In-air generation of radio signals: geomagnetic and Askaryan
“charge excess” - $N_{e-}N_{e+}$ ~0.25 E_s(GeV)

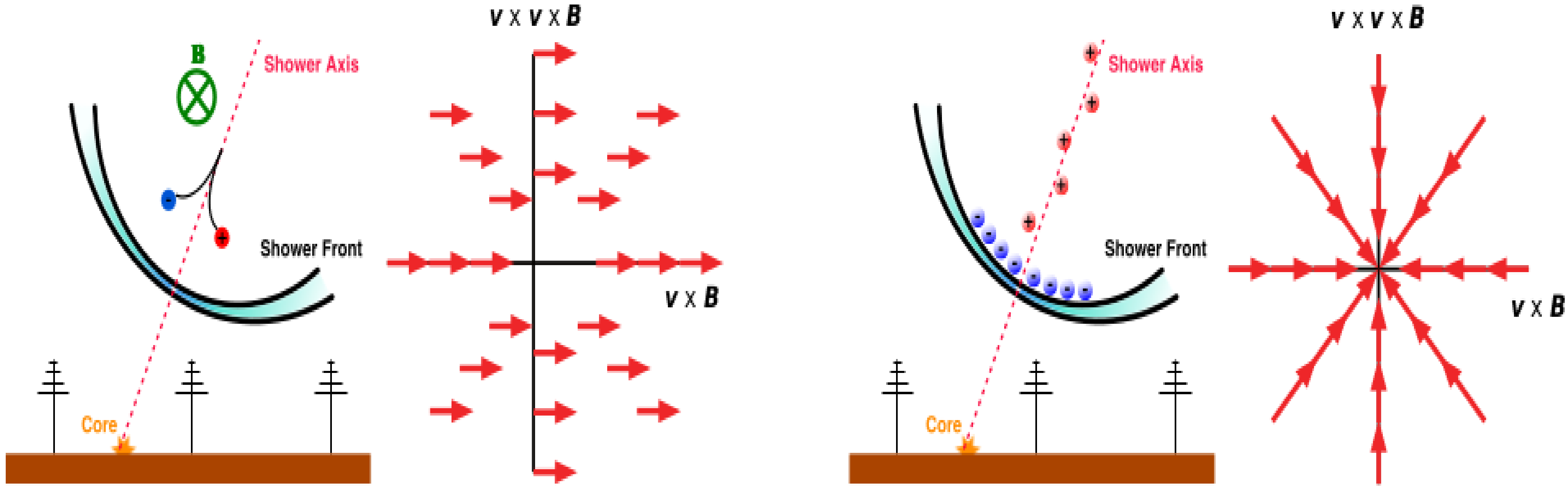
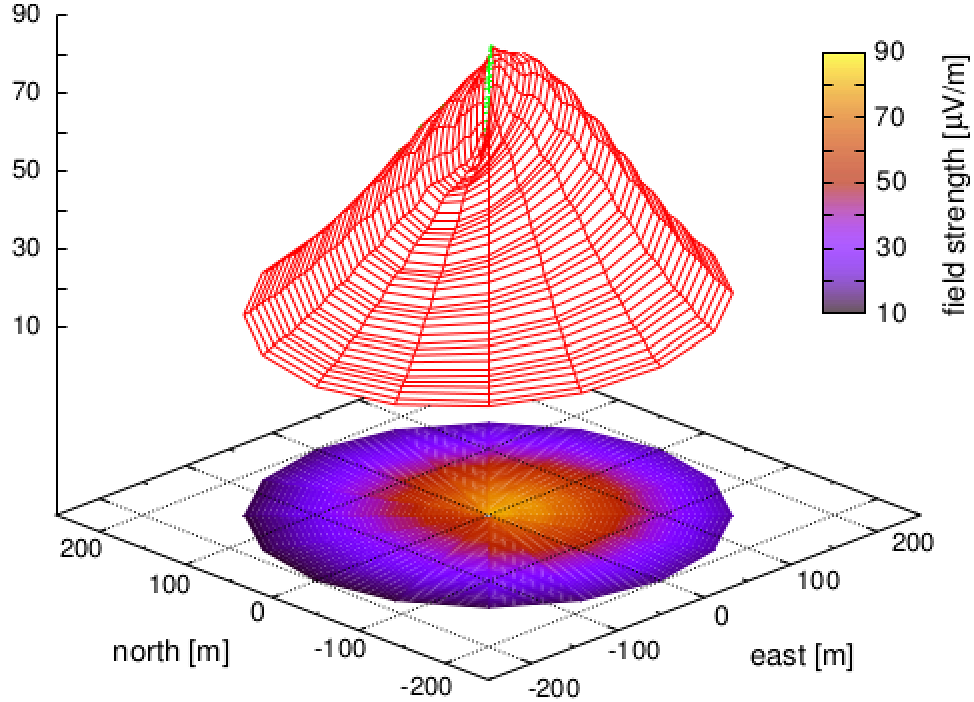


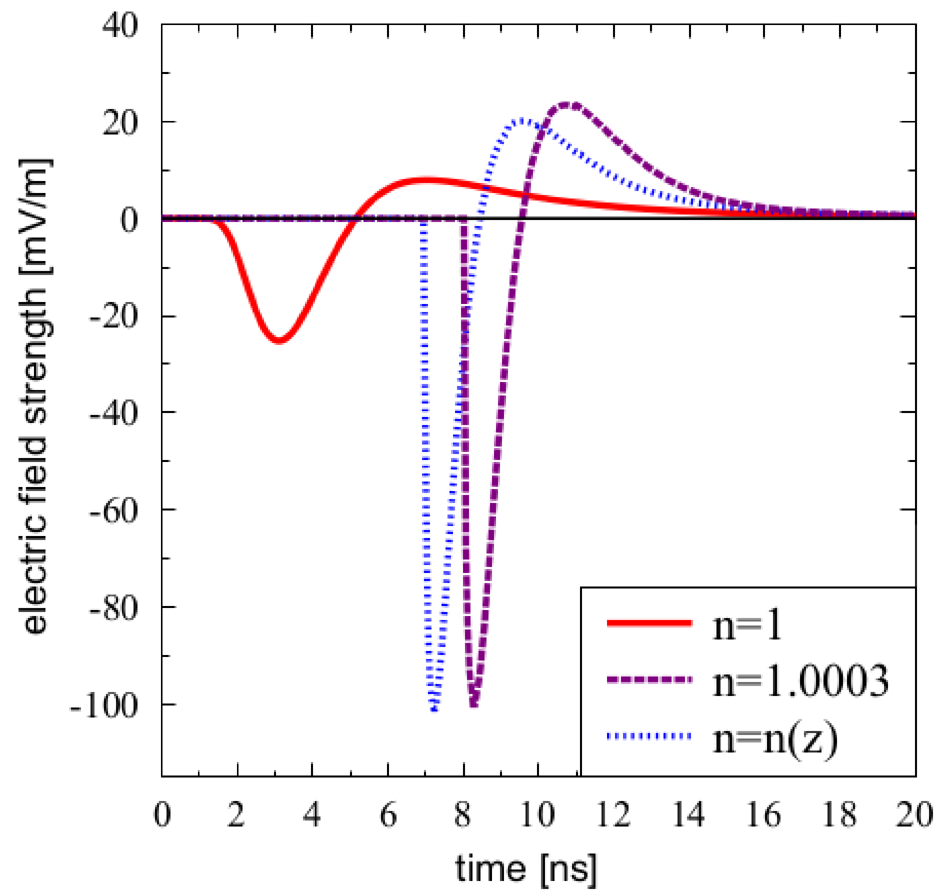
Fig. 3 Left: Characterisation of the geomagnetic radiation mechanism; the arrows denote the directions of the electric field vector in the plane perpendicular to the air shower axis. The emission is uniformly and linearly polarized along the direction given by the Lorentz force, $\vec{v} \times \vec{B}$ (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



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

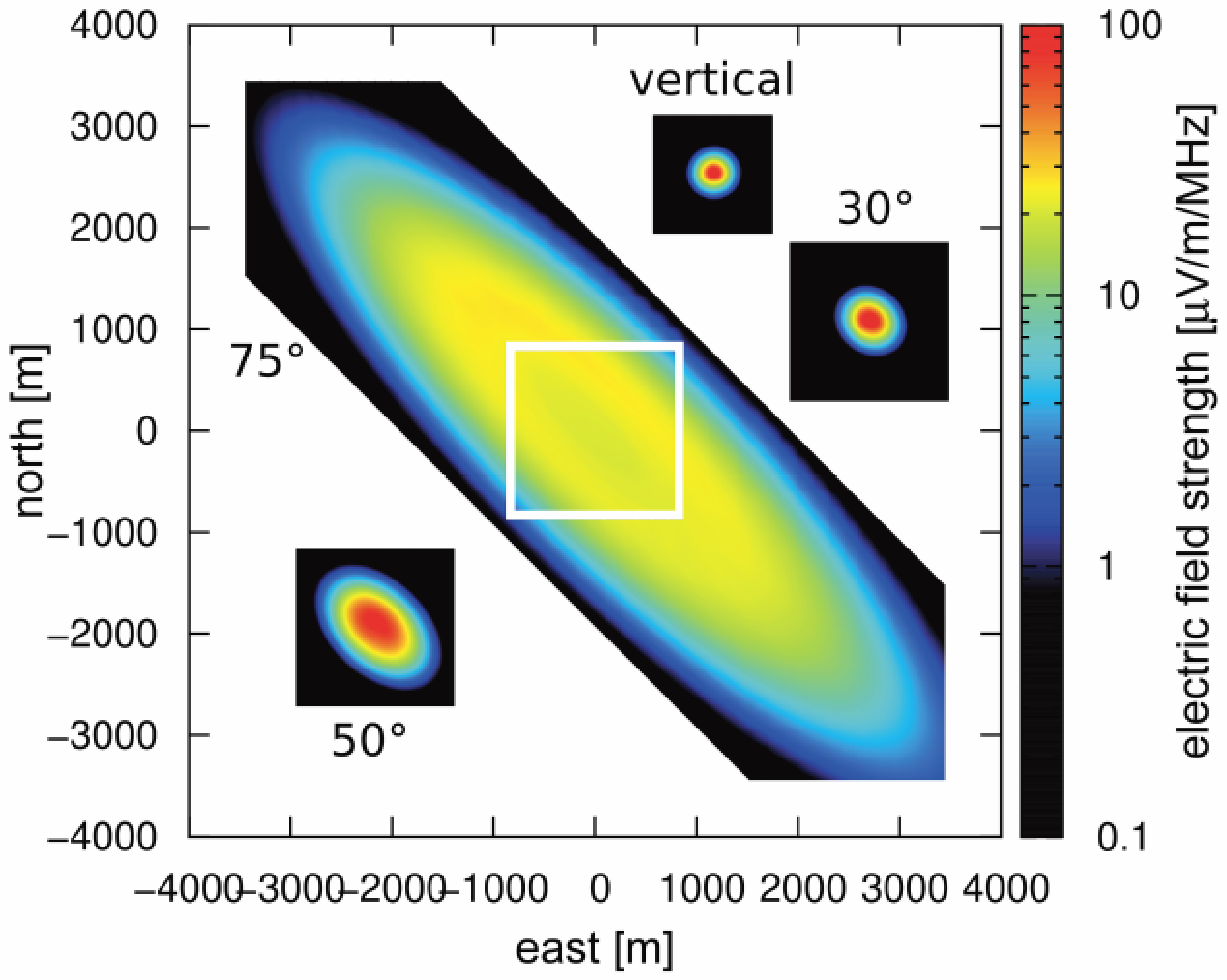
Time-domain pulse; $E=5\times10^{17}$ eV



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

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



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

Given: a) what you learned from Prof. Pravata 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

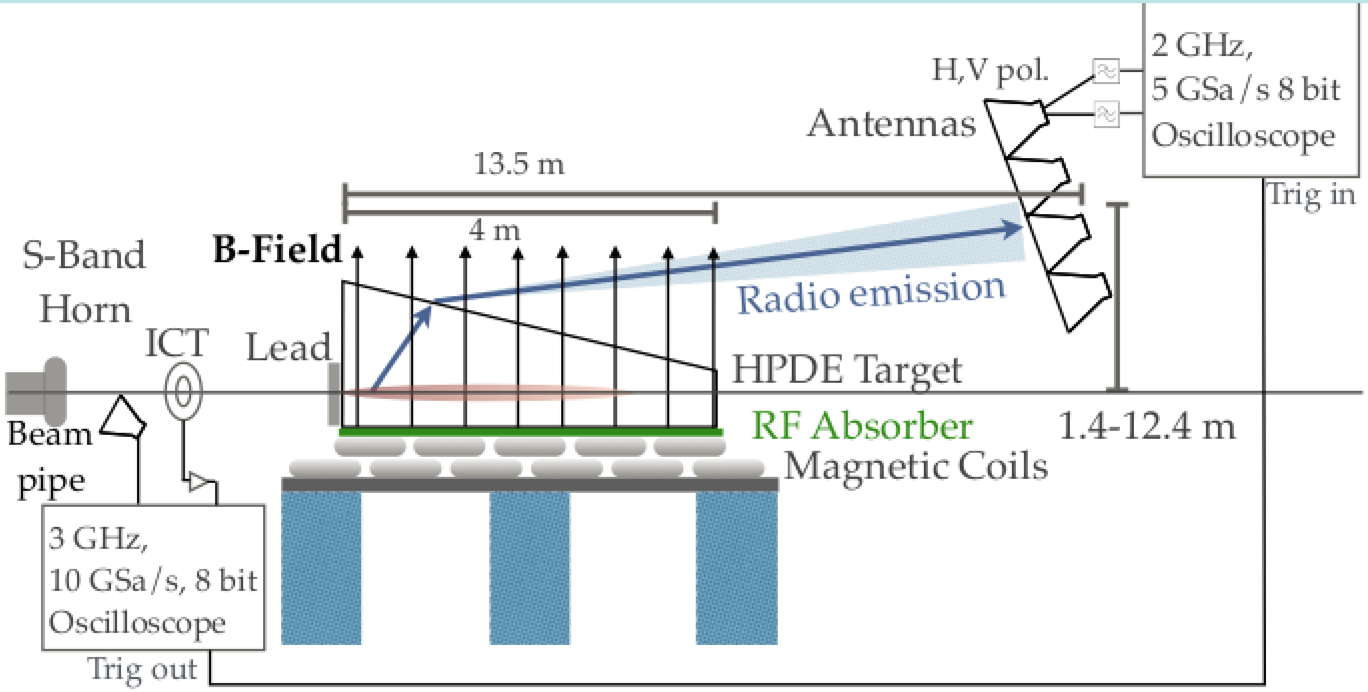


FIG. 1. Schematic of the experiment, not to scale.

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

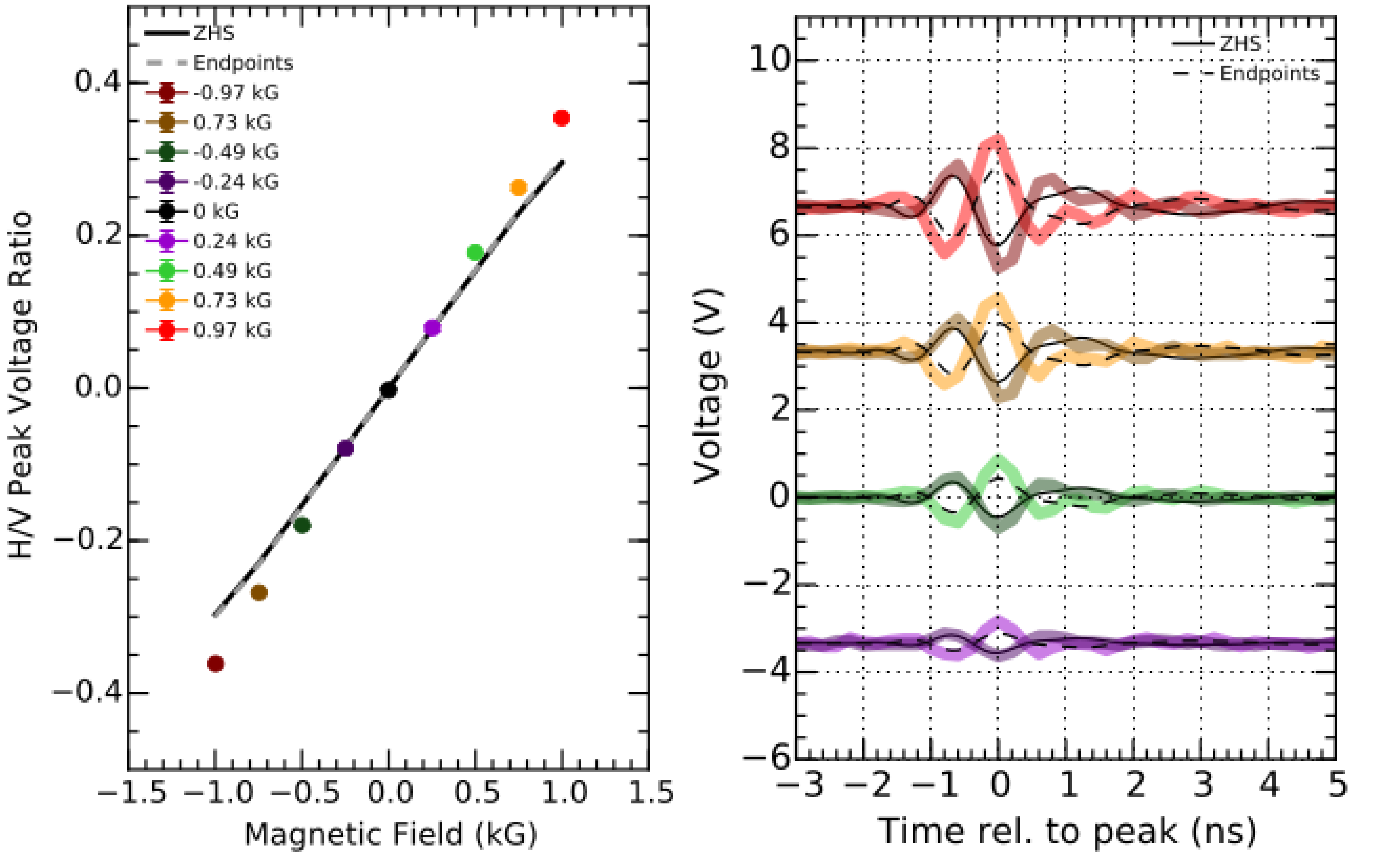


FIG. 6. Left: horizontally polarized signal normalized by vertical showing the expected linear behavior vs. magnetic field.

Q: Estimate the scale of e+/e- charge separation in an EAS

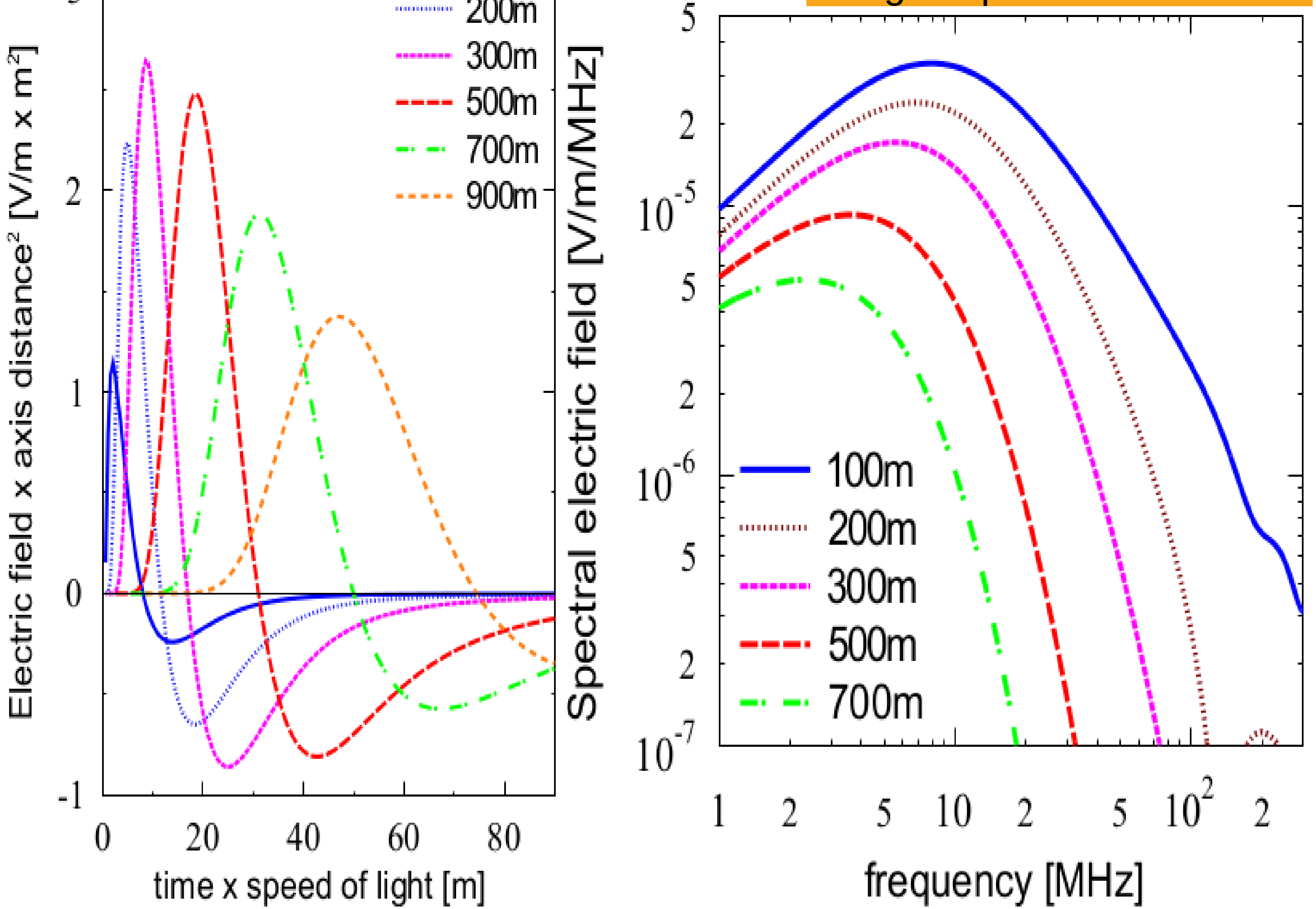


Fig. 2 Modeled radio pulses (left) due to geomagnetic effect in a 10^{17} eV air shower as observed at various observer distances from the shower axis as well as corresponding frequency spectra (right). Effects due to the refractive index of the atmosphere are not

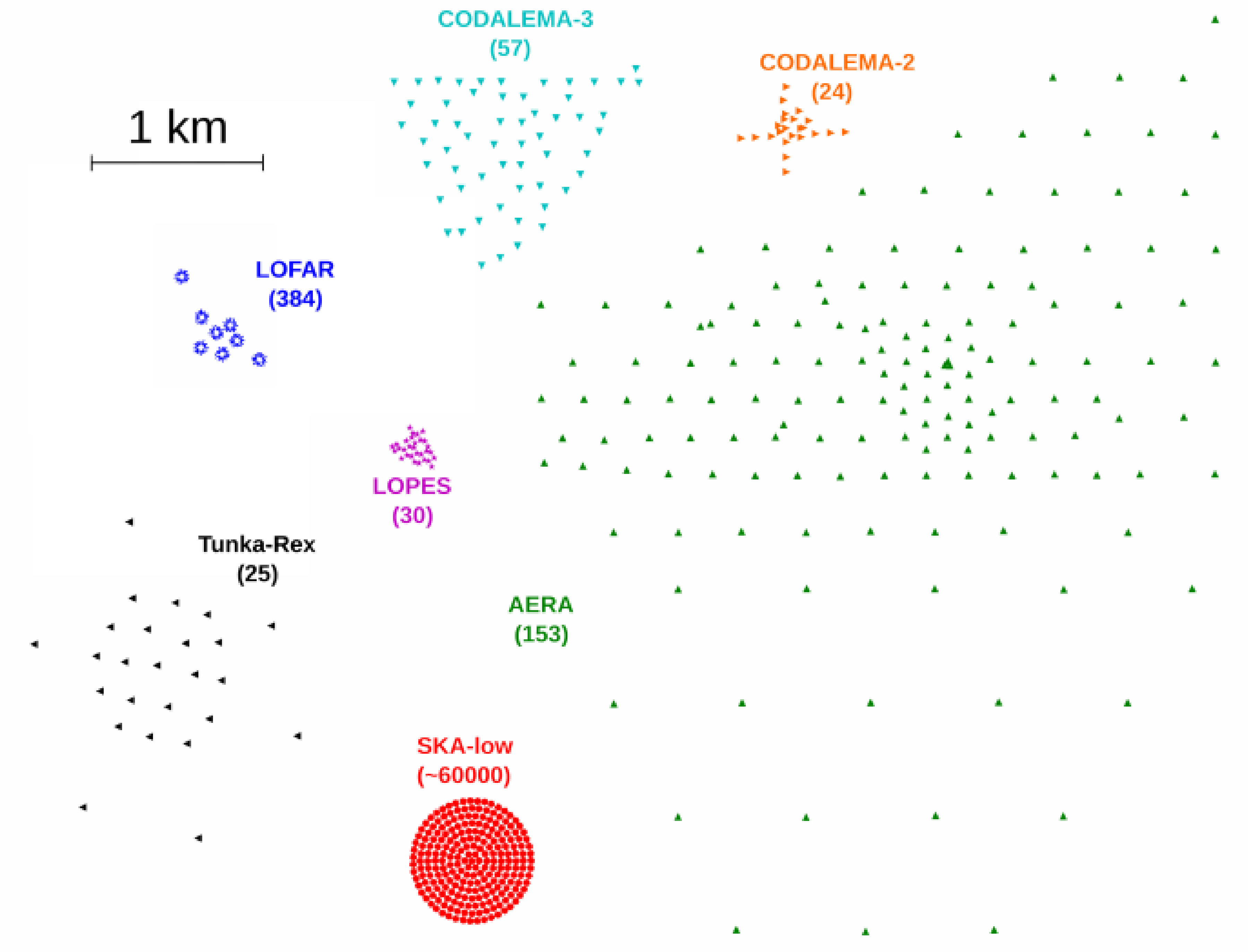
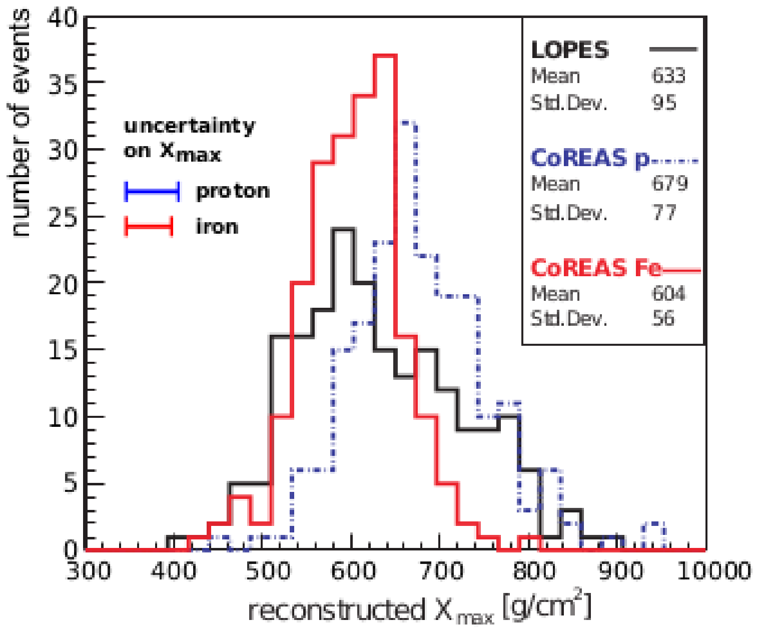
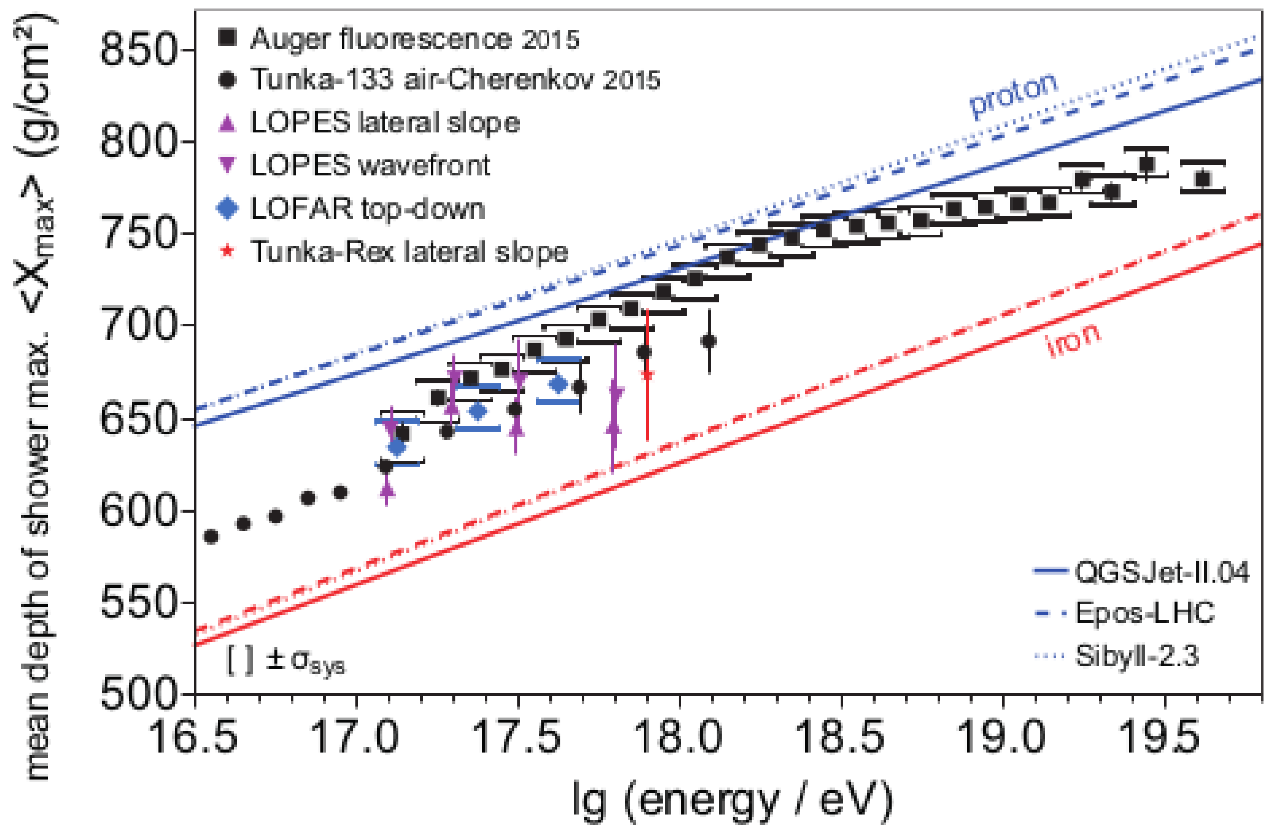


Fig. 7 Compilation of modern cosmic-ray radio detection experiments. Each symbol represents one radio detector (typically a dual-polarised antenna), except for the SKA where

Sensitivity of radio technique to shower maximum=>composition!

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



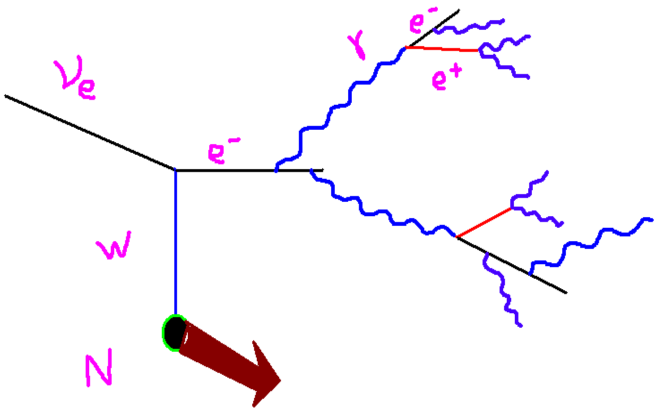


From air→ice:The long-wavelength Cherenkov CONCEPT (Askaryan), in-ice

- 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 $\gamma + e^-$ 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)

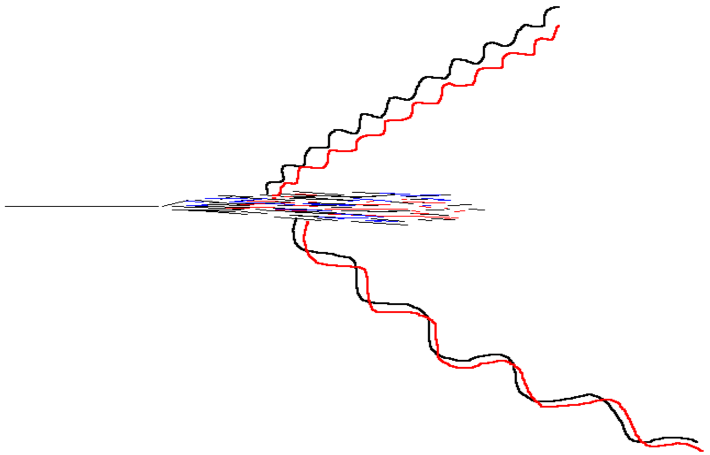
- n_e+N -> e^- + X
- High Energy e- initiates electromagnetic cascade in ice(bremsstrahlung and pair production at high energies, Compton, Bhabha, Moller, photoelectric effect…)
- Charge imbalance develops
- Net negative charge moving faster than c in ice=Cerenkov radiation



Radio Emission From EM-Showers: III

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

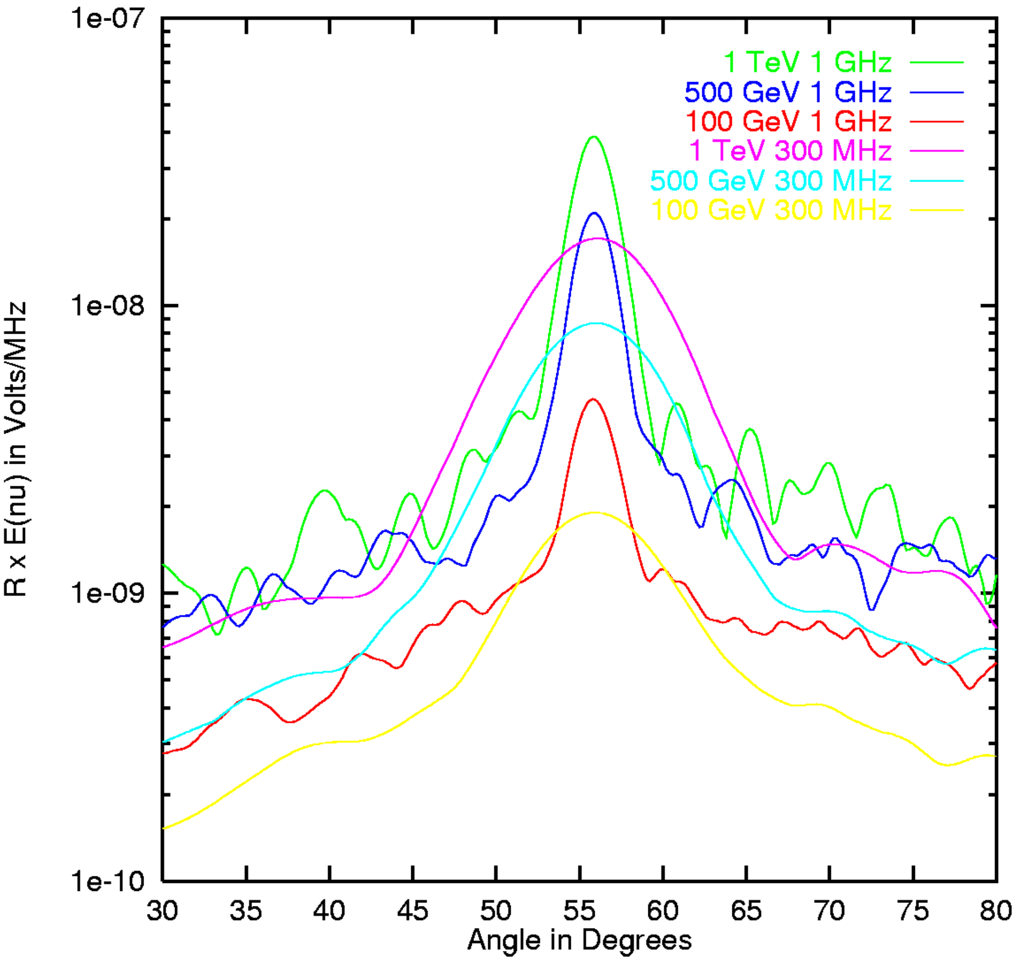
Q: Estimate the number of particles required to have $A_{radio} > A_{optical}$; assume typical radio/optical wavelengths and also assume E=hν



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



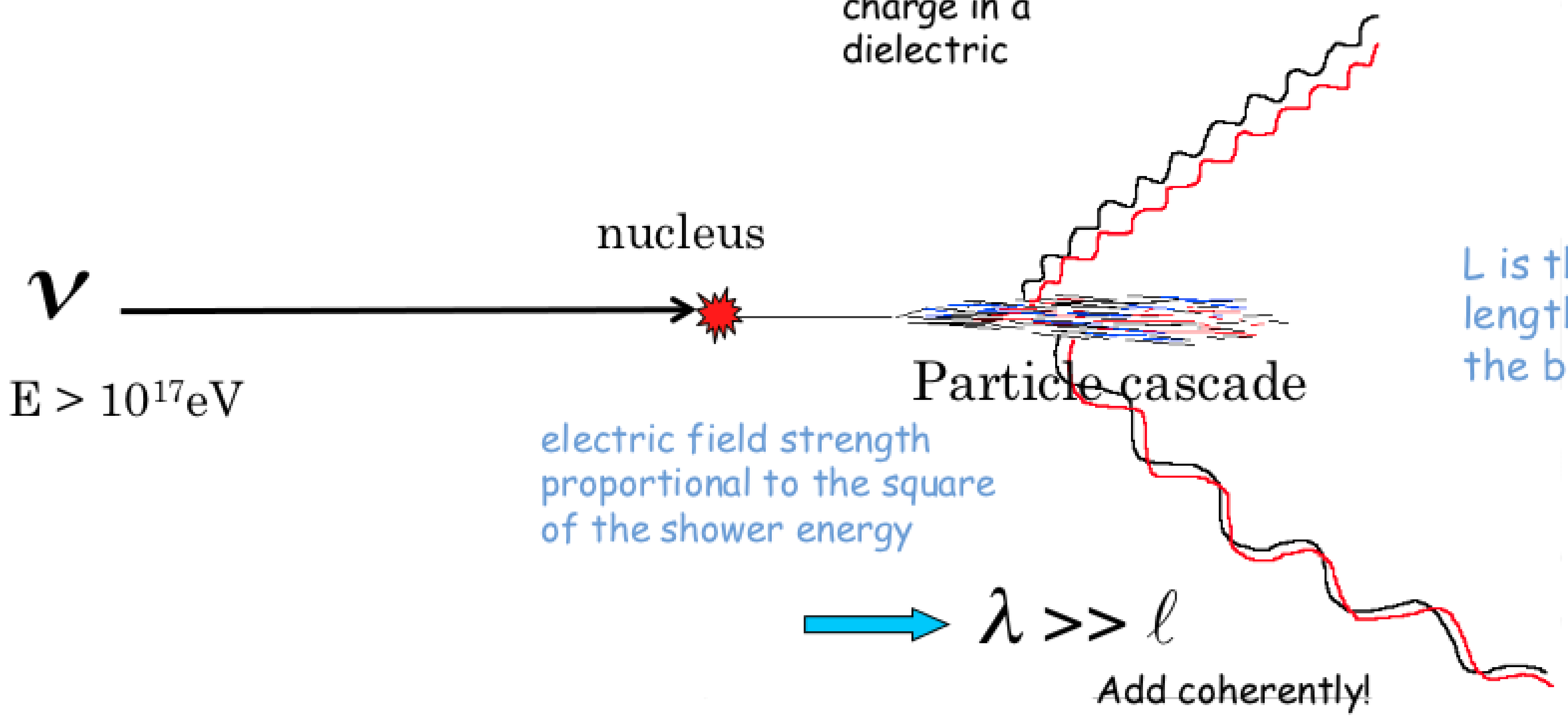
MANY Experimental results (Saltzberg, et al.) confirms coherence and Askaryan effect

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

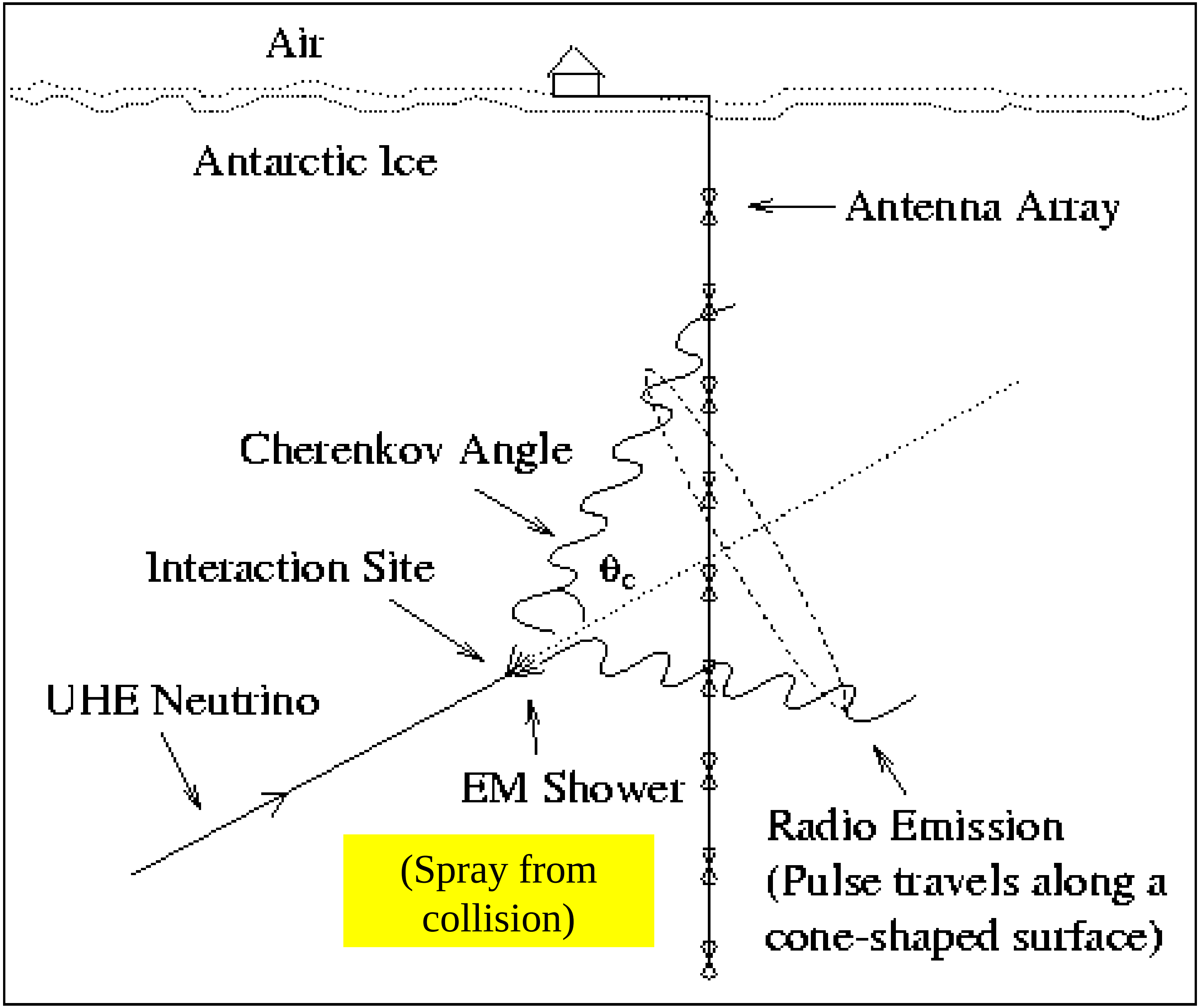
→ wavelengths shorter than the bunch length suffer from destructive interference



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

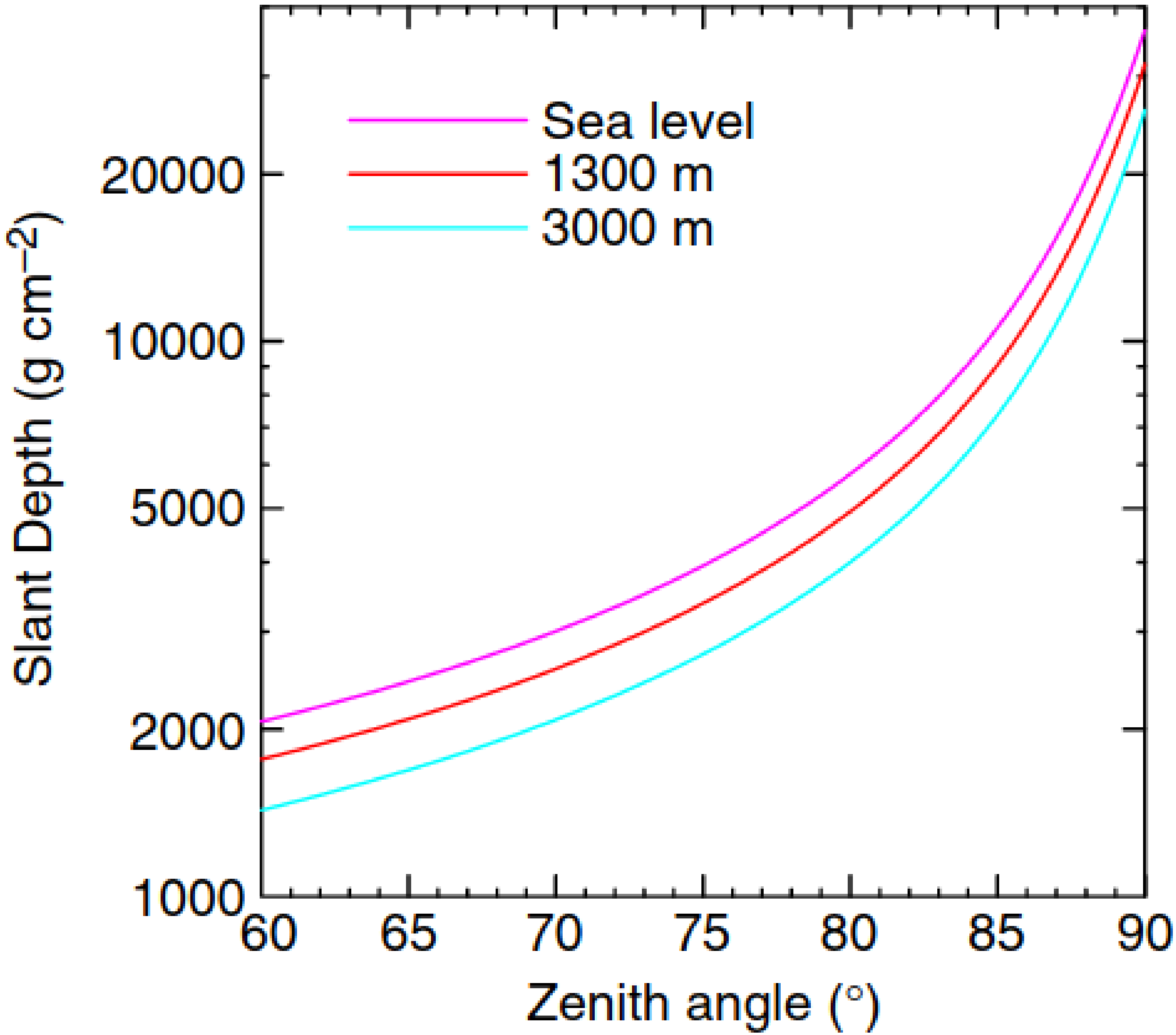
Experiments:

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-)

Neutrino-generated showers, and detection, in air and in-ice

Q: Estimate the thickness (g/cm^2) of a radio receiver looking horizontally from IITK

In-air grammage vs. slant-angle

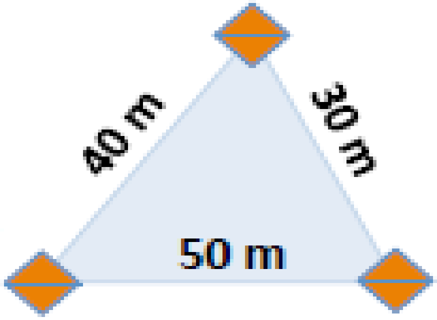


First work at Vostok

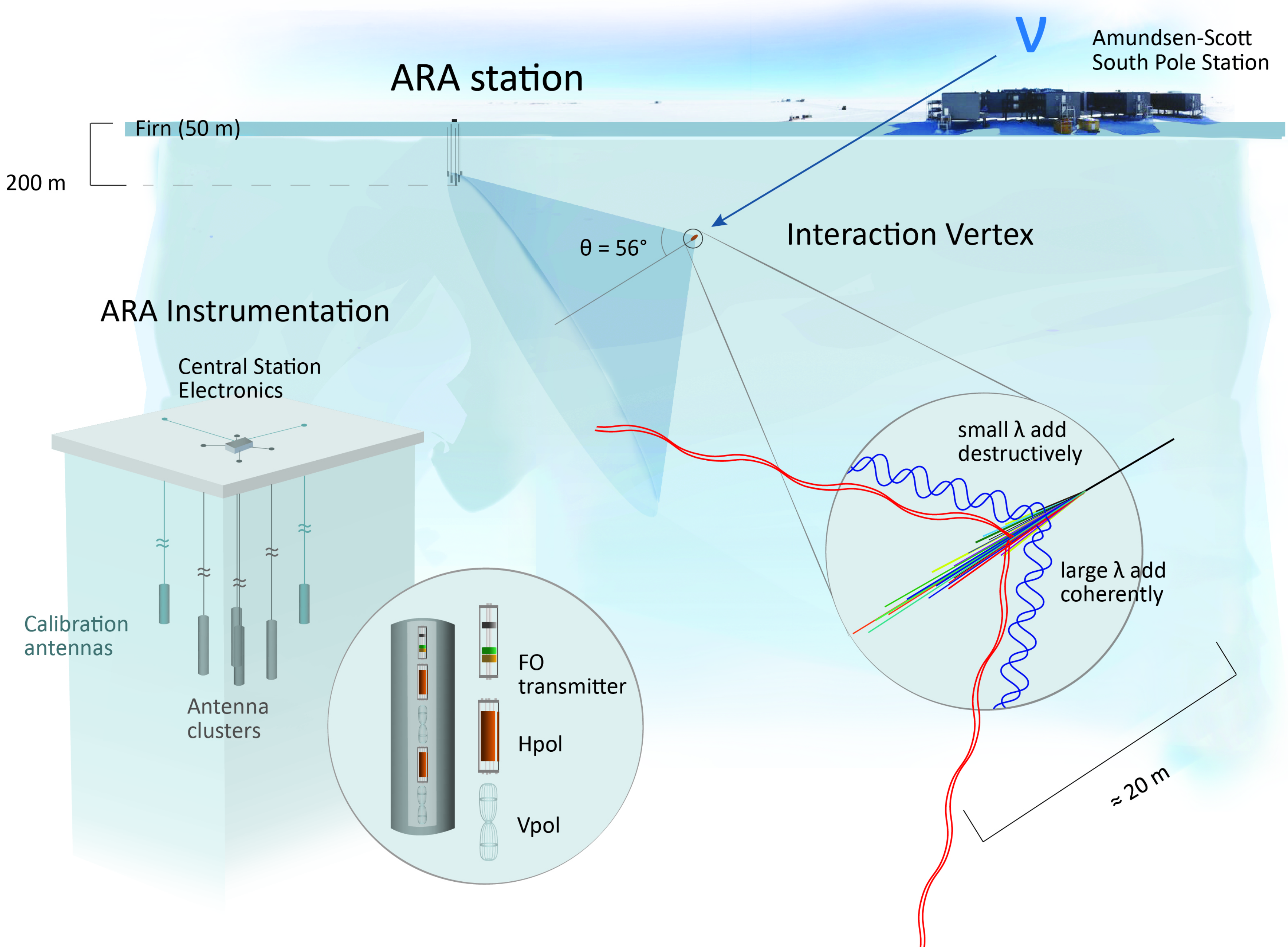
First background studies and Hydra

- 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.

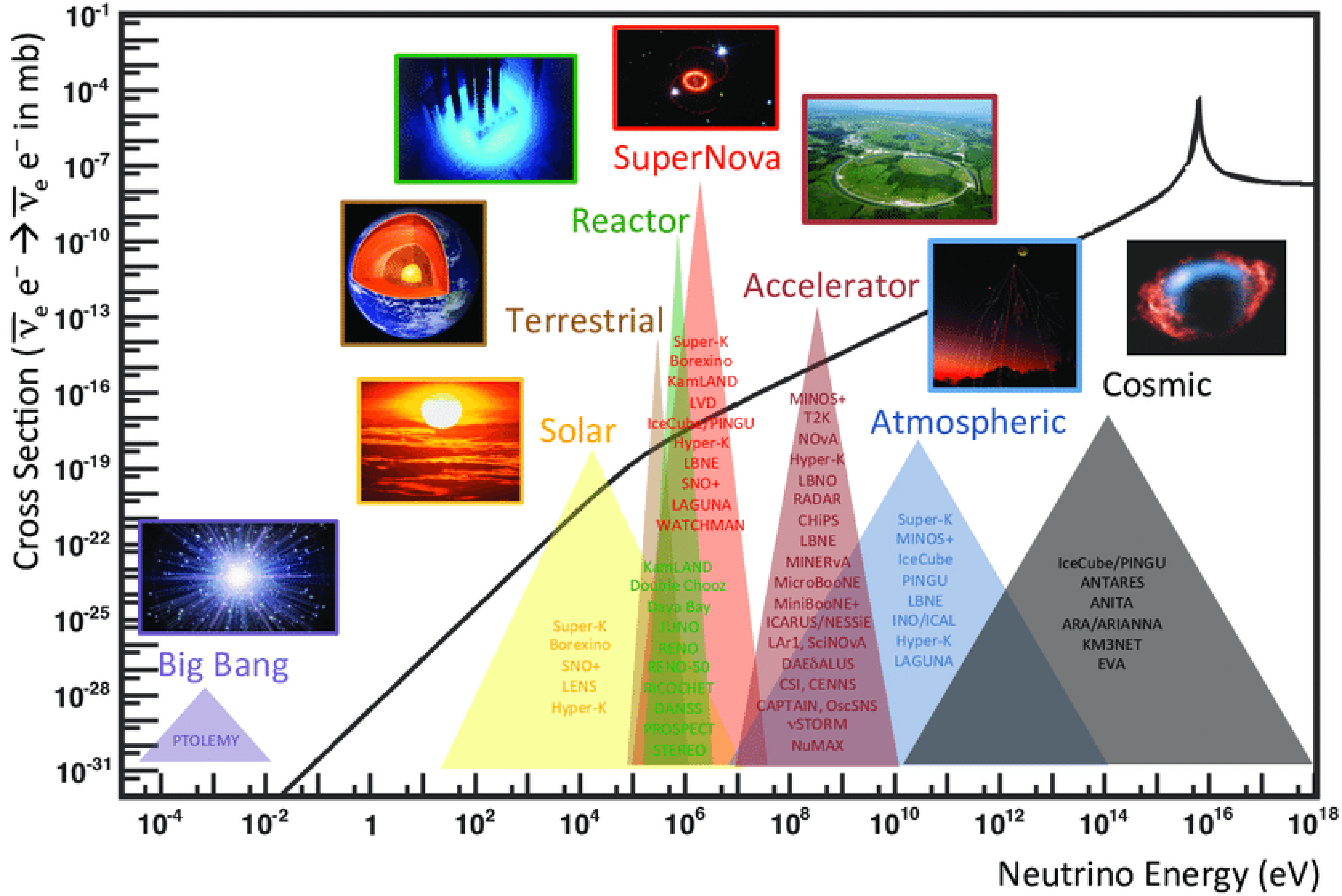


Detection of ultrahigh-energy neutrinos in ARA



Neutrino cross-sections (compare to p)

Q: From Prof. Jain's lecture, write a fomula for, and find the mfp of a Glashow resonance neutrino л in terms of the number density of targets N_e and the cross-section σ



Sources of neutrinos

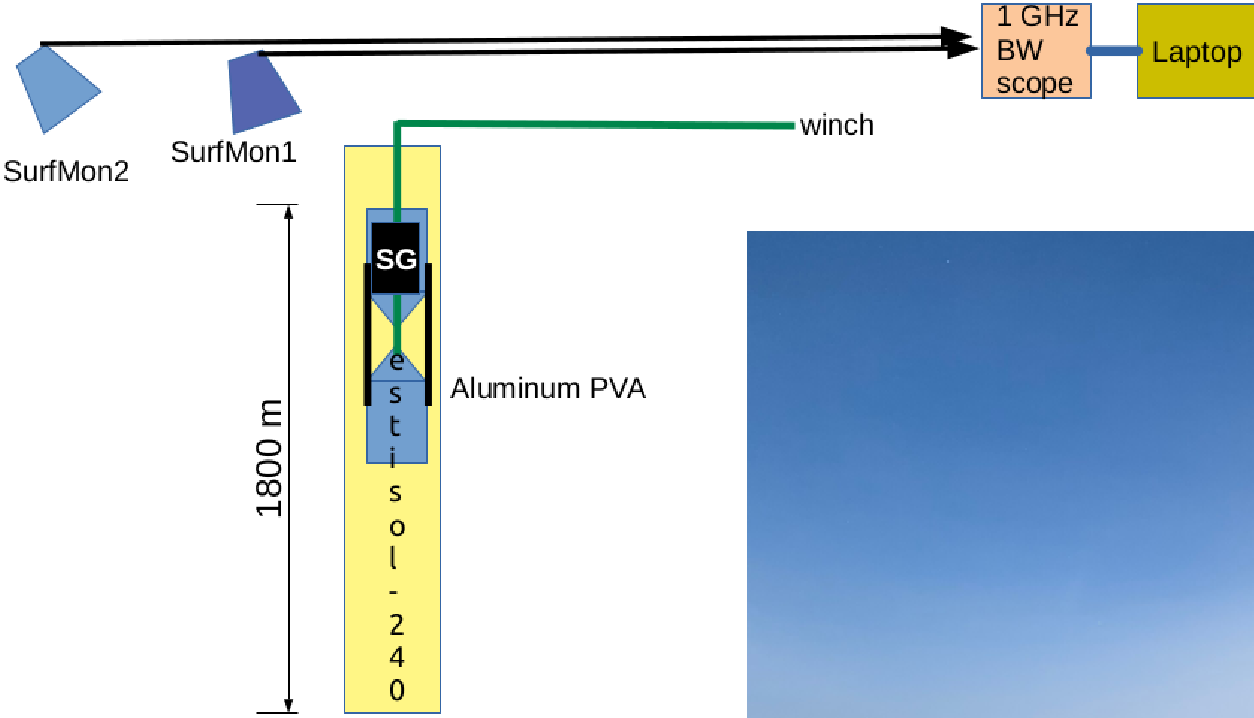
- "Low energy" - Big Bang Neutrinos (BBN), 300 per cubic centimeter, 13 billion years old. E~.001 eV
- "Medium energy" - Solar neutrinos, 60 billion per thumb per second.
  - On average, only one will be stopped by biomass per lifetime.
    - Aside: ^{40}K neutrinos in salt=>each person emits 200 million neutrinos per day
- "High energy" - Supernova neutrinos, 10^{15} eV, 1/m^2/sec
- Cosmogenic peaks at ~$10^{17.6}$ eV

Radio properties of the target (=propagation) medium dictate sensitivity of a neutrino-detection experiment!

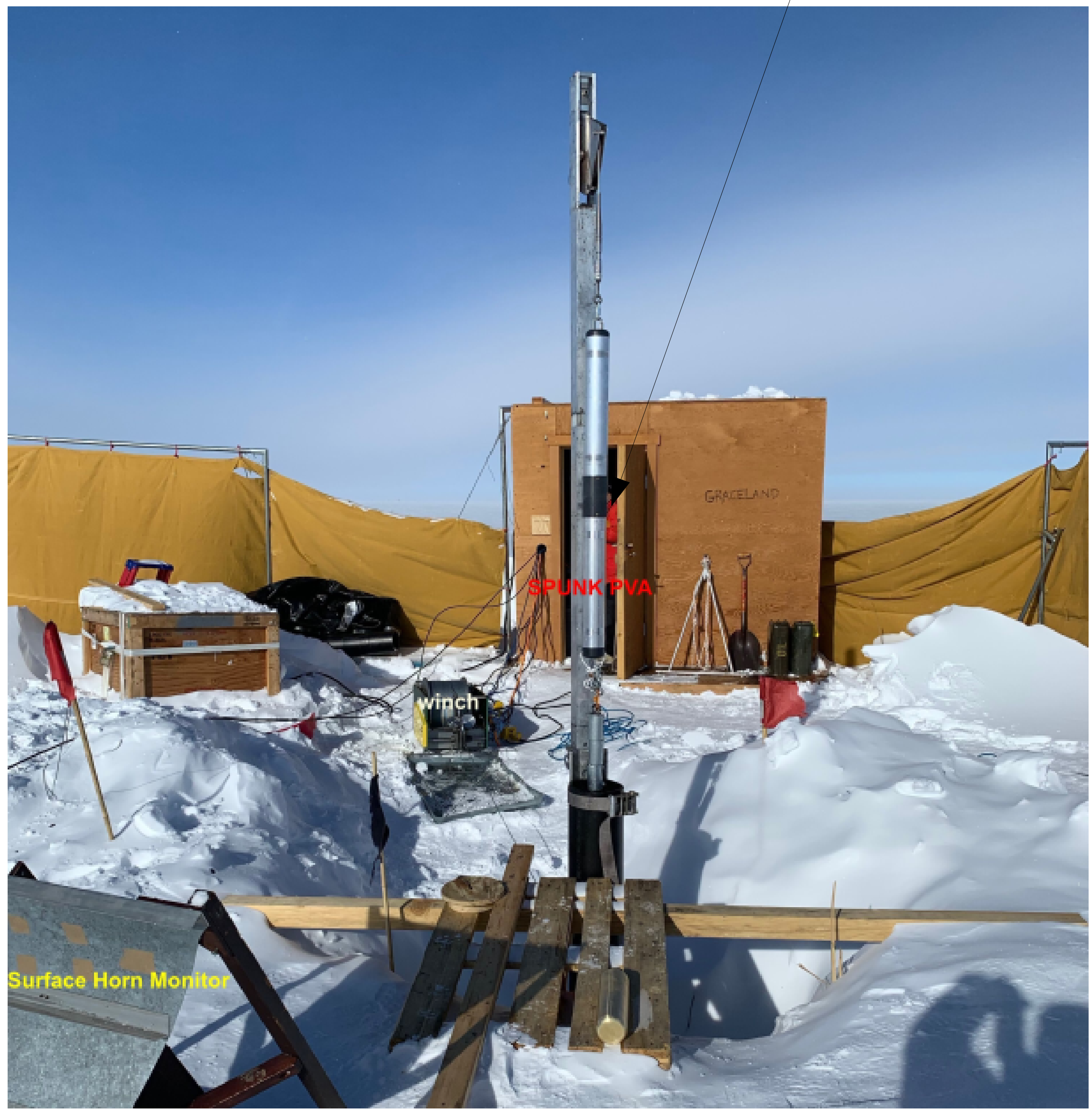
What do we know about the RF properties of cold polar ice, e.g.?

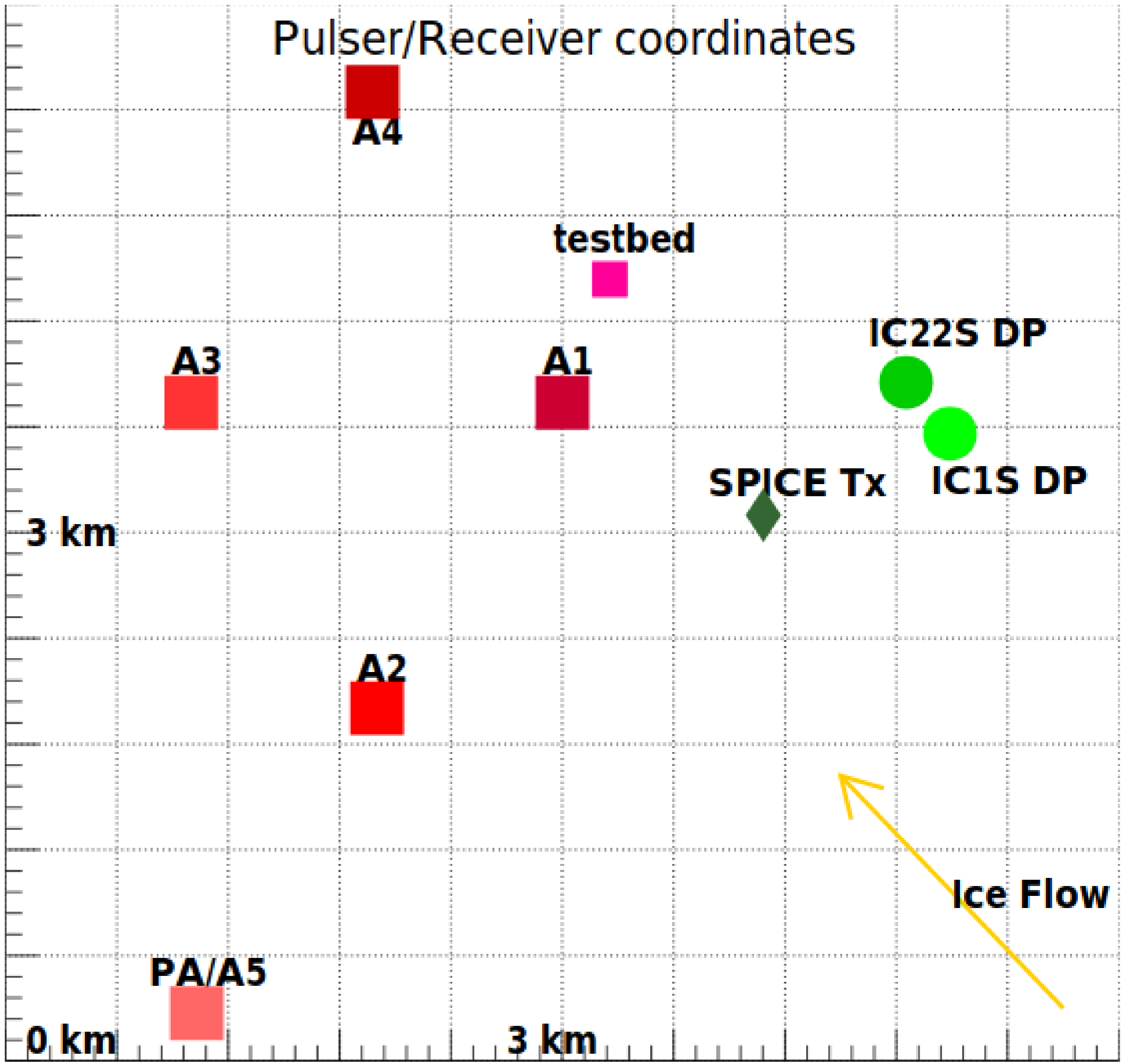
Low temperature environment testing in Lawrence, KS

the Checkers supermarket vegetable freezer



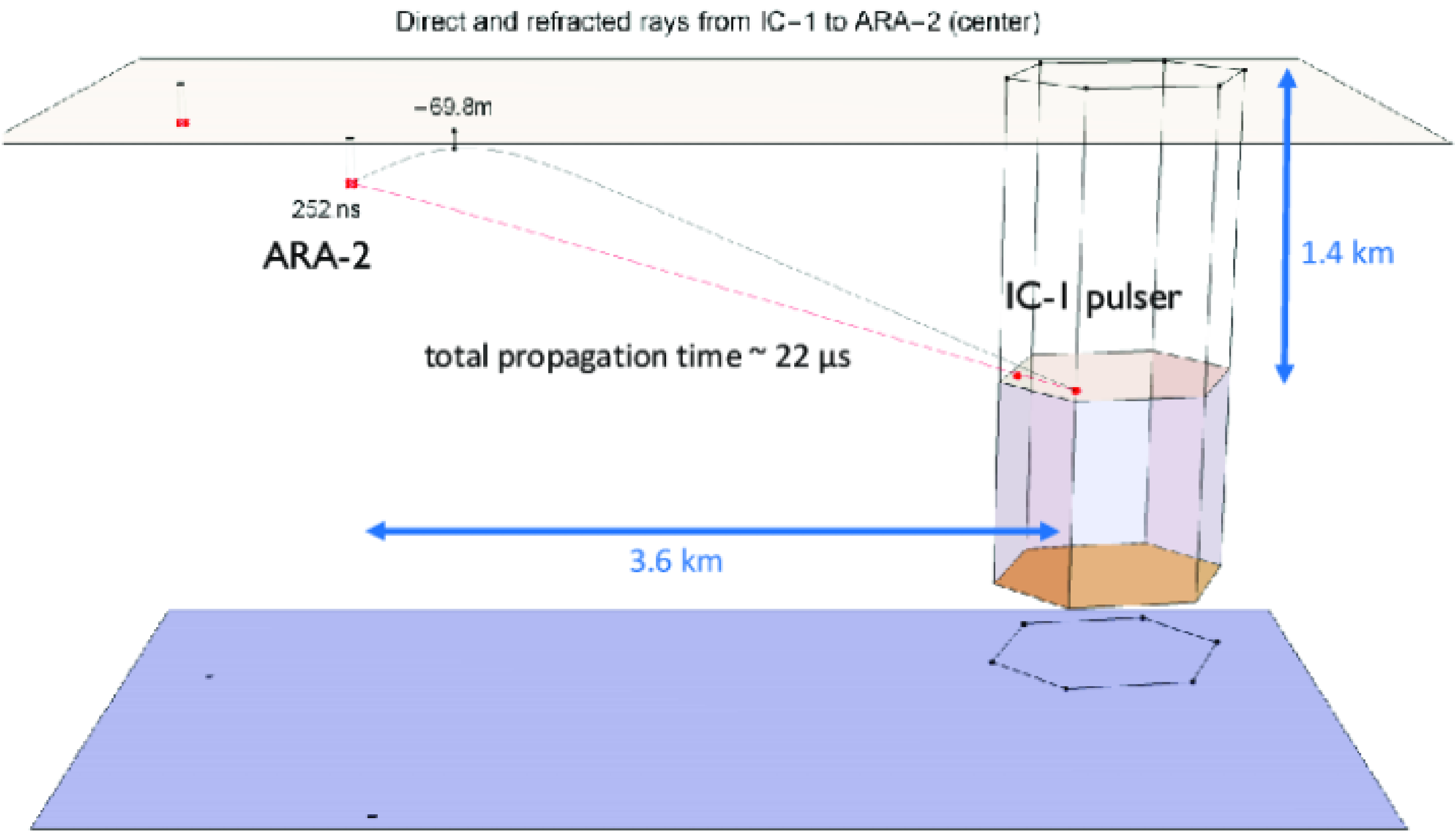
SPICE core testing (Dec., 2018)



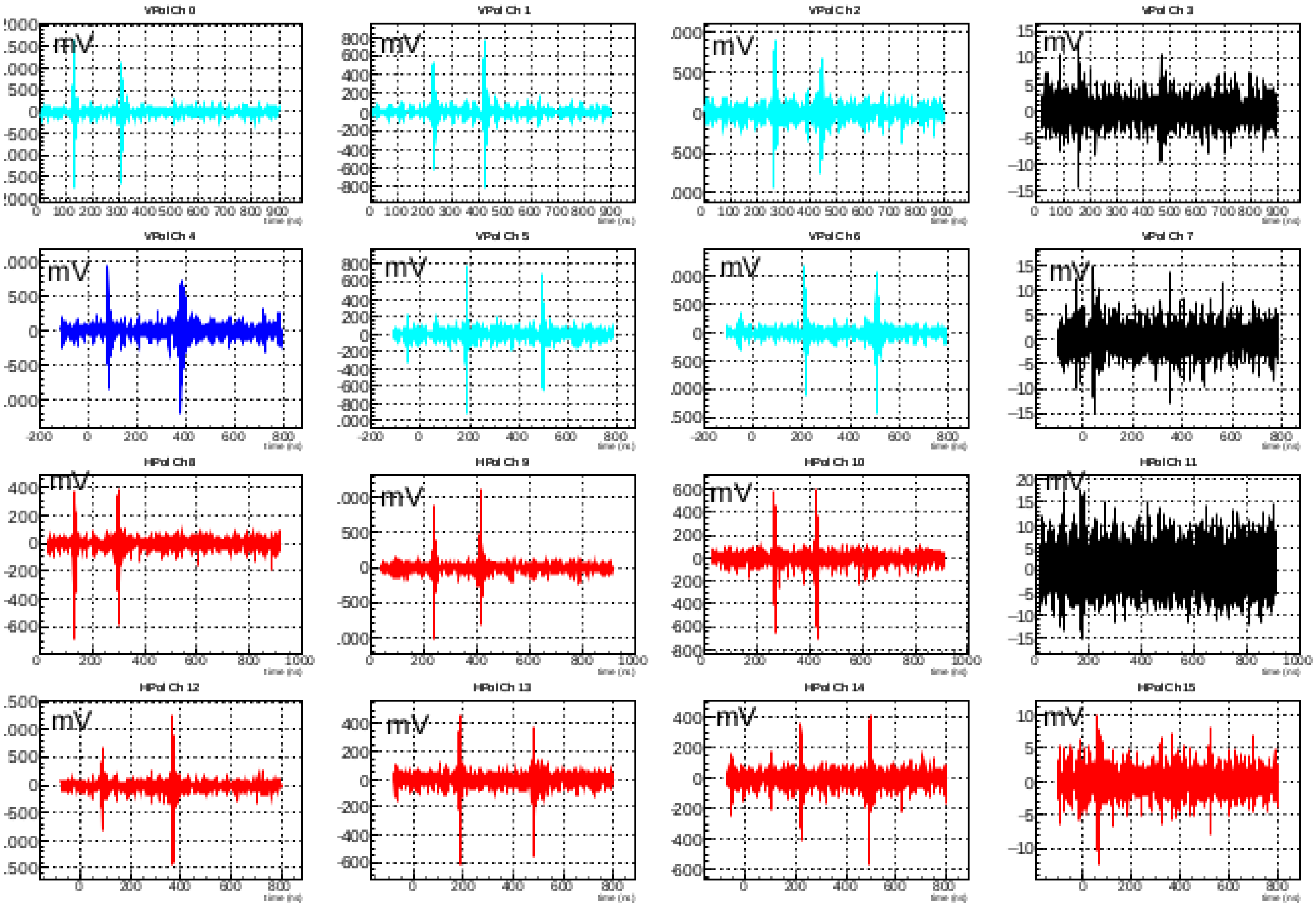


Pulser/Receiver coordinates
A4
testbed
A3
A1
IC22S DP
IC1S DP
SPICE Tx
3 km
A2
Ice Flow
PA/A5
0 km
3 km

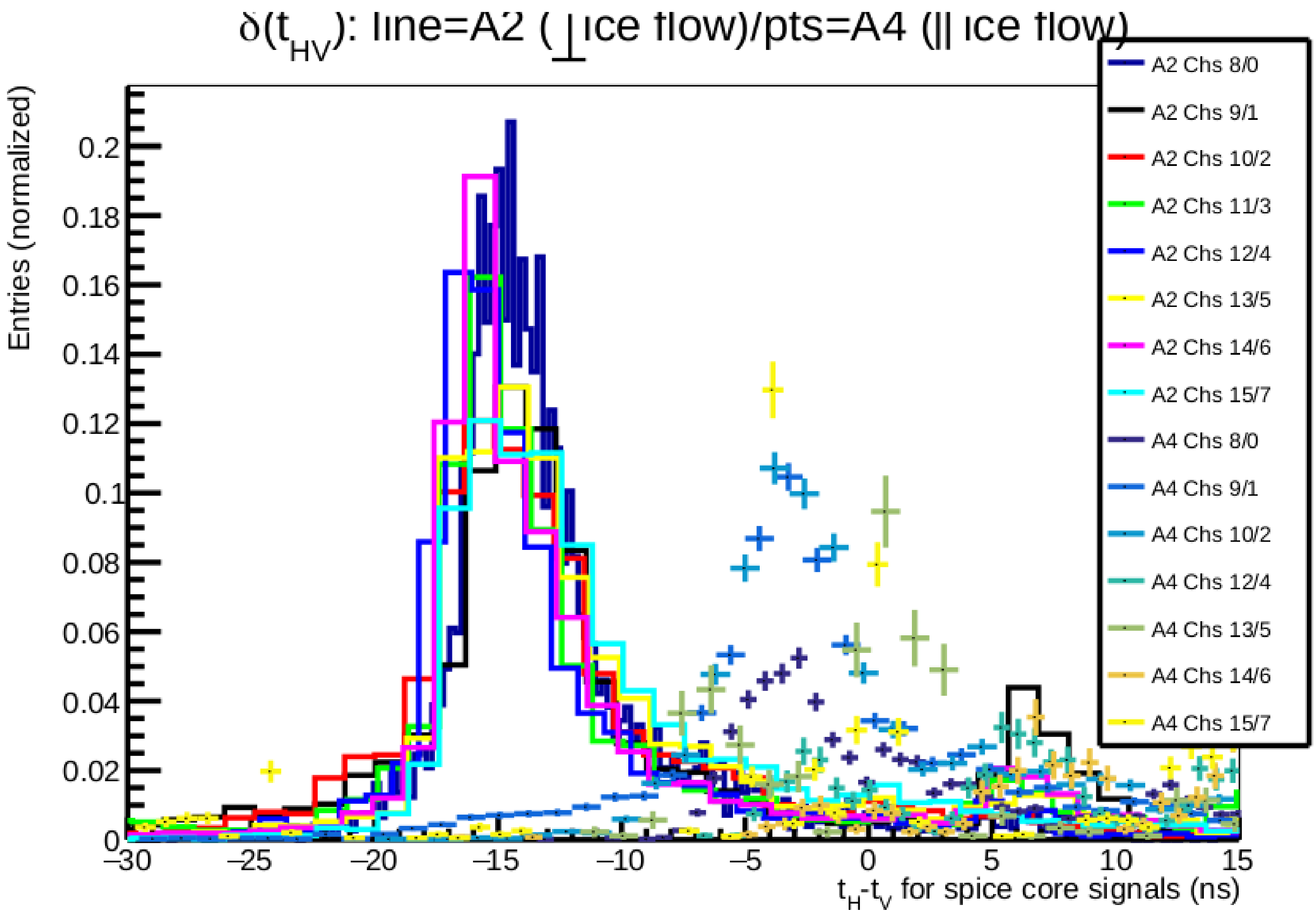
Graded index of refraction, Fermat's principle, Huygens construction, Feynman diagrams, shadow zones, and n(z)



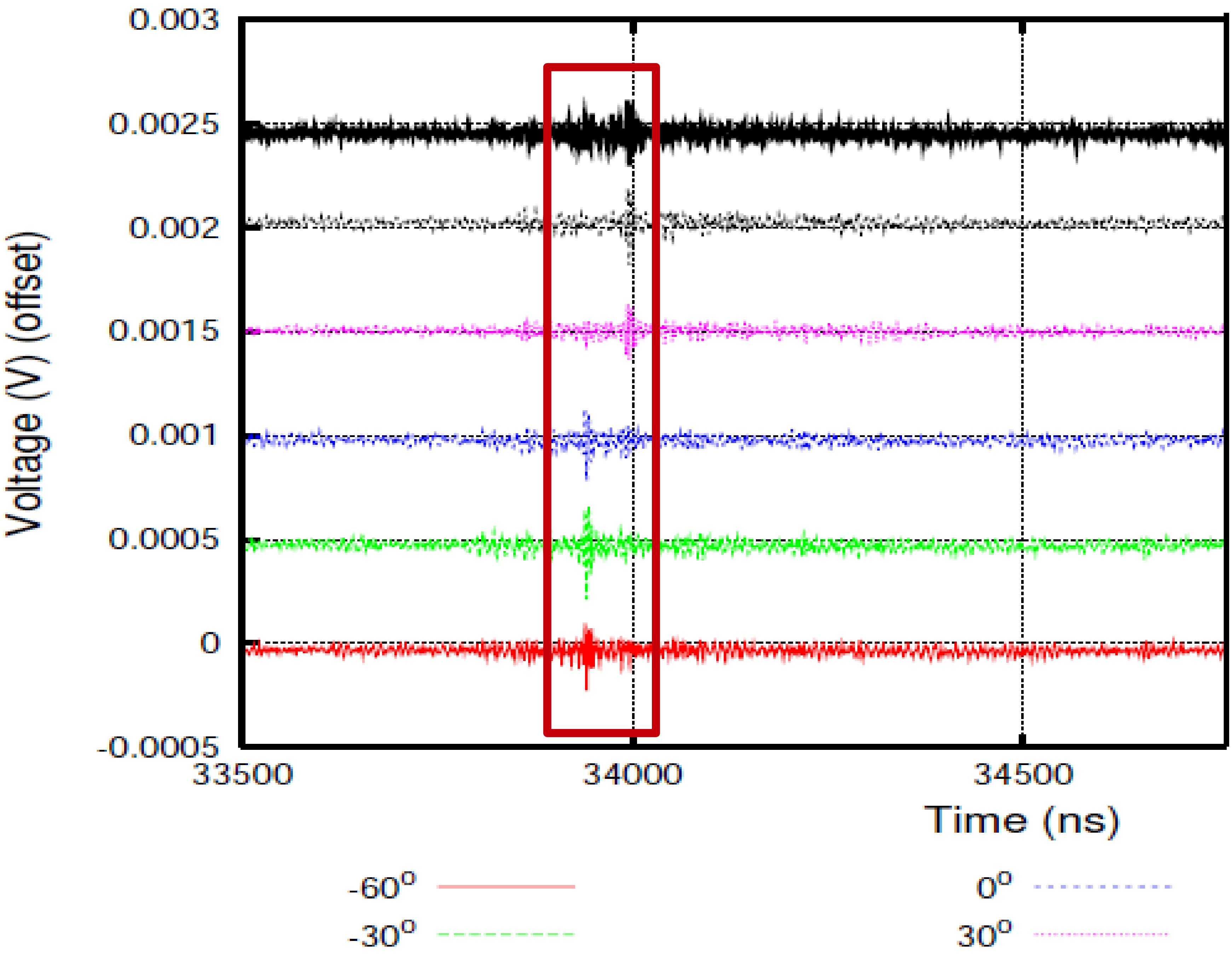
Double pulses and refraction – SPICE core data (Dec., 2018)



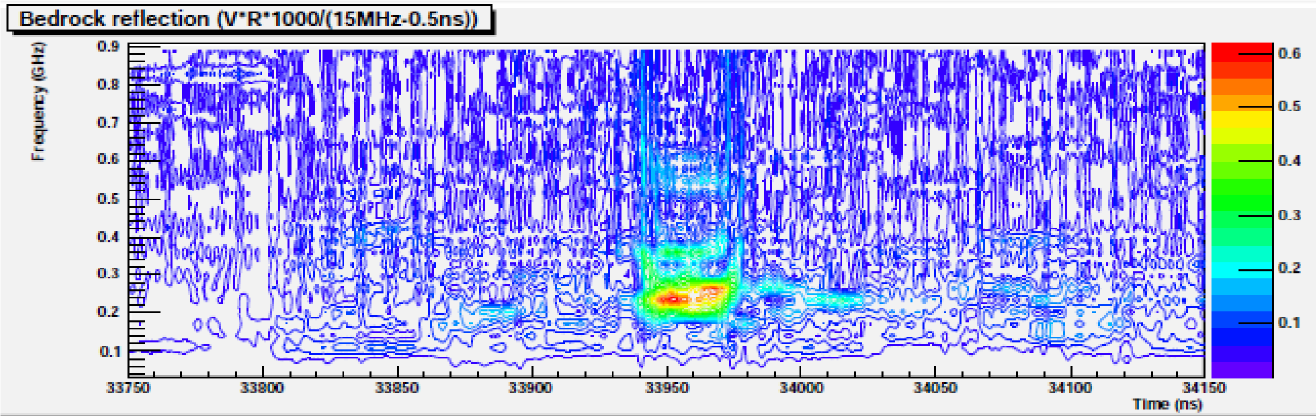
Birefringence! (Estimate n_o-n_e)

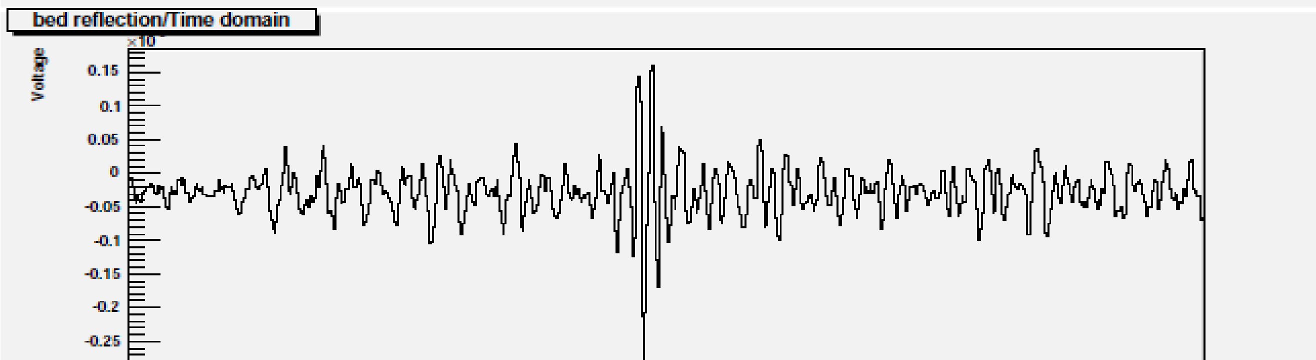


Data on ice birefringence V(polarization)



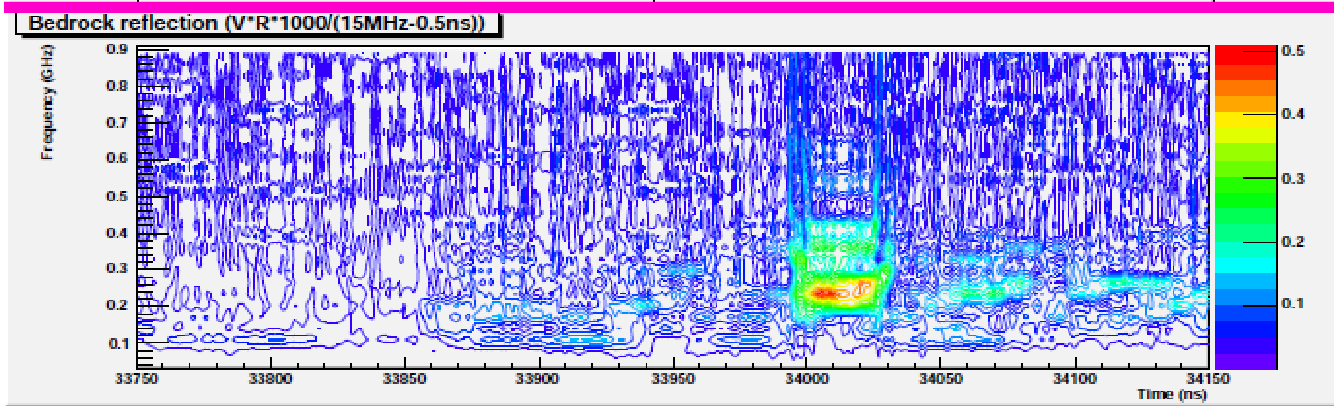
Can also derive attenuation length from this graph

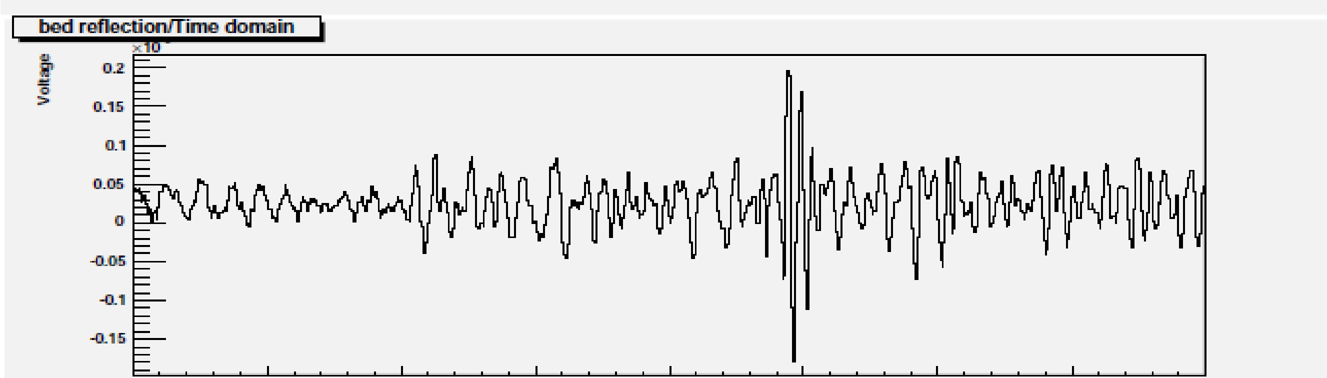




Parallel to ice-flow direction

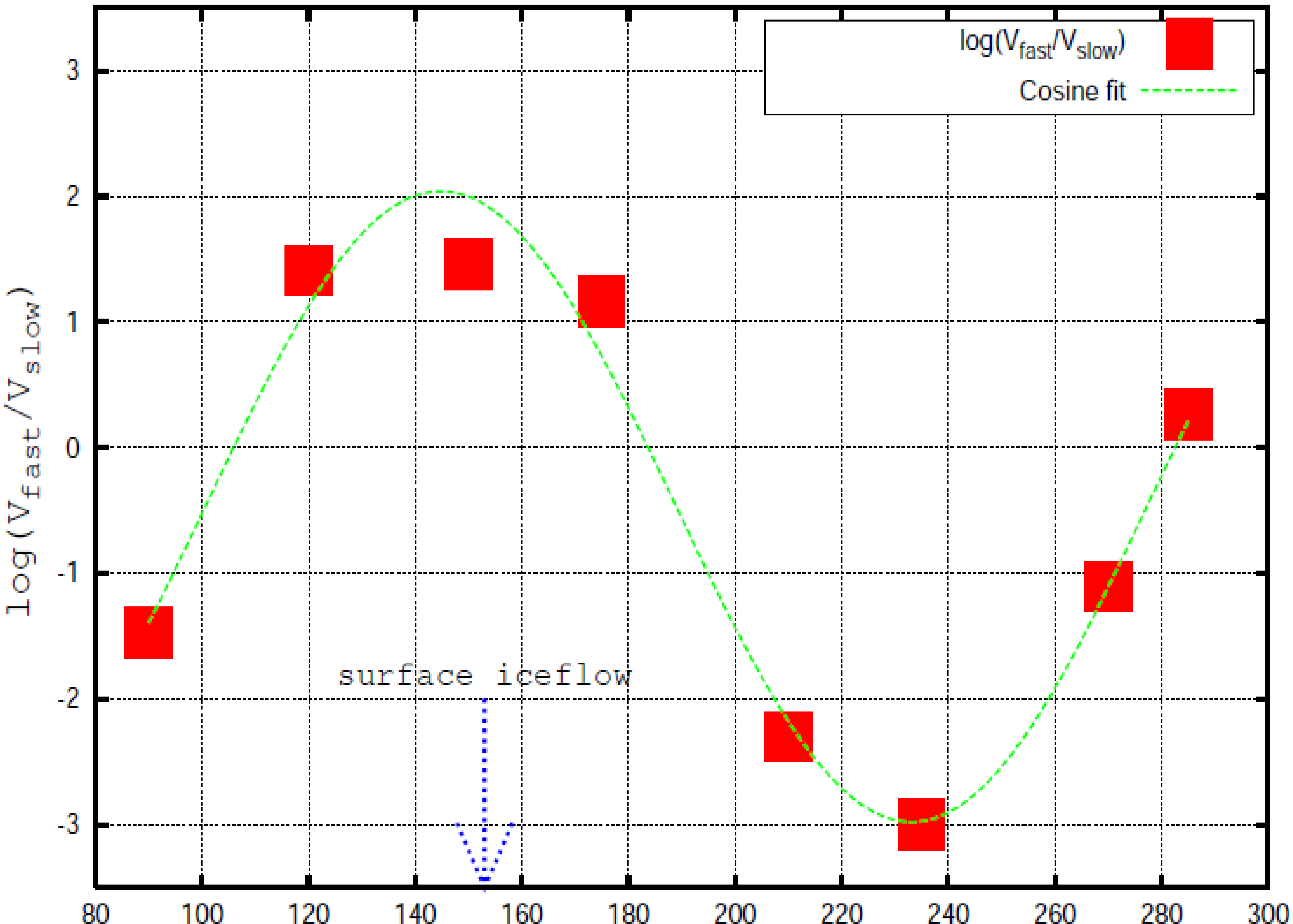
Predict the shape of A(φ)



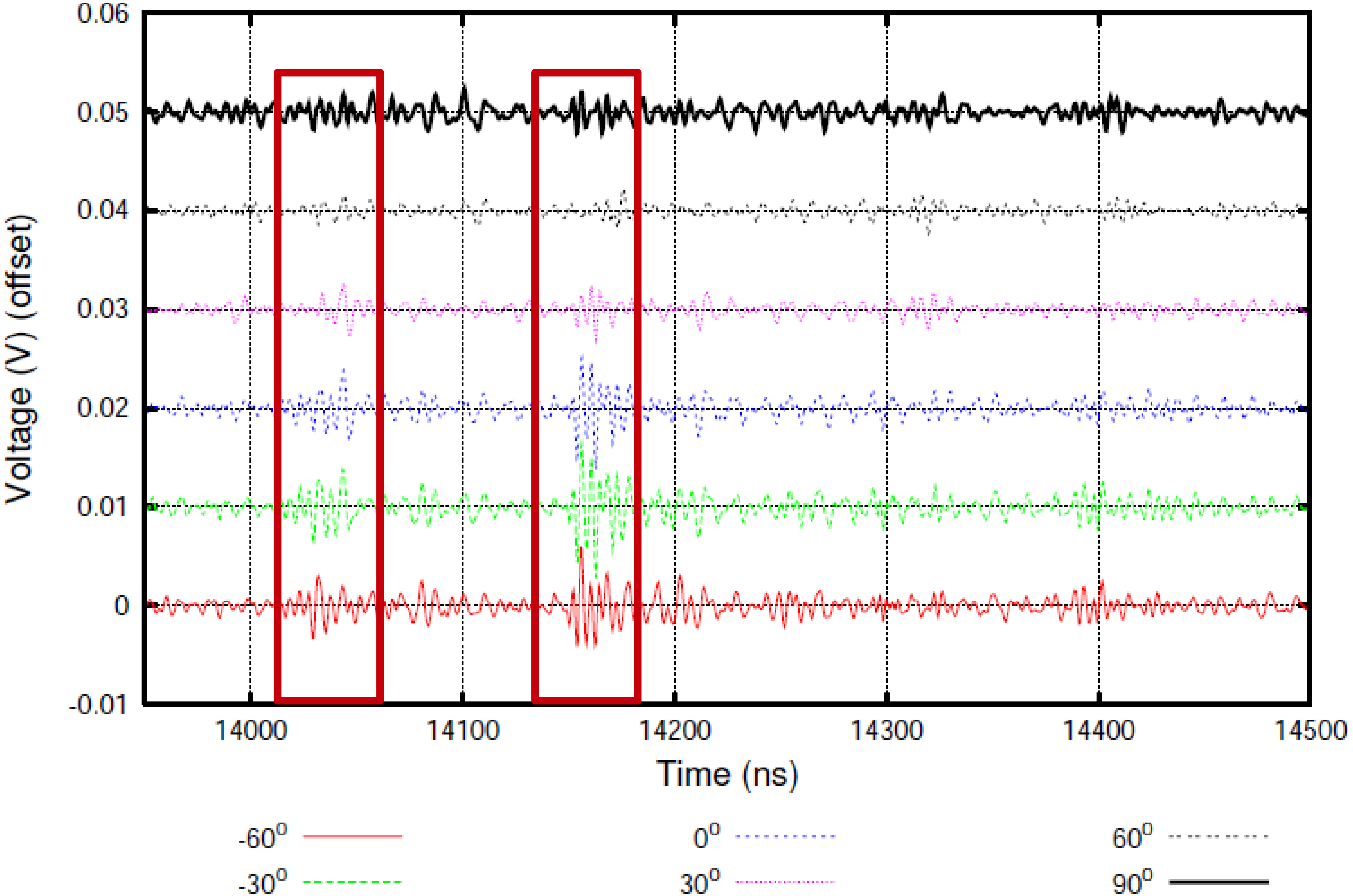


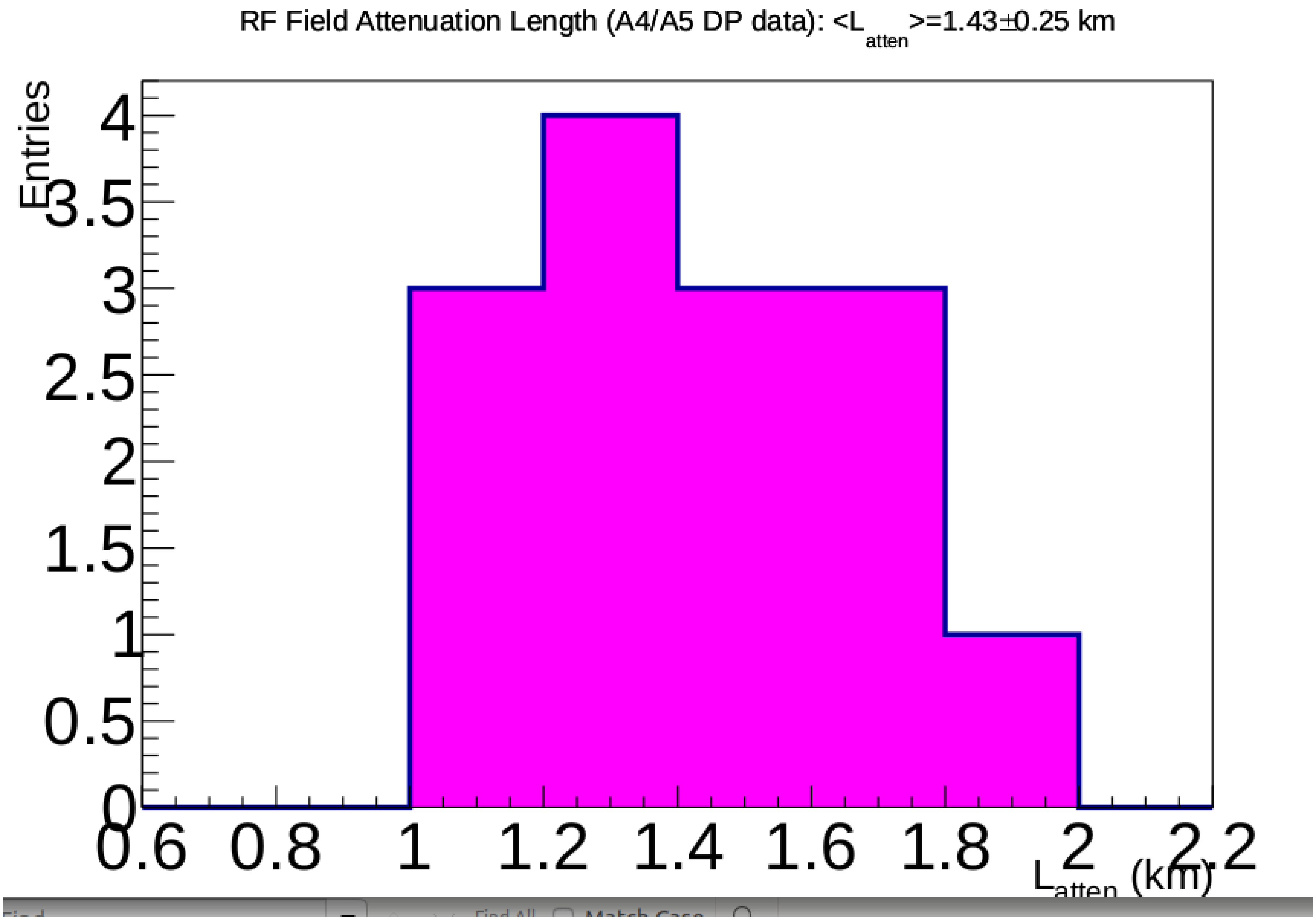
Perpendicular to ice-flow direction

Ratio of V(fast)/V(slow)



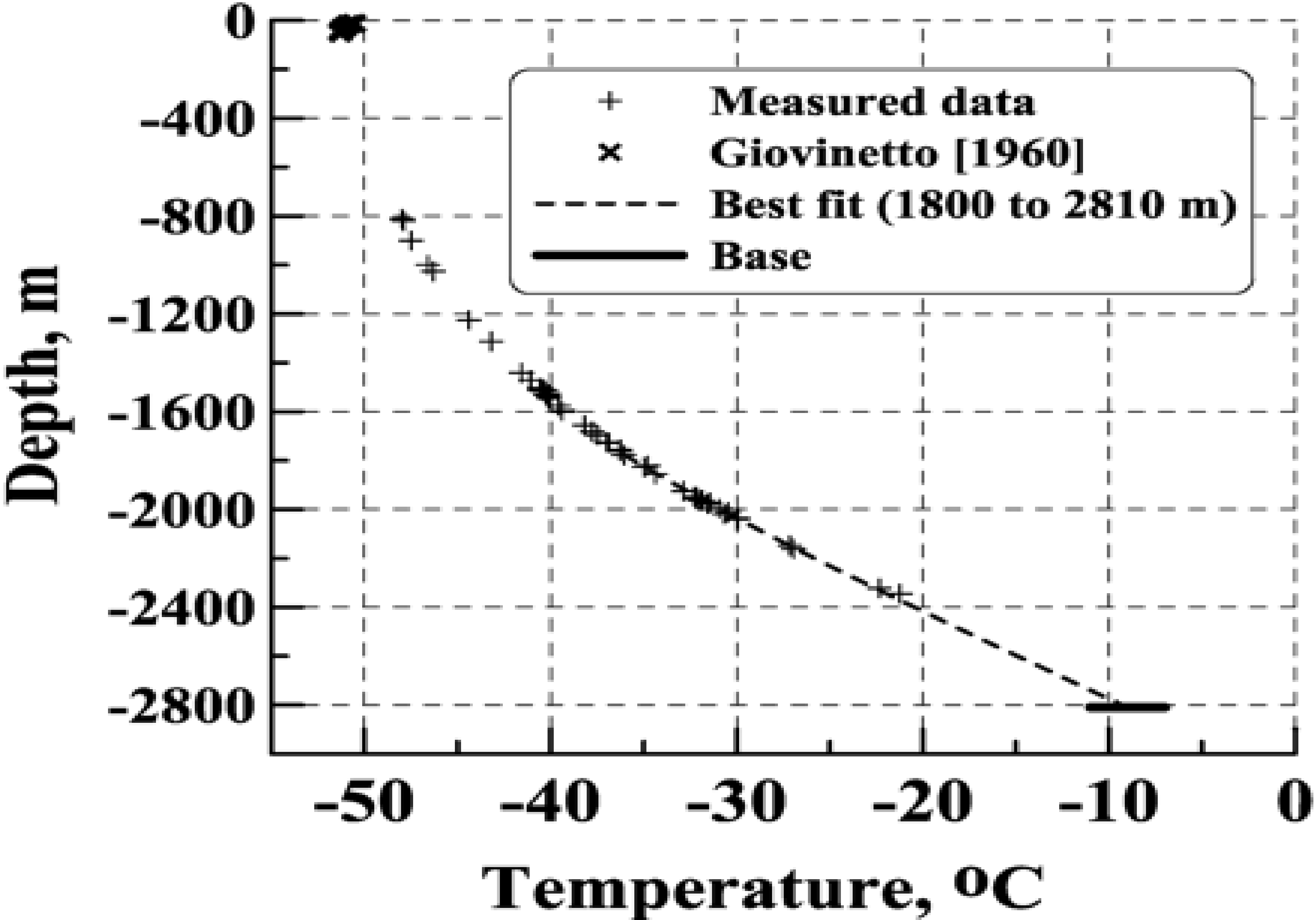
All polarizations synchronous to 1.3 km (internal layer reflections)



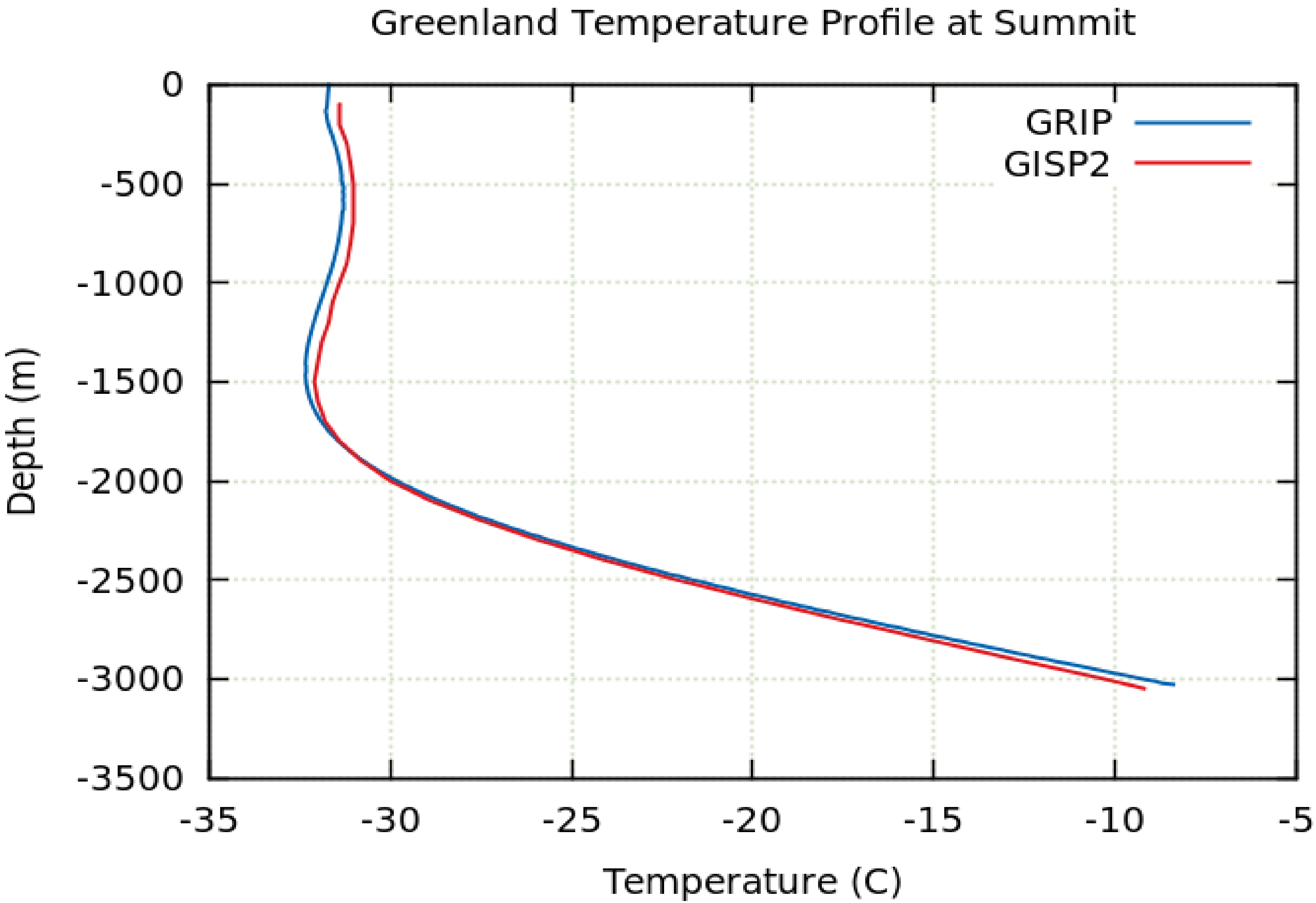


N.B. Shadow Zone effective attenuation length ~ 500 m

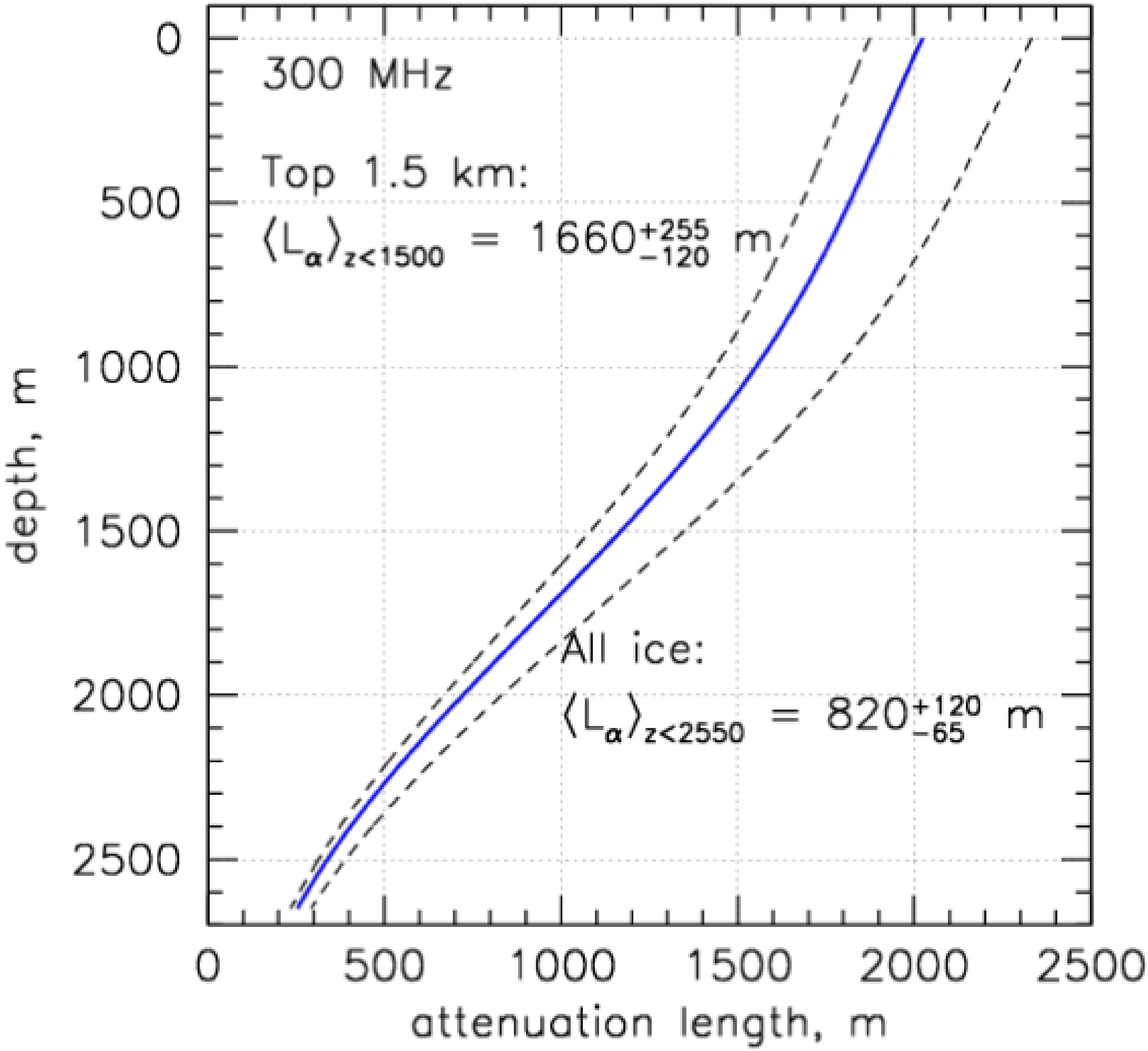
SP Temperature Profile (affects $L_{int}(z)$)



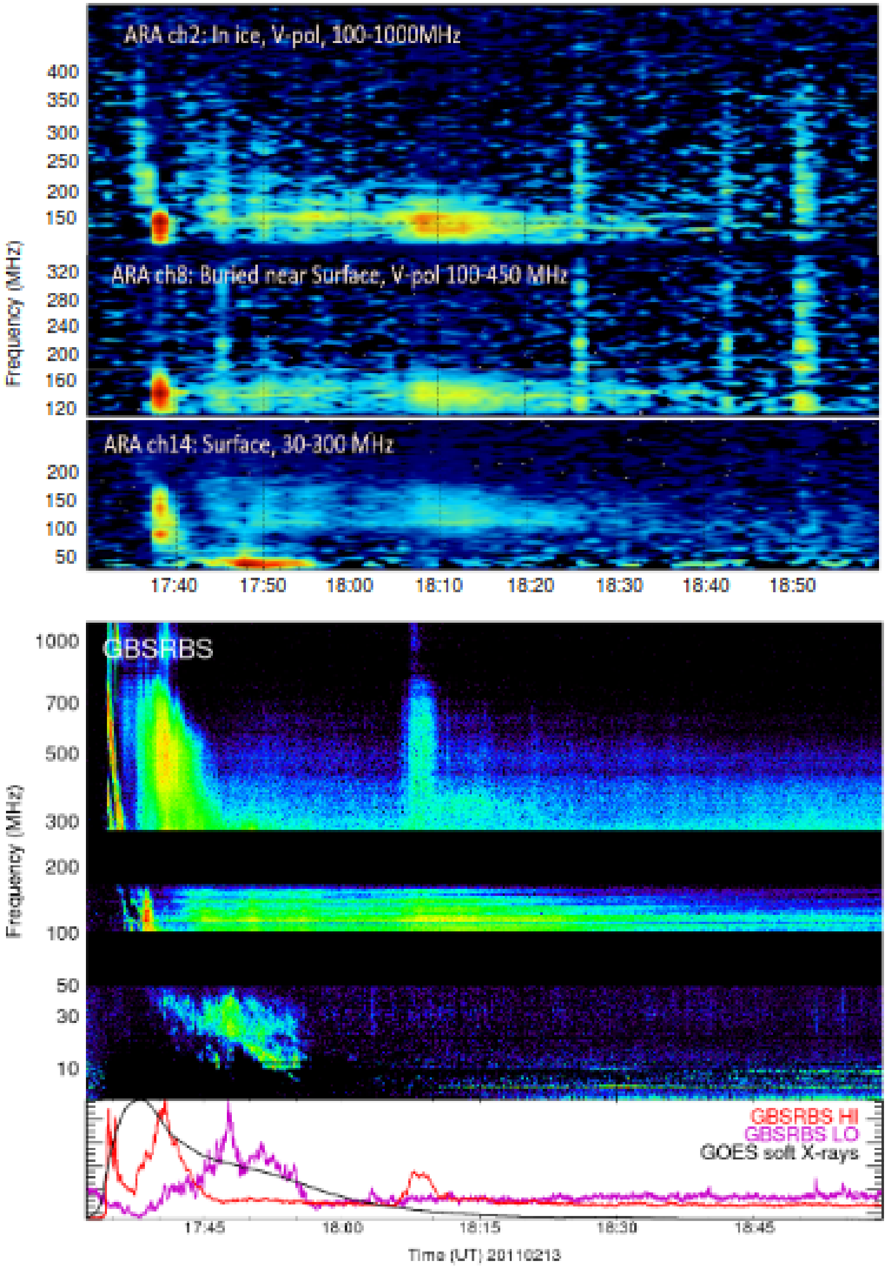
Greenland T(z)



Attenuation length as f(depth)

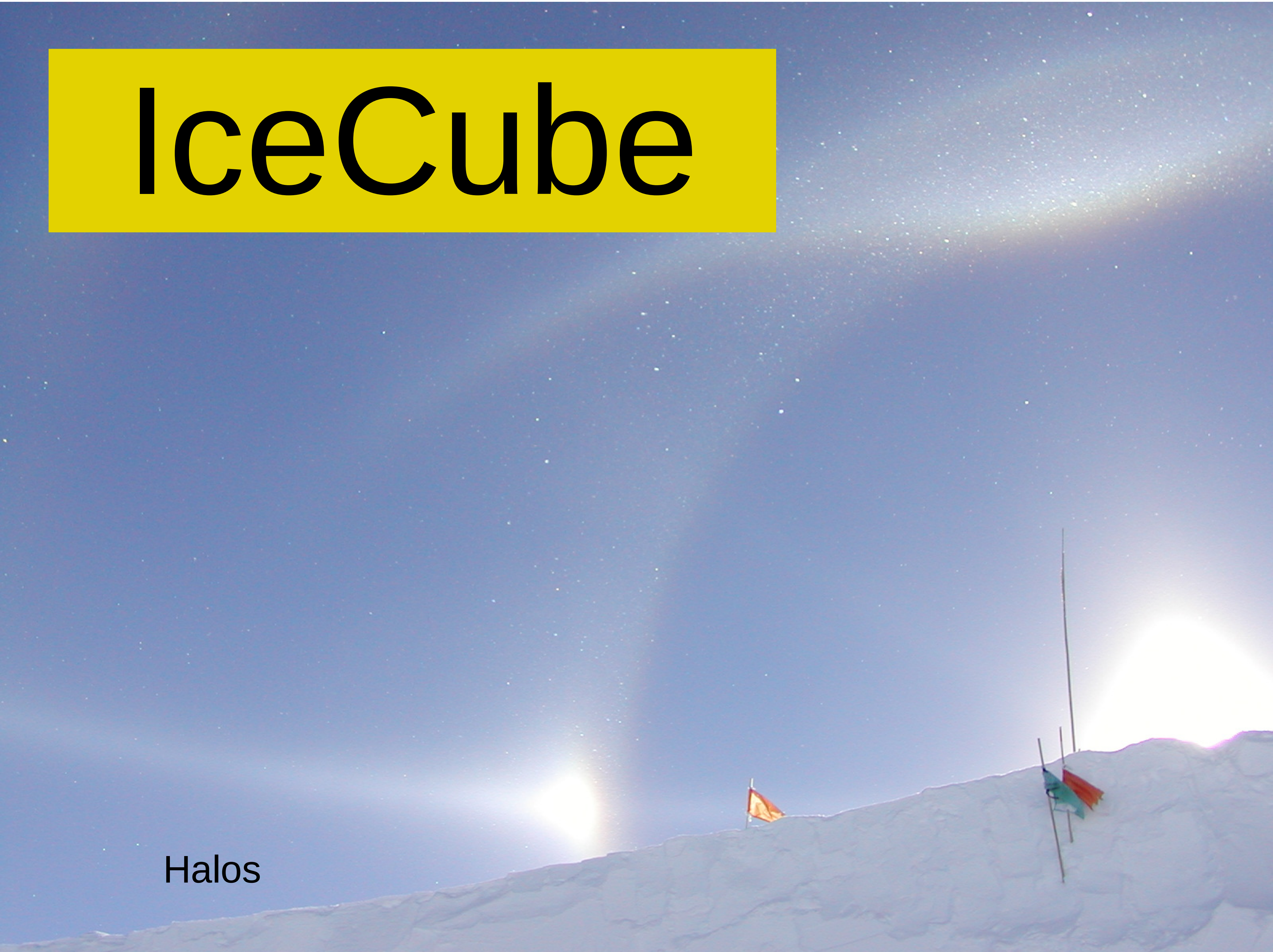


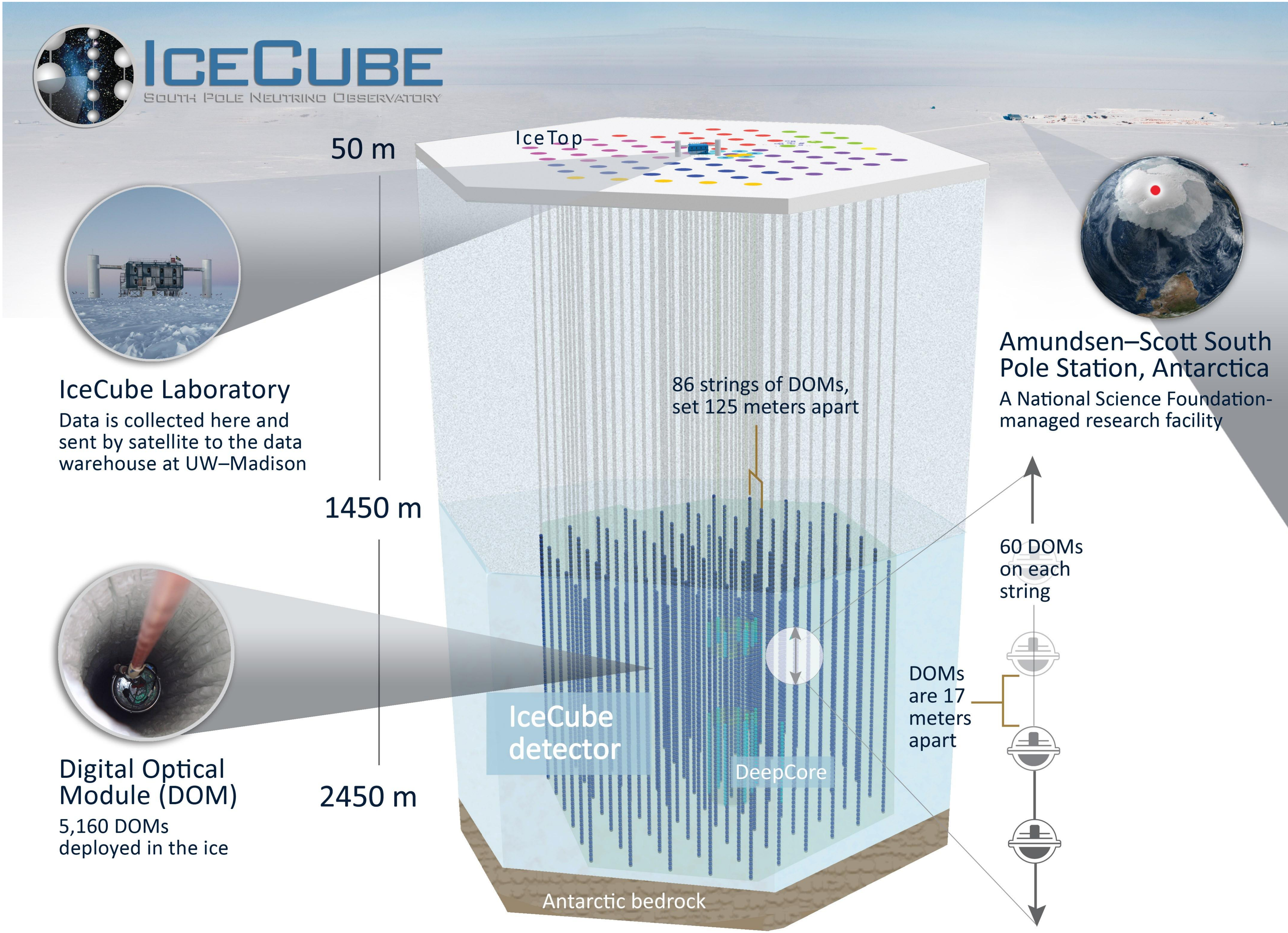
Sensitive to radio portion of solar flares



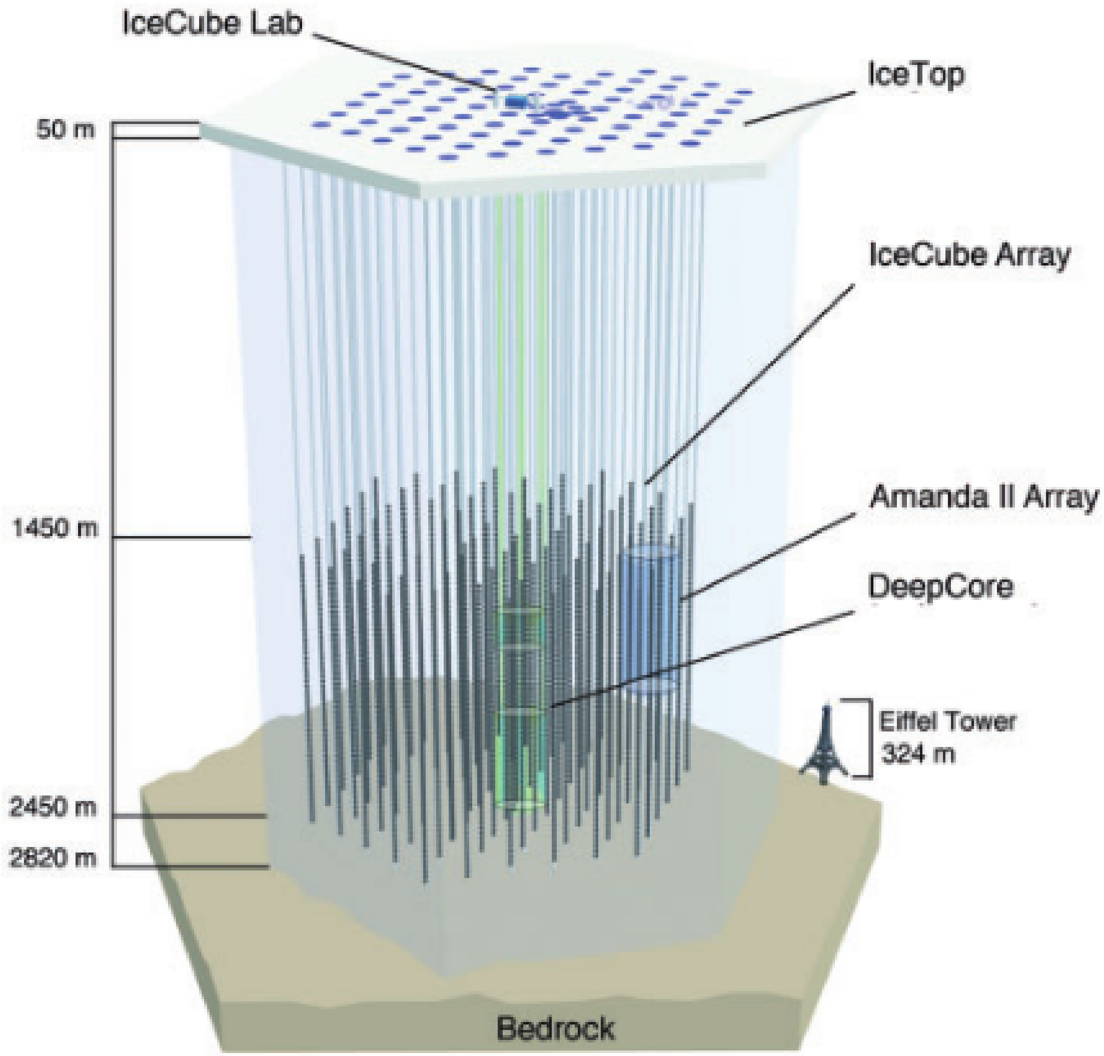
IG. 15: Solar radio burst of Feb. 13, 2011 as observed by ARA

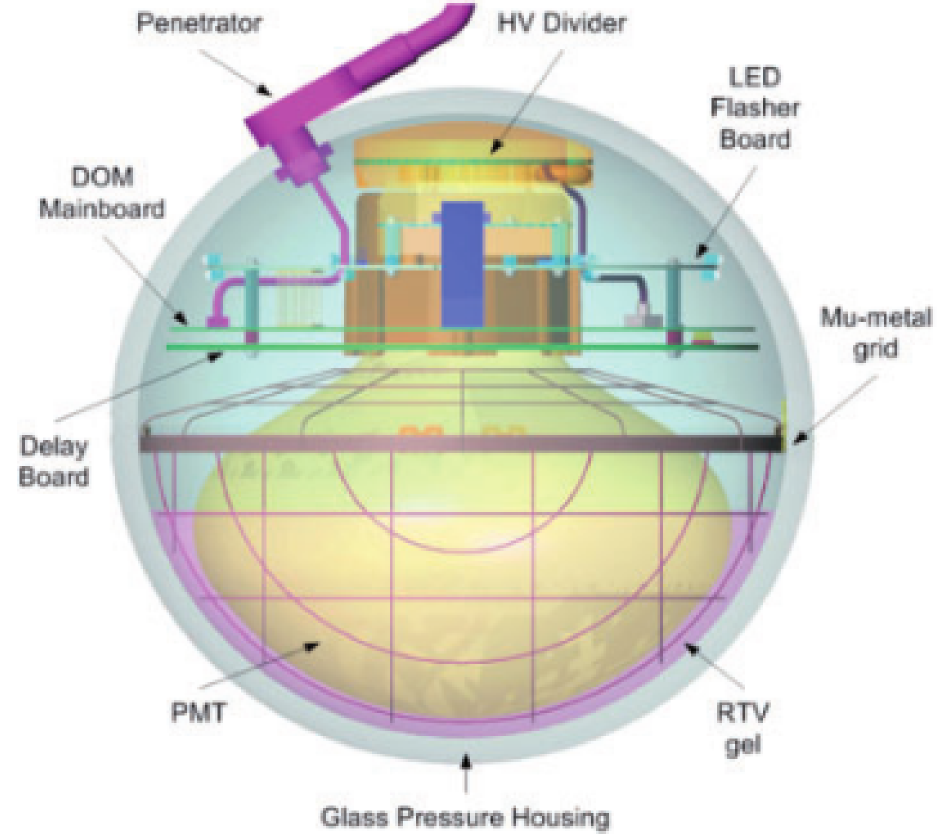
IceCube




ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

DOMs=Digital Optical Module

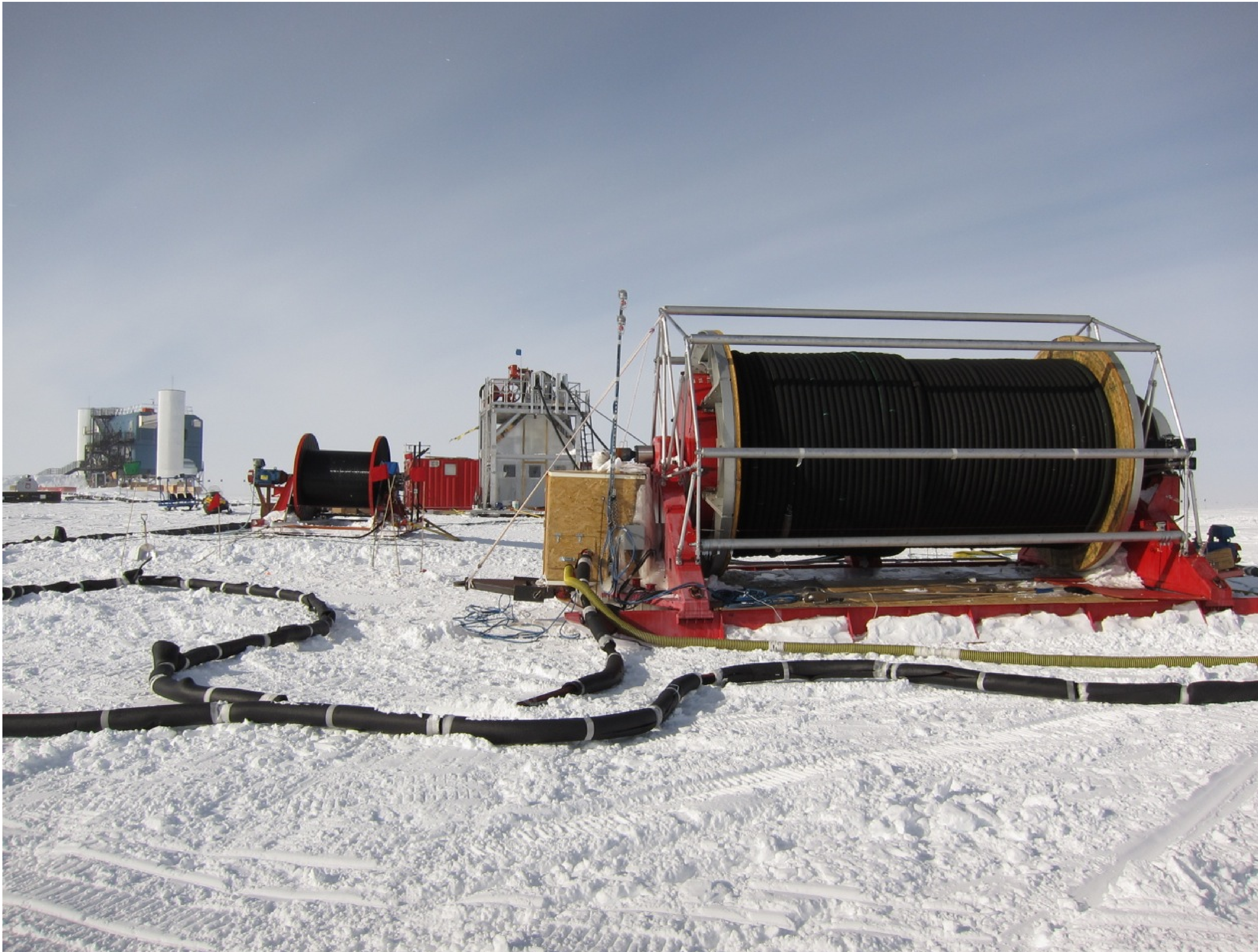


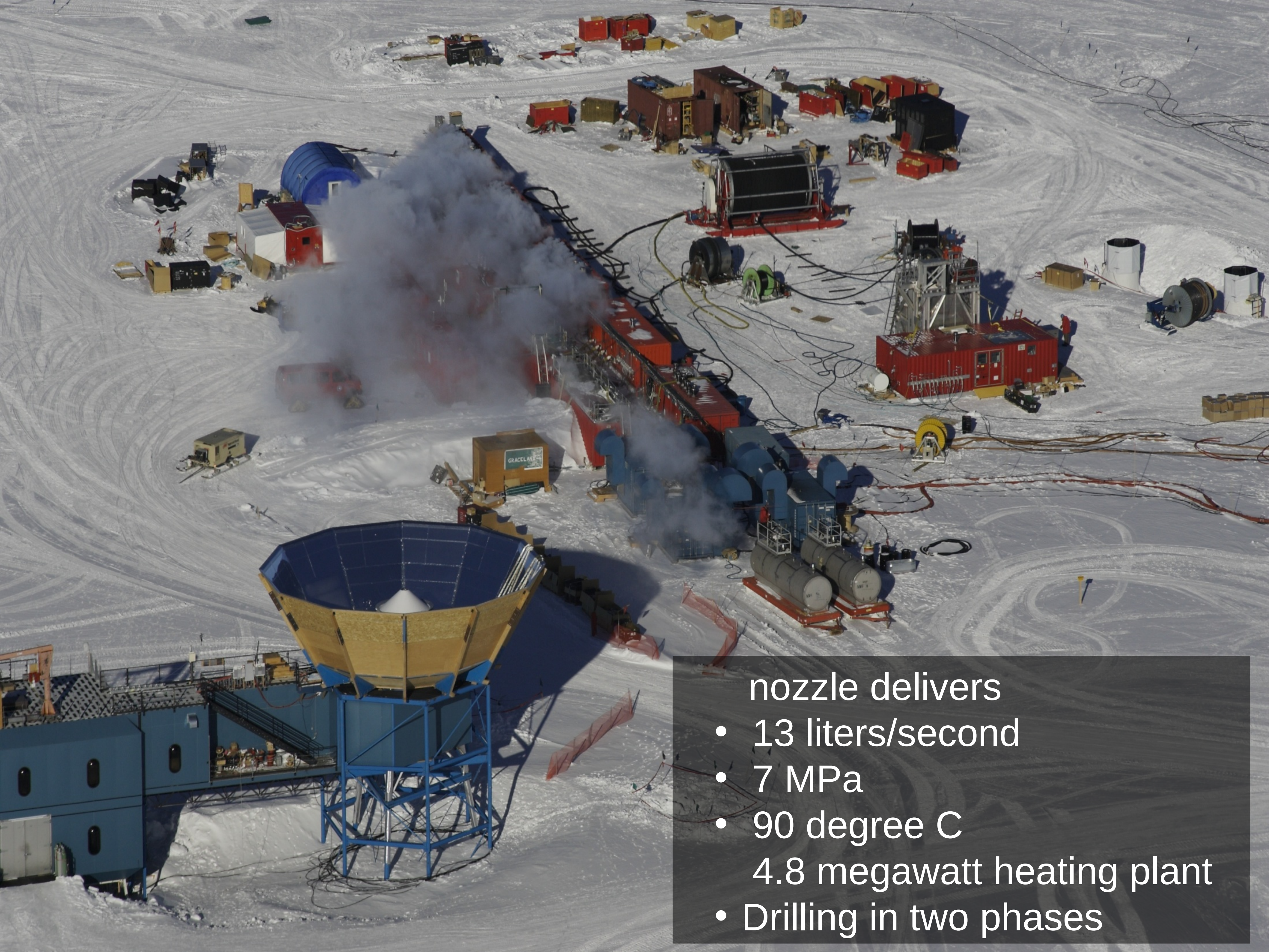


Arrival

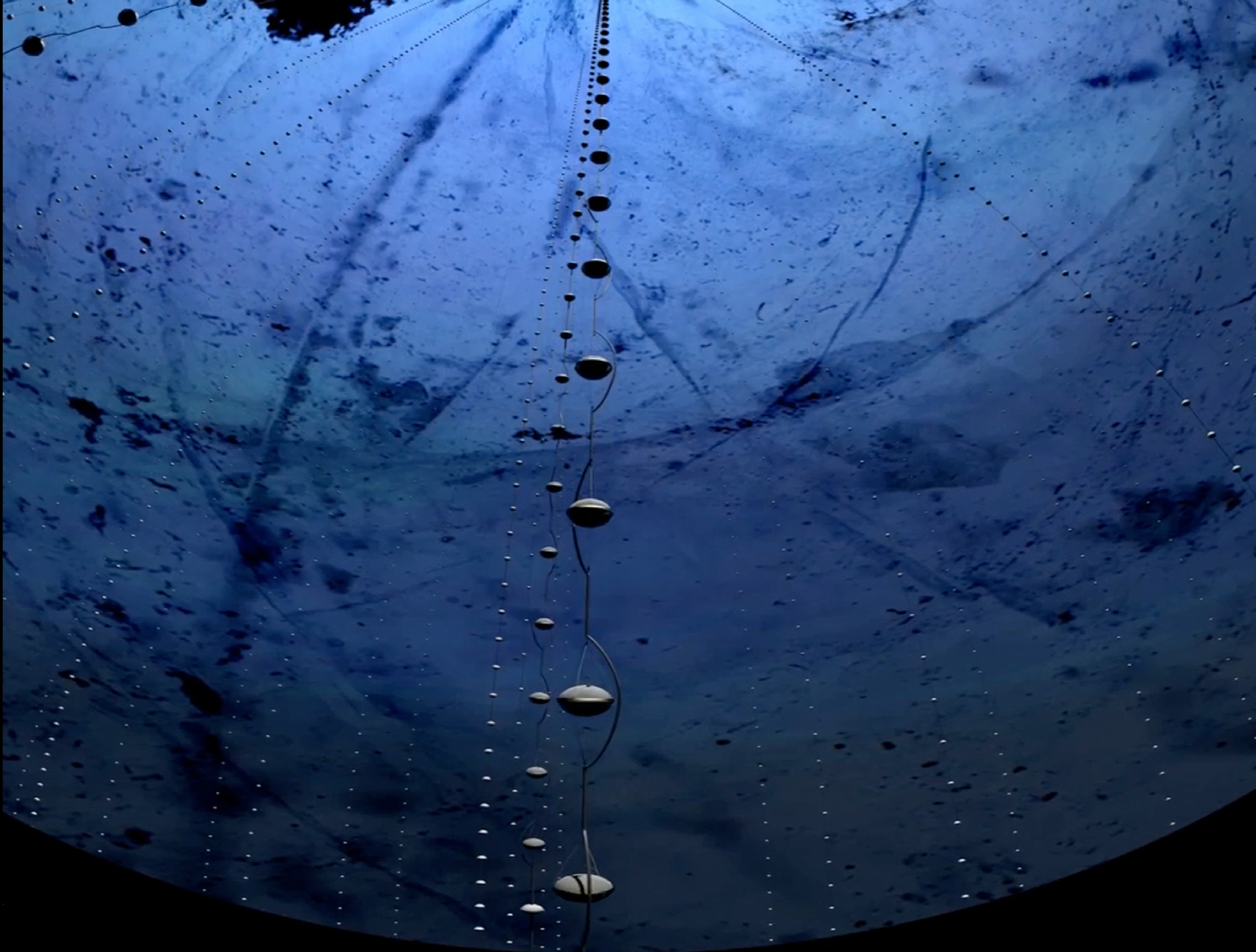
Drilling holes with hot water drill

T to drill one hole ?



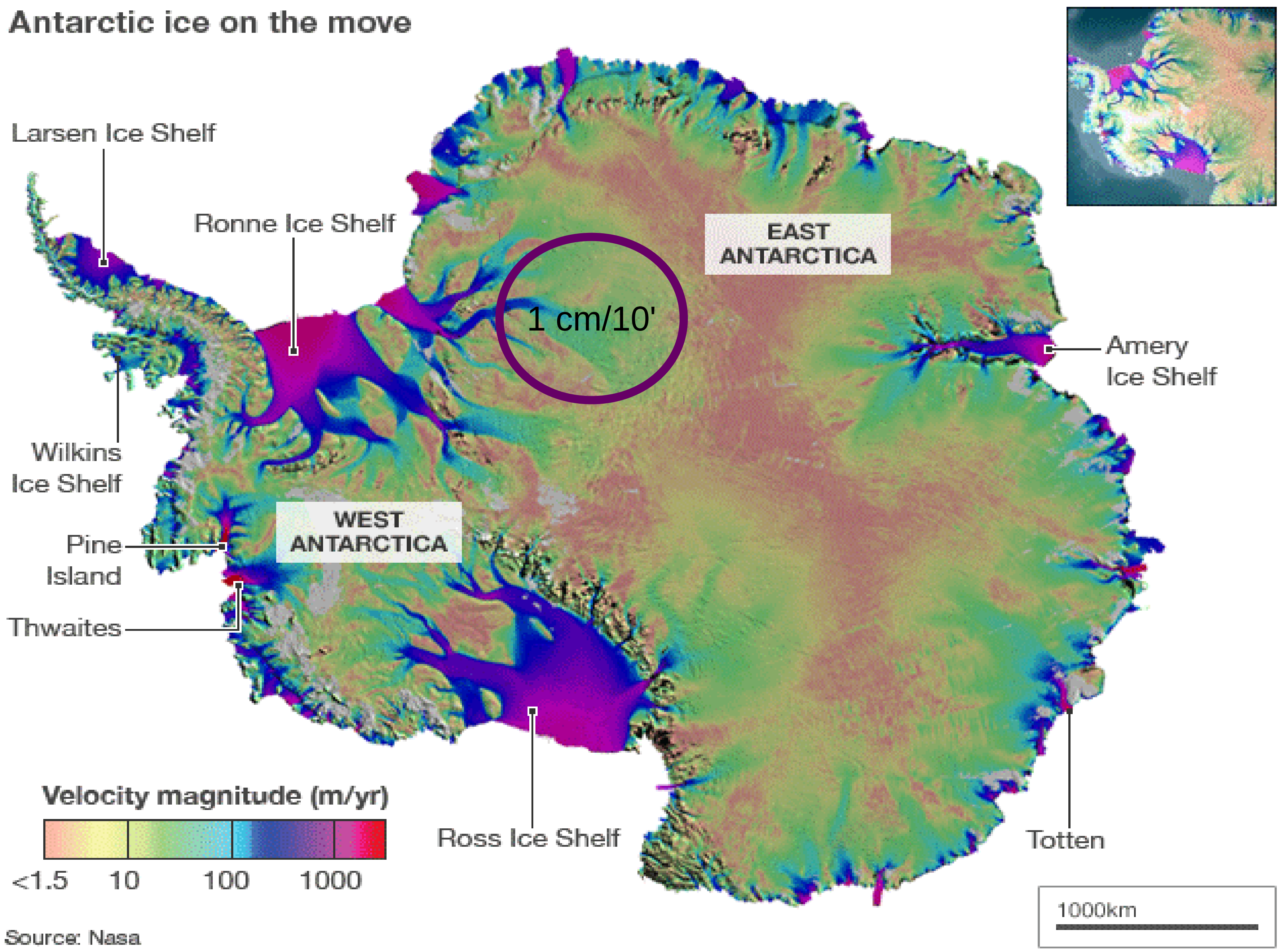

nozzle delivers
• 13 liters/second
• 7 MPa
• 90 degree C
4.8 megawatt heating plant
• Drilling in two phases

Hole drilling

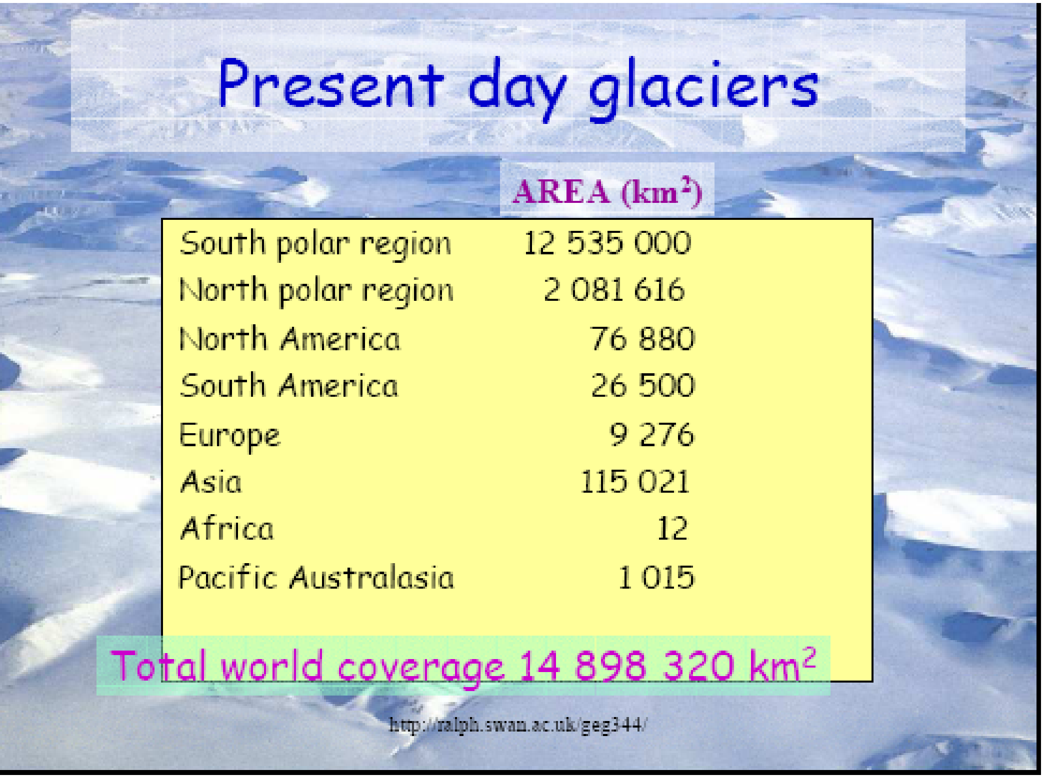


Concerns: Ice moves!!

Still, it Moves!



Ice Streams



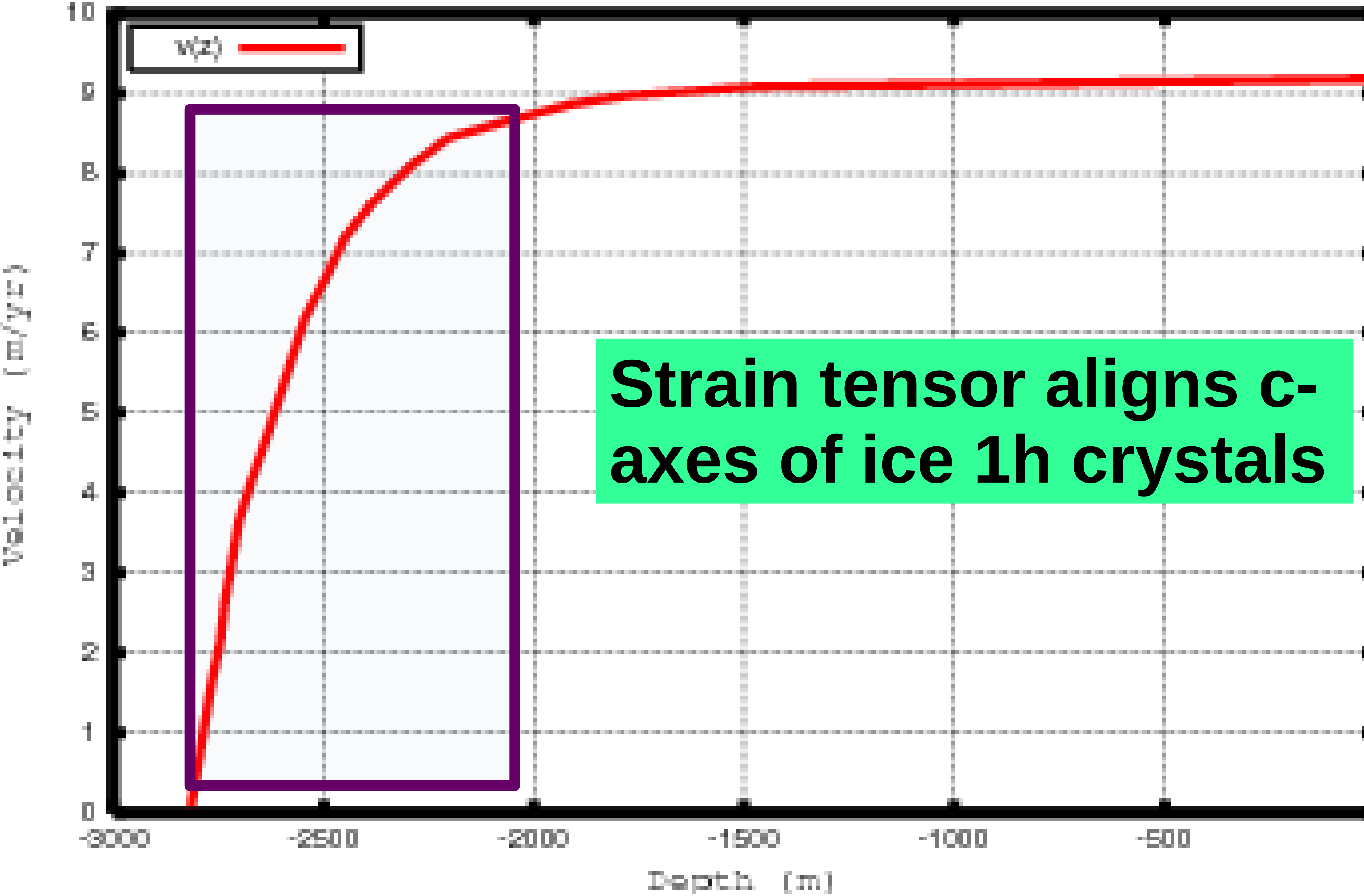
Present day glaciers

	AREA (km^2)
South polar region	12 535 000
North polar region	2 081 616
North America	76 880
South America	26 500
Europe	9 276
Asia	115 021
Africa	12
Pacific Australasia	1 015

Total world coverage 14 898 320 km^2

http://ralph.swan.ac.uk/geg344/

South Pole slip/stick Velocity profile



IceCube results: Contained events

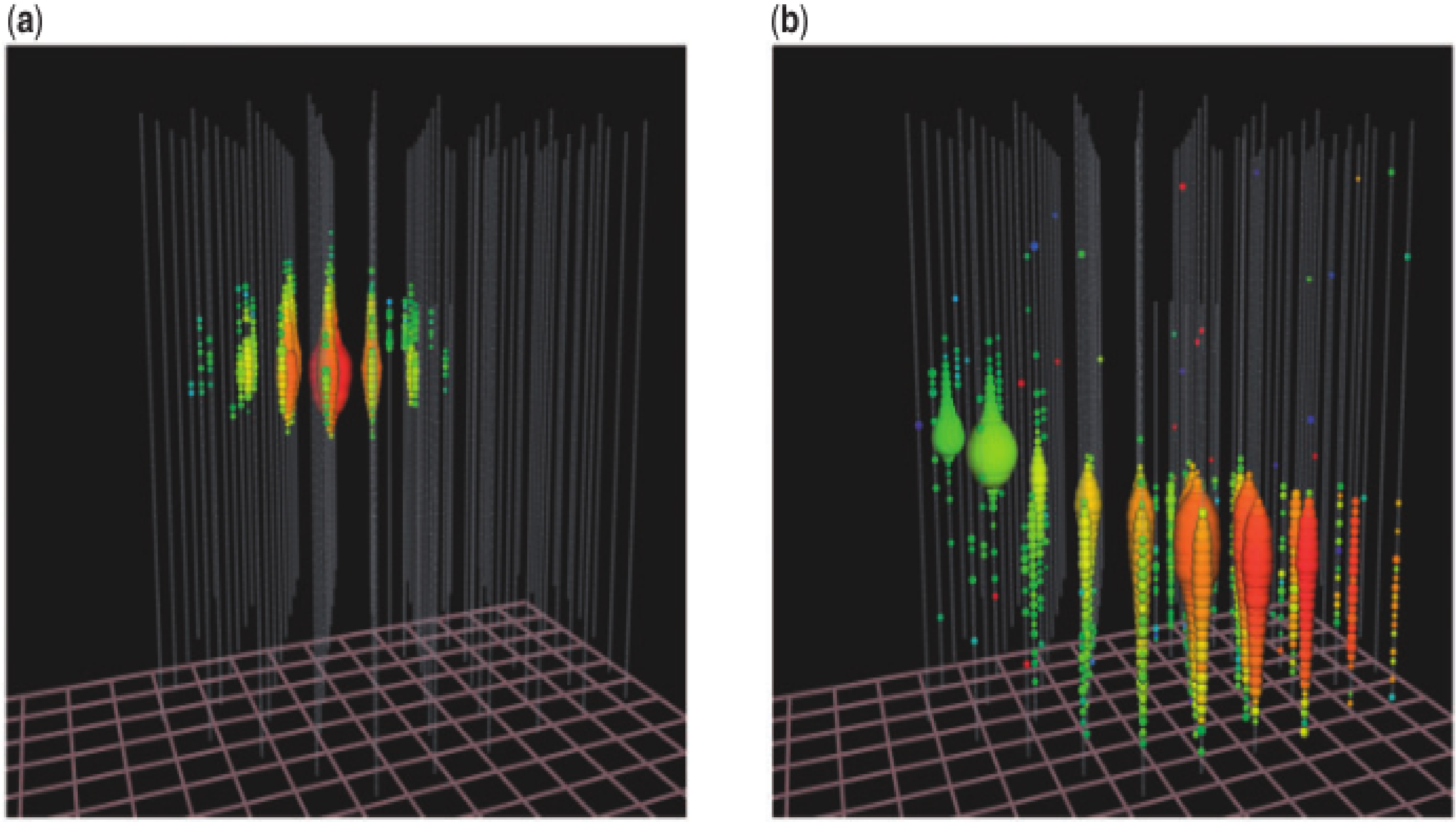
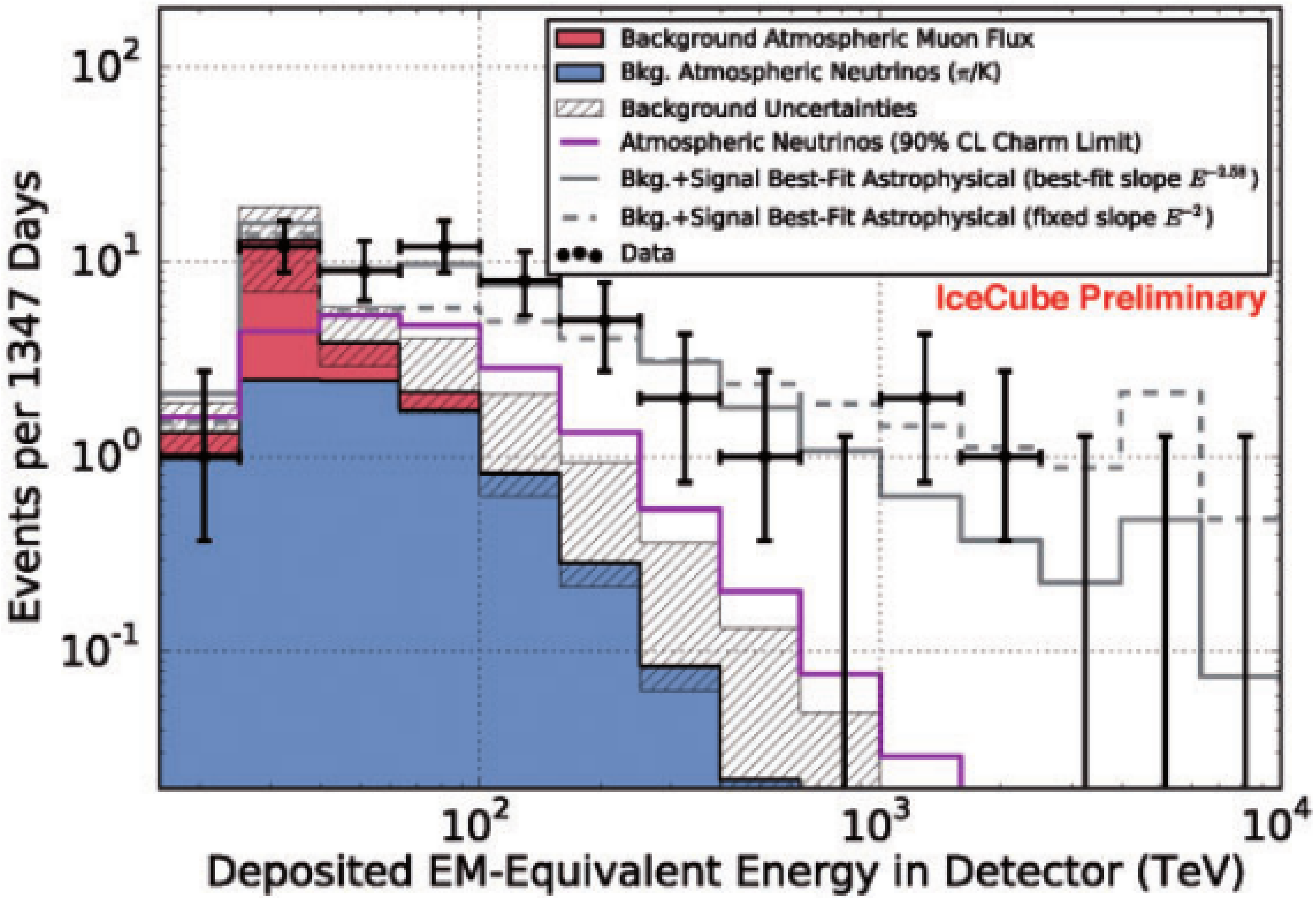
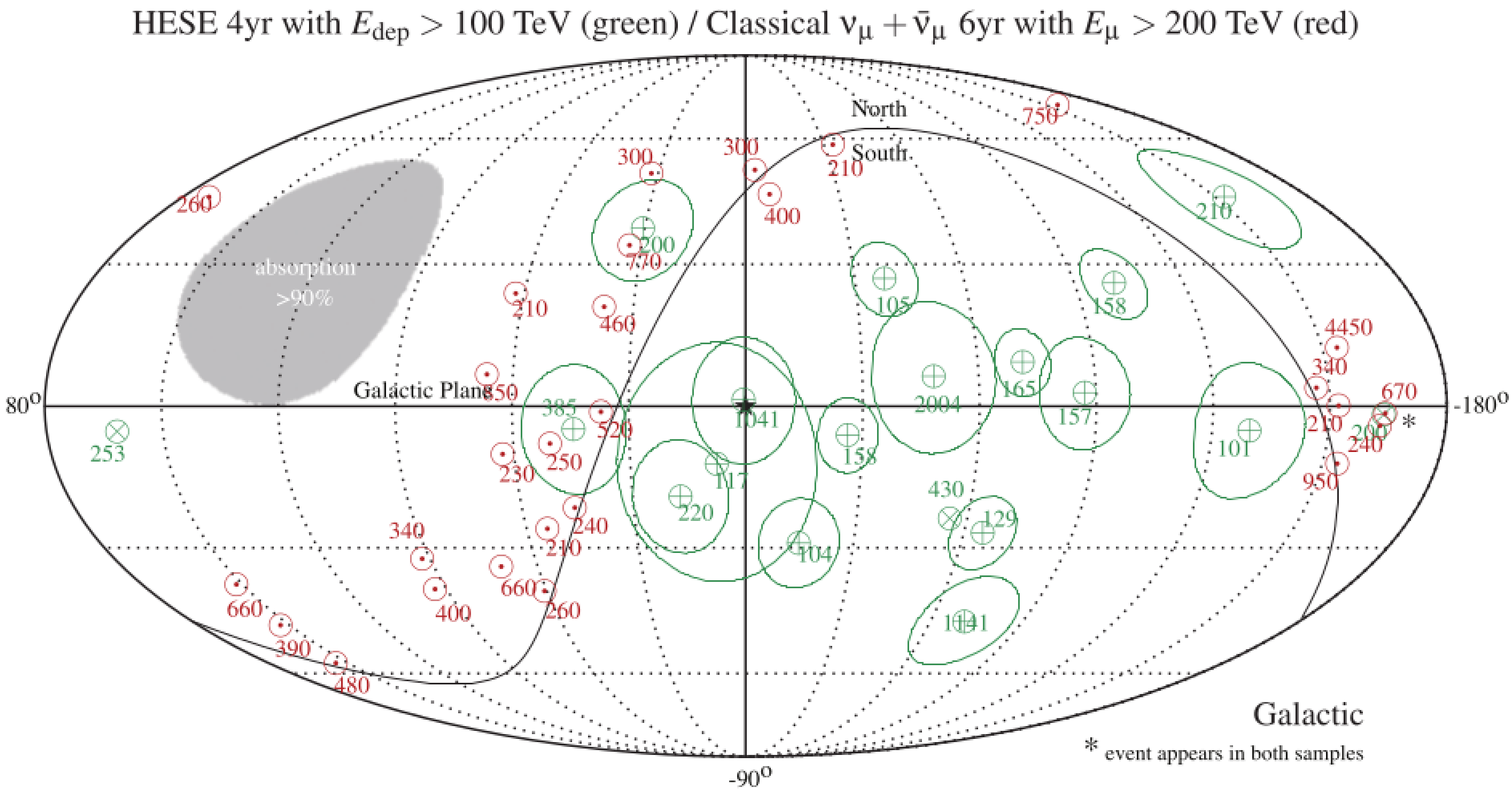


Fig. 3. (a) Light pool produced in IceCube by a shower initiated by an electron or tau neutrino. The me

Non-atmospheric neutrinos!!!

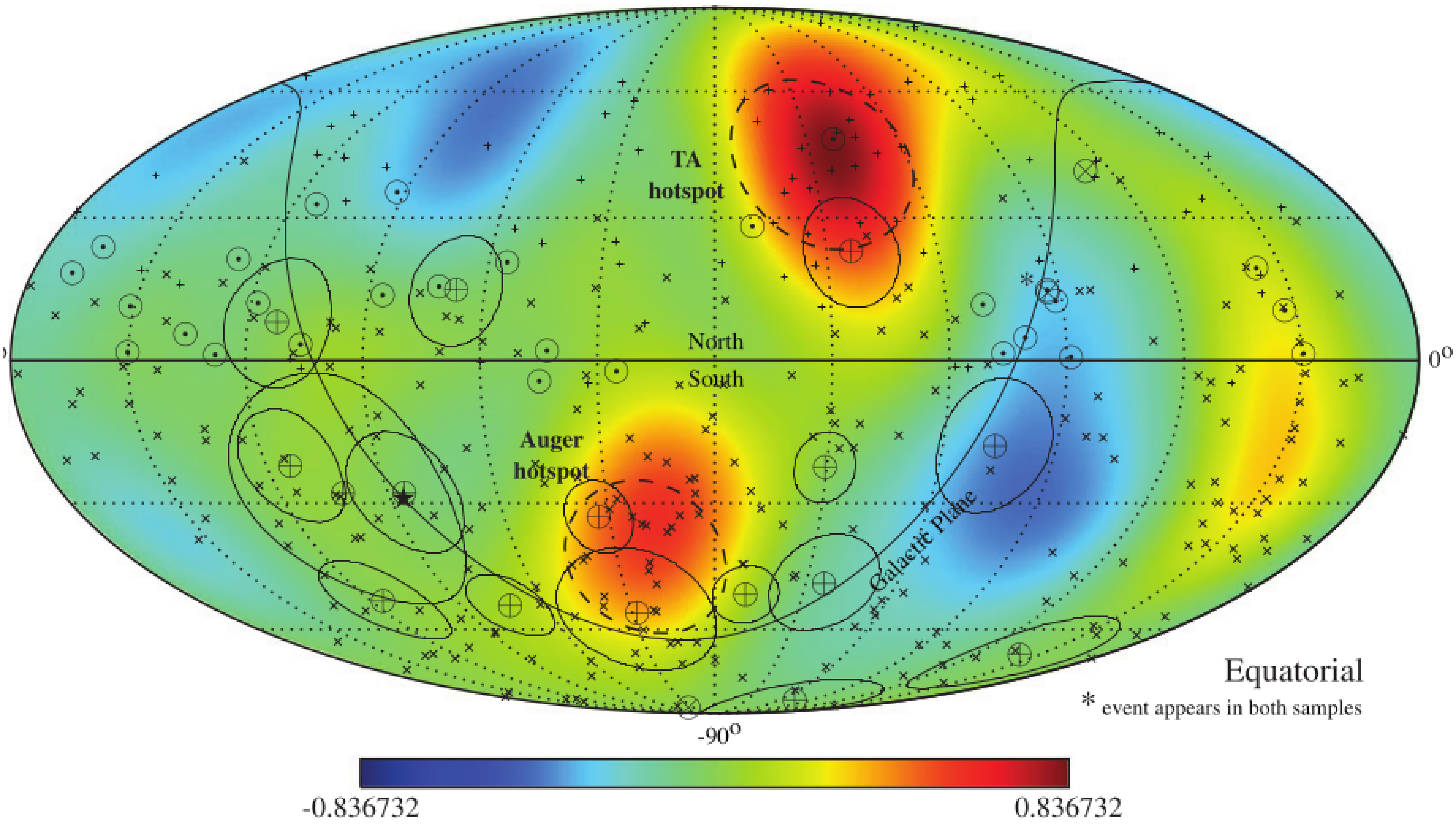


Overlay with gamma-ray catalog

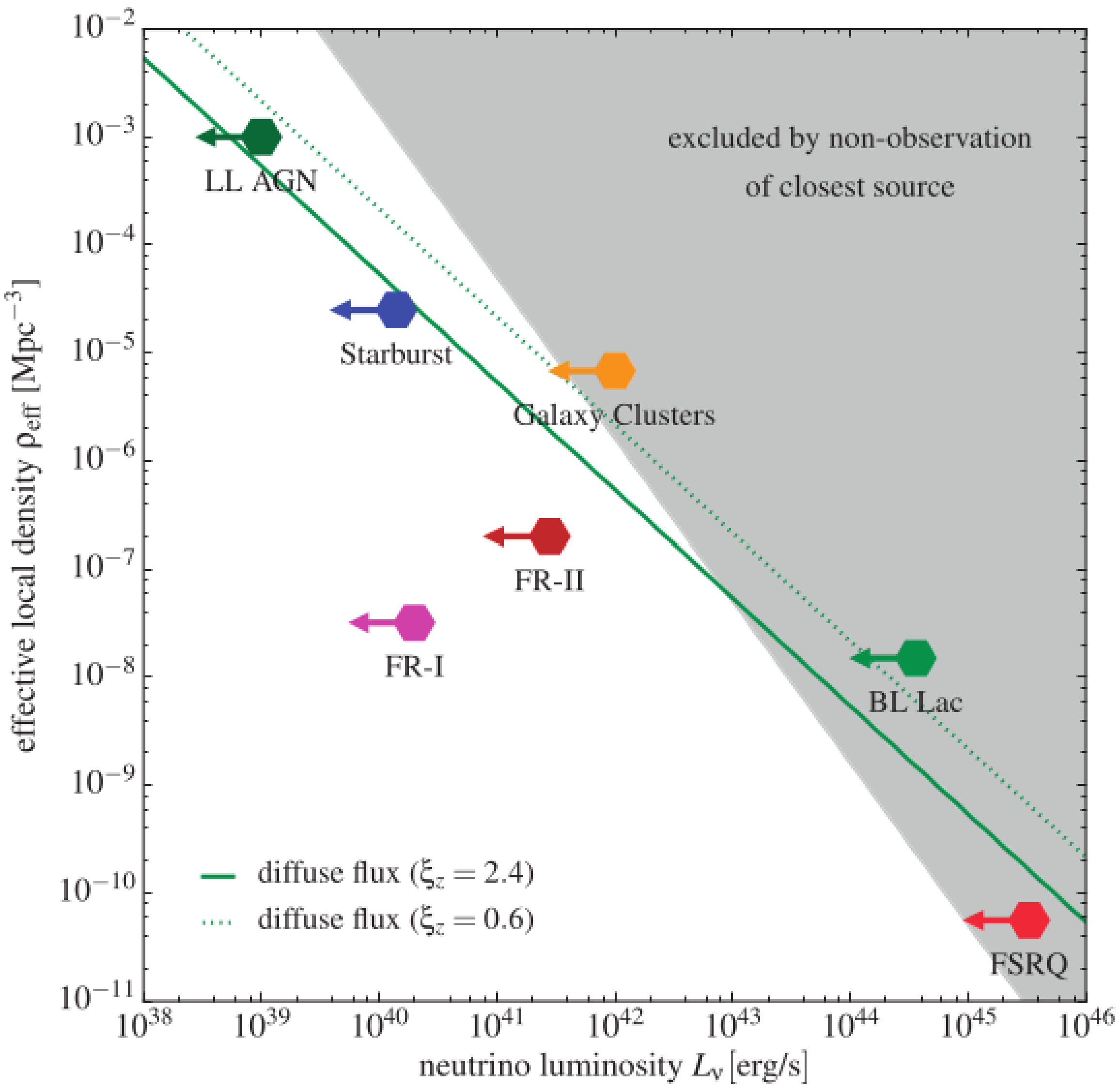


And overlay with TA/Auger

Auger 2014 E ≥ 52 EeV (×) / TA 2014 E ≥ 57 EeV (+) / smoothed anisotropy map ($\Delta\theta_{50\%} = 20^\circ$)



Place limits on neutrino source fluence



290 TeV (22Sep17) neutrino!

TXS 0506+056

From Wikipedia, the free encyclopedia

Coordi

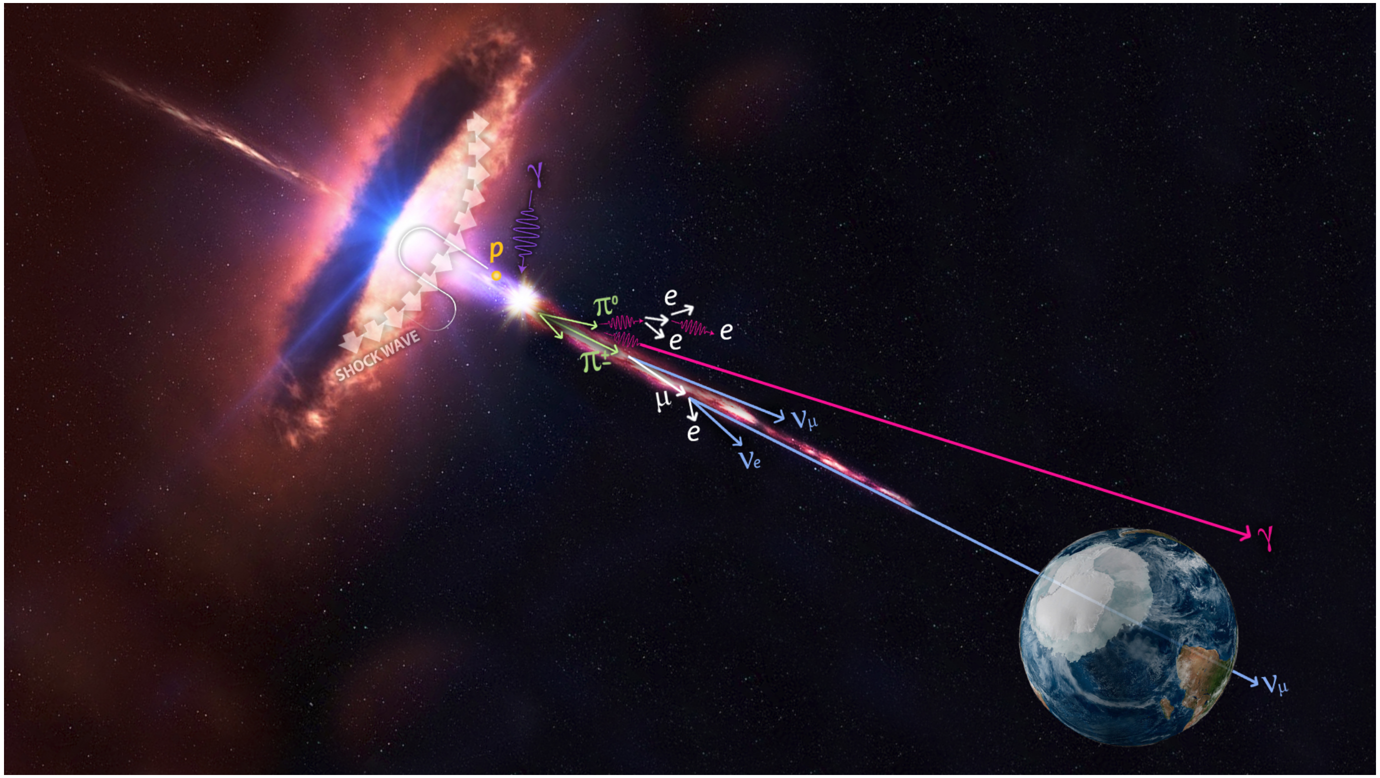
TXS 0506+056 is a very high energy blazar – a quasar with a relativistic jet pointing directly towards Earth – of BL Lac-type.[3] With a redshift of 0.3365 ± 0.0010,[3] it is about 1.75 gigaparsecs (5.7 billion light-years) from Earth.[4] Its approximate location on the sky is off the left shoulder of the constellation Orion.[5] Discovered as a radio source in 1983, the blazar has since been observed across the entire electromagnetic spectrum.

TXS 0506+056 is the first known source of high energy astrophysical neutrinos[6], identified following the **IceCube-170922A** neutrino event[7] in an early example of multi-messenger astronomy.[12] The only astronomical sources previously observed by neutrino detectors were the Sun and supernova 1987A, which were detected decades earlier at much lower neutrino energies.[6]

On September 22, 2017, the IceCube Neutrino Observatory detected a high energy muon neutrino, dubbed **IceCube-170922A**.[7] The neutrino carried an energy of ~290 tera-electronvolts (TeV); for comparison, the Large Hadron Collider can generate a maximum energy of 13 TeV.[24] Within one minute of the neutrino detection, IceCube sent an automated alert to astronomers around the world with coordinates to search for a possible source.[7]

A search of this region in the sky, 1.33 degrees across, yielded only one likely source: TXS 0506+056, was found to be in a flaring state of high gamma ray emission.[7][6] It was subsequently observed at o the electromagnetic spectrum, including radio, infrared, optical, X-rays and gamma-rays.[7][25] The de

TXS 0506+056


SHOCK WAVE
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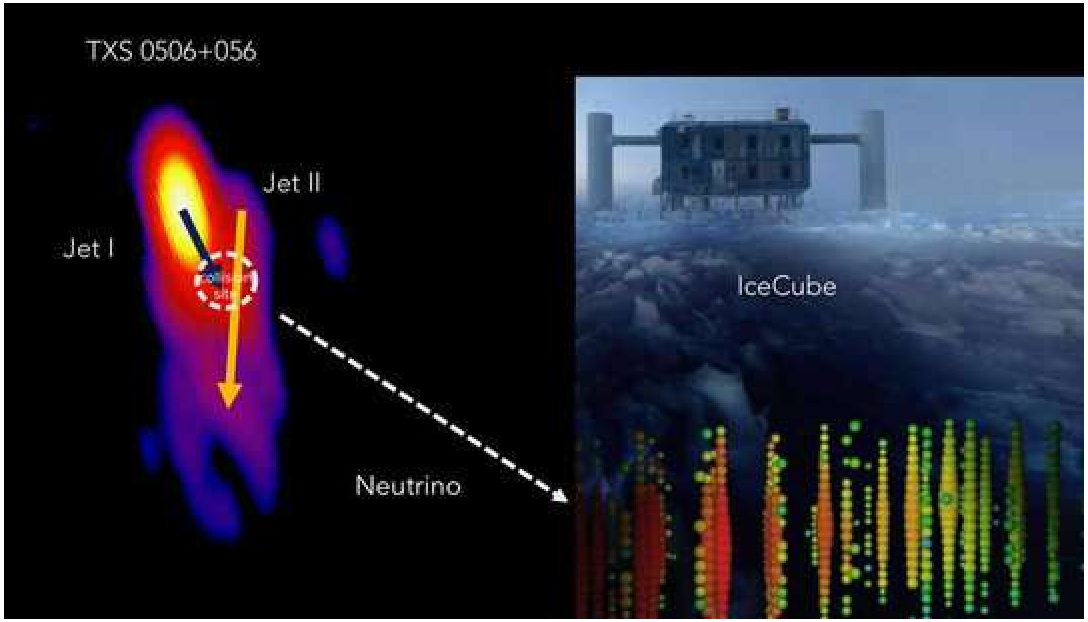
TXS 0506+056
Jet II
Jet I
IceCube
Neutrino