

Department of Physics and Astronomy

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**UCL**

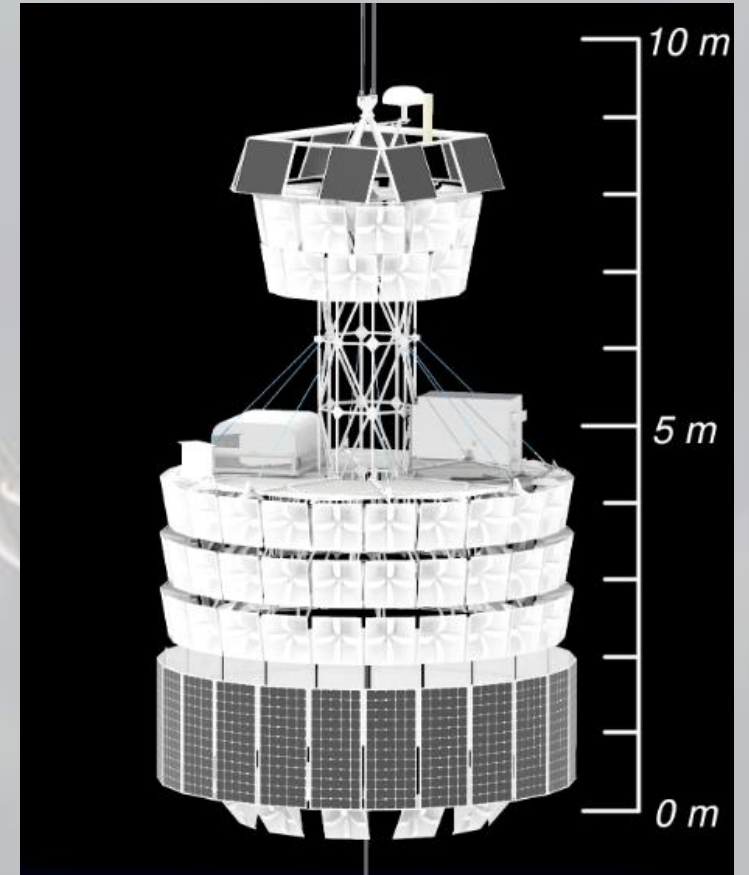


# Digital processing and filtering in the PUEO experiment

IOP HEPP  
Talk 2025

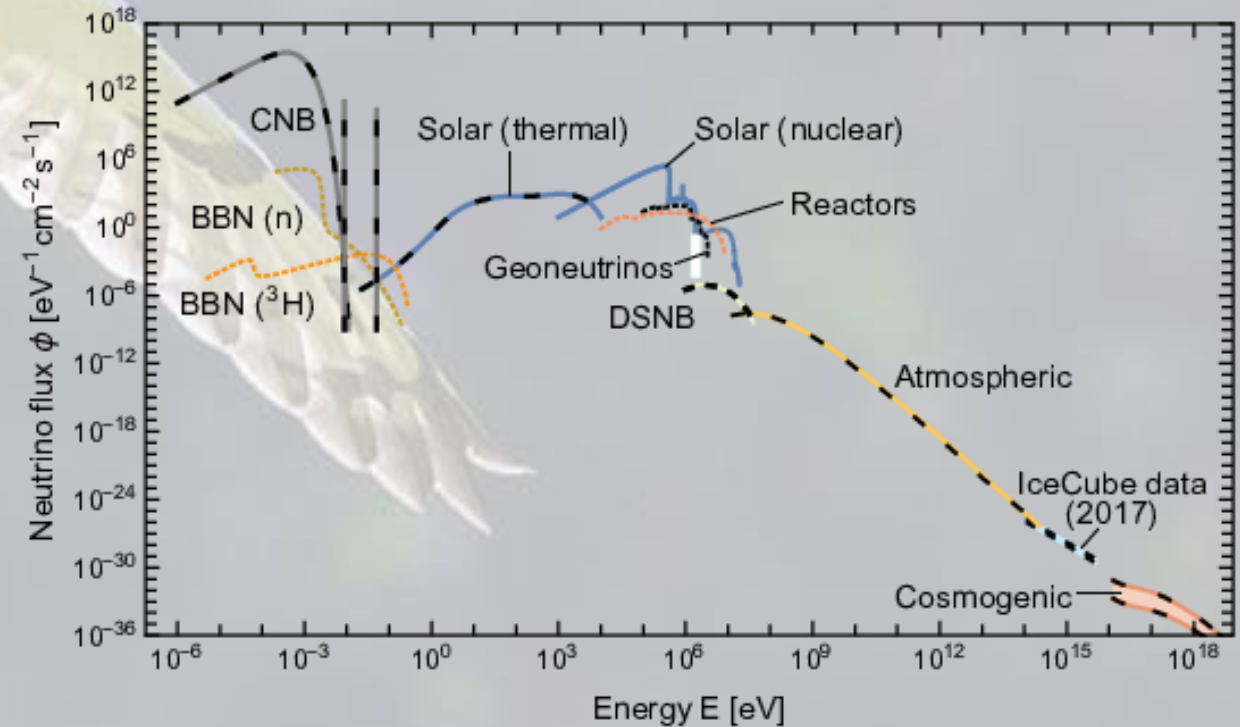
# Payload for Ultra-high Energy Observations

- PUEO aims to detect the first EeV neutrinos.
- UHE neutrinos produce a detectable radio pulse in ice
- PUEO is an aerial payload suspending radio antenna above Antarctica
- Flying over Antarctic this winter this year for up to 60 days.



PUEO payload rendering,  
PUEO Collaboration

- Cosmic rays with energy exceeding EeV have been detected by Auger, AGASA and HiRes.
- PeV neutrinos have been detected by IceCube and recently the highest energy neutrino event has been detected by KM3NeT.



Grand Unified Neutrino Spectrum, from [arXiv:1910.11878](https://arxiv.org/abs/1910.11878), E.Vitagliano, I. Tamborra, and G.Raffelt

# Ultra-High energy events

- Bottom-up models are the favoured source of Ultra-High Energy (UHE) particles.
- Possible models are possible due extreme gravitational forces in celestial bodies.
- Diffusive shock acceleration either side of a plasma shockwave.
- Explosive growth in electric fields can also accelerate particles.

- The celestial objects capable of acceleration to EeV are supernovae, supermassive black holes and neutron star.
- Stationary sources include Active Galactic Nuclei (AGN).
- Transient sources include Gamma Ray Bursts (GRB), which can occur during supernovae or neutron star mergers.

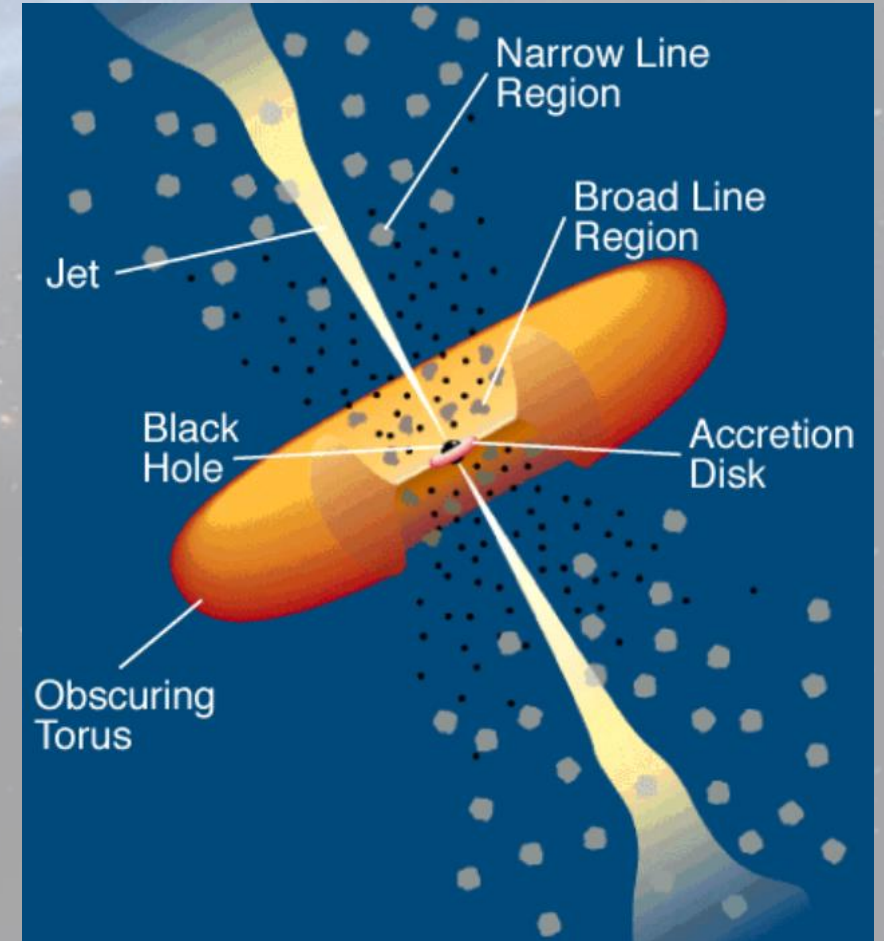


Diagram of the AGN model, Nasa, C.M. Urry and P. Padovani

# Problem with UHECR's

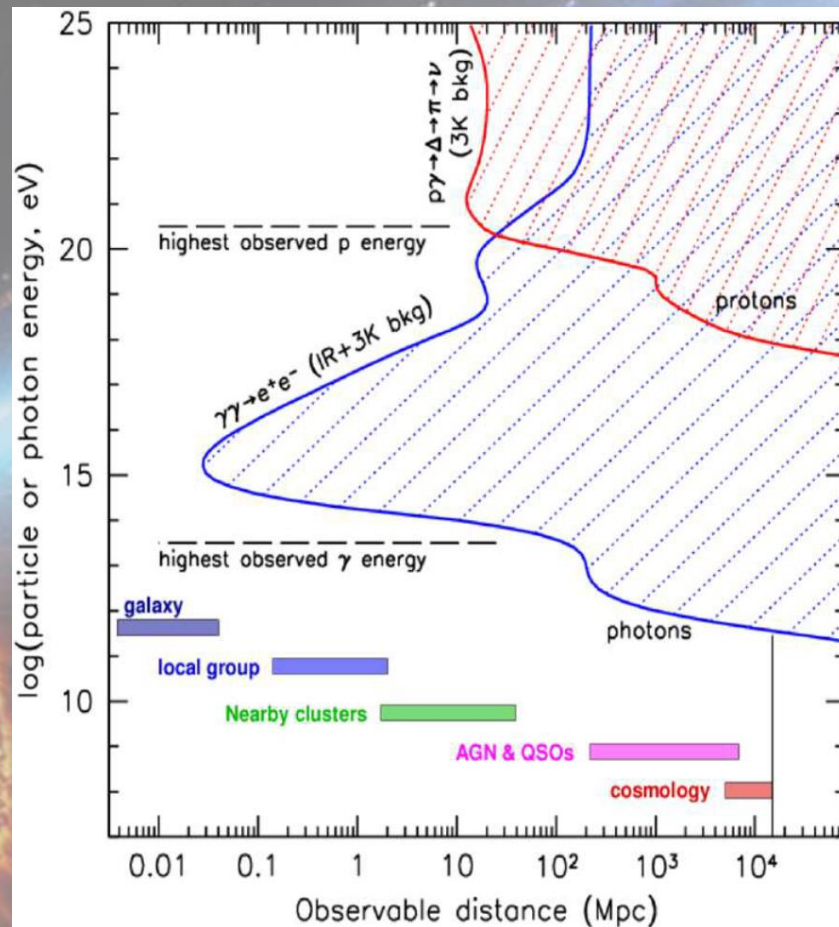
- Sources of UHECRs are extra-galactic and typically over  $\sim 100$  Mpcs from Earth.
- Interstellar magnetic fields alters the energy and direction of CRs.
- In the 1960's Greisen, Zatsepin and Kuzmin predicated protons of sufficiently high energies can interact with Cosmic Microwave Background Radiation (CMBR).
- This phenomena called the GZK effect and is possible for heavier nuclei and Extragalactic Background Light (EBL).

# GZK Effect

- Protons with energy exceeding  $\sim 50$  EeV internal structure is disrupted when interacting a CMBR photon ( $\sim 2.7$ K).
- This produces a  $\Delta$  baryon which decays to a pion and nucleon.



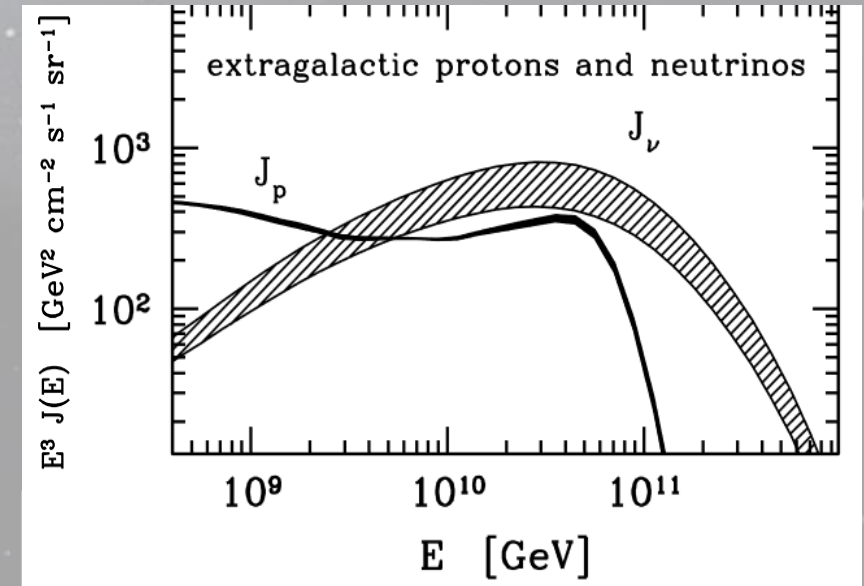
- This results in either, the proton losing 20% of it's energy or complete photodisintegration of the cosmic ray.
- The GZK volume for observable UHECR's is  $\sim 100$  Mpc



Shaded regions are not observable, Peter Gorham

# Neutrinos!

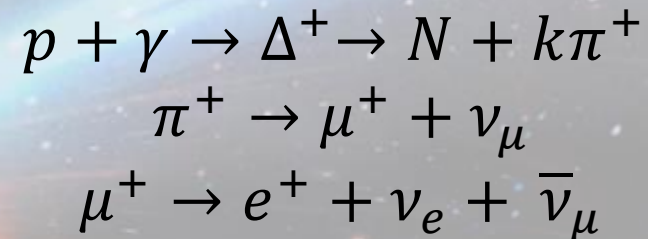
- Neutrally charged and incredibly unreactive, neutrinos will traverse space preserving energy and pointing directly back to their sources.
- The UHE neutrino flux on Earth is predicated to be larger than other multi-messengers. Especially at super GZK energies.



From [arXiv:astro-ph/0506698](https://arxiv.org/abs/astro-ph/0506698), Markus Ahlers, Andreas Ringwald and Huitzu Tu

# Neutrino production

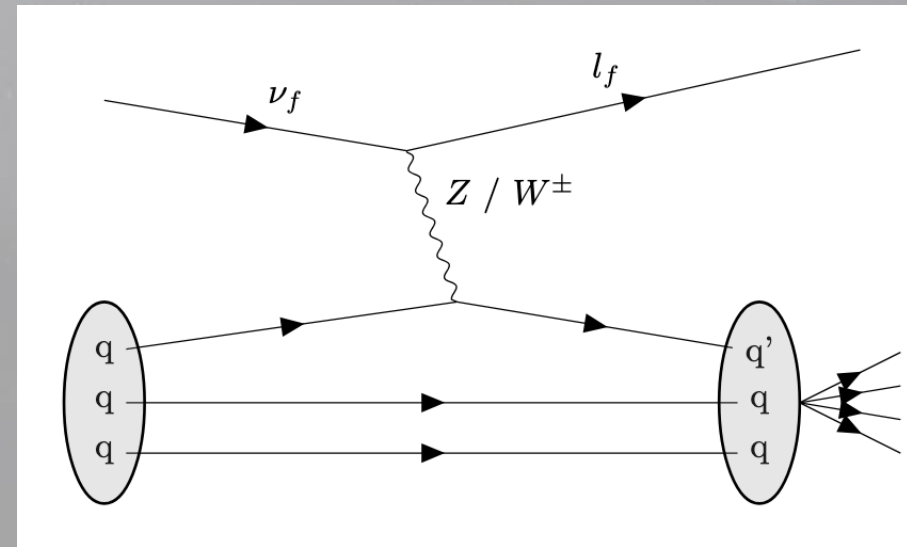
- Neutrinos are produced during the photomeson process of ultra-relativistic protons with radiation.



- This can occur within the source (astrophysical) or by the GZK effect with CMBR (cosmogenic).
- Individual neutrinos carry ~5% of the parent particles energy.

# Interaction on Earth

- Neutrinos deep-inelastically scatter off nuclei via a  $W^\pm$  charged current or  $Z^0$  neutral current channel.
- The CC channel produces an ultra-relativistic charged lepton. This may be followed by an electromagnetic shower.
- Both results in the breakup of the target nuclei and a hadron shower (followed by an EM shower).
- It is this shower that produces a detectable radio pulse via the Askaryan effect.



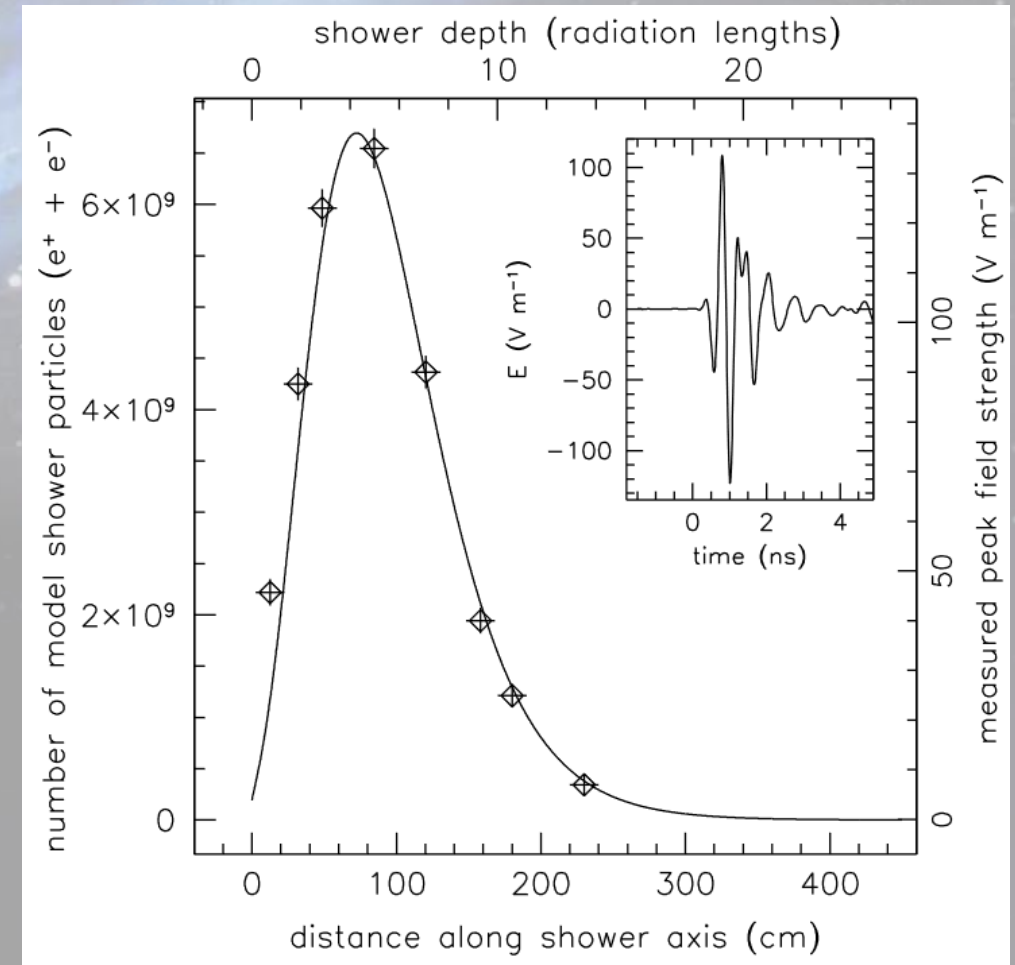
# Shower development

- Electrons are pulled into the shower from surrounding material.
- Positrons are annihilated in flight.
- This leads to a net 20-30% excess of negative charge build up in the EM shower.
- Charged particles moving faster than the local speed of light emit Cherenkov radiation.

# Askaryan Effect

- Wavelengths greater than dimensions of the compact shower add coherently.
- Shorter wavelengths add incoherently.
- In this coherent regime the intensity of radiation is proportional the excess charged particles squared.
- Emitted radiation creates a vertically polarised Cherenkov cone.

- For EeV neutrinos, this radiation will generate a detectable radio pulse.
- The Askaryan effect is only a viable at the largest energies within in the coherent regime (typically 30cm-1m).
- This is where the radiation strength is many orders of magnitude greater.



From [arXiv:hep-ex/0011001](https://arxiv.org/abs/hep-ex/0011001), SLAC

# Antarctica

- Neutrino flux and cross section are both extremely low on Earth.
- A continentally large, dense and radio transparent location with minimal radio background is required.
- By elevating a radio detection payload above Antarctica, we can maximise the instantaneous detection volume.

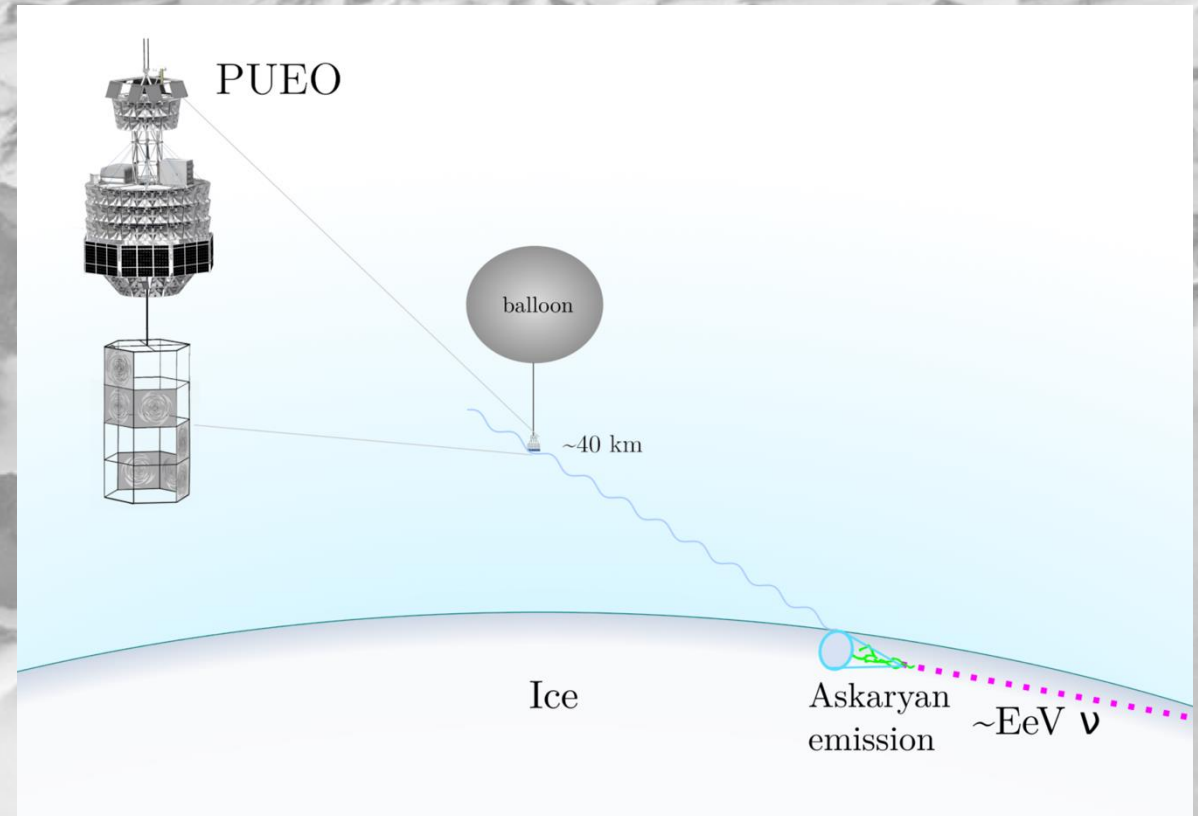
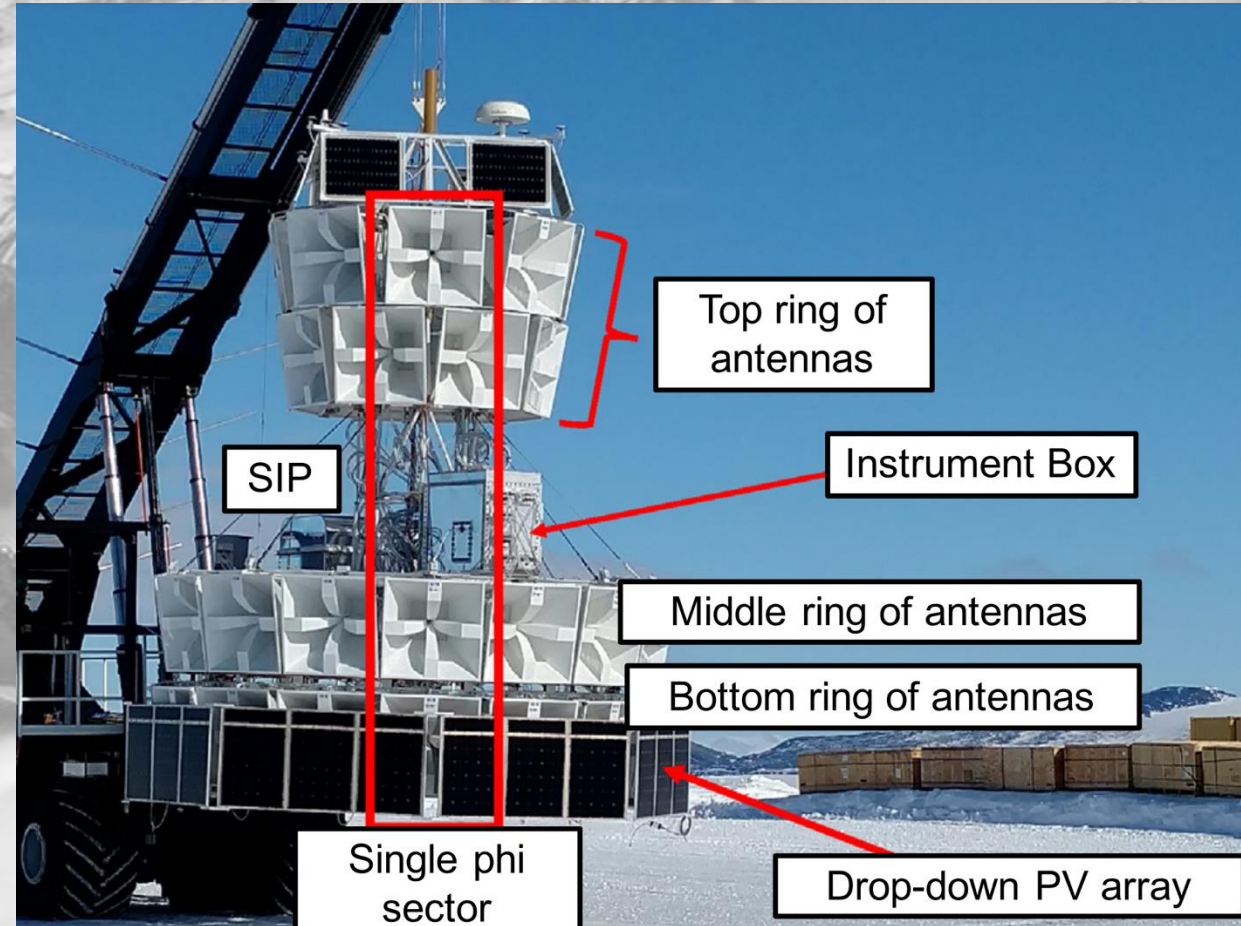


Diagram of experimental setup, PUEO Collaboration

# ANITA

- The ANtarctic Impulsive Transient Antenna is PUEO's predecessor
- ANITA's final flight was equipped with 48 horn antennas
- ANITA's main instrument was sensitive to 200-1200 MHz



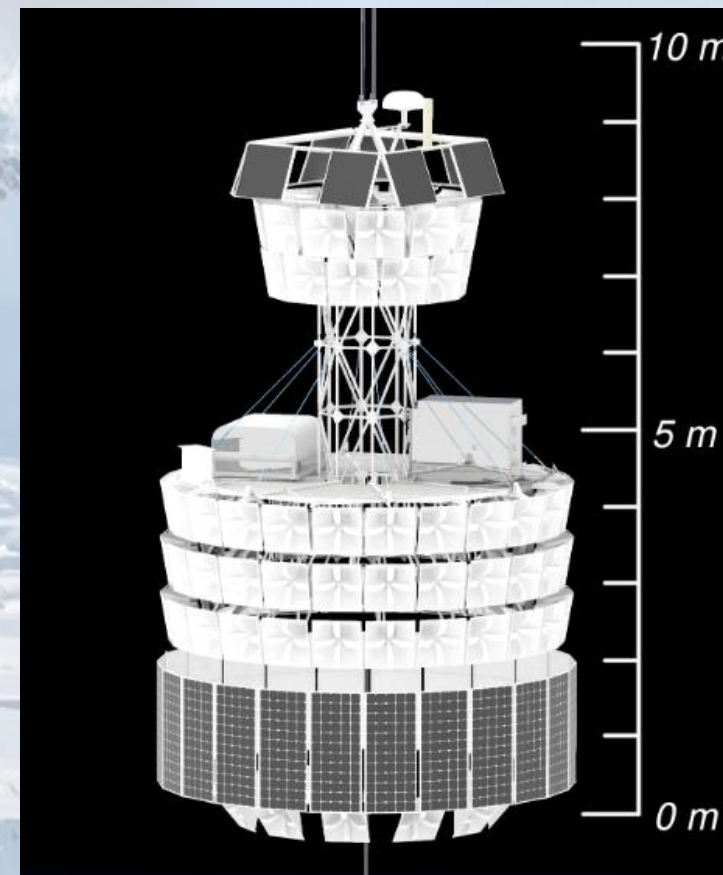
Labelled picture of ANITA-IV, PUEO Collaboration

# ANITA Results

- ANITA had 4 ~1-month flights over 10 years
- 71 UHECR events were detected
- All flights had one surviving candidate on backgrounds ~1
- No conclusive UHE neutrino observations

# PUEO overview

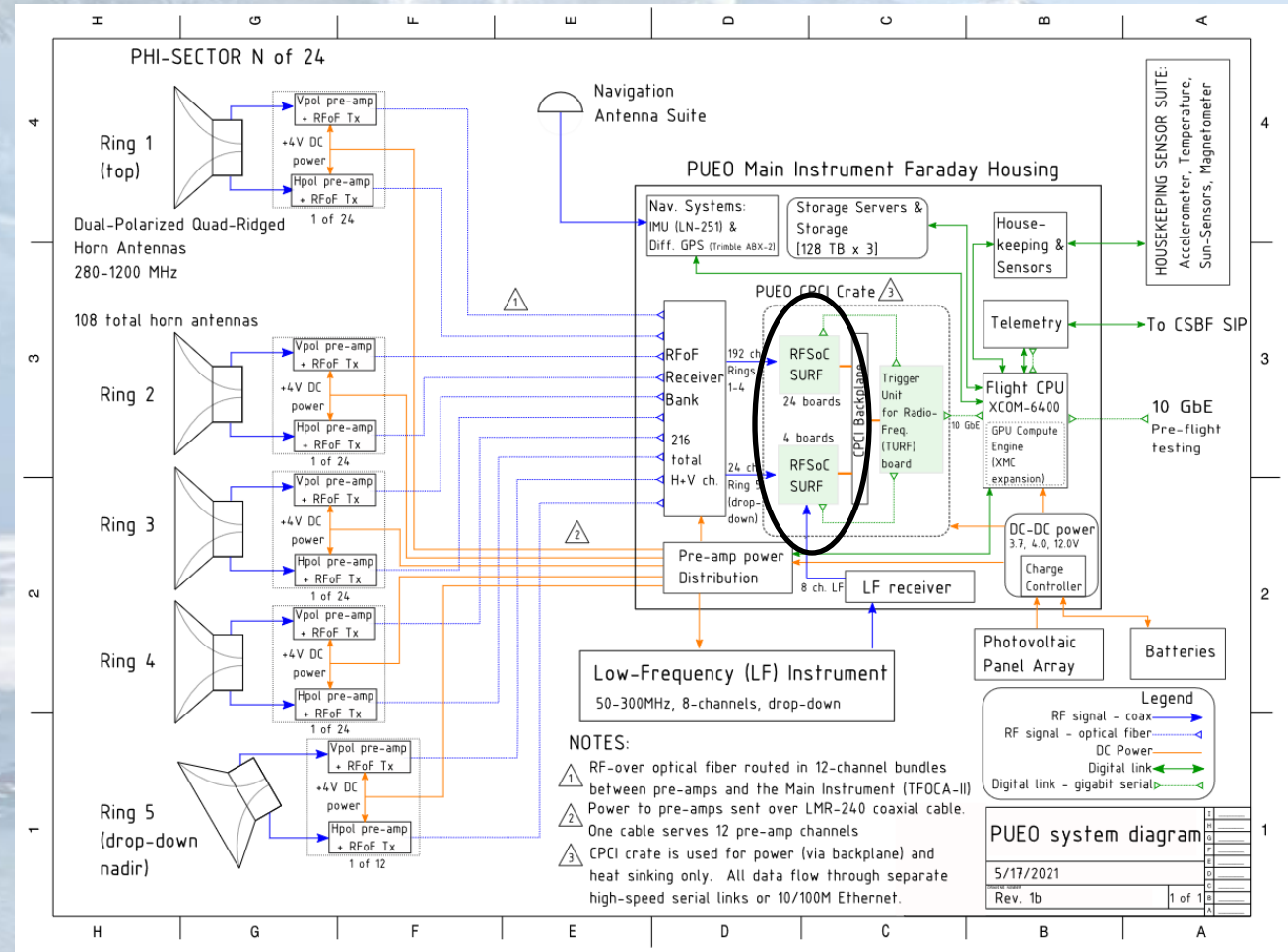
- The main instrument is sensitive from 300 to 1200 MHz.
- 96 antennas with a complete 360-degree coverage.
- Equipped with commercially available RFSoc technology and capable of real-time digital processing and trigger analysis.



PUEO payload rendering, PUEO Collaboration

# Digital Processing

- Signals will pass from the antenna rings through a receiving bank into the Radio Frequency System on Chip device (RFSoc).
- This FPGA technology is where a digital notch filter and AGC core is located.
- The flight will use a ZC28DR but testing is predominantly done with a ZCU111.

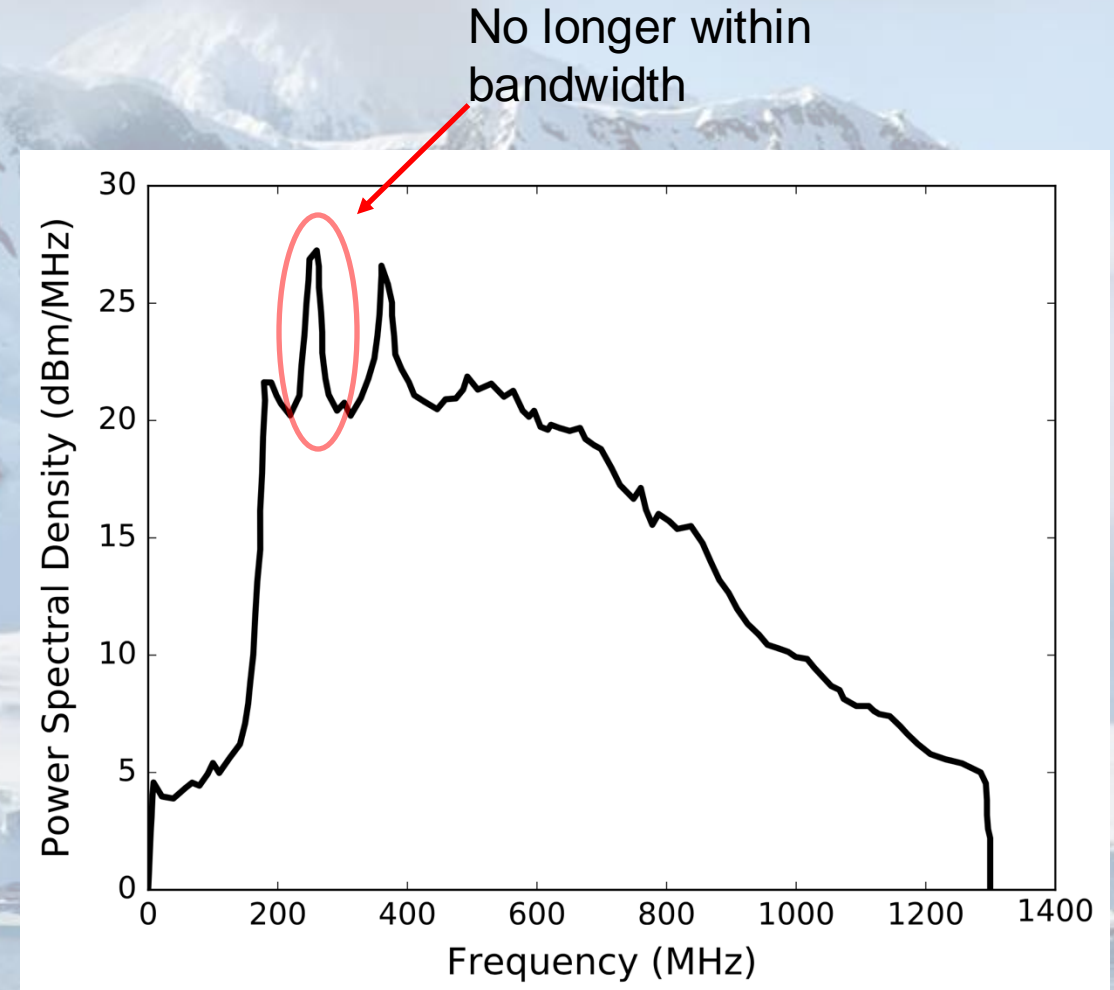


PUEO System Diagram, PUEO Collaboration

- Each Antenna has 2 channels. A Vpol and a Hpol. 192 channels in total.
- PUEO will operate with a sample rate of 3 GHz (Nyquist of 1500MHz).
- Data is recorded in clocks of 8 samples.
- Each capture is 64 clocks.
- The two filters will be placed in cascade.

# Digital Notch Filter

- PUEO has minimal background radio.
- However, known anthropomorphic radio signals are found at 375 and 460 MHz.
- This CW noise can be filtered out during the triggering phase with a digital notch filter.



Average power spectral density from ANITA-III payload, PUEO Collaboration

# Digital Notch Filter

- This is performed by a biquad filter with transfer function

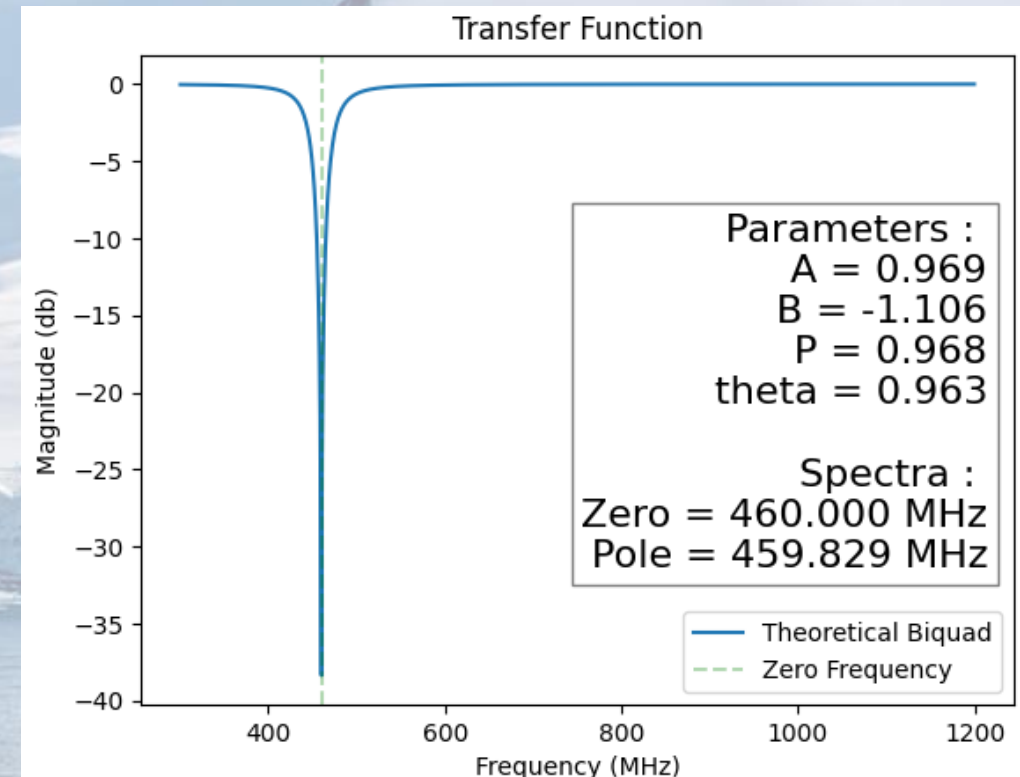
$$H(z) = \frac{A + Bz^{-1} + Az^{-2}}{1 - 2P\cos(\theta)z^{-1} + P^2z^{-2}}$$

For a notch filter, zero is defined such that,

$$2A\cos(\theta_z) + B = 0$$

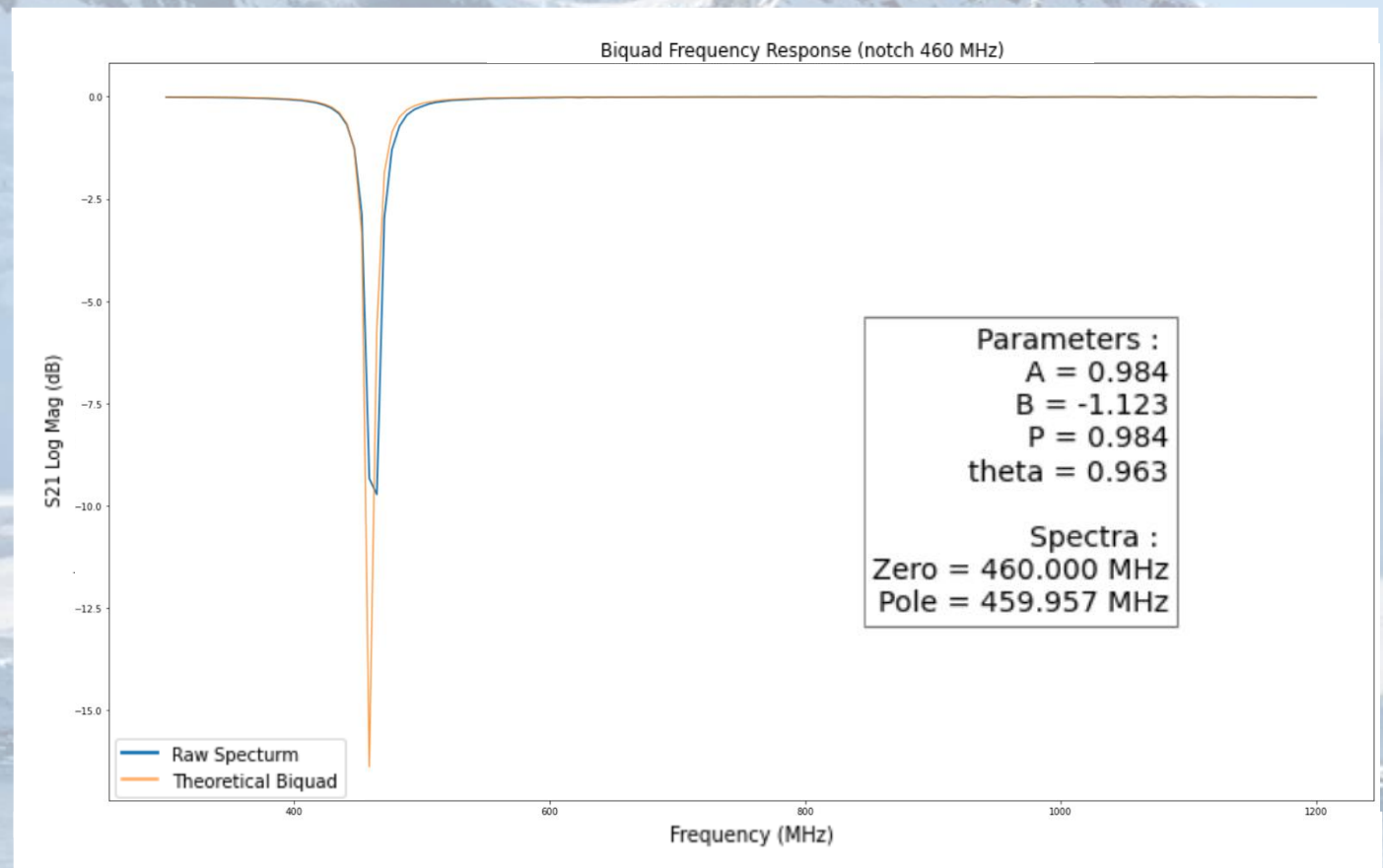
- Notch Transfer function

$$H(z) = \frac{A - 2A\cos(\theta_z)z^{-1} + Az^{-2}}{1 - 2P\cos(\theta_p)z^{-1} + P^2z^{-2}}$$

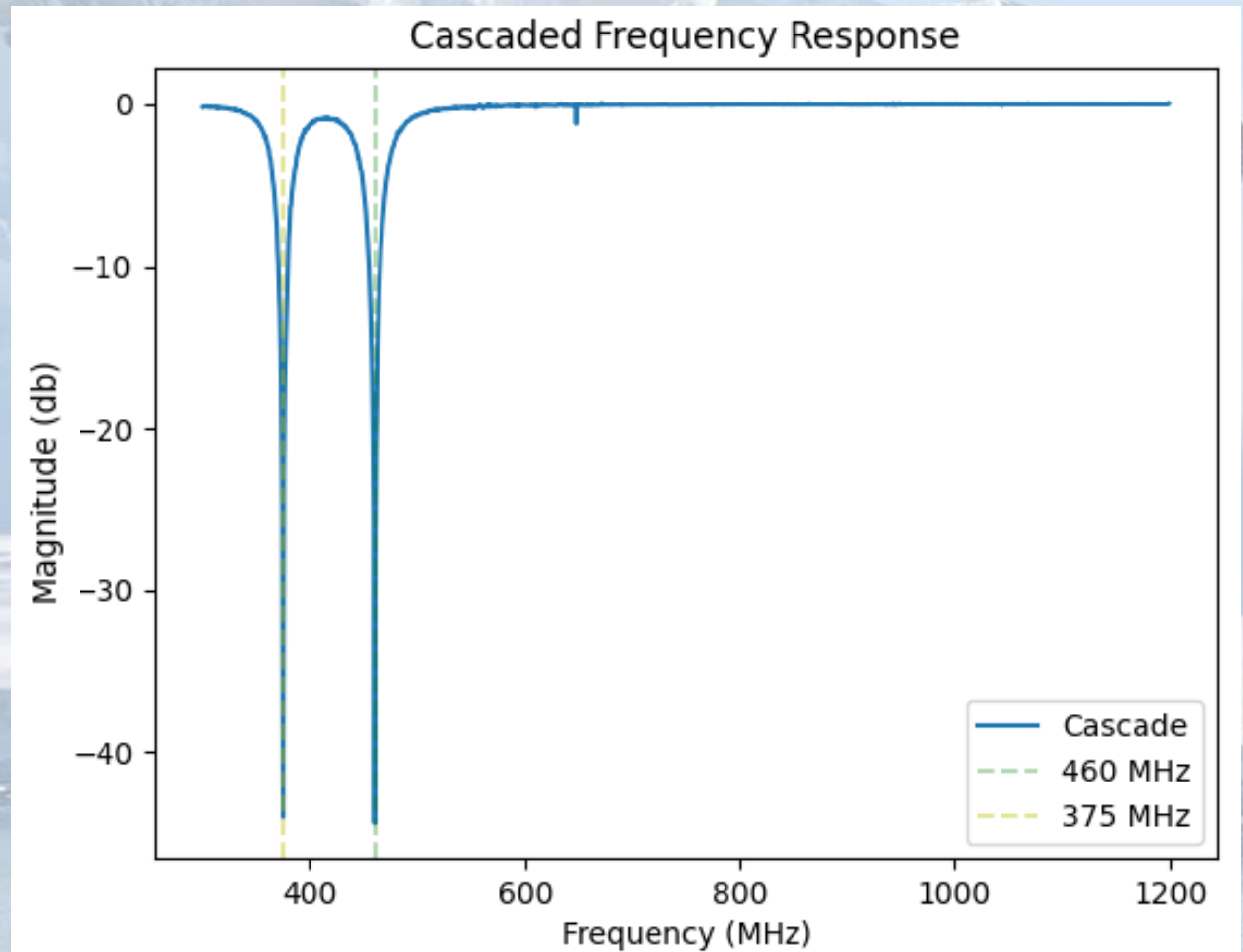


# Performance

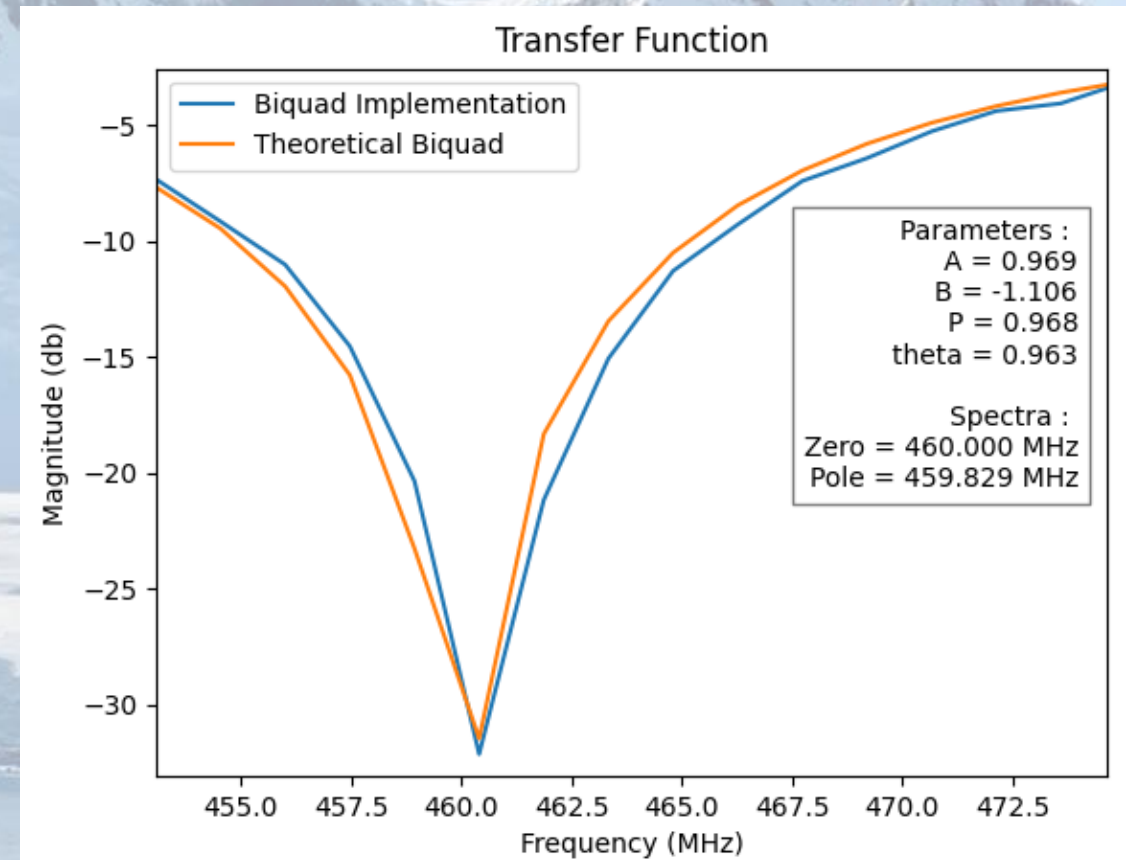
- Performance is a little limited by quantisation.
- Data collection on the test FPGA is limited by sample size and binning.



- Simulating the firmware shows allows better data collection parameters.
- Increasing the sample size to more accurately bin the notch shows a more powerful performance notch.

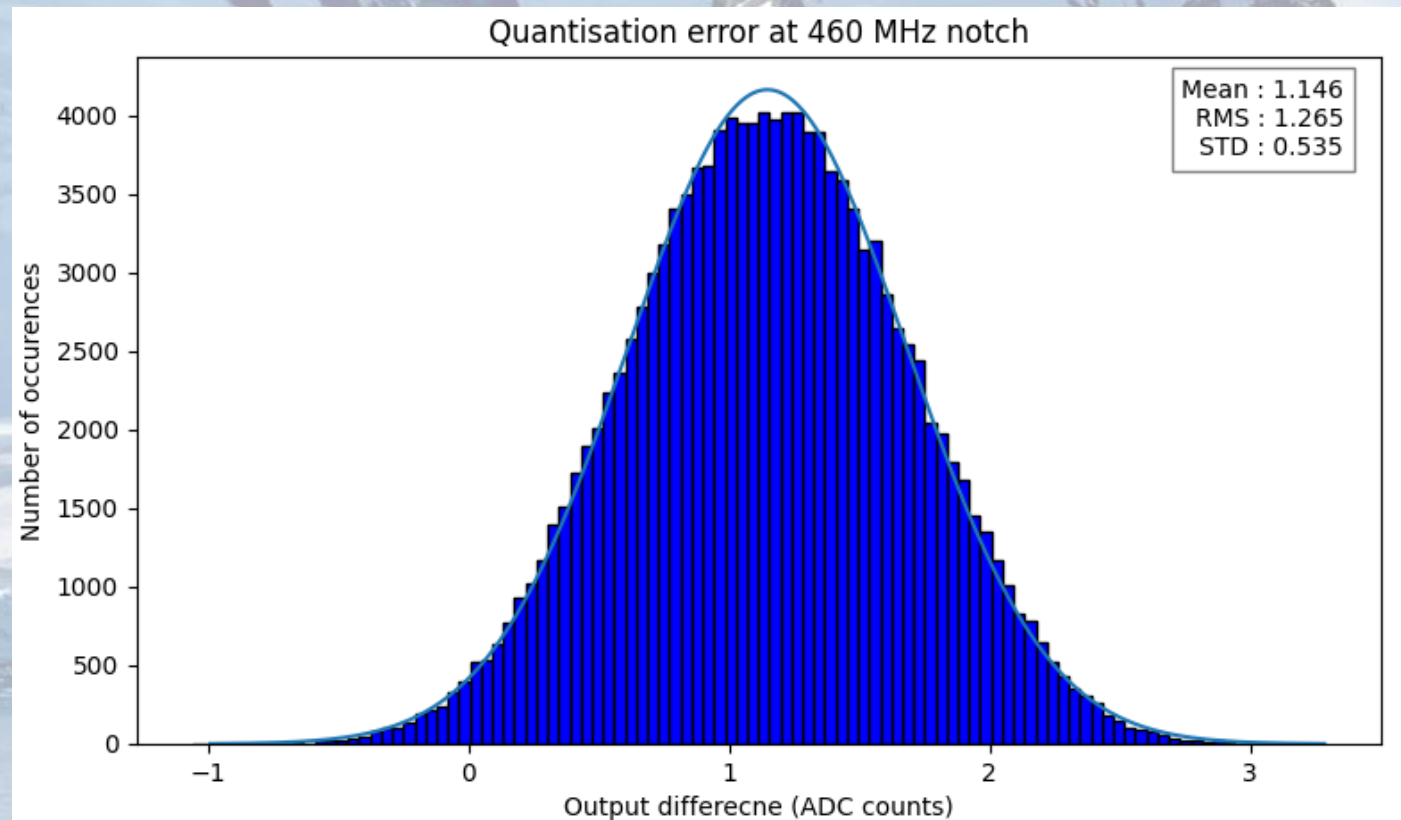


- The biquad implementation of the notch is shifted a few kHz to higher frequencies.
- The desired attenuation region is ~10 MHz wide.
- Within acceptable margins.

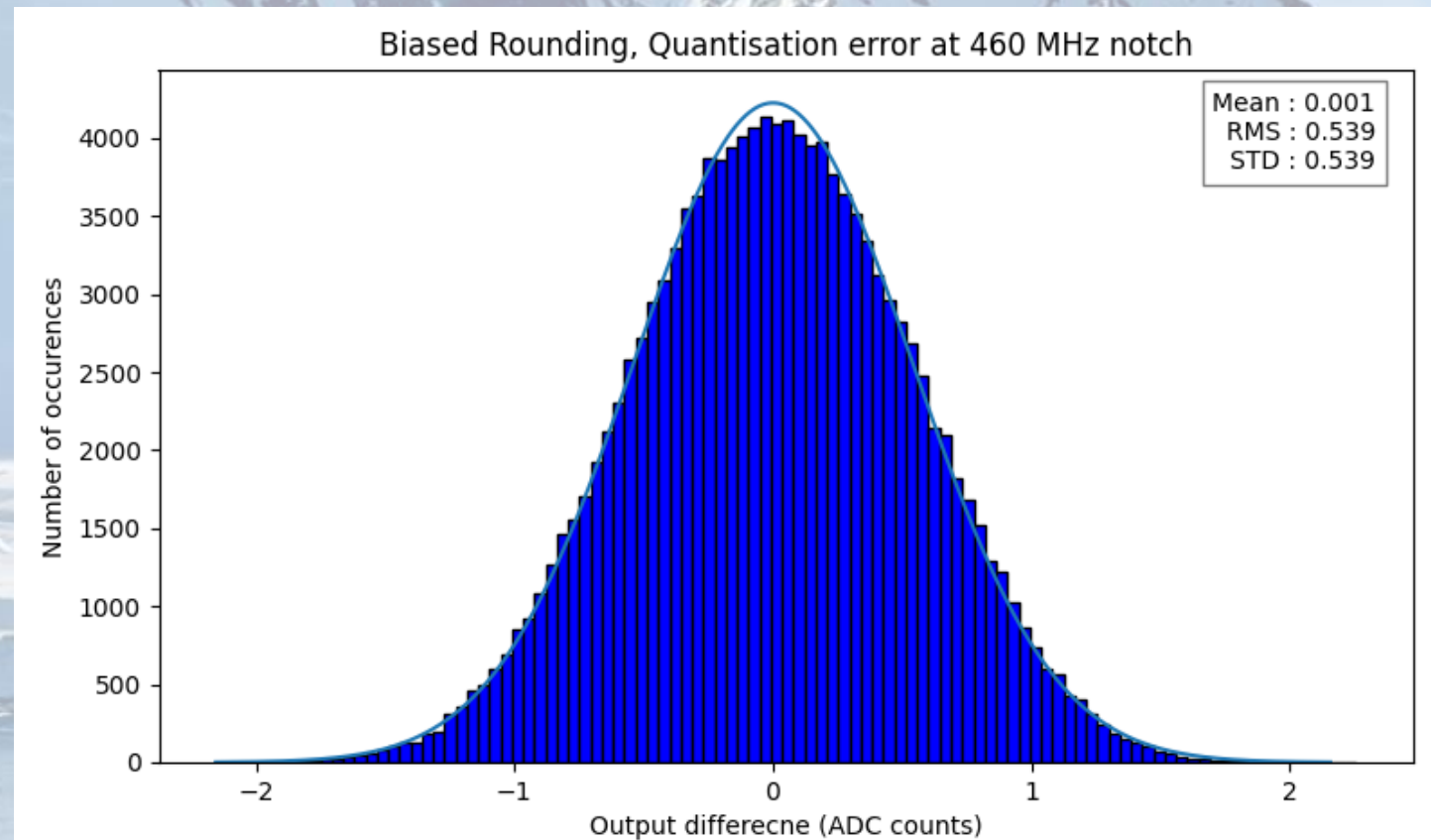


# Quantisation Error

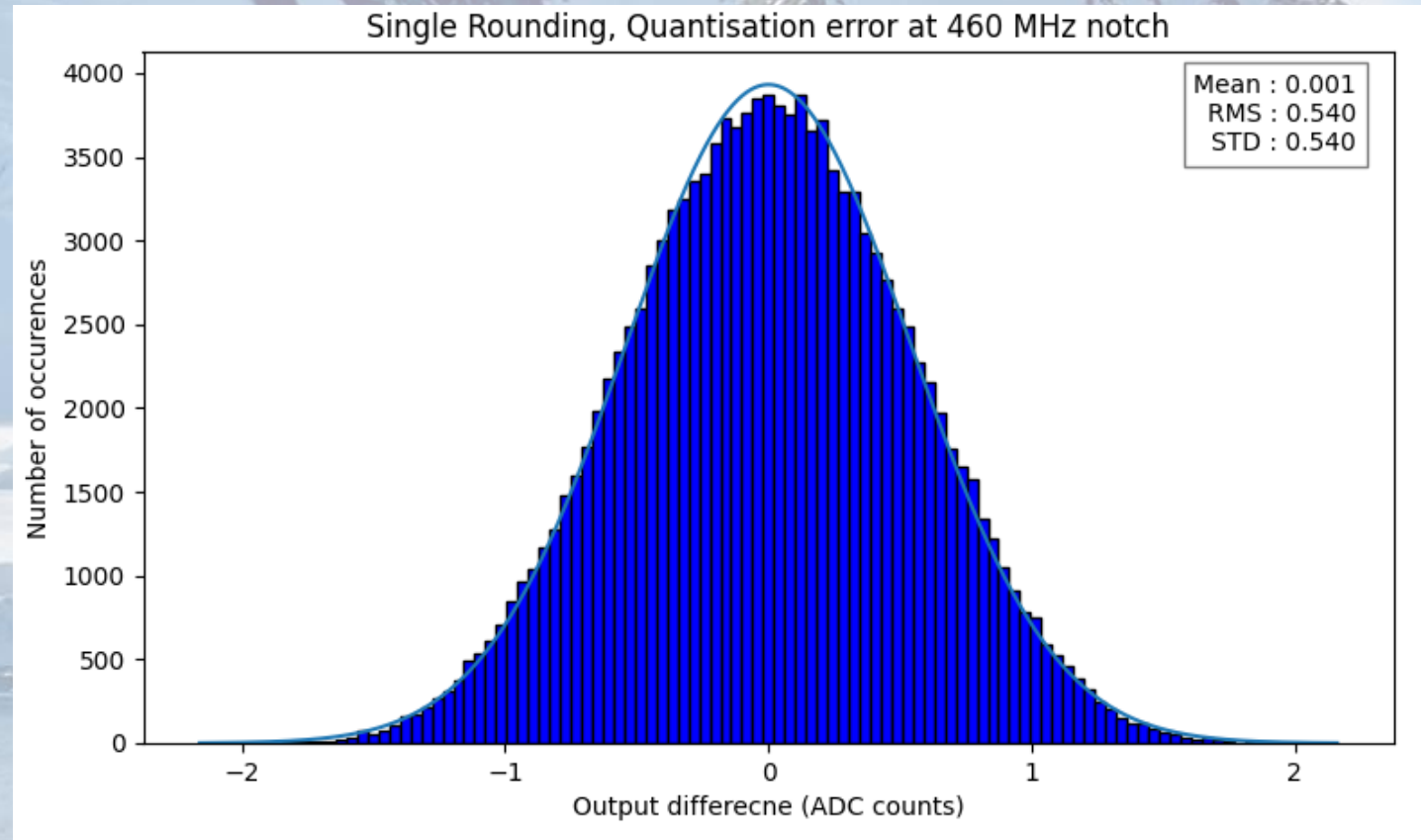
- At each calculation stage there is an associated quantisation error (rounding).
- This is predominantly a symptom of input and outputs bit-width (12-bits).
- Here the average sample is 1.146 ADC counts too small.



- This could be minimised using bias rounding at each stage.
- Effectively this is done by adding  $\frac{1}{2^{(\text{Fractional bit resolution}+1)}}$  after each implementation stage



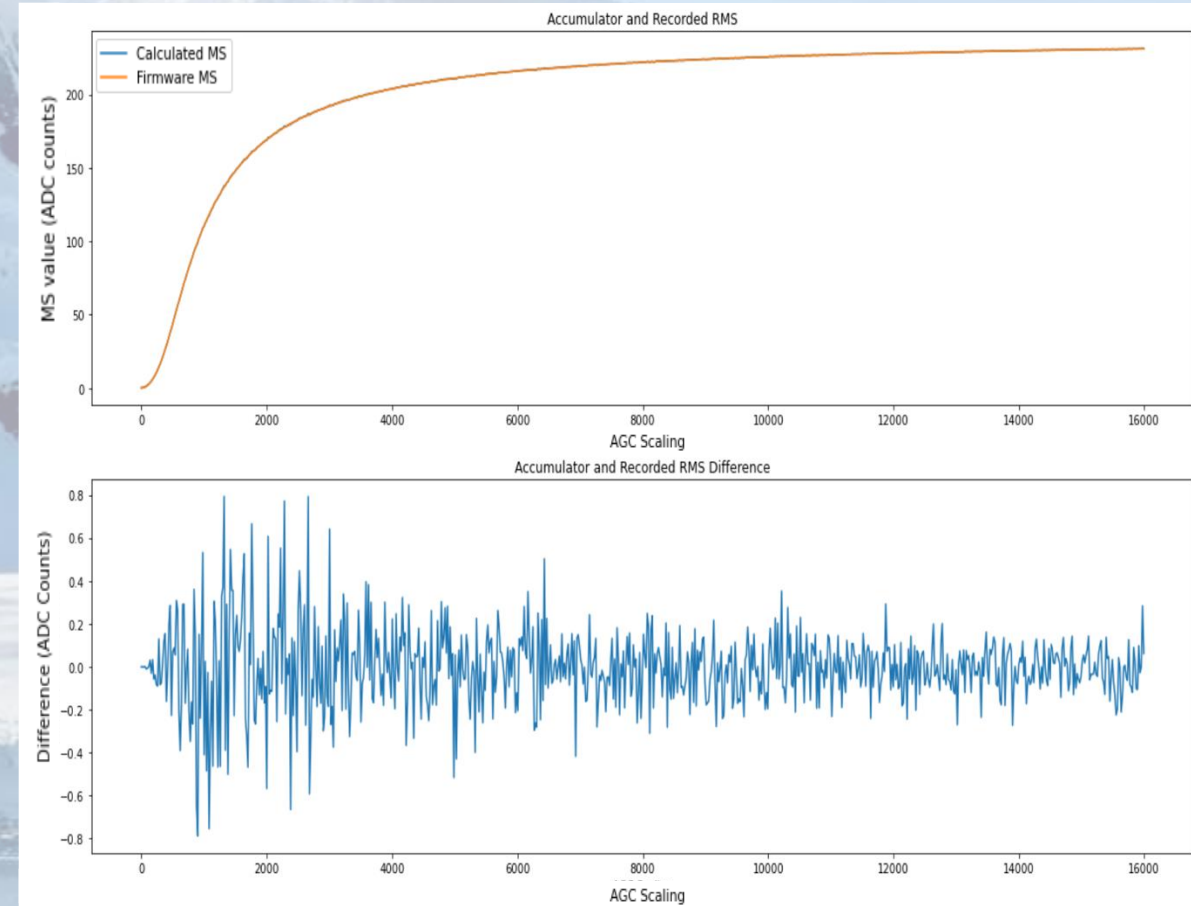
- A similar result can be achieved by simply adding 1.146 (the quantisation error for the 460 MHz notch) at the end.
- Sadly, this the result doesn't have this fractional bit width.
- Adding 1 could act as a nice compromise



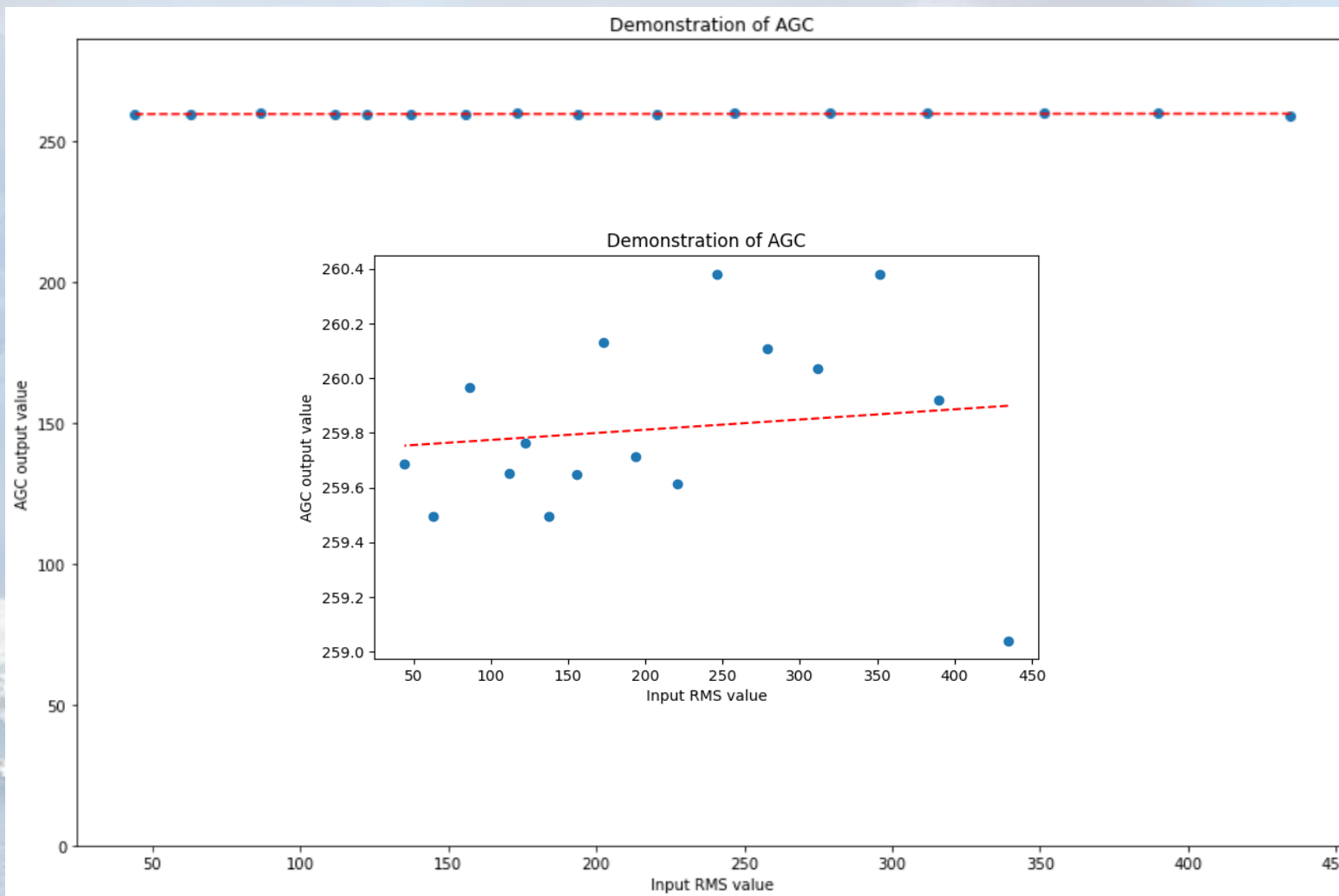
# Active Gain Control

- An active gain control is required to minimise the strain on limited storage.
- 12-bit filter outputs are truncated down to 5 bits.
- To minimise information loss, one must automatically fill the new bit width.
- Events must be attenuated down or gain up appropriately to fill the bit-width.

- RMS needs to be scaled down to  $\frac{1}{4}$  of the new bit-width. I.e. 4 standard deviations of a Gaussian fills the bit-width.
- The RMS is calculated by:
  1. Accumulating the square of one random sample per clock.
  2. Converting the tail function of inputs to the standard deviation.



Computationally cheap MS and calculated MS



Tested AGN Core. All inputs lead to the same RMS

# Conclusions

- The precise programmed parameters of the biquad need to be finalised.
- The main instrument enclosure is currently going through testing
- PUEO is scheduled to fly the winter (Antarctic summer).



Sources must obey:

- Hillas Condition - Sources magnetic field must be strong enough to contain UHE particles until they are accelerated to UHE's.

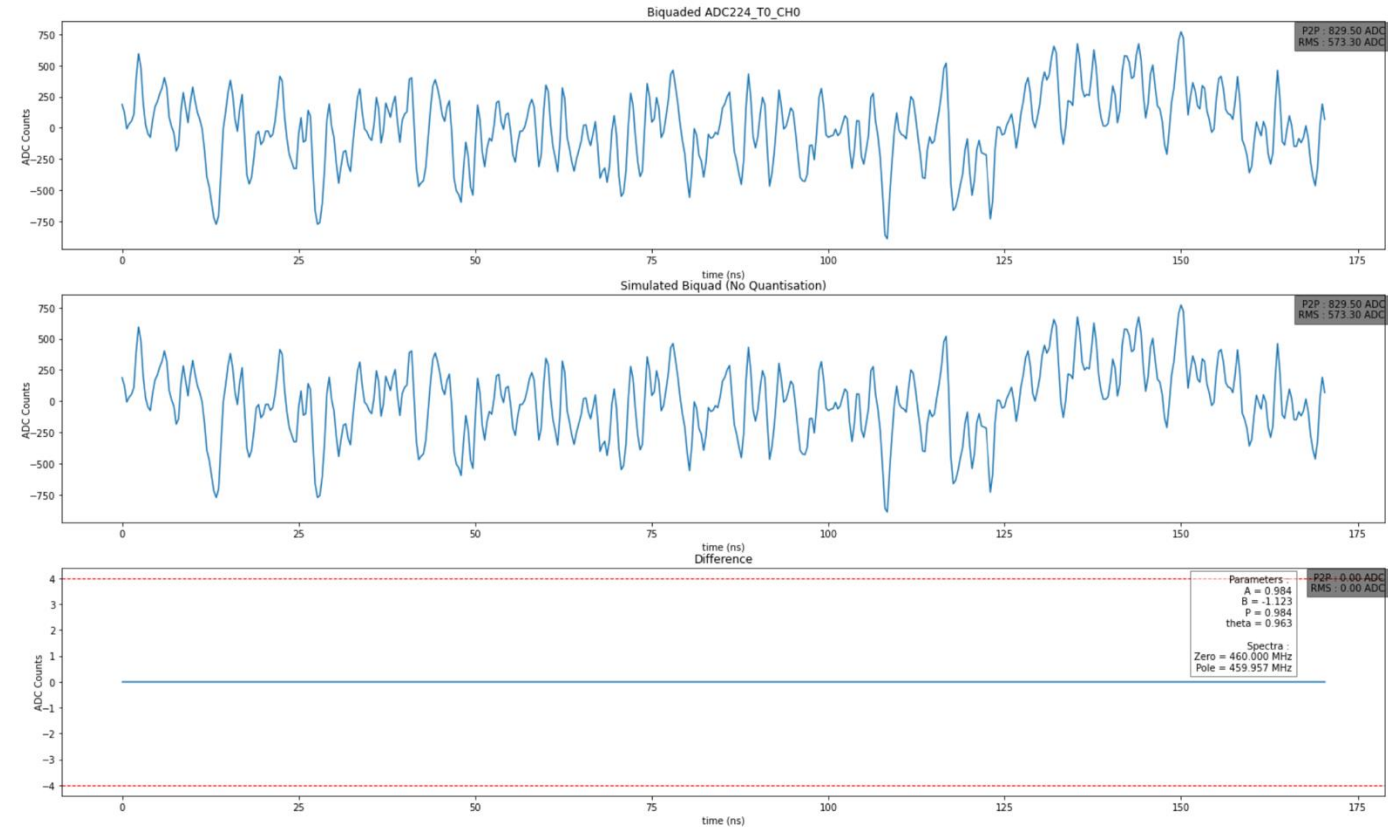
$$B > \frac{E}{ZeR_{source}}$$

- Blandford Condition - Sources require a minimum luminosity

$$L \gtrsim 3 \times 10^{42} \text{ erg/s} \frac{\gamma^2}{\beta} \left( \frac{E/Z}{5 \times 10^{18} \text{ eV}} \right)^2$$

# Simulated Biquad

- The simulated biquad is a python program that simulates the FPGA's biquad implementation. Mainly used to debug the firmware
- Except in the case of overflow it works perfectly



# PALS

- Each of PUEO's main storage unit ('PALS') consists of 6x22TB hard drives. There are 2 in total.
- Designed to attach to the main instrument in a grab and go manner.

