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Laser cooling, spectroscopy and polarization of calcium

Outline

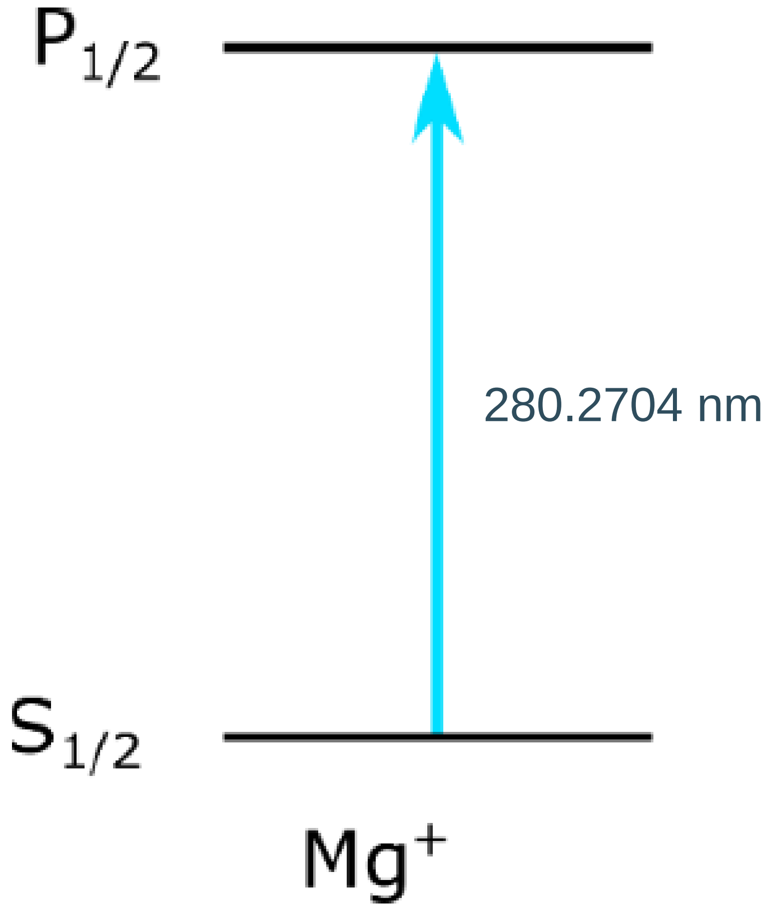
- Reminder: laser polarization of Mg^+
- Laser polarization of Ca^+
- Polarization measurements?
- Opportunities and synergies

Atomic structure of Mg^+

- Alkaline earth element, singly charged: single valence electron structure

	Structure	Energy
Ground state	$2p^6 3s\ ^2S_{1/2}$	0 eV
Excited p-state	$2p^6 3p\ ^2P^0_{1/2}$	4.422 eV
	$2p^6 3p\ ^2P^0_{3/2}$	4.433 eV
Excited D-state	$2p^6 3d\ ^2D_{5/2}$	8.864 eV
	$2p^6 3d\ ^2D_{3/2}$	8.864 eV

- Life is simple: there are closed two-level systems* with the $^2S_{1/2}$ and $^2P^0_{1/2}$/ $^2P^0_{3/2}$ states

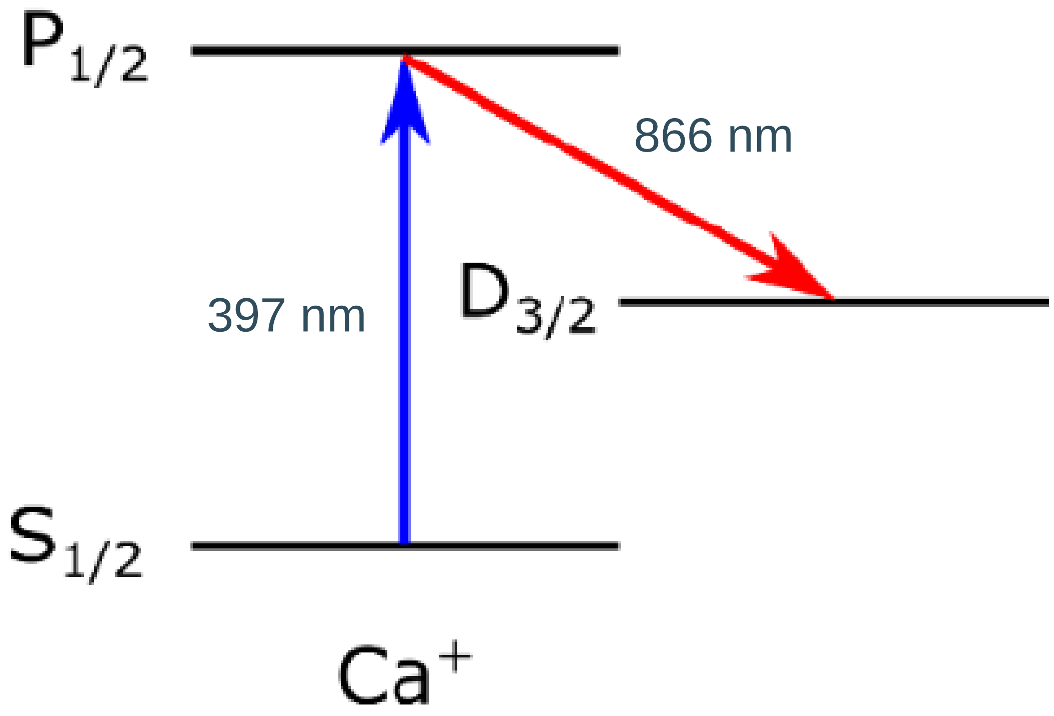


Atomic structure of Ca^+

- Alkaline earth element, singly charged: single valence electron structure

	Structure	Energy
Ground state	$3p^6 4s\ ^2S_{1/2}$	0 eV
Excited p-state	$3p^6 4p\ ^2P^0_{1/2}$	3.123 eV
	$3p^6 4p\ ^2P^0_{3/2}$	3.151 eV
Excited D-state	$3p^6 4d\ ^2D_{3/2}$	1.692 eV
	$3p^6 4d\ ^2D_{5/2}$	1.700 eV

- Life is less simple: there are no closed two-level systems
  - Ion can de-excite into metastable D-states



Atomic structure of Ca^+

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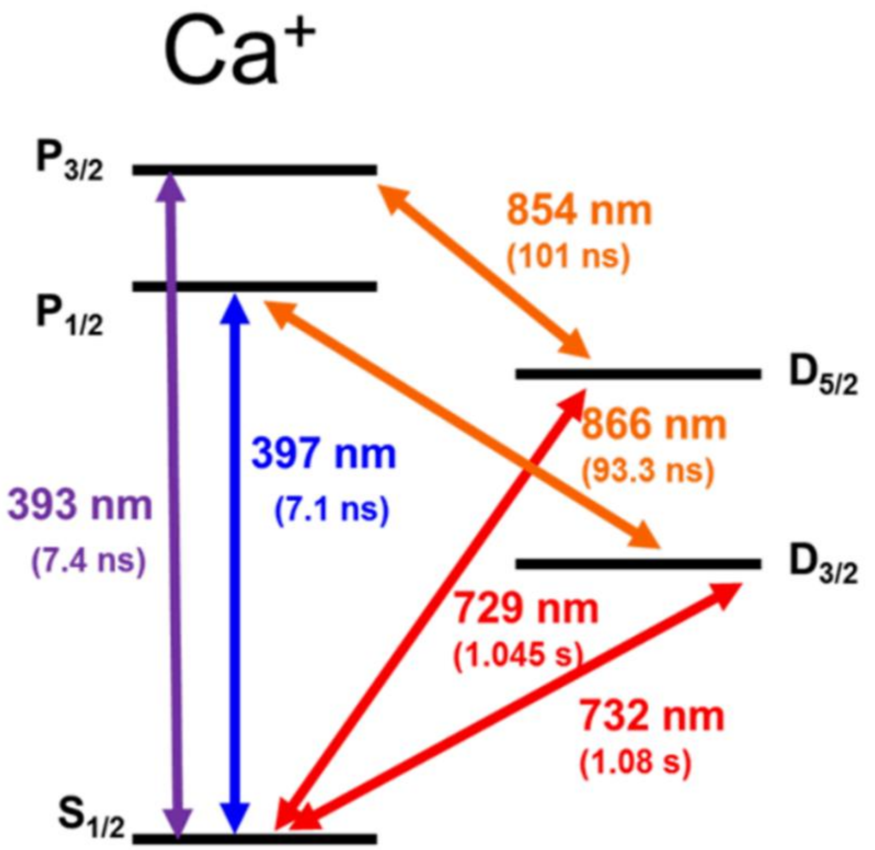
- Life is less simple: there are no closed two-level systems
- This does bring many opportunities…



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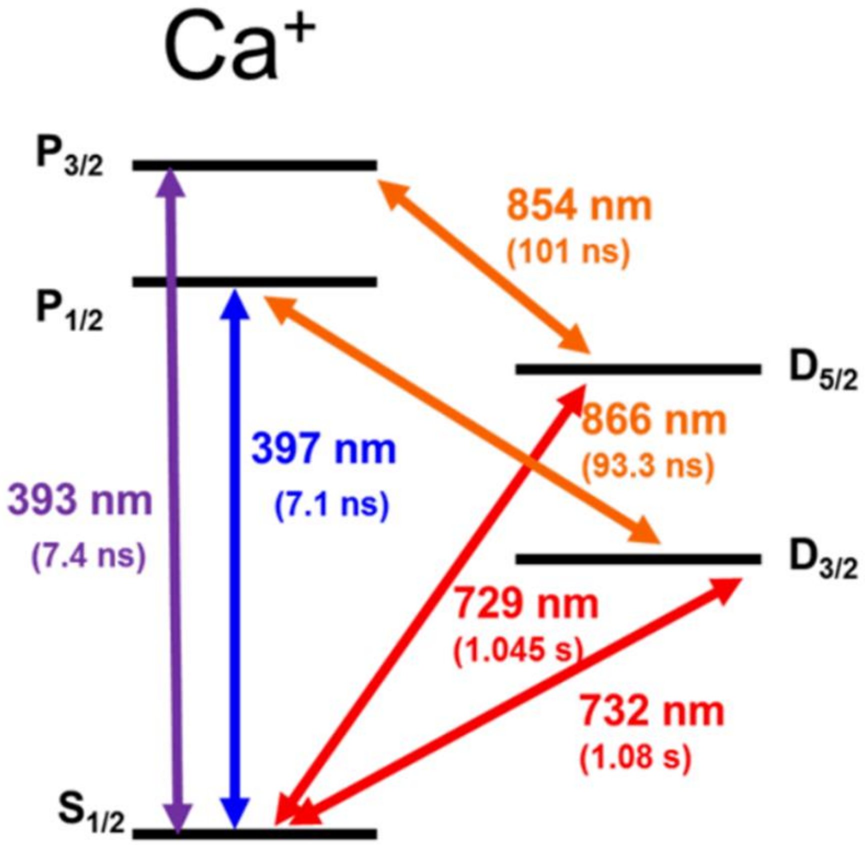
Pro and con of calcium

+ Visible and IR wavelengths rather than UV
+ More accessible states means more options for spectroscopy
+ Visible-wavelength lines to metastable D-states are interesting for metrology, quantum computing, …

- When all you want is polarization or cooling: at least two lasers required



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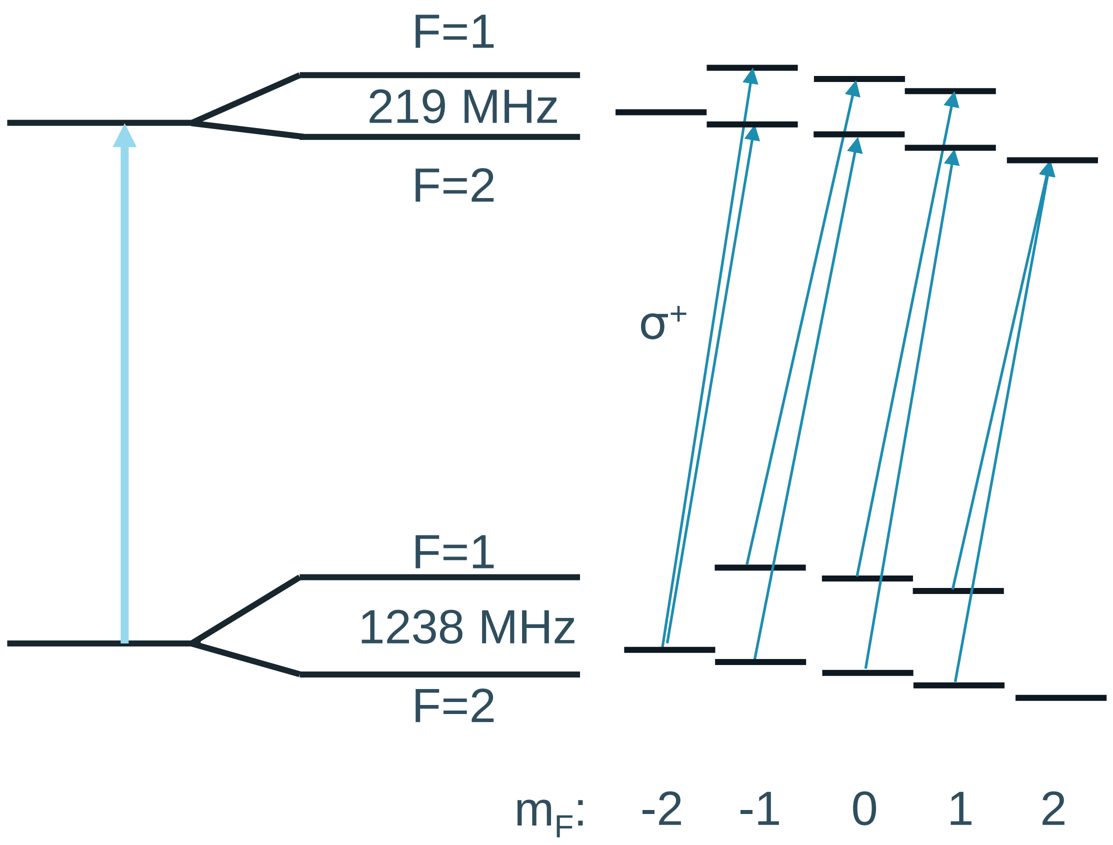
Laser polarization of Mg

- Polarization of laser light relative to external field axis determines the selection rules for absorption.
- Circular light along the magnetic field axis: projection of angular momentum changes by +/-1
- Spontaneous emission can still occur with $\Delta m = 0$
  => optical pumping into stretched states

- $(F, m_F) = (2,2)$ ⇔ $(I, m_I) = (3/2, 3/2)$
  => nuclear polarization

- Note: only way to avoid dark states is to cover all HFS-induced transitions
  - Use multiple laser beams / sidebands
  - Have broadband laser



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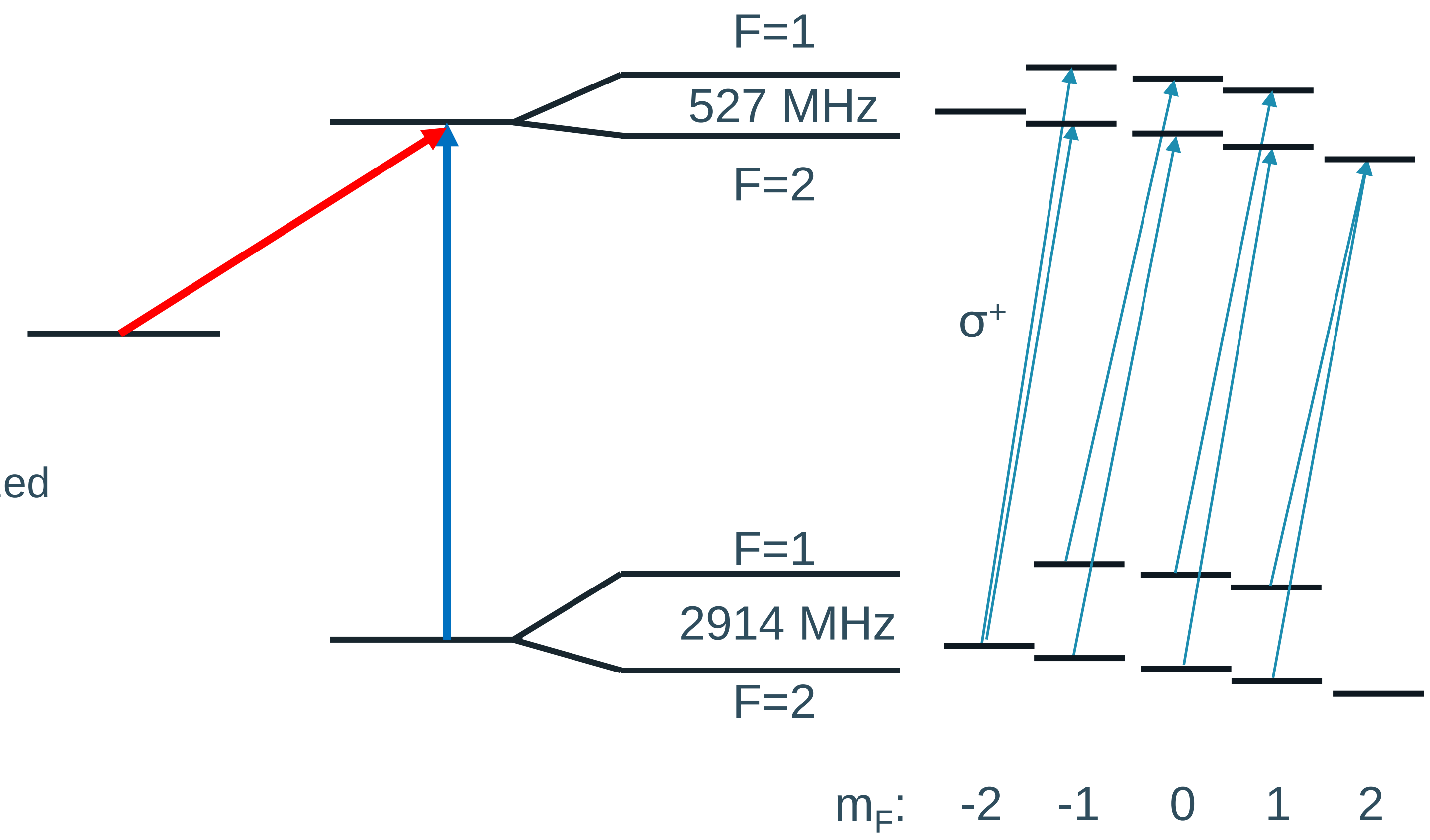
Laser polarization of Ca

- Slightly larger splitting

- A repumper laser is needed to deplete the metastable state
  - Has HFS of the order of 1 GHz wide – sidebands or broadband laser required
  - Repumper does *not* need to be polarized

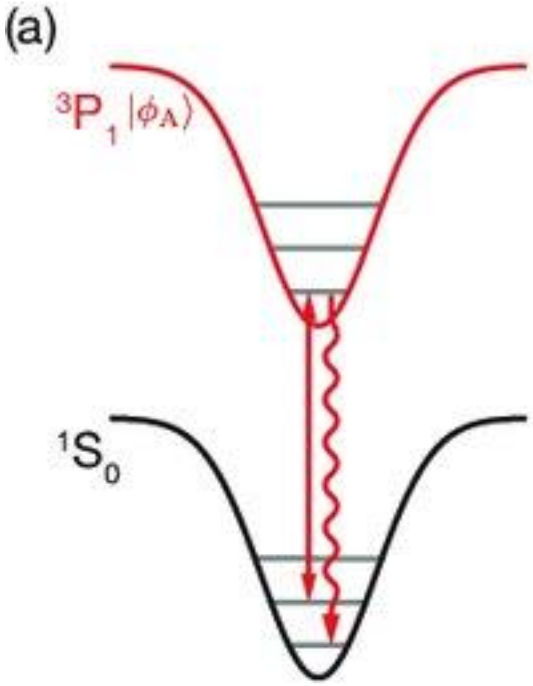
- As far as I know, radioactive calcium has never been (purposefully) laser polarized?

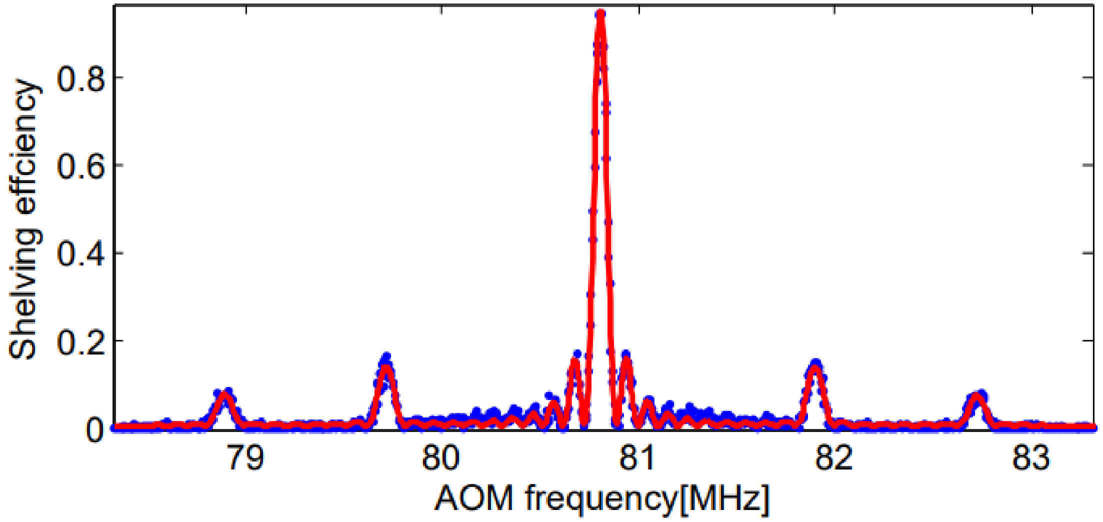


Imaged by Heritage Auctions, HA.com

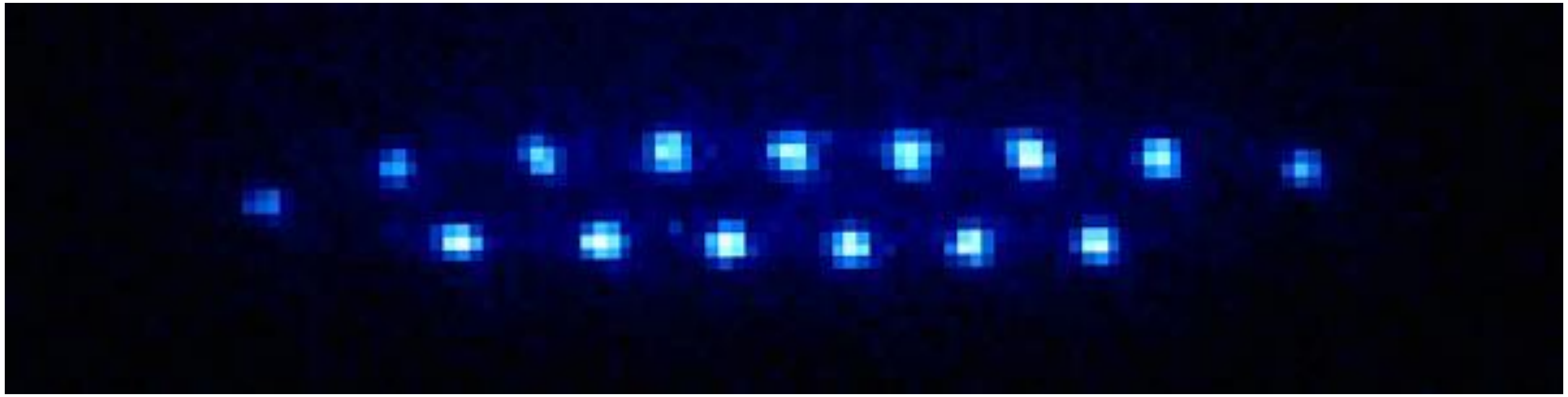
Laser cooling

- Umbrella term for a variety of techniques to reduce the temperature of an ensemble of atoms with laser beams
- Doppler cooling: ion receives momentum kick along laser axis when absorbing a photon, emits isotopically; with red-detuned laser light this results in a net slow-down after many cycles
- Ions can be cooled to low harmonic oscillator quantum number
- Resolved sideband cooling: excitation on the red sidebar to drive system to lowest HO state
  => ions as close to at rest as QM allows…





Single-ion imaging

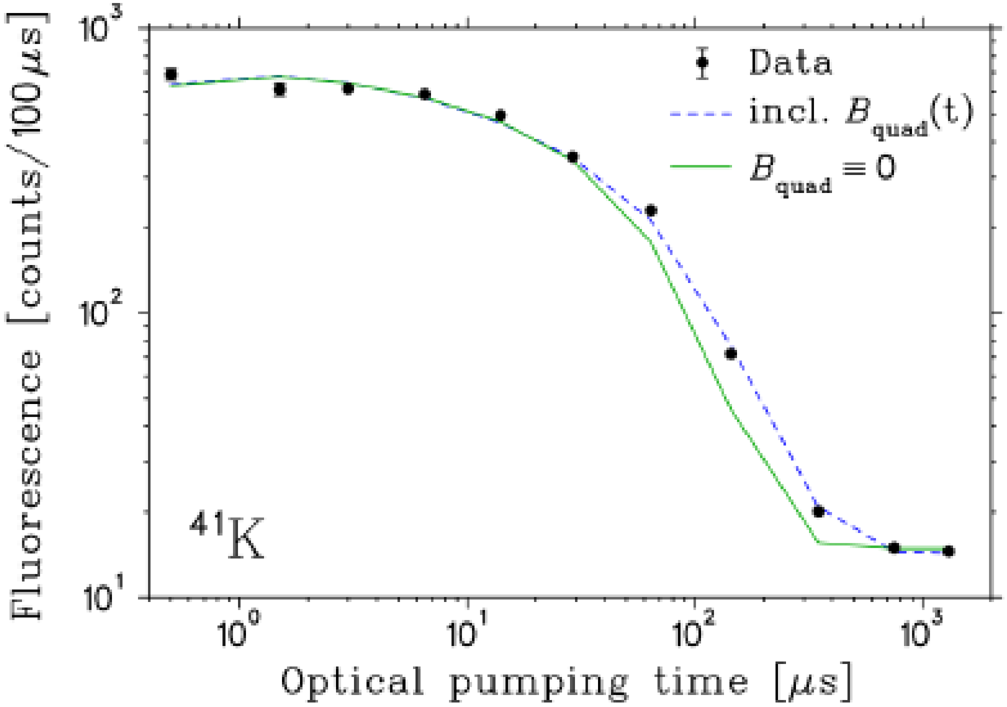


Dedicated ion traps can collect 1000s of photons/s/ion

Careful imaging enables resolving individual ions (separation: order micrometer)

Polarization measurement from fluorescence

- Use the probe laser light to inform on degree of polarization
- Demonstrated with the K mot in TRIUMF – but poor S/B with less than ~ 10^4 atoms in the trap
  - Collimation lens: 20 cm from trap center = 1:1000 geometric coverage – can we do better?



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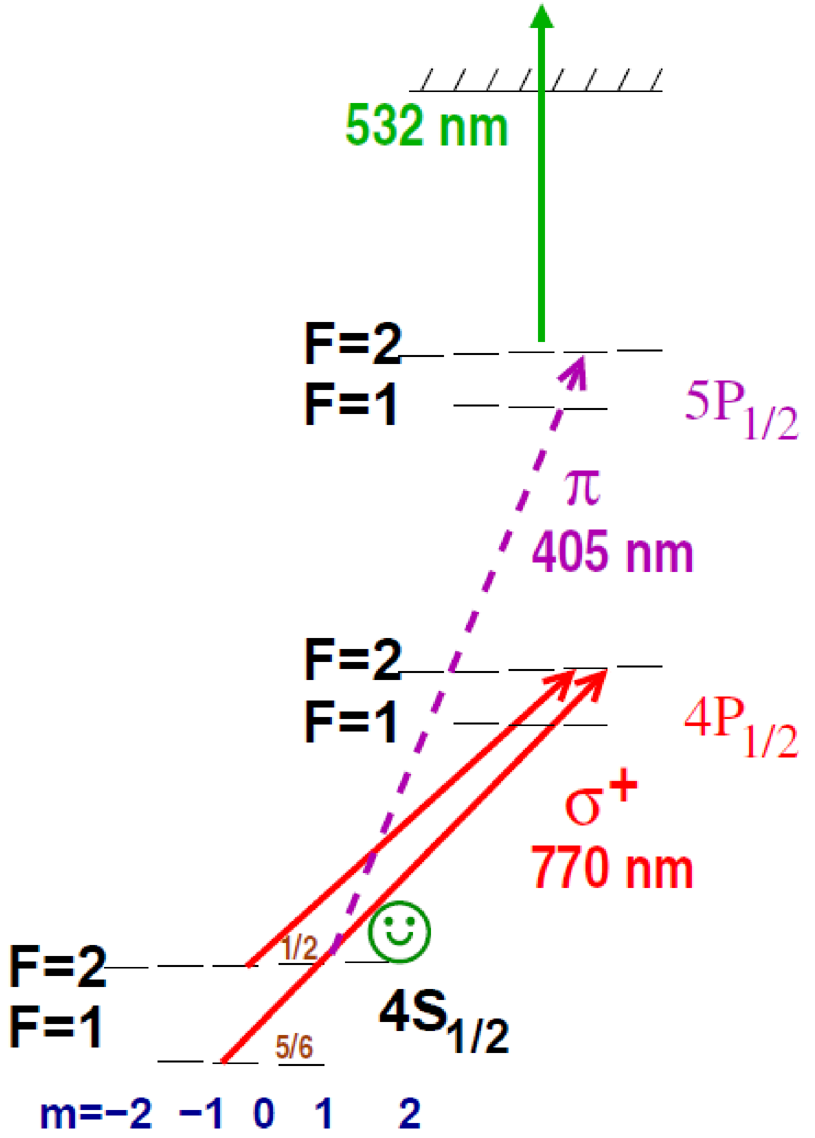
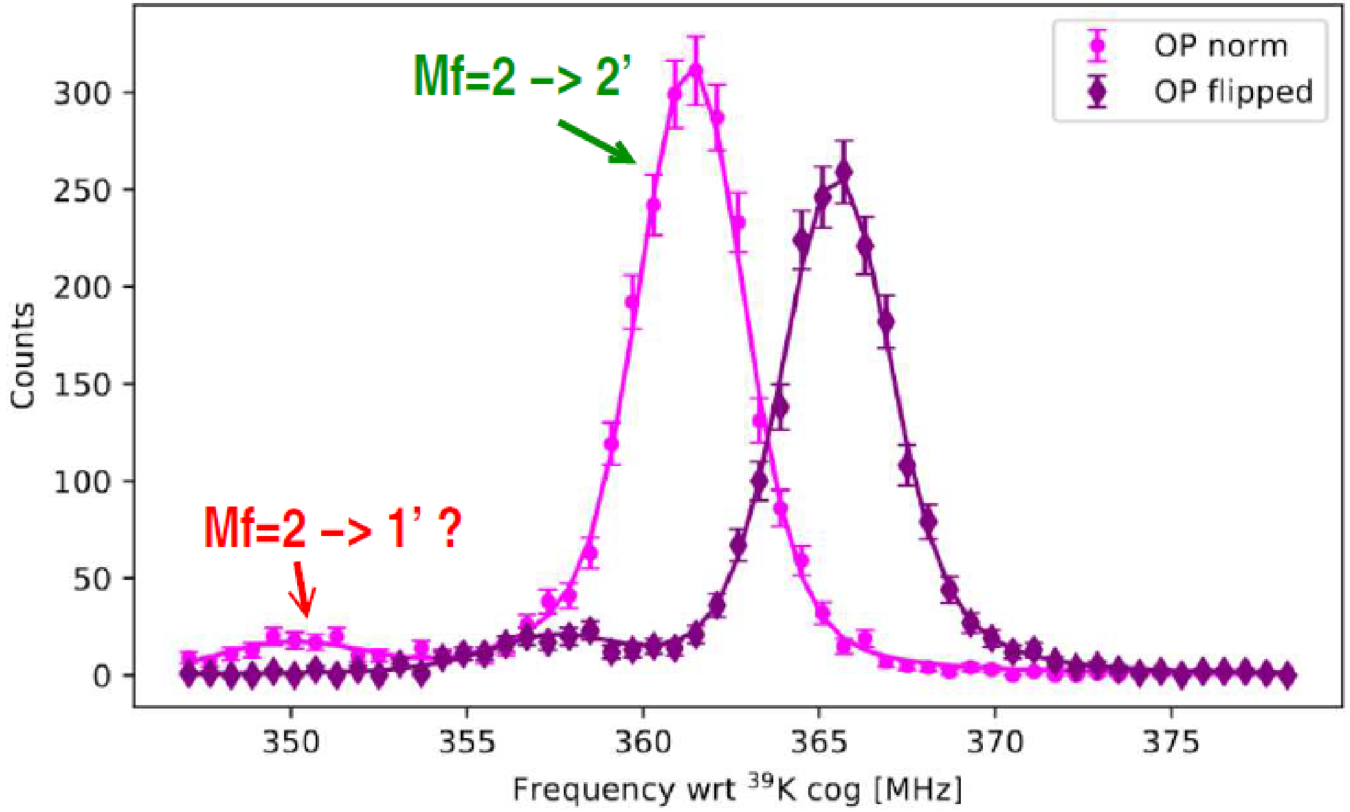
In progress: More direct probe of ^{41}K population



Our ^{37}K probe is in situ and nondestructive, but as a 1-parameter fit could use confirmation.

- $4S_{1/2} \rightarrow 5P_{1/2}$ has 1.1 Mhz FWHM, so resolves m_F levels split by our 2 Gauss Bz holding field
- Destructive and alters P but still provides useful info



Slide by John Behr (yesterday)

Polarization measurement from fluorescence

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- Demonstrated with the K mot in TRIUMF – but poor S/B with less than ~ 10^4 atoms in the trap
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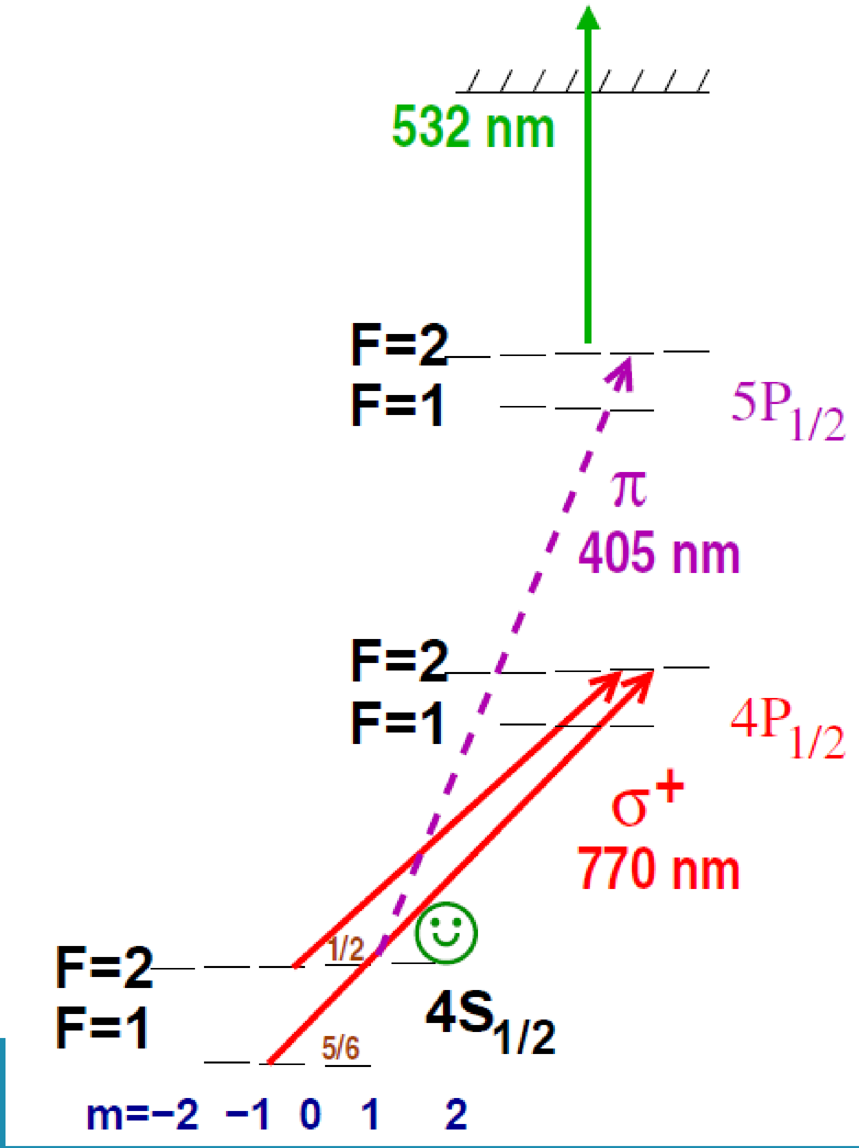
- Laser ionization?
  - Challenging for Mg^+.



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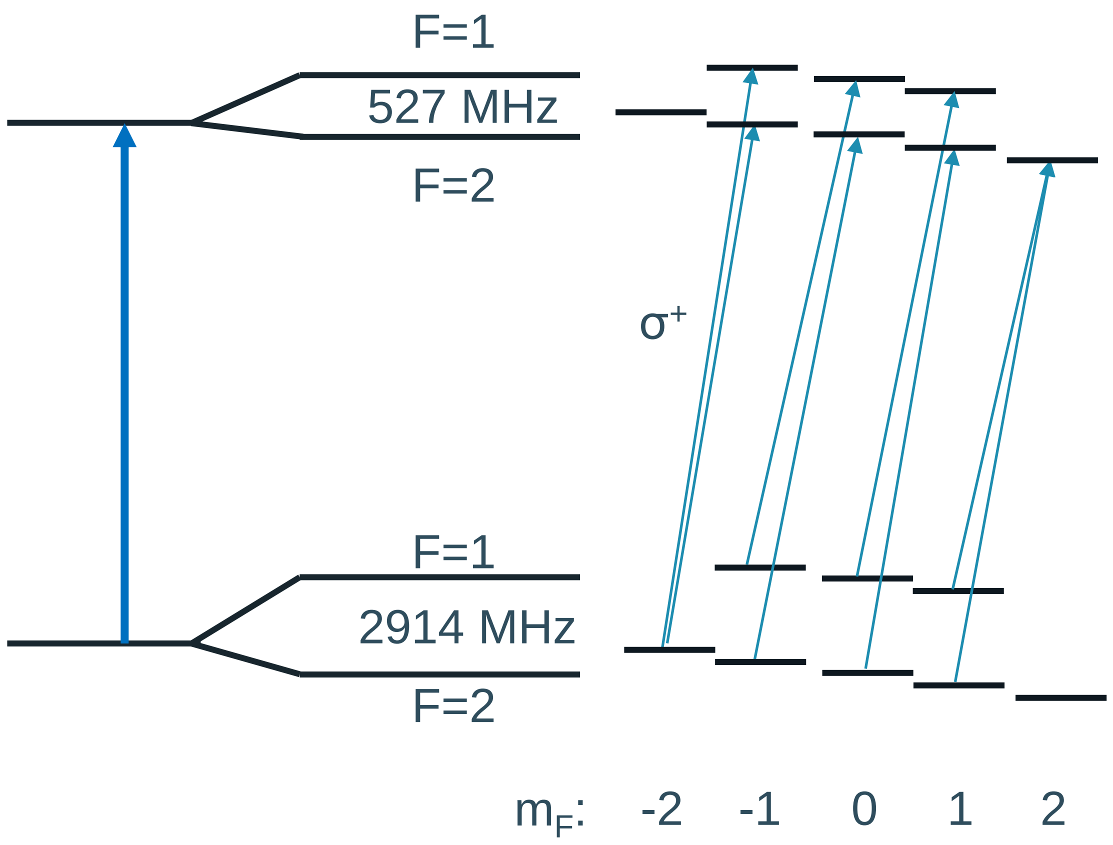
Polarization measurements

- Measure the population of the (F, m_F) substates
  - Measuring fluorescence yield for different weak probe laser frequencies
  - Comparison to model of laser-atom interaction required
- Requires resolving individual lines

  => Laser cooling required

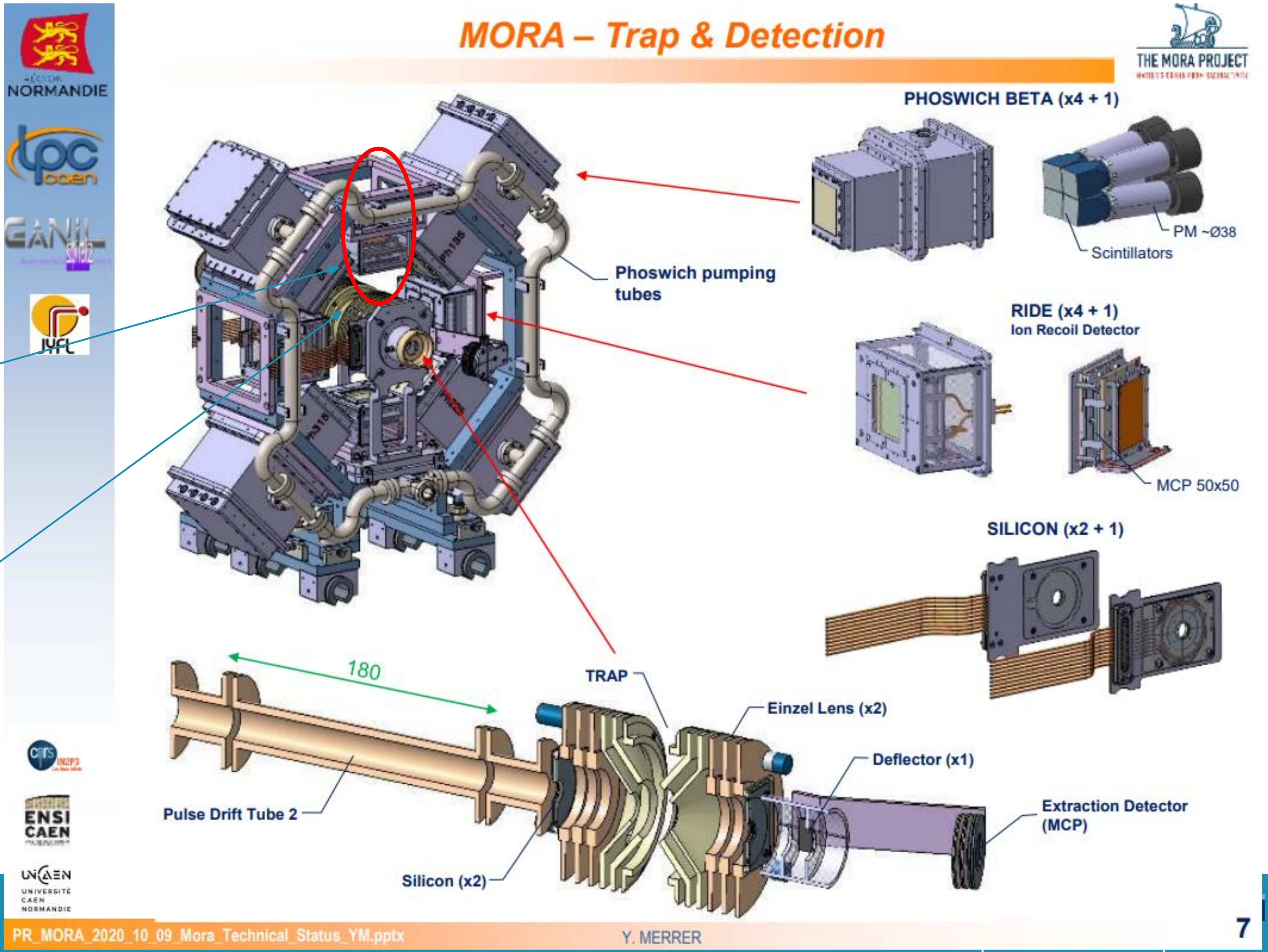
  => Narrowband laser system needed
- Use of RF excitations within the lower-state manifold may help to map more accurately?



[37]K MOT: B. Fenker et al, New J. Phys. 18 (2016) 073028

have one of RIDE removed during tests of polarization?

Insert moveable mirror to guide light to detector?



Opportunities and synergies

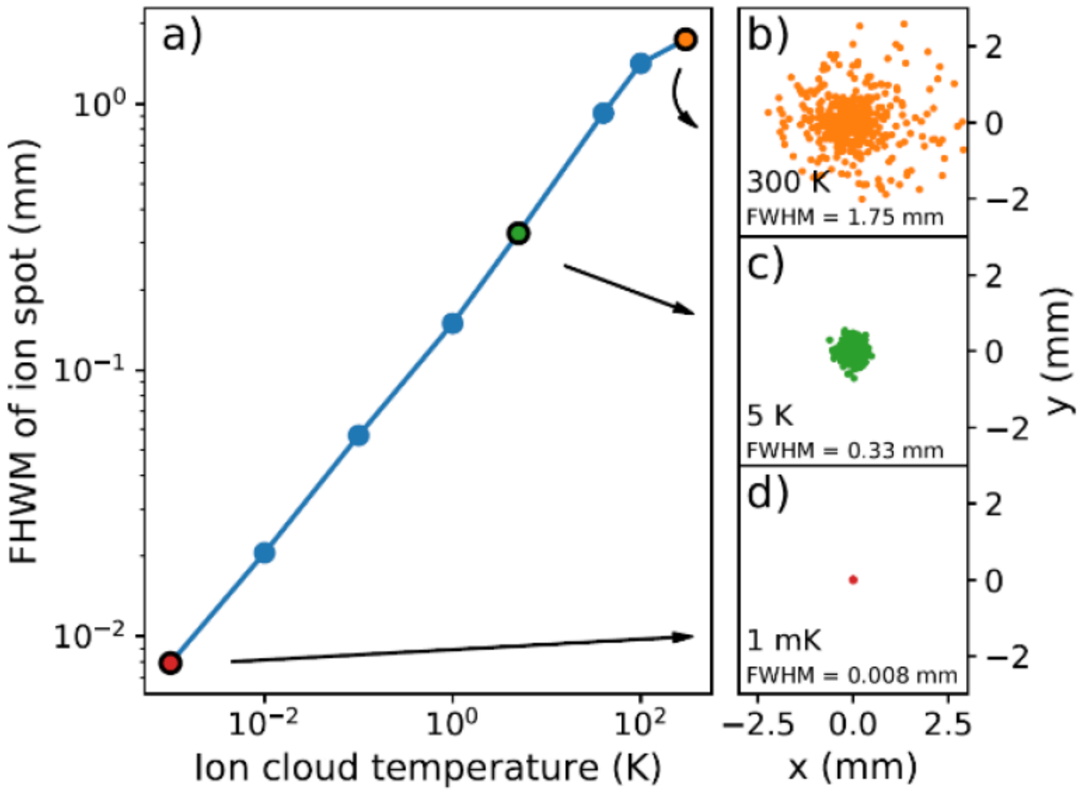
Starting point…

- Polarization of Ca is a bit more involved than Mg
- Measurements of polarization require a cw laser system
- Ideally, also laser cooling

- => Ideally, work is performed ‘offline’ to explore
- In Leuven, I have initiated the construction of a trapped-ion lab for precision optical spectroscopy

Opportunity 1: sympathetic cooling of RIBs

- Co-trapping an ion of interest into a lattice/cloud of laser-cooled ions
- Coulomb interaction cools down the non-laser-coolable ions
- Naturally, this dramatically improves the emittance of the ions once extracted from the trap.
- Potential application in ultra-high precision mass measurements
    - Translates to improved TOF resolution
    - Translates to well-localized ion clouds for phase-imaging ion cyclotron techniques



S. Sels et al., Doppler and sympathetic cooling for the investigation of short-lived radioactive ions, 2022 (under Review)

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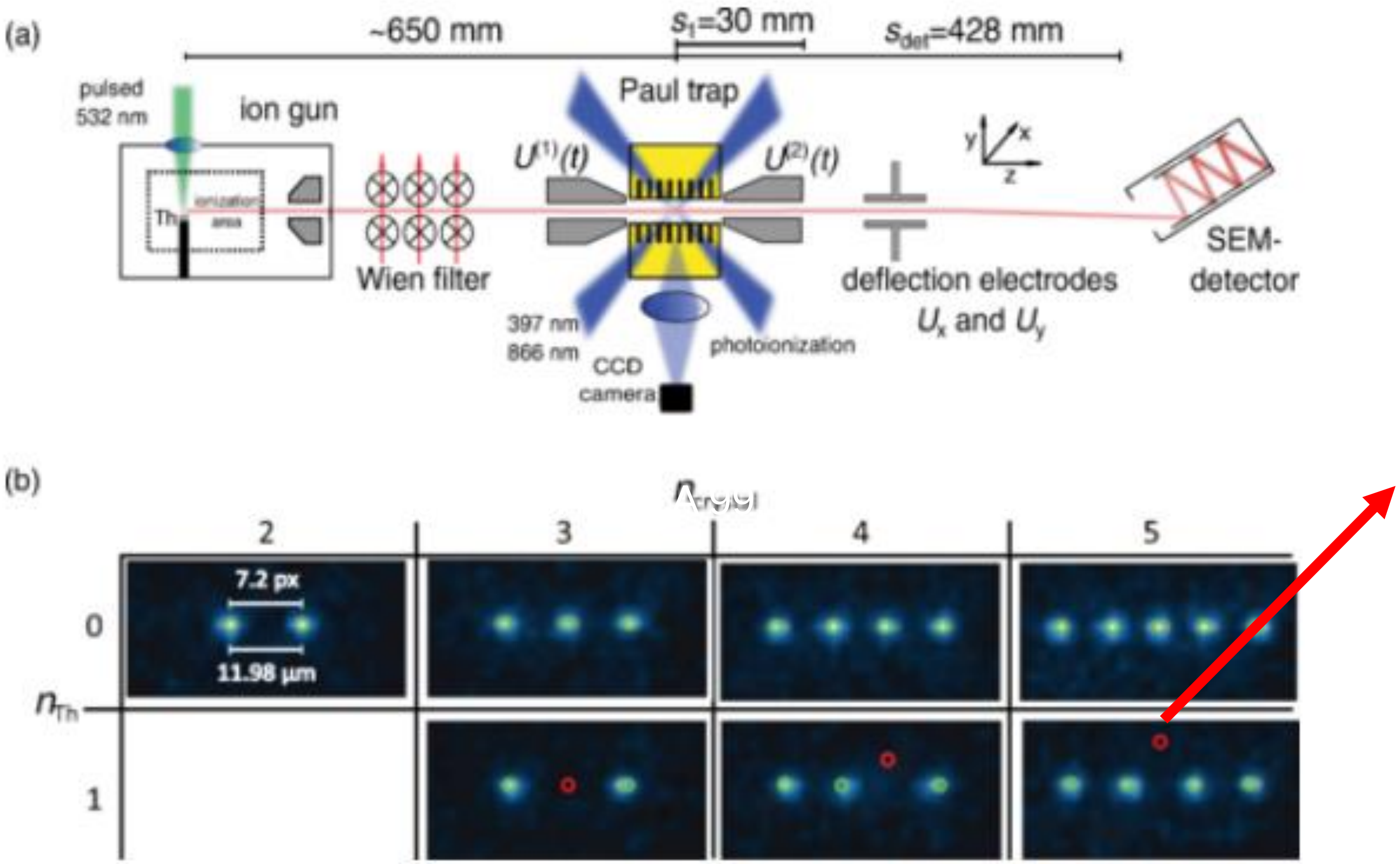
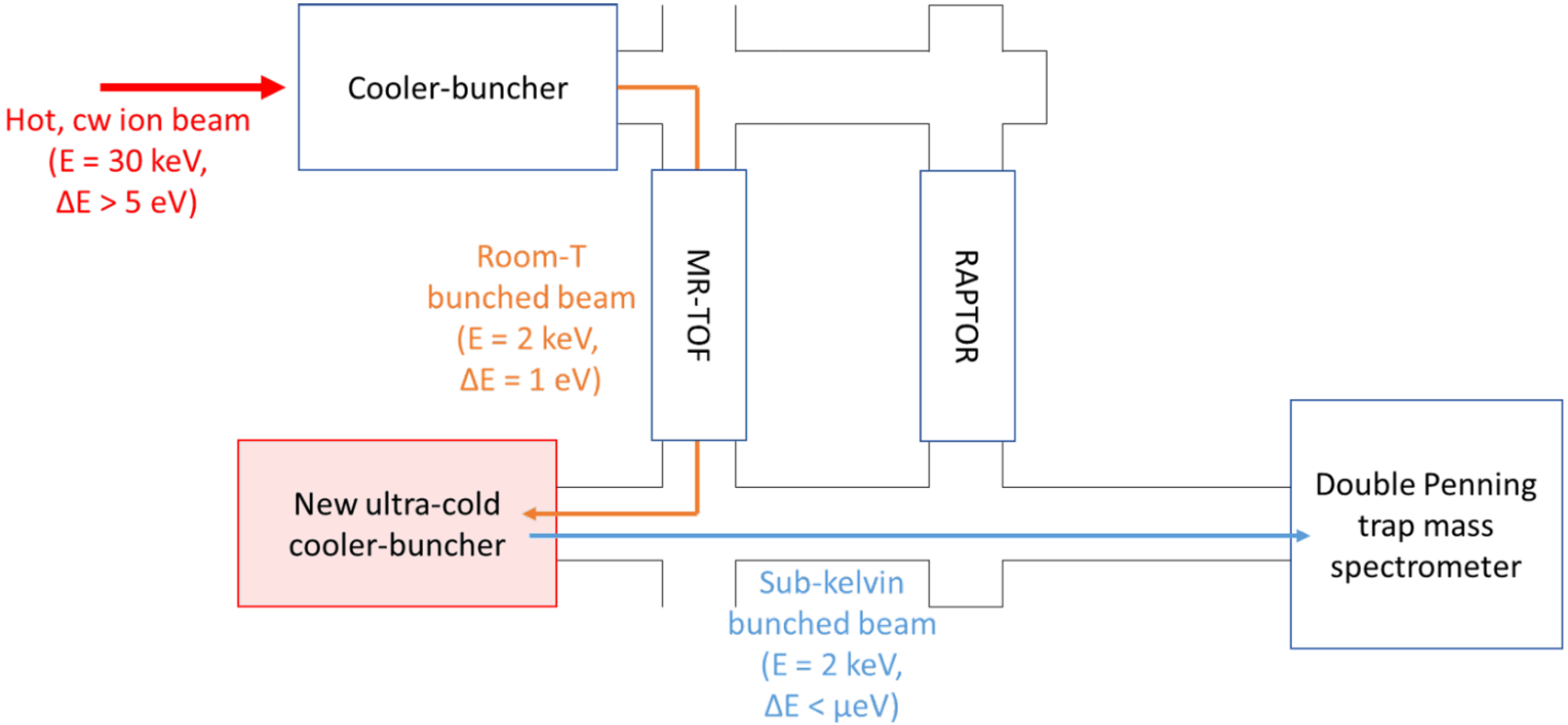


Inferred positions of Th^+ ions in laser-cooled Ca crystal

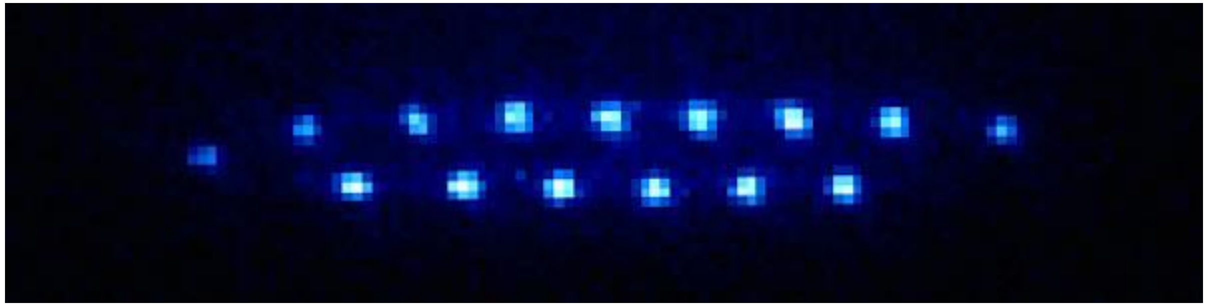
K. Groot-Benning, Phys. Rev. A 99, 023420 (2019)


Cooler-buncher
Hot, cw ion beam
(E = 30 keV,
ΔE > 5 eV)
Room-T
bunched beam
(E = 2 keV,
ΔE = 1 eV)
MR-TOF
RAPTOR
New ultra-cold
cooler-buncher
Double Penning
trap mass
spectrometer
Sub-kelvin
bunched beam
(E = 2 keV,
ΔE < μeV)

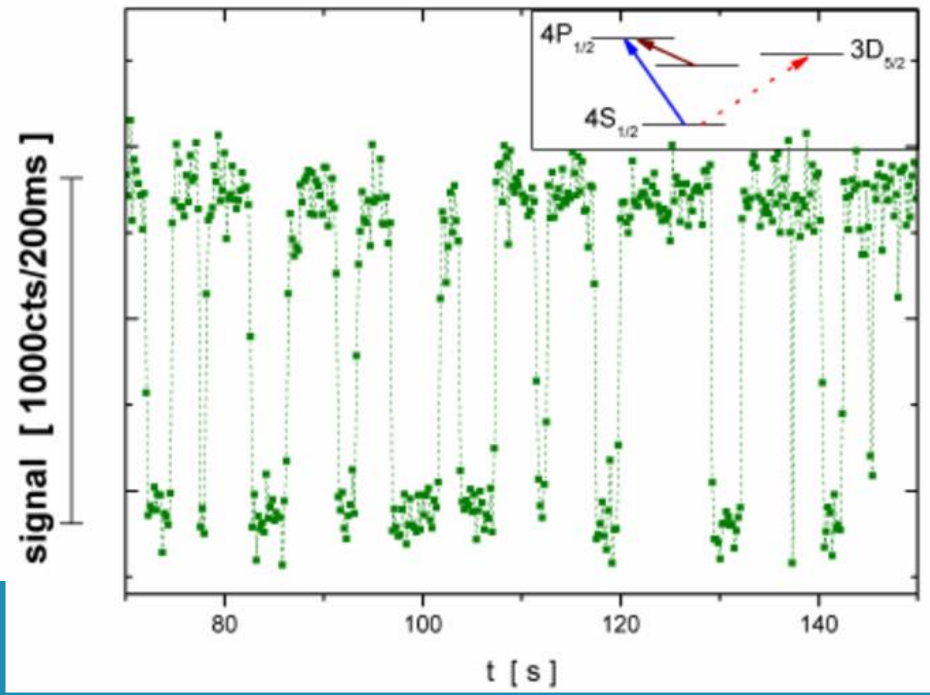
MORA

Opportunity 2: IS spectroscopy of single ions

- Once trapped and 'locked-in' the cooling cycle, a single ion can emit ~10^8 photons per second!
- Spectroscopy can be done with single ions
  - Attractive prospect for exotic isotope studies…



Single ion quantum jumps:



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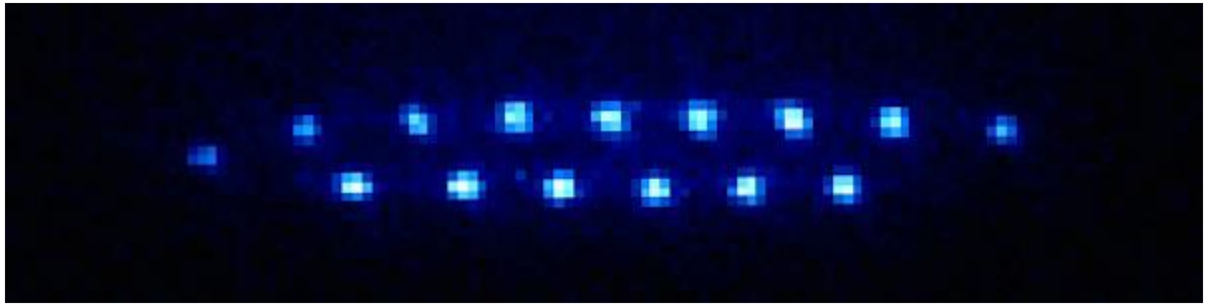
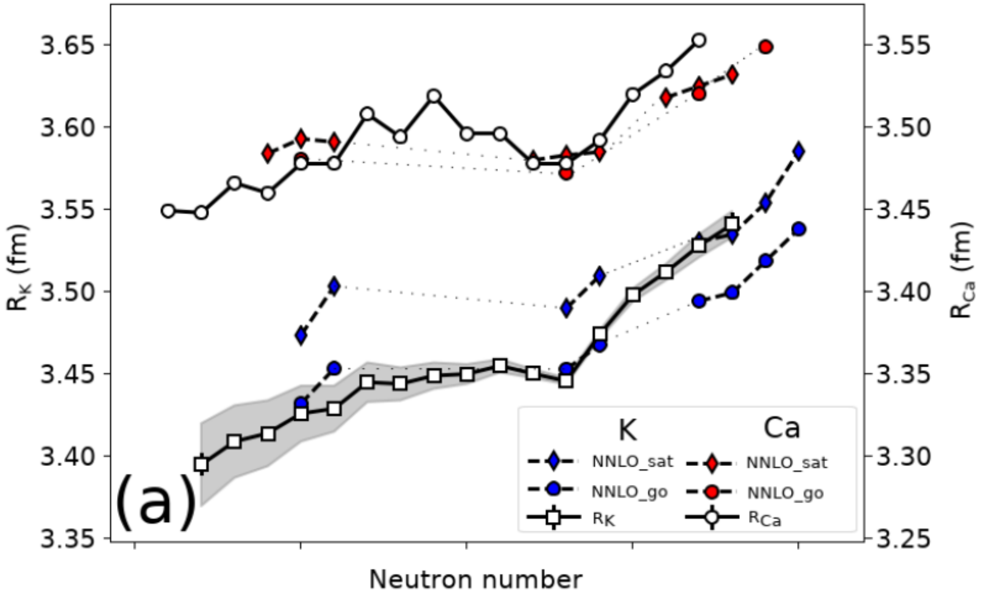
- Once trapped and 'locked-in' the cooling cycle, a single ion can emit ~10^8 photons per second!
- Spectroscopy can be done with single ions
  - Attractive prospect for exotic isotope studies…
- Charge radii of magic calcium isotopes are of considerable interest for testing state-of-the-art nuclear theories
  - Extend measurements far beyond current possibilities?





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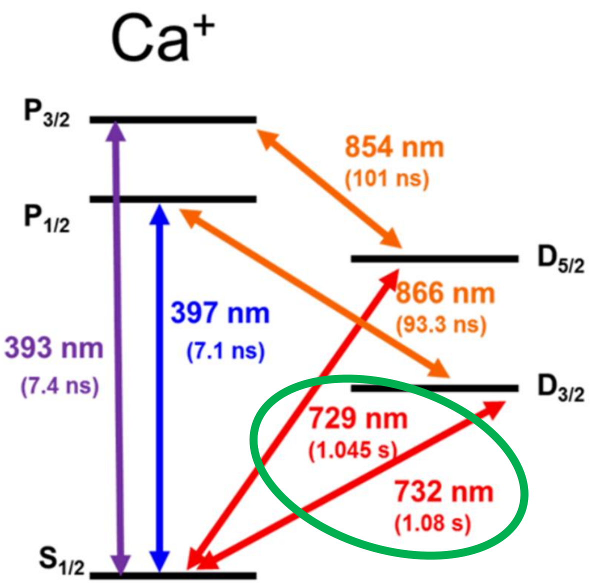
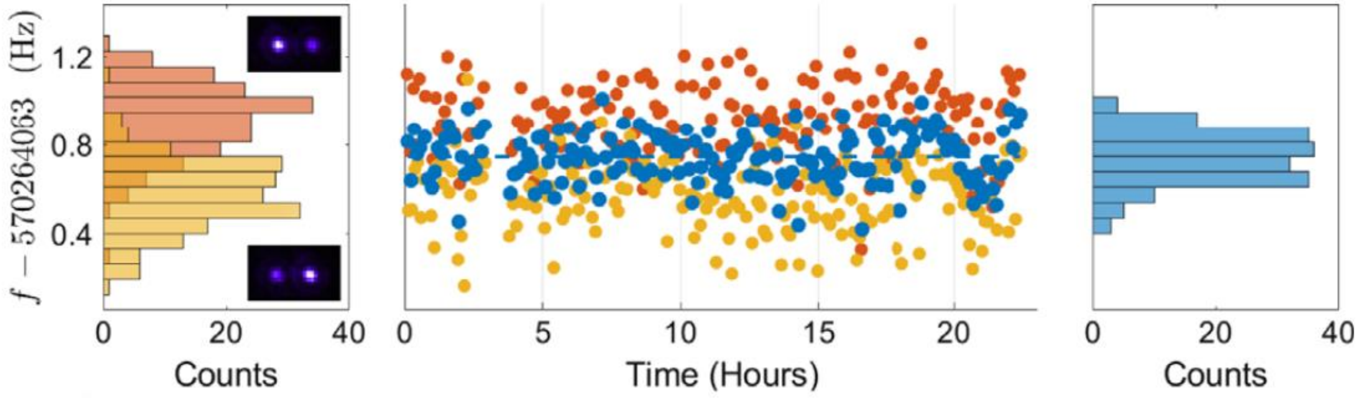
Opportunity 2: IS spectroscopy of single ions

- Isotope shift measurements of the quadrupole clock transitions to mHz levels
- Test for physics beyond the standard model?

shift, generating the slope. From a maximum likelihood fit to a linear relation, we obtain an isotope shift at null magnetic field of $\delta\nu^{S,D}_{88,86} = 570\,264\,063.435(9)(5)(8)$ Hz (total)(statistical)(systematic), which corresponds to a relative uncertainty of 1.6×10^{-11}. Our uncertainty is a $\sim 10^{-17}$ fraction of the optical transition frequency. We also measure a differ-





T. Manovitz et al, PRL 123, 203001 (2019)

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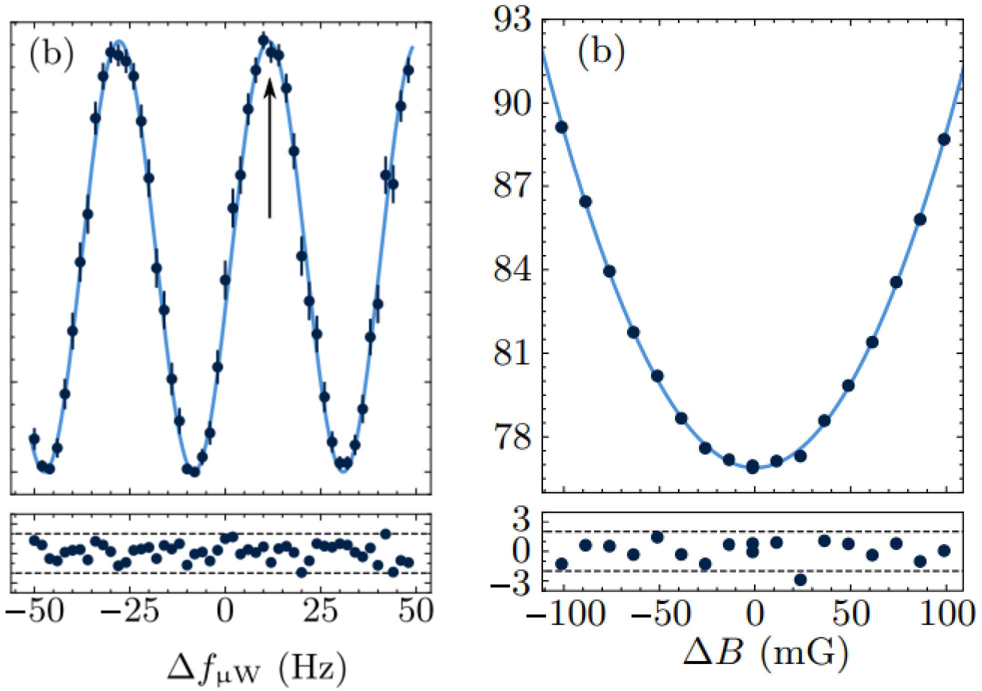
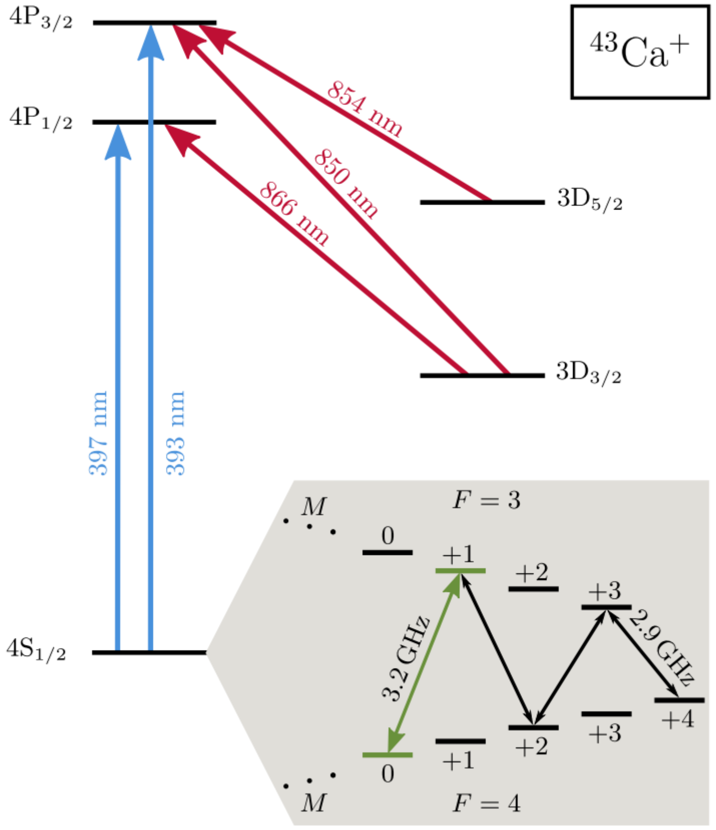
Opportunity 3: moment measurements with single ions

- Direct g-factor measurements in strong external magnetic fields $$H = hA\mathbf{I} \cdot \mathbf{J} - (\boldsymbol{\mu}_\mathbf{J} + \boldsymbol{\mu}_\mathbf{I}) \cdot \mathbf{B},$$
- Nuclear g-factor contribution typically 2000 times smaller





R. K. Hanley et al, PRA 104, 052804 (2021)

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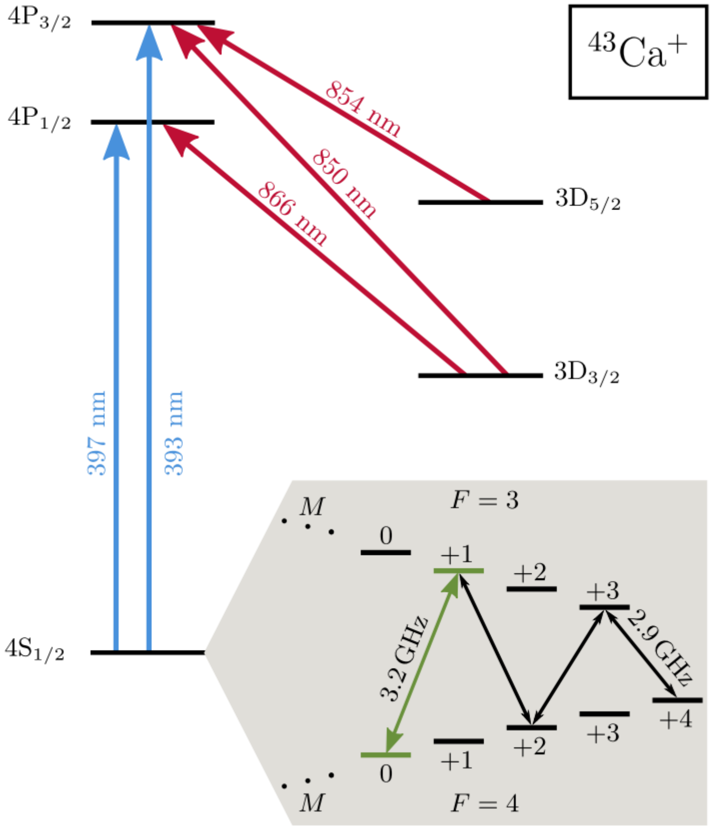
- Nuclear g-factor contribution typically 2000 times smaller

  frequency of $f = 3\,199\,941\,076.920(46)$ Hz

  from which we determine $\mu_I/\mu_N = -1.315\,350(9)(1)$

- Ratio of g-factor and magnetic moment: information on the *magnetization* radius (complimentary to *charge* radius)
  - Can also be probed from ratio of hyperfine constants, which clearly this method is also capable of determining
- Higher-order electromagnetic moments

$$\Omega\left({}^{137}\mathrm{Ba}^{+}_{\mathrm{D}_{5/2}}\right) = 0.0496(37)\ (\mu_\mathrm{N}\times\mathrm{b}),$$



R. K. Hanley et al, PRA 104, 052804 (2021)

In conclusion…

- Laser polarization of Ca will be an additional step in complexity compared to Mg… But not by too much.

- Polarization measurements in MORA require some additional thinking.
  - How to measure fluorescence (efficiently)?
  - Simultaneous with correlation measurement?
  - Laser-cooling required to resolve zeeman substates. Narrowband laser systems required.
    - => Development and investment required

- Synergy with other interesting research avenues exists
  - Laser spectroscopy, enhanced mass spectrometry, …

- Development work in Leuven may provide an interesting route (pending funding)