



# High-precision spectroscopy in Pb: Isotope shift and hyperfine structure measurements

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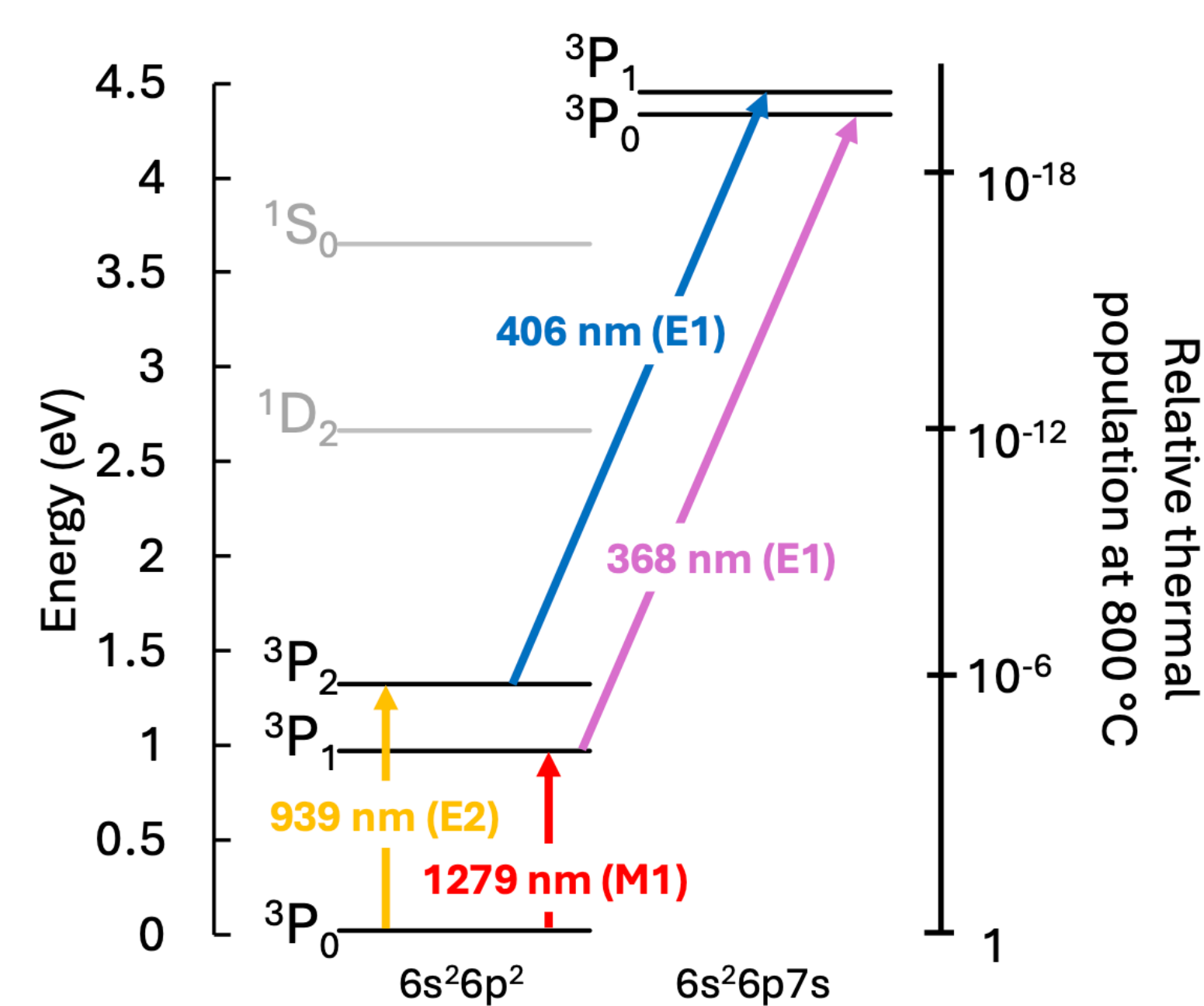
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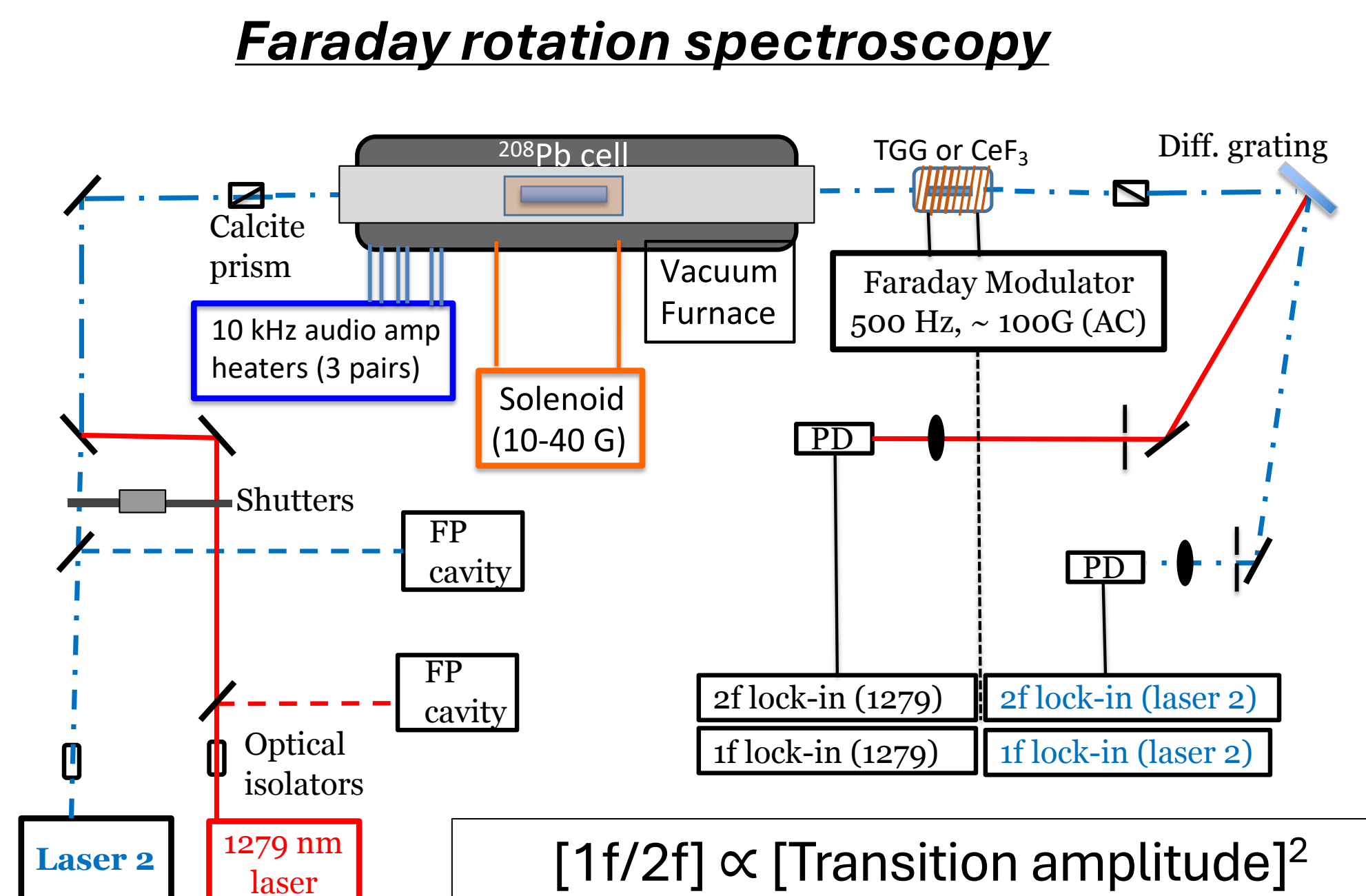
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## Background

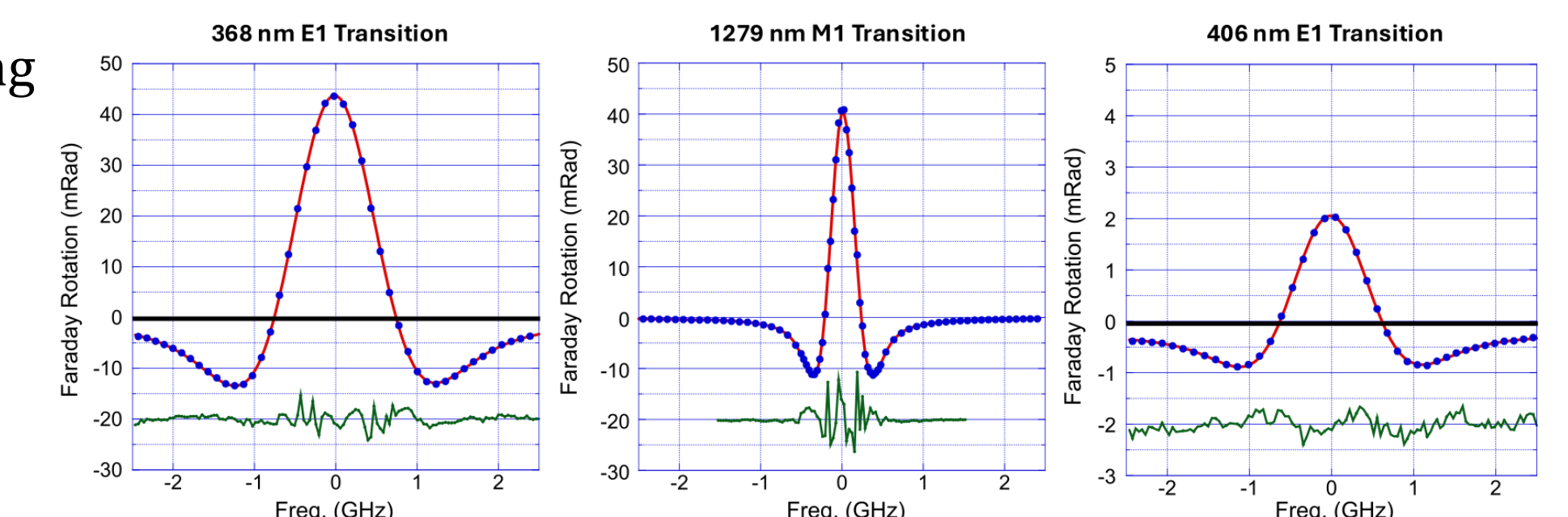
- There are few high-precision atomic structure measurements of heavy, multivalence atoms.
- Transition amplitude (TA) measurements provide benchmark tests for *ab initio* wavefunction calculations (see "Recent work") – relevant to symmetry-violating fundamental interactions.
- Transition isotope shift (TIS) and hyperfine structure (HFS) measurements provide information about nuclear structure and wavefunction behaviour close to the nucleus.
- Goal of the present work: sub-MHz level TIS and HFS measurements in Pb.



## Recent work – Transition amplitude measurements



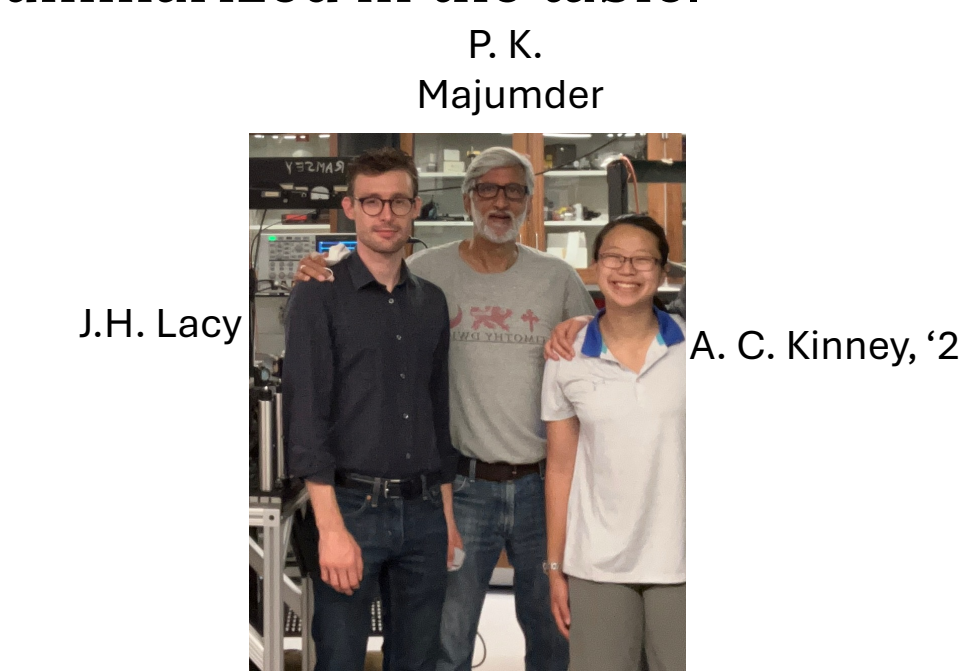
- Recent TA measurements in  $^{208}\text{Pb}$  using Faraday rotation spectroscopy.
- Excellent signal-to-noise ratio (mrad level signals measured with  $\mu\text{rad}$  level resolution) allowing for TA measurements at the sub-1% level.
- Latest results and *ab initio* theory values are summarized in the table.



Representative optical rotation spectra at 800 °C. The precisely known 1279 nm M1 transition serves as a reference.

Transition	Our measurement (a.u.)	Theory (Porsev and Saffronova) (a.u.)
939 nm (E2)	8.91(9)†	8.88(5)
368 nm (E1)	1.90(1)‡	1.92(6)
406 nm (E1)	3.01(2)‡	2.99(9)

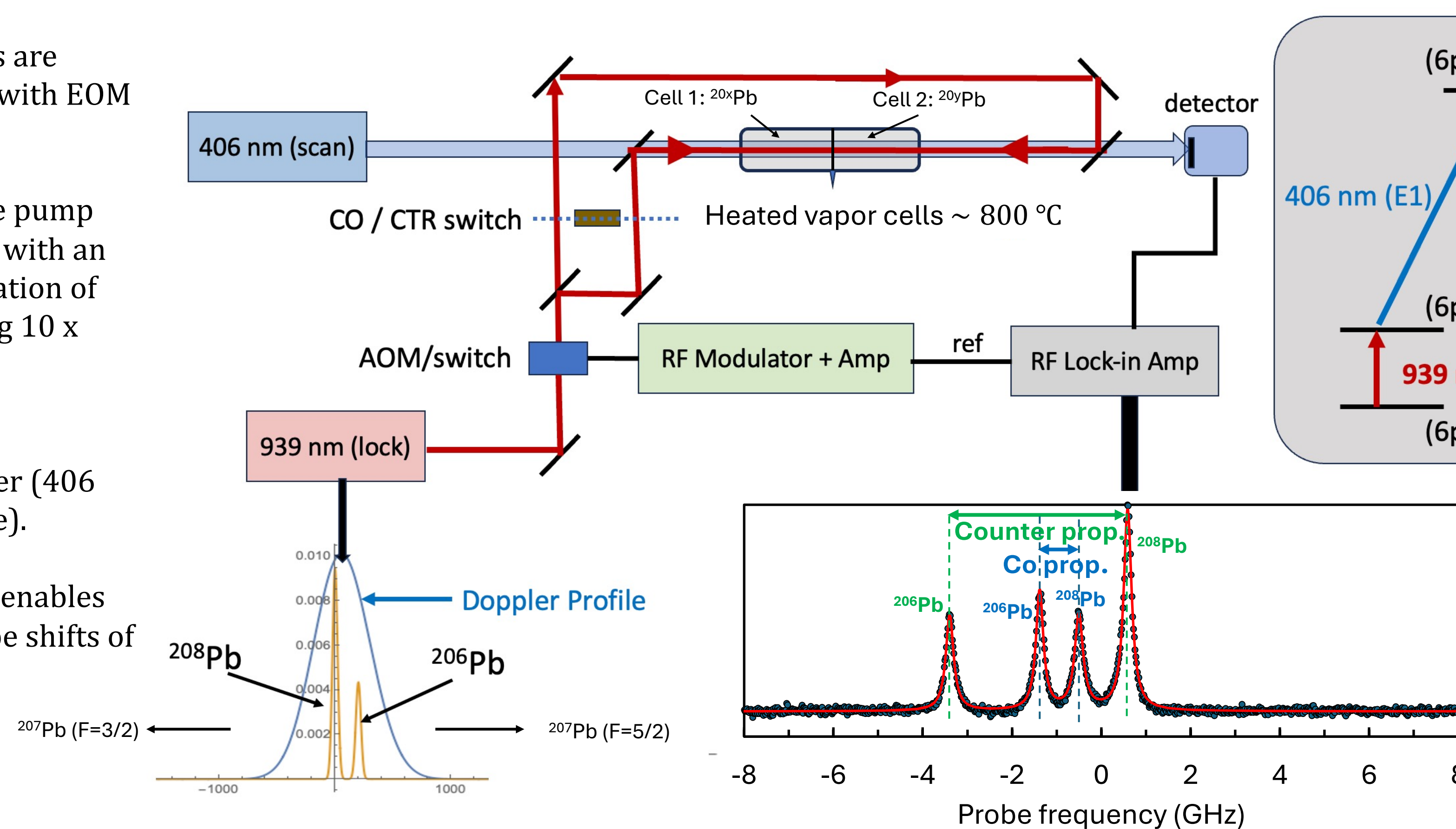
†Phys. Rev. A 100, 052506 (2019)  
‡Phys. Rev. A, 111, 042808 (2025)



## Current work - Experimental apparatus for isotope shift/HFS measurements

### Even isotope shift measurements

- Pairs of quartz vapor cells of different Pb isotopes are placed in series. A Fabry-Perot cavity (calibrated with EOM sidebands) provides the frequency reference.
- Two-step Doppler narrowing spectroscopy:** The pump laser (939 nm in figure) is modulated at ~1 MHz with an AOM + solid-state switch to prevent re-thermalization of the vapor from velocity-changing collisions, giving 10 x narrower spectra.
- Demodulated probe spectrum (406 nm) contains information on *both* the lower (939 nm) and upper (406 nm) TIS (as well as Doppler shifts from resonance).
- Use of co- and counter-propagating pump beams enables the Doppler shifts to be eliminated and the isotope shifts of *both* transitions to be measured:



$$\Delta f_{\text{co(ctr)}} = \Delta f_{406} \mp \frac{\lambda_{939}}{\lambda_{406}} \Delta f_{939}$$

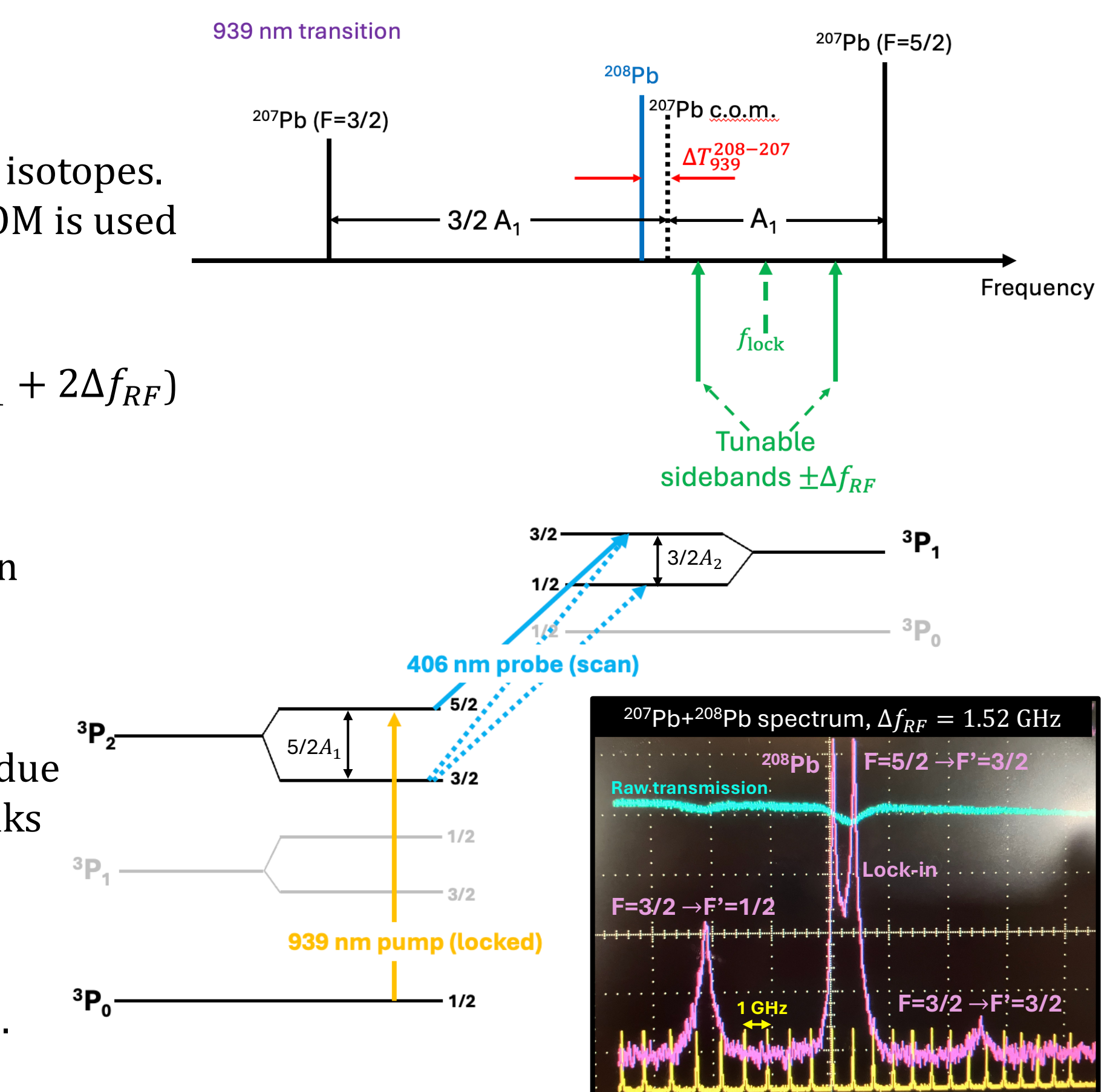
### Measurements of $^{207}\text{Pb}$

- $^{207}\text{Pb}$  peaks are outside the Doppler profile of the even isotopes. To excite  $^{207}\text{Pb}$  + even isotope, a tunable fiber-based EOM is used to provide sidebands to the pump laser.

$$\Delta f_{\text{co(ctr)}} = \Delta T_{406}^{208-207} + \left(A_1 - \frac{A_2}{2}\right) \mp \frac{\lambda_{939}}{\lambda_{406}} (\Delta T_{939}^{208-207} + A_1 + 2\Delta f_{\text{RF}})$$

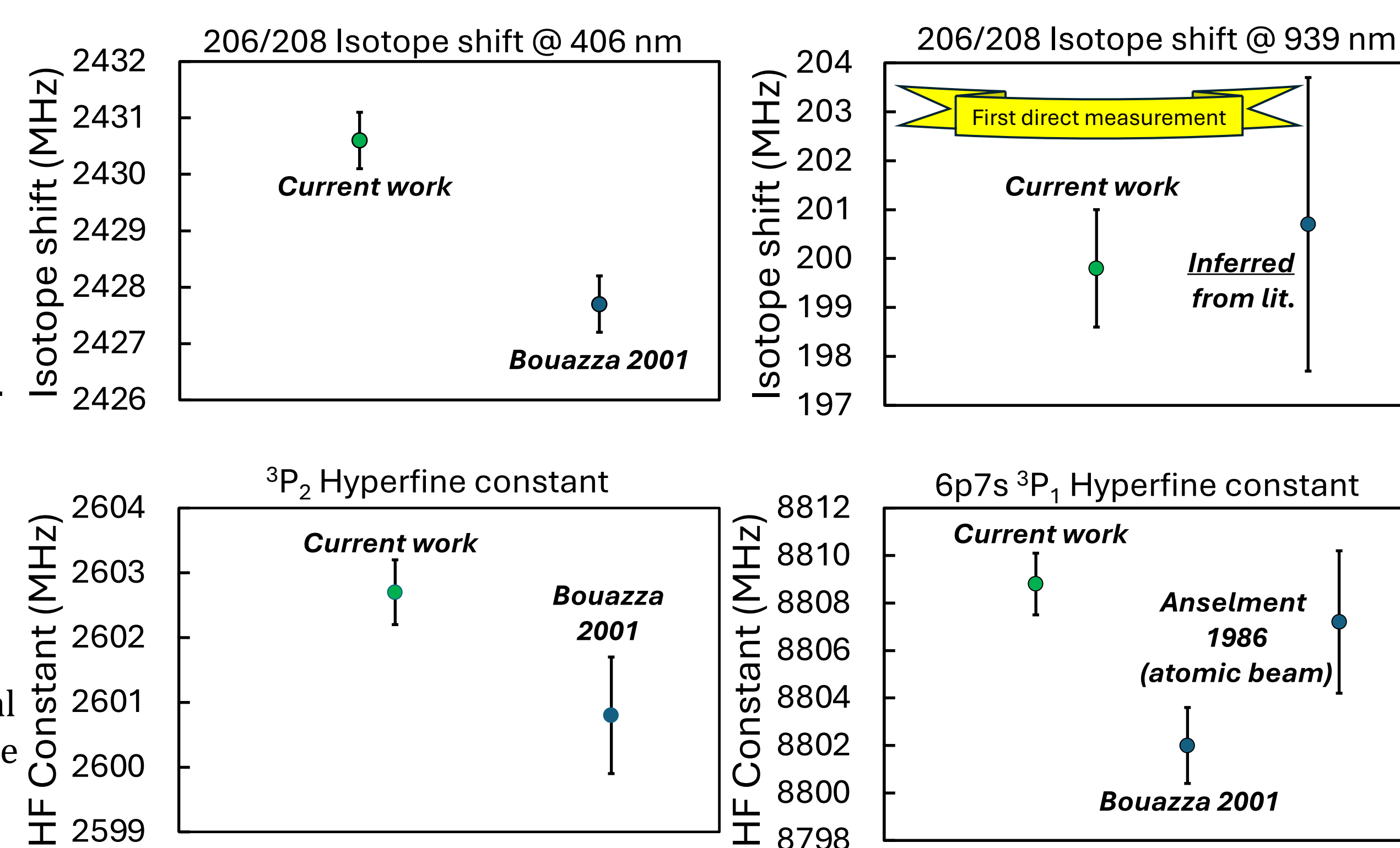
### Measuring the HF constants $A_1$ and $A_2$

- Lock pump laser to excite one hyperfine level ( $F=5/2$  in this case). Scan probe laser. Only one peak should be visible...
- ...but, we observe *all* hyperfine peaks in lock-in signal due to spin-exchange interactions. (Interestingly, these peaks are still Doppler narrowed → not velocity-changing collisions.)
- From the three  $^{207}\text{Pb}$  peaks,  $A_1$  and  $A_2$  can be obtained.



## Current work - Preliminary isotope shift/HFS results

- Subset of preliminary TIS and HF constant data (see additional table for other data values). Final data will be blinded.
- Presented data represents < 2 hours of data collection.
- Key points:**
  - First direct measurement of 939 nm TISs.
  - Small but consistent disagreement with Bouazza 2001 (sat. absorpt. in hollow cathode discharge in Ar atmosphere).
  - MHz level precision after a few dozen scans.
- Systematic effects to investigate:** collisional shifts, AC stark shifts, mixed vs single isotope cells, thermal cycling of the cells, line shape complications, pump laser power and lock point....



## Future work – Stark measurements and transverse laser cooling

### Atomic beam unit

- Static polarizability measurements with 368 nm E1 transition.**
  - Current configuration (depicted).
- Stark induced amplitude of the 1279 nm M1 transition.**
  - Modify to enable fluorescence detection of 368 nm ECDL.
- Transverse laser cooling of atomic beam using 368 nm E1 transition.**
  - Relevant for eEDM searches in Pb-containing molecules.
  - Frequency doubled CW Ti:Sapph. 368 nm cooling laser (B. L. Augenbraun).
  - Magnetic coils to avoid dark state accumulation.

