Radio Detection of High-Energy Neutrinos

Christian Glaser

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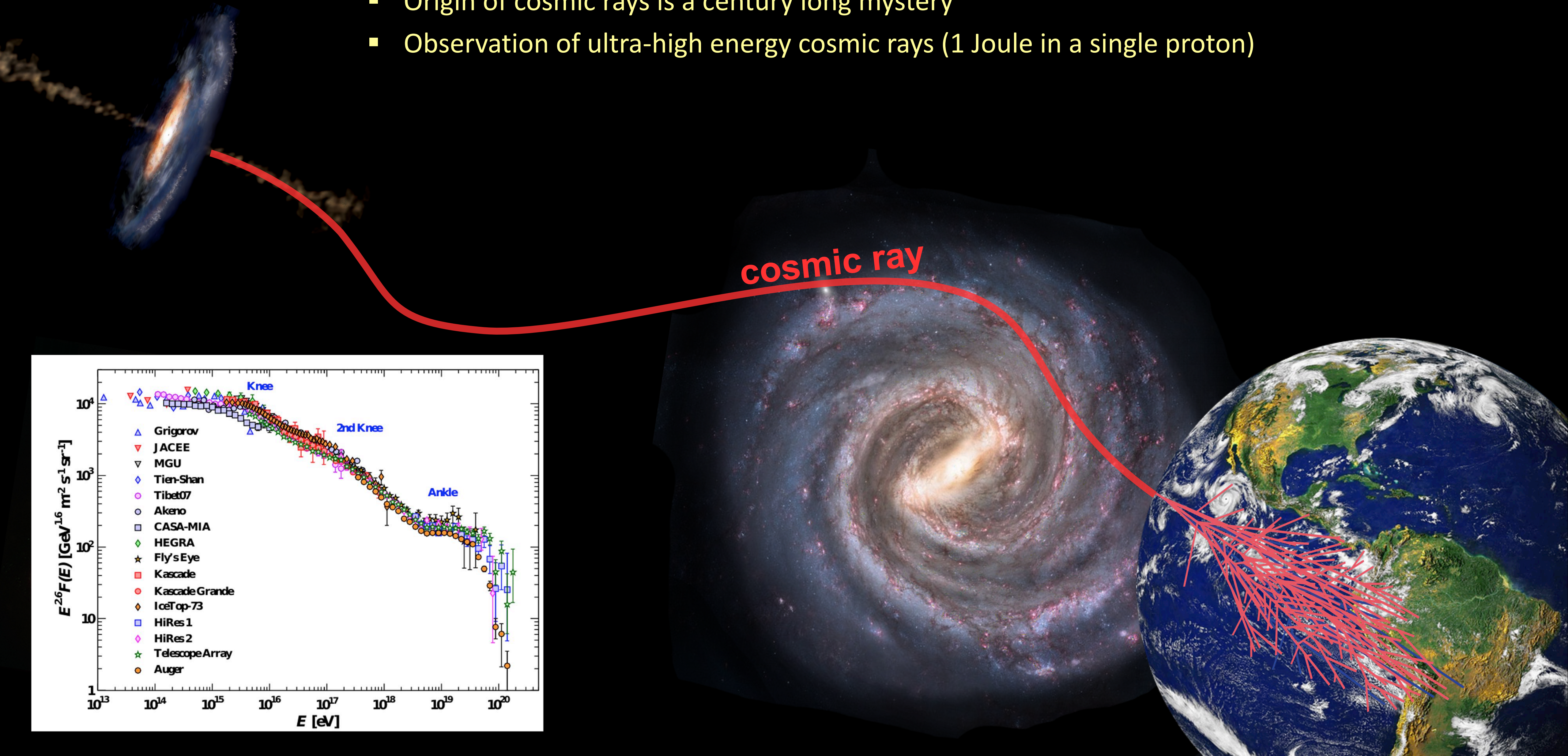
High Energy Universe

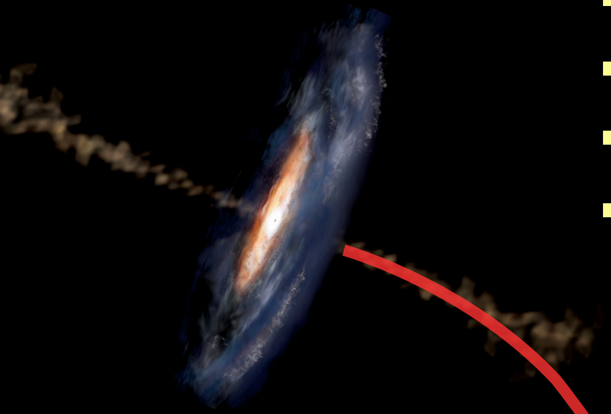
- Origin of cosmic rays is a century long mystery
- Observation of ultra-high energy cosmic rays (1 Joule in a single proton)

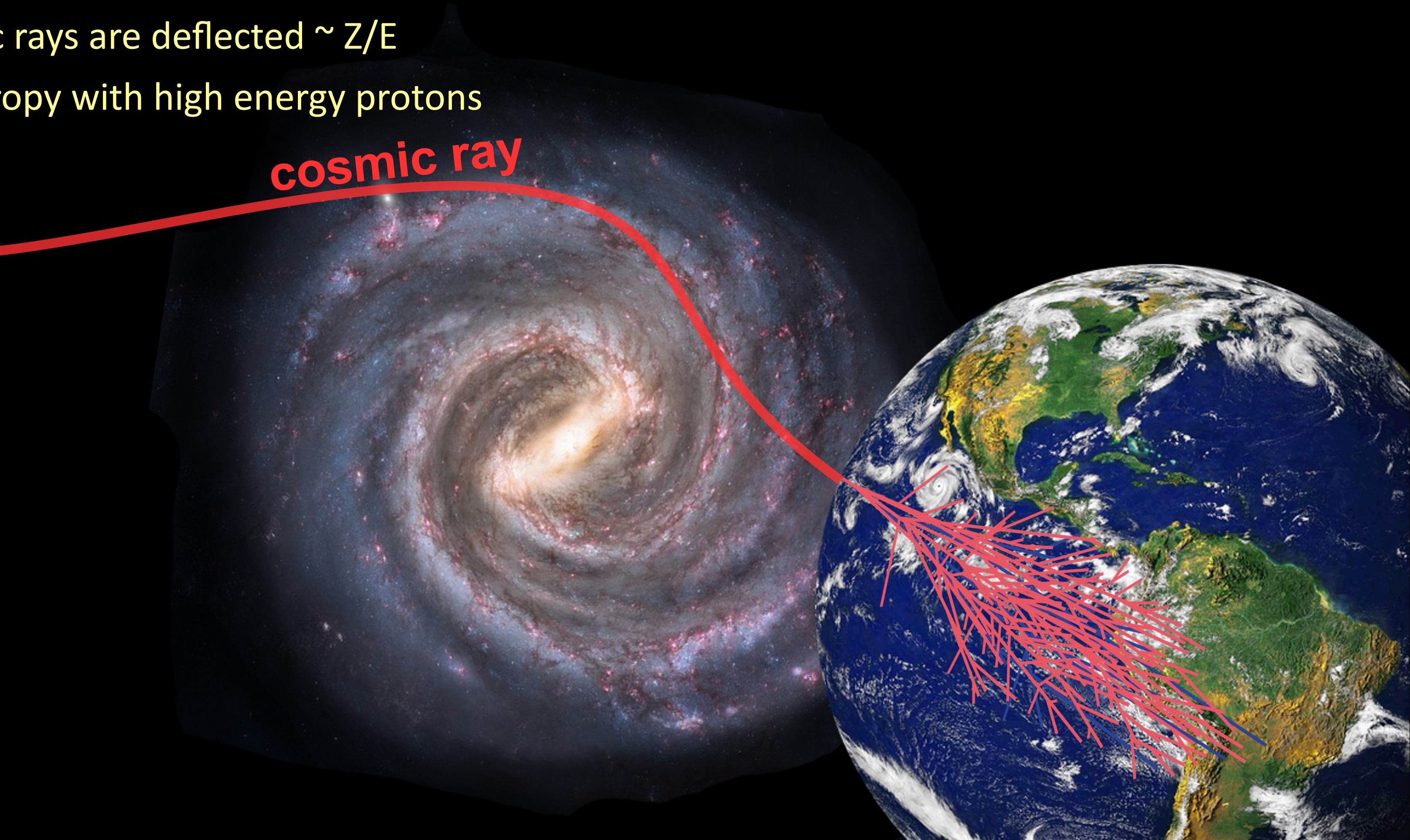


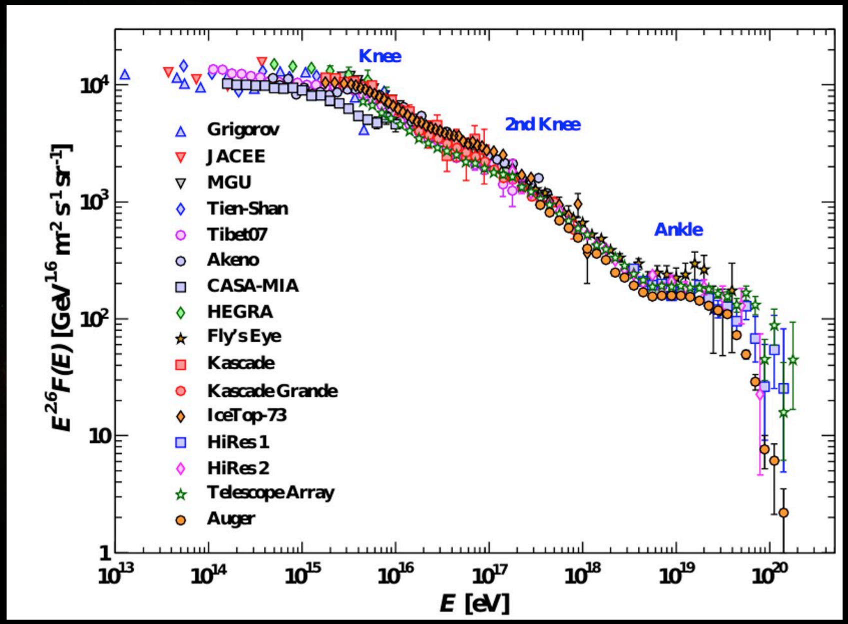
Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

High Energy Universe

- Origin of cosmic rays is a century long mystery
- Observation of ultra-high energy cosmic rays (1 Joule in a single proton)
- Insights into most violent phenomena in our universe
- Measured extensively over decades but no hint of source
    - Cosmic rays are deflected ~ Z/E
    - anisotropy with high energy protons

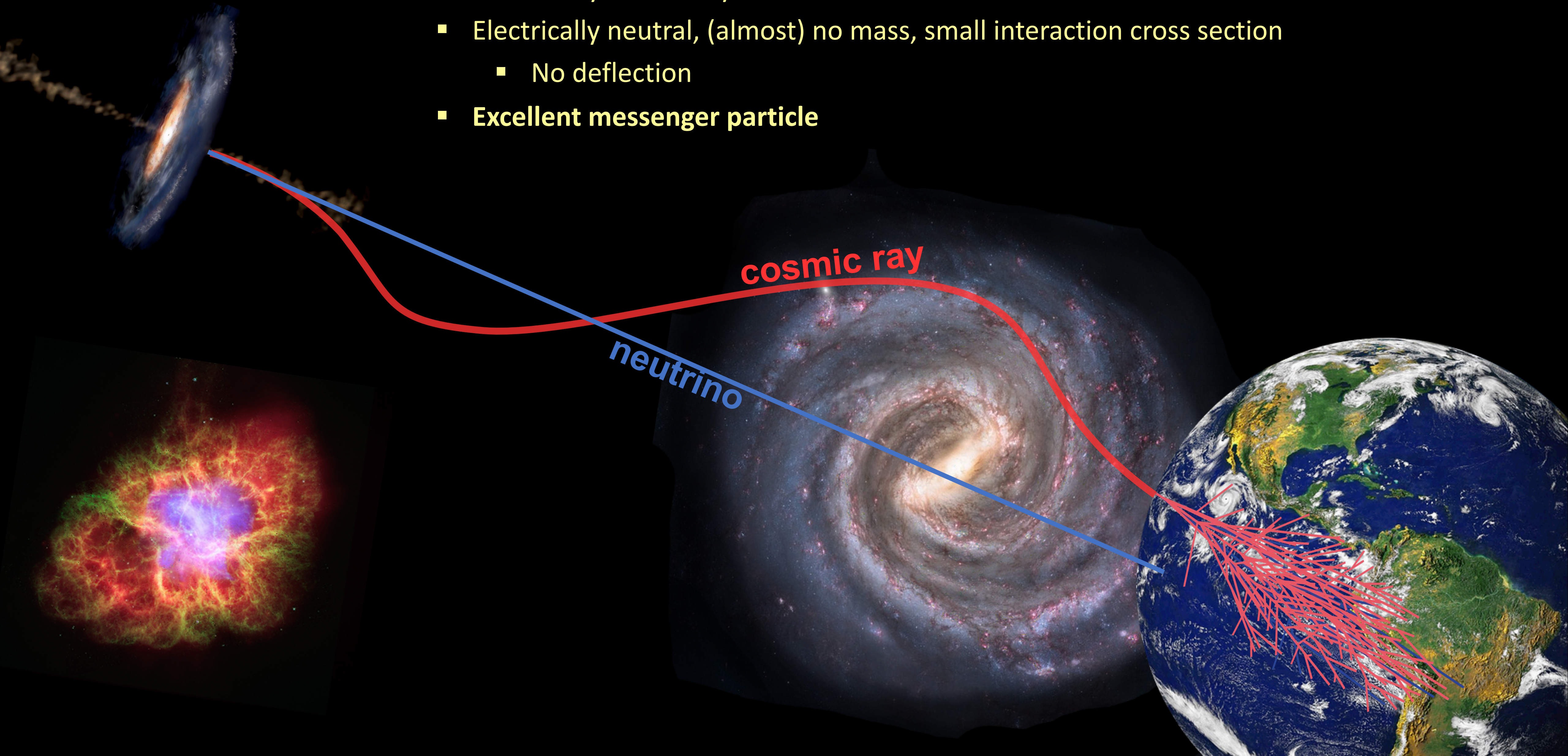






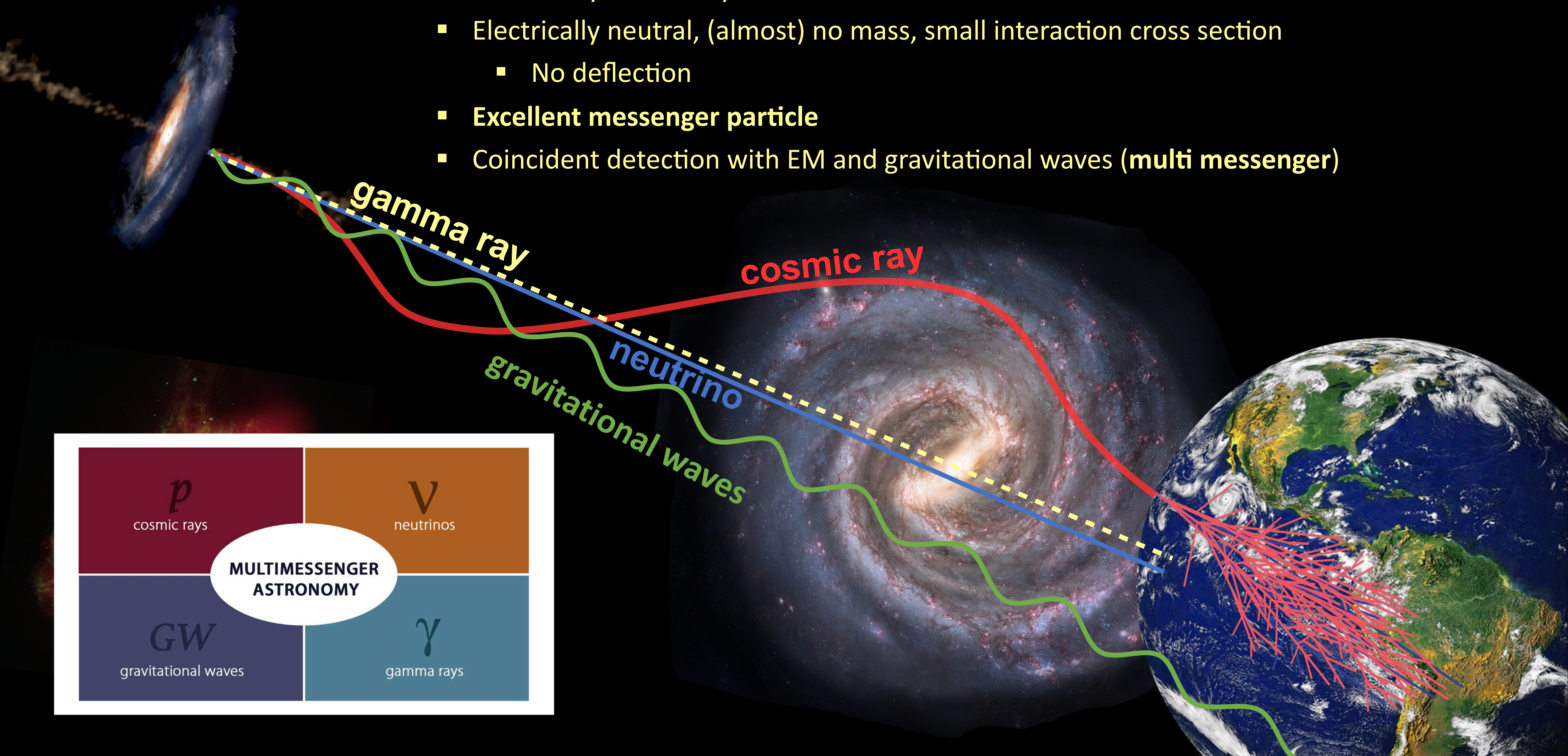
use Neutrinos instead of cosmic rays

- Created by cosmic rays at the source
- Electrically neutral, (almost) no mass, small interaction cross section
  - No deflection
- **Excellent messenger particle**



better use **Neutrinos** instead of cosmic rays

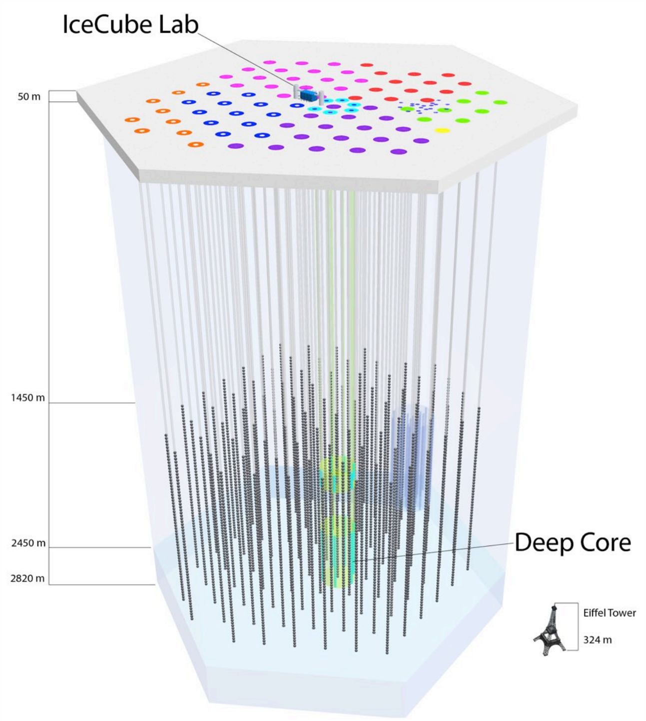
- Created by cosmic rays at the source
- Electrically neutral, (almost) no mass, small interaction cross section
  - No deflection
- **Excellent messenger particle**
- Coincident detection with EM and gravitational waves (**multi messenger**)

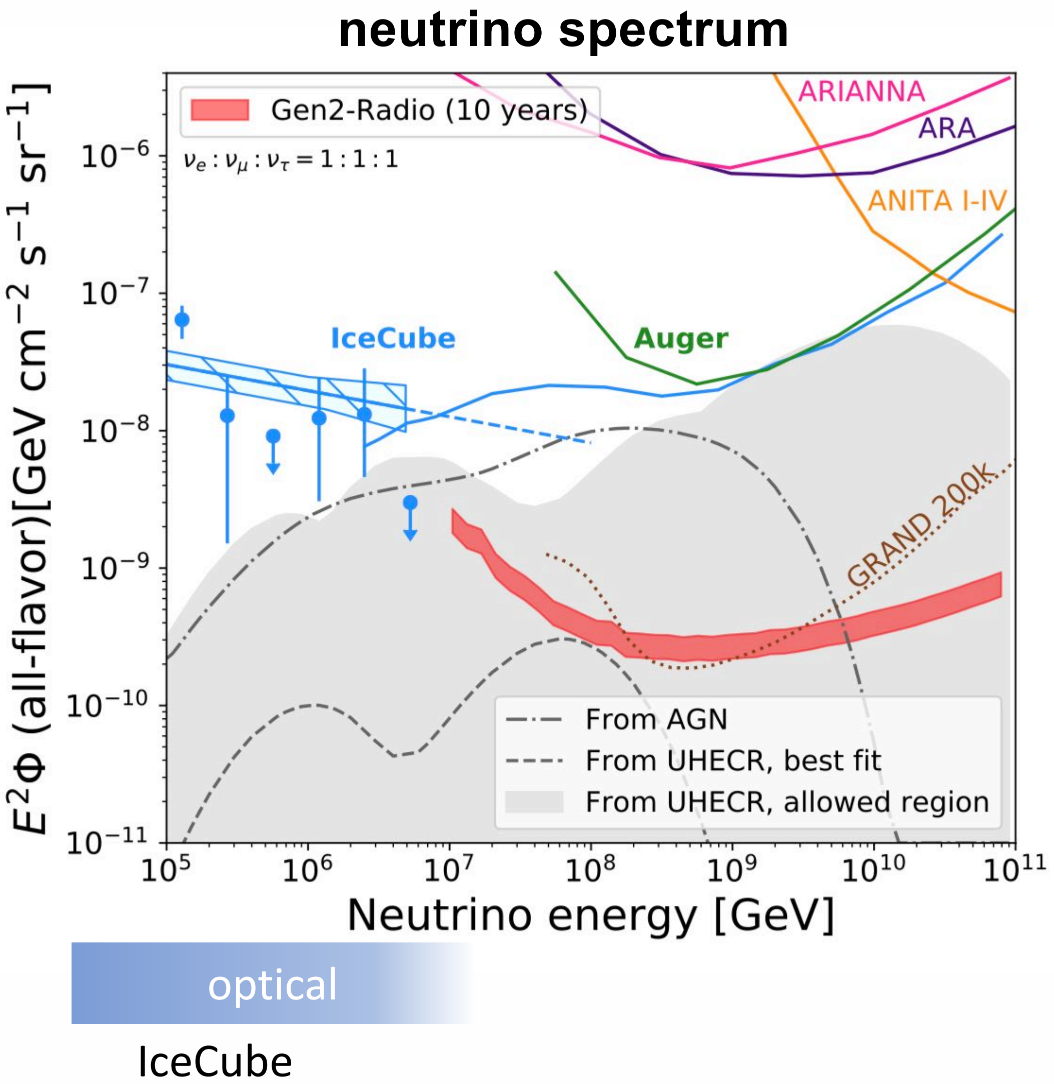


Experimental Challenges

- Low interaction cross section of neutrinos
- Very low neutrino flux

→Very large volumes needed for reasonable rates



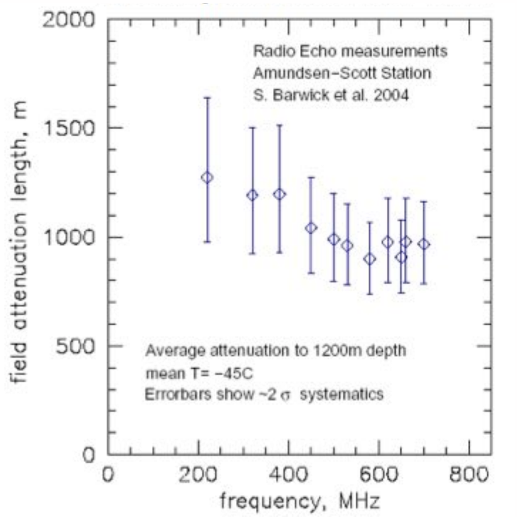


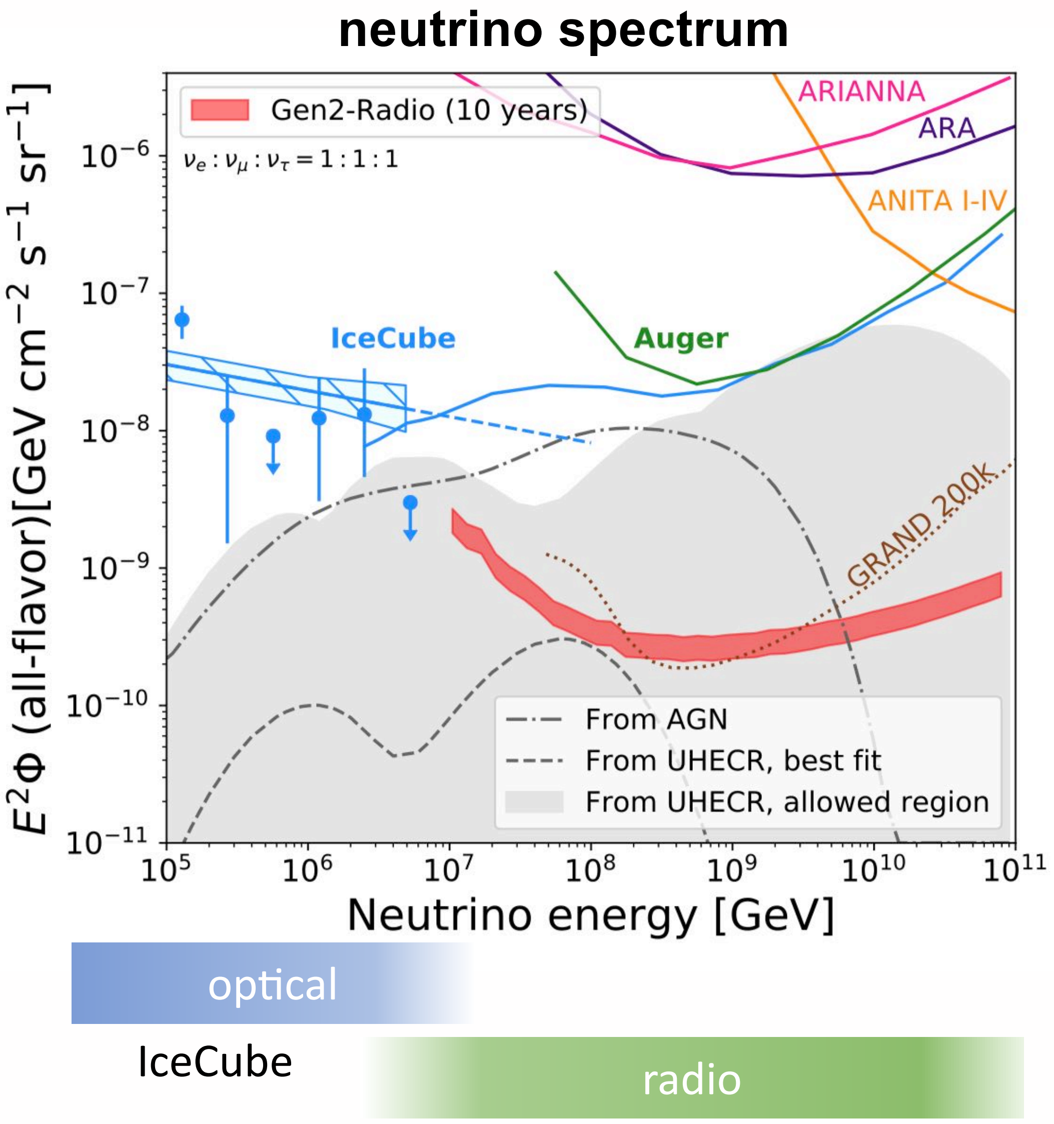
Experimental Challenges

- Low interaction cross section of neutrinos
- Very low neutrino flux

→Very large volumes needed for reasonable rates

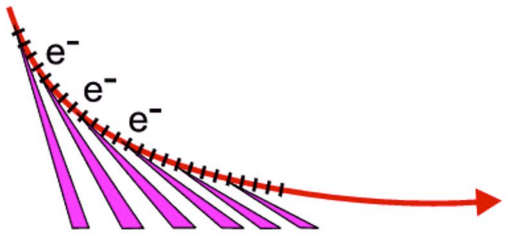
- **Solution: radio technique**
  - Large volumes at no cost: Antarctic ice
  - Ice transparent to radio waves (L ~ 1km)
  - A single radio station has 1km³ effective volume (comparable to IceCube)



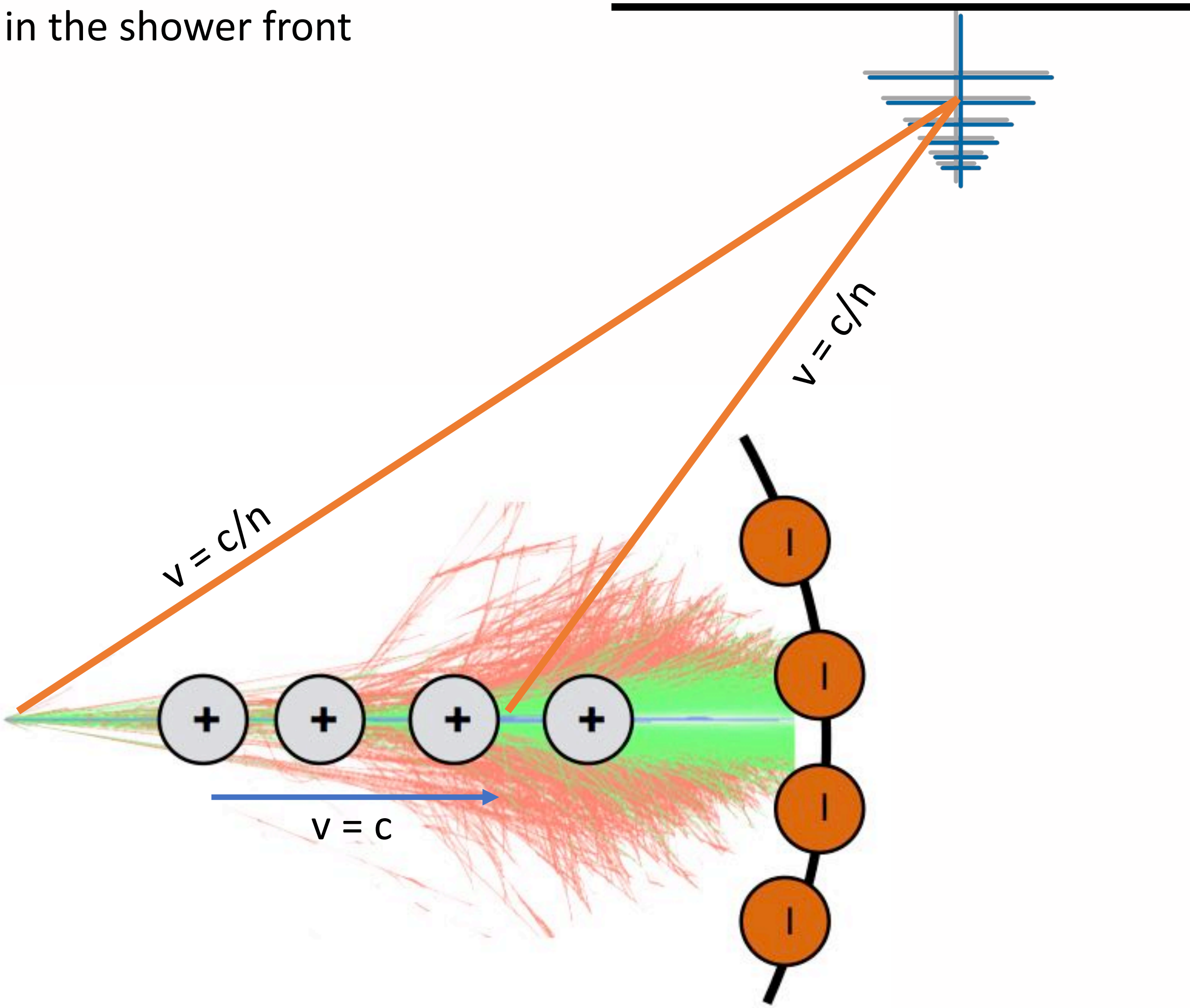


Radio Emission of Particle Showers

- Askaryan effect: Time varying negative charge excess in the shower front
- Macroscopic: Longitudinal current
- Microscopic: Acceleration and creation of charge

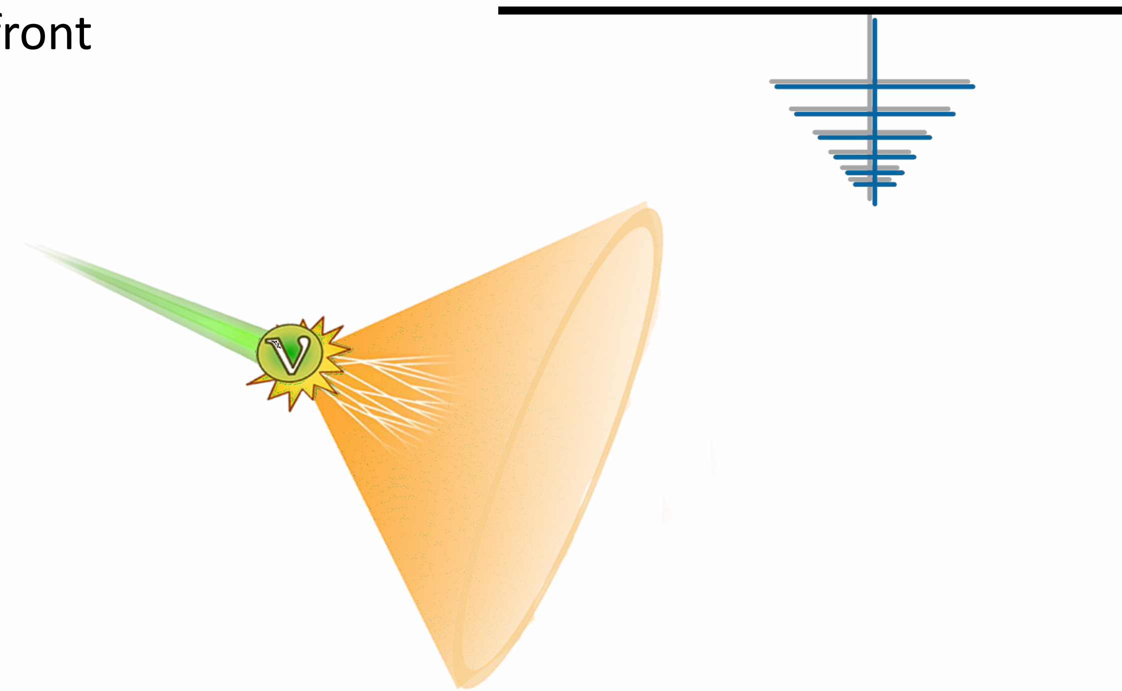


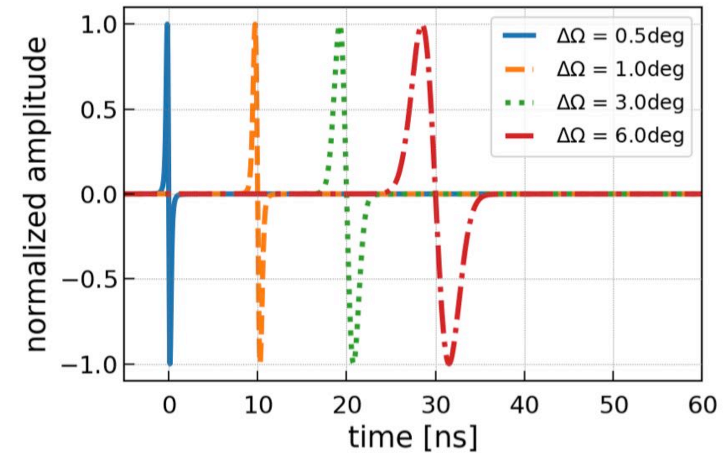
- Cherenkov-like time compression effect
- Shower is faster than its emission
- Constructive interference at the Cherenkov angle
- In ice: arccos(1/n) = 56 deg



Radio Emission of Particle Showers

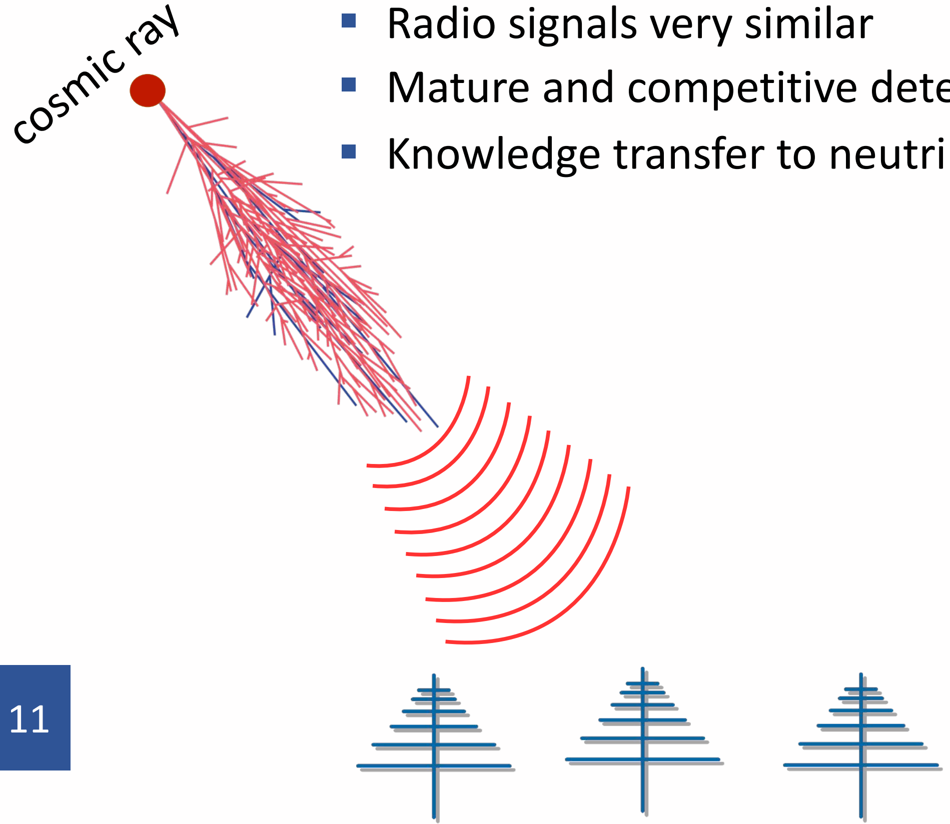
- Askaryan effect: Negative charge excess in the shower front

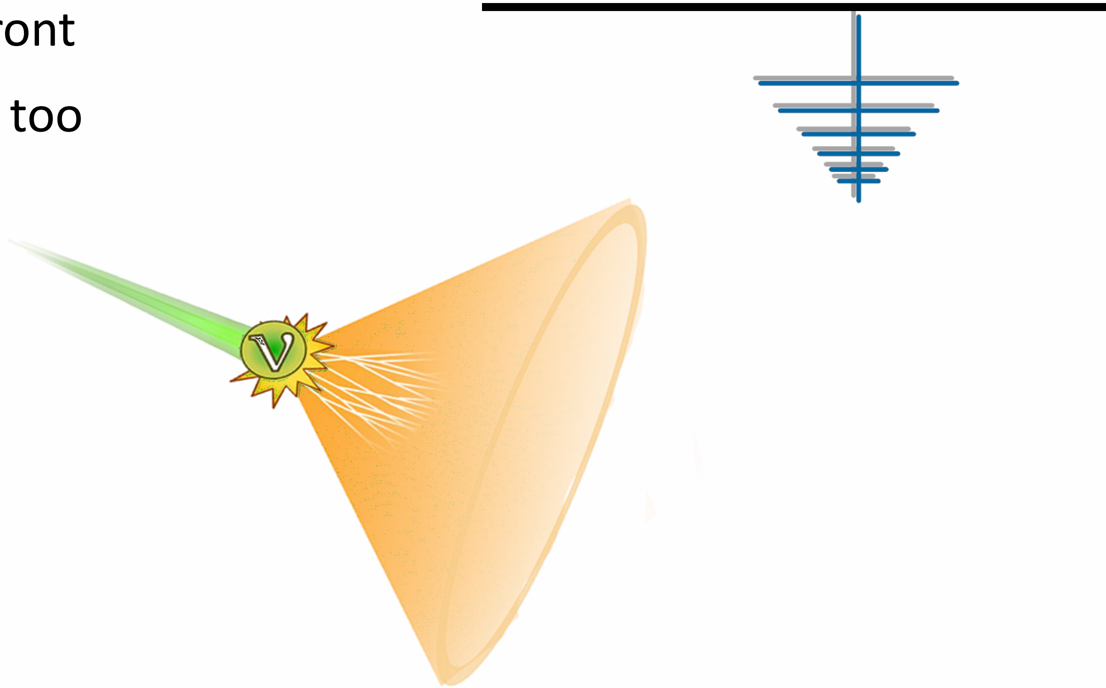


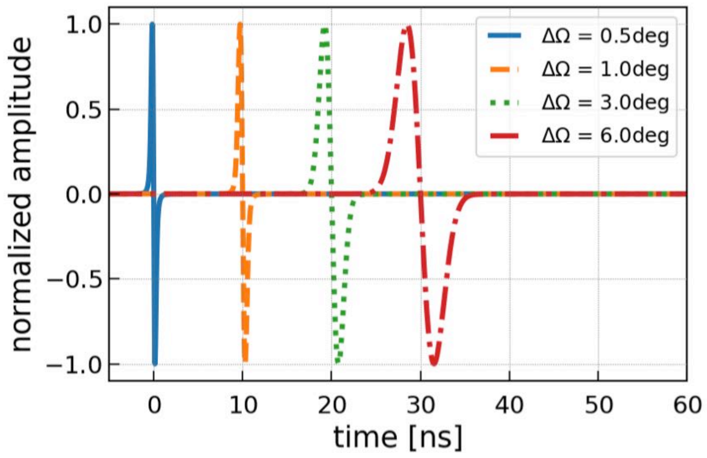


Radio Emission of Particle Showers

- Askaryan effect: Negative charge excess in the shower front
- No neutrino detected yet because current detectors are too small but
  - Askaryan pulse measured in lab
  - **Feasibility shown with cosmic-ray detectors**
    - Radio signals very similar
    - Mature and competitive detection technique
    - Knowledge transfer to neutrinos







Air Shower Experiments

- Radio detection is established technique for cosmic-ray detection
- Most achievements can be transferred to neutrino detection

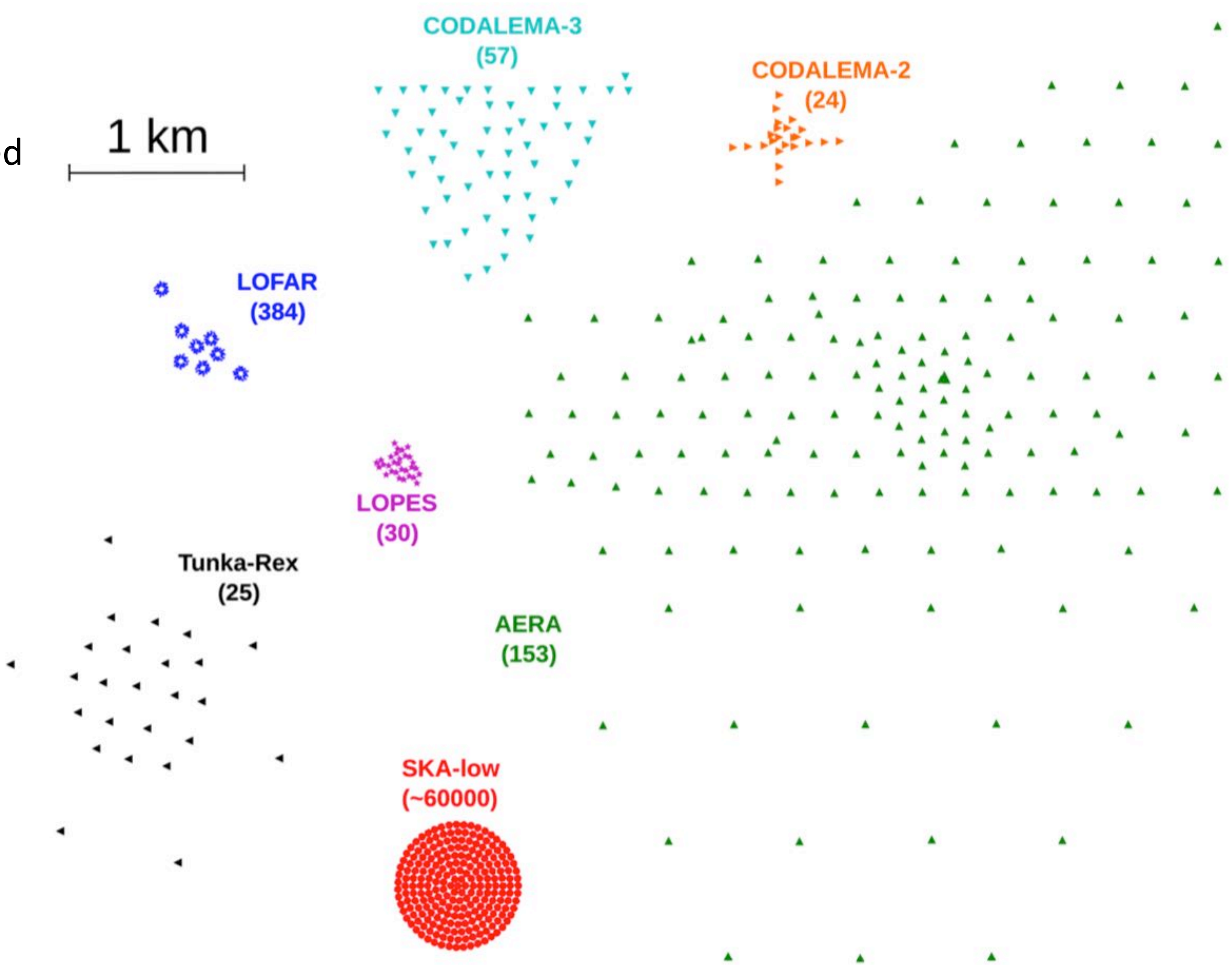


Image by Tim Huege

Achievements of Radio Detection of Cosmic Rays

Cosmic-ray quantities of interest

direction

< 1 degree

energy

~10% energy resolution
~10% systematic uncertainty

*Pierre Auger Collaboration, PRL **116** 241101 (2016), PRD **93** 122005 (2016), JINST **12** T10005 (2017), Gottowik et al., Astro Part. **103** 87-93 (2018)*

mass/ charge

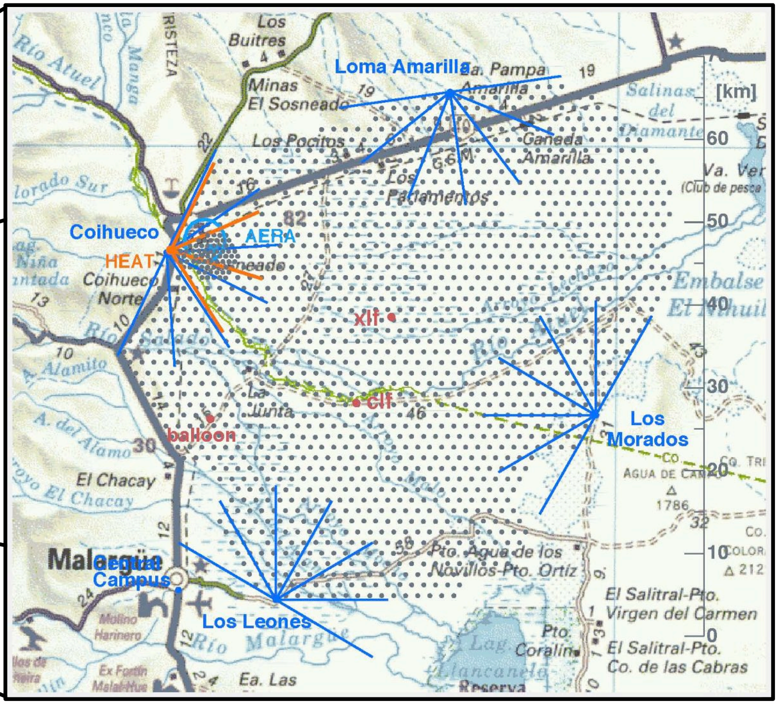
16 g/cm^2 X_{max} resolution

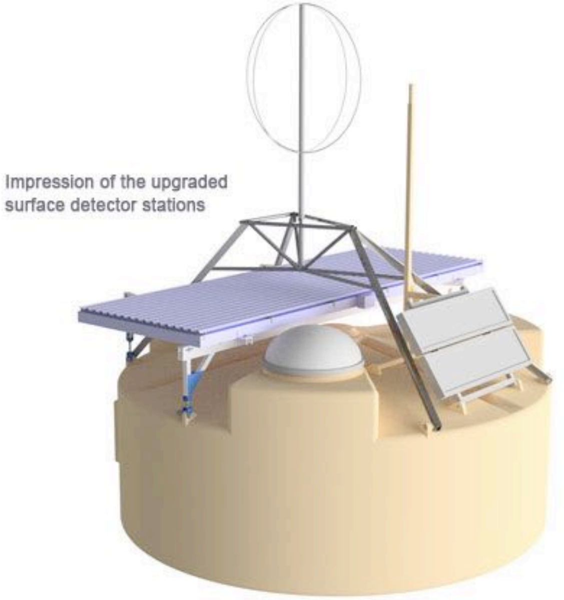
Buitink et al., PRD 90 082003 (2014)
Buitink et al., Nature 531 70-73 (2016)

Radio is competitive to traditional techniques

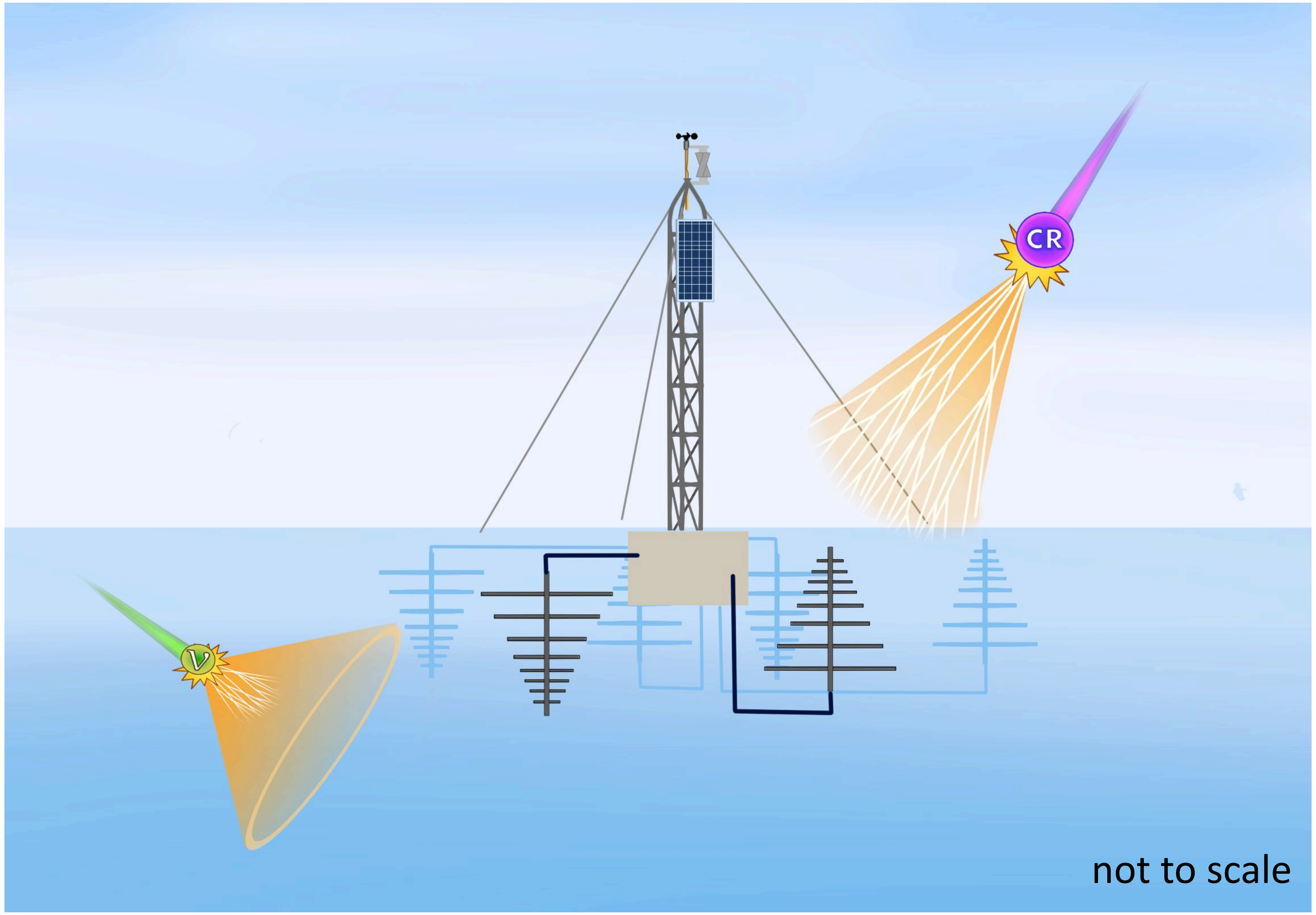
Auger Prime Upgrade

- All **1600 surface detectors** will be upgraded with scintillators and **radio antennas**
- Combine radio with particle measurement -> cosmic-ray charge/mass
- Anisotropy analysis with protons only -> chance of source discovery





Detection of High-Energy Neutrinos



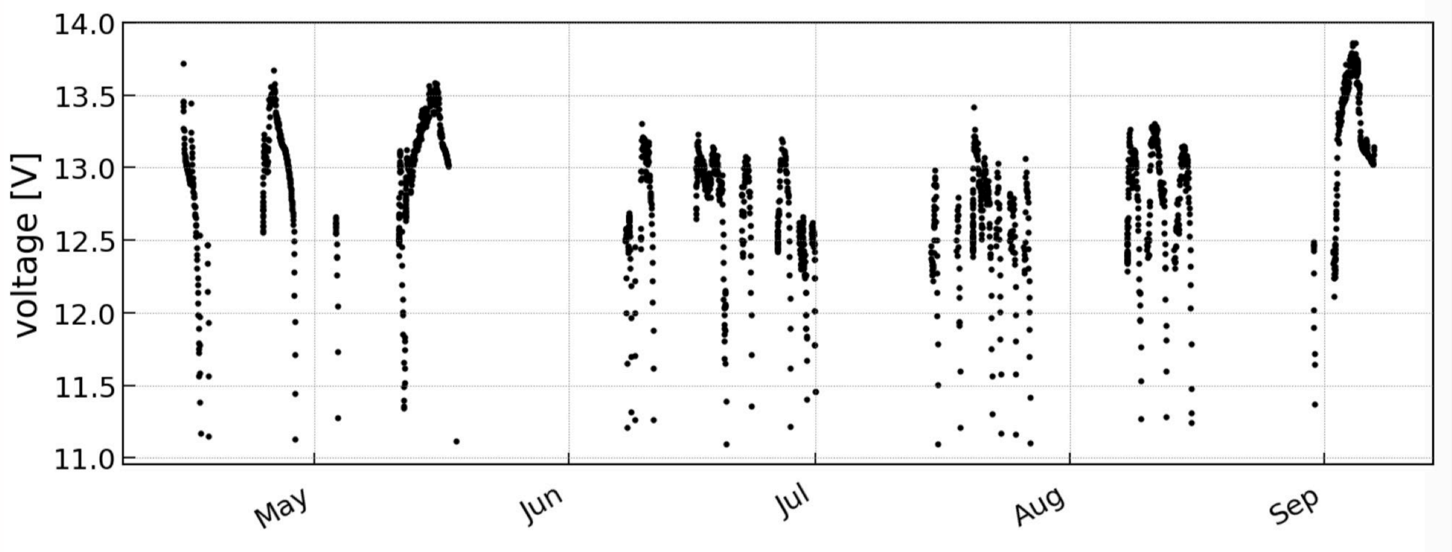
Detection of High-Energy Neutrinos

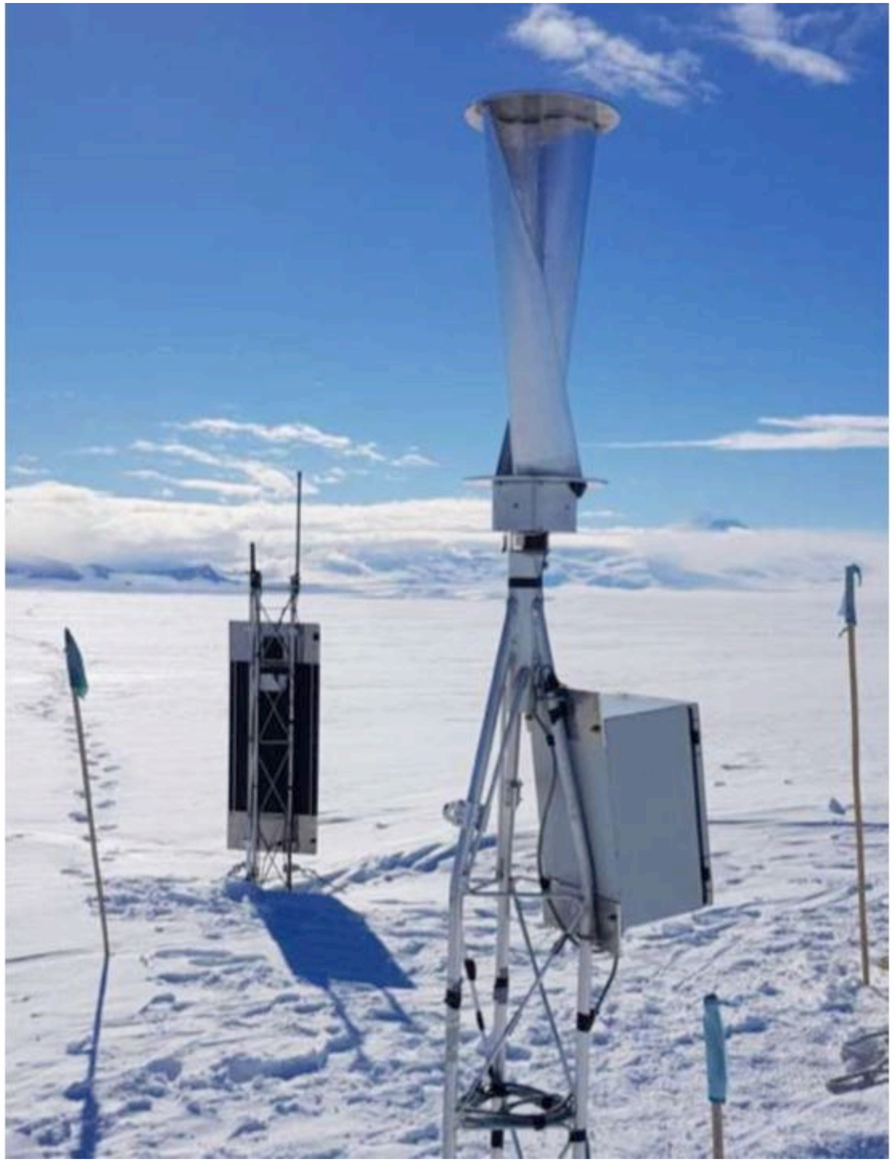
CHALLENGE 1:
WORKING DETECTOR

- Two pilot detectors
  - ARA (South Pole)
  - ARIANNA (Moor's Bay + South Pole)
- Size 1%- 5% of required size
  - no neutrino measured yet but
- Hardware proven reliable
- **Technology ready for large scale detector**

Development of wind power system

- Autonomous stations have many advantages
- Wind power system required for dark winter months
- Pioneered at Uppsala
  - current prototype survives harsh Antarctic conditions and powers station for ~50% of the time

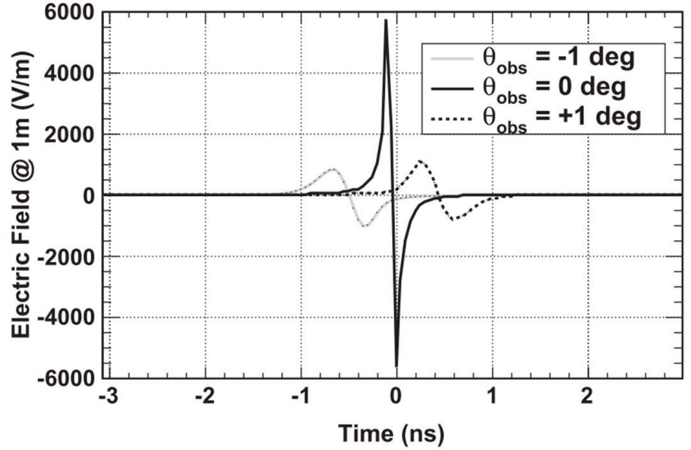




Challenge 2: Neutrino identification

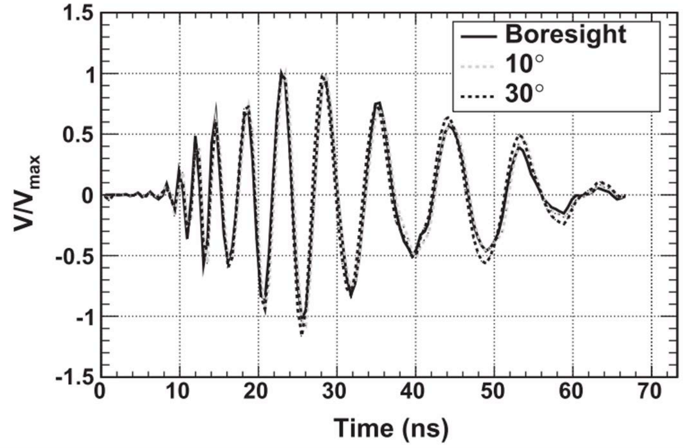
Example: ARIANNA signal search

neutrino signal



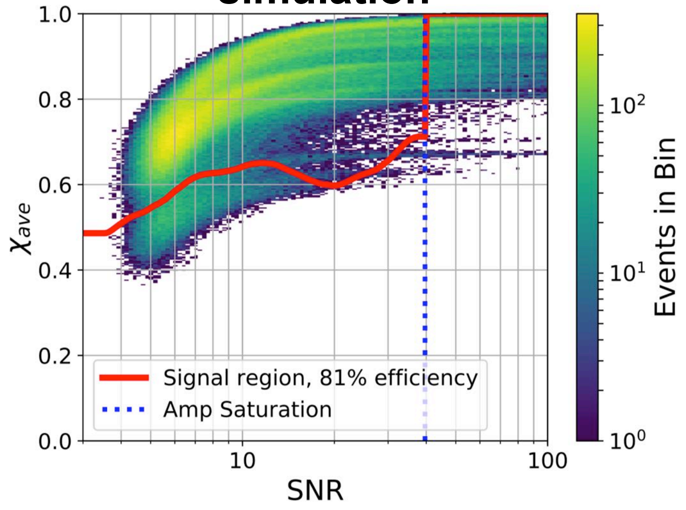
→ hardware response →

signal in detector

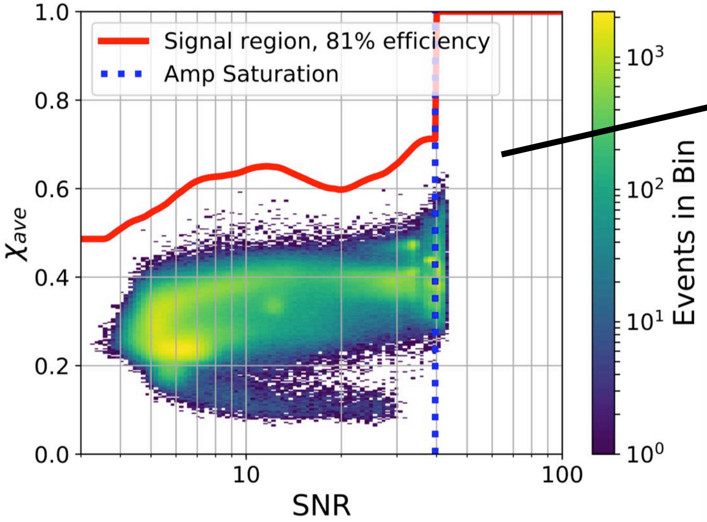


template correlation

simulation



data



no neutrino found
-> limit on neutrino flux

Challenge 3: Event Reconstruction

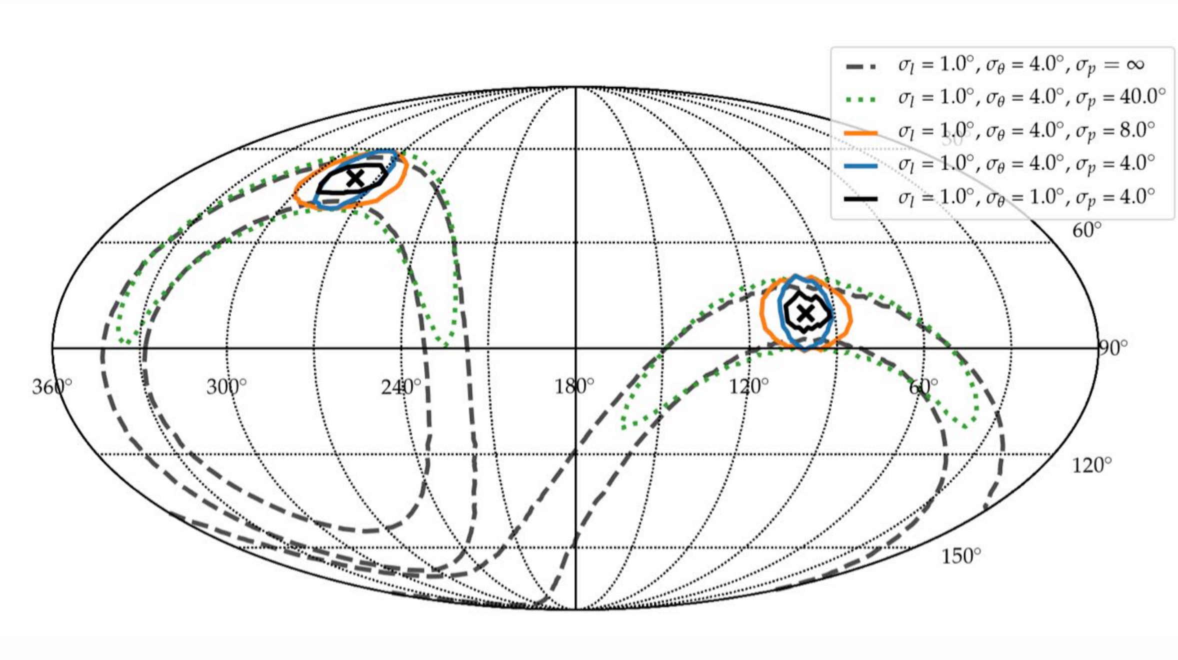
Neutrino quantities of interest

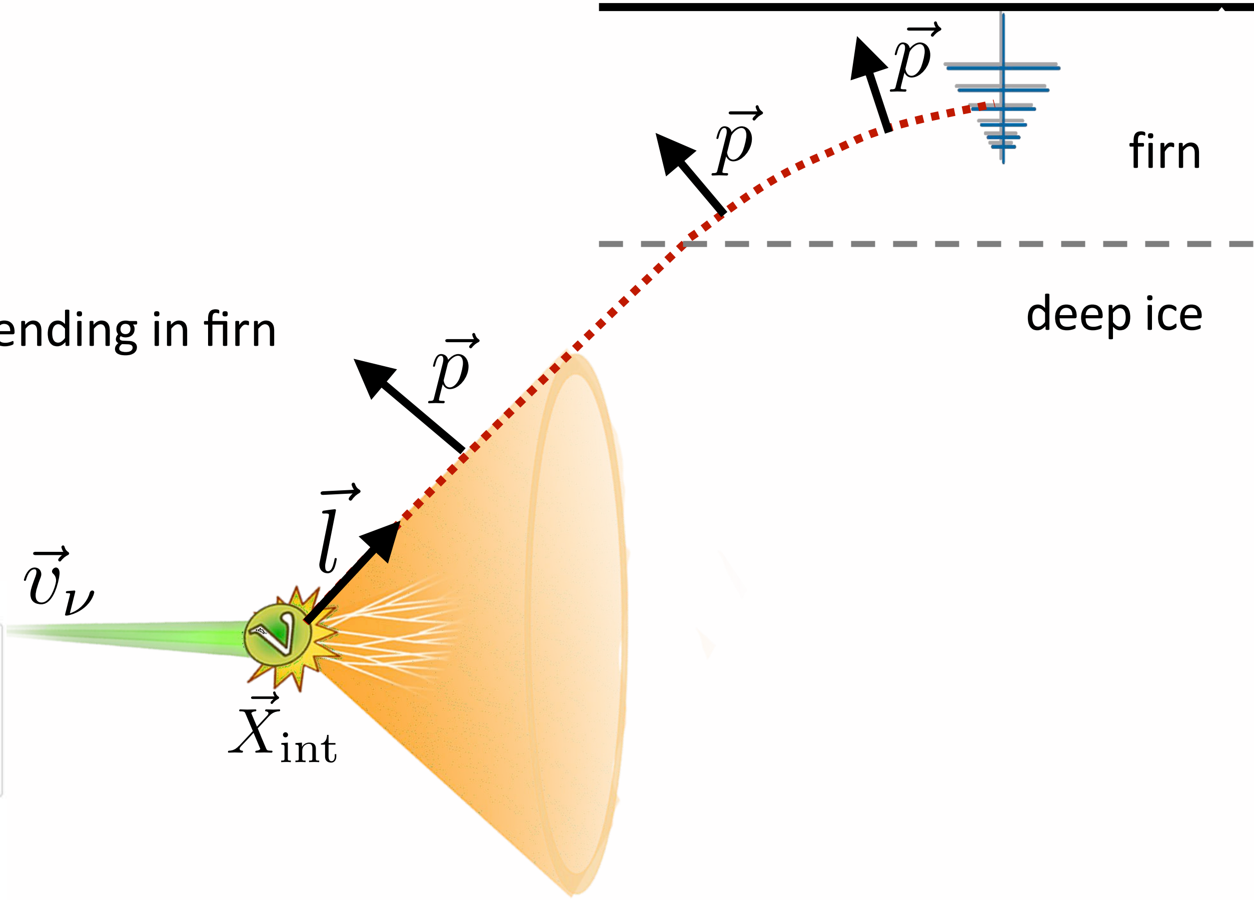
- direction
- energy
- flavor

Neutrino Direction

- The neutrino direction depends on the
  - signal arrival direction $\vec{l}$
  - signal polarization $\vec{p}$
  - viewing angle Θ
  - distance to neutrino interaction to correct for bending in firn

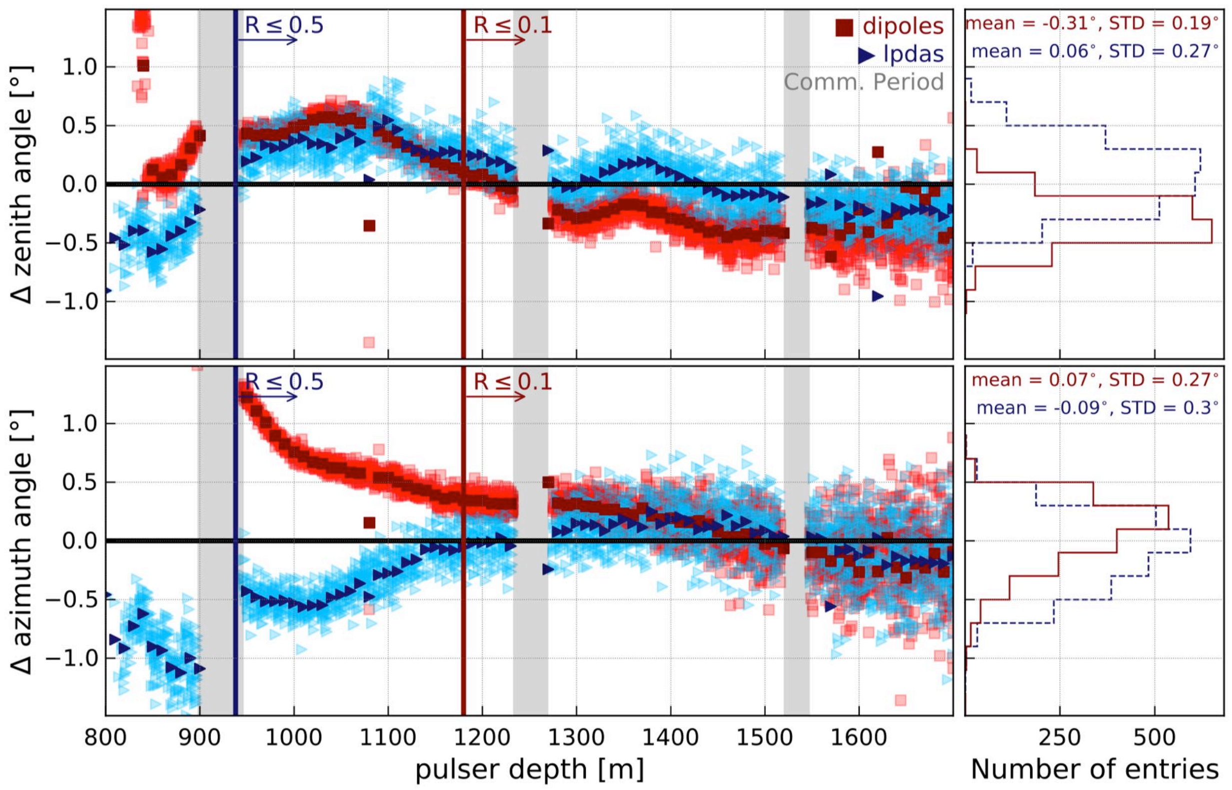
$$\vec{\hat{v}}_\nu = \sin\theta\,\vec{\hat{p}} - \cos\theta\,\vec{\hat{l}}$$

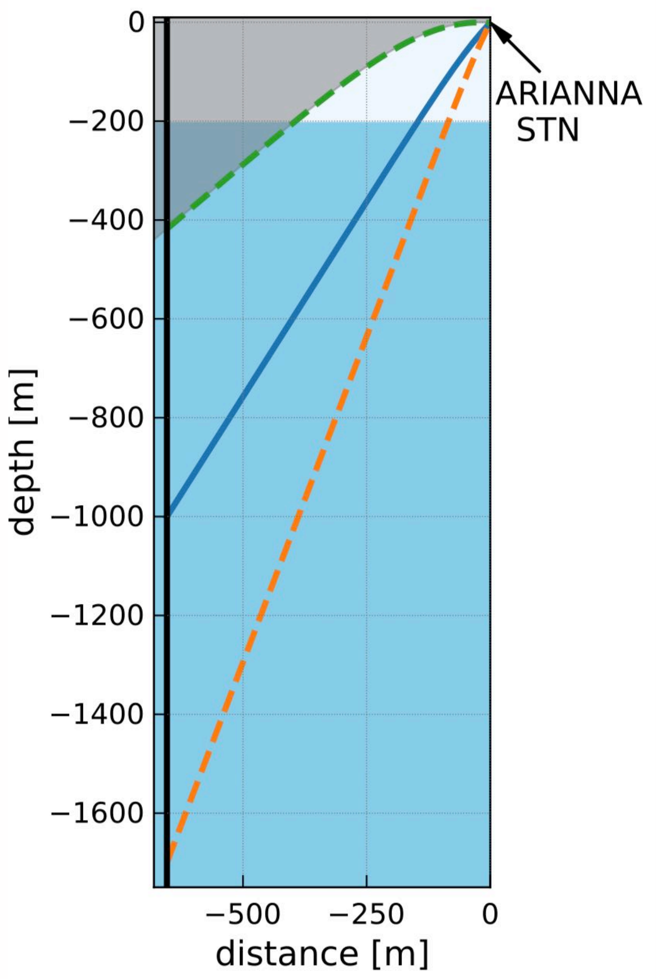




In-situ measurement at South Pole

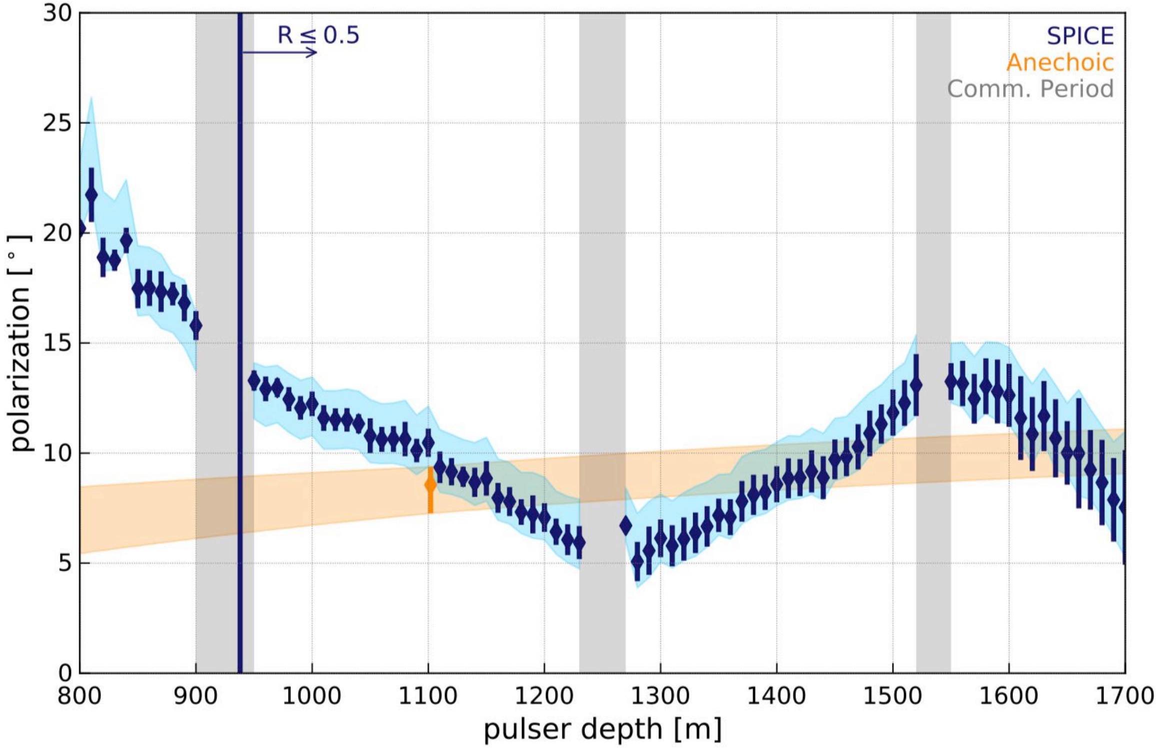
- Radio emitter lowered into ~2 km deep borehole
- signal direction: sub-degree resolution achieved (including ice correction)

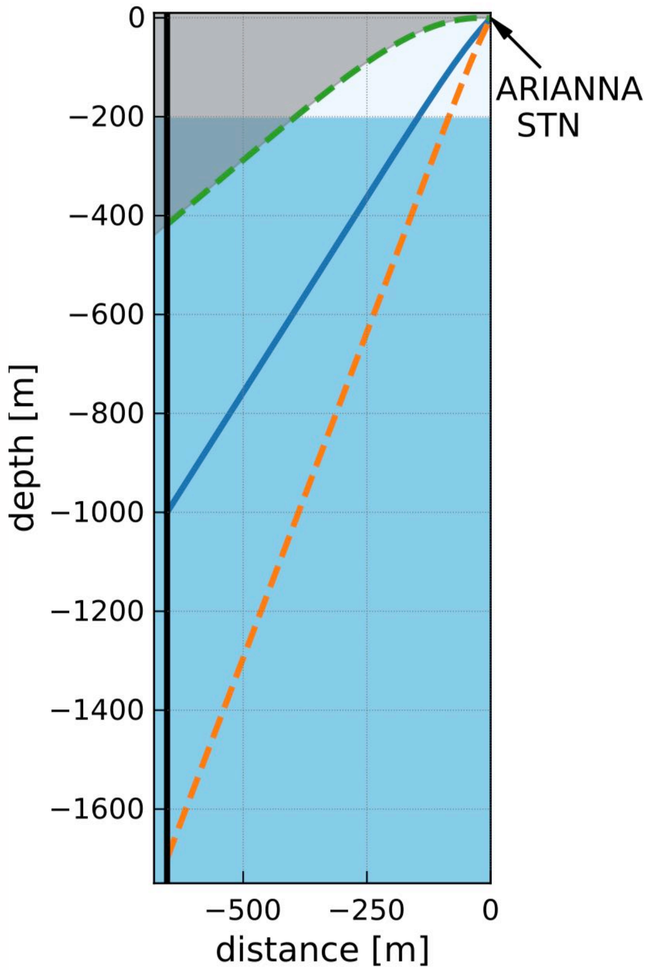




In-situ measurement at South Pole

- Radio emitter lowered into ~2 km deep borehole
- signal direction: sub-degree resolution achieved (including ice correction)
- polarization: 2.7 degree resolution-> dominates neutrino direction





Challenge 3: Event reconstruction

Neutrino quantities of interest

Getting the Neutrino Energy

- Electric field dependence

$$\vec{\mathcal{E}} = \vec{\mathcal{E}}_0(f)\,\frac{e^{-R/L(f)}}{R}\,e^{-\frac{(\Theta-\Theta_C)^2}{2\sigma_C(f)^2}}$$

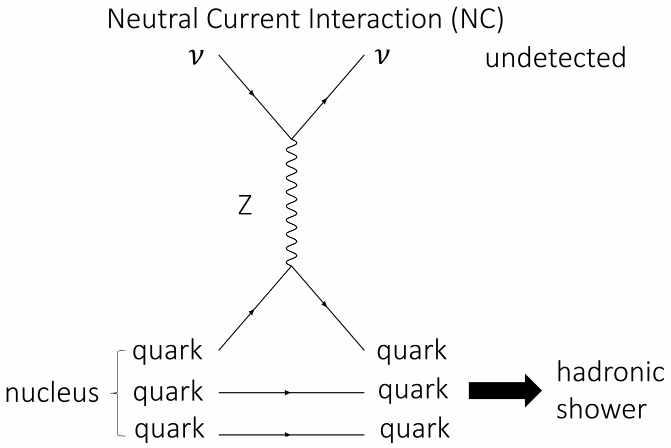
From measured voltage via antenna unfolding, requires **RF direction** and **polarization**

distance to shower

Viewing angle via **Frequency spectrum -> broadband antennas** and/or **Mapping of Cherenkov cone**

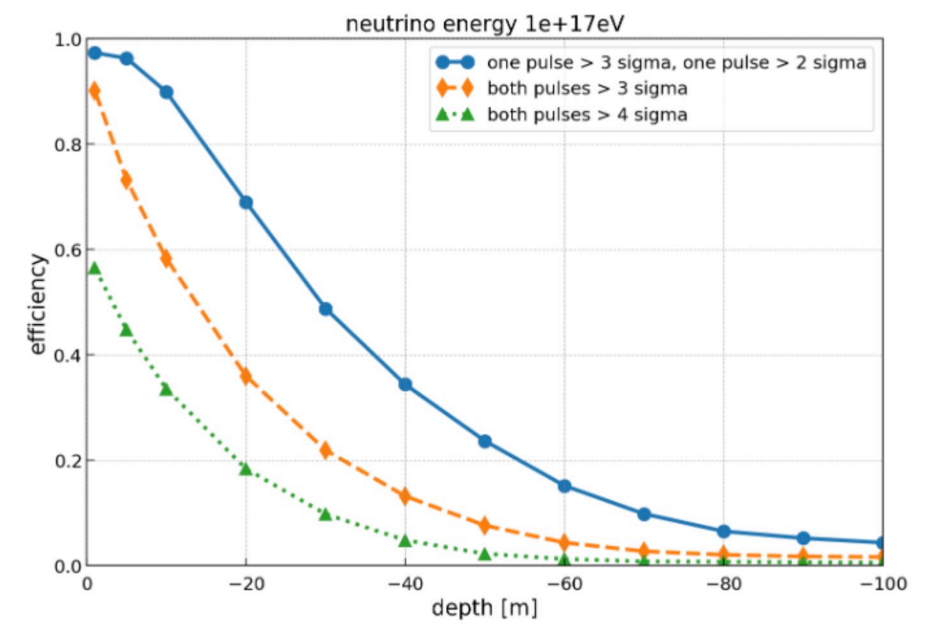
Neutrino energy to shower energy $\vec{\mathcal{E}}_0 \propto E_{\mathrm{sh}}$

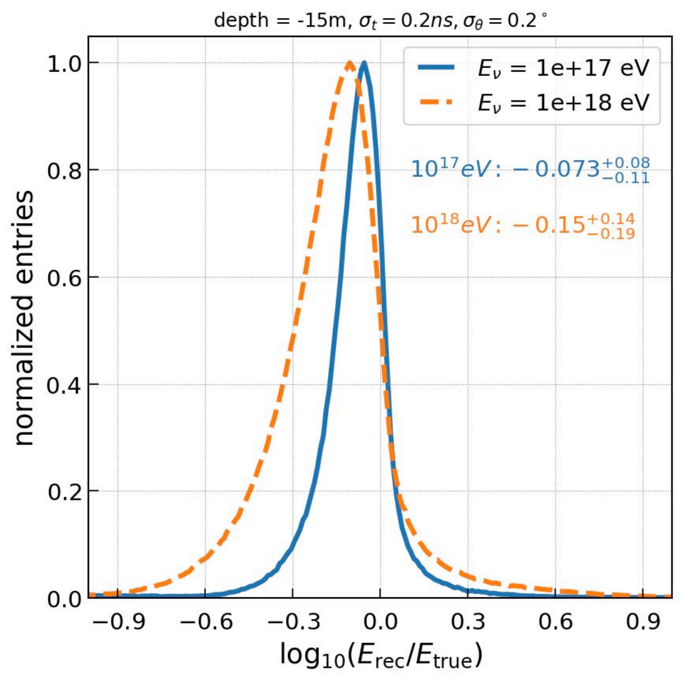
- Irreducible uncertainty from neutrino -> shower energy
  - Sets requirements for other contributions to energy resolution (~factor of 2)
  - No need to be much better than uncertainty from inelasticity

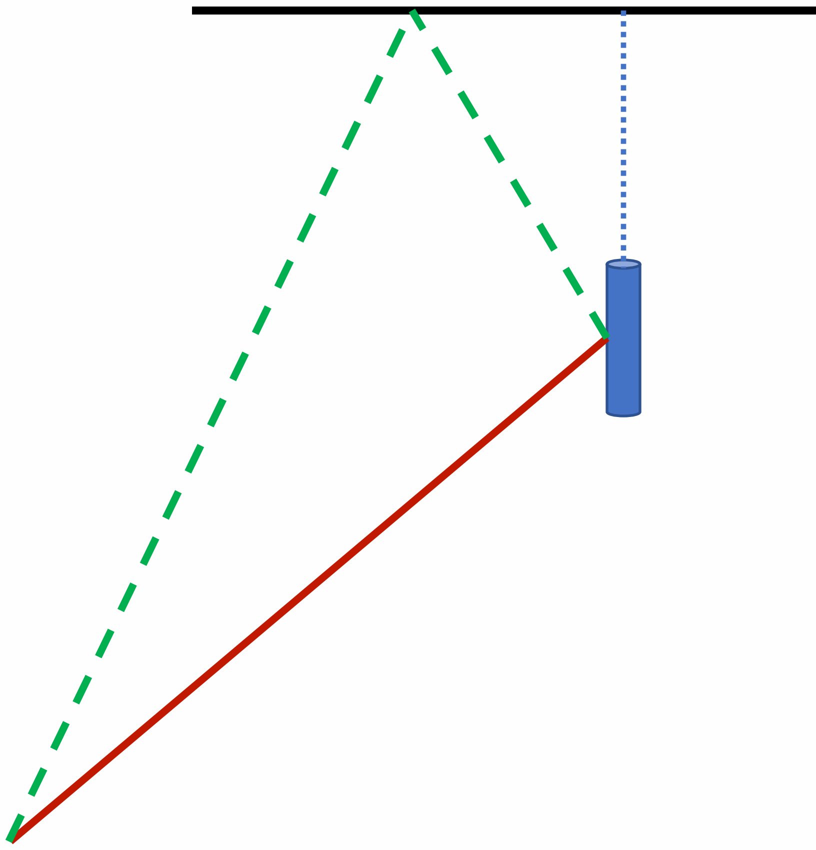


D’n’R Technique

- Antenna observes direct and reflected pulse
- Time difference ~ 1 / distance
- Efficiency + resolution~ depth of antenna



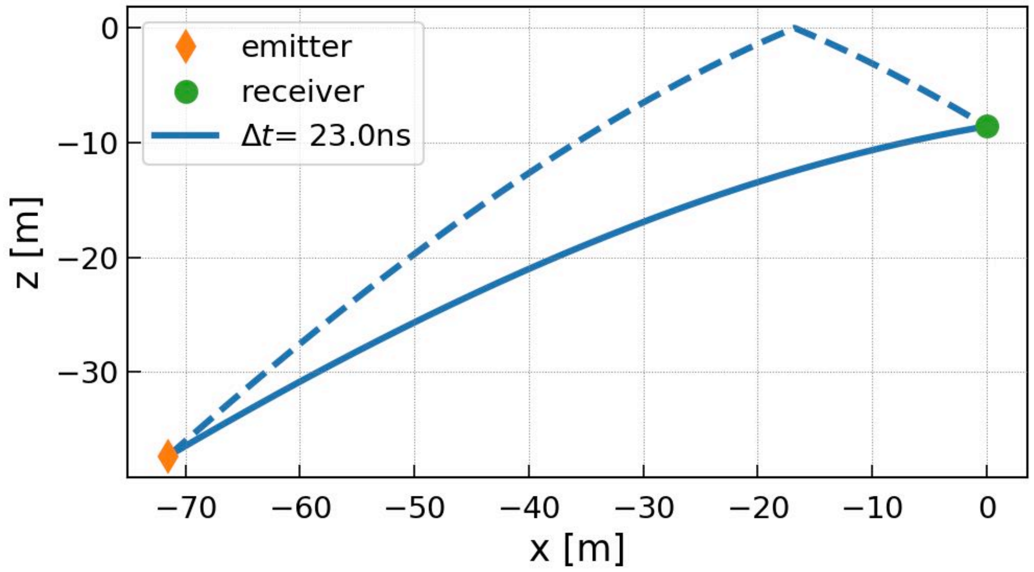


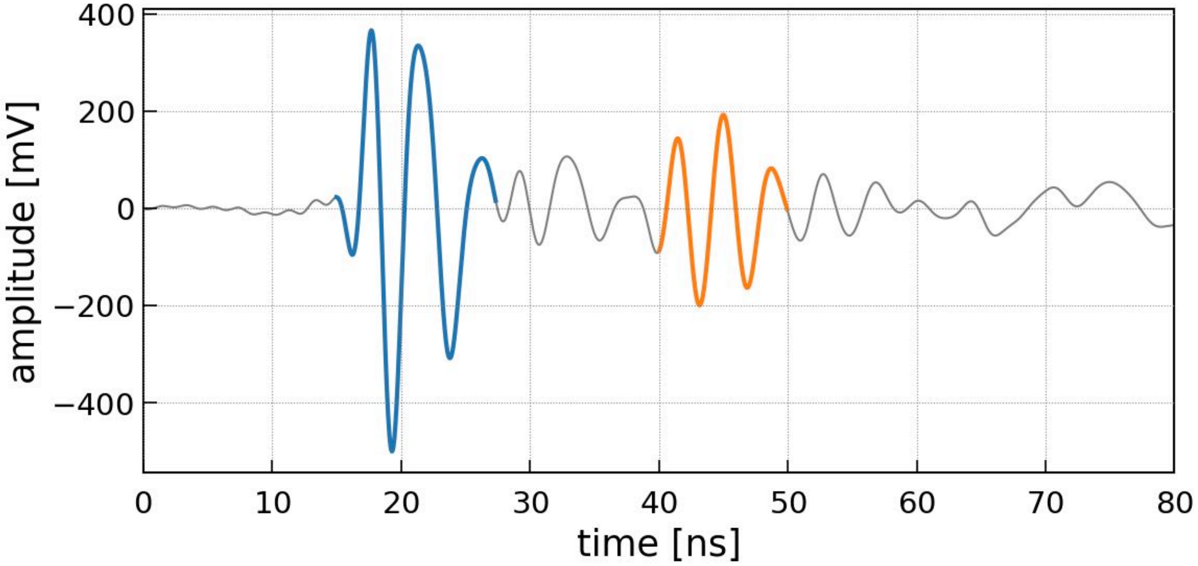


ARIANNA collaboration, JCAP 11(2019)030

First Experimental Results

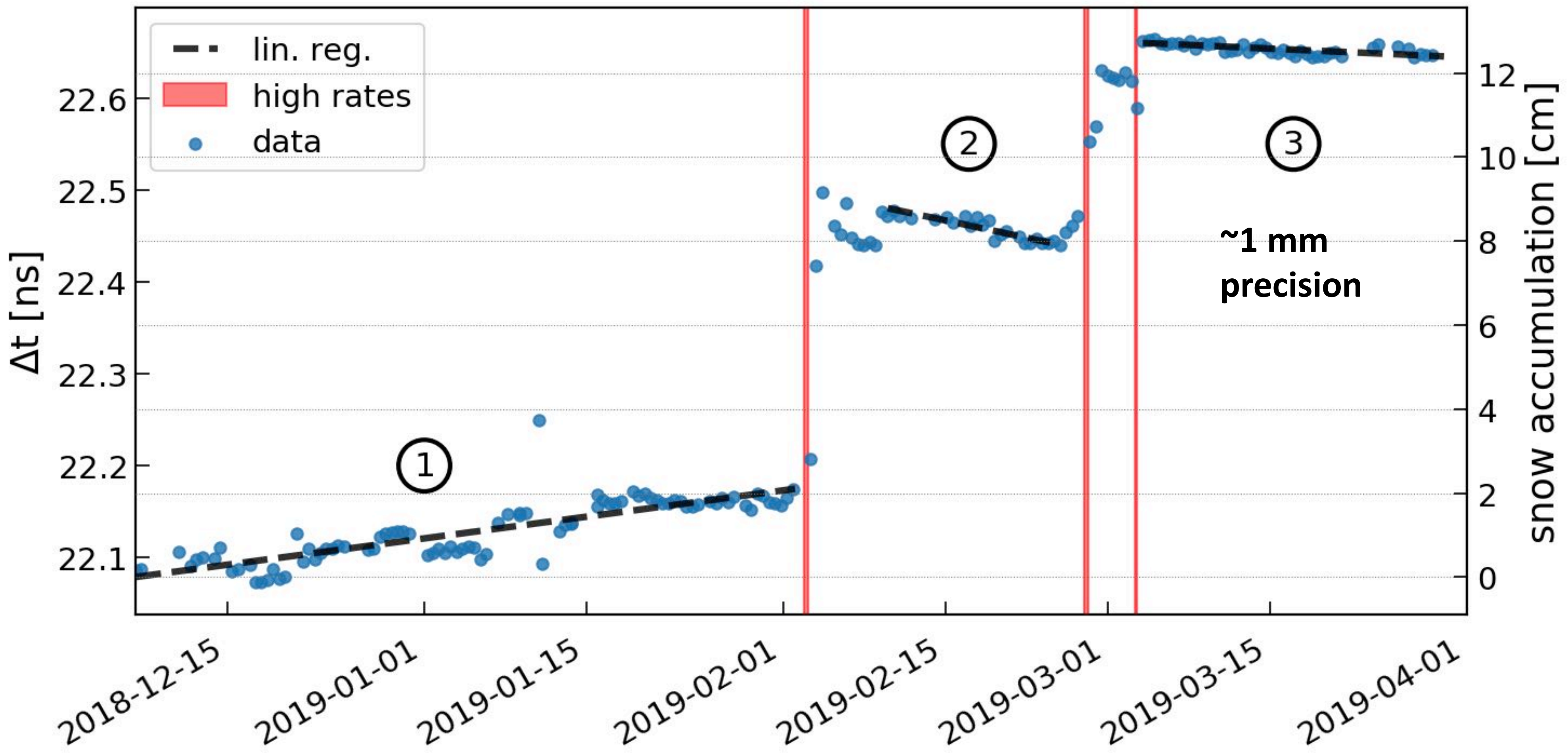
- Measurement at Moore's Bay
- 40m deep transmitter
- 10m deep receiver
- thanks to EnEX/Aachen drill





ARIANNA collaboration, JCAP 11(2019)030

Monitoring of Snow Accumulation



Challenge 3: Event Reconstruction

Neutrino quantities of interest

direction ✓

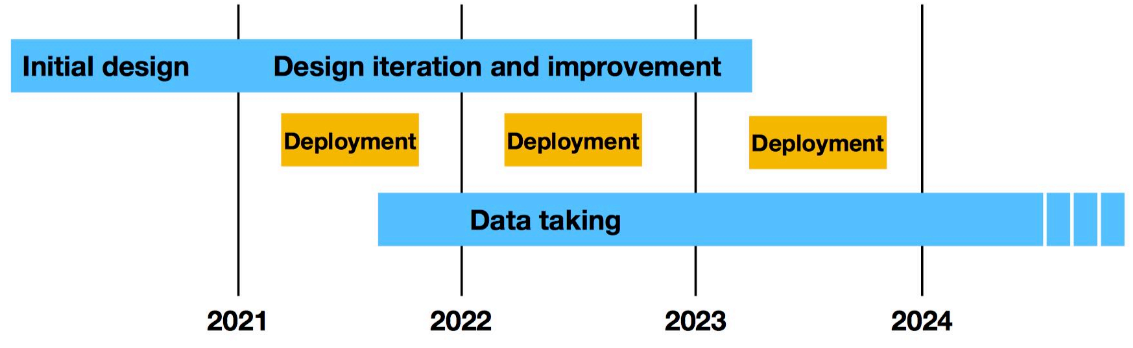
energy ✓

flavor

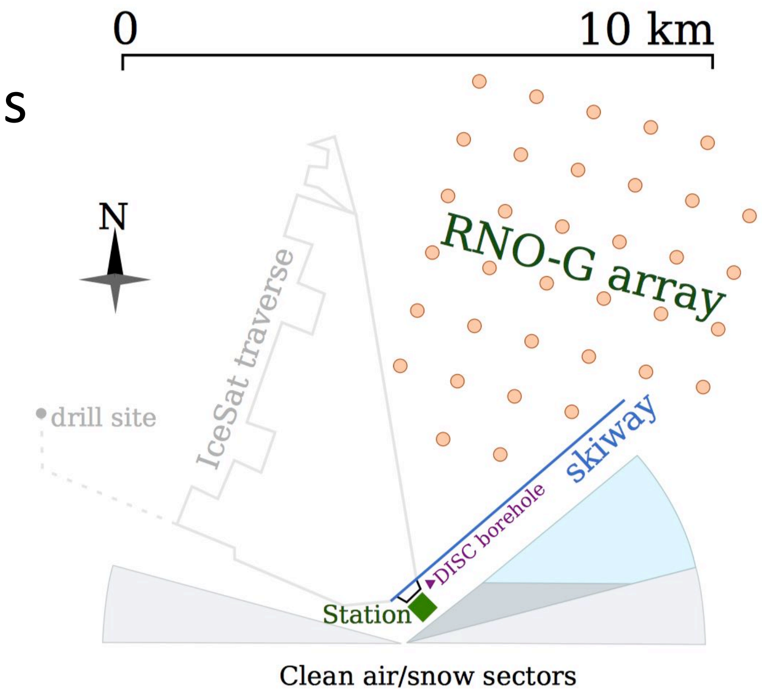
just starting to explore flavor physics
-> D. Garcia, C. Glaser, A. Nelles,
Phys. Rev. D 102, 083011 (2020)

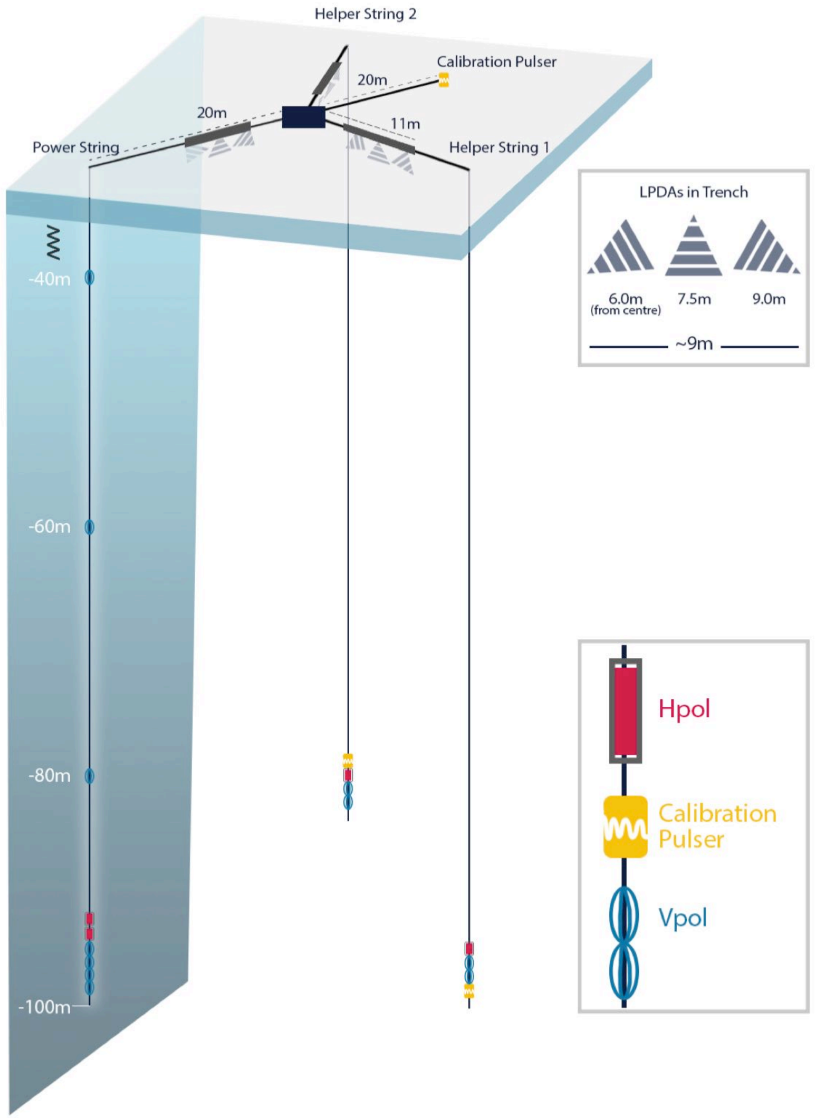
The future part I: RNO-G (Radio Neutrino Observatory – Greenland)

RNO-G collaboration, arXiv:2010.12279



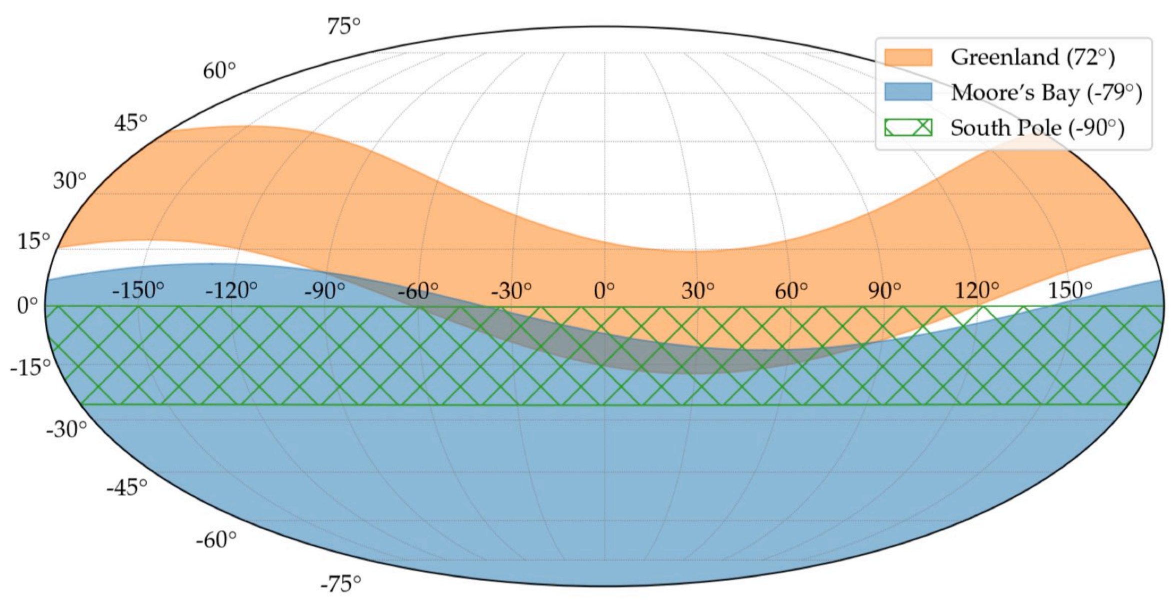
- 35 autonomous stations

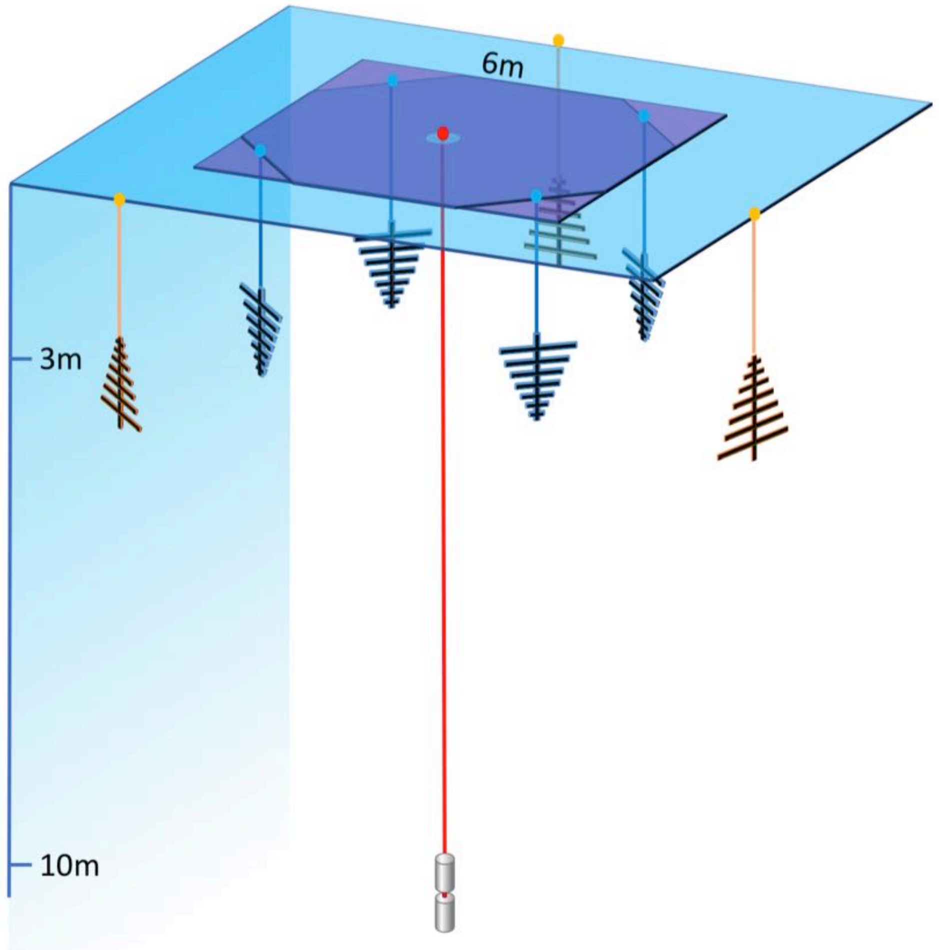




The future part I: ARIANNA-200 (proposal)

- 200 autonomous surface stations on the Ross Ice Shelf
- Advantage: large sky coverage
- Not funded yet



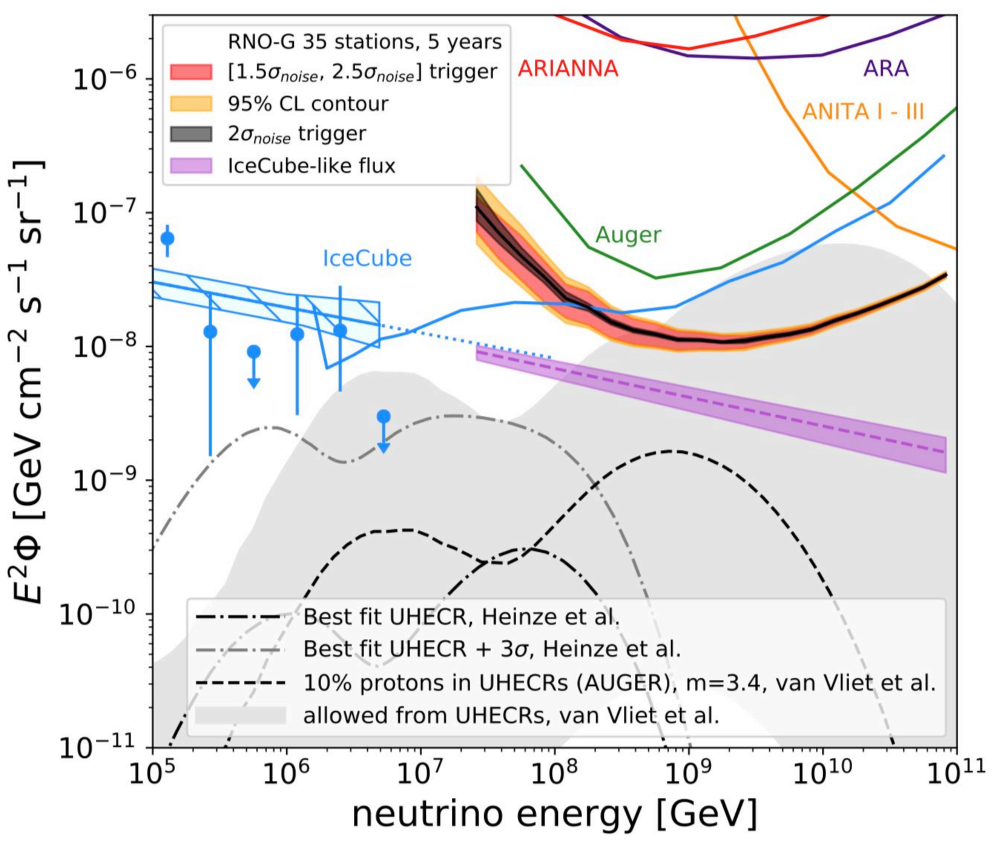


RNO-G collaboration, arXiv:2010.12279
ARIANNA collaboration, arXiv:2004.09841

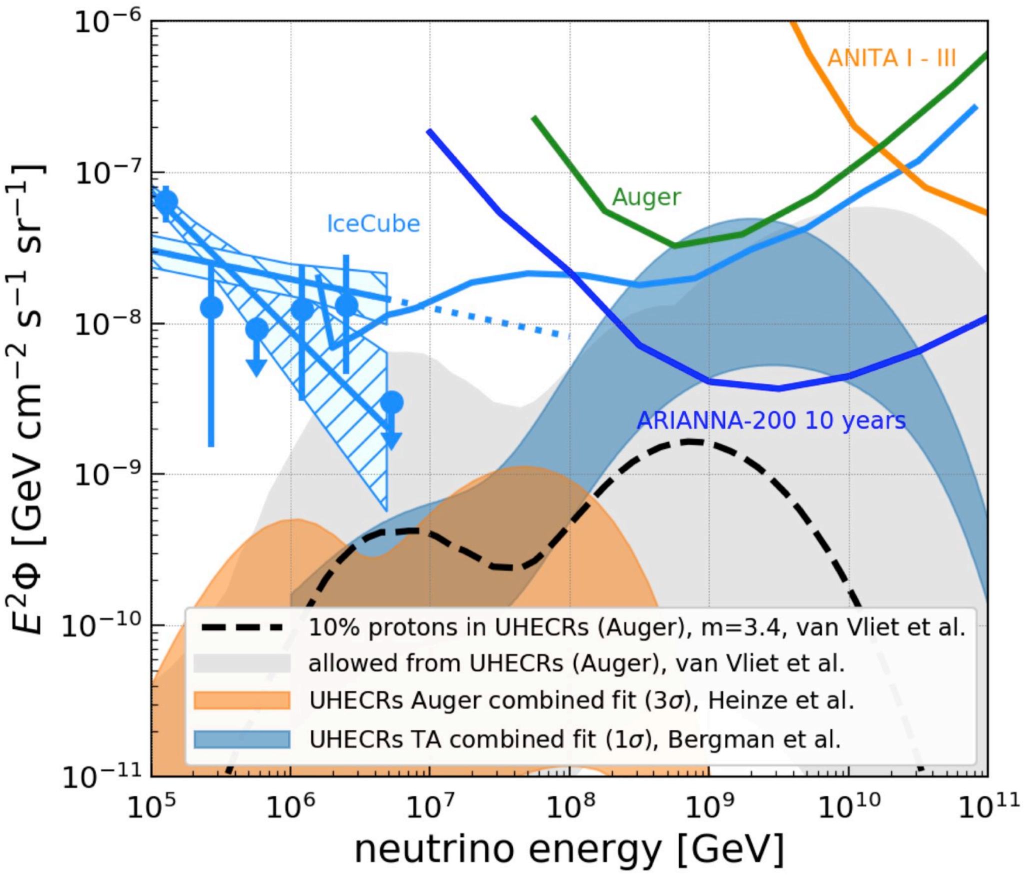
Science Potential

Diffuse neutrino flux

RNO-G



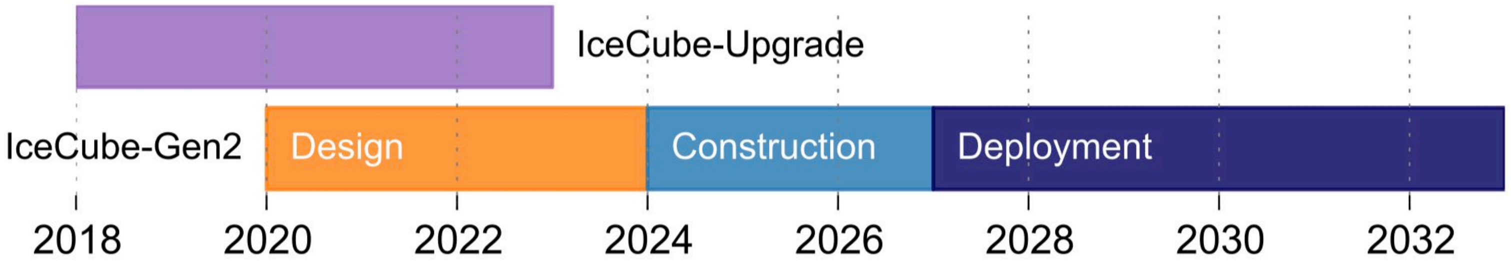
ARIANNA-200

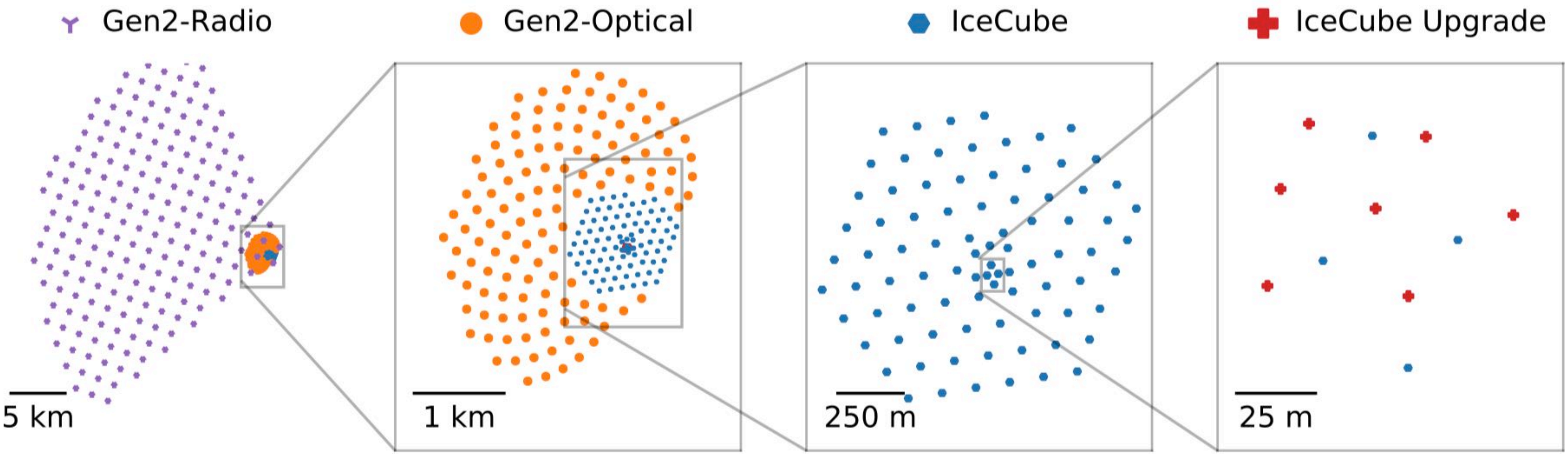


IceCube-Gen2 collaboration, arXiv:2008.04323

The future part II: IceCube-Gen2

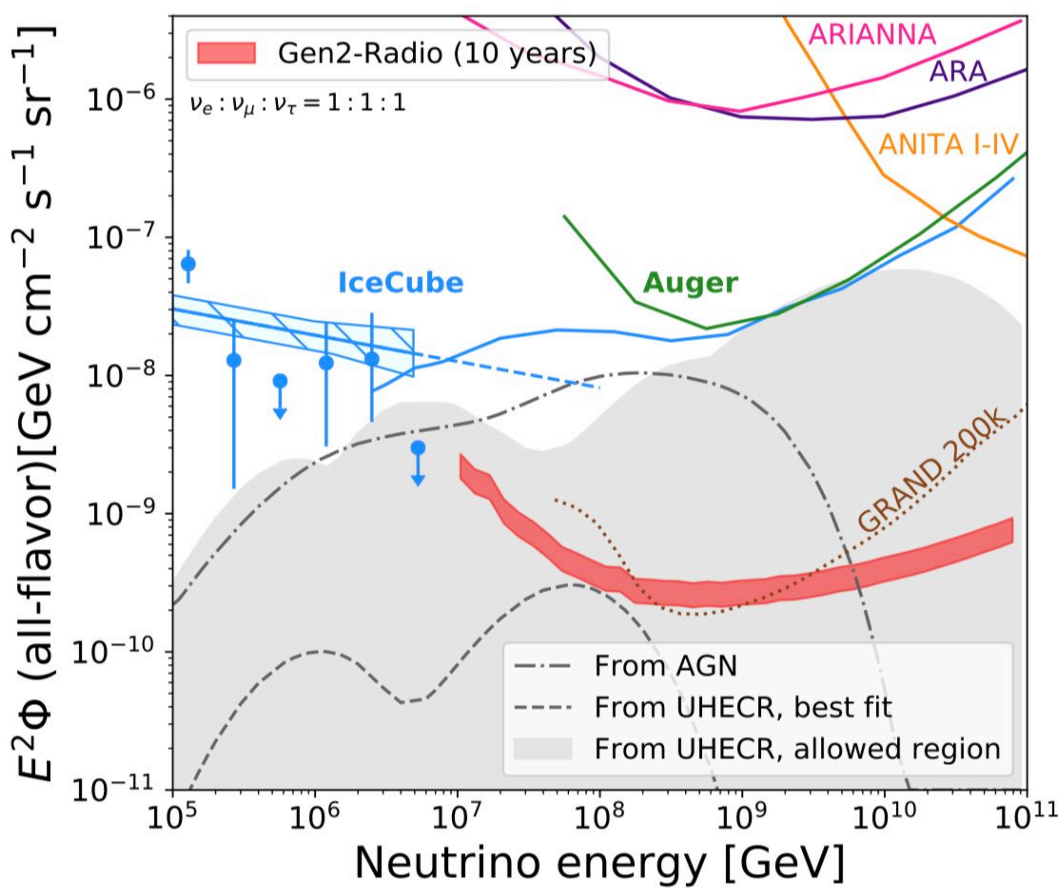
- Large radio detector is part of IceCube-Gen2
  - to increase sensitivity for $E>10^{16}$eV
- >200 radio detector stations



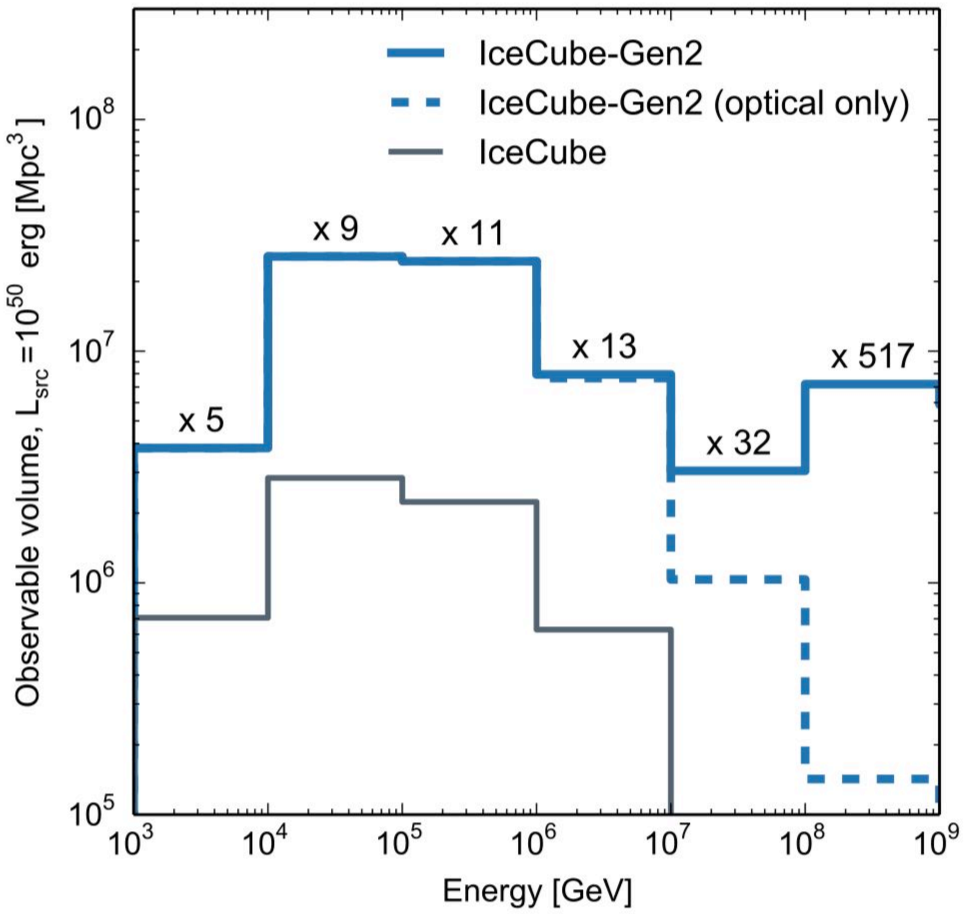


Science Potential IceCube-Gen2 Radio

Diffuse neutrino flux



Explosive sources

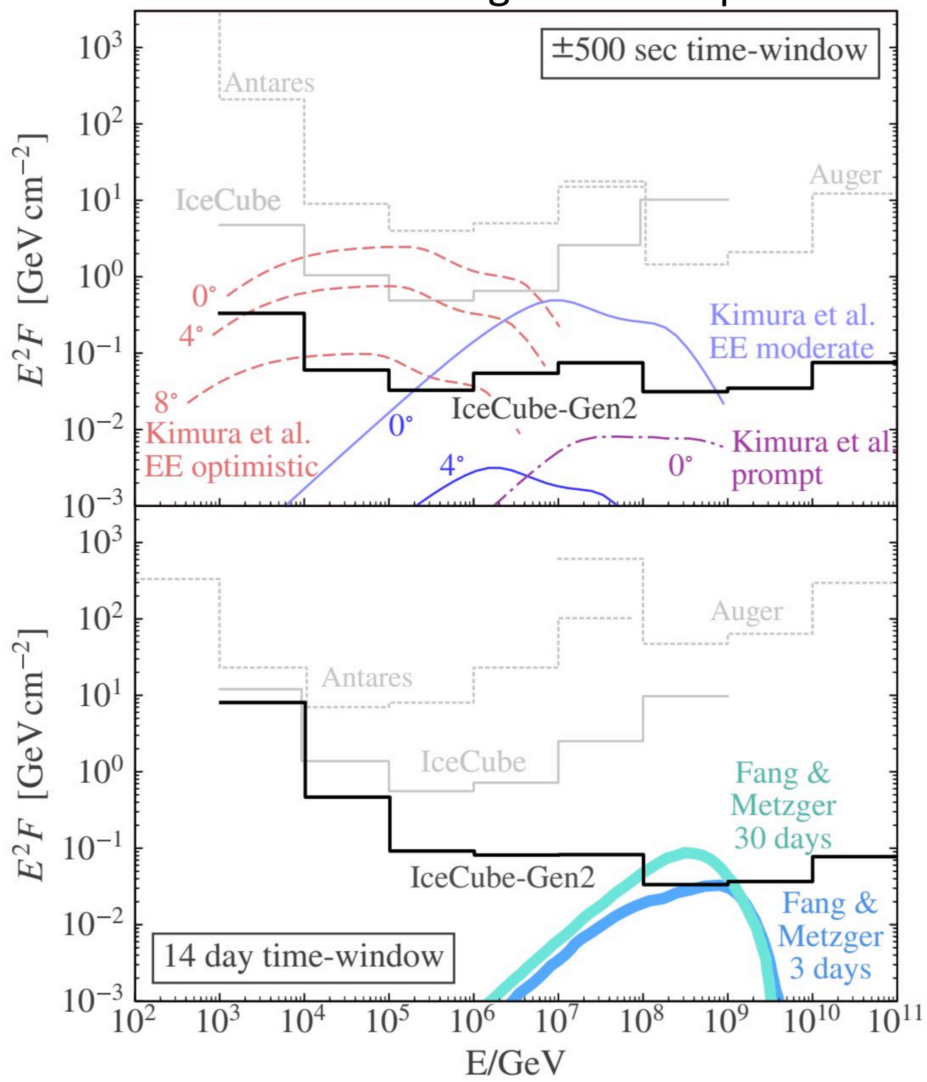


IceCube-Gen2 collaboration, arXiv:2008.04323

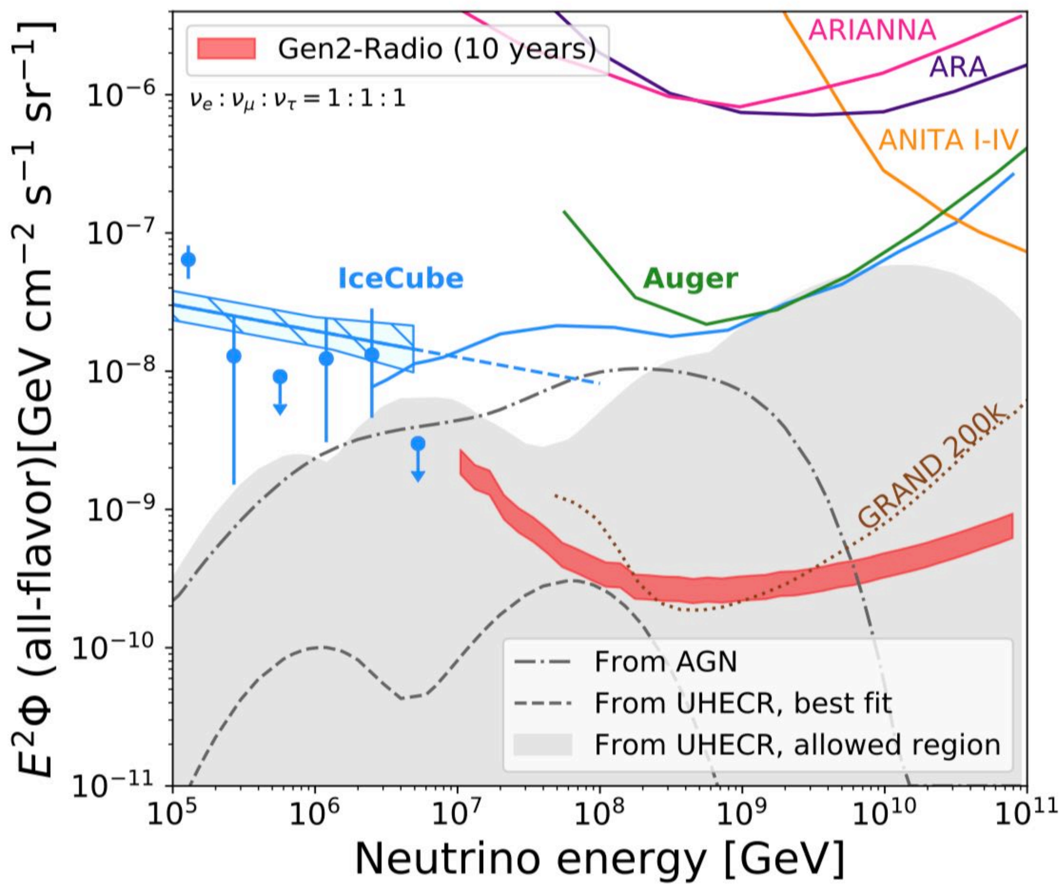
Science Potential IceCube-Gen2 Radio

Explosive sources

NS-NS merger follow up



Diffuse neutrino flux



Summary

- Radio detection is an intriguing (new) technique to detect neutrinos of the highest energies
- Emission properties well understood
- Technology proven in pilot arrays

- Future:
  - RNO-G: 35 stations in Greenland
  - Radio component of IceCube-Gen2: 200+ stations at the South Pole

NuRadioMC

Simulating the radio emission of neutrinos from interaction to detector

Christian Glaser, Daniel García-Fernández, Anna Nelles, Jaime Alvarez-Muñiz, Steven W. Barwick, Dave Z. Besson, Brian A. Clark, Amy Connolly, Cosmin Deaconu, Krijn de Vries, Jordan C. Hanson, Ben Hokanson-Fasig, R. Lahmann, Uzair Latif, Stuart A. Kleinfelder, Christopher Persichilli, Yue Pan, Carl Pfender, Ilse Plaisier, Dave Seckel, Jorge Torres, Simona Toscano, Nick van Eijndhoven, Abigail Vieregg, Christoph Welling, Tobias Winchen, Stephanie A. Wissel

European Physics Journal C 80, 77 (2020) arXiv:1906.01670

+

NuRadioReco: A reconstruction framework for radio neutrino detectors

C. Glaser, A. Nelles, I. Plaisier, C. Welling et al., Eur. Phys. J. C (2019) 79: 464

NuRadioMC Overview

- Modular python code (C++ modules for time critical operations)
- Open source: *github.com/nu-radio/NuRadioMC*
- Community wide effort (InIceMC group)

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

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

Signal Generation
- Phase and frequency
- LPM effect
- …

Signal Propagation
- Ice models
- (analytic) ray tracing
- …

Detector Simulation
- Frequency and phase response
- Flexible station layout
- Trigger simulation
- …

new

multiple interactions e.g. tau decays interference between showers

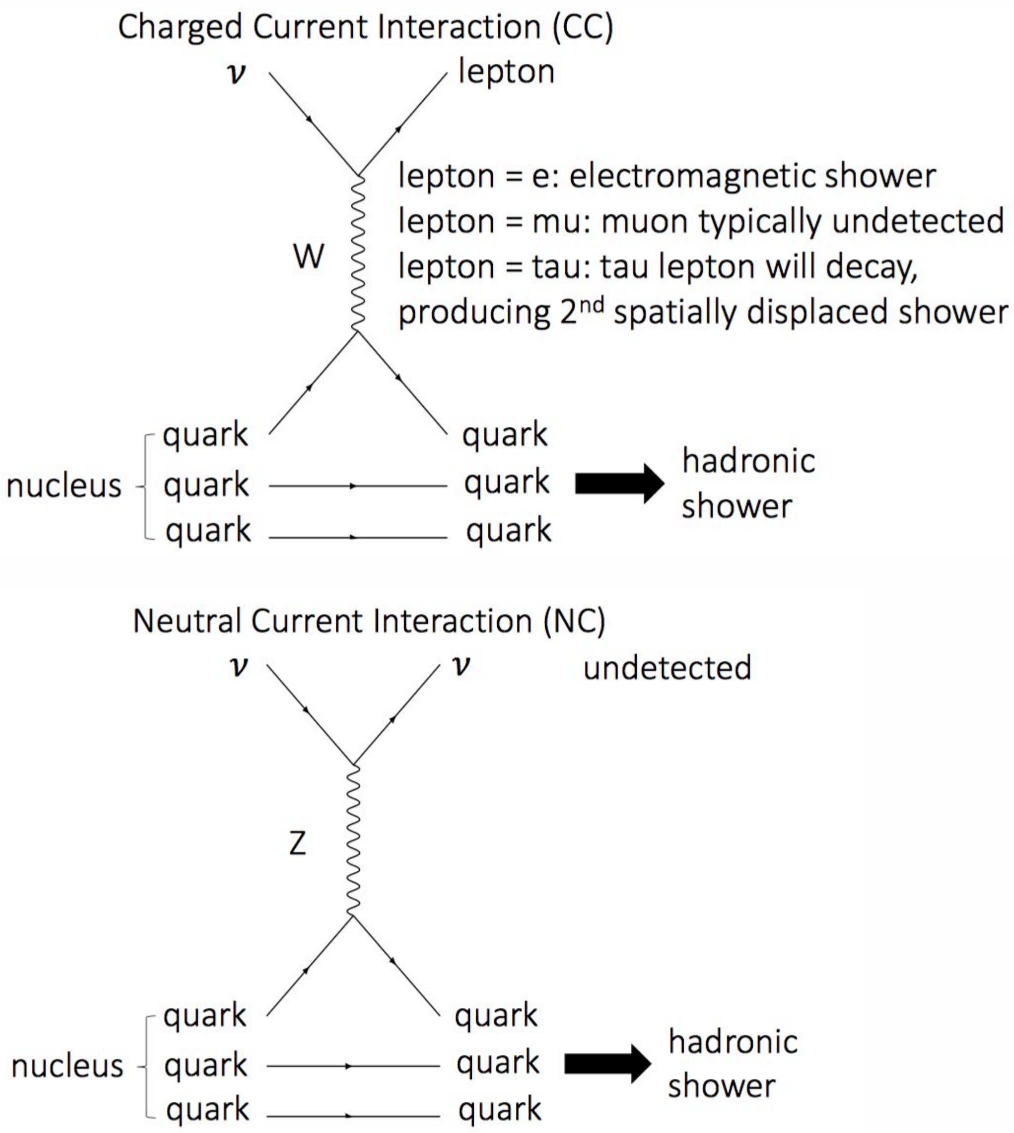
time domain calculation with realistic LPM

fast + precise analytic ray tracer

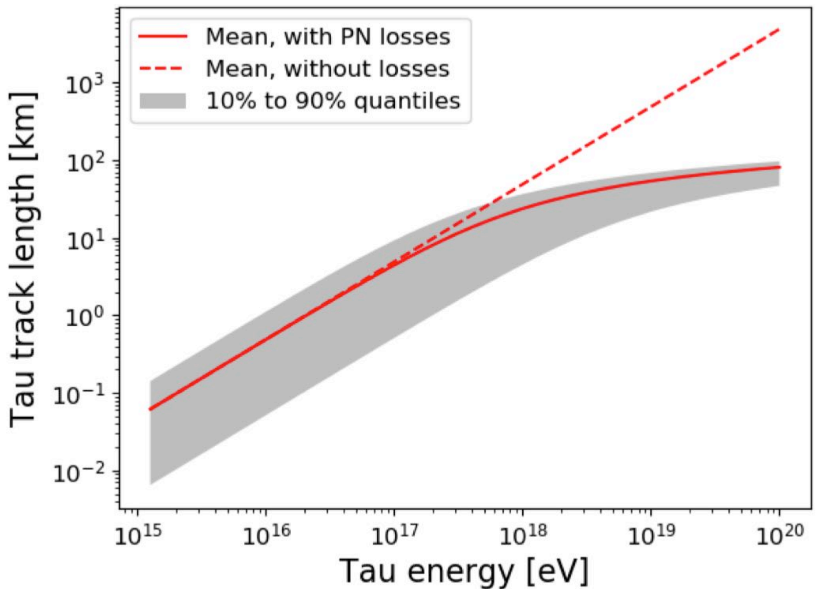
NuRadioReco: Detector simulation and event reconstruction

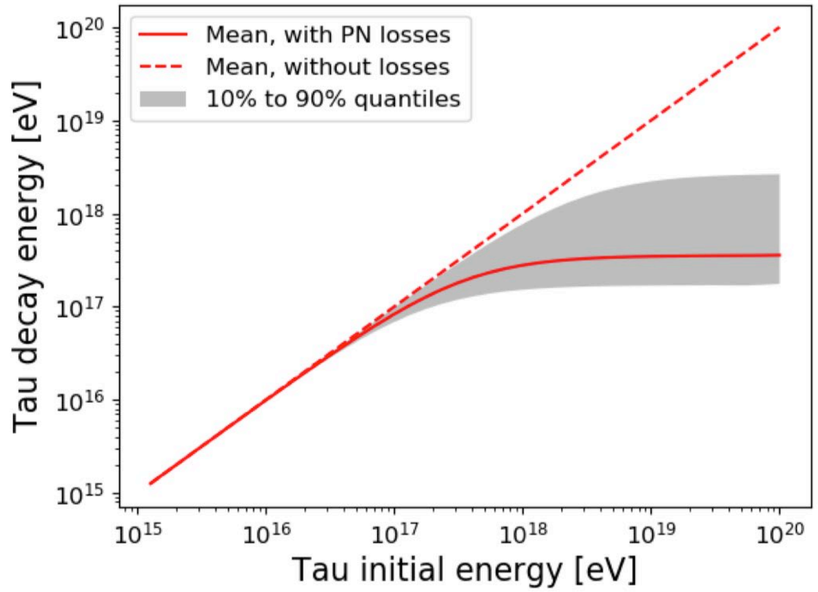
Event Generation

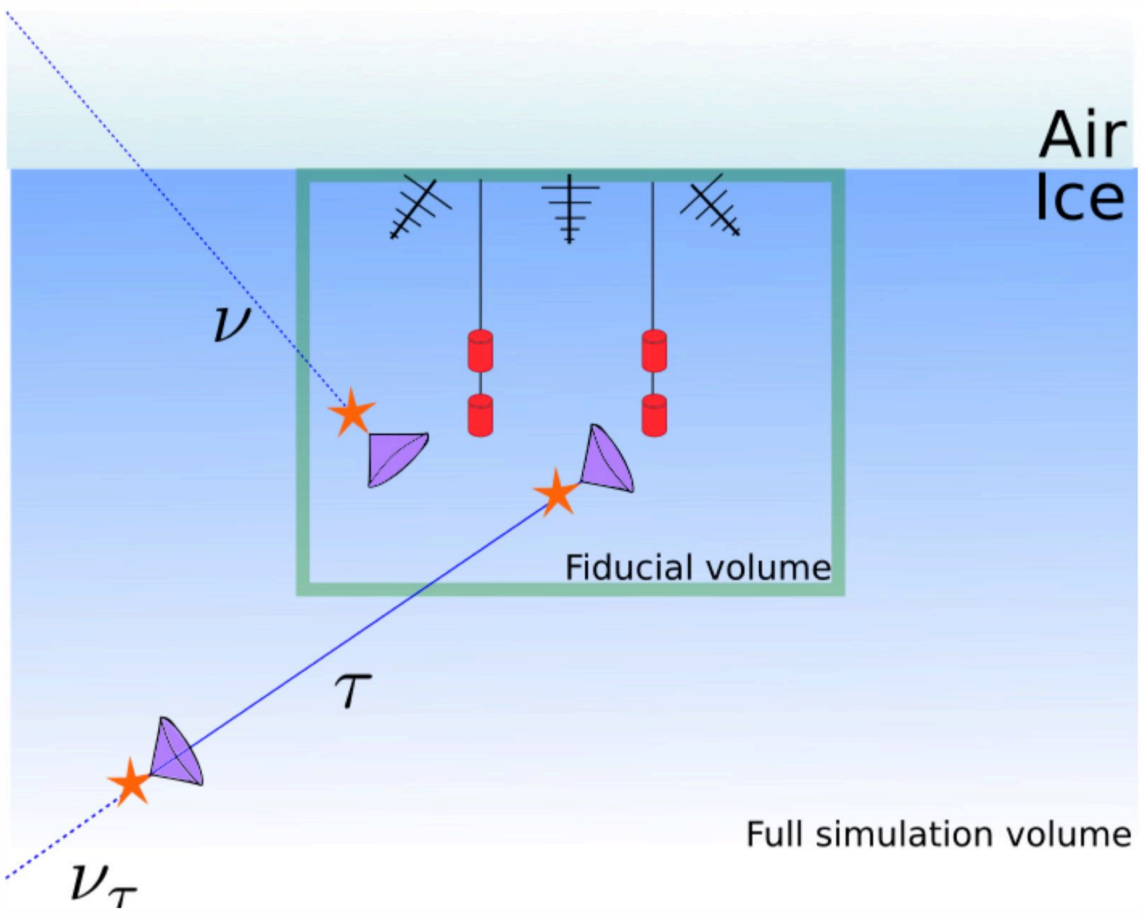
- HDF5 input file
- List of
  - shower direction
  - shower energy
  - shower position
- Easy to write custom event generator for e.g.
  - BSM physics
  - monopoles
  - calibration measurements



Simulation of secondary leptons: Tau decays



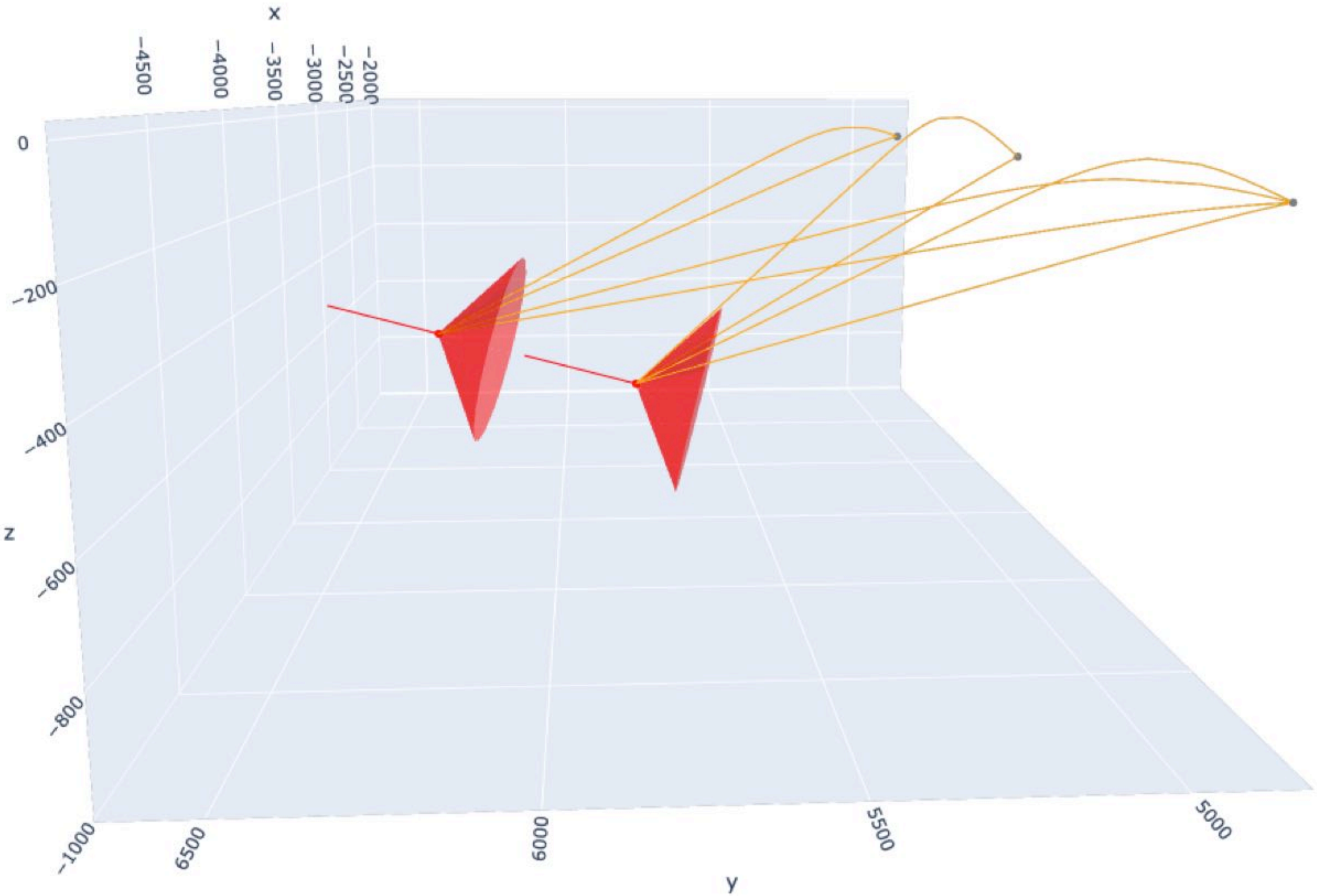




generalization: Integration of PROPSAL for lepton propagation

D. Garcia, C. Glaser, A. Nelles, Phys. Rev. D 102, 083011 (2020)

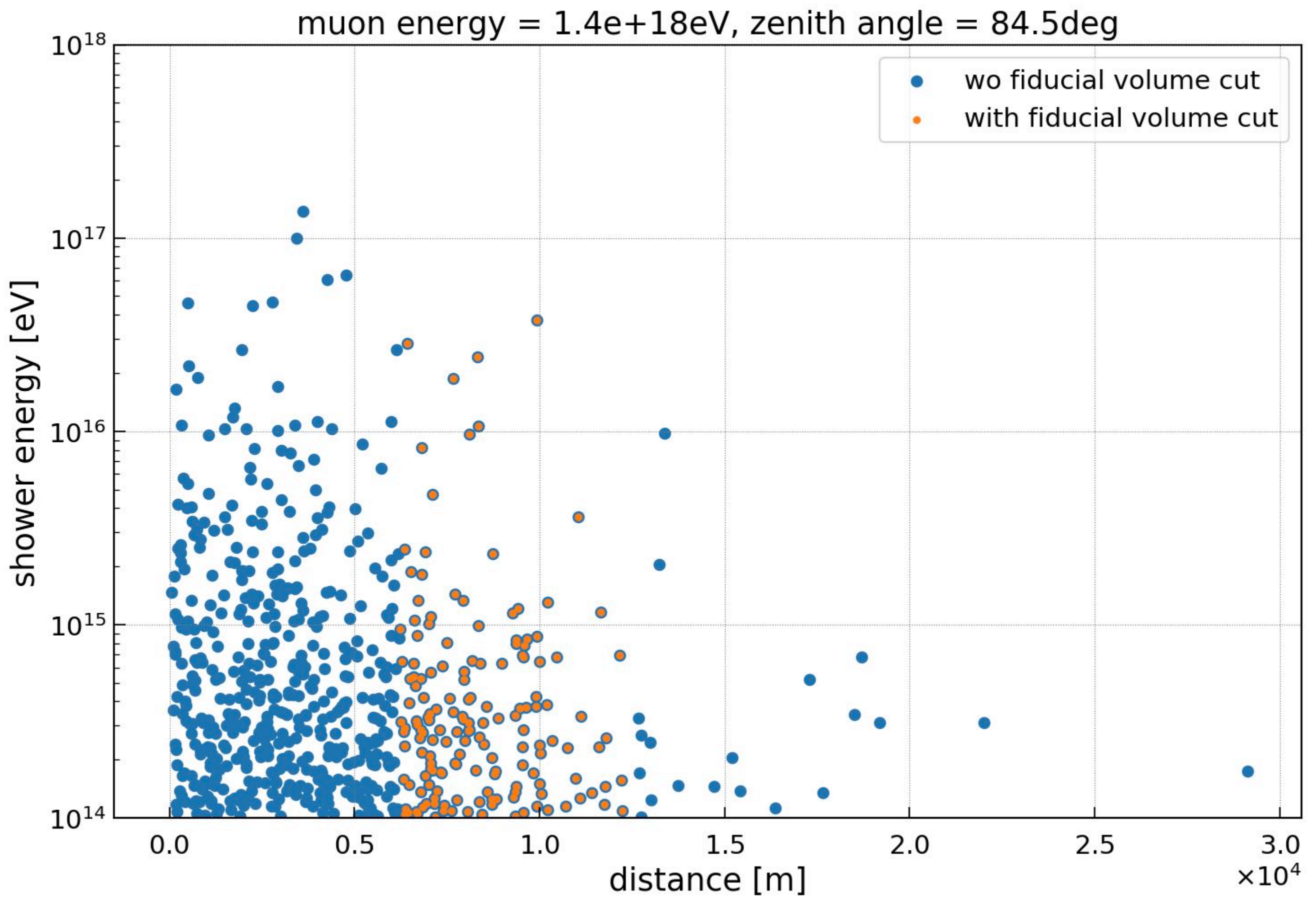
Possible event signature



D. Garcia, C. Glaser, A. Nelles, Phys. Rev. D 102, 083011 (2020)

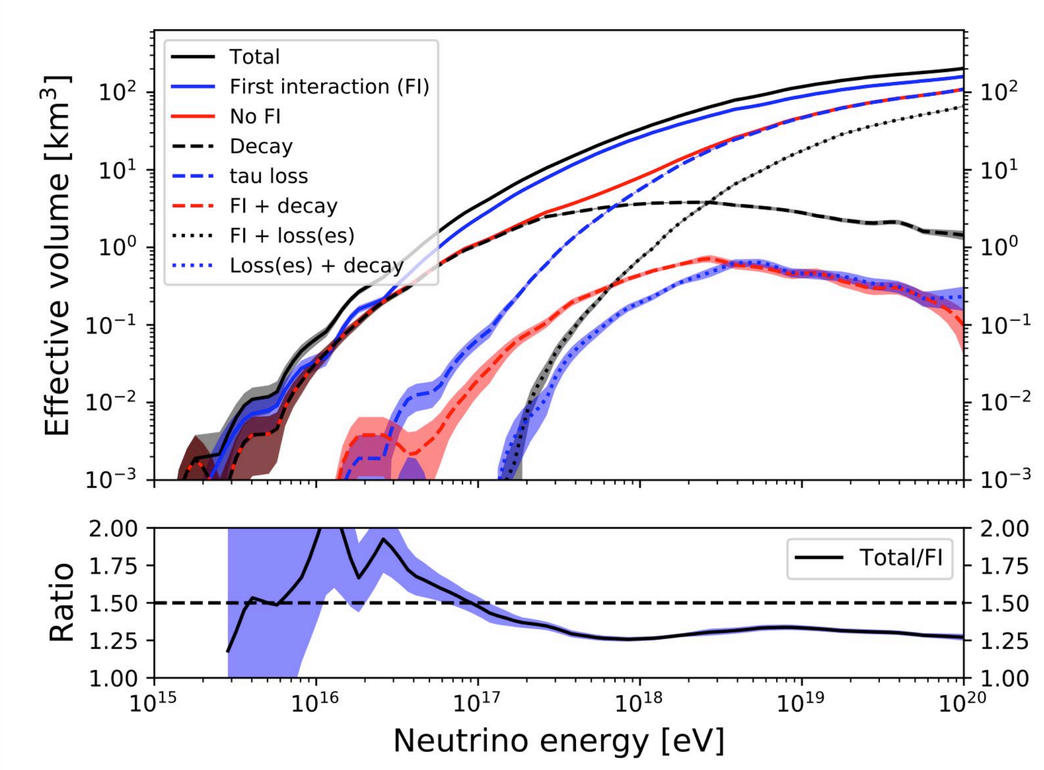
Lepton propagation through ice using PROPOSAL

- muons/taus stochastically loose energy
  - inducing many showers along their trajectory
- Example plot:
  - 1 EeV muon propagation almost horizontally through the ice
  - Askaryan signal of each shower in fiducial simulation volume is calculated and propagated to antennas

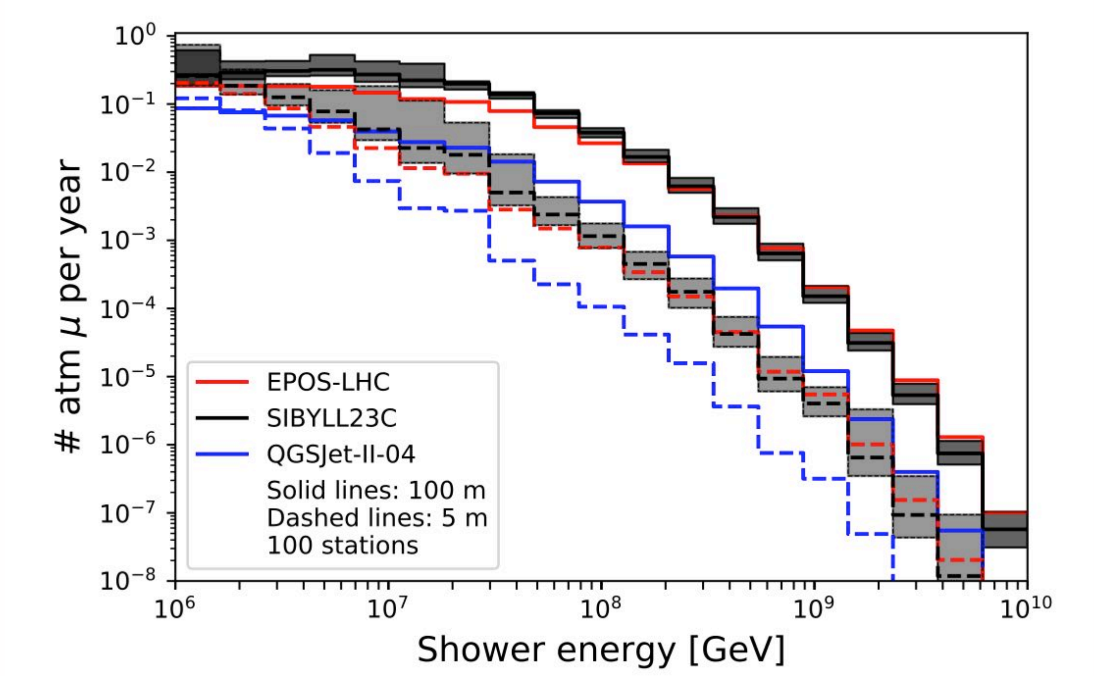


First Lepton Results

Tau neutrino effective volume



Background from atmospheric neutrinos



Signal Generation

- Well tested reference implantation of all available models

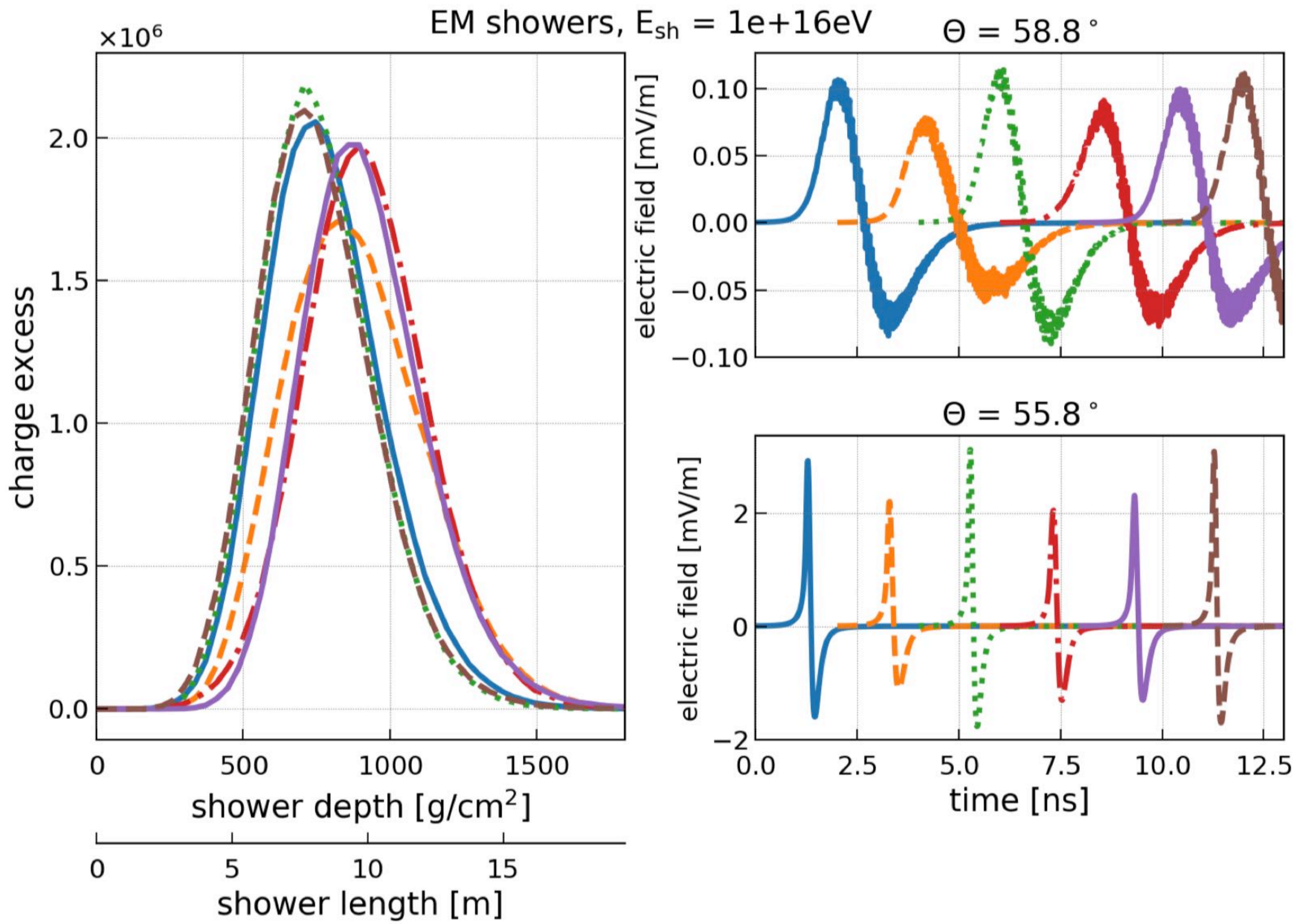
```
def get_time_trace(energy, theta, N, dt, shower_type, n_index, R, model,
```

model	advantages	shortcomings
parameterization (*Alvarez2009*)	fast, accurate representation of the signal amplitudes, includes statistical fluctuations from LPM	no phase information, only valid in far-field
fully analytic (*HCRB2017*)	fast, phase information provided, valid in near and far-field, LPM is treated as elongated shower	no statistical fluctuations from LPM, generalization, absolute amplitudes less accurate
semi analytic (*ARZ*)	phase information provided, near and far-field, realistic LPM treatment based on simulated shower library	computationally expensive
full MC	precise modelling of all details of shower development	slow, no implementation in NuRadioMC yet

*Alvarez-Muñiz et al., Phys. Rev. D **101**, 083005*

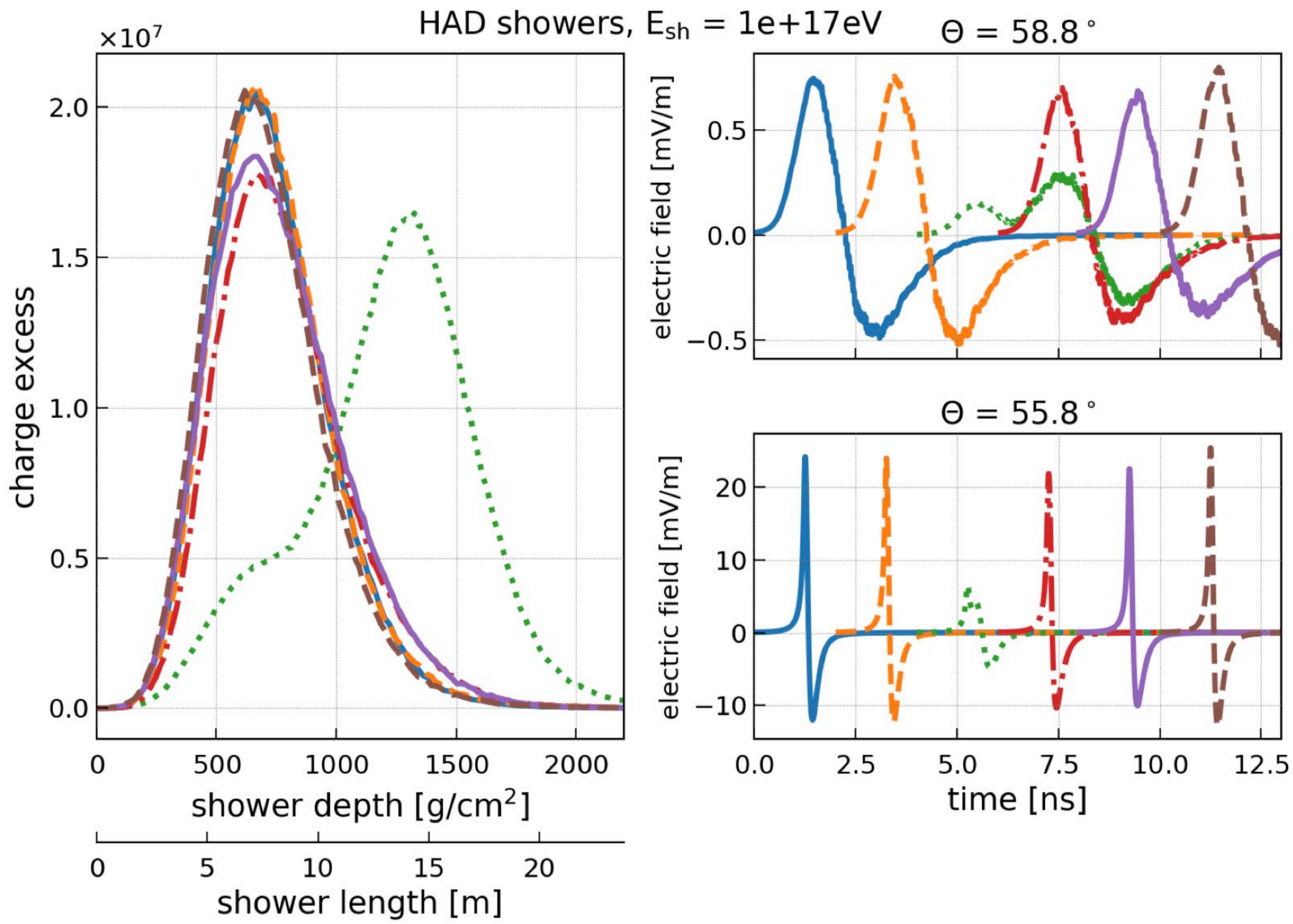
ARZ

time domain calculation based on charge-excess shower library



*Alvarez-Muñiz et al., Phys. Rev. D **101**, 083005*

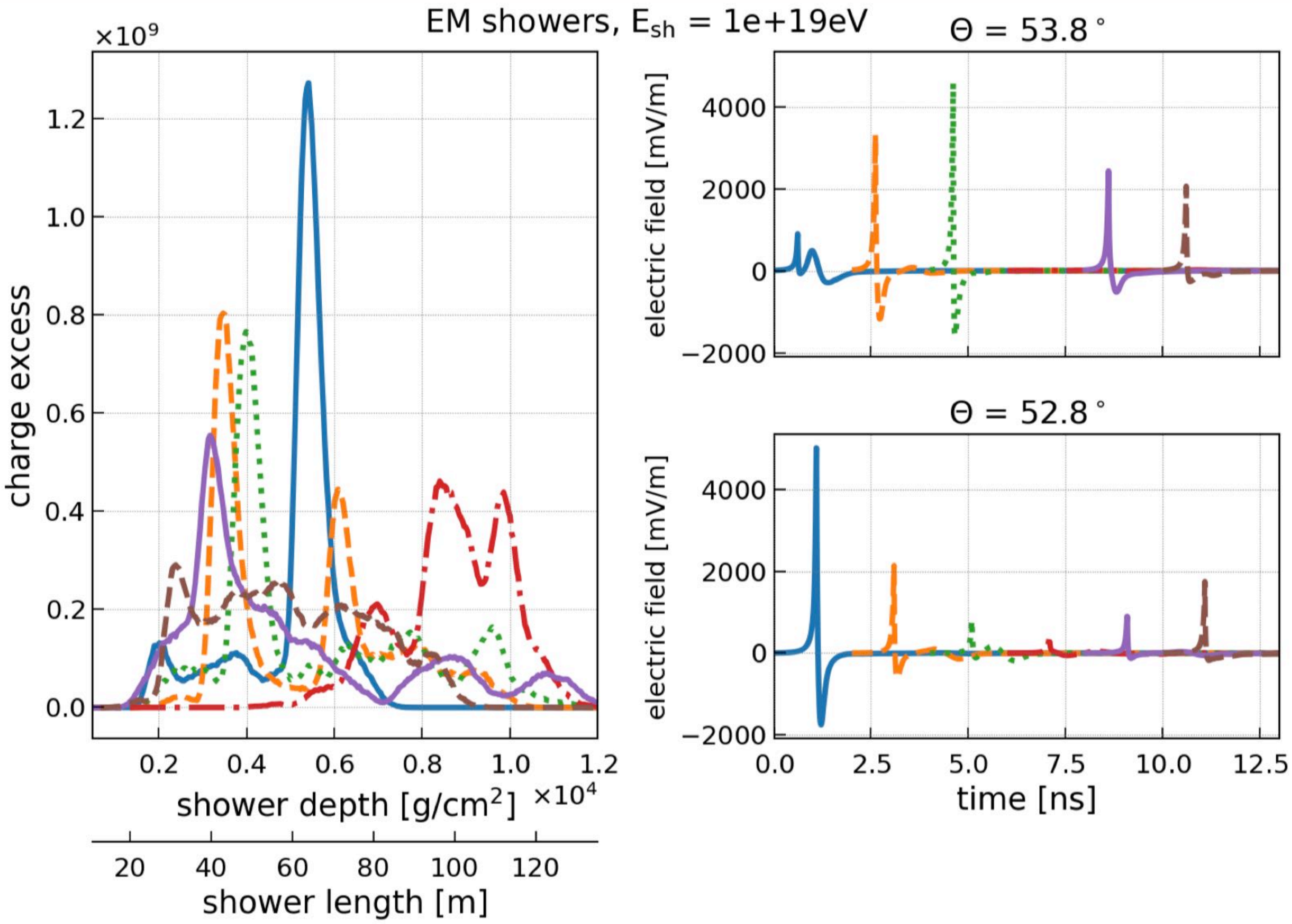
ARZ
time domain calculation based on charge-excess shower library



*Alvarez-Muñiz et al., Phys. Rev. D **101**, 083005*

ARZ

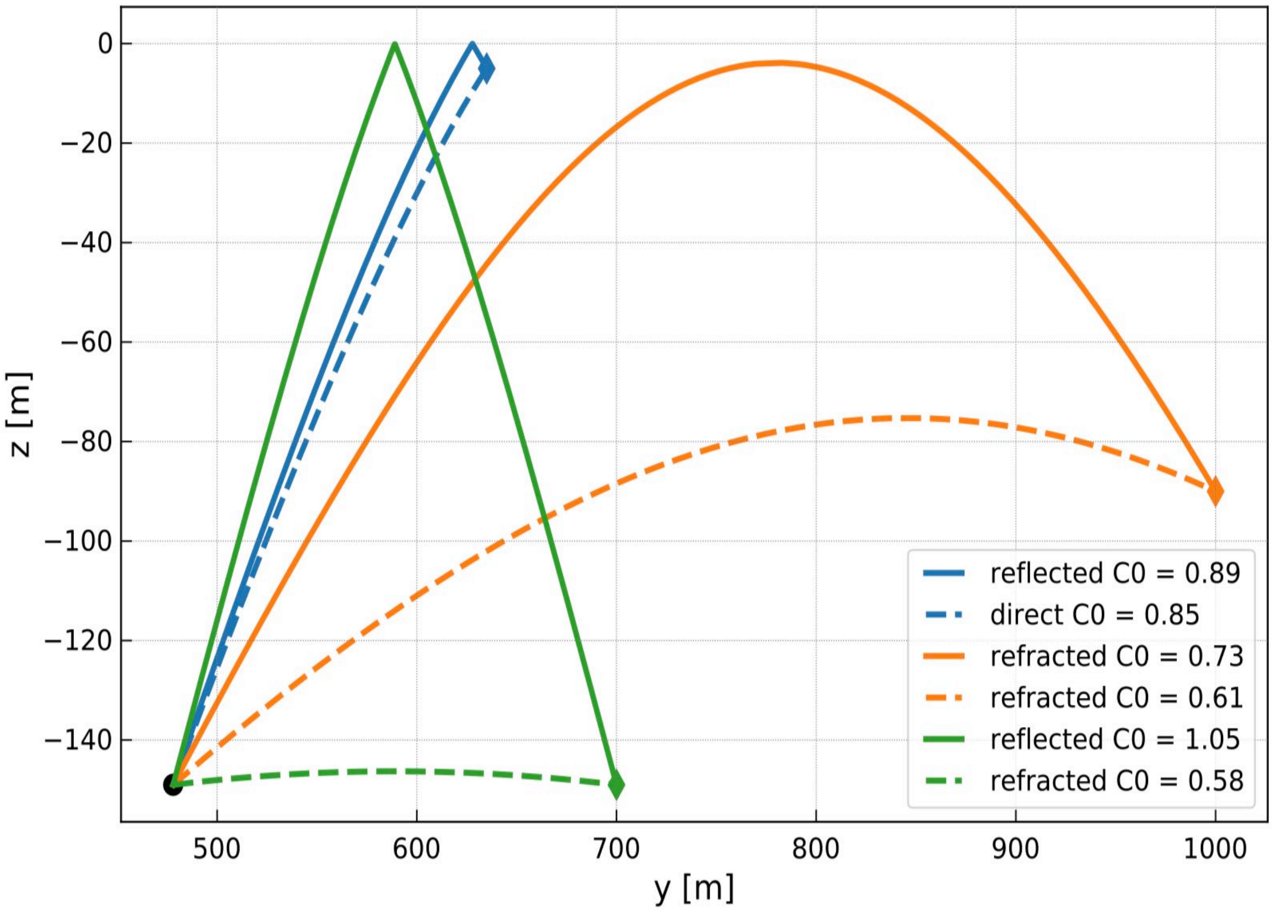
time domain calculation based on charge-excess shower library



Signal Propagation

- Analytic formula of signal path for exponential density profile $n(z) = n_{\text{ice}} - \Delta_n e^{z/z_0}$

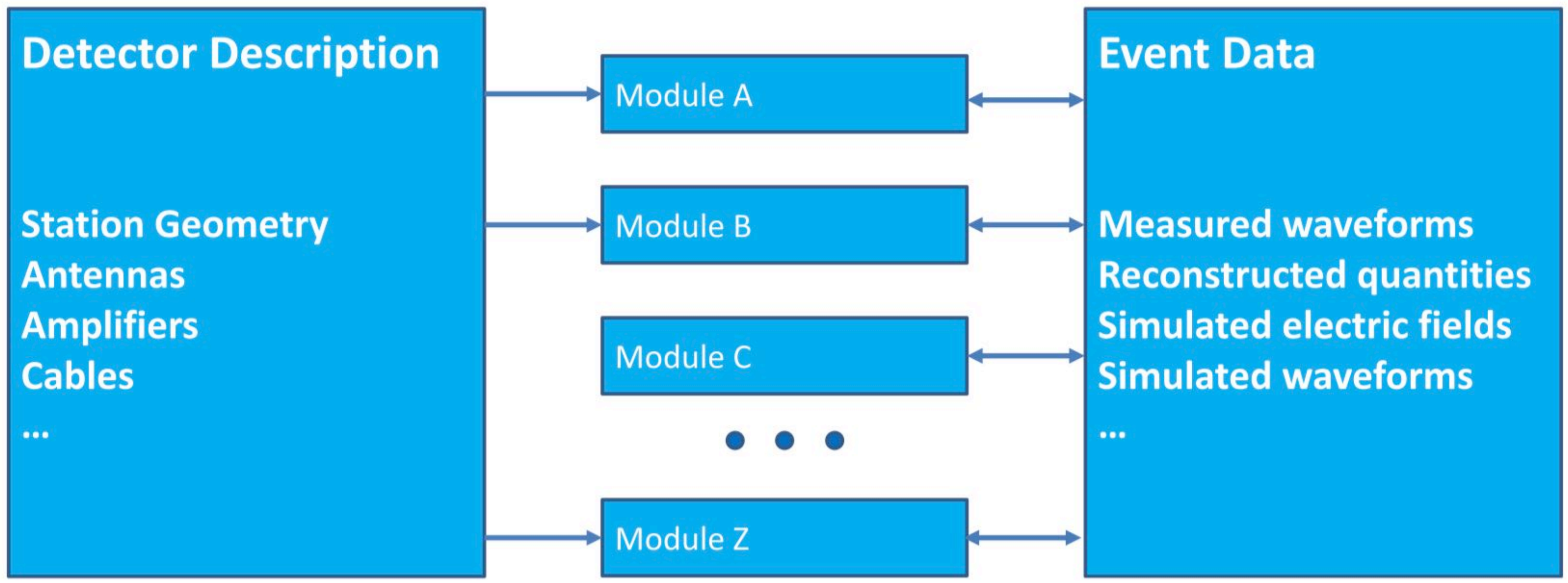
$$y(z) = \pm z_0 \sqrt{n_{\text{ice}}^2 C_0^2 - 1} \cdot \ln\left(\gamma / \left[2\sqrt{c(\gamma^2 - b\gamma + c)} - b\gamma + 2c\right]\right) + C_1$$



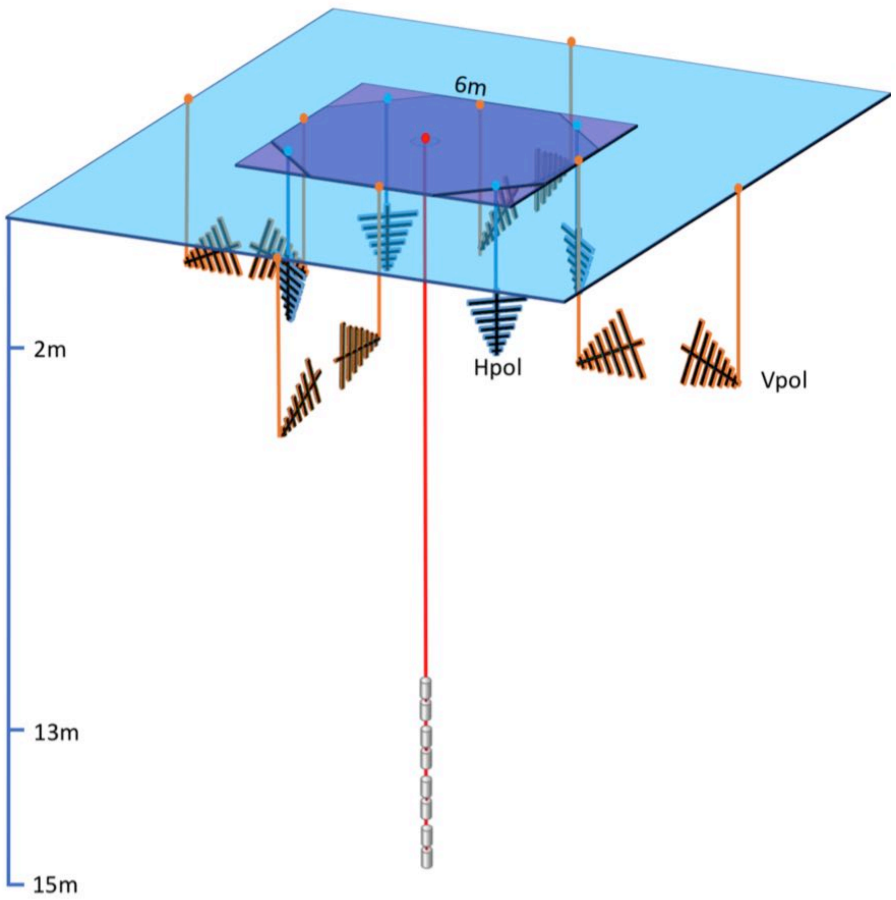
- Fast and precise calculation of signal paths
- Analytic formulas for travel time + distance
- Attenuation requires numerical integration
- C++ implementation
- Interface to RadioPropa

Detector Simulation

- **NuRadioReco**: Detector simulation and event reconstruction
  - github.com/nu-radio/NuRadioReco
  - Glaser et al., *EPJC **79**: 464 (2019) arXiv:*1903.07023
- Flexible detector layout
  - any antenna position and orientation
- Modular design



Example 1: Calculation of the sensitivity of an Askaryan neutrino detector



detector description

```
{
    "channels": {
        "1": {
            "station_id": 101,
            "channel_id": 0,
            "ant_type": "createLPDA_100MHz",
            "ant_position_x": 3,
            "ant_position_y": 0,
            "ant_position_z": -2.0,
            "ant_rotation_phi": 180,
            "ant_rotation_theta": 90,
            "ant_orientation_phi": 0,
            "ant_orientation_theta": 180,
        },
        ...
    },
    "stations": {
        "1": {
            "pos_altitude": 0,
            "pos_easting": 0,
            "pos_northing": 0,
            "pos_site": "southpole",
            "station_id": 101
        }
    }
}
```

config

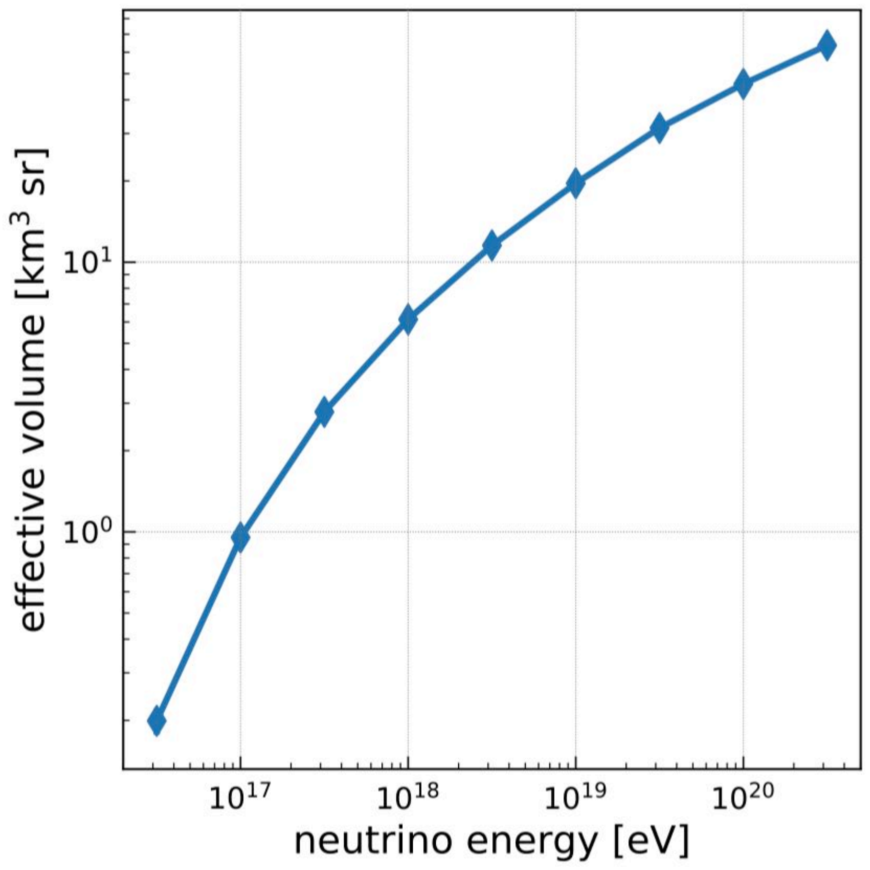
```
noise: False  # specify if simulation should
sampling_rate: 5.  # sampling rate in GHz use
speedup:
  minimum_weight_cut: 1.e-5
  delta_C_cut: 0.698  # 40 degree
propagation:
  ice_model: southpole_2015
signal:
  model: Alvarez2009
trigger:
  noise_temperature: 300  # in Kelvin
weights:
  weight_mode: core_mantle_crust # core_mantl
  #layer earth model, which considers the dif
  #core, mantle and crust. simple: use the si
  #apply a constant earth density
```

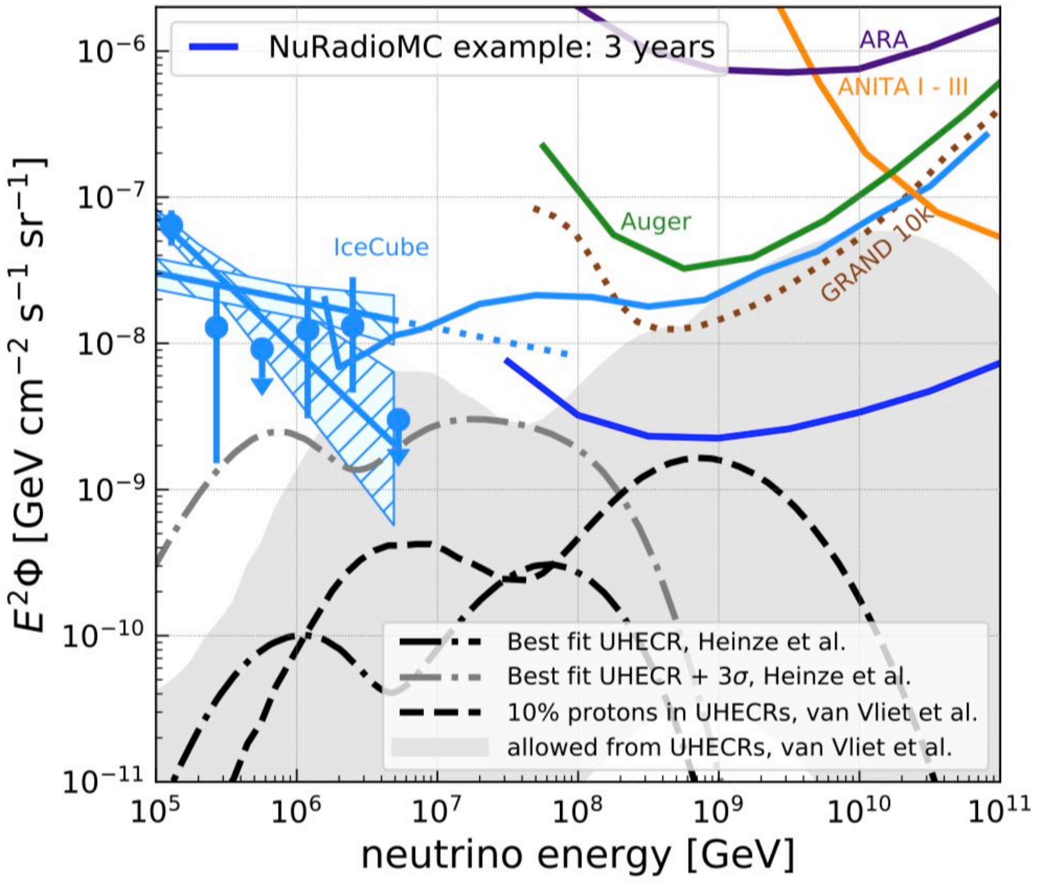
Detector simulation

```
class mySimulation(simulation.simulation):

    def _detector_simulation_filter_amp(self, evt, station, det):
        channelBandPassFilter.run(evt, station, det, passband=[80 * units.MHz, 1000 * units.GHz],
                                  filter_type='butter', order=2)
        channelBandPassFilter.run(evt, station, det, passband=[0, 500 * units.MHz],
                                  filter_type='butter', order=10)

    def _detector_simulation_trigger(self, evt, station, det):
        # first run a simple threshold trigger
        simpleThreshold.run(evt, station, det,
                            threshold=3 * self._Vrms,
                            triggered_channels=None,  # run trigger on all channels
                            number_concidences=1,
                            trigger_name='simple_threshold')  # the name of the trigger

        # run a high/low trigger on the 4 downward pointing LPDAs
        highLowThreshold.run(evt, station, det,
                                    threshold_high=4 * self._Vrms,
                                    threshold_low=-4 * self._Vrms,
                                    triggered_channels=[0, 1, 2, 3],  # select the LPDA channels
                                    number_concidences=2,  # 2/4 majority logic
                                    trigger_name='LPDA_2of4_4.1sigma',
                                    set_not_triggered=(not station.has_triggered("simple_threshold")))  # calculate more

        # run a high/low trigger on the 4 surface dipoles
        highLowThreshold.run(evt, station, det,
                                    threshold_high=3 * self._Vrms,
                                    threshold_low=-3 * self._Vrms,
                                    triggered_channels=[4, 5, 6, 7],  # select the bicone channels
                                    number_concidences=4,  # 4/4 majority logic
                                    trigger_name='surface_dipoles_4of4_3sigma',
                                    set_not_triggered=(not station.has_triggered("simple_threshold")))  # calculate more
```

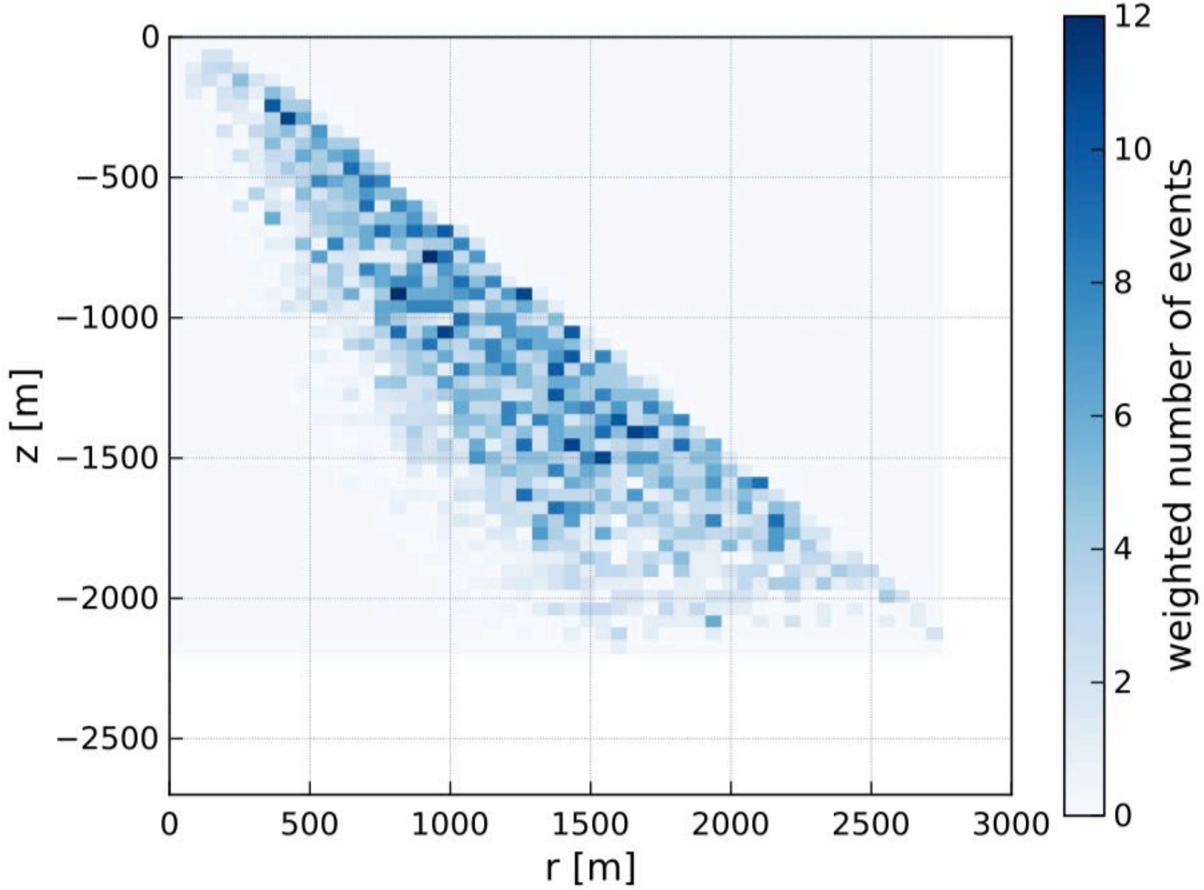
Results

- Full example: https://github.com/nu-radio/NuRadioMC/wiki/Tutorial
- Plotting scripts part of NuRadioMC

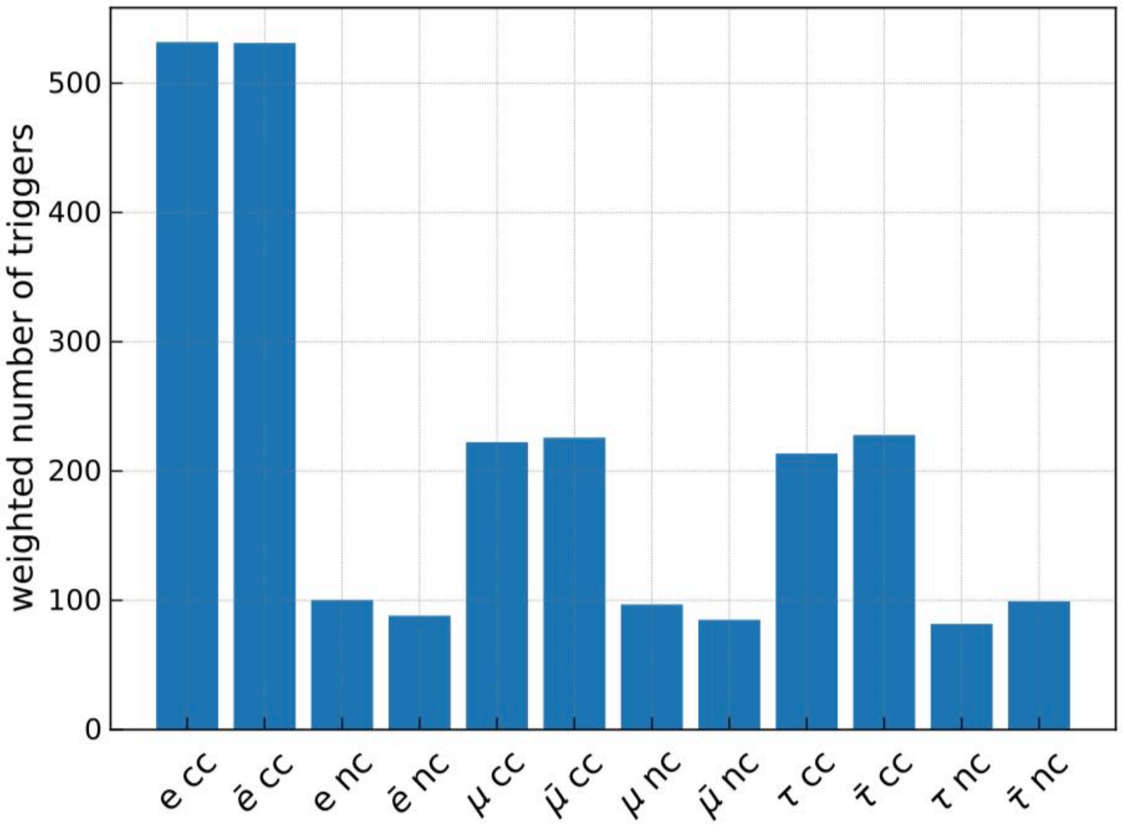




Debug Plots



0
−500
−1000
−1500
−2000
−2500
z [m]
0
500
1000
1500
2000
2500
3000
r [m]
0
2
4
6
8
10
12
weighted number of events



0
100
200
300
400
500
weighted number of triggers
e cc
ē cc
e nc
ē nc
μ cc
μ̄ cc
μ nc
μ̄ nc
τ cc
τ̄ cc
τ nc
τ̄ nc

How to get started

- Tutorial: https://github.com/nu-radio/NuRadioMC/wiki/Tutorial
- Webinar on NuRadioMC/Reco
  - https://www-zeuthen.desy.de/~anelles/NuRadioMC.mp4
  - https://www-zeuthen.desy.de/~anelles/NuRadioReco.mp4
  - https://github.com/nu-radio/NuRadioMC/tree/master/NuRadioMC/examples/06_webinar
- NuRadioMC paper: https://link.springer.com/article/10.1140/epjc/s10052-020-7612-8
- NuRadioReco paper: https://link.springer.com/article/10.1140/epjc/s10052-019-6971-5
- NuRadioMC slack channel: https://join.slack.com/t/nu-radio/shared_invite/zt-5f9vka05-kYx3cw743Y7QxM4BOSV8dw