# Trapped ion quantum computing, simulation, and sensing

John Bollinger, NIST, Boulder CO

Monday, July 2, 11:00 AM – Trapped ion quantum computing

Tuesday, July 3, 11:00 AM – Trapped ion quantum simulation

Thursday, July 5, 9:00 AM – Trapped ion quantum sensing

# Trapped ion quantum computing, simulation, and sensing

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## Thursday, July 5, 9:00 AM – Trapped ion quantum sensing

## $Al^+$ quantum logic clock (Quantum measurement, Ancilla-assisted readout)

- T. Rosenband, et al., "Frequency ratio of Al+ and Hg+ single-ion optical clocks; Metrology at the 17th decimal place," Science 319, 1808 - 1812 (2008).
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## Weak force sensing (Amplitude sensing below the zero point fluctuations)

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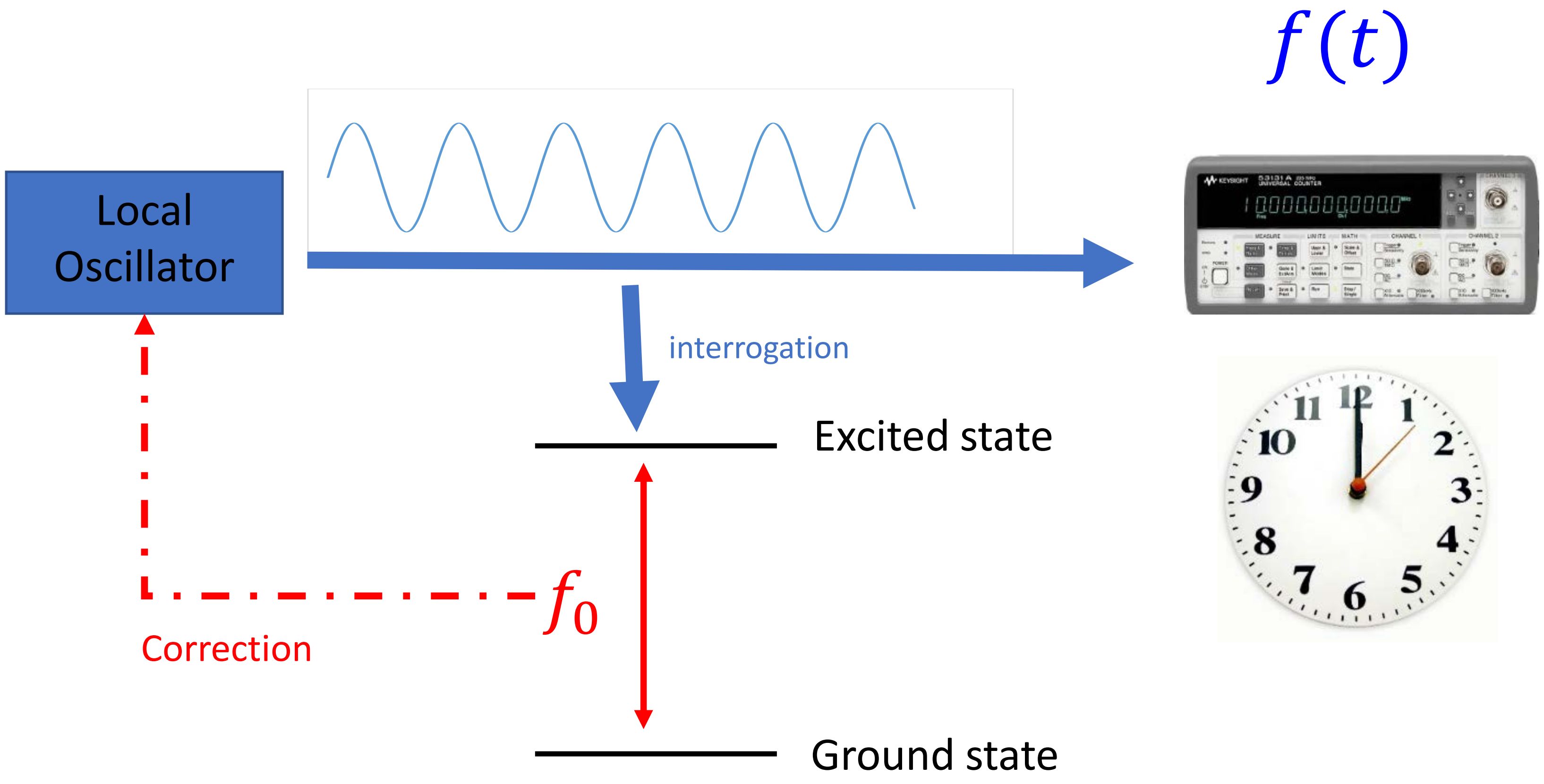
# Atomic Clock Operation Principle (Passive)




"Microwave clocks" based on Cs, Rb, etc.
"Optical clocks" based on $Al^+$, $Hg^+$, Yb, Sr, etc.

Thank you to
Sam Brewer, NIST
for slides

# Atomic Clock Performance

$$\frac{f(t)}{f_0} = 1 + \epsilon + y(t)$$

## Accuracy

- Systematic uncertainty in clock frequency.
- Two types of shifts
  1. **Field shifts** e.g. Zeeman shift and black body shift
  2. **Motional shifts** e.g. Relativistic Doppler

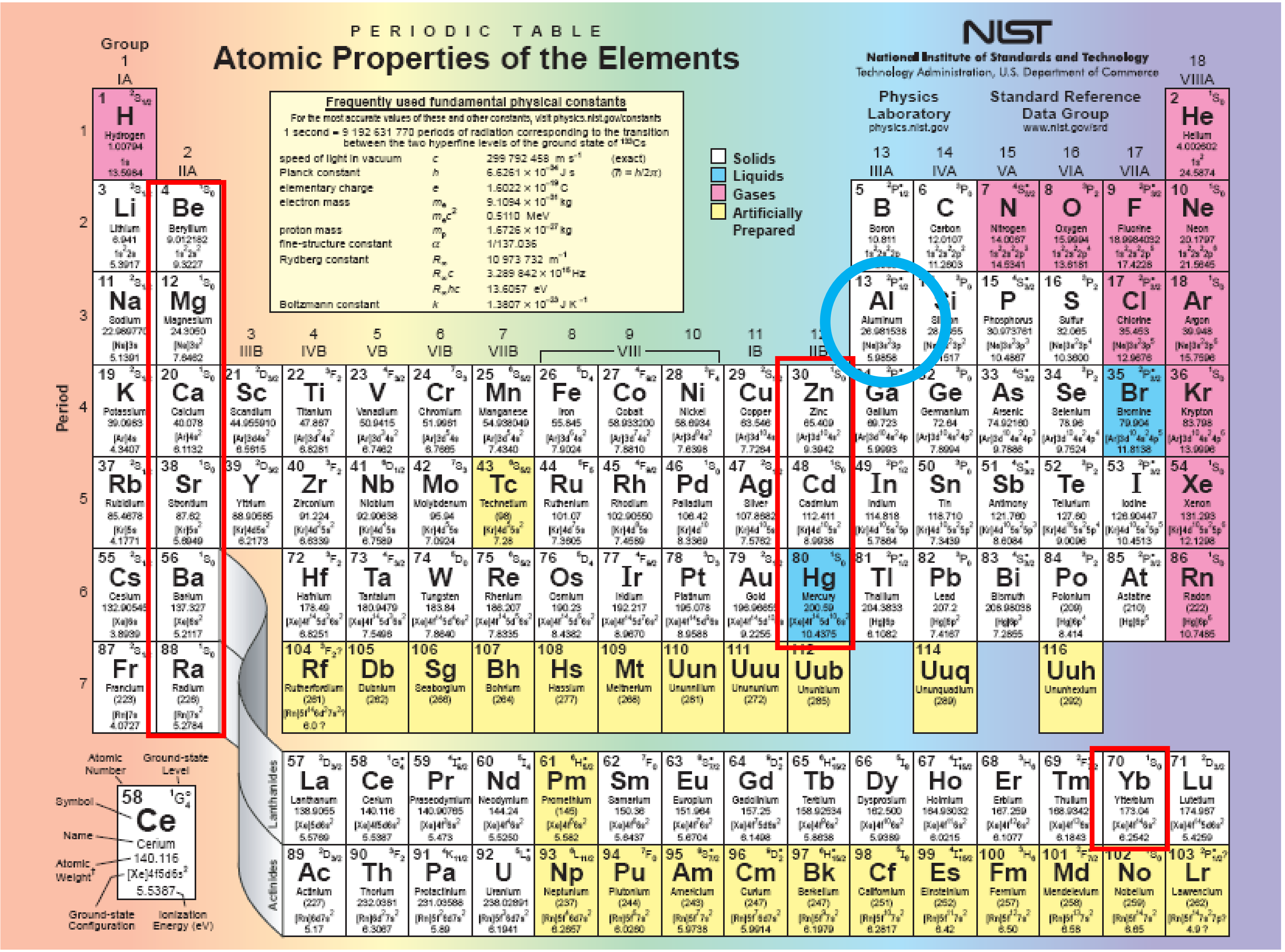
$$\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} + \cdots$$

## Stability

- Average fractional frequency variations
- Typically characterized by the *Allan deviation*:

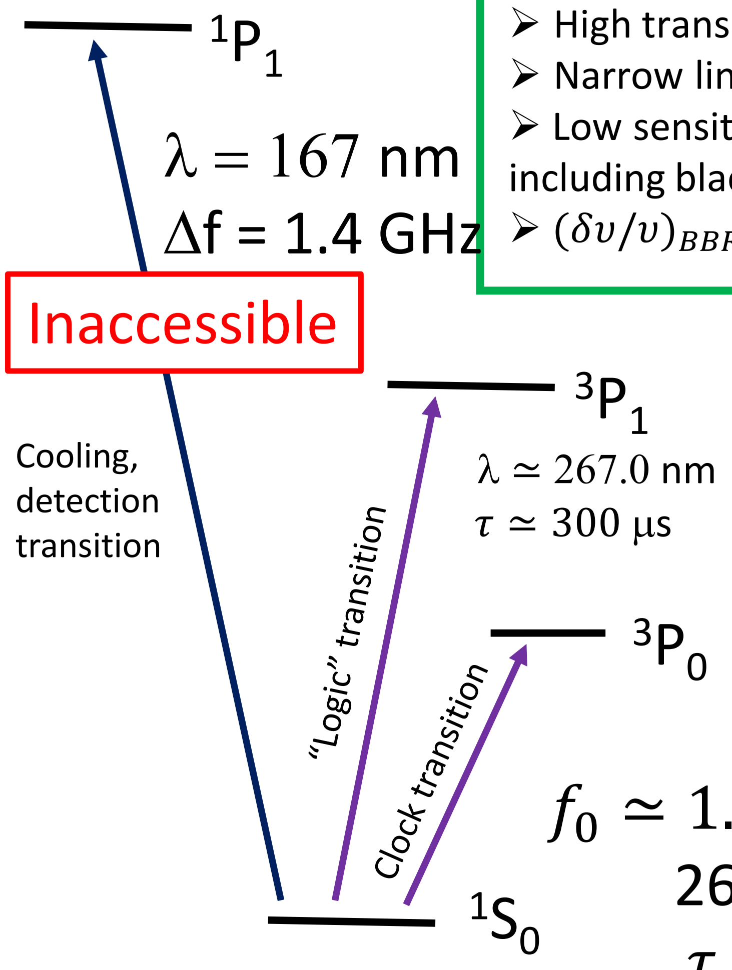
$$\sigma_y(\tau) \cong \frac{1}{Q} \frac{1}{SNR} \sqrt{\frac{T_C}{\tau}}$$

# Motivation: Why use $^{27}Al^+$?




**$Al^+$ has two electrons outside a closed shell**

# Motivation: Why use $^{27}Al^{+}$?




$f_0 \simeq 1.12$ PHz ($\lambda \simeq$ 267.4 nm)

$\tau \simeq 20$ s

**Advantages:**

- High transition frequency
- Narrow linewidth
- Low sensitivity to external fields, including blackbody radiation (BBR).
- $(\delta\upsilon/\upsilon)_{BBR}$ = (-3.0 ± 0.5) x $10^{-18}$ [1]

**Challenges:**

- Inaccessible cooling/detection transition
- Low mass leads to time-dilation shift

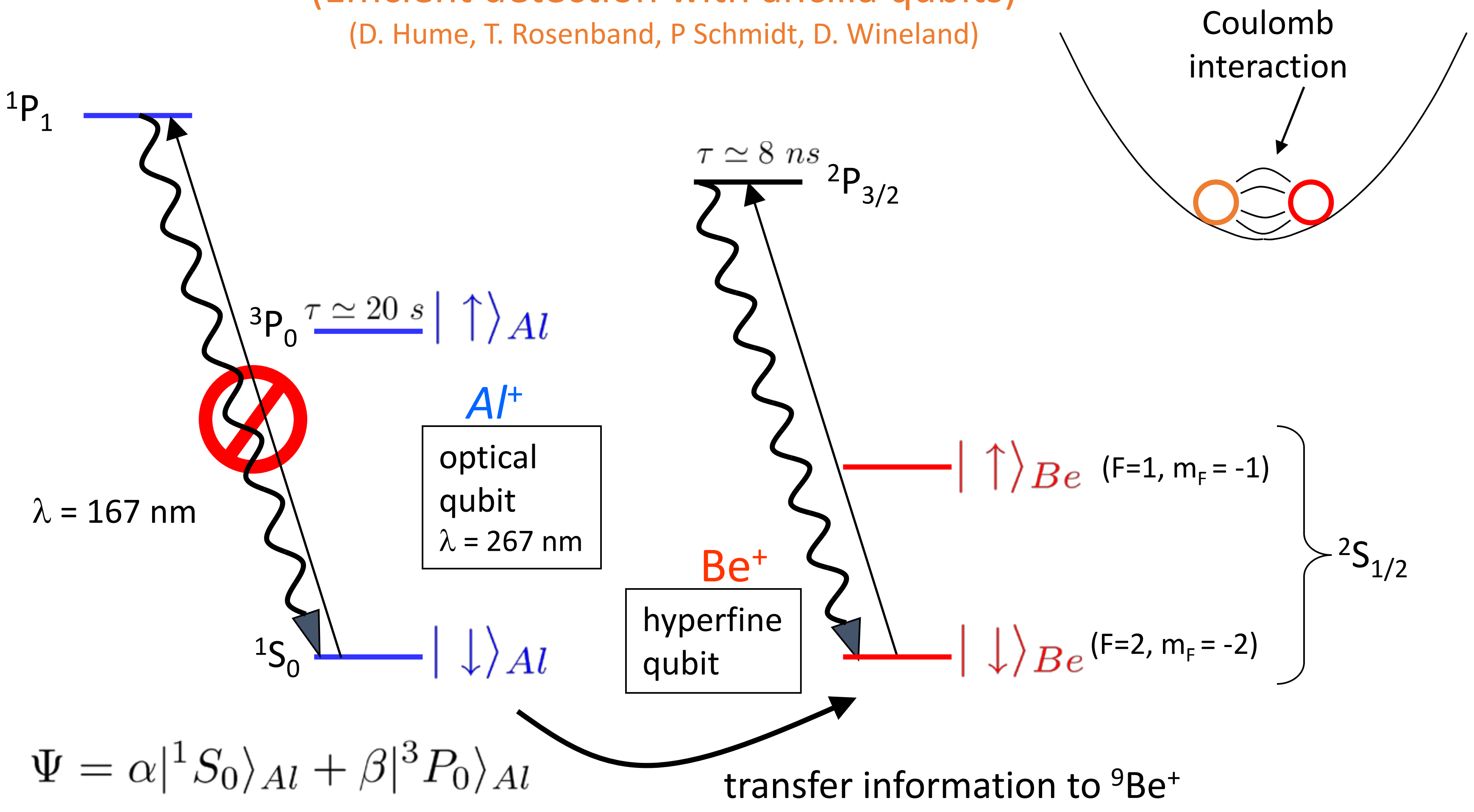
- Read-out
  - Quantum logic spectroscopy [2]
- Cooling
  - Sympathetic cooling [3]


[1] Chou, *et. al.*, private communication
[2] Schmidt, *et. al.*, Science **309**, 749 (2005)
[3] Barrett, *et. al.*, PRA **68**, 042302 (2003)

# Quantum Logic Spectroscopy - Overview

(Efficient detection with ancilla qubits)

(D. Hume, T. Rosenband, P Schmidt, D. Wineland)



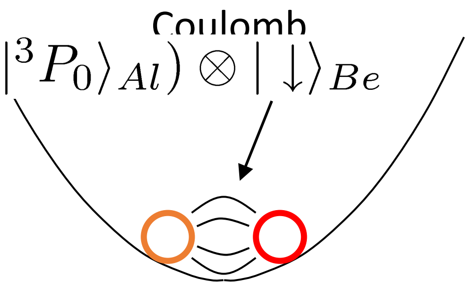
# Quantum Logic Spectroscopy - Details

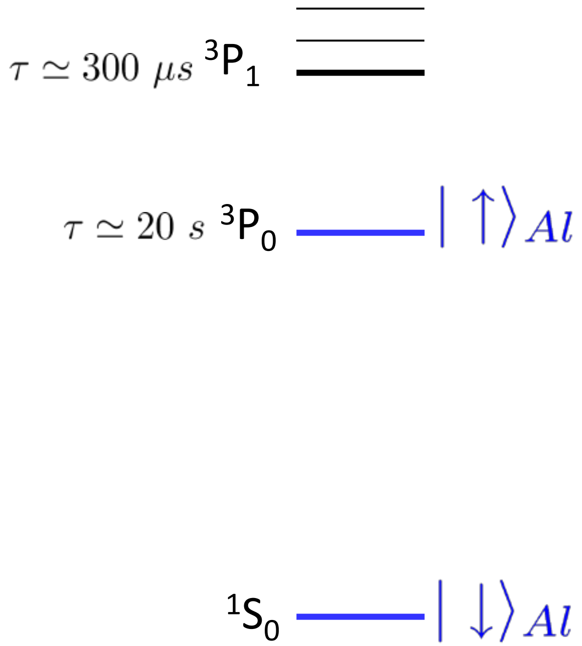
(Efficient detection with ancilla qubits)

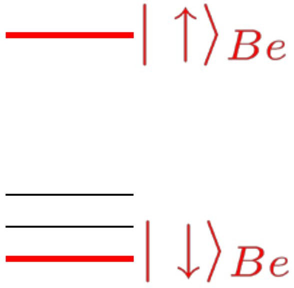
(D. Hume, T. Rosenband, P Schmidt, D. Wineland)

**Task**: determine if $^{27}Al^{+}$ qubit is in $|\downarrow\rangle$ ($^1S_0$) state

$$\Psi(0) = (\alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}) \otimes |\downarrow\rangle_{Be}$$



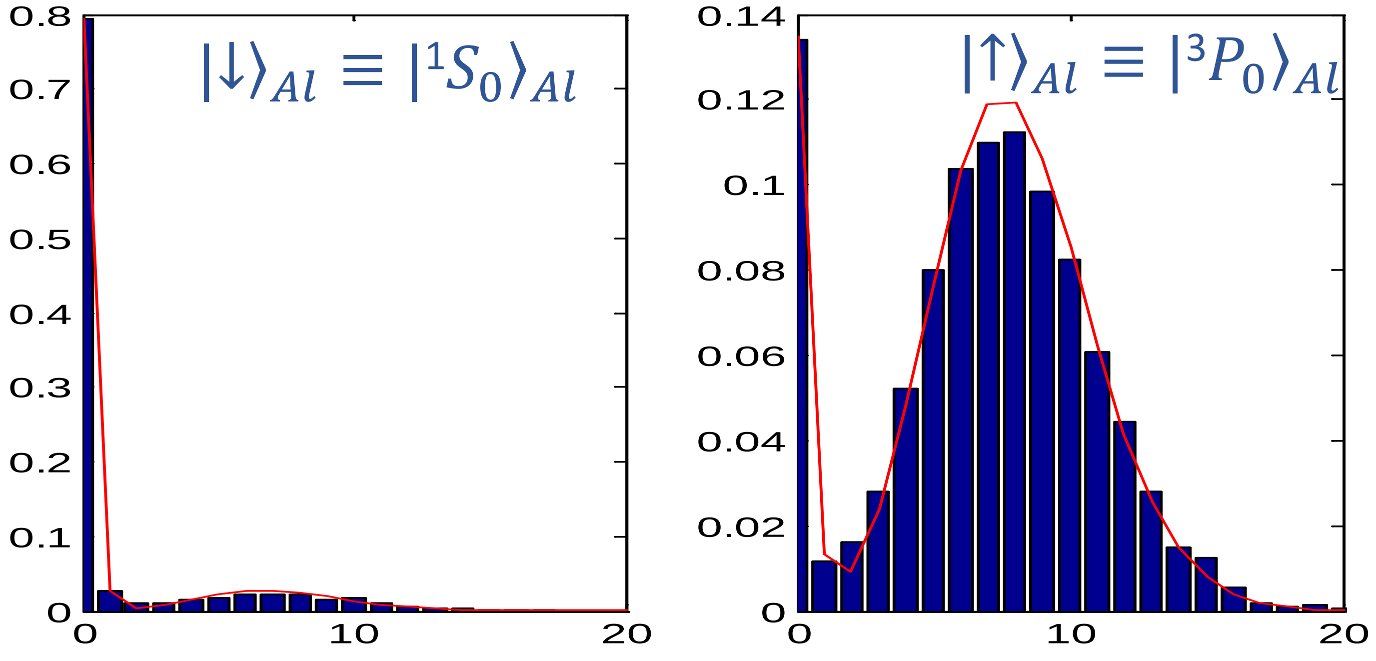



# Quantum Logic Spectroscopy - Details

**Task**: determine if $\Psi(0) = (\alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}) \otimes |\downarrow\rangle_{Be}$

Be⁺ photon count histograms

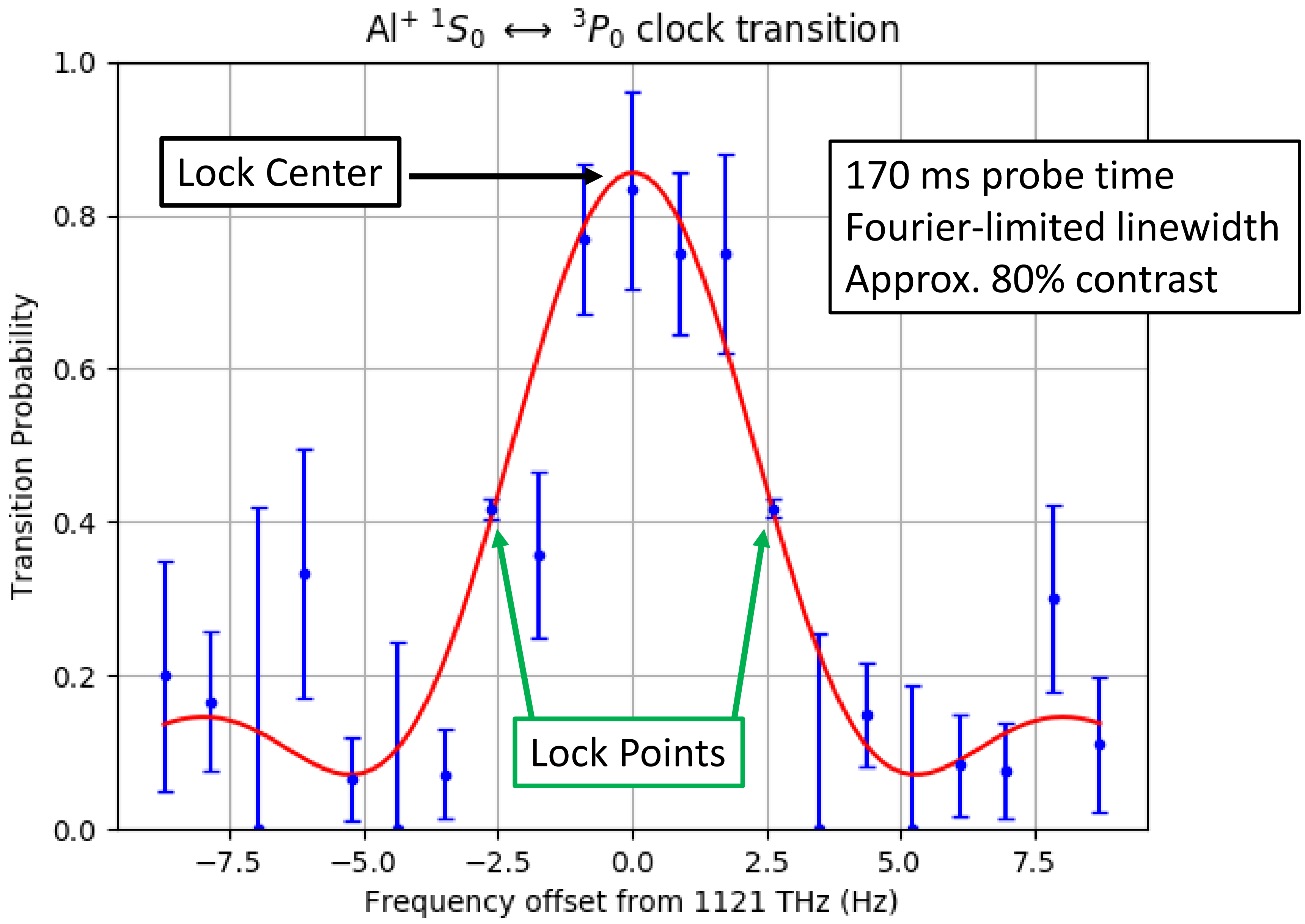



no. of photons →

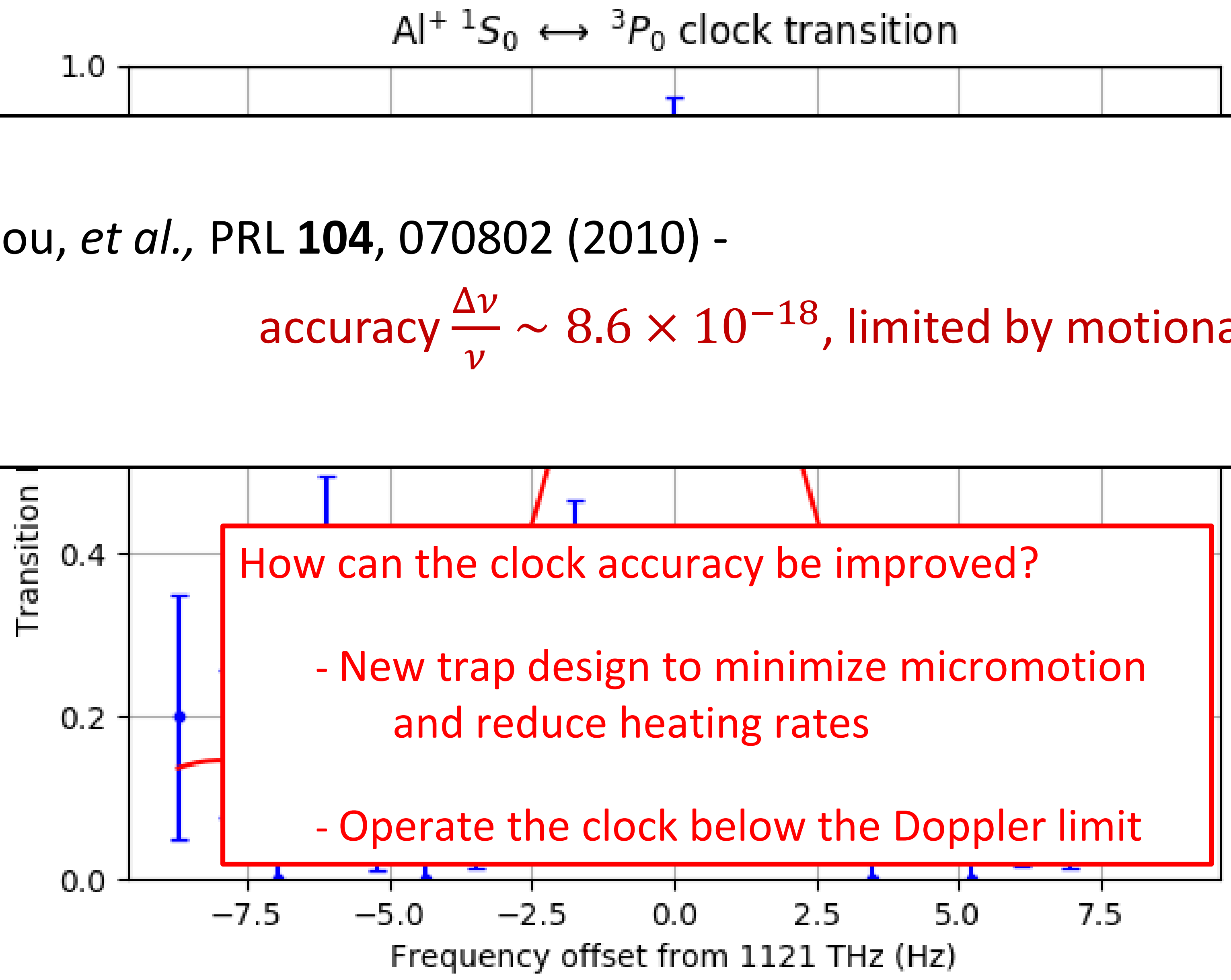
For one detection cycle, error ≅ 15%

3. Be⁺ $|\downarrow\rangle \rightarrow |\uparrow\rangle$ red sideband (RSB) pulse (7 us)  $\Psi = \alpha|^3P_1\rangle_{Al}|\uparrow\rangle_{Be} + \beta|^3P_0\rangle_{Al}|\downarrow\rangle_{Be}$
4. Be⁺ detection (200 us), record photon counts
5. $Al^+$ $^3P_1$ spontaneous decay (300 μs)

# Al⁺ quantum-logic spectroscopy



# $Al^+$ quantum-logic spectroscopy




Chou, *et al.*, PRL **104**, 070802 (2010) -

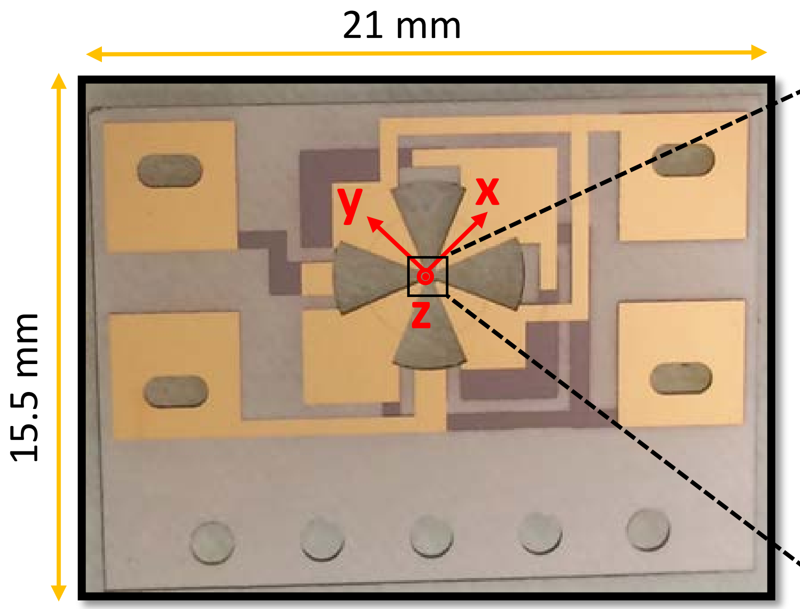
accuracy $\frac{\Delta\nu}{\nu} \sim 8.6 \times 10^{-18}$, limited by motional shifts

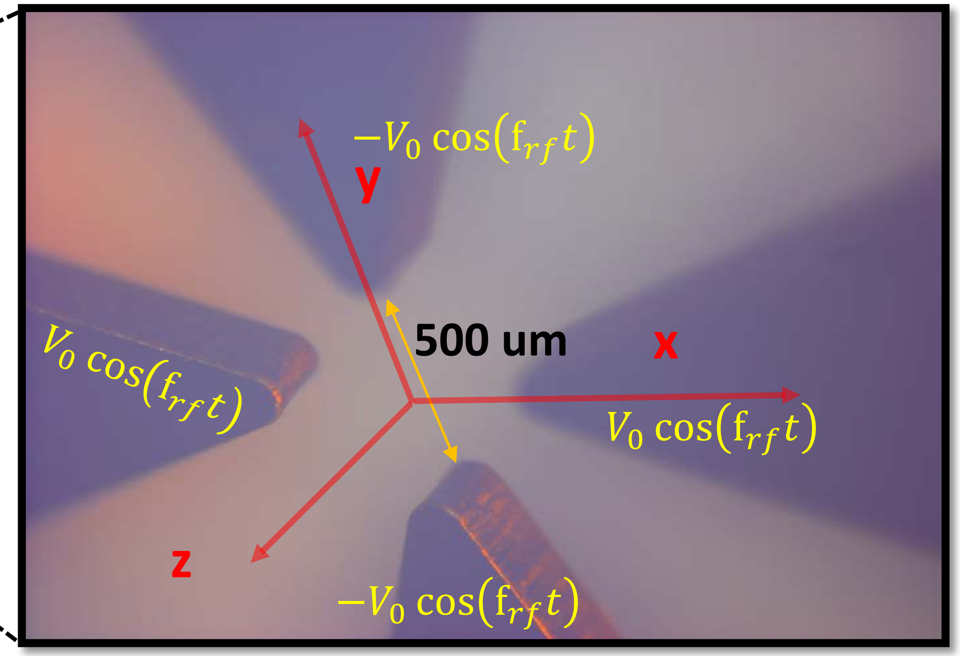
How can the clock accuracy be improved?

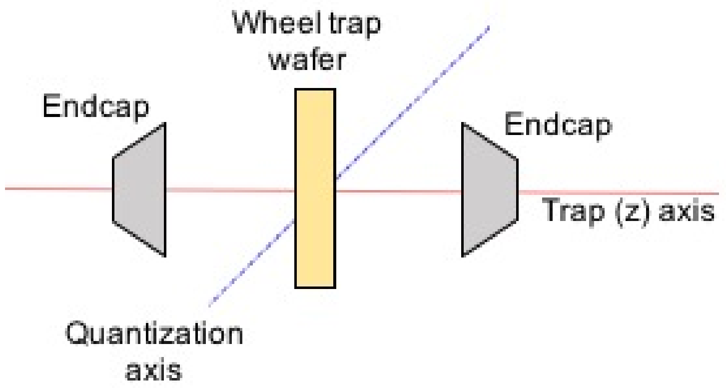
- New trap design to minimize micromotion and reduce heating rates
- Operate the clock below the Doppler limit

# New trap design

- ➢Laser-machined diamond wafer (300 μm thick)
- ➢Gold-sputtered electrodes



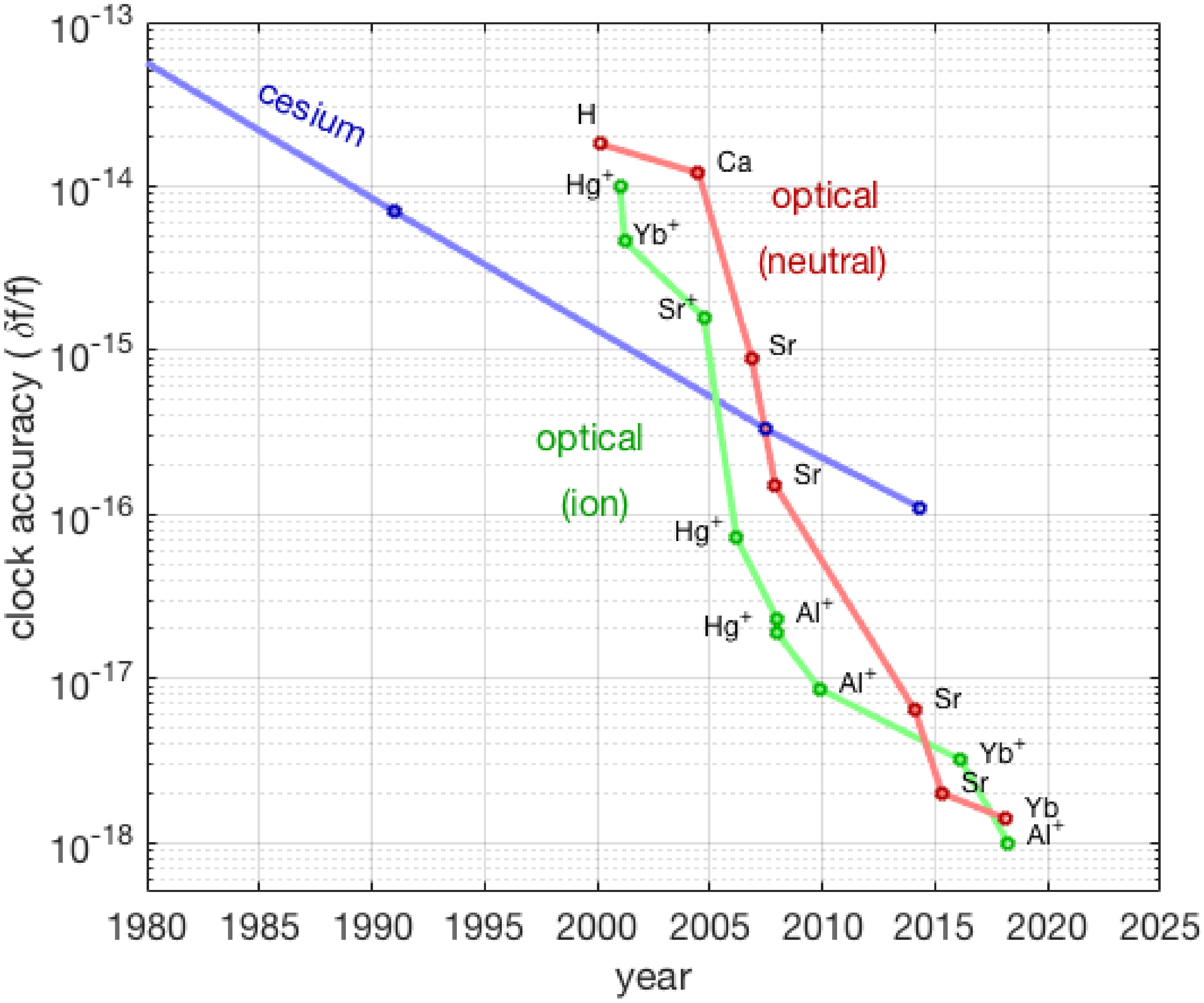

Advantages over previous traps:

- ➢Tighter manufacturing tolerance
- ➢Low emissivity
- ➢High thermal conductivity
- ➢Simpler assembly

# $Al^+$ Clock Uncertainty Budget

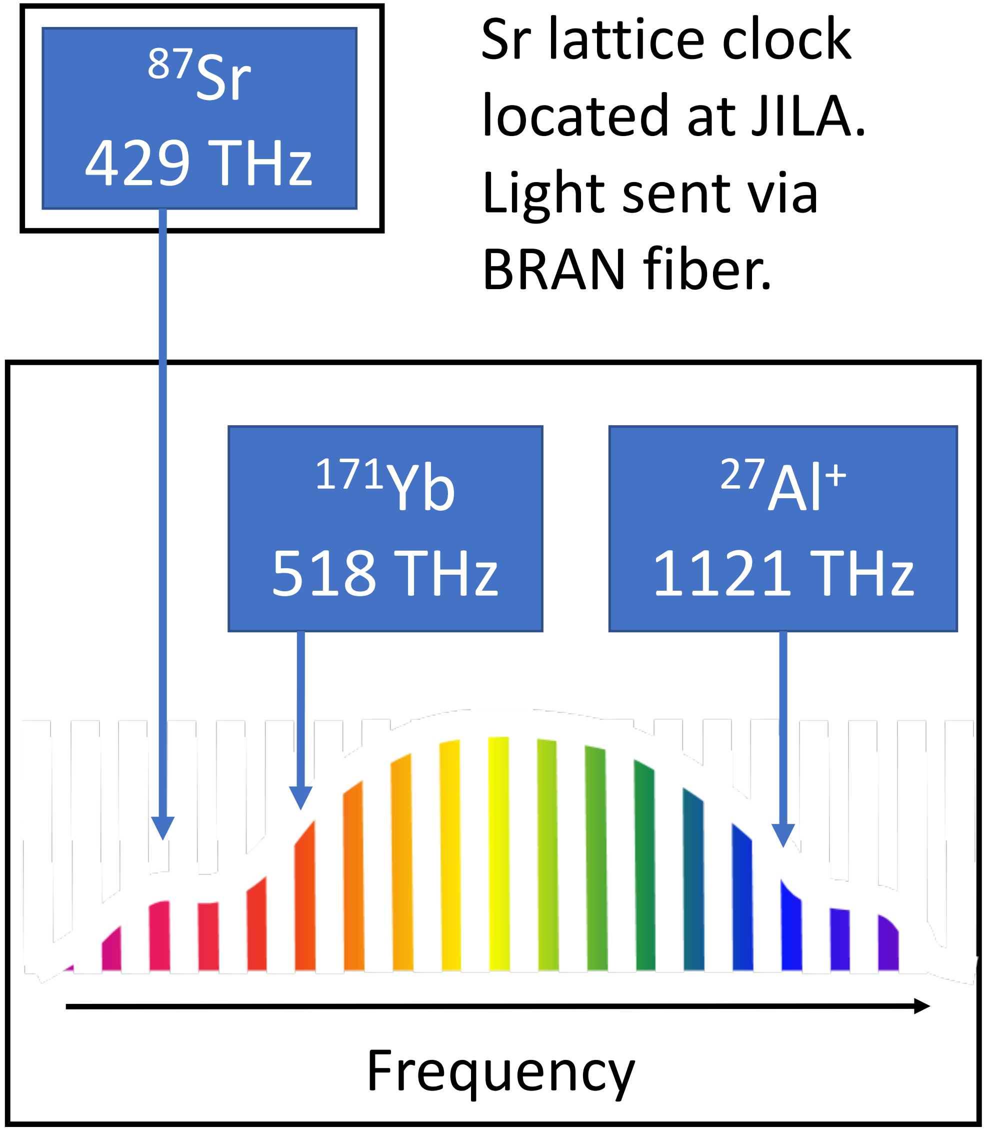
| Sources | Fractional Uncertainty ($10^{-18}$) | | |
|---|---|---|---|
| | Shift | Uncertainty | Previous clock |
| Time-dilation: Excess micromotion | -4.7 | 0.6 | -9.0(6.0) |
| Time-dilation: Secular motion | -1.8 | 0.3 | -16.3(5.0) |
| BBR shift | -2.6 | 0.3 | -9.0(3.0) |
| Cooling light shift | 0.0 | 0.0 | -3.6(1.5) |
| Quadratic Zeeman shift | -925.9 | 0.6 | -1079.9(0.7) |
| Linear Doppler shift | 0.0 | 0.2 | 0.0(0.3) |
| Clock light shift | 0.0 | 0.2 | 0.0(0.2) |
| Background gas collision | 0.0 | 0.3 | 0.0(0.5) |
| AOM phase chirp | 0.0 | < 0.1 | 0.0(0.2) |
| **Total** | **-935.0** | **1.0** | -1117.8(8.6) |

# Historical Accuracy of Atomic Clocks



# Frequency ratio measurements: $Al^+$ vs Yb vs Sr lattice clocks

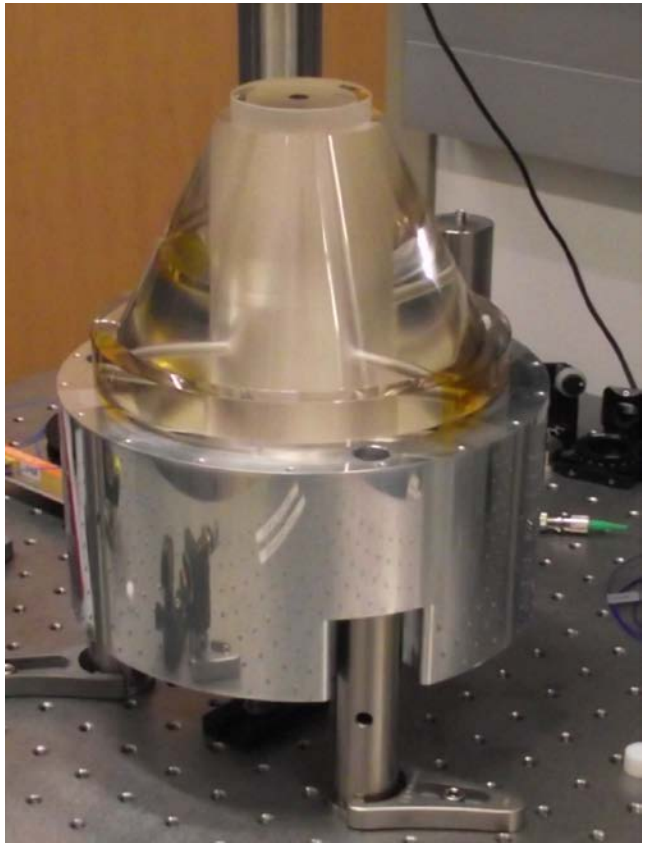
- Goal: Compare optical frequencies of $Al^+$ ion and both the NIST Yb and JILA Sr lattice clocks with a total uncertainty of $10^{-17}$ or better.
- All clocks send atom stabilized light to frequency combs in Bldg. 81.
- Current ratios involving Al+ are limited at the $10^{-16}$ level.
- Potentially interesting for investigating time-variation of the fine-structure constant.




Sr lattice clock located at JILA. Light sent via BRAN fiber.

# What about stability?

Mg⁺ - Al⁺ clock: $\sigma_y(\tau) \sim 1.2 \times 10^{-15} \tau^{-\frac{1}{2}}$



Future improvements:

- cryogenic sapphire cavity → increase probe time by more than order of magnitude

- multiple set-ups ($Ca^+$-$Al^+$), and with multiple ions

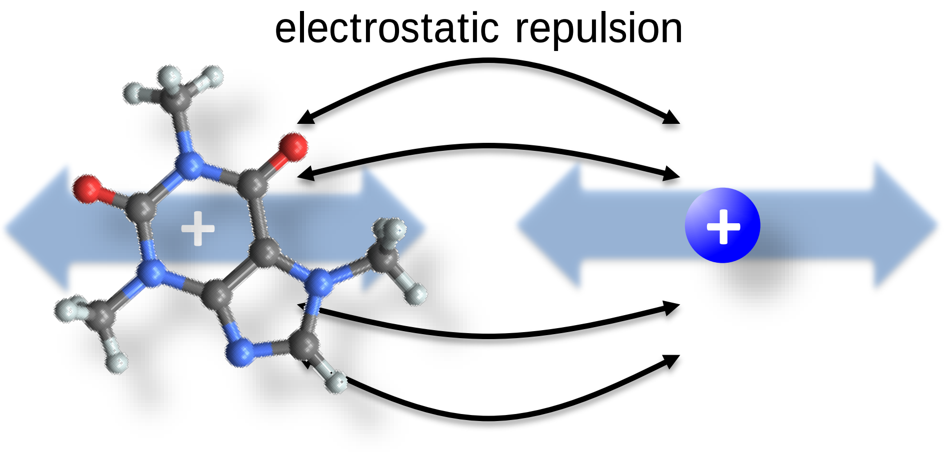
- entangled states

⇒ stabilities near $\sigma_y(\tau) \approx 10^{-16} \tau^{-\frac{1}{2}}$ appear reasonable

# Quantum Control and Precision Spectroscopy of Trapped Molecular Ions

James (Chin-wen) Chou, Dietrich Leibfried, David Leibrandt

**Quantum-logic spectroscopy** enables quantum state control and precision spectroscopy for $CaH^+$, applicable to **many species** of **molecular ions**




**applications: enable key advances in physics, chemistry and medicine**

- molecular fingerprints with unprecedented detail
- benchmarks for molecular models, reaction rate calculations in quantum chemistry and drug discovery
- better tests of dark matter, time variation of fundamental constants and the Standard Model
- controlled chemical reactions

Proposal: D. Leibfried, New J. Phys. 14, 023029 (2012);
Proof-of-principle experiment: C. W. Chou et al., Nature 545, 203 (2017)

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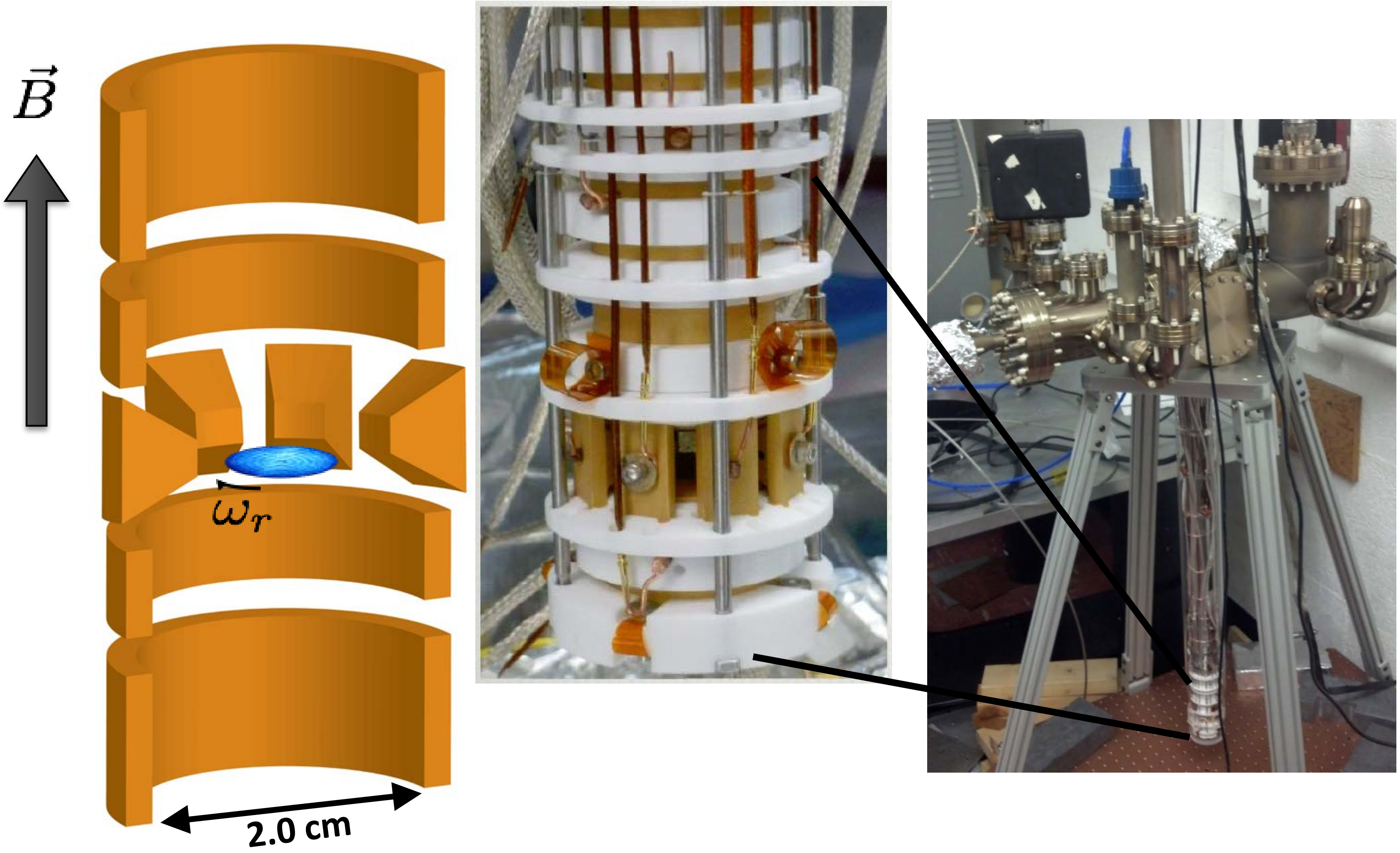
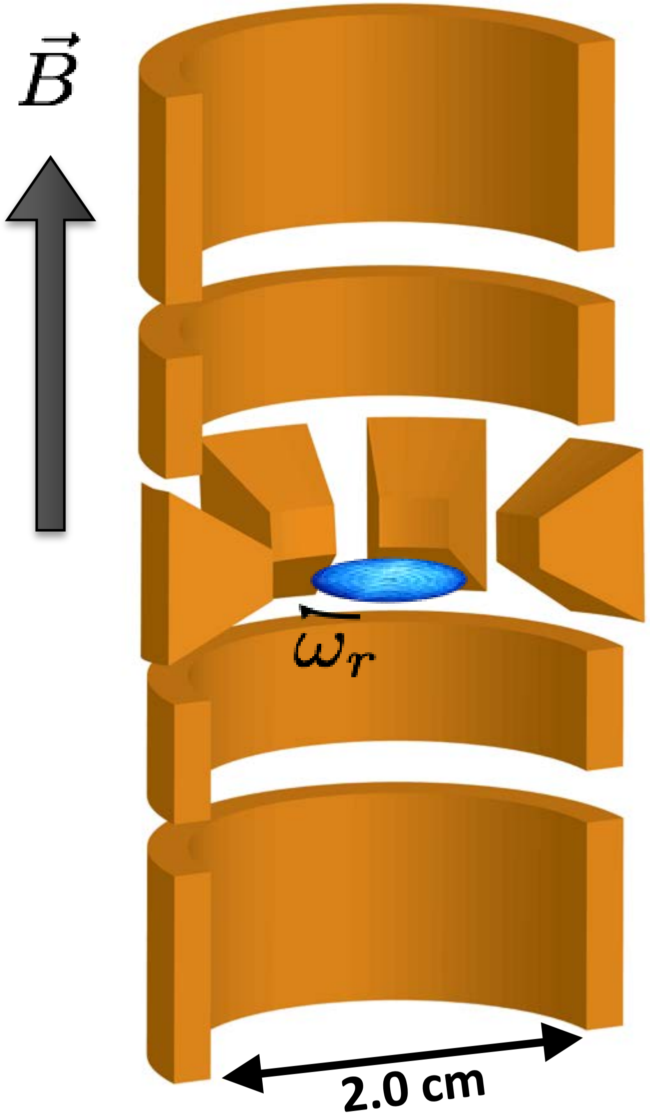
# NIST Penning trap

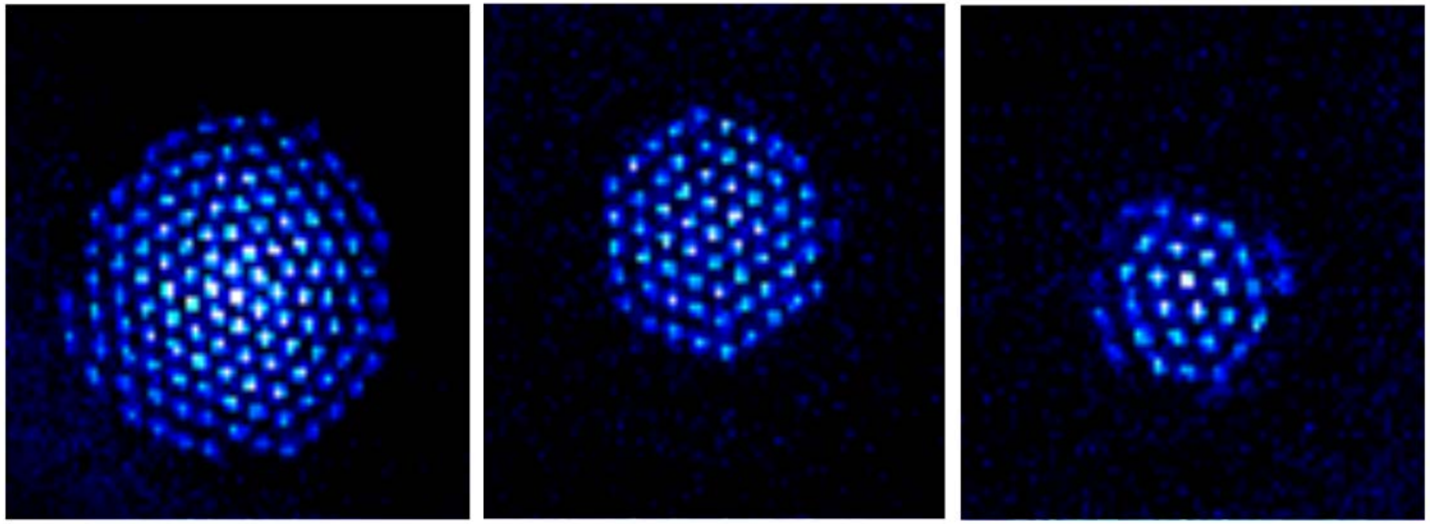



$^9Be^+$, $B_0 = 4.5$ T, $\frac{\Omega_c}{2\pi} \sim 7.6$ MHz, $\frac{\omega_z}{2\pi} \sim 1.6$ MHz, $\frac{\omega_m}{2\pi} \sim 160$ kHz

# NIST Penning trap




## Single-plane ion crystals, 20 < N < 250

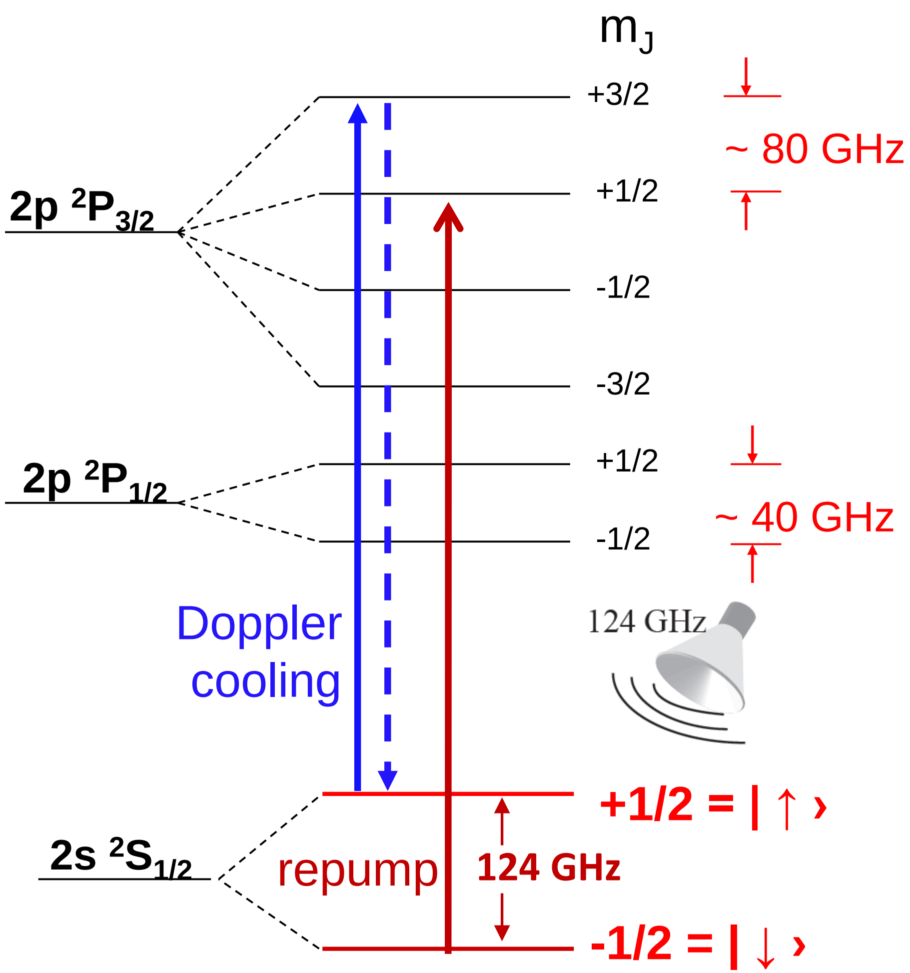


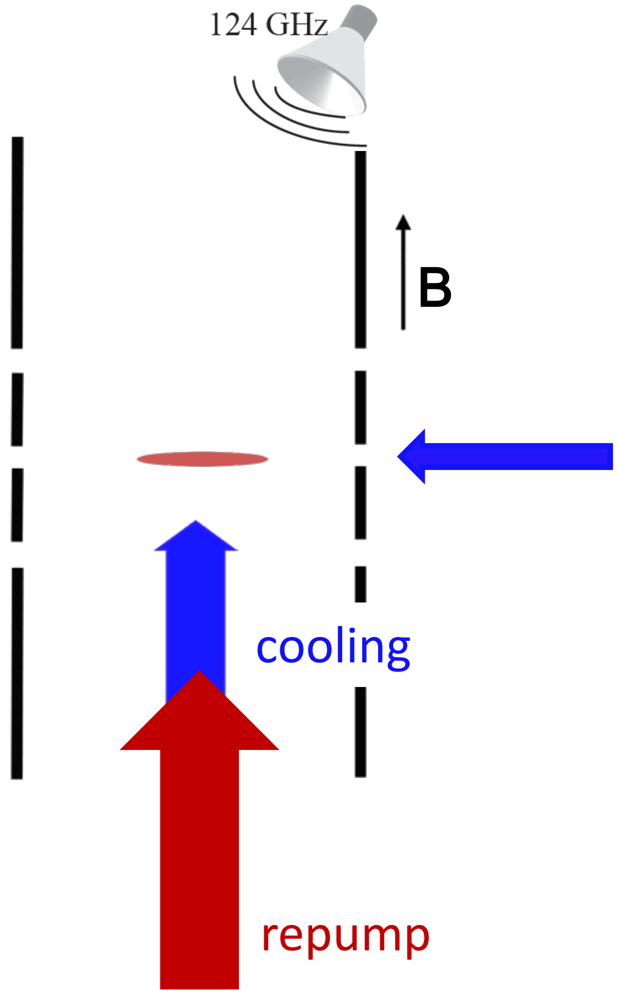
# $Be^+$ high magnetic field qubit

$^9Be^+$ , B ~ 4.5 T, $\omega_o /2\pi$ ~124.1 GHz

$$H_{\mu W} = \sum_i B_\perp \hat{\sigma}_i^x ,$$

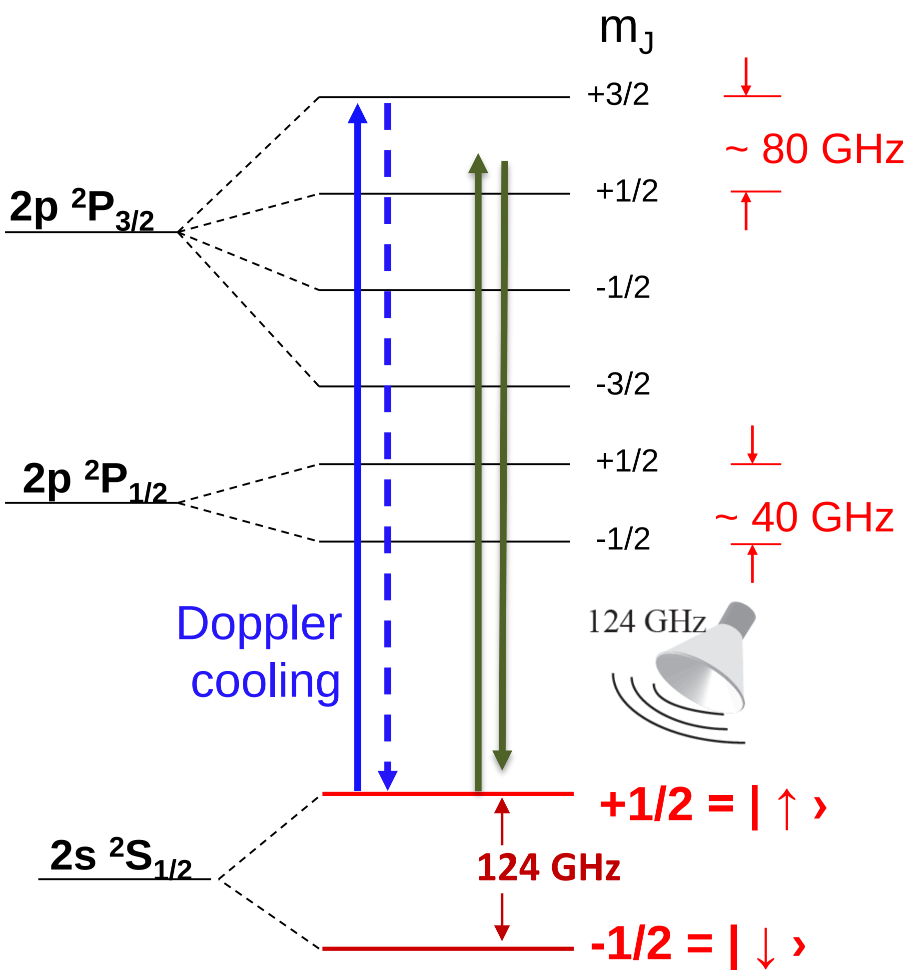
$$B_\perp > 10-15\,\text{kHz}$$

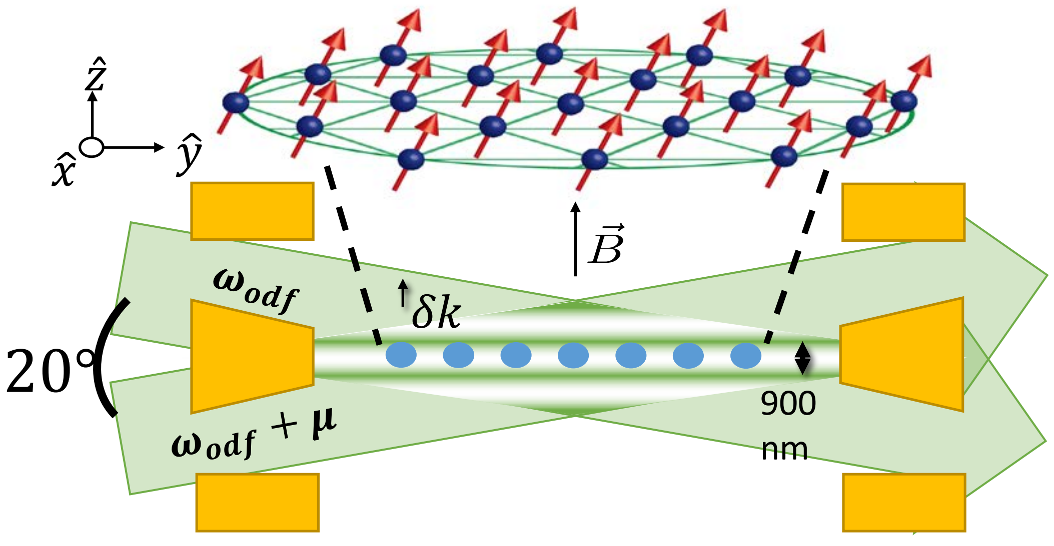


# Optical dipole force spin-motion coupling

$^{9}Be^{+}$ , B ~ 4.5 T, $\omega_o /2\pi$ ~124.1 GHz




$$H_I = \sum_i F_0 \cos(\mu t)\, \hat{z}_i \hat{\sigma}_i^z$$

# Motional amplitude sensing or
# Trapped ions as sensitive $\vec{E}$-field and force detectors

Maiwald, *et al*., Nature Physics 2009 – 1 yN Hz$^{-1/2}$

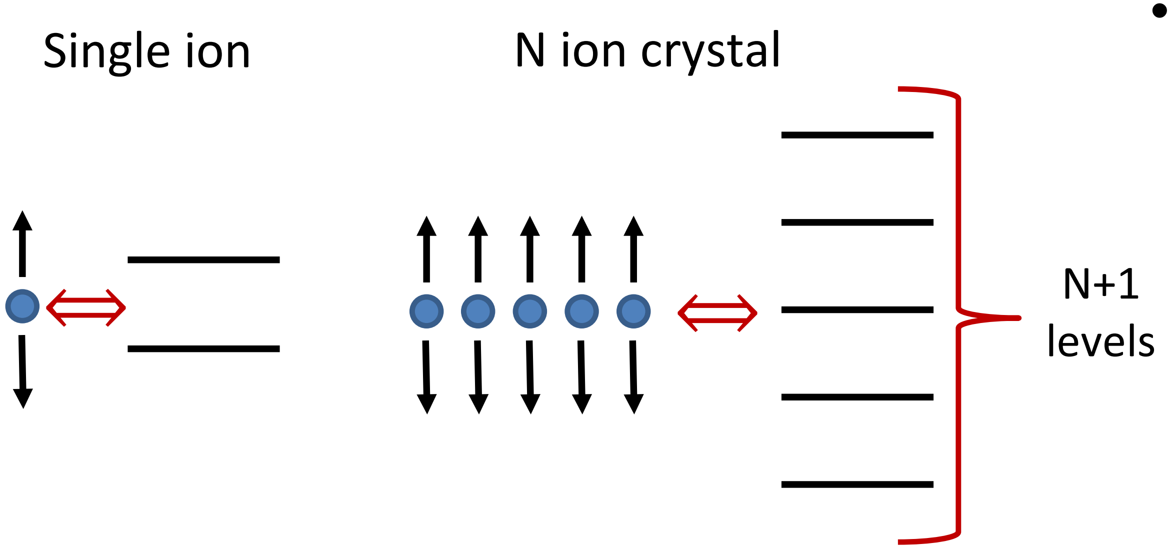
Hempel *et al*., Nature Photonics 2013 – detect single photon recoil

Shaniv, Ozeri, Nature Communications, 2017 – high sensitivity (~28 zN Hz$^{-1/2}$) at low frequencies

⋮

Biercuk *et al*., Nature Nanotechnology, 2010 – 100-ion crystal (400 yN Hz$^{-1/2}$ )

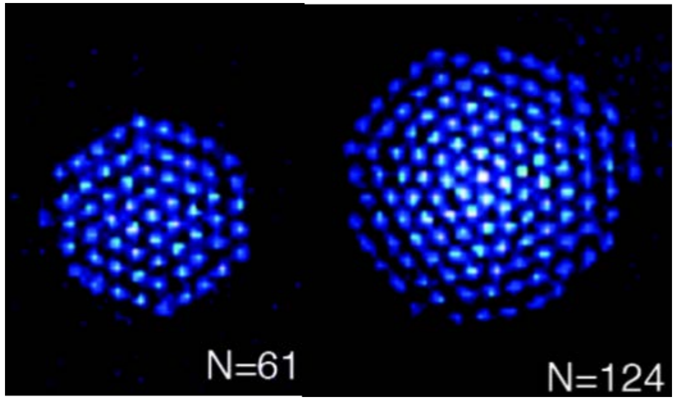
**Basic idea: map motional amplitude onto spin, spin precession**



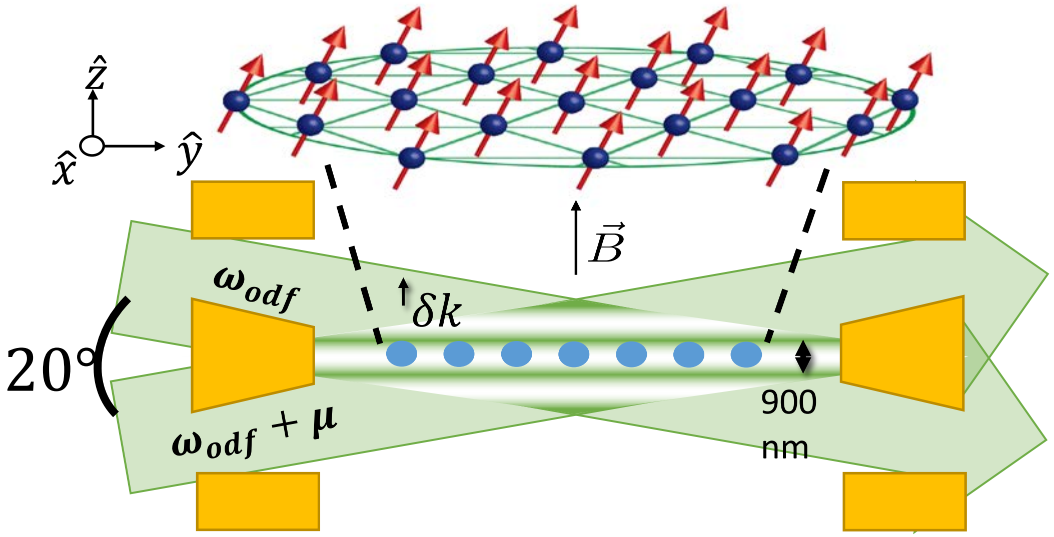

<u>N ion crystal</u>

- Less projection noise
- Smaller zero-point motion, $z_{zpt} \approx 2$ nm for N=100

$\sim \frac{1}{\sqrt{N}}$



# Sensing small center-of-mass motion




$$F_\uparrow(t) = -F_\downarrow(t) = F_0 \cos(\mu t)$$

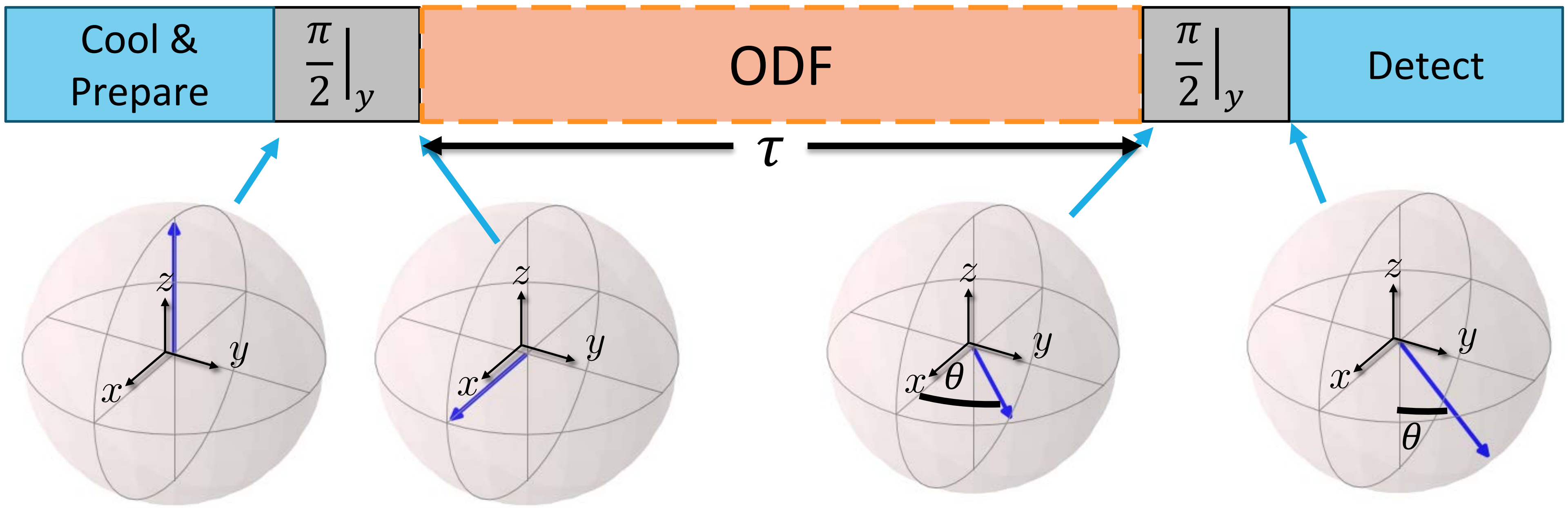
$$H_I = \sum_i F_0 \cos(\mu t)\, \hat{z}_i \hat{\sigma}_i^z$$

Implement classical COM oscillation: $\hat{z}_i \rightarrow \hat{z}_i + Z_c\, cos(\omega t + \phi)$

$$H_I \cong F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi] \sum_i \frac{\hat{\sigma}_i^z}{2}$$
$$= F_0 \cdot Z_c\, cos[(\omega - \mu)t + \phi]\ \hat{S}_z$$

For $\mu = \omega$, produces spin precession with rate $\propto F_0 \cdot Z_c \cos(\phi)$

# Measuring spin precession




Precession $\theta$,

$$\theta = \frac{F_0}{\hbar} Z_c \tau \cos(\phi)$$

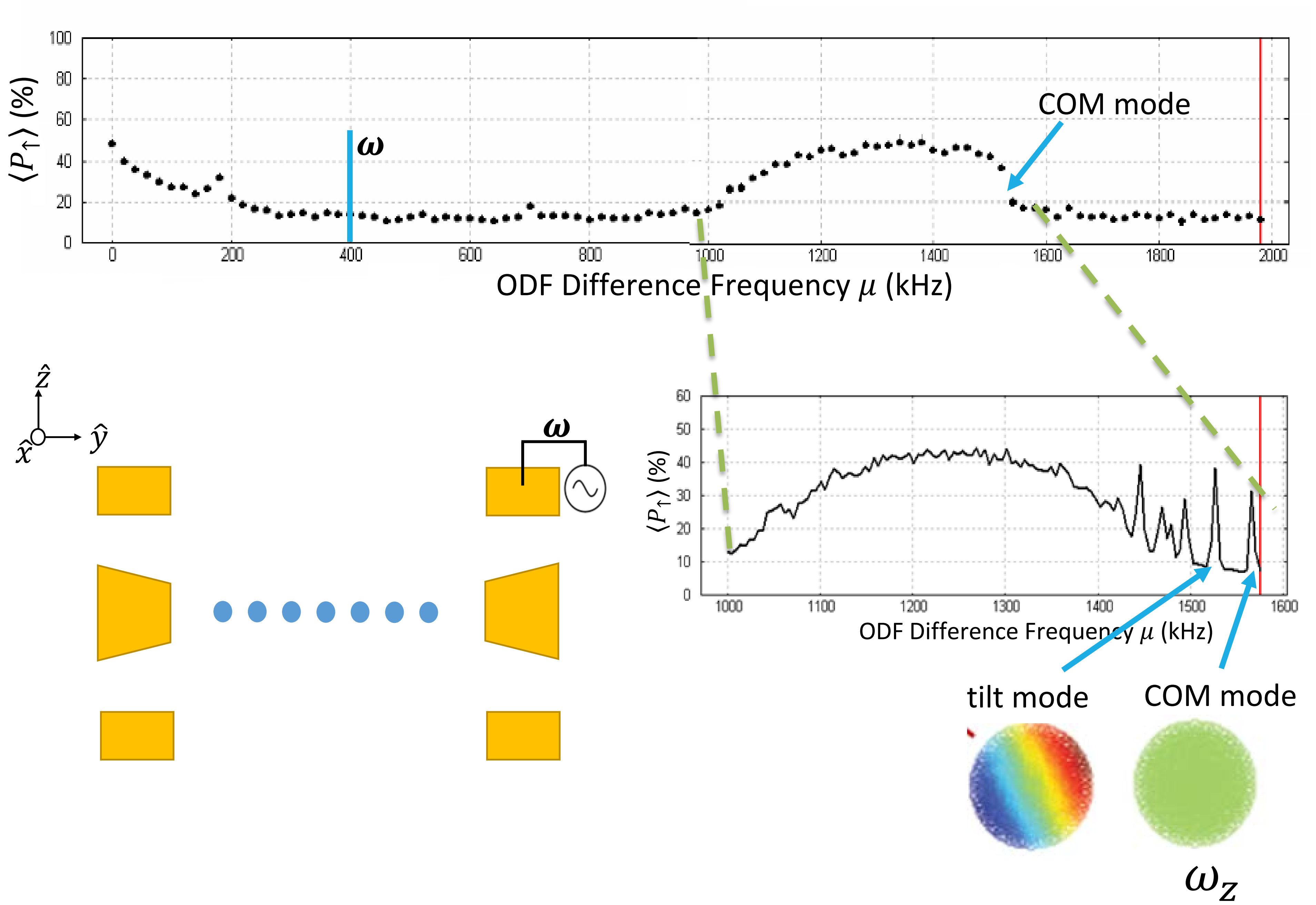
$$-\frac{F_0}{\hbar} Z_c \tau < \theta < \frac{F_0}{\hbar} Z_c \tau$$

Probability of measuring spin up:

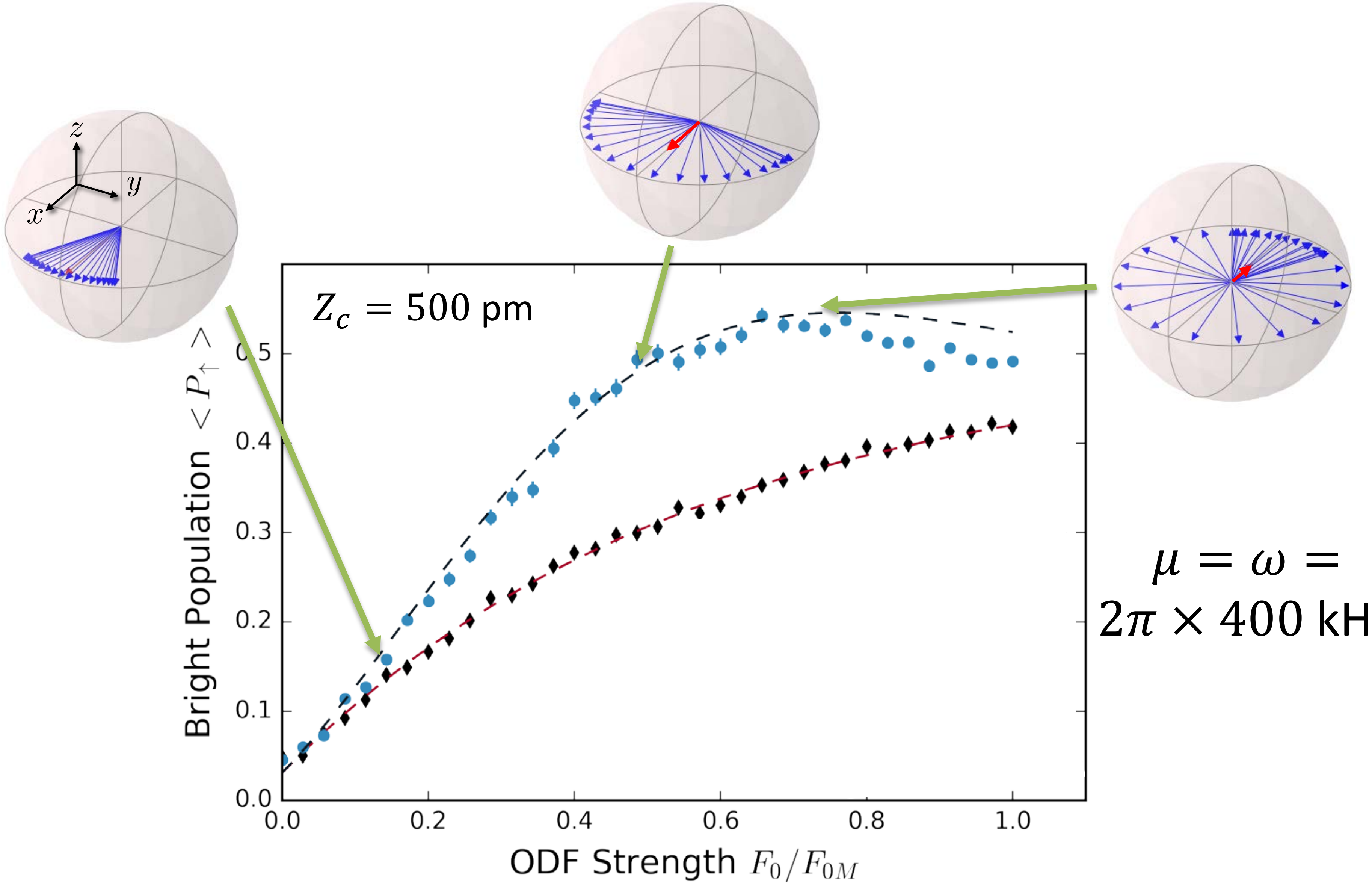
$$\langle P_\uparrow \rangle = \frac{1}{2}\left(1 - e^{-\Gamma\tau}\langle \cos\theta \rangle\right)$$

$$= \frac{1}{2}\left(1 - e^{-\Gamma\tau} J_0\left(\frac{F_0}{\hbar} Z_c \tau\right)\right)$$

# Measuring spin precession



# Spin dephasing vs measurement strength

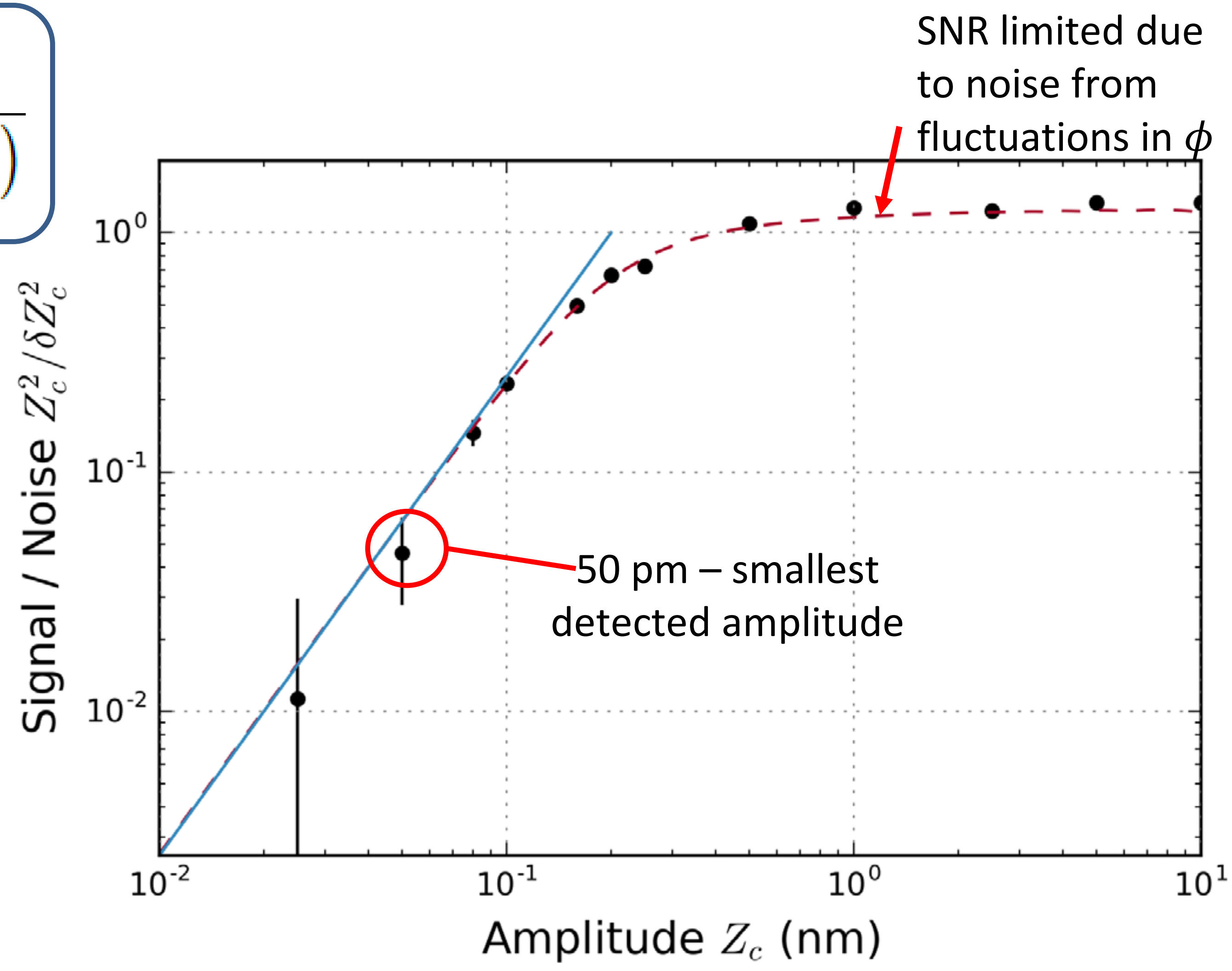



$\mu = \omega =$
$2\pi \times 400$ kHz

Gilmore *et al.*, PRL **118** (2017)

# Sensitivity limits/ signal-to-noise

$$\frac{Z_c^2}{\delta Z_c^2} \approx \frac{\langle P_\uparrow \rangle - \langle P_\uparrow \rangle_{bck}}{\delta\left(\langle P_\uparrow \rangle - \langle P_\uparrow \rangle_{bck}\right)}$$




Small signal limits due to:
projection noise
spontaneous emission

$$\left.\frac{Z_c^2}{\delta Z_c^2}\right|_{\text{limiting}} = \left[\frac{Z_c}{0.2\ \text{nm}}\right]^2$$

# Sensing small center-of-mass motion

## Summary:

- measure 50 pm amplitude – 40x smaller than the ground state wave function size $z_{zpt} = 2$ nm
- demonstrates force sensitivity of 73 yN/ion (at 400 kHz)

## Future:

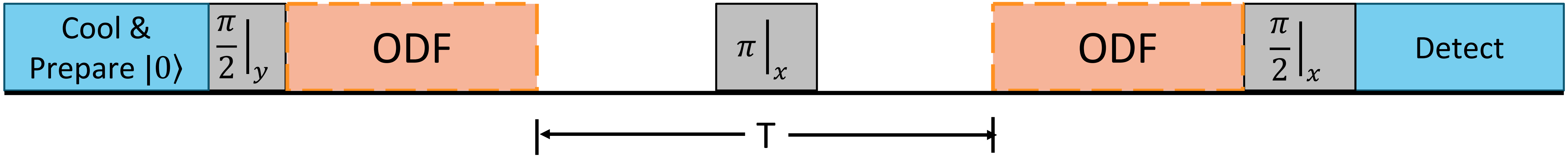
- Fixed phase sensing off-resonance (i.e. fixed $\phi$ in $Z_c cos(\omega t + \phi)$)
  - 74 pm in single experimental trial
  - 18 pm/$\sqrt{Hz}$
  - Exploit spins: squeezed states

- On-resonance with COM mode
  - Enhance force and electric field sensitivities by $Q \sim 10^6$
  - Protocols for canceling zero-point fluctuations, evading backaction ??
  - nV/m sensitivity $\Rightarrow$ potential for dark matter search (axions and hidden photons)

# Canceling zero-point fluctuations (idea)

Is this possible without violating the Heisenberg uncertainty principle?

# Canceling zero-point fluctuations (idea)




- zero-point fluctuations canceled through split ODF applications

- sensitive to weak force exciting the COM mode for T between the ODF applications

References:

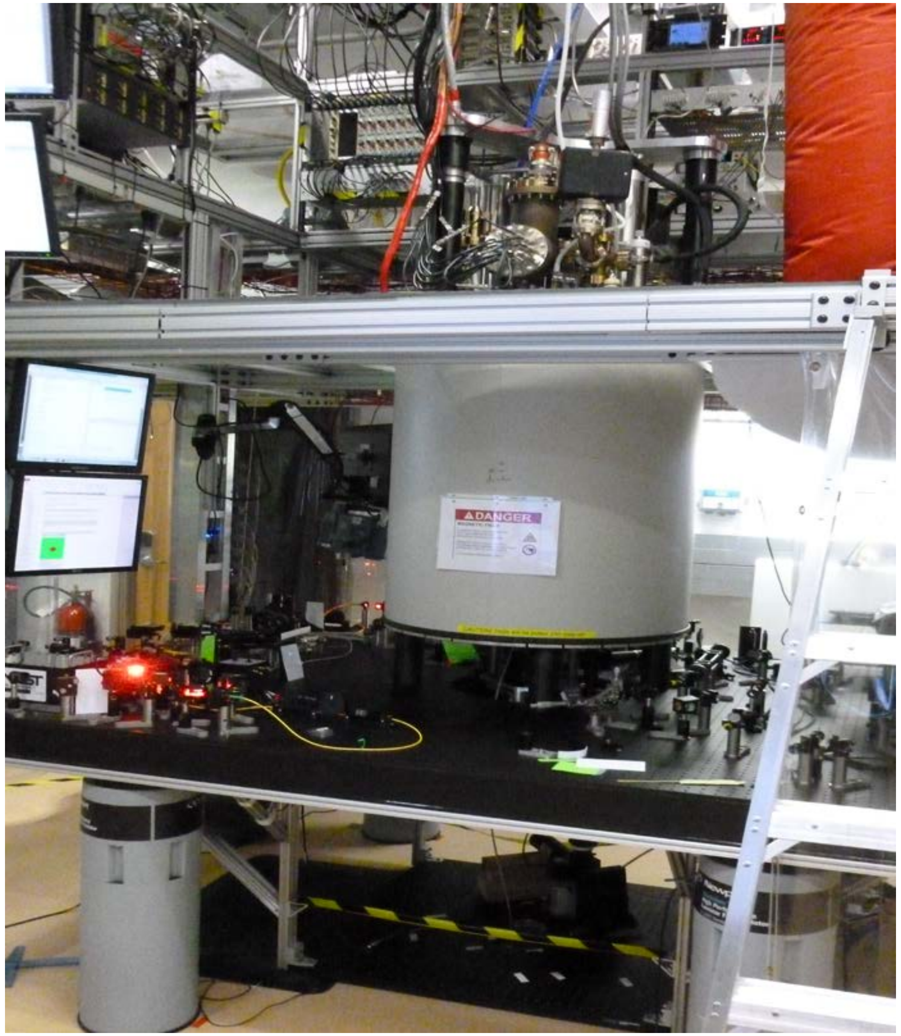

- “Entanglement-enhanced detection of single-photon scattering events, C. Hempel, B. P. Lanyon, P. Jurcevic, R. Gerritsma, R. Blatt, C. F. Roos, Nature Photonics (2013)
- “Sub-Planck phase-space structures and Heisenberg-limited measurements,” F. Toscano, D. A. R. Dalvit, L. Davidovich, and W. H. Zurek, Phys. Rev. A 73 (2006)

# Electric field sensing

20 pm amplitude from a resonant 100 ms coherent drive

- force/ion of $5 \times 10^{-5}$ yN
- electric field of 0.35 nV/m

4.5 Tesla superconducting solenoid




NOT a practical E-field sensor

# Electric field sensing

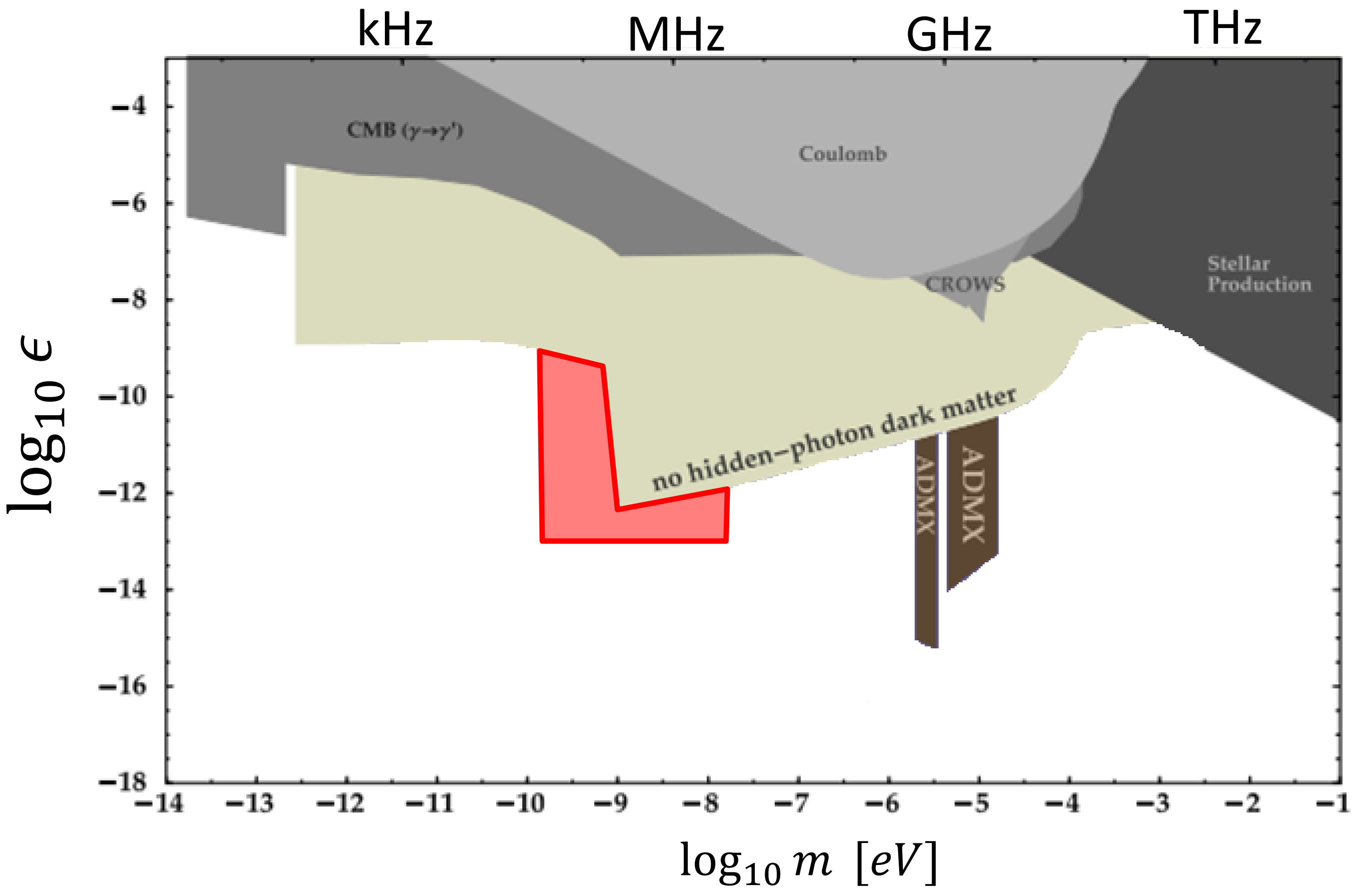
20 pm amplitude from a resonant 100 ms coherent drive

- force/ion of $5 \times 10^{-5}$ yN
- electric field of 0.35 nV/m

S. Chaudhuri, *et al.*, Phys. Rev. D (2015).

Search for hidden photons as dark matter?

$$\epsilon = \frac{E}{3.3\,\frac{\mathrm{nV}}{\mathrm{m}}} * 10^{-12}$$

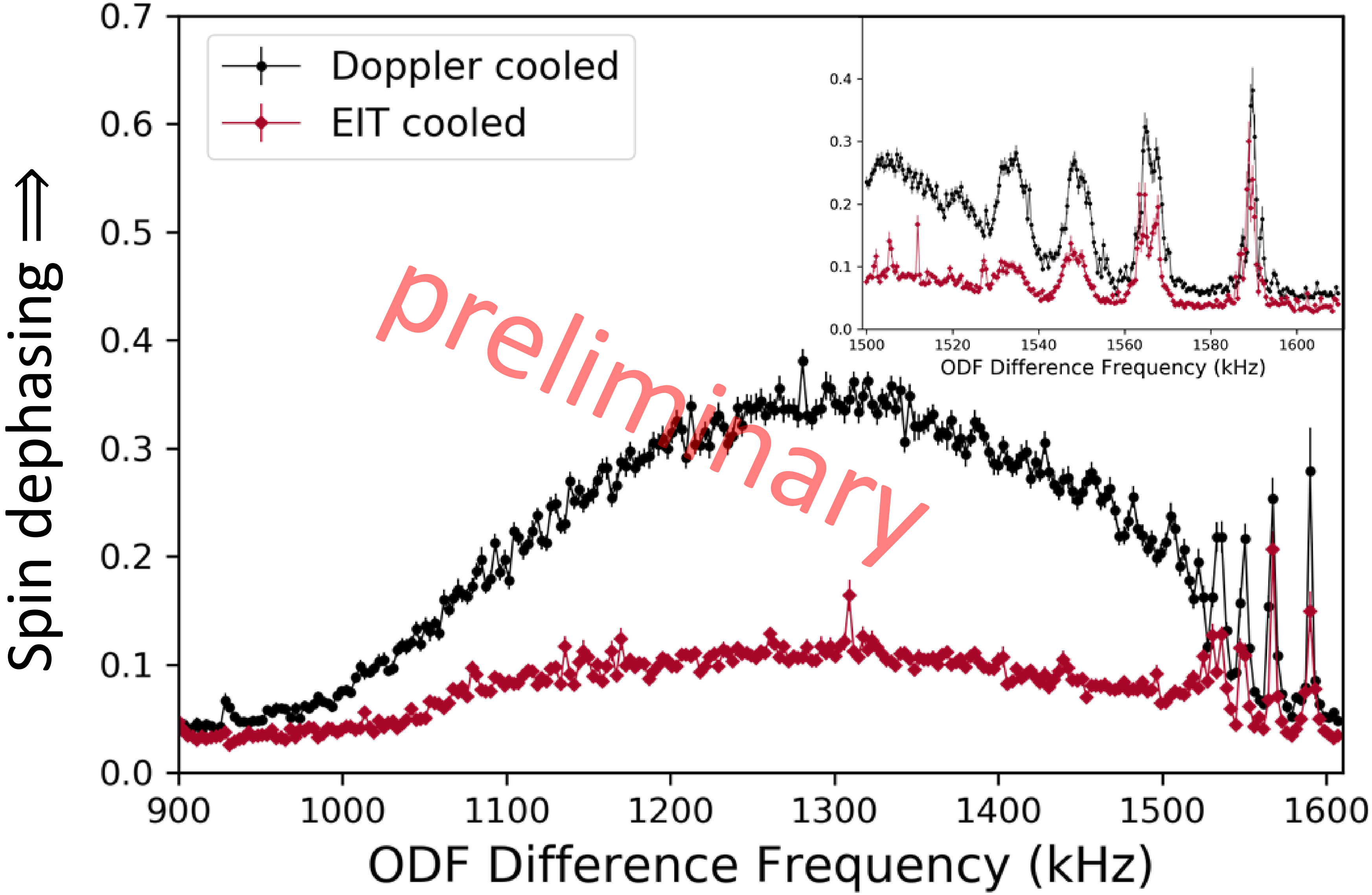


# Technical improvement – near gnd state cooling

EIT ground state cooling – Morigi et al., PRL 2000

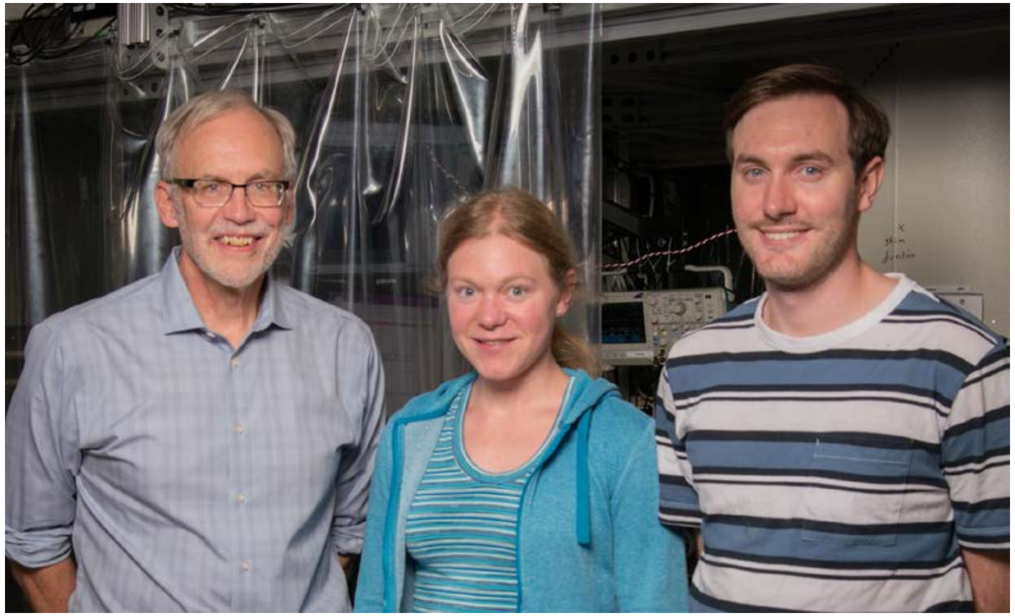
Lechner, ..., Blatt, Roos, PRA 2016

EIT cooling time 200 $\mu s$



Questions ?

## 2017



Elena Jordan
Leopoldina PD

Kevin Gilmore
CU grad student

## Theory (EIT cooling)

Murray Holland

Athreya Shankar

## Theory

Ana Maria Rey

Martin Gärttner

Michael Wall

Arghavan Safavi-Naini

Michael Foss-Feig (ARL)

# NIST ion storage group (2017)