Phys. Rev. X 7, 041034 (2017)

nEDM as a Dark Matter Detector

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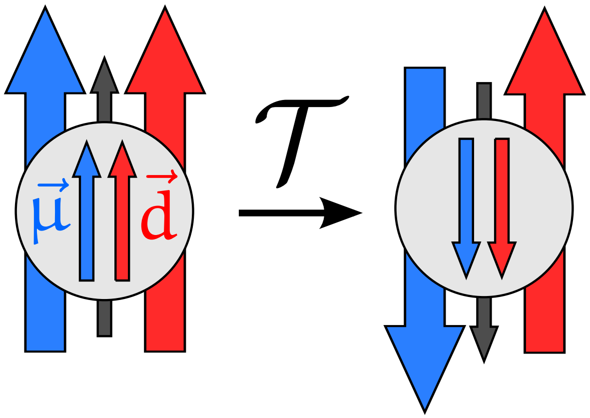
Outline

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

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 $3\text{x}10^{-26}$ e cm



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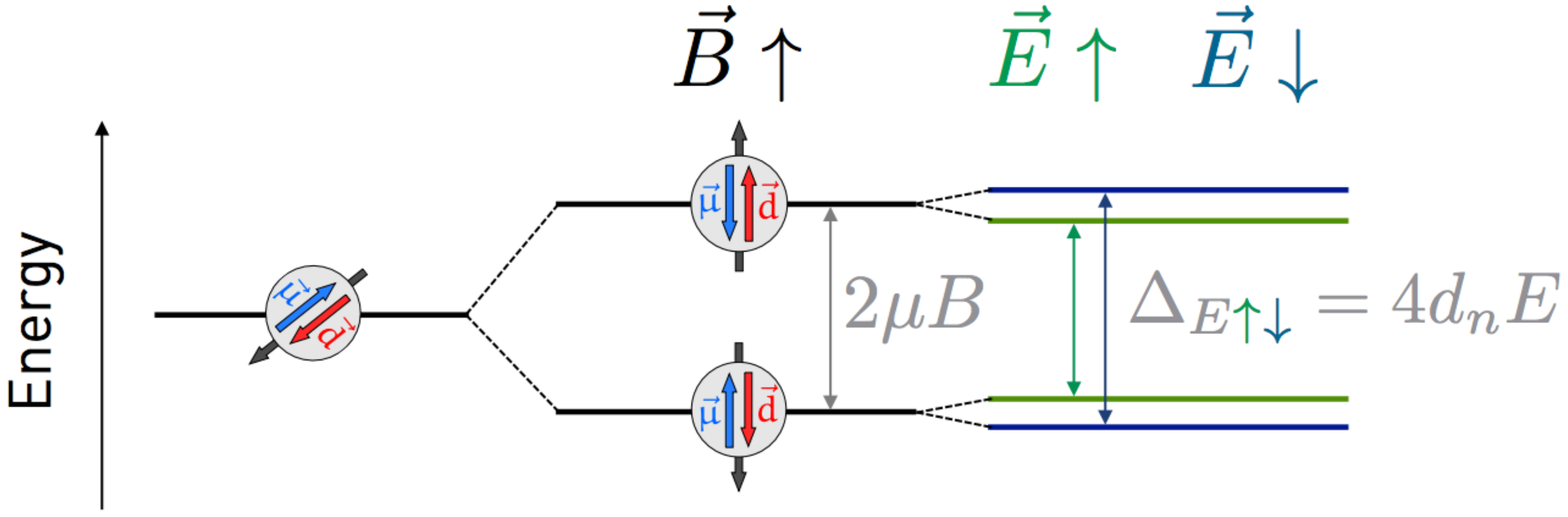
How to Measure an EDM

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



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

Two Sister Experiments

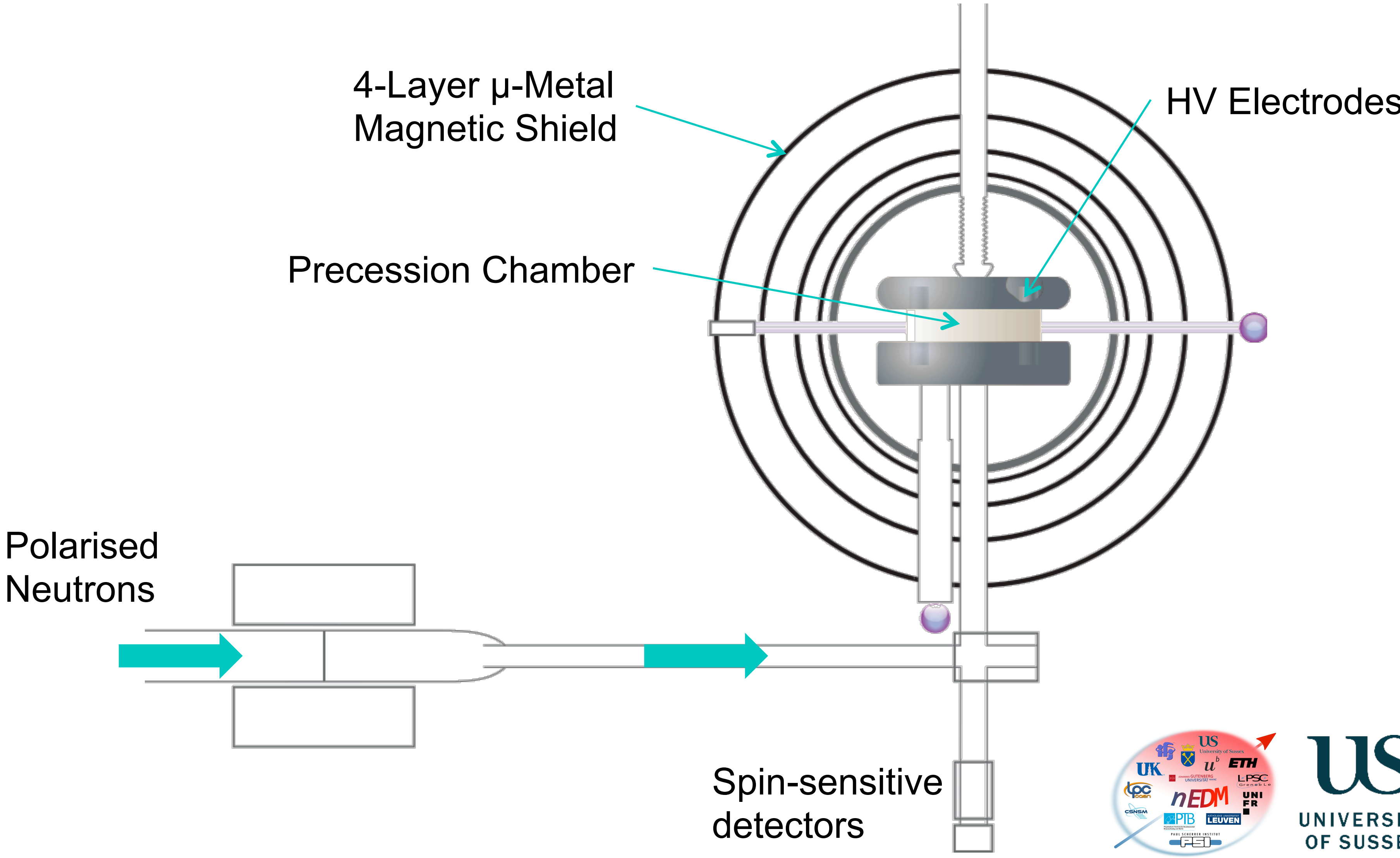
Sussex-RAL-ILL Experiment
Holds Current World Limit…

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



Axions as Dark Matter

- Ultralight axions $m \sim 10^{-22}$-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

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

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

Analysis

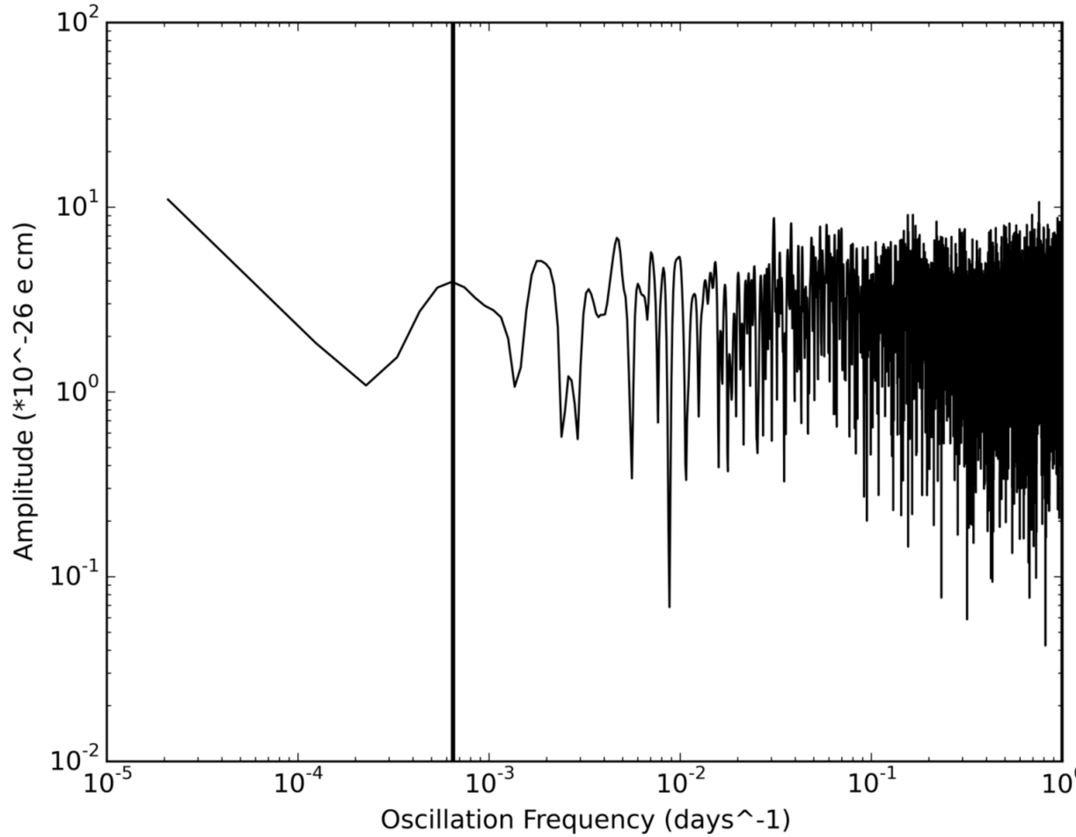
- 2 Analyses:
  - Systematics compensated data from ILL (binned by B field config) – time series of measured EDM
  - All individual (5 min) cycles from PSI (field drift-compensated)
- Extract power spectrum using Least Squares Spectral Analysis
- Monte Carlo to find probability distributions
- Use CL_S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

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

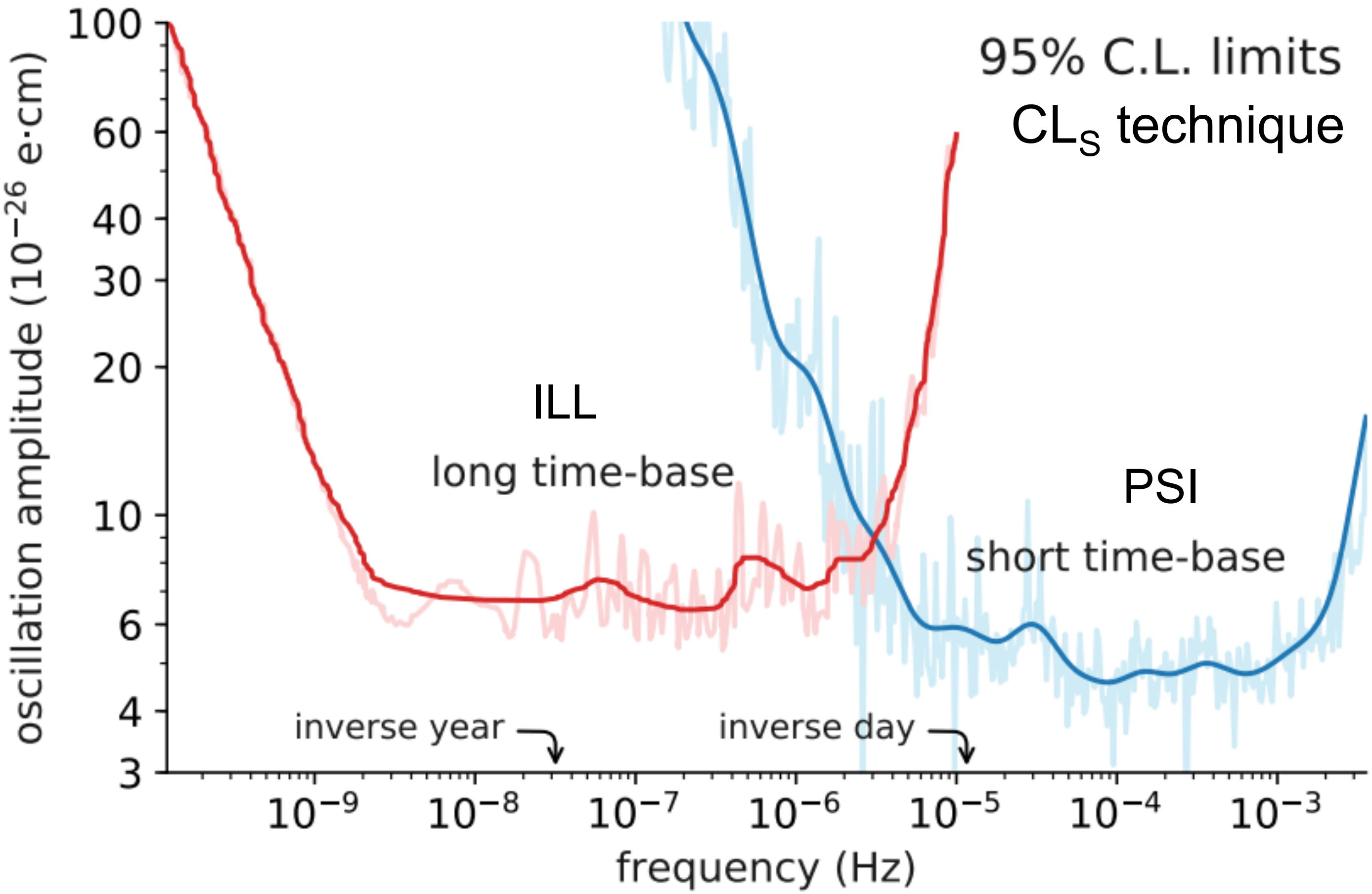
Monte Carlo

- 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

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

ILL and PSI Exclusion



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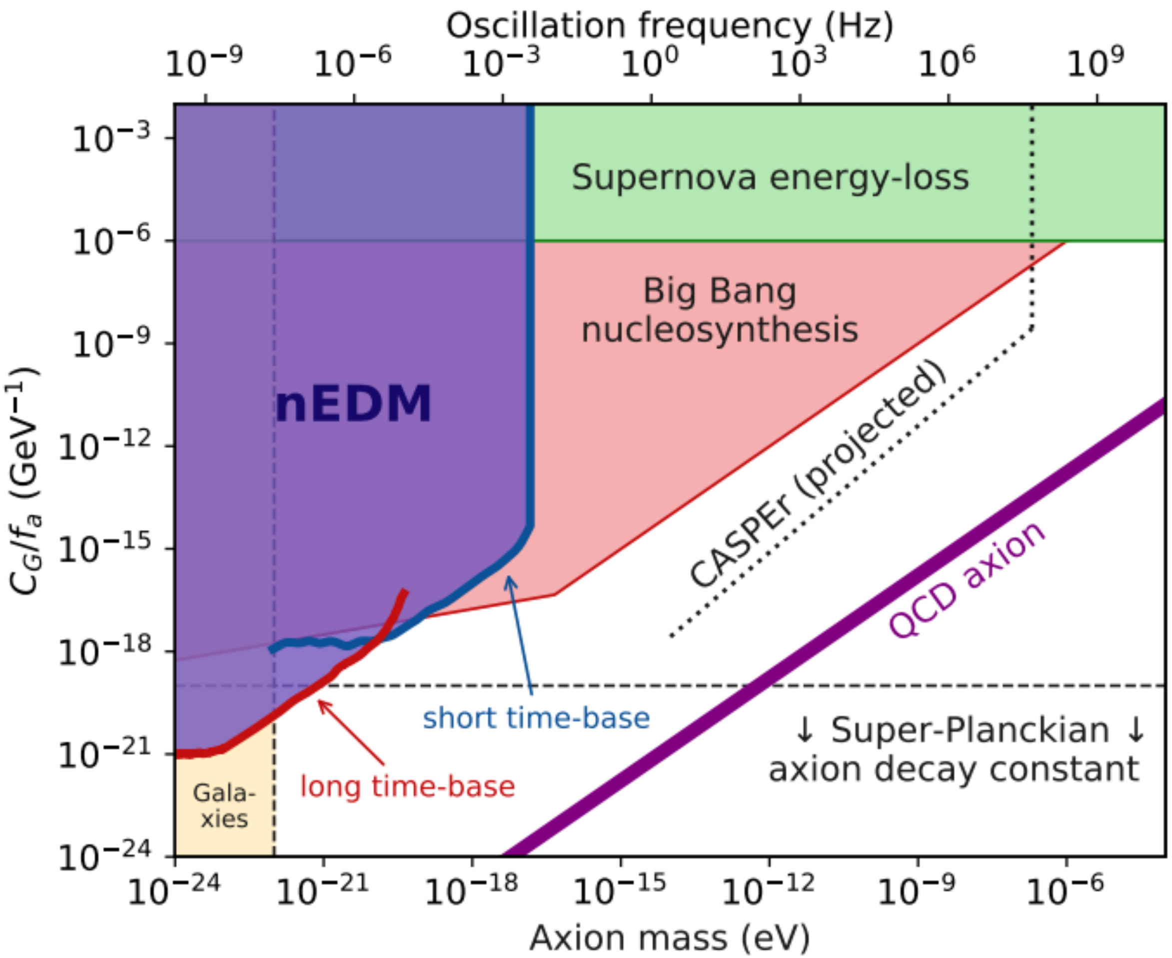
ILL and PSI Exclusion



First Laboratory Limits!

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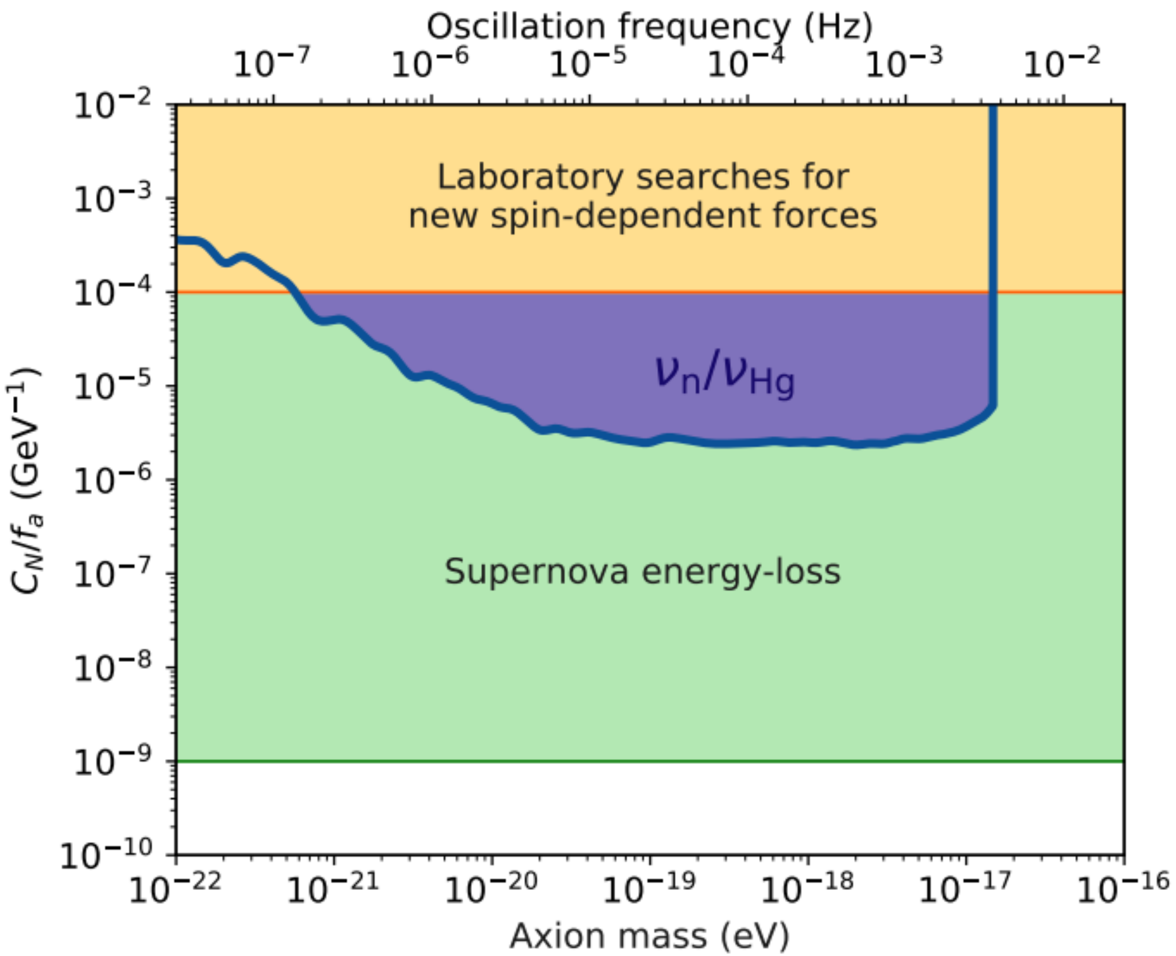
PSI: Axion-Nucleon Coupling



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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
- Paper: Phys Rev X 7, 041034

Backup Slides

Paper: Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields, C. Abel et. al. Phys Rev X 7, 041034 (2017)

Further Reading

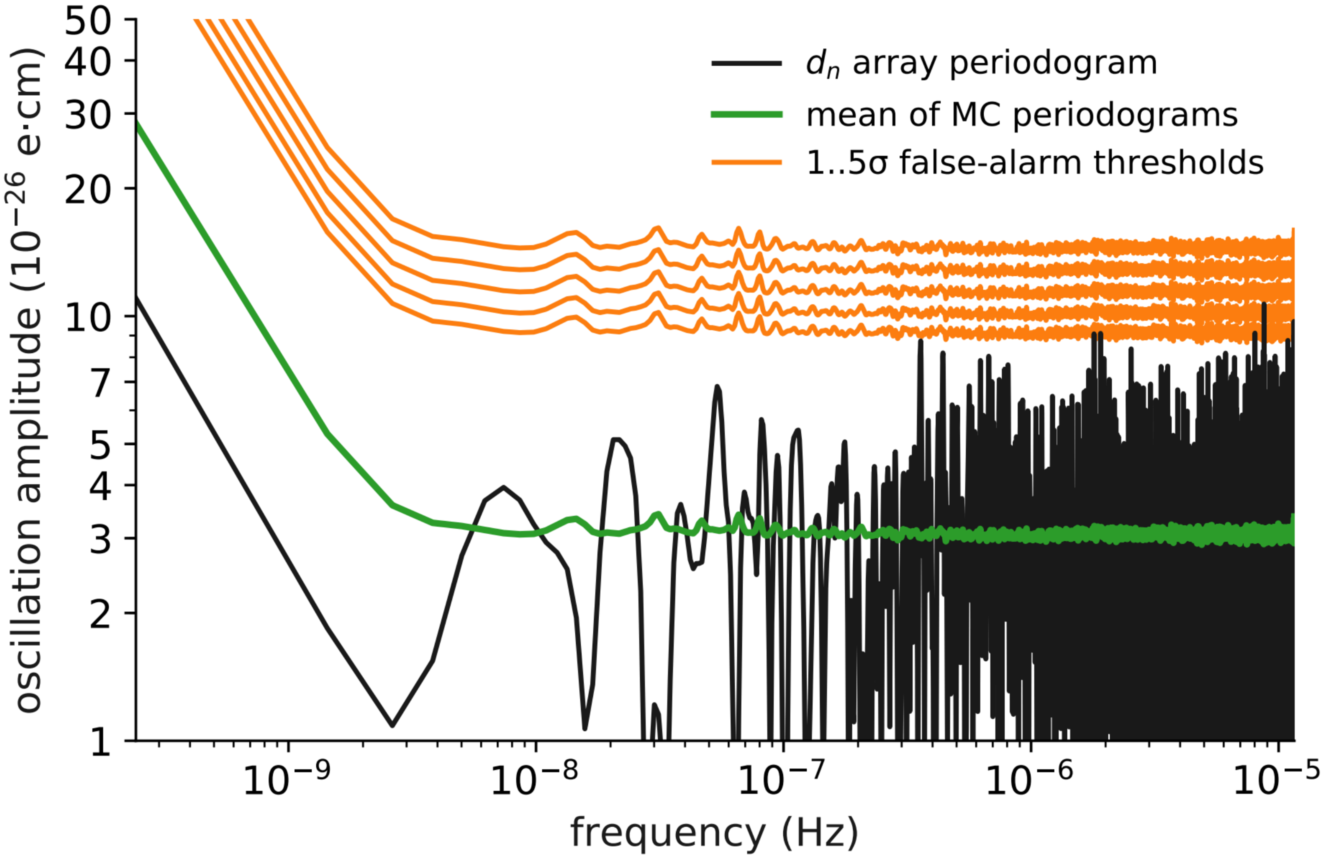
- Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields, C. Abel et. al. Phys Rev X 7, 041034 (2017)
- Axion dark matter detection with cold molecules, P. W. Graham and S. Rajendran, Phys. Rev. D 84, 055013 (2011).
- New Observables for Direct Detection of 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).

Look Elsewhere and False Alarm

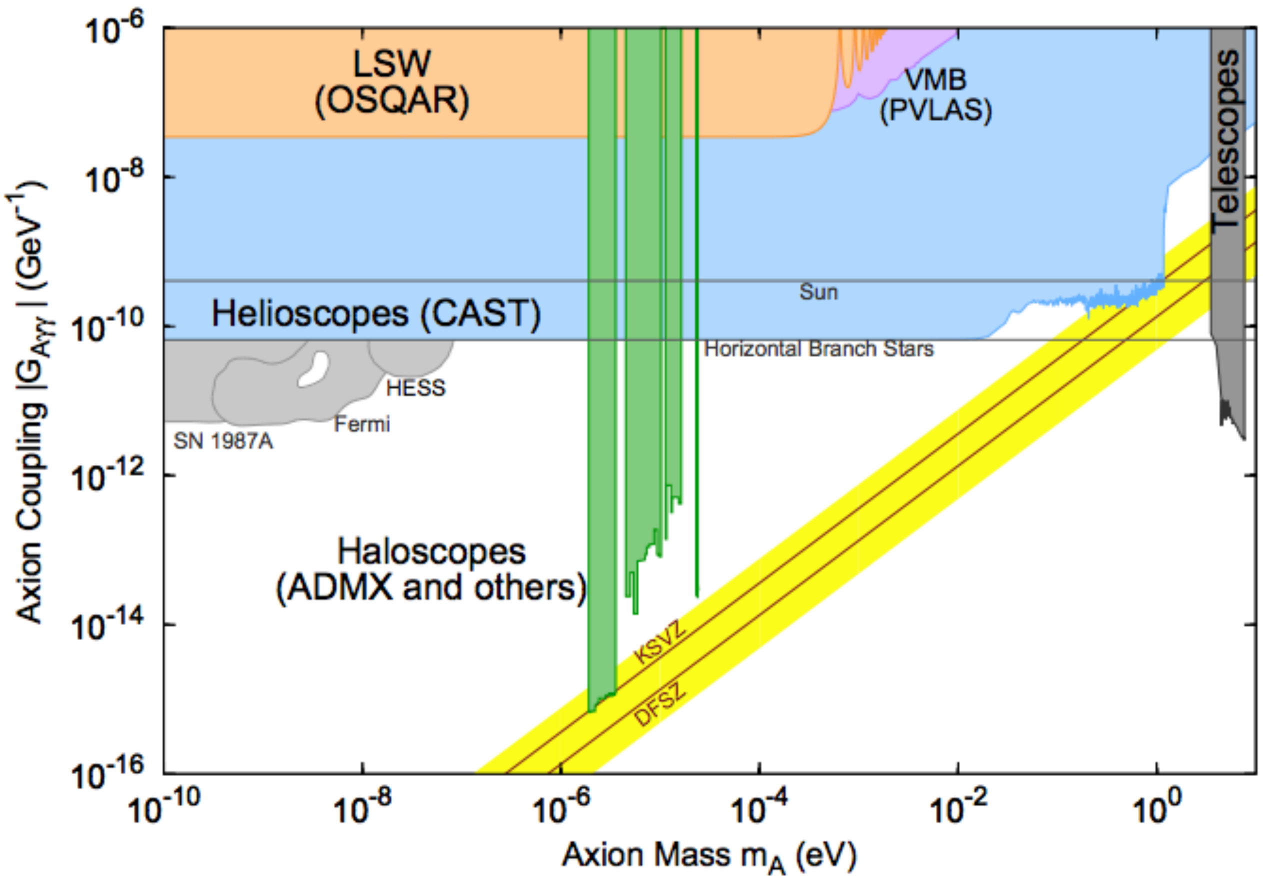
- Expect 5% false positives for P=0.05, but we test thousands of hypotheses frequencies
- Solution: inflate required p-values

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

ILL Detection



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.

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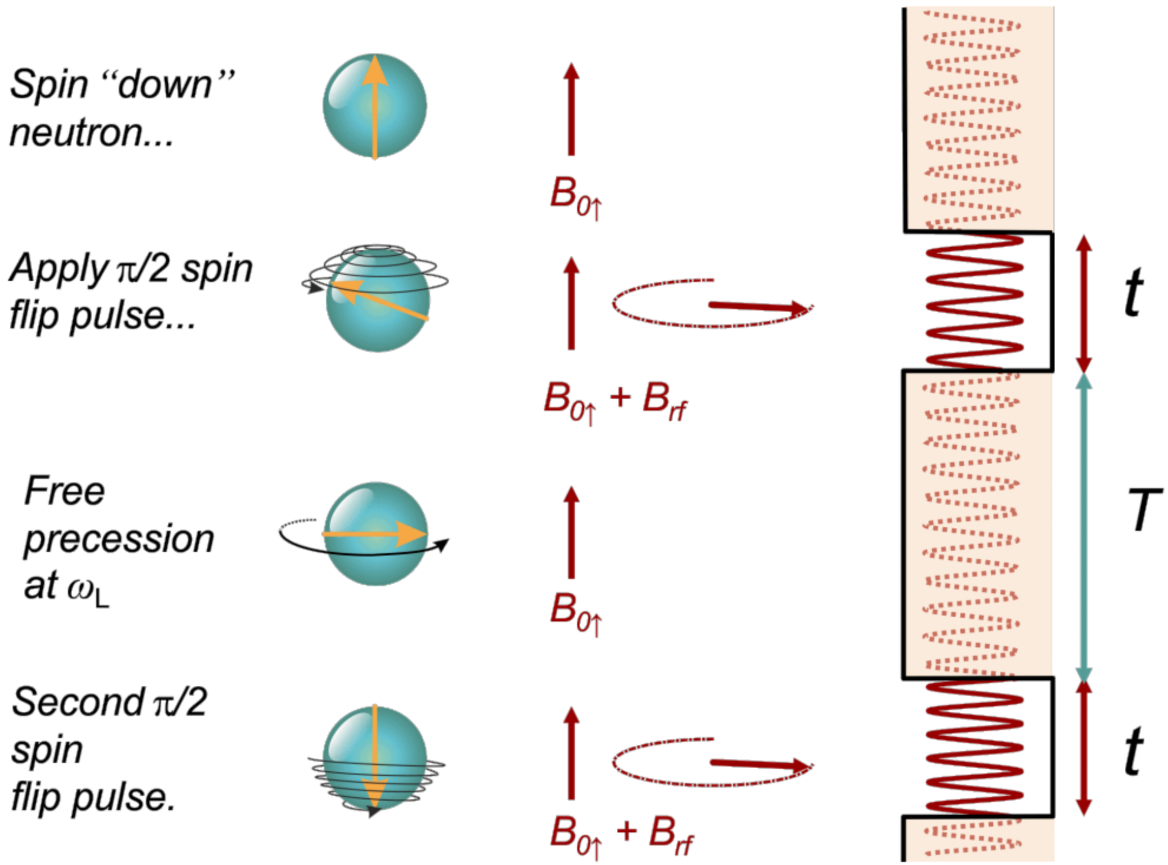
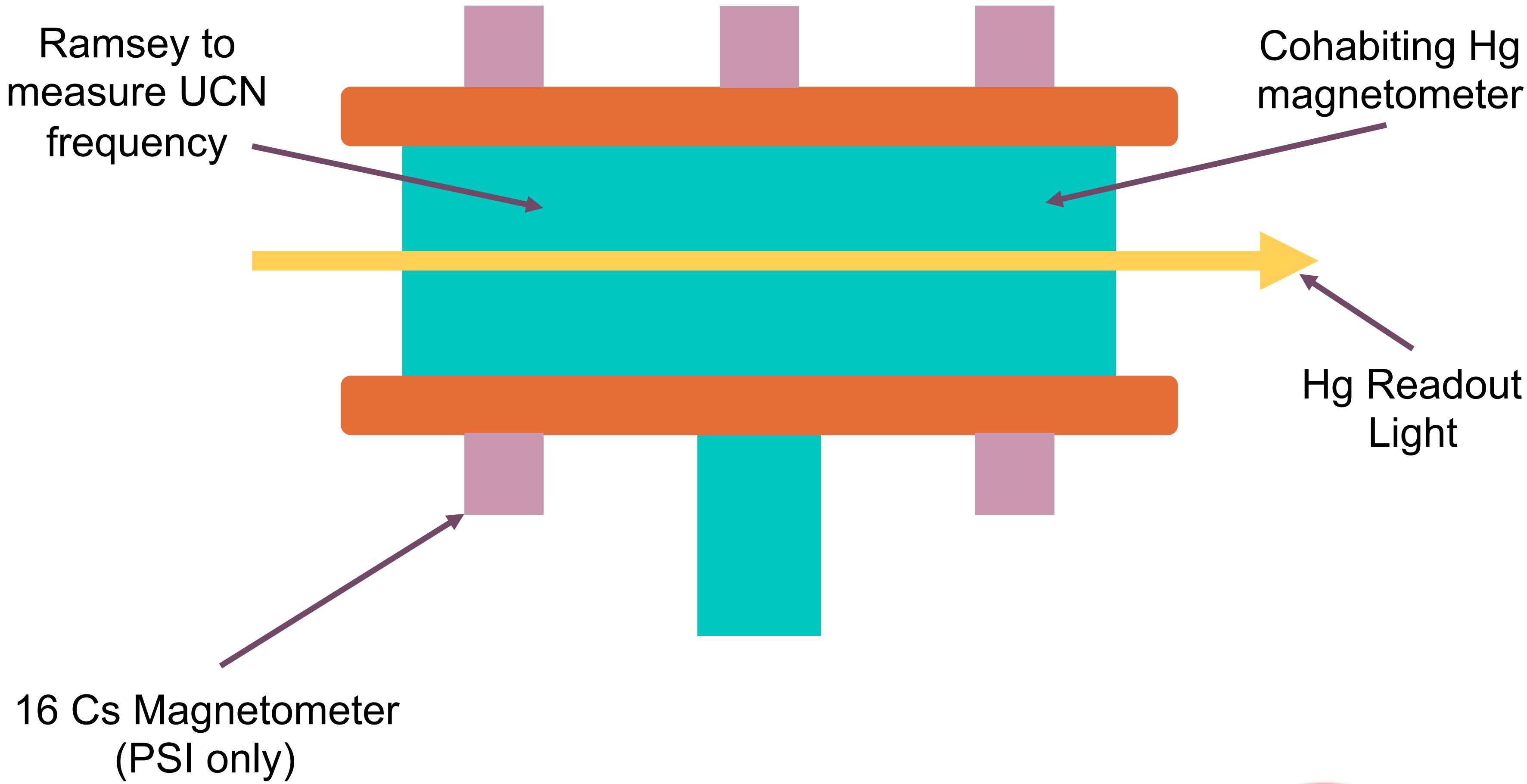
How to Measure an nEDM

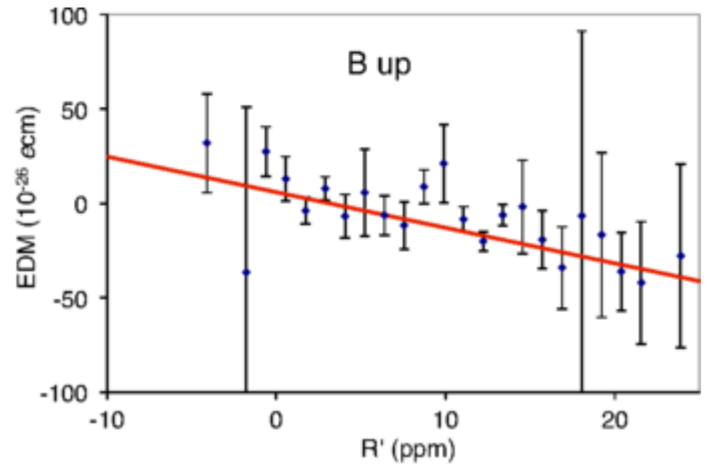


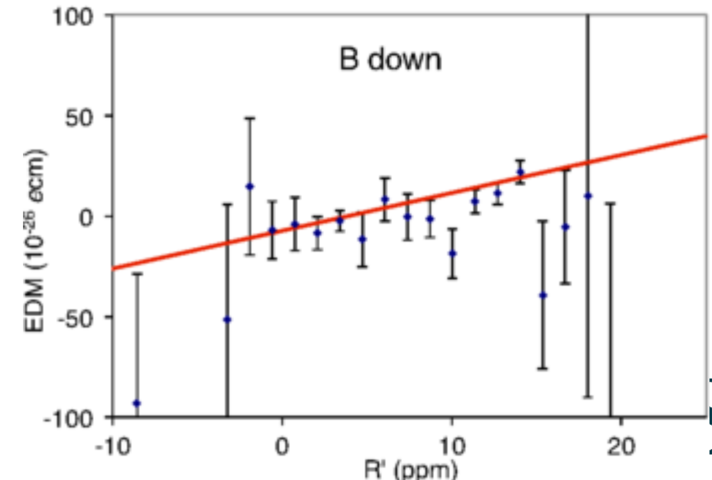
Apparatus ILL and PSI



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





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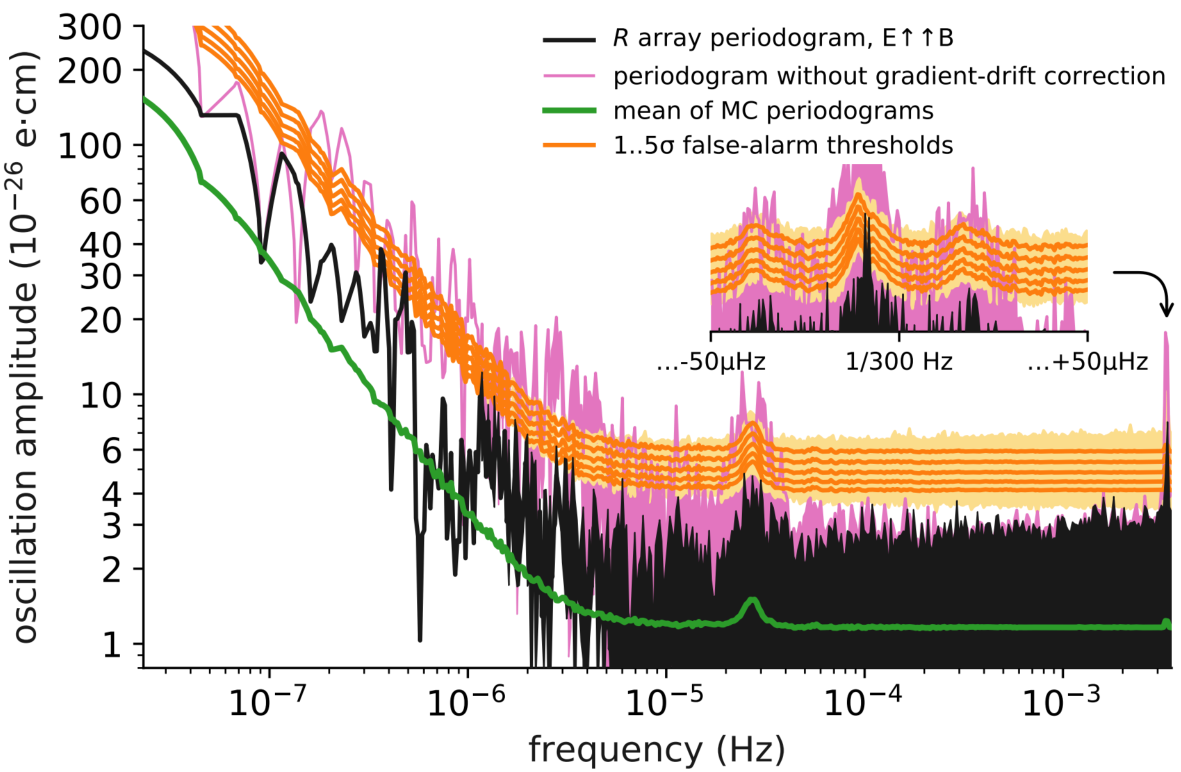
PSI Effect of Gradient Drift Correction



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.

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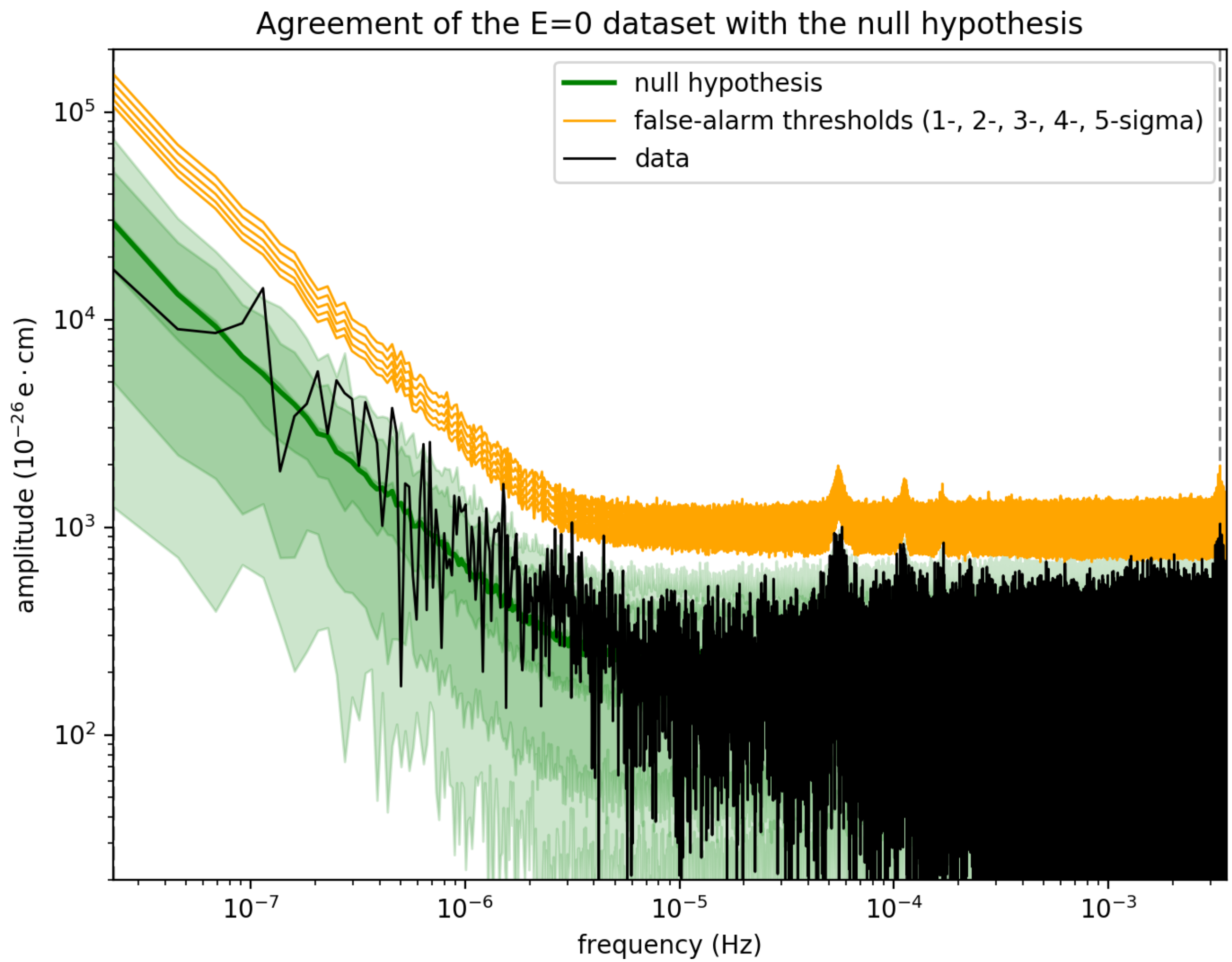
PSI Analysis Detection



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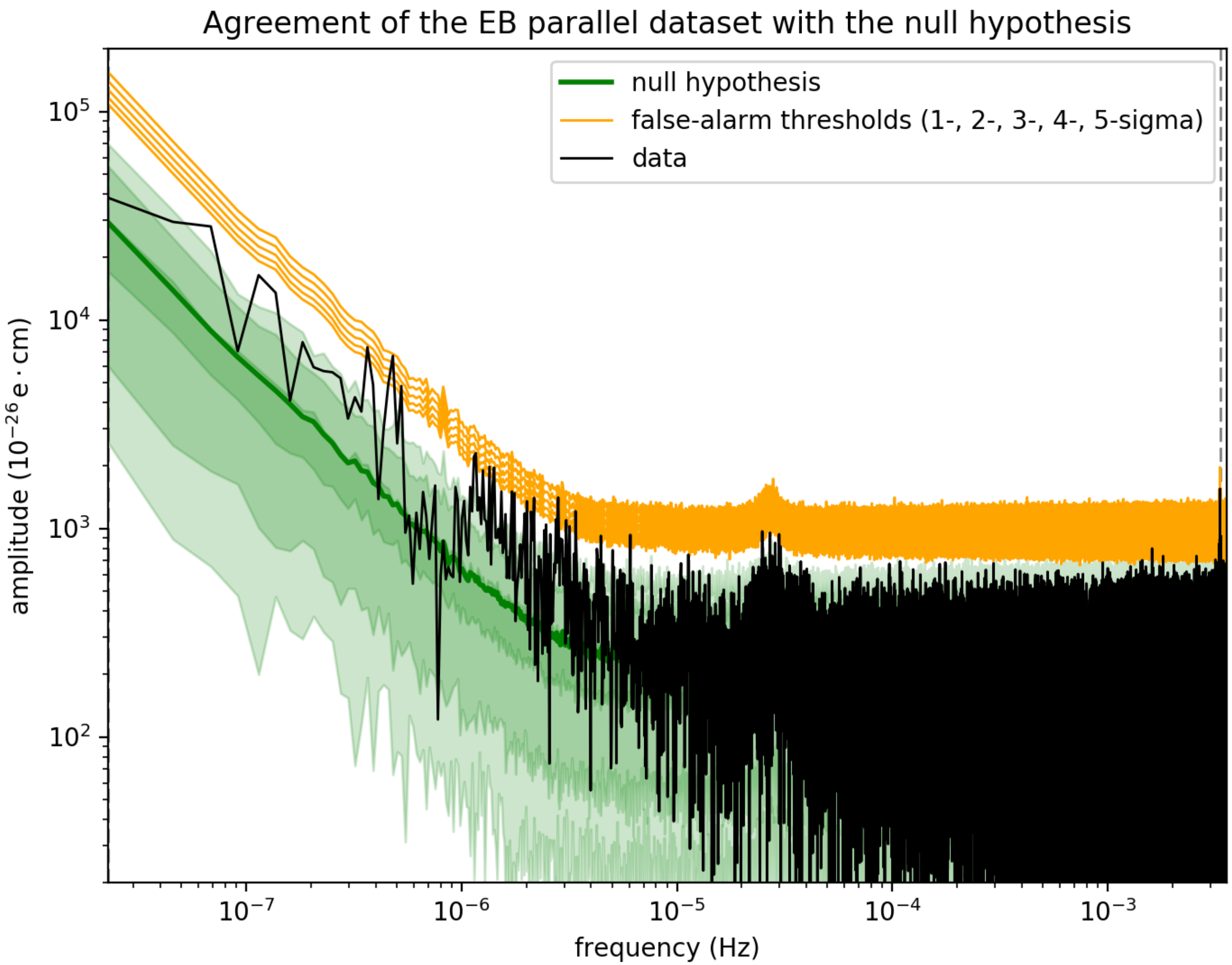
PSI Analysis Detection



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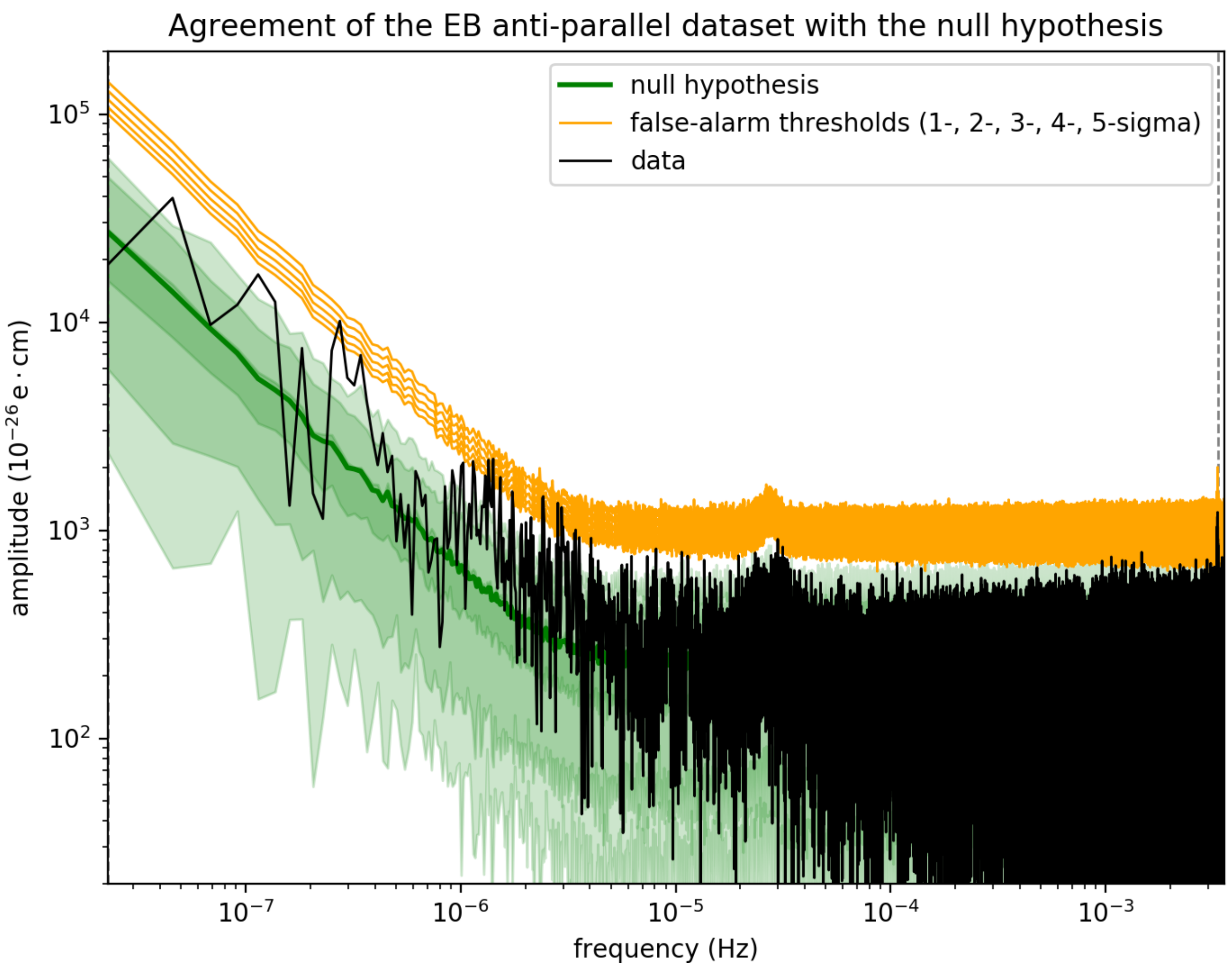
PSI Analysis Detection



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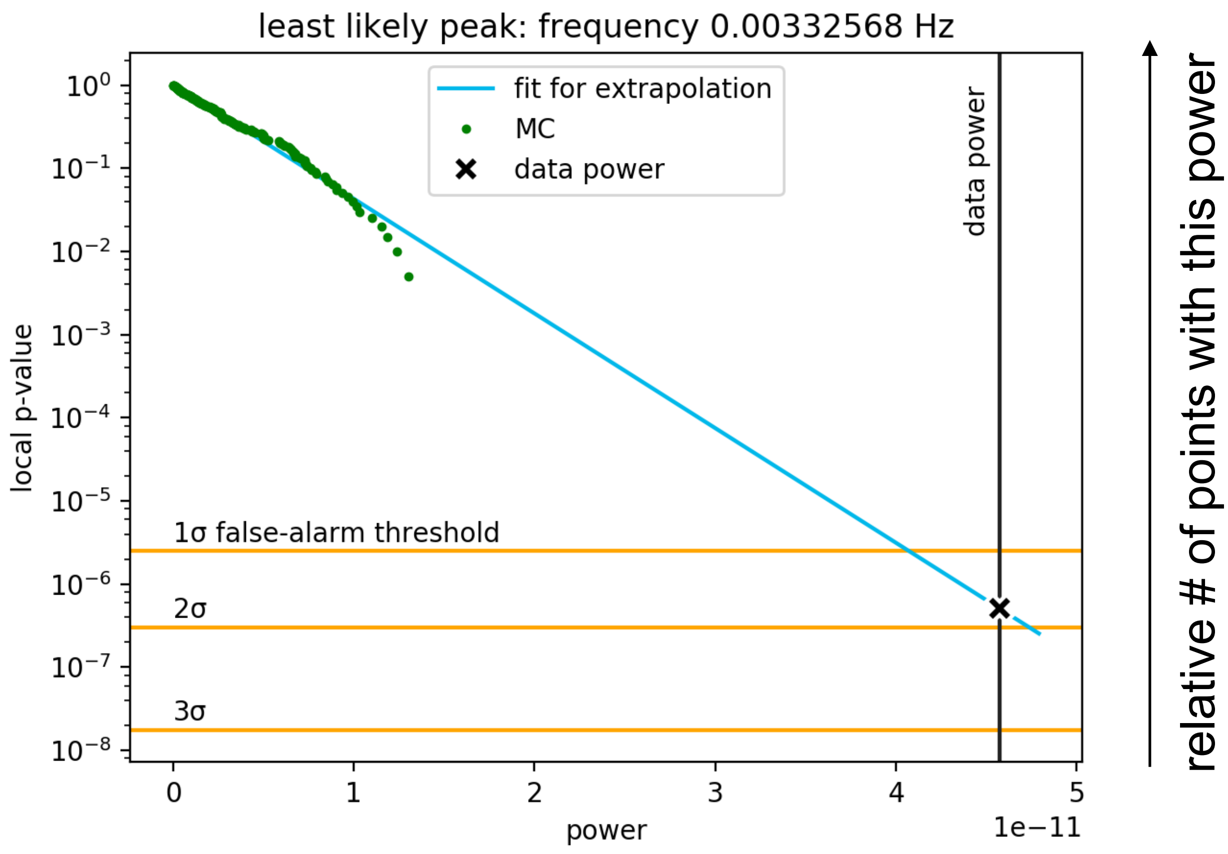
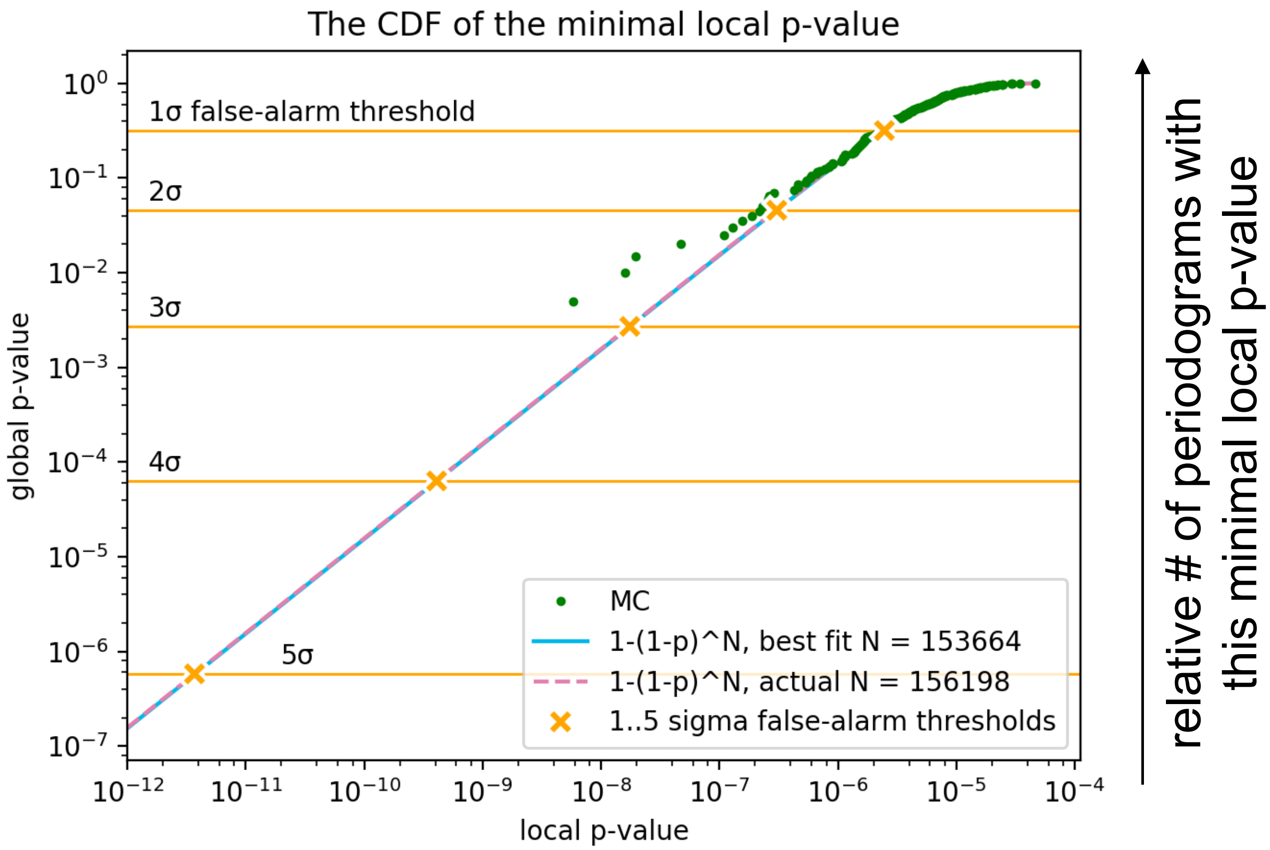
PSI MC: cumulative distribution function extrapolation for one frequency



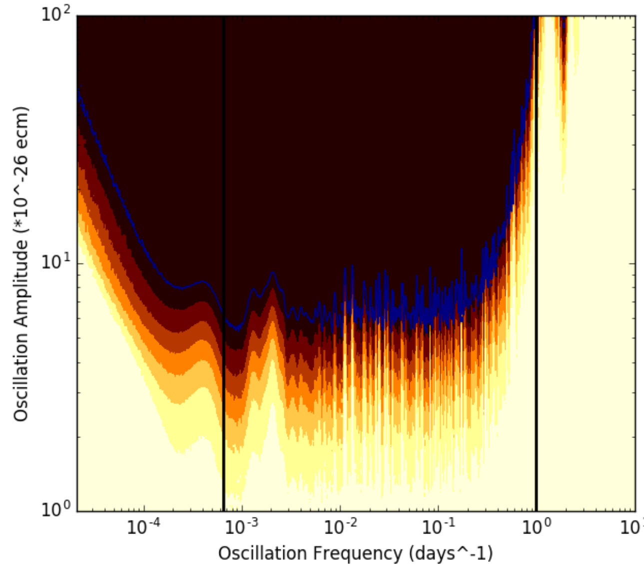
PSI MC: distribution of the global minimal p-value



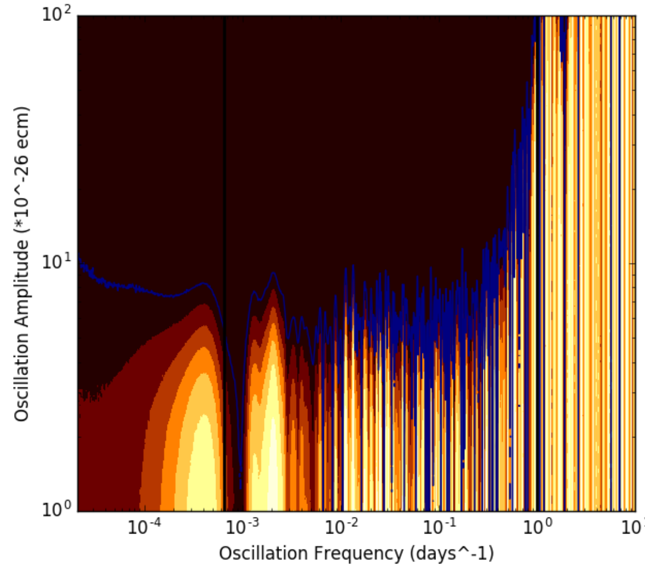
Exclusion

- 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} $days^{-1}$



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