EDM Measurements using Polar Molecules

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Two motivations to measure EDMs

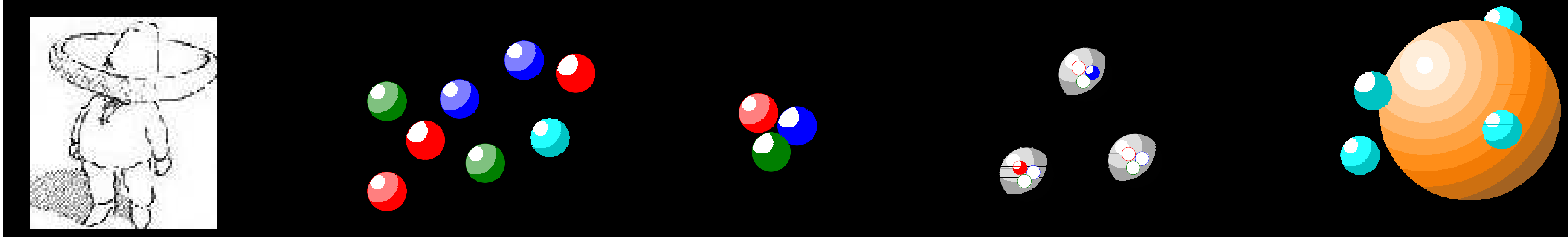
EDM violates T symmetry

➡ Deeply connected to CP violation and the matter-antimatter asymmetry of the universe

EDM is effectively zero in standard model
but
big enough to measure in non-standard models

➡ direct test of physics beyond the standard model

$\cancel{CP}$ from particles to atoms (main connections)



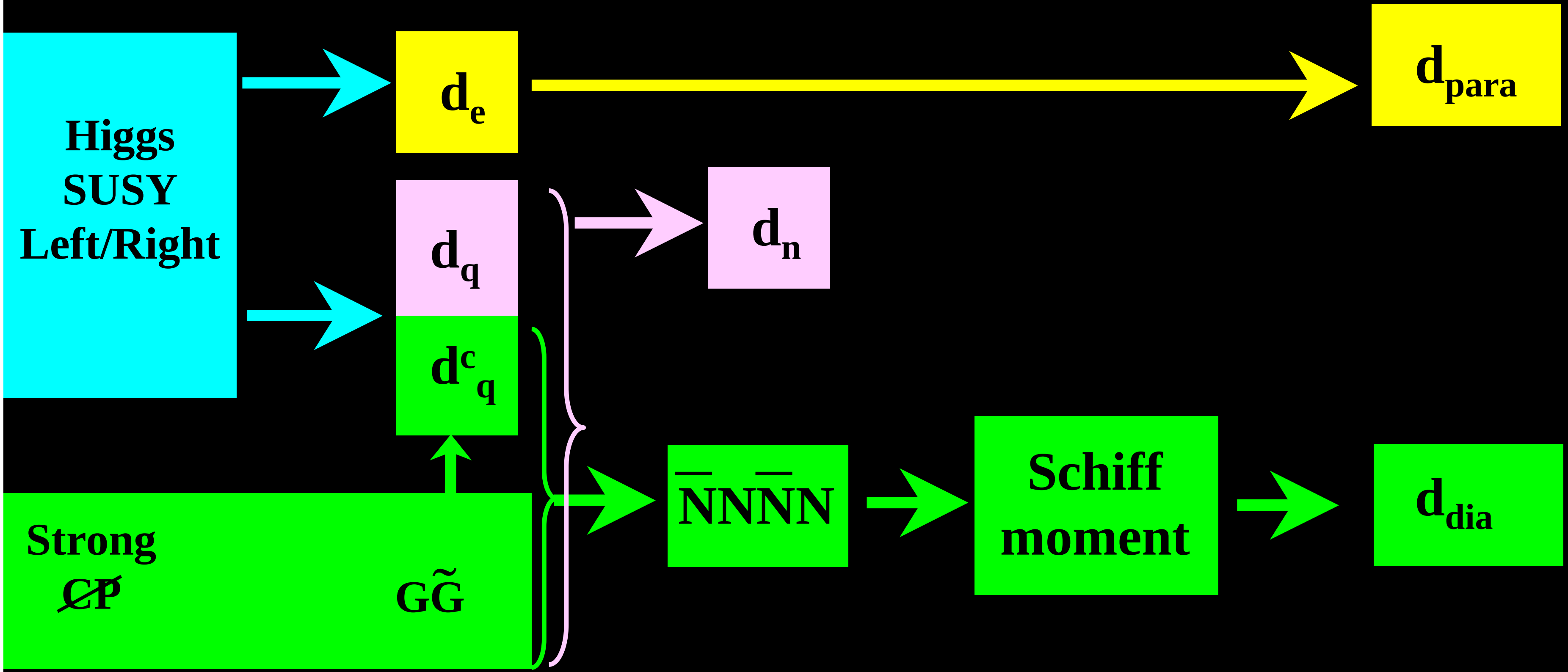
field theory
$\cancel{CP}$ model

electron/quark
level

nucleon
level

nuclear
level

atom/molecule
level



Higgs
SUSY
Left/Right

d_e

d_{para}

d_q

d_n

d^c_q

Strong
$\cancel{CP}$

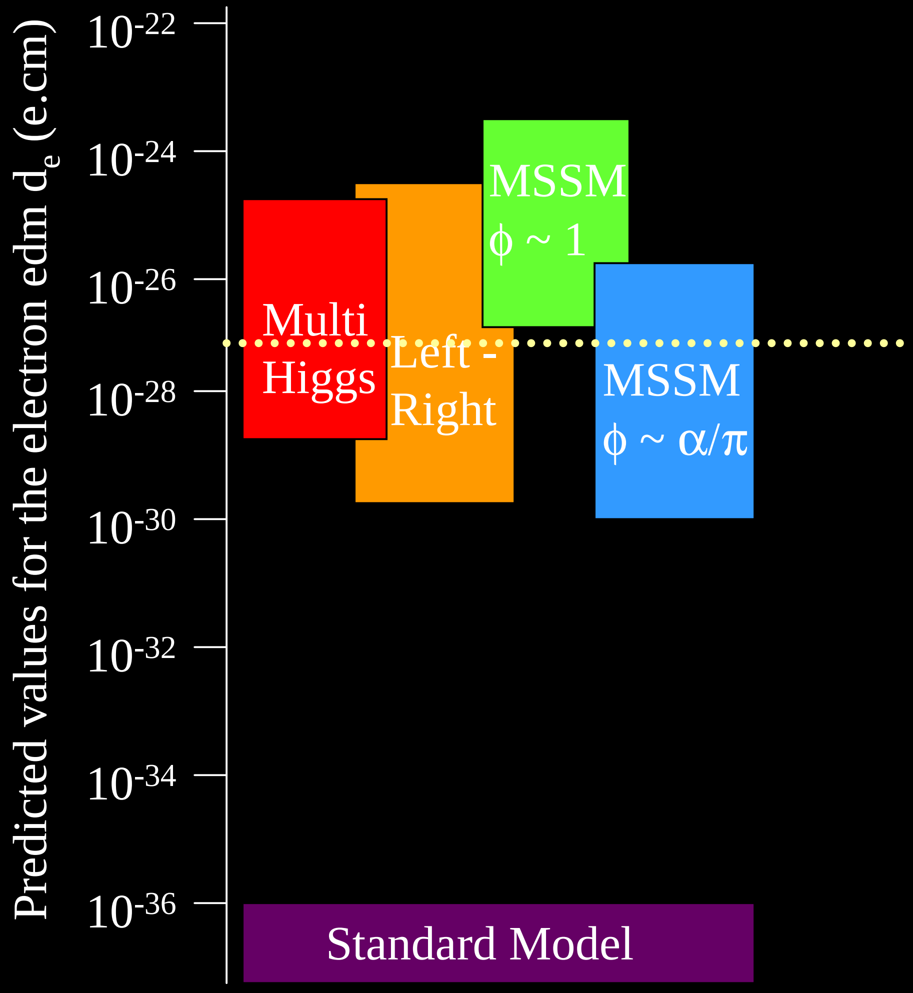
$G\tilde{G}$

$\bar{N}N\bar{N}N$

Schiff
moment

d_{dia}

Status of theory and experiment of electron EDM



Thallium experiment (2002)

$d_e < 1.6 \times 10^{-27}$ e.cm

Limited by stray and motional magnetic fields

New approach required

Using Dirac theory, the
first order edm energy is $\langle H^1 \rangle = \langle \Psi^0 | -d_e \, \beta \, \boldsymbol{\Sigma}\cdot\mathbf{E} | \Psi^0 \rangle$.

As a matrix equation this becomes

$$\langle H^1 \rangle = \left\langle \begin{matrix} f^0 \\ g^0 \end{matrix} \middle| \begin{matrix} 0 & 0 \\ 0 & 2d_e \, \boldsymbol{\sigma}\cdot\mathbf{E} \end{matrix} \middle| \begin{matrix} f^0 \\ g^0 \end{matrix} \right\rangle$$

only acts on relativistic part of
the wavefunction

$|g^0\rangle$ is only appreciable at small r, where $\mathbf{E} \approx Z\hat{\mathbf{r}}/r^2$, so

$$\langle H^1 \rangle \approx \langle g^0 | 2d_e \, \boldsymbol{\sigma}\cdot \frac{Z\hat{\mathbf{r}}}{r^2} | g^0 \rangle .$$

expanding the wavefunction $|\Psi^0\rangle$ in angular eigenstates:

$$|\Psi^0\rangle = a_s|s\rangle + a_{p1/2}|p\rangle + \cdots$$

which to leading order gives

$$\langle H^1\rangle \approx 8a_s a_{p1/2}\, Z(Z\alpha)^2\, d_e\, \langle \sigma\cdot\hat{\lambda}\rangle$$

Z from electric field near nucleus

$(Z\alpha)^2$ from the small (relativistic) wavefunction

$\hat{\lambda}$ is the axis defined by the *s*-*p* mixing

In atoms, $a_s a_{p1/2} \sim E_{ext}$, and for Z=70

$$\langle H^1\rangle_{atom} \sim d_e\, 100\, E_{ext}.$$ (Sandars, 1965)

In heavy polar molecules . . .

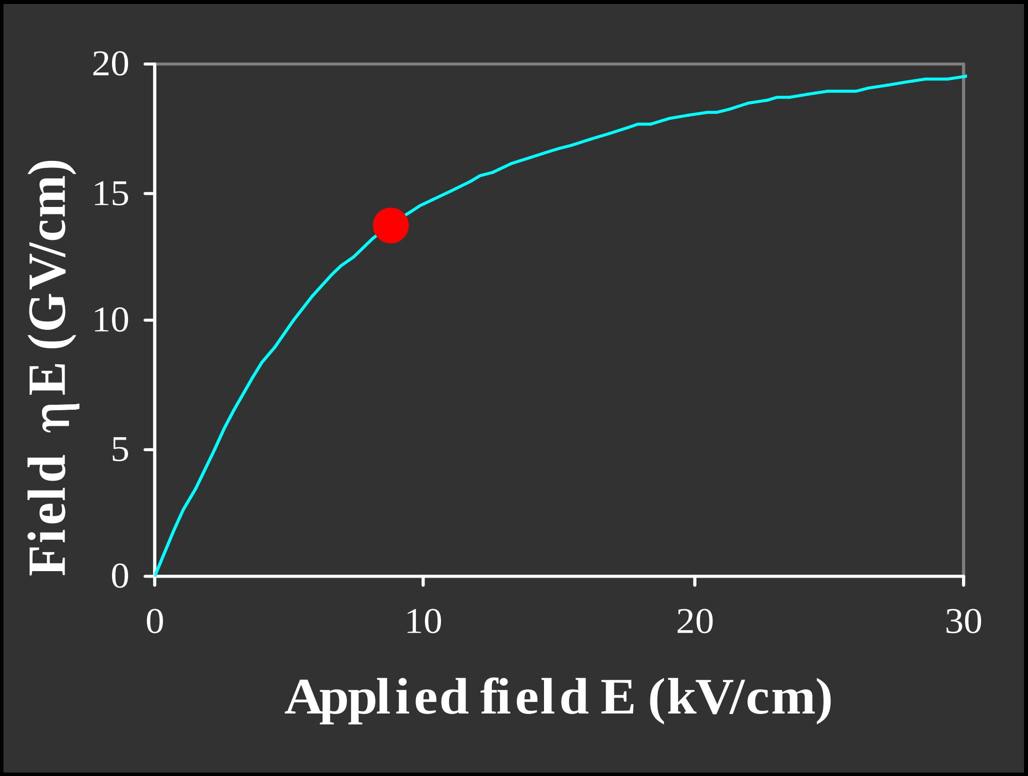
- the wavefunction is already mixed along the internuclear axis λ: $a_s a_p \sim 0.1$

- a very modest external field can polarize λ along σ

$\langle H^1 \rangle_{\text{molecule}} \sim d_e\, 10$ (in atomic units of field!)

	Effective field (GV/cm)
BaF	10
YbF	26
PbO*	30
PbF	-29
HgF	100

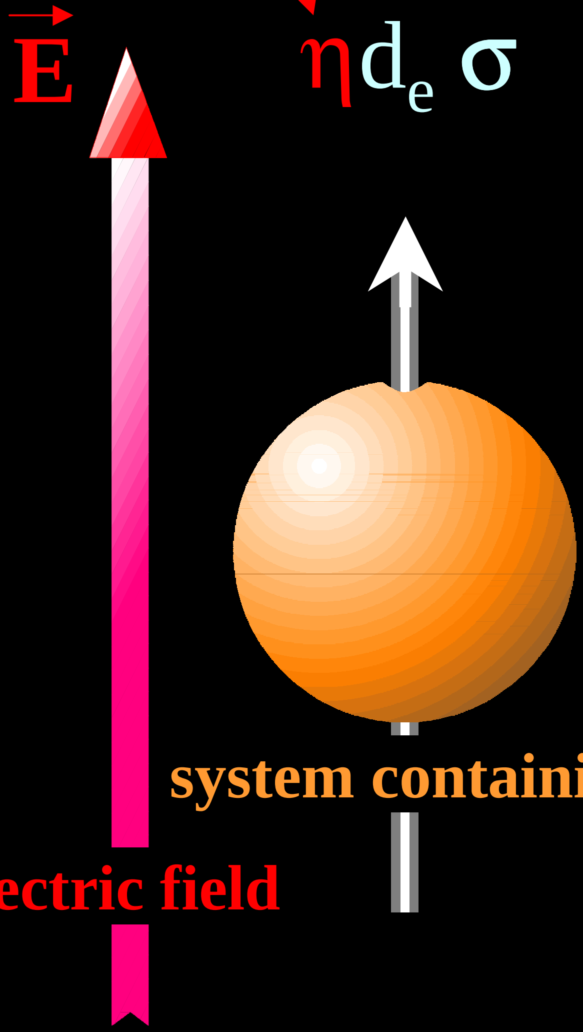
Polarization of YbF



for Tl atoms η is “only” ~ -600

E= 130kV/cm → ηE = 0.08GV/cm

The basic idea of the experiment



amplification

$\eta d_e\, \sigma$

$\vec{E}$

electric field

system containing electron

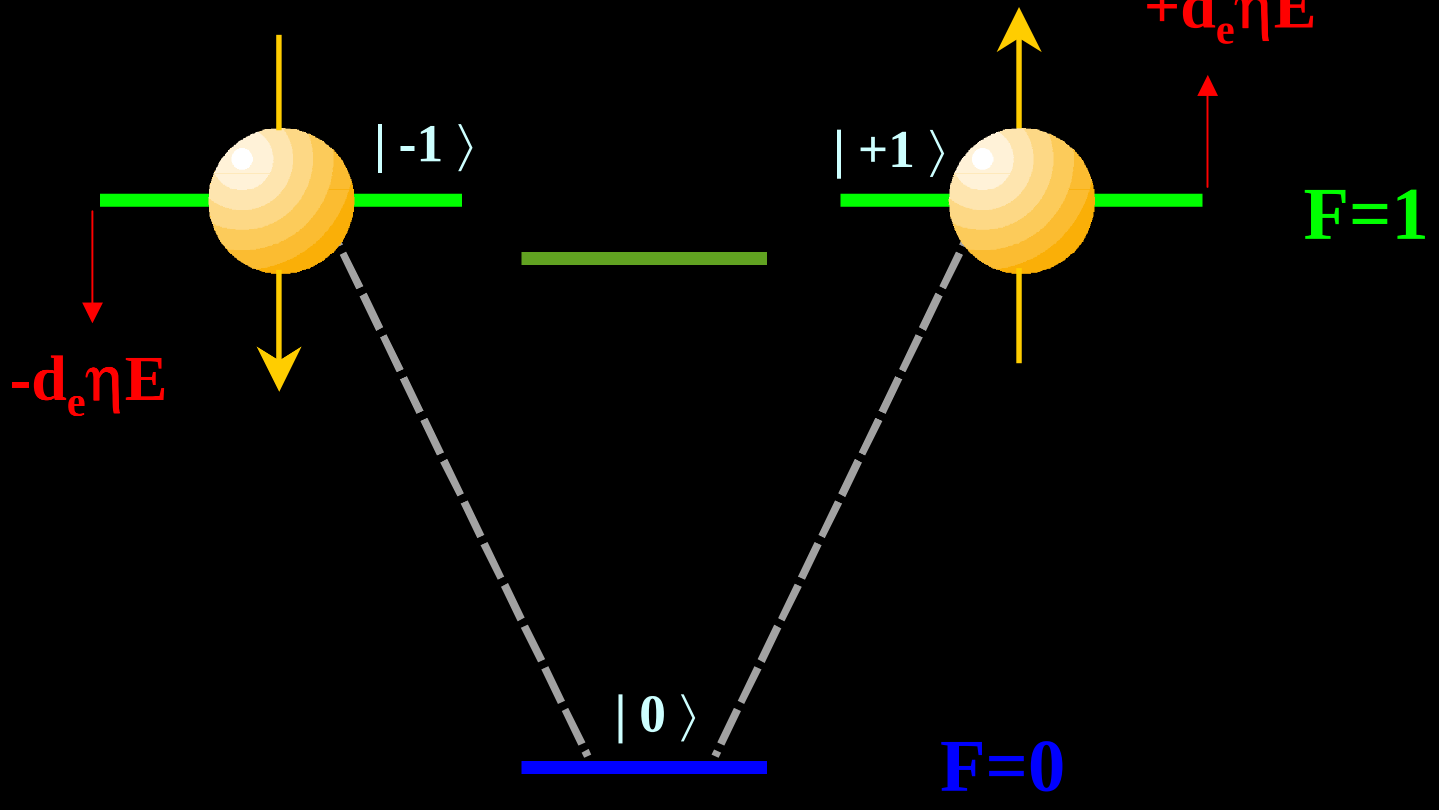
Interaction energy

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

odd under P and T

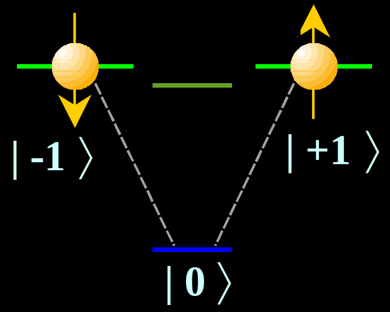
The lowest two levels of YbF in an electric field E

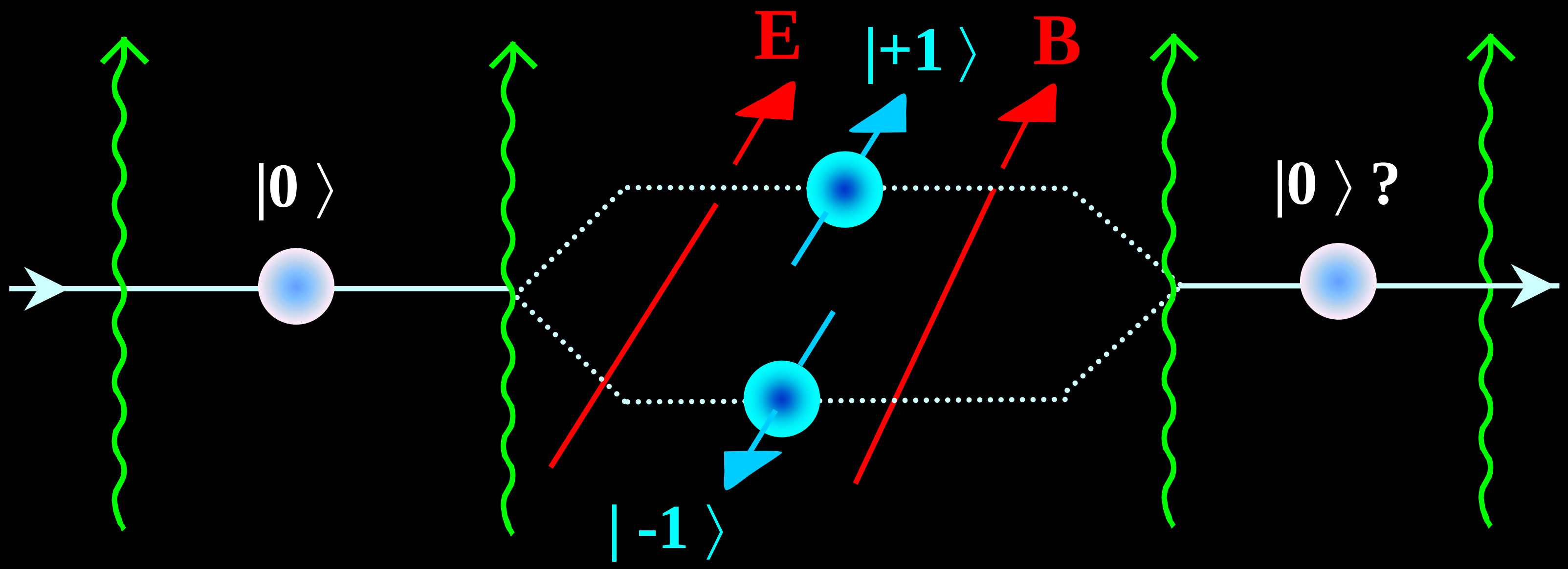
$X^2\Sigma^+$ (N = 0,v = 0)



Goal: to measure the splitting $2d_e\eta E$

Interferometer to measure $2d_e\eta E$





Pump
A-X Q(0) F=1

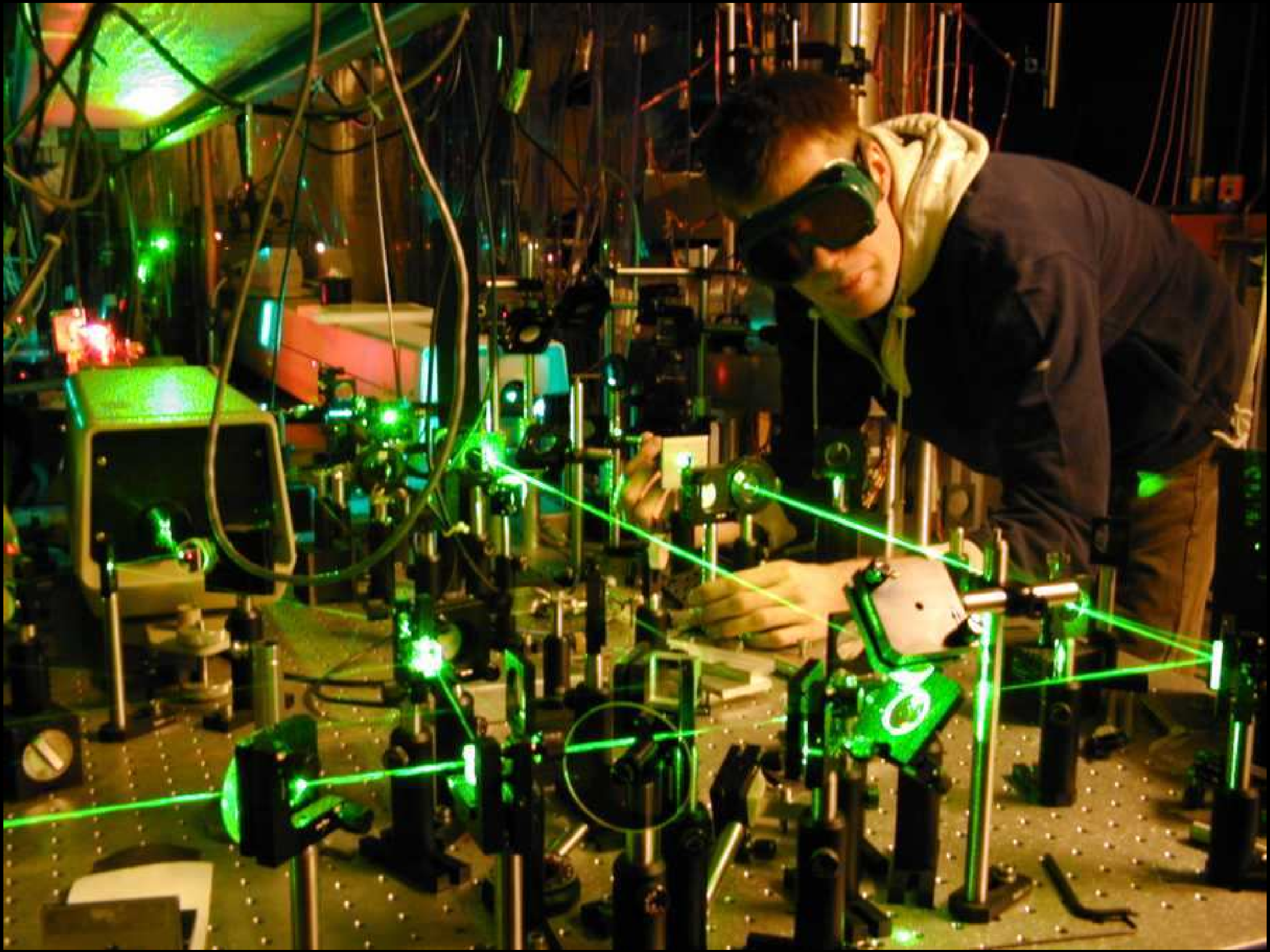
Split
170 MHz π pulse

Recombine
170 MHz π pulse

Probe
A-X Q(0) F=0

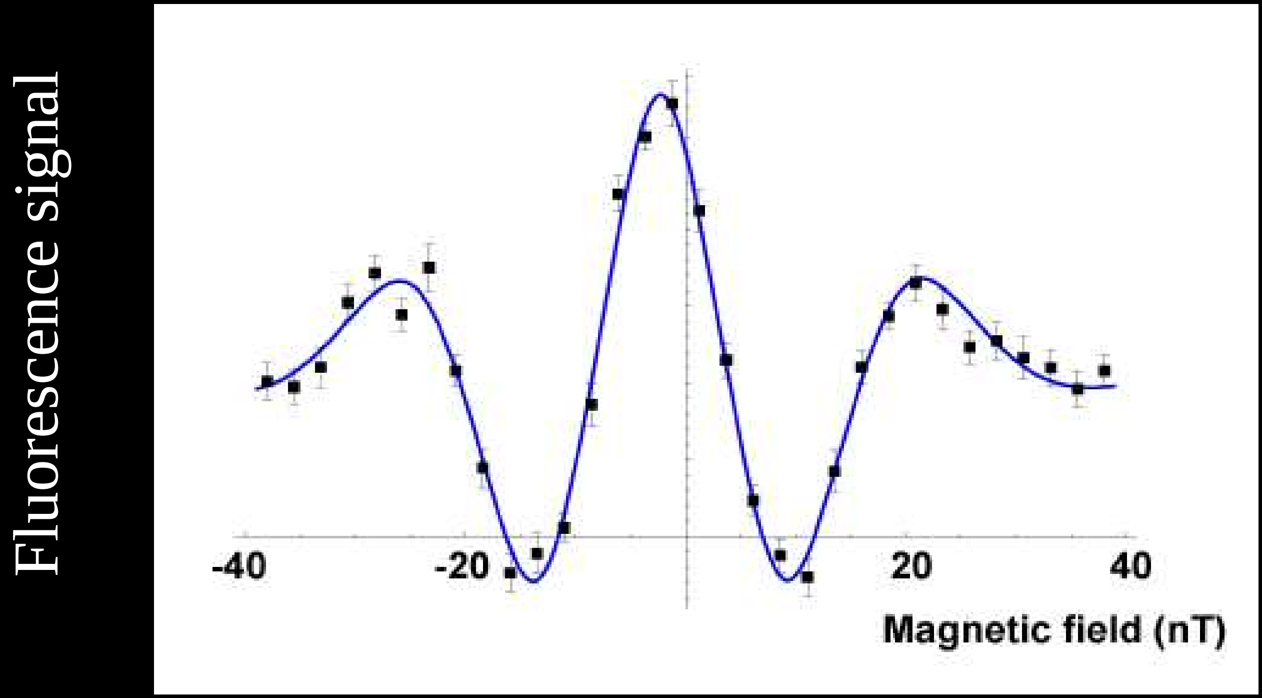
Phase difference = $2\,(\mu_B B + d_e \eta E)T/\hbar$

Part of the optical setup



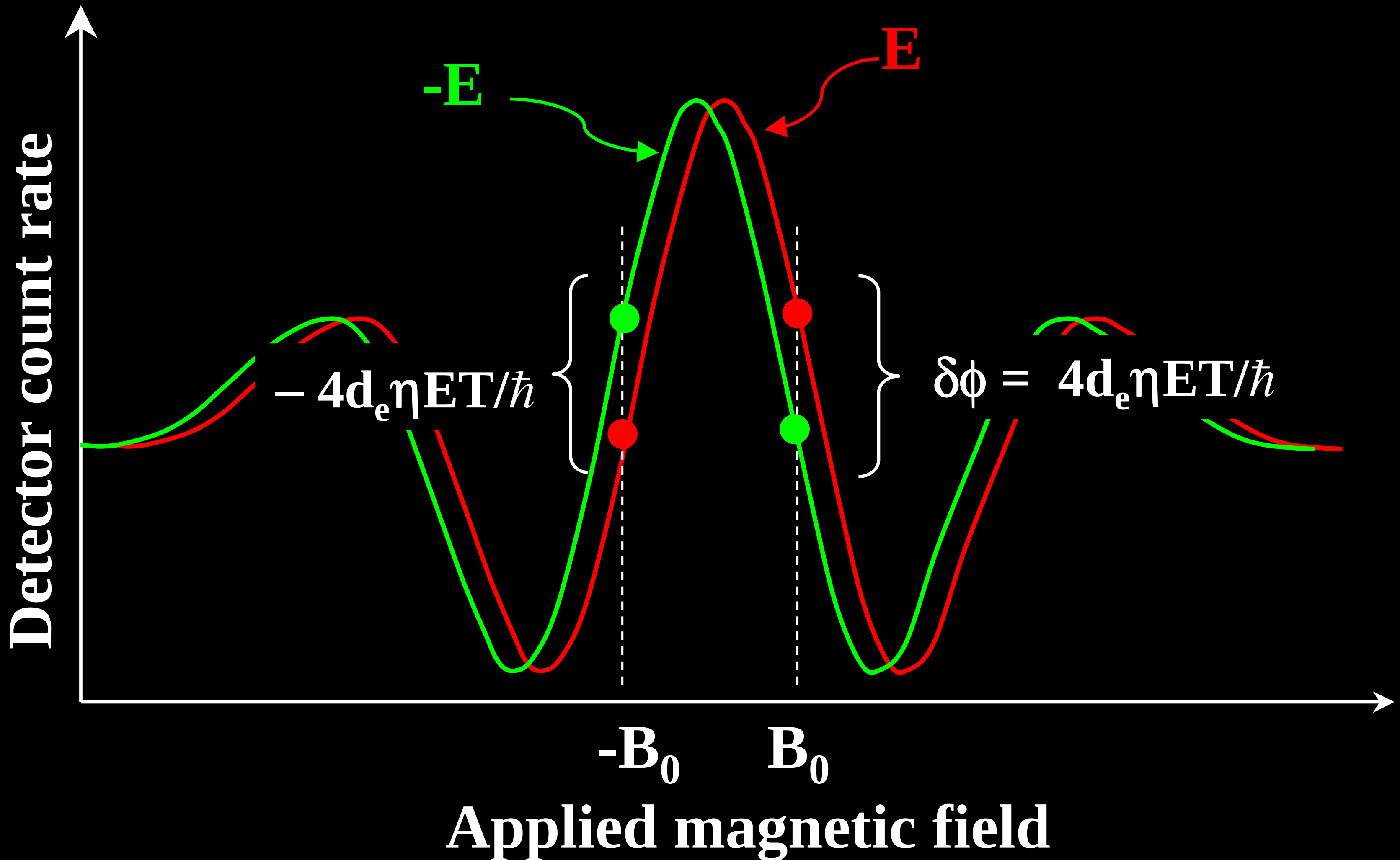
Interferometer results

- Scan a small magnetic field, measure the $|0\rangle$ signal.



Phase difference = $2(\mu_B B + d_e \eta E_{ext})T/\hbar$

Measuring the edm



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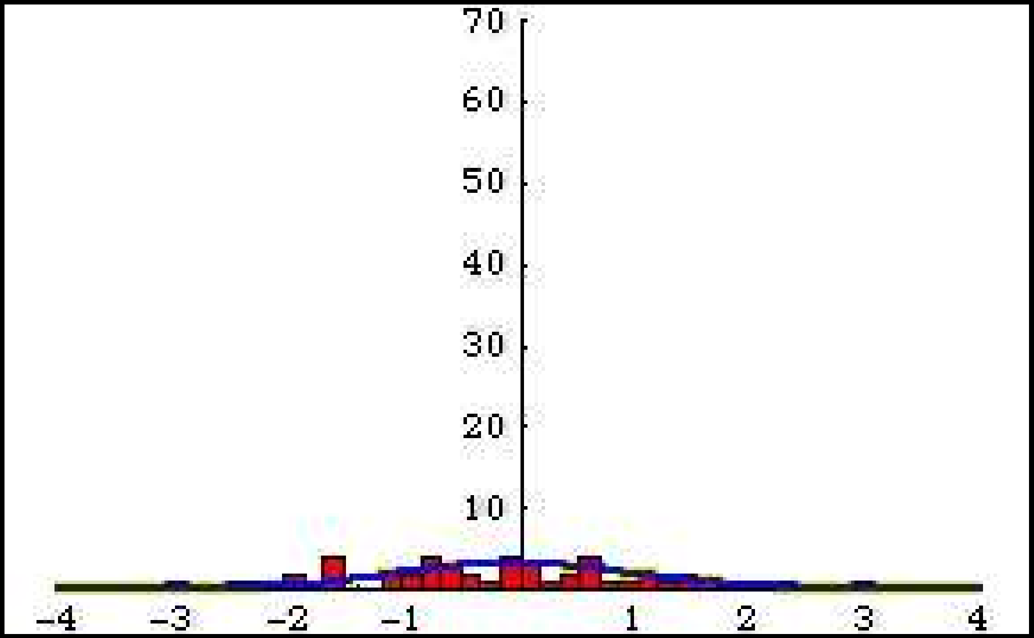
Histogram of measured d_e/σ



Mean value: $(-0.2 \pm 3.2) \times 10^{-26}$ e.cm

90 mHz

pure shot noise

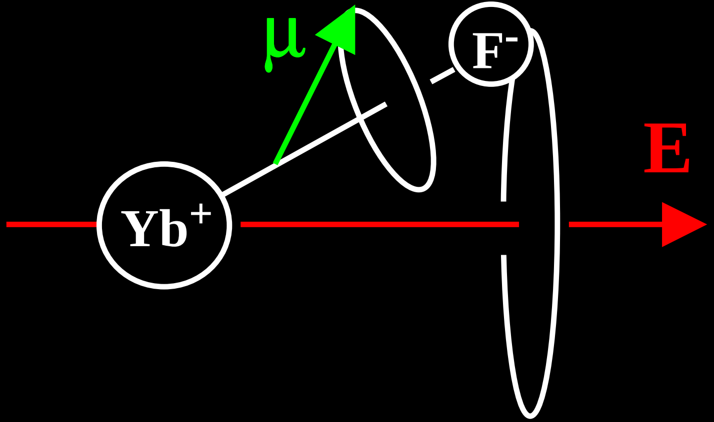
Extremely robust against systematic errors from B_{stray}

Magnetic systematics?

No coupling $\mu \cdot \mathbf{v} \times \mathbf{E}$ to motional magnetic field

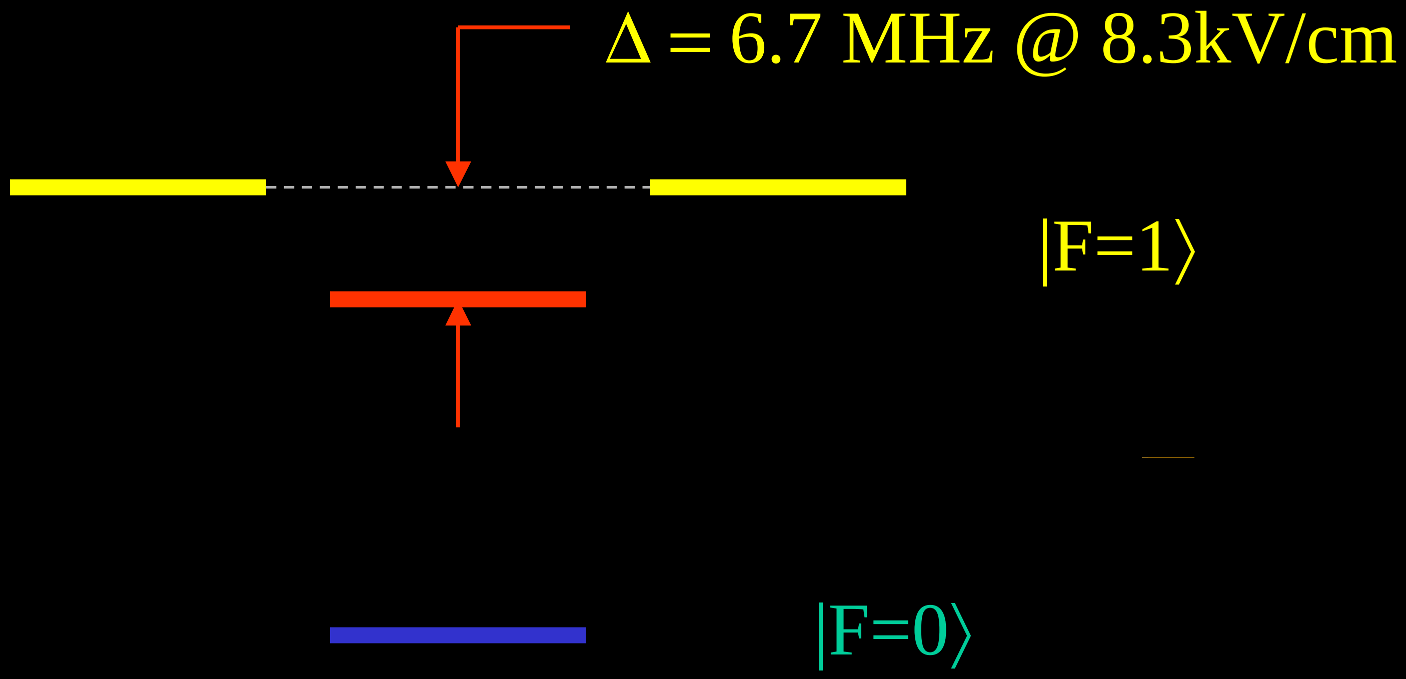
electron spin is coupled to internuclear axis

and internuclear axis is coupled to E



$\therefore \langle \mu \times \mathbf{E} \rangle = 0$ → **no motional systematic error**

YbF is practically immune to $B_\perp$:



$\Delta = 6.7$ MHz @ 8.3kV/cm

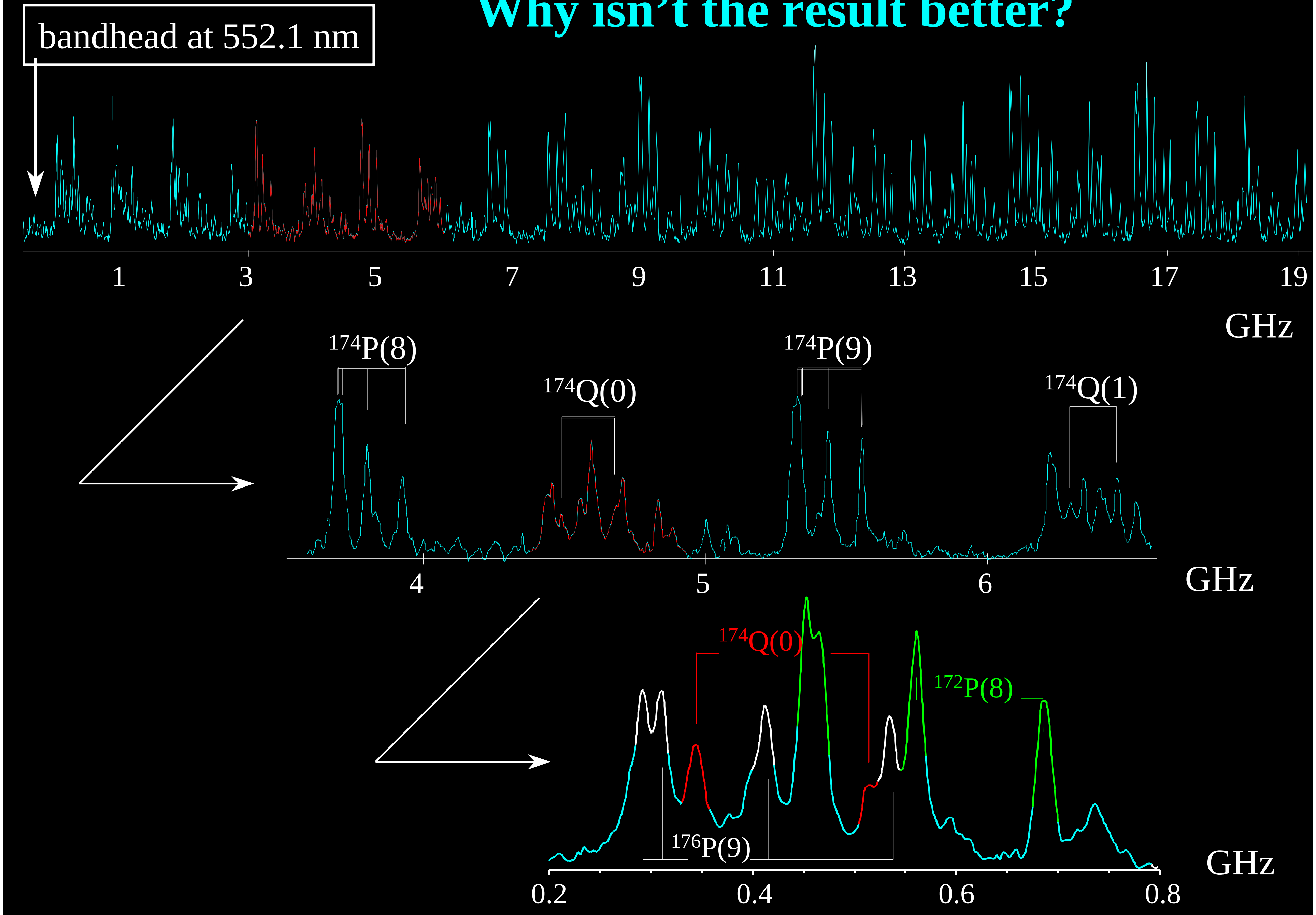
$|F=1\rangle$

$|F=0\rangle$

Extra splitting is suppressed by the factor $\frac{\mu_B^2 B_z B_\perp}{\Delta^2}$, 10^{-10}!

Not unique to molecules, e.g. Xe*

Why isn’t the result better?



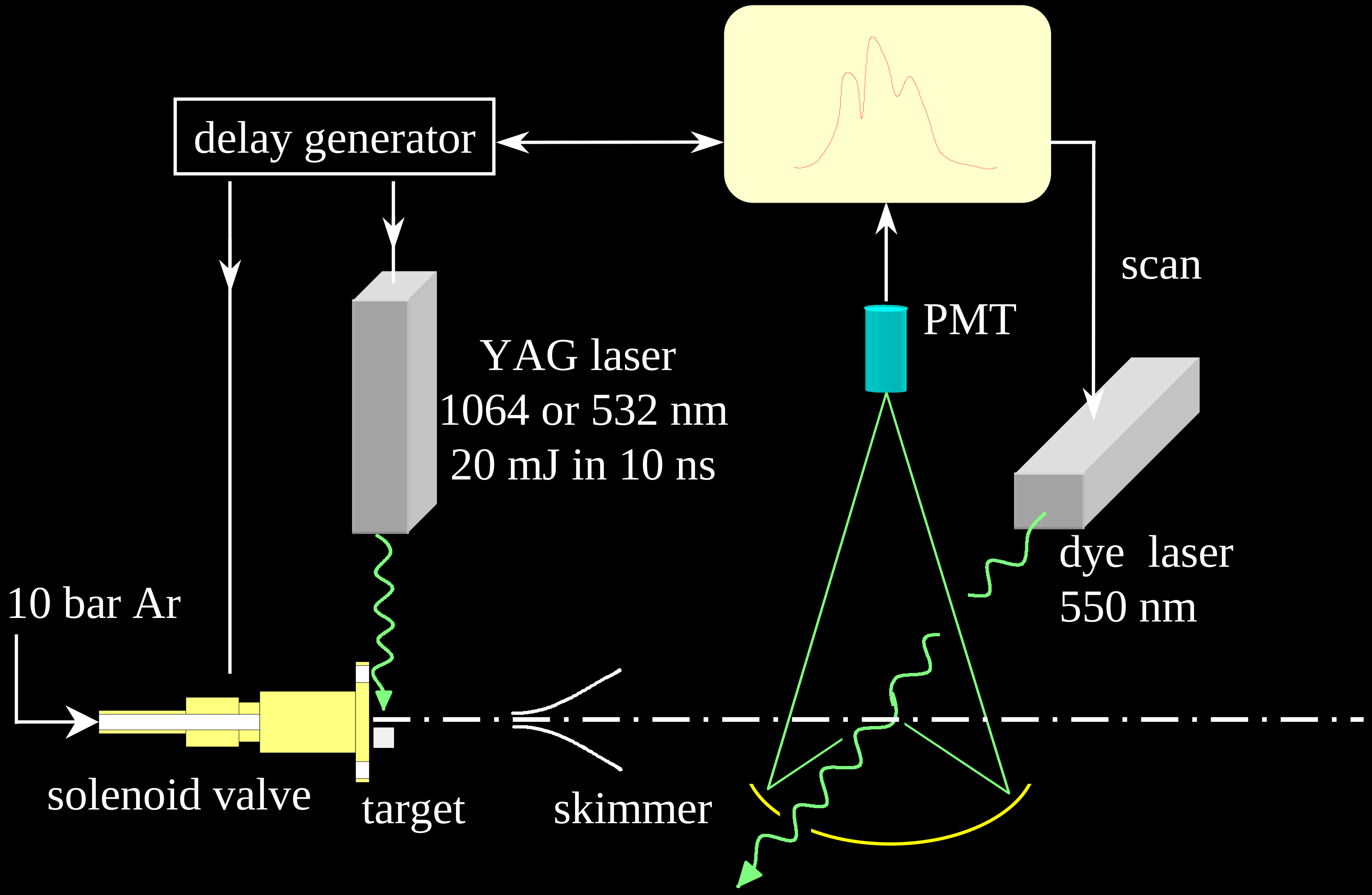
Signal to Noise ratio

$$\frac{\mathrm{S}}{\mathrm{N}} = d_e \eta \mathrm{E}_{\mathrm{ext}}\ \mathrm{T}/\hbar\ \frac{I_0\ t^{\ 1/2}}{\sqrt{I_B + I_0/2}}$$

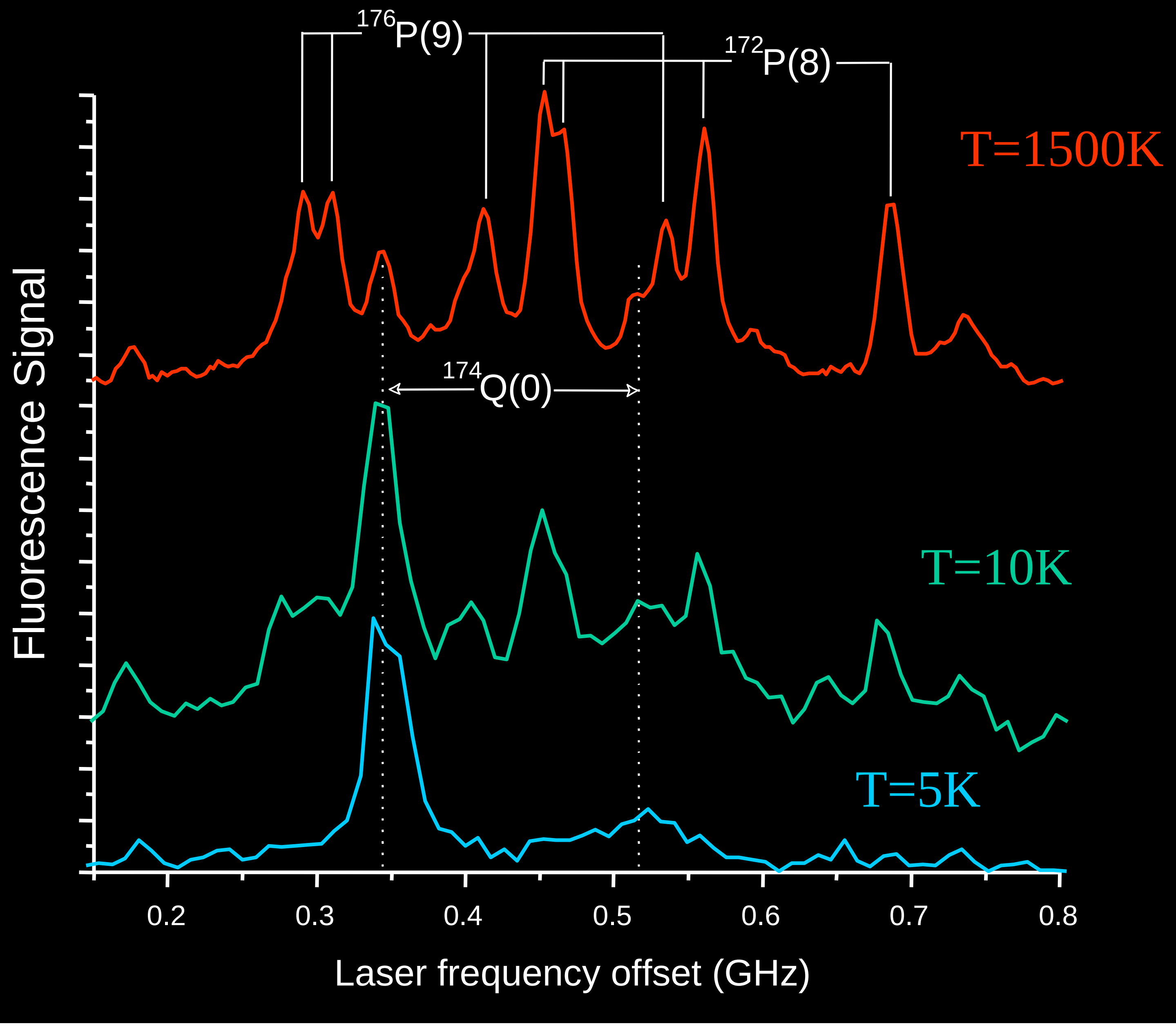
Cold molecules might help with:

- I_o more molecules in ground rotational state
- I_B less background from overlapping transitions
- T coherence time could be much longer for trapped molecules (1s vs. 1ms)

Supersonic YbF beam



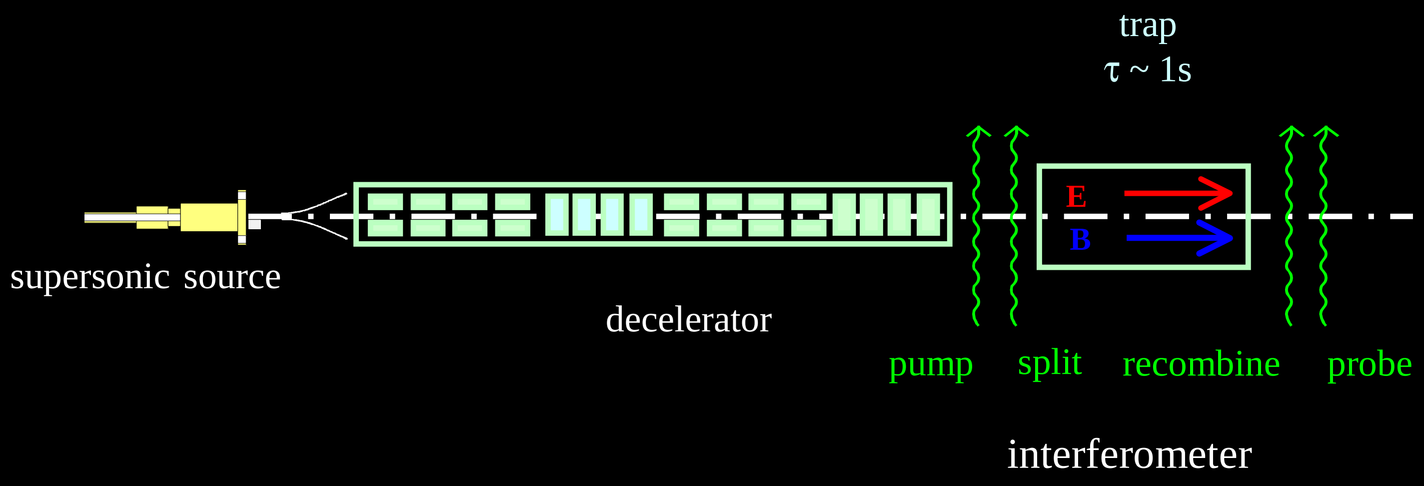
Cooling the rotational temperature

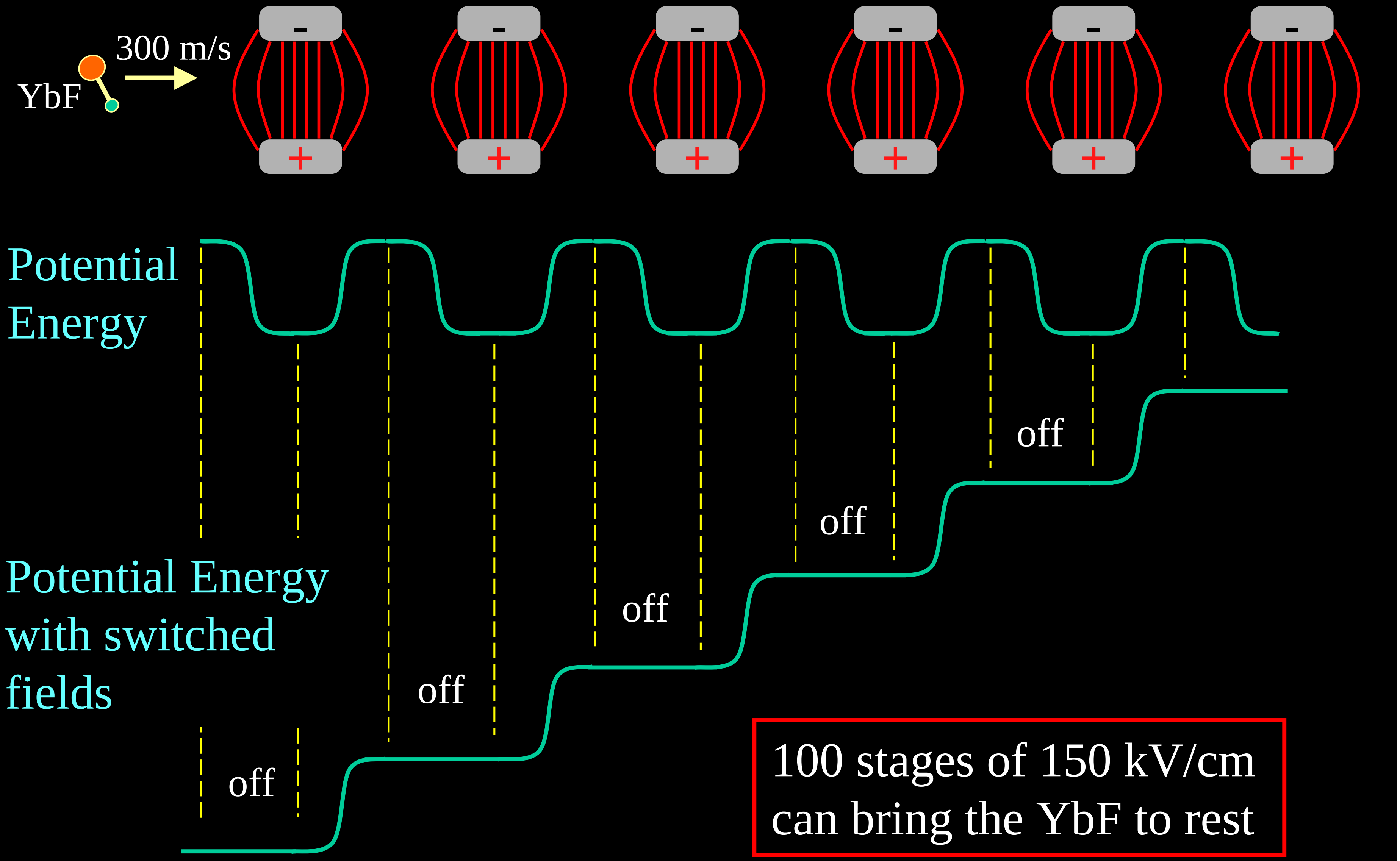


Cold slow molecules

Our approach:

- supersonic expansion gives low rotational temperature, narrow velocity distribution
- Xe carrier gas gives slow center-of-mass energy for Stark decelerator
- laser ablation is well suited to YbF, BaF etc.

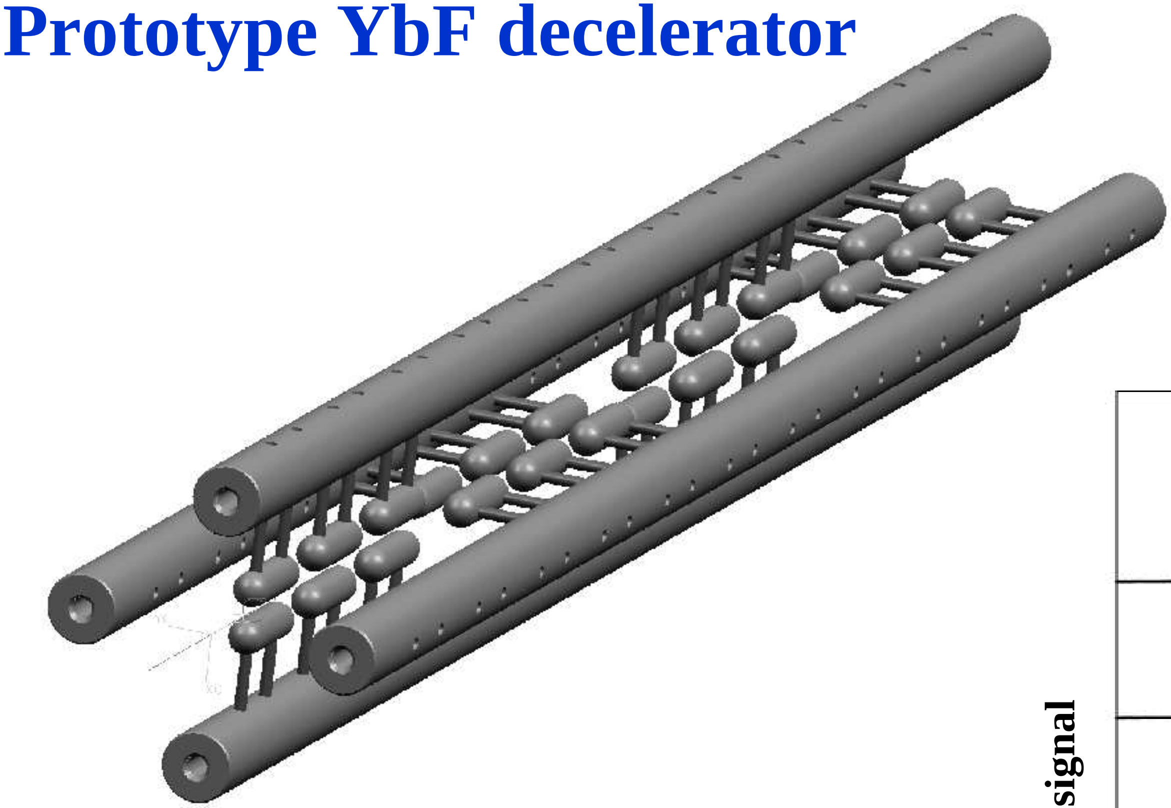




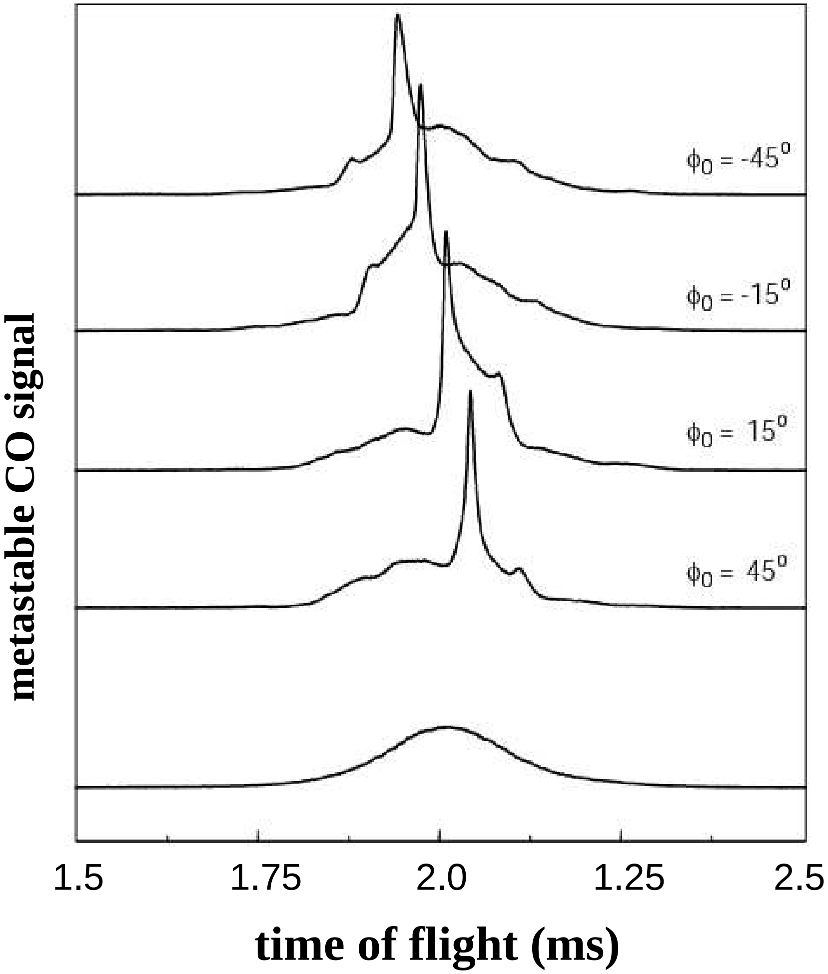
100 stages of 150 kV/cm can bring the YbF to rest

Prototype YbF decelerator

Short alternating gradient decelerator built by Rijnhuizen/Berlin group of G. Meijer and R. Bethlem



Test result using CO



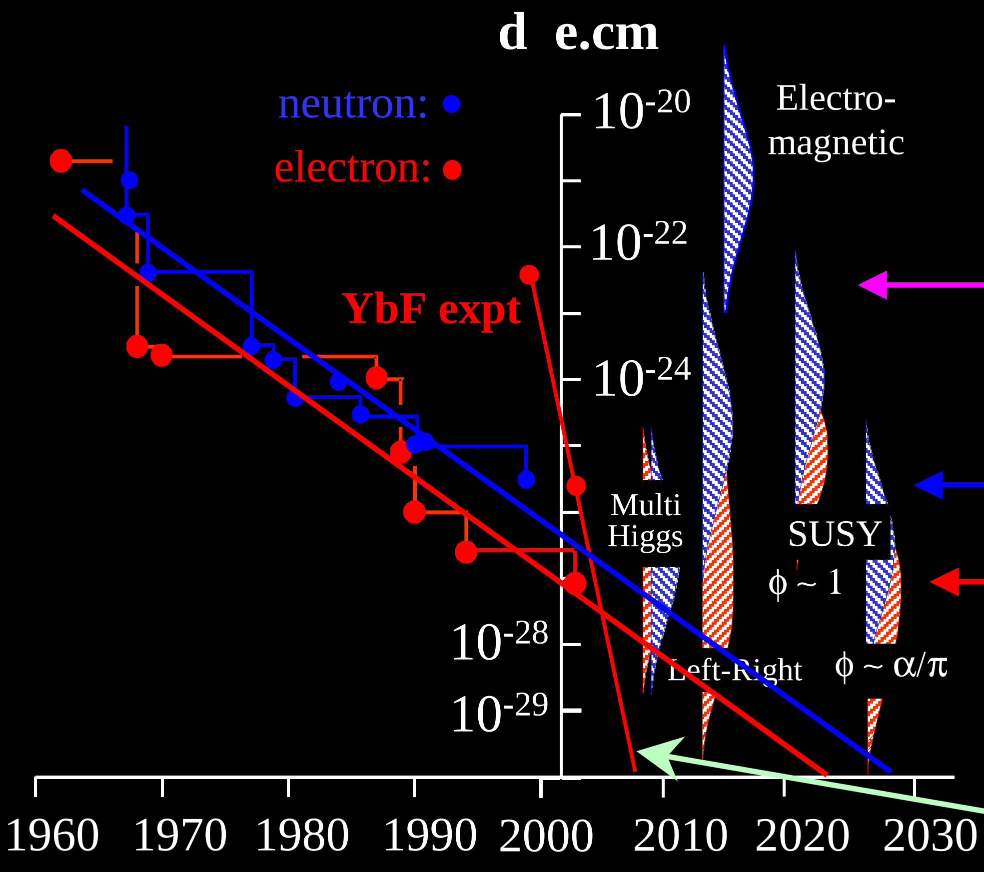
Signal:noise figures

	2002 result	supersonic beam	cold cloud
background	150kHz	640kHz	40kHz
fringe height	1.5 kHz	160 kHz	10 kHz
coherence time	1.5 ms	1 ms	1 s
d_e in 1 day	$3\ 10^{-26}$ e cm	$6\ 10^{-28}$ e cm	$3\ 10^{-30}$ e cm

long time = narrow fringes

Current status of EDMs

d(muon) < 7×10^{-19}



d(proton) < 6 × 10^{-23}

d(neutron) < 6 × 10^{-26}

d(electron) < 1.6 × 10^{-27}

cold
molecules