Run 1B: High resolution data analysis

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(Weekly meeting on Tuesdays at 5:30 PM Eastern)

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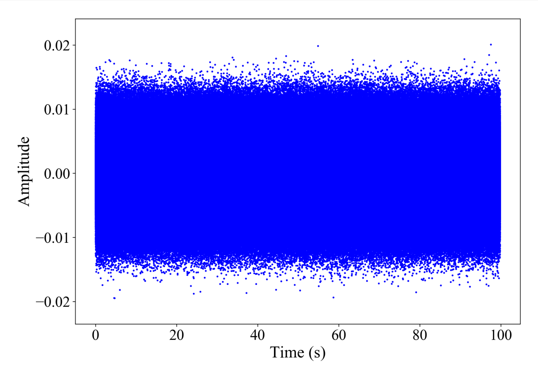
Overview

- Time series data $\rightarrow$ Fourier transform.
- Data cuts.
- Contamination in HiRes.
- Exclusion plot.

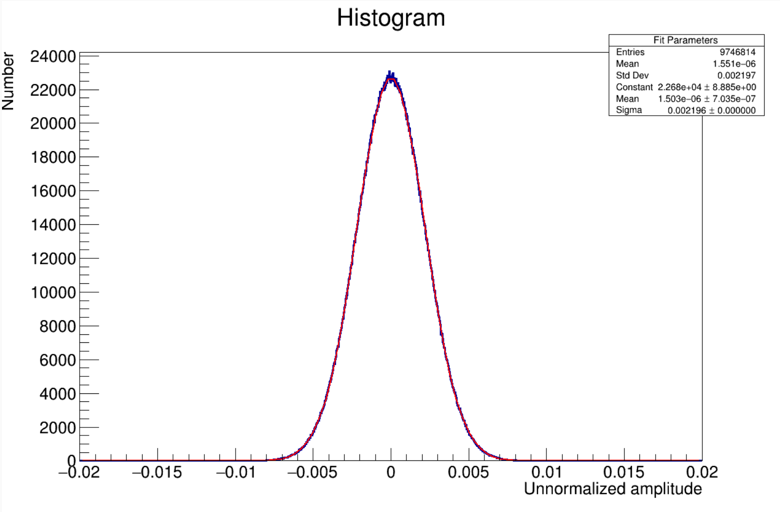
Time domain



Time series data

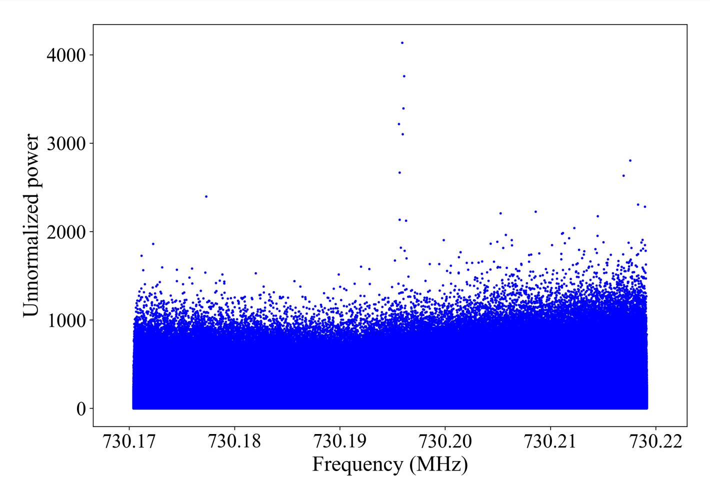
- Run 1B data $\rightarrow$ JSON format.
- HiRes data dominated by noise.
- T $=$ 100s, $\delta t = 10.24\mu$S.

Histogram of time series data



Number of points in the histogram = 9,746,814.

Power vs frequency spectrum

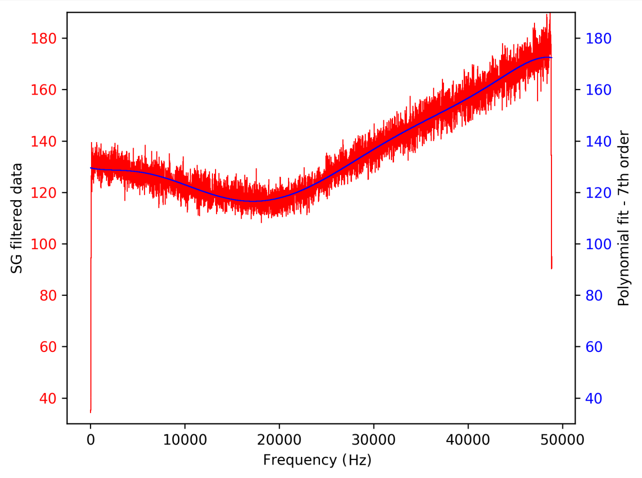


Fourier transform of time series data. $N = \frac{N_T}{2} + 1$.

Spectral shape of noise

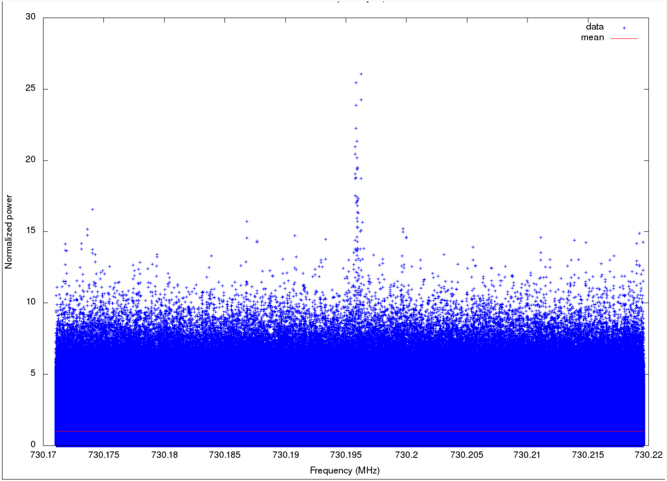
- Transfer function of some of the RF components depends on frequency.
- How to remove? $\rightarrow$ Savitzky - Golay filter or Polynomial fit.
- Dividing the unnormalized data by this fit removes the spectral shape.

Spectral shape of noise



A comparison of Savitzky - Golay and Polynomial fit of 7^{th} order.

Removal of spectral shape



The units on y-axis is $\sigma = 1$, the standard deviation. Red line is the mean $\mu = 1$.

The statistics of noise

- Two variable Gaussian, with x and y as sine and cosine components,

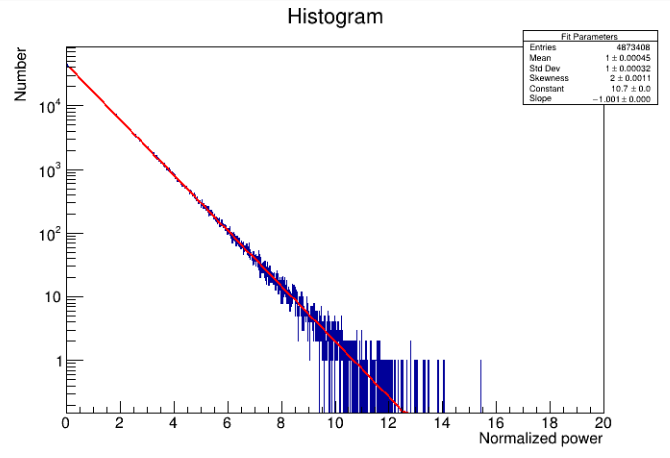
$$P(x,y) = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\ \frac{1}{2\pi\sigma_p^2} e^{-\frac{x^2+y^2}{2\sigma_p^2}}. \tag{1}$$

- Because I plot power vs. frequency, the statistics of noise power is,

$$\frac{dP(p)}{dp} = \frac{1}{\sigma} e^{-\frac{p}{\sigma}} = \frac{n}{N}. \tag{2}$$

- Exponential distribution
- Mean, $\mu = 1$ and Standard deviation $\sigma = 1$.

Its a straight line !

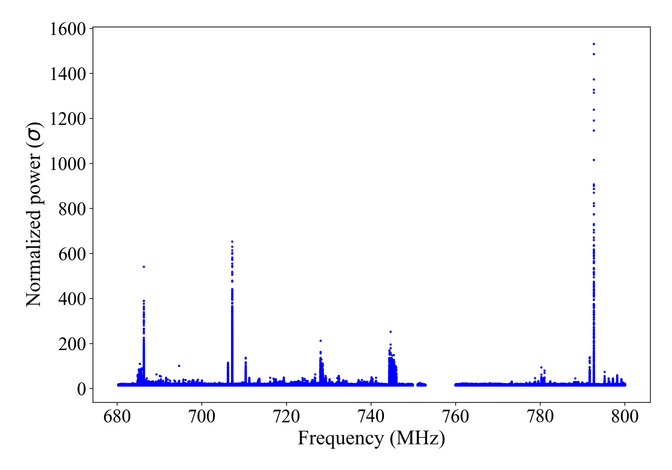


The fit intersects the $y = 1$ line at $P = 10.7\sigma$.
$P = (10.7 + \sqrt{10.7})\sigma = 14\sigma$ was chosen as the 1^{st} cut.

Analysis

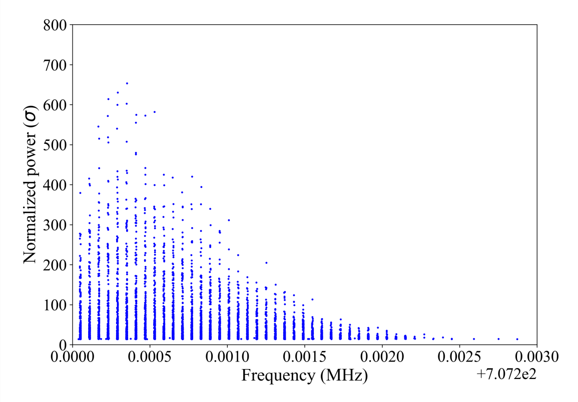
- Number of triggers per scan is, $n = Ne^{-p}$.
- $N = \mathcal{O}(4.8 \times 10^6)$, $p = 14\sigma \rightarrow n = \mathcal{O}(4)$.
- Fourier transform of $93,499$ scans.
- For $93,499$ scans, $n = \mathcal{O}(360,000)$.
- $\mathcal{O}(55)$ synthetic axion $\rightarrow$ Run 1B $\rightarrow$ used as a test bench $\rightarrow$ removed.

Triggers



Triggers above 14σ.

Synthetic axions



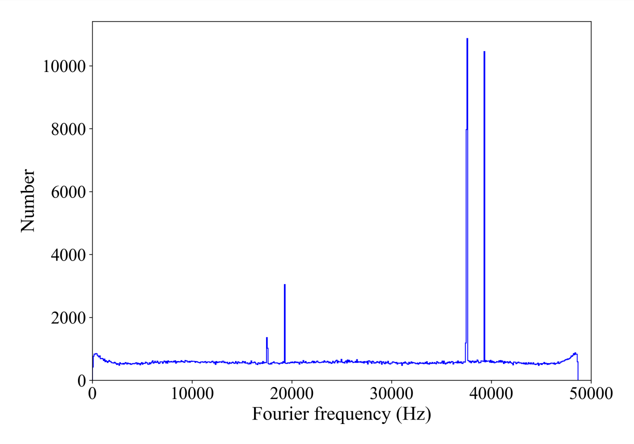
Synthetic axion injection at 707.2 MHz

Mimic a Maxwellian $\rightarrow$ 50 Hz difference $\rightarrow$ $\mathcal{O}(3)$ kHz BW.

Cuts

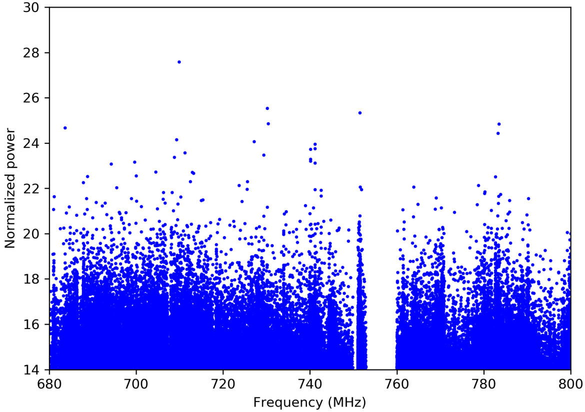
- Q cut: data with bad Q ($10000 \leq Q \leq 90000$)
- frequency cut: data outside the med res frequency range $\sim$ 680 - 800 MHz
- Removed the RF and IF contamination
- FWHM (L-cut): data outside the FWHM of the cavity
- Diurnal and annual modulation

Contamination - Histogram



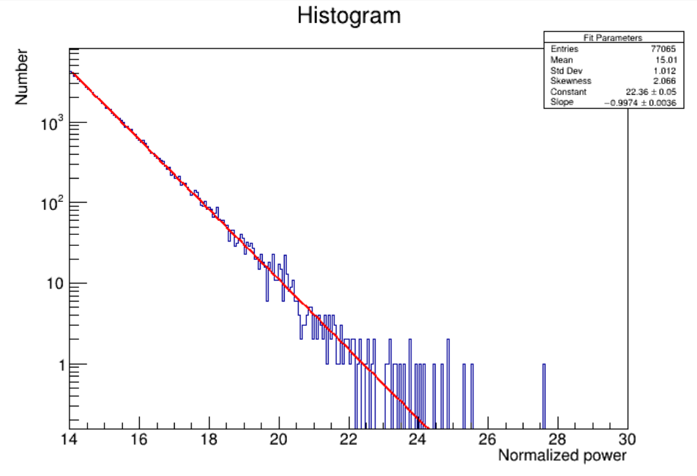
Contamination - intermediate frequency (IF) - expected to be flat

Triggers that survived all the cuts



Normalized power vs frequency - 77065 triggers remaining

Histogram



Remaining triggers

Cold axion flow - 1

- The total energy of an axion E_a is,

$$E_a = \hbar\omega = m_a c^2 + \frac{1}{2} m_a \left(\vec{v} \cdot \vec{v}\right). \tag{3}$$

Here, $\vec{v}$ is the axion's velocity in detector's frame of reference.

- This can be written as,

$$\vec{v} = \vec{v_a} - \vec{v_D}. \tag{4}$$

Here, $\vec{v_a}$ is the axion's velocity in galaxy's reference frame, and $\vec{v_D}$ is the velocity of the detector.

- The detector's velocity is given by,

$$\vec{v_D} = \vec{v_\odot} + \vec{v_o} + \vec{v_r} \cos\lambda. \tag{5}$$

Cold axion flow - 2

- Because of the motions of Earth relative to the axion flow $\rightarrow$ Doppler shift $\rightarrow$ frequency changes with time.
- Differentiate E_a with time,

$$\frac{df}{dt} = \frac{m_a}{h}\left[(\vec{v}_a - \vec{v}_\odot) \cdot \left(\frac{d\vec{v}_o}{dt} + \frac{d\vec{v}_r}{dt}\right)\right]. \tag{6}$$

- Are the remaining triggers persistent ?
- Frequency difference of any two triggers - Δf_t, difference in time when these two frequencies were scanned - ΔT_t.
- Would a trigger satisfy the condition below?

$$\Delta f_t \leq \frac{\delta f}{\delta t} \Delta T_t. \tag{7}$$

- If yes, how many times?

Persistence

- I define the Persistence ratio, Υ, as,

$$\Upsilon = \frac{\text{number of doppler allowed triggers}}{\text{number of times a given frequency is scanned}}. \quad (8)$$

- Kept $\Upsilon \geq 0.3$, threw away the rest $\rightarrow$ No persistent trigger found.
- Exclude the frequency range scanned $\rightarrow$ at what confidence level (CL)?
- Go back to exponential distribution:

$$P_{CL} = \int_0^N dp \frac{1}{\sigma} e^{-\frac{p}{\sigma}} \sim 0.95. \quad (9)$$

- At $N = 3\sigma$, $P_{CL} = 95\%$.
- But, $\sigma = kTb$.

Exclusion limit - 1

- The effective signal power I saw would become,

$$P_E = P_T - N = 11\sigma. \tag{10}$$

for one scan.

- But we look for 30 % persistence.
- If a signal is scanned $n = 20$ times, in how many scans do we expect the axion?

$$m = 0.3n = 6\,\mathrm{scans} \tag{11}$$

- Binomial distribution,

$$f(m; n, p) = \binom{m}{n} p^m (1-p)^{(n-m)} \tag{12}$$

Exclusion limit - 2

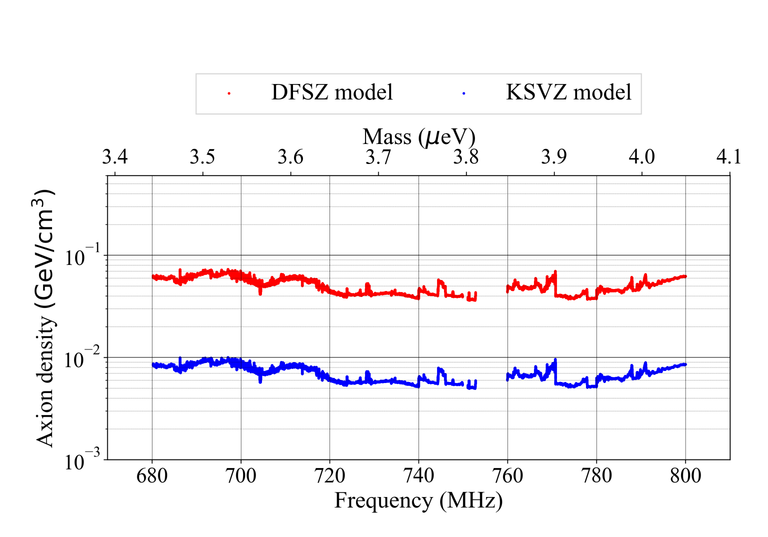
- The effective threshold reduces to, $P_E = 12\sigma$
- Power due to axion conversion can be related to noise temperature measured,

$$P_E \eta = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C_{010} Q_L. \tag{13}$$

- Here, η is the effective contribution, which includes,
  - 50 % of the power gets deposited in the walls
  - All of the axion power is not in a single bin
  - Axion signal may not exactly be at the resonant frequency of the cavity.
- I calculate the limit on density as,

$$\frac{\rho}{\rho_a} = \left(\frac{12\eta k T b}{3.3 \times 10^{-23}\mathrm{W}}\right)\left(\frac{0.4}{C_{010}}\right)\left(\frac{0.36}{g_\gamma}\right)^2\left(\frac{740\,\mathrm{MHz}}{f}\right)\left(\frac{45000}{Q}\right). \tag{14}$$

Exclusion limit - 3



Exclusion limit at a 95 % CL.

Exclusion limit - 4

- Limit set on the density of the cold axion flow with a narrow line-width.
  - I set the limit on the worst density - maximum value of ρ.
  - Density limits:
    - ≥ 0.0728 GeV/cm^3 - DFSZ model
    - ≥ 0.0010 GeV/cm^3 - KSVZ model

  at a 95 % CL.

Summary

- Run 1B
  - Studied the synthetic axion injections and removed them from the data.
  - Removed contamination both RF and IF. Origin of IF leakage ?
  - Cuts on the data
  - Studied the diurnal and annual modulation of an axion signal - more on this later.
  - No axions were found ☹ $\rightarrow$ Exclusion limit ☺.
  - Multi-resolution analysis - Chelsea

Thank you !