Prospects for neutrino-flavor physics with in-ice radio detectors

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based on Phys. Rev. D ***102*** *083011 (2020)*
with new developments presented in this talk

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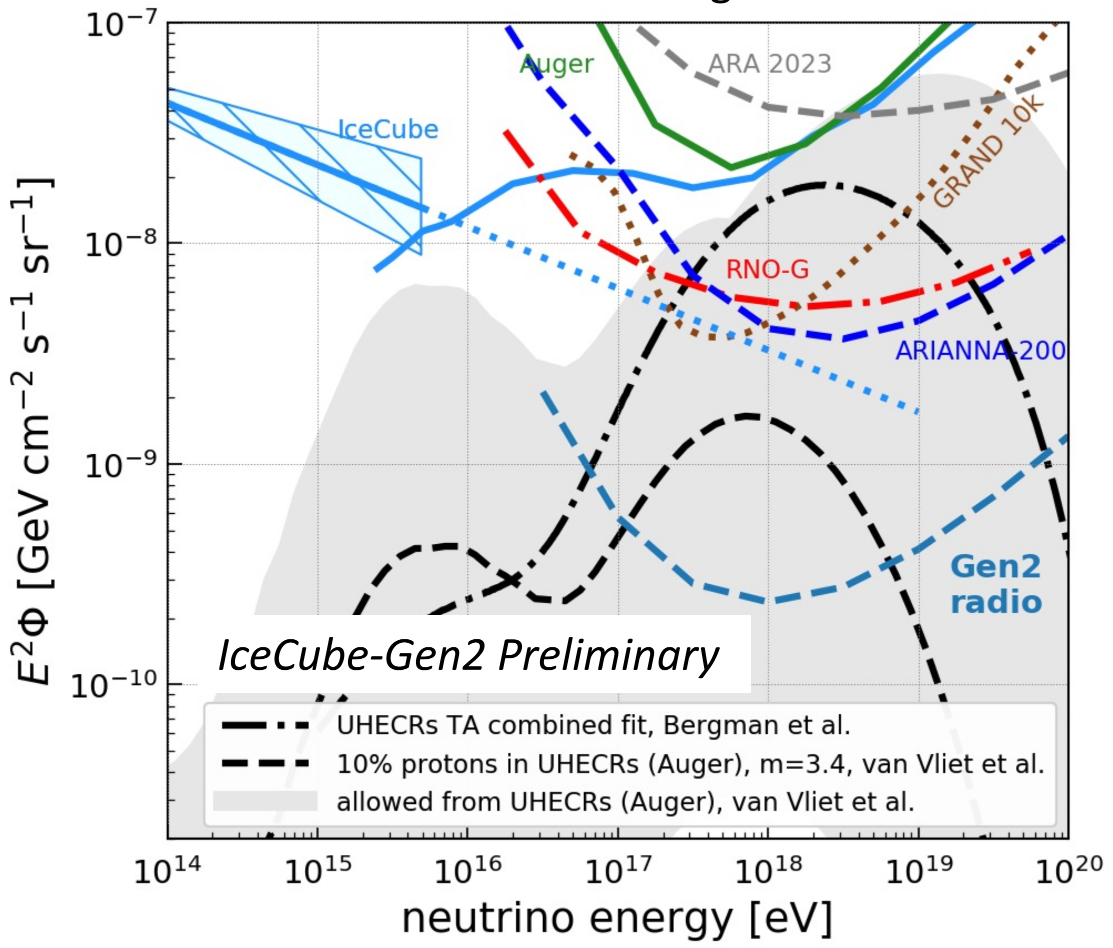
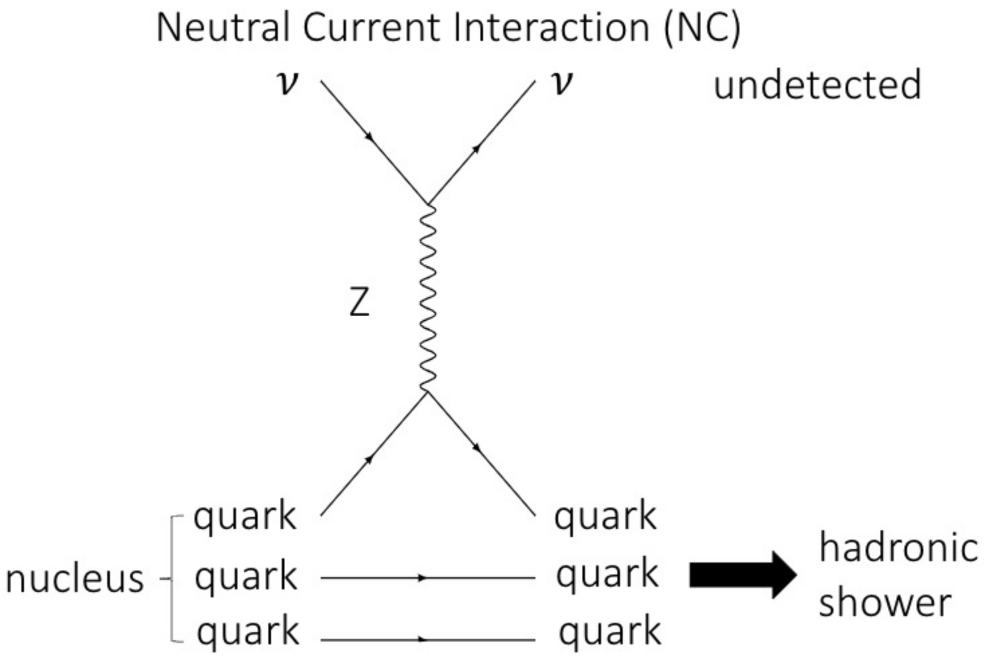
EeV neutrino astronomy

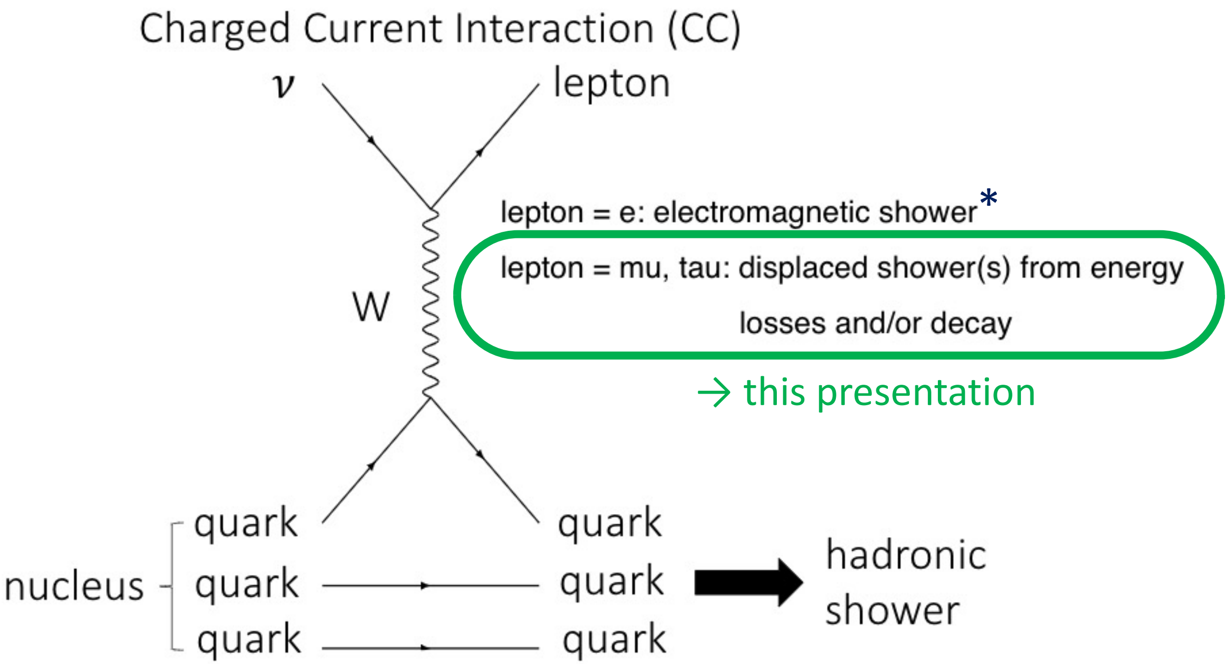
- In-ice radio detectors provide unprecedented sensitivity to EeV (10^{18} eV) neutrinos
- Technology developed in pilot arrays (ARA, ARIANNA)
- Discovery-size detectors underway
  - RNO-G in Greenland (under construction, *see #1058*)
  - ARIANNA-200 (proposed, *see #1190*)
- Large scale detector planned for IceCube-Gen2 *(see #1183)*

Figure from *#1183*



Neutrino interactions at EeV energies

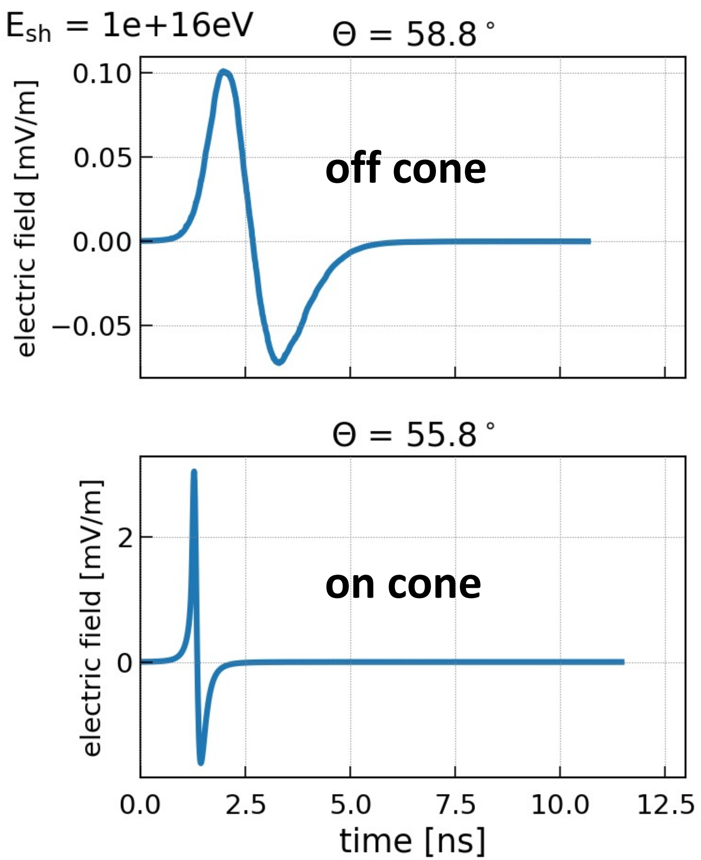


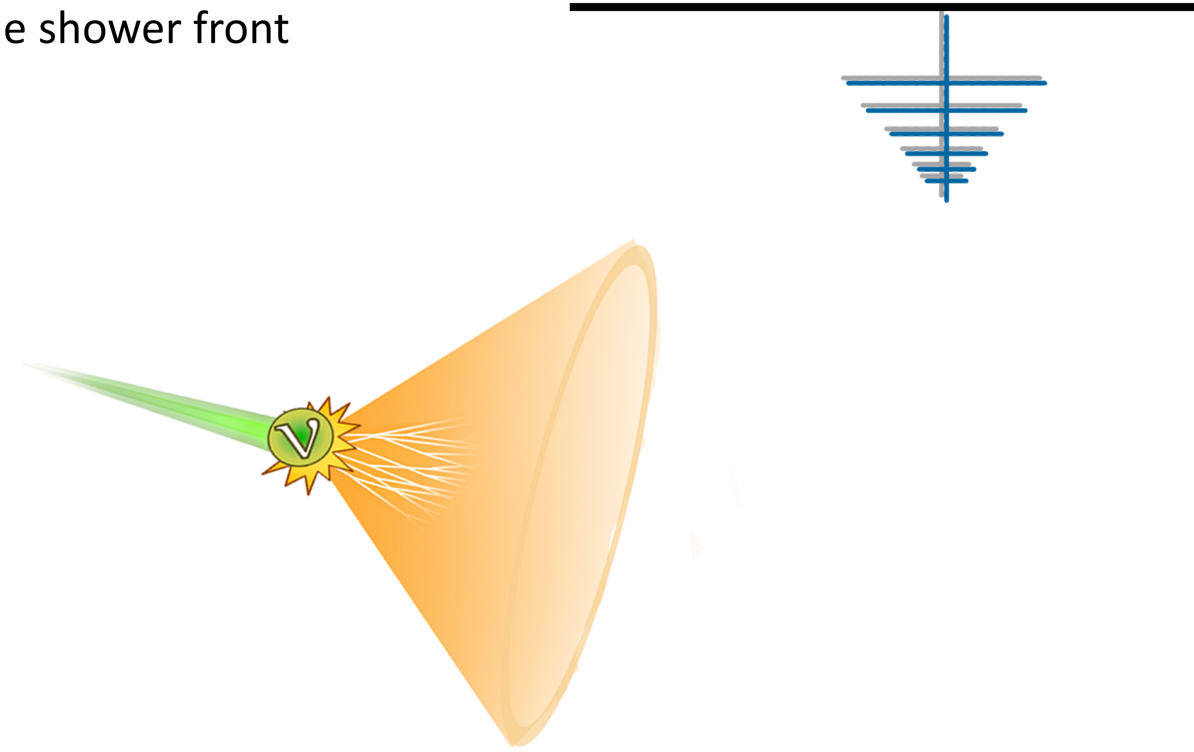


*: ν_e-CC interactions also provide flavor sensitivity due to the LPM effect, see #1055

Detection principle of Askaryan radio detectors

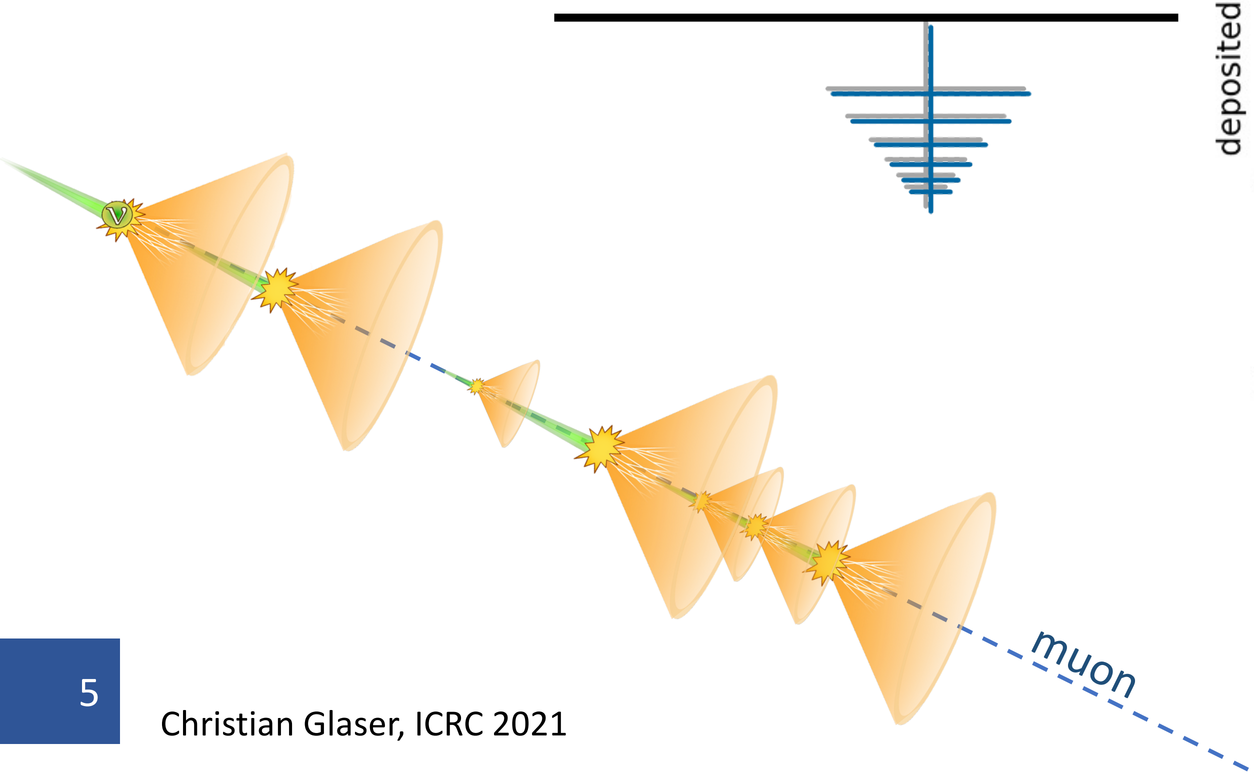
- Askaryan effect: Time varying negative charge excess in the shower front
- Cherenkov-like time compression effect
- In ice: arccos(1/n) = 56 deg

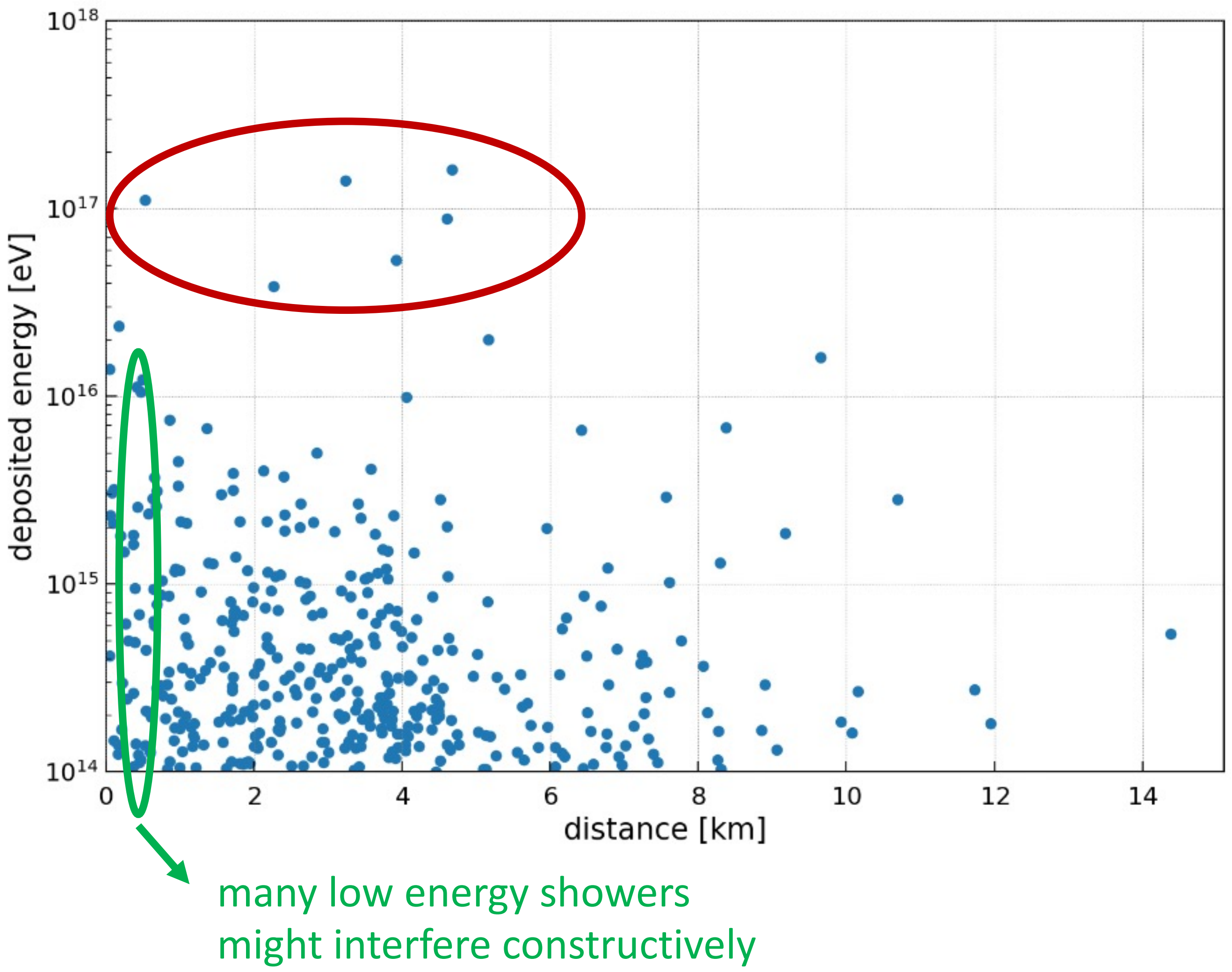




Energy losses of high-energy muon

- 1 EeV muon propagating through ice
- Simulated using *PROPOSAL*
- Stochastic energy losses > 10^{14} eV shown





new compared to Garcia et al., PRD **102** 083011 (2020)
*: github.com/nu-radio/NuRadioMC

Generalization of NuRadioMC*

- NuRadioMC calculates radio signals in detector from an arbitrary number of showers
  - a single hadronic shower for NC interactions
  - one hadronic and one EM shower for ν_e CC interactions
  - many showers from muon or tau propagation
- Enables simulation of any emission scenarios (BSM physics, manual modelling of LPM, …)

internal looping structure

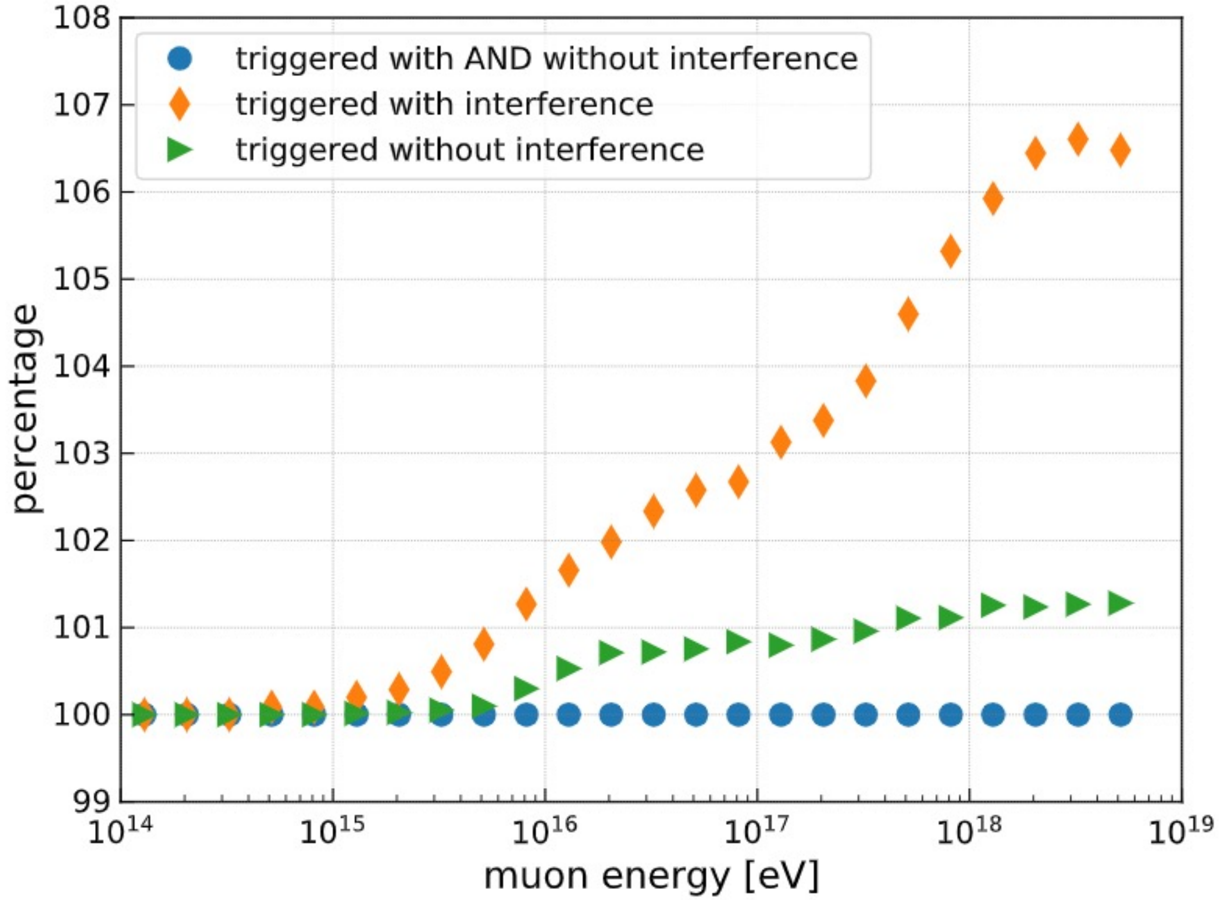
- event group (consists of an arbitrary number of showers)
  - detector station (each station is treated independently)
    - shower
      - channel (all antennas of this station)
        - signal trajectories (from shower vertex to antenna)
          - Askaryan signal at antenna is calculated
          - Detector simulation is performed -> voltage trace seen by readout system
    - signals are grouped into multiple events based on signal arrival times
    - events
      - channel (all antennas of this station)
        - Voltage traces from all showers and signal trajectories of this event are combined
      - Trigger simulation

Effect of interference

new

*compared to Garcia et al., PRD **102** 083011 (2020)*

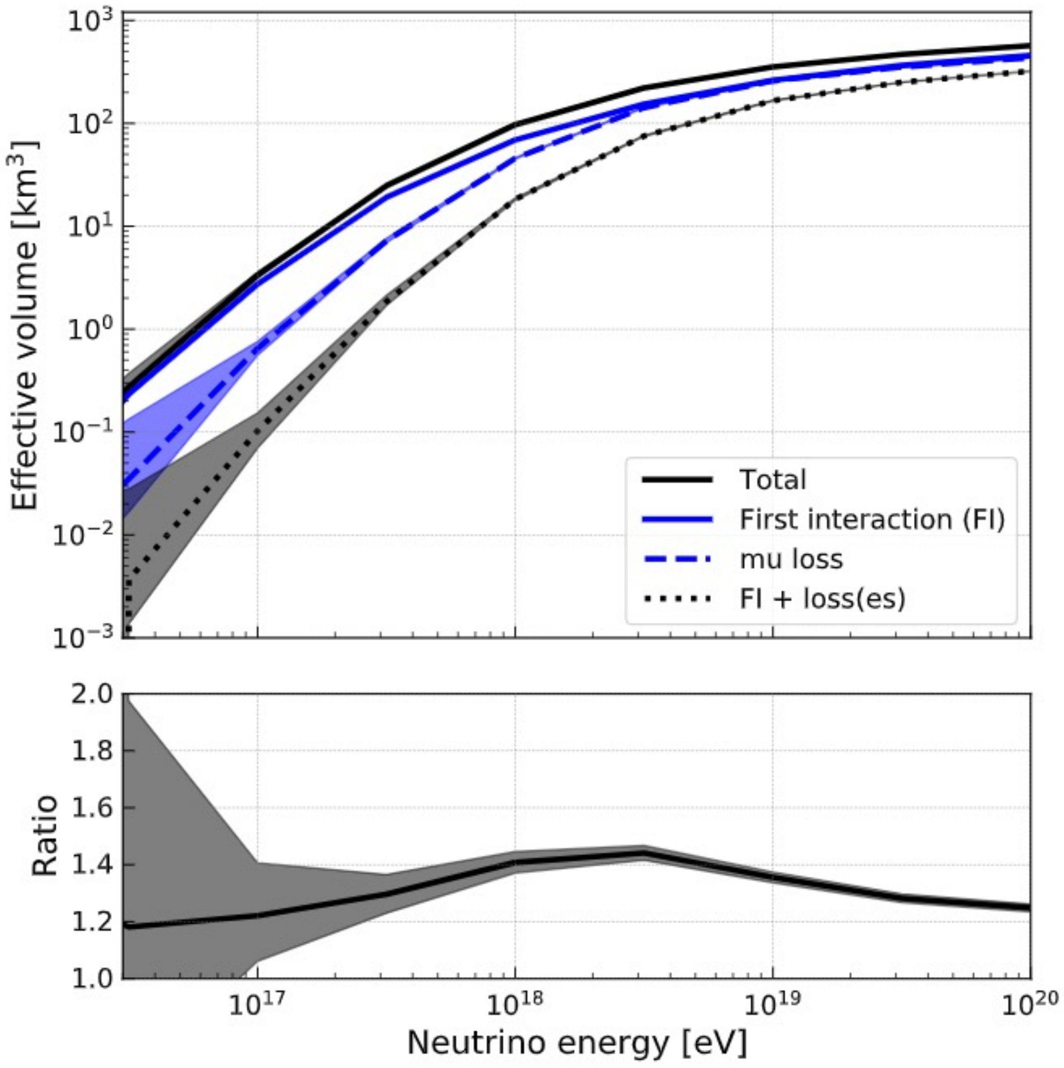
- Simulation of interference vs. all showers independently
- Constructive interference more likely than destructive interference
- Up to 7% more observable events
- Effect on pulse shapes likely more important than increase in event numbers



new

*compared to Garcia et al., PRD **102** 083011 (2020)*

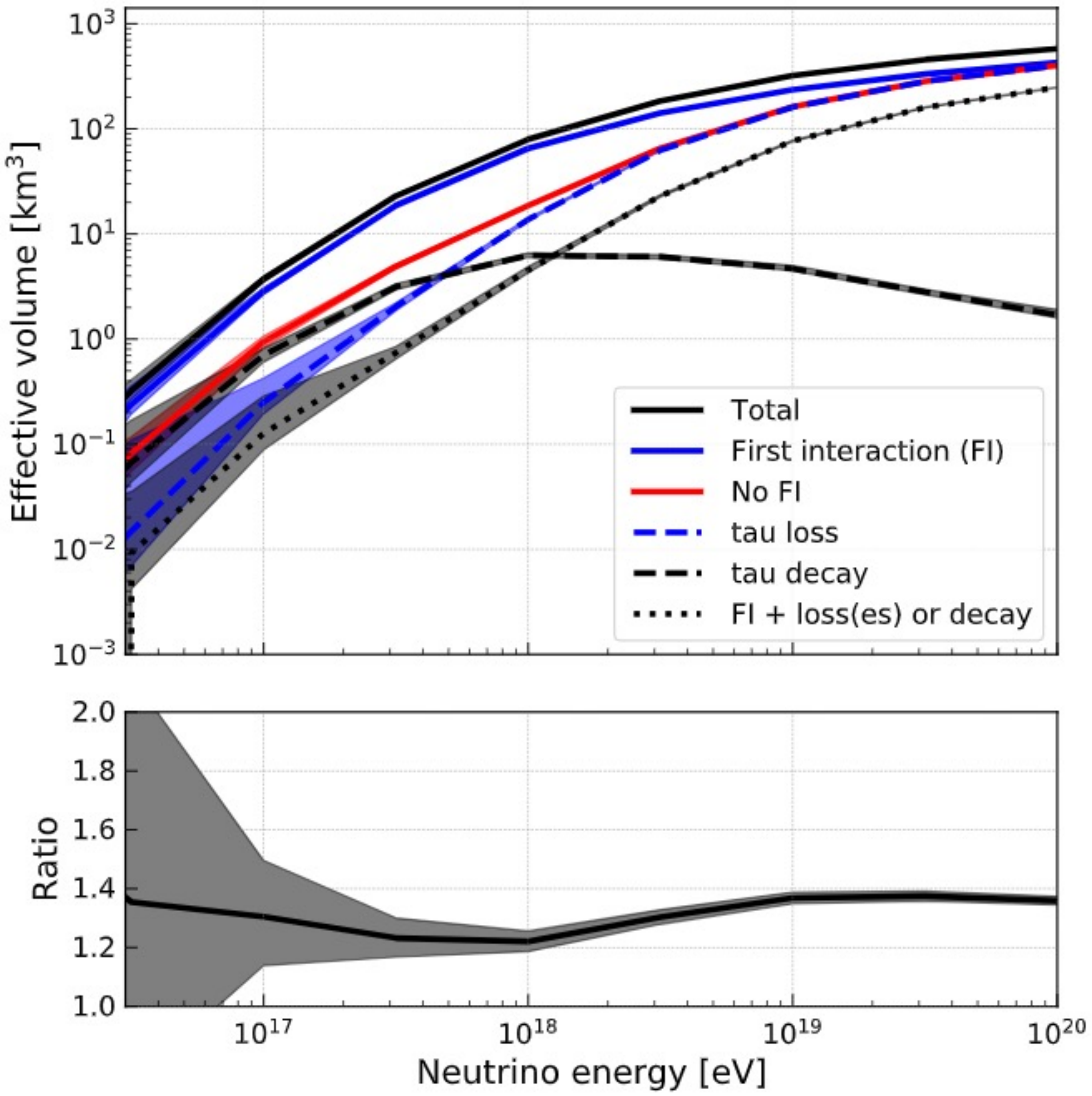
Muon neutrino effective volume



- Generic array with 2km spacing and 200m deep receivers at the **South Pole**
- Secondary interaction of muons increase sensitivity by up to 40%
- At high energies, first and a secondary interaction detected simultaneously

Tau neutrino effective volume

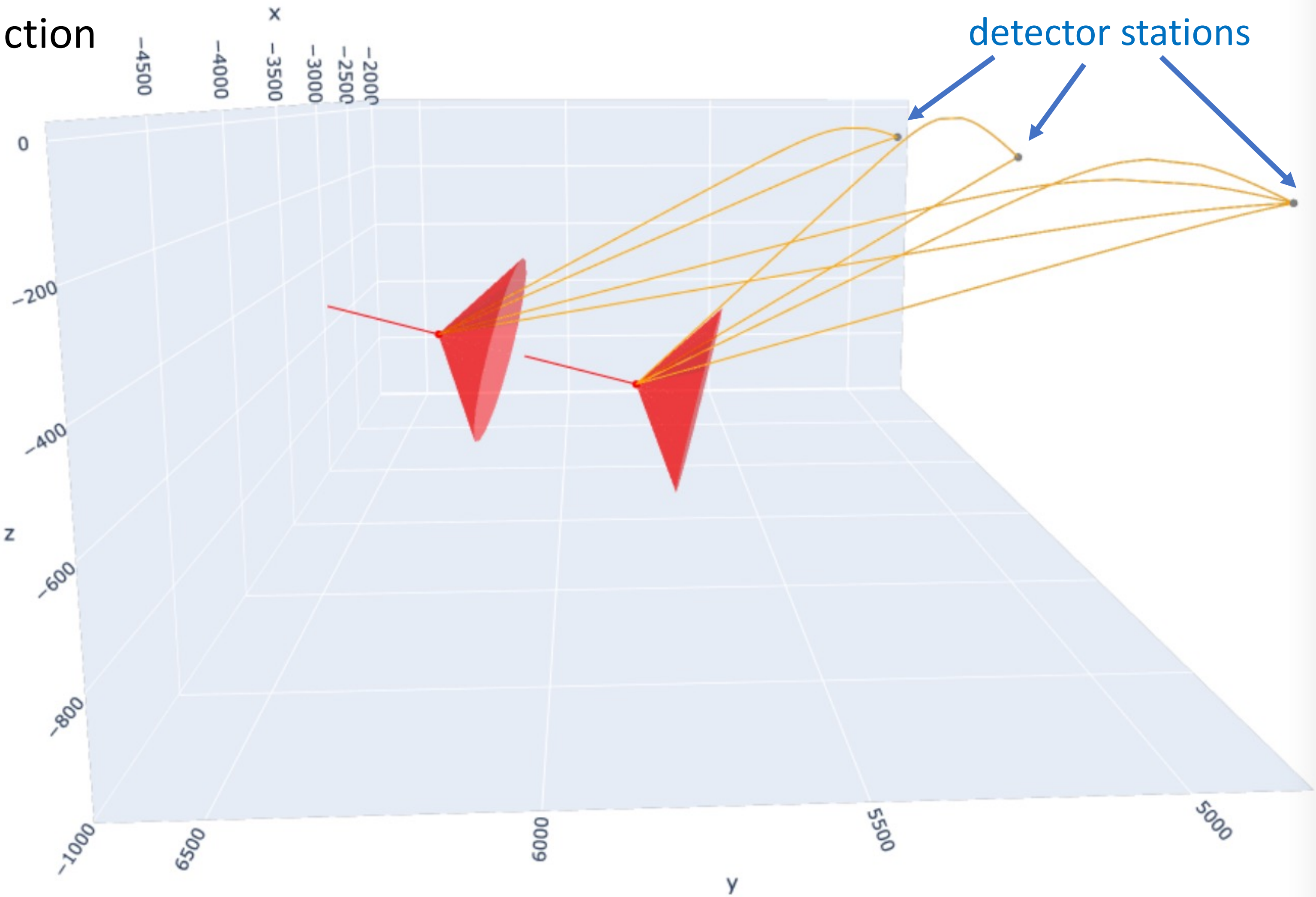
new compared to Garcia et al., PRD **102** 083011 (2020)



- Generic array with 2km spacing and 200m deep receivers at the **South Pole**
- Secondary interaction of taus increase sensitivity by up to 40%
  - at low energies tau decay channel dominates
  - > 5×10^{17} eV: tau energy losses dominate
- At high energies, many first and a secondary interaction detected simultaneously
  - flavor sensitivity

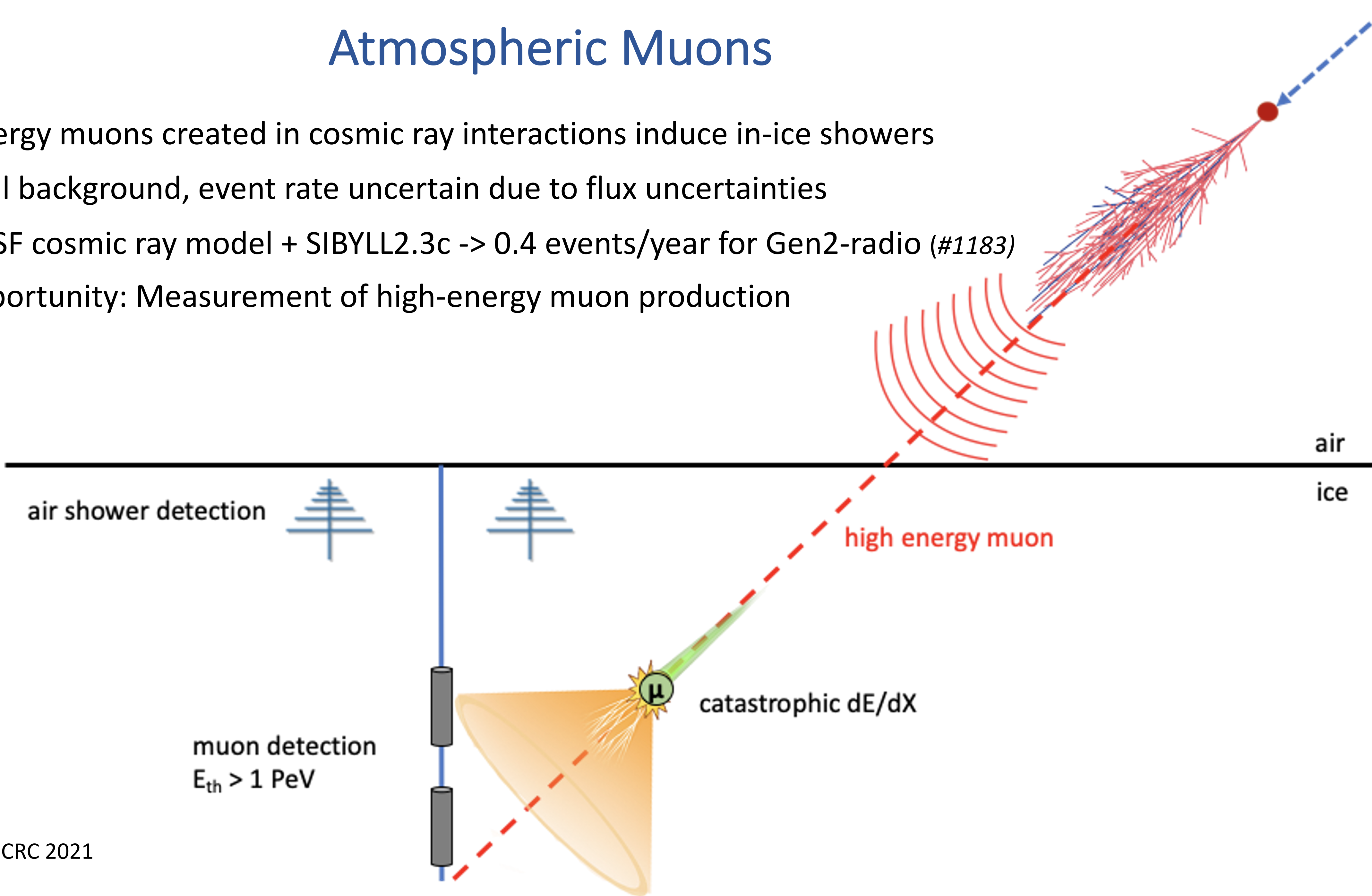
Golden event signature

- Simultaneous detection of first and secondary interaction
- Clear signature for muon or tau neutrino CC interactions
- Improved event reconstruction



Atmospheric Muons

- High energy muons created in cosmic ray interactions induce in-ice showers
- Potential background, event rate uncertain due to flux uncertainties
- Using GSF cosmic ray model + SIBYLL2.3c -> 0.4 events/year for Gen2-radio *(#1183)*
- Also opportunity: Measurement of high-energy muon production



Summary

see also
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PoS(ICRC2021)1231

- Radio emission from secondary interactions of leptons integrated into NuRadioMC
- Muon/tau leptons generated in neutrino CC interactions
  - generate visible signals in radio neutrino detectors
  - increase number of observable events by up to 40%
  - provide flavor sensitivity
  - first and secondary interaction observed simultaneously in 50% (μ)/25% (τ) at 10^{19} eV for array at the South Pole with 200m deep receivers and 2km spacing
  - See also *#1055* for flavor sensitivity from ν_e-CC interactions
- NuRadioMC generalized to calculate radio signals in detector for any number of in-ice showers
  - study of arbitrary emission scenarios