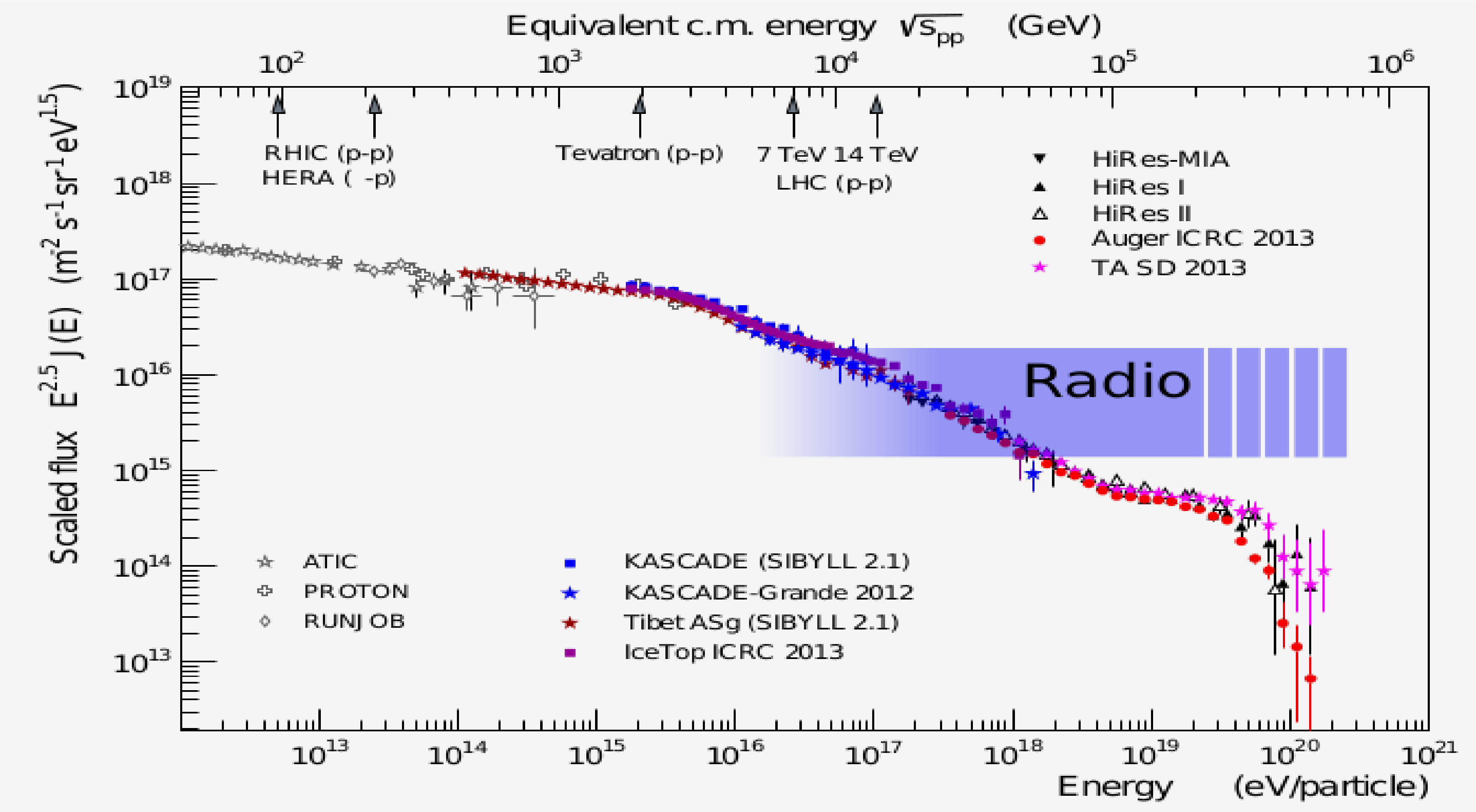
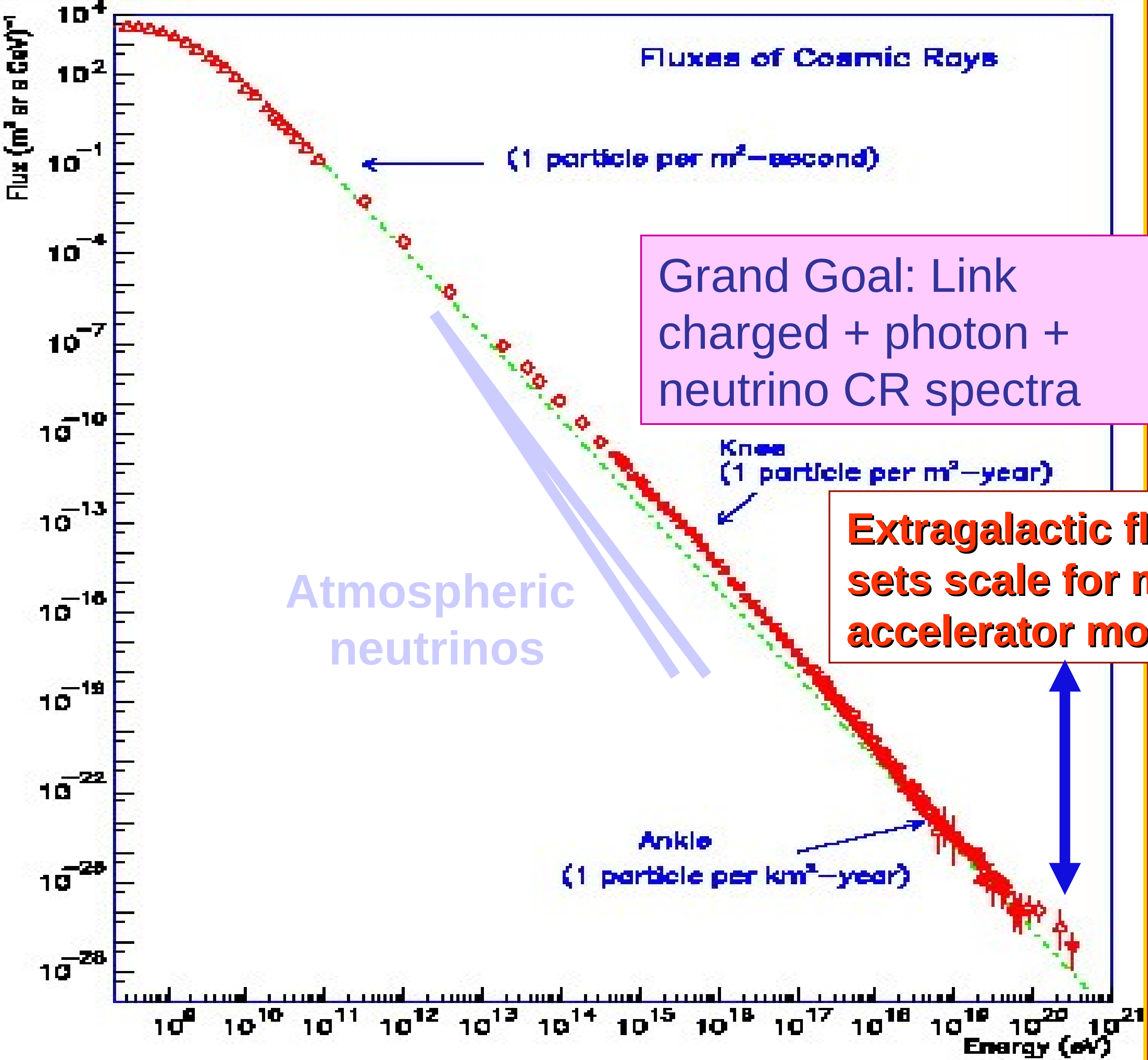
Production of radio waves and radio detection of CR/ν



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?

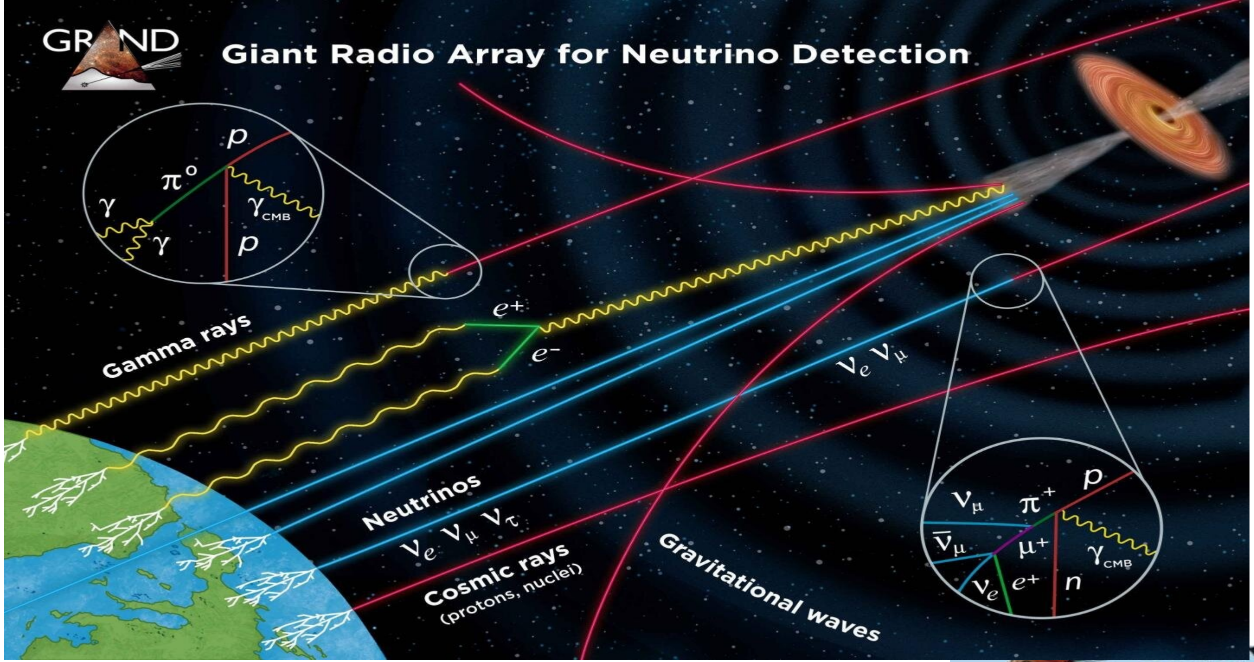
Science Drivers: Cosmic Ray and Neutrino Energy Spectra

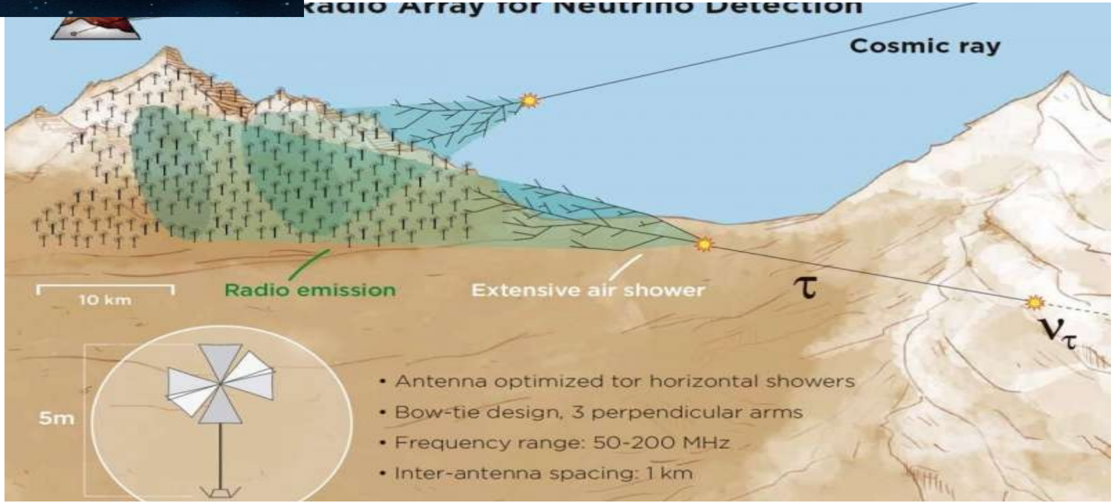


Grand Goal: Link charged + photon + neutrino CR spectra

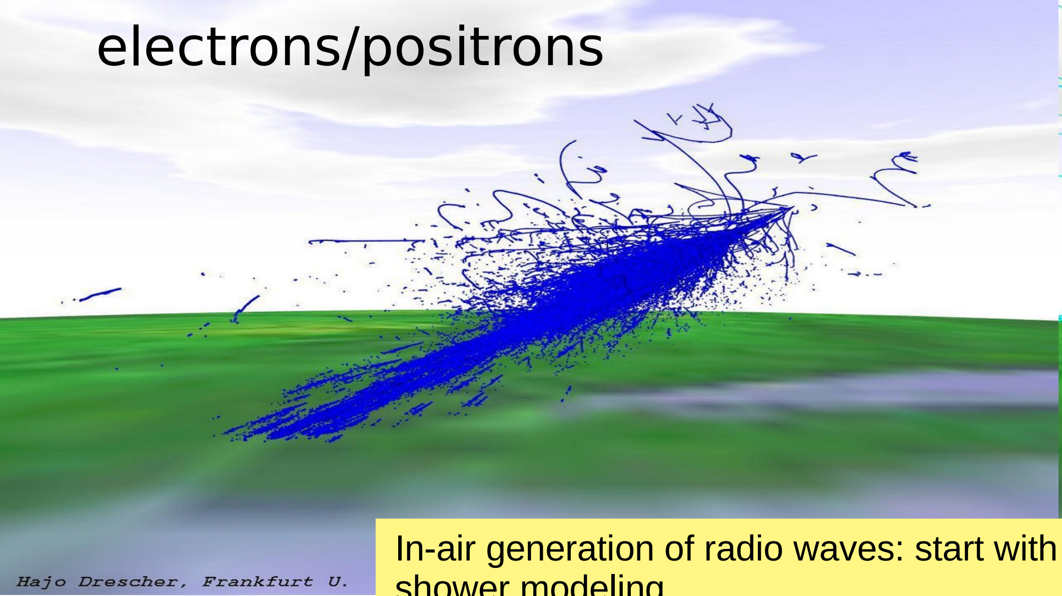
Extragalactic flux sets scale for many accelerator models

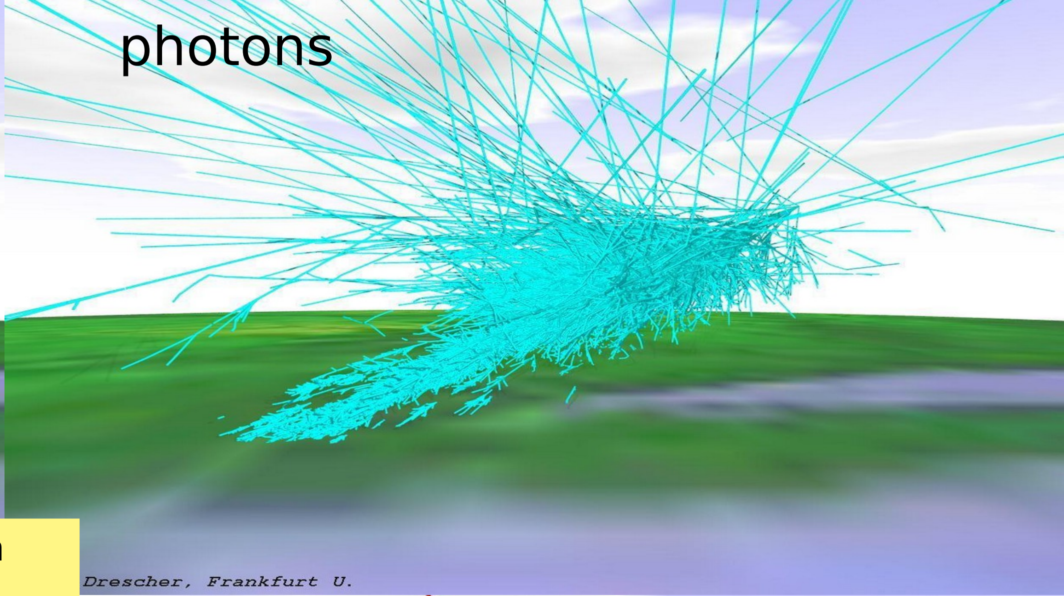
In-air UHECR detection using radio techniques





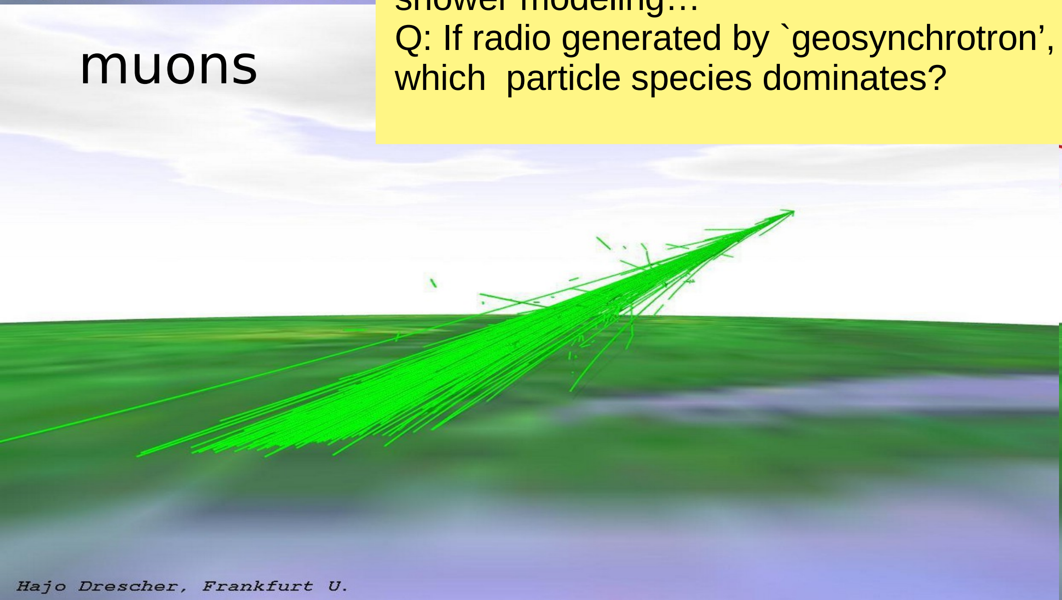
20 separate, independent sub-arrays, each of 10 000 radio antennas deployed over 10 000 km^2

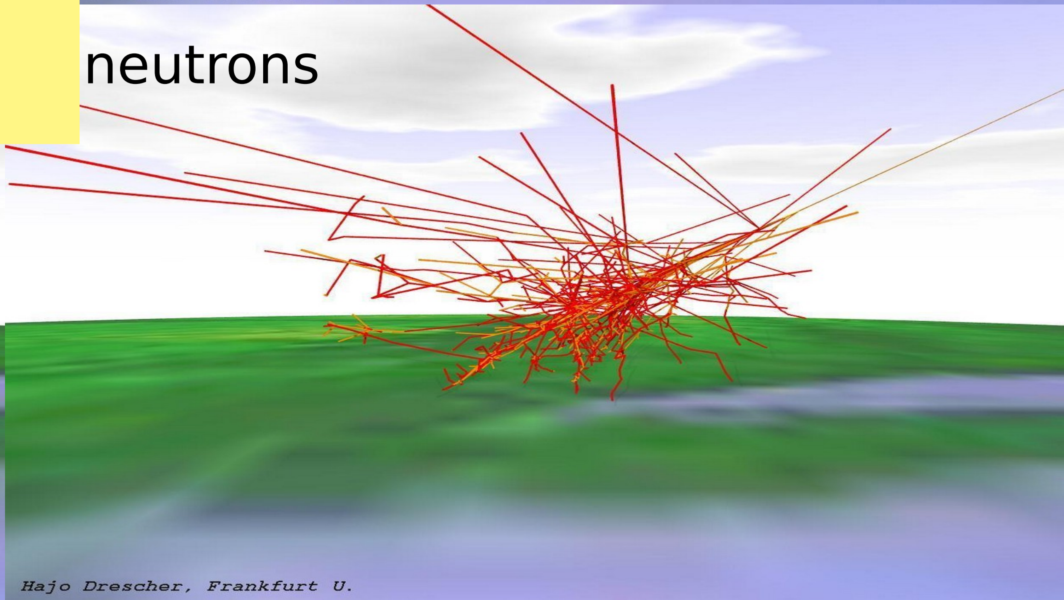




In-air generation of radio waves: start with shower modeling…

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)

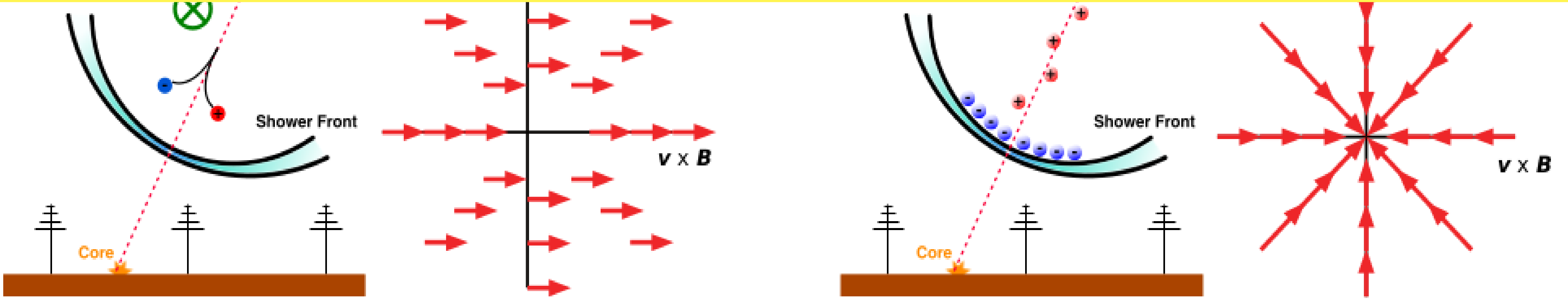


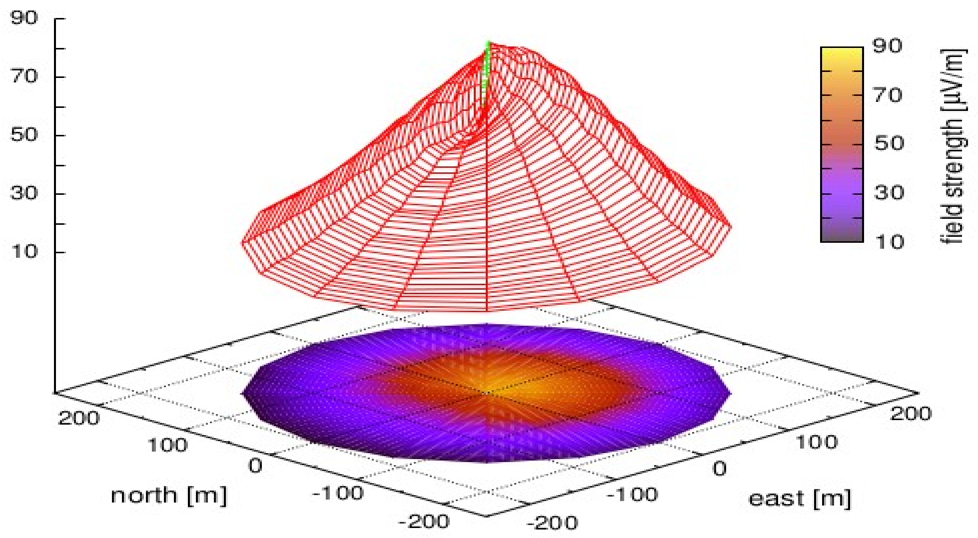
Fig. 3 Left: Characterisation of the geomagnetic radiation mechanism; the arrows denote the directions of the electric field vector in the plane perpendicular to the air shower axis. The emission is uniformly and linearly polarized along the direction given by the Lorentz force, $\vec{v} \times \vec{B}$ (east-west for vertical air showers). Right: Characterisation of the charge-excess (Askaryan) emission. The arrows denote the direction of the electric field vectors which are

Intermezzo: DAQ architecture

1) Note that the geomagnetic signal on the ground is collimated into a cone

This is NOT Cherenkov radiation (I.e, this would happen for n=1); it is only because there is a particular angle (the C-angle) at which all frequencies are in-phase.

2) For NS-aligned B-fields at intermediate latitudes, the v x B geomagnetic signal is predominantly E-W (i.e., Hpol!)

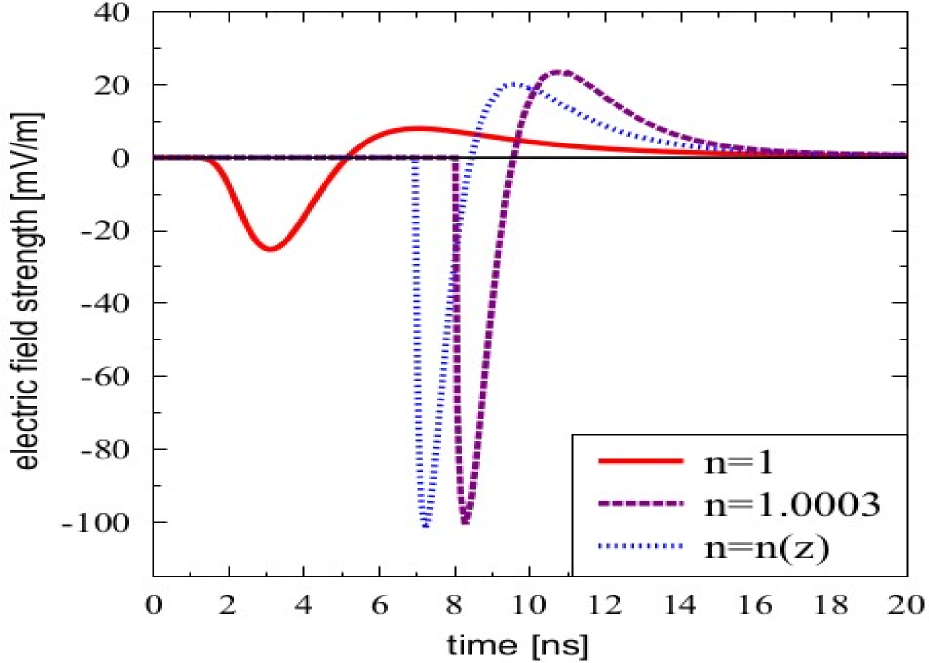


Footprint of radio signal on the ground
(asymmetry due to overlap of geomagnetic and Askaryan signals);
Compare to thermal noise (kTB)

Q: From the above graph, estimate the direction of the magnetic field, as well as the relative strength of the geomagnetic:askaryan signals

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; $E=5\times10^{17}$ eV



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

Given: data on 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

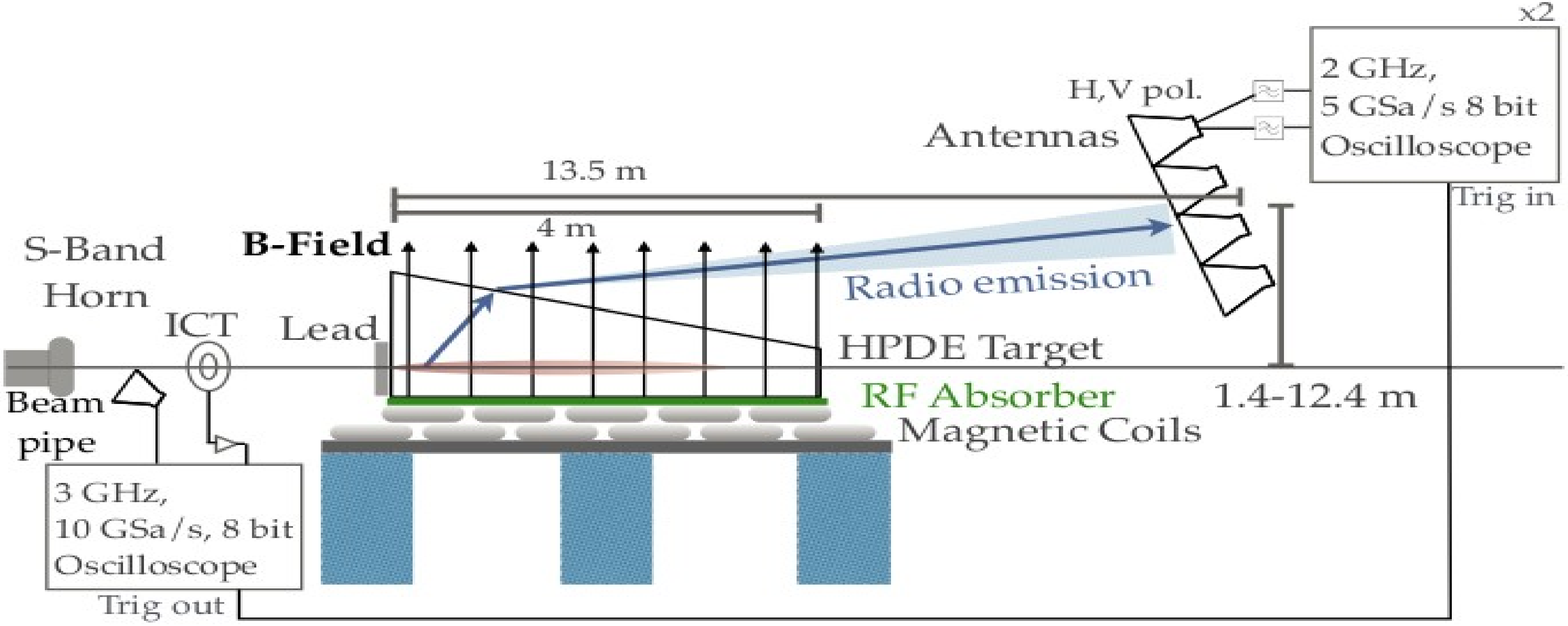


FIG. 1. Schematic of the experiment, not to scale.

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

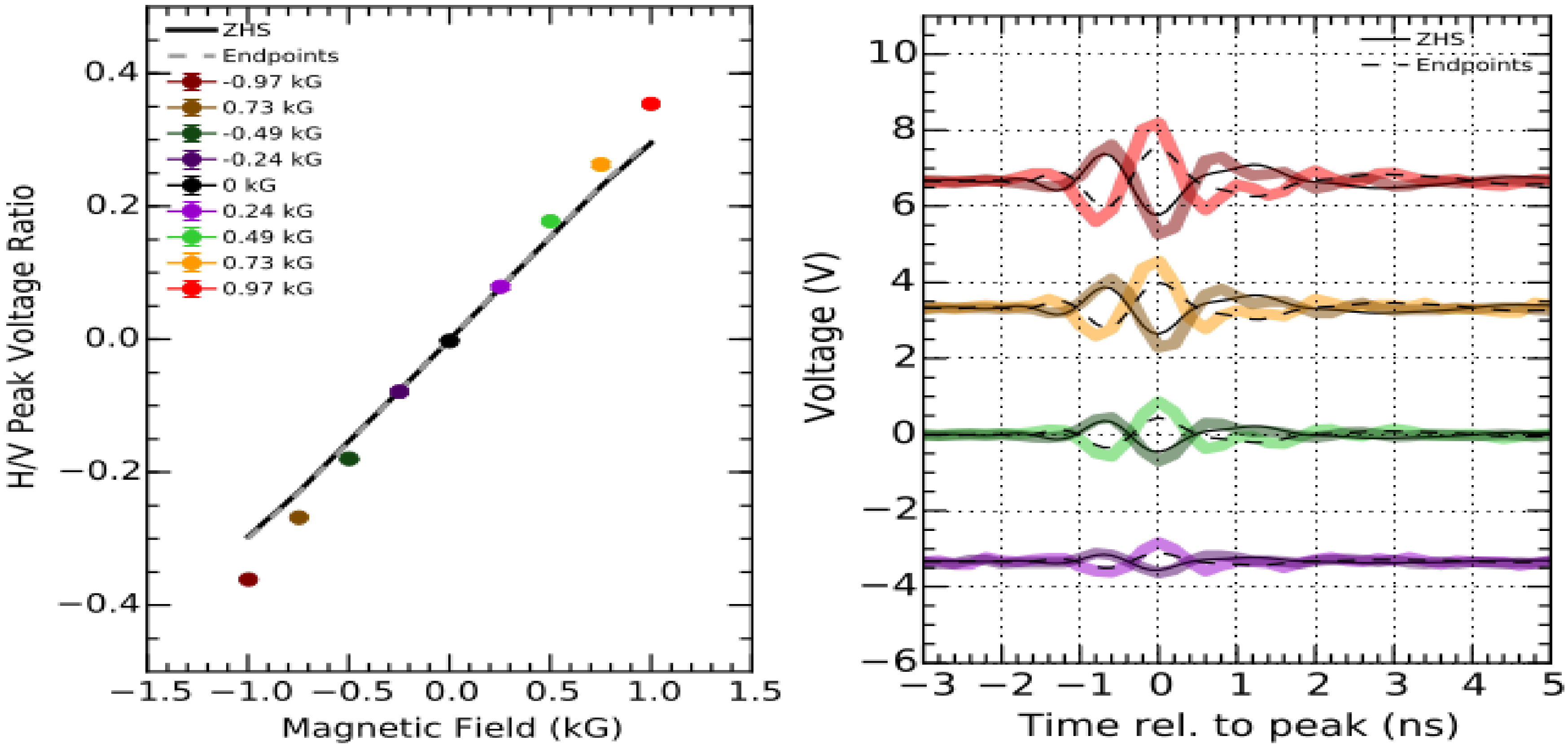


FIG. 6. Left: horizontally polarized signal normalized by vertical showing the expected linear behavior vs. magnetic field.

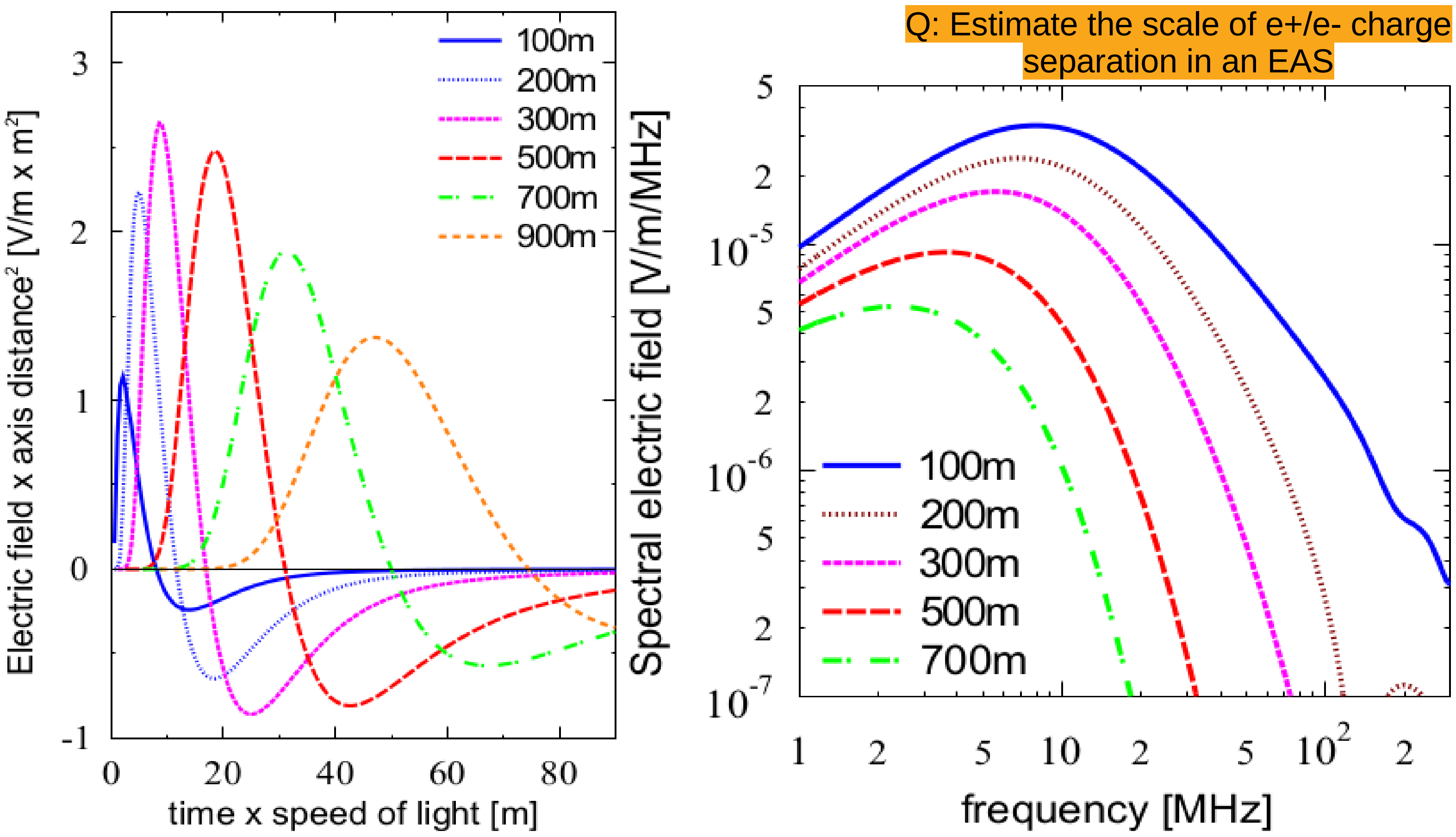


Fig. 2 Modeled radio pulses (left) due to geomagnetic effect in a 10^{17} eV air shower as observed at various observer distances from the shower axis as well as corresponding frequency spectra (right). Effects due to the refractive index of the atmosphere are not

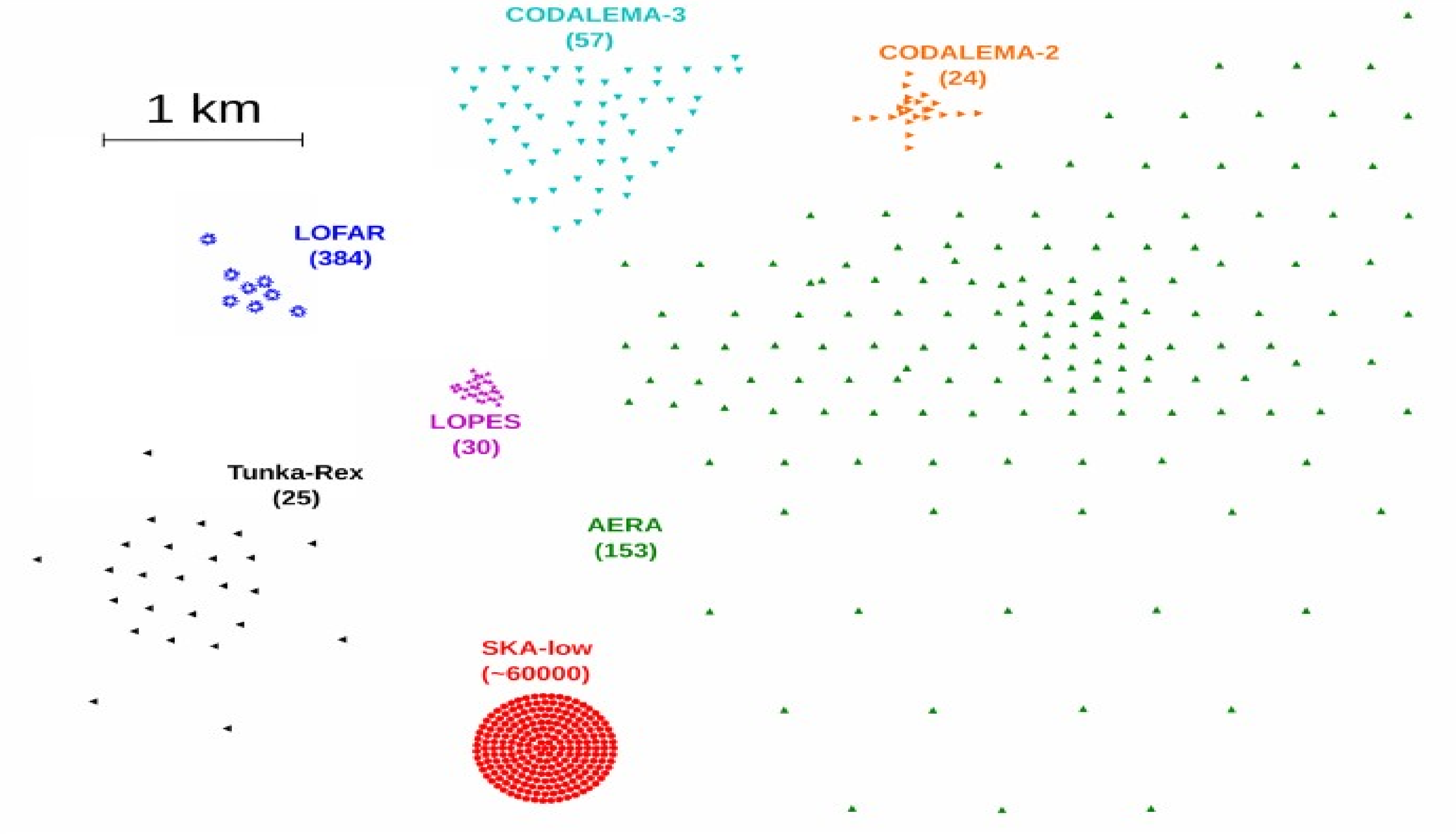
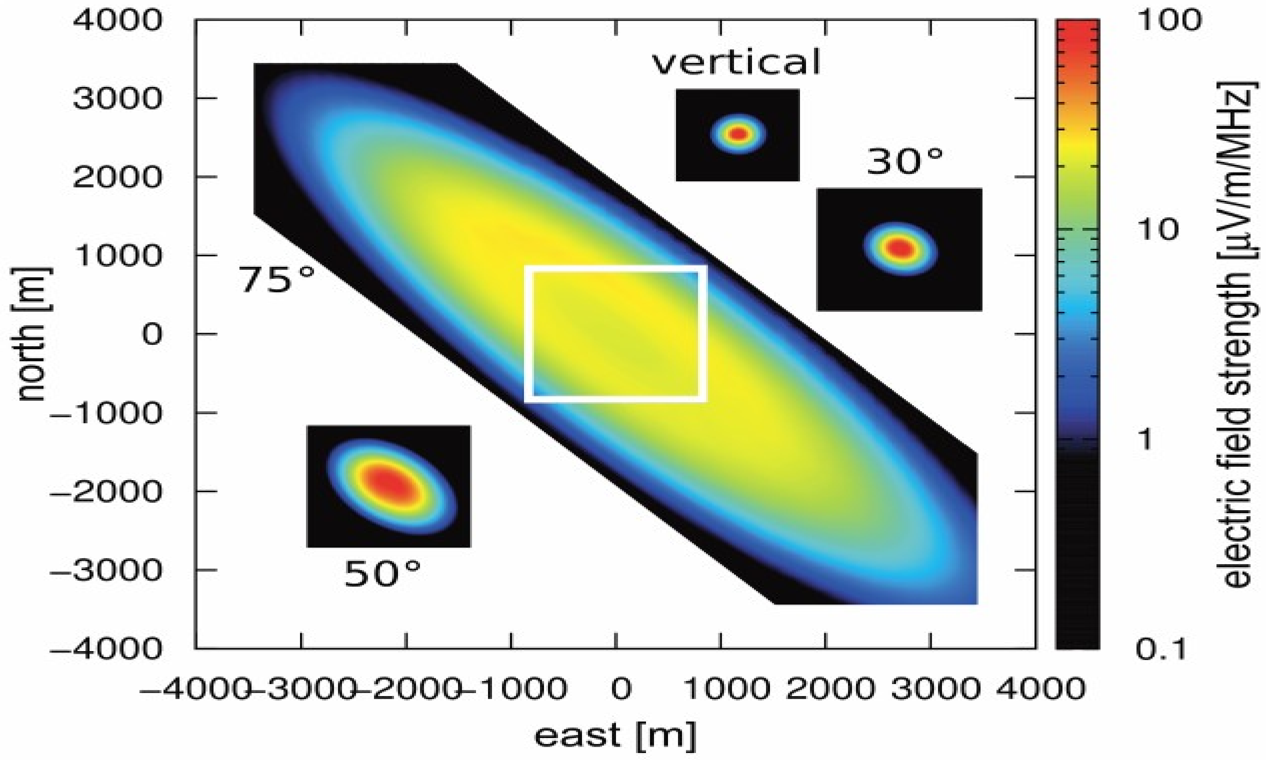


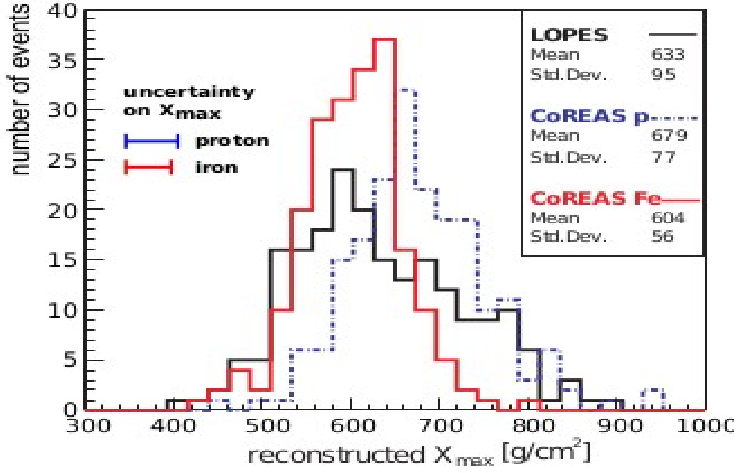
Fig. 7 Compilation of modern cosmic-ray radio detection experiments. Each symbol represents one radio detector (typically a dual-polarised antenna), except for the SKA where

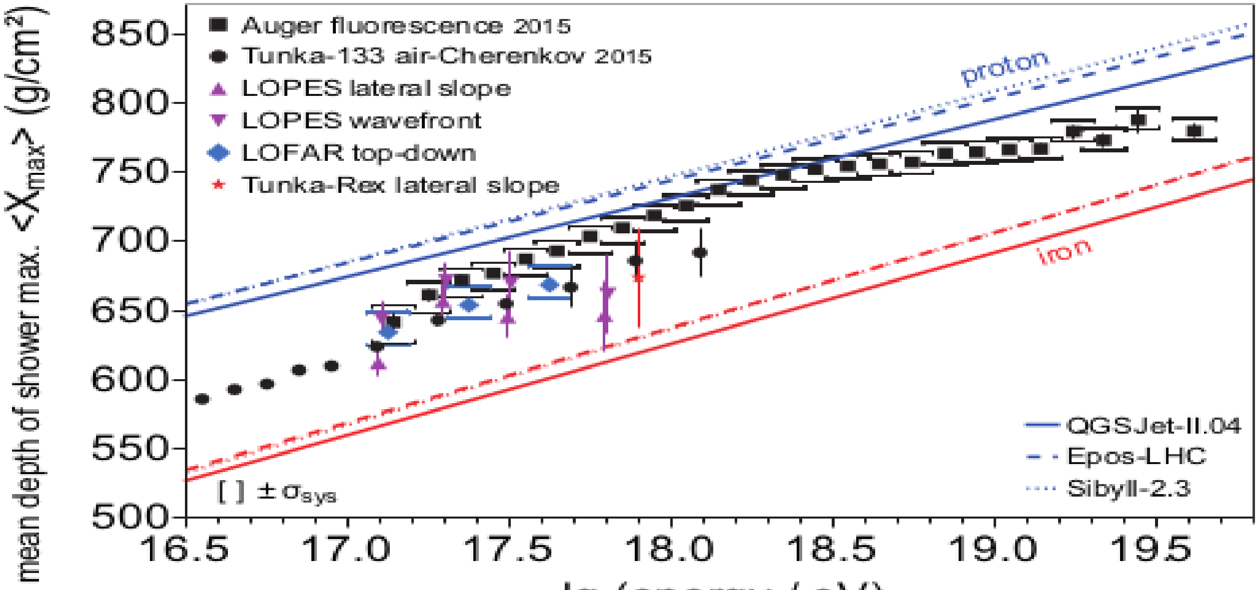
E=5 x 10^{18} eV: Dependence of on-grond radio footprint on zenith angle. Note scale!!!



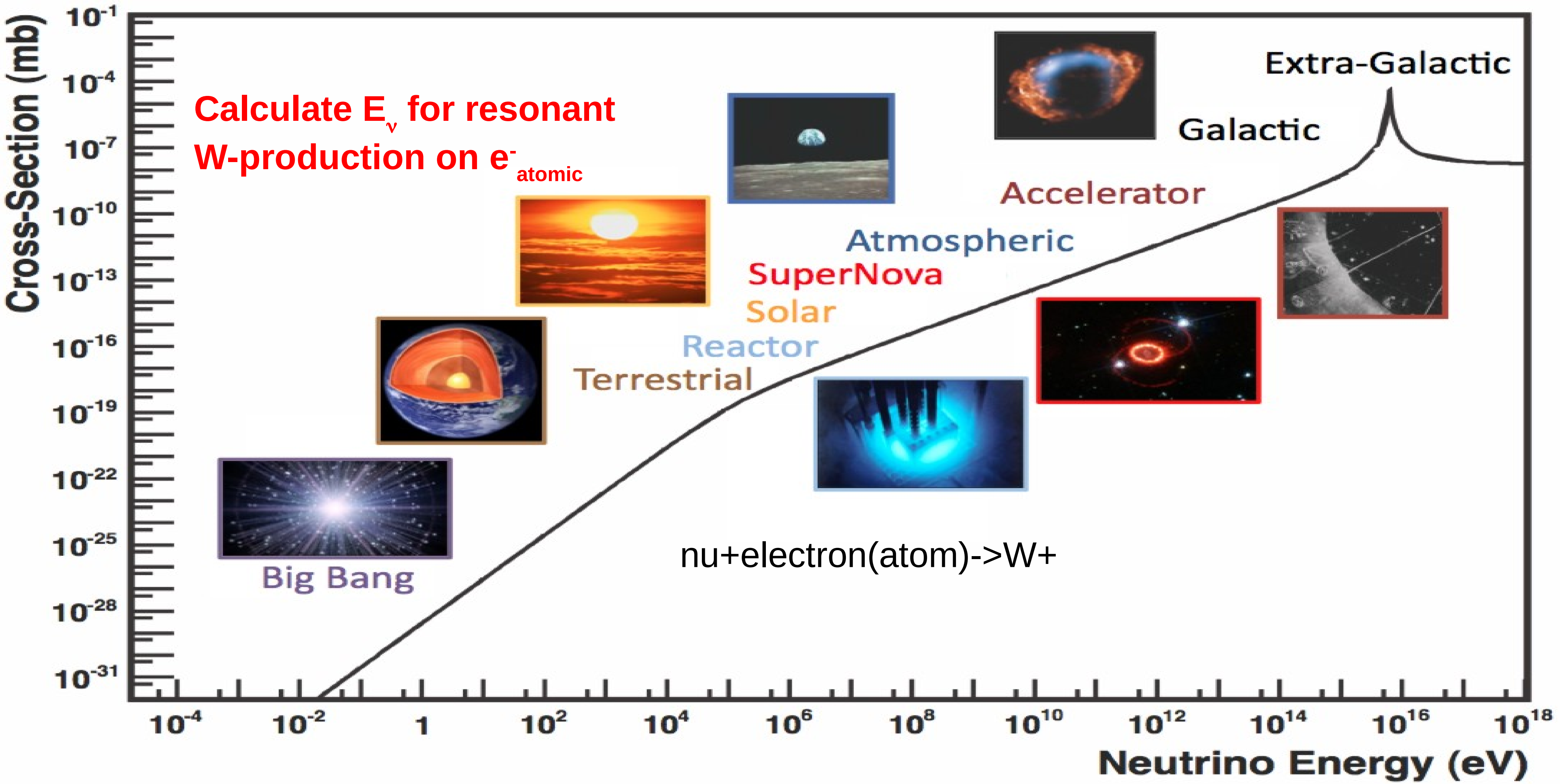
Sensitivity of radio technique to shower maximum=>composition!

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





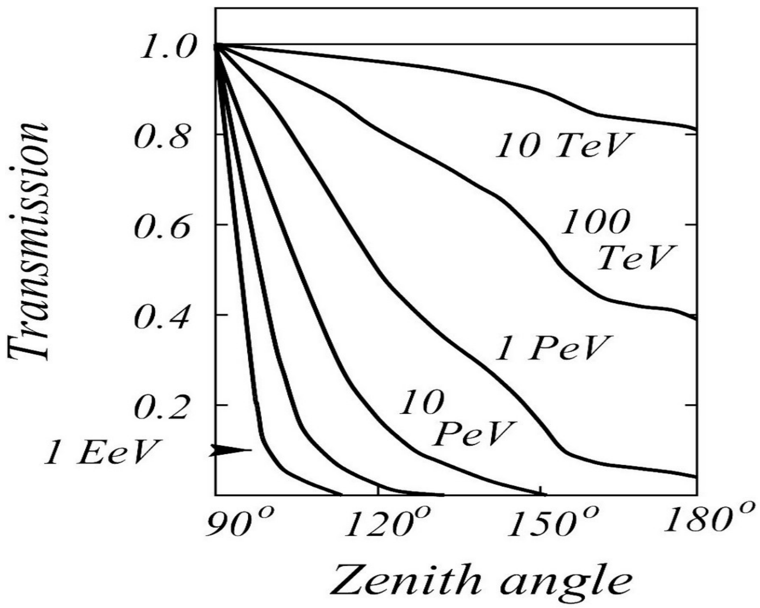
For detection rates, must fold in Neutrino Cross-Section (note Glashow resonance)

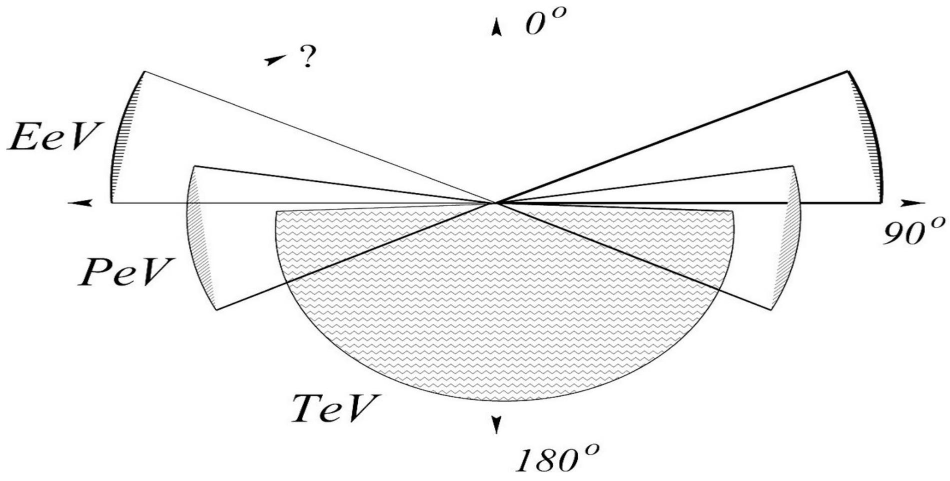


Calculate E_ν for resonant W-production on e^-_{atomic}

nu+electron(atom)->W+

Shadowing effect of the Earth



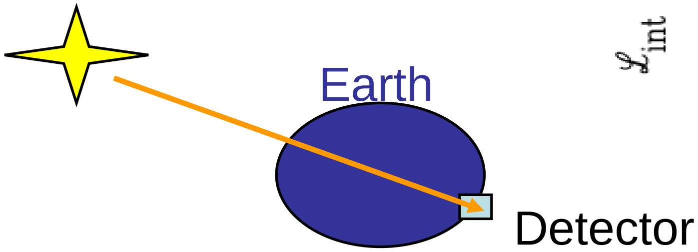


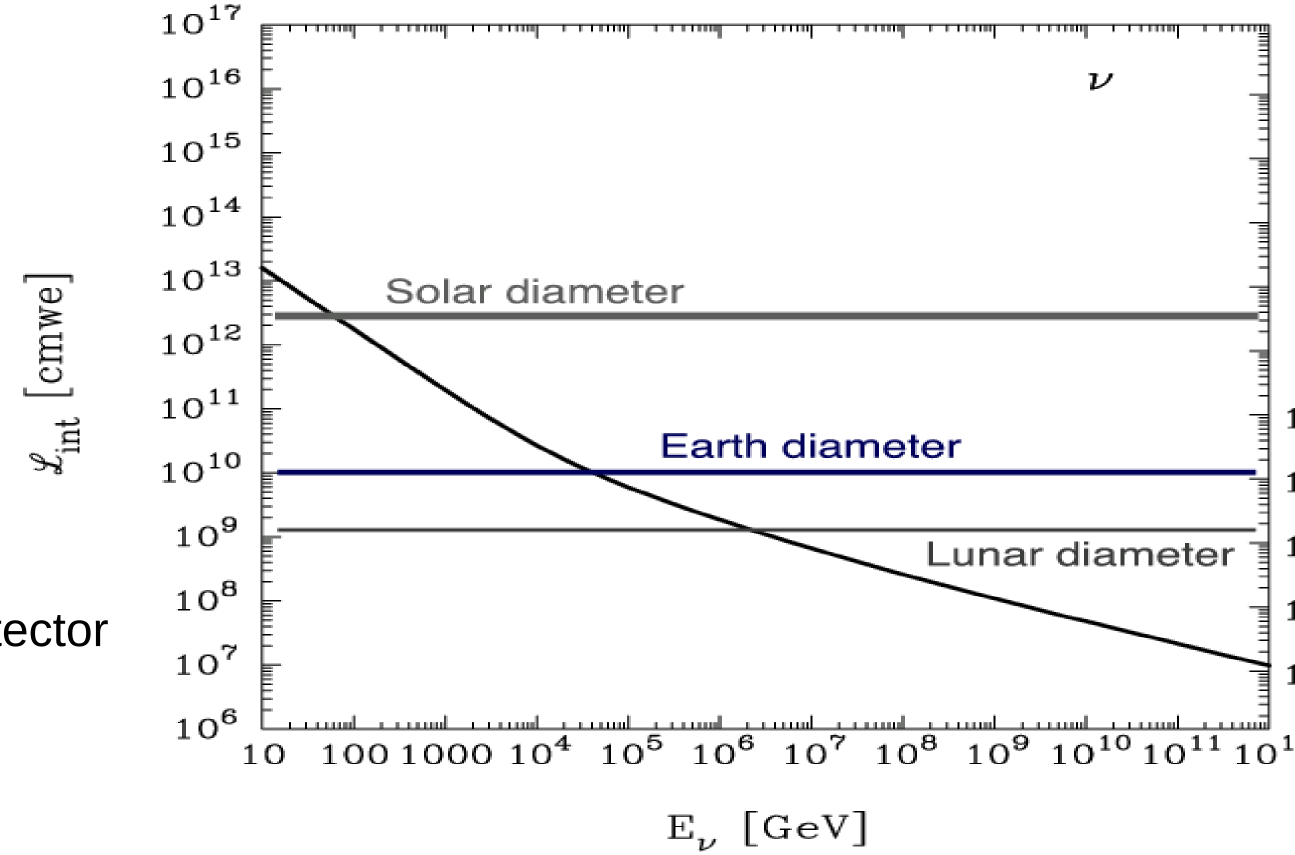
PeV acceptance around horizon

EeV acceptance above horizon

Earth attenuation

- High energy neutrinos interact in the Earth:

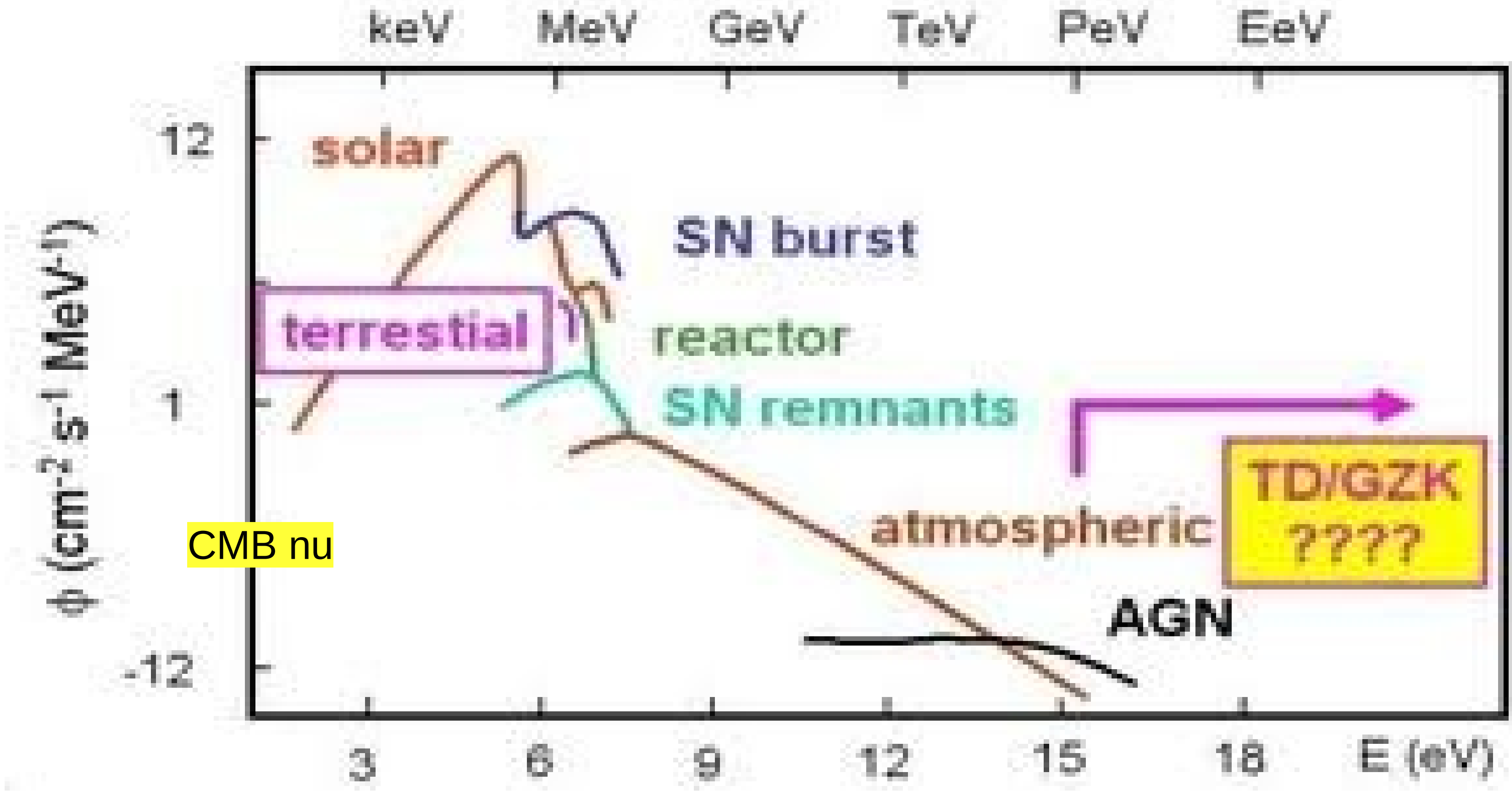




- However: Tau neutrino regeneration through $\nu_\tau \Rightarrow \tau \Rightarrow$ (17%) $\mu + \nu_\mu + \nu_\tau$

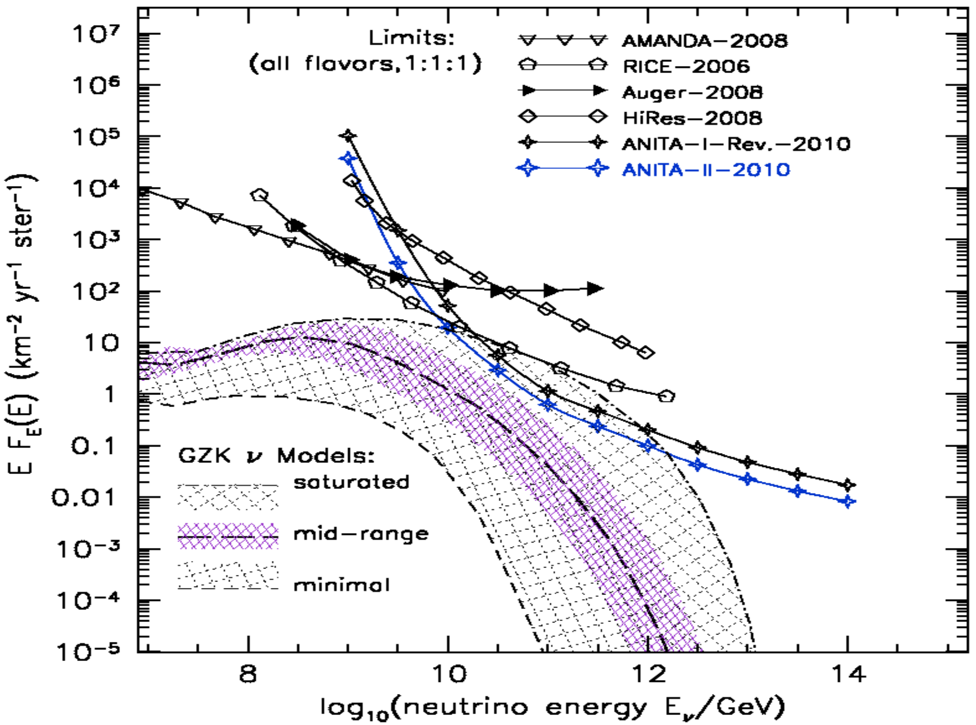
Earth is opaque to neutrinos above 1 PeV!

What does the expected Neutrino flux look like?



Cosmogenic (GZK) neutrinos

- UHECR exist, therefore
  - Neutrino production occurs during propagation via $p + \gamma_{CMB}$ -> π+ ν + ...
  - $E_{th} \sim 5 \times 10^{19}$ eV
  - Even if no ν from CR sources
- Intensity depends on
  - Spectrum at sources
  - Evolution of sources
  - Composition of UHECR (Heavy nuclei give less ν)



ANITA arXiv:1011.5004

If neutrons can escape:
Source of cosmic rays

Neutrinos produced in ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow$ Cosmogenic neutrinos

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

π^+/π^0 determines ratio between neutrinos and gamma-rays

$$\pi^0 \rightarrow \gamma + \gamma$$

Cosmic messengers

High energetic gamma-rays; might cascade down to lower E

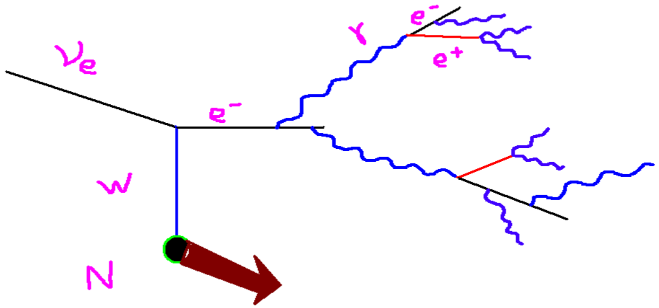
Cosmogenic ν and γ

From air→ice:The long-wavelength Cherenkov CONCEPT (Askaryan), in-ice

- 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 γ $+e^-$ 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)

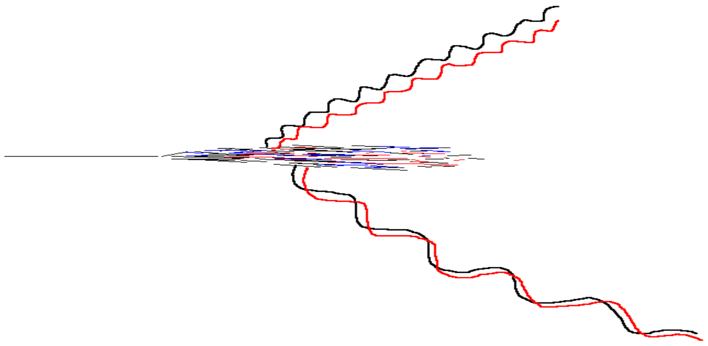
- n_e+N -> e^- + X
- High Energy e- initiates electromagnetic cascade in ice(bremsstrahlung and pair production at high energies, Compton, Bhabha, Moller, photoelectric effect…)
- Charge imbalance develops
- Net negative charge moving faster than c in ice=Cerenkov radiation



Radio Emission From EM-Showers: III

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

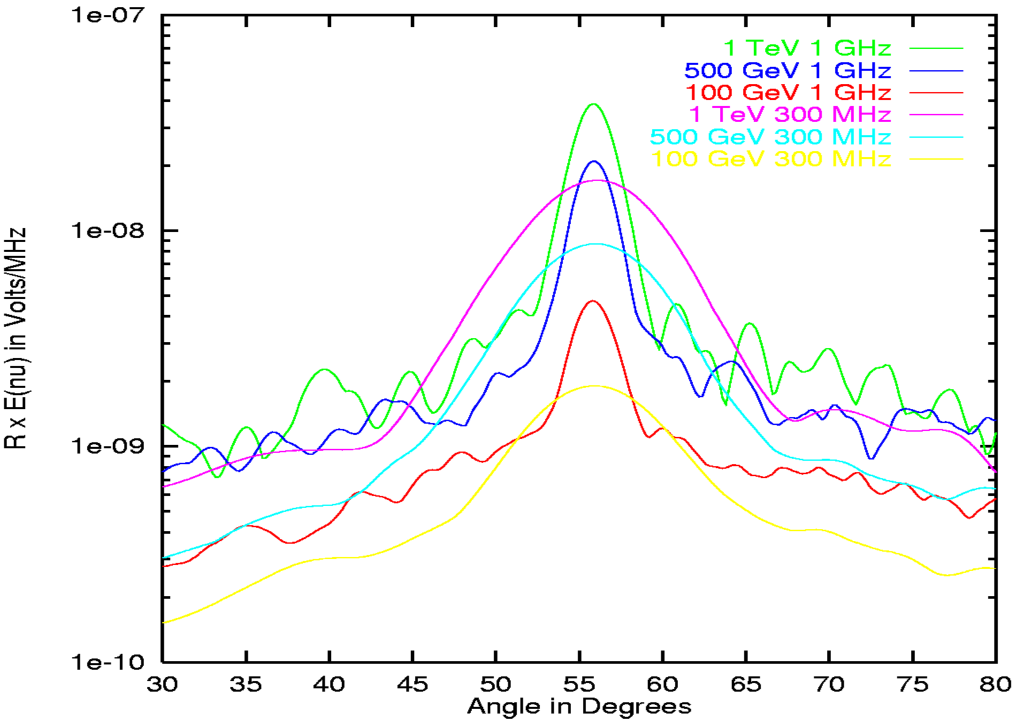
Q: Estimate the number of particles required to have A_{radio}>$A_{optical}$; assume typical radio/optical wavelengths and also assume E=hν



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



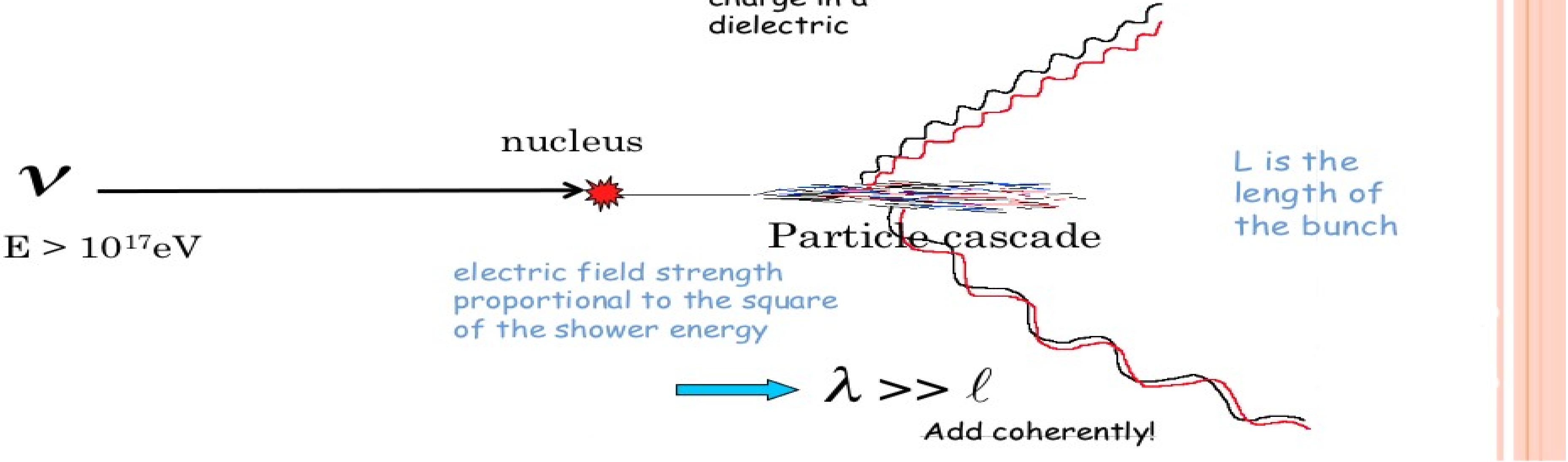
MANY Experimental results (Saltzberg, et al.) confirms coherence and Askaryan effect

Coherent radio emission

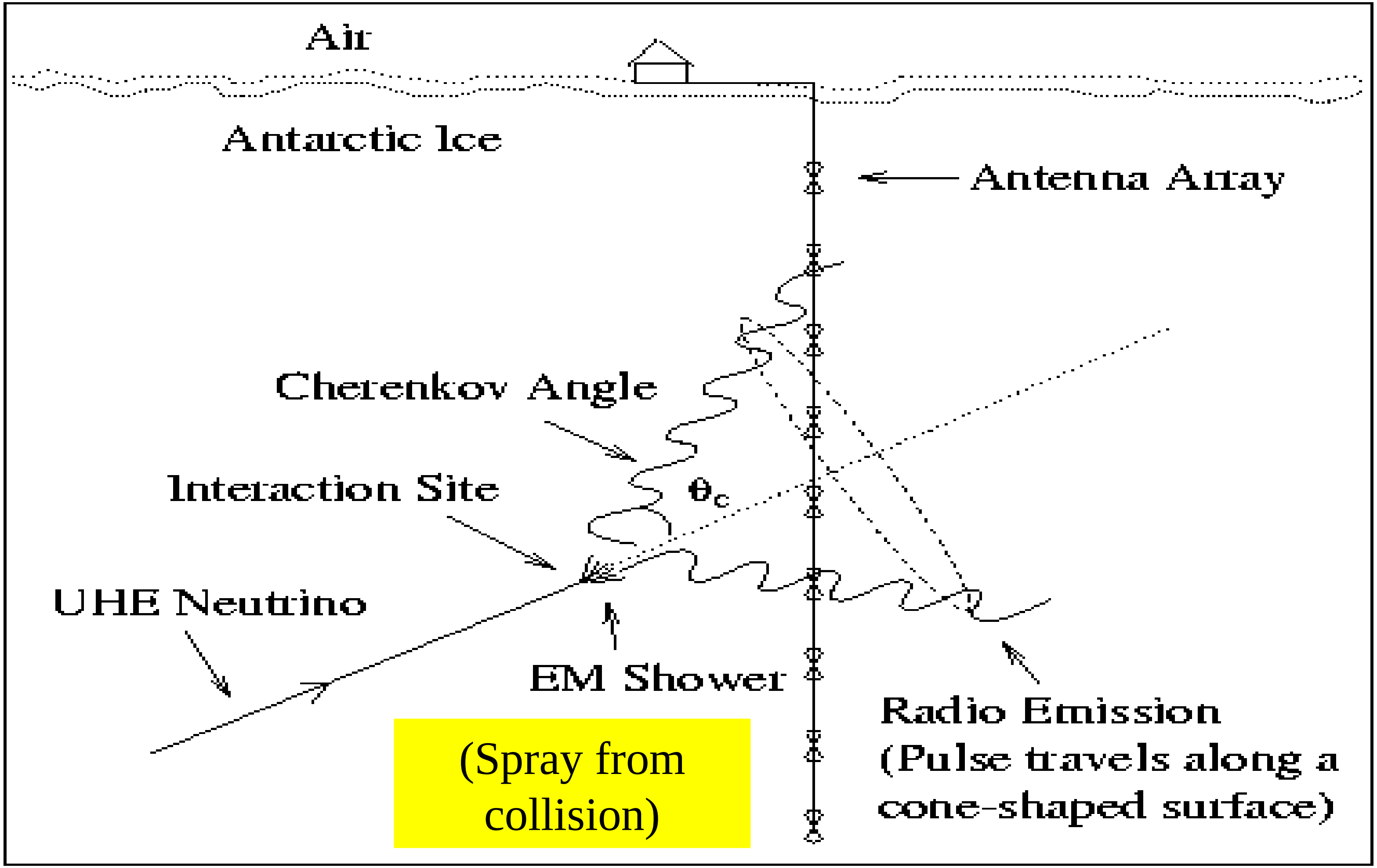
charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower

→ 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



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:

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

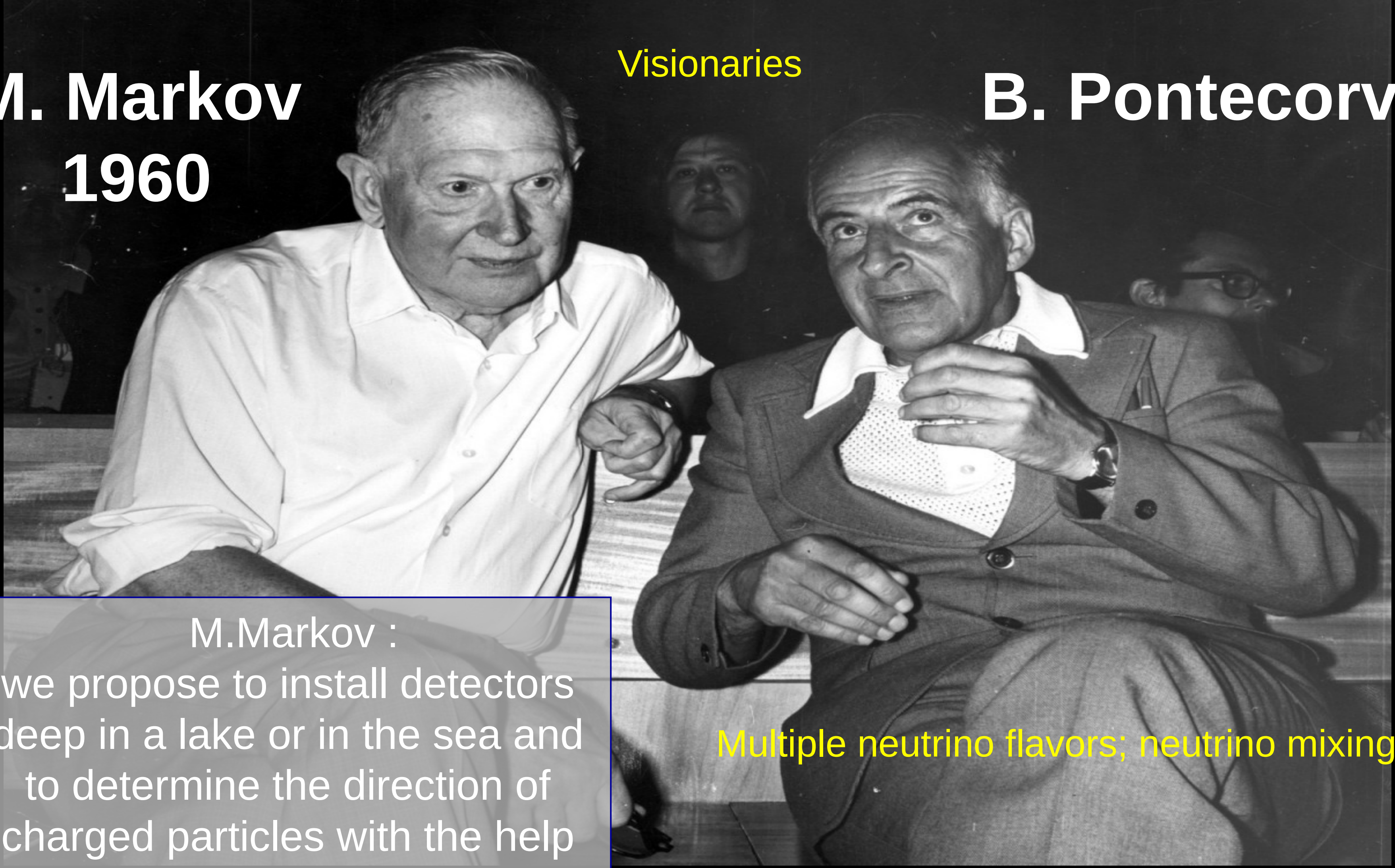
Experiments:

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-)

Visionaries

M. Markov 1960

B. Pontecorvo



M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

(1987): Deployment in ice at Vostok

Multiple neutrino flavors; neutrino mixing

First work at Vostok

First background studies and Hydra

- 1985-1986:
  - noise studies w/ single module
- 1986-1987: Hydra
  - 3 broadband receiver channels
  - Pinger locations reconstructed
  - Man-made backgrounds investigated (sources coincide with station objects)
  - Upper limit on flux of impulse pulses from ice obtained

Proc. 20th Inter. Cosmic Ray Conference. Moscow, "NAUKA", 1987, vol. 6, pp. 472-275.

Detection of ultrahigh-energy neutrinos in ARA