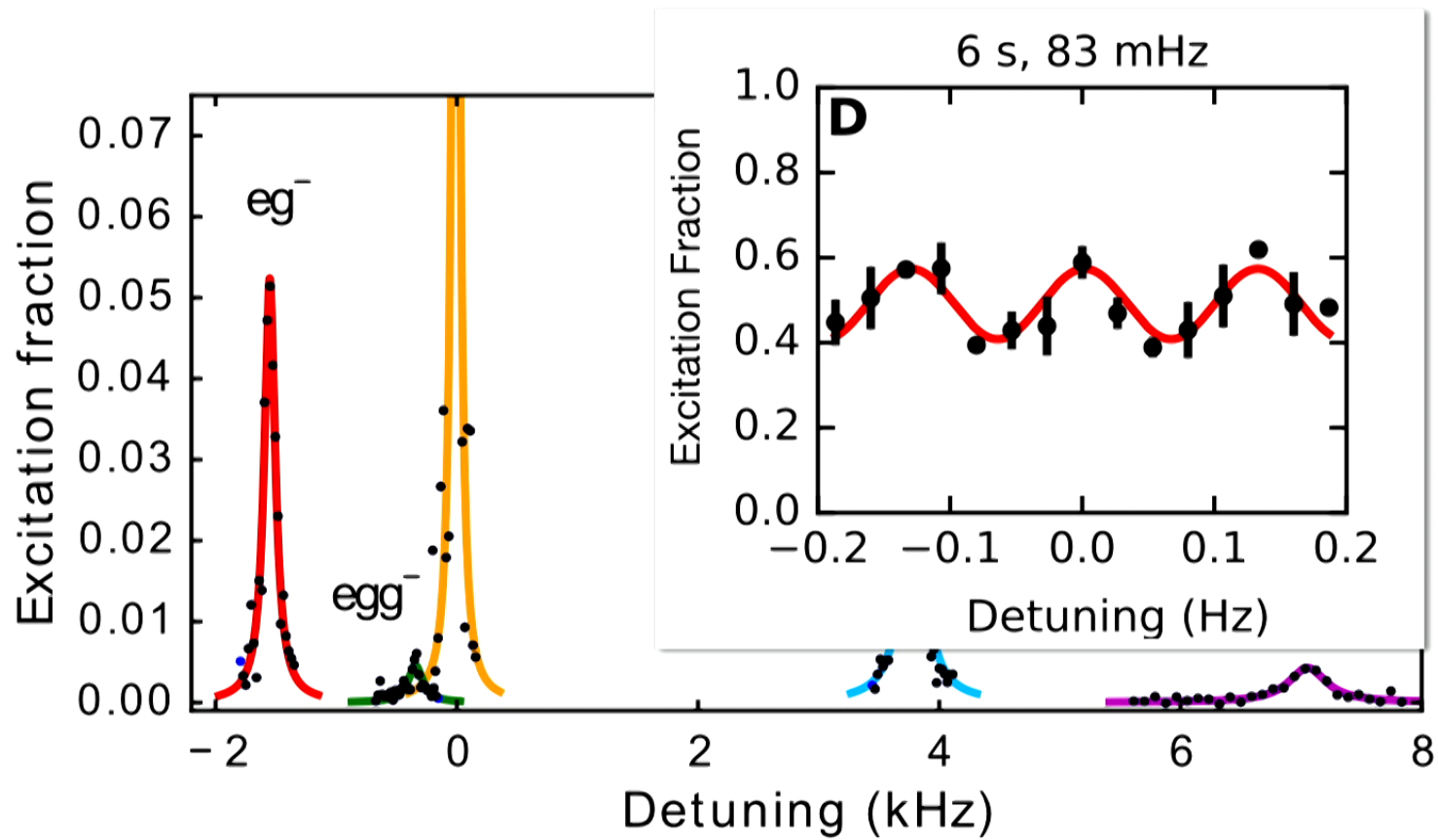


# Resolving interactions: 3D lattices

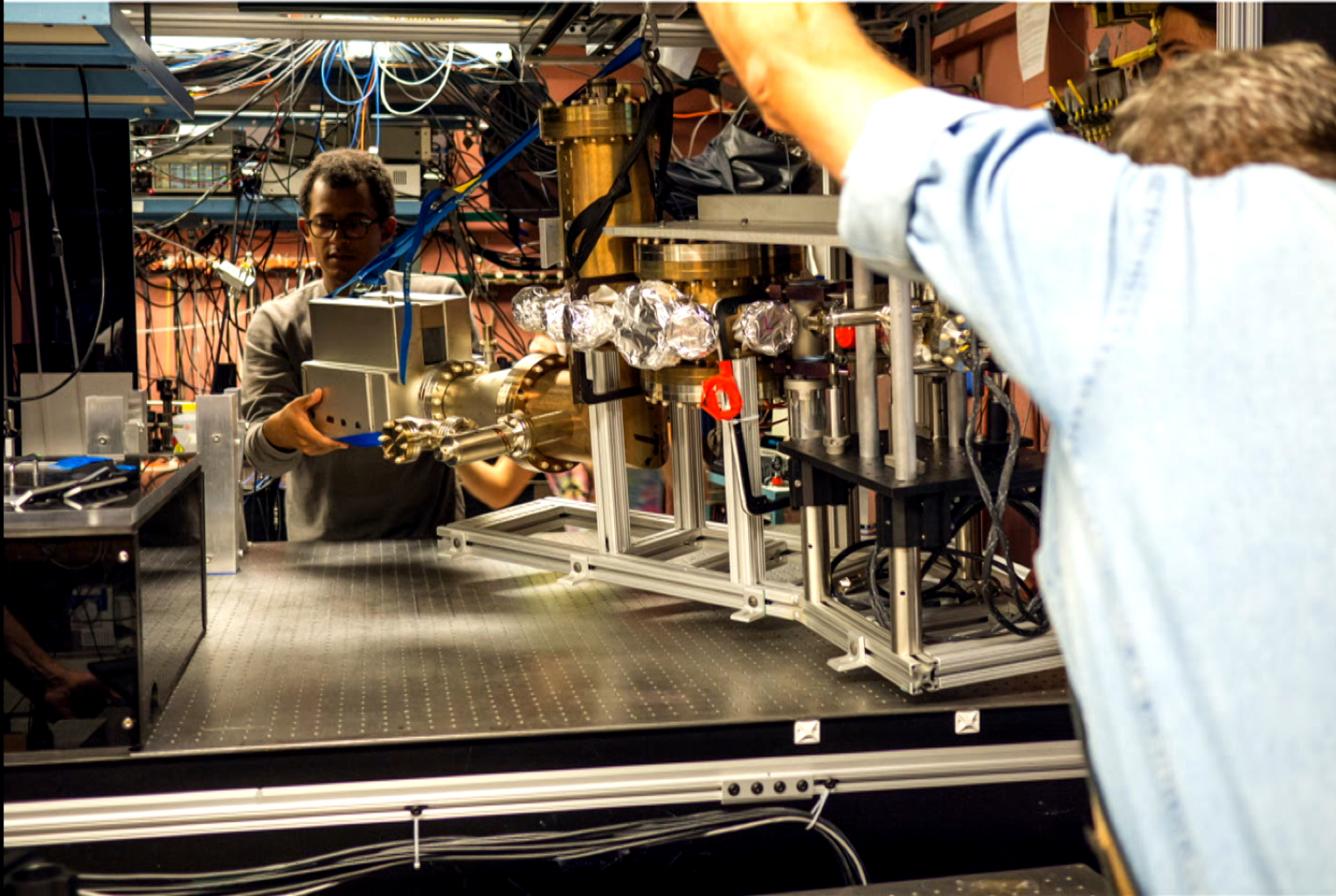




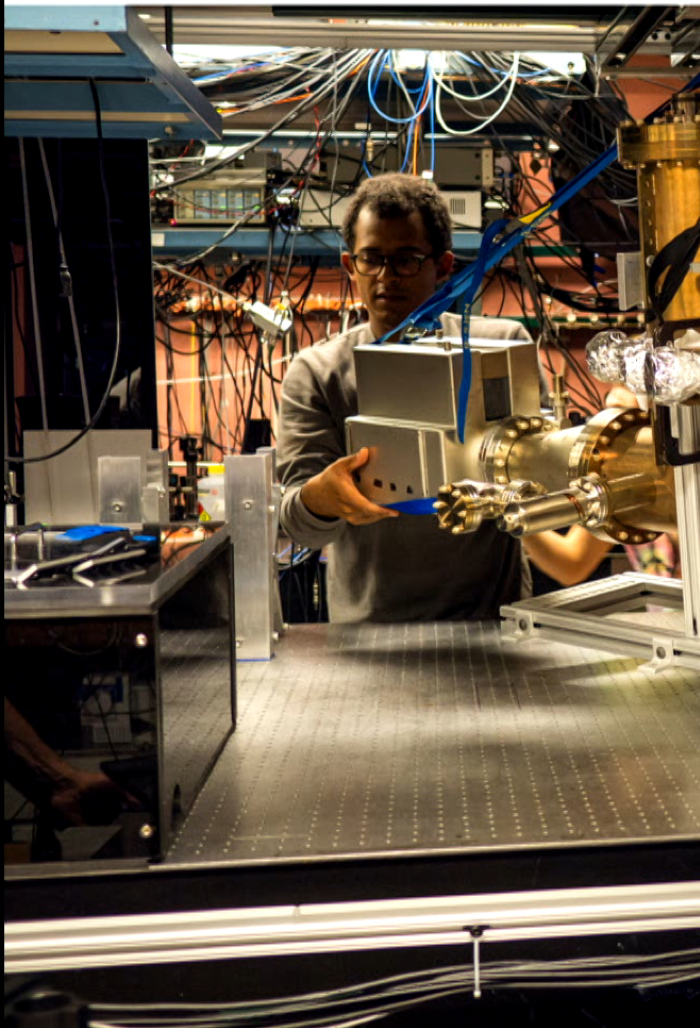
# Resolving interactions: 3D lattices



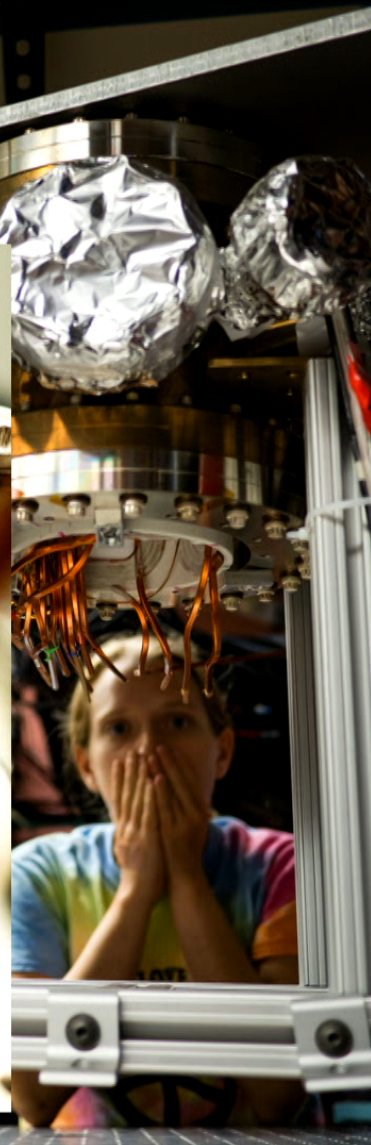
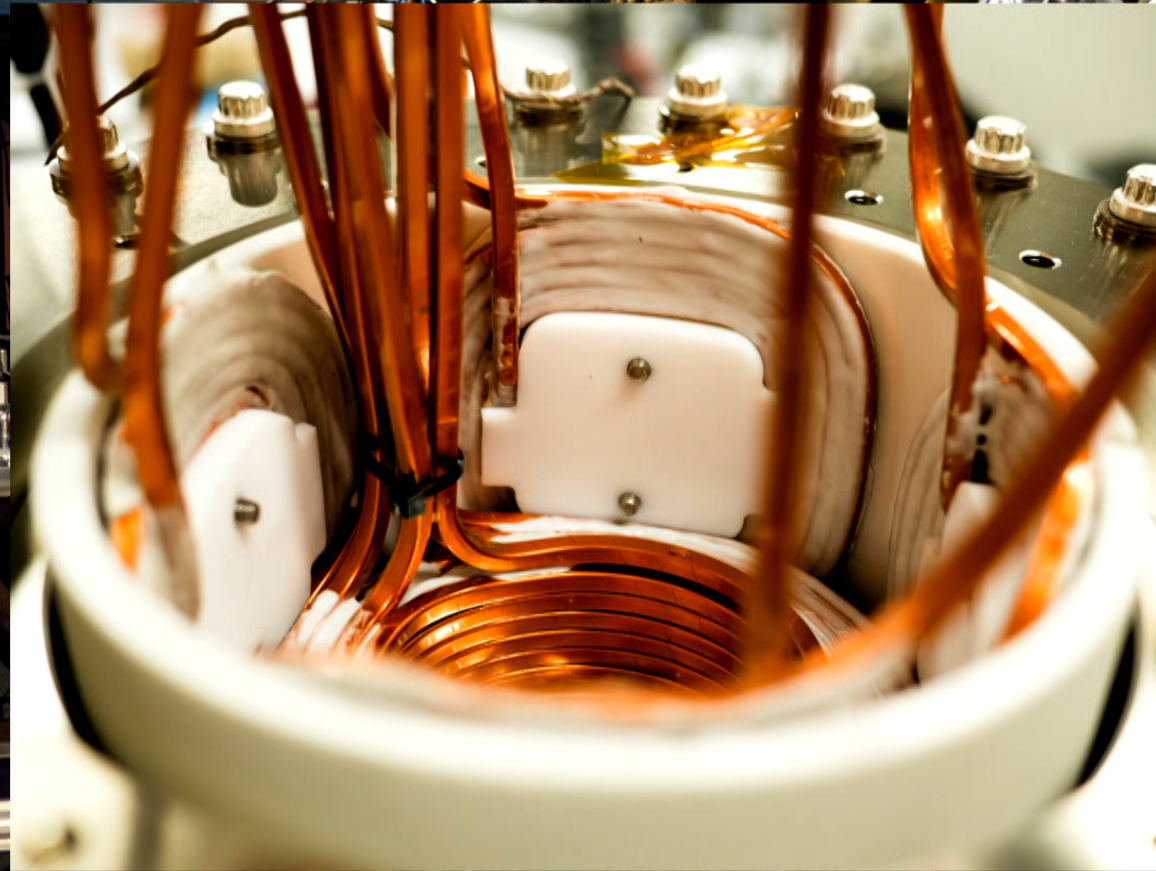
# Fermi-degenerate 3D optical lattice clock



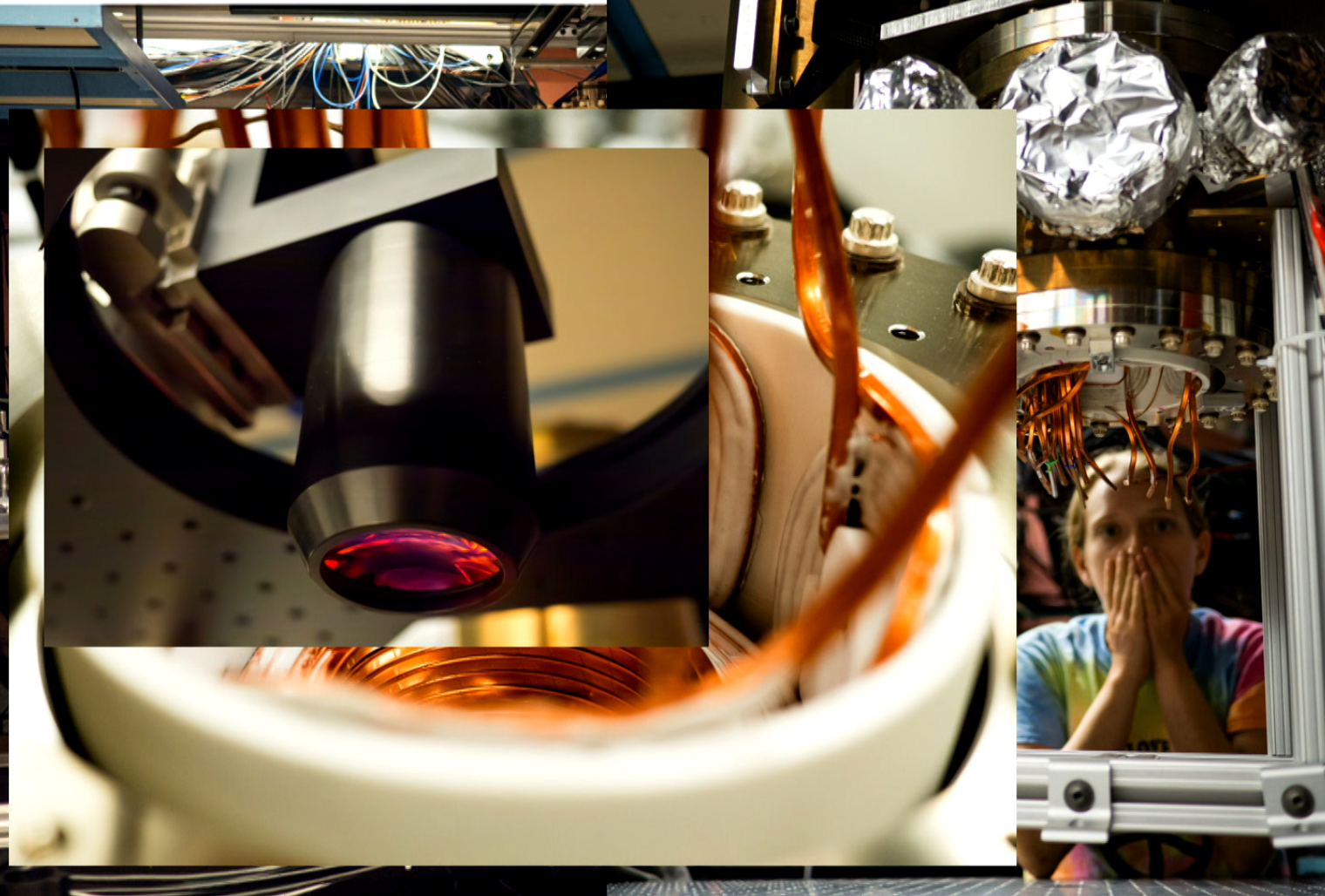
# Fermi-degenerate 3D



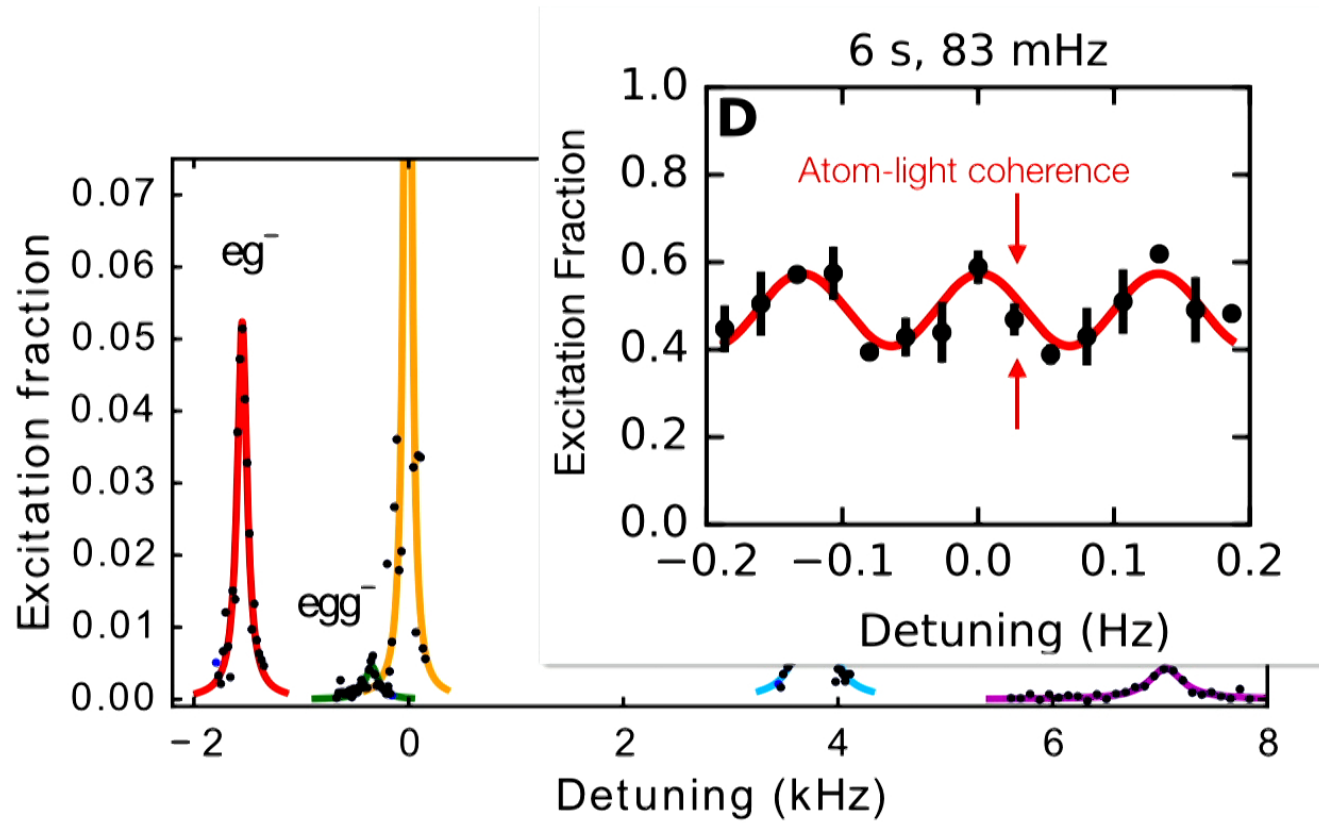
# Fermi-degenerate 3D



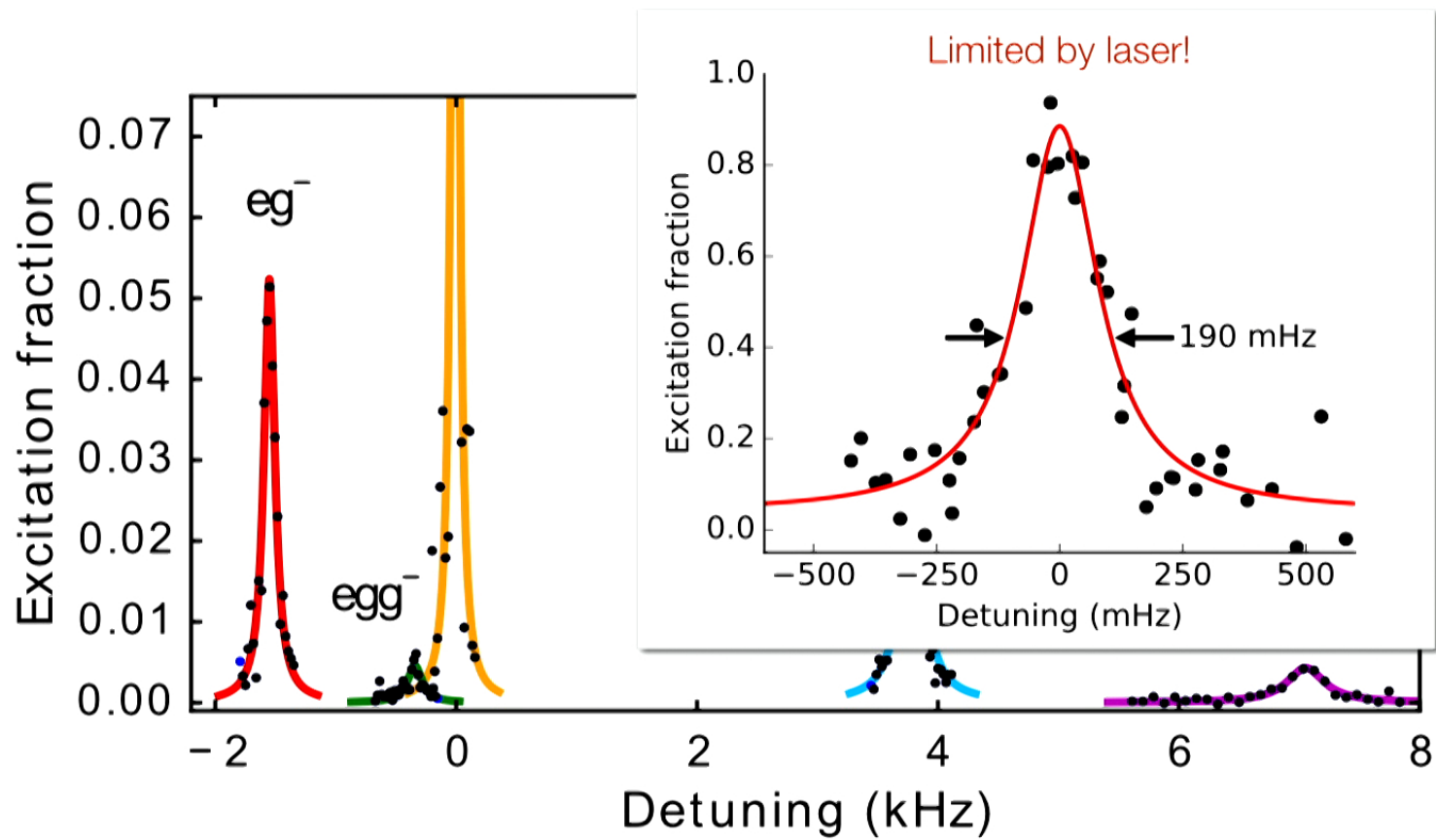
# Fermi-degenerate 3D



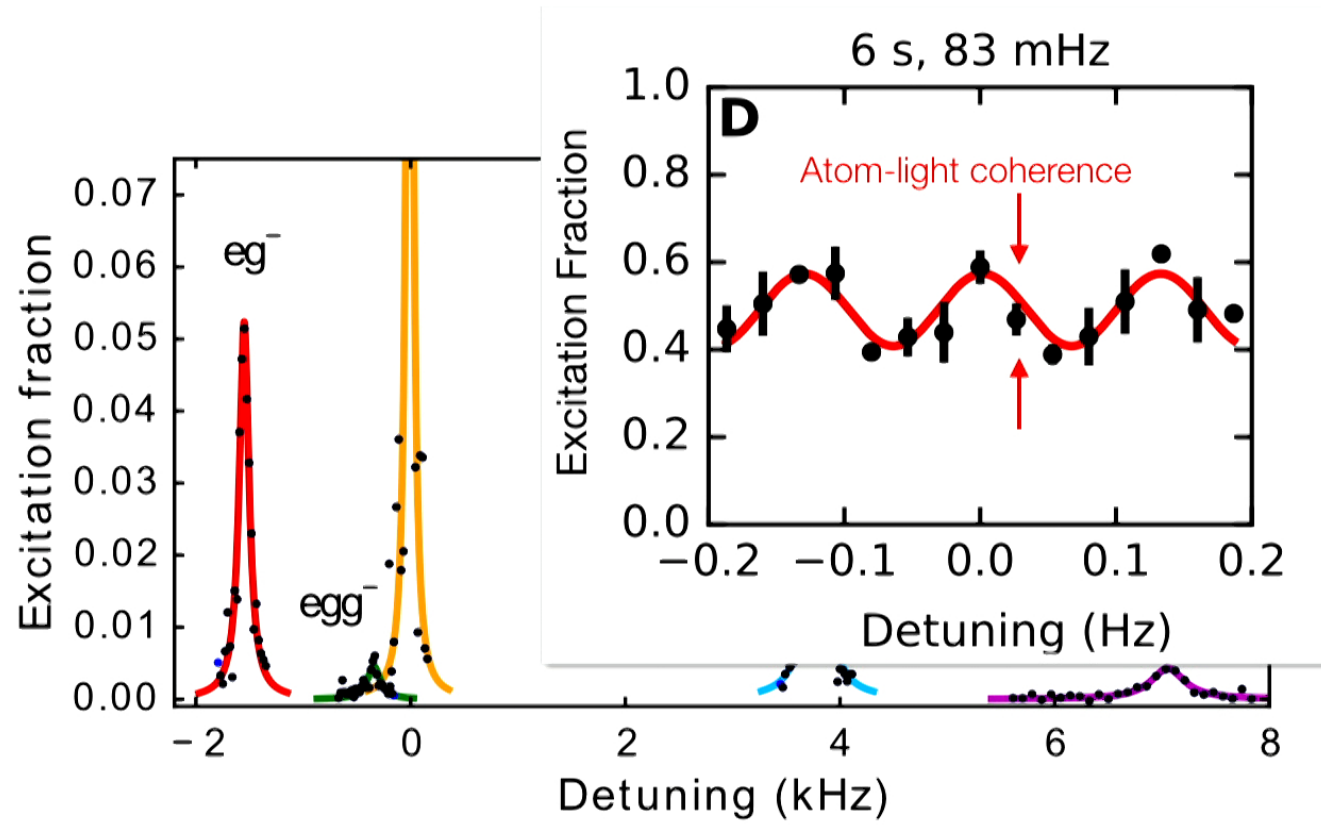
# What's the limit?



# Resolving interactions: 3D lattices

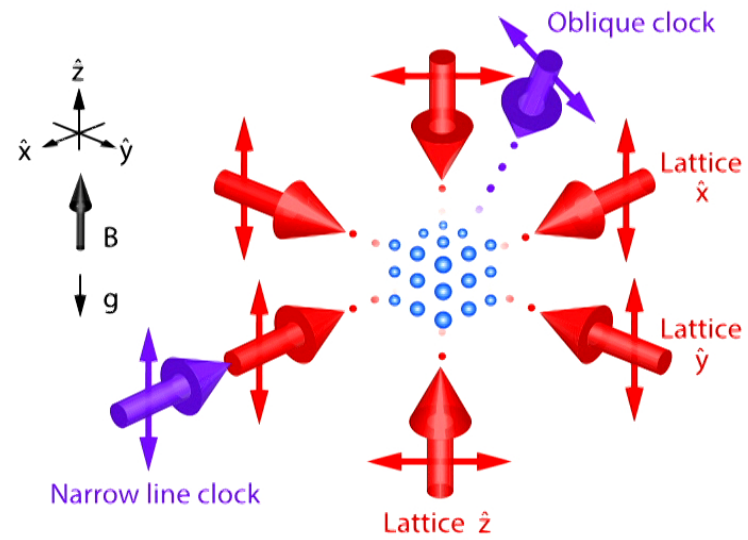
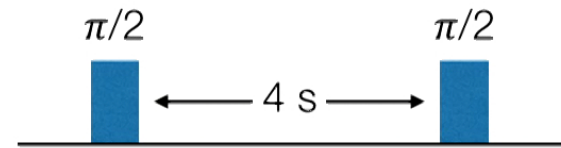


# What's the limit?

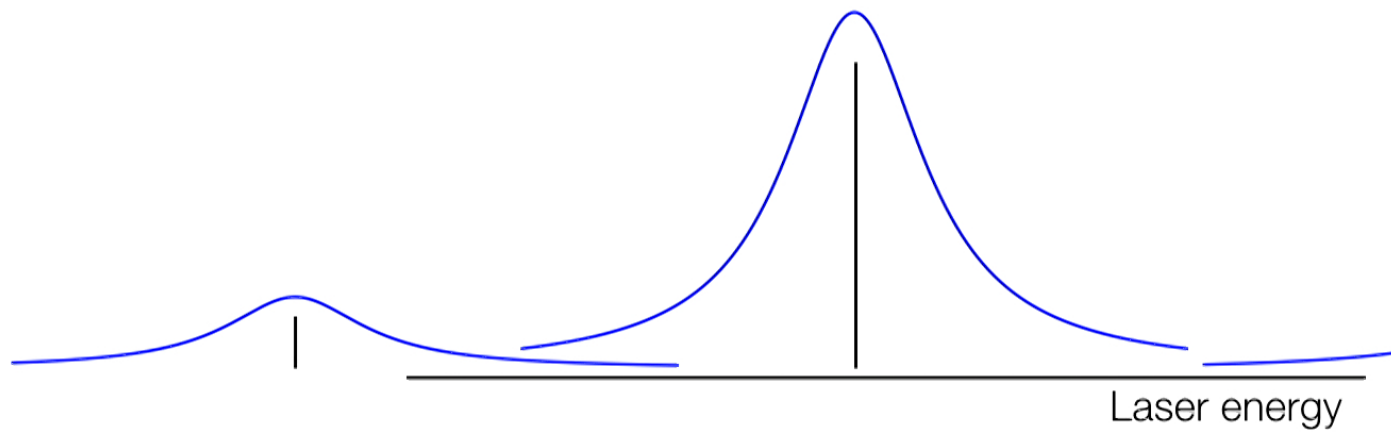
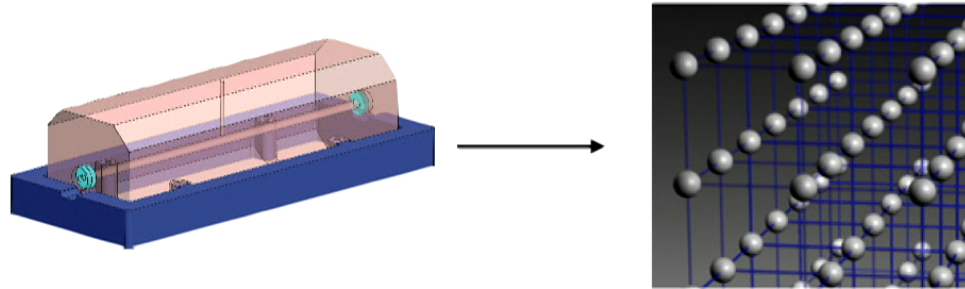




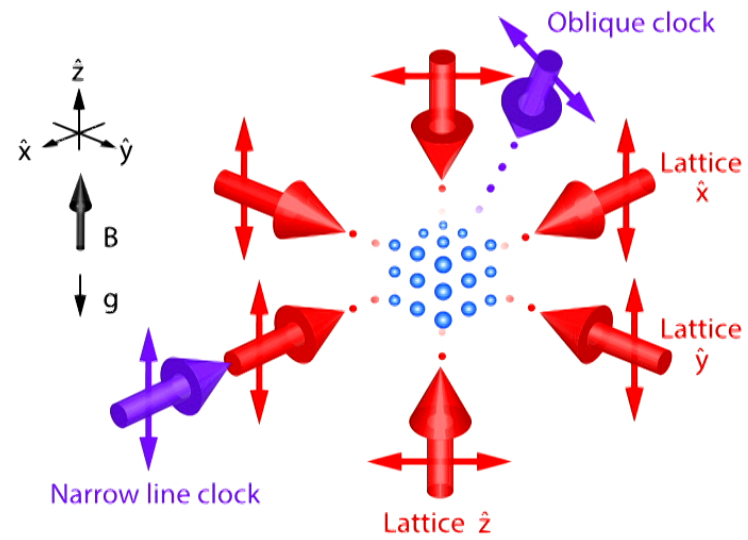
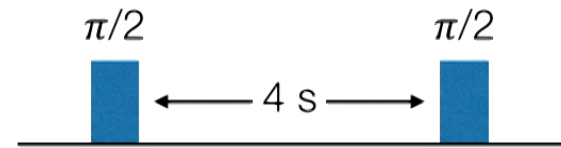
# Atom-atom coherence



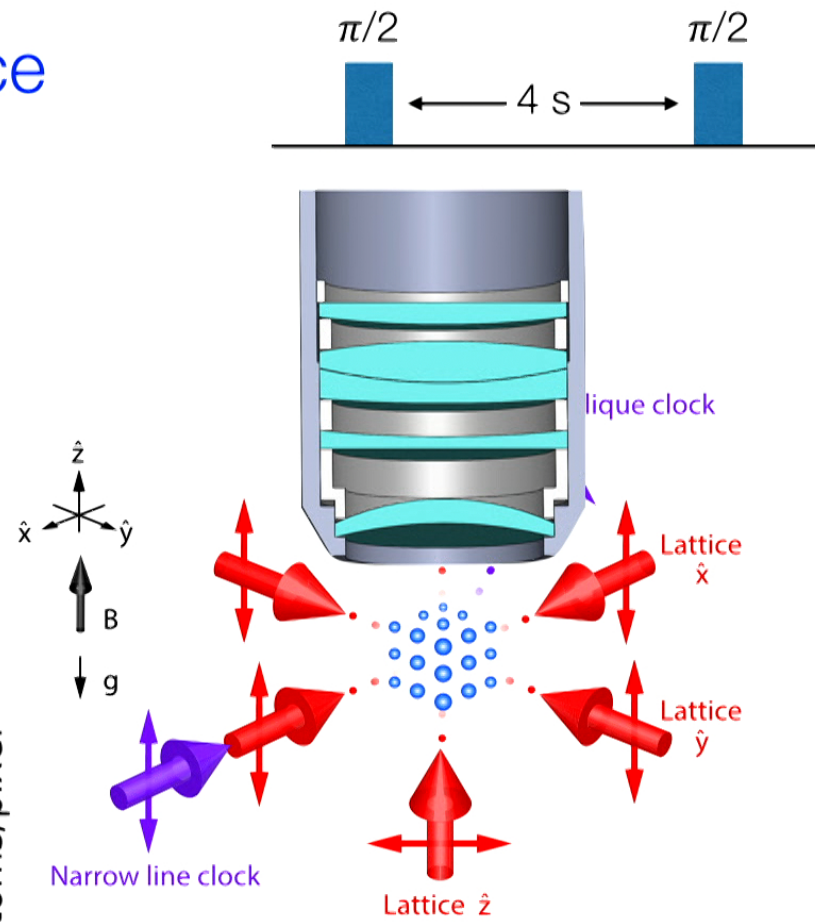
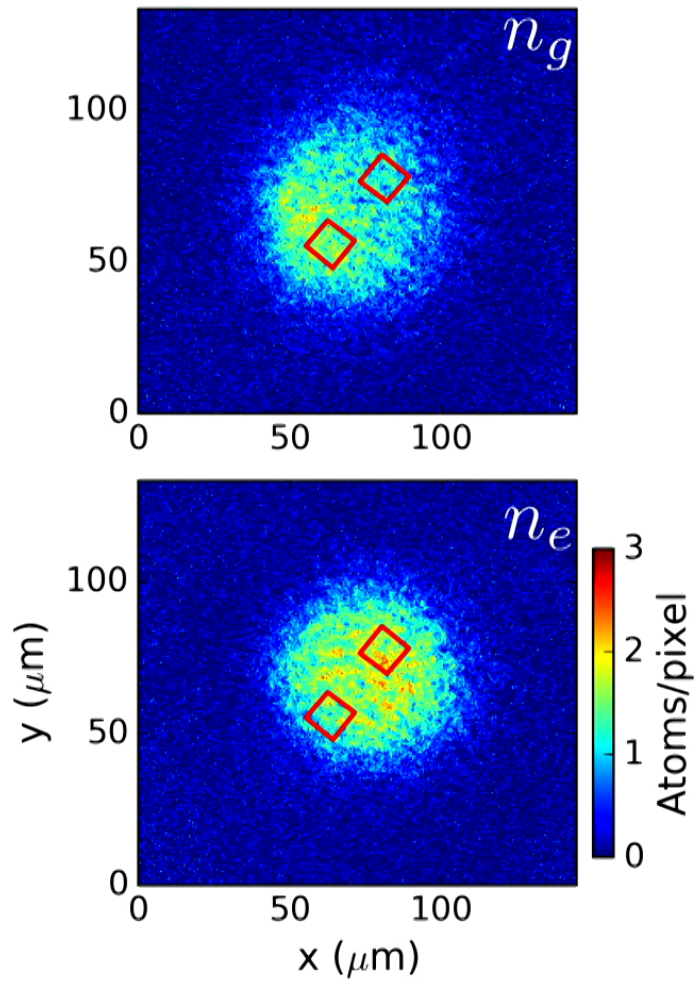
# Resolving interactions: 1D to 3D lattices



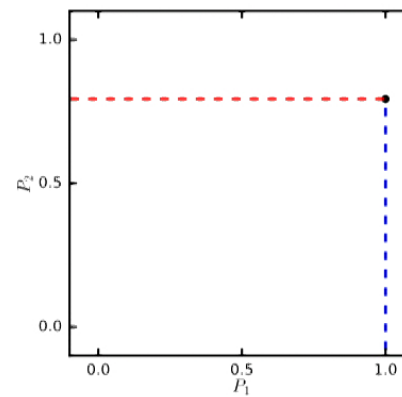
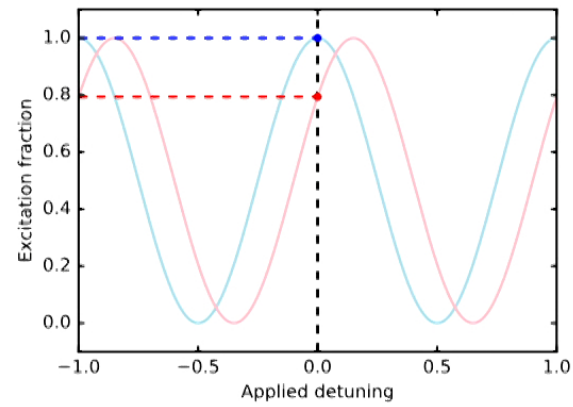
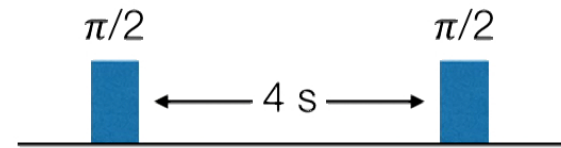
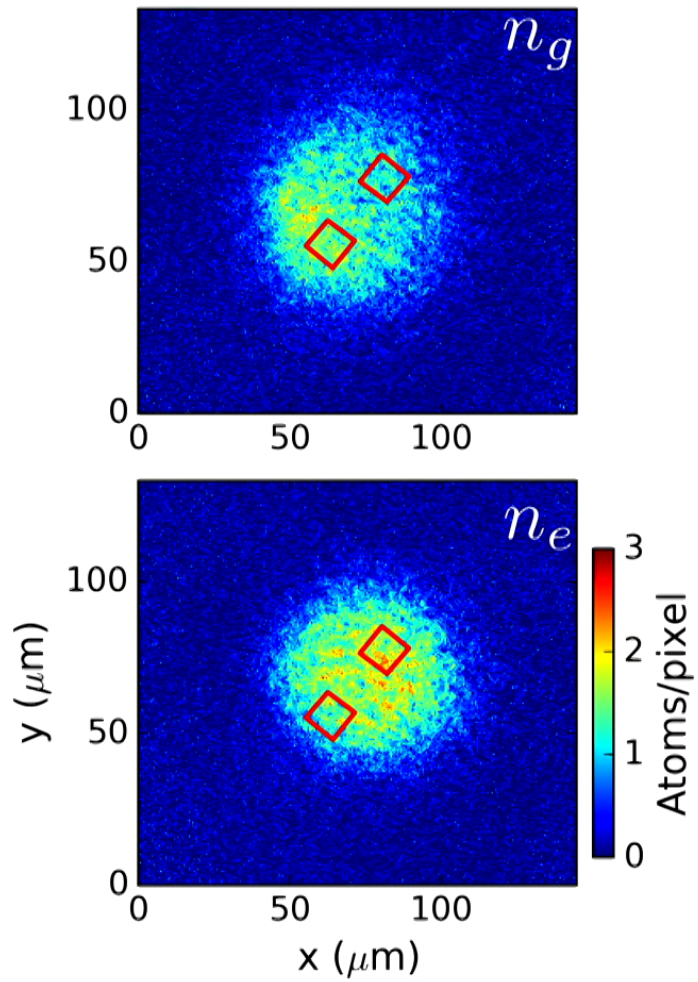
# Atom-atom coherence



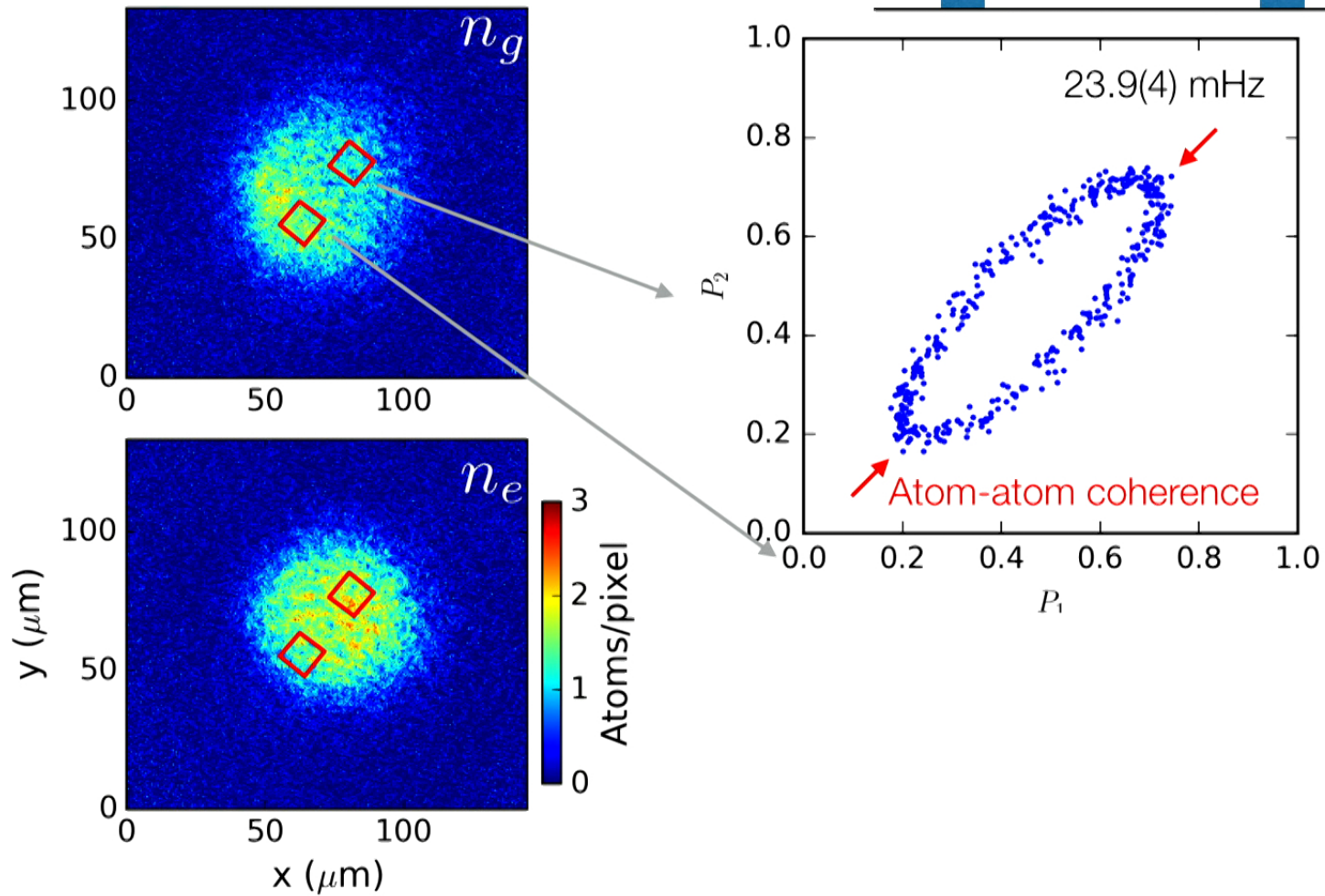
# Atom-atom coherence



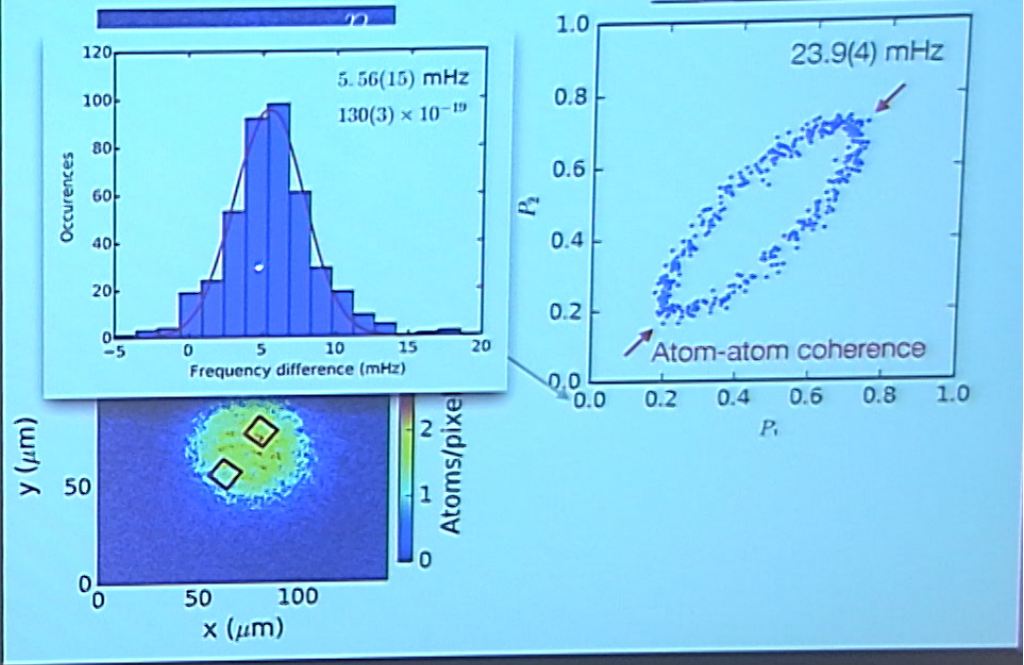
# Atom-atom coherence



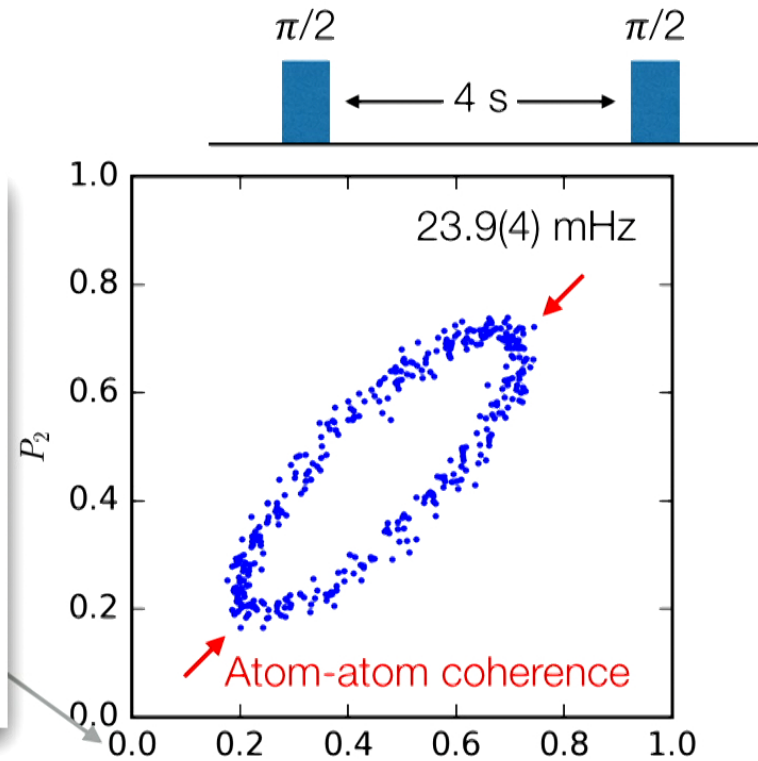
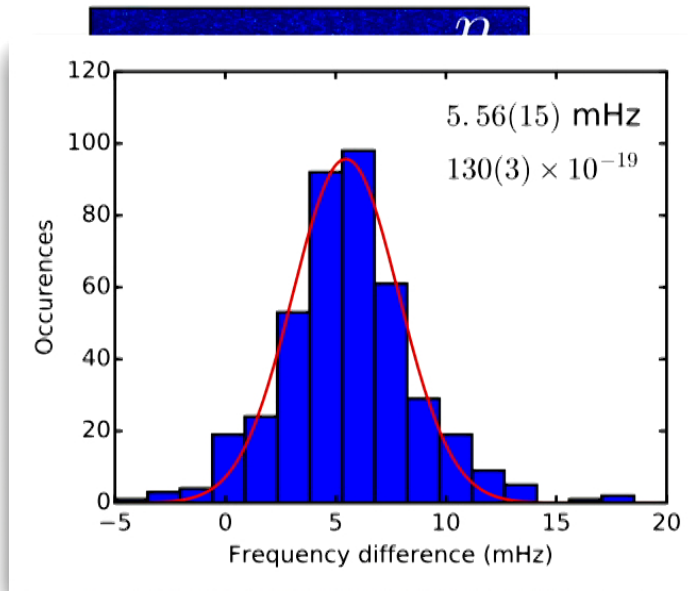
# Atom-atom coherence



# Atom-atom coherence



# Atom-atom coherence



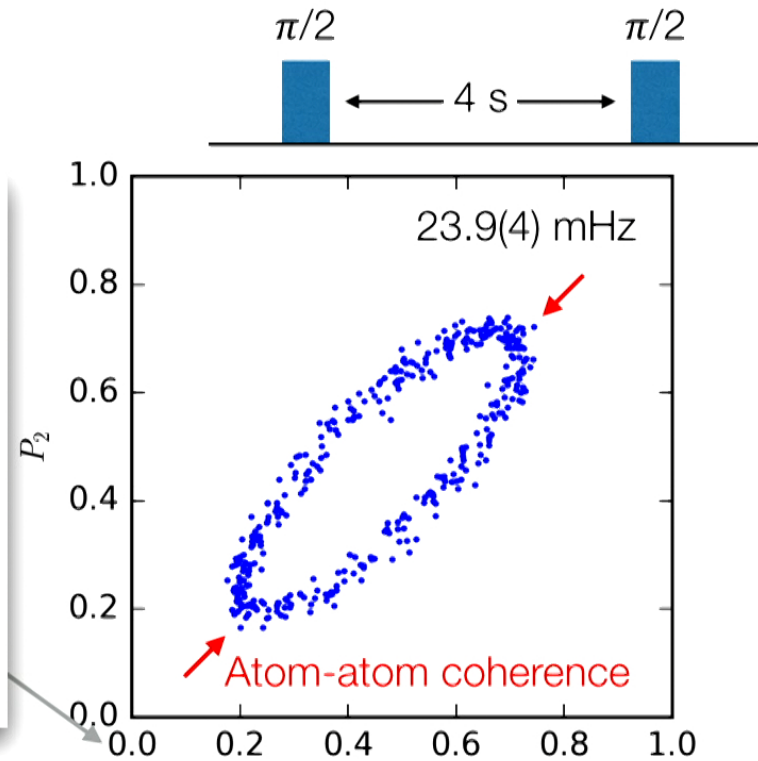
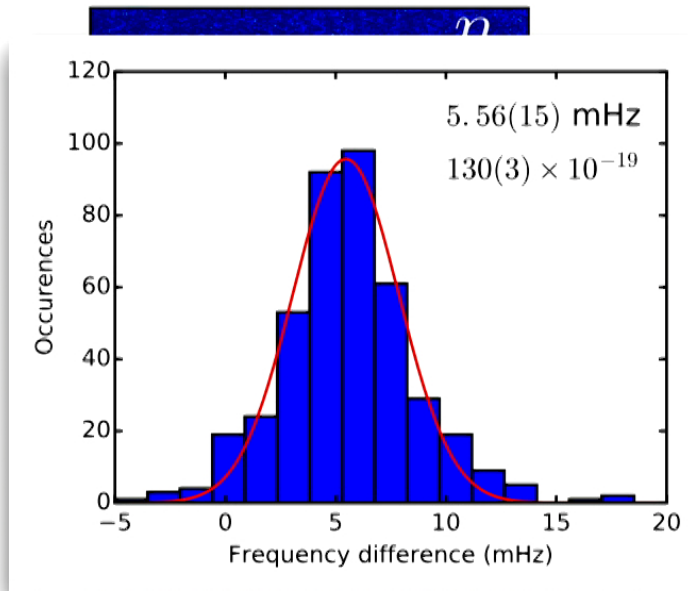
y ( $\mu\text{m}$ )

- ▶ Atom-shot-noise limit of 6000 atoms for 6 seconds

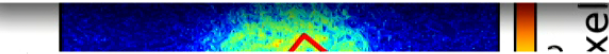
x ( $\mu\text{m}$ )



# Atom-atom coherence



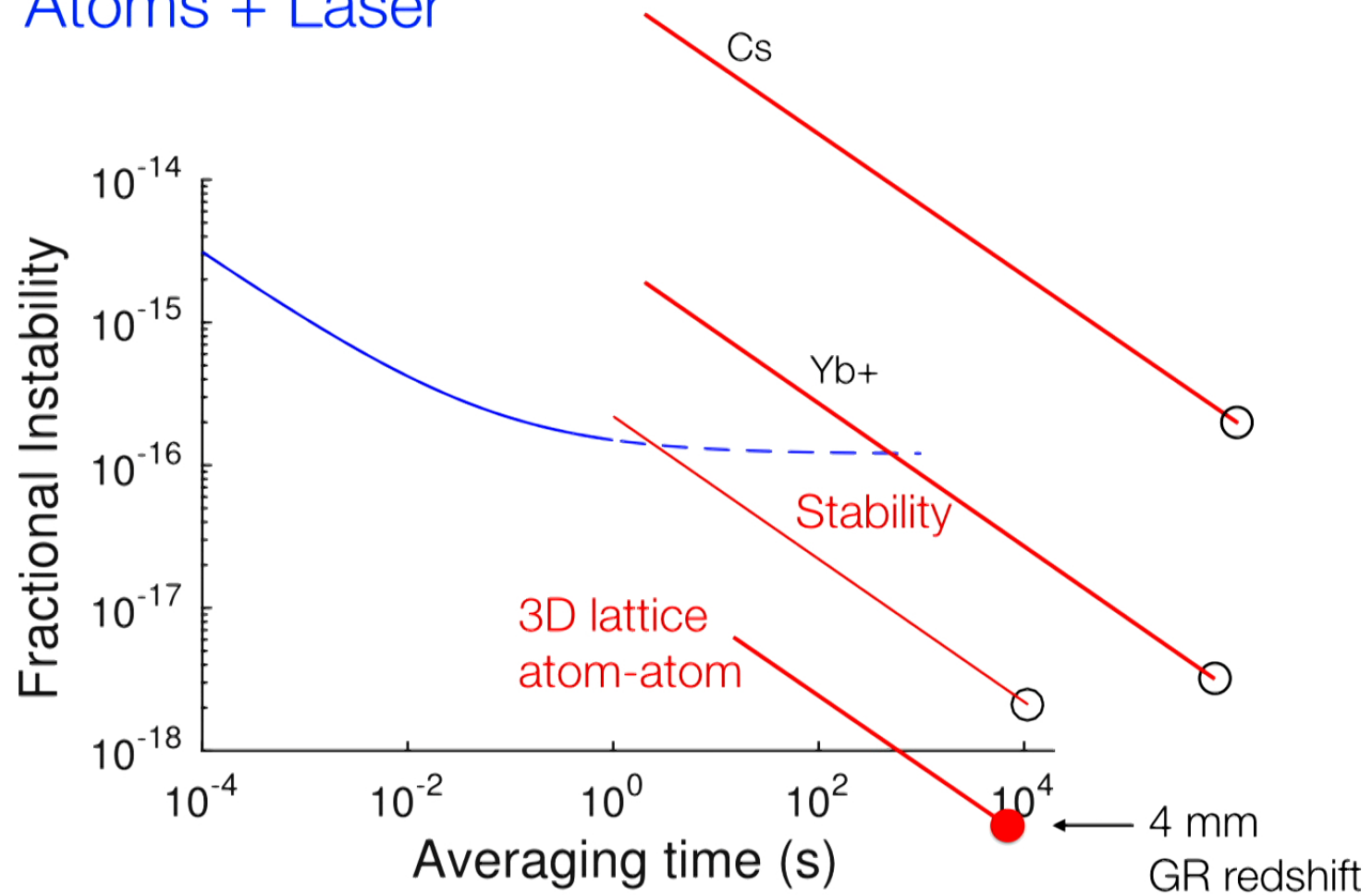
y ( $\mu\text{m}$ )



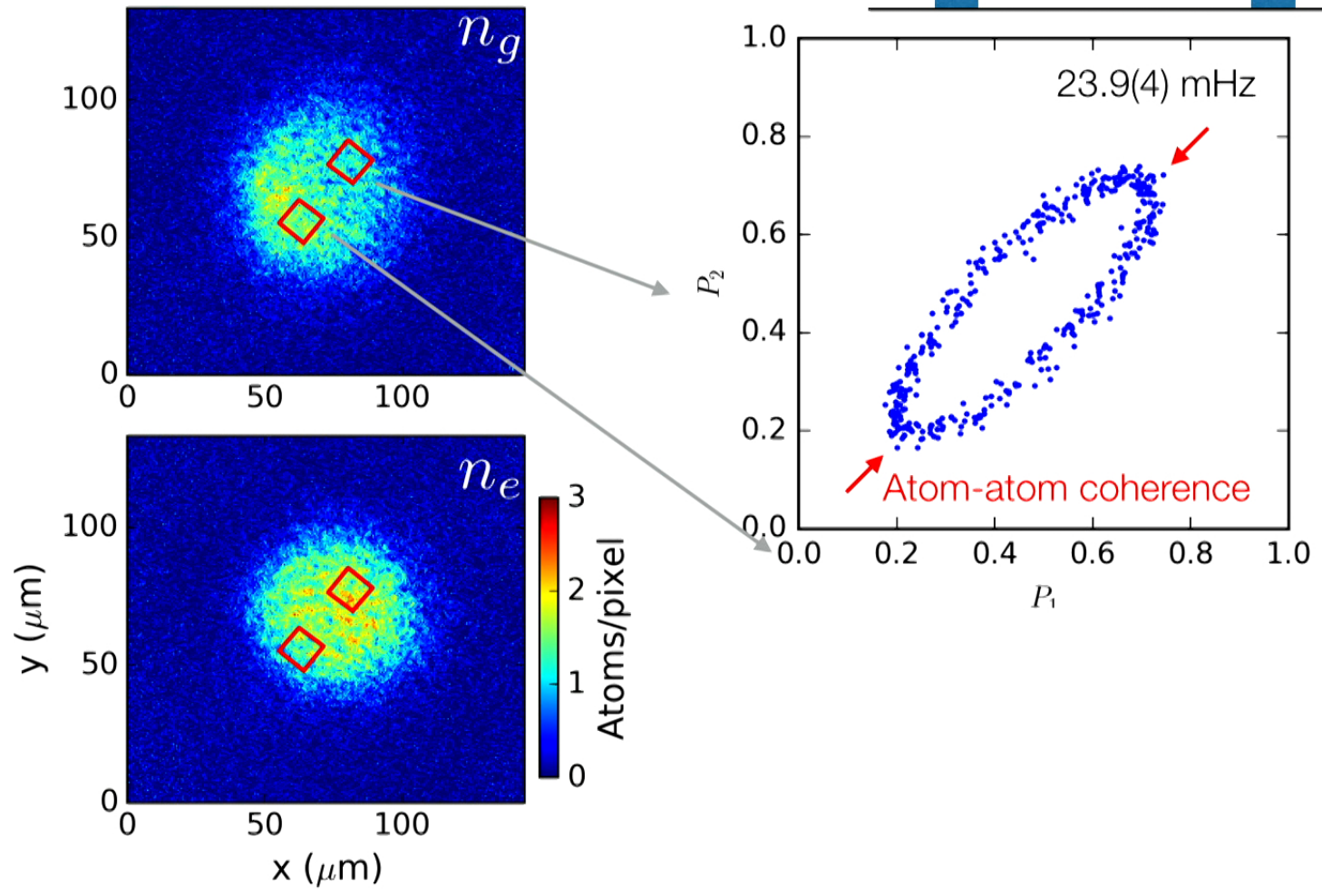
- ▶ Atom-shot-noise limit of 6000 atoms for 6 seconds
- ▶  $1 \times 10^{-18}$  in 15 minutes ( $3 \times 10^{-19}$  in 3 hours)
- ▶ Testing limit of conventional (Lamb-Dicke) approach

x ( $\mu\text{m}$ )

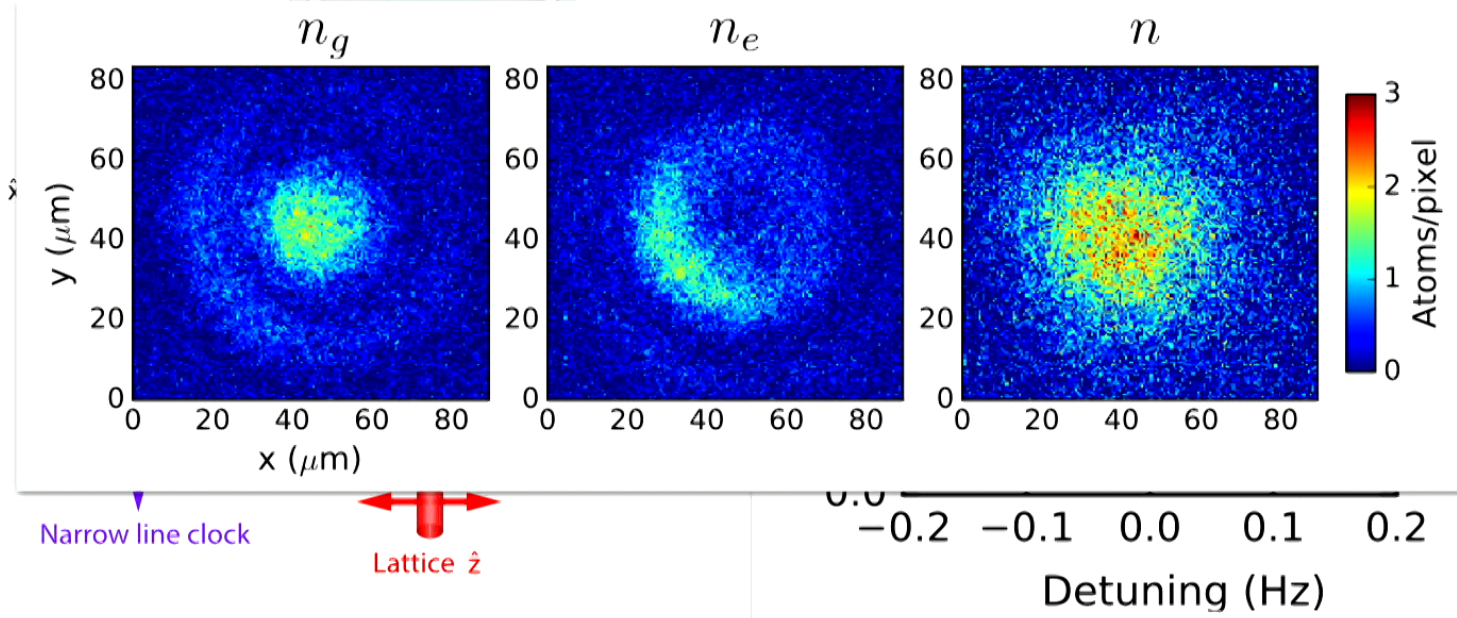
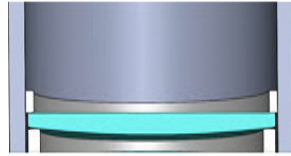
# Atoms + Laser



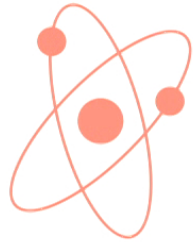
# Atom-atom coherence



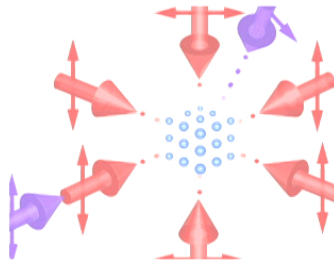
# Fermi-degenerate 3D optical lattice clock



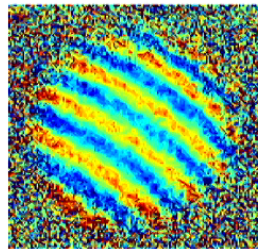
# Outline



**Optical lattice clocks**

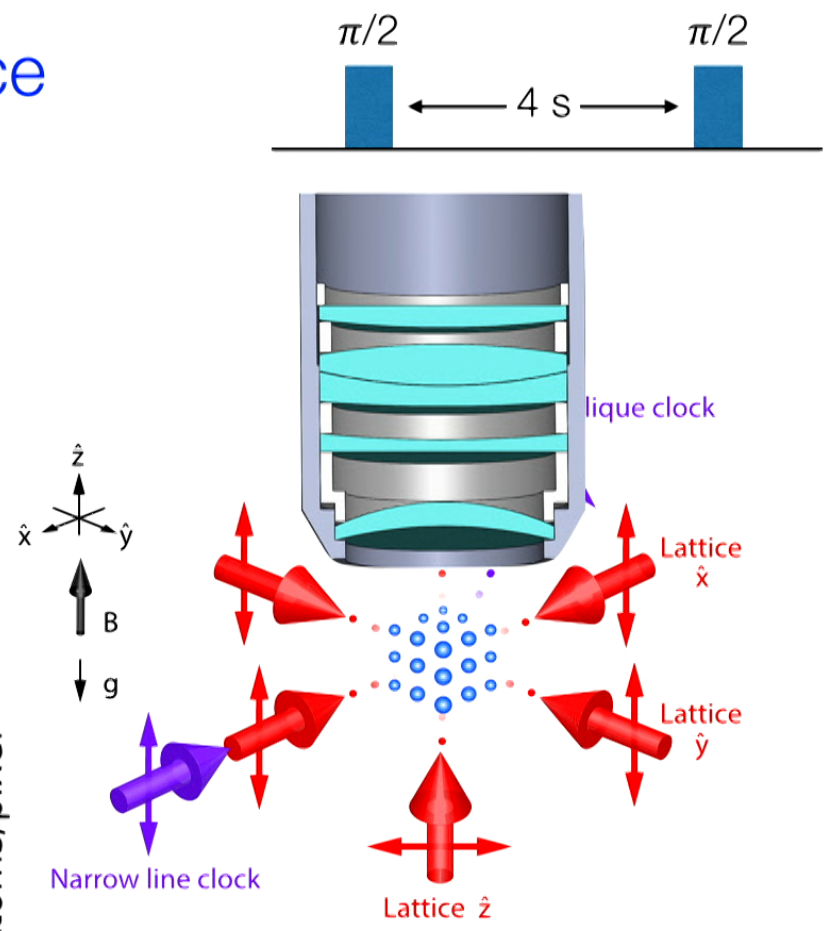
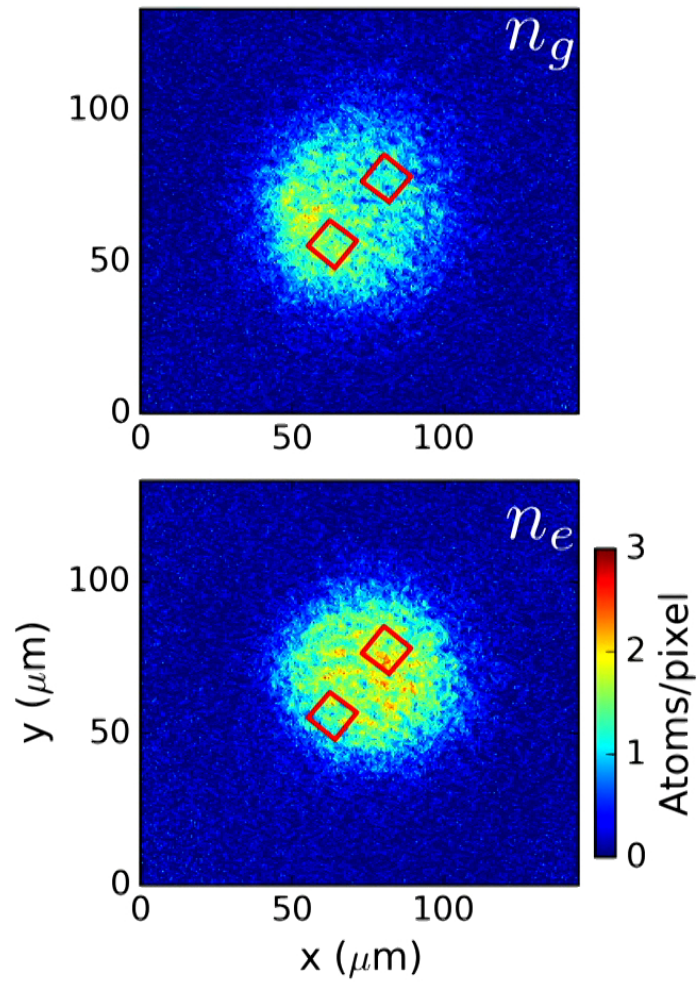


**3D lattice clock**  
Record Q-factor



**Atom-atom coherence**  
Record synchronous stability

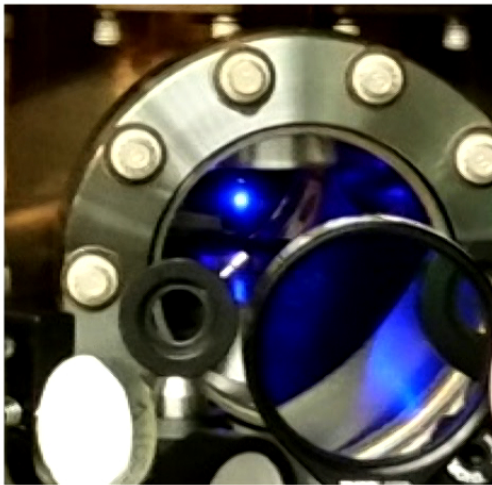
# Atom-atom coherence



## What's next?

### ***Next-generation clocks***

- ▶ Eliminate BBR shift (cryogenics)
- ▶ Improve all other inaccuracies
- ▶ Better lasers and stability



## What's next?

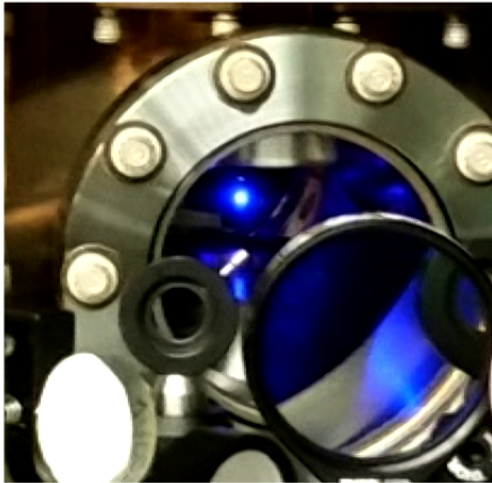
### ***Next-generation clocks***

- ▶ Eliminate BBR shift (cryogenics)
- ▶ Improve all other inaccuracies
- ▶ Better lasers and stability

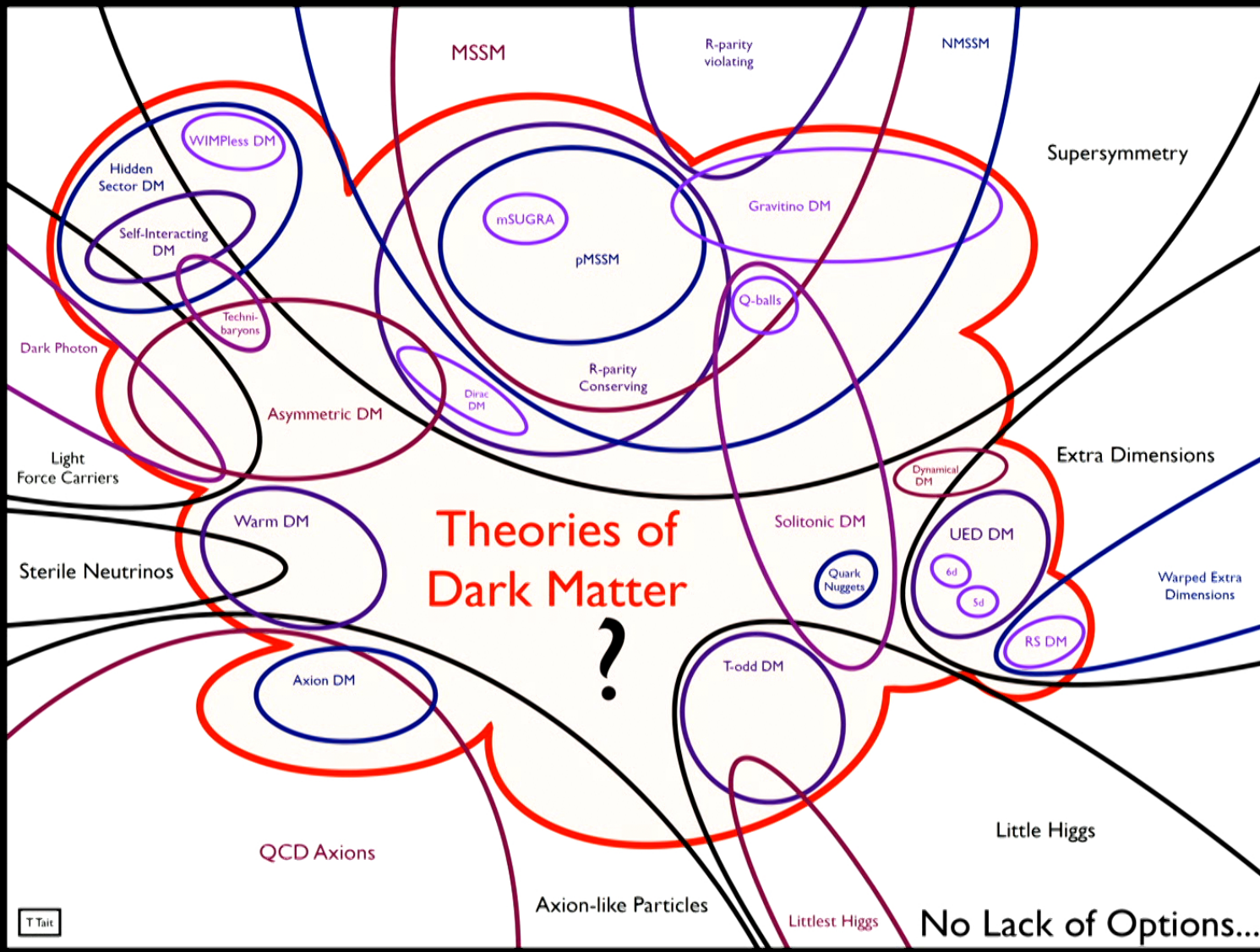


### ***Many-body physics***

- ▶ Long-range dipole-dipole coupling
- ▶ Quantum gas tools to reduce uncertainty
- ▶ Subradiant states







“Two birds with one stone” approach

## “Two birds with one stone” approach

- ▶ **Unrelated physics problem**

Why are some forces so much weaker than others?

- ▶ **Solution to unrelated question**

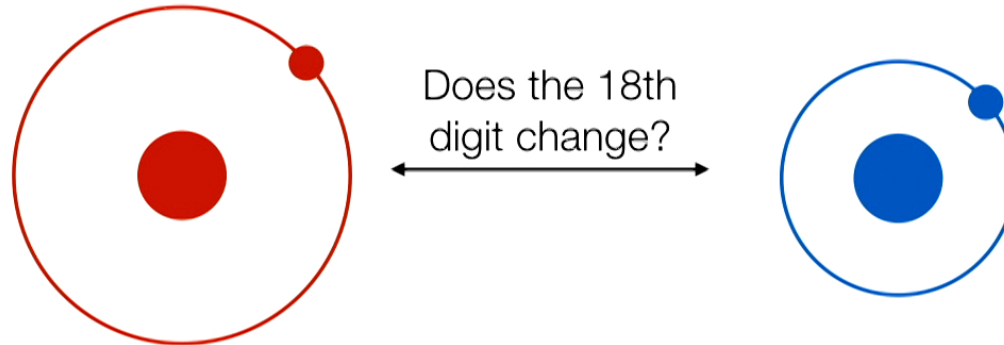
Maybe “fundamental constants” are not constant

In new theories, they are set by new fields

- “1 atm”: average property of gas in this room

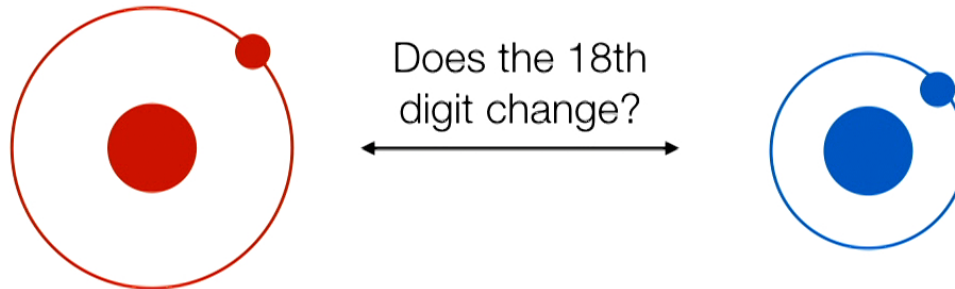
# “Two birds with one stone” approach

- ▶ **Unrelated physics problem**  
Why are some forces so much weaker than others?
- ▶ **Solution to unrelated question**  
Maybe “fundamental constants” are not constant  
In new theories, they are set by new fields
  - “1 atm”: average property of gas in this room
- ▶ **See if solution predicts dark matter, too**  
These fields generate light particles that could be dark matter
- ▶ **Now our dark matter has extra properties to search for**  
Detect “fundamental constants” changing



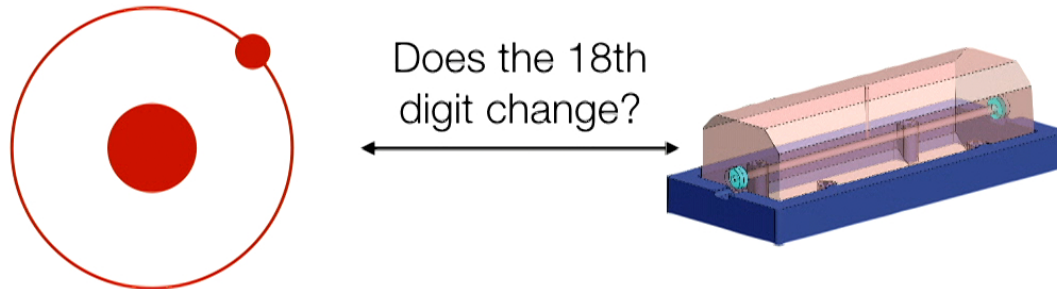
# Dark matter search

- ▶ Fine-structure constant ( $\alpha$ ):  $1/137.035\ 999\ 084(51)$



# Dark matter search

- ▶ Fine-structure constant ( $\alpha$ ):  $1/137.035\ 999\ 084(51)$
- ▶ Clock comparisons: no change in 17th digit/year



Godun, *et al.*, PRL **113**, 210801 (2014)  
Huntemann, *et al.*, PRL **113**, 210802 (2014)

# Dark matter search

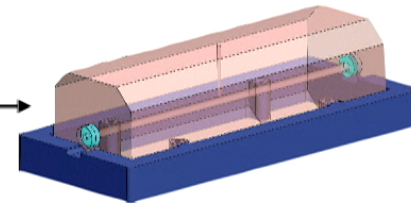
- ▶ Fine-structure constant ( $\alpha$ ): 1/137.035 999 084(51)
- ▶ Clock comparisons: no change in 17th digit/year

$$\frac{1}{2}\alpha^2 m_e c^2$$

$$\hbar \frac{nc}{Na_0} \propto \alpha m_e c^2$$

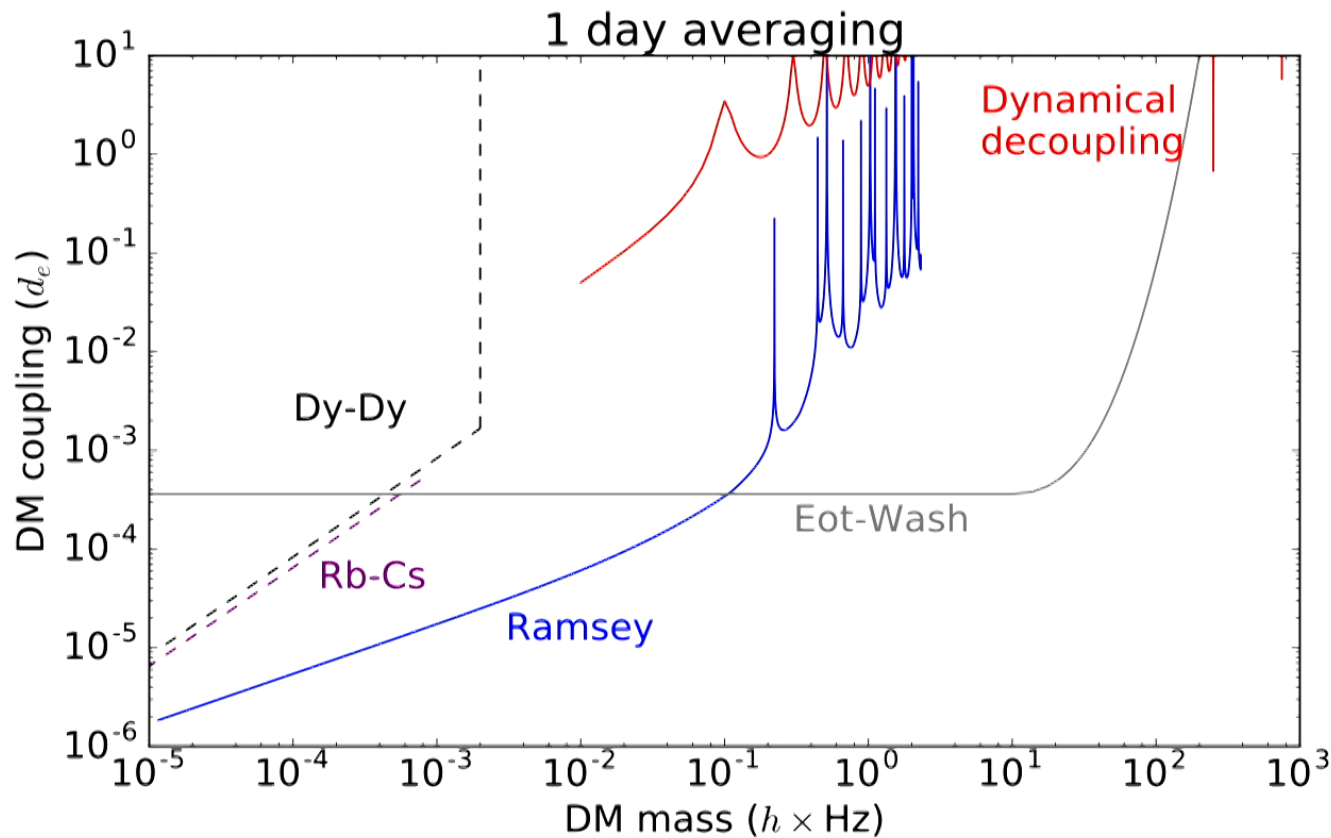


Does the 18th  
digit change?



Godun, *et al.*, PRL **113**, 210801 (2014)  
Huntemann, *et al.*, PRL **113**, 210802 (2014)

# Dark matter search: *proposed* exclusion area

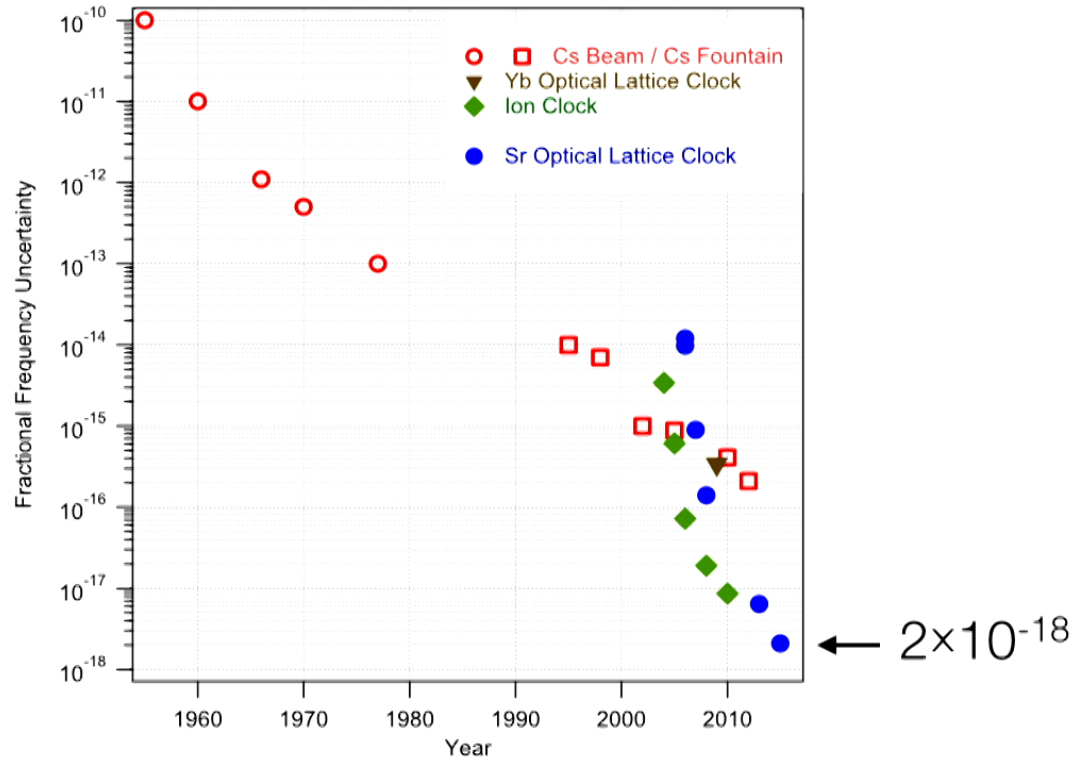


Arvanitaki, *et al.*, PR D **91**, 015015 (2015)  
Van Tilburg, *et al.*, PRL **115**, 011802 (2015)



# Conclusion

*What does the 19th digit, and beyond, tell us about new physics?*



# The End

Jun Ye

Sara Campbell

Ross Hutson

Aki Goban

Will Milner

Nelson Darkwah-Oppong

Rees McNally

Travis Nicholson