Multi-photon clock atom interferometry

2nd Terrestrial Very-Long-Baseline Atom Interferometry Workshop

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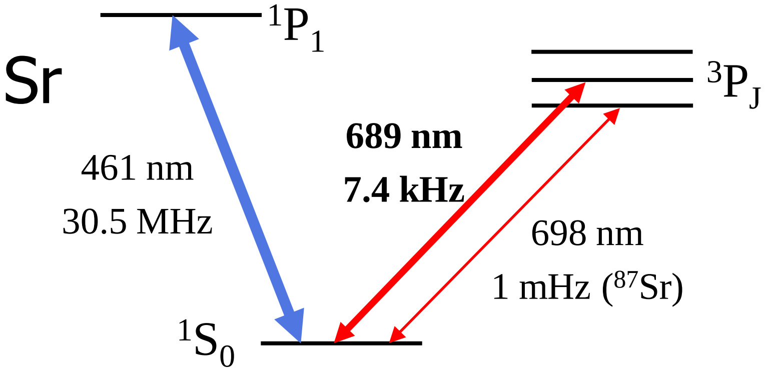
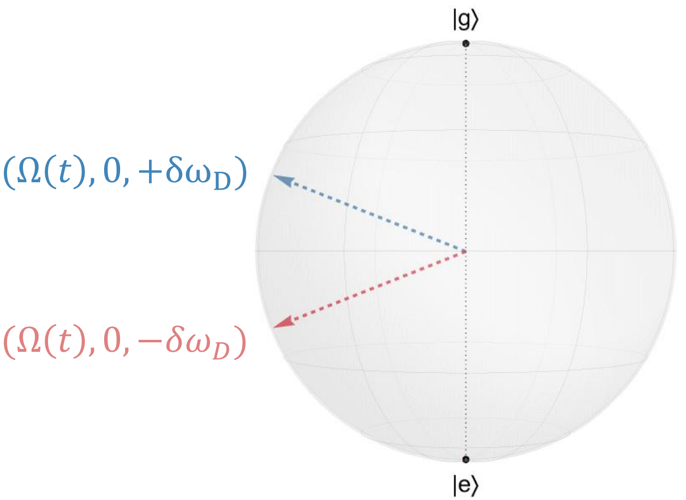
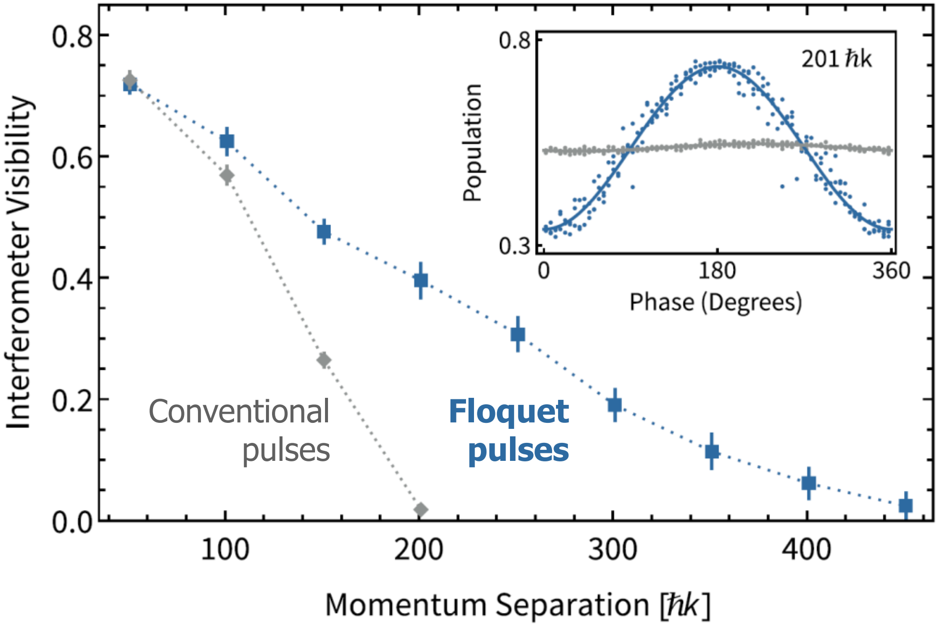
Broadband LMT Clock Atom Interferometry

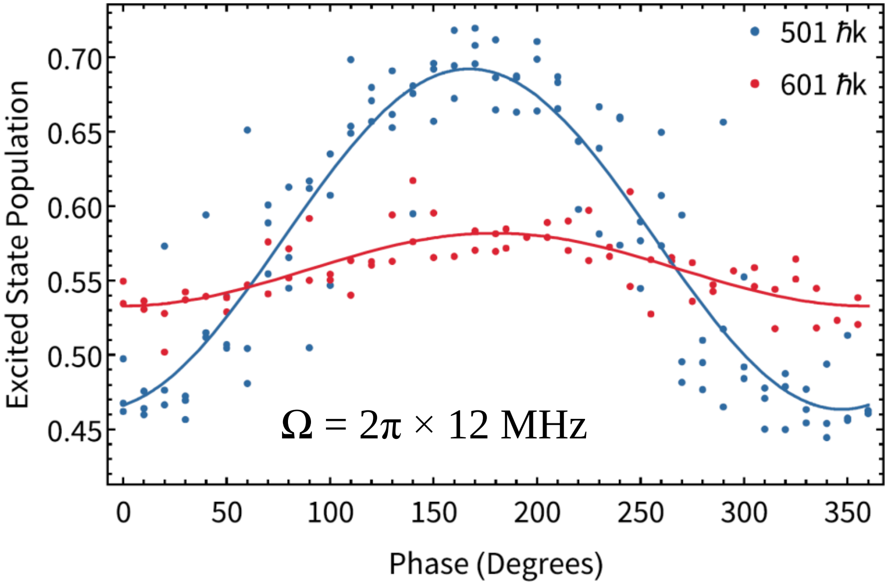


- ^{88}Sr, $^1S_0 \rightarrow {}^3P_1$ transition (689 nm)
- **Broadband**: laser cooled atoms (red MOT)
- **Fast**: 601 ħk splitting in ~20 μs



Floquet modulation technique to symmetrically drive both arms



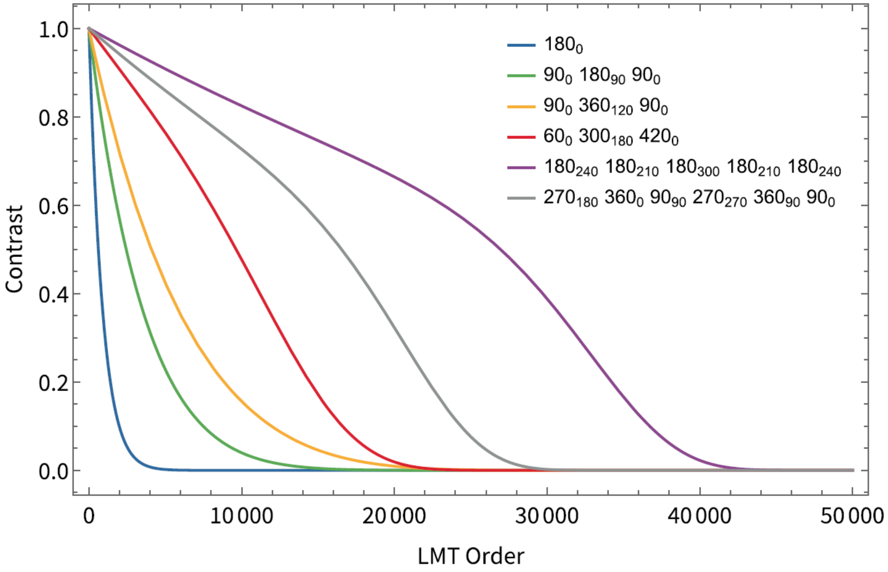


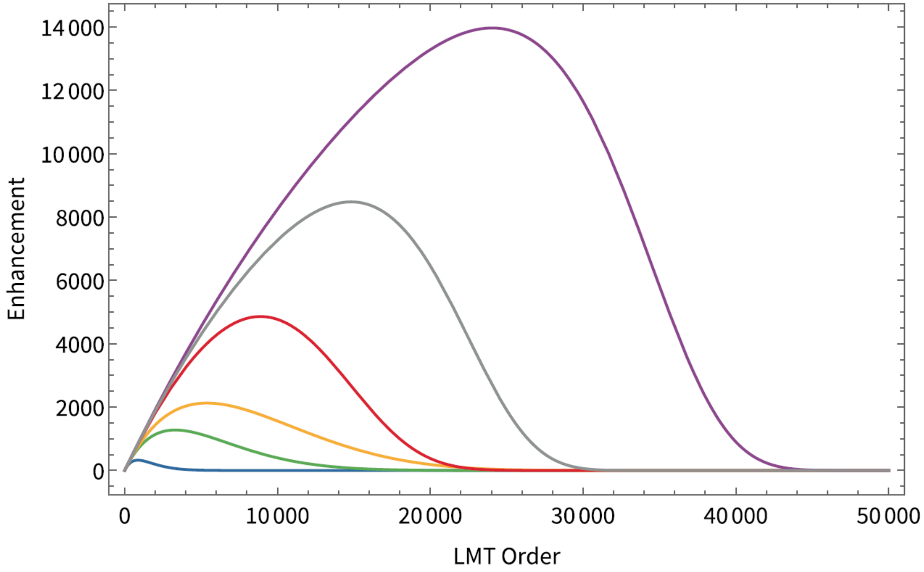
Narrowband LMT Clock AI Limits

- For gravitational wave detection in MAGIS, need the $^1S_0 \rightarrow {}^3P_0$ **transition (698 nm)**
- Full scale MAGIS detector (on Earth) requires extreme LMT, beyond state-of-the-art
- Simulation effort to understand future limits

Constrained optimization includes:

- Spontaneous emission decay
- Off-resonant scattering
- Detuning errors (Doppler, laser noise)
- Intensity inhomogeneities
- Timing jitter





- Laser: 5W, 1 Hz linewidth
- ^{87}Sr DFG, matter wave lens

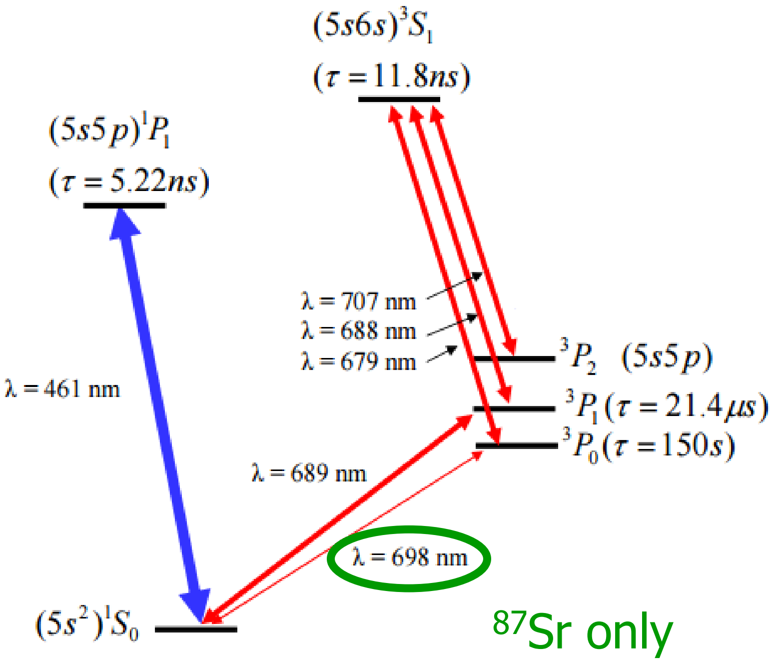
Interferometer enhancement factors $>10^4$ theoretically possible, but transitions are **too slow** (at this power)

Multiphoton Clock Atom Interferometry Motivation

$^1S_0 \rightarrow {^3P_0}$ clock transition in Sr at 698 nm is only naturally allowed in fermionic ^{87}Sr

Bosons have interesting properties:

- Scalar polarizability of clock states
- Zero linear Zeeman shift in ground state
- High natural abundance
- Reduced interaction strength (e.g., ^{88}Sr)
- Easier state preparation (I=0)
- Possible to make BEC (e.g., ^{84}Sr)

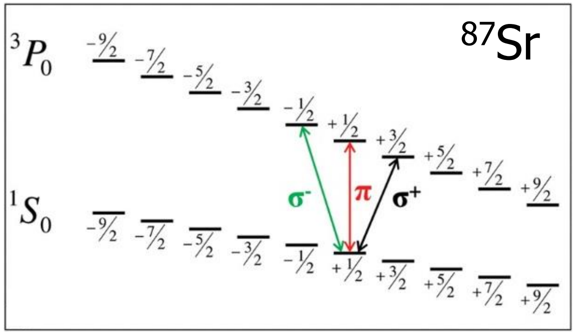


^{87}Sr only

Proposal: Use multi-photon excitation to populate $^3P_0$ state for atom interferometry

$$^1S_0 \rightarrow {^3P_1} \rightarrow {^3S_1} \rightarrow {^3P_0}$$

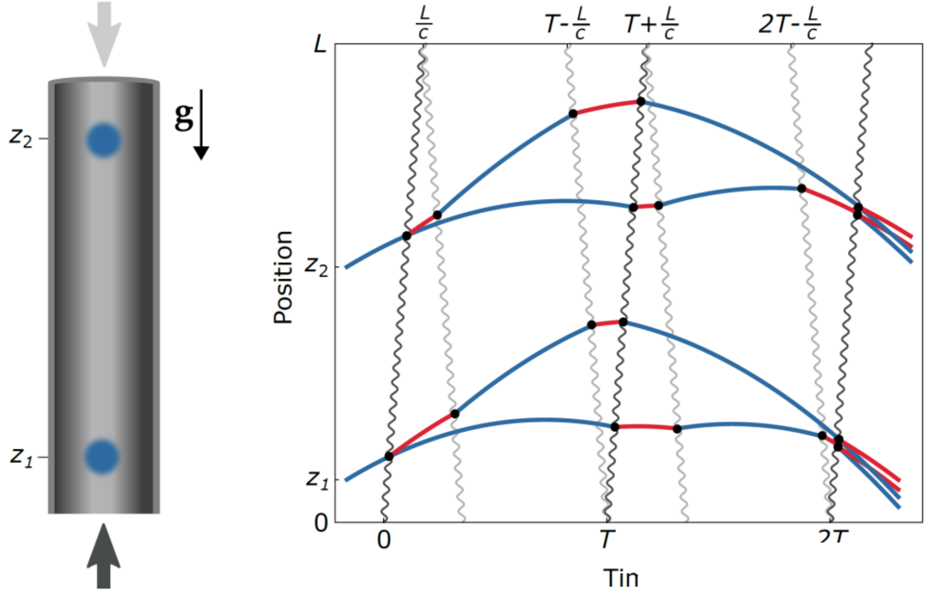
Potential to engineer the effective coupling strength for faster pulses, better LMT

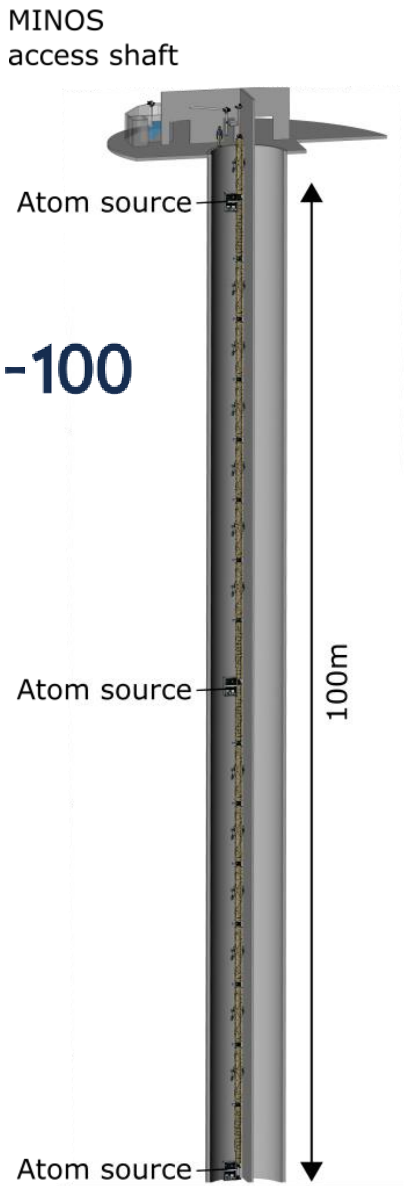


Boyd et al., *Science* (2006).

Gradiometer configuration requires collinear light

- Long baseline gradiometry for gravitational wave, dark mater detection
- Light pulses from alternating directions (LMT enhancement)
- For ~~single photon~~ *single direction* transitions, laser noise is common

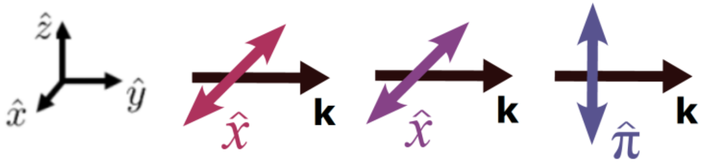


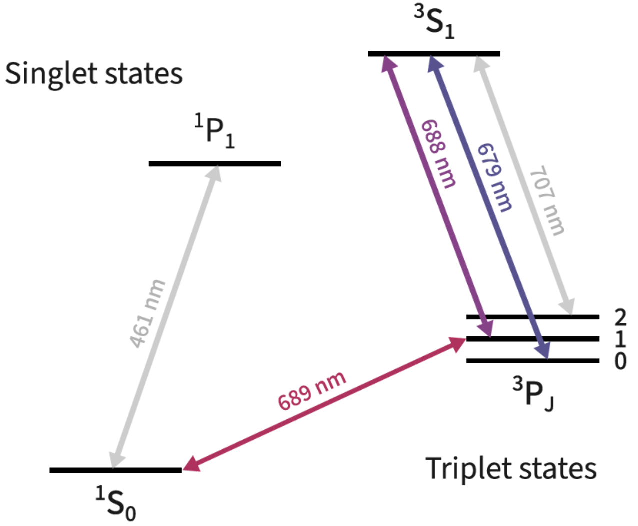


MAGIS-100

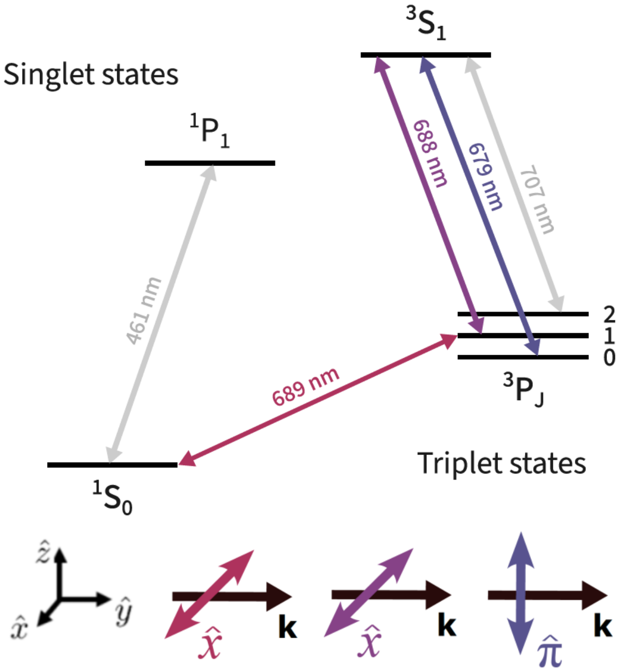
For three photon gradiometer, all light must be **collinear**.

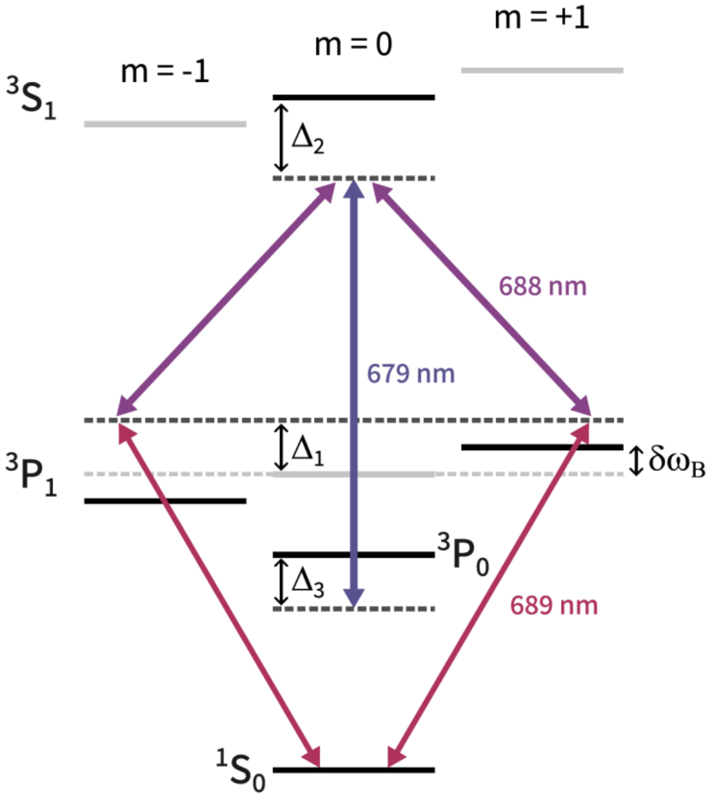
For example: $x - x - z$



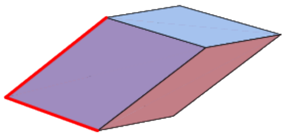


Polarization requirements





Coupling $\propto \mathbf{E}_{689}\cdot(\mathbf{E}_{688}\times\mathbf{E}_{679})$



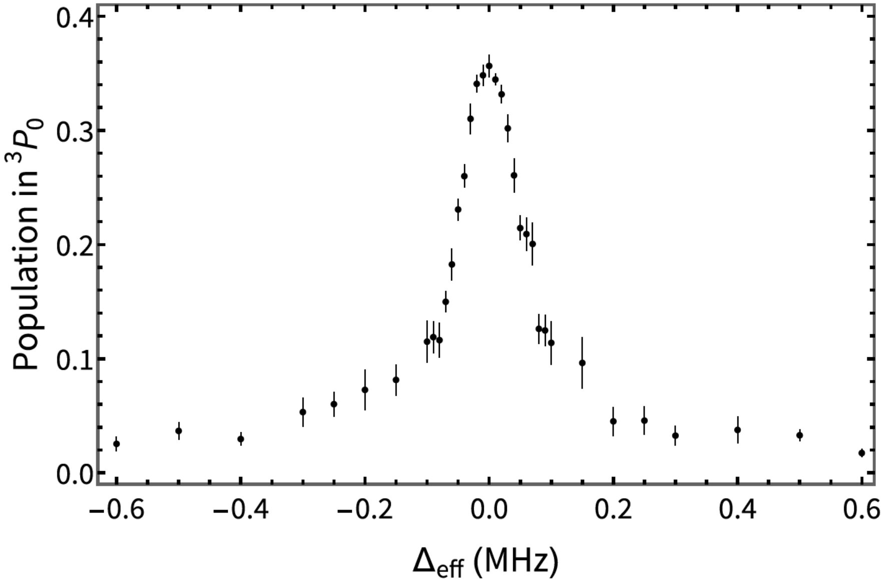
For x-x-z polarization, there is **destructive interference** between two paths:

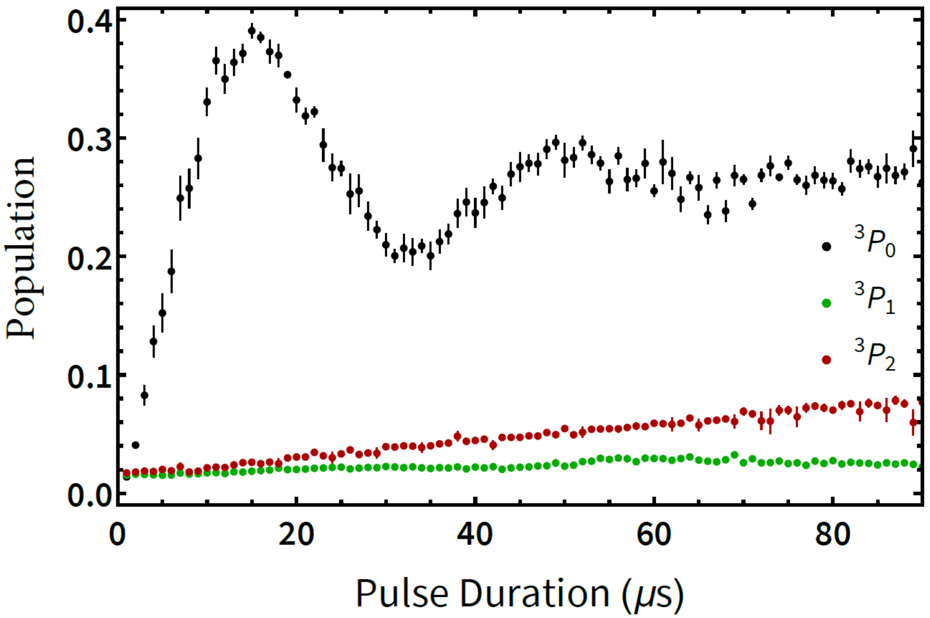
$$\Omega_{\text{eff}} = \frac{\Omega_1\Omega_2\Omega_3}{4\Delta_2}\left(\frac{1}{\Delta_1-\delta\omega_B}-\frac{1}{\Delta_1+\delta\omega_B}\right)$$

Zeeman shift

Solution: Small magnetic field breaks the symmetry and results in a non-zero coupling

Three photon Rabi oscillations





$$\Omega_{\text{eff}} = \frac{\Omega_1\Omega_2\Omega_3\delta\omega_B}{2(\Delta_1^2 - \delta\omega_B^2)\Delta_2}$$

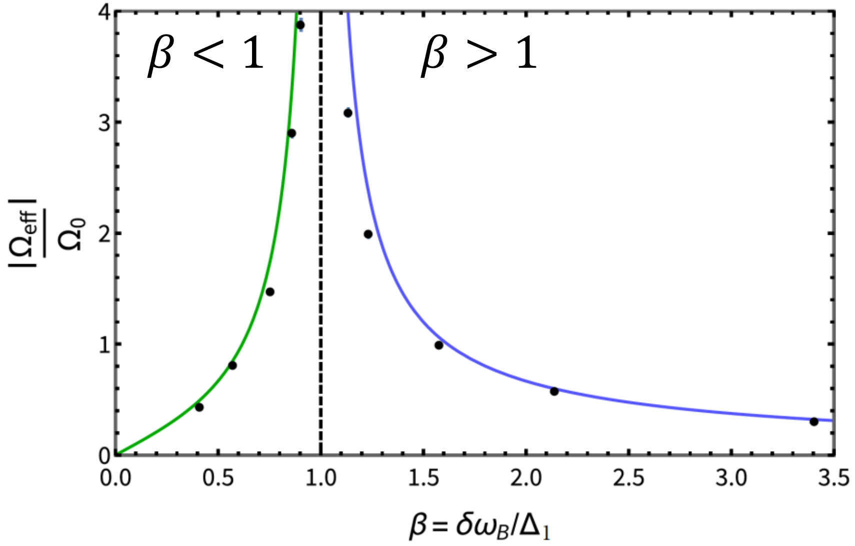
- 689 nm, 688 nm, 678 nm lasers locked to frequency comb; scan three photon resonance
- Detection using state-selective repump followed by 461 nm push pulse
- Verified that transition requires all **four** fields
- We observe minimal decay to unwanted states, consistent with density matrix simulation

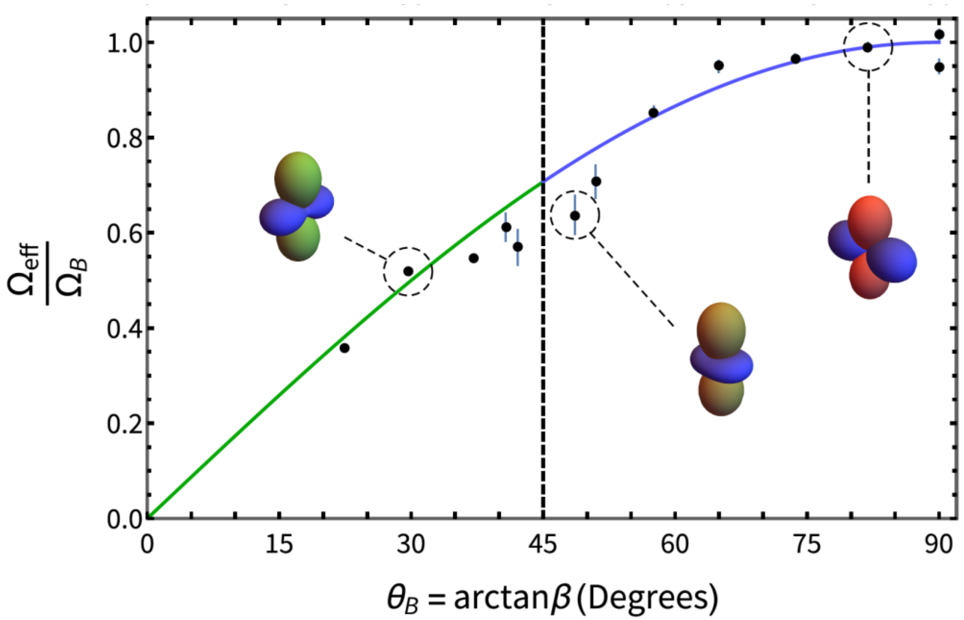
- Here: 29 kHz Rabi frequency with 10 Gauss field, 5 W/cm^2 (360 micron beam)
- 2.5 GHz detuning of 688 nm, 9.9 MHz detuning of 689 nm
- Peak transfer limited by intensity inhomogeneity in this proof of principle

Magnetic tuning of three photon Rabi coupling

Three photon coupling depends on: $\beta = \delta\omega_B / \Delta_1$ (ratio of Zeeman shift to 689 nm detuning)

Two regimes:





Some examples:

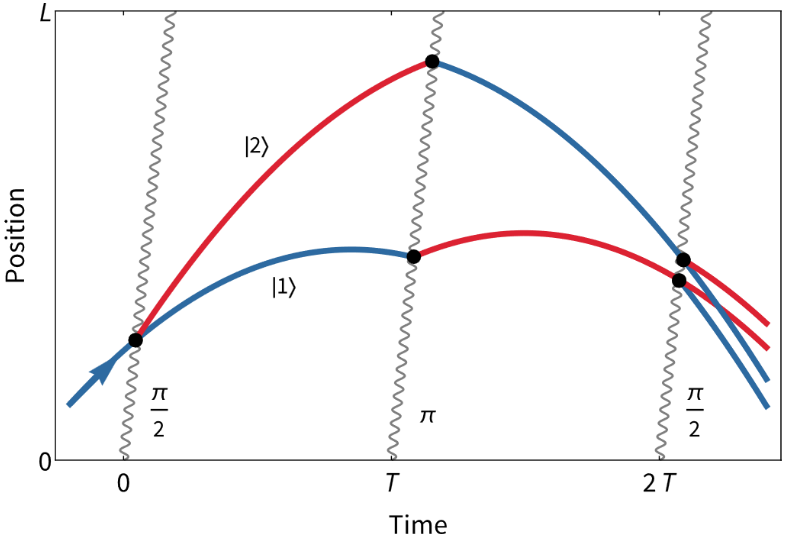
- 12 kHz Rabi frequency at 4 Gauss field
- 49 kHz Rabi frequency at 19 Gauss field

High Rabi frequency with modest magnetic fields, intensities

The magnetic field tunes the effective dipole moment by angle θ_B, changing the projection onto the light polarization:

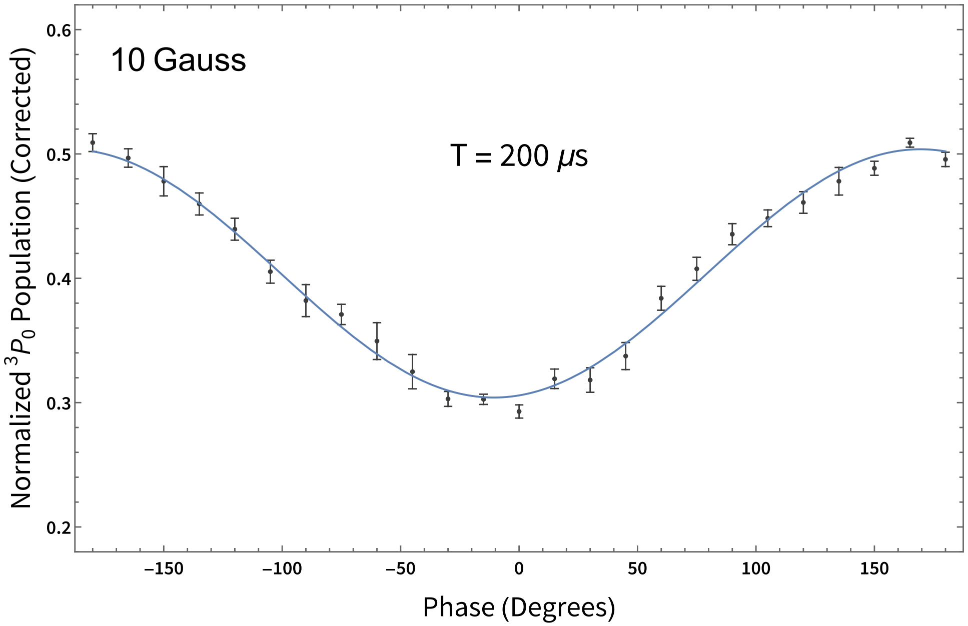
$$\Omega_{\text{eff}} = \Omega_B \left(i \sin\theta_B \hat{\mathbf{x}} + \cos\theta_B \hat{\mathbf{y}} \right) \cdot \mathbf{e}^{(1)}$$

Atom interferometry demonstration



Mach-Zehnder sequence

- Shows phase coherence over longer times
- Proof of concept for future long-baseline atom interferometer applications



Atom interferometry between $^1S_0 \rightarrow {}^3P_0$ levels of ^{88}Sr using the three photon transition

Summary

- Three photon transition opens up the use of bosons for atom interferometry and clocks
- Small magnetic field allows for collinear light, otherwise forbidden by selection rules
  - → Semi-classically, the magnetic field adds a torque that "rotates" the atomic state on a timescale faster than the natural lifetime
- Demonstrated proof of concept atom interferometer

Next steps

- Higher power laser, bigger beams to reduce inhomogeneous loss
- Optimize parameters (magnetic field, 689 detuning) to minimize spontaneous emission – ultimate limits?
- Possible alternative to ^{87}Sr 698 nm transition for MAGIS-100 (?)
  - → May offer an advantage for LMT atom optics by engineering an effective transition with strong coupling but long excited state lifetime