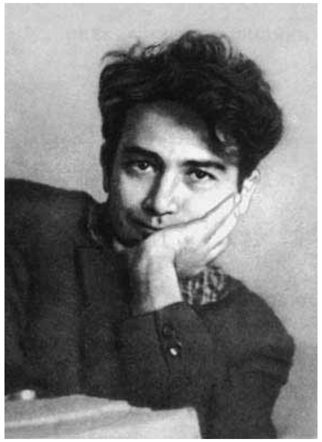
End to end calibration of the ARA detector

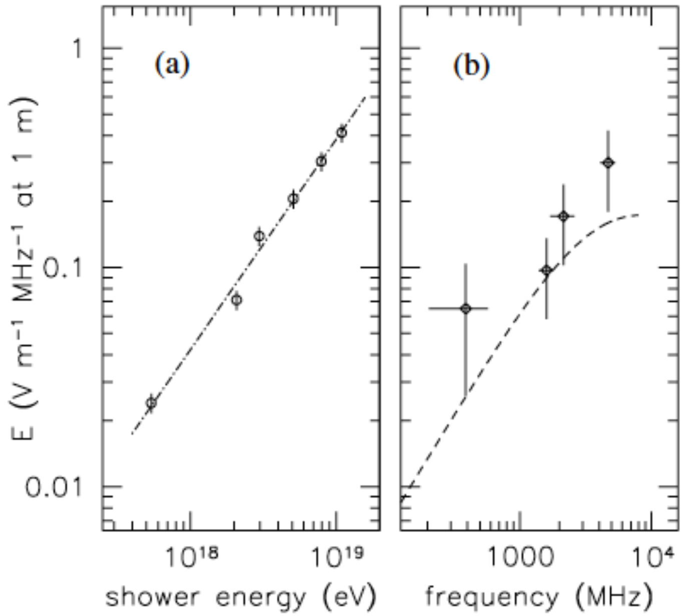
K. Mase, Chiba Univ.
for the ARA collaboration

Radio wave through Askaryan effect

- 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation) → **Askaryan effect**
- 2000: Attempt to measure Askaryan effect with Argonne Wakefield Accelerator (AWA) (P. W. Gorham et al., PRE 62, 6 (2000))
- 2001: **First experimental detection of Askaryan effect** at SLAC with silica sand (D. Saltzberg et al., PRL 86, 13 (2001))
- 2005: Observation of Askaryan effect in rock salt at SLAC (P. W. Gorham et al., PRD 72, 023002 (2005))
- 2007: Observation of Askaryan effect in ice at SLAC (P. W. Gorham et al., PRL 99, 171101 (2007))
- We will measure the Askaryan radio wave using the Telescope Array (TA) LINAC and use it for end-to-end calibration of the ARA detector



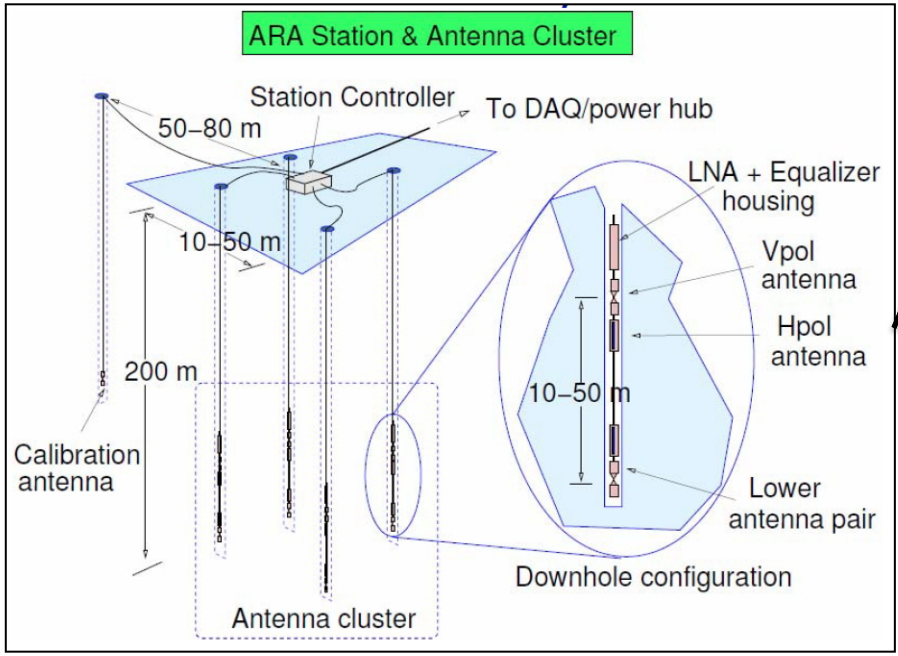
G. Askaryan

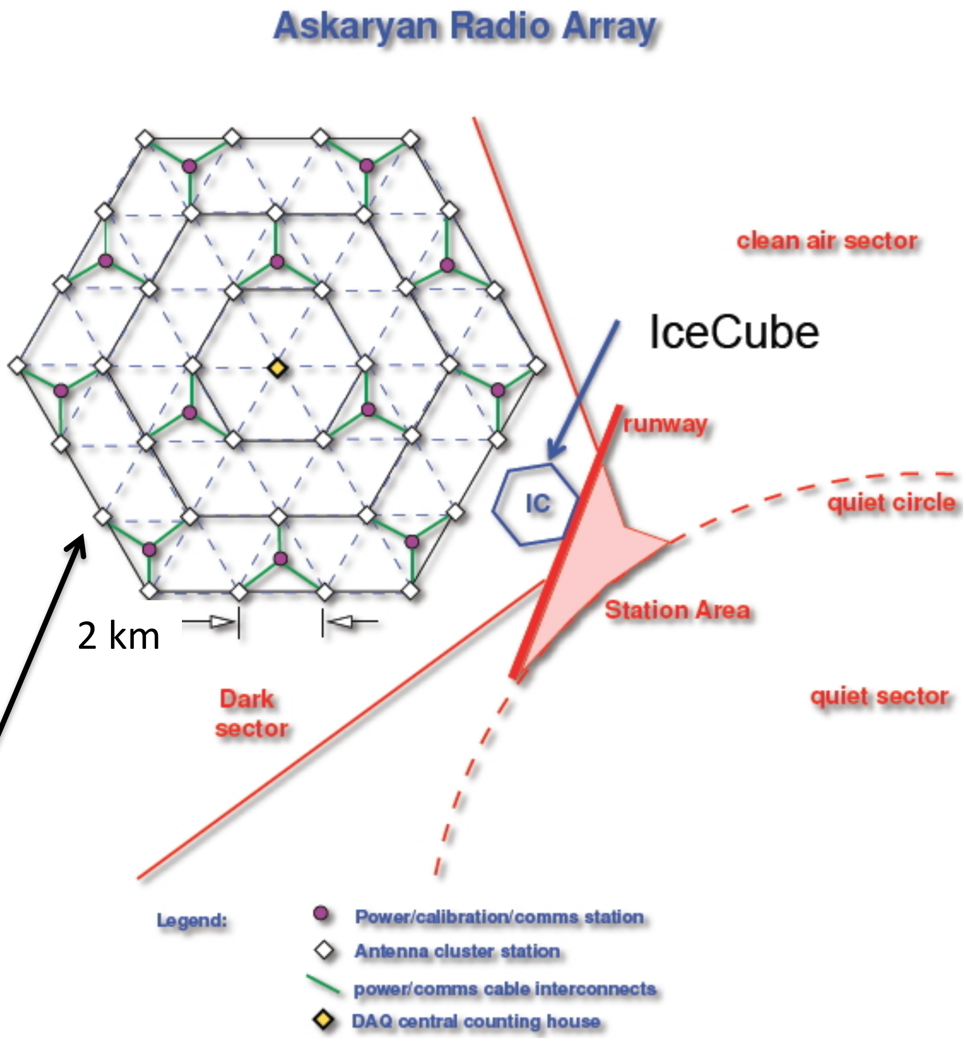


D. Saltzberg et al., PRL 86, 13 (2001)

Askaryan Radio Array (ARA)

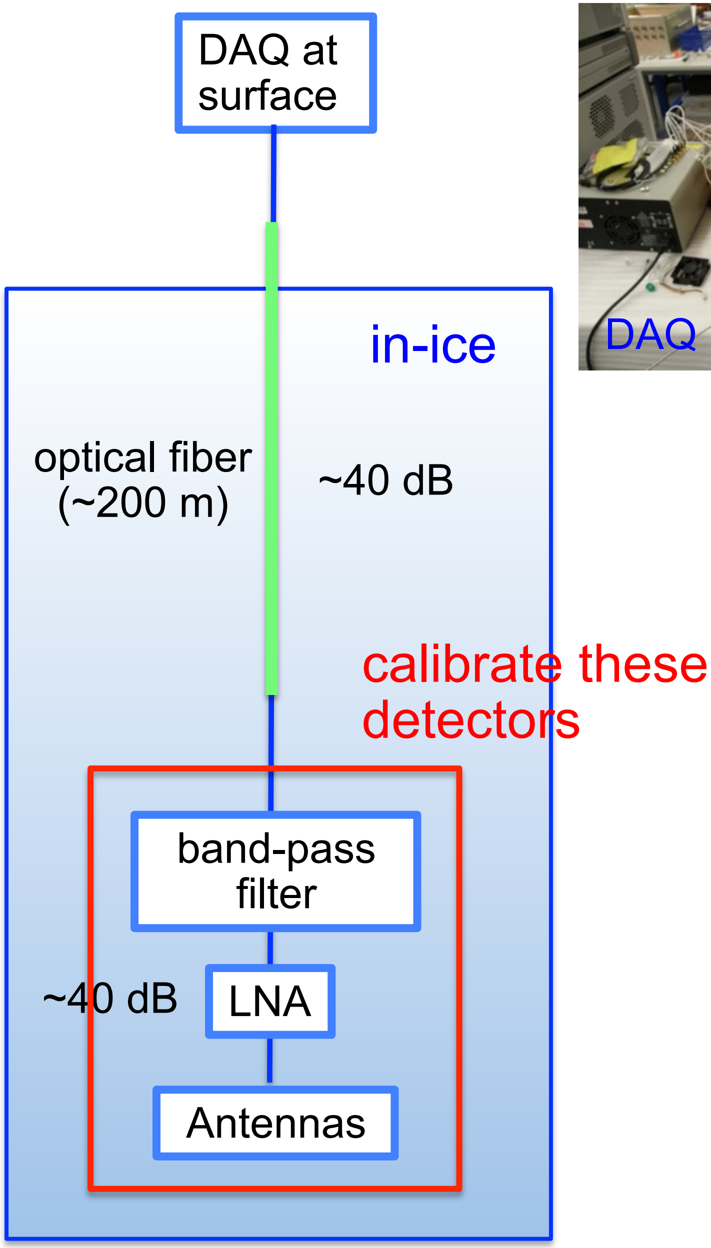
- Designed to observes high energy neutrinos above 100 PeV
- 37 stations (3 stations deployed so far)
- Each station has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (~200–800 MHz)
- Total surface area ~100 km^2

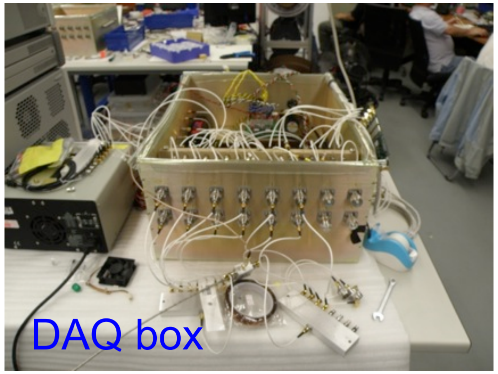


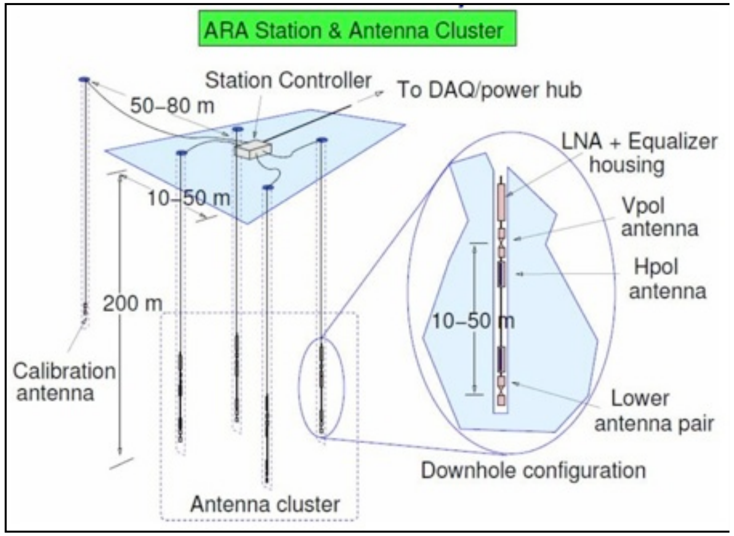


Astroparticle Physics **35** (2012) 457–477

The ARA system







V-pol antenna

Bicone

150-850 MHz

H-pol antenna

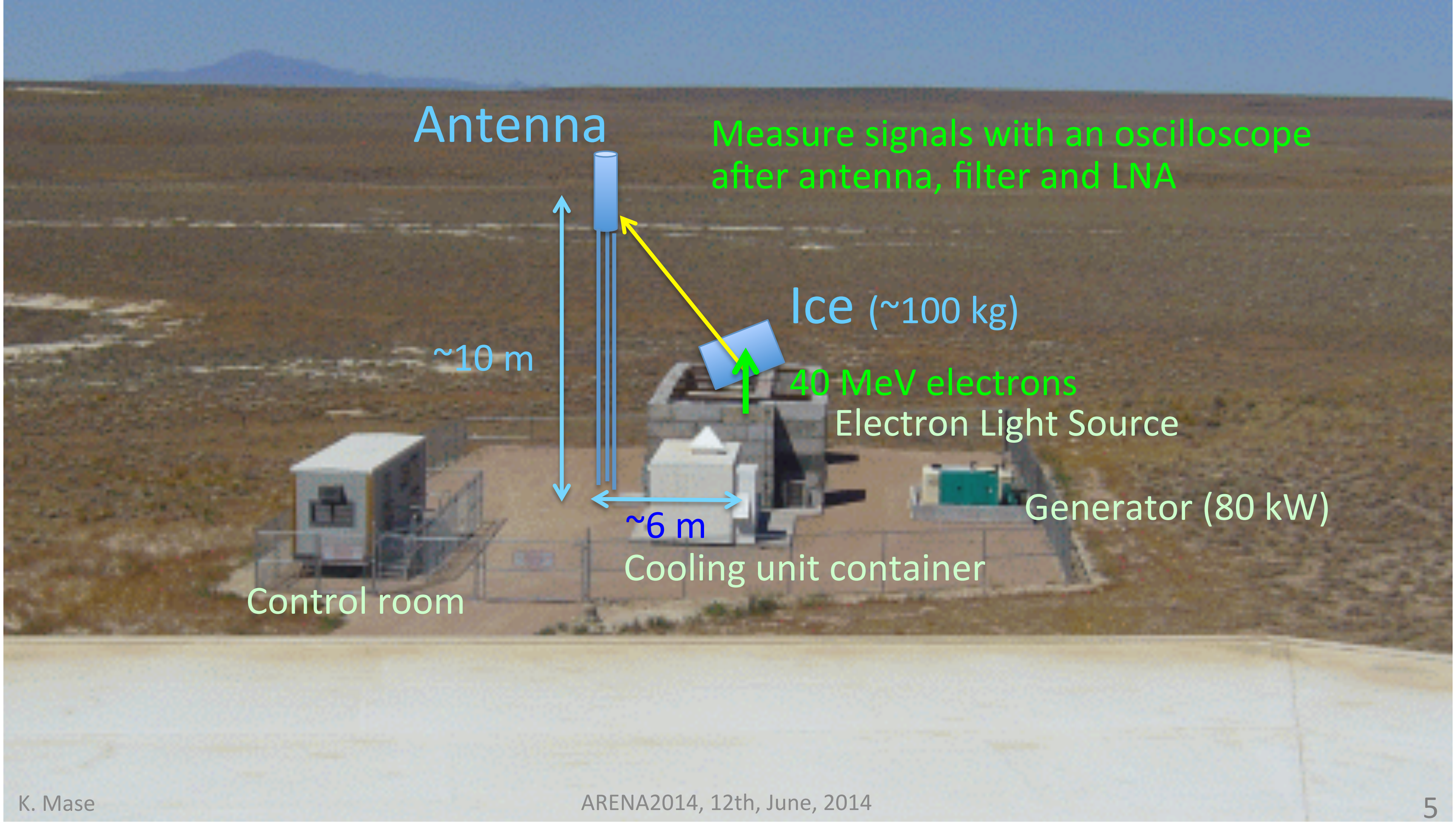
Quad-slot cylinder

200-850 MHz

Gain similar to dipole (+2 dBi)

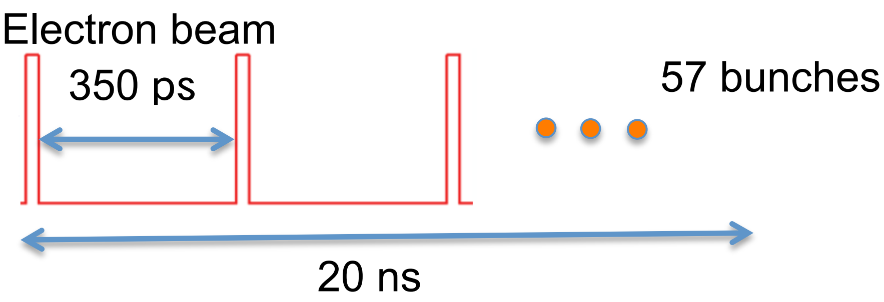
■ End to end calibration with the TA LINAC

LINAC at Telescope Array (TA) site @Utah

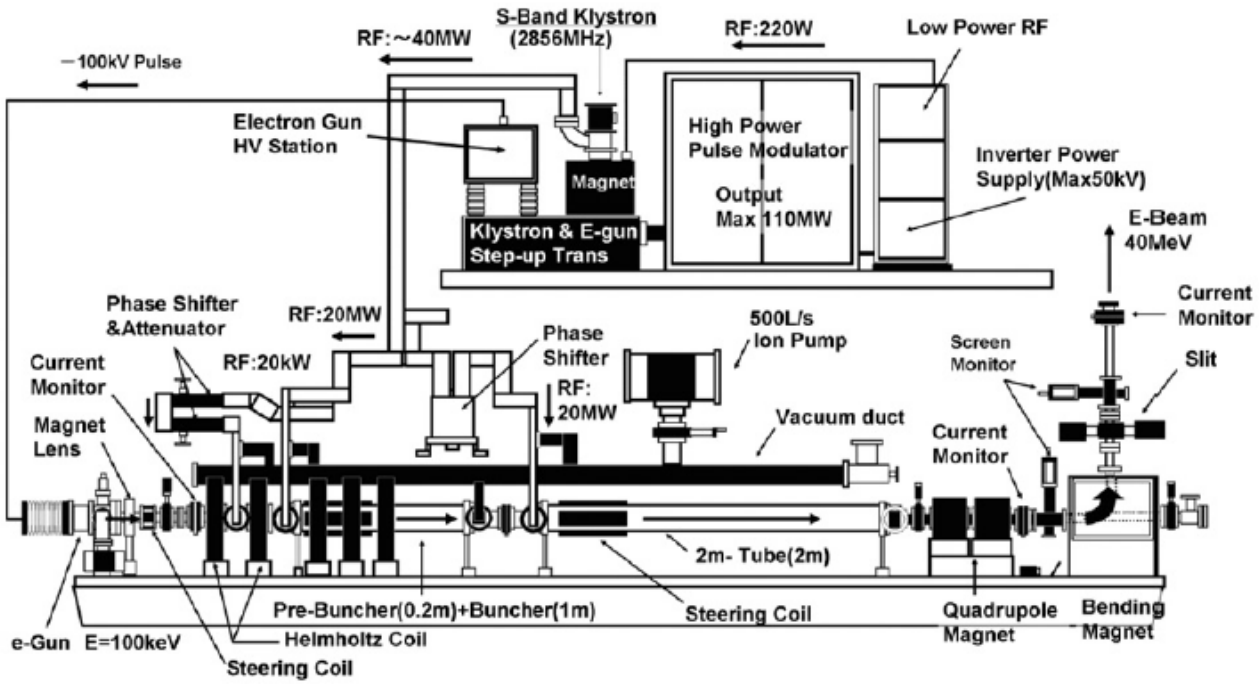


TA LINAC

- ✓ 40 MeV electron beam
- ✓ Maximum electron number per bunch: 10^9
- ✓ Pulse frequency: 2.86 GHz
  → pulse interval: 350 ps
- ✓ Bunch duration is 20 ns
- ✓ Output beam width: 7 mm
- ✓ Trigger signal available

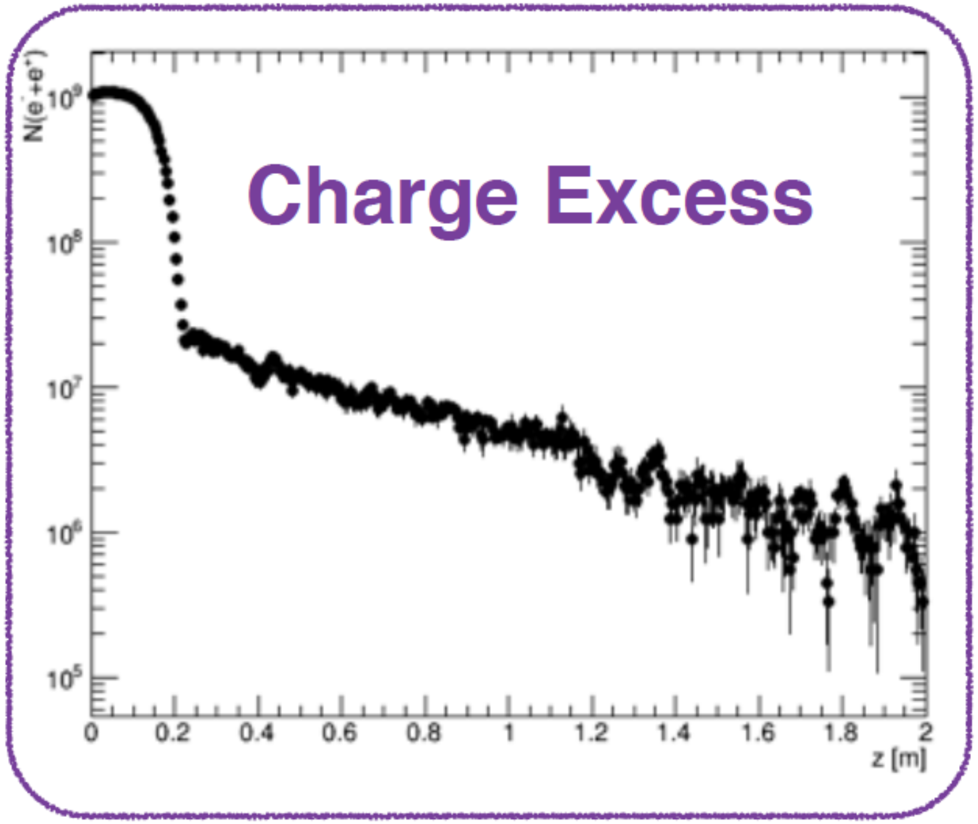


T. Shibata et al., NIMA 597 (2008) 61



Electron charge excess distribution

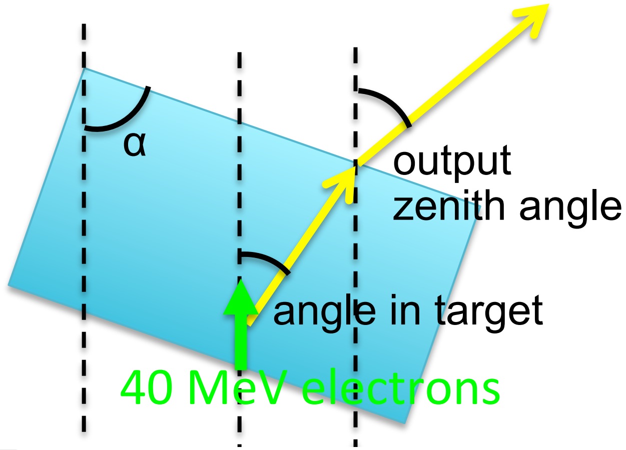
- ✓ Simulated with GEANT4
- ✓ 10^9 40 MeV electrons
- ✓ Medium is ice
- ✓ Most of particles stop in 20 cm in ice
- ✓ Compton scattered electrons above 20 cm by gammas produced through Bremsstrahlung (a few percent)



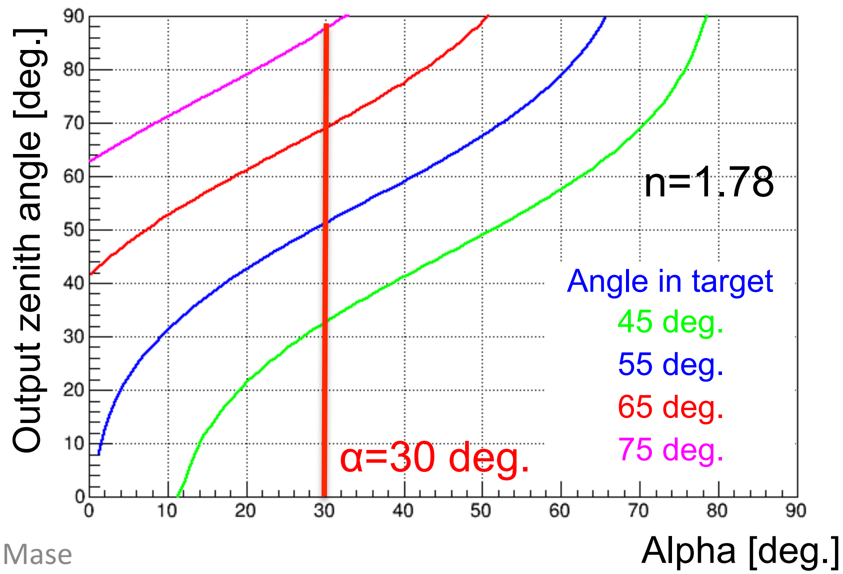
Angular distribution and the target structure

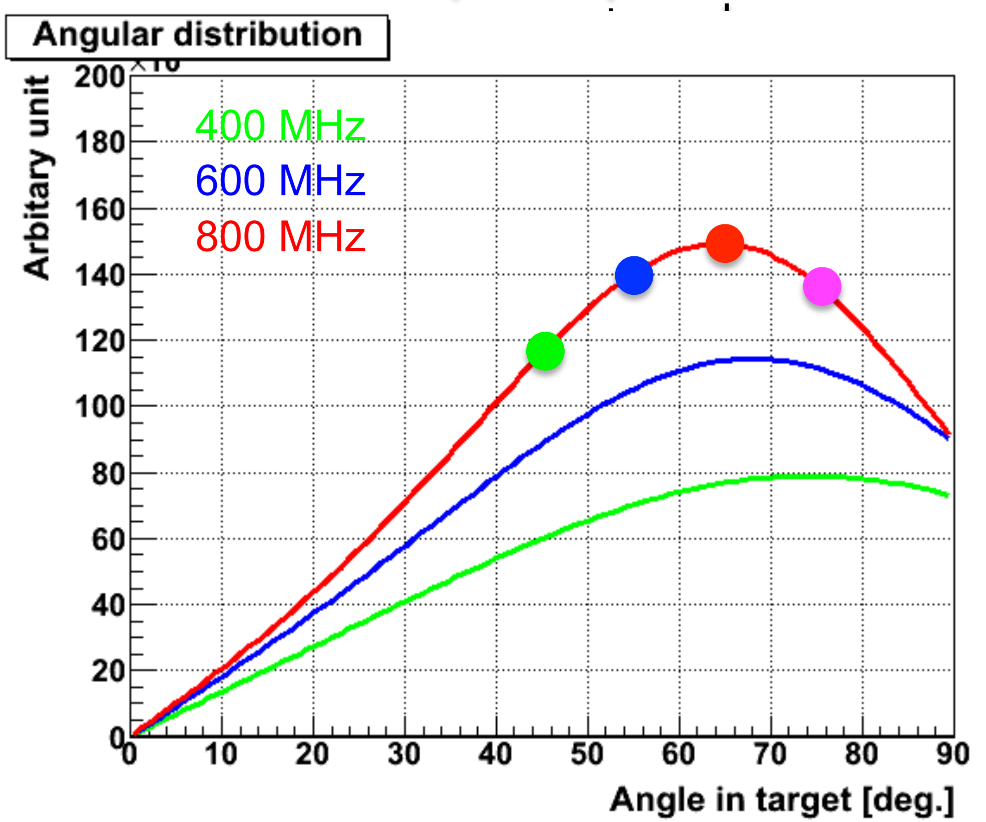
PRD 72, 023002 (2005)

$$\left|R\vec{E}(f)\right| = \sqrt{2\pi}\,\mu\mu_0 QLf \sin\theta e^{-(kL)^2(\cos\theta - 1/n)^2/2}$$

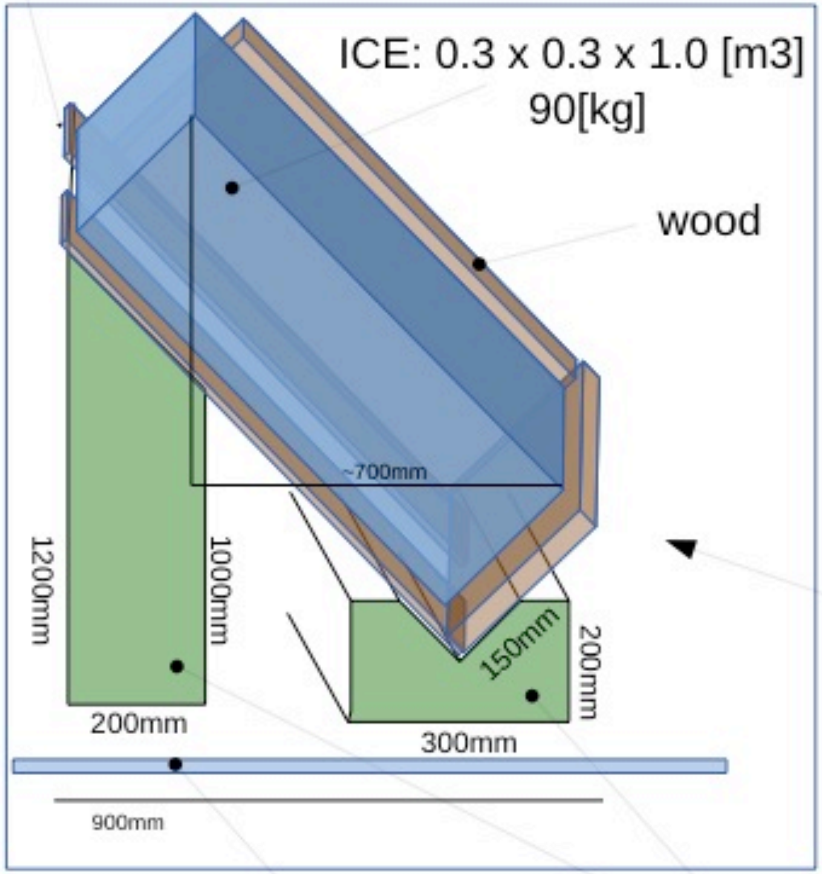


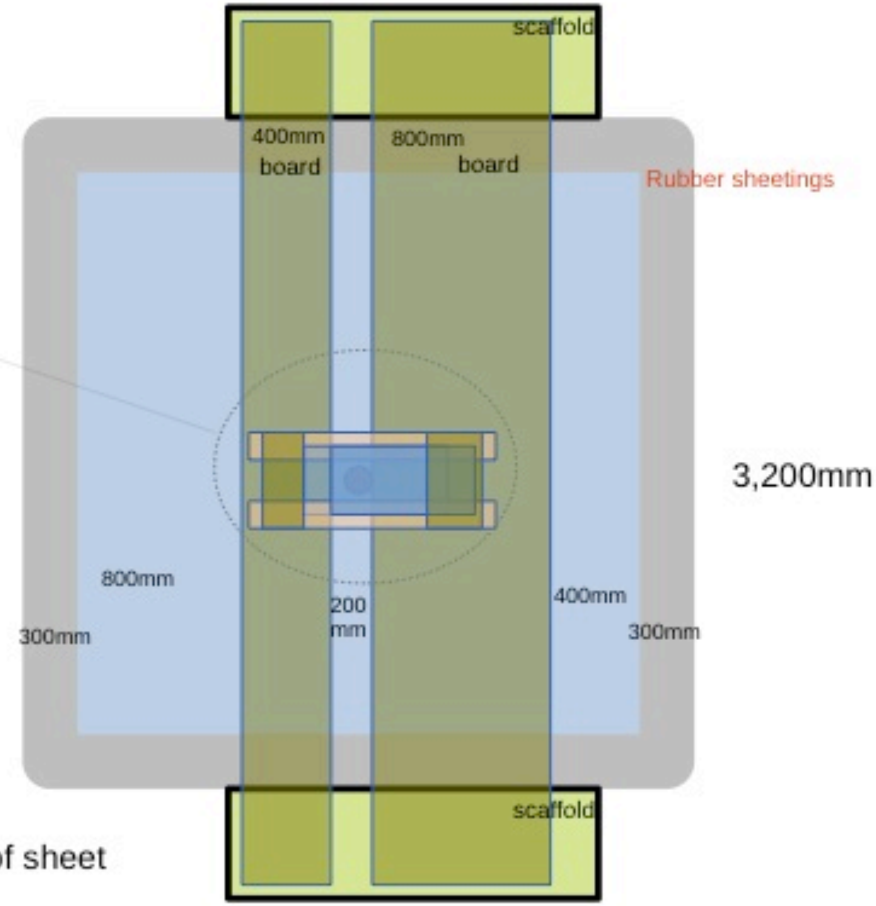
- ✓ Rough estimation with a Gaussian of L = 6.8 cm
- ✓ Angular distribution is wide due to short electron charge excess distribution
- ✓ Peak is not Cherenkov angle (56 deg.), but shifted due to the sin(θ) term (effective shower length)
- ✓ Precise MC will be followed





The support for the ICE at TA-LINAC

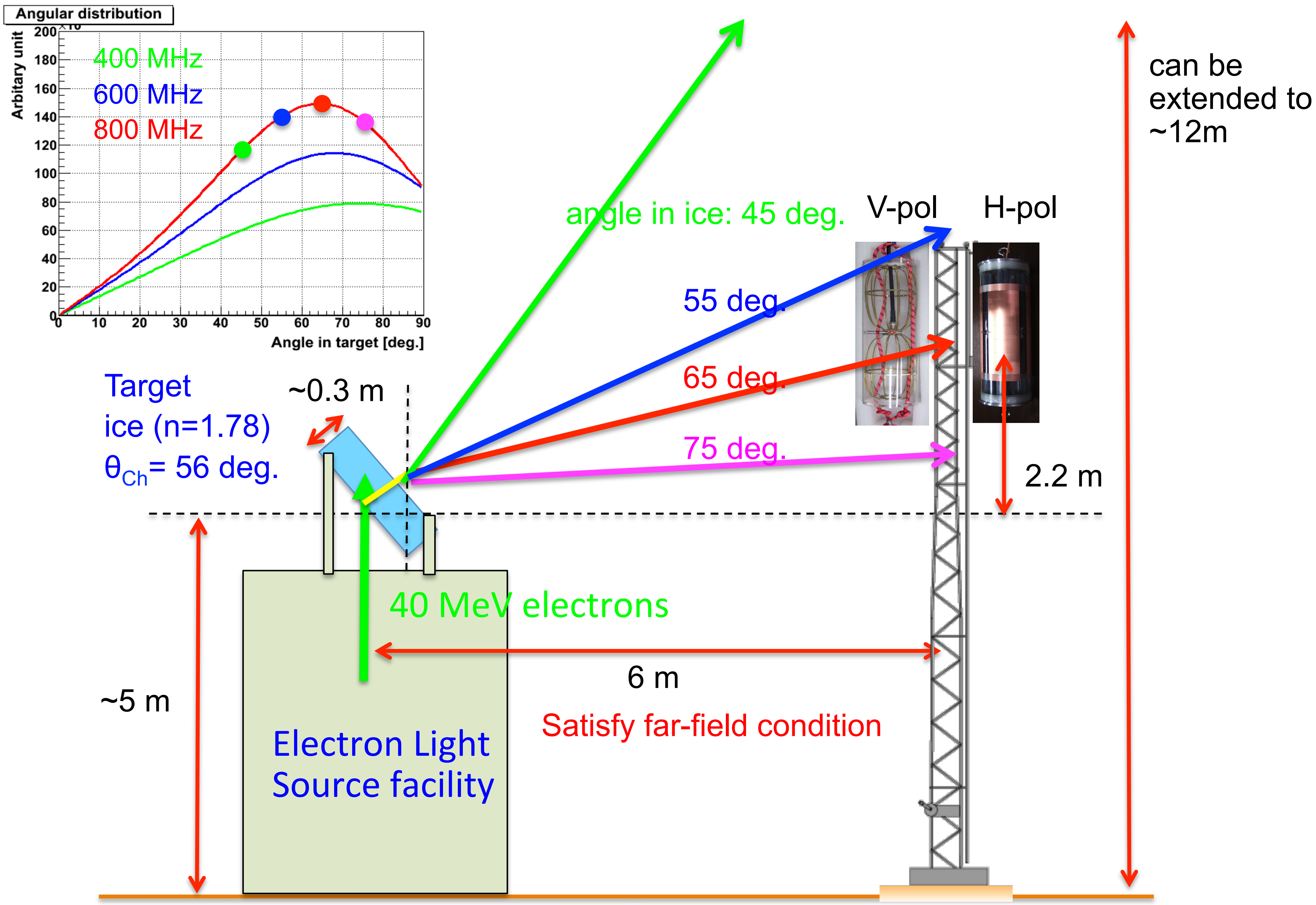




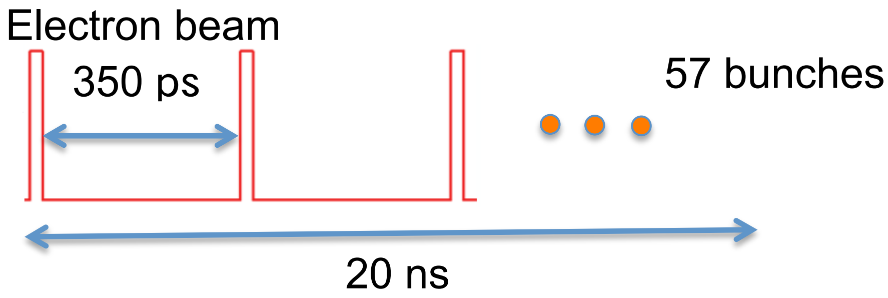
wood

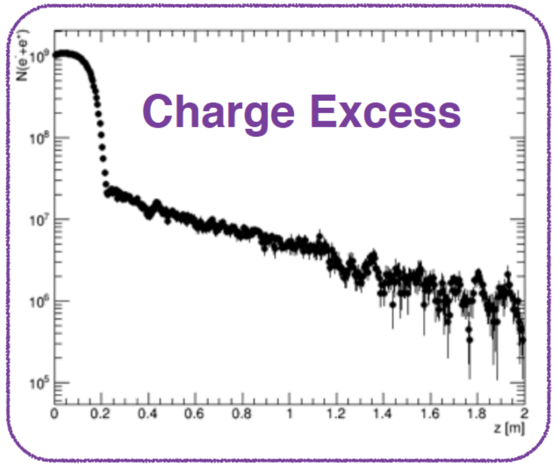
a sheet to prevent leakage
Rubber or acrylic plate or just a blue tarpaulin type of sheet

Antenna support structure



Expected electric field

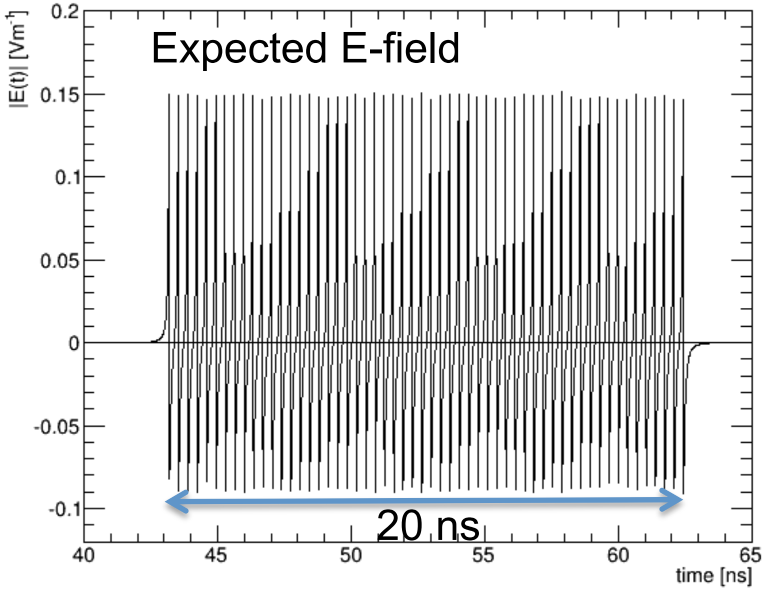


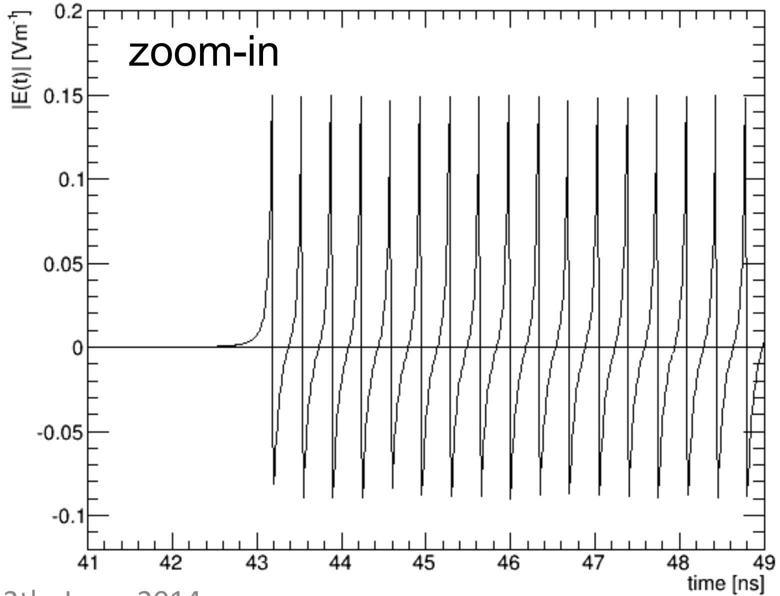


Calculate E-filed according to Jaime's prescription (the Form factor)

$$\vec{A}(\theta,t) = \frac{\mu}{4\pi R}\sin\theta\hat{p}\int_{-\infty}^{\infty} dz' Q(z') F_p\left(t - \frac{nR}{c} - z'\left[\frac{1}{v} - \frac{n\cos\theta}{c}\right]\right)$$

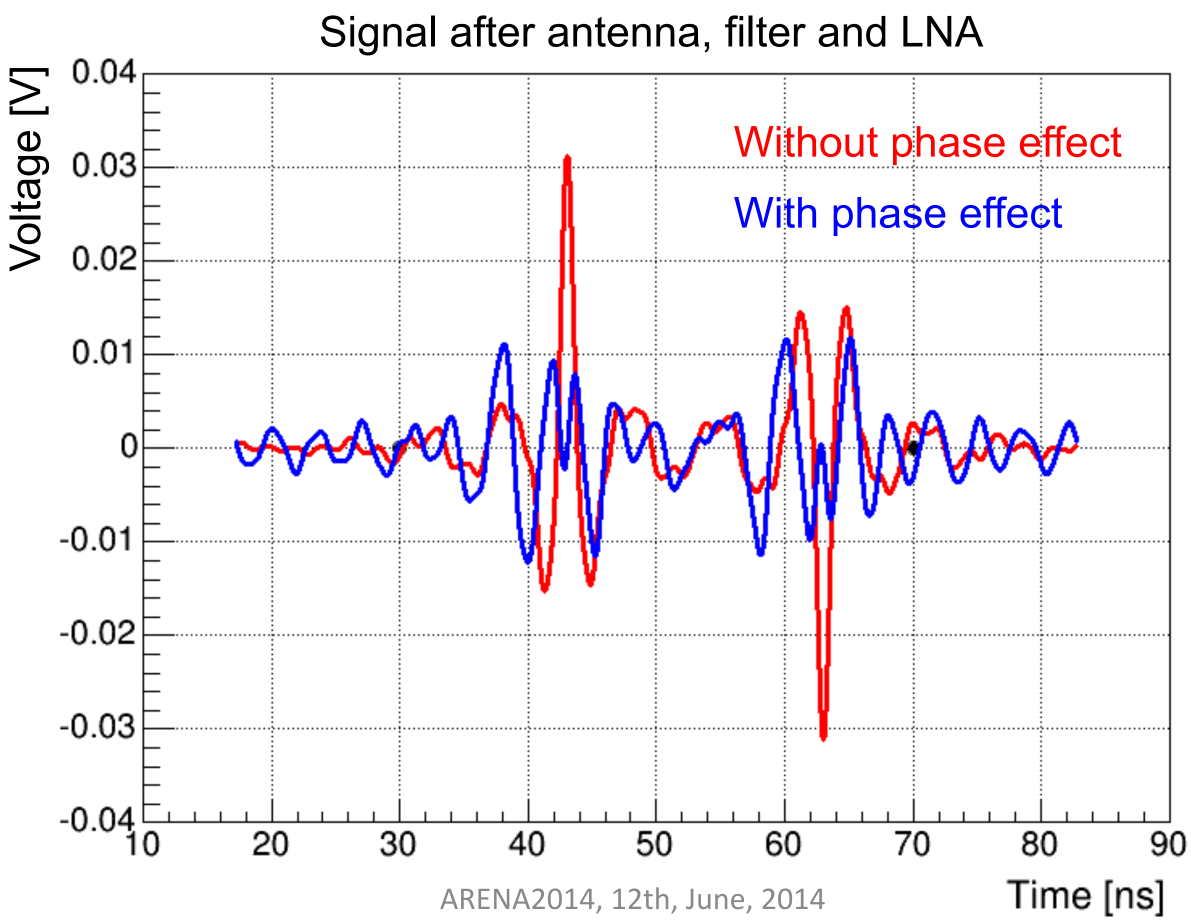
Jaime et al., PRD, 84, 103003 (2011)





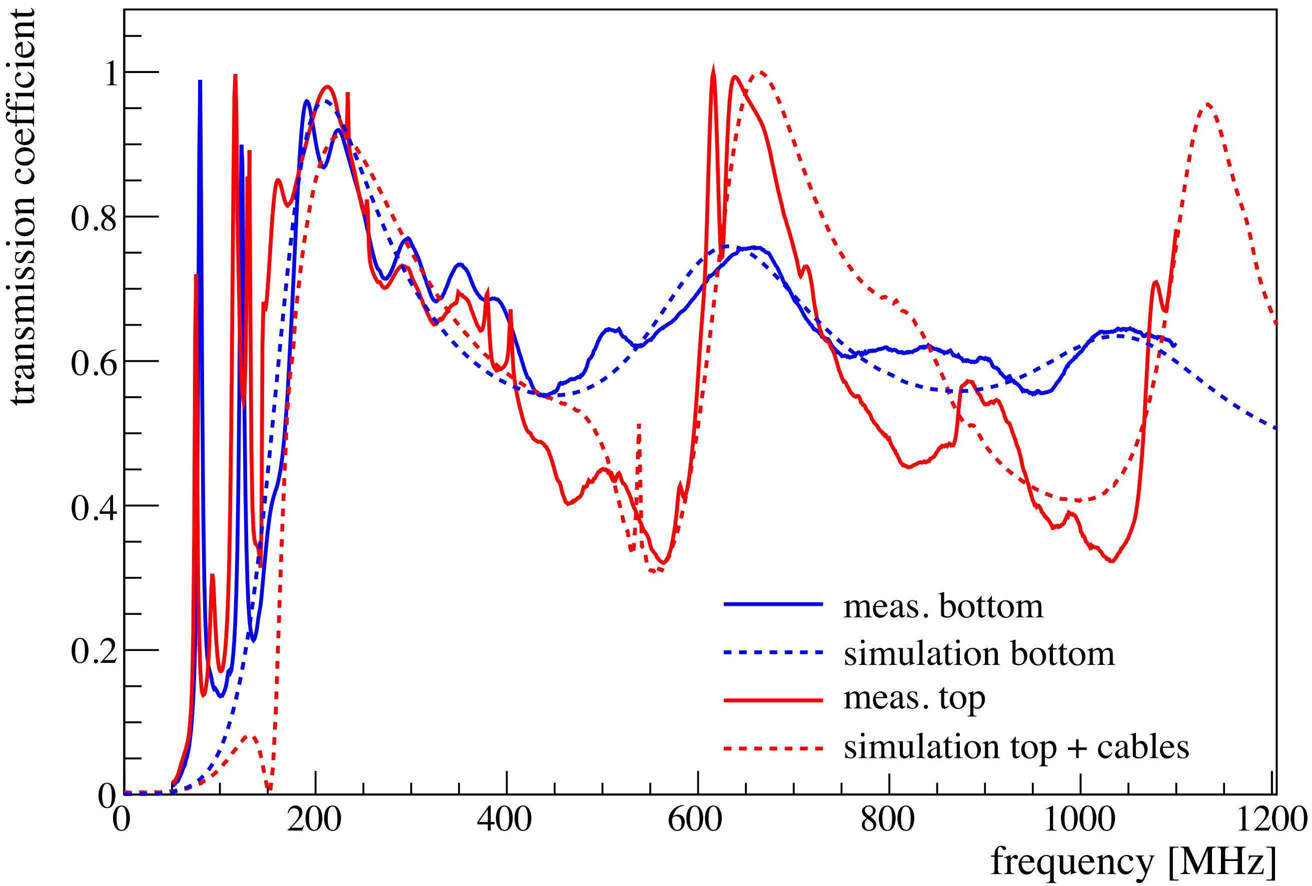
Expected signals

- ✓ Antenna, LNA and band-pass filter included
- ✓ Multi pulse structure disappeared
- ✓ Waveform changes by including the phase information
- ✓ The detector response can be calibrated from the waveform shape

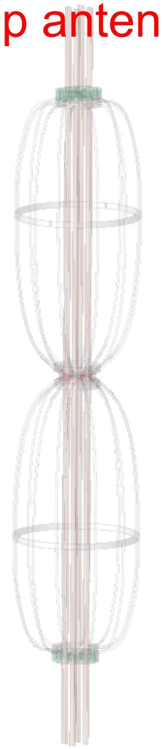


Antenna transmission coefficient

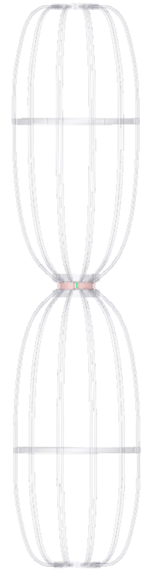
- ✓ Measured by network analyzer
- ✓ Simulation with XFdtd
- ✓ Measurement consistent with simulation
- ✓ The difference of top and bottom antenna due to pass-through cables



Top antenna



Bottom antenna

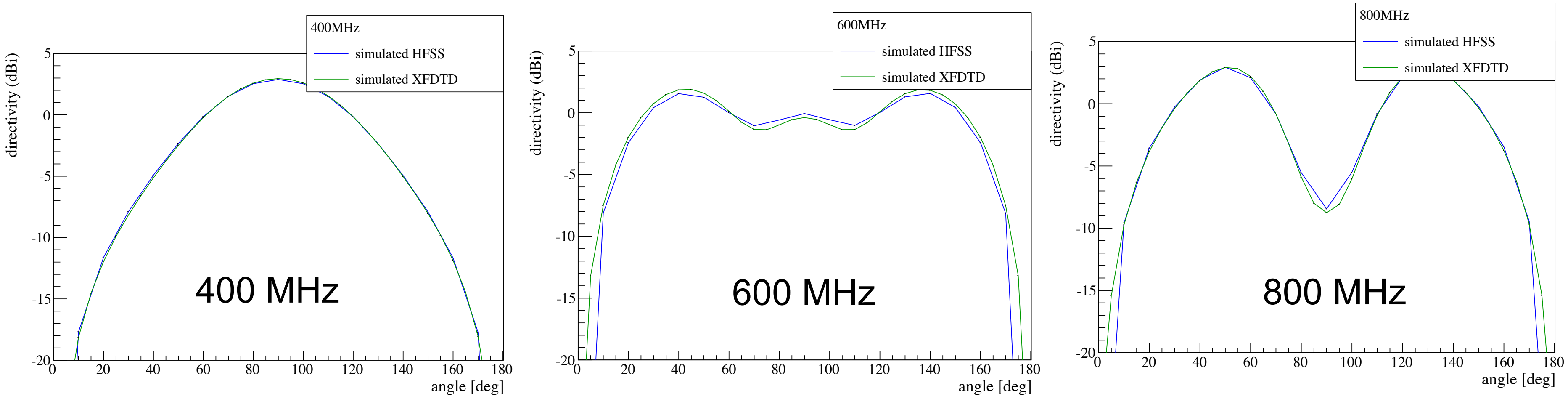


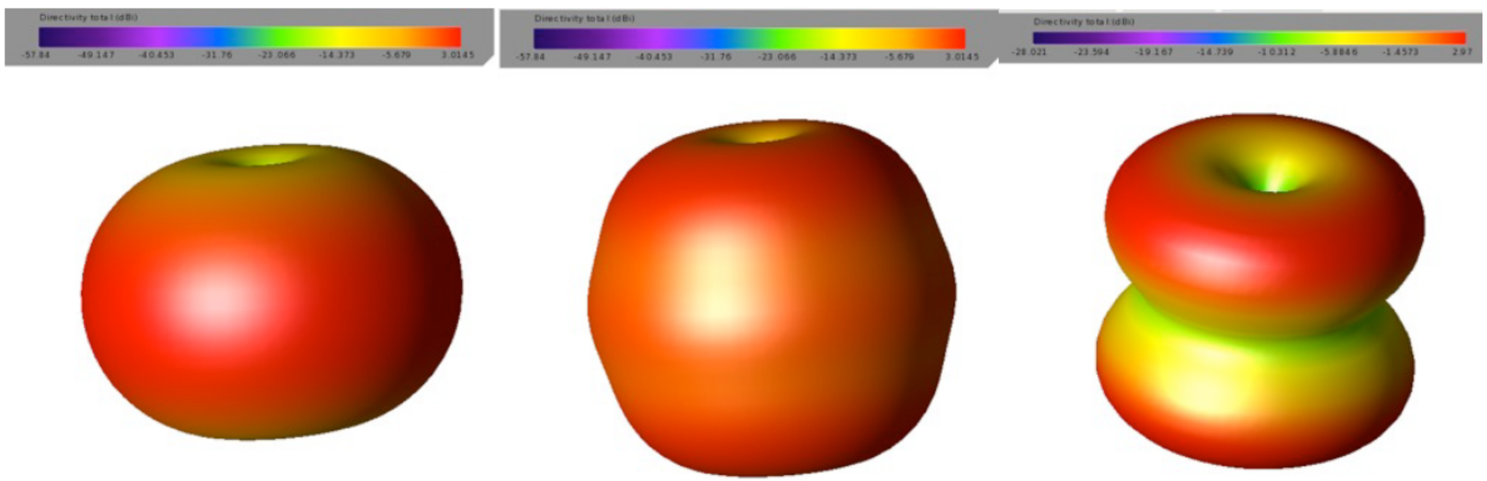
Antenna pattern

- ✓ Same results from two simulations (HFSS and XFdtd)
- ✓ Measurements are on-going

HFSS

XFdtd





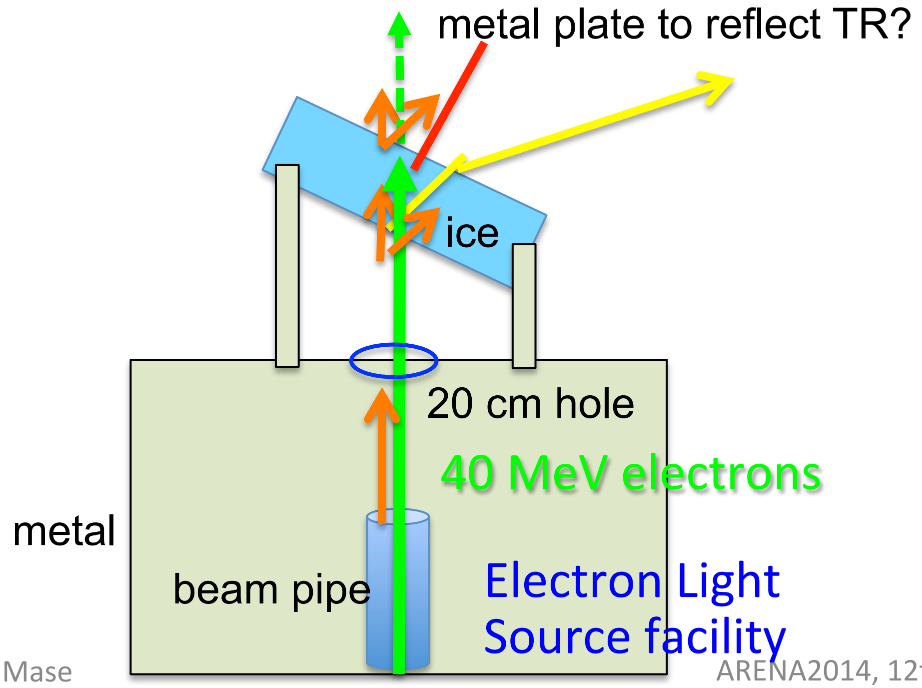
Transition radiation

- ✓ Transition Radiation (TR) was a severe background for the experiment performed by AWA
- ✓ Several places where TR is expected
- ✓ At the beam end cap (metal → air): only vertical direction
- ✓ Air → ice: TR suppressed because electrons terminated before the formation zone. The angle closed to the Cherenkov angle
- ✓ Ice → air: less electrons. The angle is close to the Cherenkov angle → metal plate to reflect TR?
- ✓ Evaluate more precisely with simulation

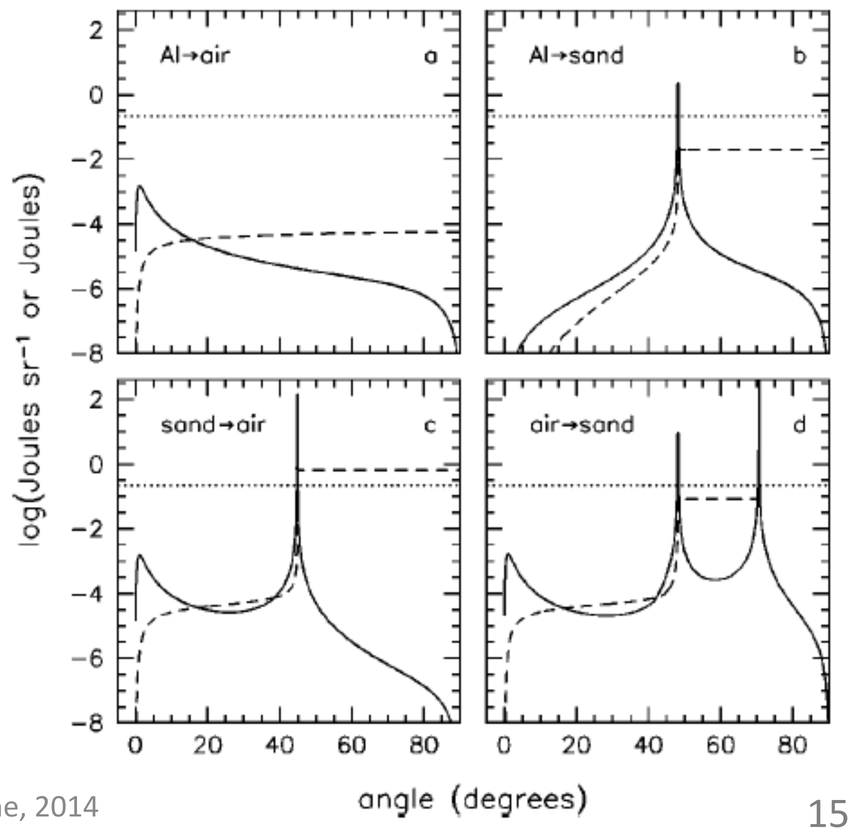
Formation zone

$$L_f = \frac{2\pi\beta c}{\left|\omega(1 - n_2 \beta \cos\theta)\right|}$$

$$\approx \lambda$$



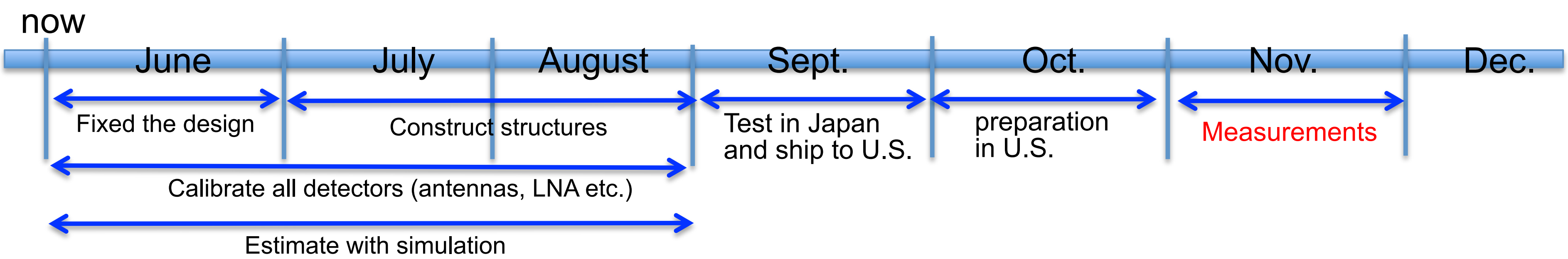
P. W. Gorham et al., PRE 62, 6 (2000)



Summary and Future Plan

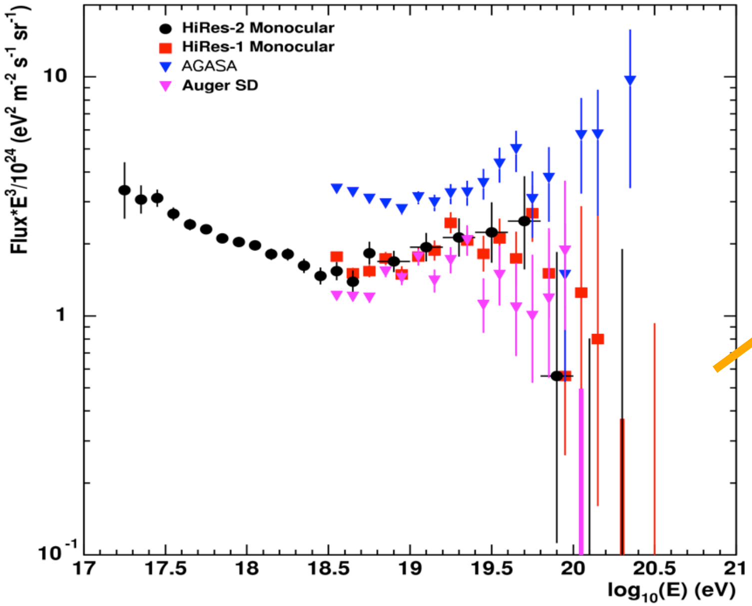
- ✓ We are planning to observe Askaryan-like radio wave at Utah with TA LINAC
- ✓ The ARA detectors will be calibrated end-to-end
- ✓ If we understand the detector, we can investigate the Askaryan effect
- ✓ Rough design for the measurement such as the target and the antenna support structure
- ✓ The expected signal was calculated with simulation
- ✓ The antenna measurement and simulation performed for the better understanding

- ✓ This proposal will be discussed by the TA collaboration
- ✓ If approved, we will perform this measurement this winter

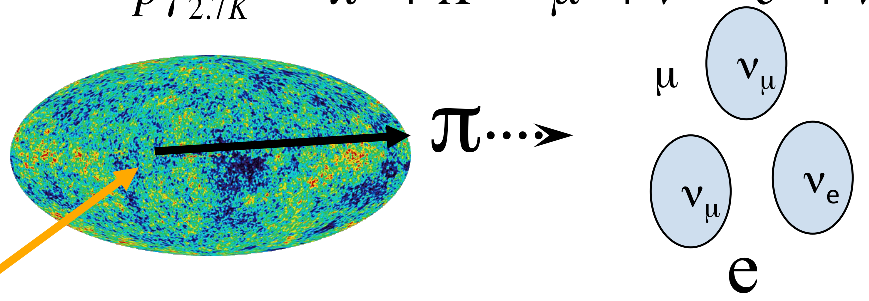


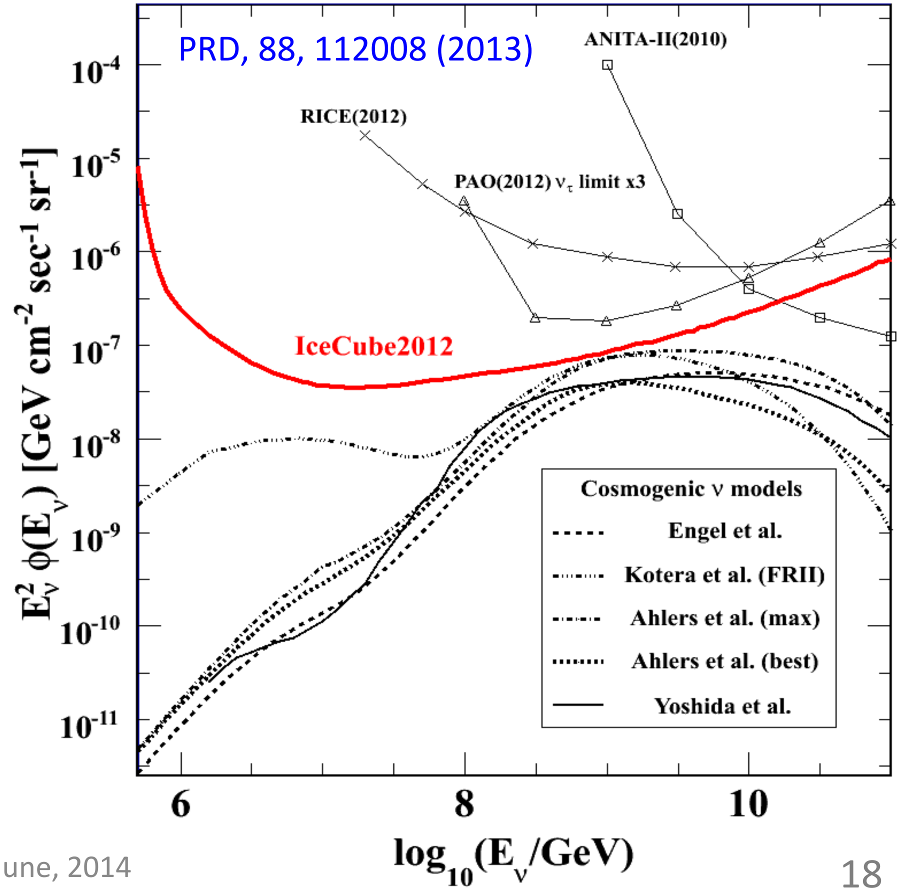
Backups

The origin of Ultra High Energy Cosmic Rays



$$p\gamma_{2.7K} \rightarrow \pi^{\pm} + X \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu' s$$





Shed light on the UHECR origin

- ✧ Source evolution
- ✧ Composition (proton/iron)?
- ✧ Source position

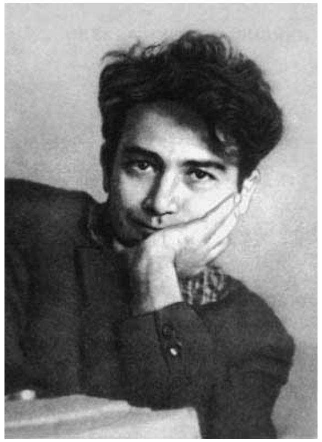
IceCube: ~1 event/year expected

-> want MORE!

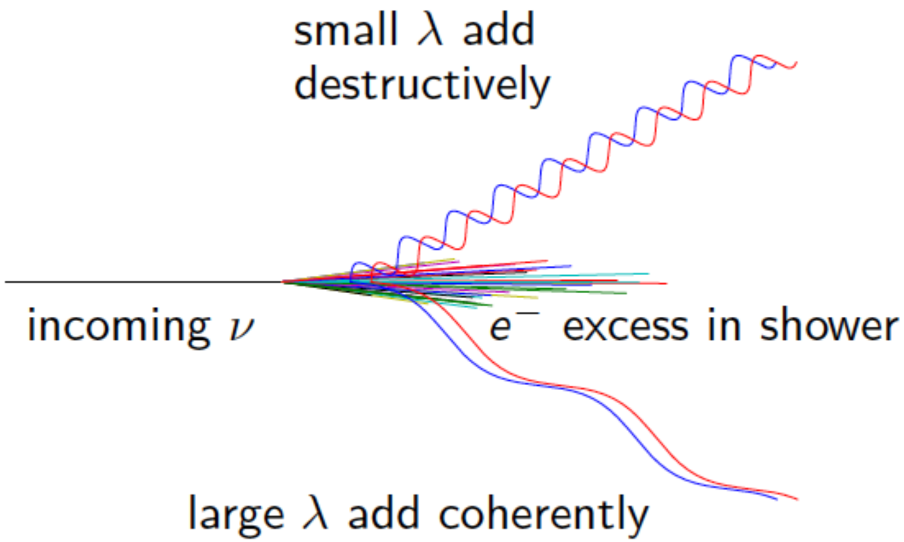
Askaryan effect

✧ 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation)

→ **Askaryan effect**



G. Askaryan



Shower size << λ to be coherent

Cherenkov emission (Frank-Tumm result)

$$\frac{d^2W}{d\nu dl} = \frac{4\pi^2\hbar}{c}\alpha z^2\nu\left(1-\frac{1}{\beta^2 n^2}\right)$$

in case N electrons,

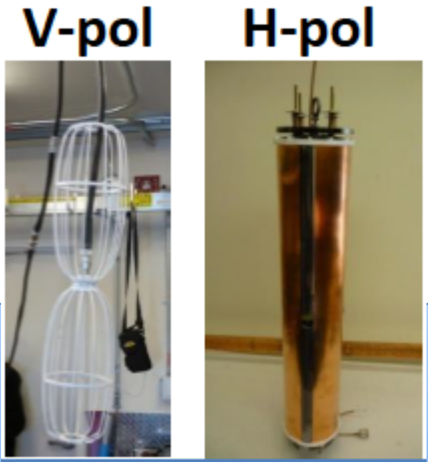
z=1 (not coherent) → $W \propto N$

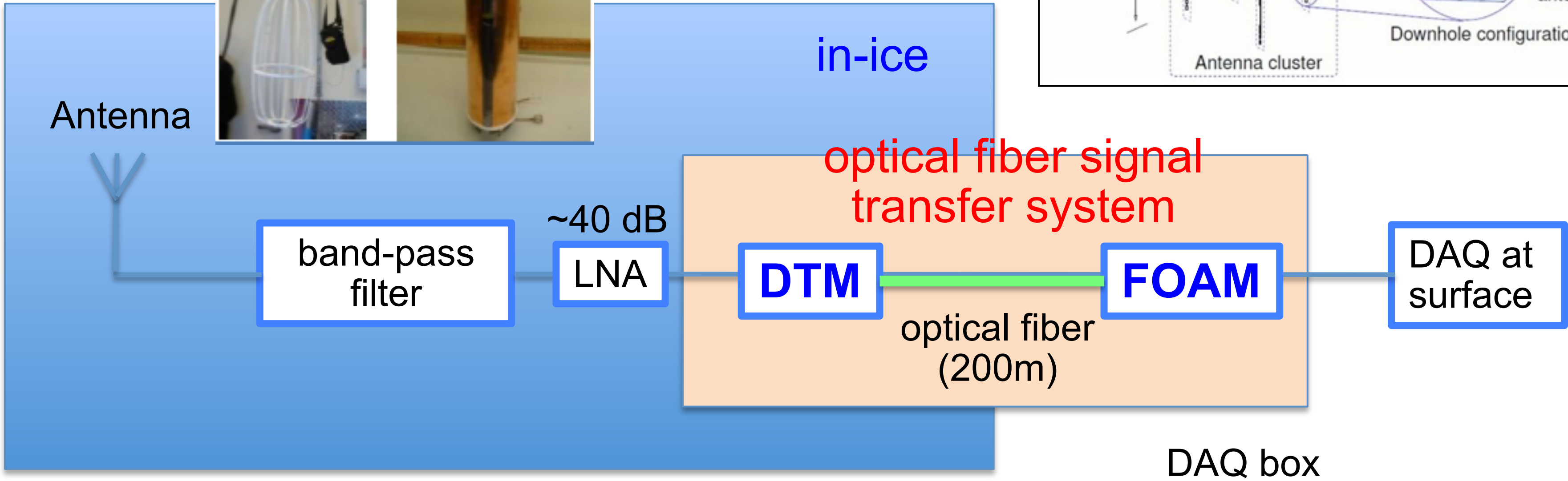
z=N (coherent) → $W \propto N^2$

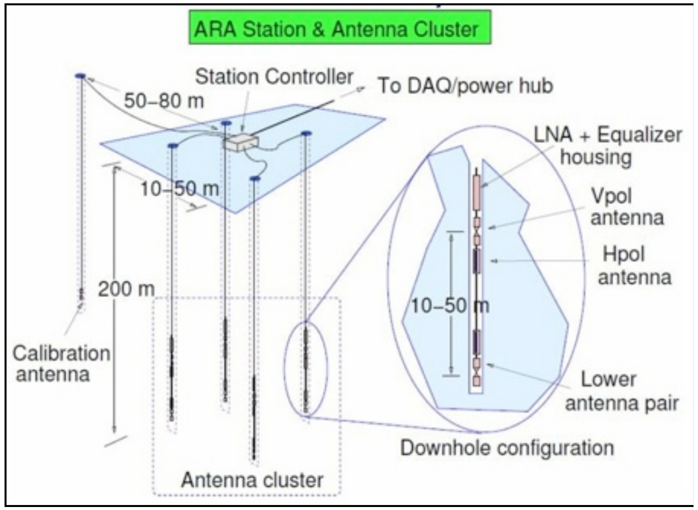
Power $\propto \Delta q^2$, thus prominent at EHE (>~ 10 PeV)

Attenuation length in ice ~ 1 km

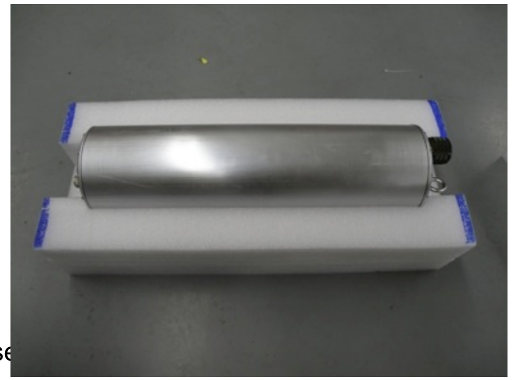
Schematic of the ARA system



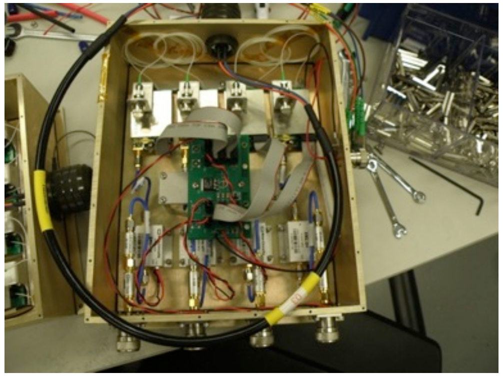




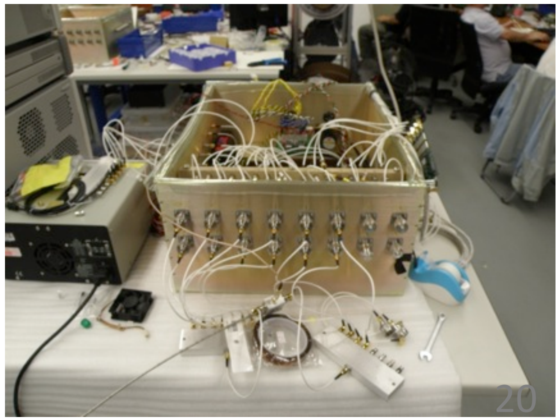
DTM



FOAM



DAQ box

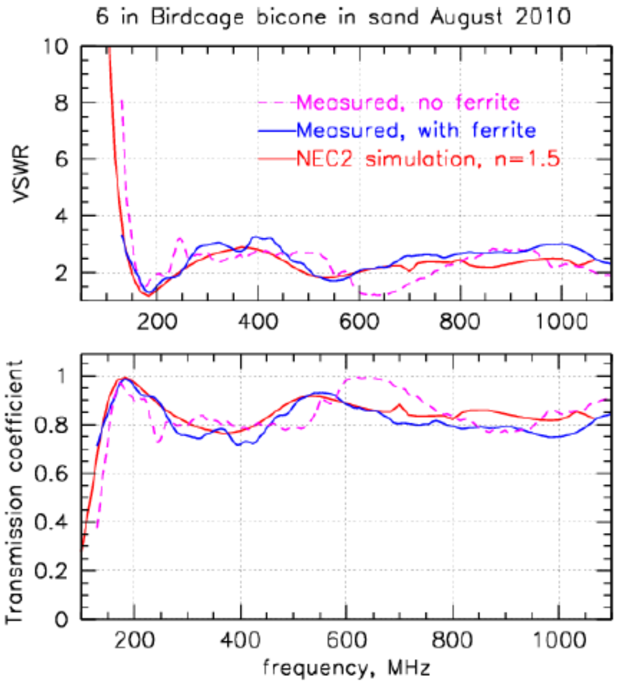


Antennas

V-pol antenna

Bicone

150-850 MHz

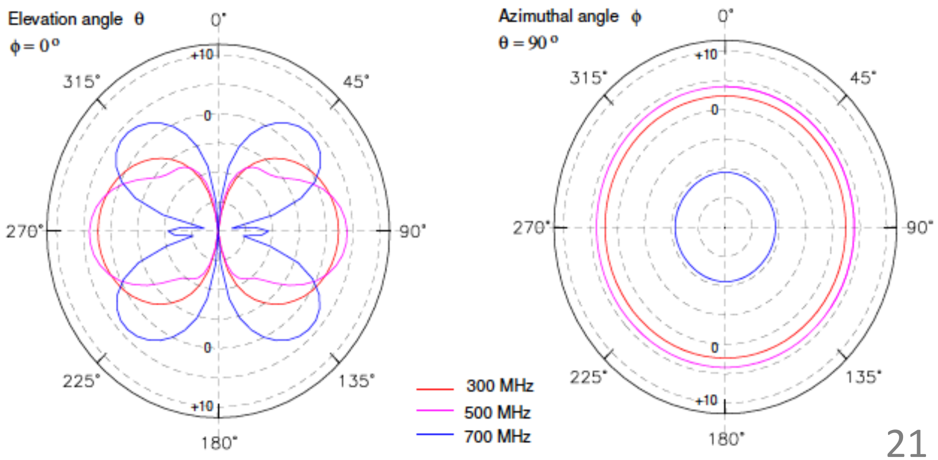


H-pol antenna

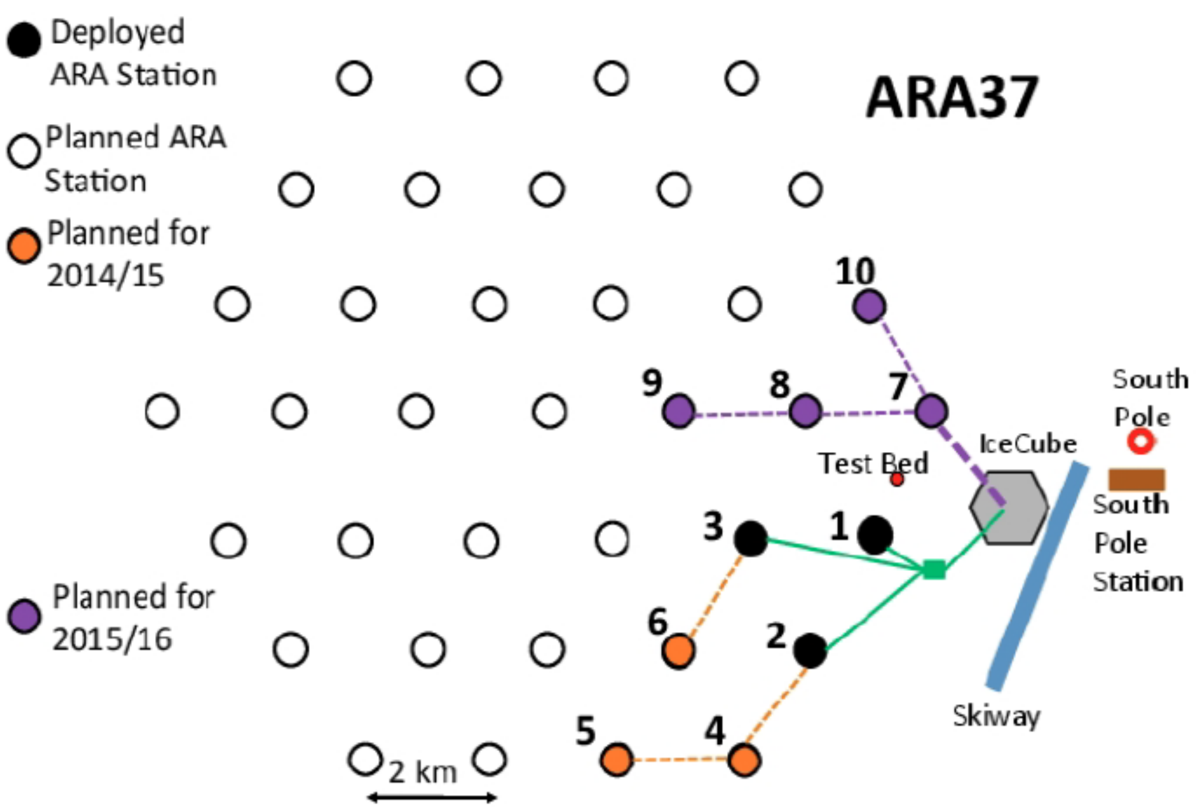
Quad-slot cylinder

200-850 MHz

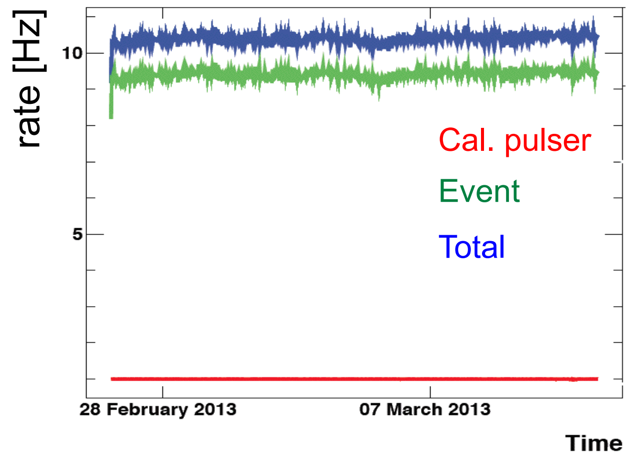
Gain similar to dipole (+2 dBi)



Current status and further plan

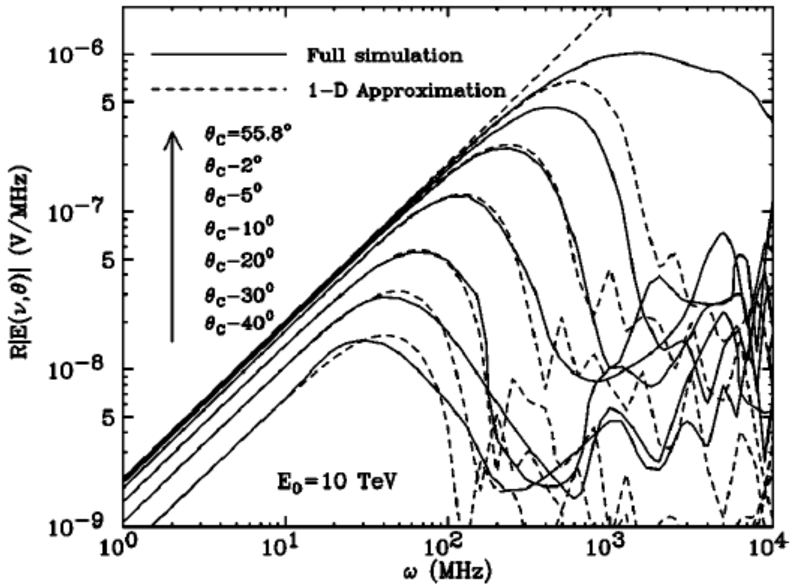


ARA3 event rate



- ✧ 3 stations operational
- ✧ 3 planned for 2014/2015
- ✧ More to come

Parameterization of Askaryan radio wave

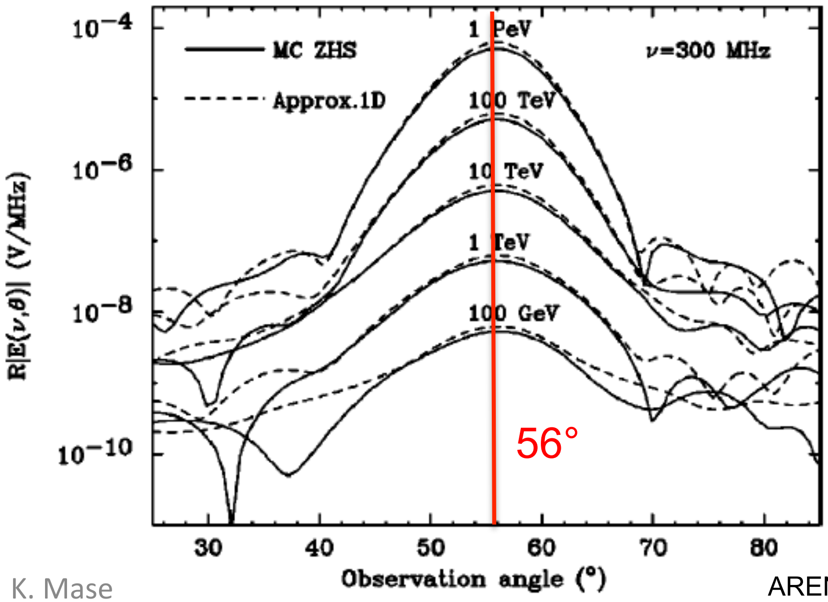


J. Alvarez Muniz et al., PRD 62, 063001 (2000)

Signal amplitude

$$R\left|\vec{E}(\omega,R,\theta_c)\right| \cong 2.53\times10^{-7}\left[\frac{E_{em}}{1\,TeV}\right]\left[\frac{\nu}{\nu_0}\right]\left[\frac{1}{1+(\nu/\nu_0)^{1.44}}\right] VMHz^{-1}$$

$$\nu_0 = 1.15\,GHz$$



J. Alvarez Muniz et al., Physics Lett. B, 411 (1997) 218

Signal spread

$$E(\omega,R,\theta) = E(\omega,R,\theta)e^{-\ln 2\left(\frac{\theta-\theta_c}{\Delta\theta}\right)^2}$$

$$\Delta\theta = \begin{cases} 2.7^\circ \dfrac{\nu_0}{\nu}\left(\dfrac{E_0}{1\,PeV}\right)^{-0.03} & for\ E_0 < 1\,PeV \\ 2.7^\circ \dfrac{\nu_0}{\nu}\left(\dfrac{E_{LPM}}{0.14E_0 + E_{LPM}}\right)^{0.3} & for\ E_0 > 1\,PeV \end{cases}$$

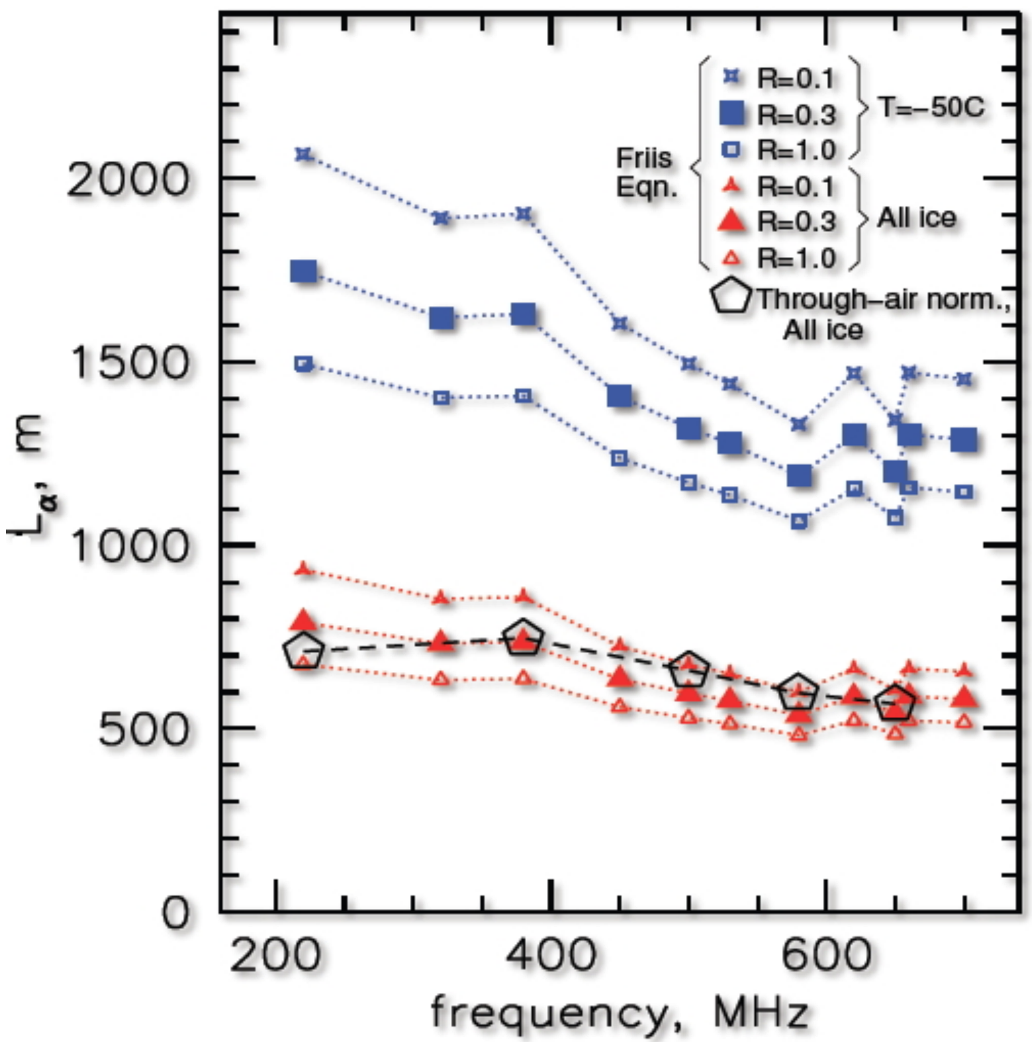
$$\nu_0 = 500\ MHz$$

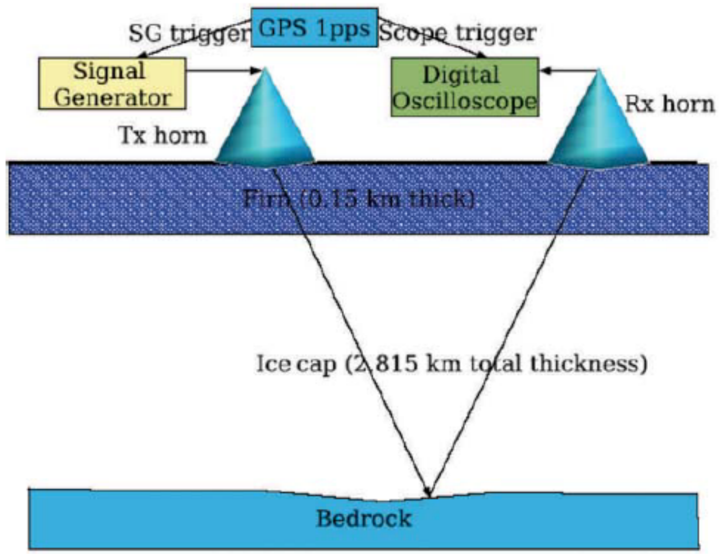
Incident particle energy → signal characteristics

Note: confirmed at SLAC

Why radio wave?

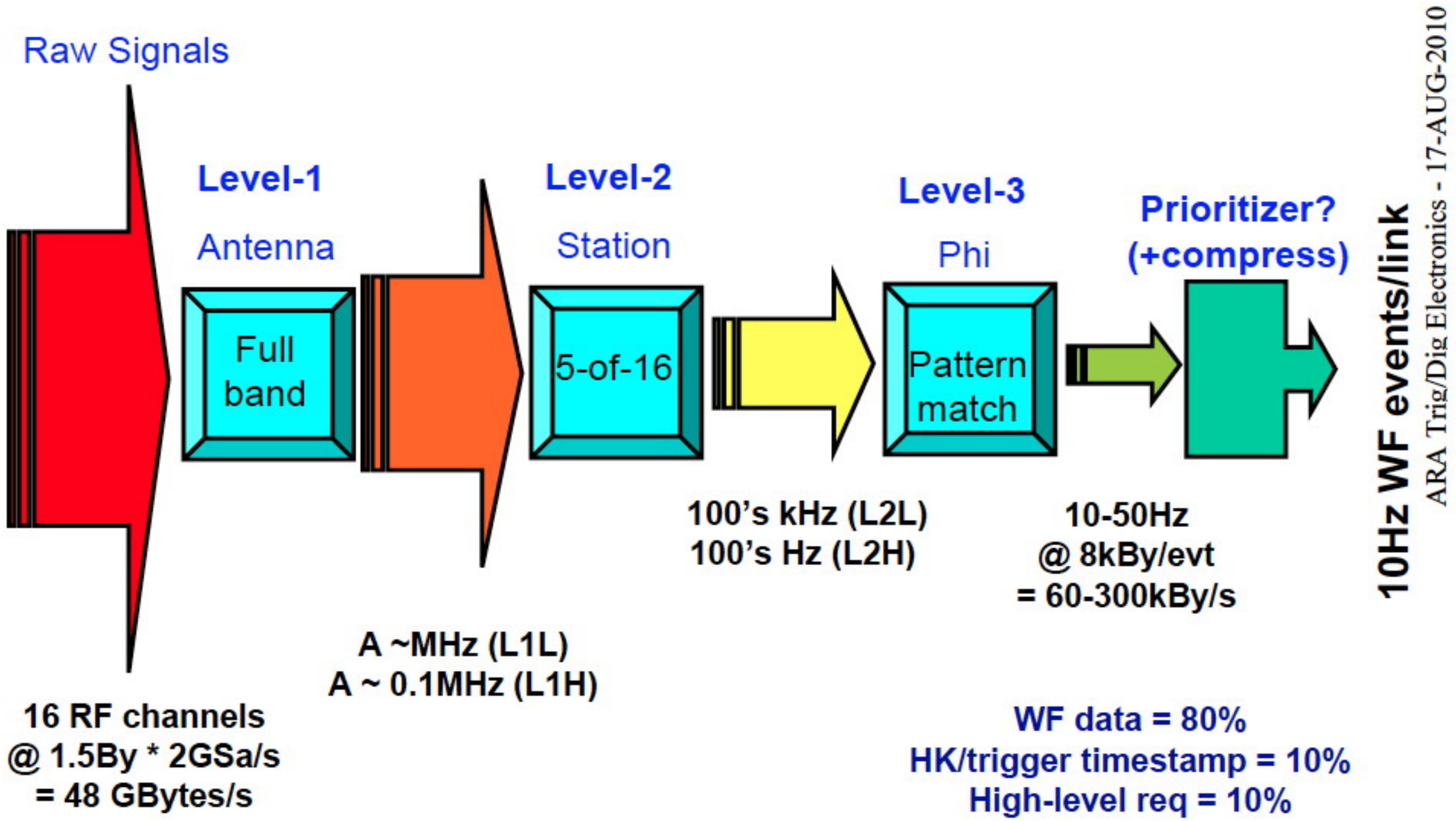
Barwick, Besson, Gorham Saltzberg,
J. Glaciology, Vol 51, 2005, p 231



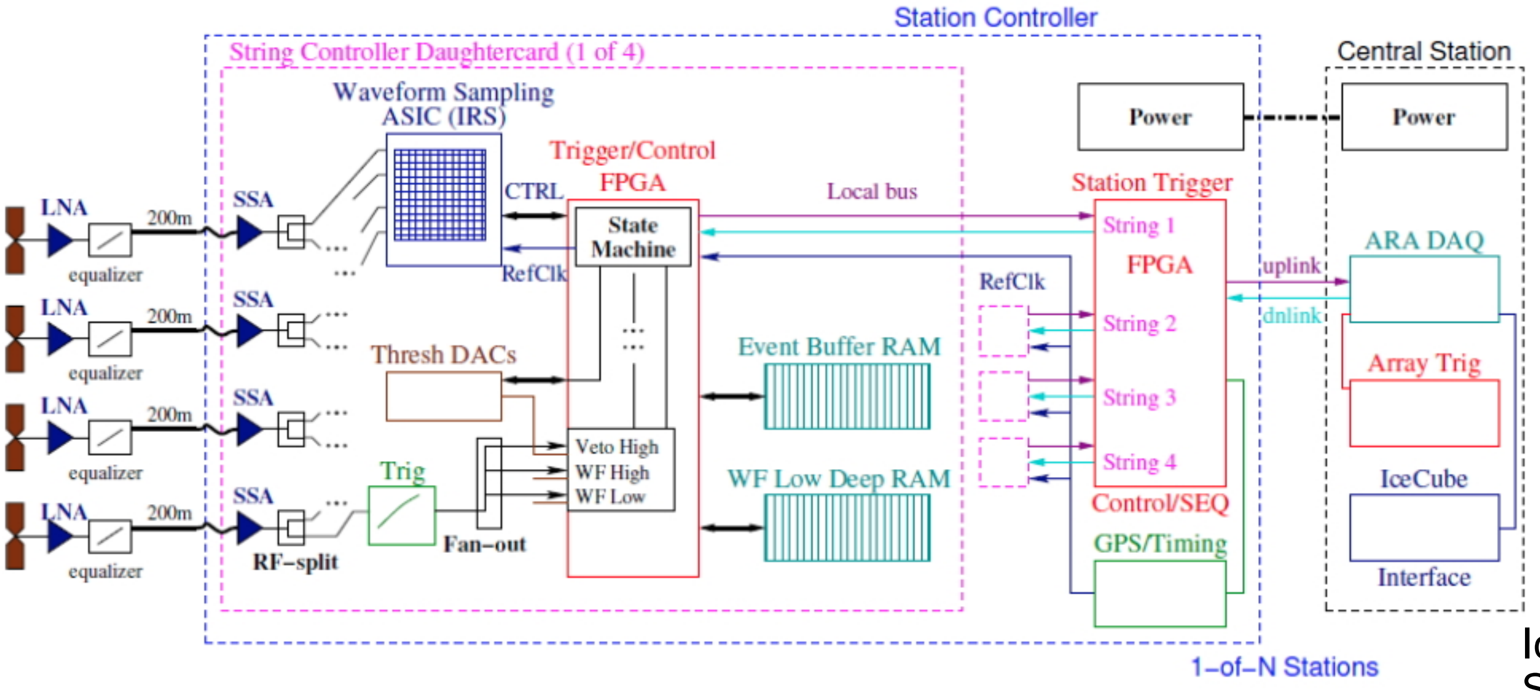


- Attenuation length of the south pole ice
  - Optical: ~100m
  - **Radio: ~1km**
- Easier to make a bigger detector in an economical way

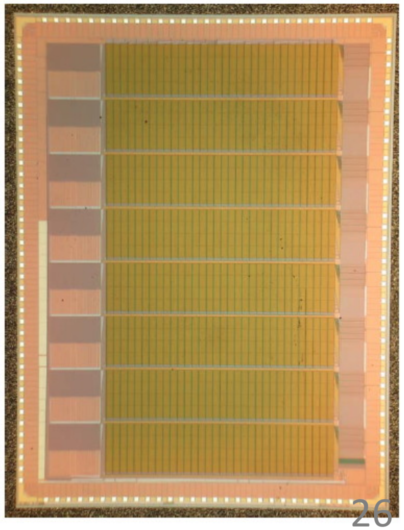
Station Data Reduction (self-trigger)



The DAQ system and trigger

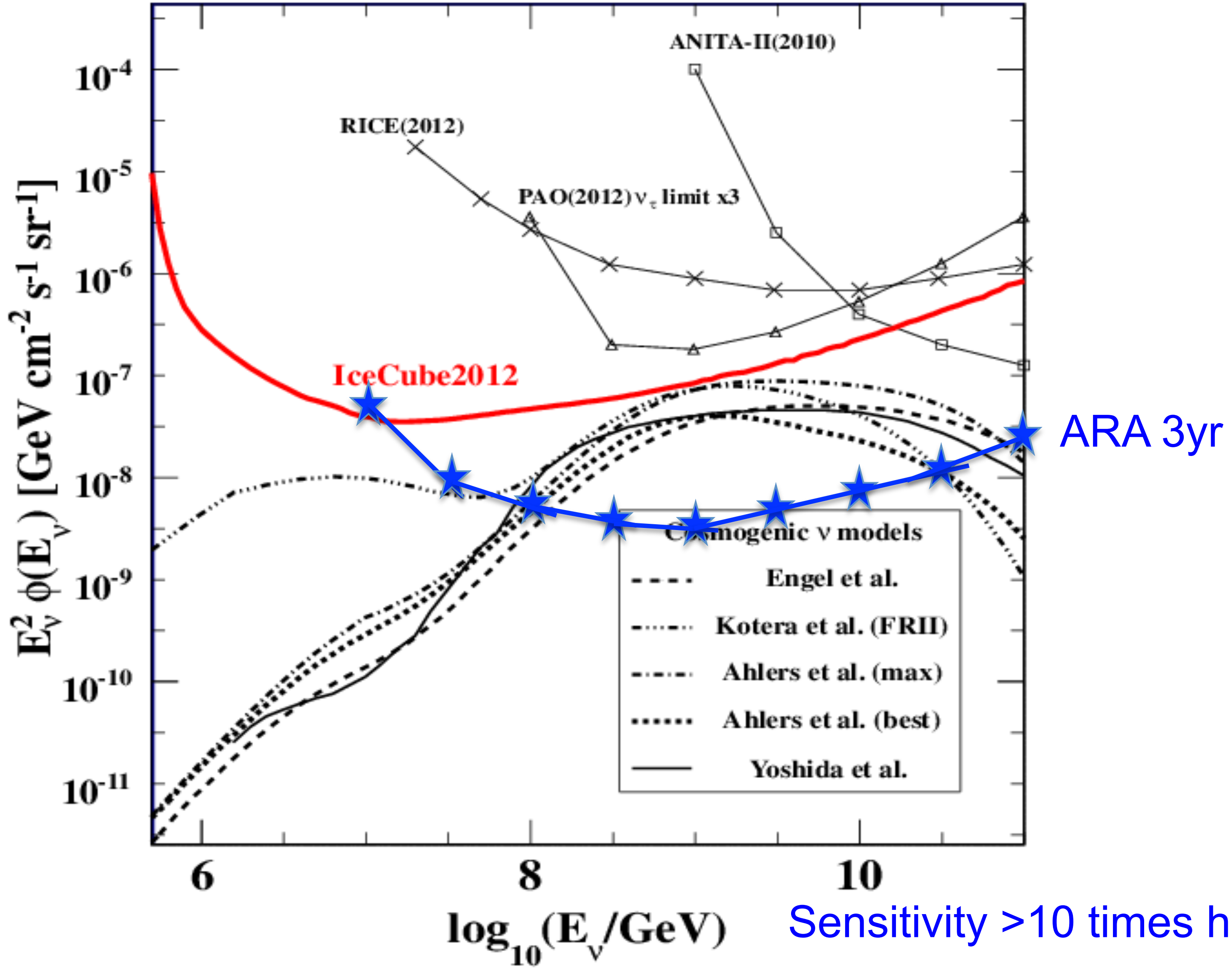


Ice Radio Sampler (IRS)



- Signal split for trigger
- Triggered when > 3 channels in one polarization (8 channels) within 110 ns
- Digitizer 12bit 2G sample/s

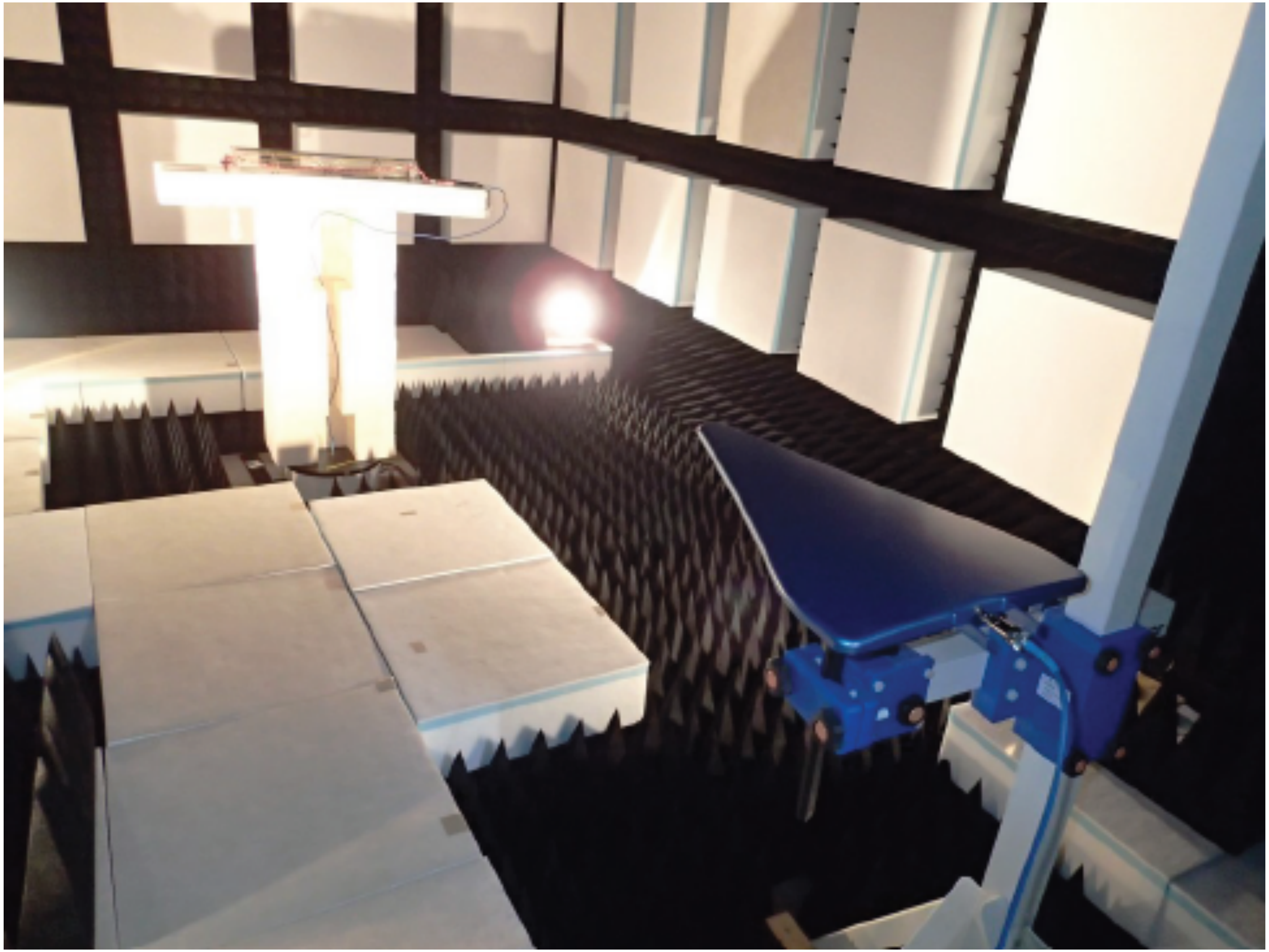
The ARA sensitivity



Sensitivity >10 times higher

>~10 events/yr

Antenna calibration



Multi-pulses Vs. single pulse