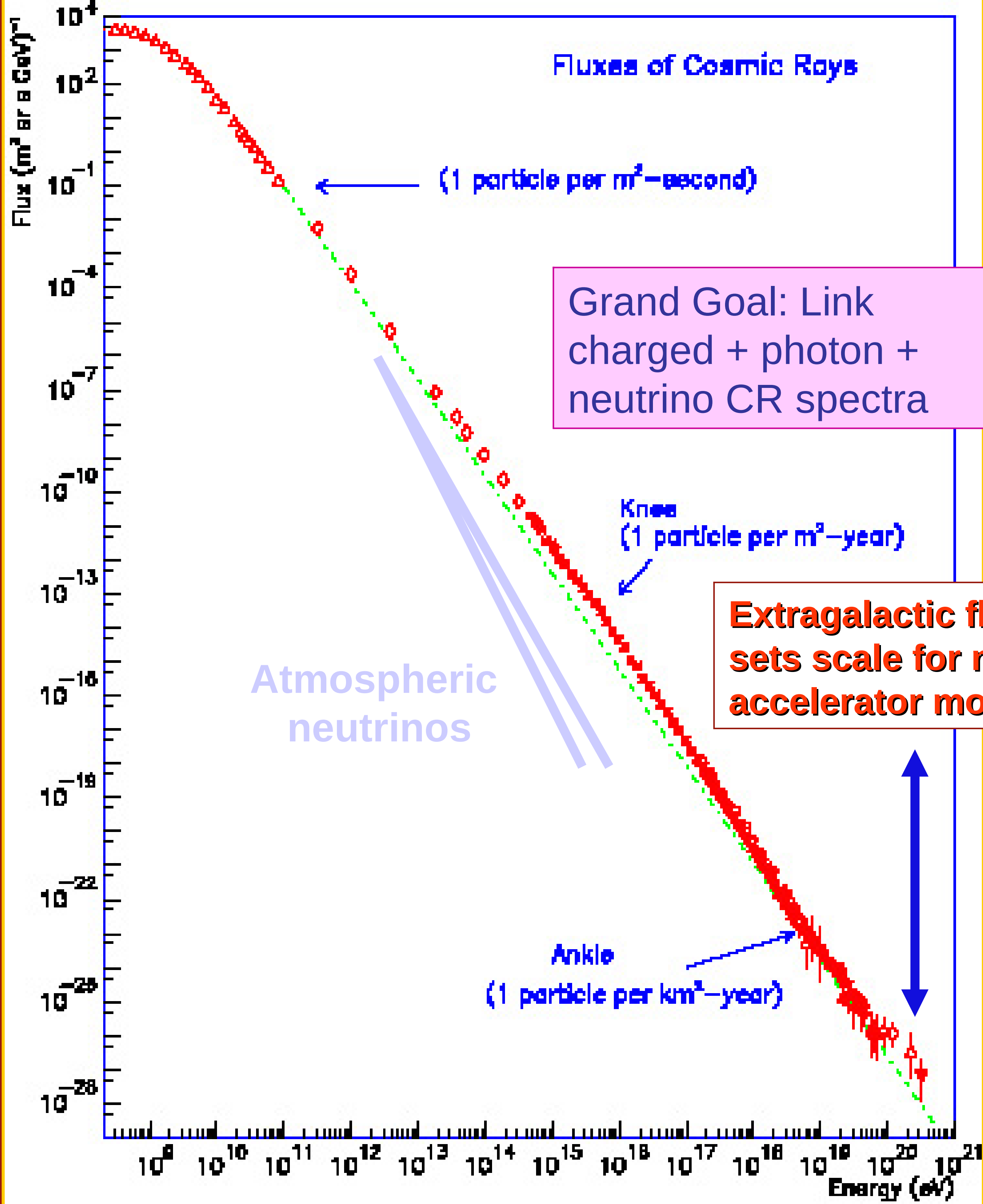
Production of radio waves and radio detection

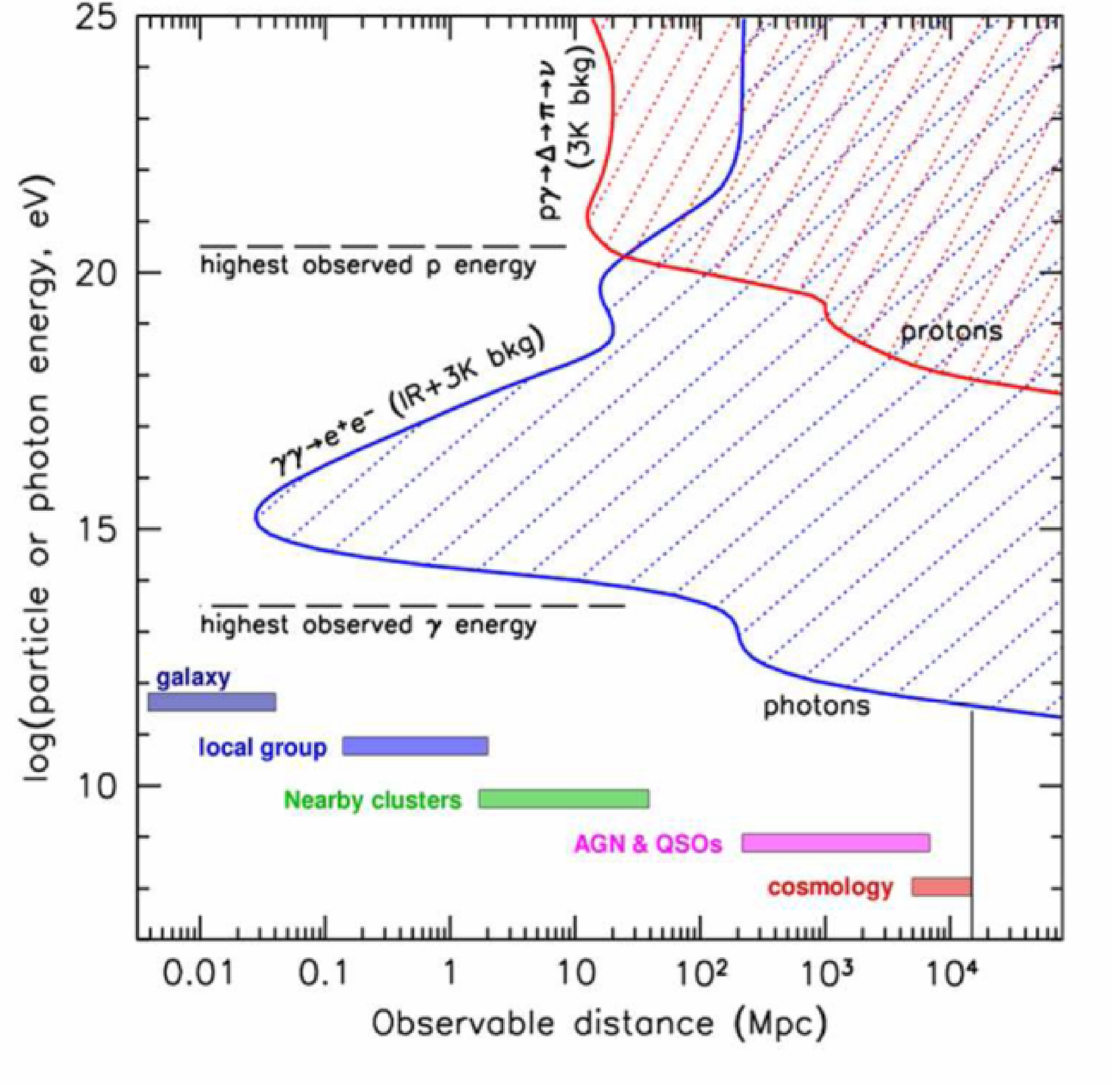
Science Drivers: Cosmic Ray and Neutrino Energy Spectra



Grand Goal: Link charged + photon + neutrino CR spectra

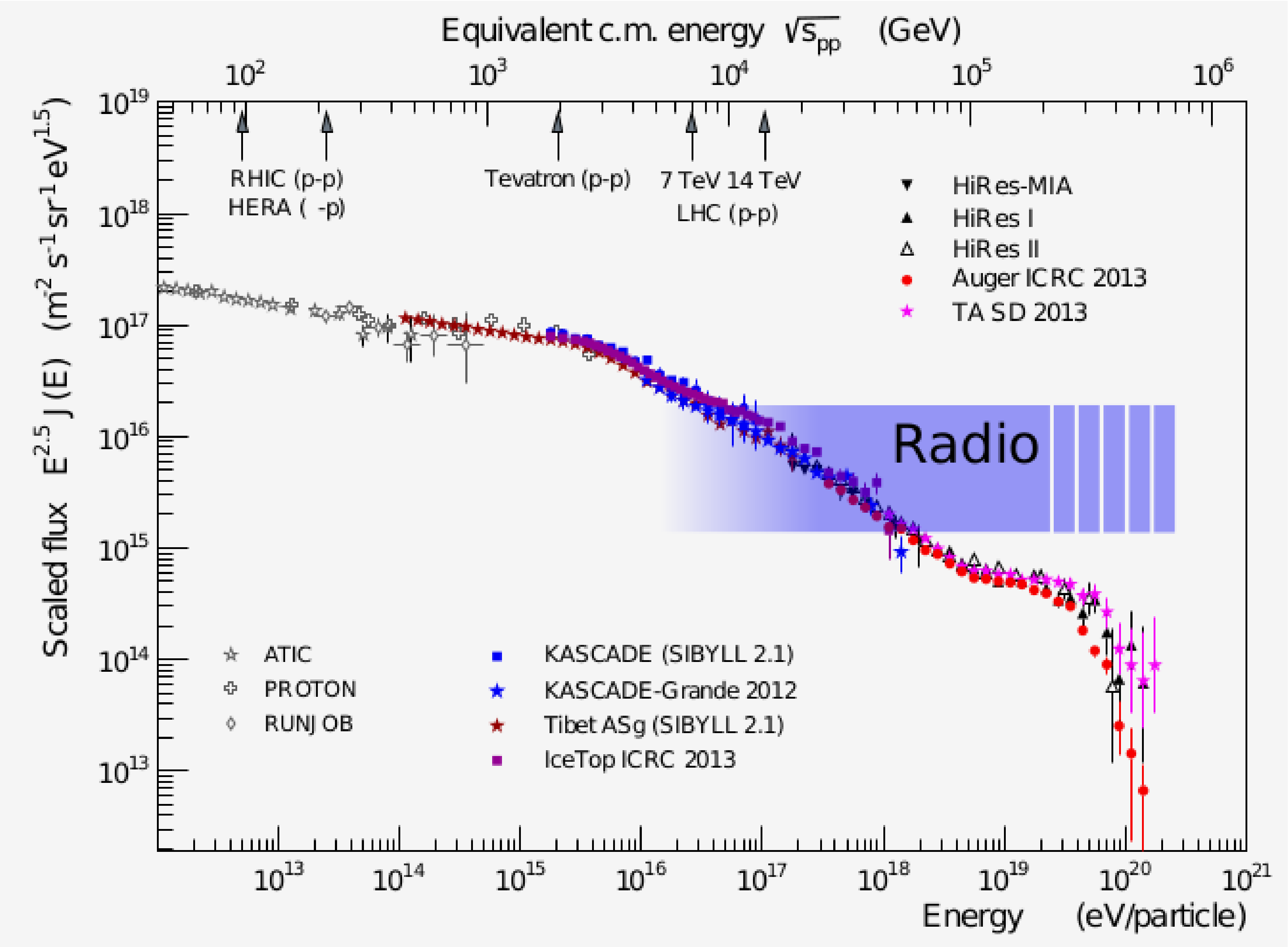
Extragalactic flux sets scale for many accelerator models

GZK, redux



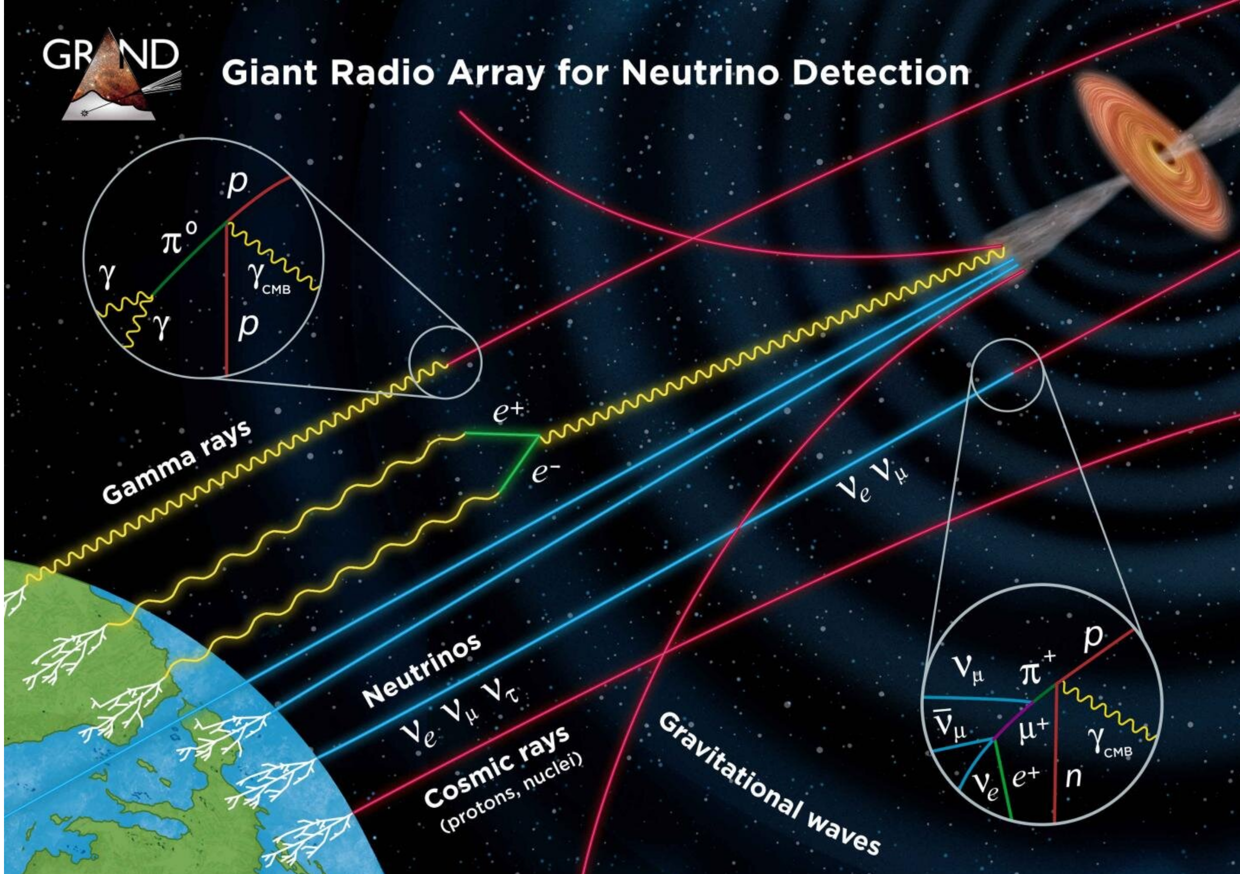
pγ→Δ→π→ν
(3K bkg)
highest observed p energy
γγ→e⁺e⁻ (IR+3K bkg)
protons
highest observed γ energy
galaxy
photons
local group
Nearby clusters
AGN & QSOs
cosmology
log(particle or photon energy, eV)
25
20
15
10
0.01
0.1
1
10
10²
10³
10⁴
Observable distance (Mpc)

Radio (no phasing)

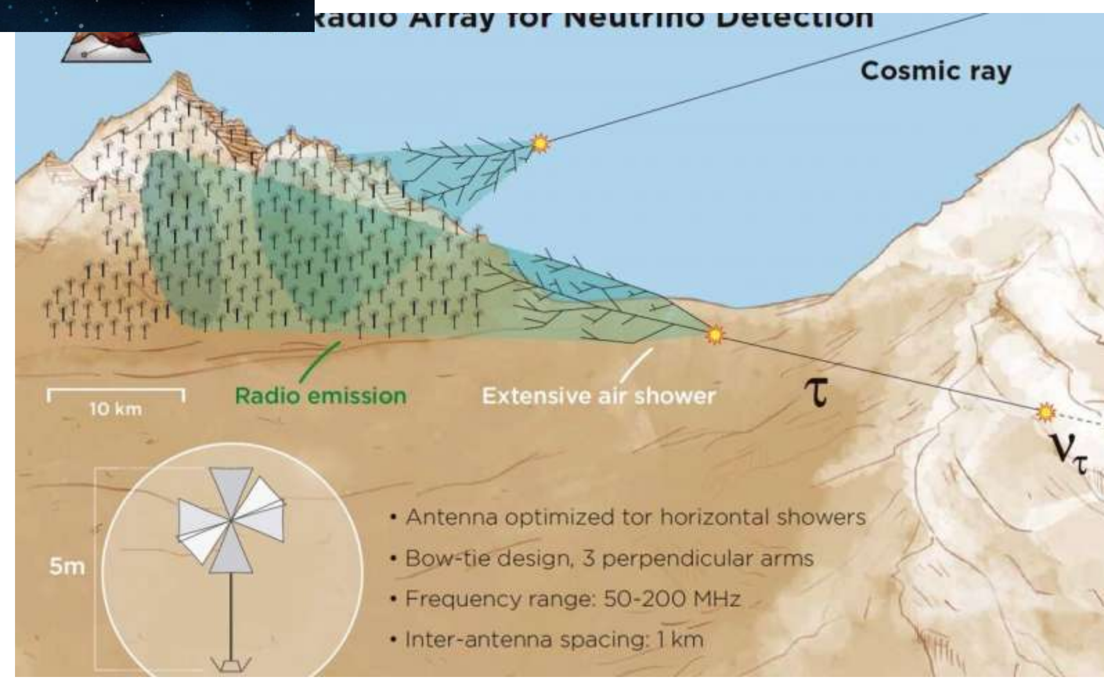


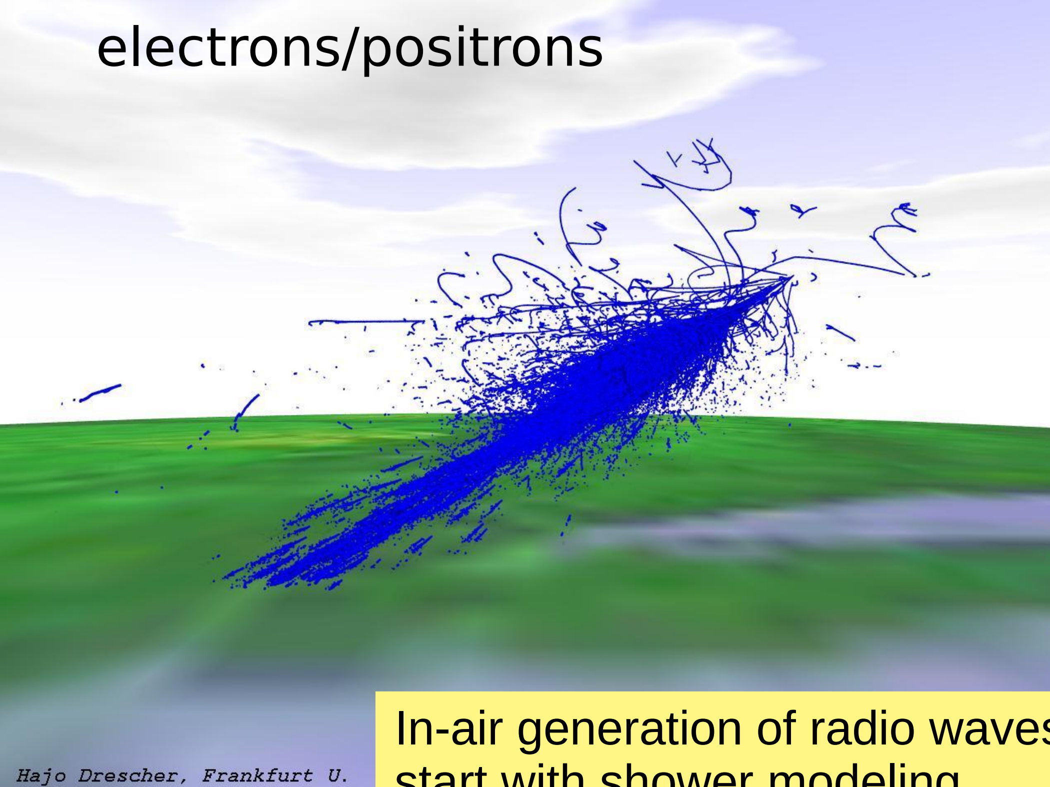
Q: The nominal energy threshold of in-air radio detection is 100 PeV. Assuming an $E^{-2.7}$ charged spectrum, how many more events (roughly) do you detect by phasing (perfectly) 16 antennas?

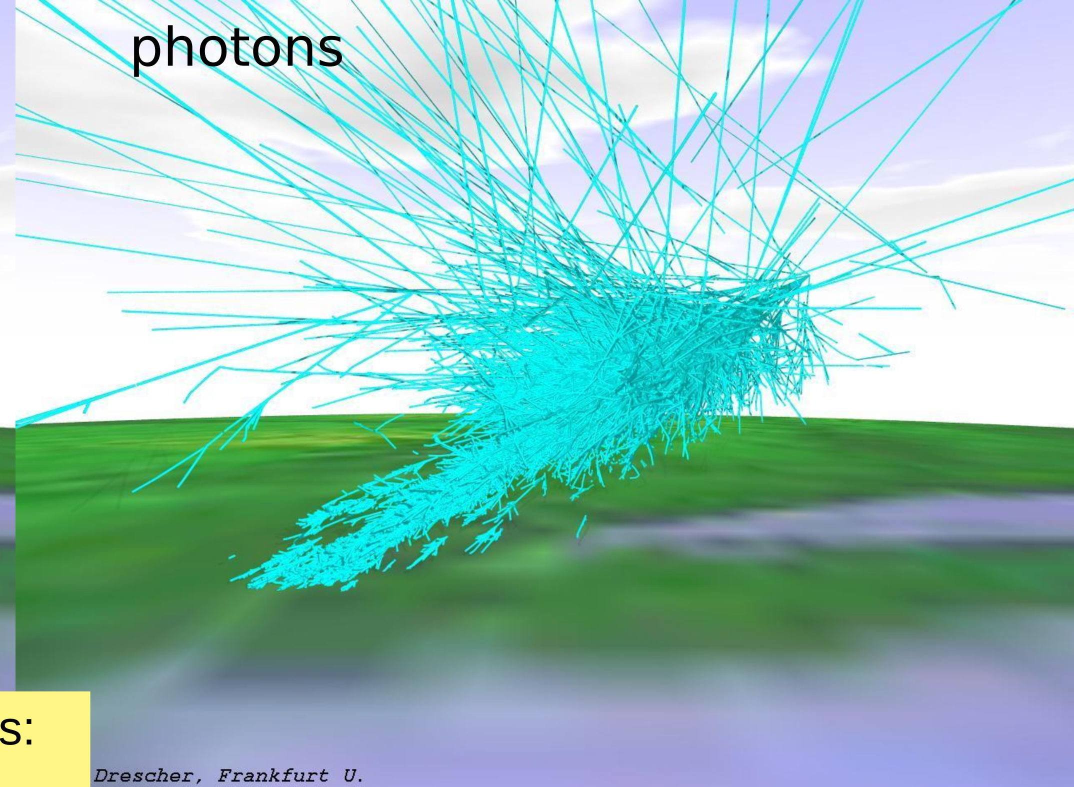
In-air UHECR detection using radio techniques



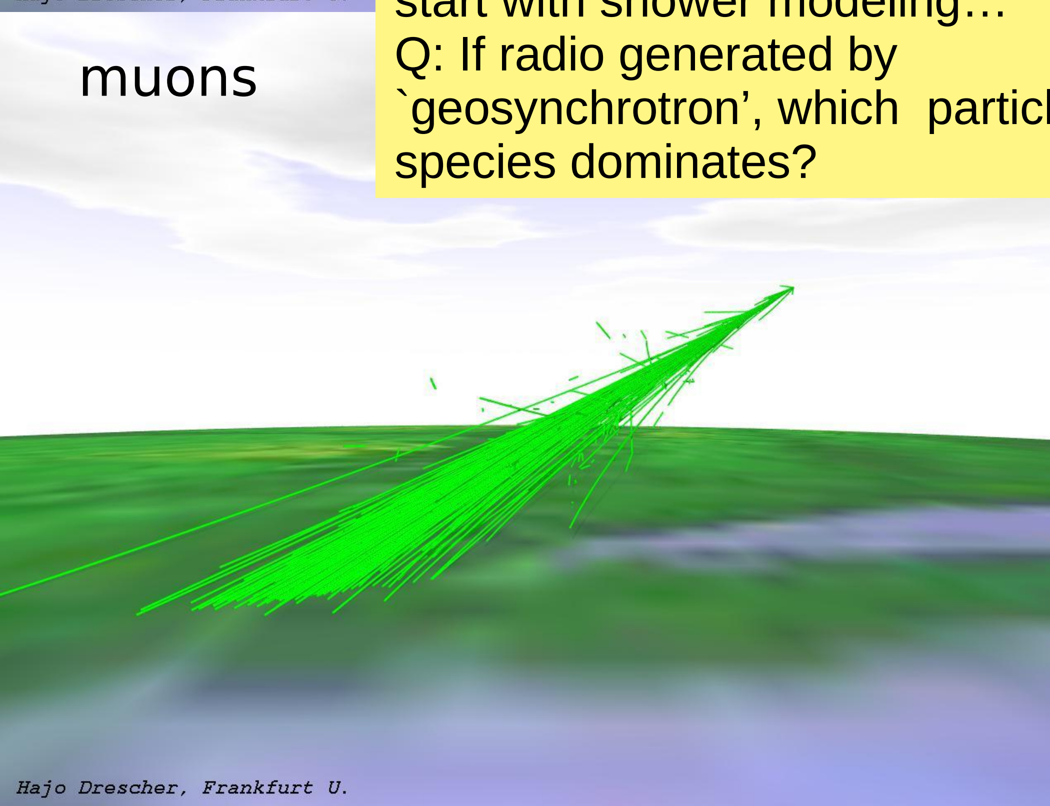
20 separate, independent sub-arrays, each of 10 000 radio antennas deployed over 10 000 km^2

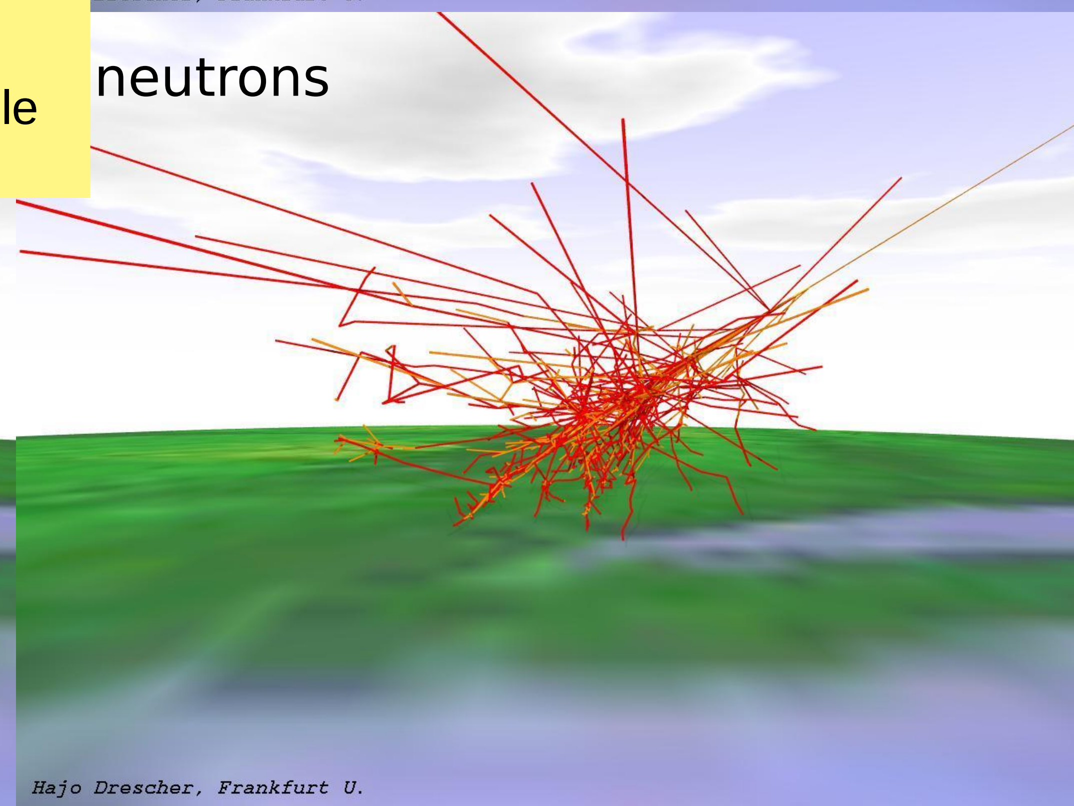


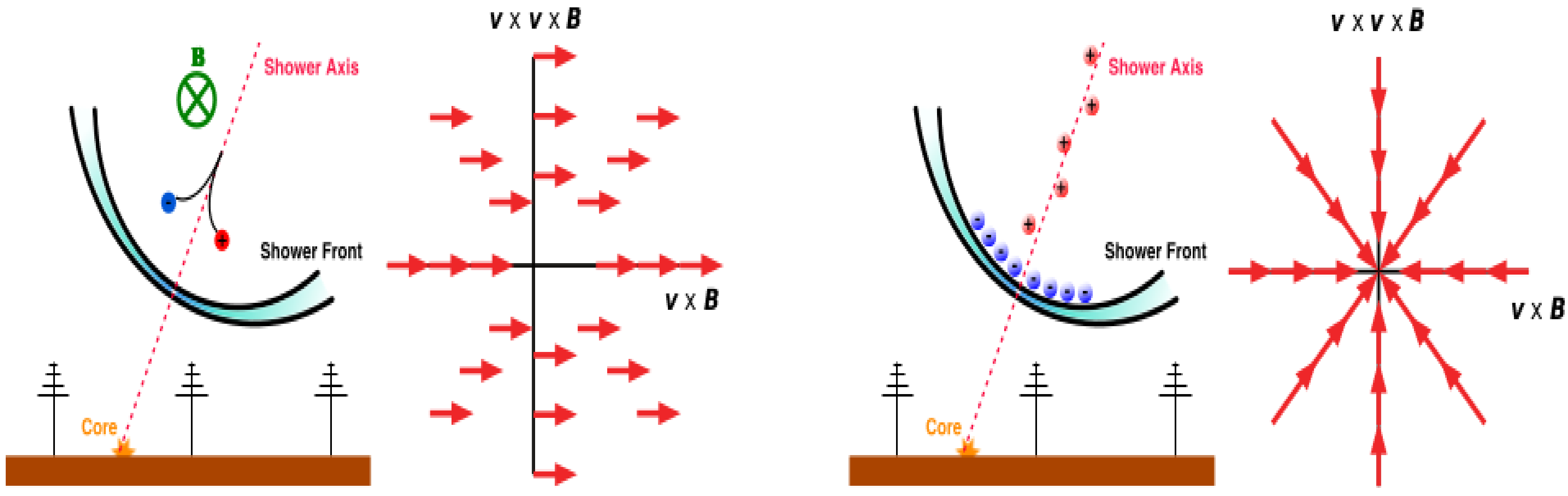




In-air generation of radio waves:
start with shower modeling…
Q: If radio generated by `geosynchrotron', which particle species dominates?



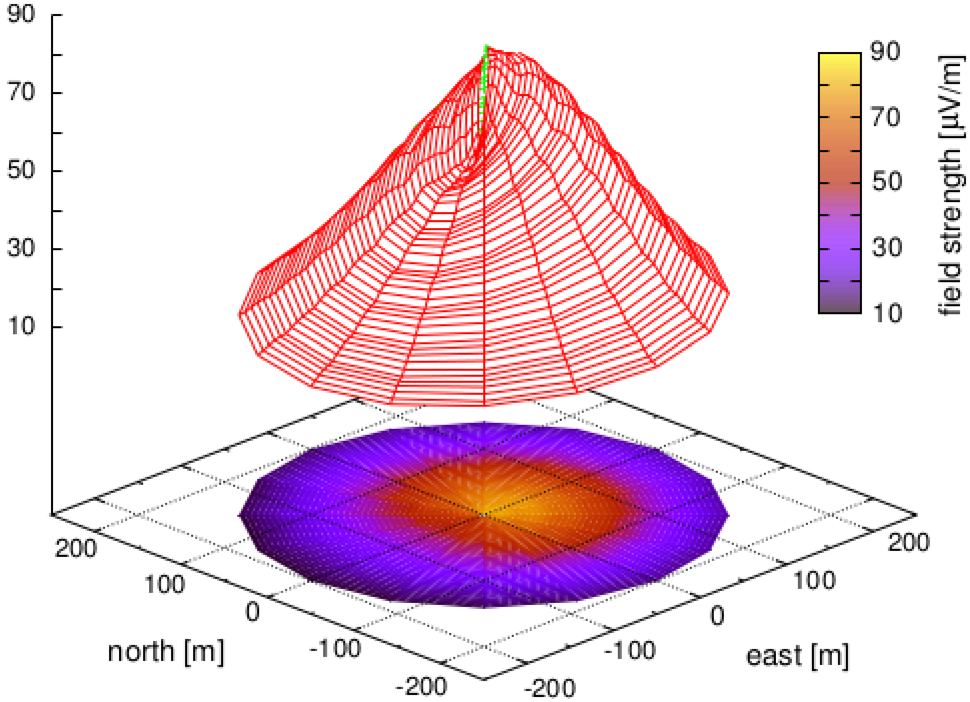




In-air generation of radio signals: geomagnetic and Askaryan

“charge excess” - $N_{e-}N_{e+}$ ~0.25 E_s(GeV)

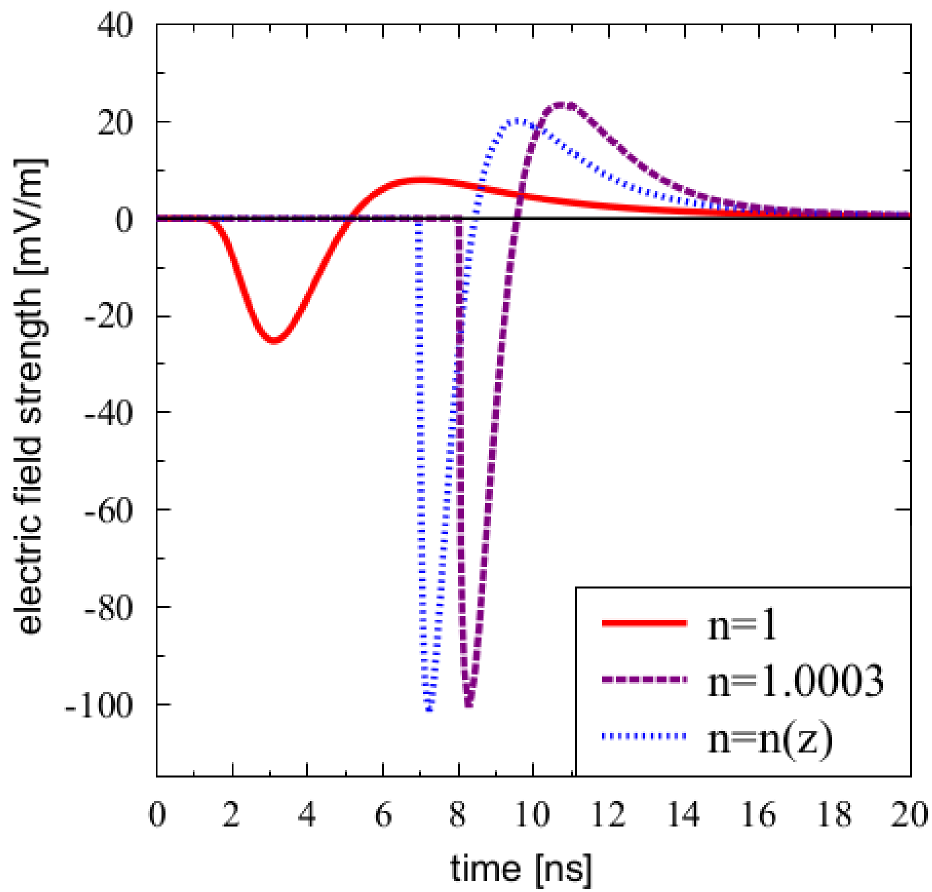
Q: Which is which?



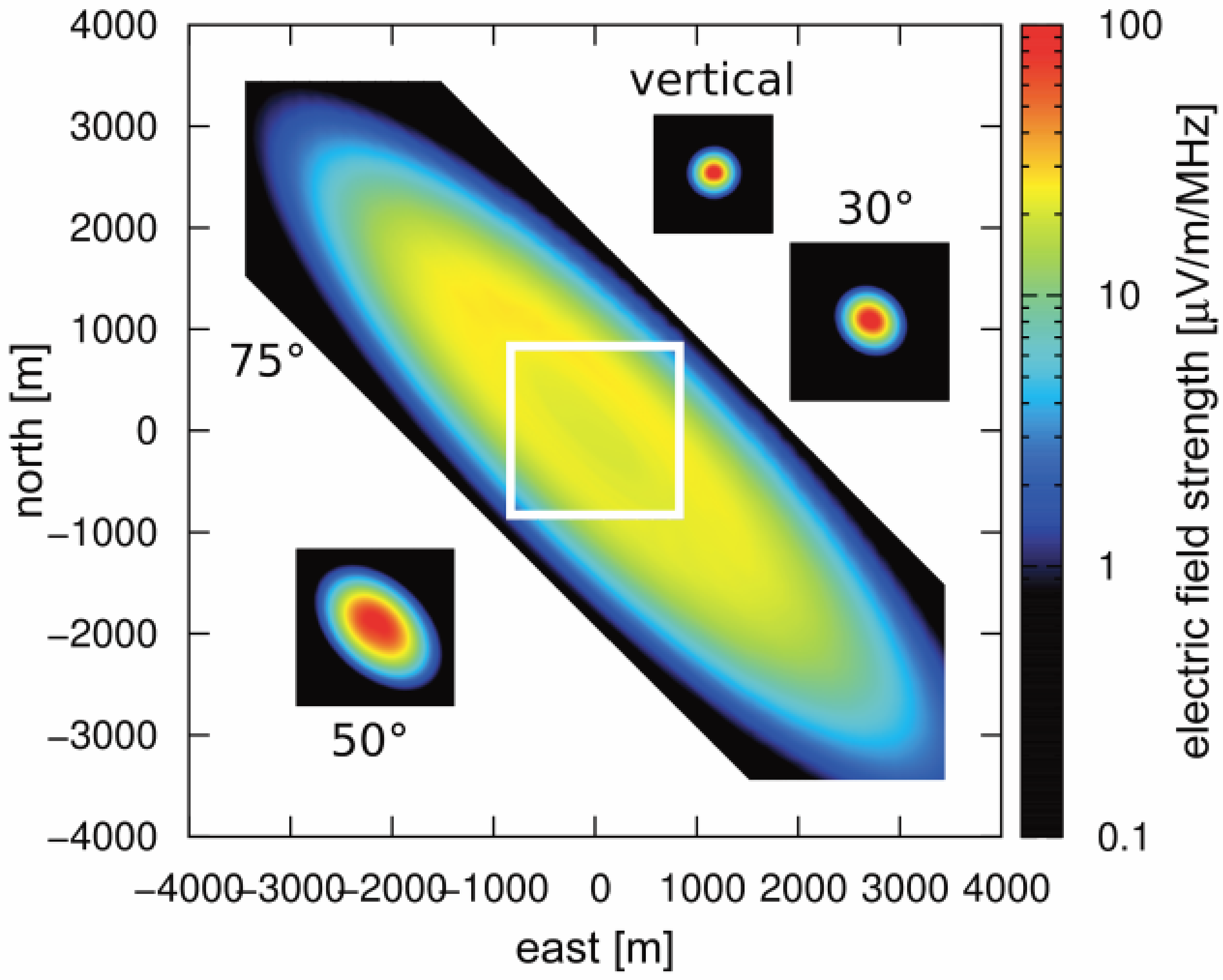
Footprint of radio signal on the ground
(asymmetry due to overlap of geomagnetic and Askaryan signals);
Compare to thermal noise (kTB)

Q: Estimate the thermal noise voltage over a 50 MHz bandwidth at room temperature, into a standard 50-Ohm input impedance DAQ.

Time-domain pulse; E=5x10^{17} eV



E=5 x 10^{18} eV: Dependence of on-grond radio footprint on zenith angle



T-510: Slam an electron beam into an HDPE target in a B-field.

Given: a) what you learned yesterday about the critical energy in an EM shower, b) the fact that the beam energy is 10 GeV, c) estimate the B-field strength required to simulate air-showers in tthis testbeam environment

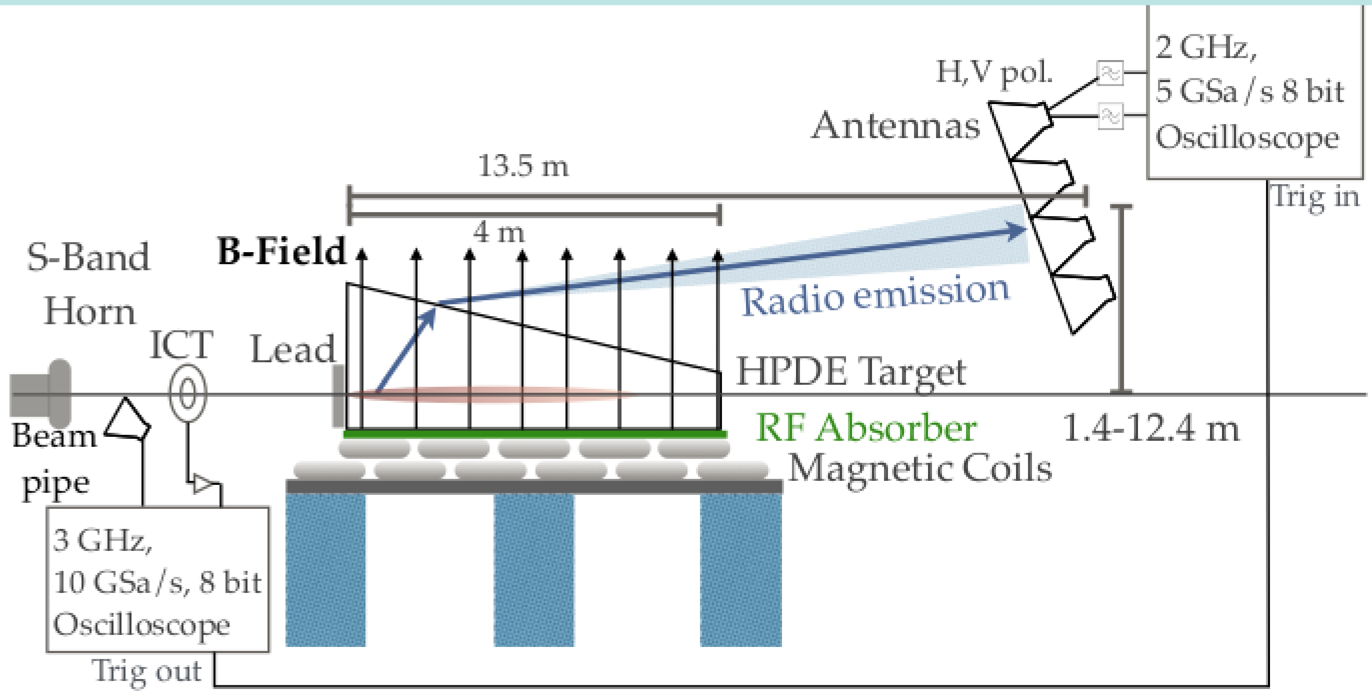


FIG. 1. Schematic of the experiment, not to scale.

SLAC T-510 testbeam experiment

FIG. 2. Left: The HPDE target and magnetic field coils. Right: horn antenna array in ESA.

SLAC T-510 testbeam experiment

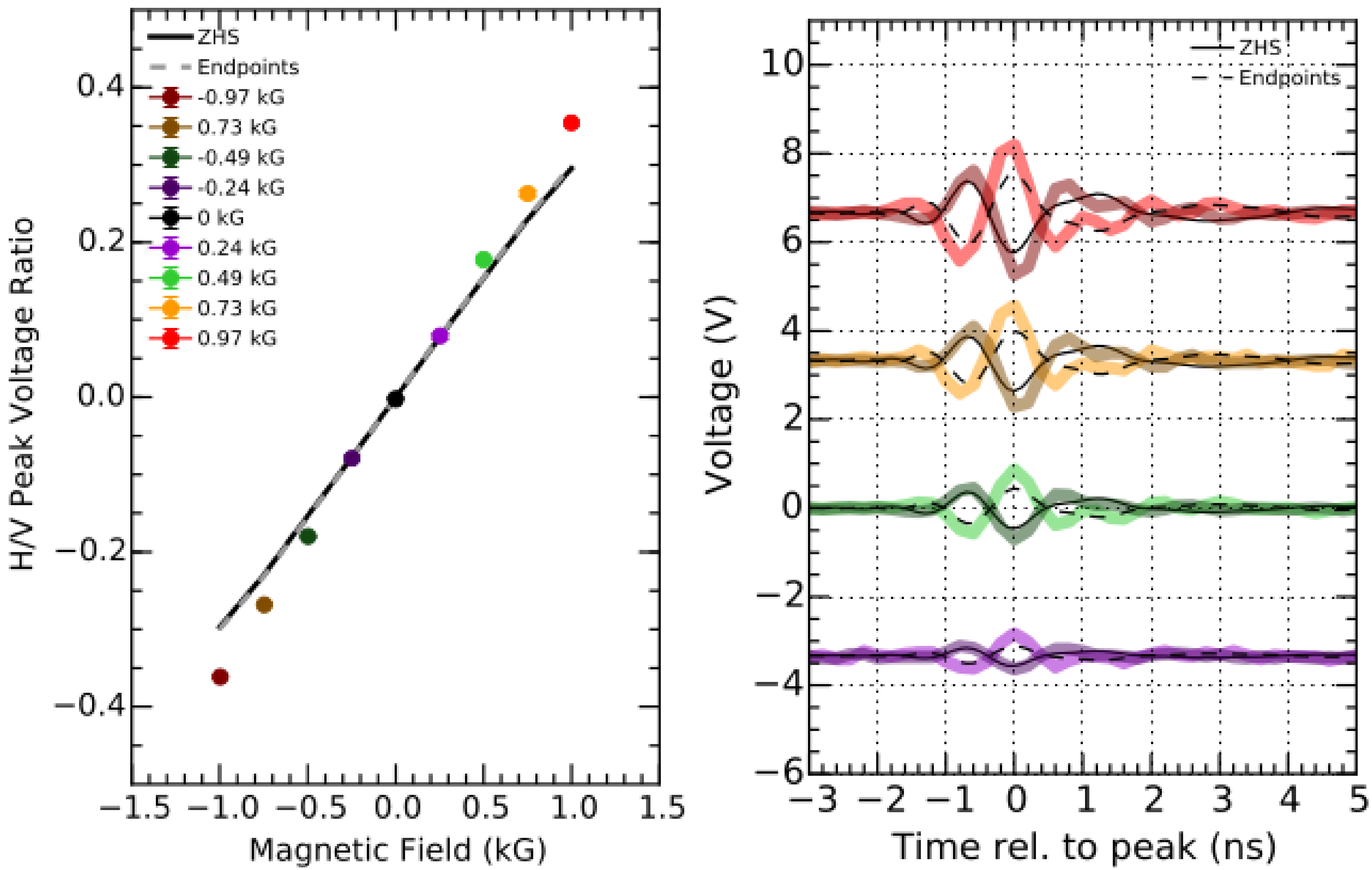


FIG. 6. Left: horizontally polarized signal normalized by vertical showing the expected linear behavior vs. magnetic field.

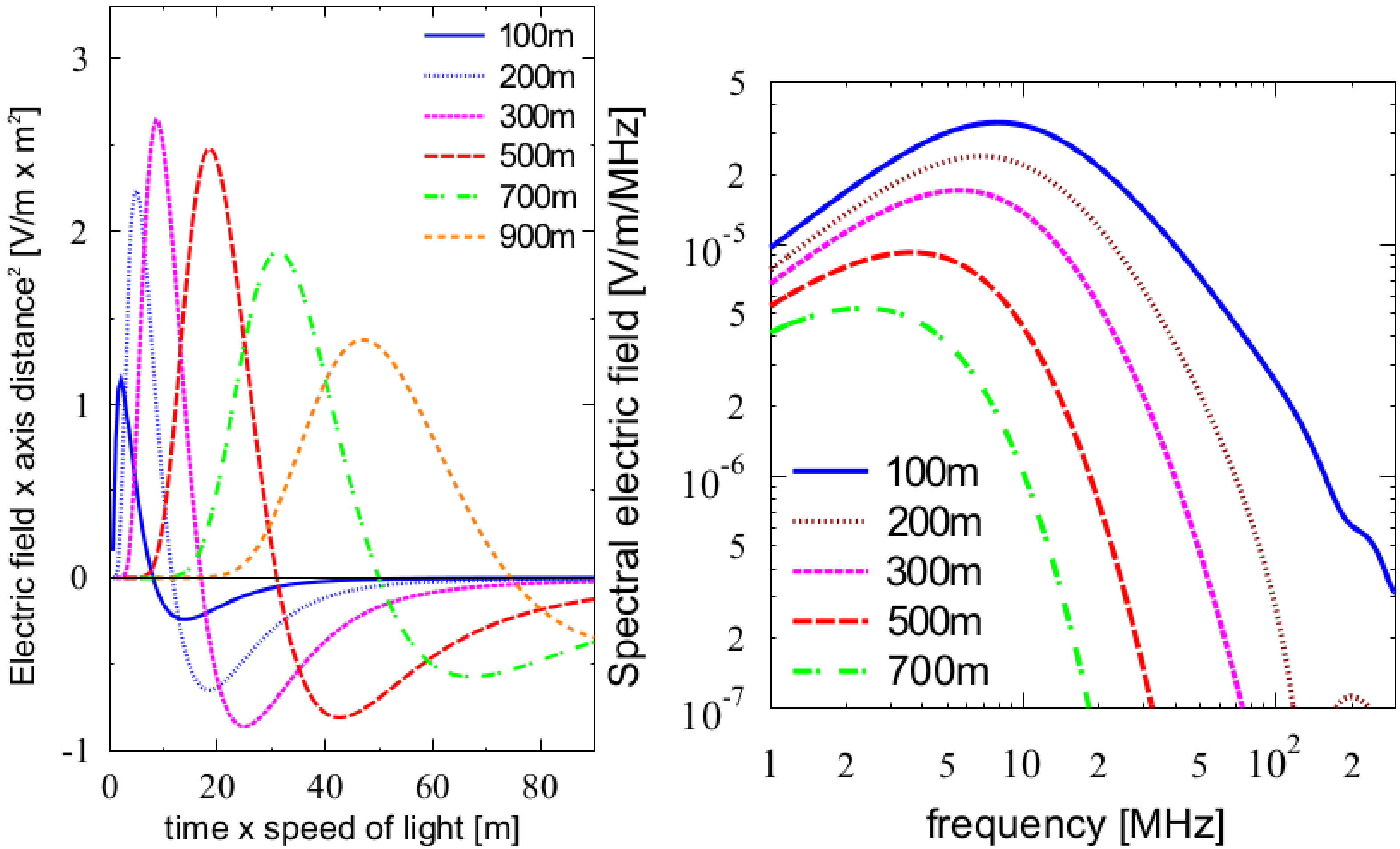


Fig. 2 Modeled radio pulses (left) due to geomagnetic effect in a 10^{17} eV air shower as observed at various observer distances from the shower axis as well as corresponding frequency spectra (right). Effects due to the refractive index of the atmosphere are not

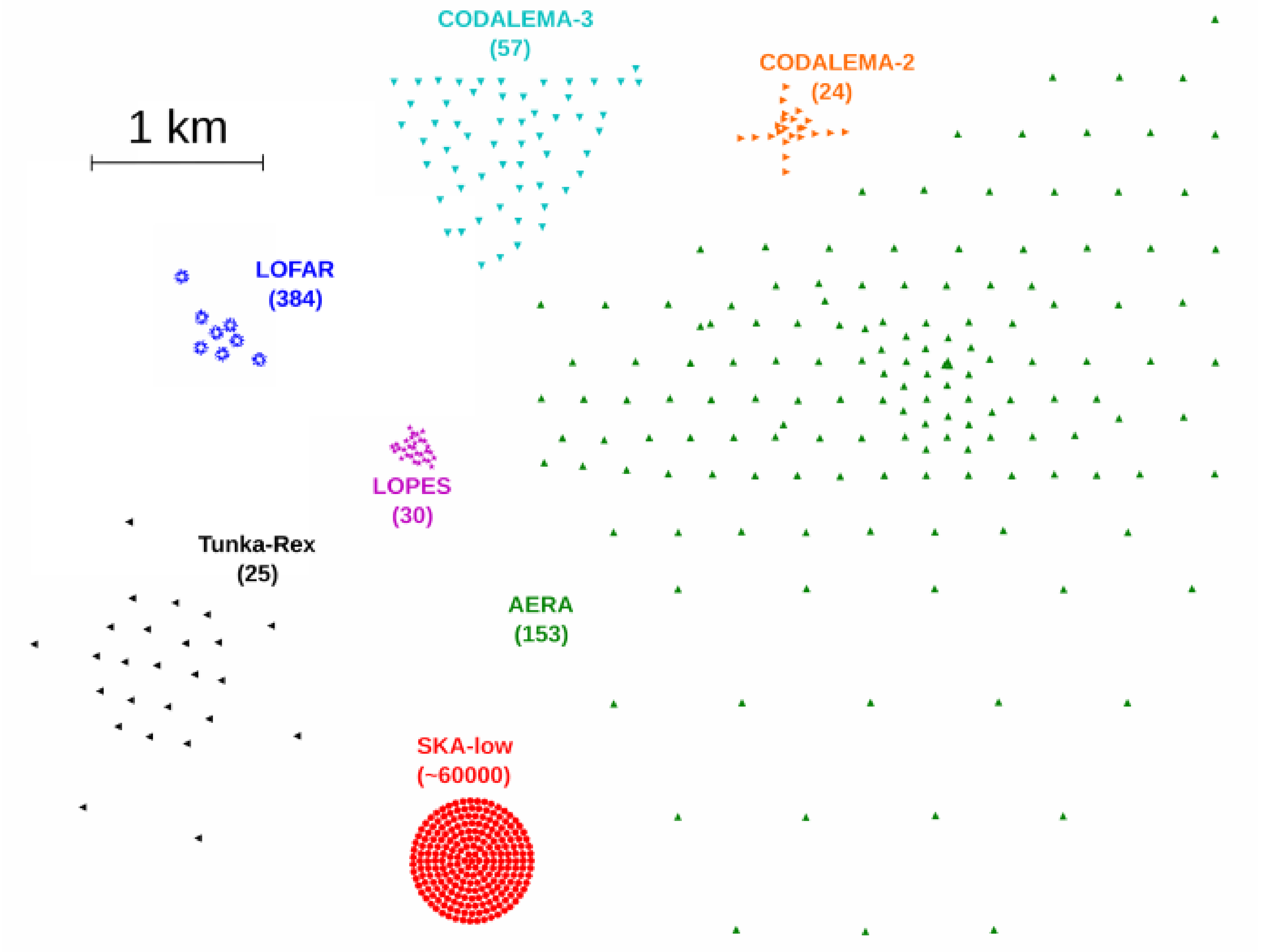
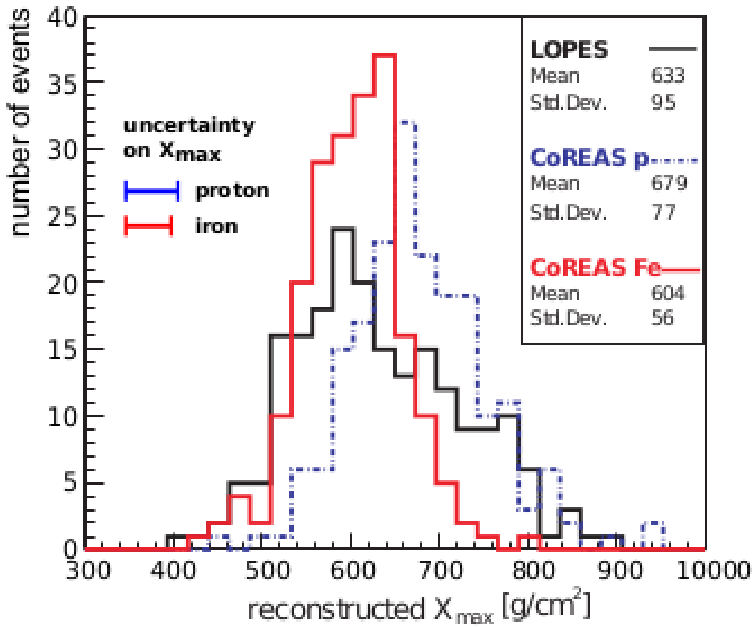
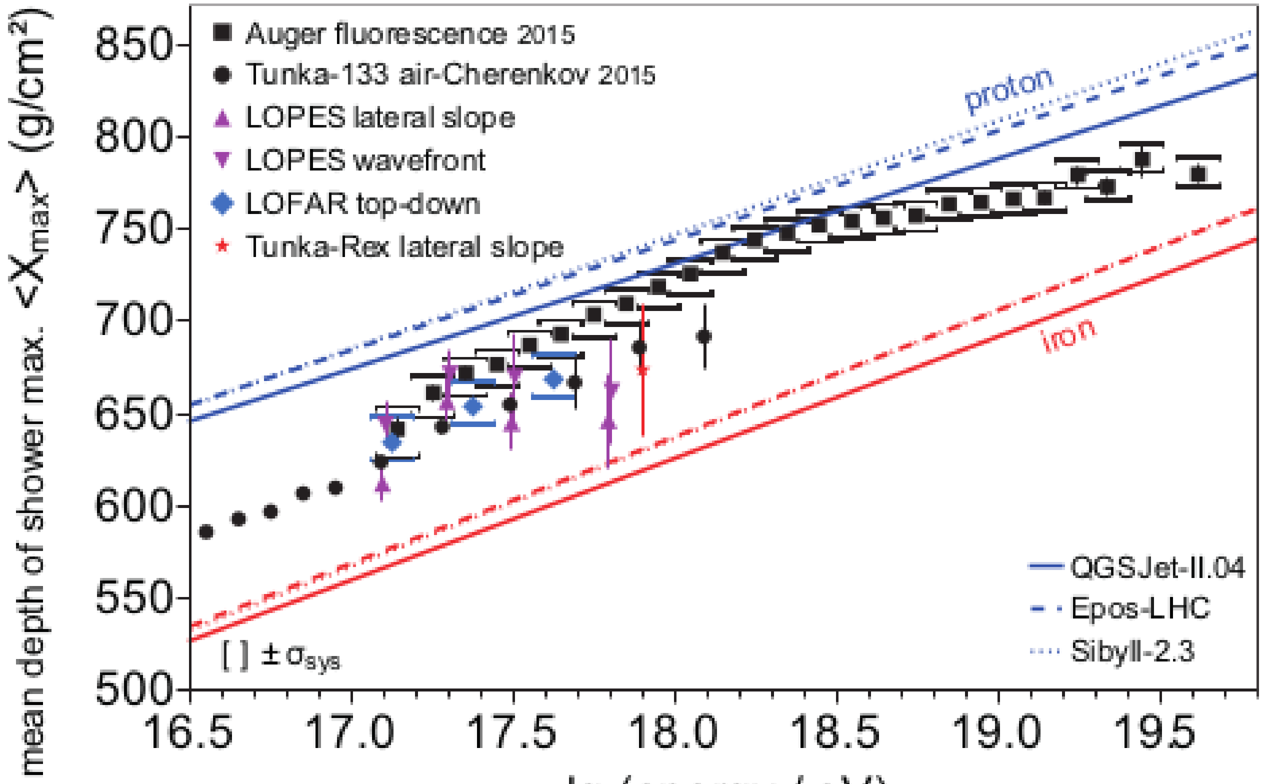


Fig. 7 Compilation of modern cosmic-ray radio detection experiments. Each symbol represents one radio detector (typically a dual-polarised antenna), except for the SKA where

Sensitivity of radio technique to shower maximum=>composition!

Q: Which species penetrates further into atmosphere before reaching max (and why?)



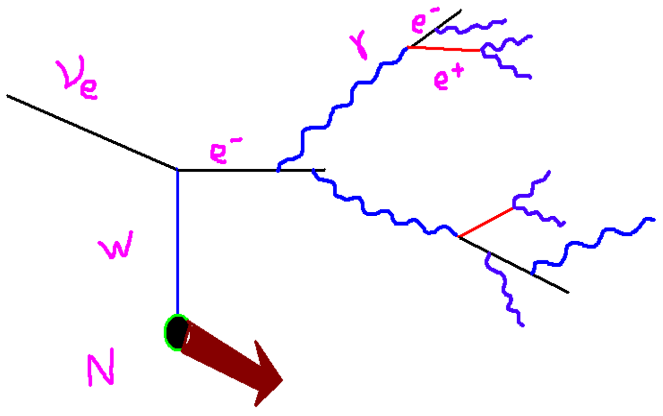


The long-wavelength Cherenkov CONCEPT

- Look for Ultra High Energy neutrinos $E_{\nu e} > 10^{14}$ eV
- Look at the reaction $\nu_e + n \rightarrow p + e^-$ in a dense medium (We use ICE at the South Pole)
- $e^+ \rightarrow e^+ e^- \gamma$ shower develops and $\gamma + e^-$ and $e^+ e^-$ collisions sweep negative charge into the developing shower
- Each particle emits Cerenkov radiation that is radio “coherent” but is incoherent in the short wavelengths

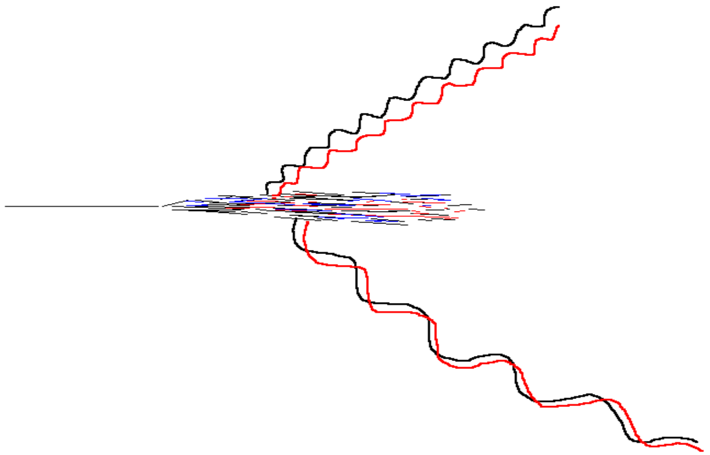
Idea of Radio Detection (RICE: E>100 PeV)

- n_e+N -> e^- + X
- High Energy e- initiates electromagnetic cascade in ice(bremsstrahlung and pair production at high energies, Compton, Bhabha, Moller, photoelectric effect…)
- Charge imbalance develops
- Net negative charge moving faster than c in ice=Cerenkov radiation



Radio Emission From EM-Showers: III

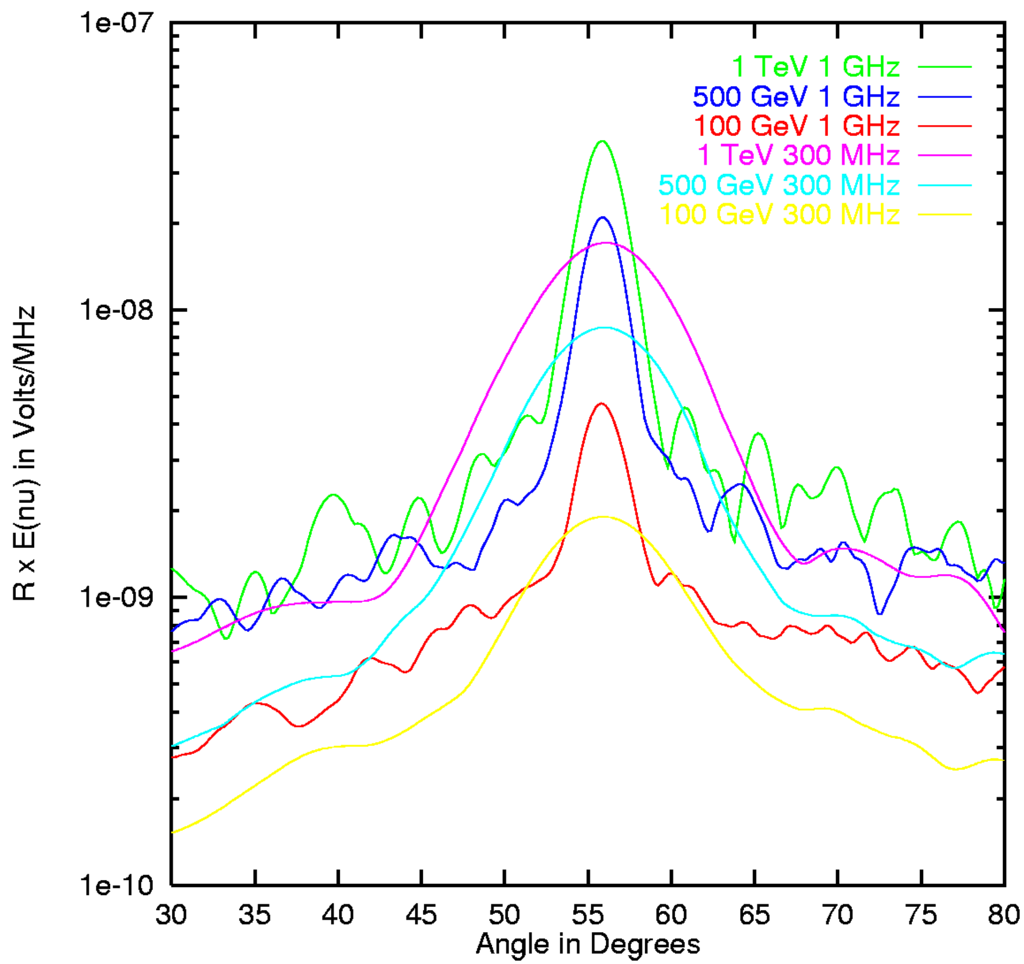
- Each charged particle emits broadband radiation. Shorter wavelength radiation interferes destructively



Q: How does the width of the Cherenkov cone vary with frequency?
N.B. cf muon-generated C-cones

EM Pulse generation

1. Pulse increases with Energy
2. Narrows with frequency
3. Some ~10% numerical differences between codes
4. ~Single-slit source



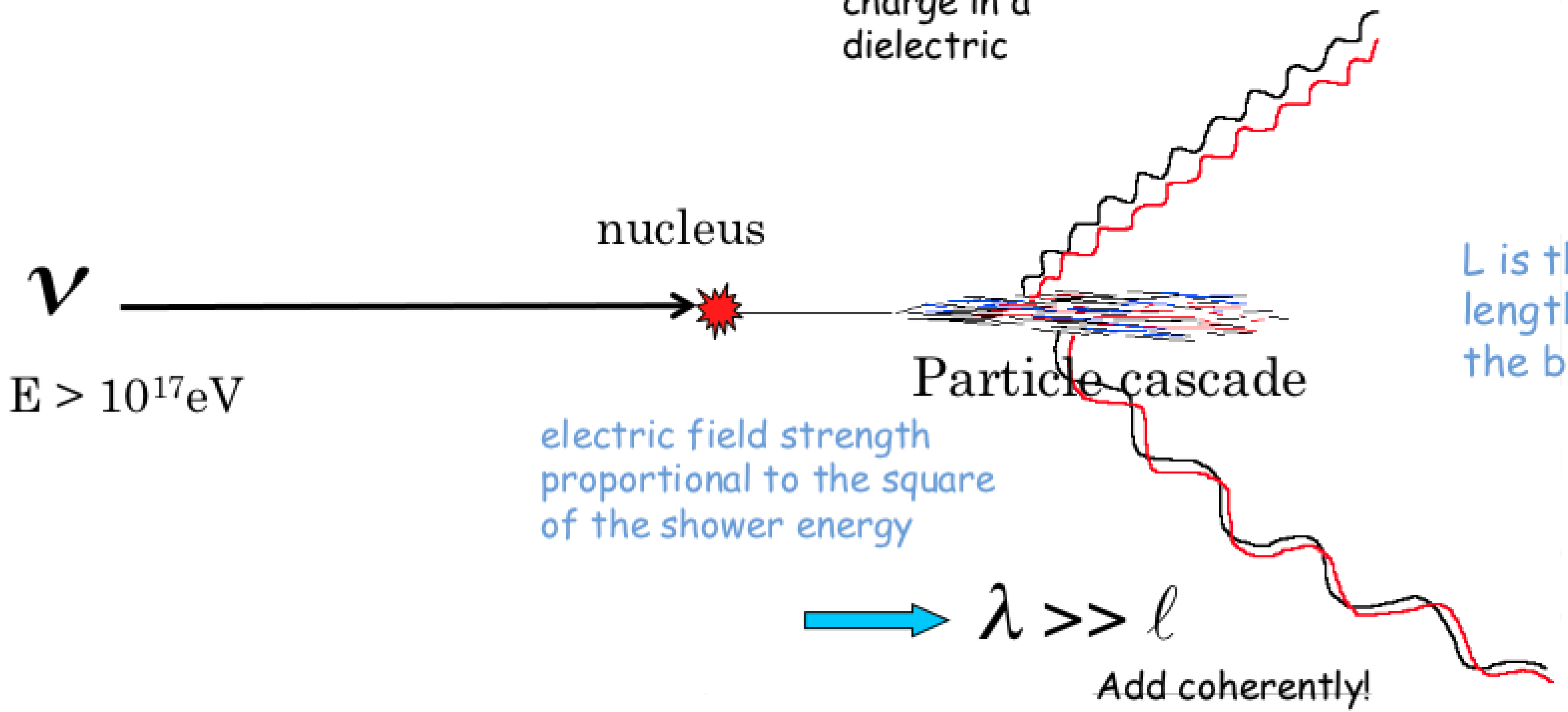
MANY Experimental results (Saltzberg, et al.) confirms coherence and Askaryan effect

Coherent radio emission

charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower

→ moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric

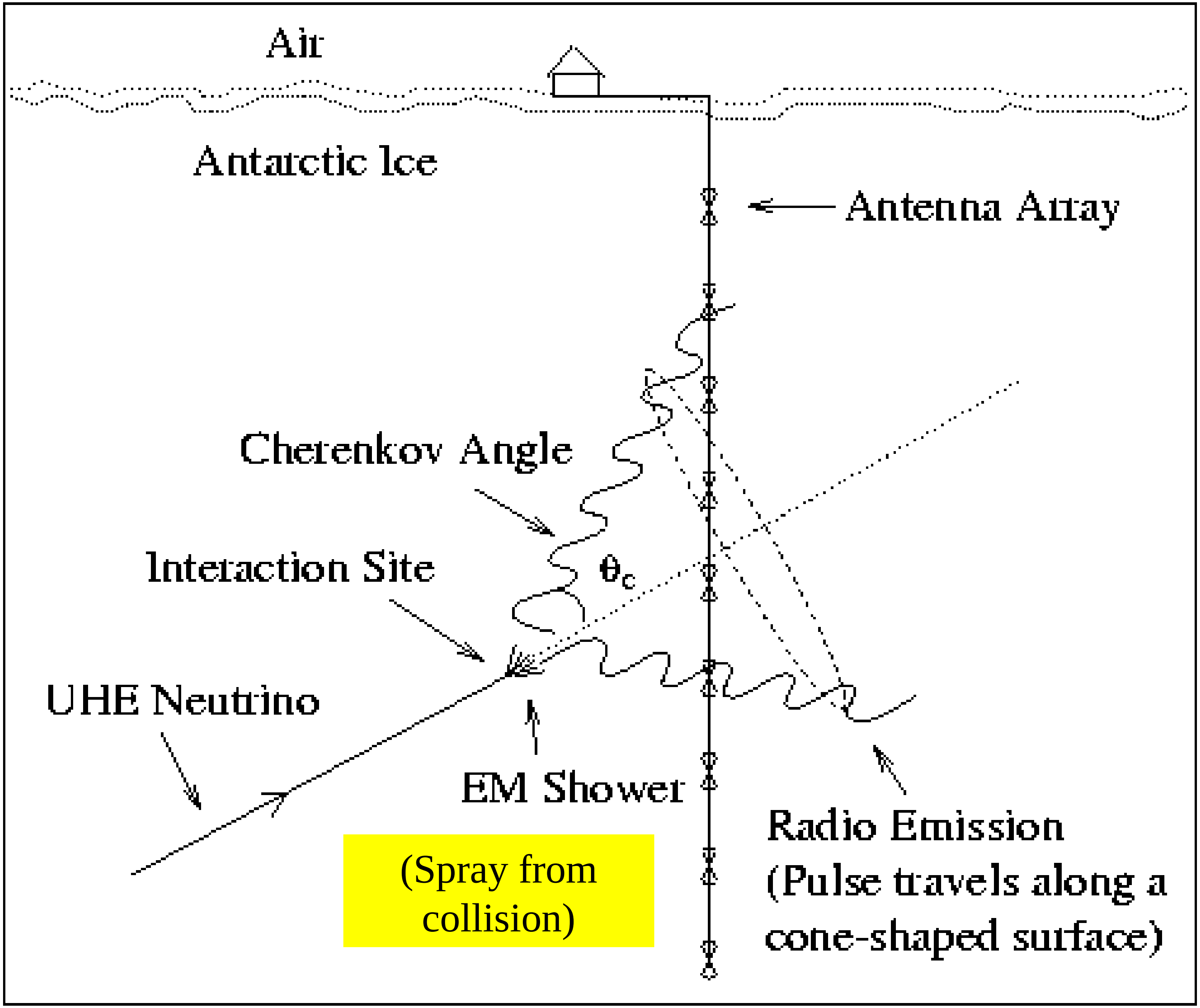
→ wavelengths shorter than the bunch length suffer from destructive interference



L is the length of the bunch

electric field strength proportional to the square of the shower energy

Schematically:



Q: Estimate the energy at which $A_{radio} > A_{optical}$

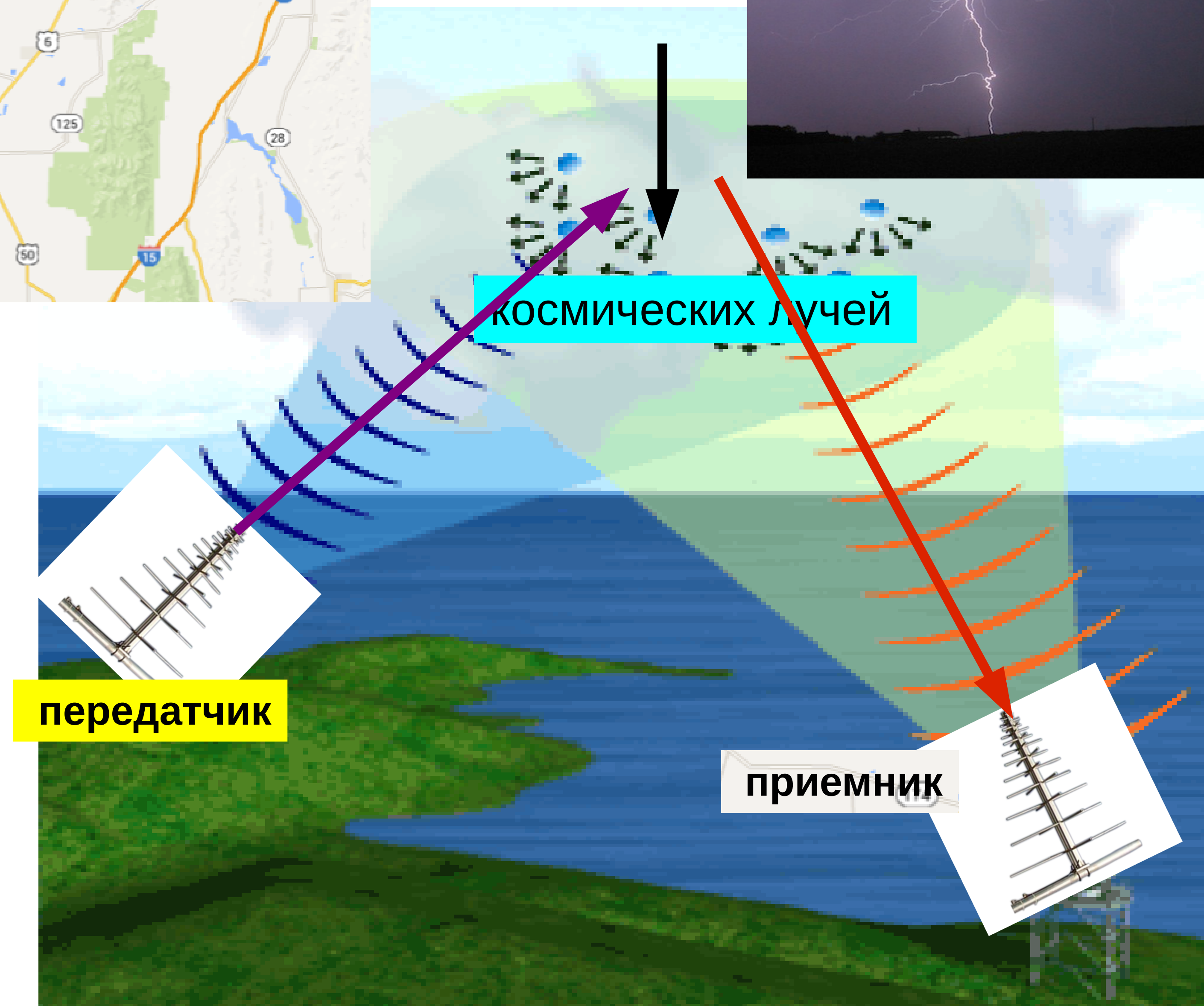
Inputs: Optical BW: 200 nm (incoherent), Radio BW: 500 MHz (coherent).

Frank-Tamm formula: $$\frac{d^2E}{dx\,d\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

Experiments:

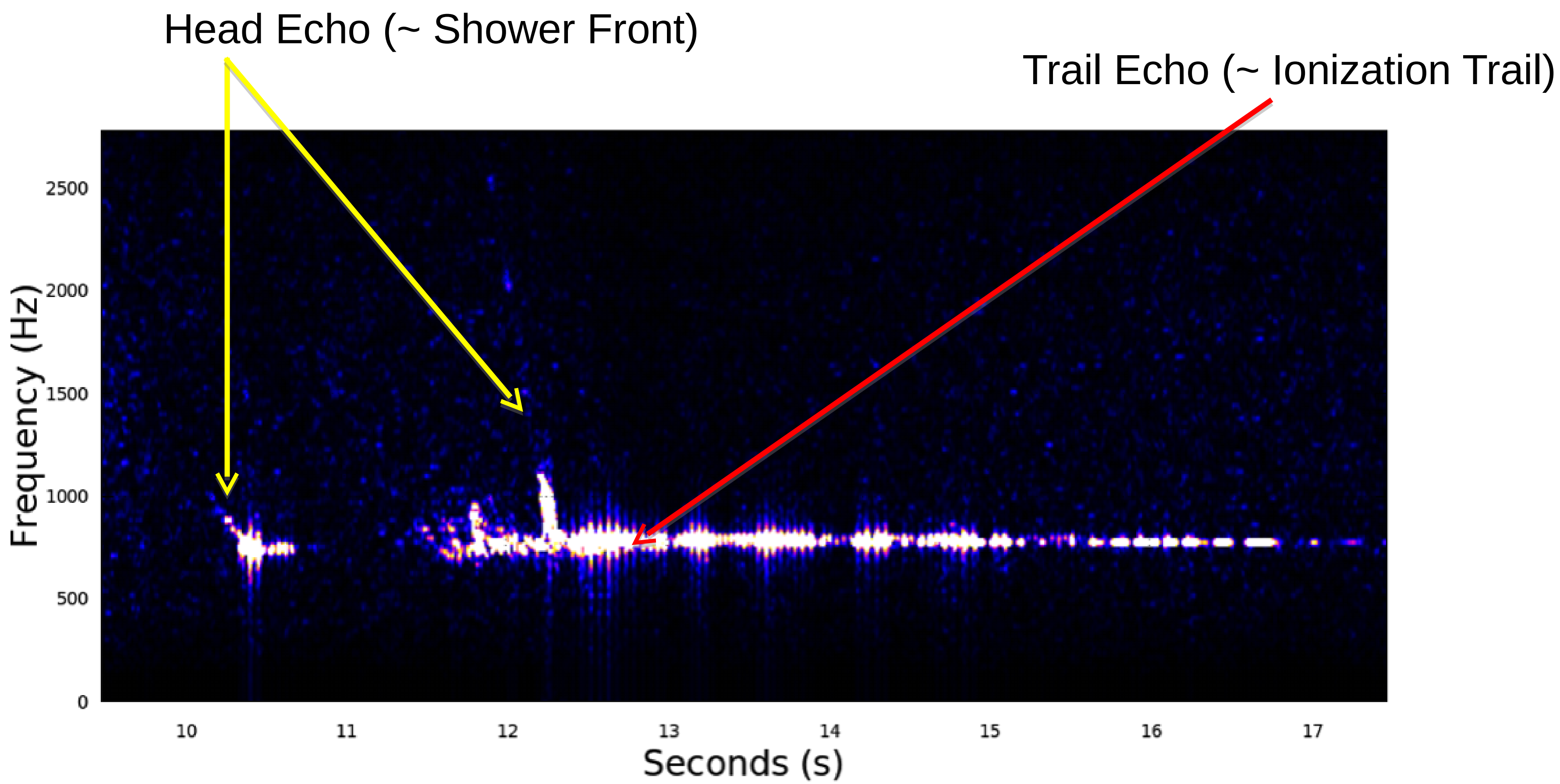
1) Vostok 3-antenna proto-array (1990-putsch)
2) RICE (1995-2011)
3) AURA (2008-2012)
4) ARA (2009-)
5) ARIANNA (2005-)
6) ANITA (2004-)

Radar approaches



Q: Chirp up or down?

TARA Meteorite (80 km elevation; no LOS)



Tx : TARA Utah Back lobe

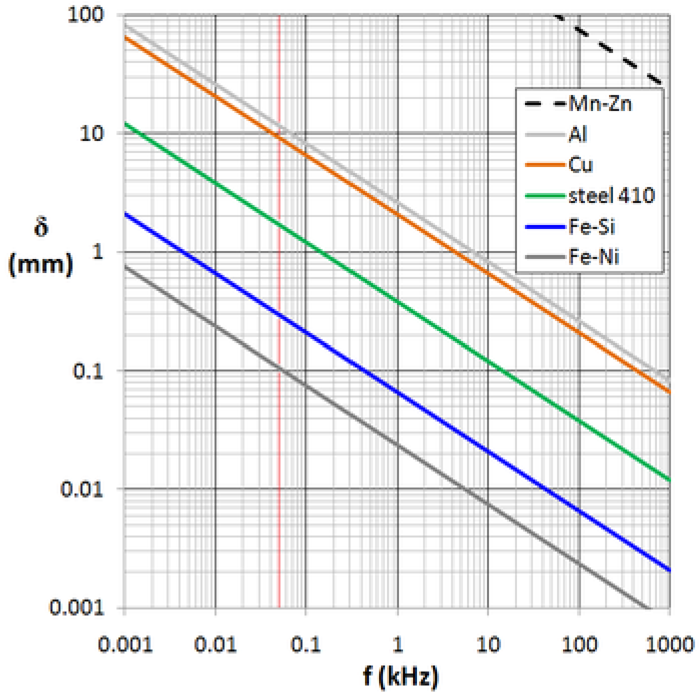
Rx : Lawrence, KS

1600 km

Quick primer on plasma frequencies!

Recall Prof. Pravata's slide on particle number vs. radial distance from core. For small particle number density, scattering is at individual-particle level; for large particle number density, can have coherent response

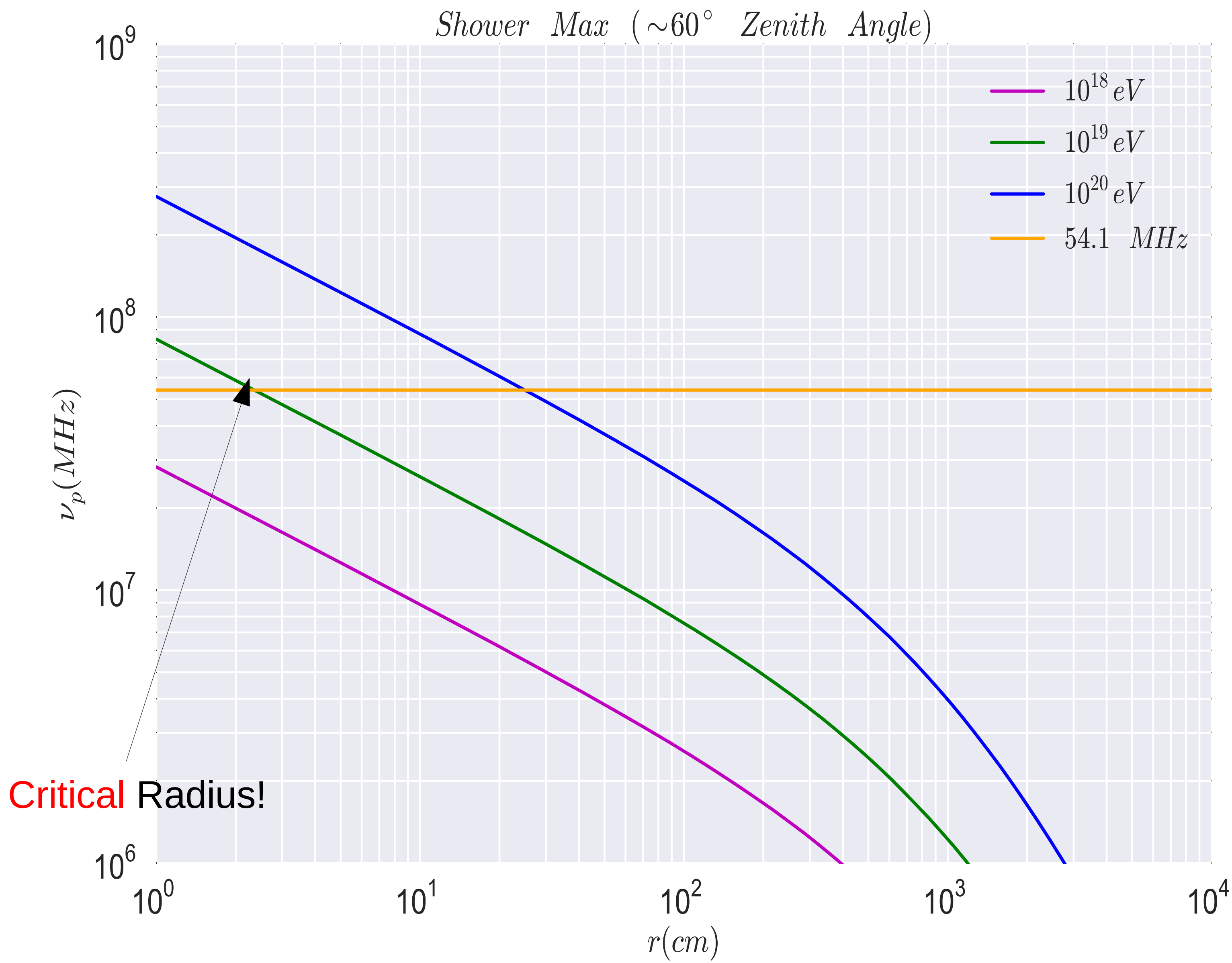
Q: To get coherent return signal, want ω_{radar} > or < ω_{plasma}?



For TARA, e.g., need plasma frequency above 54.1 MHz carrier

~~Under – dense($\nu > \nu_e$)~~
Fatal!

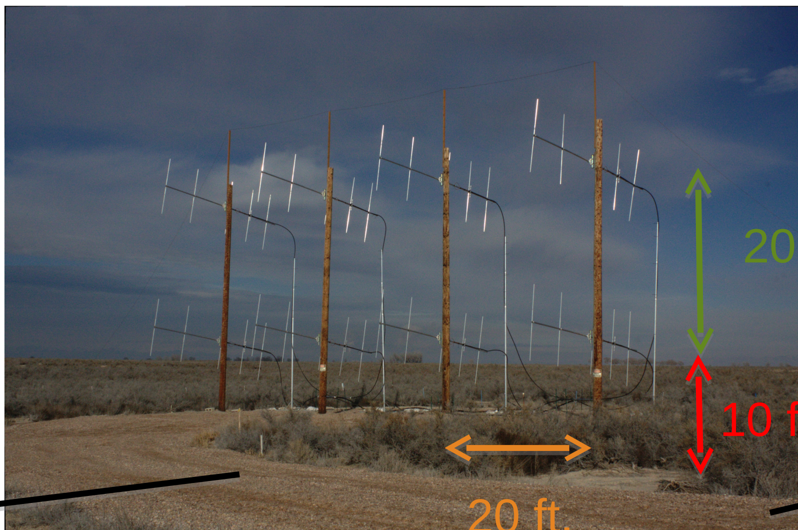
Over - dense ($\nu < \nu_e$)
Thin Wire approximation!



Transmitter

~ 20 – 40 KW at *54.1 MHz*

Phased Yagi Array



39 km to receiver

100 ft.

Power Amplifier

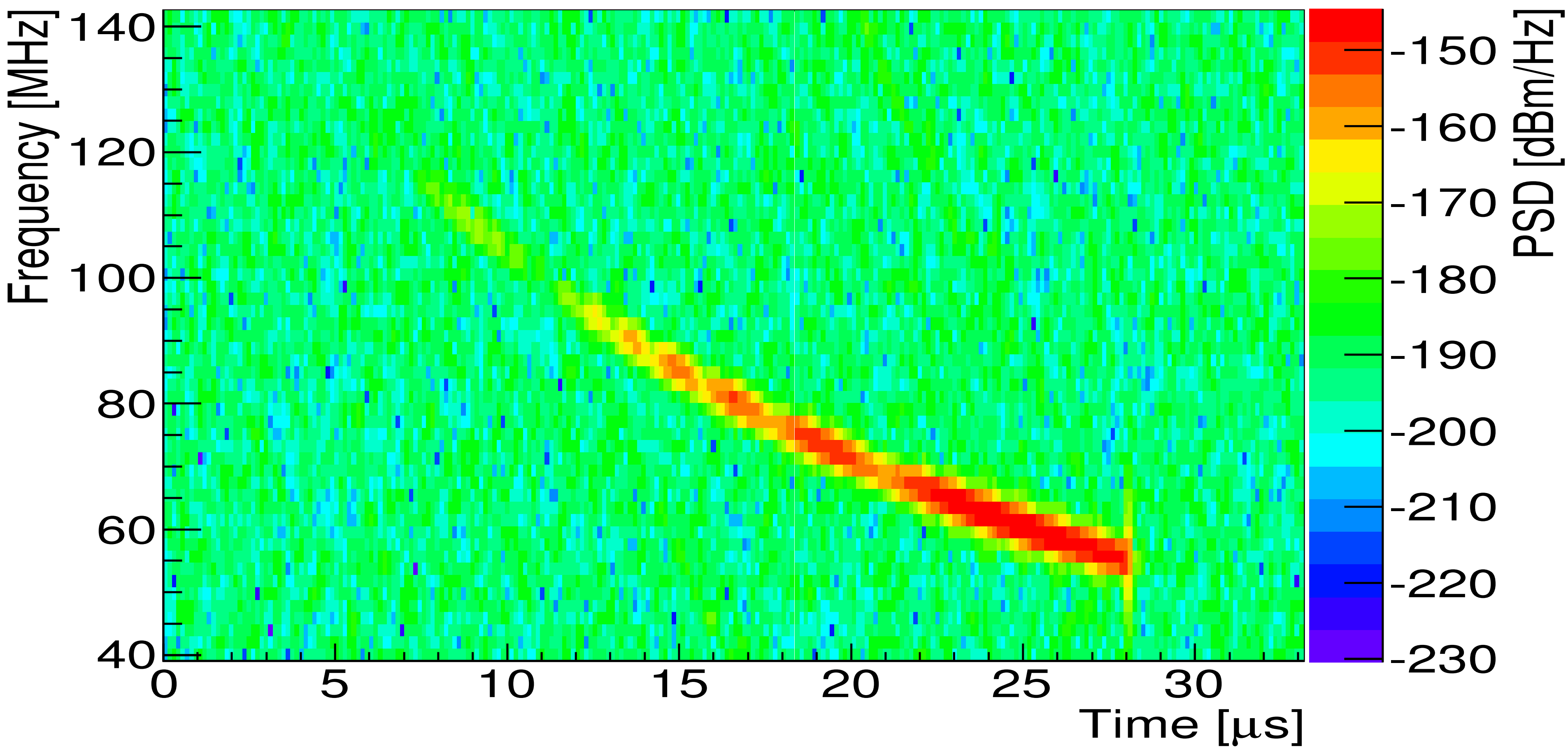
Filters

KUTV(20 KW)

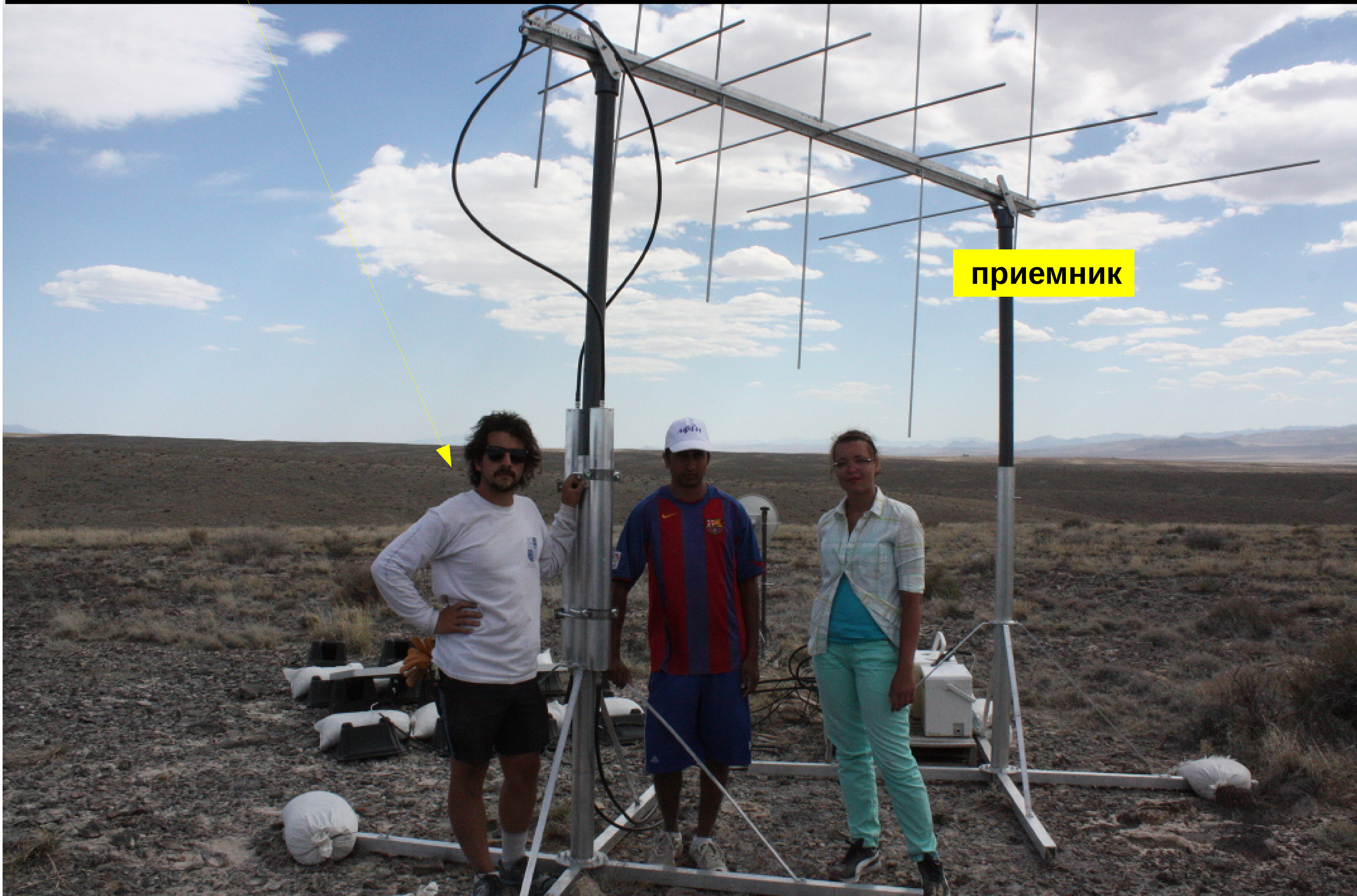
KTVN (20KW)

Forward *Gain* : *22.6 dBi*
Horizontal Beam Width : *12°*
Vertical Beam Width : *10°*

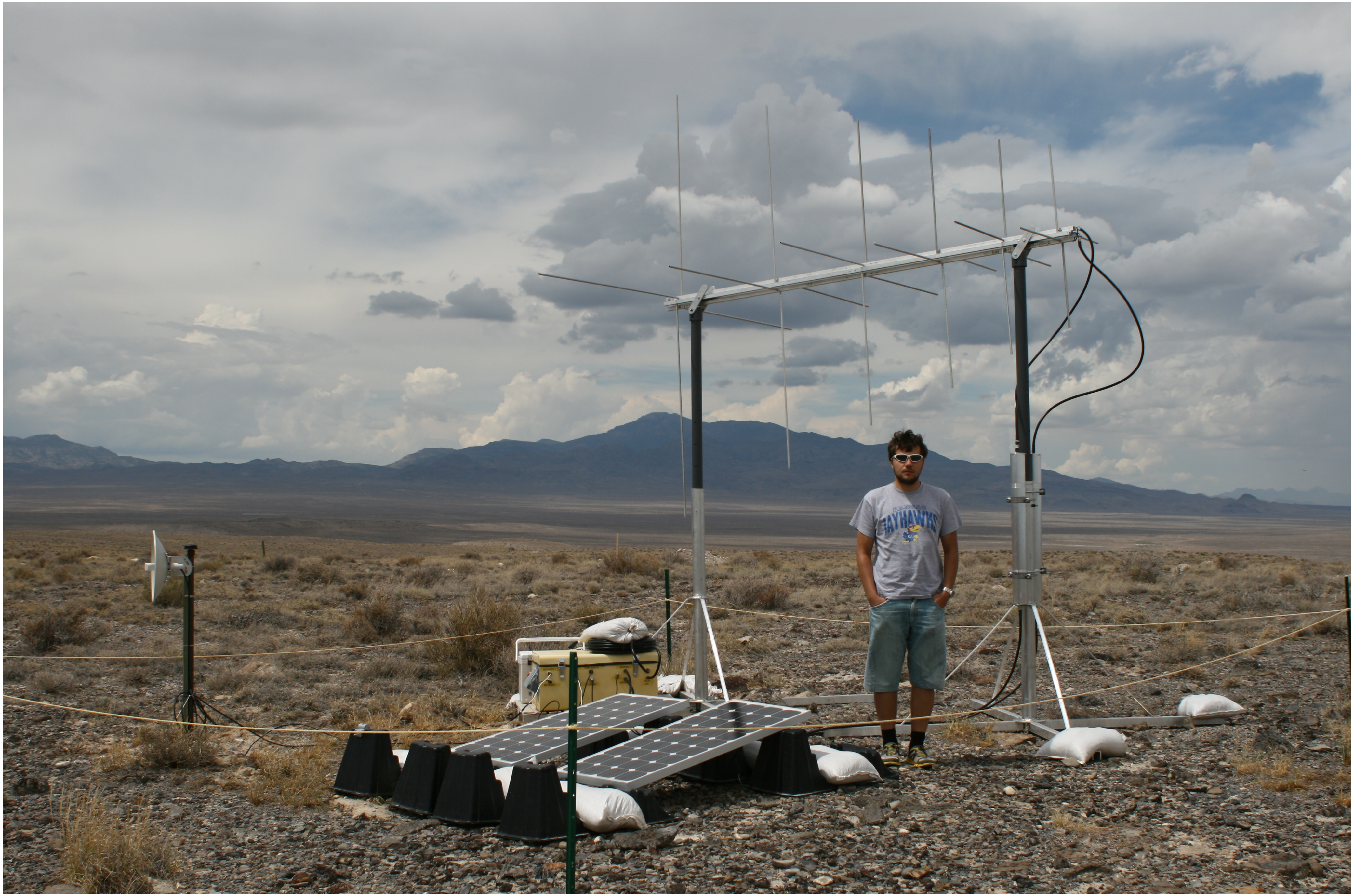
Simulated Chirps!



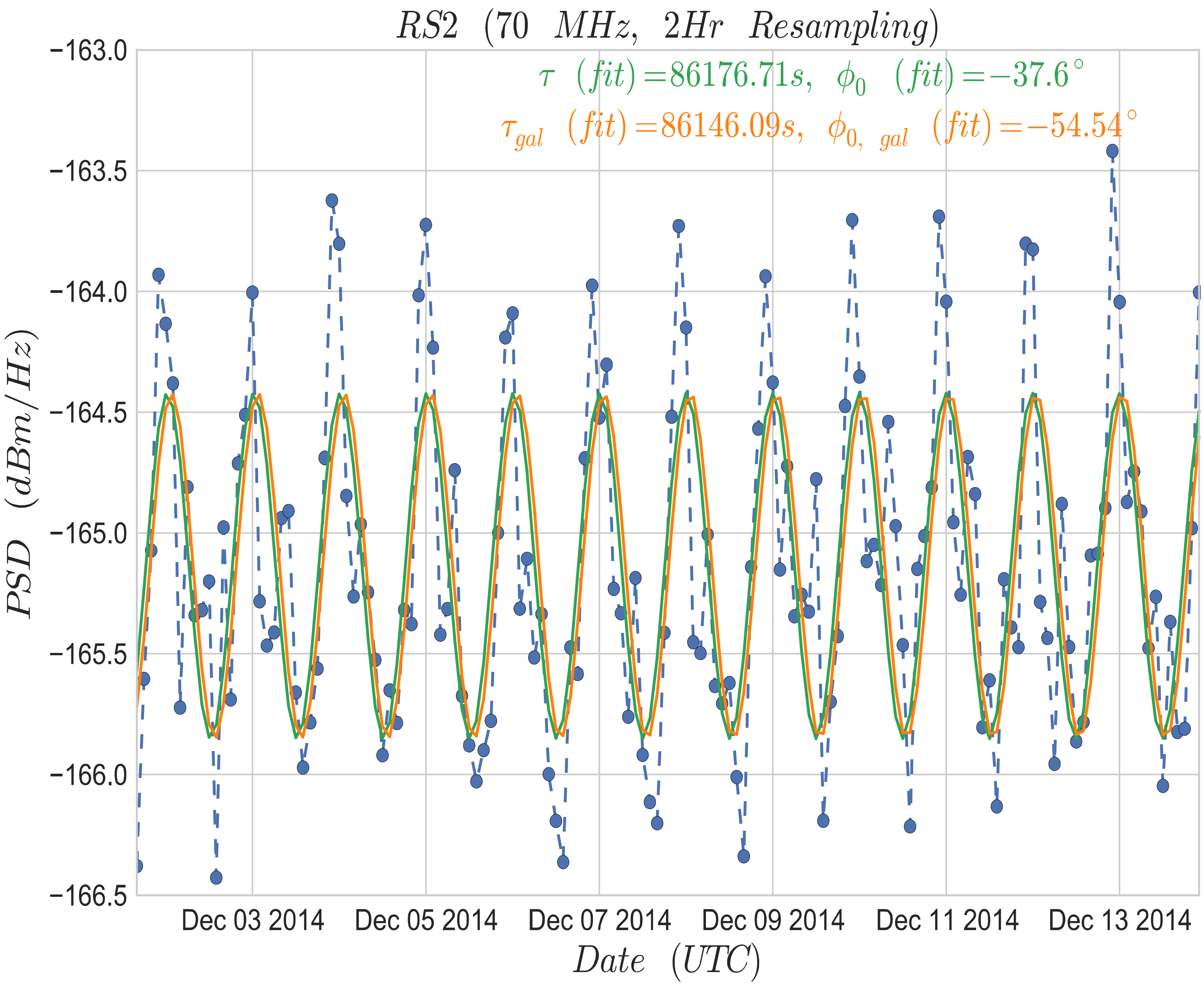
Steven, Sam and Марина (28.06.14)



Саша (18.08.14) (ремонт)

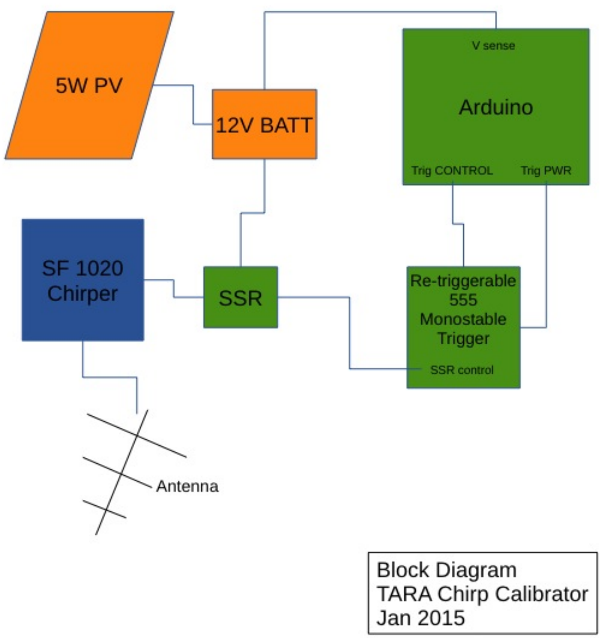


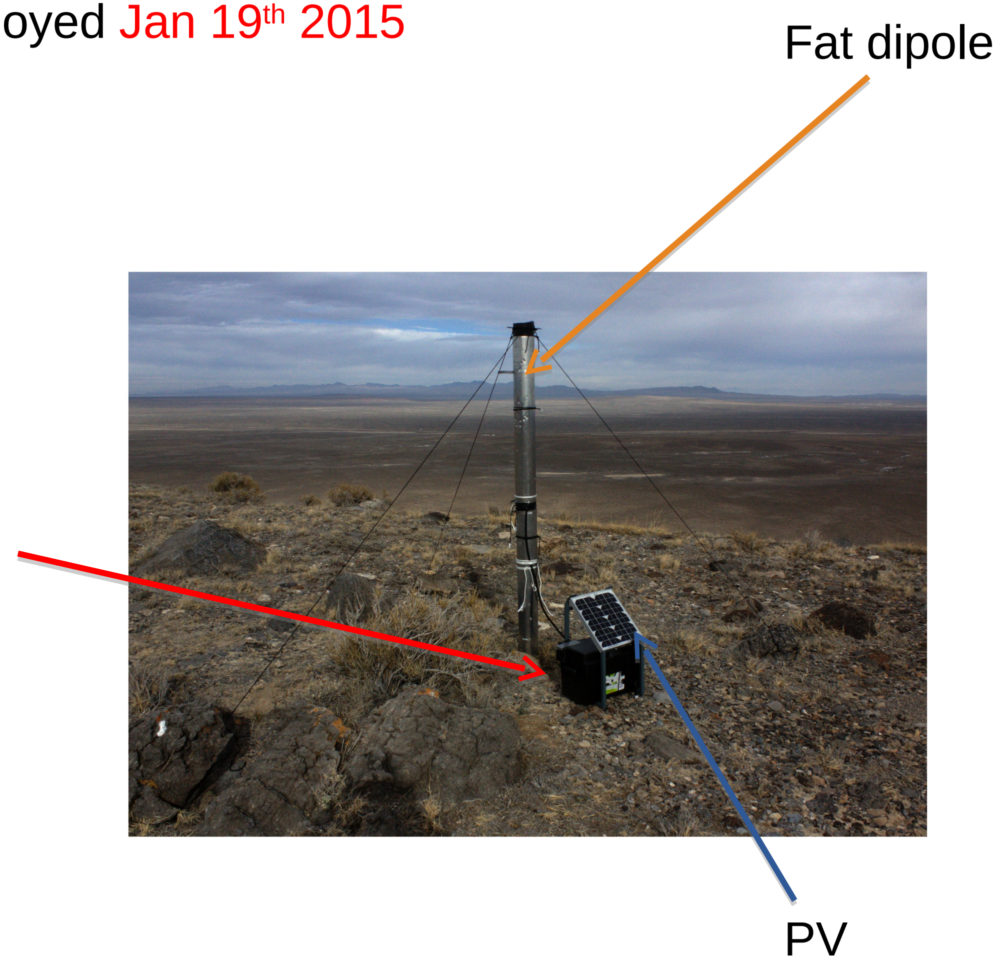
Sidereal Variation (wrt Sagittarius A*)



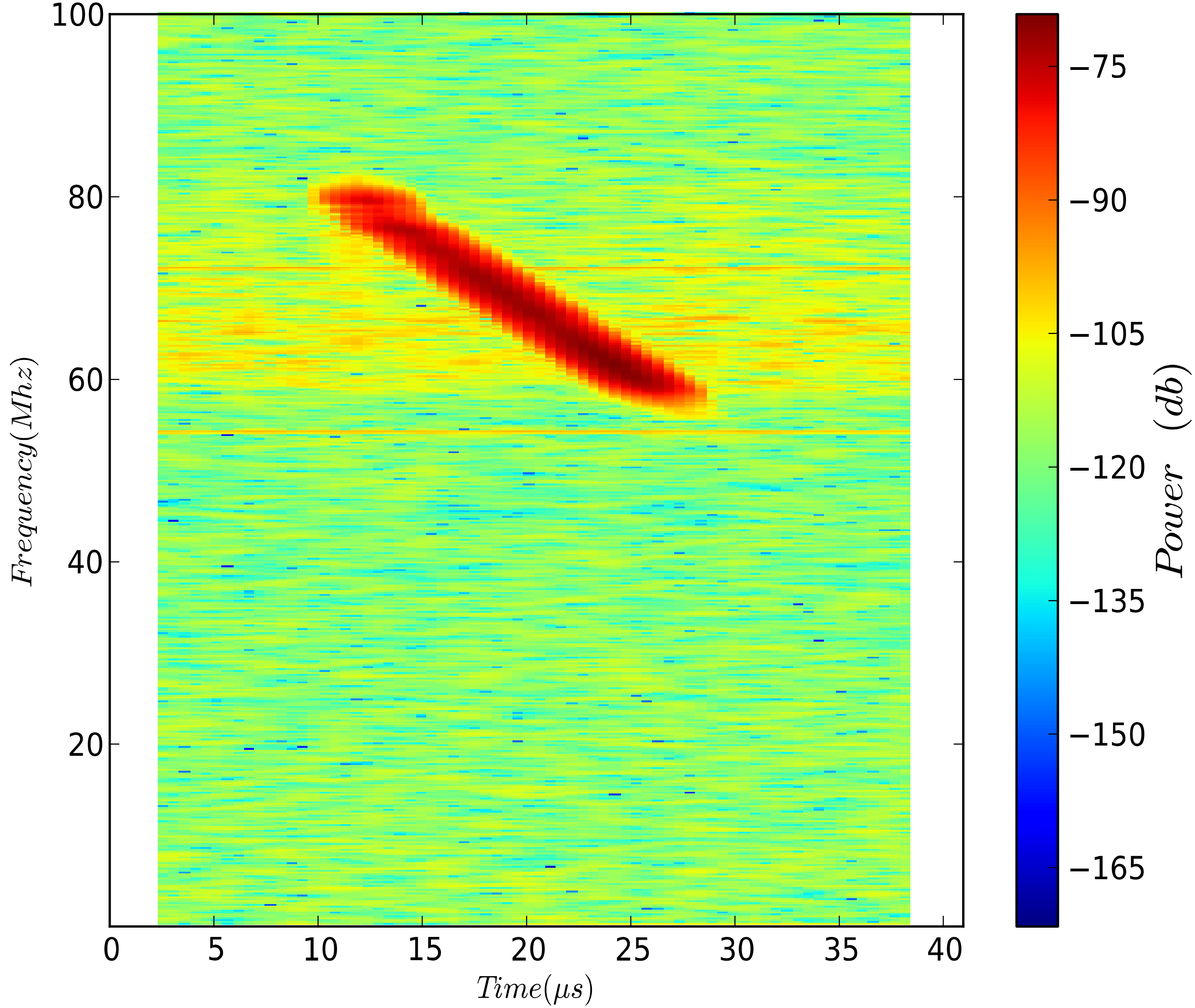
Chirp Calibration Unit (CCU)

Deployed Jan 19th 2015

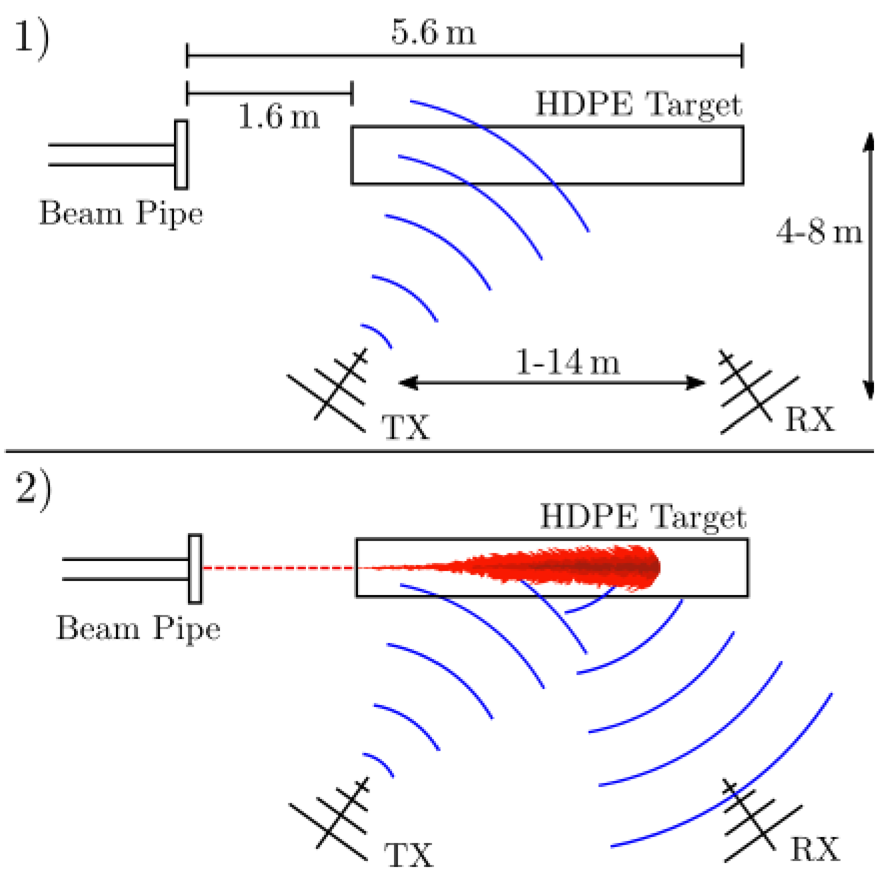


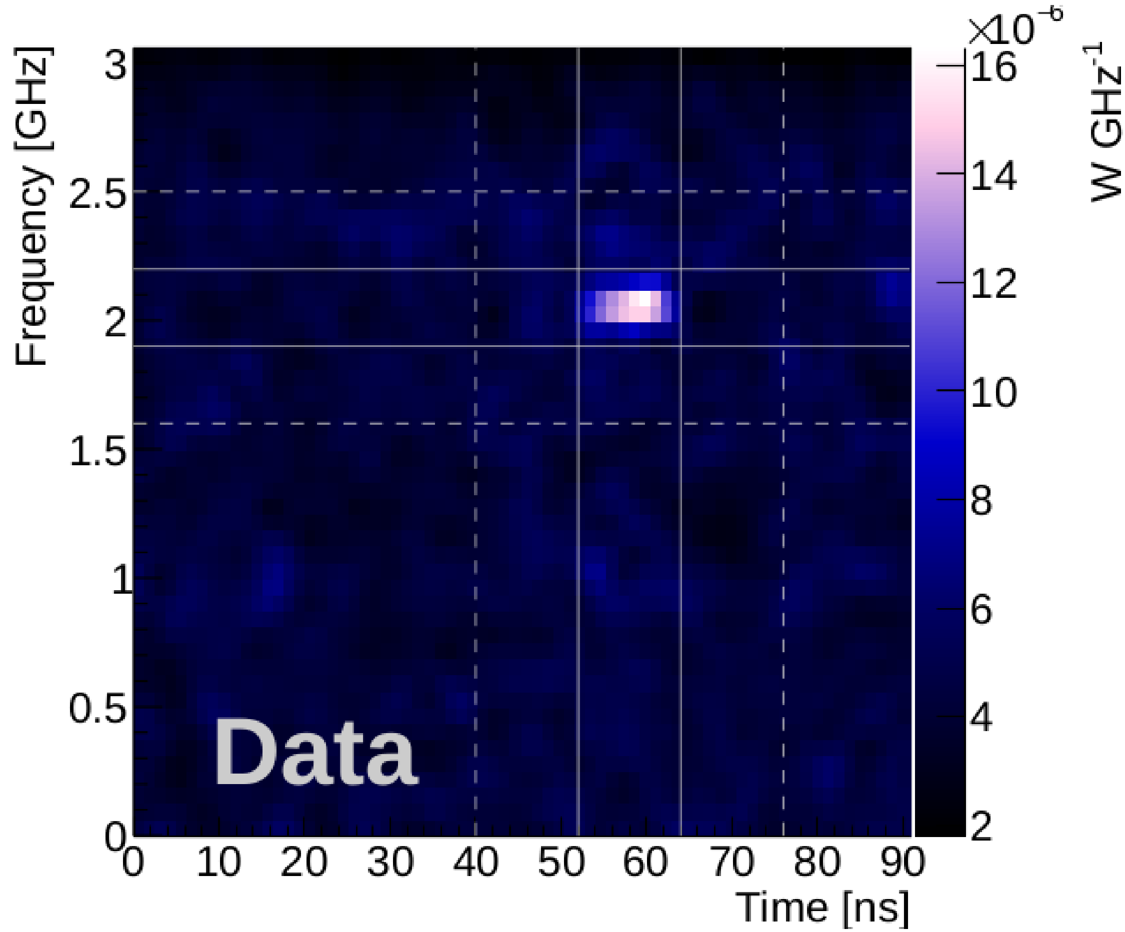


Field Calibration Chirp



T-576 → RET-CR and RET-NU





Comparison to Askaryan:
2pi coverage rather than limited C-cone;
distinctive chirp-pattern recognition;
Arbitrarily high transmitter strength

https://arxiv.org/pdf/1710.02883