Phys. Rev. X 7, 041034 (2017)

nEDM as a Dark Matter Detector

Nicholas Ayres, University of Sussex on behalf of the PSI nEDM collaboration

With: Michał Rawlik, ETH Zürich

M. Fairbairn, D.J.E. Marsh, Kings College London

V.V. Flambaum, University of New South Wales

Y.V. Stadnik, Johannes Gutenberg Universität Mainz

UNIVERSITY OF SUSSEX

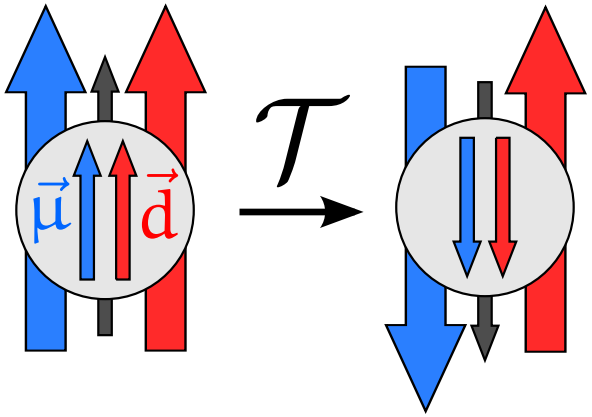
Outline

- Intro to the Neutron Electric Dipole Moment
- Axions and ALPs as Dark Matter, and why an EDM might oscillate
- Analysis
- Results

UNIVERSITY OF SUSSEX

The Neutron EDM

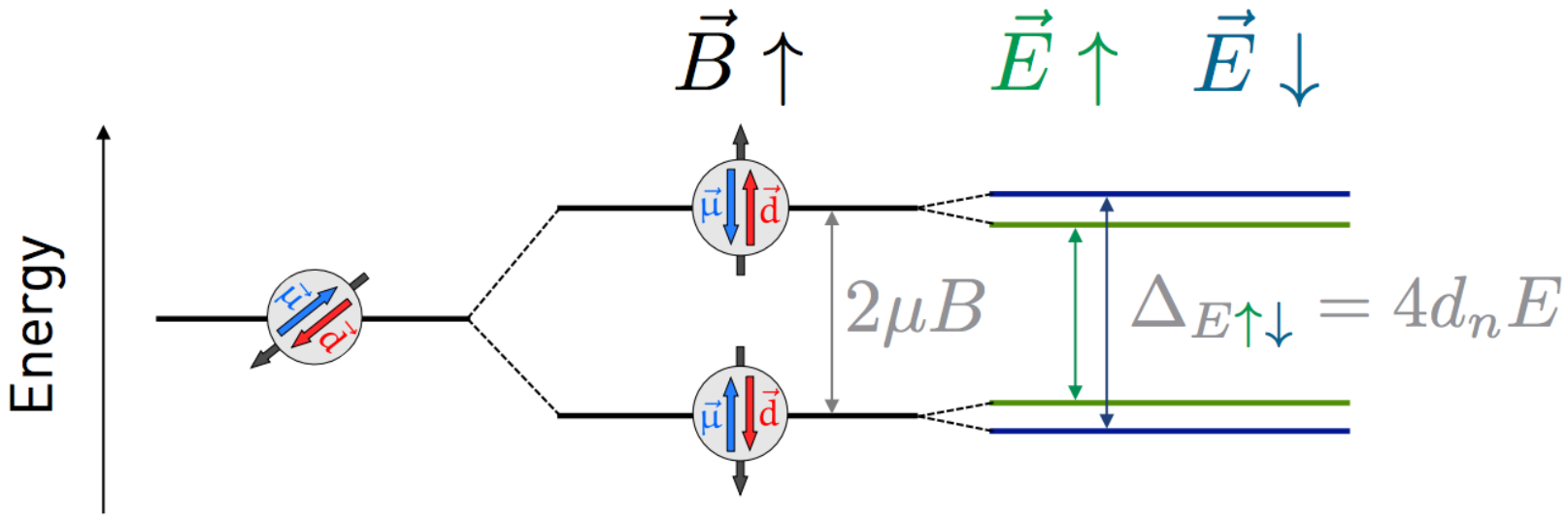
- Nonzero EDM violates P,T
- Static EDM measured since 1951, with developments ongoing worldwide
- SM nEDM: $<10^{-31}$ e cm (CKM)
- BSM CPv new physics can cause large enhancements
- Current limit 3×10^{-26} e cm



UNIVERSITY OF SUSSEX

How to Measure an EDM

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



Search for a shift in the NMR frequency under an electric field

UNIVERSITY OF SUSSEX

Two Sister Experiments

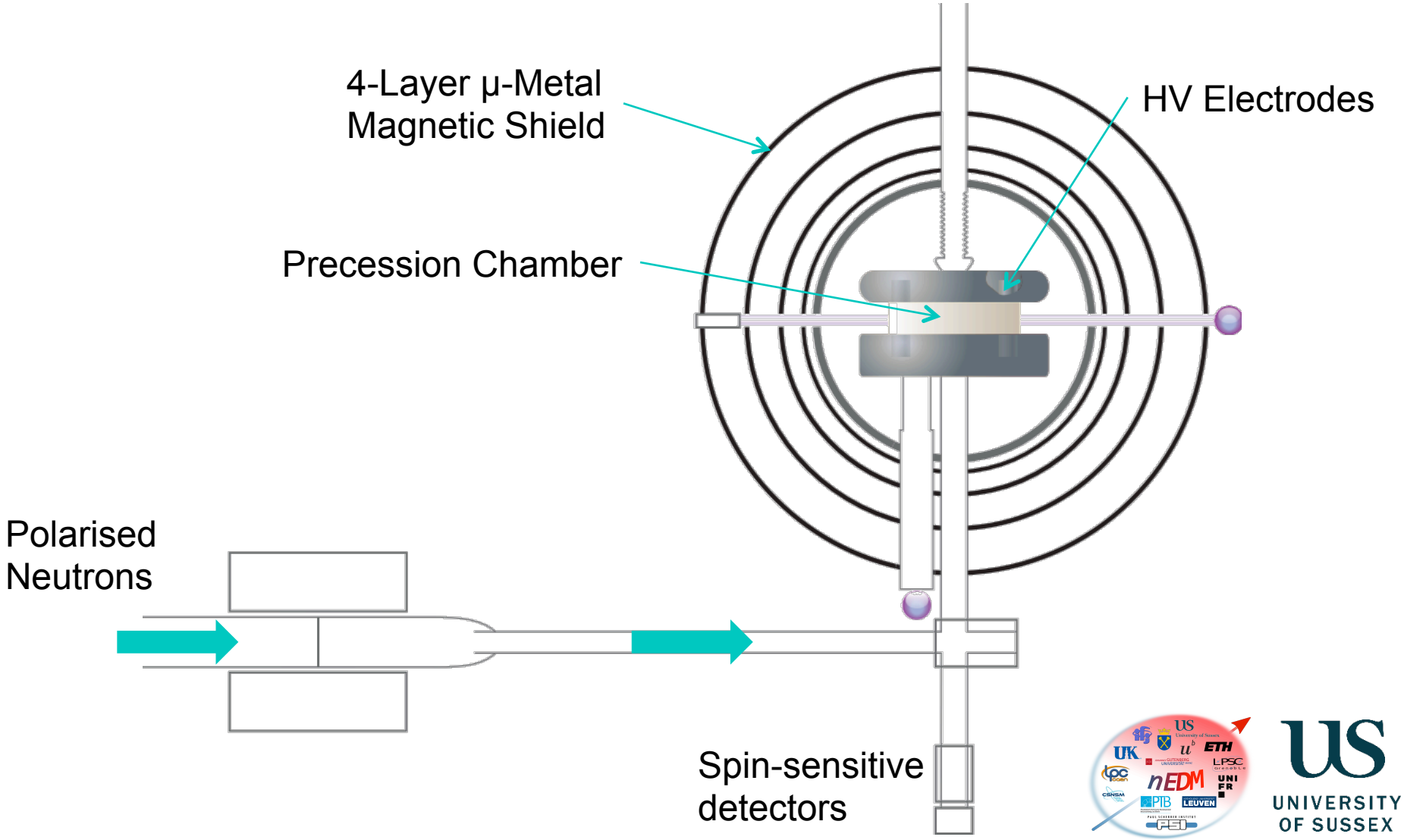
Sussex-RAL-ILL Experiment
Holds Current World Limit…

PRL 97, 131801
PRD 92, 092003

nEDM Experiment at PSI
...New Result Soon

Hyperfine Interact (2016) 237: 142
Physics Proceedia (2011) 17, 159-167

nEDM at PSI Experiment



UNIVERSITY OF SUSSEX

Axions as Dark Matter

- Ultralight axions m~10^{-22}-10^{-17}eV can be DM
- Acts like coherently oscillating classical field with frequency ~ mass
  - 10^{-22} eV => 1 inverse year
- Strategy: Assume all dark matter is axions, and try to measure couplings between these axions and neutrons

UNIVERSITY OF SUSSEX

Axion-Neutron interactions

$$\mathcal{L} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^b_{\mu\upsilon}\tilde{G}^{b\mu\upsilon} - \frac{C_N}{2f_a}\partial_\mu a \bar{N}\gamma^\mu\gamma^5 N$$

Axion-gluon coupling
Induces neutron EDM oscillation through same mechanism as QCD theta

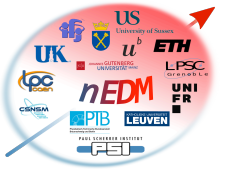
Axion-nucleon coupling
Non E dependant frequency modulation

$$\mathcal{L} = \frac{g^2}{32\pi^2}\theta G^b_{\mu\upsilon}\tilde{G}^{b\mu\upsilon}$$

UNIVERSITY OF SUSSEX

Analysis

- 2 Analyses:
  - Systematics compensated data from ILL (binned by B field config) – time series of measured EDM
  - All individual (5 min) cycles from PSI (field drift-compensated)
- Extract power spectrum using Least Squares Spectral Analysis
- Monte Carlo to find probability distributions
- Use CL_S technique for exclusions



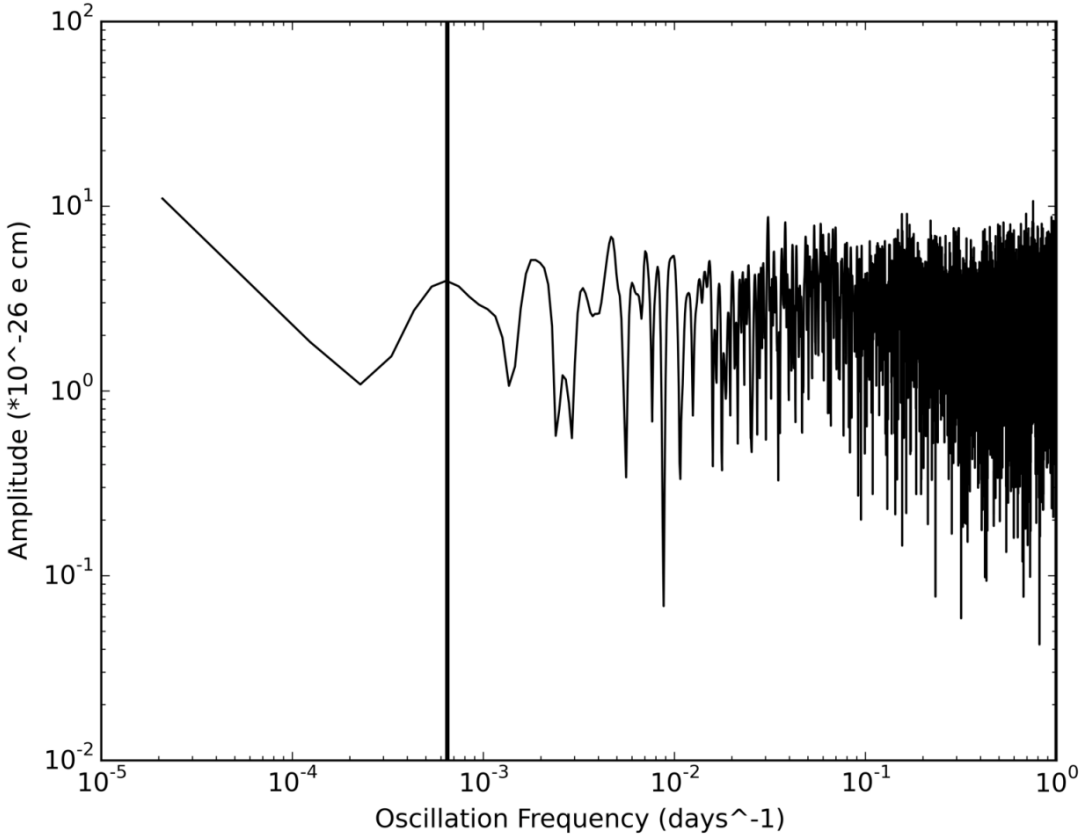
UNIVERSITY OF SUSSEX

Least Squares Spectral Analysis

- Fit for each ω:

$$d_n(t) = A\cos\omega t + B\sin\omega t$$

- Equivalent to Fourier transform, but allows uneven time spacing and errors



LSSA of ILL Data

UNIVERSITY OF SUSSEX

Monte Carlo

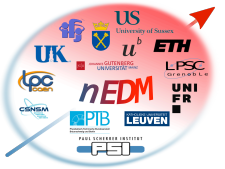
- Generate fake data (Gaussian noise with same timings as data) and do Least Squares Spectral Analysis
- Analyse for each frequency
- Fit expected exponential distribution to extrapolate to unlikely events

UNIVERSITY OF SUSSEX

Look Elsewhere and False Alarm

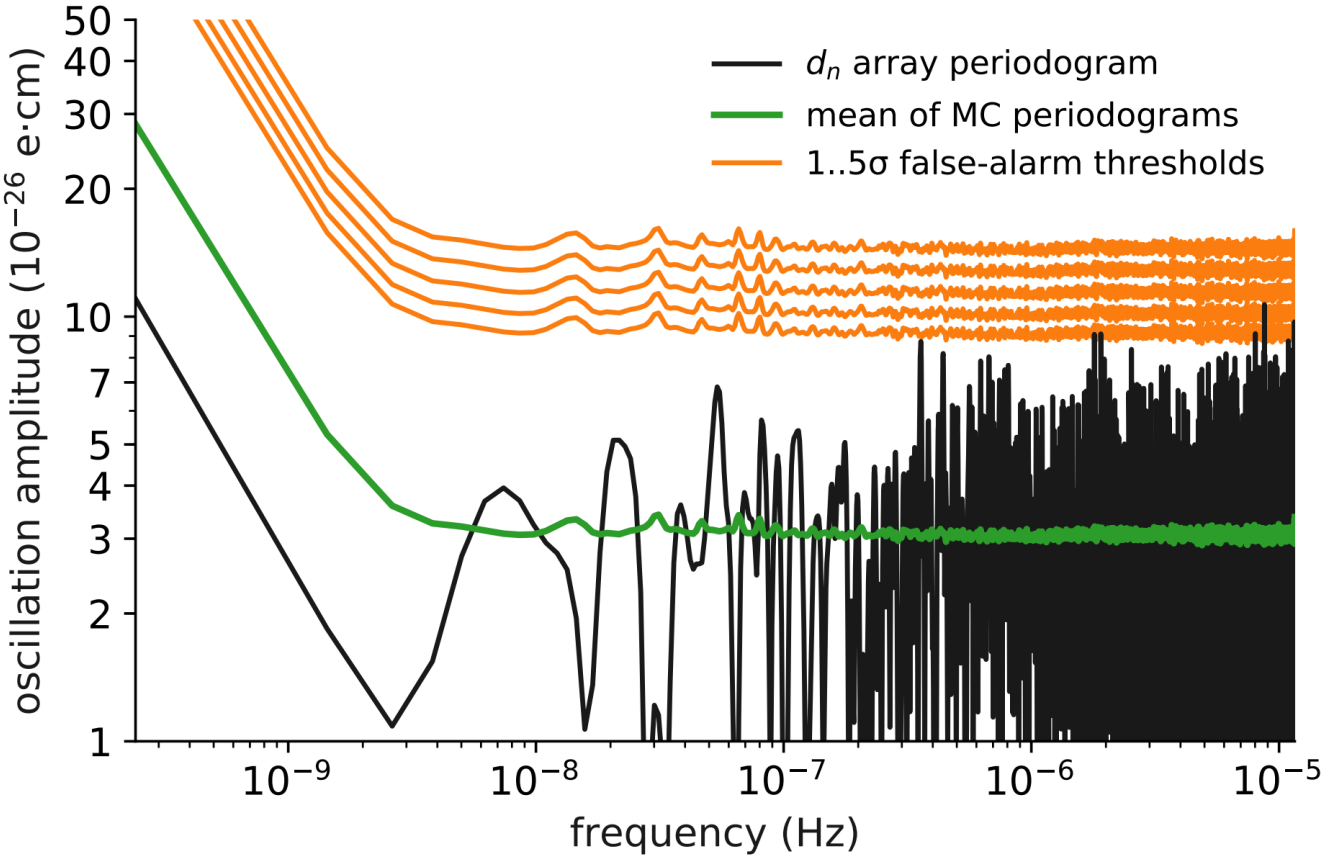
- Expect 5% false positives for P=0.05, but we test thousands of hypotheses frequencies
- Solution: inflate required p-values

$$P_{\text{global}} = 1 - (1 - P_{\text{local}})^{N_{\text{effective}}}$$



UNIVERSITY OF SUSSEX

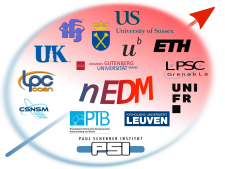
ILL Detection



UNIVERSITY OF SUSSEX

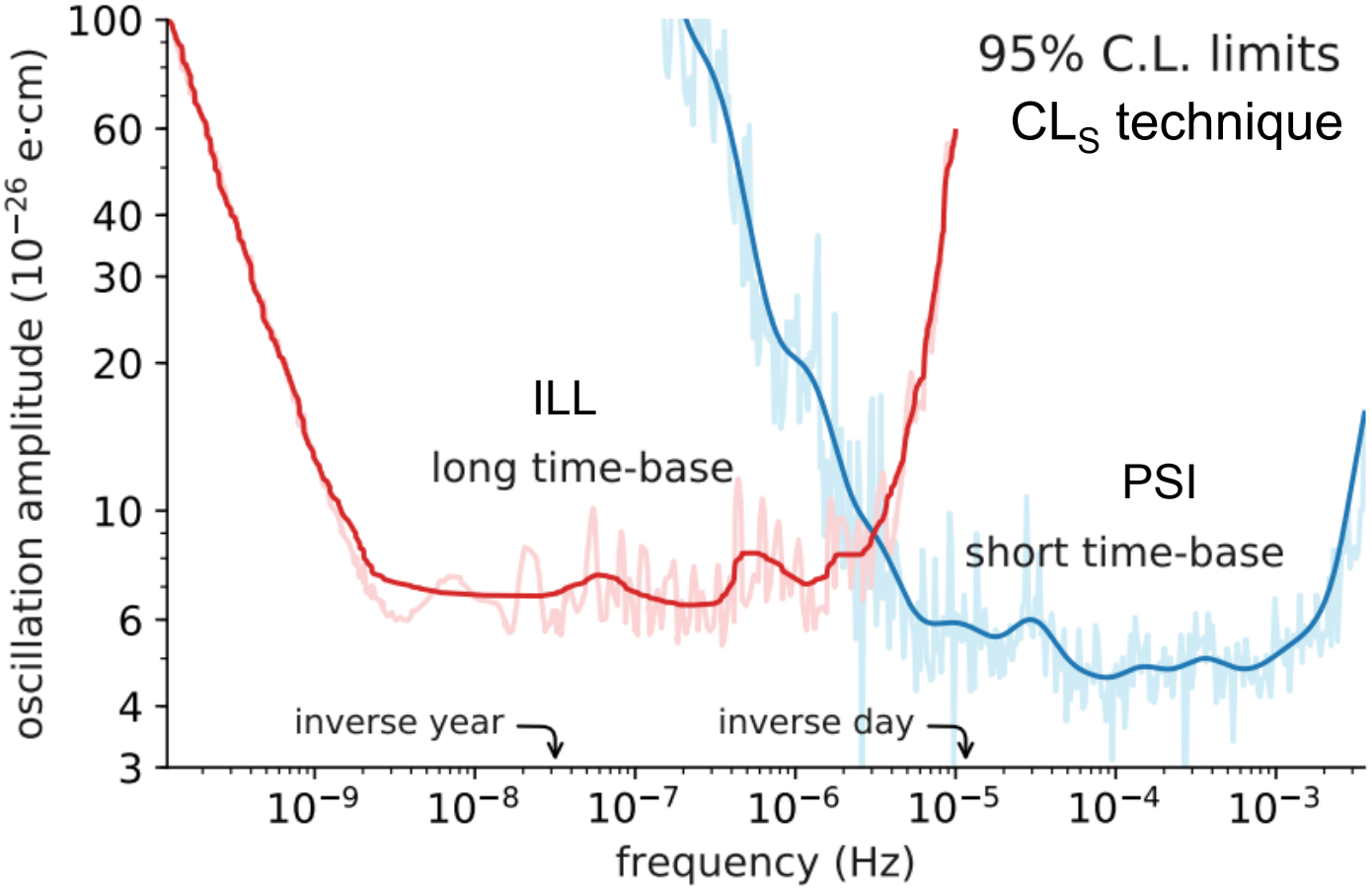
Analysis of the PSI data

- For each cycle, estimate neutron frequency
- Analyse time series of neutron frequency, sorted by E and B field
- Add free offset to each magnetic field configuration to account for all systematics
- Can access axion-nucleon coupling and varying EDM

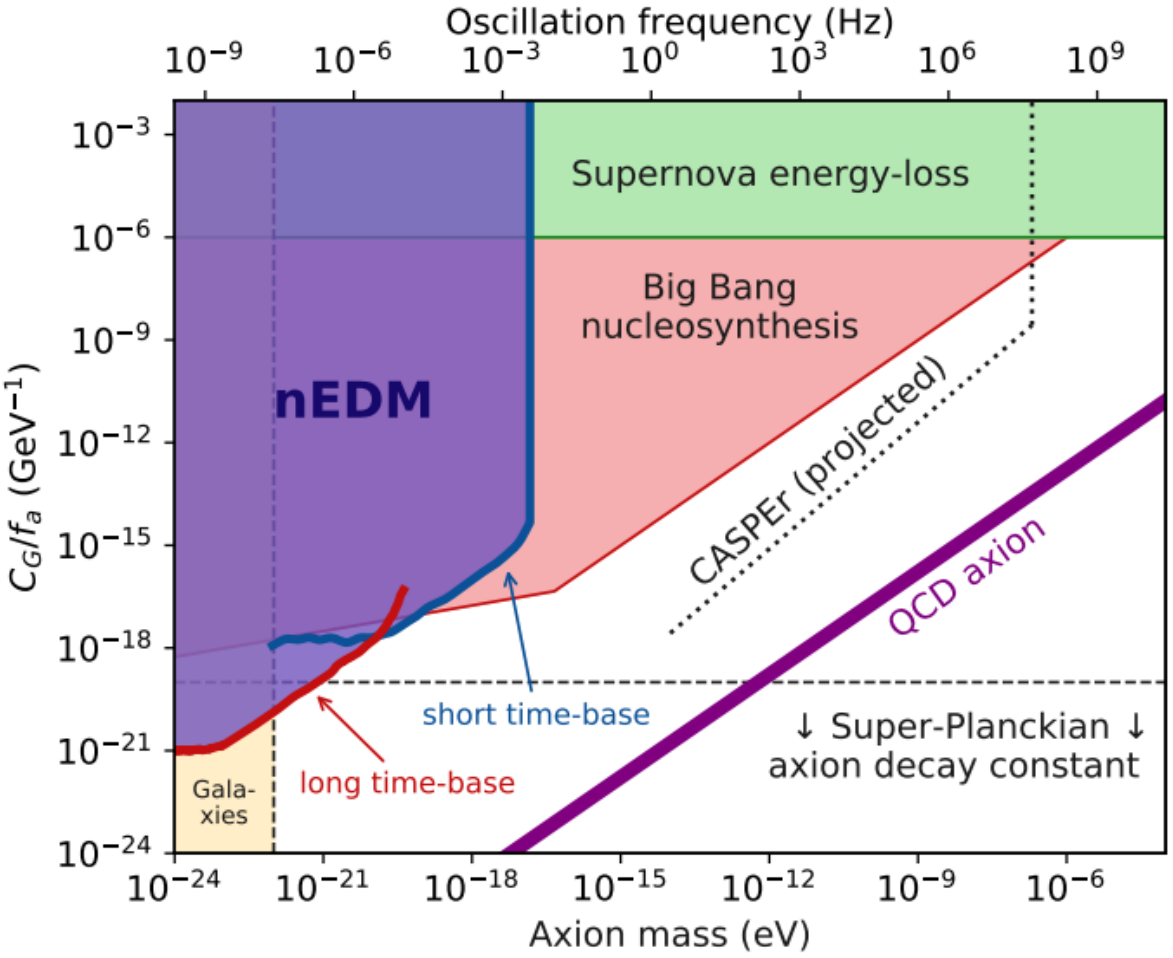


UNIVERSITY OF SUSSEX

ILL and PSI Exclusion



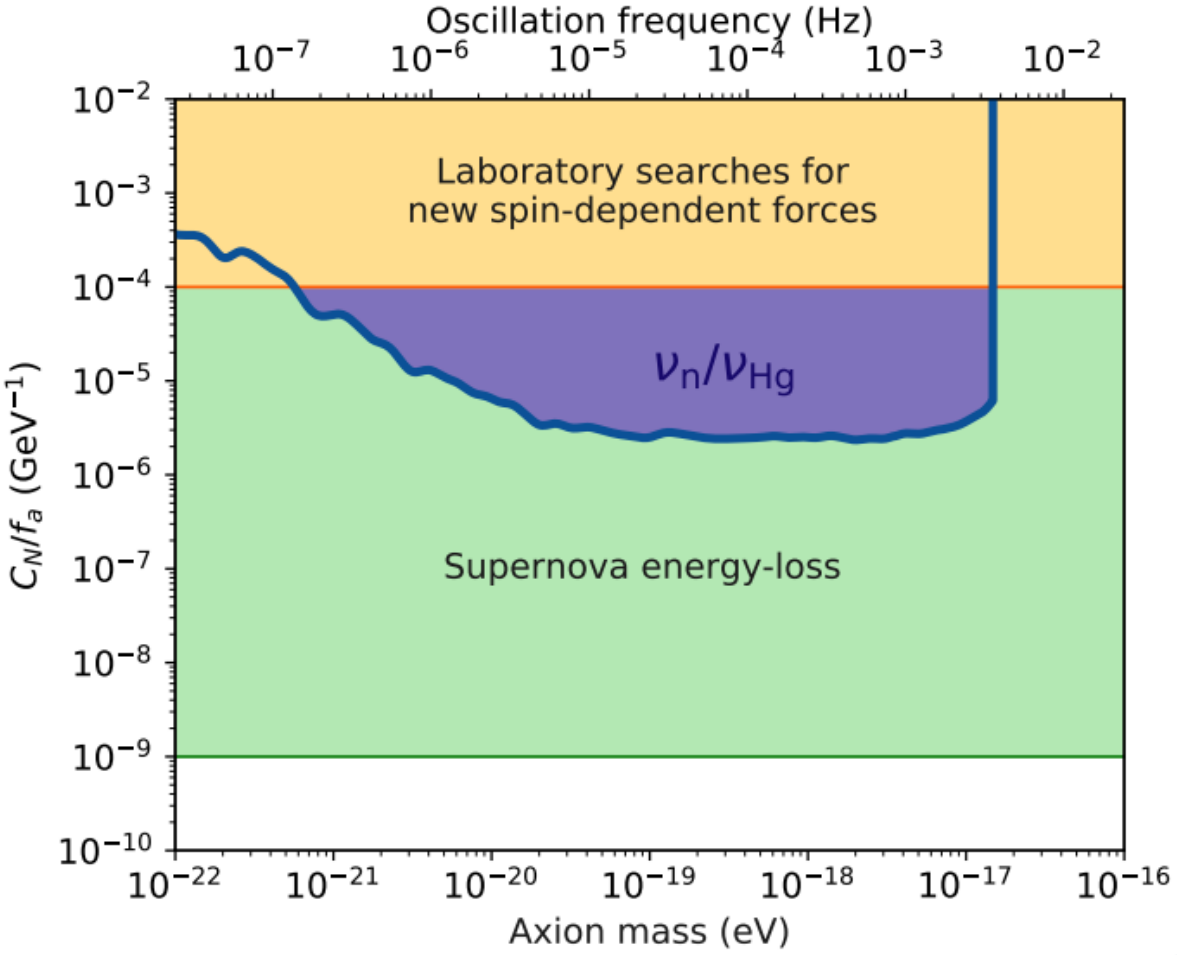
ILL and PSI Exclusion



First Laboratory Limits!

UNIVERSITY OF SUSSEX

PSI: Axion-Nucleon Coupling

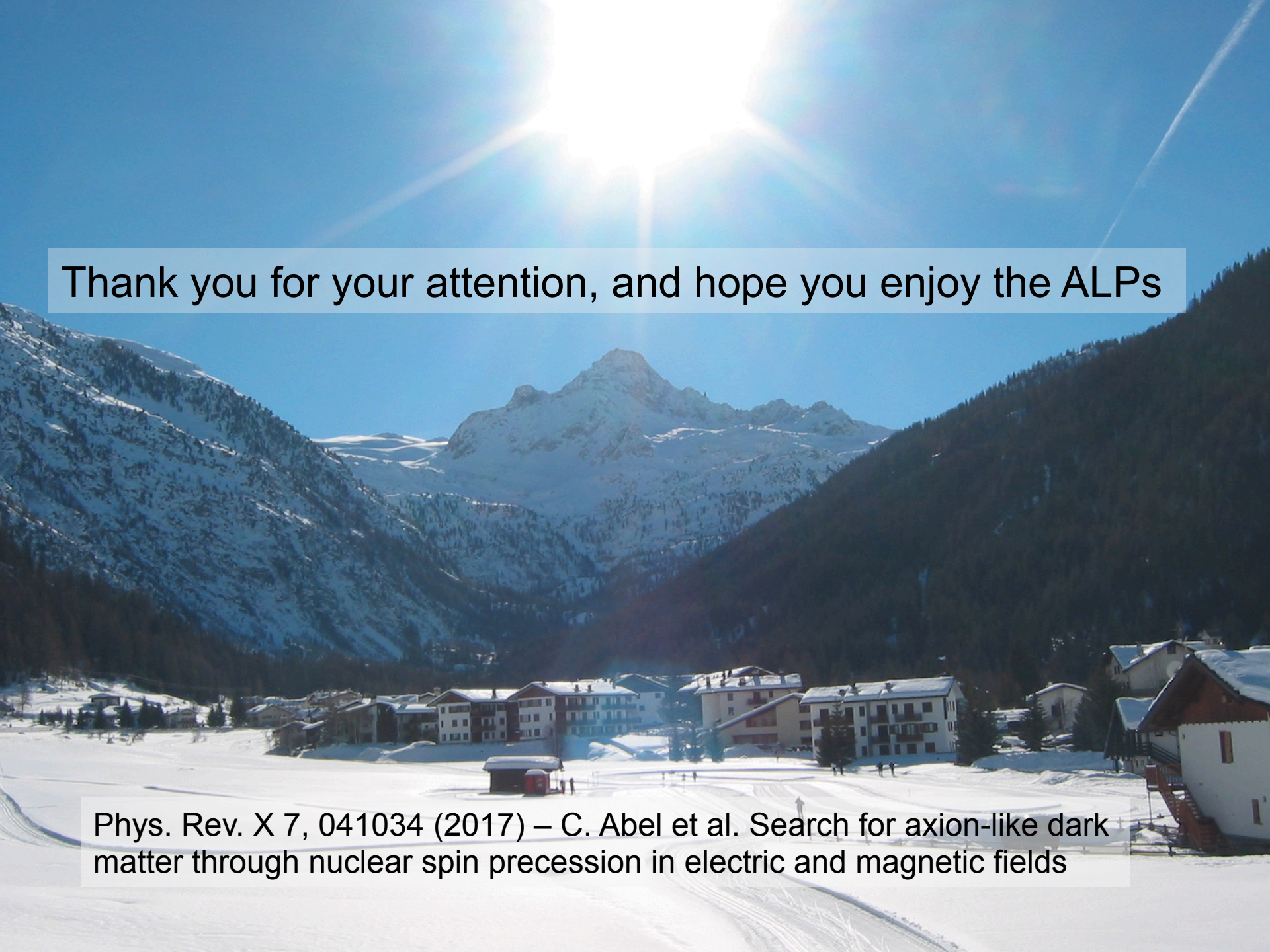


UNIVERSITY OF SUSSEX

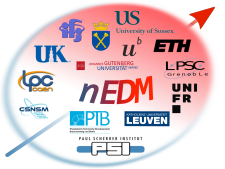
Conclusion:

- Null result
- First laboratory limits on axion-gluon coupling, improving upon limits from astrophysics by up to 3 orders of magnitude
- 40x better than previous lab limits on axion-nucleon coupling

UNIVERSITY OF SUSSEX


Thank you for your attention, and hope you enjoy the ALPs
Phys. Rev. X 7, 041034 (2017) – C. Abel et al. Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields

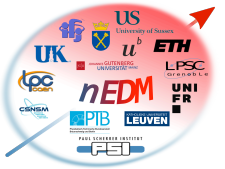
Backup Slides



UNIVERSITY OF SUSSEX

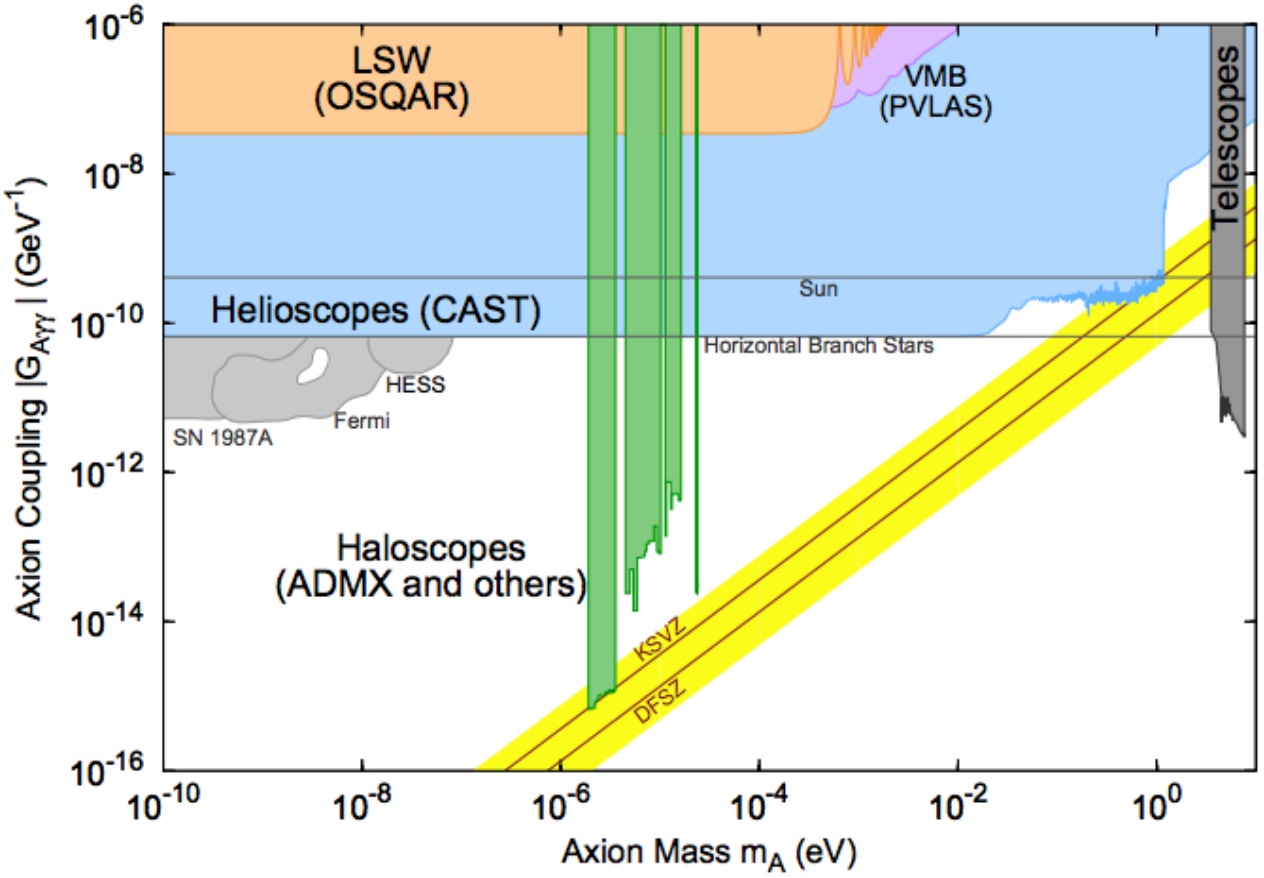
Further Reading

- Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields, C. Abel et. al. arXiv 1708.06367 - (accepted subject to minor corrections at PRX)
- Axion dark matter detection with cold molecules, P. W. Graham and S. Rajendran, Phys. Rev. D 84, 055013 (2011).
- New Observables for Direct Detection of Axion Dark Matter P.W. Graham and S. Rajendran, Phys Rev D 88, 035023 (2013)
- Axion-induced effects in atoms, molecules, and nuclei: Parity nonconservation, anapole moments, electric dipole moments, and spin-gravity and spin-axion momentum couplings, Y. V. Stadnik and V. V. Flambaum, Phys. Rev. D 89, 043522 (2014).
- Proposal for a cosmic spin axion spin precession experiment (CASPEr) D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran, and A. O. Sushkov, Phys. Rev. X 4, 021030 (2014).



UNIVERSITY OF SUSSEX

Axion-Photon Coupling

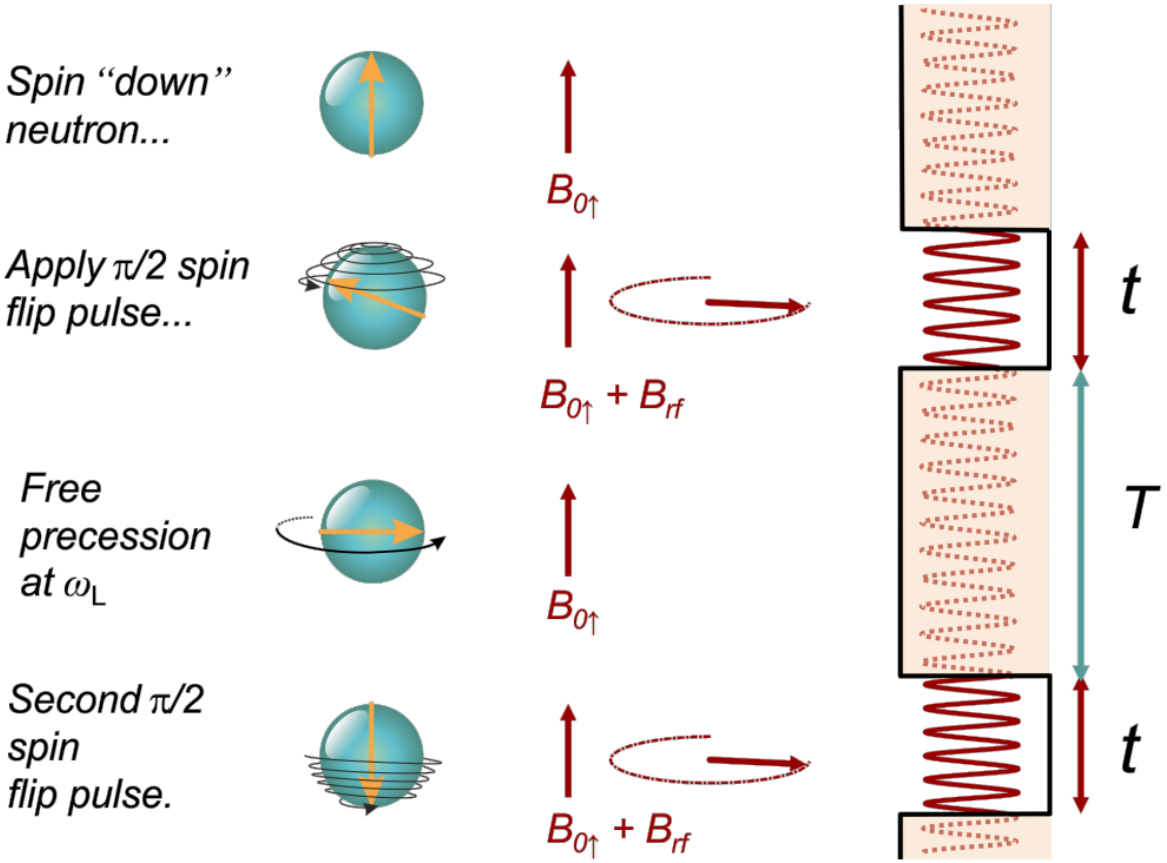


Most experimental limits on axions apply to the coupling to photons

Fig 61.1 from PDG RPP - C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.

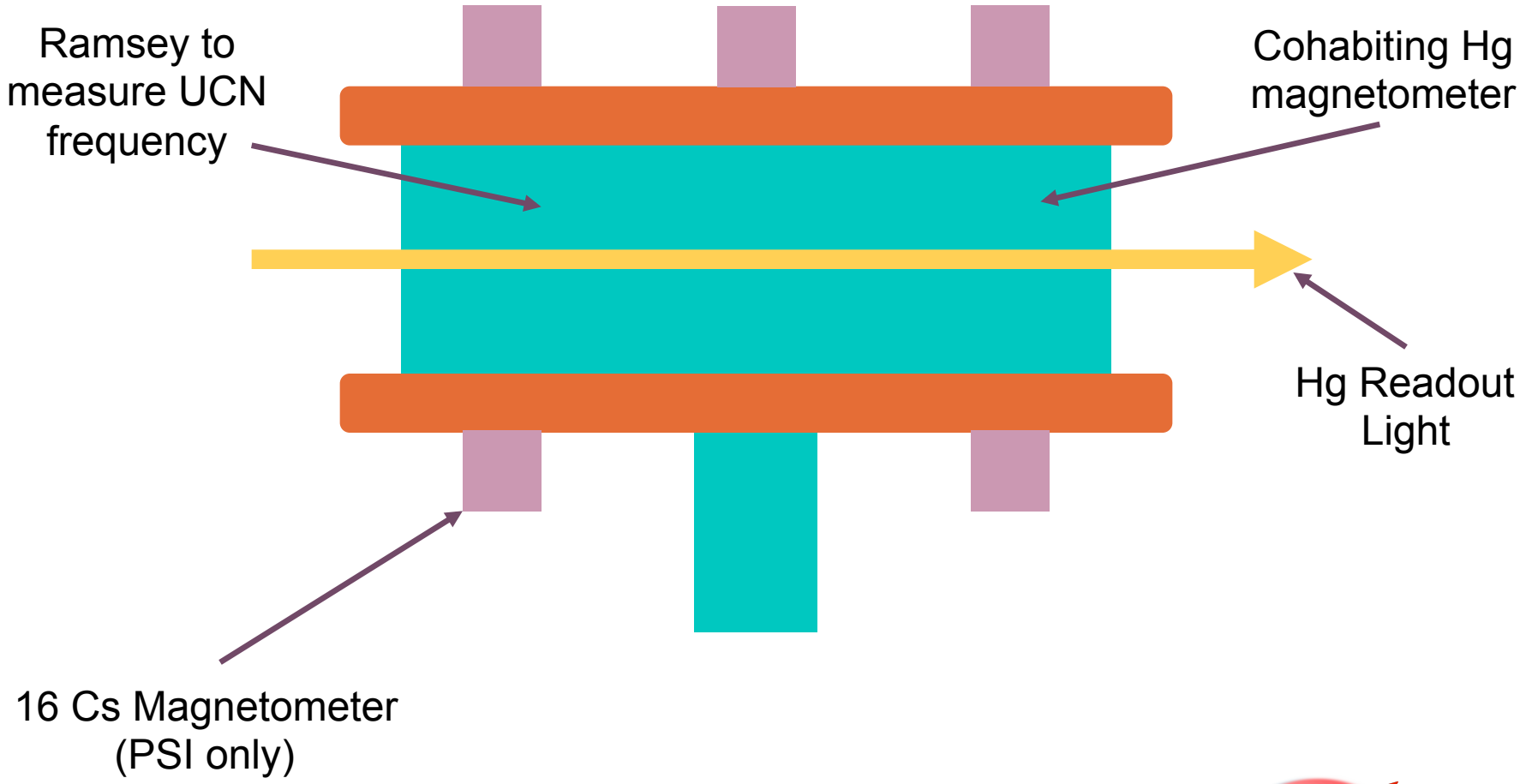
UNIVERSITY OF SUSSEX

How to Measure an nEDM



UNIVERSITY OF SUSSEX

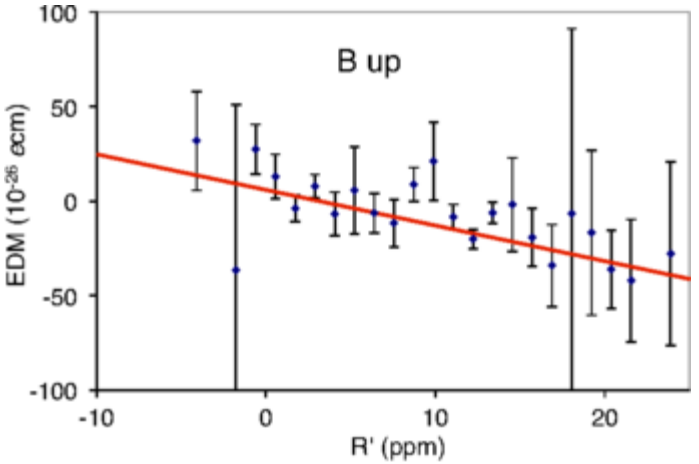
Apparatus ILL and PSI

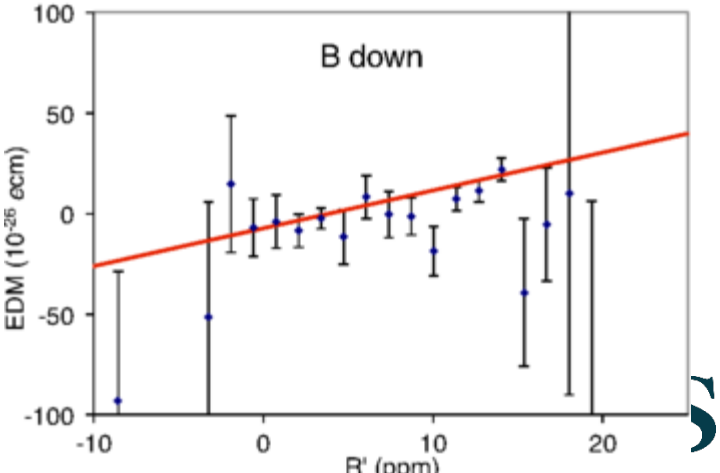


UNIVERSITY OF SUSSEX

Data Preparation- ILL

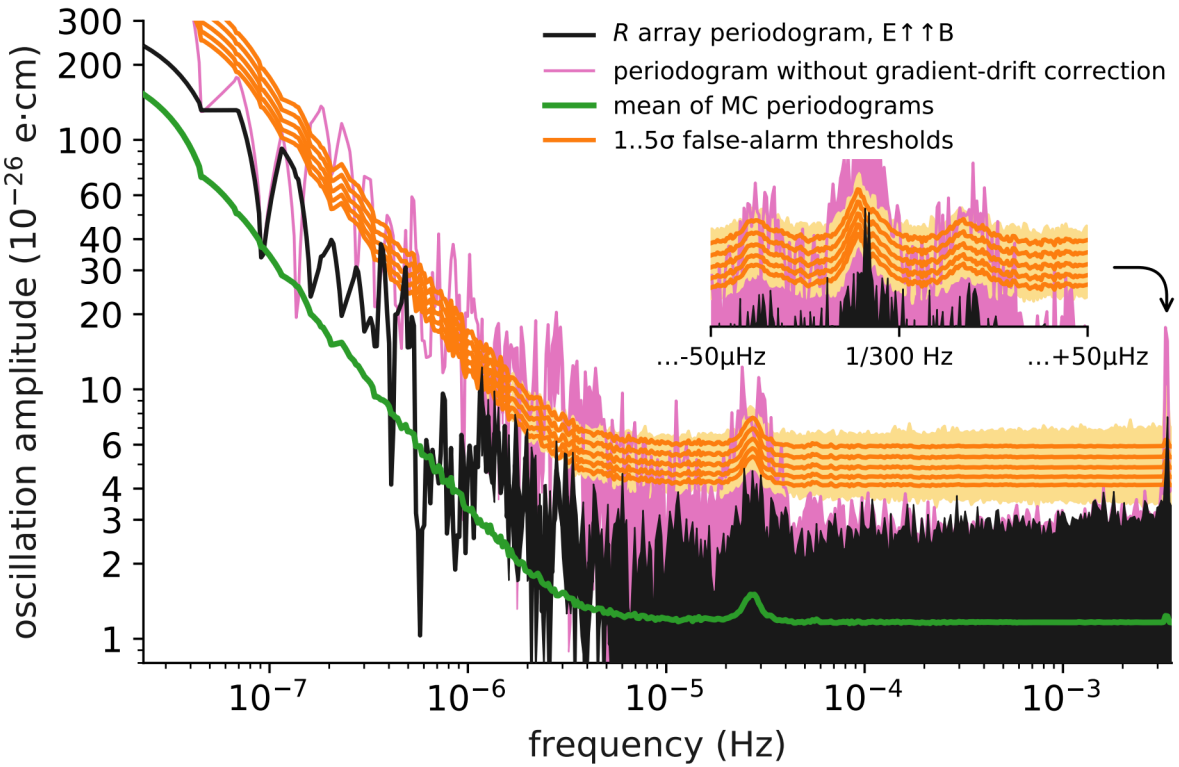
- Classic Sussex-RAL-ILL analysis technique
- Use $R = \frac{\upsilon_{\mathrm{n}}}{\upsilon_{\mathrm{Hg}}}$ as gradiometer to compensate false EDM
- Fit Crossing Lines
- Subtract fit from data to analyse EDM residuals





UNIVERSITY OF SUSSEX

PSI Effect of Gradient Drift Correction

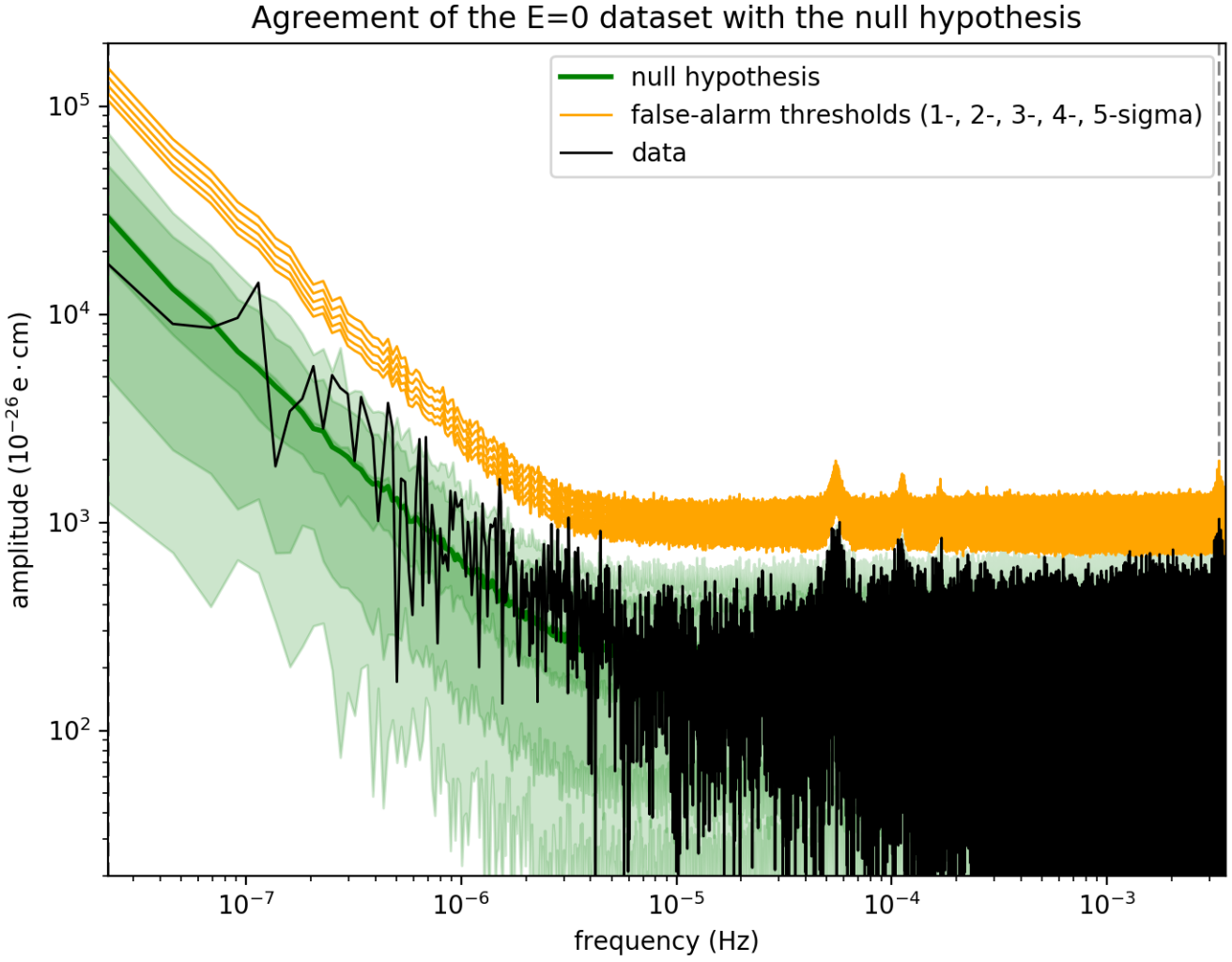


Inter-cycle drifts in vertical gradient were corrected with Cs magnetometers.

We expect peaks at 28μHz (inverse of 10 hours) and 3.3mHz (inverse of 300 seconds) due to patterns in datataking.

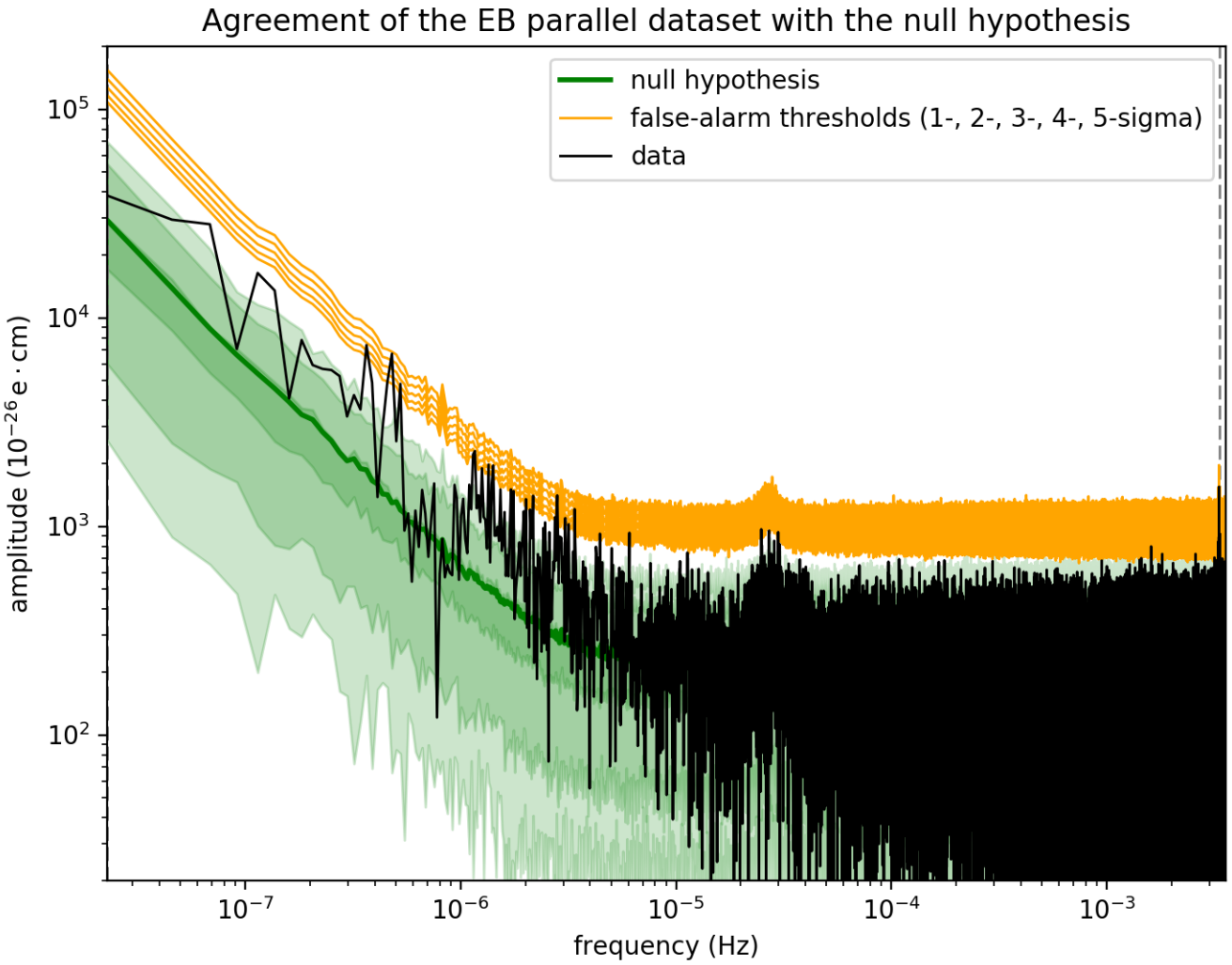
UNIVERSITY OF SUSSEX

PSI Analysis Detection



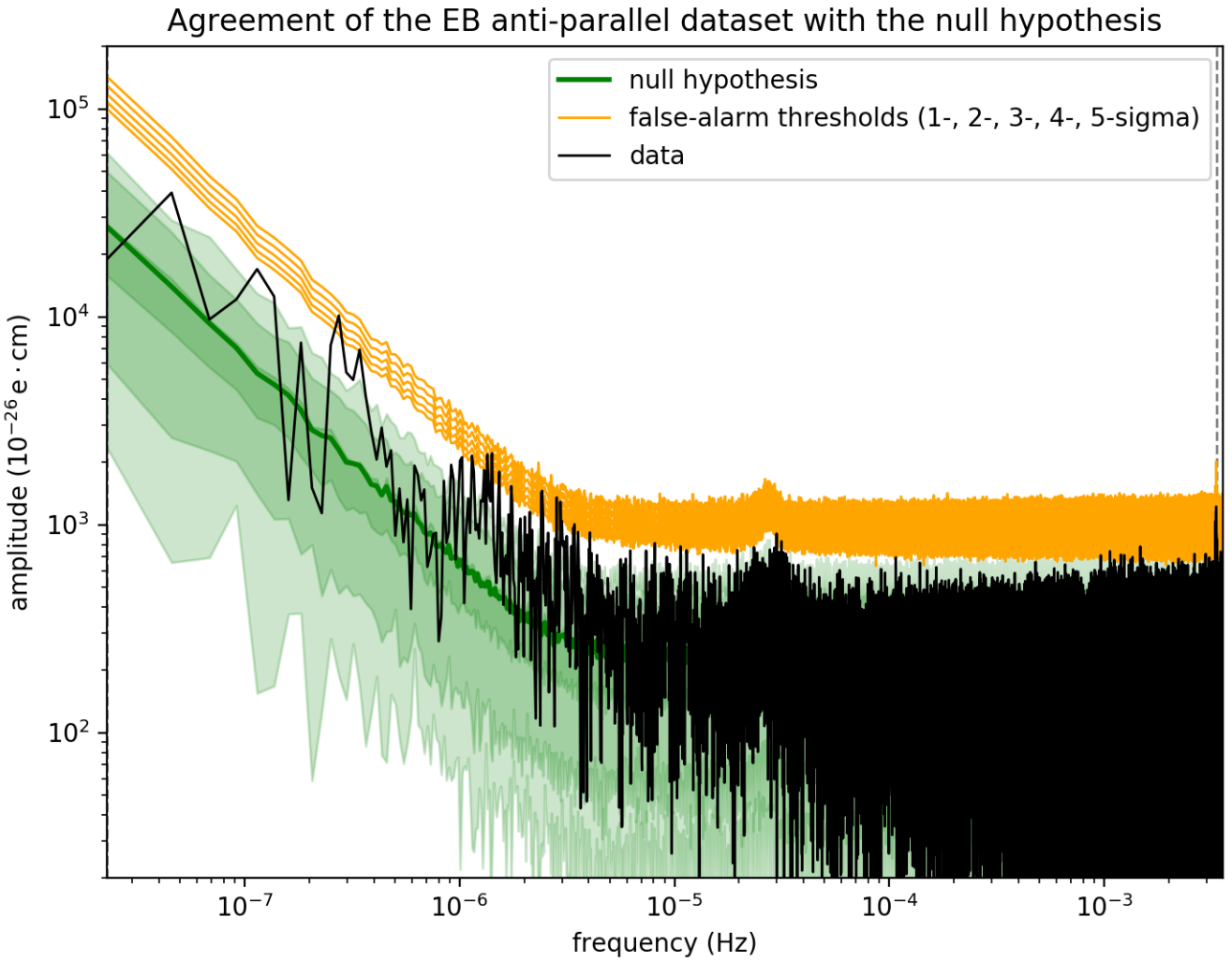
UNIVERSITY OF SUSSEX

PSI Analysis Detection



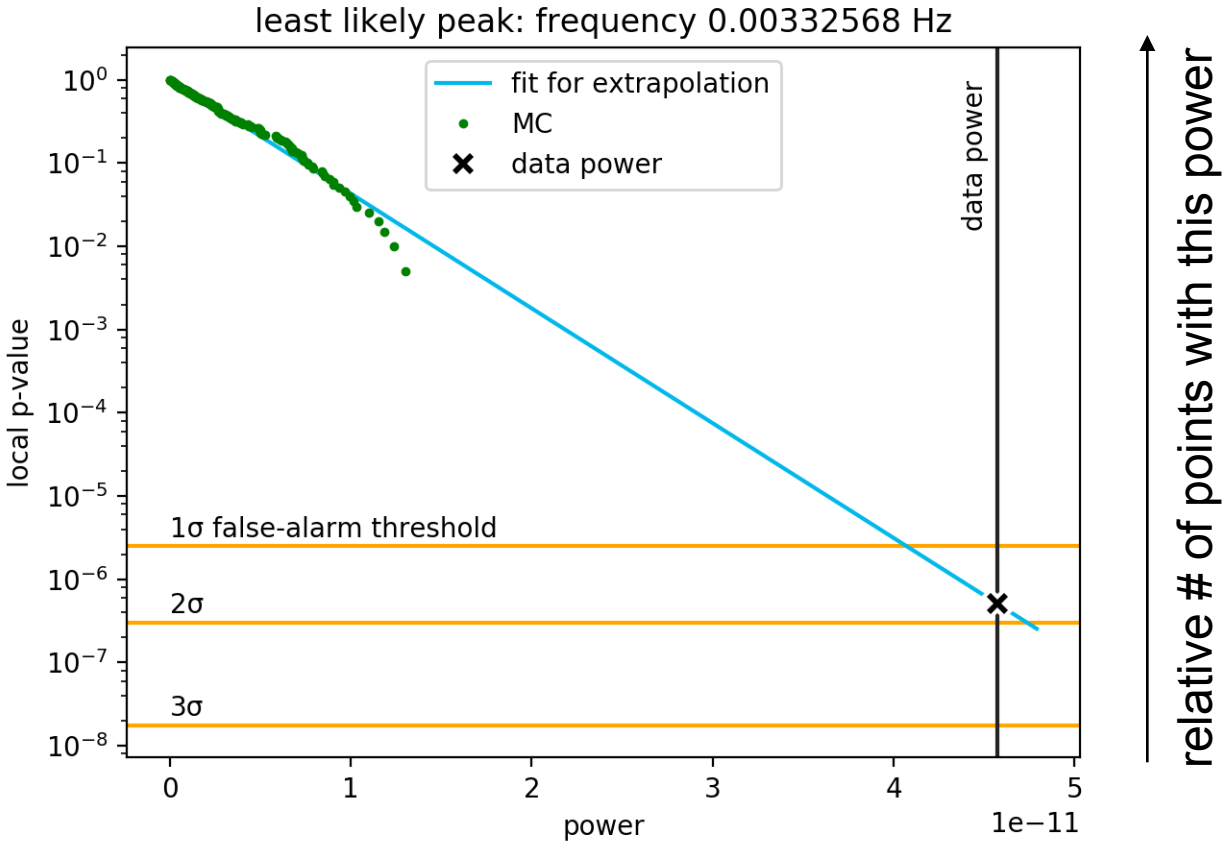
UNIVERSITY OF SUSSEX

PSI Analysis Detection



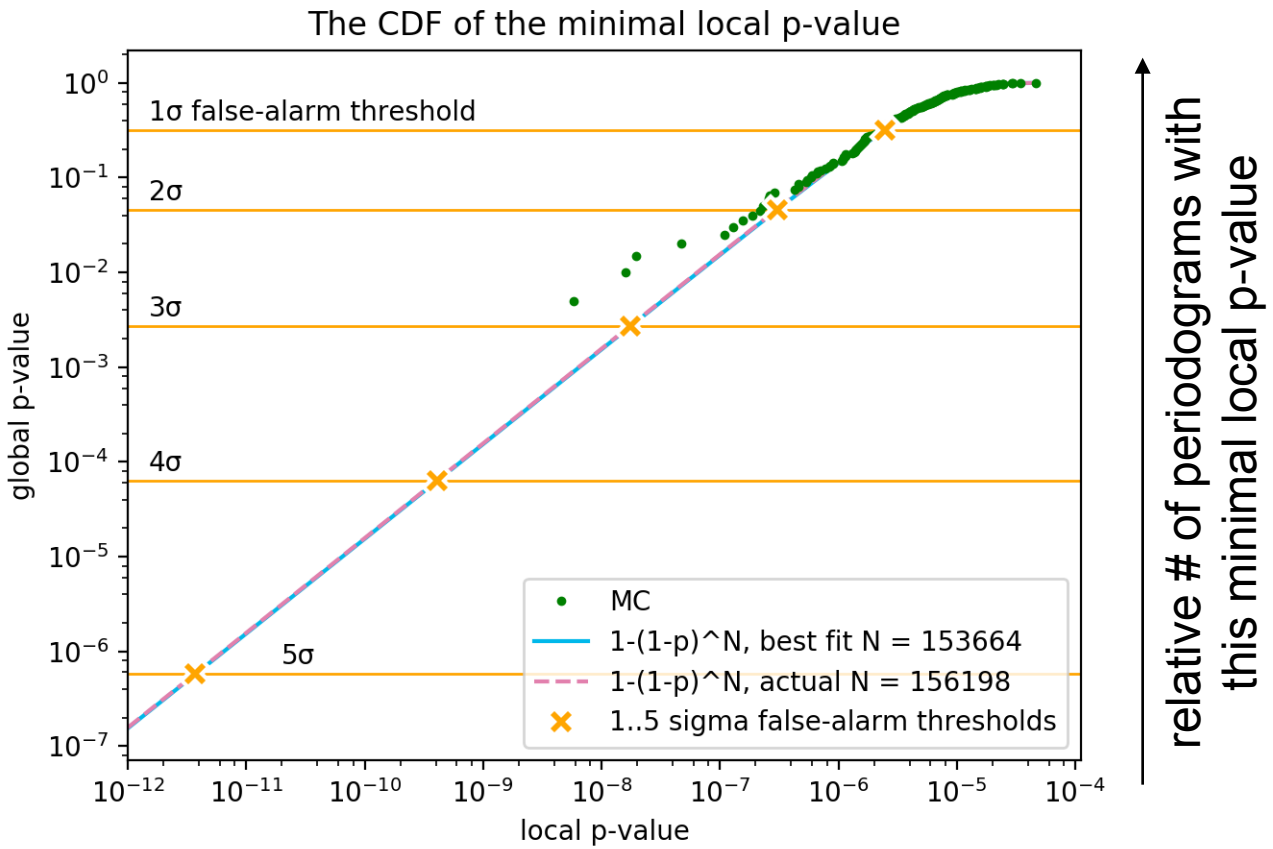
UNIVERSITY OF SUSSEX

PSI MC: cumulative distribution function extrapolation for one frequency



UNIVERSITY OF SUSSEX

PSI MC: distribution of the global minimal p-value

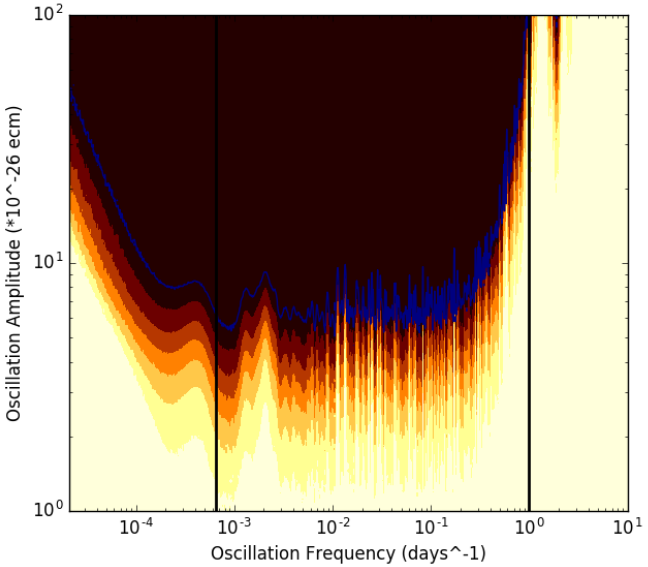


UNIVERSITY OF SUSSEX

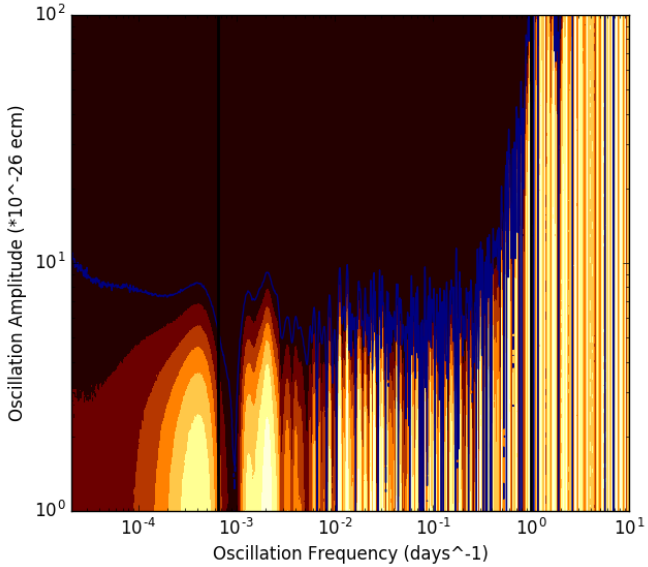
Exclusion

- Define $CL_S = CL_{S+B} / CL_B$
- Avoids claiming exclusion where we are not sensitive
- Black = Excluded

Example CL_S Exclusion



Without CL_S Correction
Unphysically strong exclusion around 10^{-3} days^{-1}



UNIVERSITY OF SUSSEX