ALPHA Data Analysis and Statistical Inference

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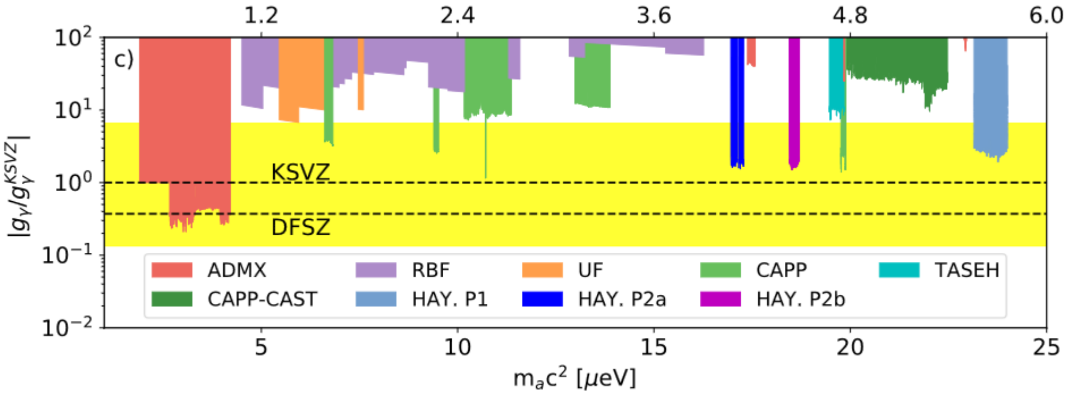
ALPHA and Axion Overview

- Axions were theorized to solve strong CP problem, are also a DM candidate
- Can convert into photons in the presence of a magnetic field
- Haloscopes search for axions by tuning cavity TM_{010} mode to match axion resonance frequency
- ALPHA is a Haloscope with resonance determined by wire spacing rather than cavity size

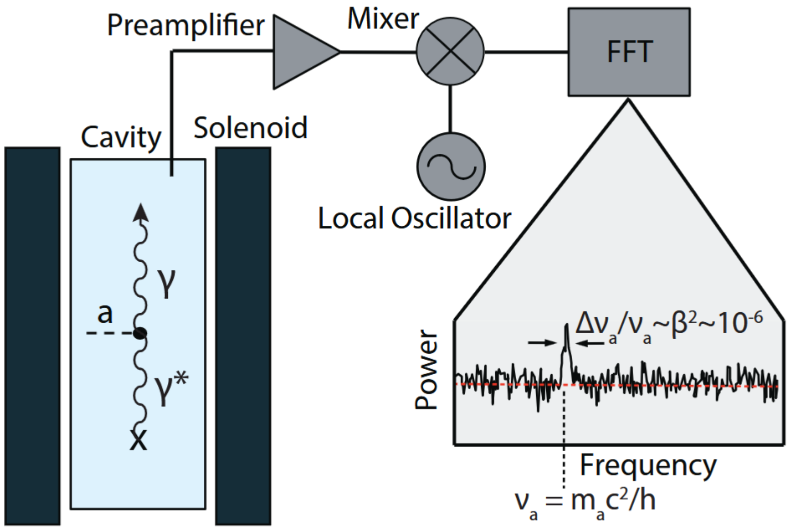
Axion-Photon Coupling Limits



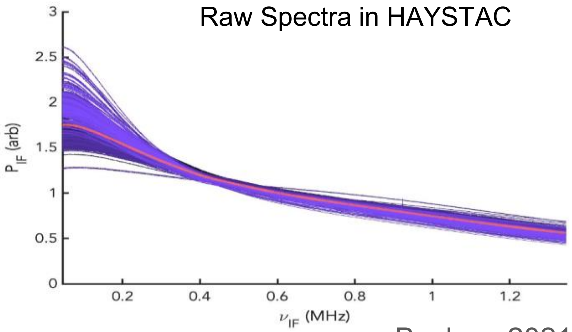
HAYSTAC, 2023 https://arxiv.org/abs/2301.09721

Data Acquisition

- Cavity is tuned to a particular resonance frequency
- Receiver in the cavity measures power at a range of frequencies near resonance
- Signal generator and IQ mixer convert amplified power readings from radio frequency (RF) to intermediate frequency (IF)
- Raw spectra for any single scan measures power at a range of frequencies around cavity resonance
- Most of the power spectra is thermal noise in the cavity or electronics, want to reduce this as much as possible



Rapidis et al 2018. [arXiv:1809.02246v2]

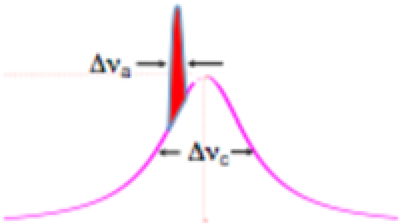


Backes, 2021

Baseline Removal

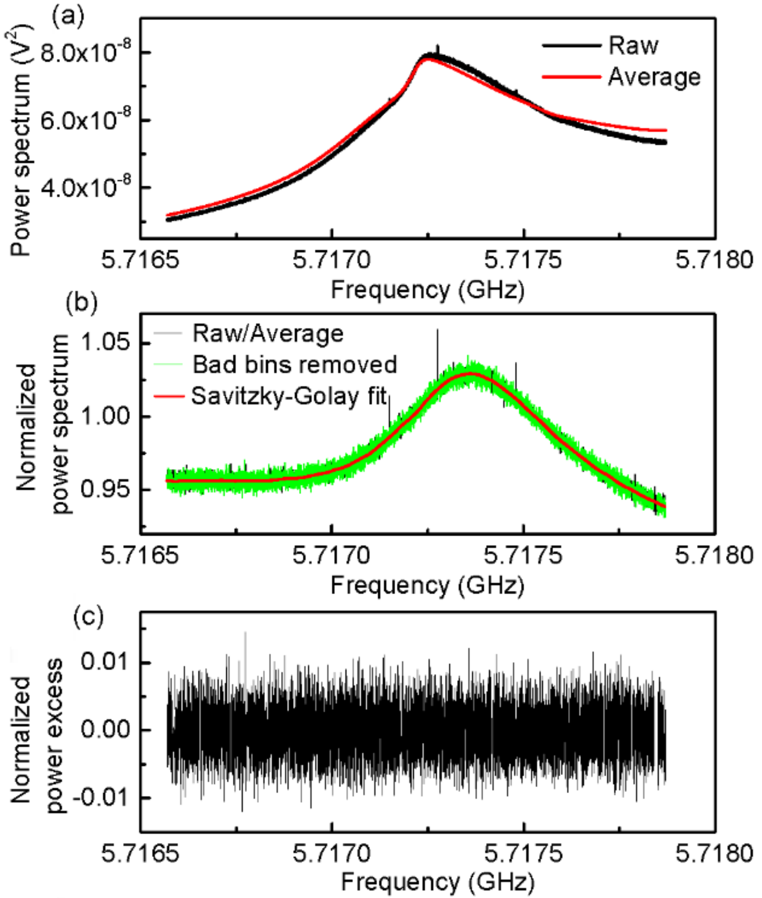
- Both IF and RF contribute to baseline
- Averaging all IF spectra together and applying Savitzky-Golay Filter obtains IF noise baseline, can be subtracted with no risk of removing signal
- Average IF baseline subtracted from each individual spectra and converted back into RF
- Each RF spectra has unique, roughly Lorentzian baseline characterized by cavity bandwidth, which is much wider than true axion bandwidth
- RF spectra individually fit to another SG filter to remove RF baselines, leaving Gaussian noise
- Normalize all baseline-subtracted spectra by SNR

Axion and Cavity Bandwidths



Shokair et al, 2014 https://arxiv.org/abs/1405.3685

HAYSTAC example raw spectrum

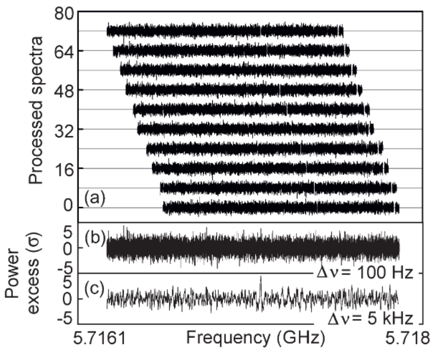


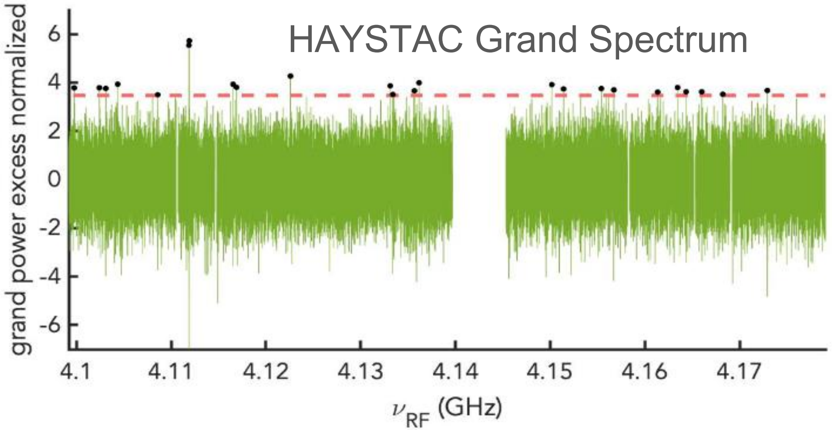
Brubaker, 2018 arXiv:1801.00835

HAYSTAC's Approach: Combining Spectra

- Vertically combine all normalized spectra into a single spectrum
- Horizontally combine bins using maximum likelihood weights to create the final "grand" spectrum
- With data processed into grand spectrum, look for power excesses and rescan them
- If excess remains, do further tests, if not, set exclusion limits
- HAYSTAC's original approach to exclusion used fixed thresholds- "Geometric" method
- Current approach uses Bayesian inference to update axion probability from all scans performed- "Bayesian" method

Brubaker, 2018 arXiv:1801.00835

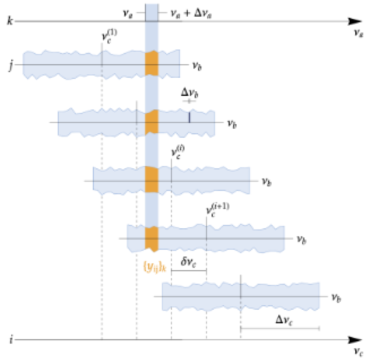




Backes, 2021

New Exclusion Approach: Likelihood Analysis

- New approach for ALPHA developed by Stockholm University group
- Use maximum likelihood to set rescan threshold based on previous result
- Instead of combining spectra, combines axion likelihoods from different experimental configurations
- Uses Frequentist Analysis to set exclusion limits based on non-observance of axion in every configuration



Likelihood ratio

See e.g. Gallo Rosso et al.

Data $\{y_{ij}\}_t$

Fluctuations $x = \sum_{i \in \mathcal{I}} \sum_{j=1}^{N_i} \frac{w_{ij} y_{ij}}{\sigma_{ij}^2}$

Configurations $u = \sum_{i \in \mathcal{I}} \sum_{j=1}^{N_i} \frac{w_{ij}^2}{\sigma_{ij}^2}$

$$X_{i,\nu} \sim \mathcal{N}(\mathbb{A} u_{i,\nu}, \sqrt{u_{i,\nu}})$$

$\mathbb{A}$: true coupling (e.g. $C_{a\gamma}^2$)
$u_{i,\nu}$: alias for the SNR

Image Credit: Andrea Gallo Rosso

$$p_A = P(\text{get data at least as unfavorable to A as the observed data} \mid A)$$

$$P_A\left(q_A(\hat{A}, M) \geq q_A^{\text{obs}}\right) = \sum_{m=1}^{N_s} P_A\left(M = m\,, q_A(\hat{A}, m) \geq q_A^{\text{obs}}\right) \equiv \alpha$$

Image Credit: Andrea Gallo Rosso

Comparison Between Approaches

- New Likelihood-Based Approach should significantly improve exclusion sensitivity
- Should set better limits on coupling than Geometric or Bayesian approaches
- Work in progress, still needs more refining

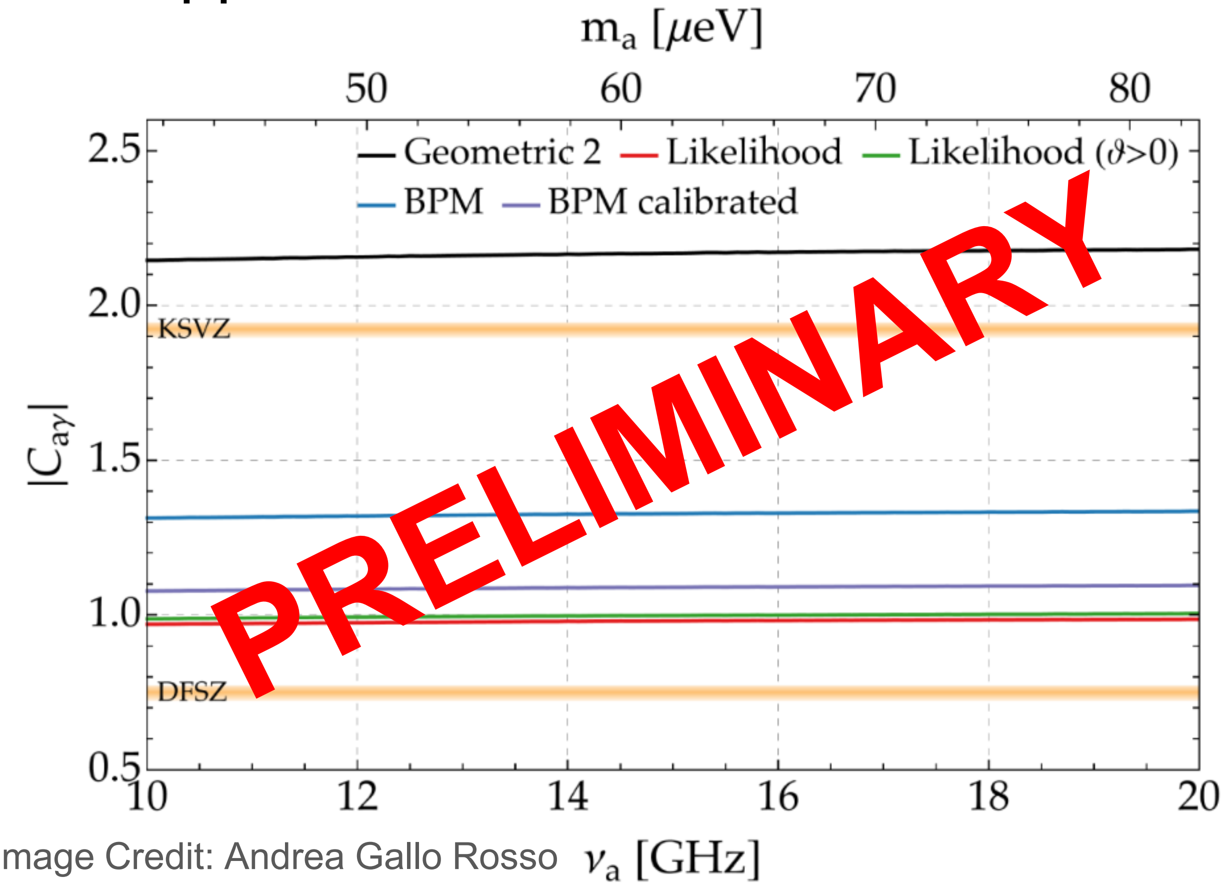


Image Credit: Andrea Gallo Rosso

Modular Data Analysis Software

- Currently under development software for doing varied haloscope analyses, development led by Johns Hopkins University group
- Modular Python code that can easily be configured to run different analyses or different data processing methods
- Initial plan is to have it work with either HAYSTAC or ALPHA, with configurations for different data formats, electronics setups, and final analyses
- Will be used to run all aforementioned analysis approaches on ALPHA science data
- Eventual plan is to make broadly general software for any haloscope experiment

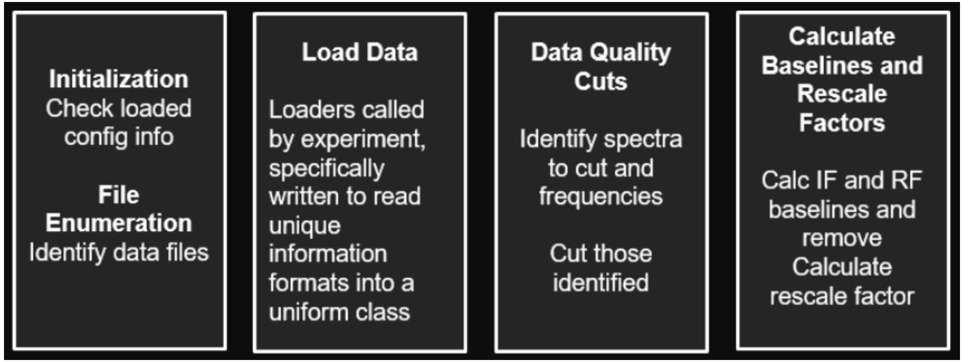


Image Credit: Chloe Greenstein

Conclusions

- We have good sensitivity to axions in 10-20 GHz range and some novel analysis methods to look for them
- Running Dark Photon run in next few months, Axion run in 2028

2025 ALPHA Collaboration Meeting, Yale

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ALFRED P. SLOAN FOUNDATION

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Swedish Research Council

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Backup Slides

Baseline Removal

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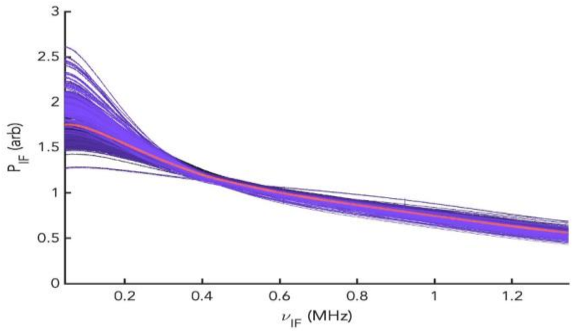
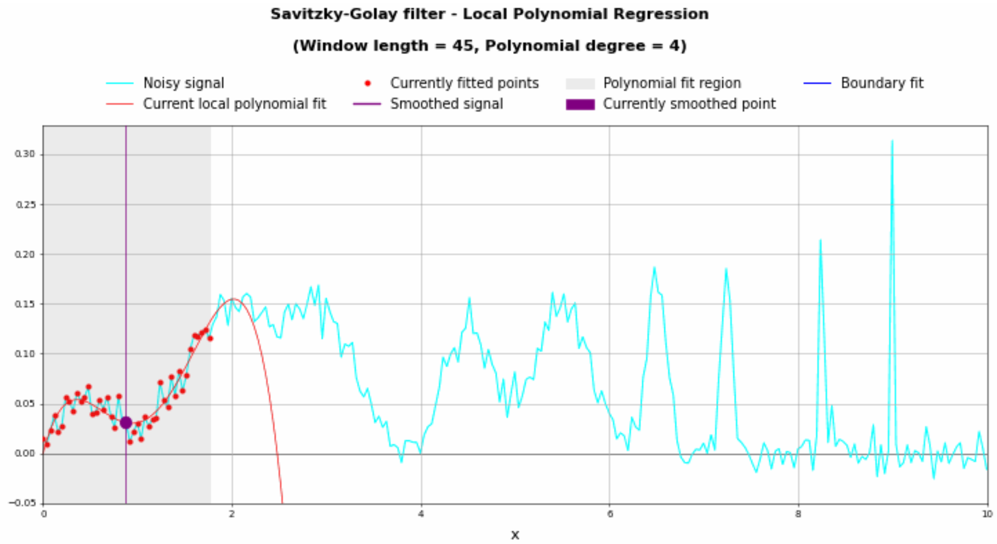


- Both IF and RF contribute to baseline
- Averaging all IF spectra together and applying Savitzky-Golay Filter obtains IF noise baseline, can be subtracted with no risk of removing signal
- SG Filter is a moving window, fits point and its 2W-1 neighbors to a D-degree polynomial

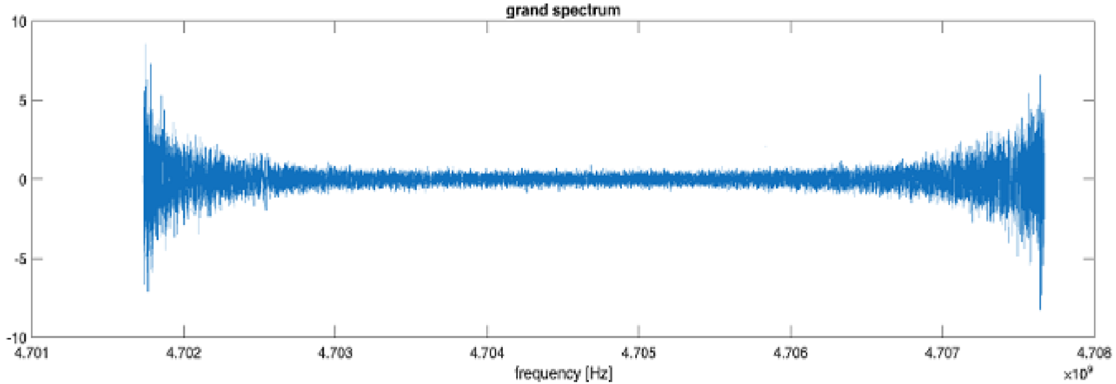


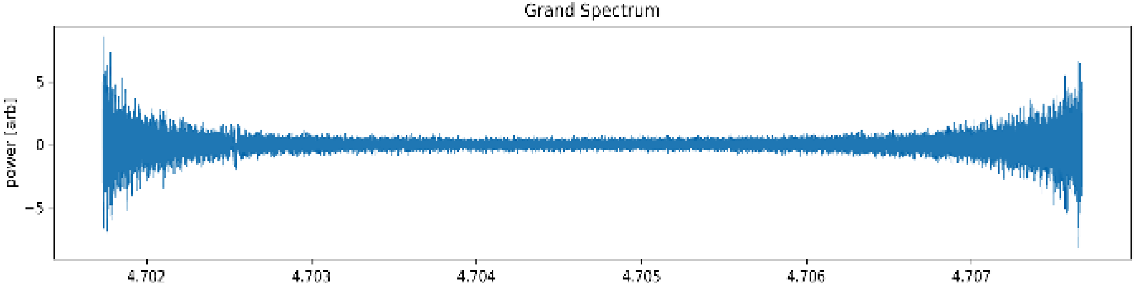
MothNik - CC0, https://commons.wikimedia.org/w/index.php?curid=164353357

Modifying for ALPHA

- HAYSTAC electronics and data outputs are very similar to ALPHA, so spectrum processing will also be very similar
- Biggest difference is the lack of a squeezed-state receiver in ALPHA
- We have access to HAYSTAC's data processing and analysis code and some of their dataset, and can adapt it for our purposes
- Started by rewriting HAYSTAC code from MATLAB into Python- our translated code now works for processing HAYSTAC data
- This code is hard to update or maintain- need a more flexible approach for different experiments or analyses

(MATLAB version)

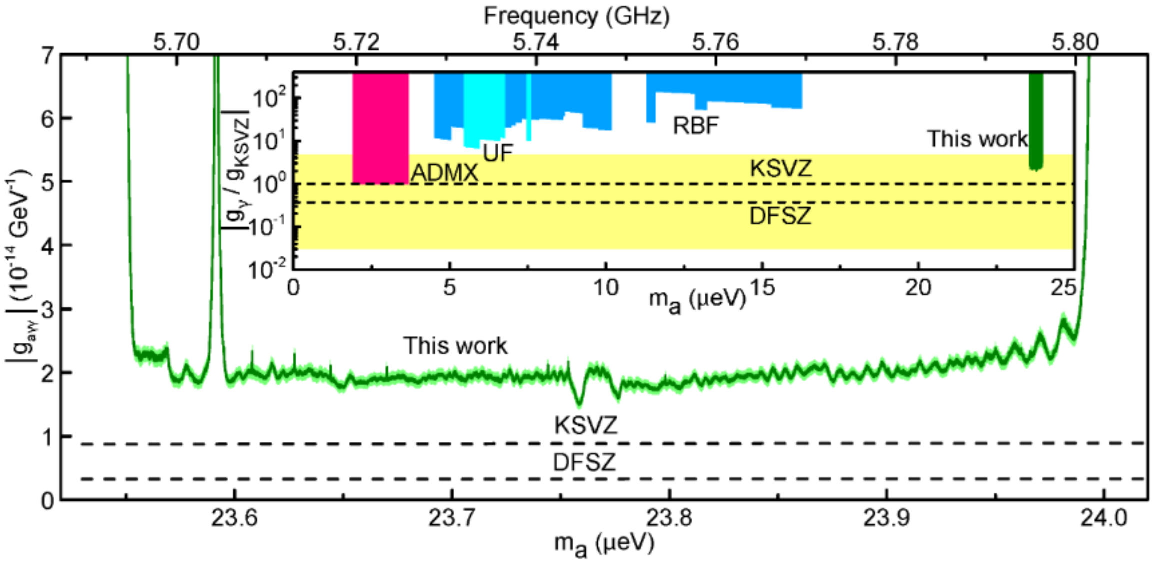




(Python version)

Exclusion Approach 1: Geometric

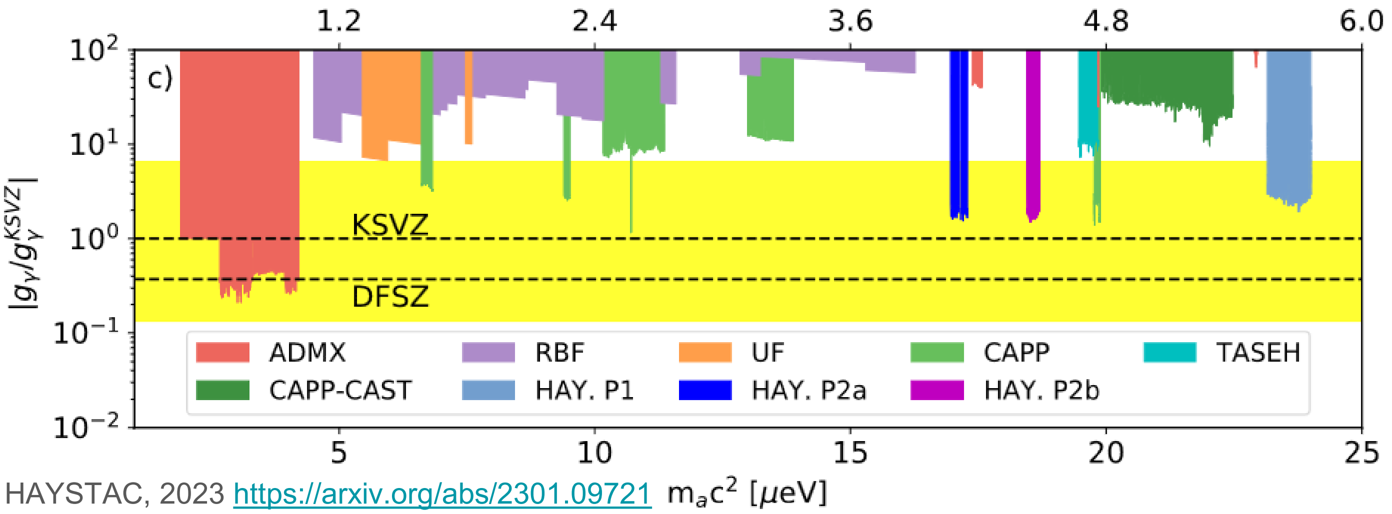
- HAYSTAC's first approach, developed by Brubaker in 2017
- Set rescan threshold to trigger 95% of the time if true axion signal exists
- If no axion found, report 95% exclusion level across frequencies searched and coupling constant that would have triggered threshold
- This is overly conservative because it doesn't consider the magnitude by which a signal is above/below threshold, or use info from all scans performed



Brubaker, 2018 arXiv:1801.00835

Exclusion Approach 2: Bayesian

- HAYSTAC's current approach, developed by Palken in 2020
- Uses Bayes' theorem on candidates scanned repeatedly to update axion exclusion probability
- This makes use of all collected data and gives more accurate results, but can limit exclusion coverage compared to geometric approach



HAYSTAC, 2023 https://arxiv.org/abs/2301.09721

Comparison Between Approaches

$$\theta = \mathbb{A}\sqrt{u_1}$$
$$\vartheta = A\sqrt{u_1}$$
$$\beta = b_1/\sqrt{u_1}$$
$$\omega = u_2/u_1$$

$(\theta = 0, \alpha = 0.1)$

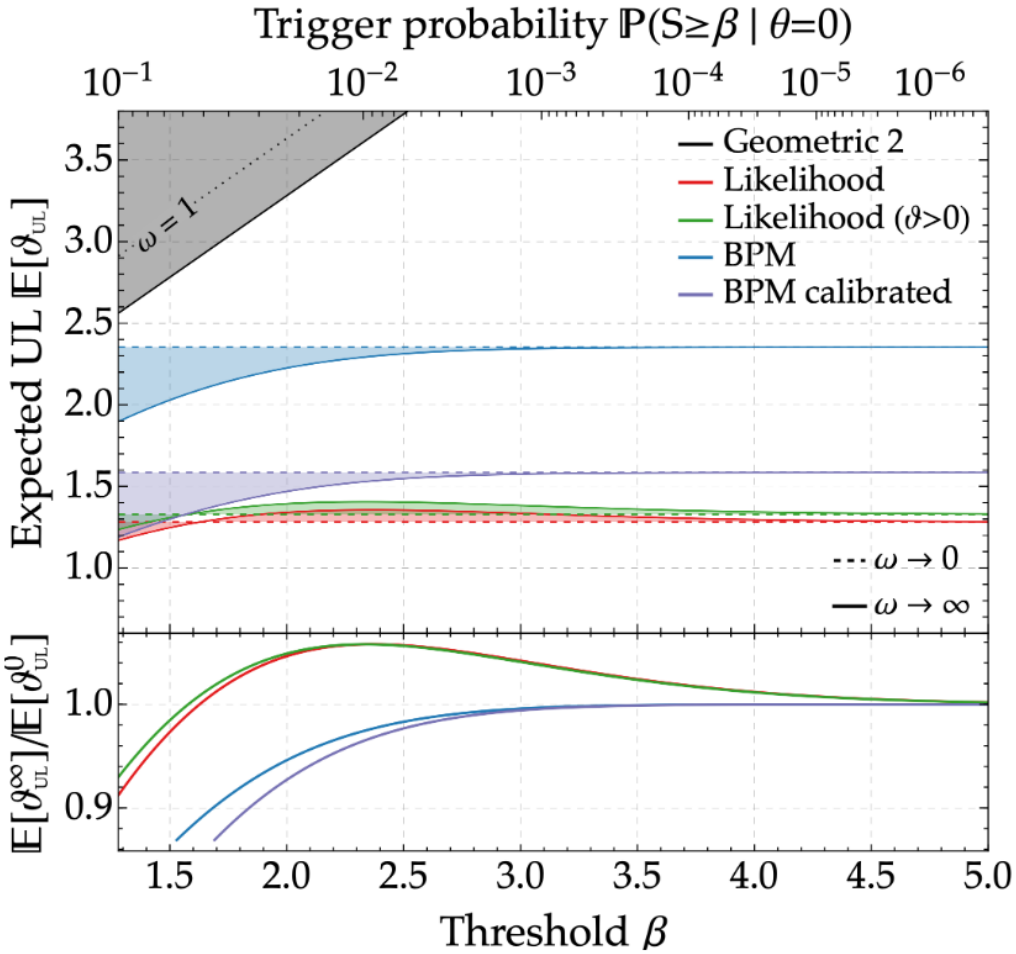


Image Credits: Andrea Gallo Rosso