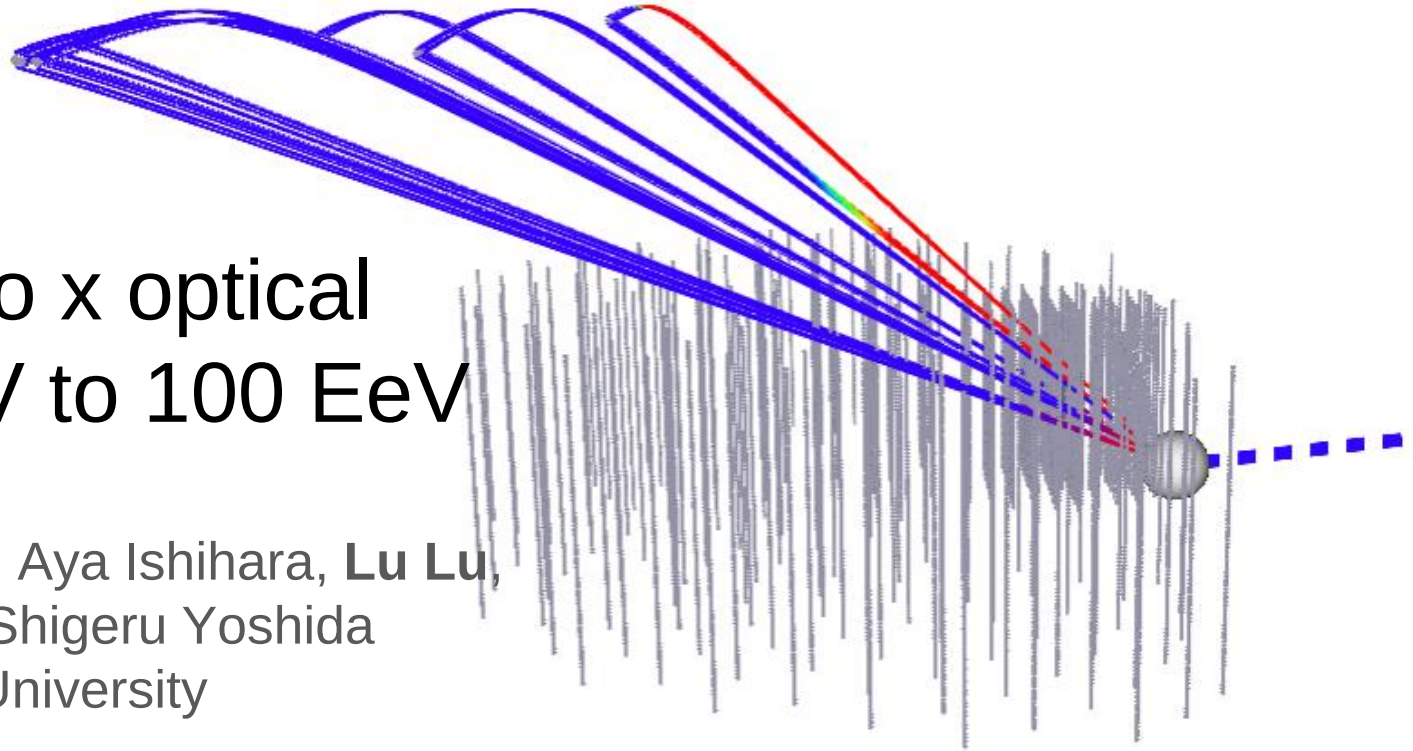
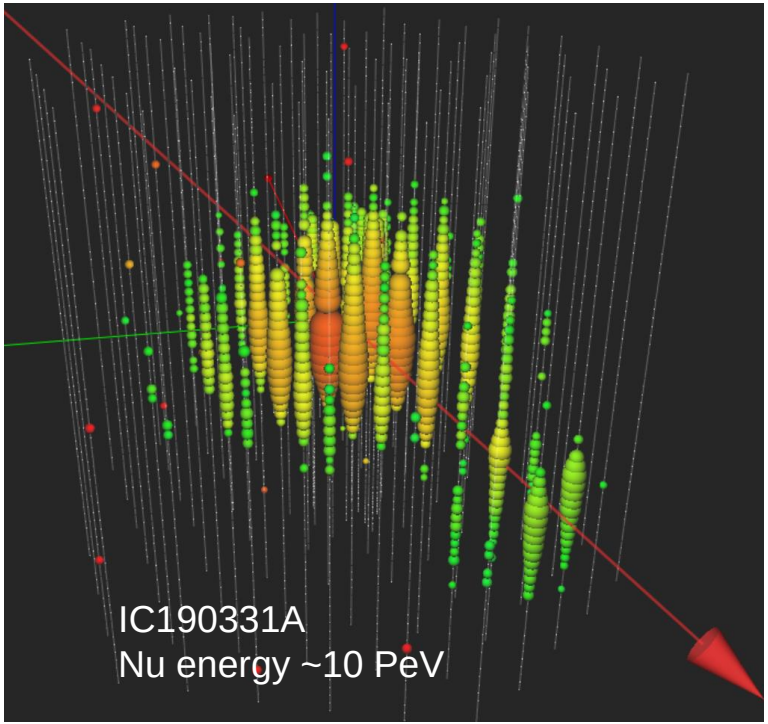


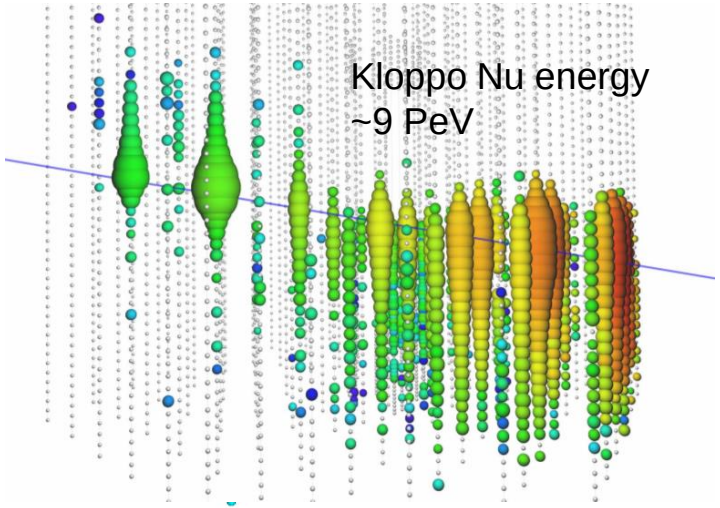
In ice radio x optical
From 10 PeV to 100 EeV

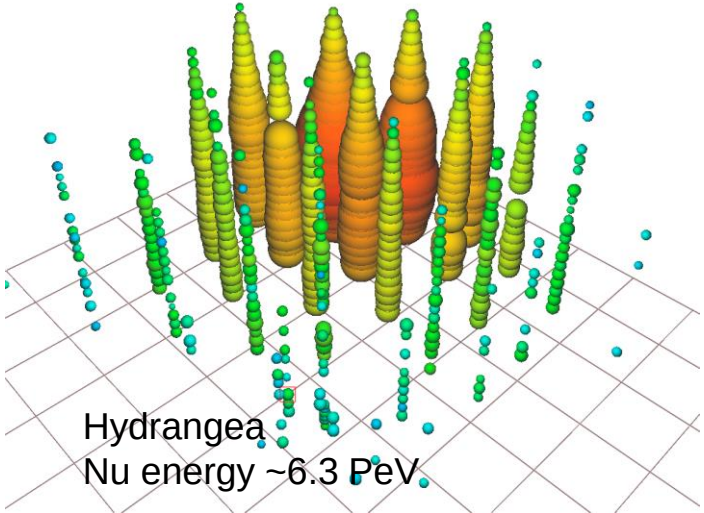
Simon Archambault, Aya Ishihara, **Lu Lu**,
Keiichi Mase, Shigeru Yoshida
Chiba University

3 highest ν energy events in ~10 years of IceCube

To scale up with Gen2/radio but need good angular resolution for astronomy. Optical is difficult (saturations,scatterings, sparse strings)







10 PeV+ AstroNumy

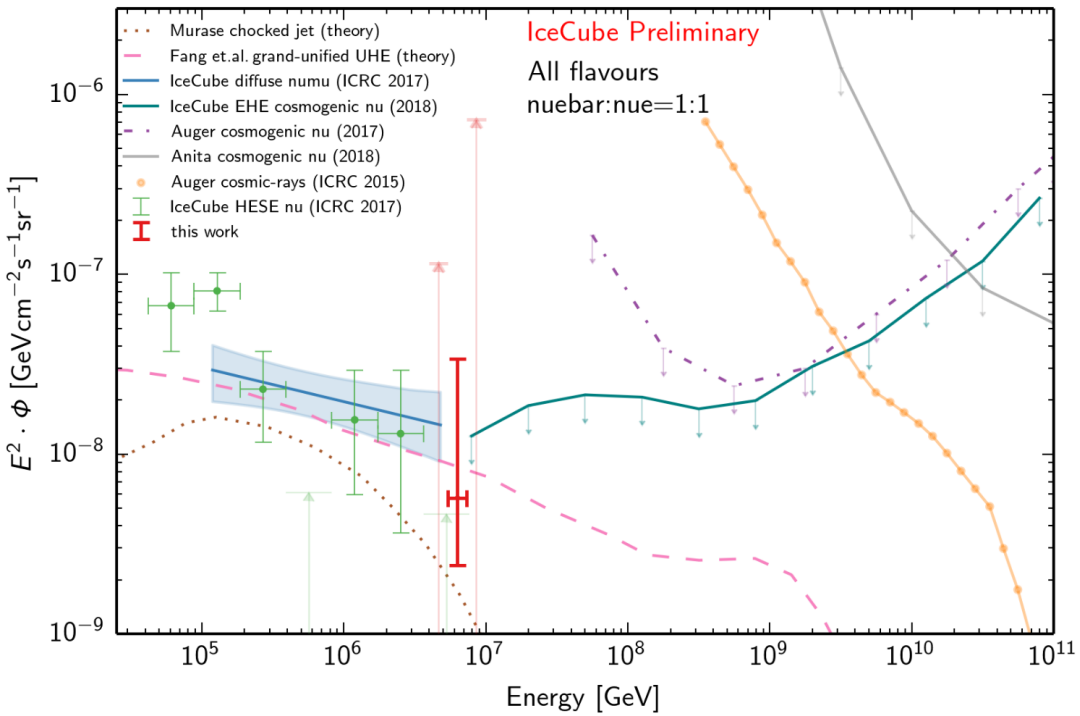
10 PeV+ good signal prob. And connects to UHE

‘Guaranteed flux at 10 PeV’

Unknown flux for cosmogenic

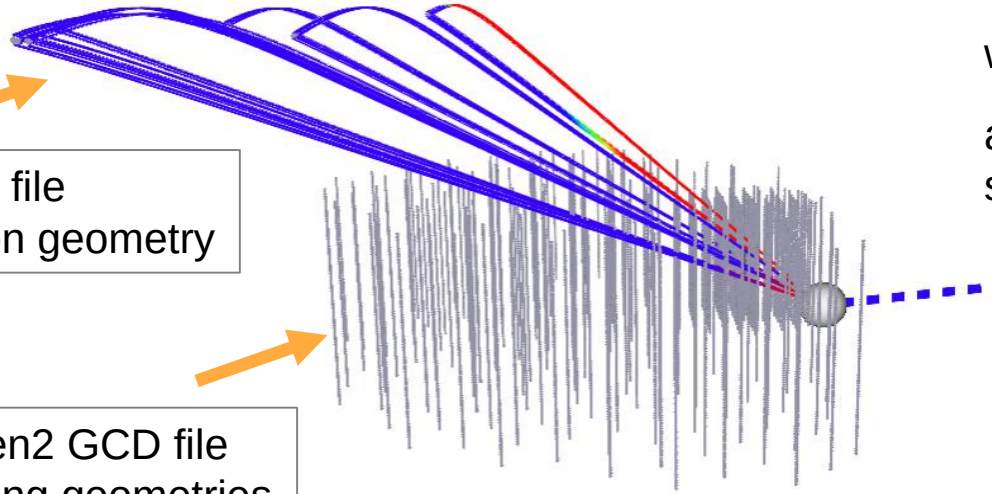
Two physics topics:

- IceCube x ARA5 for EHE
- A new radio-optical Gen2 hybrid proposal for 10 PeV (motivated by angular resolution)



Radio + optical combined simulation

Handle radio/optical event generation in the unified scheme

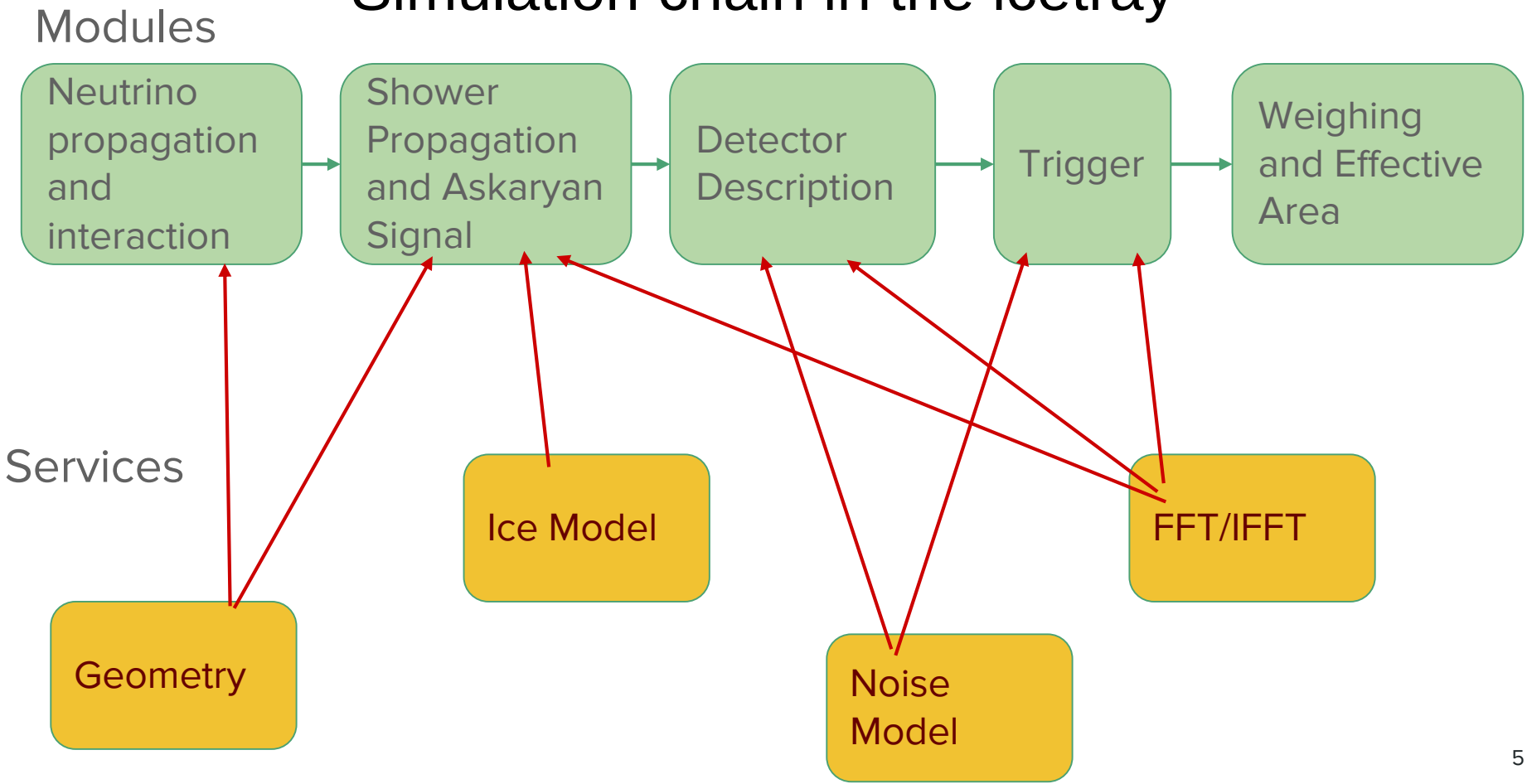


“ARA-5” GCD file
sets the station geometry

IceCube-gen2 GCD file
sets these string geometries

- icetray-based simulation chain
  - well –modularized
  - allow icecube+radio analyses simultaneously as one package

Simulation chain in the icetray

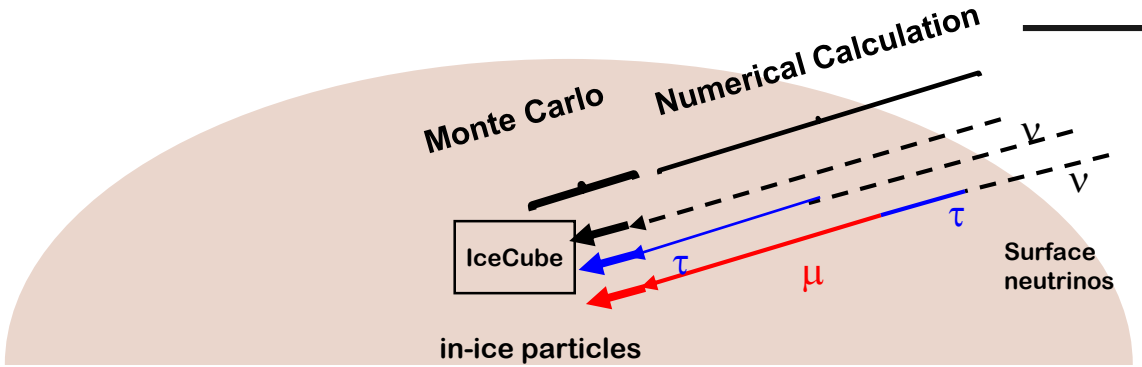


Simulation chain in the icetray

Modules

- Independent analysis software from current software used by ARA for crosschecks
- Seamless integration with IceCube
  - Easily used to study coincidence events and rates
  - Can be used to estimate overall sensitivity

JULIeT: EHE simulator for IceCube



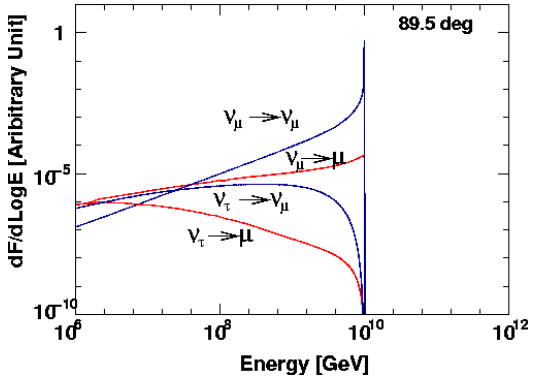
SY+ PRD **69** 13004 (2004)

$$\frac{dJ_\nu}{dX} = -N_A \sigma_{\nu N,CC+NC} J_\nu + \frac{m_l}{c\rho\tau_l^d} \int dE_l \frac{1}{E_l} \frac{dn_l^d}{dE_\nu} J_l(E_l)$$

$$+ N_A \int dE'_\nu \frac{d\sigma_{\nu N,NC}}{dE_\nu} J_\nu(E'_\nu)$$

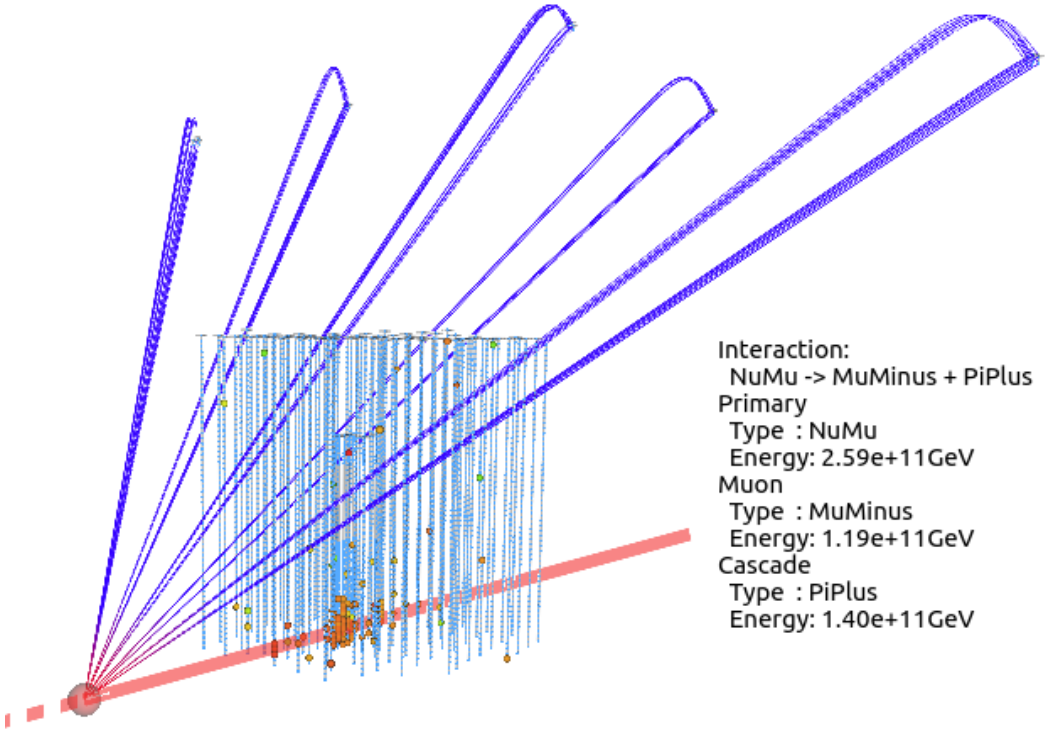
$$+ N_A \int dE'_l \frac{d\sigma_{lN,CC}}{dE_\nu} J_l(E'_l),$$

in-ice particle energy distribution from 10^{10} GeV ν_μ

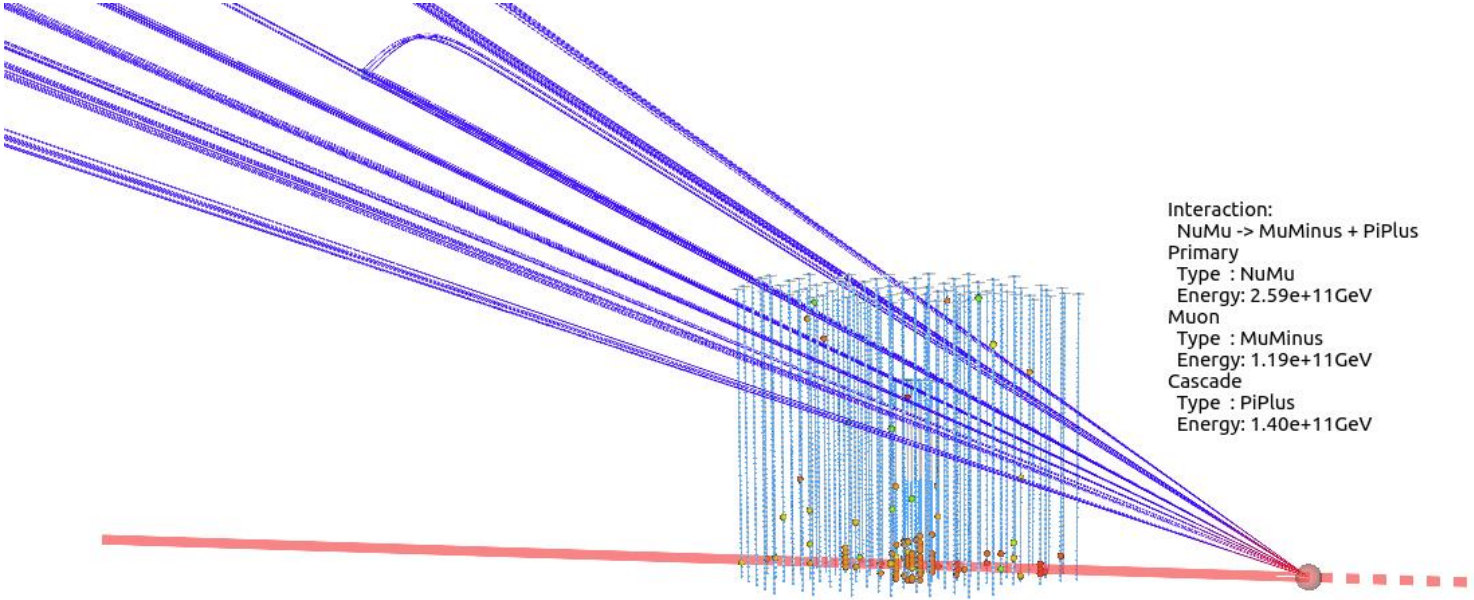


We can simulate in-ice muon also for radio

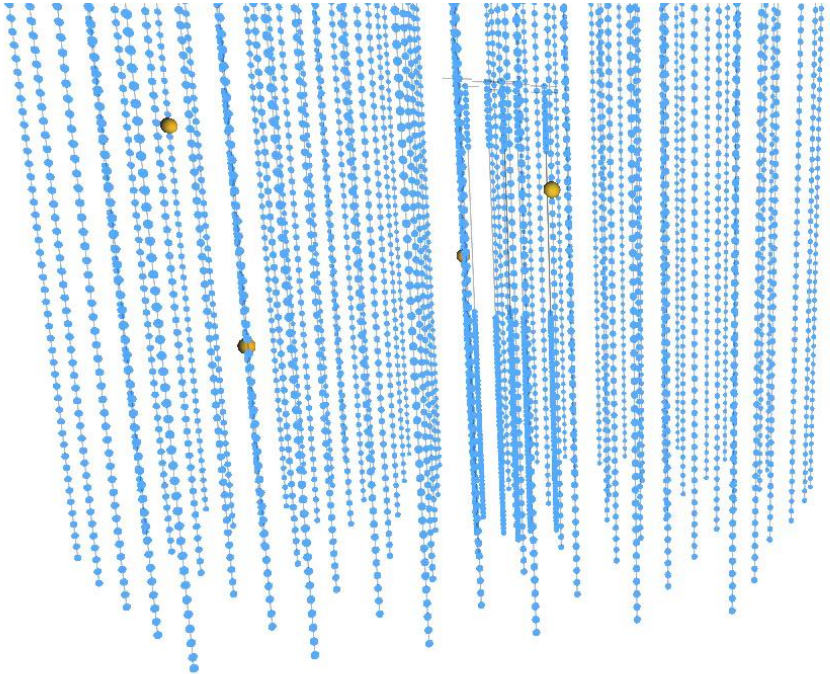
An example


Interaction:
NuMu -> MuMinus + PiPlus
Primary
Type : NuMu
Energy: 2.59e+11GeV
Muon
Type : MuMinus
Energy: 1.19e+11GeV
Cascade
Type : PiPlus
Energy: 1.40e+11GeV

An example

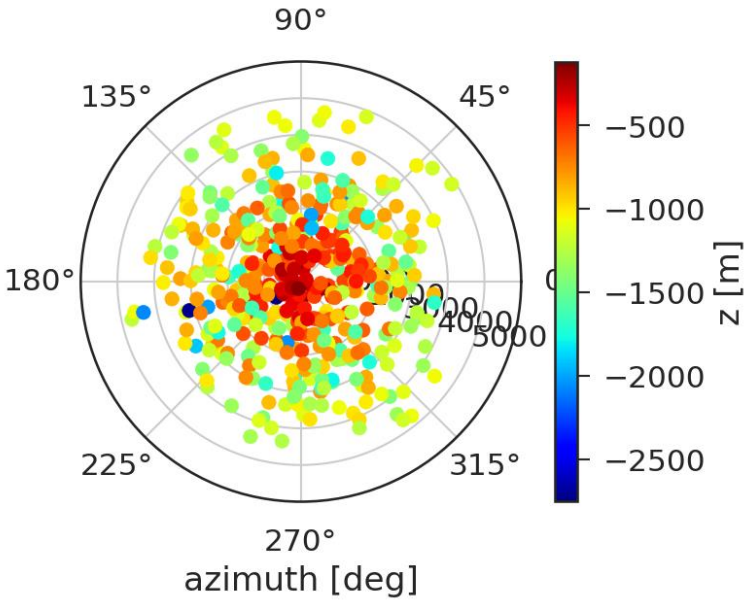

Interaction:
NuMu -> MuMinus + PiPlus
Primary
Type : NuMu
Energy: 2.59e+11GeV
Muon
Type : MuMinus
Energy: 1.19e+11GeV
Cascade
Type : PiPlus
Energy: 1.40e+11GeV

a cascade event

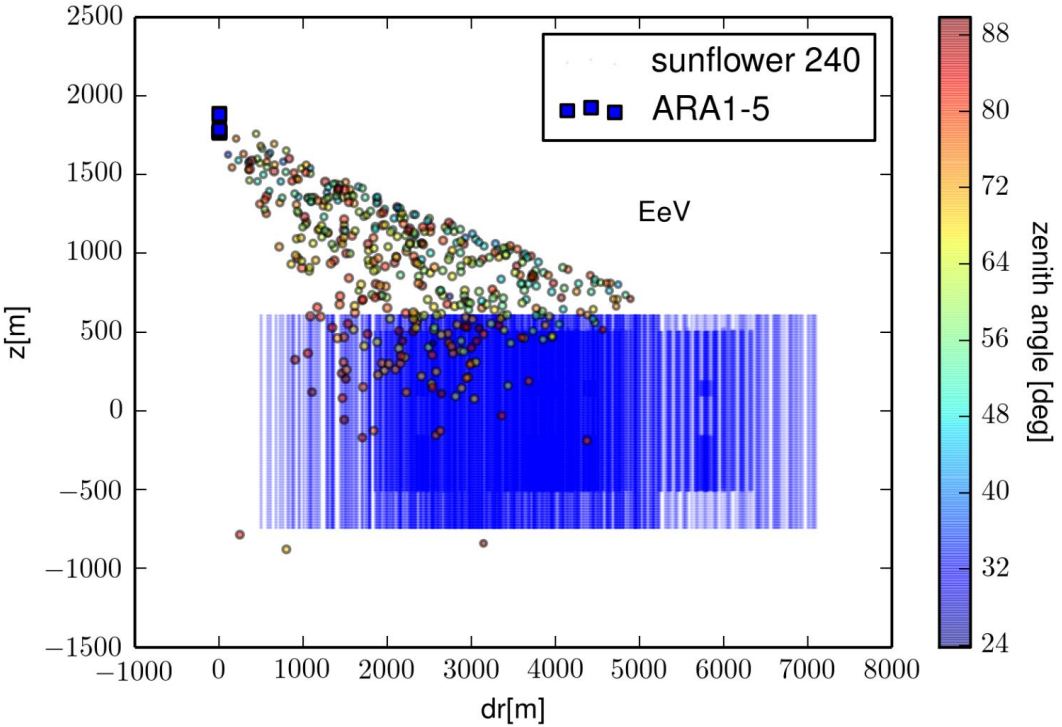


Interaction:
NuE -> PiPlus + EMinus
Primary
Type : NuE
Energy: 3.85e+11GeV
Cascade
Type : EMinus
Energy: 3.84e+11GeV

Example of EeV simulations



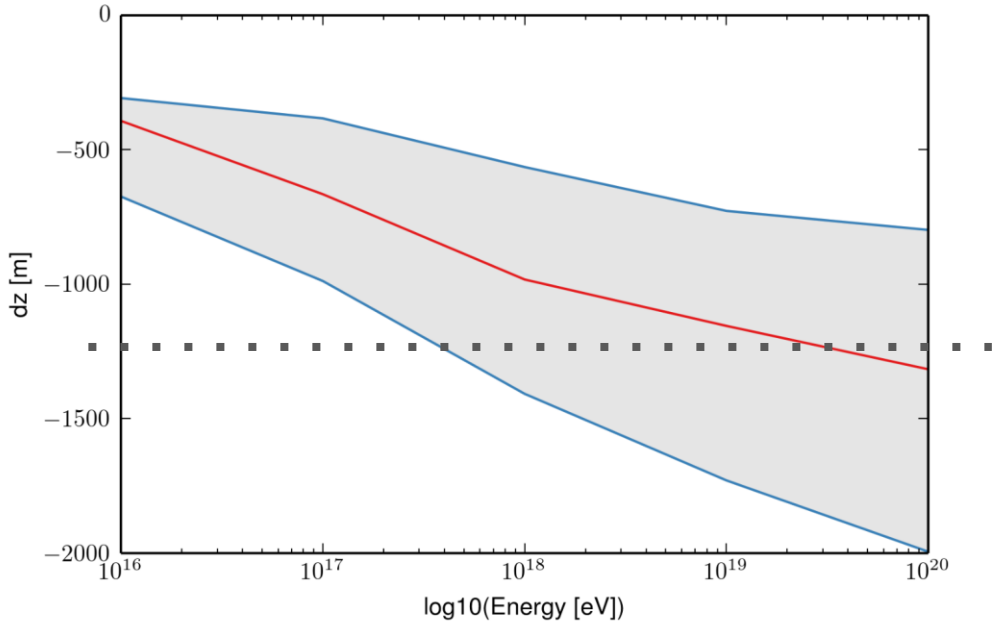
Polar coordinate
Radial distance correlated with depth



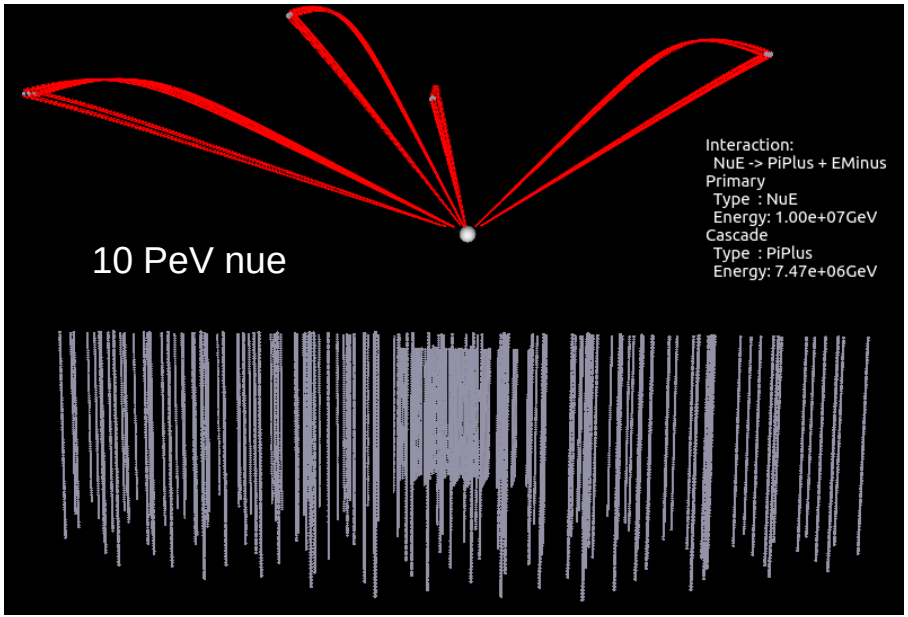
Each dot shows vertex of nu which triggered ARA

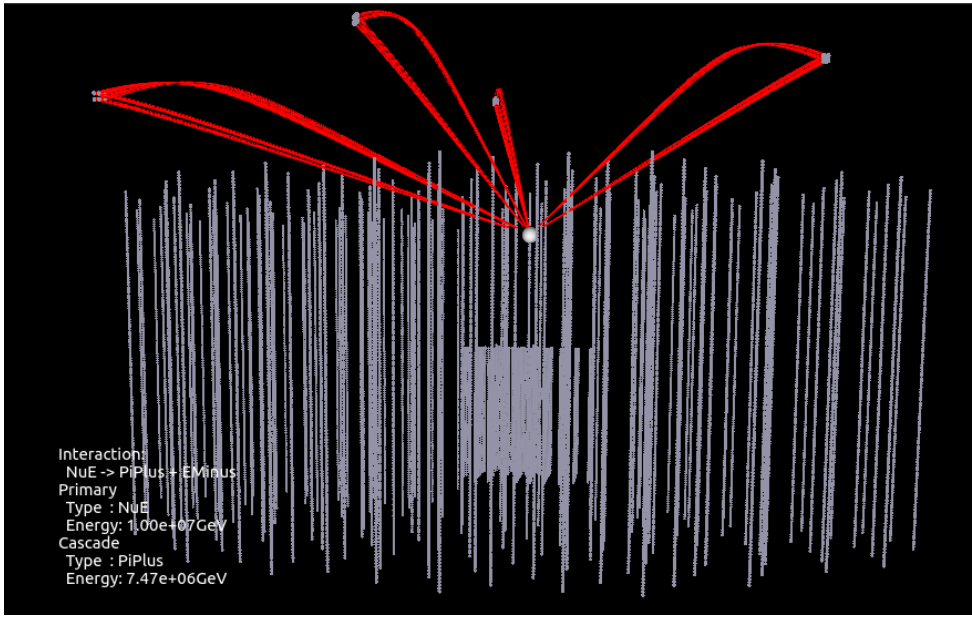
z-depth distribution of cascade vertices triggering ARA-like stations

if we want to be sensitive to energies < 100 PeV, we need shallow optical detectors for overlaps



Recap: 3 weeks ago Gen2 call a proposal for shallow optical

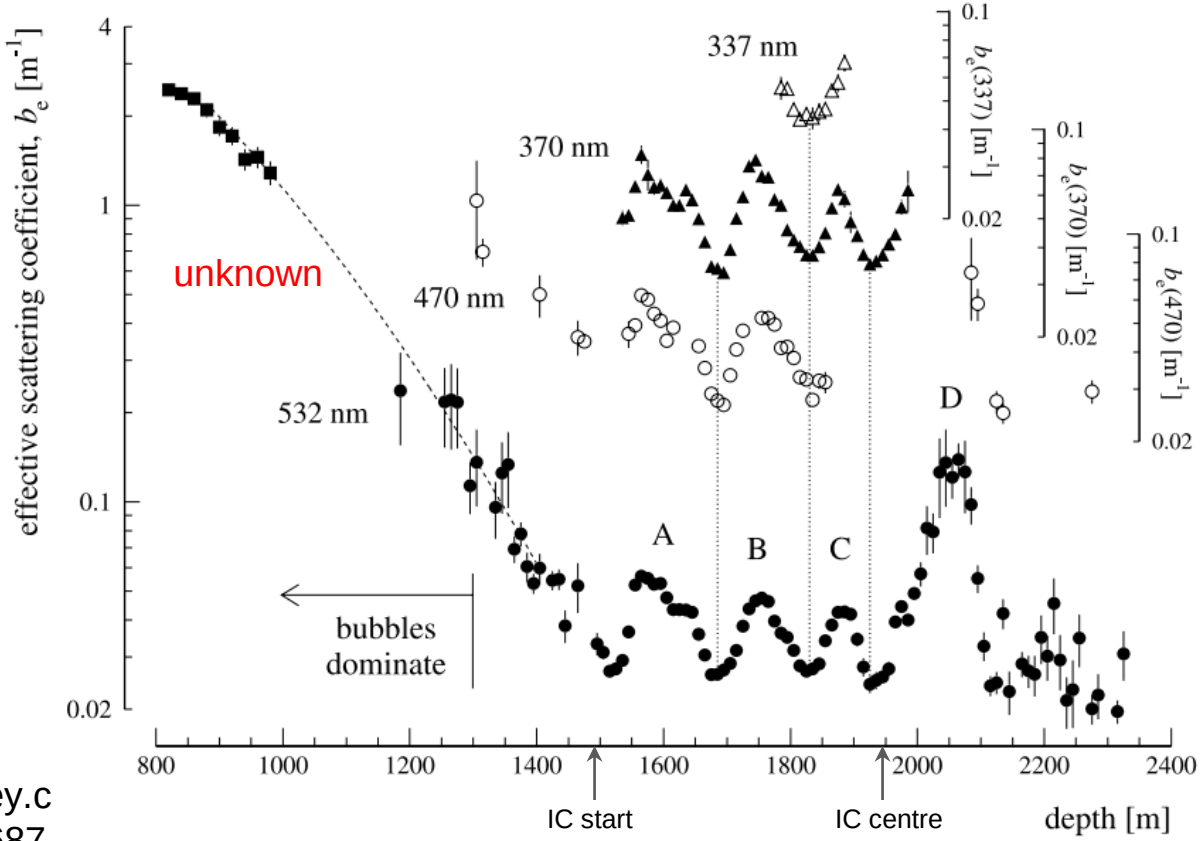




Dustlayer-like (up to 1300 m)

Large uncertainty

Unmeasured region



https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2005JD006687

Figure 13. Depth dependence of the effective scattering coefficient measured with pulsed sources at four wavelengths. Data at 337, 370, and 470 nm are rescaled for clarity according to the axes to the right. The four peaks labeled A through D correspond to stadials in the last glacial period. A broad dust peak due to the Last Glacial Maximum, expected at ~1300 m, is masked by bubble scattering. The points between 800 and 1000 m, where scattering is dominated by bubbles and does not depend on wavelength, are weighted means of previously published measurements at 410–610 nm [*Askebjer et al.*, 1997b].

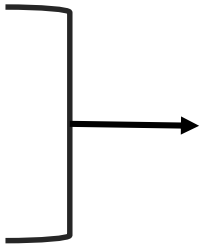
New idea : Radio ***in-ice***

Merits in Radio

- inexpensive detectors
- long attenuation length
- **no scattering**

Demerits in Radio

- considered unreliable



Totally hybrid radio/optical array

- excellent angular resolution for PeV cascades!

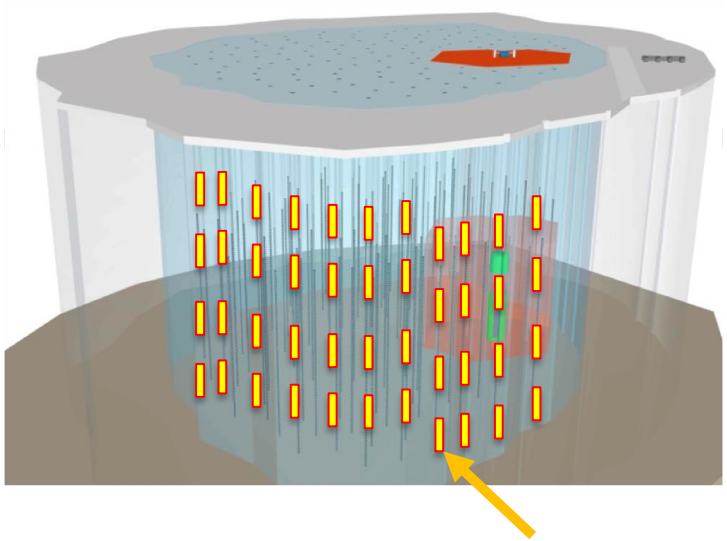
  critical for doing astronomy

- automatic verification of the radio measurements

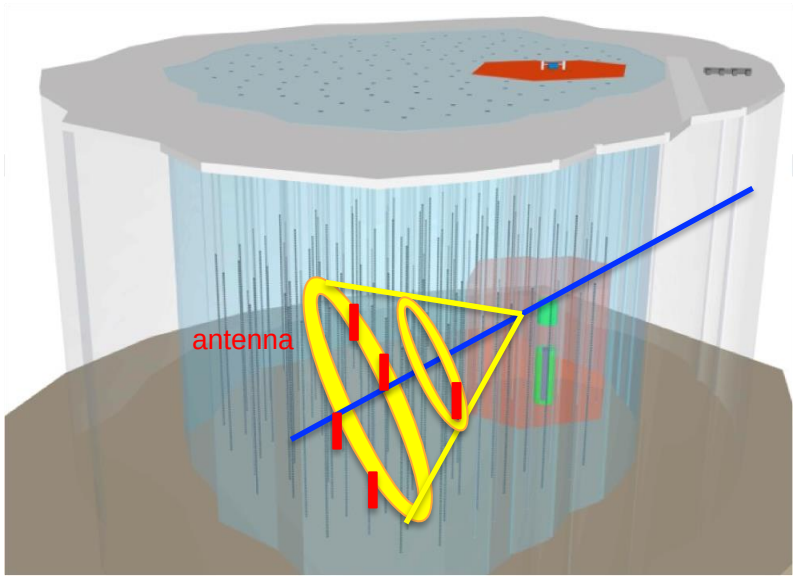
  People would believe us

Hybrid Gen2 in-ice

multiple *on-cone* radio detection

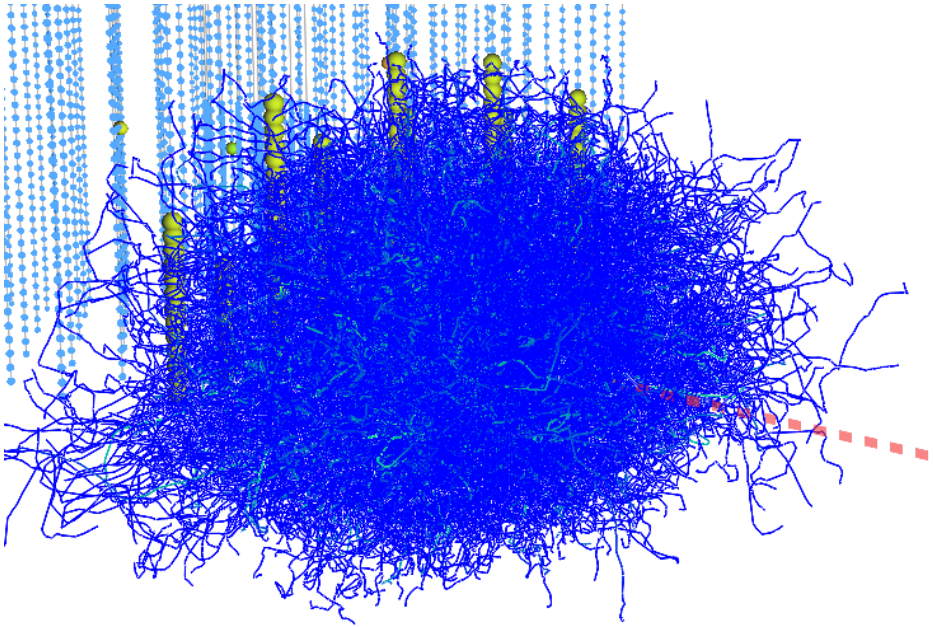


a bunch of radio detectors

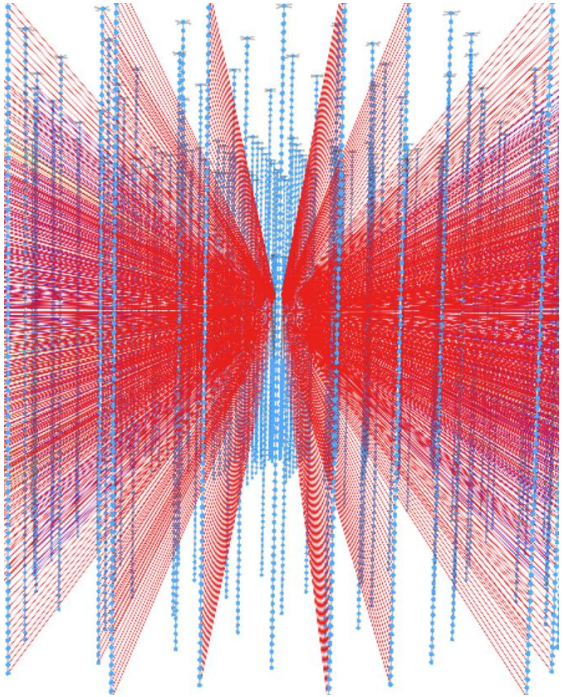


Hybrid Gen2 in-ice

really messy in optical



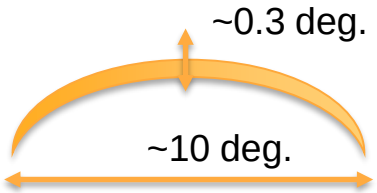
straight in radio



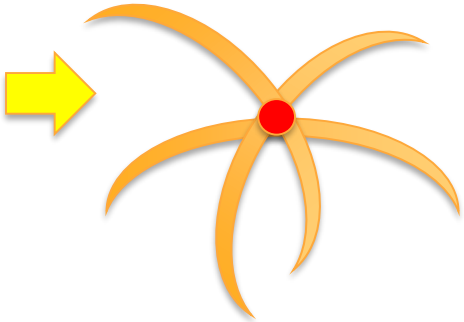
Why angular resolutions are expected?

analogy to florescence detectors for UHECR detections

Single station (ARA)



Stereo technique



We started simulation study

1st results are expected to come before the ICRC

summary

- The simulation modules in the icetray framework have been developed

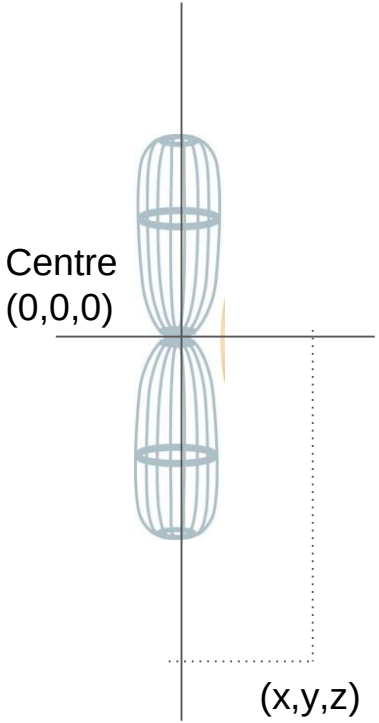
  you can easily swap to your own module

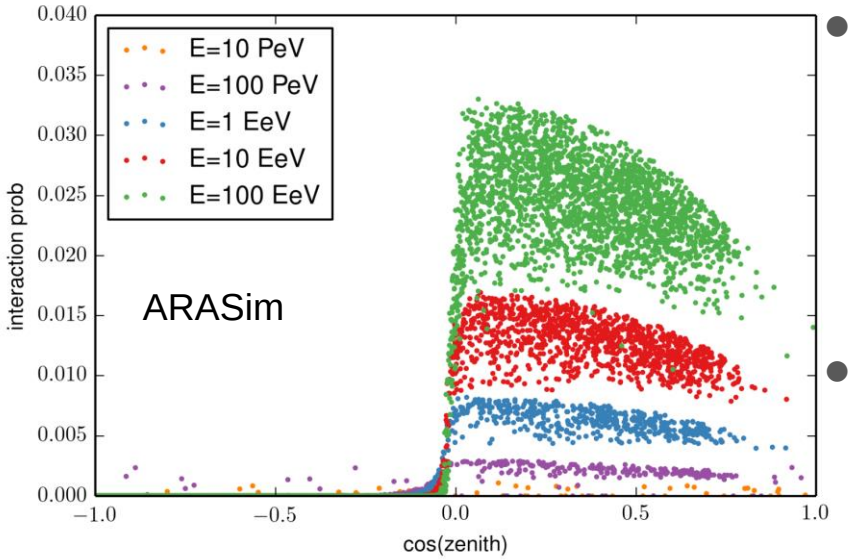
  e.g. a different algorithm for ray tracing

  start simulation of not just cascades but muon/tau tracks

- we would like to propose hybrid in-ice array for doing PeV ν astronomy

ARA radio simulations at trigger level





Highest energies down-going
Earth absorption

ARA Triggering scheme:

- One ARA station is made of 16 antennas, 8 of Vertical Polarization (VPol) and 8 of horizontal polarization (HPol)
- A station triggers when 3 of 8 of the same polarization are significantly above noise level
- Each station triggers independently from each other