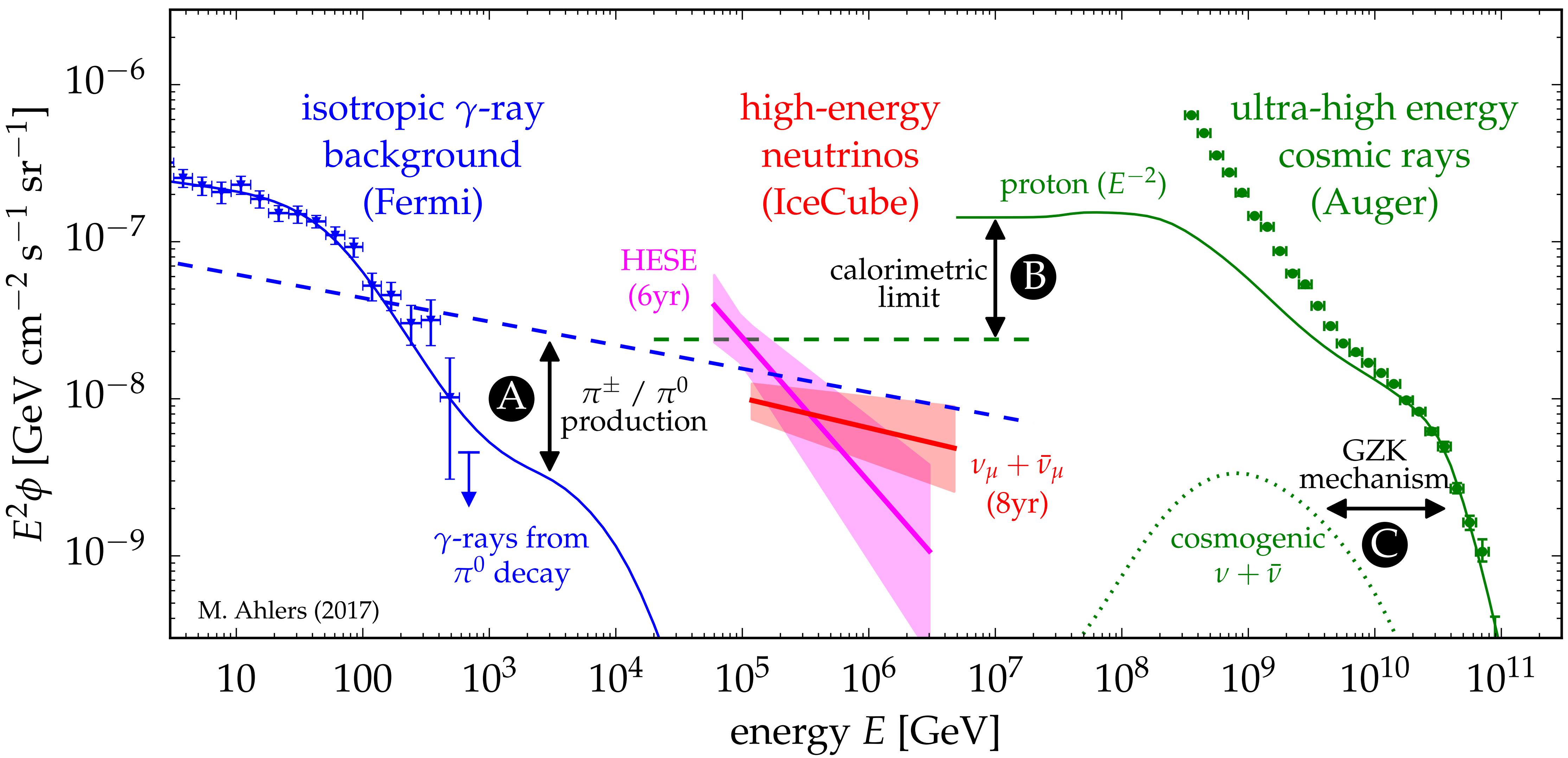
Radio detection of neutrinos

Anna Nelles
Emmy-Noether group leader
HU Berlin & DESY Zeuthen

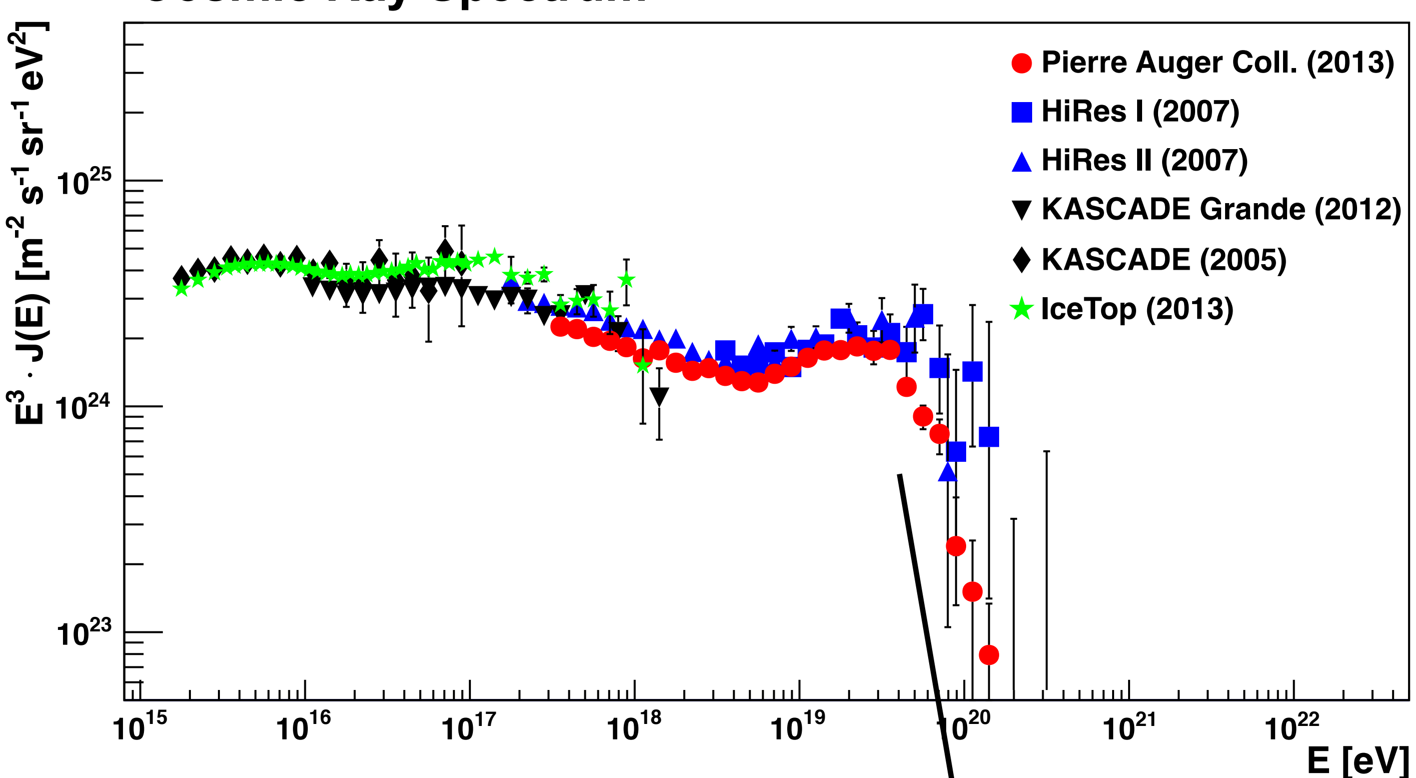
Highest energies?

Ahlers & Halzen, 2018

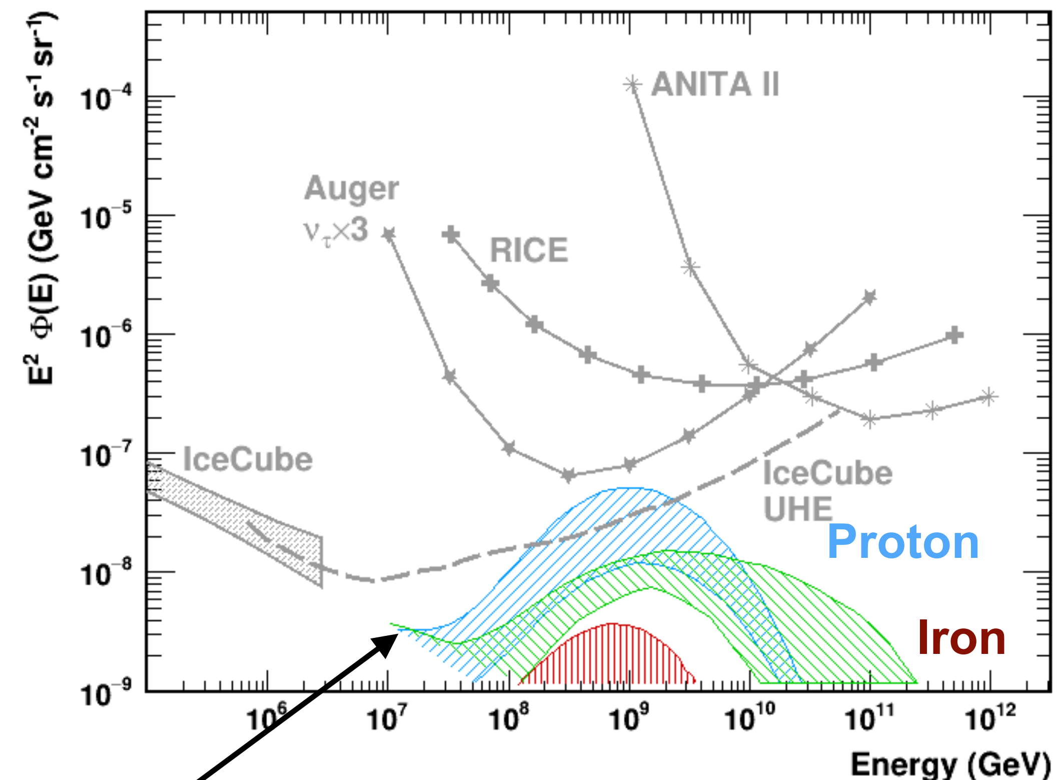


Even higher energies

Cosmic Ray Spectrum



Neutrino Spectrum



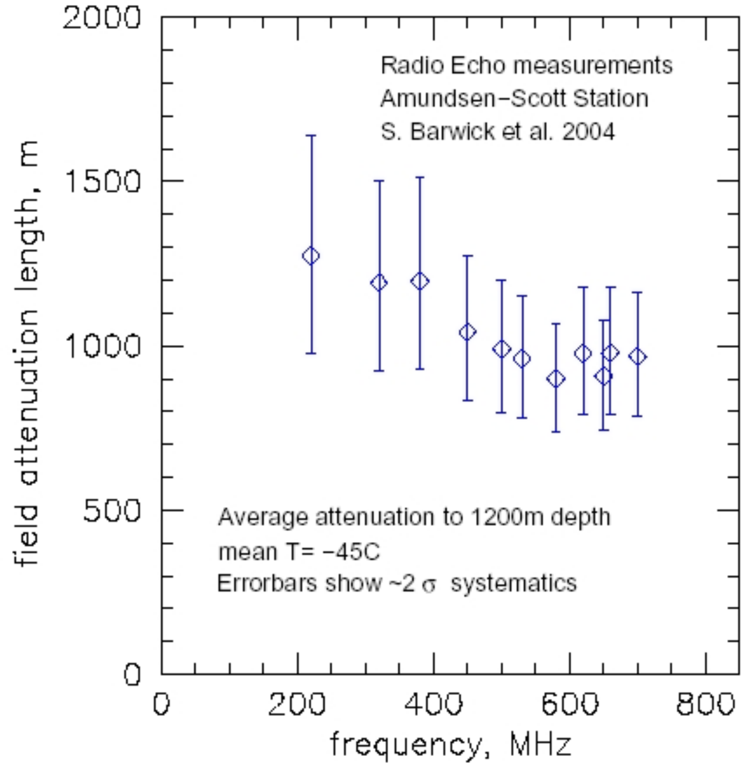
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi^+ \rightarrow \nu$$

Detector volumes of ~100 bigger than current IceCube needed

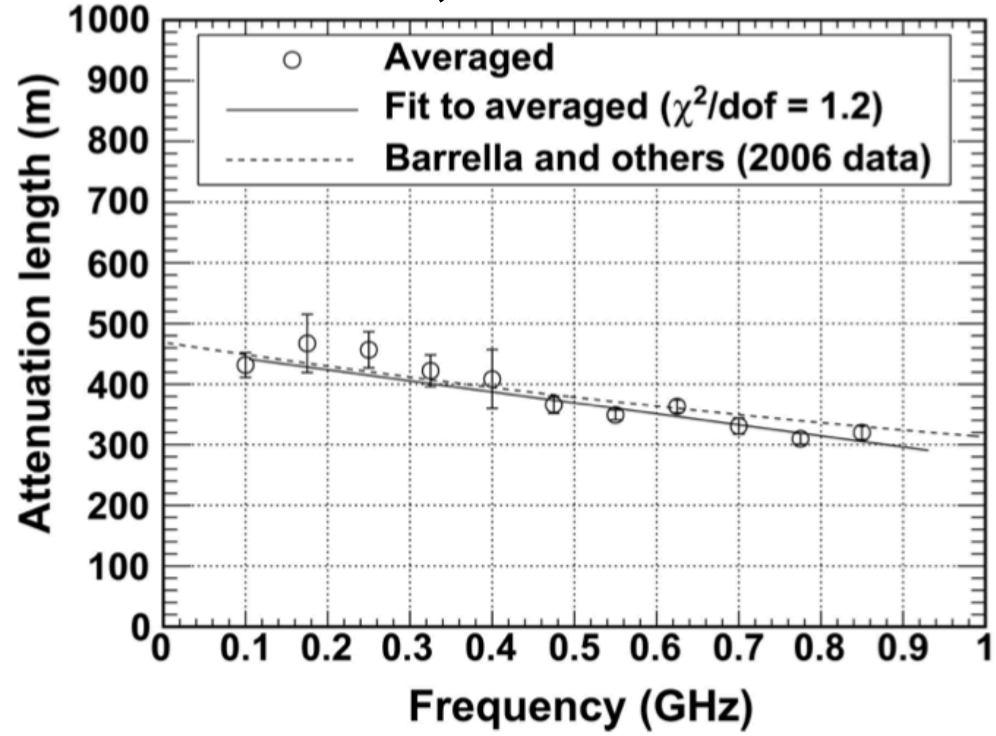
Why radio?

- Large volumes of dense medium with reasonable attenuation length, at no cost

South pole, cold ice: 1km



Ice-shelf, “warmer” ice: 400m



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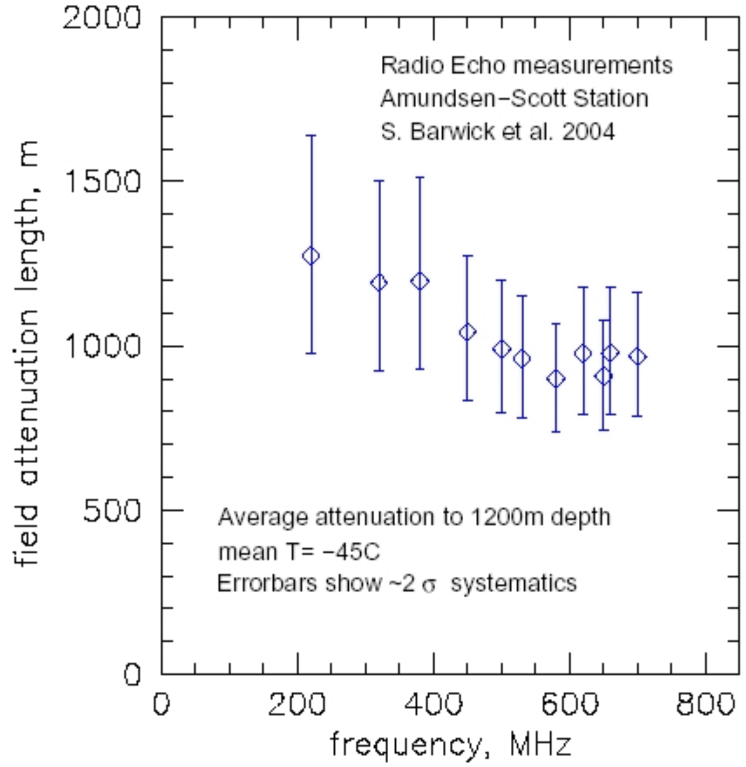

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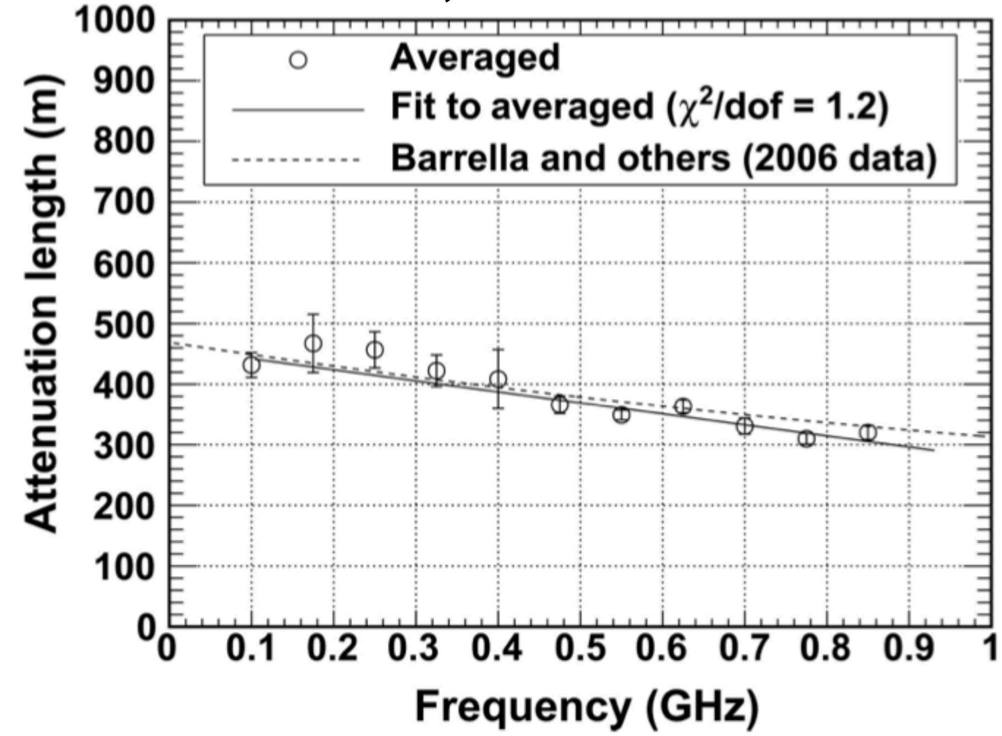
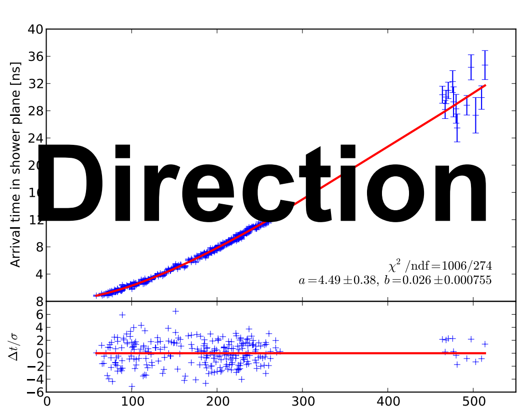
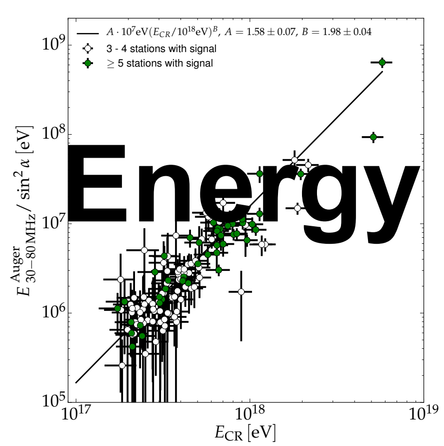
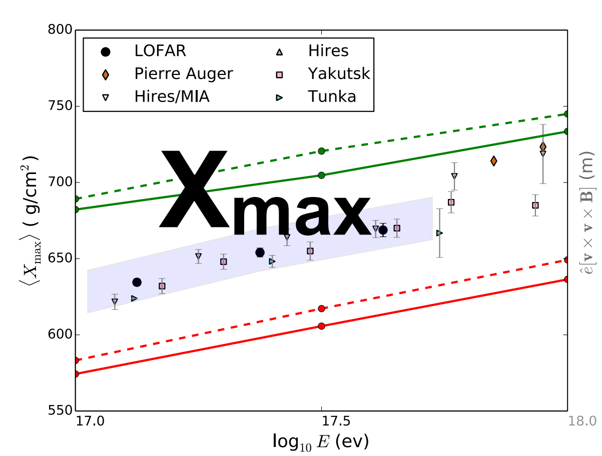
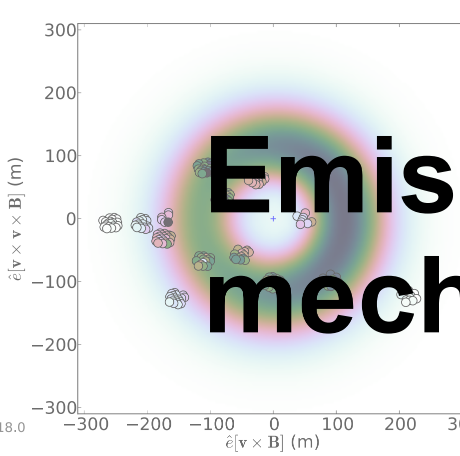


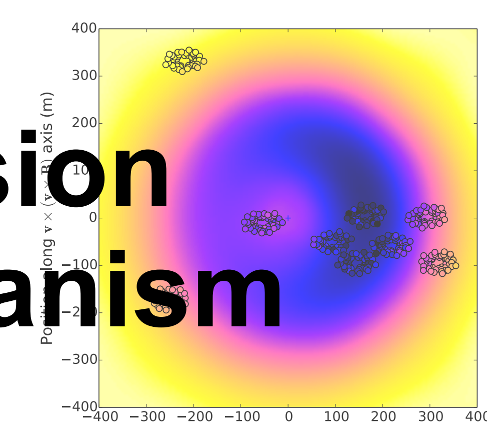
- Air shower arrays (LOFAR, AERA, Tunka-Rex, …) have shown feasibility:





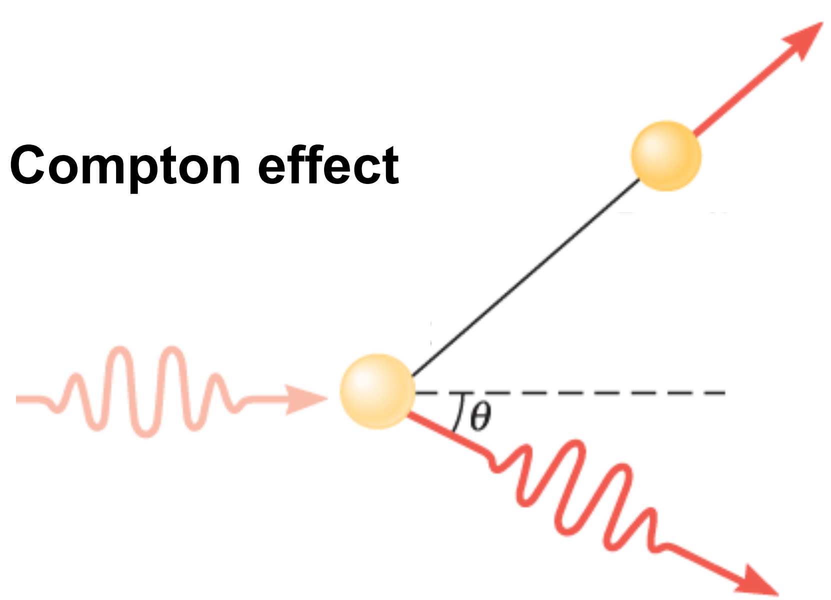


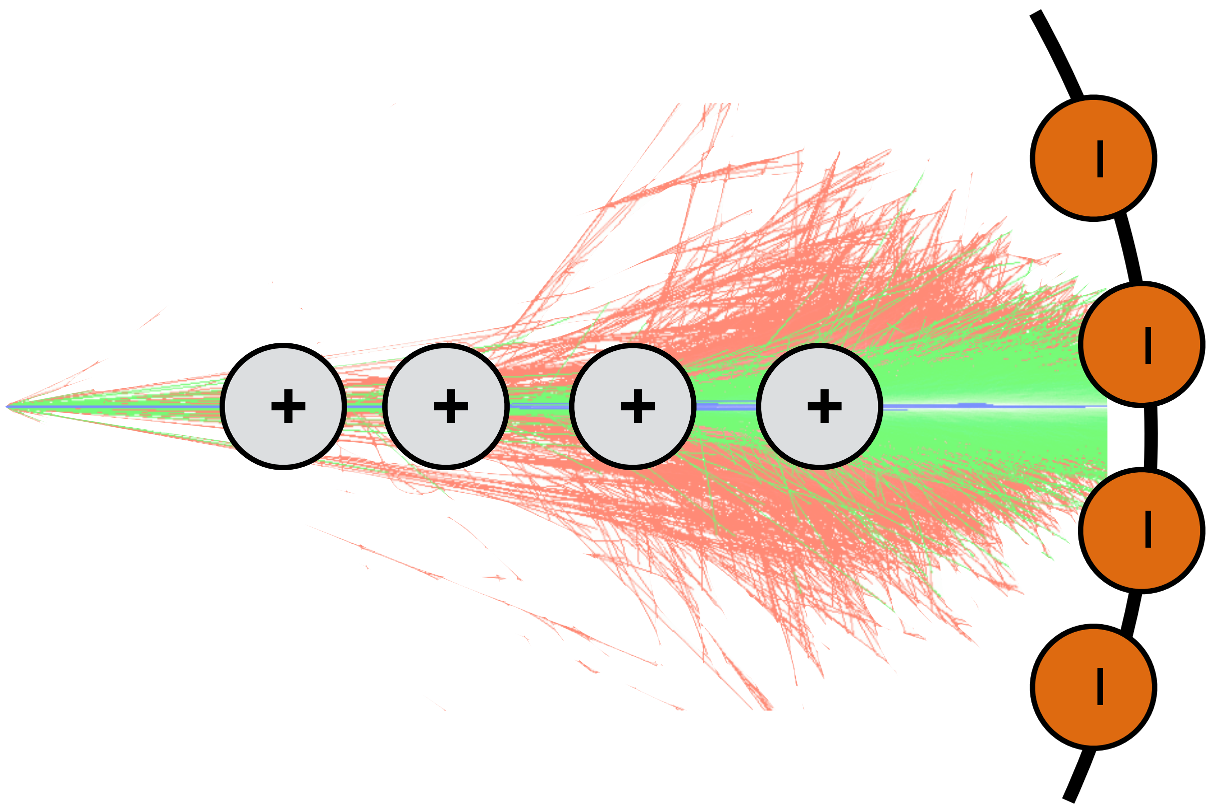




Askaryan effect

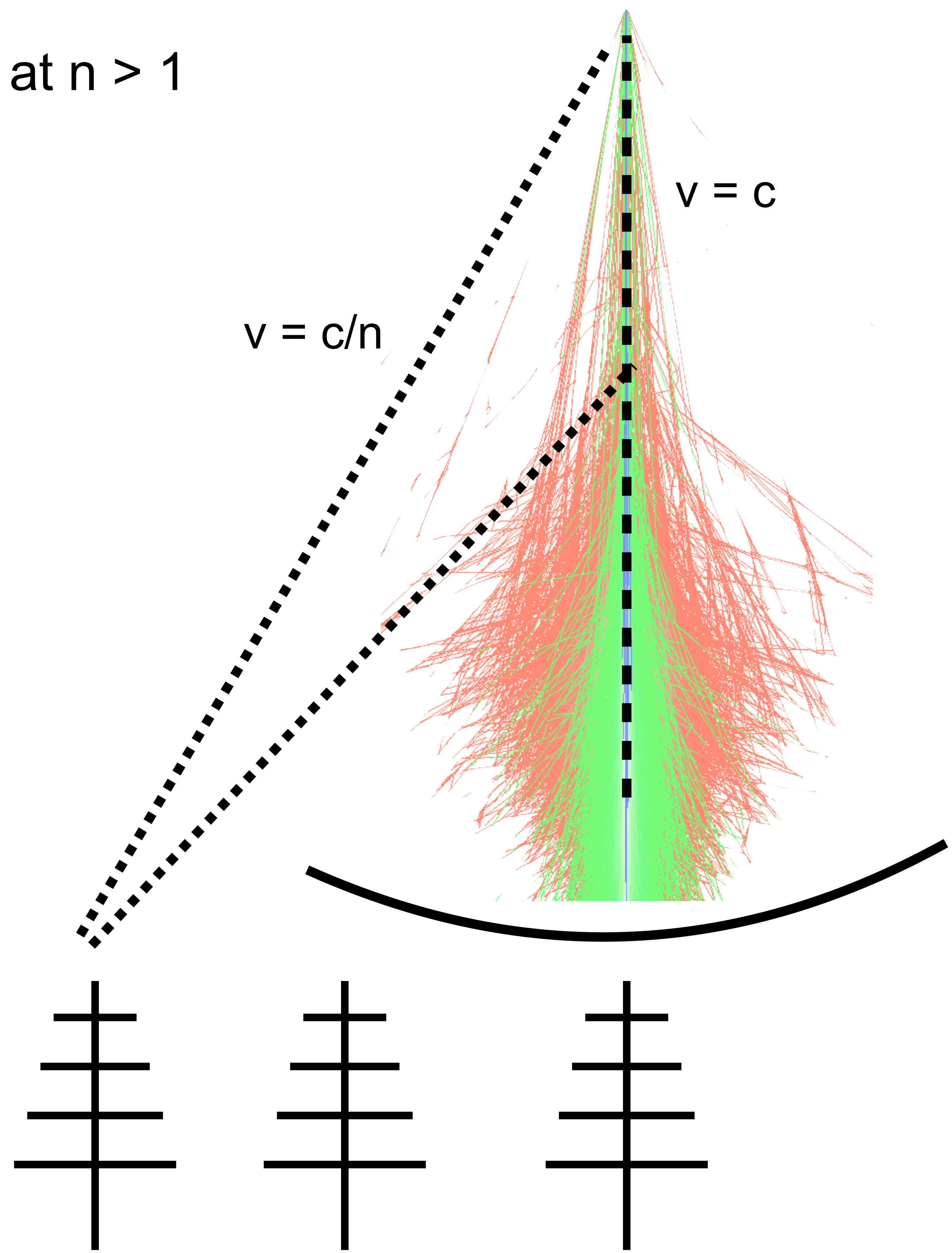
- Neutrino interaction creates (hadronic/electromagnetic) shower
- During shower development, shower front accumulates negative charge
- Macroscopic: Changing current along axis, changing as function of time/distance propagated
- Changing current induces electric emission
- Subtle differences between hadronic and electromagnetic showers





Cherenkov-like effects

- Shower is faster than its emission at n > 1



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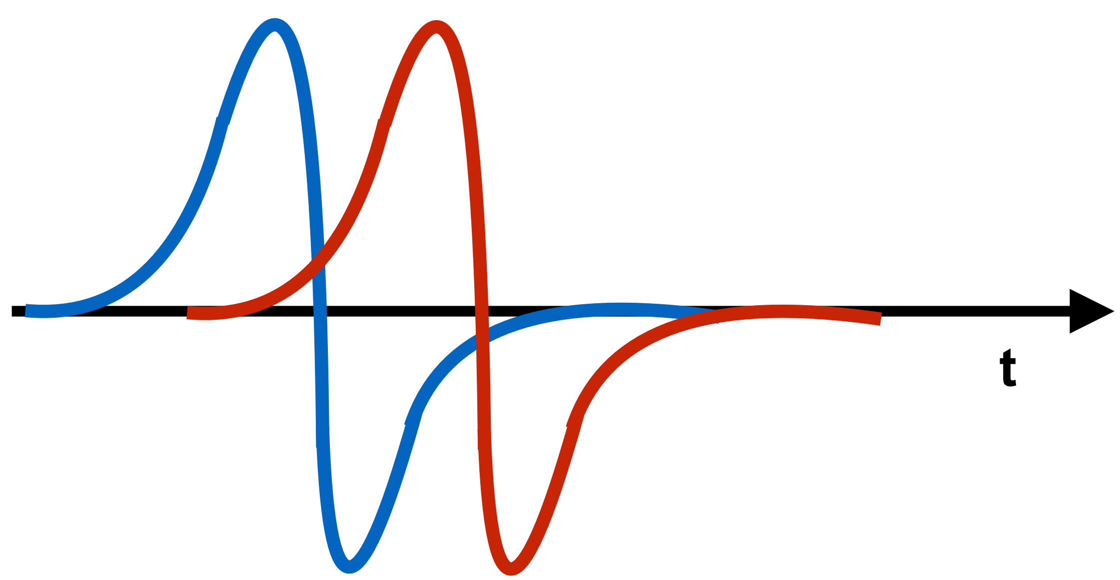
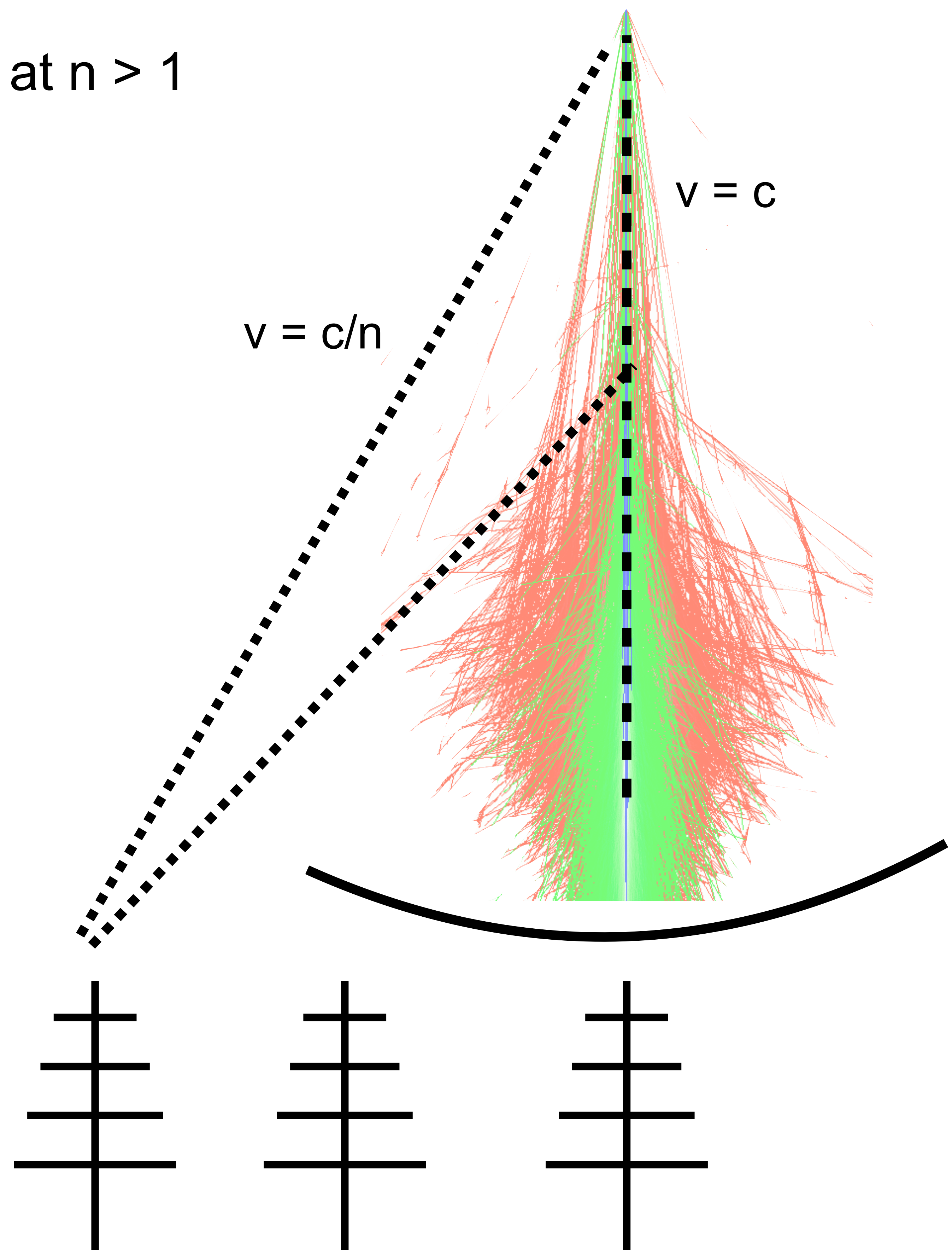




- Signal gets enhanced when it arrives in phase = coherence
- Enhancement at the Cherenkov angle

Experimental concepts

- Several concepts compete to detect ultra-high energy neutrinos

In, on, above ice

this talk
and more detail in Neutrino Astronomy 3, Wed

Experimental concepts

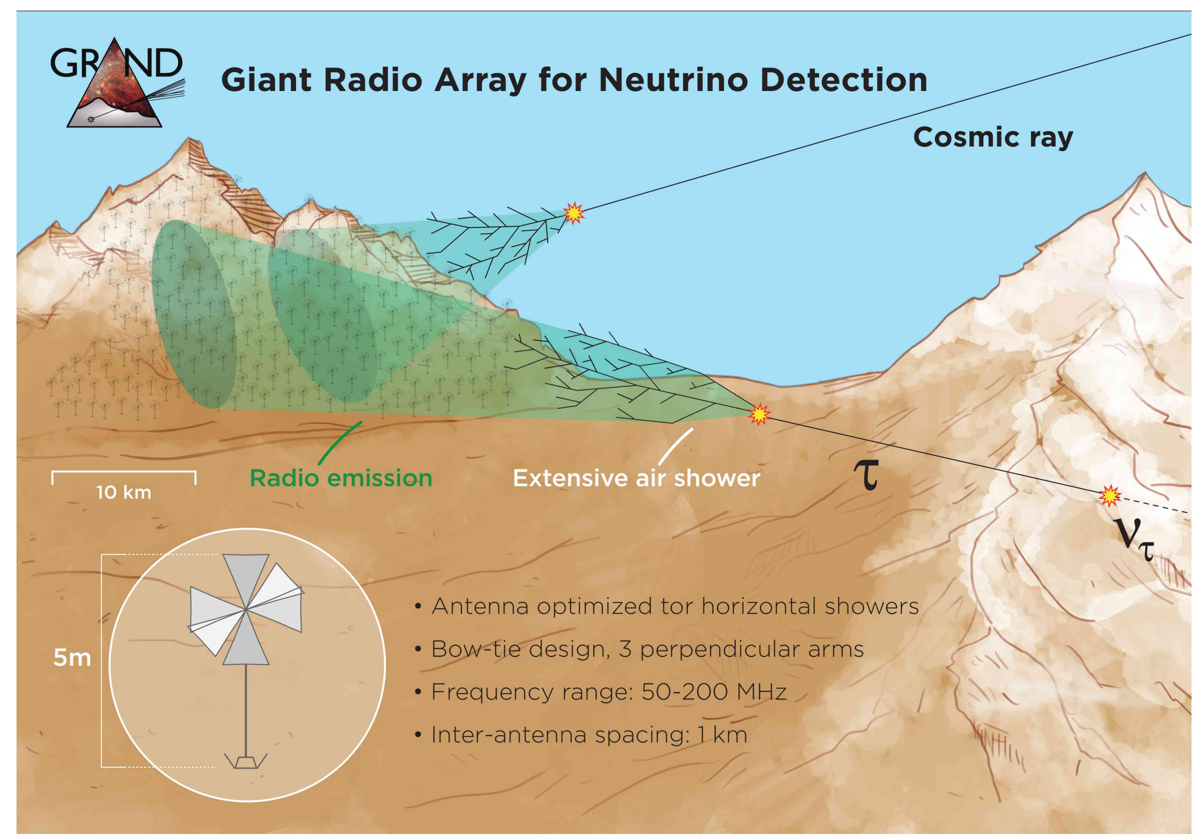
- Several concepts compete to detect ultra-high energy neutrinos

In, on, above ice

this talk
and more detail in Neutrino Astronomy 3, Wed

Near, on, at mountains

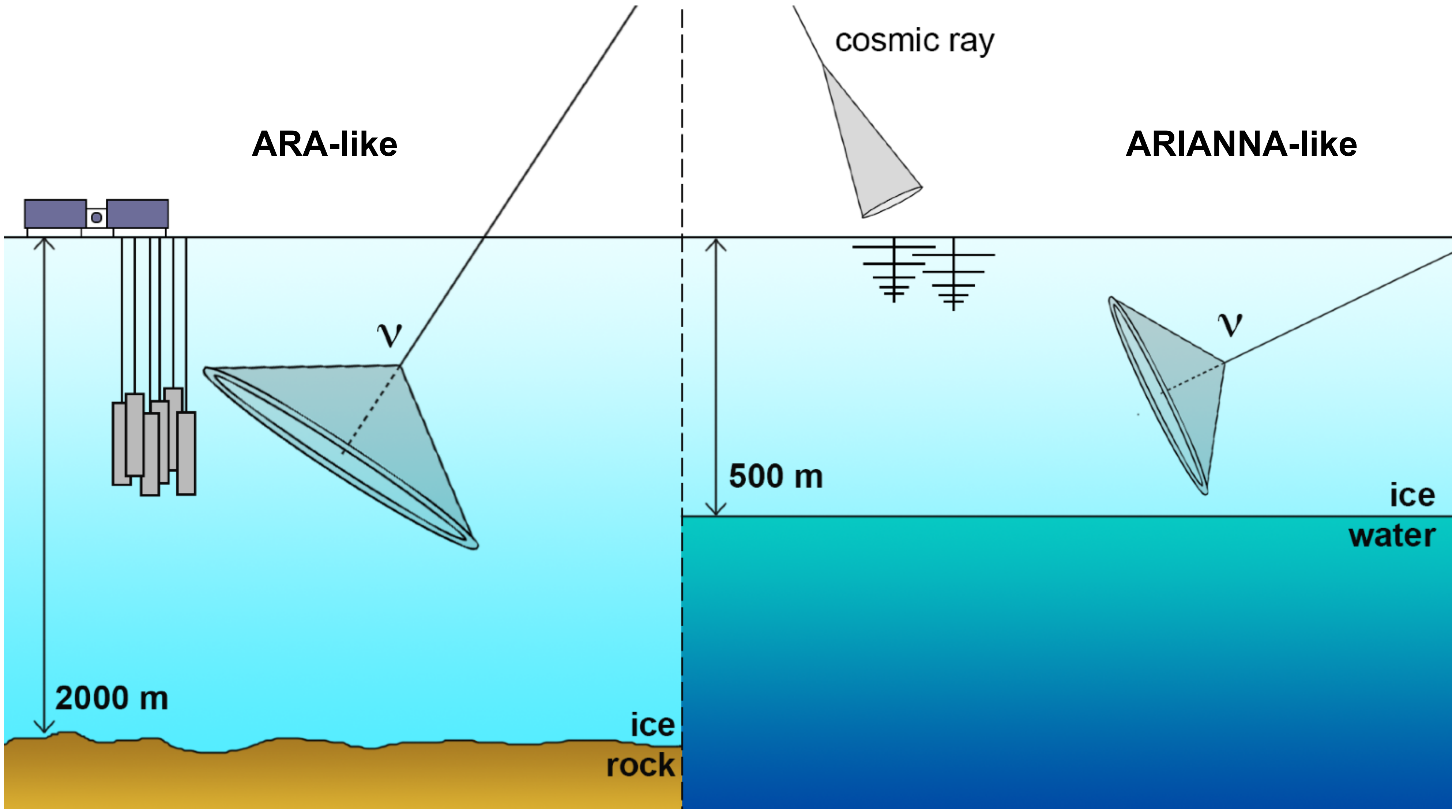
GRAND, TAROGE, BEACON, …



see talk Tuesday by Kotera and
poster by Bustamante

Experimental concept

- Several concepts compete to detect ultra-high energy neutrinos
- Main difference: Deep vs. shallow
  - Attached: cost/effective volume, background rejection, sky coverage, energy and direction resolution, power consumption, …



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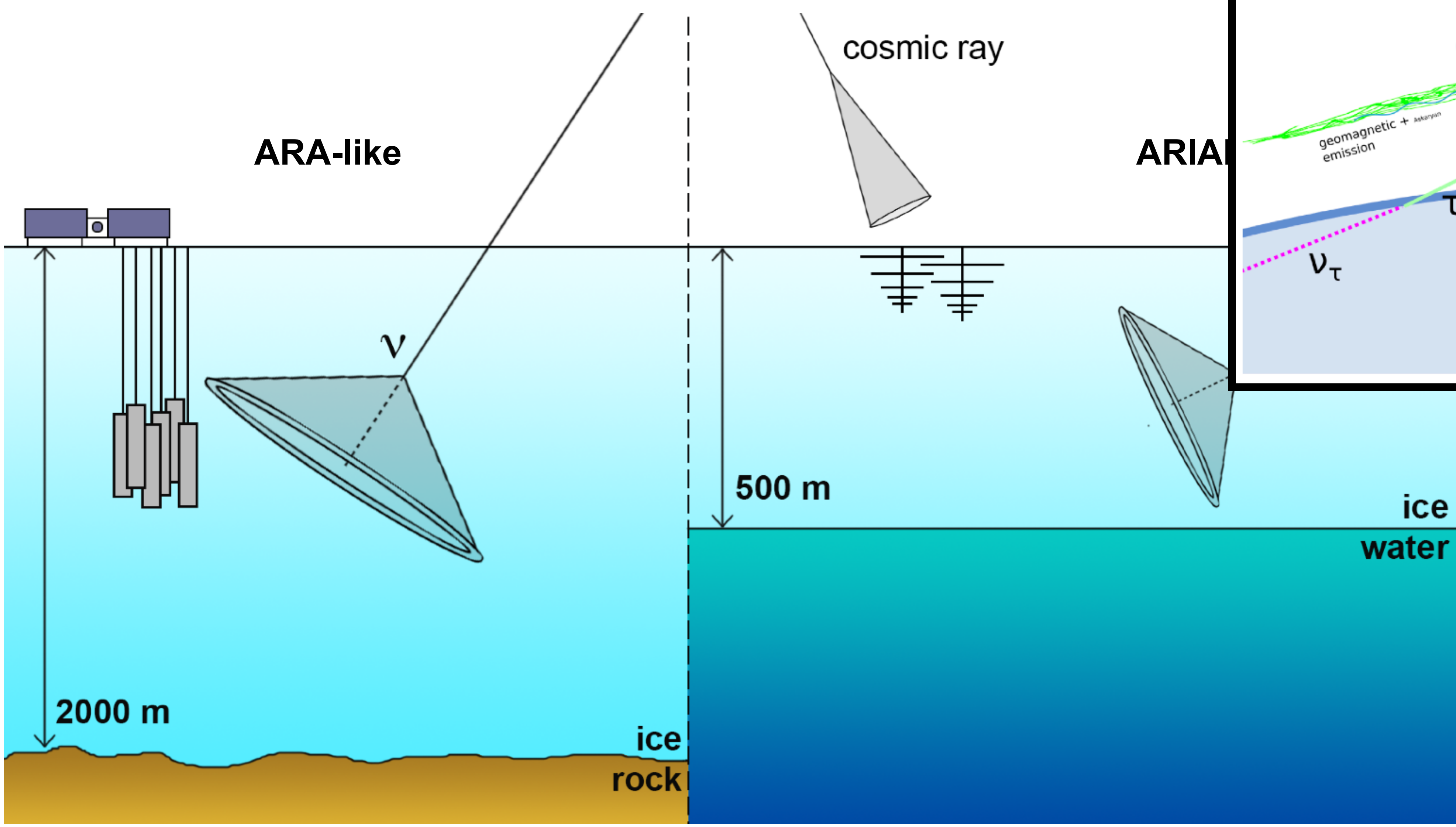
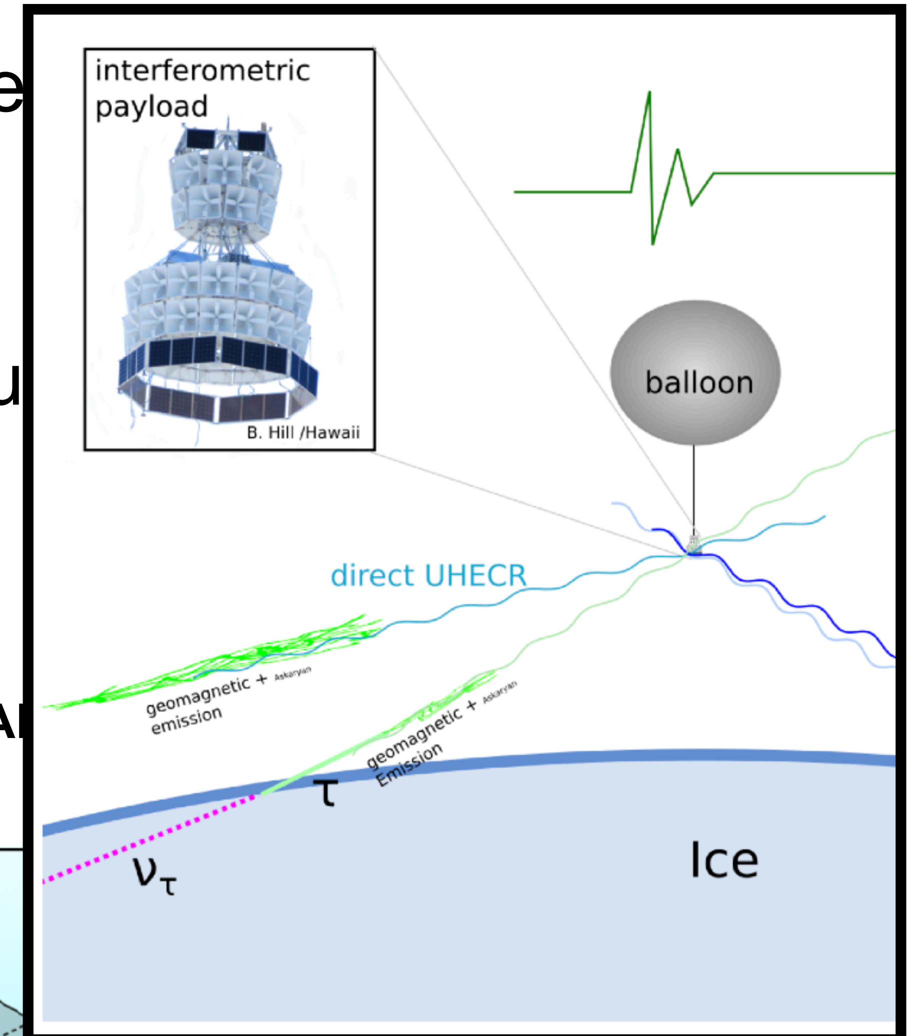


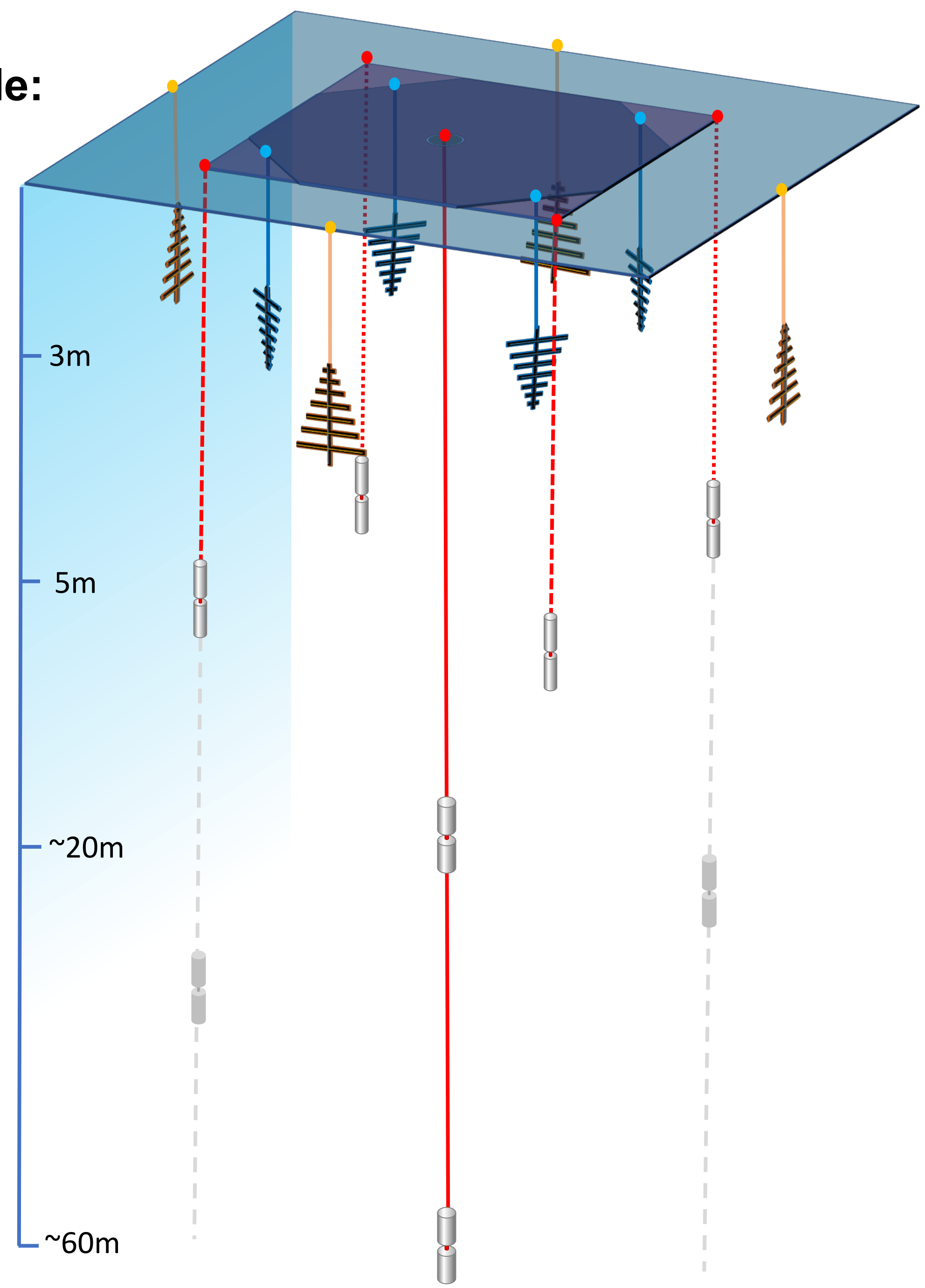


see Strutt,
Neutrino Astronomy 3

Experimental concept

- The future: pick and choose the best components

For example:



- **Deep:** better ice, larger effective volume per antenna, farther away from human background, higher costs, limited by borehole geometry, likely better energy resolution
- **Shallow:** better cosmic ray rejection, more flexibility in antenna design, cheaper, likely better polarization (=direction) resolution
- **Combine the best of both**

Experimental concept

+ some “technical details” …

Power:

OR

Comms:

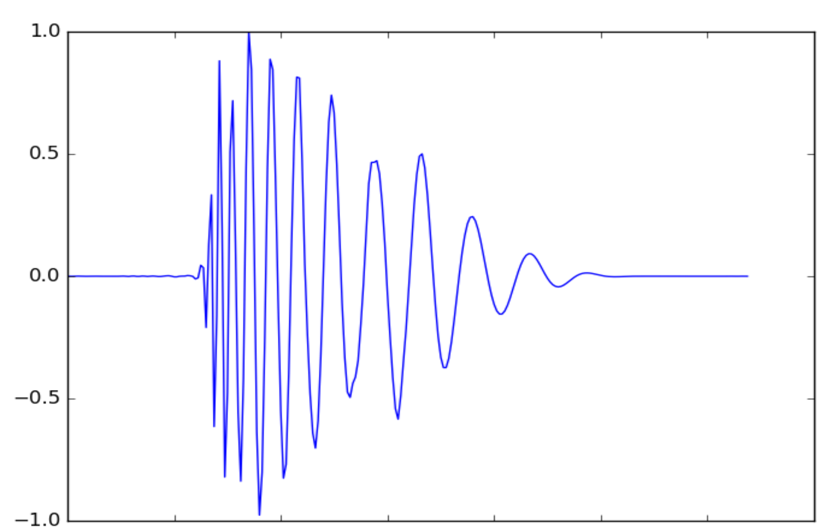
OR

DAQ boards, trigger strategy, …

Results so far

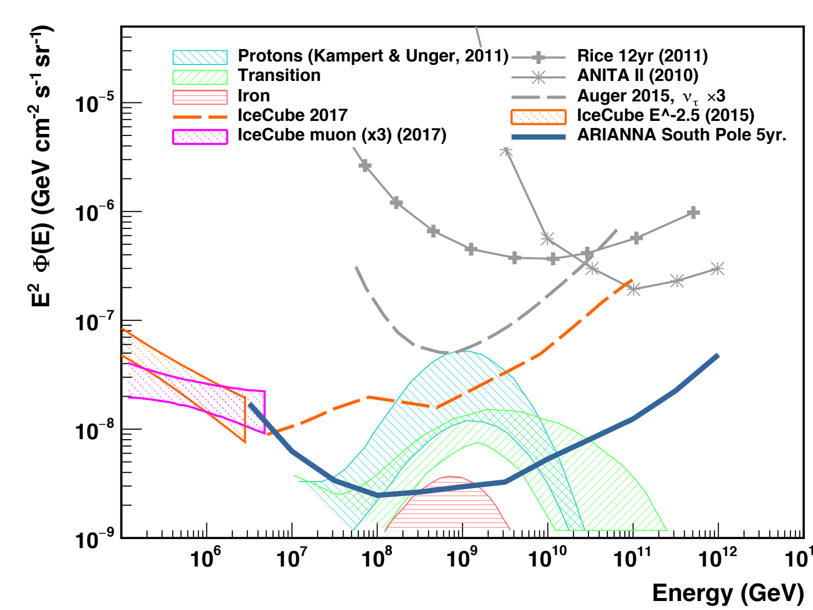
BACKGROUNDS

SIGNALS



140 ns

SENSITIVTIES

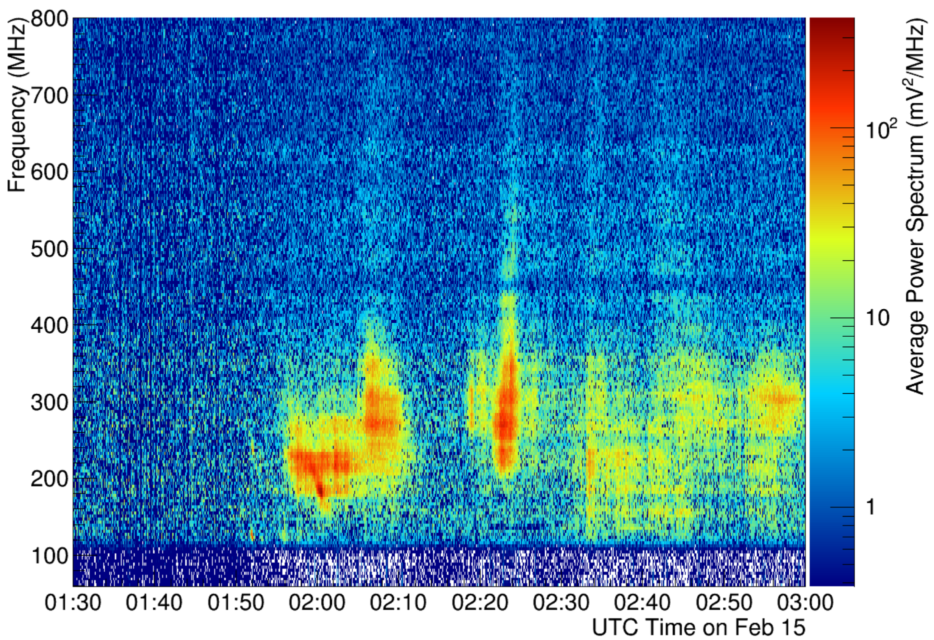


Backgrounds

- ***If detector can distinguish in-air signals from in-ice signals, no particle physics background***

- **Astronomical background:** Diffuse Galactic emission (not pulse-like) and solar flares (point to sun)

ARA Coll.



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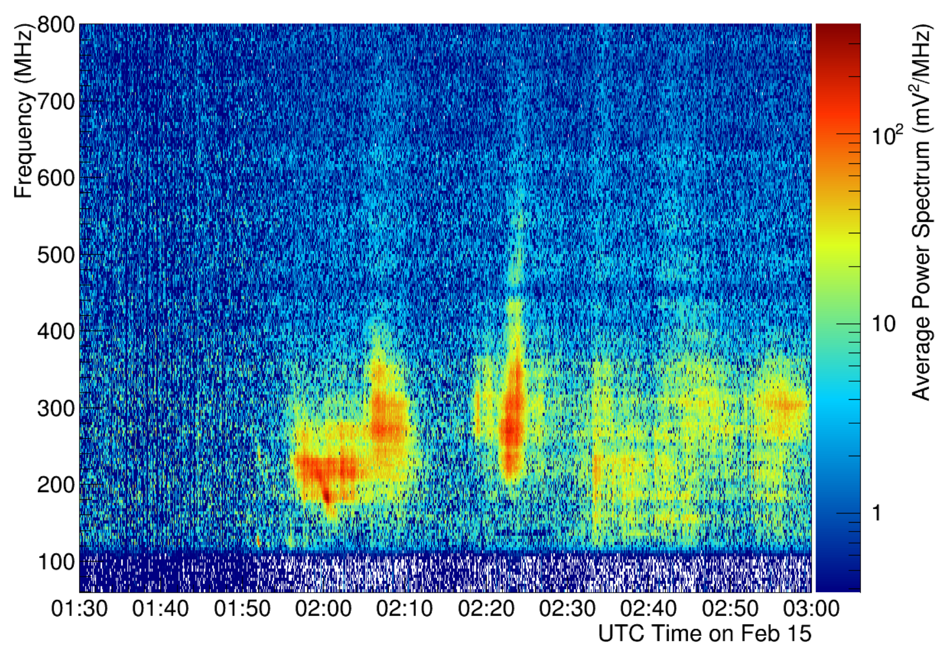
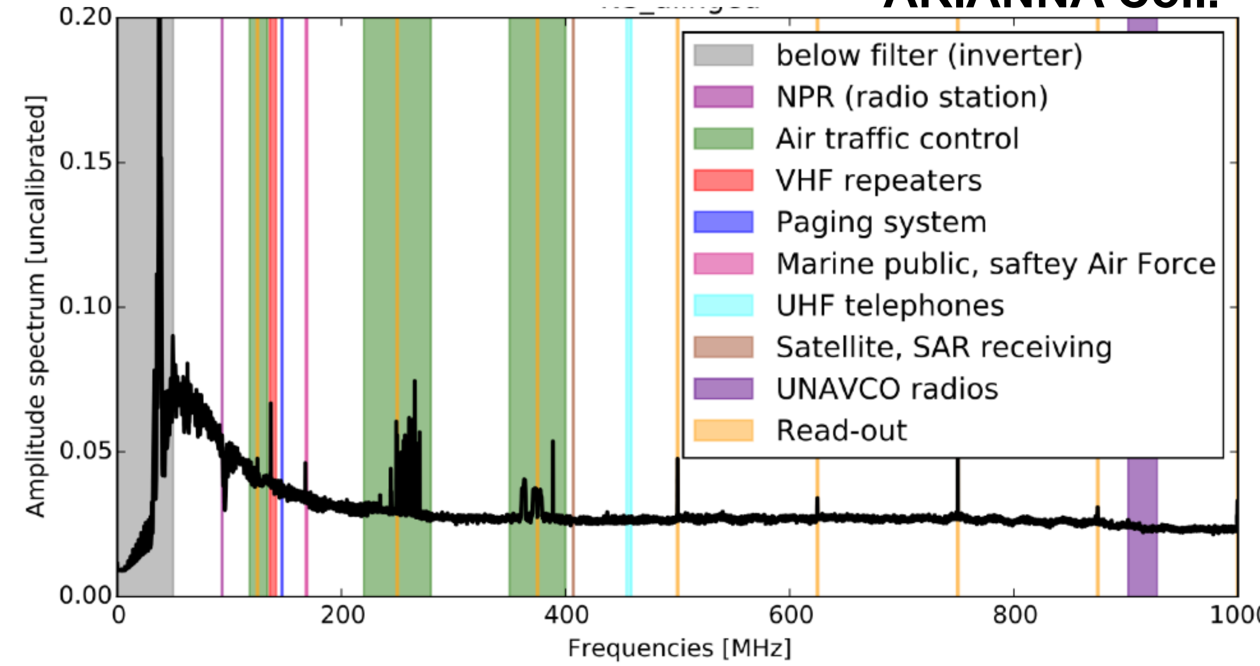


- Most *dangerous* background: humans

ARIANNA Coll.



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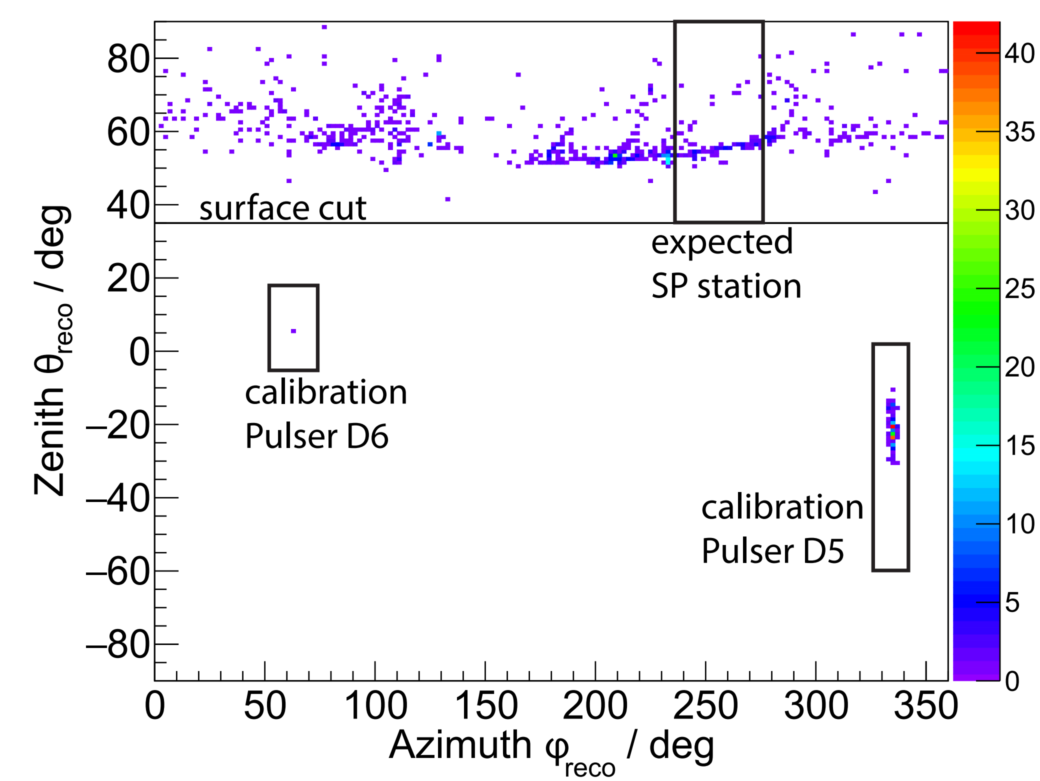
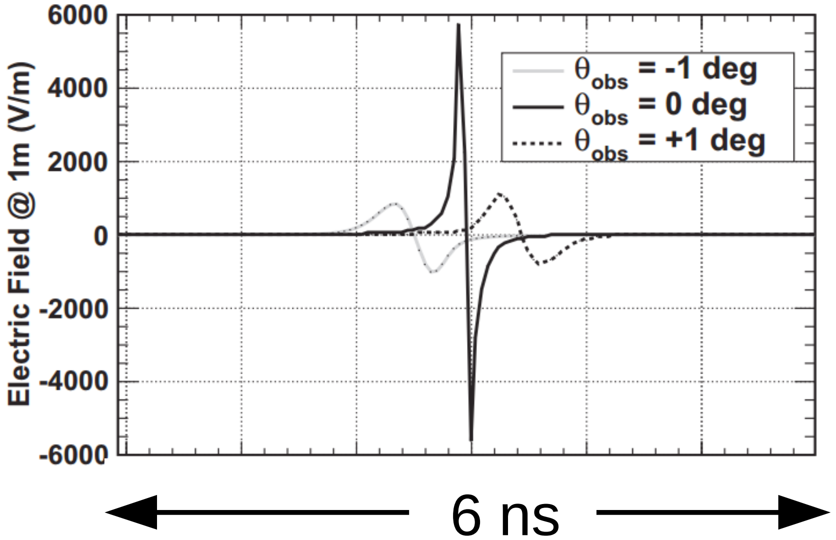


(One) Signal search strategy

Simulated signal



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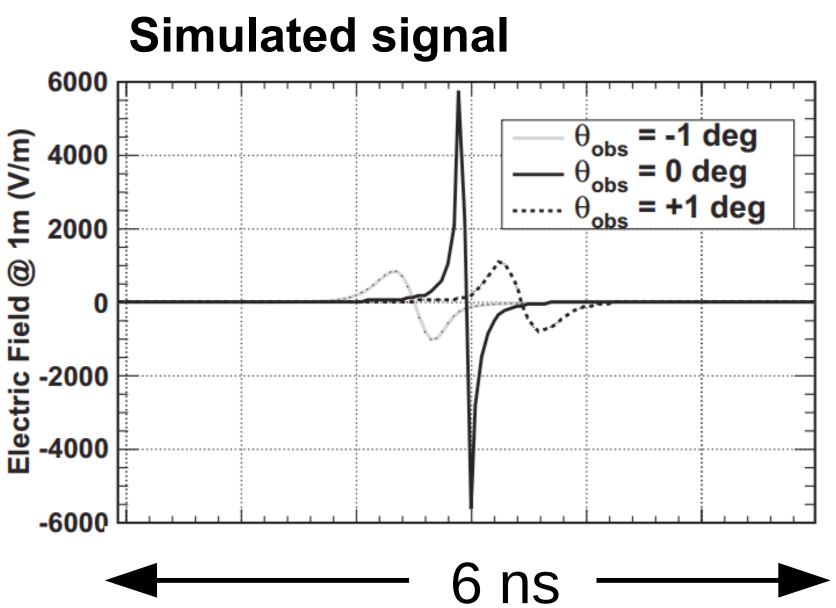

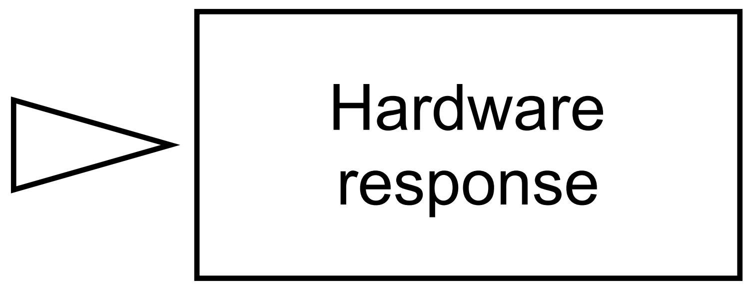

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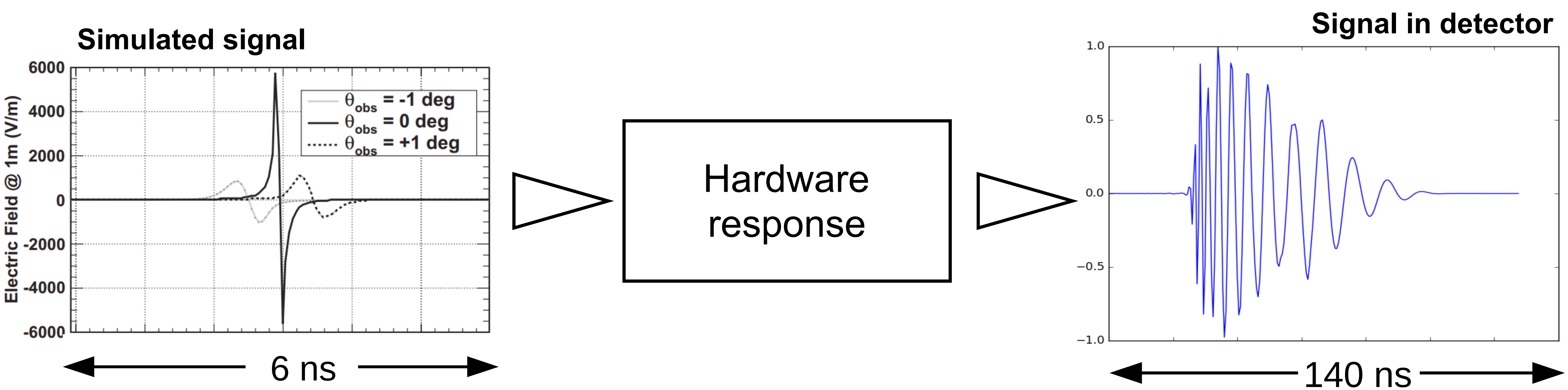

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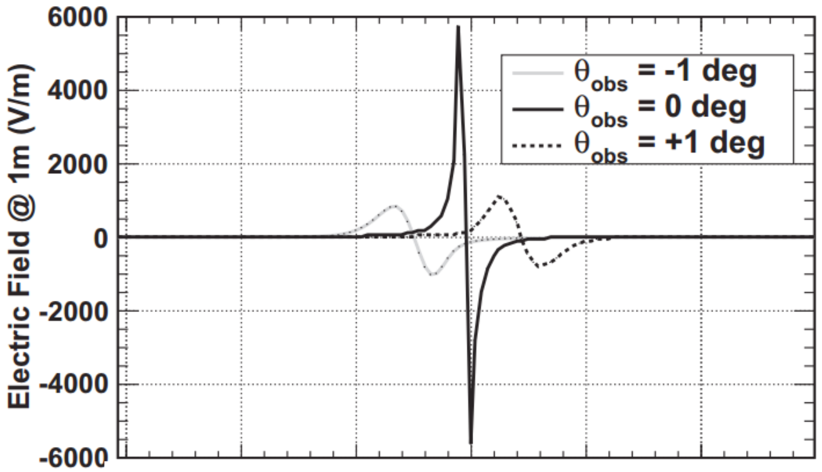
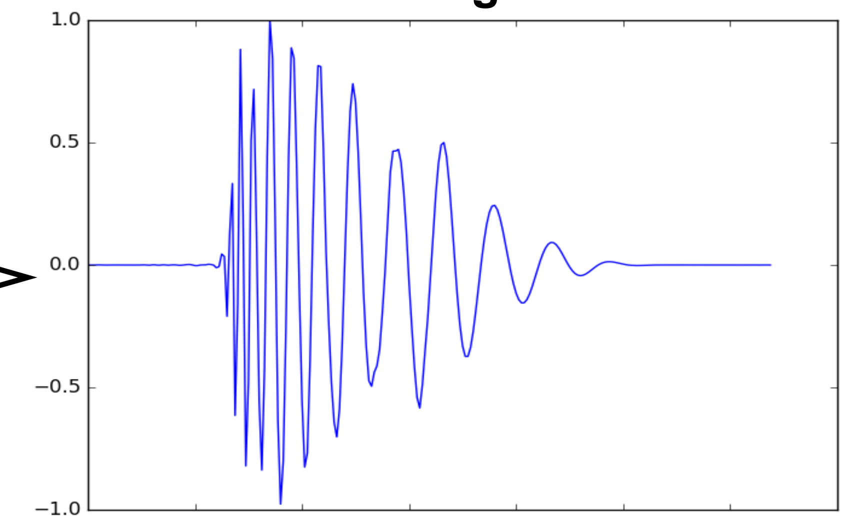


6 ns

Hardware response

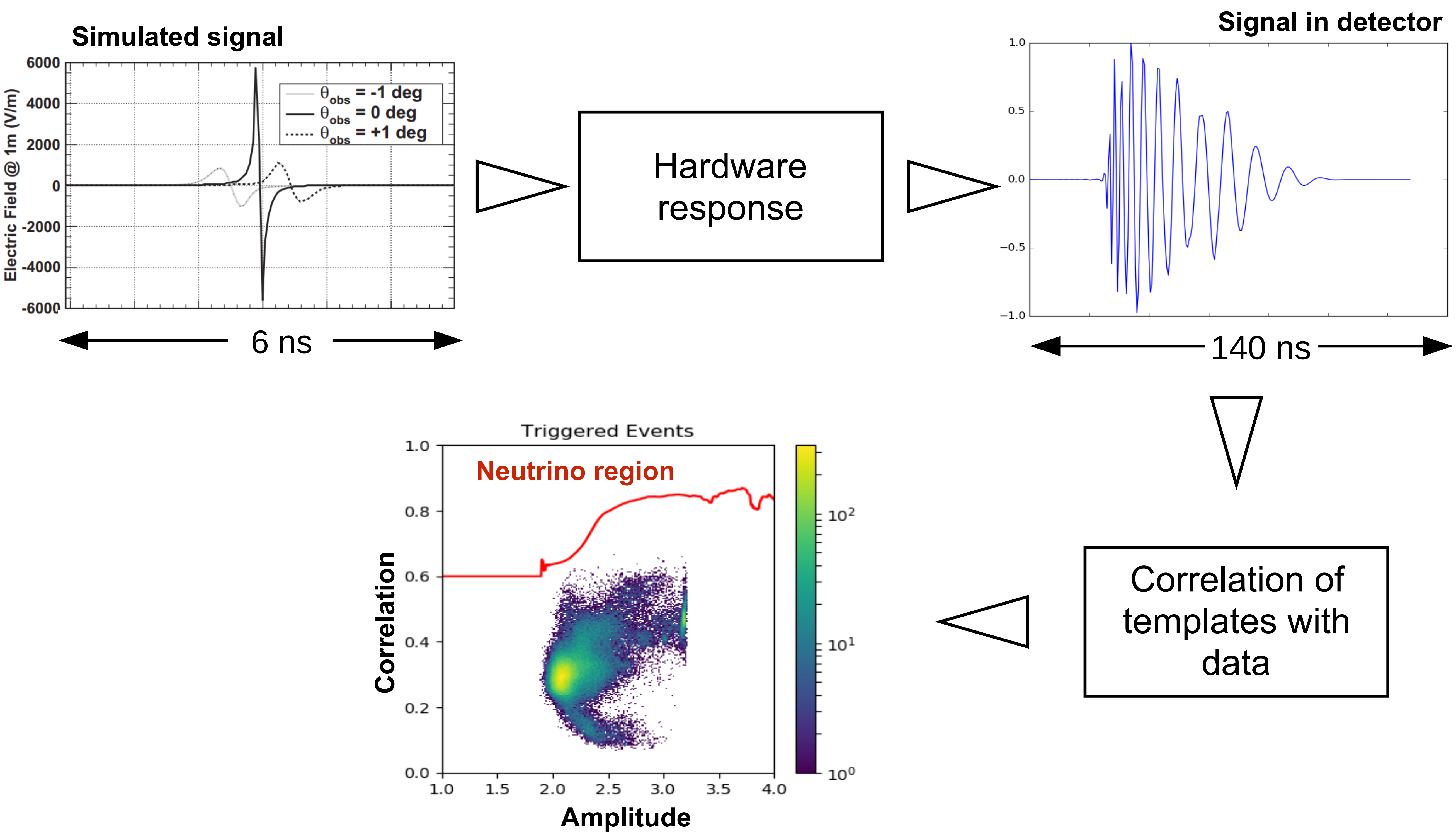
Signal in detector



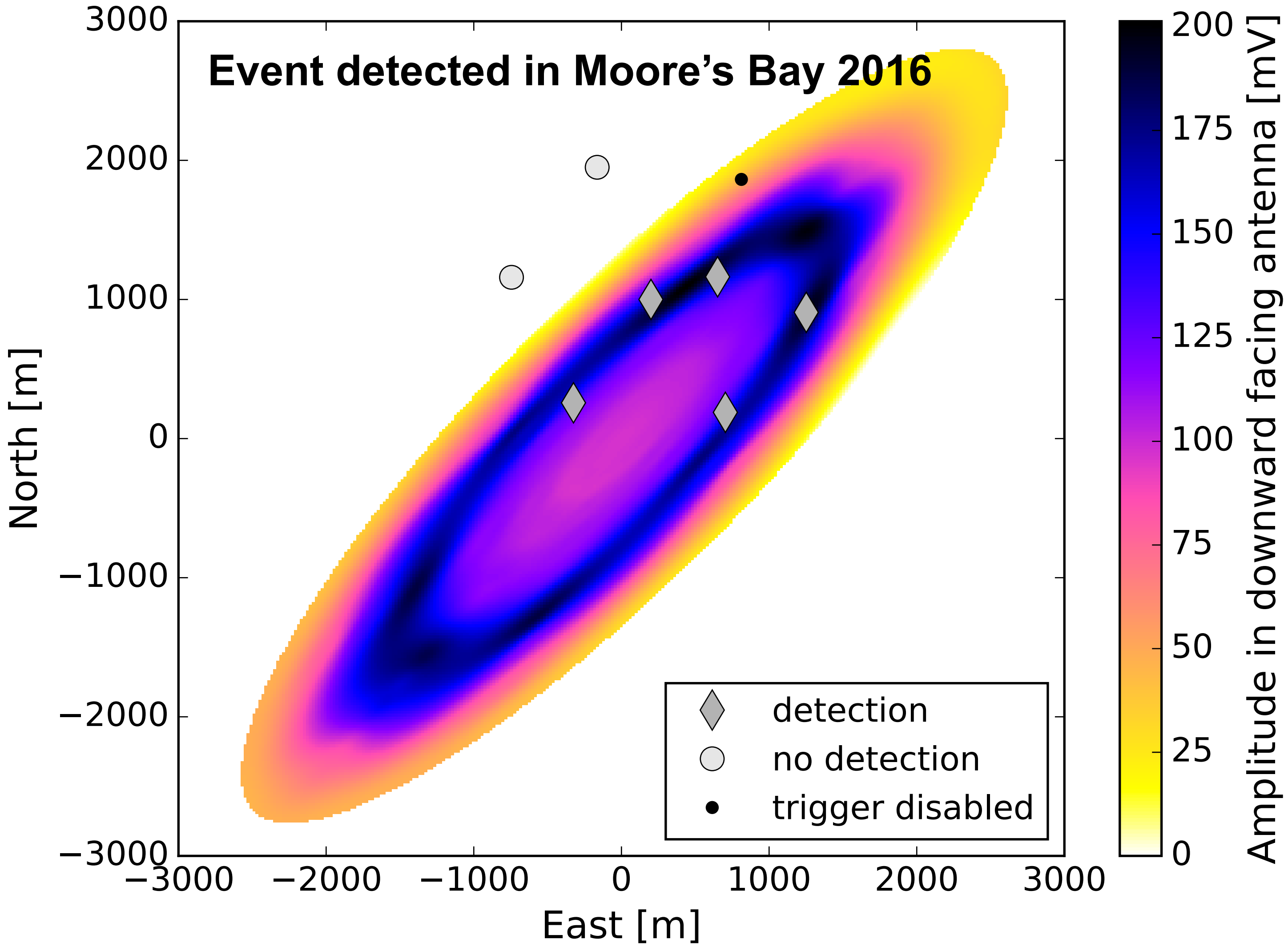
140 ns

Correlation of templates with data

(One) Signal search strategy

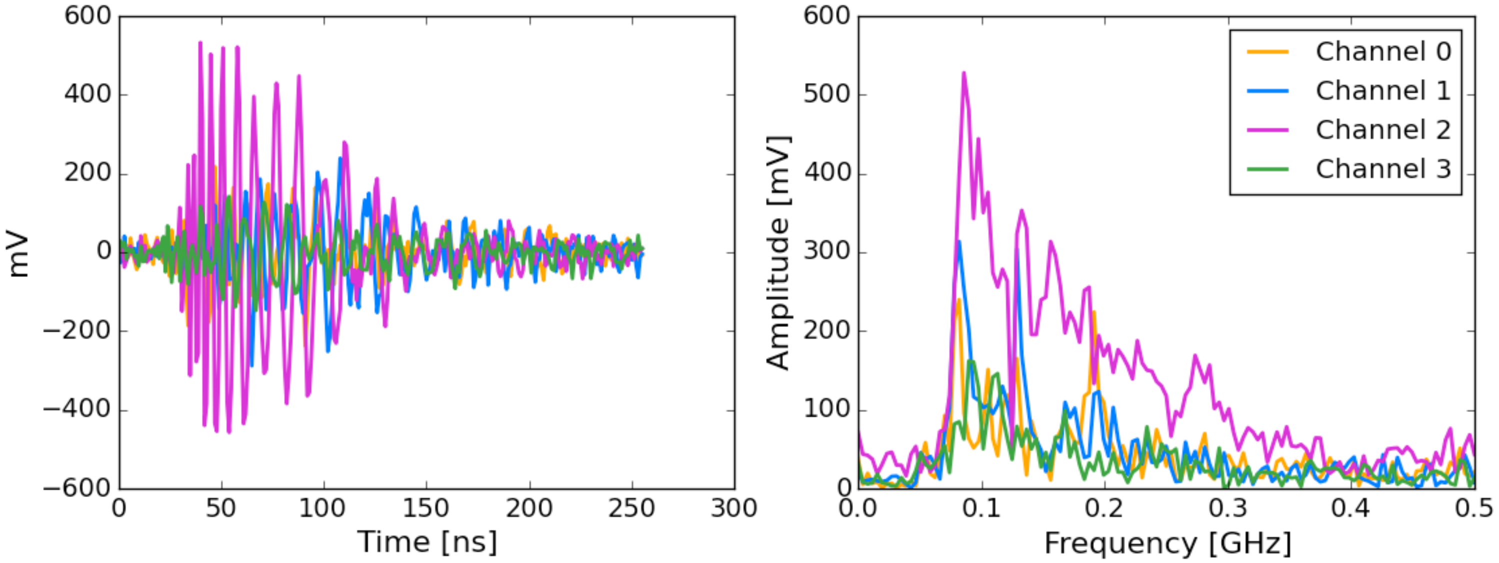


Cosmic rays



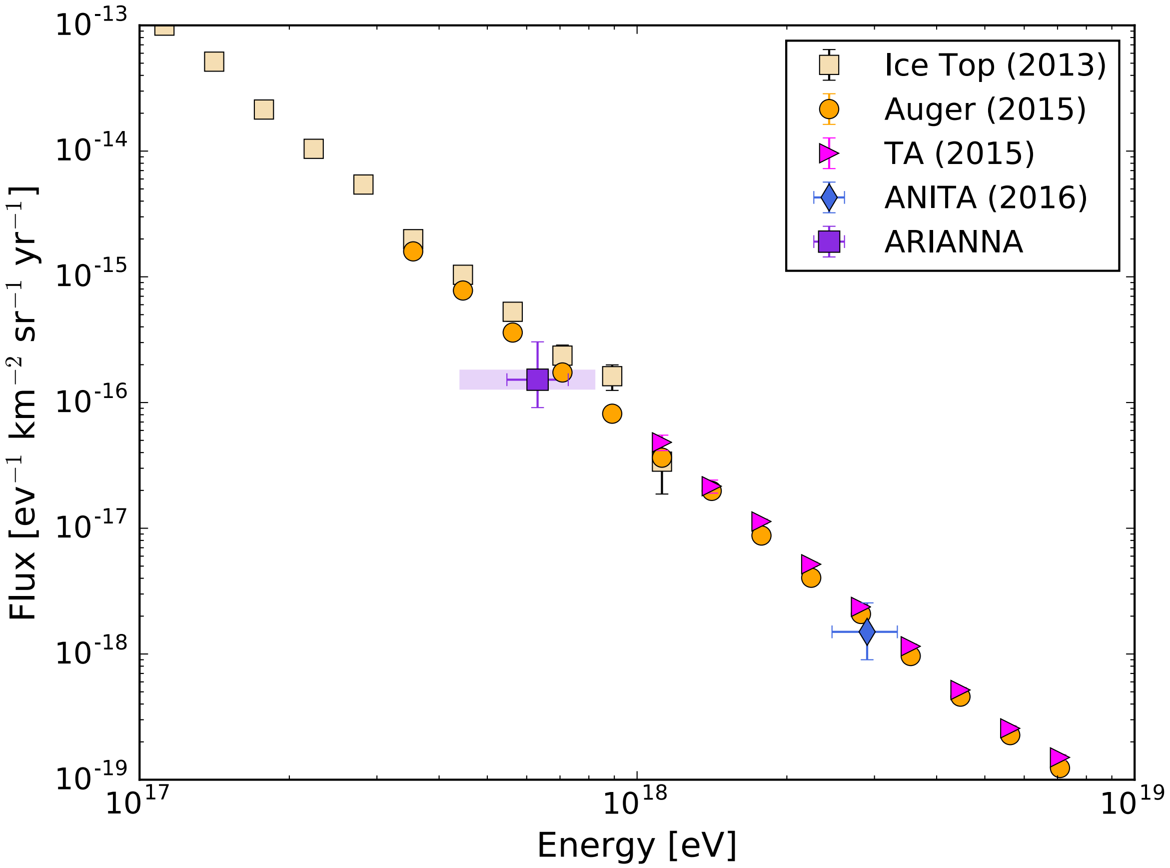
- Since arrays are very small, no neutrino detection yet
- But cosmic rays act as proof-of-principle

Astroparticle Physics 90 (2017) 50-68



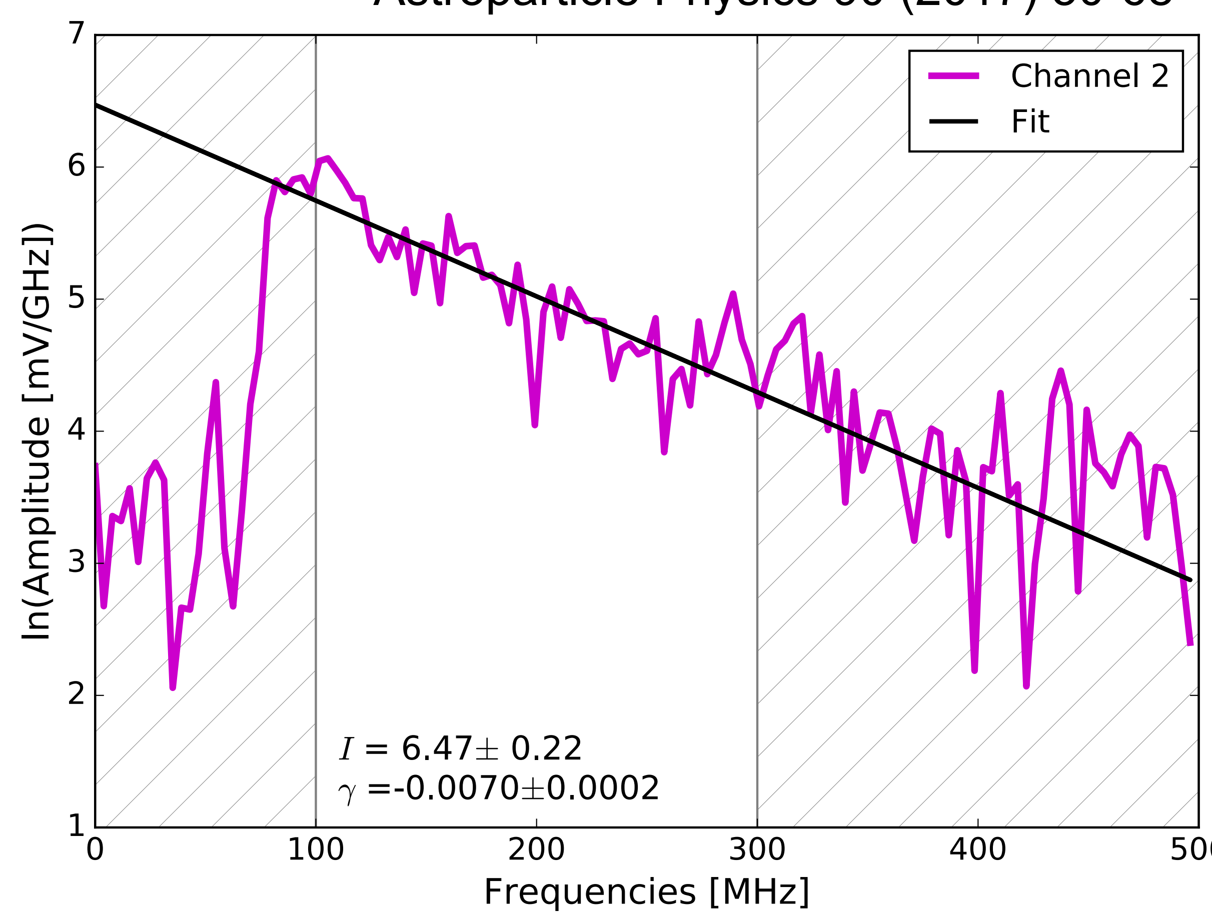
- Both calibration signals and science case itself

Cosmic rays



- Neutrino detectors work in a different frequency range than cosmic ray radio detectors
- Broad-band response provides opportunities, but new algorithms needed

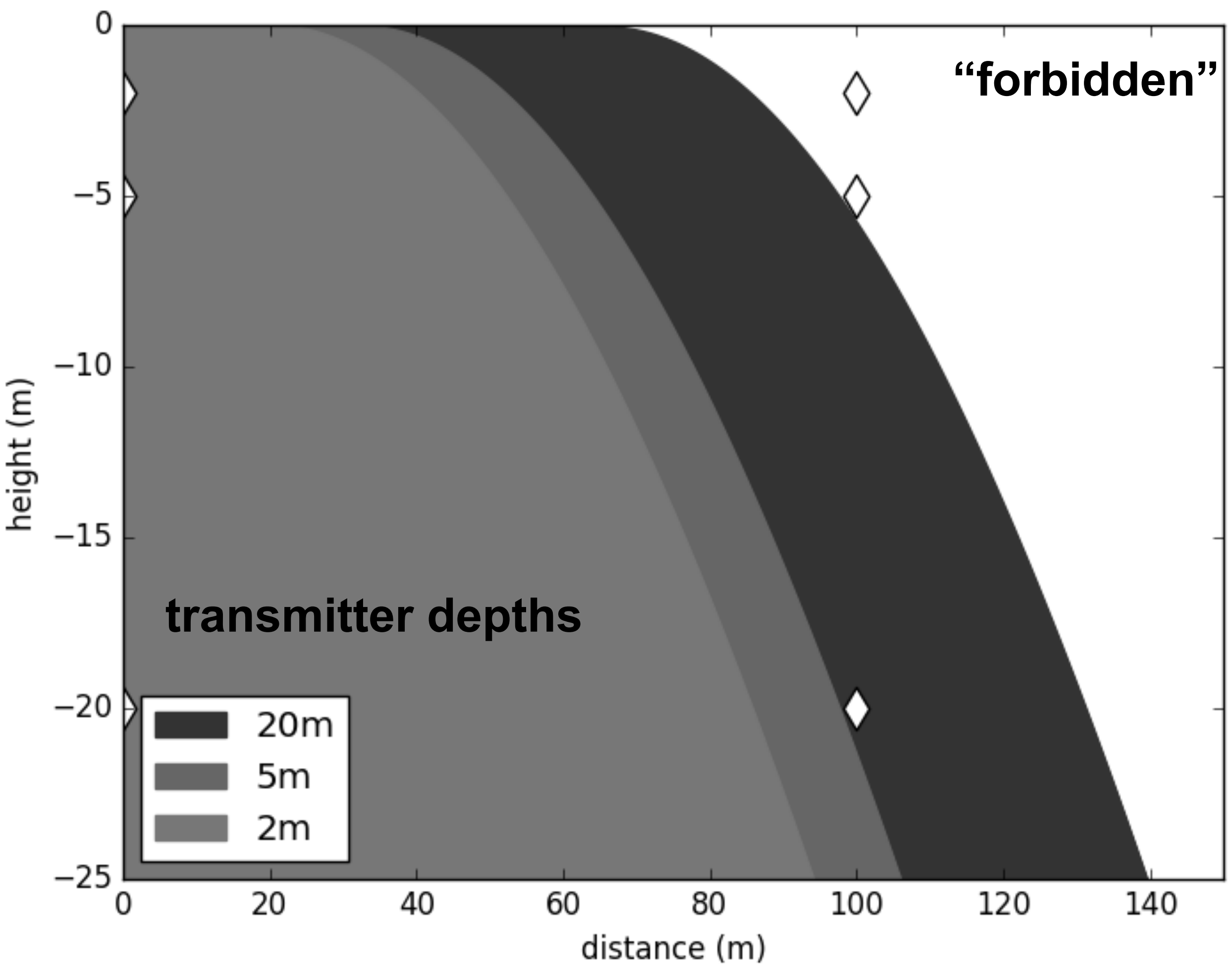
Astroparticle Physics 90 (2017) 50-68



- For example: Combination out integral and slope is excellent **energy estimator**
- Work in progress

Signal propagation

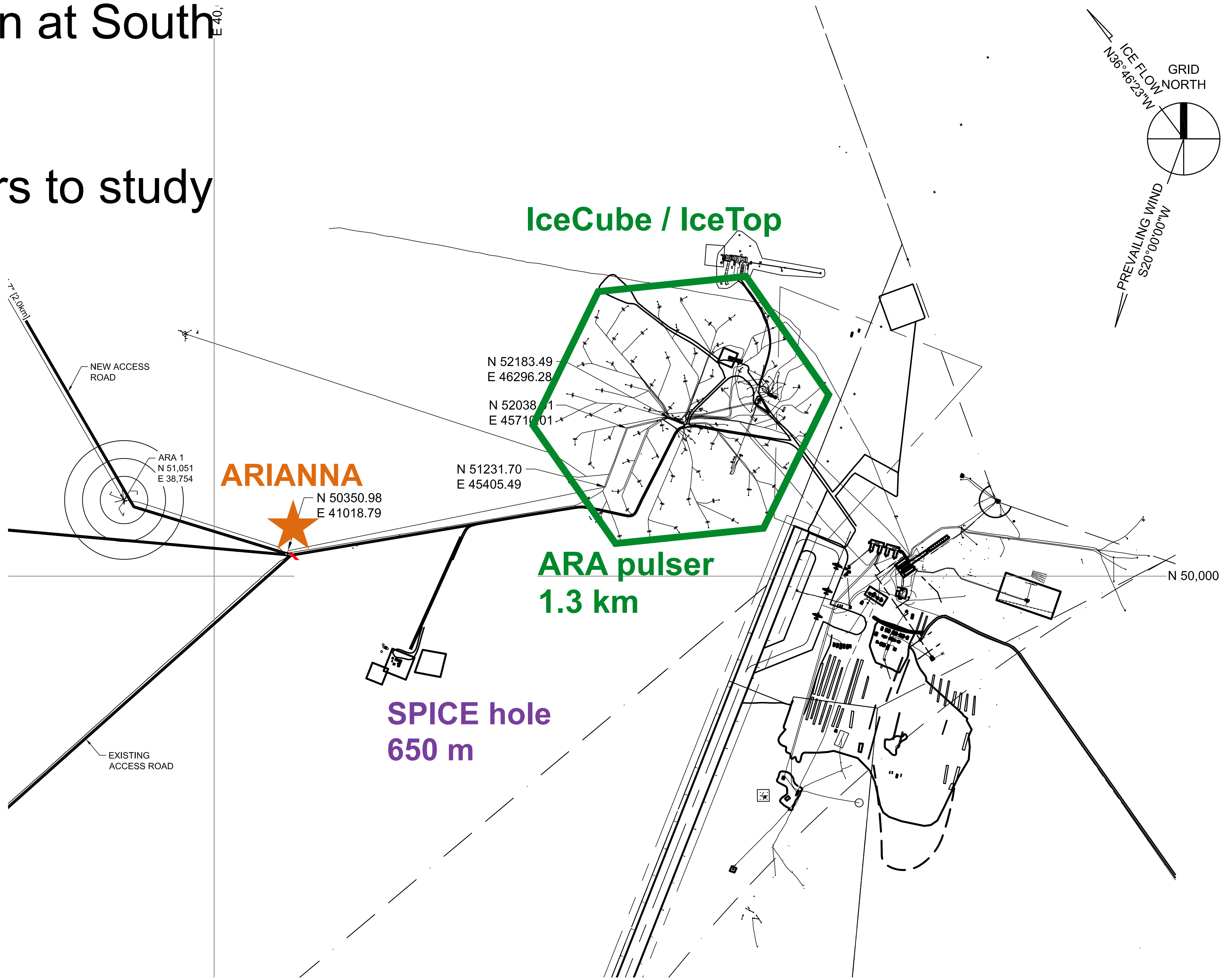
JCAP 07(2018)055



- Polar ice has a density gradient with depth
- Classically, signals will be bent towards higher densities, leading to "forbidden" regions
- Strongly affects effective volume of neutrino detectors as certain signals will be unable to reach detector

Signal propagation

- ARIANNA station at South Pole:
- Use deep pulsers to study ice and station performance



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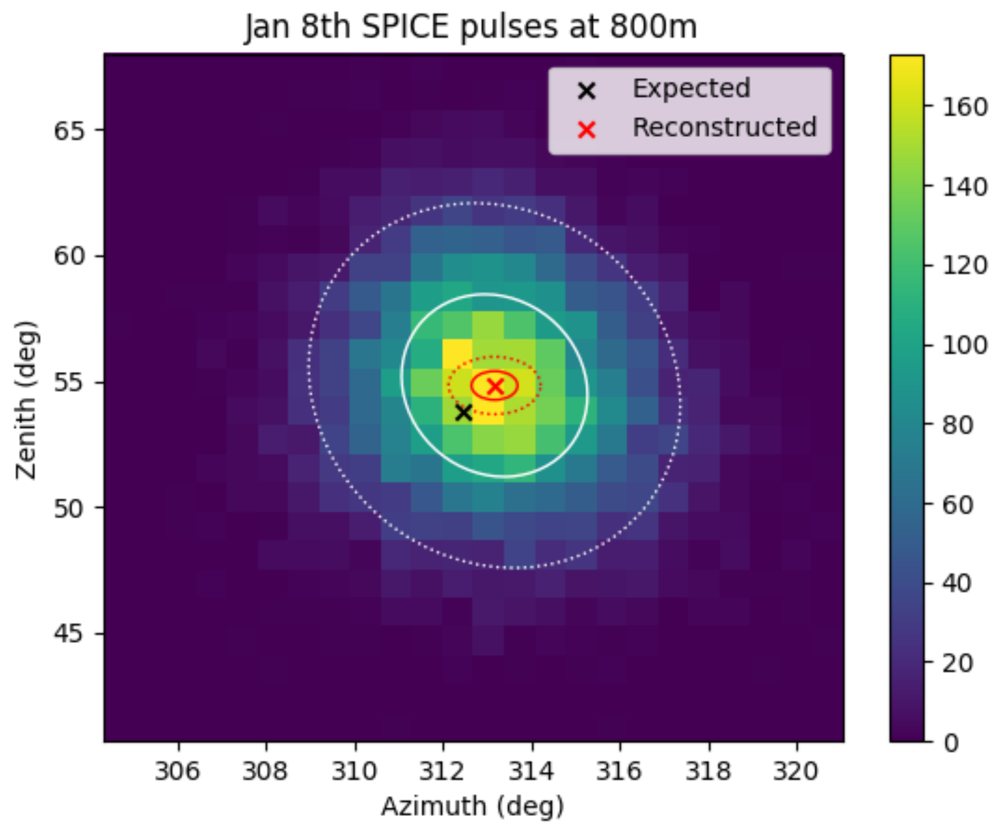
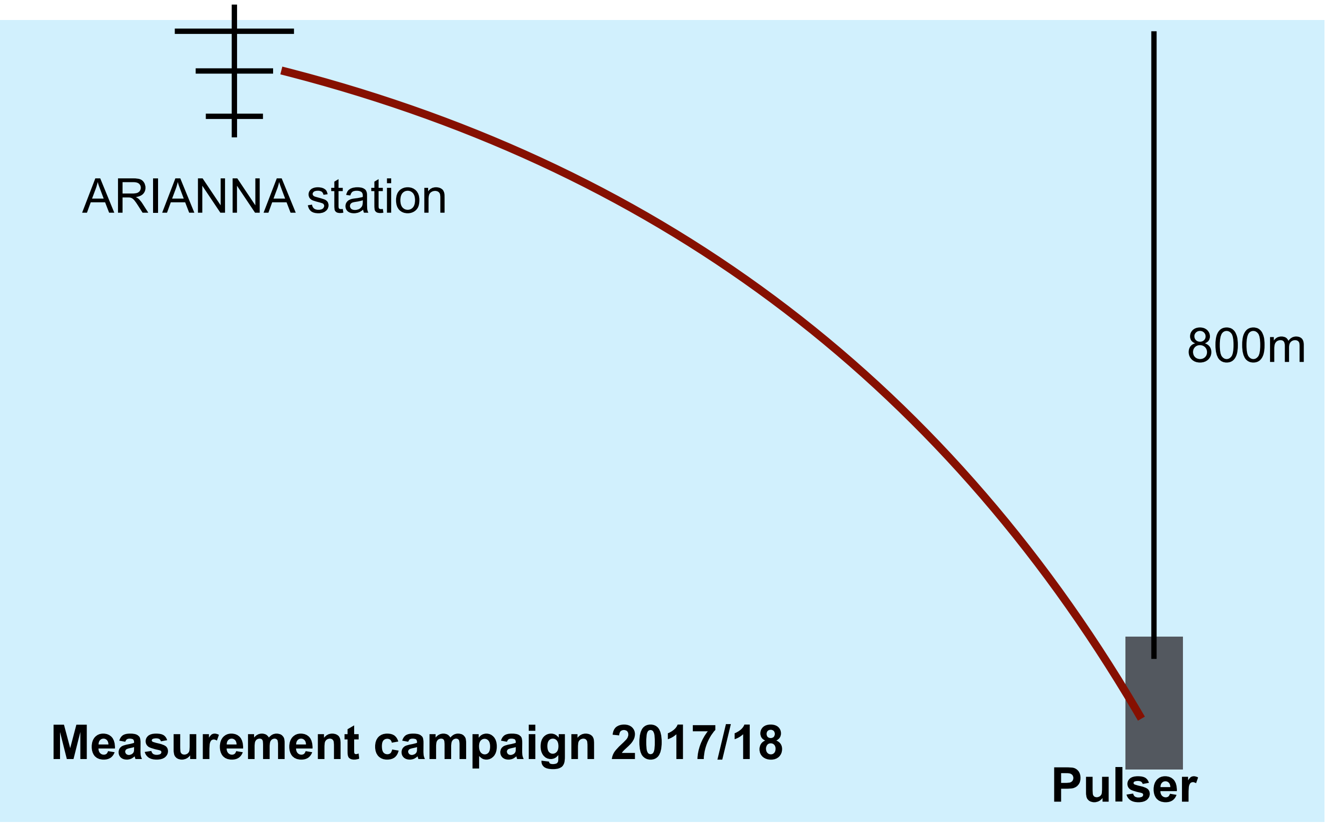
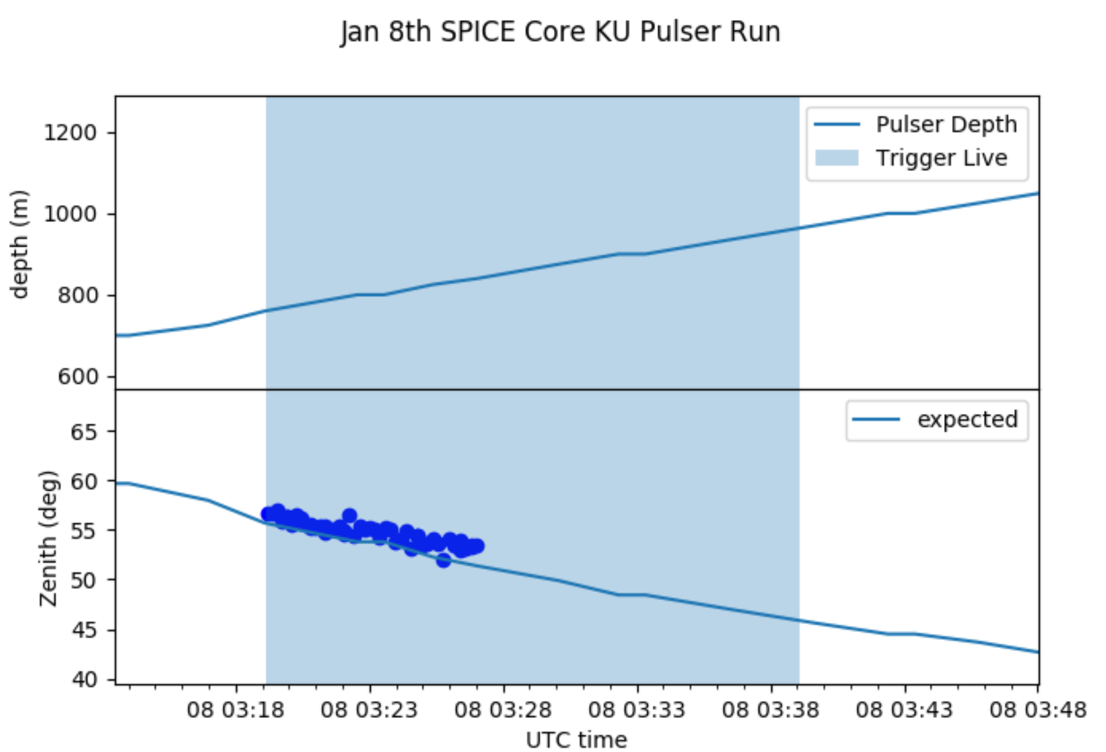
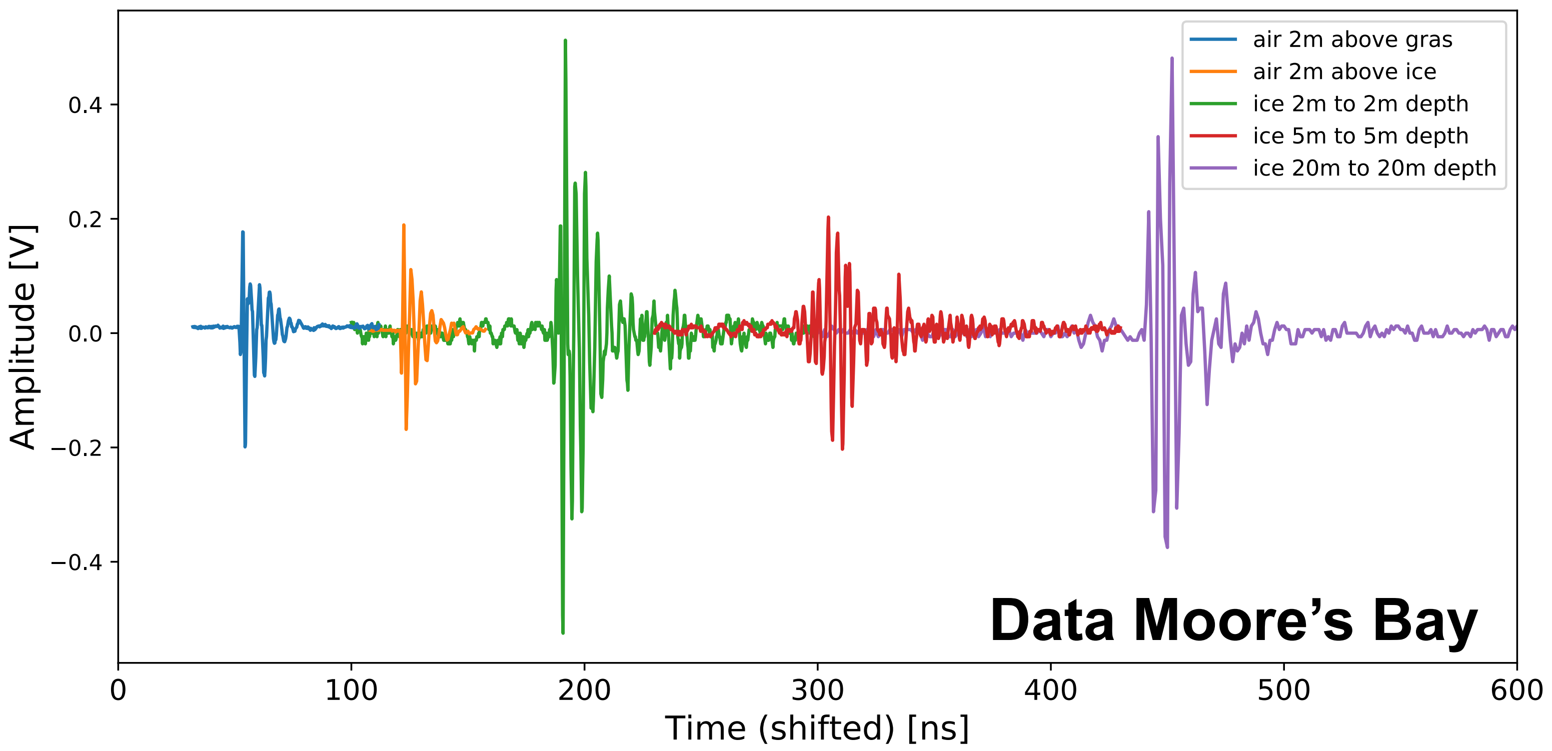




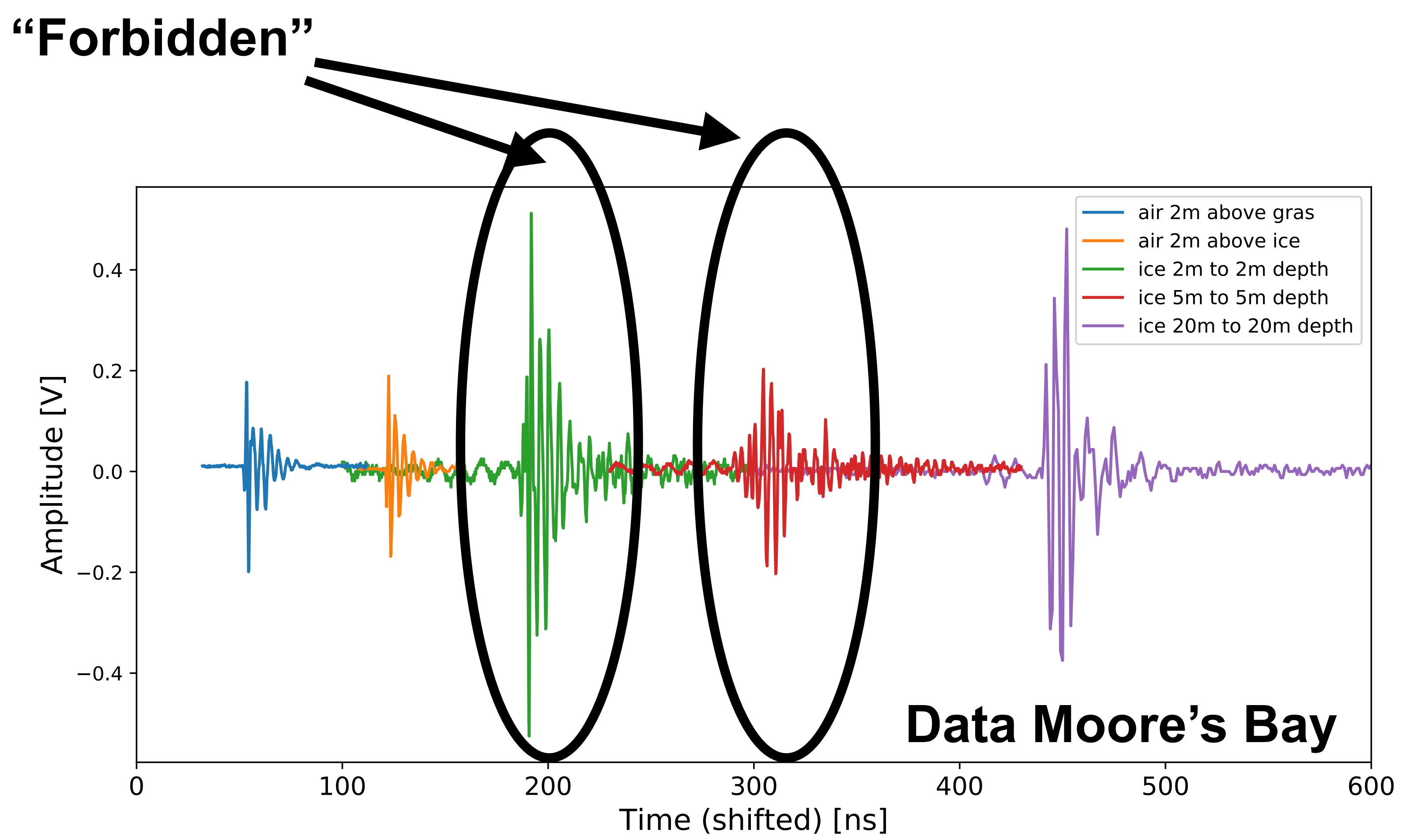


- Excellent angular reconstruction of pulse in deep ice
- Resolution of 0.8 degrees for station
- Systematic offset likely related to station geometry and uncertainties in the ice modeling

But …


air 2m above gras
air 2m above ice
ice 2m to 2m depth
ice 5m to 5m depth
ice 20m to 20m depth
Data Moore's Bay
Amplitude [V]
Time (shifted) [ns]
0.4
0.2
0.0
−0.2
−0.4
0
100
200
300
400
500
600

But …



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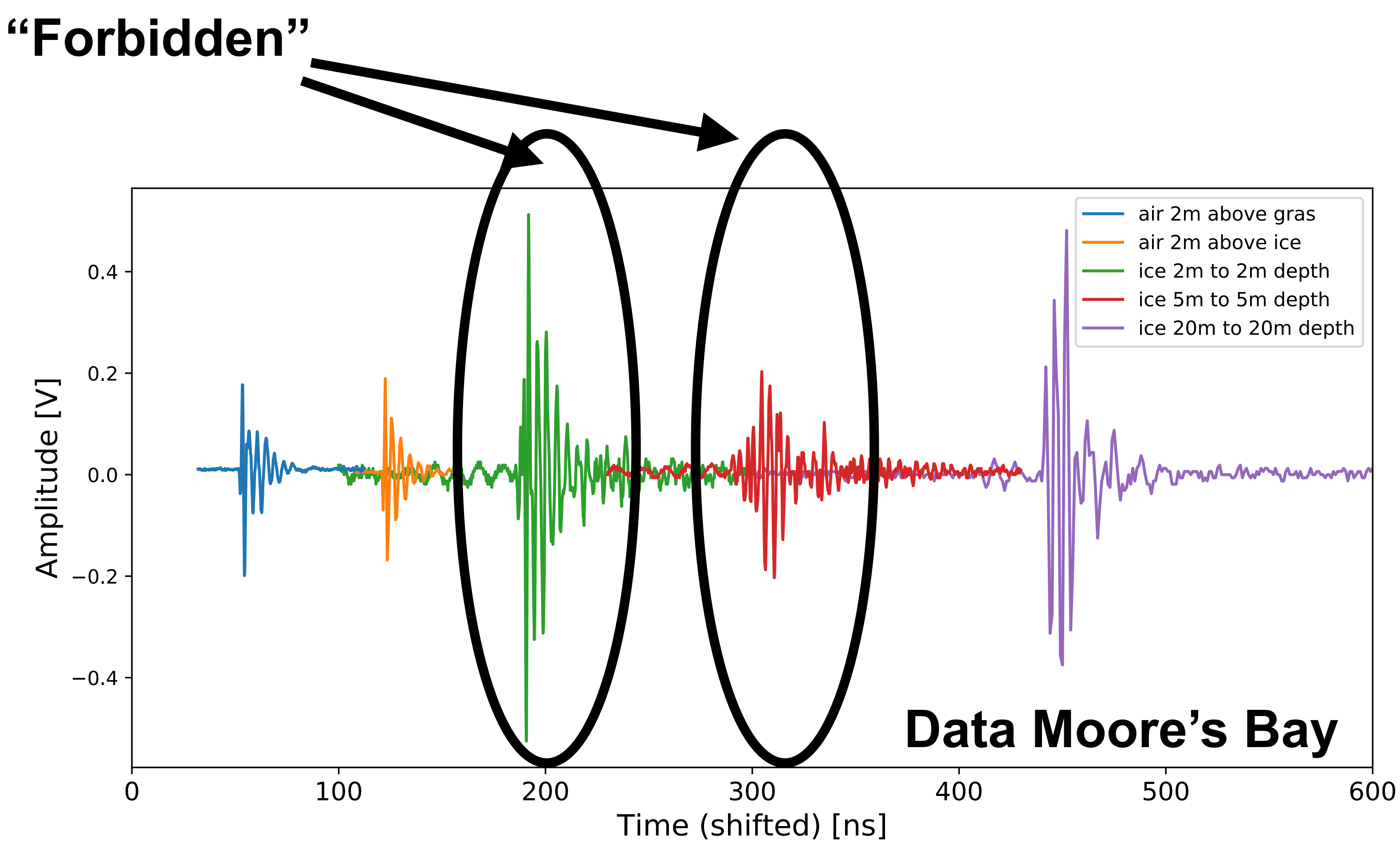
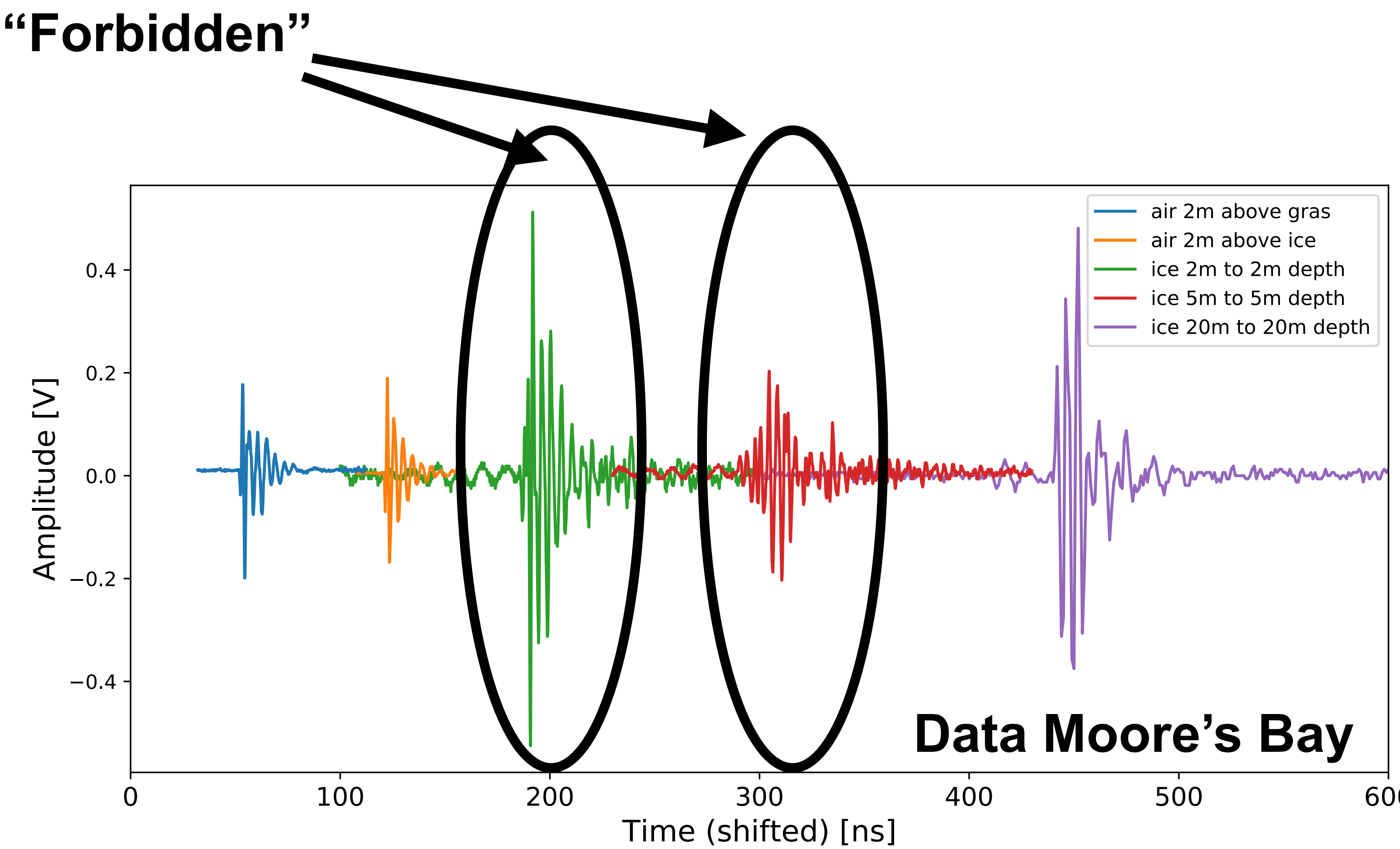
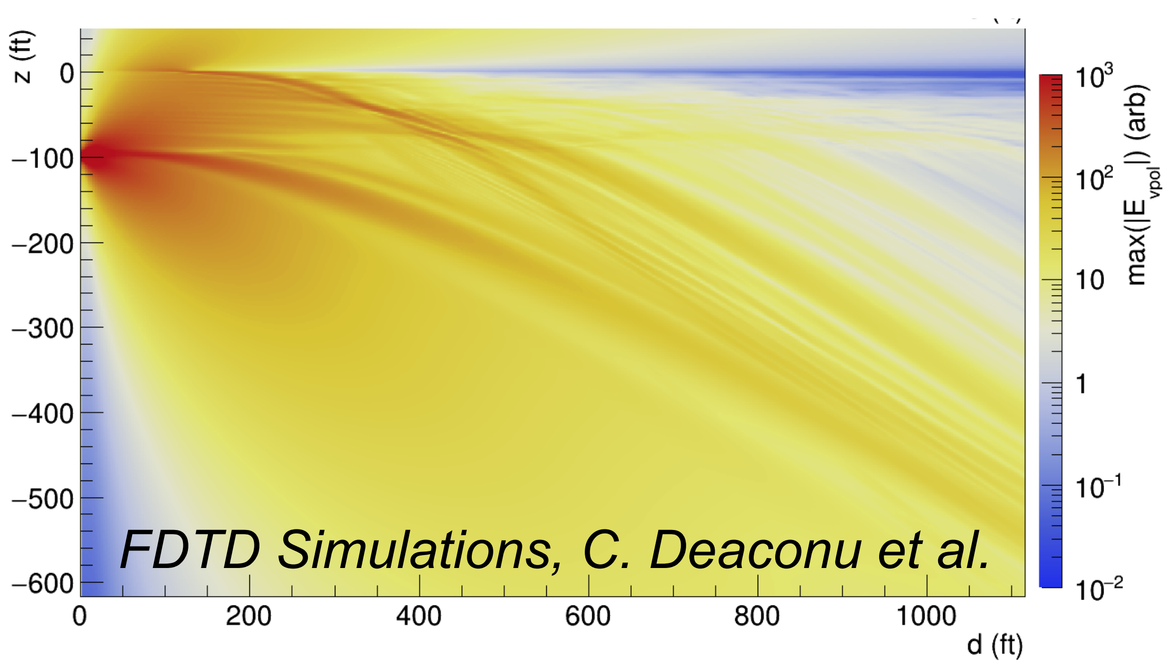


- At South Pole, Moore’s Bay and Greenland also signals observed that should be ‘forbidden’
- **Tentative explanation:** Ice is layered, not smooth gradient as usually assumed
- Density fluctuation lead to ray trapping and horizontal propagation

But …





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Signal propagation

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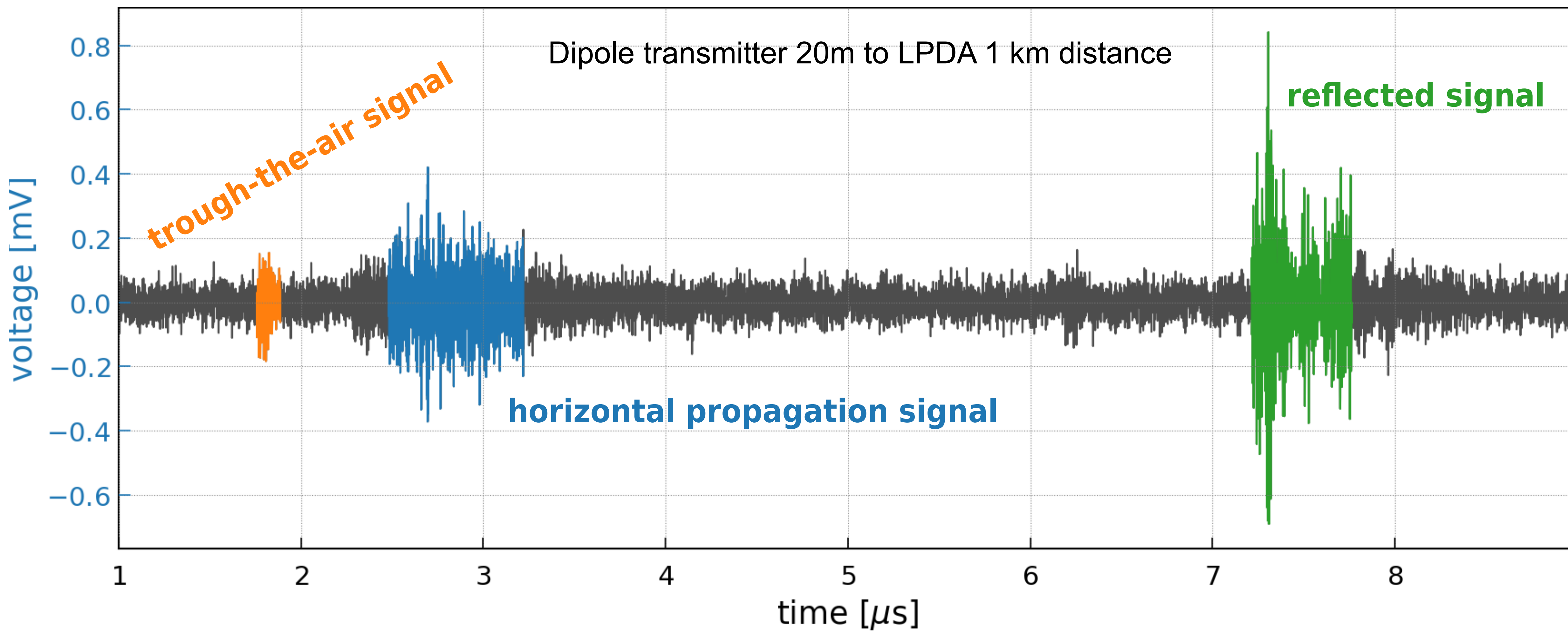
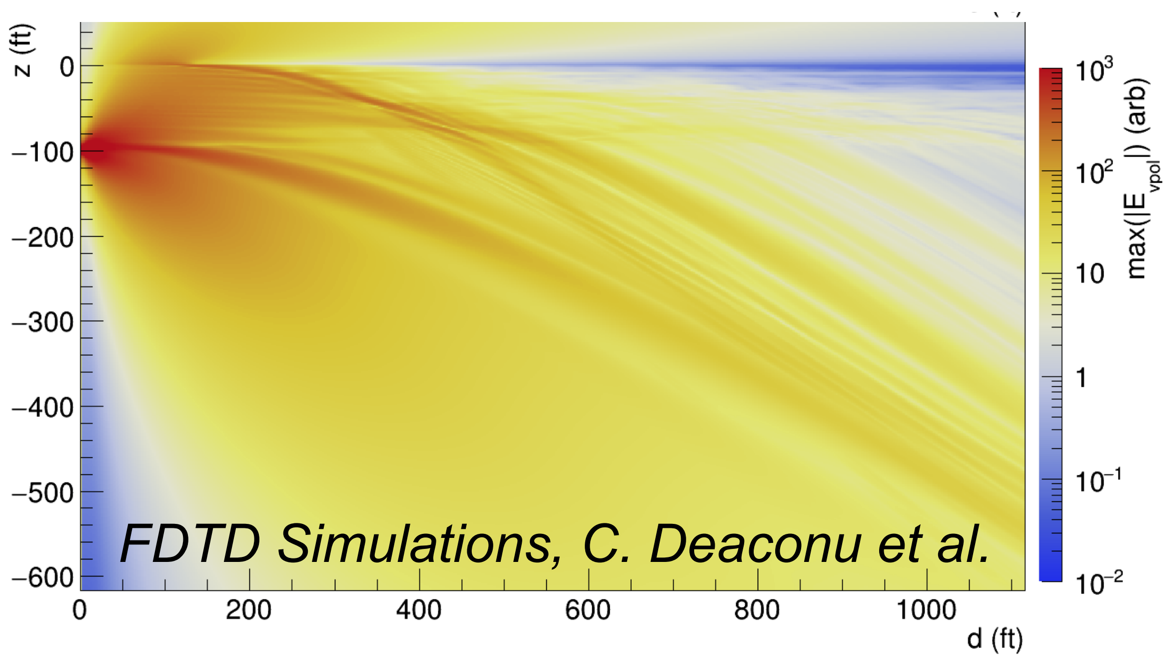




- Understanding of ice propagation is coming together
- Modeling critical for understanding signal propagation

Simulation: NuRadioMC

ARASim | **ShelfMC**

- Non-modular, very specific to location and detector design

NuRadioMC
https://github.com/nu-radio/NuRadioMC

- Modular, python based, open source

Event Generation → **Signal Generation** → **Signal Propagation** → **Detector Simulation**

Event Generation
- Cross-section
- Flavor-ratio
- Arrival direction
- …

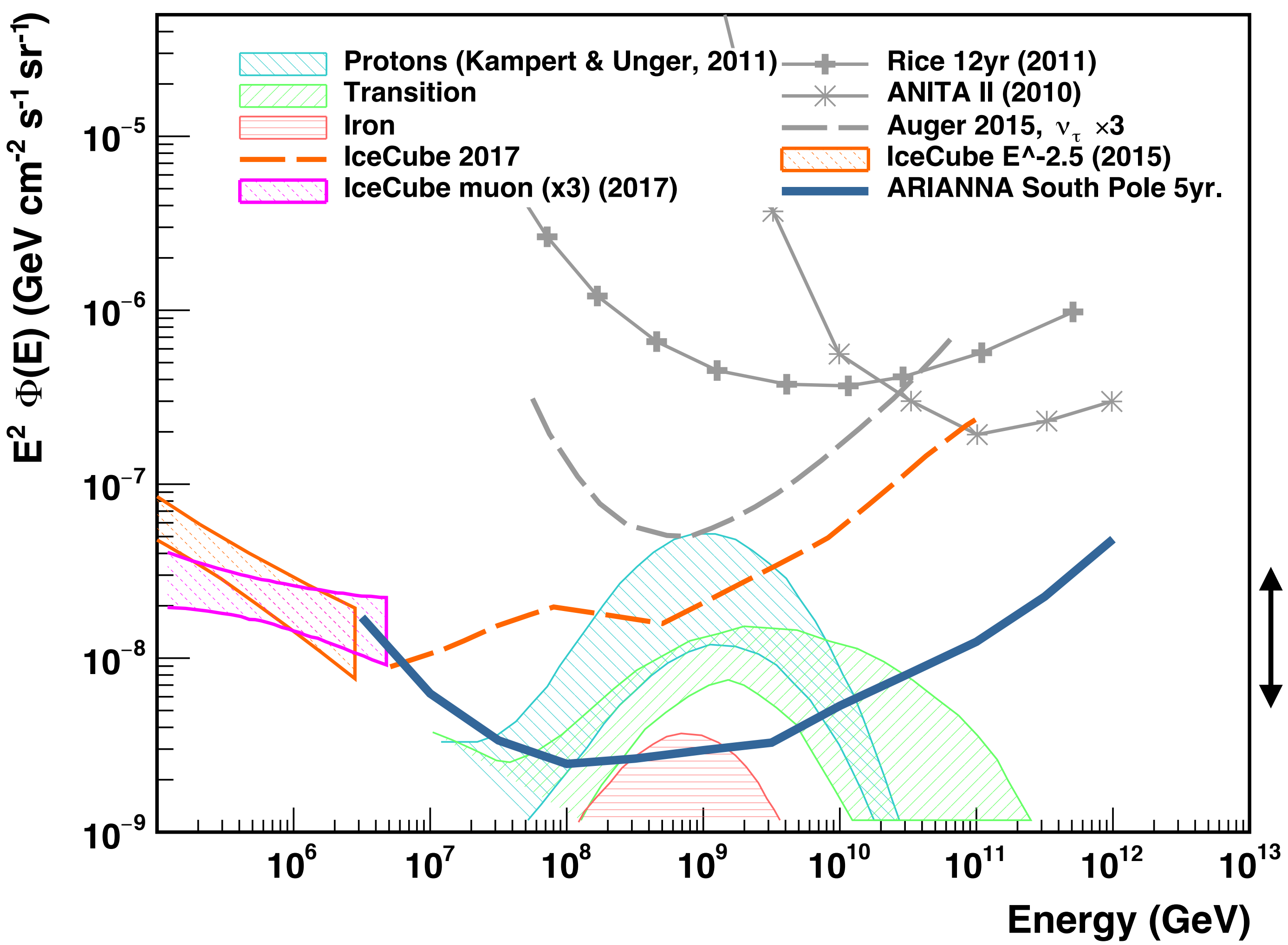
Signal Generation
- Phase and frequency
- LPM
- …

Signal Propagation
- Realistic ice models
- (analytic) Ray-tracing
- …

Detector Simulation
- Frequency and phase response
- Fully flexible station layout
- …

Sensitivities to neutrinos

- Diffuse flux from cosmic rays and cosmic microwave background



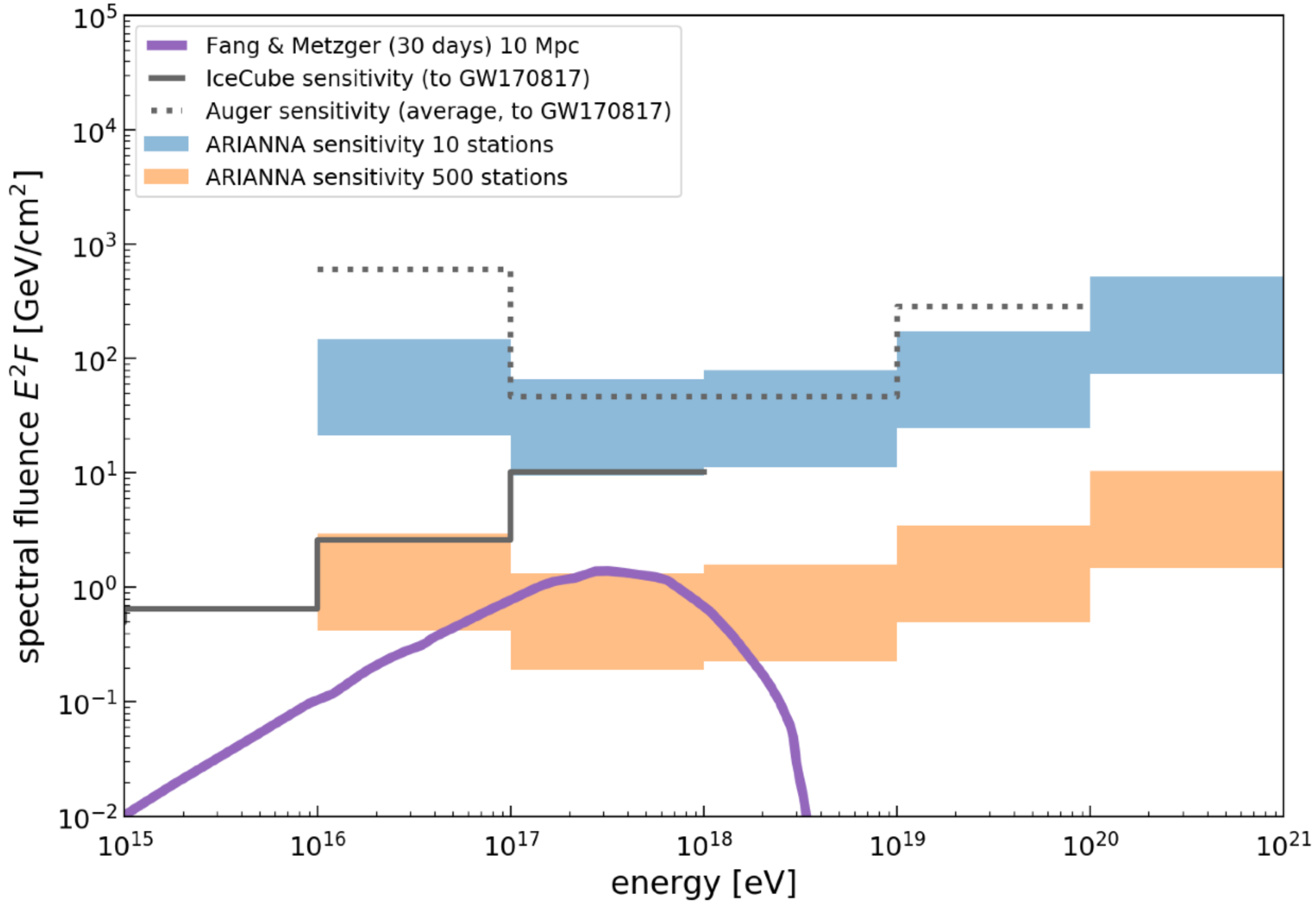
Scales linearly with number of stations

- Here:
  - 300 stations, South Pole
  - 5 years, 90% uptime
  - 90% analysis efficiency

- *"Sensitivity a linear function of money"*
- *Needs a target sensitivity*

Sensitivities to neutrinos

- Transient flux from explosive events (here NS-NS merger)



- Radio arrays will have excellent sensitivity to explosive events
- Already existing arrays, promising sensitivity — uptime a challenge in Antarctica

Outlook - Large neutrino array

- Radio detection is a intriguing (new) technique to detect neutrinos of the highest energies and solve long-standing questions
- Emission properties well understood
- Sufficient previous experiences in building detectors
- Neutrino community is coming together to propose a large array which has discovery potential