Radio Detection of Neutrino-Induced Tau Lepton Air Showers at Altitude

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TeVPA 2017

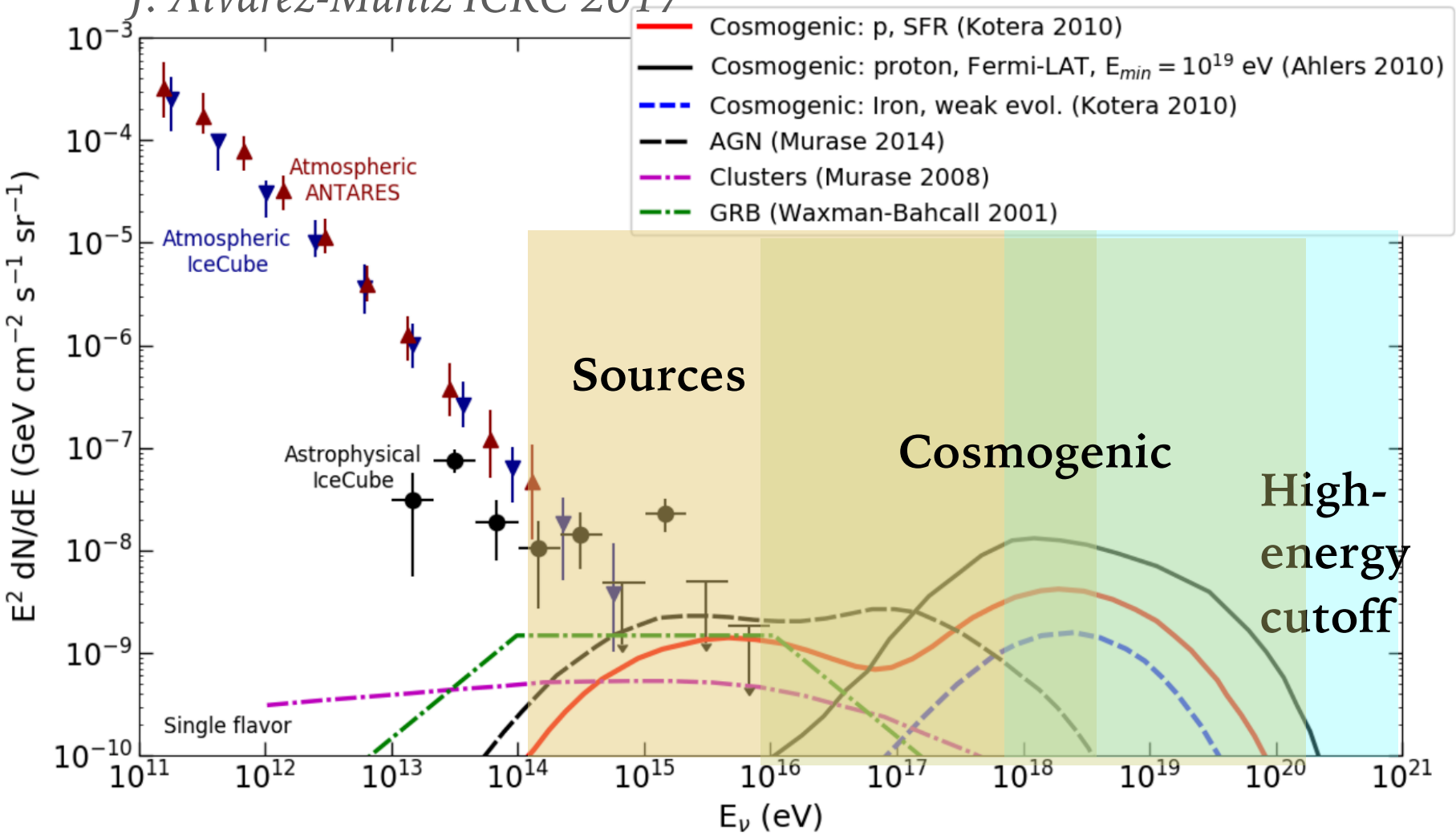
in collaboration with Jamie Alvarez-Muñiz, Washington Carvalho, Jr., Harm Schoorlemer, Andrés Romero-Wolf, Enrique Zas

CAL POLY

Radio Detection of PeV to EeV Tau Neutrinos

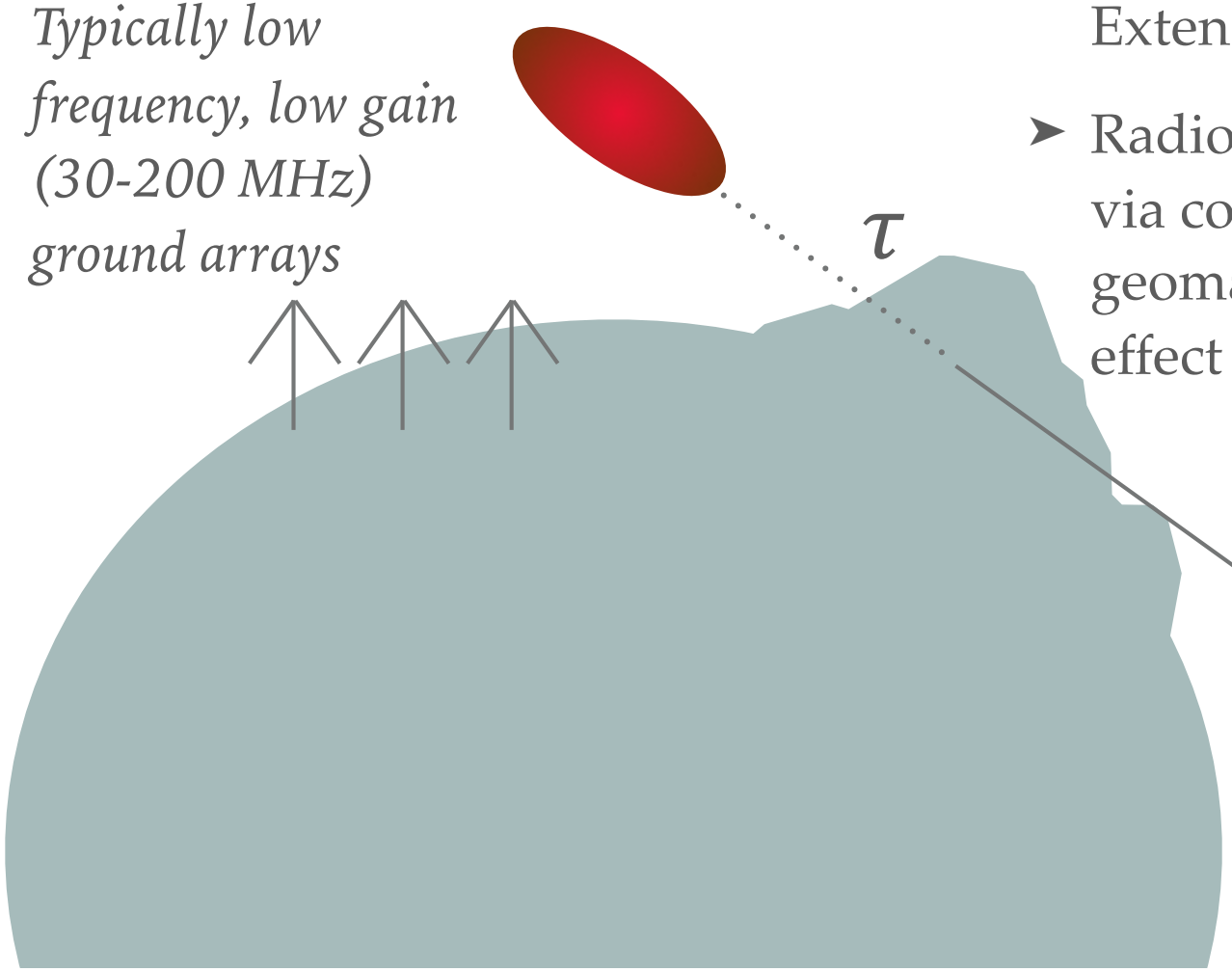
- UHE neutrinos from both sources and cosmic ray propagation
- Extension of the IceCube neutrinos to EeV energies
- Taus are unambiguous signature of astrophysical origin

J. Alvarez-Muniz ICRC 2017



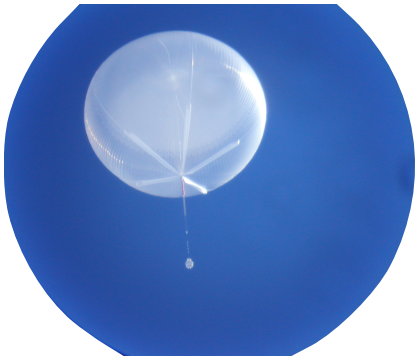
Radio Detection of Tau Lepton Showers

- Tau neutrino propagates through the Earth via tau regeneration
- Tau lepton exits Earth
- Tau lepton decays to produce Extensive air shower
- Radio emission from tau showers via combination of the geomagnetic effect and Askaryan effect



GRAND, A. Zilles Talk

Radio Detection of Tau Lepton Showers



High frequency (200-1200 MHz) high-gain antennas

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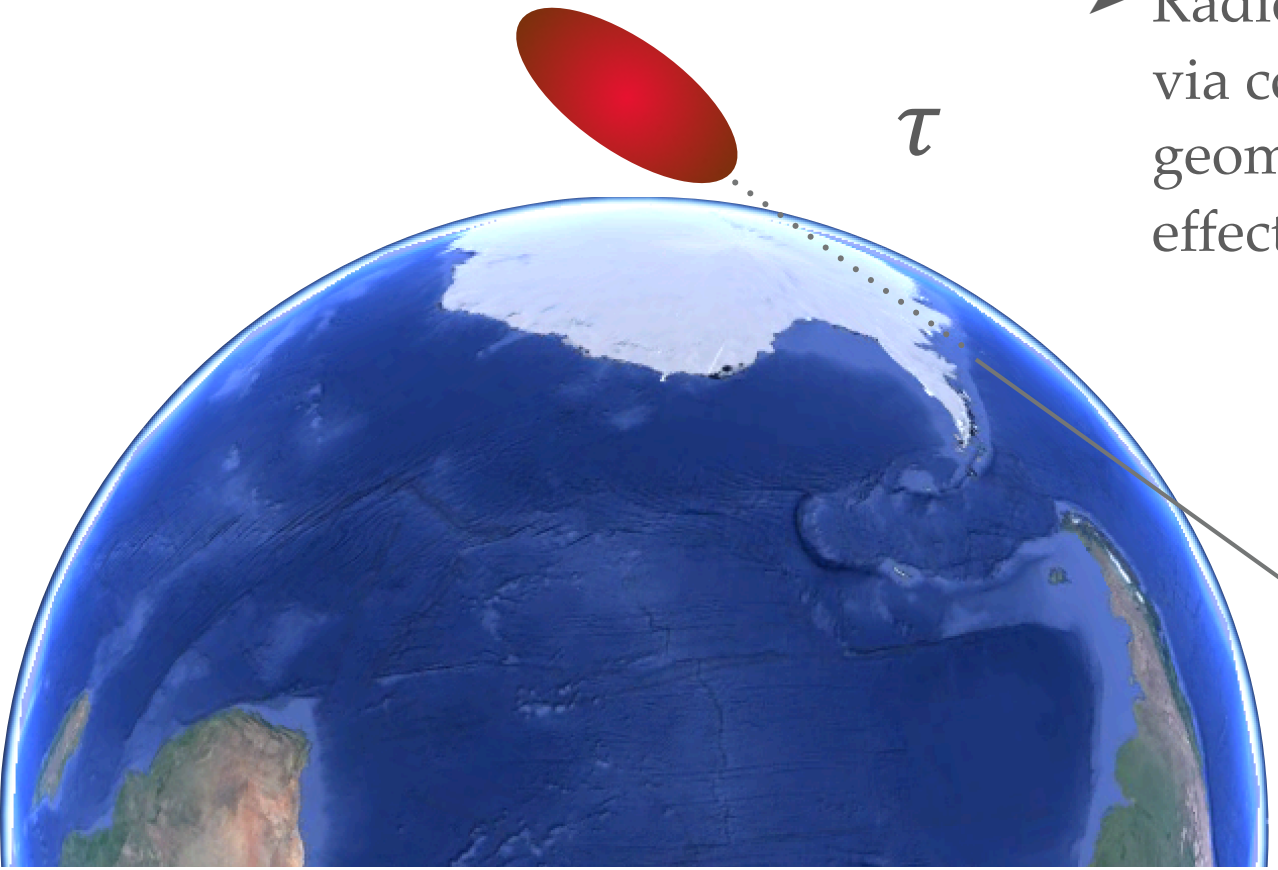
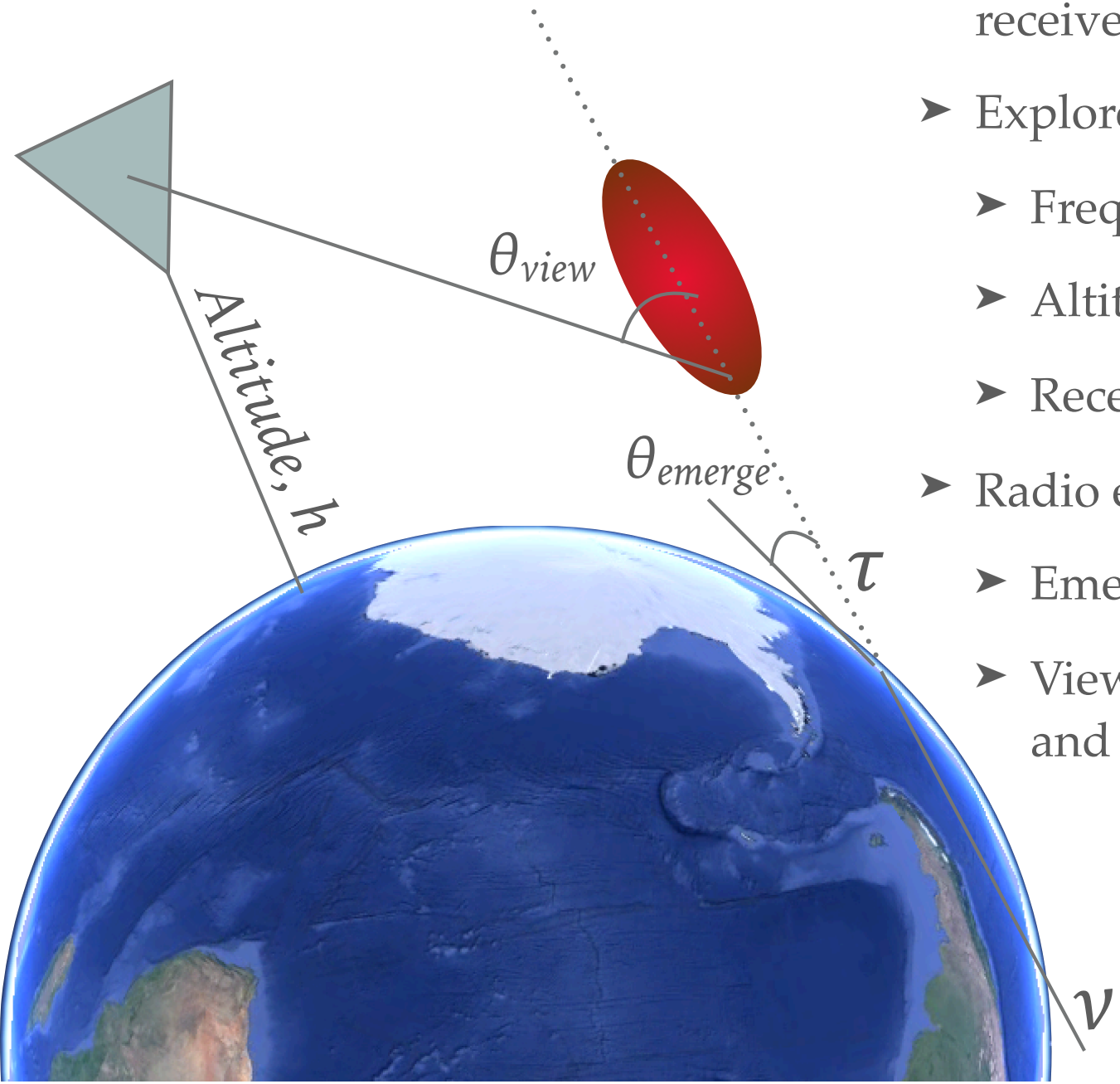


Romero-Wolf, ICRC 2017

ANITA PRL 2017

Optimal Single Detector for Taus?

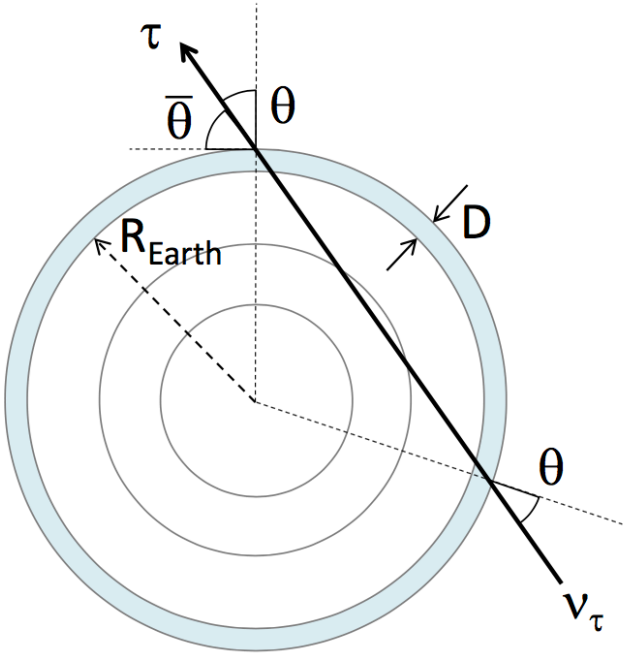


- What is the best altitude and receiver for taus?
- Explore by varying:
  - Frequency band
  - Altitude
  - Receiver gain
- Radio emission depends on:
  - Emergence angle of tau
  - View angle between antenna and Xmax

Analytical acceptance calc. in Motloch, et al. AstroPart. 54 2014 40-43

Simulations of Upgoing Tau Neutrino RF

- Simulation package that includes the effects of t propagation
  - Ice or ocean layers of varying thickness
  - Tau neutrino regeneration



- Settable neutrino-nucleon interaction cross-section and tau lepton energy loss due to photonuclear interactions.

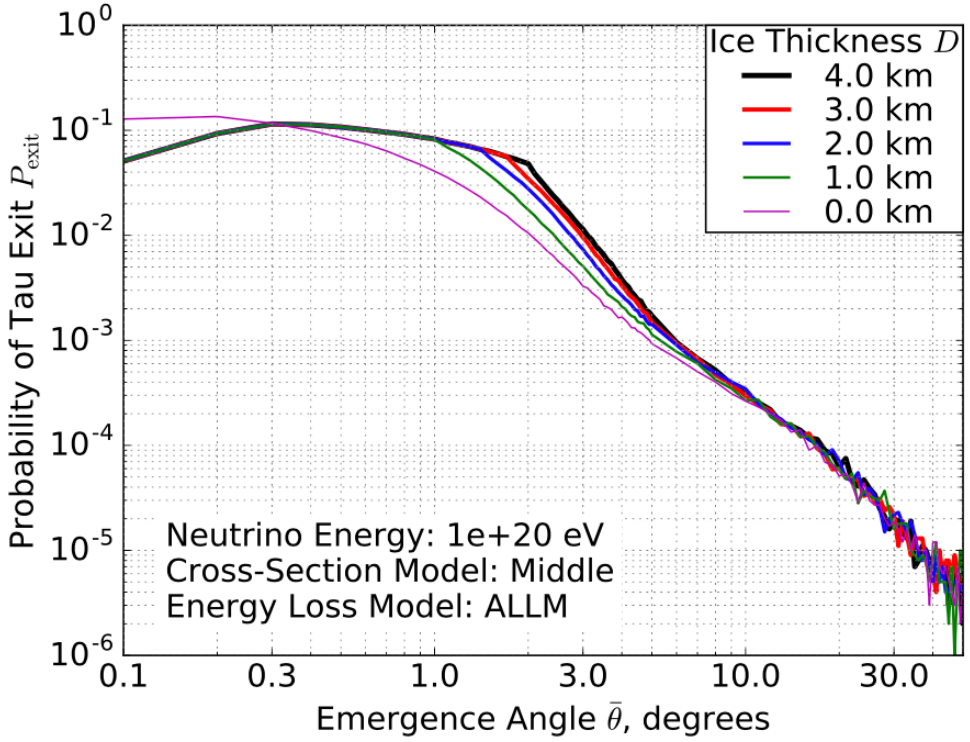
Alvarez-Muñiz, et al. arXiv:1707.00334

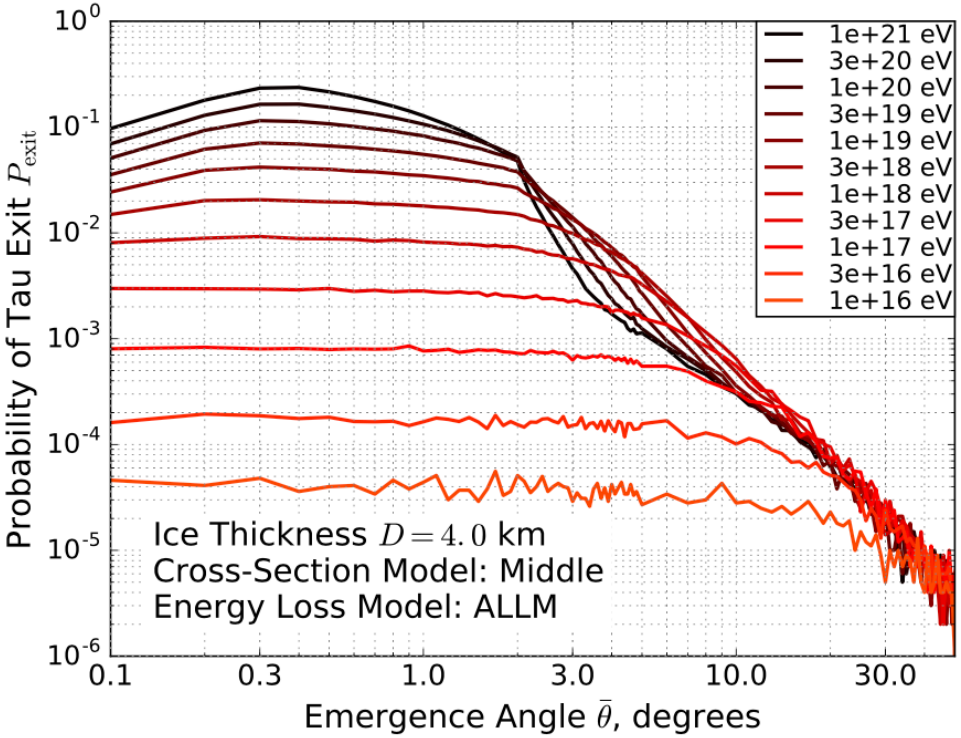
- Radio emission simulations using ZHAireS and exponentially sampled tau decay length

- Studies of radio detection for detectors at altitude.

Tau Exit Probability

- Emergence angle acts as a (energy) spectrometer for tau neutrinos
- Factor of ~5 increase in exit probability from increase in ν-nucleon cross-sections in water vs. rock.





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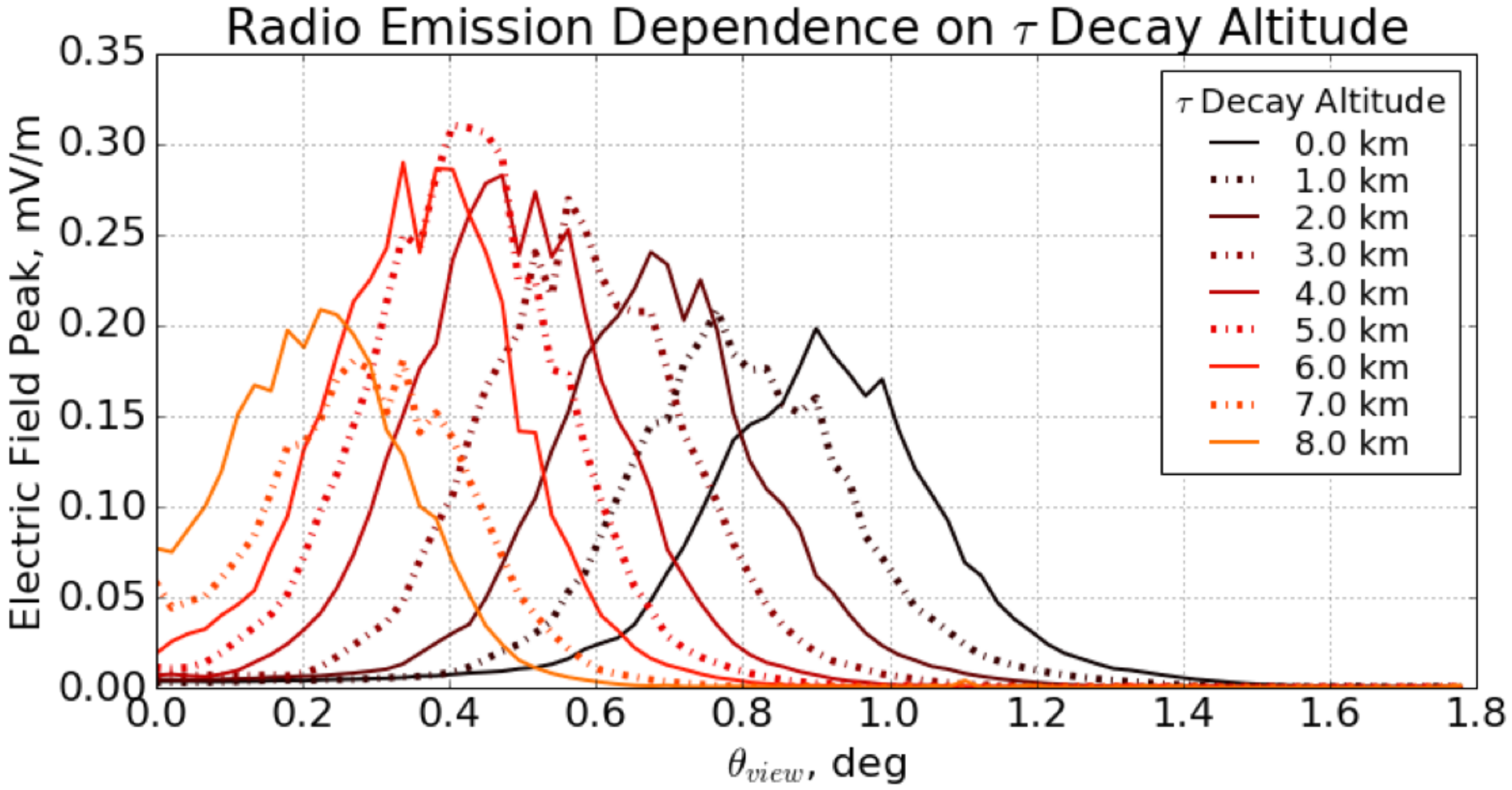
Radio Emission at Altitude

ZHAireS simulations of radio emission from tau-lepton induced air shower

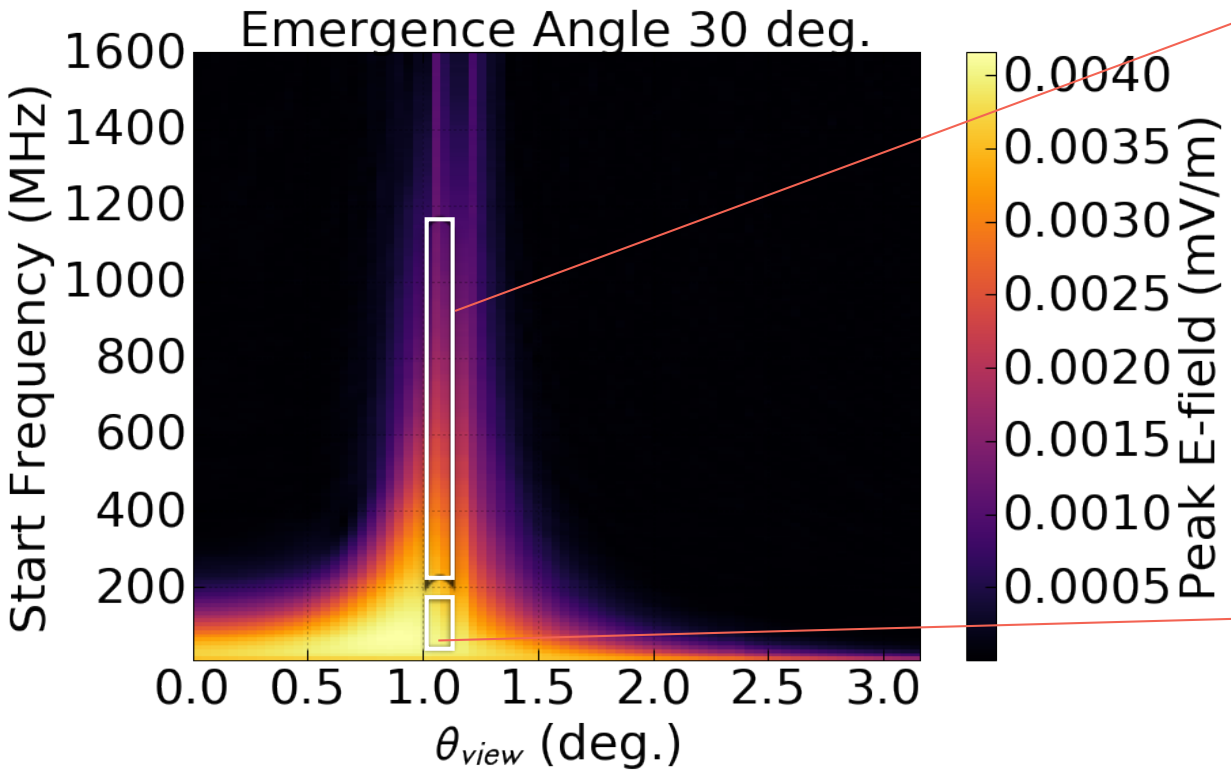


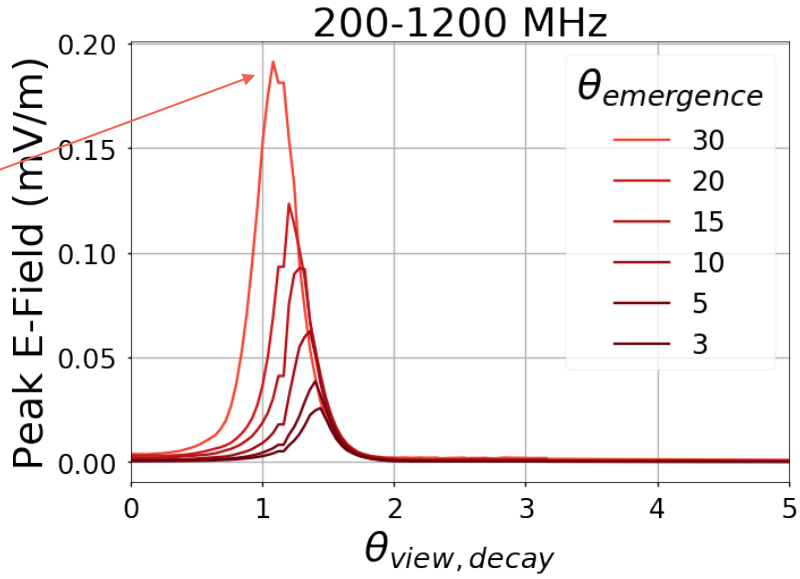
10^{17} eV tau lepton showers at 35° emergence angle

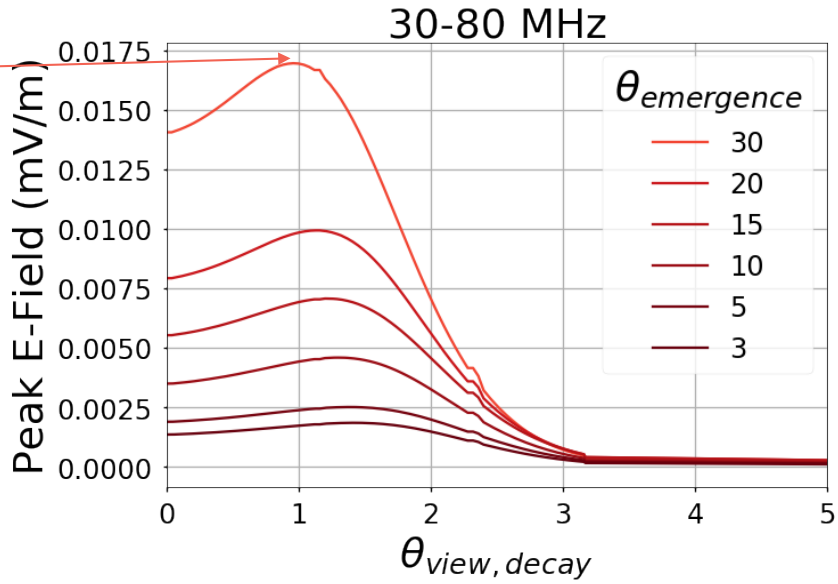
with 200-1200 MHz receiver at 37 km

Beam Pattern At 37 km

Showers at 0-km tau decay altitude







Narrowly peaked (~1°) Cherenkov cone at high frequencies. Broader (~2.5°) degrees at lower frequencies

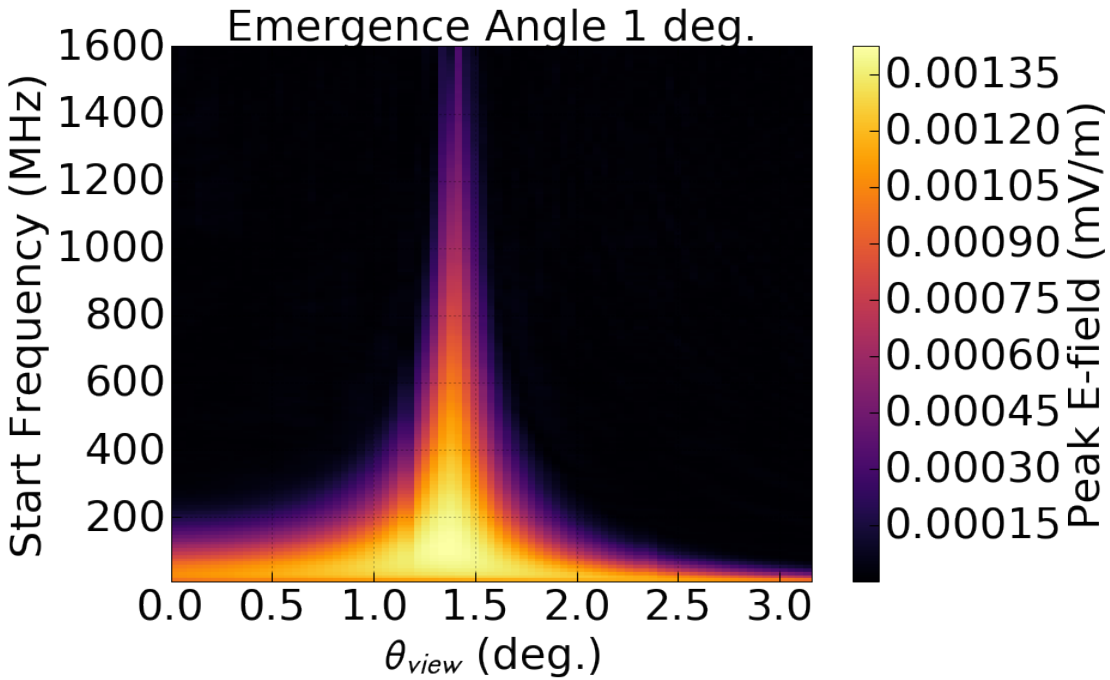
Beam Pattern At 3 km

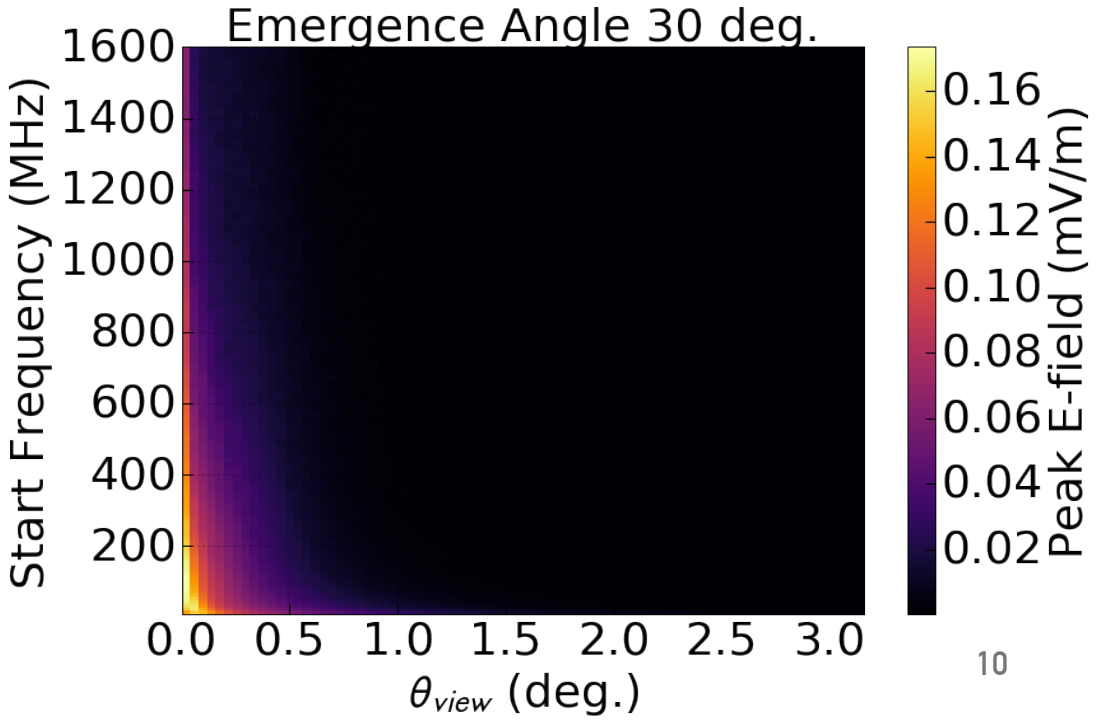
Peak electric field on cone stronger as detector moves closer to Xmax.

Tau lepton decay more likely to occur beyond detector at 10^{20} eV

For lower altitude antennas and at wider emergence angles, detector moves inside Cherenkov cone

Showers at 0-km tau decay altitude

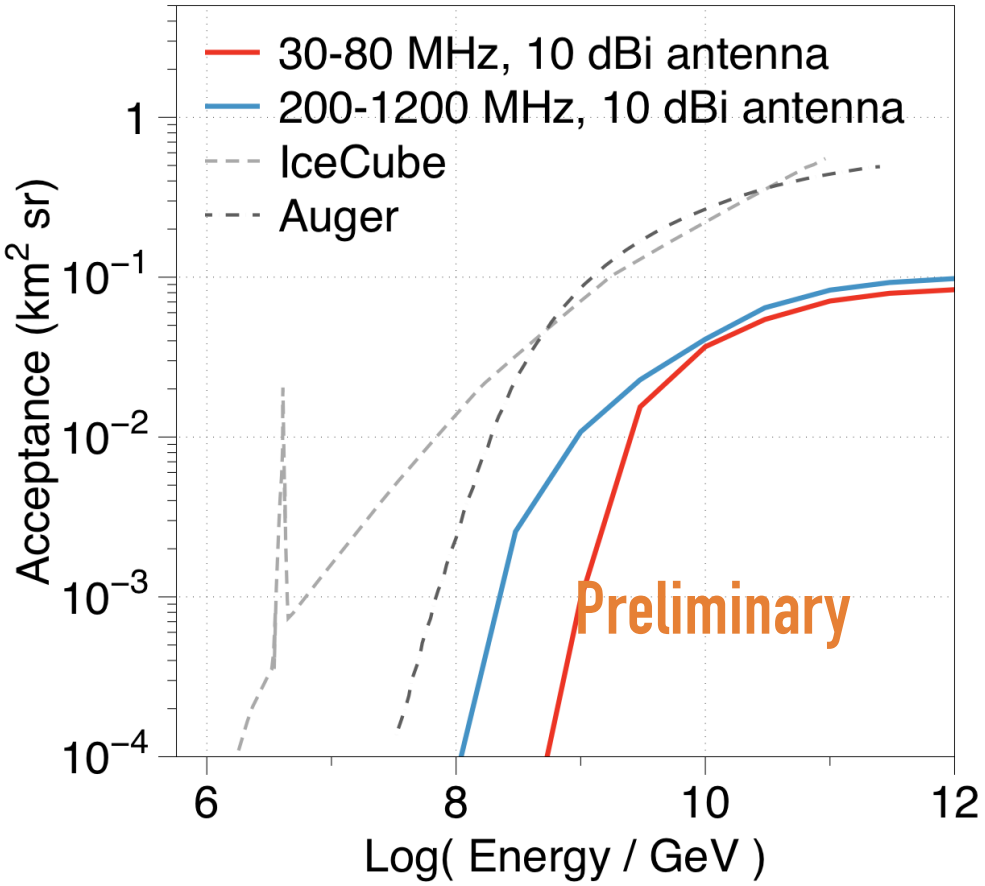




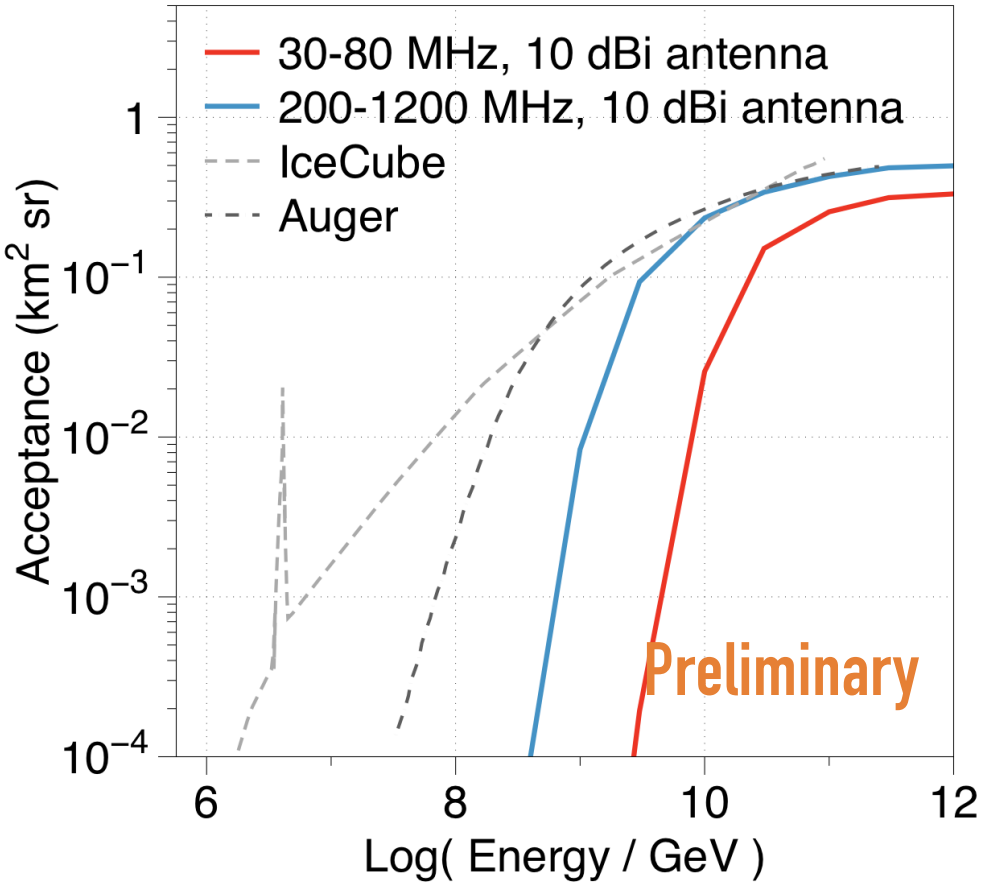
Single High-Gain Antenna at Altitude

IceCube PRL 2016
Auger PRD 2015

3 km Mountain Altitude



37 km Balloon Altitude



4 km water/ice, standard tau cross-sections and energy loss

N.B.: Need factor of ~12 higher acceptance on a balloon to compare to event rate of ground array

Add Phased Array to Increase Gain

- Voltage SNR increases as $\sqrt{N_{ant}}$
  - Signal voltage increases as N_{ant}
  - Uncorrelated noise voltage increases as $\sqrt{N_{ant}}$

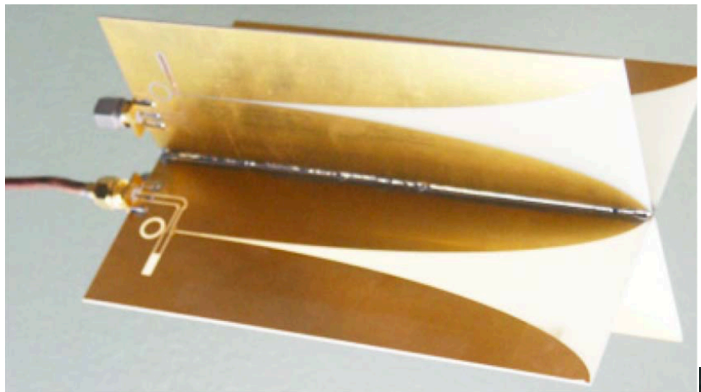
Vieregg et al JCAP 2015
Avva et al NIM 2017
among others

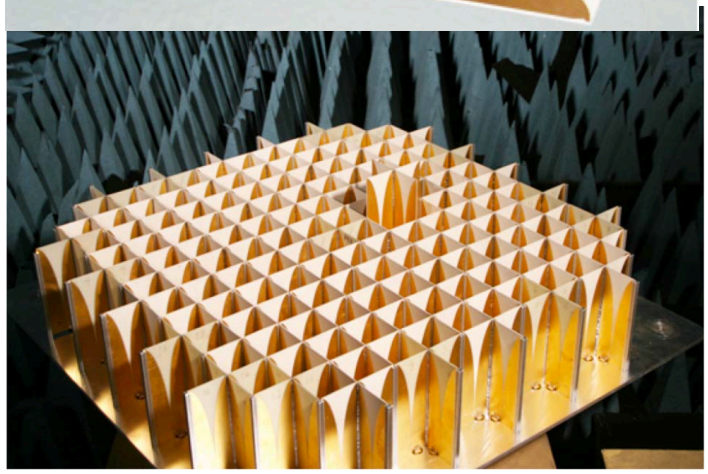
- Effective gain: $G_{eff} = 10\log_{10}(N_{ant}) + G$ *Ried et al IEEE 2012*

N_{ant}	G (dBi)	G_{eff} (dBi)
36	6	21.5
256	6	30

N.B: Reflectors can also be used to increase gain.

e.g. EVA Astropart. Phys. 2011



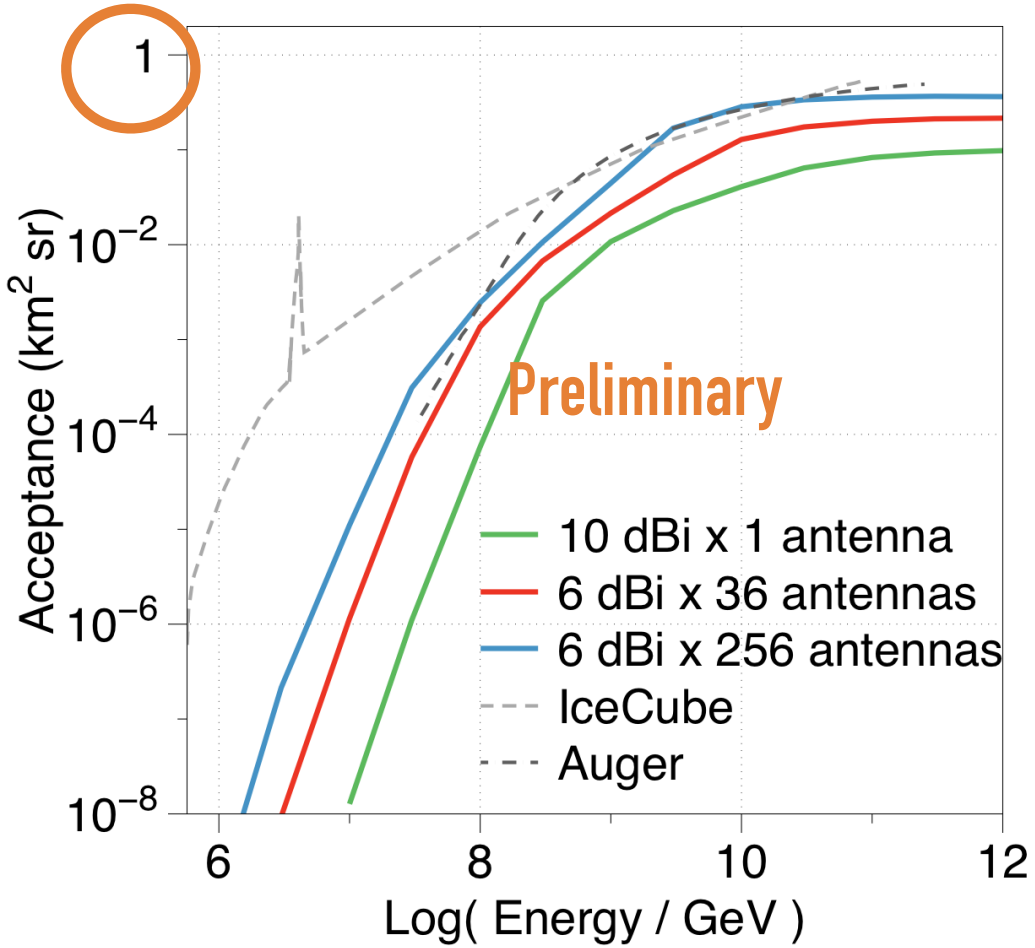


Add Phased Array to increase the Gain

- Effective gains of 10, 21, 30 dBi at 200-1200 MHz

IceCube PRL 2016
Auger PRD 2015

3 km Mountain Altitude



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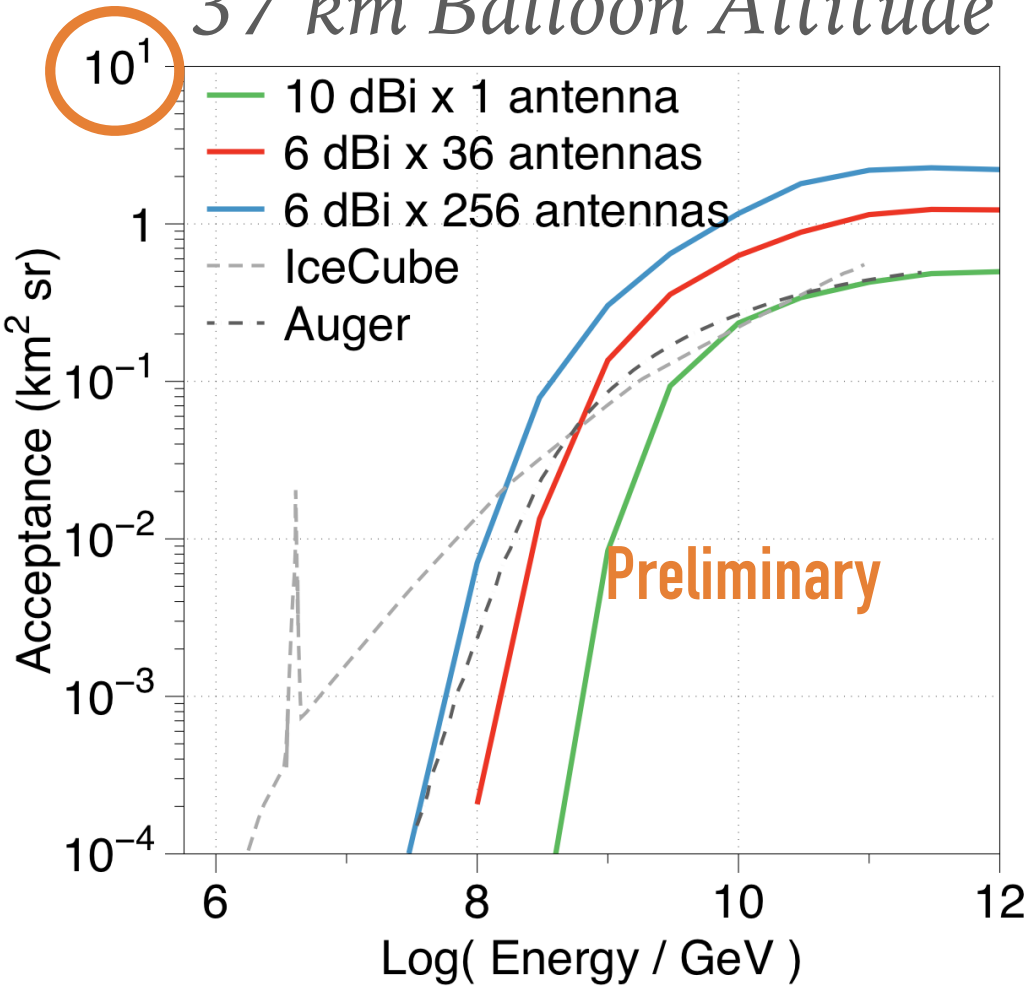


4 km water/ice, standard tau cross-sections and energy loss

Outlook

- **Simulations of radio detection from tau neutrinos** include tau regeneration, tau decay, & ZHAireS shower simulations at **varying detector altitudes**
  - Updated soon with tau showers at altitude, frequency scan, reflector study

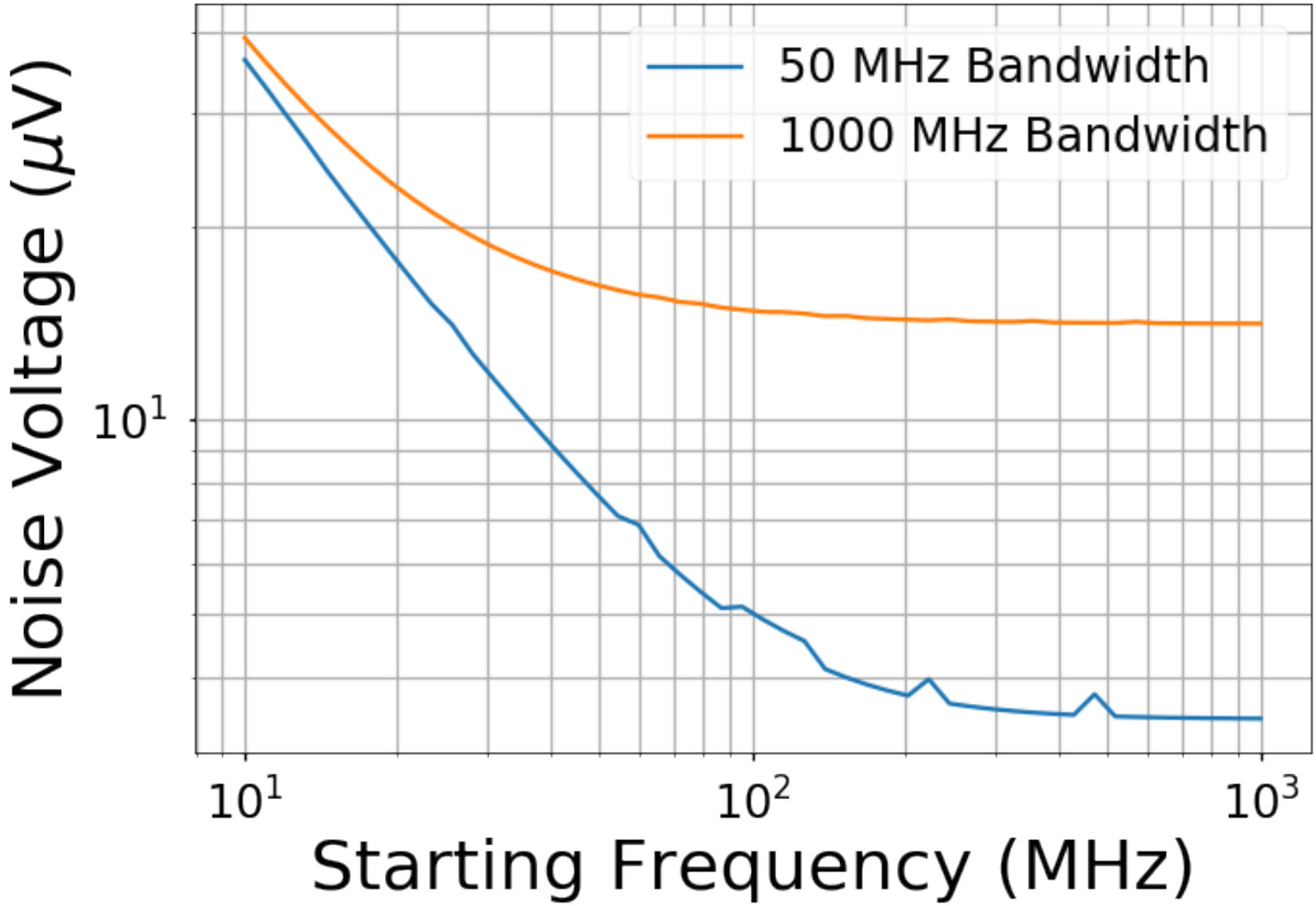
- Balloon-borne phased array achieves high instantaneous acceptance to tau neutrino events at the highest energies ($>10^{18}$ eV) → **Transient searches & high-energy cosmogenic**

- **Novel mountaintop detector** attractive way to **lower energy threshold** and achieve **high acceptance**
  - Complexity is minimized going from balloon to the ground
  - Arrays of 10-100 feasible
  - Open question is noise limitations at the tops of mountains

Extra

Radio-Frequency Noise Model

- Combination of galactic synchrotron noise (Dulk A&A 2001), thermal noise, and system noise : $T = G\ (1/2\ T_{gal} + 1/2\ T_{thermal} + T_{sys}) N_{ant}$



Geometric Acceptance

- Acceptance is integral over visible area and solid angle of the radio beam

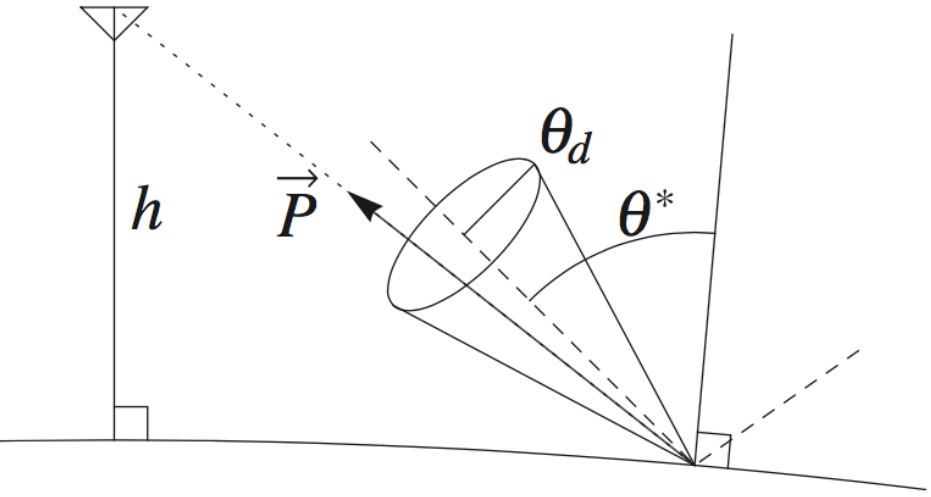
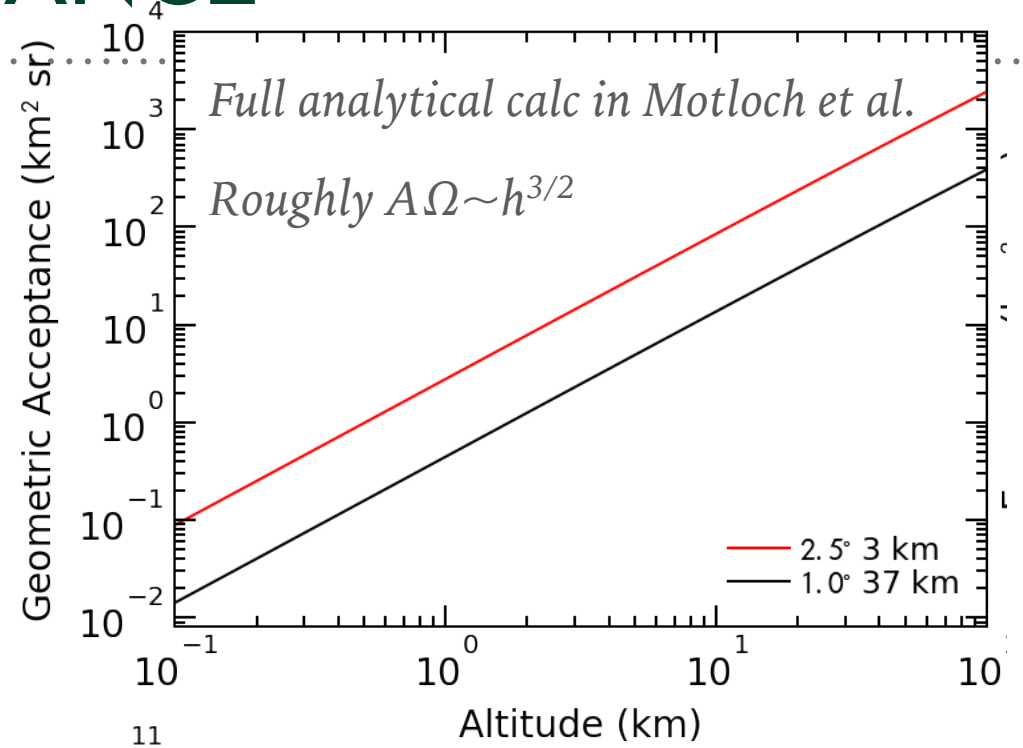
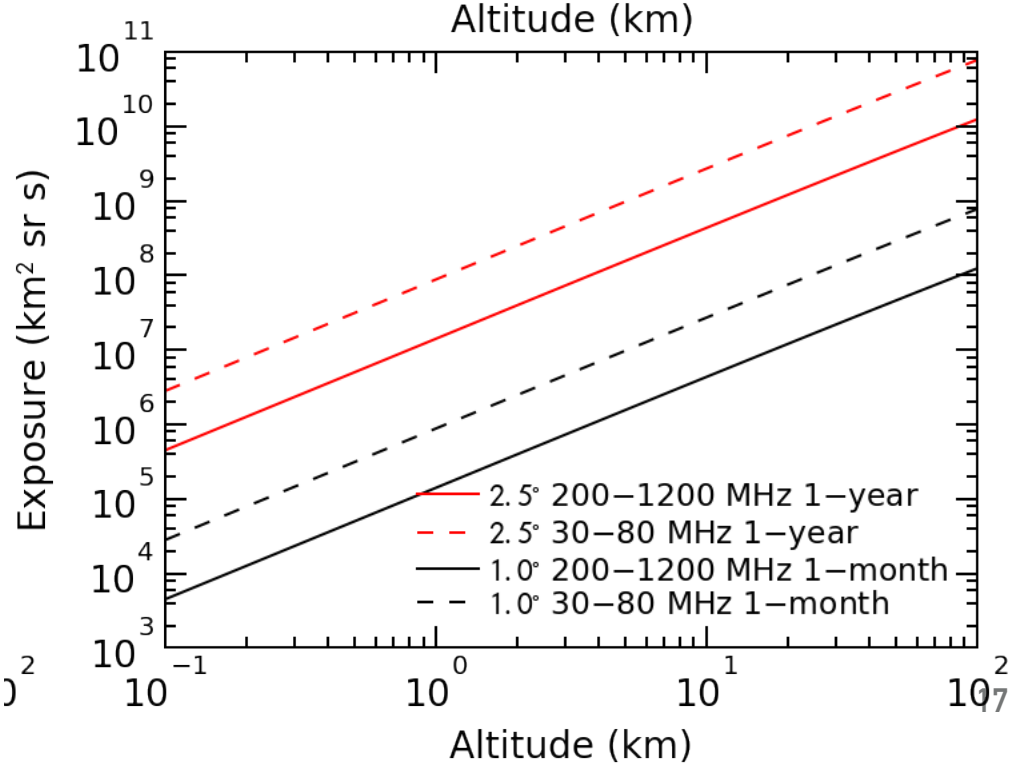


Fig. 1. Geometry of cosmic ray detection by a high altitude antenna.

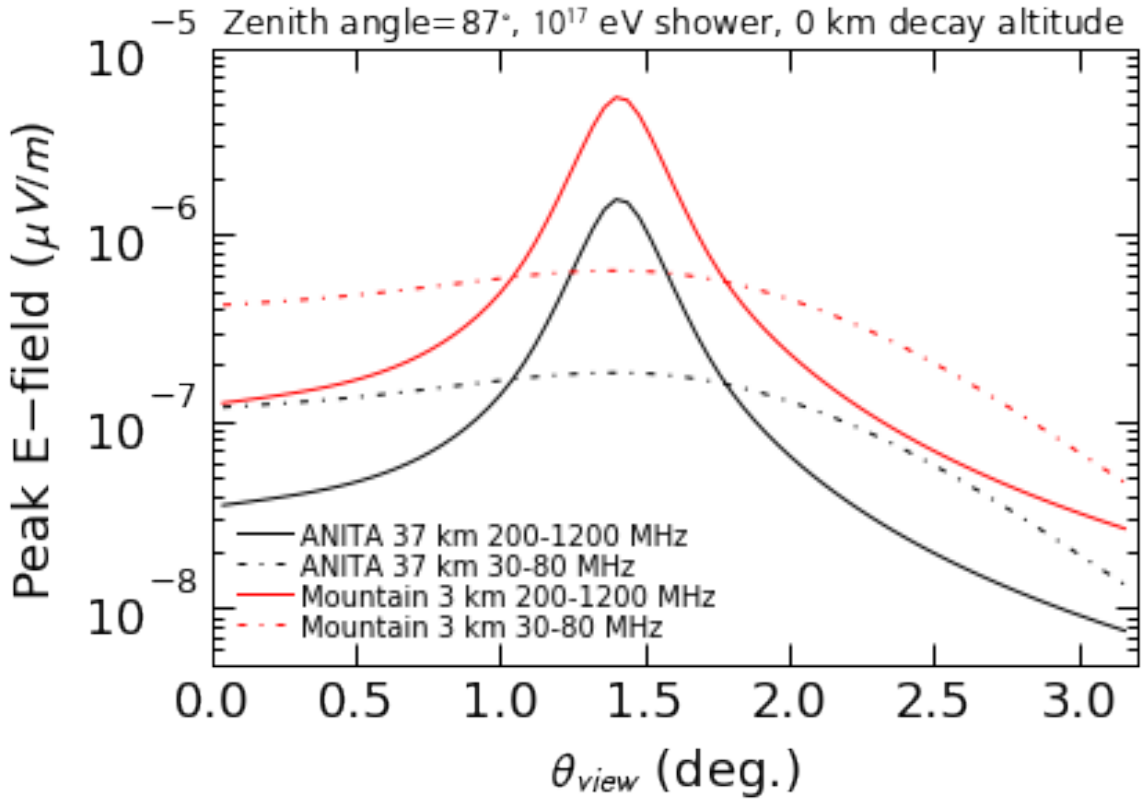
Motloch, et al. AstroPart. 54 2014 40-43

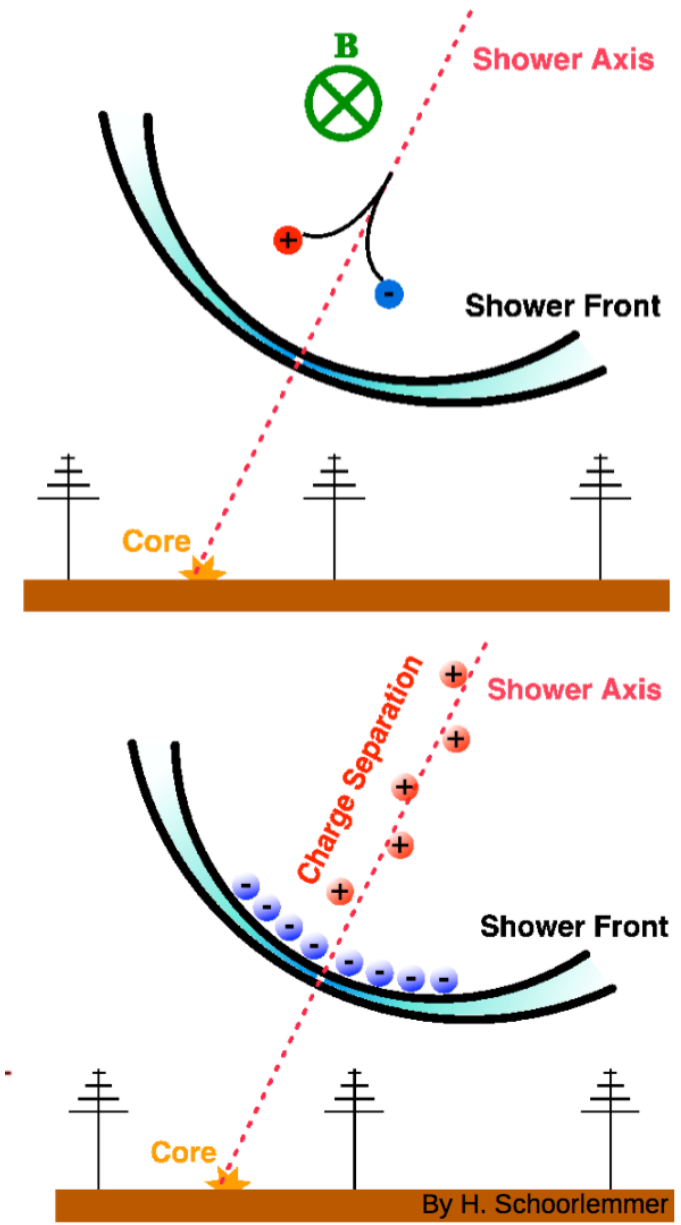




Radio Emission from Air showers

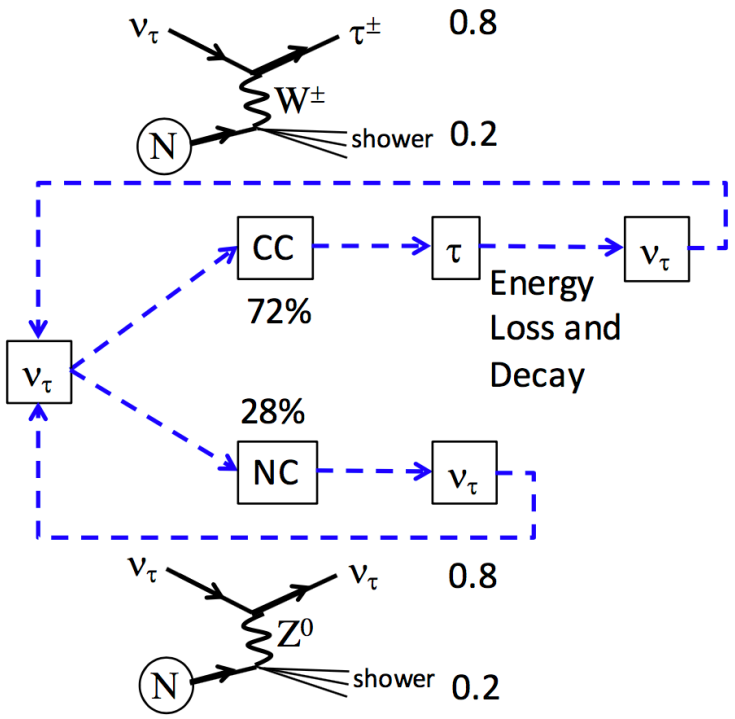
- Two main emission mechanisms:
- **Geomagnetic emission:** separation of positive and negative charges in shower due to Lorentz force.
- **Askaryan emission**: radiation from net negative charge excess in shower
- Radio beam is wider at low frequencies
  - 2.5° for 30-80 MHz
  - 1.0° for 200-1200 MHz



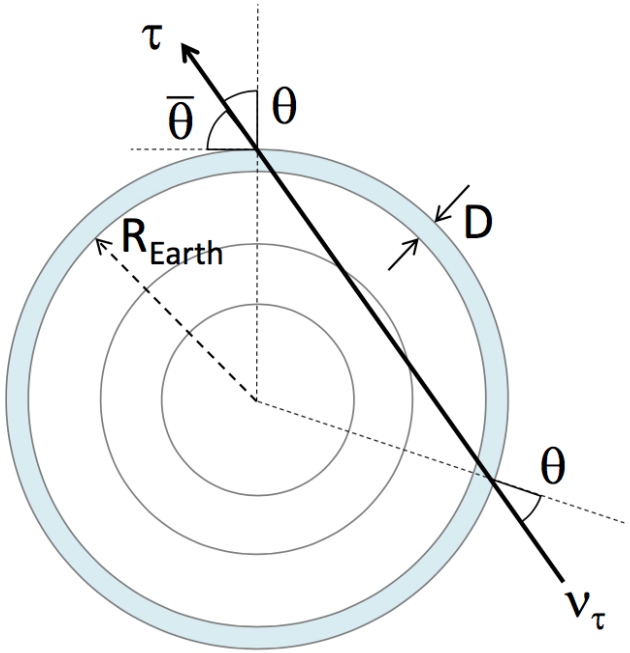


Tau Propagation

- **Skimming tau neutrinos:**
  1. **Interact** with nucleons in the Earth via CC or NC interactions
  2. **Regenerate** through tau lepton decay, and
  3. Propagate through and may produce an **exiting tau lepton**



- Probabilities of tau lepton exit include:
  - Differentiated layers of rock
  - Ice or ocean layers of varying thickness
  - Tunable neutrino-nucleon interaction cross-section and tau energy loss due to photo nuclear interactions



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