Upgrading the ACME Electron Electric Dipole Moment (e-EDM) Search with a Molecular Lens

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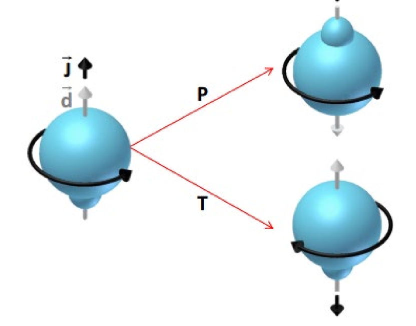
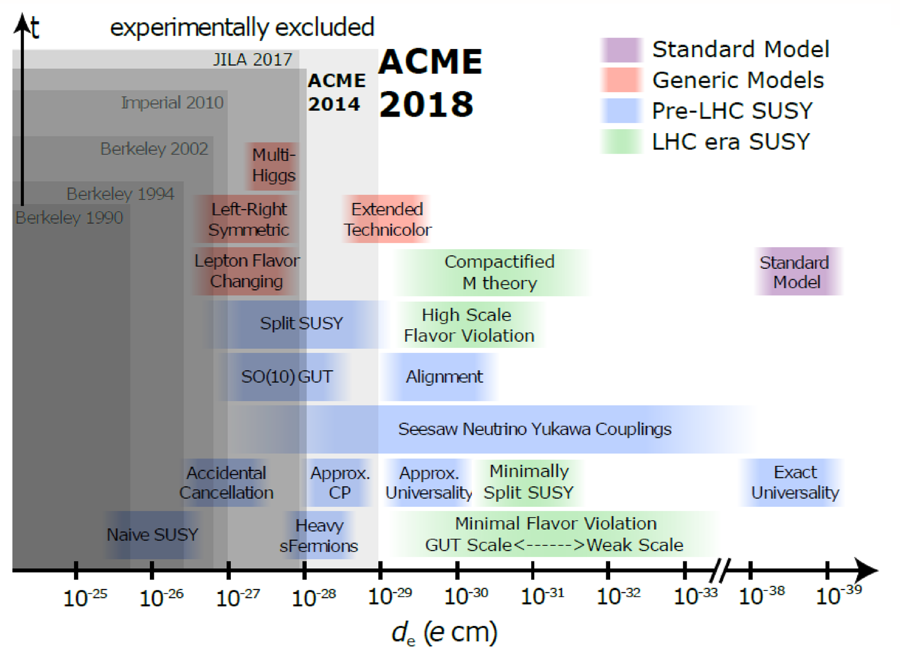
Motivation

$$H_d = -\vec{d}_e \cdot \vec{\mathcal{E}}$$



A permanent electric dipole of a fundamental particle violates both T- and P-symmetry

$$\delta d_e = \frac{1}{2T\mathcal{E}_{eff}\sqrt{N}}$$

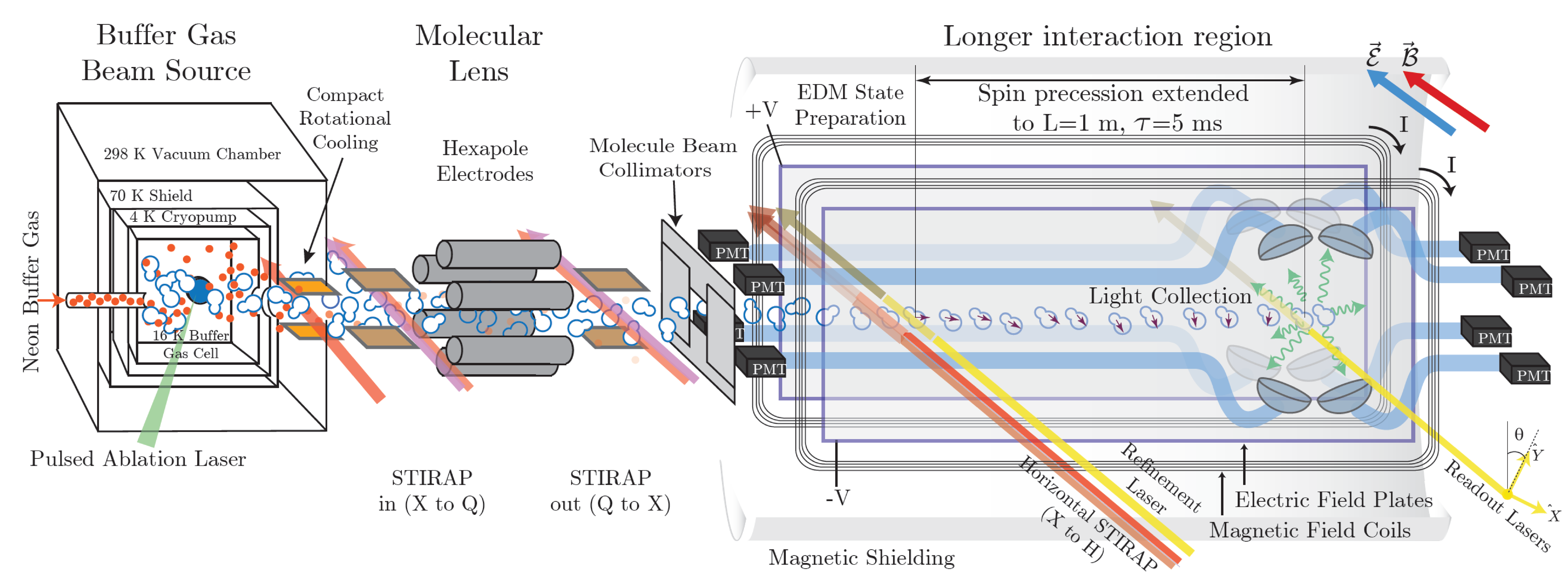


Many theories beyond the Standard Model predict *T*-violation and associated EDMs at current experimental precision

eEDM sensitivity of ACME II is at ~4x10^{-30} e•cm.

We optimize the sensitivity by maximizing the detected molecule number

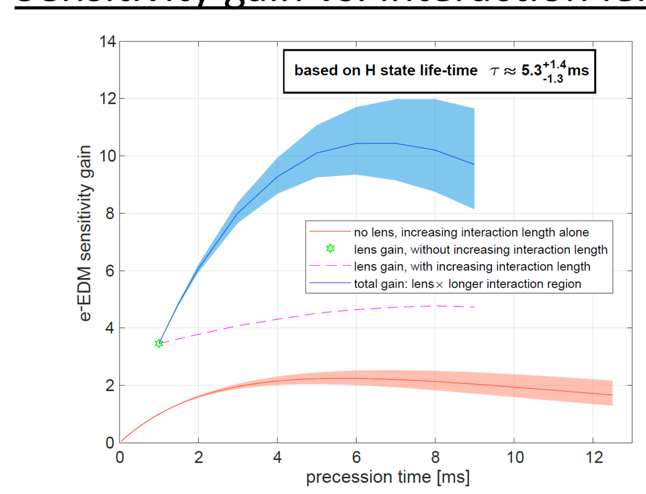
ACME Gen III overview



Proposed sensitivity improvement

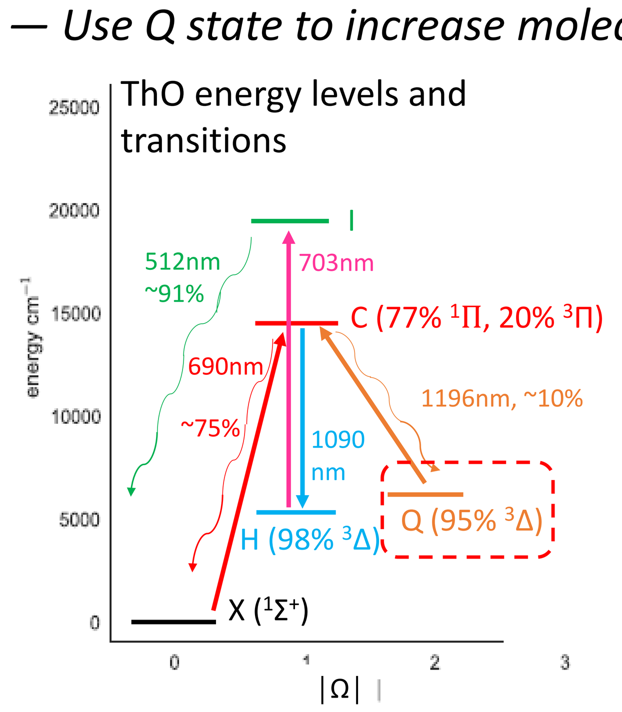
Improvement	Signal Gain	EDM Sensitivity Gain
Increased Precession Time	0.20	2.3
Electrostatic Lens	20.5	4.5
SiPM Detector Upgrade	2.3	1.5
Timing Jitter Noise Reduction	1	1.7
Total	9.4	26.4

Sensitivity gain vs. interaction length



Property of Q ($^3\Delta_2$) state of ThO

— *Use Q state to increase molecule flux & suppress systematics*



Q state:

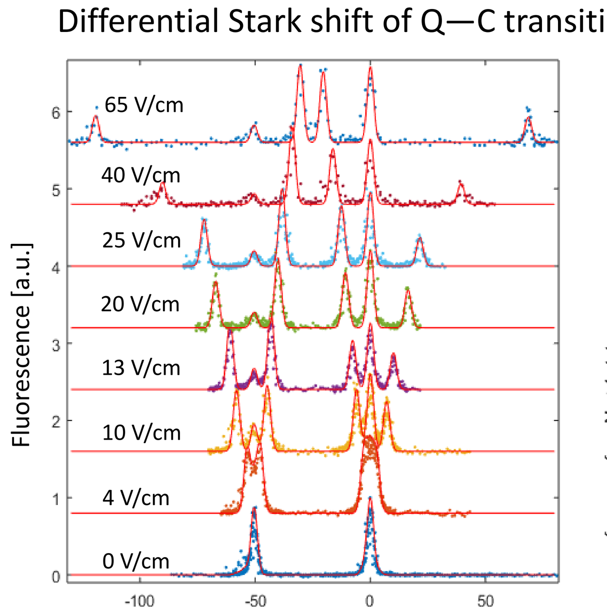
- Paramagnetic, $g_Q \approx g_L \Lambda + g_S \Sigma = 2$, compared to g_H =4.4x10^{-3} & g_X <10^{-3} allows **magnetic lensing** & **co-magnetometer**
- Long lived (measured lifetime bound >98 ms)
- Linear Stark shift due to Ω-doublet (<<100kHz) , efficient **electrostatic lensing**

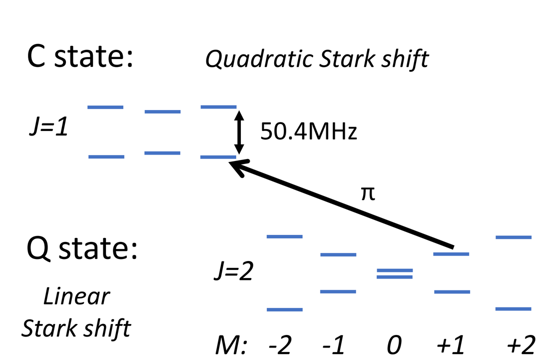
H state: for EDM measurement

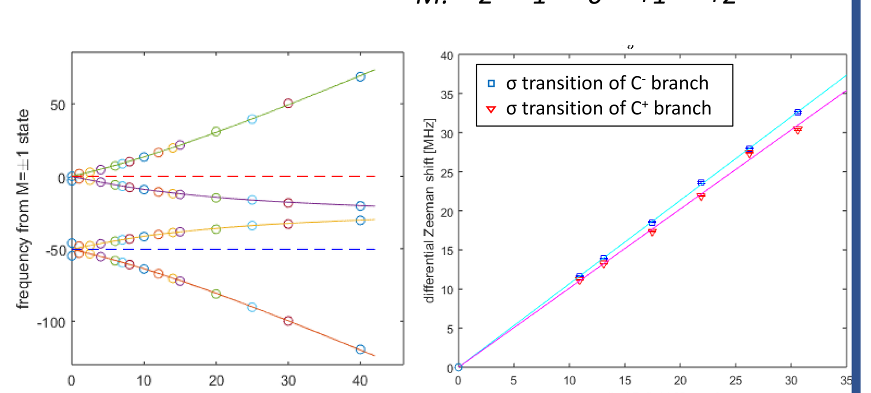
X-C-H STIRAP: EDM state preparation

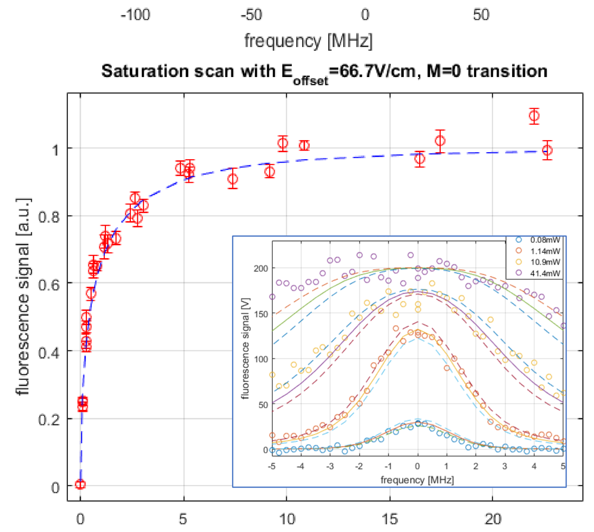
I state: read out via 512nm LIF detection

Characterization of Q—C transition









Large electric & magnetic dipole

- Extracted molecule frame dipole: D_Q=4.07D (Q state), D_C=2.60D (C state)
- From Zeeman shift measurement: G_Q=2.06μ_B, G_C=1.22μ_B

Strong transition dipole to C state

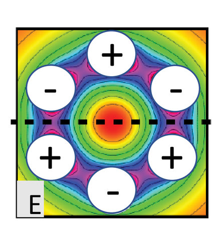
- Power saturation scan of Q—C transition: D_{Q-C} = 1.0±.12 D

Increase useful molecule flux with beam focusing

- Molecules exiting the beam source have high divergence – solid angle subtended by EDM measurement region ~0.05% in ACME II, and worse for longer interaction region
- Lensing-state of ThO: X-C-Q STIRAP to a single M=2 or -2 level in Q (J=2) state

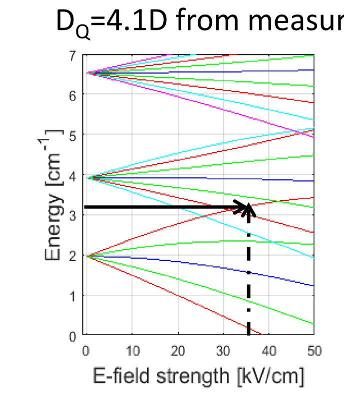
Electric hexapole lens

- Electrode voltage 22.5 kV, .75" radius: ≈1.8K trap-depth
- Control and minimize possible X-ray production
- Expect **factor of ~15 increase** in signal (molecular flux)

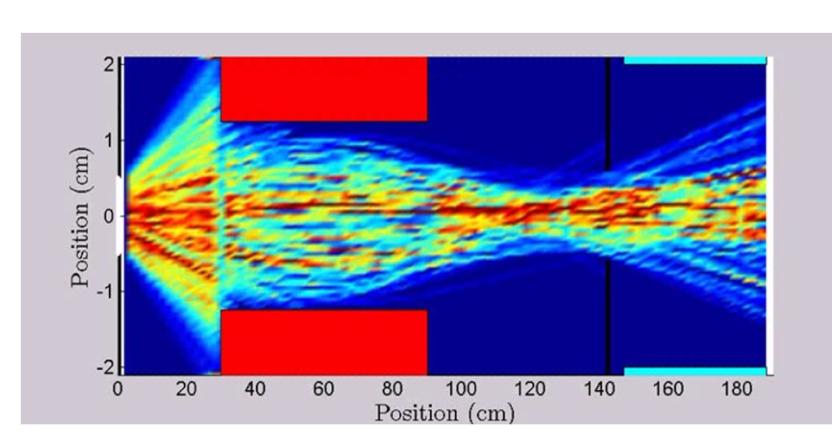


DC Stark shift of Q state

D_Q=4.1D from measurement

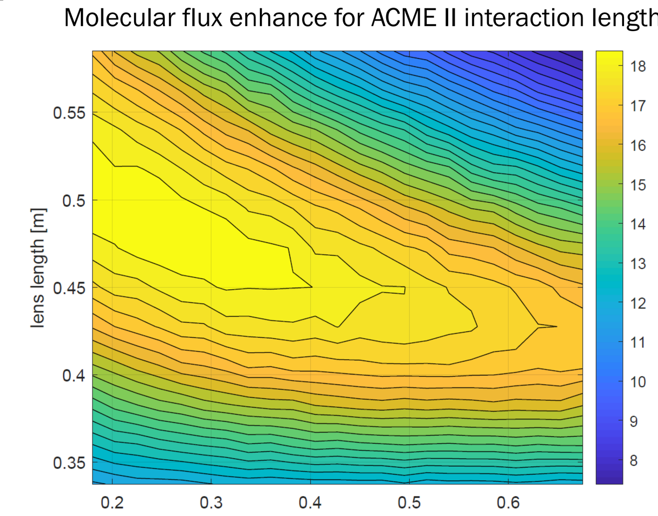


Trajectory simulation for molecular lens design



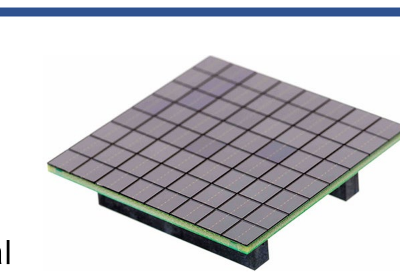
Simulation of molecule focusing with electrostatic lens. Red is lens, black is collimator

Molecular flux enhance for ACME II interaction length



Increase quantum efficiency

- Silicon photomultipliers (SiPMs) for more efficient fluorescence detection
- PMTS ~25% efficient. SiPMs ~ 50%, giving **factor ~2 increase** in signal
- **Challenge:** large dark current, large capacitance (slow), unstable gain
- **Solution:**
  - Custom high-gain, low-noise, high-bandwidth amplifiers
  - moderately low temperature (-20 C°) suppresses dark current sufficiently
  - with nonimaging optical concentrator (Winston cone)
  - dynamically adjust bias voltage and temperature for stable gain



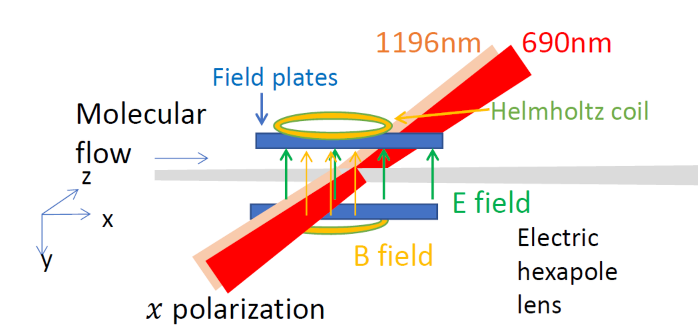
large-area SiPM array

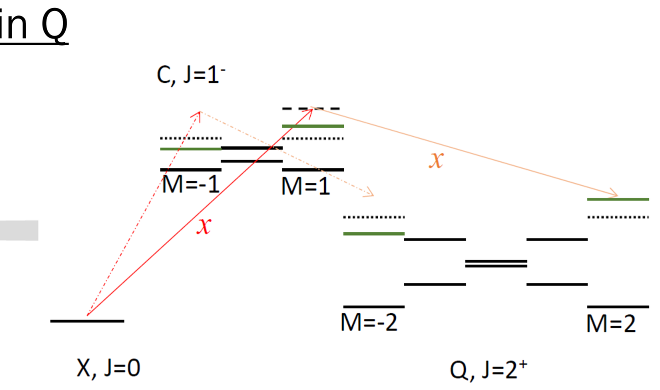
Demonstrate 'double' STIRAP between X and Q ($^3\Delta_2$) state of ThO

Scheme to prepare single M level in Q

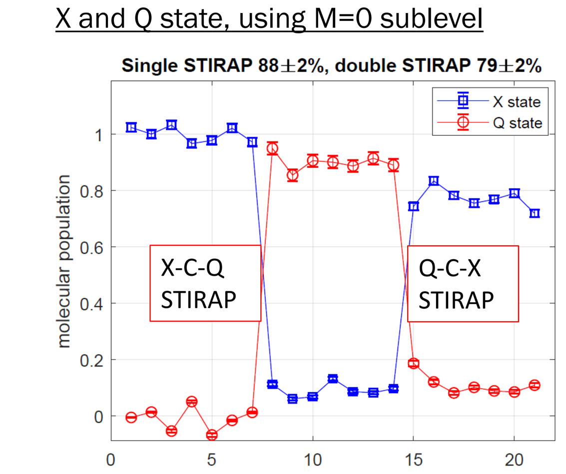
Main challenges:

- In a molecular beam: extended spatial and velocity distribution
- For molecular lens to work effectively, need to cover Δv_{tran} = ± 10m/s, i.e. FWHM 2-photon linewidth of 6MHz
- Complex ambient E and B field environment
- Need efficient STIRAP both before and after the Lens!

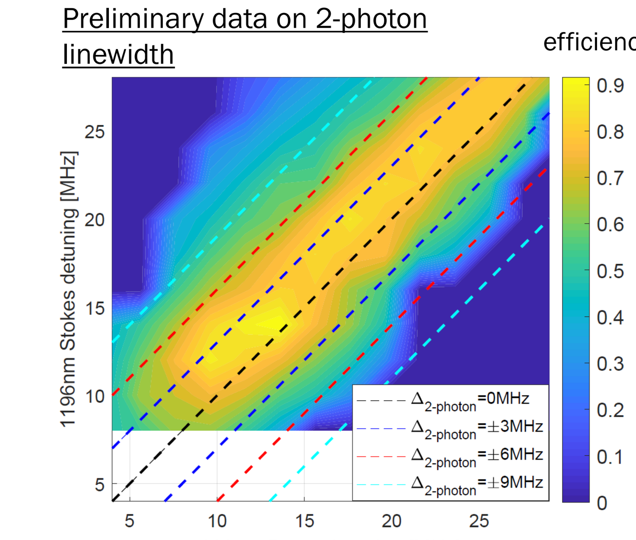




Very first signal of double STIRAP between X and Q state, using M=0 sublevel



Preliminary data on 2-photon linewidth



Compact rotational cooling stage

- Minimize the distance between source and Lens entrance, to increase the spatial acceptance into Molecular Lens
- Necessary to cover 15MHz FWHM Doppler distribution. Spectrally broadened by mixing 90 sidebands at 330kHz spacing (natural linewidth of C state).
- Single optical path for both rotational line, switch between frequencies, E field, and polarizations