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Laser cooled YbF and the electron electric dipole moment

Ben Sauer

Beyond standard model and the eEDM

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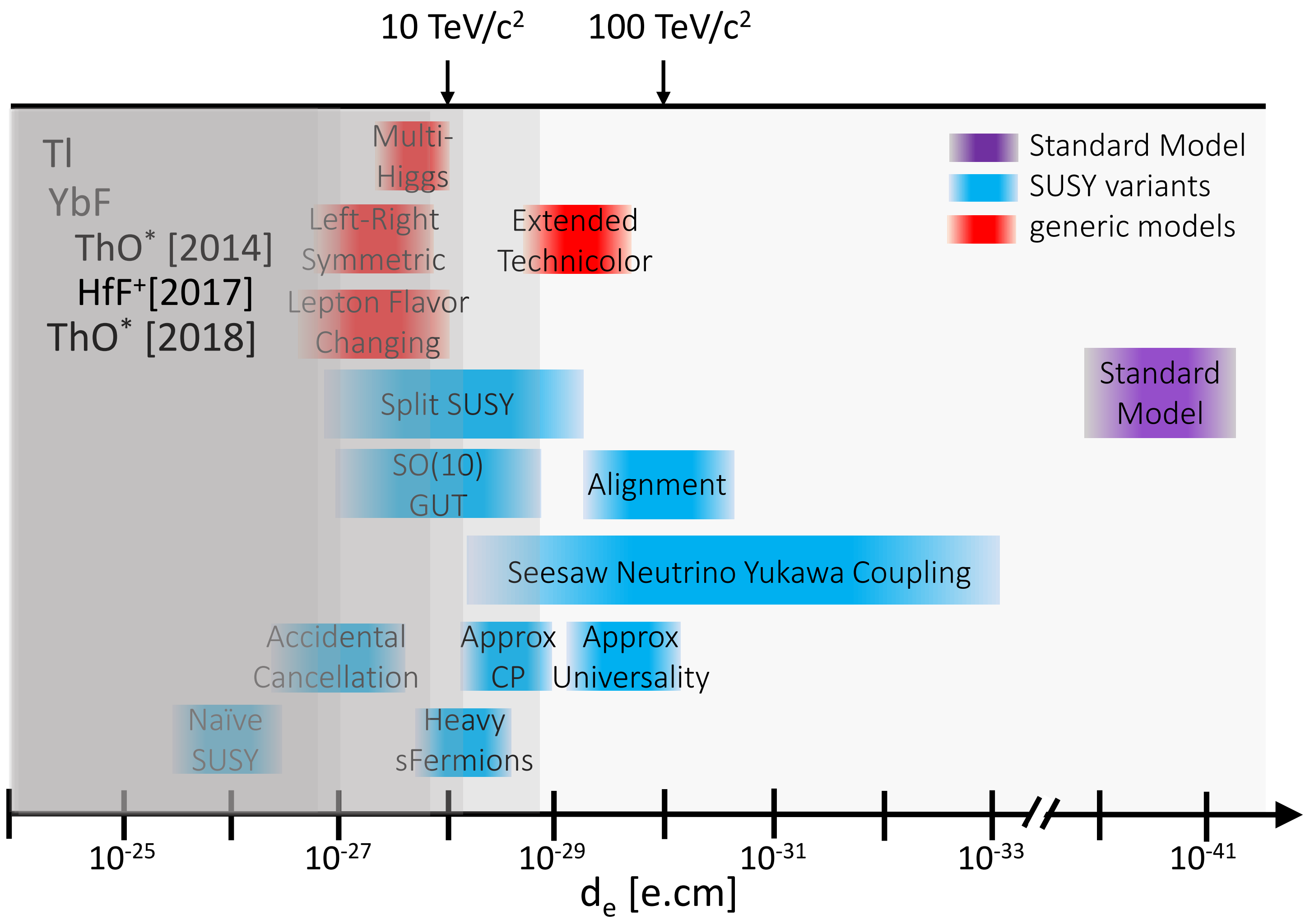


Imperial: Nature **473** 493 (2011), *ACME*: Science **343** 269 (2014), Nature 562, 355-360 (2018), *JILA*: PRL **119** 153001 (2017)
Figure adapted from Ben Spaun, PhD Thesis, Harvard University, (2014).

SUSY and the eEDM scale

n-loop diagram

CP-violating phases

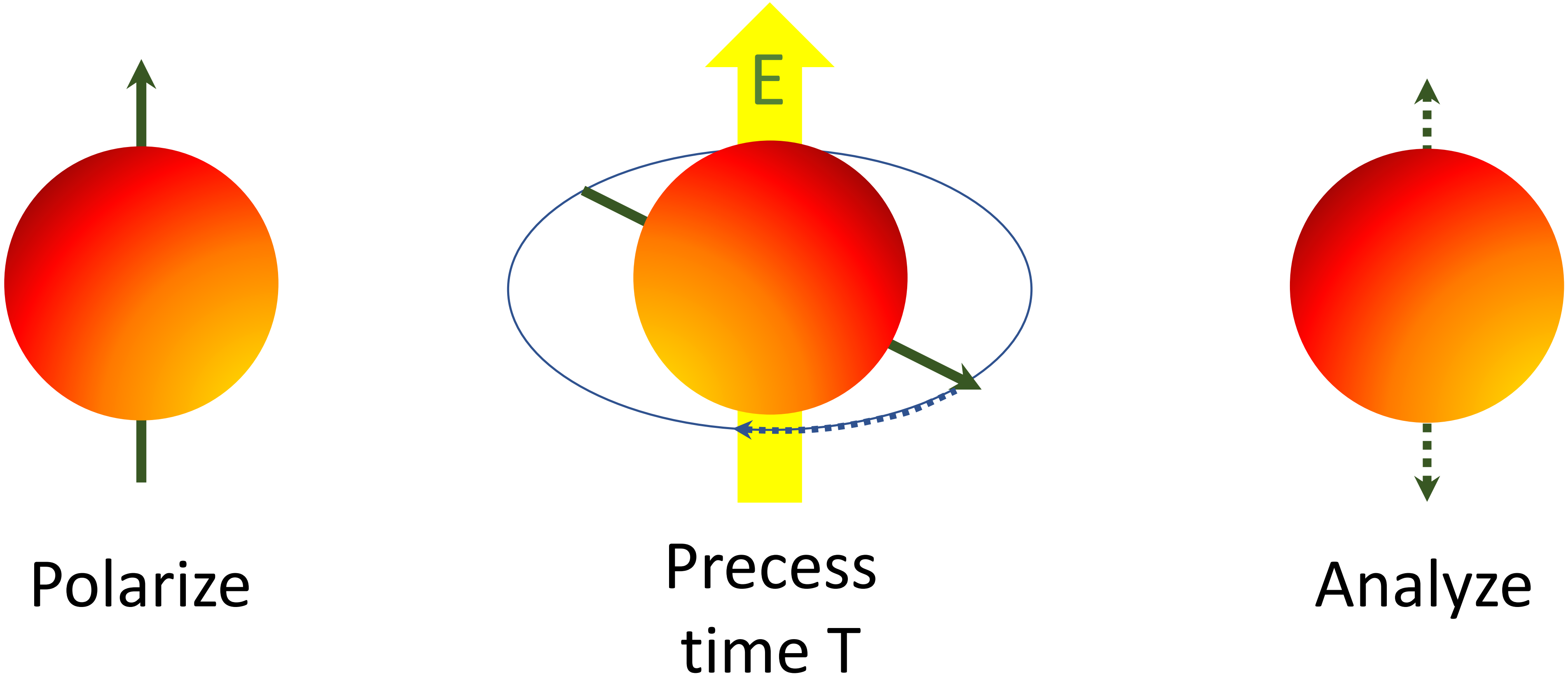
$$\frac{d_e}{e} \sim h\,c \left(\frac{\alpha}{4\pi}\right)^{n} \left(\frac{m_e c^2}{\Lambda^2}\right) \sin(\phi_{\mathrm{cp}})$$

Energy scale for new particles

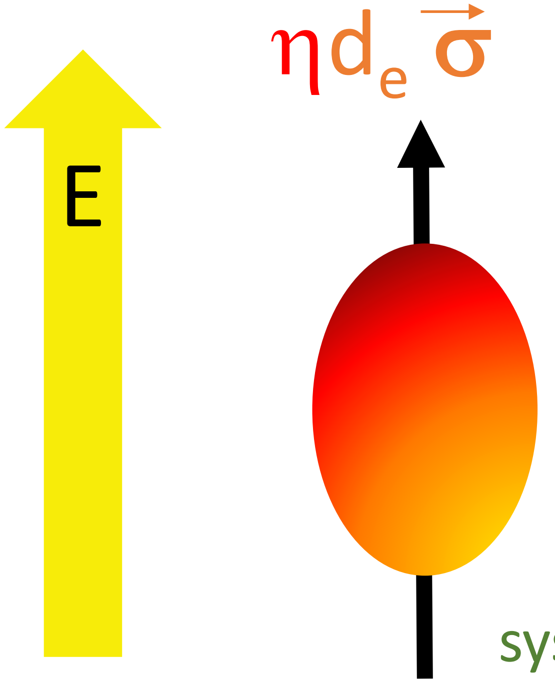
When $n = 1$ and $\sin(\phi_{\mathrm{CP}}) \sim 1$:

$d_e = 10^{-29}$ e.cm corresponds to $\Lambda \approx 30$ TeV

An EDM experiment



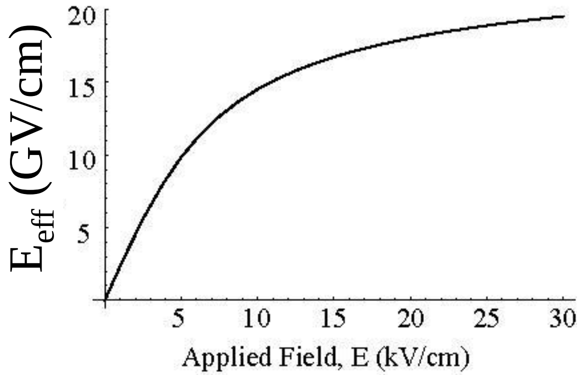
Why polar molecules?



system containing electron

electric field

Example: YbF



Interaction energy

$$-\eta d_e \vec{E} \cdot \vec{\sigma}$$

Analogous to magnetic dipole interaction $-g_e\mu\, \underline{B}.\underline{\sigma}$ but violates P&T

Factor η includes both relativistic interaction $\sim Z^3$, and polarization. η can be very large!

Sensitive molecules:
BaF, YbF, ThO*, HfF^+

YbF (fast beam) vs. ThO* (metastable beam)

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Effective field E_{eff} in YbF is 26 GV/cm

when molecule is fully polarized

For ThO* E_{eff} is about 84 GV/cm (x 3.2 more sensitive)

Mostly relativistic: $\left(\frac{Z_{Th}}{Z_{Yb}}\right)^3 = 2.1$

(*also depends on structure*)

Both experiments have $\tau \approx$ 1ms,
ThO* metastable,
YbF by fast beam.

ThO* can be fully polarized! (*factor of 2*)

YbF

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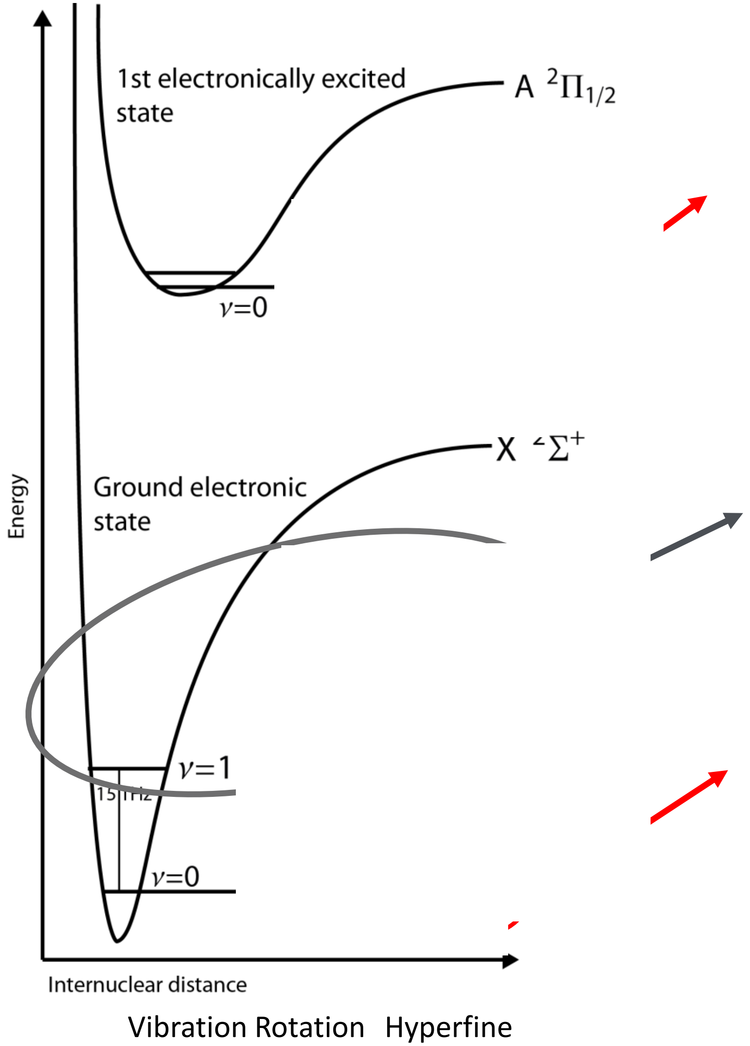
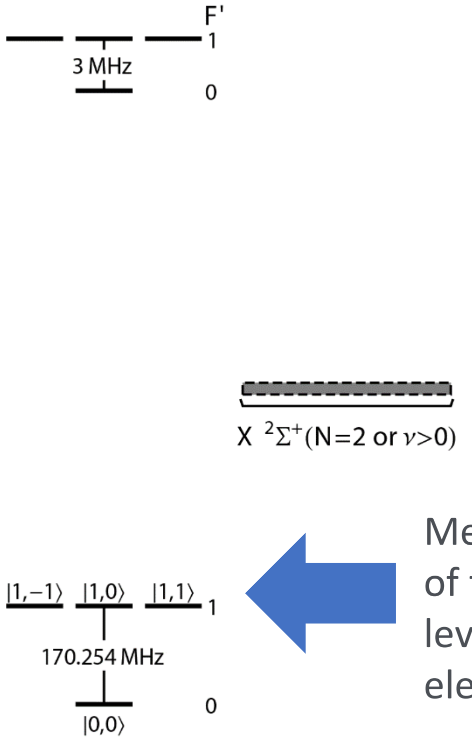
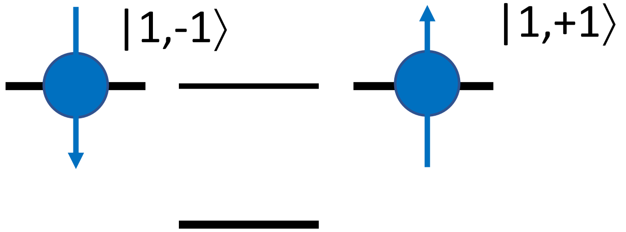


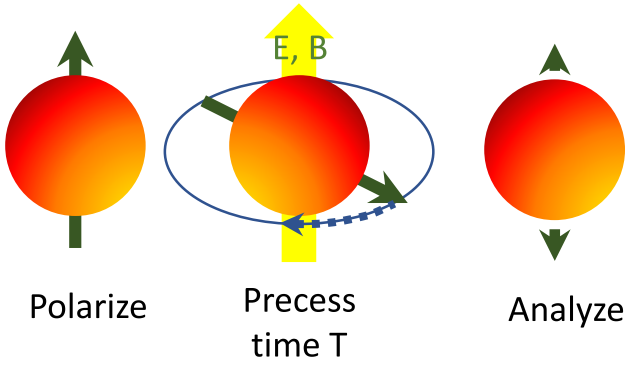
Relevant levels





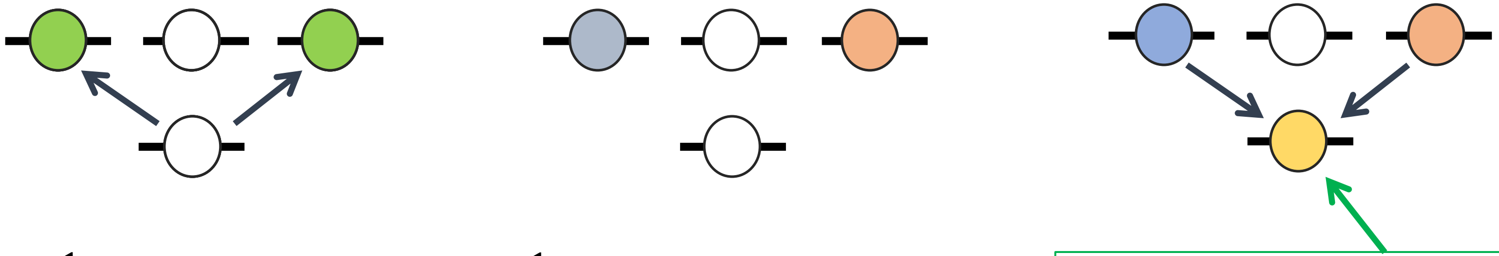
Measure the splitting of the $|1,-1\rangle$ and $|1,1\rangle$ levels in an applied electric field

YbF eEDM measurement



$$\varphi_B = g\mu_B \,\boldsymbol{\sigma} \cdot \boldsymbol{B}\, \boldsymbol{T}$$

$$\varphi_E = \eta d_e \,\boldsymbol{\sigma} \cdot \boldsymbol{E}\, \boldsymbol{T}$$



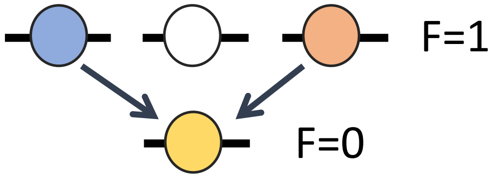
$$\frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$

$$\frac{1}{\sqrt{2}}\left(e^{i\varphi}|+\rangle + e^{-i\varphi}|-\rangle\right)$$

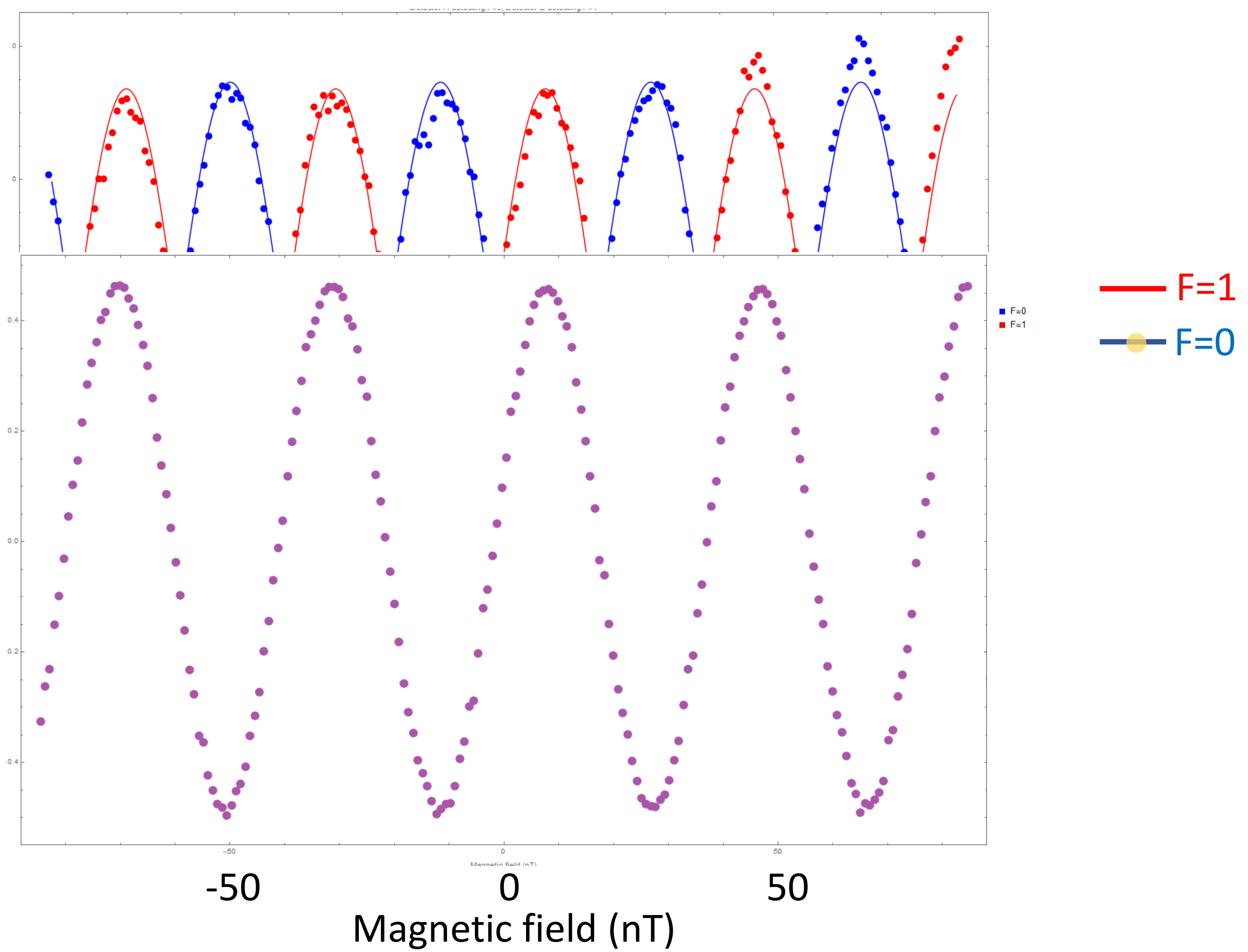
Measure population
in F = 0, F = 1

$$N\cos^2(\phi) \quad N\sin^2(\phi)$$

A magnetic field scan



$$\frac{F=1 - F=0}{F=1 + F=0}$$



A magnetic field scan with E reversed

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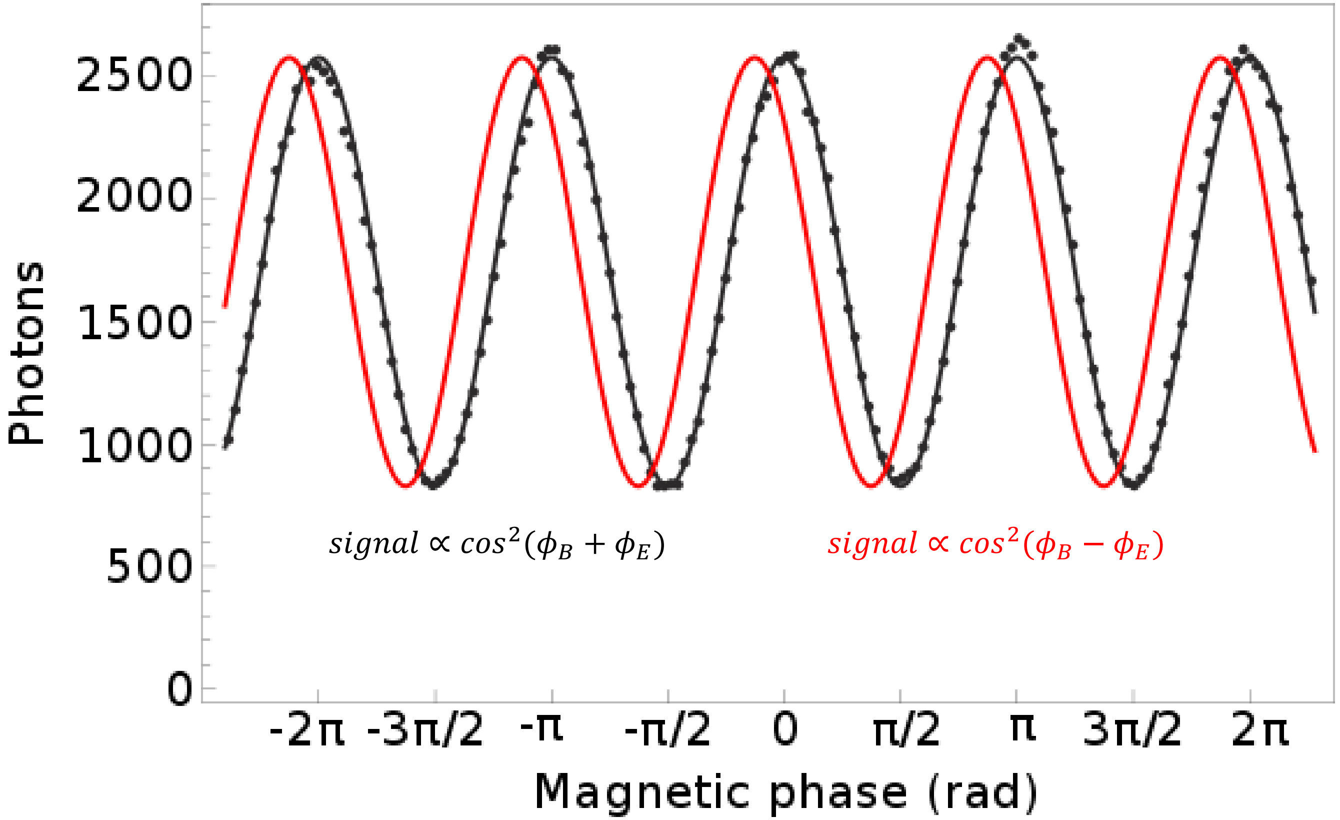
Reverse E relative to B



Looking for a shift of less than 2 μrad

Sensitivity Limit

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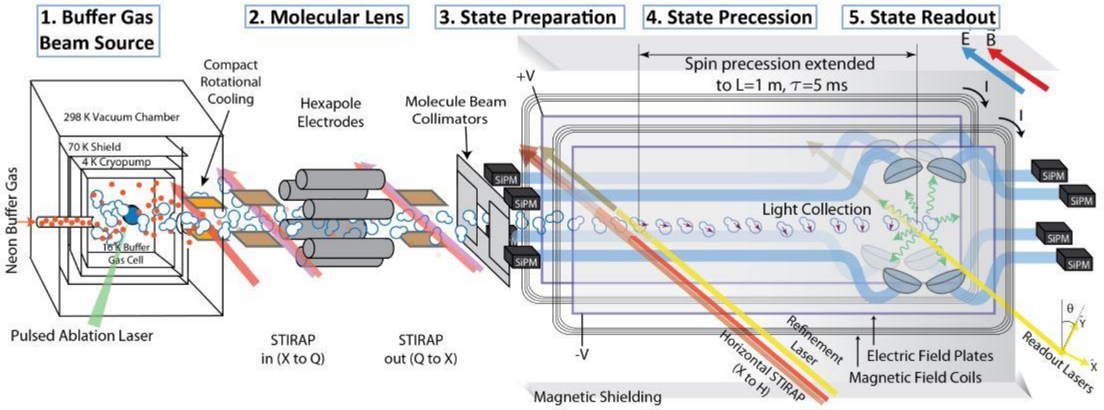
Quantum projection noise : $\sigma_{d_e} \simeq \dfrac{\hbar}{2E_{eff}\,\mathcal{C}\;\tau\;\sqrt{N}}$

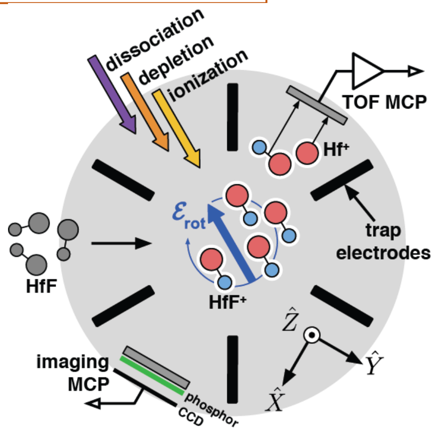
Get more molecules

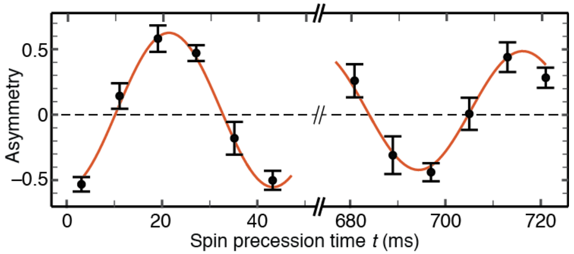
Fixed by molecule

Contrast - do experiment better!

Interaction time







Beam method (YbF, ThO*)

- Large N
- Small τ

How to get both?

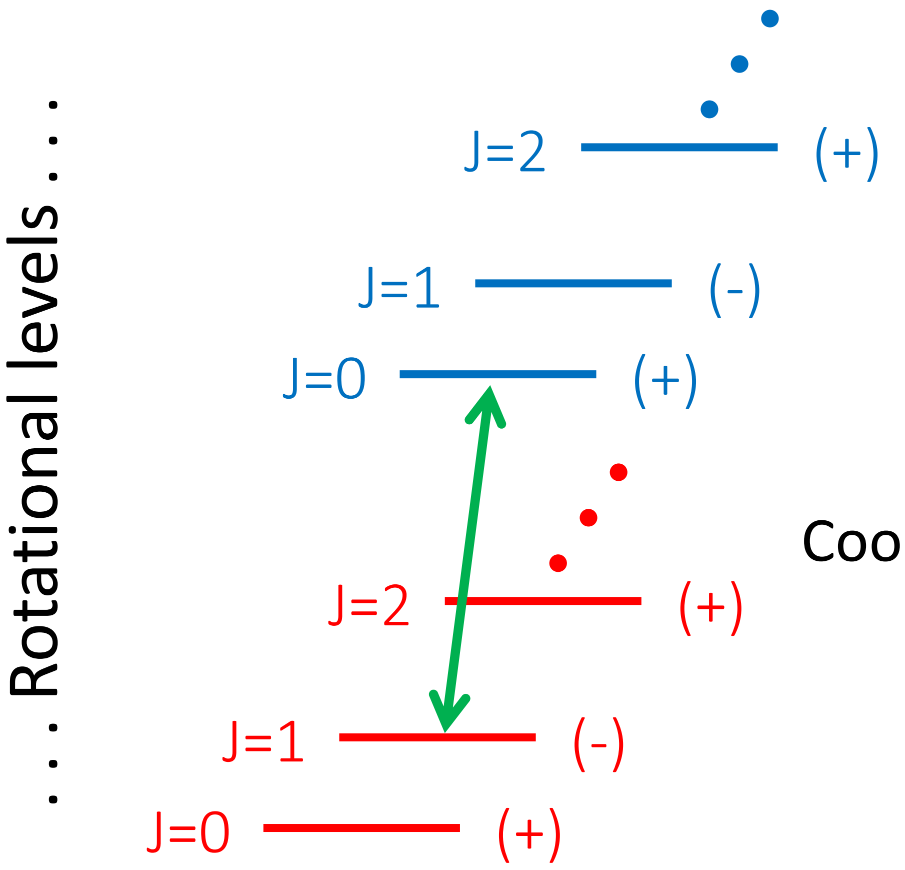
Ultracold molecules!

Trap method (HfF+: JILA)

- Small N
- Large τ

Laser cooling molecules: Closed cycling transition

- Angular momentum J can only change by 0, ±1.
- Parity of rotational state $(-1)^J$ must change from (+) ⇔ (–).



Need to cycle $10^4 \sim 10^5$ photons

Cool on J=1 → J=0 transition, P(1) line.

Cooling YbF: Closing vibrational leaks

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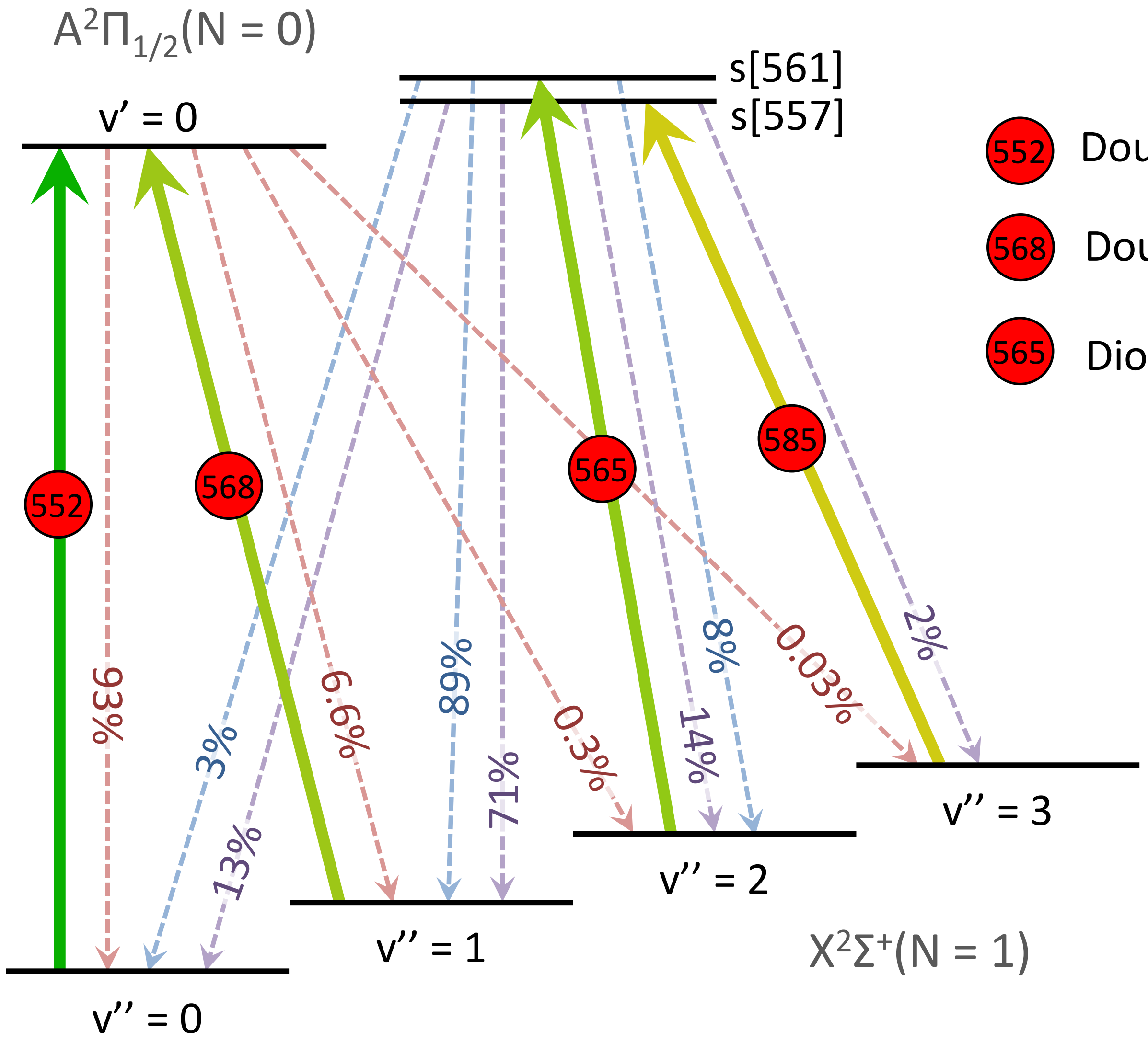


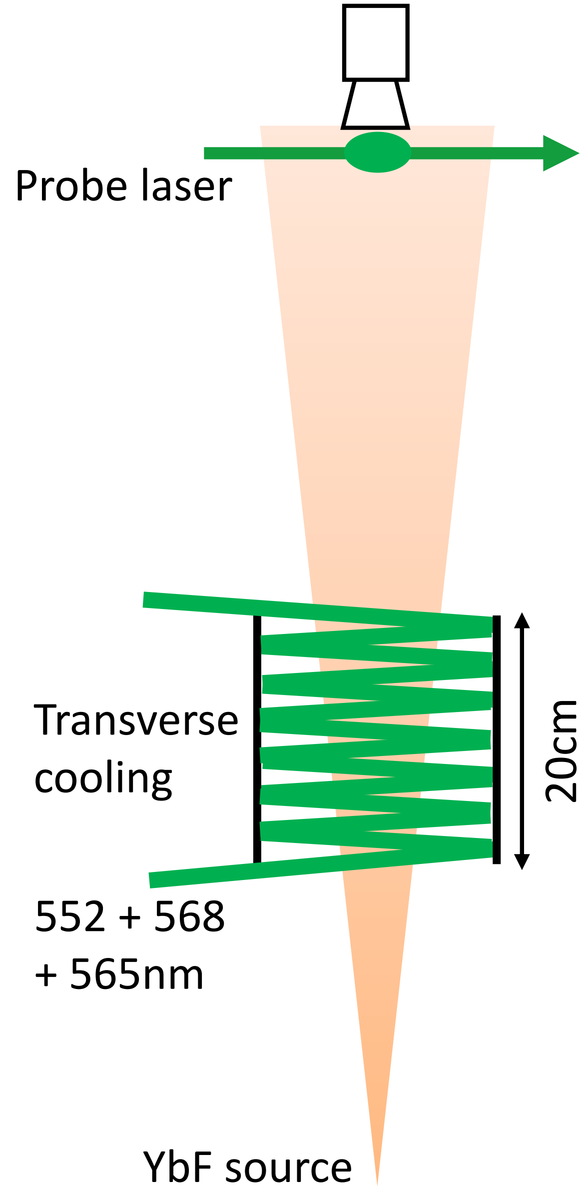
552 Doubled fibre amplifier, 800mW

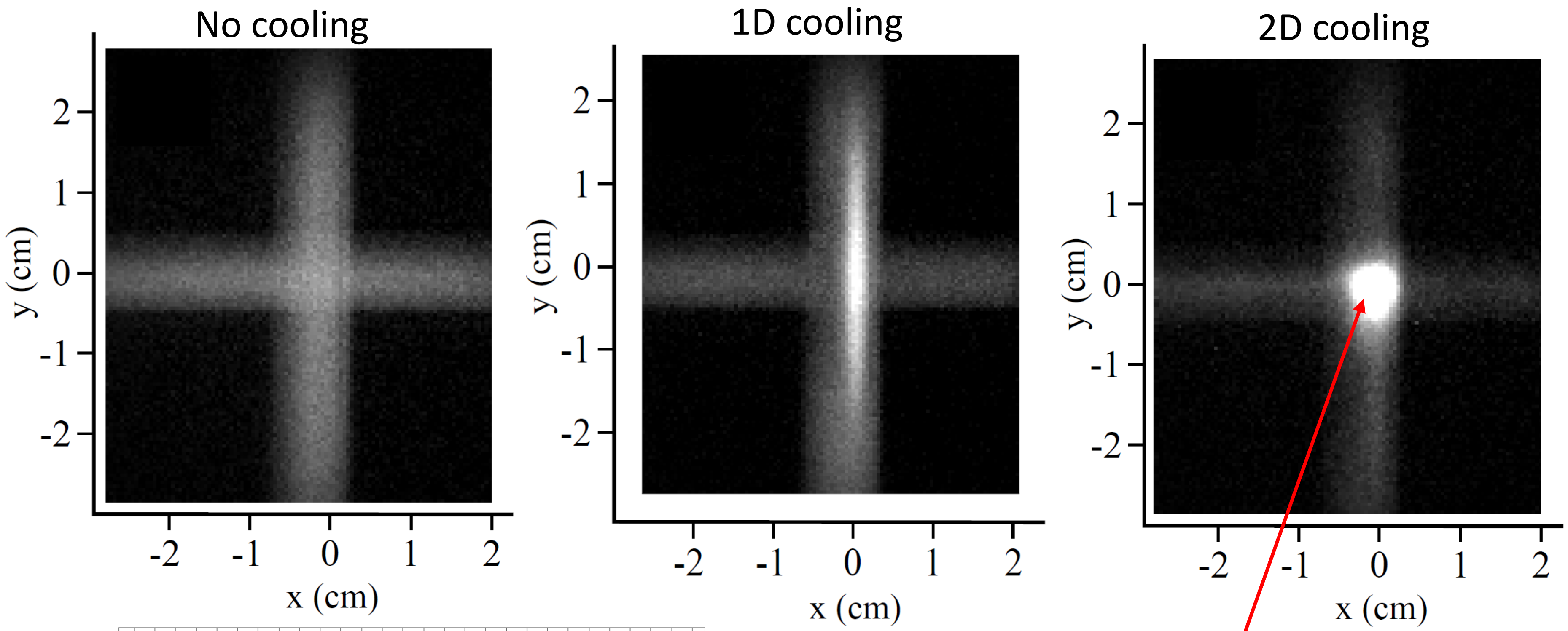
568 Doubled Raman fibre amplifier, 1W

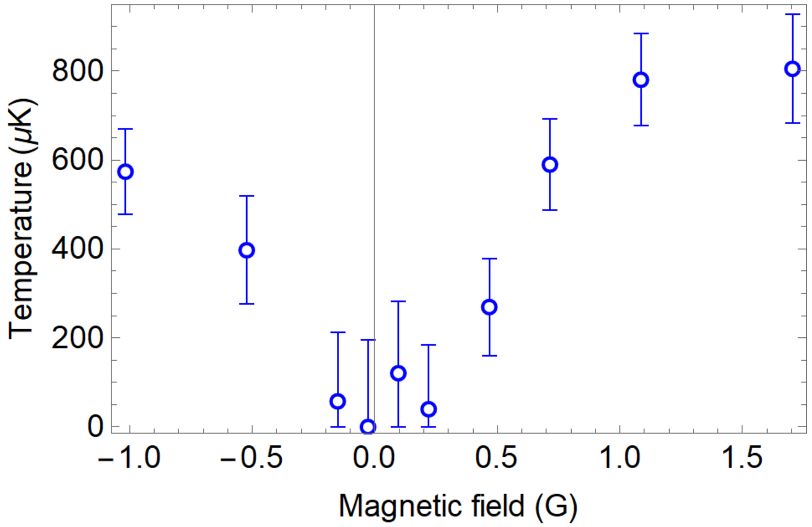
565 Diode + TA + doubler, 70mW

J. Mol. Spectrosc., **300**, 3 (2014)

YbF 2-d transverse cooling







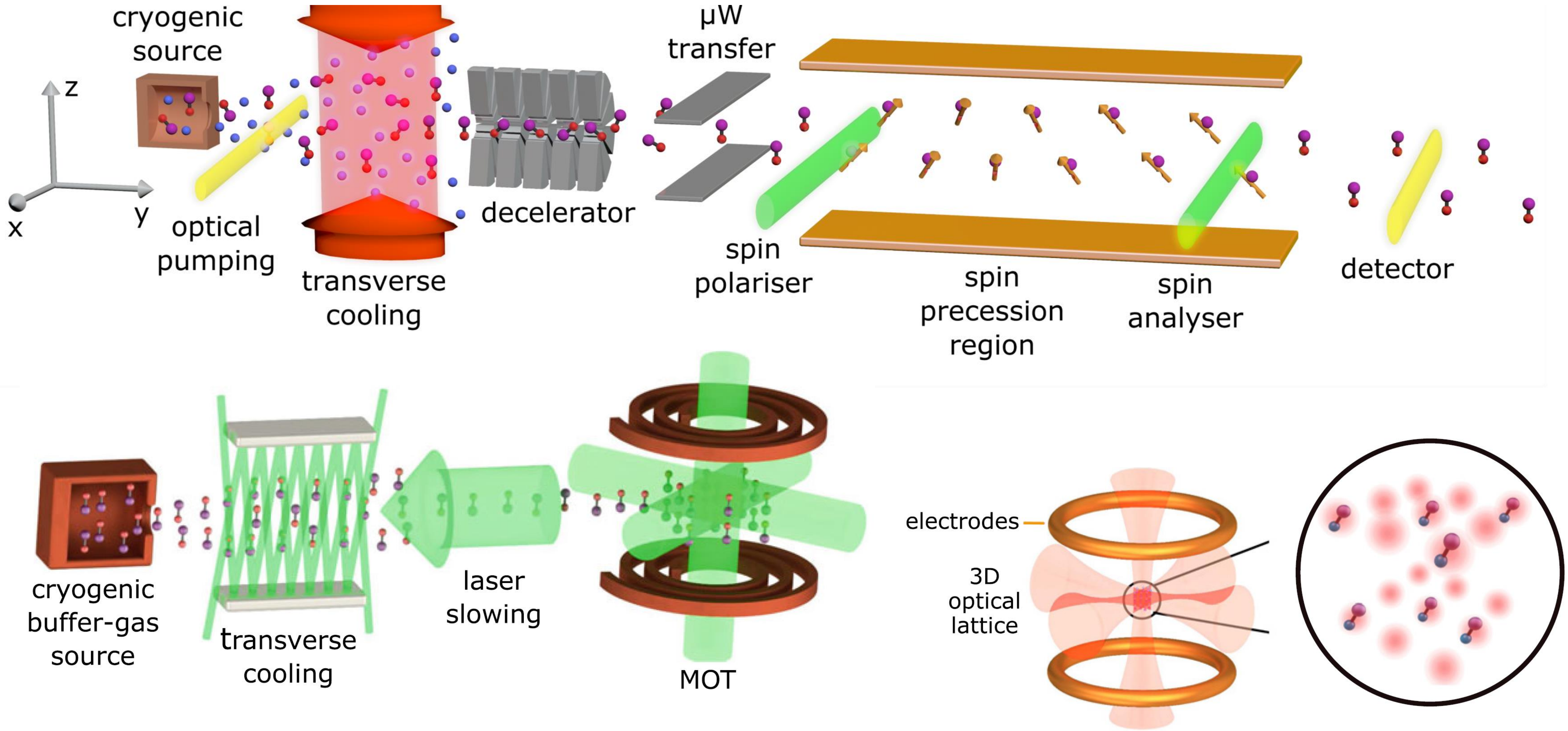
About 10^6 ultracold molecules per shot

Beam brightness increased by at least a factor 300

With N = 10^6 per shot and τ = 100 ms, shot-noise limited edm uncertainty is 2×10^{-31} e.cm in one day

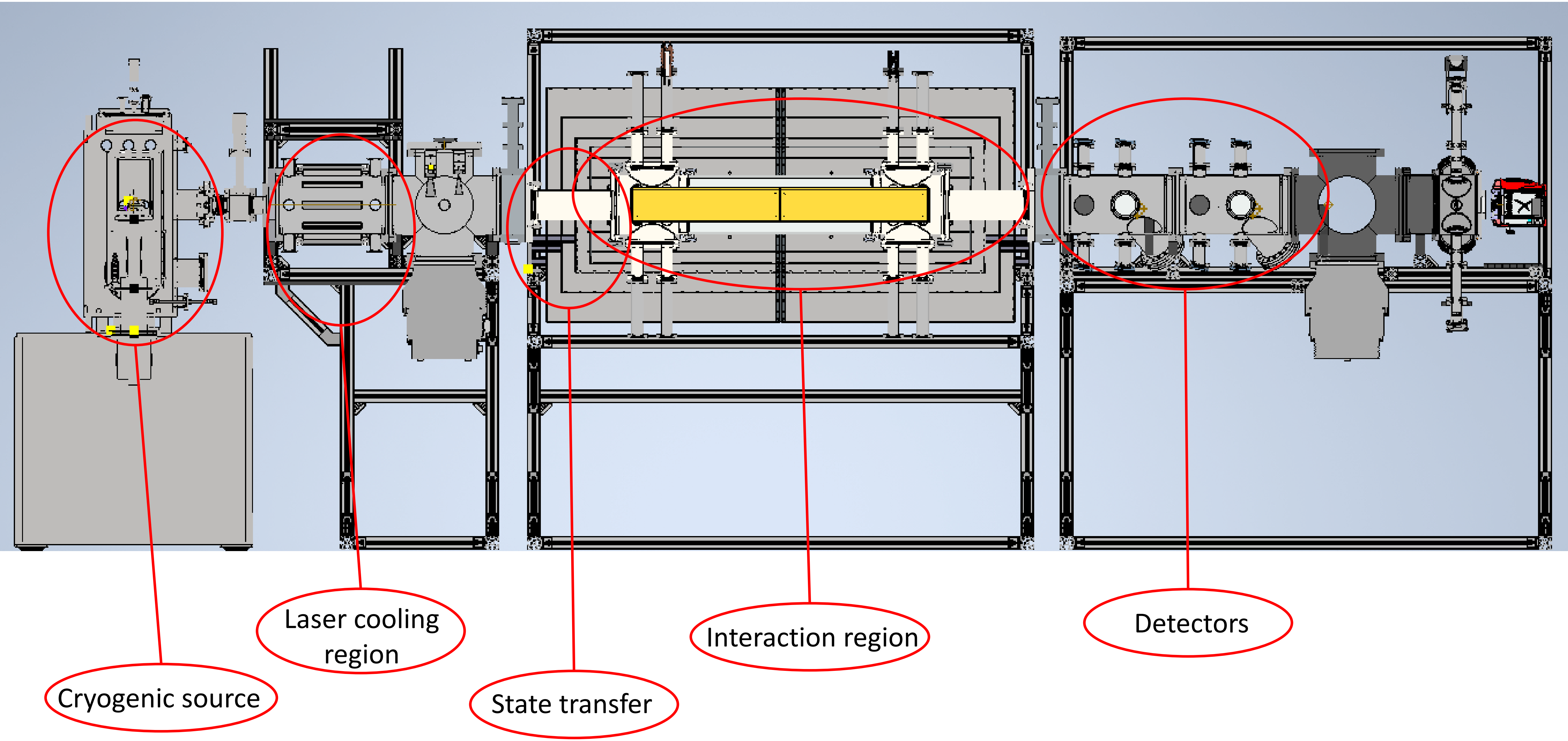
X. Alauze et al., Quantum Sci. Technol. **6**, 044005 (2021)

Ways to measure eEDM using ultracold YbF



N. J. Fitch et. al. Quantum Sci. Technol. **6**, 014006 (2021)

Ultracold YbF eEDM beamline



YbF eEDM: The magnetic field nightmare

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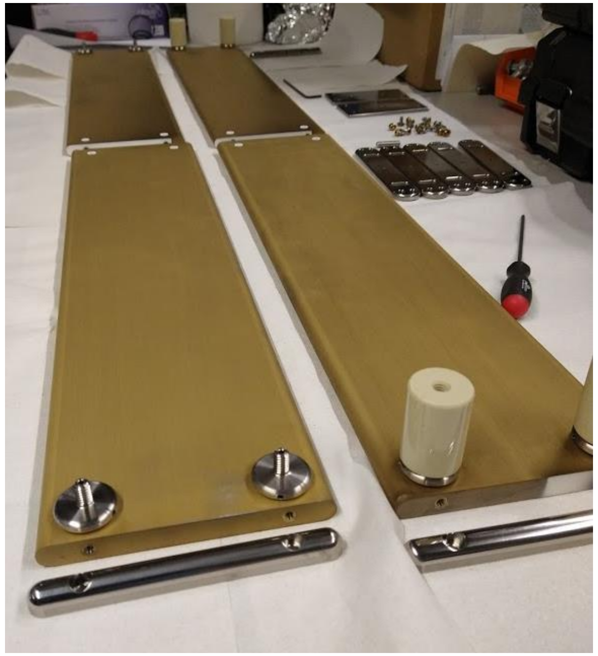
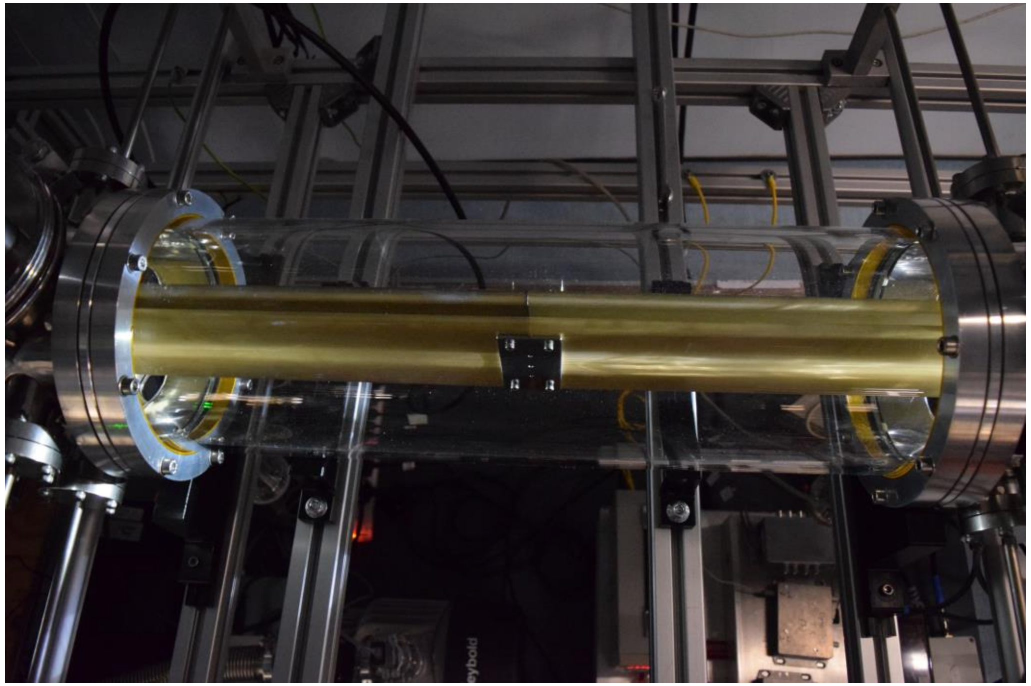
- Magnetic moment of ground state YbF is 1 μ_B (14 Hz/nT)
- 1 fT = 4 x 10^{-30} e.cm

- Background magnetic field below 1 pT
- Gradients below 10 pT / cm
- Magnetic noise below 20 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ at the E-switch frequency (equivalent to 2 x 10^{-31} e.cm in one day)
- Measure E-correlated magnetic fields with noise floor below 20 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$
- Reduce E-correlated leakage currents below 10 pA (at 20 kV/cm)
- Eliminate all ferromagnetic material
- Eliminate metals from spin-precession region – they generate too much Johnson noise
- Magnetic shield with shielding factor >10^6 (in direction of E-field)

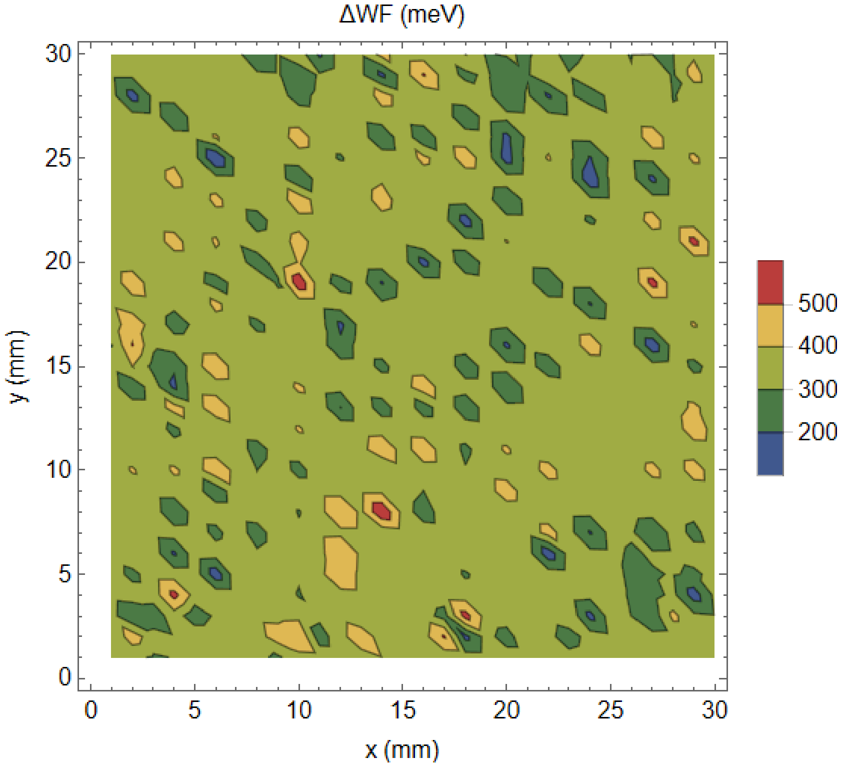
Electric field plates without metal



Alumina (Al_2O_3) field plates coated with titanium nitride. Small metal parts are titanium



Mounted inside glass vacuum chamber with titanium chambers at either end



- For 100 ms coherence time, Johnson-noise equivalent to 1 x 10^{-31} e.cm in a day
- Flatness of 10 μm over 1 m length
- Work function has standard deviation of 54 mV. Corresponding systematic due to geometric phase is below 3 x 10^{-33} e.cm
- No electrical discharges observed for fields up to 1 MV/cm
- At 20 kV/cm leakage currents are below 1 nA (limited by ammeter sensitivity; picoammeters designed and built)

YbF eEDM: Summary

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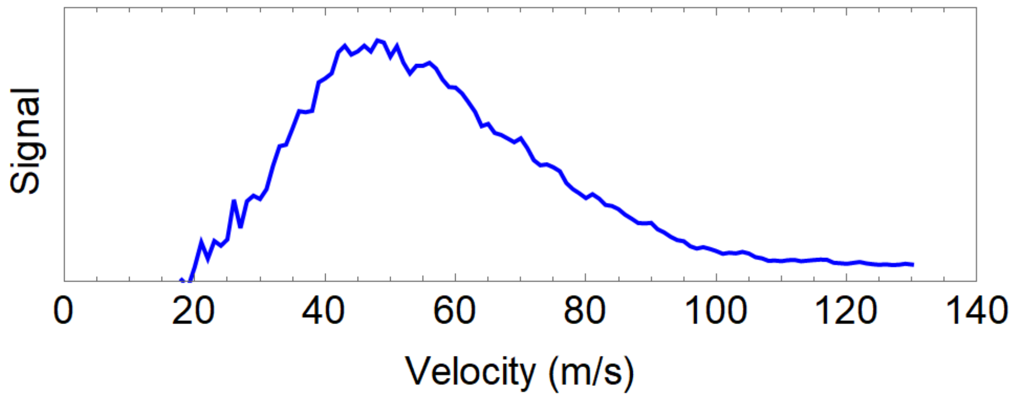
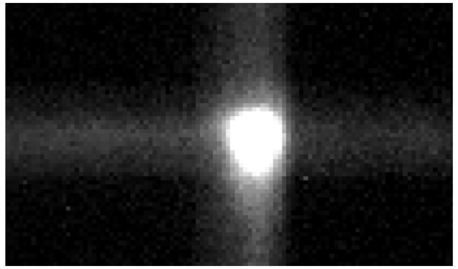
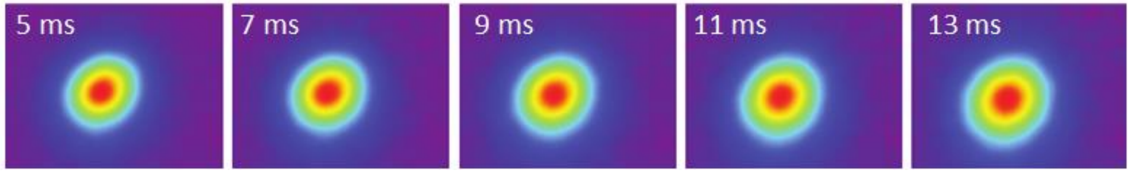
High flux of molecules with speeds below 40 m/s

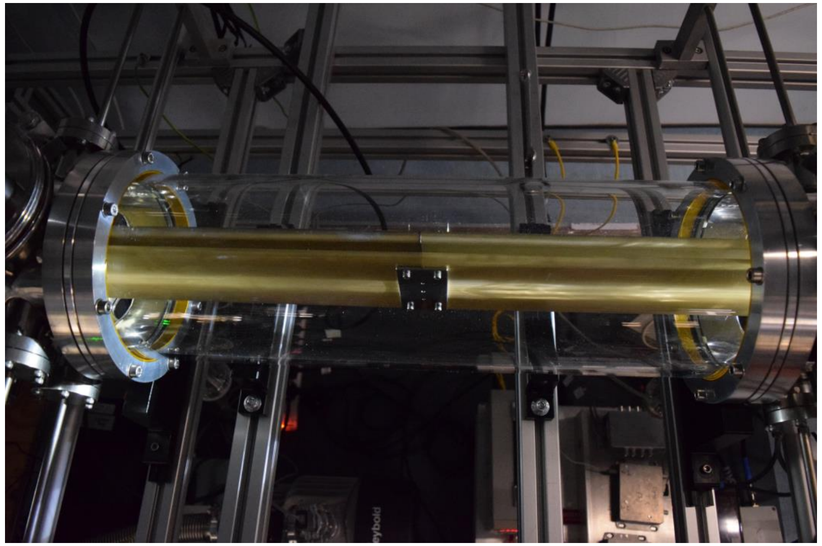




Beam cooled to below 100 uK;
Long spin-precession time possible

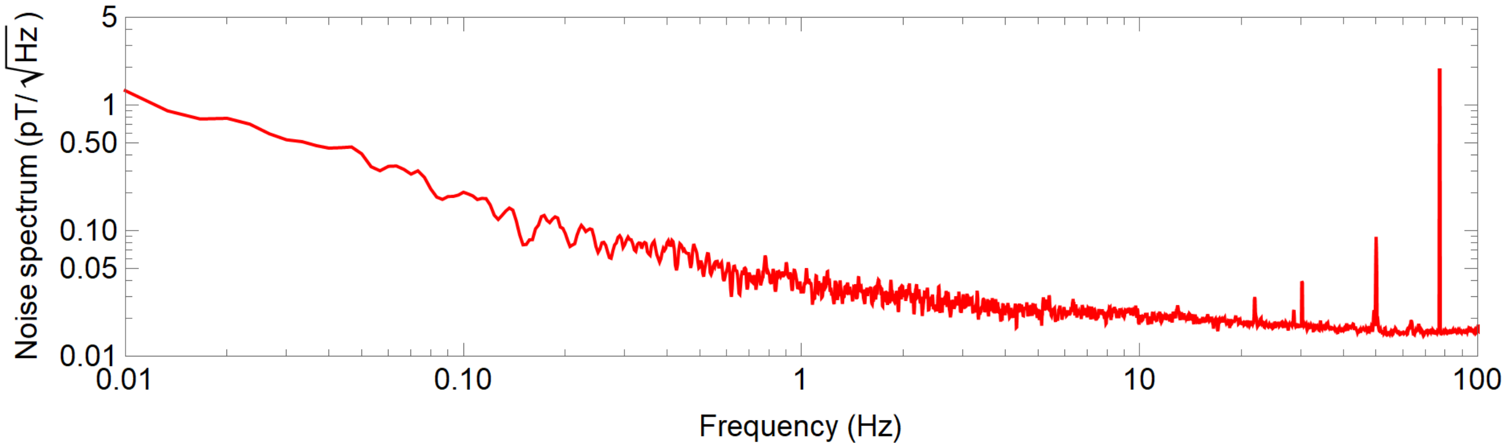
Trapping & deep cooling established for CaF





Beamline built with low Johnson noise interaction region

Magnetic noise remains very challenging, but progress is good



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What we might learn from different experiments

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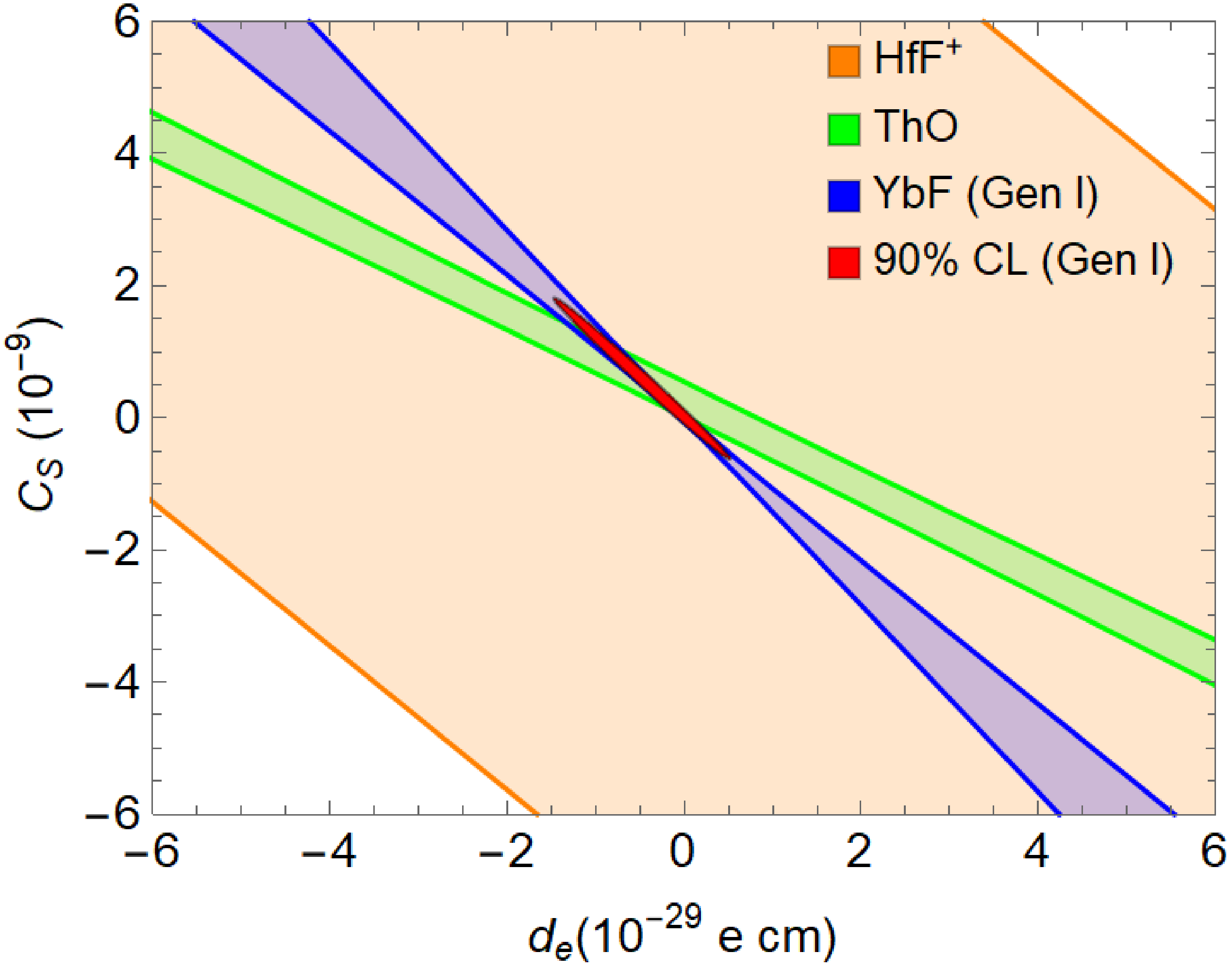

YbF eEDM: Magnetic shielding

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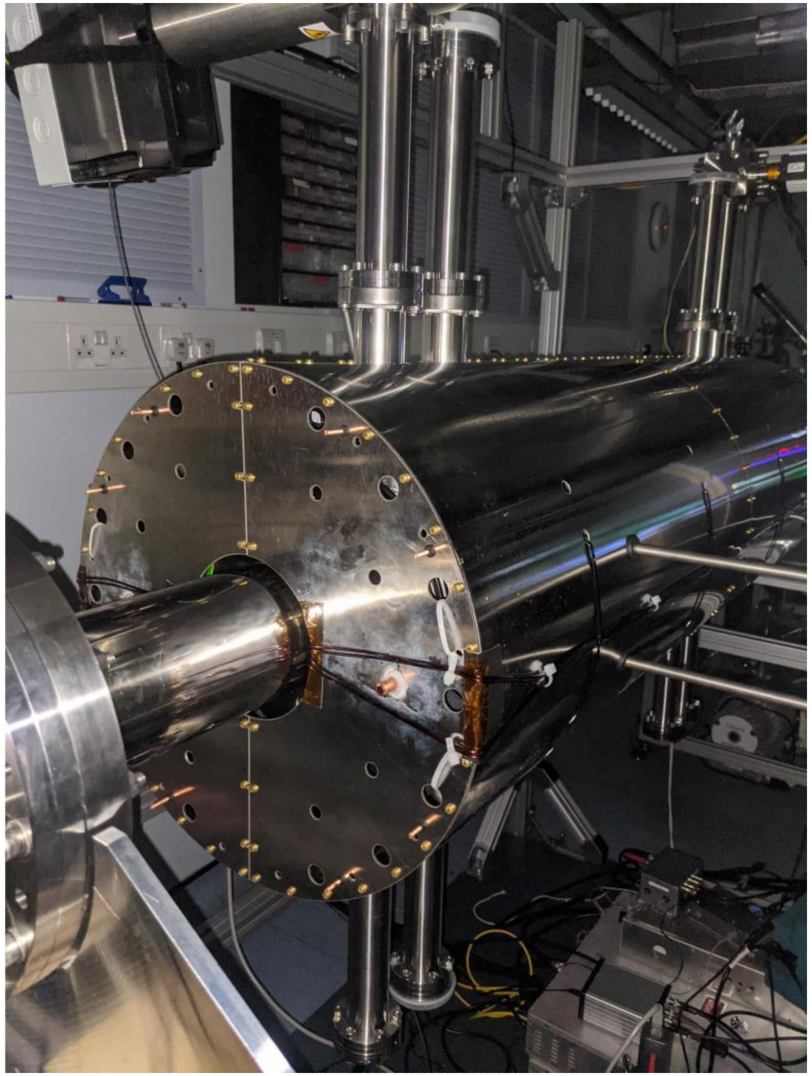

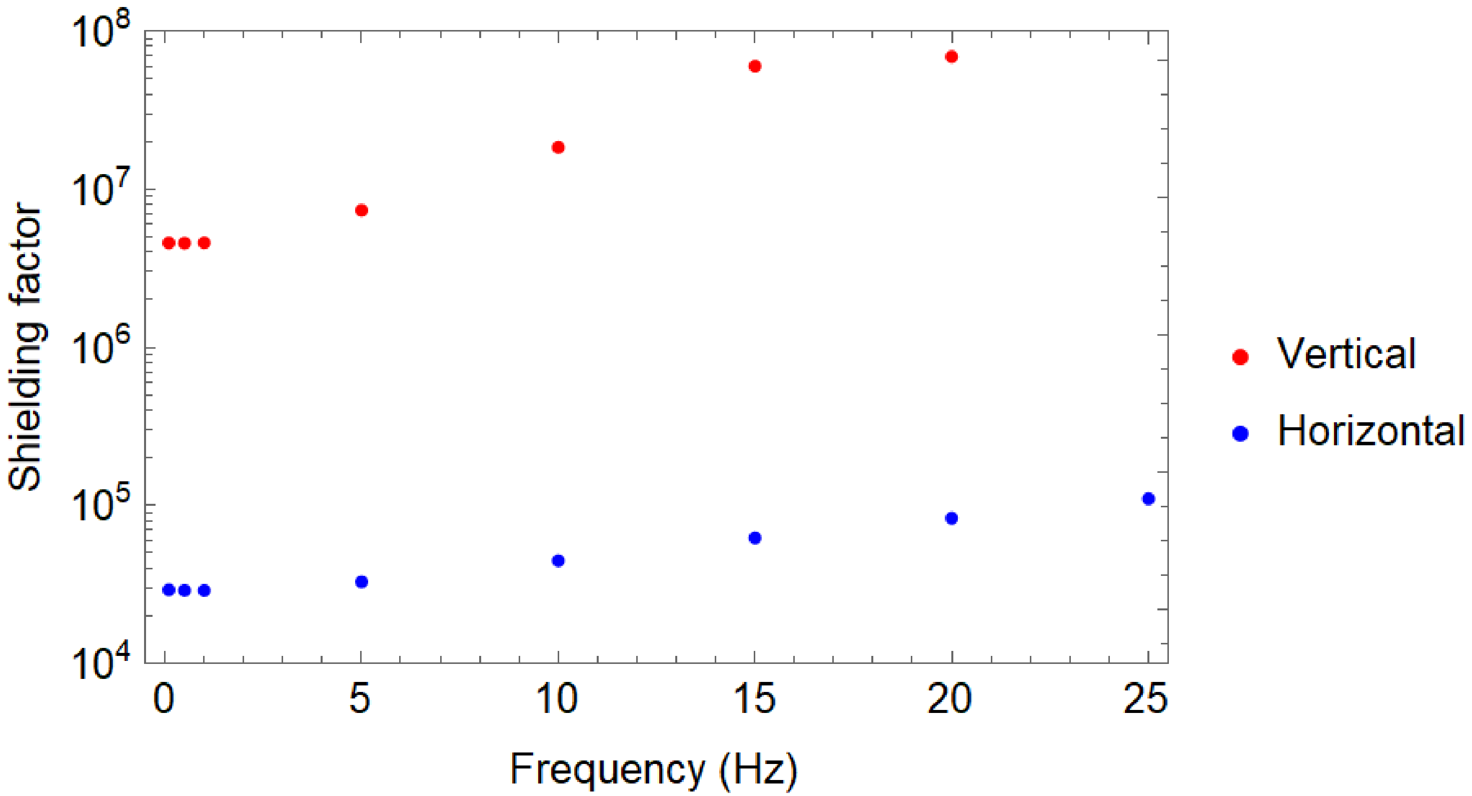

Option for co-magnetometry

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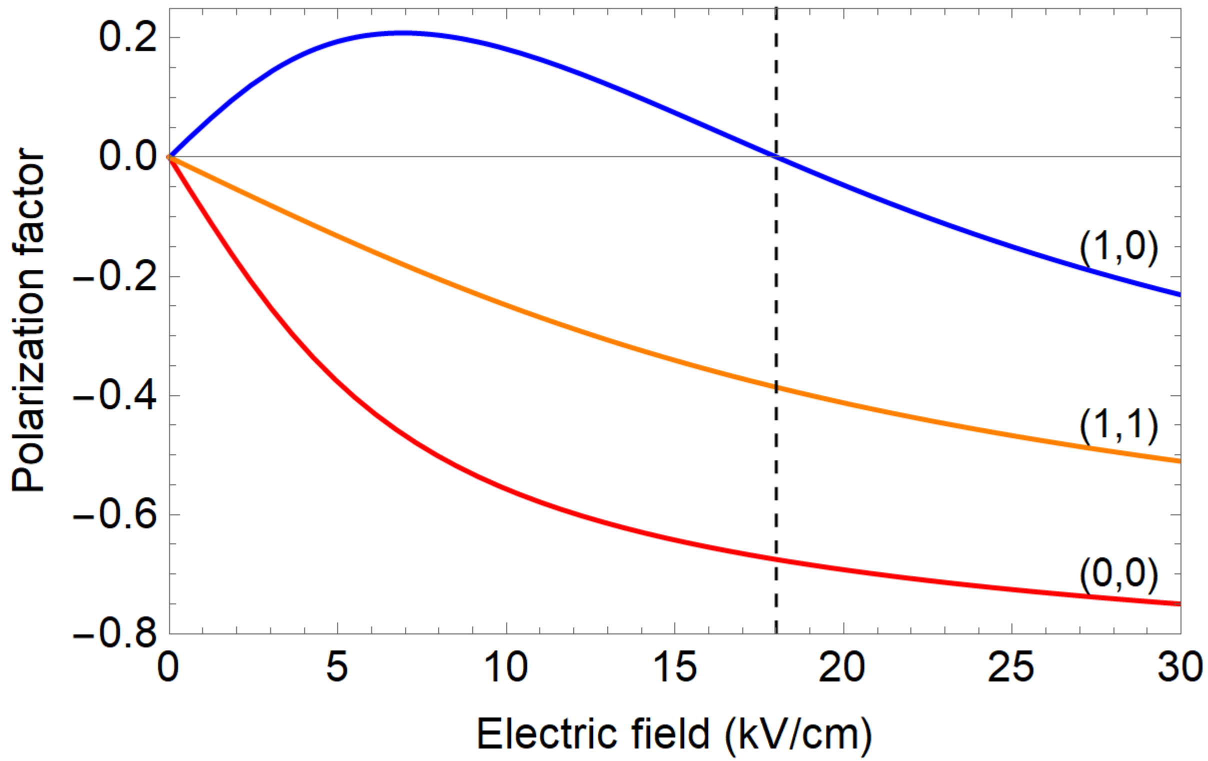

Insensitive to d_e , sensitive to μ

Insensitive to d_e and μ

Sensitive to d_e and μ

Rotational states labelled by (N, M_N)