

Radio Askaryan Neutrino Telescopes

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TeV Particle Astrophysics

August 27th, 2013



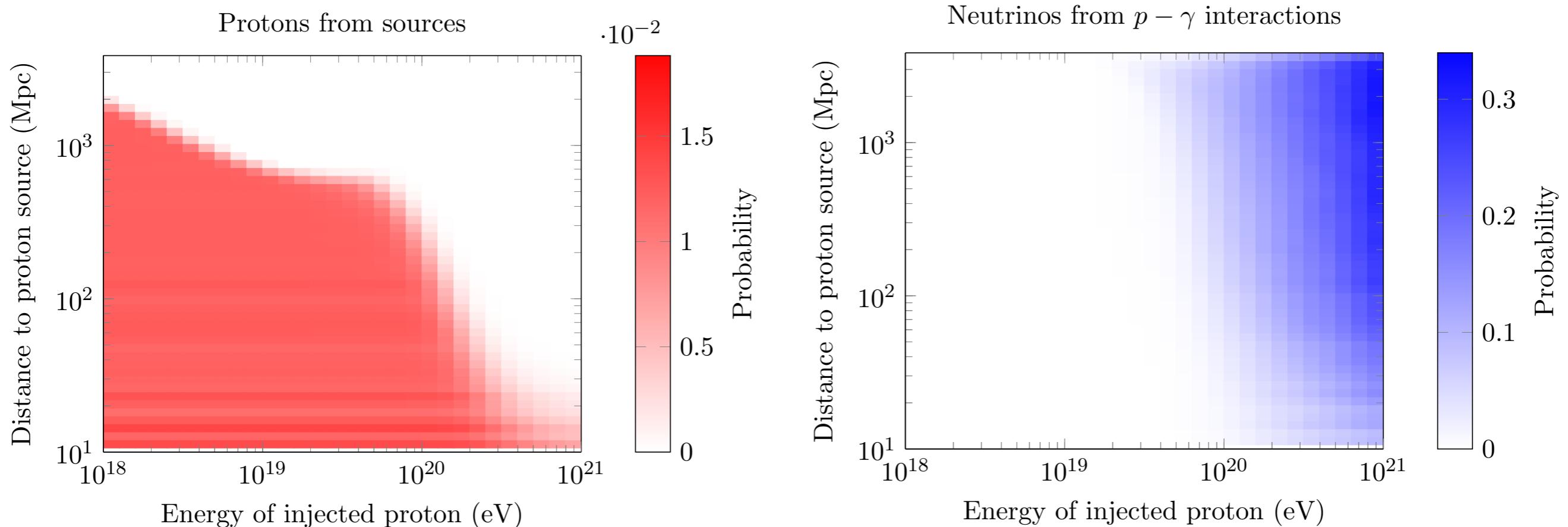
Outline

- **Motivation**
- **Introduction to radio Cerenkov technique**
- **Experiments**
- **Future**
- **Conclusions**

Motivation

Neutrinos are Unique Probes of UHE Astrophysics

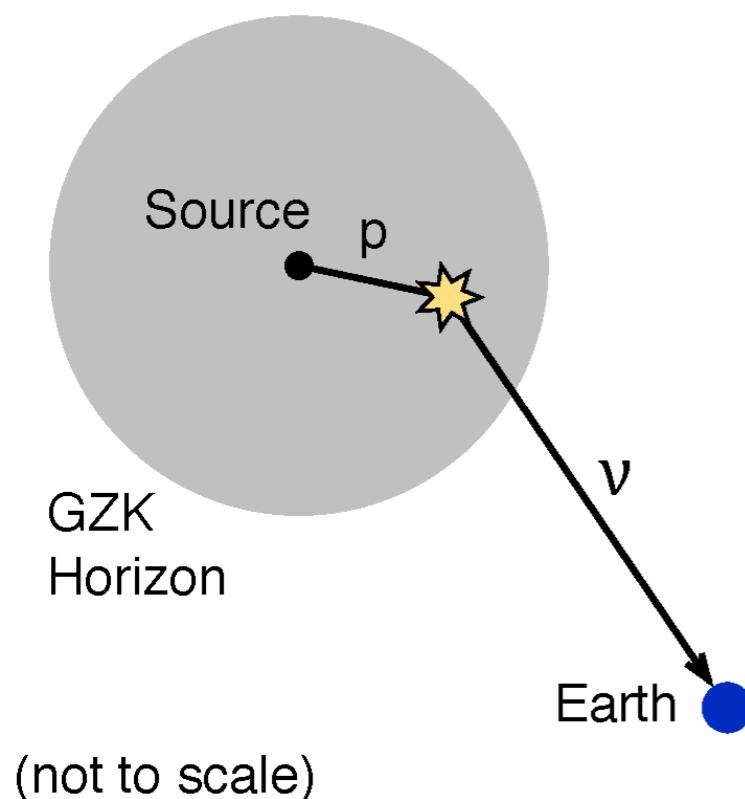
- Neutrinos only particles $>10^{19.5}$ eV from $\gtrsim 100$ Mpc



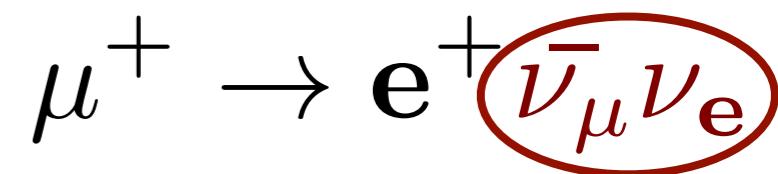
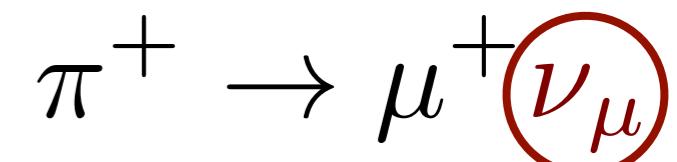
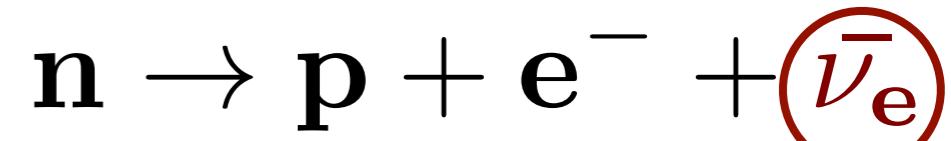
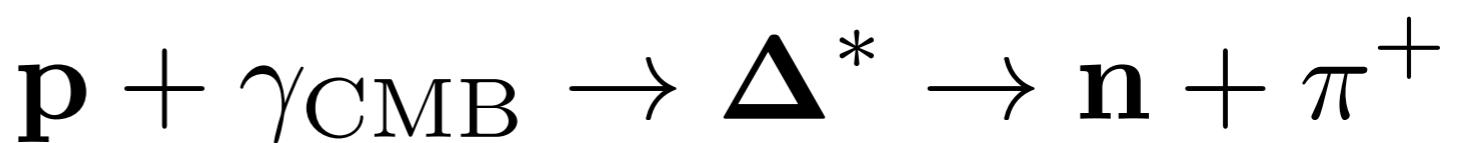
Plots made with the help of CRPropa 2.0
 E^{-1} spectrum, flat redshift evolution

Motivations for ultra-high energy (UHE) neutrinos ($>10^{17}$ eV)

1. **Expect UHE neutrinos from GZK (Greisen-Zatsepin-Kuzmin) process:** Cosmic rays $>10^{19.5}$ eV slowed by cosmic microwave background (CMB) photons within ~ 50 Mpc:

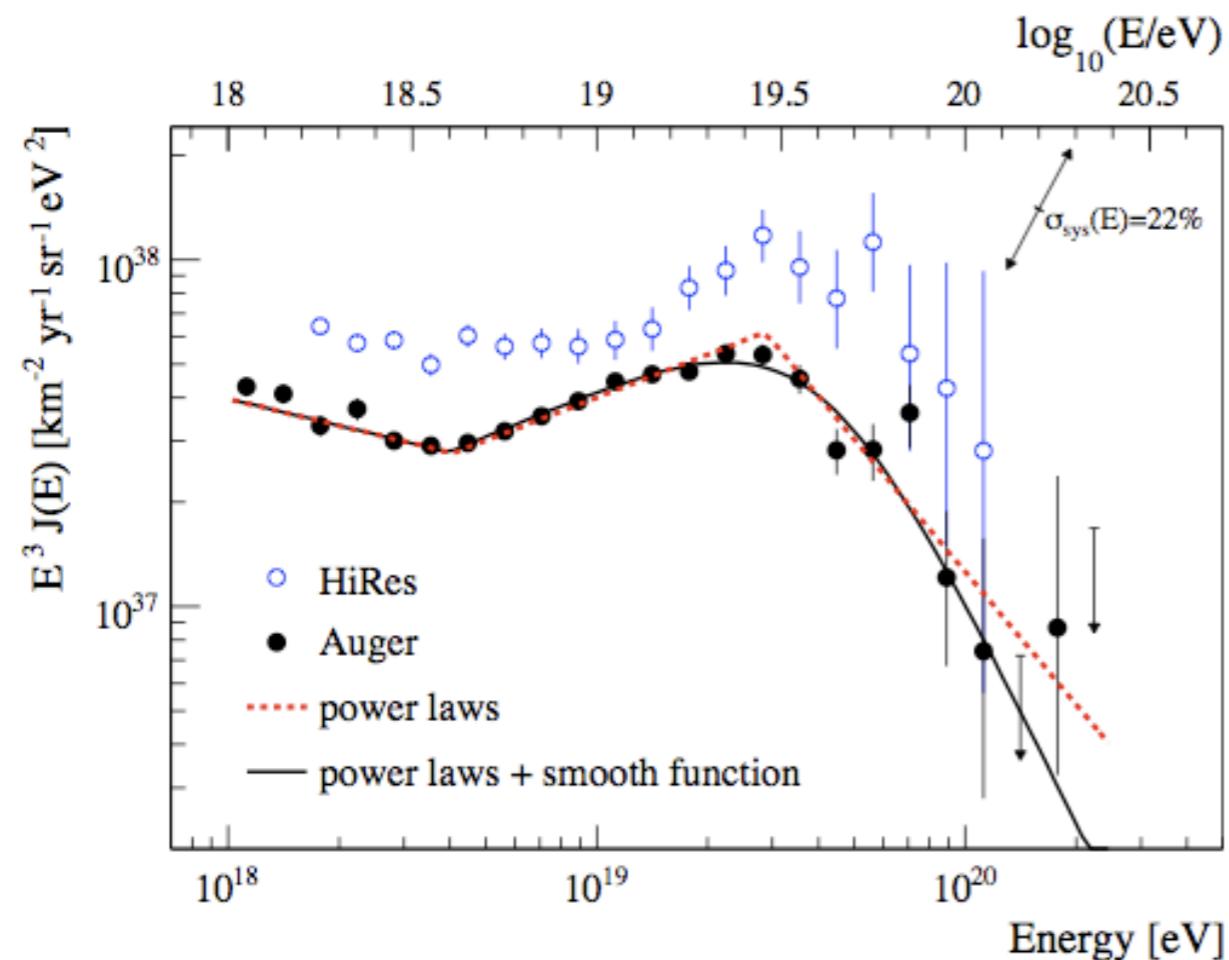


v's from GZK process first pointed out by Berezinsky and Zatsepin (1969)



2. **Expect UHE neutrinos from UHECR sources:** should produce UHE neutrinos through γ -hadronic interactions⁵

Evidence points to a GZK cutoff...



- Cosmic ray data points to cutoff at GZK threshold
 - If this is indeed due to GZK process, UHE neutrinos have to be there!*
- * if CRs=heavy nuclei, UHE neutrino flux from GZK process greatly reduced

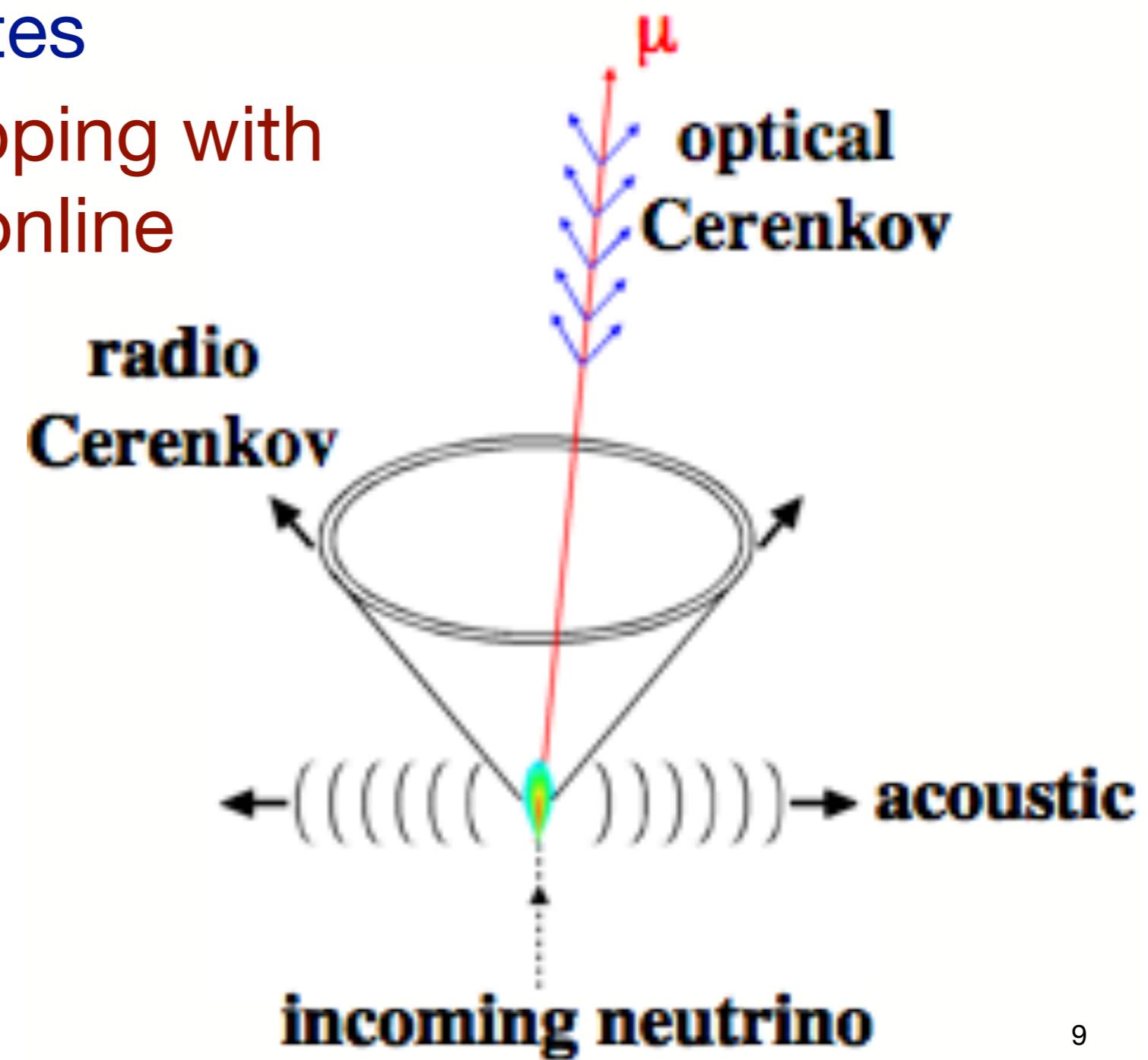
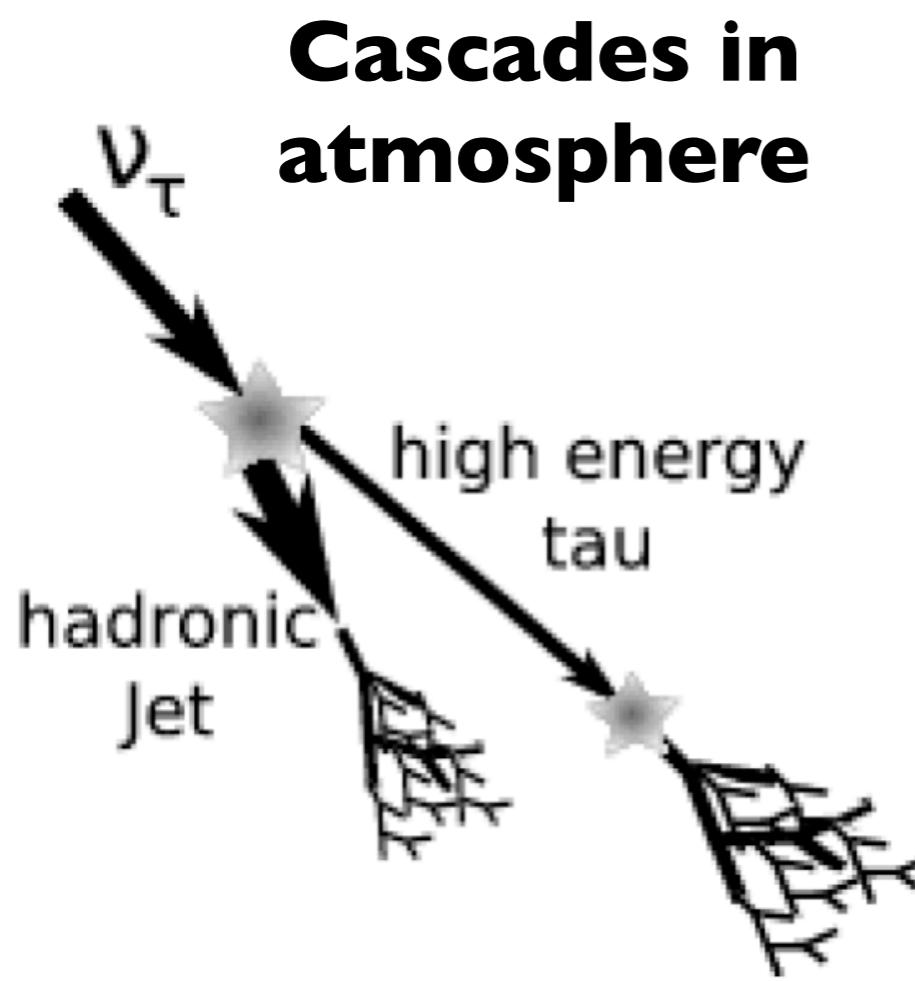
...and we must search for them!

- UHE neutrinos unique messengers to cosmos:
 - Will be only UHE particles $>10^{19.5}$ eV from $\gtrsim 100$ Mpc
 - No magnetic deflections
- Particle physics probes exceeding LHC energies
 - 10^{18} eV neutrino interaction $\rightarrow 45$ TeV!
 - 10^{19} eV $\rightarrow 140$ TeV!

Introduction to radio Cerenkov technique

Detection Techniques

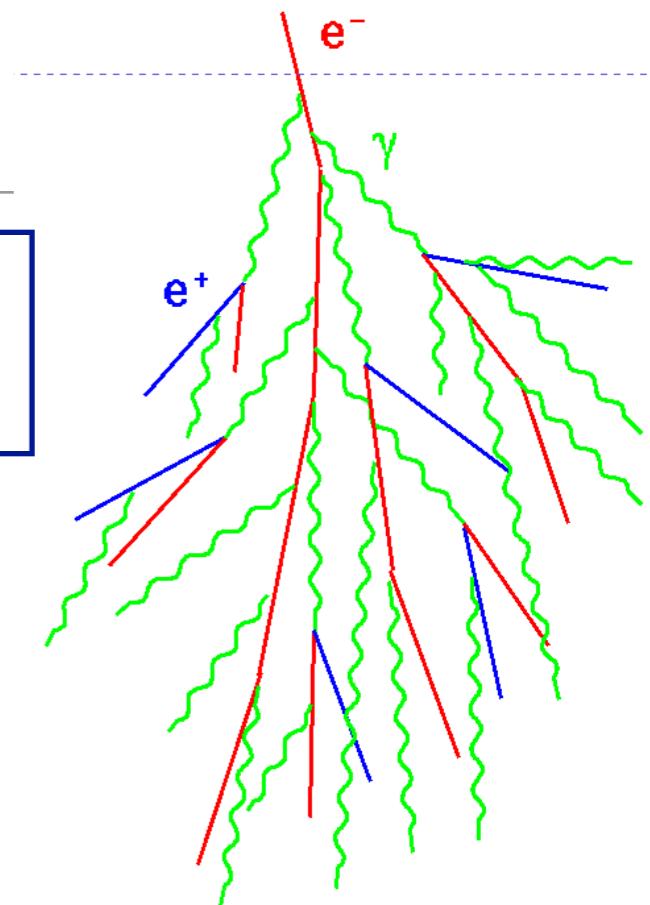
- $<10^{18}$ eV: optical dominates current constraints
- $>10^{18}$ eV: radio dominates
 - Radio thresholds dropping with experiments coming online



Radio Cerenkov Technique (Askaryan Effect)

- Coherent Cerenkov signal from net “current,” instead of from individual tracks
- A ~20% charge asymmetry develops (mainly Compton scattering)
- Excess moving with $v > c/n$ in matter
 - Cherenkov Radiation $dP \propto v dv$
- If $\lambda \gg R_{\text{Moliere}}$ → Coherent Emission
 $P \sim N^2 \sim E^2$
 - Radio/Microwave Emission

Idea by Gurgen Askaryan (1962)

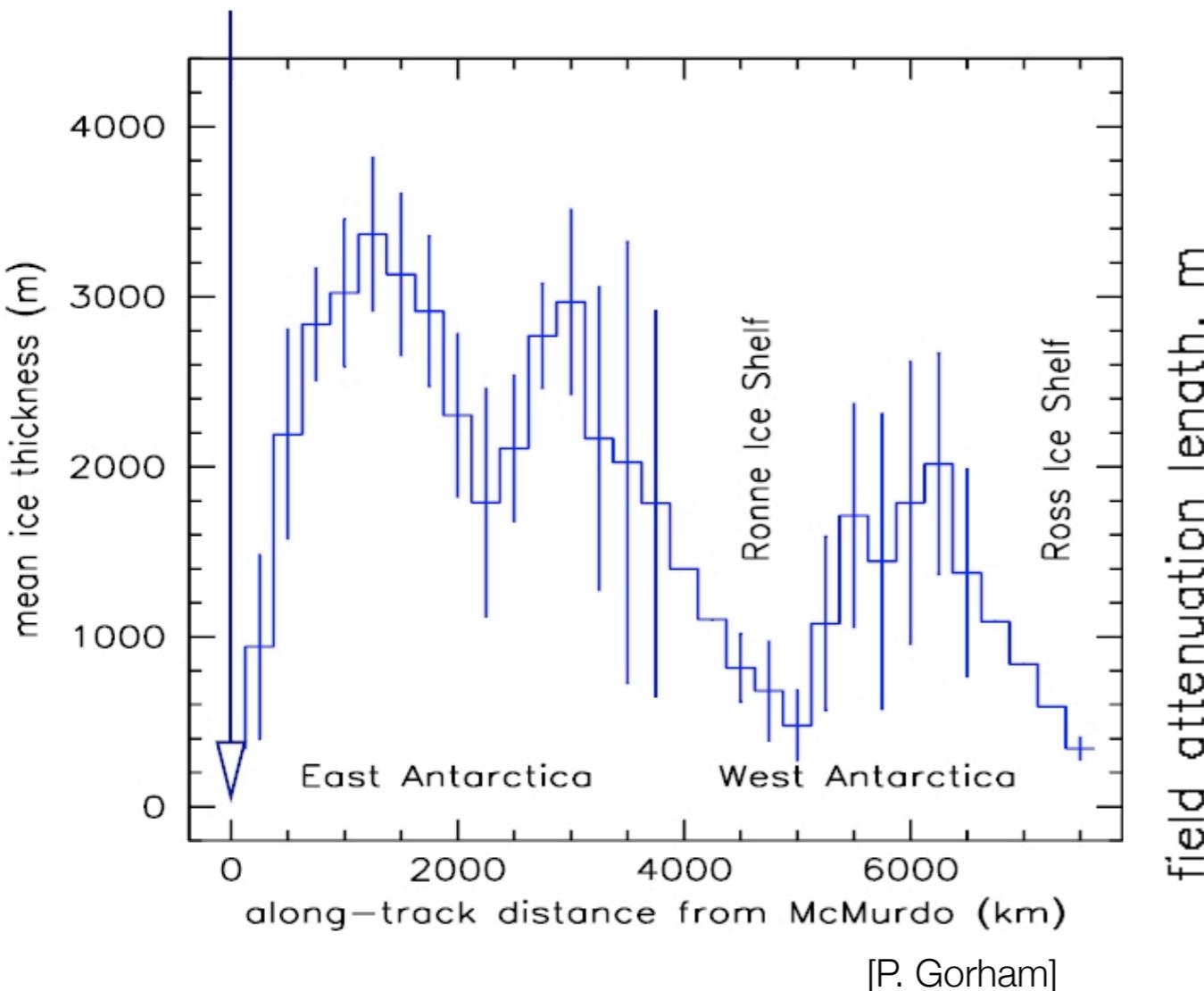


This effect has been confirmed experimentally in sand, salt, ice:
PRL 86, 2802 (2002)
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)
PRL 99, 171101 (2007)

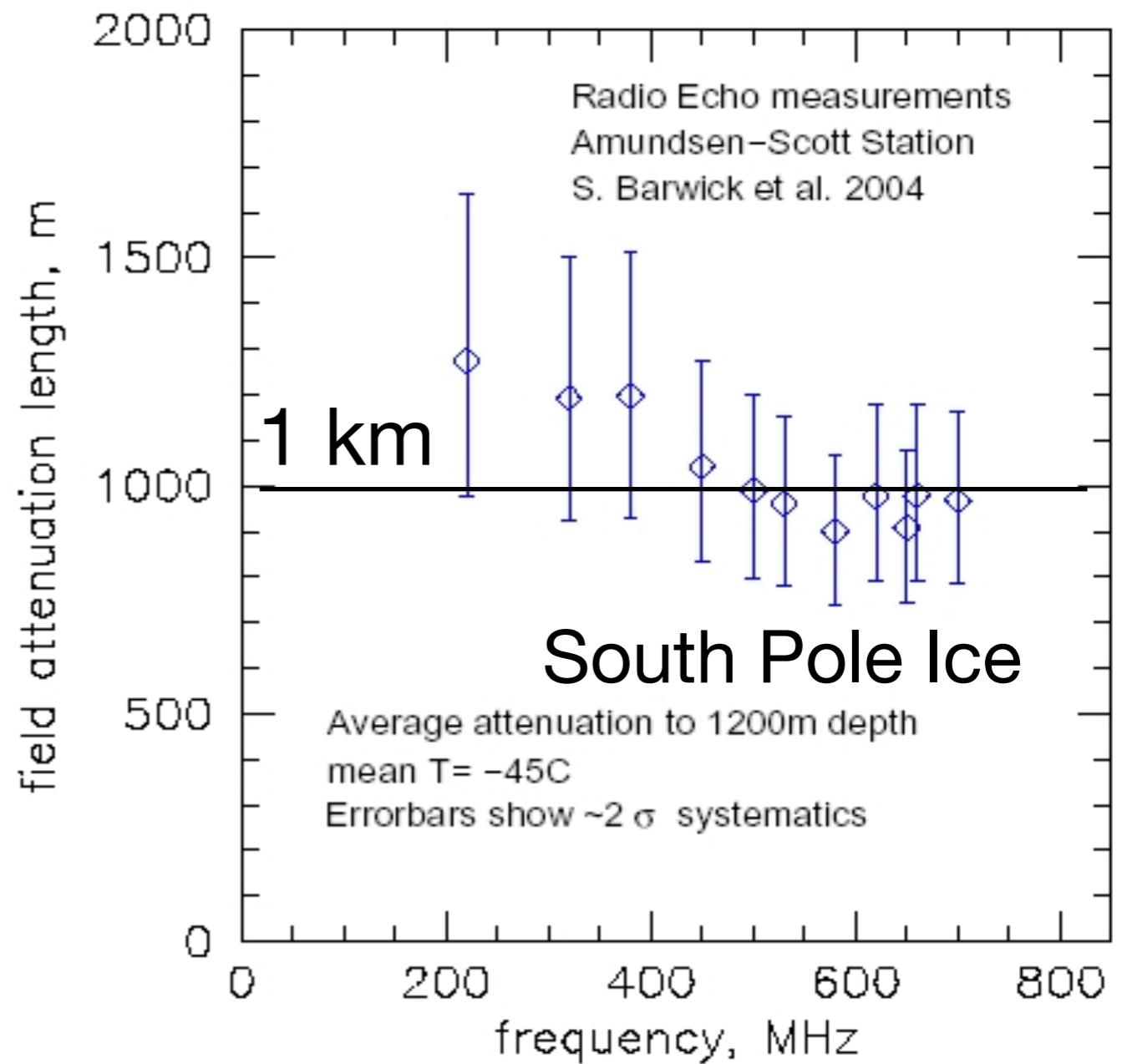
$R_{\text{Moliere}} \approx 10 \text{ cm}$, $L \sim \text{meters} \rightarrow \text{Radio!}$

Antarctic Ice

Ice thicknesses



Radio Attenuation Lengths

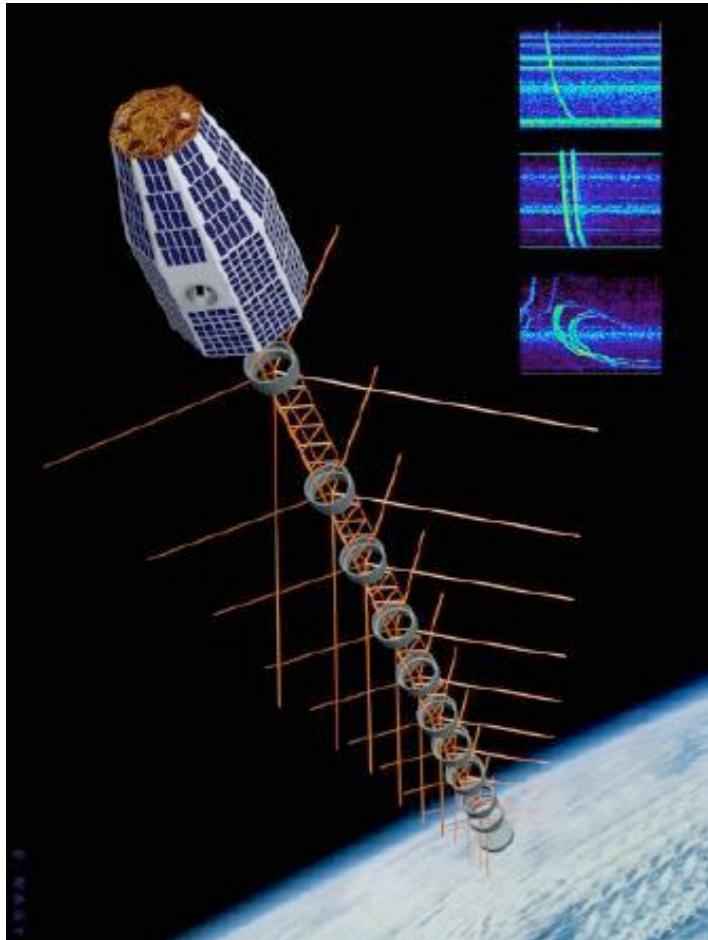


2 km depths are typical
across the continent

Experiments

Pioneering Experiments

FORTE



FORTE 97-99
Greenland Ice
Log periodic antenna,
20-300 MHz
 $A=10^5 \text{ km}^2 \text{ sr}$

GLUE



GLUE/Goldstone 99:
In Lunar regolith
~2 GHz
 $A=6 \cdot 10^5 \text{ km}^2 \cdot \text{sr}$

RICE

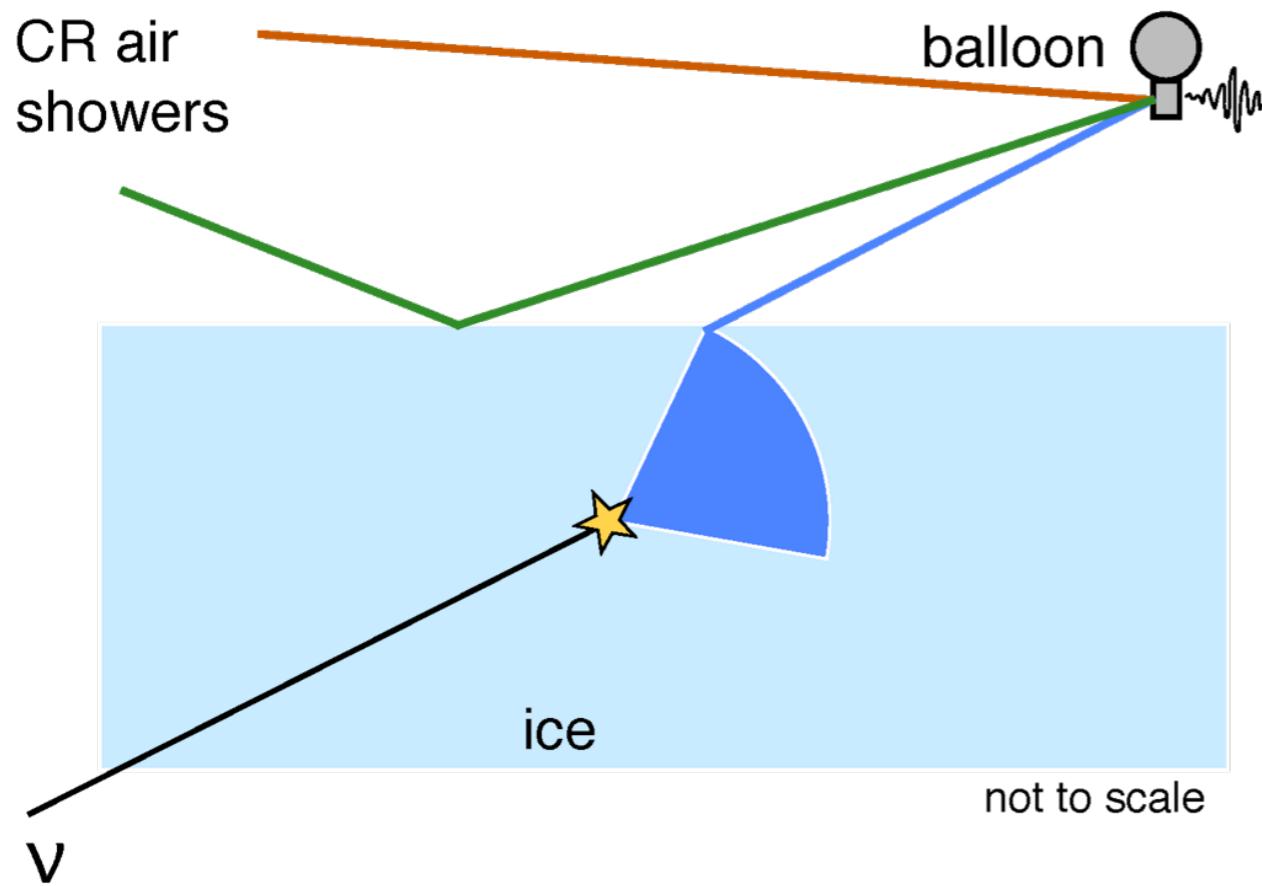


RICE 1999-present
Antennas on
AMANDA strings
100-1000 MHz
dipoles
 $V \sim 10 \text{ km}^3 \cdot \text{sr}$
Latest publication
2011

Radio Cerenkov: Balloons vs. ice in situ

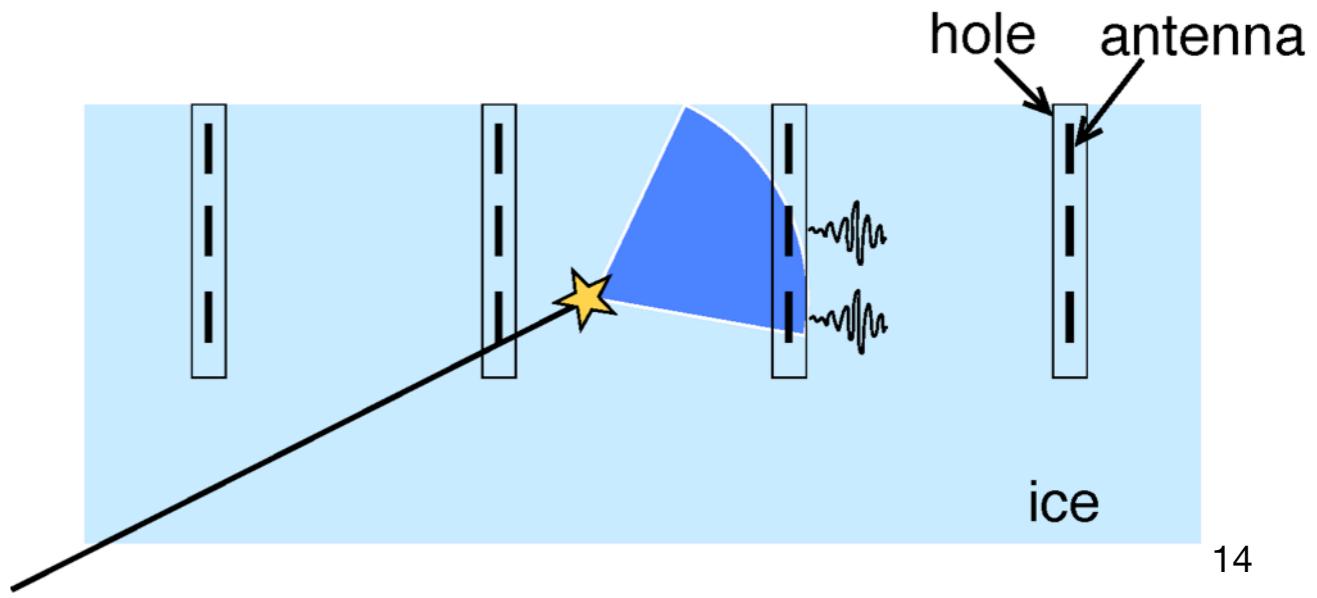
Balloons

- Large area of ice in view
- High threshold
- View declinations near horizon



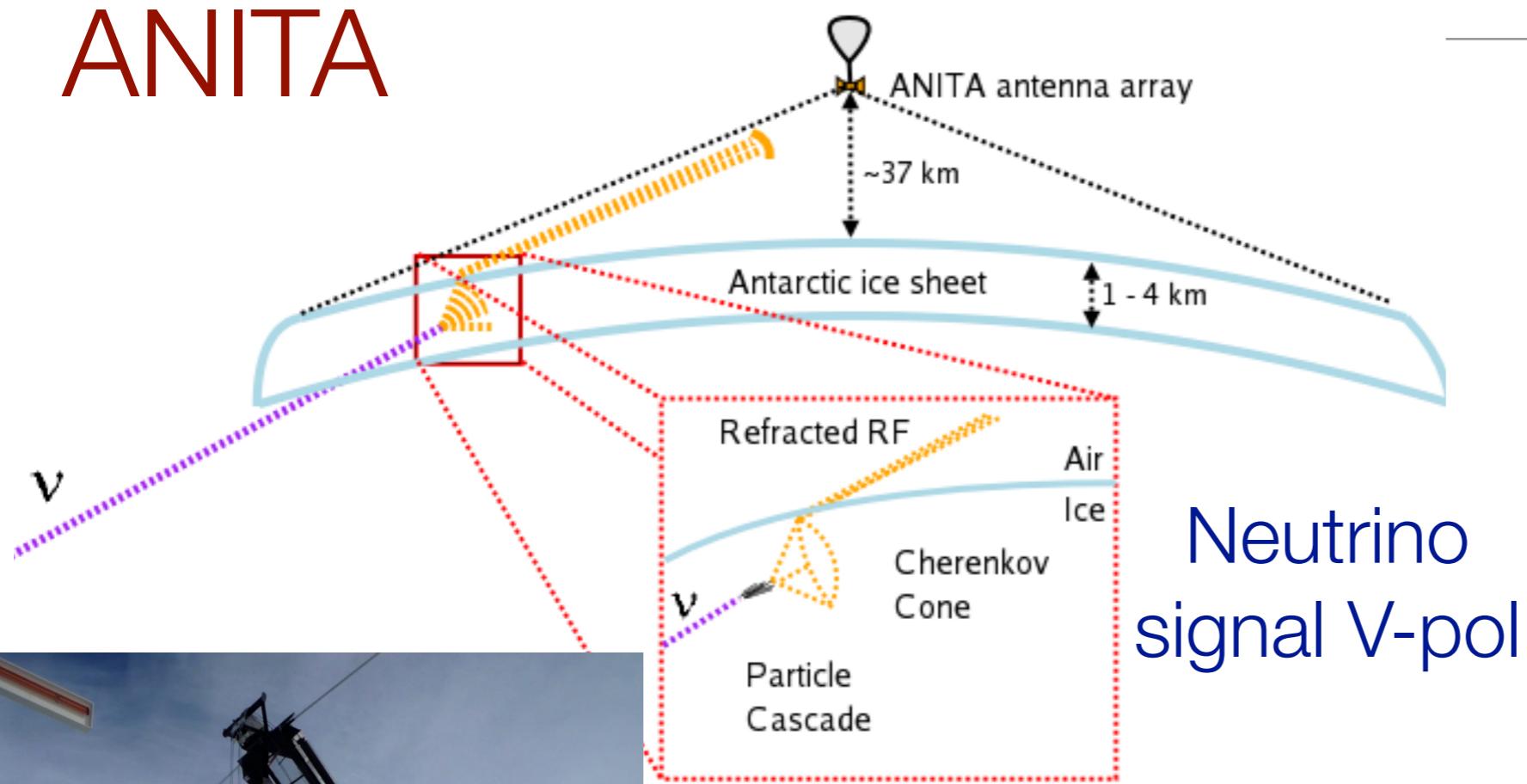
In-situ

- Limited by volume you can instrument
- Low threshold
- View upper sky
- Better reconstruction



Balloon Experiments

ANITA



Neutrino
signal V-pol

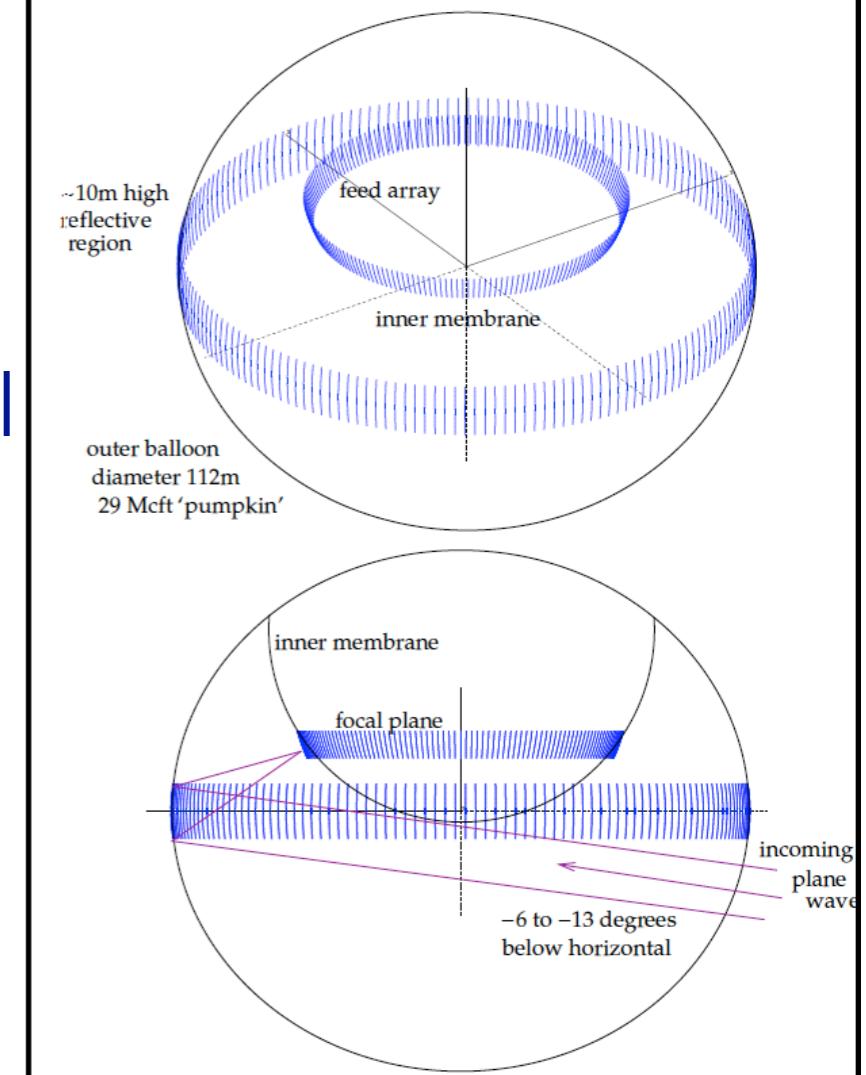
Long duration balloon
program operated by
NASA

ANITA 1: 2006-2007

ANITA 2: 2008-2009

ANITA 3: 2014-2015

Exavolt Antenna (EVA)





ANITA

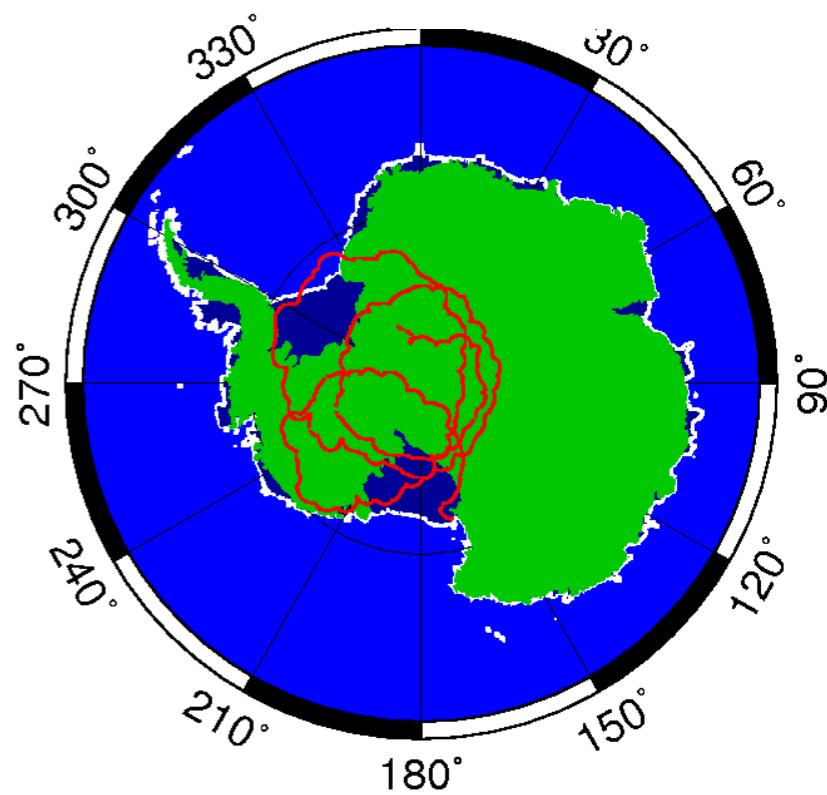
University of Hawaii, UCLA, National Taiwan University,
SLAC, JPL, Univ. of Kansas, Washington Univ. St. Louis,
Ohio State Univ., Univ. of Delaware, UCL



ANITA 1:

2006 - 2007

18 days good livetime
1.2 km average depth



ANITA 2:

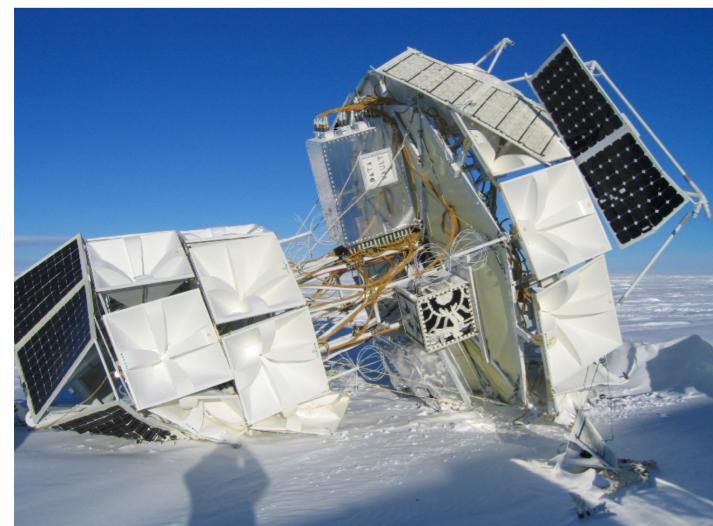
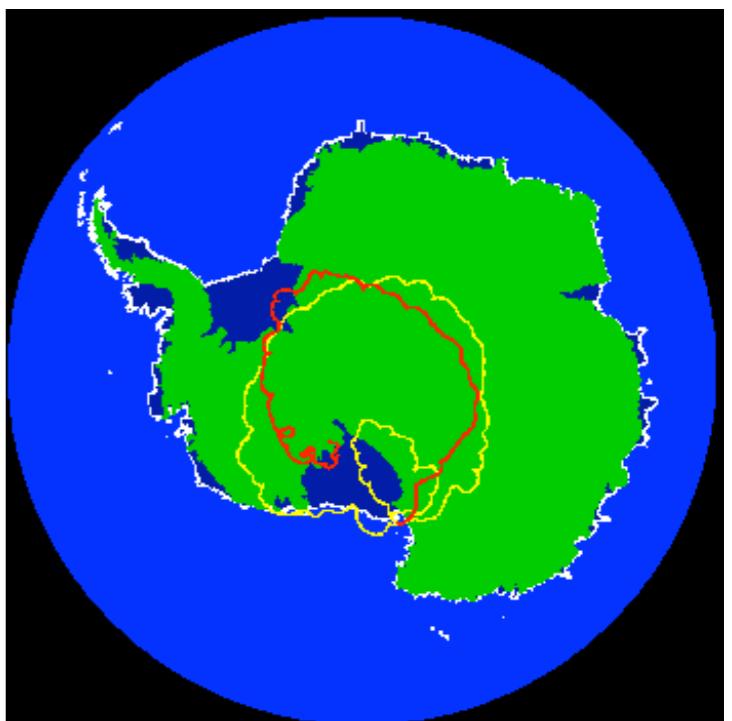
2008-2009

8 more antennas

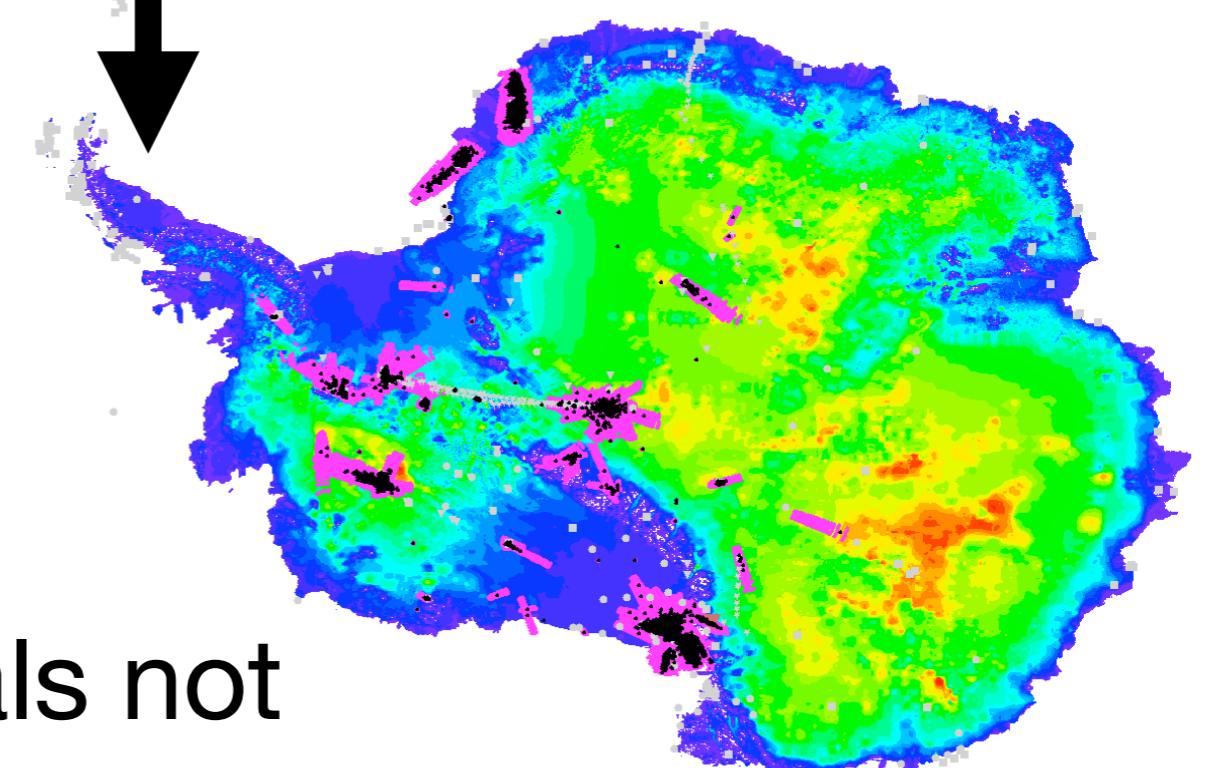
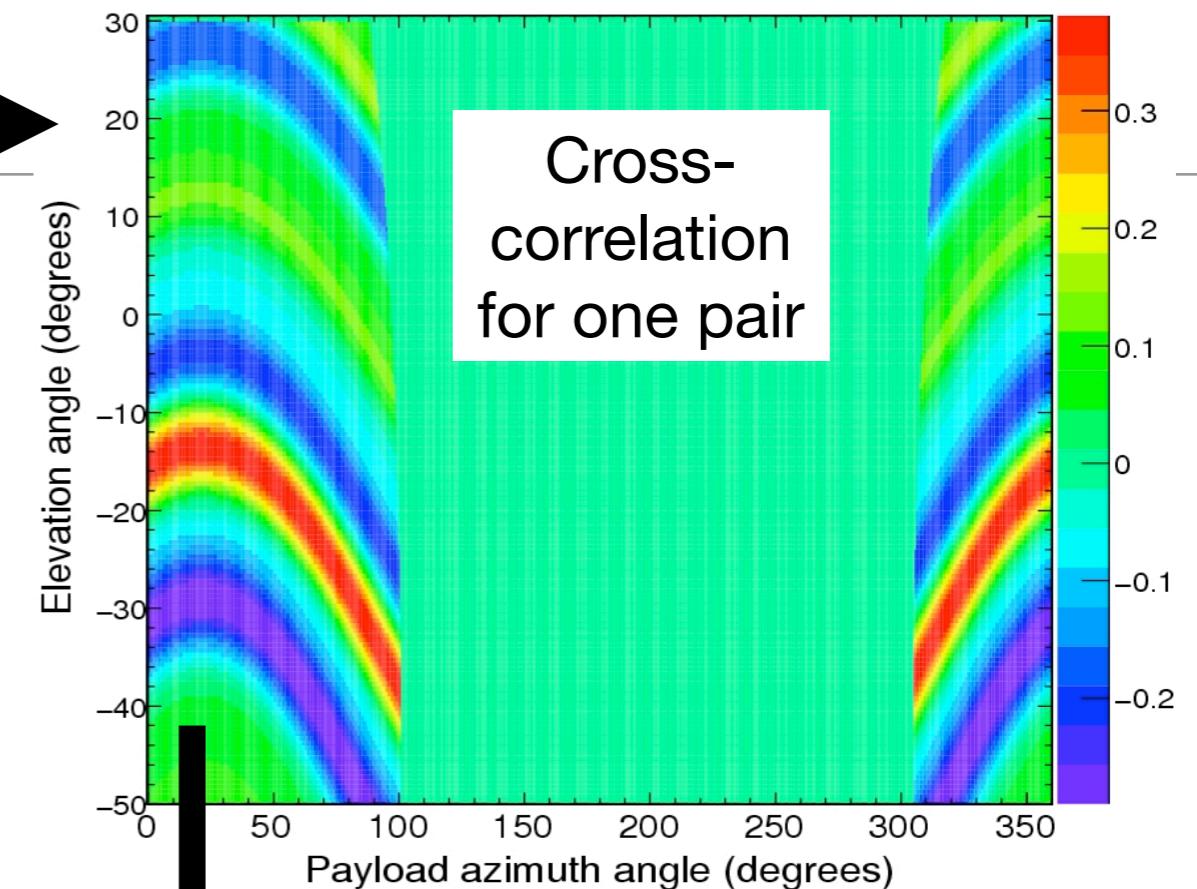
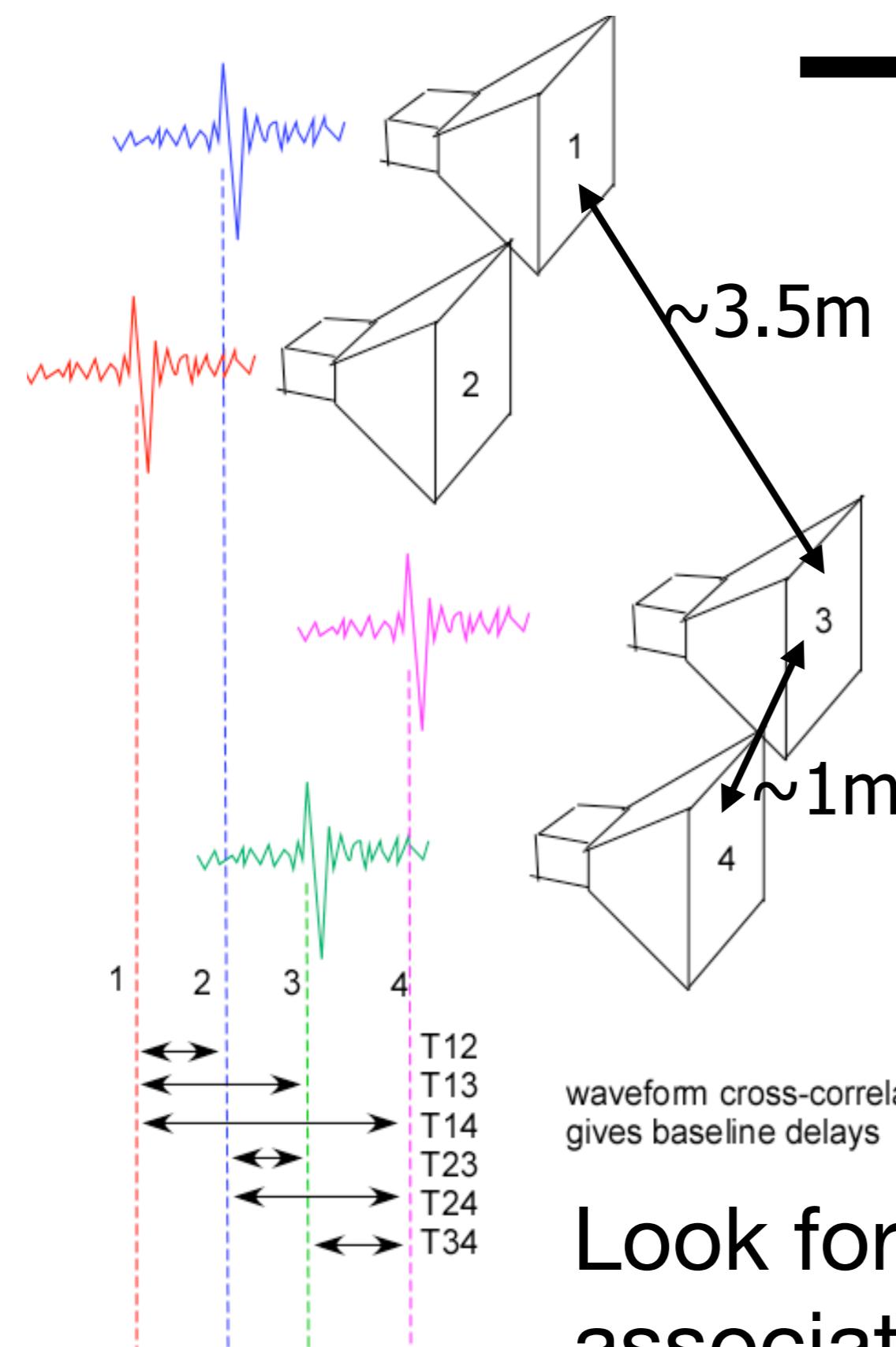
Lower noise amplification

Directional mask

Optimized trigger



Event Reconstruction



Look for signals not associated with any other base or event

Anita Results

Vertical Polarization (neutrino search)

	Expected Background	Observed Events
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Anita 1:	1	1
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Anita 2:	1	1
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Horizontal Polarization (cosmic rays)

	Expected Background	Observed Events
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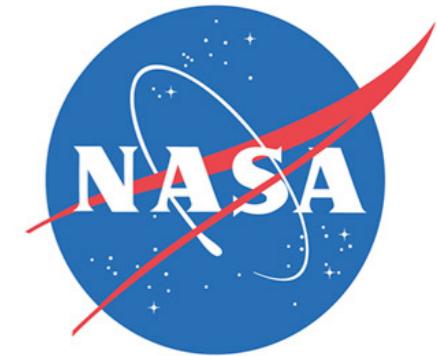
Anita 1:	2	16
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Anita 2: no H-pol trigger

Cosmic rays
from the
geomagnetic
effect

ExaVolt Antenna (EVA) concept

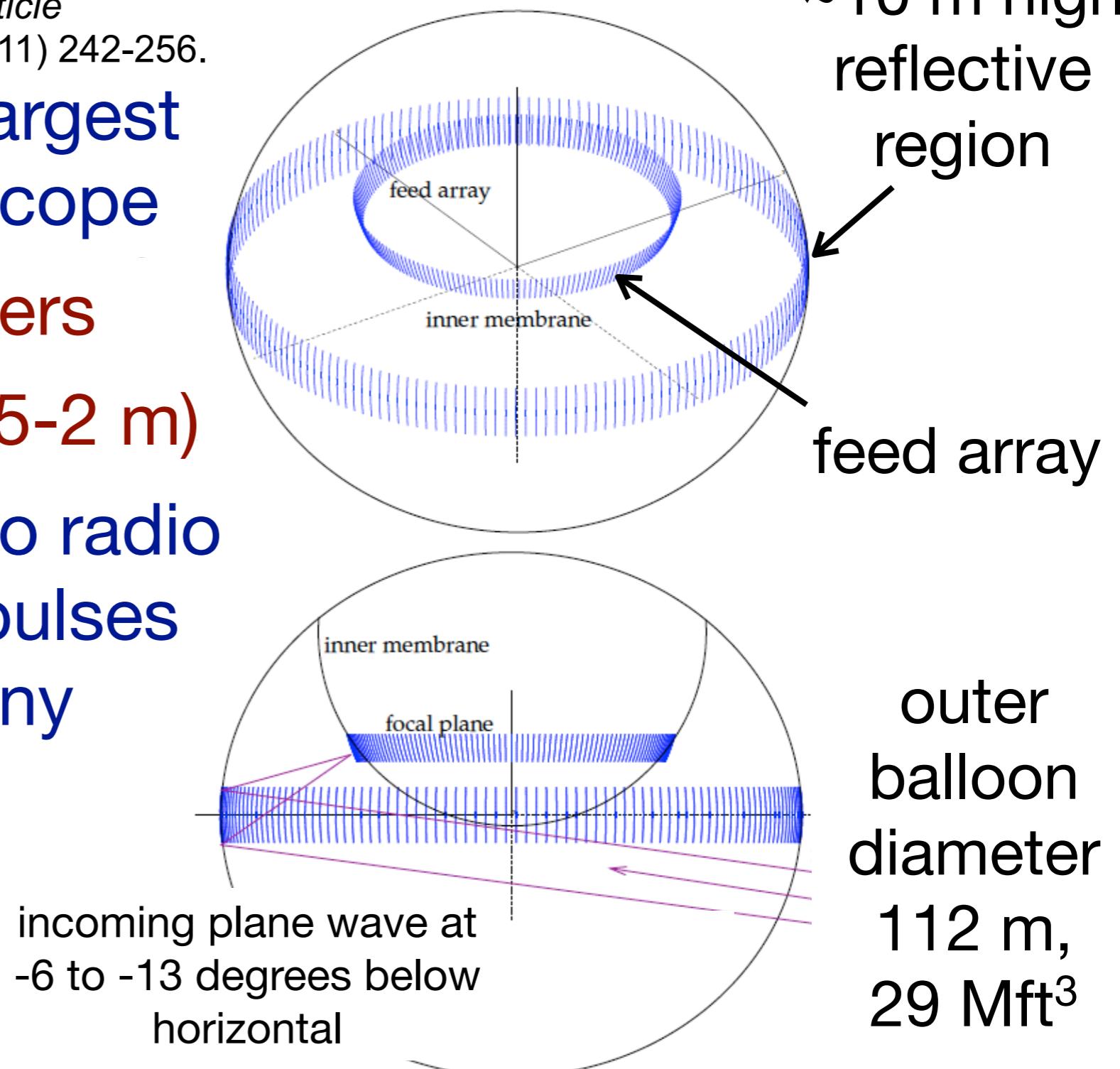
University of Hawaii, Ohio State Univ., JPL, George Washington Univ.



P. W. Gorham et al., *The ExaVolt Antenna: A Large-Aperture, Balloon-embedded Antenna for Ultra-high Energy Particle Detection*, Astroparticle Physics, 35 No. 5 (2011) 242-256.

- Would be the world's largest aperture airborne telescope
 - 1000's of square meters
 - 150-600 MHz ($\lambda_{\text{air}} \approx 0.5\text{-}2 \text{ m}$)
- Increase in sensitivity to radio frequency neutrino impulses by factor of 100 over any previous experiment

3 year engineering study funded by NASA



~10 m high reflective region
feed array
outer balloon diameter
112 m,
 29 Mft^3

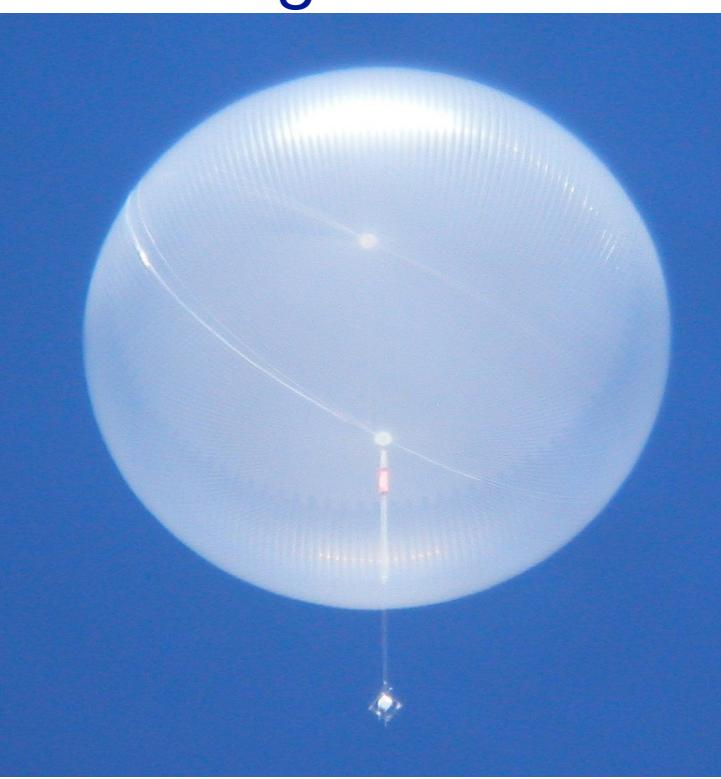
Zero Pressure Balloons (ZPB) vs. Super Pressure Balloons (SPB)

Zero Pressure Balloons (e.g., ANITA)

- Balloon pressure at equilibrium with ambient pressure at float altitude
- Shape can change dramatically with thermal environment
 - ANITA: 40% drop in volume while over east Antarctica

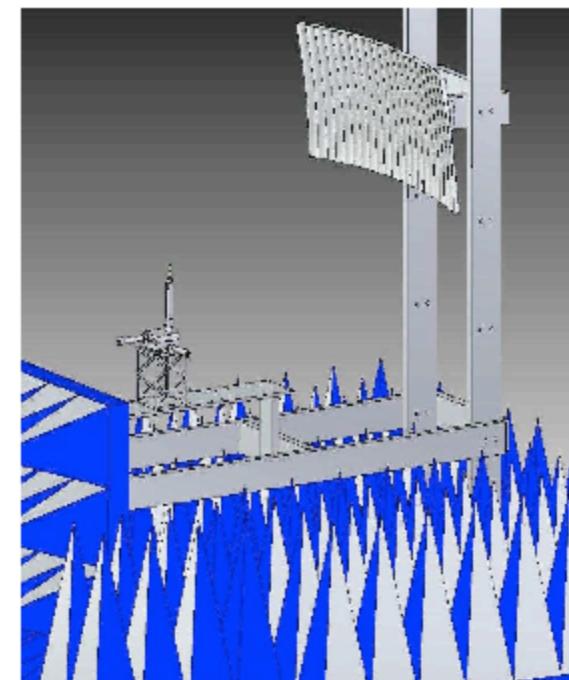
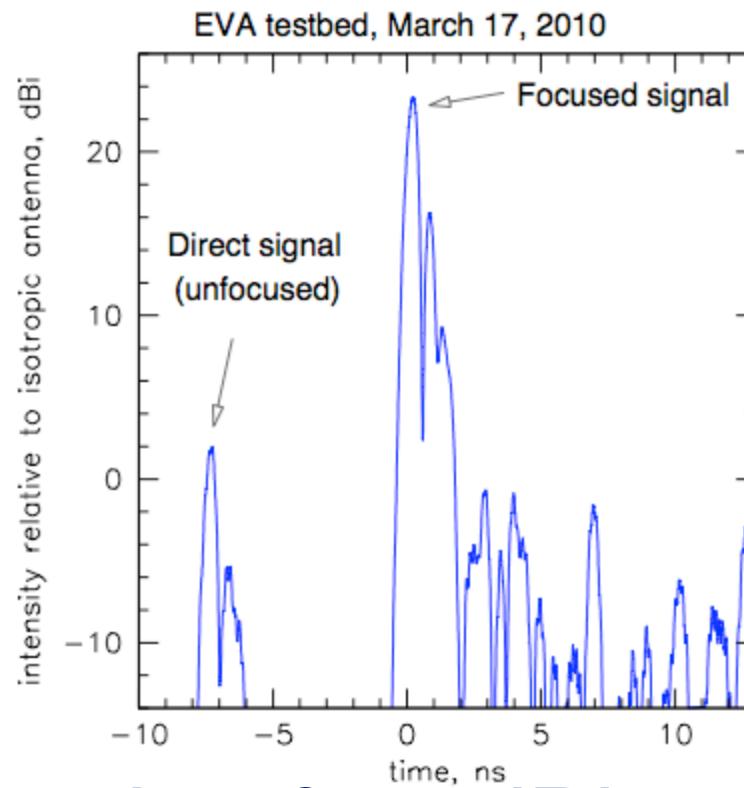
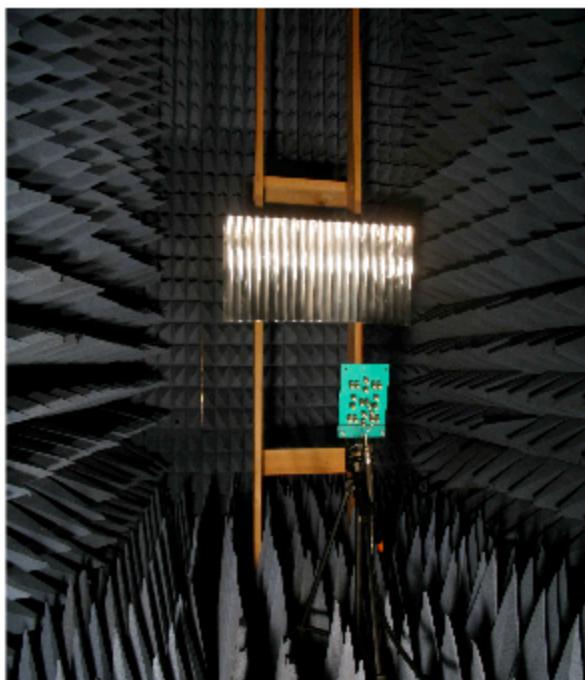
Super Pressure Balloons (under development, proposed for EVA)

- Balloon pressure higher than outside pressure
- Height, diameter changed by 1% in 54 day flight 591NT (December 2008) 7Mft³ over Antarctica
- SPB launches continue with larger balloons of long duration flights. Early 2011: Antarctic flight 616NT 14 Mft³



Scaled down model at University of Hawaii

- At UH, Gorham *et al.* constructed microwave scale model testbed to test a reflector section
- 1/35 and 1/26 scale models of a 25 Mft³ SPB

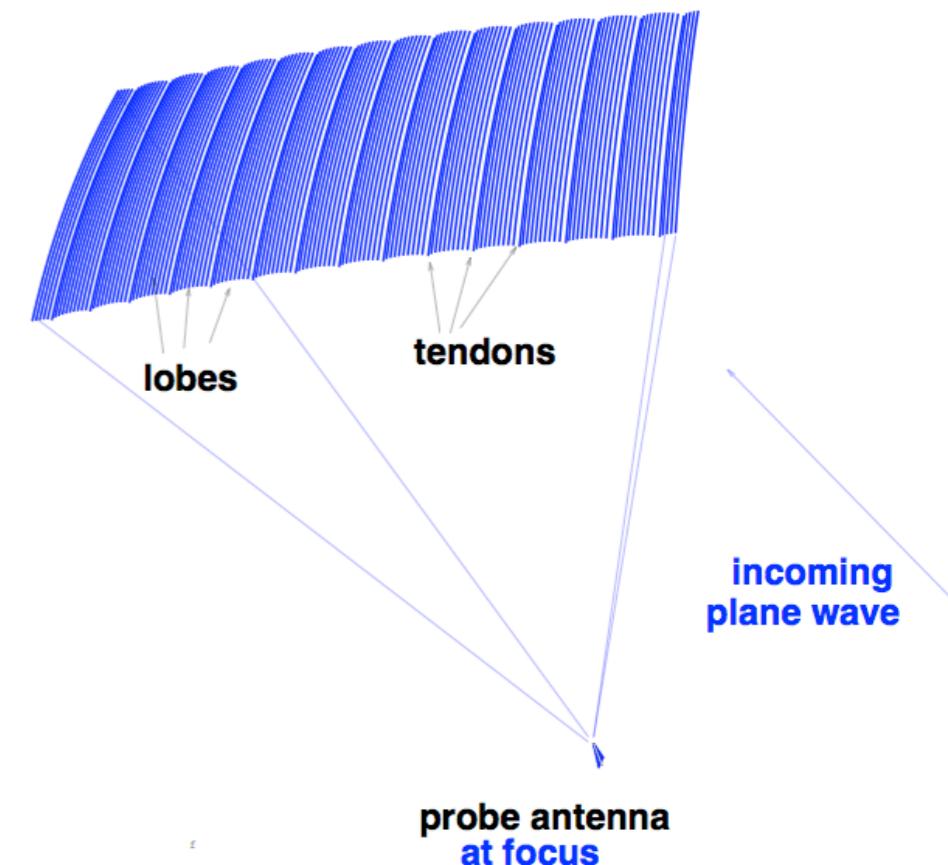


Gorham *et al.* (2011)

- Measure directivity gain of 22 dBi at 6.6 GHz corresponding to 260 MHz for full scale
- Measured focal region (scaled to full size balloon)
~1.14m (Φ) x 3-4m (θ) x >3m

EVA

- Hang test at NASA's Wallops Flight Facility of 1/20 scale prototype planned for Fall 2014 or Spring 2015
- Stayed tuned for the full EVA!



Gorham *et al.* (2011)

Askaryan Radio Array (ARA)

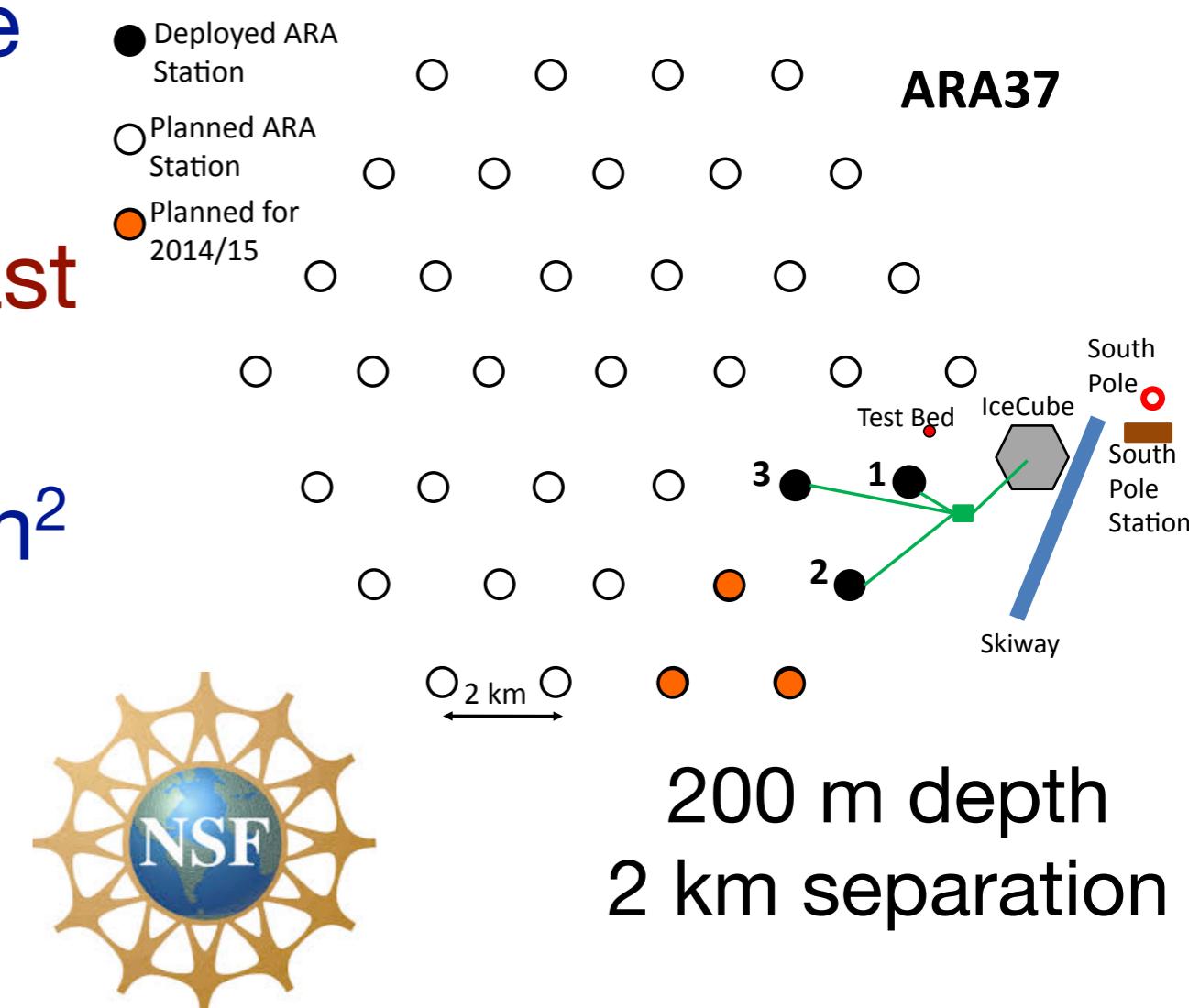
University of Wisconsin, Ohio State University and CCAPP, University of Maryland and IceCube Research Center, University of Kansas and Instrumentation Design Laboratory, University of Bonn, National Taiwan University, University College London, University of Hawaii, Universite Libre de Bruxelles, Univ. of Wuppertal, Chiba Univ., Univ. of Delaware

- Radio array at the South Pole

- Testbed station,
Stations 1,2&3 deployed last
3 seasons

- Phase 1: 37 stations $\sim 100 \text{ km}^2$

- Establish flux
 - Begin astronomy/ particle
physics exploitation



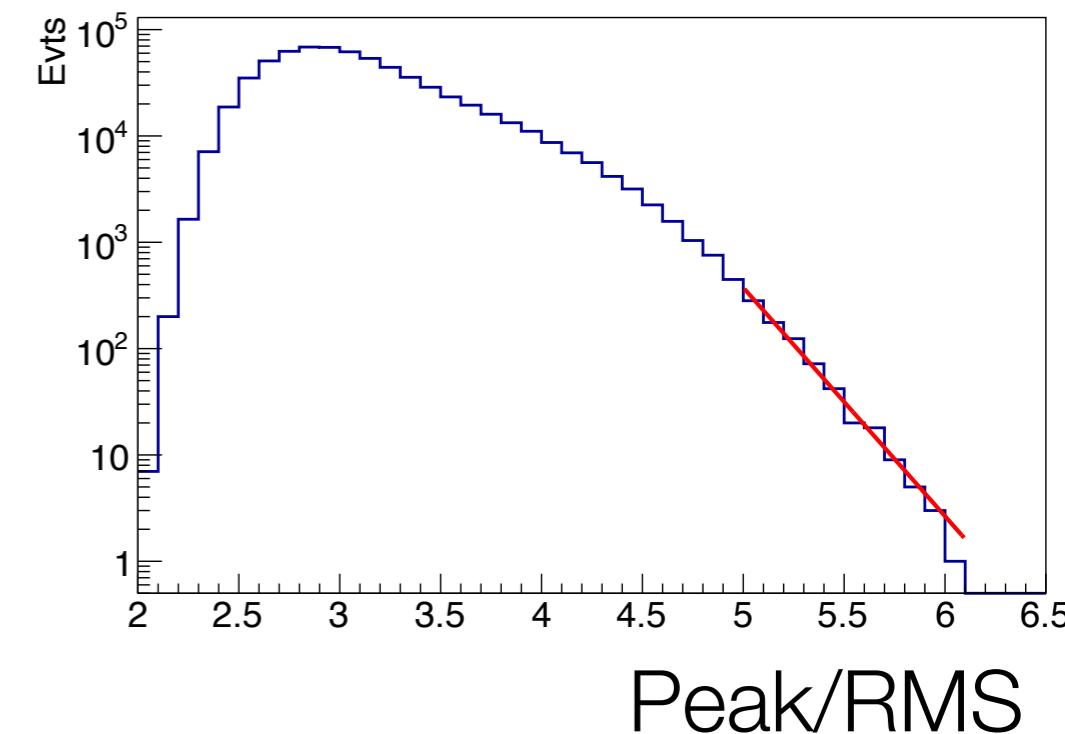
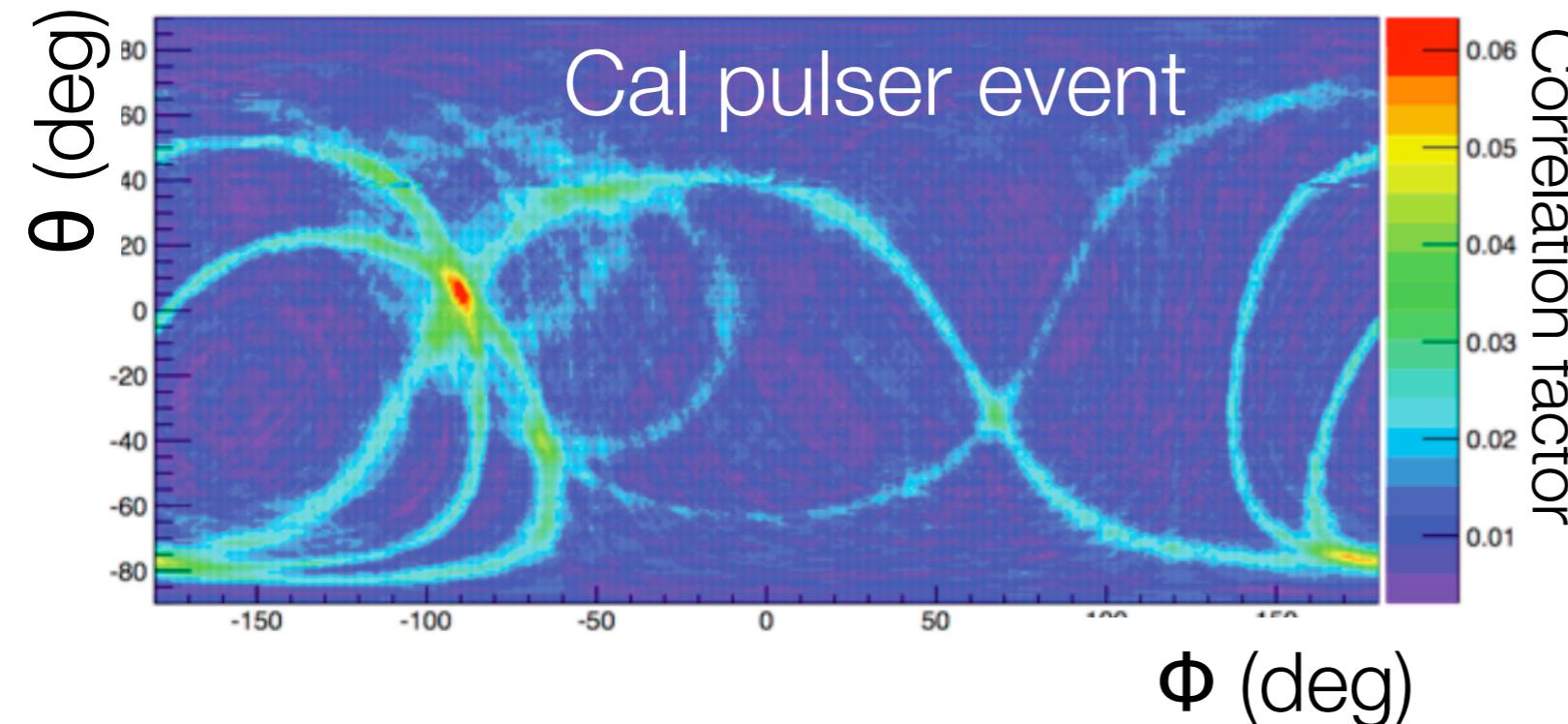
NSF has funded Testbed+3 Stations. Propose to deploy another 3 stations in 2014-2105 (ARA6)

Askaryan Radio Array (ARA): Testbed analyses

Cut-based analysis

- Guided by data and simulation
- Optimized for best sensitivity
- Require impulsive, not CW, quality reconstruction

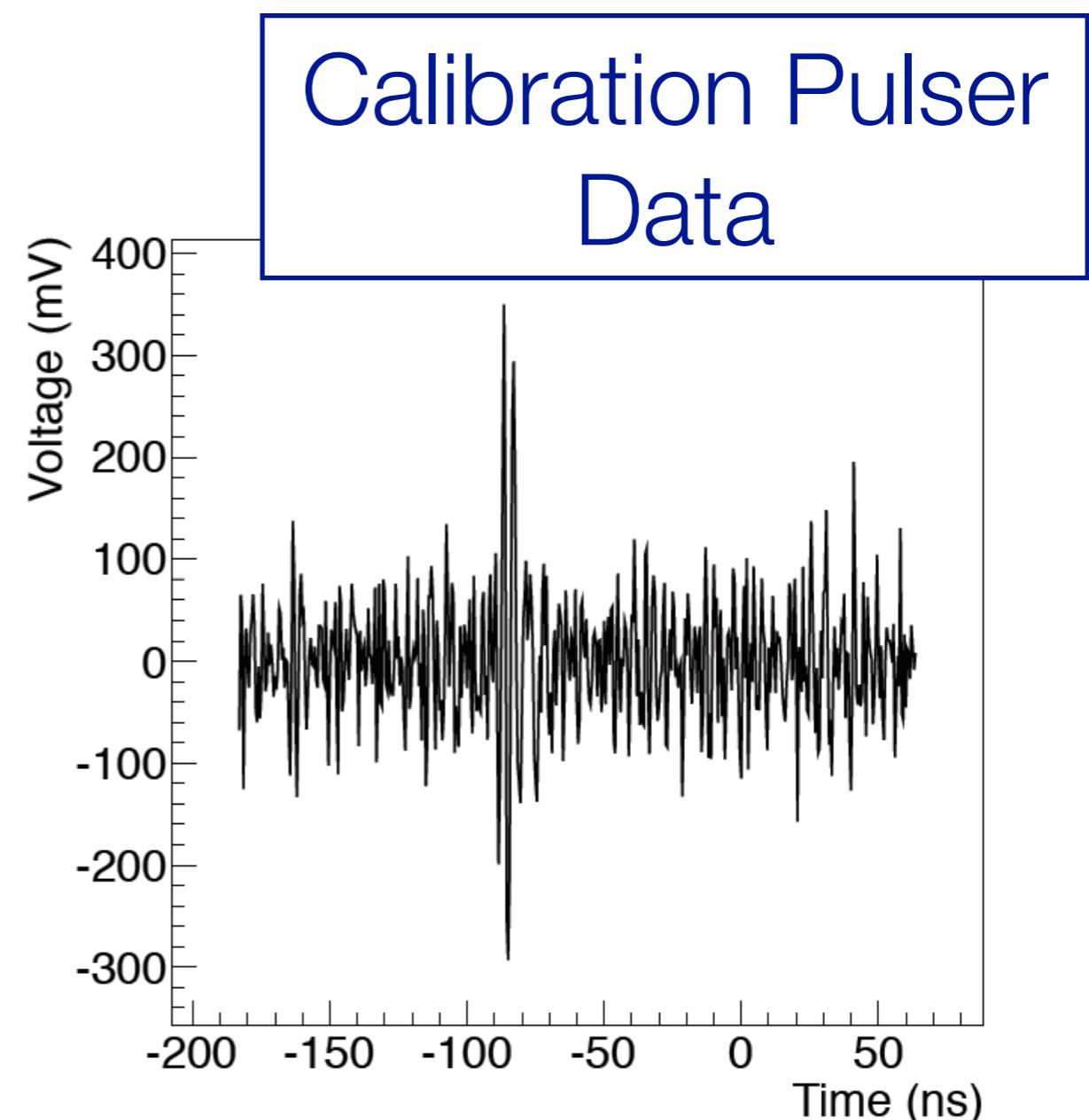
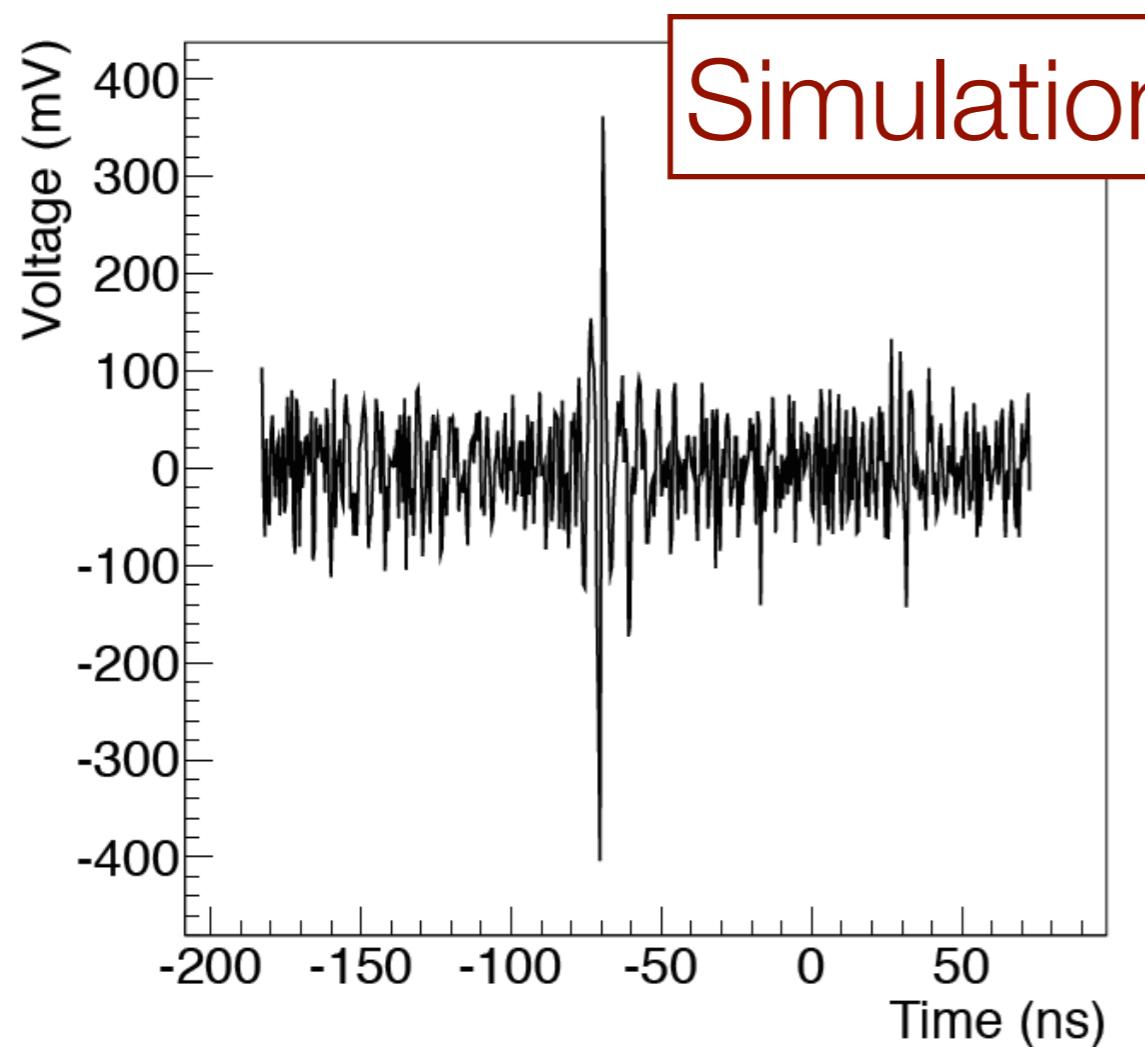
Both analyses blind
to 90% of data set



Template-based analysis: From RICE
experience: search for unique signals that do not
correlate with other events

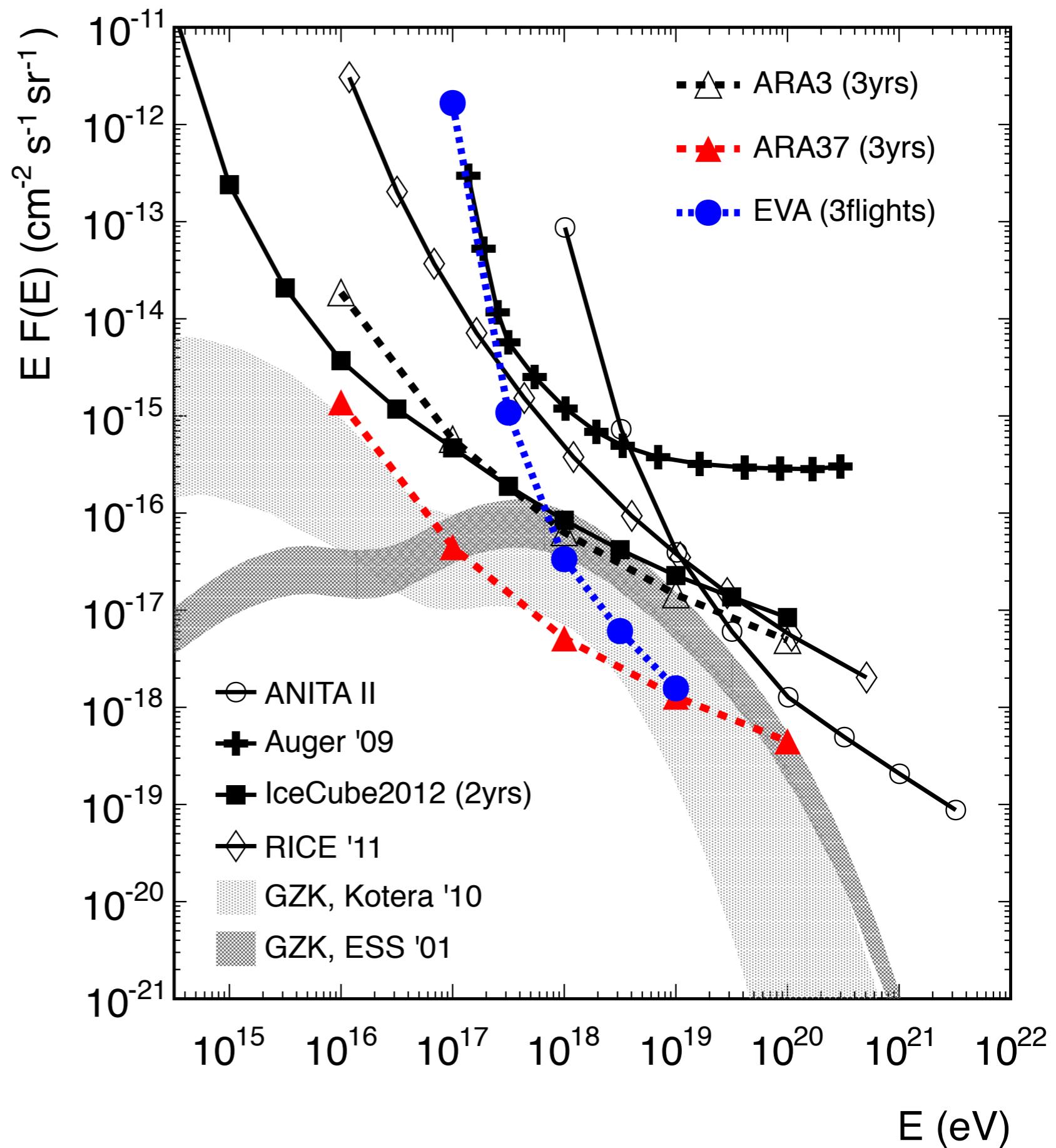
Simulated neutrino events written as data (ARA and ANITA)

- Neutrinos now written in data format to allow
 - Improved cut optimization
 - Calibration to data
 - Perform reconstructions



Sensitivities

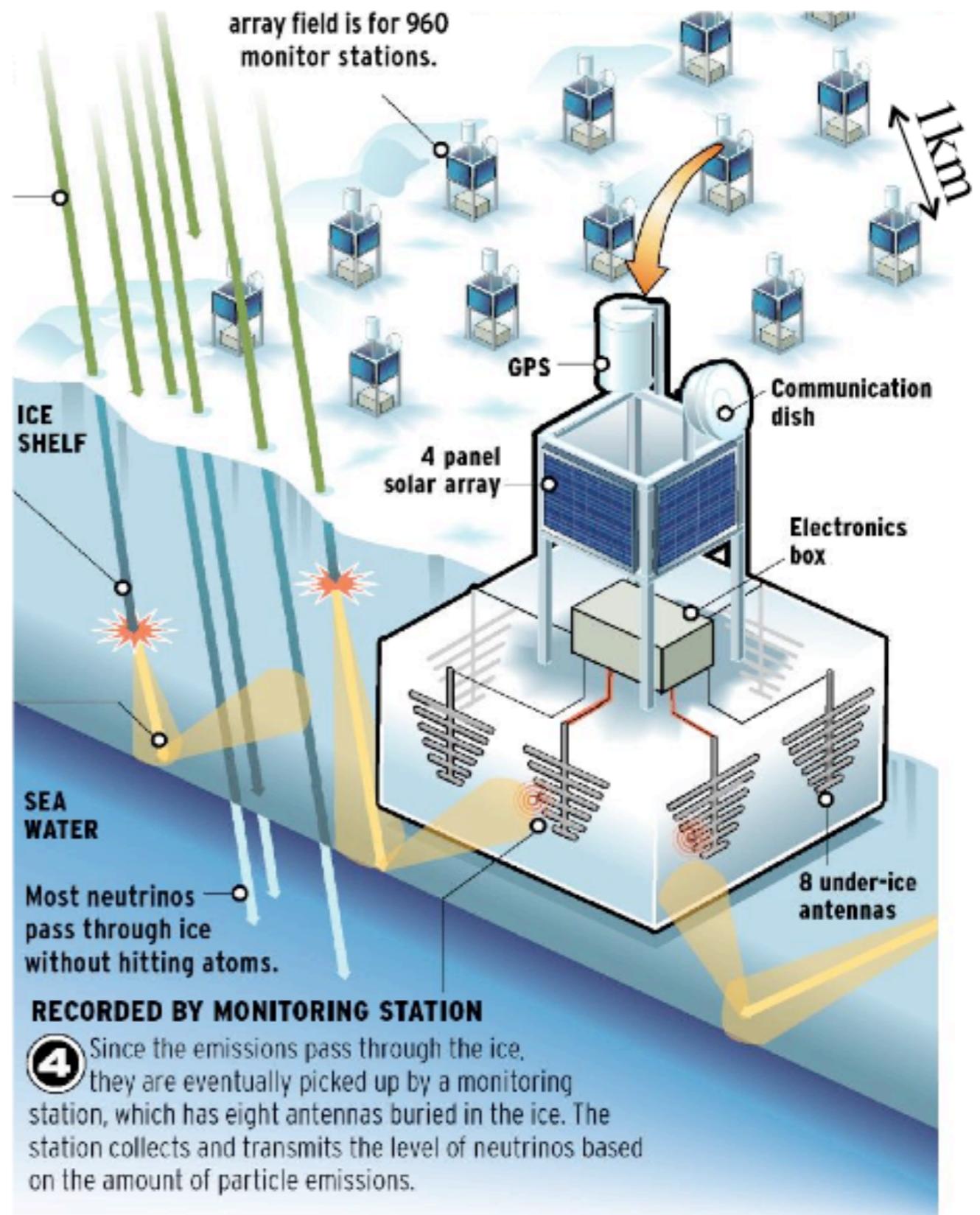
- Projections are expected 90%CL constraints
- Using trigger-level sensitivity only
- (EVA does extend above 10^{19} eV)



ARIANNA

- Radio array on Ross Ice Shelf
<http://arianna.ps.uci.edu>
- On track for completing 7 station array in Dec. 2013
- Propose 960 station array

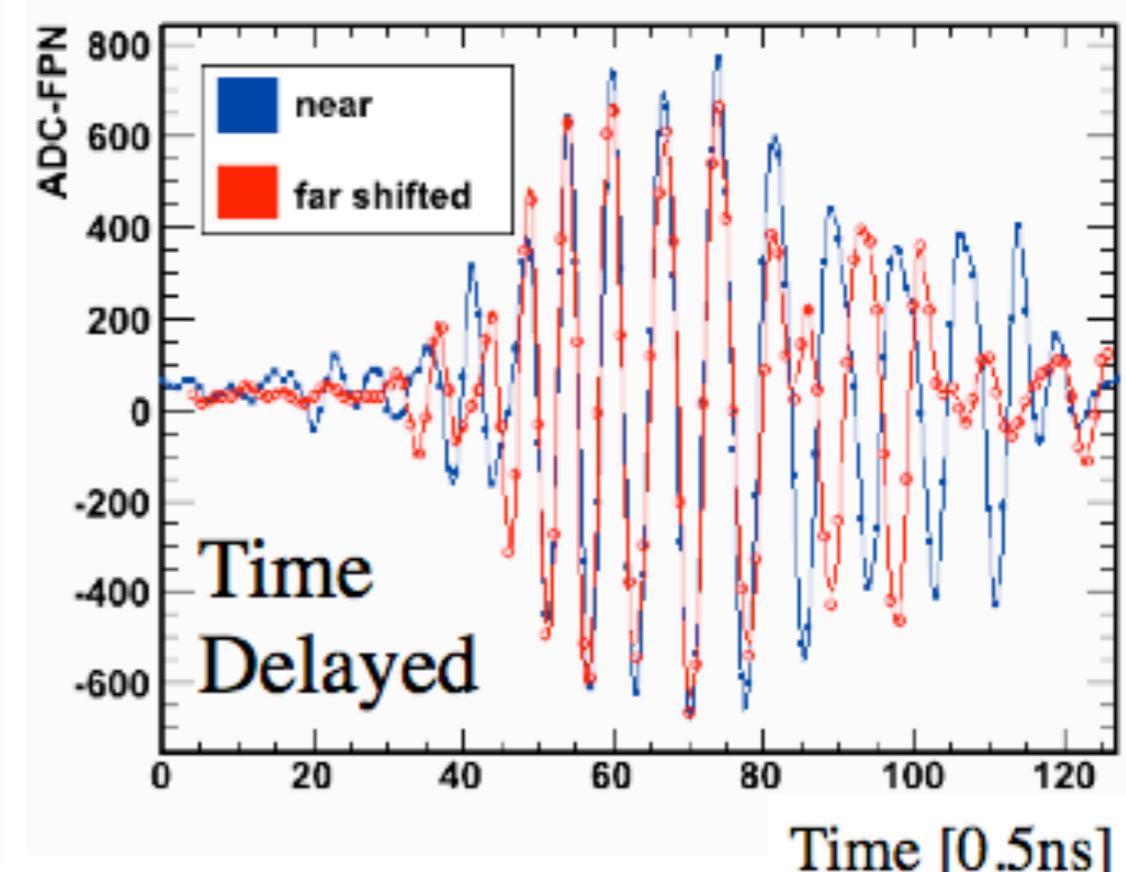
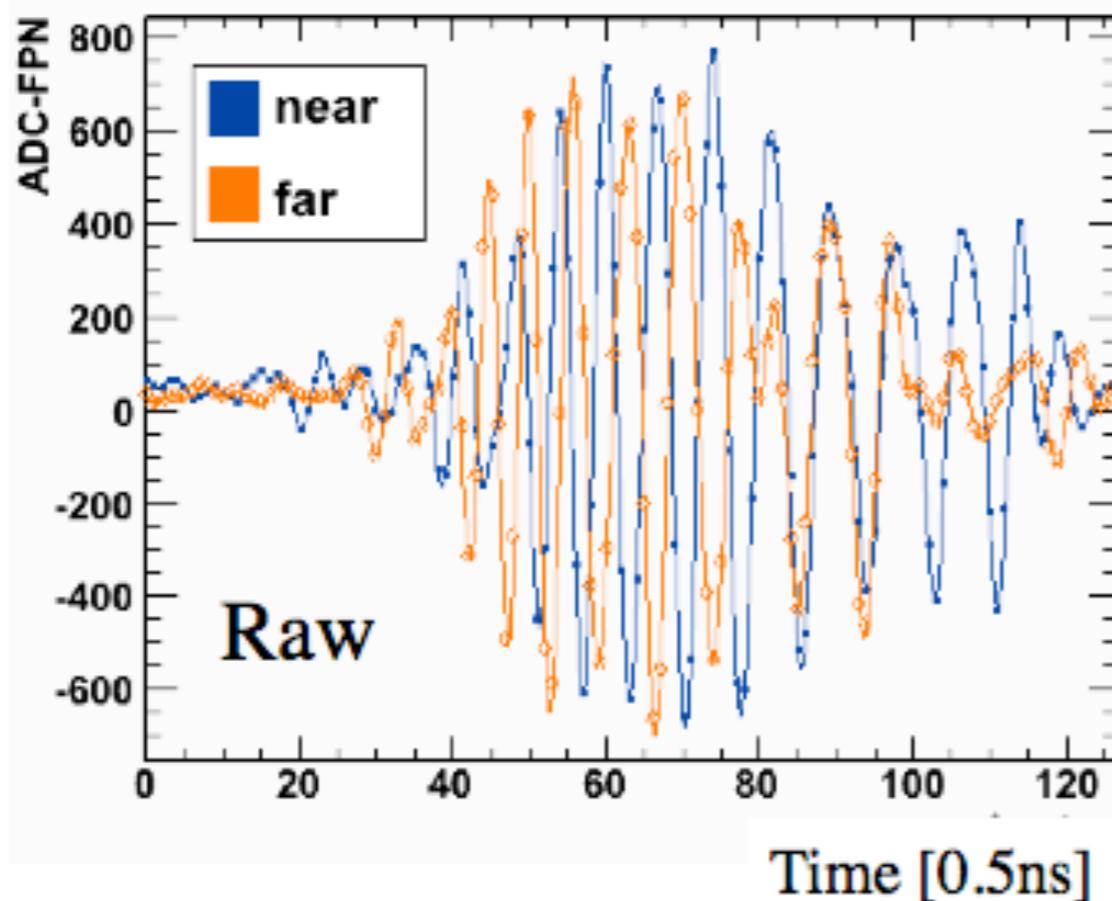
US
Sweden
New Zealand





Bounce Tests

Pulser->Seavey TRX->Station



Notes: Time delays are determined from all 4 antennas,
compatible with plane wave



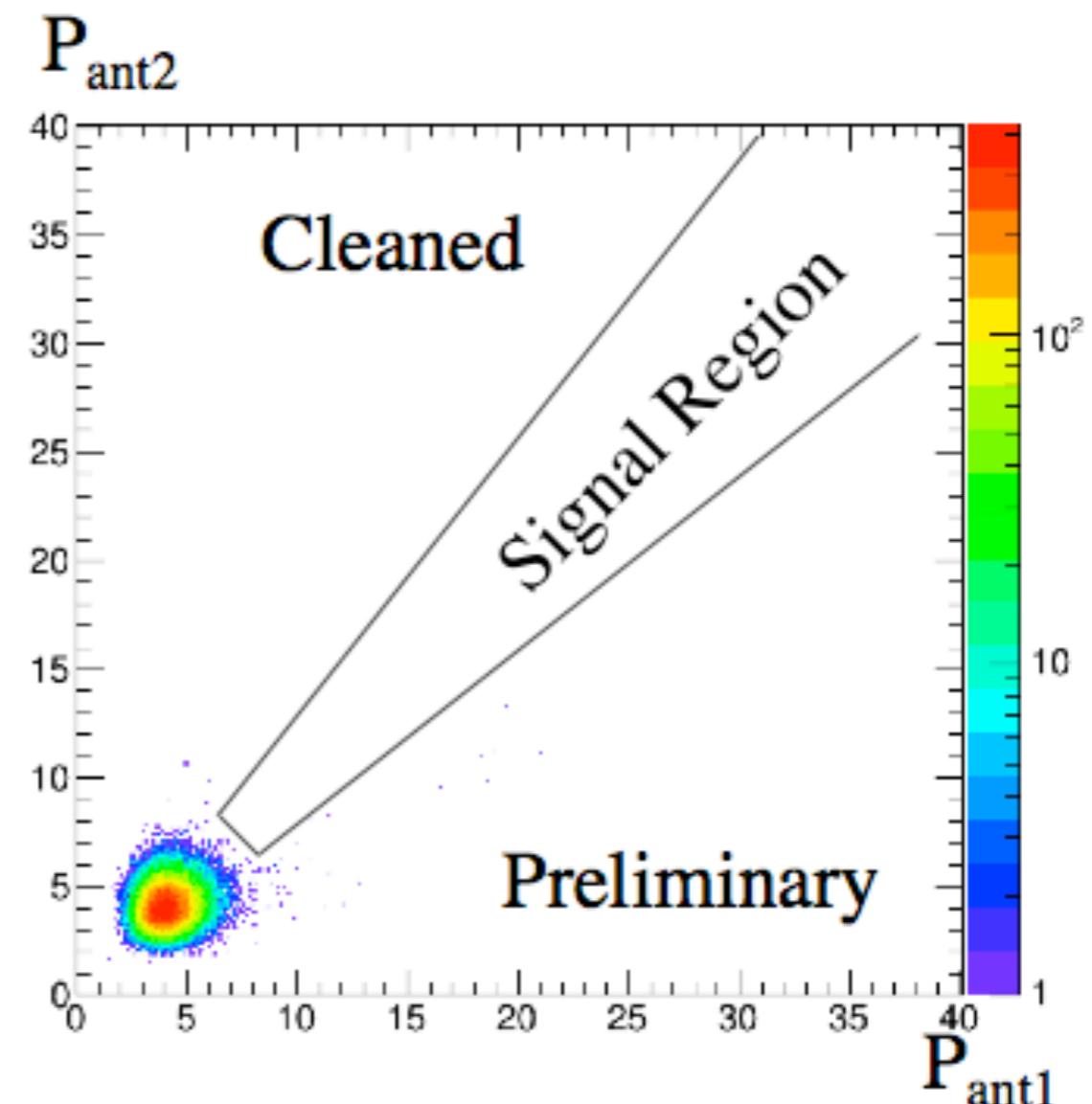
Data Analysis: HRA Station 3

(Dec 15, 2012 - Mar 15, 2013)

552473 events collected in
2/4 majority logic at 5 sigma
thresholds on each channel

Remove event if

- (1) Too much power below highpass
- (2) Unusual peaks in power spectrum
- (3) No waveforms consistent with time domain expectation
- (4) Inconsistent power in parallel antenna



Complete rejection of BG without timing or event reconstruction

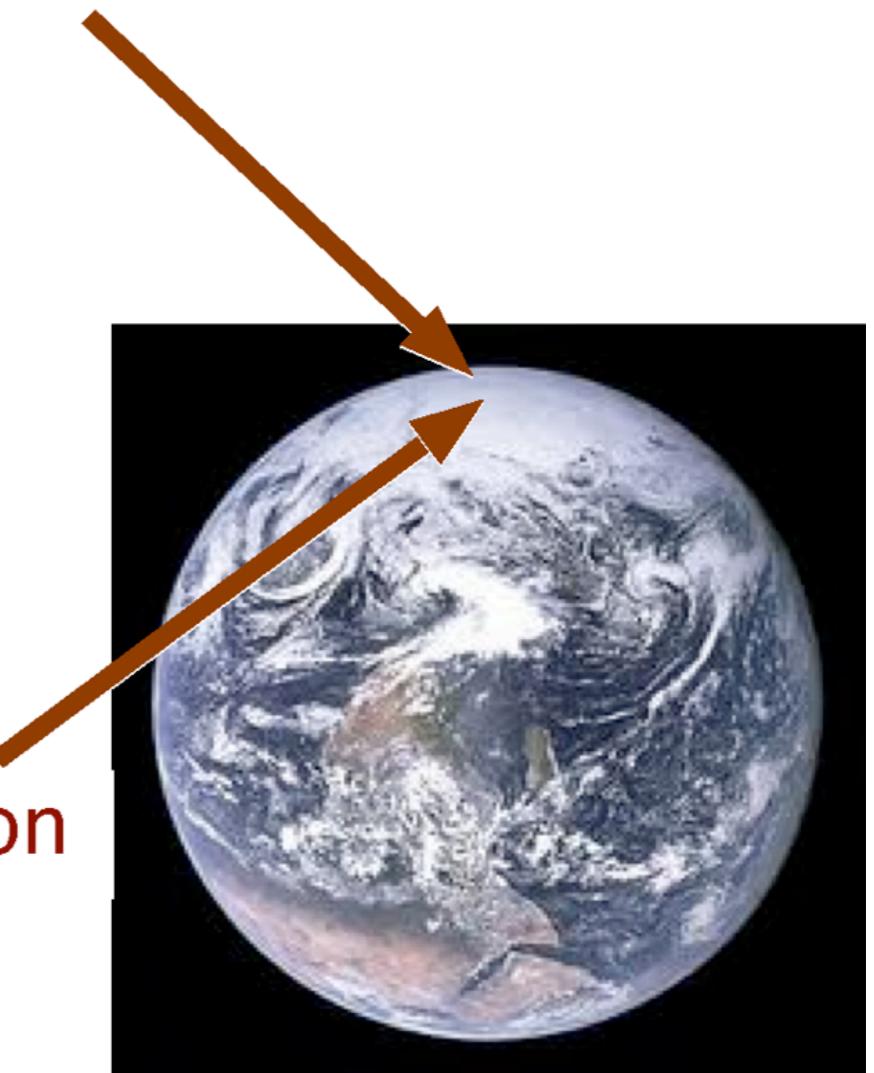
A couple of my favorite reasons why UHE neutrinos are going to be exciting...

νN Cross Section Measurement with a Neutrino Telescope

- Once an UHE ν sample is measured:
- The distribution of ν zenith angles θ_z would be sensitive to νN cross sections
- For $E_\nu = 10^{18}$ eV,
 $E_{CM} = 45$ TeV!

Less absorption

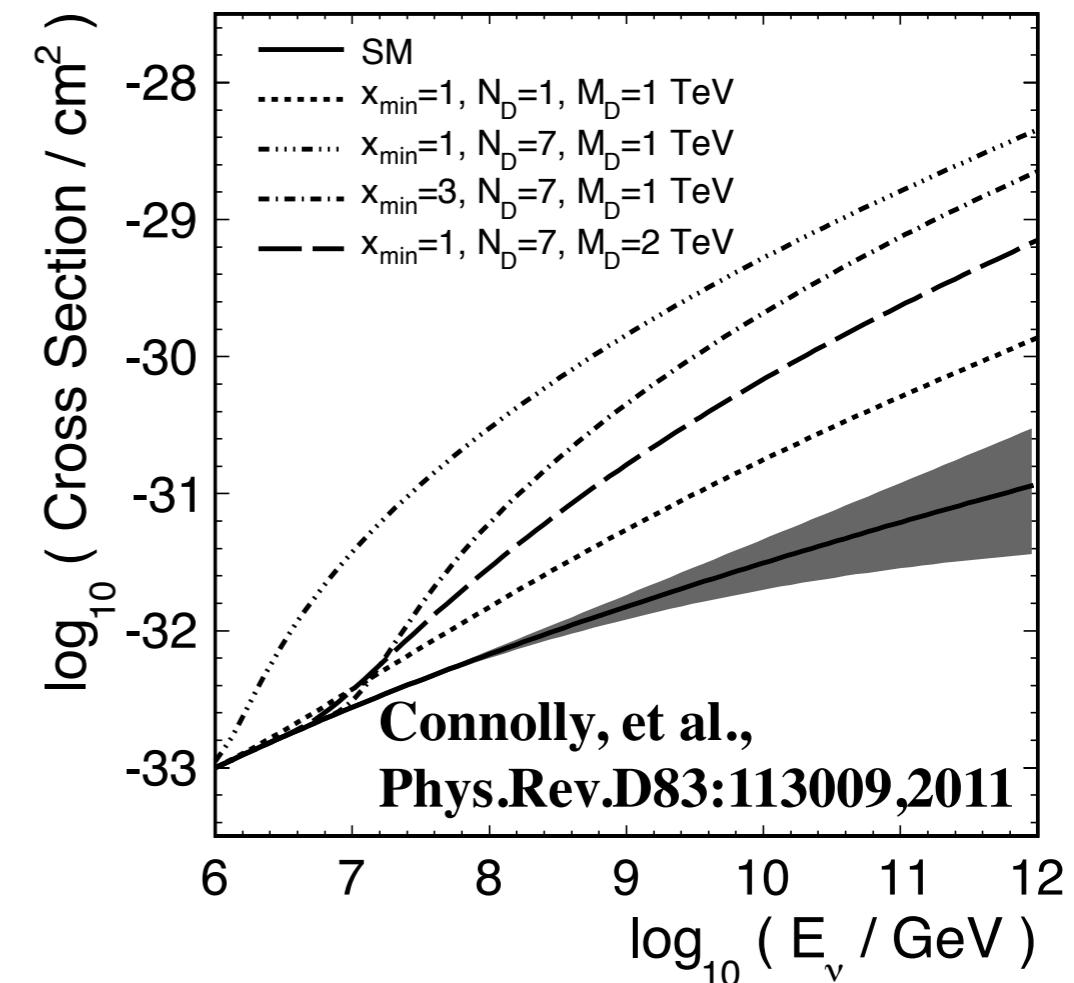
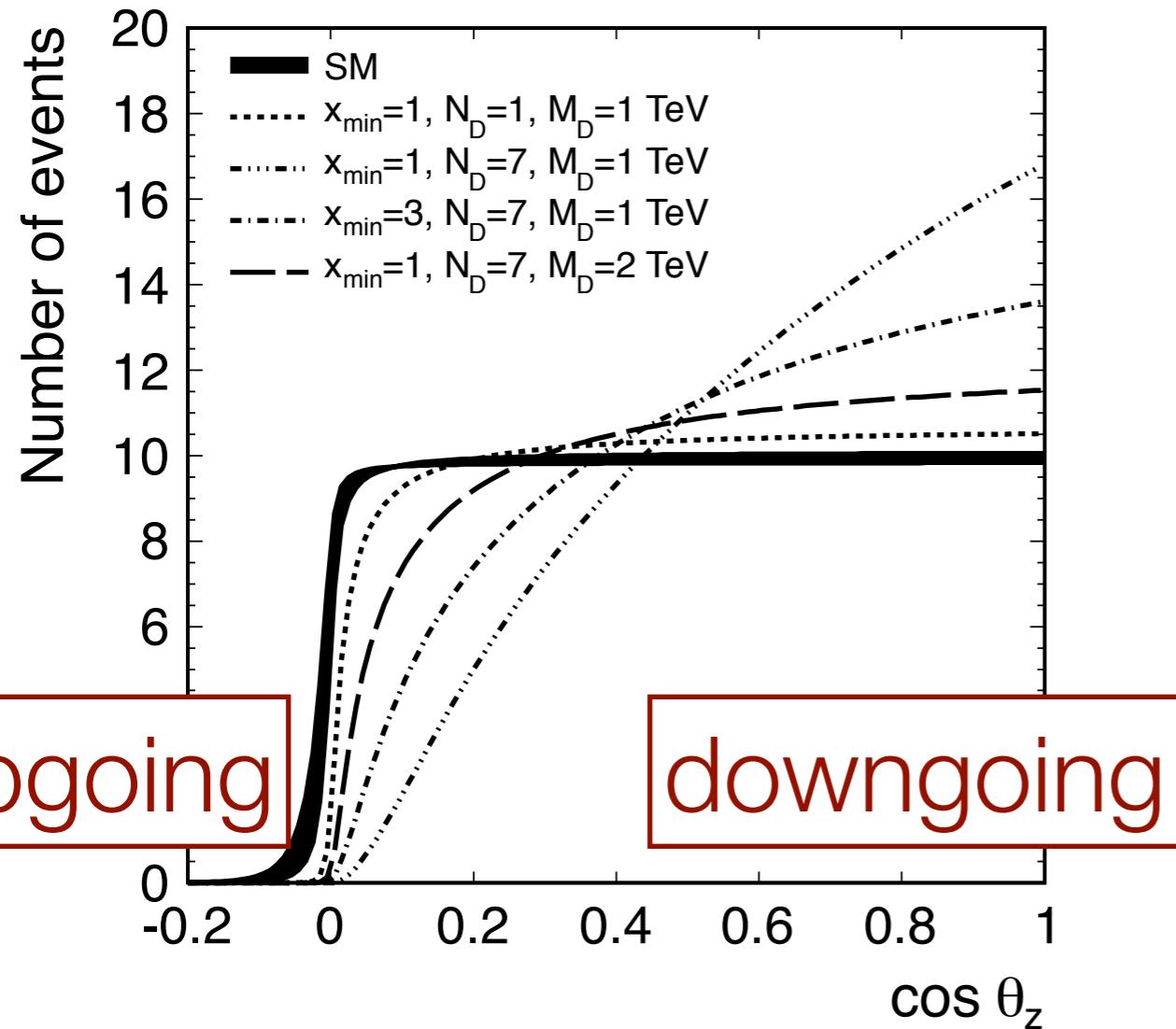
More absorption



Enhanced Cross Sections

- Models with extra space-time dimensions lead to enhanced νN cross sections due to micro-black hole production

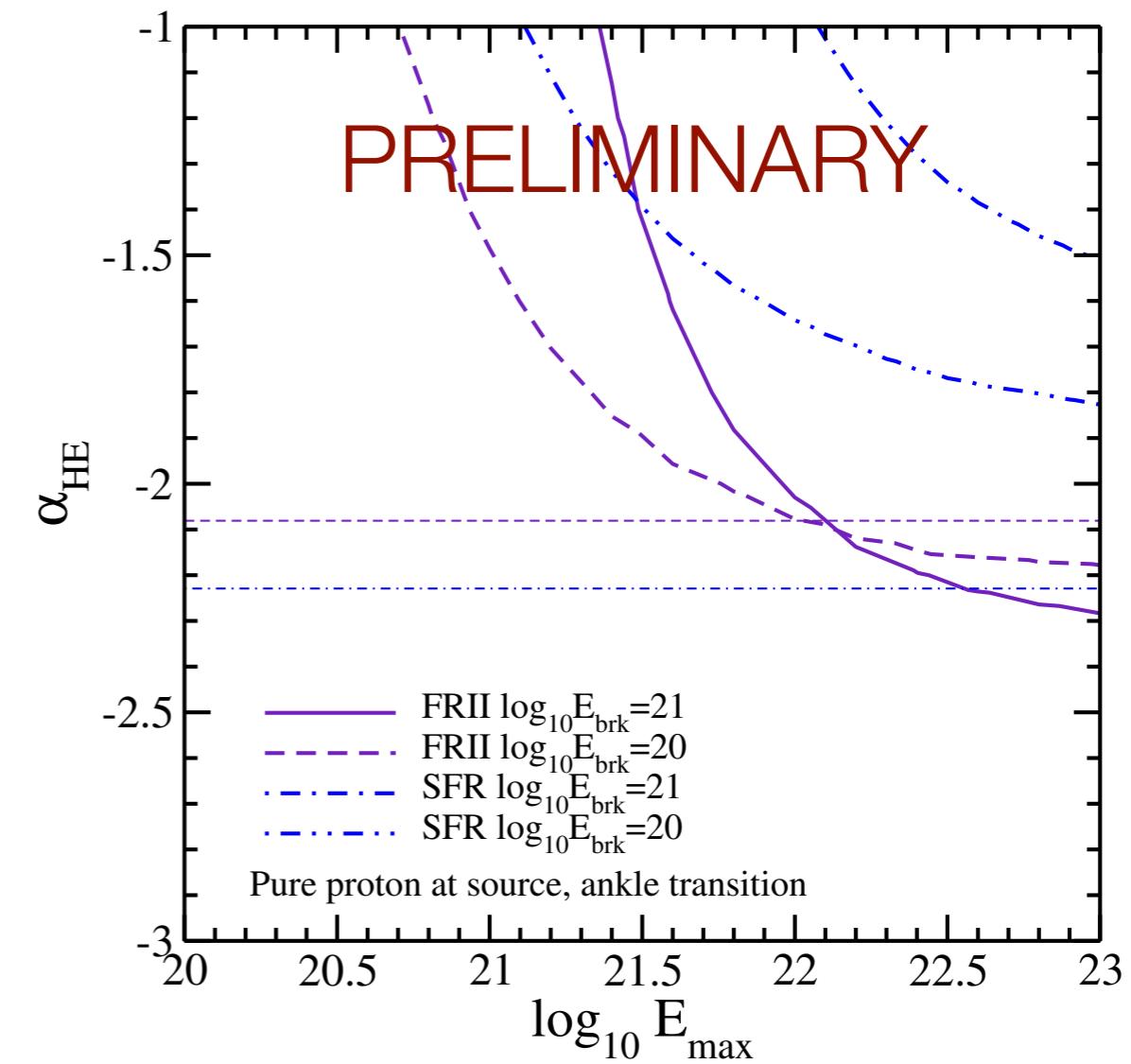
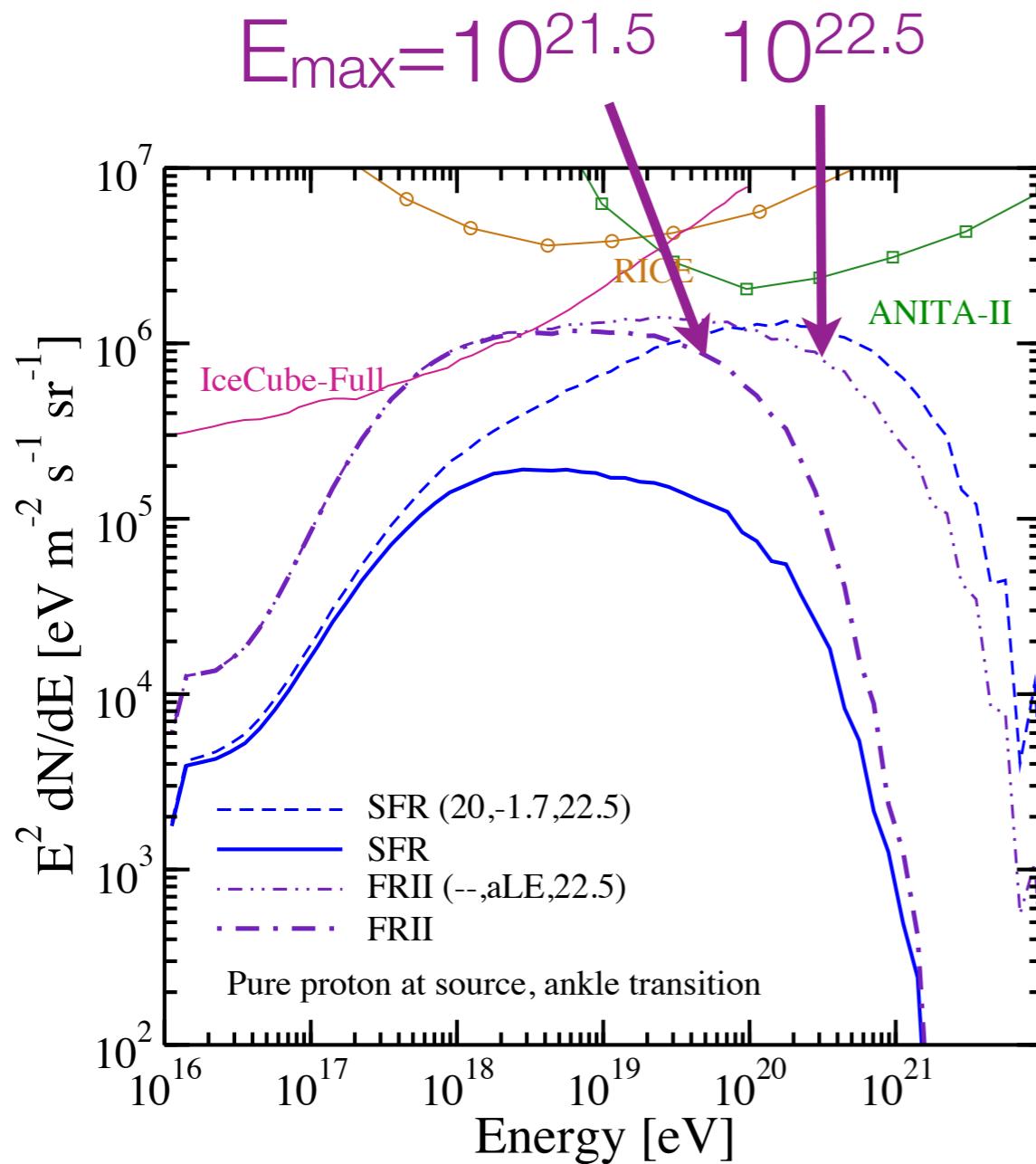
J. Alvarez-Muniz and E. Zas,
Phys. Lett. B411, 218 (1997)



- These would modify the θ_z distributions from the Standard Model (SM) expectation
- $N_D = \# \text{ extra dimensions}$,
 $M_D = \text{reduced Planck scale}$,
 $X_{\min} = M_{\text{BH}}^{\text{min}} / M_D$

Neutrinos: Only Probes of Ultimate Cosmic Acceleration Energy

- Highest energy cosmic rays are all local - not cosmic probes



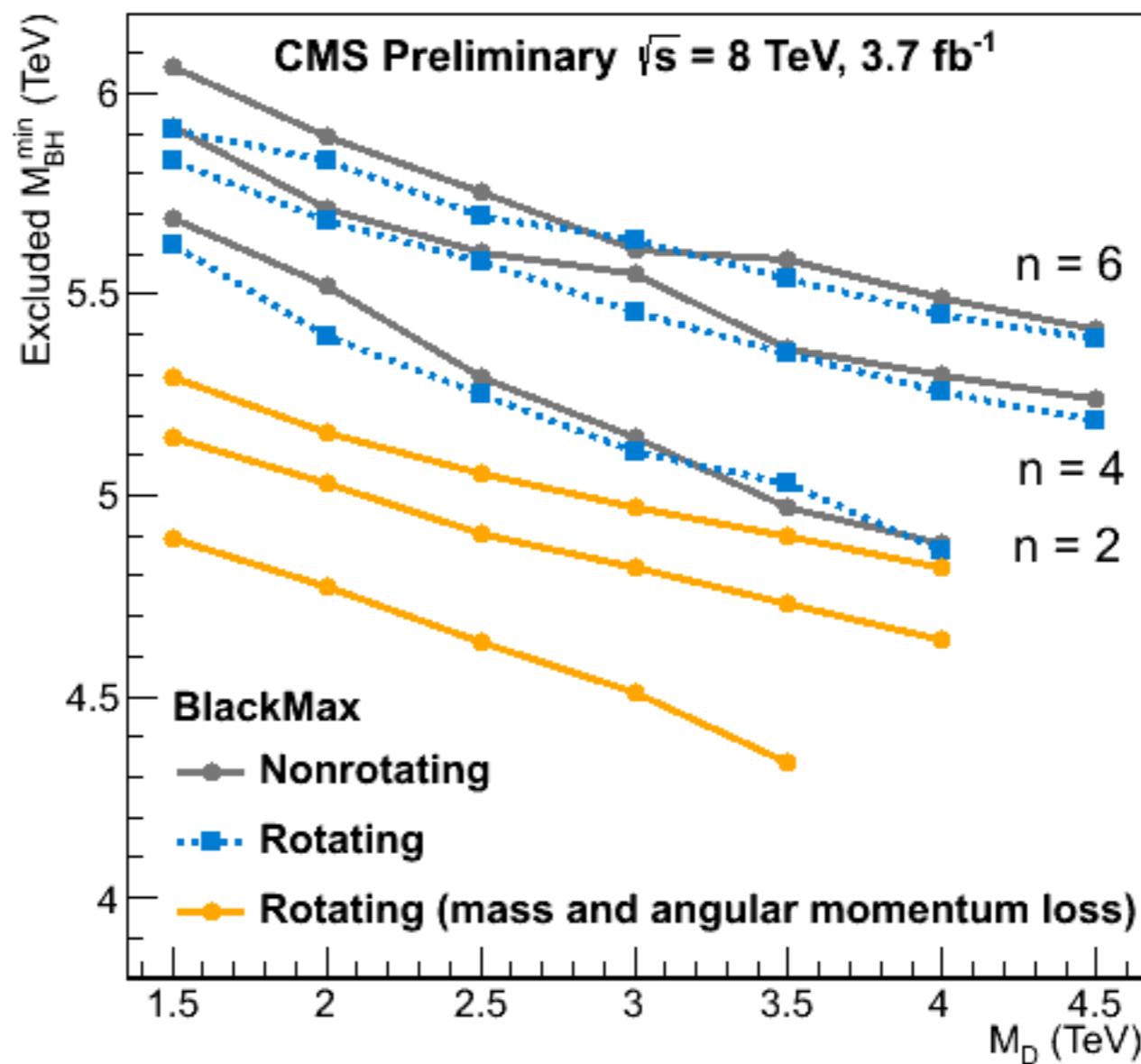
Summary

- UHE neutrino detection is approaching!
- Once UHE neutrinos are observed, will be unique laboratories for
 - particle physics at super-LHC energies (cross sections)
 - unique view of UHE universe at cosmic distances



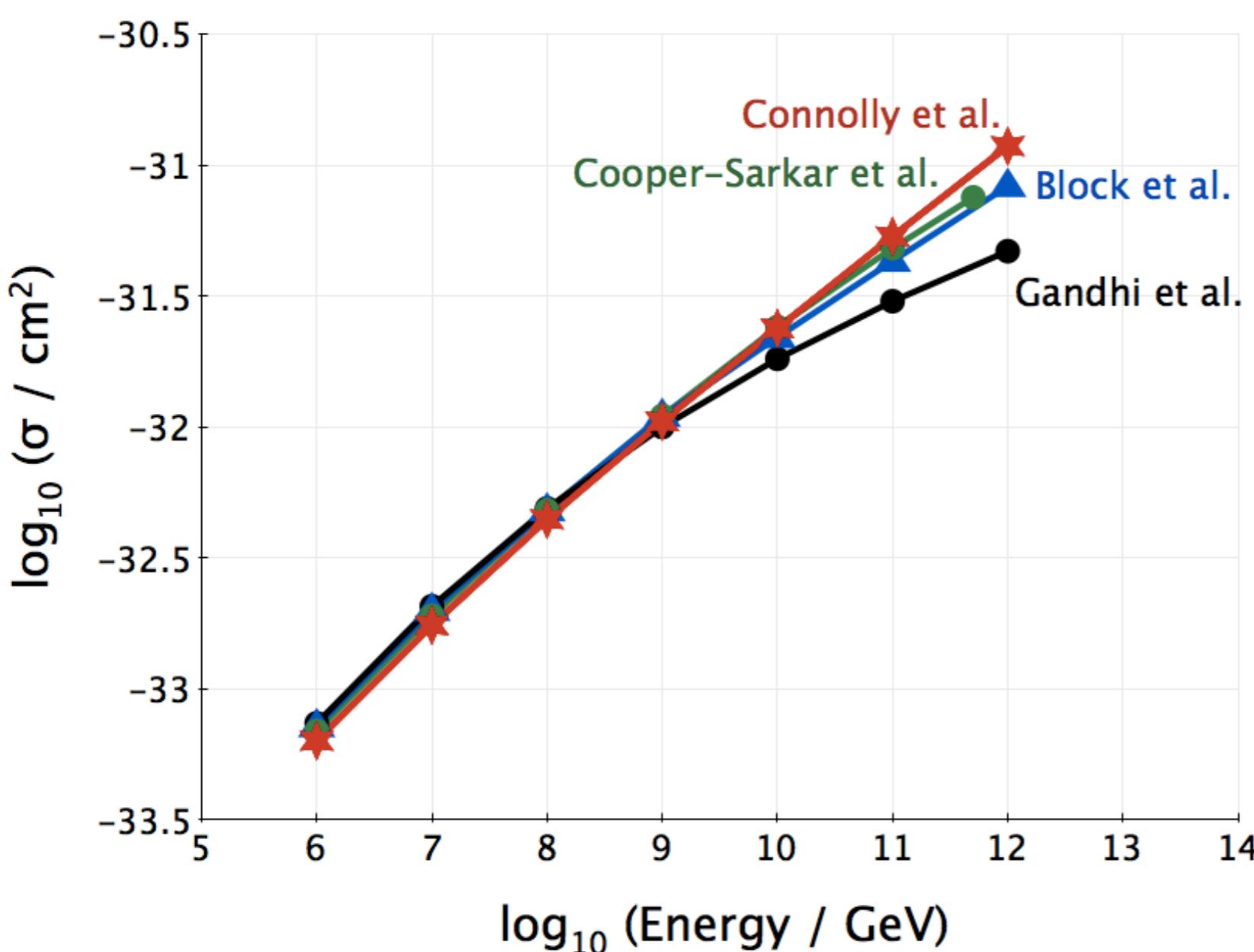
Backup Slides

CMS constraints for reference



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>

vN Cross Section calculations



R. Gandhi, C. Quigg,
M.H. Reno, I. Sarcevic (1998)

A. Connolly, R. Thorne
and D. Waters (2011)

Cooper-Sarkar, Mertsch
and Sarkar (2011)

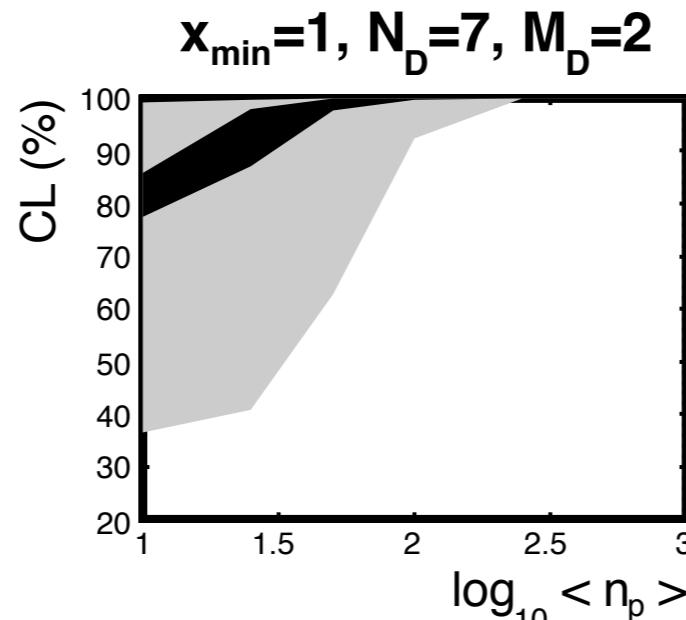
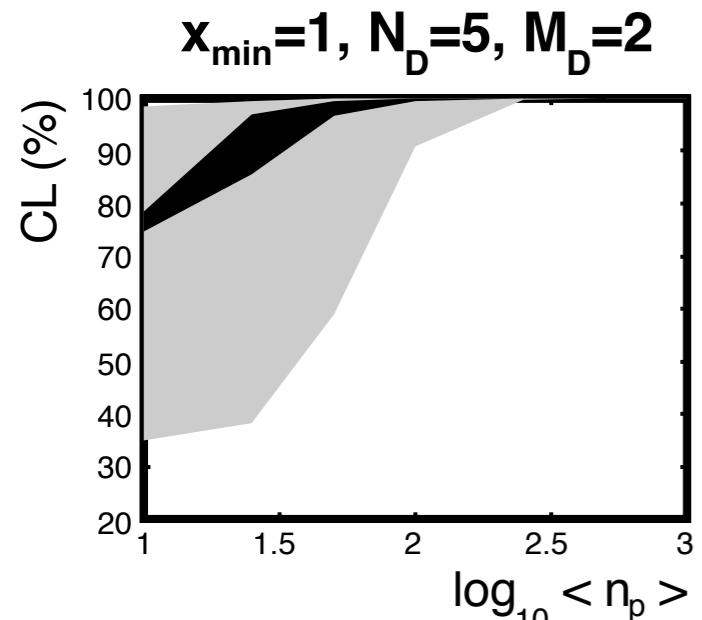
M. Block, L. Durand, P. Ha,
D. McKay (2013)

Weaker low-x
dependence
gives lower
cross sections
at high energies

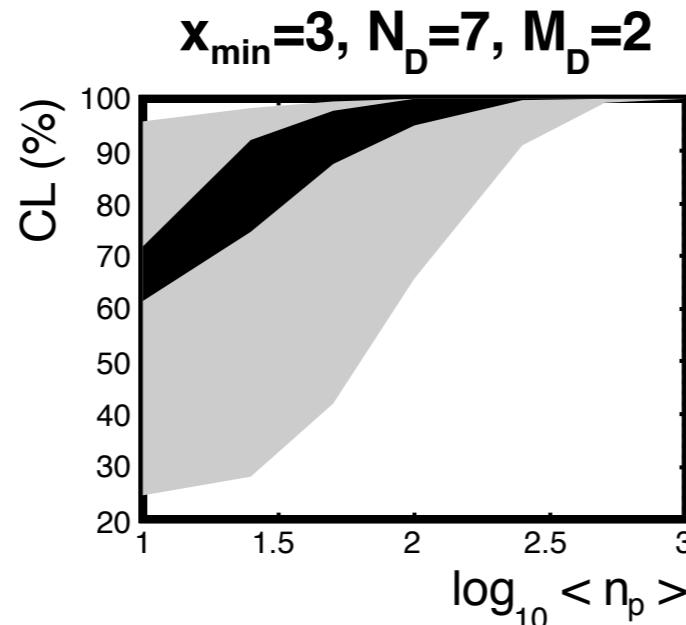
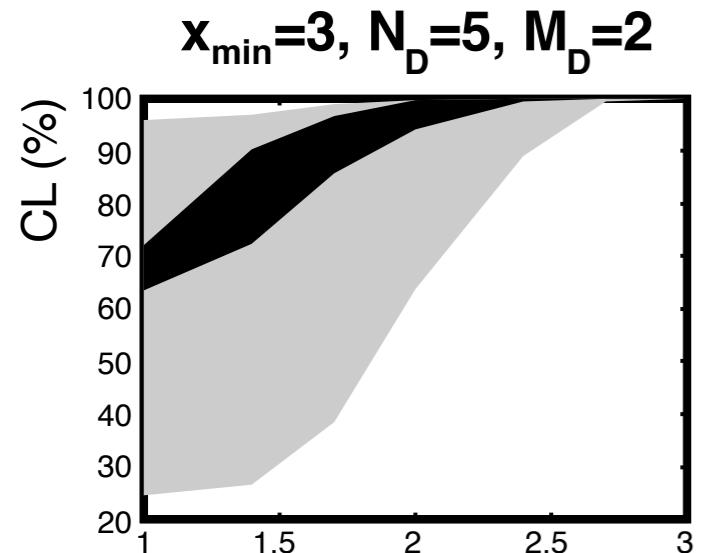
Why are νN cross sections interesting?

- Center of mass (COM) of UHE neutrino interactions with nuclei well exceed LHC energies
 - $\sqrt{s} = \sqrt{2M_N E_\nu}$, $E_\nu = 10^{18} \text{ eV} \rightarrow \sqrt{s} = 45 \text{ TeV!}$
- Predictions of SM νN cross section (σ) at high energies rely on measurements of quark, anti-quark number densities at low x (parton momentum fraction) inaccessible with accelerators
 - $E_\nu > 10^{17} \text{ eV} \rightarrow x \lesssim 10^{-5}$
 - HERA measures $x \gtrsim 10^{-4} - 10^{-5}$
- νN σ 's at all energies needed to model experiments

Expected Constraints



- Black bands: systematic uncertainty on SM cross sections
- Gray bands: statistical uncertainties
- On average, with 100 events, expect to exclude:
 - $X_{\min} = 1, M_D = 1, N_D \geq 2$
 - $X_{\min} = 3, M_D = 1, N_D \geq 3$
 - $X_{\min} = 1, M_D = 2, N_D \geq 3$

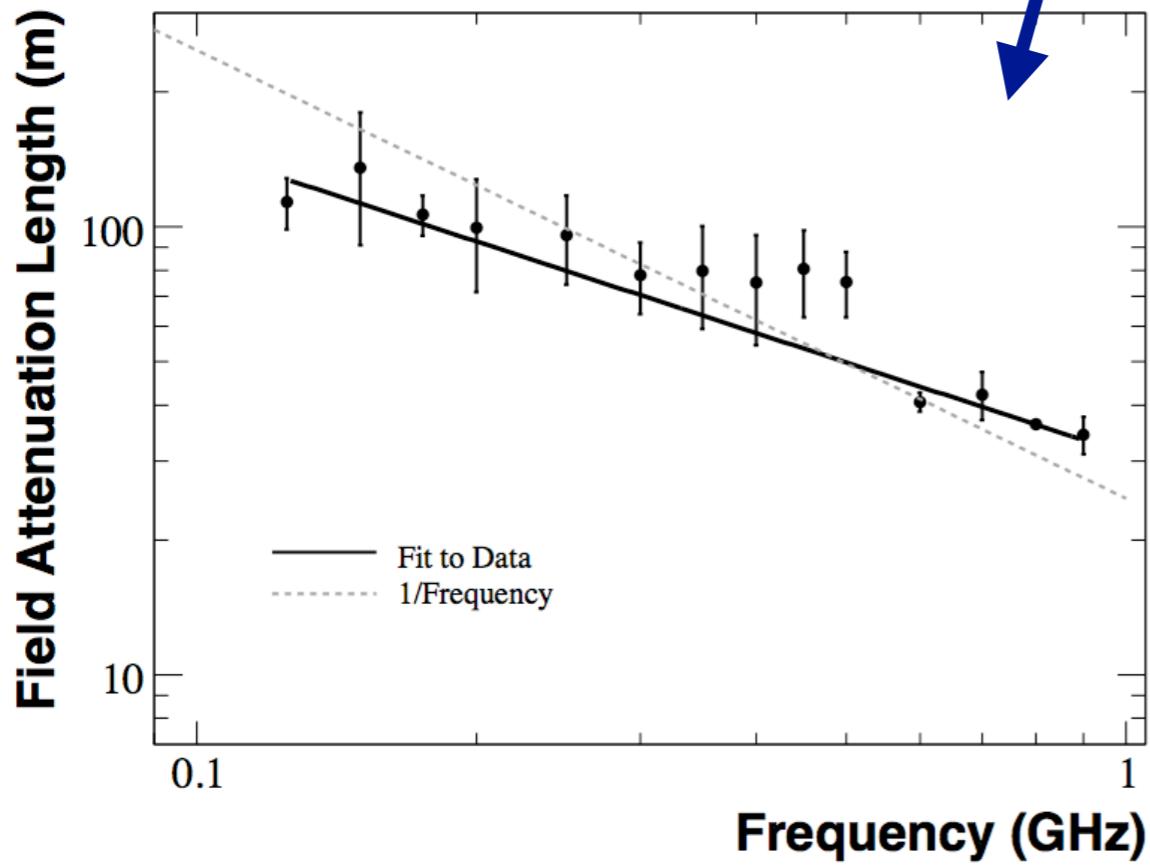


Connolly, et al.,
Phys. Rev. D83:113009, 2011

- $X_{\min} = 3, M_D = 2, N_D = 7$ excluded with 110 events

Most of these already excluded by the LHC. BUT unique opportunity to probe the theory w/ UHE neutrinos

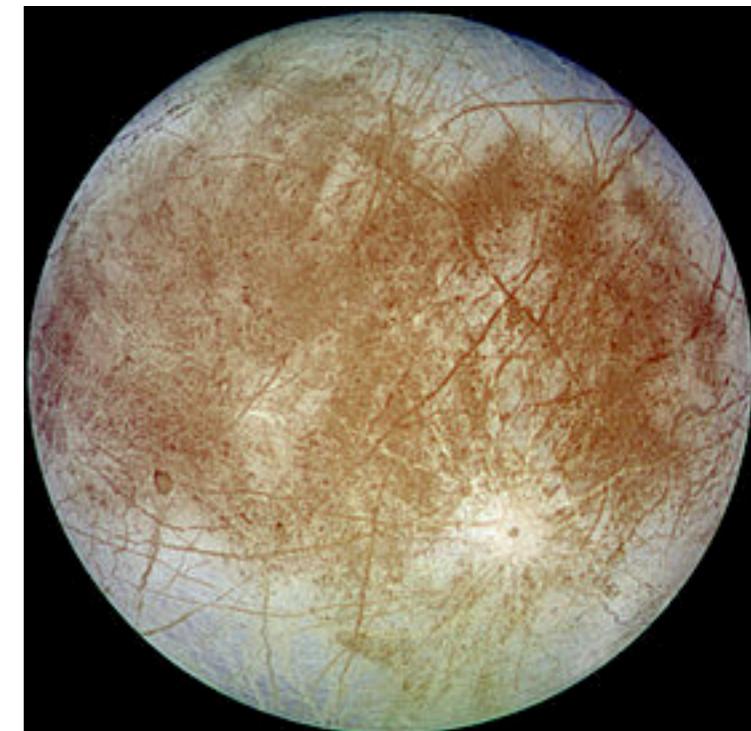
Other Media?



Salt - measured attenuation lengths $> \sim 100$ m

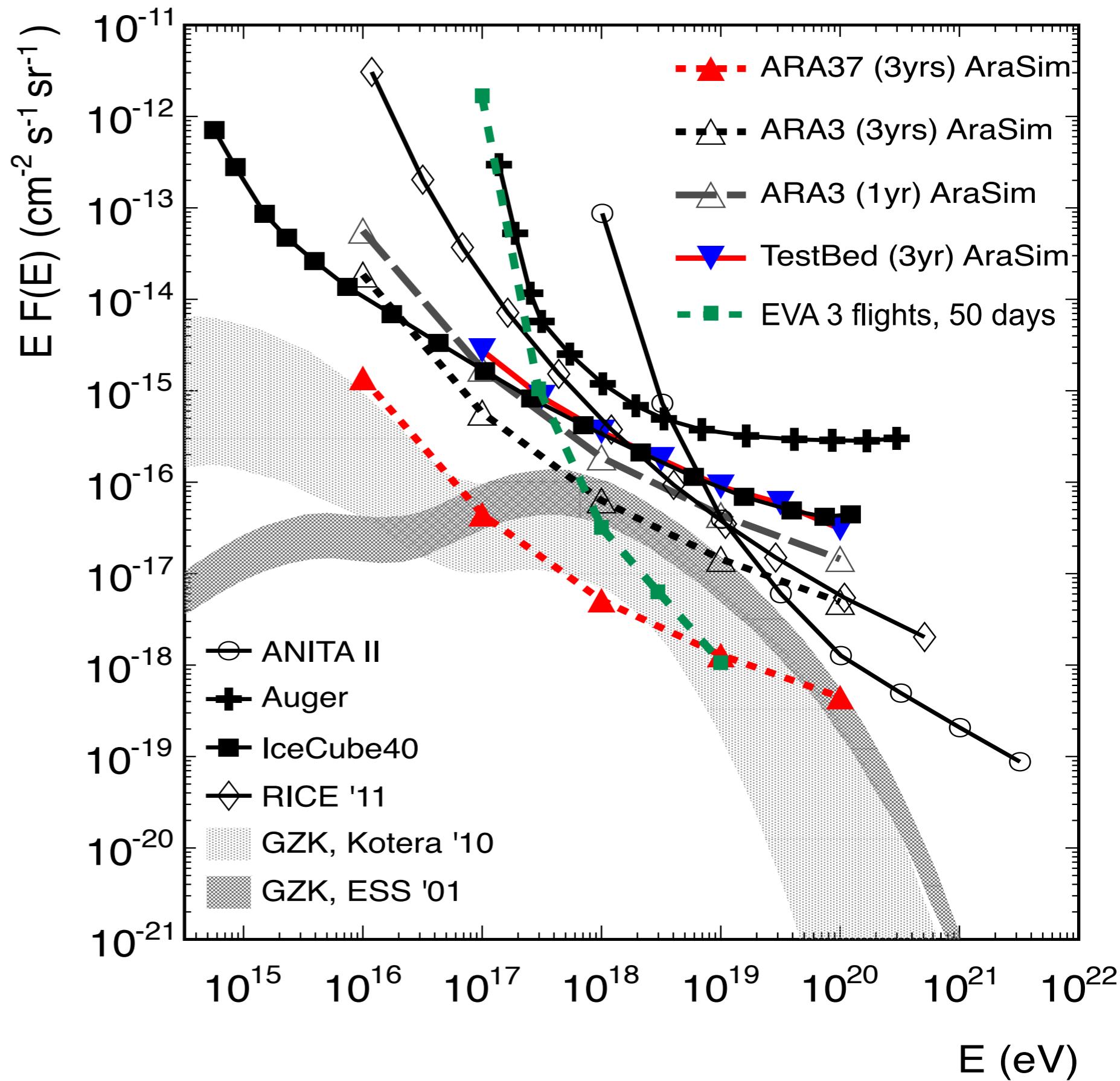
Greenland ice?

Icy Moons?



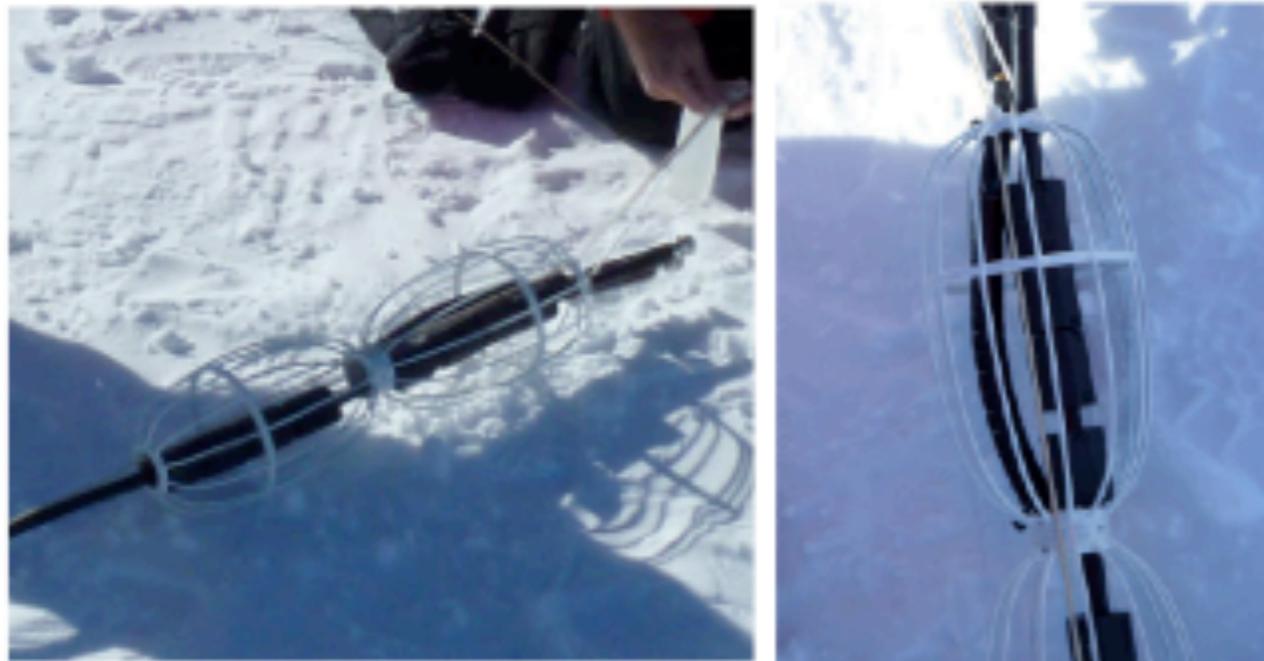
Sensitivities

- Projections are expected 90%CL constraints
- Using trigger-level sensitivity only



Antennas

V-pol bicone



H-pol slotted cylinder

