ETH zürich

Search for axion dark matter with ultracold neutrons

Michał Rawlik

ETH Zürich, Switzerland

on behalf of the **nEDM** collaboration

with: **AYRES, N. J.** *(University of Sussex, UK)*
FLAMBAUM, V. V. *(University of New South Wales, Australia)*
STADNIK, Y. V. *(Johannes Gutenberg-Universität Mainz, Germany)*
FAIRBAIRN, M. *(King's College London, UK)*
MARSH, D. J. E. *(King's College London, UK)*

Motivation

27%

Dark Matter

Universe content:

27%

local galactic neighbourhood:

(observations of stellar orbits)

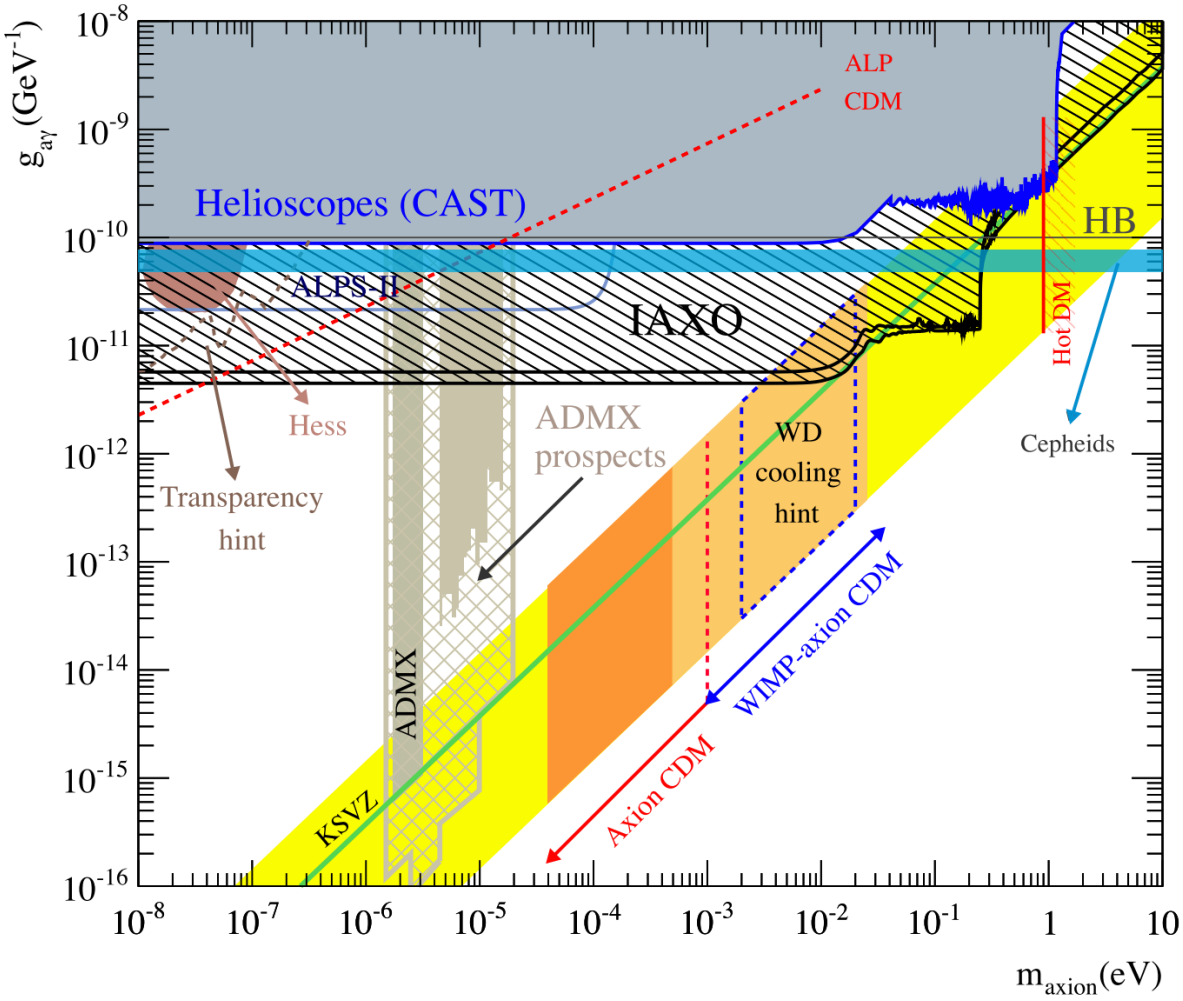
0.4 GeV/cm^3

mean dark matter energy density:

1.3×10^{-6} GeV/cm^3

Axions

Axion – photon coupling



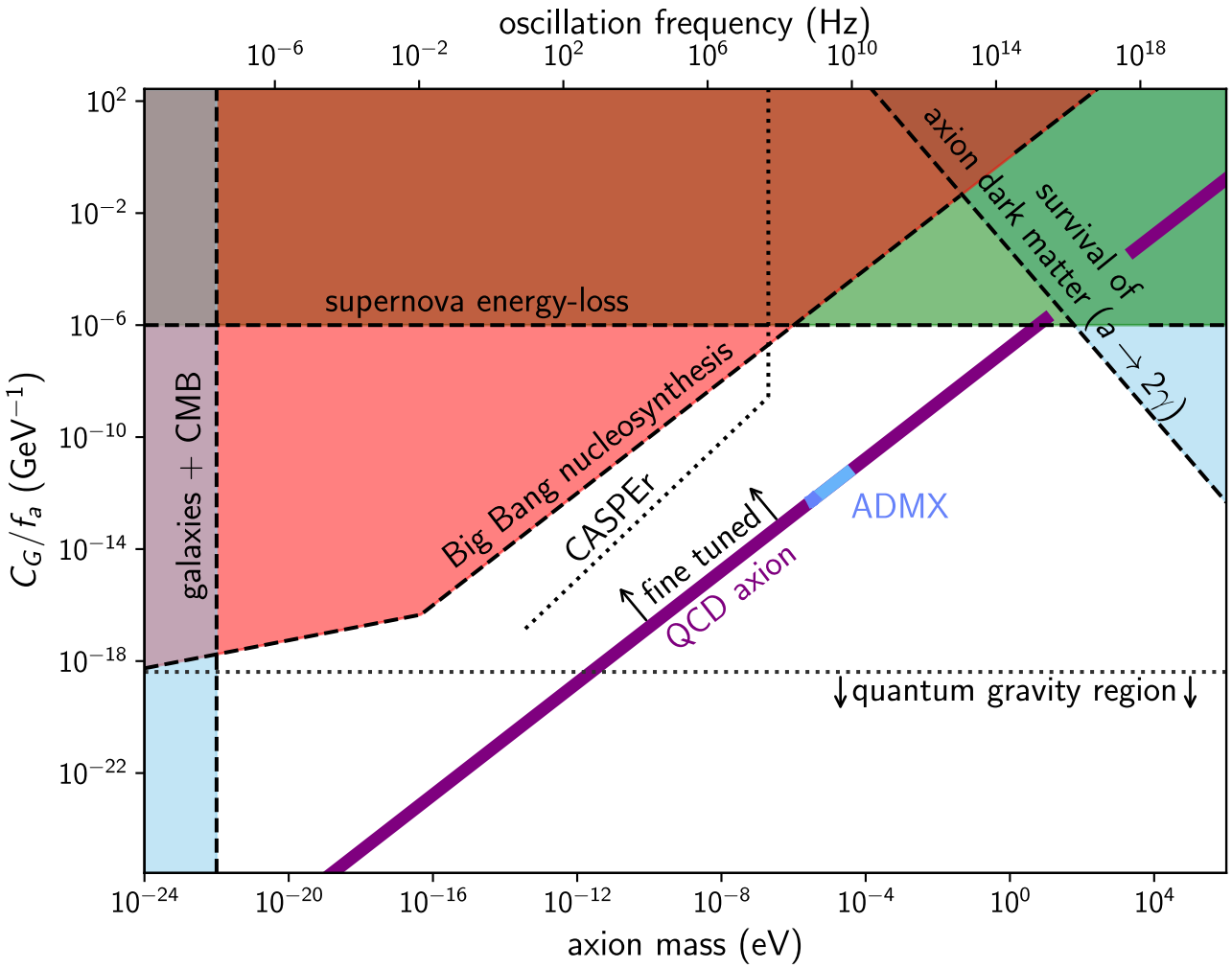
source: G. Carosi et al., ArXiv e-prints (2013), 1309.7035.

Couplings

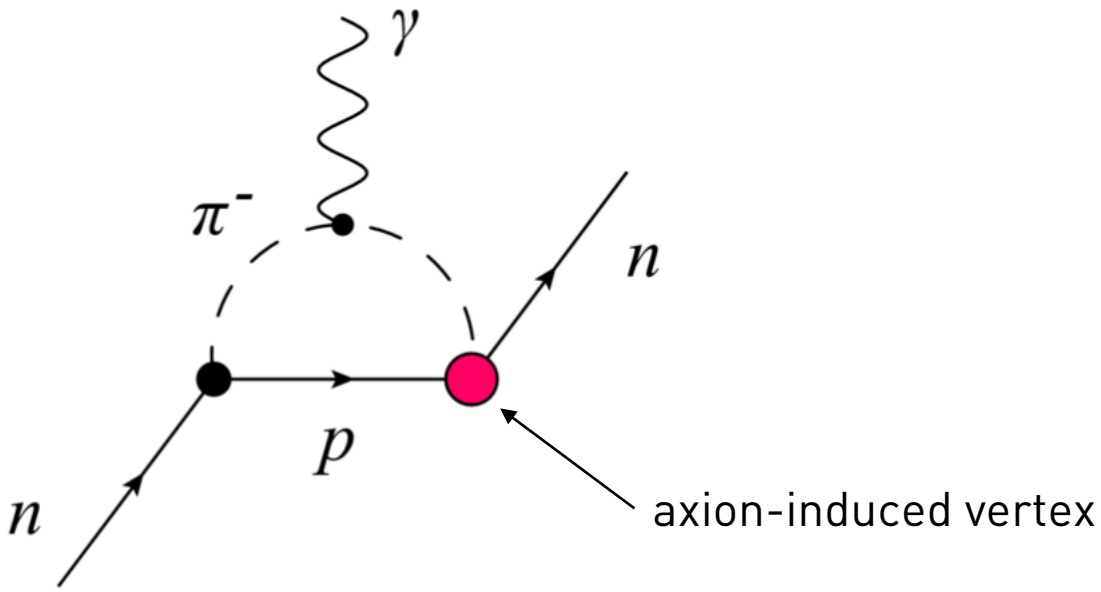
Gluon couplings to the Standard Model:

$$\mathcal{L}_{\text{int}} = \frac{C_G}{f_a} \frac{g^2}{32\pi^2} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Axion – photon coupling

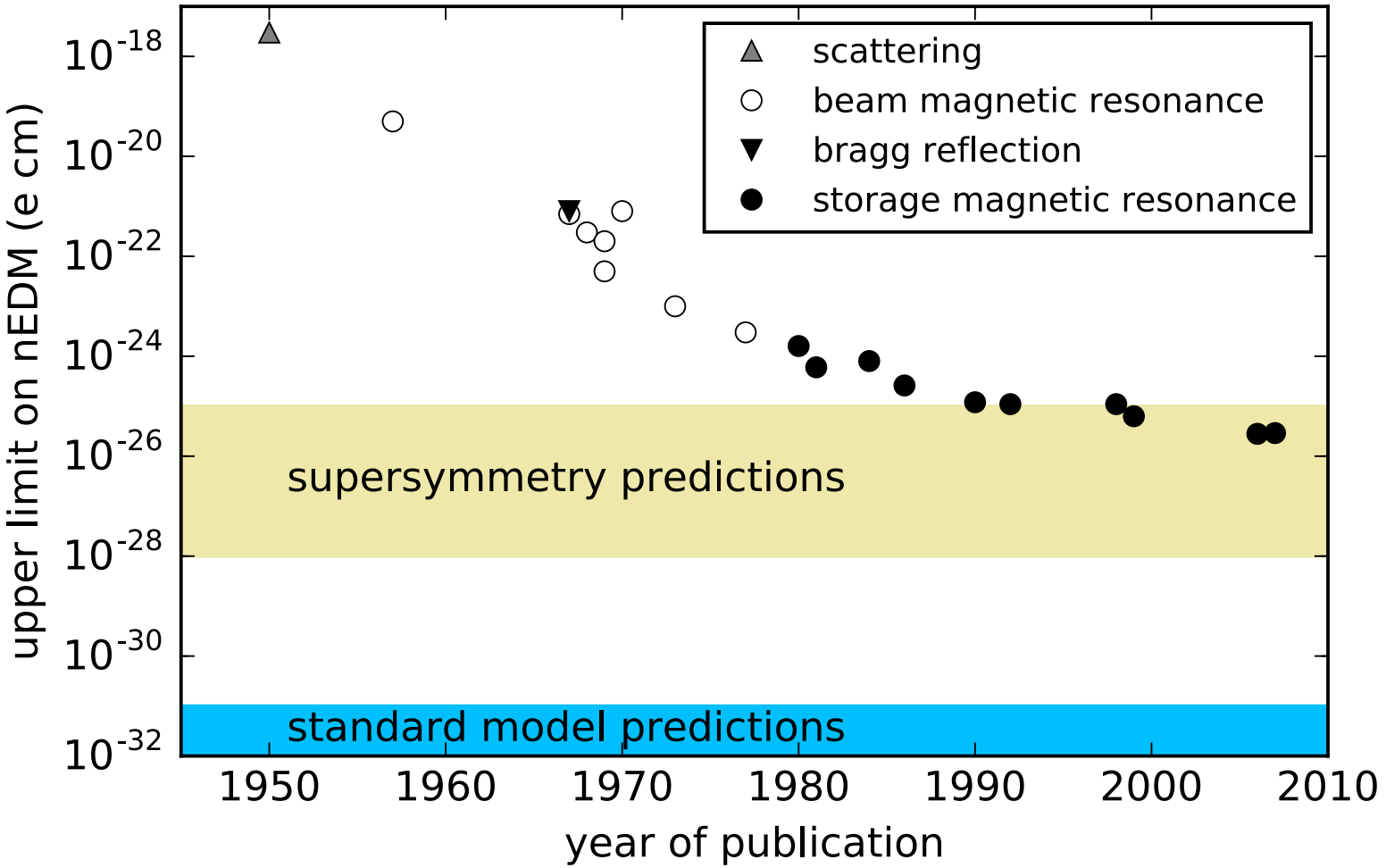


Axion-induced neutron electric dipole moment



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

nEDM measurements

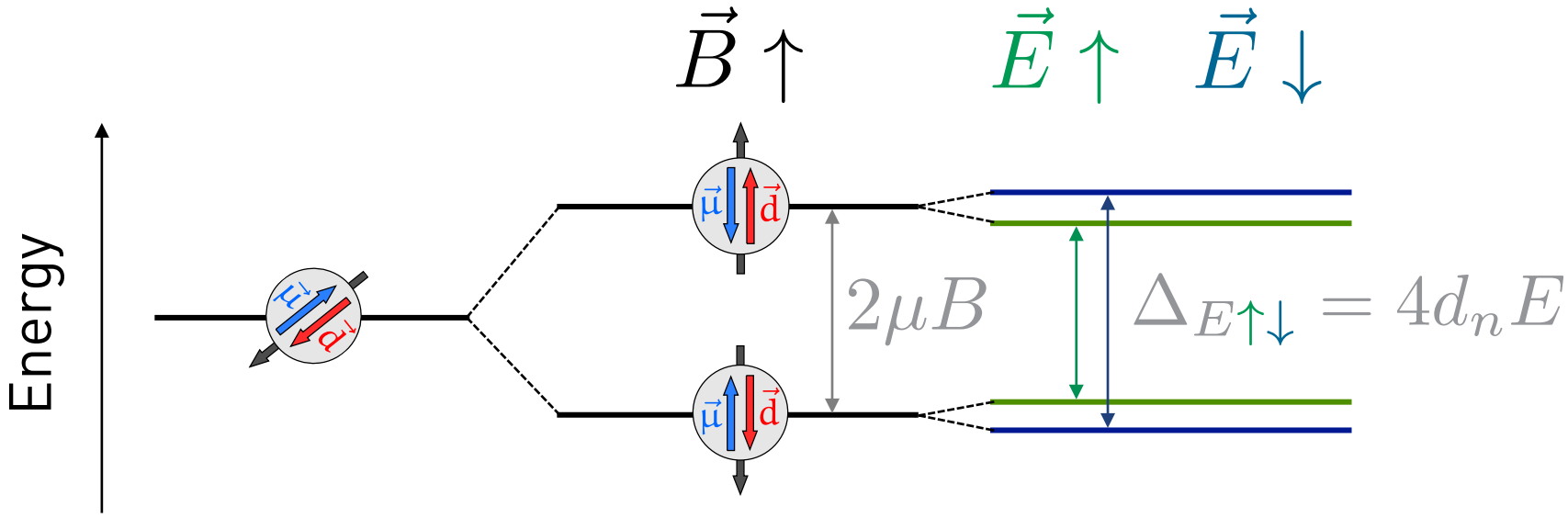


Institut Laue–Langevin, Grenoble, France

Paul Scherrer Institute, Villigen, Switzerland

How to measure the nEDM

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

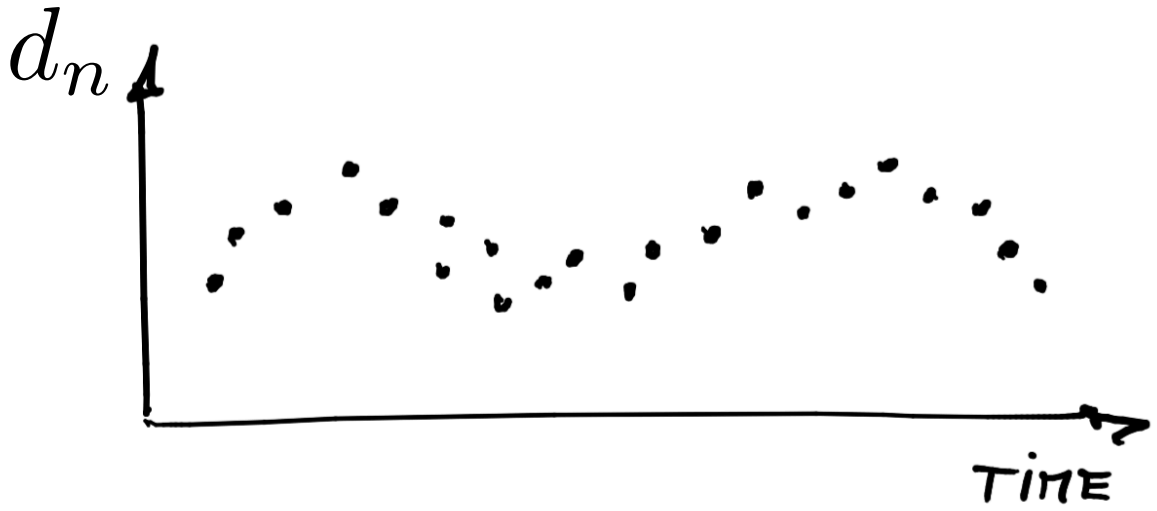


Measure a change in the transition frequency in a presence of an electric field.

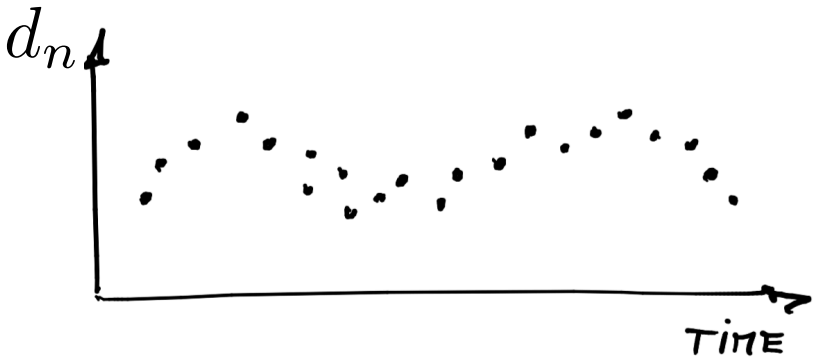
Run-base analysis – ILL data

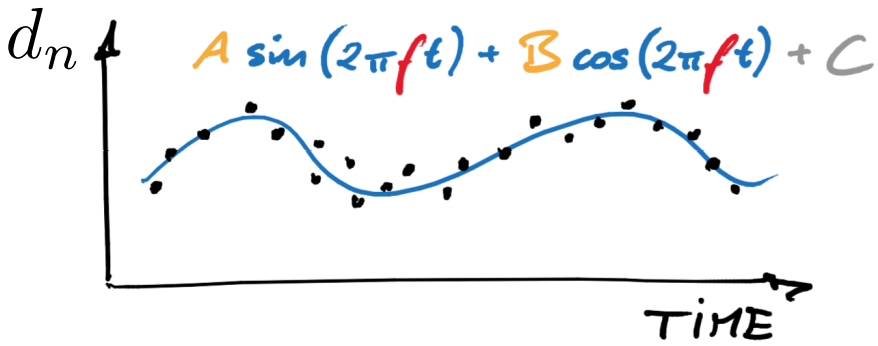
Work of Nicholas Ayres, University of Sussex, UK

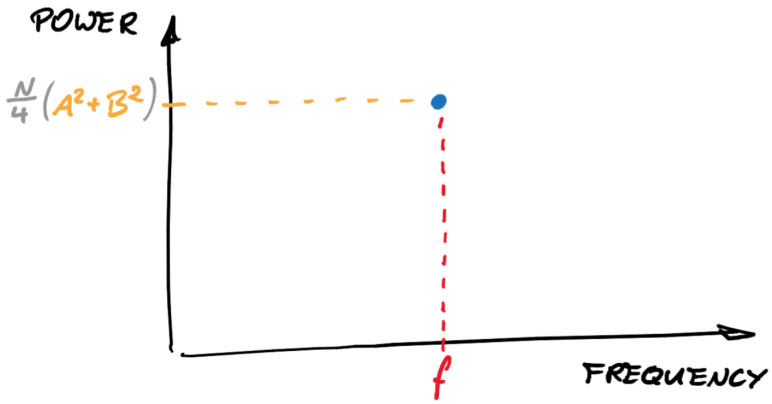
We get an d_n estimate every 1-73 hours.

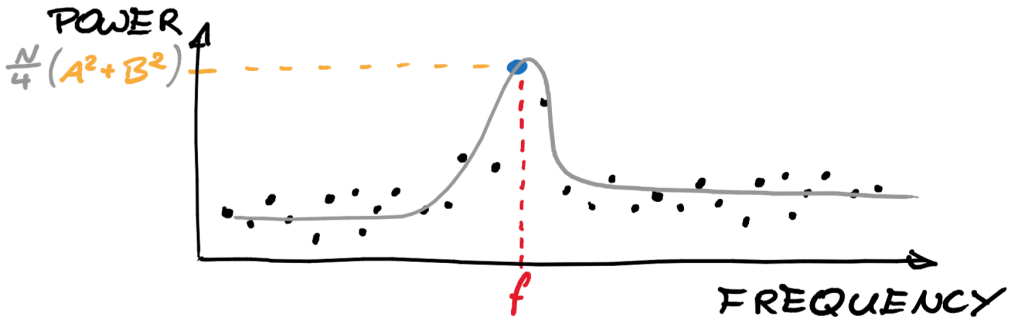


Least Squares Spectral Analysis (LSSA)

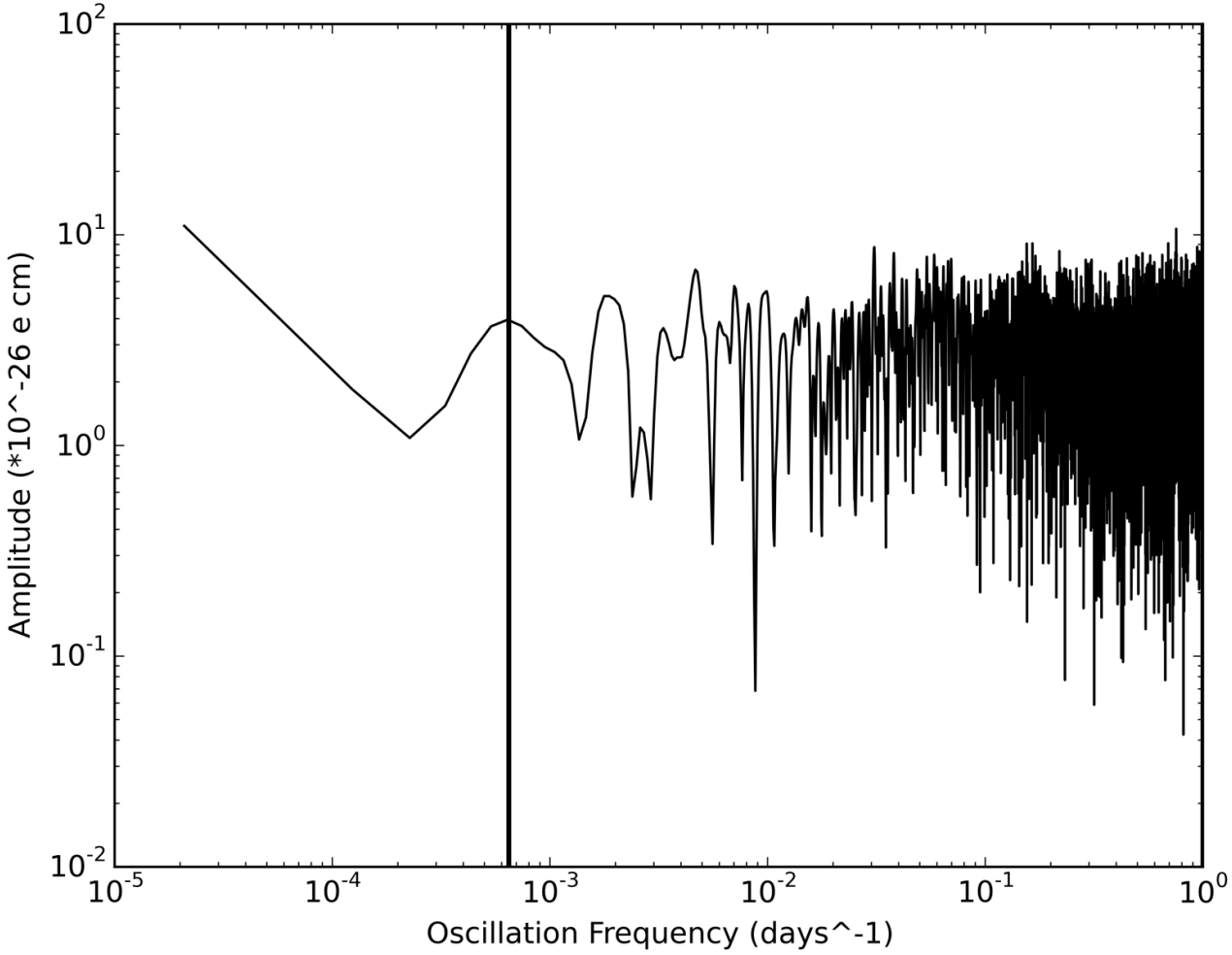




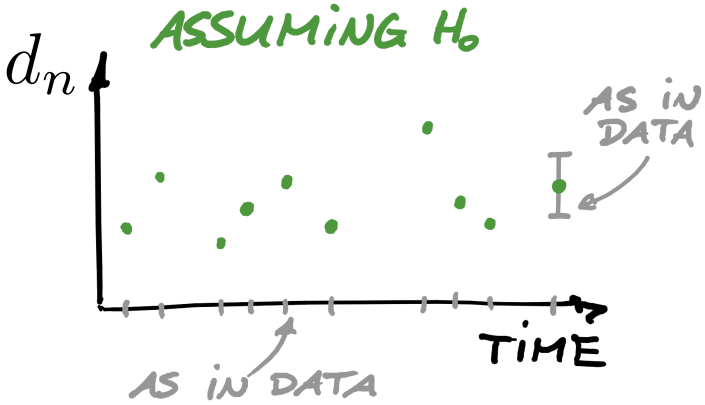


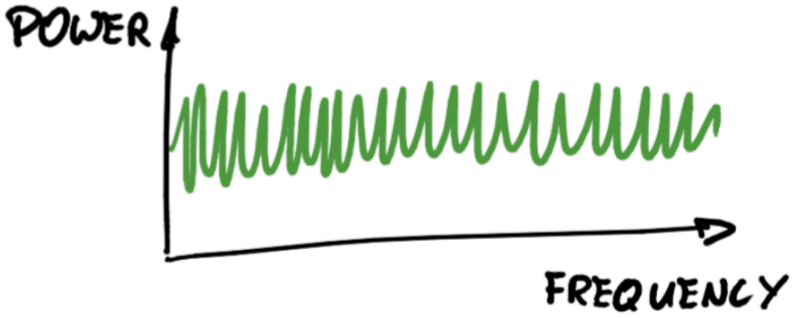


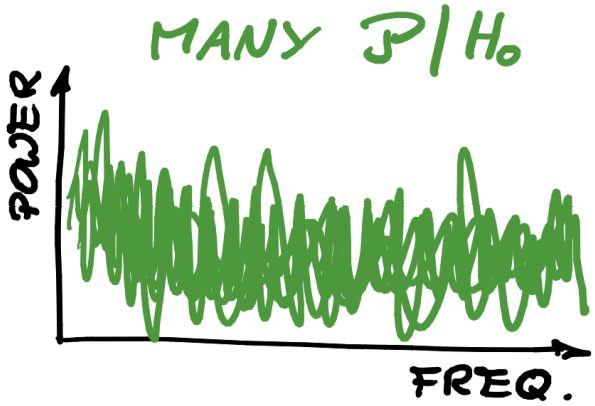
The Data Periodogram

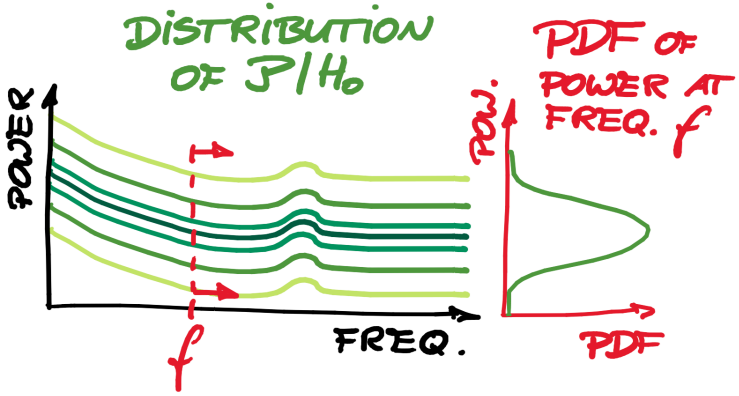


The Periodogram Under the Null Hypothesis

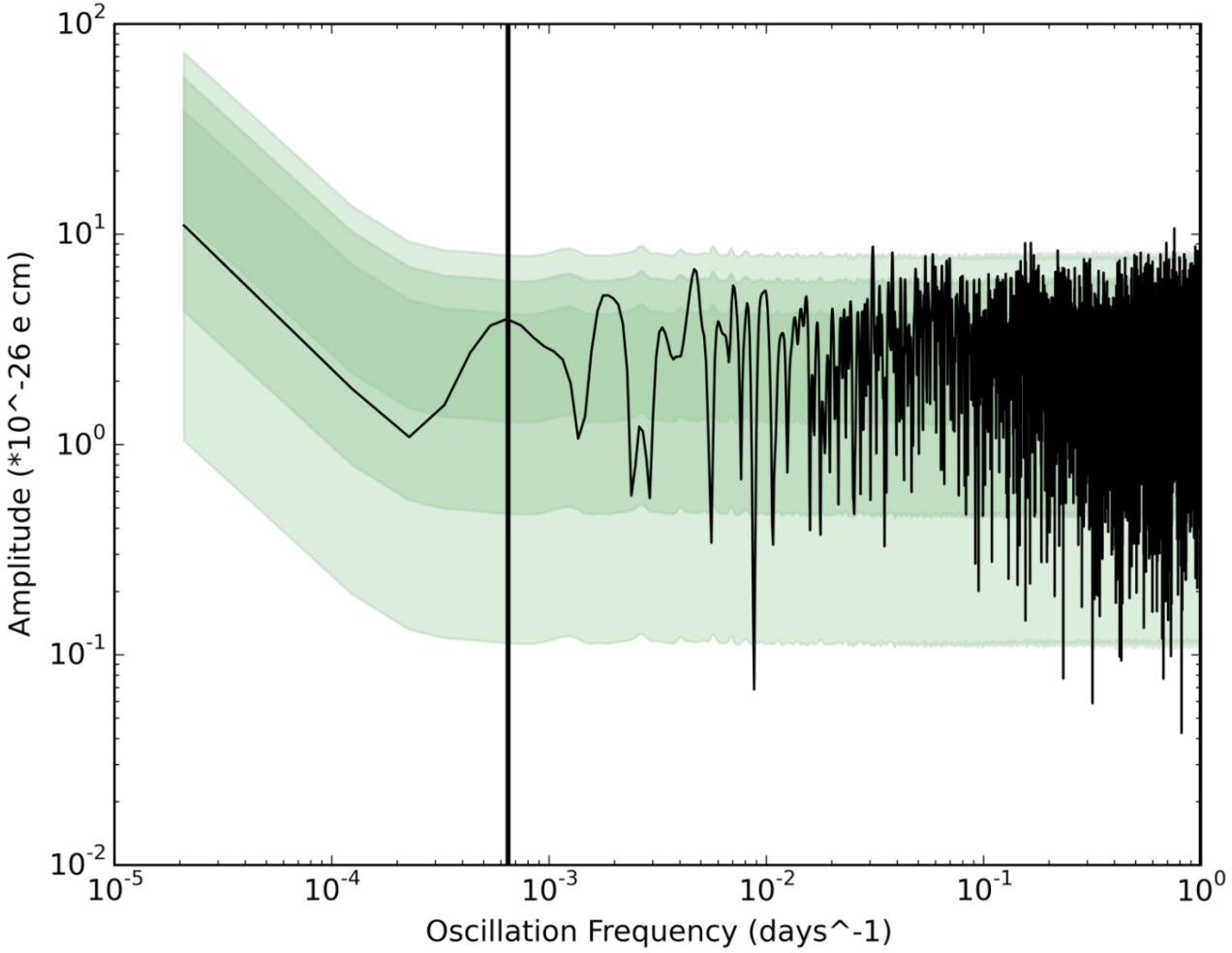




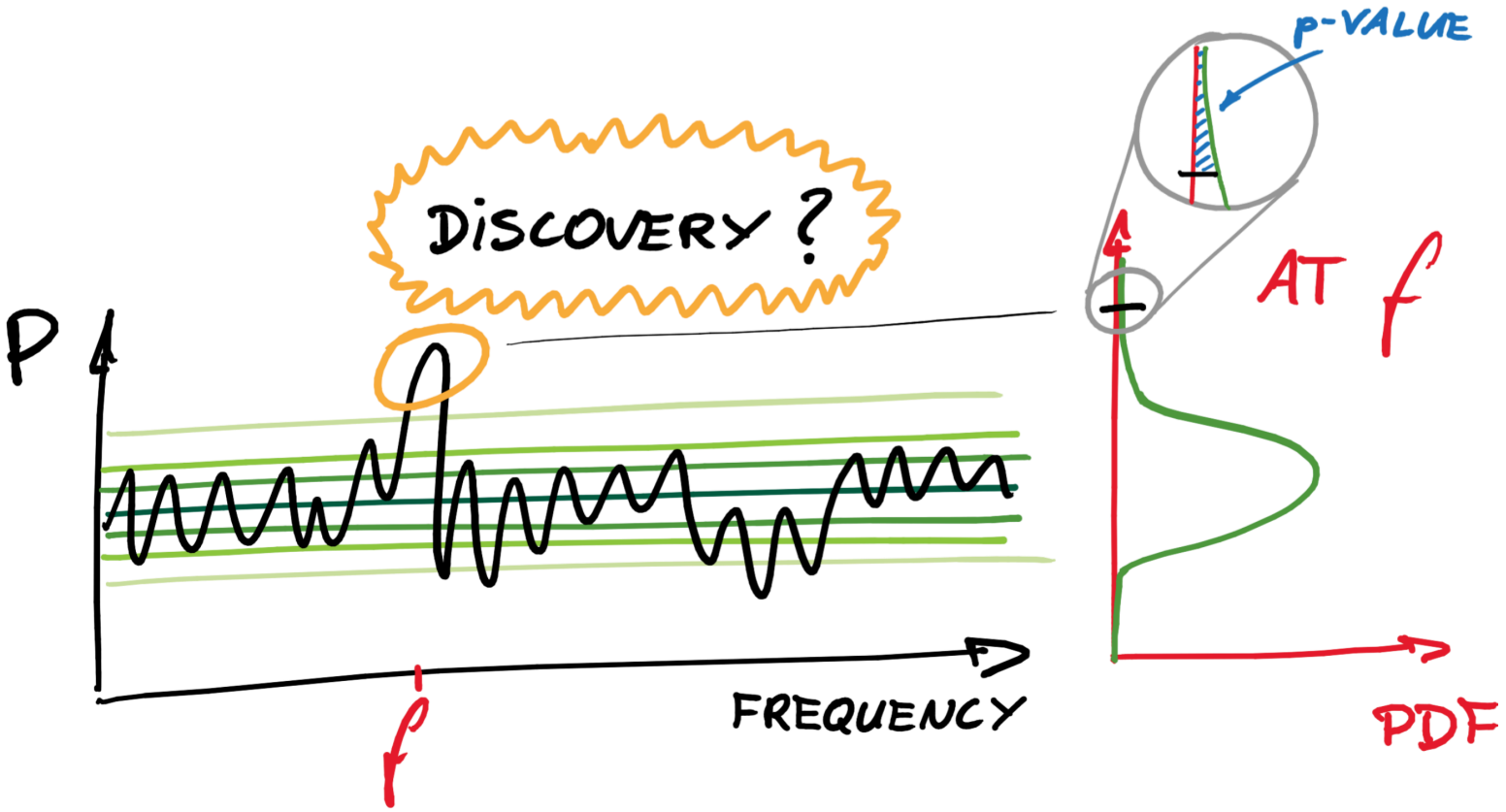




The Data Periodogram vs. the Null Hypothesis



The Null Hypothesis Test



The Look-Elsewhere Effect

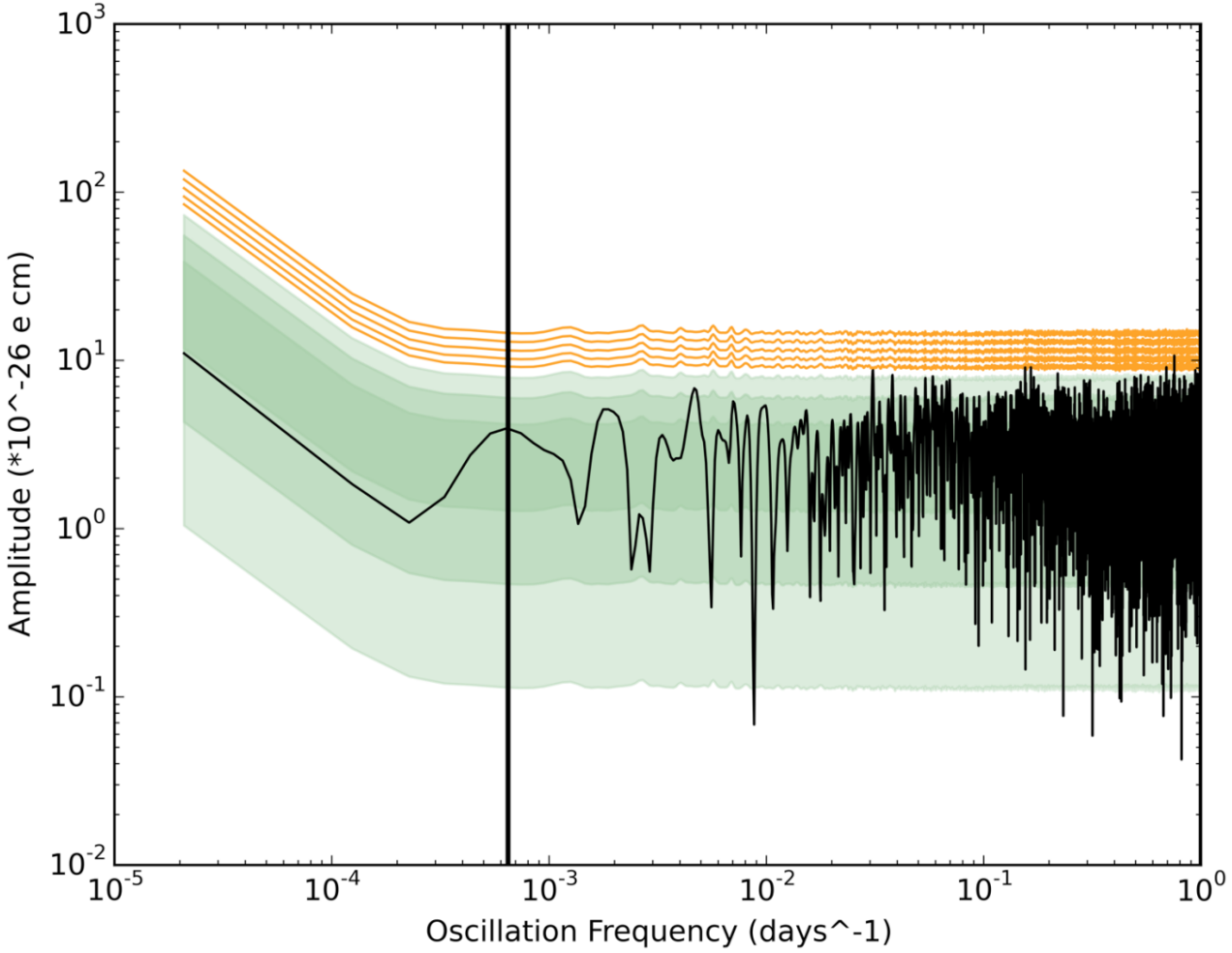
$$p_{\text{global}} = 1 - (1 - p_{\text{local}})^{\text{number of frequencies}}$$

number of frequencies = 1 000 000

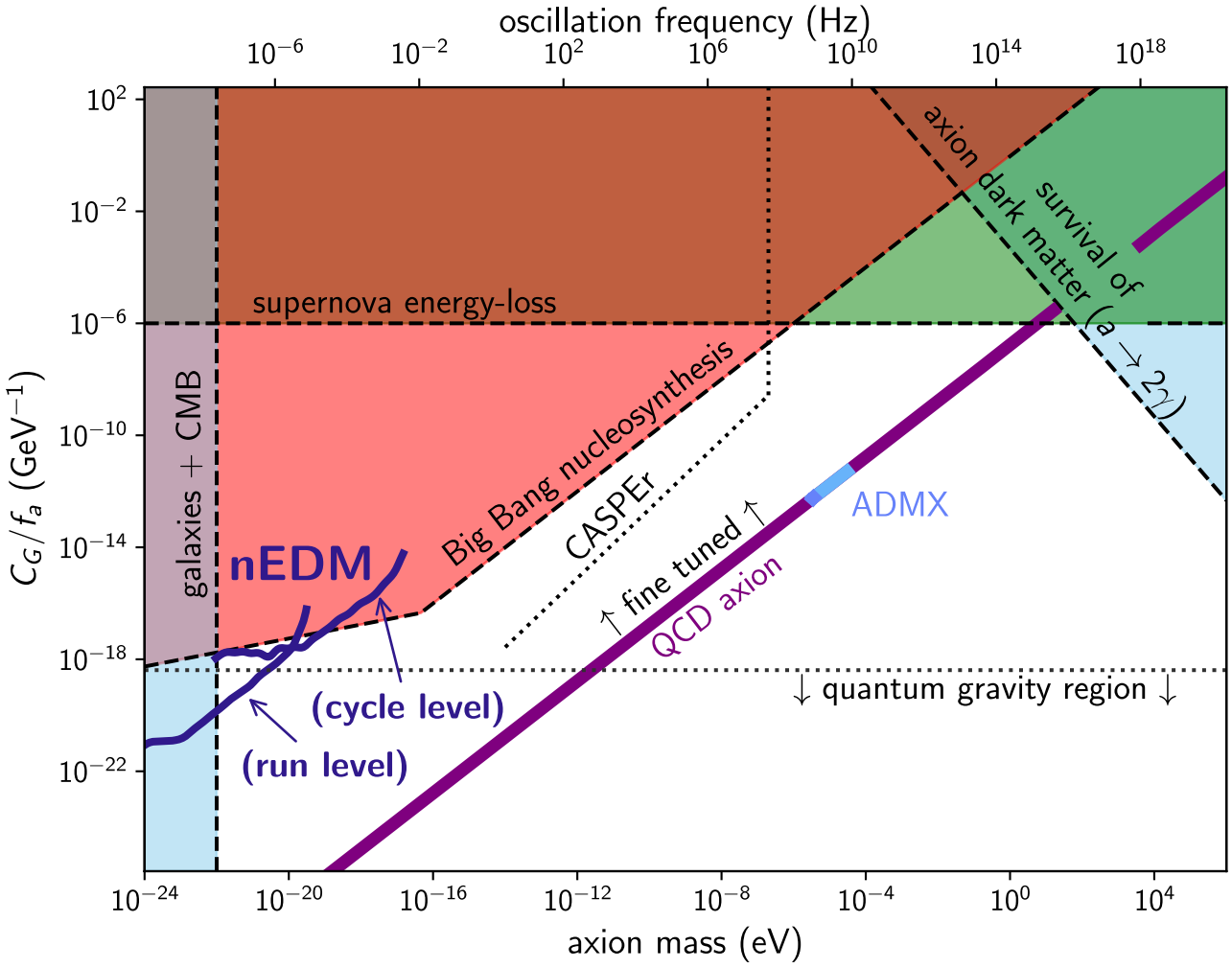
p_{global} = 3-sigma level

p_{local} = 6-sigma level

False-Alarm Thresholds



Limits


oscillation frequency (Hz)
10^{-6}
10^{-2}
10^{2}
10^{6}
10^{10}
10^{14}
10^{18}
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
C_G/f_a (GeV^{-1})
supernova energy-loss
galaxies + CMB
nEDM
Big Bang nucleosynthesis
CASPEr
↑ fine tuned ↑
ADMX
QCD axion
↓ quantum gravity region ↓
(cycle level)
(run level)
axion dark matter
survival of
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{0}
10^{4}
axion mass (eV)

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Thank you for your attention!

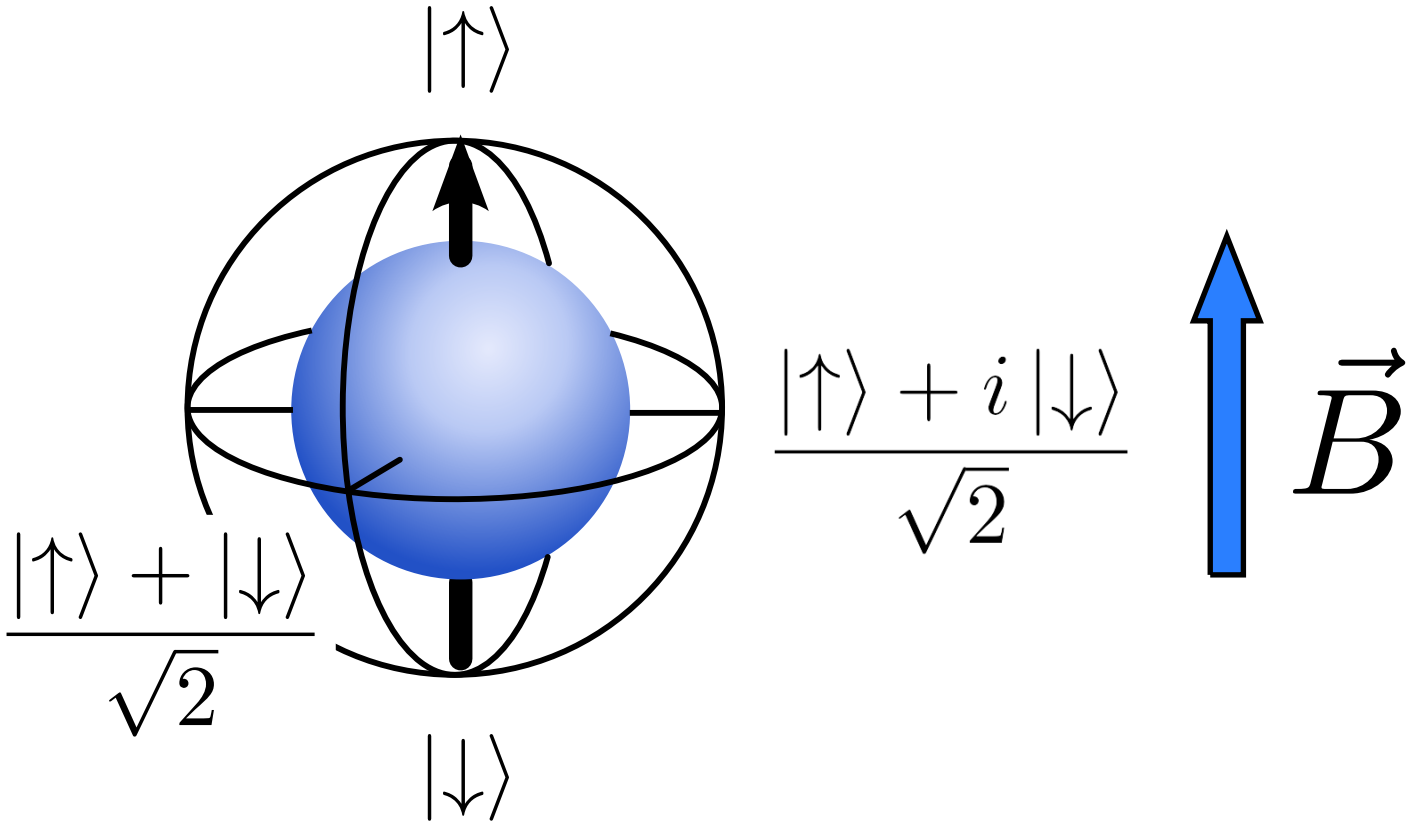
Further reading:

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)

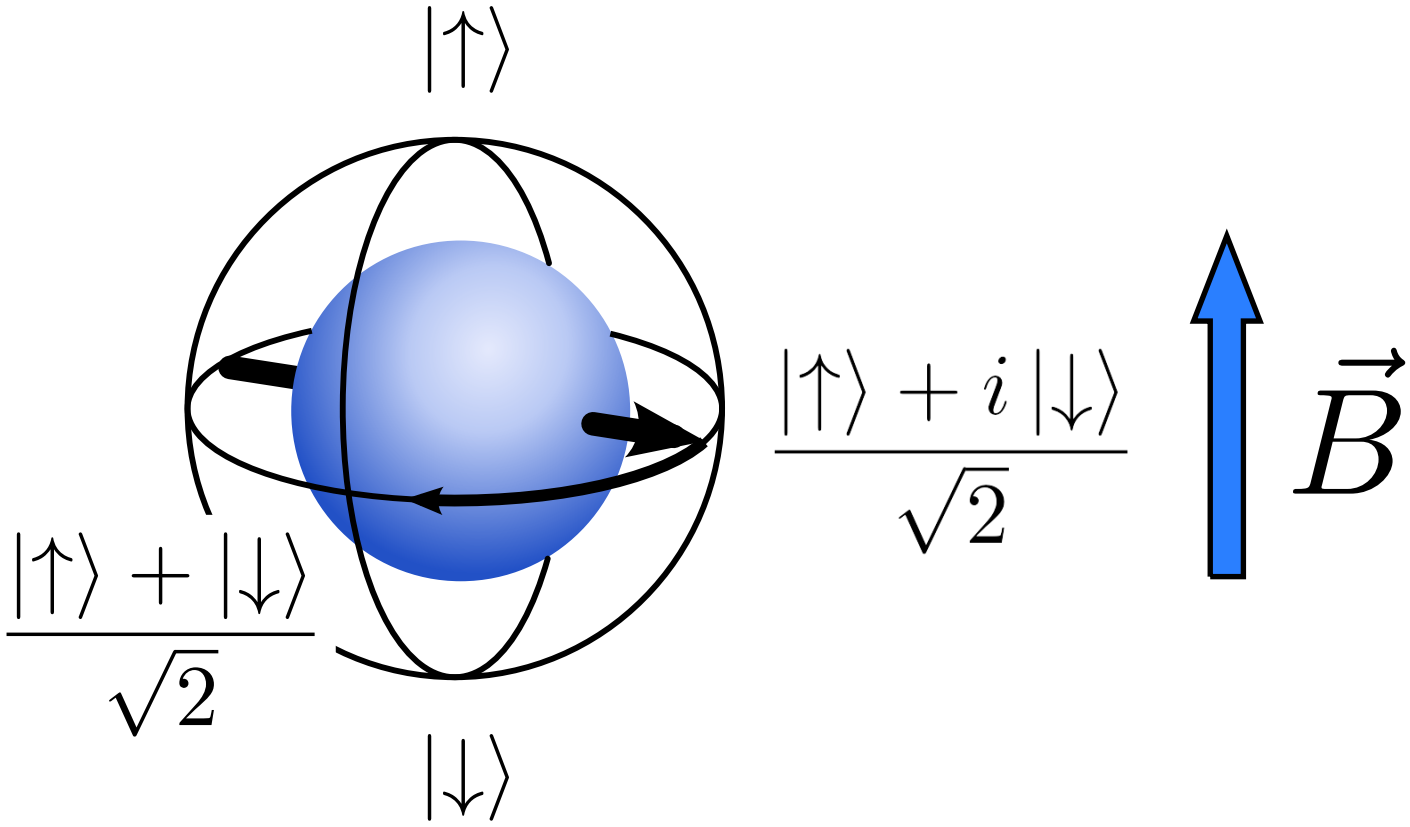
How to measure the nEDM?

Thou shall measure frequency.

Bloch sphere



Larmor precession



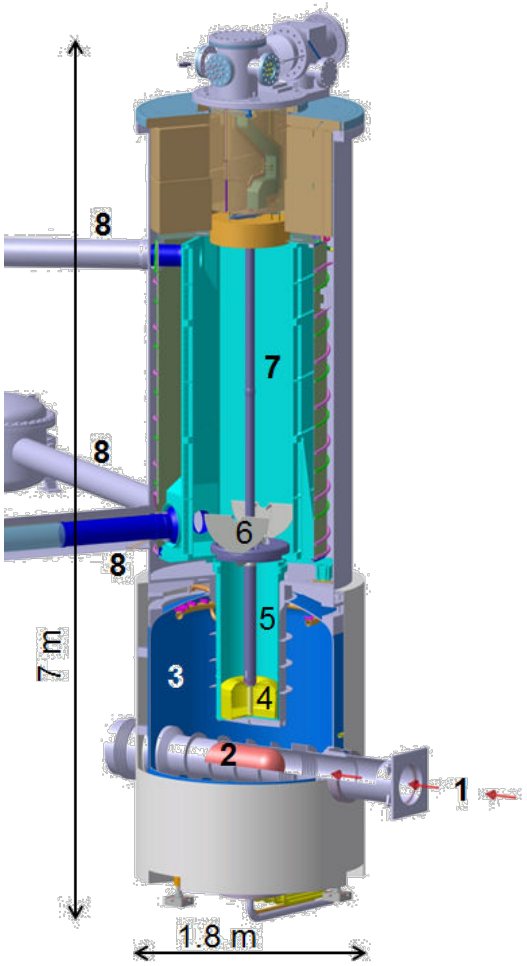
Gyromagnetic ratio of the neutron: $-29.1646943(69)\ \frac{\mathrm{Hz}}{\mu\mathrm{T}}$

Ultra-Cold Neutrons source

FROZEN DEUTERIUM

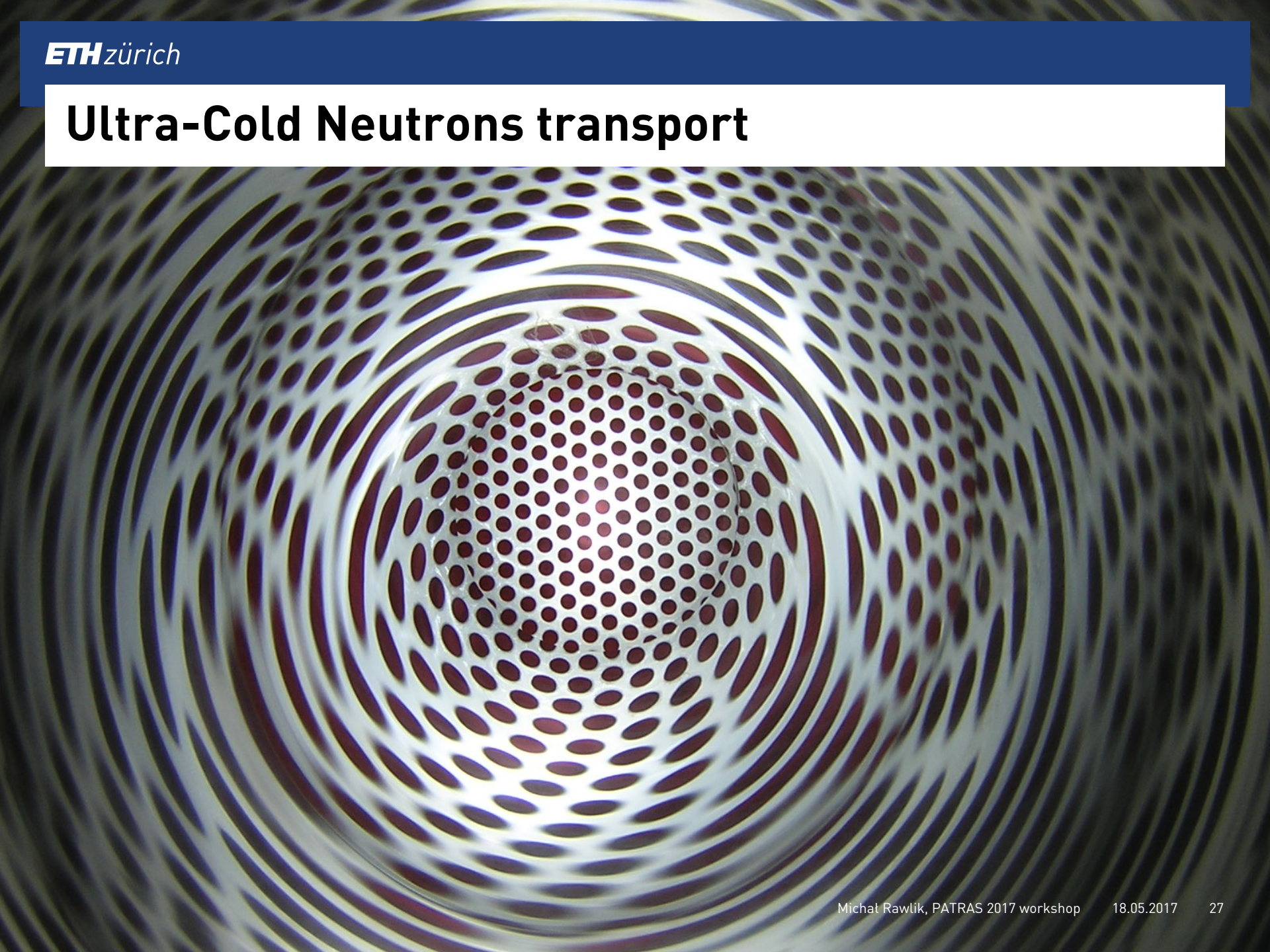
UCN storage in high Fermi potential bottle

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

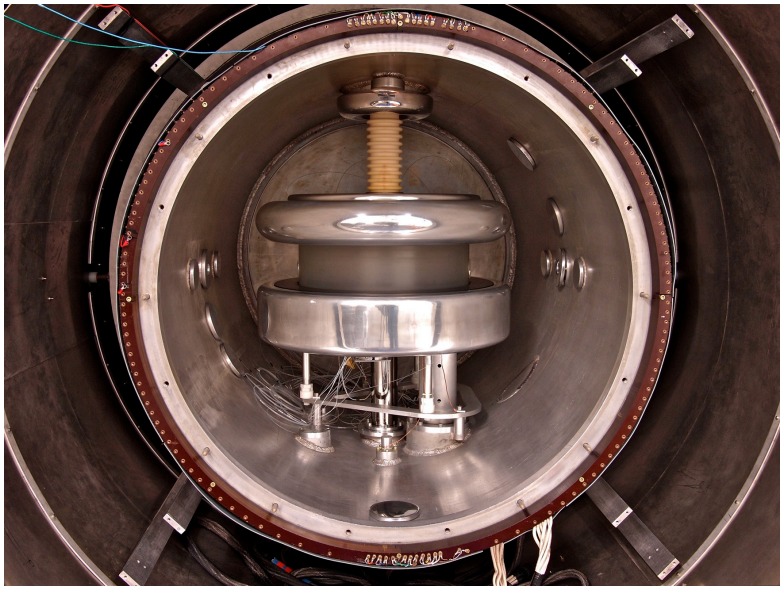


2 mA of **590 MeV** protons

Ultra-Cold Neutrons transport



The nEDM cycle



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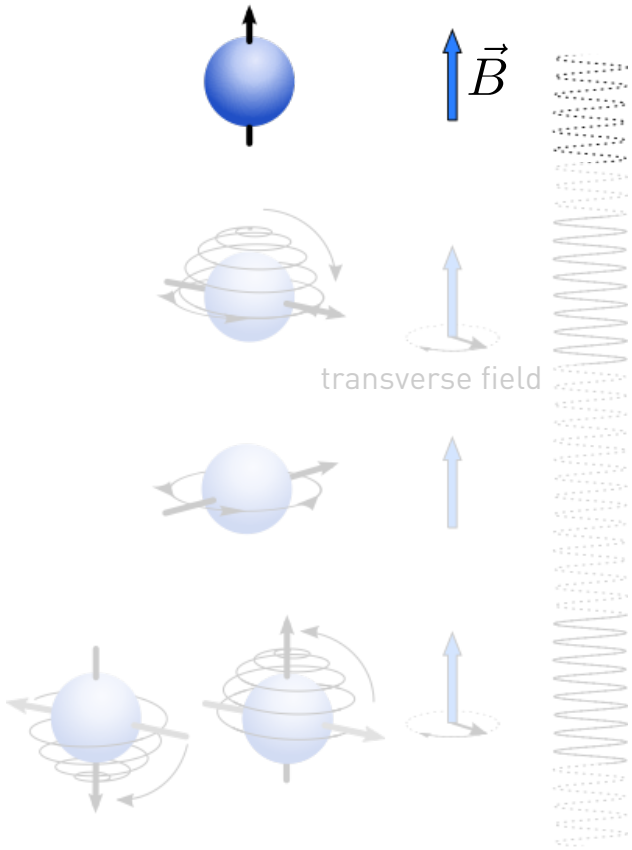

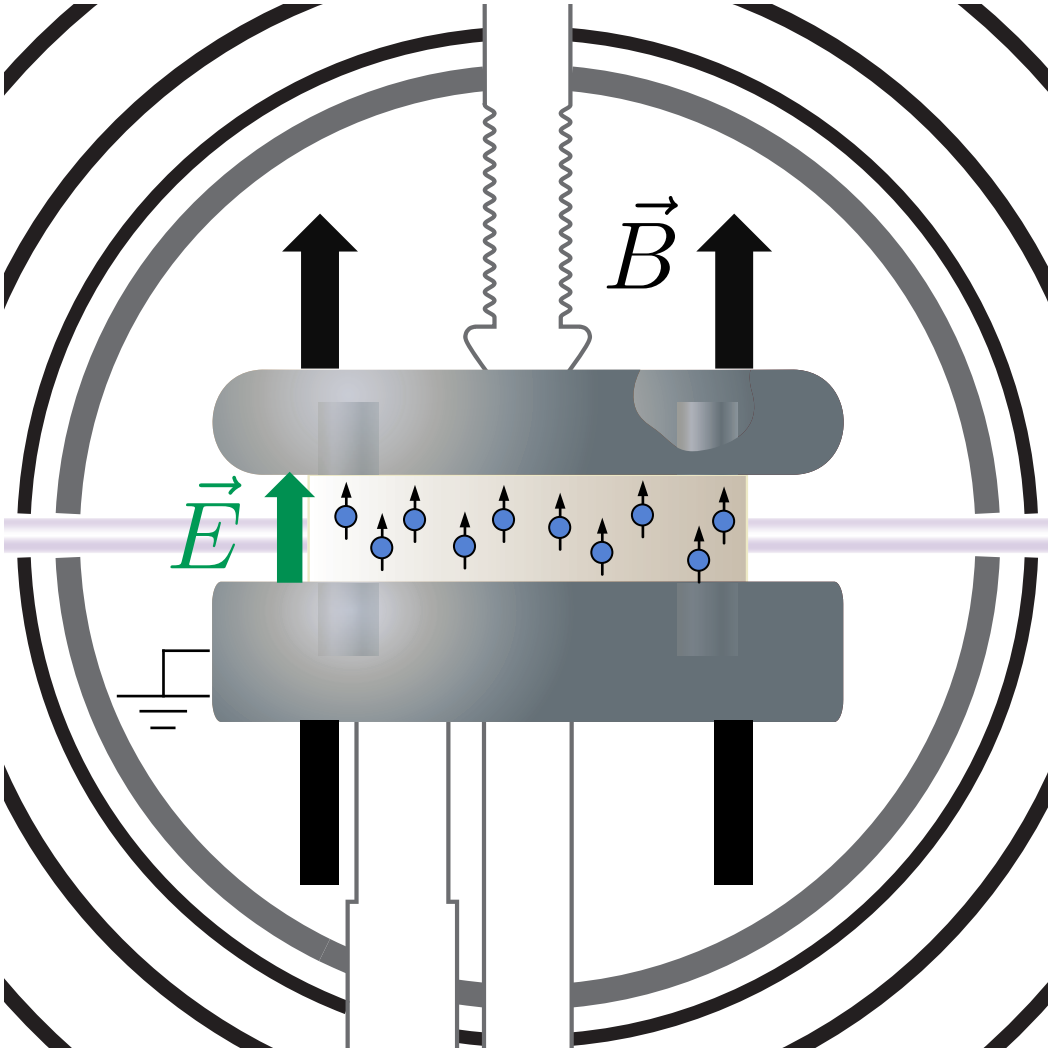

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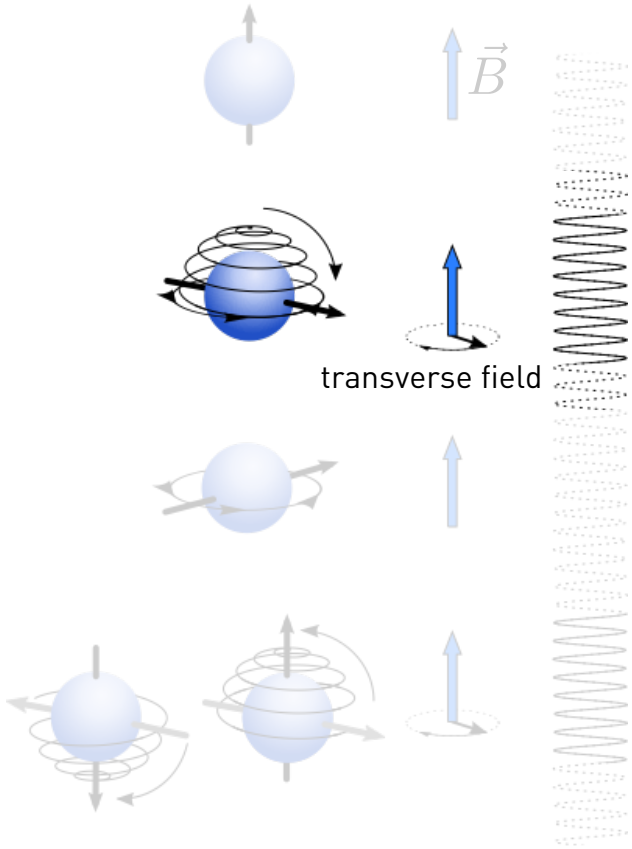
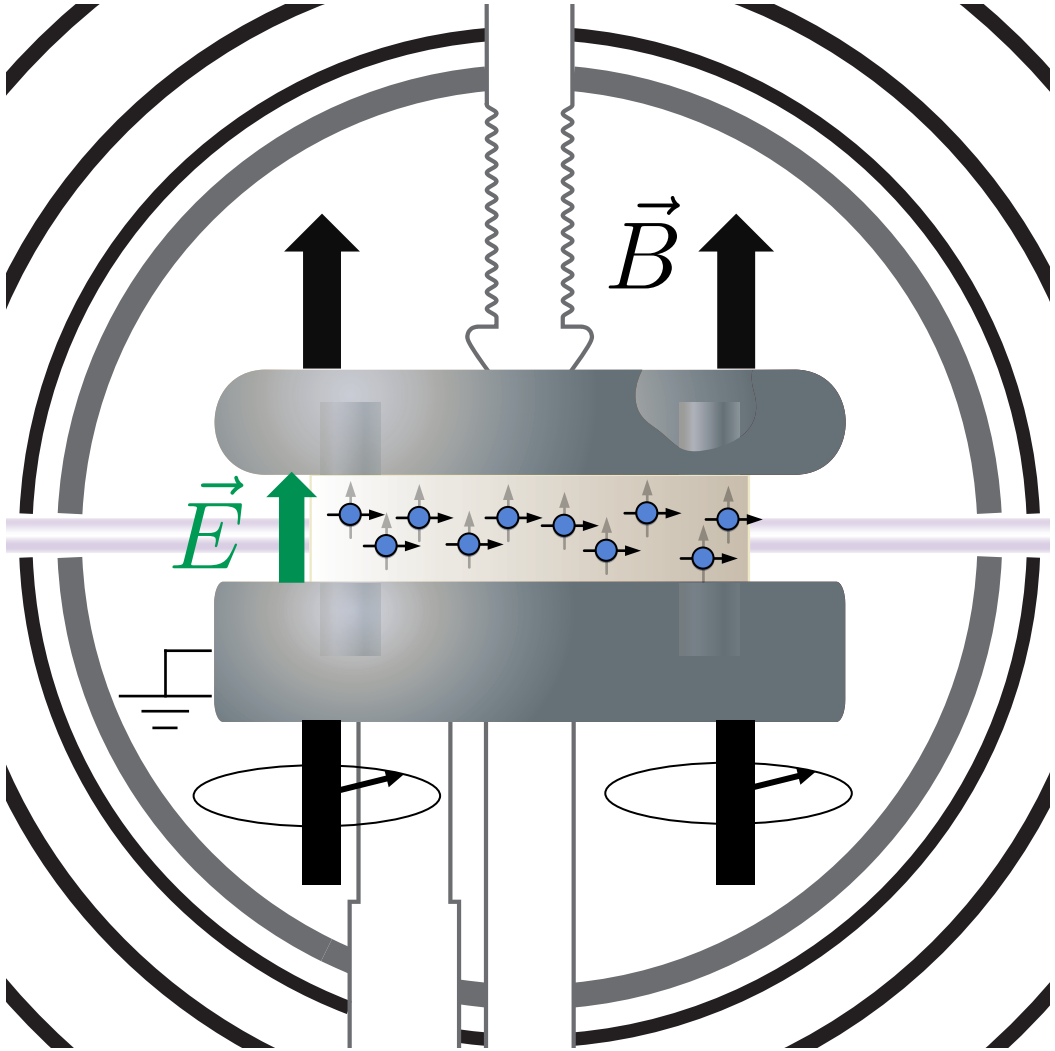
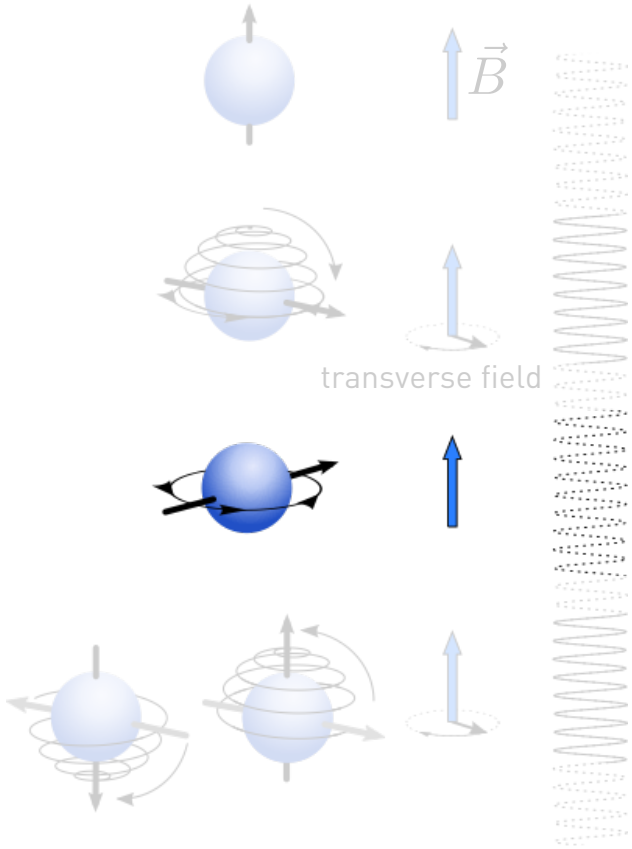
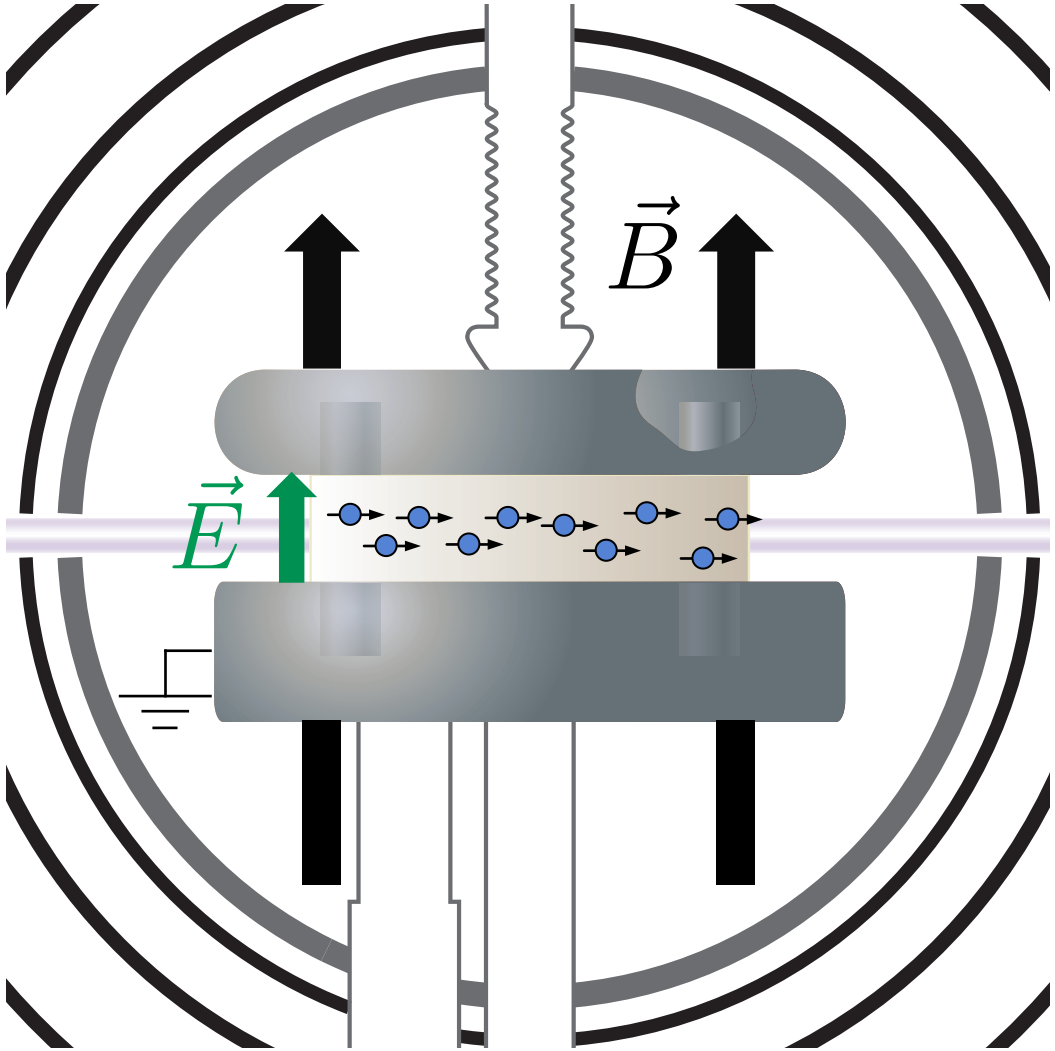


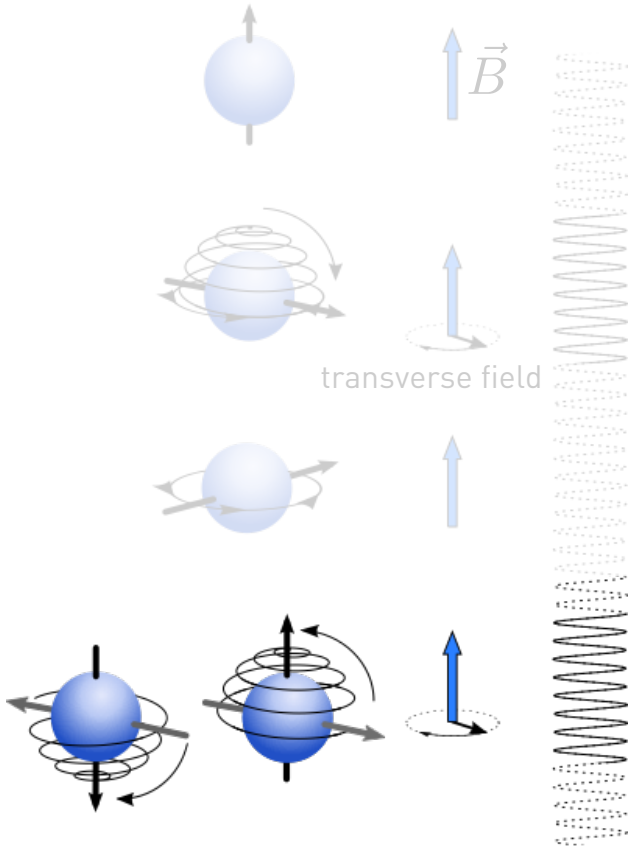


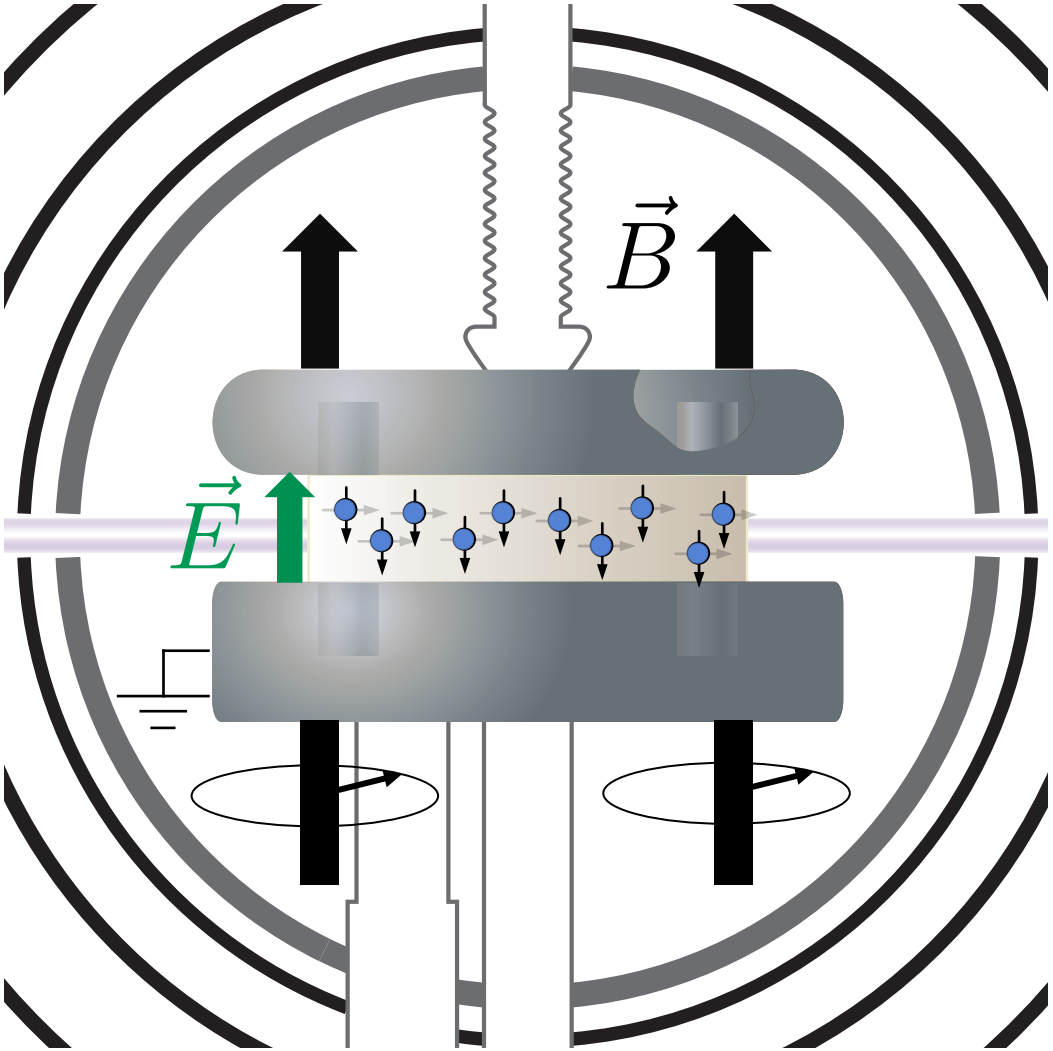
The nEDM cycle





The nEDM cycle





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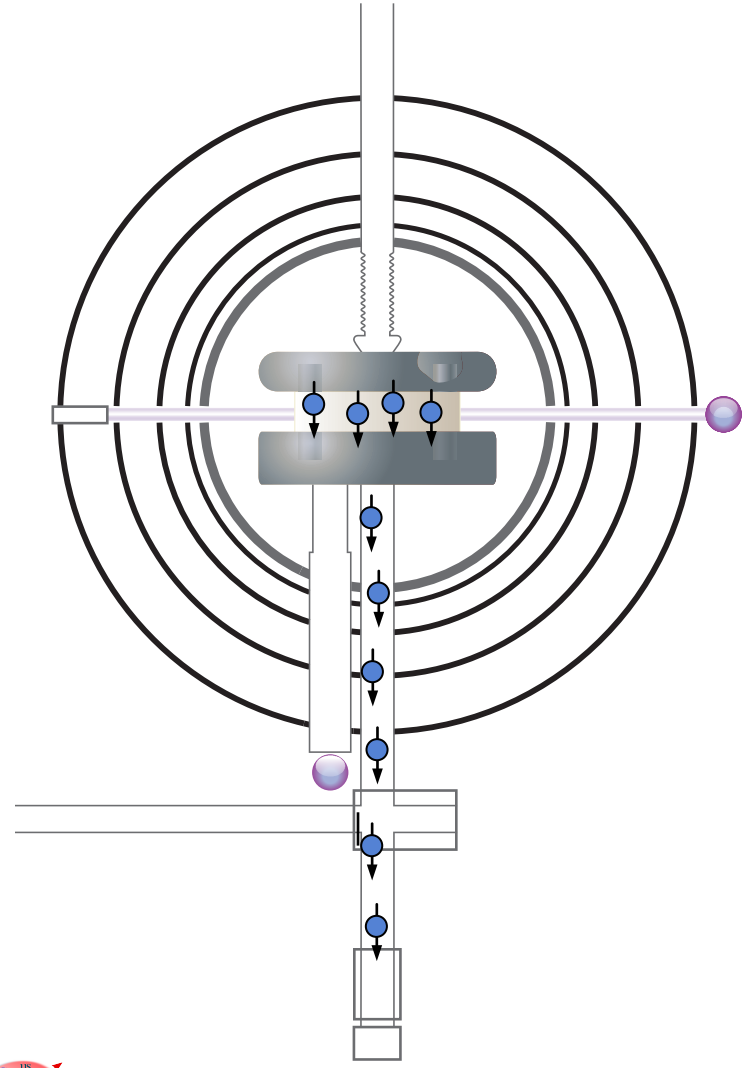
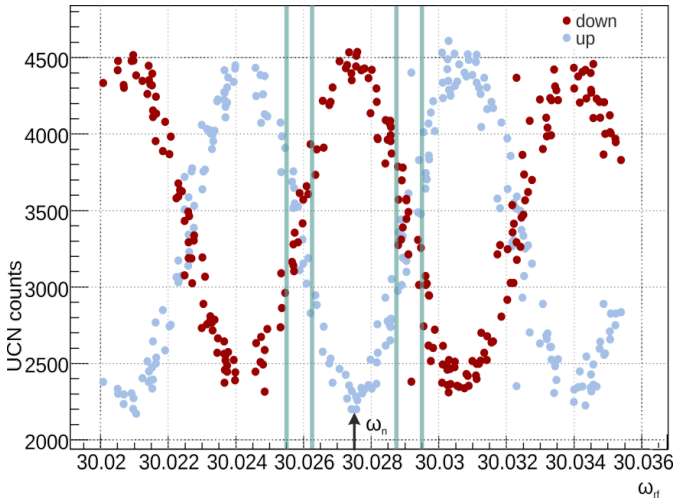
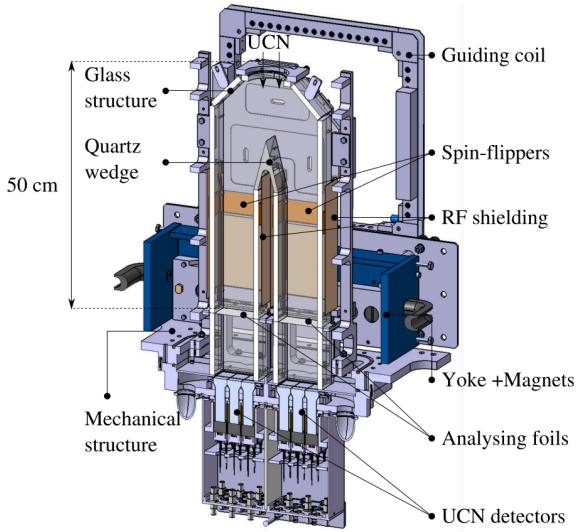
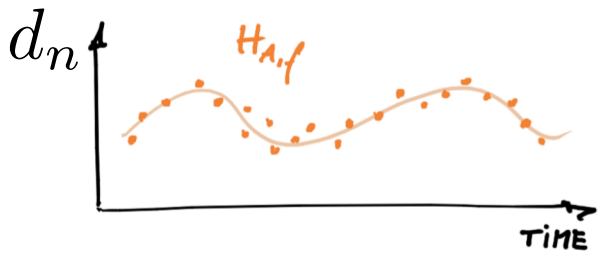
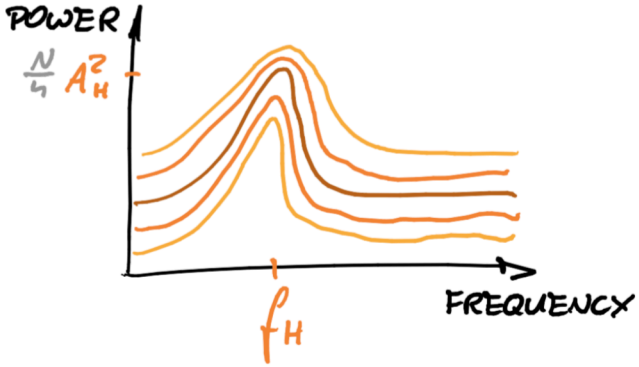


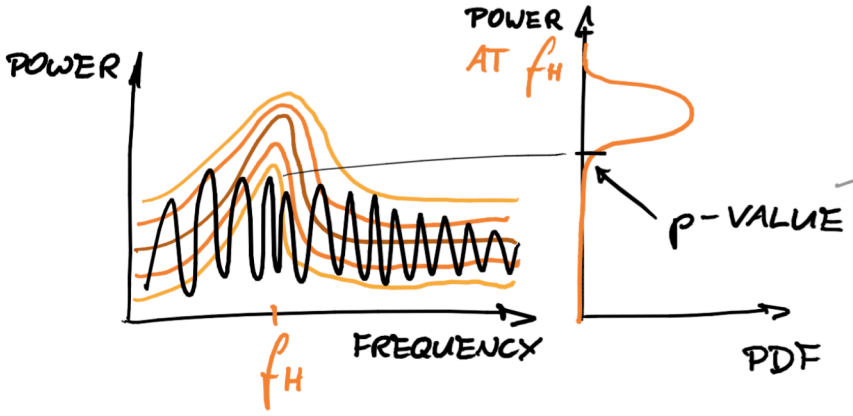


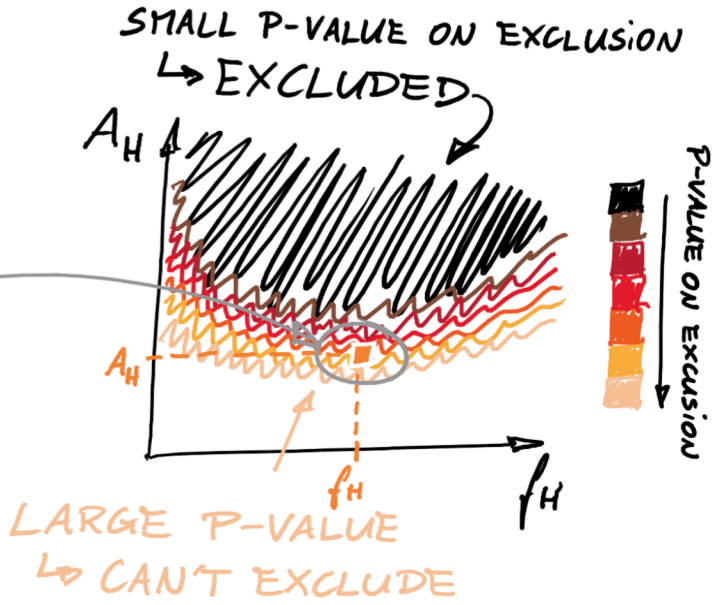


determining the exclusion region

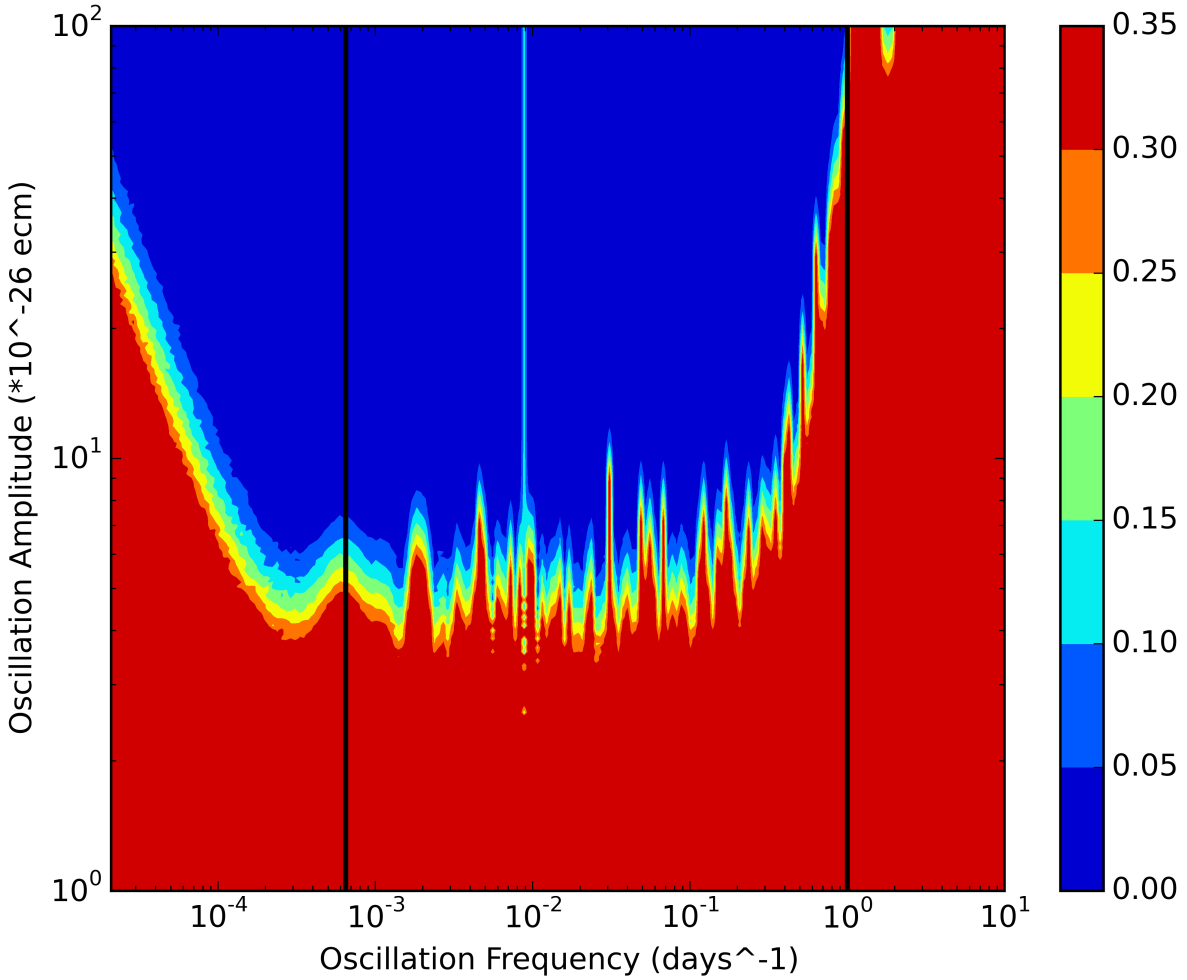




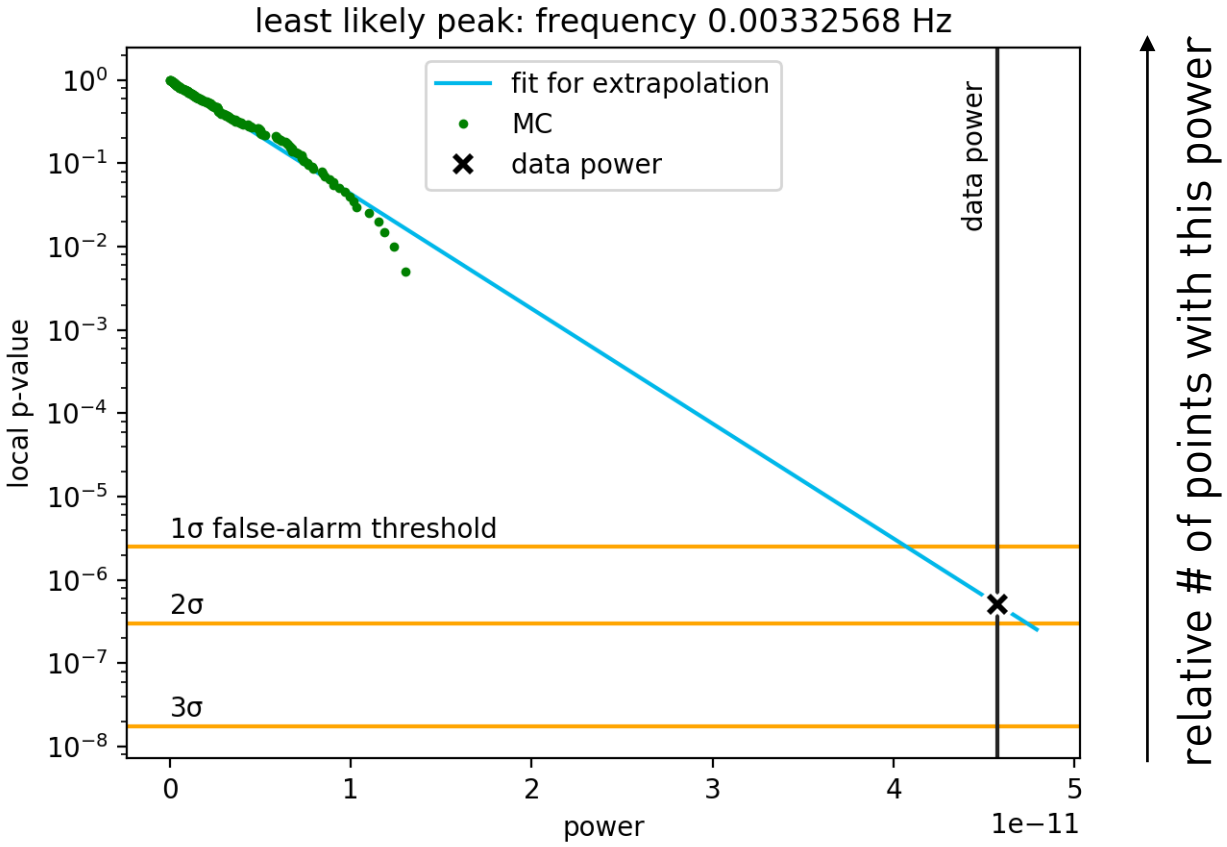




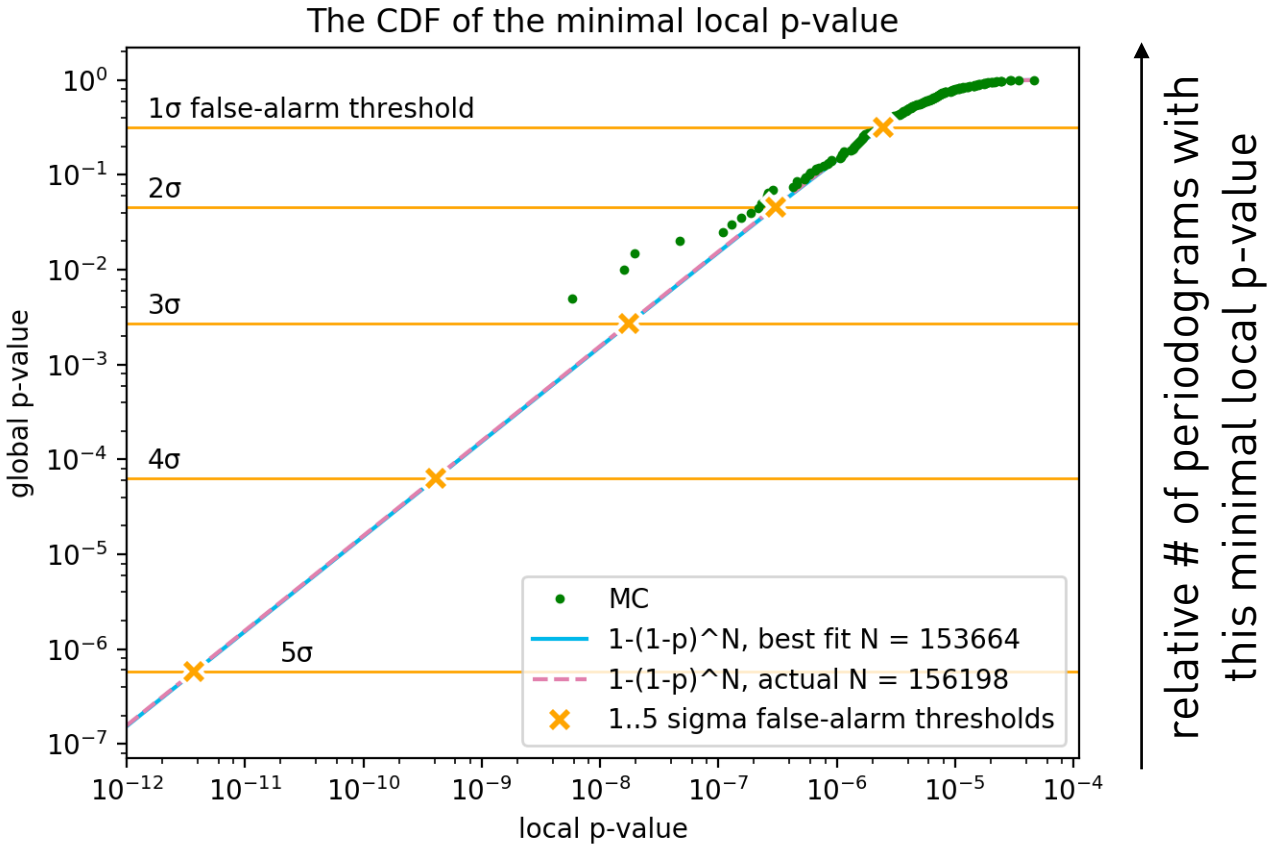
determining the exclusion region



CDF extrapolation



CDF extrapolation



Cycle-base analysis

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

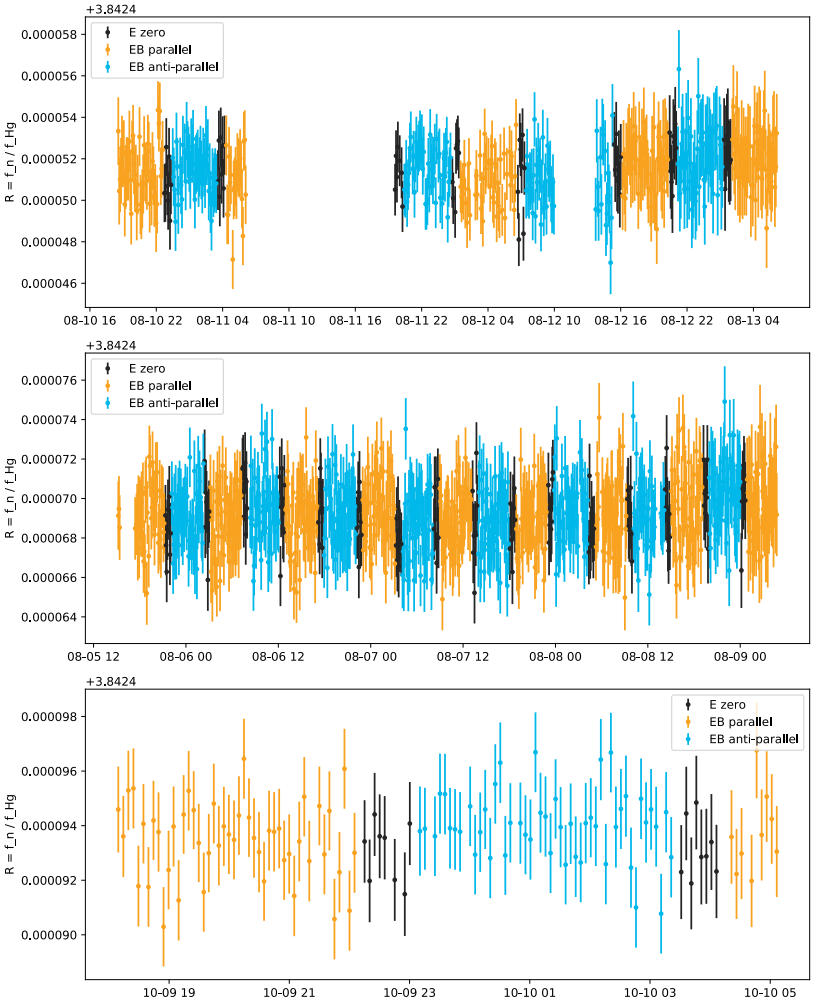
ILL & PSI
nEDM measurements:

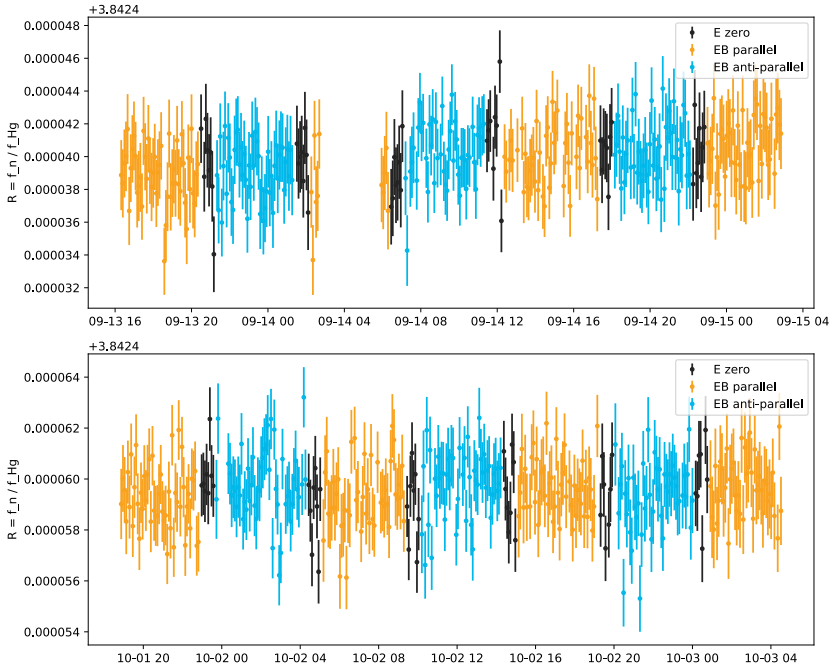
$$h\nu = -2\vec{S} \cdot \left(\mu \vec{B} + d_n \vec{E}\right)$$

neutron precession frequency

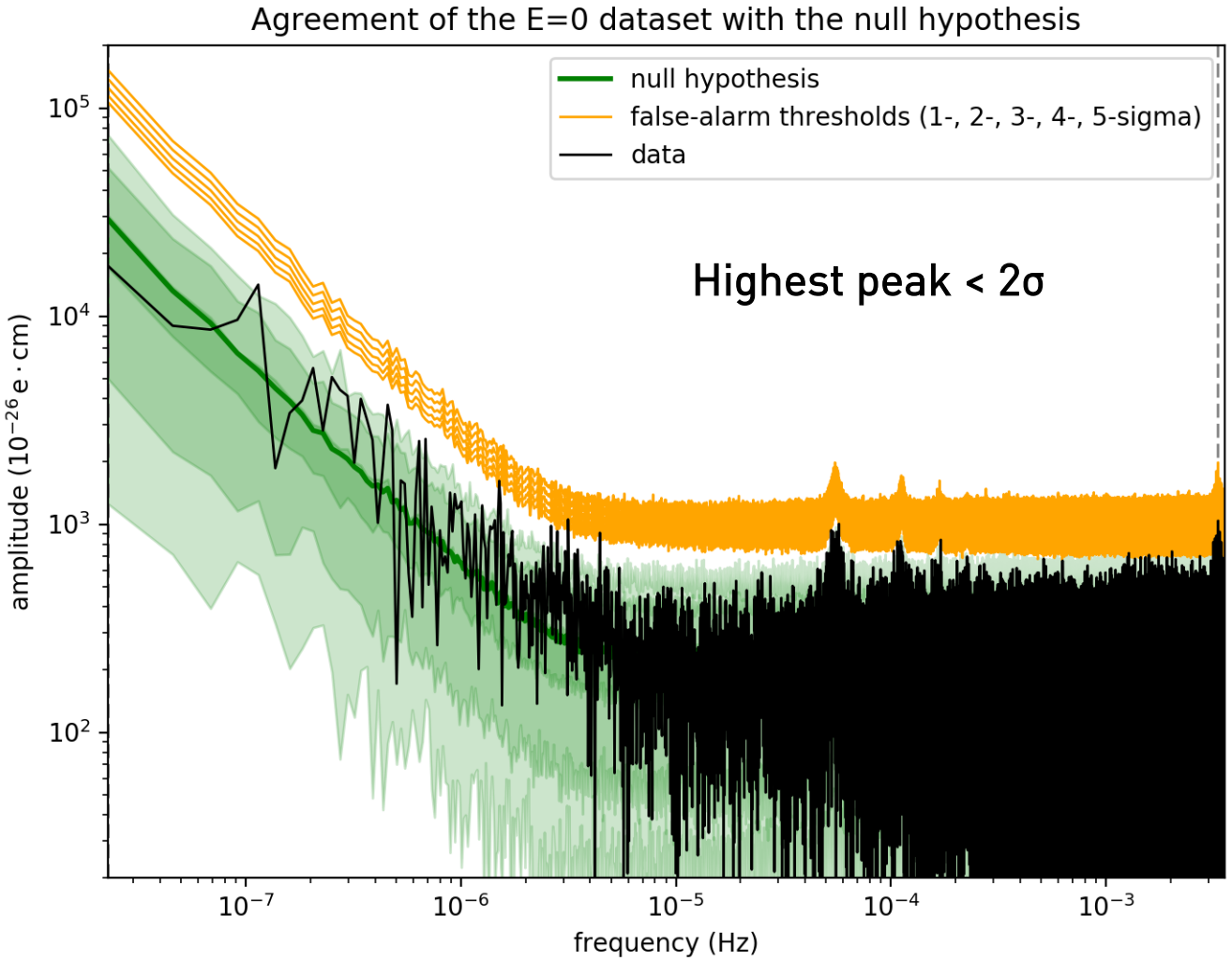
If d_n oscillates, ν will oscillate too.

Cycle-level analysis – R time series

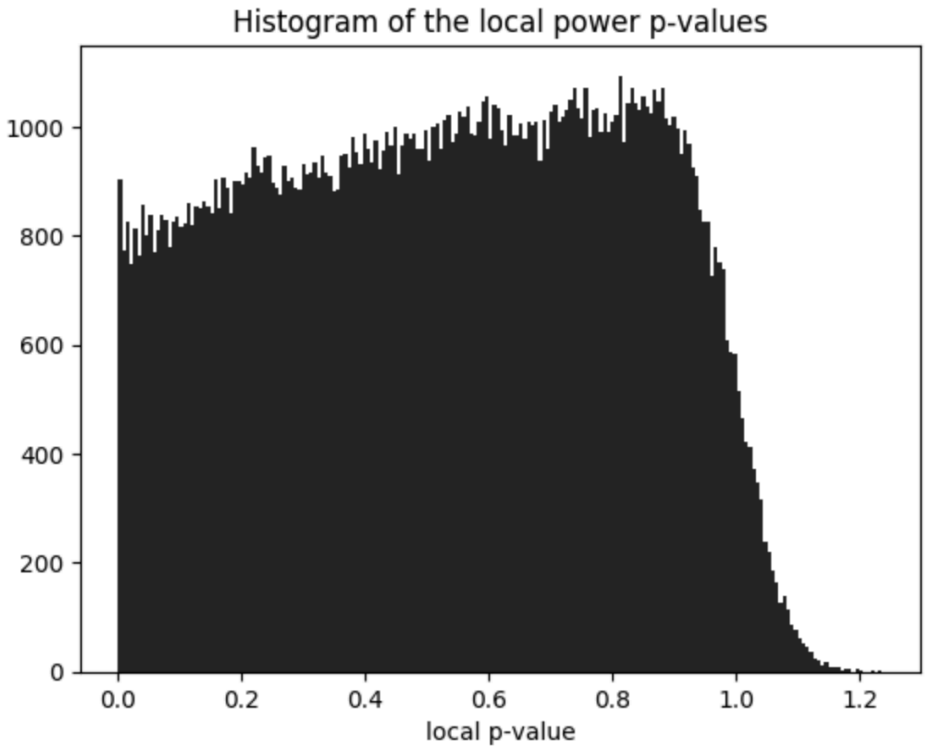




Cycle-level analysis: E = 0

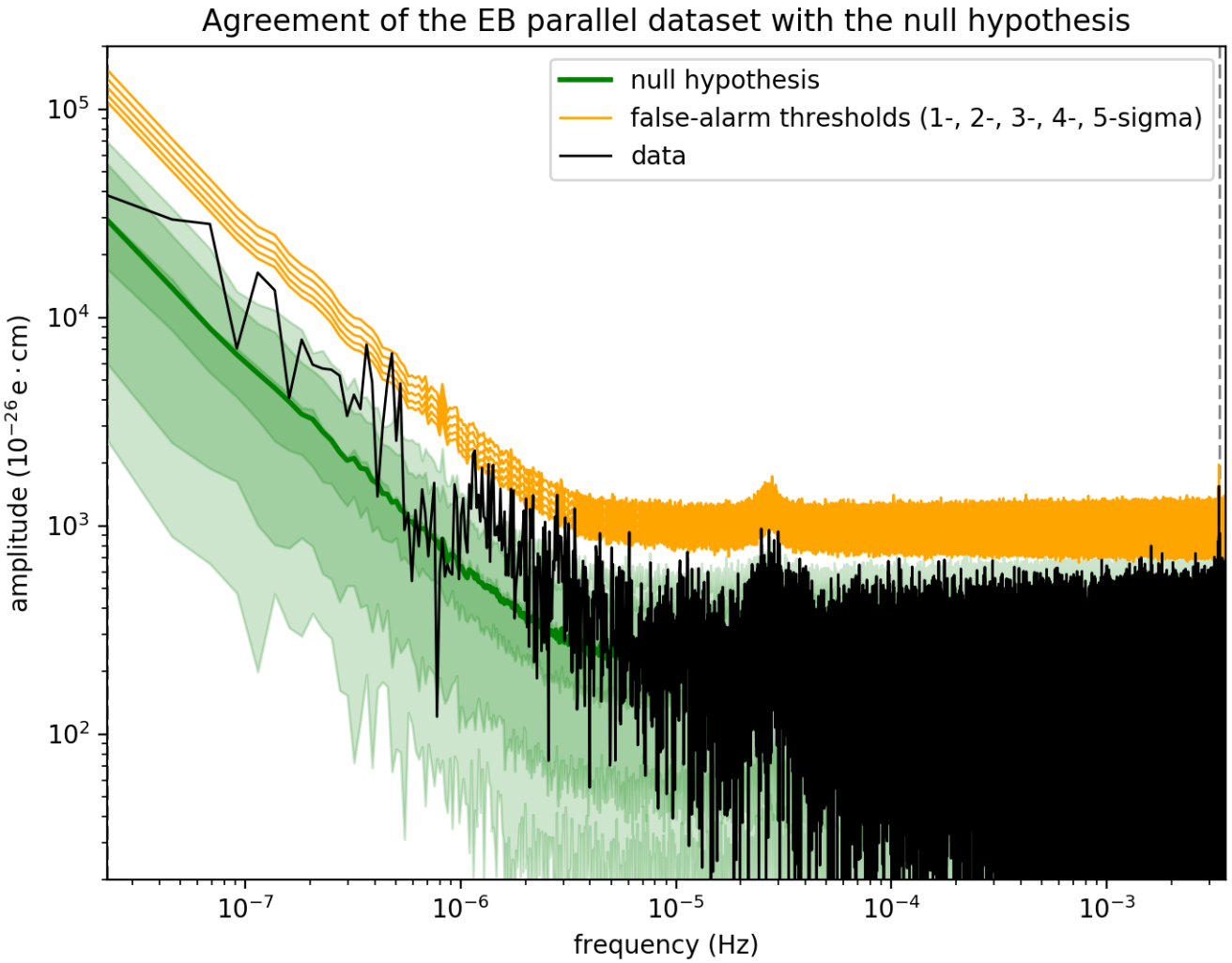


Cycle-level analysis: E = 0, p-value distribution

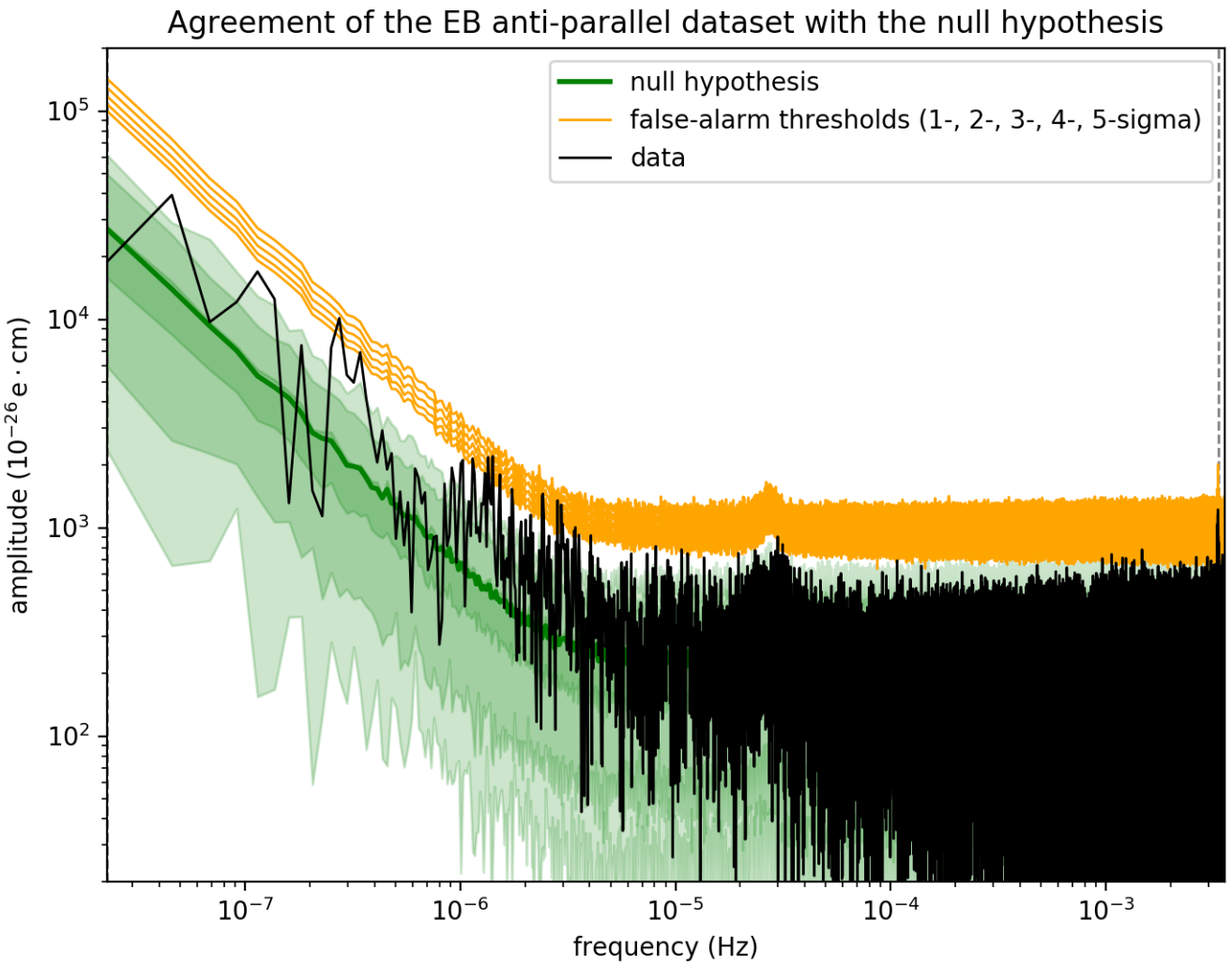


error bars too big

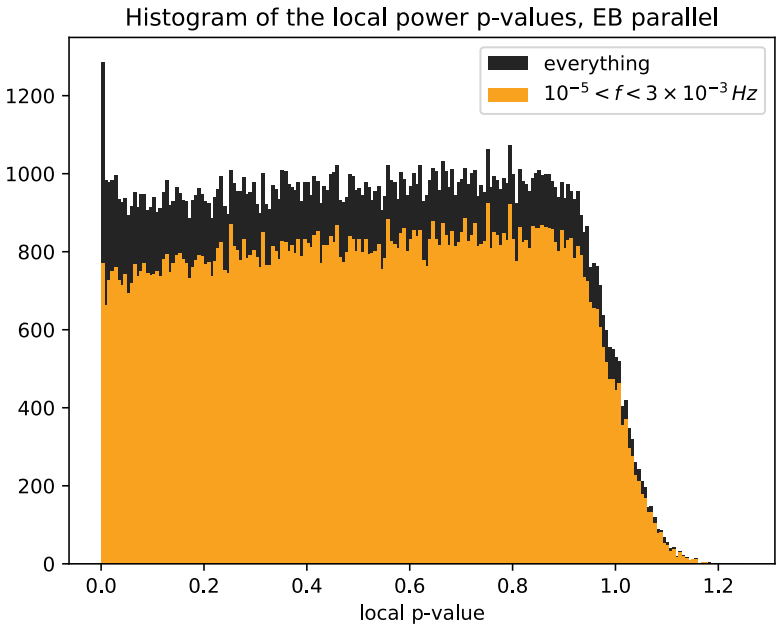
Cycle-level analysis: E ≠ 0



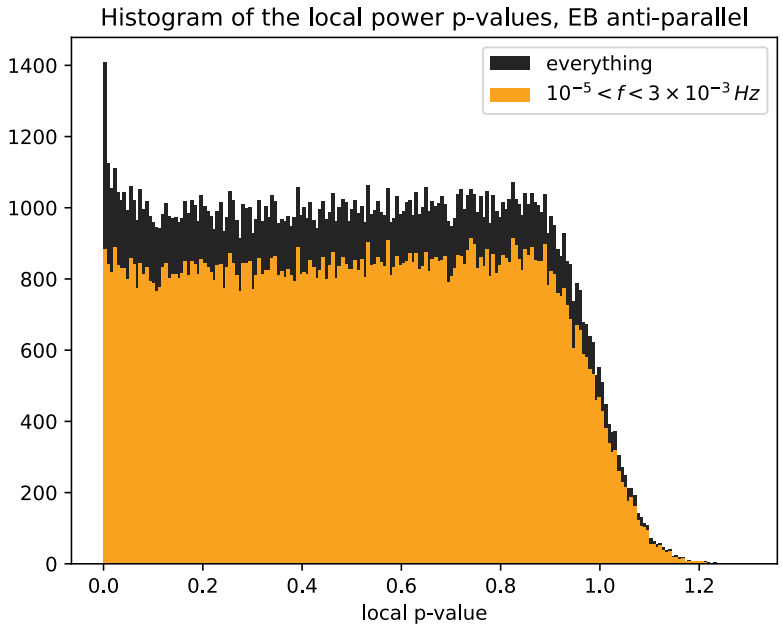
Cycle-level analysis: E ≠ 0



Cycle-level analysis: E ≠ 0, p-value distribution

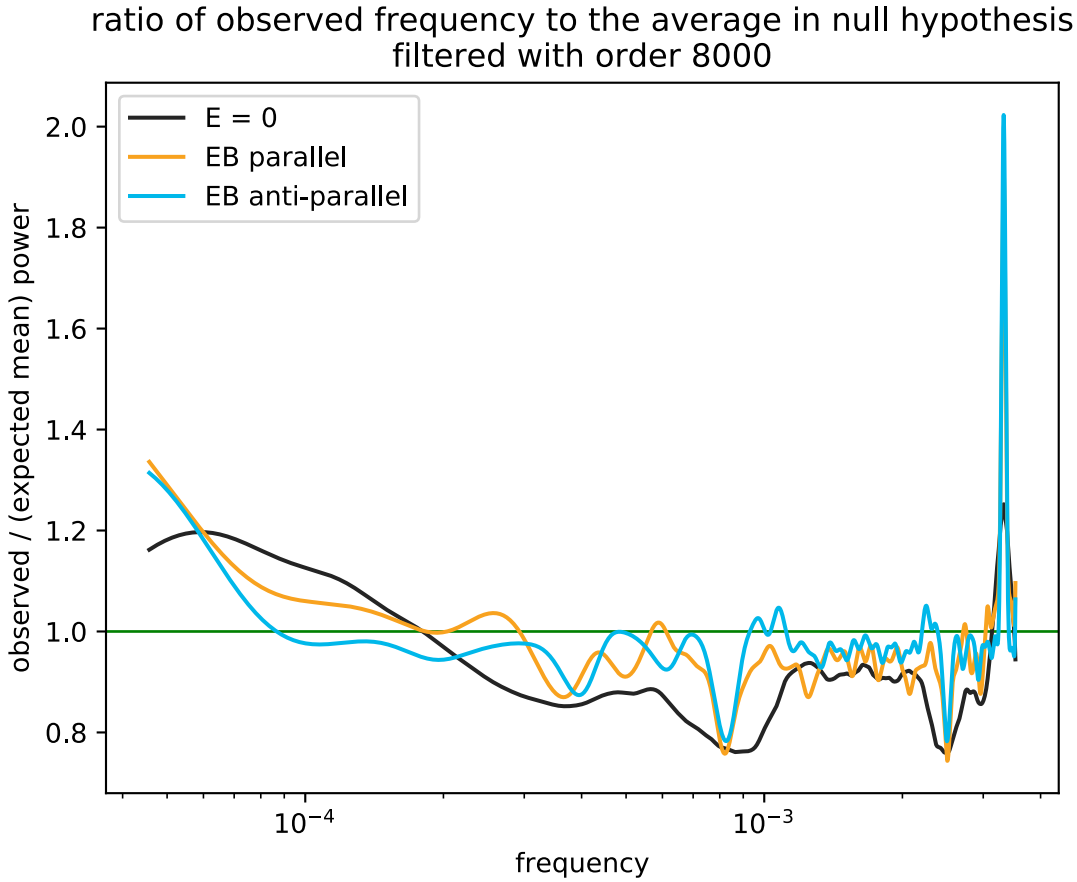


EB parallel



EB anti-parallel

Non-statistical behaviour



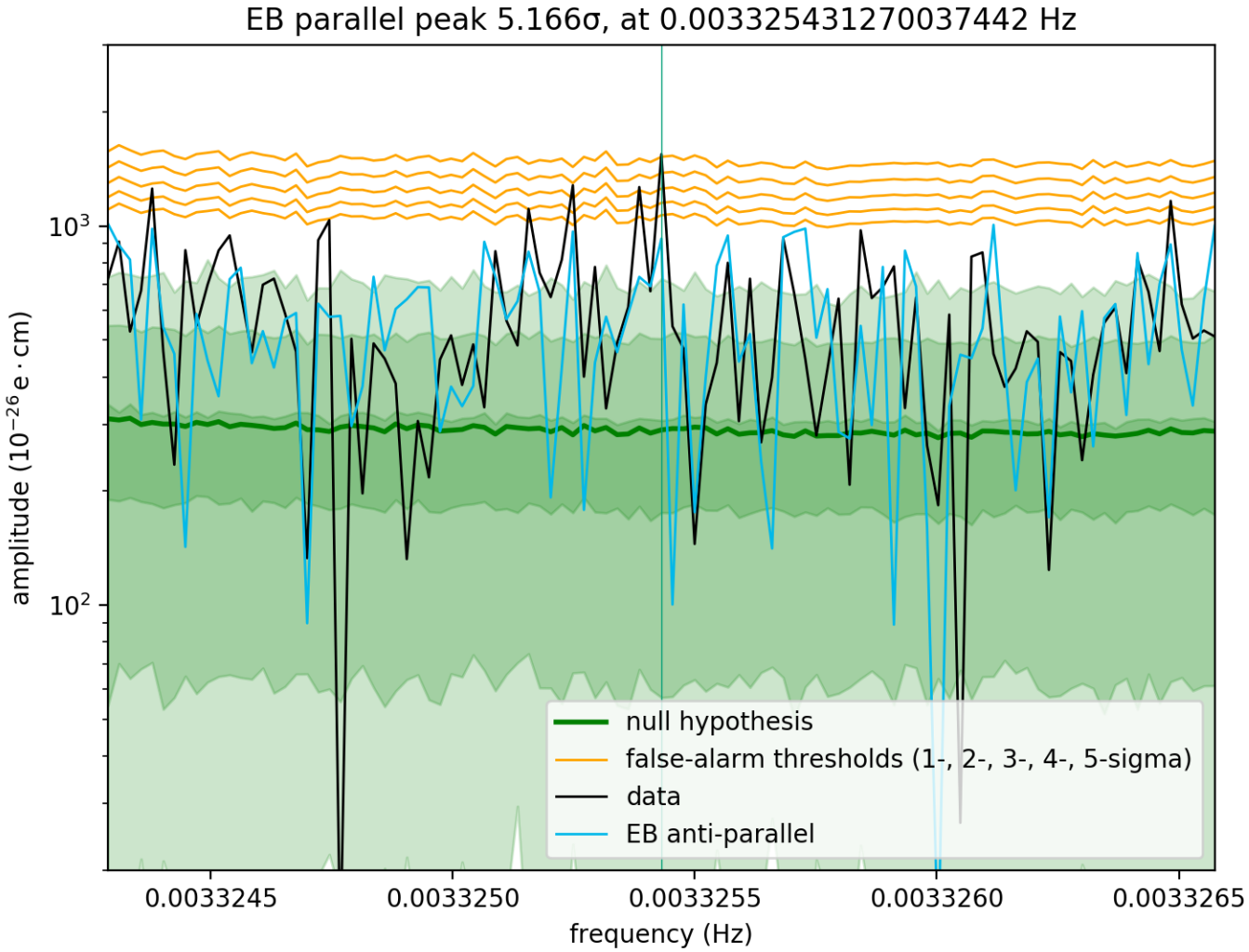
Peak statistics

EB parallel:
highest peak: **5σ**
7 peaks > 3σ
17 peaks > 2σ

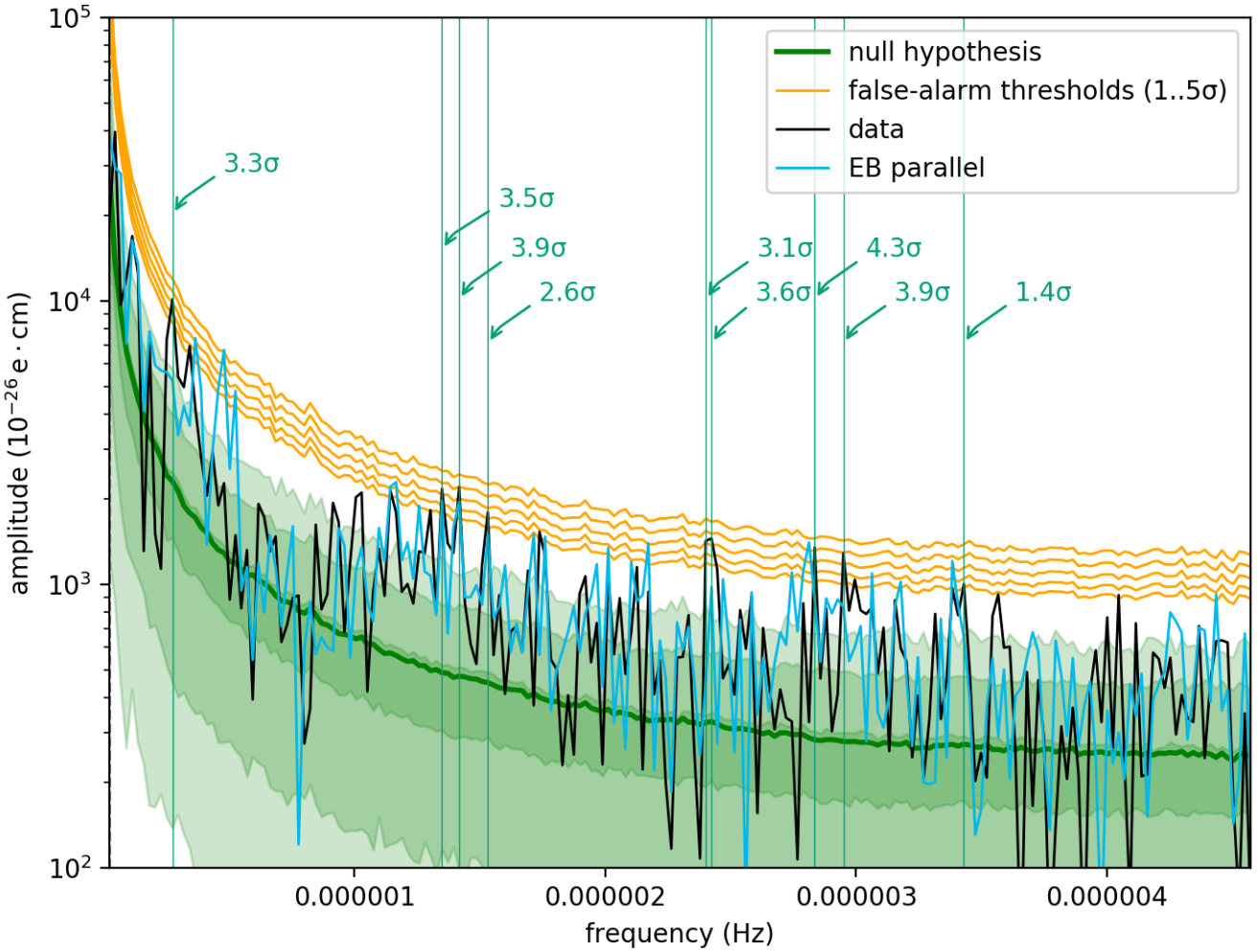
EB anti-parallel:
highest peak: **5σ**
8 peaks > 3σ
15 peaks > 2σ

(156 198 frequencies in total)

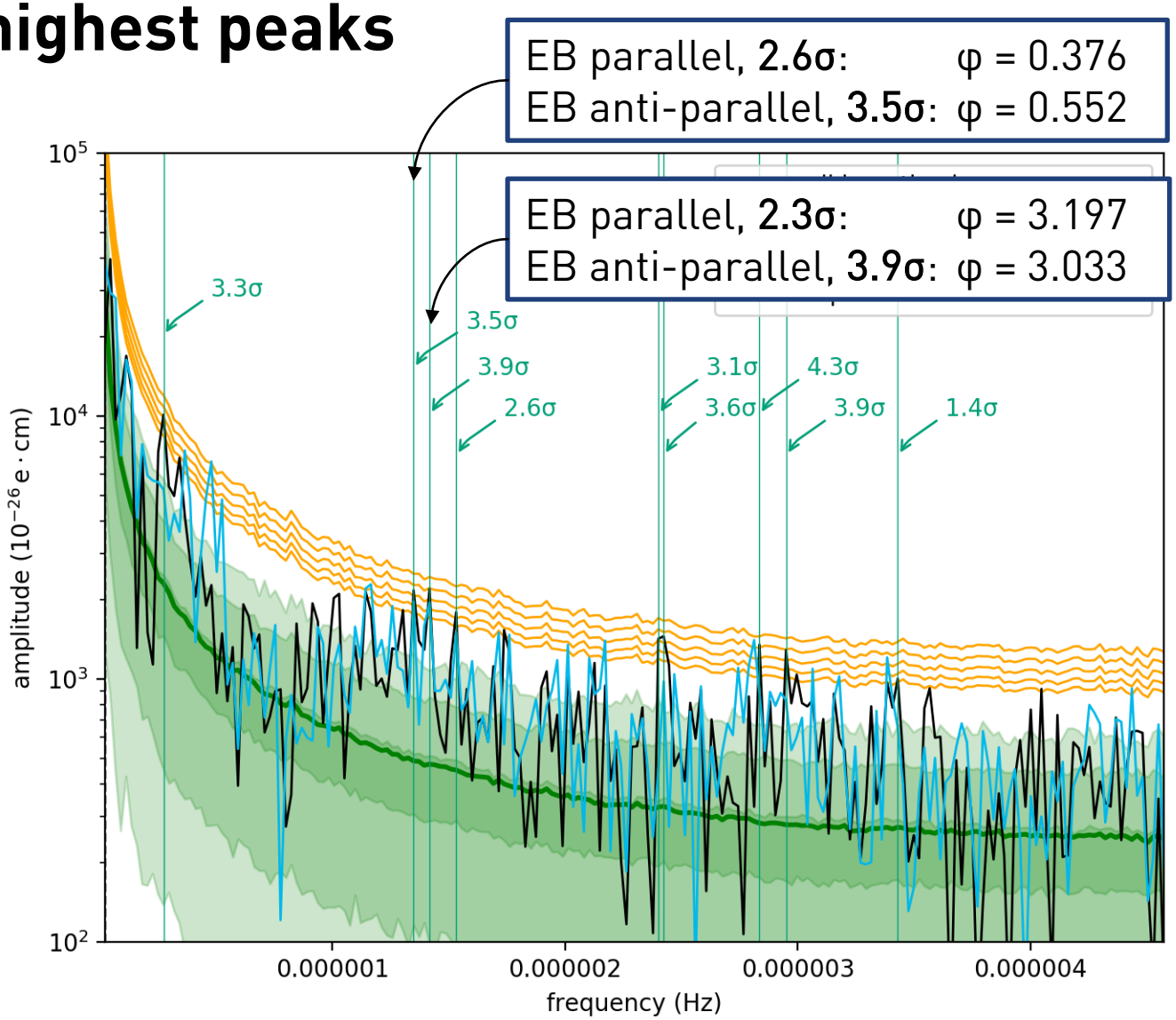
The highest peaks



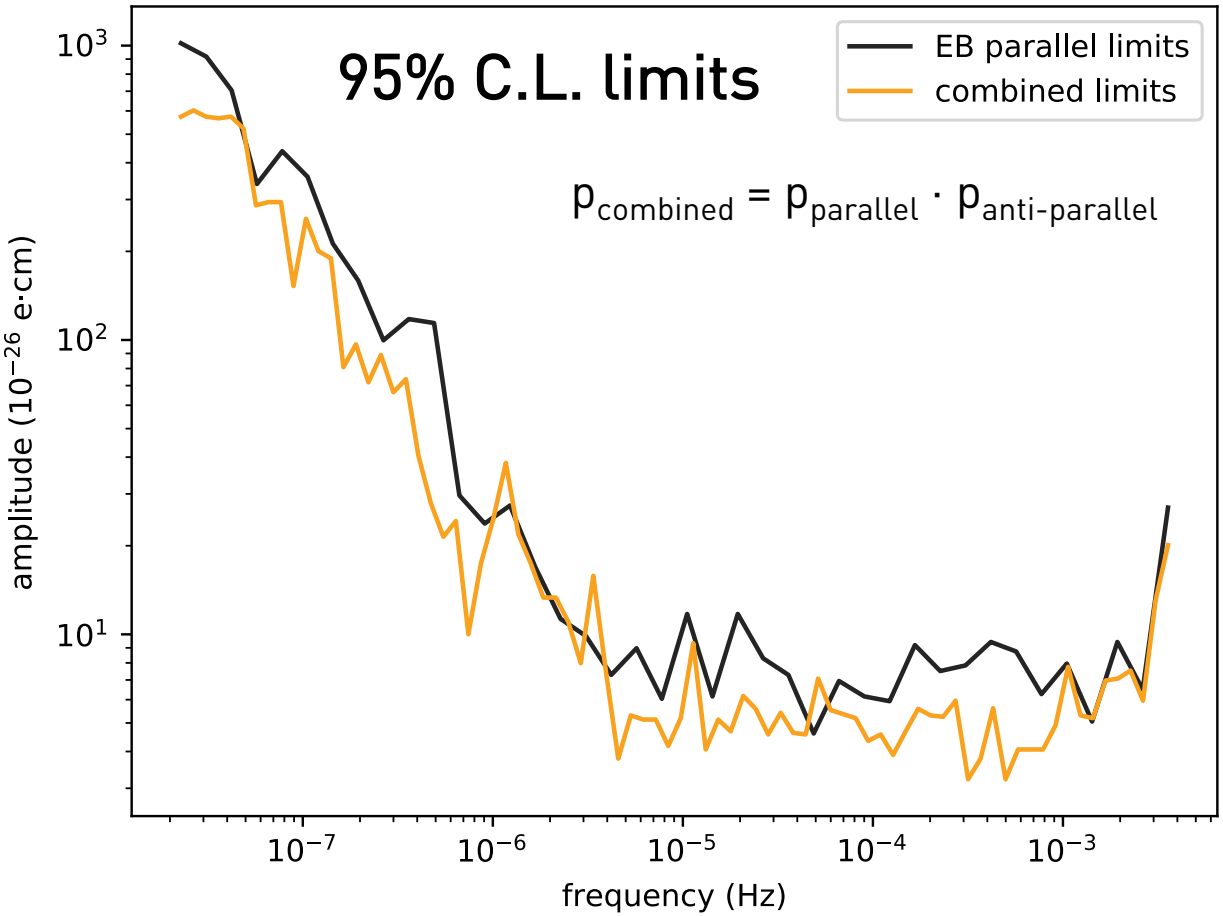
The highest peaks



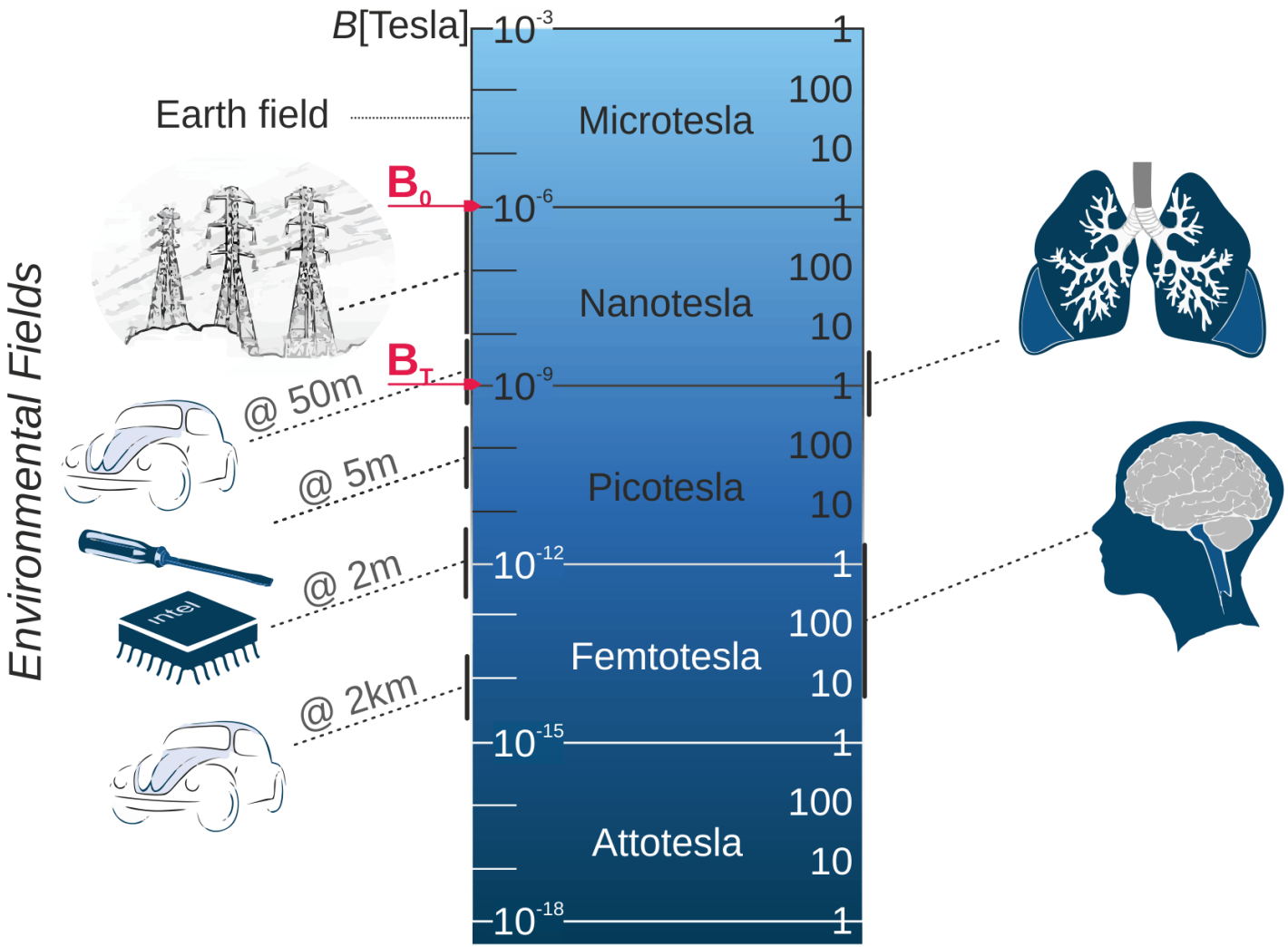
The highest peaks



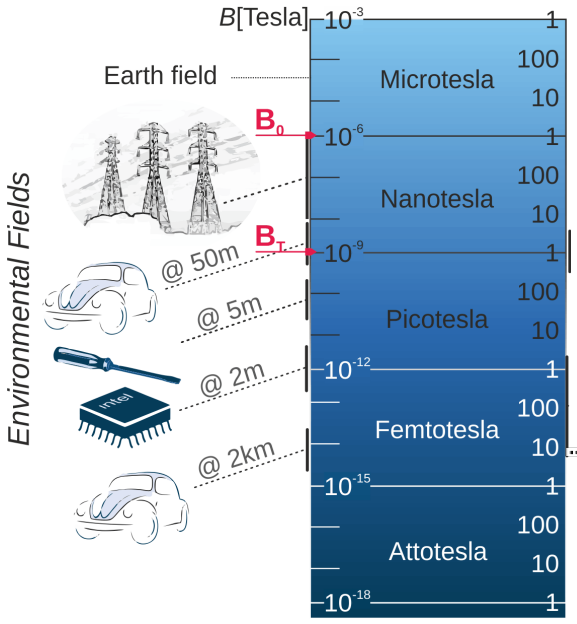
Cycle-level analysis: limits on oscillating nEDM

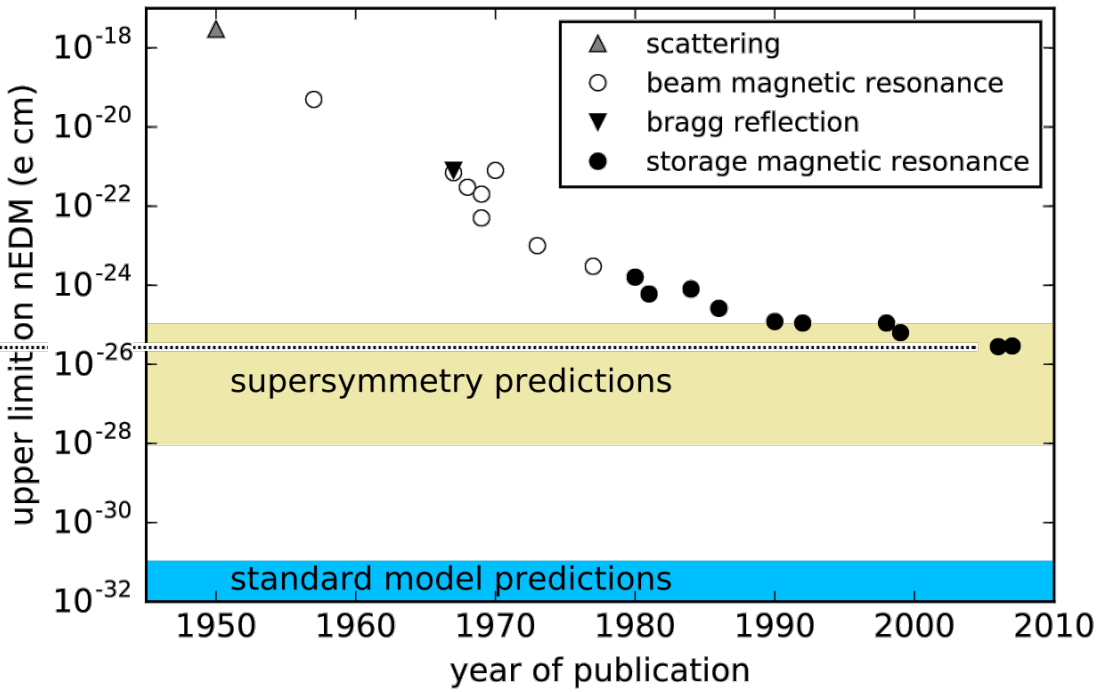


Role of magnetic fields

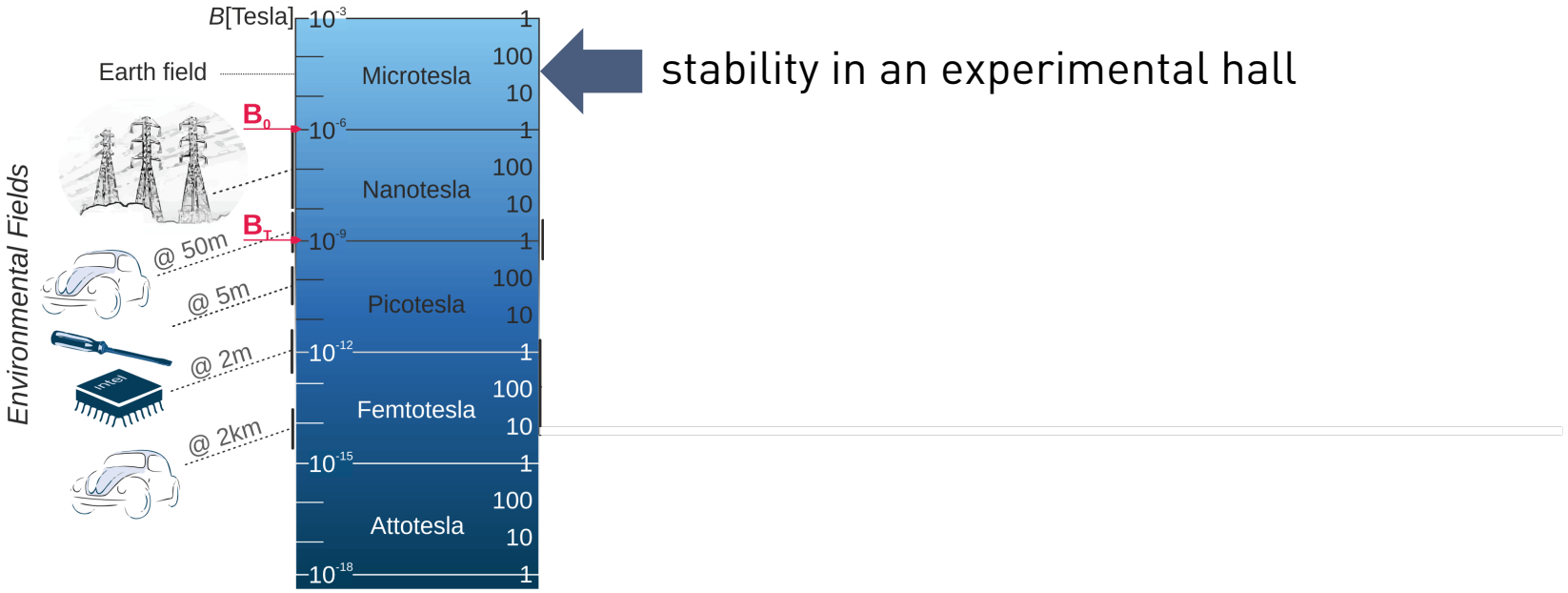


Role of magnetic fields

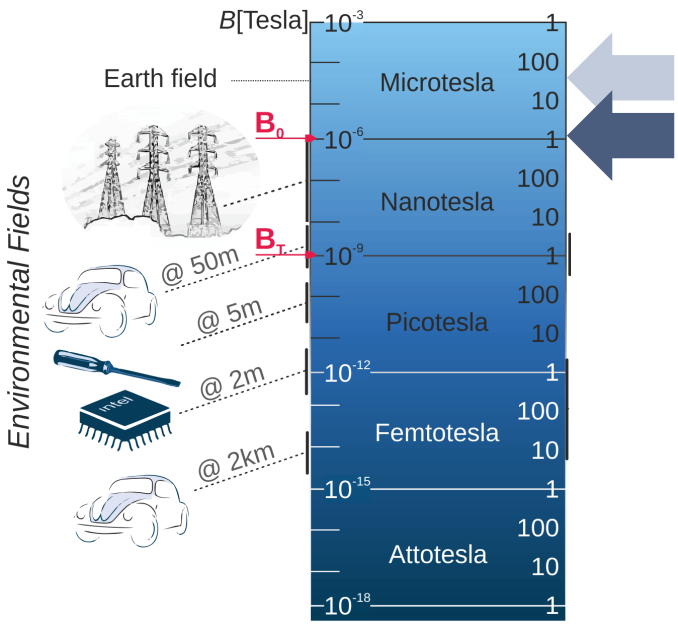


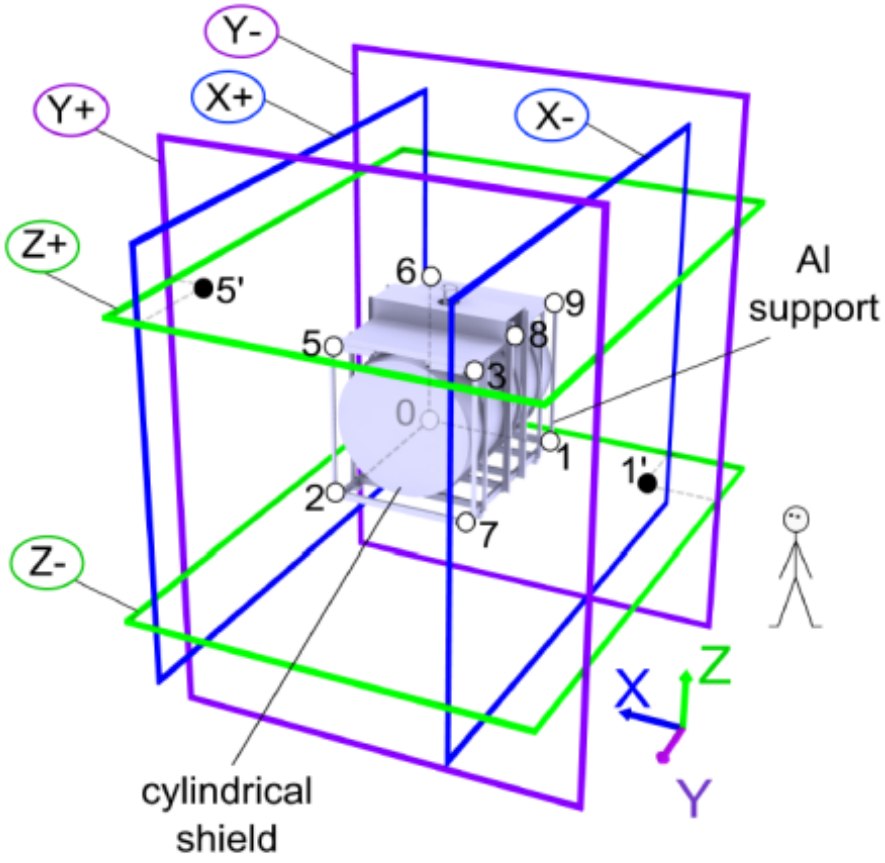


Role of magnetic fields

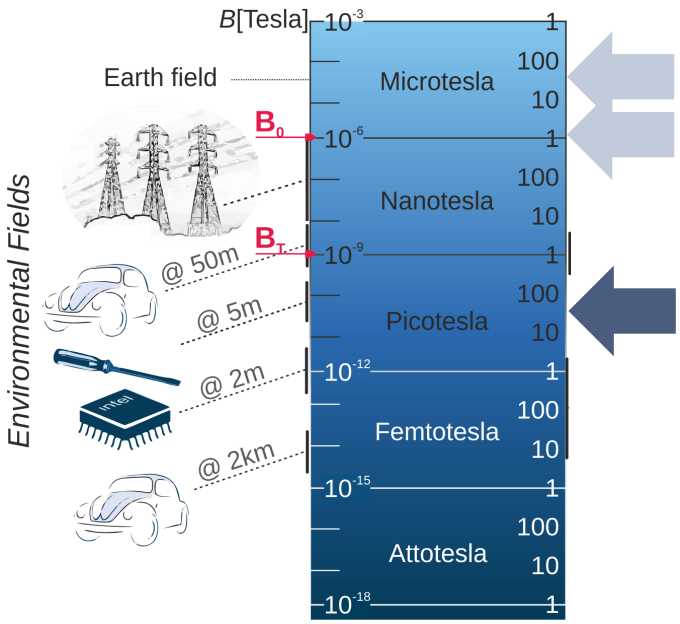


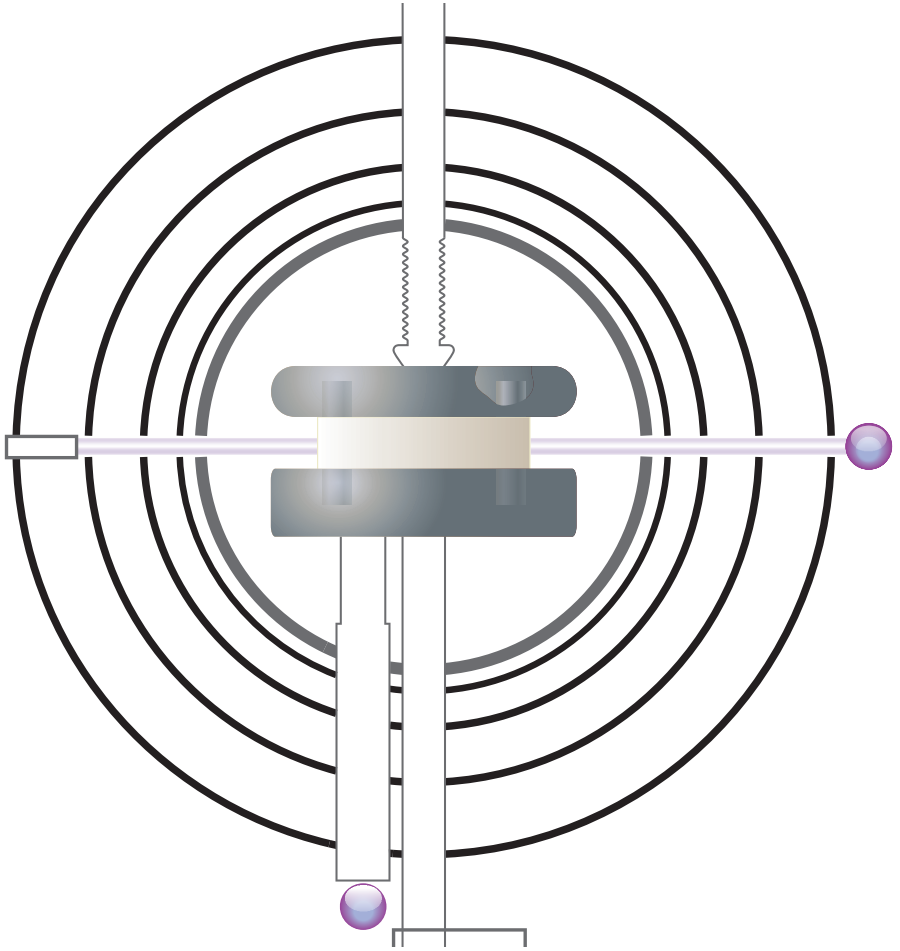
Active Magnetic Field Stabilisation



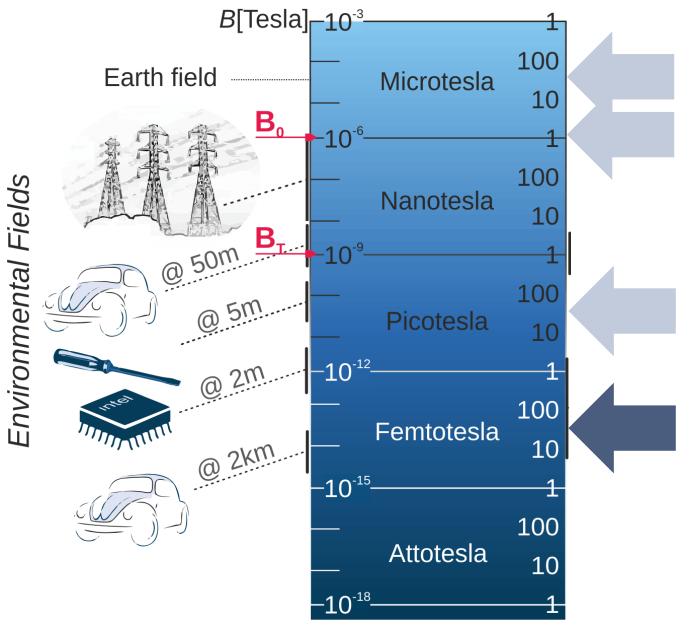


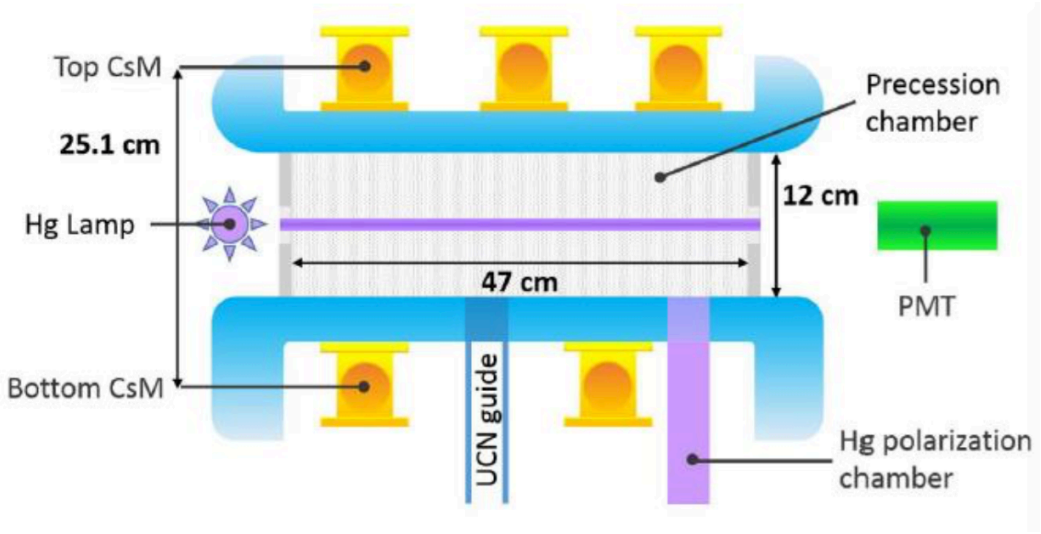
Shielding – 4 layers of μ-metal

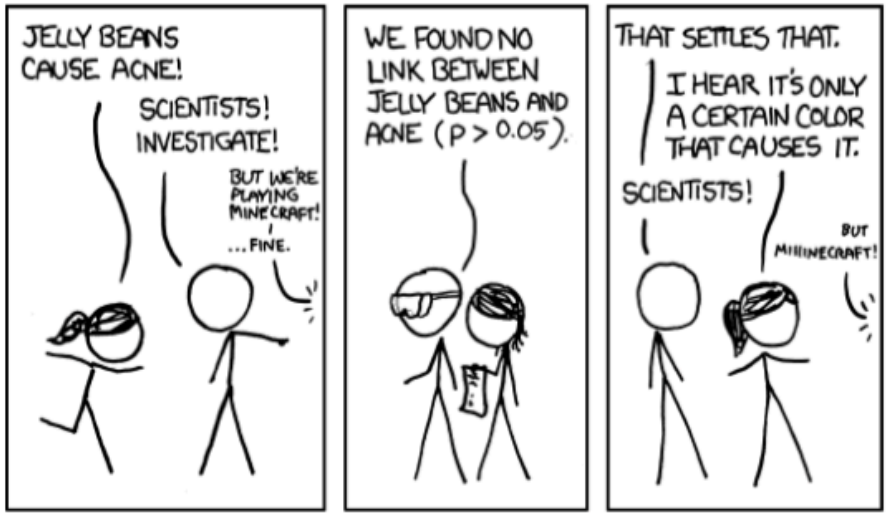


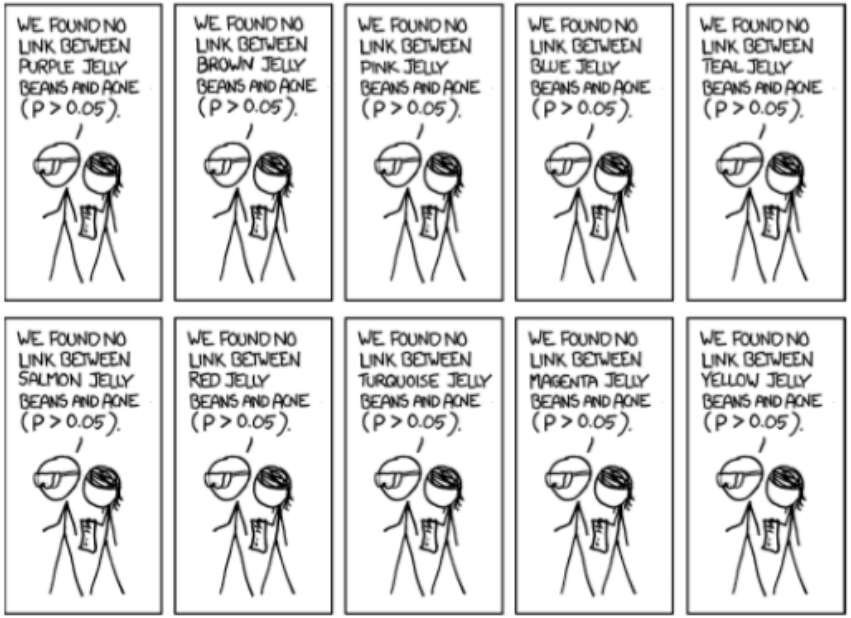


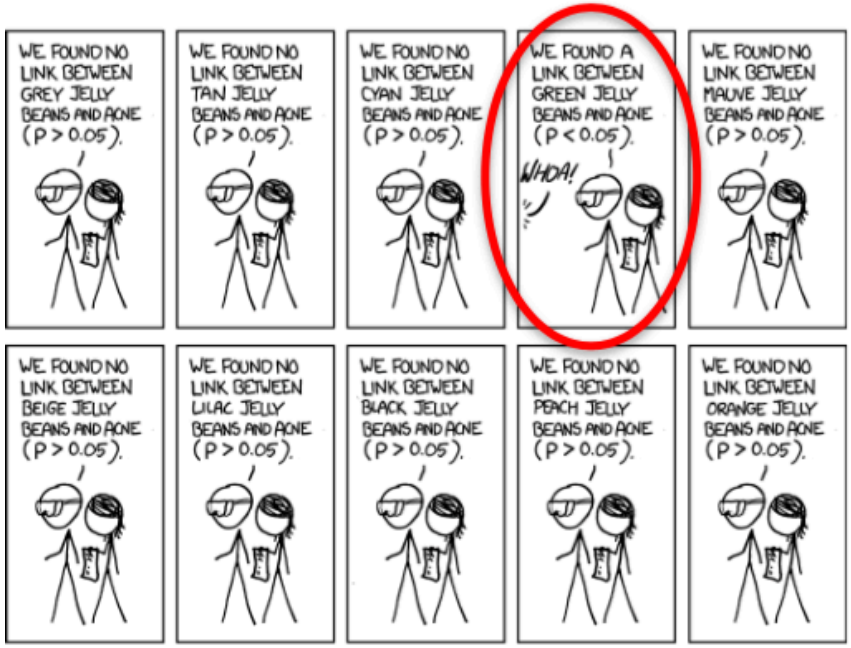
Magnetometry

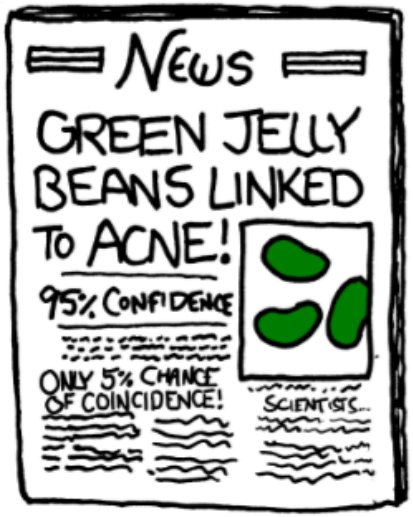




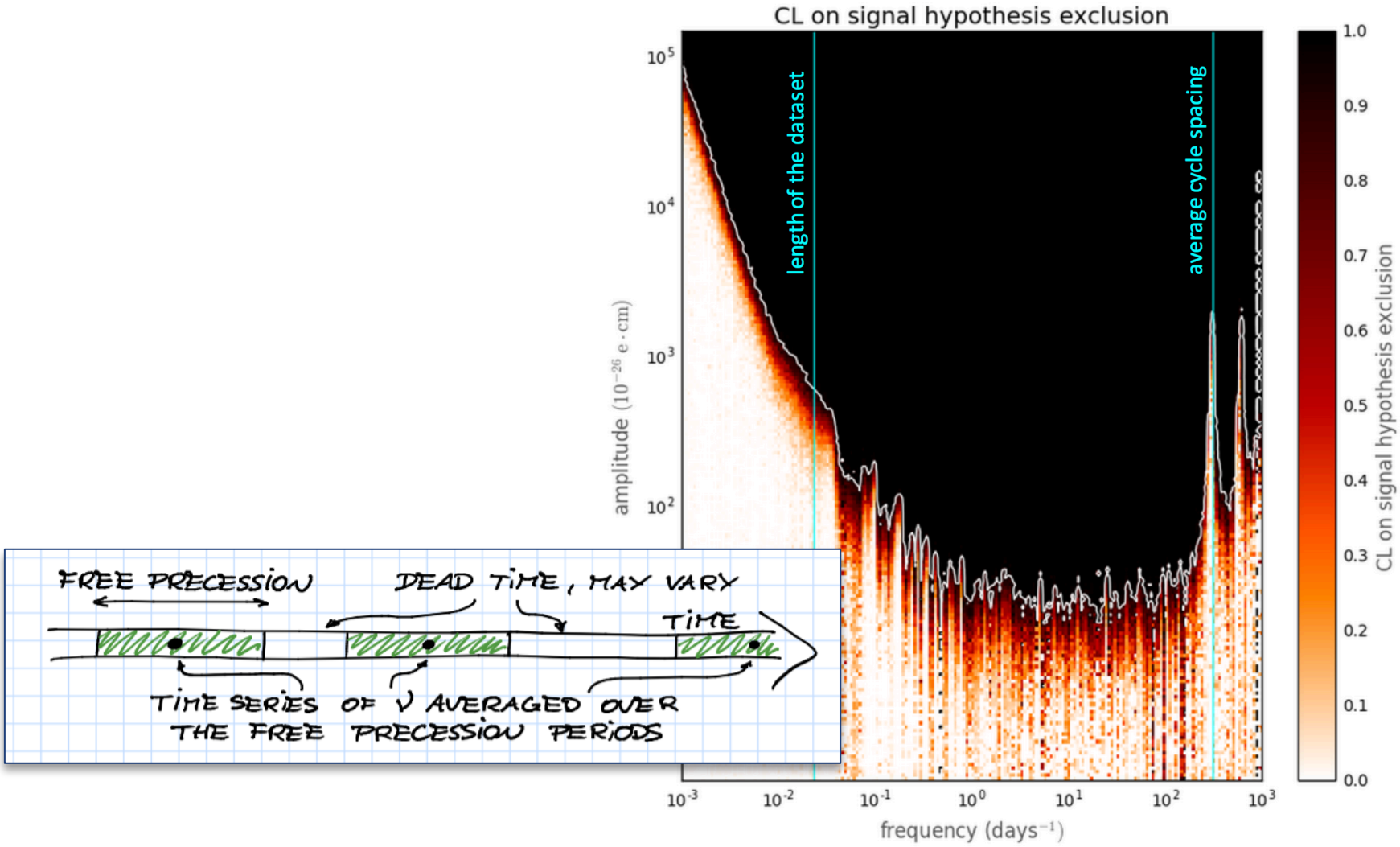

JELLY BEANS CAUSE ACNE!
SCIENTISTS! INVESTIGATE!
BUT WE'RE PLAYING MINECRAFT!
...FINE.
WE FOUND NO LINK BETWEEN JELLY BEANS AND ACNE (P > 0.05).
THAT SETTLES THAT.
I HEAR IT'S ONLY A CERTAIN COLOR THAT CAUSES IT.
SCIENTISTS!
BUT MIIIINECRAFT!


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).

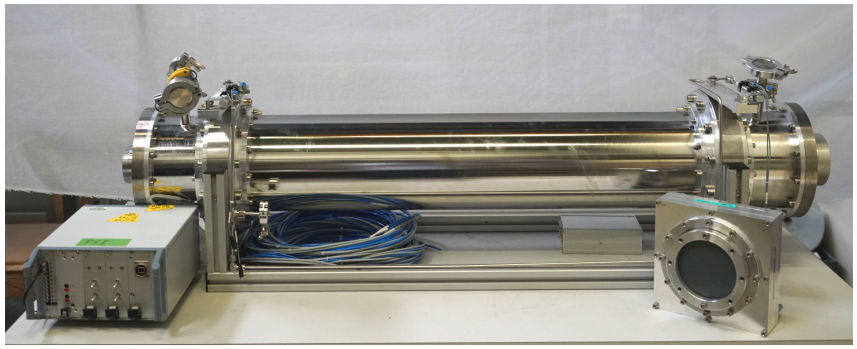

WE FOUND NO LINK BETWEEN GREY JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN TAN JELLY BEANS AND ACNE (P > 0.05).
WE FOUND NO LINK BETWEEN CYAN JELLY BEANS AND ACNE (P > 0.05).
WE FOUND A LINK BETWEEN GREEN JELLY BEANS AND ACNE (P < 0.05).
WHOA!
WE FOUND NO LINK BETWEEN MAUVE JELLY BEANS AND 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).

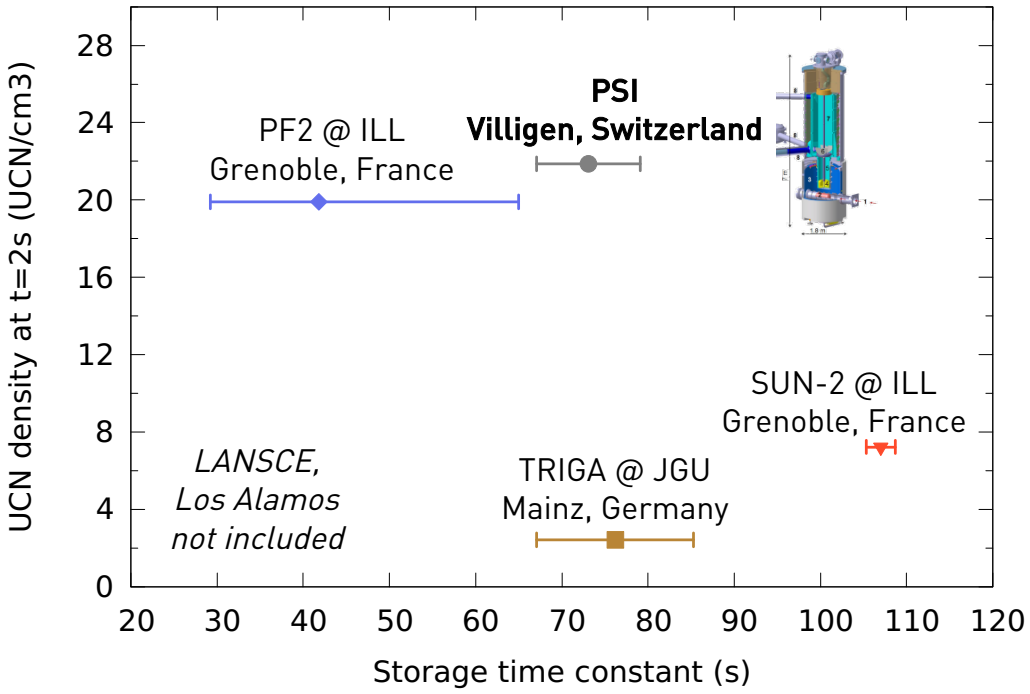

NEWS
GREEN JELLY BEANS LINKED TO ACNE!
95% CONFIDENCE
ONLY 5% CHANCE OF COINCIDENCE!
SCIENTISTS...

the exclusion region



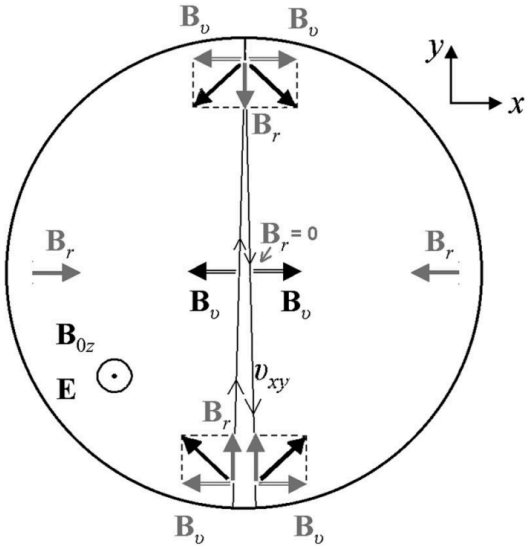
World's strongest UCN source



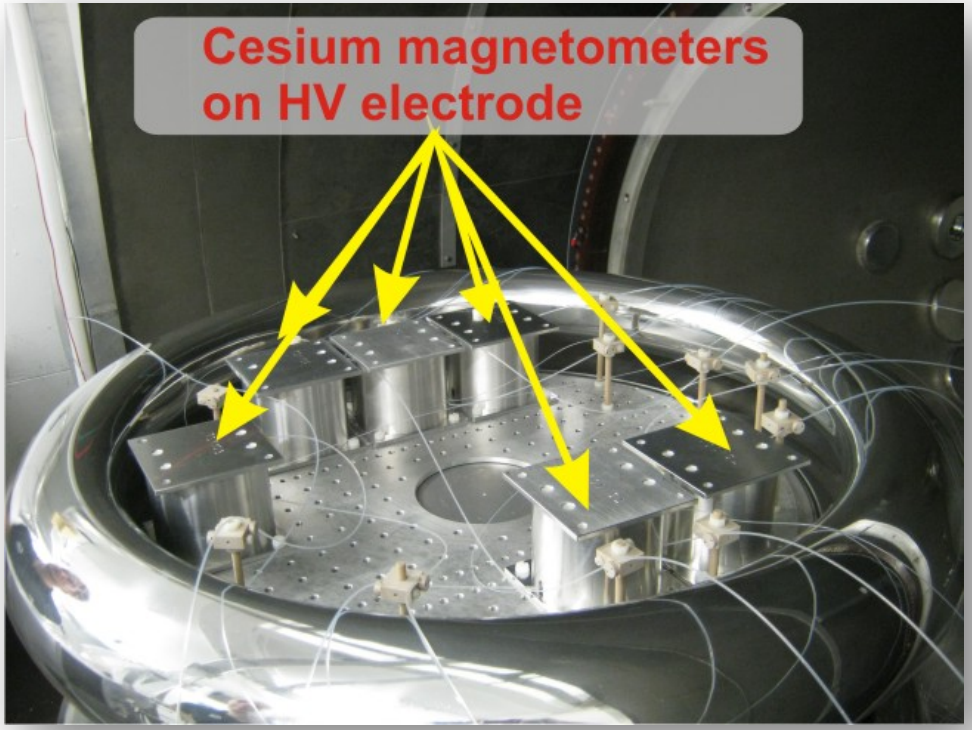


Systematic effects

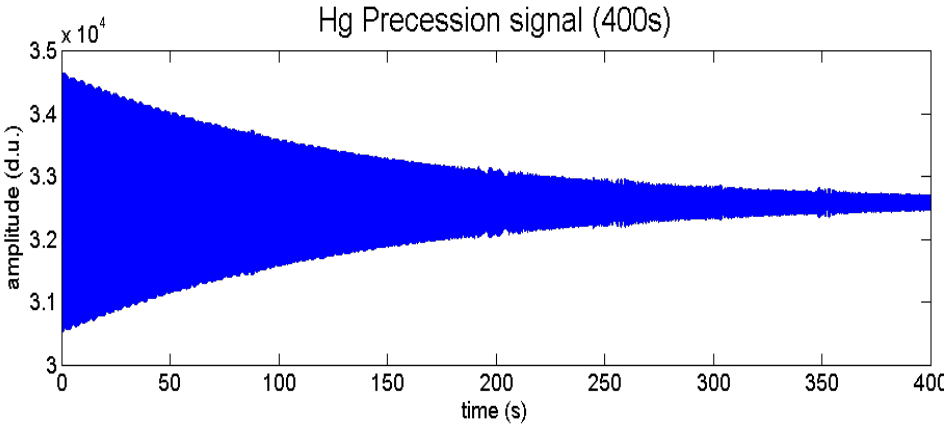
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}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

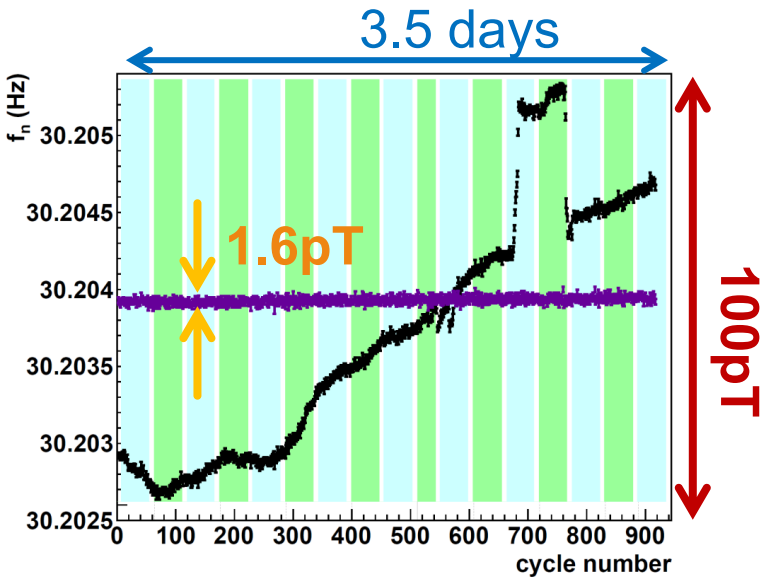


Atomic Cesium magnetometers

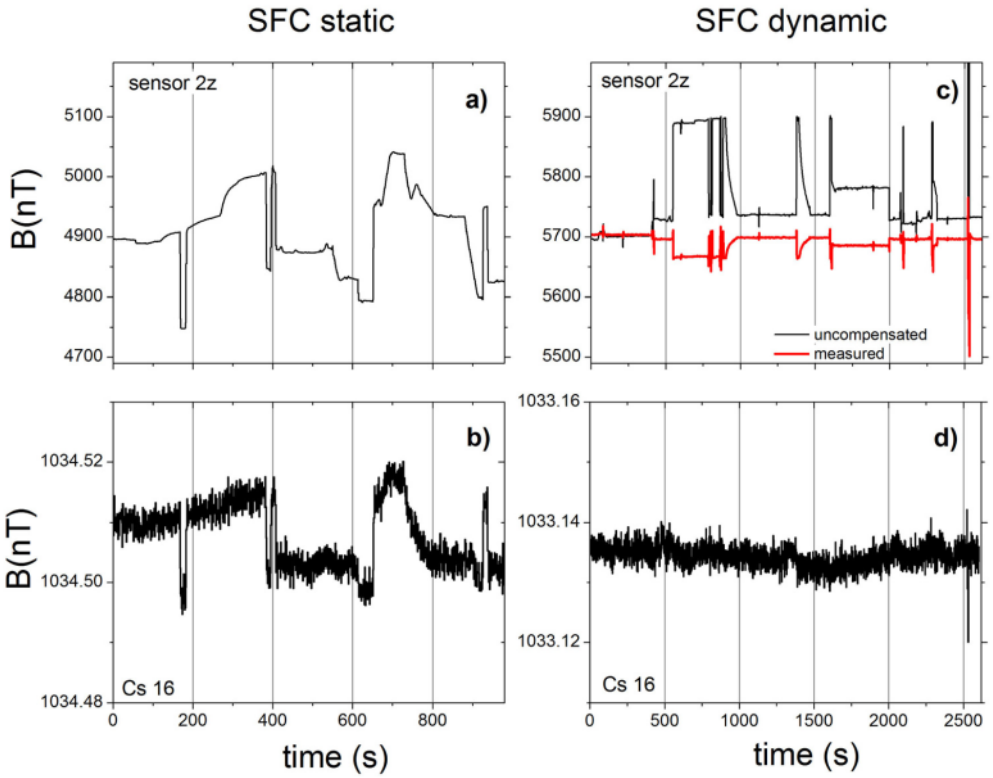


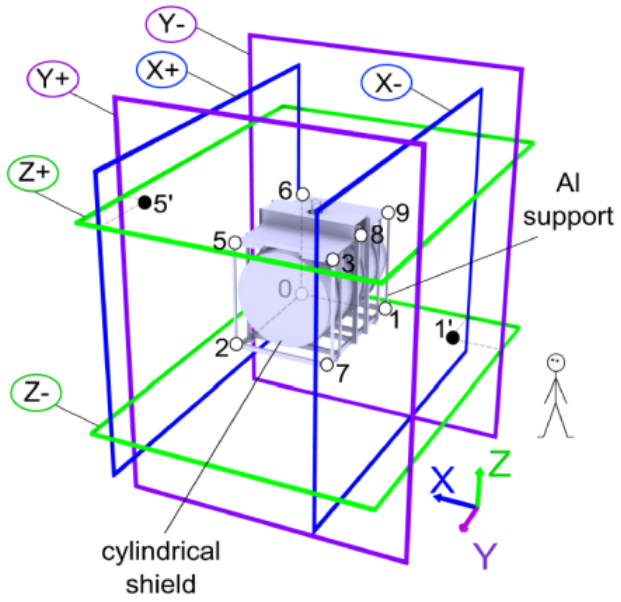
Mercury cohabiting magnetometer





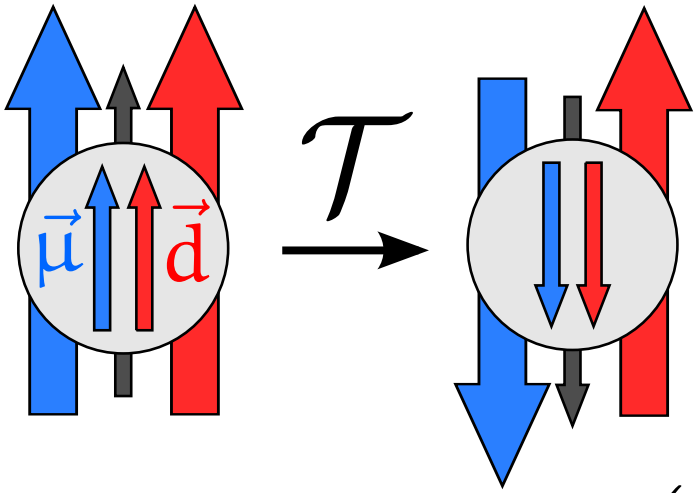
Surrounding Field Compensation System





Electric dipole moment

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



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