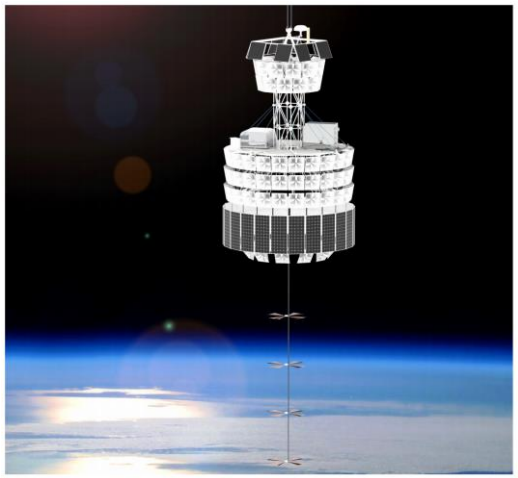
Probing extreme-energy universe with EeV neutrino detection

Improving Radio Frequency Detectors with Programmable Logic at ANITA and PUEO

C. Xie
University College London



PAYLOAD FOR ULTRAHIGH ENERGY OBSERVATIONS

RF integrated Programmable Logic
(RADIO FREQUENCY SYSTEM-ON-CHIP)

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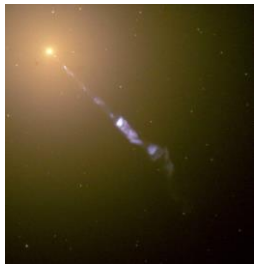

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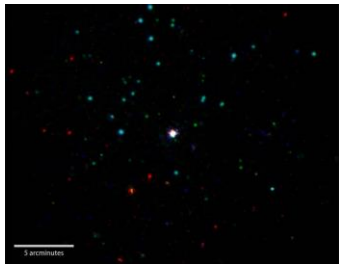

GRB 151027B

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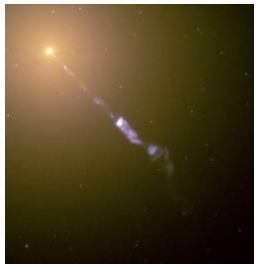

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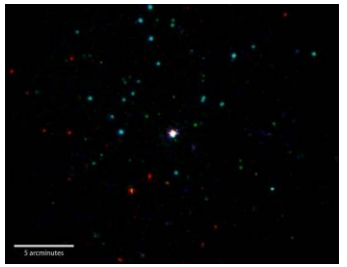

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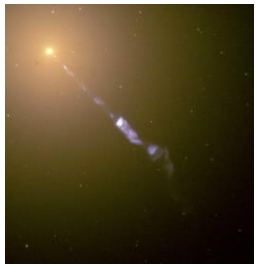

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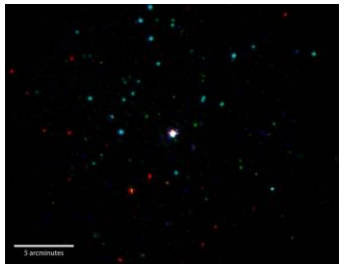

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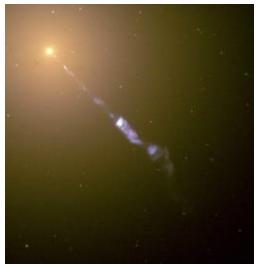

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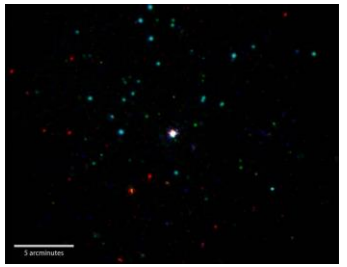

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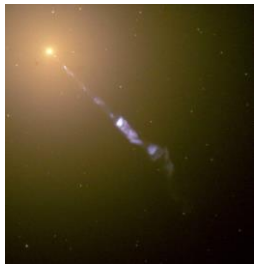

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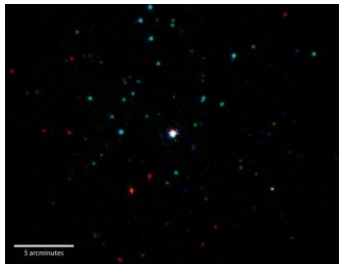

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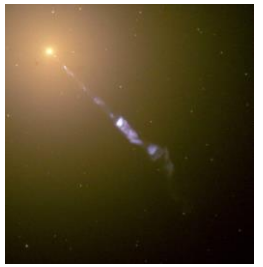

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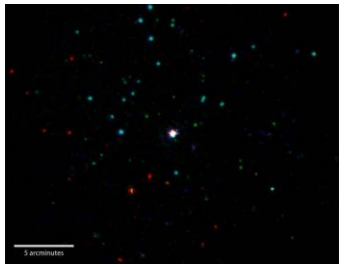

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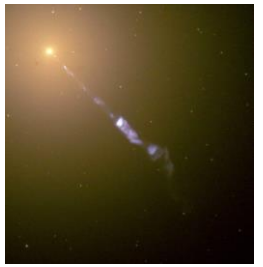

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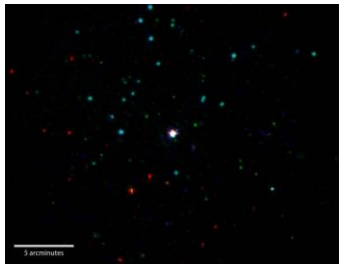

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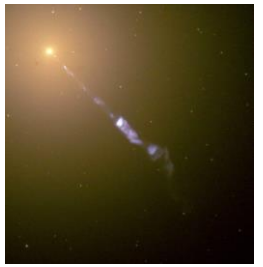

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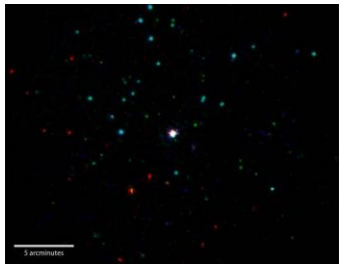

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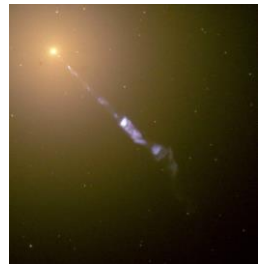

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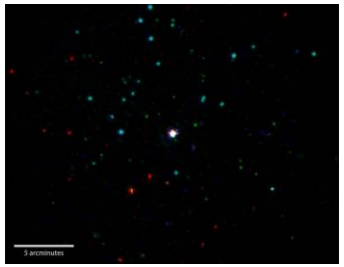

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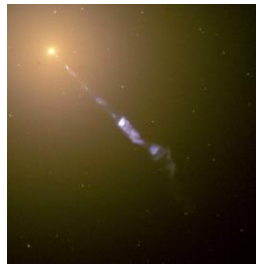

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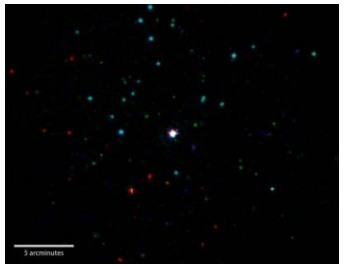

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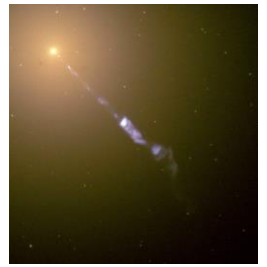

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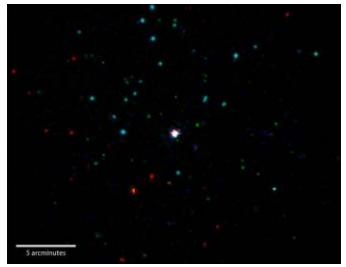

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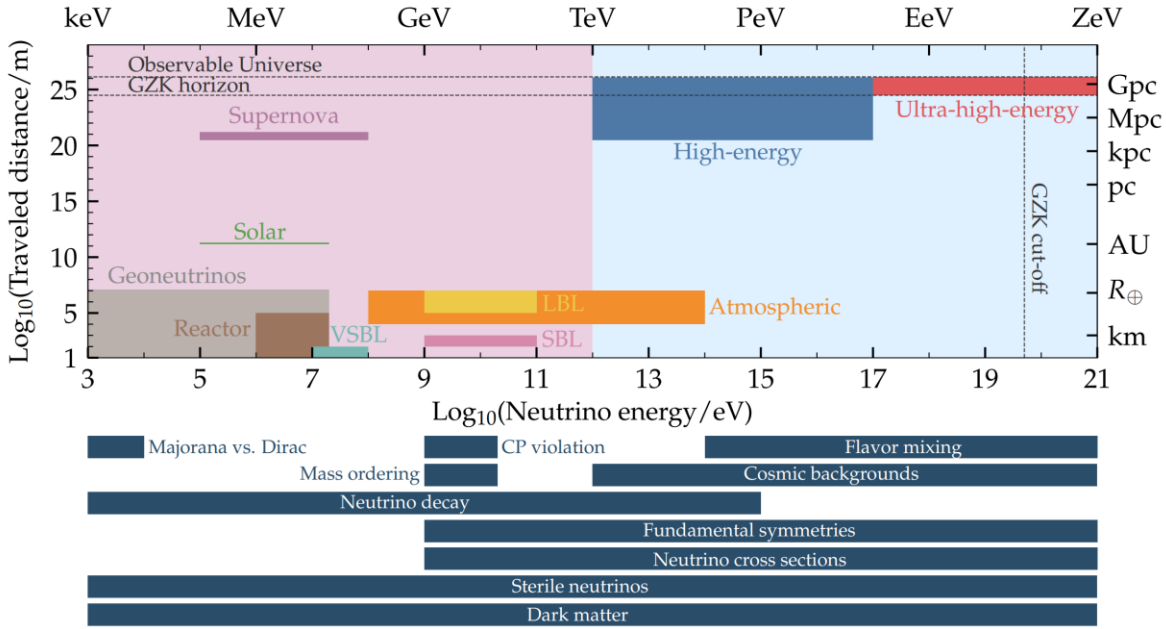

arXiv 1903.04333

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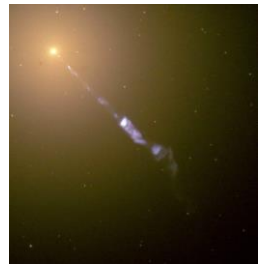

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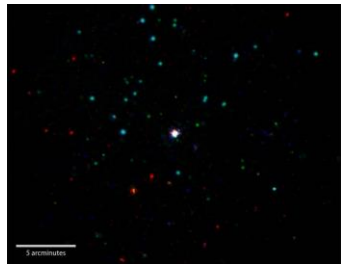

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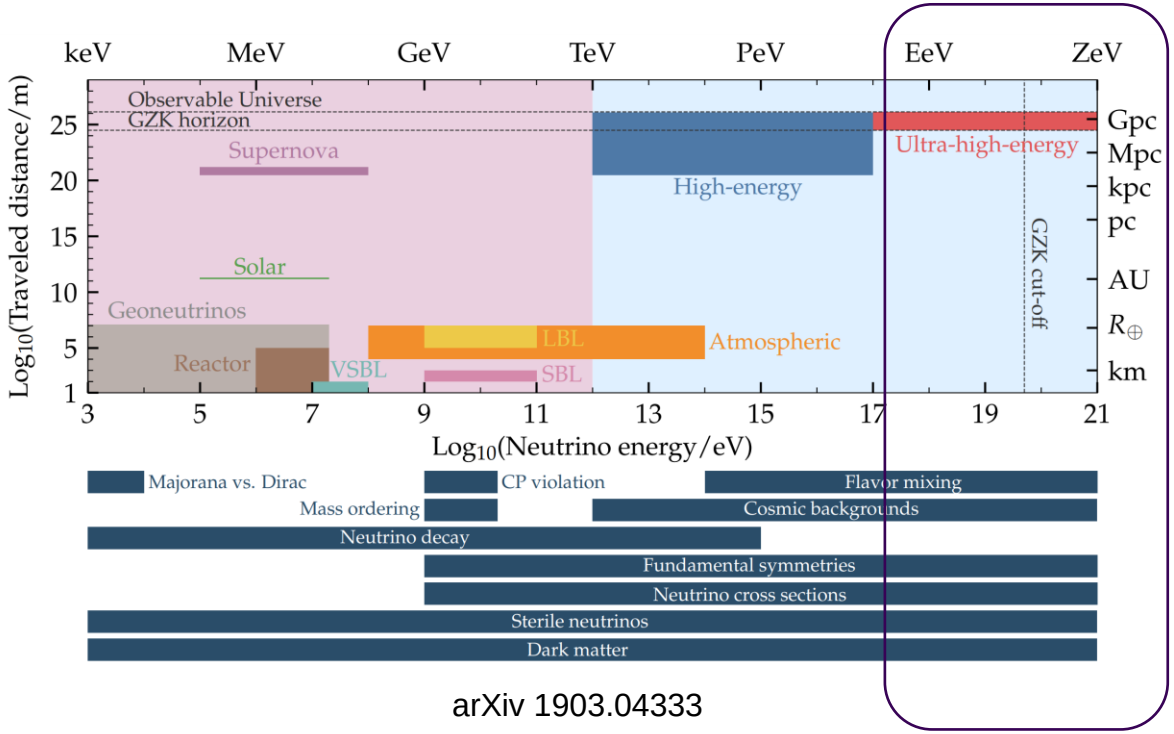

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ANITA overview

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Antarctic Impulsive Transient Antenna

- Long duration balloon payload

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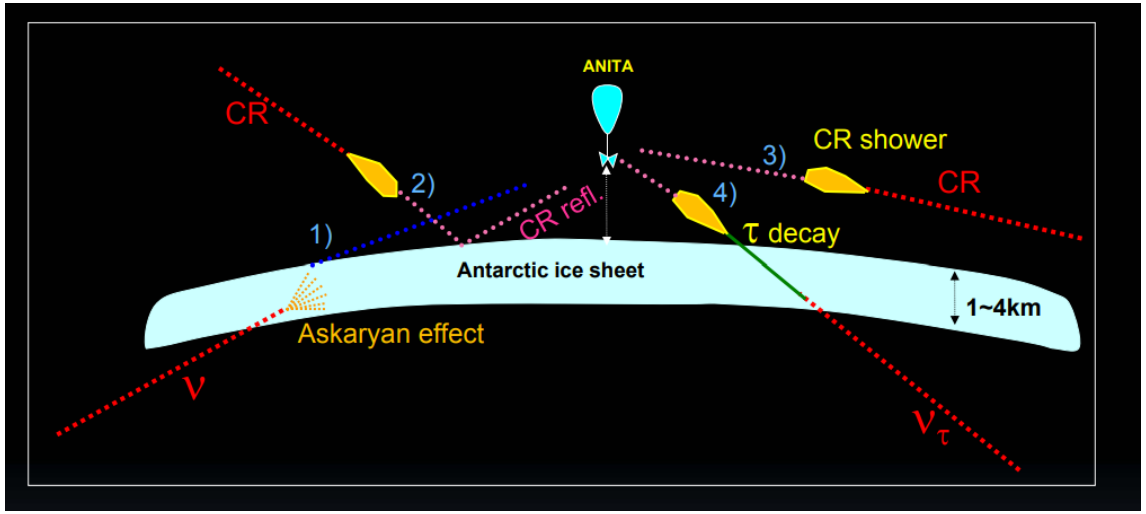
ANITA & PUEO - main signatures



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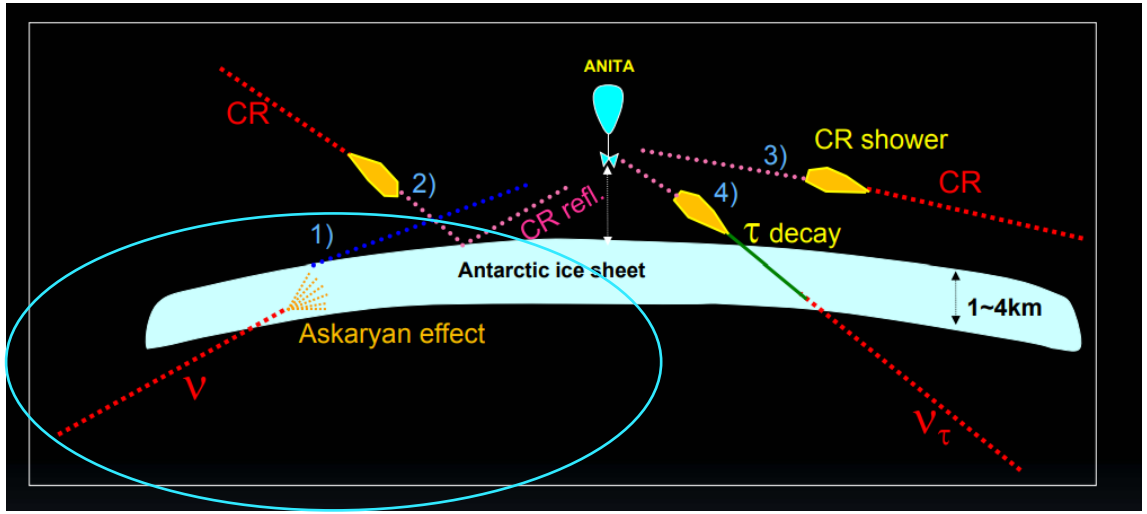

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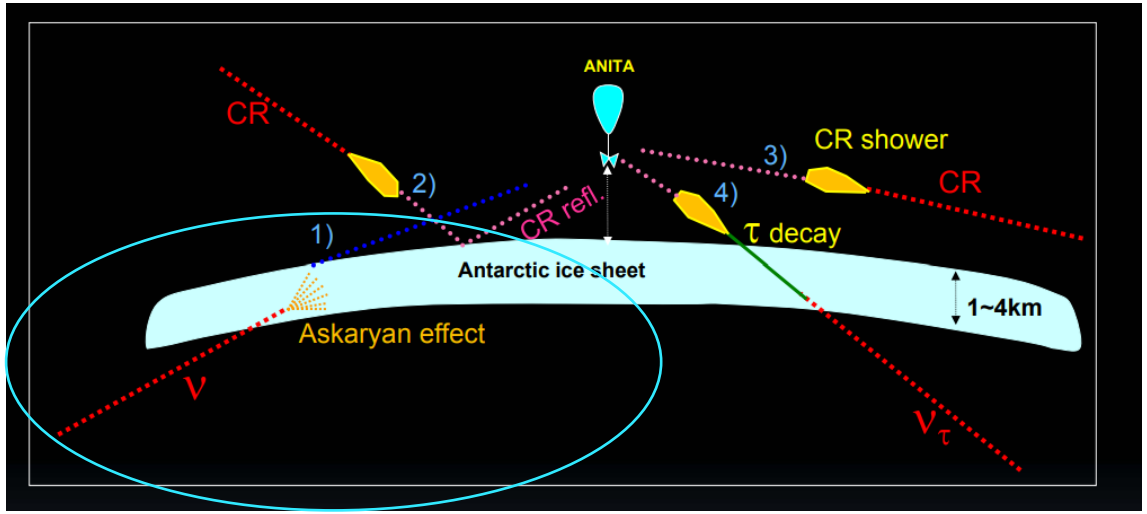

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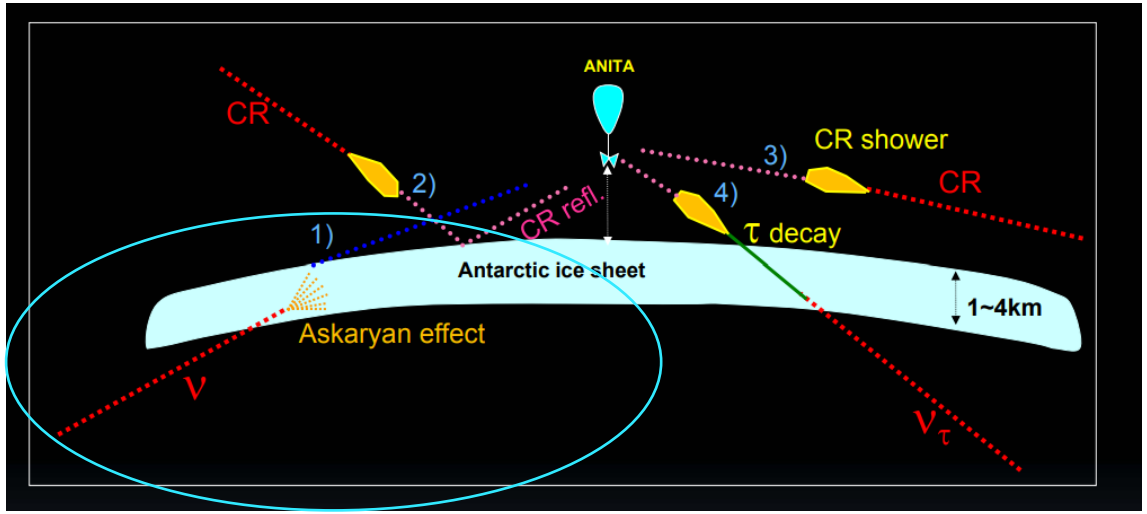

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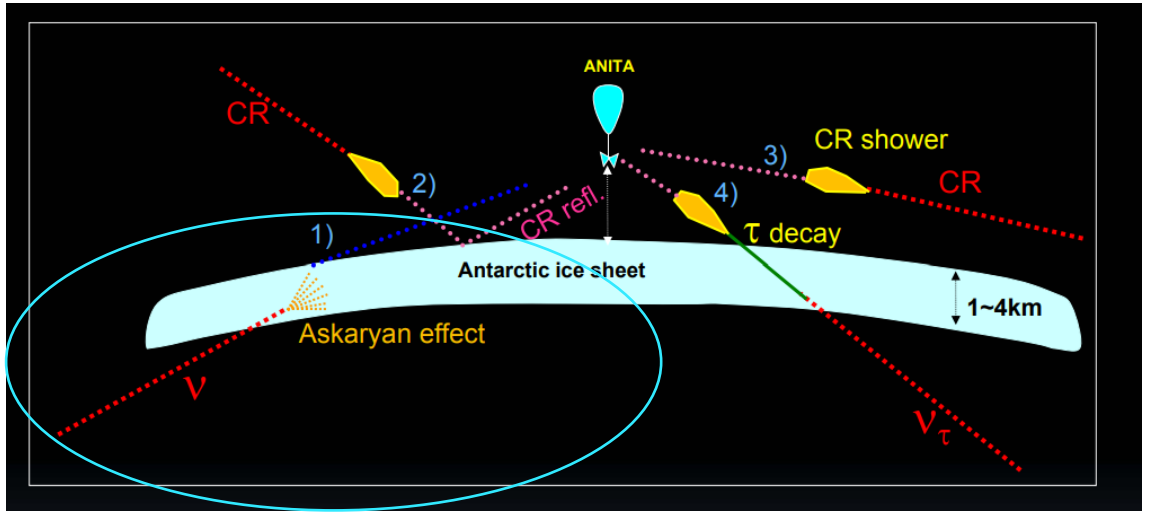

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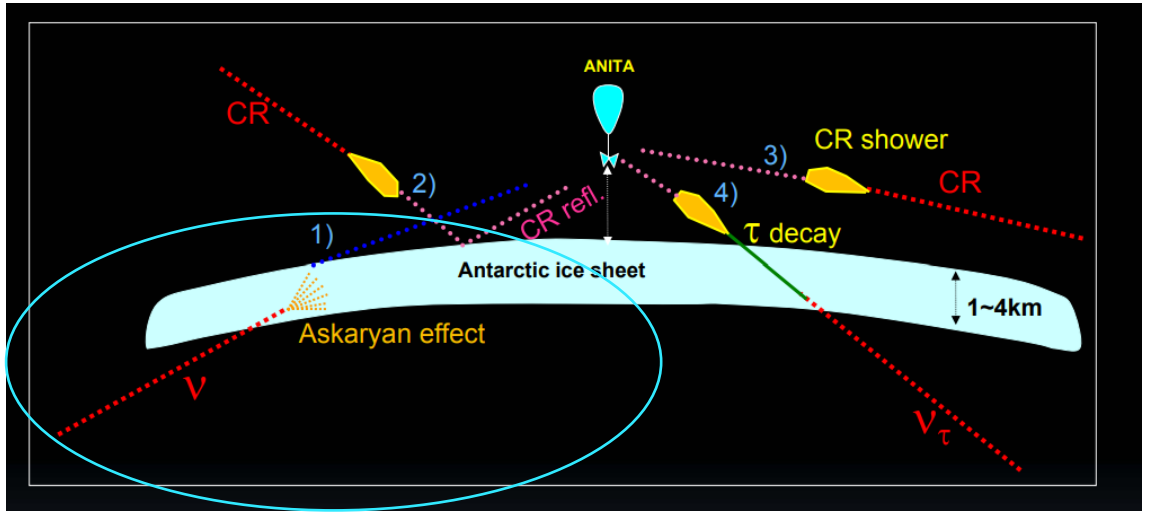

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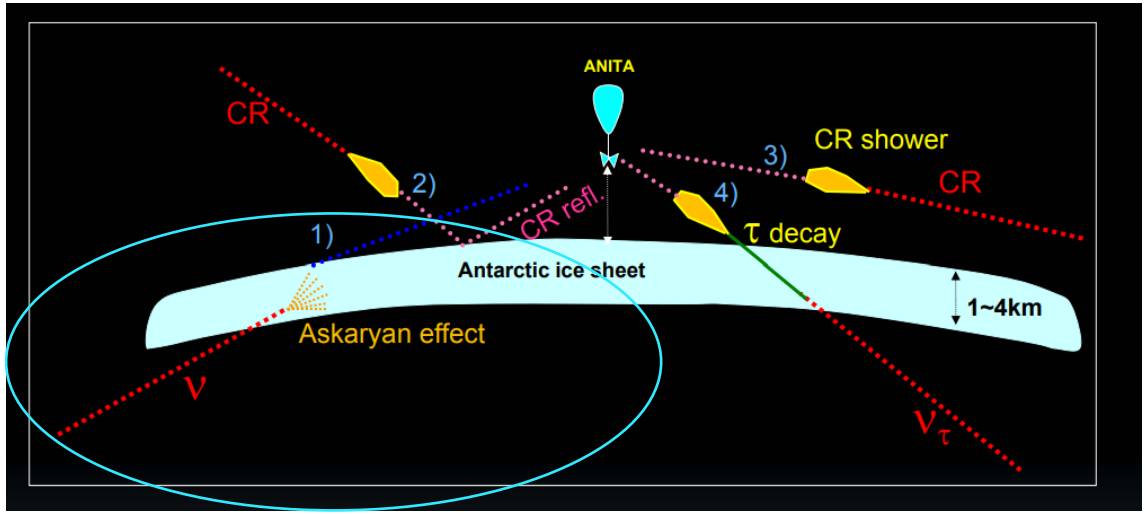

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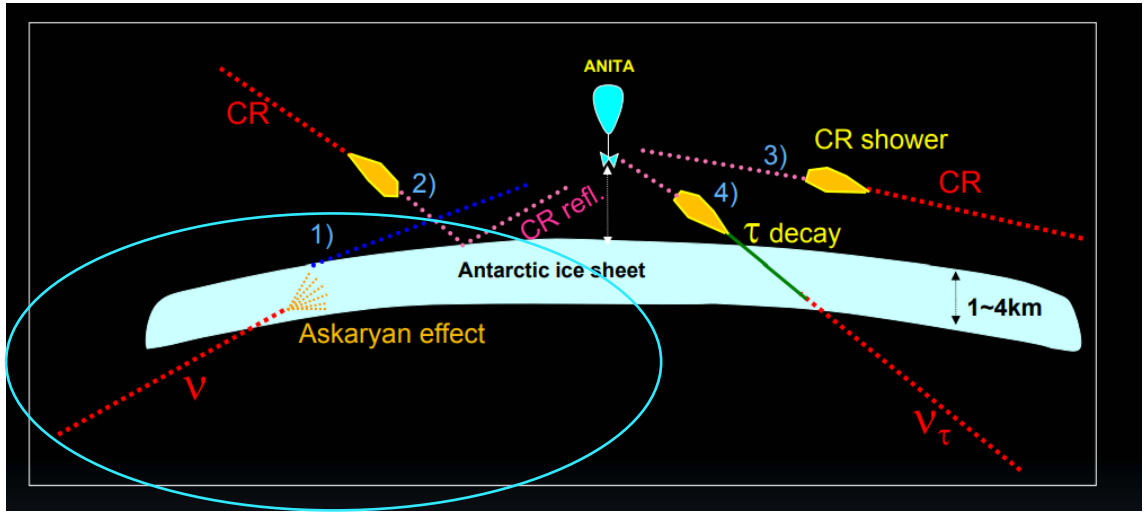

PUEO overview

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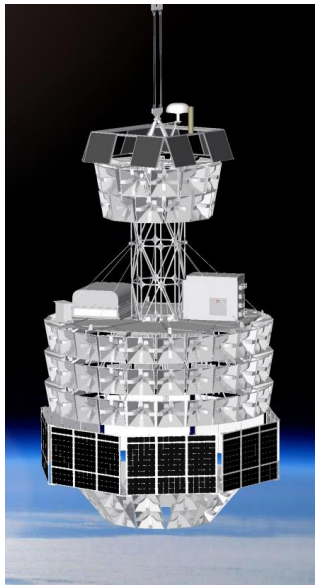
Next generation: Payload for Ultrahigh Energy Observations

ANITA

PUEO



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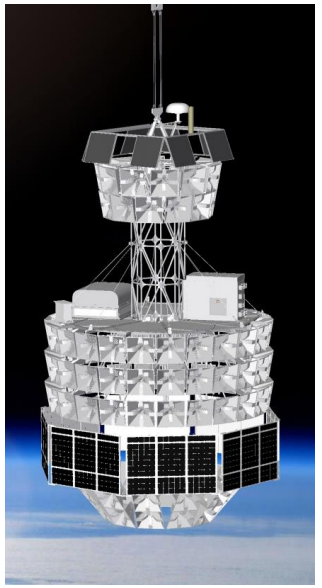
Next generation: Payload for Ultrahigh Energy Observations

216 antennas (vs. 48 on ANITA-IV) + Programmable Hardware (RFSoC)

ANITA

PUEO



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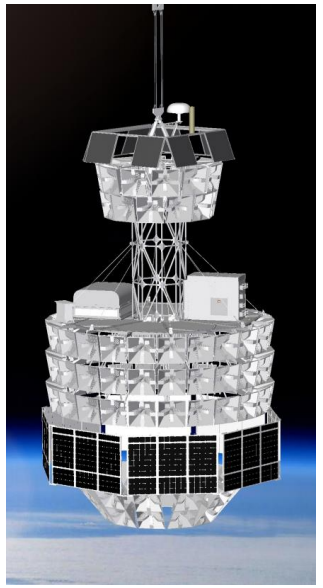

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Programmable hardware

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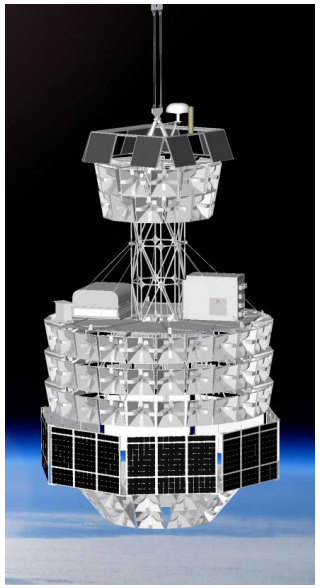

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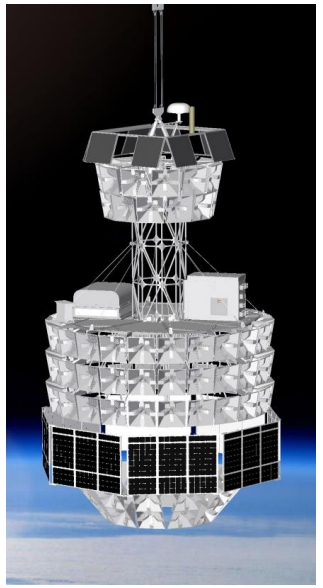
- Additional benefits
  - Real time digital filtering of radio interference
  - Improved pointing resolution

ANITA

PUEO



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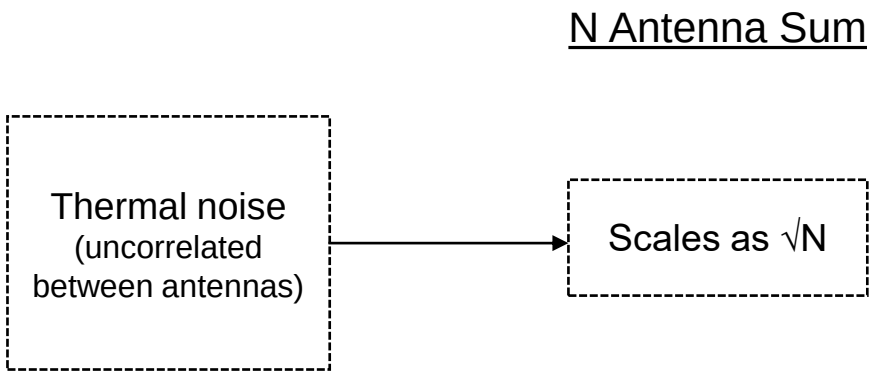

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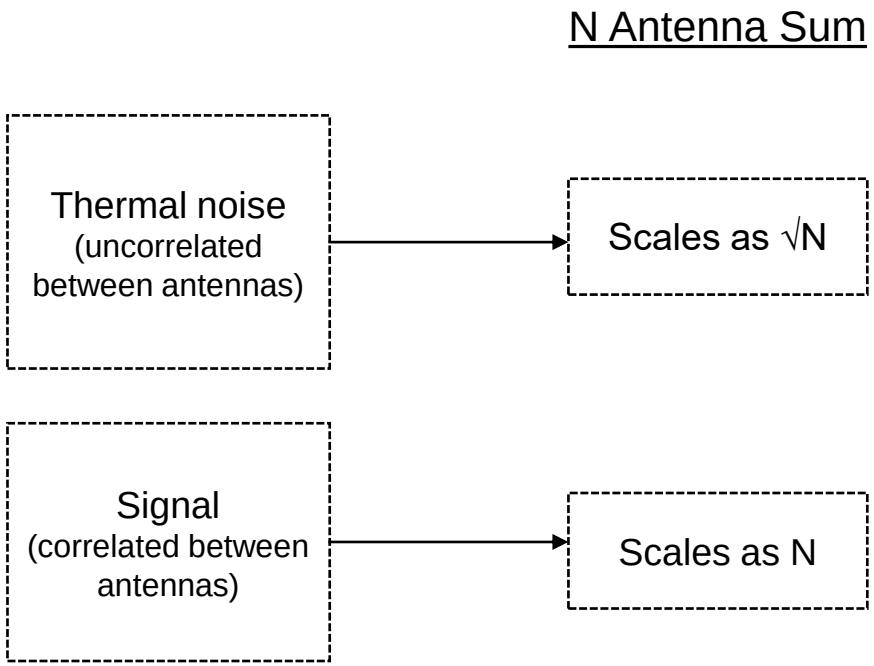

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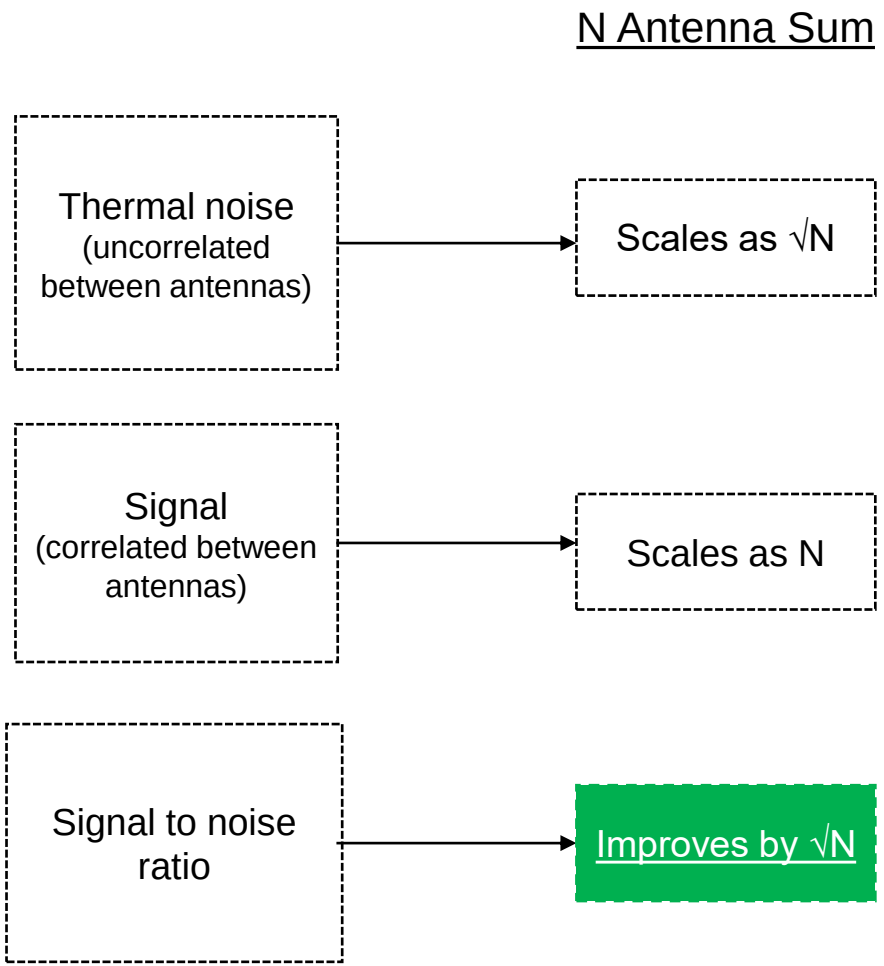

➔ Lowers trigger threshold, improving detector sensitivity

Beamforming – why and how?

N Antenna Sum

Thermal noise (uncorrelated between antennas) → Scales as √N

Signal (correlated between antennas) → Scales as N

Signal to noise ratio → Improves by √N

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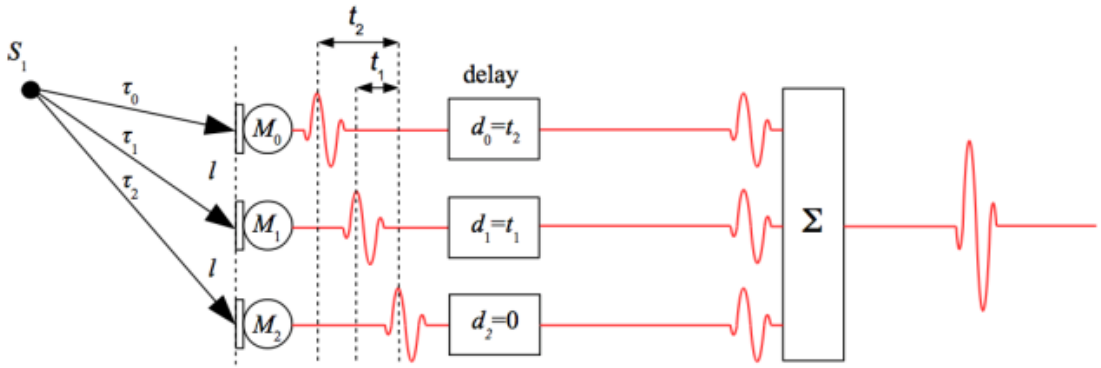
Geometry requires ‘delay and sum’



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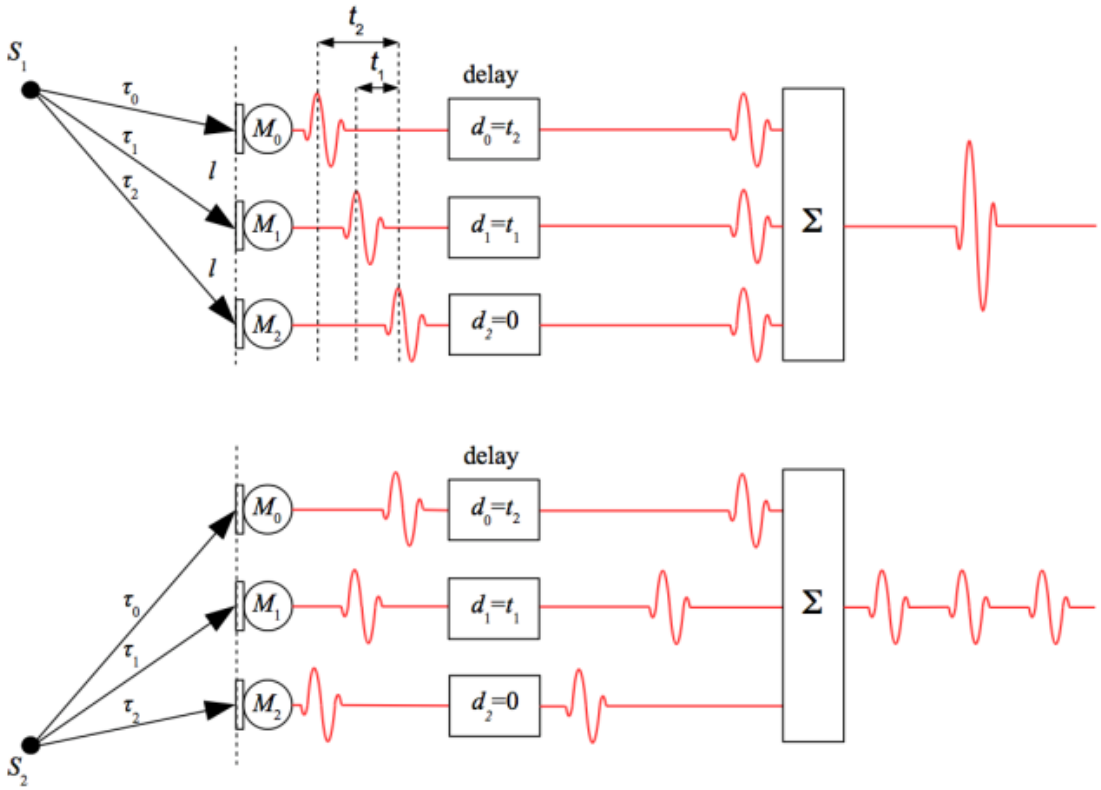

➔ Multiple beams required for different sources locations

Beamforming – why and how?

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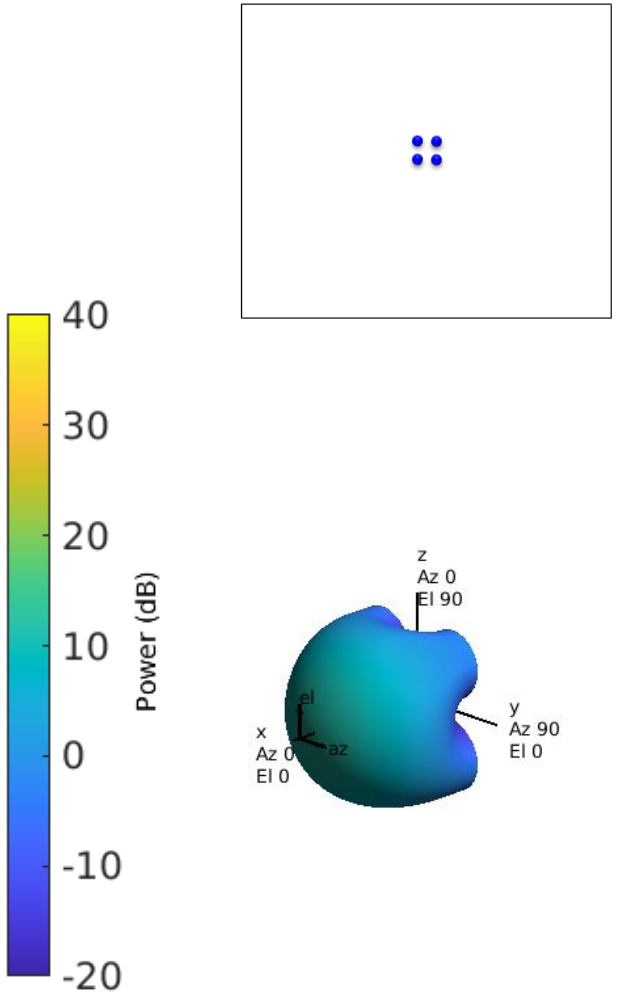

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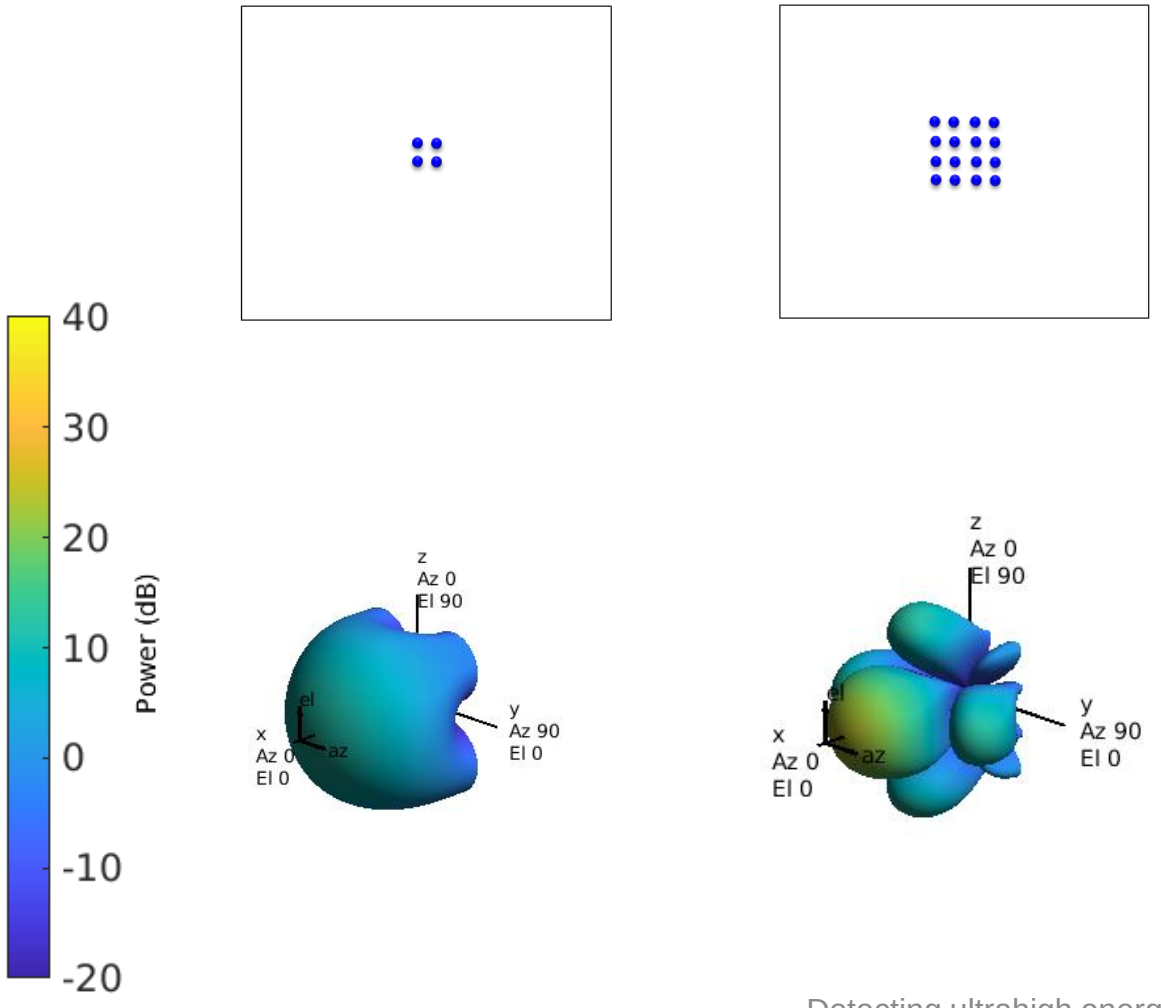

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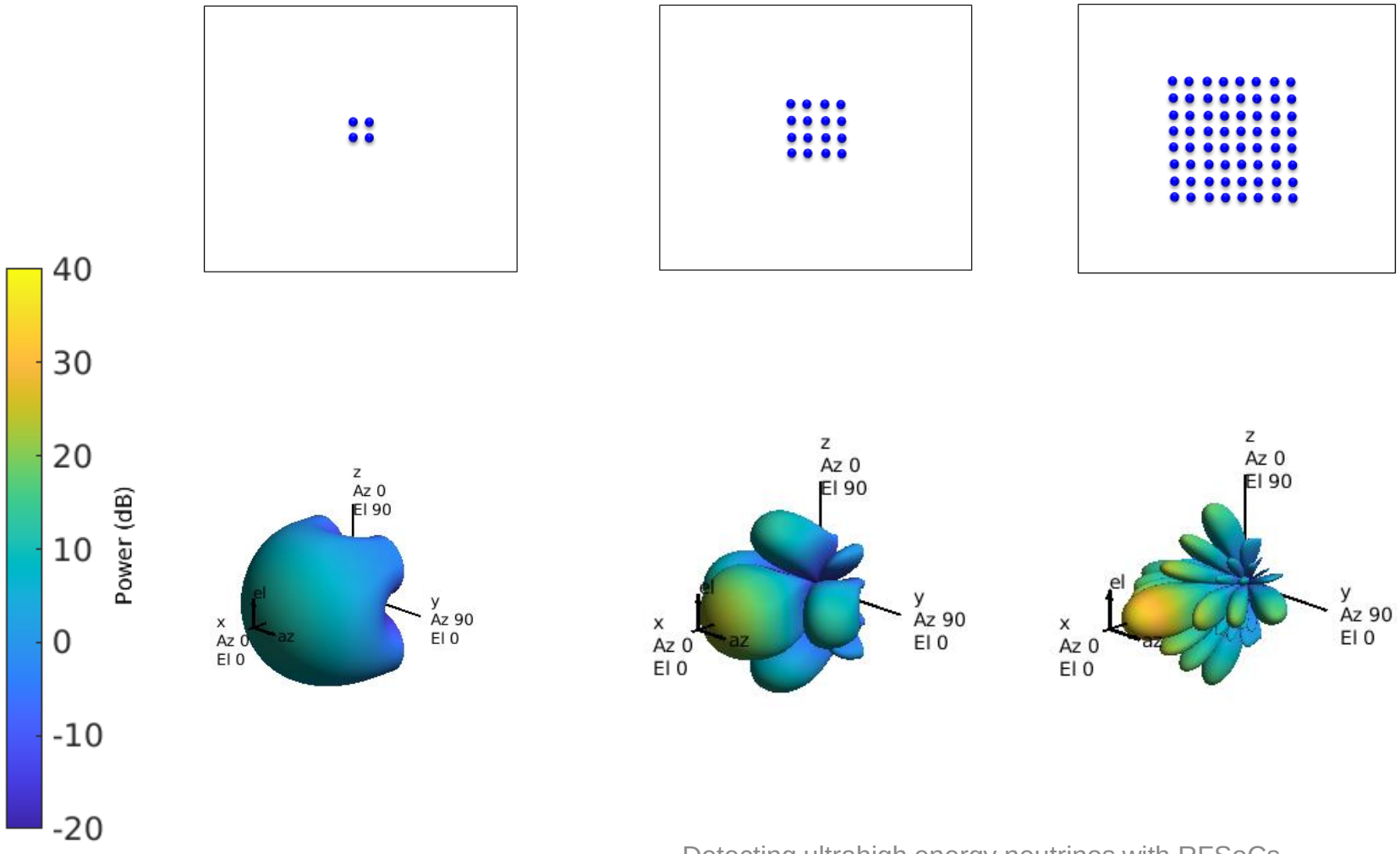

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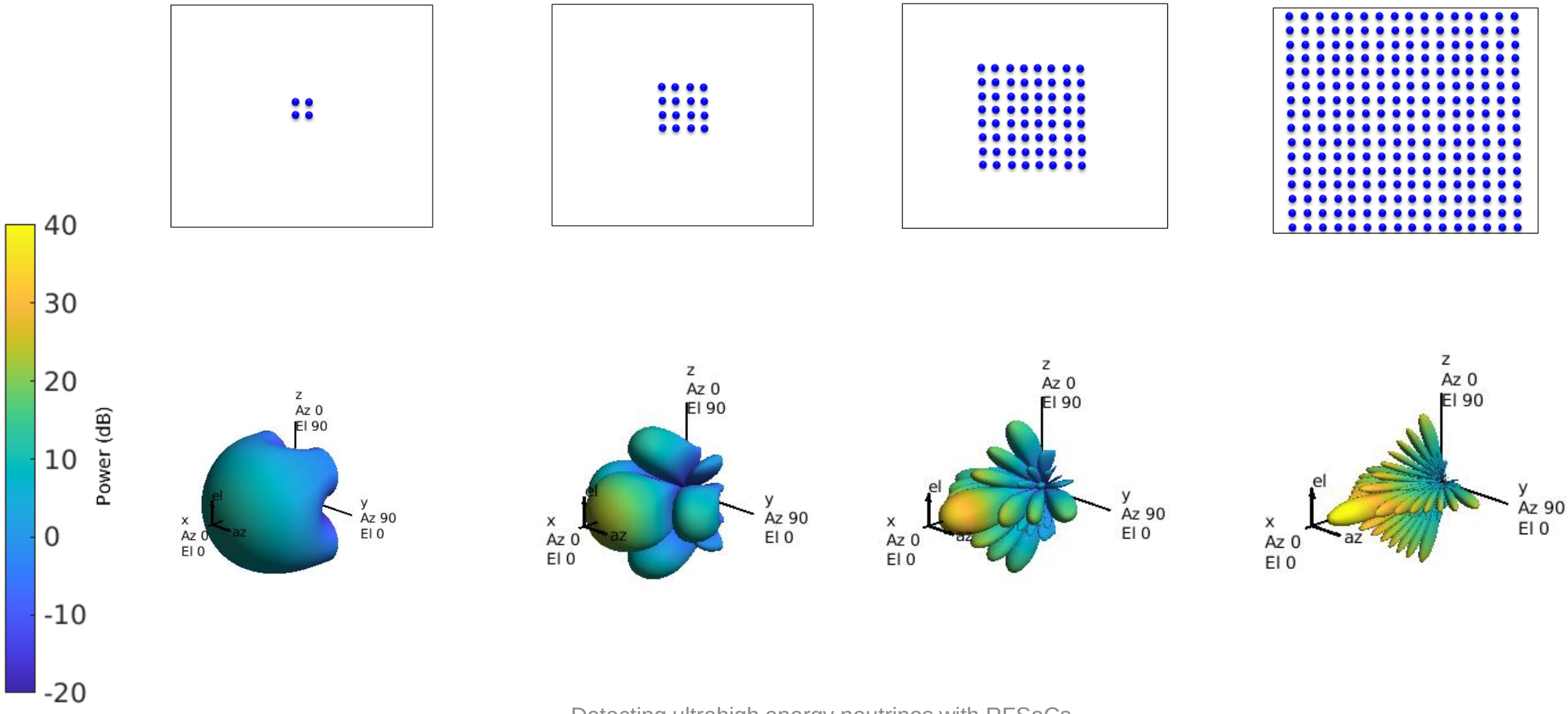

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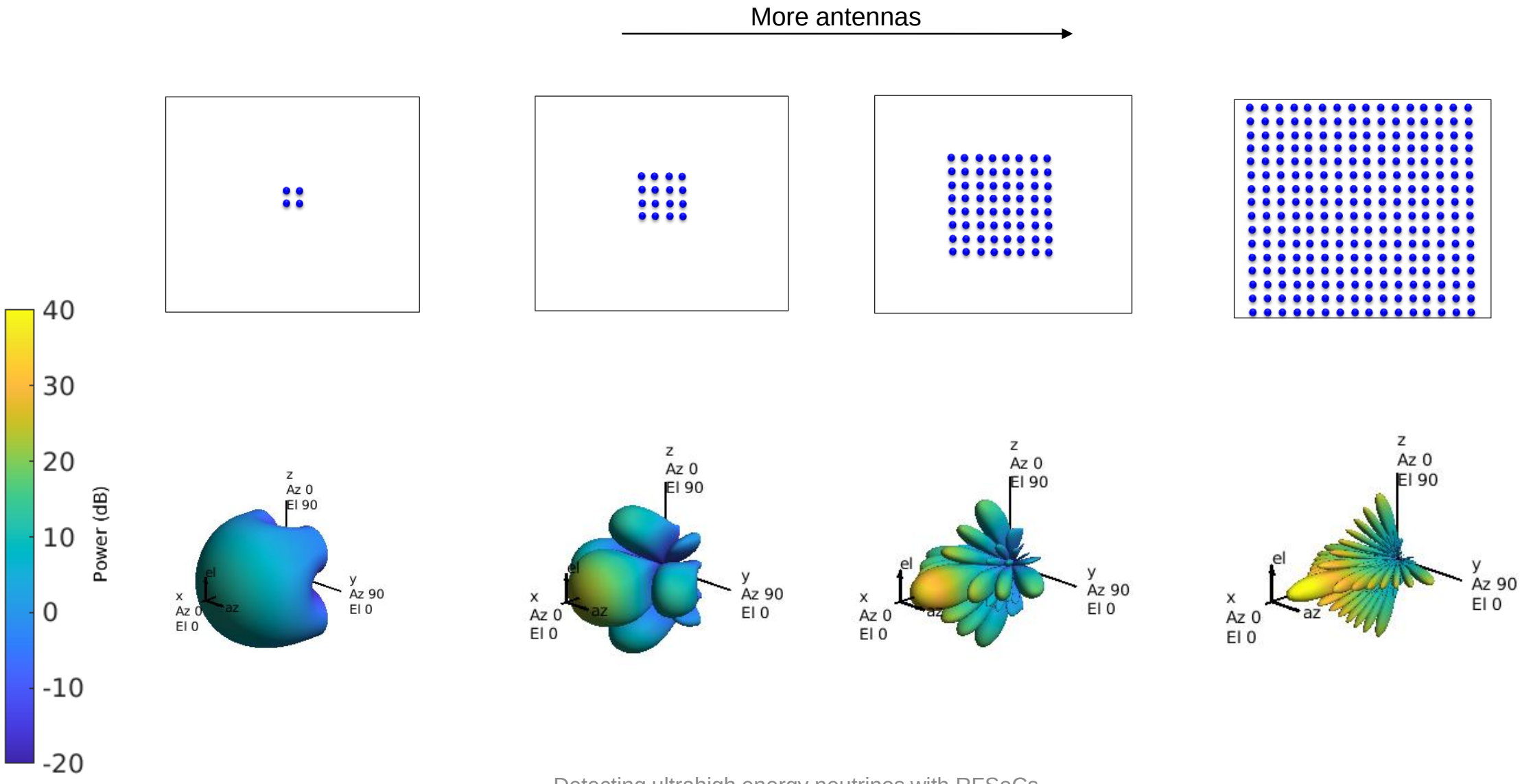
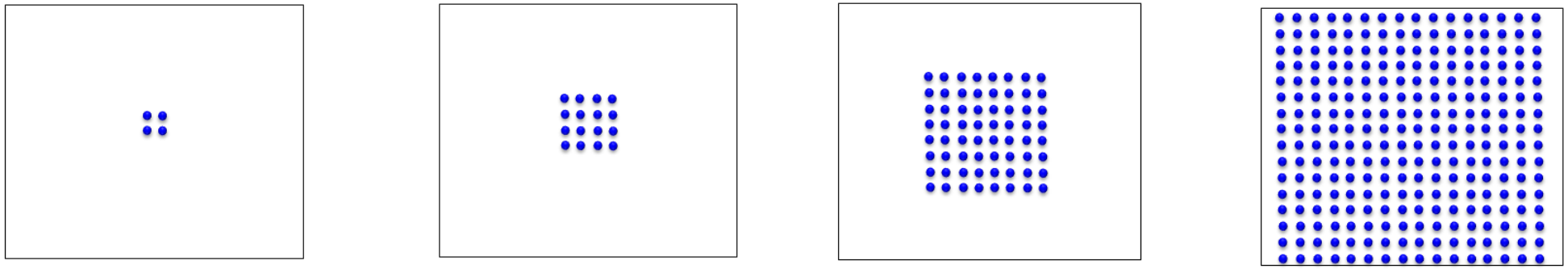
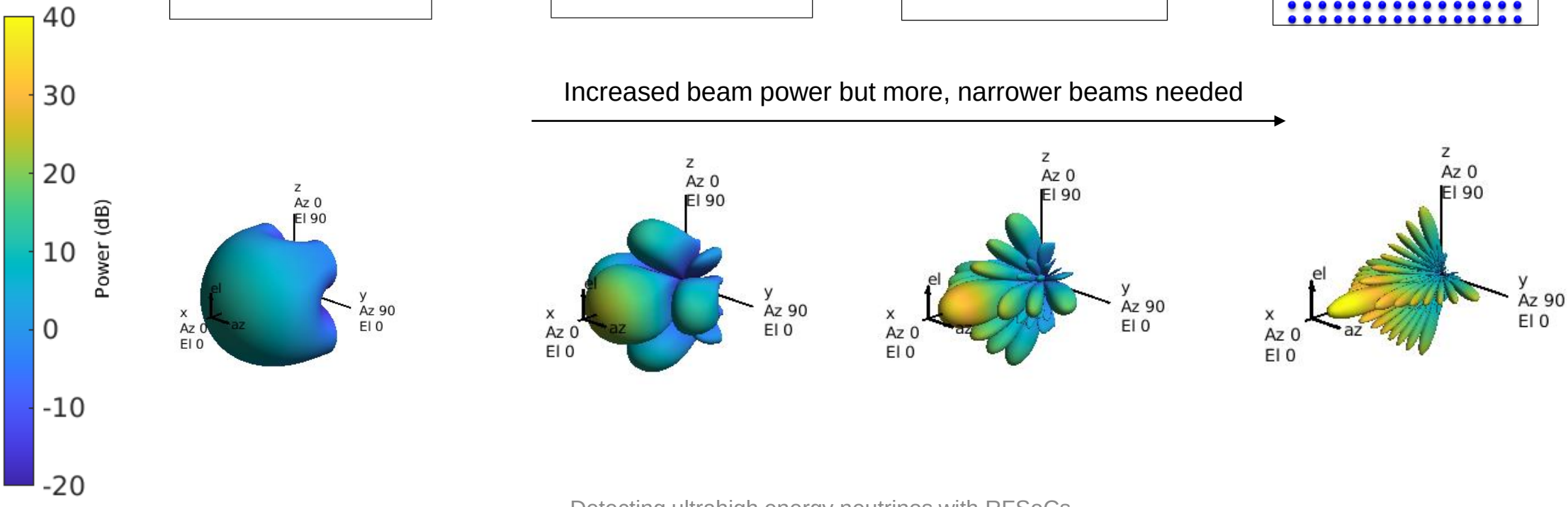


Beamforming – why and how?

More antennas



Increased beam power but more, narrower beams needed



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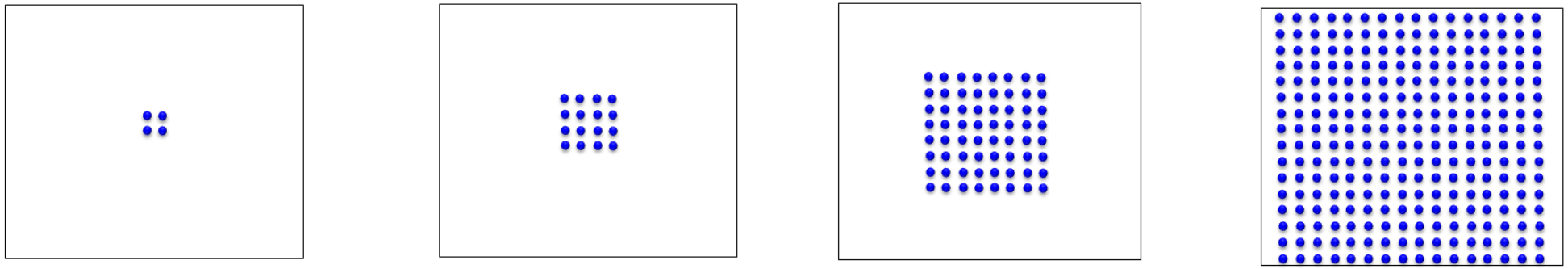

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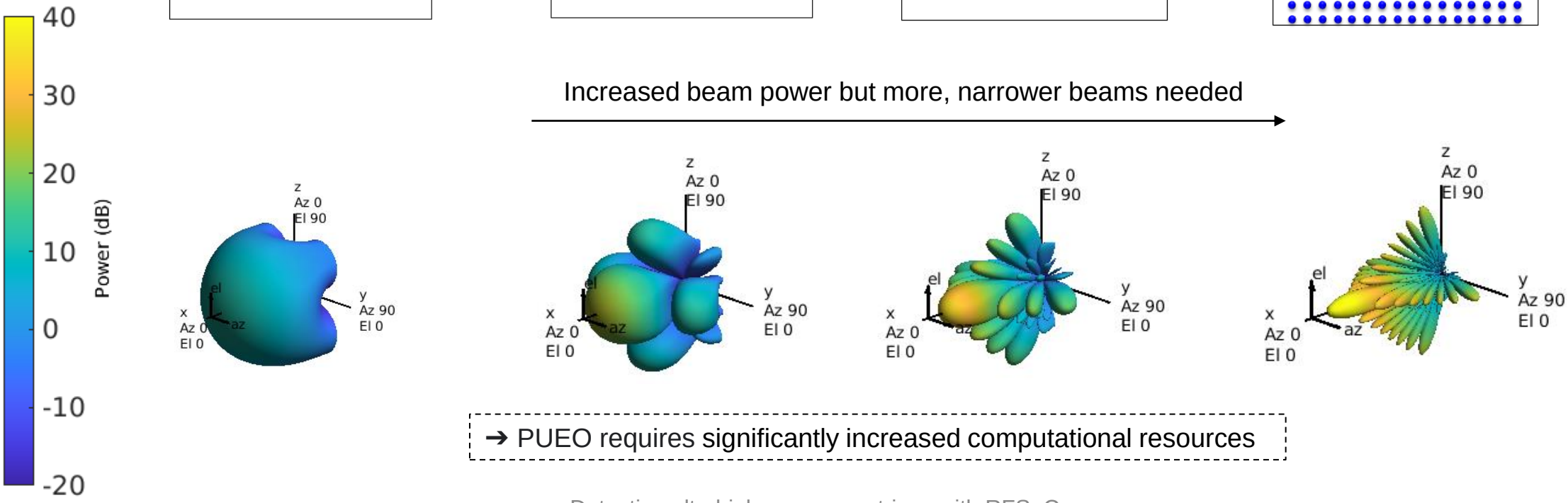


➔ PUEO requires significantly increased computational resources

Why digital beamforming with RFSoC…

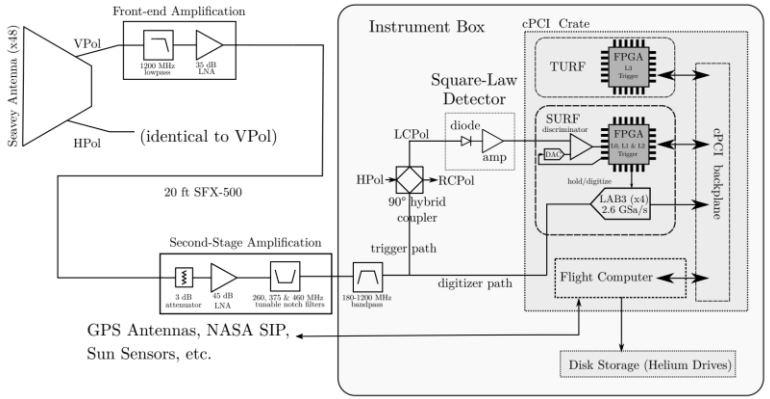
Why digital beamforming with RFSoC…

Digitisation combines functionality of many analogue components

Why digital beamforming with RFSoC…

Digitisation combines functionality of many analogue components

ANITA analogue trigger



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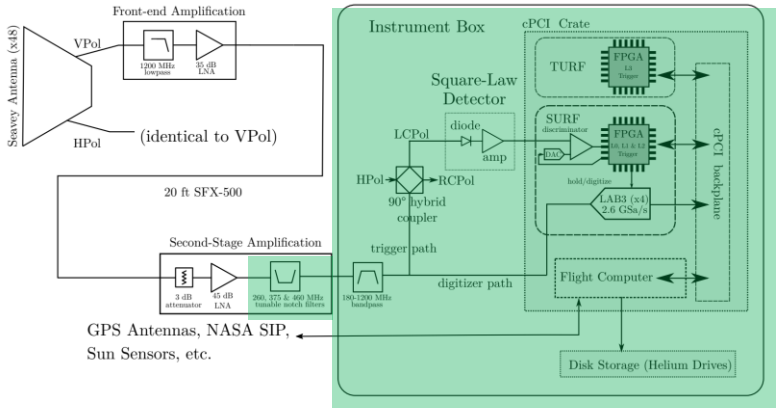

+ beamforming

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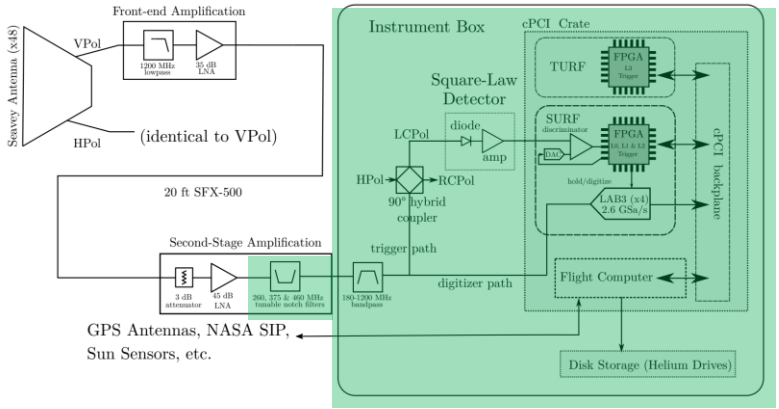

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PUEO digital trigger with RFSoC

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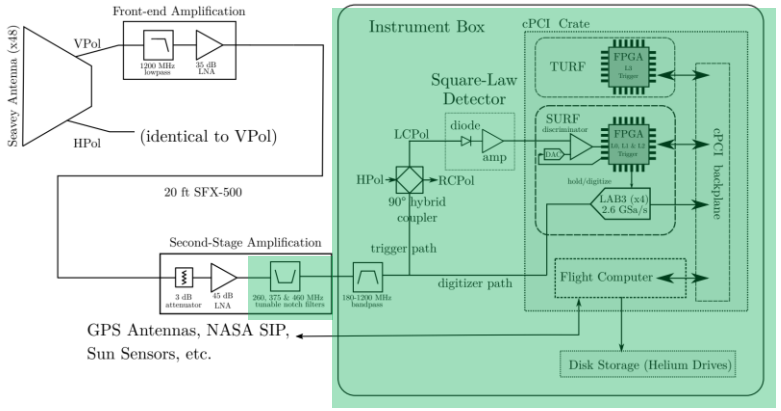

+ beamforming

PUEO digital trigger with RFSoC

RADIO FREQUENCY SYSTEM-ON-CHIP

- High computational power: FPGA with 4000+ digital signal processing slices
- Natively multichannel
- High fidelity:12-14 bit
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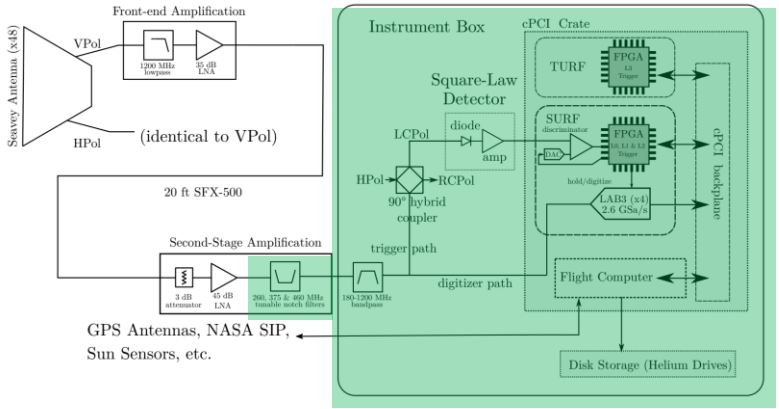

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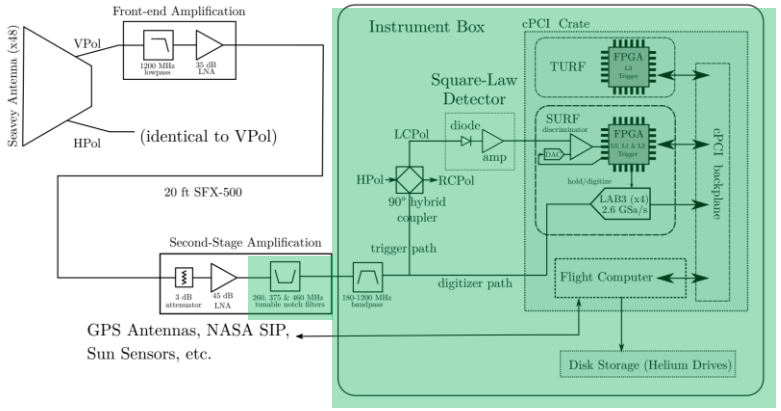

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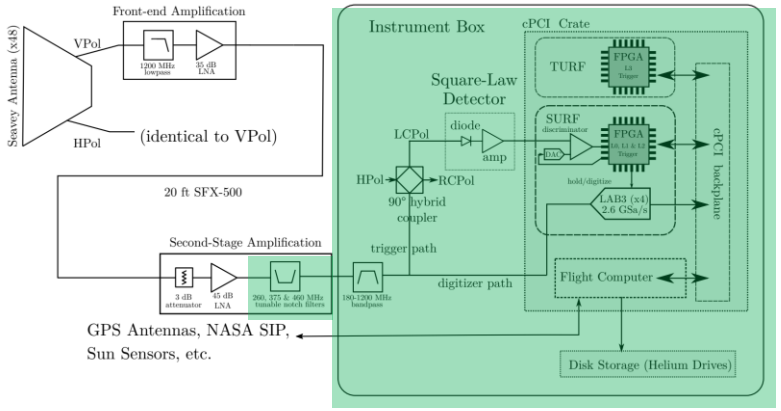

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- ✓ Increased computational capacity
- ✓ Low power
- ✓ Reconfigure In-flight

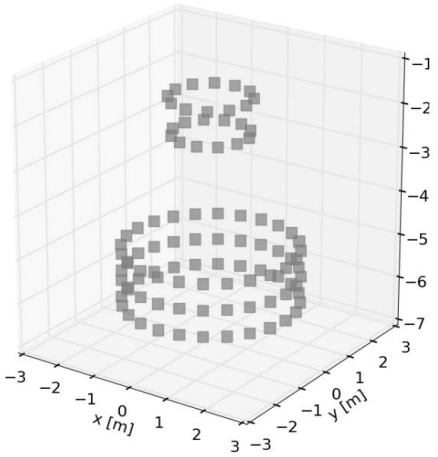
Prototyping for PUEO

PAYLOAD FOR ULTRAHIGH ENERGY OBSERVATIONS – improving on the ANITA experiments

Prototyping for PUEO

PAYLOAD FOR ULTRAHIGH ENERGY OBSERVATIONS – improving on the ANITA experiments

216 antennas



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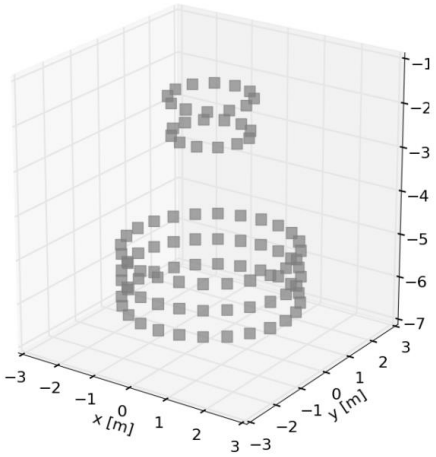
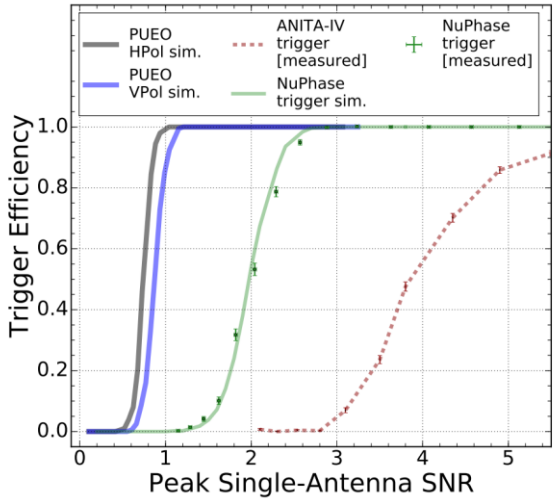


5x lower energy threshold vs. ANITA



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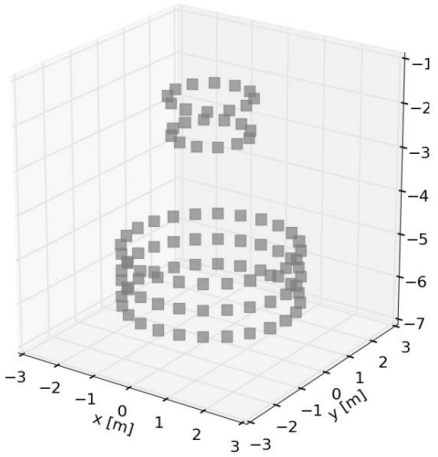

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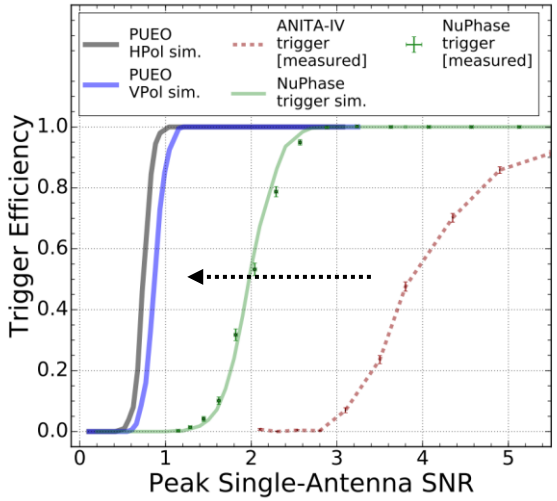

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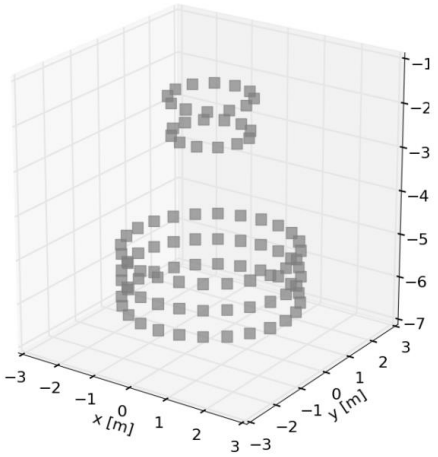

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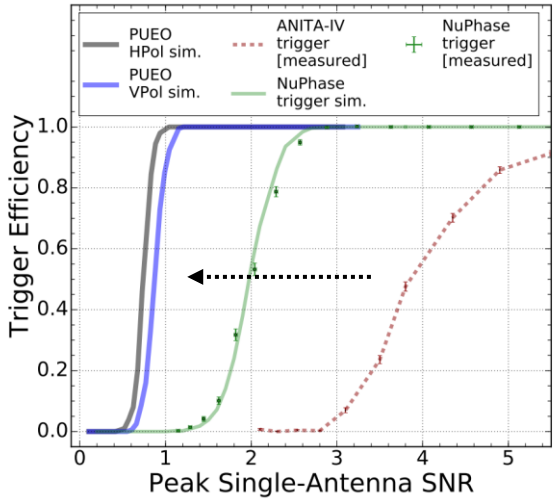
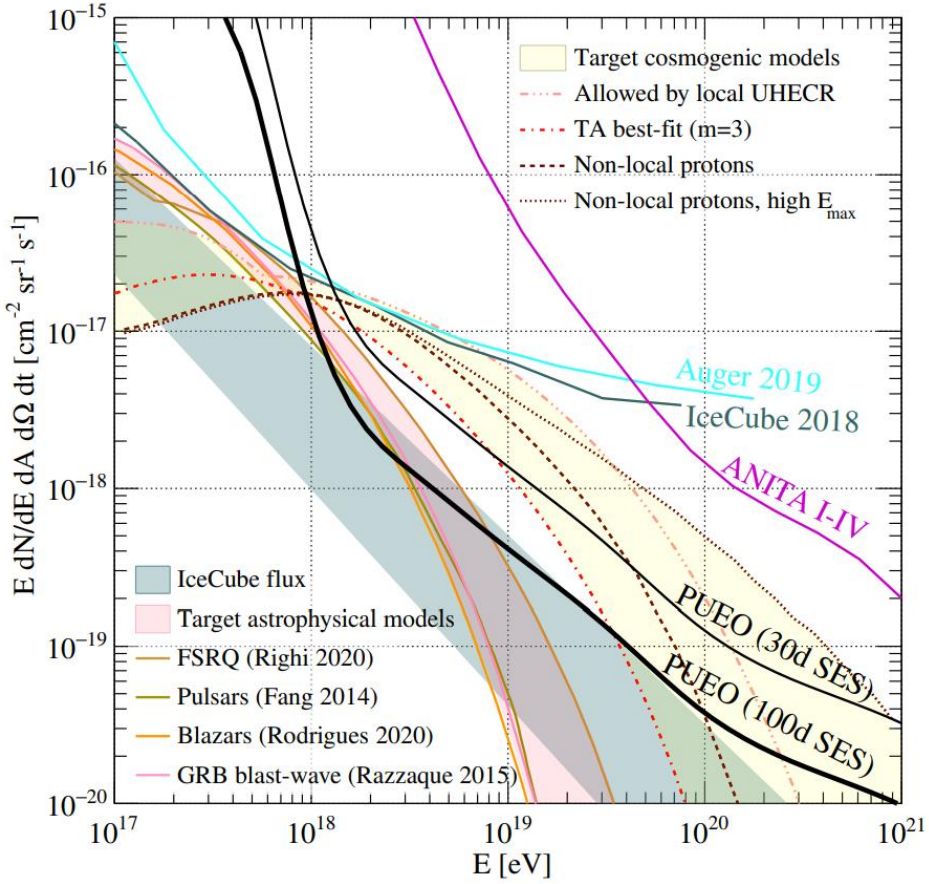


Greatly increased sensitivity to cosmogenic model space!



arXiv 2010.02892

Prototyping for PUEO

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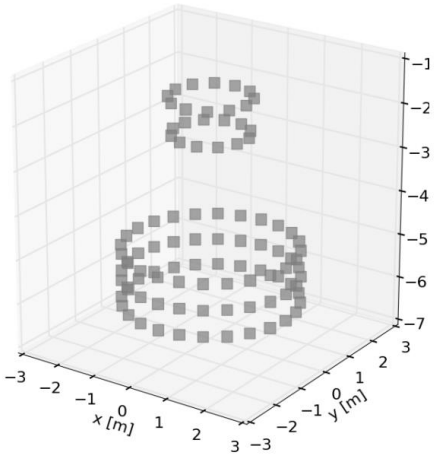

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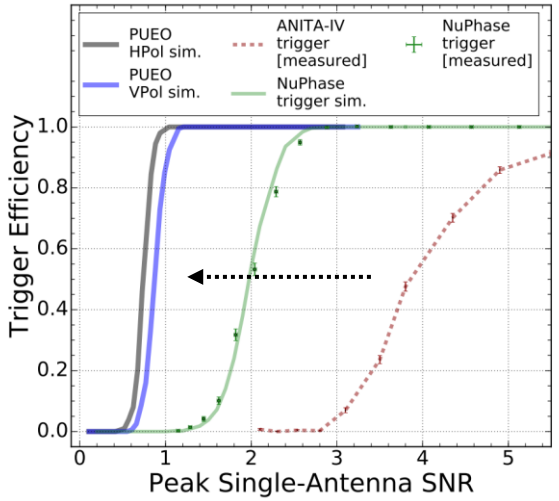

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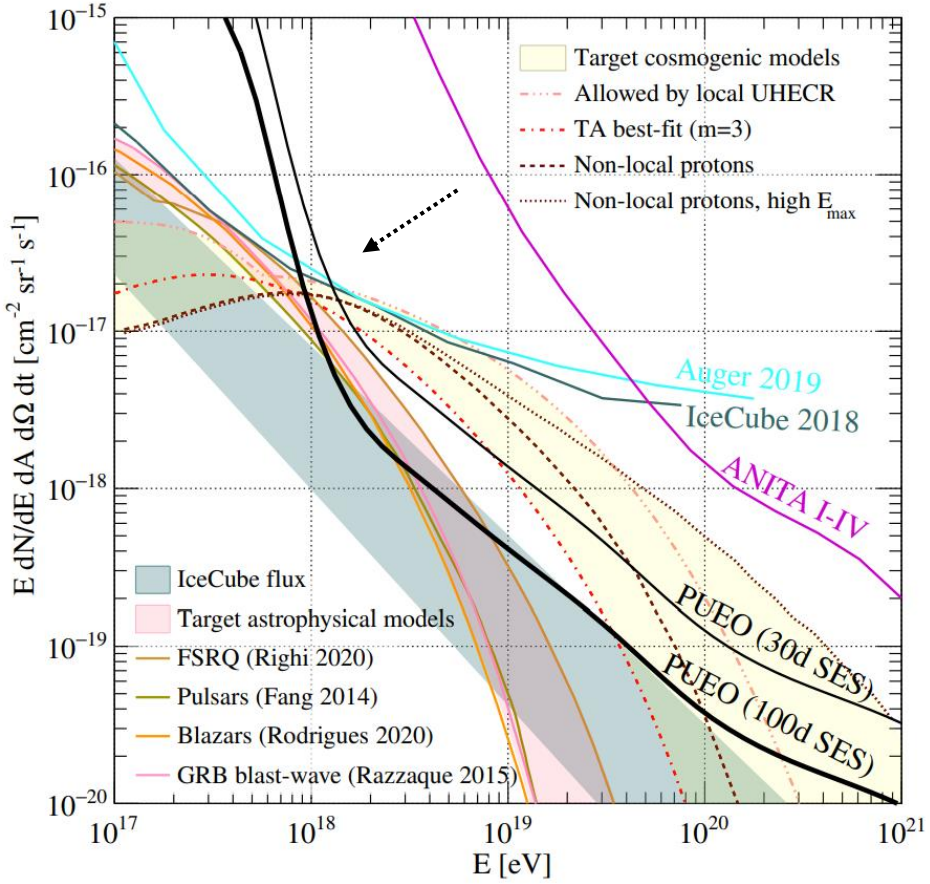

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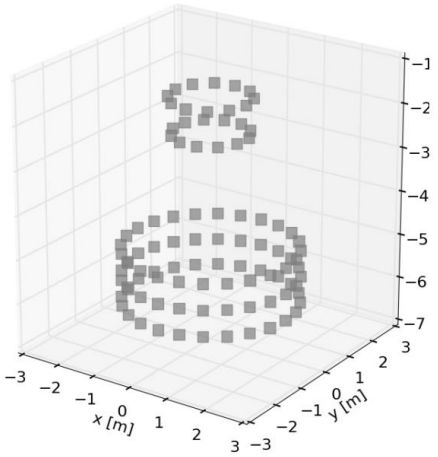

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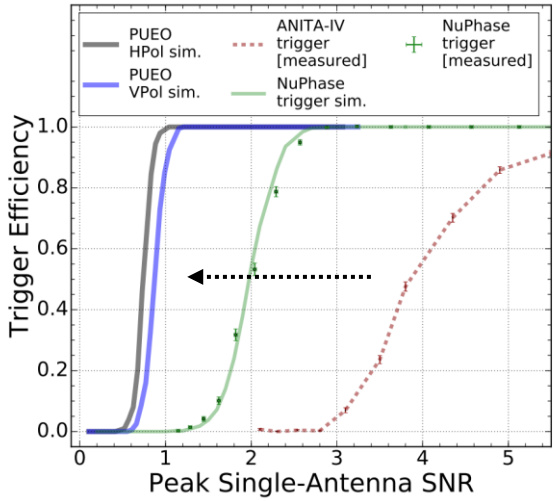

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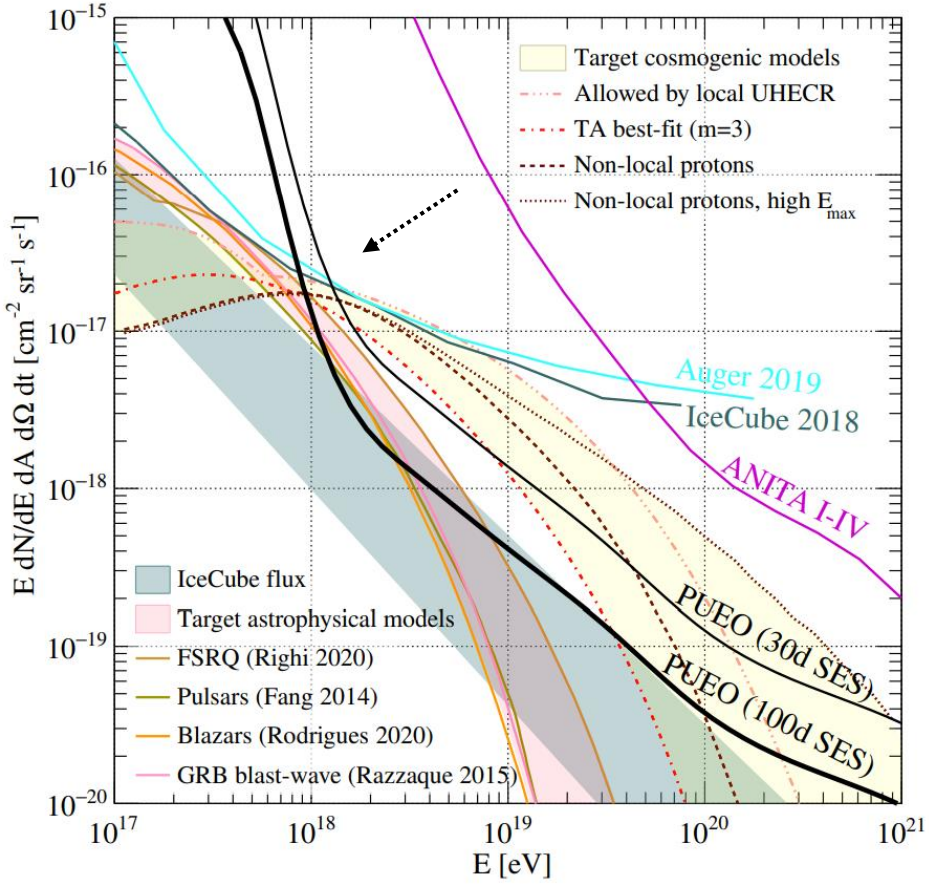


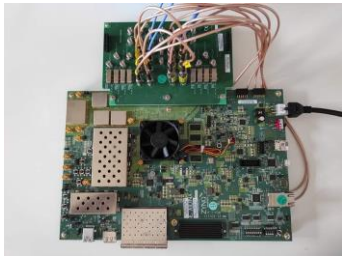
Prototype goals…

I. Demonstrate on hardware
II. Quantify resources
III. Improve performance
IV. Demonstrate digital filtering

arXiv 2010.02892

I. Demonstrate on hardware

Beamforming prototype

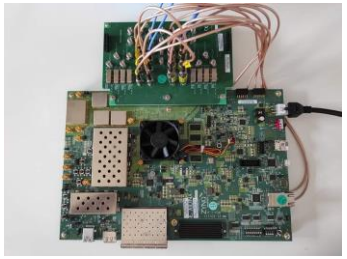


I. Demonstrate on hardware

Beamforming prototype

Programmable logic

- Manufacturer tools + hardware description language



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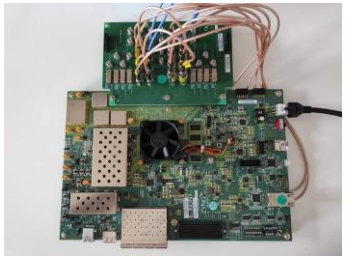

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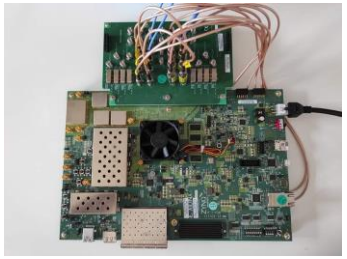

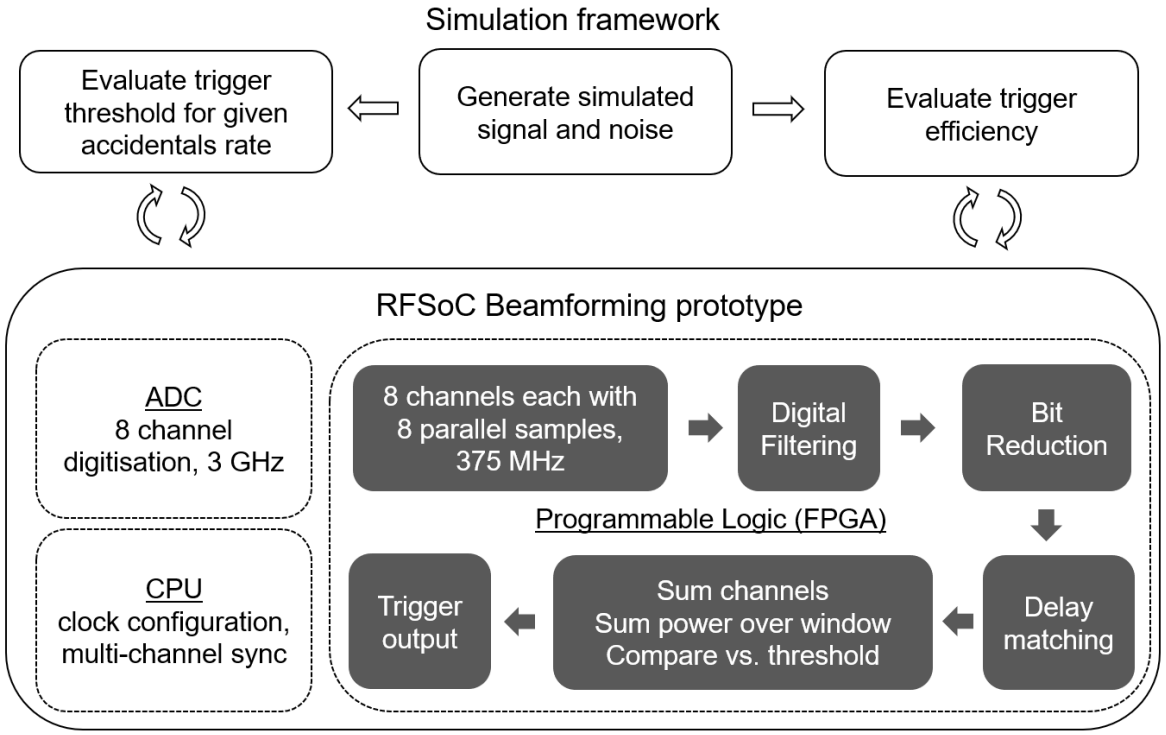

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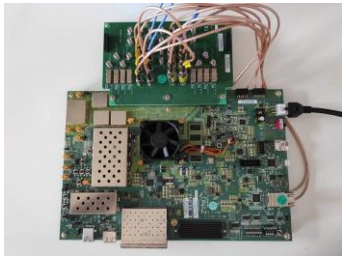
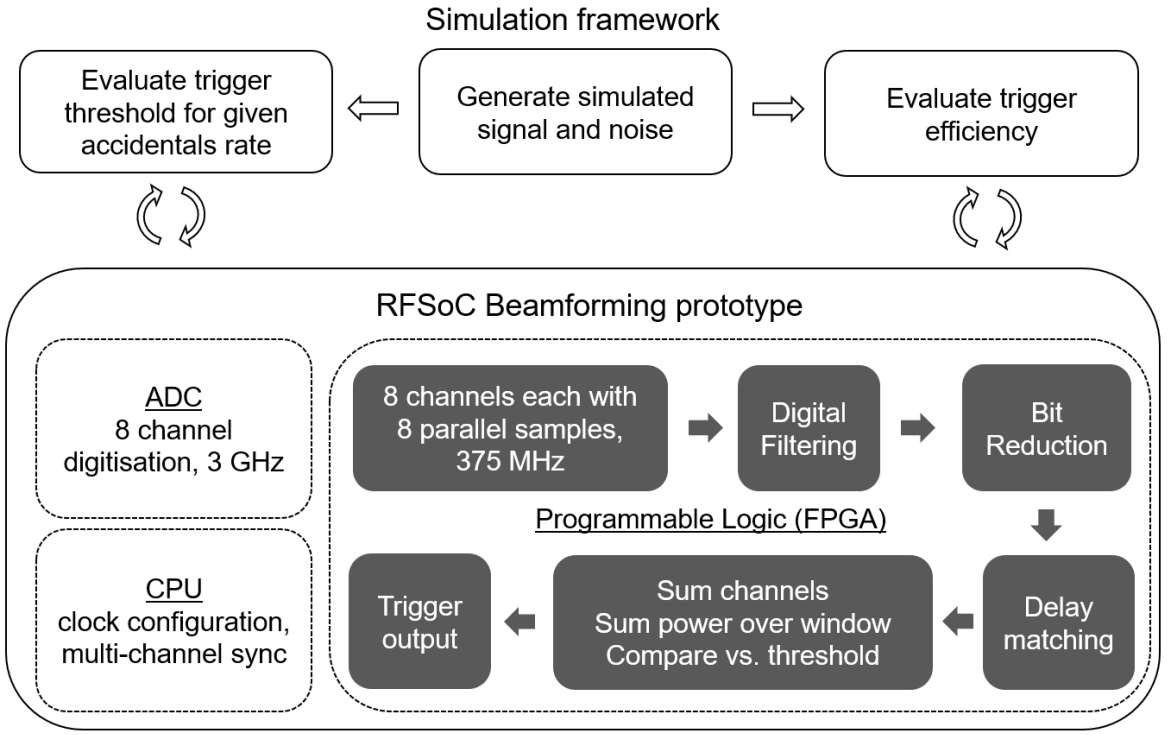
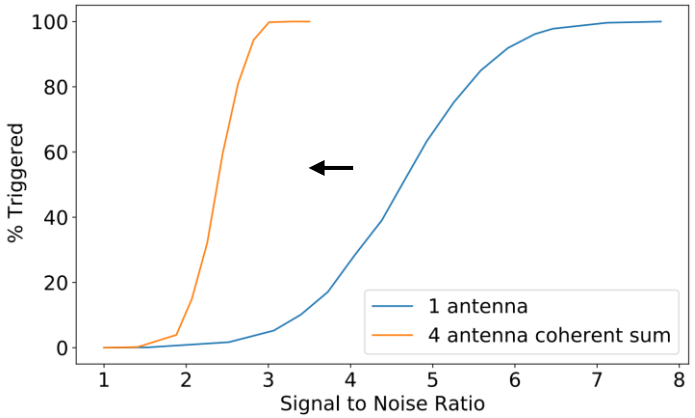




Improved signal to noise ratio

Demonstrated beamforming improvement for trigger threshold



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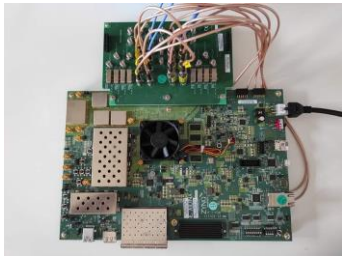

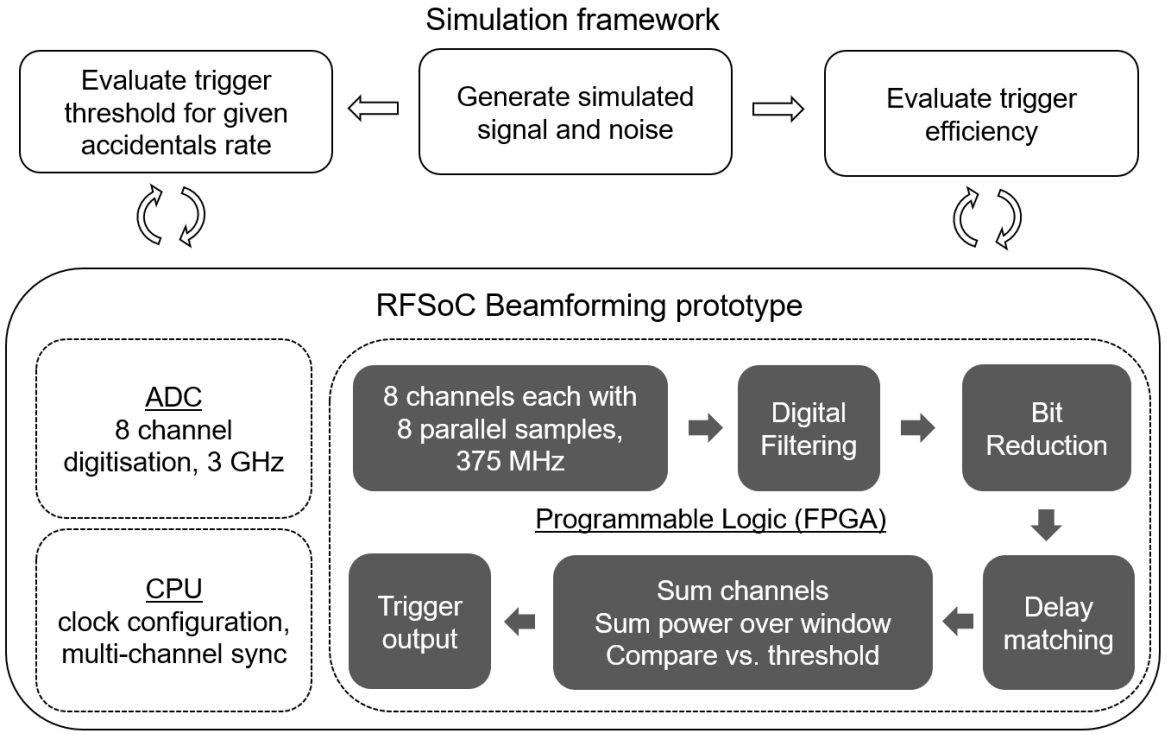

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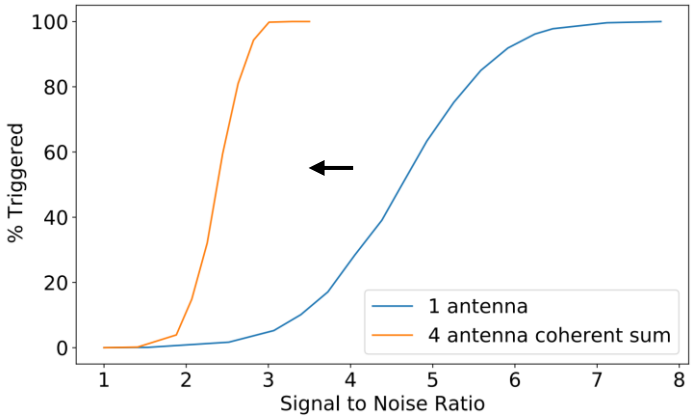
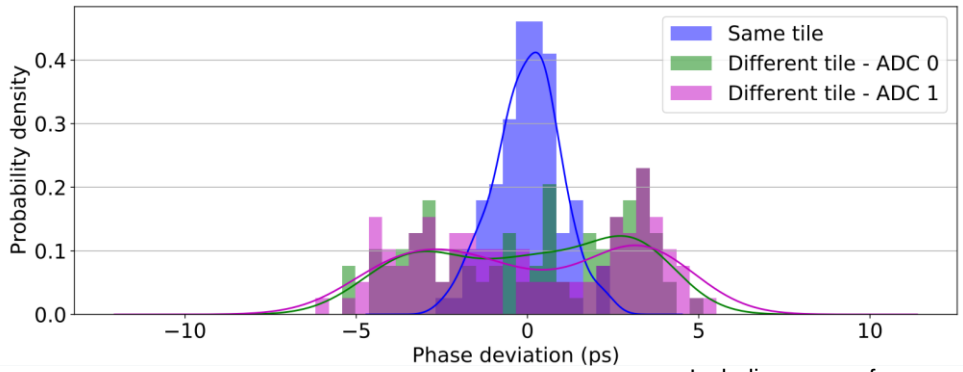


Cross-Channel alignment achieved

Phase jitter under 0.01ns ≪ 0.33ns sample period



Including across frequencies

I. Demonstrate on hardware

Result: shown hardware capable of beamforming

Beamforming prototype

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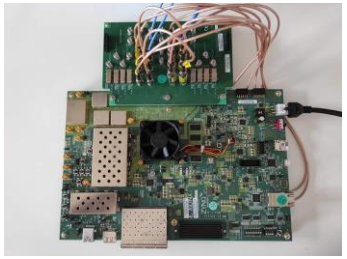

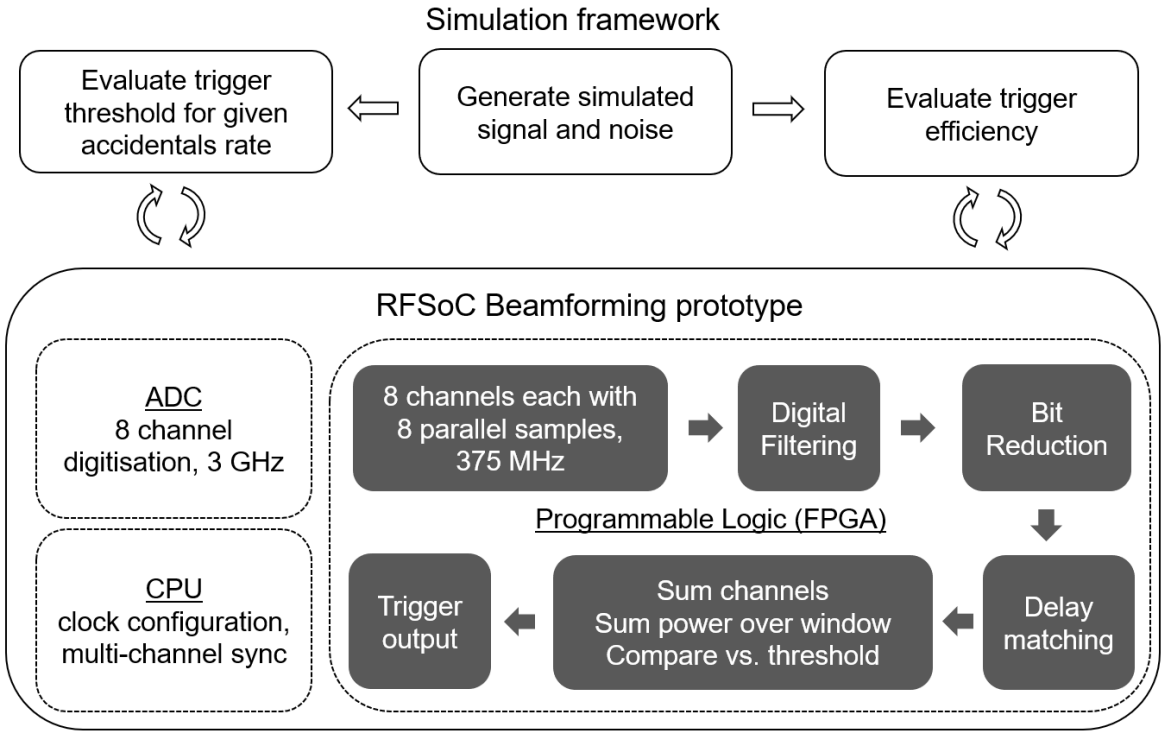

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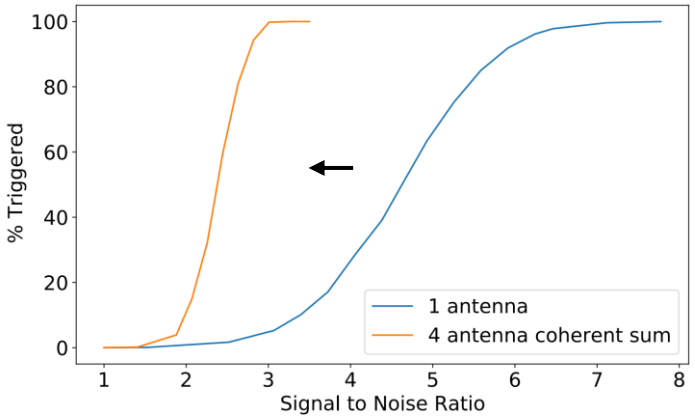

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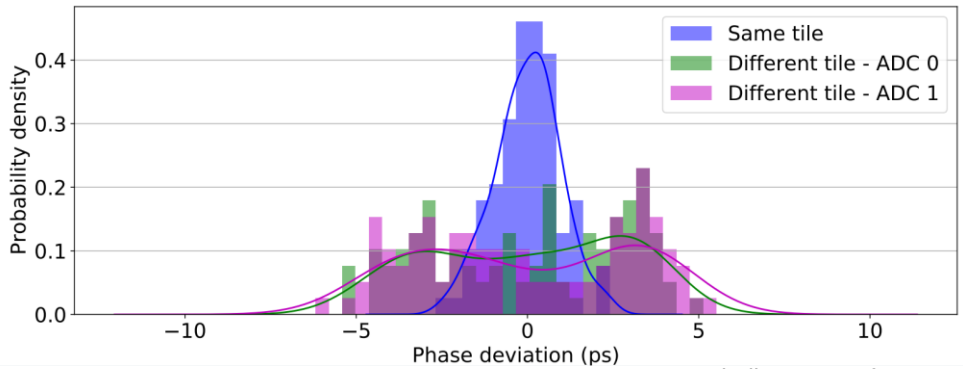

Including across frequencies

II. Resources

Achieved required ~100 beams per RFSoC

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Resource utilisation*
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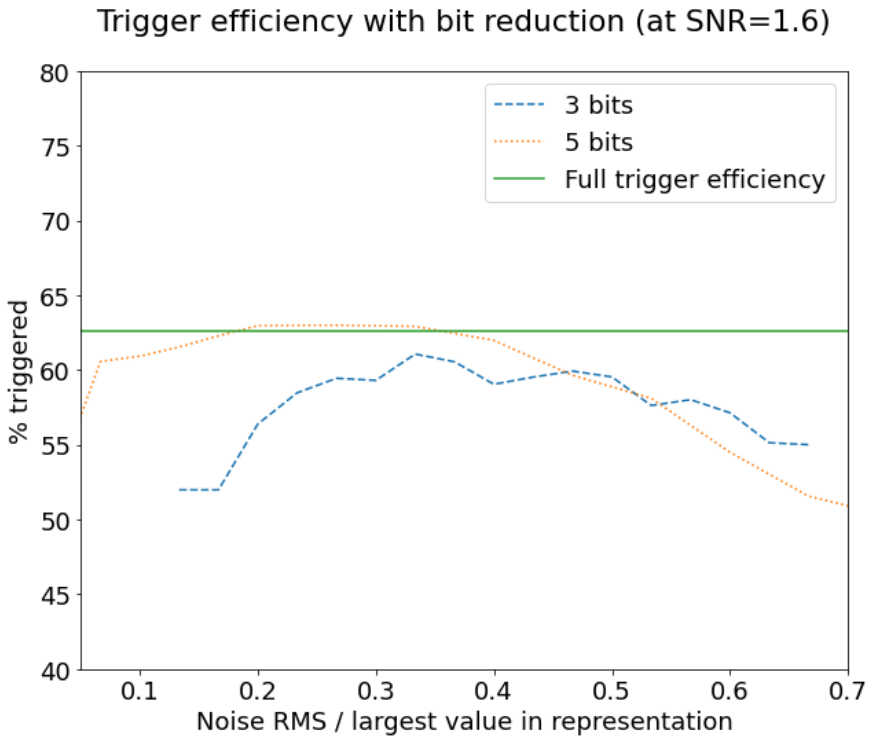

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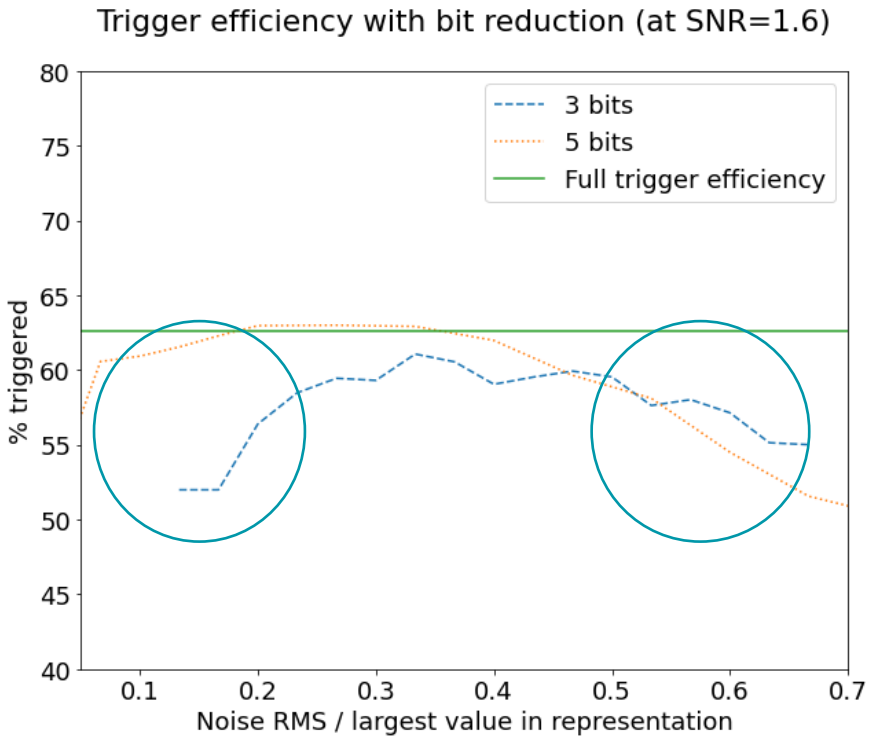

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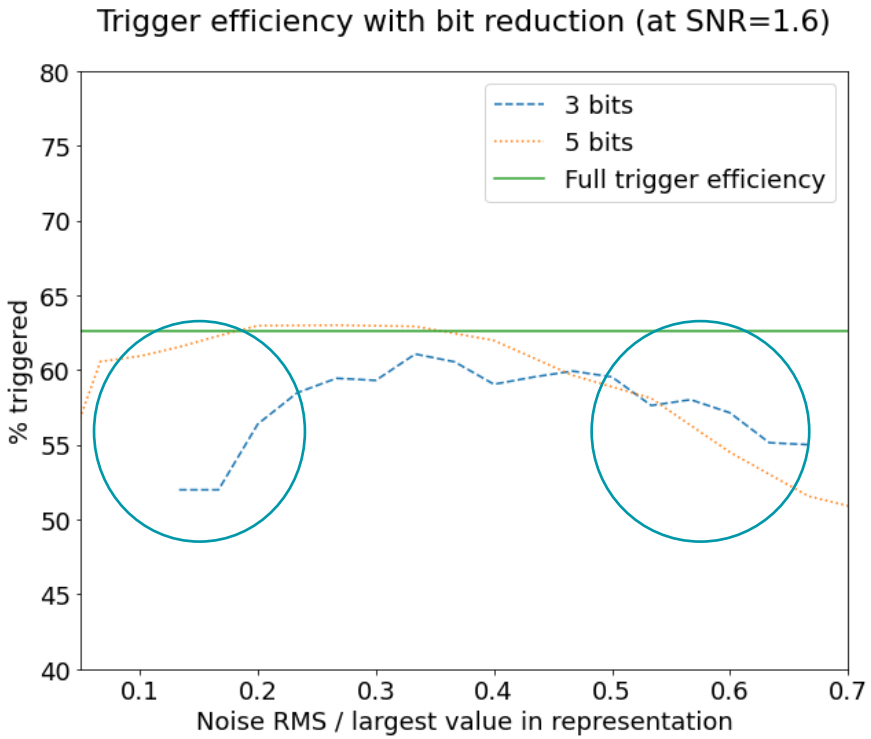

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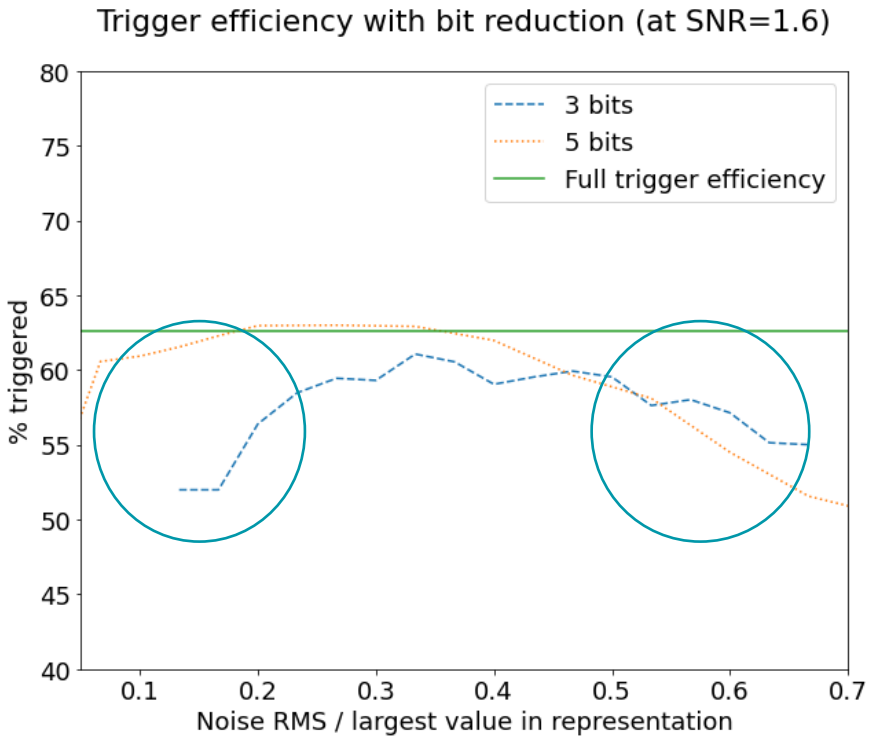

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II. Resources

Result: demonstrated techniques for adequate computational resources for beamforming

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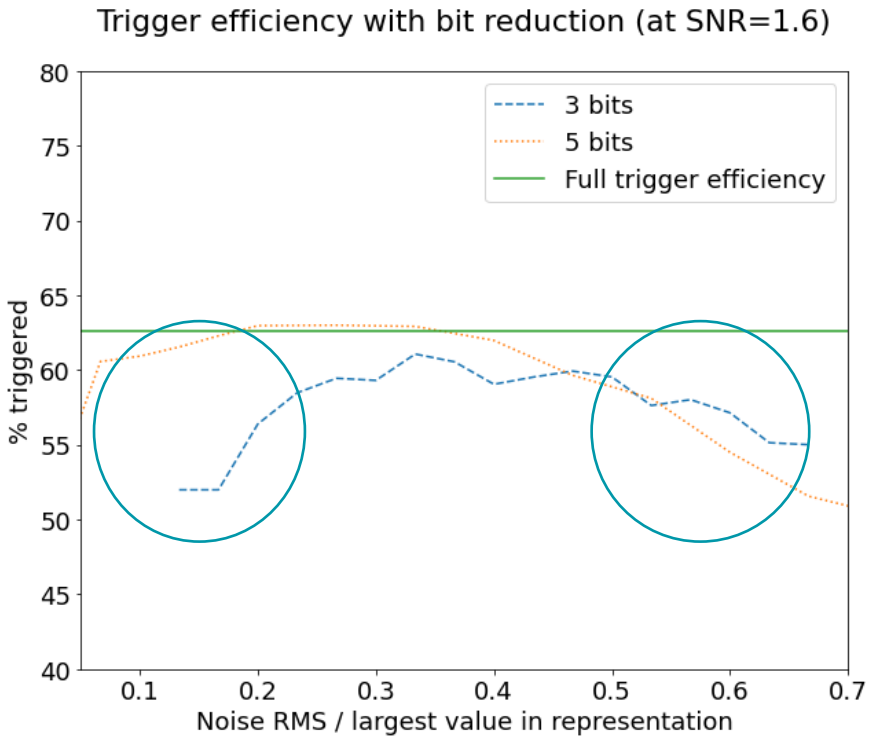

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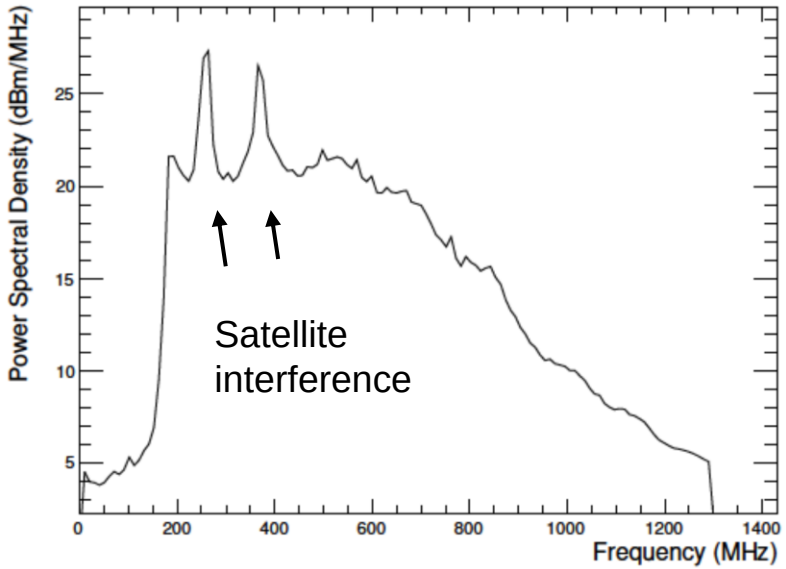
IV. Filtering

ANITA-III flight snapshot



arxiv 1709.04536

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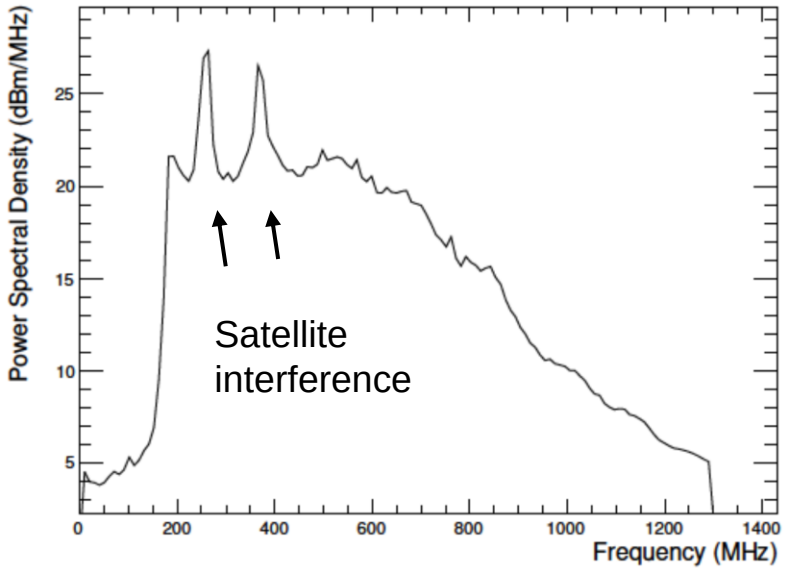

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Interference reduces trigger sensitivity

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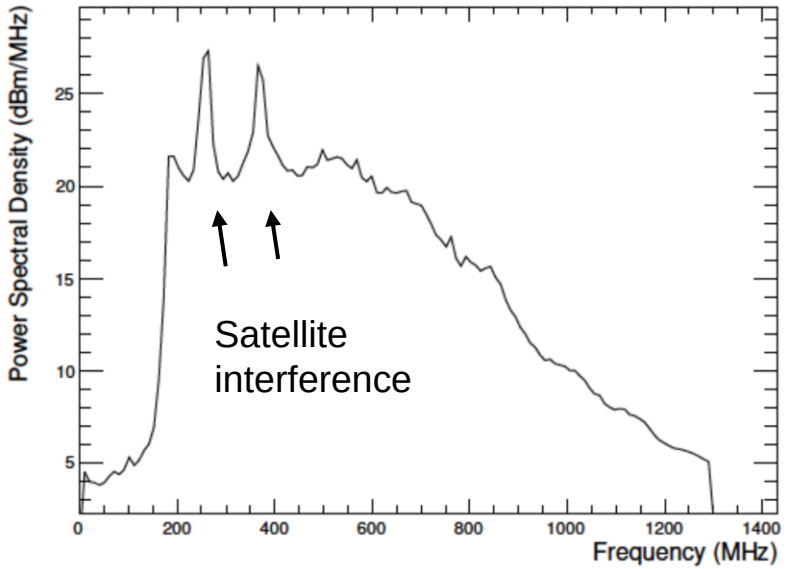

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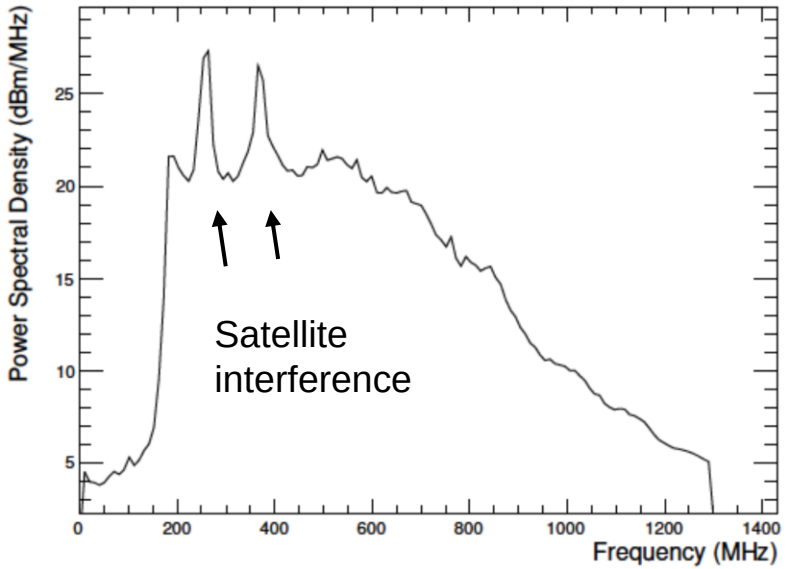

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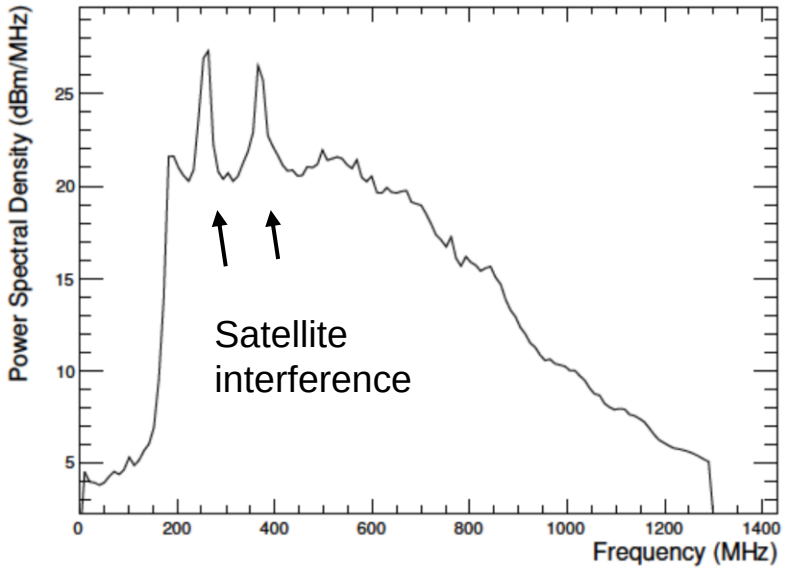

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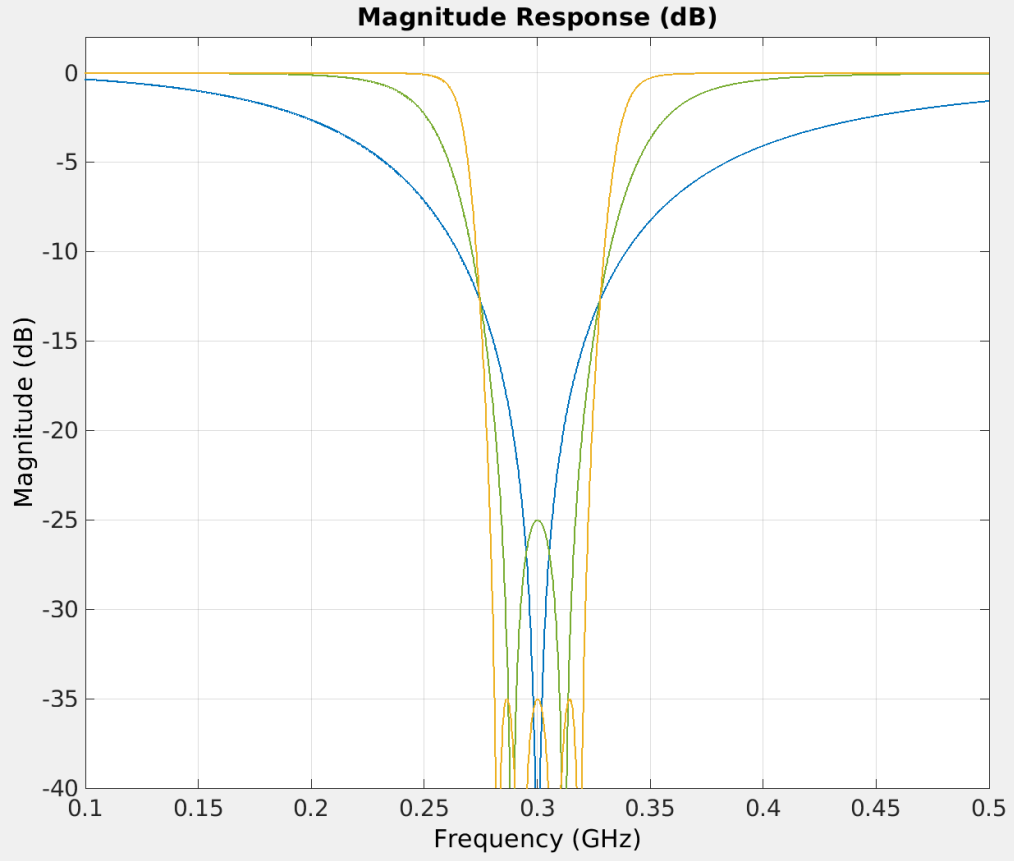
Want tuneable filters – can programmable logic help again?

IV. Filtering – examples

“Notch” filters



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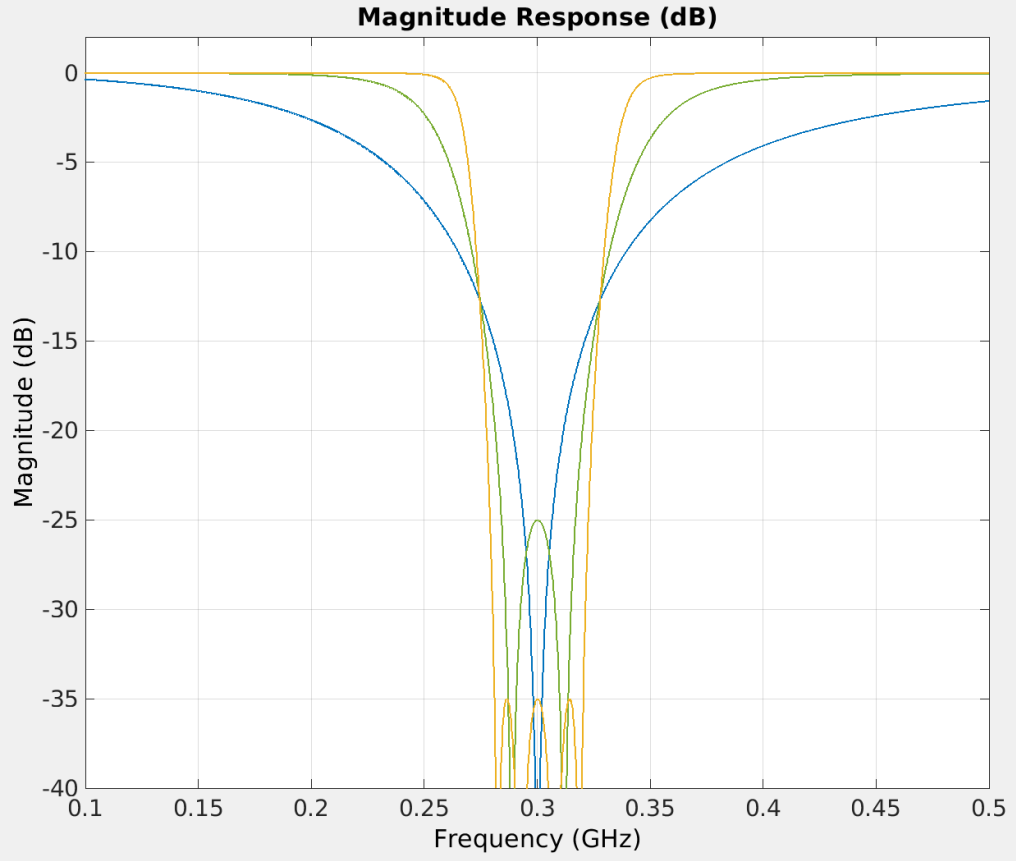

DSP utilisation per filter

Utilisation	Width to -10dB
10%	230MHz
20%	60MHz
40%	15MHz

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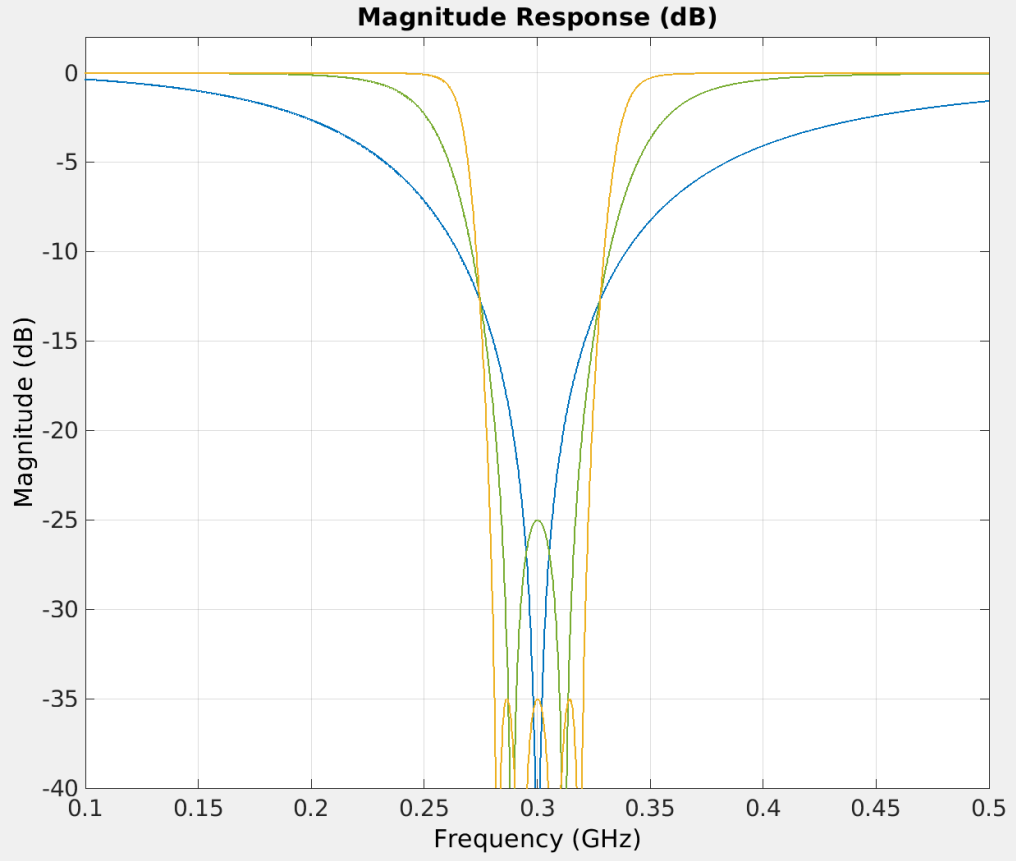

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Centre of stopband tuneable with simple change to filter coefficients

IV. Filtering – examples

Result: tuneable digital filter possible but requires significant resources and implementation effort

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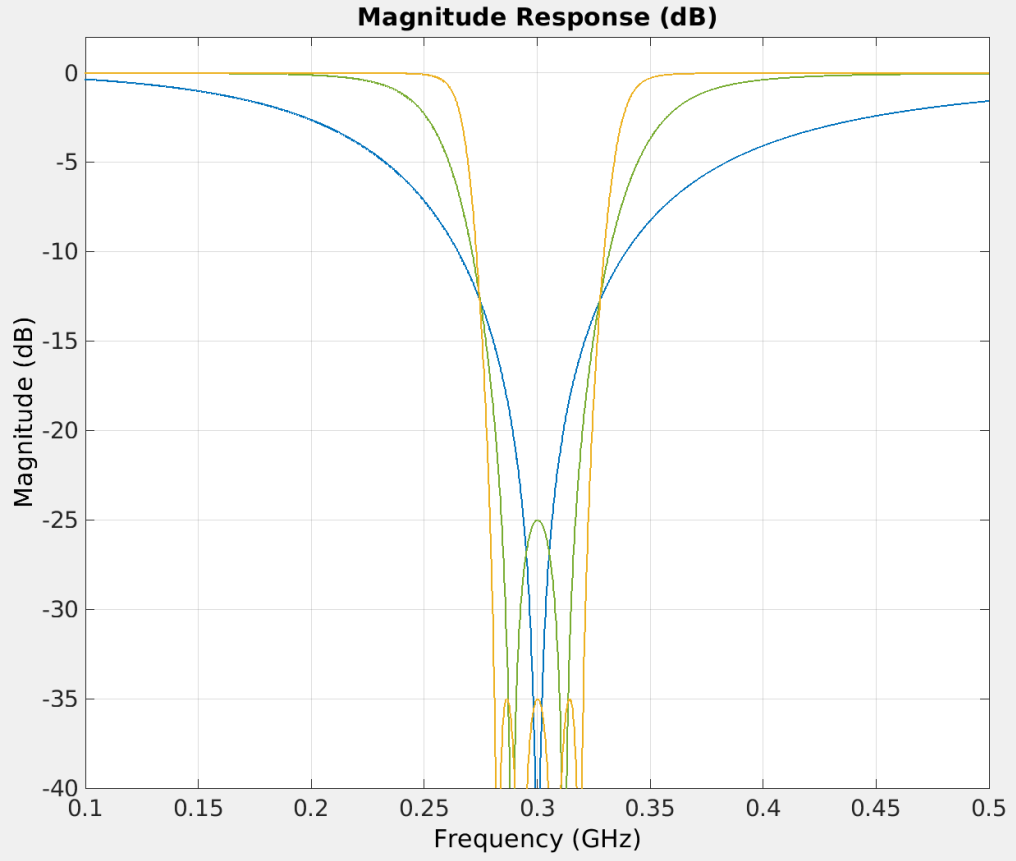

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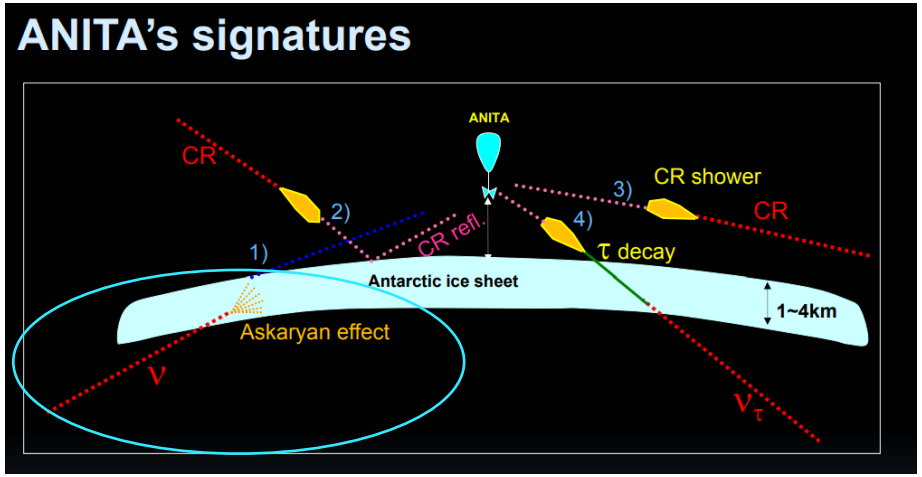
PUEO has potential to discover highest energy neutrinos ever measured (by multiple orders of magnitude)



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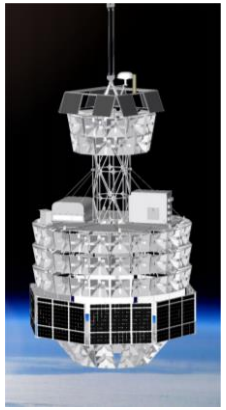
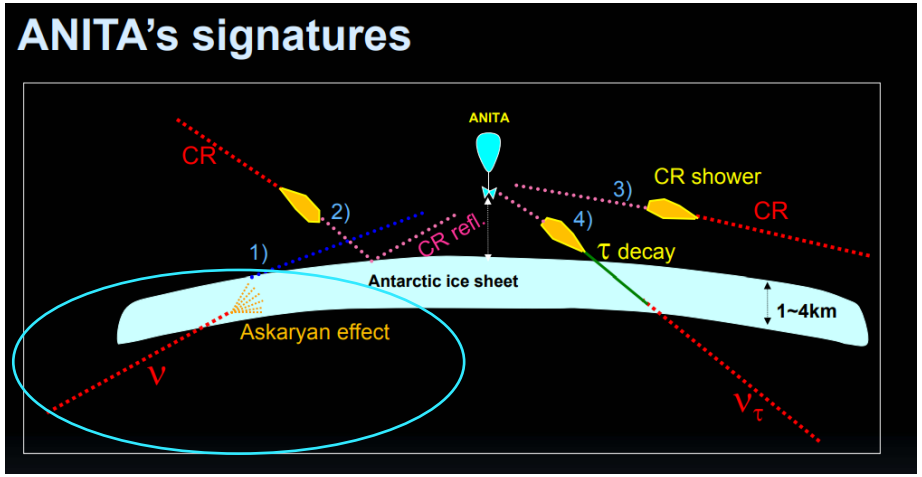
5x improvement in sensitivity





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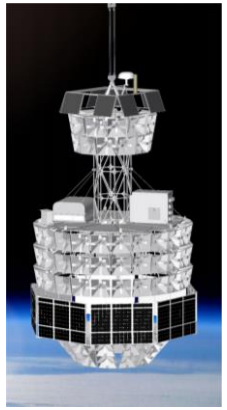

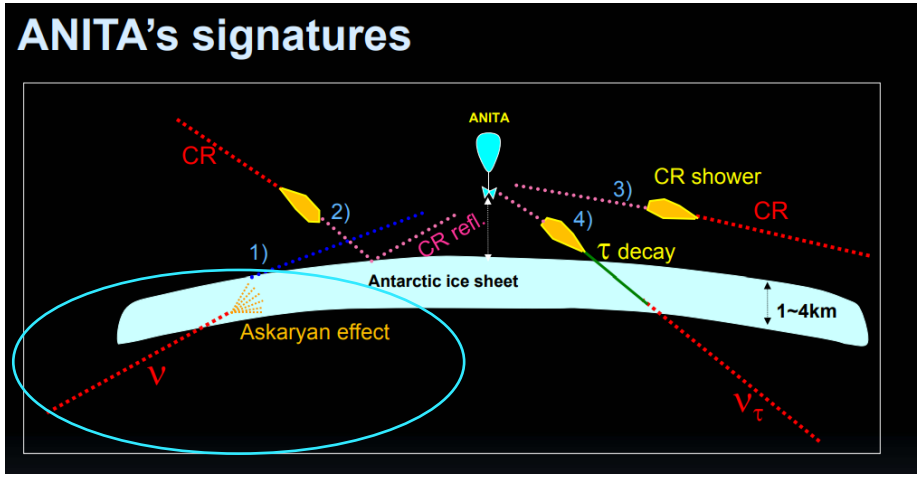

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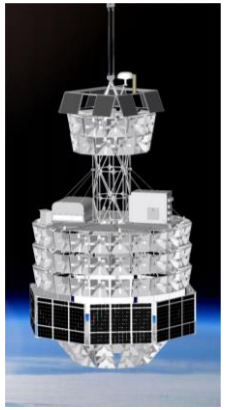

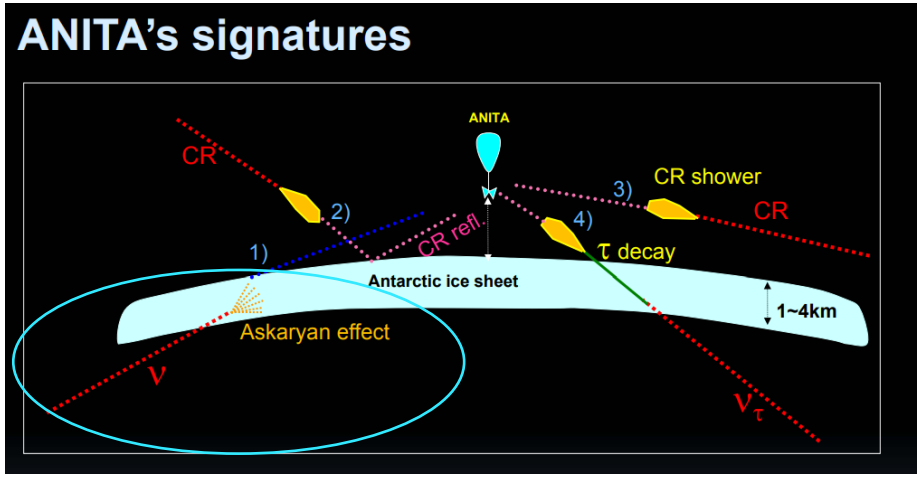

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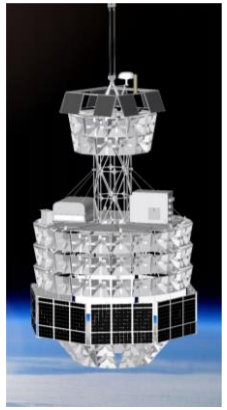

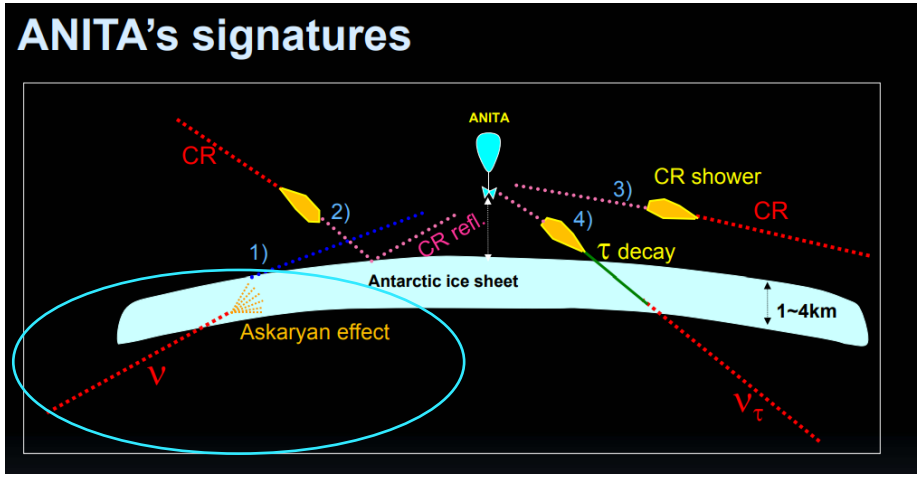

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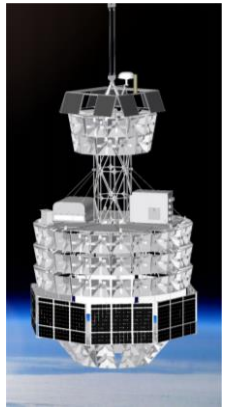

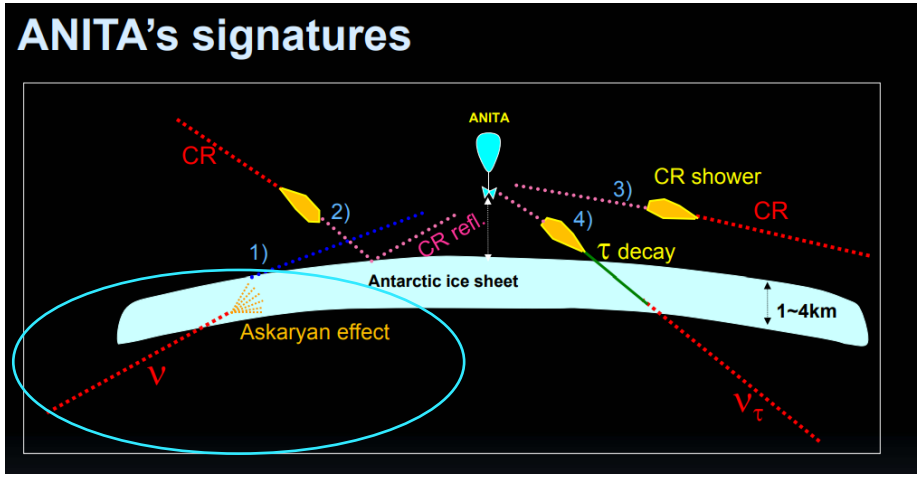

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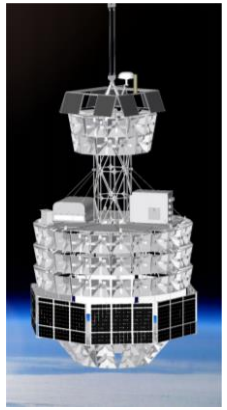

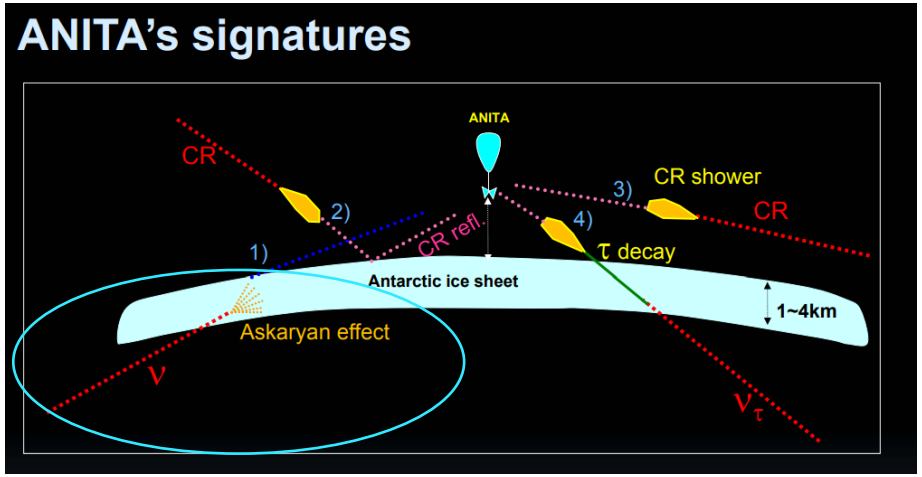

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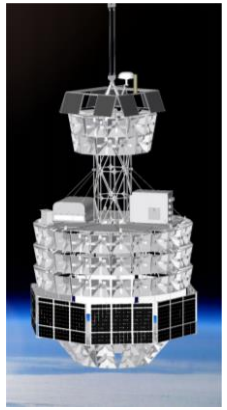

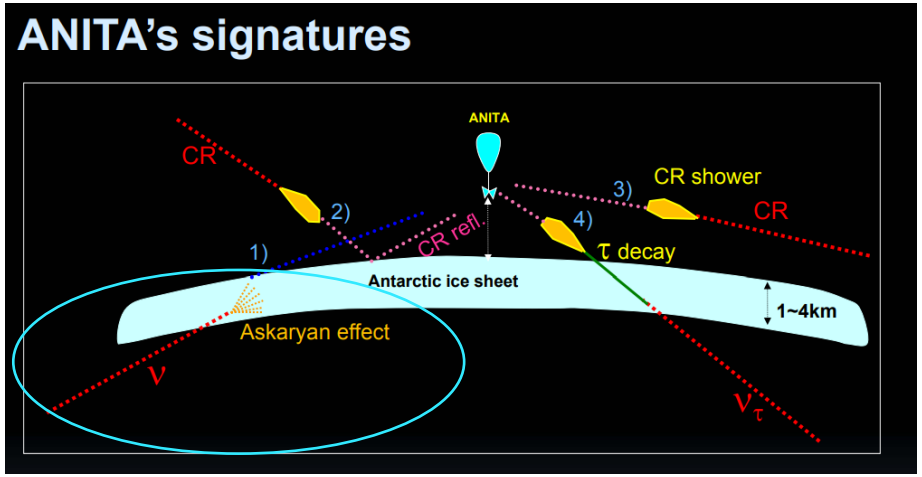

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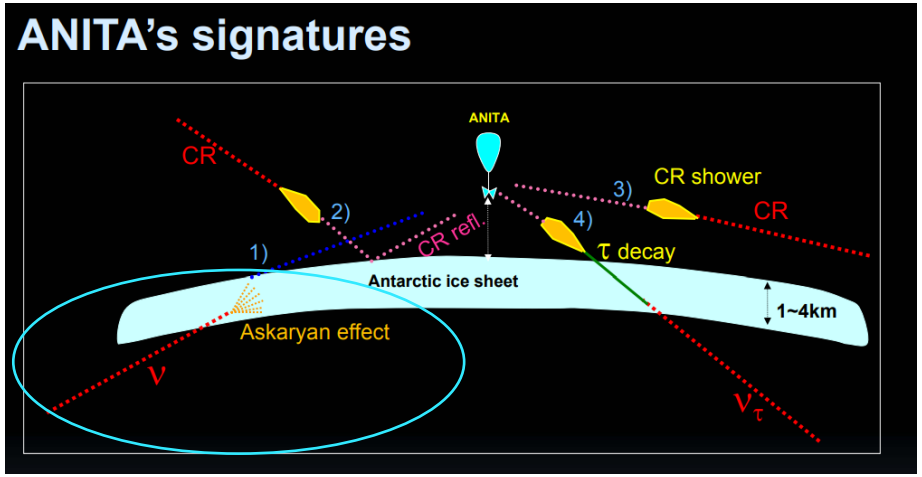

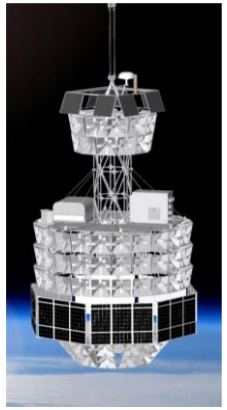

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- Expect neutrino detection from several cosmogenic models