Fundamental Physics with Askaryan Arrays

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Snowmass
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Outline

- **Introduction to radio Cerenkov technique and experiments**
- **Cross-sections**
- **Lorentz Invariance Violation**
- **UHE Astrophysics**
- **Conclusions**

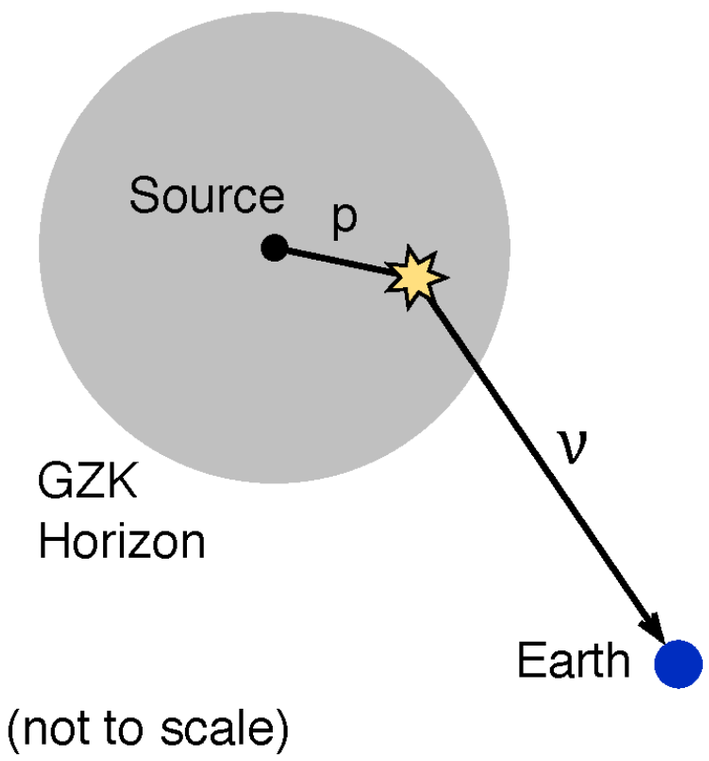
See tomorrow's talk by Abby Vieregg for more details on neutrino searches

2

Introduction to radio Cerenkov technique and experiments

Motivations for ultra-high energy (UHE) neutrinos (>10^{18} 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:



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

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

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

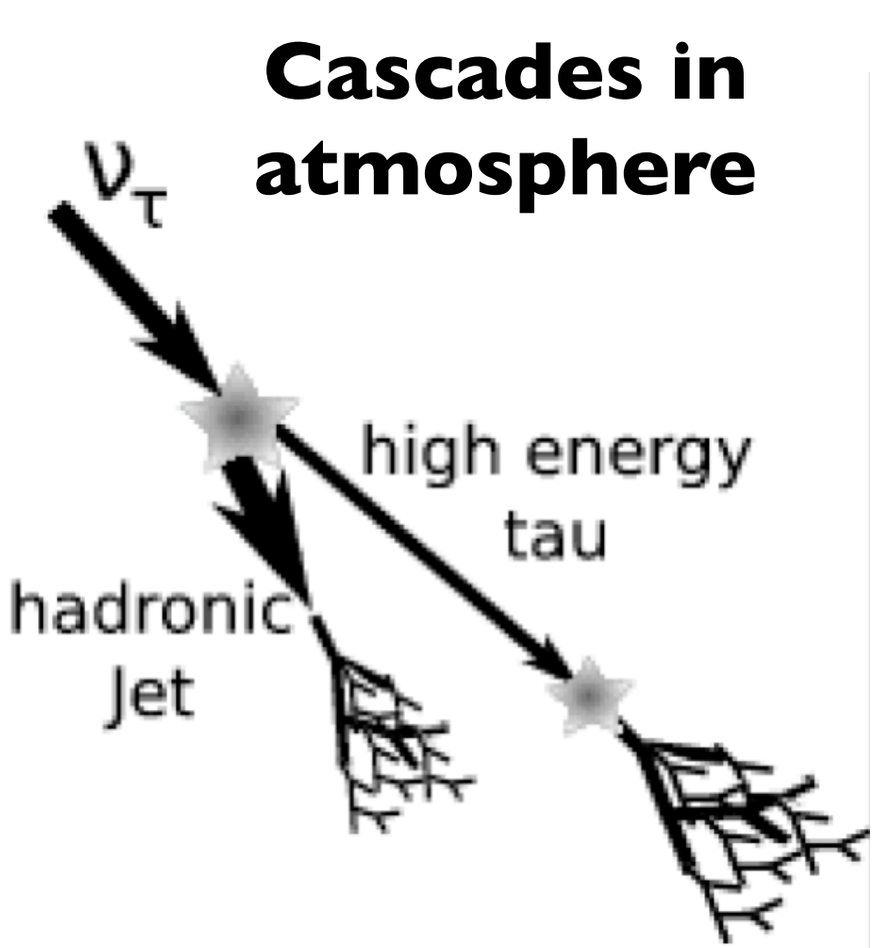
$$\mu^+ \rightarrow \mathbf{e}^+ \bar{\nu}_\mu \nu_{\mathbf{e}}$$

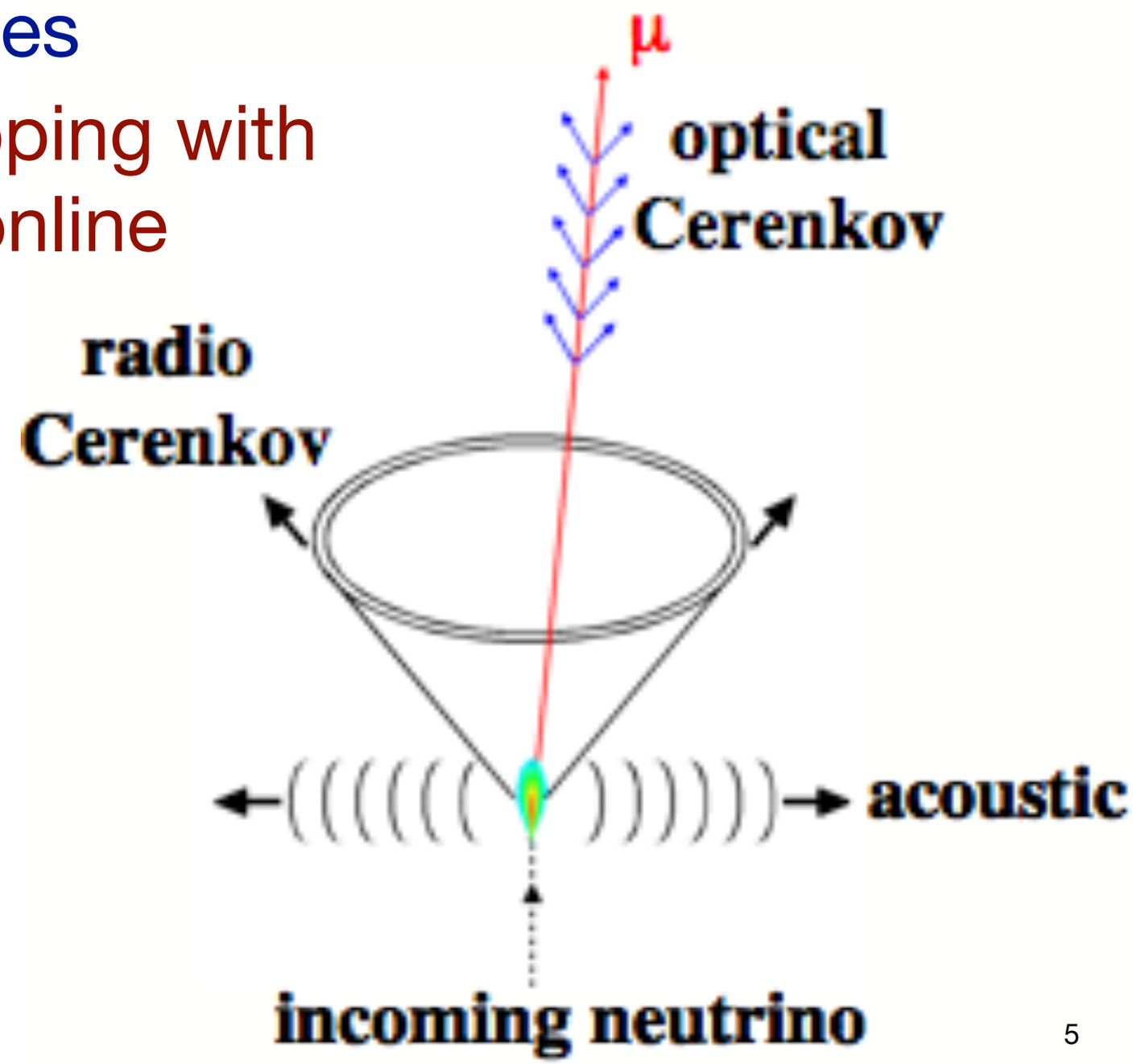
ν's from GZK process first pointed out by Berezinsky and Zatsepin (1969)

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

Detection Techniques

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





5

Radio Cerenkov Technique (Askaryan Effect)

- Coherent Cerenkov signal from net "current," instead of from individual tracks

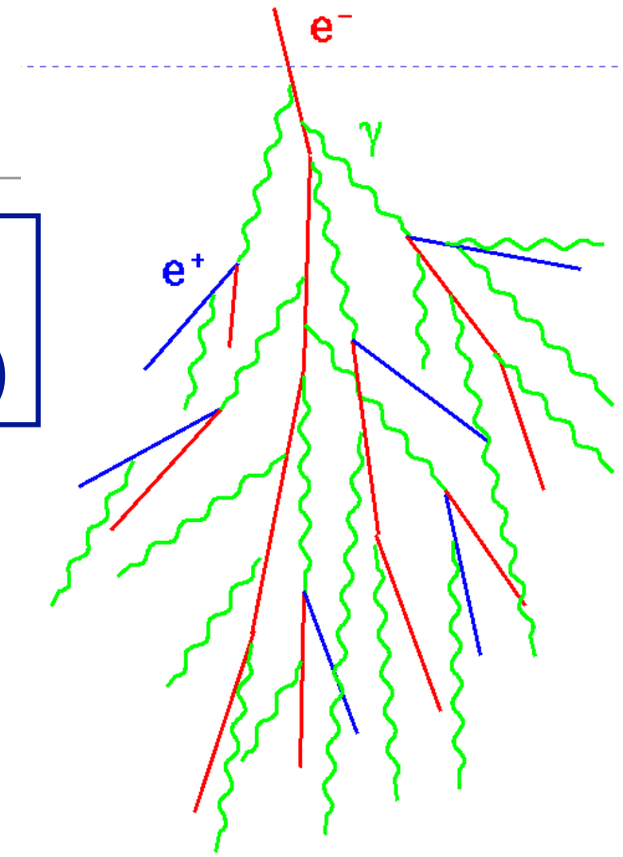
Idea by Gurgen Askaryan (1962)

- A ~20% charge asymmetry develops (mainly Compton scattering)
- Excess moving with $v > c/n$ in matter

  → Cherenkov Radiation $dP \propto v\, dv$
- If $\lambda >> R_{Moliere}$ → Coherent Emission $P \sim N^2 \sim E^2$

  $\lambda > R_{Moliere}$ → Radio/Microwave Emission

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



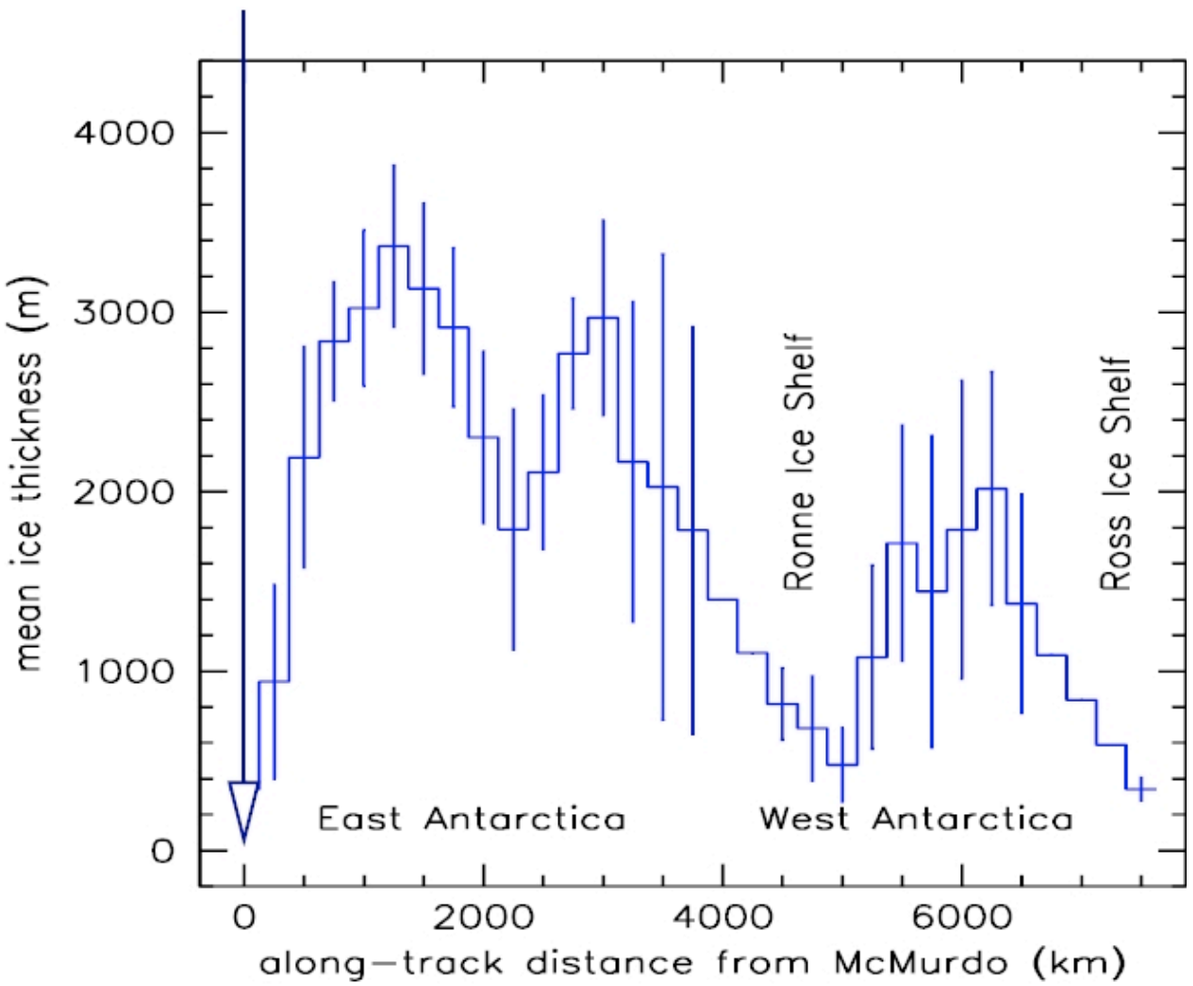
This effect has been confirmed experimentally in sand, salt, ice:

PRL 86, 2802 (2002)
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)
PRL 99, 171101 (2007)

6

Antarctic Ice

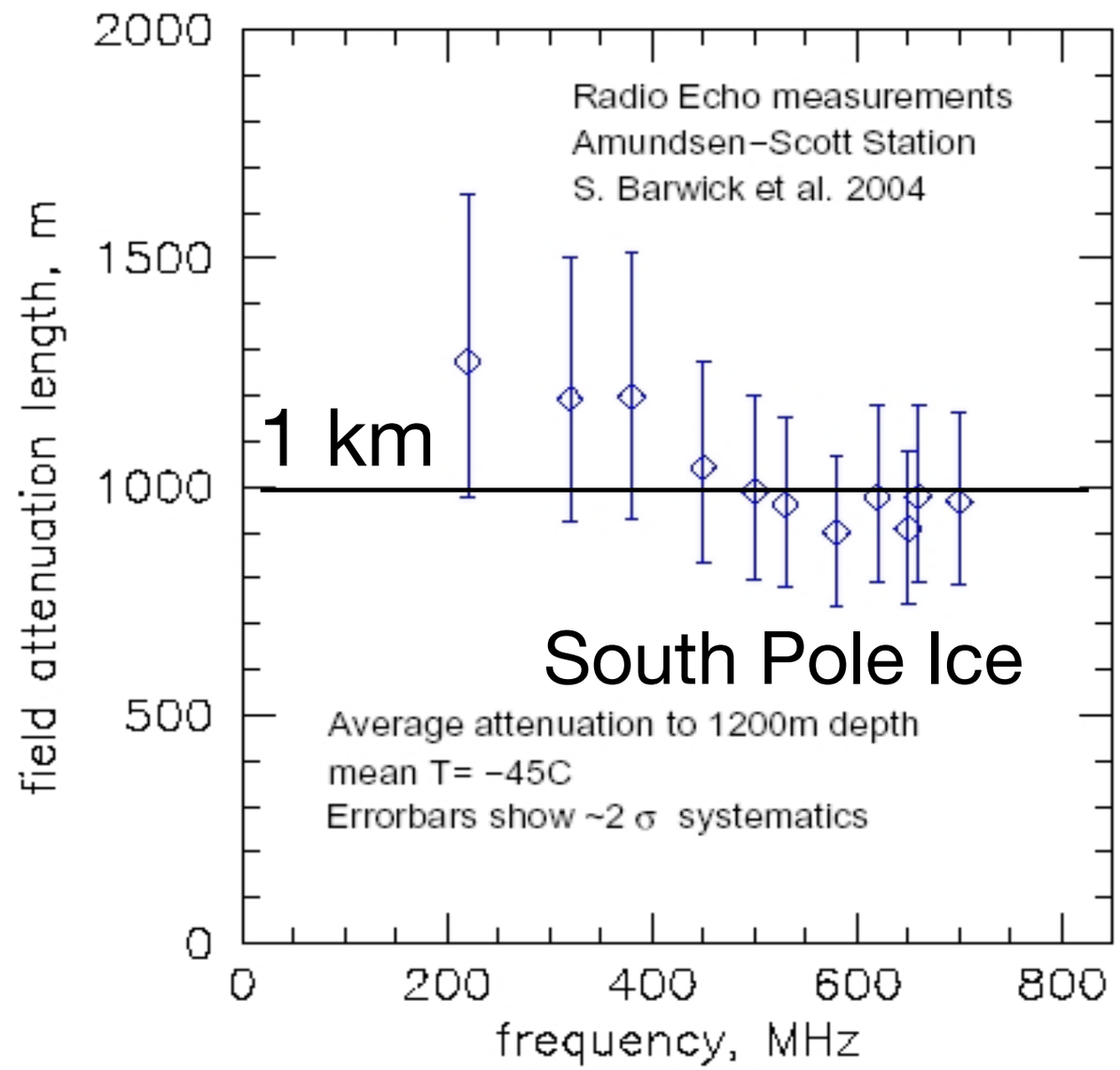
Ice thicknesses



[P. Gorham]

2 km depths are typical across the continent

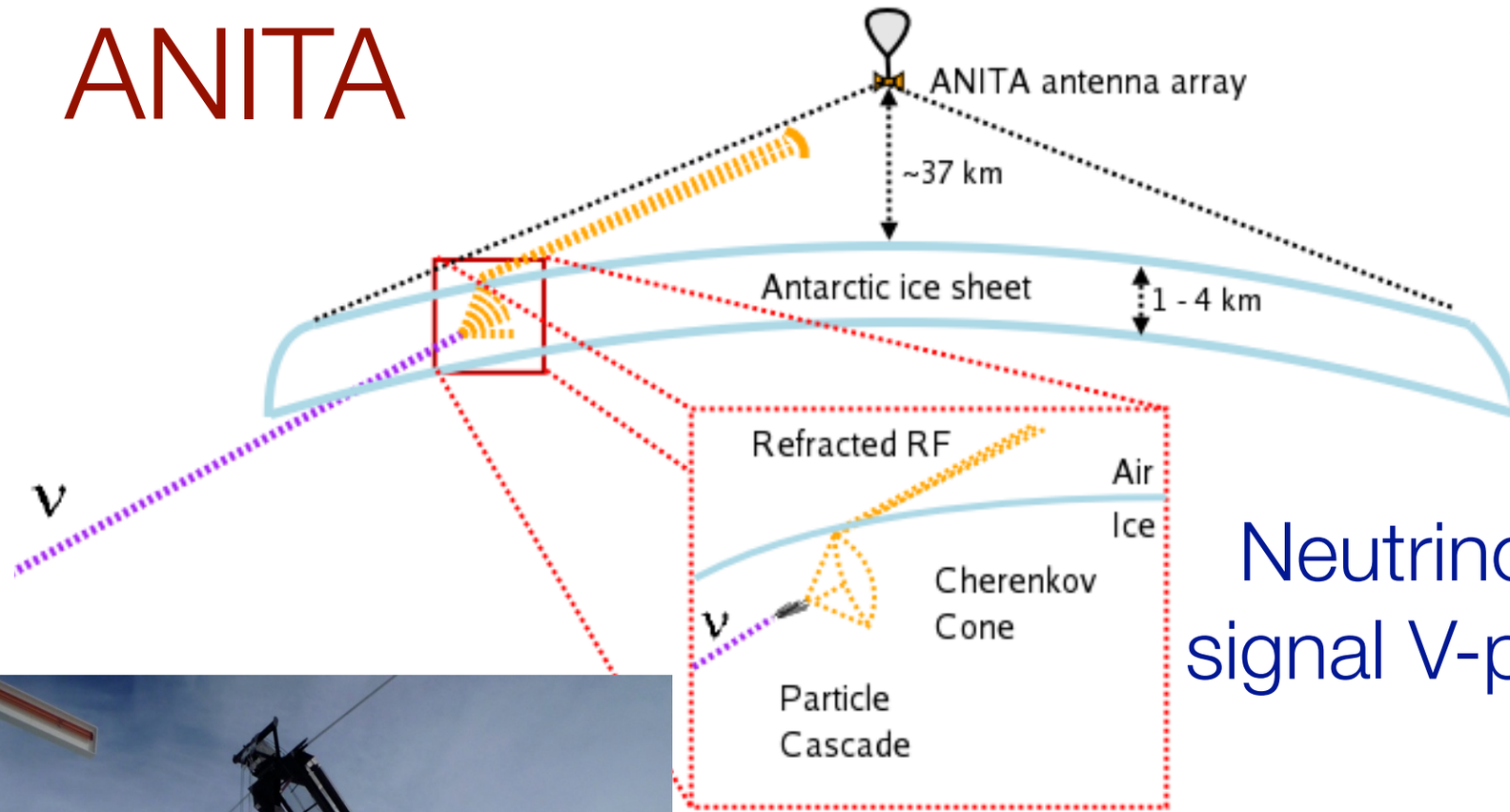
Radio Attenuation Lengths



7

Balloon Experiments

ANITA

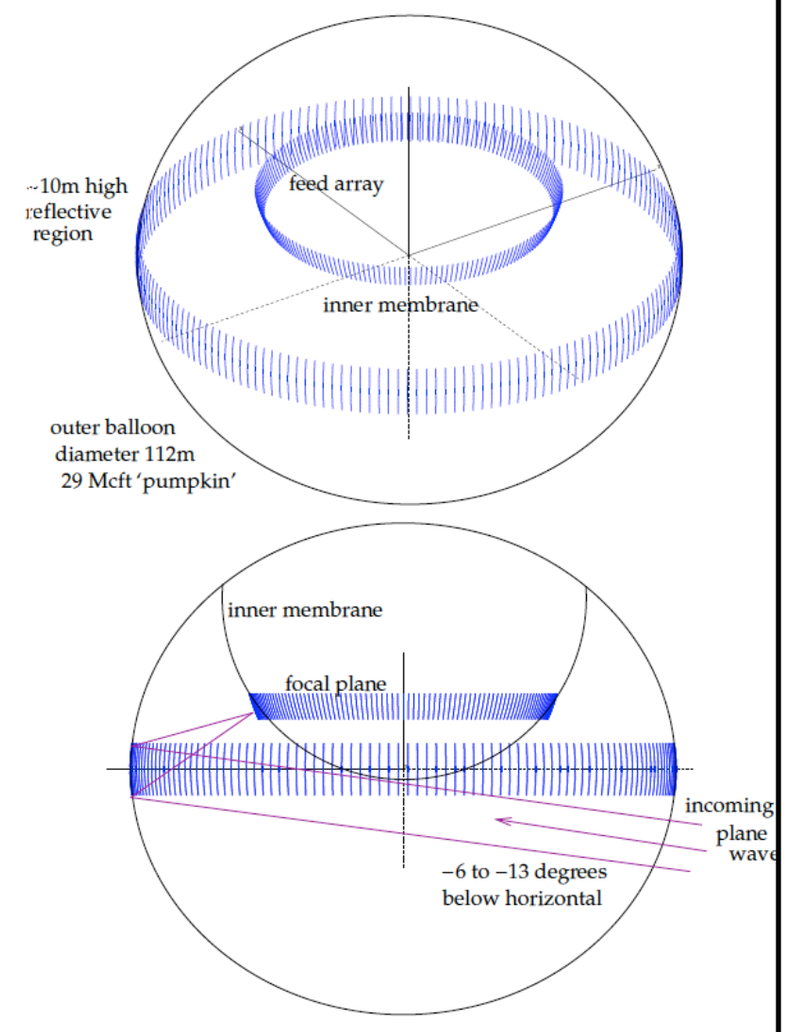


Neutrino signal V-pol

Long duration balloon program operated by NASA

ANITA 1: 2006-2007
ANITA 2: 2008-2009
ANITA 3: 2014-2015

Exavolt Antenna (EVA)



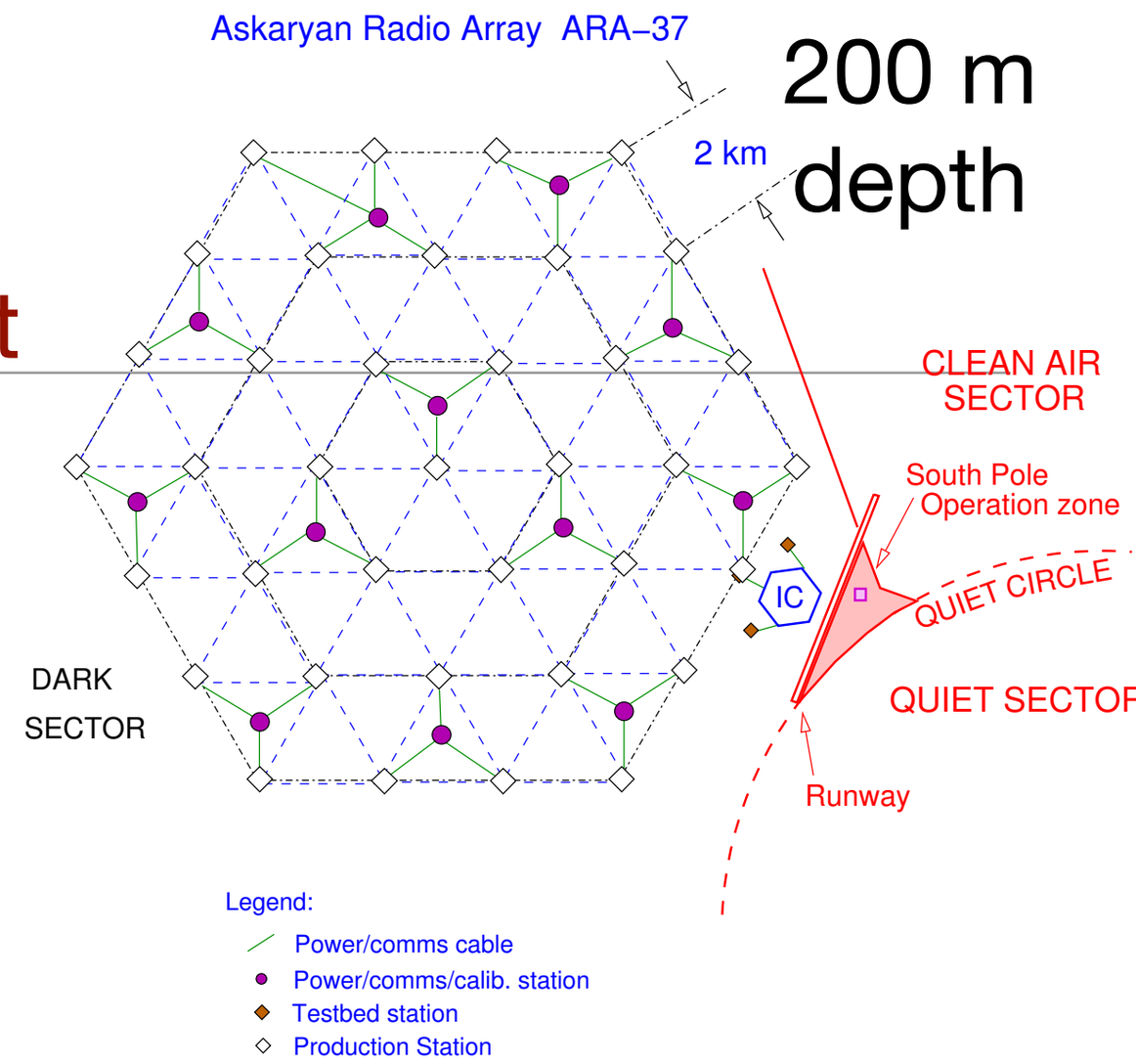
3 year NASA grant for engineering phase

8

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
- Phase1: 37 stations ~100 km^2
  - Establish flux
- Phase 2: ~1000 km^2
  - High statistics astronomy/ particle physics exploitation

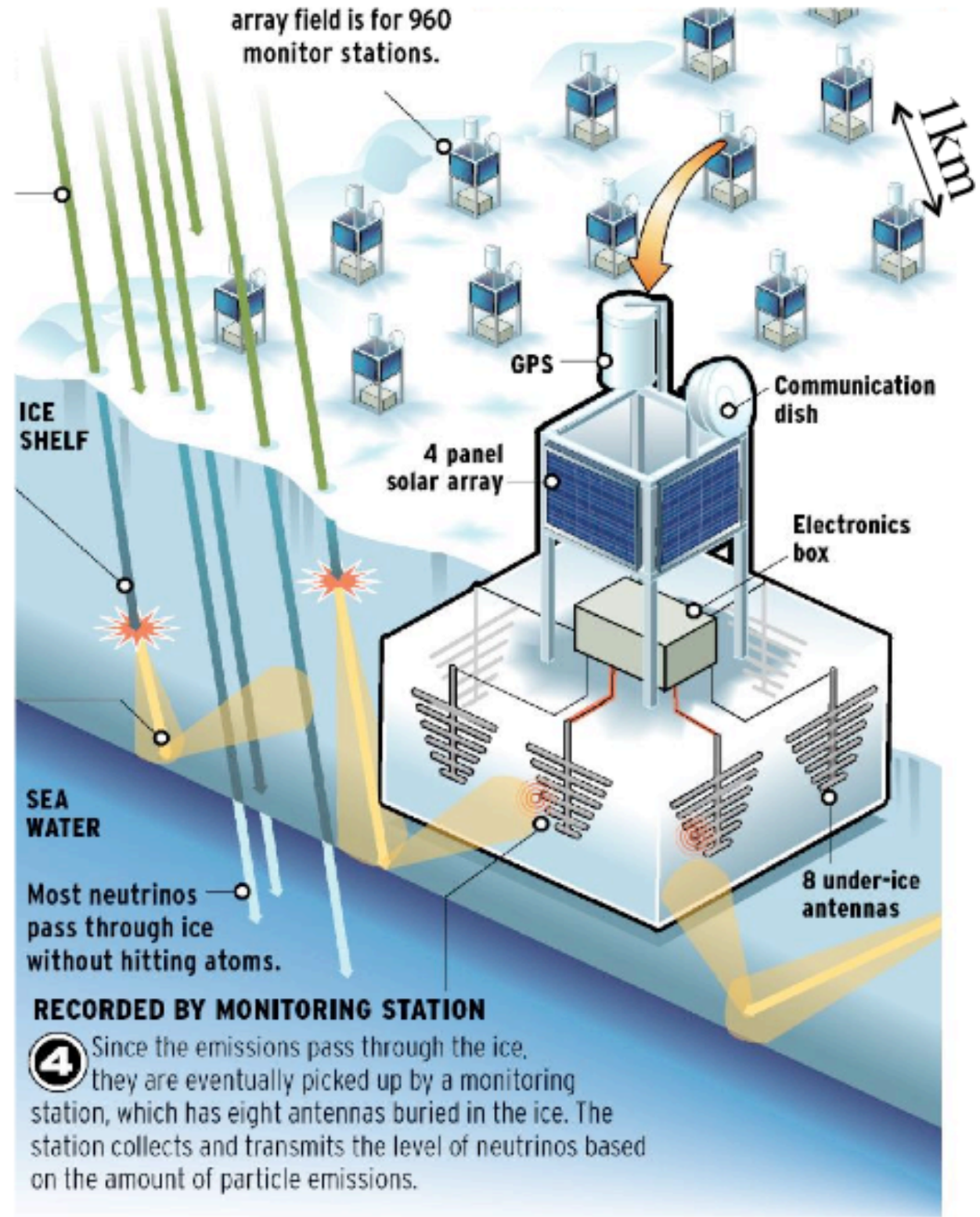


NSF has funded Testbed+3 Stations.
Pending approval for next phase

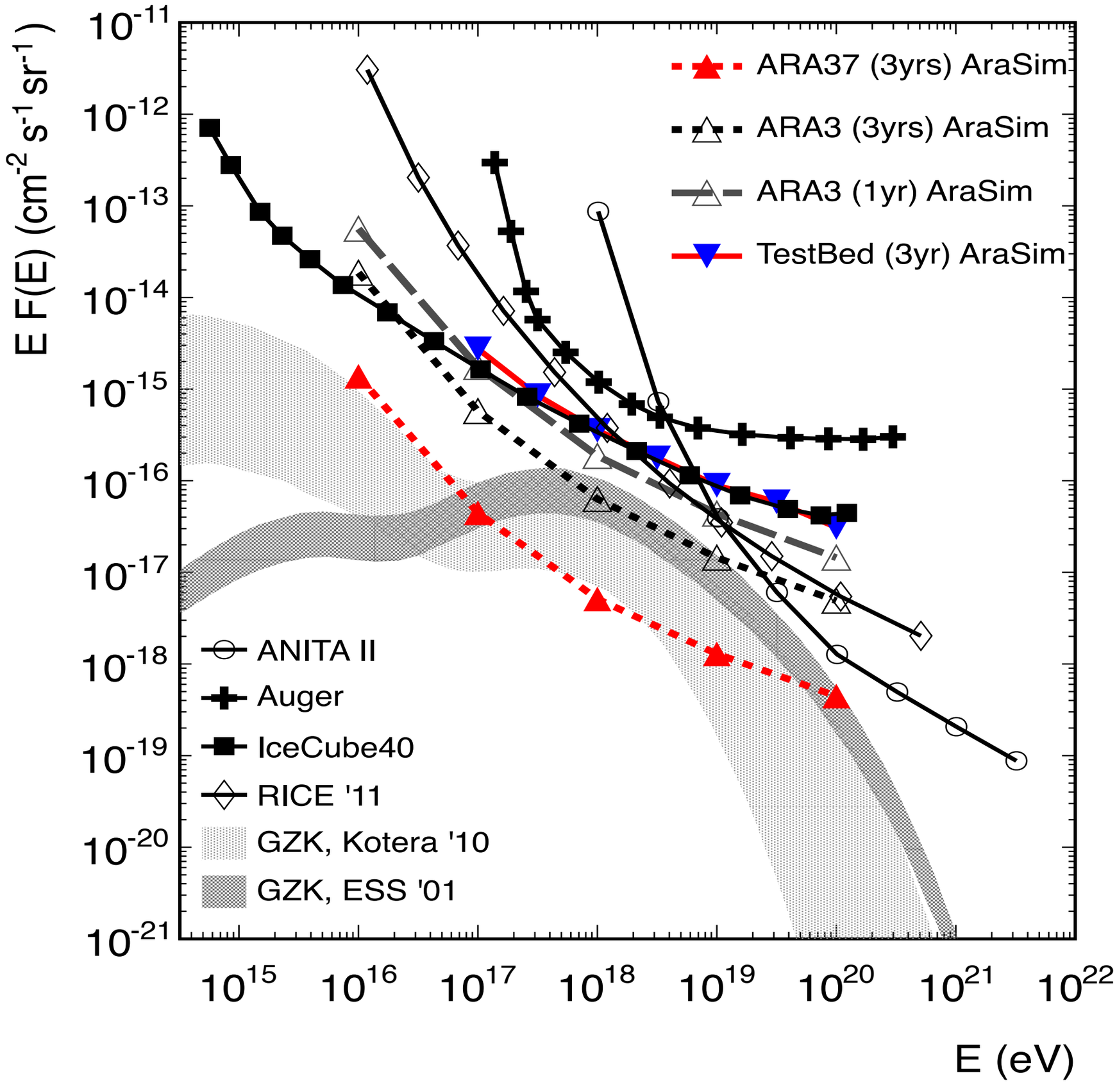
ARIANNA

- 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



From OC Register 2012


ARA37 (3yrs) AraSim
ARA3 (3yrs) AraSim
ARA3 (1yr) AraSim
TestBed (3yr) AraSim
ANITA II
Auger
IceCube40
RICE '11
GZK, Kotera '10
GZK, ESS '01
E F(E) (cm^{-2} s^{-1} sr^{-1})
E (eV)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
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10^{22}

11

Cross sections

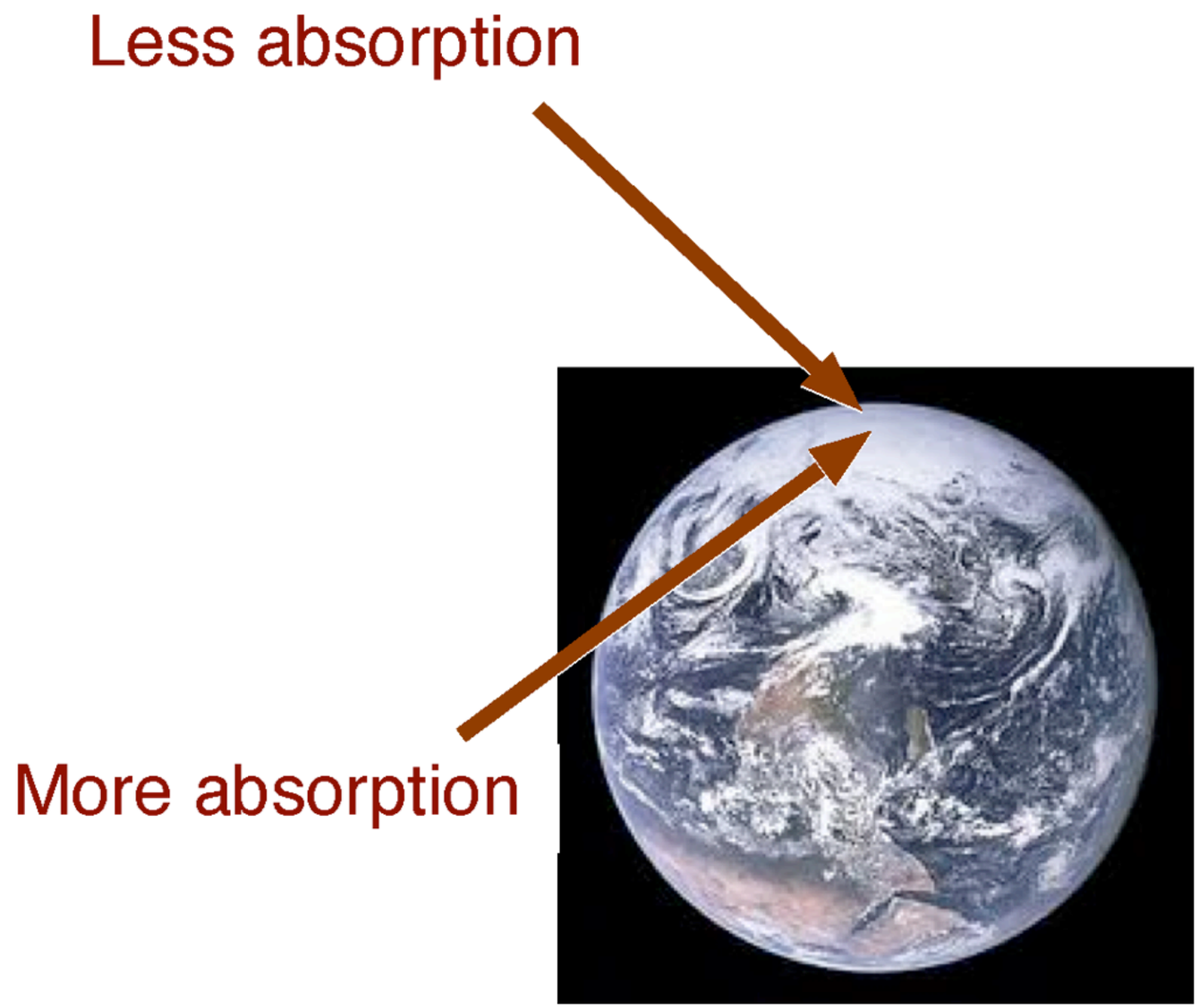
Why are νN cross sections interesting?

- Center of mass (COM) of UHE neutrino interactions with nuclei well exceed LHC energies
  - $\sqrt{s}=\sqrt{2M_N E_\nu}$, $E_\nu=10^{18}$ eV → **$\sqrt{s}$=45 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
  - $E_\nu > 10^{17}$ eV → $x \lesssim 10^{-5}$
  - HERA measures $x \gtrsim 10^{-4}$ - 10^{-5}
- νN σ's at all energies needed to model experiments

13

νN Cross Section Measurement with a Neutrino Telescope

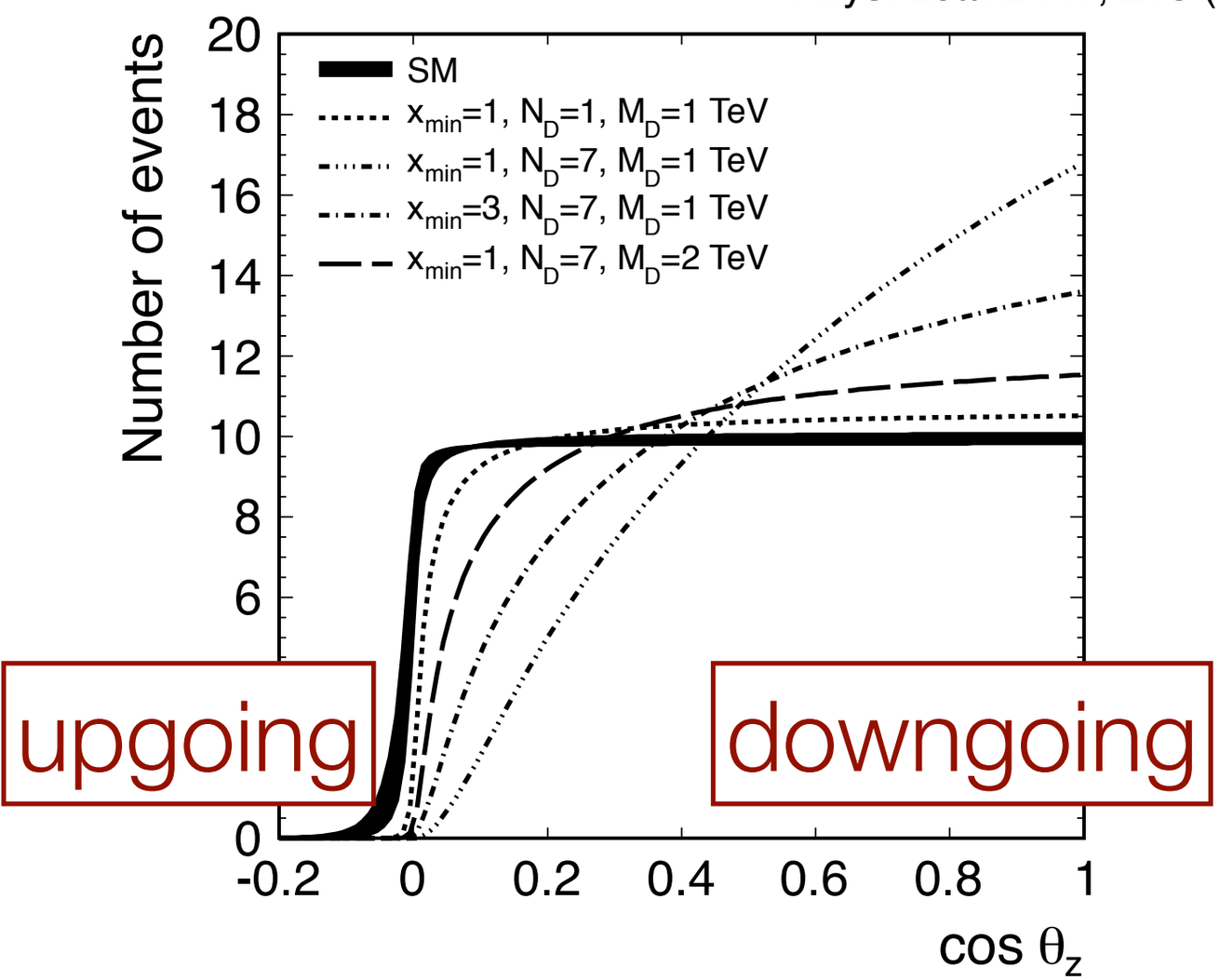
- Once an UHE ν sample is measured:
- The distribution of ν zenith angles θ_z would be sensitive to νN cross sections
- For $E_\nu = 10^{18}$ eV, $E_{CM} = 45$ TeV!

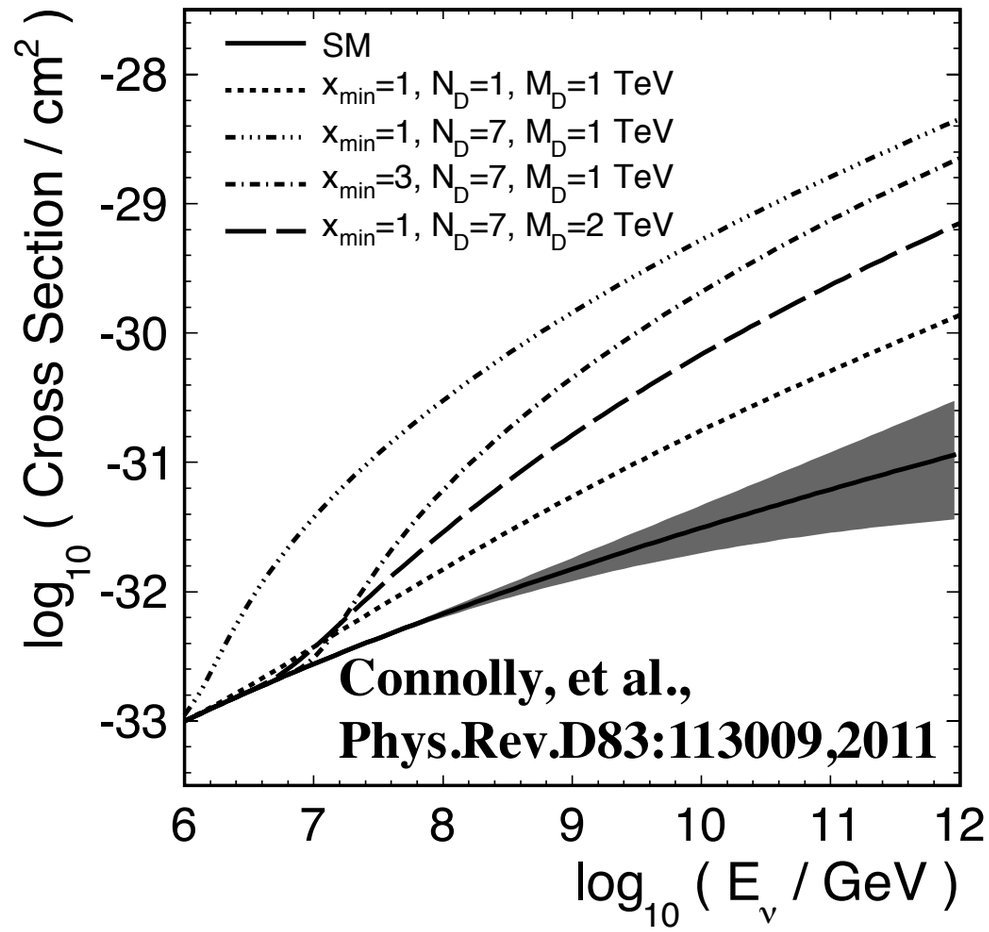


Enhanced Cross Sections

- 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)

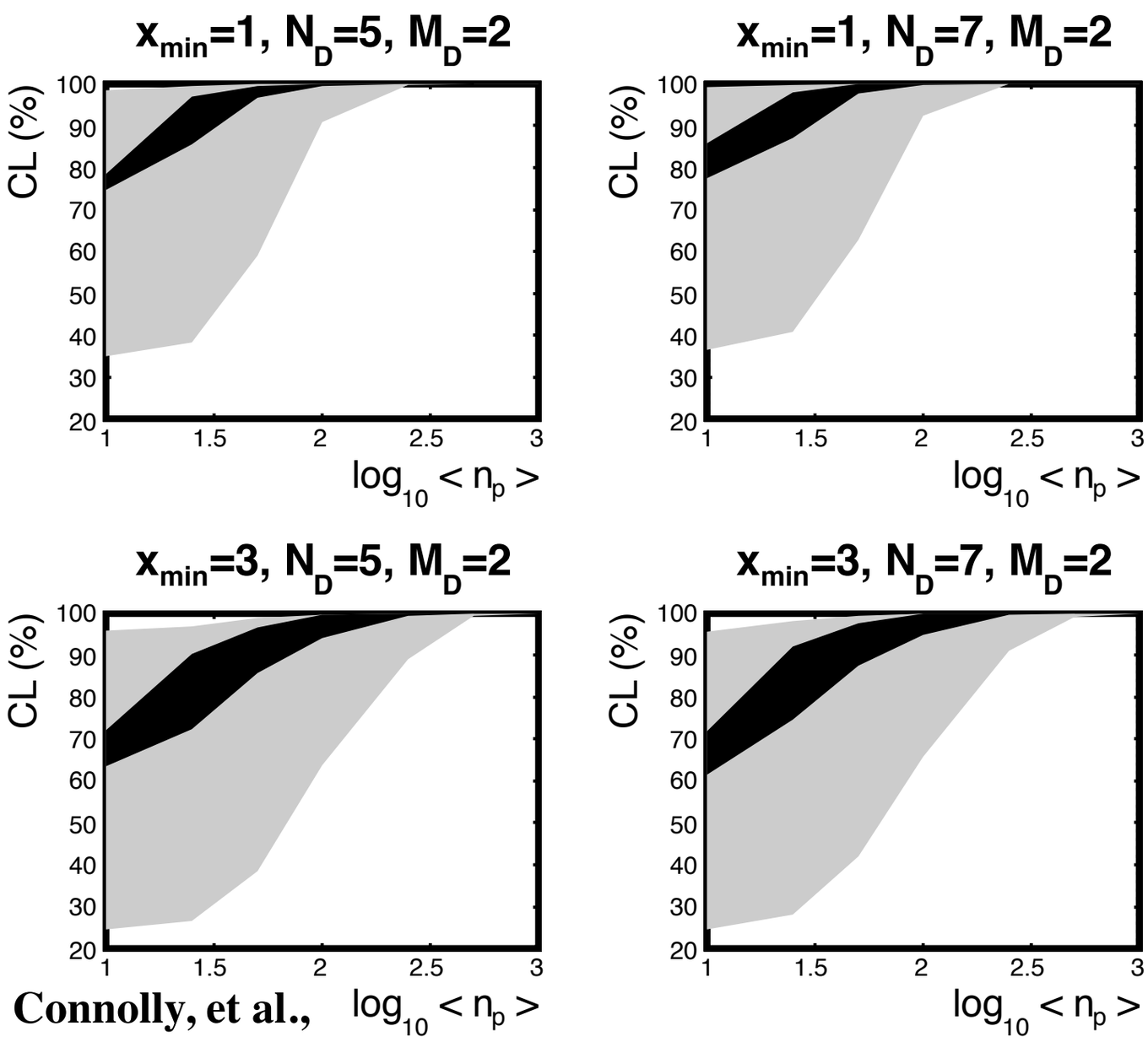




- These would modify the θ_z distributions from the Standard Model (SM) expectation
- N_D = # extra dimensions, M_D = reduced Planck scale, $x_{min} = M^{BH}_{min} / M_D$

15

Expected Constraints



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

- Black bands: systematic uncertainty on SM cross sections
- Gray bands: statistical uncertainties
- On average, with 100 events, expect to exclude:
- $x_{min} = 1$, $M_D = 1$, $N_D \geq 2$
  $x_{min} = 3$, $M_D = 1$, $N_D \geq 3$
  $x_{min} = 1$, $M_D = 2$, $N_D \geq 3$
- $x_{min} = 3$, $M_D = 2$, $N_D = 7$ excluded with 110 events

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

16

Lorentz Invariance Violation

Lorentz Invariance Violation, Really?

- Neutrinos are the only particles we can see from cosmic distances at the highest energies observed
  - It is natural that we should use them to test LIV
- LIV falls naturally from many GUT models, L. Maccione, A. M. Taylor, D. M. Mattingly, & S. Liberati, JCAP 0904:022, (2009), P. Horava, Phys. Rev. D79, 084008 (2009); Phys. Rev. Lett. 102, 161301 (2009).
- It has been proposed that the photon could be a Goldstone boson arising from LIV, R. Bluhm and V.A. Kostelecký, Spontaneous Lorentz Violation, Nambu-Goldstone Modes, and Gravity, Phys. Rev. D 71, 065008 (2005), Bjorken (1963)
- It has been proposed that the graviton could be a Goldstone boson arising from LIV, V.A. Kostelecký and R. Potting, Gravity from Spontaneous Lorentz Violation, Phys. Rev. D 79, 065018 (2009)
- It is possible that both the photon and graviton are *both simultaneously* Goldstone bosons from LIV

18

Lorentz Invariance Violation (LIV)

- If neutrinos can exceed speed of light then can "brem"
  - $\nu \rightarrow \nu' e^+ e^-$ (Coleman and Glashow)
  - Neutrino loses ~3/4 of its energy
- Effectively a "decay" with time constant:

$$\tau_\nu = \tau_{\mathrm{CG}}\ \mathbf{E}_{\nu,\mathrm{GeV}}{}^{-\mathbf{5}}\ \alpha_\nu{}^{-\mathbf{3}}\ \mathrm{s}$$

with $\tau_{CG}=6.5 \times 10^{-11}$ s

  - α_ν is a measure of level of LIV $E_\nu=p_\nu c(1+\alpha_\nu)$
- Over cosmic distances, neutrinos above an energy will all brem, show up at lower energies

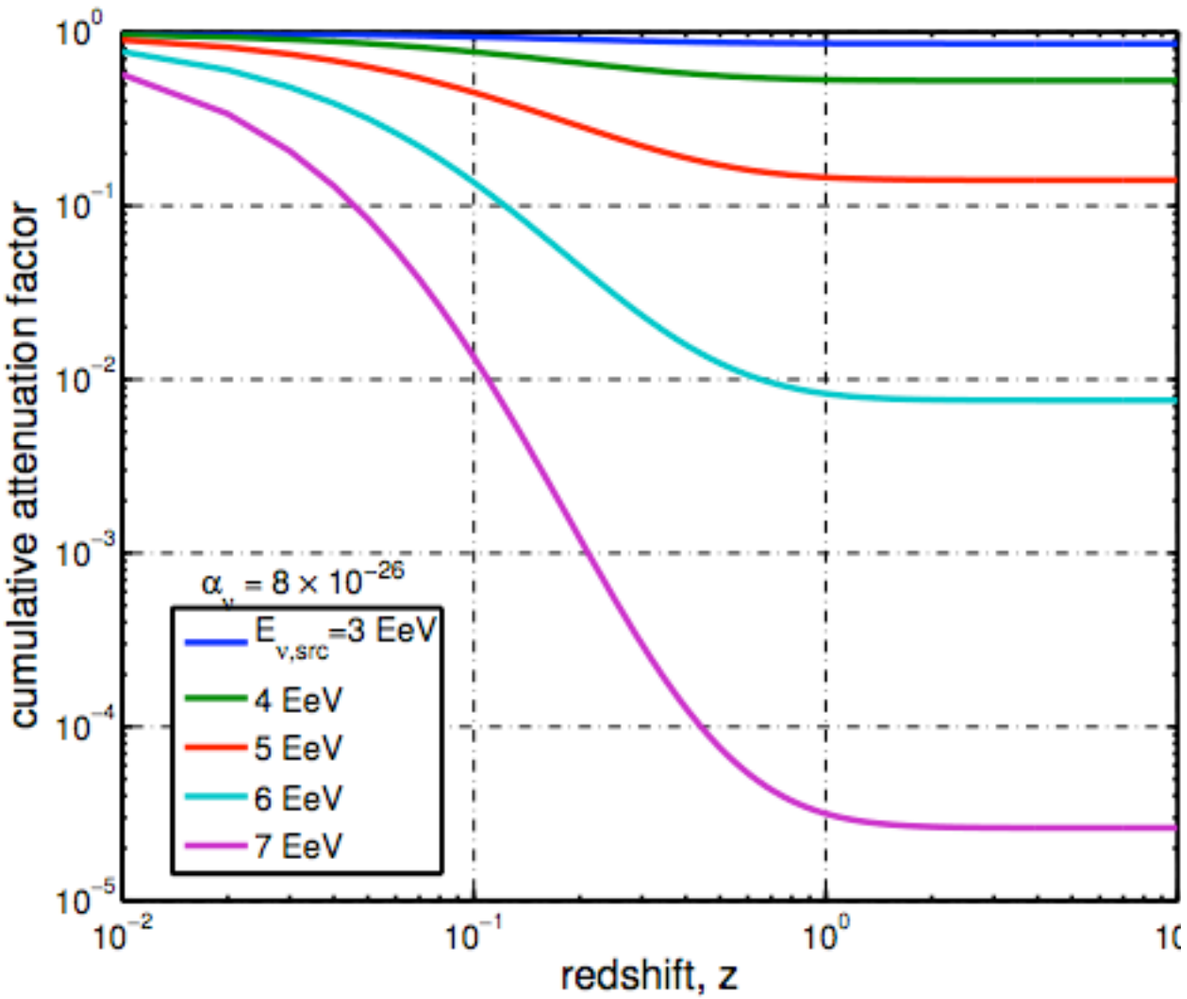
P.W. Gorham, A. Connolly et al., Phys.Rev. D86 (2012) 103006

19

Lorentz Invariance Violation (LIV)

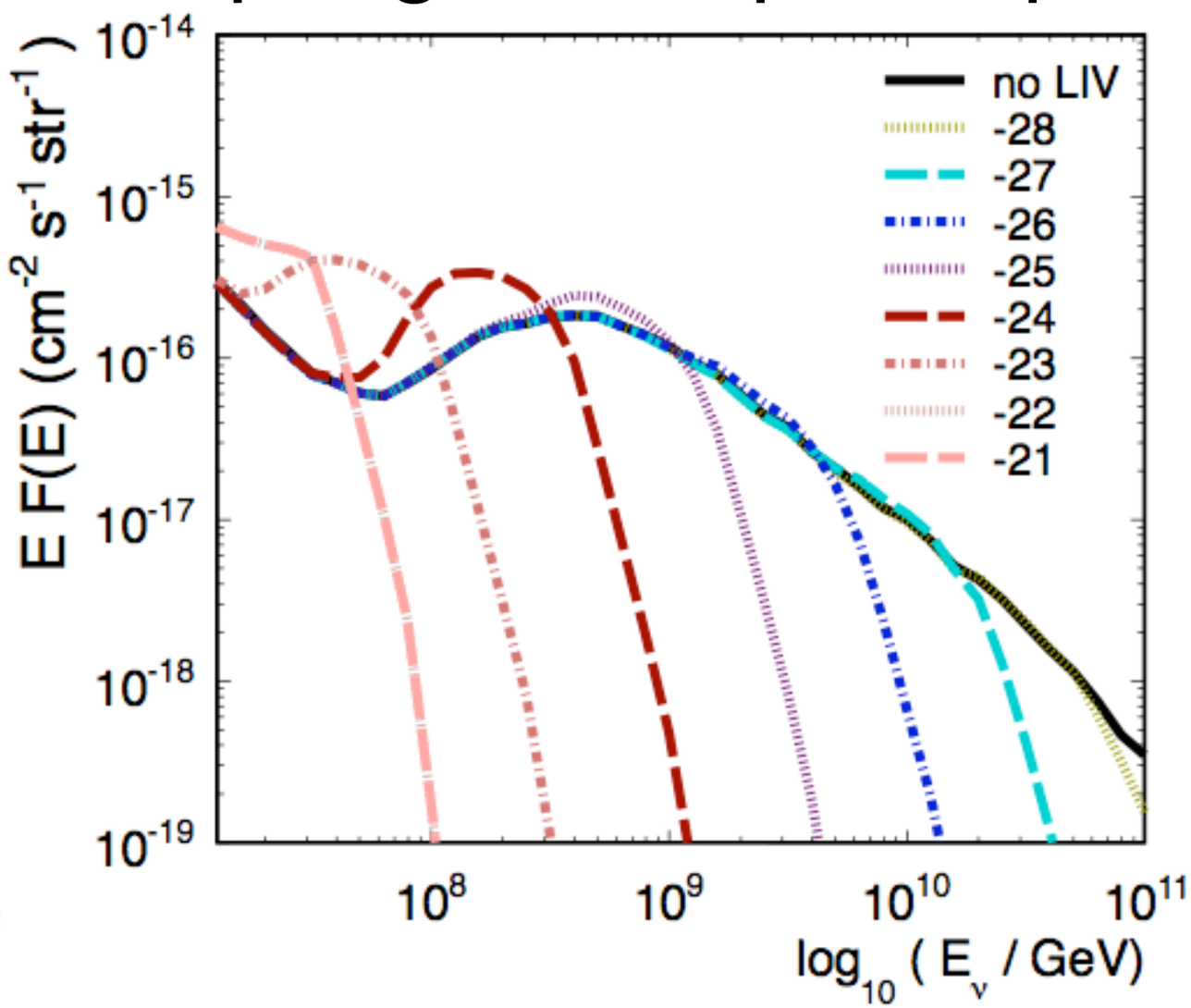
P.W. Gorham, A. Connolly et al., Phys.Rev. D86 (2012) 103006

Attenuation vs. redshift



Different energies, same $\alpha_\nu = 8 \times 10^{-26}$

Observed neutrino spectra, adapting CRPropa outputs



Different values of $\log_{10} \alpha_\nu$

ANITA Results

- Set lower limit on LIV parameter α_ν assuming LIV was the reason for the models evading detection

Model & references	ANITA/RICE predicted N	lower limit on LIV
Barger *et al.* 2006 [27]		
ANITA-II	3.5	2×10^{-27}
RICE2011	12	2×10^{-25}
Berezinsky 2005 [33]		
ANITA-II	5.1	3×10^{-28}
RICE2011	3.4	2×10^{-27}
Kalashev *et al.* 2002 [34]		
ANITA-II	5.6	2×10^{-28}
RICE2011	2.9	10^{-28}

All the experimental results searching for violations of Lorentz invariance (Data Tables for Lorentz and CPT violation) published in Rev. Mod. Phys.83:11 (2011); the annually updated version can be found here arXiv:0801.0287.

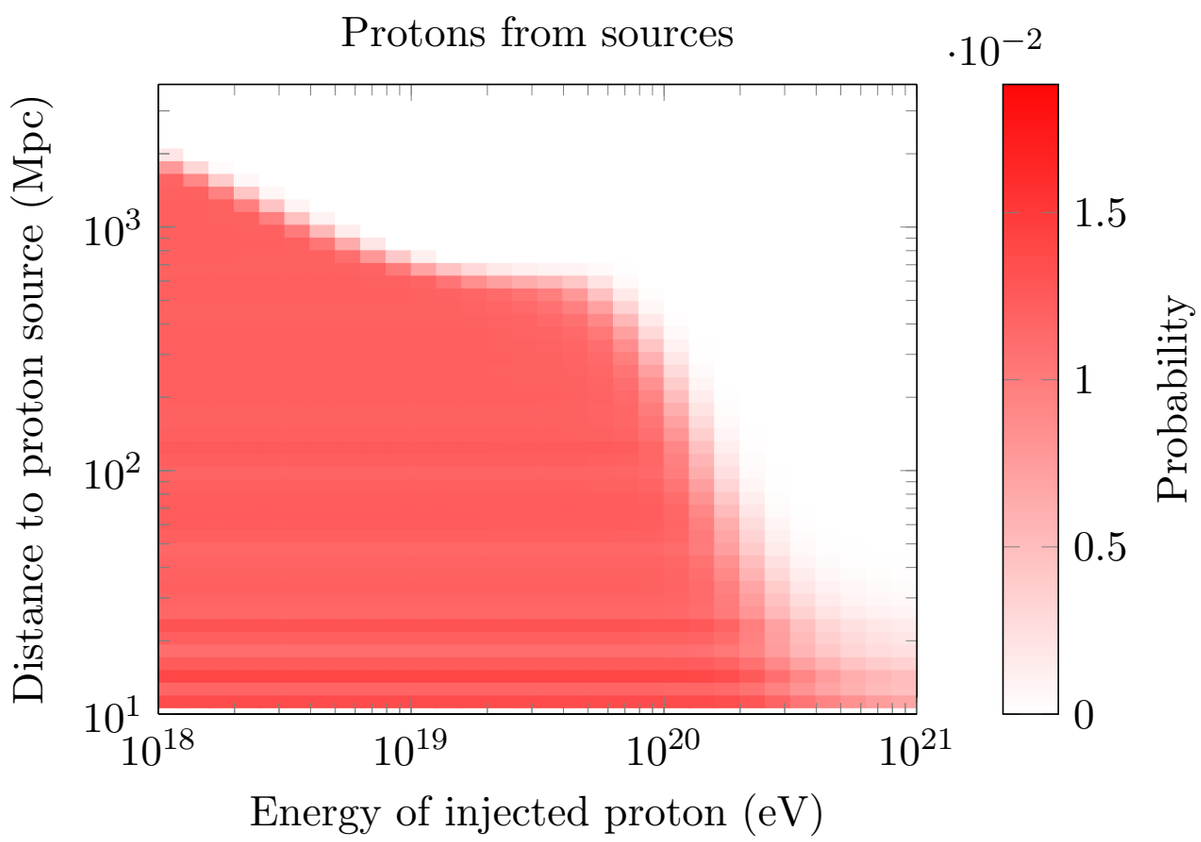
P.W. Gorham, A. Connolly et al., Phys.Rev. D86 (2012) 103006

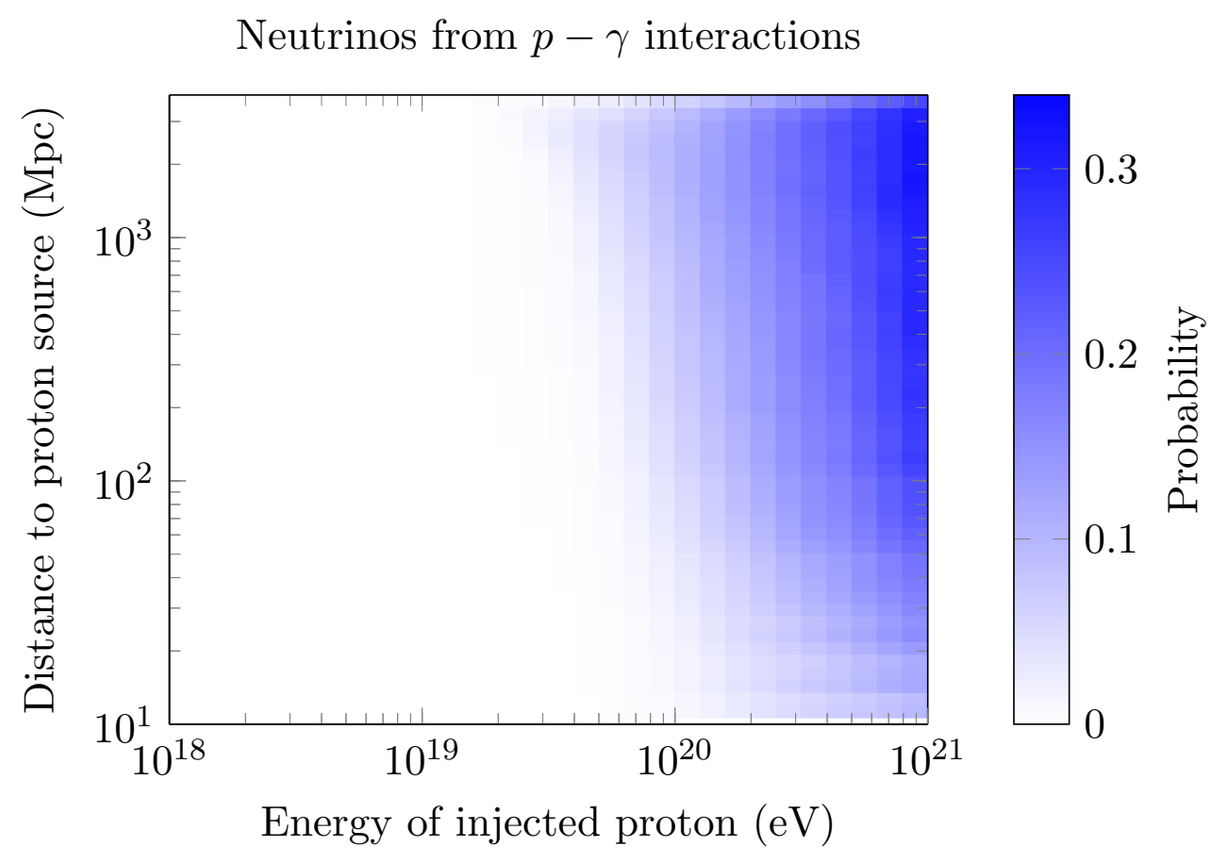
21

UHE Astrophysics

Neutrinos are Unique Probes of UHE Astrophysics

- Will be only particles >$10^{19.5}$ eV from ≳100 Mpc



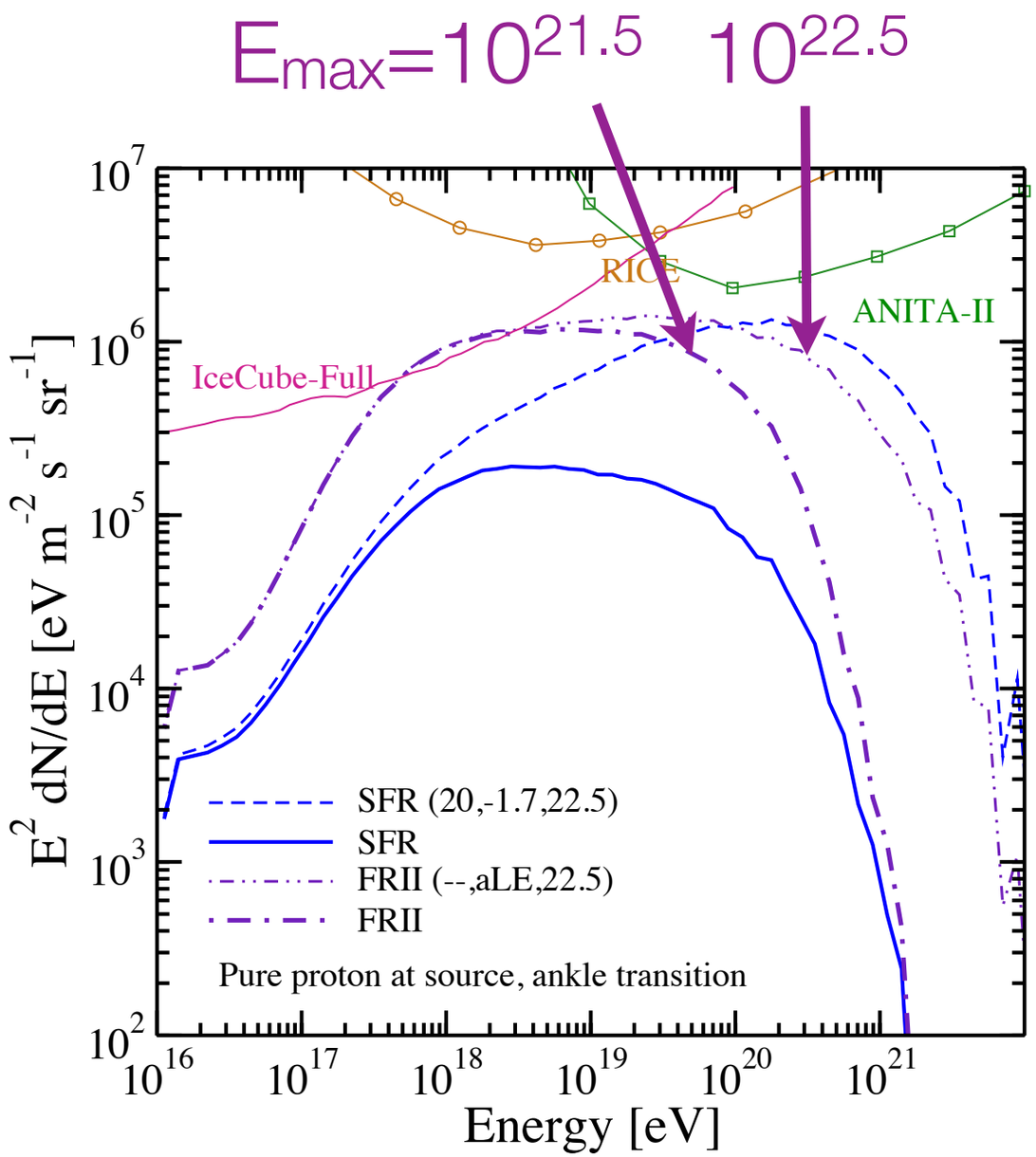


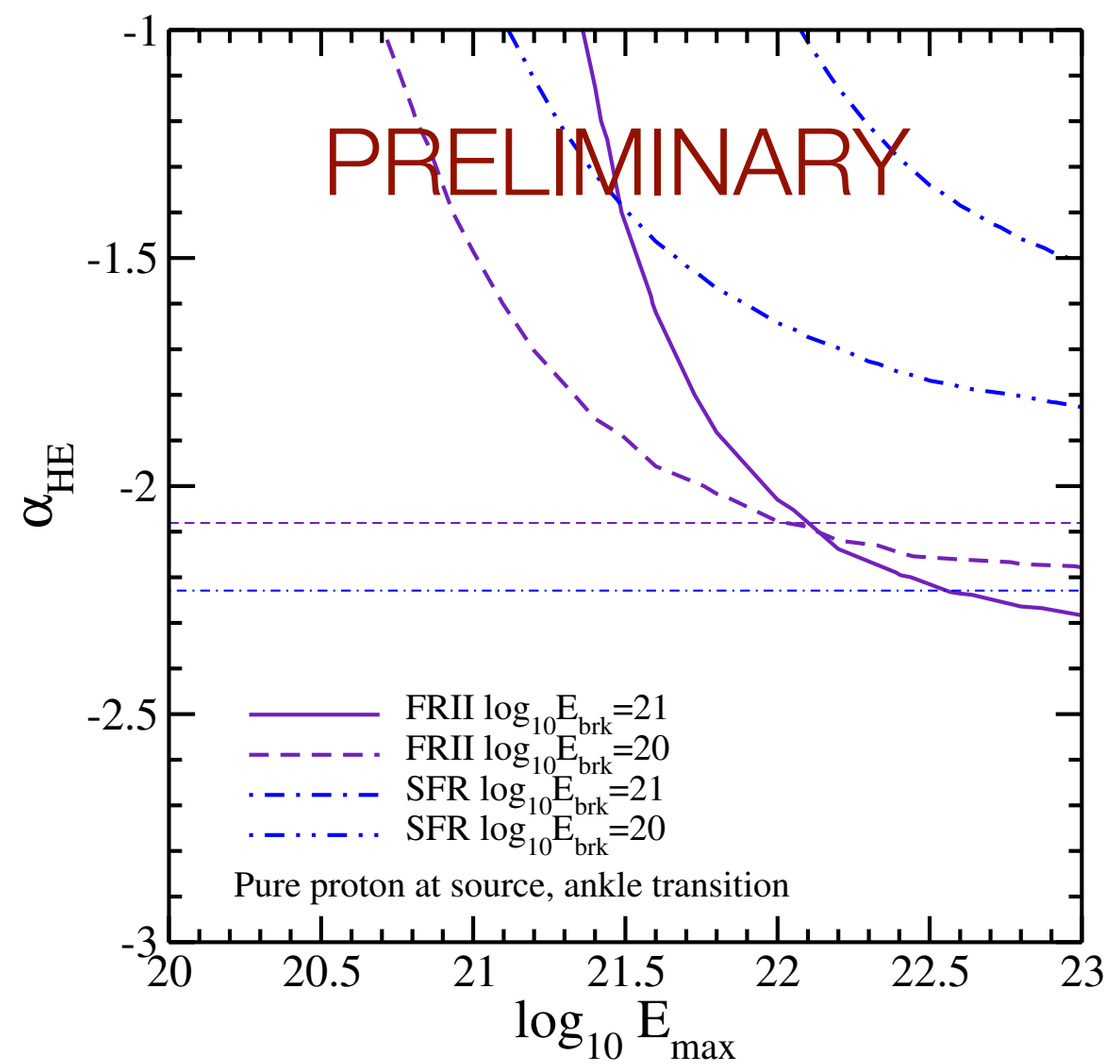
Plots made with the help of CRPropa 2.0
E^{-1} spectrum, flat redshift evolution

23

Neutrinos: Only Probes of Ultimate Cosmic Acceleration Energy

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





A. Connolly, S. Horiuchi, N. Griffith, paper in preparation

24

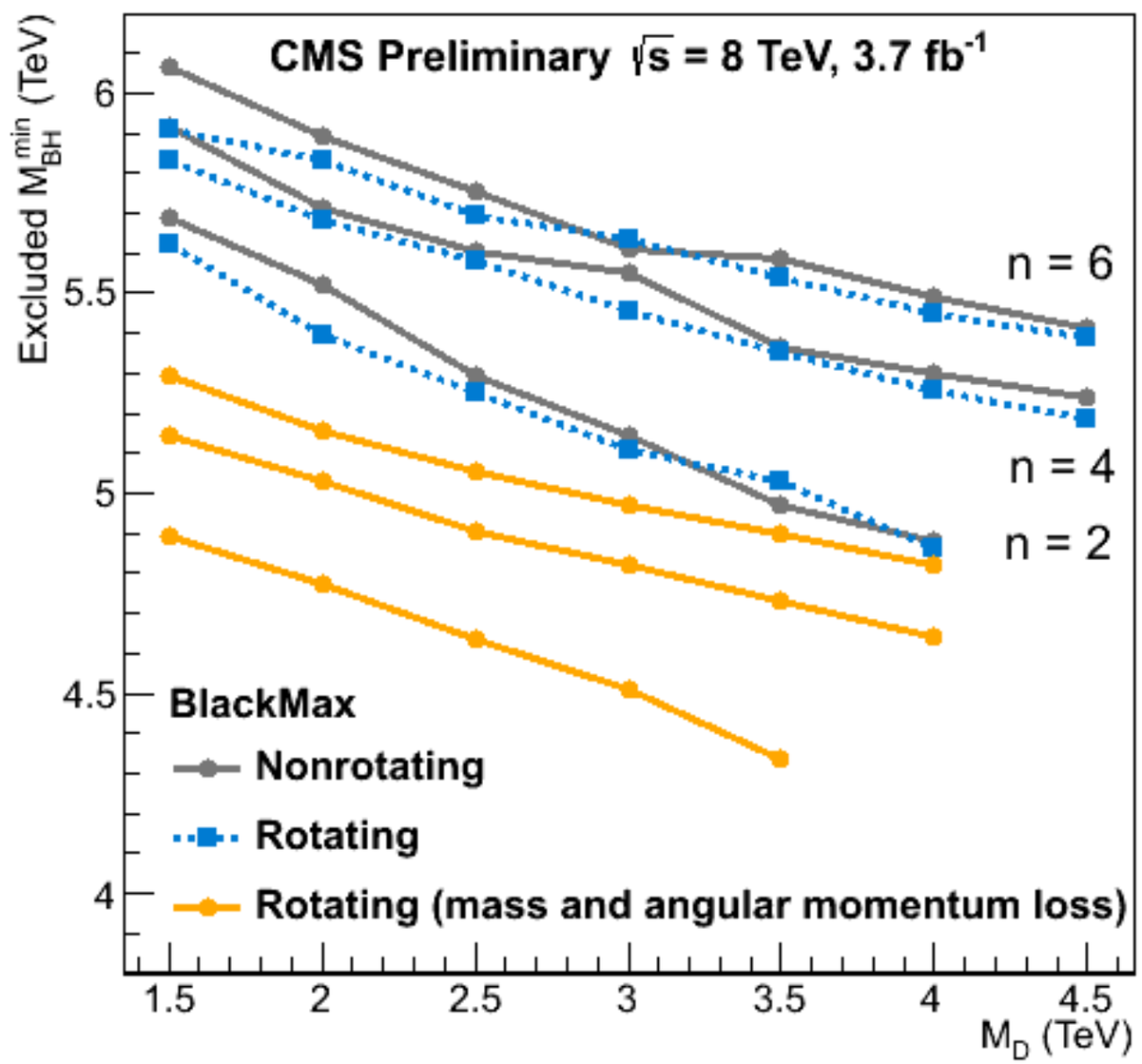
Summary

- Although radio Cerenkov experiments built as single purpose detectors for UHE neutrinos, variety of fundamental physics results:
  - LIV
  - did not have time to discuss magnetic monopoles, quark nuggets
- 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

25

Backup Slides

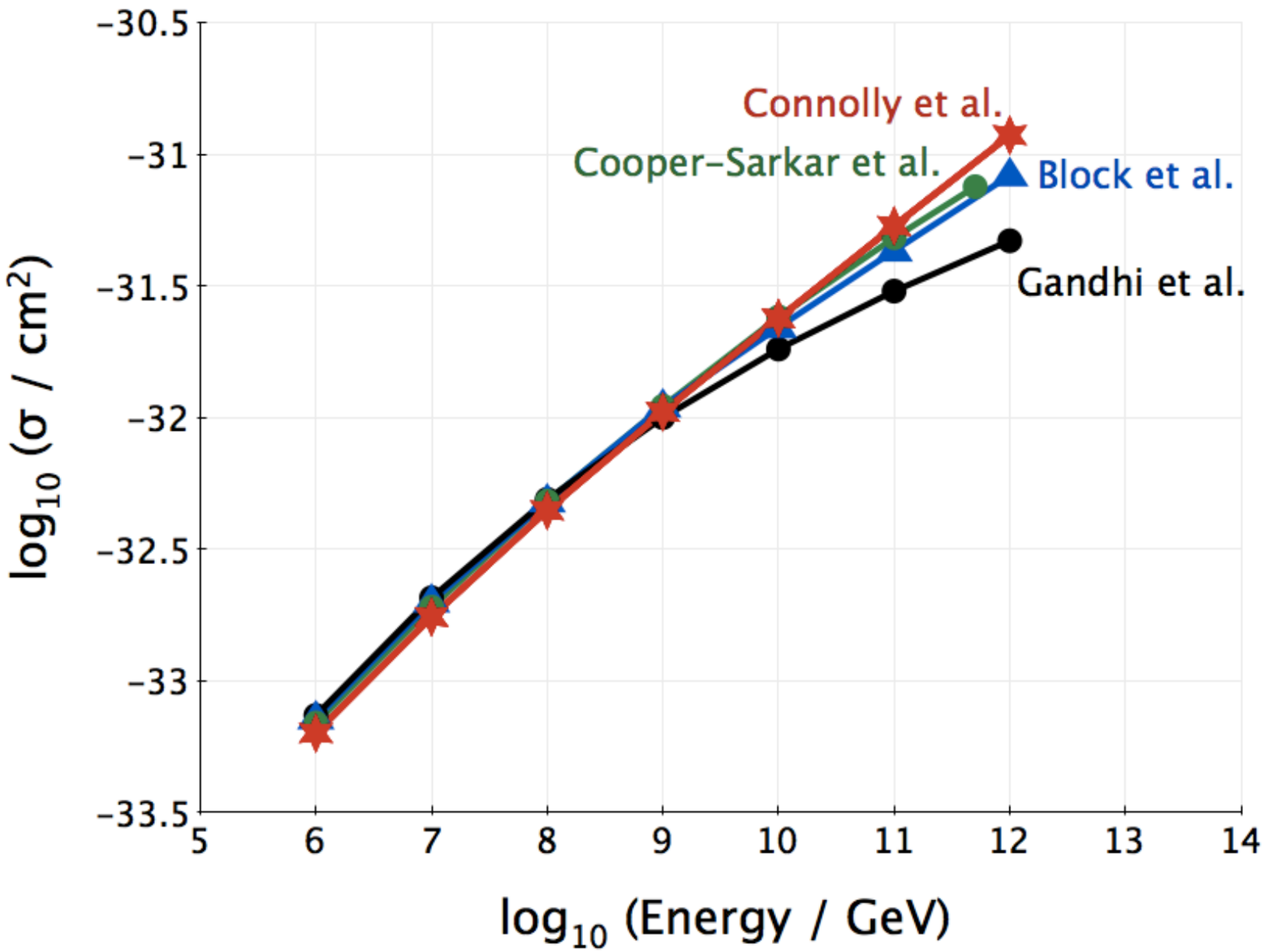
CMS constraints for reference



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

27

νN 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