arXiv 1708.06367 - Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields

nEDM as a Dark Matter Detector

Constraints on Axion-like Dark Matter from Limits on an Oscillating EDM

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Axions and ALPs

- QCD θ-term allows strong CPv, however this is not observed, requiring fine tuning to 10^{-10}
- 1977: Peccei-Quinn propose solution: promote θ to a field which relaxes to zero: resultant particle is the axion
- Axion-like particles (ALPs) have similar couplings, but do not necessarily solve strong CP

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Axions as Dark Matter

- Ultralight axions $m \sim 10^{-22}$-10^{-17}eV can be DM, in place of conventional WIMP DM.
- Can be produced non-thermally in early universe through vacuum misalignment
- Acts like coherently oscillating classical field with frequency ~ mass

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Axion-neutron interactions

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

Axion-gluon coupling
Causes oscillating EDM
through same mechanism as
QCD theta

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

Axion-nucleon
coupling
Causes “axion wind”
as we pass through
cosmic axion field
Non E dependant
frequency modulation

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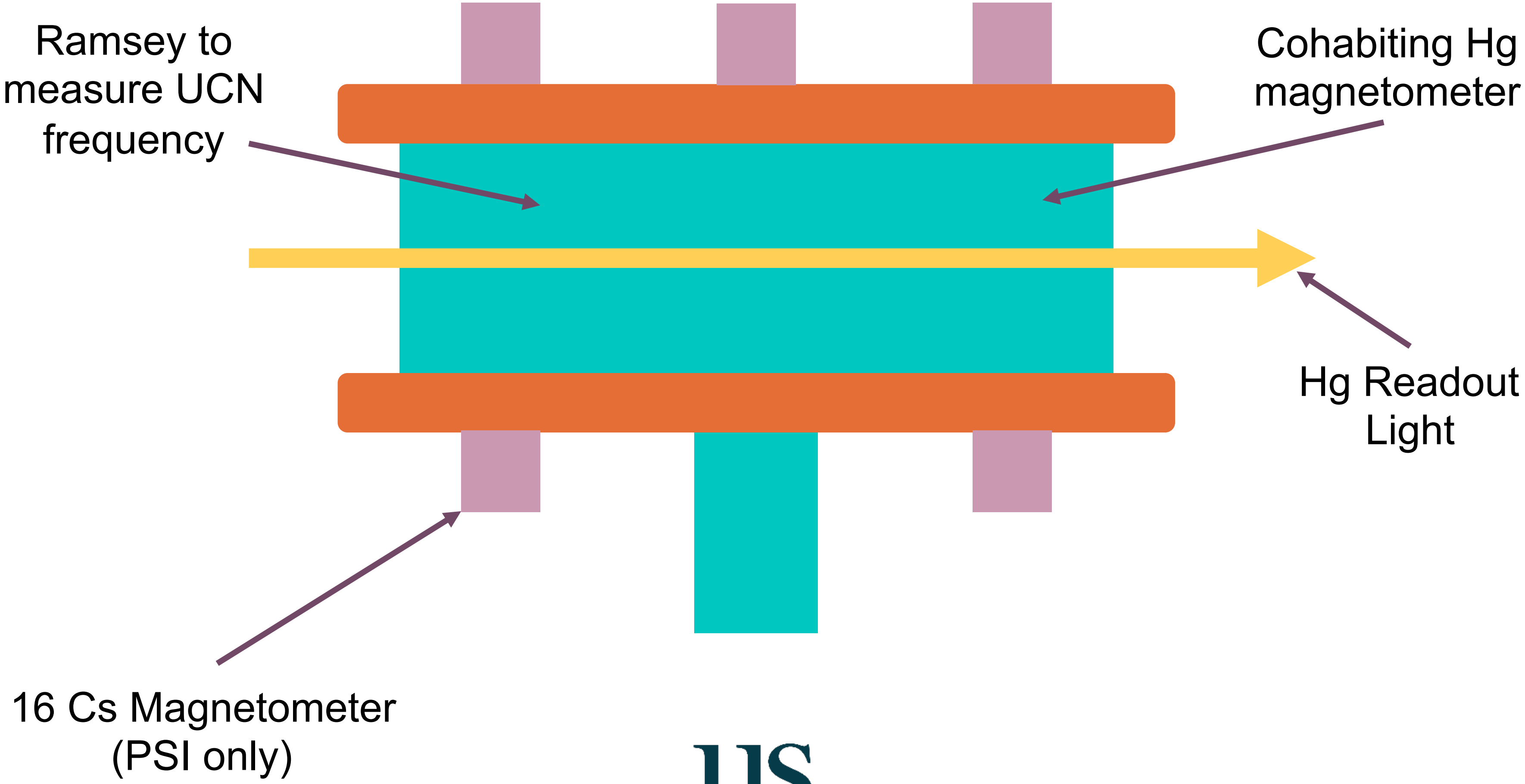
Apparatus ILL and PSI

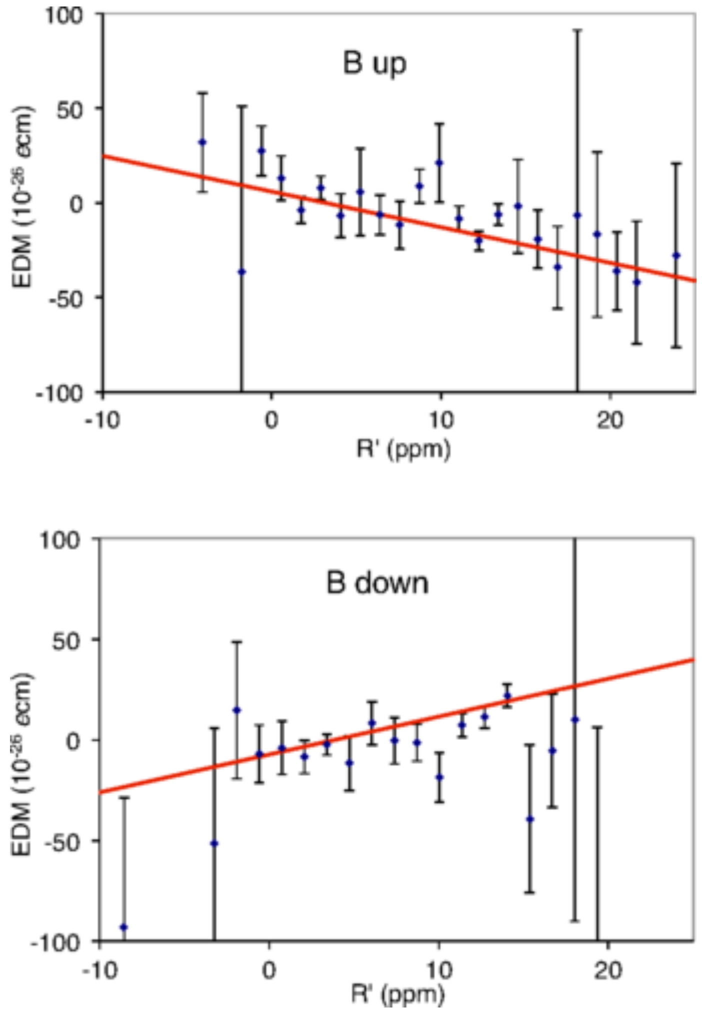


Analysis

- 2 Analyses:
  - All whole (1 day) runs from Sussex-RAL-ILL 1998-2002
  - All individual (5 min) cycles from PSI 2015-2016
- Extract power spectrum using Least Squares Spectral Analysis
- Monte Carlo to find probability distributions
- Use CL_S technique for exclusions

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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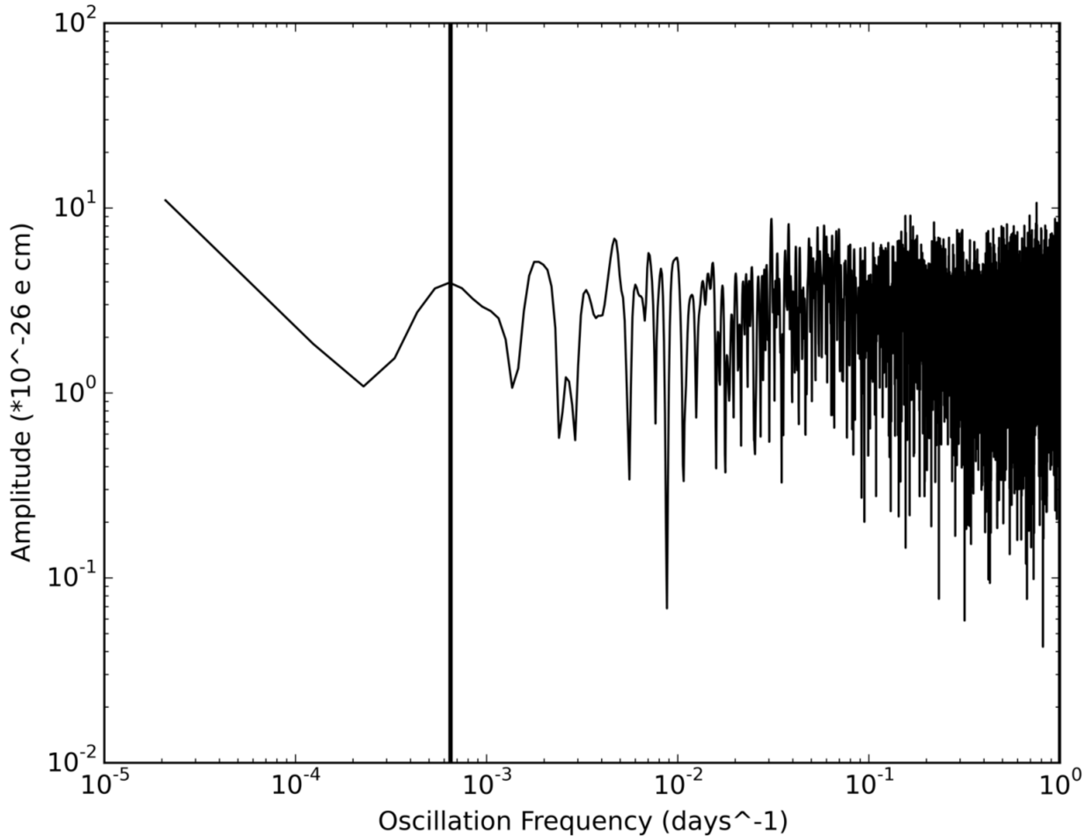
Least Squares Spectral Analysis

- 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

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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

Look Elsewhere and False Alarm

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

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

- Fit MC data for "effective number of frequencies"

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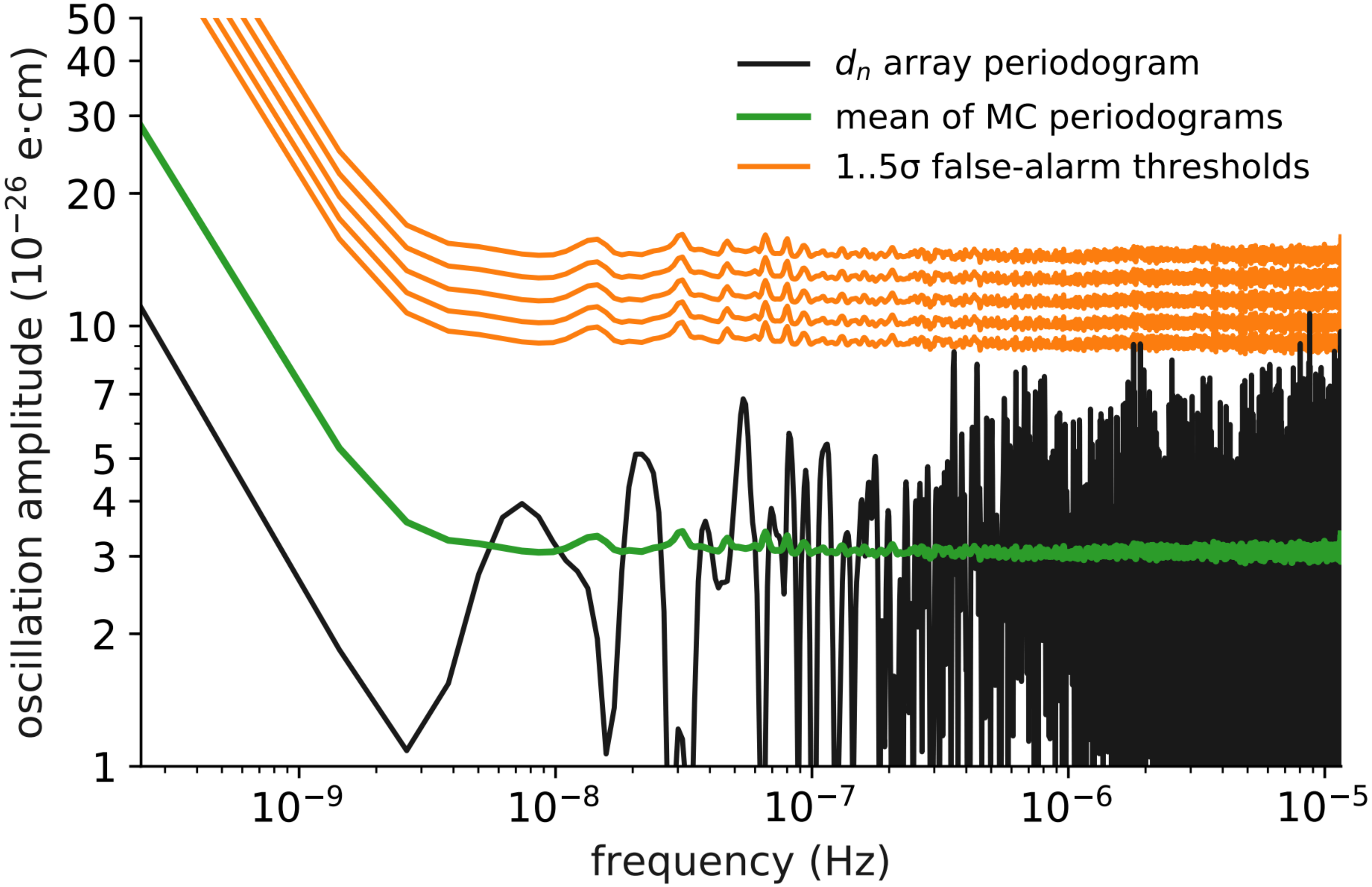
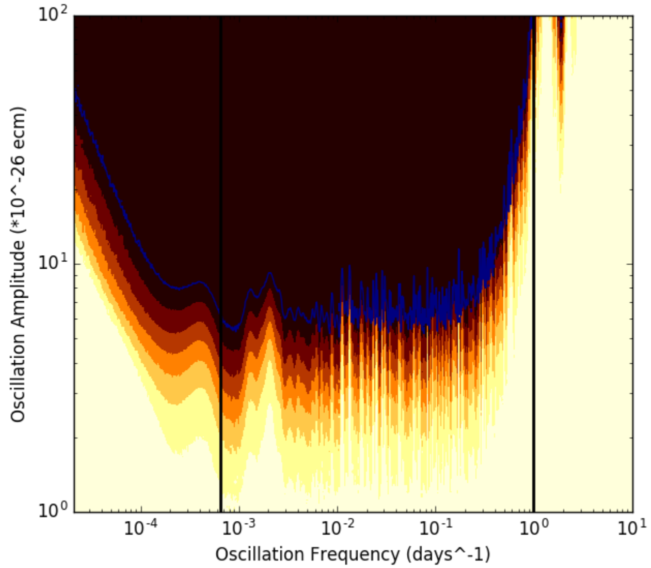
ILL Detection



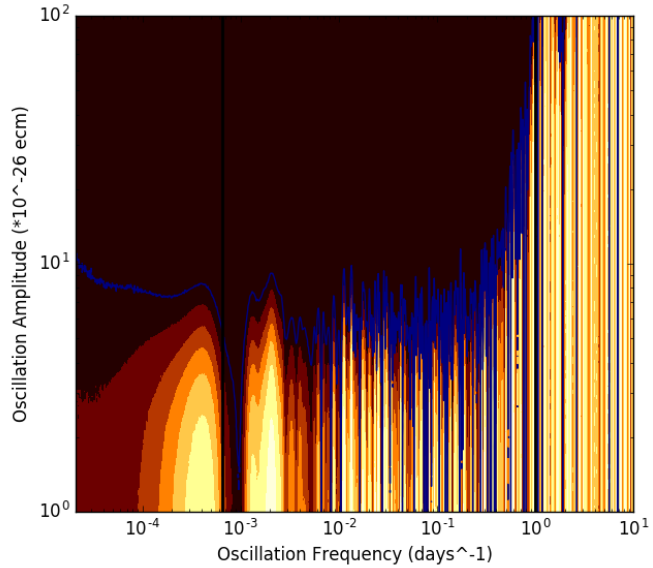
Exclusion

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

Example CL_S Exclusion



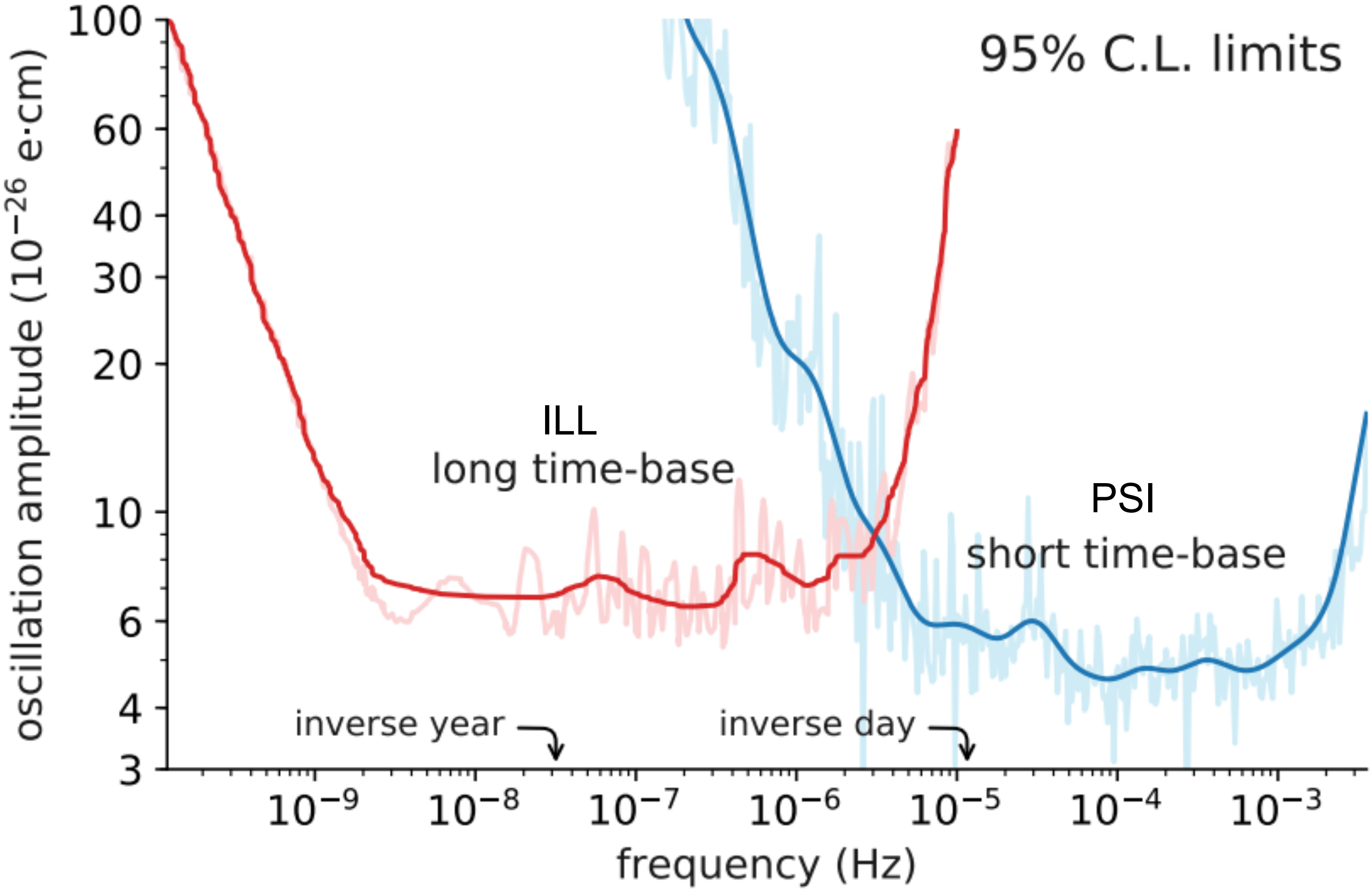
Without CLS Correction
Unphysically strong
exclusion around 10^{-3} $days^{-1}$



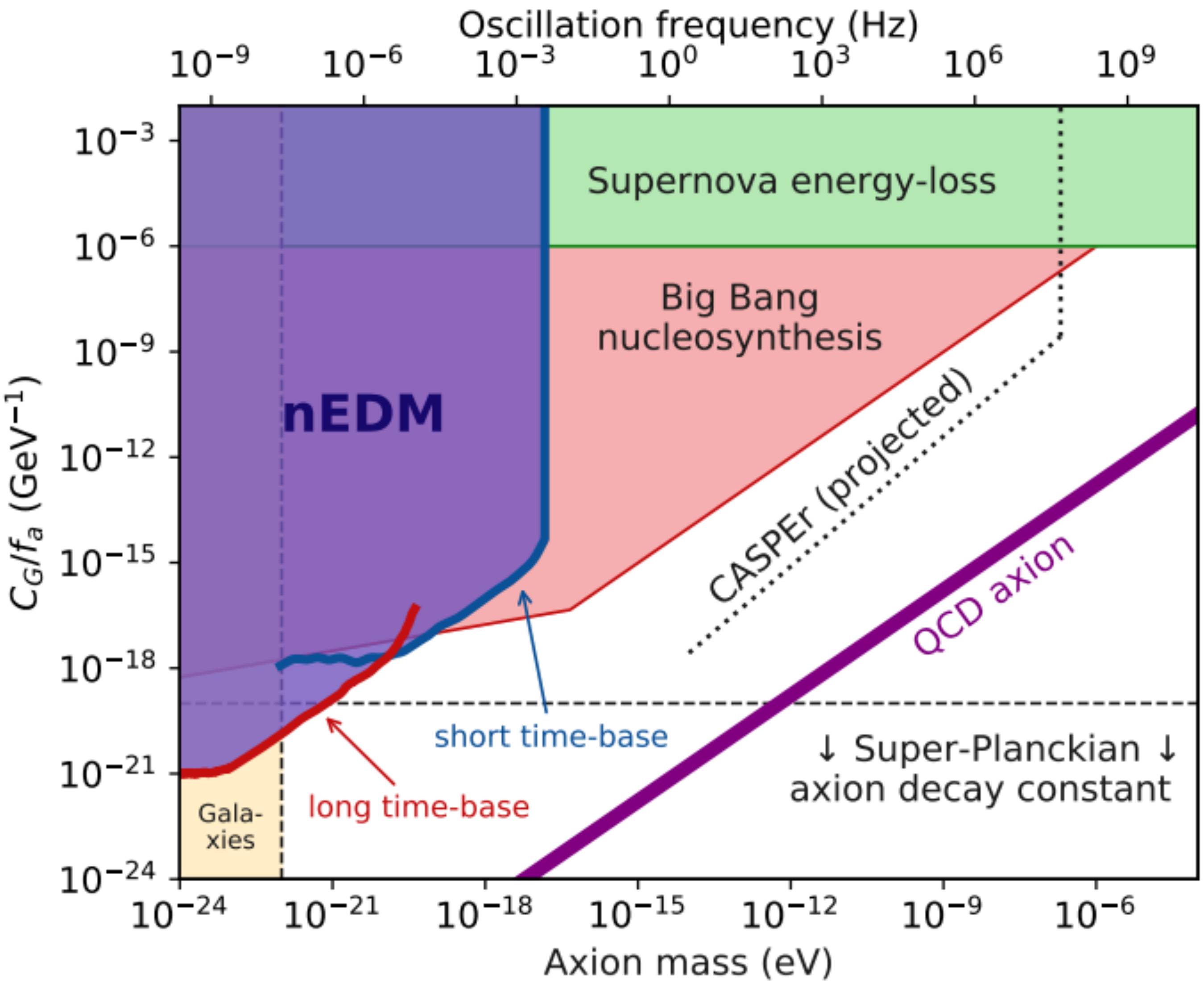
Analysis of the PSI data

- For each cycle, estimate υ_n from neutron counts
- Analyse time series of R(t) from all individual cycles, sorted by E field
  - Add free offset to each run to account for all systematics
  - Can access axion wind and varying d_n

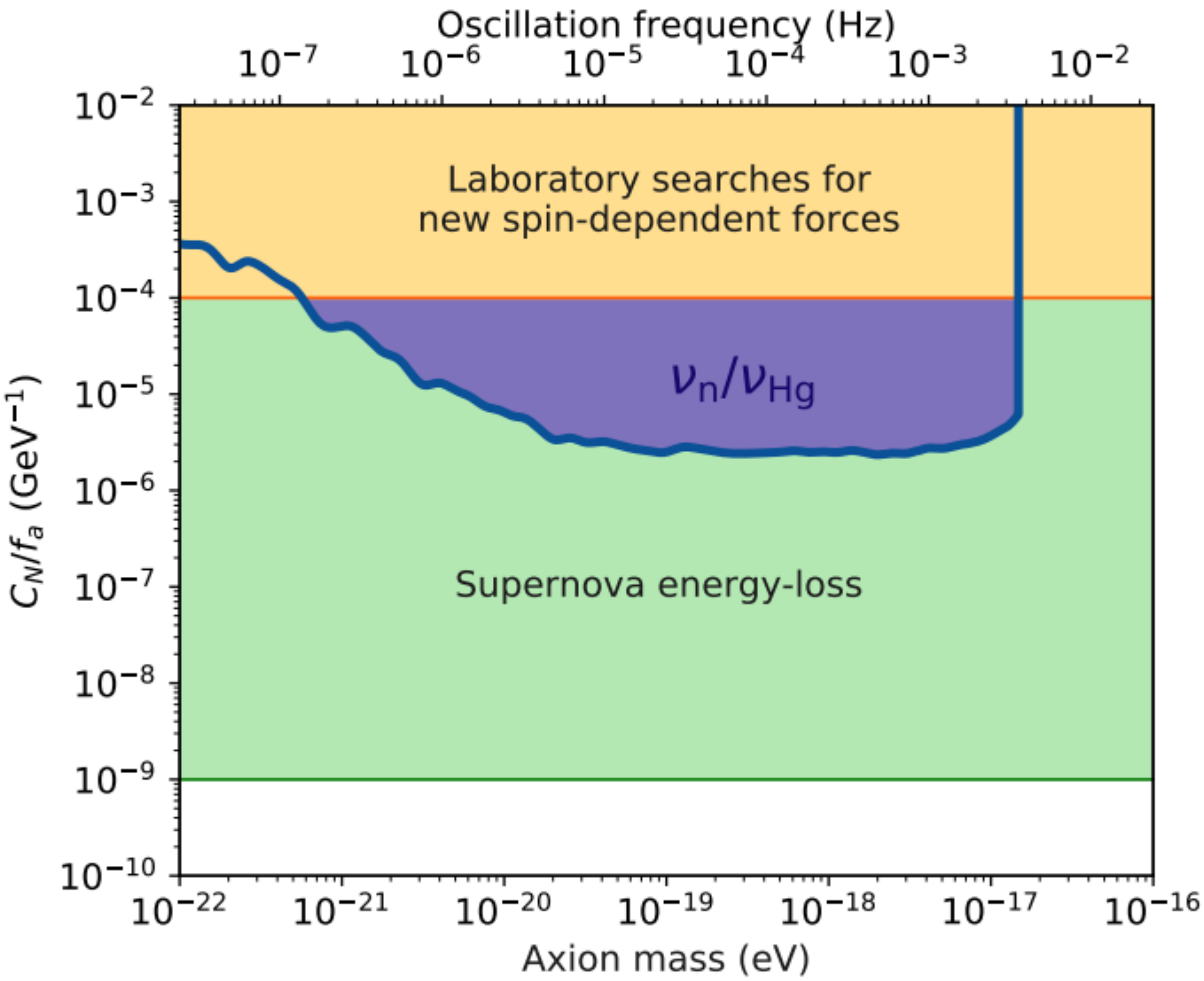
ILL and PSI Exclusion



ILL and PSI Exclusion



PSI: Wind Exclusion



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 results axion-nucleon
- Paper: arXiv 1708.06367 – Accepted to PRX (subject to minor corrections)

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Backup Slides

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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).

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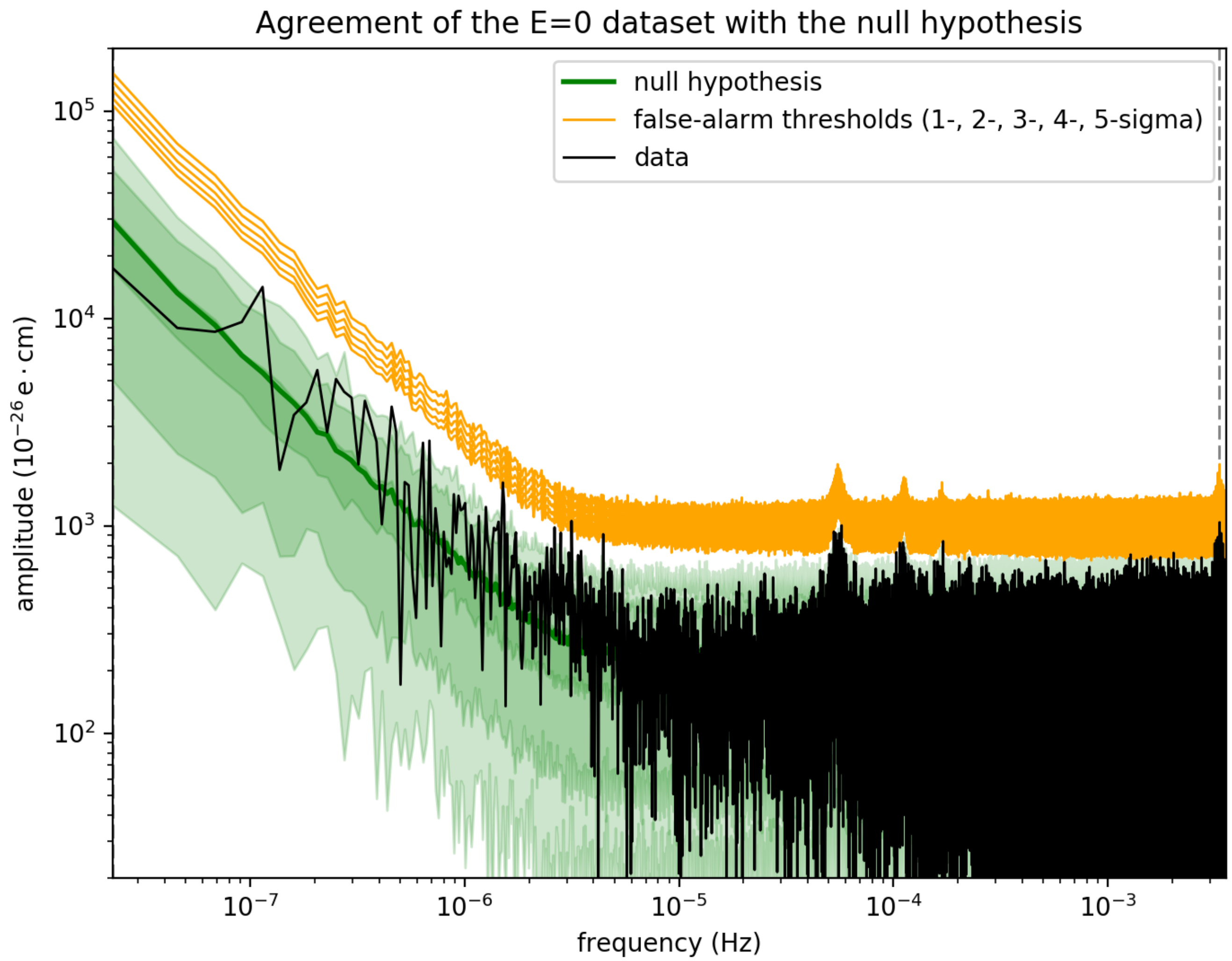
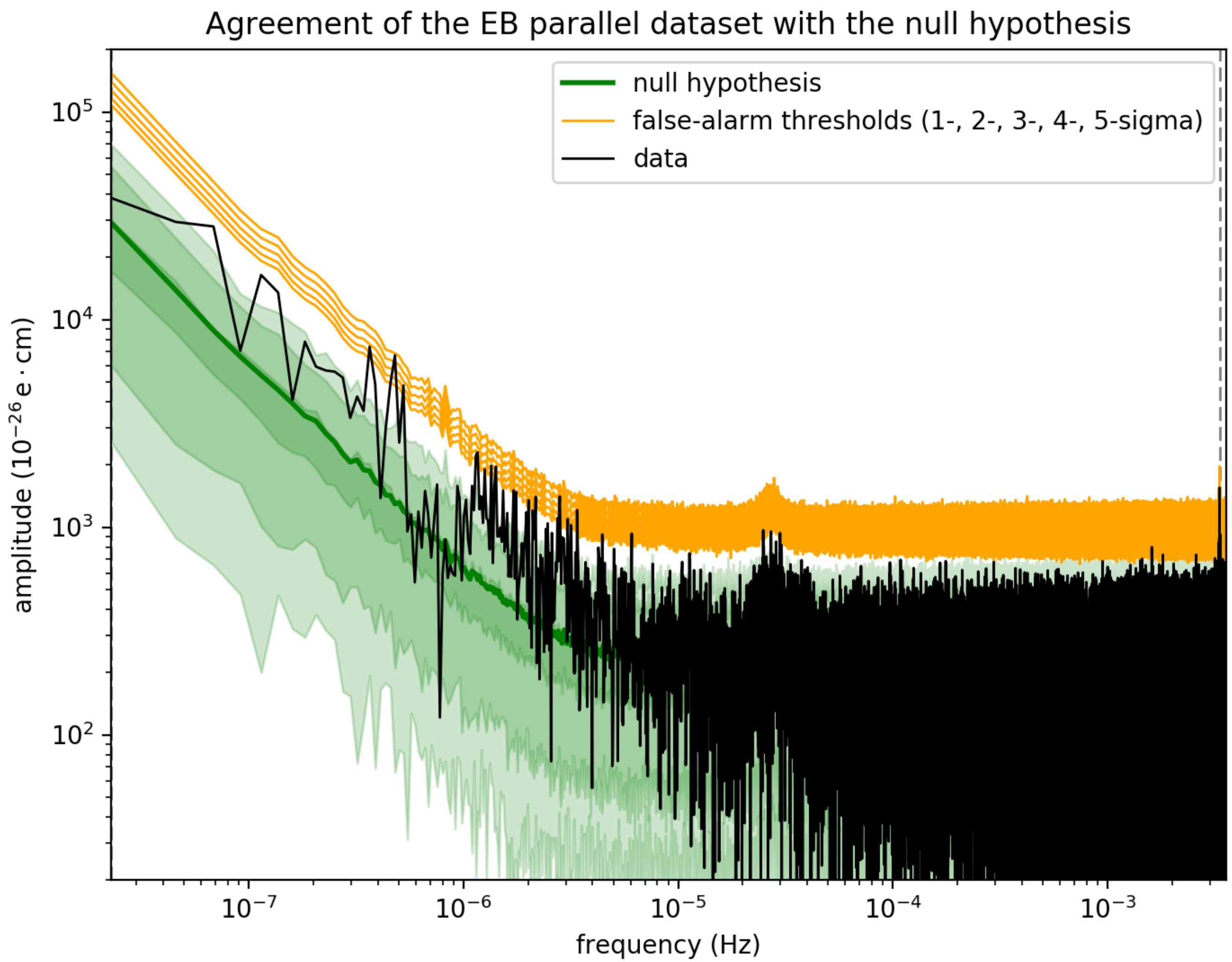
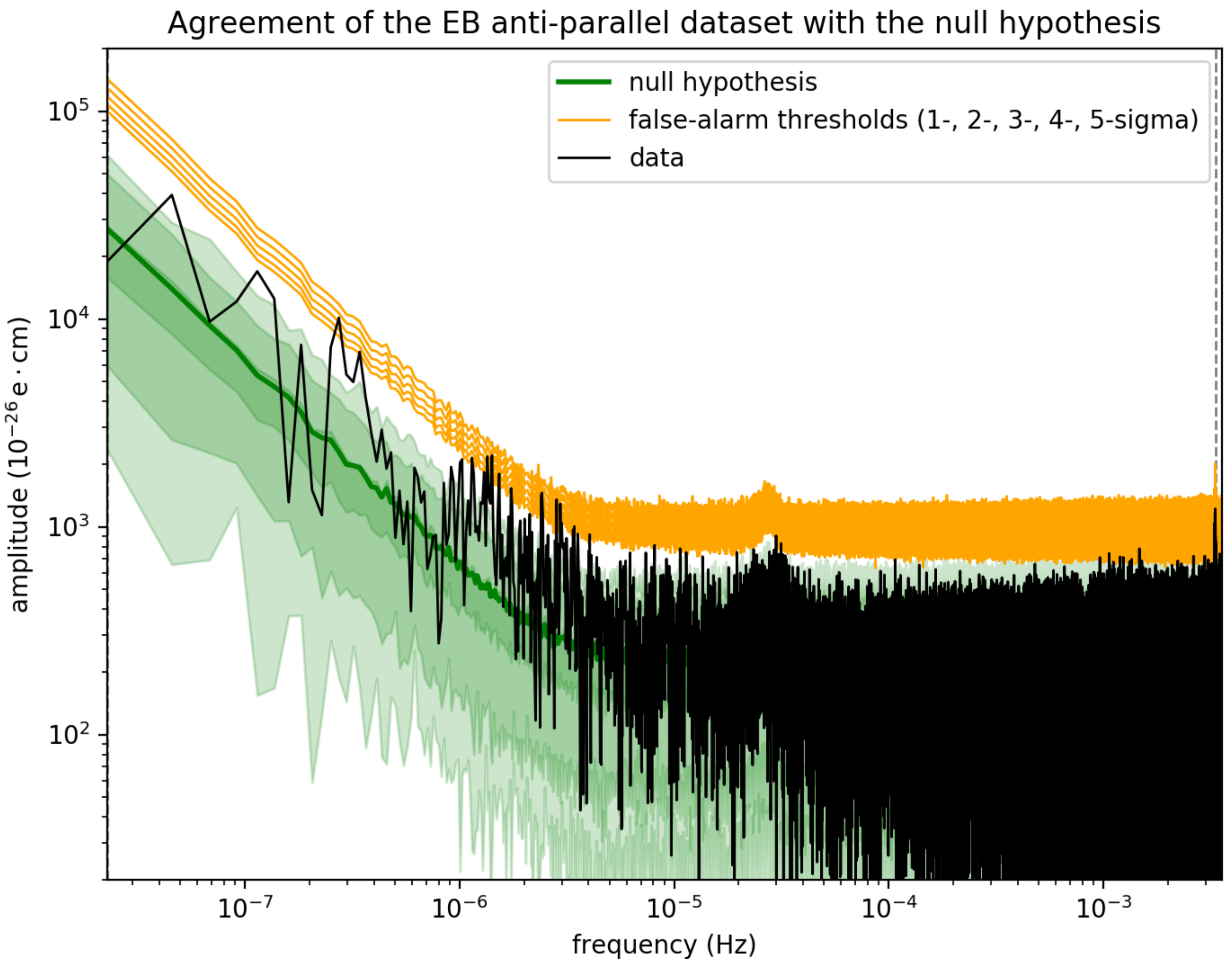
PSI Analysis Detection



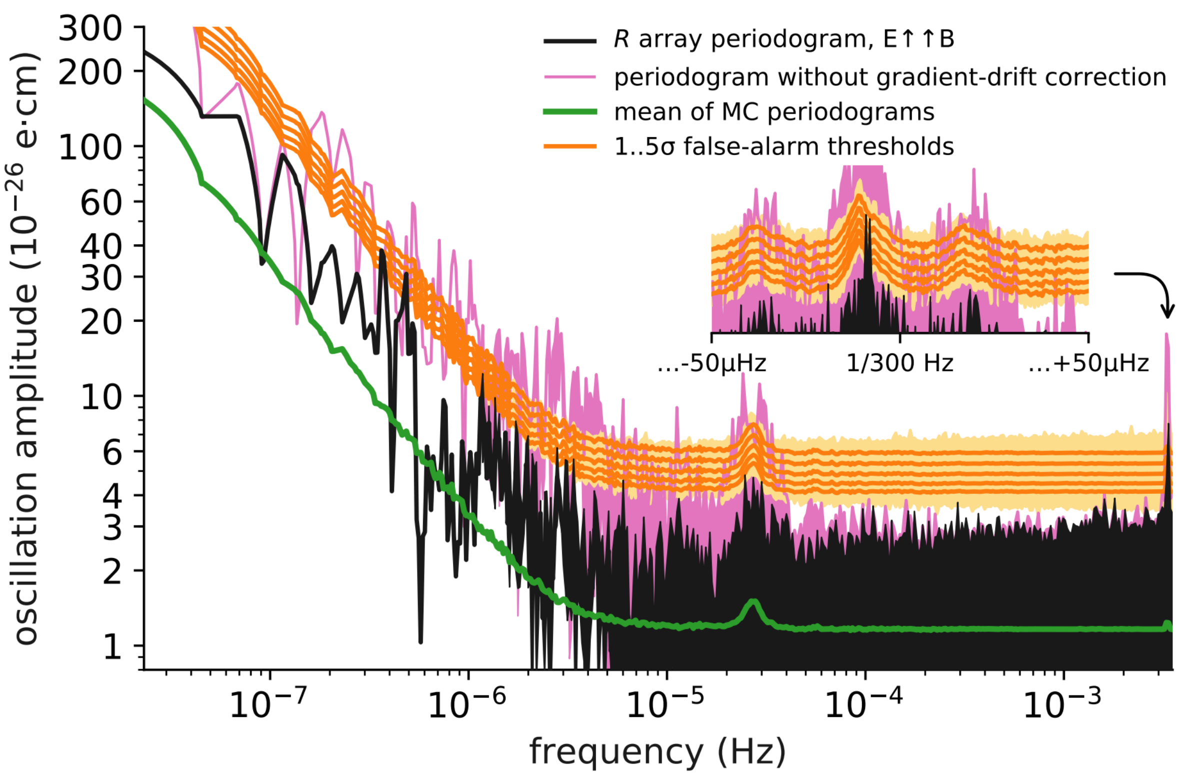
PSI Analysis Detection



PSI Analysis Detection



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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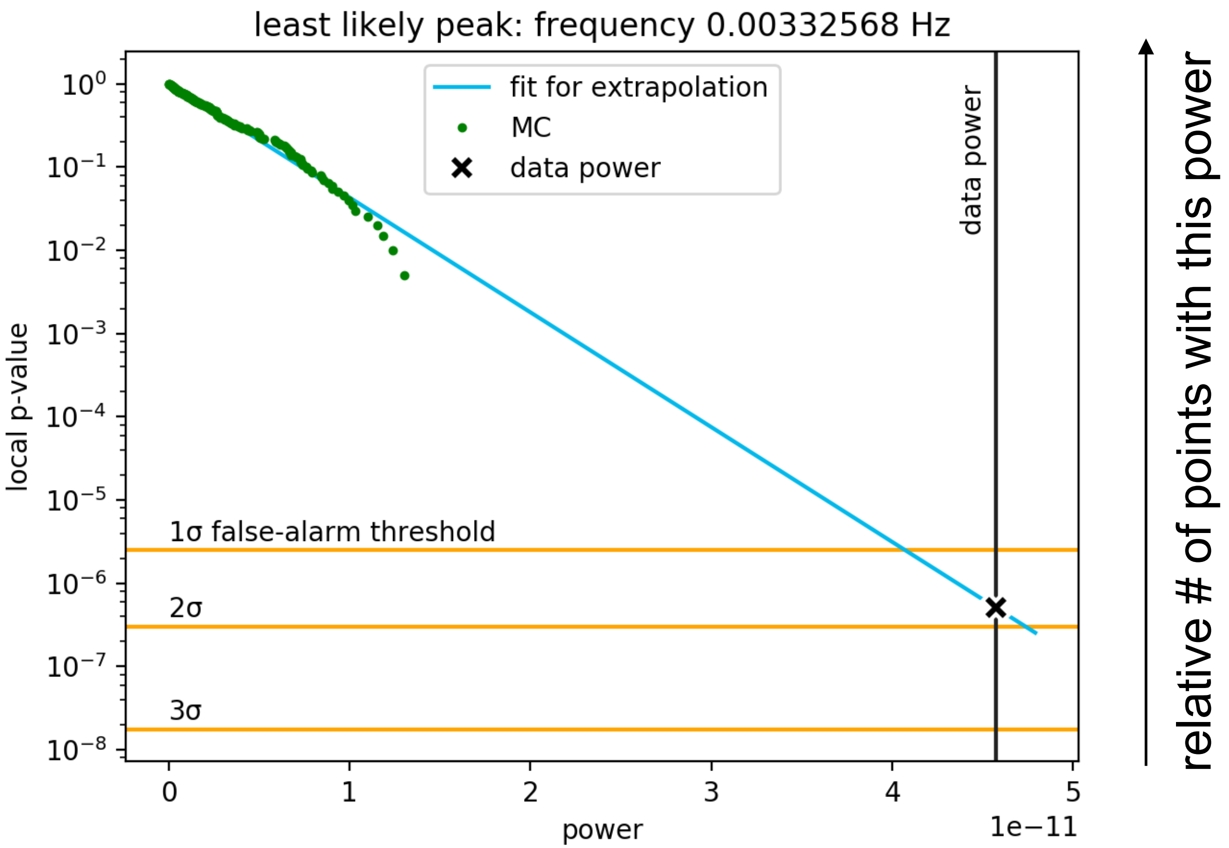
PSI MC: cumulative distribution function extrapolation for one frequency



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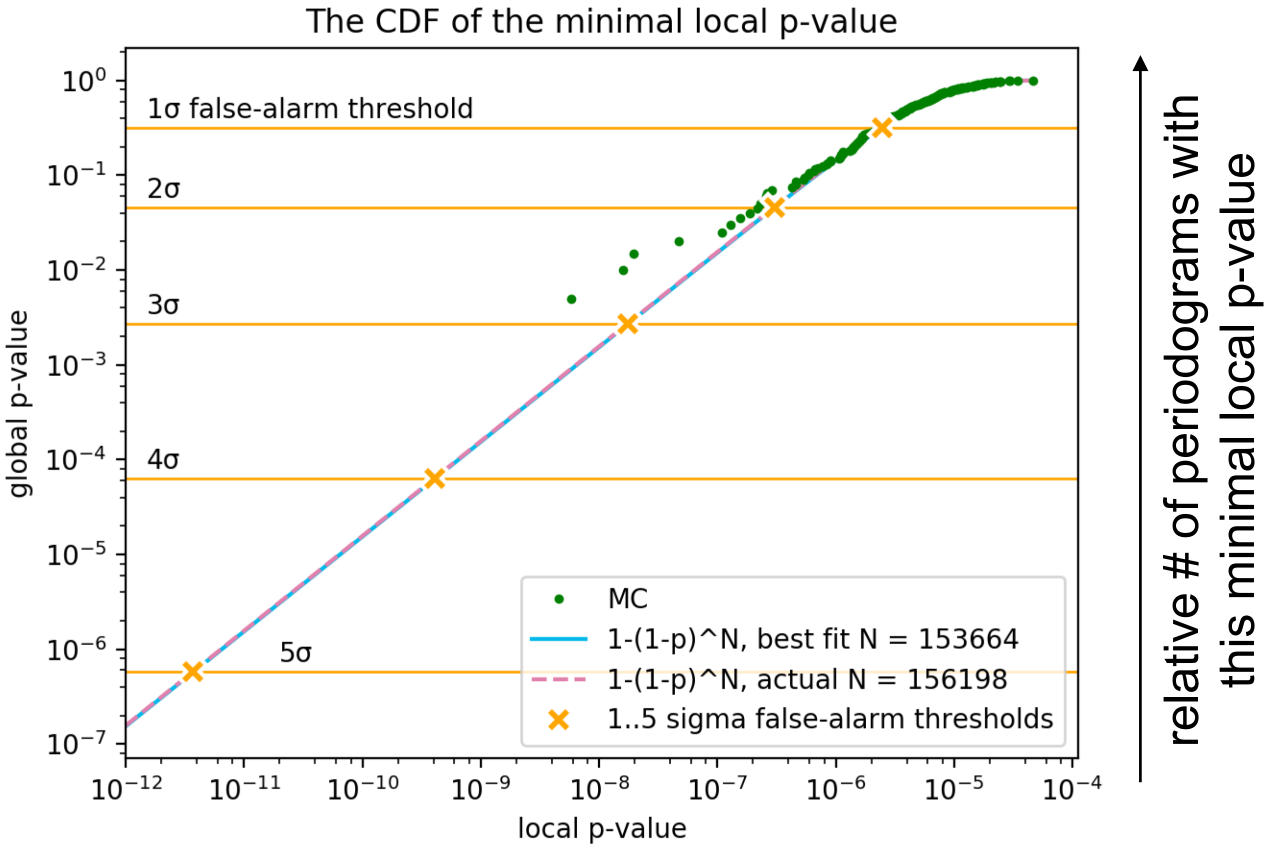
PSI MC: distribution of the global minimal p-value



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