Imperial College London

Measurement of the electron's electric dipole moment

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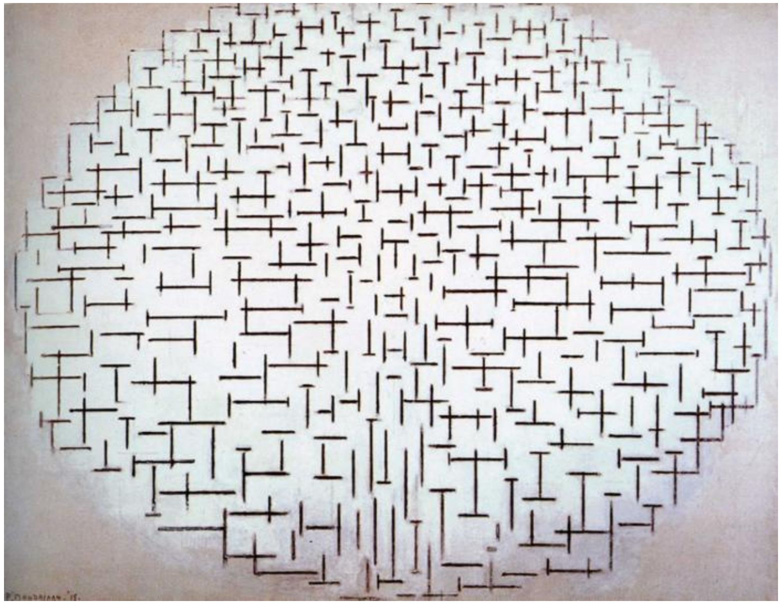
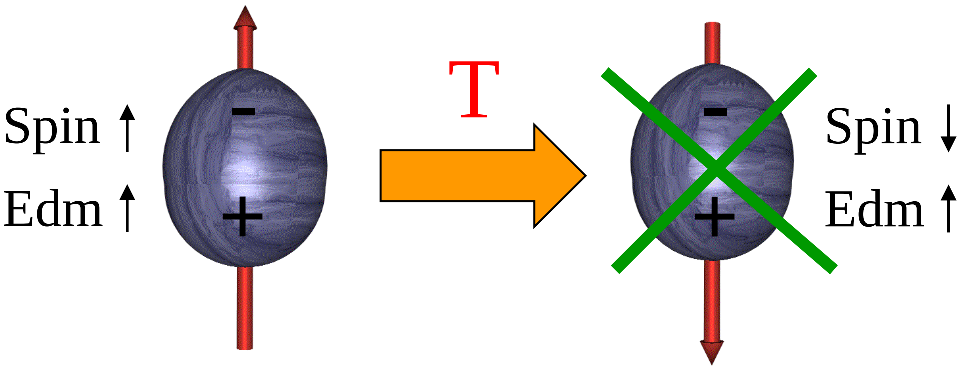


'Pier and Ocean' , Mondrian

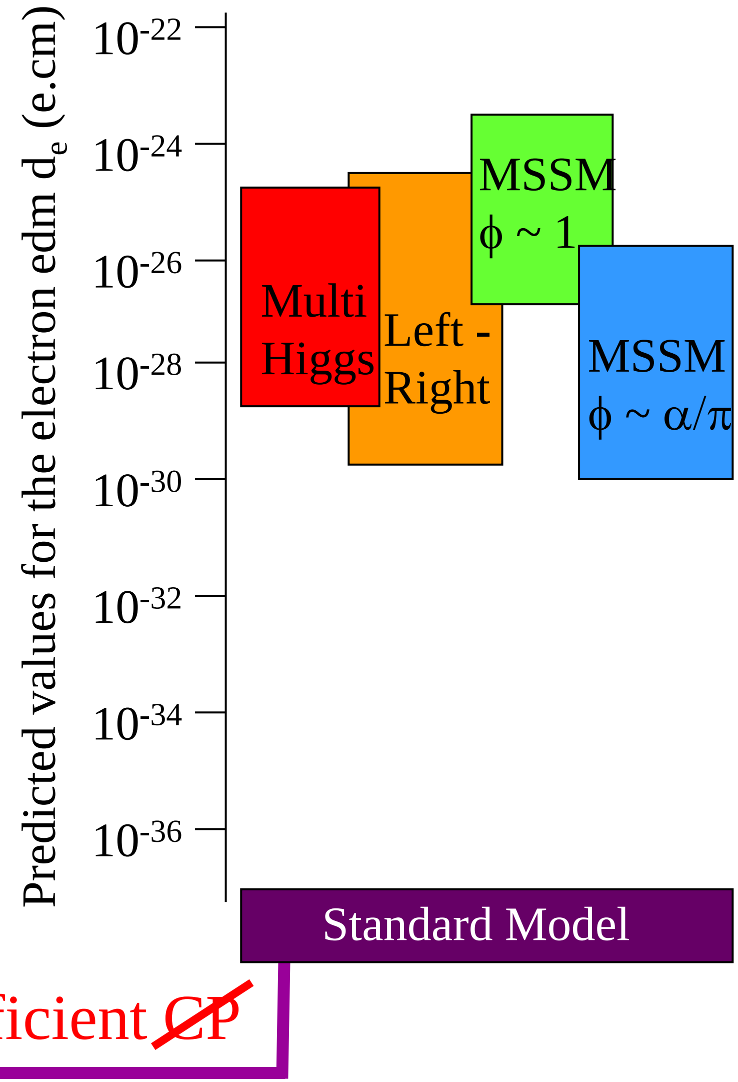
University of Birmingham, 6th March 2013

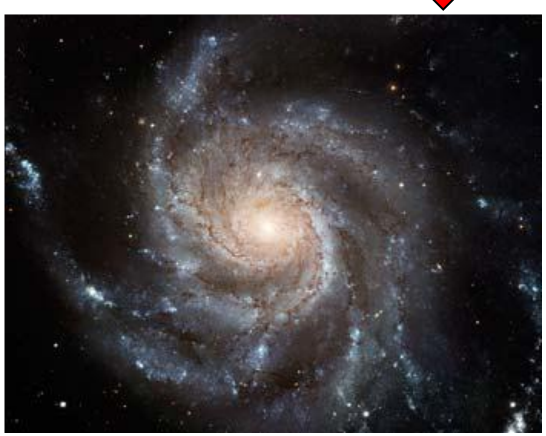
The electron's electric dipole moment (EDM, d_e)



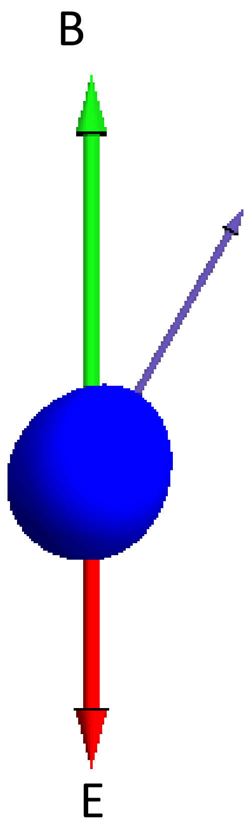
Either $d_e = 0$, or $\not{T}$

$\not{T}$ implies $\not{CP}$





Measuring the EDM – spin precession



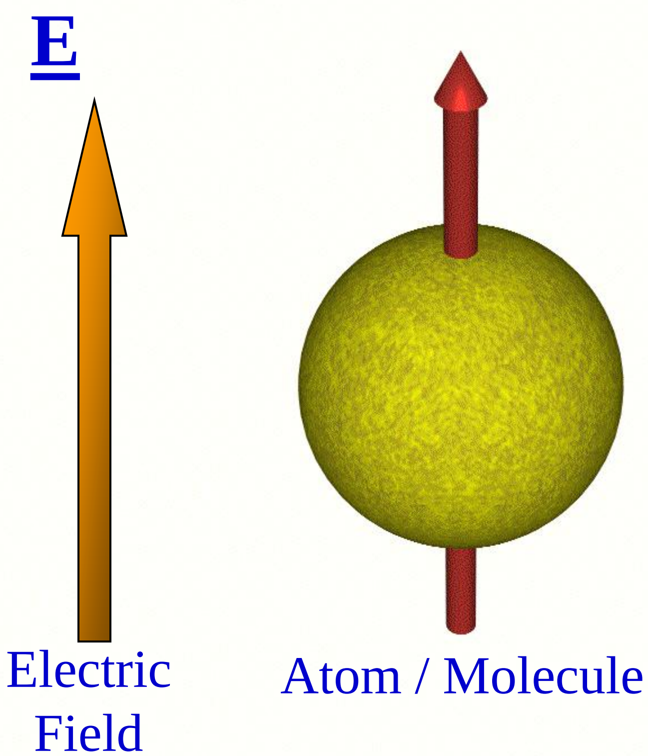
Particle precessing in
anti-parallel magnetic
and electric fields

Measure change in precession rate when electric field direction is reversed

Using atoms & molecules to measure d_e

For a free electron in an applied field **E**, expect an interaction energy $-\mathbf{d_e}.\mathbf{E}$

N.B. Analogous to interaction of magnetic dipole moment with a magnetic field, $-\underline{\mu} \cdot \underline{B}$



Interaction energy = $-\,\mathbf{d_e} \cdot \mathbf{E_{eff}}$

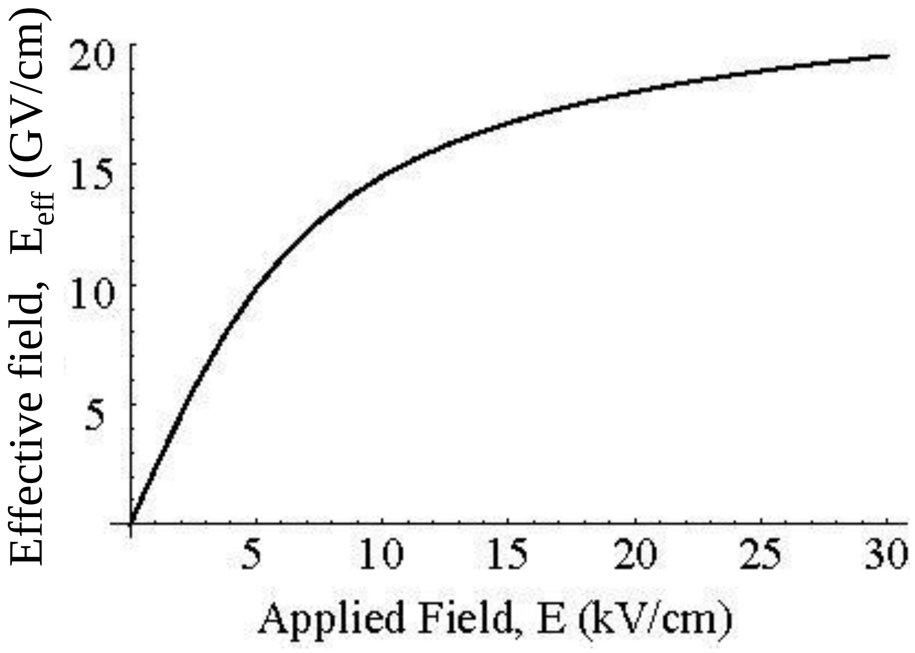
$E_{eff} = F\,P$

Structure dependent, $\sim 10\,(Z/80)^3$ GV/cm (F)

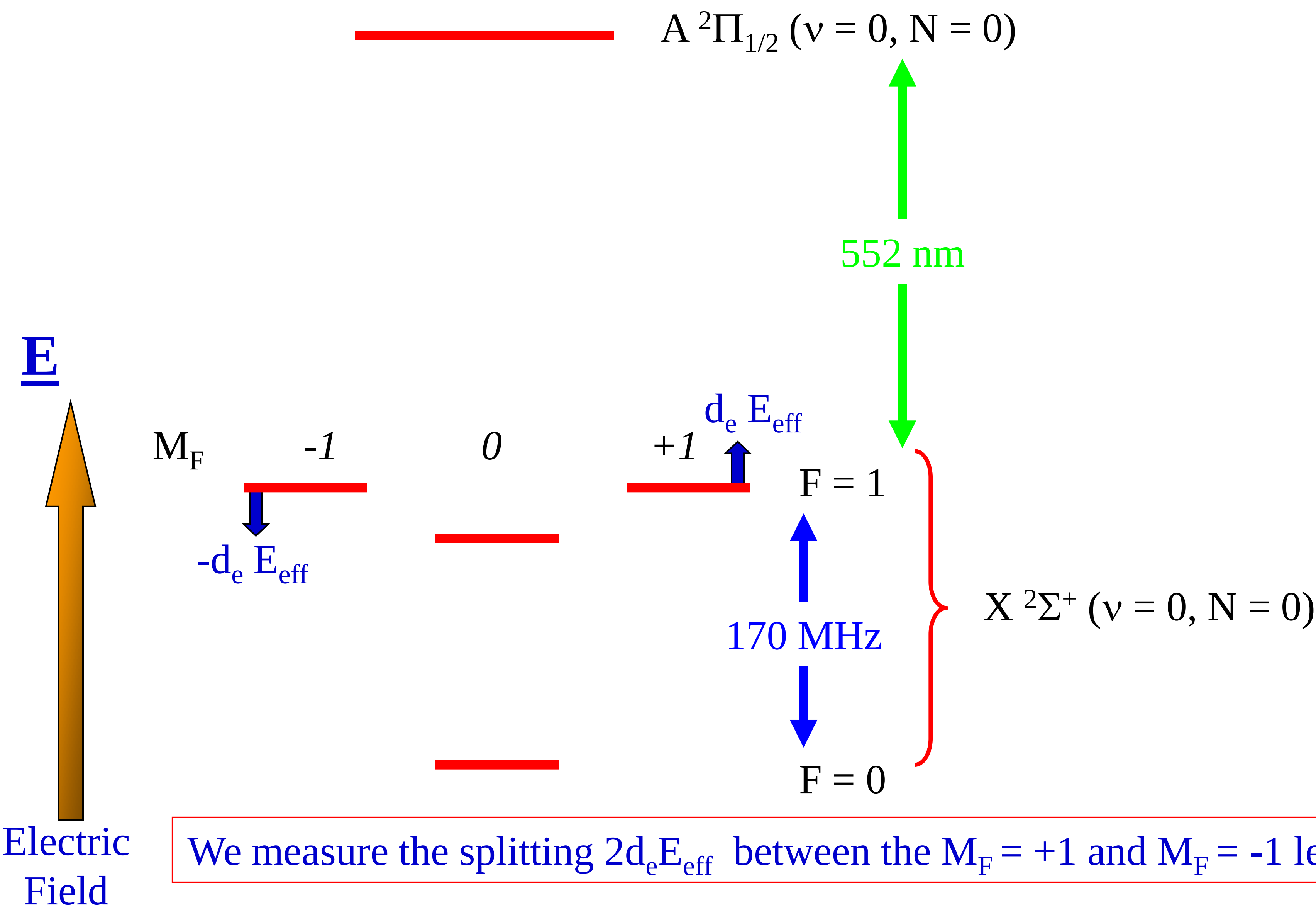
Polarization factor (P)

For more details, see E. A. Hinds, Physica Scripta T70, 34 (1997)

We use a molecule – YbF

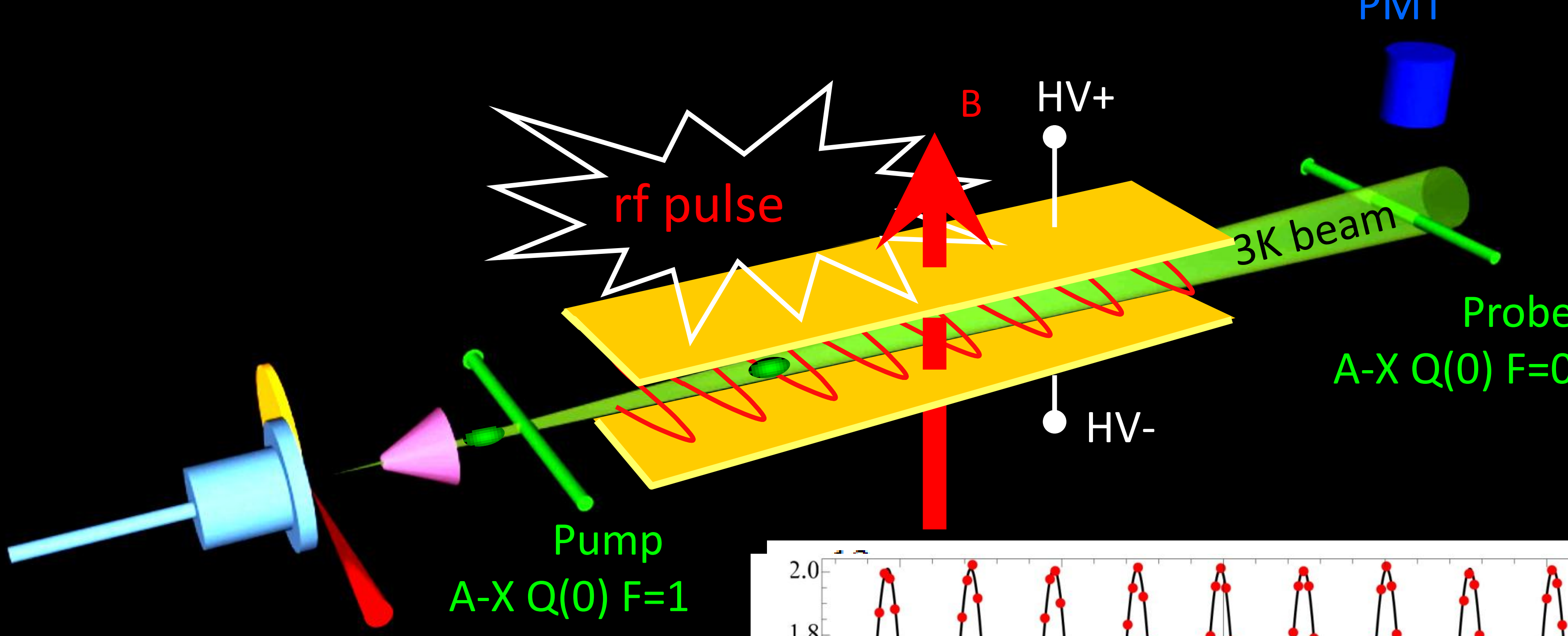


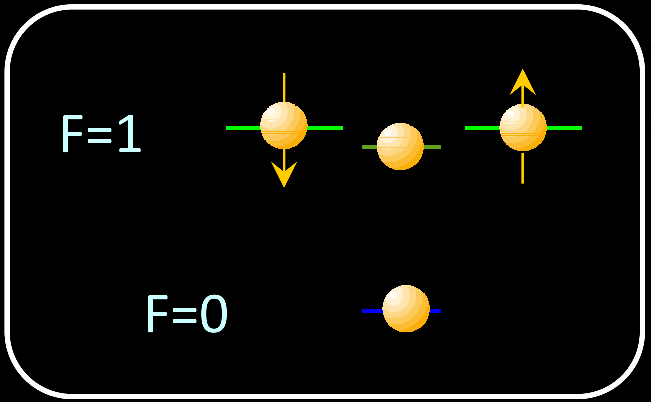
Relevant energy levels in the YbF molecule

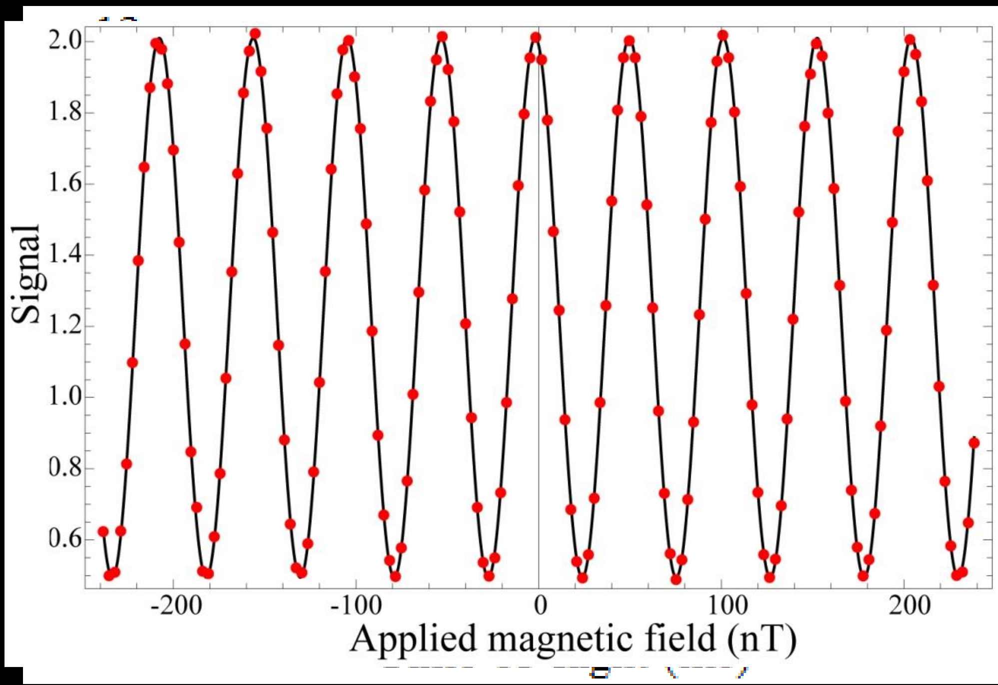


We measure the splitting $2d_eE_{eff}$ between the $M_F = +1$ and $M_F = -1$ levels

Measurement scheme – a spin interferometer

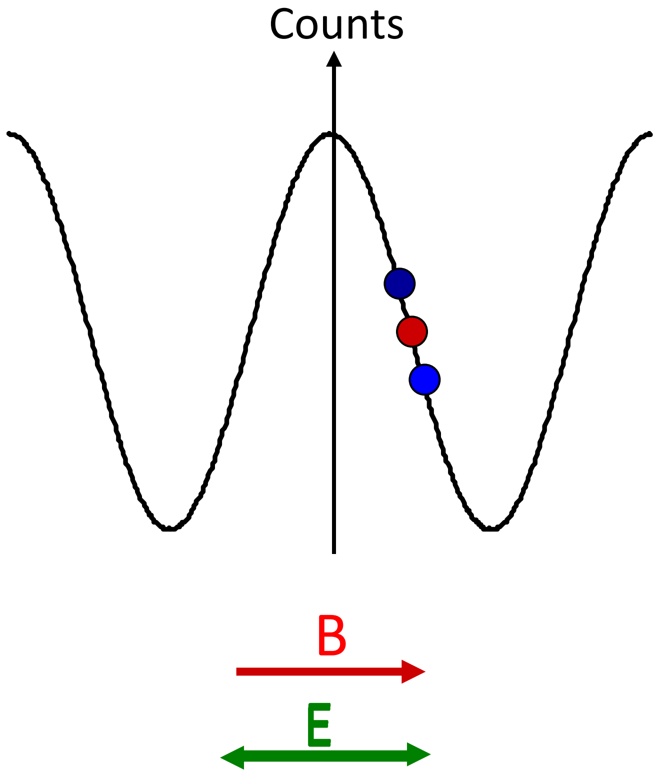




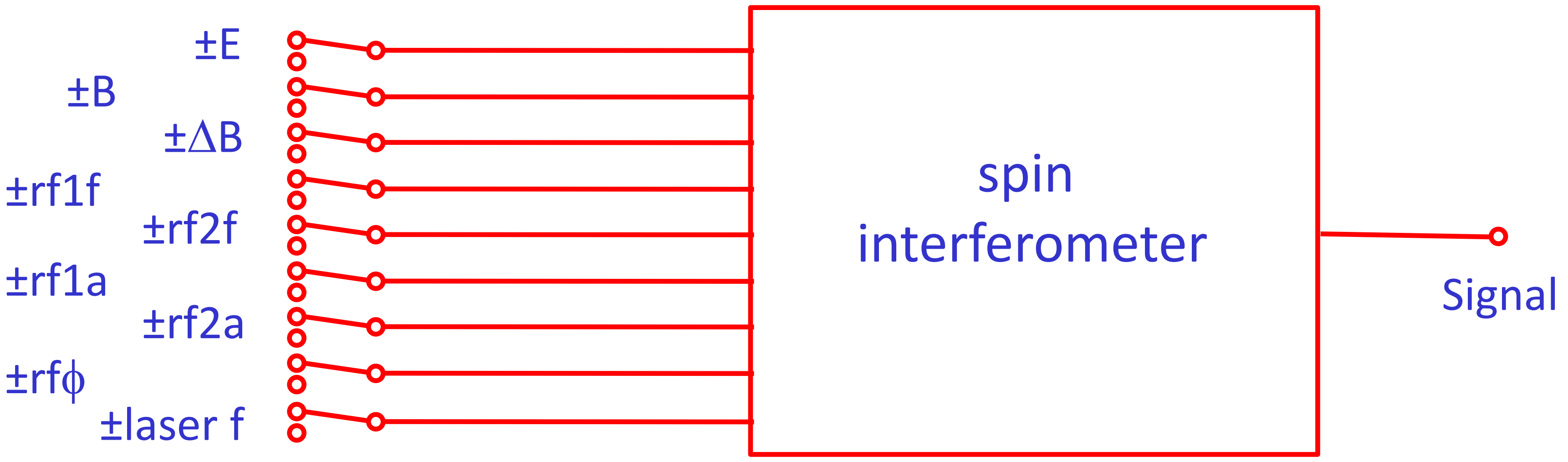


Measuring the edm with the interferometer

$$\text{Signal} \propto \cos^2[\phi/2] = \cos^2[(\mu_B B - d_e E_{eff})\, T / \hbar]$$



Modulate everything



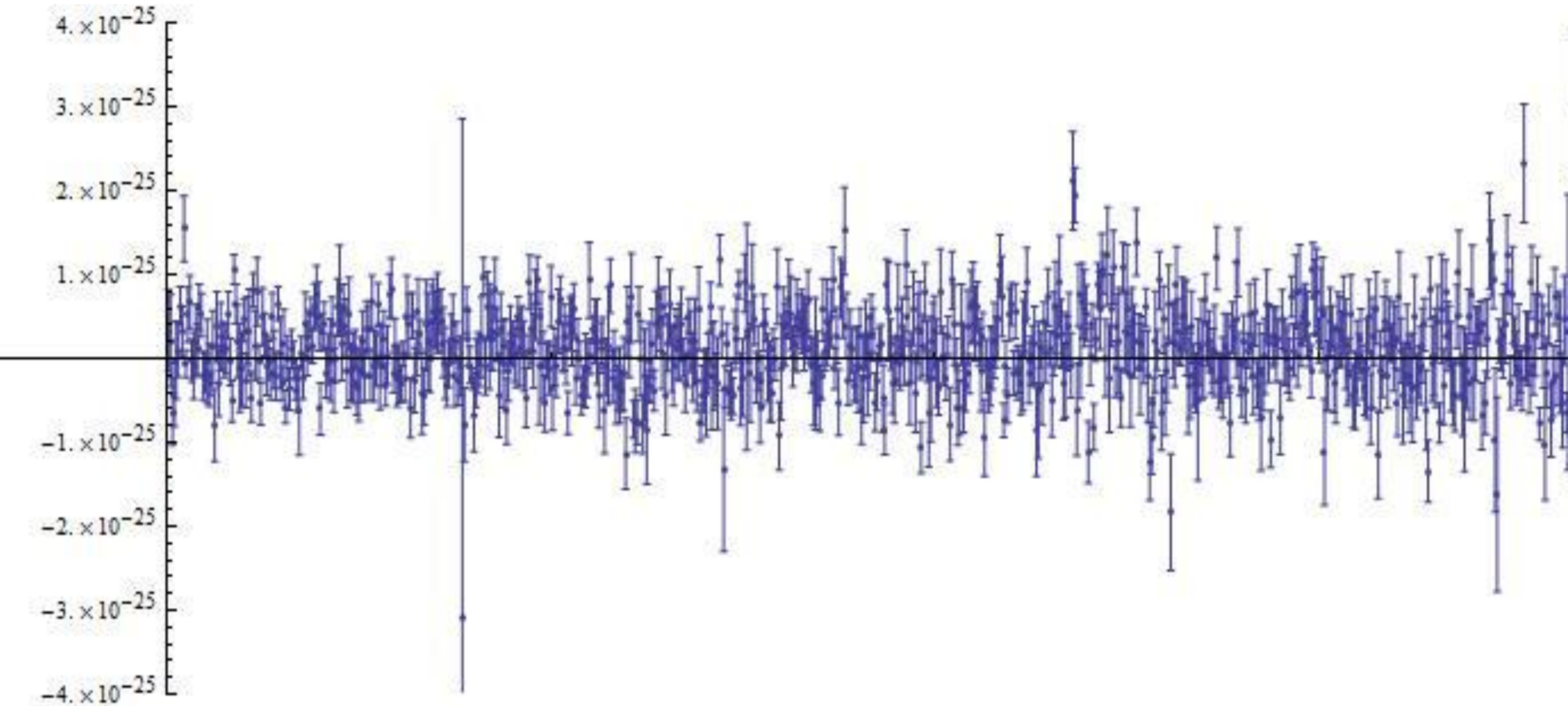
9 switches:

512 possible correlations

- The EDM is the signal correlated with the sign of E.B
- We study all the other 511 correlations in detail

Result (2011)

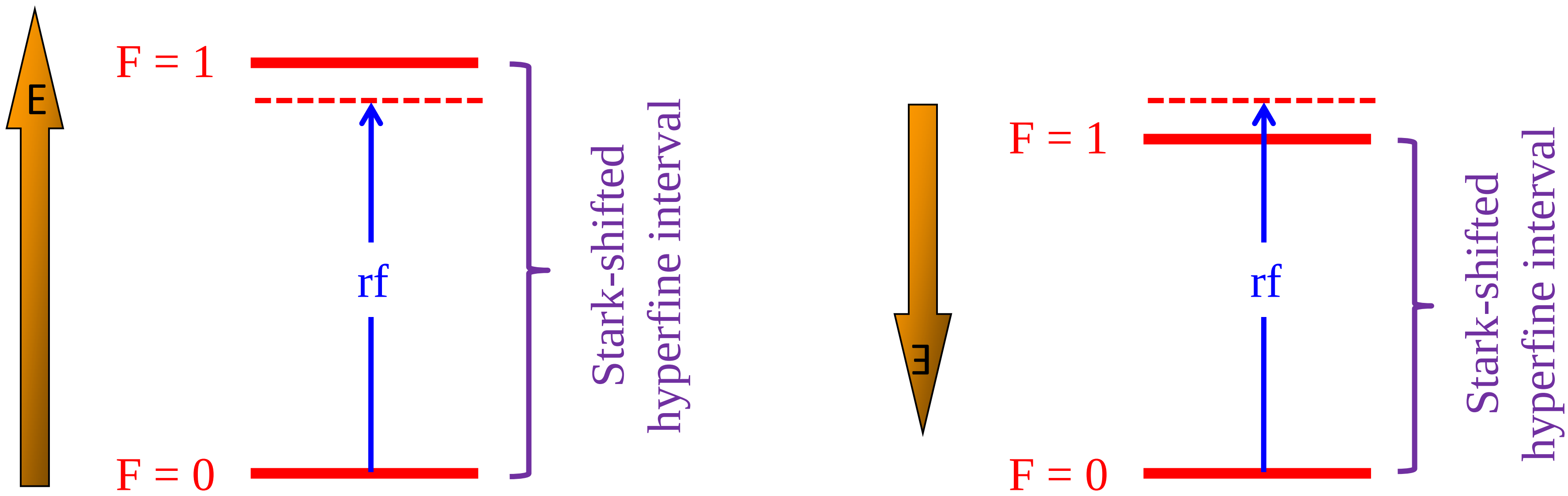
- 6194 measurements of the EDM, each derived from 4096 beam pulses
- Each measurement takes 6 minutes



- $d_e = (-2.4 \pm 5.7_{stat} \pm 1.5_{syst}) \times 10^{-28}\ e$.cm
- $|\,d_e\,| < 10.5 \times 10^{-28}$ e.cm (90% confidence level)

Nature 473, **493** (2011)

Correcting a systematic error



rf detuning → phase shift: ~100 nrad/Hz

Imperfect E-reversal → Changes detuning via Stark shift

→ Phase correlated with E-direction

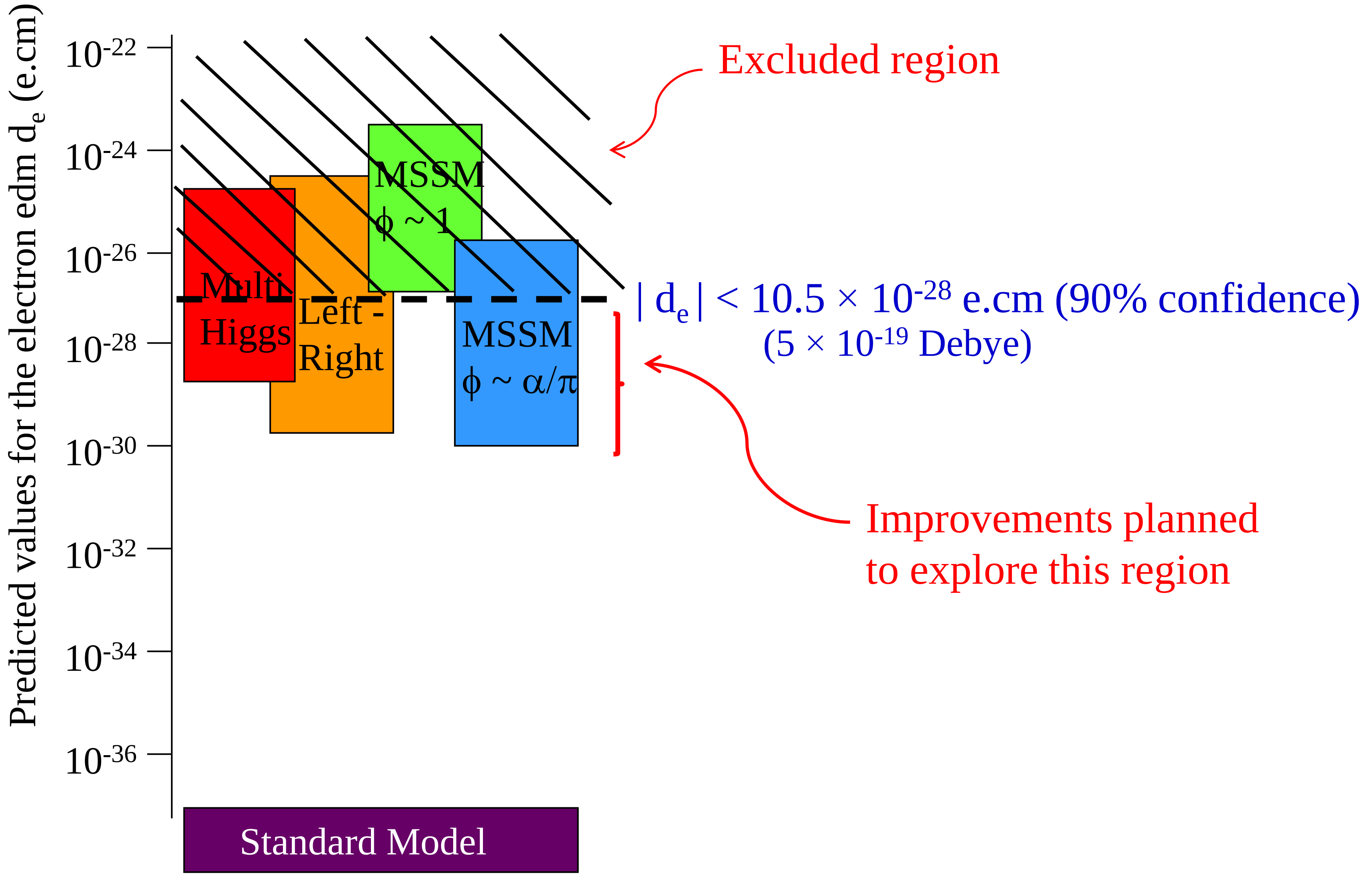
Correction to EDM: $(5.5 \pm 1.5) \times 10^{-28}$ e.cm

Systematic uncertainties

Effect	Systematic uncertainty (10^{-28} *e*.cm)
Electric field asymmetry	1.1
Electric potential asymmetry	0.1
Residual RF1 correlation	1.0
Geometric phase	0.03
Leakage currents	0.2
Shield magnetization	0.25
Motional magnetic field	0.0005

Result

$d_e = (-2.4 \pm 5.7_{stat} \pm 1.5_{syst}) \times 10^{-28}\ e.\mathrm{cm}$



How to do better

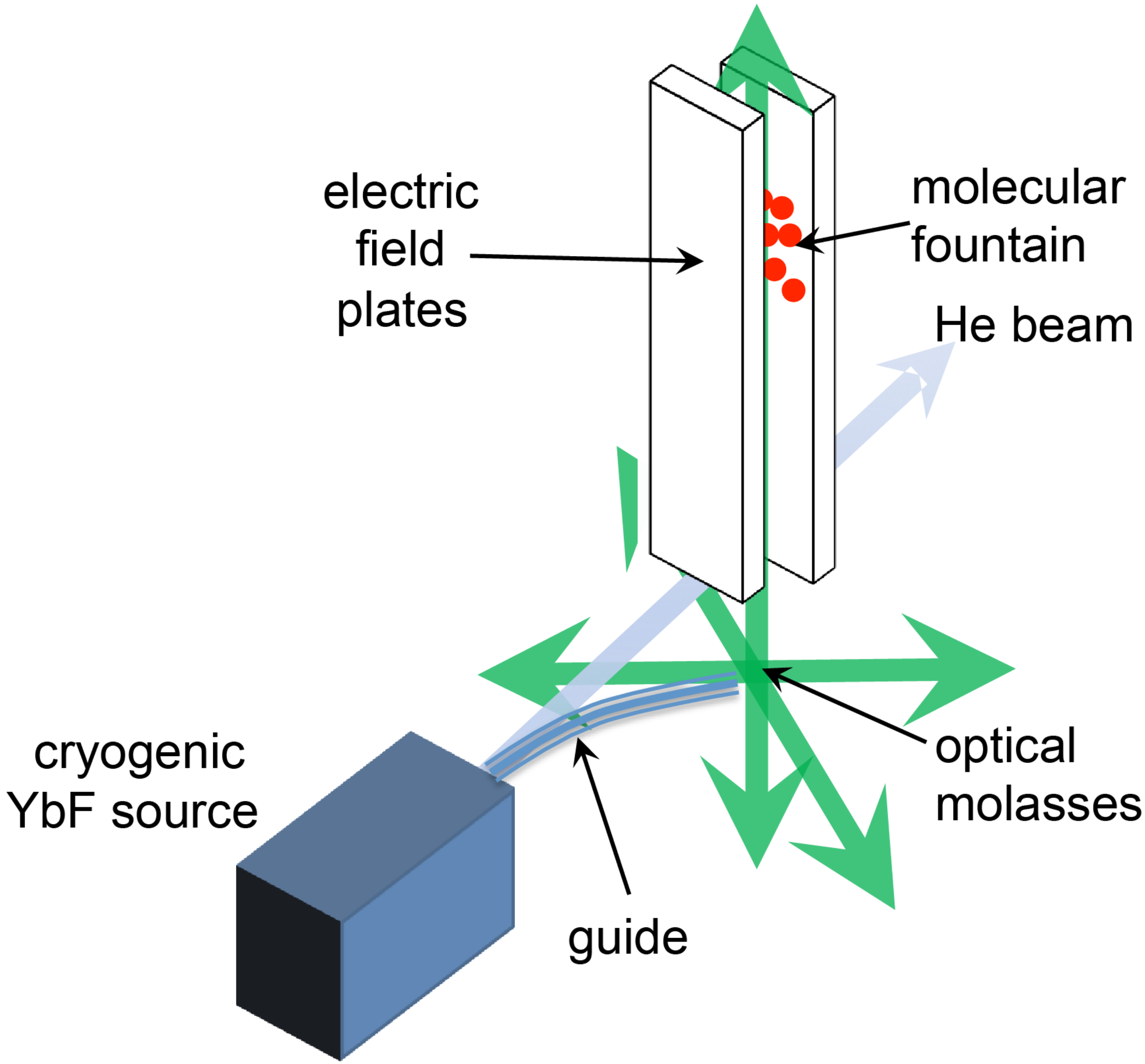
The statistical uncertainty scales as: $$\frac{1}{\sqrt{N}} \times \frac{1}{T} \times \frac{1}{E}$$

Total number of participating molecules

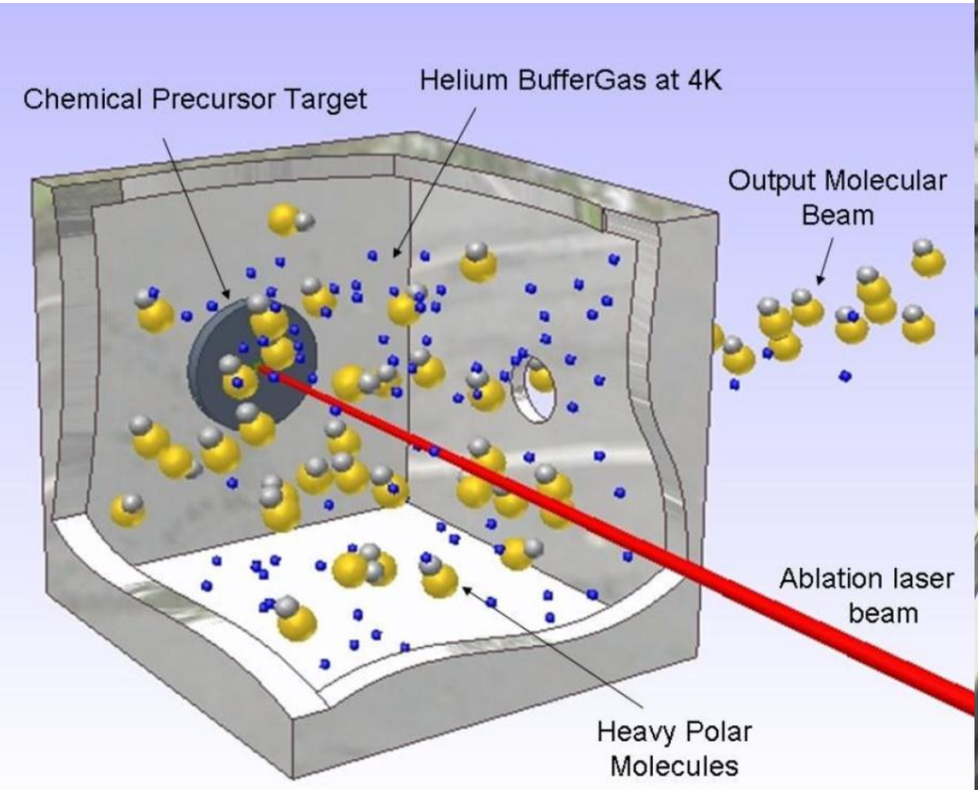
Coherence time

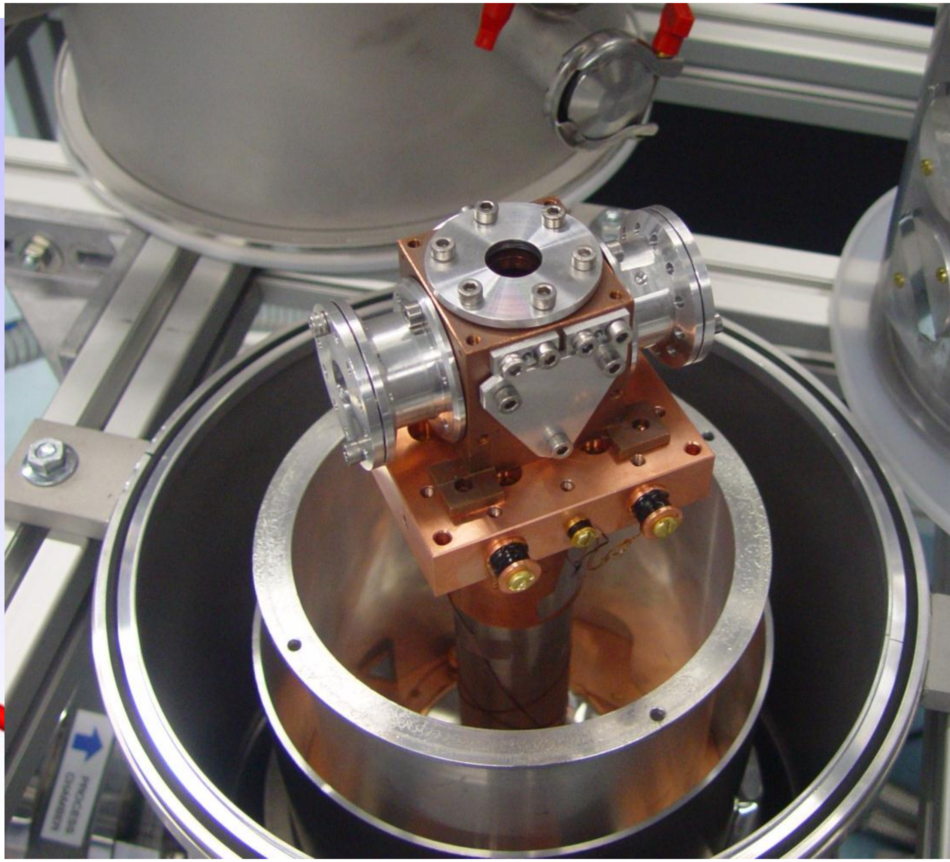
Electric field

Our dream experiment



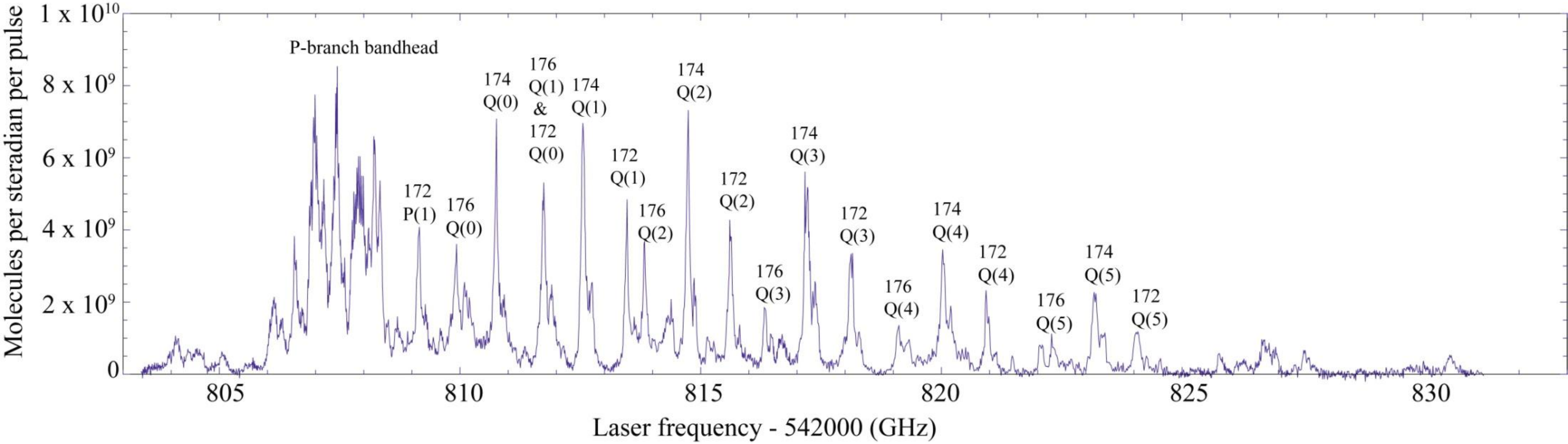
Cryogenic source of YbF





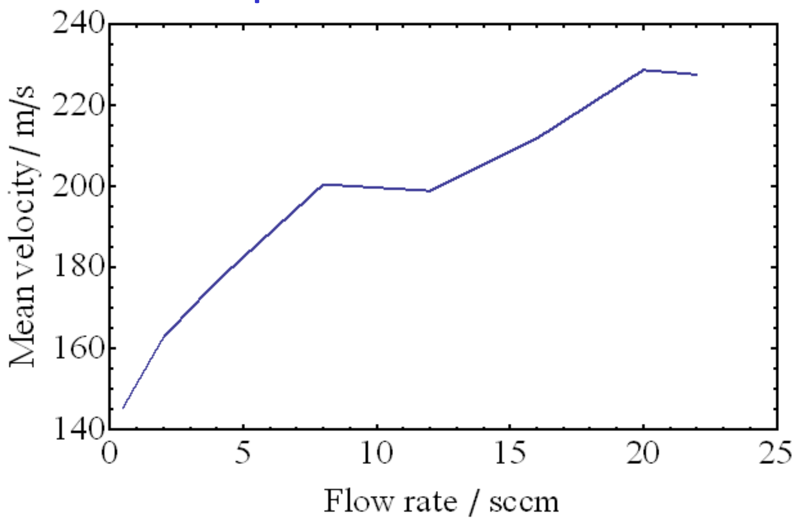
- Produce YbF molecules by ablation of Yb/AlF_3 target into a cold helium buffer gas
- Helium is pumped away using charcoal cryo-sorbs
- Produces intense, cold, slow-moving beams

Cold, slow beam of YbF molecules

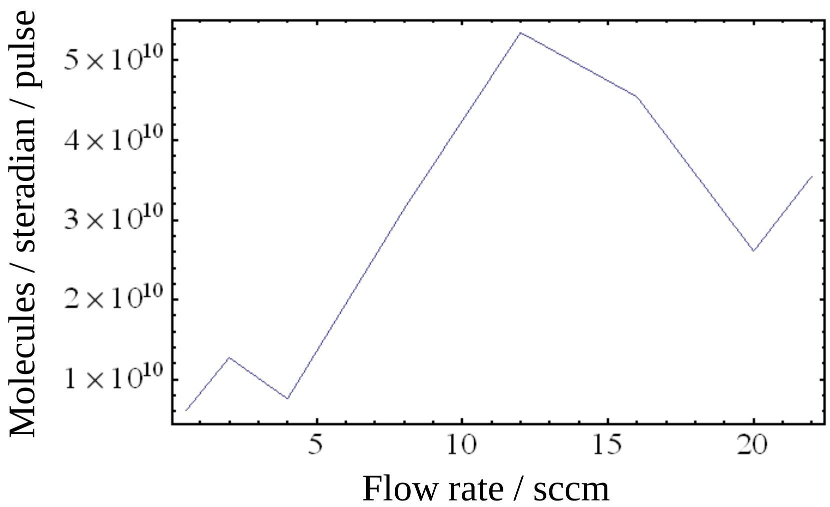


- Rotational temperature: 4 ± 1 K
- Translational temperature: 4 ± 1 K

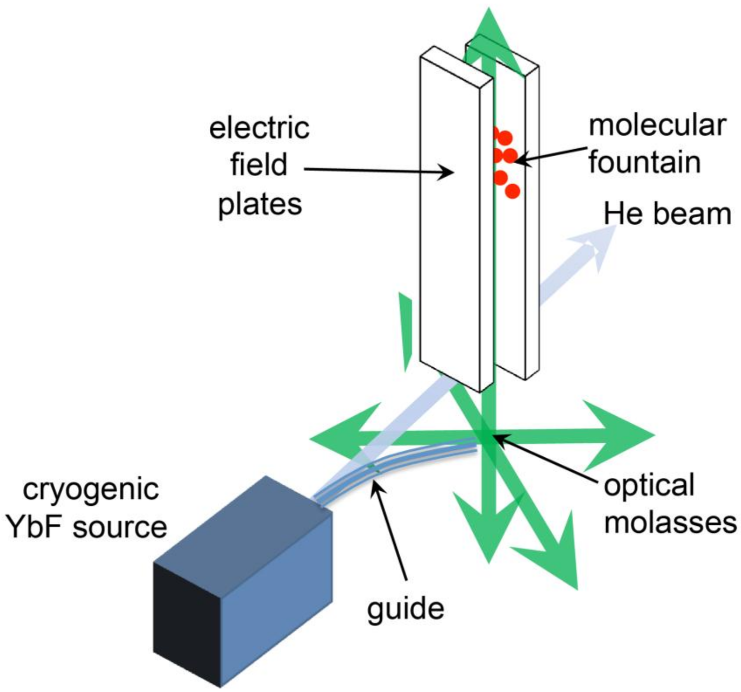
Speed vs helium flow

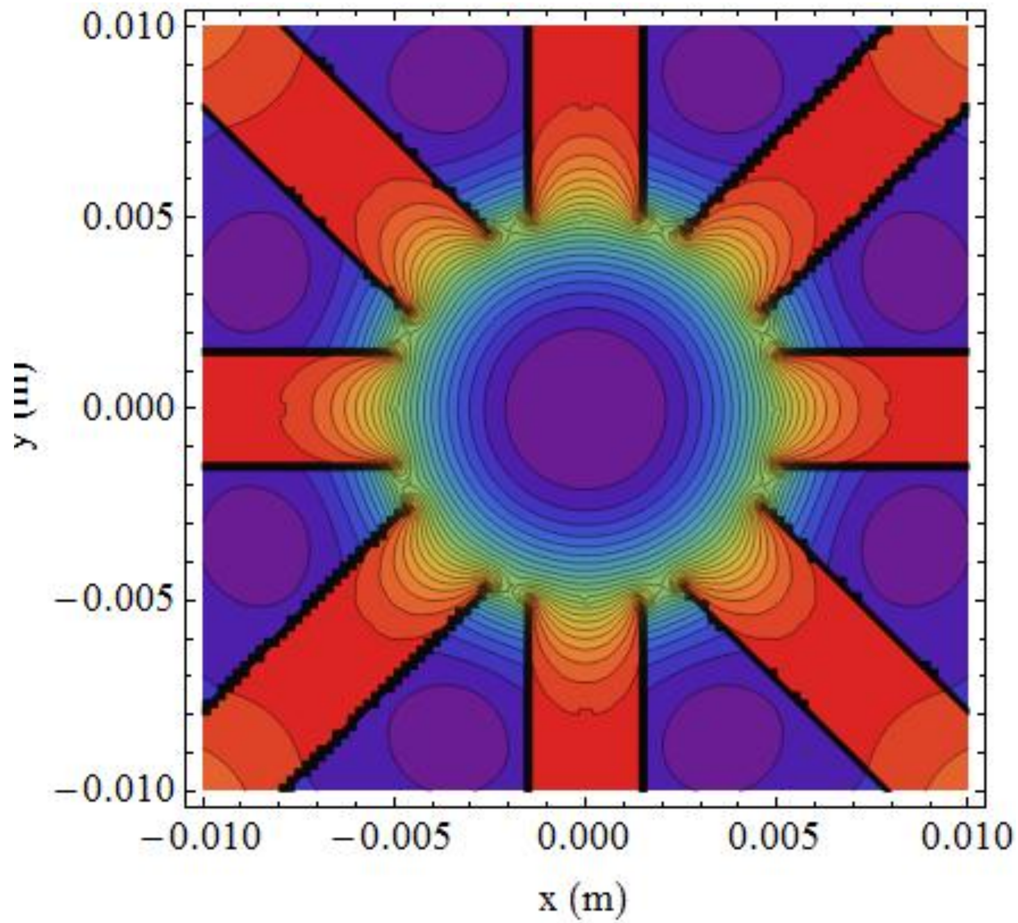


Flux vs helium flow



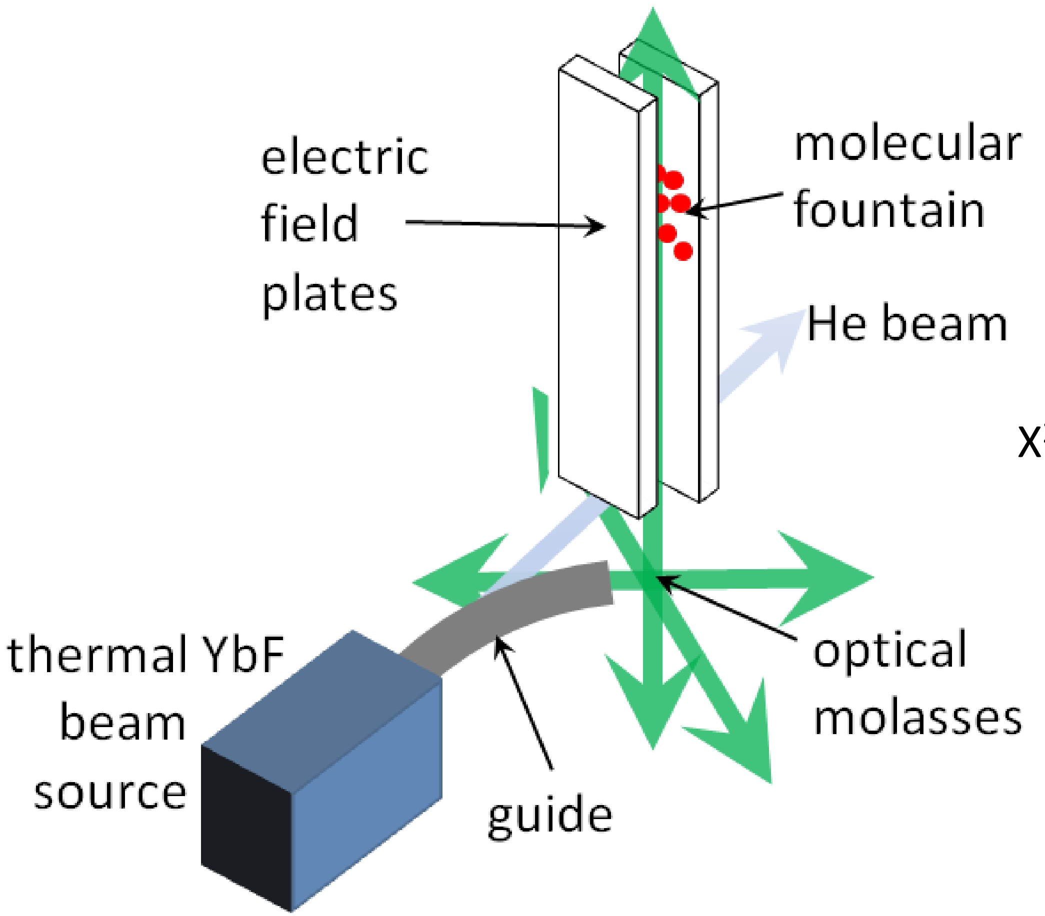
Magnetic guide

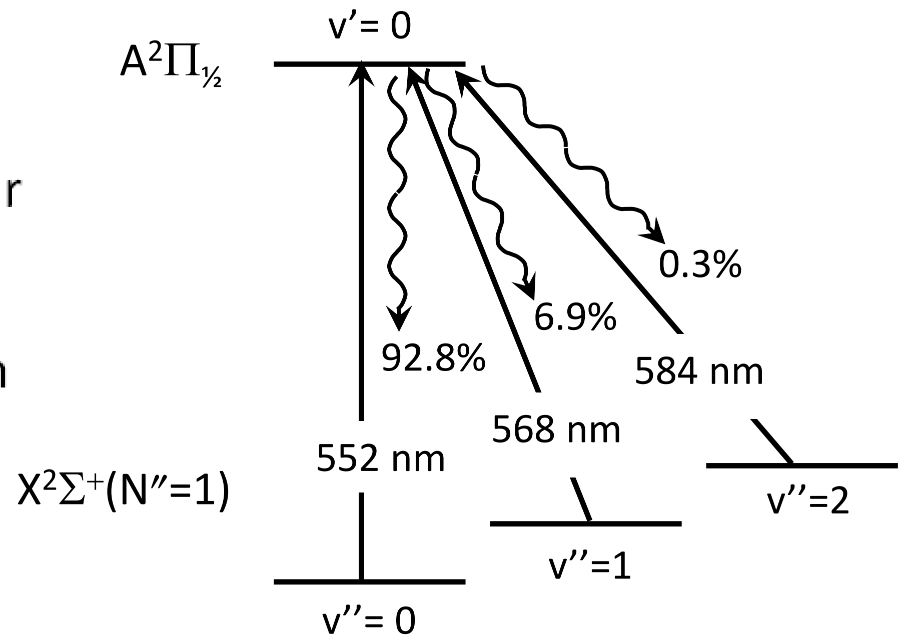


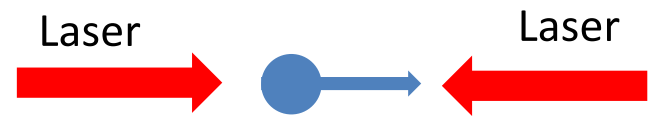


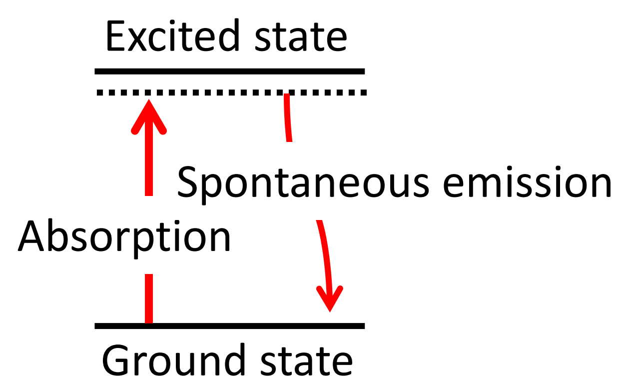
- ➢ Permanent magnets in octupole geometry, depth of 0.6 T
- ➢ Separates YbF molecules from helium beam
- ➢ Guides 6.5% of the distribution exiting the source

Laser cooling



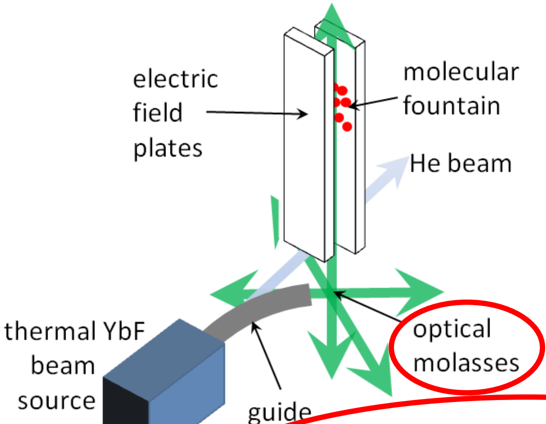




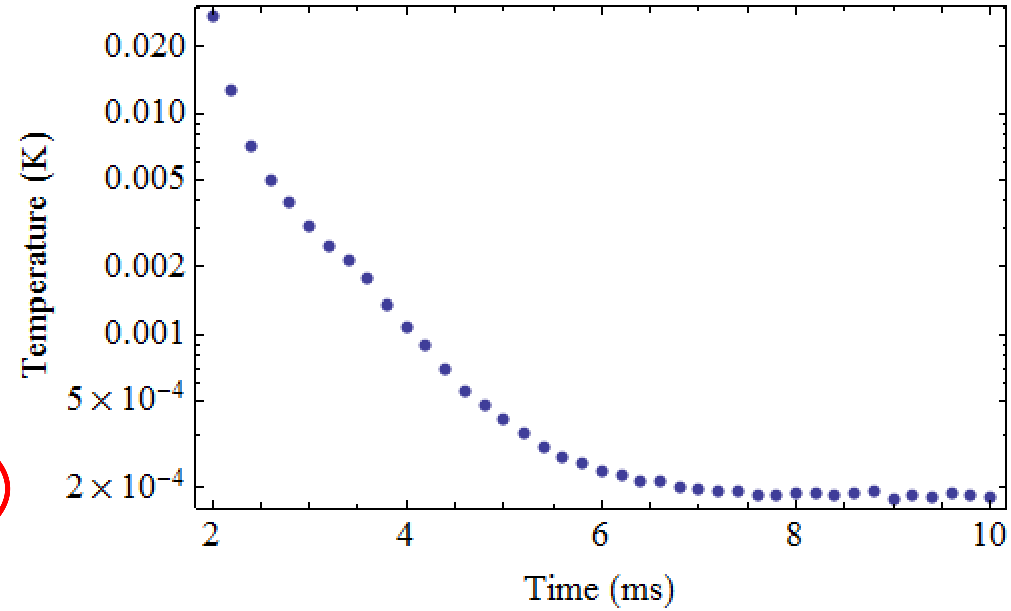


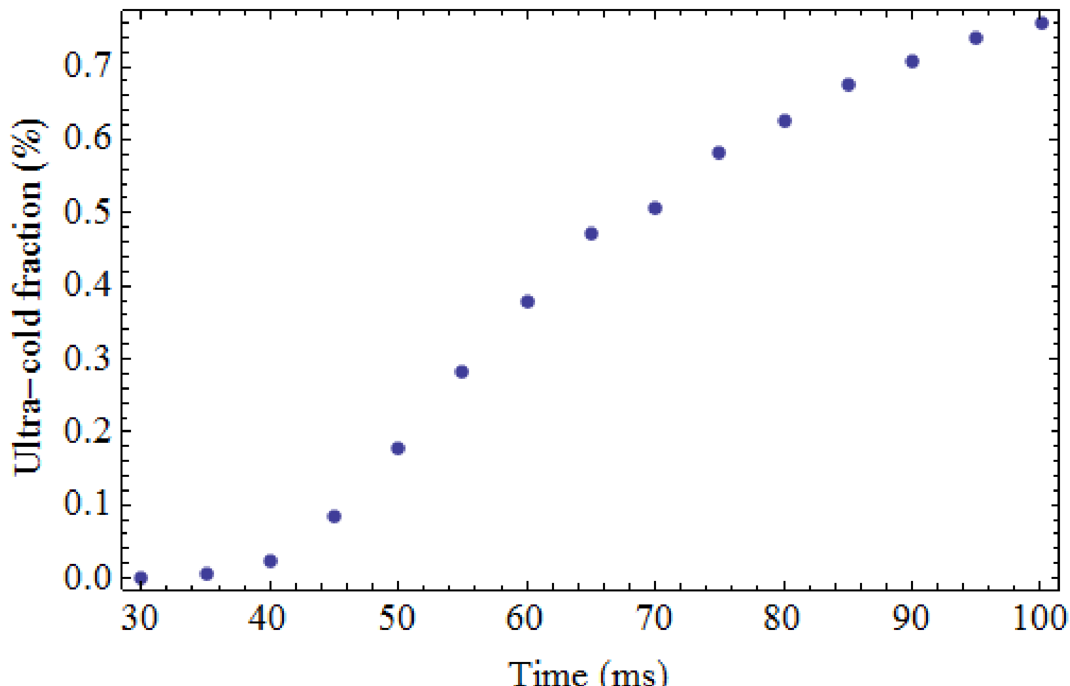
- ➢ Laser cooling is the key step!!

Simulations for YbF in an optical molasses



6 beams each containing 12 frequencies from 3 separate lasers – 750 mW total



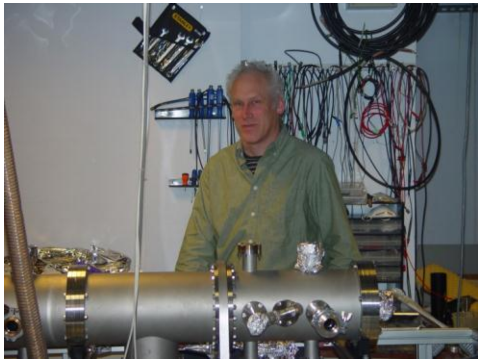


Sensitivity of an EDM fountain experiment

Quantity	Value	How determined?
Molecules in cell	10^{13}	Measured by us
Extraction efficiency	0.5 %	Measured by Doyle group
Fraction in relevant rotational state	24 %	Boltzmann distribution
Fraction accepted by guide	6.5 %	Magnetic guide simulation
Fraction cooled in molasses	0.76 %	Molasses simulation
Rotational state transfer efficiency	100 %	Pi-pulse
Fraction though fountain	7.5 %	Free-expansion at 185μK
Detection efficiency	100 %	Fluorescence on closed transition
Coherence time	0.25 s	By design
Repetition rate	2 Hz	By design
EDM sensitivity in 8 hours	**6 x 10^{-31} e.cm**	**Statistical sensitivity**

Thanks...

Jony Hudson



Ben Sauer

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EDM measurement:

Joe Smallman

Jack Devlin

Dhiren Kara

Buffer gas cooling:

Sarah Skoff

Nick Bulleid

Rich Hendricks

Laser cooling:

Thom Wall

Aki Matsushima

Valentina Zhelyazhkova

Anne Cournol

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