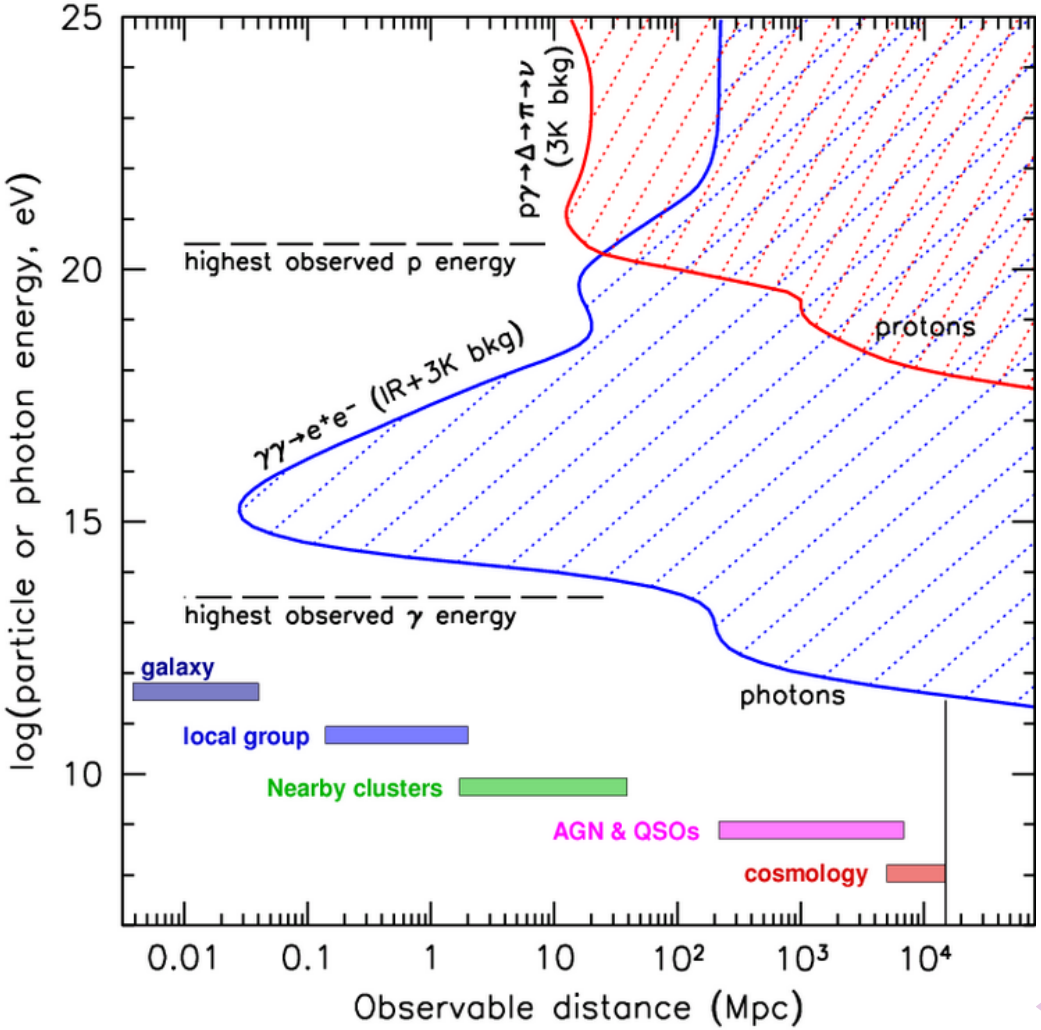
Radiowave Detection of Neutrinos

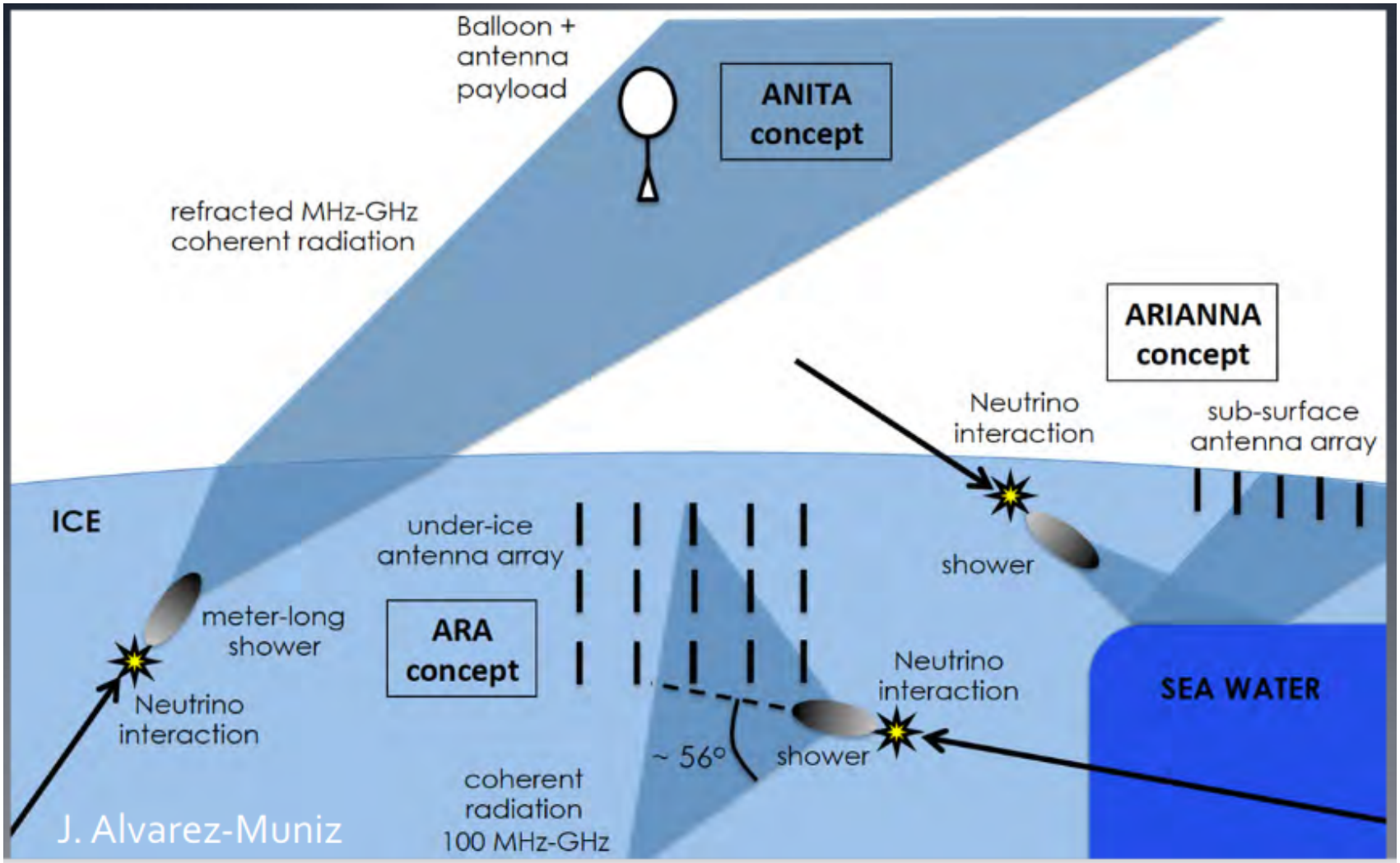
Cosmogenic Neutrinos via GZK-effect

$p\gamma_{CMB} \rightarrow \Delta \rightarrow N\pi$; $\pi \rightarrow \mu\overline{\nu}_{\mu}$; $\mu \rightarrow e\overline{\nu}_{e}\nu_{\mu}$

Also $\gamma\gamma_{CMB} \rightarrow e^{+}e^{-} \Rightarrow$protons and photons have limited range.



Small $\sigma_\nu \Rightarrow$use huge target (Antarctic ice sheet)

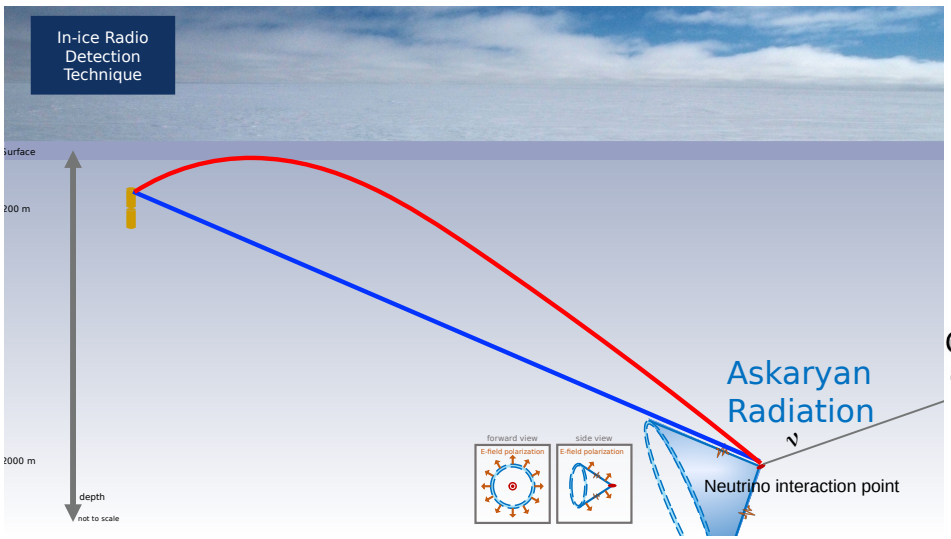


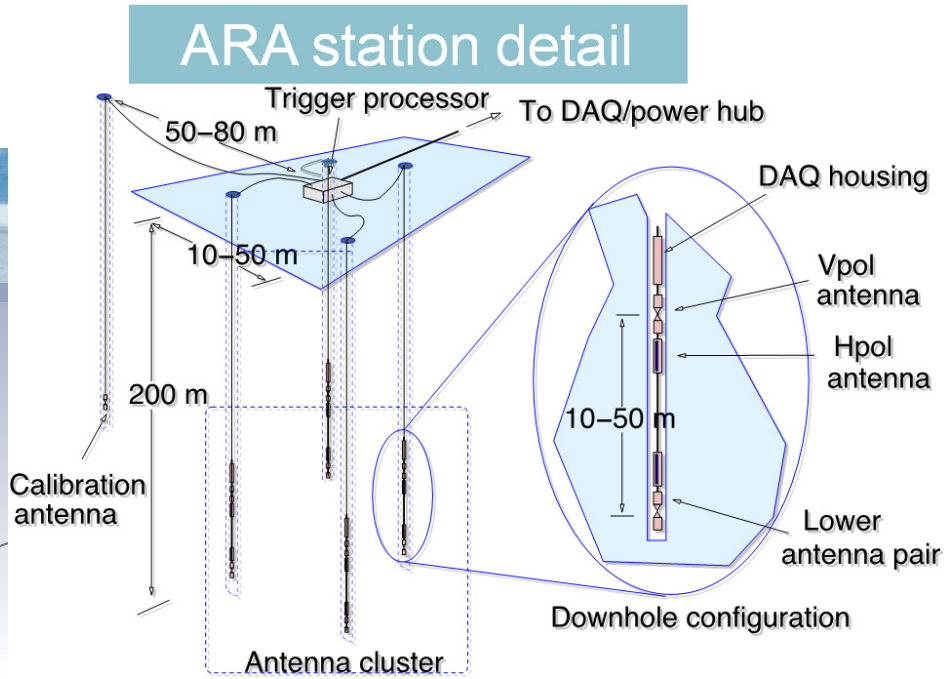
Experimental Efforts Current/Planned

- ARA (South Pole, Antarctica)
- ARIANNA (Moore's Bay and South Pole, Antarctica)
- ANITA/PUEO (NASA balloon, Antarctica)
  - HiCal (NASA balloon, Antarctica; ANITA-calibrator [MEPhI/KU])
- RNO-G (Greenland); first deployment summer 2020→2021
- RET-CR / RET-N (Taylor Dome, Antarctica) - RADAR technique!
- BEACON: Scan down from mountaintop for upcoming radio
- TAROGE-M: Scanning down from Antarctic mountaintop down for upcoming radio signals
  - $\nu_\tau + X \rightarrow \tau + X$; $\tau \rightarrow$EM shower⇒radio emissions
- AERA/GRAND-200K in-air radio-emissions from Earth-skimming ν

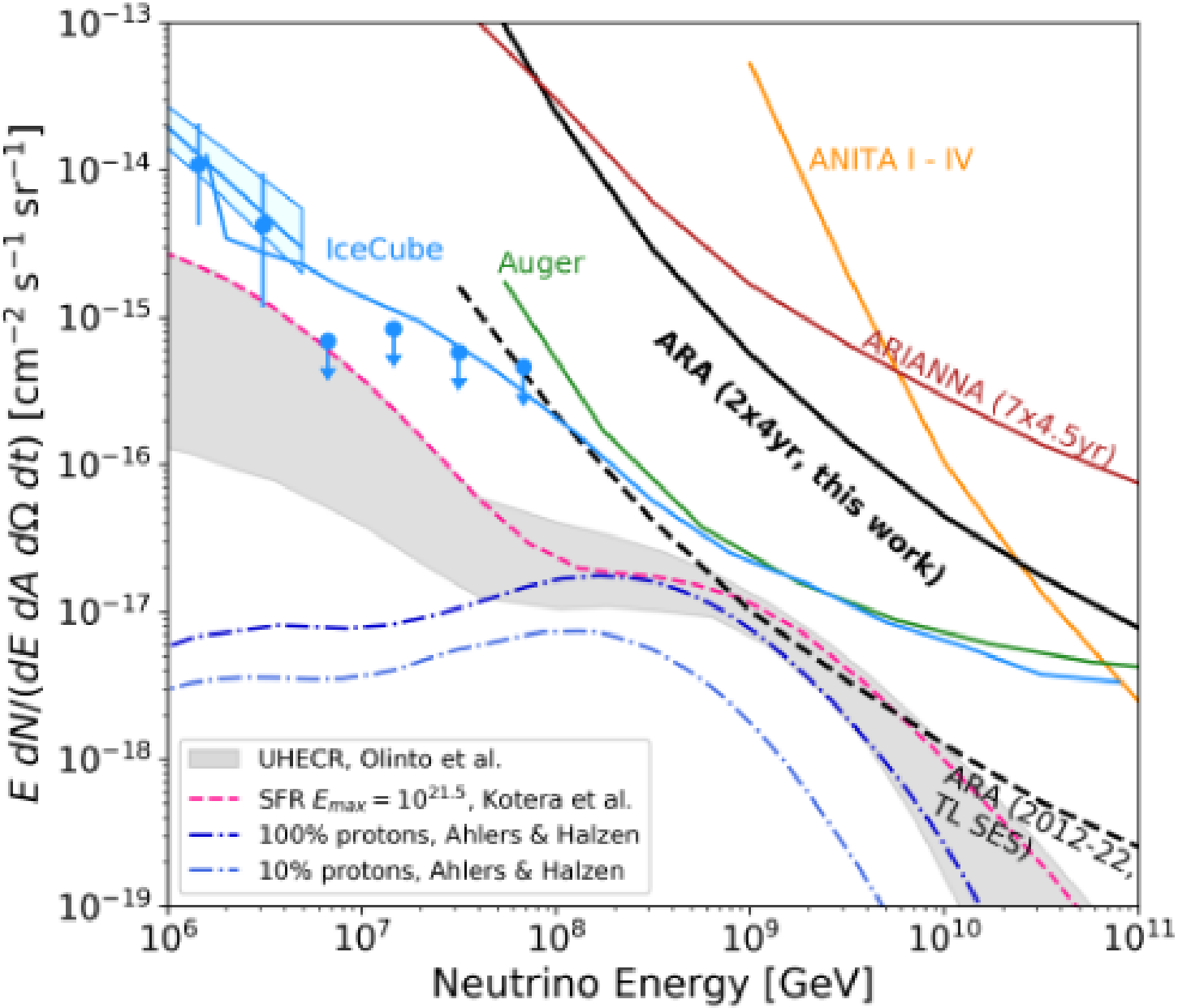
Time Limitations⇒focus on ice-target experiments (idea originated with Markov & Zheleznykh; INR, Moscow, 1986)

Askaryan Radio Array: in-ice ν detector

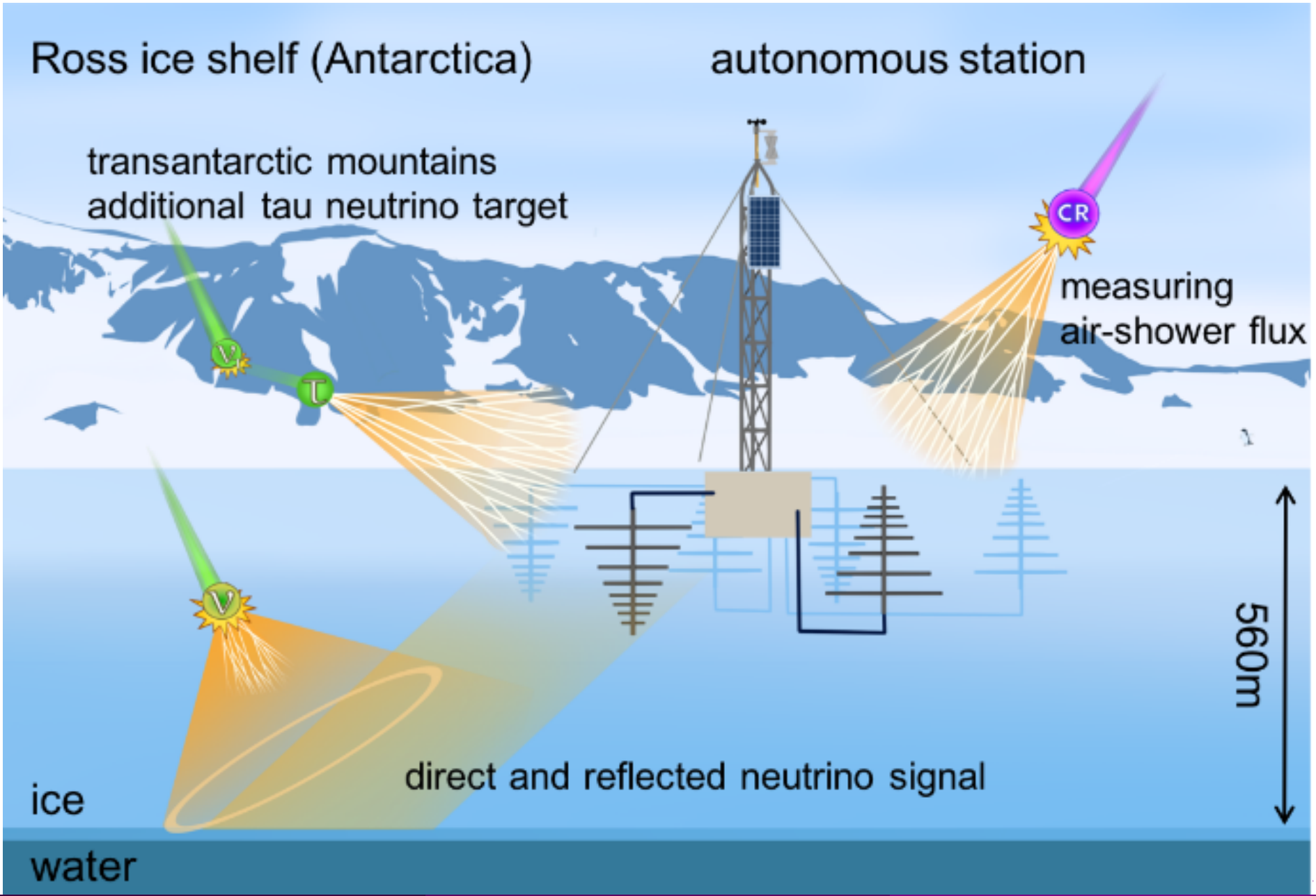




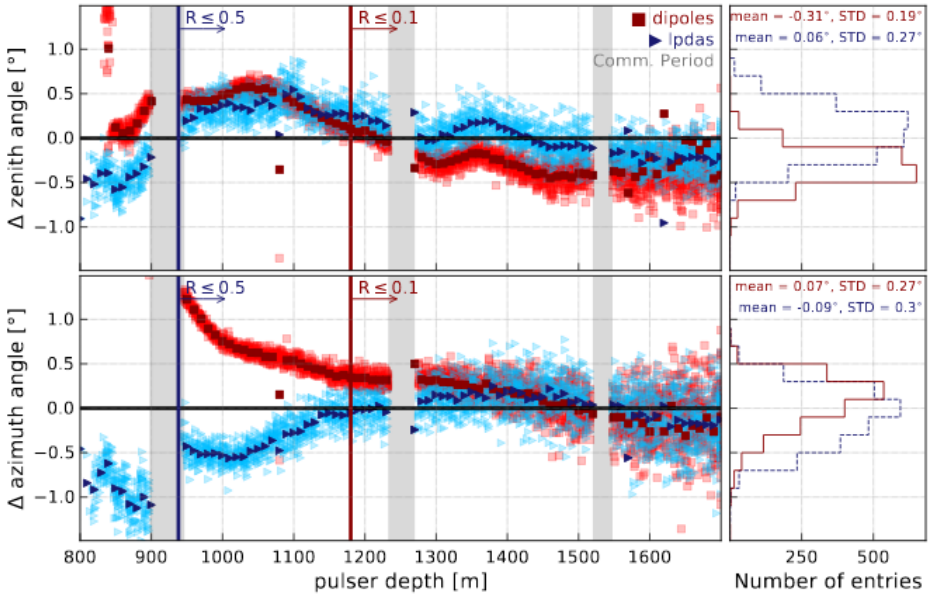
ARA neutrino sensitivity limits

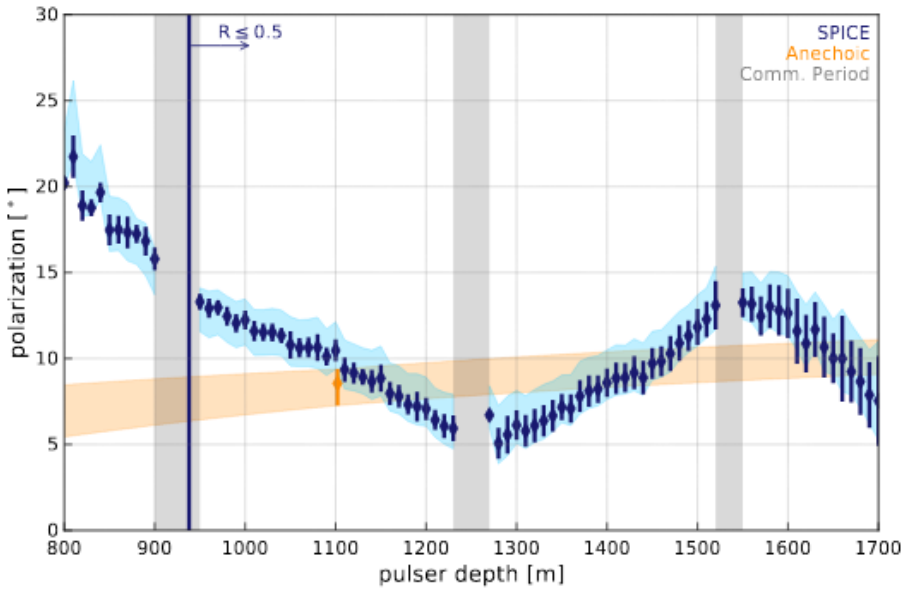


ARIANNA concept



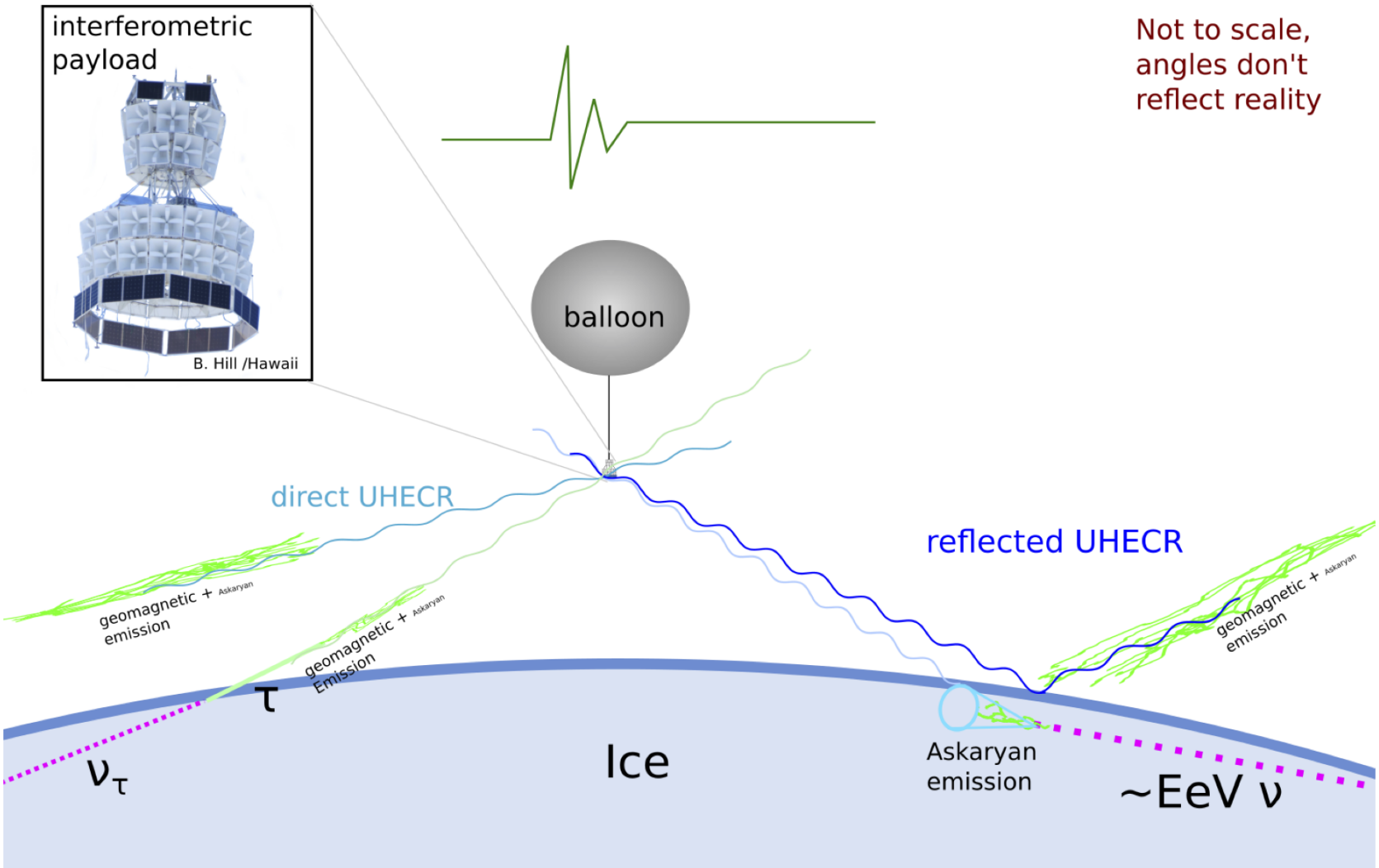
ARIANNA polarization and $\delta\theta$ measurements



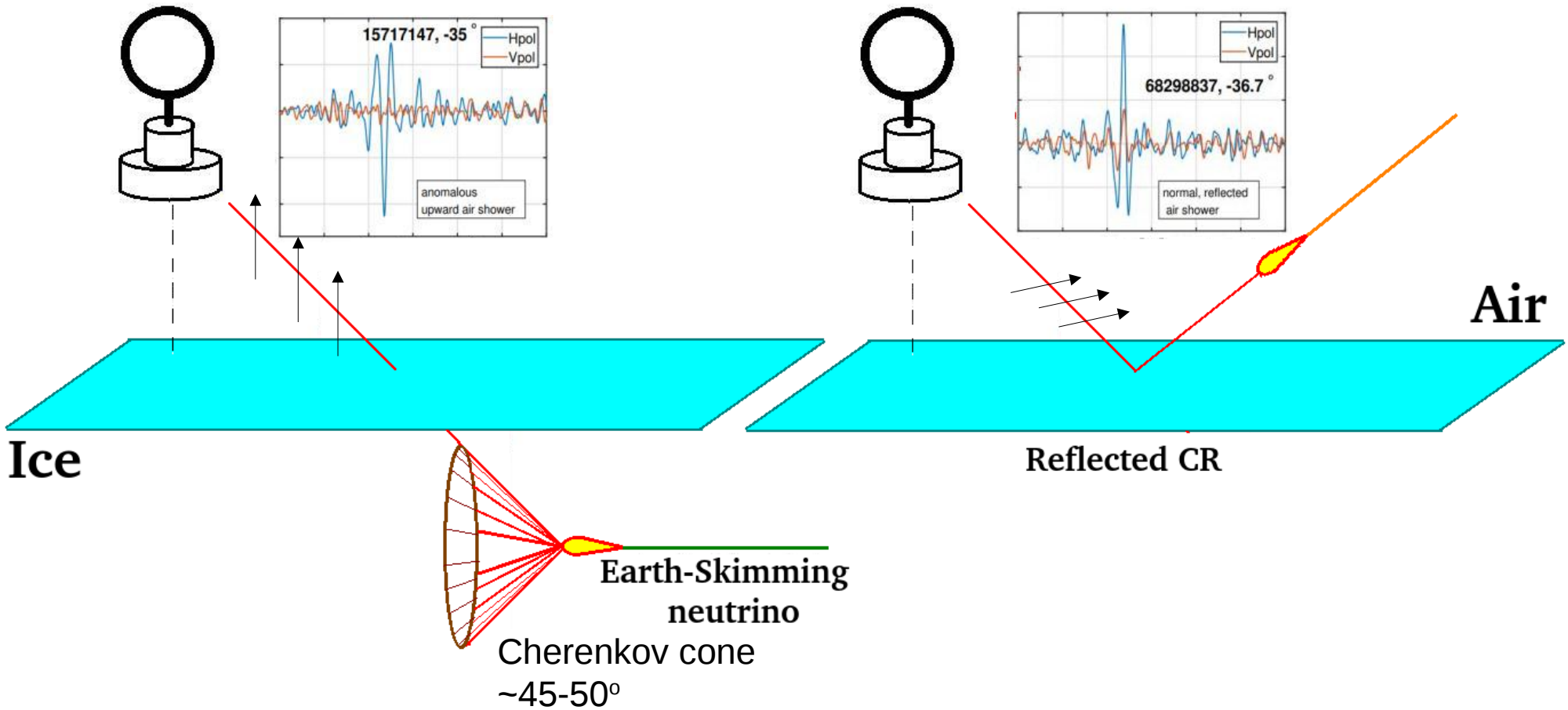


ANITA: synoptic strategy sensitive to ν and Extensive Air Showers (EAS) from UHECR

Scan Antarctic ice (low-noise environment)



Signal Type (Neutrino VS. EAS)

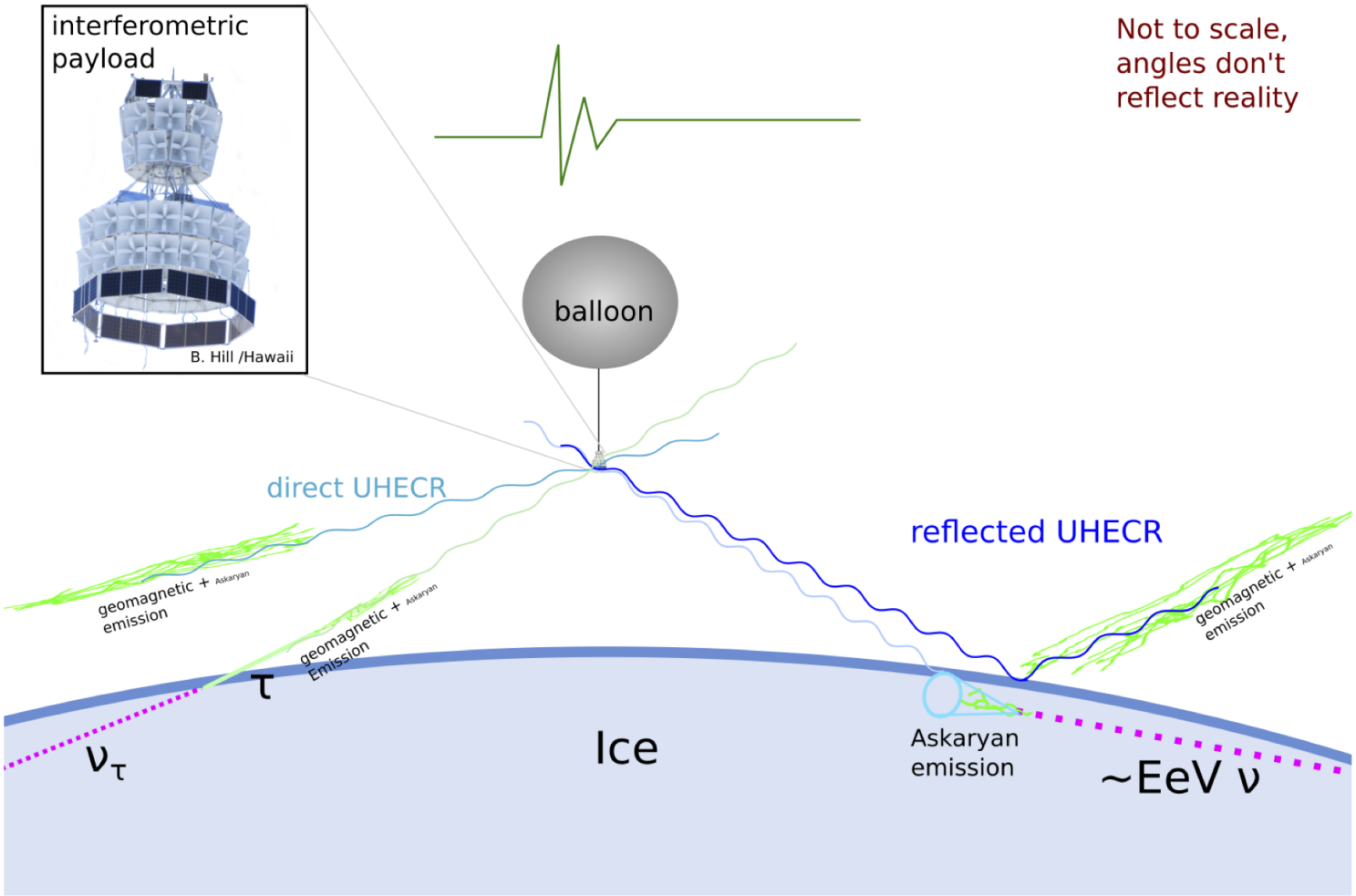


Askaryan radiation

Geomagntic radiation

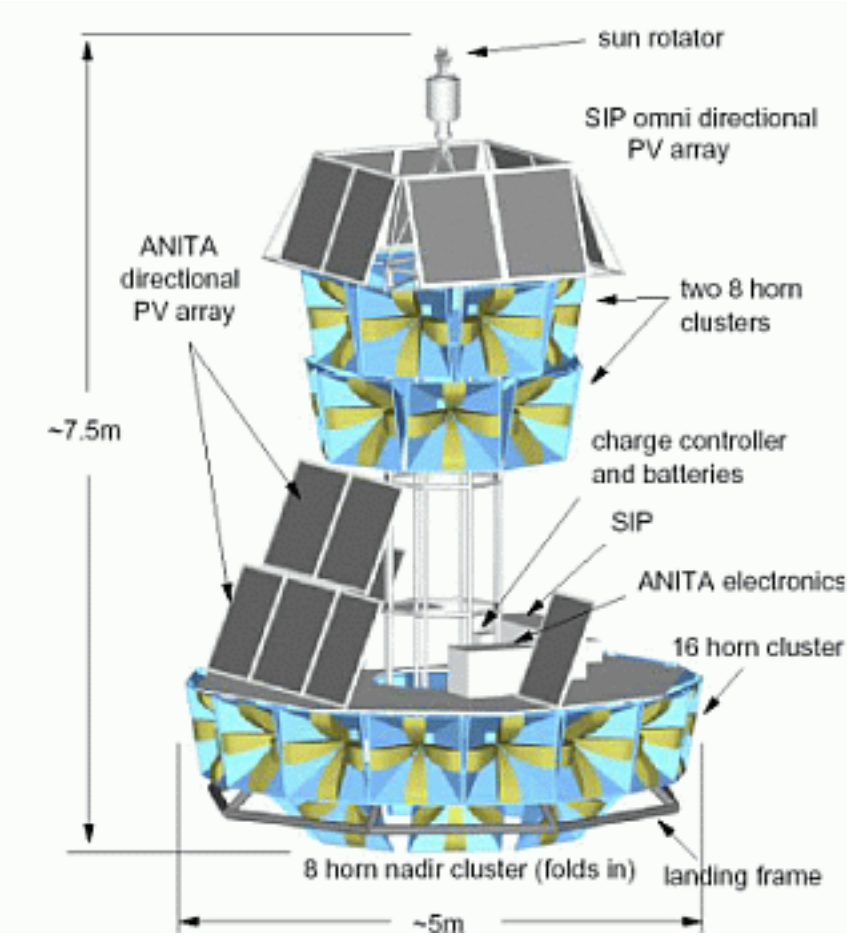
UHECR and ν have opposite signal polarity!

(due to inversion after surface reflection of UHECR)

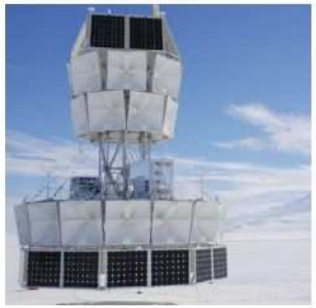


Filling Balloon at Launch

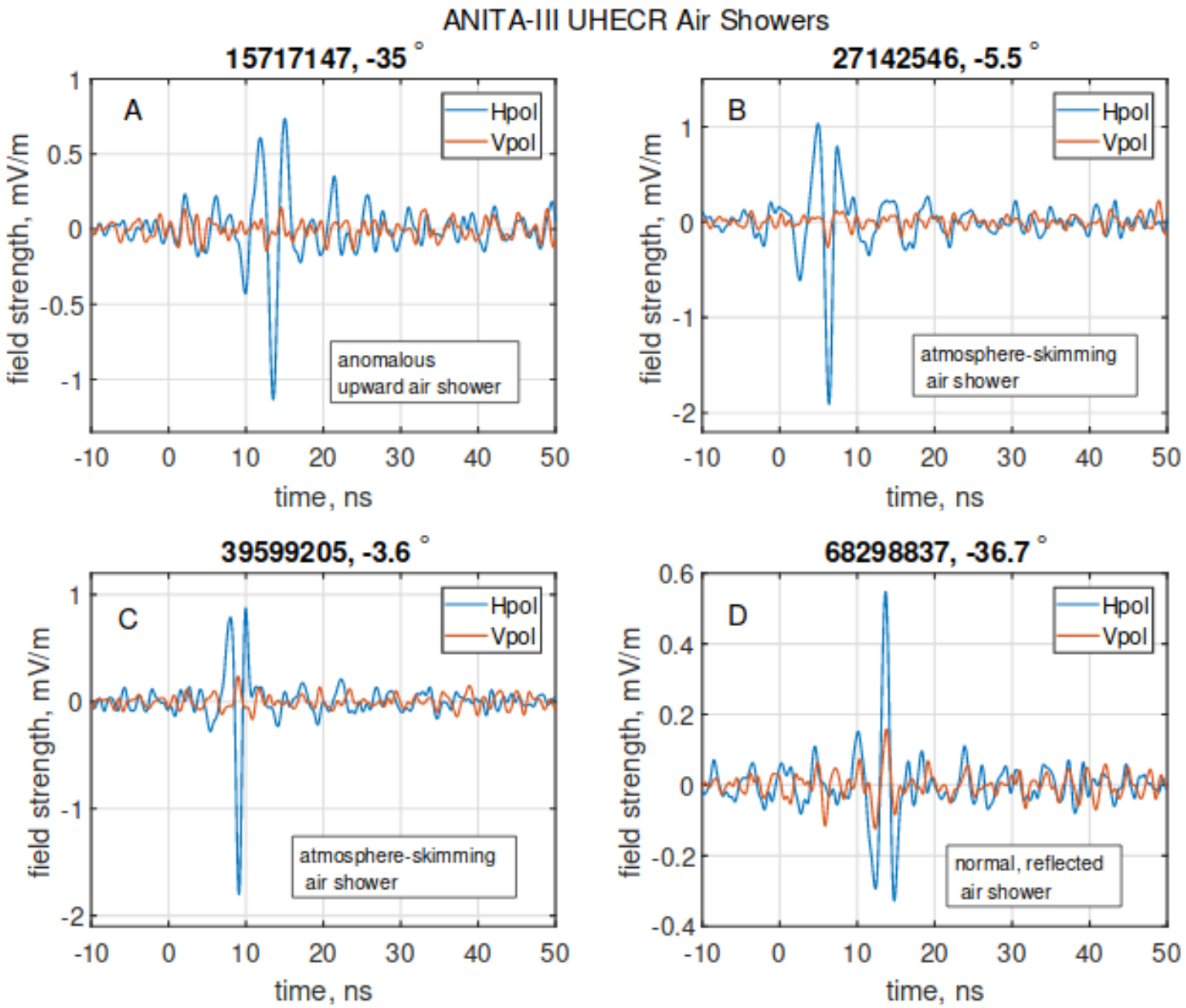
The ANITA Instrument



ANITAs

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger
Analyzed	Analyzed	Analyzed	**Recently analyzed**	Analysis Ongoing

A3 Mystery Evt (15717147 vs. 68298837)

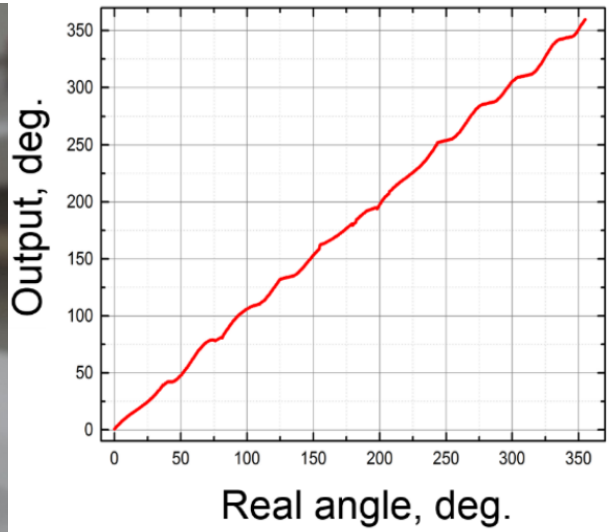


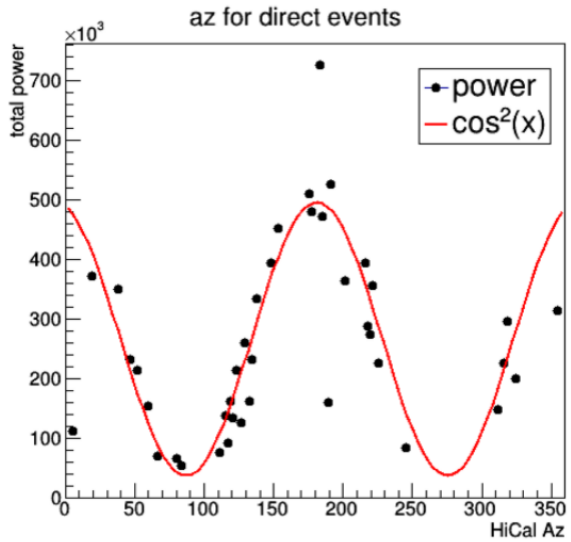
caveats

- 'Mystery' based on only one observable (POLARITY)!
  - Neutrino possibility ruled out by Earth absorption
- Waveforms shown after unfolding ANITA detector response
  - All band-limited signals look identical
  - Mystery events otherwise indistinguishable from UHECR in FFT, etc.
- These routines are NOT C++ ROOT standard, and are custom codes!
- Antarctic surface (and sub-surface) not monolithic
  - Ridges, crevasses, etc.
- Radio from UHECR hitting surface is also accompanied by
  - "Transition radiation"
  - "Stopping radiation"
  - "There are more things in heaven and Earth than are dreamed of in your philosophy" (Hamlet)

HiCal (MEPhI/KU) calibrates surface reflections

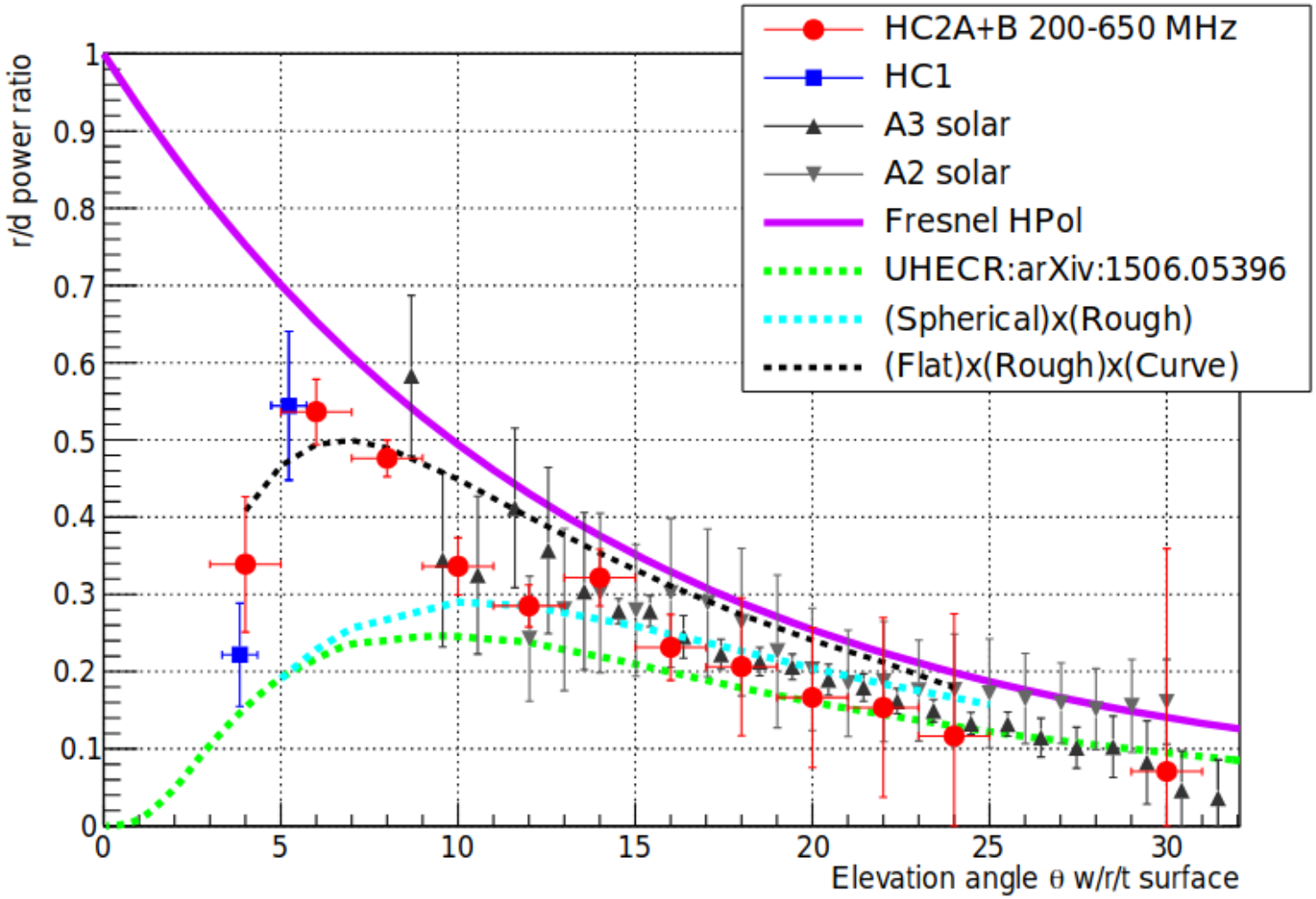
Balloon-borne (barbeque-lighter) transmitter separated from ANITA by 200–800 km.





SPUNK Transmitter orientation measurements

Calibrate surface reflectivity to Expectation

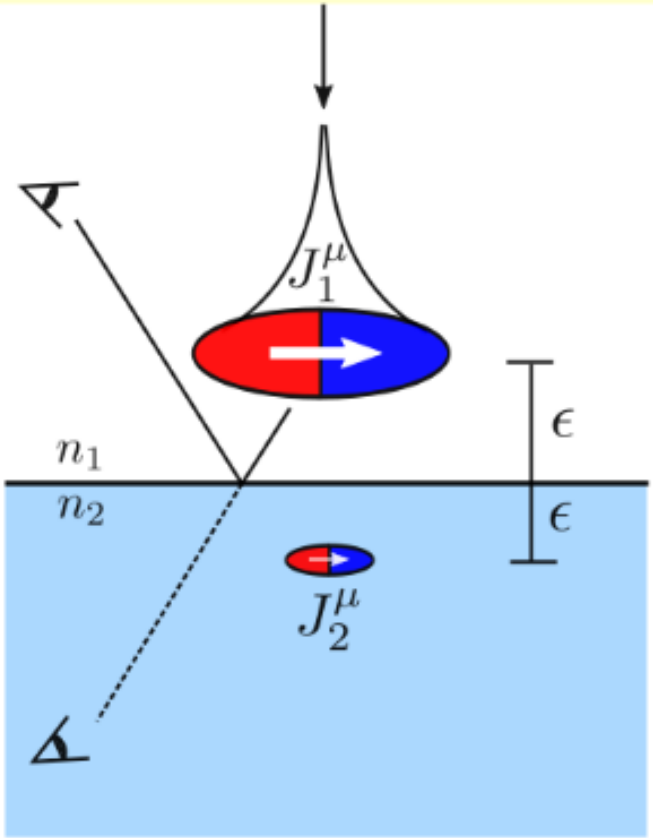


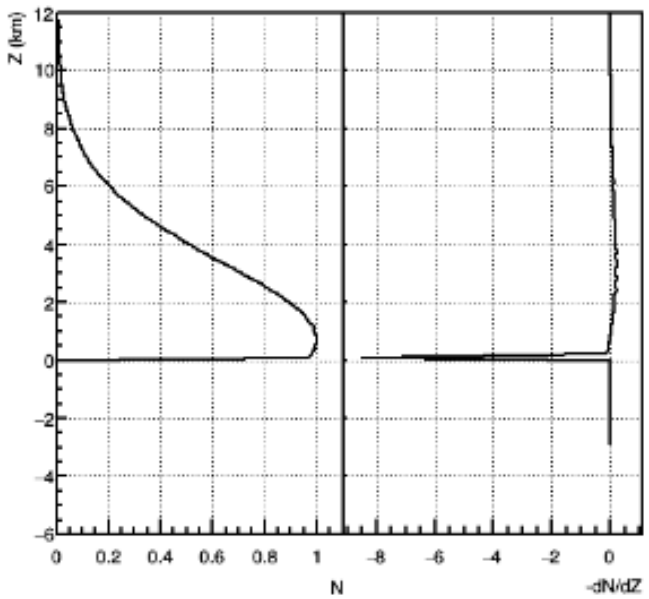
Tagline: Wrong polarity likelihood $<1\%$ per CR

Conventional explanation for mystery events

transverse current

- significant current arrives at air/ice boundary if:
  - energies >= 1e17 eV and
  - zenith angles < 70 degees
- AND amount of charge increases dramatically with high surface elevations



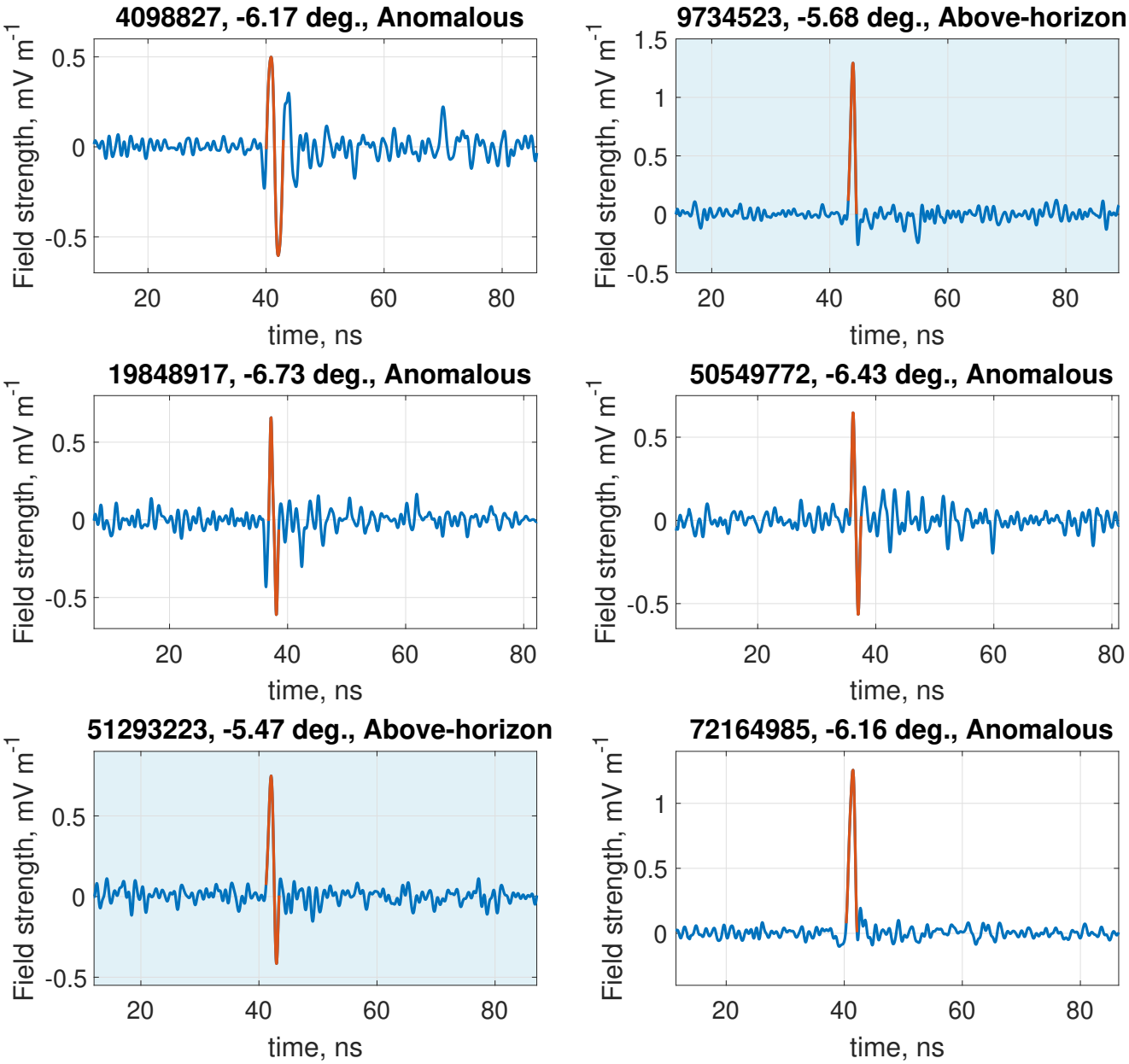


ex: 50 deg shower @ 3km elevation

- the transverse current, as well as the path itself *vanishes* resulting in a strong shock in the potential
  - producing the corresponding E-field
  - polarized along geomagnetic

4 March 19 coherent TR--S Prohira--K.D. de Vries

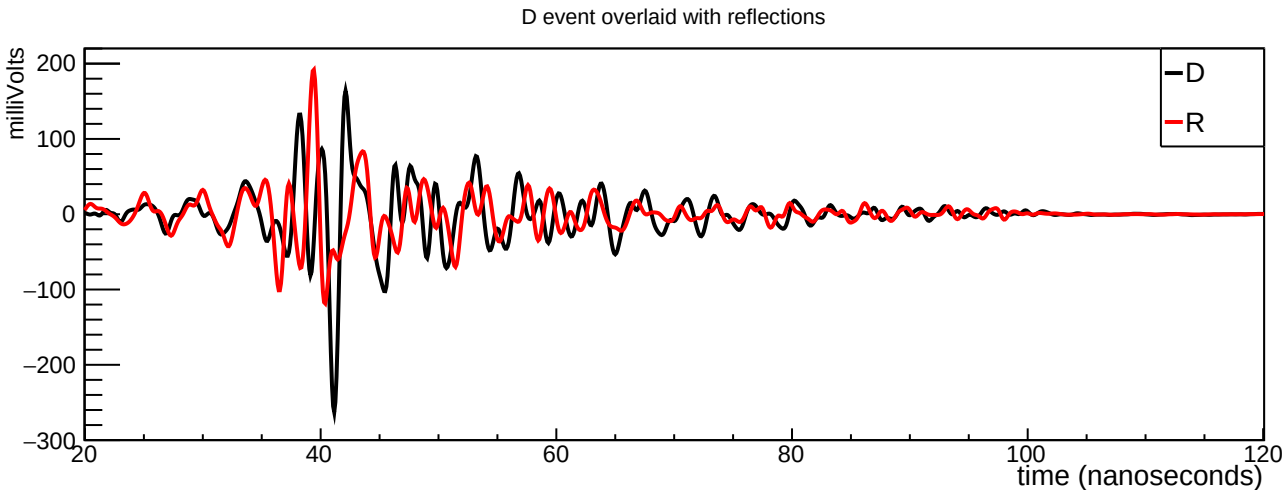
ANITA-4: 4 more ME (3.2σ (7/20))

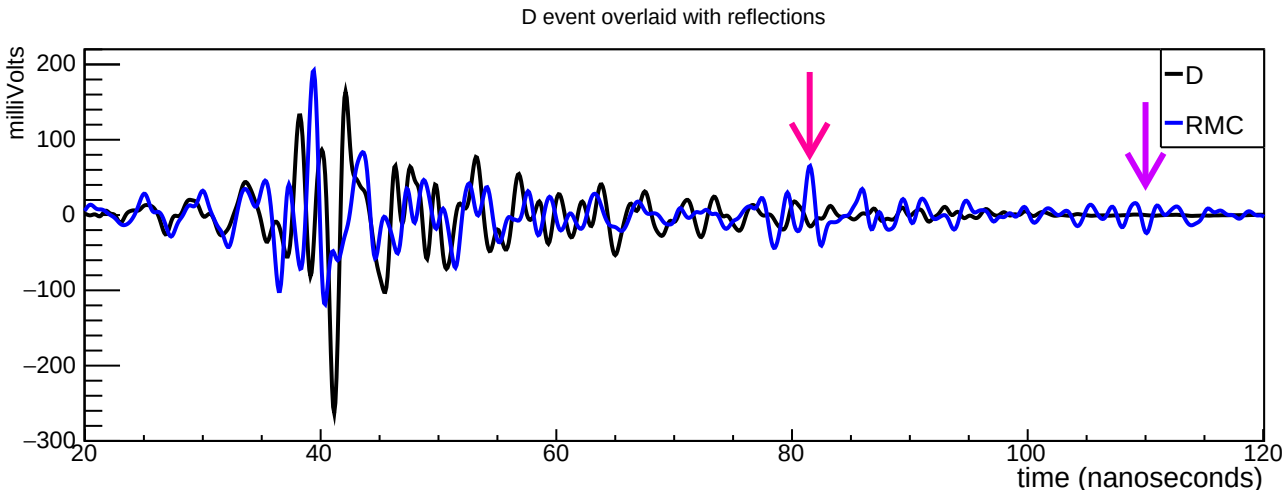


Sub-surface reflectors?

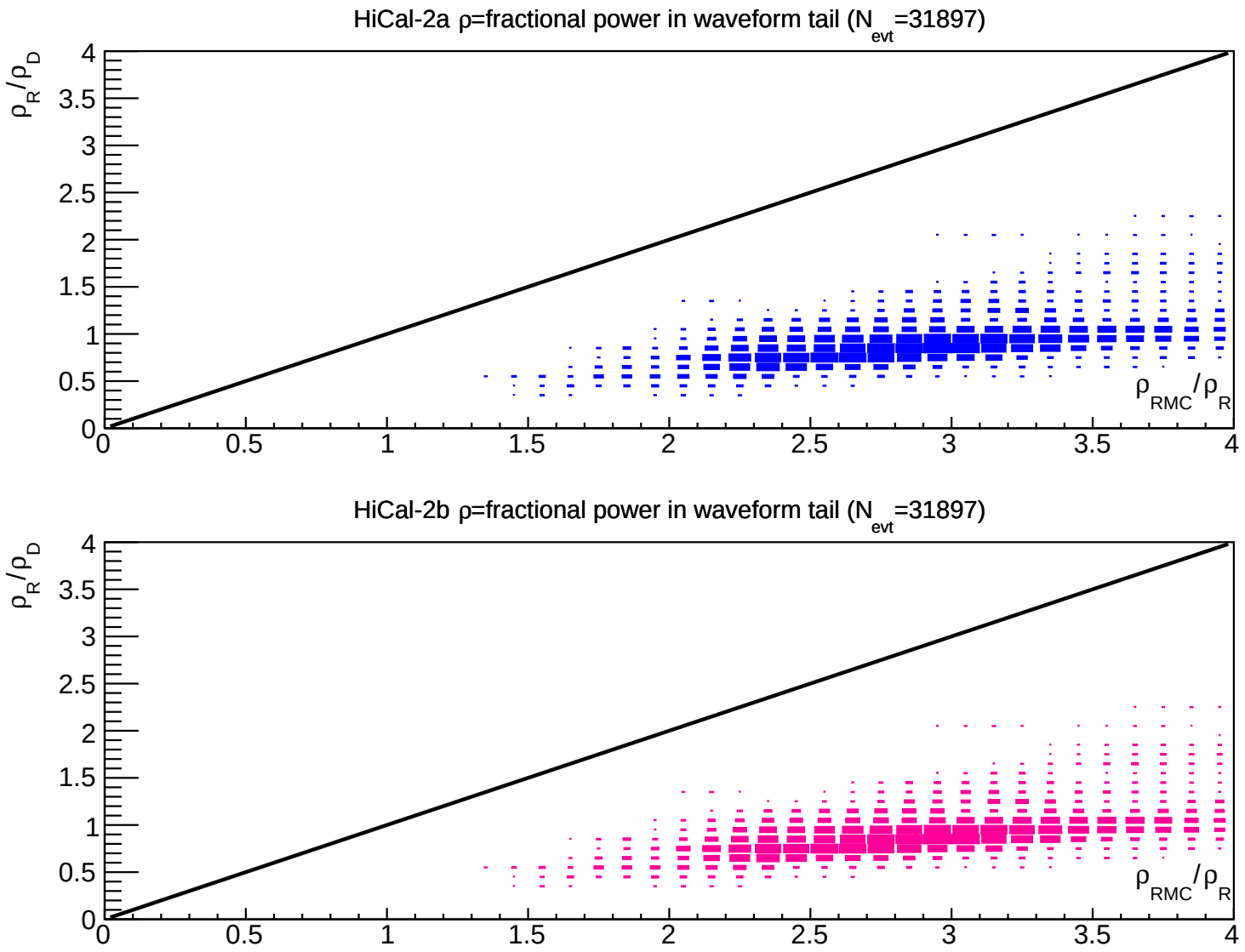
Reflections on the anomalous ANITA events: the Antarctic subsurface as a possible explanation

Ian M. Shoemaker (a1), Alexander Kusenko (a2) (a3), Peter Kuipers Munneke (a4), Andrew Romero-Wolf (a5) ...





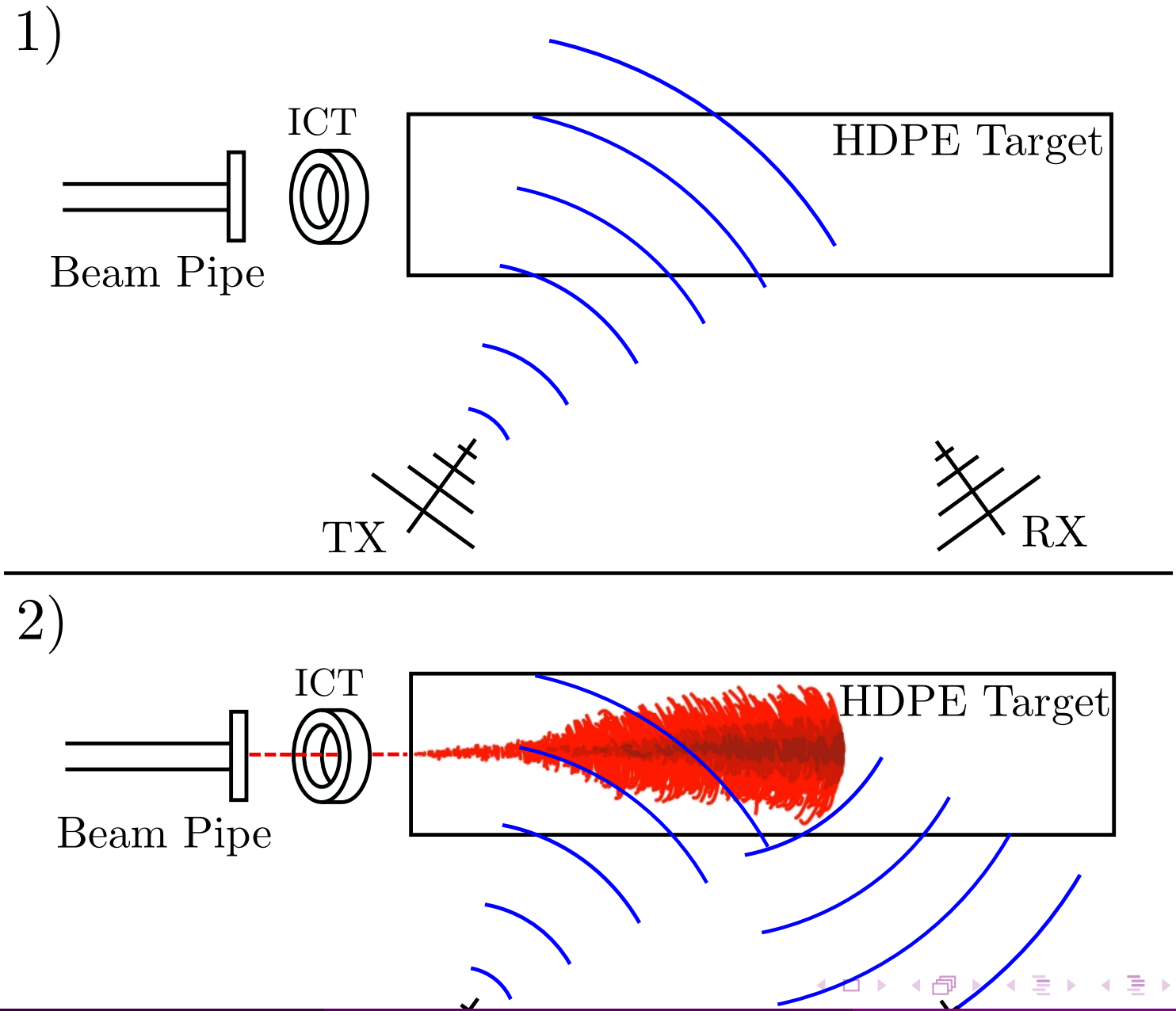
Testing Sub-surface reflector model



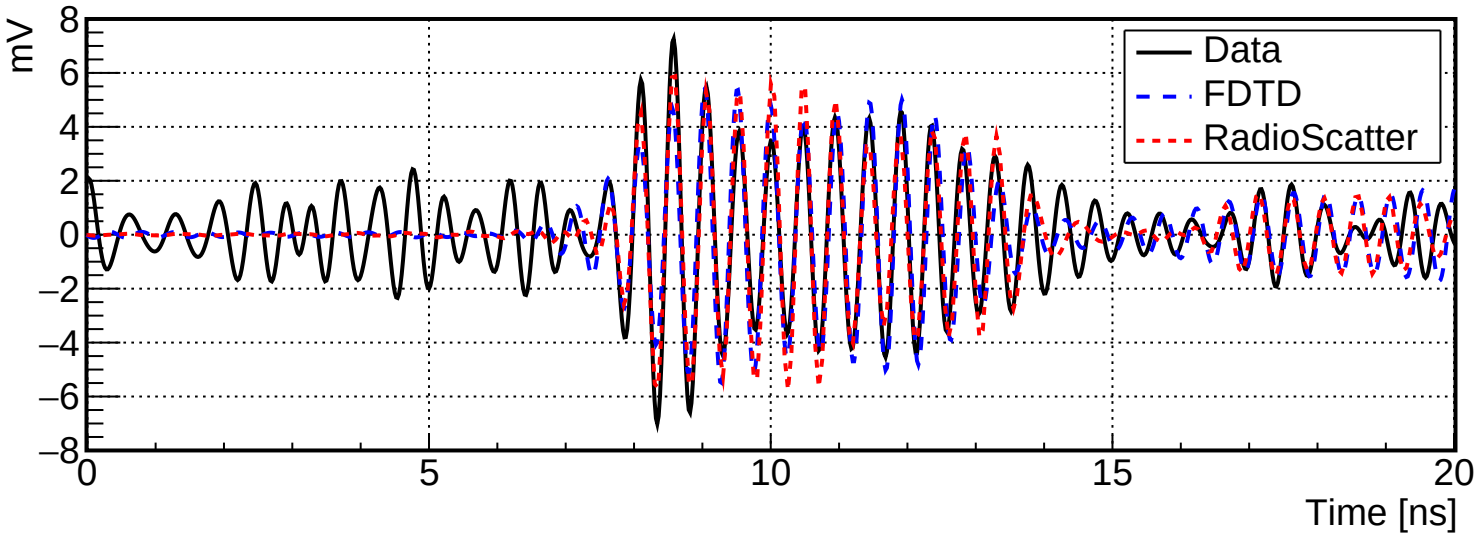
Triboelectric Effect? (see M. Mikhailova talk from Tuesday!)

- Analyze data from RICE and AURA experiments at South Pole
- Perform statistical correlation between trigger rates for each experiment and local wind speed
- Find:
  - Clear evidence for enhanced radio-frequency emissions during high wind times
  - Threshold $\sim$10-12 meters/second
- Frequency spectrum analysis$\Rightarrow$model/simulation under construction
  - Mikhailova/E. Bondarev

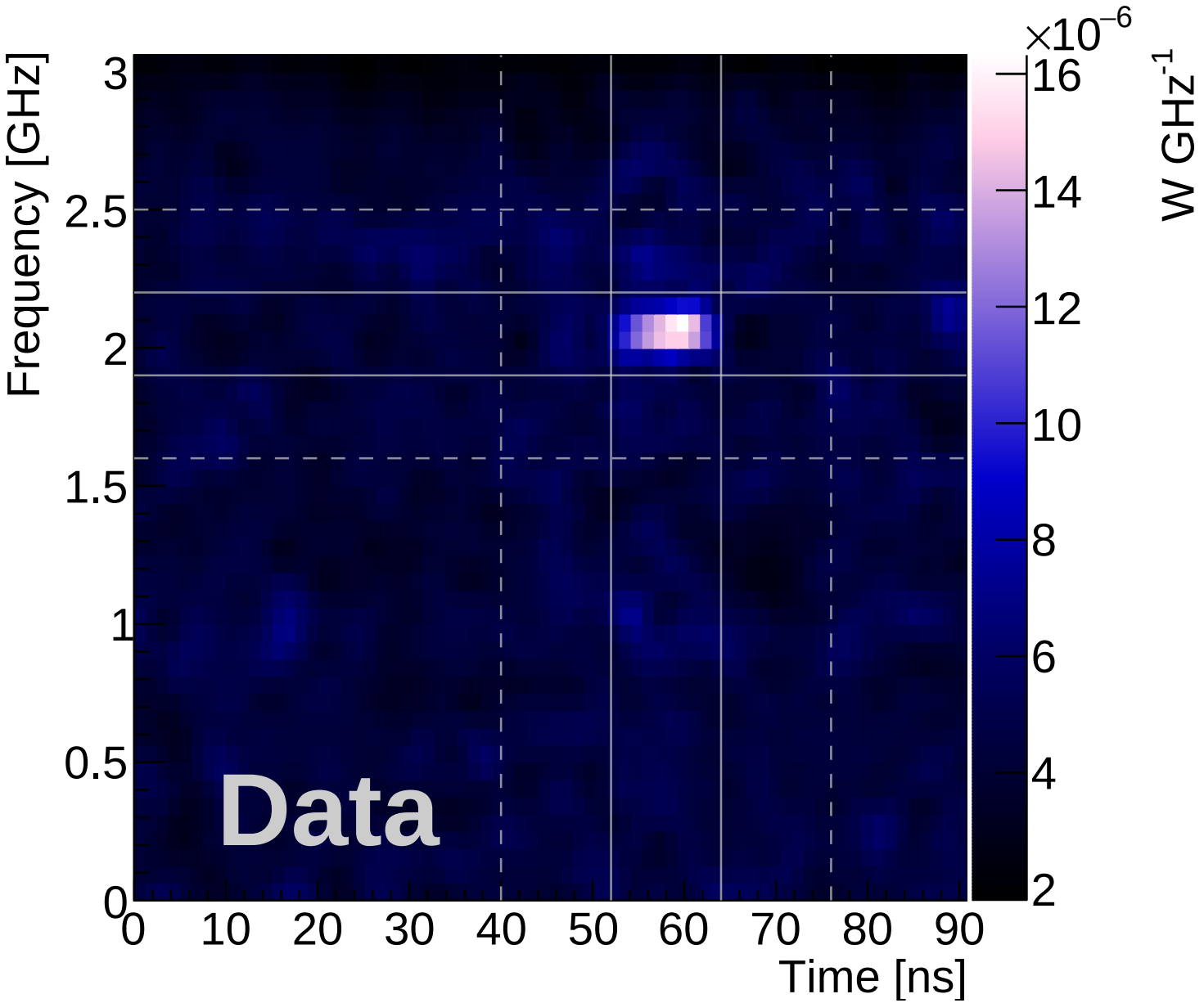
Radar detection of ultra-high energy showers



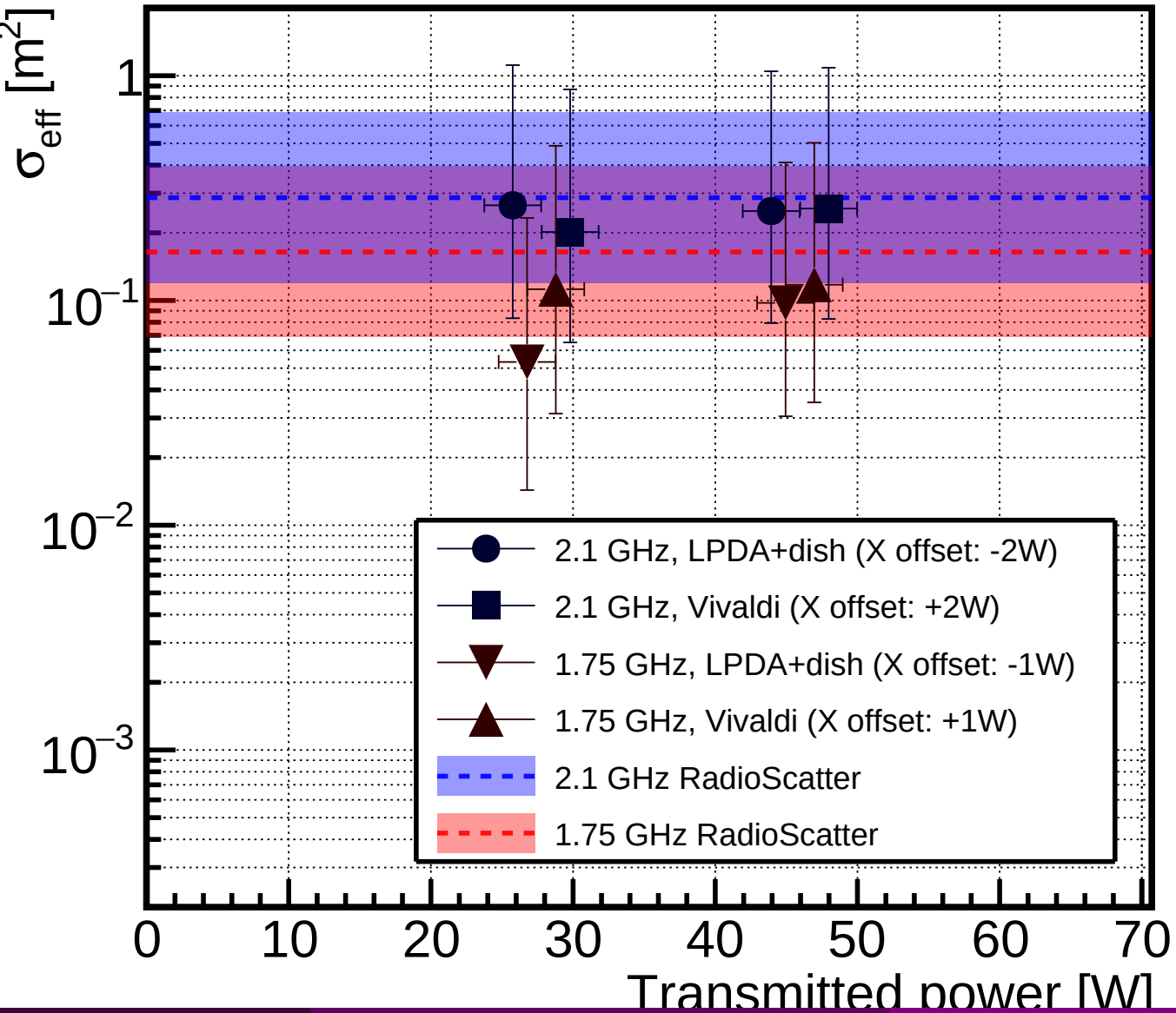
Time-domain radar echo



Data signal with right time and frequency structure!



Measured Power(ω)



Future Experiments

- ANITA-IV = last flight in ANITA series
  - PUEO proposed as NASA 'Pioneer Class' mission
  - Beam-forming interferometry at trigger level
    - Reduce trigger threshold from SNR$\sim$6$\rightarrow$SNR$\sim$2 based on ARA experimence
  - Antarctic flight 2024
- RET radar, Taylor Dome, Antarctica 2024

2024+ IceCube Gen-2 radio (10 PeV–10 EeV)