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Karlsruhe Institute of Technology

Calibration provided by the Gen2 Surface Array to IceCube-Gen2 in-ice arrays

Frank G. Schroeder

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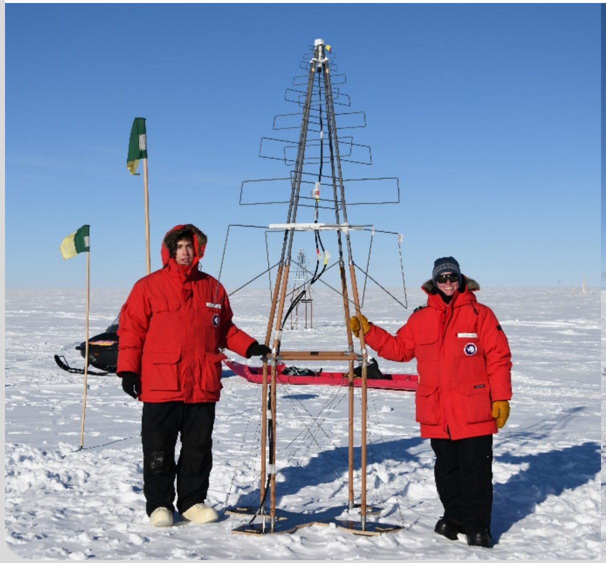
and Karlsruhe Institute of Technology (KIT), Institute for Nuclear Physics , Karlsruhe, Germany



Content: Potential Calibrations provided by Surface Array

- General thoughts on calibration regarding the surface array

- Cosmic-Ray Calibration in a wider sense
  1) in-situ measurement of cosmic-ray flux that produces atmospheric backgrounds in the ice
  2) veto: calibrate / cross-check estimations for signalness of neutrino candidates

- Calibrations provided by Gen2 surface array, to other detector components
  - muon calibration of the optical array → see Bai's talk
  3) uncontained IceTop/IceCube coincidences
  4) energy scale of shallow radio antennas
  5) cosmic-ray showers detected by in-ice radio array

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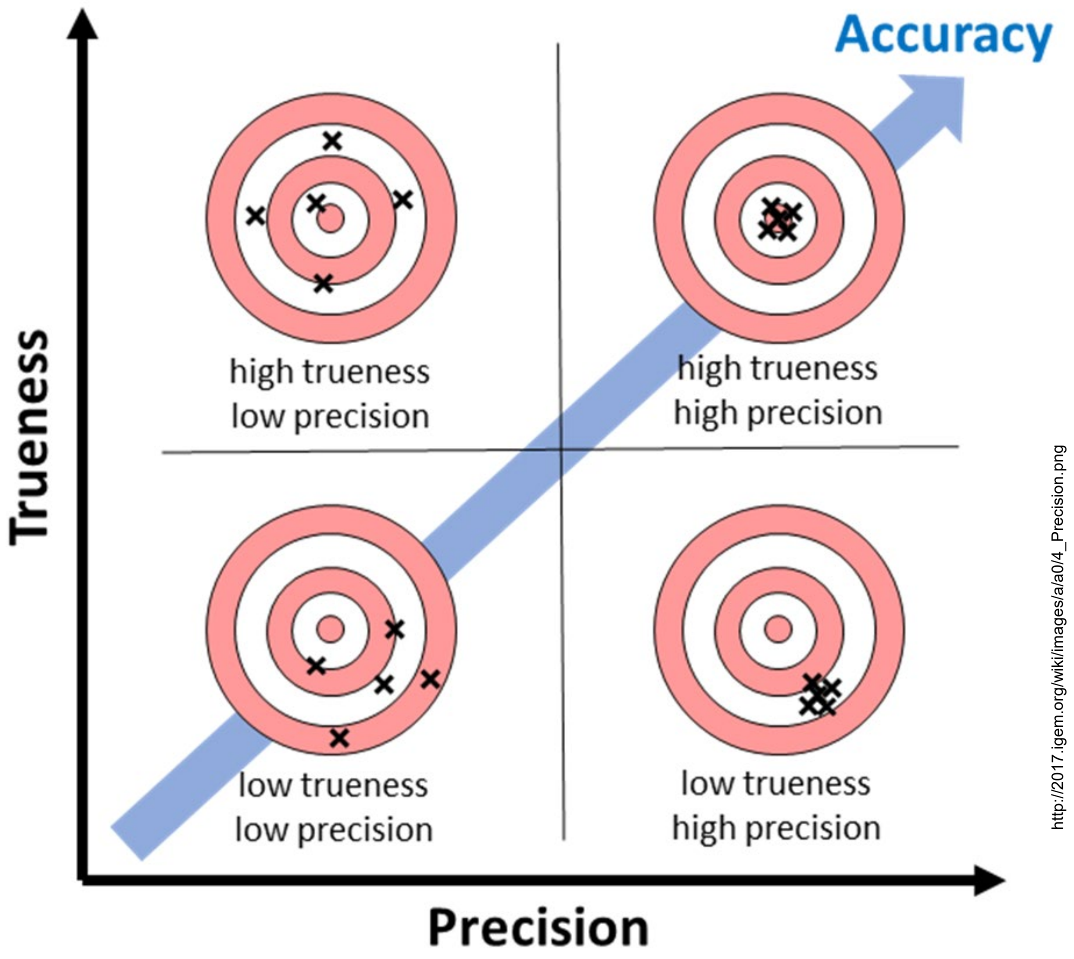
Calibration: Improve Accuracy by Reducing Syst. Uncertainties

- Higher accuracy for
  - particle energy, type, direction
  - signalness of neutrino candidates
  - …..
- by improving precision
  - statistics → not calibration
  - detector-to-detector variations, e.g., by production
  - event-to-event variations, e.g., due to temperature
- by improving trueness
  - systematic offsets (biases)
  - interpretation of detector signals using models



Definitions by ISO 5725
(valid since 1994)

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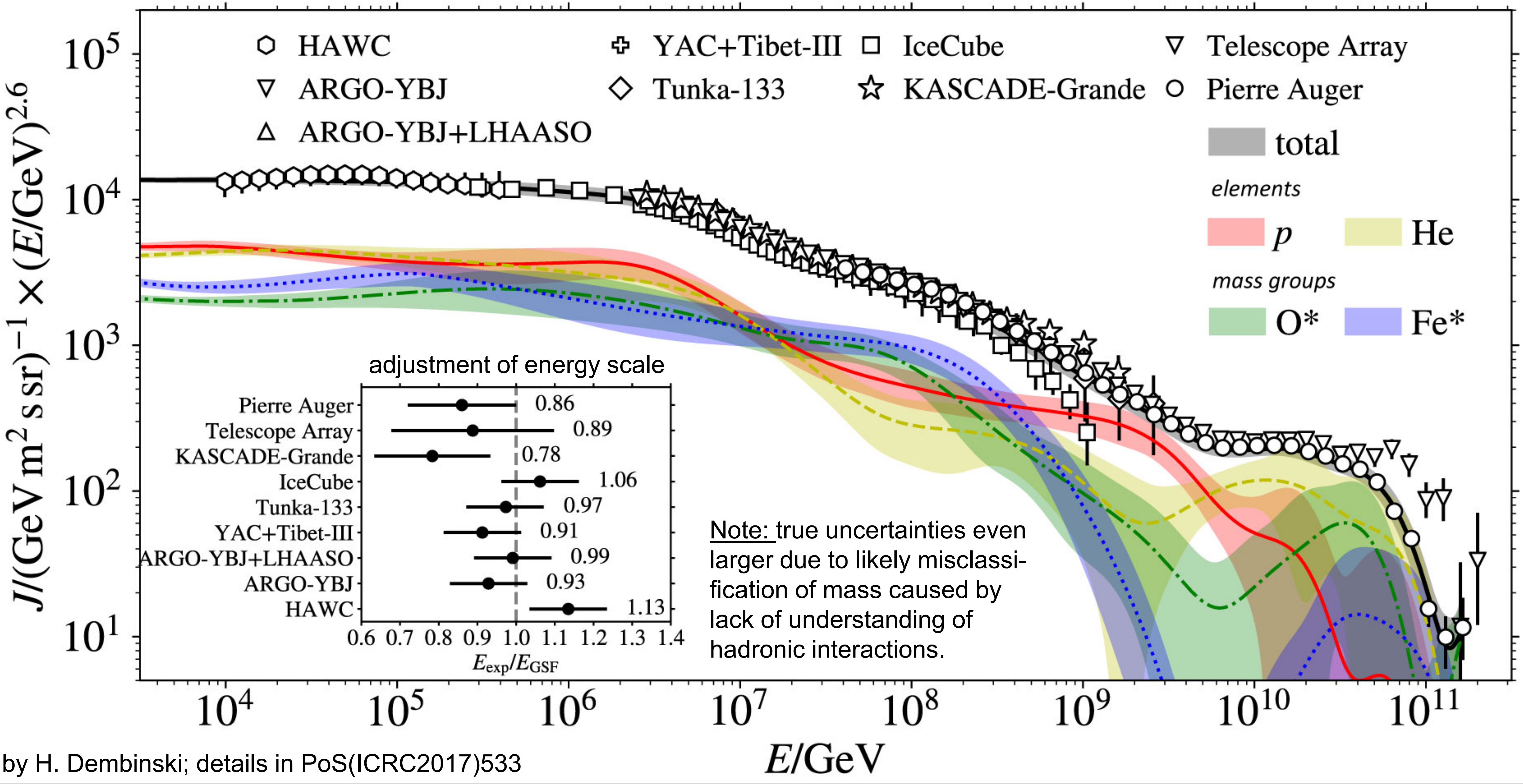
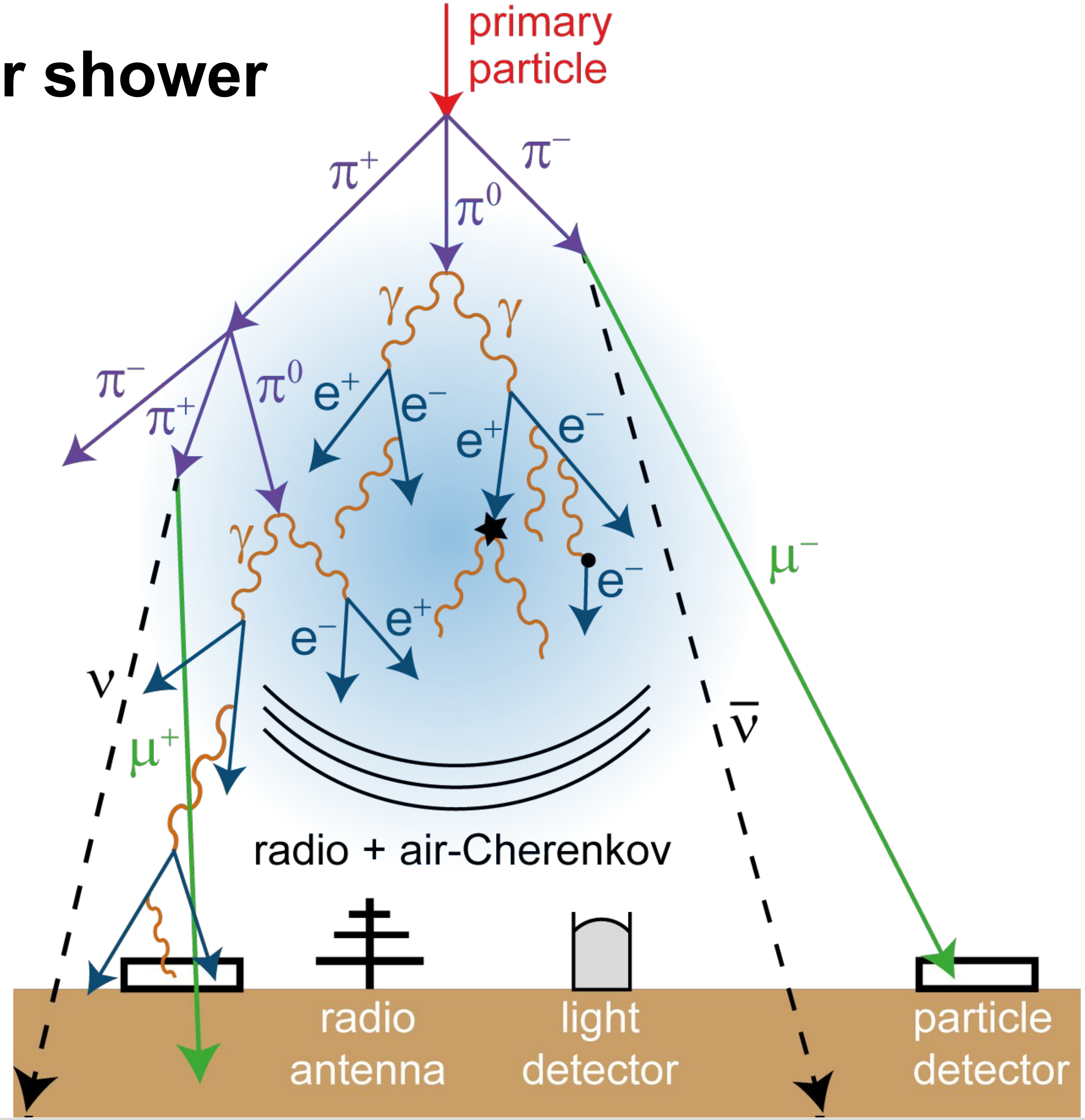
Large Uncertainties in Mass Composition of Cosmic Rays



Note: true uncertainties even larger due to likely misclassification of mass caused by lack of understanding of hadronic interactions.

plot by H. Dembinski; details in PoS(ICRC2017)533

Air shower



Cosmic-Ray Air Showers

- Muons, electrons and electromagnetic emission detectable at ground
- Flux of muons and neutrinos in the ice has systematic uncertainties due to not fully understood *hadronic interactions* and due to the *mass composition* of the primary CRs

→ Mass composition important for astrophysical neutrinos and for atmospheric backgrounds.

Complementary Techniques for CR

- IceCube: Electrons + GeV muons with surface detector, TeV muons in the ice
- Combination with radio (shower maximum) provides desired increase of overall accuracy for the energy and mass of primary particle

Radio detection of cosmic-ray air showers and high-energy Neutrinos"

F.G. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1, arXiv: 1607.08781

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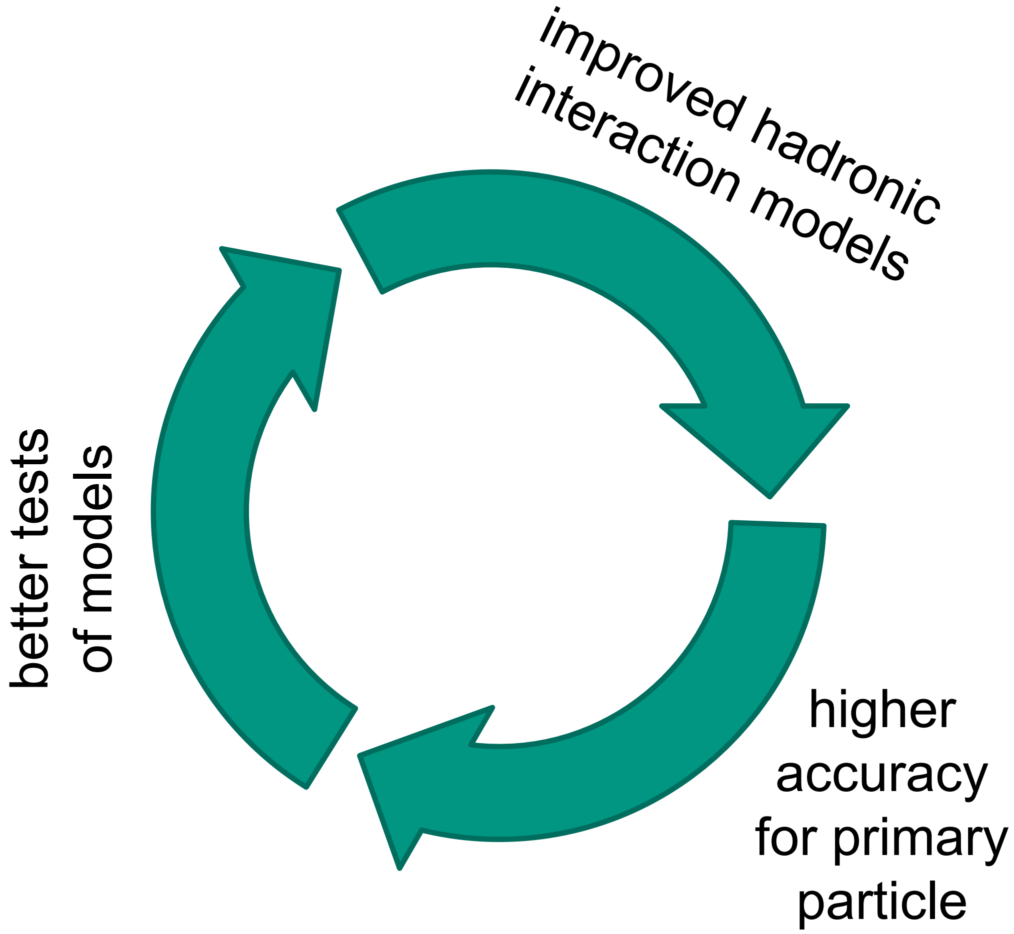
Indirect Cosmic-Ray Measurements

- Accuracy of **energy** measurement limited by absolute antenna calibration
- Accuracy of **mass** of primary particle depends on interpretation of air-showers observables measured by detectors
  - unknown systematic uncertainty for interpretation of muons (all models out of range)
  - small systematic uncertainty for interpretation of X_{max} (approx. H to He difference)
- IceCube can help to constrain models which will enable a more accurate interpretation of data already recorded.

virtuous circle of cosmic-ray physics



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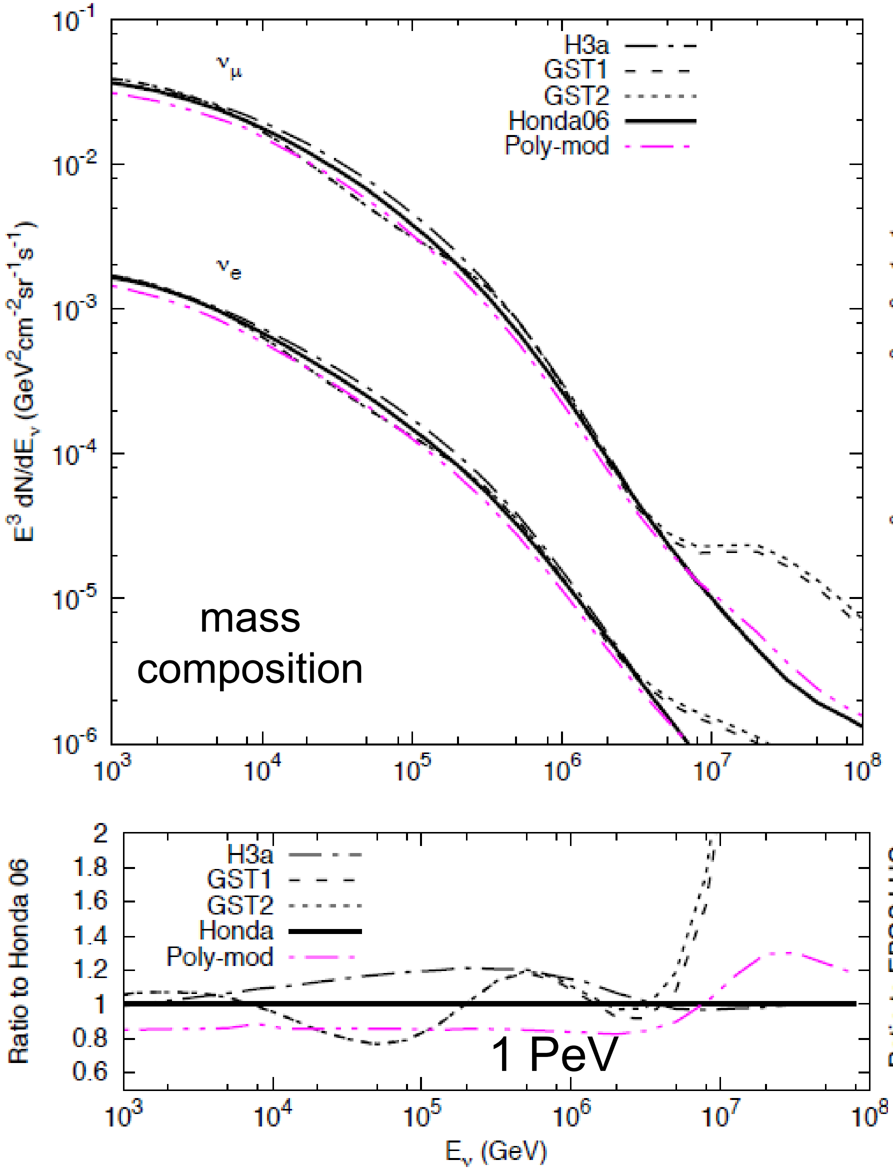
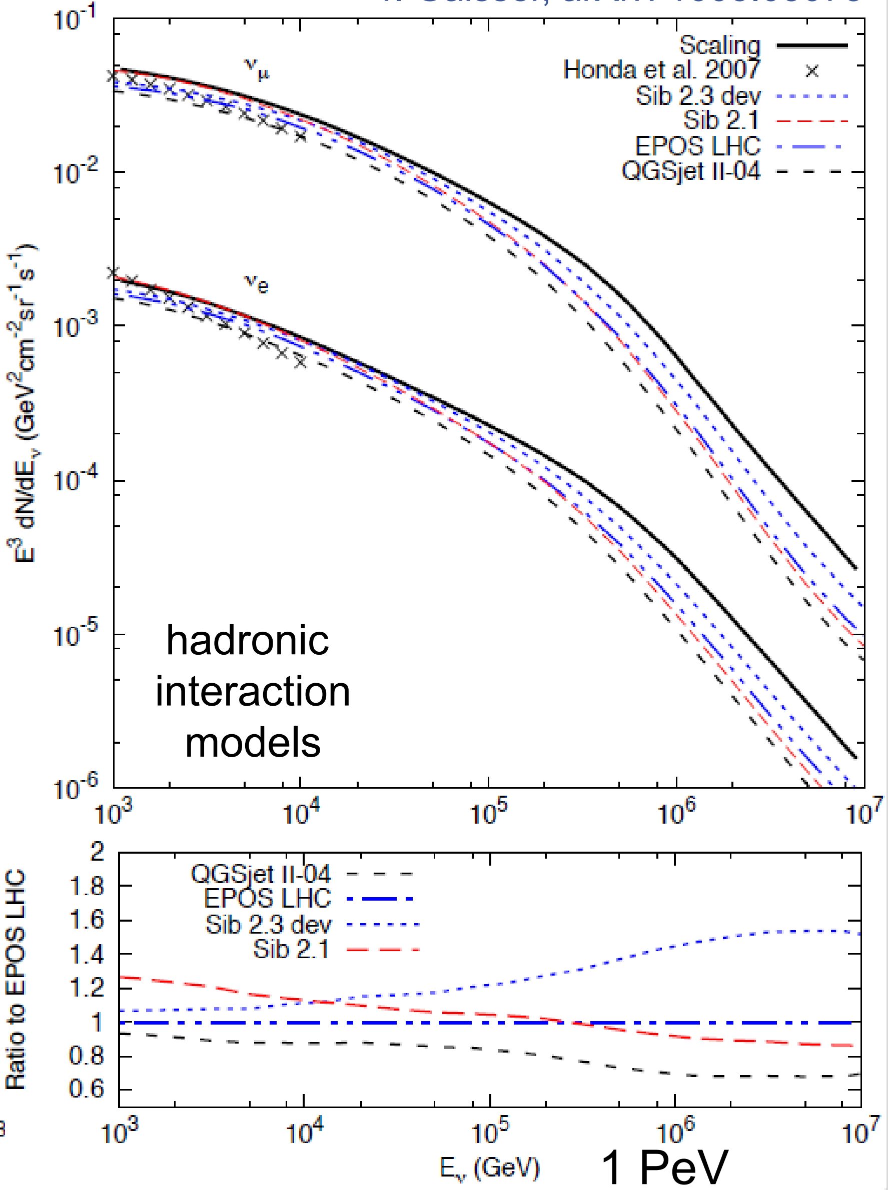
Uncertainties on Atmospheric Neutrino Flux

T. Gaisser, arXiv: 1605.03073

- **Hadronic Interactions**
  - several 10% uncertainty on atm. neutrino flux
  - by unknowns in air-shower interactions (e.g., prompt neutrino production by charms).
- **Absolute CR flux** in energy per nucleon
  - several 10% uncertainty on atm. neutrino flux by
  - **mass composition**
  - **energy scale**





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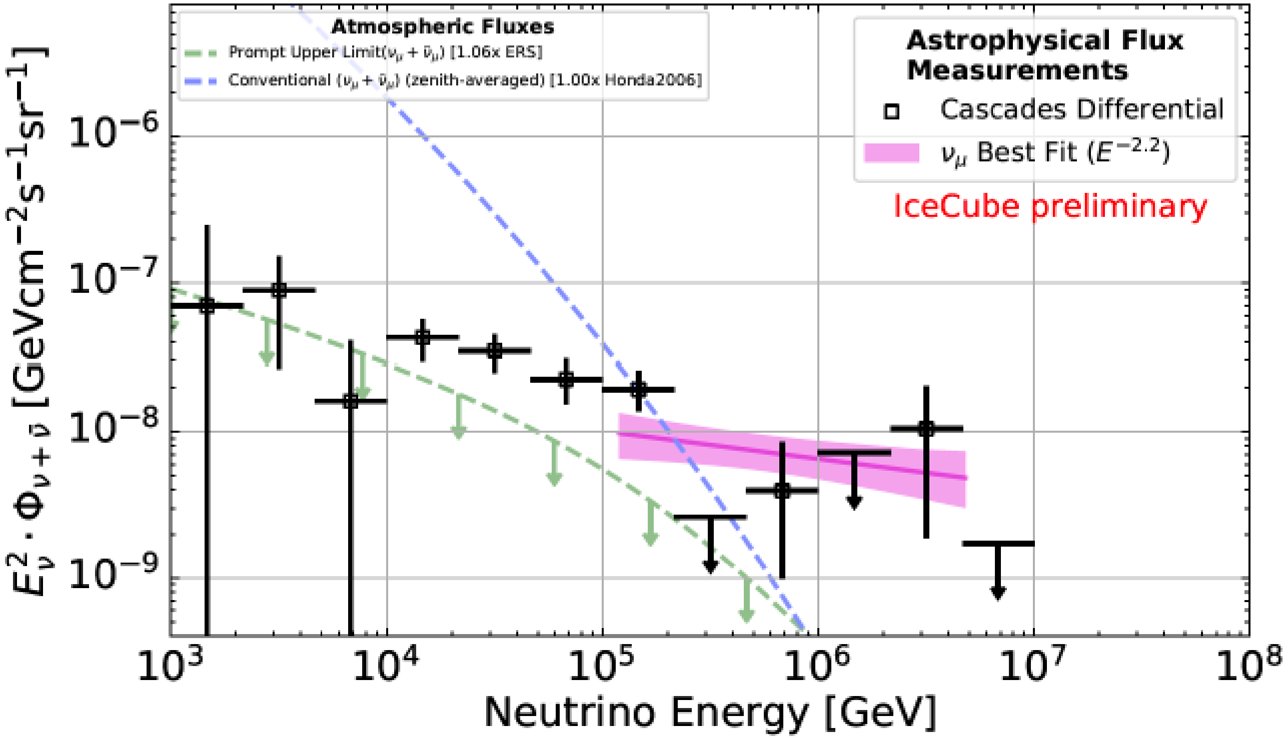
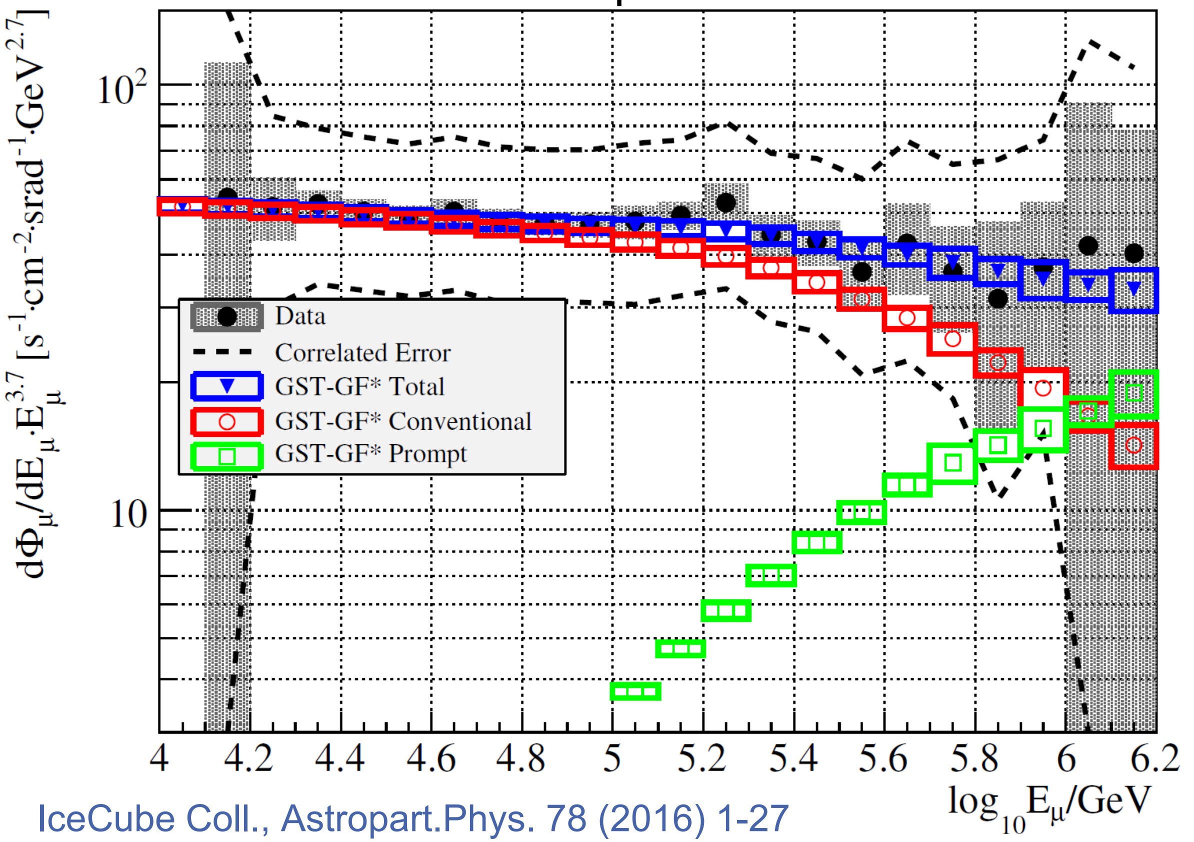
1) Calibration of atmospheric backgrounds in the ice

- Surface Array will provide *in-situ measurement of cosmic-ray flux*
  - improve understanding of *atmospheric muons*: conventional and prompt
  - improve estimation of *atmospheric neutrino flux*

atmospheric neutrinos



atmospheric muons



IceCube Coll., Astropart.Phys. 78 (2016) 1-27

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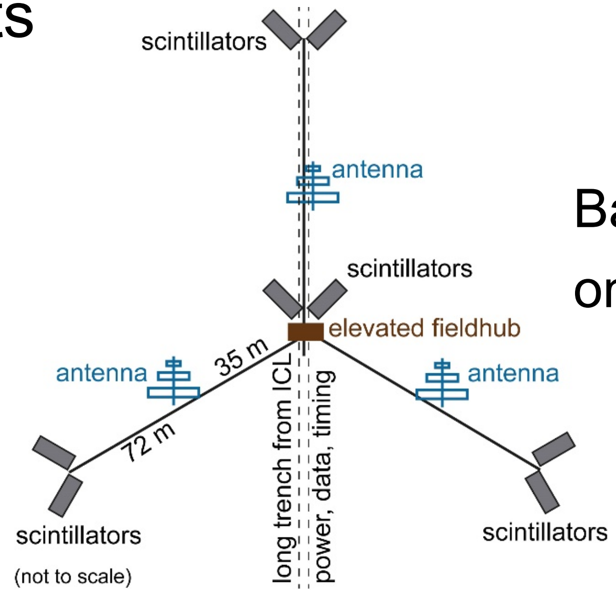
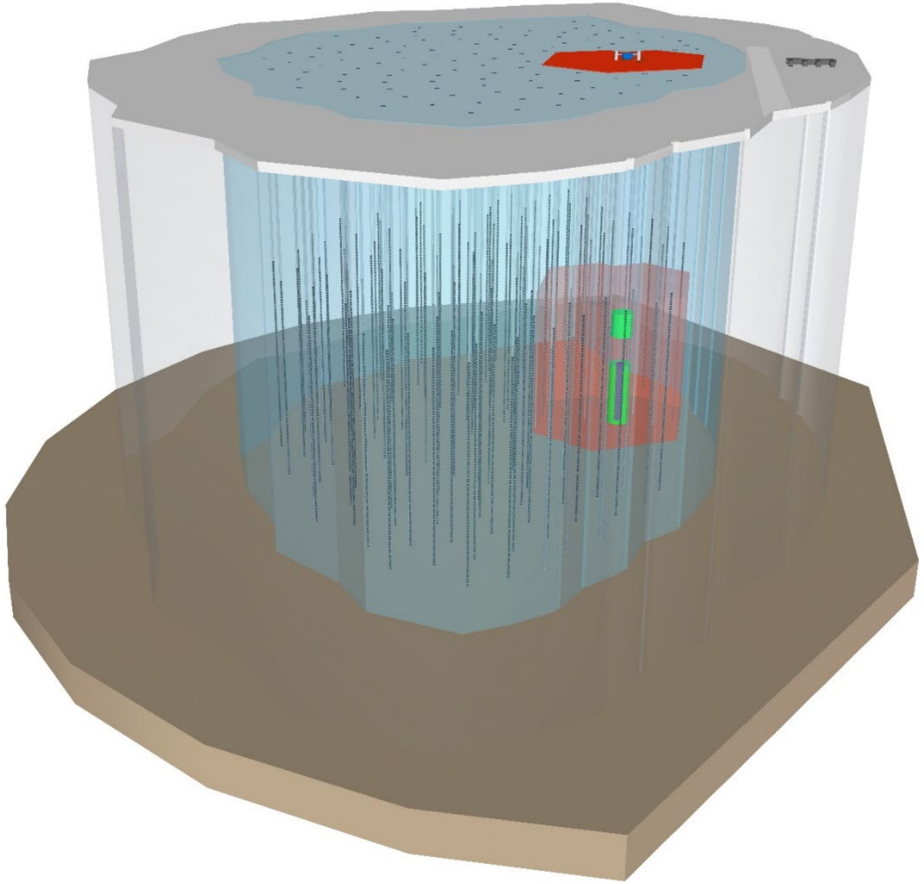
Veto by Gen2 Surface Array

- Direct (tracks through surface array) and indirect (check any candidates) veto for the optical array

→ Potential for consistency check: is the predicted signalness of neutrino candidates consistent with the fraction of vetoed events





Baseline design of Gen2 Surface Array: one station per optical string (122)

- 4 pairs of scintillators enabling low threshold for veto
- 3 radio antennas increasing accuracy at high energies

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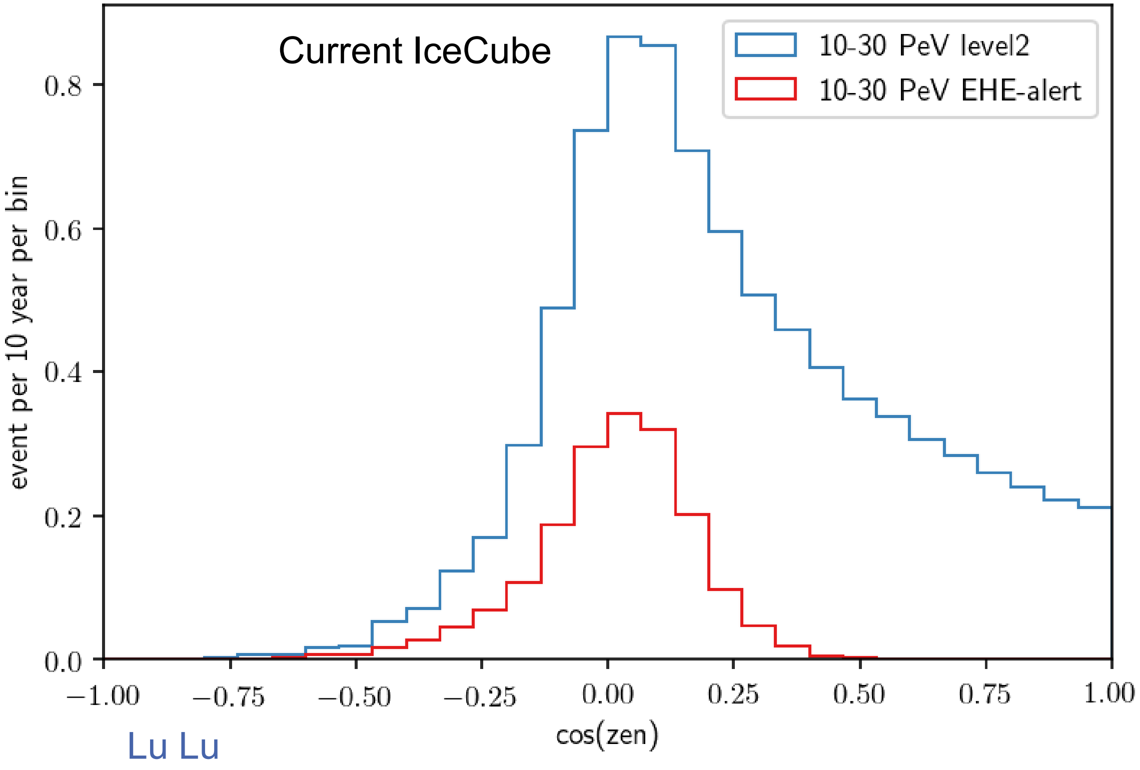
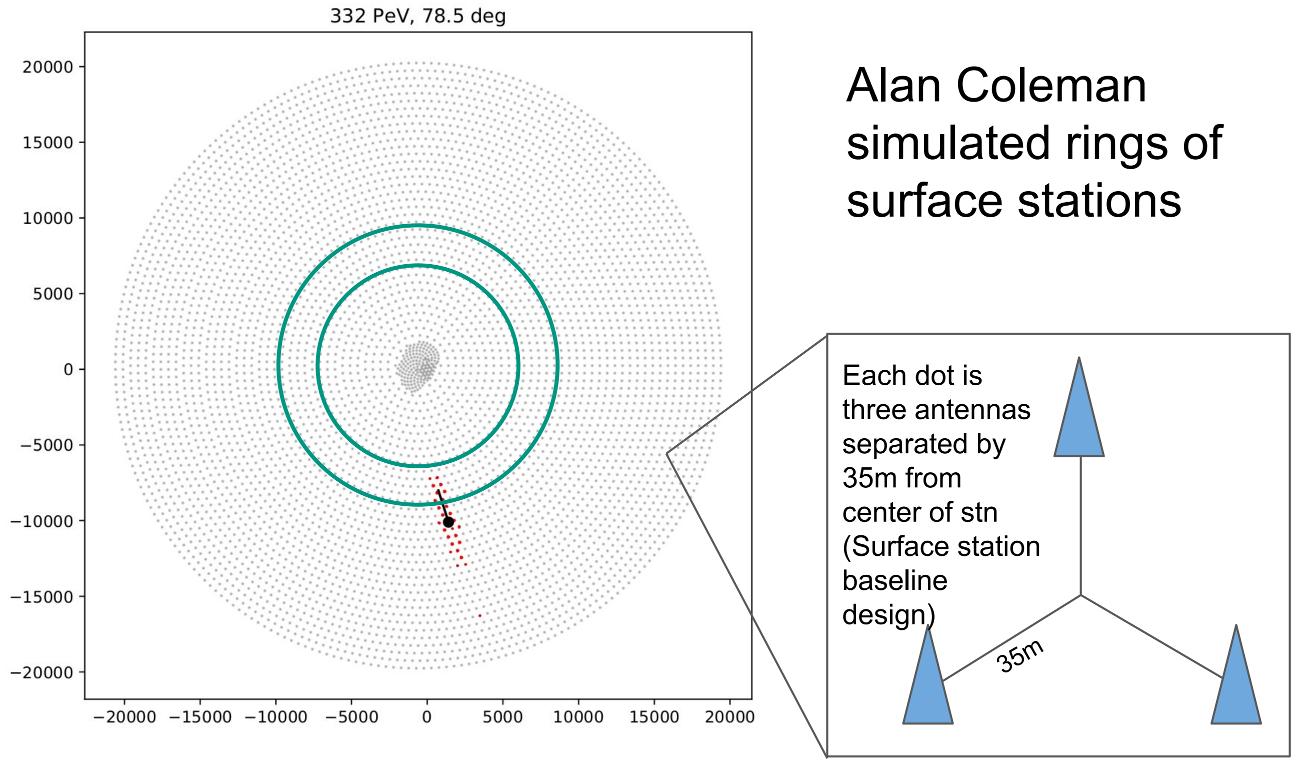
2) New idea under investigation: radio veto for inclined showers

- Partial veto of inclined showers to improve detection of 10+ PeV neutrinos
  - IceCube-Gen2 could have 1-2 candidates of 10+ PeV neutrinos per year at 70-90° zenith
  - Surface antennas can provide partial veto where $N_{background} \approx N_{signal}$



Lu Lu



Alan Coleman

Alan Coleman simulated rings of surface stations

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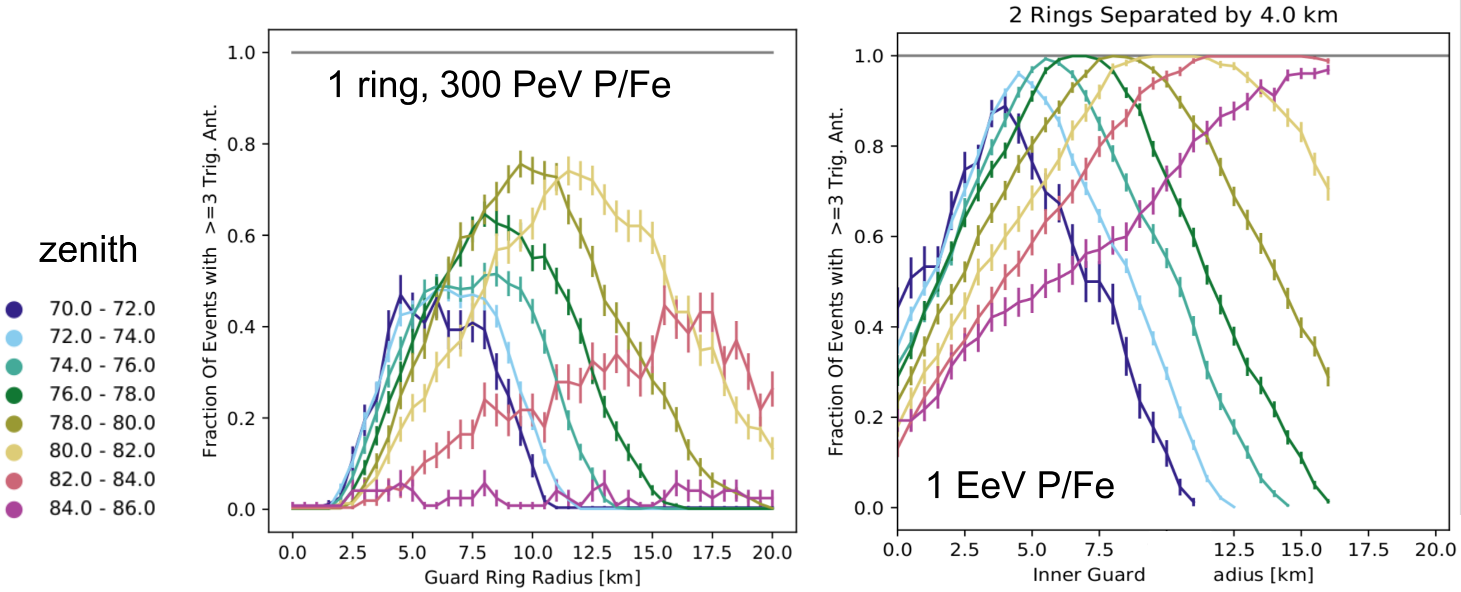
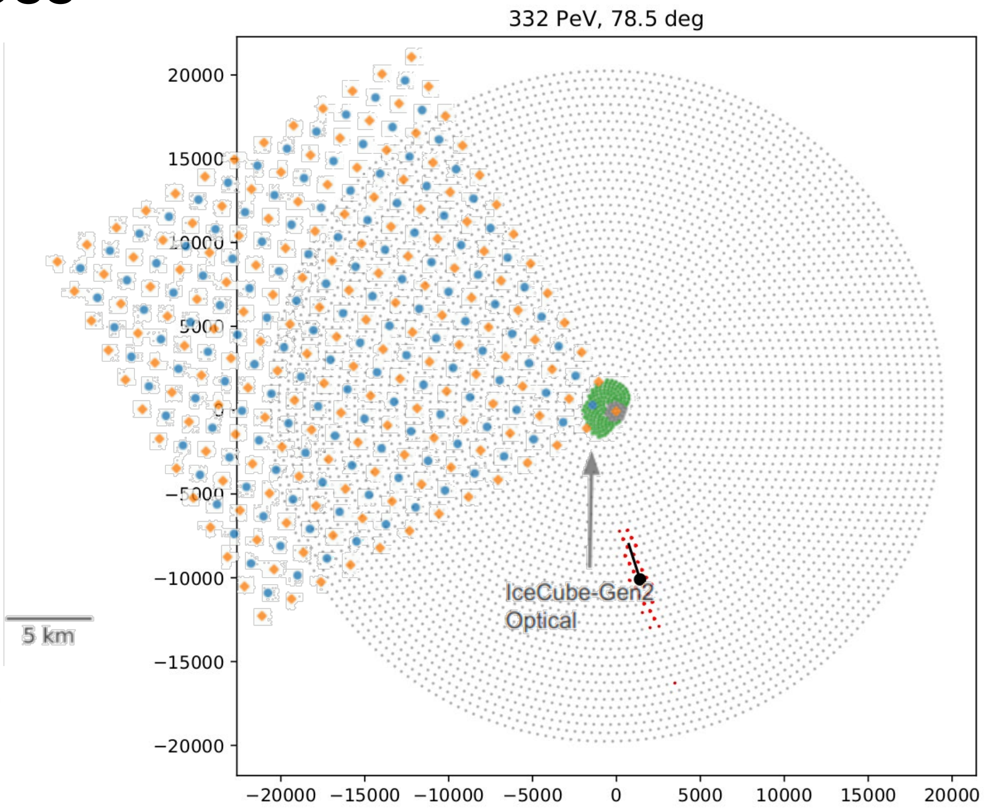
Possible synergy with radio array

- Can surface antennas at the radio array provide a partial veto for 10+ PeV neutrinos for the optical array?
- Optimized layout may yield a few extra neutrinos.
- Also may be used to *calibrate and test signalness* models of neutrino searches by optical array.





Details: see Alan Coleman's talk at collaboration meeting

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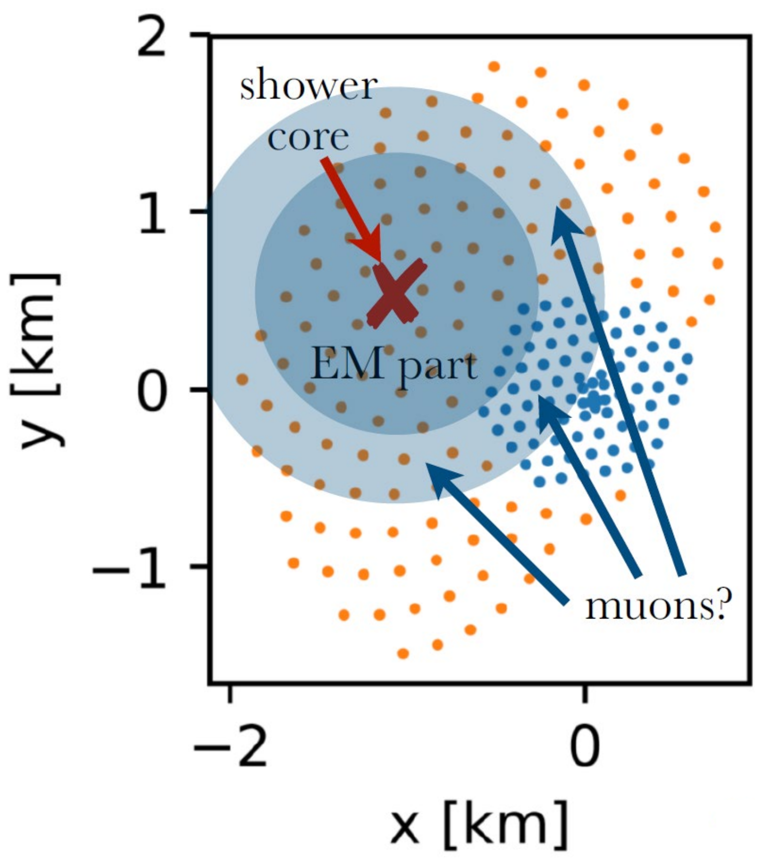
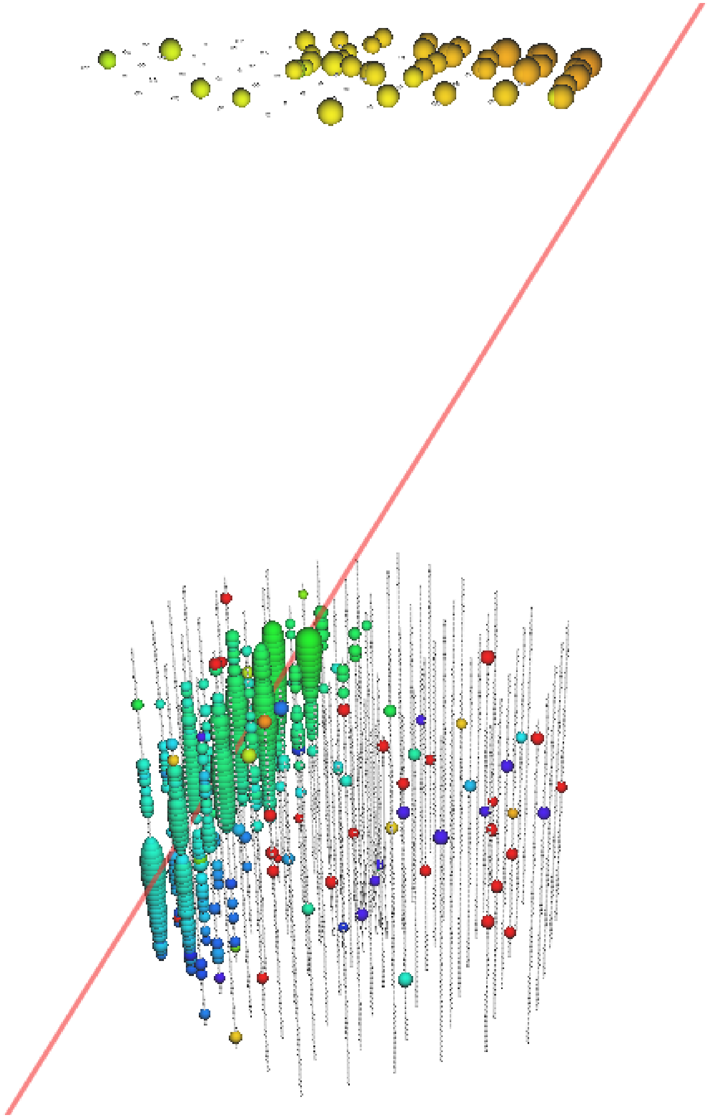
3) Calibrate IceTop for uncontained showers

- IceTop has a large exposure of contained events with the shower axis determined by the in-ice detector.
- With the Gen2 surface array we can check the reconstruction accuracy of such uncontained events

→ improve ~15 years of IceTop data on tape by then

- These are valuable for muon measurements and for ultra-high-energy showers.





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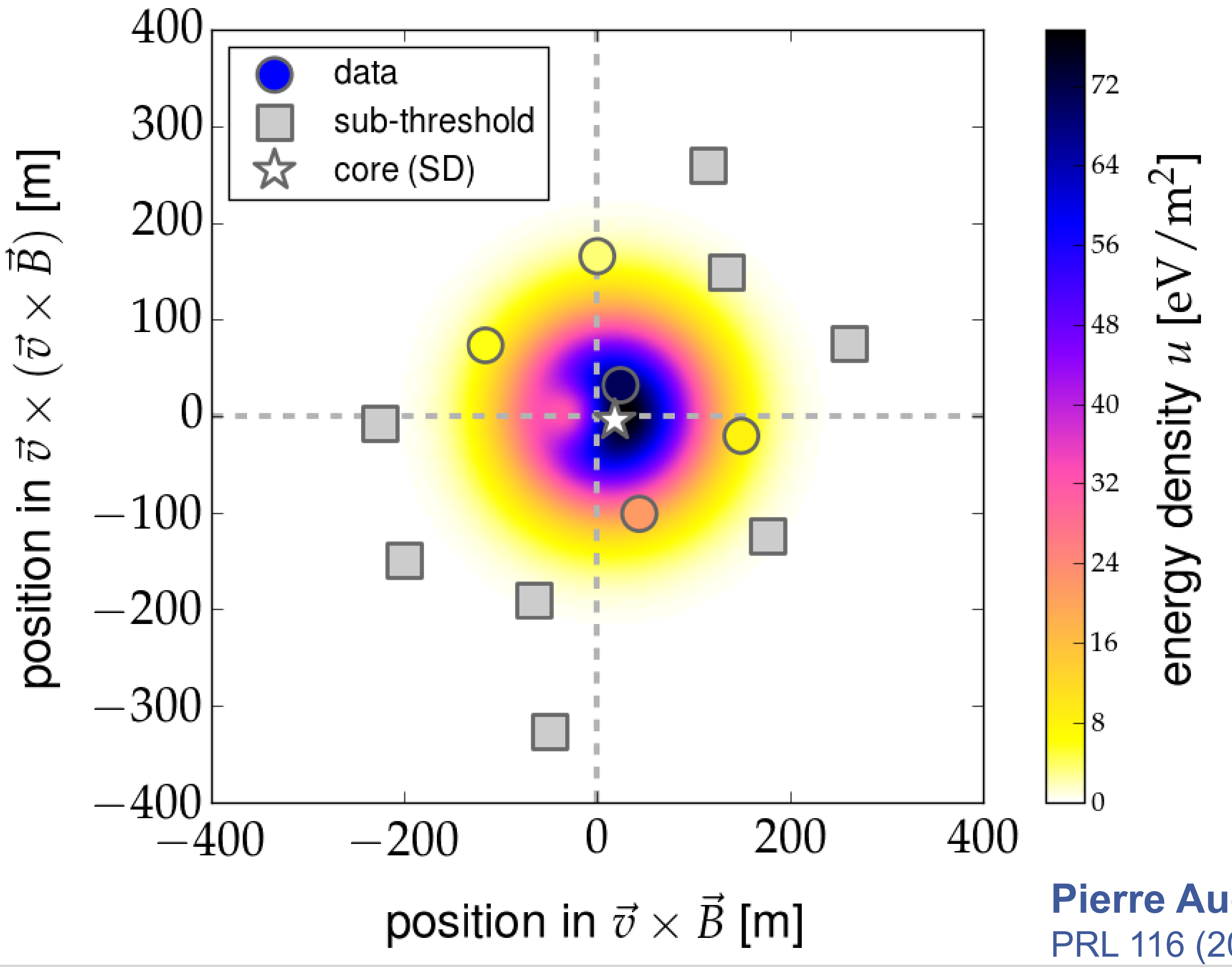
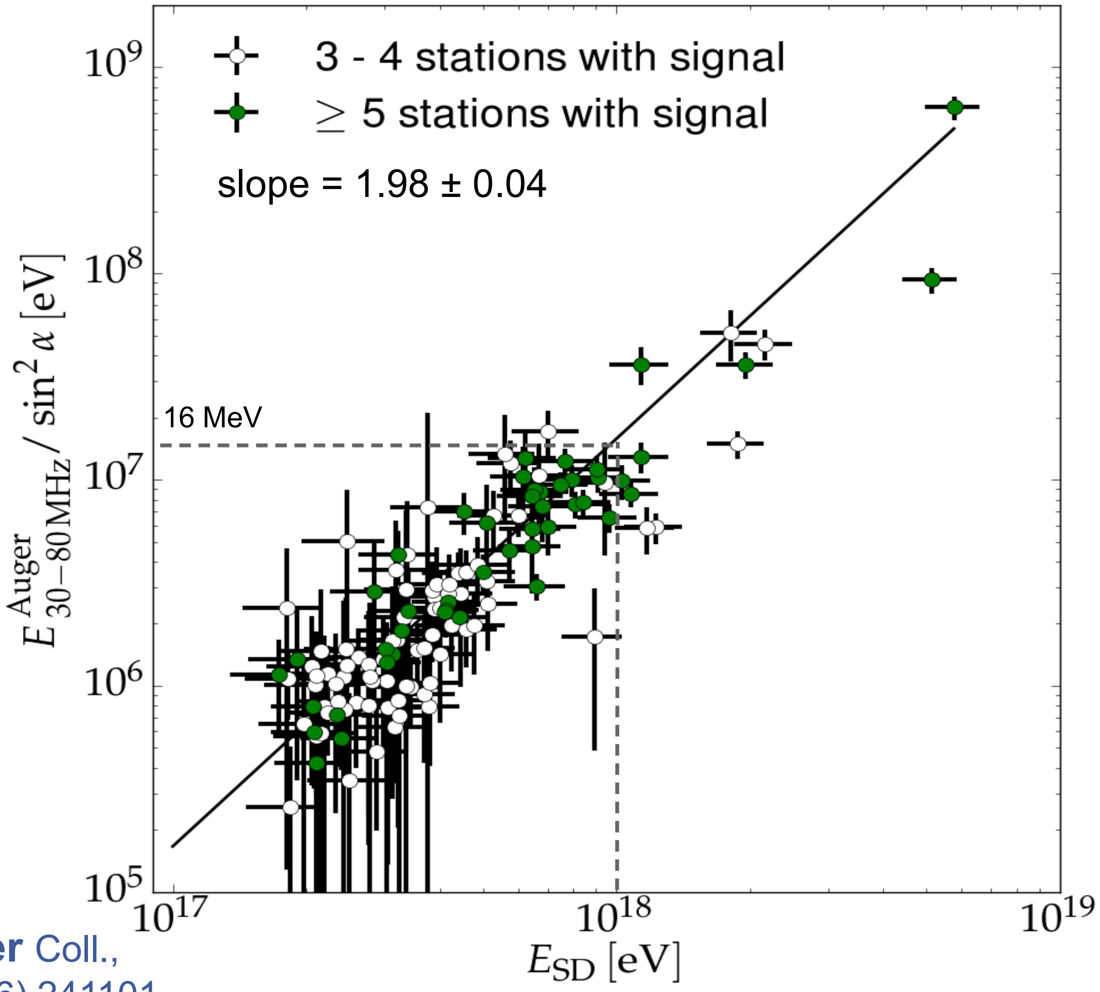
4) Calibrating Radio Array: Common Energy Scale

- Integral over radio footprint provides accurate estimator of absolute energy





Pierre Auger Coll.,
PRL 116 (2016) 241101

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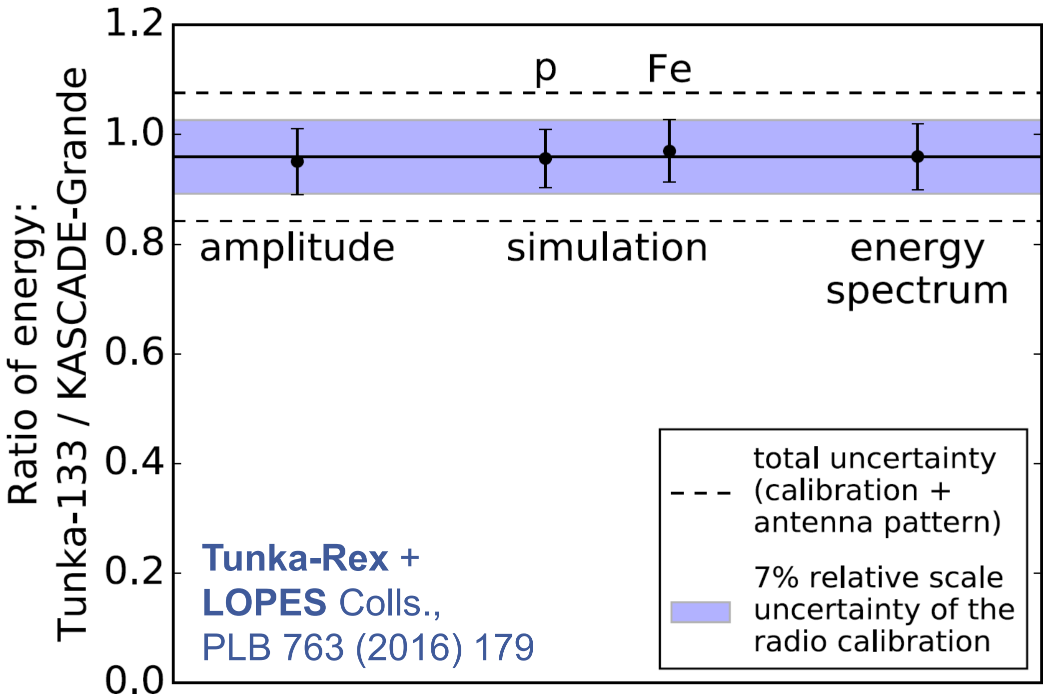
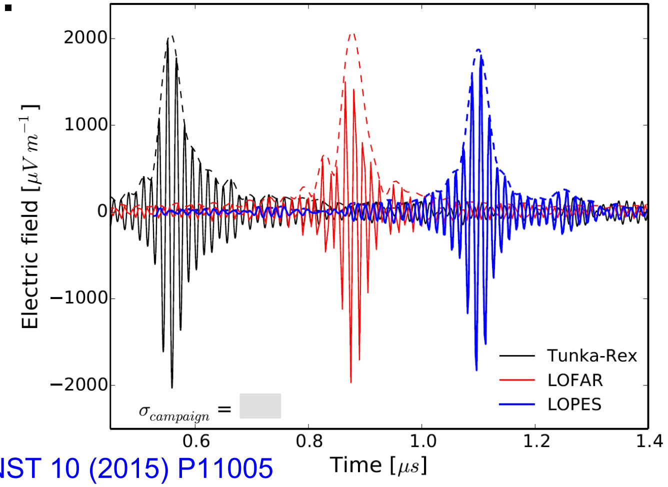
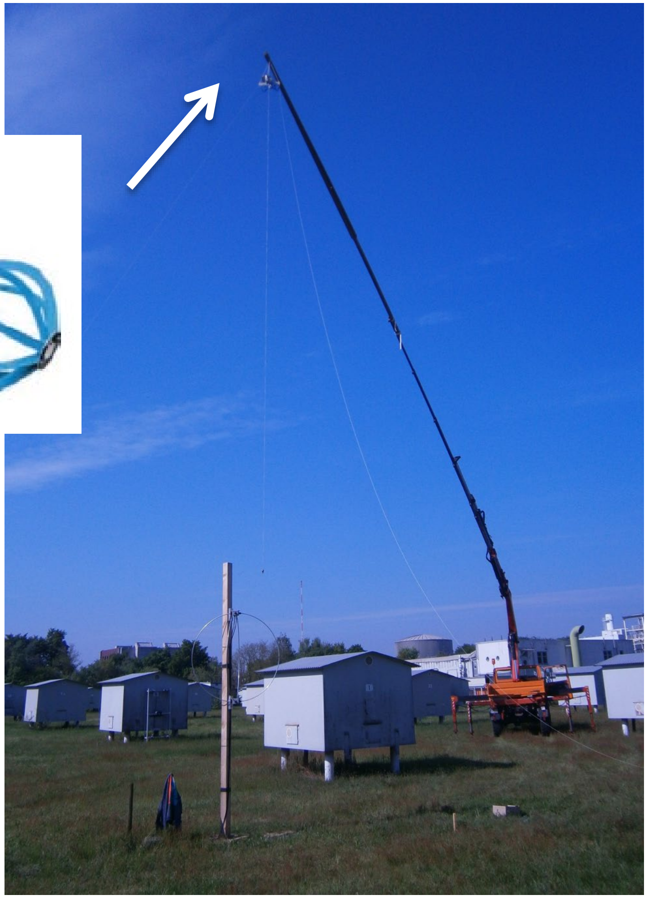
Radio can be used to calibrate energy scales

- External reference and/or same antenna type between experiments gives *absolute scale*
- Can be used to compare IceTop to *other CR air-shower arrays* and to *in-ice radio*.





JINST 10 (2015) P11005



LOPES, LOFAR, and Tunka-Rex antennas all absolutely calibrated with exactly same reference source.

Even better would be to use the same physics antennas → K. Mulrey plans to check other arrays with SKALA v2.

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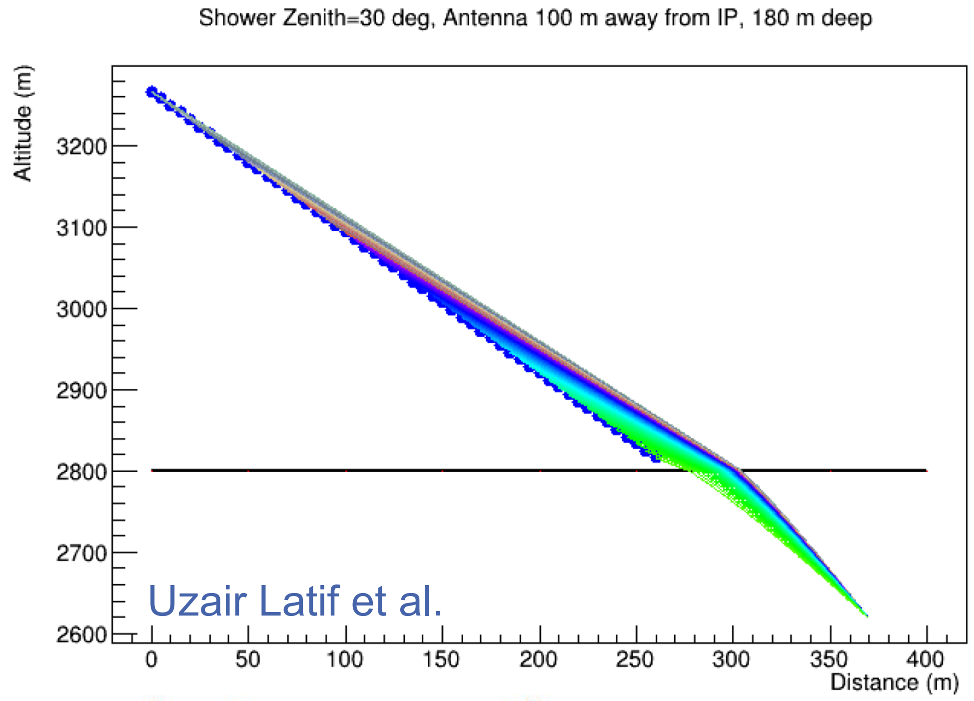
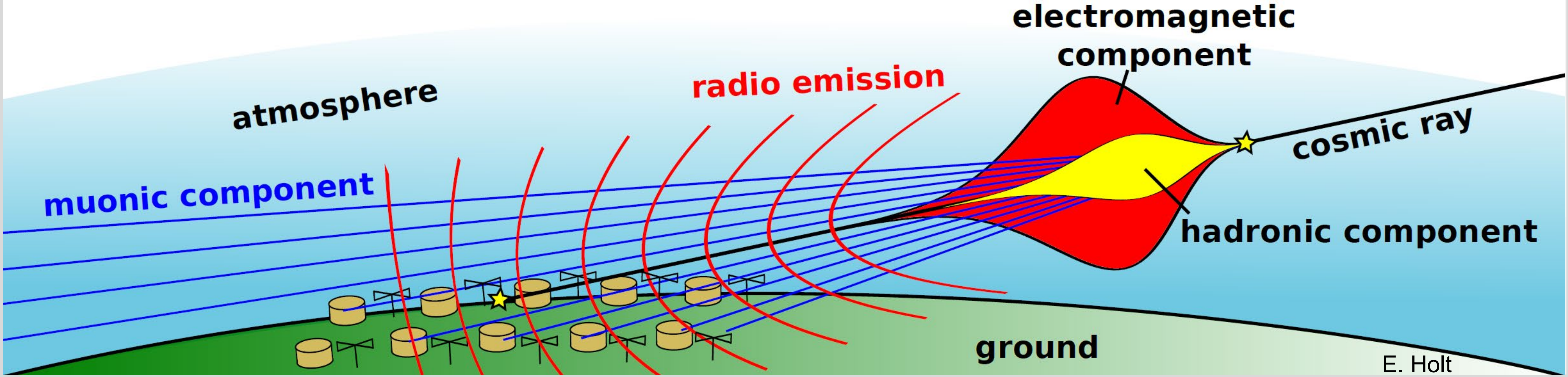
Calibration of Shallow Radio Stations

- For inclined showers the complete radio emission is released in the atmosphere
- Surface antennas would measure same radiation energy as in-ice antennas

→ can be used to calibrate energy scale of shallow radio stations to IceTop scale





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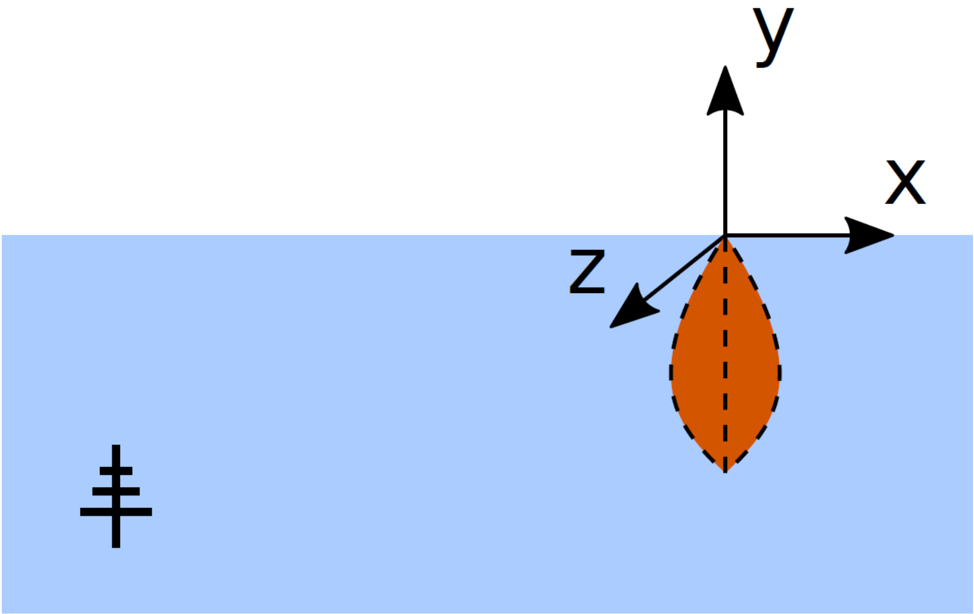
5) Calibration of in-ice *radio* stations by surface stations

- A small overlap of the surface an in-ice radio arrays can be used for calibration on coincident air-shower events by *deep vertical showers*
  - Scintillators will measure shower at the surface
    - energy, direction, and impact point
  - Shower propagates into the ice and is detected by shallow and deep radio antennas
  - Surface reconstruction can be used to test direction and energy reconstruction of in-ice radio array
  - Caveats:
    - geometry different from neutrino-induced showers
    - shower will develop in firn instead of deep ice
    - radio emission in air partly by geomagnetic effect
      → can be mitigated by observing showers parallel to geomagnetic field



see talk by Simon de Kockere yesterday

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Conclusions

- Gen2 Surface Array provides calibration in a wider sense
  - more accurate *in-situ measurement of cosmic-ray flux* (energy scale, mass composition) → atmospheric in-ice signals/backgrounds
  - extends IceTop's role for IceCube-Gen2
- Various cross-checks of in-ice-detectors
  - optical array: muons, veto/signalness, uncontained showers
  - radio array: energy scale, cross-check of shower reconstruction
- Many ideas at stage of brainstorming and first discussions to be continued in Gen2 Surface Array Working Group
  - bi-weekly calls Thursdays 11am; typical duration ~ 60-100min
  - Wikipage: https://wiki.icecube.wisc.edu/index.php/Gen2_Surface_Array

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Science Goals: Overview – Resorted by preliminary priority

Science Goal	Scientific Measurements and Observables
Cosmic-Ray Physics	1) Hadronic interactions: improvements in surface muon measurements over Gen1; larger range of zenith angles for in-ice coincidences, higher energies, prompt muons 2) CR anisotropies: Close the anisotropy gap (no significant measurements between few PeV and EeV) using ~10x increase in aperture at high energies 3) Extend Mass composition over energy to higher energies: overlap with Auger and TA for Galactic-extragalactic transition at a competitive accuracy
Veto	1) Check down-going real-time alerts. IceTop retracted 3 alerts in 2020. Also the Gen2 surface will be used in automated checks for selection of candidates. 2) Veto for small zenith angles with increased solid angle compared to Gen1.
Calibration of in-ice detectors	1) Physics calibration of the in-ice atmospheric leptons (prompt and regular atm. neutrinos + muons): **in-situ calibration of the cosmic-ray flux** 2) Calibration of **in-ice radio** antennas with air-showers detected by surface array: cross-calibrate absolute energy scales 3) Muon bundles / single **muons** can be used **as a cross-check** of the dedicated calibration instruments in the ice and of the overall track reconstructions
Other	1) PeV photon search with surface array for Galactic Center and with in-ice coincidences for increased solid angle. → Discovery potential for Galactic sources. Fits multi-messenger mission of IceCube.

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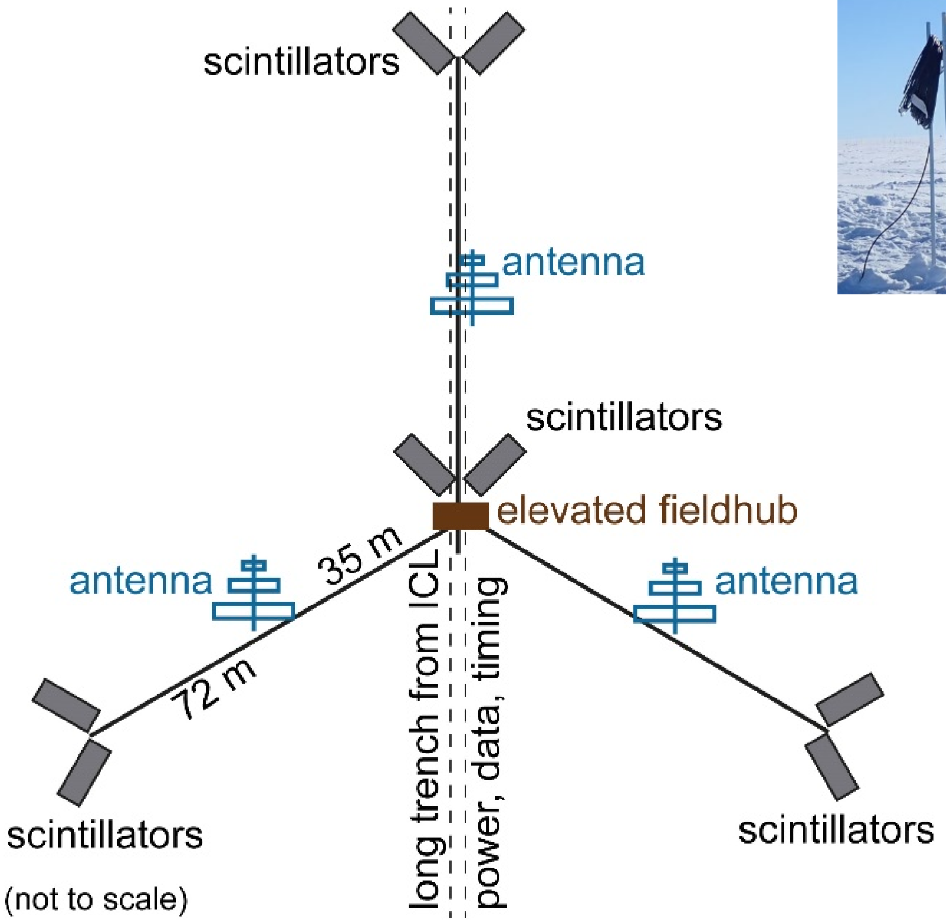
Baseline Design Follows Planned Enhancement of IceTop

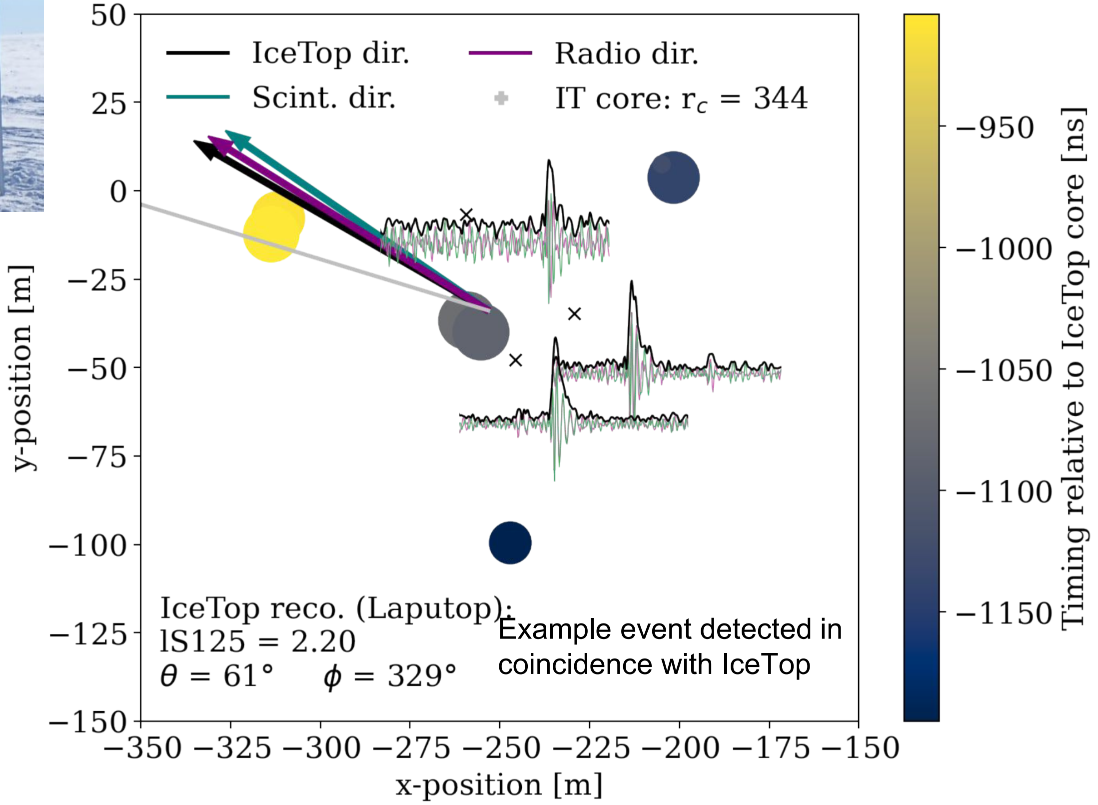
Station Design:

4 pairs of scintillators + 3 antennas



- Complete prototype station since 2020: scintillator + radio + IceTop coincidences

  → **See Delia's talk yesterday**



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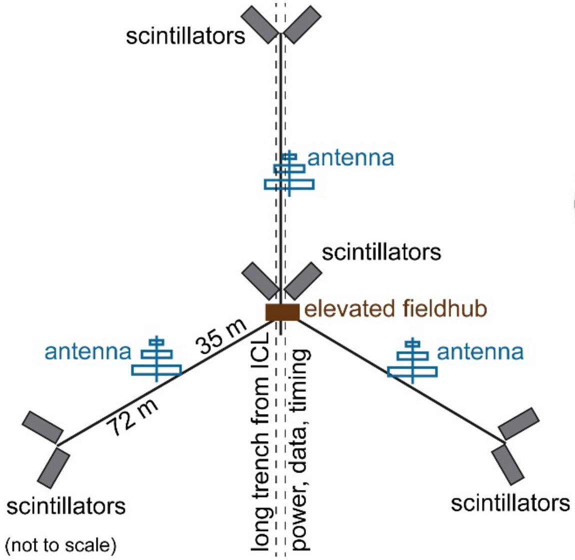
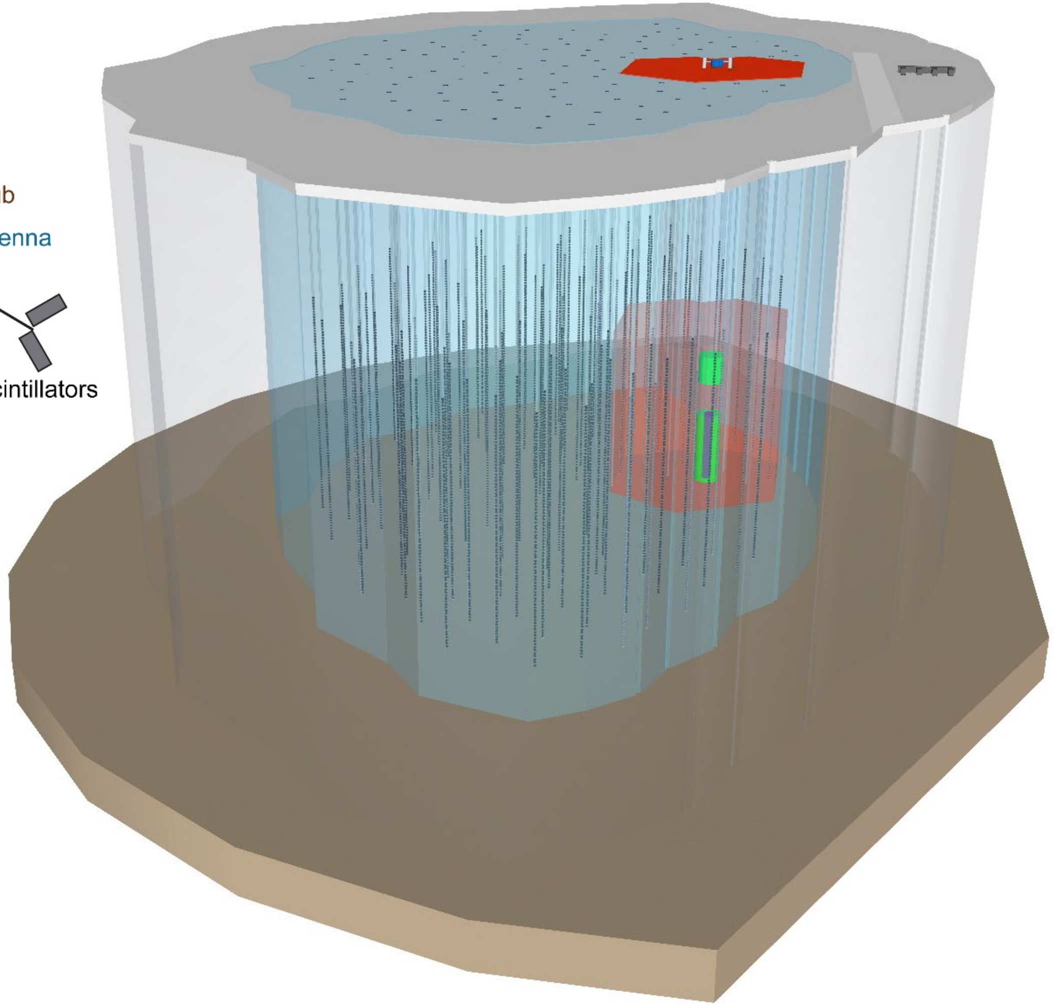
Gen2 Surface Array – Baseline design according to Whitepaper

- Baseline Design
  - 1 station per optical string (122)
  - + fill gaps to Gen1 array
  - + few at in-ice radio stations
- Higher aperture for increase in max. energy and precision
  - 8-10x aperture surface only
  - 30x aperture for coincidences with optical in-ice array
- Under discussion beyond Gen2 Whitepaper (pending justification and review)
  - shallow muon detectors up to 200m
  - IceAct as instrument for low-energy cosmic rays





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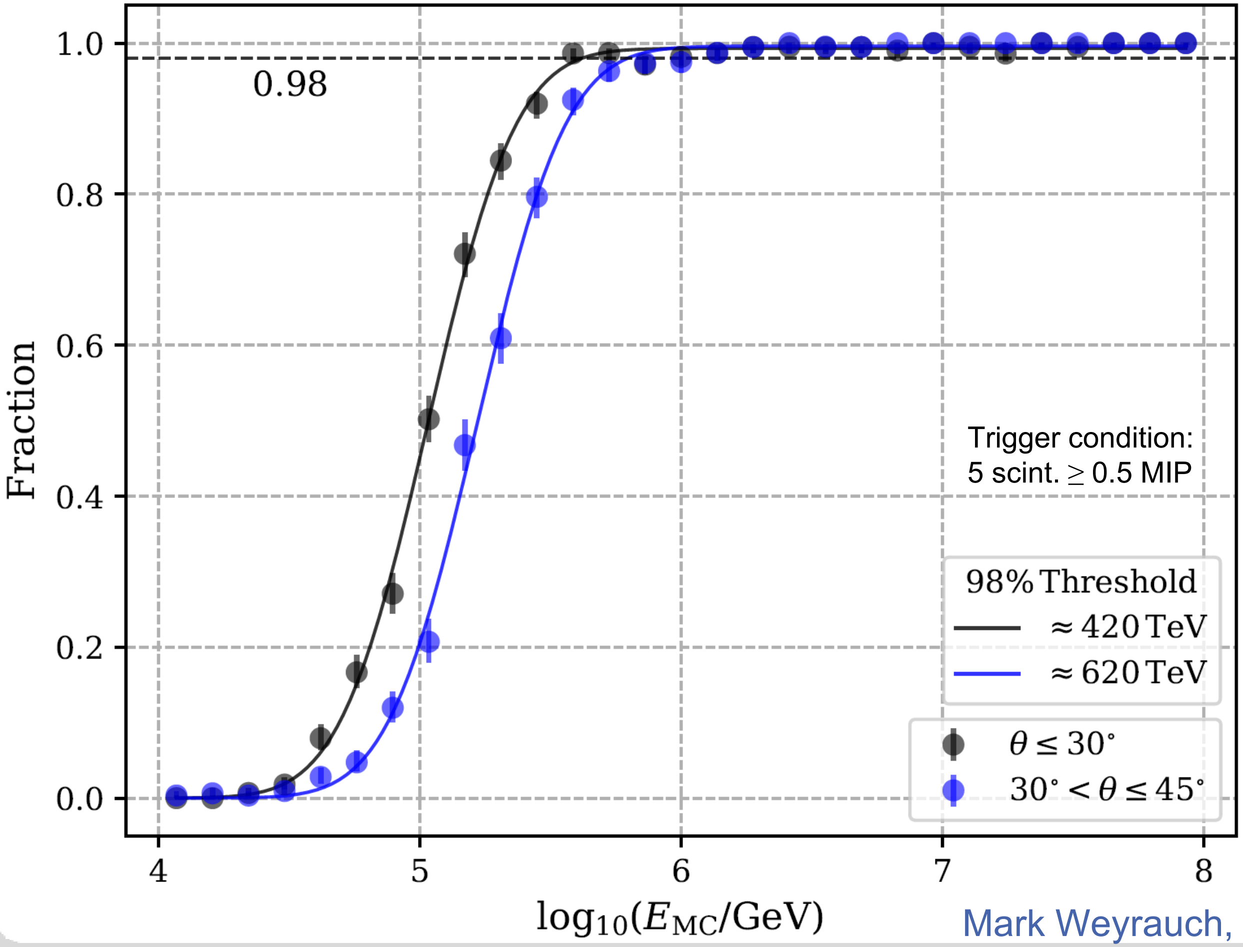
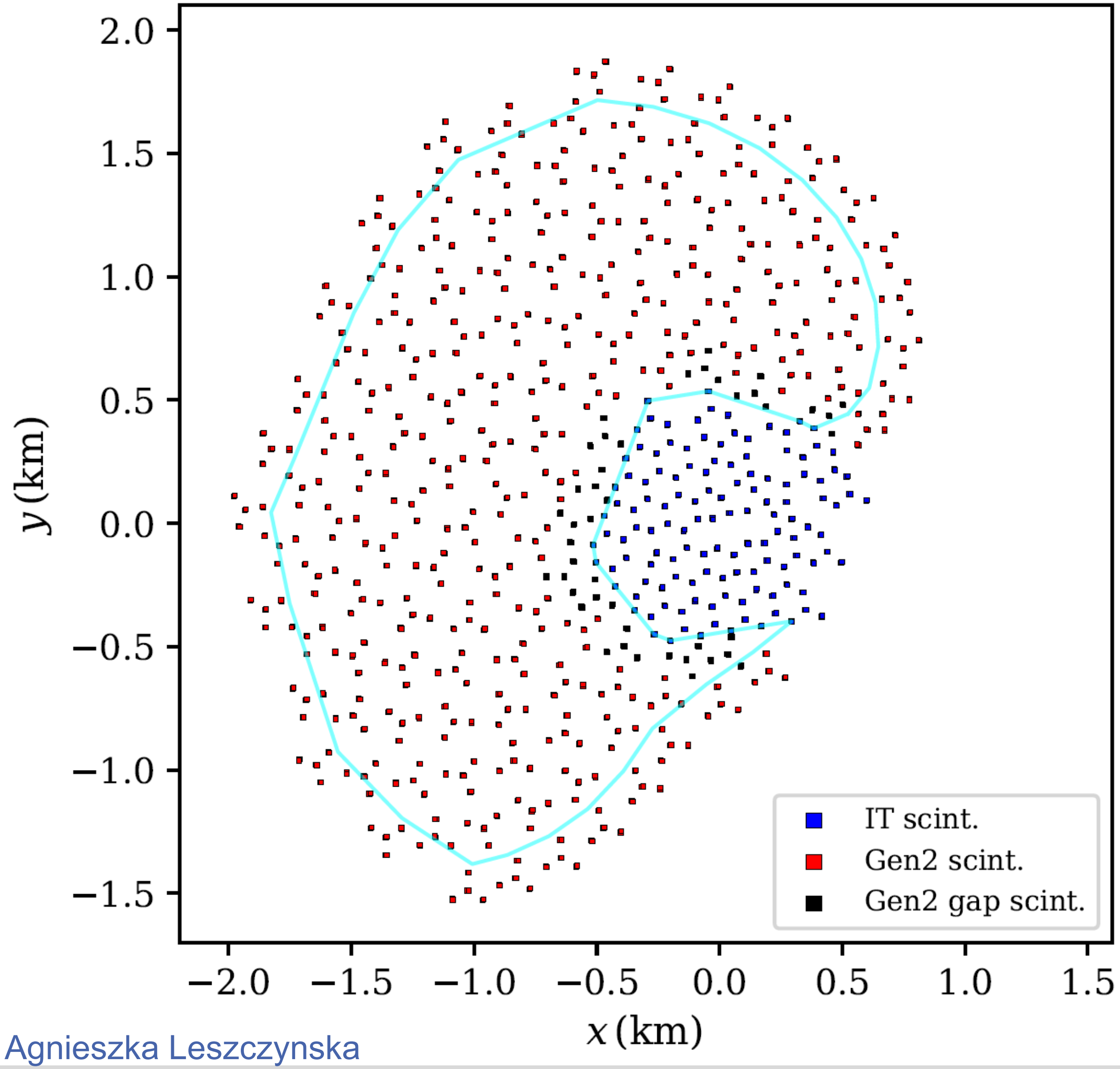
Simulation of Baseline Design

- Low threshold important for veto: expected threshold around 0.5 PeV



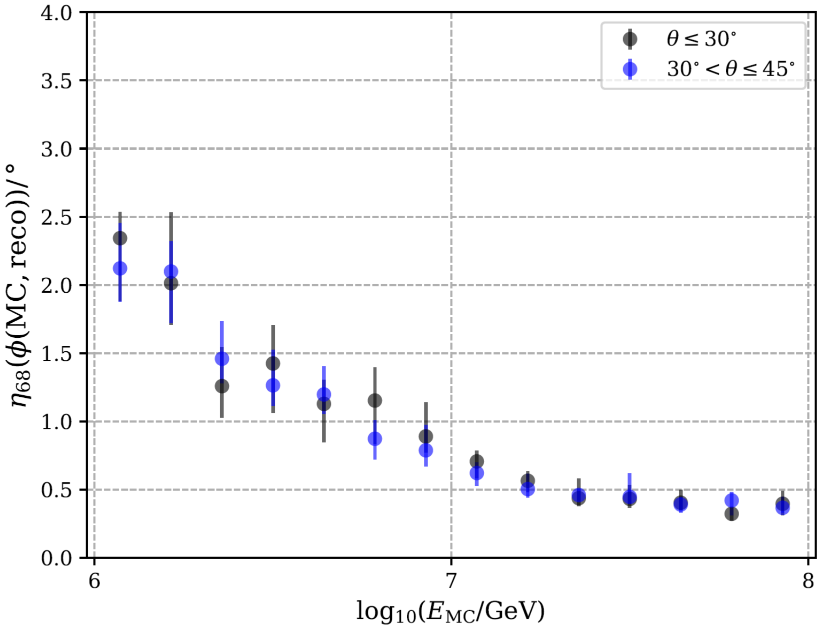


Mark Weyrauch, Agnieszka Leszczynska

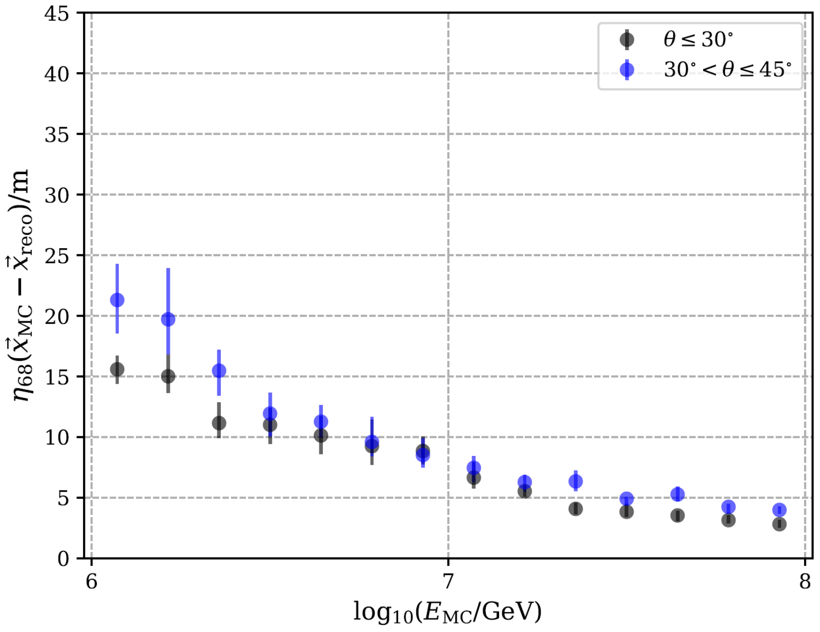
Simulation of Baseline Design

- Reconstruction resolution improves with energy (and with number of detectors)
- Simulation study still ongoing
  - in-ice coincidences: shower at the surface + TeV muons in the ice
  - surface antennas provide calorimetric energy and X_{max} at high energies

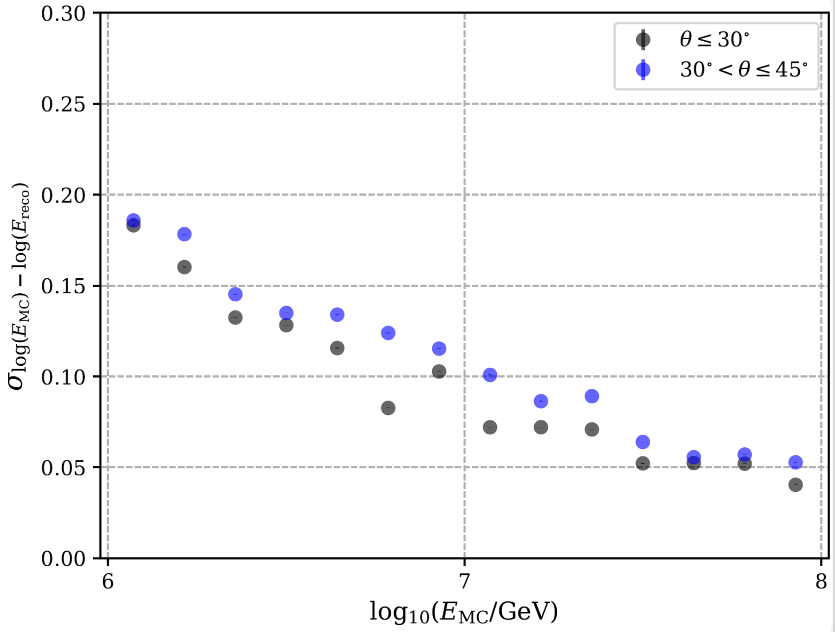
Direction resolution



Core position resolution



Energy resolution (in lg E)



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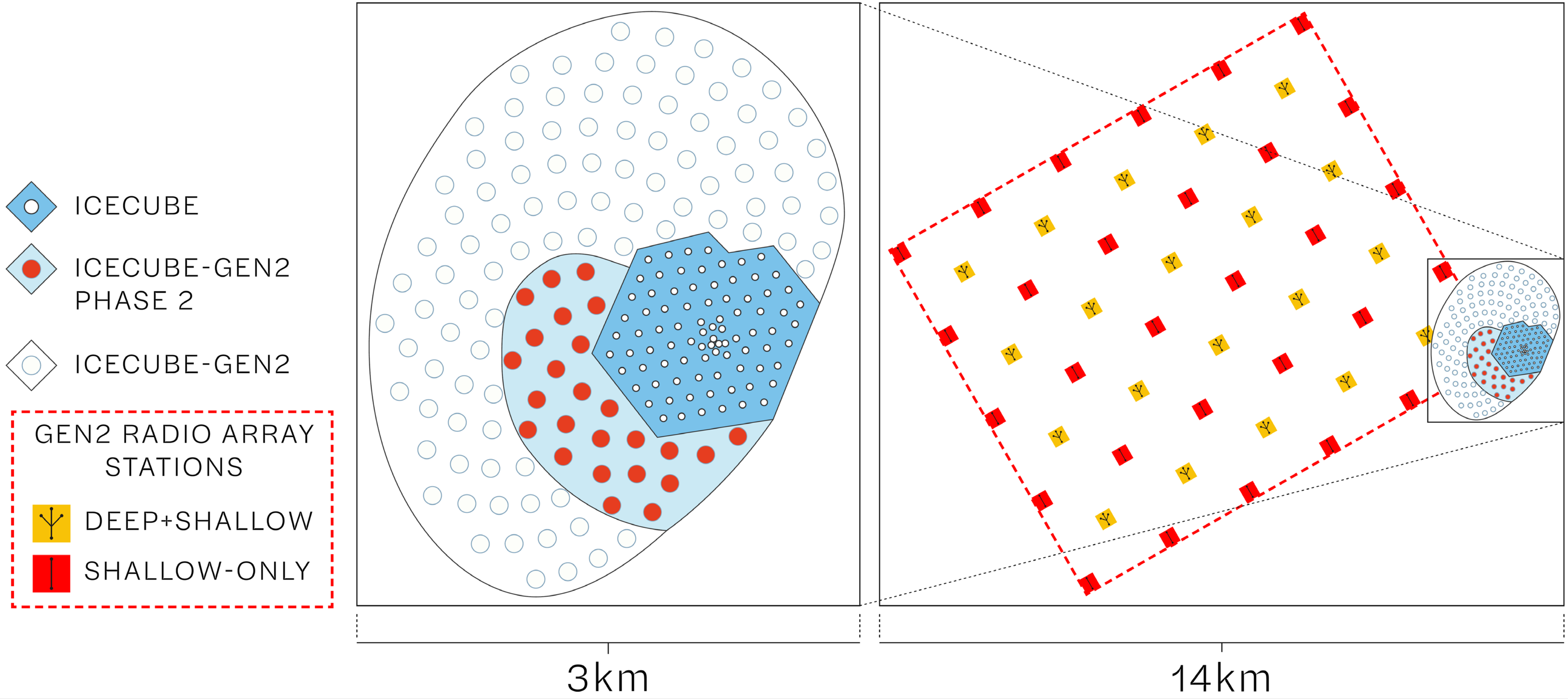
Surface Array in MSRI2 Preproposal Gen2 Phase2 - Layout

- One station of scintillators + antennas per optical string, i.e., per red circle



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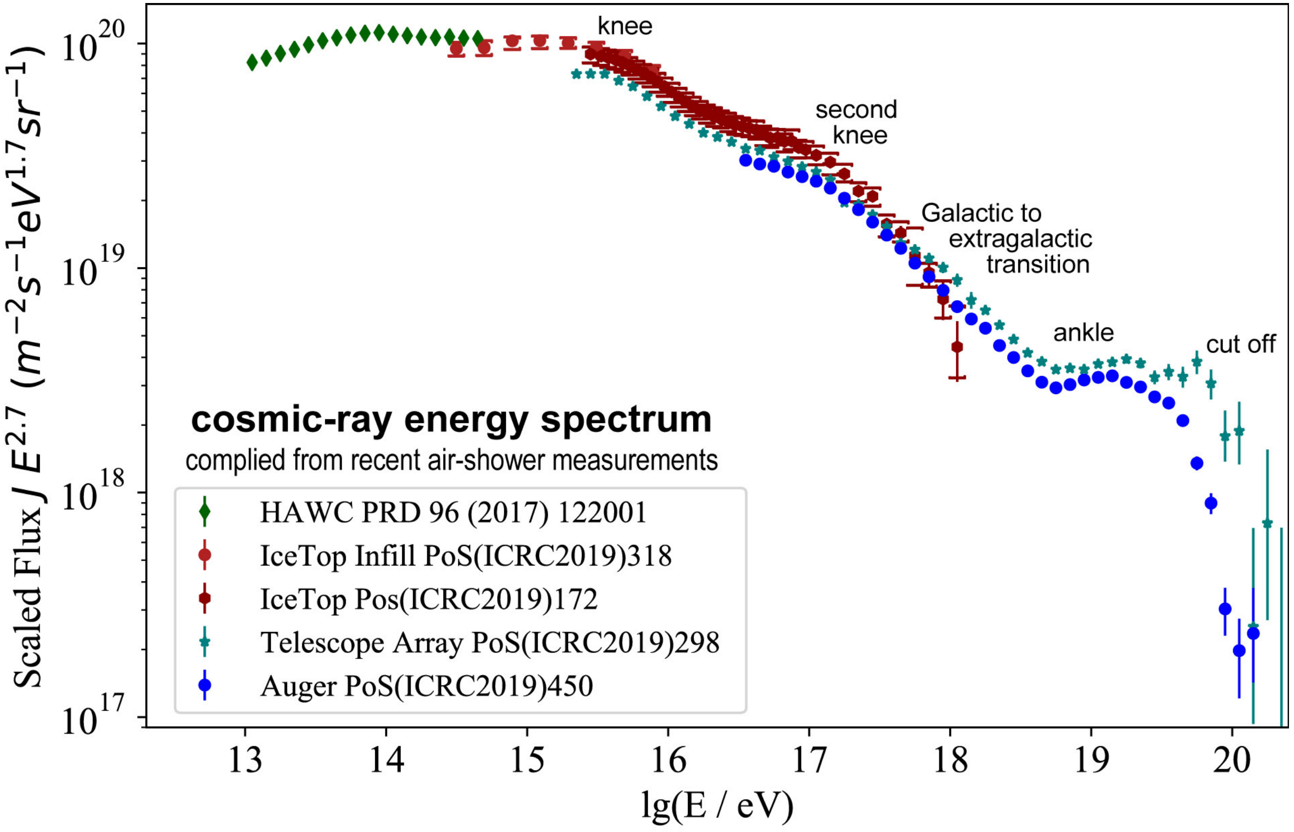
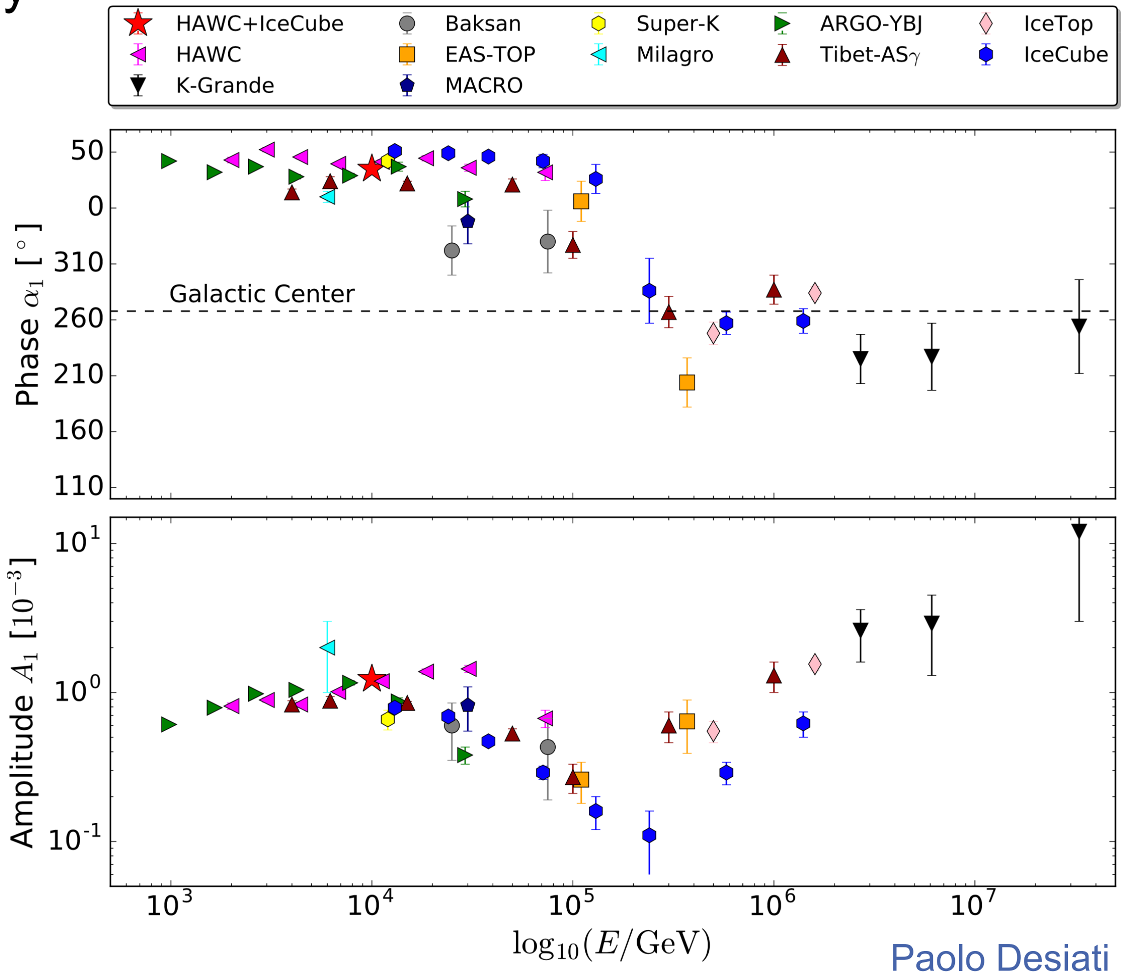
Cosmic-Ray Energy Spectrum and Anisotropy

- Goal: Origin of the most energetic Galactic CR and transition to extragalactic CR
  - energy spectrum, mass composition, anisotropy
  - IceCube will remain a key player in the field





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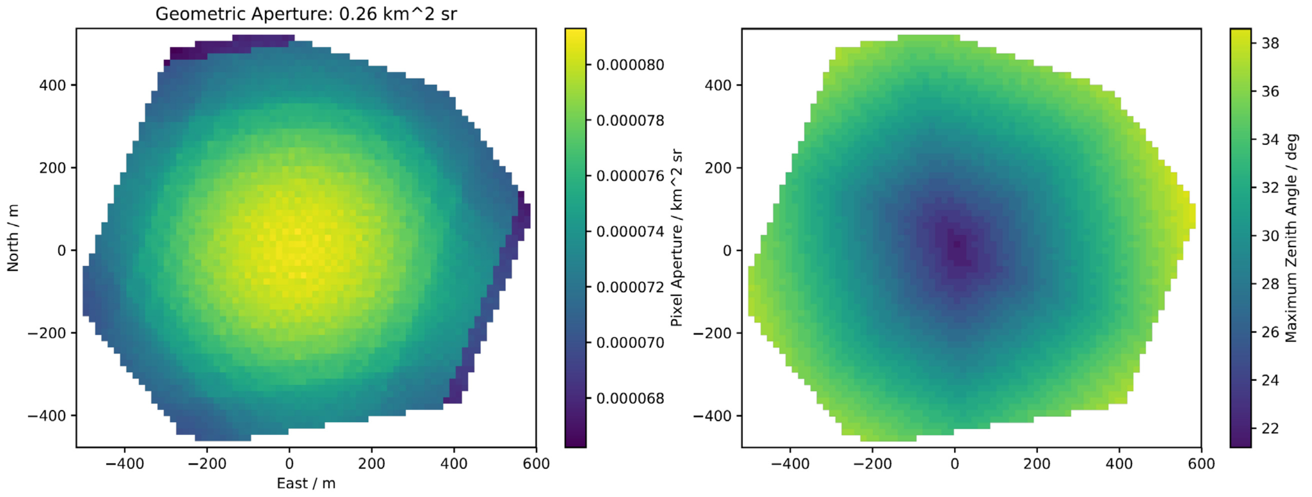
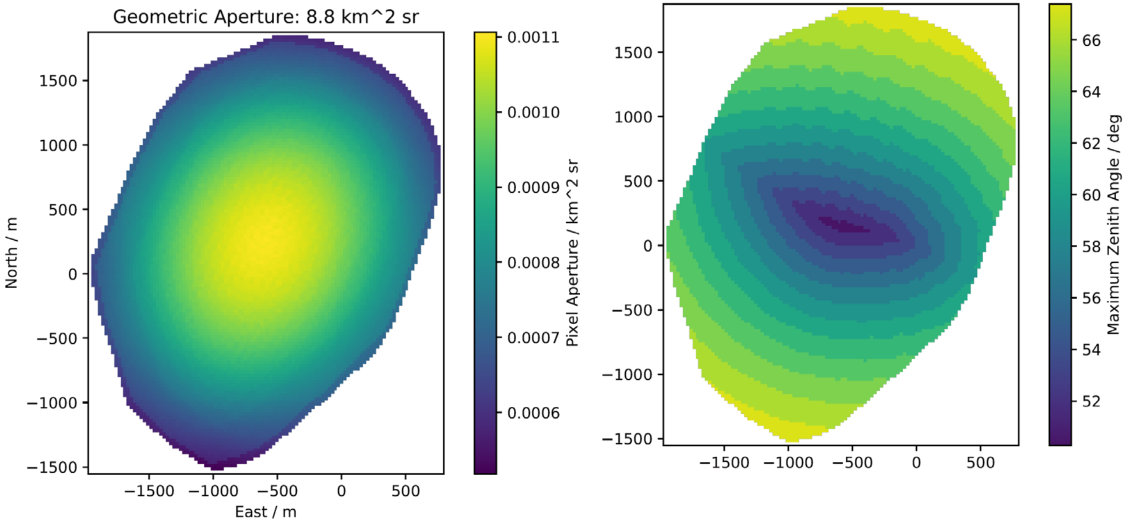
Increase of aperture

- Surface-only aperture 8x larger for contained events,
  10x larger when requiring at least 100m distance from boarder: 0.515 km² → 5.22 km²
- Aperture for in-ice coincidences (2d hull of scintillators, 3d hull of strings)
  34x larger: 0.26 km² sr → 8.8 km² sr
- All apertures valid above full-efficiency threshold

Enhanced IceTop



Gen2 Surface Array



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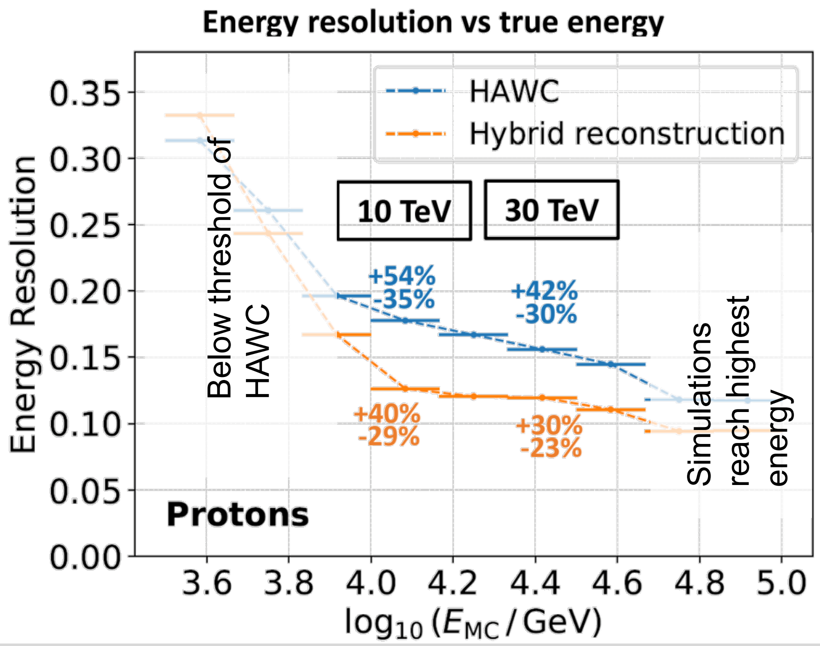
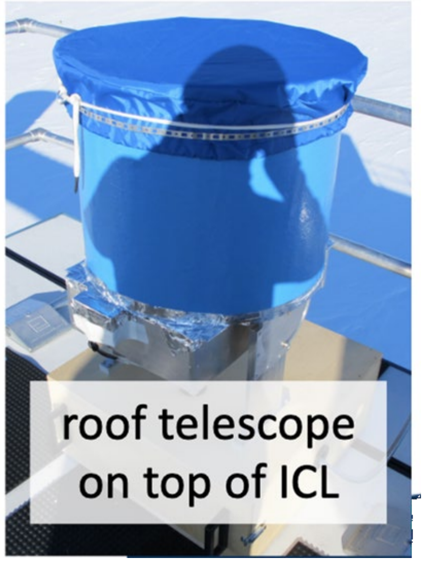
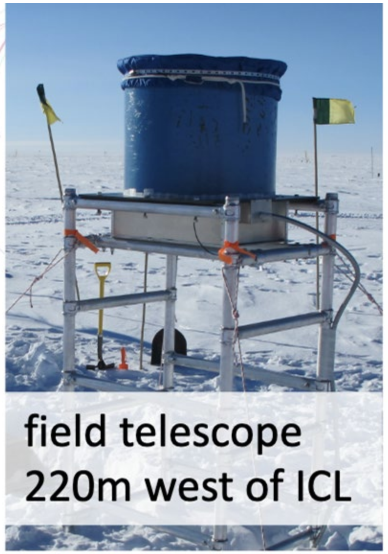
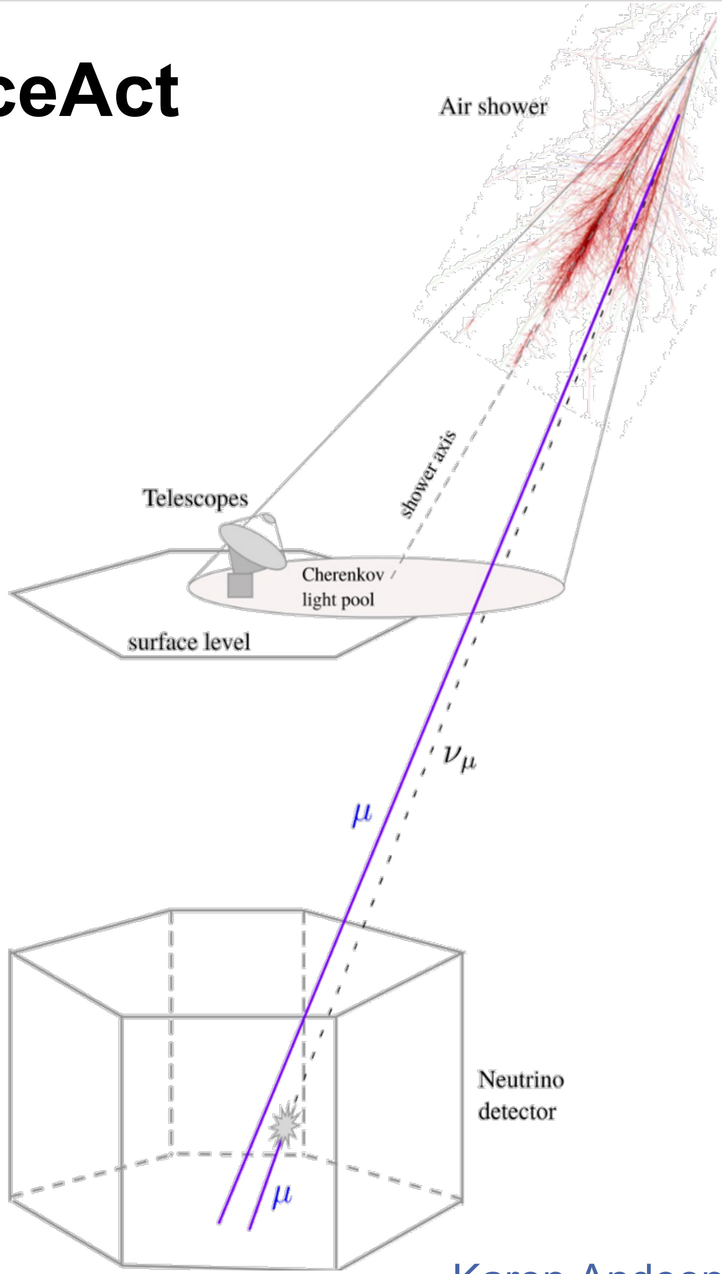
Proposal 1 to extend design of Surface Array: IceAct

- IceAct can contribute to and extend the science case of the Gen2 surface array
  - depends on number of telescopes and configuration of array
- Lower energy threshold than other surface detectors
  - energy spectrum, mass composition, coincidences with in-ice array starting at 10 TeV









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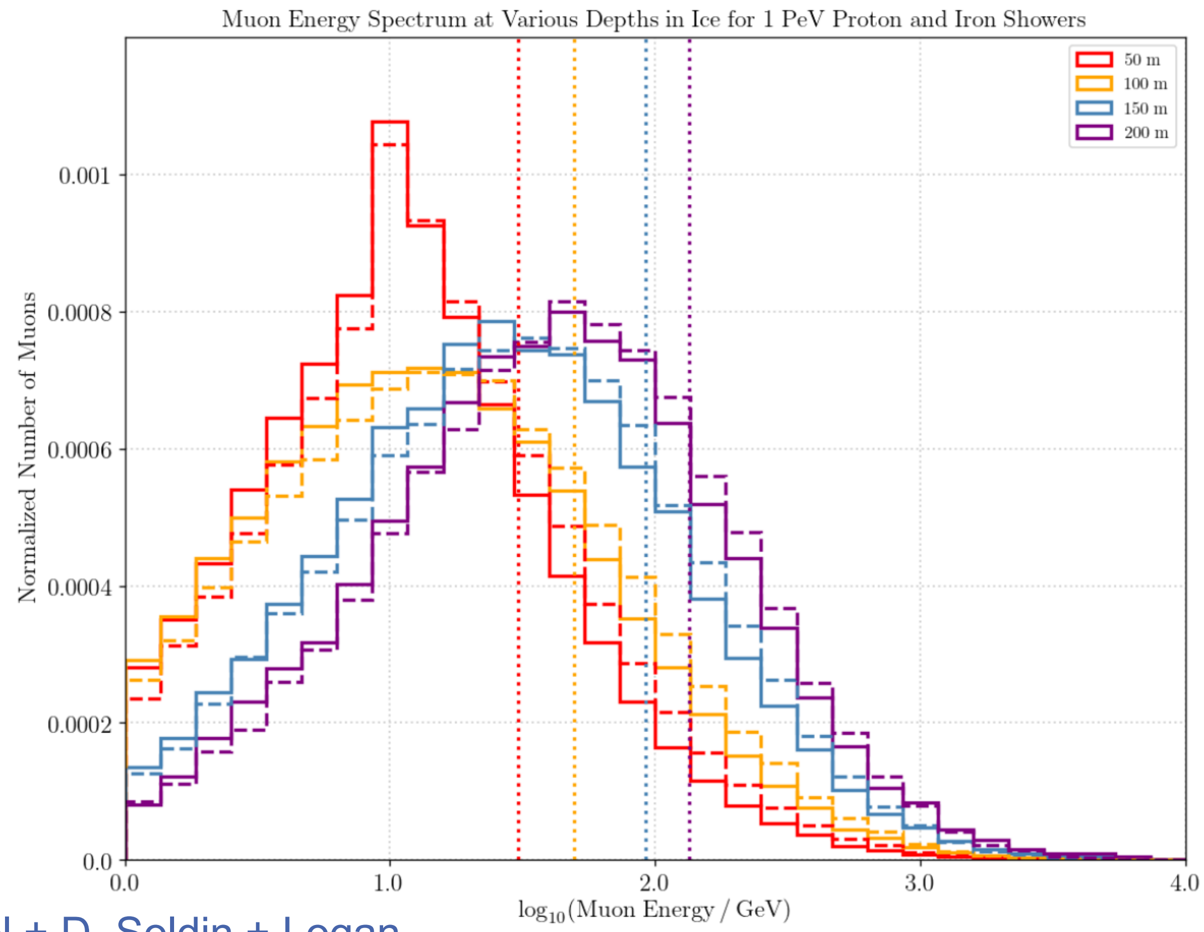
Proposal 2 to extend the baseline design: Buried muon detectors

- Muon spectroscopy would be enabled by dedicated muon detectors at different depths, e.g., between 50-200 m below the surface

- Under investigation
  - Additional gain in science needs to be quantified
  - What type of detectors?
  - How many?
  - How expensive?

- Need to discuss how this could fit into the schedule for phase 2 or phase 3; or additional add-on possible?



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