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Neutron EDM measurement at PSI

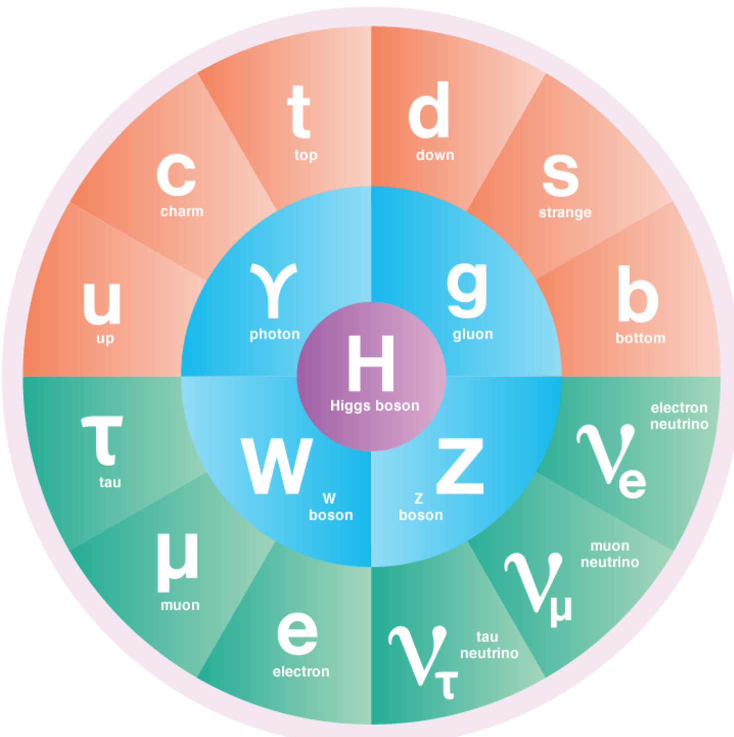
Michał Rawlik

ETH Zürich, Switzerland

on behalf of the **nEDM** collaboration

Motivation

Problems of modern particle physics



dark energy?

dark matter?

baryon asymmetry?

why is there so much more matter than antimatter?

The strong CP problem

For there to be more matter than antimatter
the **CP** symmetry needs to be violated.

(one of the three Andrei Sakharov criteria)

Electric dipole moment

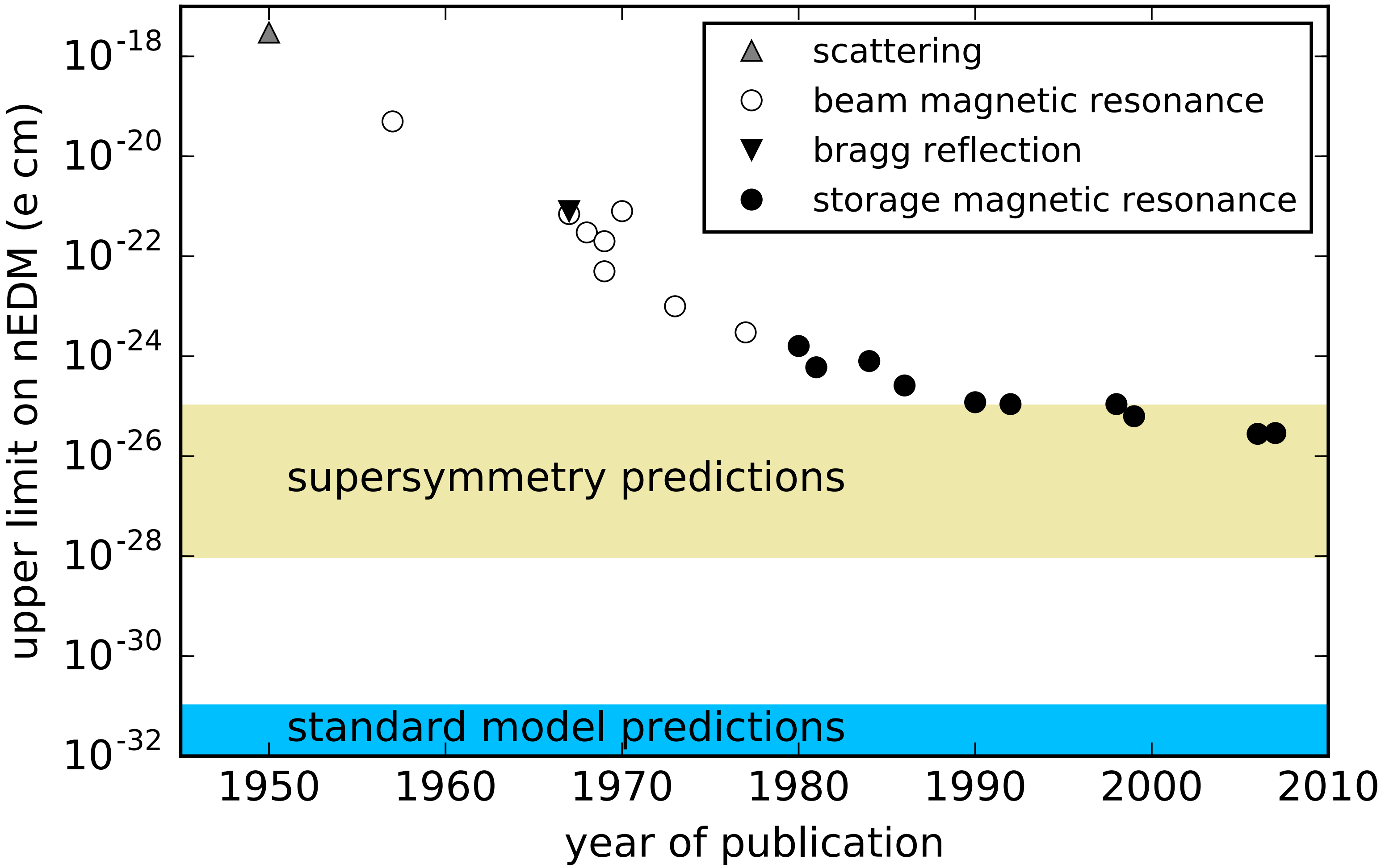
Static electric dipole moments of non-degenerate systems (atoms, elementary particles) violate the **T** symmetry.

$$\mathcal{H} = -\hat{s} \cdot \mu \vec{B}$$

$$\mathcal{H} = -\hat{s} \cdot \left(\mu \vec{B} - d_n \vec{E} \right)$$

T symmetry breaking implies **CP** breaking (given **CPT** conservation)

nEDM measurements

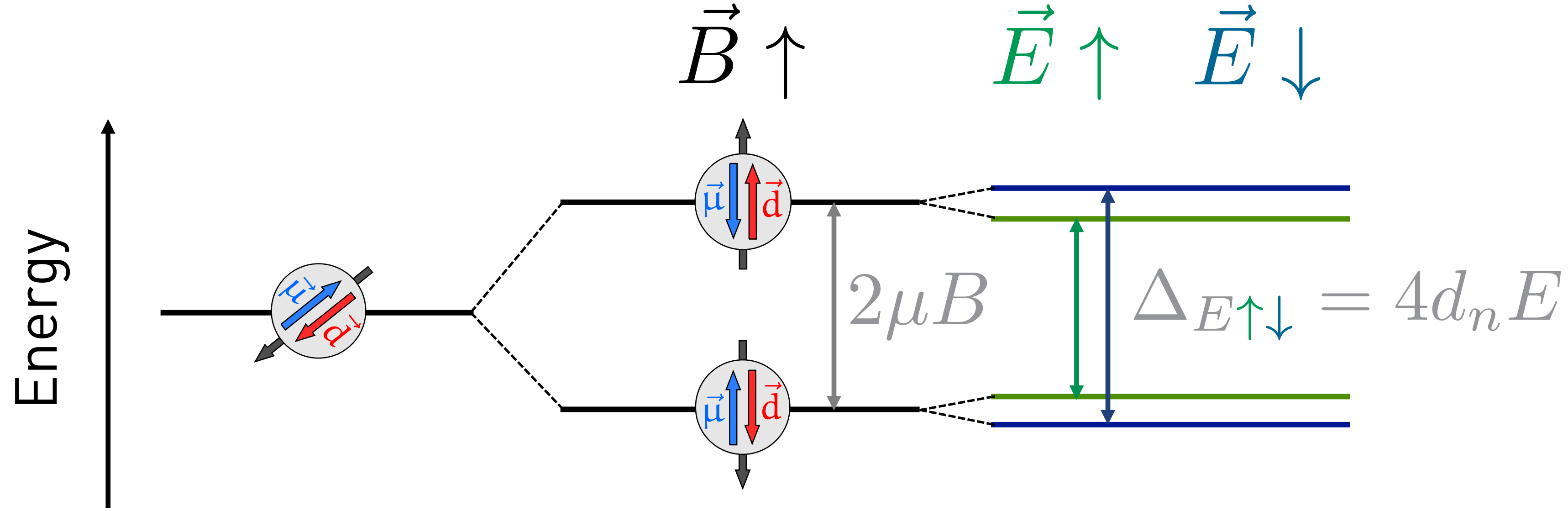


How to measure the nEDM?

Thou shall measure frequency.

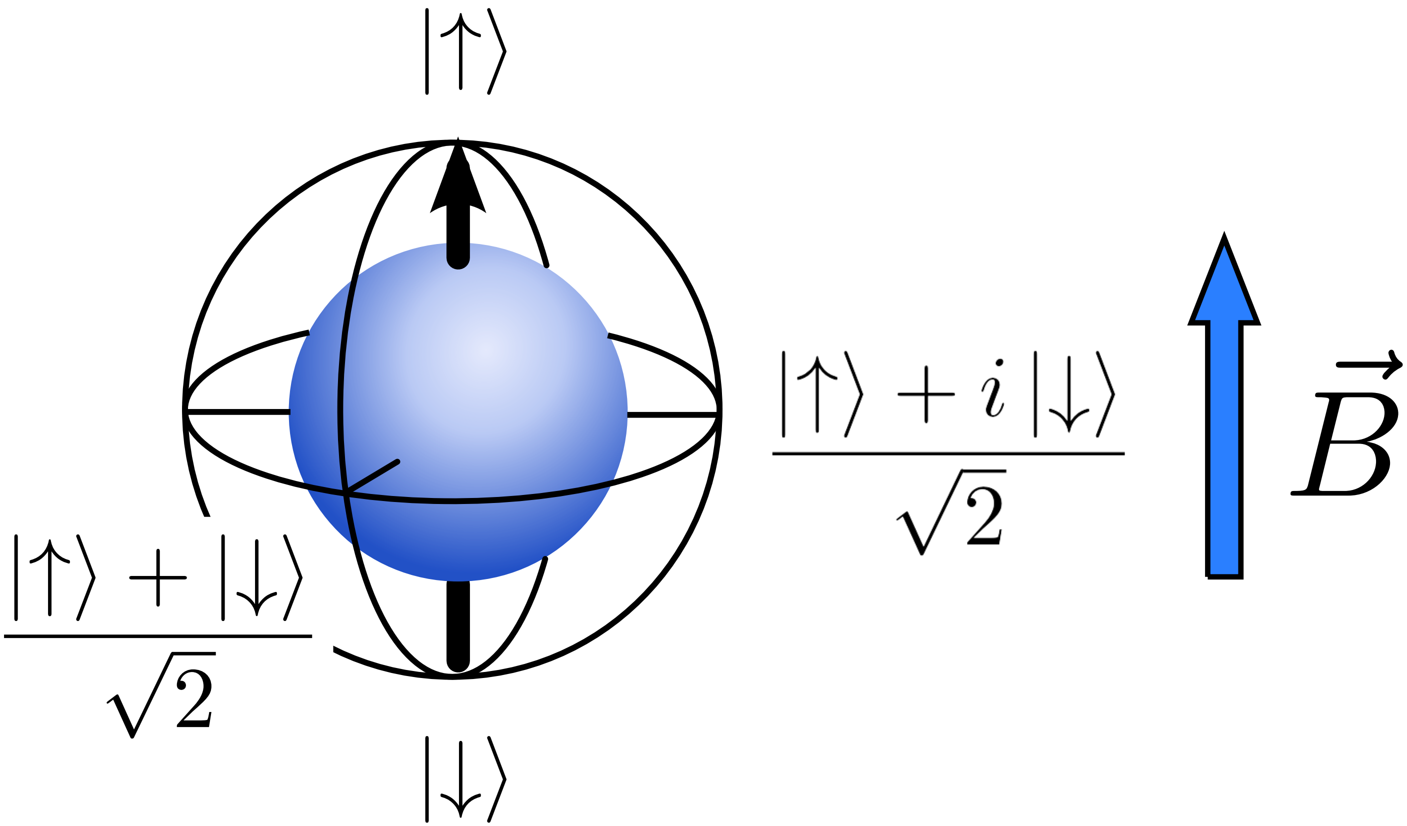
How to measure the nEDM

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d_n} \cdot \vec{E}$$

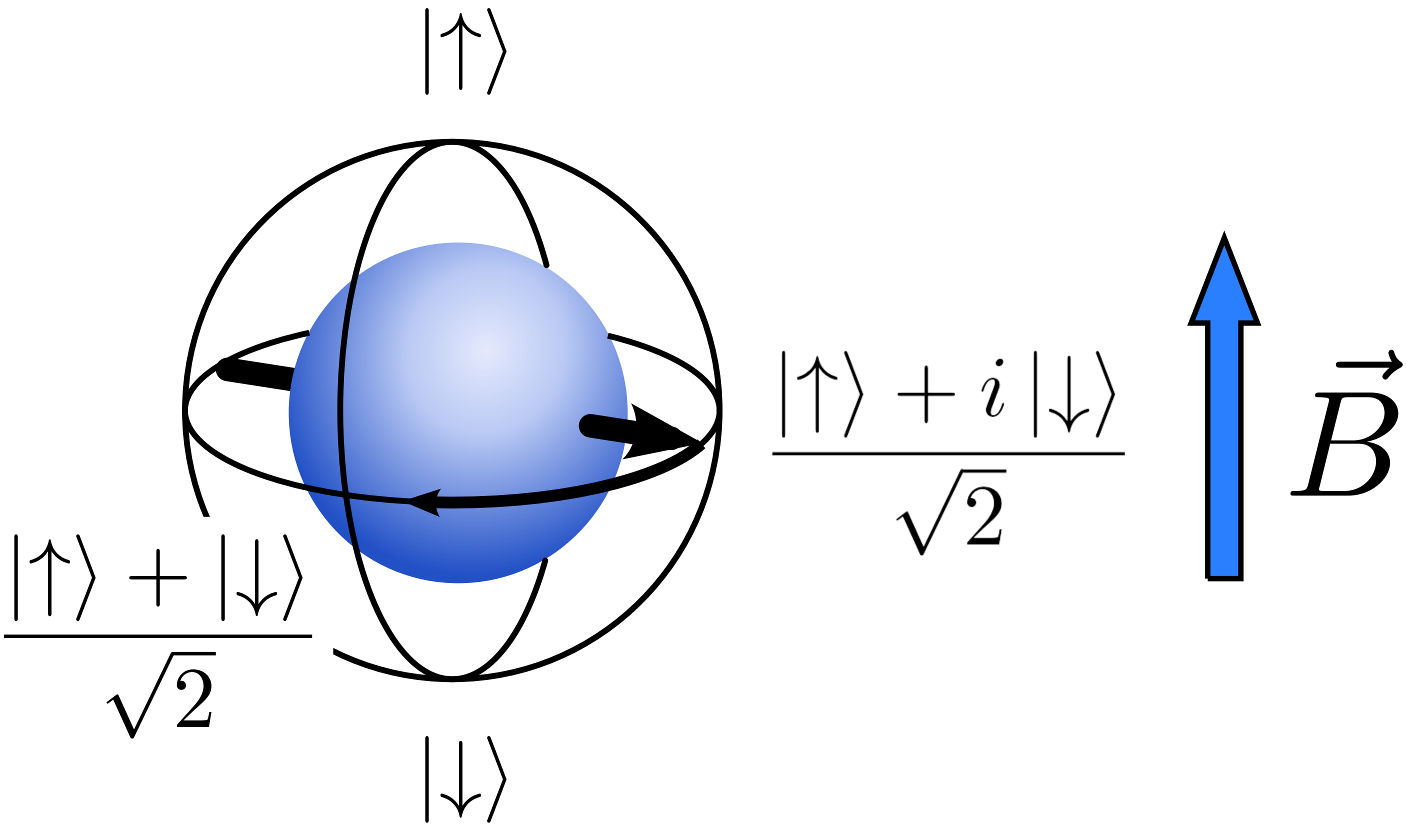


Measure a change in the transition frequency in a presence of an electric field.

Bloch sphere



Larmor precession



Gyromagnetic ratio of the neutron: $-29.1646943(69)\,\frac{\mathrm{Hz}}{\mu\mathrm{T}}$

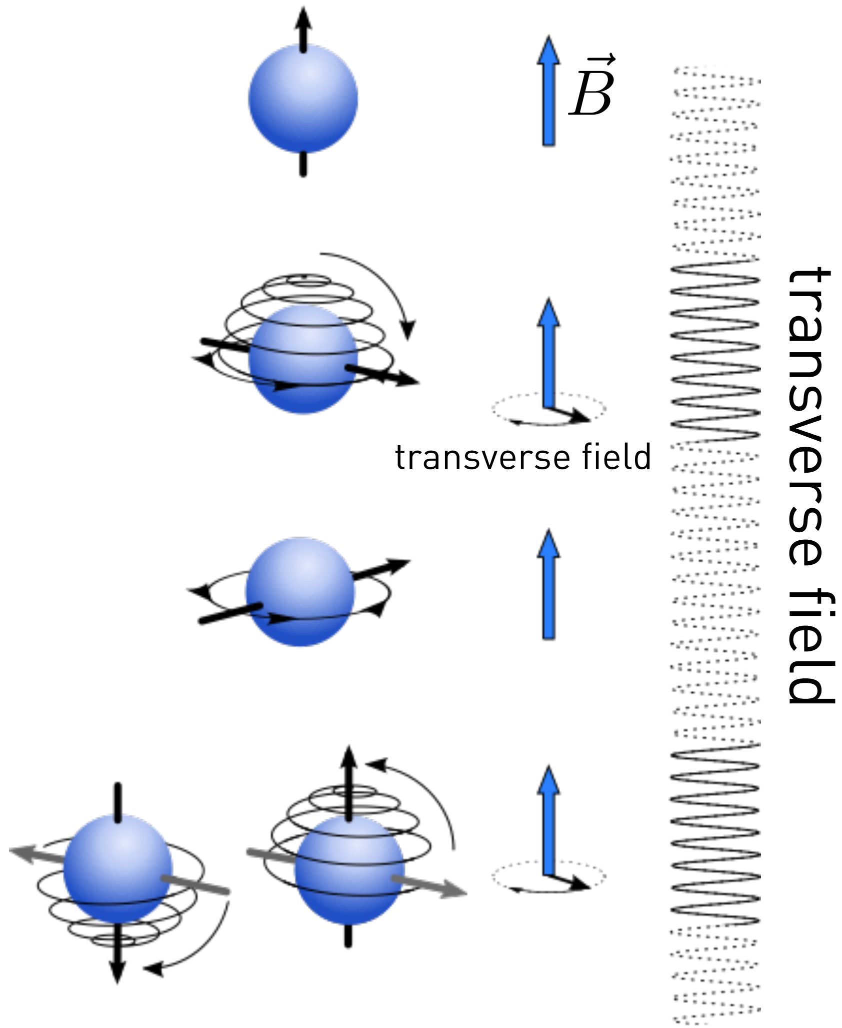
Ramsey method – frequency measurement

polarised sample

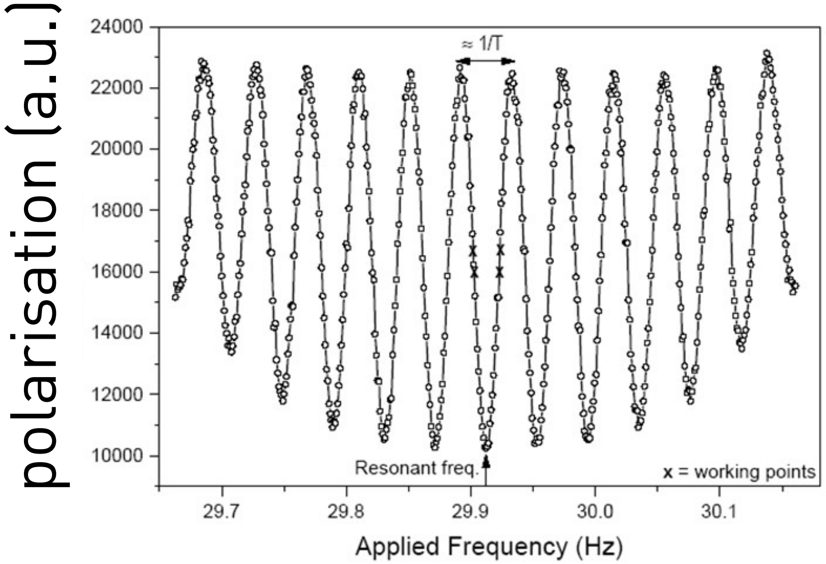
π/2 flip

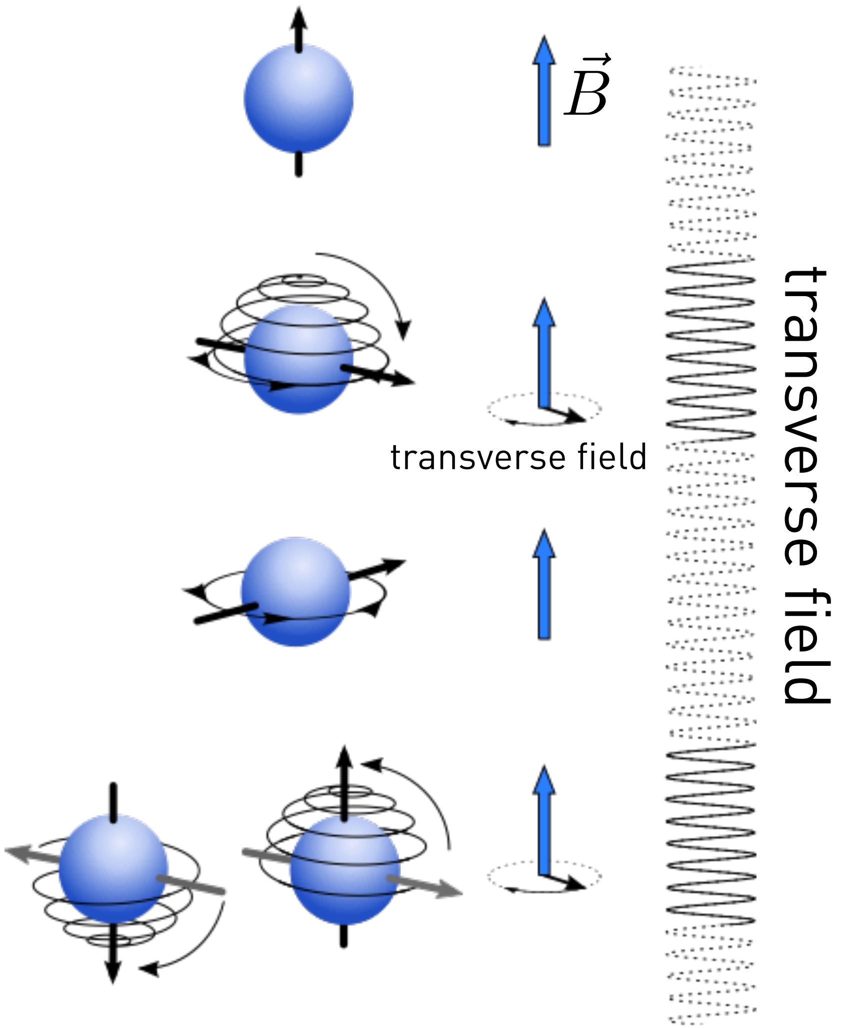
free precession

π/2 flip

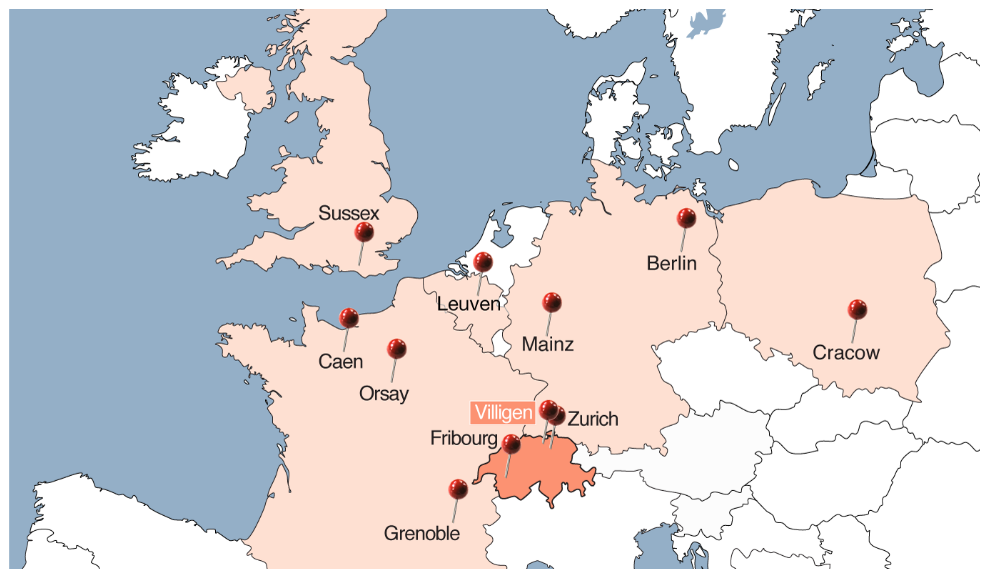


Ramsey method – frequency measurement





the nEDM at PSI collaboration



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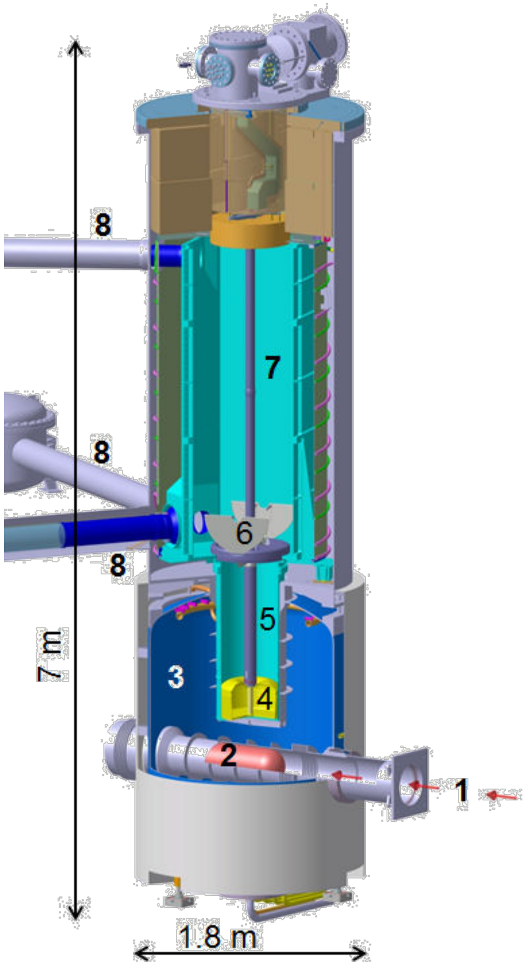
Paul Scherrer Institute, Villigen, Switzerland

Ultra-Cold Neutrons source

FROZEN DEUTERIUM

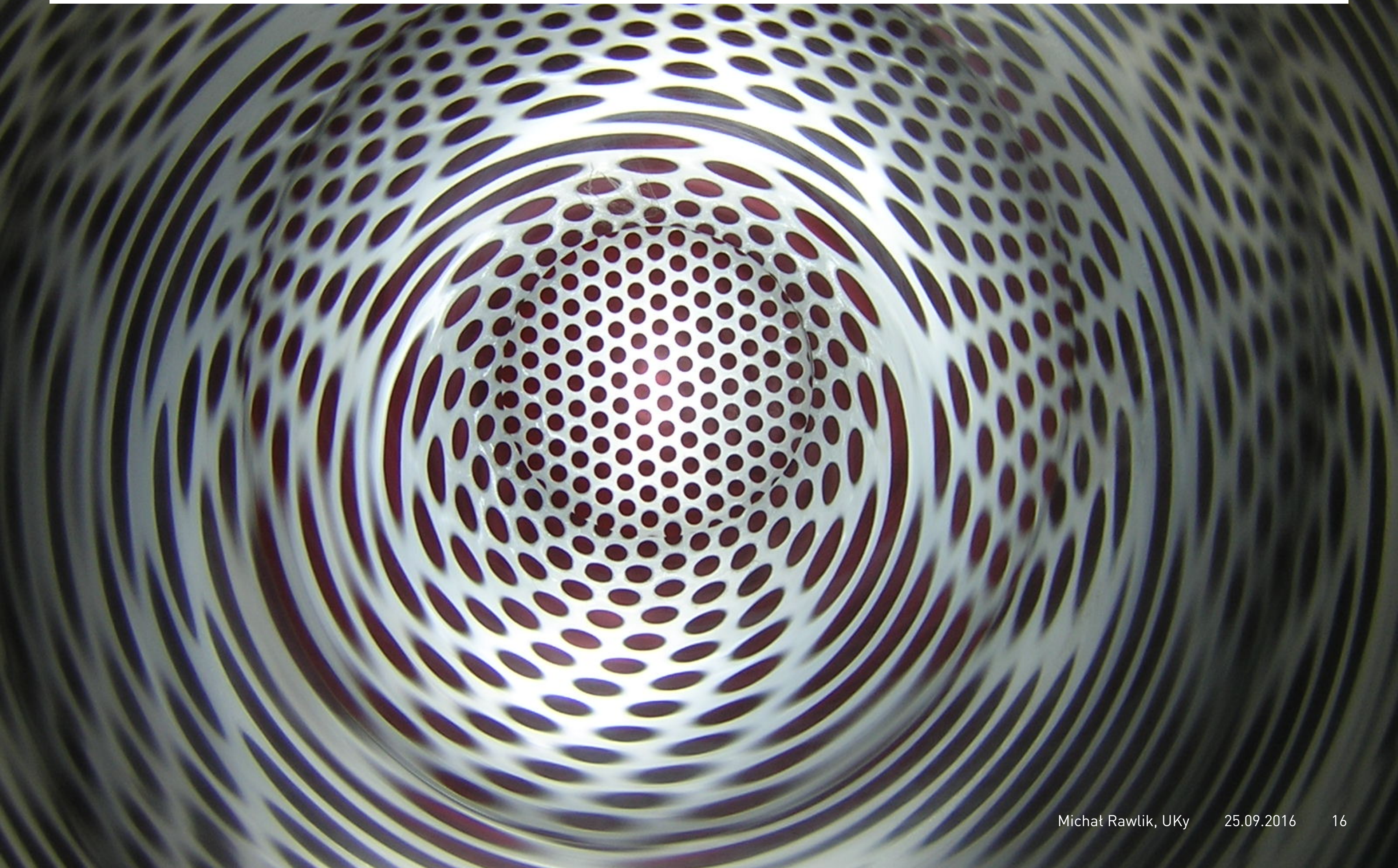
UCN storage in
high Fermi potential
bottle

moderation and cooling
down to < **300 neV**

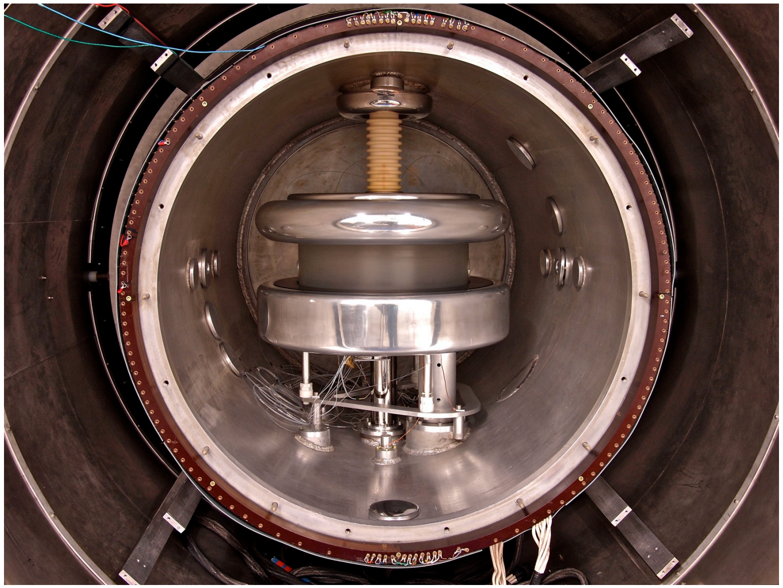


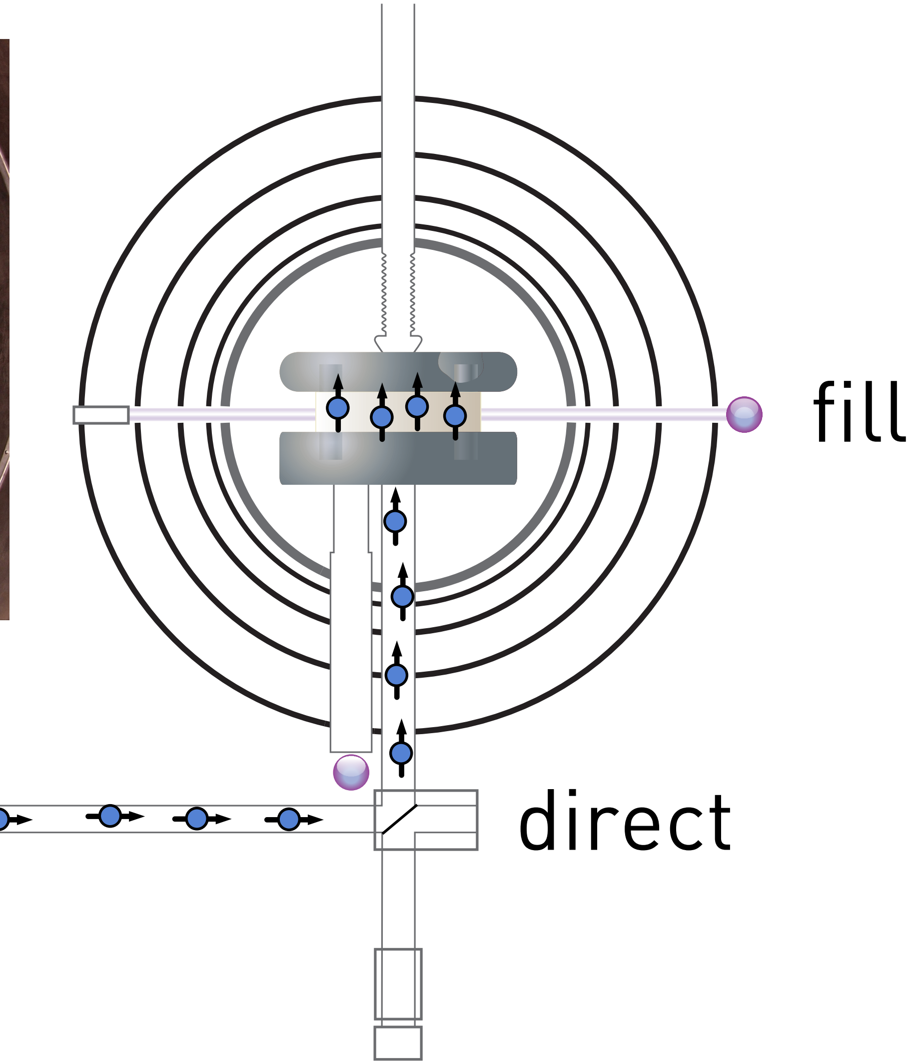
2 mA of
590 MeV
protons

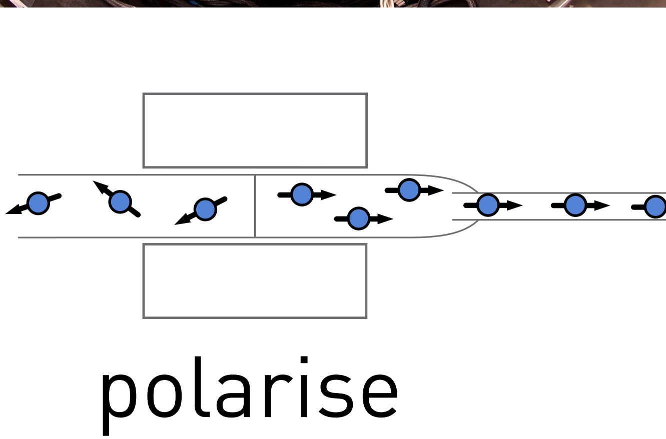
Ultra-Cold Neutrons transport



The nEDM cycle







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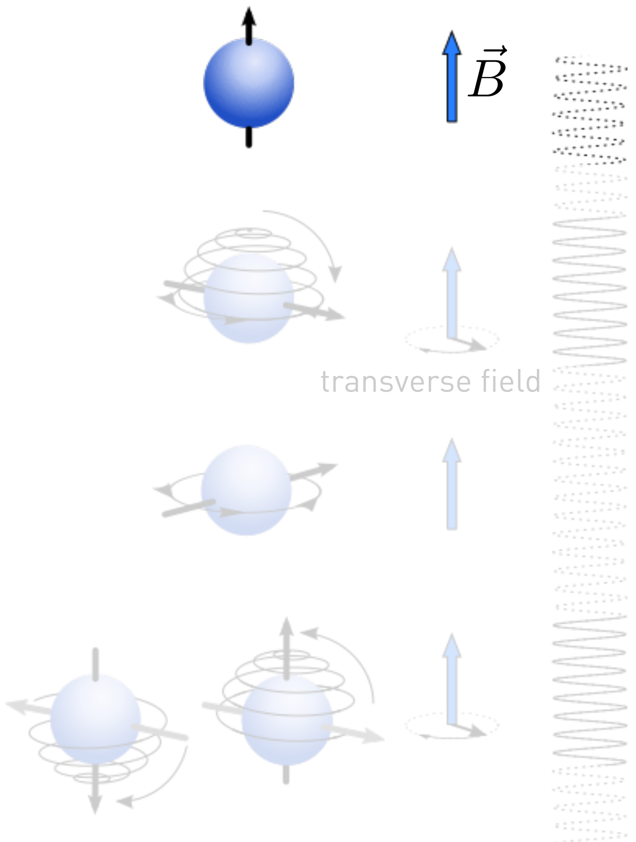

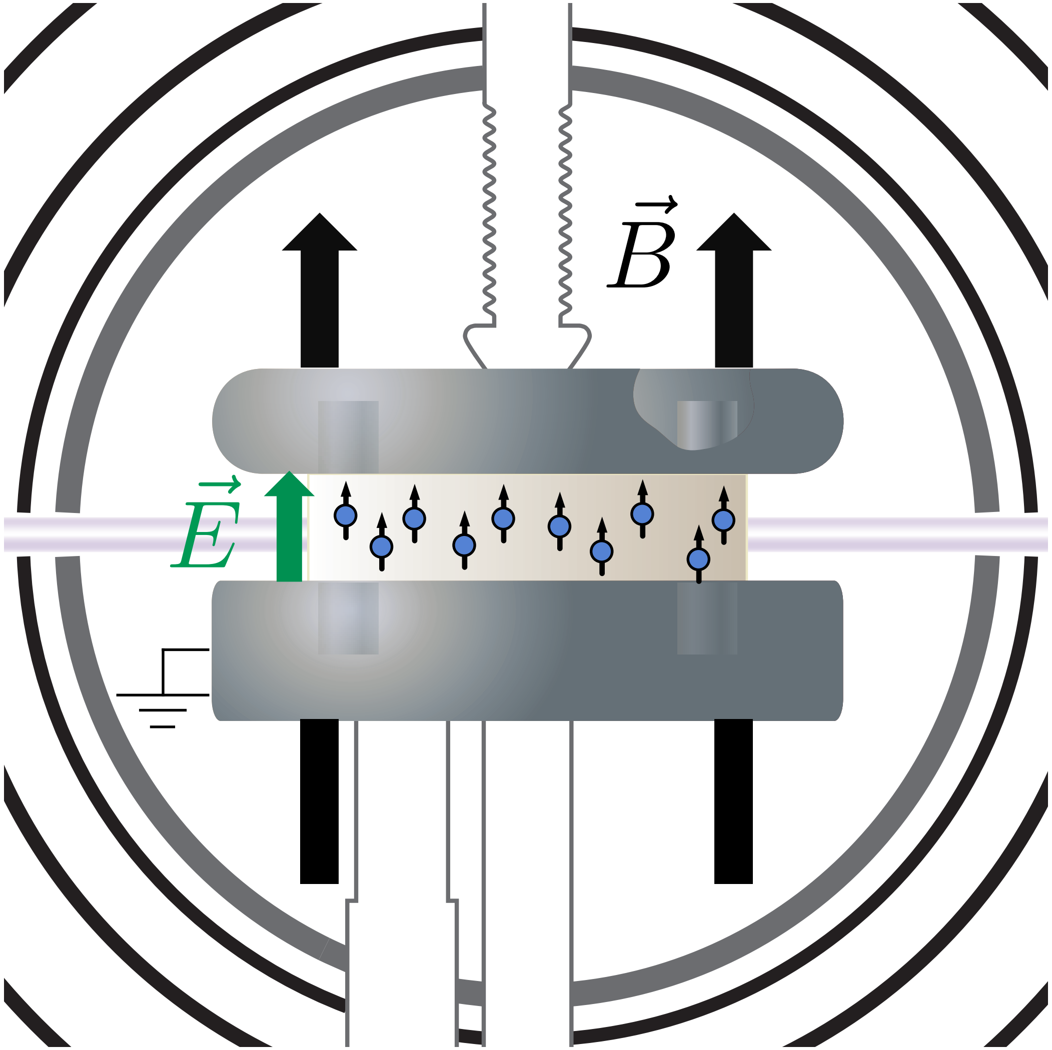

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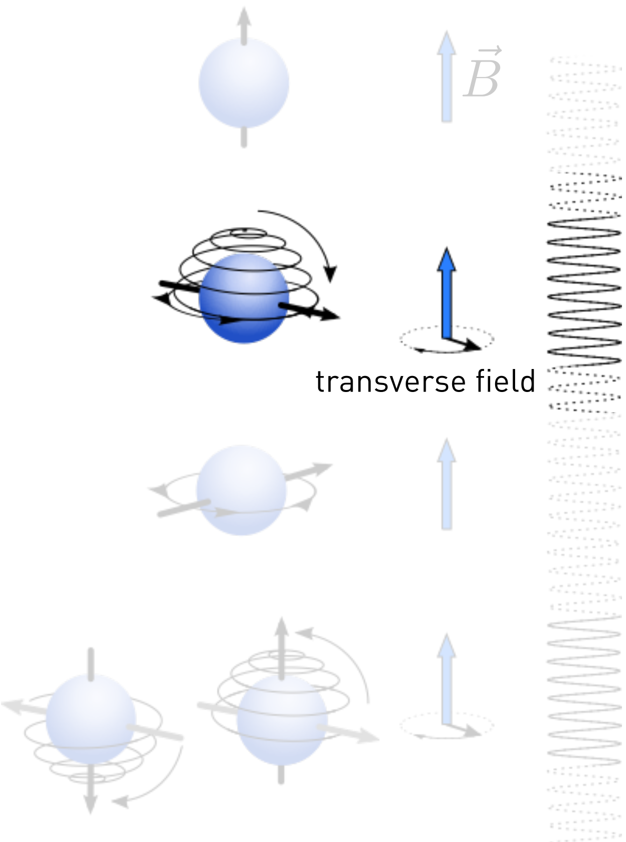
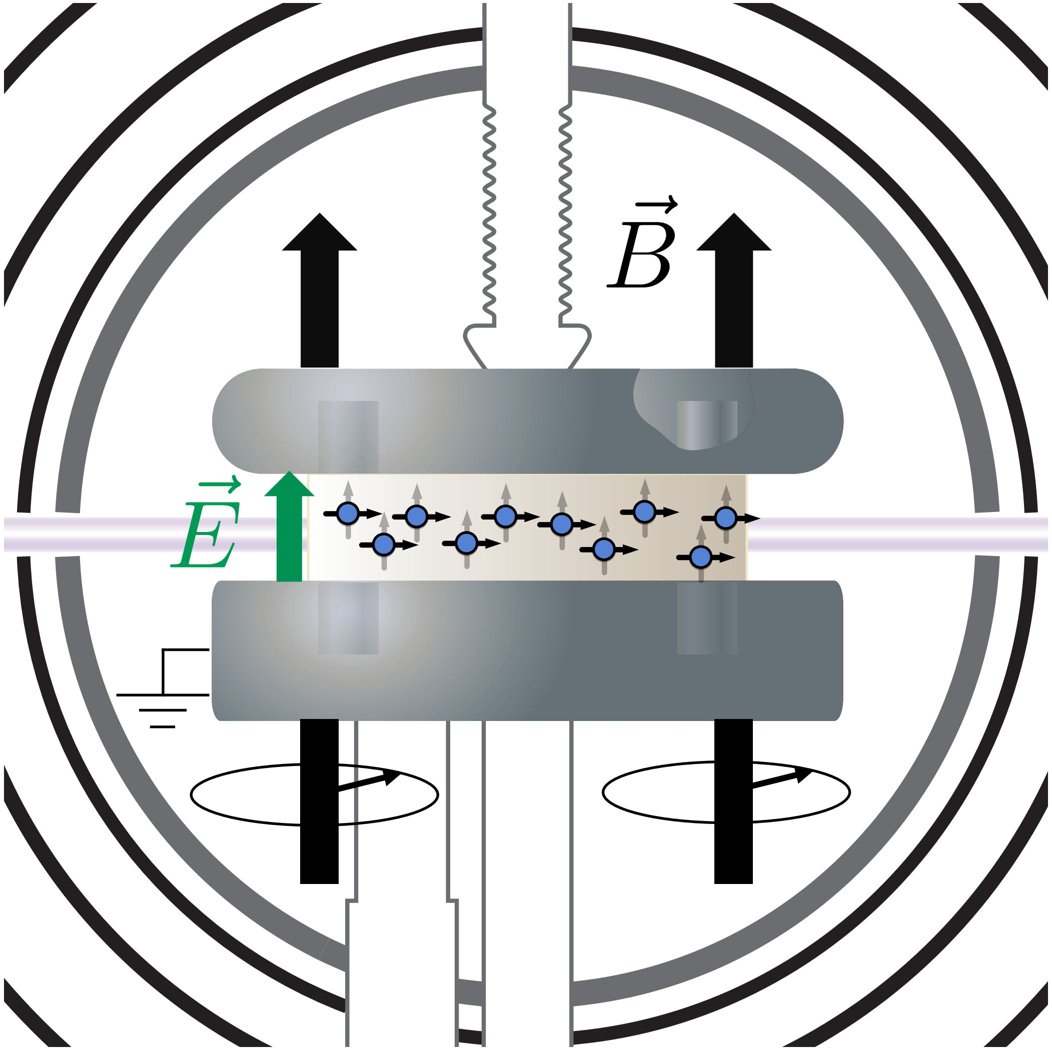
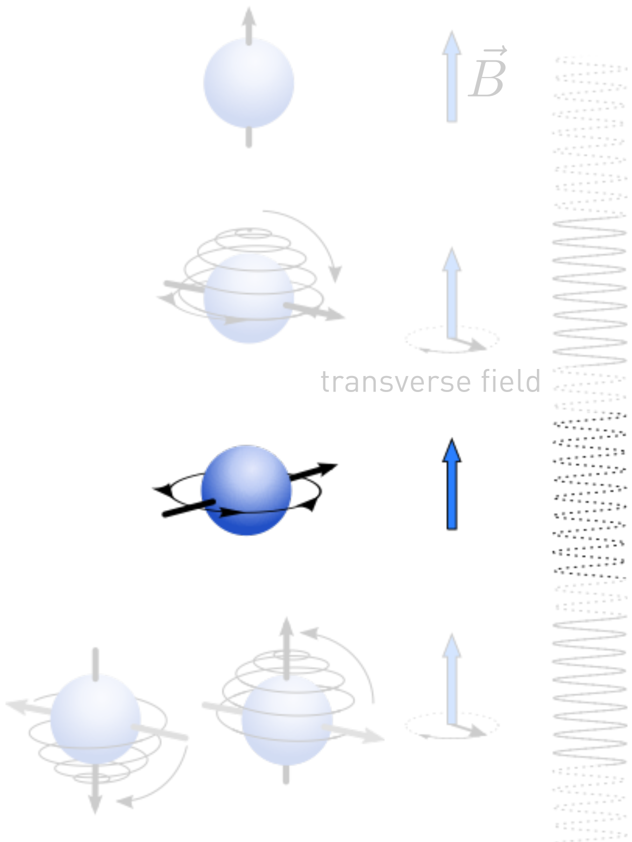
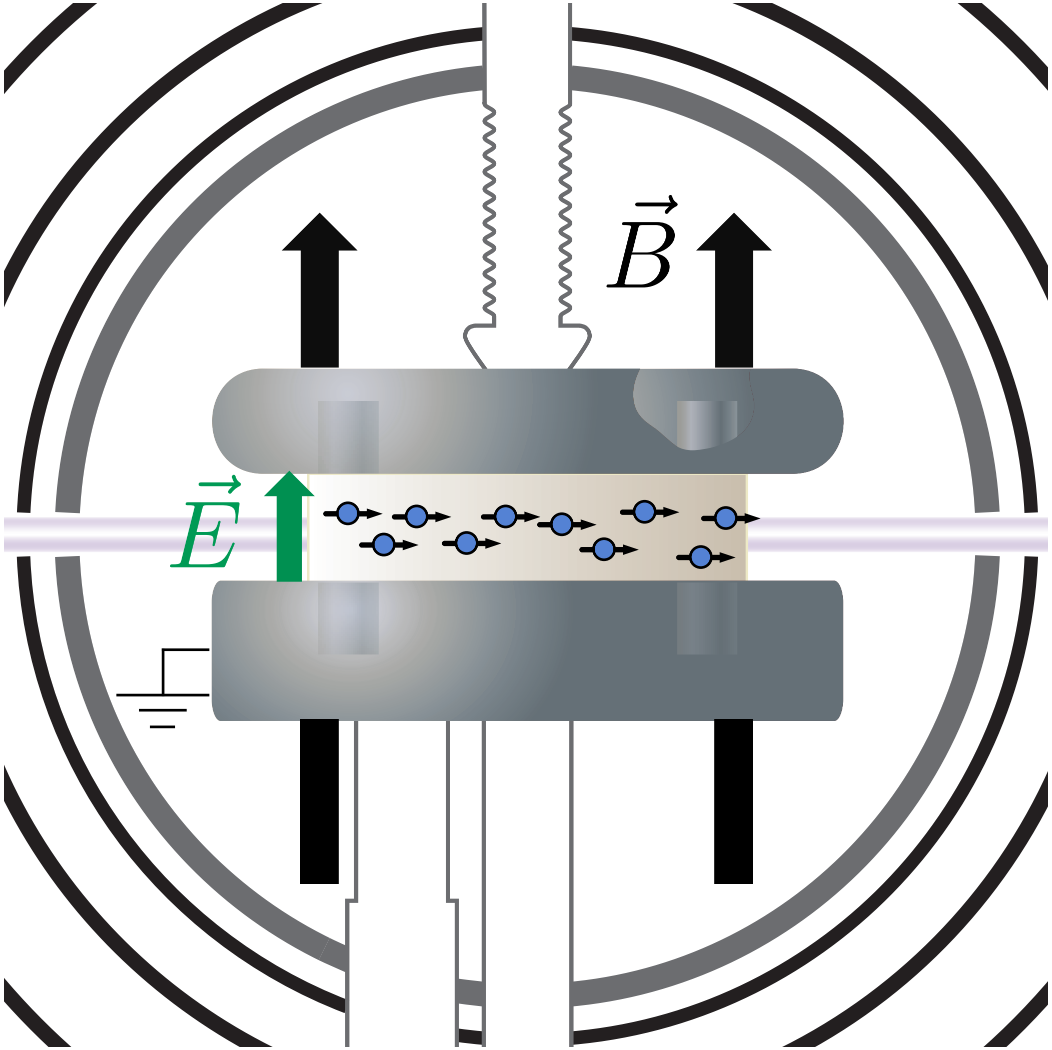


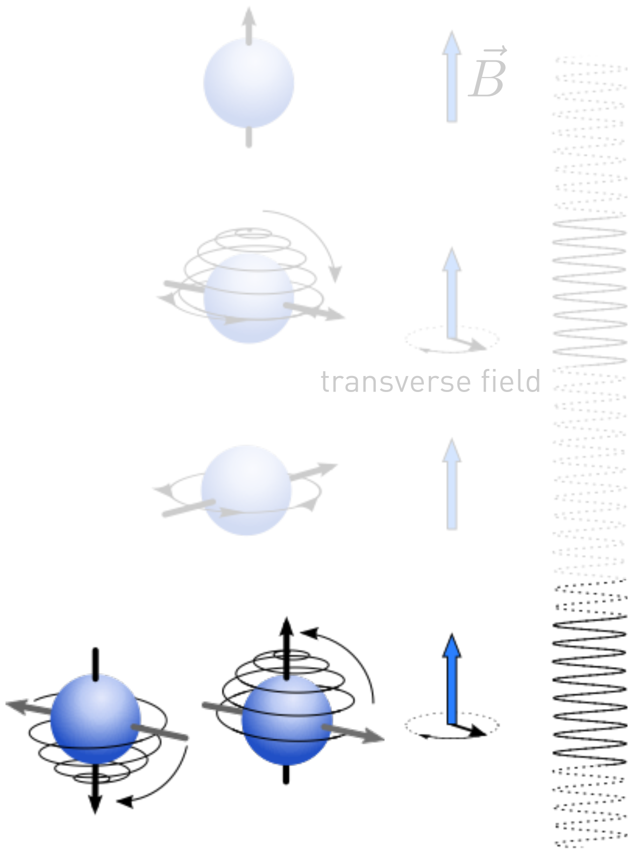


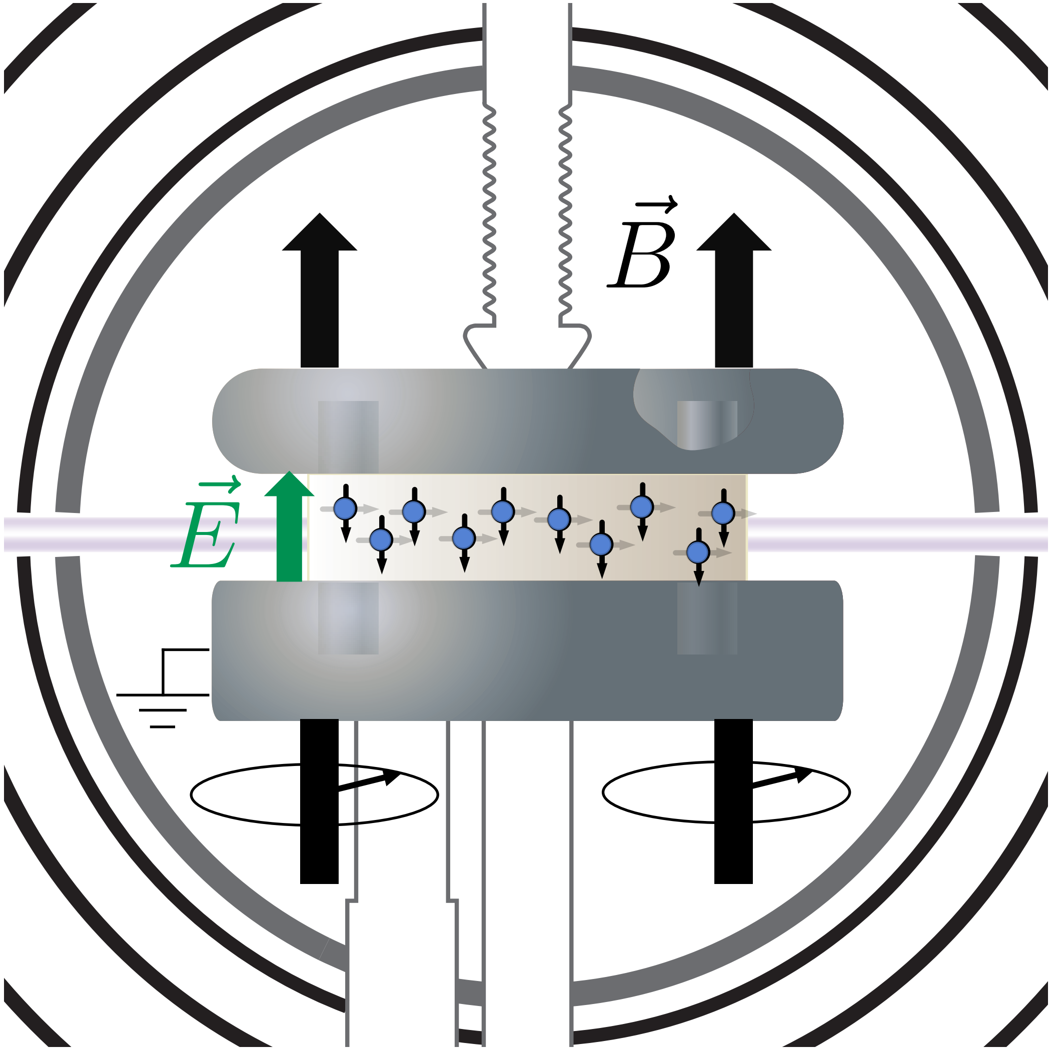
The nEDM cycle



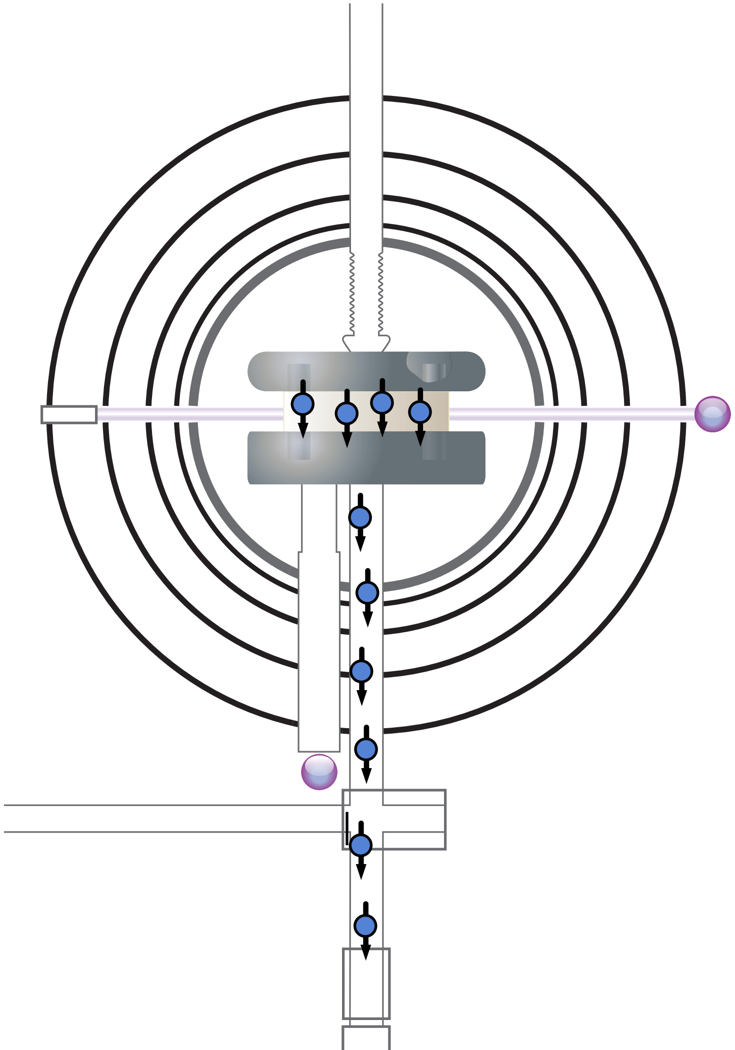


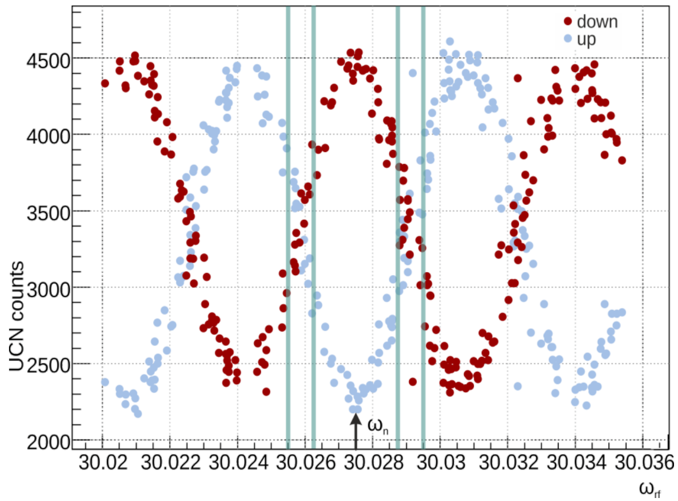
The nEDM cycle

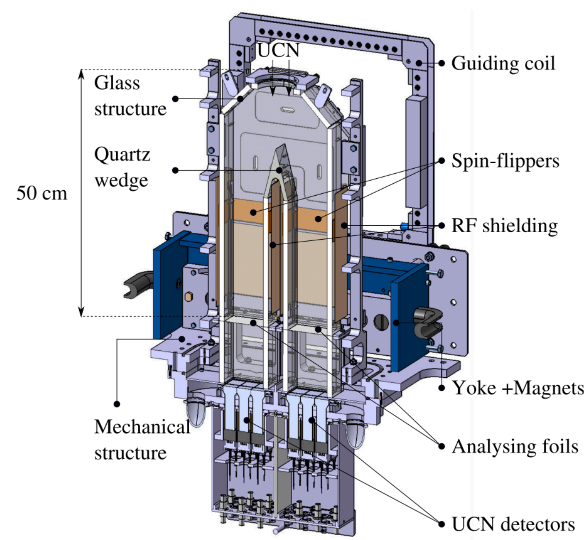




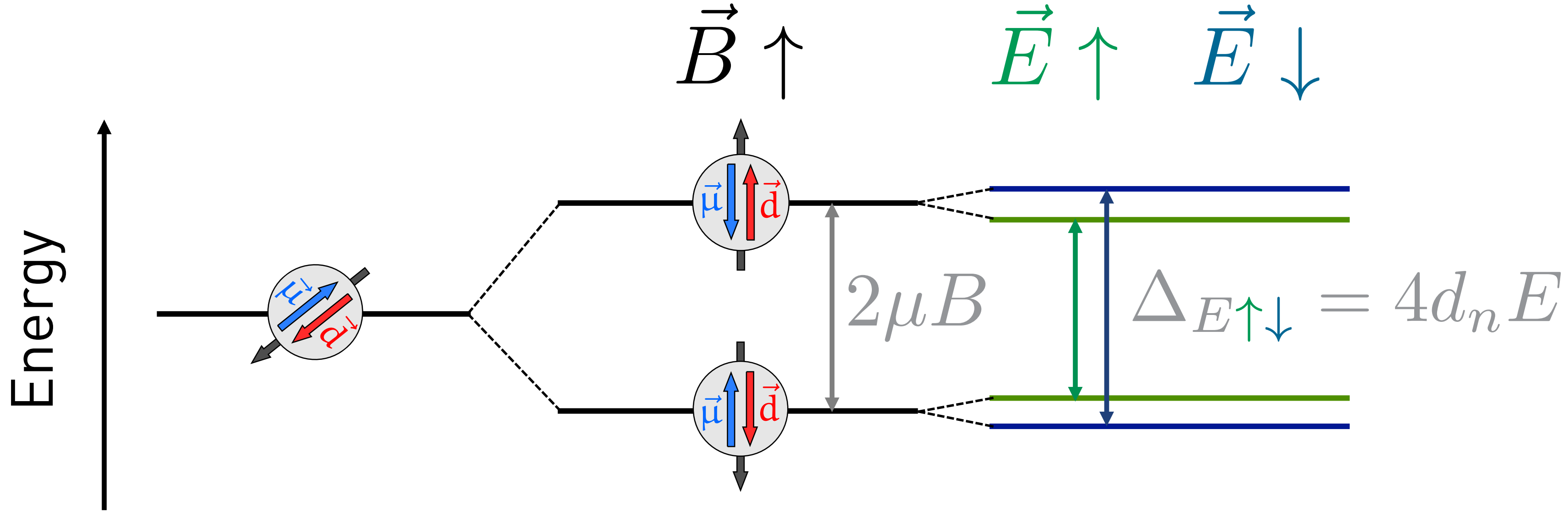
The nEDM cycle



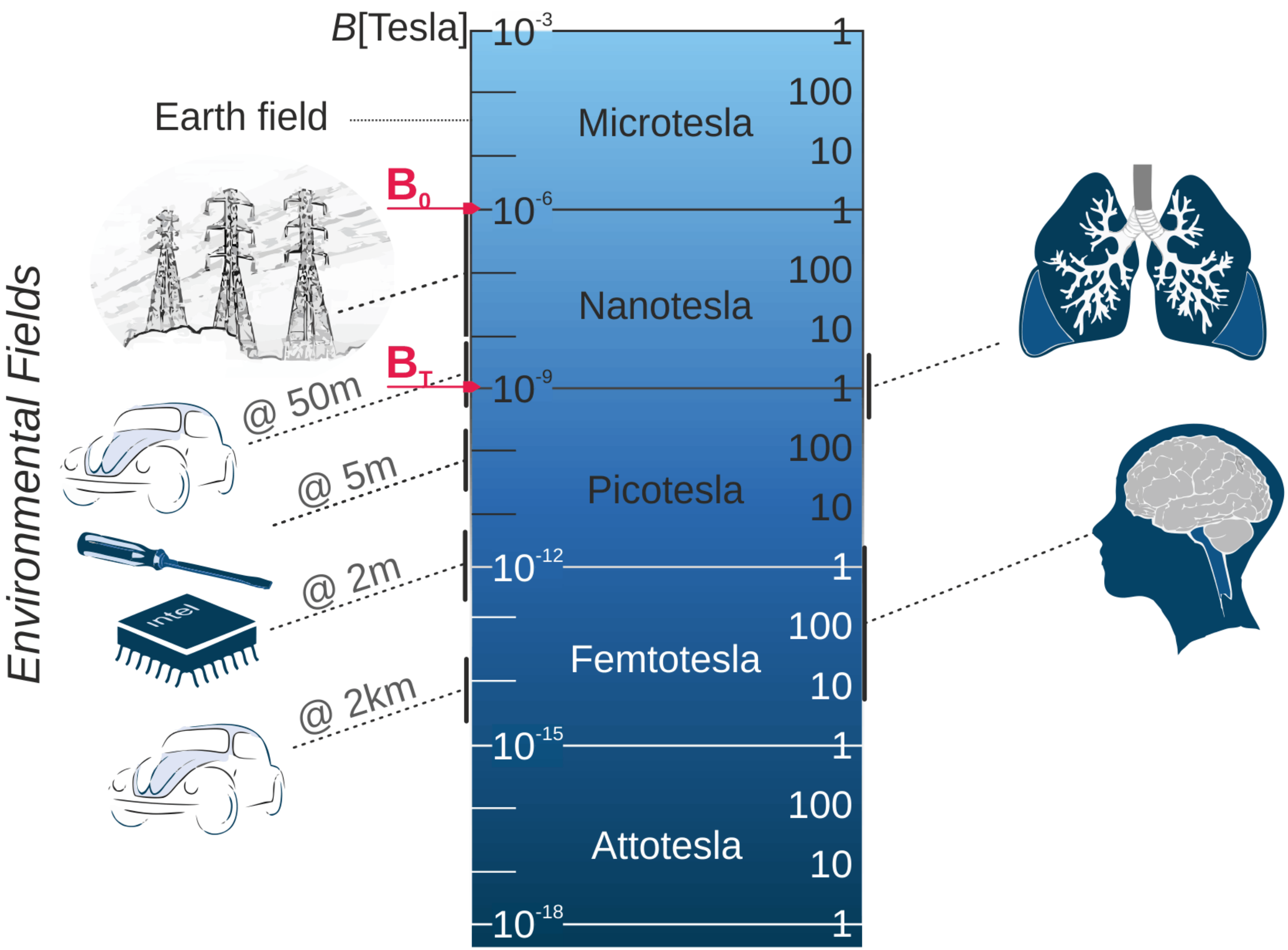




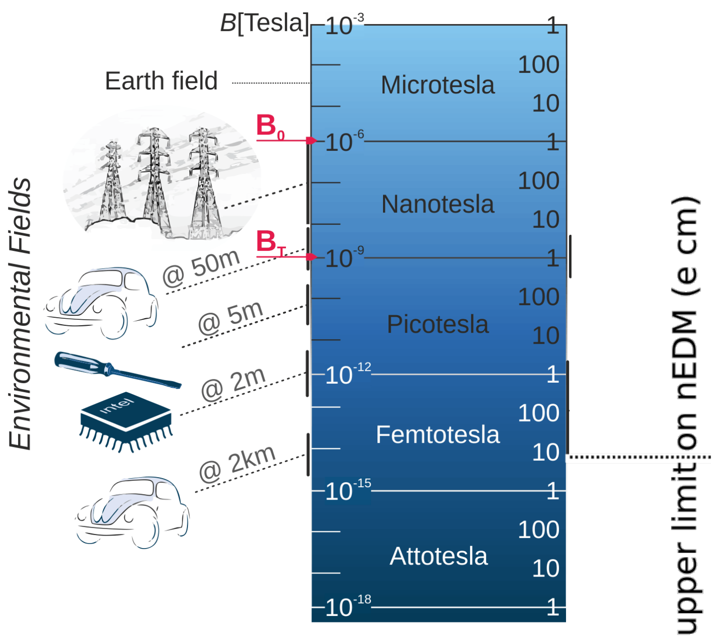
How to measure the nEDM

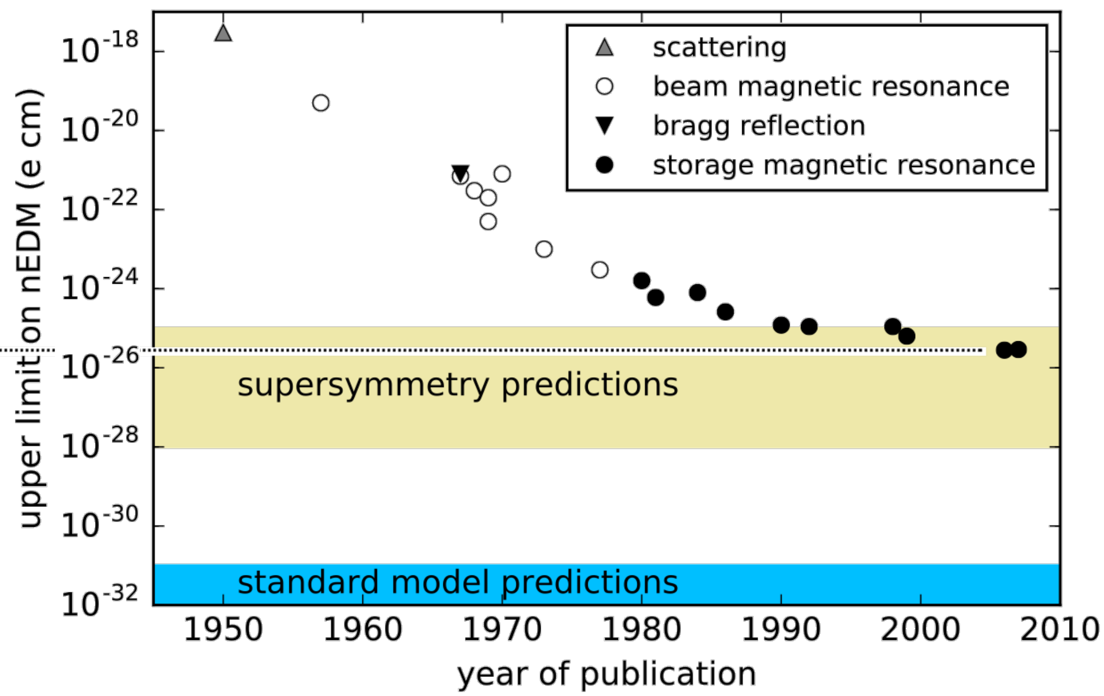


Role of magnetic fields

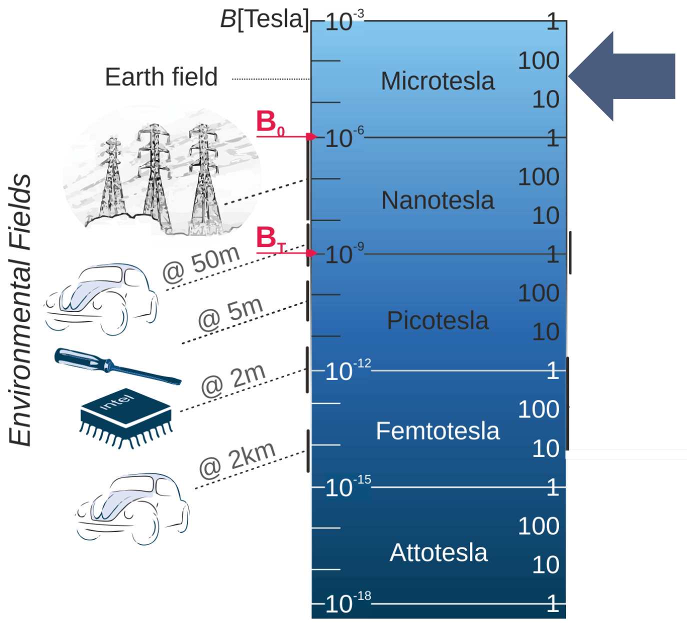


Role of magnetic fields



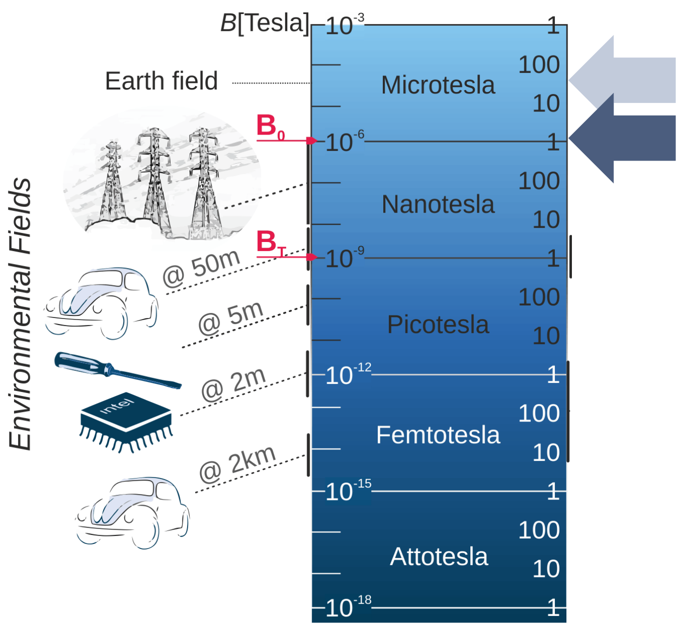


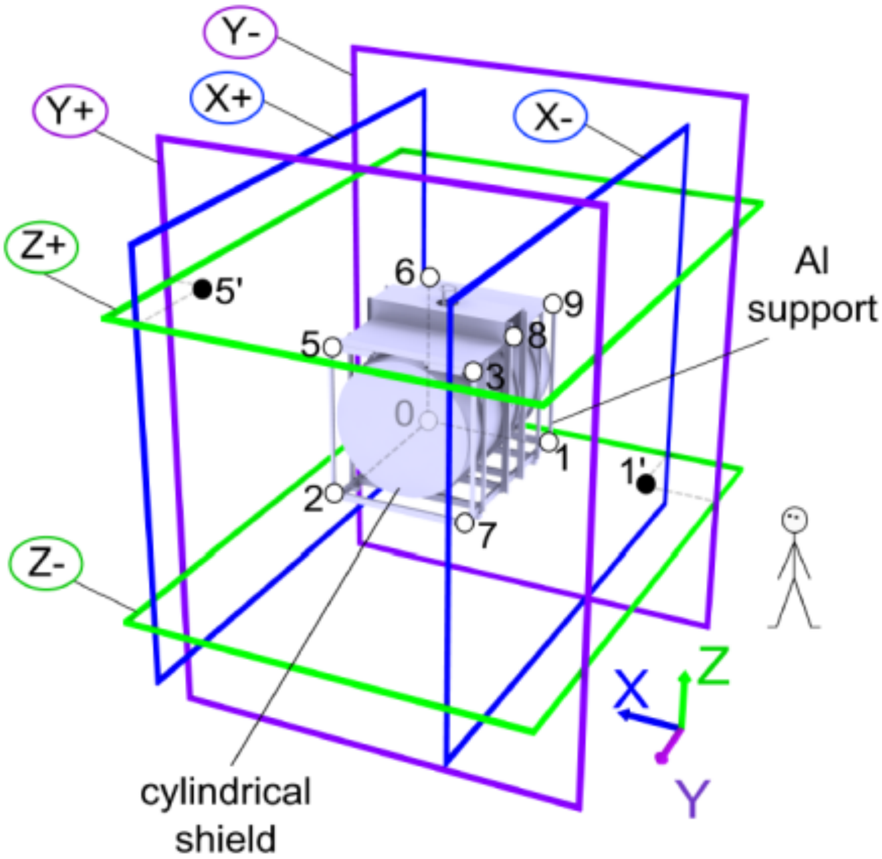
Role of magnetic fields



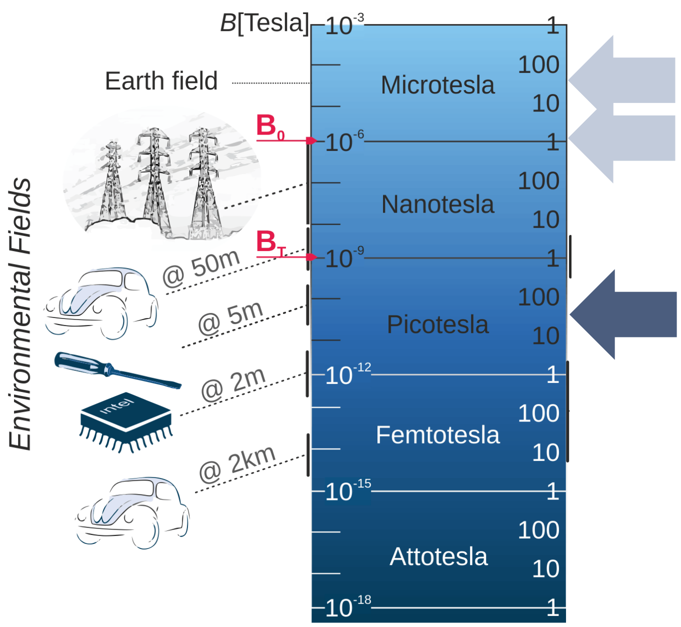
stability in an experimental hall

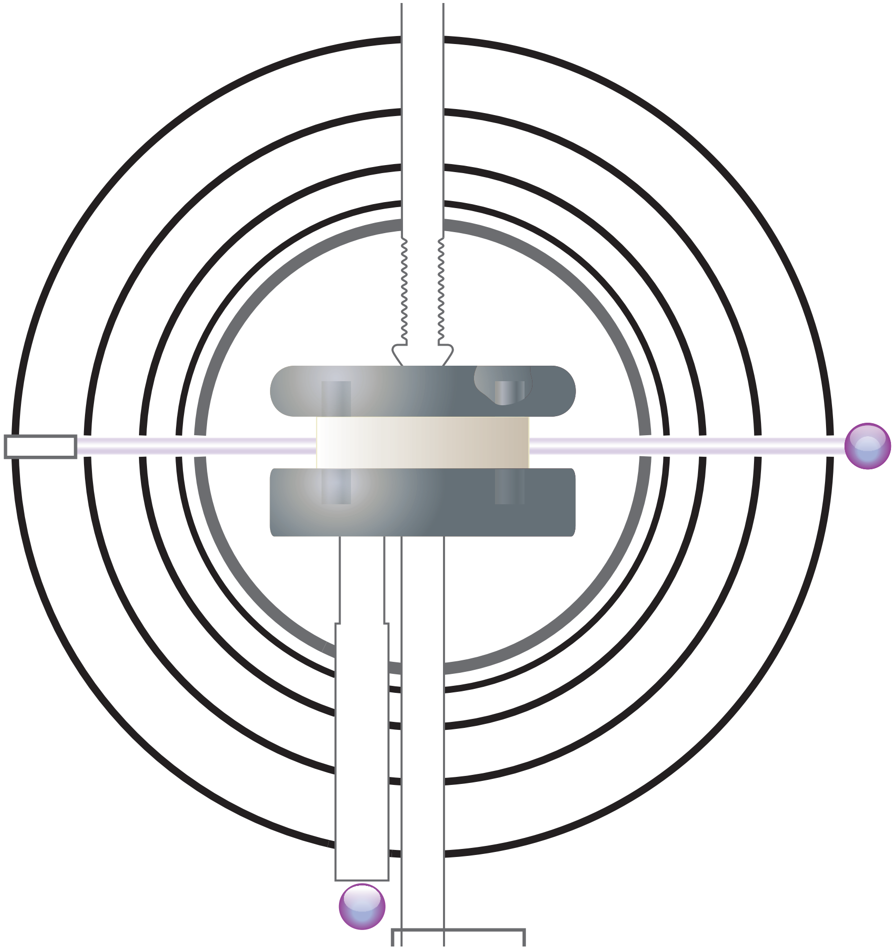
Active Magnetic Field Stabilisation



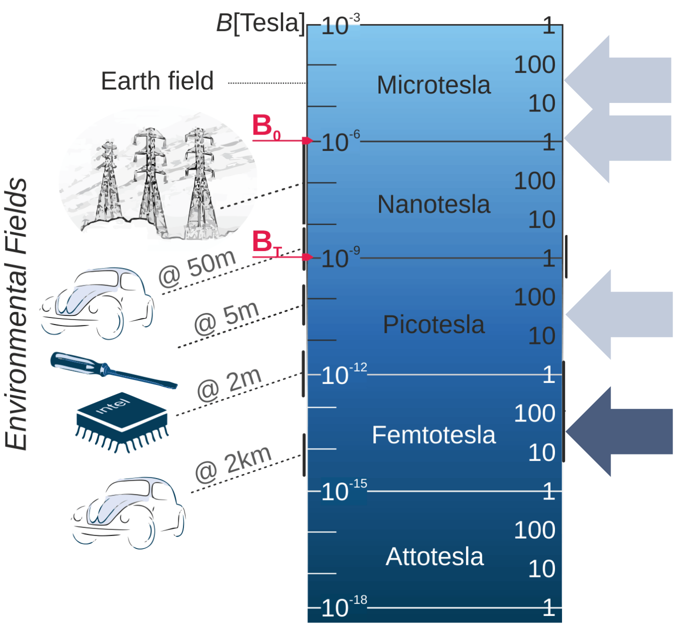


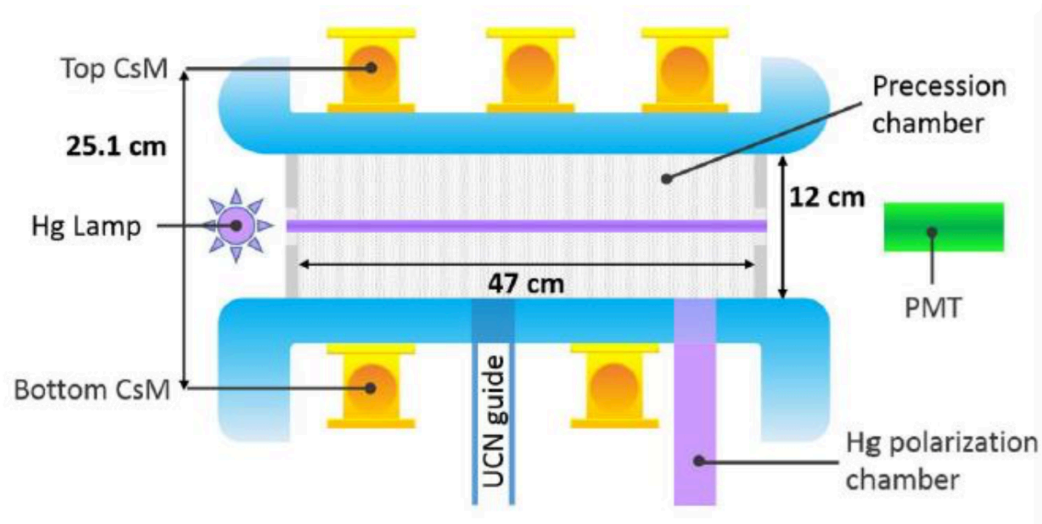
Shielding – 4 layers of µ-metal





Magnetometry

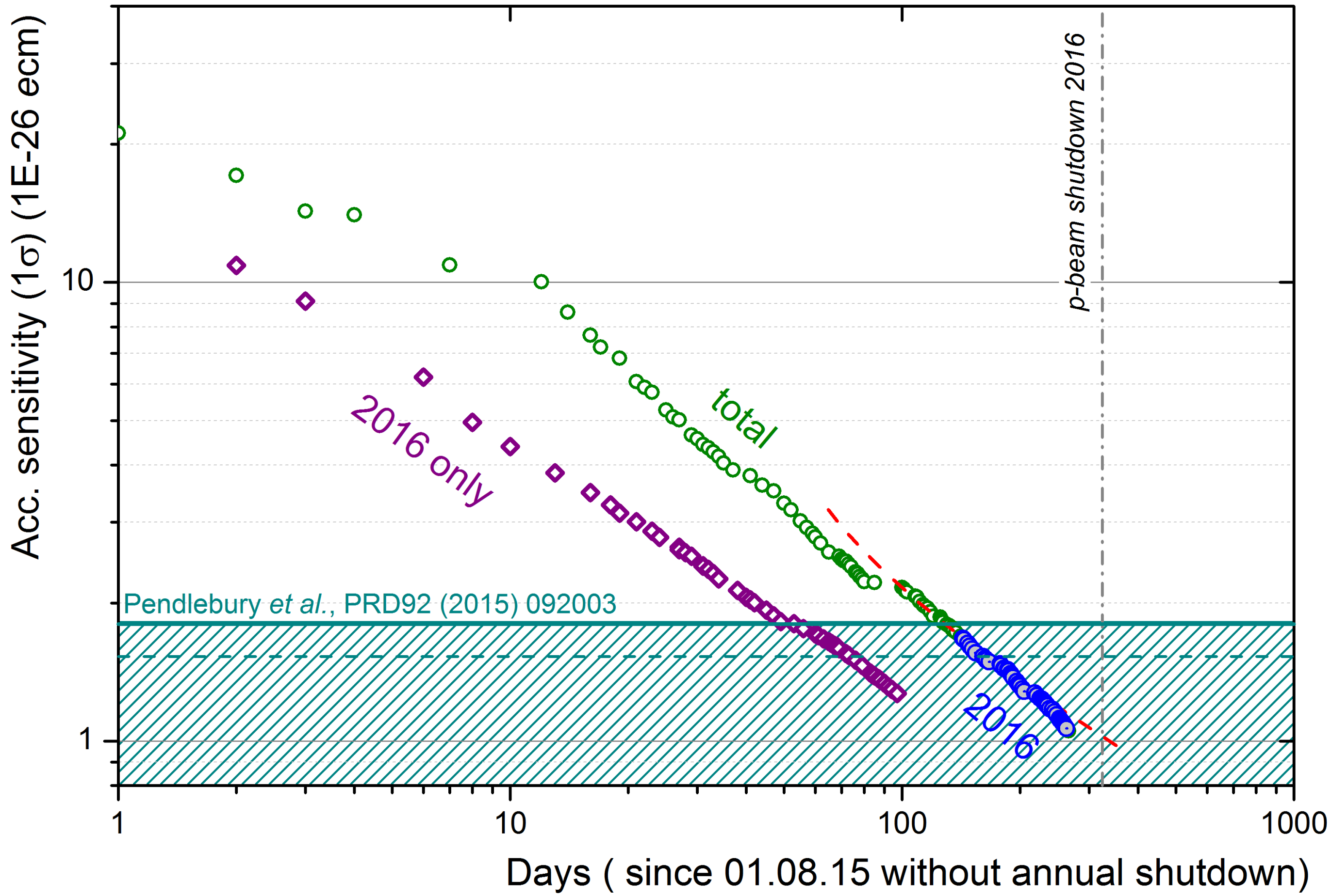




^{199}Hg

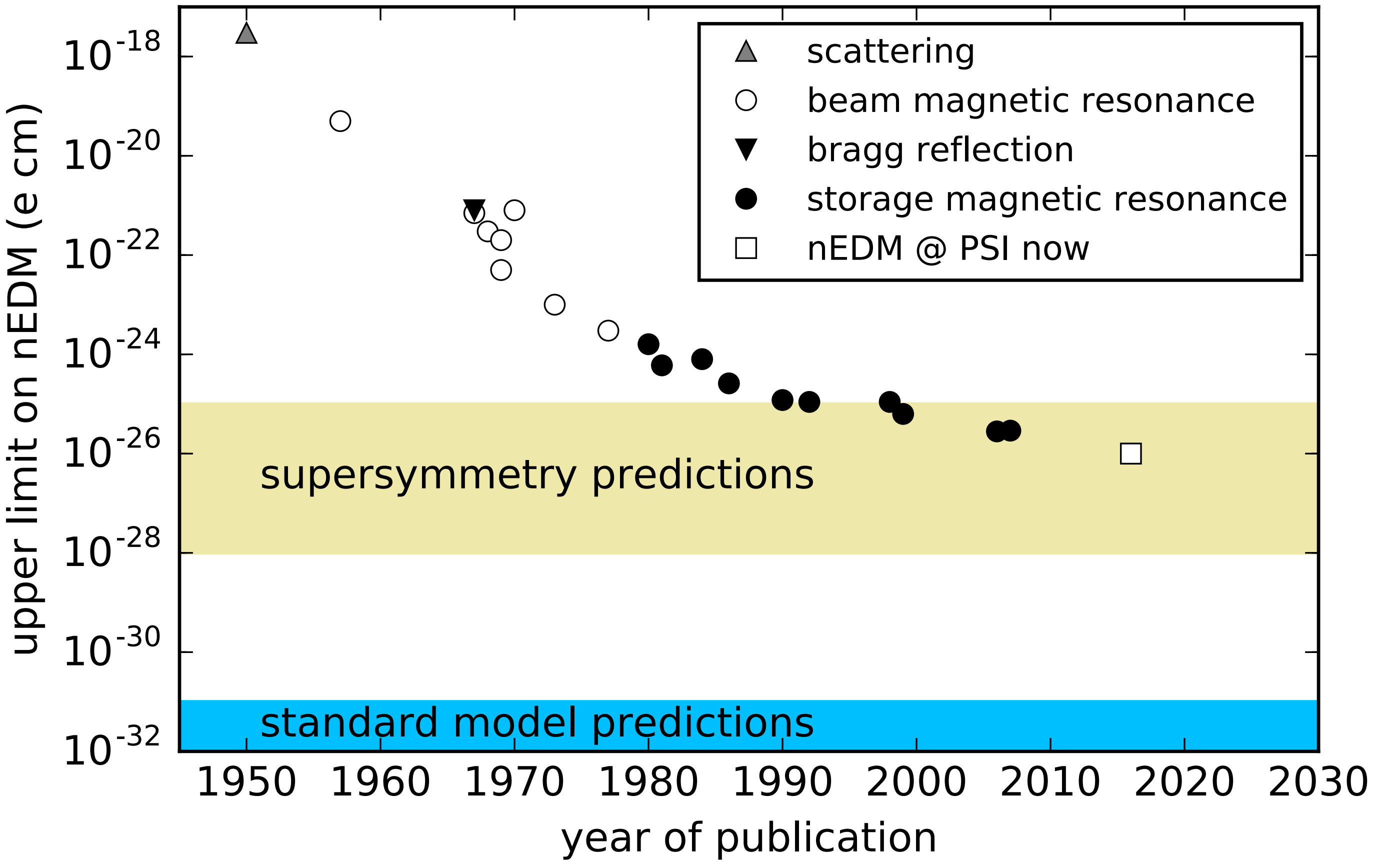
UCN

Most sensitive nEDM measurement ever!



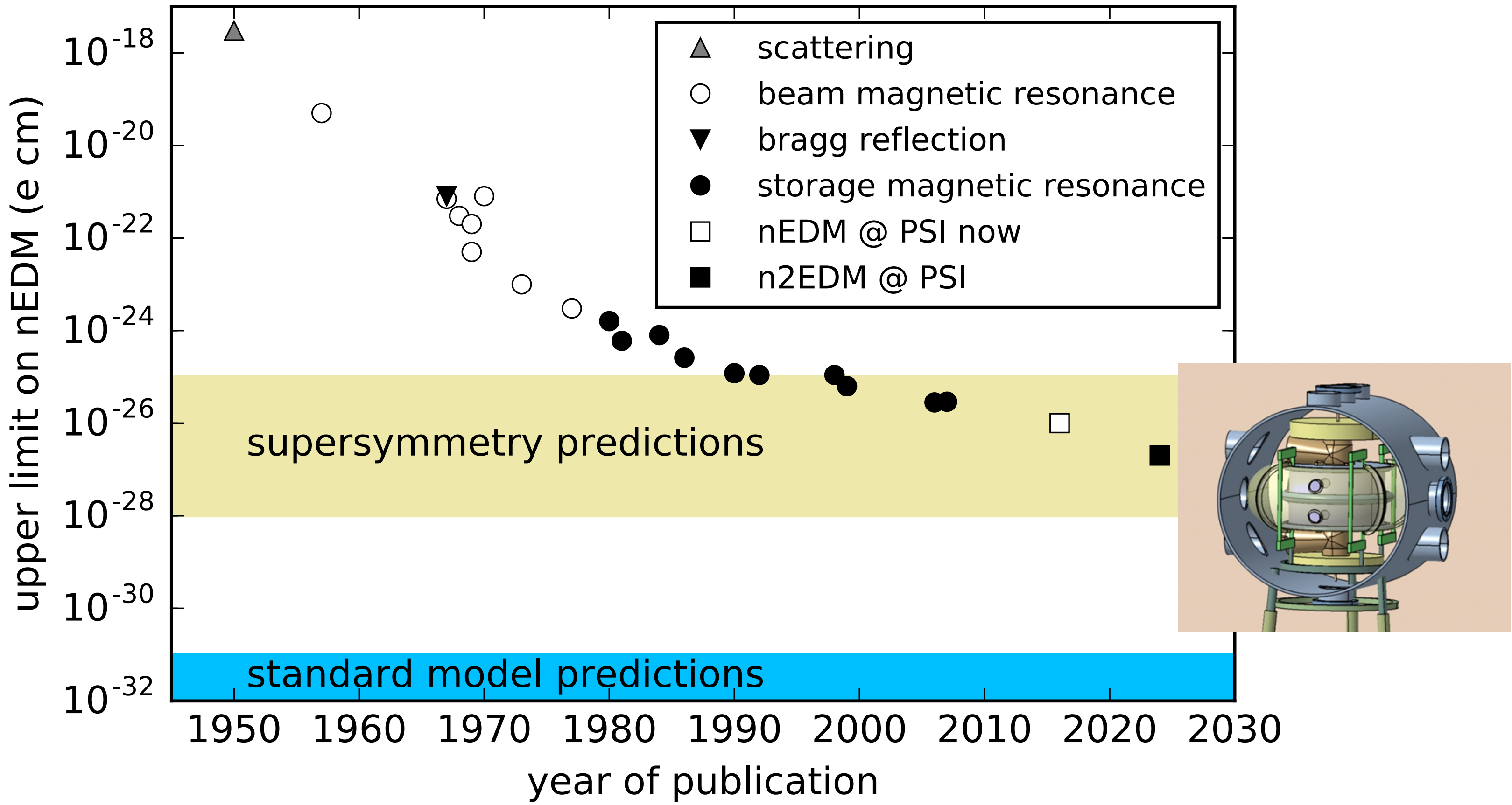
psw 19/09/16

Conclusion



upper limit on nEDM (e cm)
10-18
10-20
10-22
10-24
10-26
10-28
10-30
10-32
scattering
beam magnetic resonance
bragg reflection
storage magnetic resonance
nEDM @ PSI now
supersymmetry predictions
standard model predictions
1950
1960
1970
1980
1990
2000
2010
2020
2030
year of publication

Conclusion


scattering
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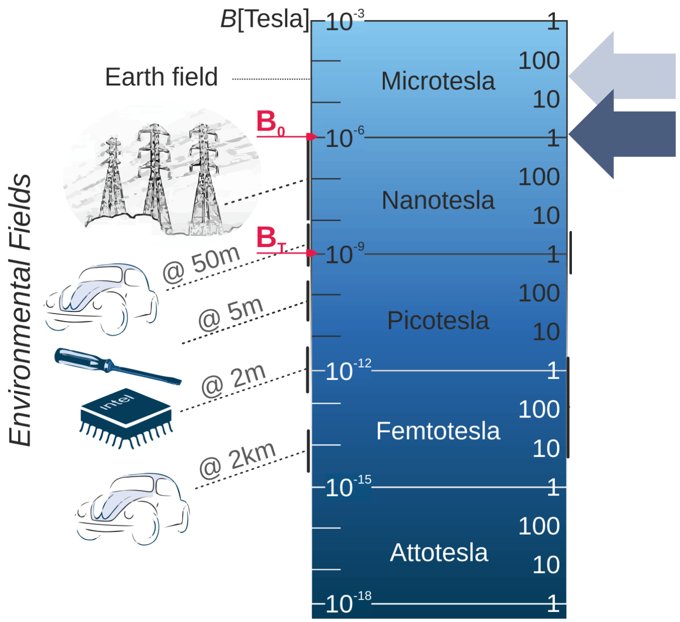
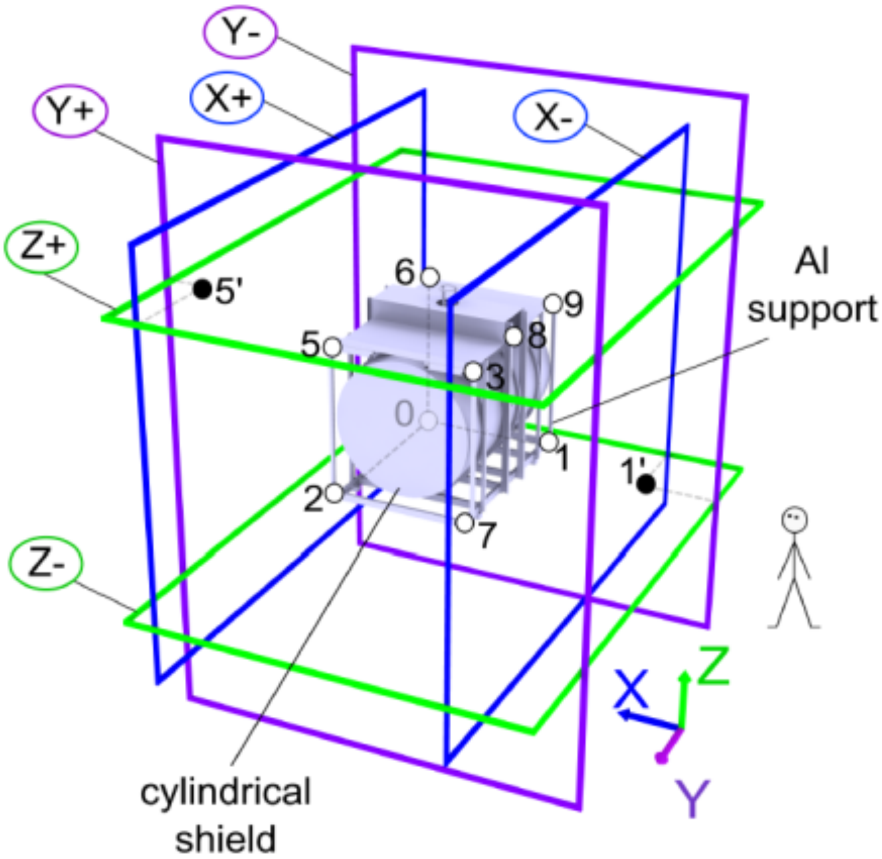
upper limit on nEDM (e cm)
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
1950 1960 1970 1980 1990 2000 2010 2020 2030
year of publication

Active Magnetic Field Stabilisation






PSI-West
seen from
a satellite
UltraCold Neutrons source
nEDM experiment
PhD Semina
Hauptstrasse
8
Villigen
24/7 FOOD!
WBGA
Experimentierhalle
source: Google Maps

PSI-West
seen from
a satellite
SUpraLeiter Test ANlage
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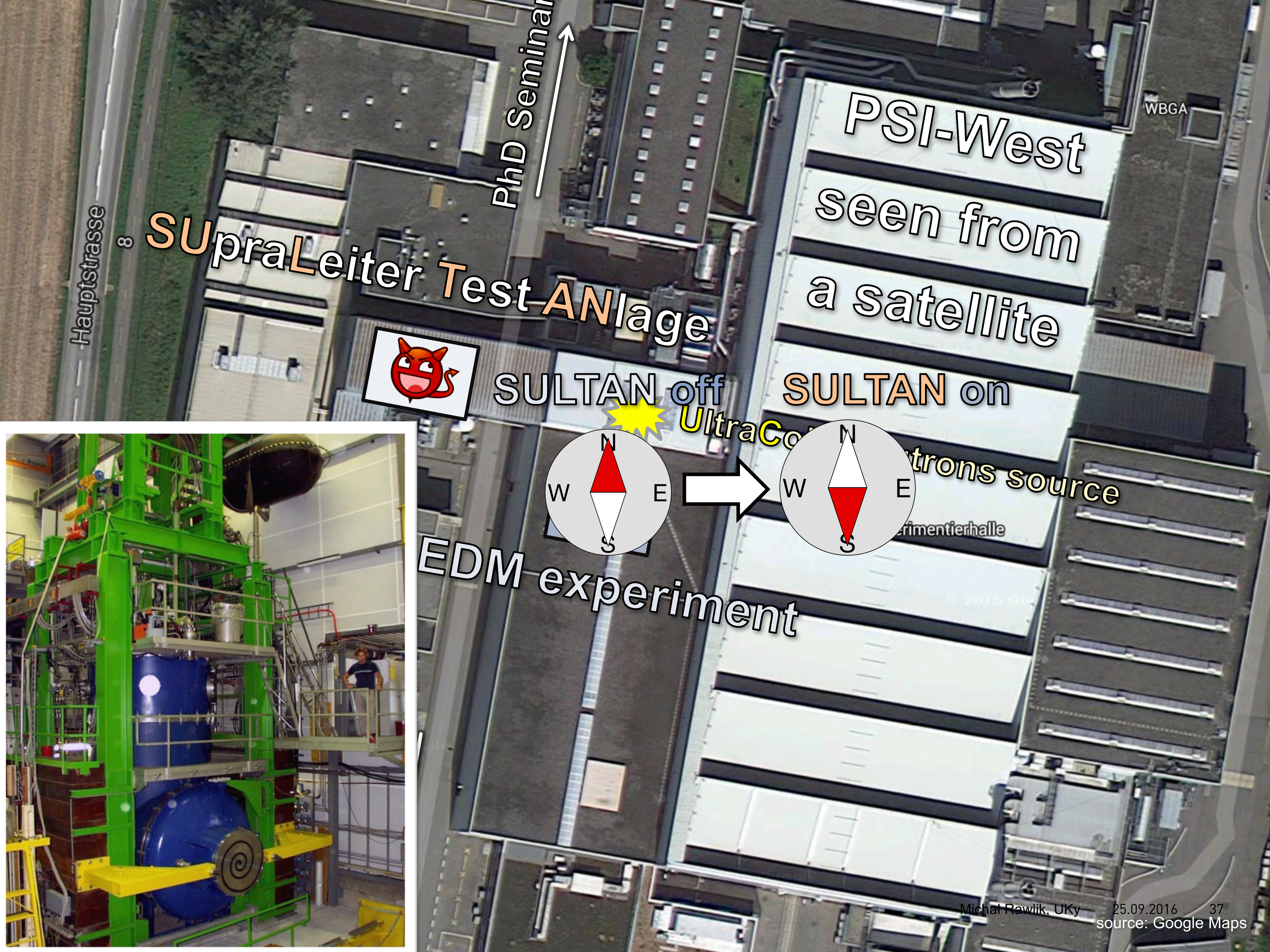
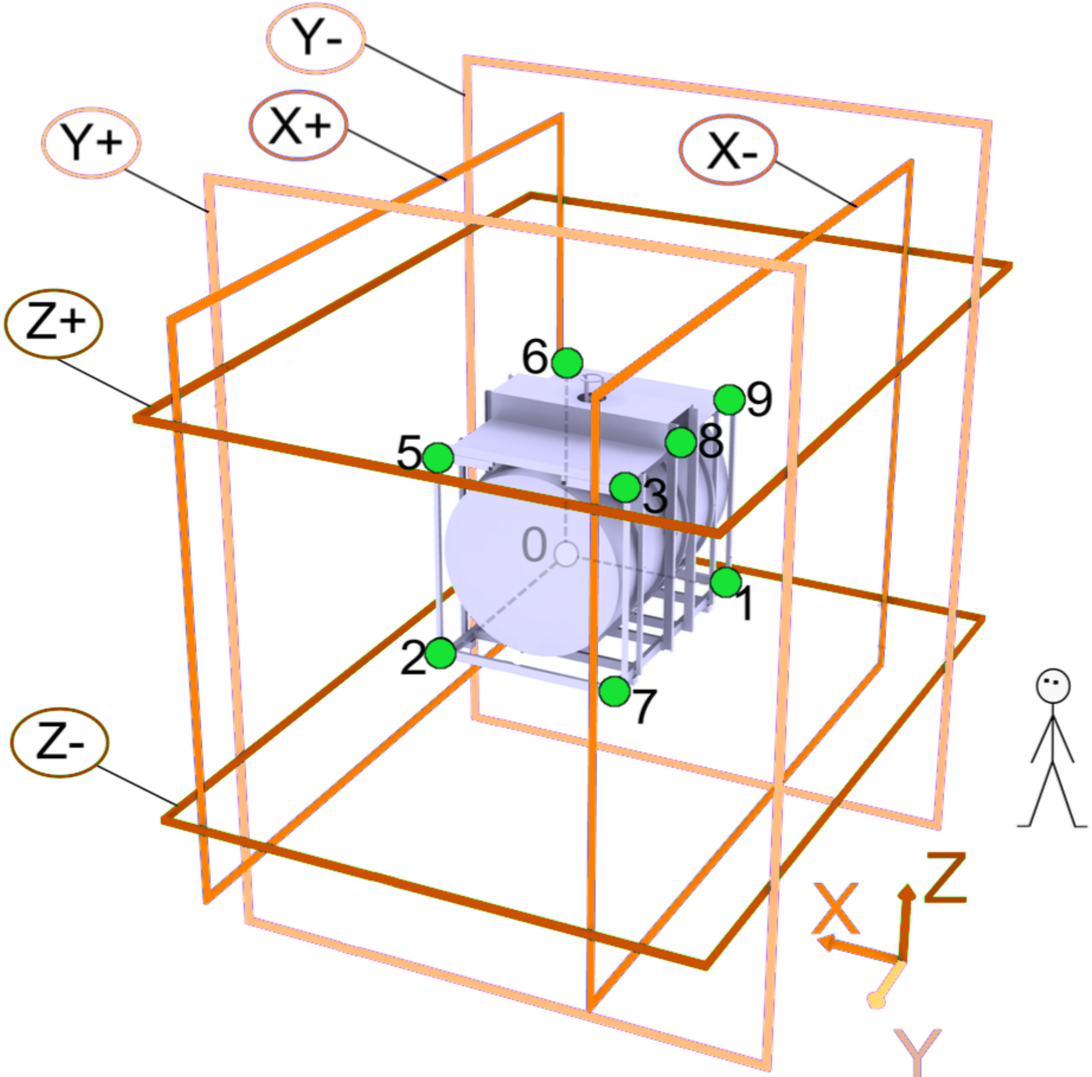


source: Google Maps

Active stabilisation

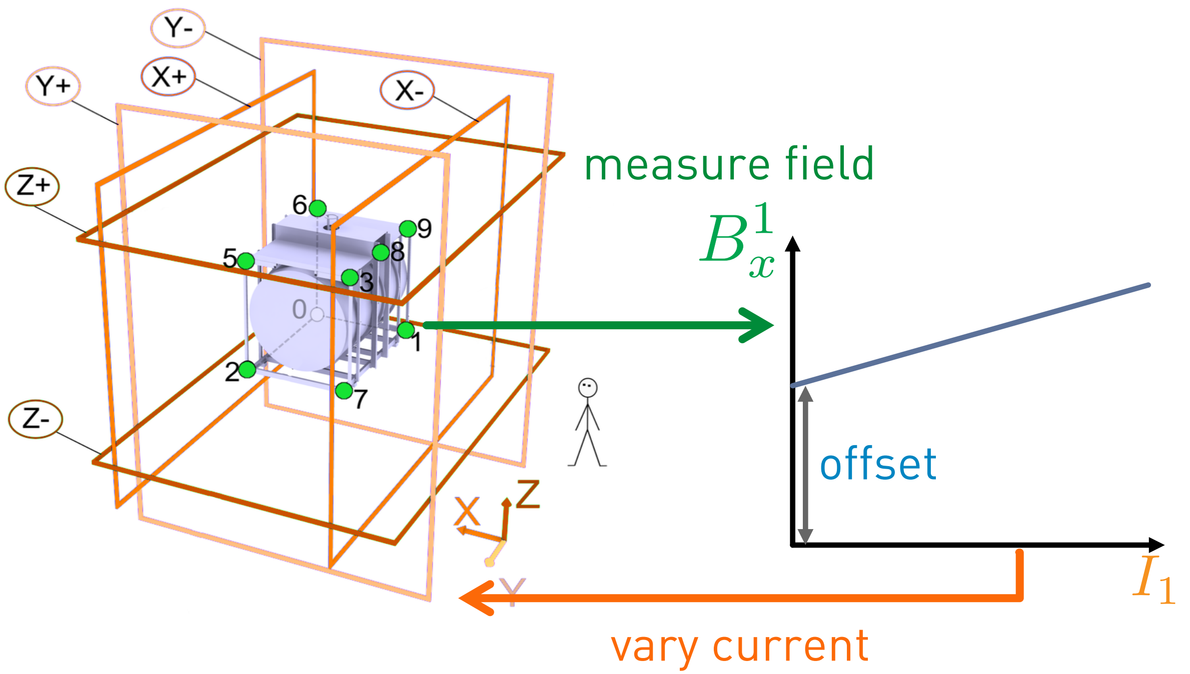


coils

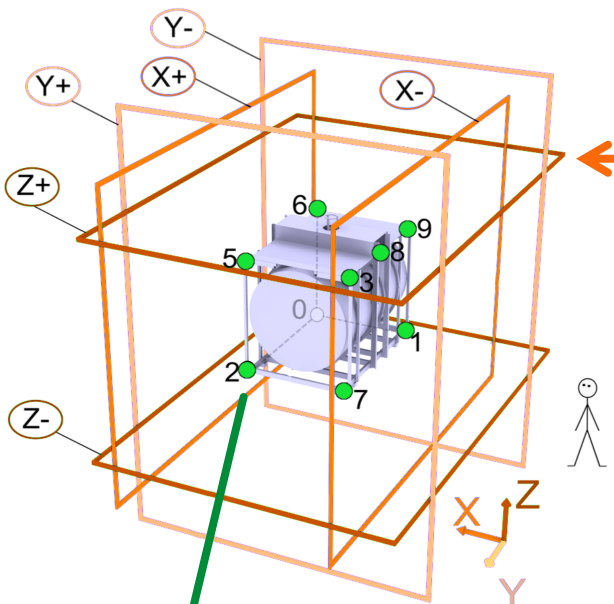
3-axis magnetic field sensors

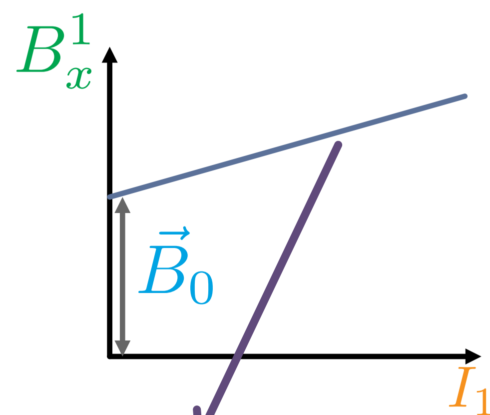
source: PhD thesis of Dr. Beatrice Franke

Measurement of the matrix



Measurement of the matrix





$$\begin{pmatrix} B_x^1 \\ B_y^1 \\ \vdots \end{pmatrix} = \begin{pmatrix} \frac{\partial B_x^1}{\partial I_1} & \frac{\partial B_x^1}{\partial I_2} & \cdots \\ \frac{\partial B_y^1}{\partial I_1} & \frac{\partial B_y^1}{\partial I_2} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \end{pmatrix} + \vec{B}_0$$

$$\vec{B} = M\,\vec{I} + \vec{B}_0$$

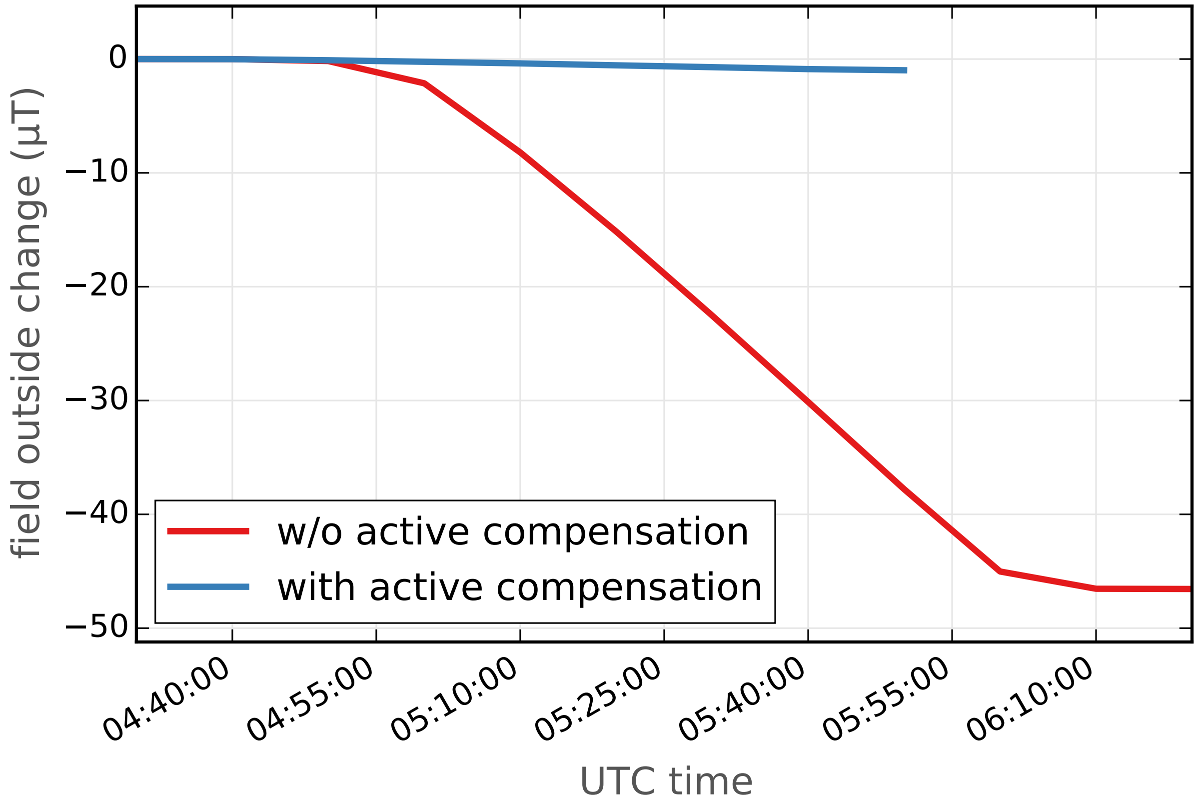
We want $\vec{I}$ that makes $\vec{B} = 0$

minimise $\sum_i |\vec{B}_i|$, that is $\sum_i B_i^2$

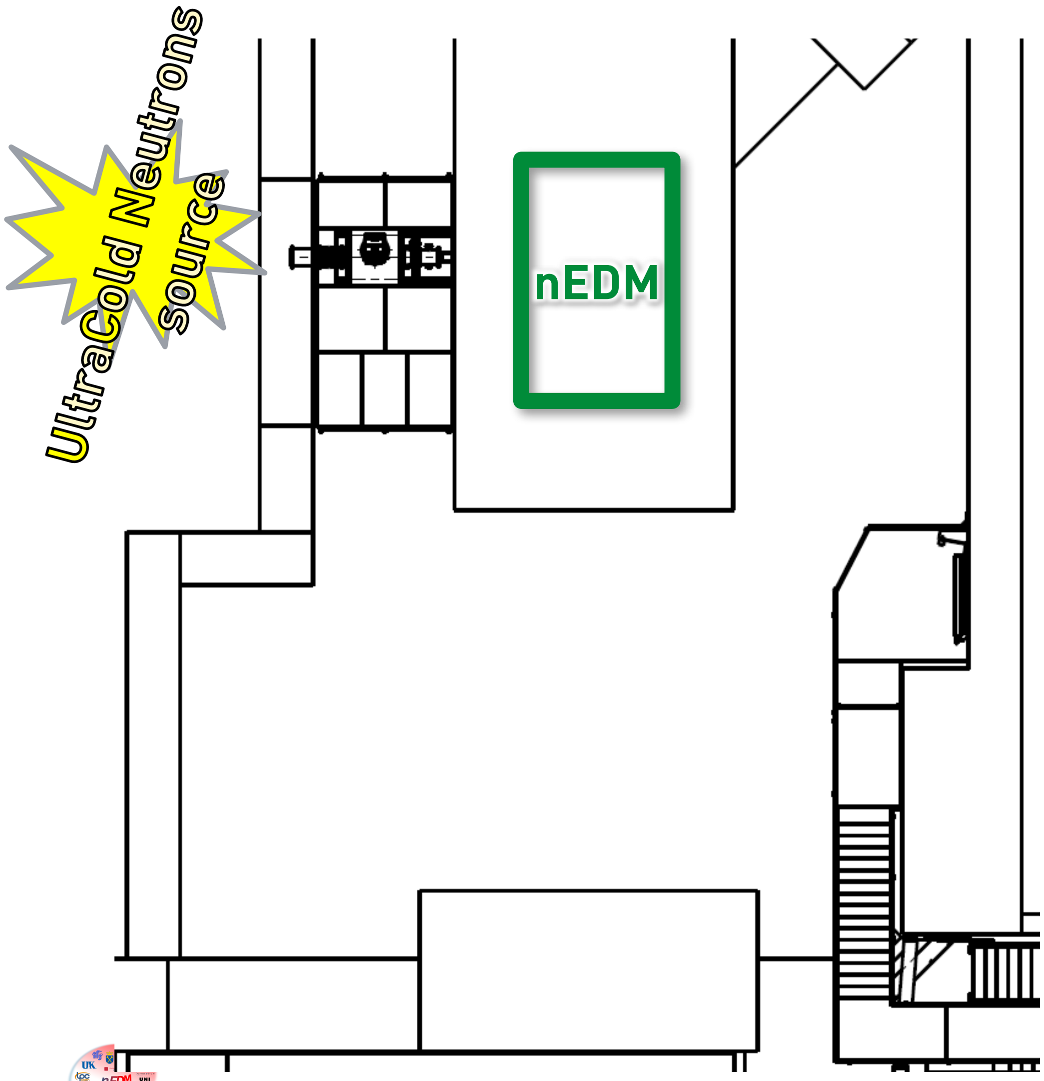
which is simply a linear least-squares problem.

in MATLAB syntax: `I = M \ (0 - B)`

SULTAN magnet ramping



Coil design for n2EDM



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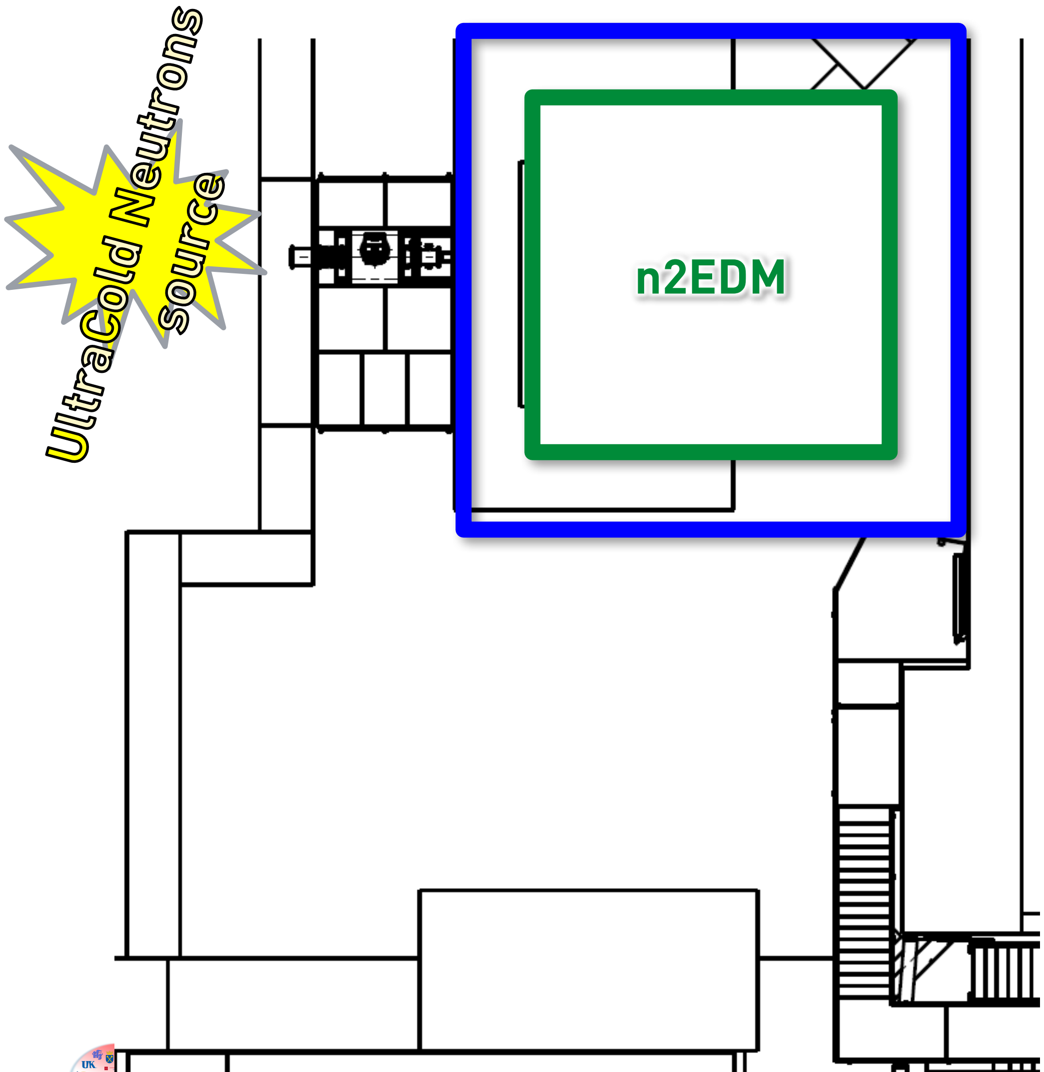
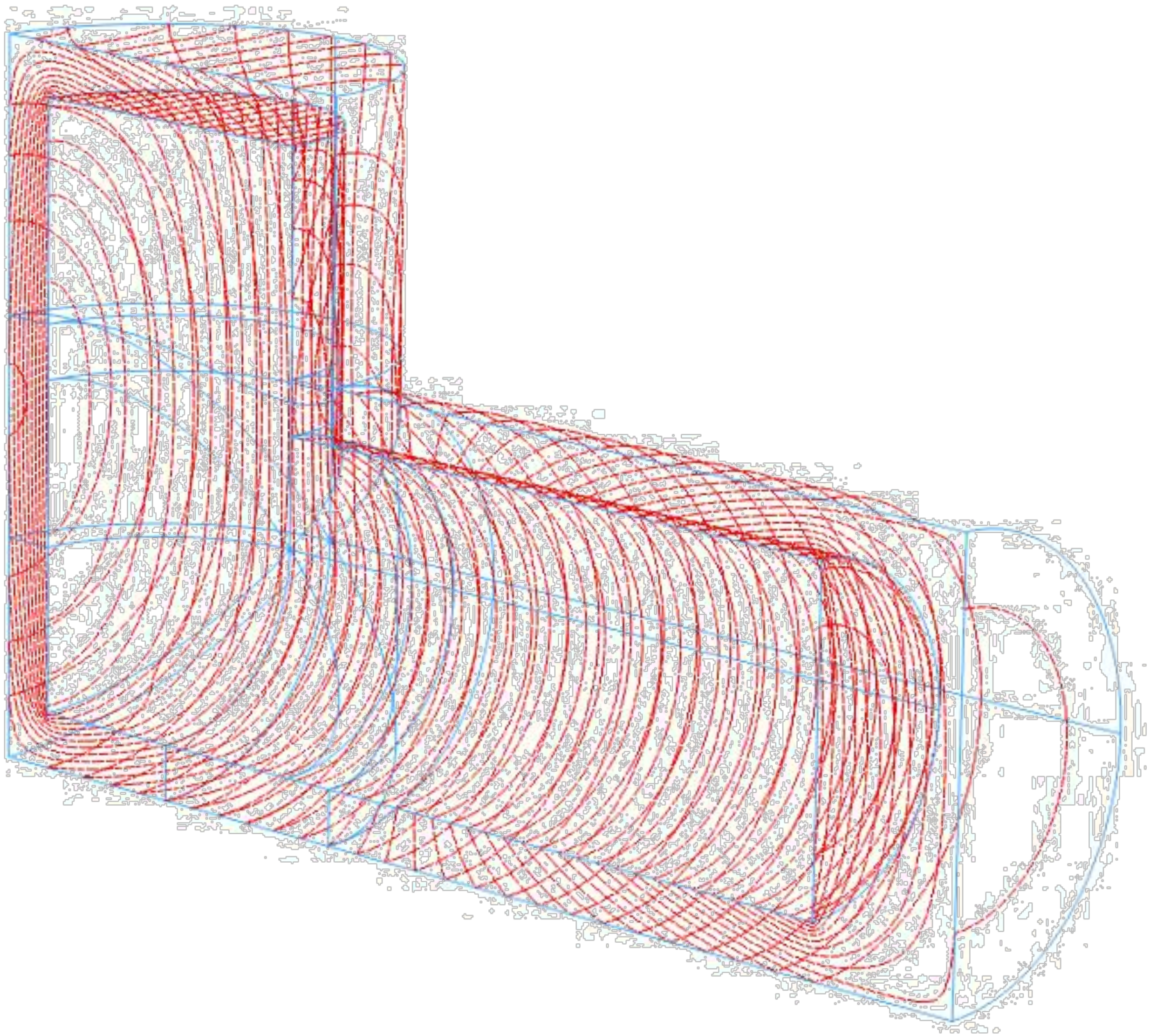
Coil design for n2EDM



Use coils to bring any homogeneous field down to

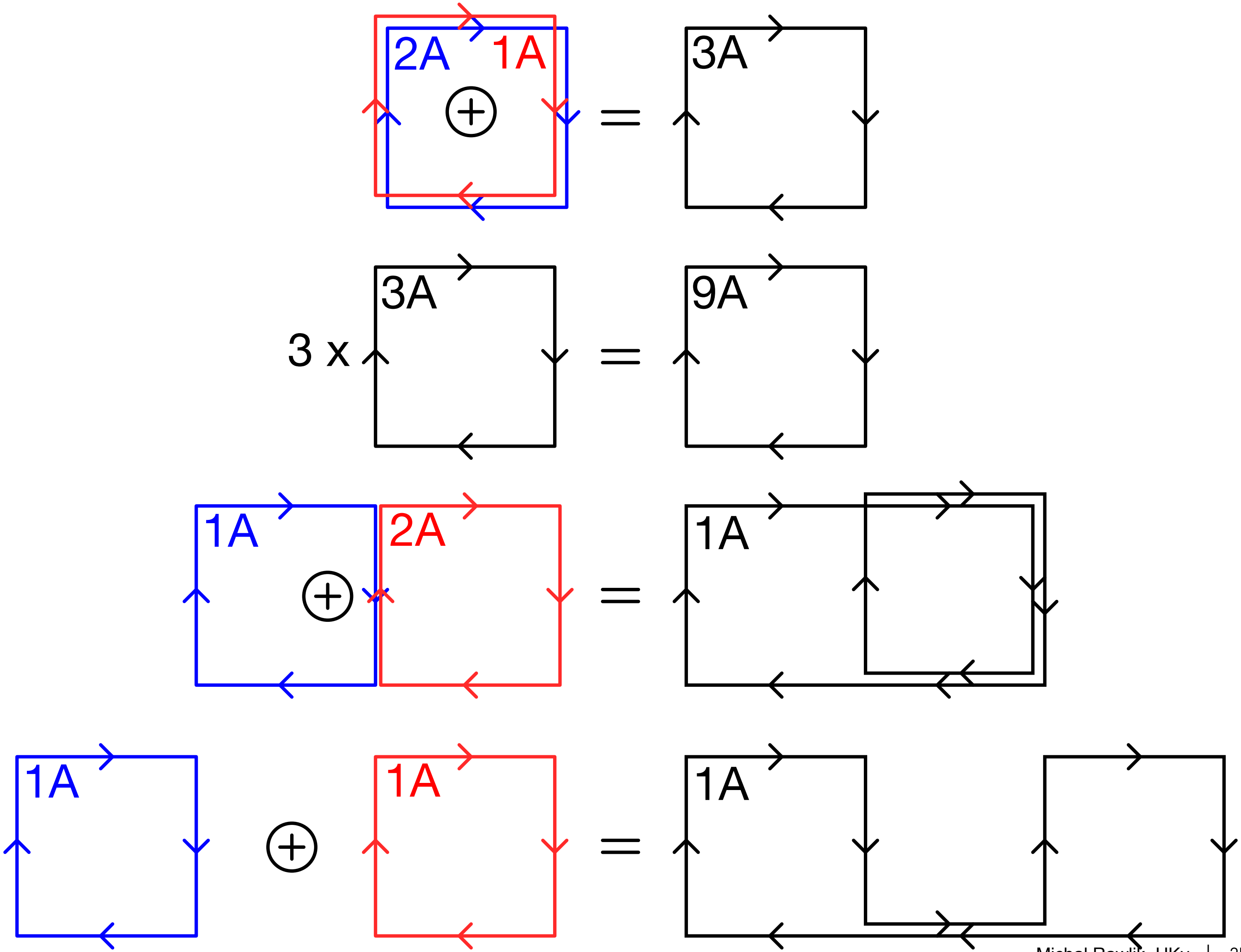
< 5%

in the whole experiment volume

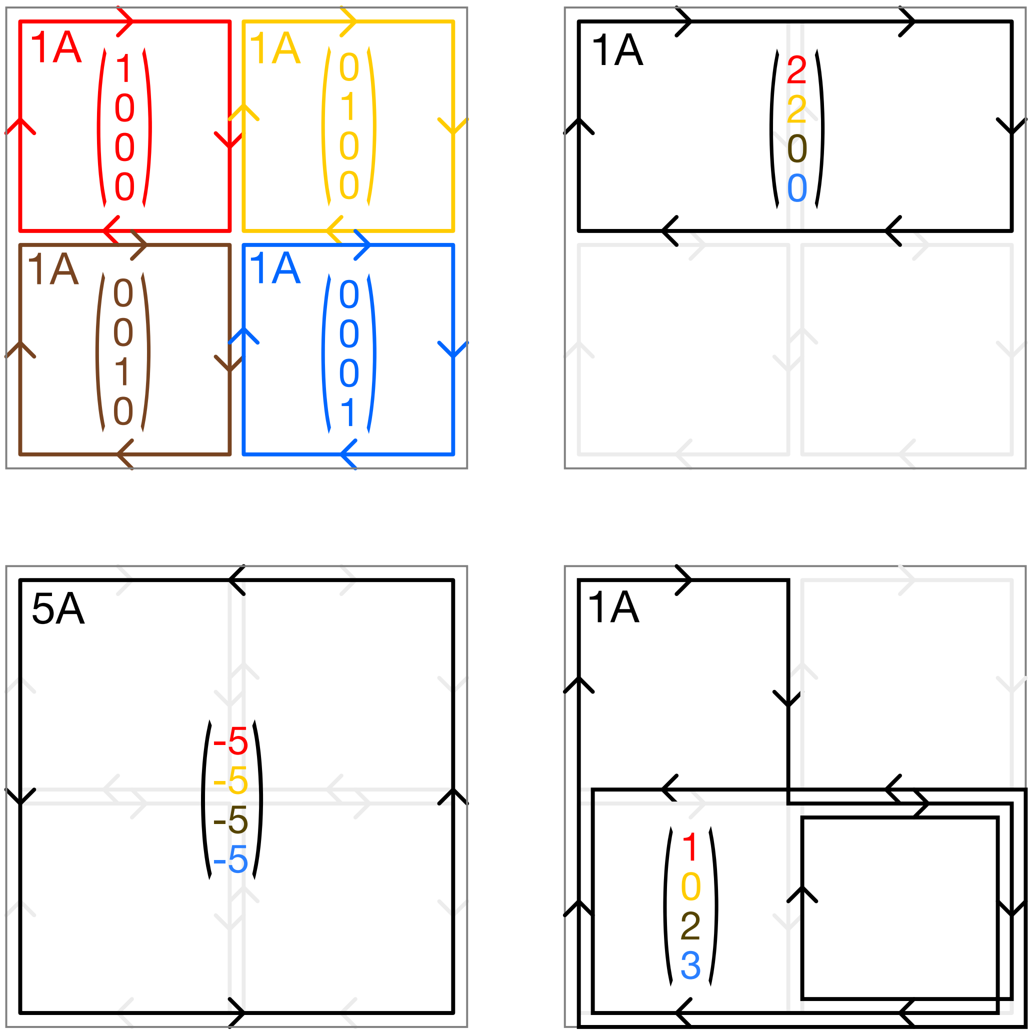


source: Christopher Crawford

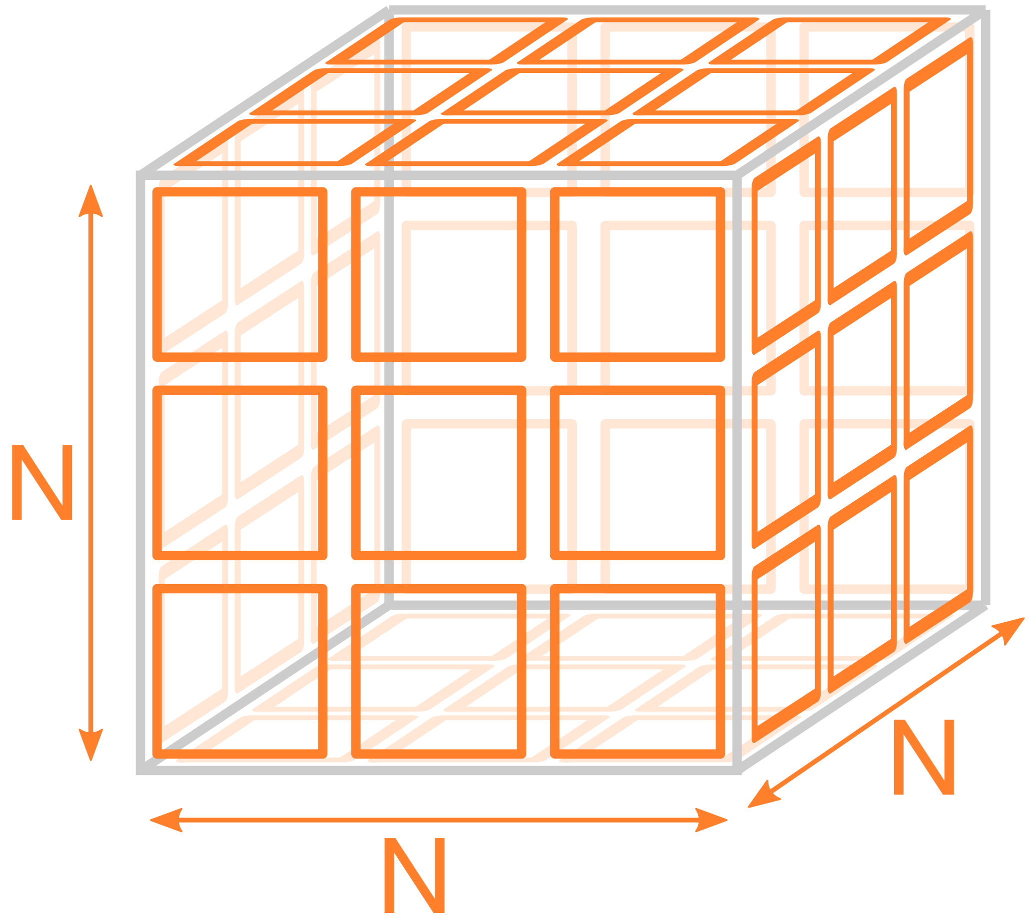
Coil Algebra



a basis in the space of possible coils



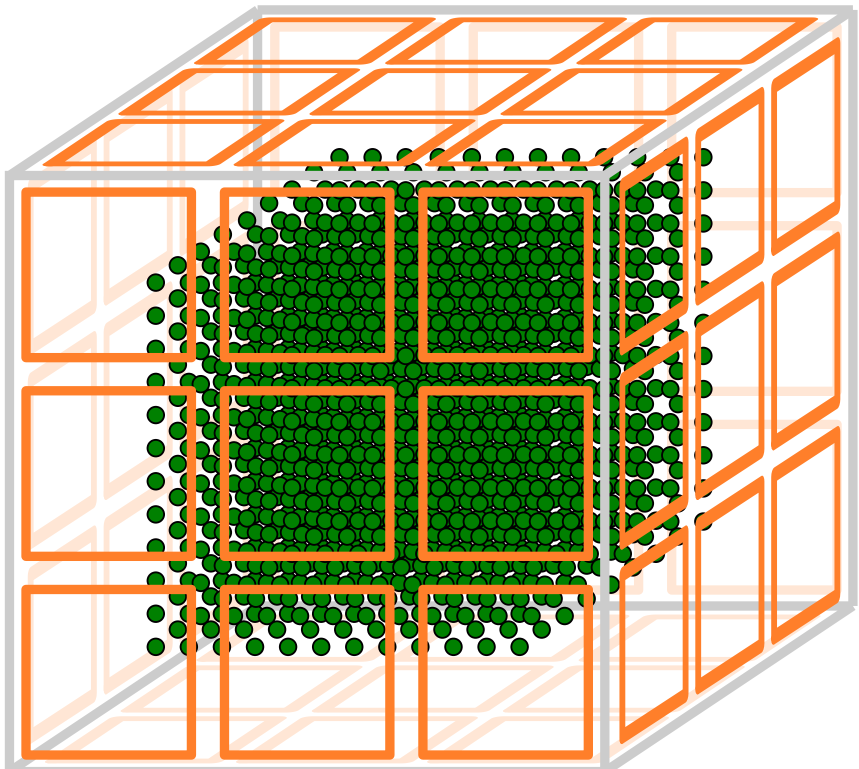
a basis in the space of possible coils



a coil is described with $6N^2$-1 numbers – it is a vector in the coil space

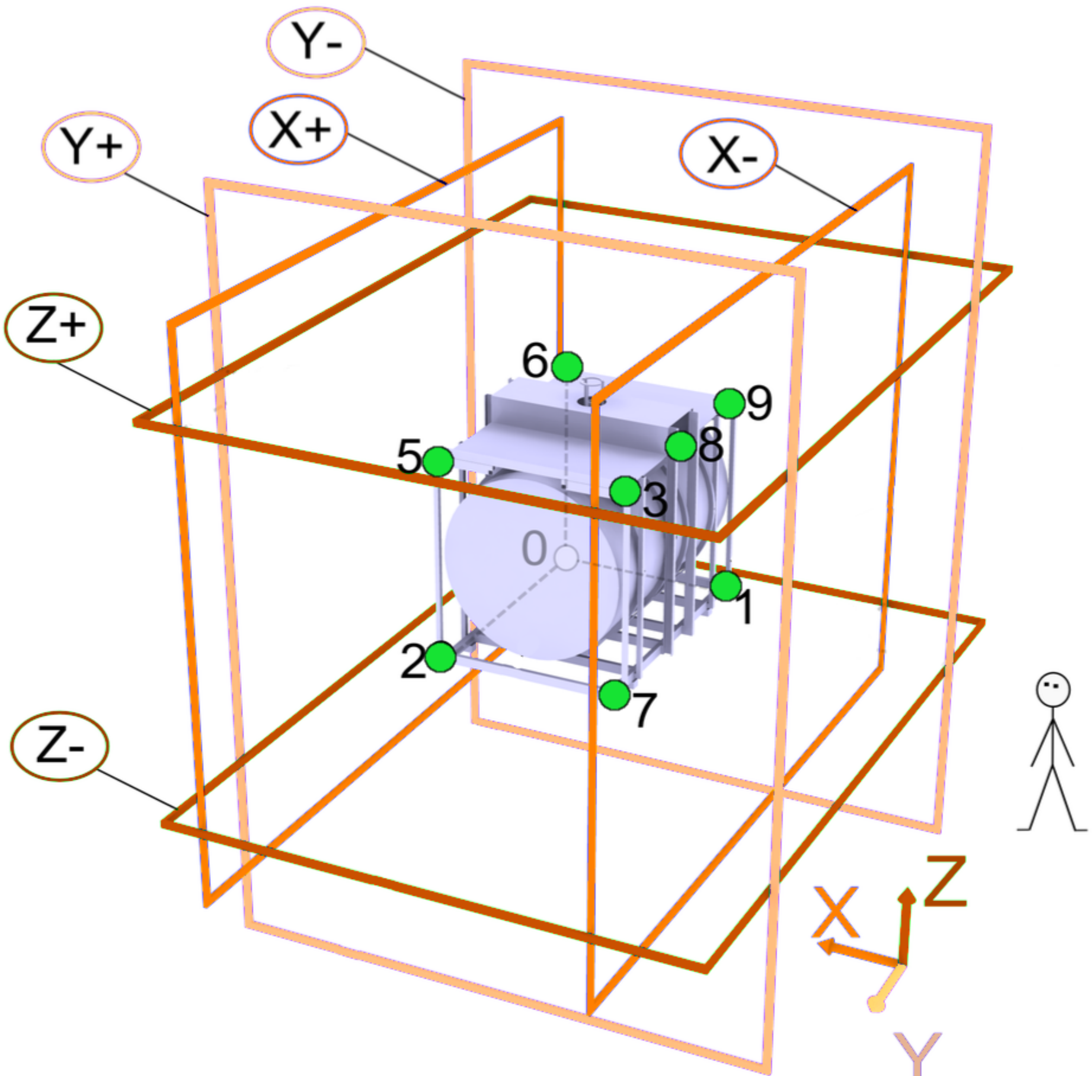
Virtual *Sensors*

coils



sensors

Active stabilisation



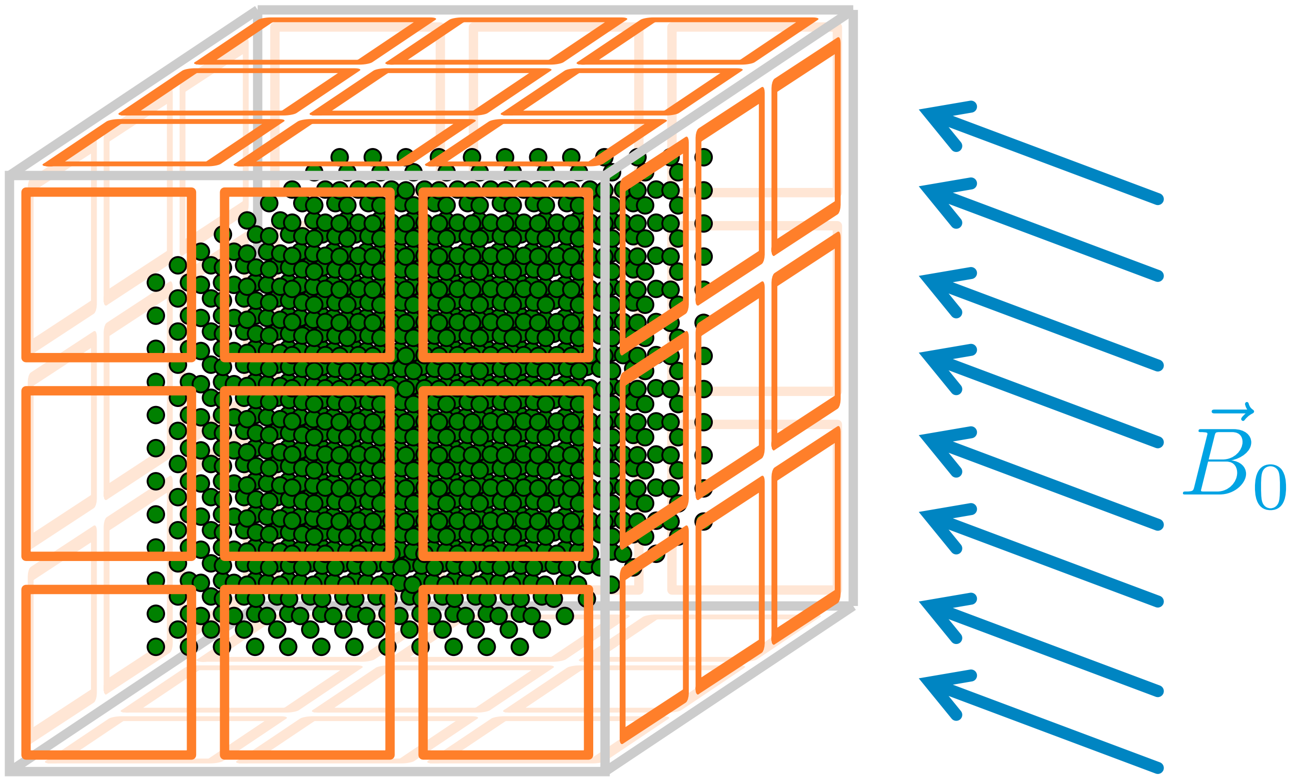
coils

3-axis magnetic field sensors

source: PhD thesis of Dr. Beatrice Franke

The Coil for Given B_0

coils



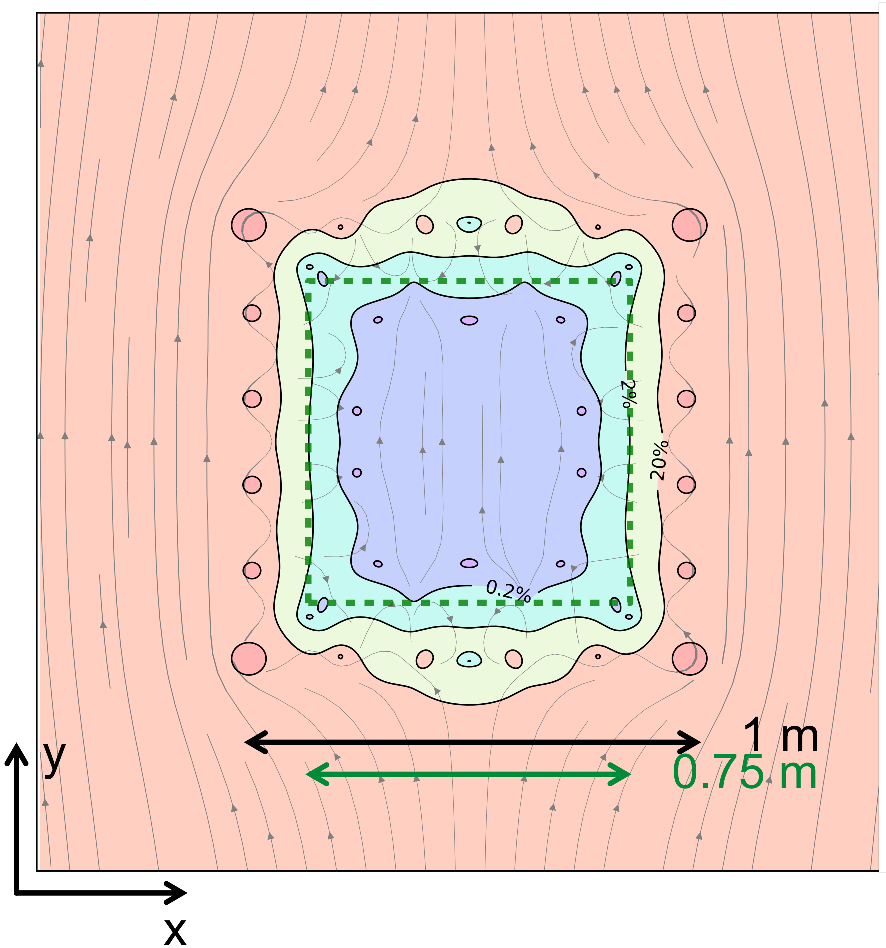
sensors

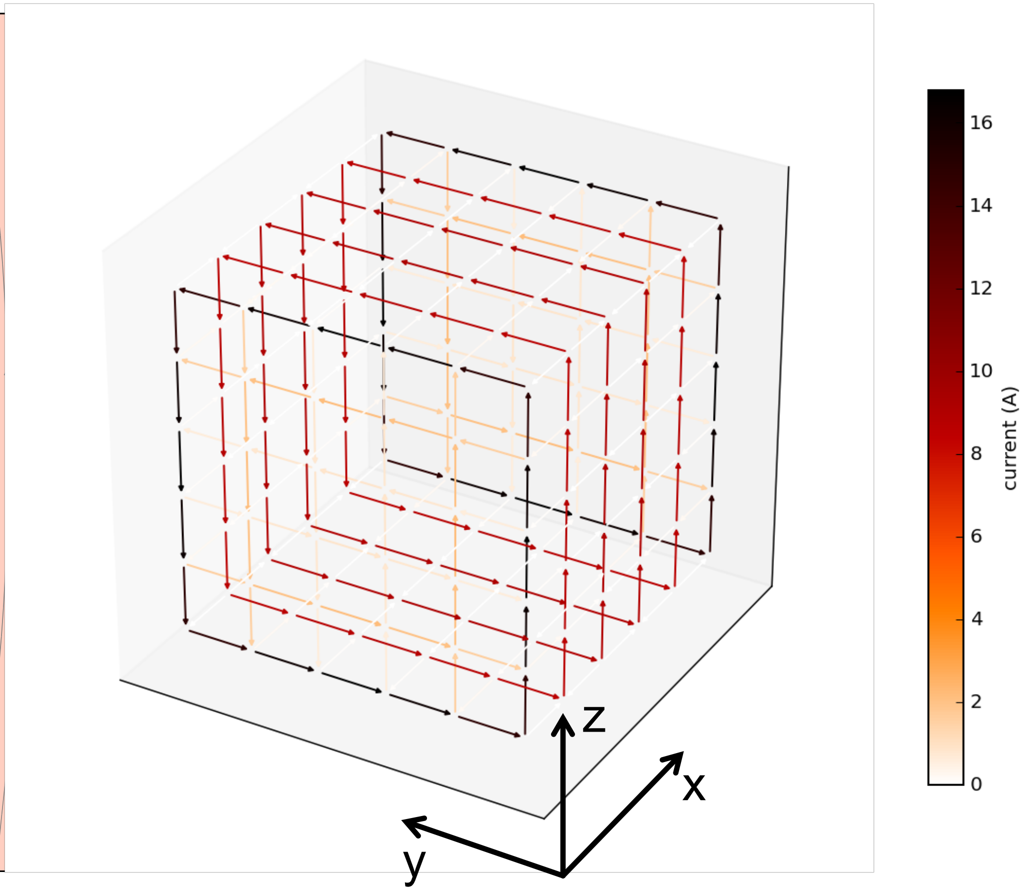
$$\vec{B} = M\,\vec{I} + \vec{B}_0 \qquad \vec{B} \stackrel{!}{=} 0$$

in MATLAB syntax: `I = M \ (0 - B)`

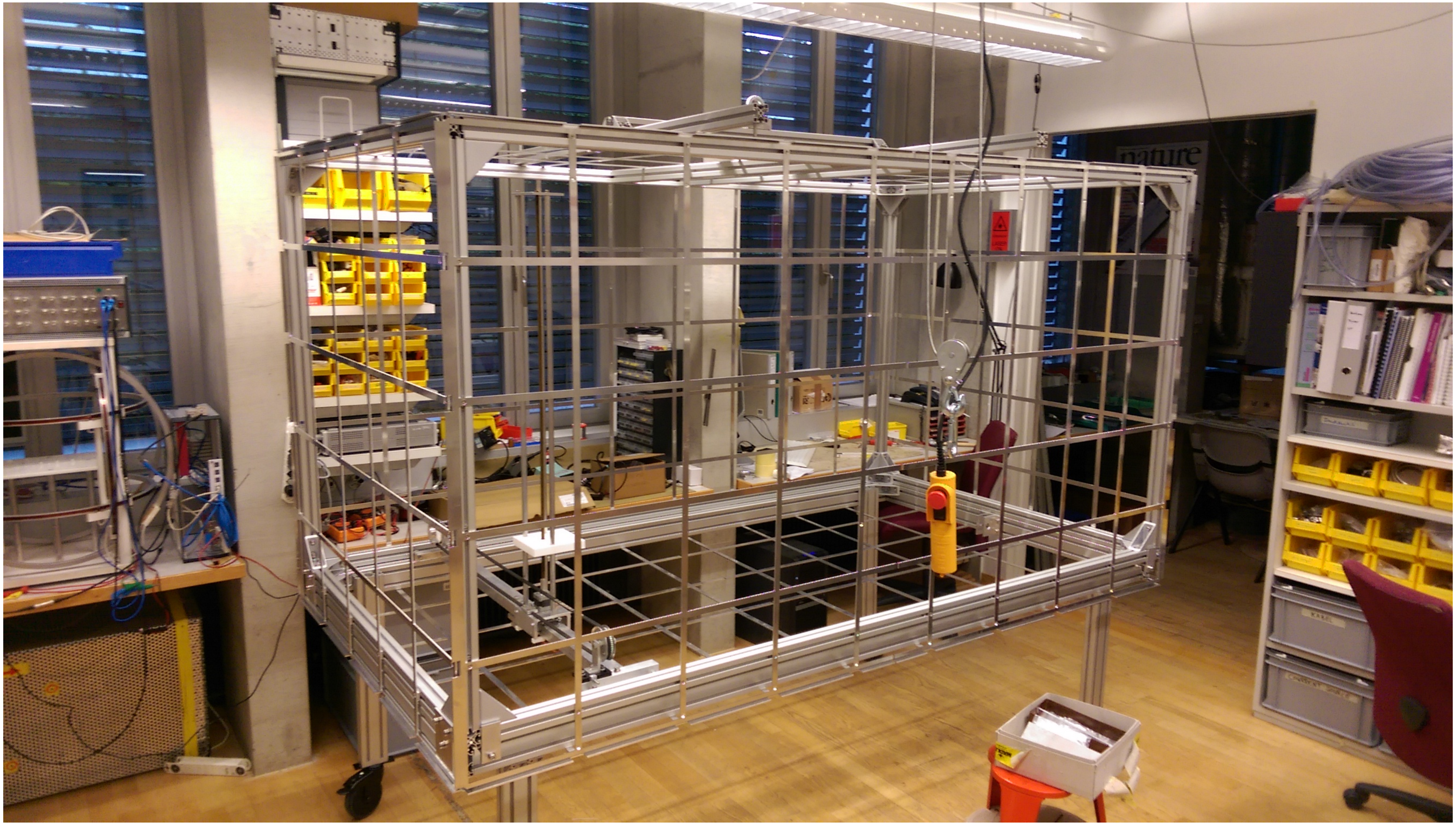
B_0 = Homogeneous Field in y

XY-cut in the middle





ETH n2EDM SFC prototype



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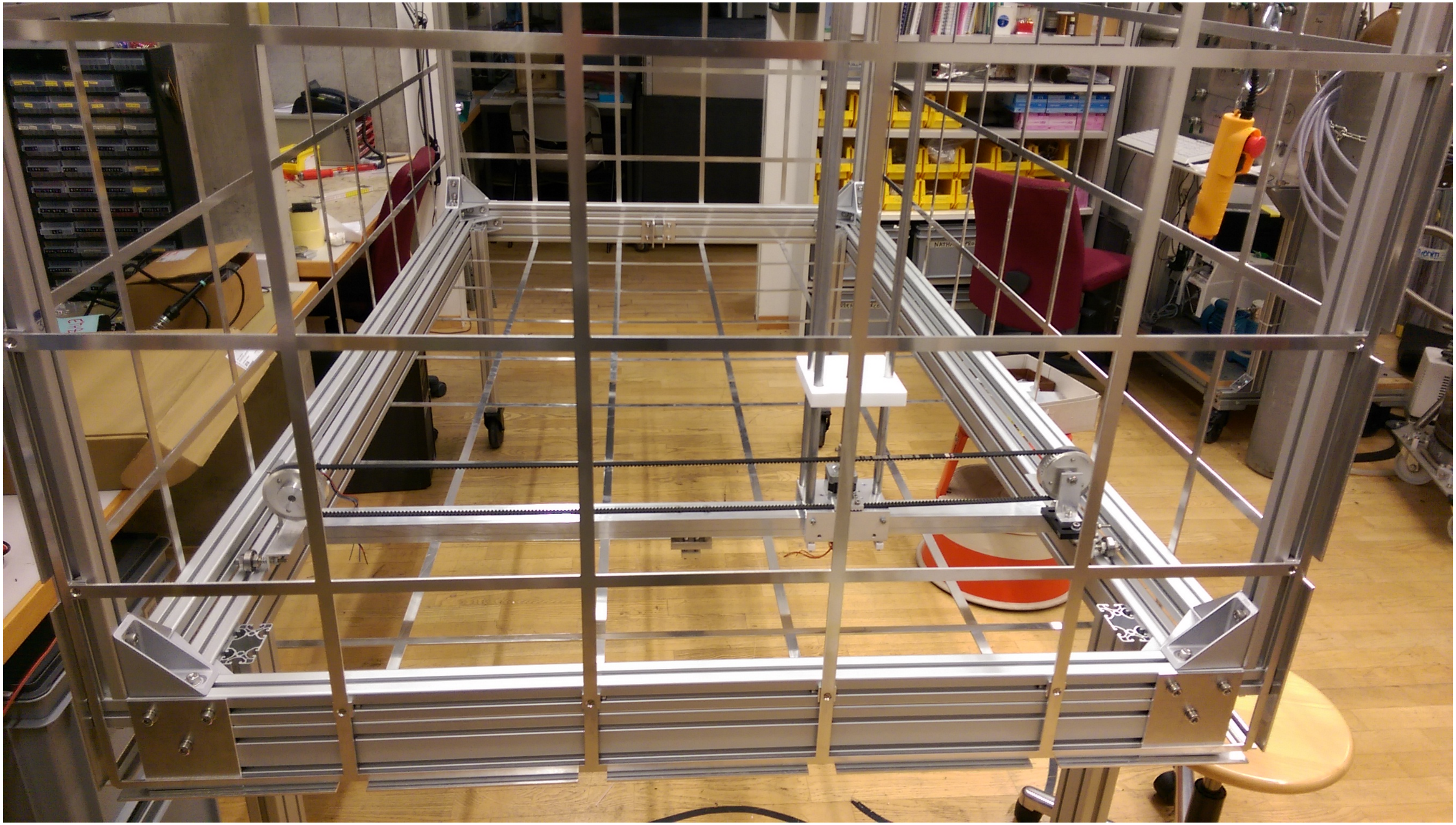

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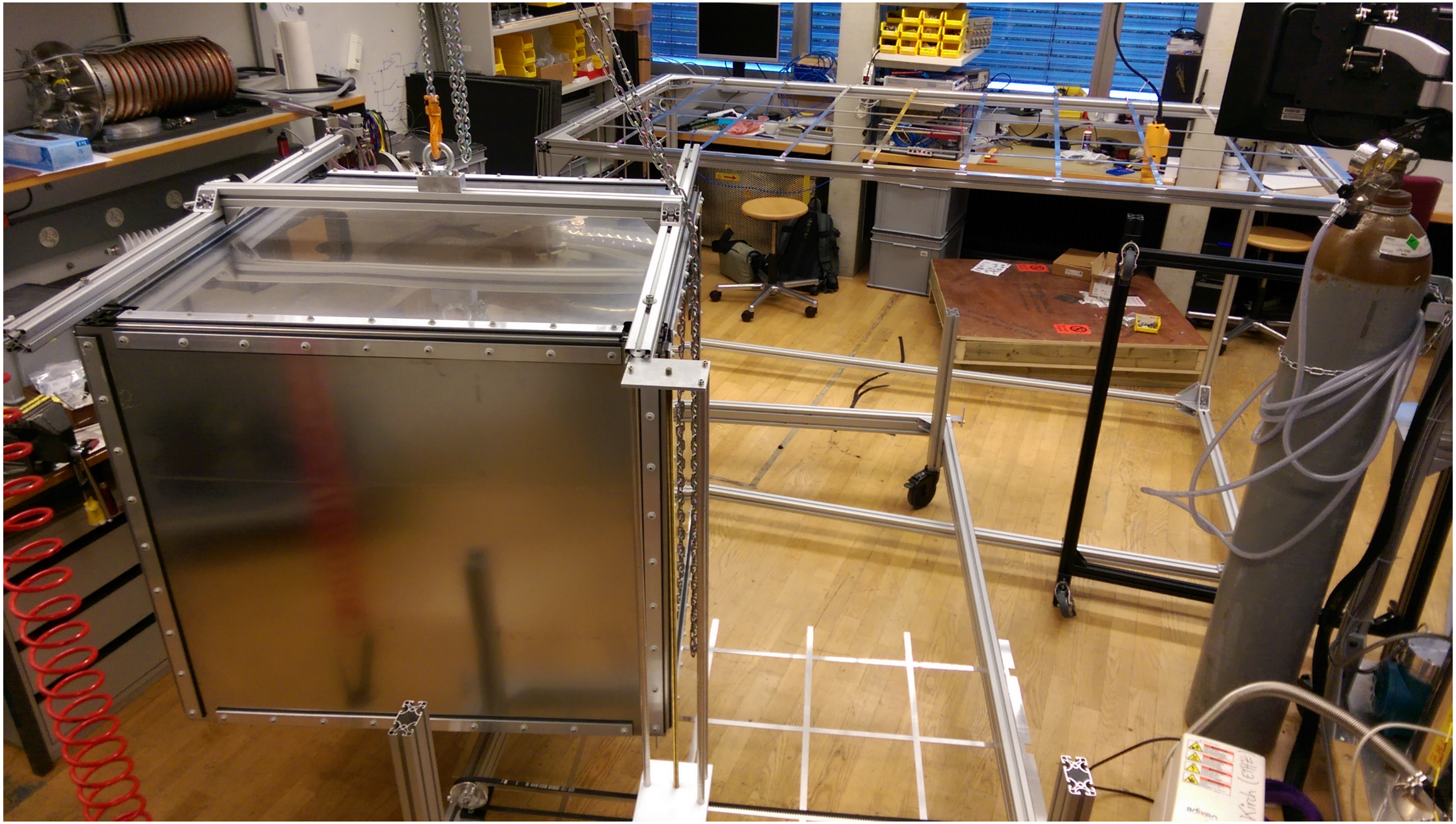

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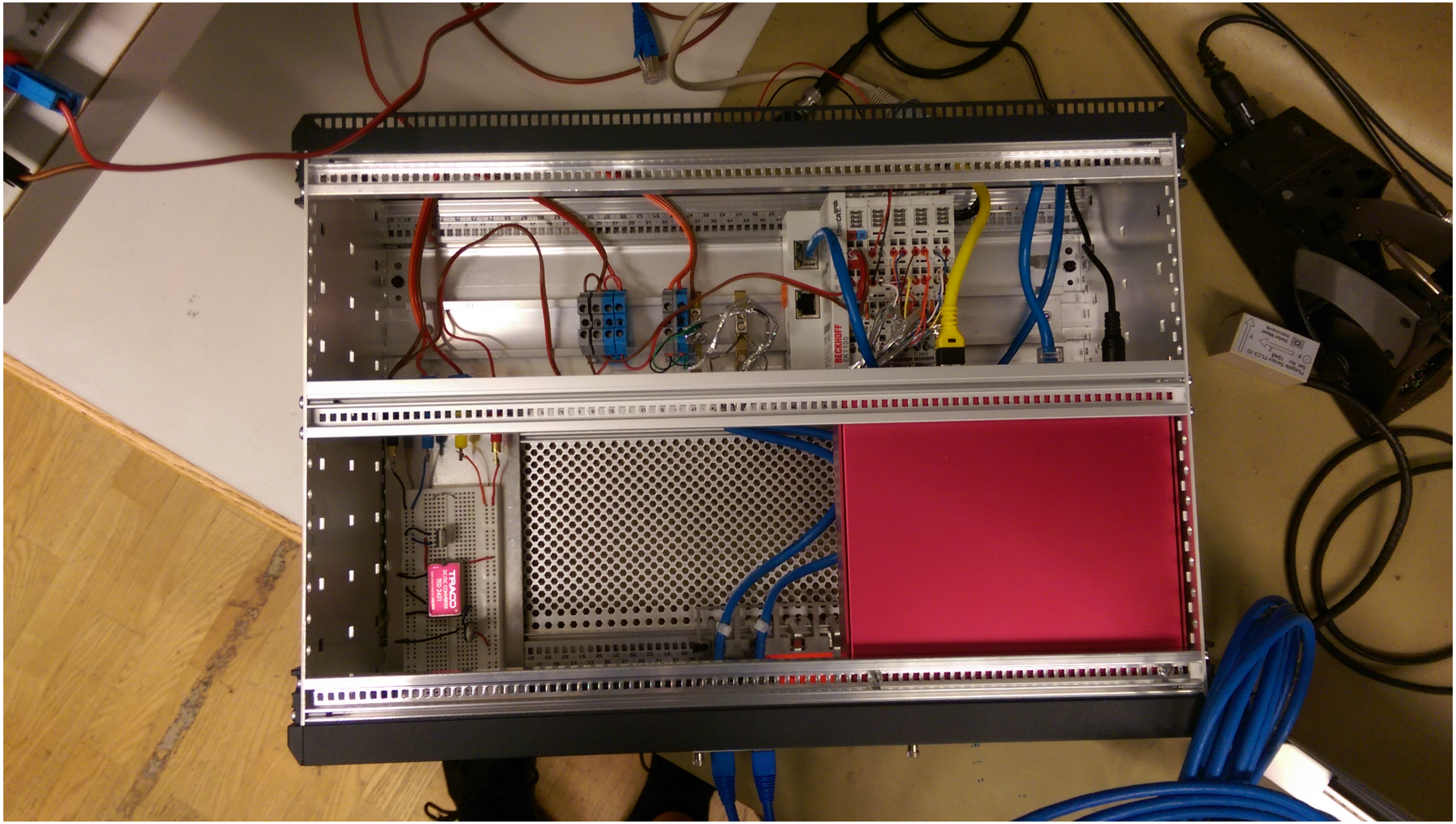
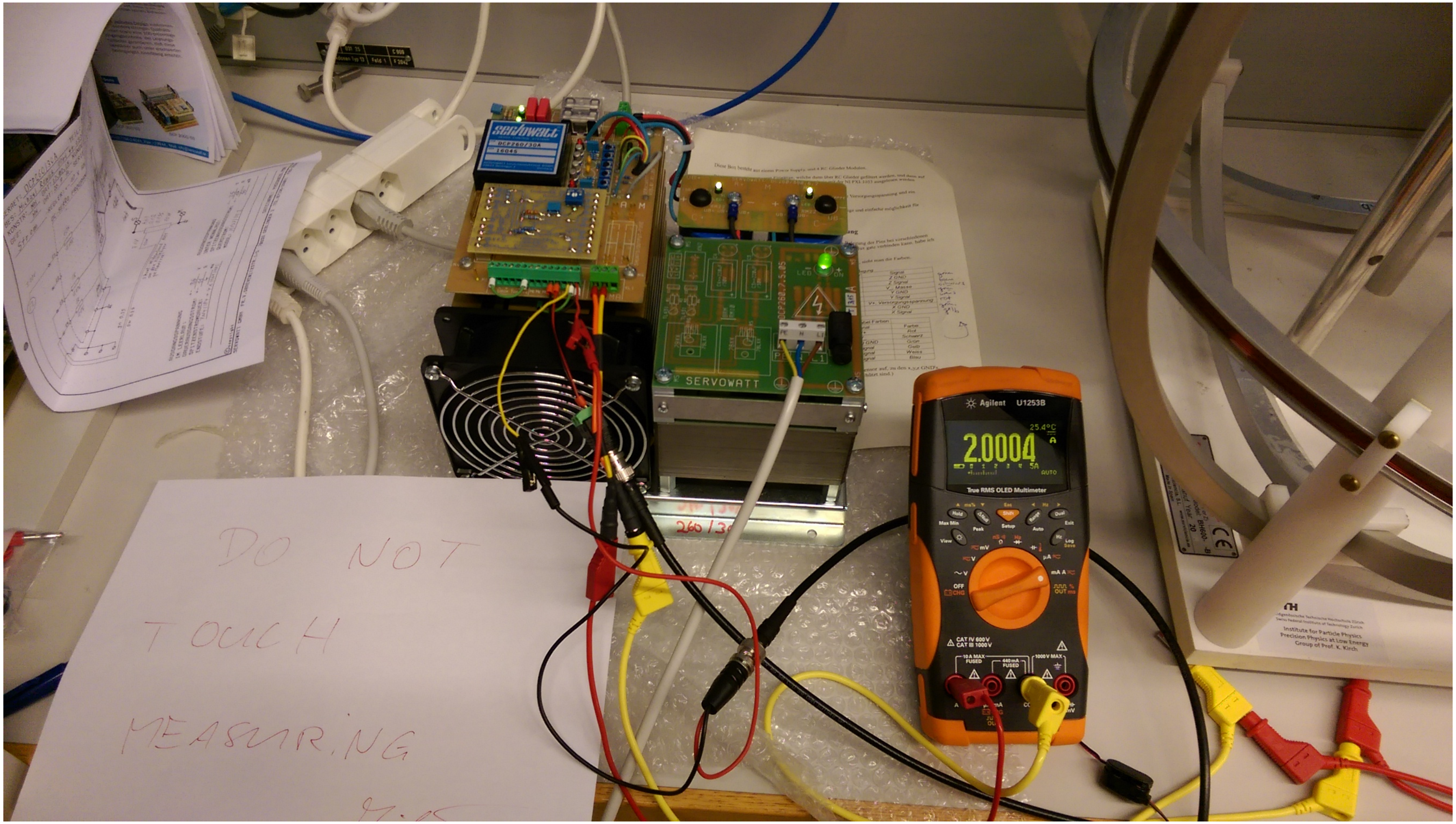
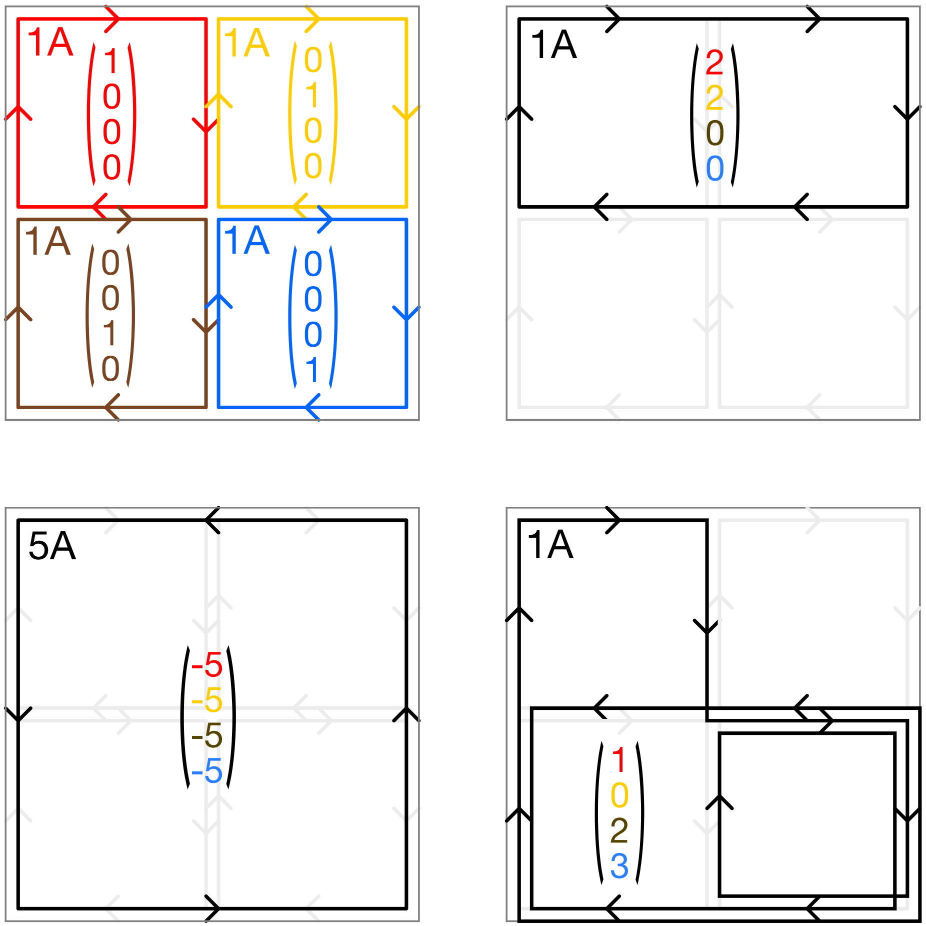


ETH n2EDM SFC prototype



Wrap-Up



$$I = M \setminus (0 - B)$$

ETH zürich

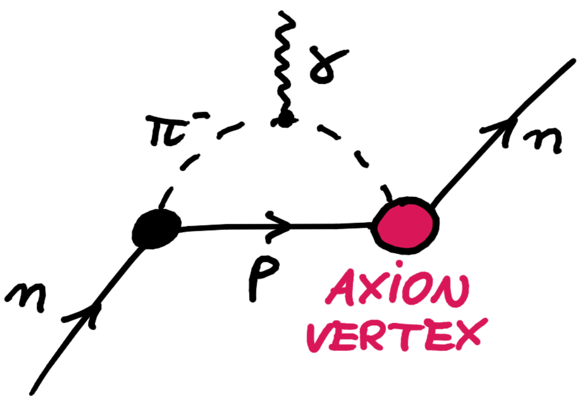
Looking for axions with nEDM experiments

Michał Rawlik on behalf of the **nEDM** collaboration

with: N. Ayres, M. Fairbairn, V. V. Flambaum, D. J. E. Marsh, Y. V. Stadnik

What is an axion?

- Axions tackle two problems of the modern physics:
  - The **strong CP problem** of QCD.
  - **Dark matter**, being a candidate therefor.
- Most searches focus on an axion coupling to photons.
- Recently, searching for a **gluon coupling** has been proposed:



Axion-induced nEDM oscillation

$$d_n(t) \approx 5.9 \times 10^{-22} C_G \left(\frac{10^{-22}\mathrm{eV}}{m_a}\right)\left(\frac{10^{16}\mathrm{GeV}}{f_a}\right)\cos(m_a t)\ e\cdot\mathrm{cm}$$

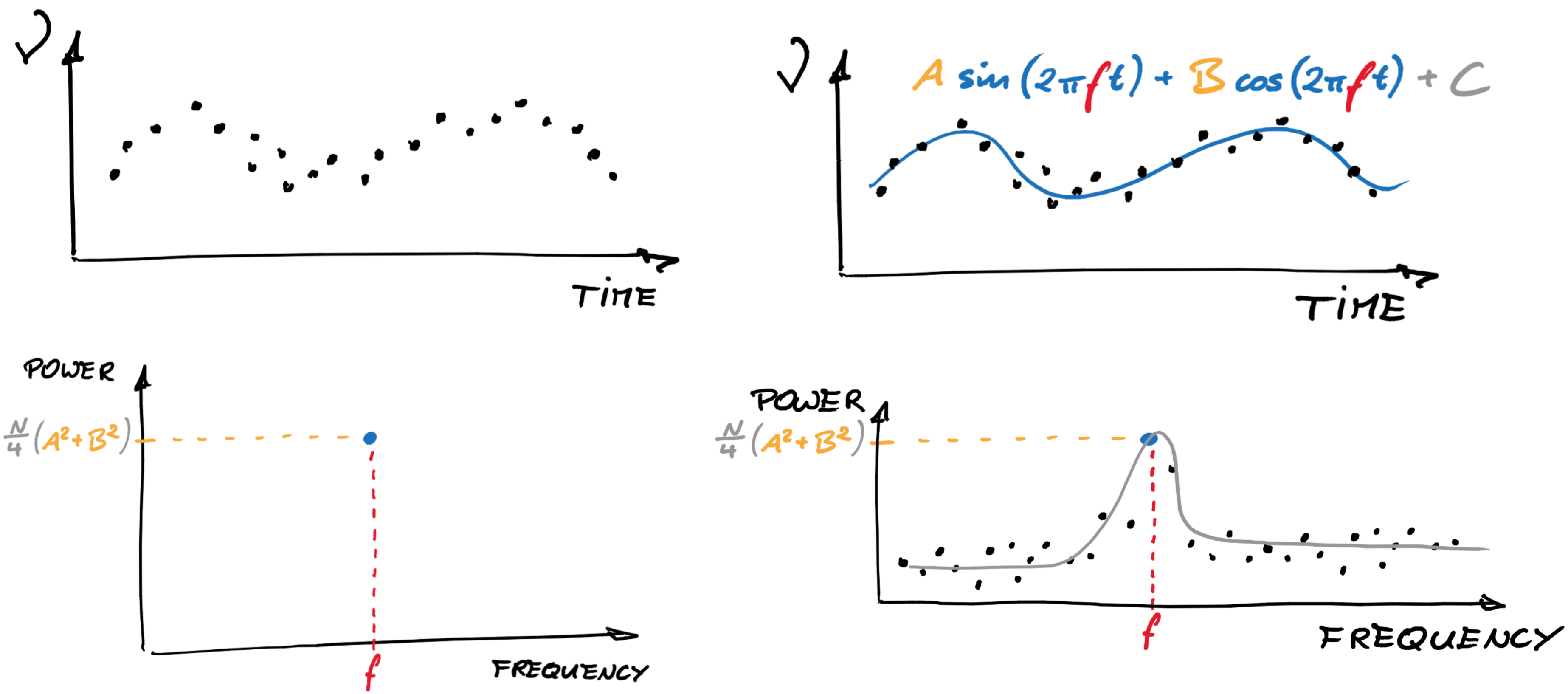
ILL & PSI
nEDM measurements:

$$h\nu = -2\vec{S}\cdot\left(\mu\,\vec{B} + d_n\,\vec{E}\right)$$

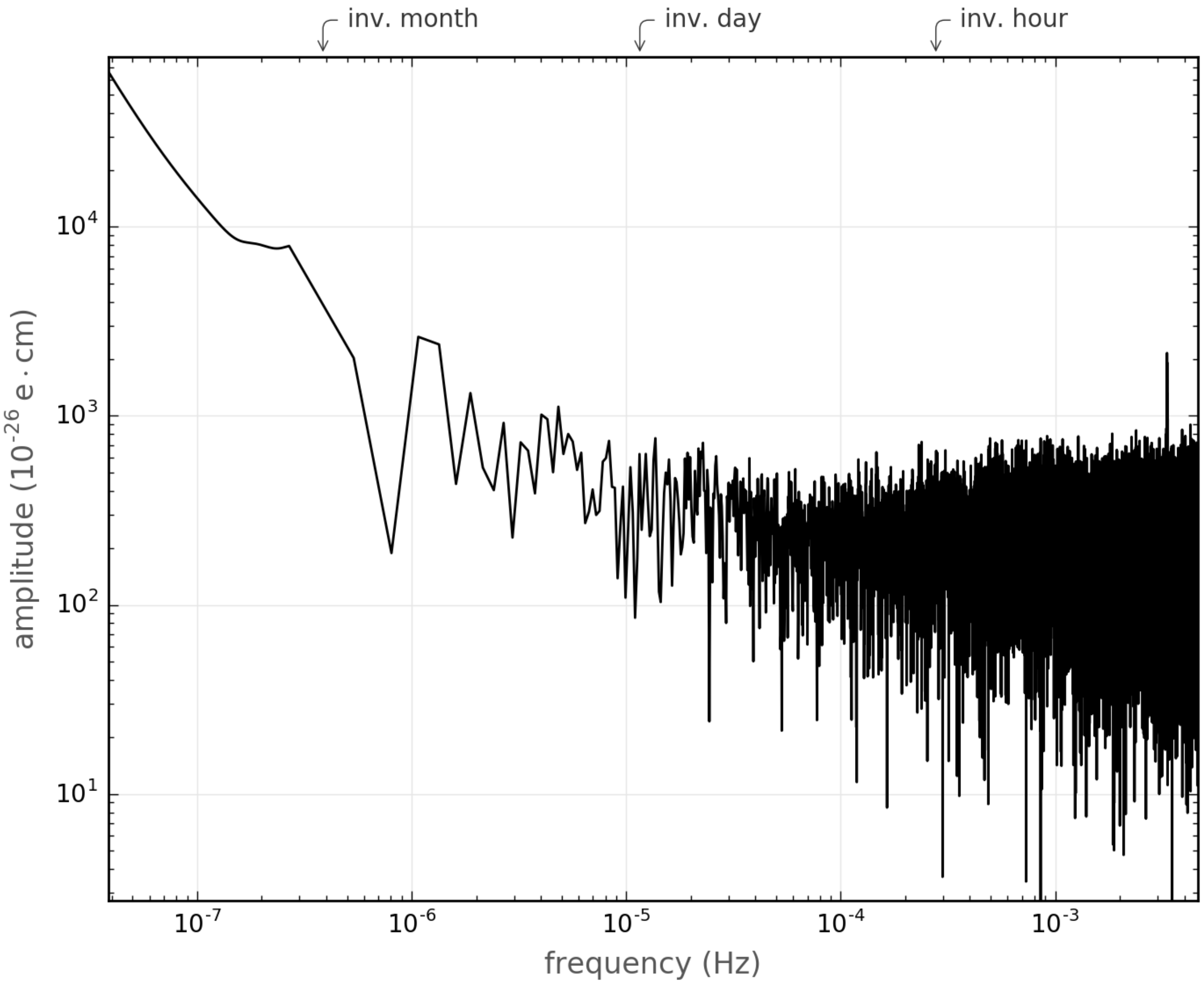
neutron precession frequency

If d_n oscillates, ν will oscillate too.

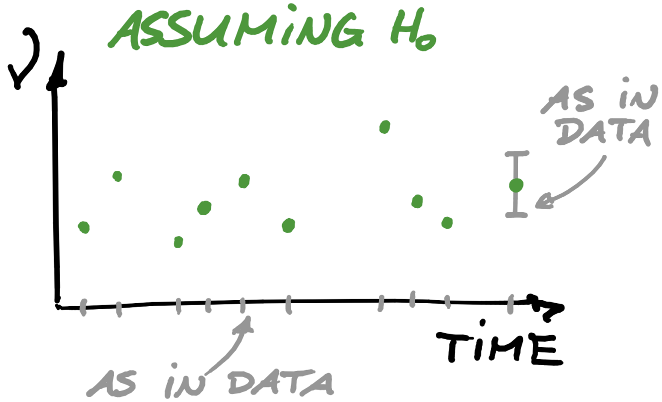
Least Squares Spectral Analysis (LSSA)

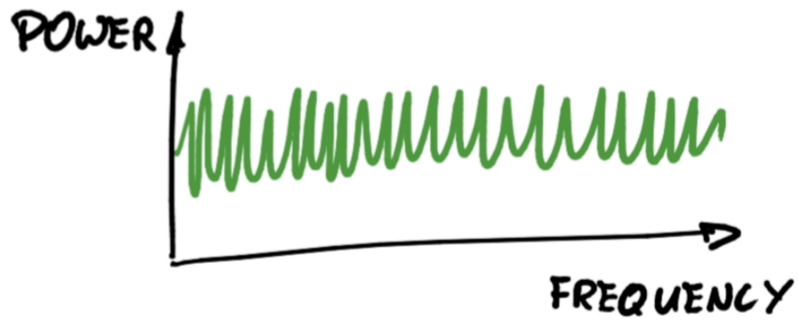


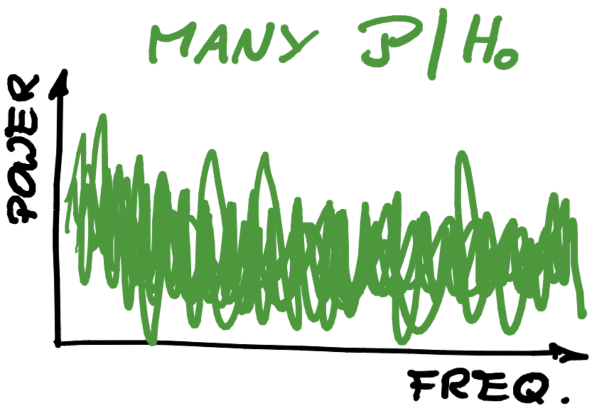
The Data Periodogram

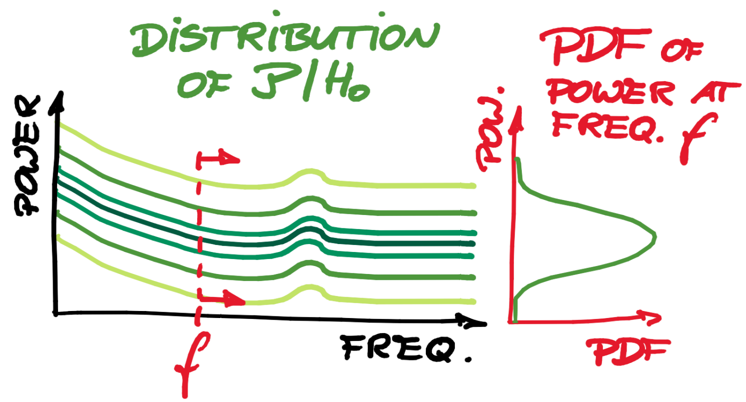


The Periodogram Under the Null Hypothesis

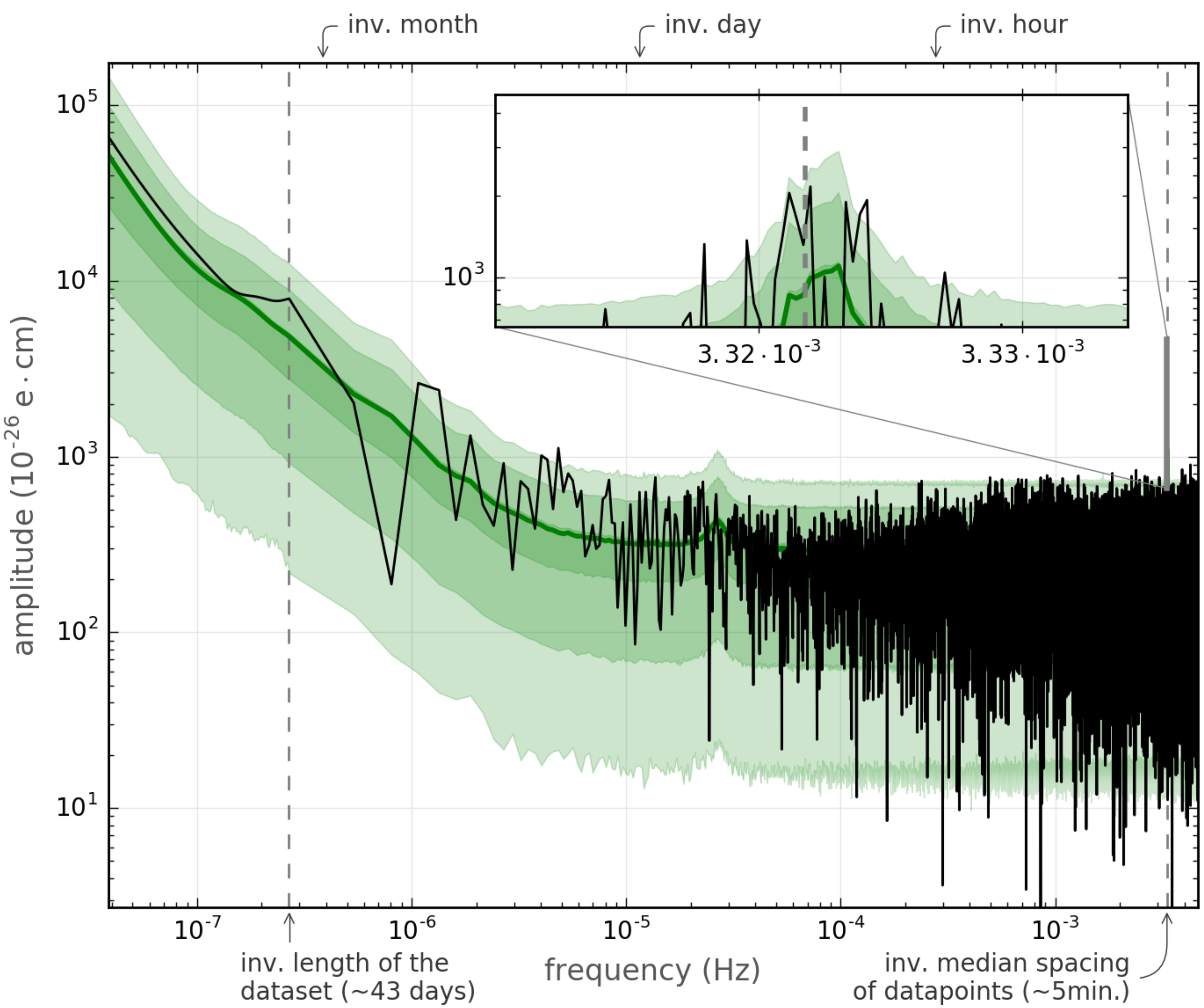




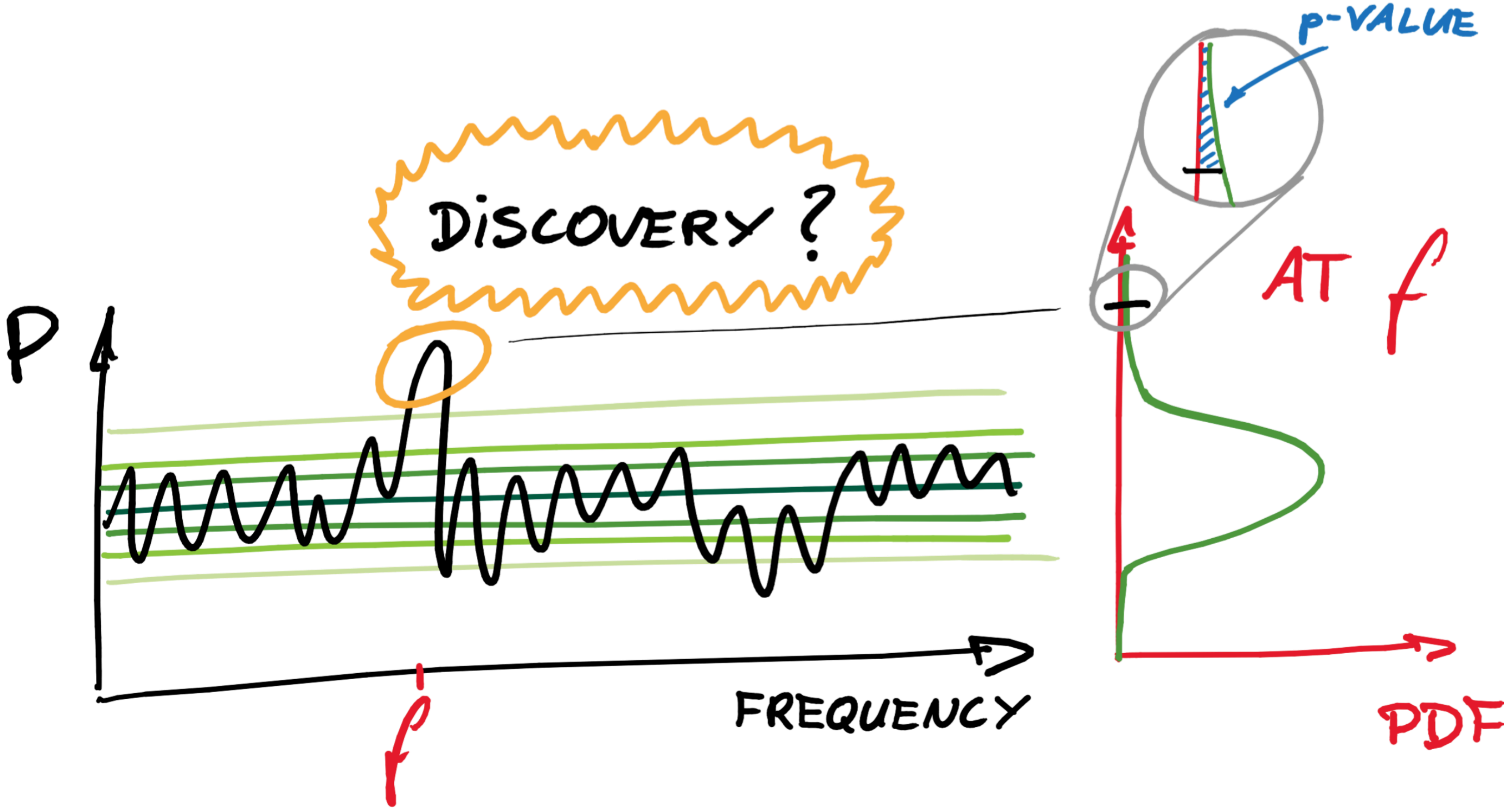




The Data Periodogram vs. the Null Hypothesis



The Null Hypothesis Test



The Look-Elsewhere Effect

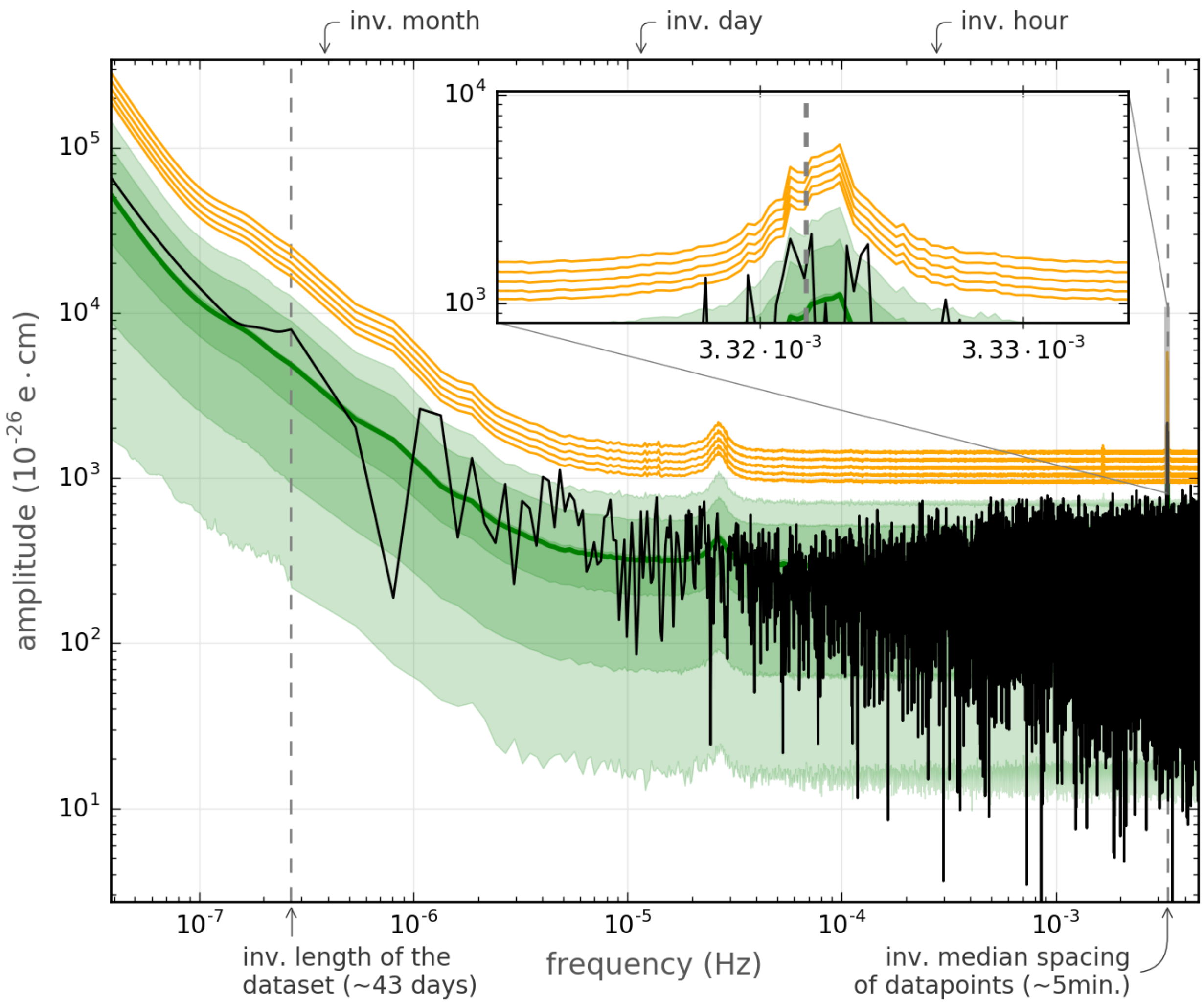
$$p_{\mathrm{global}} = 1 - (1 - p_{\mathrm{local}})^{\mathrm{number\ of\ frequencies}}$$

number of frequencies = 1 000 000

p_{global} = 3-sigma level

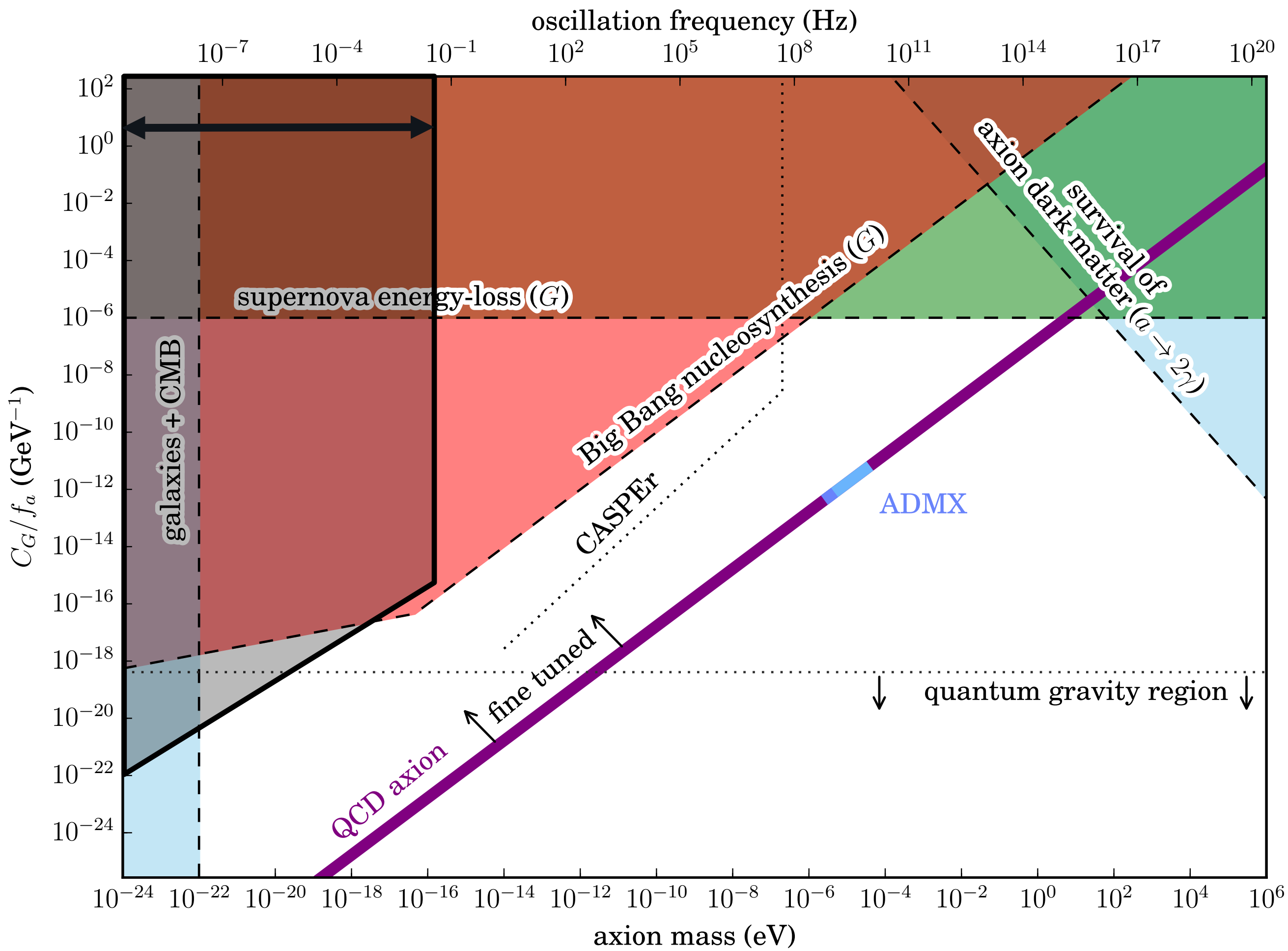
p_{local} = 6-sigma level

False-Alarm Thresholds



First Experimental Limits on the Axion-Gluon Coupling

We cover periods from minutes to decades.



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Thank you for your attention!

Further reading:

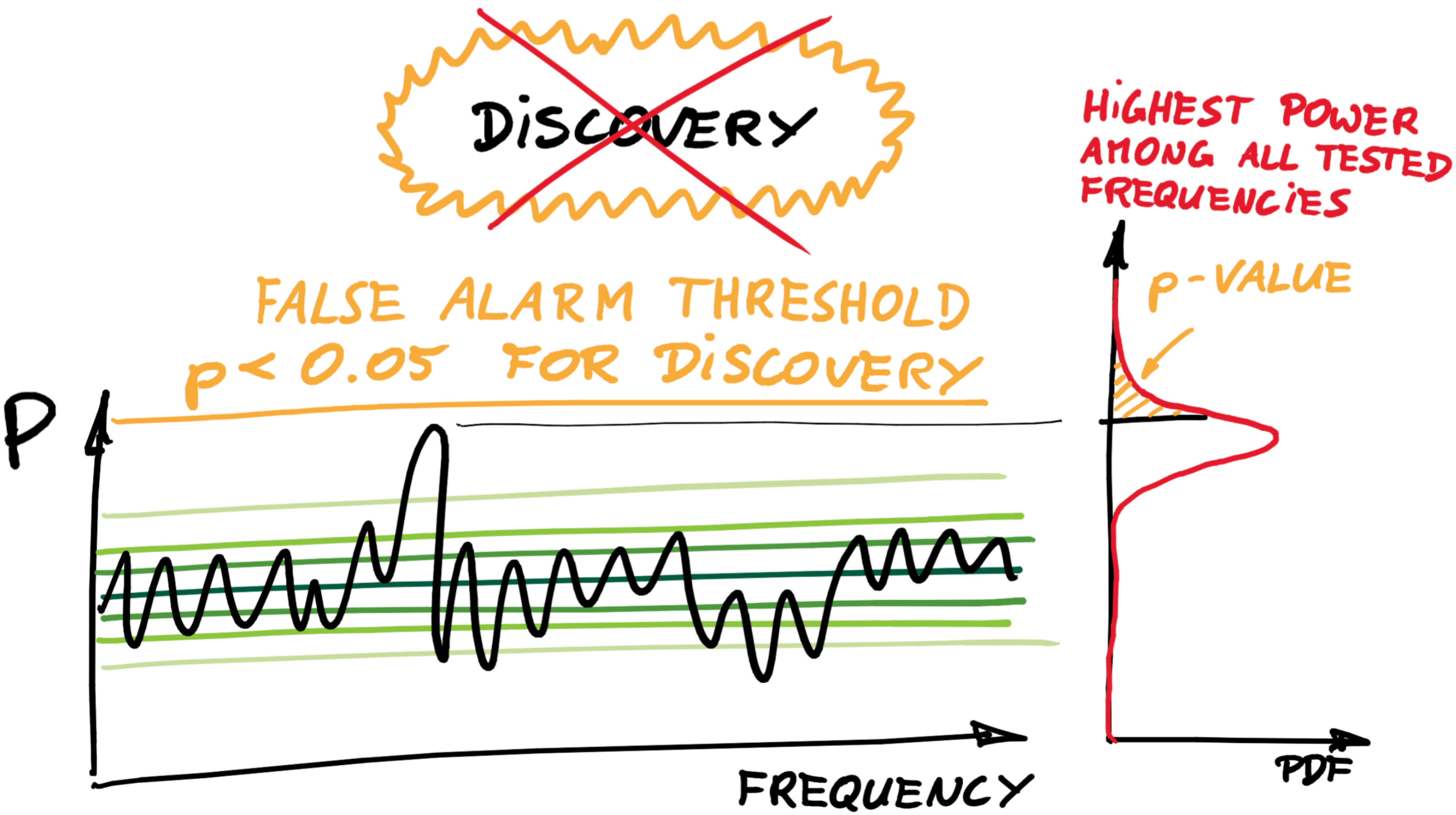
D. J. E. Marsh, Phys. Rep. **643**, 1 (2016)

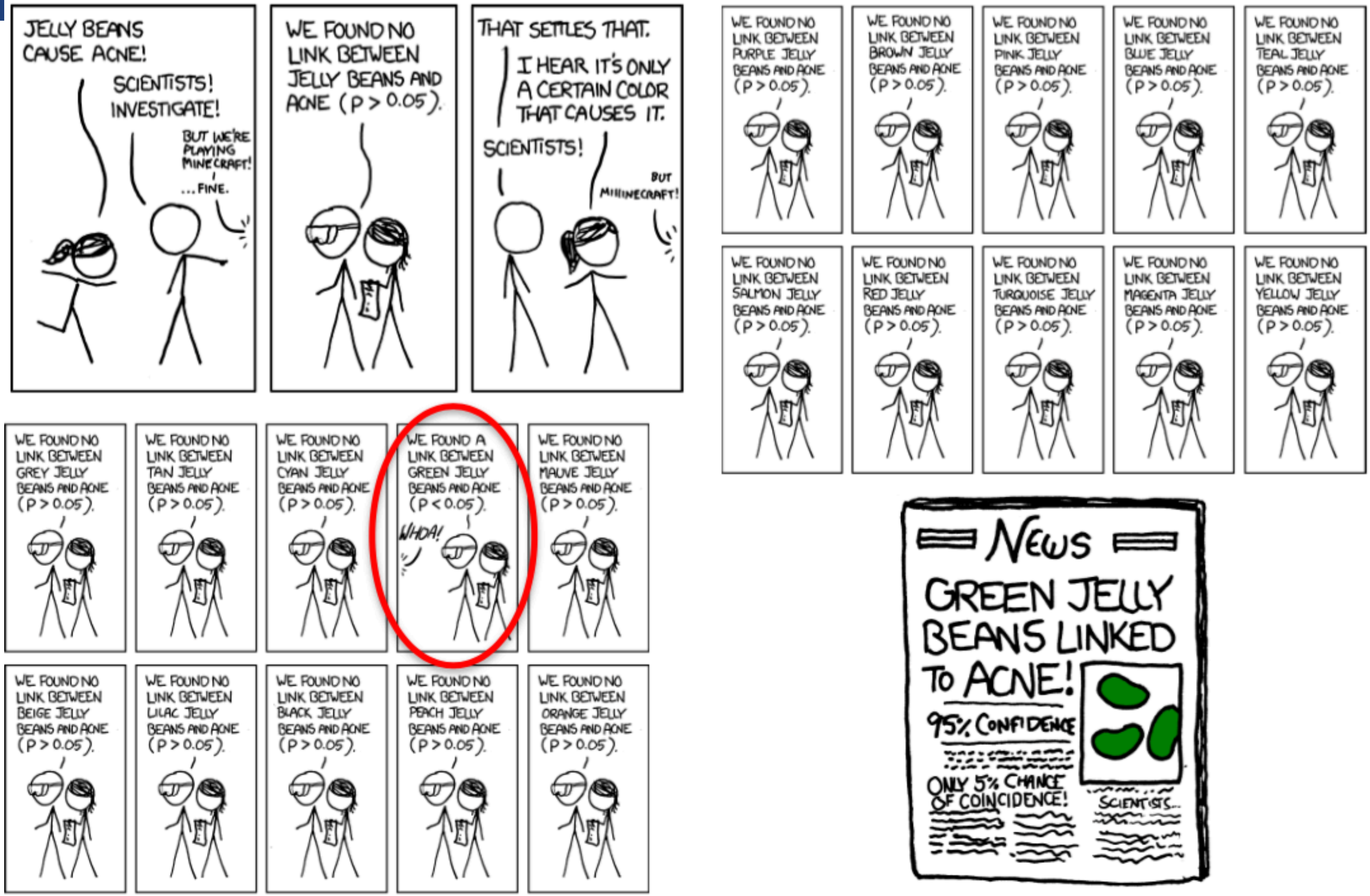
Y. V. Stadnik, V. V. Flambaum, Phys. Rev. D **89**, 043522 (2014)

J. D. Scargle, Astrophys. J. **263**, 835 (1982)

S. Algeri, J. Conrad, D. A. van Dyk, B. Anderson, arXiv:1602.03765 (2016)

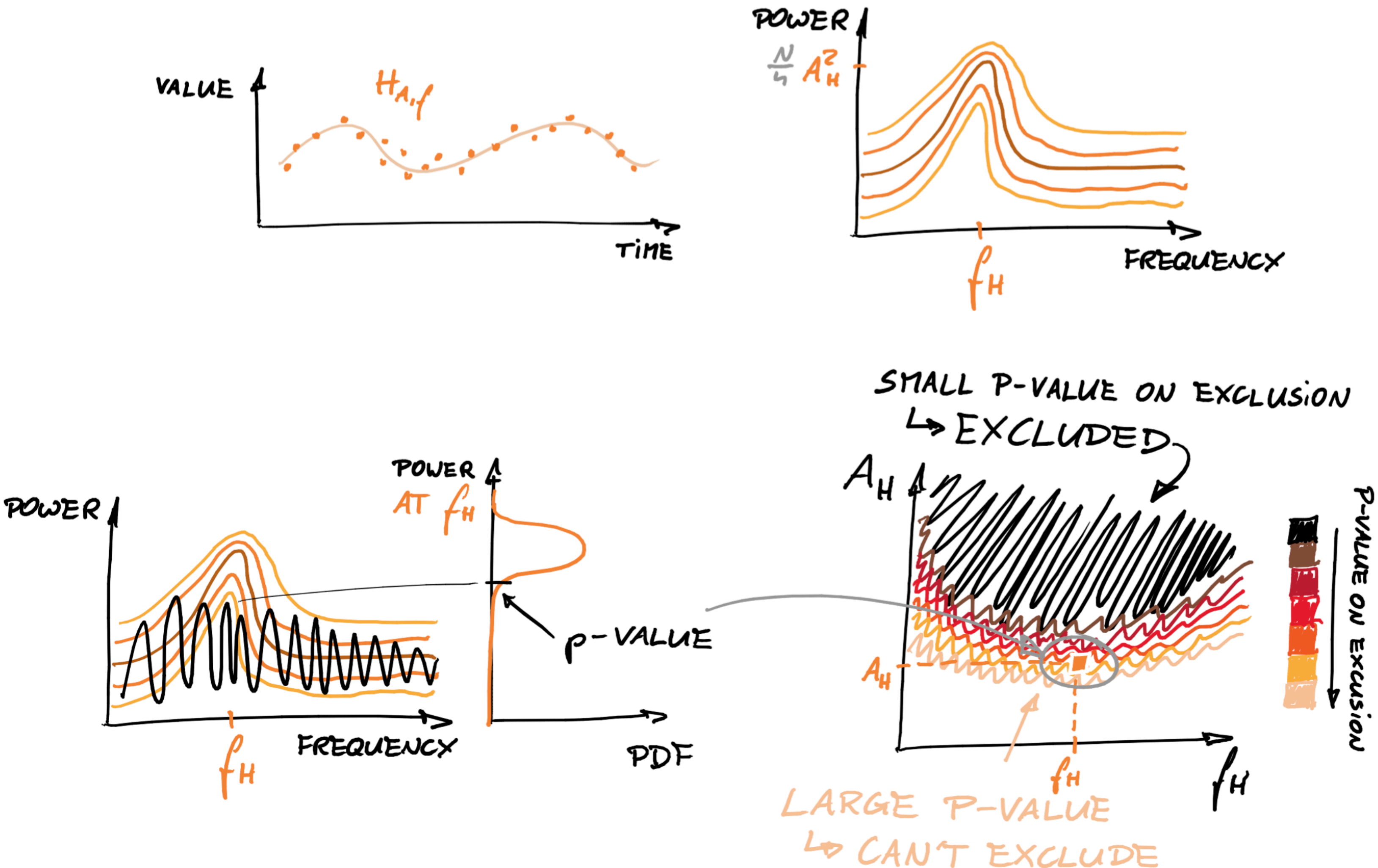
the look-elsewhere effect



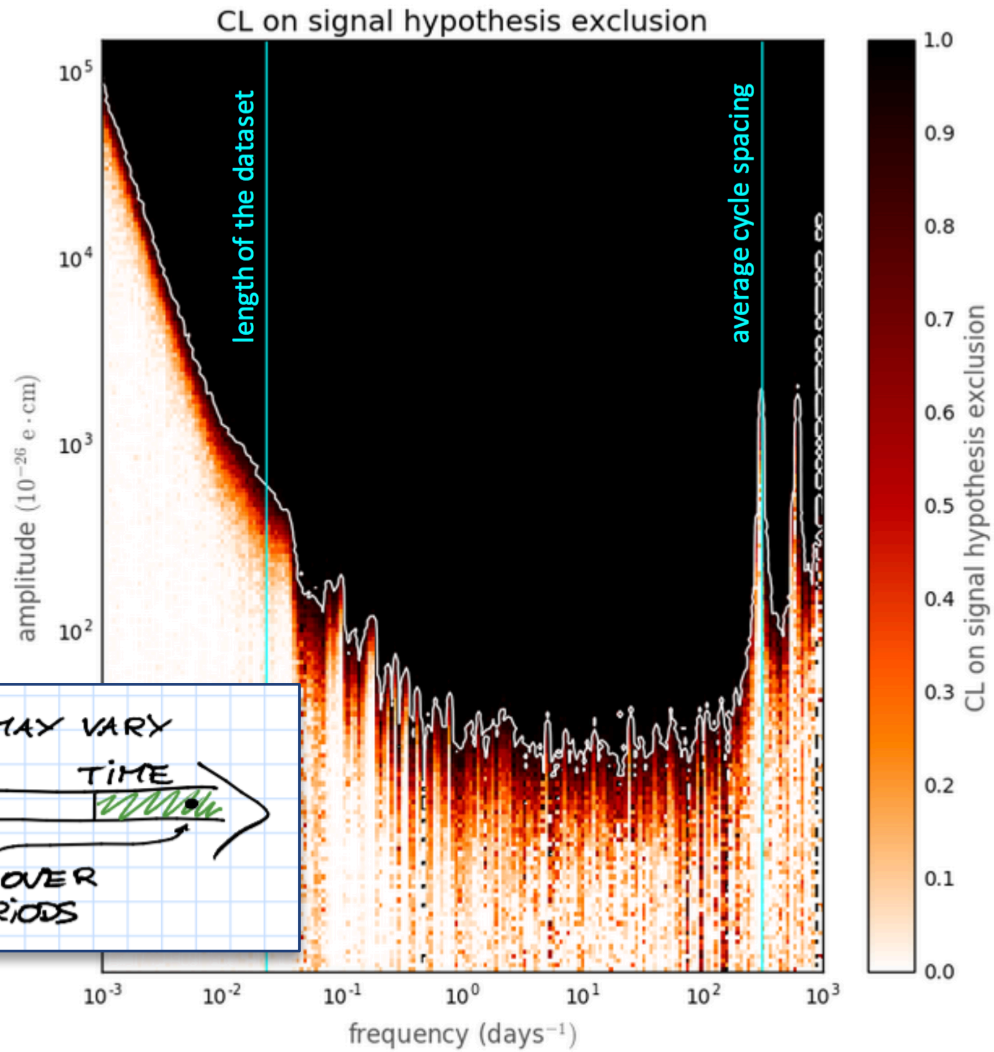

JELLY BEANS CAUSE ACNE!
SCIENTISTS! INVESTIGATE!
BUT WE'RE PLAYING MINECRAFT!
... FINE.
WE FOUND NO LINK BETWEEN JELLY BEANS AND ACNE (P > 0.05).
THAT SETTLES THAT.
I HEAR IT'S ONLY A CERTAIN COLOR THAT CAUSES IT.
SCIENTISTS!
BUT MIIINECRAFT!
WE FOUND NO LINK BETWEEN PURPLE JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN BROWN JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN PINK JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN BLUE JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN TEAL JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN SALMON JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN RED JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN TURQUOISE JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN MAGENTA JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN YELLOW JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN GREY JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN TAN JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN CYAN JELLY BEANS AND ACNE (P > 0.05).
WE FOUND A LINK BETWEEN GREEN JELLY BEANS AND ACNE (P < 0.05).
WHOA!
WE FOUND NO LINK BETWEEN MAUVE JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN BEIGE JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN LILAC JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN BLACK JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN PEACH JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN ORANGE JELLY BEANS AND ACNE (P > 0.05).
NEWS
GREEN JELLY BEANS LINKED TO ACNE!
95% CONFIDENCE
ONLY 5% CHANCE OF COINCIDENCE!
SCIENTISTS...

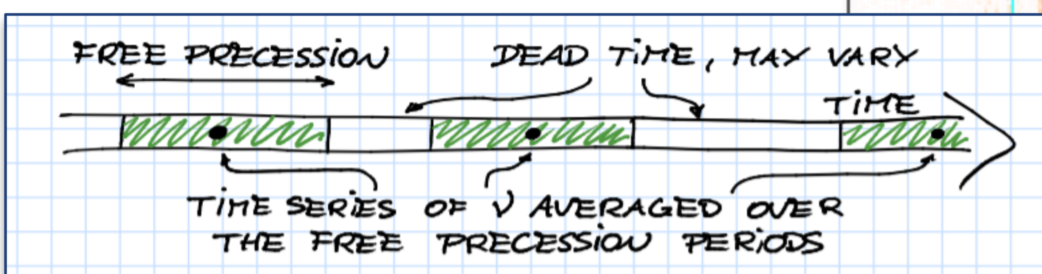
ETH zürich

determining the exclusion region



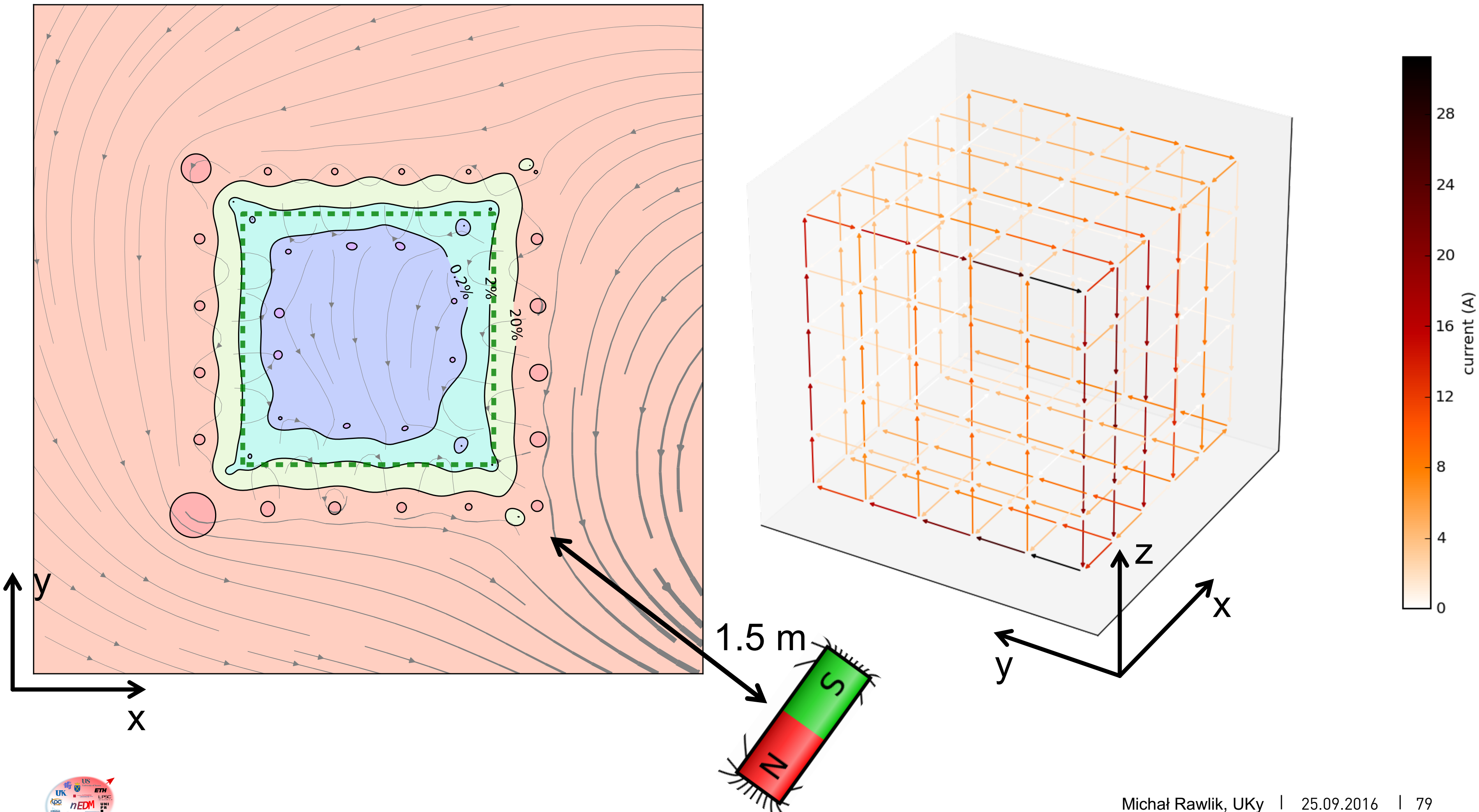
the exclusion region



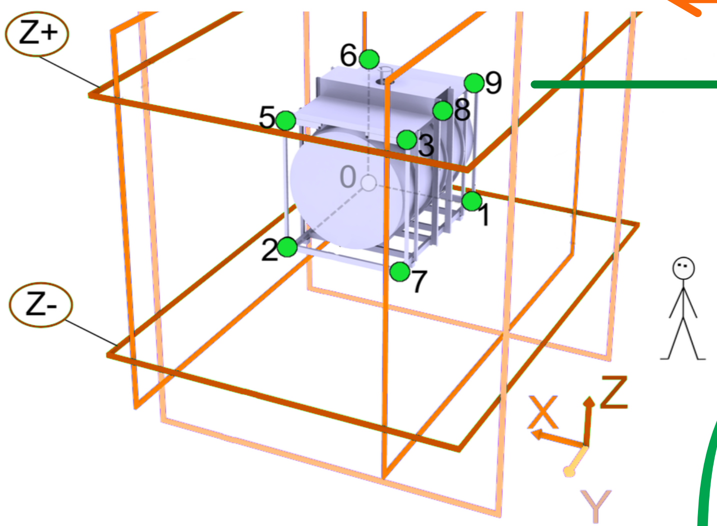


B_0 = Dipole Source 1.5m away

XY-cut in the middle



Feedback



$$? \begin{pmatrix} B_x^1 \\ B_y^1 \\ B_z^1 \\ B_x^2 \\ B_y^2 \\ \vdots \end{pmatrix} + ? = \begin{pmatrix} I_{X+} \\ I_{X-} \\ I_{Y+} \\ I_{Y-} \\ I_{Z+} \\ I_{Z-} \end{pmatrix}$$

Feedback with a Pseudoinverse

$$\vec{B} = M\,\vec{I} + \vec{B}_0$$

$$\vec{I} = M^i\left(\vec{B} - \vec{B}_0\right)$$

solve `I = M \ (B - B)`
for all `(B - B)`

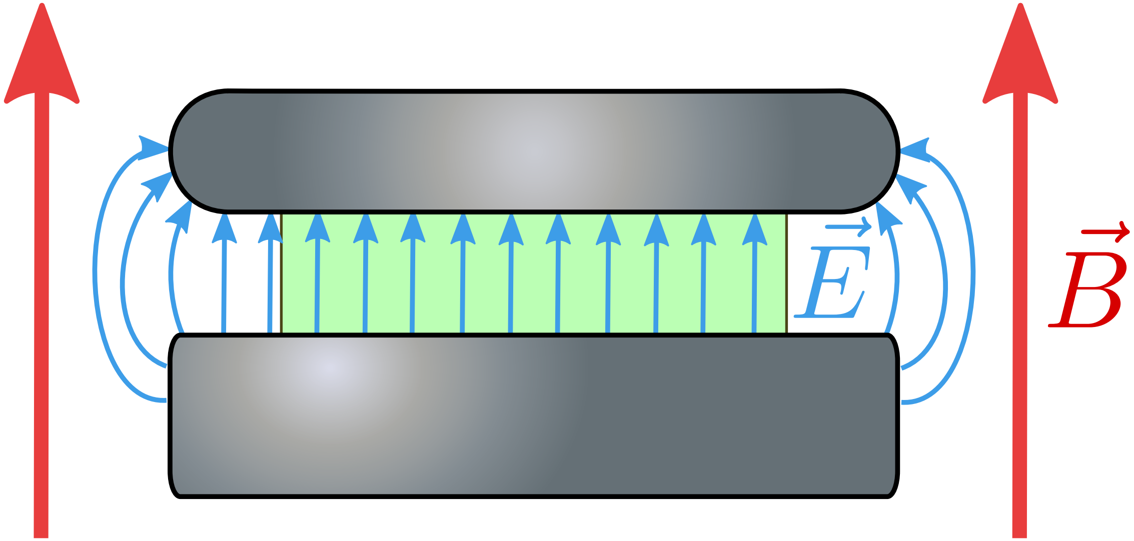
measure $\vec{B}$

$$\vec{B} = M\,\vec{I}_n + \vec{B}_0$$

$$\vec{B} \overset{!}{=} 0$$

$$\begin{aligned}\vec{I}_{n+1} &= -M^i\,\vec{B}_0 \\ &= -M^i\left(\vec{B} - M\,\vec{I}_n\right) \\ &= \vec{I}_n - M^i\,\vec{B}\end{aligned}$$

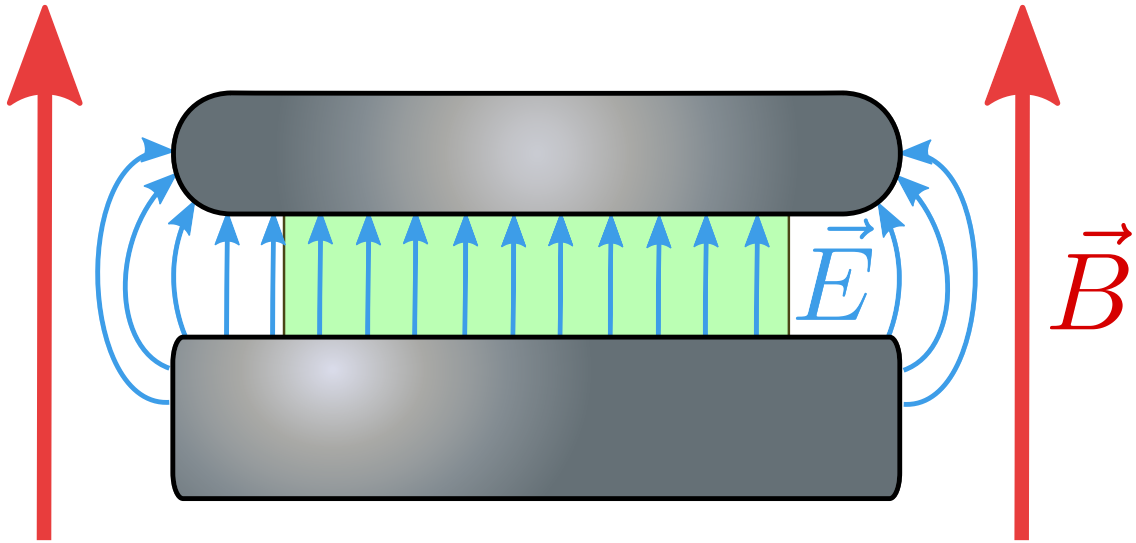
Measurement of the electric dipole moment of the neutron



$$f_n = \frac{2}{h}\left(\vec{\mu}_n \cdot \vec{B} + \vec{d}_n \cdot \vec{E}\right)$$

$\vec{B} \uparrow\uparrow \vec{E}$ $\vec{B} \uparrow\downarrow \vec{E}$

Measurement of the electric dipole moment of the neutron

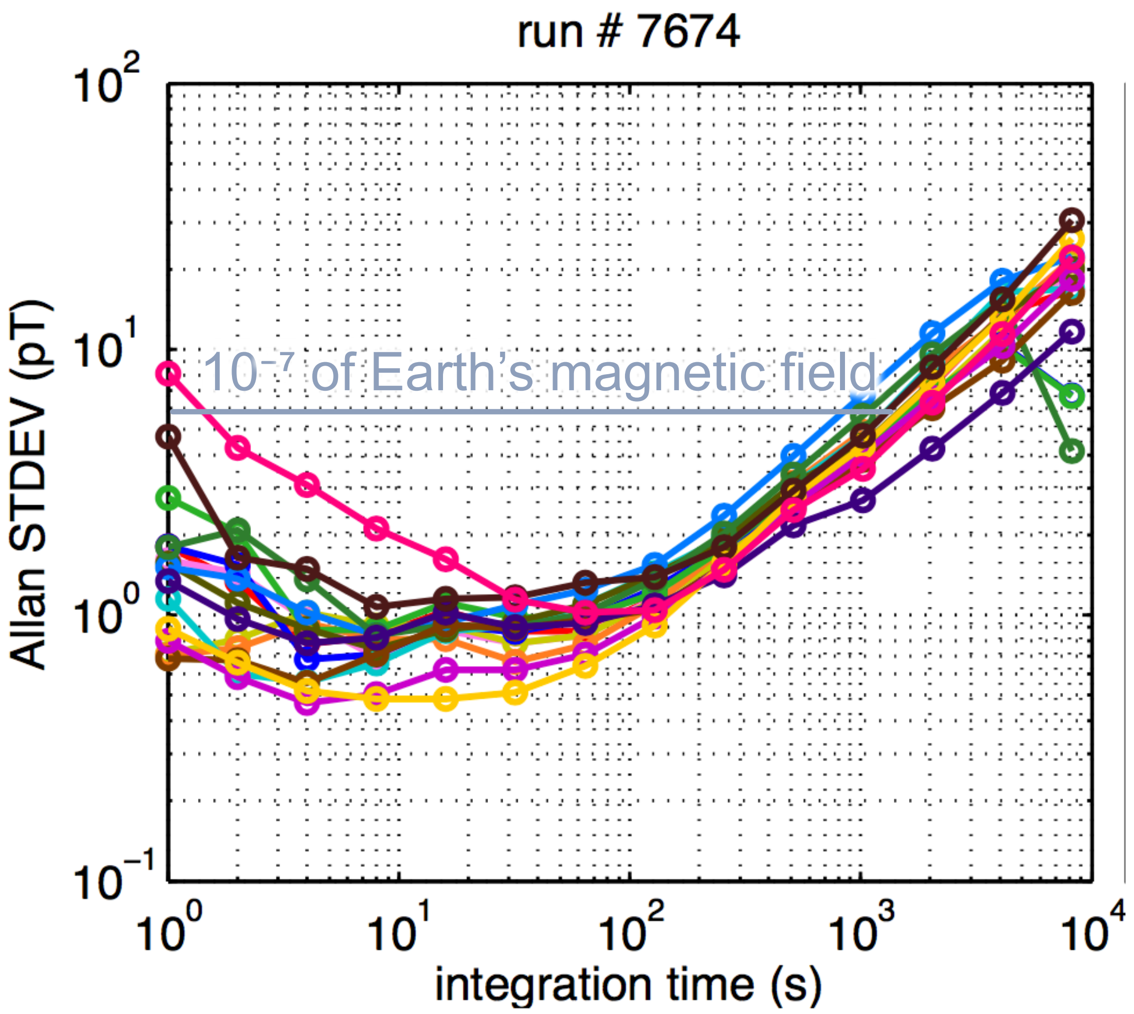


$$d_n = \frac{1}{2E}\left(h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) + \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

$$d_n = \frac{1}{2E}\left(h\Delta f_n + \mu_n \Delta B\right)$$

Stability of the magnetic field

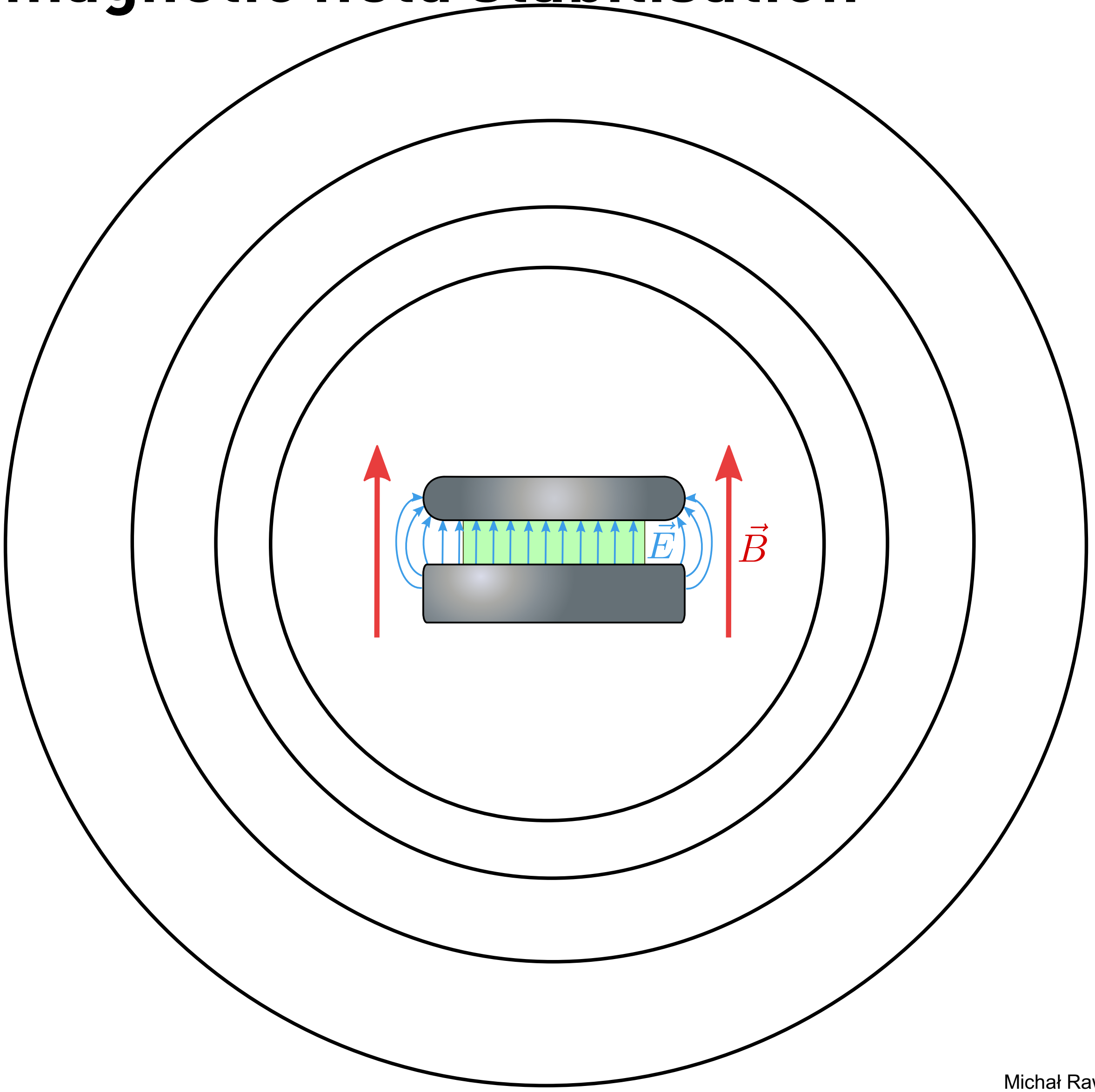
the field is this stable…



… when averaged this long

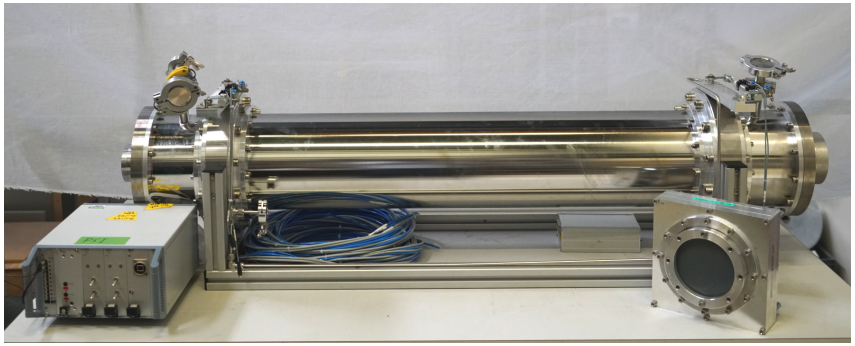
source: PhD thesis of Dr. Beatrice Franke

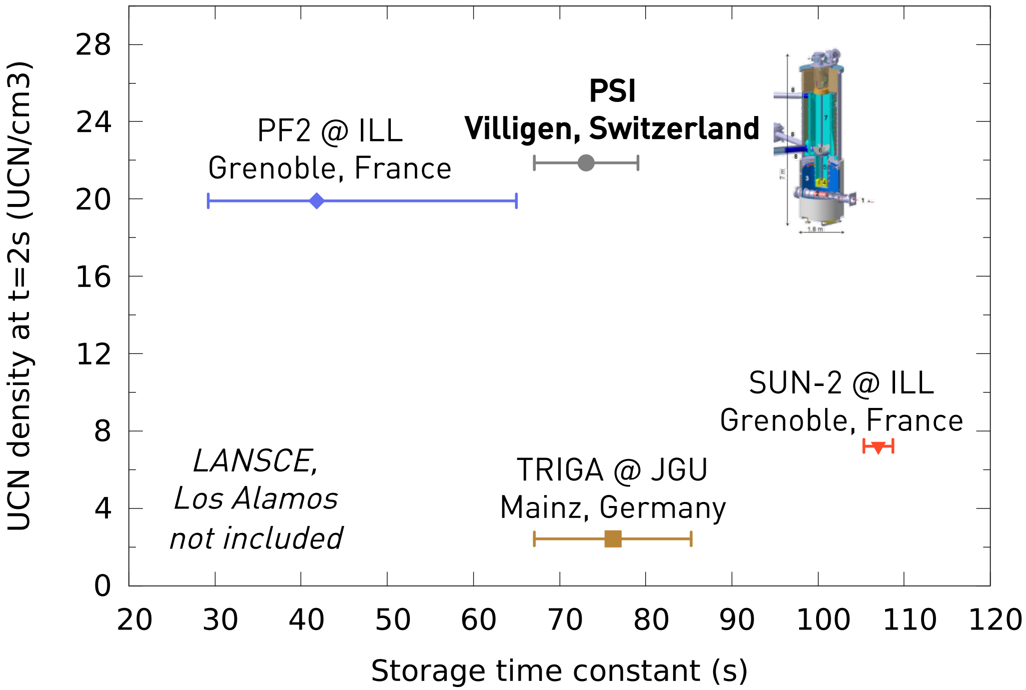
Passive magnetic field stabilisation



Thank you for your attention!

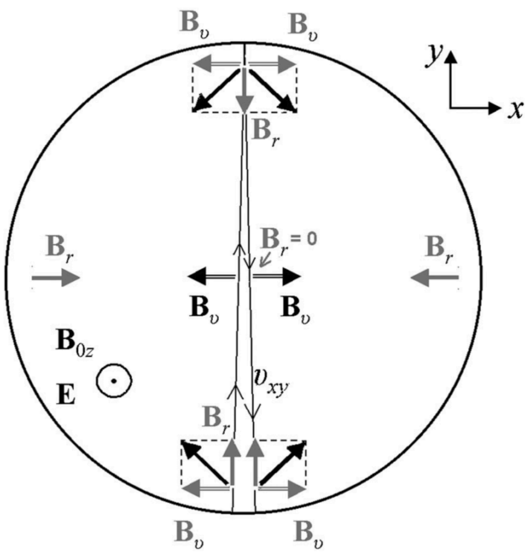
World's strongest UCN source



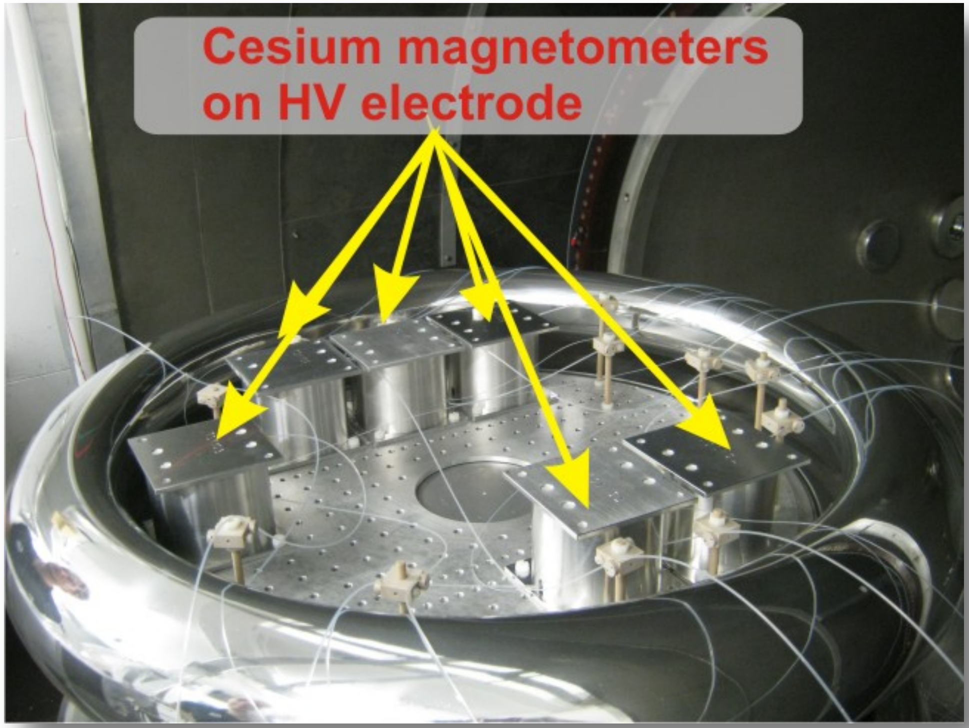


Systematic effects

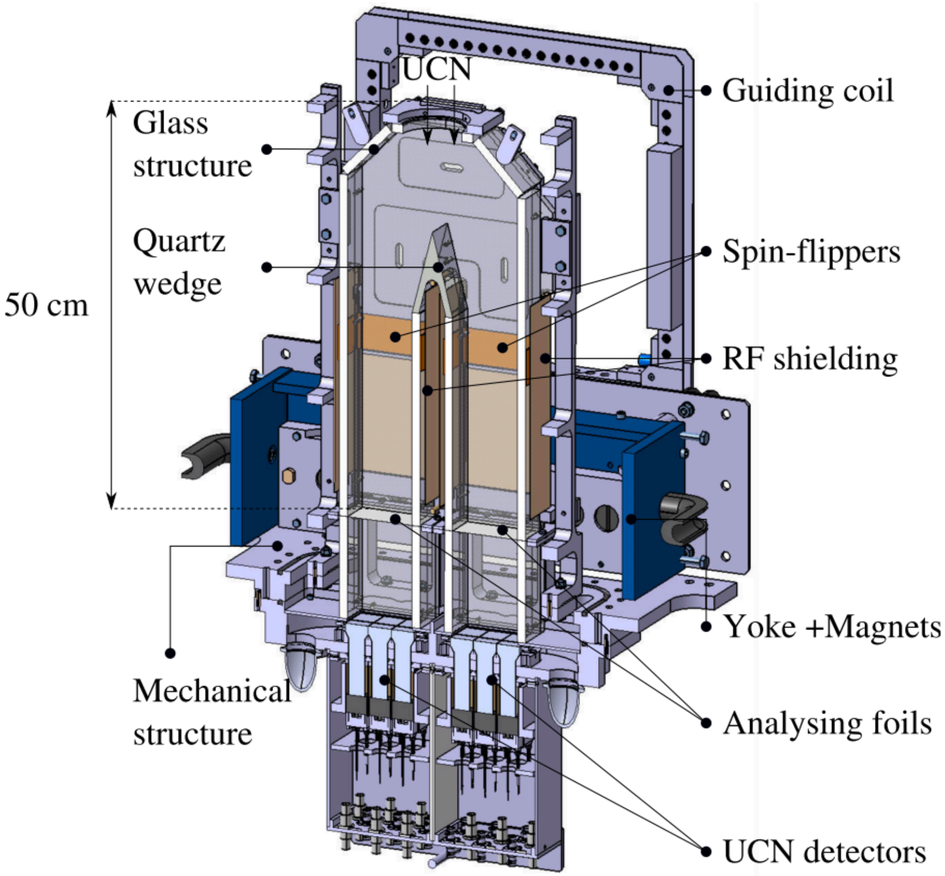
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle {B^2}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}} \right)$$

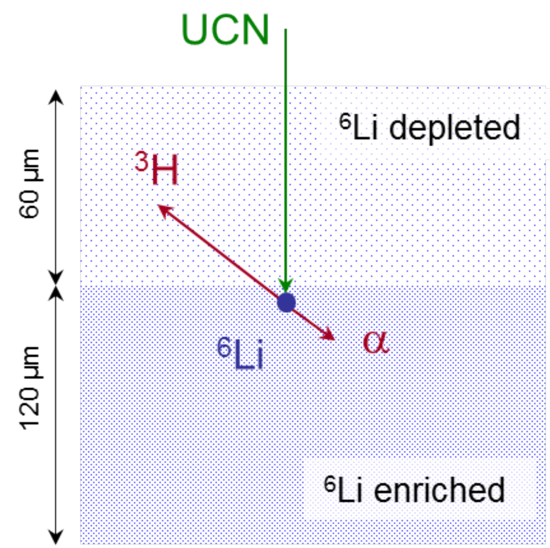


Atomic Cesium magnetometers

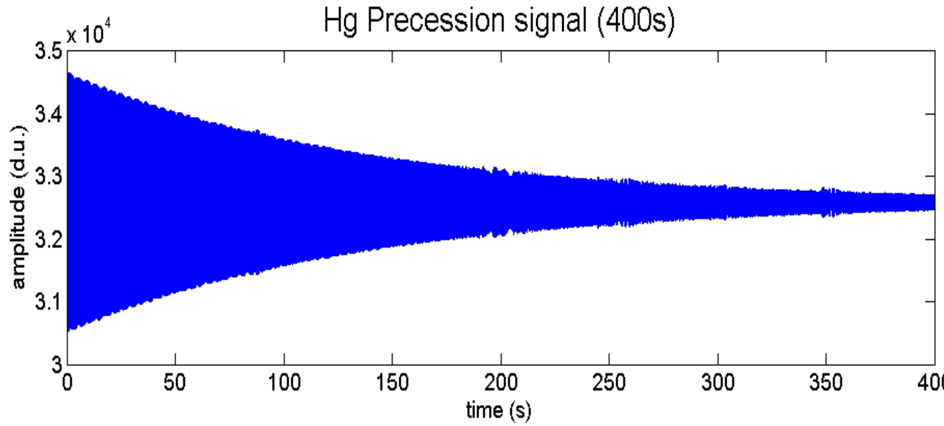


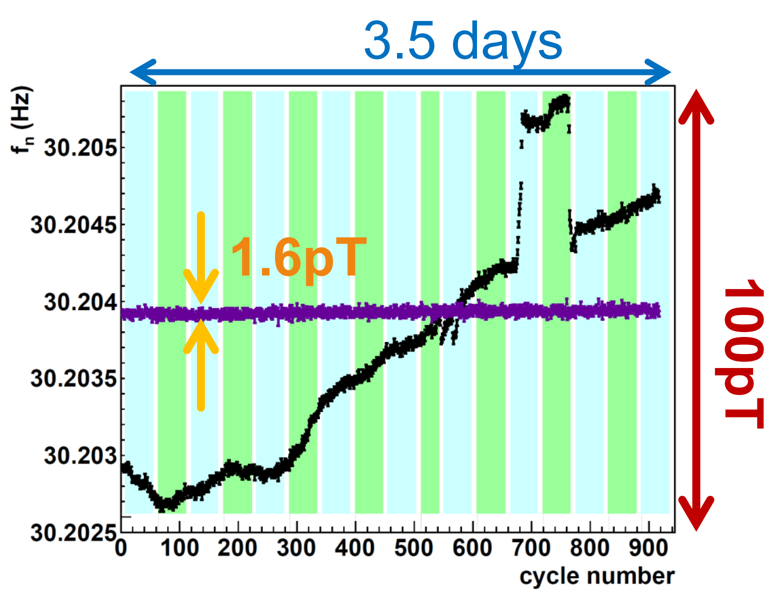
Detection system



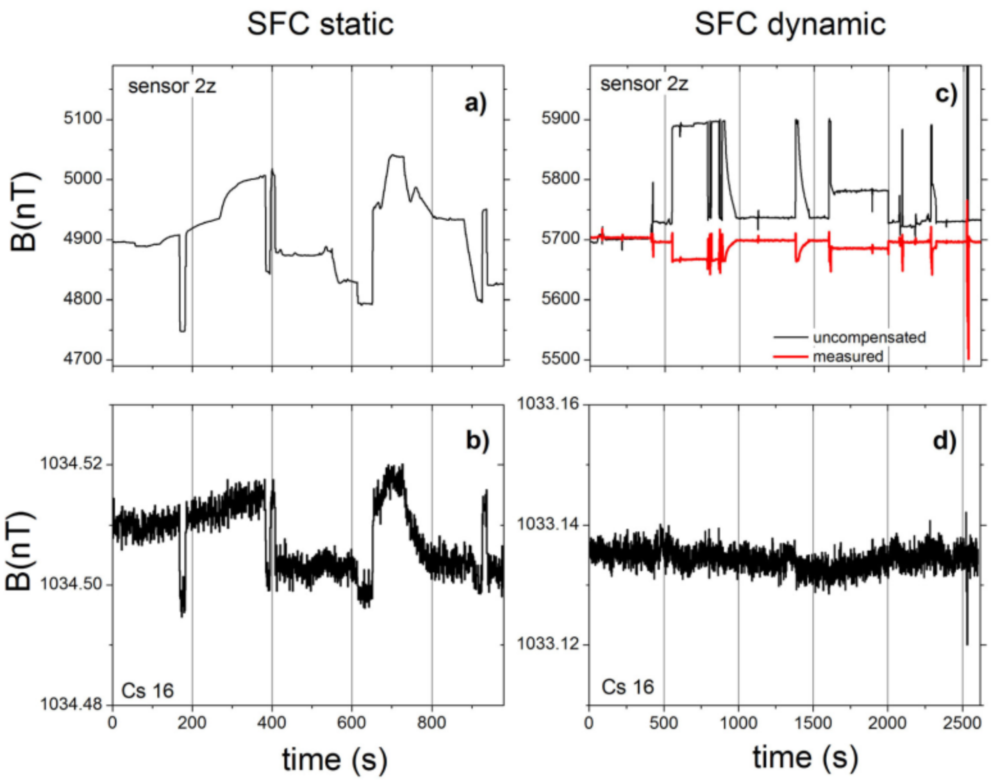


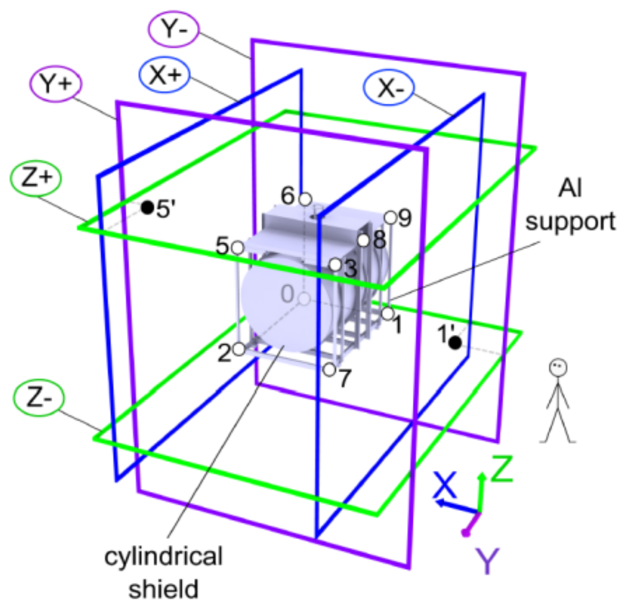
Mercury cohabiting magnetometer





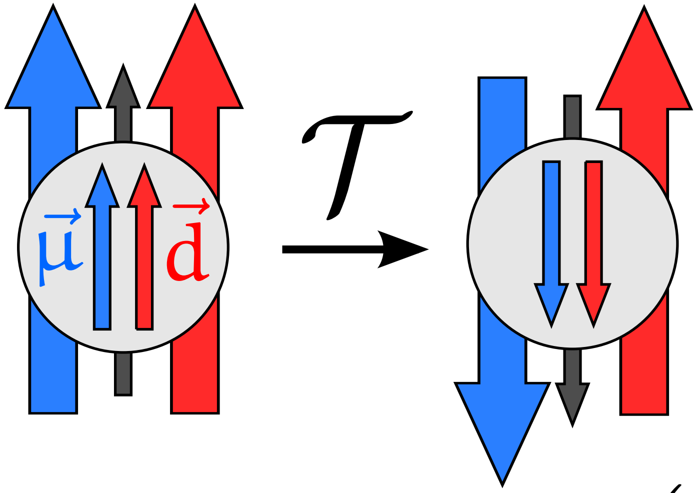
Surrounding Field Compensation System





Electric dipole moment

$$\mathcal{H} = -\hat{s} \cdot \left(\mu \, \vec{B} - d_n \, \vec{E} \right)$$



$$\mathcal{H}_{\mathcal{T}} = -\left(-\hat{s}\right) \cdot \left(\mu \left(-\vec{B} \right) + d_n \, \vec{E} \right)$$
$$= -\hat{s} \cdot \left(\mu \, \vec{B} + d_n \, \vec{E} \right)$$

The strong CP problem

For there to be more matter than antimatter the CP symmetry needs to be violated.

(one of the three Sakharov criteria)

$$\mathcal{L}_{QCD} = \ldots + \frac{g^2}{32\pi^2}\, \theta_{QCD}\, G\tilde{G}$$

expect: $\theta_{QCD} \sim 1$

measured: $\theta_{QCD} \lesssim 10^{-10}$

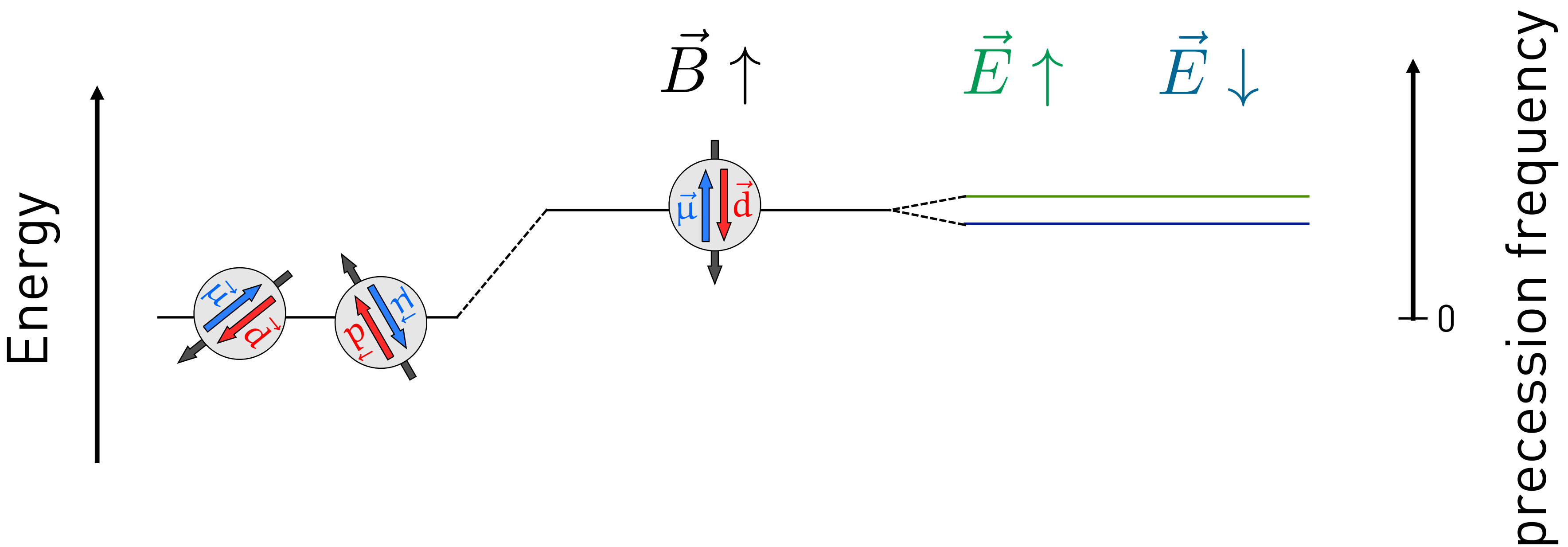
Neutron Electric Dipole Moment

$$d_n^{QCD} = (-2.9 \pm 0.9) \cdot 10^{-16} \; \theta_{QCD} \quad \mathrm{e\,cm}$$

neutron electric dipole moment (nEDM)
(from lattice QCD calculations)

How to measure the nEDM?

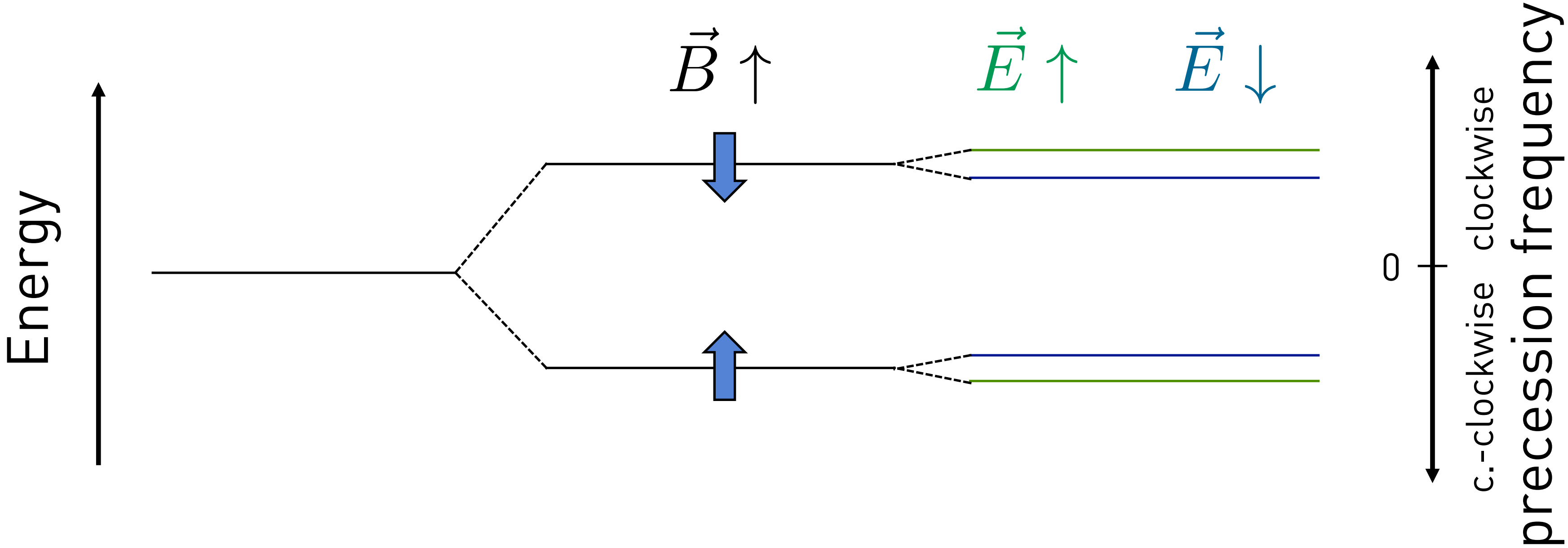
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d}_n \cdot \vec{E}$$



Measure a change in precession frequency in a presence of an electric field.

How to measure the nEDM?

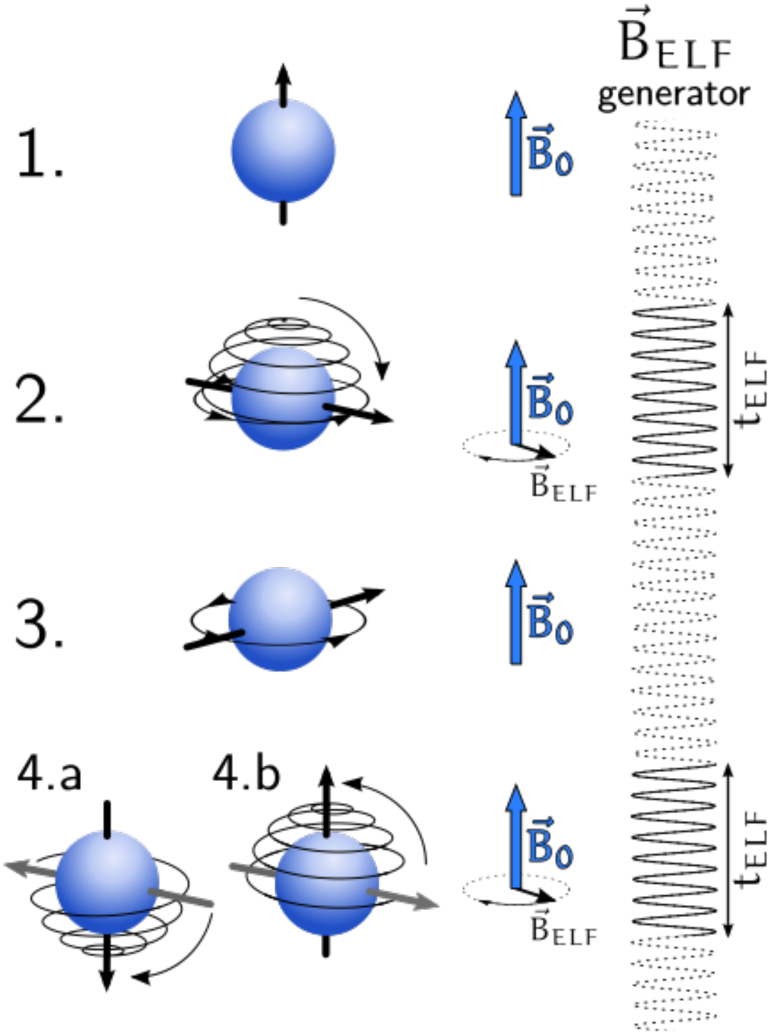
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d}_n \cdot \vec{E}$$

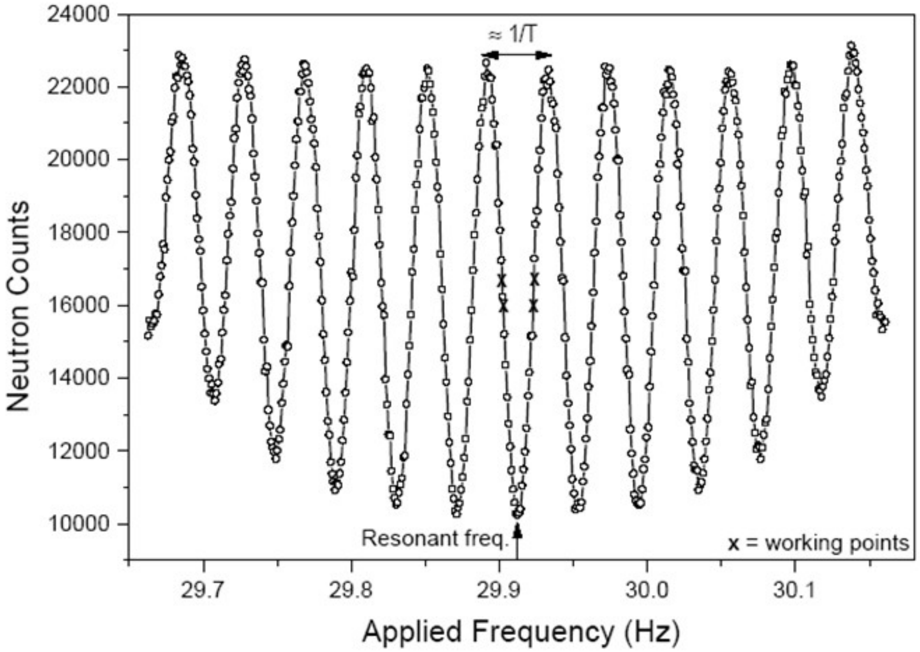


Measure a change in precession frequency in a presence of an electric field.

Spallation target

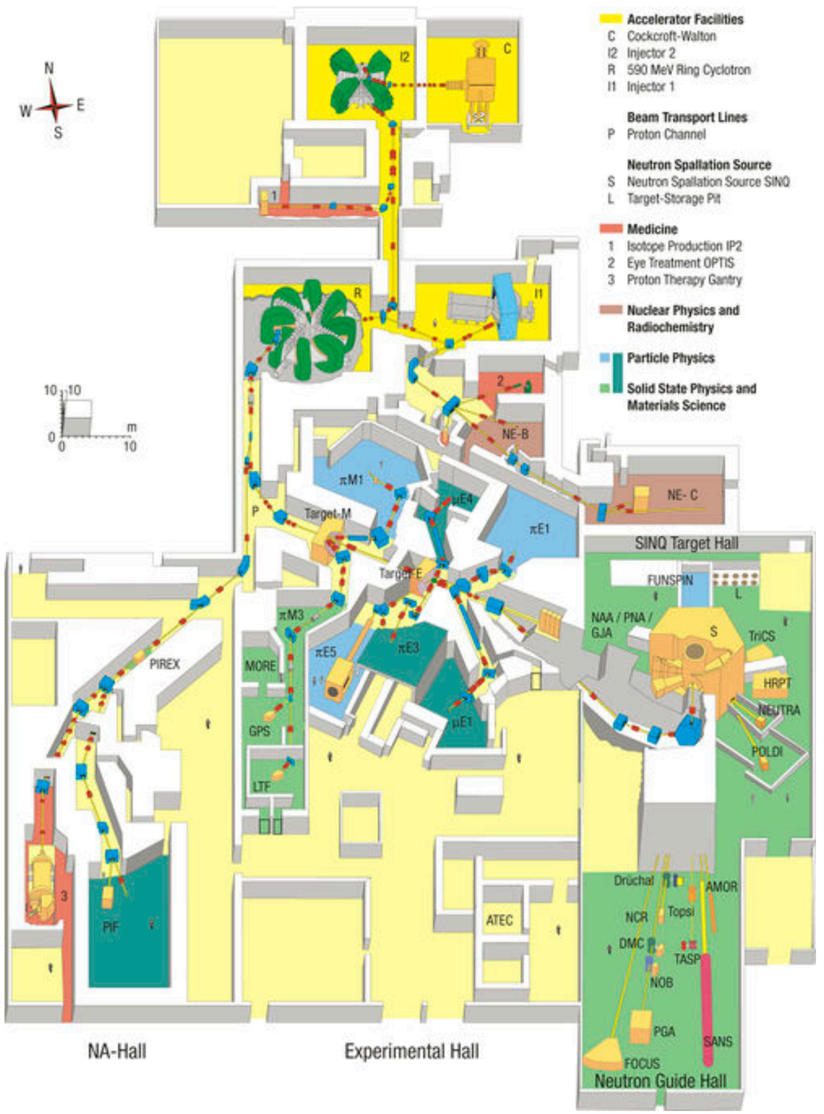
Ramsey method – frequency measurement

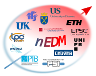




Paul Scherrer Institute

2mA
590MeV
protons





SFC and mu-metal

Mercury and Cesium comagnetometry

Mention gravity and the CM offset –
that's why Cs are needed

Exotic physics

make two slides

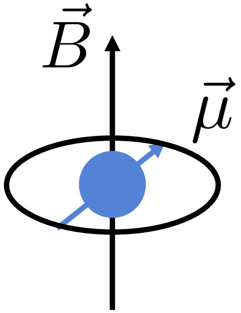
Exotic physics

How to measure the nEDM?

Thou shall measure frequency.

Bloch equation: $$\partial_t \langle \vec{\mu} \rangle = \gamma \langle \vec{\mu} \rangle \times \vec{B}$$

Spin precession:



Gyromagnetic ratio of the neutron: $$-29.1646943(69)\,\frac{\mathrm{Hz}}{\mu\mathrm{T}}$$

Surrounding Field Compensation System