STATUS OF THE ARA PROJECT

MING-YUAN LU, UW-MADISON

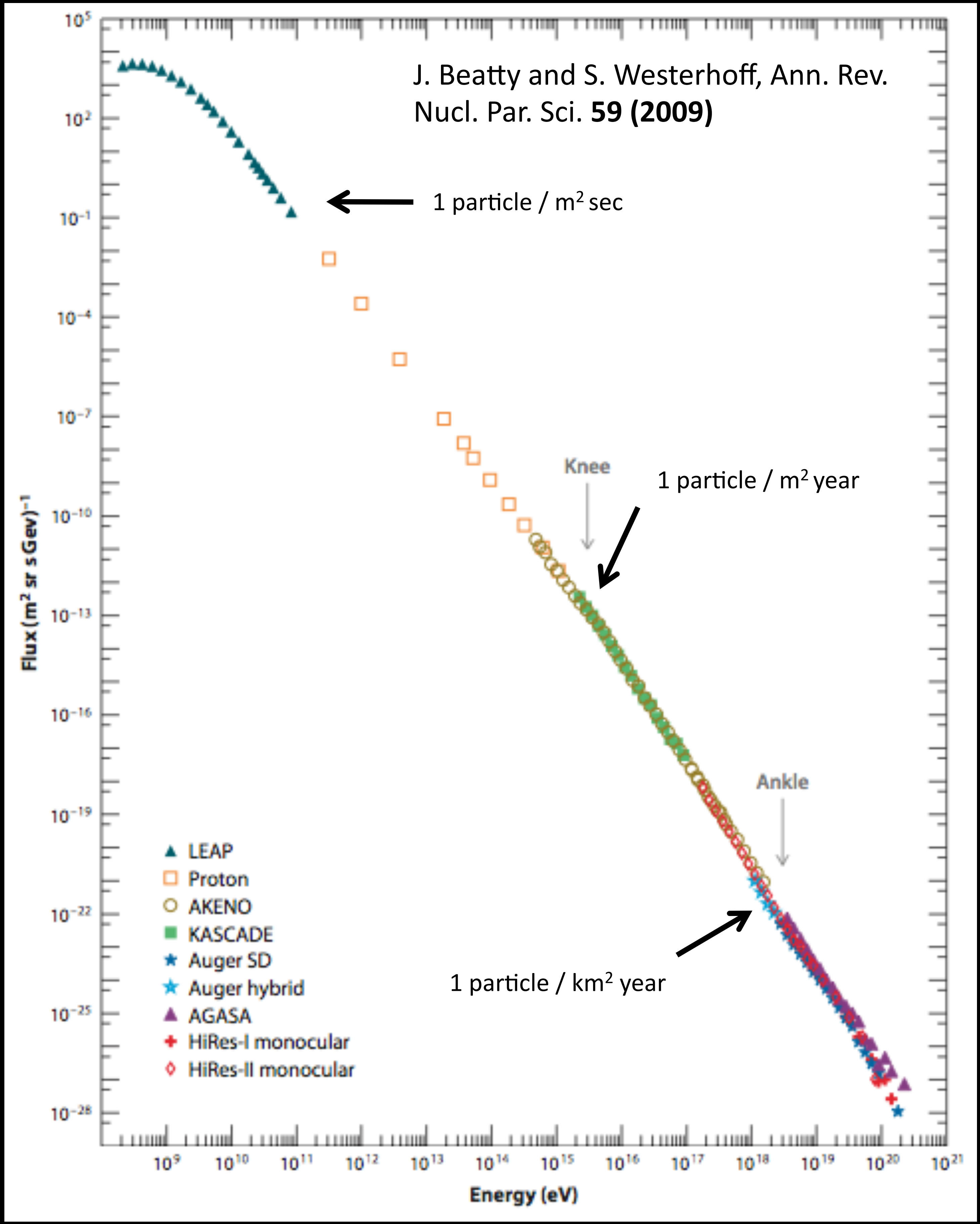
LAKE LOUISE WINTER INSTITUTE '16

SOUTH POLE ASKARYAN RADIO ARRAY

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

COSMIC RAYS

- Cosmic ray flux observed across 11 orders of magnitude
- Most energetic events: several * 10^{20}eV
- Puzzles: origin & acceleration mechanism for such ultra-high energy (UHE) cosmic rays



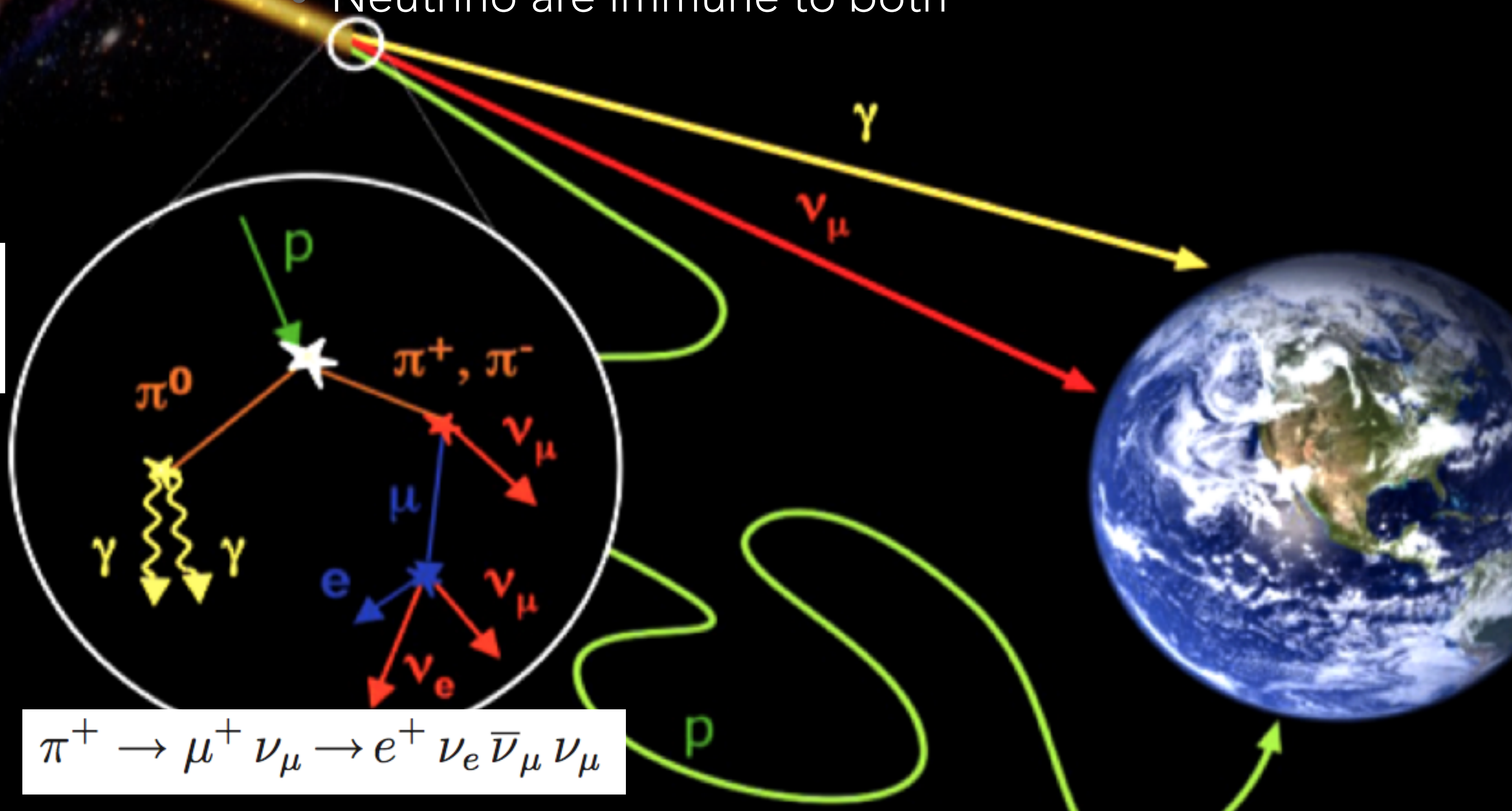
NEUTRINO-COSMIC RAY CONNECTION

- Neutrinos and gamma rays are produced when cosmic rays interact with ambient matter/radiation field
- Cosmic rays ~<10^{19}eV bent by magnetic fields in flight. Gamma rays absorbed/cascade down ~>TeV
- Neutrino are immune to both

$$p\gamma \rightarrow \begin{matrix} p\pi^0 \\ n\pi^+ \end{matrix}$$

$$p\,p \longrightarrow \begin{cases} p\,p\,\pi^0 \\ p\,n\,\pi^+ \end{cases}$$

Astrophysical beam dump



$$\pi^0 \rightarrow \gamma\,\gamma$$

$$\pi^+ \longrightarrow \mu^+\,\nu_\mu \longrightarrow e^+\,\nu_e\,\overline{\nu}_\mu\,\nu_\mu$$

COSMOGENIC NEUTRINOS

- Photohadronic interaction between UHE cosmic rays ($>10^{19.5}$ eV) and CMB photons

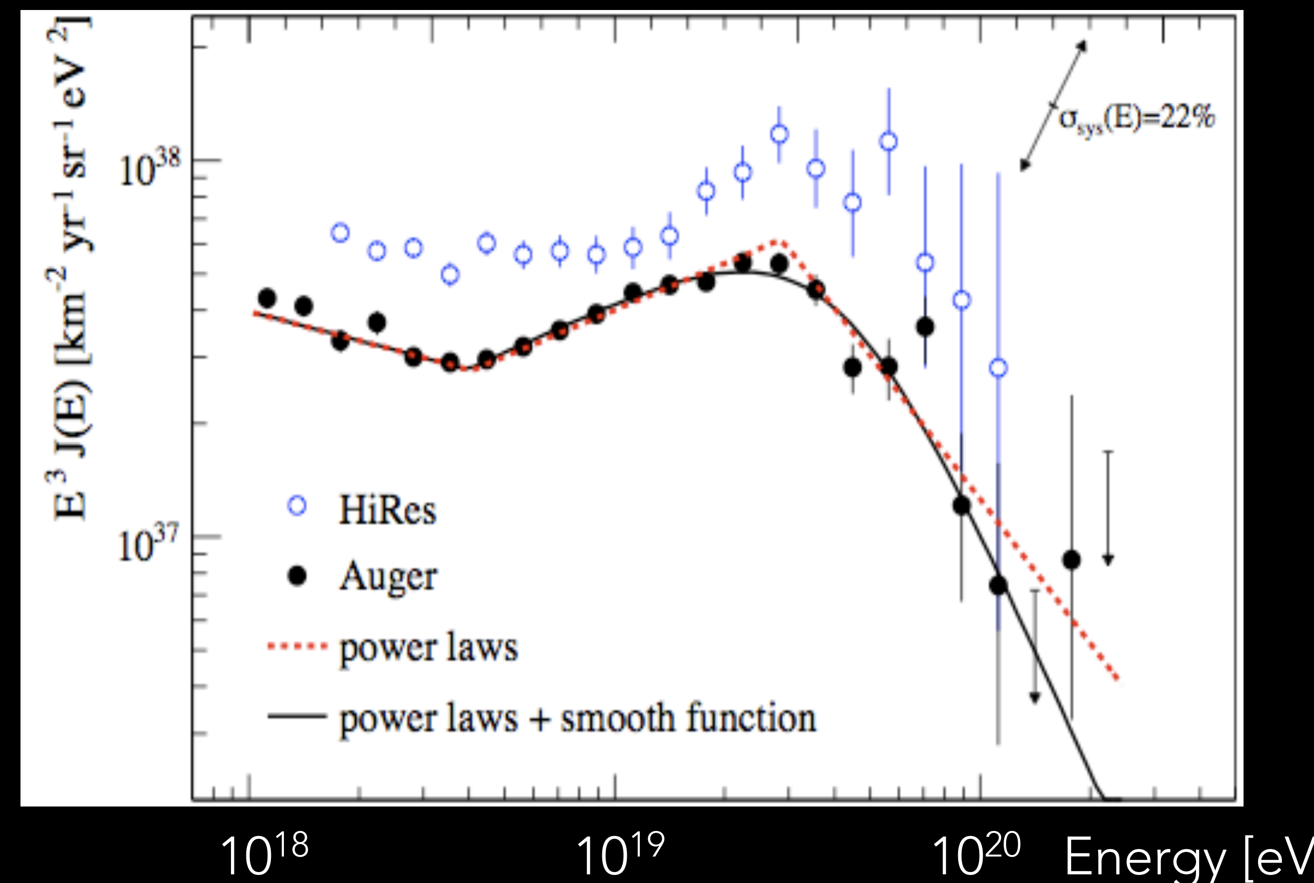
$$\mathbf{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathbf{\Delta}^* \rightarrow \mathbf{n} + \pi^+$$

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_{\mathbf{e}}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow \mathbf{e}^+ \bar{\nu}_\mu \nu_{\mathbf{e}}$$

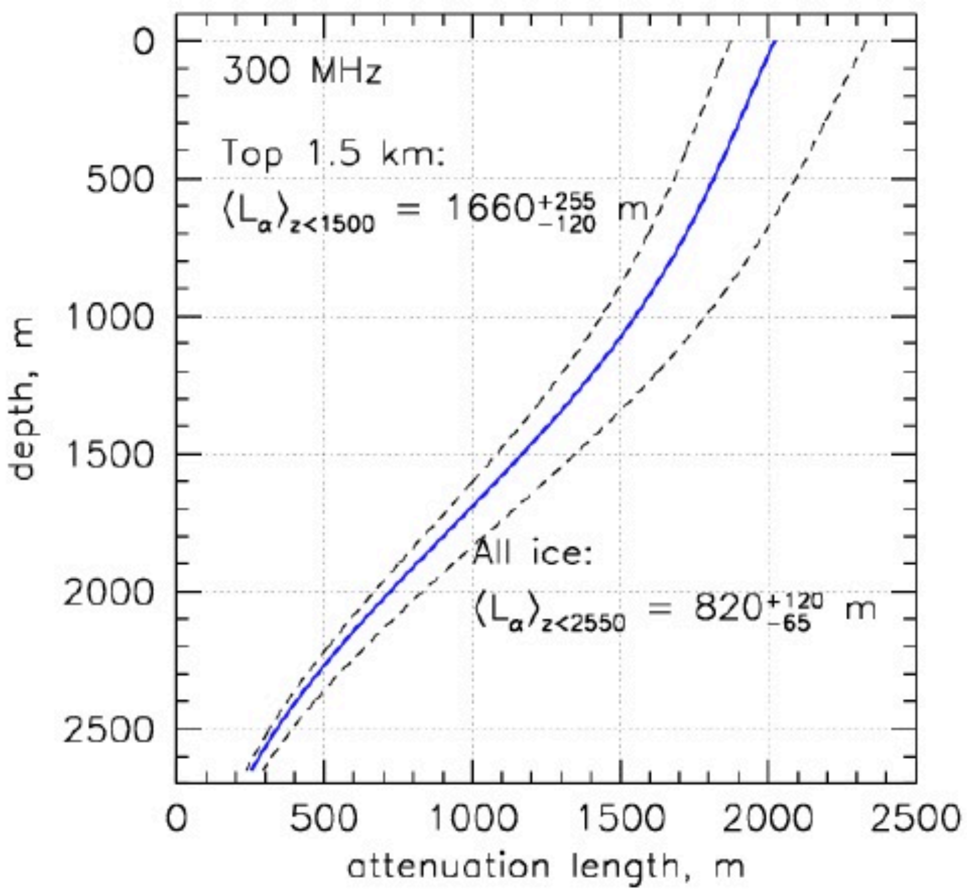
- This is the Greisen-Zatsepin-Kuzmin (GZK) process - a 'guaranteed" neutrino flux



RADIO DETECTION

- Estimated event rate: ~<1/km^3/yr
- Demands for detector ~100km^2

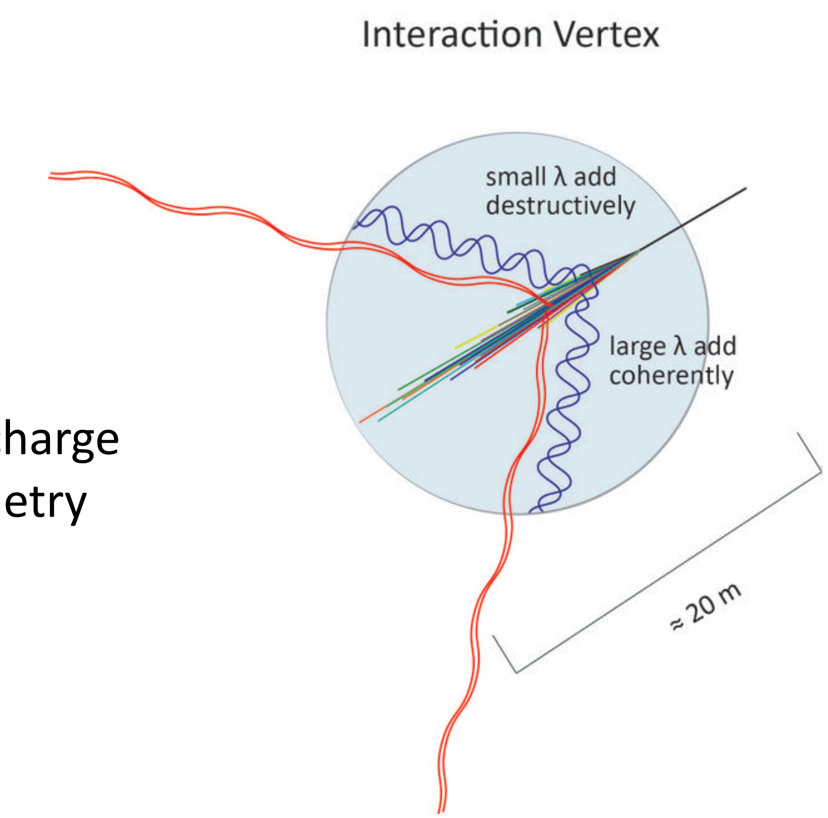
Radio transparency in ice



Kilometer-scale attenuation length for radio signal in South Pole ice

The Askaryan Effect

~20% charge asymmetry



Peak emission 0.1~1GHz

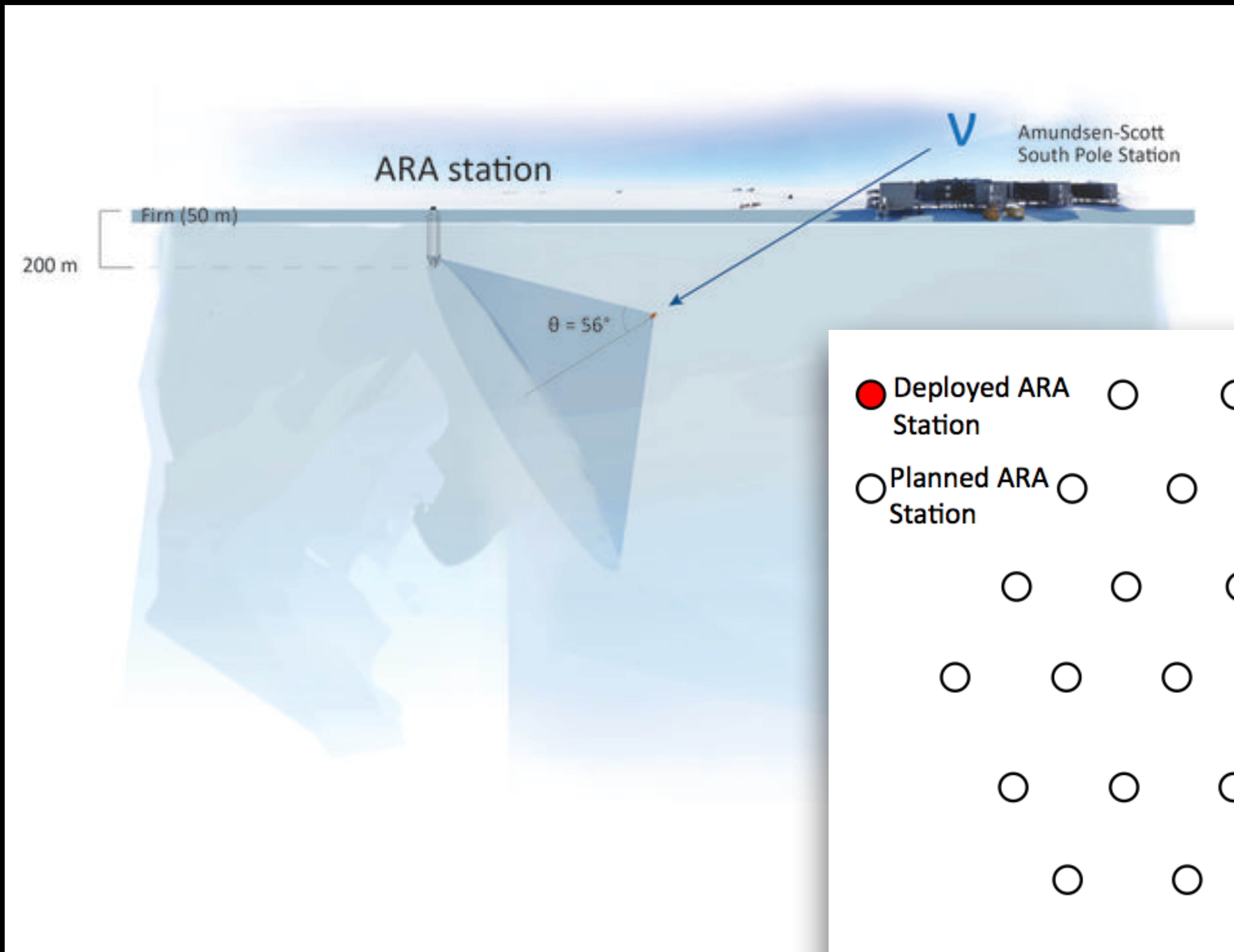
P ~ N_e^2 ~ E^2

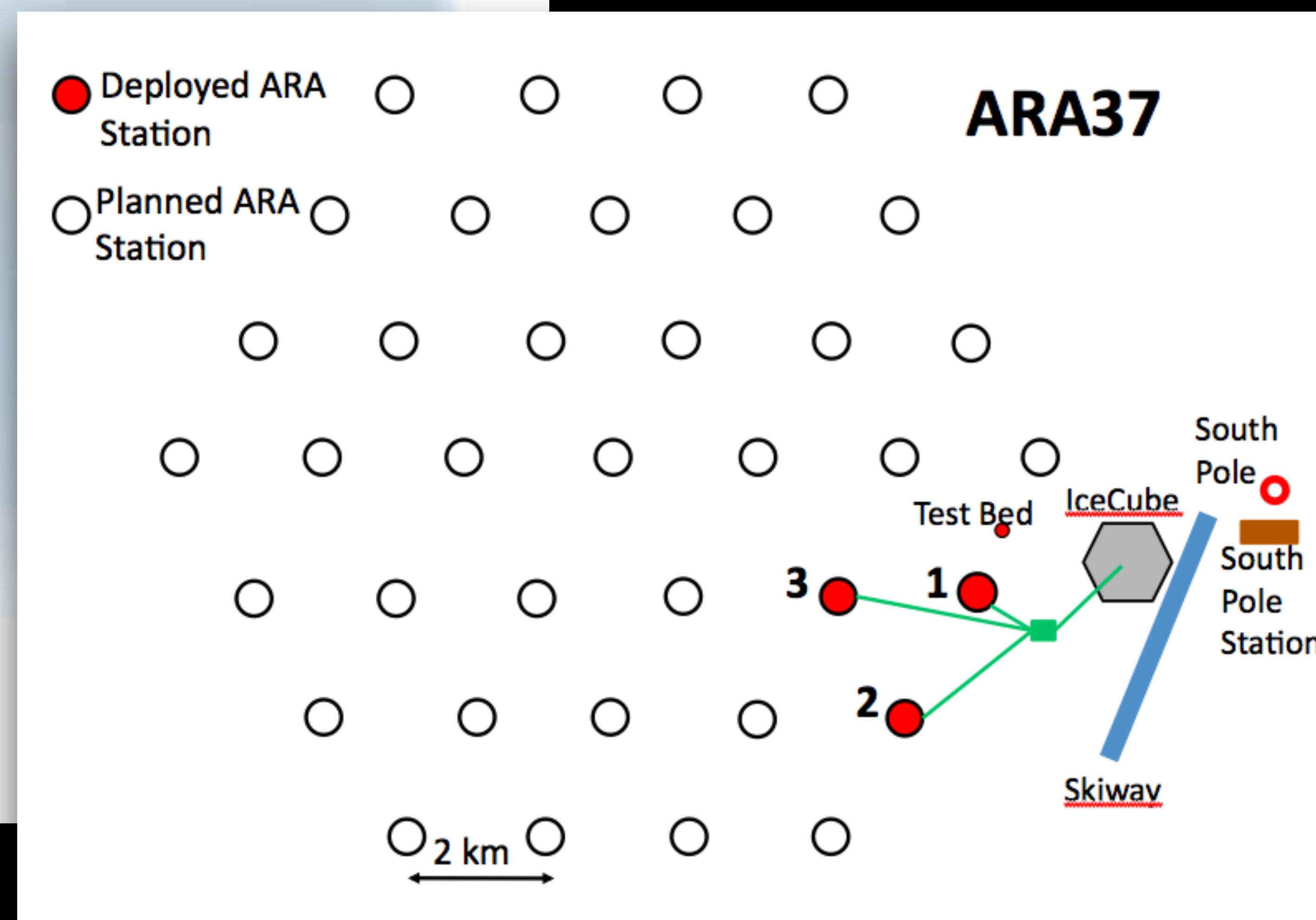
Highly polarized broadband signal

Confirmed detection in ice, SLAC 2006

(Phys. Rev. Lett. 99:171101)

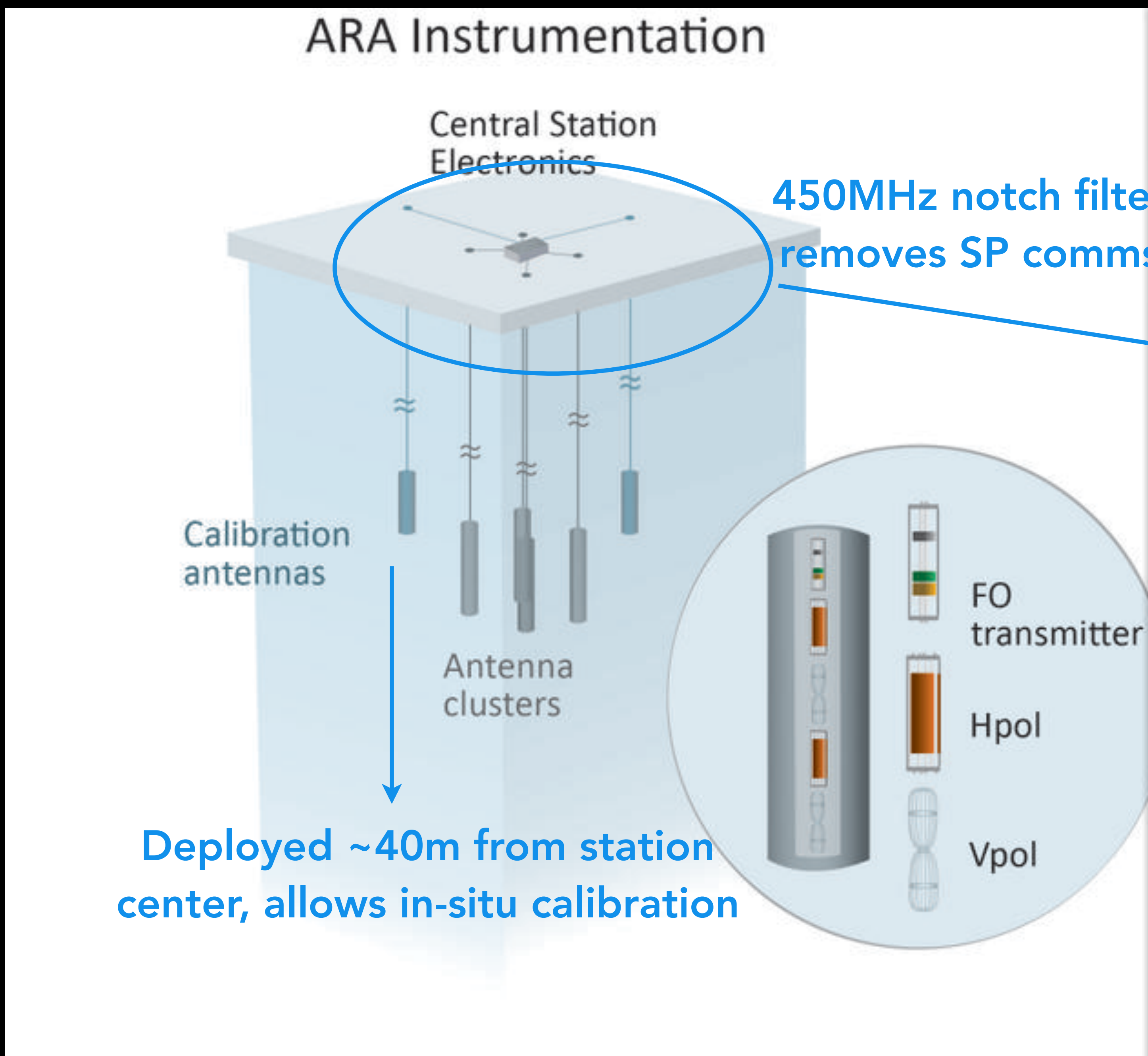
ASKARYAN RADIO ARRAY

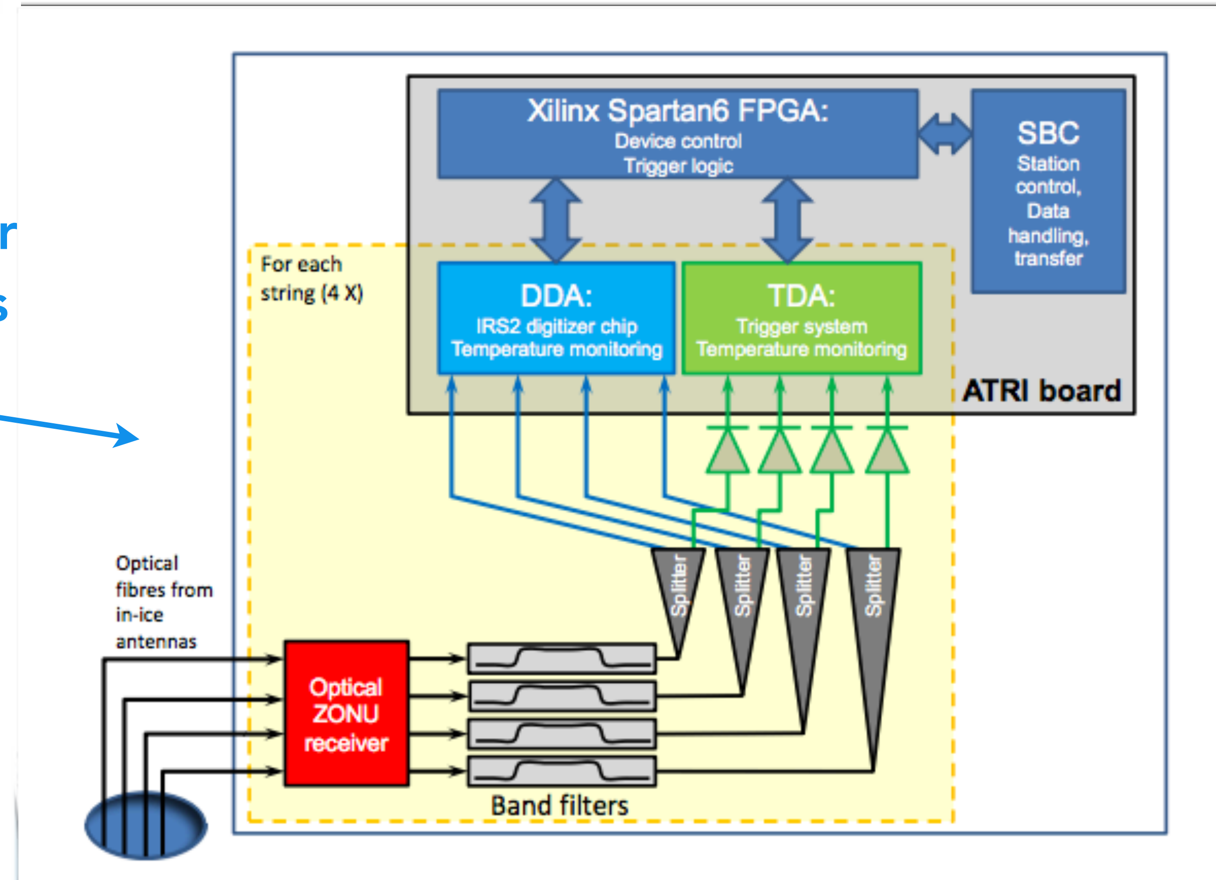


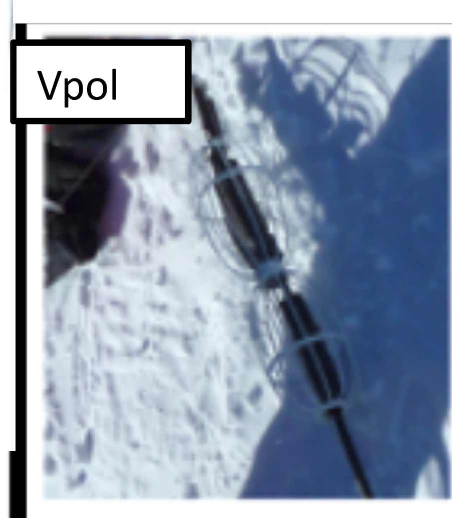


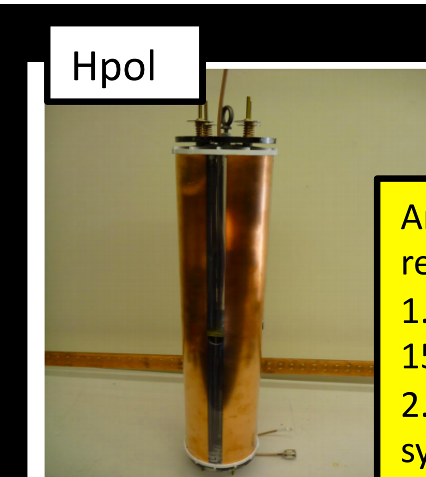
Full ARA37 covers ~100km^2

HARDWARE





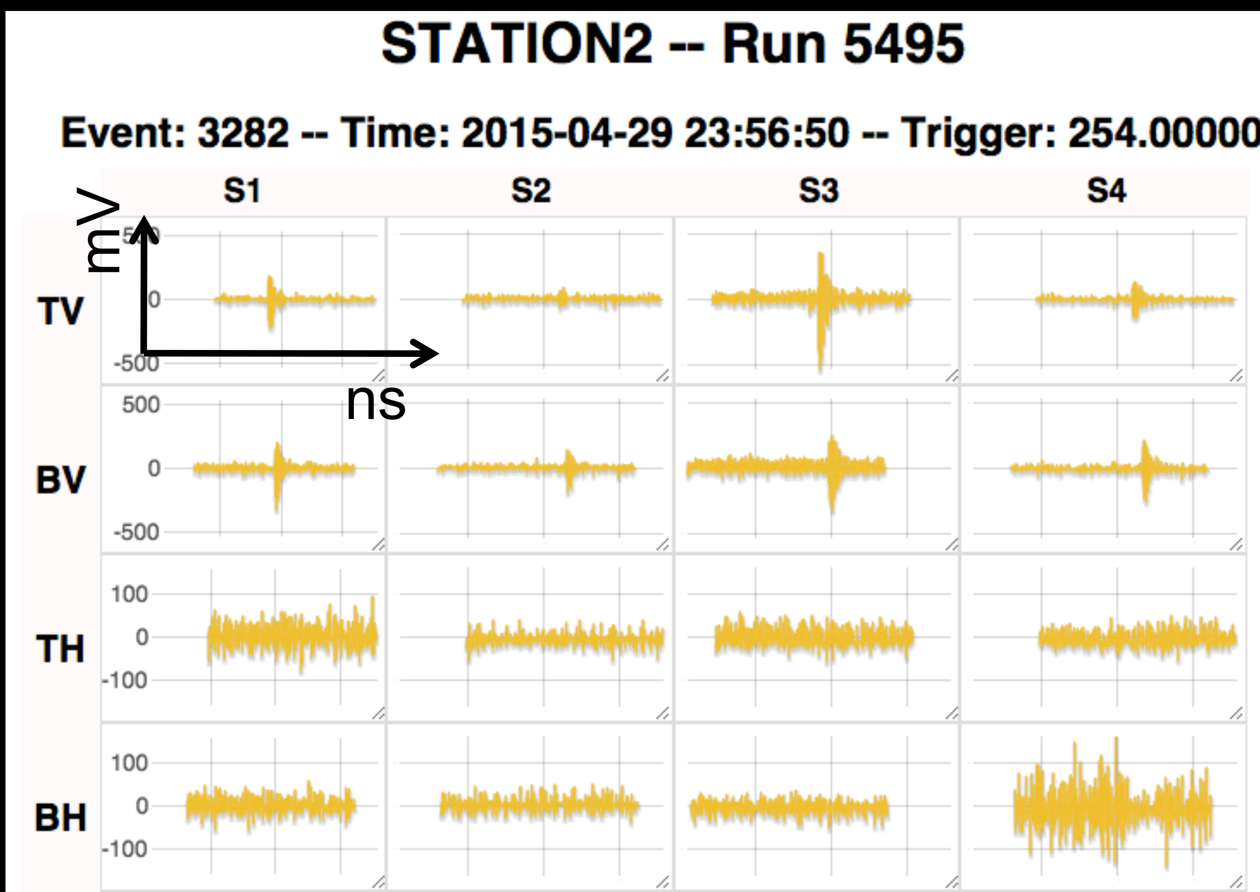




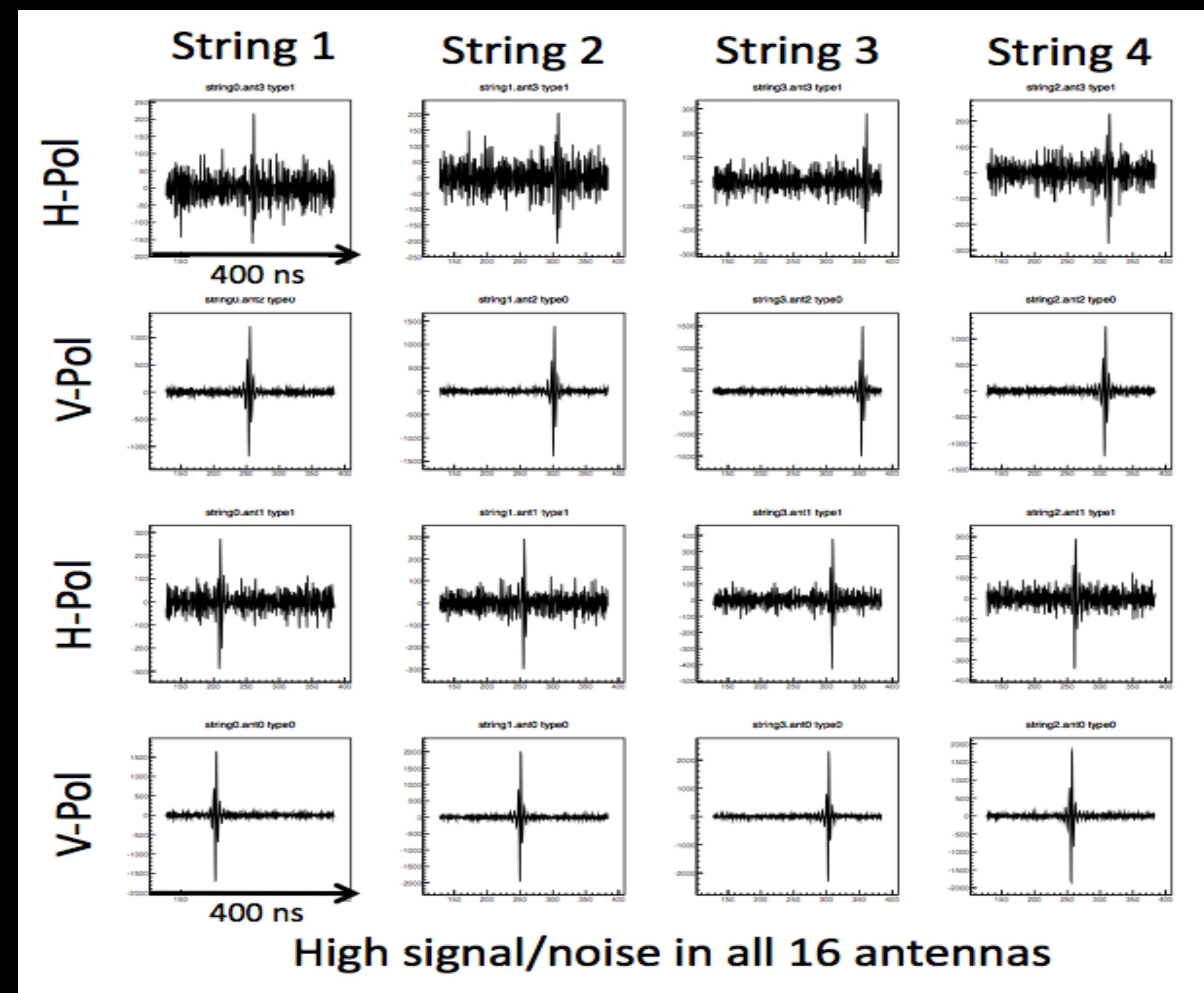
Antenna requirements:
1. Broadband 150~850MHz
2. Azimuthal symmetry
3. Fit in the hole

ARA DATA

3 ARA stations operational



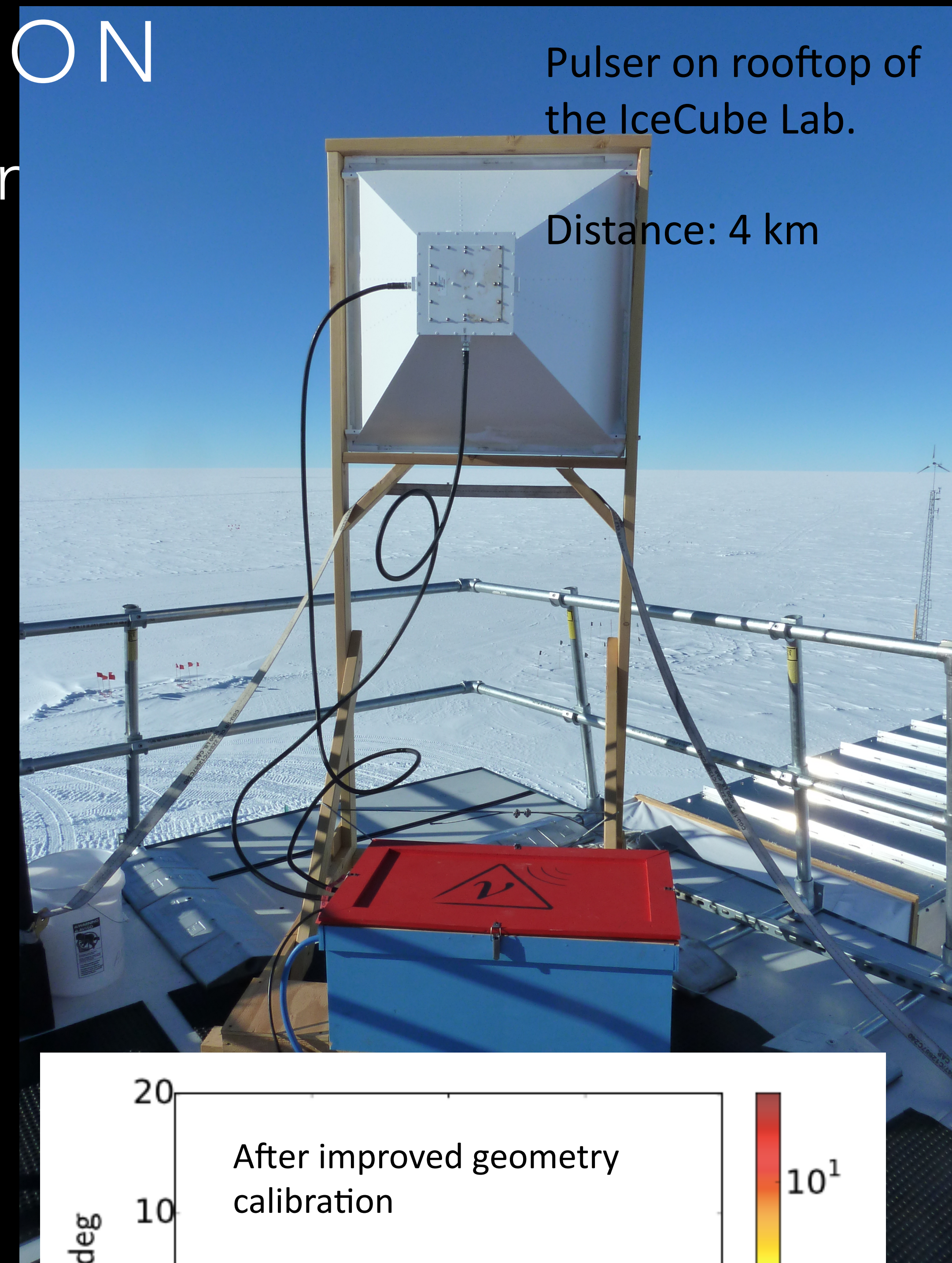
ARA02 Vpol calibration pulser event

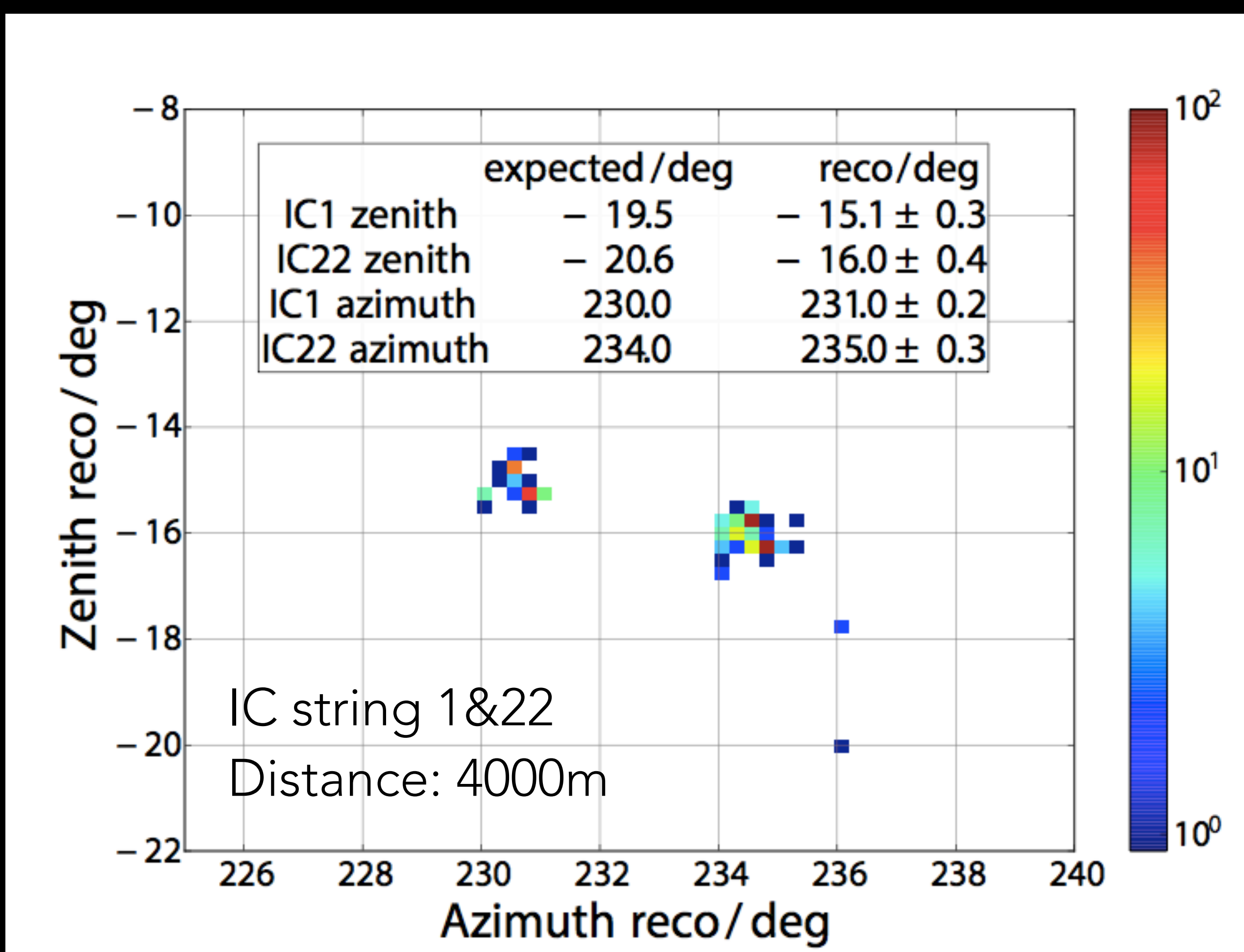


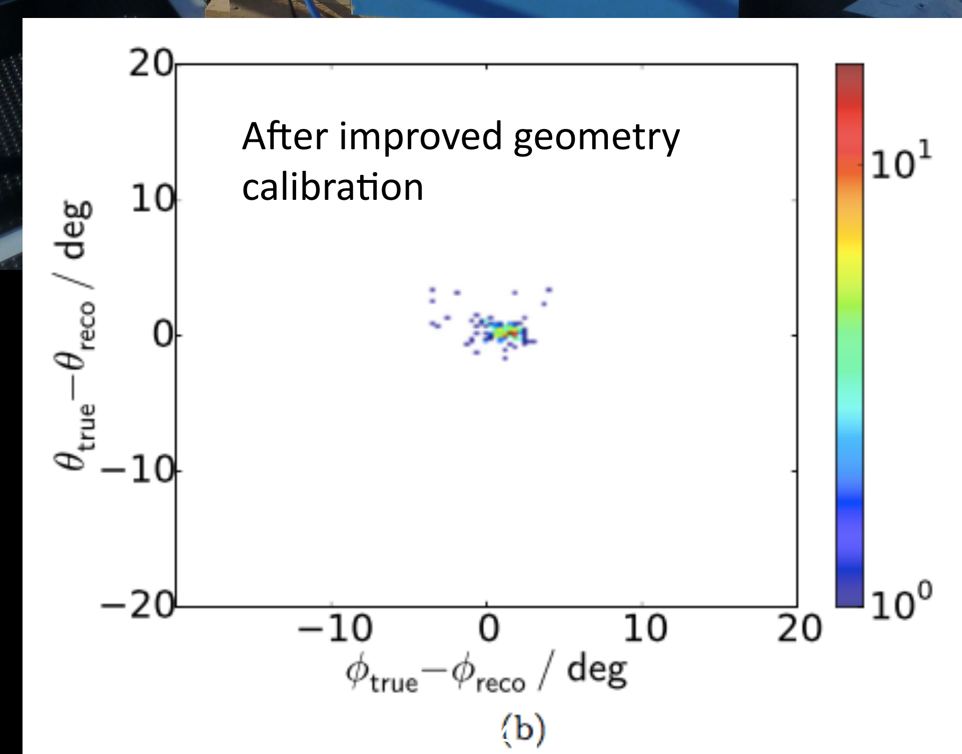
Simulated on-cone 10^{18}eV event 1.2km away

CALIBRATION

- No physical background for calibration
- Man-made calibration source:
  Local cal pulser
  IceCube Deep pulser(~1.5km deep)
  IceCube rooftop pulser
  Mobile surface pulser



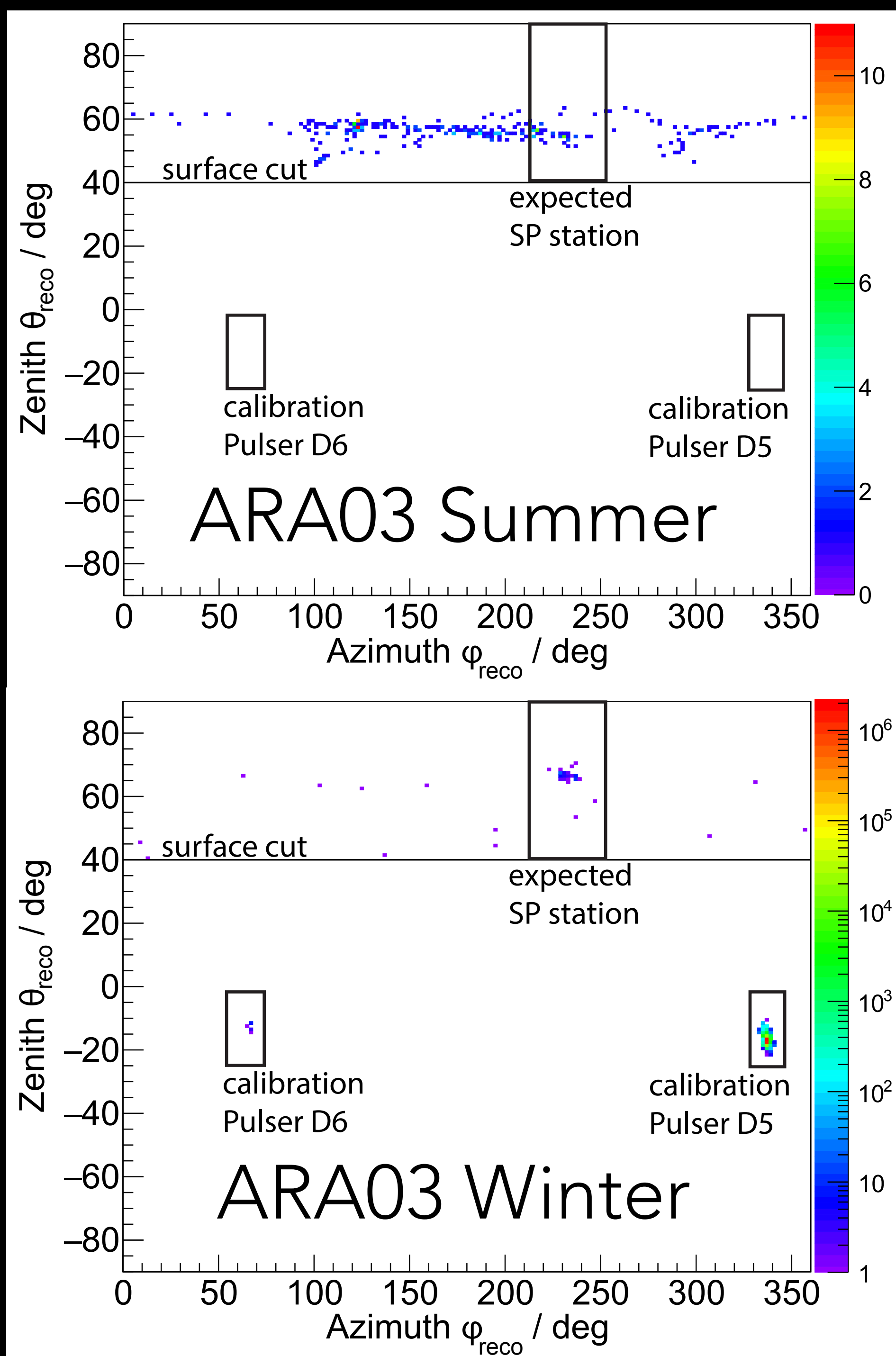


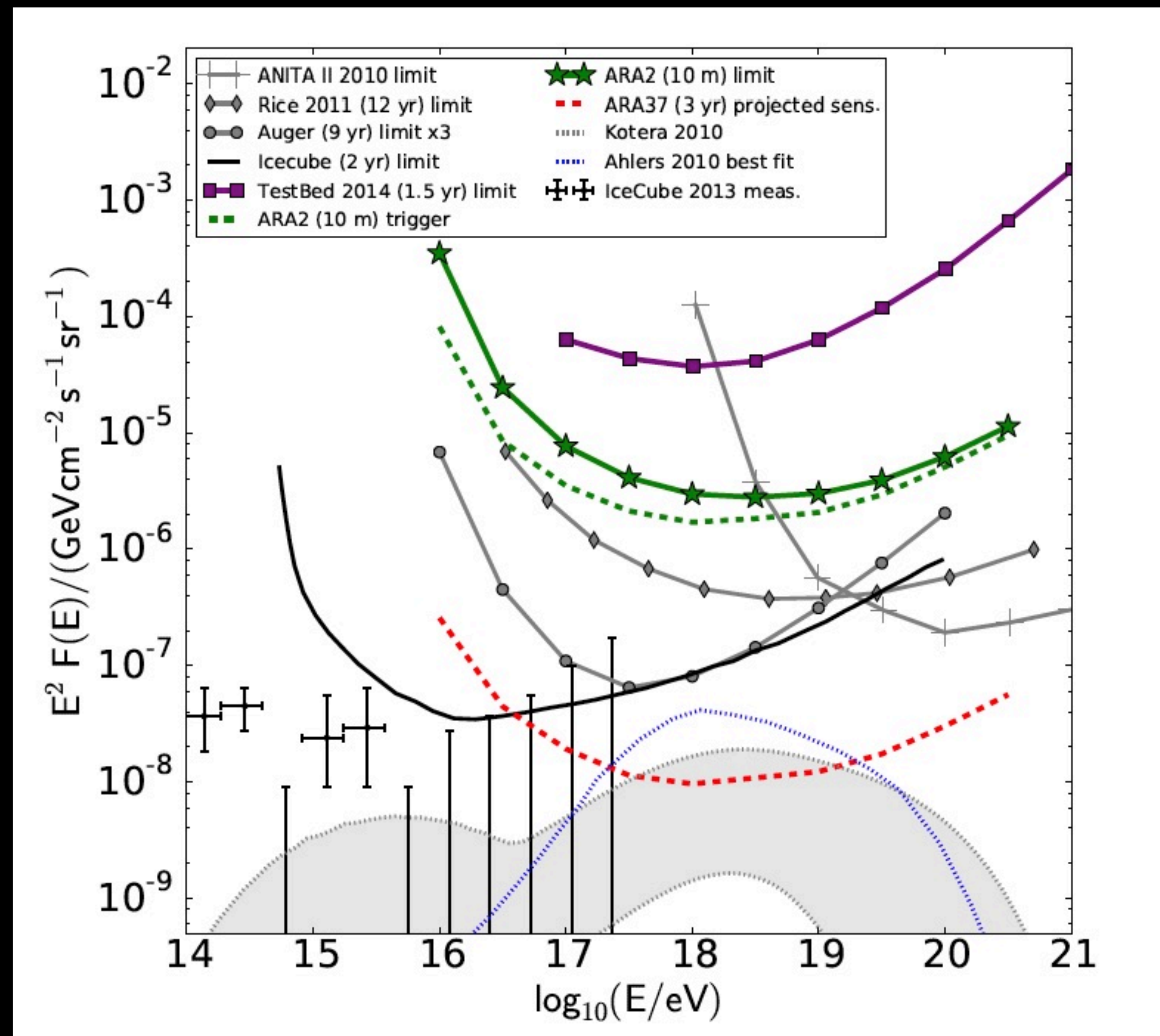


stitute

2 STATIONS ANALYSIS

- Data from station 2 & 3 in 2012-13 season was used in neutrino search
- No candidate found in 10 month period.
  Expected neutrino: 0.11 +- 0.002
  Expected background: ARA02 0.009+-0.010, ARA03 0.011+-0.015
  (Allison et al. arXiv:1507.08991)





INTERFEROMETRIC RECONSTRUCTION (PRELIMINARY)

- In principle, Askaryan signals should behave similarly in time-domain across registered receiving antenna
- Cross correlating a pair of different waveforms indicates the signal "delay" between two channels
- For reconstruction, set of delays associated with each point in the sky is computed. Cross correlation values are computed per these delays and summed

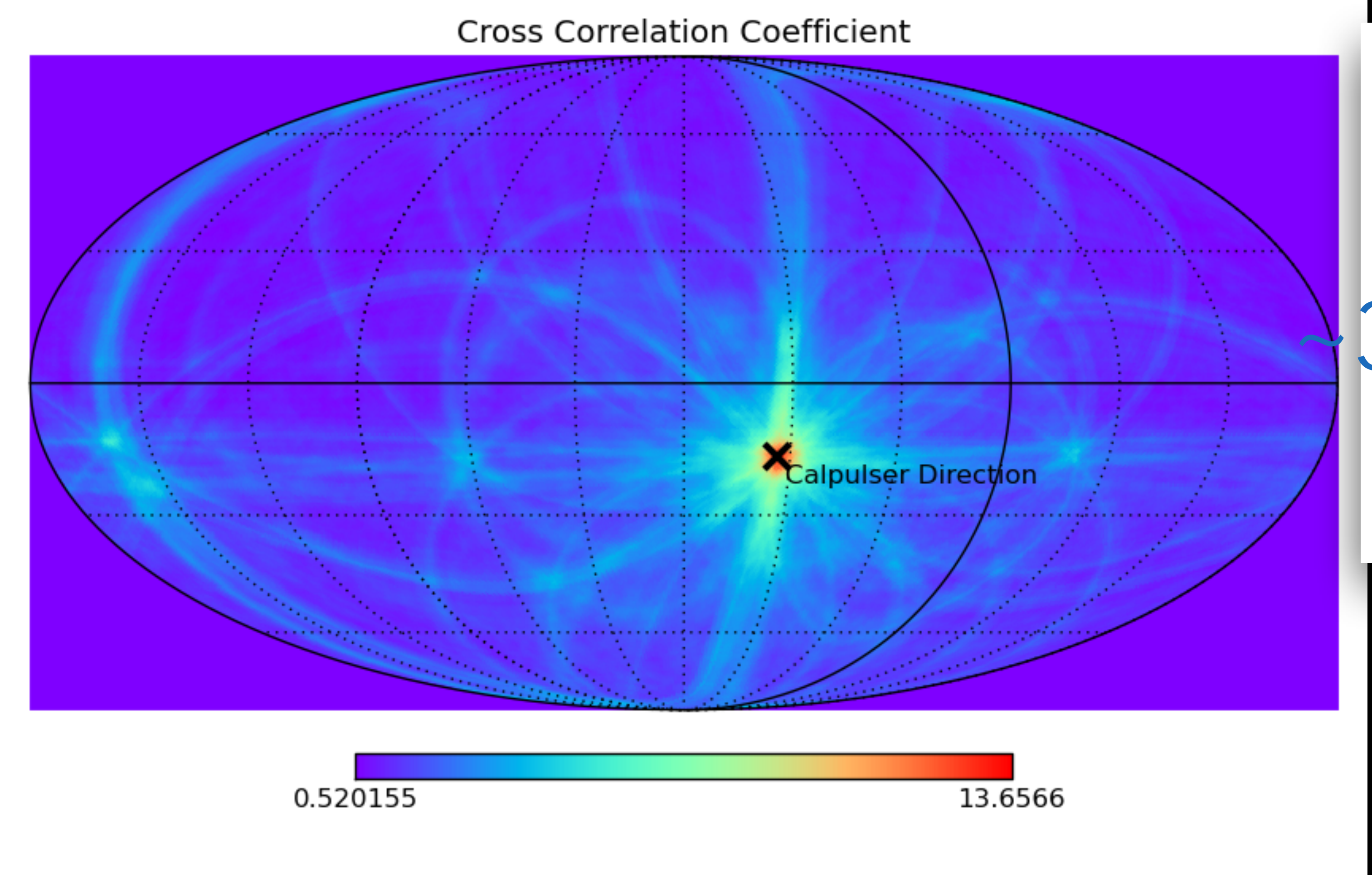
$$P_{\Sigma}(\hat{r}) = \frac{1}{Z_L T} \int_0^T \sum_{i=1}^{N_A} \sum_{j=1}^{N_A} dt \cdot v_i(t+\tau_i(\hat{r})) v_j(t+\tau_j(\hat{r}))$$

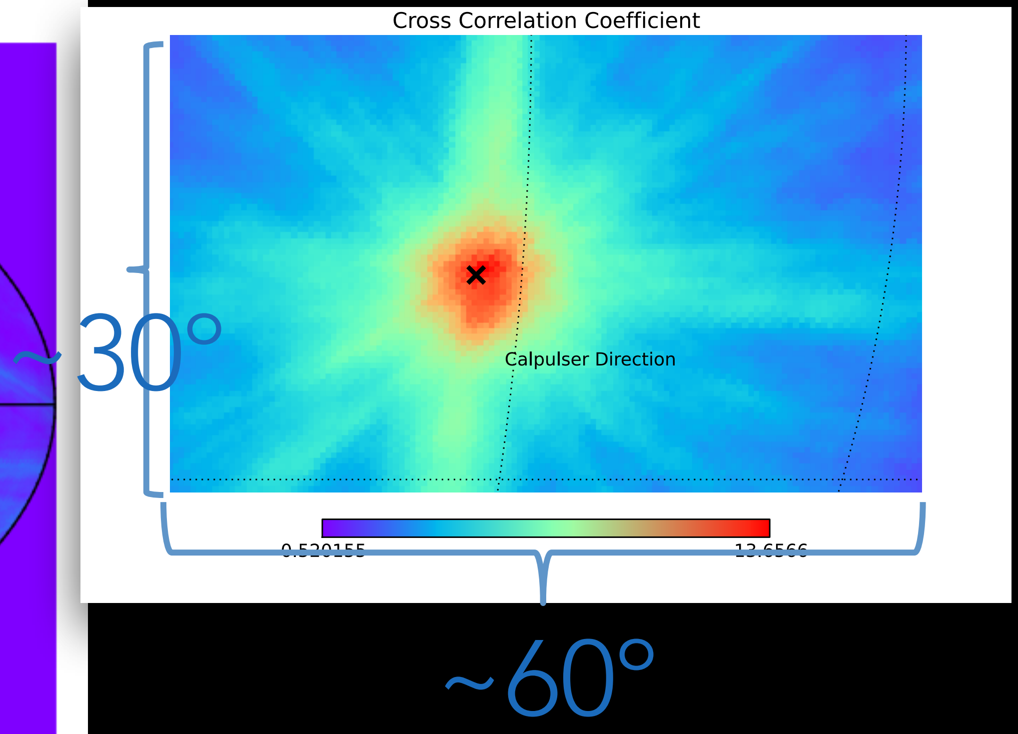
$$= \sum_{i=1}^{N_A} P_i + \frac{1}{Z_L T} \sum_{i=1}^{N_A} \sum_{j \neq i} v_i \otimes v_j(\hat{r}),$$

$$P_i = \frac{1}{Z_L T} \int_0^T dt \cdot v_i^2(t)$$

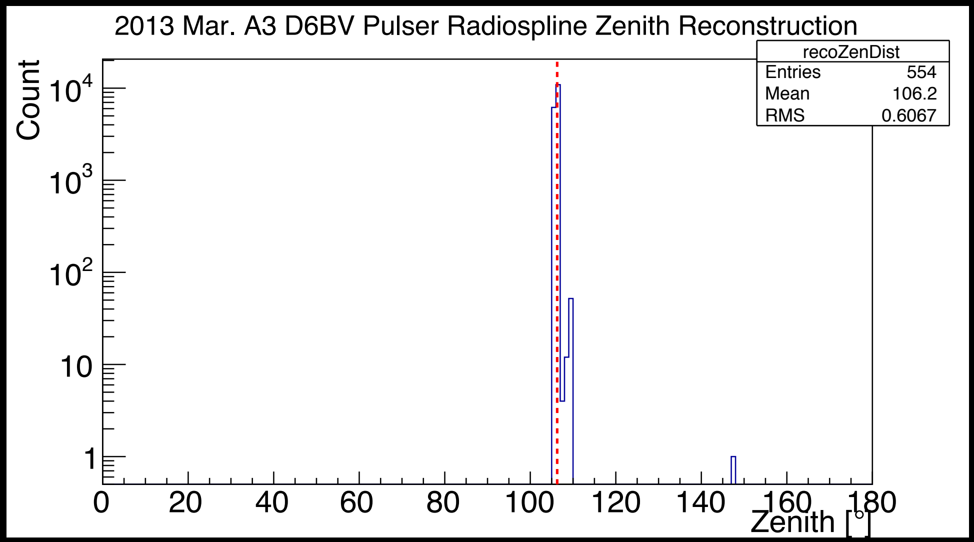
"COHERENCE", CONTAINS VERTEX POSITION INFO

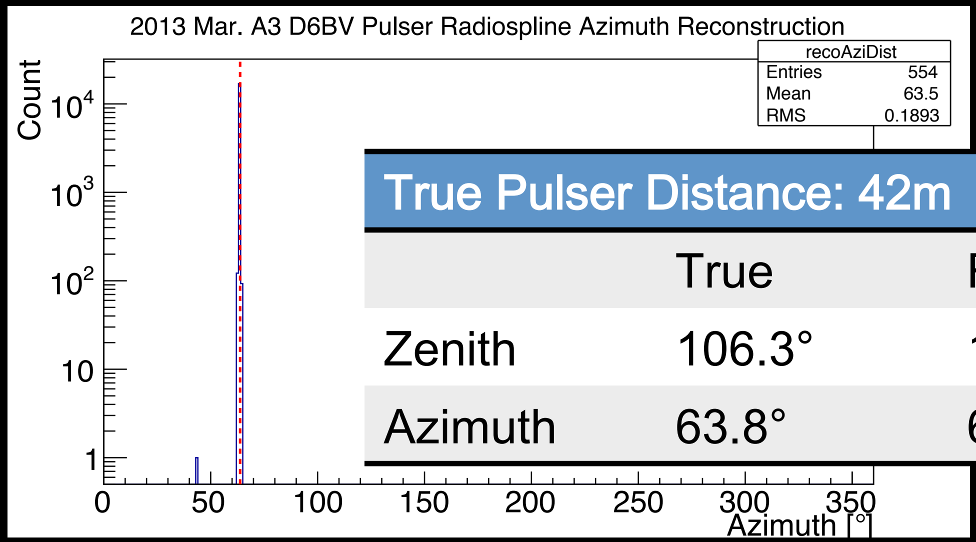
ANGULAR RECONSTRUCTION -CALIBRATION PULSER





- 2013 ARA03 March filtered events -D6BV pulser
- Pulser distance fixed as known (42m)



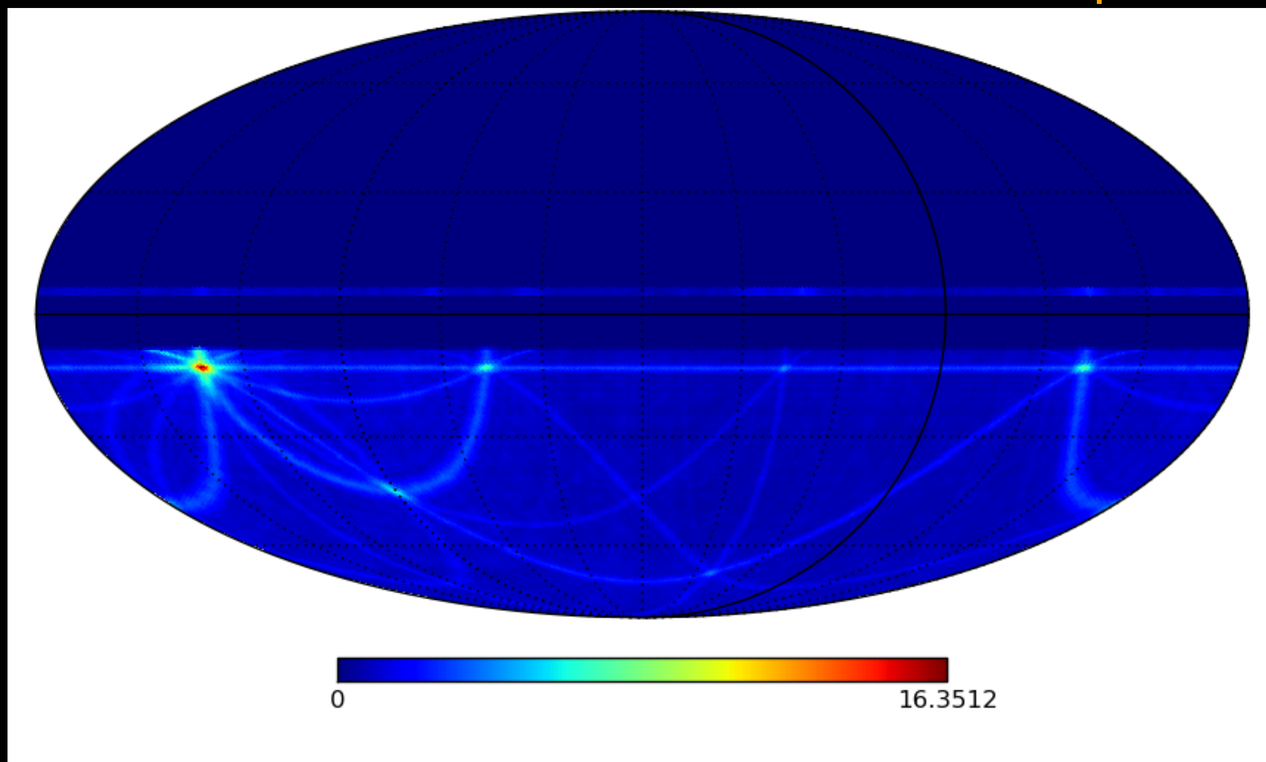


True Pulser Distance: 42m

	True	Reco Mean	Diff.
Zenith	106.3°	106.2°	-0.1°
Azimuth	63.8°	63.5°	-0.3°

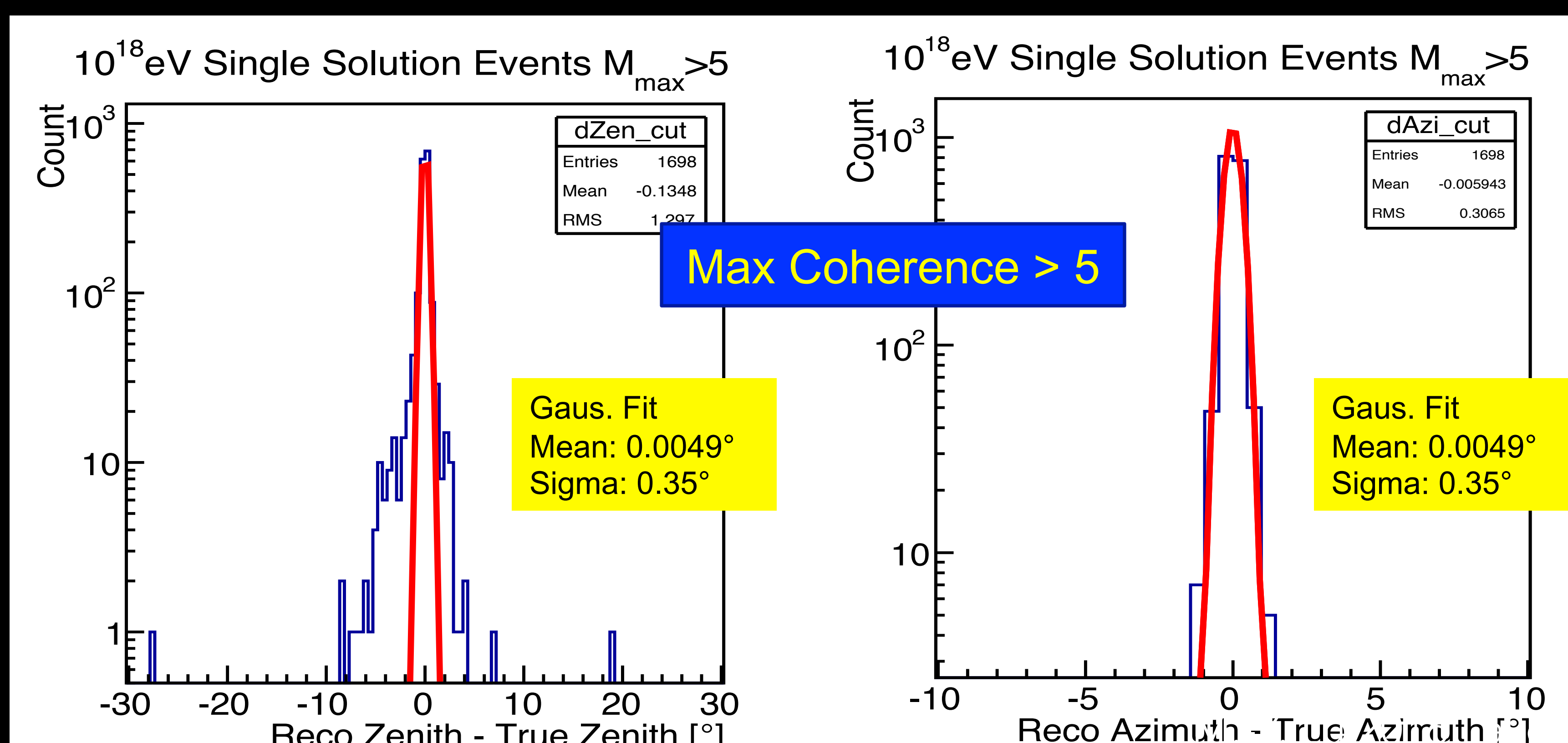
ANGULAR RECONSTRUCTION - SIMULATION (PRELIMINARY)

- Data set: 10^{18}eV neutrinos vertices randomly scattered around single ARA station, up to 5km



Example Event

True Vertex Distance: 2581m			
	True	Reco	Diff.
Zenith	102.74°	102.94°	0.2°
Azimuth	222.69°	222.89°	0.2°



SUMMARY

- 2 ARA stations taking data for more than 3 years. Analysis of 2 stations×year data finds no neutrino candidate. Analysis chain established and detector largely understood

- New analysis techniques to be applied to recent data.
  Coherence cut ✔: σ_θ:1.3° σ_ϕ:0.31°

- Funded 2017/18 for 2 more stations (5 total). GZK discovery potential ~ IceCube

- Full ARA37 will be most cost-effective determining cosmic neutrino flux > 100PeV, complementary to IceCube

- Very young field. R&D to be done to lower energy threshold, cost

THANK YOU

Published:
TestBed Performance: Astroparticle Physics 35 (2012) 457 (**arXiv:1105:2854**)
TestBed Diffuse Limit: Astroparticle Physics 70 (2015) 62 (**arXiv:1404.5285**)
TestBed GRB limit: **arXiv:1507.00100** (subm to Astrop. Phys.)

In publication:
Recently the first paper submitted on ARA design station result:
ARA2 Diffuse Limit: **arXiv:1507.08991**

BACK-UP SLIDES

CALCULATION OF COSMOGENIC NEUTRINO FLUX

$$F(E_\nu) = \frac{c}{4\pi E_\nu} \cdot \int \int L(z, E_p^s) Y(E_p^s, E_\nu, z) \frac{dE_p^s}{E_p^s} dz.$$

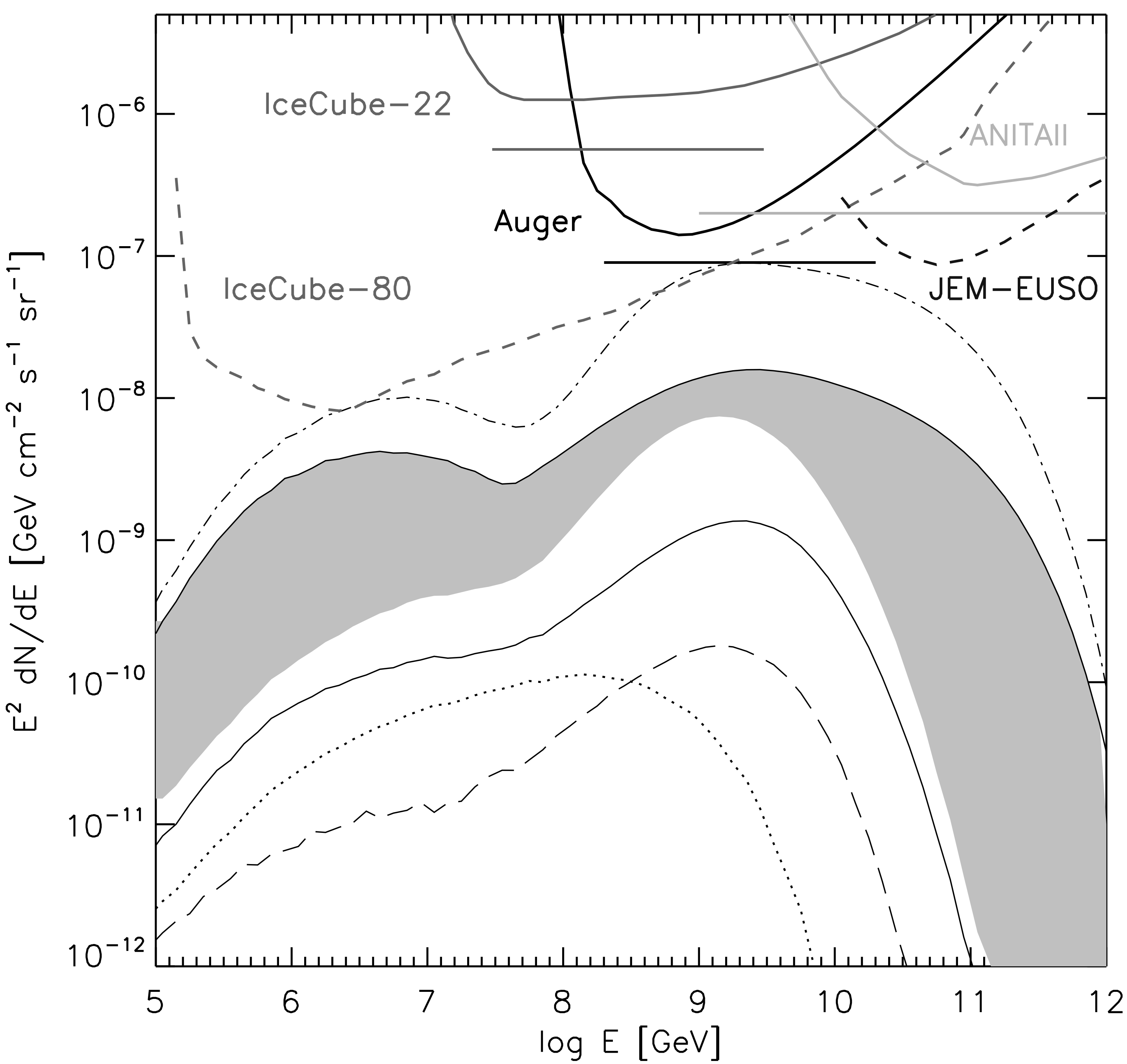
primary energy

source function

neutrino yield

R. Engel, D. Seckel. T. Stanev
Phys.Rev.D64:093010,2001

FLUX DEPENDENCIES



A. Olinto, K. Kotera, D. Allard
arXiv: 1102.5133 (2011)

Dash-dotted: FRII strong source evolution, pure proton composition

Grey region: A range of SFR source evolutions, mixed composition

Solid: grey + uniform source evolution

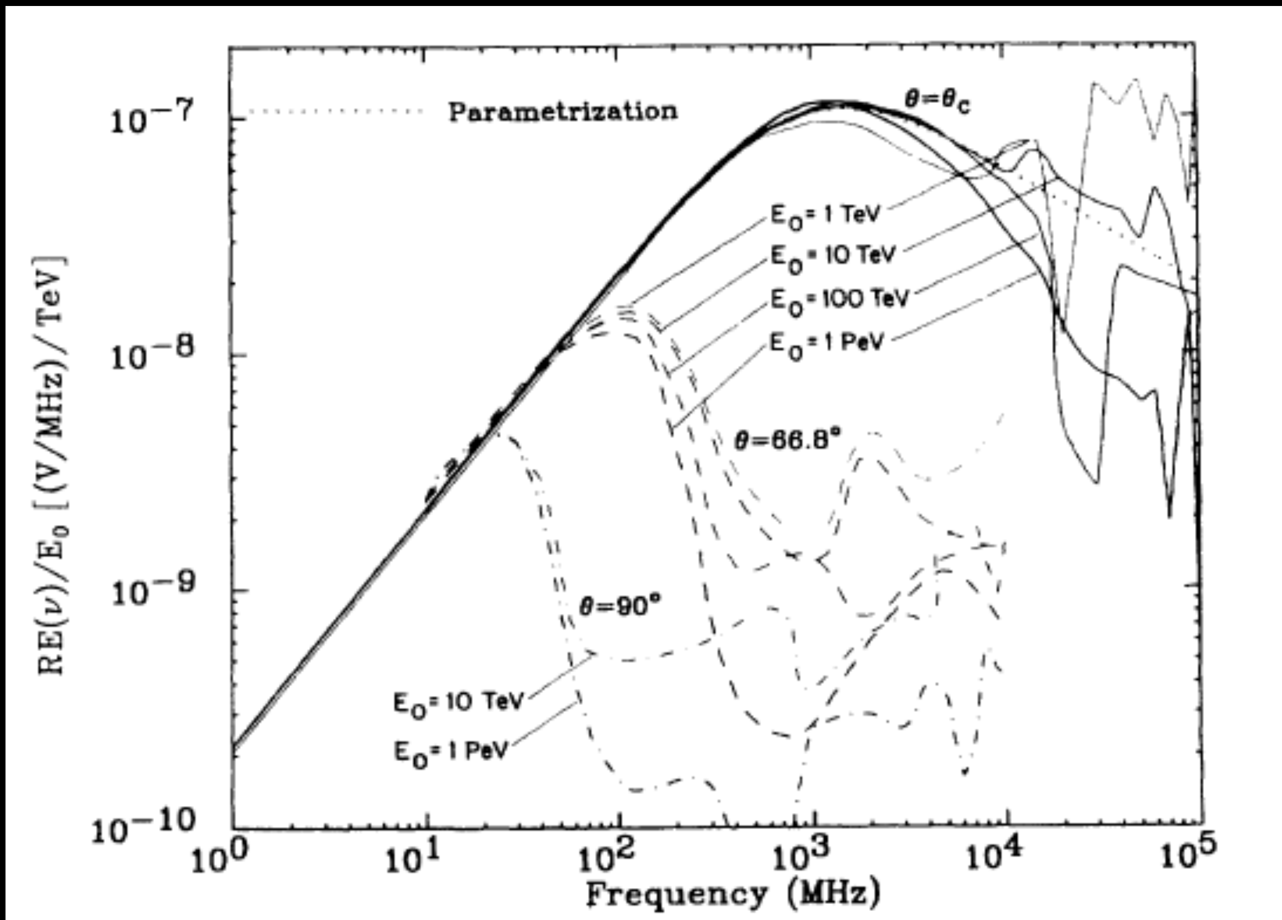
Dotted: uniform source evolution, iron-rich composition, low Ez_{max}

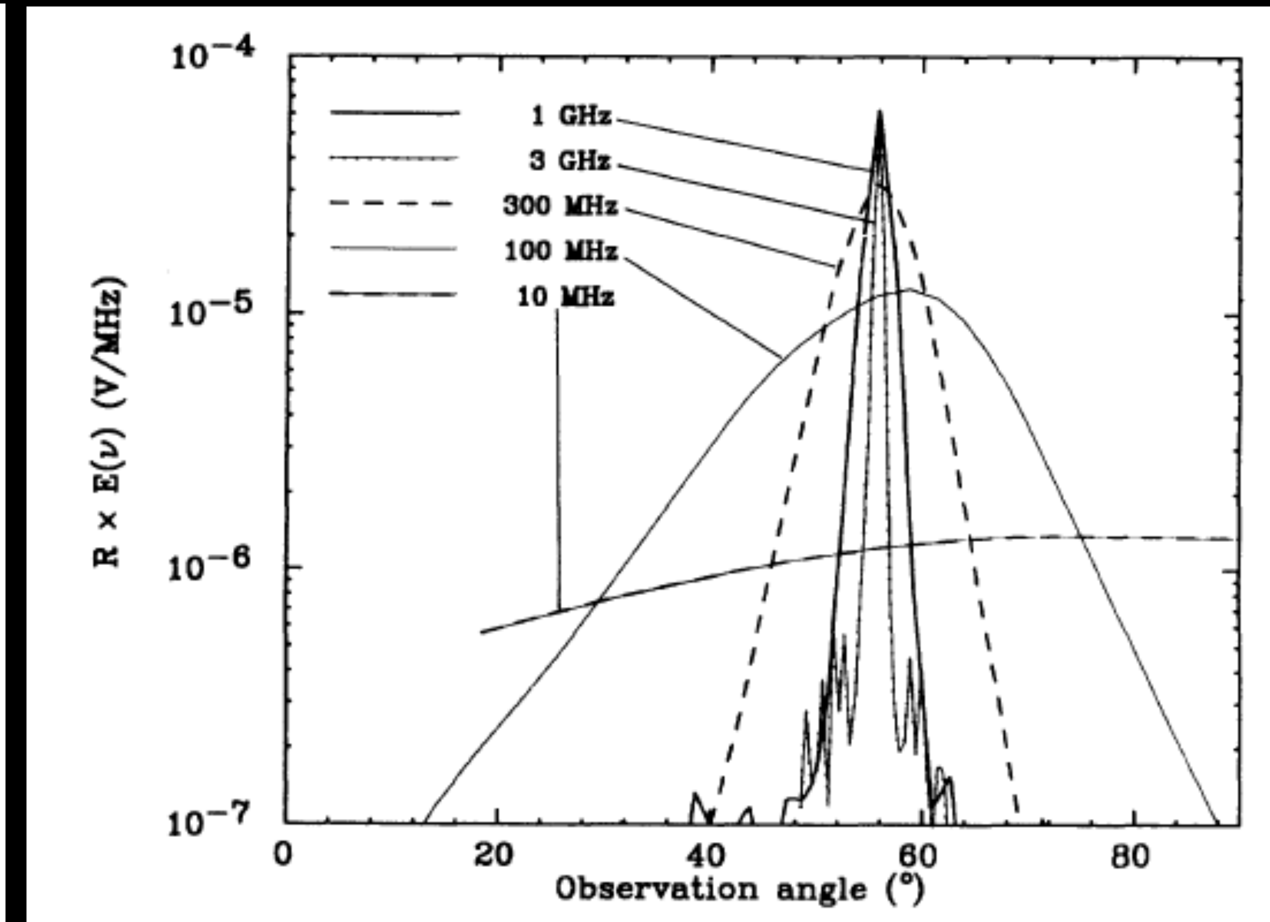
Dash: uniform source evolution, pure iron composition, high Ez_{max}

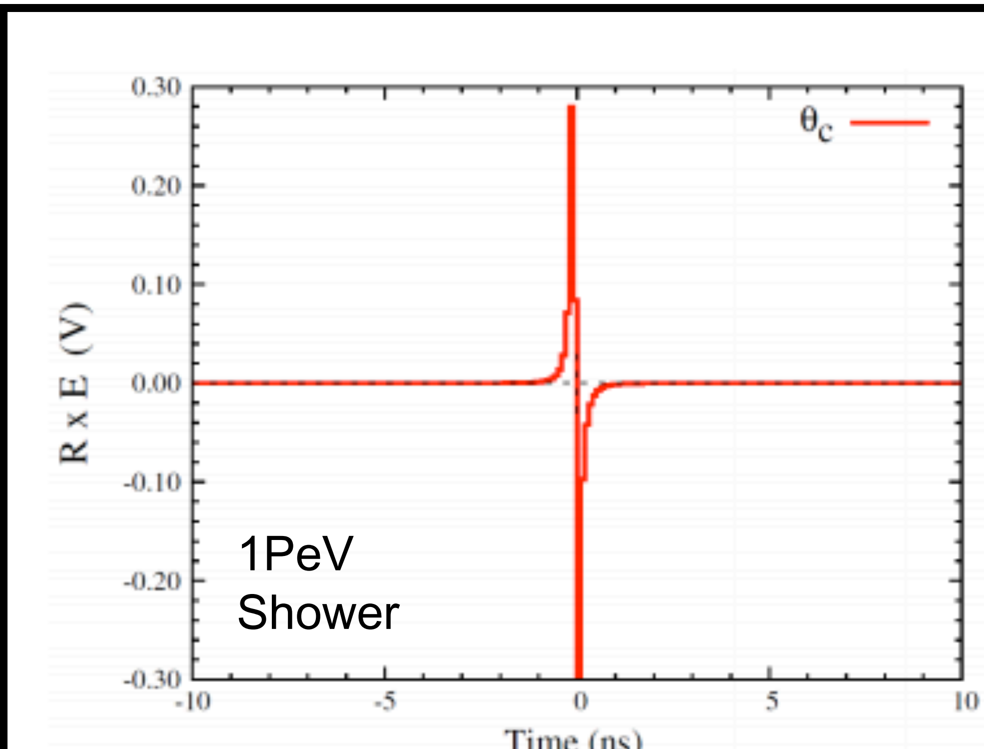
Measurement of the neutrino flux:

1. Correlation with astrophysical sources
2. Implication on cosmic ray composition
3. Constrain source distribution
4. Particle physics at the highest energies

ASKARYAN SIGNAL MODELING



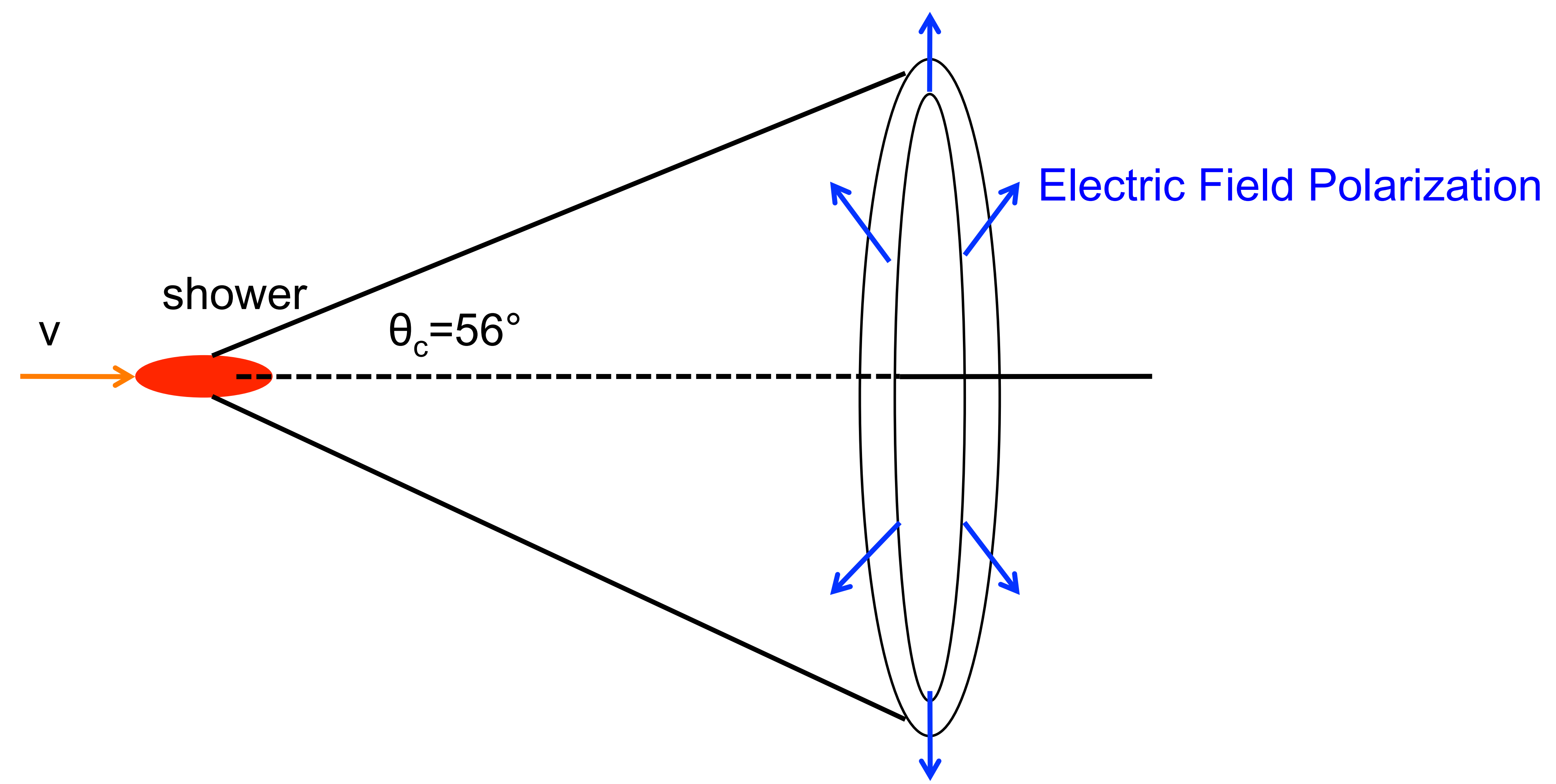




Detection in silica sand (Phys. Rev. Lett. (2001) 86.2802)
Detection in rock salt (Phys. Rev. D72(2005) 032002
Detection in ice, SLAC (Phys. Rev. Lett (2007). 99:171101)

Peak emission 0.1~1GHz
$P \sim N_e^2 \sim E^2$
Highly polarized broadband signal

ASKARYAN SIGNAL POLARIZATION



LPM EFFECT & NC/CC INTERACTIONS

LPM Energy threshold ~ several PeV

PHYSICAL REVIEW D **61** 023001

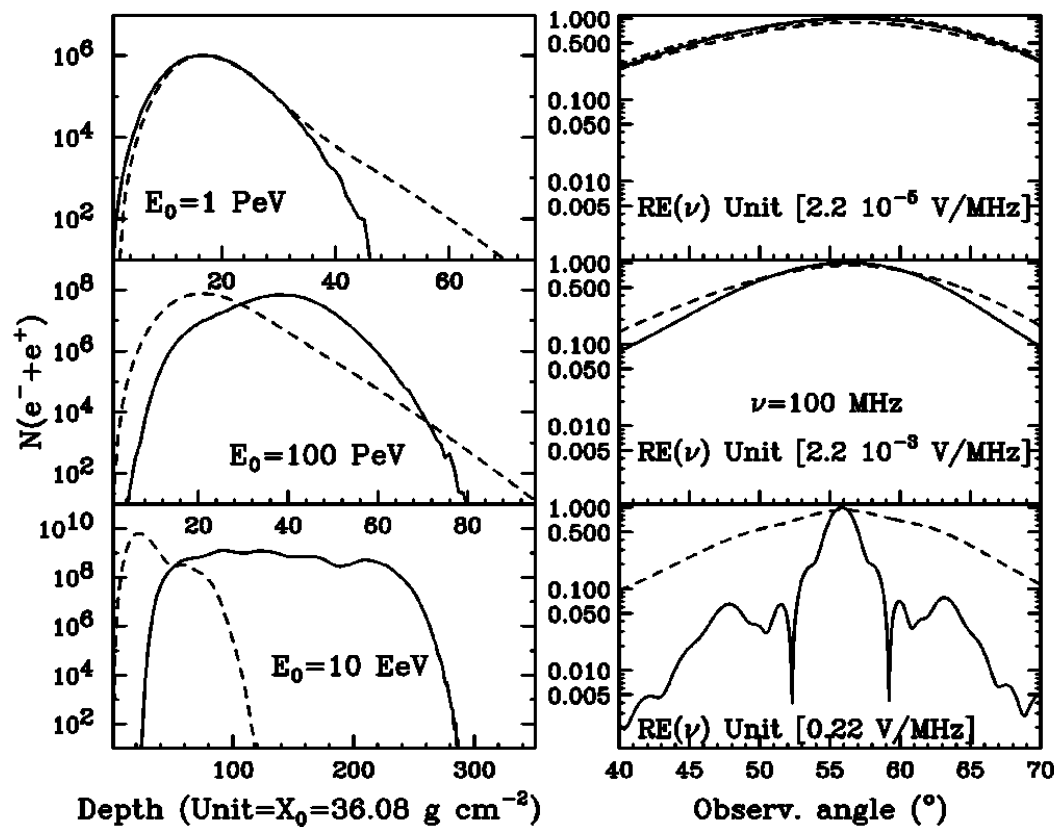


FIG. 1. Left: longitudinal development of electromagnetic (solid lines) and hadronic (dashed lines) showers in ice for different energies. Right: angular distribution of the electric field amplitude emitted by the showers shown on the left. Shown is the value $|E(\nu)R|$ where R is the distance to the shower, normalized to its maximum at the Cherenkov angle ($\theta_C = 56°$). The units, that is the precise values at the maximum, are marked in the figure. For the 1 PeV case the electric field amplitude obtained in a complete simulation [13] (dot-dashed line) is also shown to compare with the approximation used [Eq. (3)].

LPM EFFECT & NC/CC INTERACTIONS

LPM Energy threshold ~ several PeV

J. ALVAREZ-MUÑIZ, R. A. VÁZQUEZ, AND E. ZAS   PHYSICAL REVIEW D **61** 023001

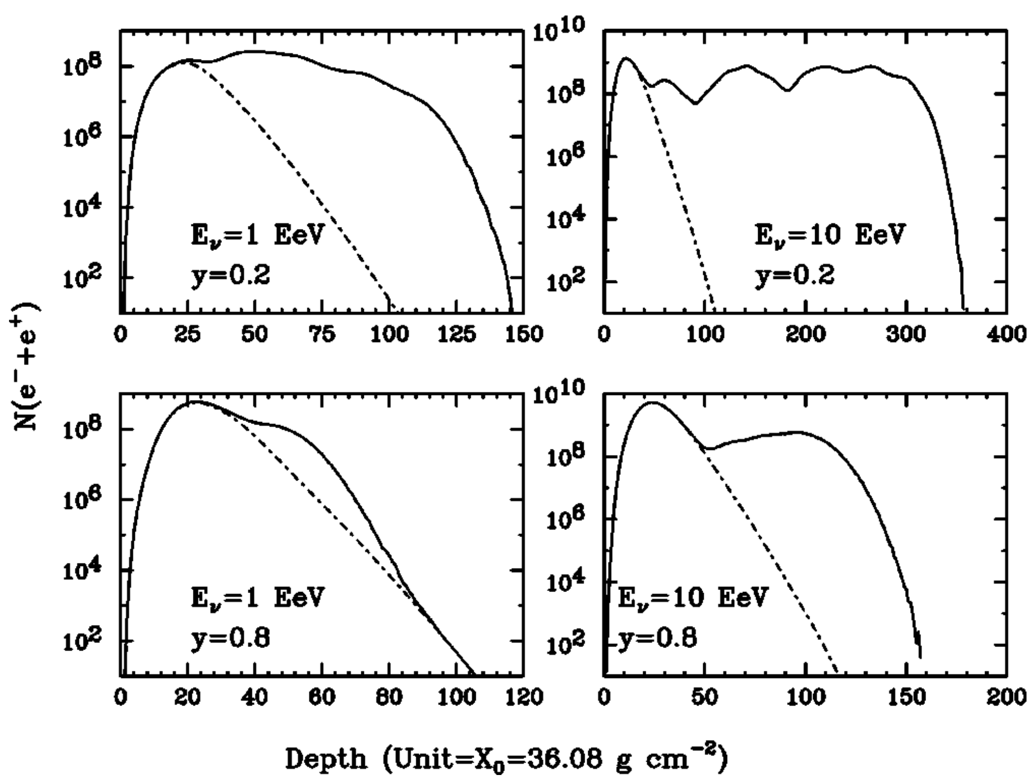


FIG. 3. Longitudinal development of hadronic (dot dashed lines) and mixed showers (solid lines) initiated by neutrino interactions in ice (see text) for different values of neutrino energy and y as marked.

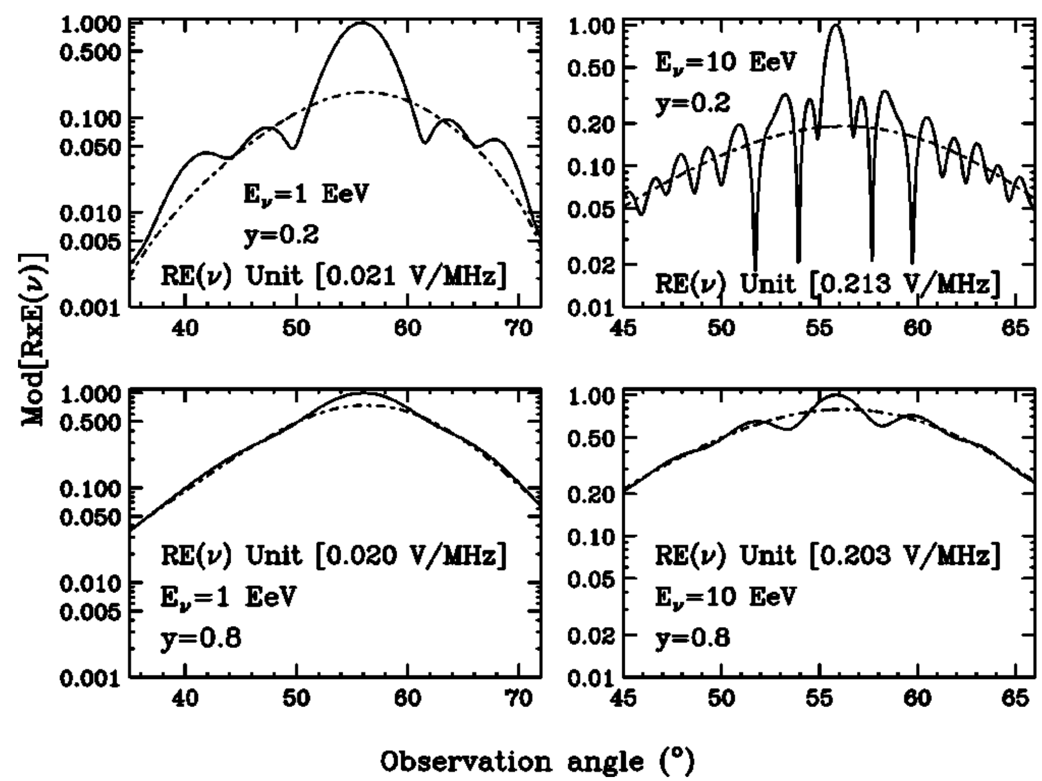


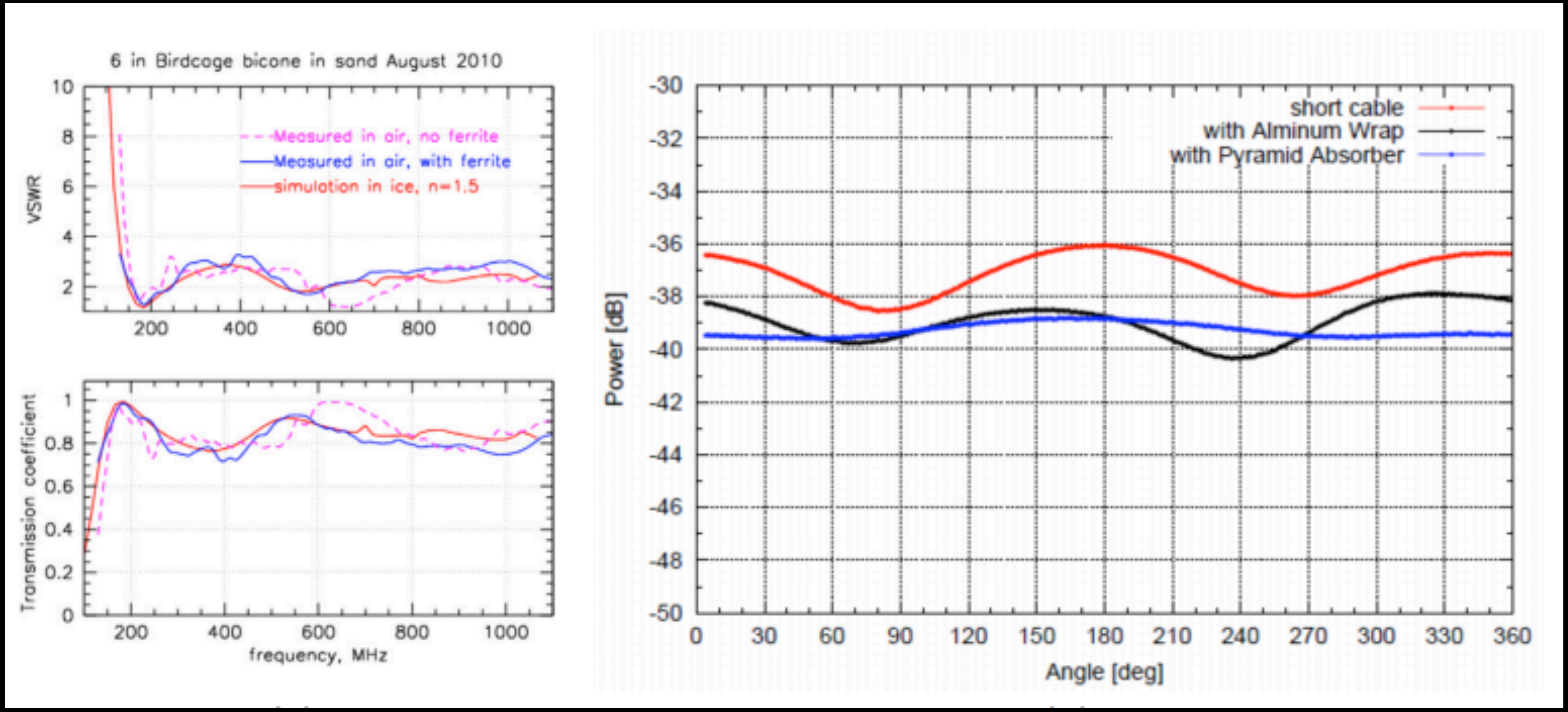
FIG. 4. Interference pattern for $\nu = 100$ MHz corresponding to the showers of Fig. 3. The figure plots $|E(\nu)R|$ following the convention of Fig. 1.

DRILLING AND DEPLOYMENT

Hot-water drilling
Water pumped out and leaves dry hole
Hole diameter ~15cm
Design depth 200m (8 hr)

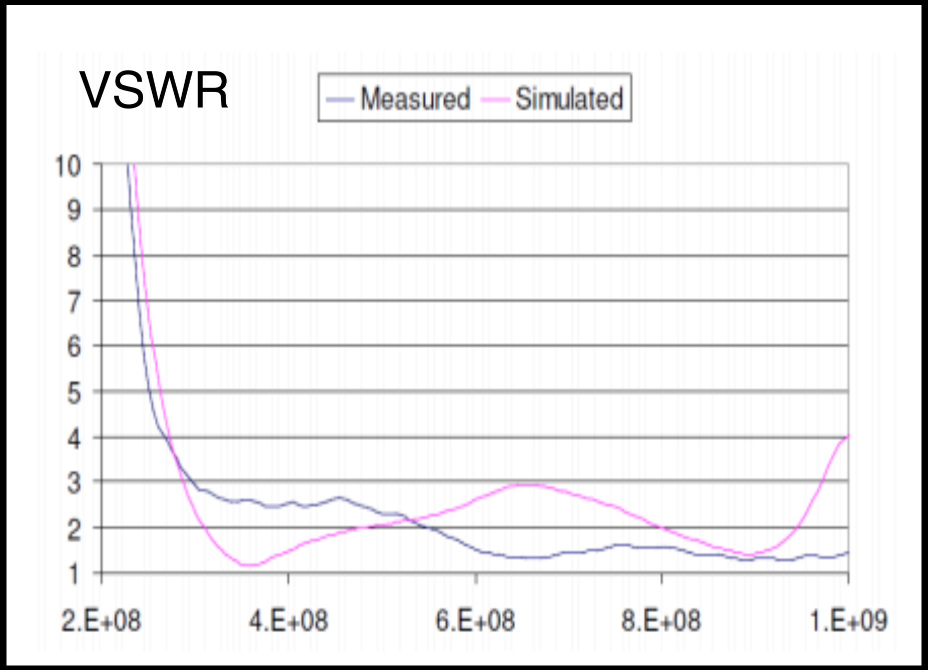
ANTENNA DESIGN

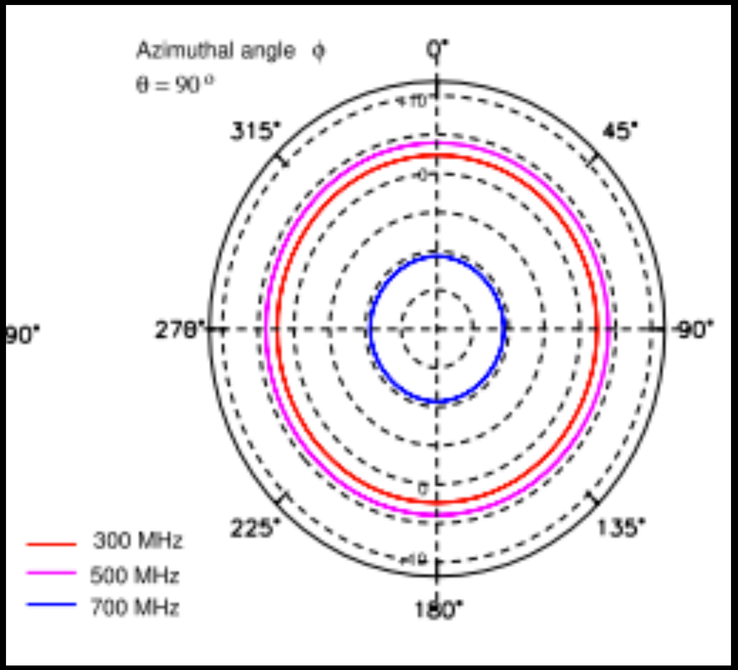
Vertically Polarized (Vpol)



ANTENNA DESIGN

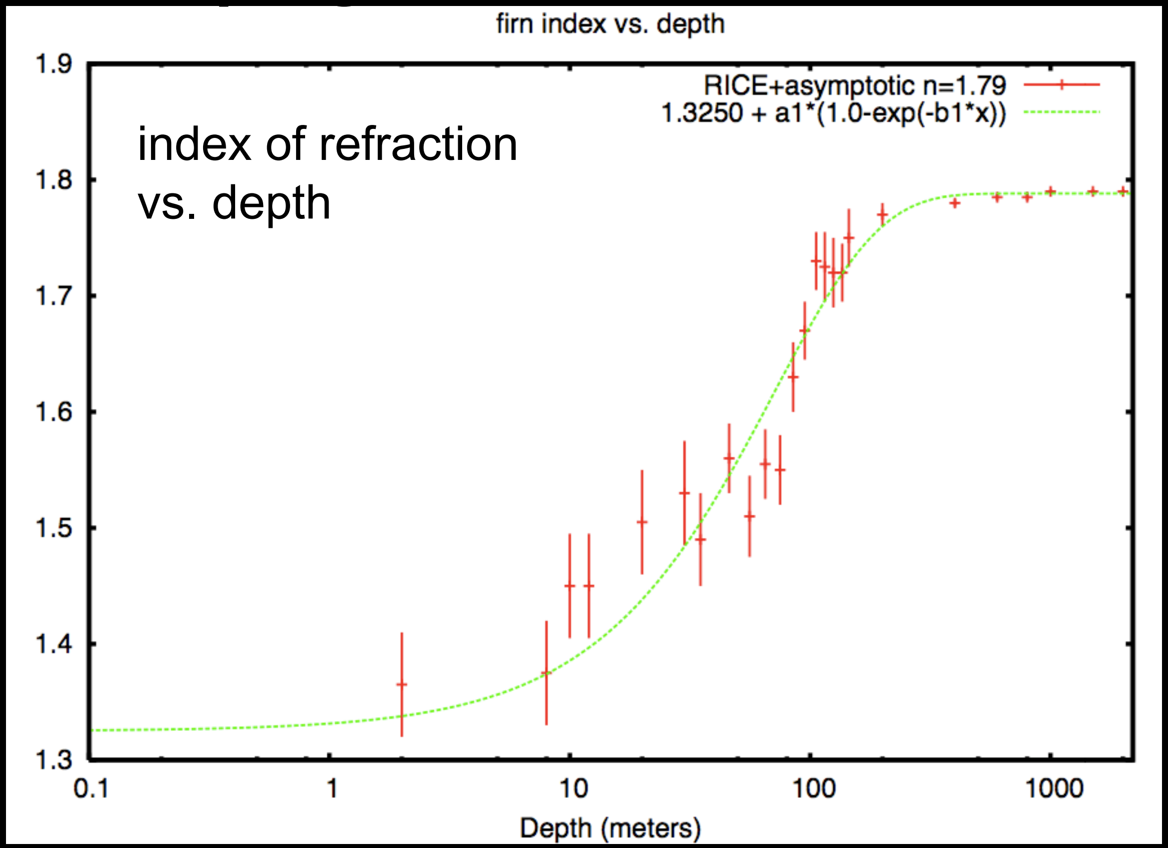
Horizontally Polarized (Hpol)

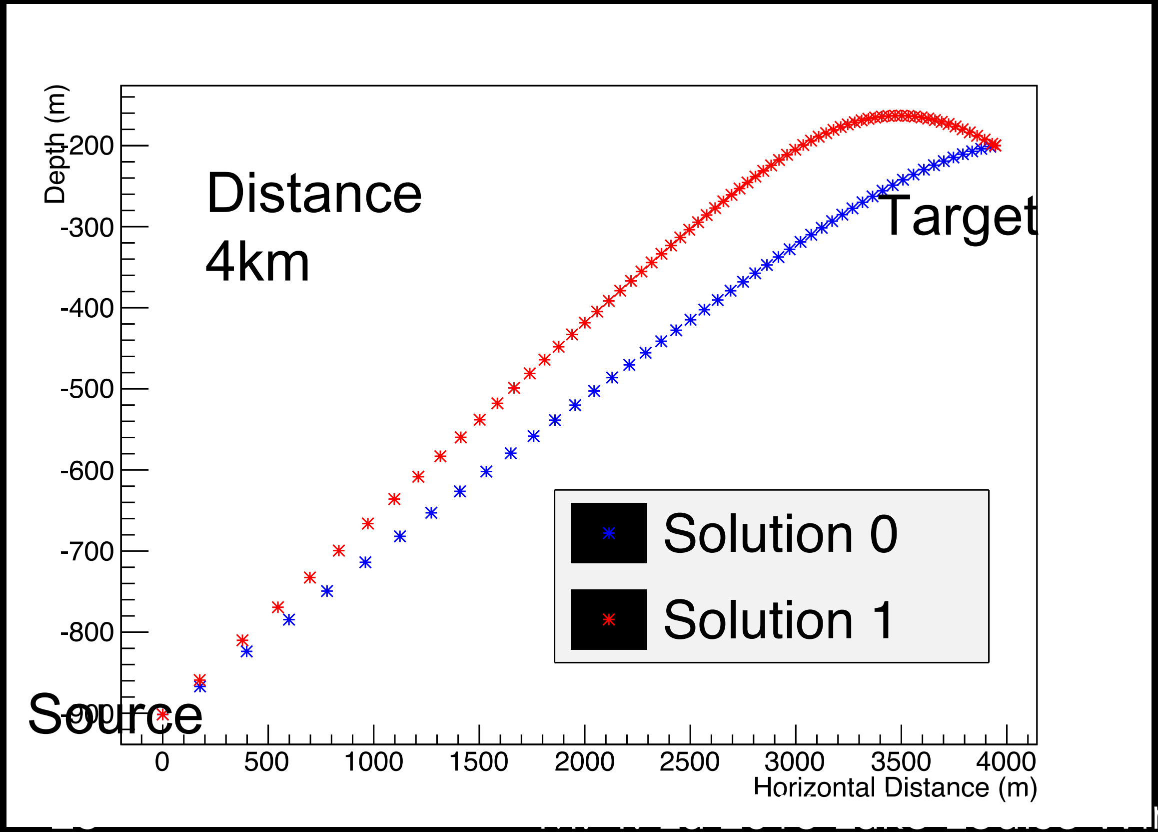




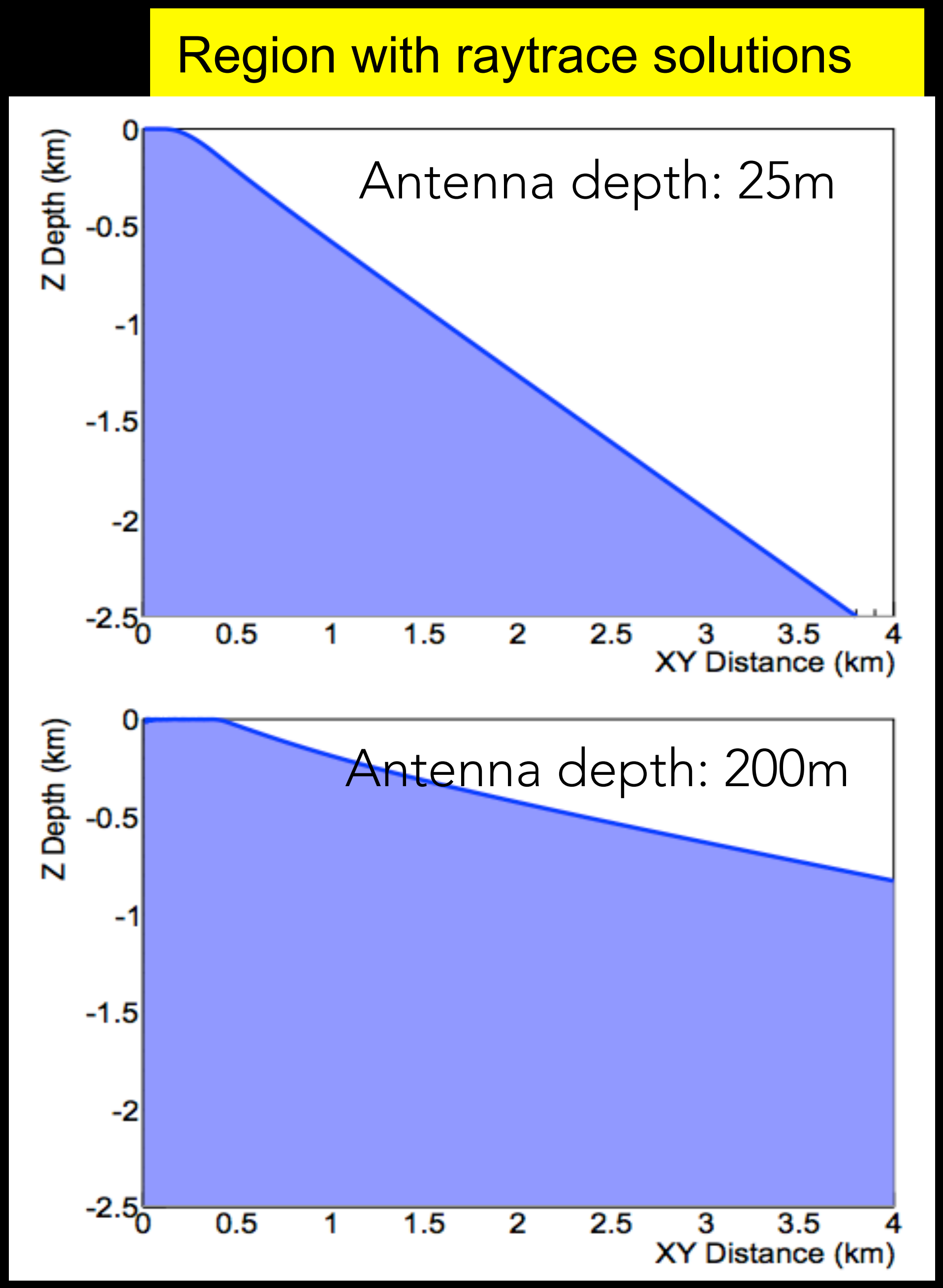
DELAY COMPUTATION

- Ice index of refraction varies with depth. Change is most drastic near surface (firn) -> EM waves travel in curved paths - raytracing
- Ideal direction/distance reconstruction need to take account raytracing effect
- Semi-analytical approach to compute ray paths. Tabulate and fit with B-Spline the delays thus computed





RETRACE SHADOW BOUNDARY



Ray Tracing

C. Weaver

- The problem is a system of ODEs so one can use standard ODE techniques, such as Runge-Kutta
- In particular, such methods can use an adaptive step size to move very quickly where the ray varies slowly

$$\frac{dx}{ds} = \sin(\theta) \qquad \frac{d\theta}{ds} = -sin(\theta)\frac{1}{n(z)}\left.\frac{dn}{dz}\right|_z$$

$$\frac{dz}{ds} = \cos(\theta) \qquad \frac{dt}{ds} = \frac{n(z)}{c} \qquad \frac{d\tau}{ds} = \frac{\tau}{A(z,f)}$$

(where τ is amplitude and A(z,f) is attenuation length as a function of depth and frequency)

Identifying Solutions

C. Weaver

- In general, we have two endpoints, and we want to know the properties of the ray(s) which connect them
- Solving the differential equations requires an initial angle which is unknown
- In general, must use trial and error to find a ray which travels from the source to the target, within some margin of error
- Allowing for reflections complicates matters

Semi-Analytical Approach

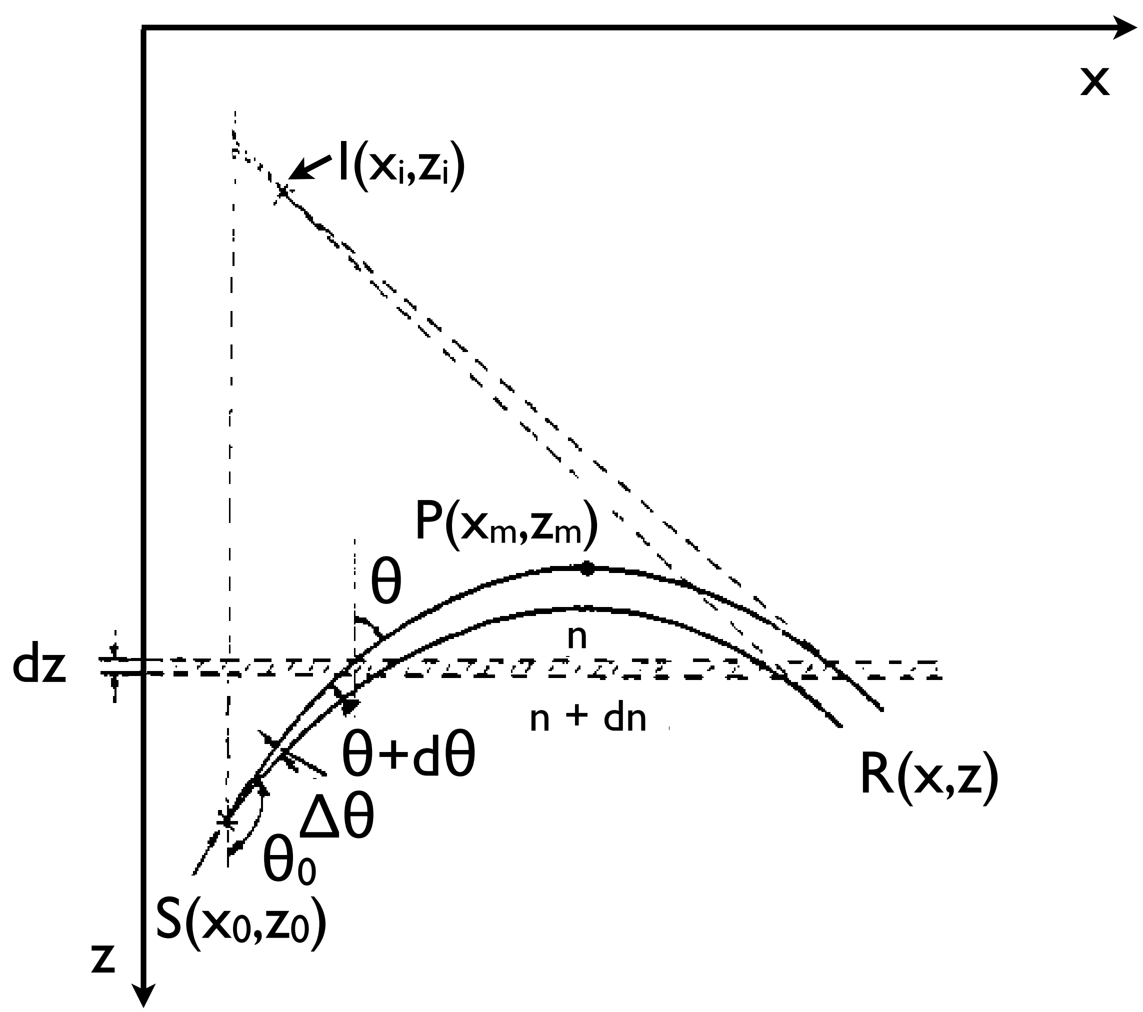
C. Weaver

- Casting lots of test rays is expensive!
- Sohda et al.: "Image formation in an optically stratified medium: optics of mirage and looming" (1967)
- For the case of a pure exponential index of refraction, the authors derive a functional form for the direct ray path
- Our index of refraction is a very similar form:

Sohda, et al.:	South Pole Ice:
$n(z) = Be^{Cz}$	$n(z) = A + Be^{Cz}$

C. Weaver

Schematic



(Base figure from Sodha et al.)

Sketch of Derivation

- From Snell's law: $n(z_0)\sin(\theta_0) = n(z)\sin(\theta)$
- Substituting n(z) and solving for θ gives:

$$\theta = \arcsin\left(\sin\theta_0 \frac{A + Be^{Cz_0}}{A + Be^{Cz}}\right)$$

- Also, we have: $\frac{dx}{dz} = \tan(\theta)$
- Substituting and rearranging gives:

$$x - x_0 = \int_{z_0}^{z} \tan\left(\arcsin\left(\sin\theta_0 \frac{A + Be^{Cz_0}}{A + Be^{Cz'}}\right)\right) dz'$$

Condition for Direct Ray

C. Weaver

- We arrive at:

$$\frac{C\sqrt{A^2-\sigma_0^2 n_0^2}}{\sigma_0 n_0}(x_0 - x) = \ln\left(\frac{\sqrt{n^2-\sigma_0^2 n_0^2}+\sqrt{A^2-\sigma_0^2 n_0^2}}{n-A} + \frac{A}{\sqrt{A^2-\sigma_0^2 n_0^2}}\right) - \ln\left(\frac{\sqrt{n_0^2-\sigma_0^2 n_0^2}+\sqrt{A^2-\sigma_0^2 n_0^2}}{n_0-A} + \frac{A}{\sqrt{A^2-\sigma_0^2 n_0^2}}\right)$$

where $\sigma_0 \equiv \sin(\theta_0), n_0 \equiv n(z_0), n \equiv n(z)$

- This cannot be solved analytically for σ_0, but it can be done numerically

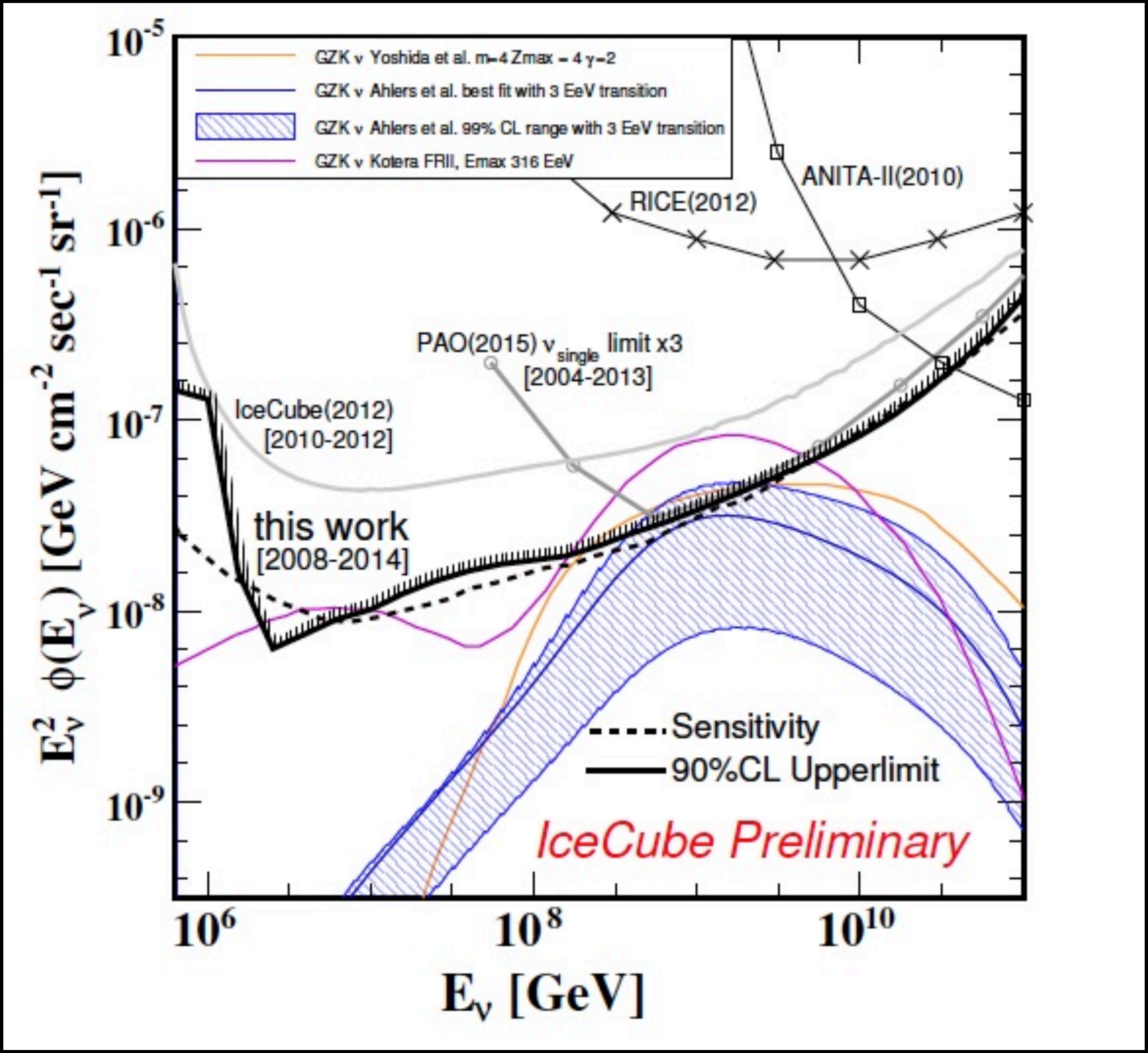
- This is much faster than doing the same thing (root finding), but using a ray-cast for each evaluation

DISCOVERY POTENTIAL

Model & references	N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:			
Protheroe & Johnson 1996 [27]		0.6	59
Engel, Seckel, Stanev 2001 [28]		0.33	47
Kotera,Allard, & Olinto 2010 [29]		0.5	59
Strong source evolution models:			
Engel, Seckel, Stanev 2001 [28]		1.0	148
Kalashev *et al.* 2002 [30]		5.8	146
Barger, Huber, & Marfatia 2006 [32]		3.5	154
Yuksel & Kistler 2007 [33]		1.7	221
Mixed-Iron-Composition:			
Ave *et al.* 2005 [34]		0.01	6.6
Stanev 2008 [35]		0.0002	1.5
Kotera, Allard, & Olinto 2010 [29] upper		0.08	11.3
Kotera, Allard, & Olinto 2010 [29] lower		0.005	4.1
Models constrained by Fermi cascade bound:			
Ahlers *et al.* 2010 [36]		0.09	20.7
Waxman-Bahcall (WB) fluxes:			
WB 1999, evolved sources [37]		1.5	76
WB 1999, standard [37]		0.5	27

ARA collaboration
arXiv:1105.2854

ICECUBE 6YRS EHE LIMIT



A. Ishihara for the IceCube collaboration, TAUP '15

ATTENUATION OF RADIO SIGNAL IN ICE

Dielectric const. $\varepsilon = \varepsilon' - i\varepsilon''$

Index of refrac. $n = \sqrt{\varepsilon'} = \sqrt{\mathrm{Re}(\varepsilon)}$

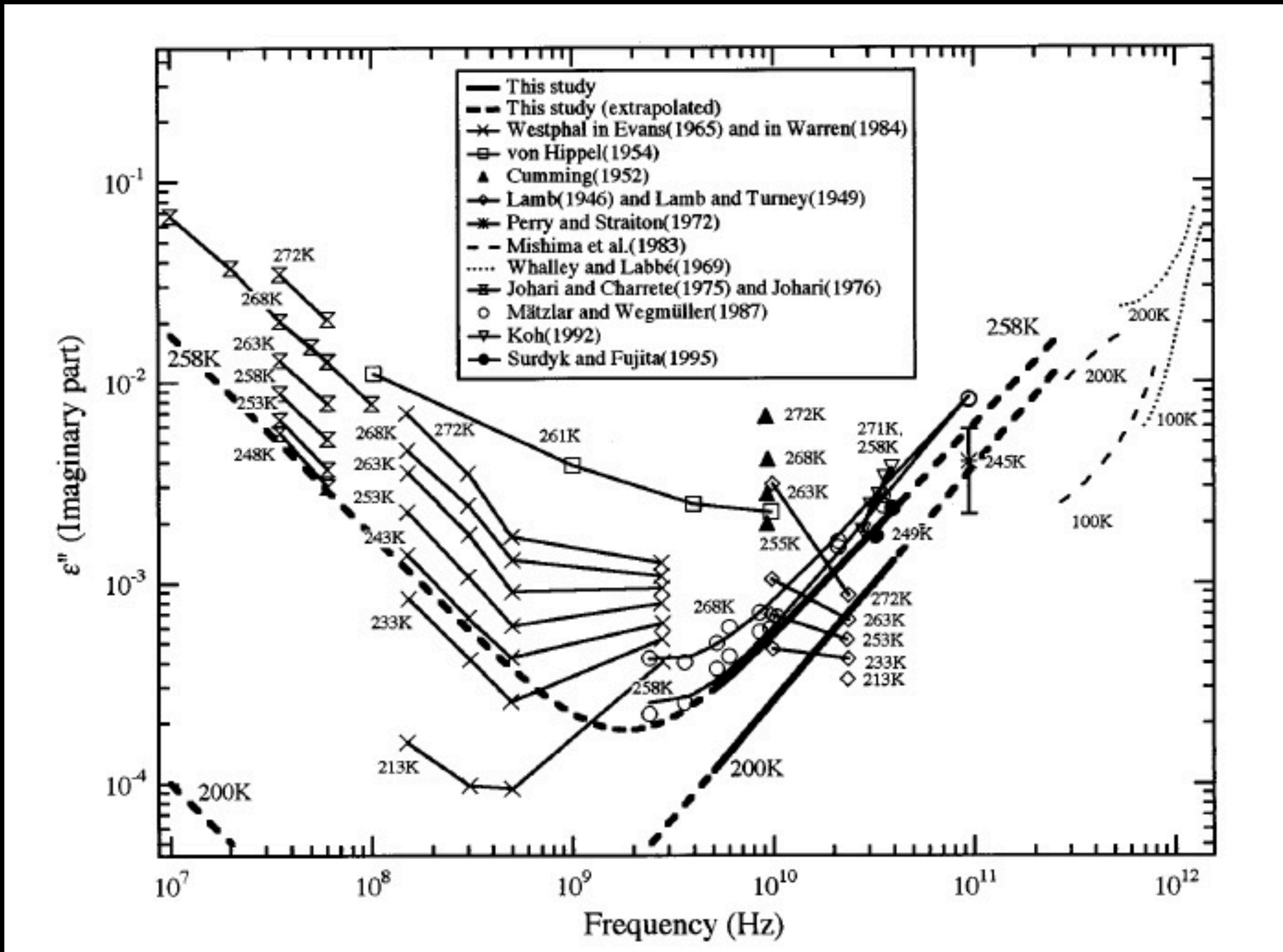
$$Loss(dB/m) = 8.686 \frac{\omega}{2c_0} \sqrt{\varepsilon'} \tan\delta$$

Loss tangent $\tan\delta = \varepsilon''/\varepsilon'$

Attenuation length $L_\alpha \sim (1/f)\,\varepsilon'/\varepsilon''$

Here, c_0 is the electromagnetic wavespeed *in vacuum*, and ω ($=2\pi f$) is the angular frequency. The absorption of radiofrequency electromagnetic radiation can result in either bulk conductivity (in ice, due to the mobility of proton defects (Petrenko, 1999), and growing with frequency) or polarization of the medium itself (due to rotation of the ice molecules at their fixed sites, having a resonance pole at $f \sim 10^3$ Hz and a magnitude decreasing with frequency away from the resonance pole). In the frequency regime 0.1–2 GHz, due to the dominant polarization and lattice vibration effects, we expect that $\epsilon'' \sim 1/f$, or $L_\alpha \sim$constant.

ATTENUATION OF RADIO SIGNAL IN ICE



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