Isotropic Microwave Emission from Extensive Air Showers

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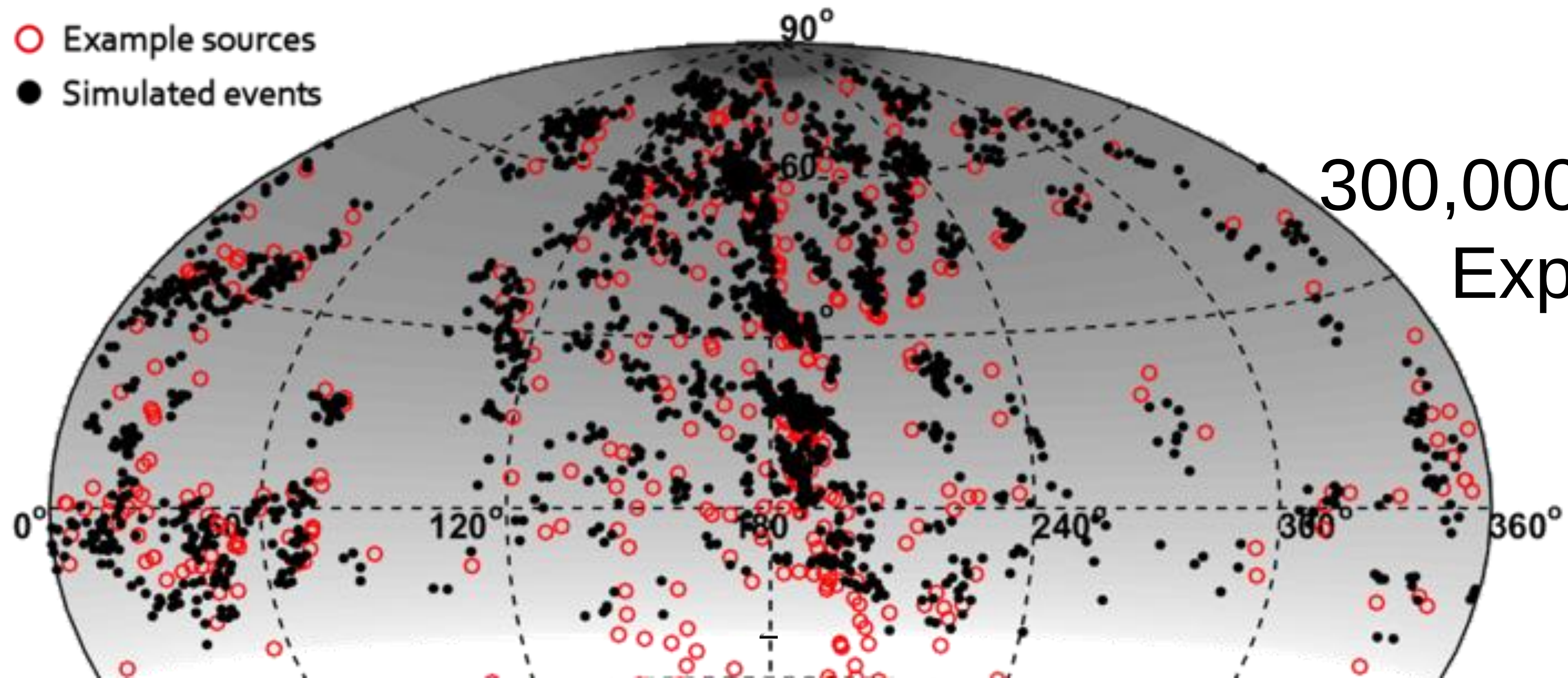
UHECR Future Requirements

1.) Origin of Cosmic Rays?
2.) Composition of Cosmic Rays?

Larger Event Sample!

but a larger sample of events must also be
<u>high quality data</u>

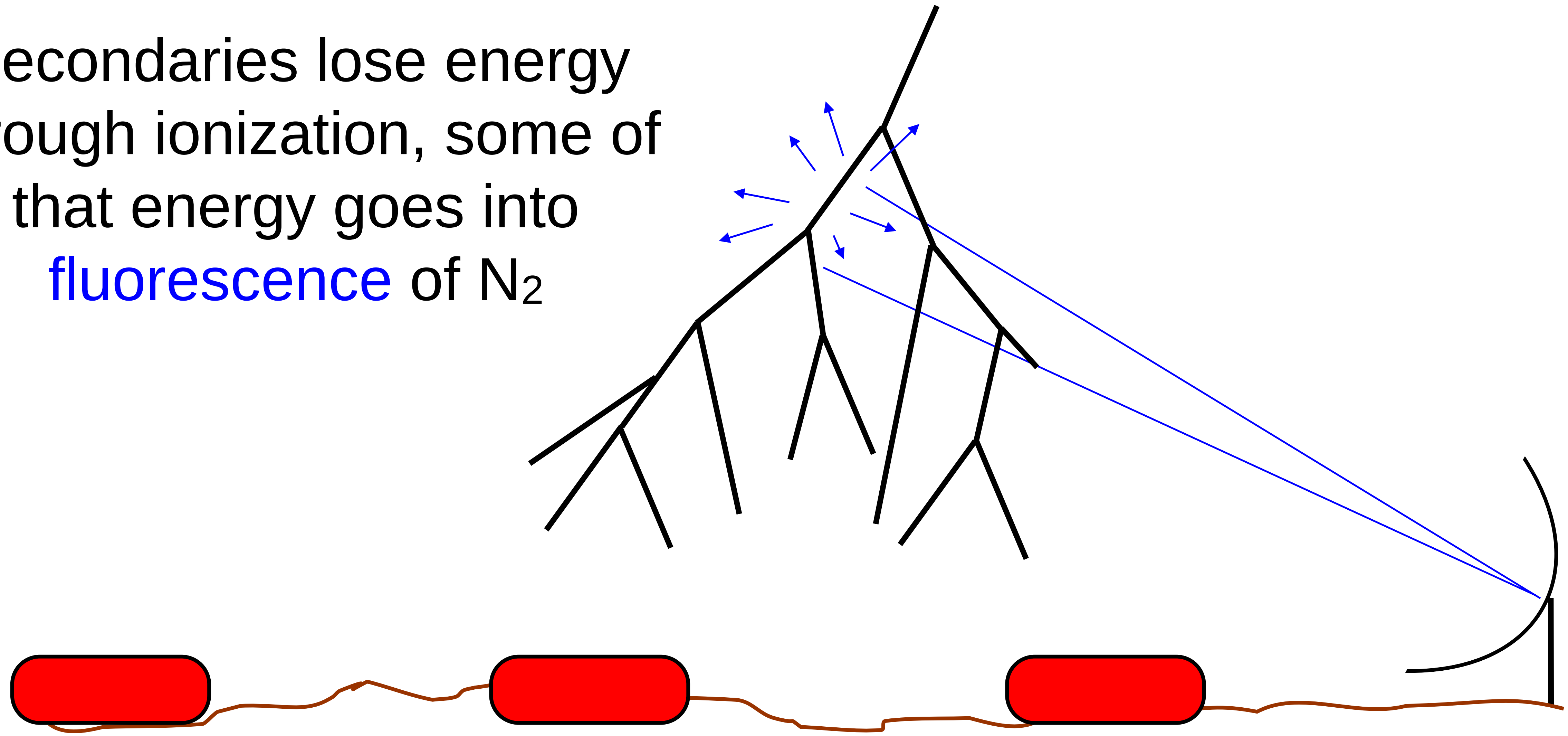


300,000 km^2 sr yr Exposure

Standard Hybrid Detector

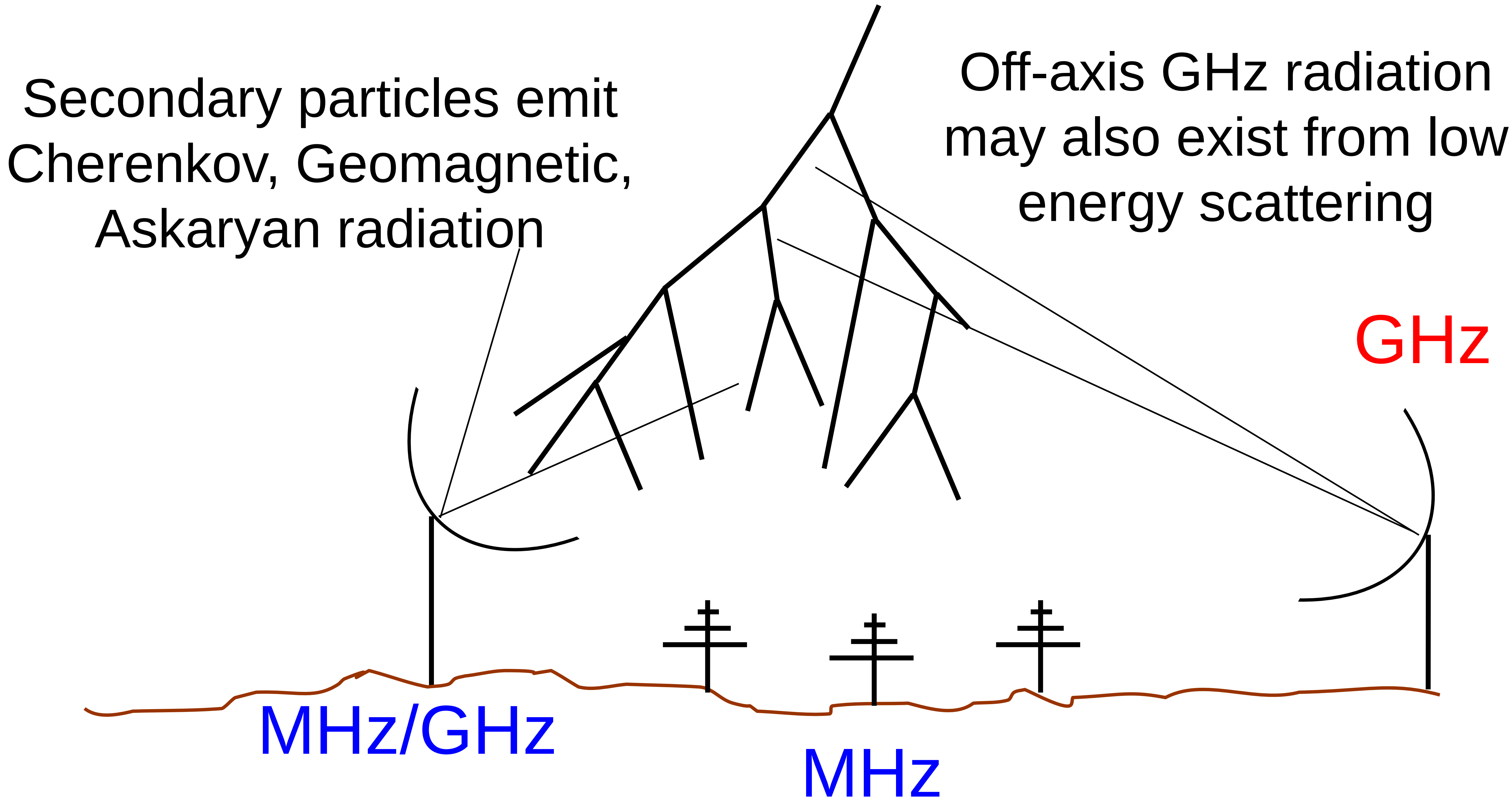
High energy primary particle initiates cascade of secondary particles

Secondaries lose energy through ionization, some of that energy goes into fluorescence of N_2



Electrons and muons reach ground detectors

Radio Detectors

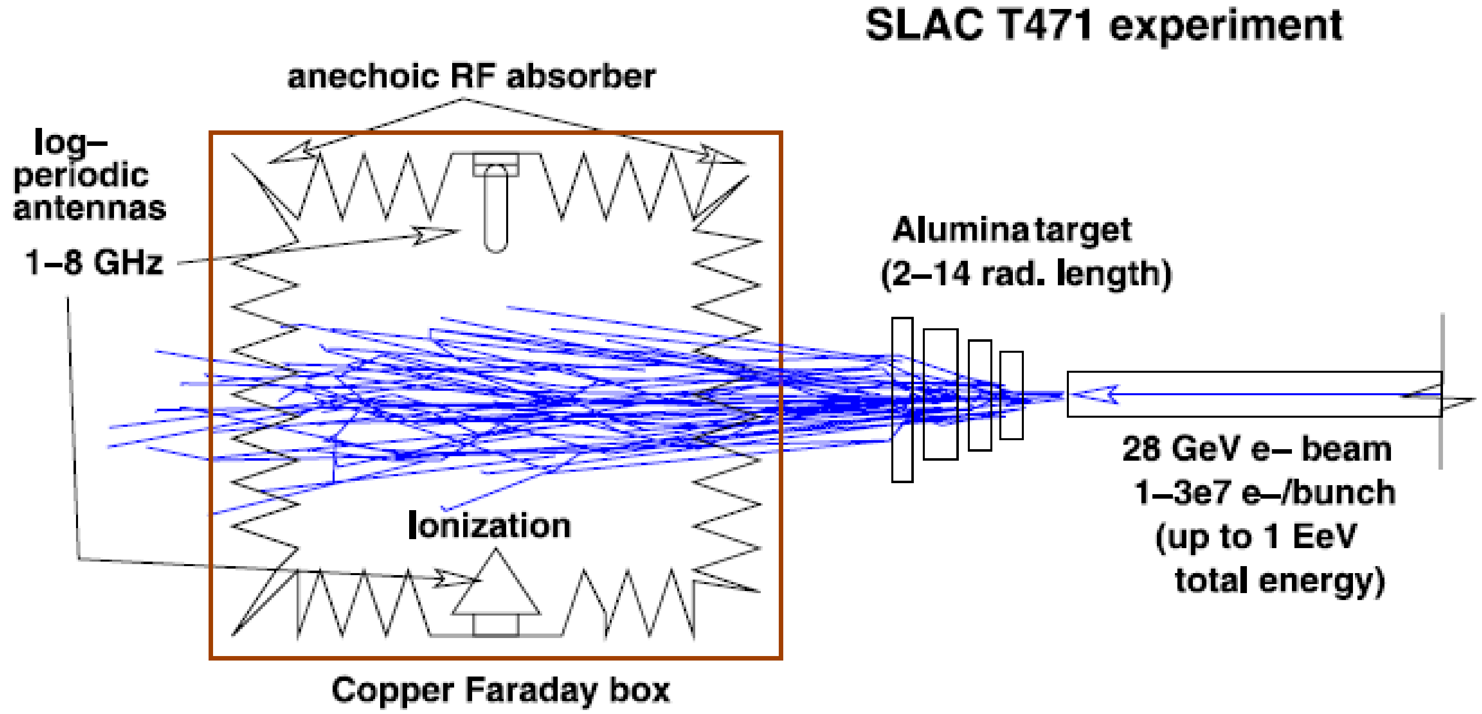


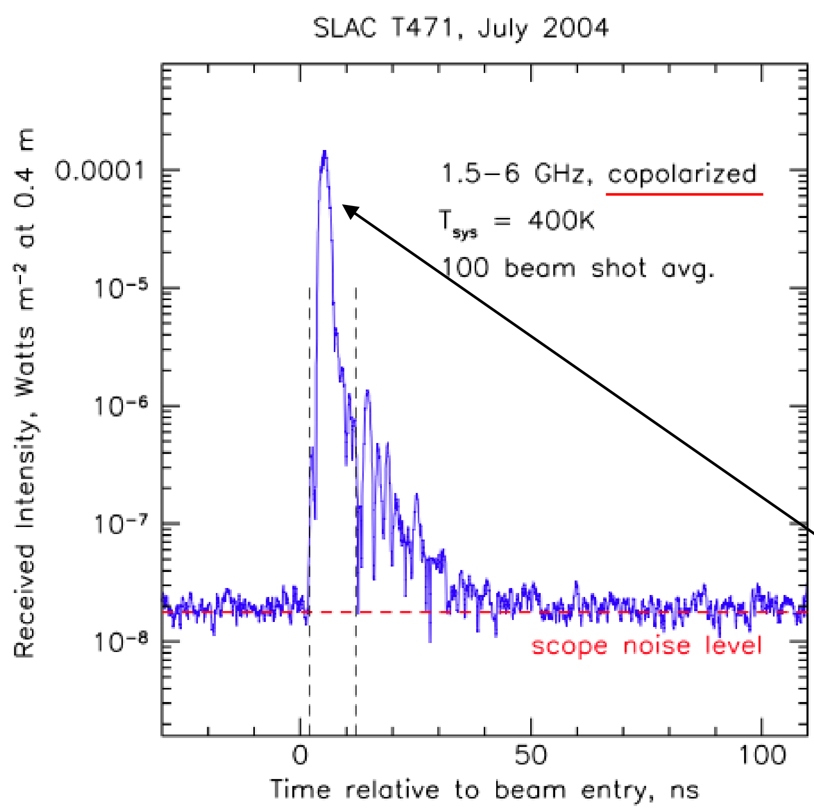
Molecular Bremsstrahlung Emission

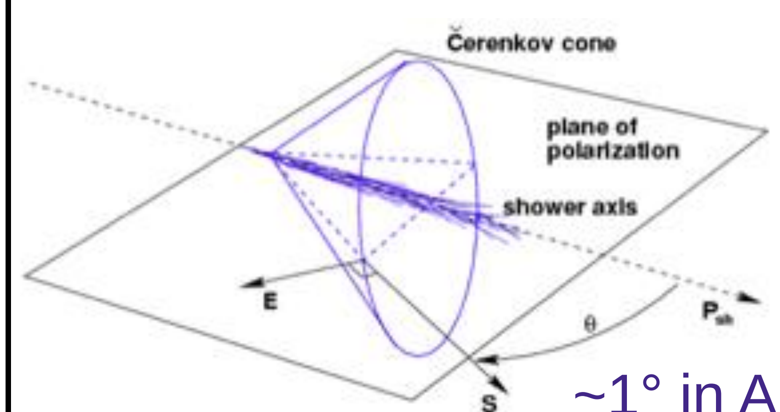
- EAS particles dissipate energy through ionization
- Produces plasma with $T_e \sim 10^4$-10^5K
- Low energy tail of free electrons produce Bremsstrahlung emission in microwave regime from scattering interactions with neutral air molecules
  - Trace number of shower particles as in FD
- Emission is unpolarized and isotropic

Potential exists for an FD-like detection technique capable of measuring the shower's longitudinal development with nearly 100% duty cycle, limited atmospheric effects and low cost (ability to cover large area)

Previous Beam Measurements







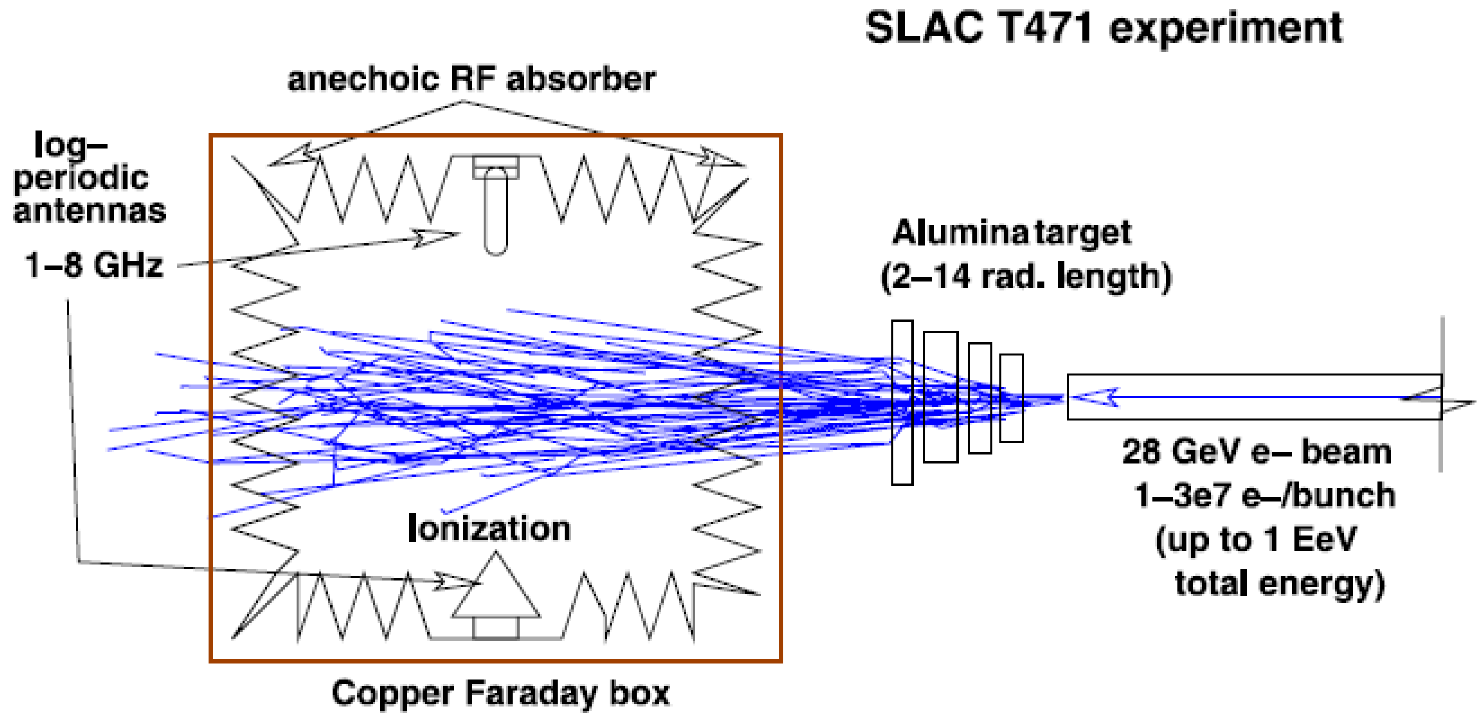
Dense bunch of high energy electrons emit coherently and polarized away from beam axis

~1° in Air

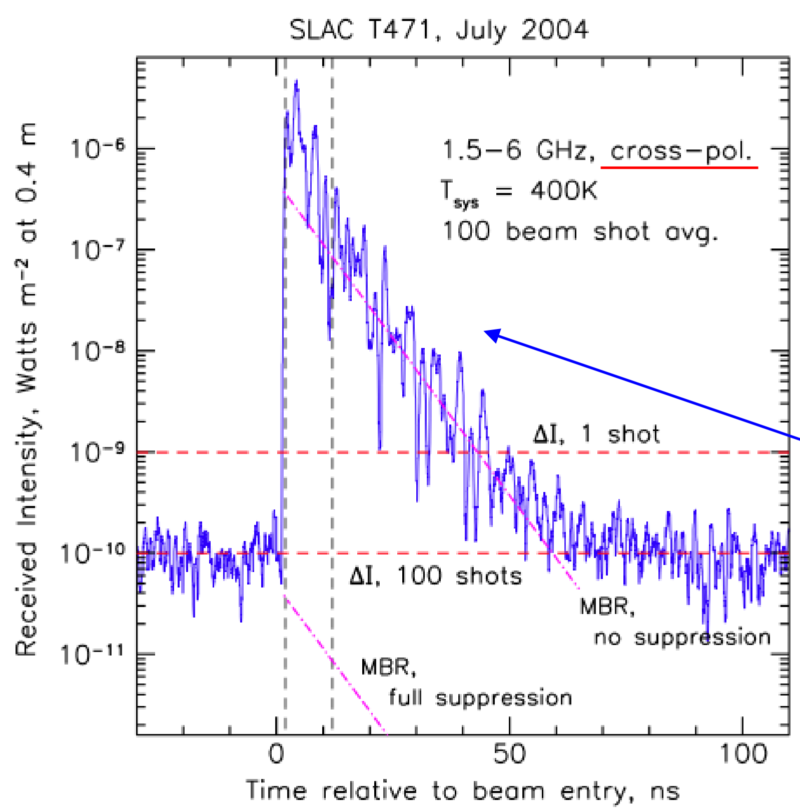
Prompt emission likely Cherenkov signal or Transition radiation at chamber entrance

P.W. Gorham *et al.,* “Observations of microwave continuum emission from air shower plasmas”, Phys. Rev .D. **78**, 032007 (2008)

Previous Beam Measurements



Cross polarized orientation should be insensitive to Cherenkov if chamber well shielded



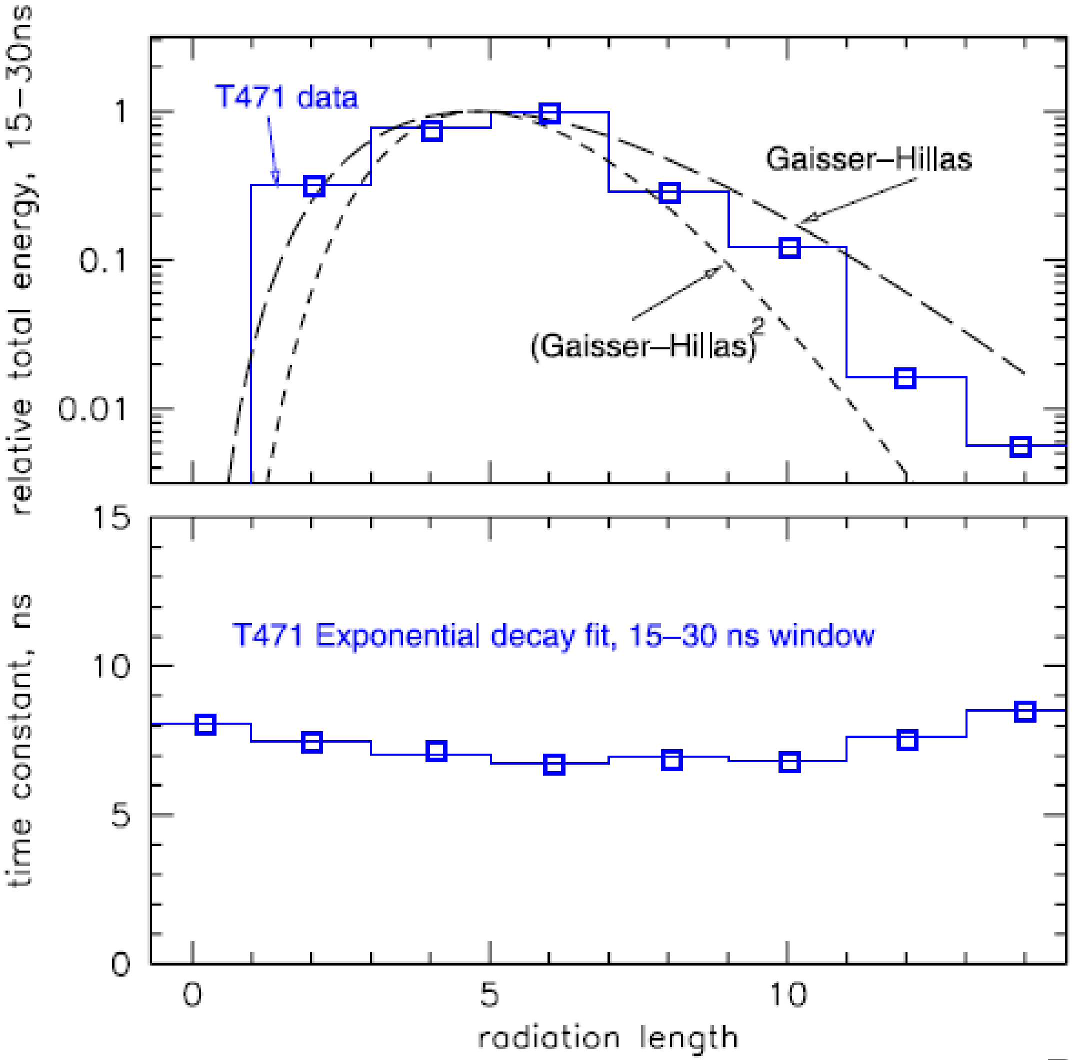
10 ns decay constant, compatible with plasma cooling.

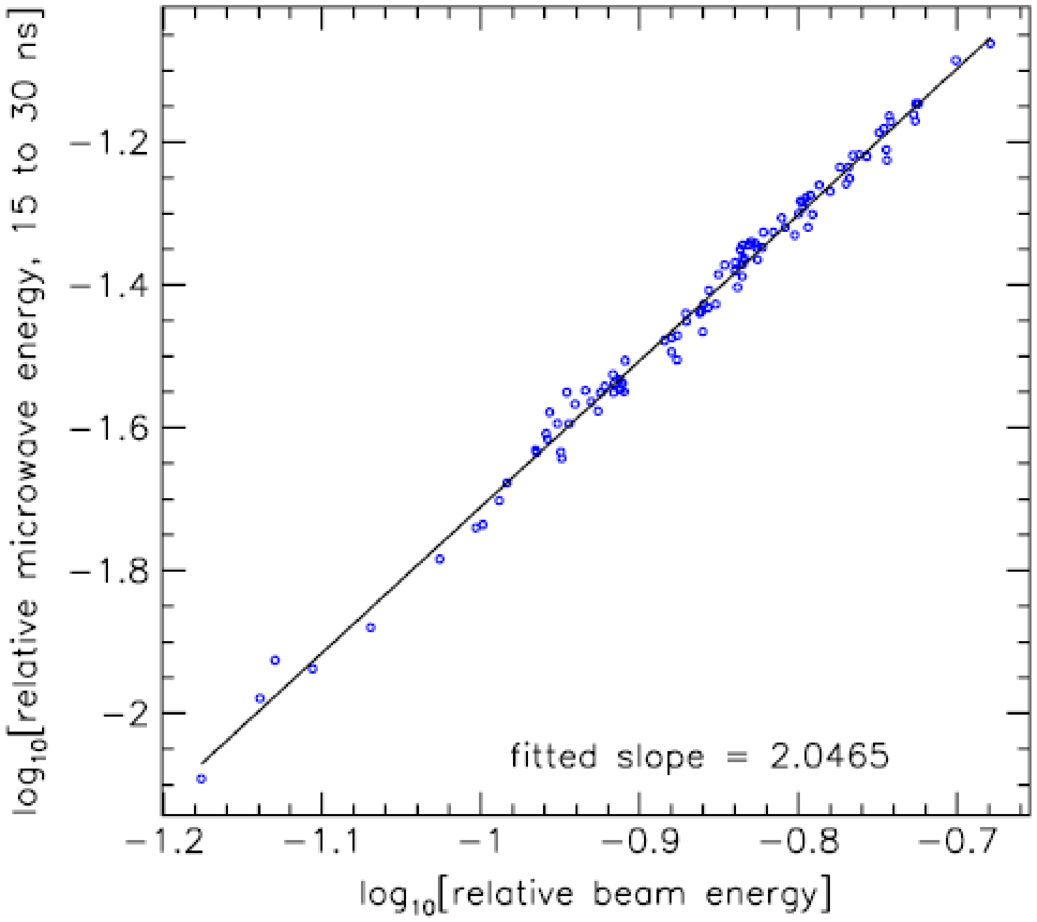
P.W. Gorham *et al.,* "Observations of microwave continuum emission from air shower plasmas", Phys. Rev .D. **78**, 032007 (2008)

Previous Beam Measurements

Plasma properties (density) determine level of signal coherence

Fully coherent plasma: $P_{tot}=(N_e)^2 \times P_1$
Incoherent plasma: $P_{tot}=N_e \times P_1$





SLAC beam test measured coherent emission

G-H fits suggest the plasma scaling in the beam may not match EAS scaling

P.W. Gorham *et al.,* "Observations of microwave continuum emission from air shower plasmas", Phys. Rev .D. **78**, 032007 (2008)

MIcrowave Detection of Air Showers Design

$I_{0,sh} = 2.8\ 10^{-16}$ W/m²/Hz
$E_0 = 3.4\ 10^{17}$ eV

@ 10 Km →

$I = 2.8\ 10^{-24}$ W/m²/Hz

$$\Delta I = \frac{k_B T_{sys}}{A_{eff}\sqrt{\Delta t \Delta f}}$$

T_{sys}=100K A_{eff} = 10 m²
Δt = 100ns Δf = 1GHz →

$\Delta I = 1.6\ 10^{-23}$ W/m²/Hz

Detection Threshold

$E_{quad} \sim 2\ 10^{18}$ eV
$E_{lin} \sim 10^{19}$ eV

P.W Gorham *et al.*, "Observations of microwave continuum emission from air shower plasmas", Phys. Rev .D. **78**, 032007 (2008)

Large collection area	~ 10 m²	Use 4.5m dish already installed at U of C
Pixel field of view	~1.5° ~ λ/D	Extended C-Band
Total field of view	~15°	~50 channels
Time domain	100 ns resolution	Fast power detector
Trigger for fast transient events		Flash ADC acquisition with FPGA trigger

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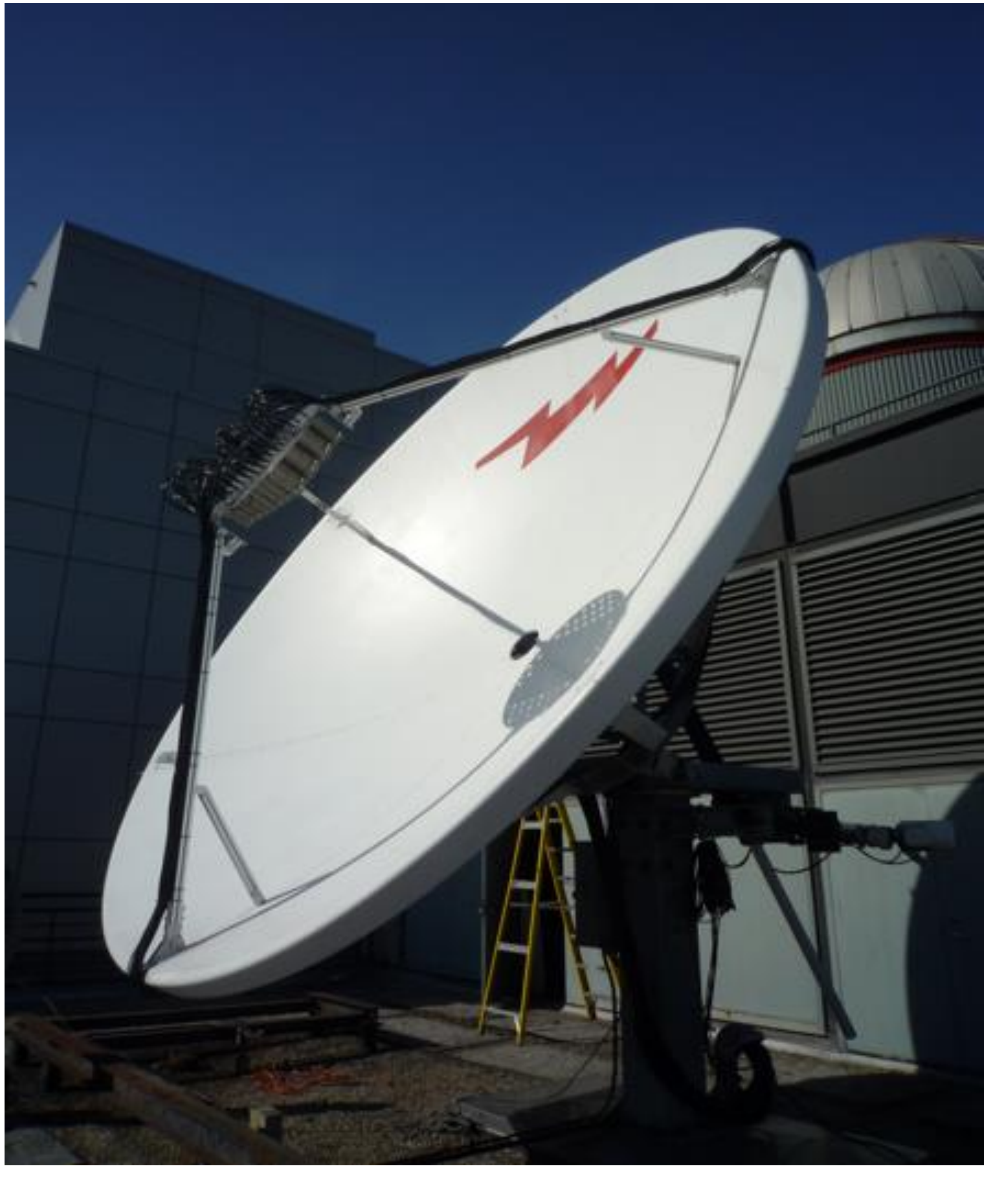
MIDAS Detector

- 4.5 m prime focus parabolic reflector
- On the roof of U of C Physics Building
- Designed for receivers in Ku-band (18 GHz)
- Fully steerable astronomic mount



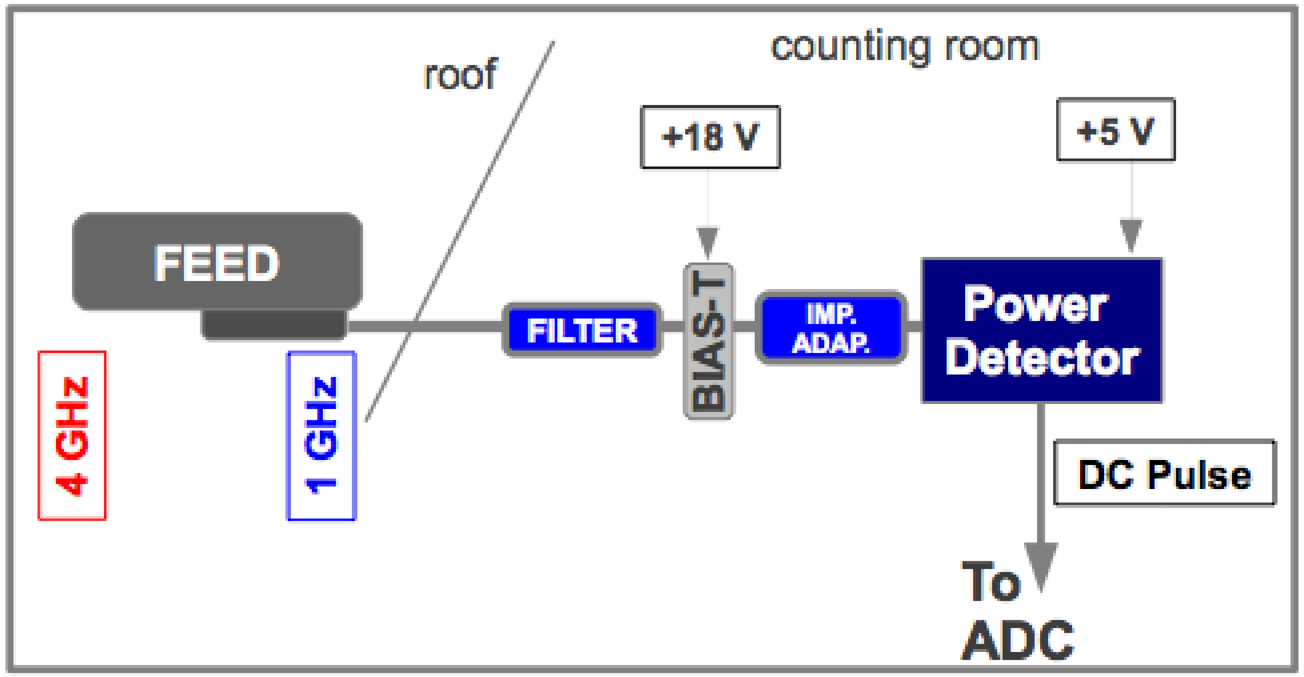
NIM **A719**, 70 (2013)

MIDAS Camera

- 53 Commercial Extended C-Band Feeds (**Very Cheap!**)
- Feed Horn + LNA + Down Converter (3.4-4.2 GHz)

- Measured 17K noise floor
  60 dB amplification
- 20° x 10° FOV

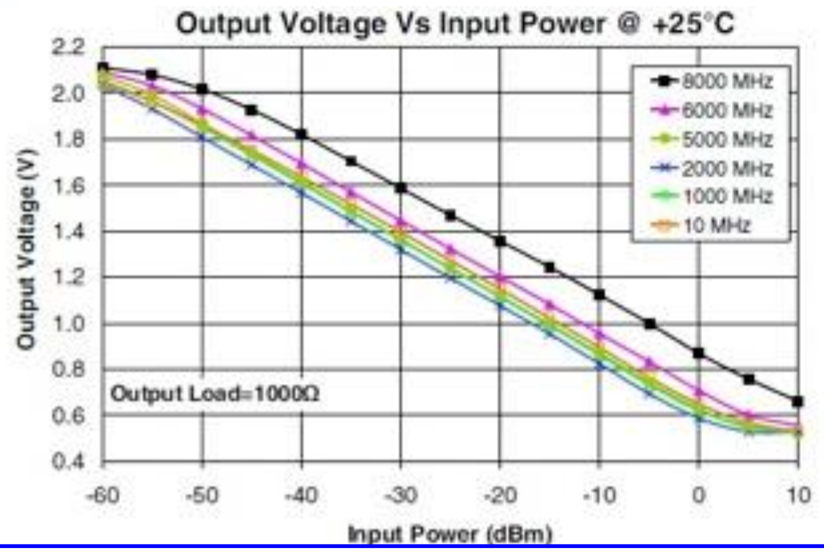
MIDAS Analog Board

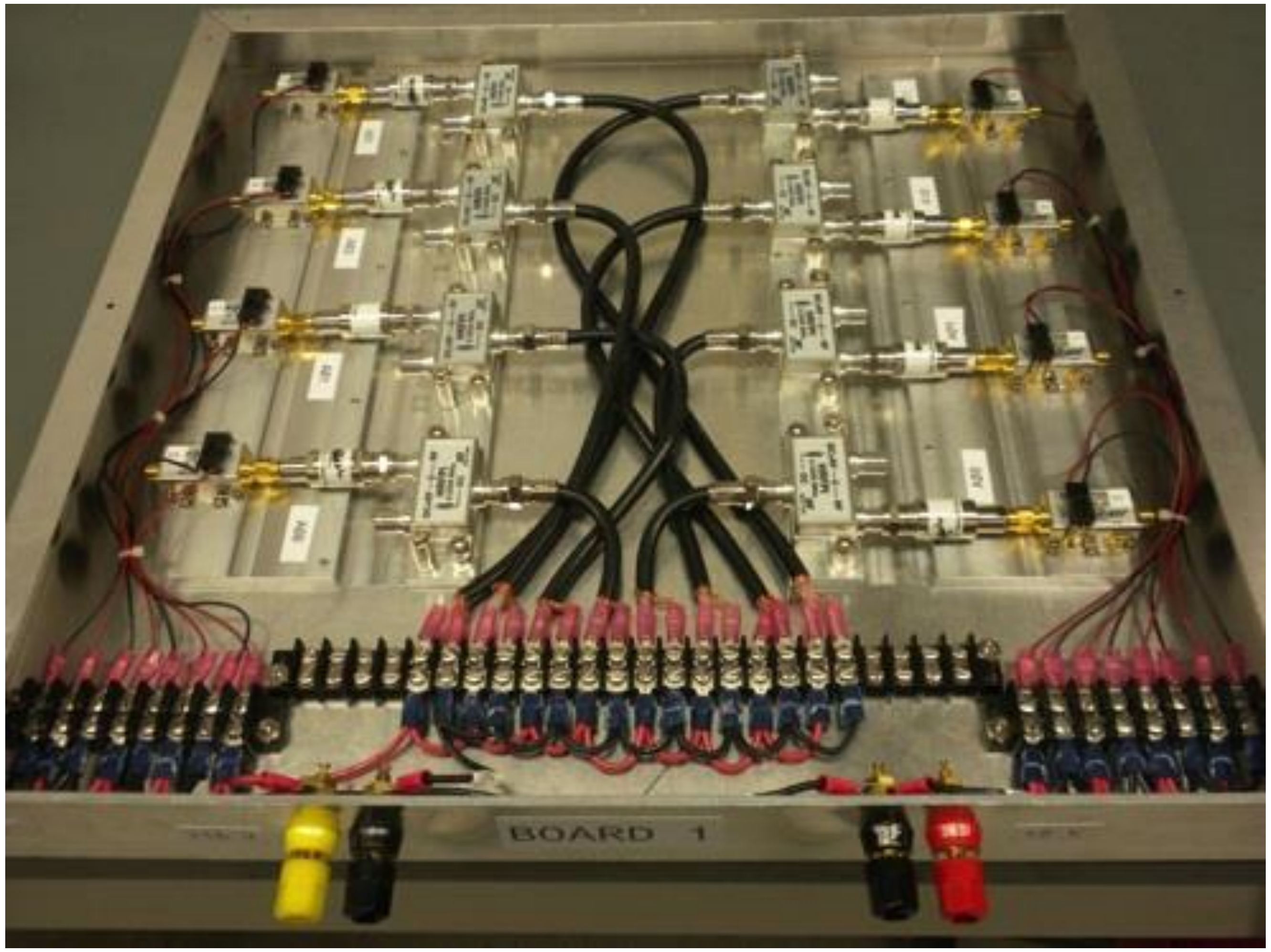


- Most components on analog side are commercially sourced
- Custom band-pass filter to deal with aviation interference in Chicago

Power detector

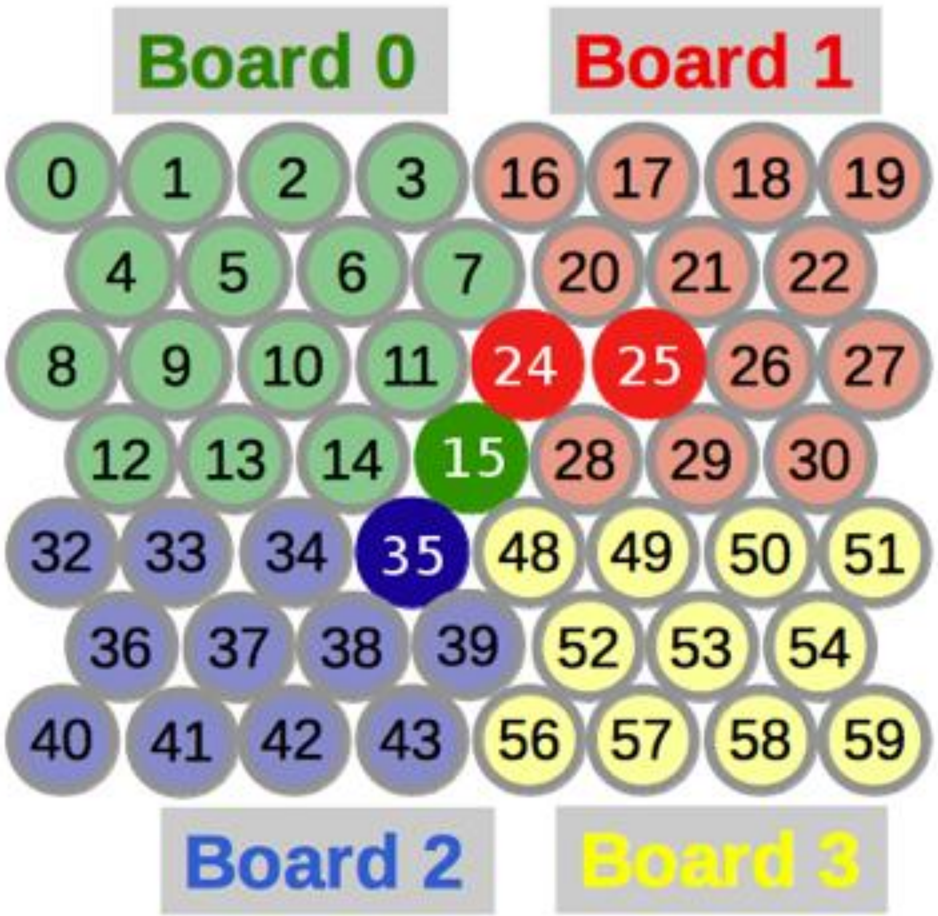
0-2 V DC output, log response
10MHz to 8GHz bandwidth
100 ns time resolution





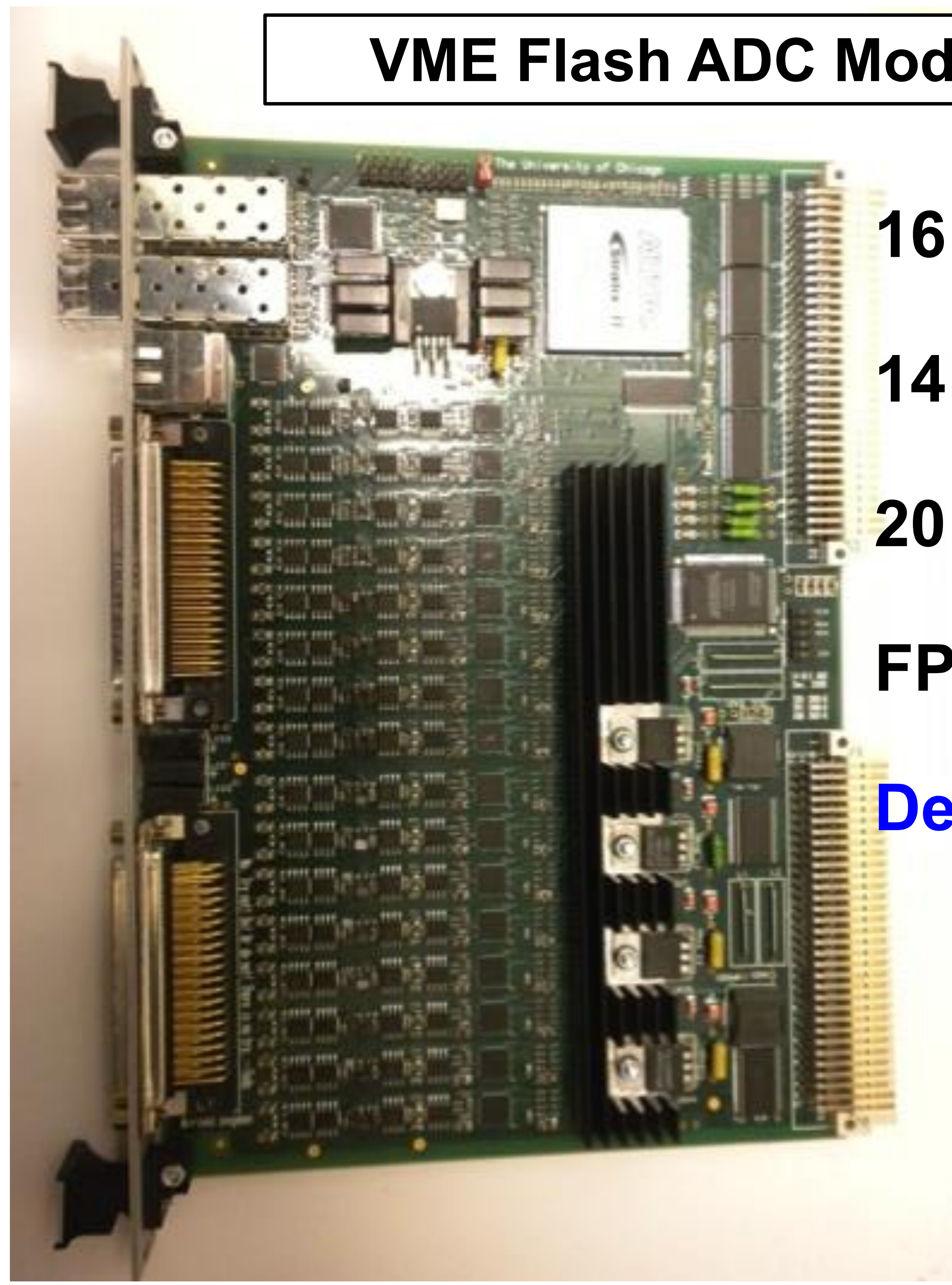
MIDAS Digitizer Board

$$n_{adc} = n_0 - k\,P_{dB} = n_0 - k\,\log(P_{lin})$$



- Instrument composed of 5 VME Modules
- 4 modules for camera pixel digitization and FLT
- 1module for master trigger
- Hold digitized trace in 100 μs circular buffer

VME Flash ADC Module



16 channels

14 bit

20 MHz

FPGA trigger

Developed @ EFI

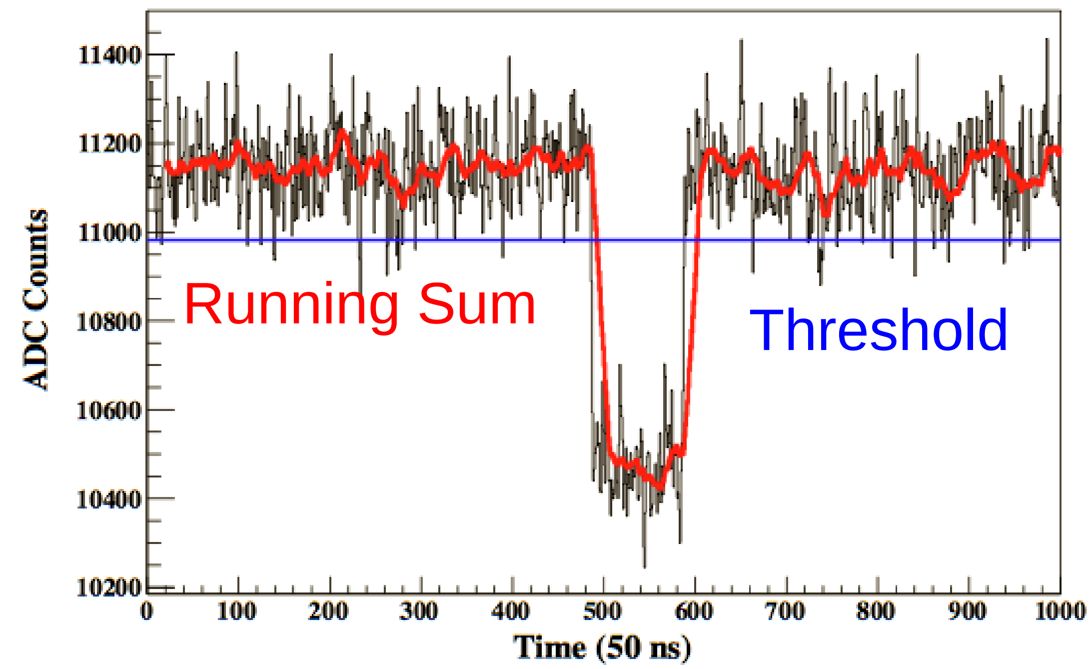
MIDAS Trigger

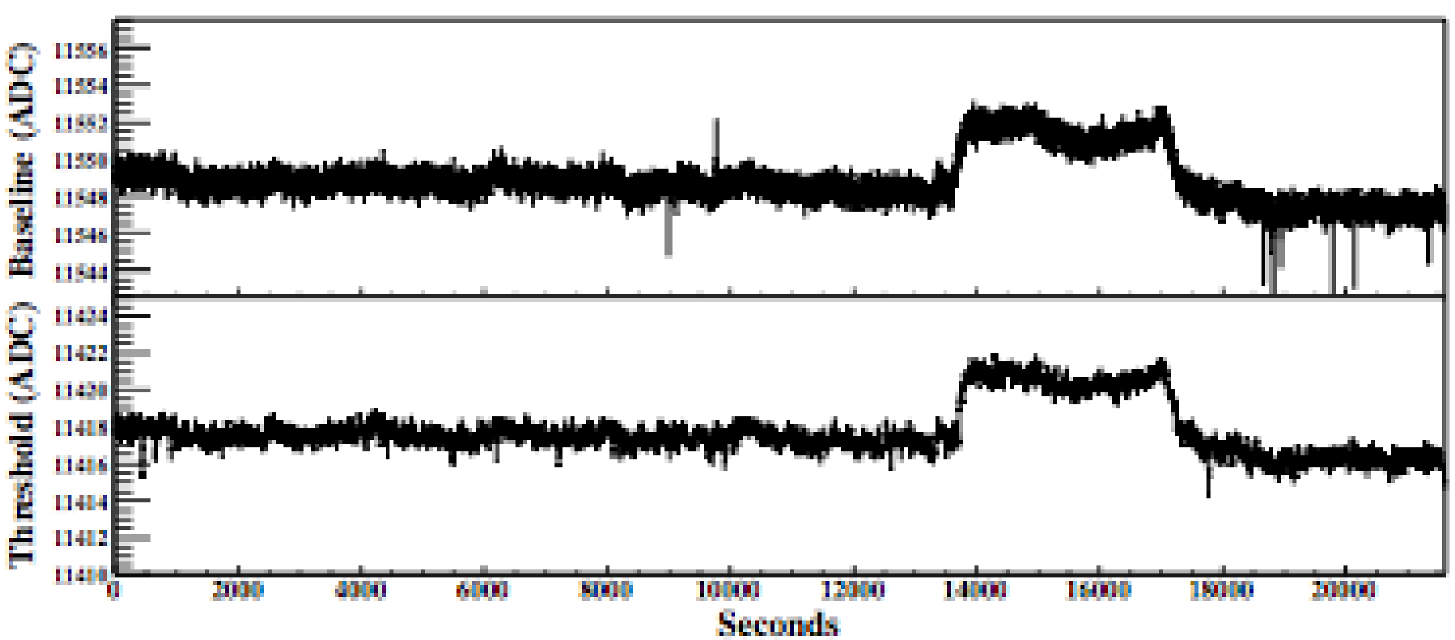
<u>First Level Trigger:</u>

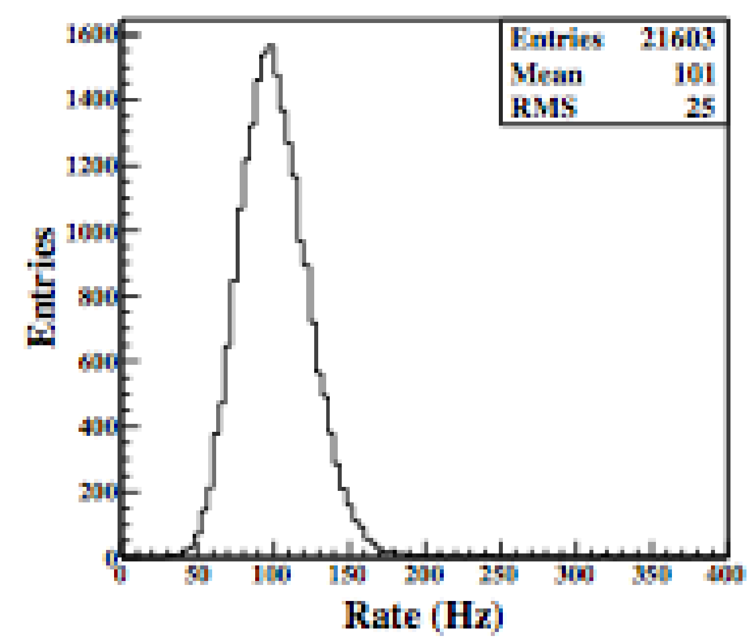
-1μs running sum performed after 20 MHz ADC in FPGA

-Over threshold trigger

-Each feed has self-regulated threshold to hold rate at 100Hz







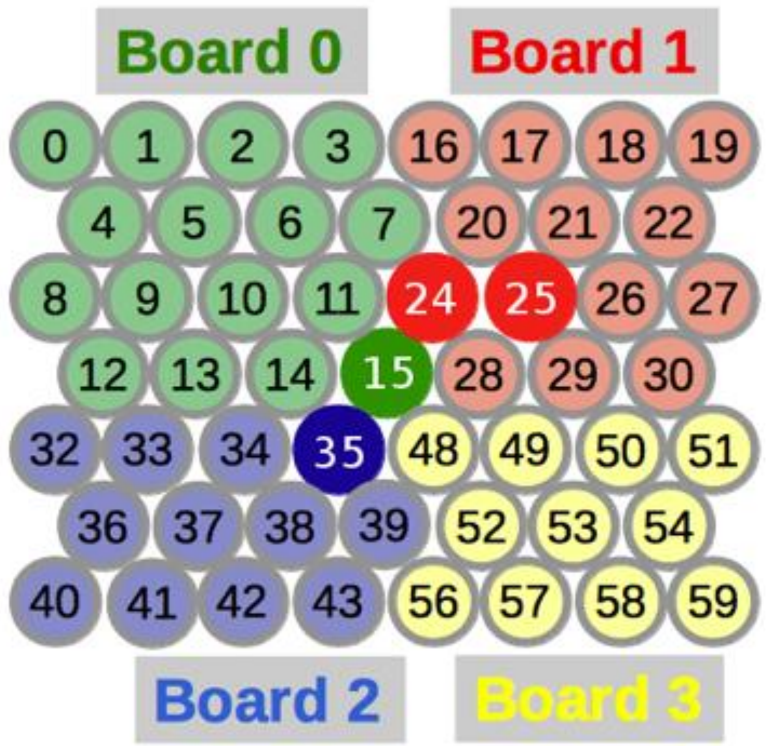
MIDAS Trigger

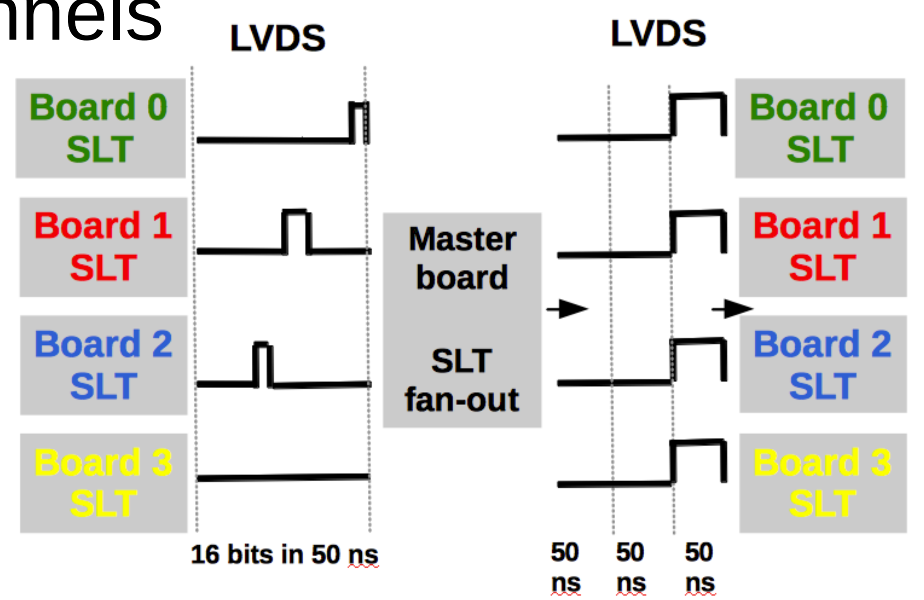
Second Level Trigger:

-Require 4 FLTs within 10 μs match 1 of 767 specified pixel patterns

-Pattern topology matches track-like patterns expected for EAS

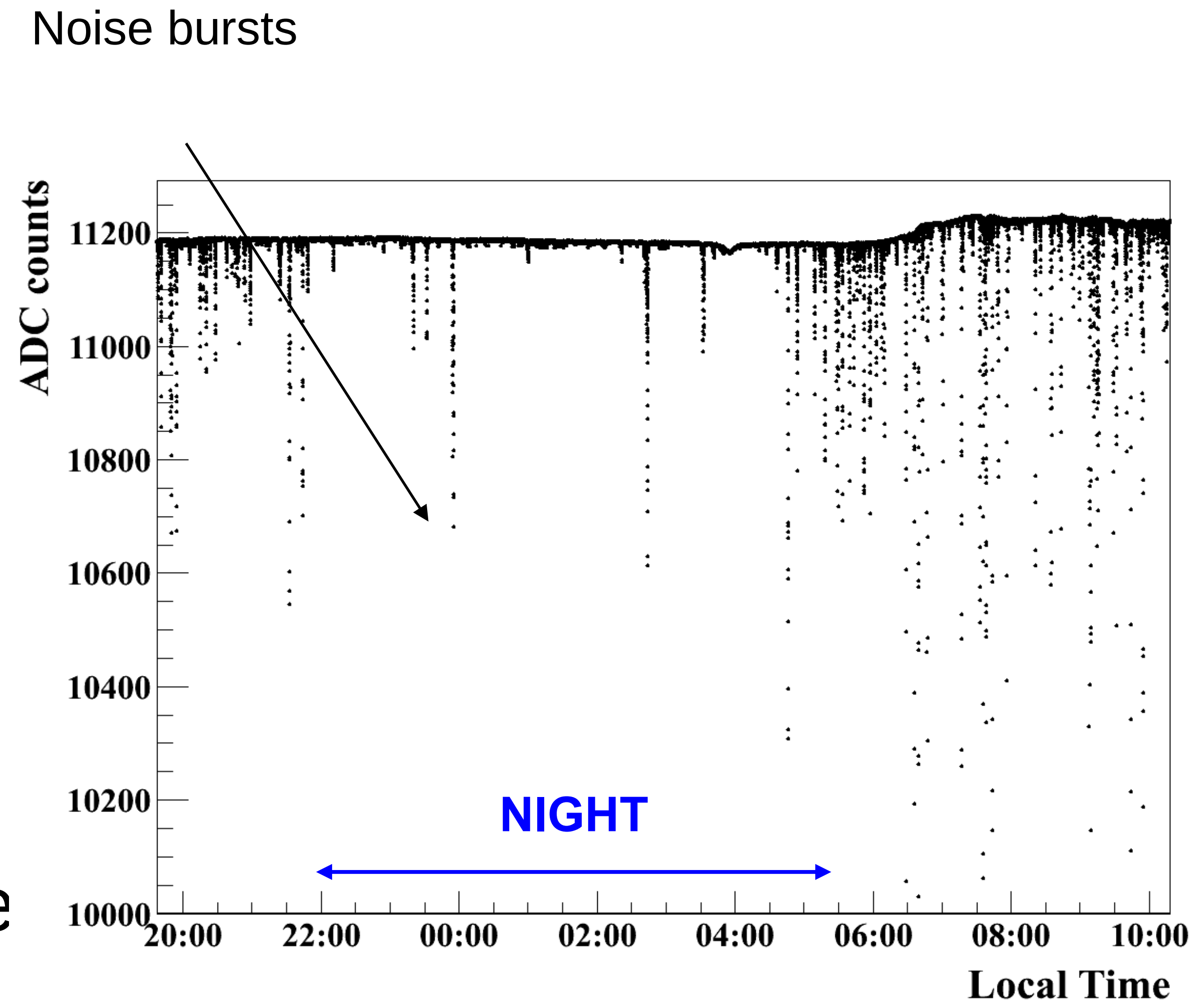
-When SLT found, master trigger board freezes trace buffers and writes 100 μs of time stream data for all channels





High-Level Veto: Inhibits trigger when SLT exceeds preset value. Filters periods of noise bursts improving livetime.

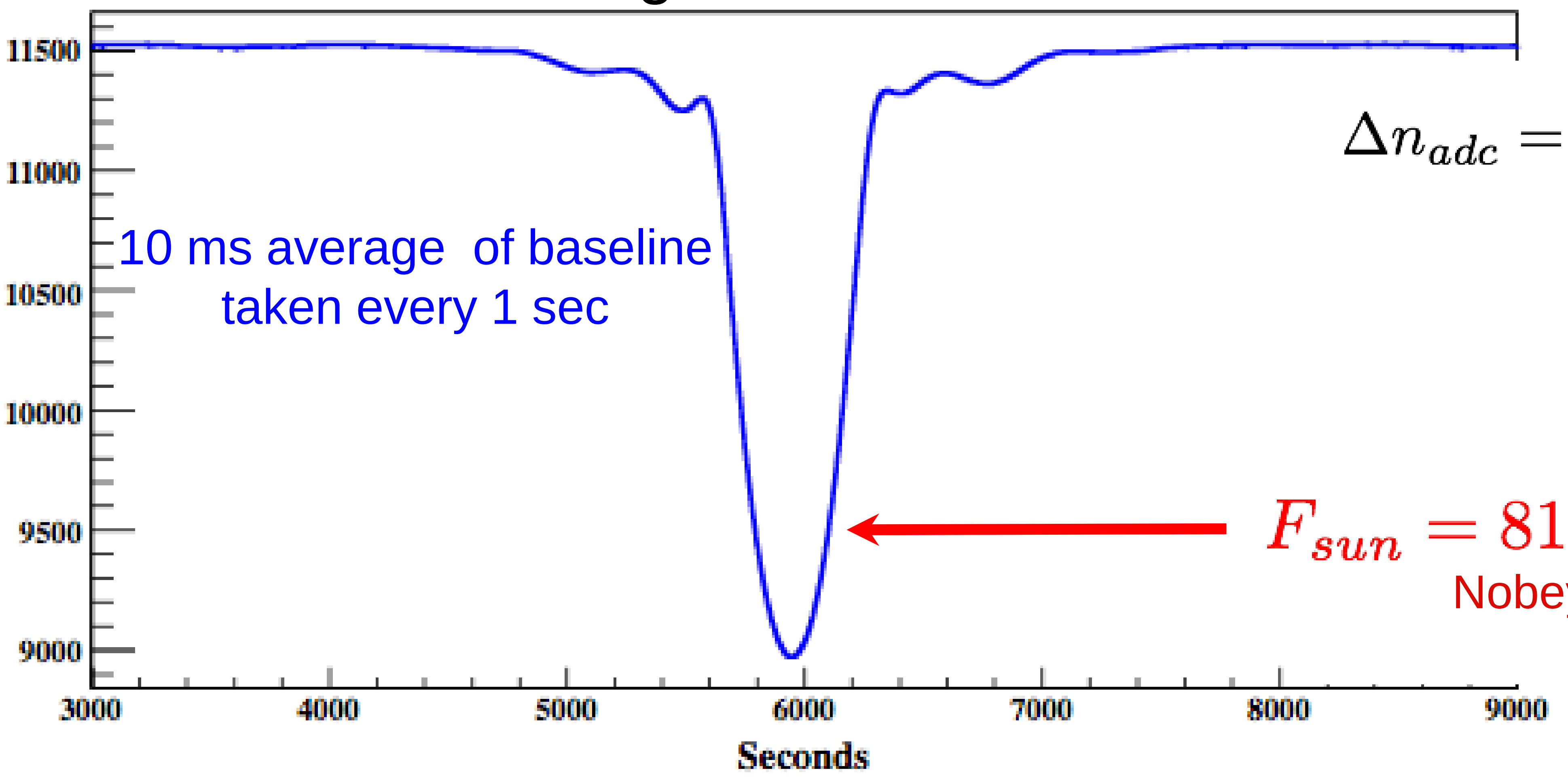
Band-pass filter also helps with this noise



MIDAS Absolute Calibration

Astrophysical sources provide a calibration of system temperature

Sun Signal in Central Pixel



$$\Delta n_{adc} = 10\ k\ log(1 + \frac{P_{sun}}{P_{sys}})$$

$$\Delta n_{adc} \simeq 2500$$

$$F_{sun} = 81 \times 10^{-22} W/m^2/Hz$$

Nobeyama Radio Observatory

$$F_{sys} \simeq 1.5 \times 10^{-22}\ W/m^2/Hz \longrightarrow T_{sys} \simeq 65\ \mathrm{K}$$

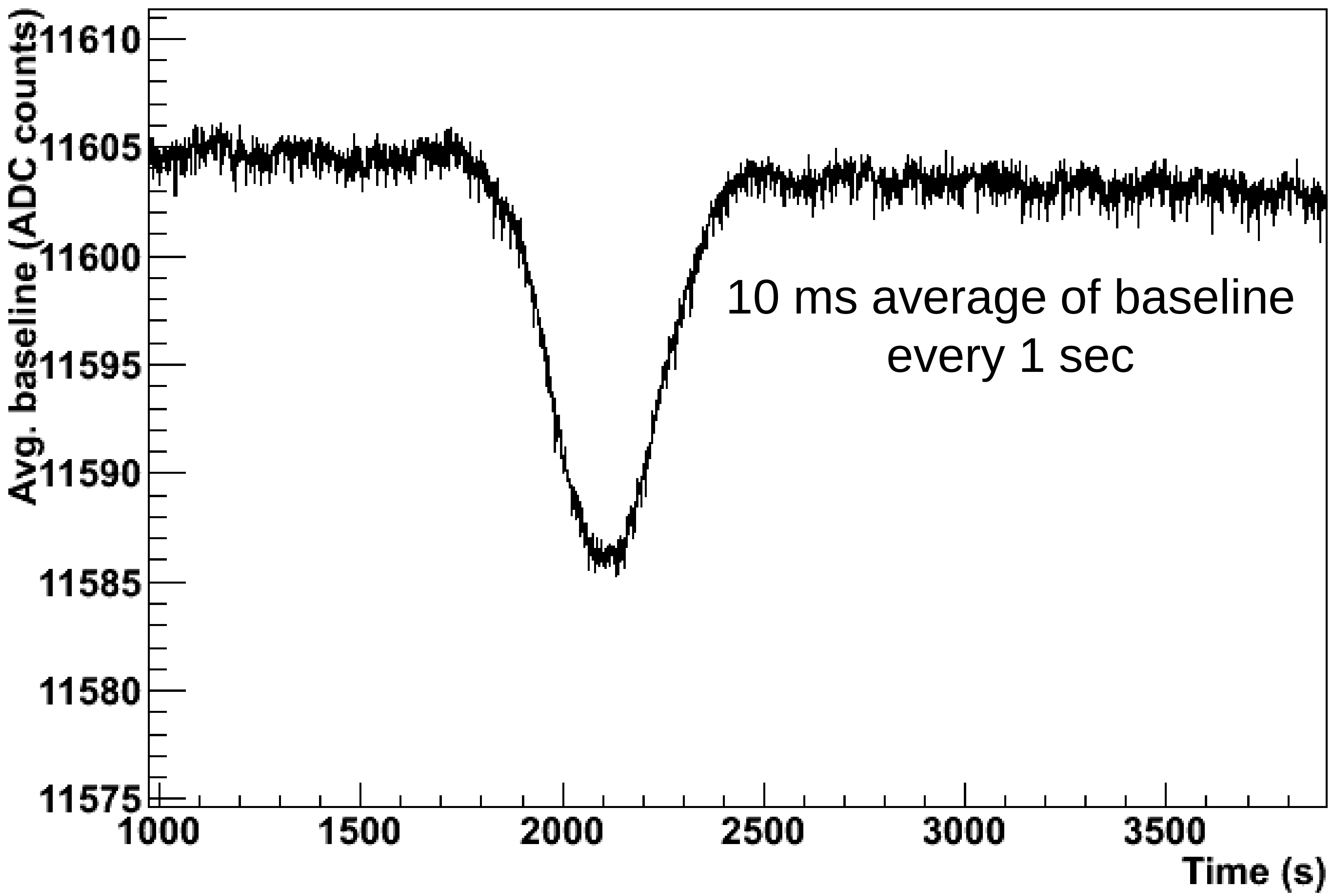
$$F_{sys} = \frac{2k_B T_{sys}}{A_{eff}}$$

also have observed moon (sun/100) and crab nebula (sun/1000)

MIDAS Absolute Calibration

Astrophysical sources provide a calibration of system temperature

Crab Nebula



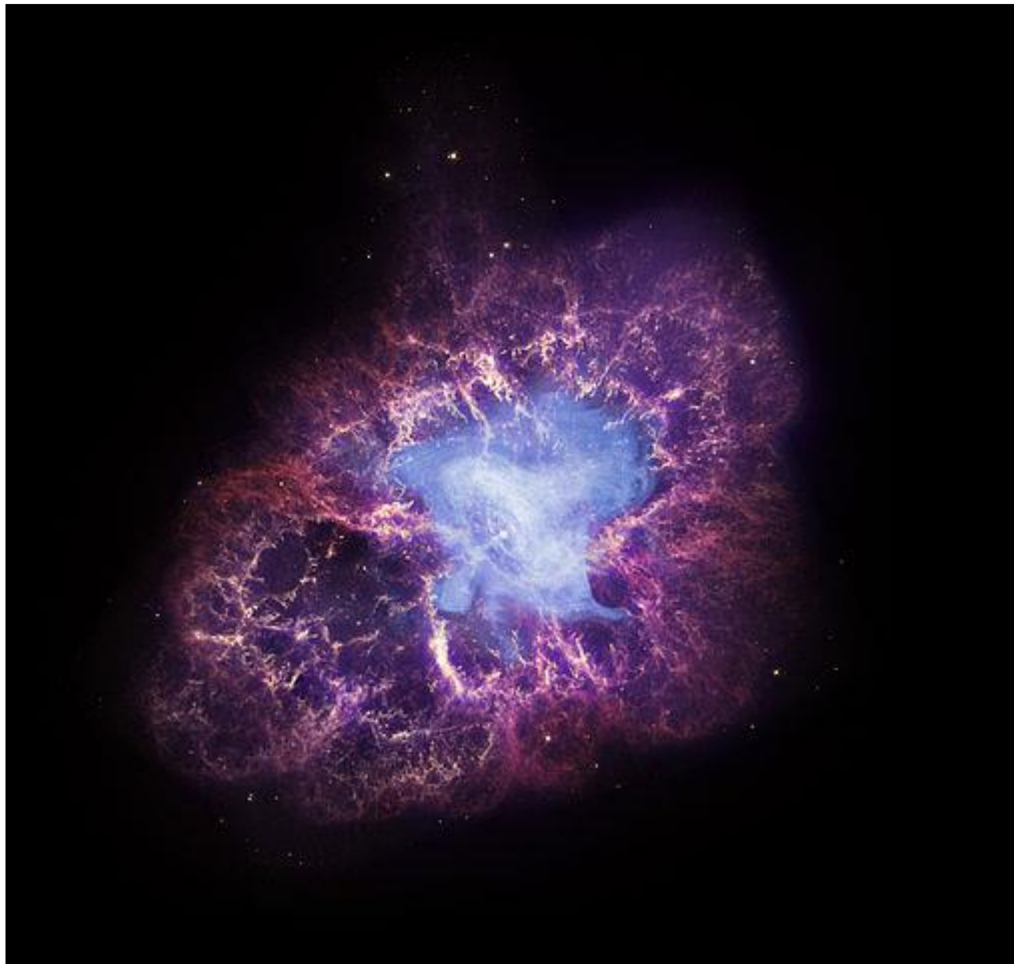
$$\Delta n_{adc} = 10k \log\left(1 + \frac{P_{crab}}{P_{sys}}\right)$$

$$\Delta n_{adc} \simeq 19$$

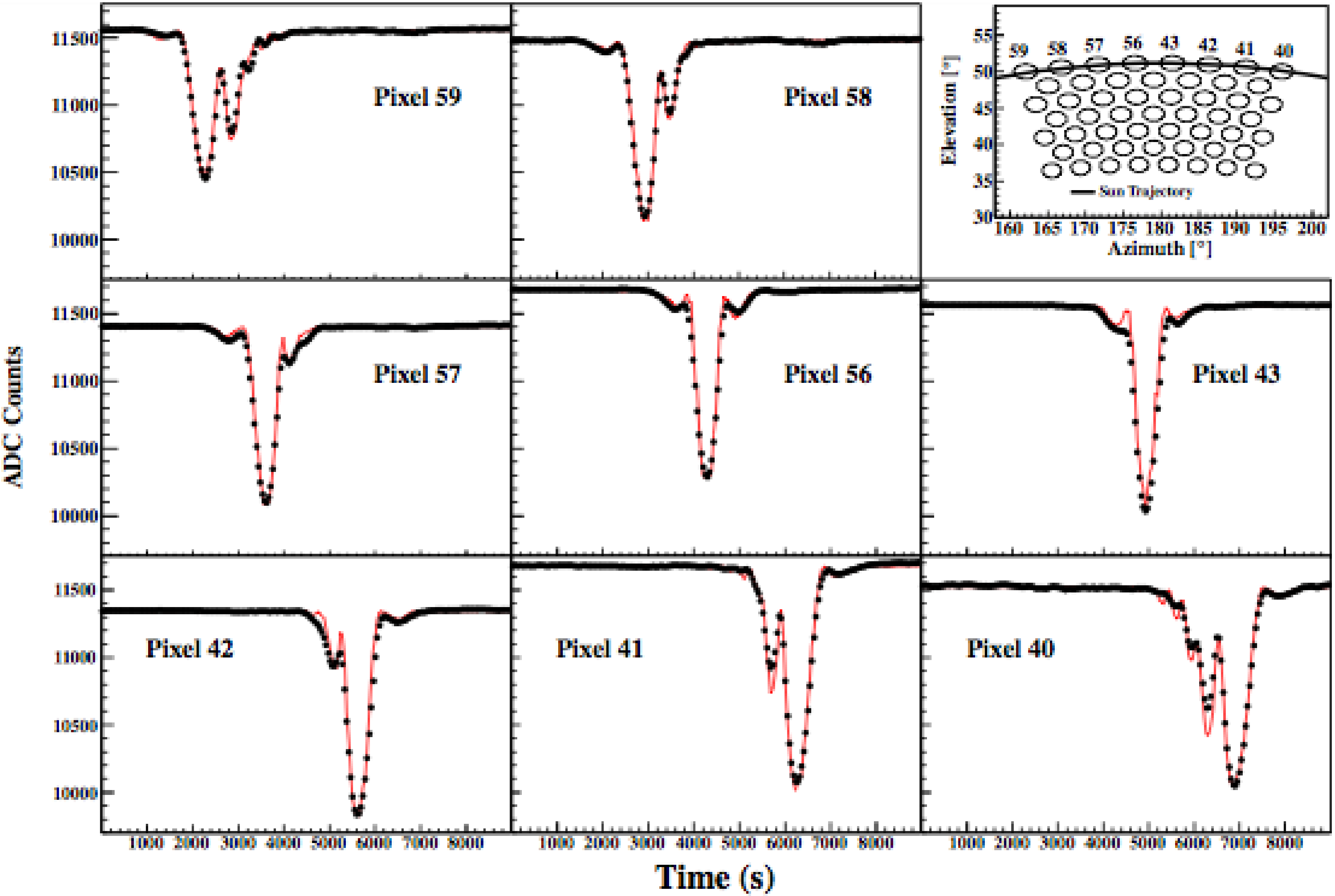
$$F_{Crab} \simeq 750 Jy$$

$$F_{Crab} \simeq 718 \pm 43 Jy$$

J.W.M. Baars et al., A&A, **61** (1977) 99



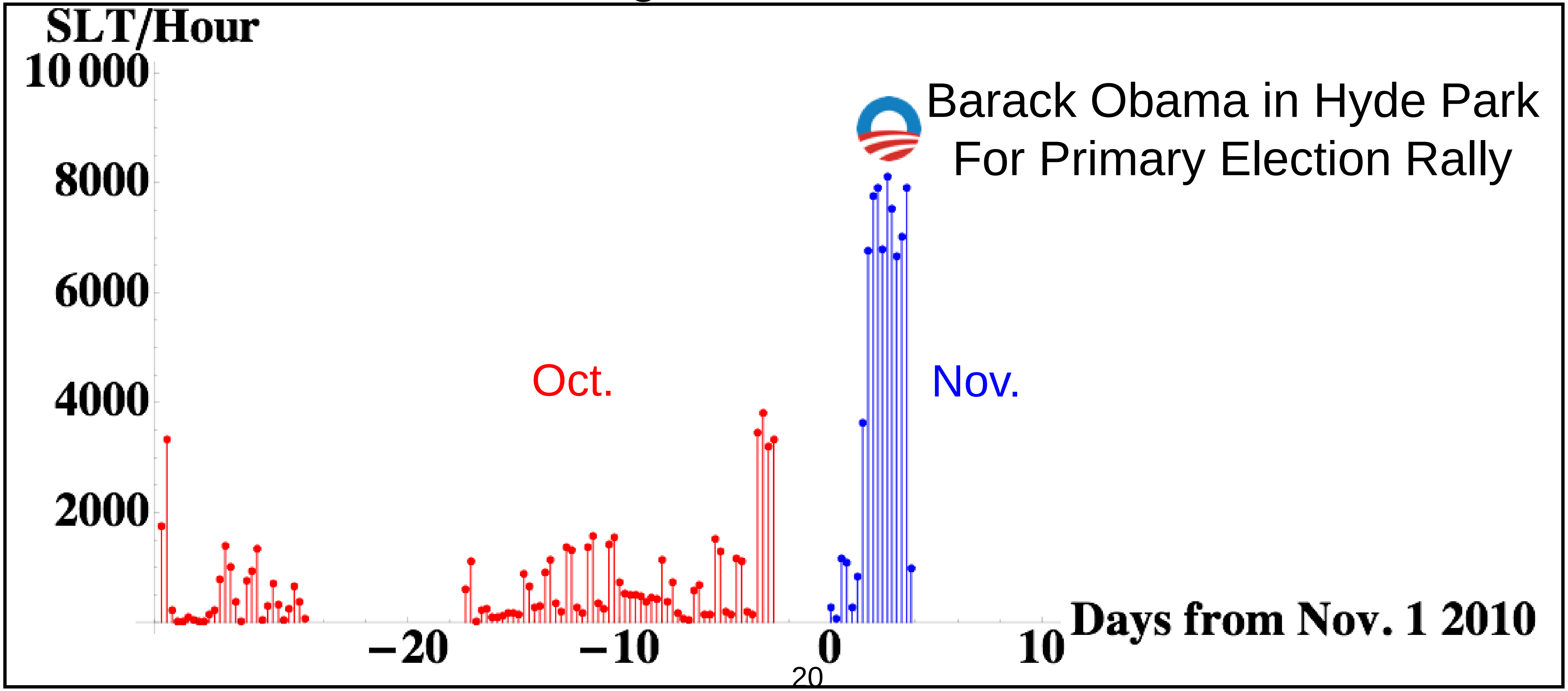
Full Camera Calibration



- Sun calibration done for all pixels

MIDAS Data Collection

- Collected data over approximately 5 months, stopping occasionally for calibration or other maintenance
- Large swings in trigger rates over this period, source unidentified
- For science sample we use 6 hour periods with <15,000 SLTs
- 61 days of livetime after accounting for data set selection and dead time associated with writing events



Event Search Program

TABLE I. Table of cuts used in search program and their effect on selected data sample

Cut		Events Remaining After Cut
(1)	Less than three FLT pixels outside the SLT time window	625 012
(2)	All SLT patterns are time-ordered down-going	4112
(3)	SLT pattern crossing time greater than 400 ns	1432
(4)	Traces in triggered SLT patterns contain only 1 pulse $>5\sigma$	979
(5)	Pulses $>5\sigma$ have a shape consistent with power detector's time constant	924
(6)	FLT pixels matching a 5-pixel pattern topology with down-going time order	21
(7)	Visual inspection of candidate events	0

- 5-Pixel search program to find events well above any thermal noise background, 4-Pixel rate well above thermal expectations
- Cuts designed to eliminate anthropogenic noise
- Select expectations for EAS events
- Pseudo-blind analysis not trained on Monte Carlo data
- Null Result used to set emission limit

Microwave Emission Limits

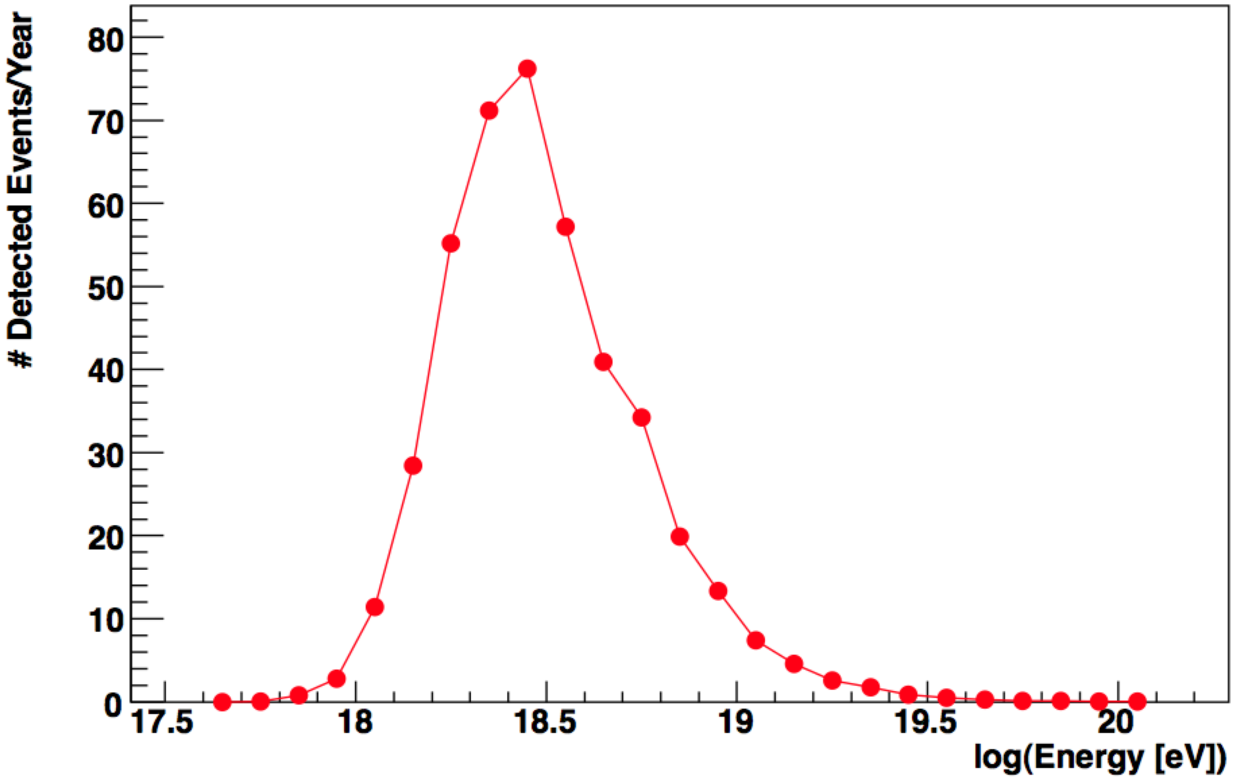
- Emission Parameterized in power flux and scaling

$$I_f = I_{f,ref} \cdot (\rho/\rho_0) \cdot (d/R)^2 \cdot (N/N_{ref})^\alpha$$

- For parameter space exploration use simulation to make spectrum between log E= 17.65 and log E= 20.05
- $I_{f,ref}$ runs between 2.31×10^{-16} W/m^2/Hz and 4.61×10^{-15} W/m^2/Hz
- α between 1 and 2
- Detection spectrum produced by weighted observed events with Auger spectrum

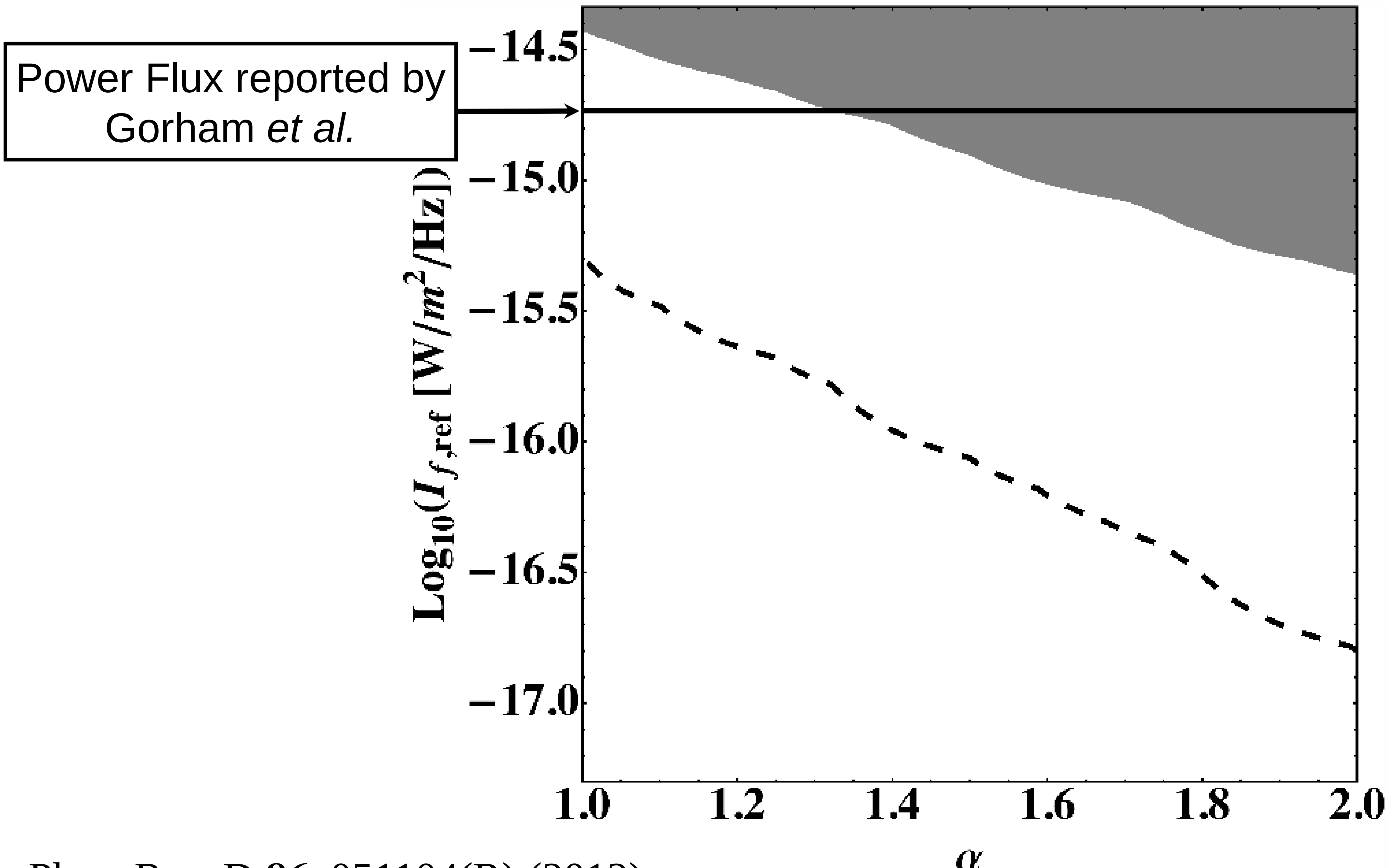
Detection Spectrum

$I_{f,tot} = 1.73 \times 10^{-15}$ W/m^2/Hz $\quad \alpha = 2$



Microwave Emission Limits

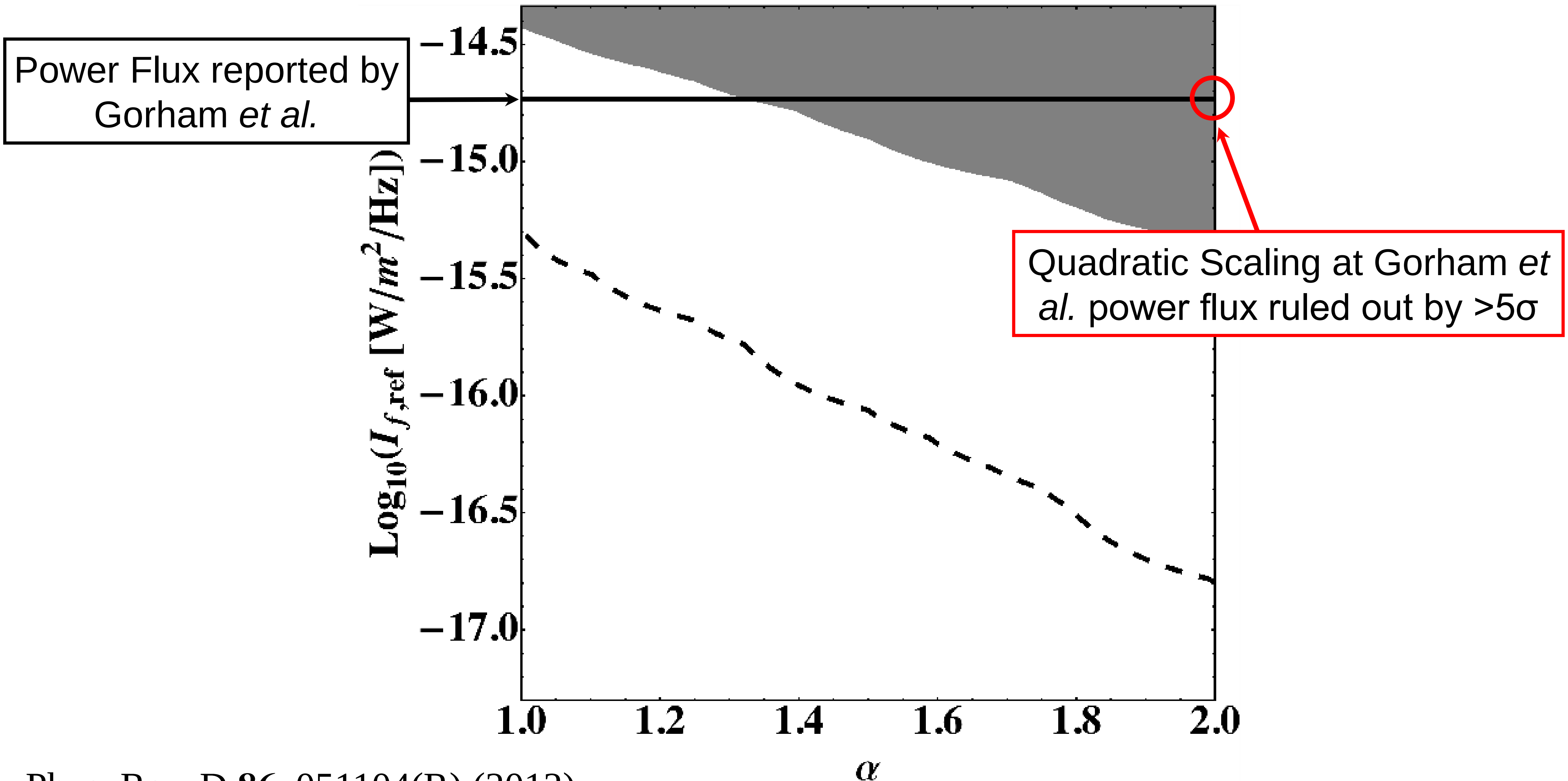
95% confidence exclusion with 5-pixel search and 61 days of livetime data from University of Chicago campus



Phys. Rev. D **86**, 051104(R) (2012)

Microwave Emission Limits

95% confidence exclusion with 5-pixel search and 61 days of livetime data from University of Chicago campus



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Microwave Emission Limits

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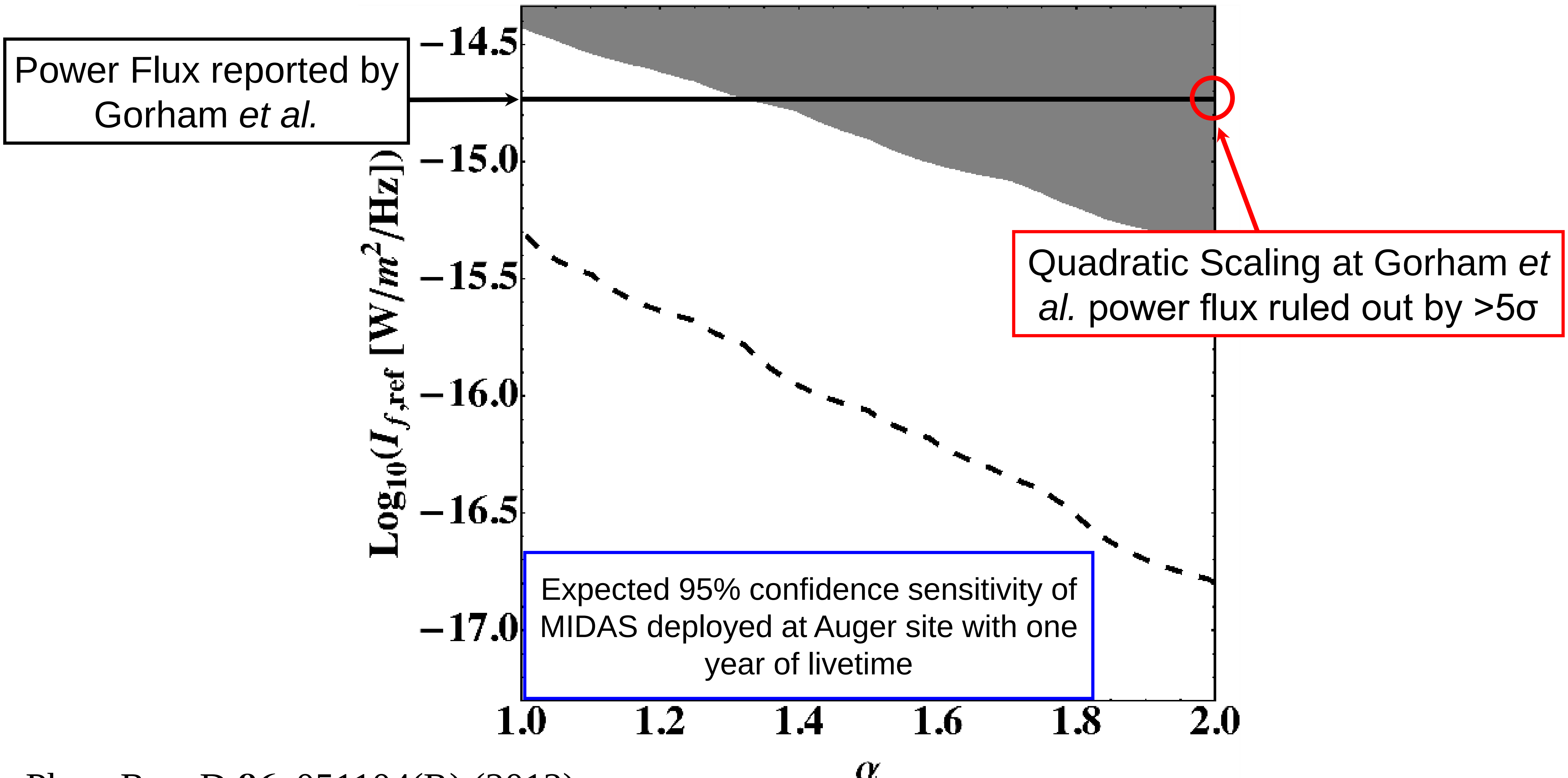
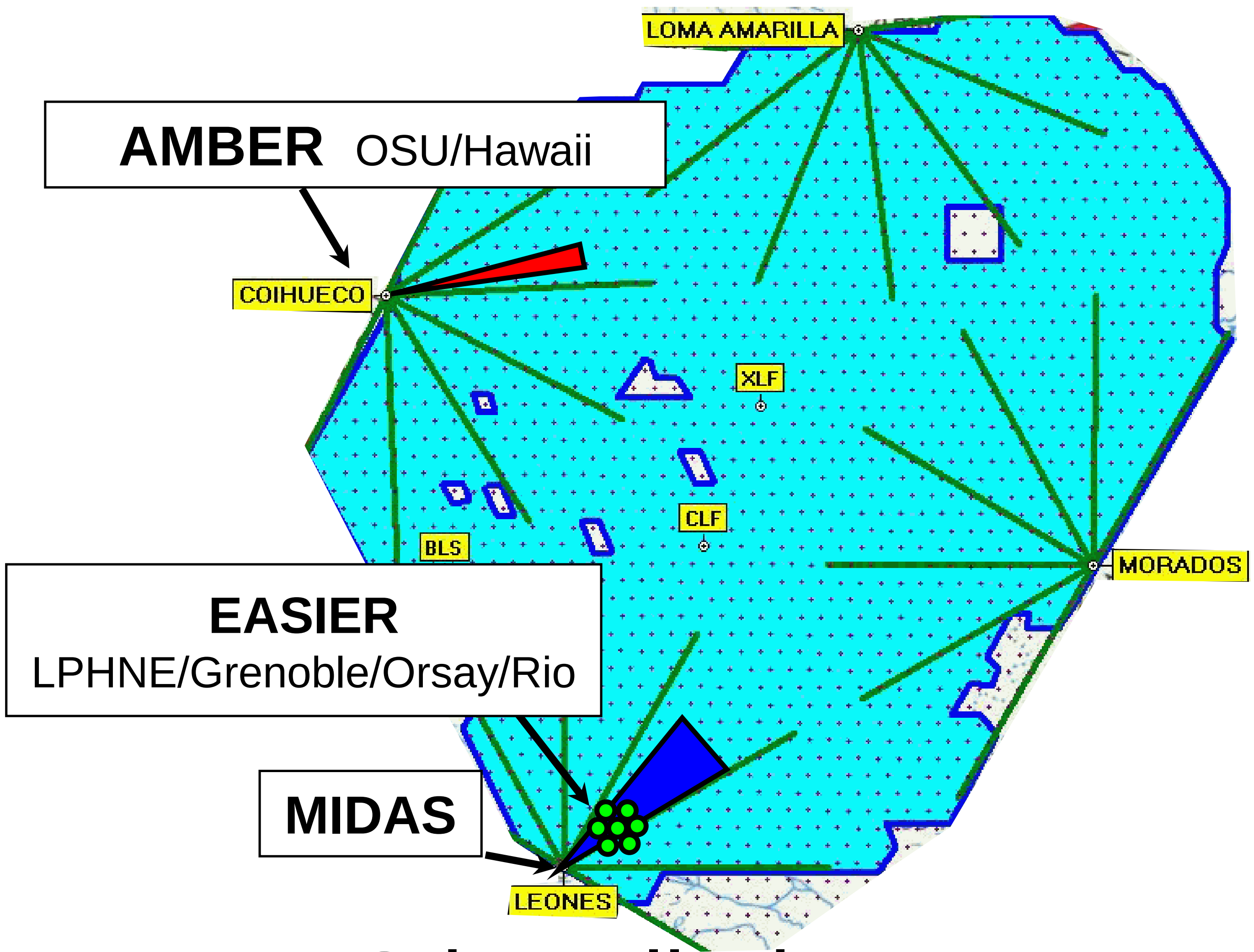


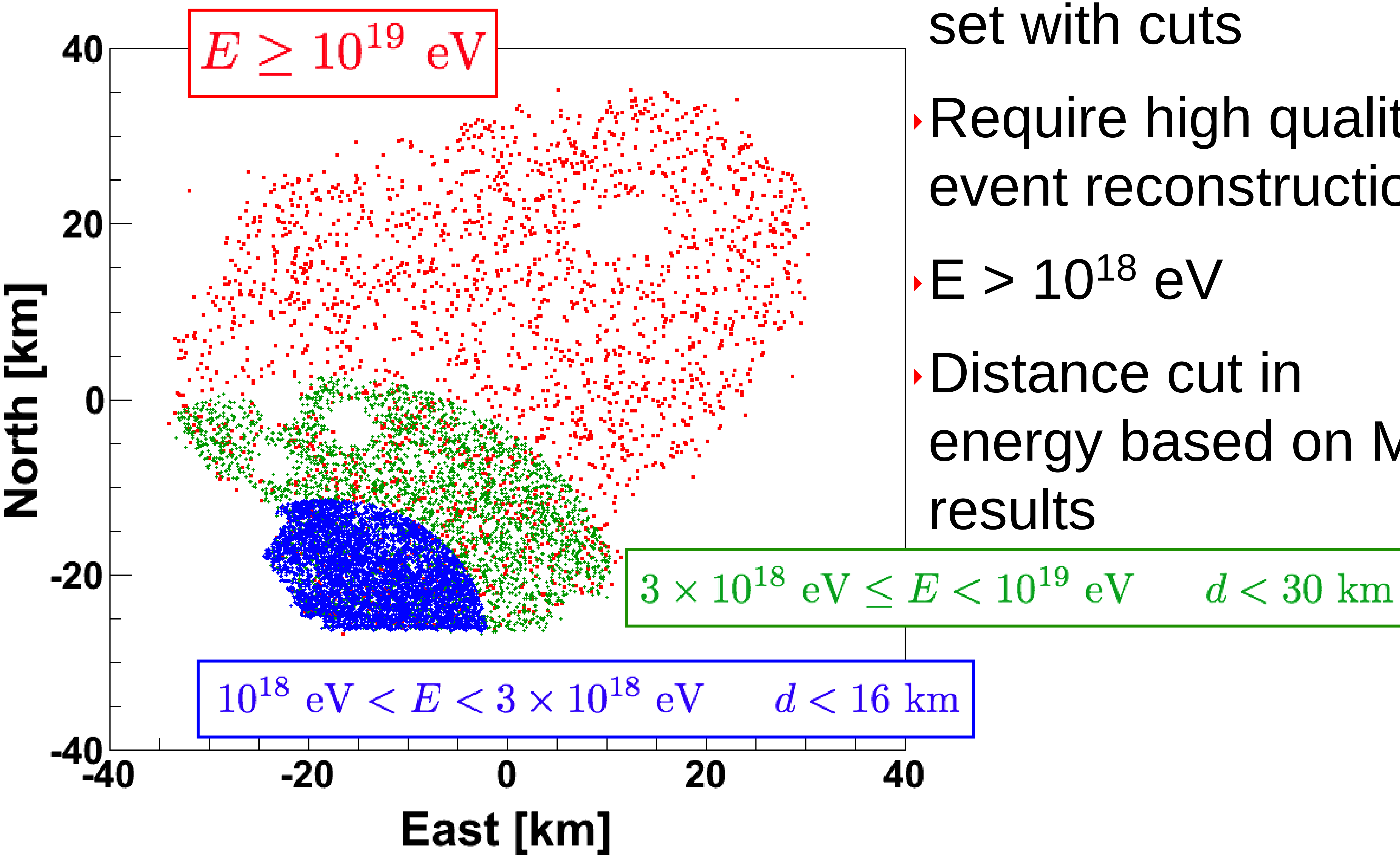
Phys. Rev. D **86**, 051104(R) (2012)

MIDAS at Auger



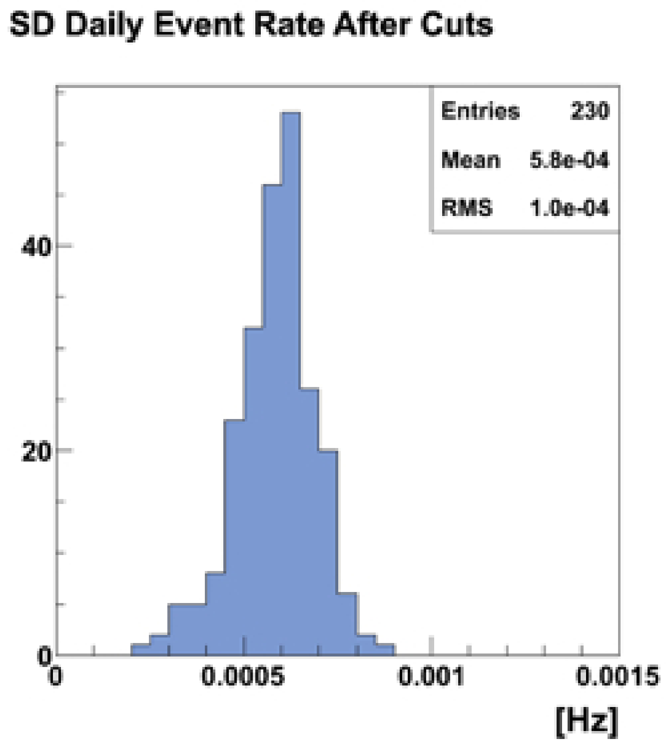
- MIDAS installed at Auger in Sept. 2012
- Data taking operations underway
- Sun calibration pending

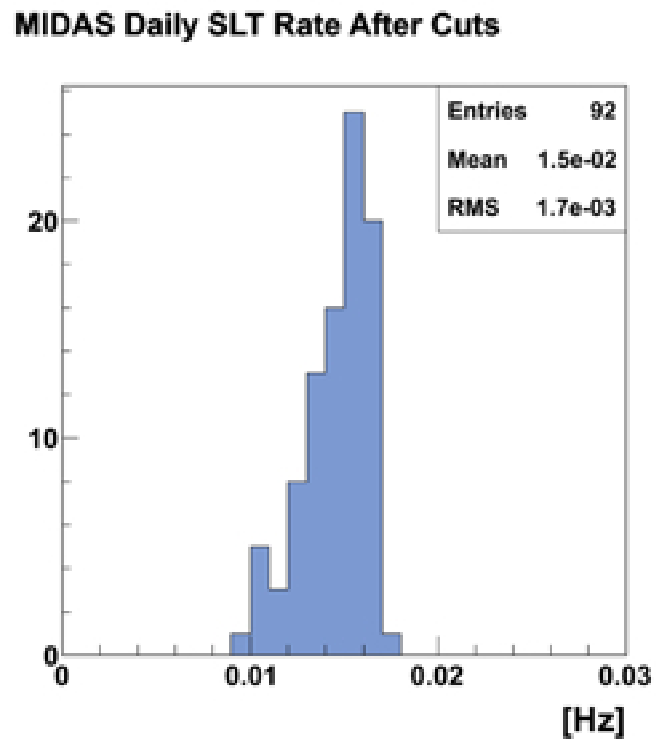
SD Event Matching



- Using Auger SD Data set with cuts
- Require high quality event reconstruction
- E > 10^{18} eV
- Distance cut in energy based on MC results

SD Event Matching

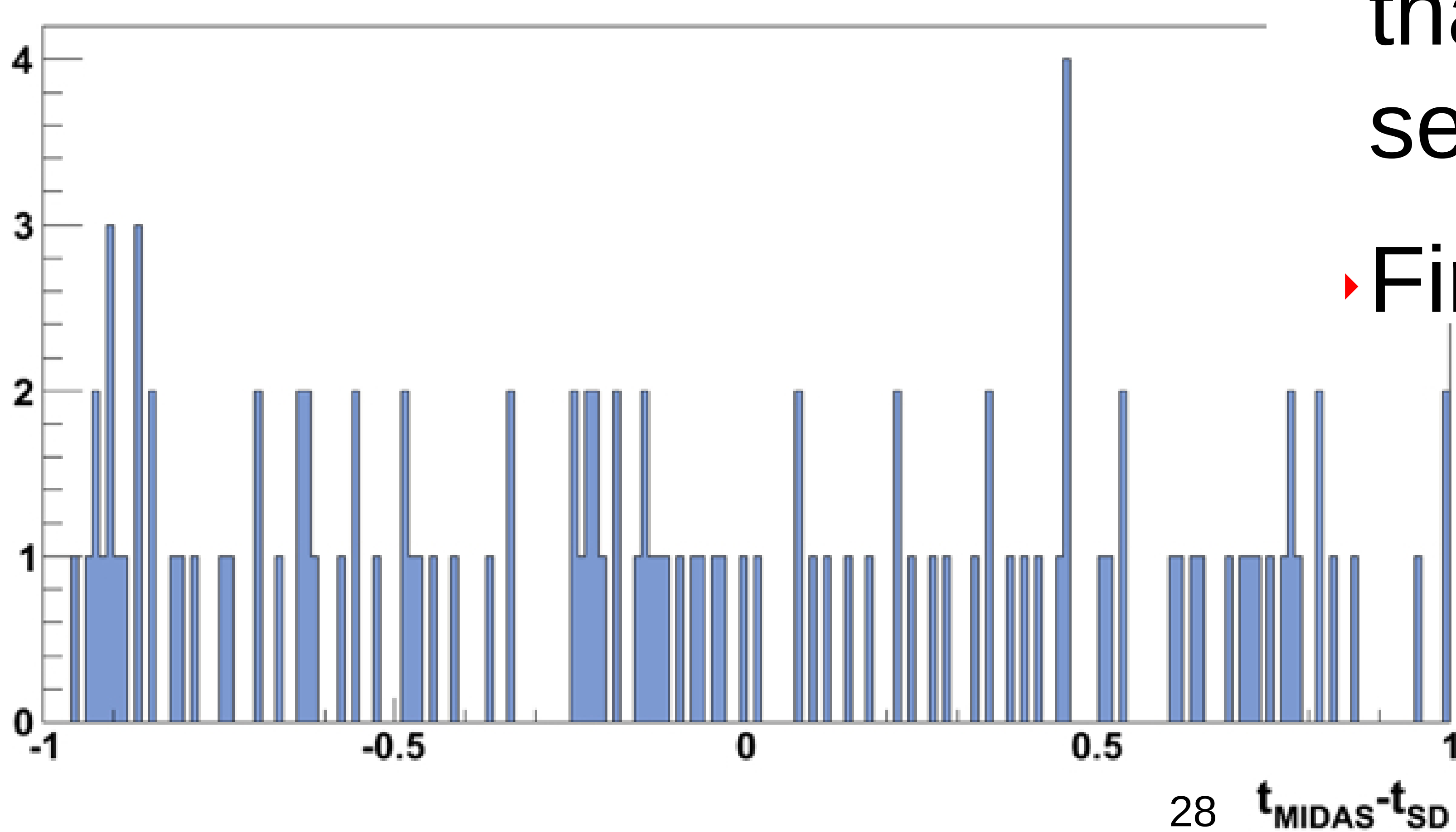




- Use MIDAS SLT Events which are isolated in time by at least 1 second
  - Livetime: 66 days
- Match With SD events that occur within ±1 second
- Find 110 events

$$r_c = r_{SD} \cdot r_{MIDAS} \cdot \tau$$

  - Expect 99.2±9.96 in livetime randomly

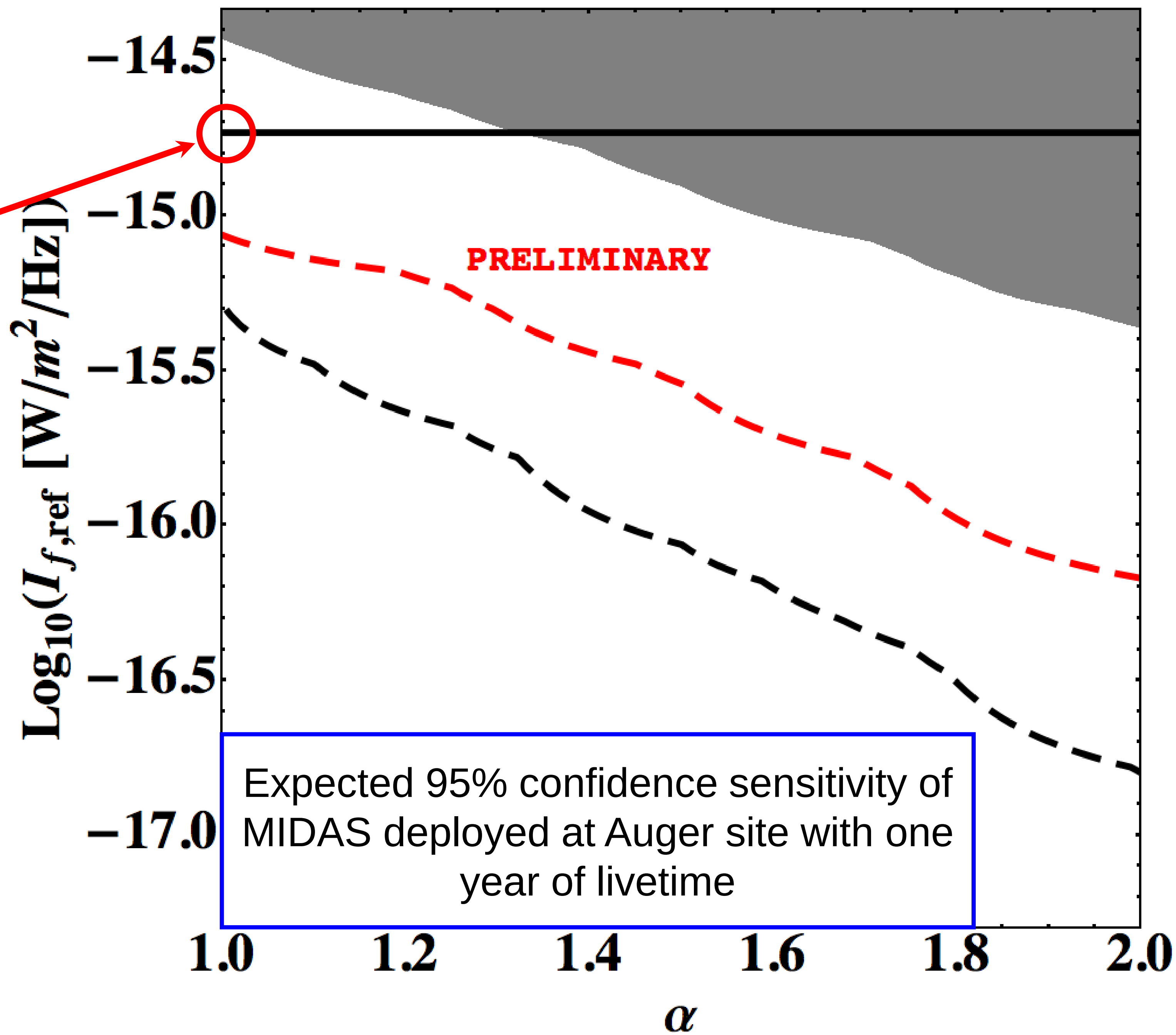


SD Event Matching

95% confidence exclusion with SD event matching and 66 days of livetime data from Auger

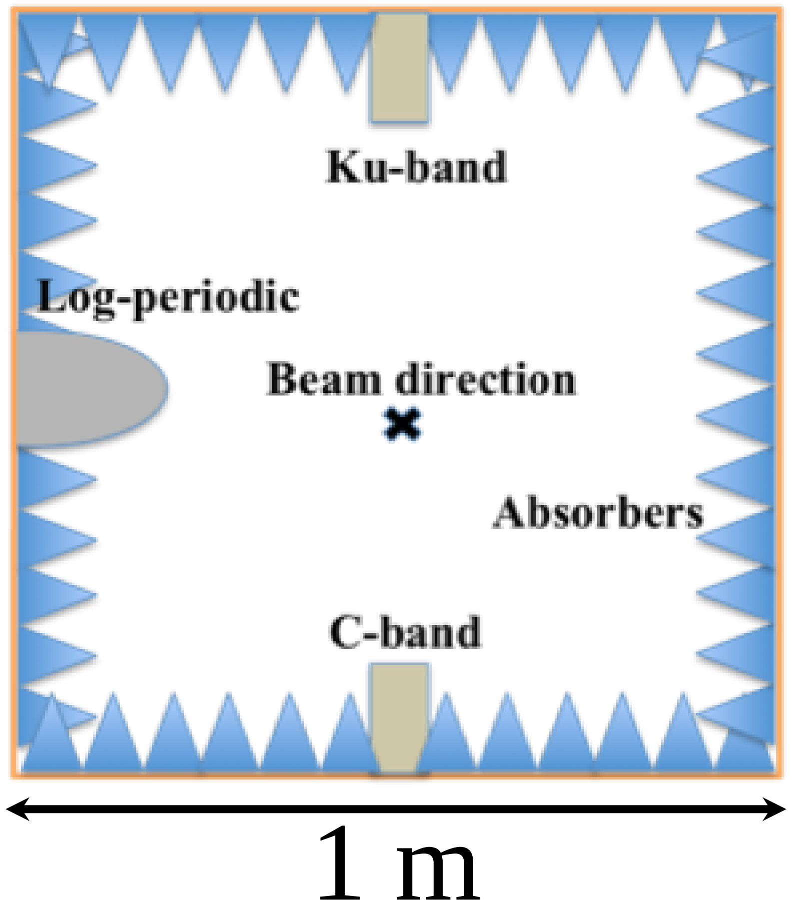
- Assume Chicago MIDAS Calibration

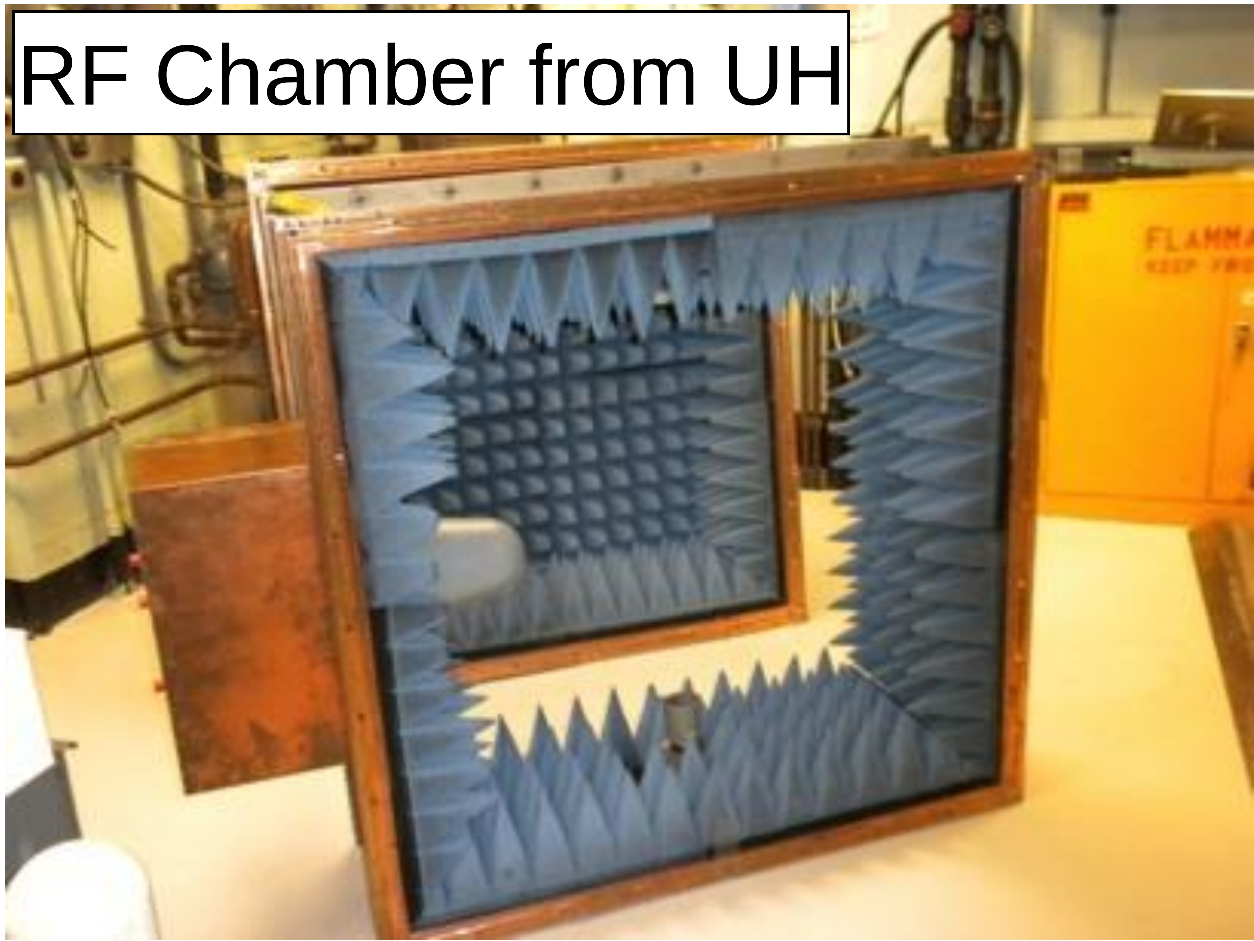
Linear Scaling at Gorham *et al.* power flux ruled out by >4σ



MAYBE Test Set-up

- 1 m^3 RF anechoic chamber, Absorber atten. >30 dB above 1 GHz
- Instrumented with three feed horns
- Main Receiver 850 MHz to 26.5 GHz R&S Log Periodic Antenna
  - Both Pols accessible through physical rotation of antenna
- 3 Miteq low noise amplifiers and low loss coax cable
  - Amplifiers operate well outside stated frequency range



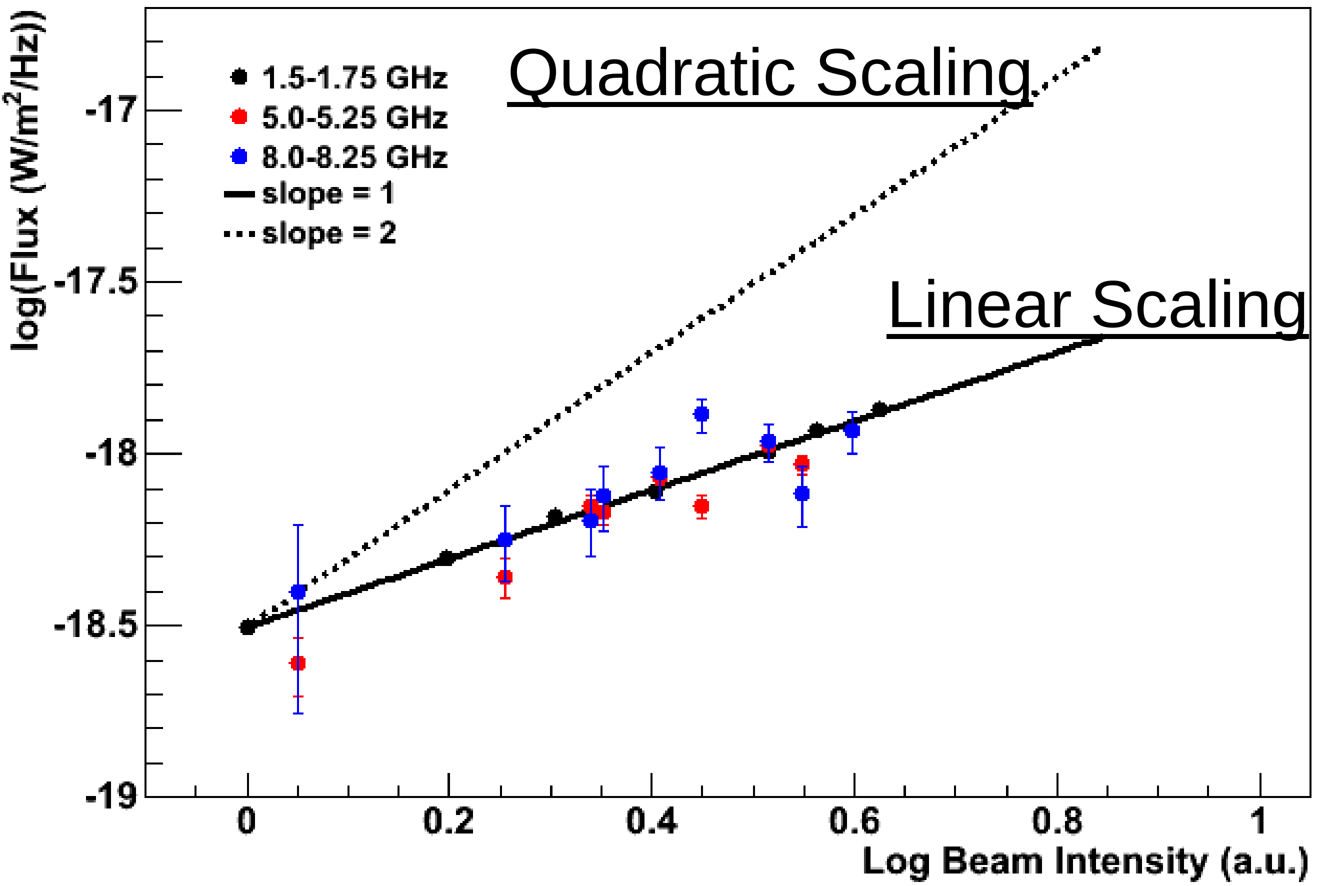


Accelerator

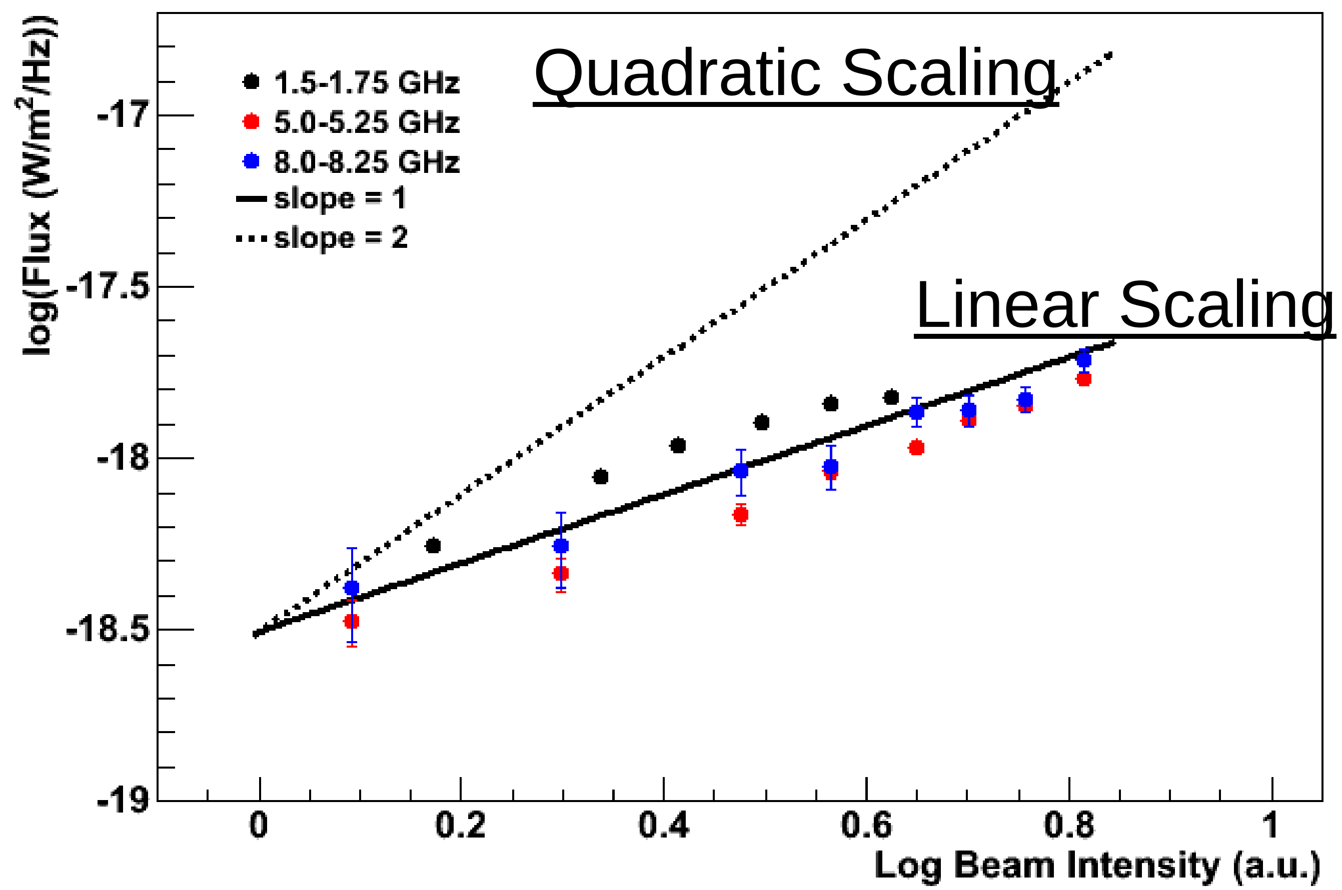
- 3 MeV Van de Graaff at Argonne National Lab, Chemistry Division
- Electrons below Cherenkov threshold
- Pulse length 5 ns to 1 ms
- 1 μs pulse for most data taking

Linearity

Cross-Polarized

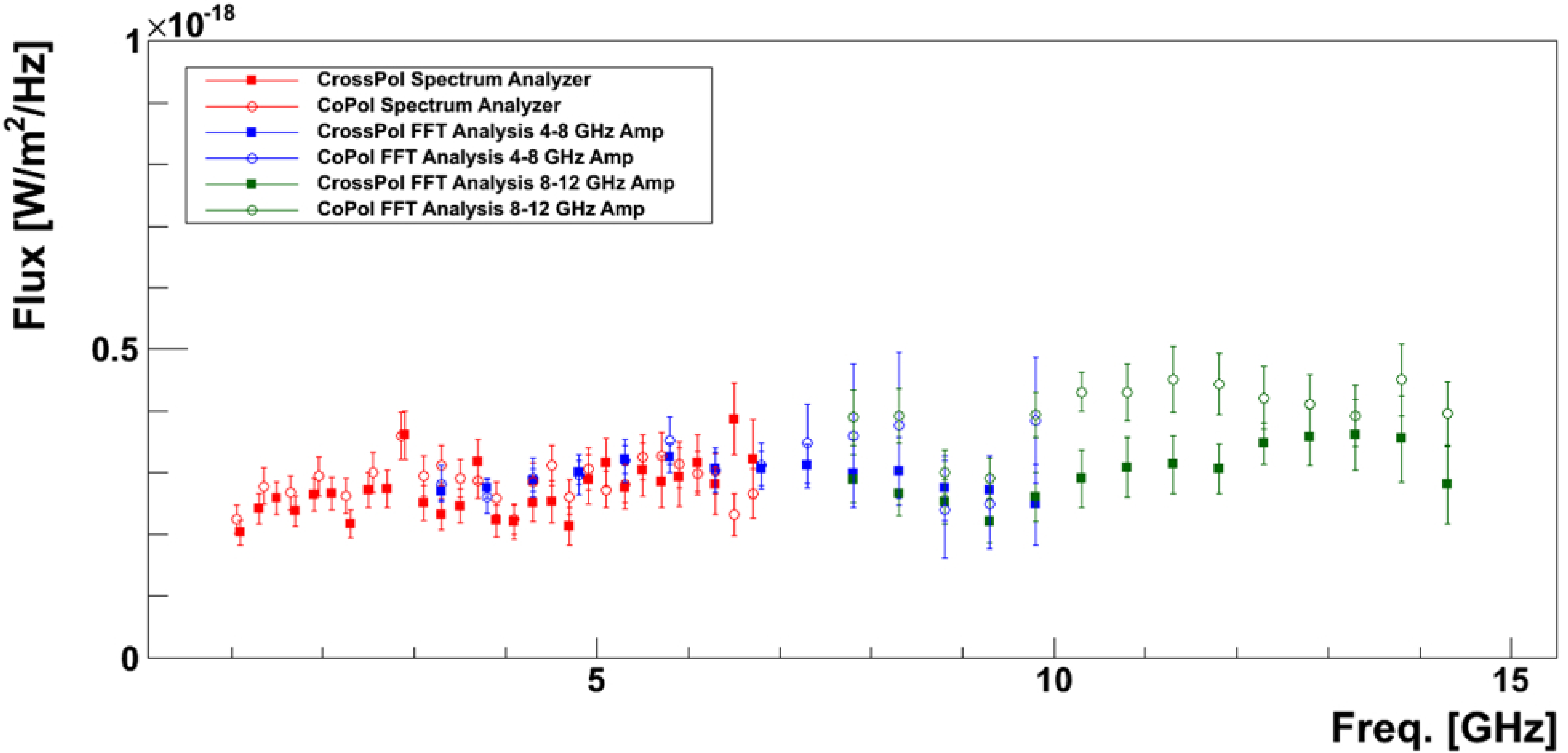


Co-Polarized



- Scan in beam intensity, changing instantaneous electron number
- Average flux from 1000s of traces
- Noise contamination in 1-2 GHz traces creating systematic shift
- Measurement consistent with linear scaling

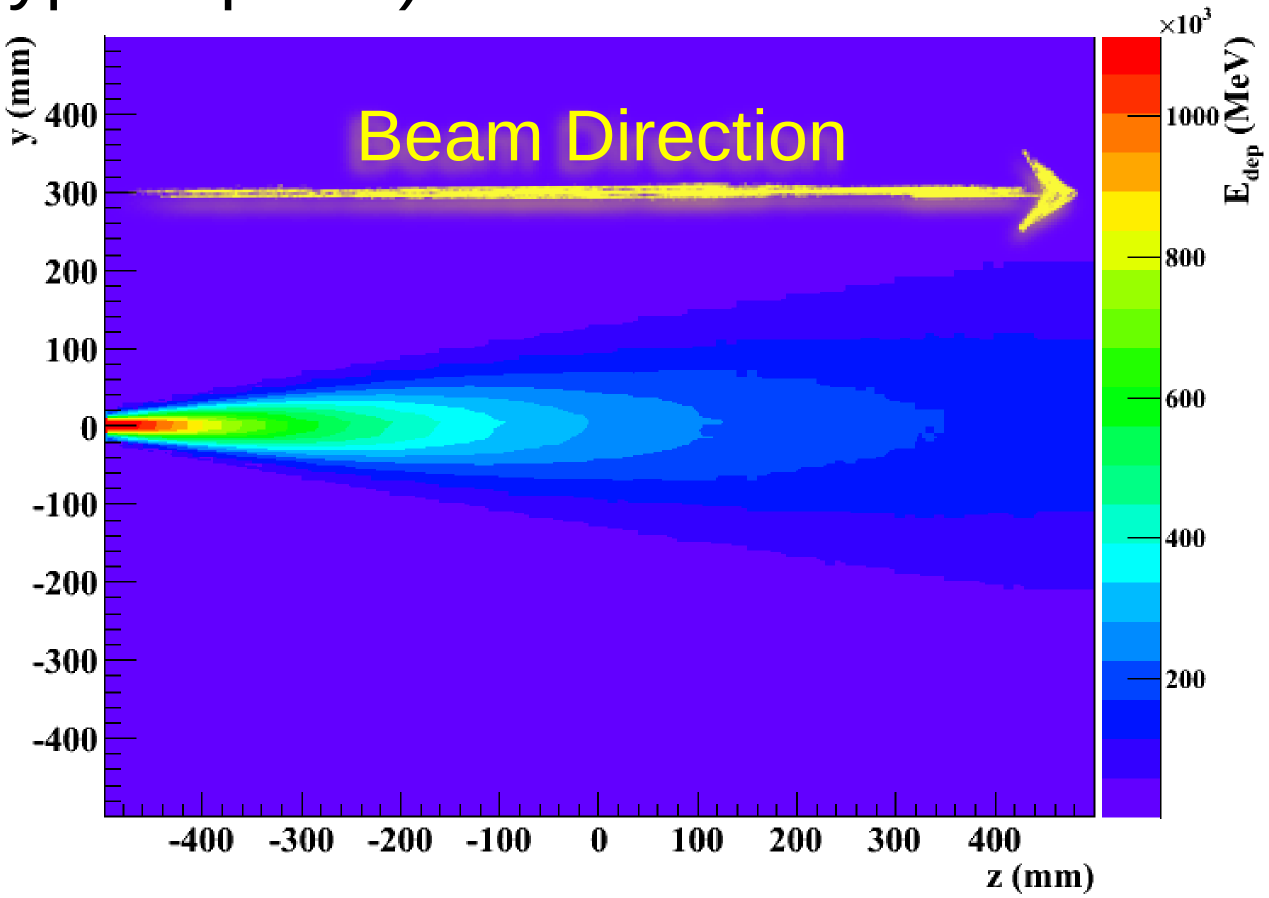
Spectrum

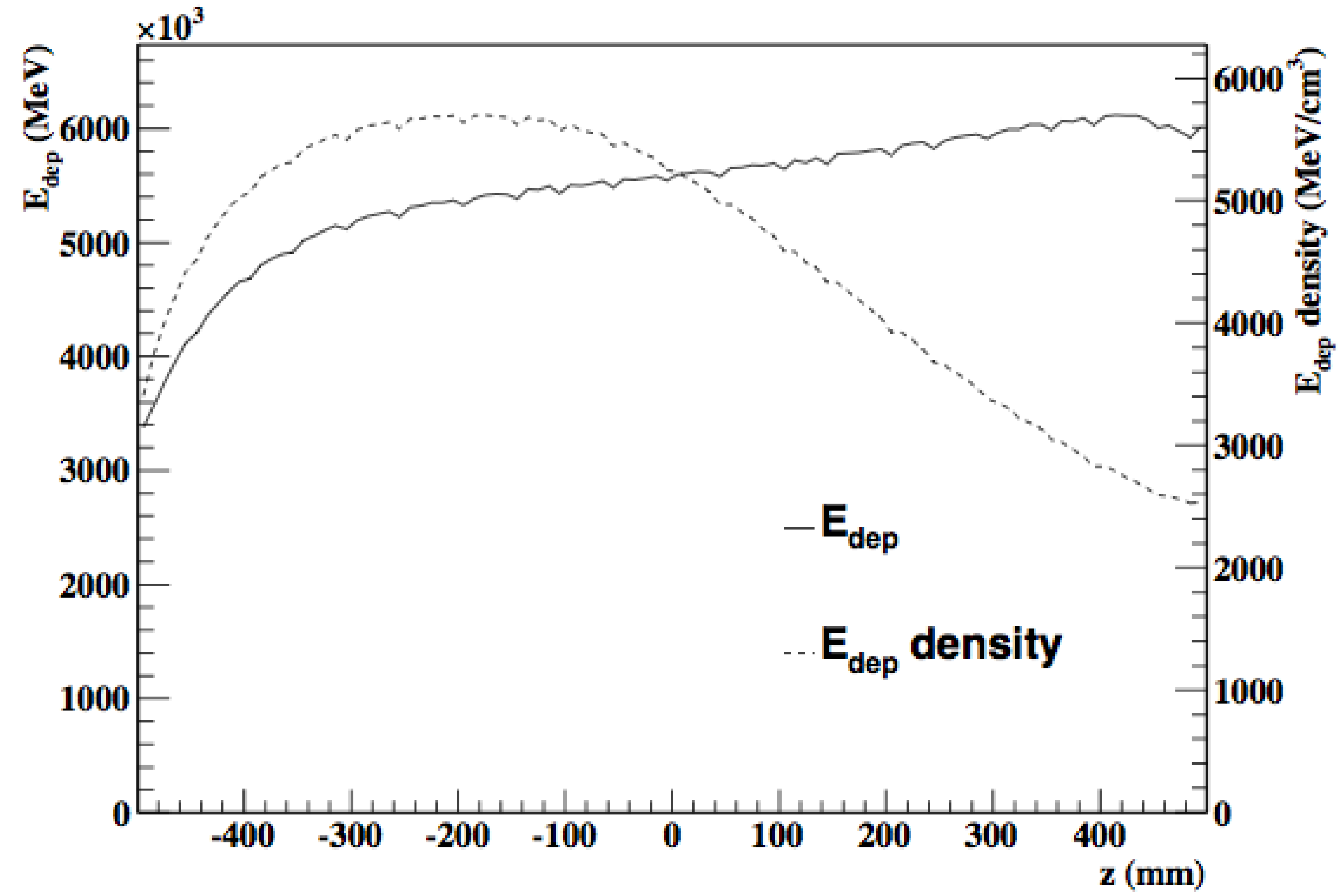


- Emission is unpolarized with a flat spectrum from 1 to 15 GHz
- Consistent with expectations for molecular Bremsstrahlung emission

Simulation

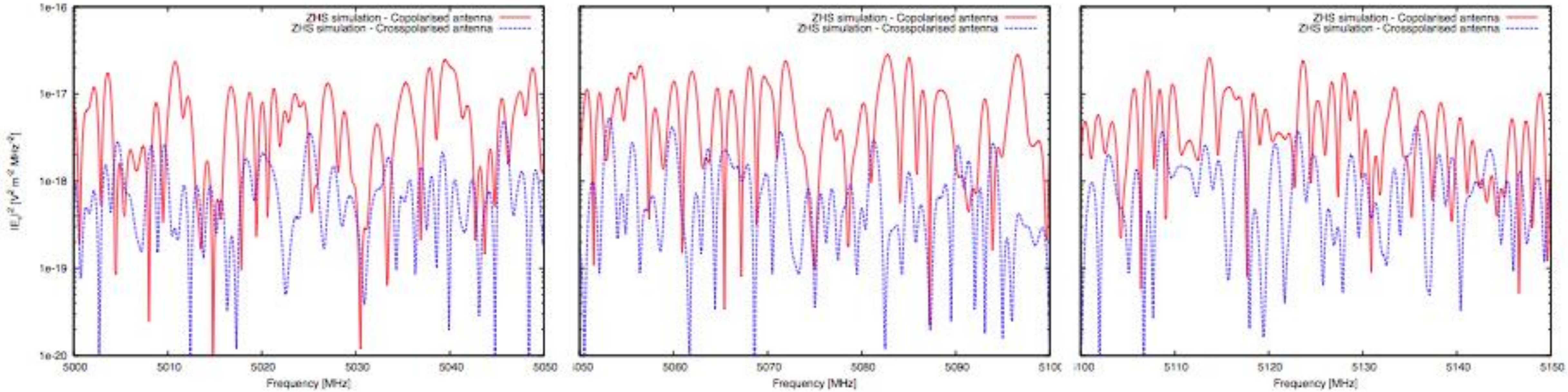
The energy deposit in the chamber is proportional to the number of ionization e^- in the plasma. Simulations for 3×10^9 3 MeV electrons (number of e^- in 3ns for a typical pulse):





- The RMS of the energy deposit cone goes from a few mm to about 15 cm.Total E deposit in the chamber typically: 10^{14}-10^{15} eV (equivalent to the energy deposit at Xmax by a p shower of 10^{18}-10^{19} eV).Edep density: 10^7-10^8 e^-/cm^3 (assuming all the energy deposit is invested in ionization)
- Frequency Domain EM Simulation of electron beam produces a RF signal of similar strength and flat spectrum in the MAYBE frequency range.

Simulation



F_ν units of 10^{-18} W m^{-2} Hz^{-1} - 10^{13} electrons			
Band	1.5 - 1.75 GHz	5 - 5.25 GHz	8 - 8.25 GHz
copol	0.76	0.77	0.78
Cross-pol	0.25	0.25	0.26

Within 50% of measured signal

- The RMS of the energy deposit cone goes from a few mm to about 15 cm.Total E deposit in the chamber typically: 10^{14}-10^{15} eV (equivalent to the energy deposit at Xmax by a p shower of 10^{18}-10^{19} eV).Edep density: 10^{7}-10^{8} e^{-}/cm^{3} (assuming all the energy deposit is invested in ionization)
- Frequency Domain EM Simulation of electron beam produces a RF signal of similar strength and flat spectrum in the MAYBE frequency range.

Beam to EAS Scaling

For an air shower of 3×10^{17} eV, assuming linear scaling, emission at maximum:

$$I_{f,ref}^{\mathrm{MAYBE}} \leq 10^{-20}\ \mathrm{W/m^2/Hz}$$

- This value much lower than previous measurements (1.85×10^{-15} W/m^2/Hz)
- Possible Cherenkov contamination in Gorham *et al.*?

→ Caveats:

→ Plasma created by beam not identical to air showers in electron spectrum

→ Size scale of energy deposit in shower larger than test beam conditions

→ Measurement by detectors operating in coincidence with existing UHECR experiments only way to solve this puzzle

Conclusions

- Using the results of MIDAS and MAYBE we have set the strongest limits to date on the isotropic microwave emission from EAS
- Building microwave replacements for UHECR detectors remains very challenging
- Microwave designs continue to be pursued to detect EAS forward emission.

- Future…Go Bigger! Get Composition!