Time Reversal and the electron electric dipole moment

Ben Sauer

Mysteries of physics

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events
Random article
Donate to Wikipedia
Wikipedia store

Interaction

Help
About Wikipedia
Community portal
Recent changes
Contact page

Tools

What links here
Related changes
Upload file

Article Talk

List of unsolved problems in physics

From Wikipedia, the free encyclopedia

Some of the major unsolved problems in physics are theoretical, meaning that existing theories seem are experimental, meaning that there is a difficulty in creating an experiment to test a proposed theory

There are still some deficiencies in the Standard Model of physics, such as the origin of mass, the strc matter and dark energy.[1] Another problem lies within the mathematical framework of the Standard M that one or both theories break down under certain conditions (for example within known spacetime si

Contents [hide]

1 Unsolved problems by subfield
- 1.1 General physics/quantum physics
- 1.2 Cosmology and general relativity
- 1.3 Quantum gravity
- 1.4 High-energy physics/particle physics
- 1.5 Astronomy and astrophysics
- 1.6 Nuclear physics
- 1.7 Atomic, molecular and optical physics
- 1.8 Condensed matter physics

Mysteries of physics

Cosmology and general relativity [edit]

Problem of time

How can time be reconciled with general relativity?

Cosmic inflation

Is the theory of cosmic inflation correct, and, if so, what are the details of this epoch? What is the hypothetical inflaton field giving rise to inflation? If inflation happ
sustaining through inflation of quantum-mechanical fluctuations, and thus ongoing in some extremely distant place?[9]

Horizon problem

Why is the distant universe so homogeneous when the Big Bang theory seems to predict larger measurable anisotropies of the night sky than those observed? C
generally accepted as the solution, but are other possible explanations such as a variable speed of light more appropriate?[10]

Origin and future of the universe

How did the conditions for anything to exist arise? Is the universe heading towards a Big Freeze, a Big Rip, a Big Crunch, or a Big Bounce? Or is it part of an infin

Size of universe

Baryon asymmetry

Why is there more matter than antimatter in the observable universe?

What is the identity of dark matter?[10] Is it a particle? Is it the lightest superpartner (LSP)? [Or] Do the phenomena attributed to dark matter point not to some form of matter but actually to an extension of gravity?

Dark energy

What is the cause of the observed accelerated expansion (de Sitter phase) of the universe? Why is the energy density of the dark energy component of the same magnitude as the density of matter at present when the two evolve quite differently over time; could it be simply that we are observing at exactly the right time? Is dark energy a pure cosmological constant or are models of quintessence such as phantom energy applicable?

Dark flow

Is a non-spherically symmetric gravitational pull from outside the observable universe responsible for some of the observed motion of large objects such as galactic clusters in the universe?

Ecliptic alignment of CMB anisotropy

Some large features of the microwave sky at distances of over 13 billion light years appear to be aligned with both the motion and orientation of the solar system. Is this due to systematic errors in processing, contamination of results by local effects, or an unexplained violation of the Copernican principle?

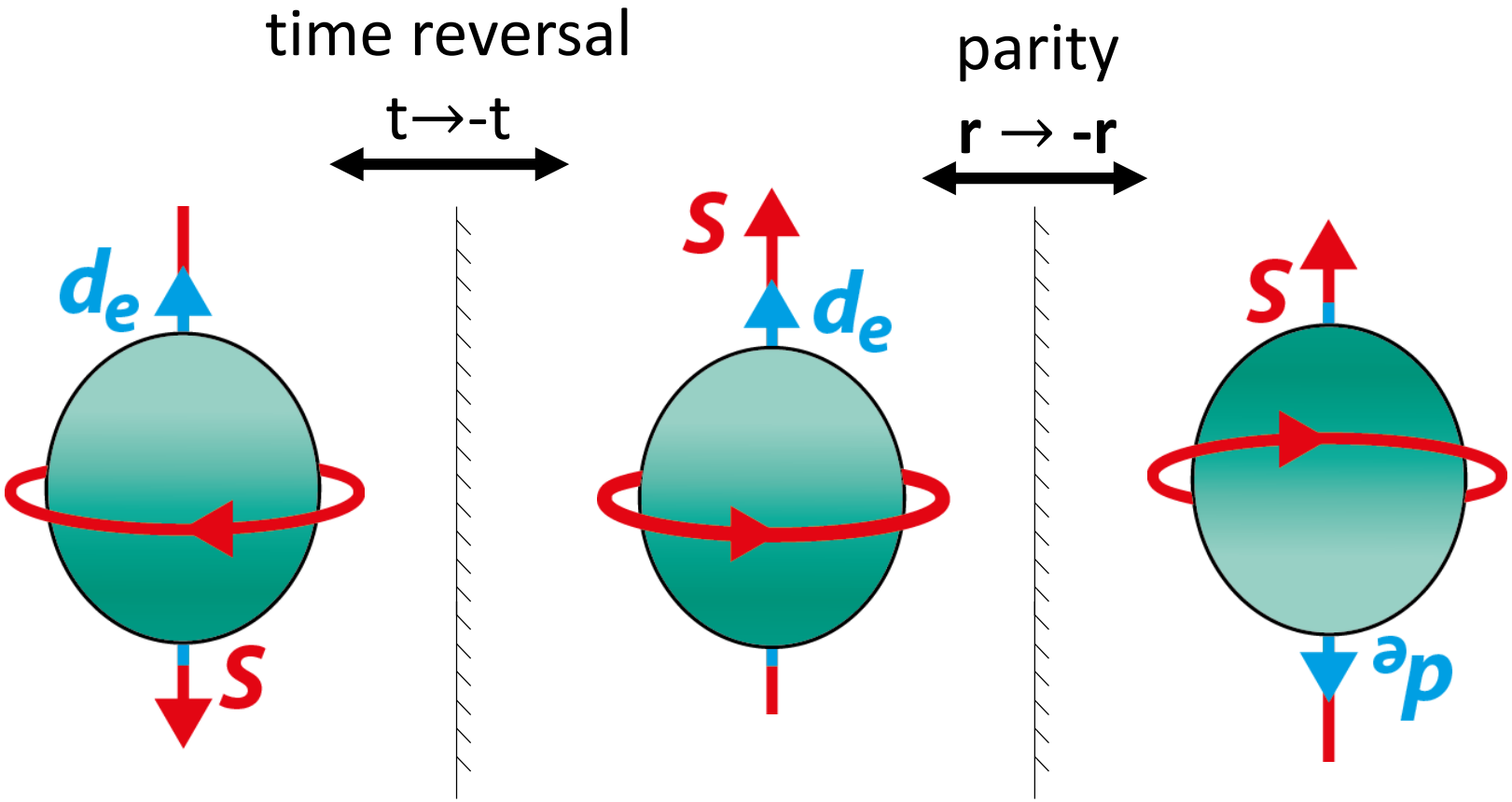
Shape of the universe

What is the 3-manifold of comoving space, i.e. of a comoving spatial section of the universe, informally called the "shape" of the universe? Neither the curvature n

Estimated dist
dark energy ir

Breaking P and T symmetry

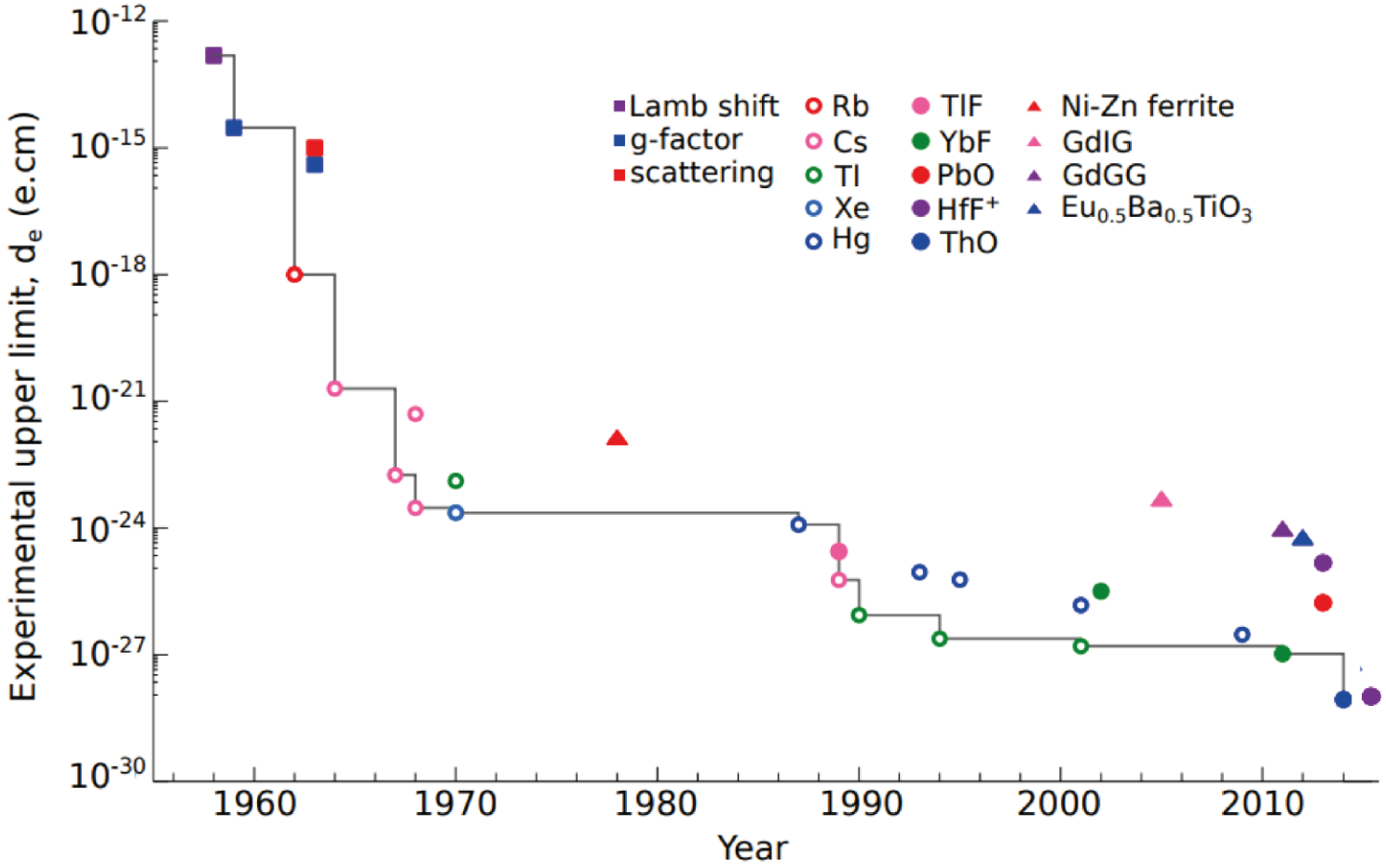
Imperial College London



$d_e \neq 0$ breaks P & T. CPT tells us CP is broken → matter/antimatter asymmetry

eEDM limits over time

Imperial College London

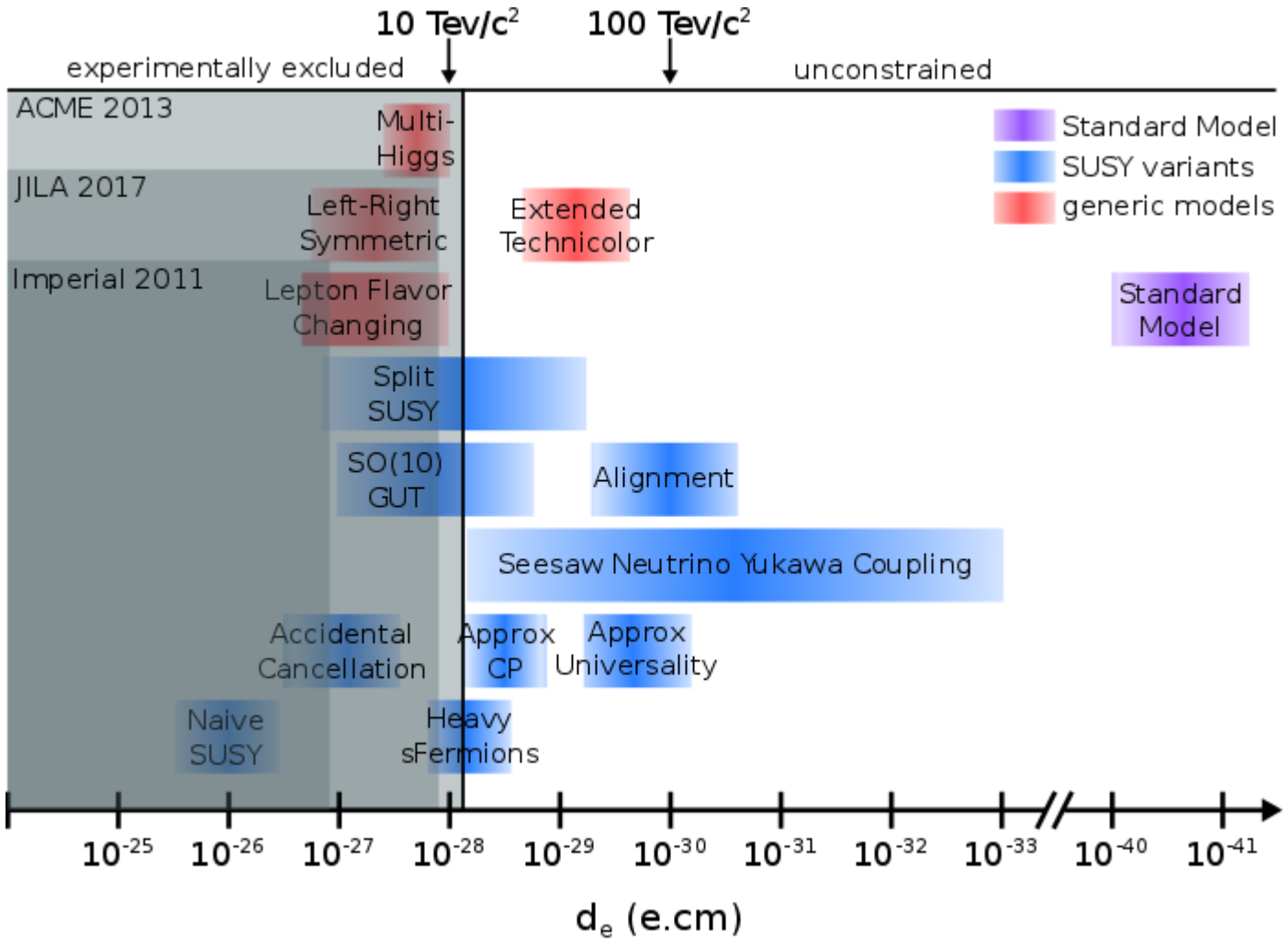


60 years of measuring

zero

Beyond standard model and the eEDM

Imperial College London

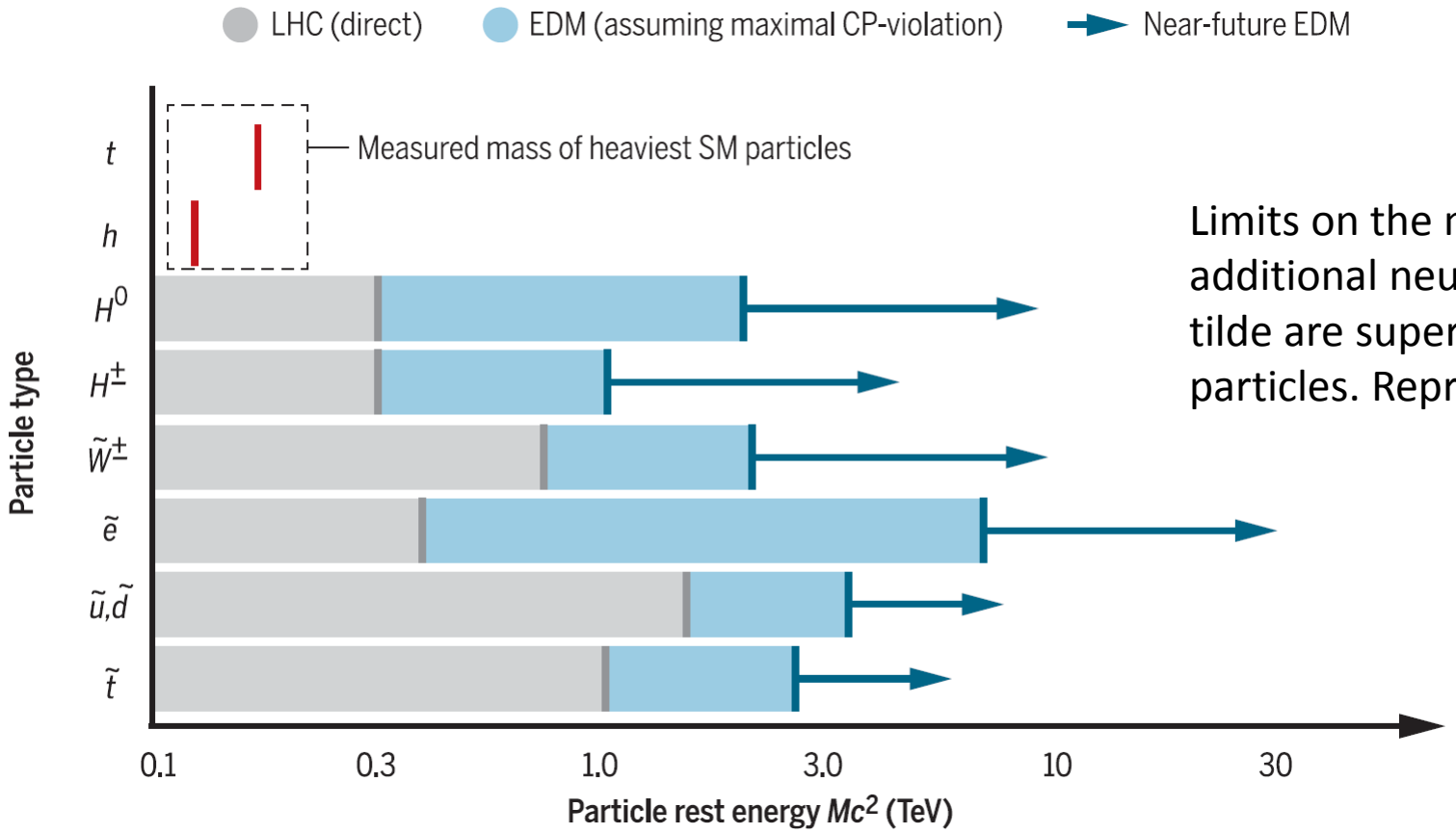


Imperial: Nature **473** 493 (2011), *ACME*: Science **343** 269 (2014), *JILA*: PRL **119** 153001

Figure adapted from Ben Spaun, PhD Thesis, Harvard University, (2014).

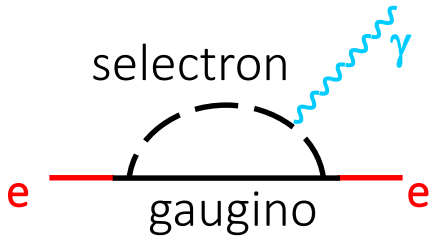
eEDM sensitivity to new physics

Imperial College London



Limits on the masses of hypothetical particles. H^0 and $H^{\pm}$ are additional neutral or charged Higgs particles, and those with a tilde are supersymmetric partners of the standard model particles. Reproduced from Science **357** 990-994 (2017).

The vacuum is complicated



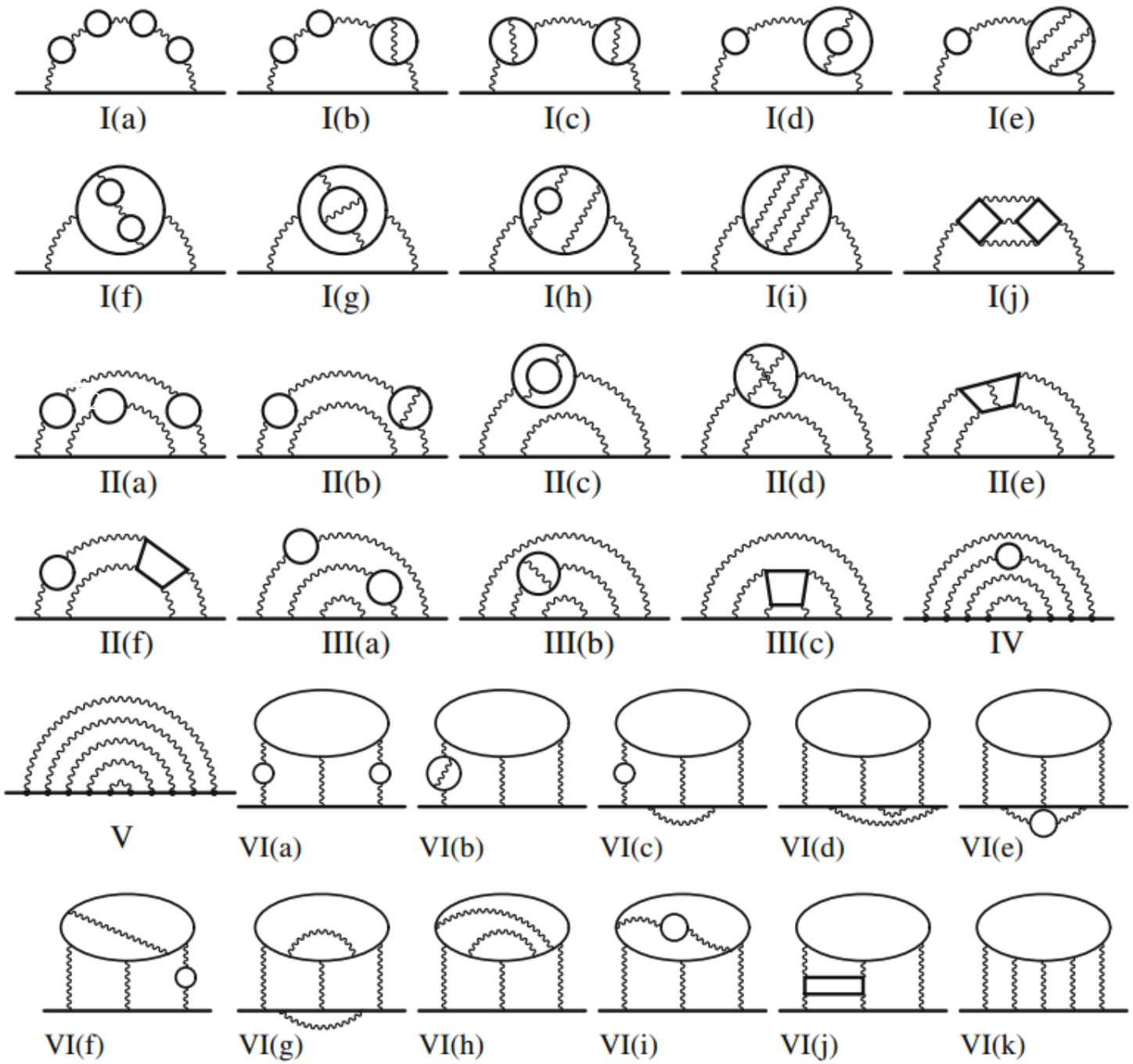
SUSY electron edm

naturally α/π

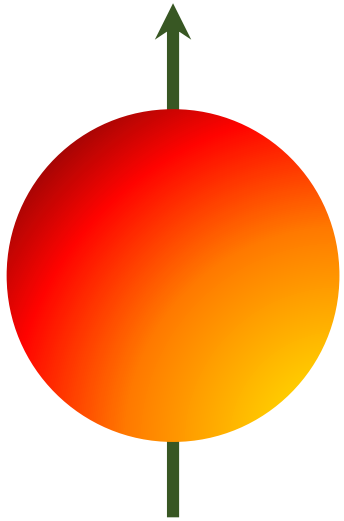
$$d_e \sim (\text{loop}) \times \frac{m_e}{\Lambda^2} \sin \varphi_{CP}$$

scale of SUSY naturally 200GeV

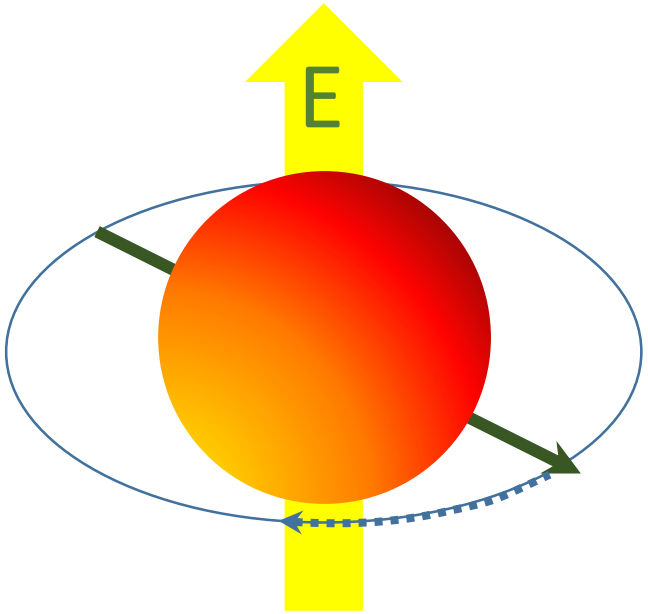
d_e naturally about 5×10^{-25} e.cm



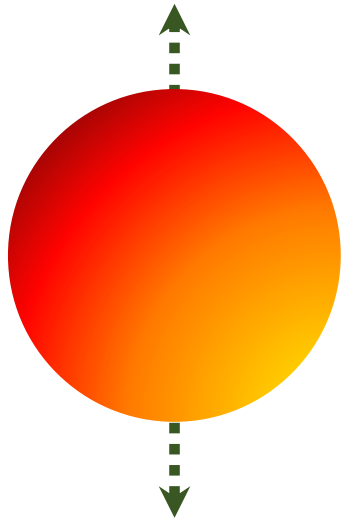
An EDM experiment



Polarize

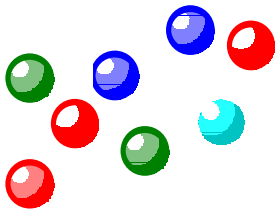


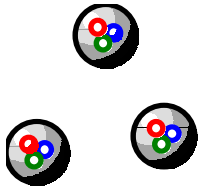
Precess
time T

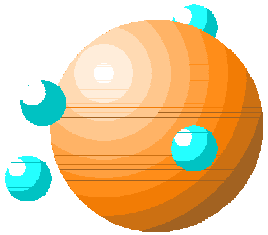


Analyze

~~CP~~ from fields to particles to atoms







field theory
~~CP~~ model

electron/quark level

nucleon level

nuclear level

atom/molecule level

Higgs
SUSY
Left/Right
T-weak

muon?

$d_{e,}$ C_s

d_q

d^c_q

n, p

YbF, Cs
ThO*, HfF^+

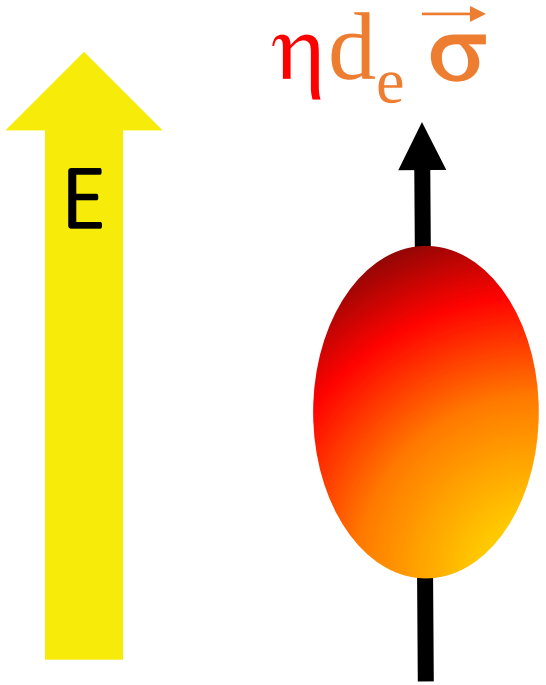
Strong ~~CP~~ $\theta G\tilde{G}$

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

Schiff moment

Hg
TlF

Why polar molecules?



electric field

system containing electron

Interaction energy

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

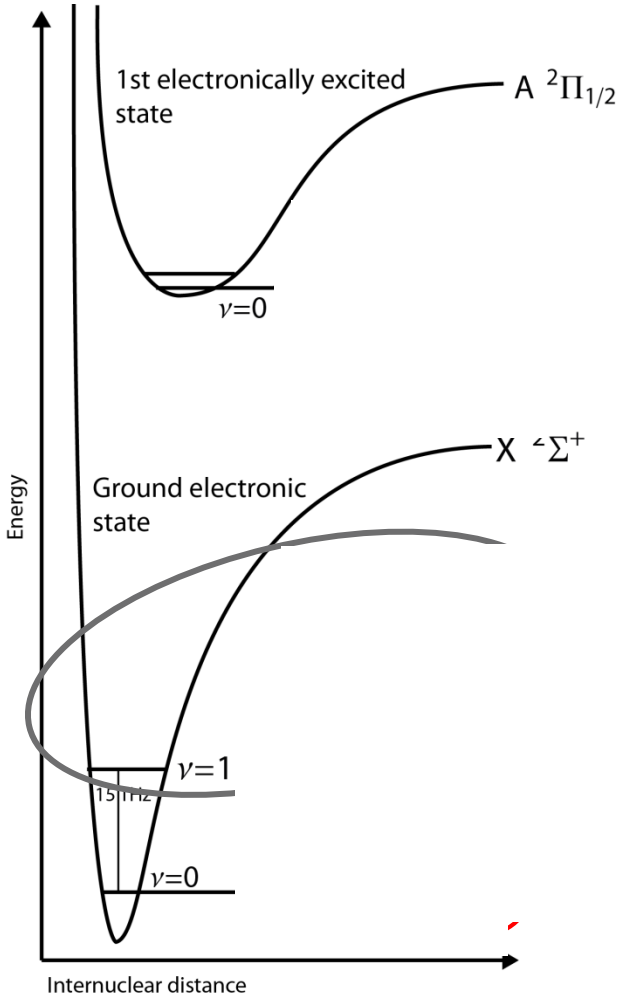
Analogous to magnetic dipole interaction $-g_e \mu \underline{B}.\underline{\sigma}$ but violates P&T

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

© Imperial College London

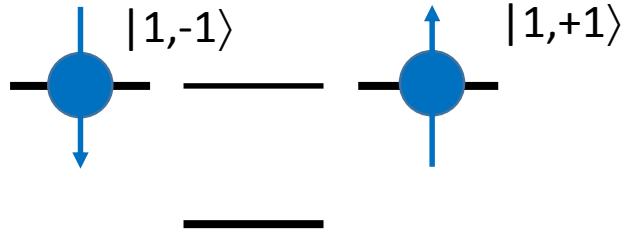
YbF

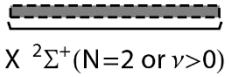
Imperial College London

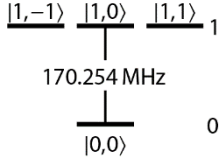


Vibration Rotation Hyperfine

Relevant levels

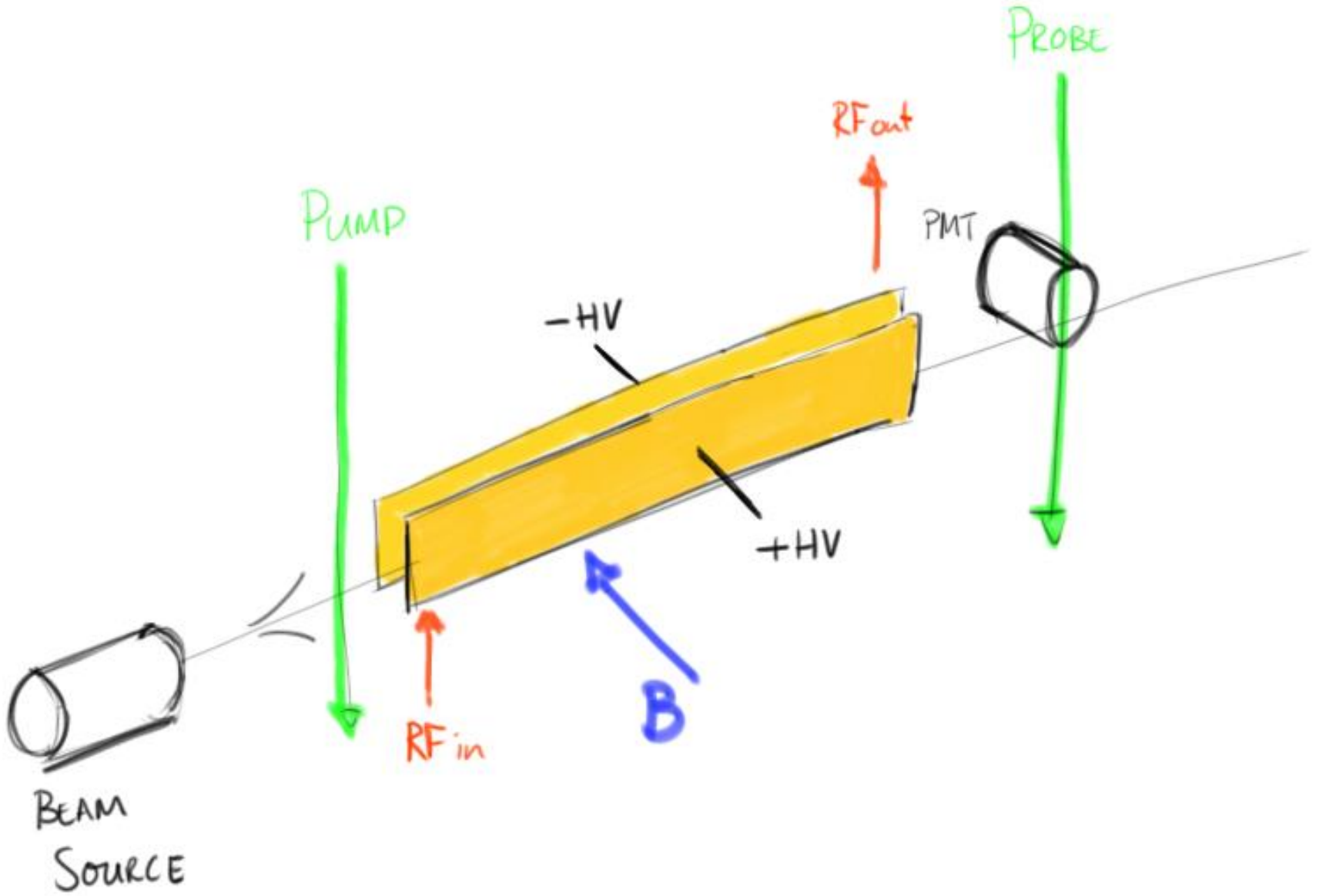






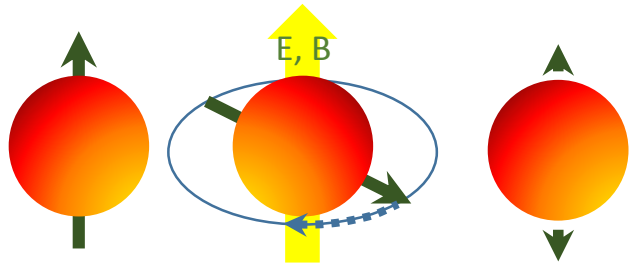
Measure the splitting of the $|1,-1\rangle$ and $|1,1\rangle$ levels in an applied electric field

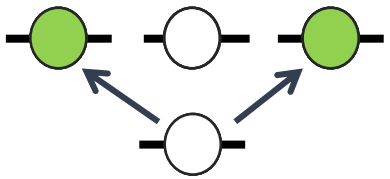
YbF eEDM measurement



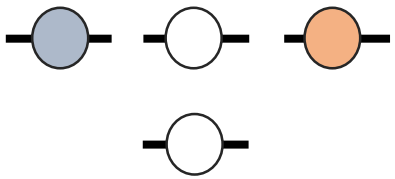
© Jony Hudson

YbF eEDM measurement

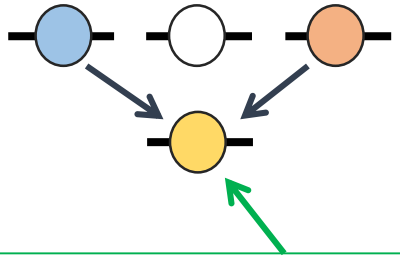




$$\frac{1}{\sqrt{2}}\left(|+\rangle+|-\rangle\right)$$



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

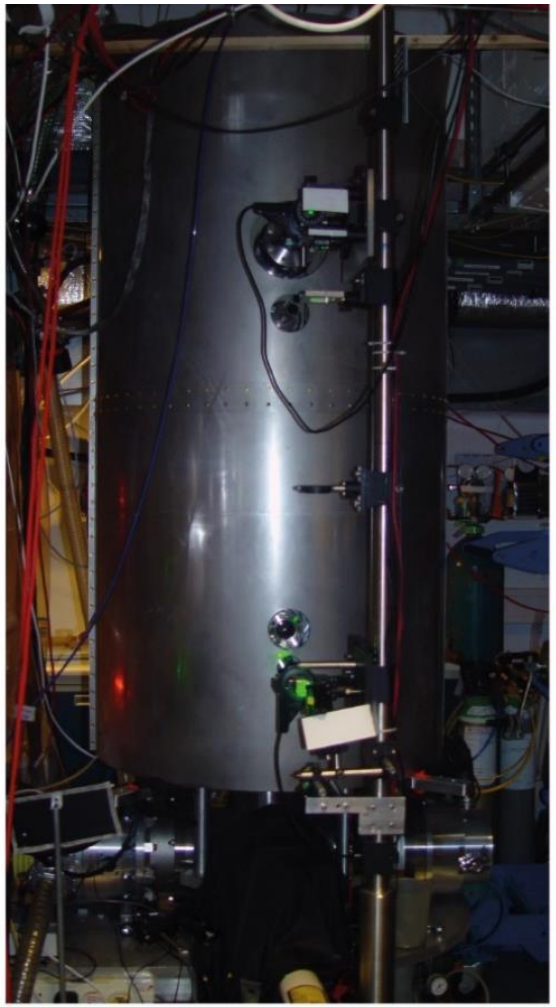


Measure population in F = 0

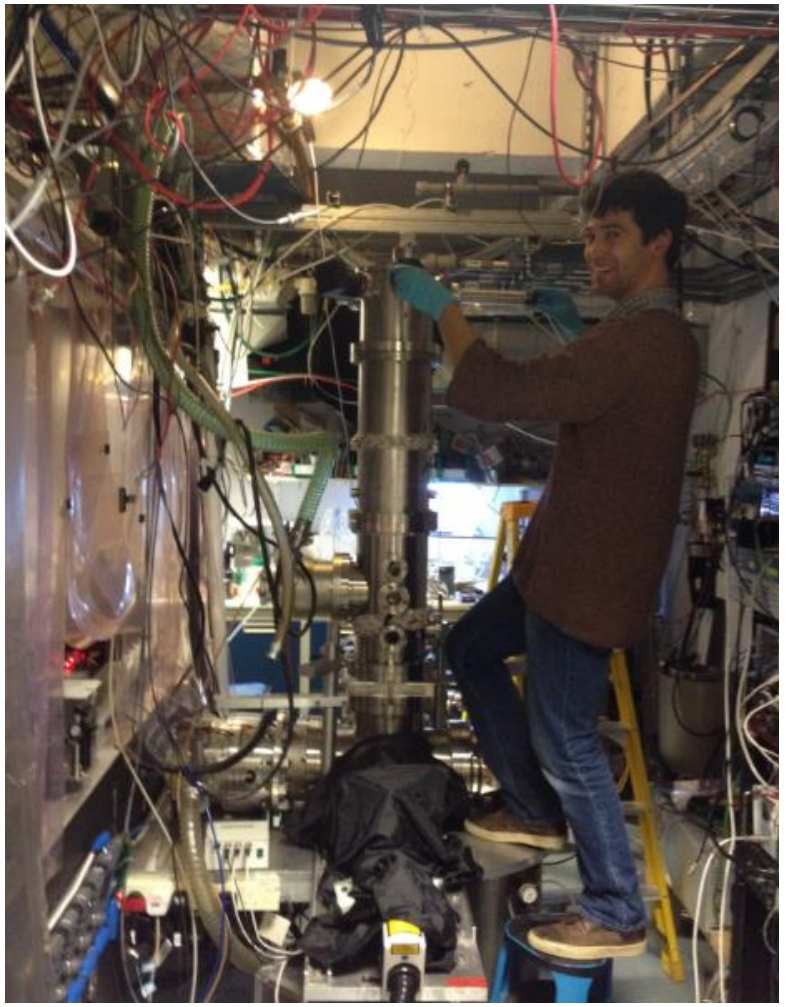
$$N\cos^2(\varphi)$$

The scale of the apparatus

Imperial College London



magnetic shields



vacuum chamber

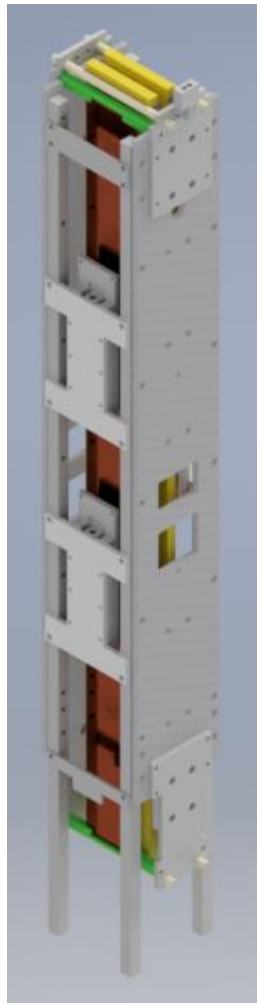
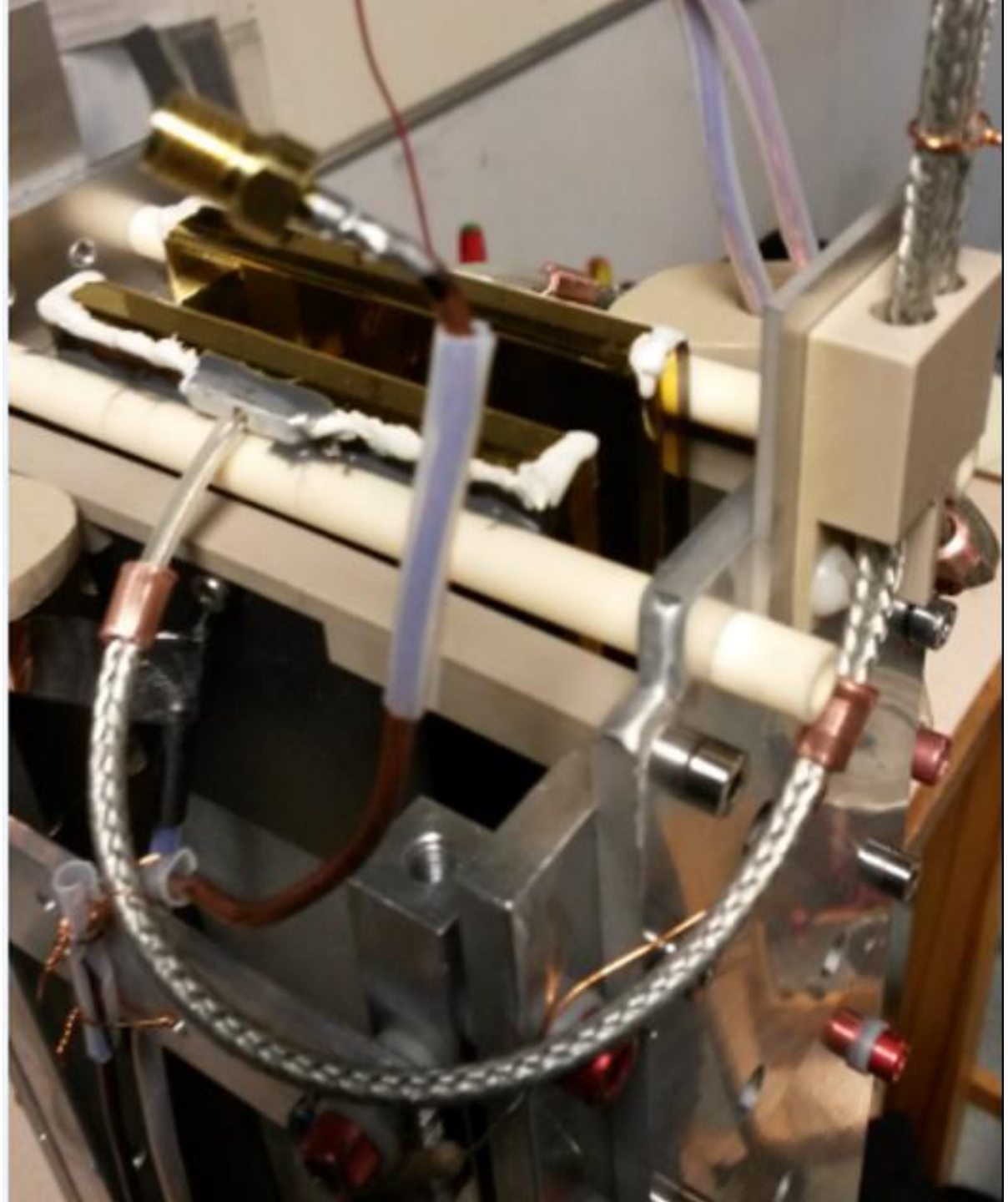
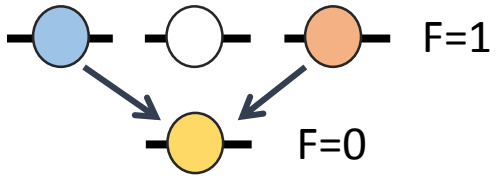


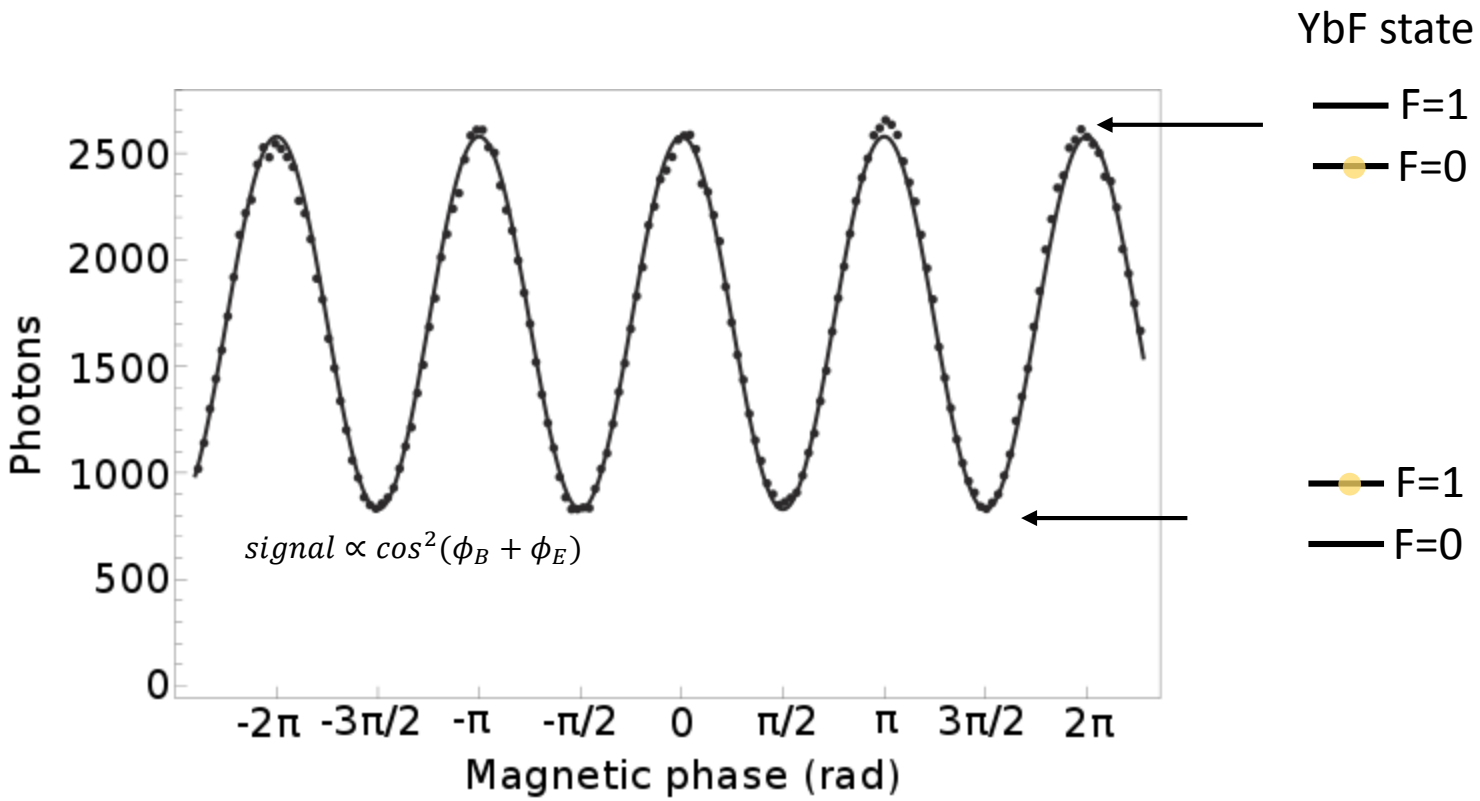
plate structure



A magnetic field scan

Imperial College London

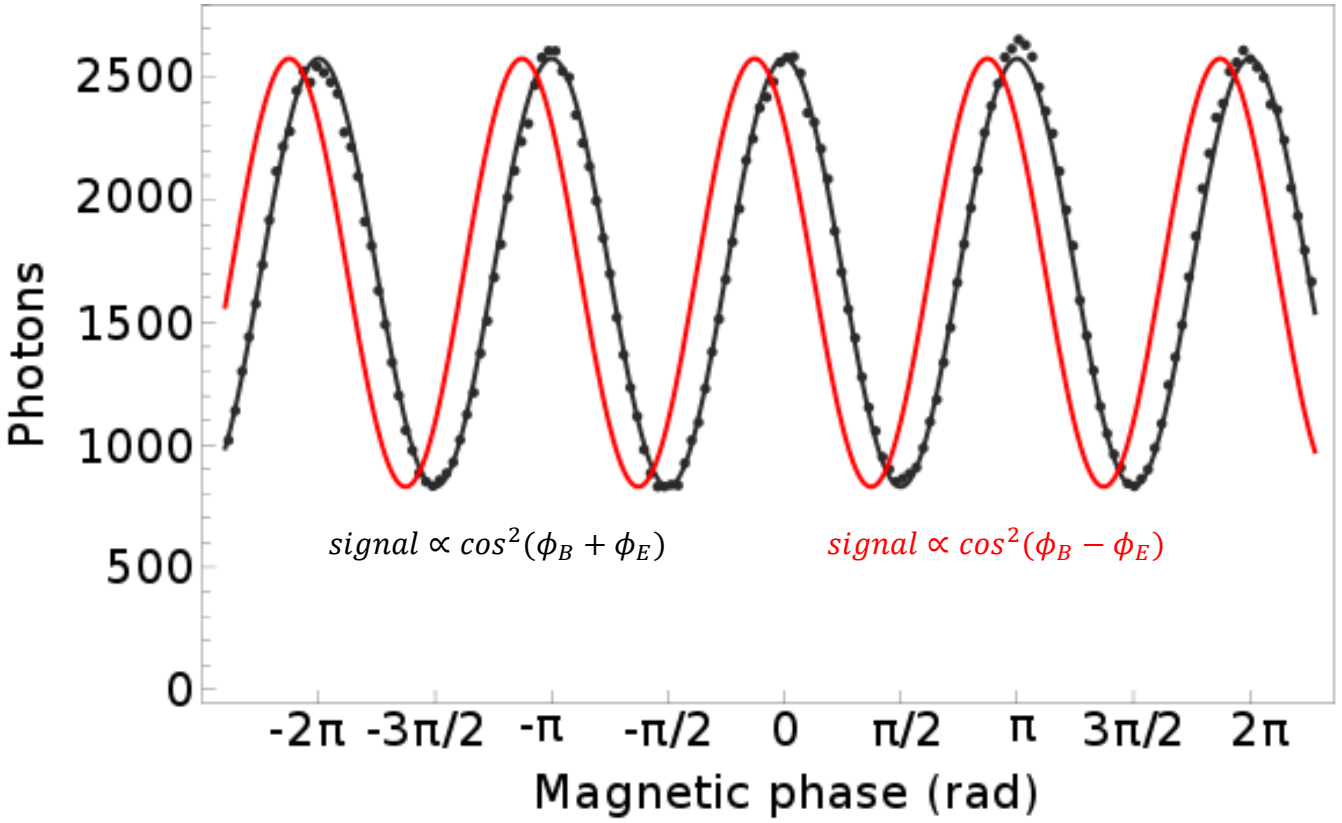




A magnetic field scan with E reversed

Imperial College London

Reverse E relative to B

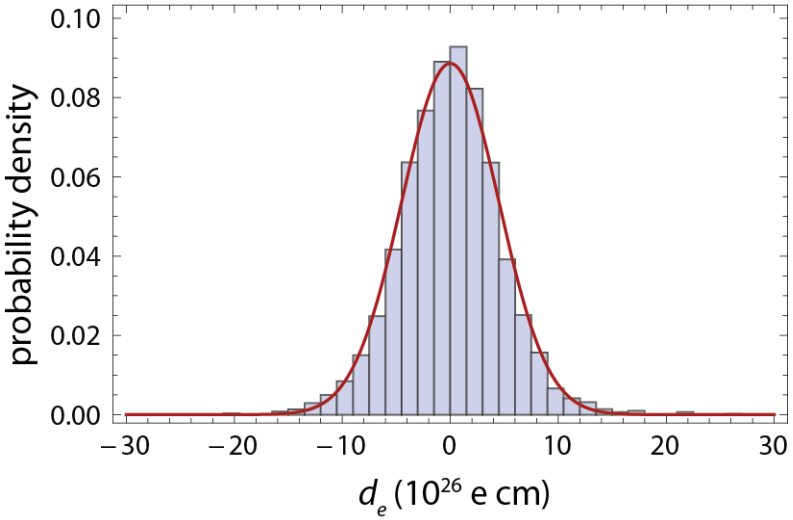


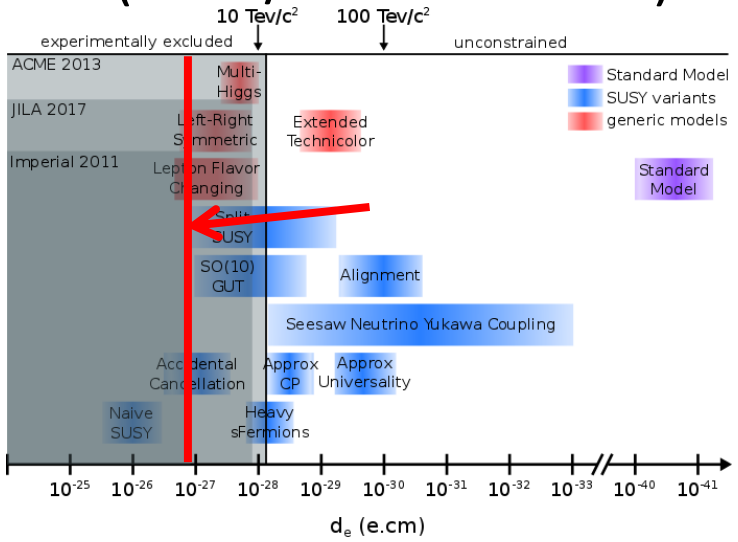
Looking for a shift of less than 2 μrad

2011 result

Imperial College London

- 2011 dataset: 6194 measurements (6min/measurement)





$$d_e = \left(-2.4 \pm 5.7_{stat} \pm 1.7_{syst}\right) \times 10^{-28} e.cm$$

$$d_e < 1 \times 10^{-27} e.cm \text{ with 90\% confidence}$$

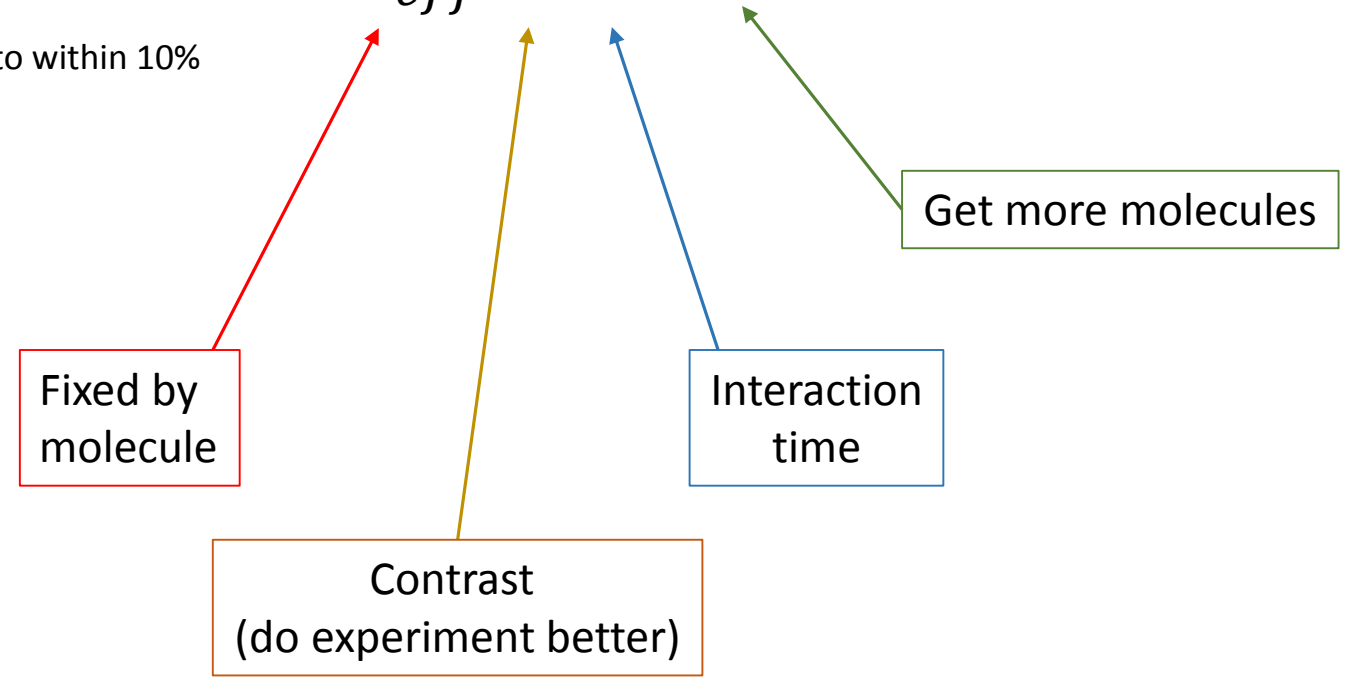
J J Hudson et al. Nature 473 493-496 (2011)
D M Kara et al. New. J. Phys. 14 103051 (2012)

Sensitivity Limit

Imperial College London

Photon shot noise : $\sigma_{d_e} \simeq \frac{\hbar}{2E_{eff} \times \mathcal{C} \times \tau \times \sqrt{N}}$

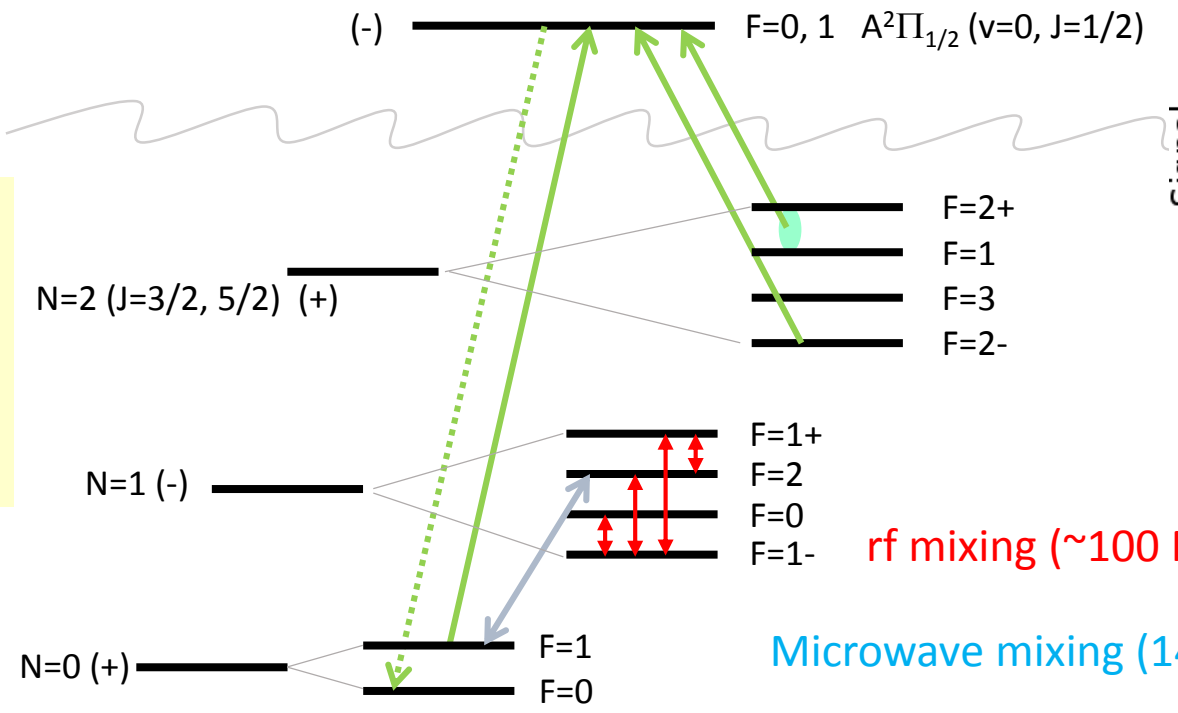
Agrees with final error in 2011 to within 10%



More molecules

Use cycling transition to optically pump molecules into ground rotational state.

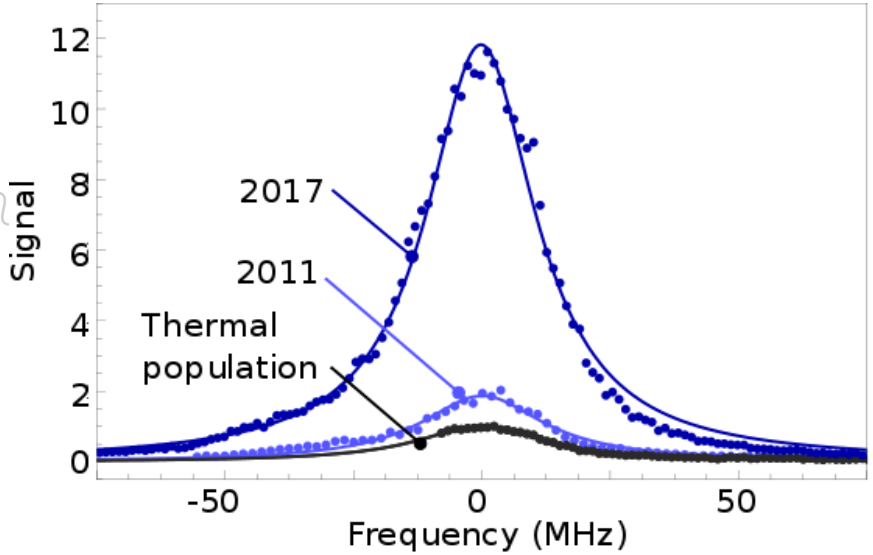
Scheme increases population by a factor of 7, sensitivity by 2.6



rf mixing (~100 MHz)

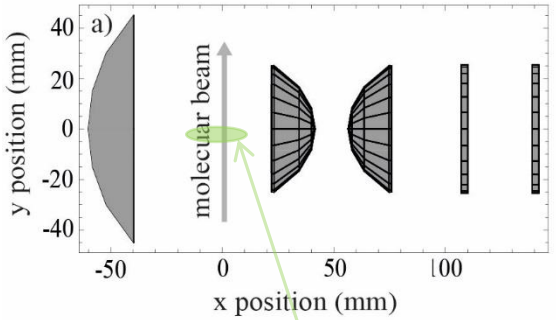
Microwave mixing (14 GHz)

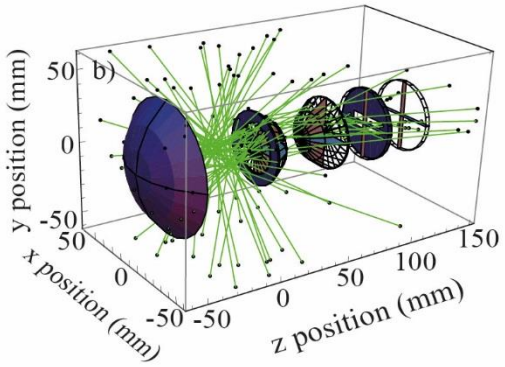
Optical pumping (N=2 rotational state)

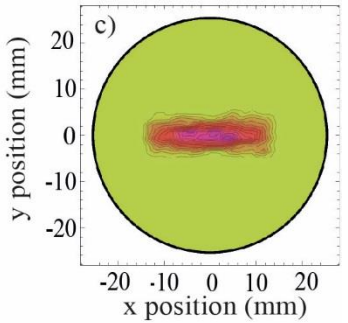


More molecules (better detection)

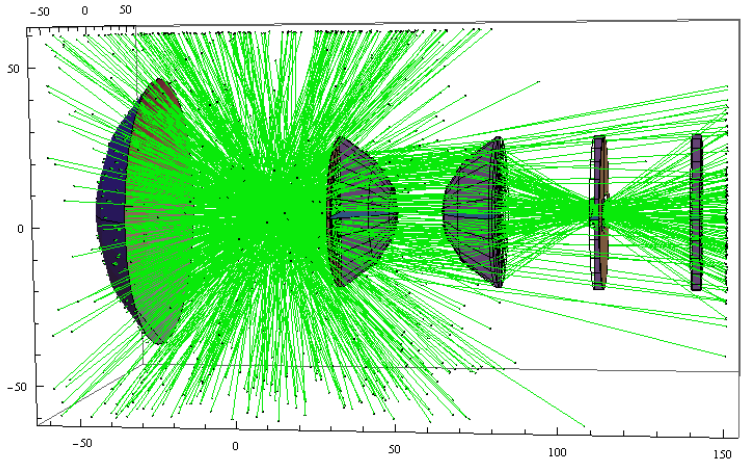
Fluorescence detection is only about 0.7% efficient





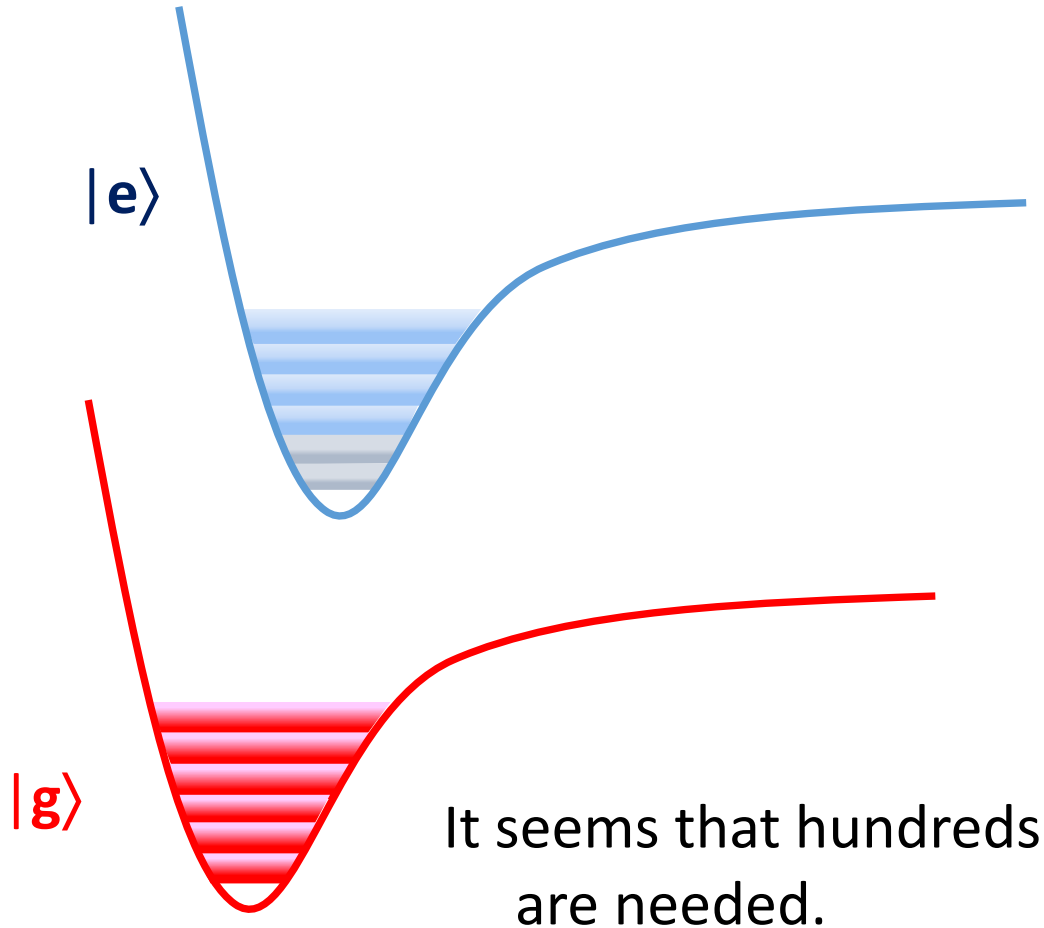


Probe laser beam



An interlude on laser cooling molecules

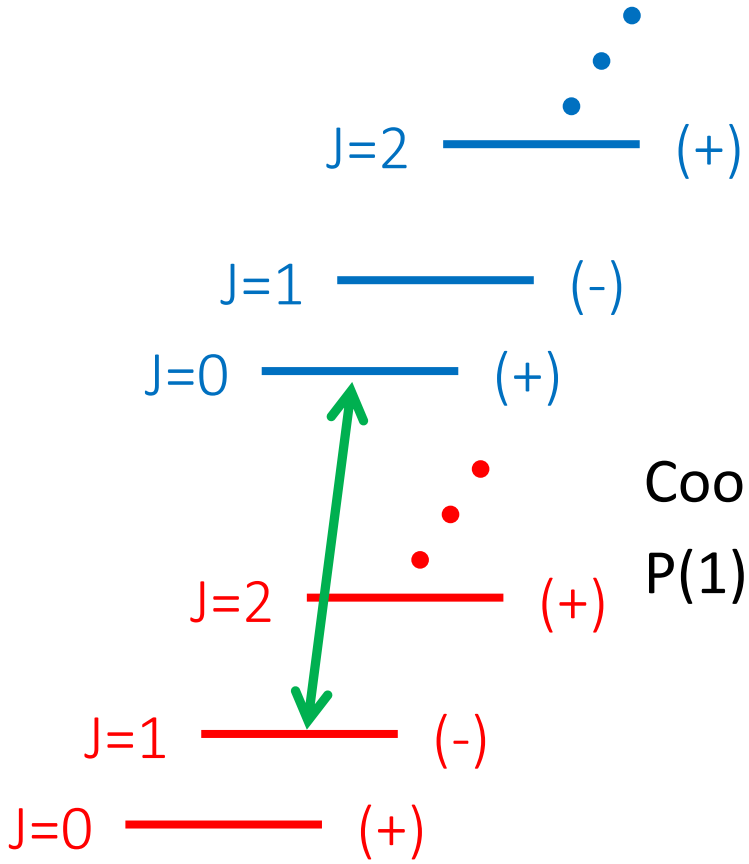
Molecules have many levels, and we need to scatter 10,000 photons.



It seems that hundreds of repump lasers are needed.

Laser cooling molecules: Rotation

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

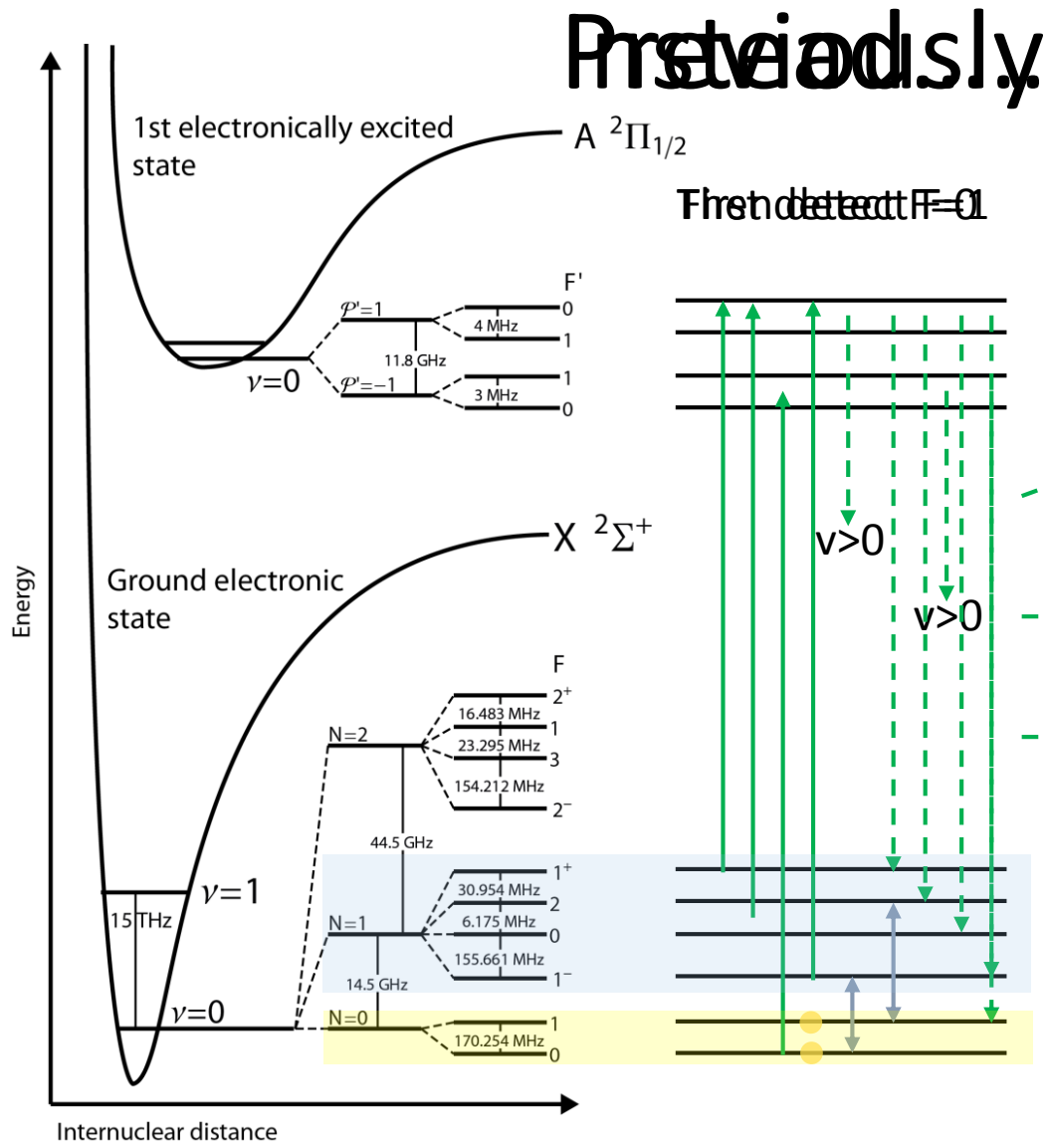


Cool on J=1 → J=0 transition,

P(1) line.

Improved state detection scheme

Imperial College London



- 1 extra laser around 552 nm with rf 3 sidebands to drive $P_1(F=1^+)$, $P_1(F=2,0)$ $P_1(F=1^-)$
- MW: 14 458 087 kHz

1.3 photons per molecule.
With 0.6% total detection efficiency,
most photons not captured

Up-to 14 photons per molecule.
With 0.6% total detection efficiency,
still only 5% detected, but 11 times more than before

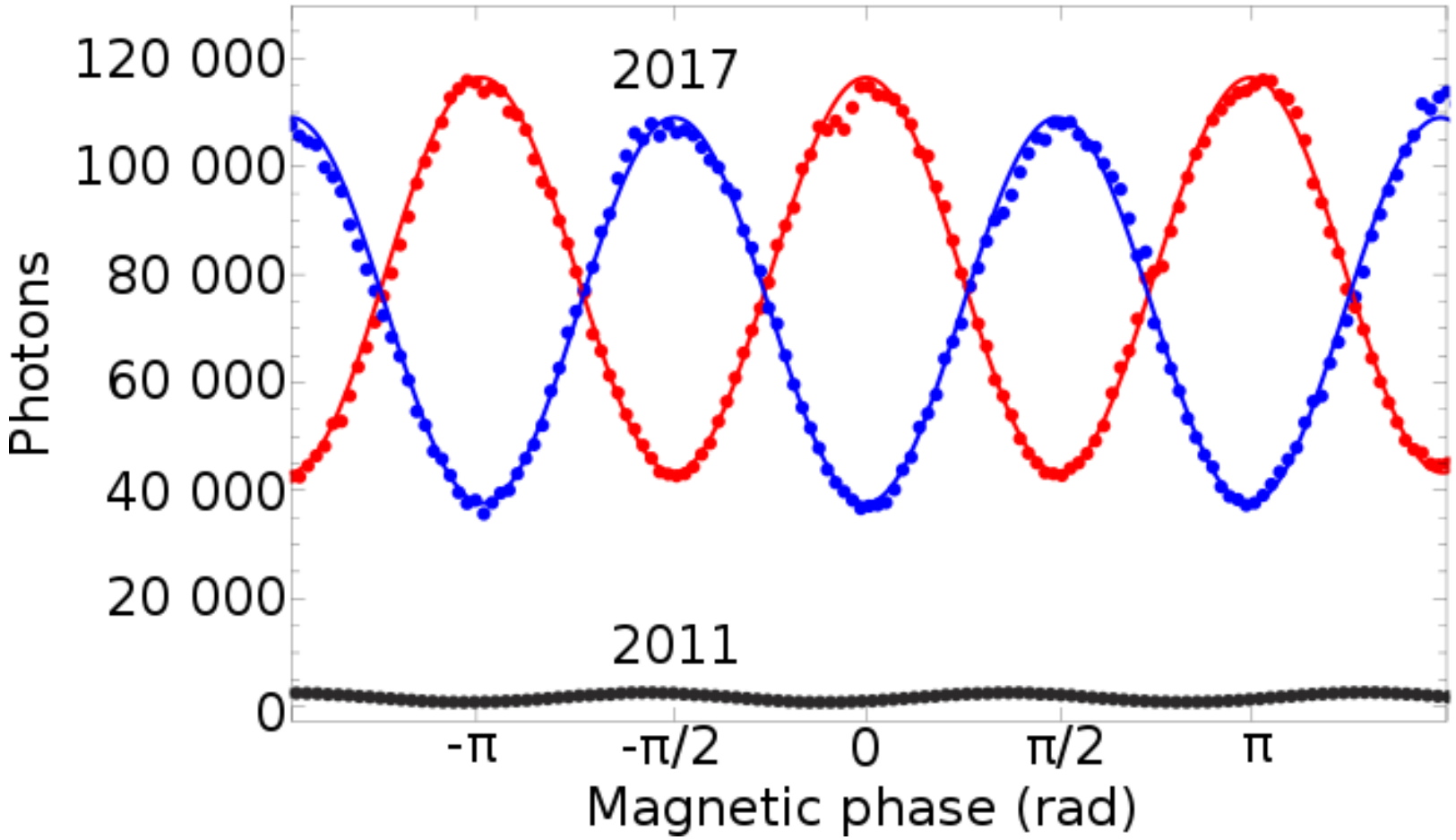
Another factor of two in signal

New magnetic scan curves

Imperial College London

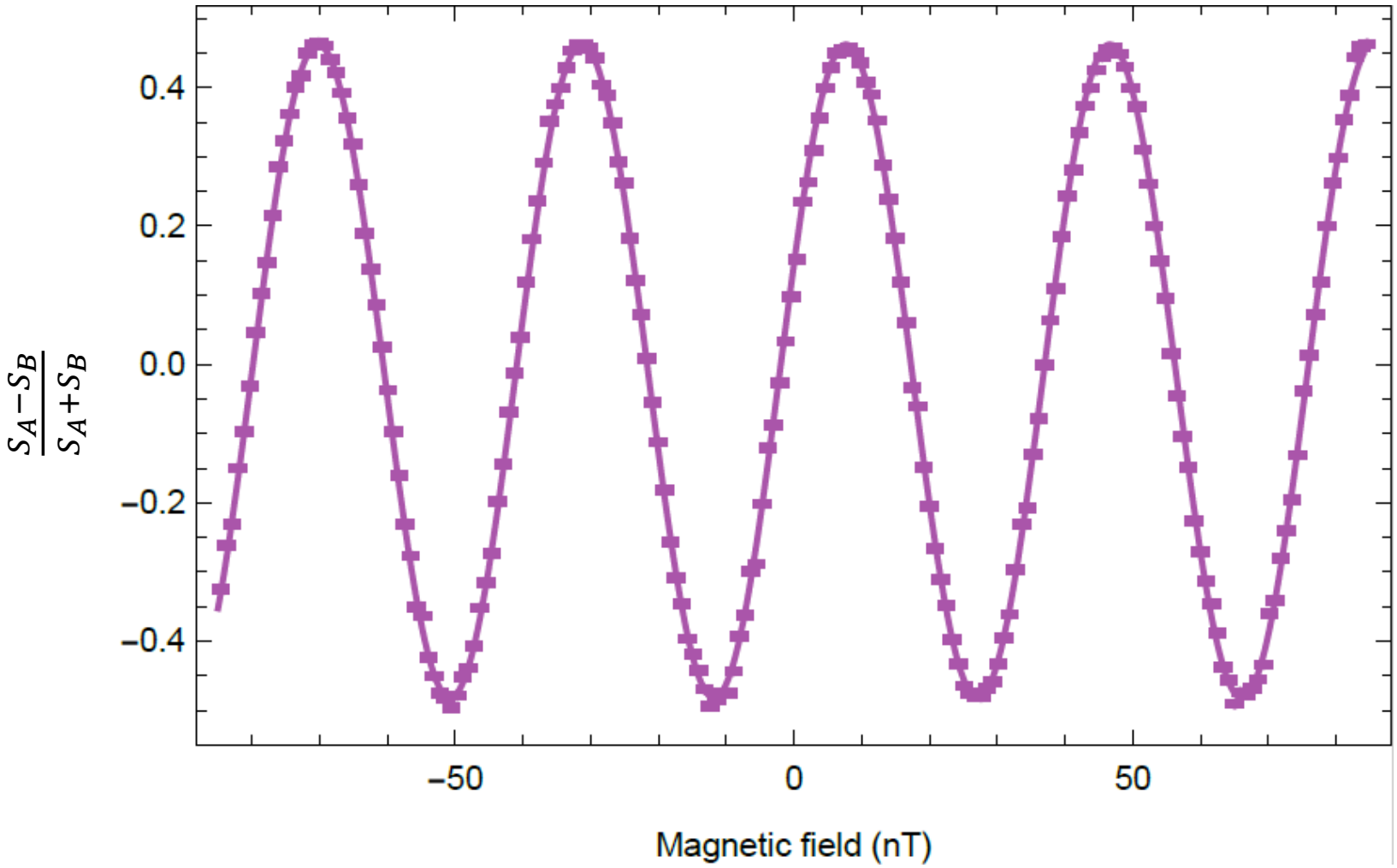
Single shot: ~1000 molecules → ~100 000 molecules

- Can detect both quadratures
- New detection scheme increases sensitivity by $\sqrt{11.5} = 3.4$ in each detector



Combine quadrature detectors

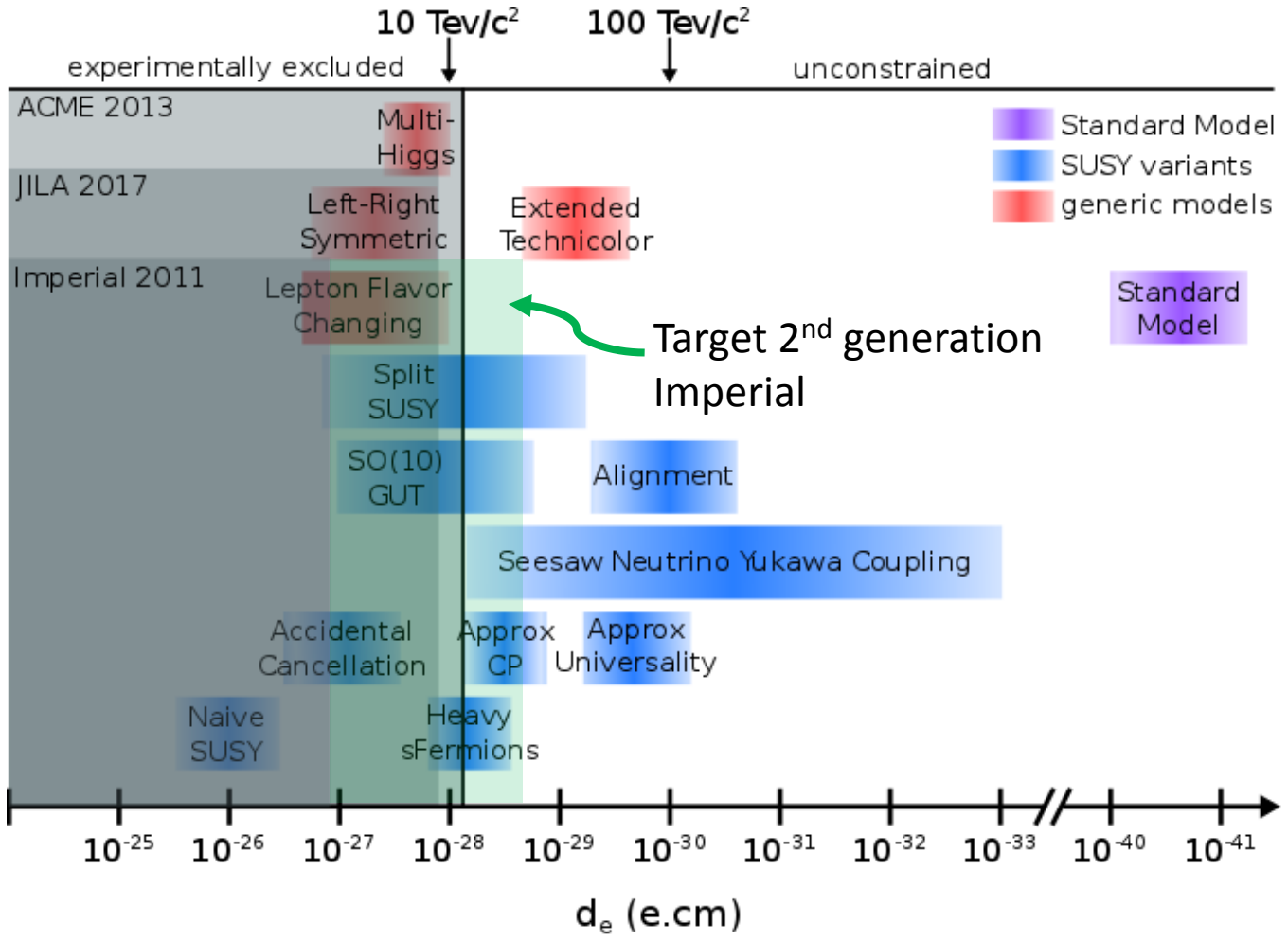
Imperial College London



Robust to source fluctuations

Sensitivity outlook

Imperial College London



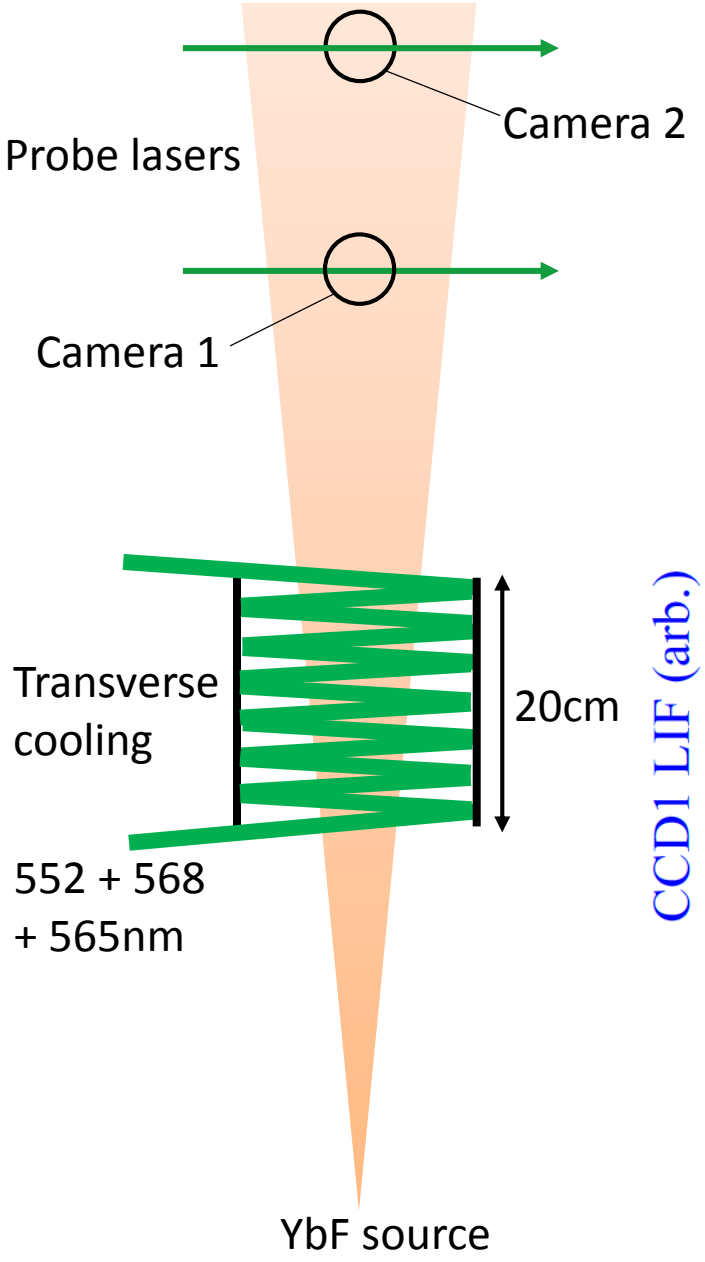
2011 sensitivity:

$$2.9 \times 10^{-27}\ e.\mathrm{cm}/\sqrt{\mathrm{day}}$$

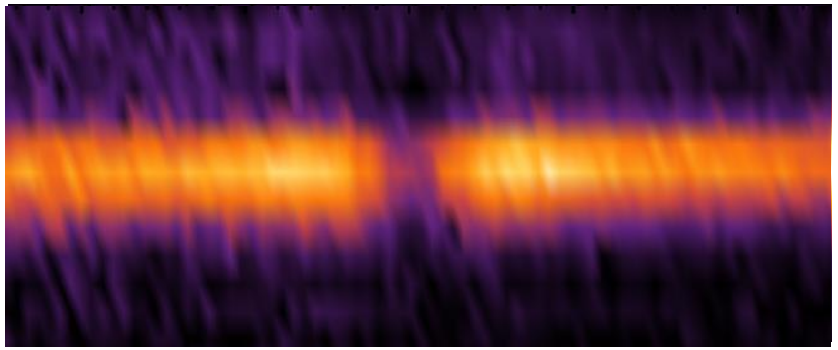
2018 (expected) sensitivity:

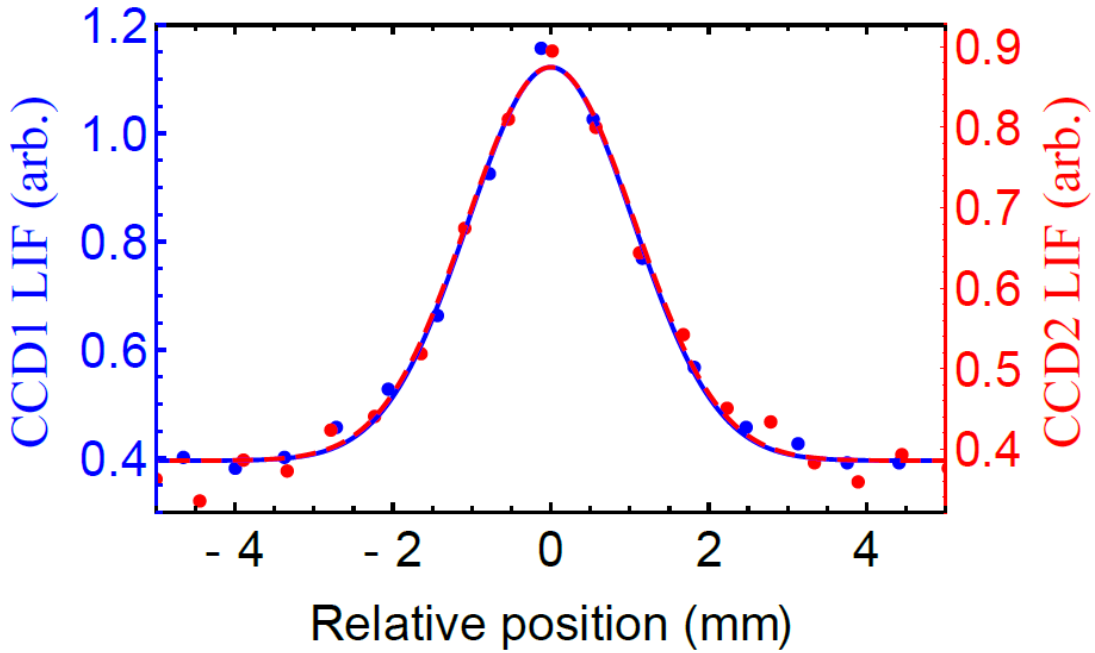
$$0.15 \times 10^{-27}\ e.\mathrm{cm}/\sqrt{\mathrm{day}}$$

Transverse cooling of YbF



Red-detuned



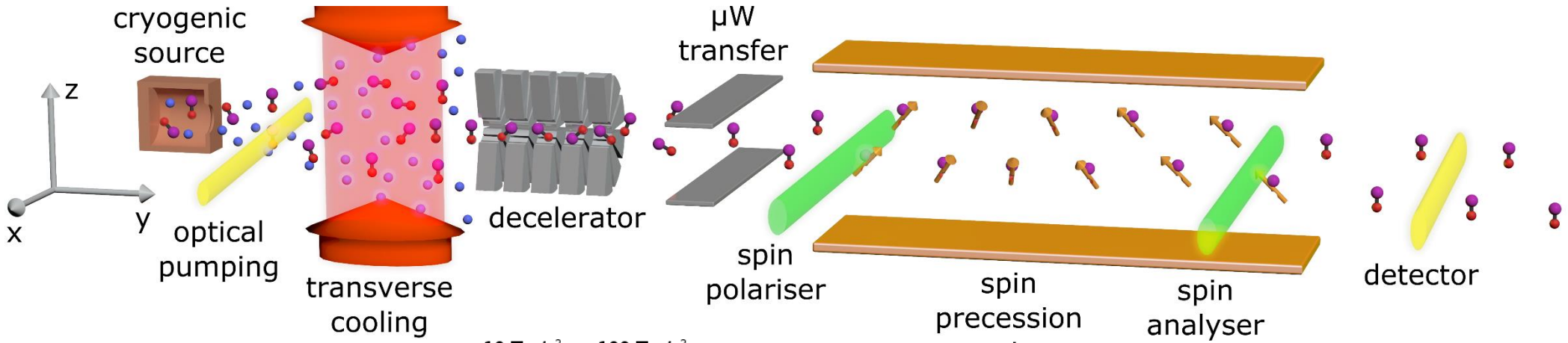


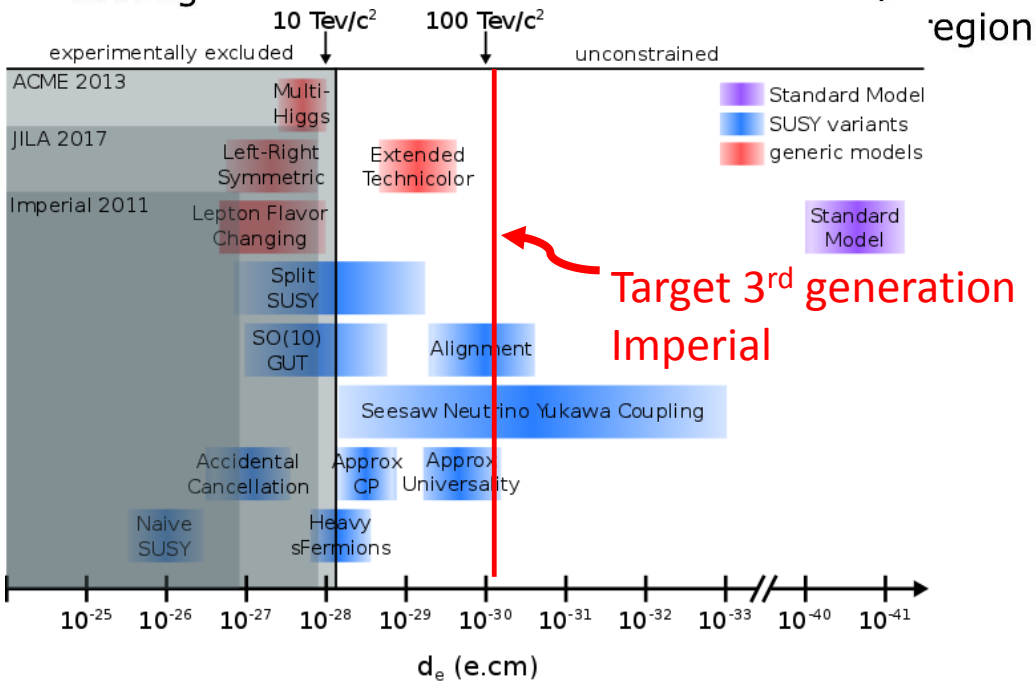
T < 50 μK

Ultracold molecules for measuring the electron's electric dipole moment
J. Lim, J. R. Almond, M. A. Trigatzis, J. A. Devlin, N. J. Fitch, B. E. Sauer, M. R. Tarbutt, E. A. Hinds; arXiv 1712:02868

Sensitivity outlook

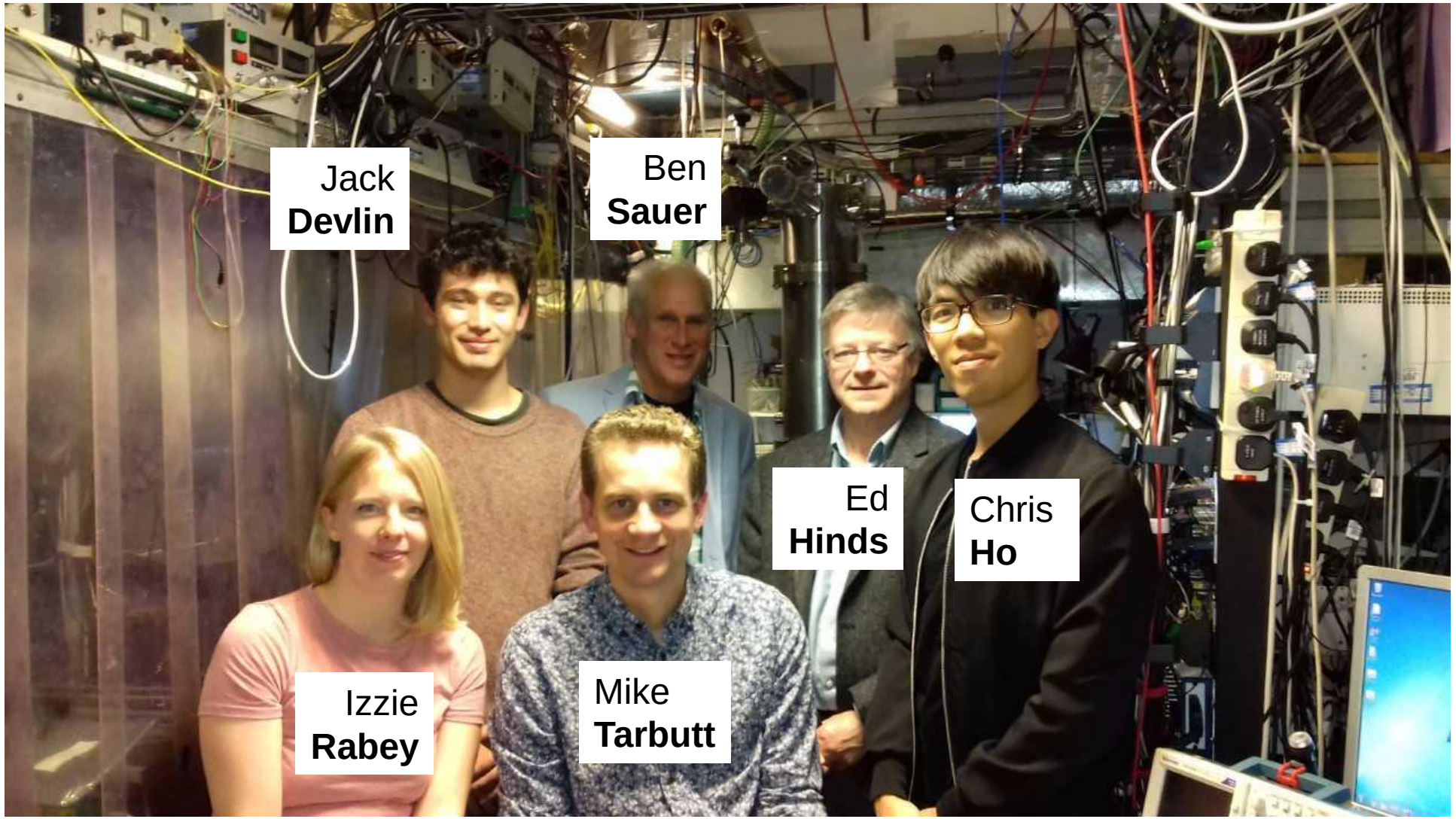
Imperial College London





Team EDM

Imperial College London



ThO*: huge internal field

Effective field E_{eff} in YbF is 26 GV/cm
when molecule is fully polarized
For ThO* E_{eff} is about 84 GV/cm (factor of 3.2 more sensitive)

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

(also depends on structure)
ThO* can be fully polarized!

Comparing some atomic and molecular systems

- YbF, 2011: $|E_{eff}| = 14.5$ GV/cm ($\eta = 0.56$)

  $|d_e| < 1.0 \times 10^{-27}$ e.cm (90% c.l.)
- Tl, 2002: $|E_{eff}| = 72$ MV/cm ($E_{eff} = -582\ E_{applied}$)

  $|d_e| < 1.6 \times 10^{-27}$ e.cm (90% c.l.)
- PbO*, 2013: $|E_{eff}| = 25$ GV/cm

  $|d_e| < 1.7 \times 10^{-26}$ e.cm (90% c.l.)
- $Eu_{0.5}Ba_{0.5}TiO_3$, 2012:

  $|d_e| < 6 \times 10^{-25}$ e.cm (90% c.l.)
- ThO*: $|E_{eff}| = 84$ GV/cm (factor of 6 on 2011 YbF)

  $|d_e| < 8.7 \times 10^{-29}$ e.cm (90% c.l.)