Electric Dipole Moment Experiments: Neutron and Electron

PPAP meeting, RAL, July 17, 2018

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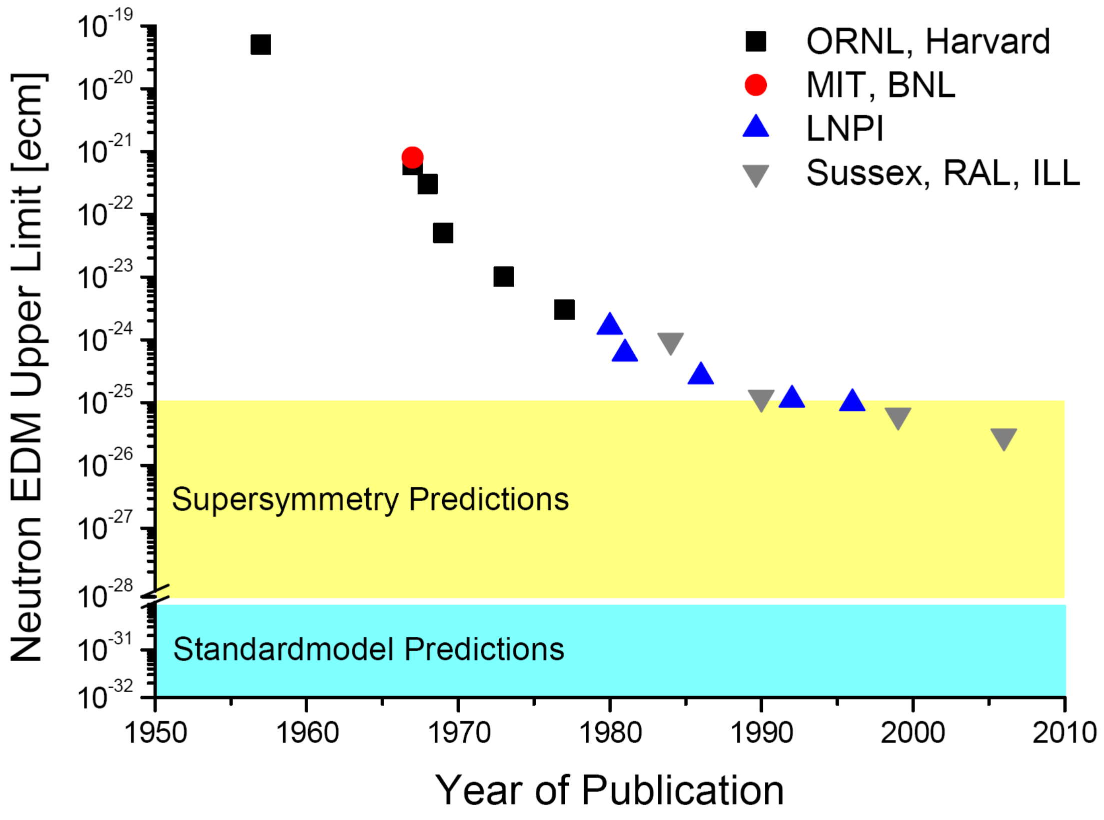
Electric Dipole Moments

- permanent EDM of a particle/atom/molecule violates T and P
  - with CPT theorem → implies CP violation
- Standard Model EDM predictions are vanishingly small
  - any nonzero measurement is a *background free* signal of CP violating *new physics!*
  - SM CP violation is too small to account for baryogenesis
    - BSM extensions preferably allow for new sources of of CP violation = *measurable EDMs*

- EDM experiments have an excellent potential for BSM *discovery*

neutron EDM - history



$$d_n \approx \left(\frac{300\,\mathrm{GeV}}{\Lambda_{SUSY}} \right)^2 \sin\varphi_{CP} \times 10^{-24}\,\mathrm{e.cm}$$

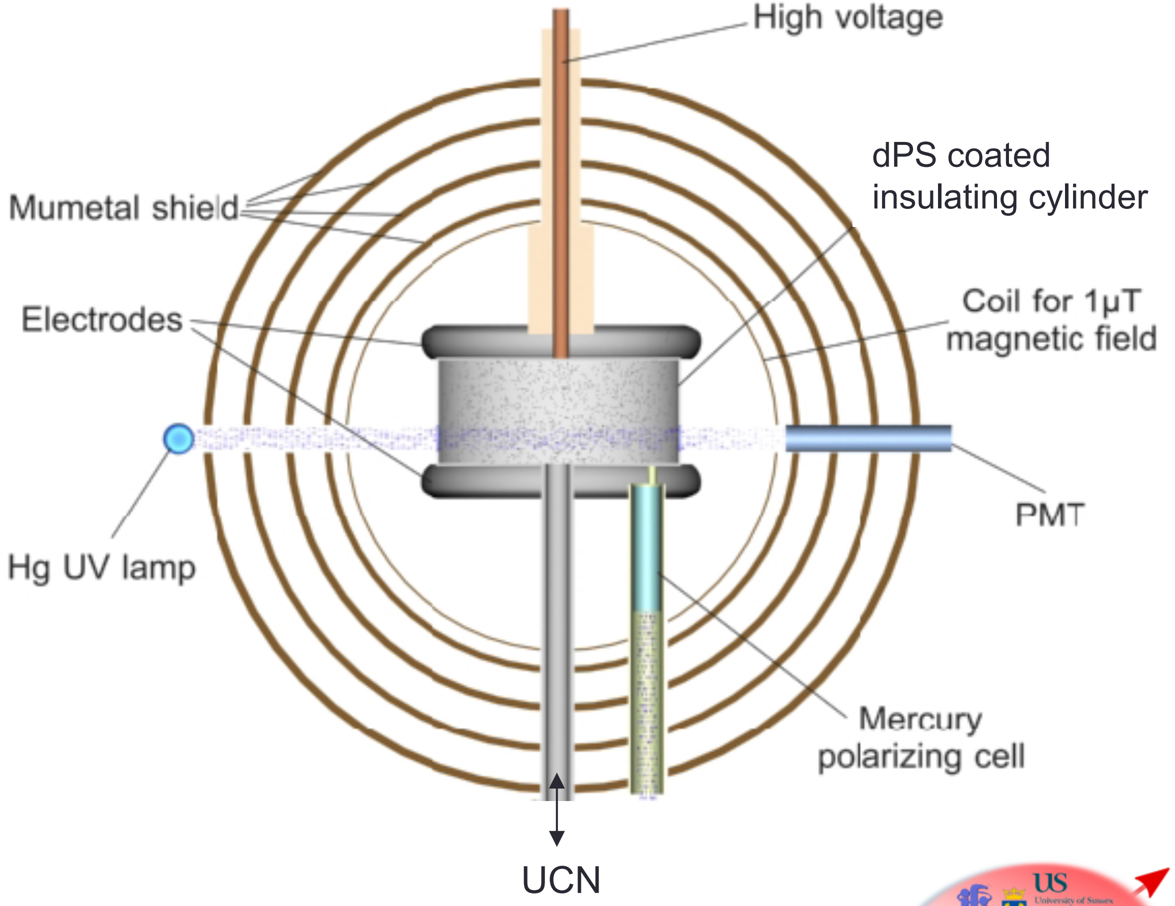
$|d_n| < 3 \times 10^{-26}$ *e* cm

2006 result – Sussex/RAL/ILL reanalysed in 2015 accounting for gravitational depolarisation systematic

UK has had world lead since 1999

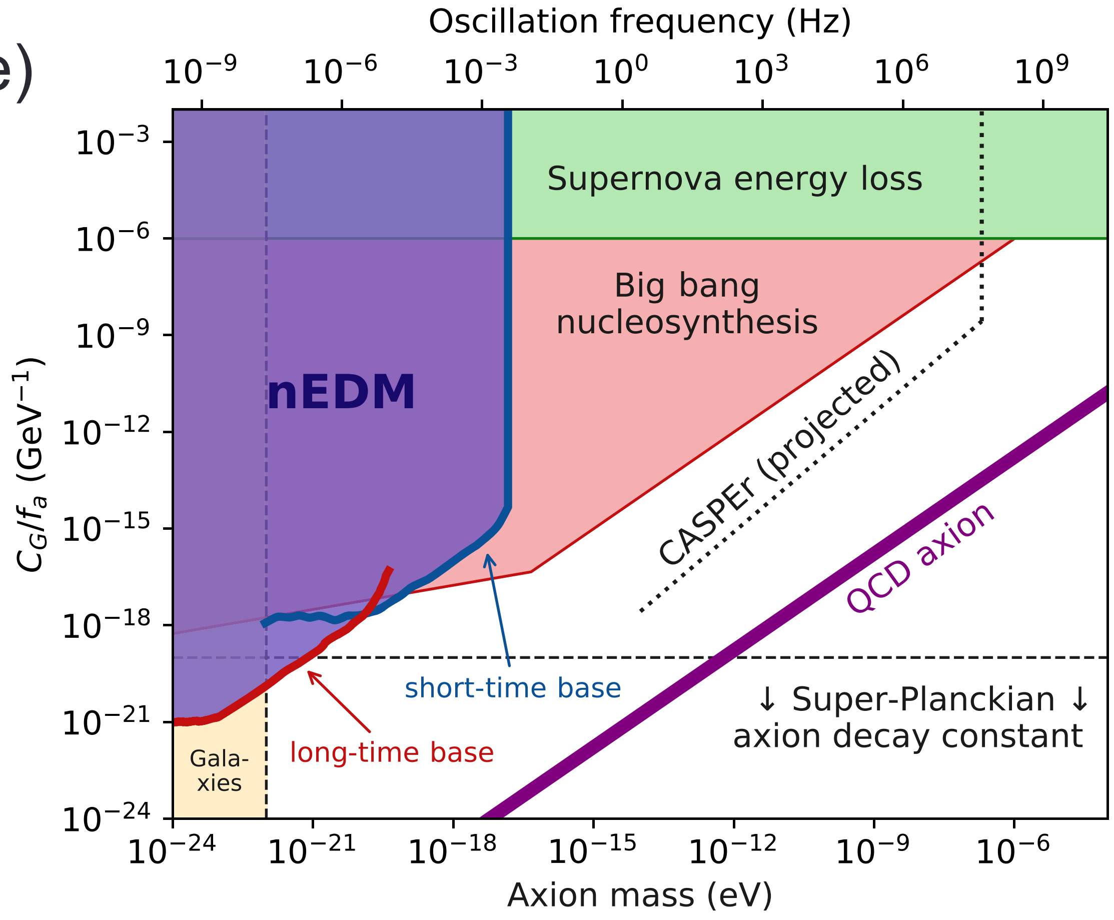
PSI nEDM

- UK conceived apparatus from ILL result
  - NMR on ultracold neutrons (UCN) stored in same volume as a Hg comagnetometer
- moved to PSI superthermal UCN source
  - world leading UCN source
  - added Cs magnetometer array
    - extremely important for controlling systematics
  - also: additional external field compensation, better UCN detectors...
  - first blinded nEDM measurement
    - based on Sussex developed algorithm



nEDM: dark matter detector

- Axion like particles (possible DM candidate) generate a time varying EDM
- Existing neutron EDM data analysed for oscillating signals
  - *co-led by Sussex PhD*
  - Sussex-RAL-ILL: long-time base
  - PSI: short-time base
  - gives best constraints on axions over a range of axion masses
    - through an axion-quark coupling
    - first laboratory based constraints!



Phys Rev X, **7**, 041034 (2017)

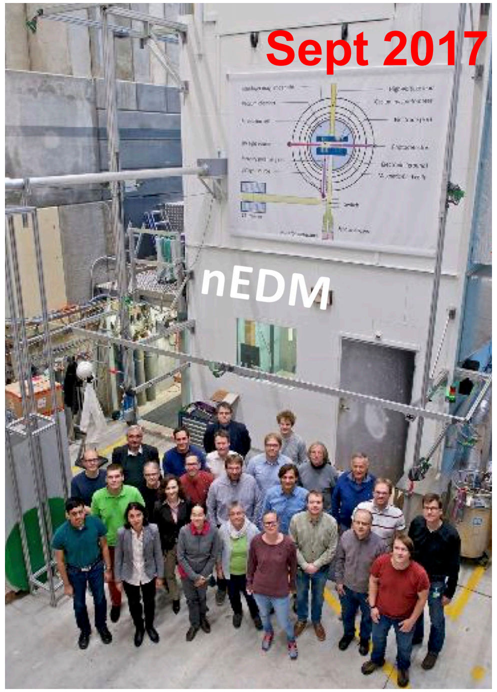
PSI nEDM – current status

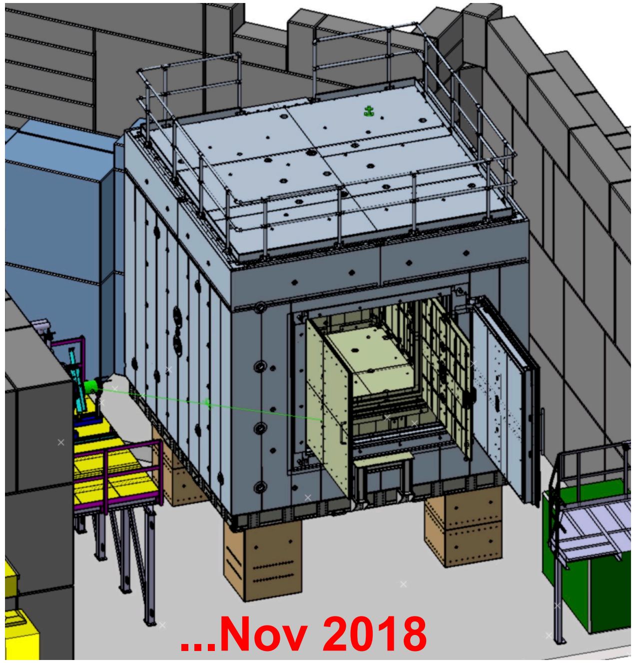
- Data taking complete in Oct. 2017
- Analysis in progress
  - *major contributions from Sussex:*
    - magnetic field mapping of the apparatus and analysis of the maps
    - studies of systematic HV correlated shifts in Cs magnetometer readings
    - Sussex PhD currently co-leading one of two analysis teams
  - unblinding expected in the next few months
    - 1σ sensitivity at 10^{-26} ecm
- As of early 2018, apparatus disassembled to make way for n2EDM

	nEDM@ILL 2006	nEDM@PSI 2016	n2EDM@PSI 2020
Chamber	1	1	2
Diameter (cm)	47	47	80
Neutron/cycle	14 000	15 000	121 000
E(kV/cm)	8.3	11 (15)	15
T(s)	130	180	180
α	0.45 (0.6)	0.75 (0.80)	0.8
Sens/day(e.cm)	$30*10^{-26}$	$11*10^{-26}$	$2.6*10^{-26}$
Sens (500 days)	$1.3*10^{-26}$	$5.0*10^{-27}$	$1.2*10^{-27}$

$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

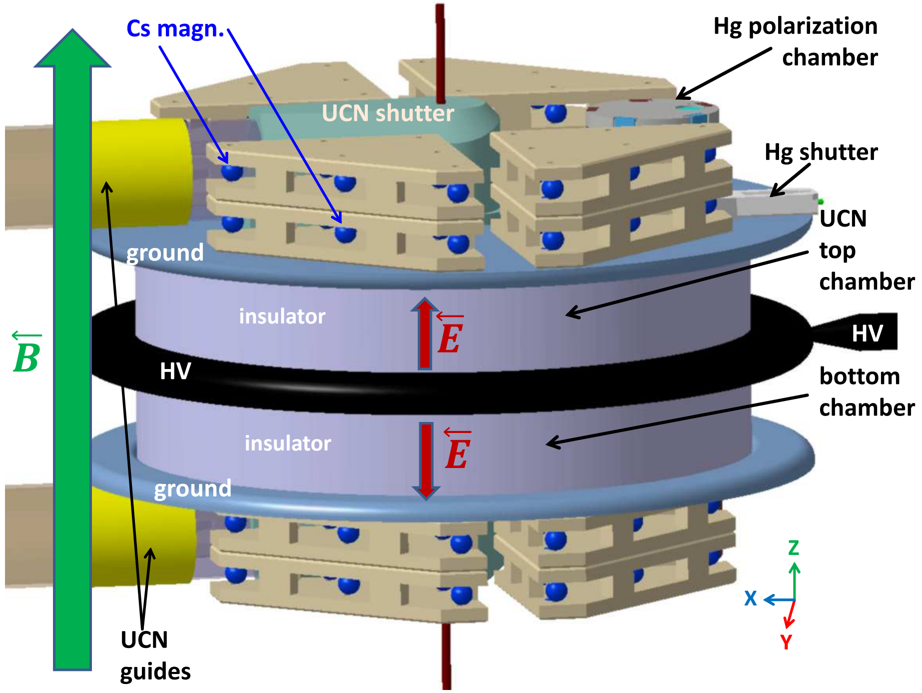
PSI – transition to n2EDM

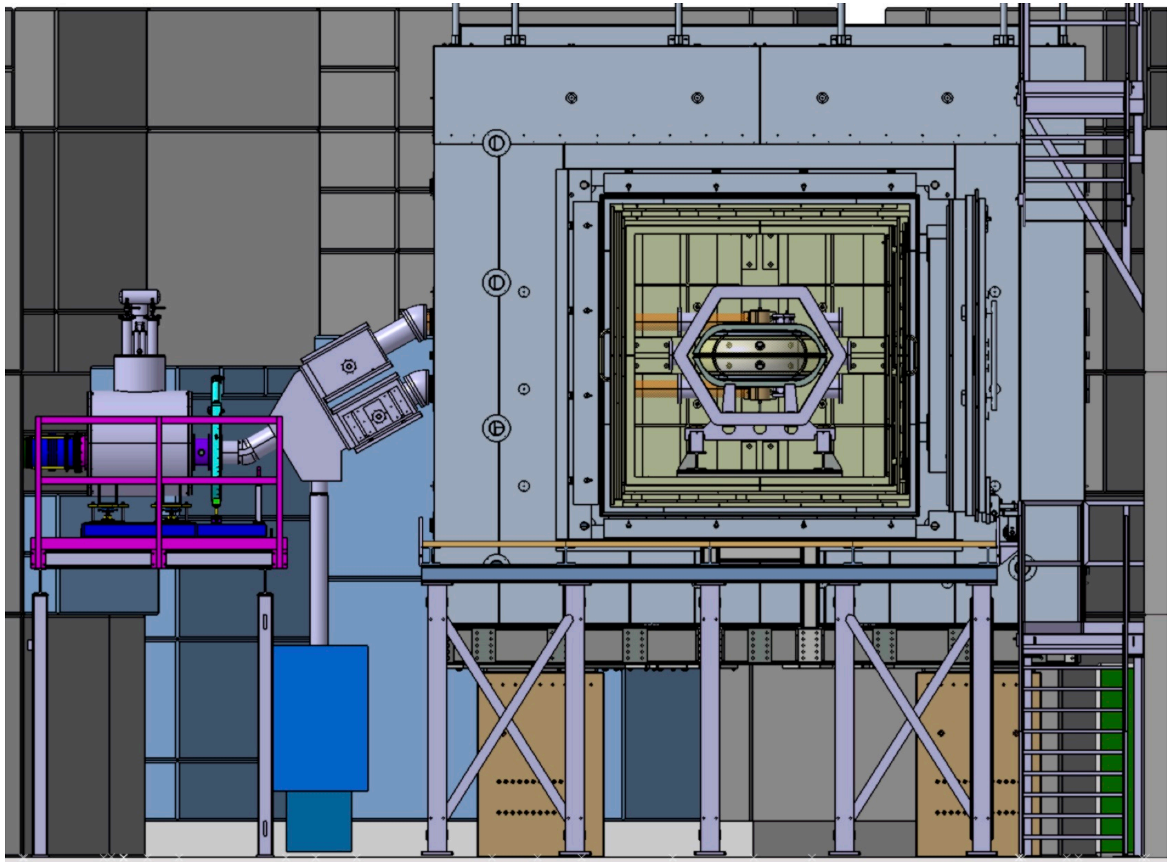




- First installation: magnetic shield
  - 5x5x5 m^3 external dim., 6 layers mu-metal, ~10^5 shielding factor
  - large internal space, 3x3x3 m^3 for B field coils and vac. tank
  - first mu-metal panels delivered to PSI in past month

PSI – n2EDM





- based on well established techniques/technology
  - *mostly previously tested in PSI-nEDM*
- large double precession chambers, 80 cm diam.
- Hg comagnetometer with 254 nm laser readout
- > 50 Cs magnetometer array

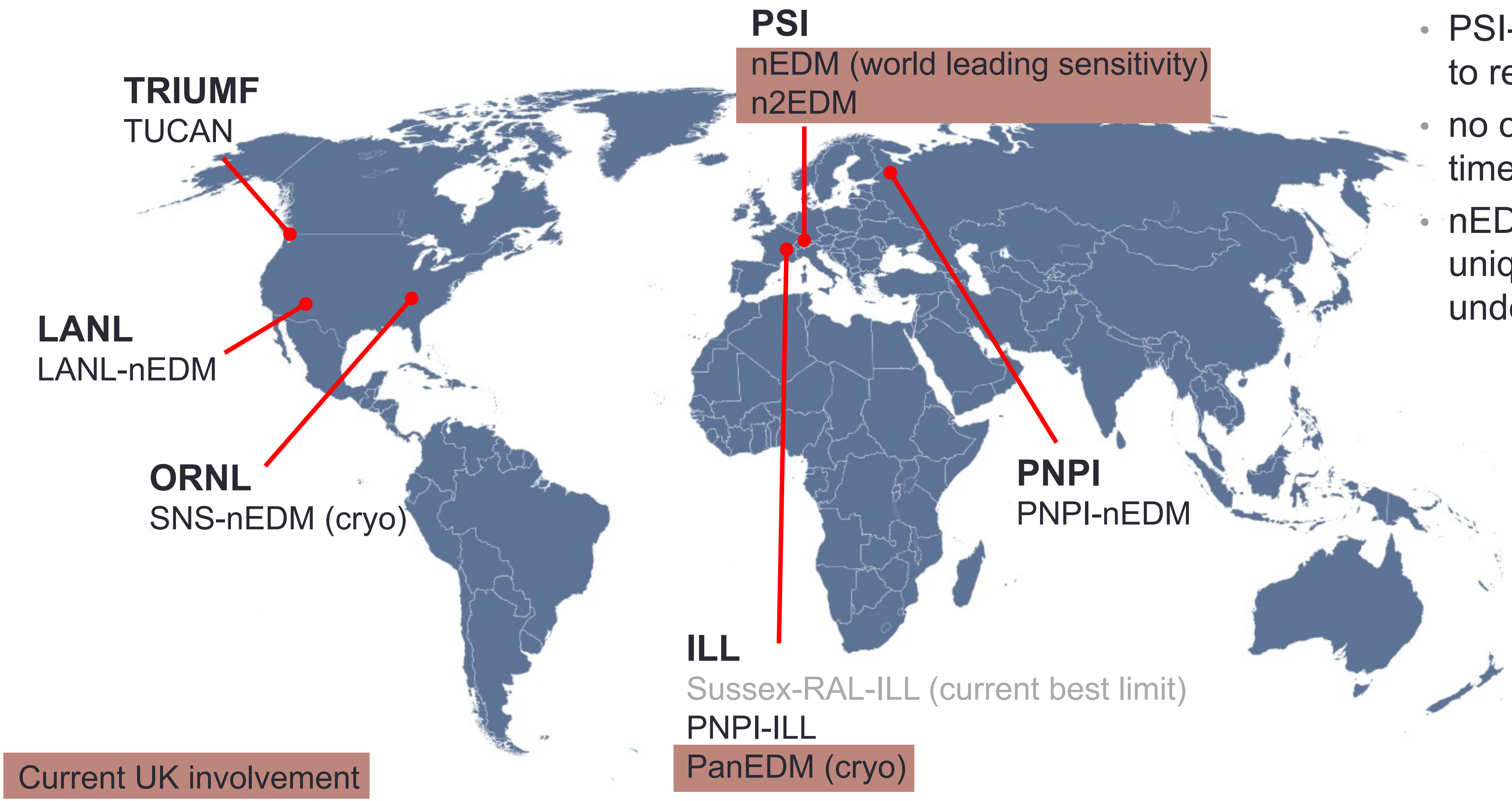
- Plan to have first data in 2020
- Designed to reach ~1x10^{-27} *e*cm stat. sensitivity in a few years
- Further upgrades can push this to 6 x 10^{-28} *e*cm
  - larger precession chambers, improved wall coatings to store higher energy UCN

PSI–n2EDM

- under current funding limitations, UK/Sussex can still make scaled back, but substantial contributions
  - leakage current monitors, ^{3}He magnetometry for accuracy calibration of Cs sensors
  - intellectual leadership in systematics, reviewing/determining overall magnetometry system, CB chair
- n2EDM is well positioned to reach 10^{-27} *e*cm first and maintain world limit (or reach discovery)
  - well established, dedicated collaboration with ***extensive experience*** running an nEDM measurement
    - *unique in the world currently*
  - well supported UCN source facility with demonstrated (and improving) performance over multiple years

The UK has been recognised world leaders in nEDM for several decades – continued leadership on n2EDM keeps this role for years to come

Neutron EDM – worldwide efforts



2018 external review panel for PSI findings:

- PSI-n2EDM uniquely placed to reach 1e-27 sensitivity
- no clear competitor in 5-year time-scale
- nEDM gives collaboration unique expertise and understanding of systematics

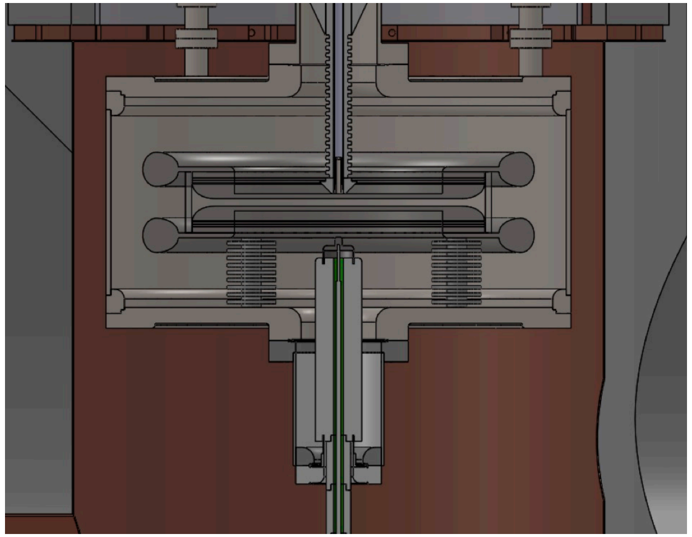
The future

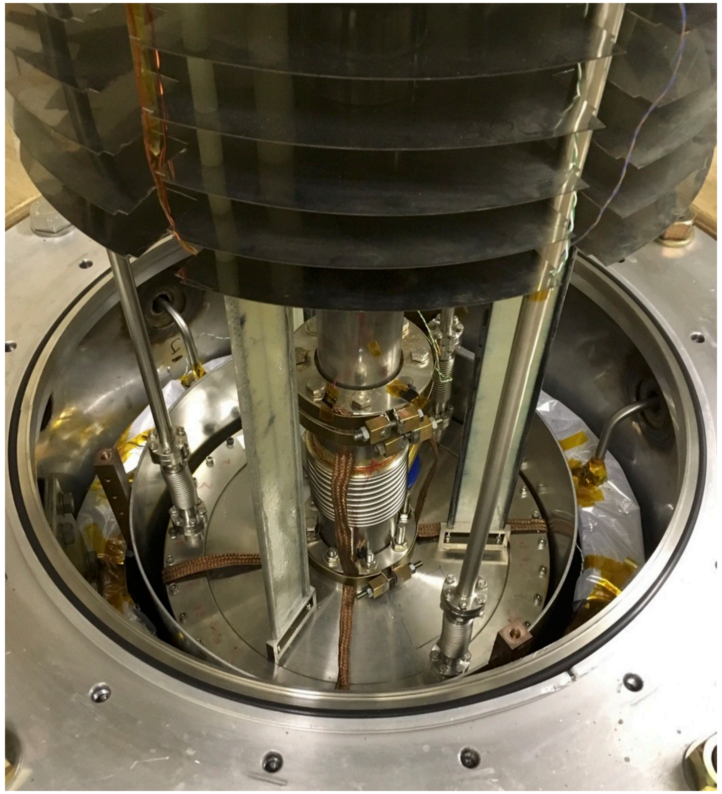
n2EDM (and other double chamber experiments) will likely reach the limits of the room temperature stored UCN approach in the next decade

- Cryogenic
  - superfluid He has its benefits
    - higher *E* fields (10 kV/cm →100 kV/cm)
    - potentially high UCN density (for in-situ production **transport losses a big issue**)
    - longer UCN storage times
    - superconducting mag. shields and persistent currents for *B* generation
  - CryoEDM demonstrated the daunting technical challenges of a cryogenic experiment
  - US SNS cryogenic experiment has been difficult to realise as well
    - delayed start date (2012 → 2023)
- Beam nEDM revisited
  - beam experiments abandoned previously due to $\vec{v}\times\vec{E}$ systematic
  - use pulsed beam (ESS) for velocity dependence, potential for ~5×10^{-28} *e*cm stat. sens. (100 days)
    - F. Piegsa, U. Bern, Phys Rev C 88 045502 (2013)

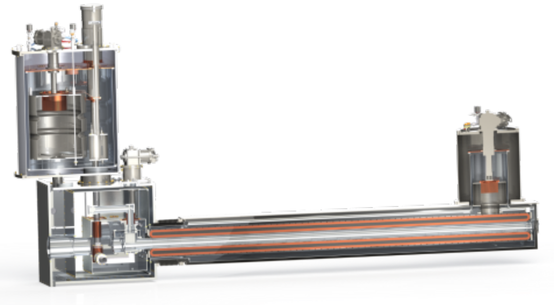
Cryogenic nEDM R&D

- while room temperature experiments expected to lead the field well into the next decade...
- UK groups maintaining small cryogenic R&D efforts
  - RAL: cryogenic UCN guide and source development
    - involvement in the PanEDM collaboration
  - Sussex: electric fields in cryogenic liquids
    - have demonstrated > 60 kV/cm E fields in LHe in a mock cryogenic nEDM precession chamber
      - storage volume: 24 cm diam, 1.6 cm height



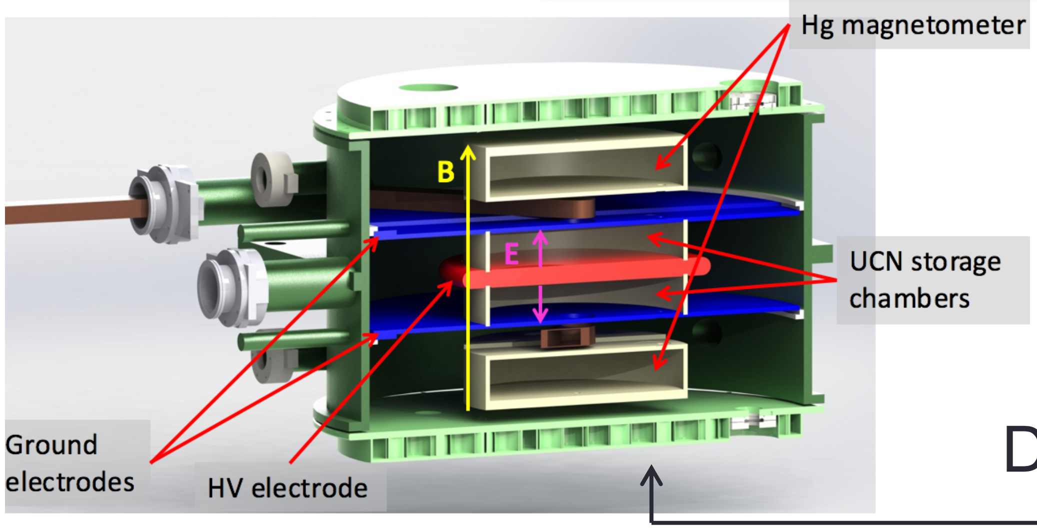


Cryogenic nEDM R&D at ILL

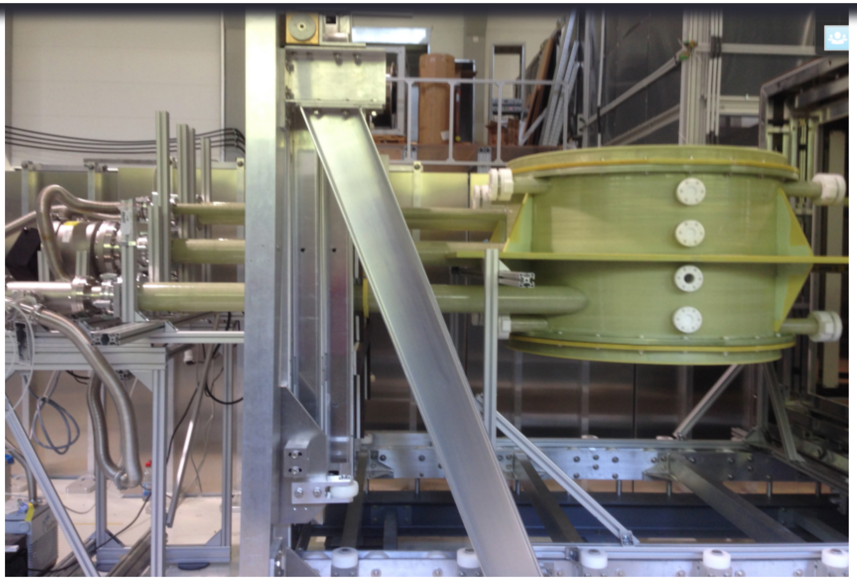


PanEDM – two stage programme towards a cryogenic nEDM (ILL/TUM/RAL/PNPI+US institutes)

- Aims to provide a next generation nEDM experiment following the room temperature era
- Super-thermal LHe UCN source coupled to nEDM:
  - room temperature – first tests w/UCN planned early 2019
  - fully cryogenic experiment to follow



EDM chambers
Design - Manufacture



Cryogenic nEDM R&D at ILL

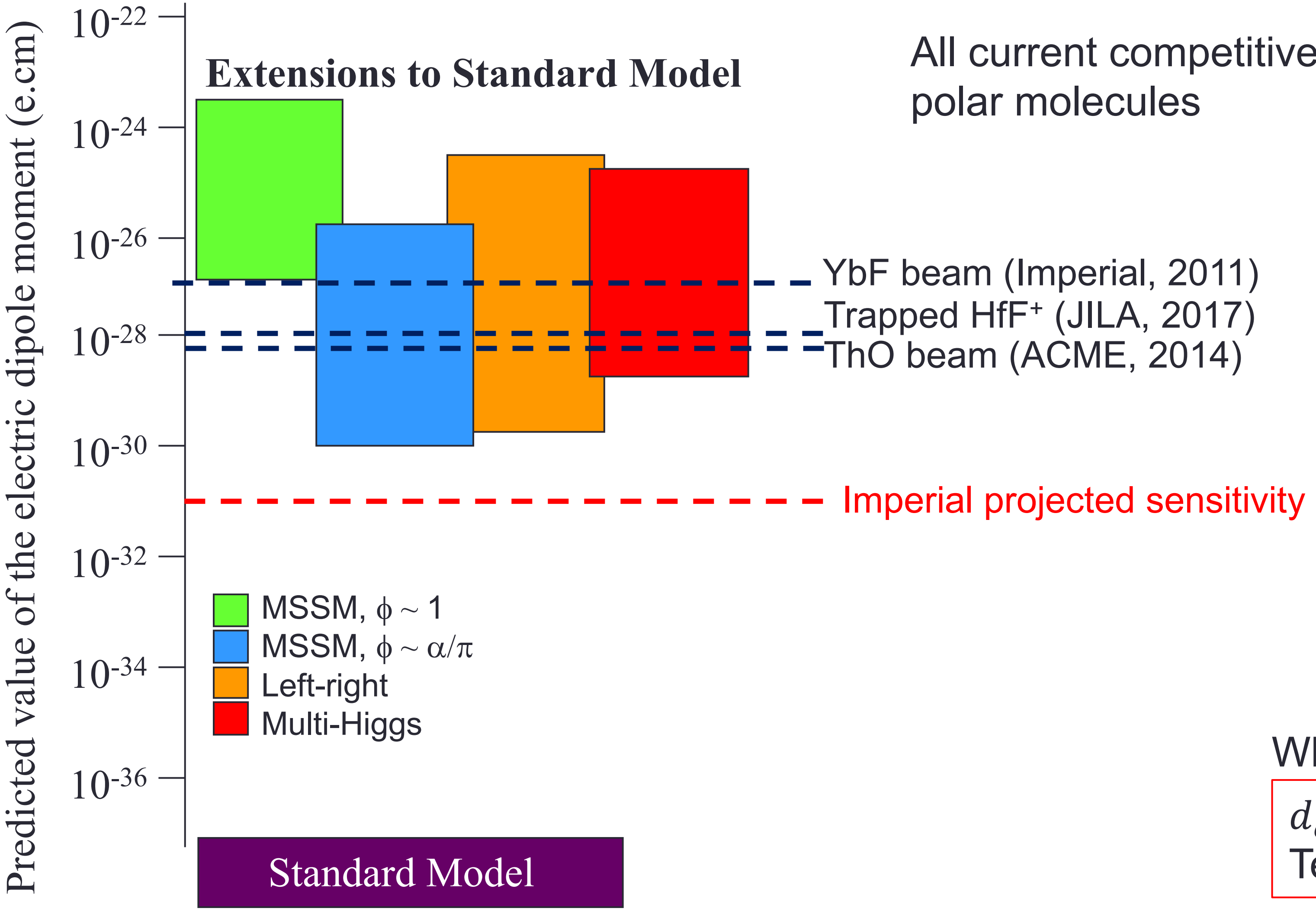
- Higher neutron densities
- Higher electric field

PanEDM

- Dedicated beamline at ILL being installed
- UCN source Cryostats being finalised
- EDM components (Ramsey chamber, magnetic shielding, …) being installed at ILL
- UCN technologies being advanced at RAL – UCN guides & super-thermal UCN source components
- RT stage aims to reach ~10^{-27} e·cm, cryogenic experiment ~10^{-28} e·cm

Magnetic shielding chamber being installed at ILL: 5 fT/100 sec stability, 10^{-10} T/m gradient over 1 m^3.

Electron EDM – current status



All current competitive experiments are done using polar molecules

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

n-loop diagram

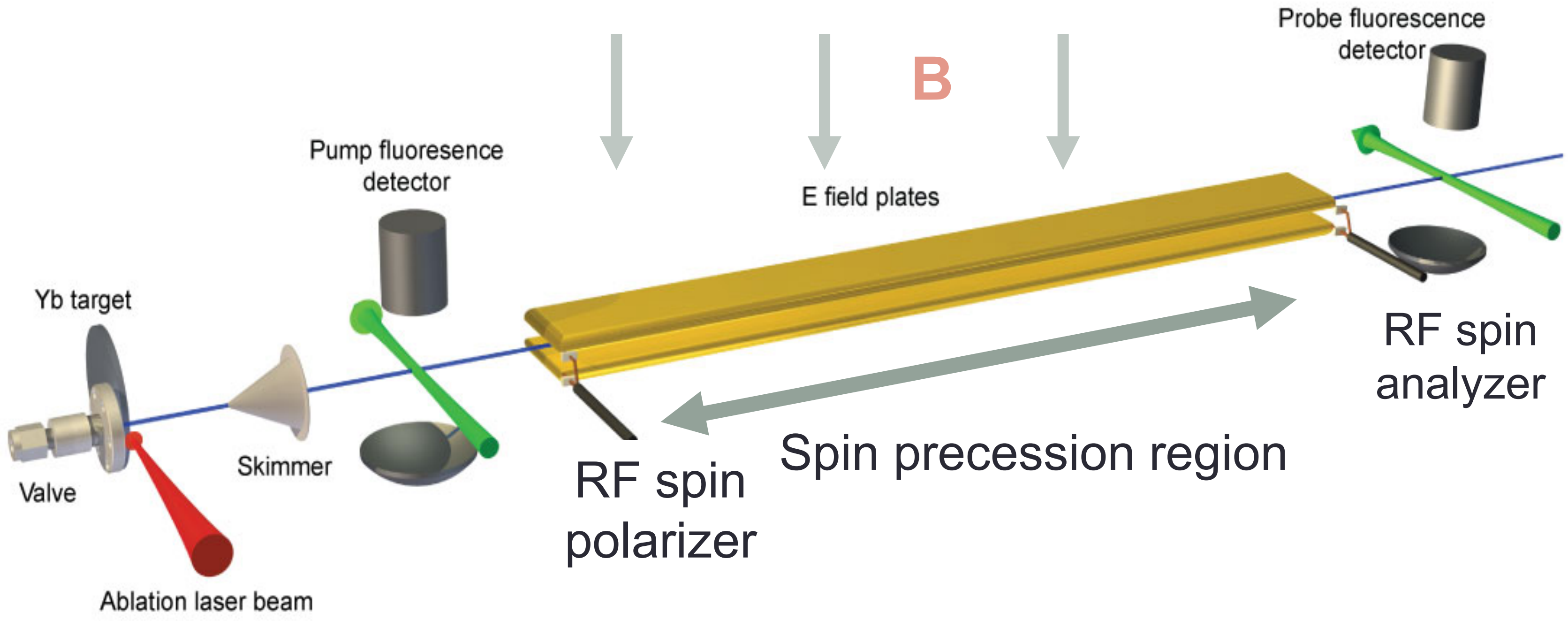
CP-violating phases

Energy scale for new particles

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

$d_e = 10^{-30}$ e.cm corresponds to $\Lambda \approx 100$ TeV

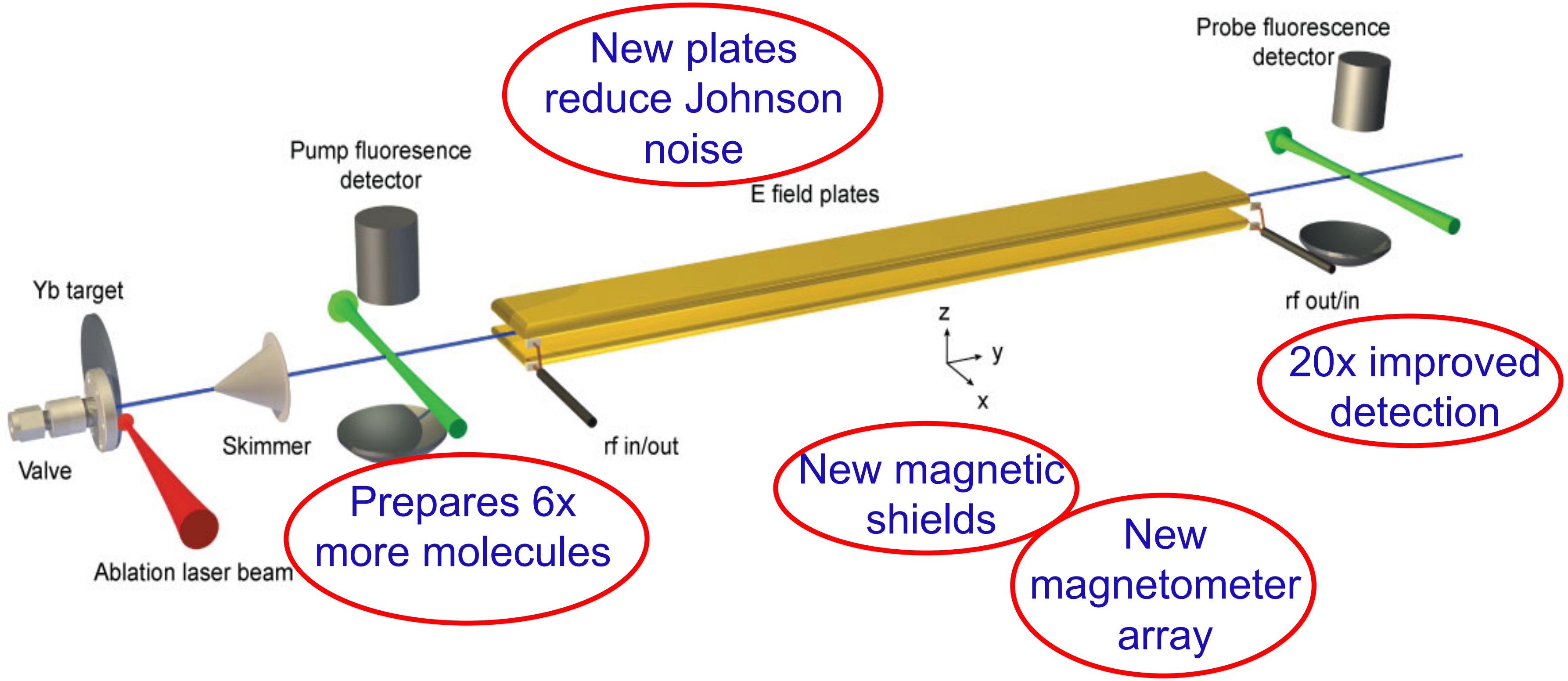
Current eEDM experiment at Imperial



Supersonic YbF beam
Temperature: 4 K
Speed: 590 m/s

To increase precision:
(1) Increase number of detected molecules
(2) Reduce magnetic noise
(3) Increase spin-precession time

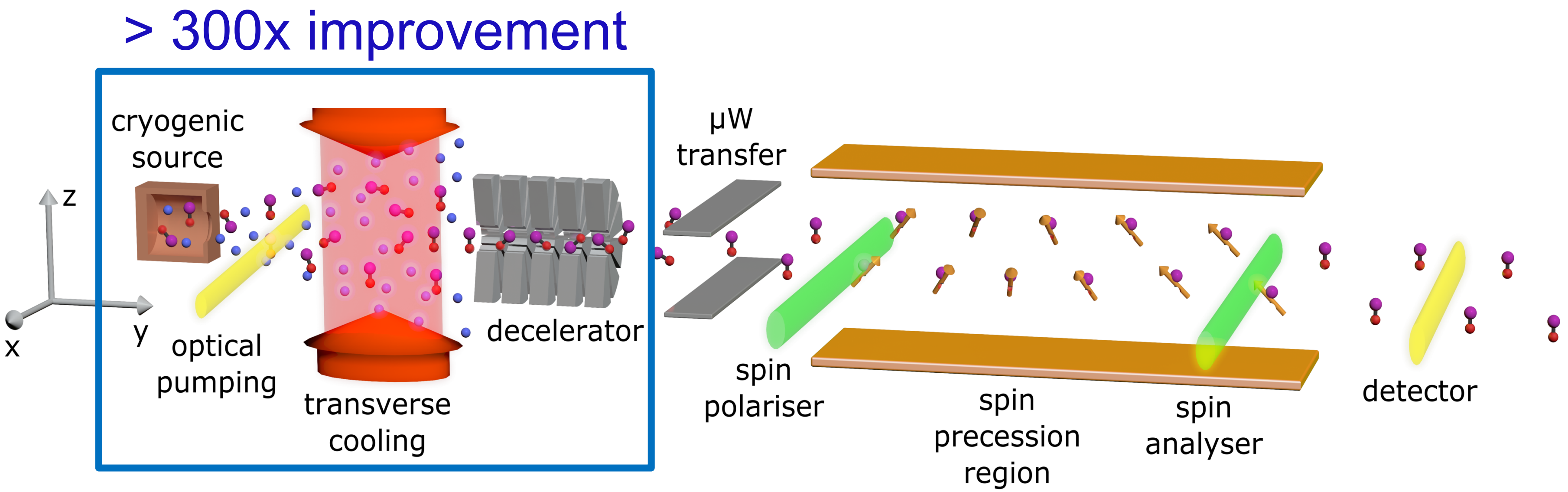
More molecules and reduced magnetic noise



- x20 improved eEDM sensitivity relative to 2011 result
- 2019: aim for new measurement with uncertainty of 5 x 10^{-29} e.cm
- 2020: improve limit to 2 x 10^{-29} e.cm
- This is limit of current method - to go further, must increase spin precession time

Proposed new experiment

- Spin precession time limited by thermal expansion of beam – need ultracold molecules
- Have recently demonstrated laser cooling of YbF molecules to 100 μK



- 2019-2022: build this apparatus and demonstrate eEDM sensitivity at 10^{-30} e.cm level
- Longer term: use the apparatus to measure eEDM with uncertainty below 10^{-31} e.cm
- PPRP funding decision pending; additional funding from Templeton Foundation secured

EDMs and European strategy

- EDMs will continue to be an extremely important background free probe for new CP violating physics at $\gg$ TeV energy scales.
- Critical to keep pushing sensitivity in multiple systems
  - **neutron**, **electron**, *proton*, *muon*, nuclear (^{199}Hg, ^{225}Ra, ^{129}Xe, *deuteron*) *storage rings*
  - allows deciphering of underlying CP violation in case a signal is found
    - e.g. QCD θ or SUSY
  - requires support of university based (atoms/molecules) and at larger facilities:
    - n,p,μ,D $\rightarrow$ ILL, PSI, CERN, ESS...
- **neutron**
  - room temperature stored UCN experiments *(n2EDM)* will continue to dominate well into next decade, but will then likely reach their limit
  - next generation will require a change in approach: cryogenic, pulsed beam
- **electron**
  - polar molecules will continue to be most sensitive – key for advances is ultracold molecules *(Imperial has pioneered these techniques!)*

Thank You!

- Sussex nEDM collaborators: Chris Abel, Nick Ayres, Mike Hardiman, Phil Harris, Jacob Thorne, Ian Wardell.
- PSI collaboration
- PanEDM slides: Maurits van der Grinten (RAL).
- YbF slides: Michael Tarbutt (Imperial College).

  http://www.imperial.ac.uk/centre-for-cold-matter/research/edm/

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