Precise atomic structure measurements in Pb using vapor-cell and atomic-beam spectroscopy

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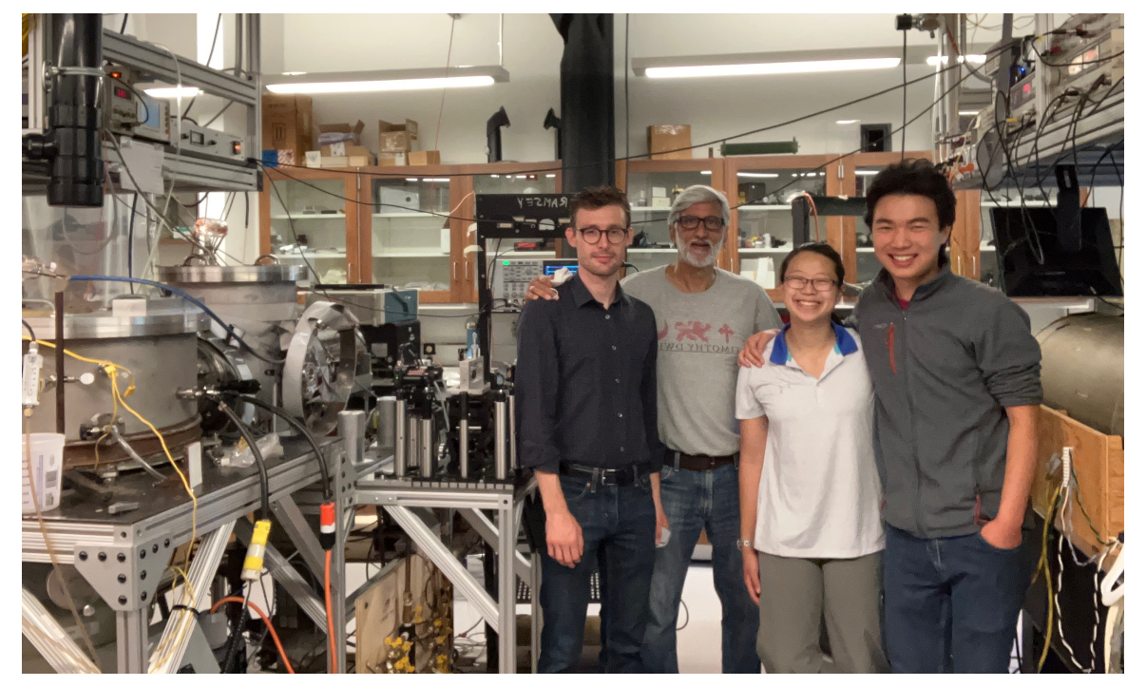


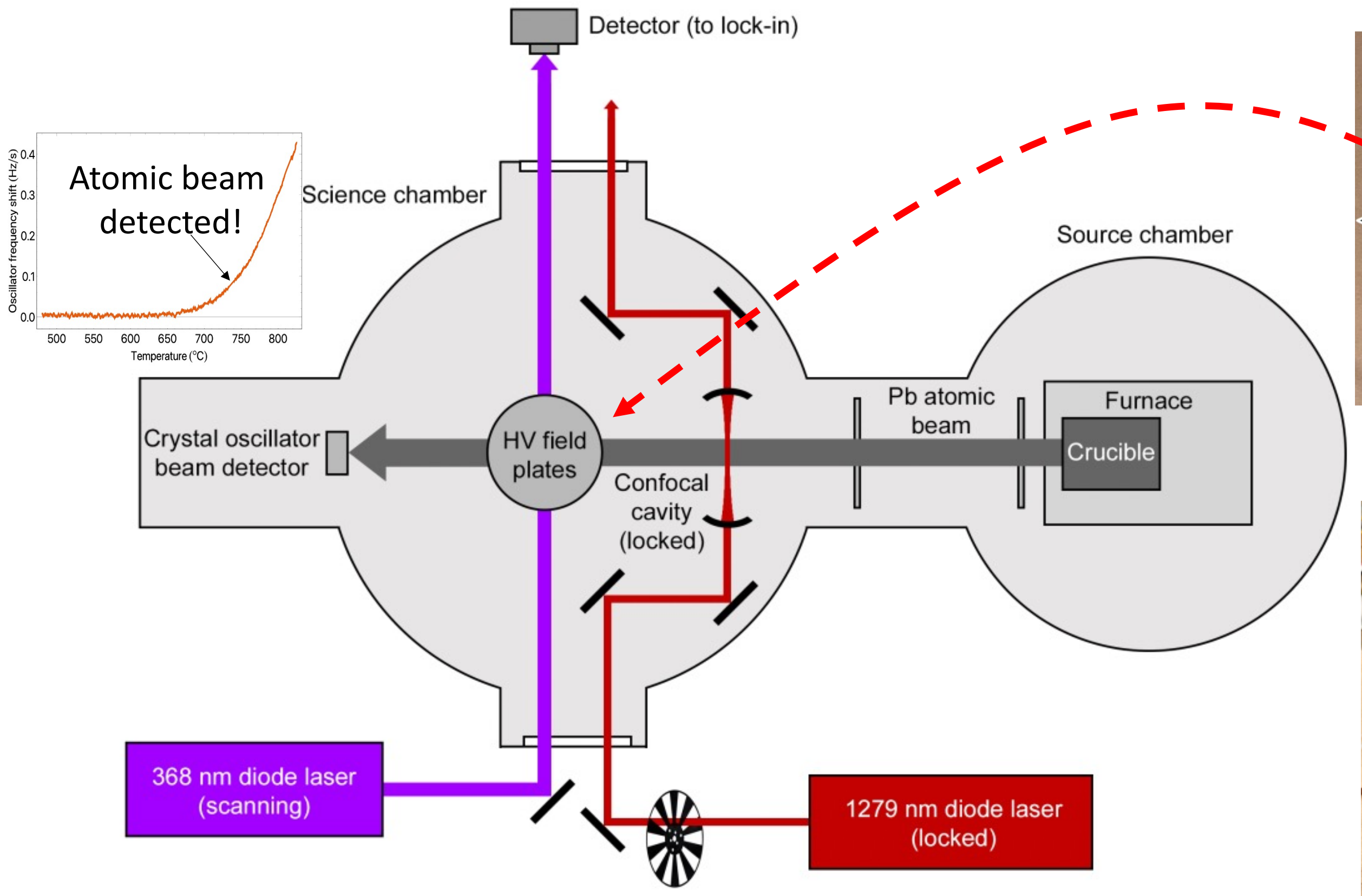
Background

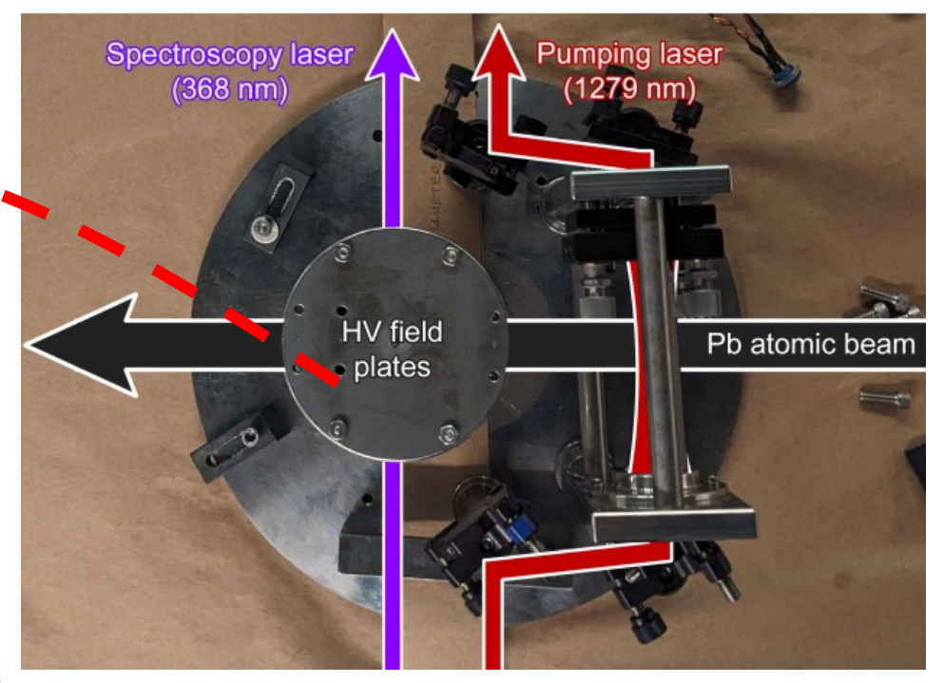
- Heavy, multivalence elements are good testbeds for testing fundamental particle physics interactions → effects scale as ~Z^3. → Atomic theory is challenging!
- Previous work with Group IIIA In and Tl tested *ab initio* multi-valence wavefunction models (Majumder + Safronova group collaborations).
- New focus is on Group IV Pb (two existing precise PNC experimental results). Improved atomic theory, but requires new, accurate experimental benchmarks…

Towards Pb Scalar Polarizability Measurements in an Atomic Beam

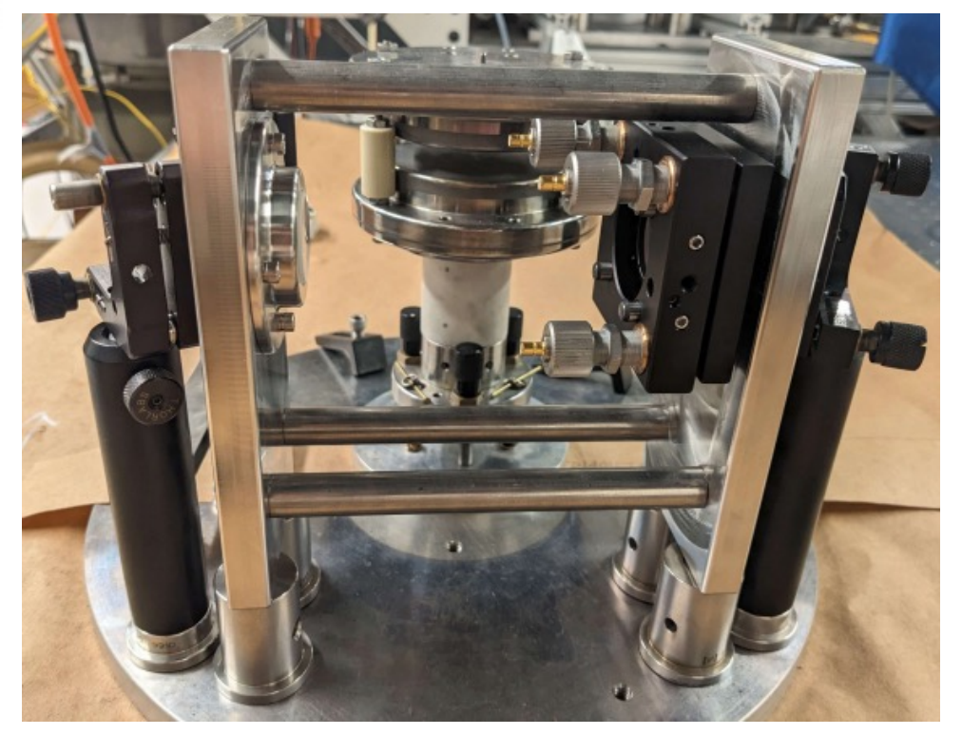
- Quadratic Stark shift: $\Delta E = -\frac{1}{2}\alpha_0\mathcal{E}^2$
- Scalar polarizability, α_0, calculable given atomic wavefunctions → measurements of α_0 serve as excellent benchmark test of theories.
- Expected shift of ~ 50 MHz for $^3P_1 \rightarrow (6p7s)\ ^3P_0$ E1 transition with $\mathcal{E} \approx 20$ kV/cm - easily resolvable

Indium ABU / polarizability results:
2013, 2016, 2018





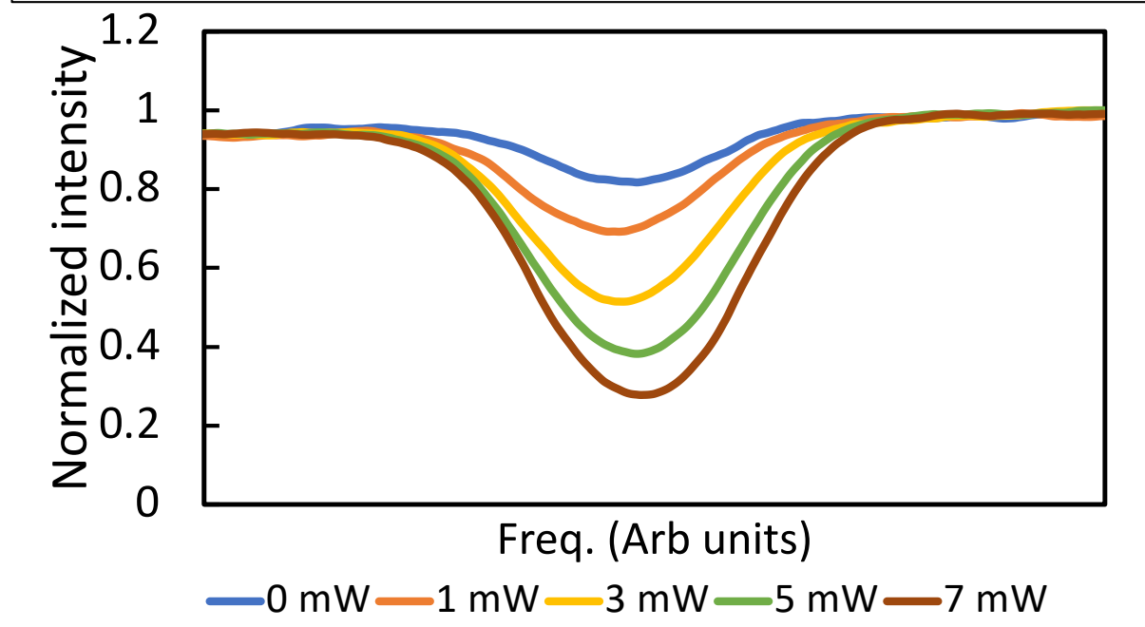
Enhancement cavity



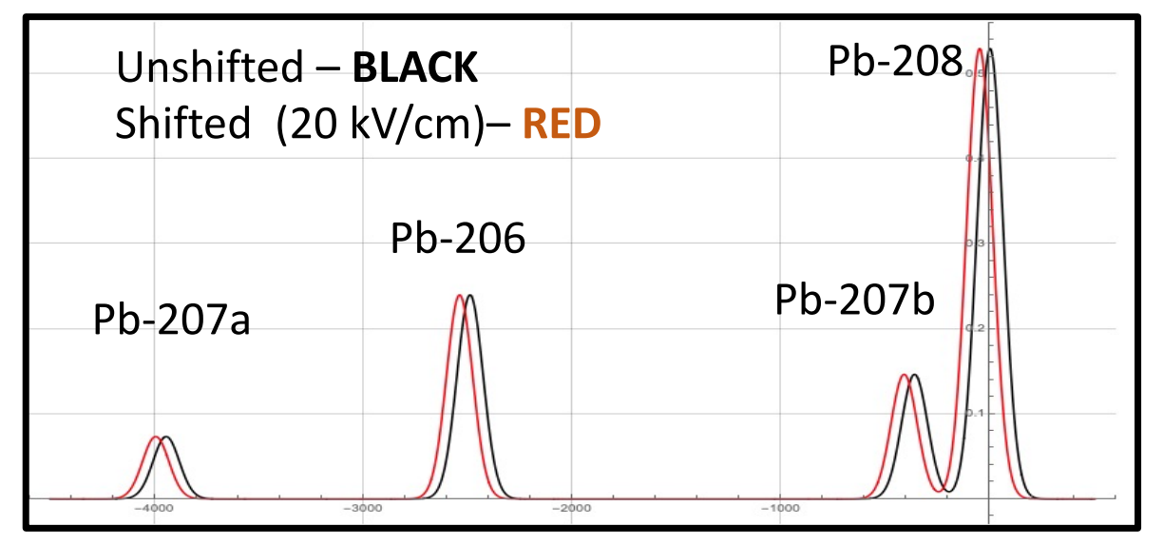
Enhancement procedure:

1. Lock 1279 nm laser to $^3P_0 \rightarrow {}^3P_1$ transition (1279 nm).
2. Lock enhancement cavity to steep edge of a Fabry-Perot fringe.
3. $^3P_1$ population enhanced (x50) as atomic beam passes through cavity (τ ~ 0.25 s).
4. Probe $(6p^2)\ ^3P_1 \rightarrow (6p7s)\ ^3P_0$ transition (368 nm) under high $\mathcal{E}$-field.

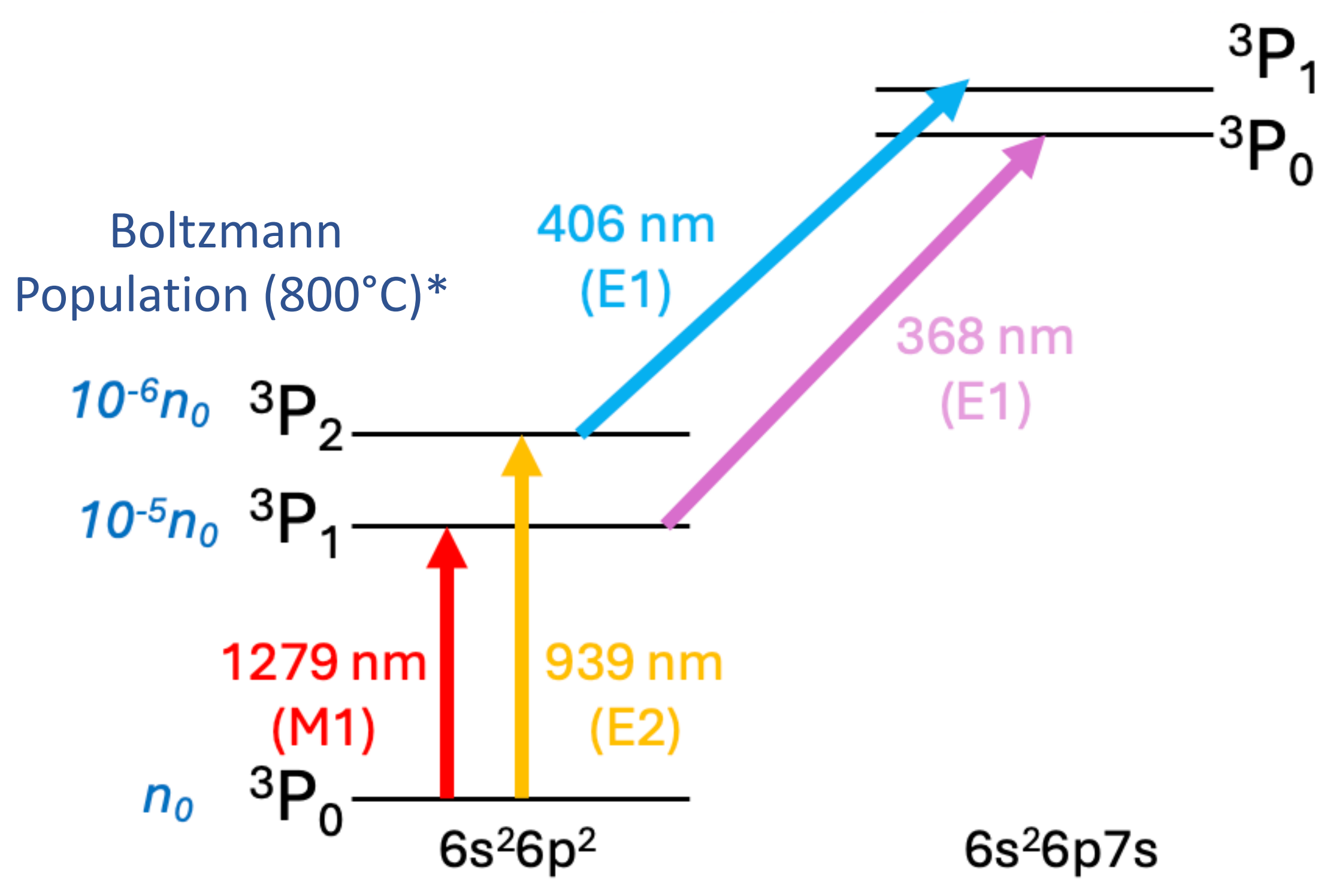
Single pass enhancement (vapor cell)



Quantity (rel. to vapor cell @ 800 °C)	Vapor cell in furnace	Atomic beam (@ 1050°C)
Peak absorption cross section	σ_0	σ_0 ×10 (Doppler narrowing)
$^3P_1$ number density	n_0	n_0 × 50 (M1 pre – pumping) × 10 (thermal/Boltzmann) × 10^{-4} (Geometrical loss)
Interaction length	ℓ	ℓ × 0.2 (atomic beam width)
Optical depth	**1**	**0.01 - 0. 1**

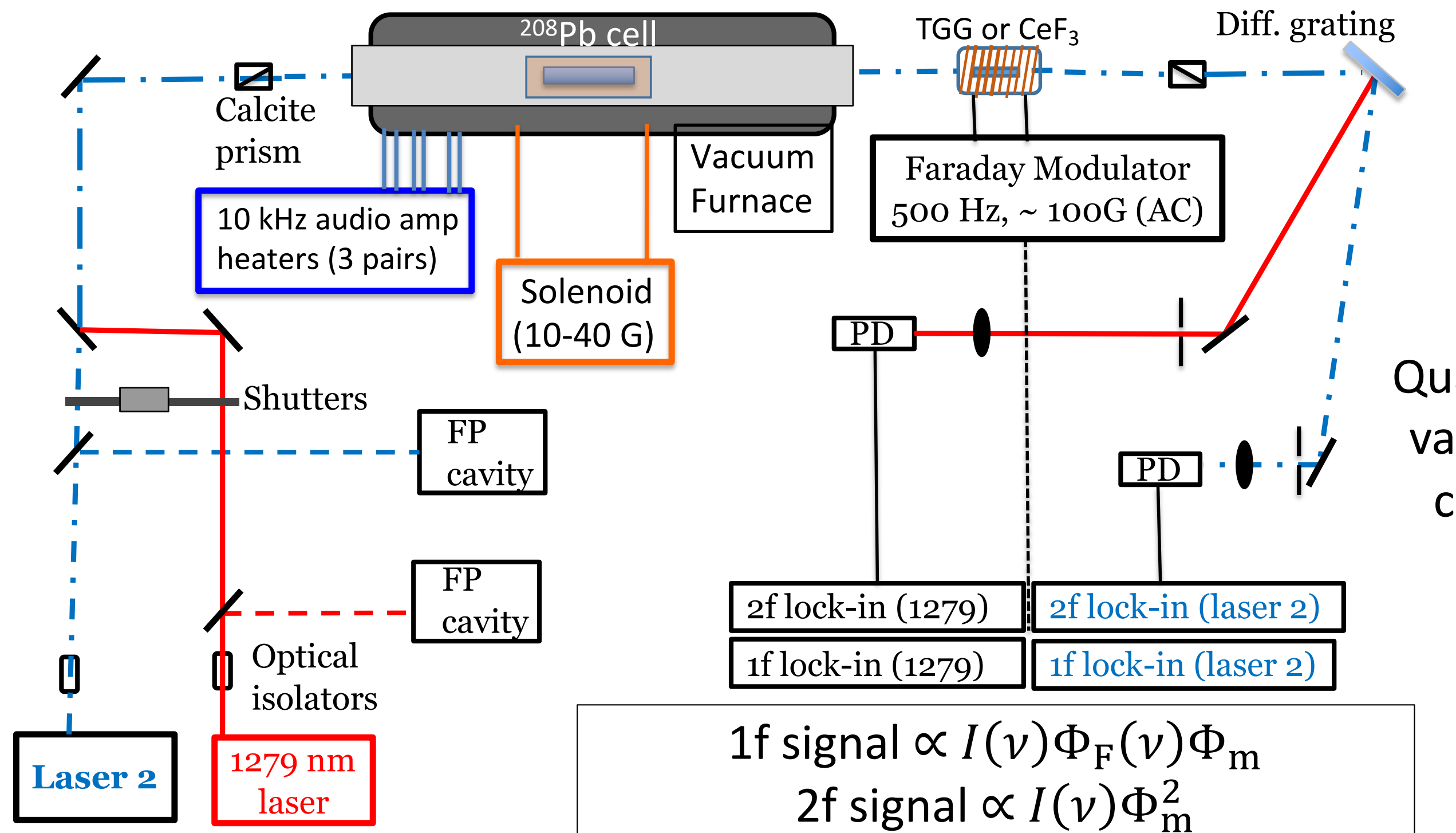


Pb energy levels (group IV)



**E1 transition amplitude measurements require accurate determination of thermal population*

E1 transition amplitudes of (thermally) excited states using Faraday rotation spectroscopy

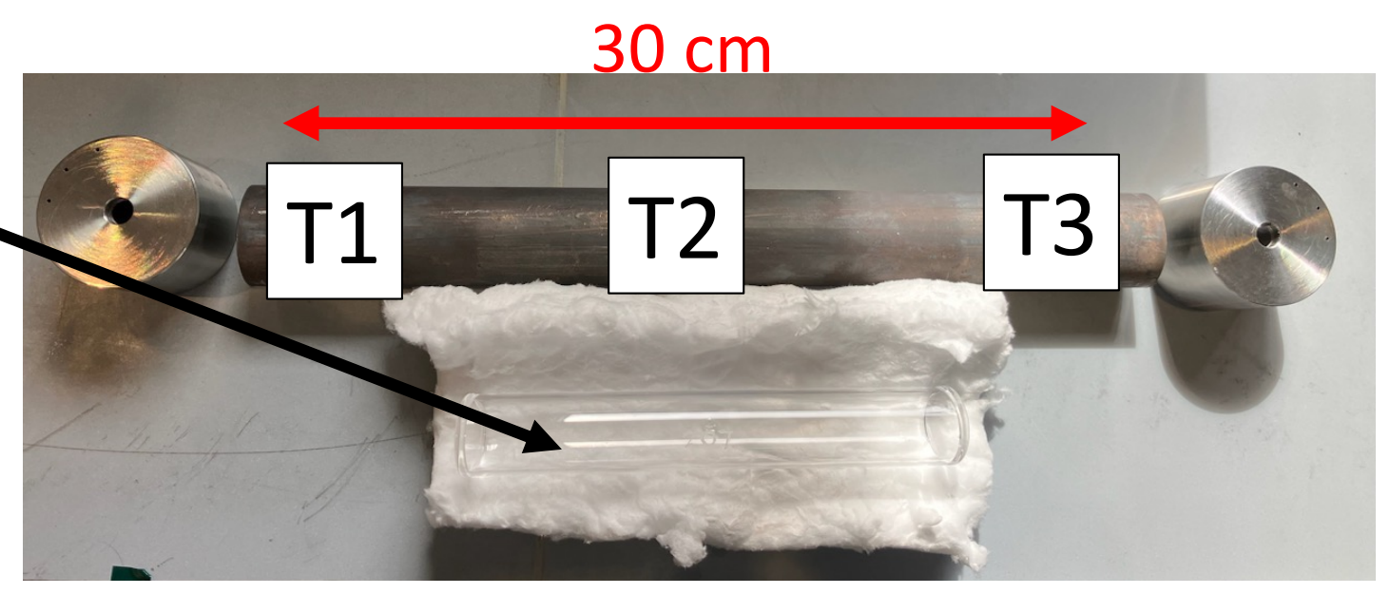


$$1\text{f signal} \propto I(\nu)\Phi_F(\nu)\Phi_m$$
$$2\text{f signal} \propto I(\nu)\Phi_m^2$$
$$\rightarrow [1f/2f] \propto \Phi_F(\nu)/\Phi_m$$

Faraday line shape Crystal λ-dependent property (requires calibration)

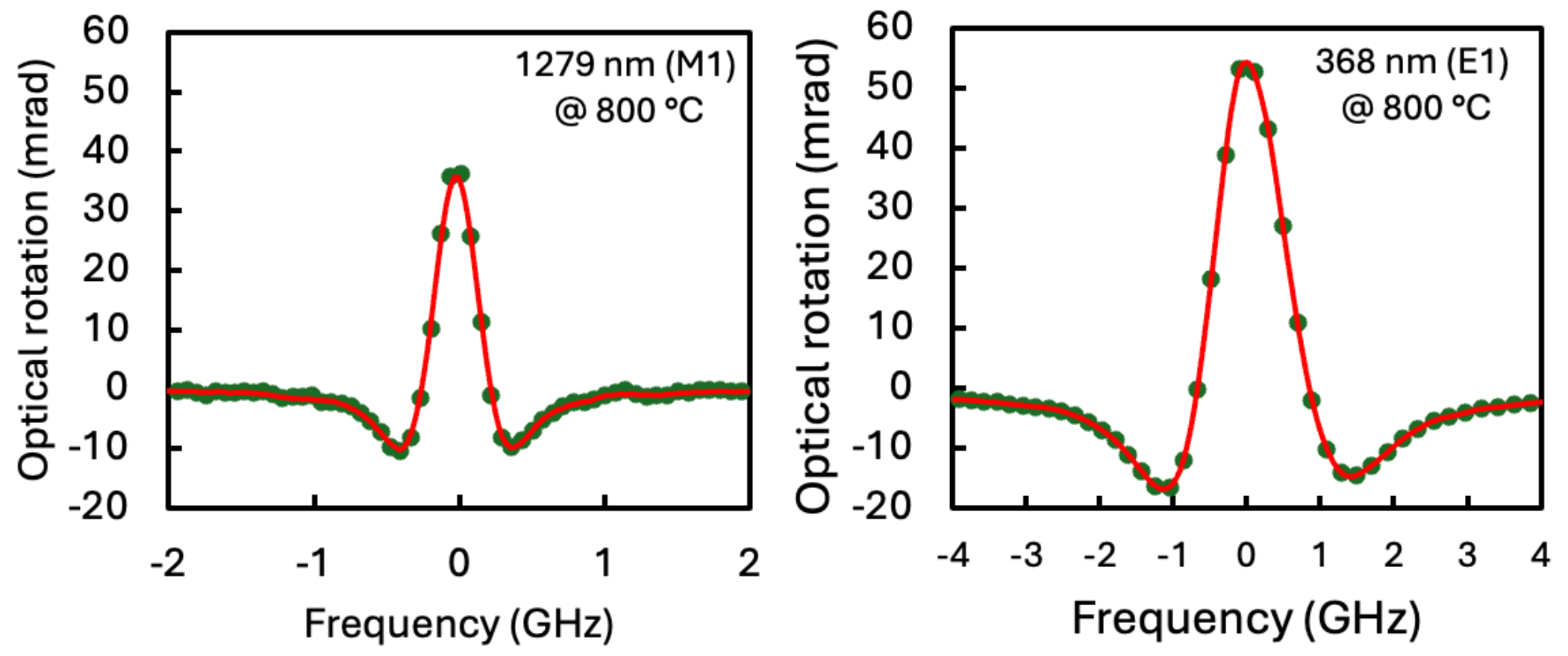
- Evacuated Furnace
- Quartz cell embedded in SS tube + endcaps
- 3-zone heating elements for ‘uniformity’
- 3 S-type TC’s (± 1.5° K) + SR630 reader

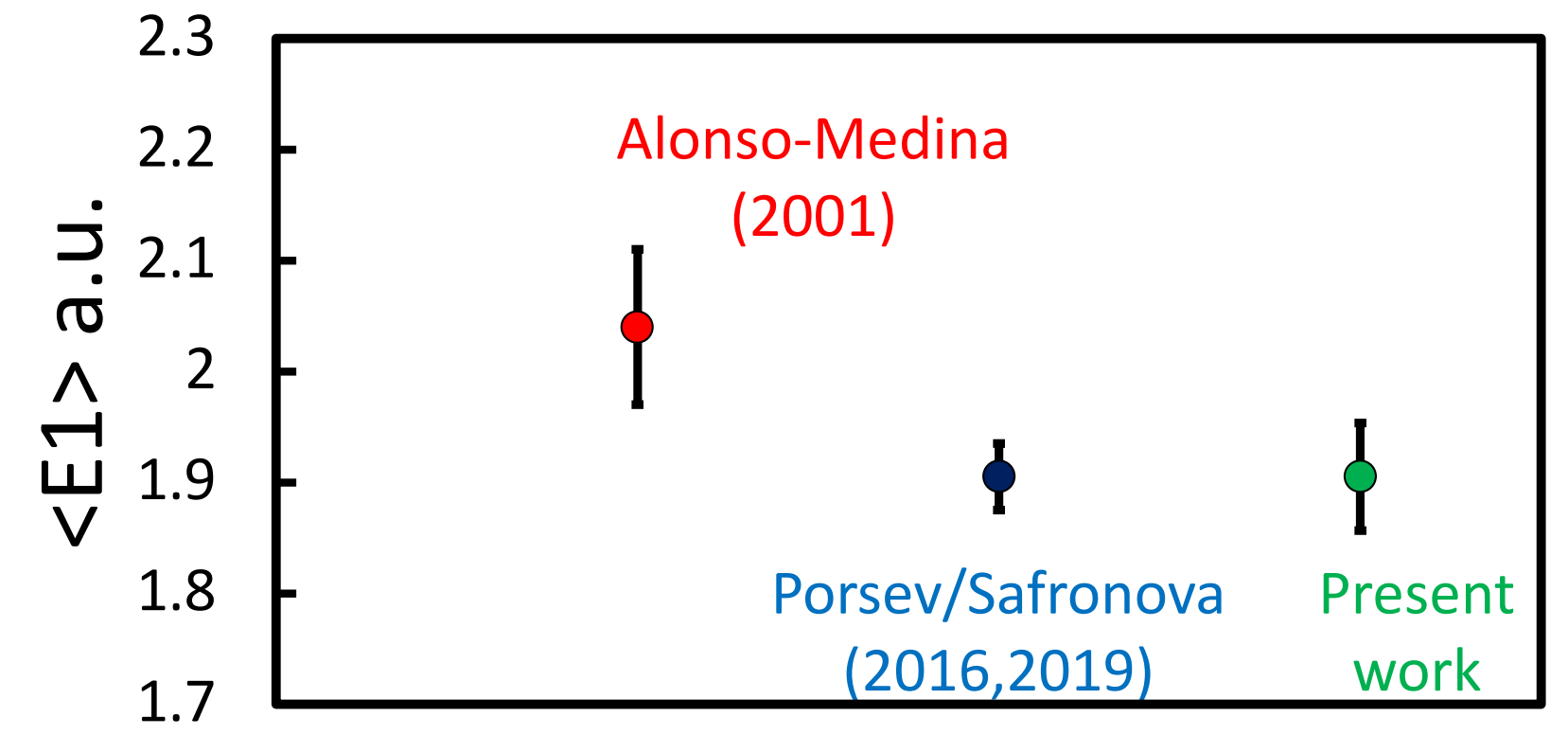
Quartz vapor cell



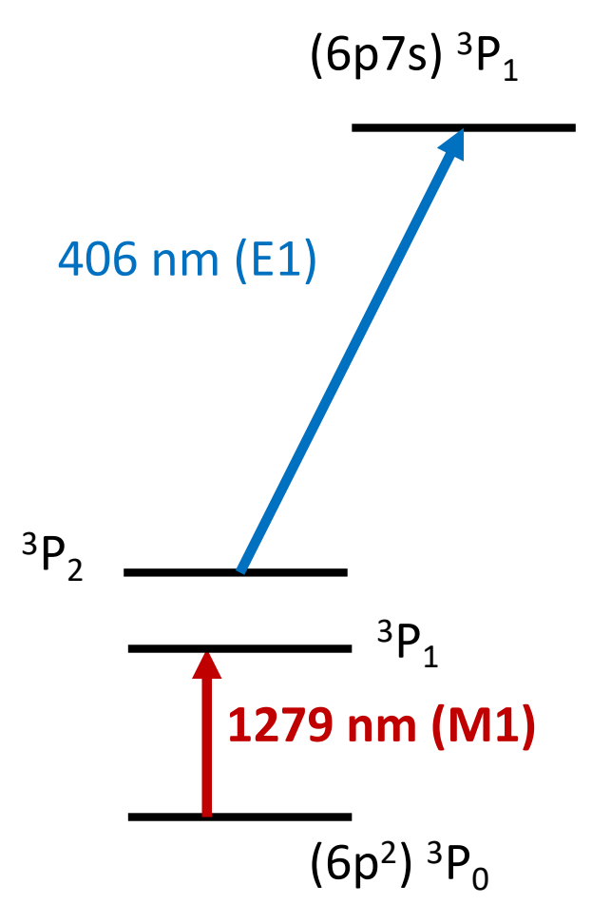
- → overall Temp variance/accuracy: ~ ±1 °K
- → ~ 0.5% contribution to <E1> uncertainty

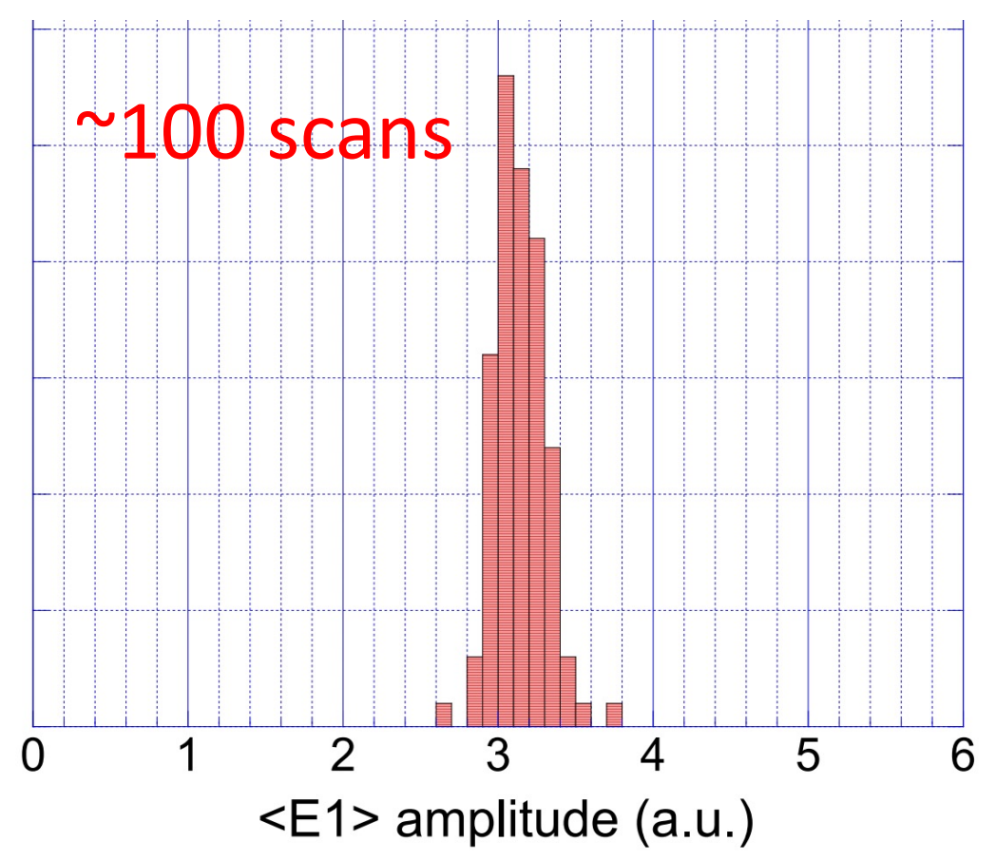
$(6p^2)\ ^3P_1 \rightarrow (6p7s)\ ^3P_0$





$(6p^2)\ ^3P_2 \rightarrow (6p7s)\ ^3P_1$



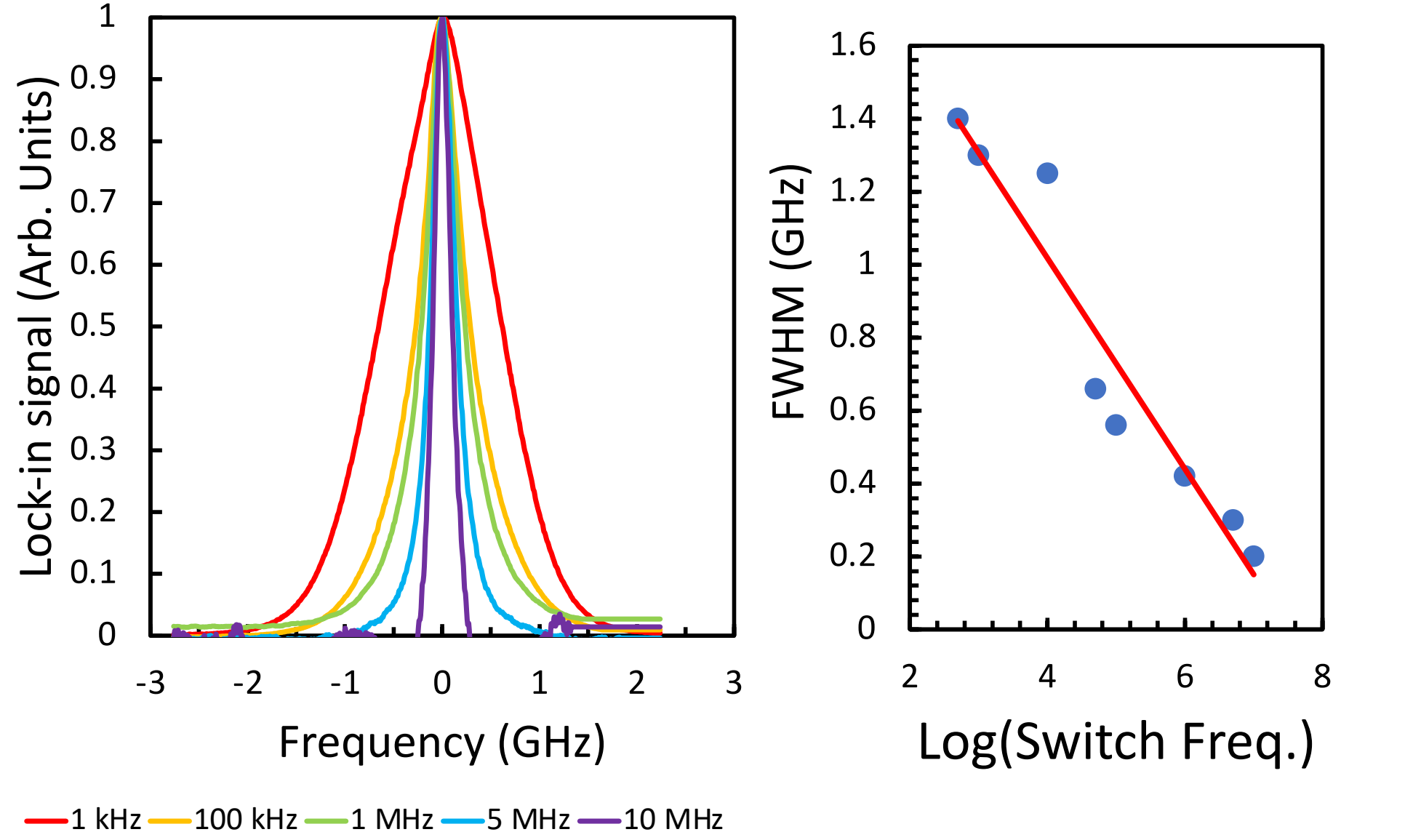


	<E1> a.u.
Alonso-Medina (2001)	3.1(2)
Penkin (1963)	3.0(3)
Theory	–
Our value**	**3.13(2)(10)**

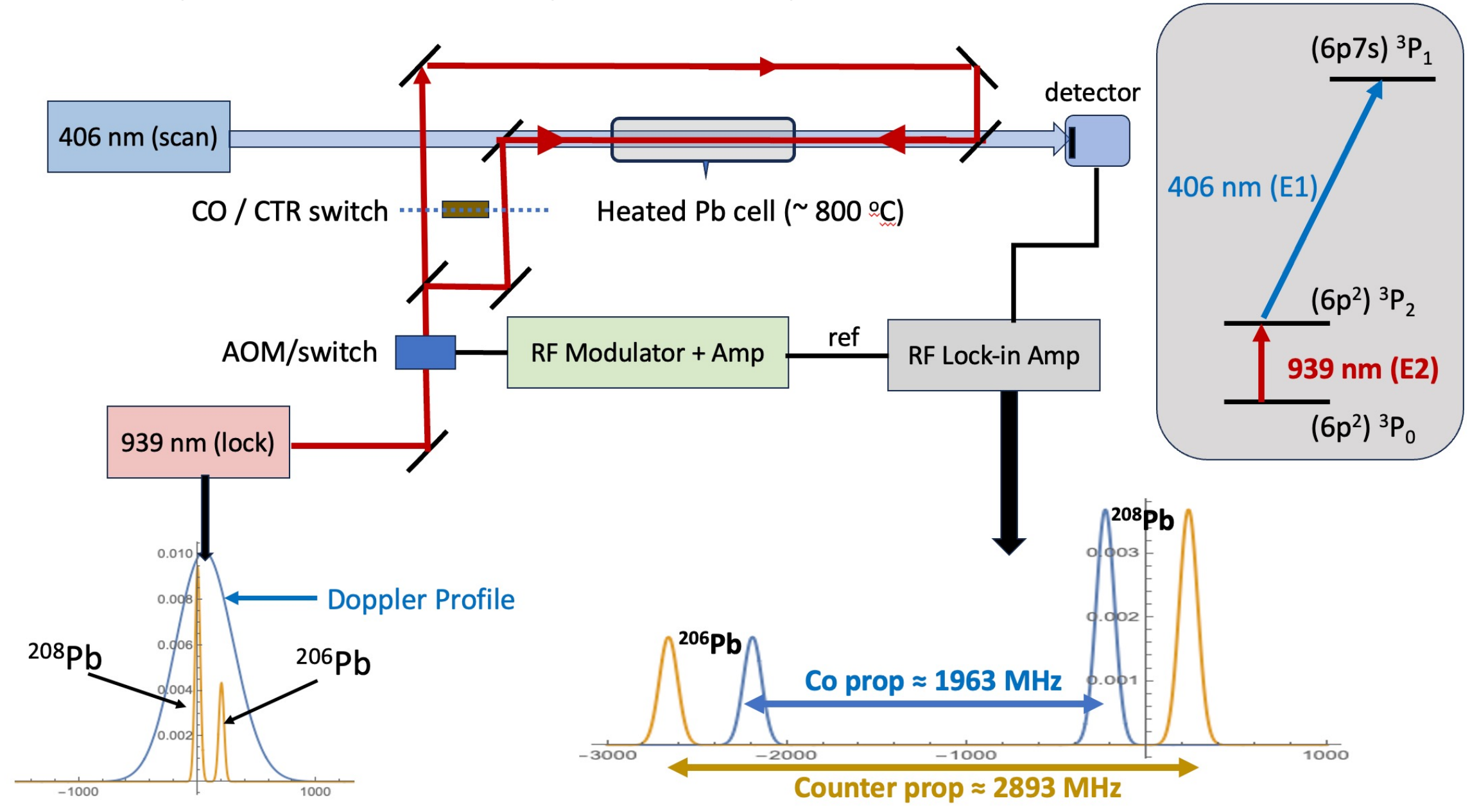
Doppler narrowed two-step spectroscopy in Pb

- Few forbidden transition isotope shift measurements in Pb exist.
- Measurement precision limited by velocity-changing collisions.
- ***Solution:*** use fast-switching (kHz→MHz) AOM and lock-in detection
  - Lock pump (939 nm) laser to ^{208}Pb and ^{206}Pb midpoint.
  - Scan 406 nm laser.
  - Counter and co-propagating configurations allow for isotope shifts of both the $(6s^2)\ ^3P_1$ and $(6p7s)\ ^3P_0$ levels to be determined.

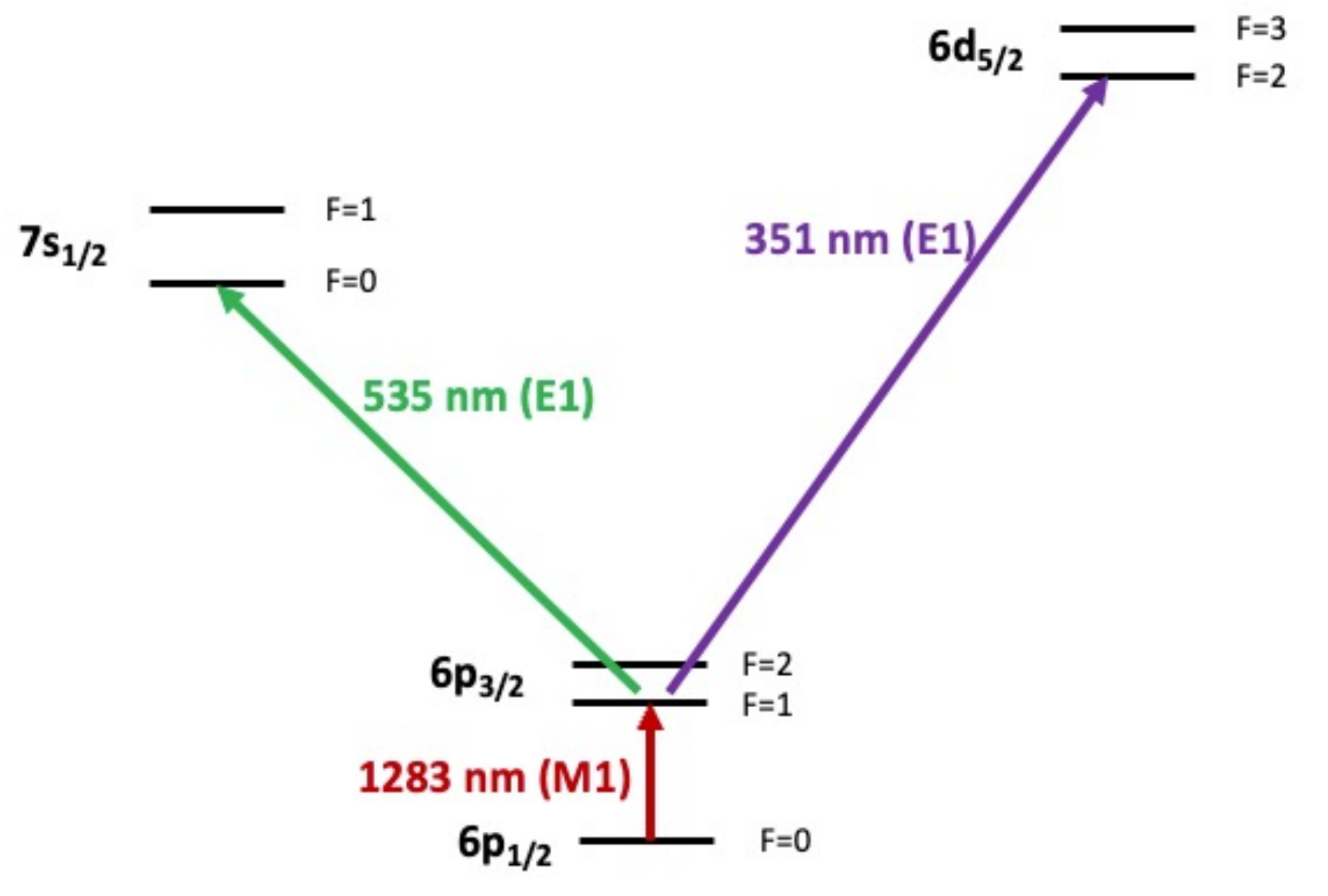
Doppler narrowing observed in ^{208}Pb (406 nm transition)



Experimental setup for isotope shift measurement



Future Work



Tl-205 (70%), Tl-203 (30%), both I=1/2

- Isotopically pure Tl-205 cell for <E1> amplitude measurements:
  - Faraday rotation spectroscopy and/or transmission spectroscopy (as above) to measure $\frac{\langle E1\rangle}{\langle M1\rangle}$ ratio.
  - <M1> precisely calculable, serves as reference
  - Generate green or near UV light via fiber-based frequency doubling
- Natural abundance (205/203) cell for Isotope Shifts:
  - M1 pump with fast switch / lock-in detection of Doppler-free E1 transmission signal (as above).
  - CO / CTR signals again reveal both upper state and $6p_{3/2}$ – state isotope shift (never measured)