Cosmic Particles: Overview of Opportunities

- Science Goals
- Some brief highlights of recent results
- The US program
- Survey of Current Instruments and Future plans
  - Gamma Ray Astronomy
    - HAWC - future
  - Neutrino Astronomy
    - IceCube Upgrade
    - Radio arrays – ARA, ARIANNA, GNO
  - UHE Cosmic Rays
    - TAx4
    - Auger Upgrade
    - JEM-EUSO

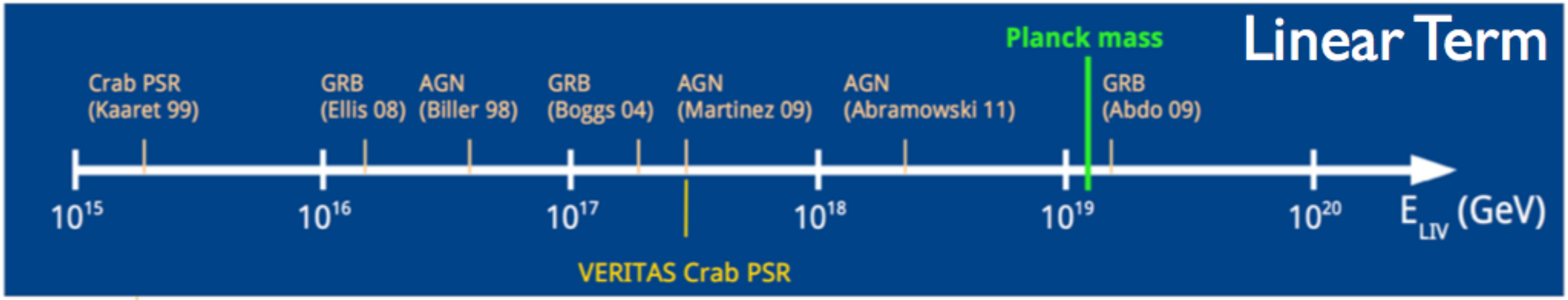
Science Goals

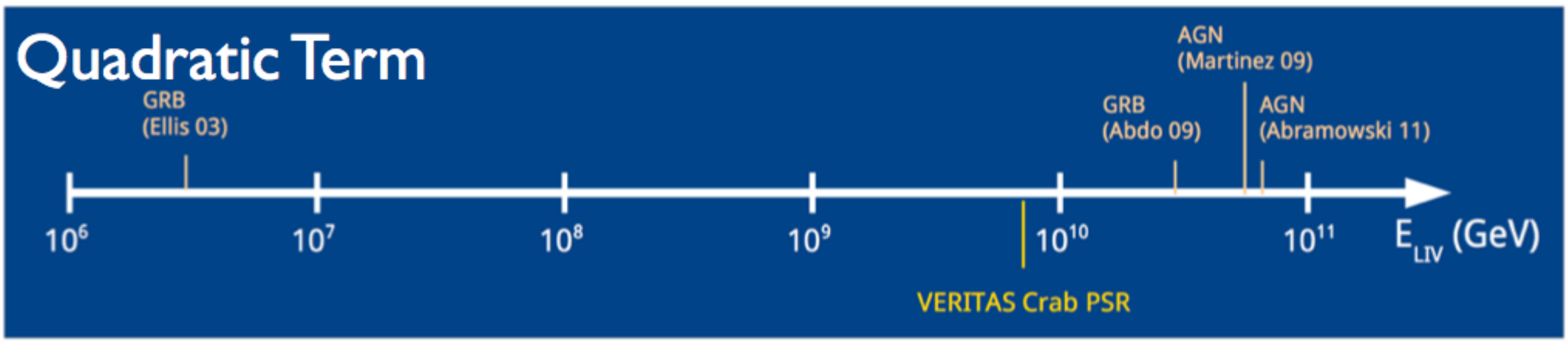
- Understanding the origin and acceleration of the highest energy cosmic rays
- Studying interactions at energies well beyond the LHC
- Looking for Dark Matter
- Studying physics in most extreme environments in the Universe
  - Black Holes
  - GRBs
  - Using information from these sources to study the physics of acceleration and propagation as well as the history of the Universe
- Lorentz Invariance Violation (LIV)
- Looking at the Universe with new eyes

Recent Results

- Discovery of cosmic-ray acceleration in supernovae - solving a >100 year old mystery
- Discovery of high-energy astrophysical neutrinos
- Limits on dark matter from Fermi that get down to the thermal limit
- First measurements (not lower limits) on the EBL (from Fermi and HESS)
- Constraints on Lorentz invariance violation that reach the Planck scale

Current Limits on LIV

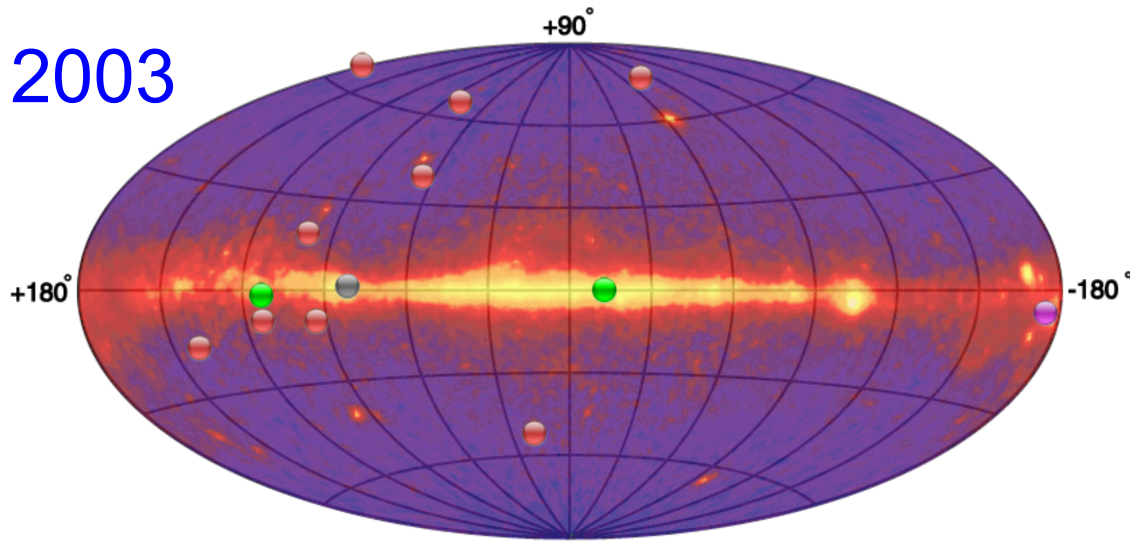


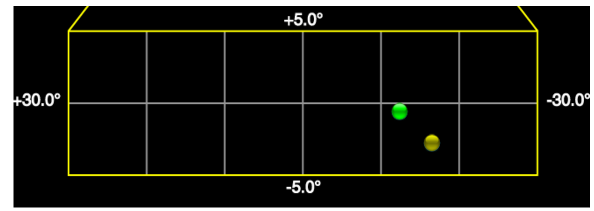


from O. Nepomuk Snowmass

Changing View of the High Energy Sky

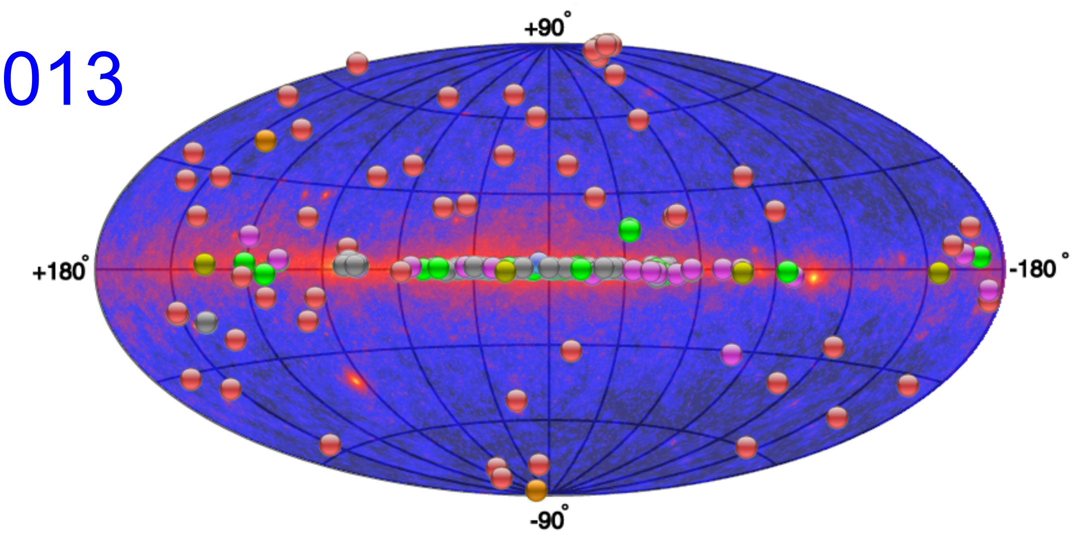
2003

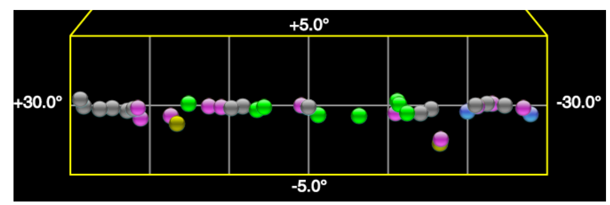




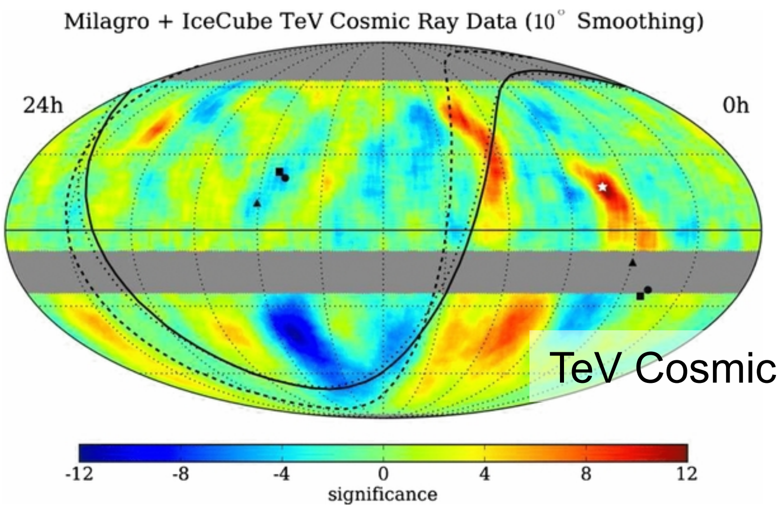
Galactic Center

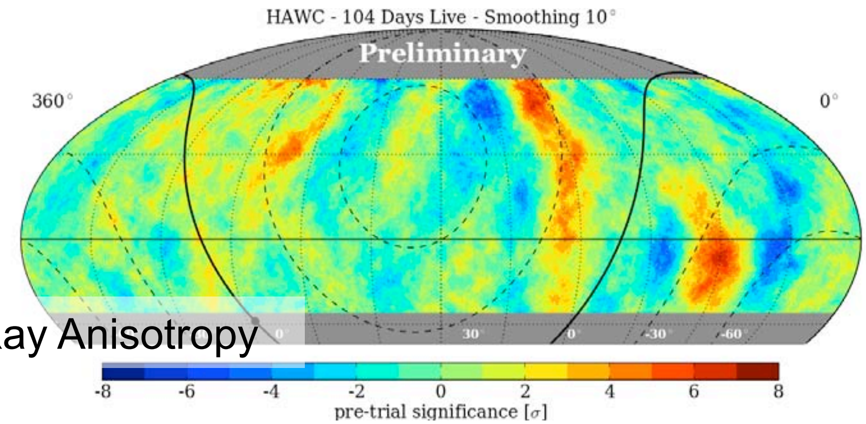
2013



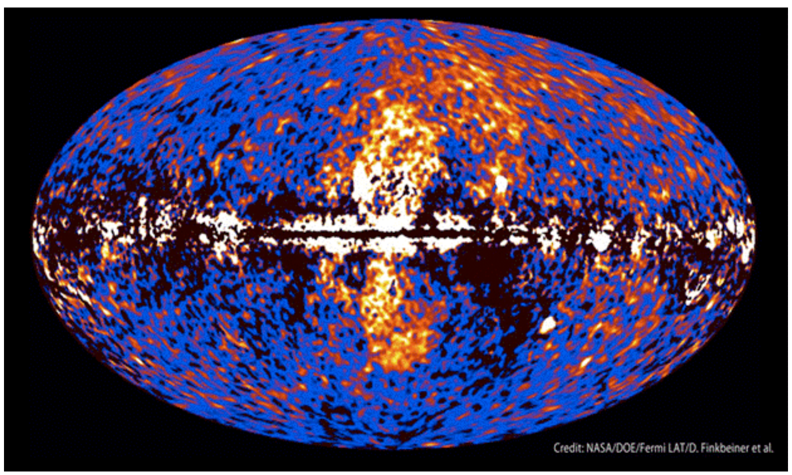


The Unexpected

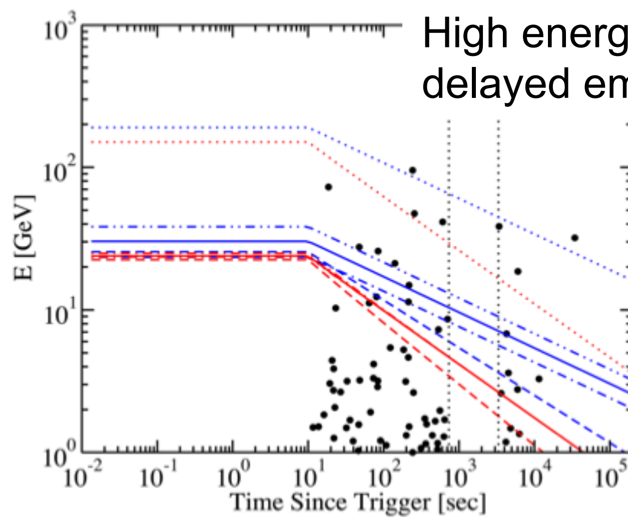




TeV Cosmic Ray Anisotropy



Fermi Bubbles



High energy delayed emission

GRB 130427a

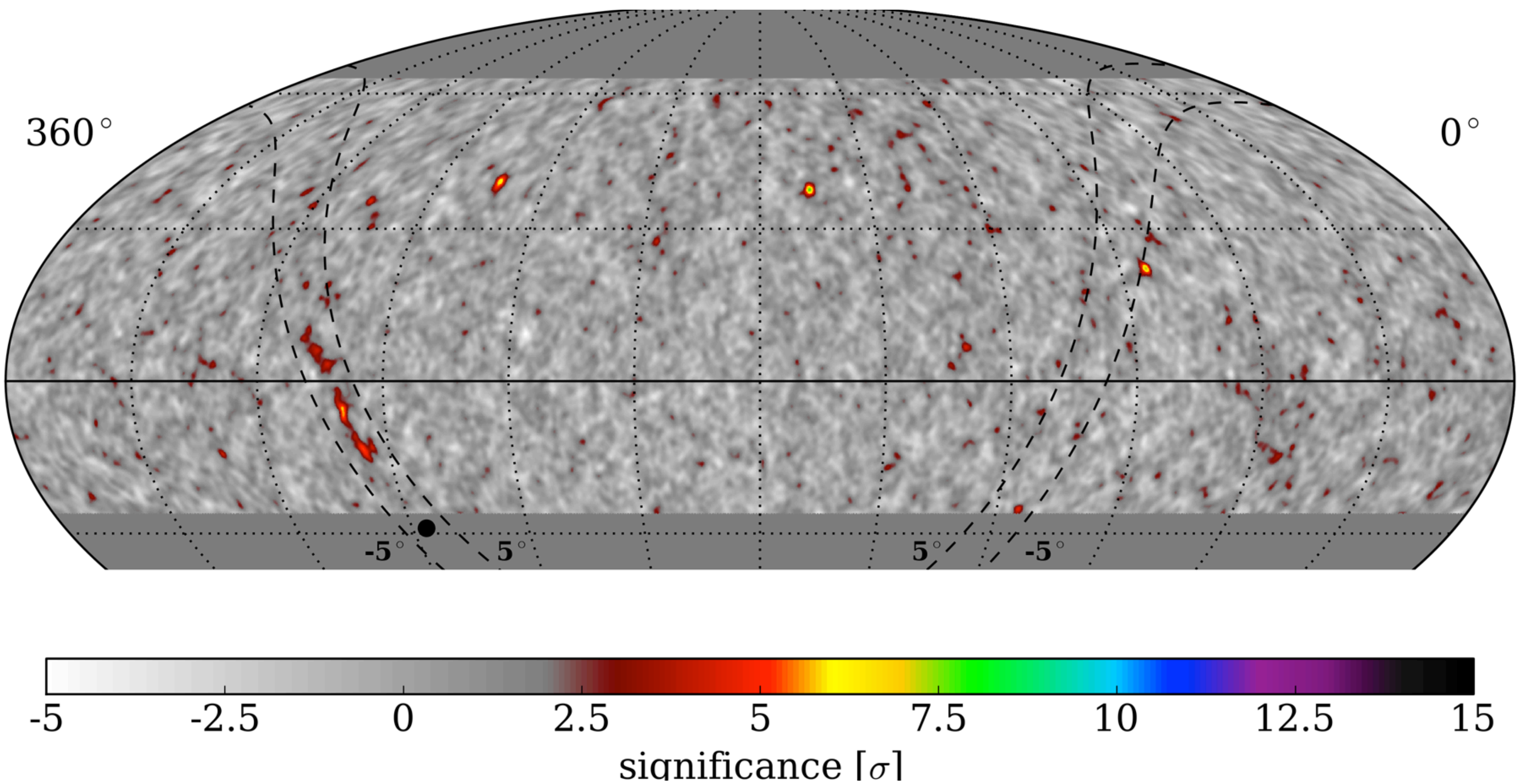
The US Program

- Gamma Rays
  - Built and launched satellites detecting GeV γ's in space with EGRET (NASA) and Fermi (NASA, DOE)
  - Pioneered ground-based TeV gamma ray astronomy with the IACT technique with Whipple and VERITAS (DOE, NSF, Smithsonian)
  - Developed the wide-field telescope with Milagro & HAWC (NSF, DOE)
- Neutrino detectors
  - Lead the way with AMANDA and now IceCube (NSF)
  - Developed Radio with ANITA and now several in-ice detectors (NSF)
- UHE Air Showers
  - Developed the fluorescence technique with Fly's eye/ HiRes (NSF)
  - A leading role in AUGER (NSF, DOE) and TA (NSF)
  - Developed the OWL/ JEM-EUSO concept
- The US scientists who have pioneered this field have come from and been supported by particle physics at DOE and NSF

HAWC

HAWC

HAWC Preliminary Sky

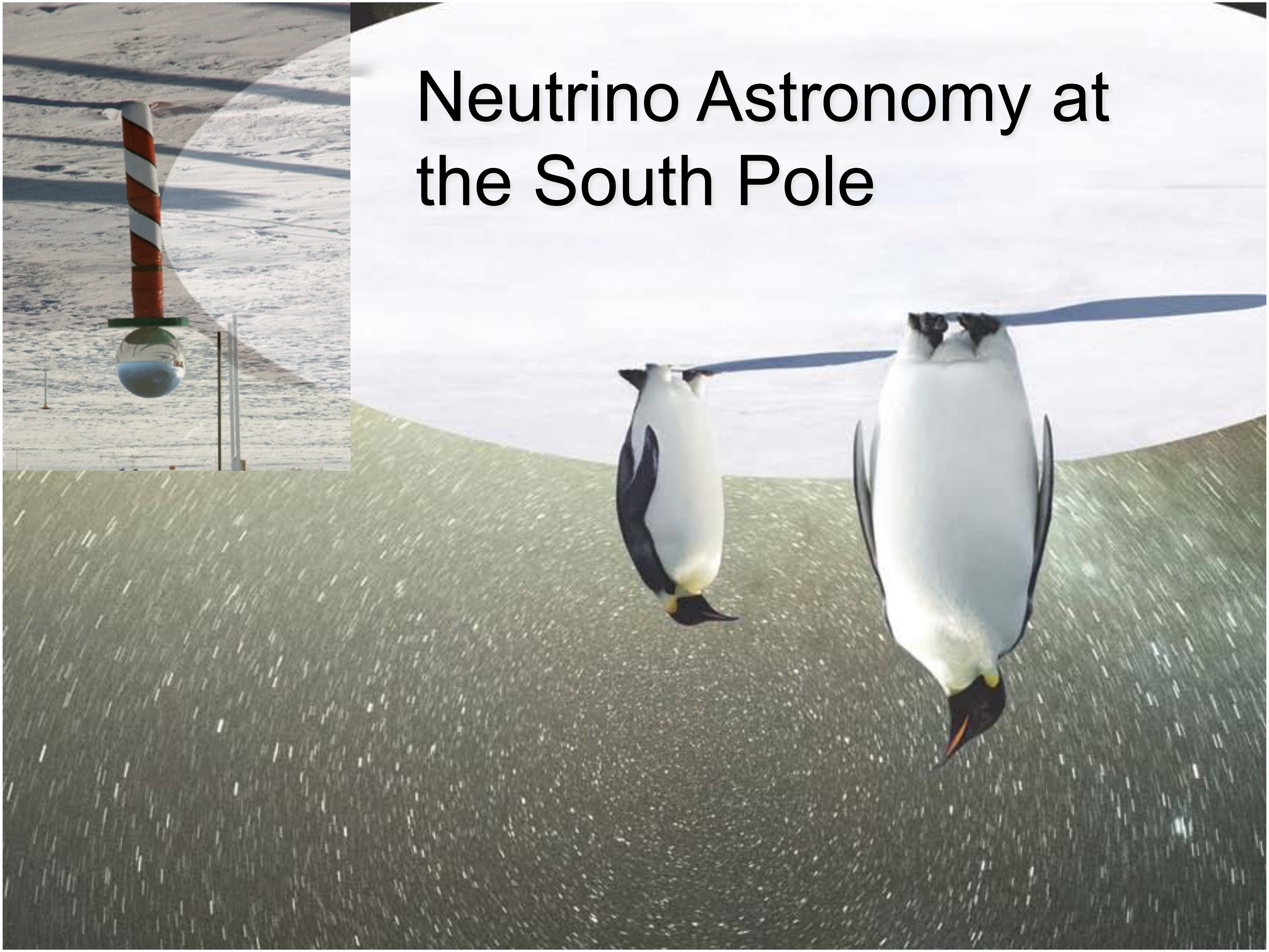


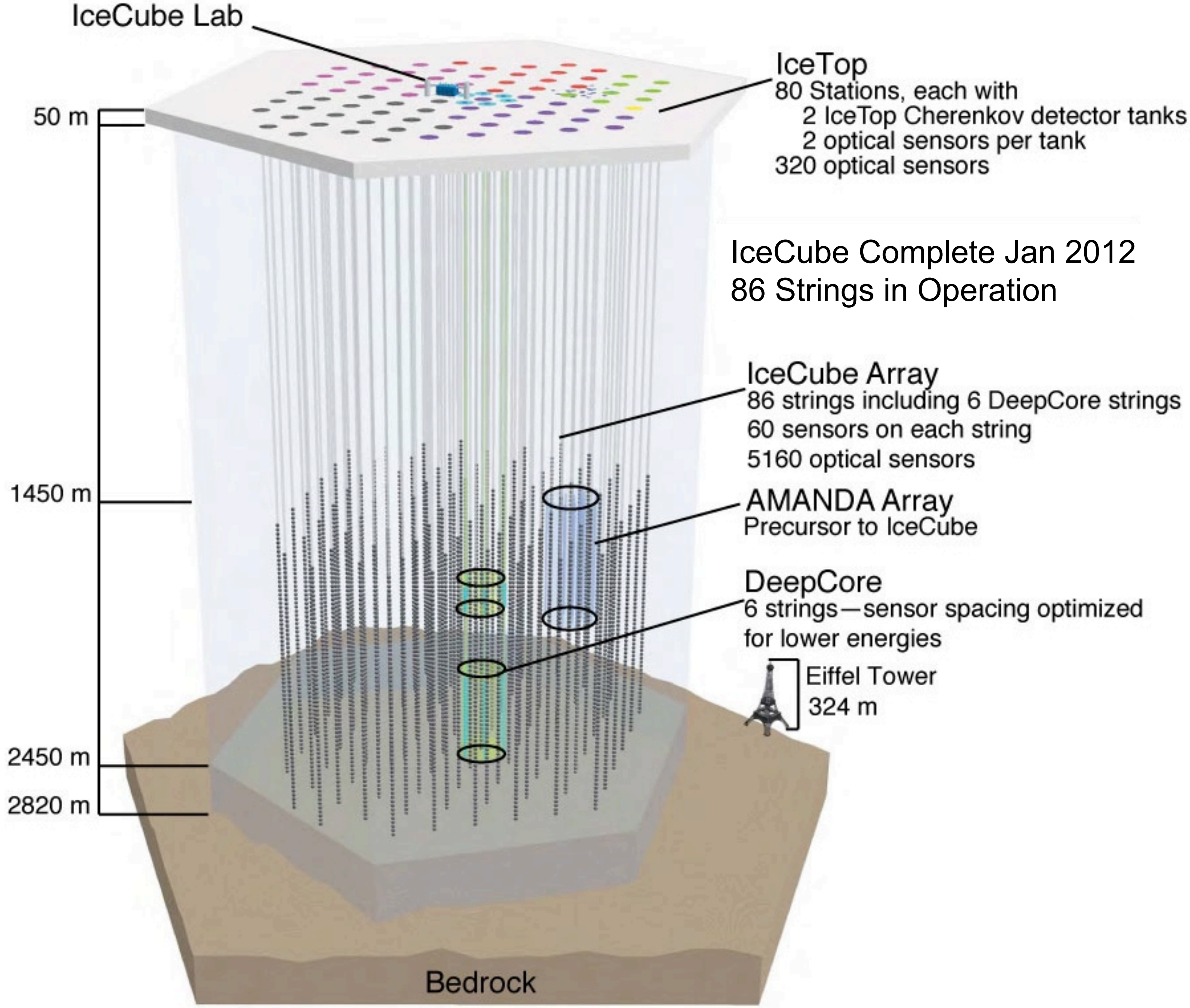
~6 weeks of data with 1/3 of the array while still in under construction

HAWC

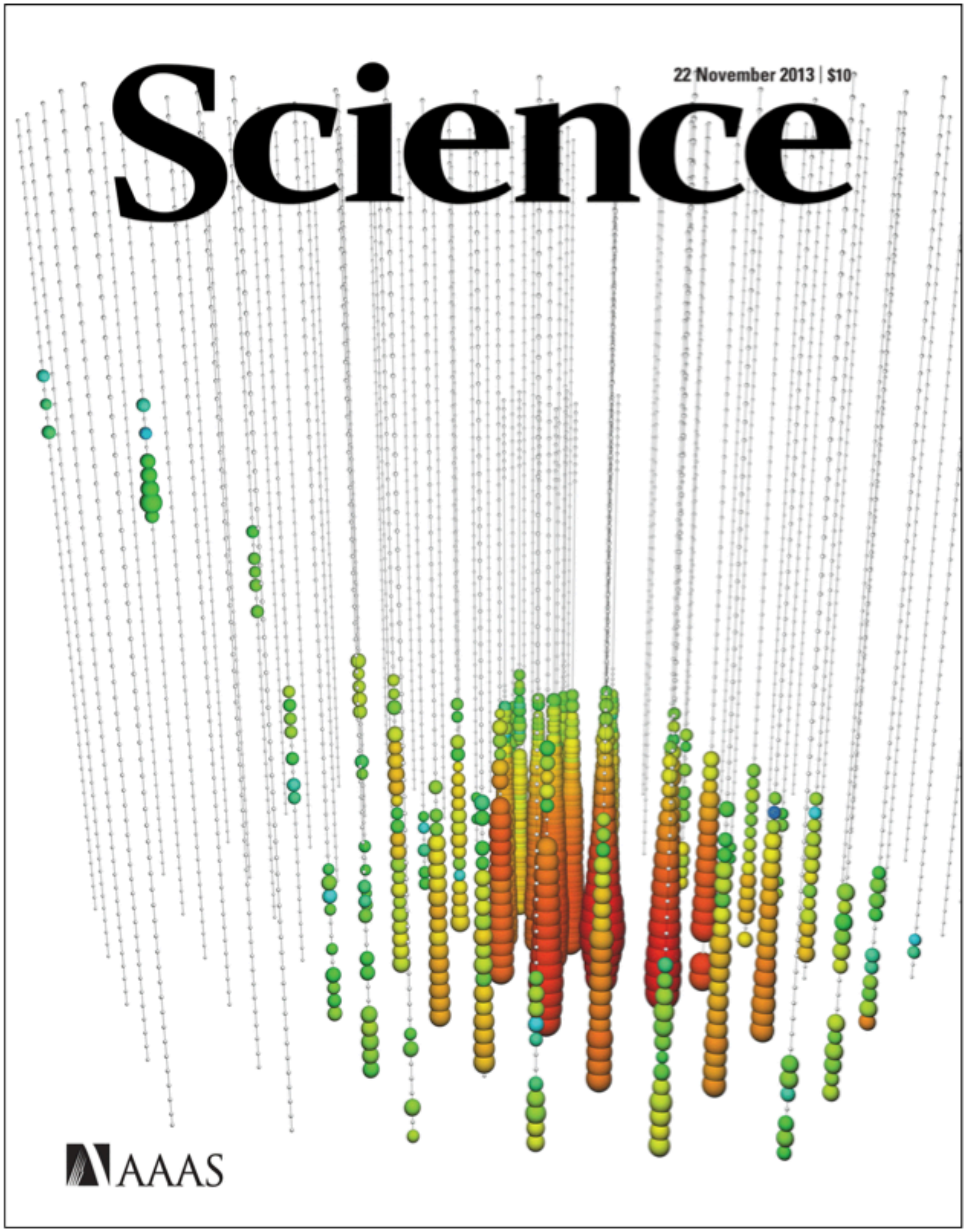
- HAWC will view the northern sky at TeV energies
  - Monitor flaring/transient sources (for astrophysics and LIV)
  - GRBs – to understand their high energy properties and EBL
  - Look for Dark Matter halos
- HAWC possible future upgrade (in 2-3 years)
  - New electronics
  - Outriggers
  - Cost $2-3M – Mostly from Mexico
  - HAWC sensitivity still scales like size (not $\sqrt{\text{size}}$) & with altitude
- Depending on what HAWC shows us (~3-5 years)
  - Build another one in the Southern Hemisphere?
  - Go to higher elevation -> lower energies
  - Complement CTA
  - Cost ~$20M – would require an international effort

Neutrino Astronomy at the South Pole





IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
50 m
IceCube Complete Jan 2012
86 Strings in Operation
IceCube Array
86 strings including 6 DeepCore strings
60 sensors on each string
5160 optical sensors
1450 m
AMANDA Array
Precursor to IceCube
DeepCore
6 strings—sensor spacing optimized
for lower energies
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



22 November 2013 | $10

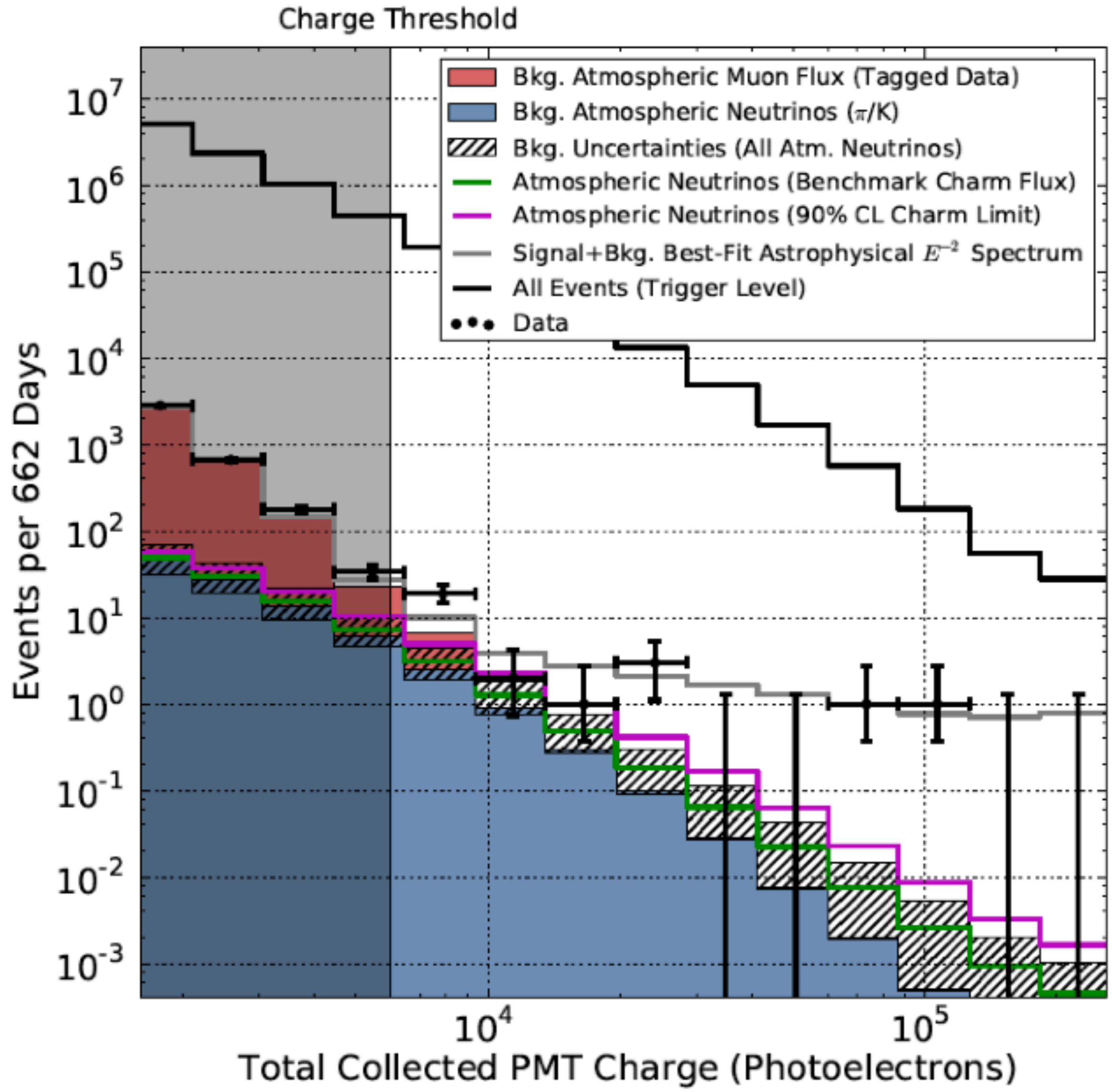
First observation of high energy extra-terrestrial neutrinos

Sciencexpress

Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A

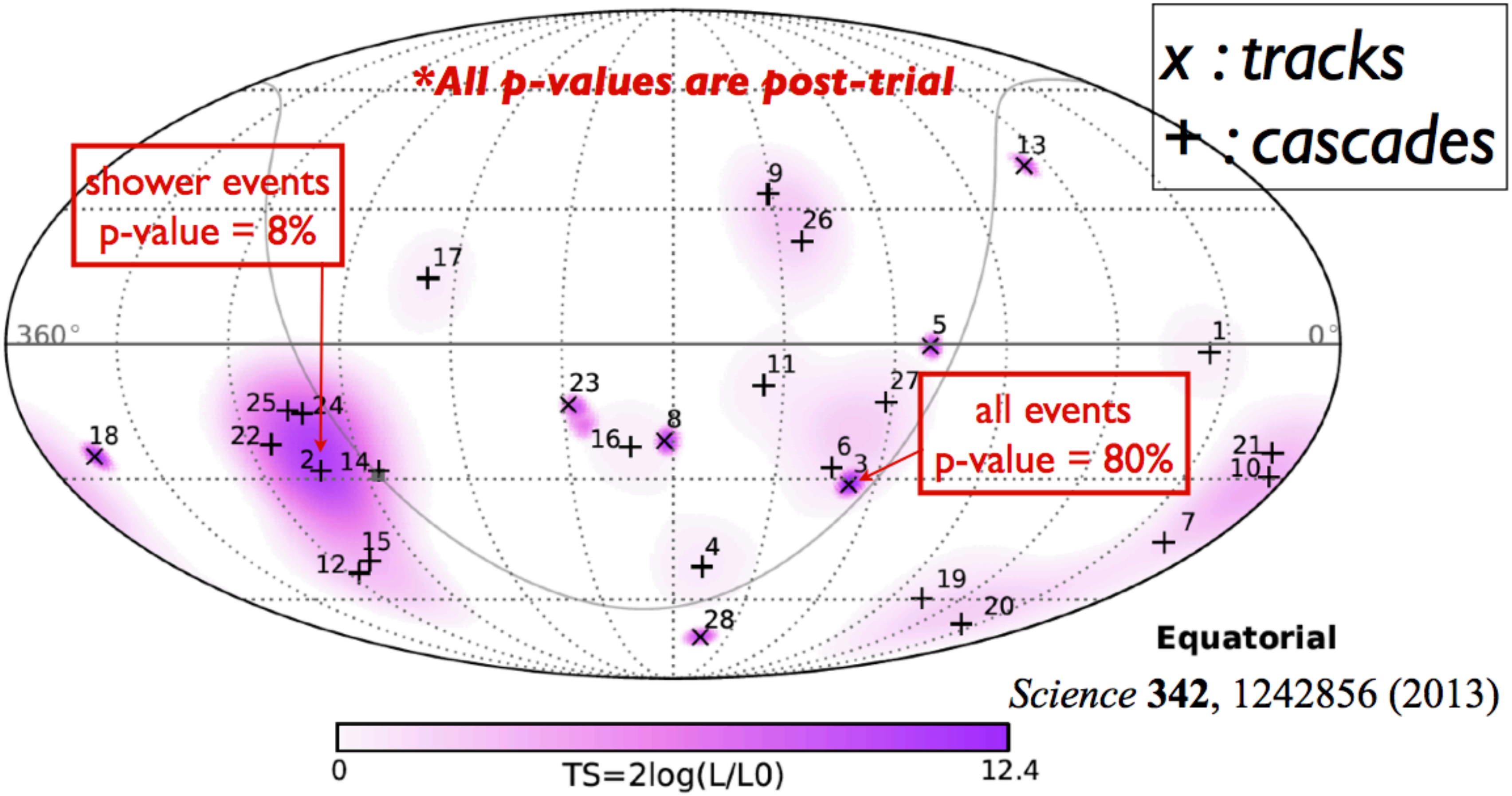
21 November 2013

Astrophysical Neutrinos



Science **342**, 1242856 (2013)

The Era of Neutrino Astronomy has Begun!

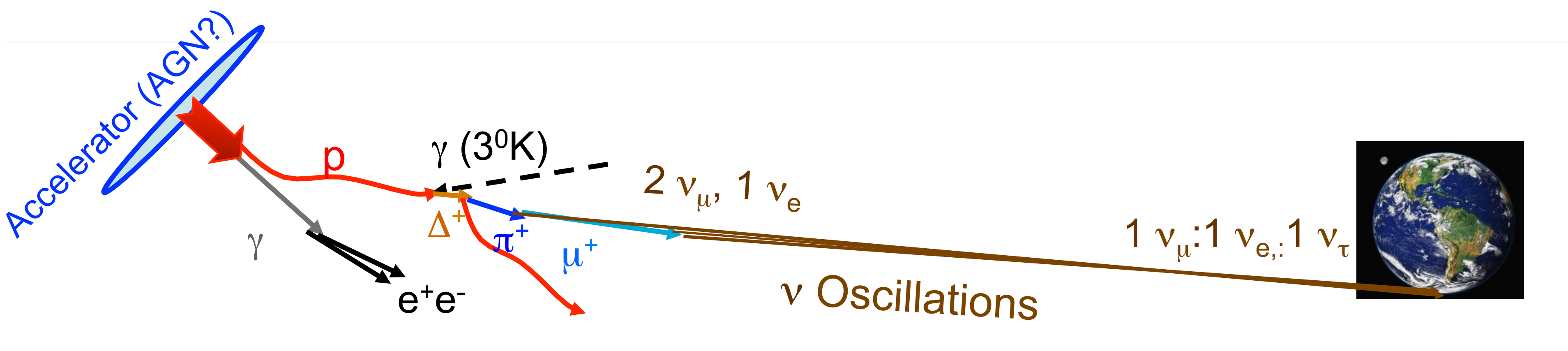


Science **342**, 1242856 (2013)

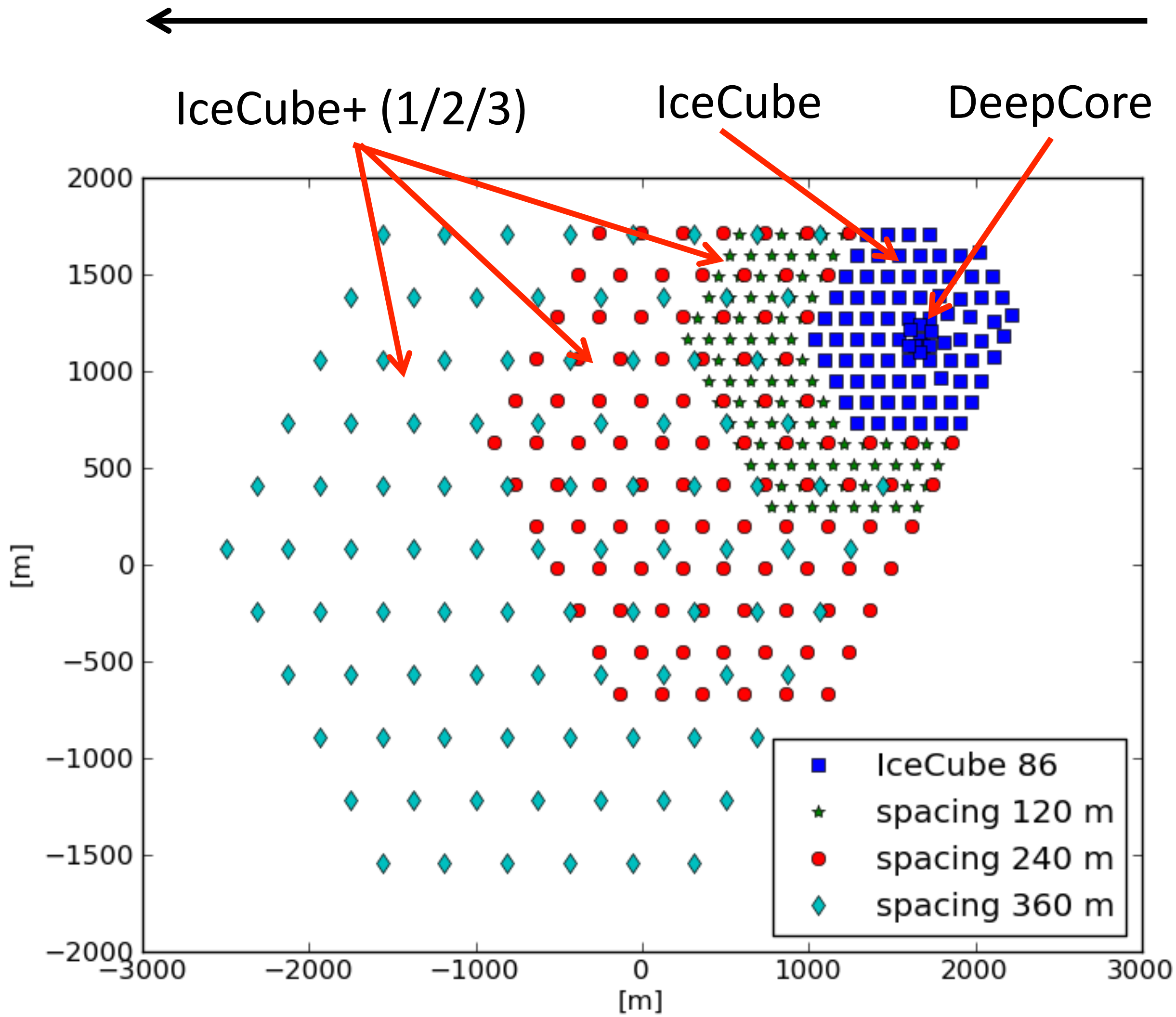
No significant source found

UHE ν Astronomy

- ν's are the only probe of the extremely-high-energy universe with a range above 100 Mpc
- The neutrino flux depends on the cosmic-ray composition & the evolution of the universe
- Above 10^{17} eV need > 100 km^3 detector (assuming mostly P's)
- GZK flux allows measurement of neutrino nucleon cross section at 10^{18} eV



IceCube threshold: ~ 1 TeV
IceCube+ upgrade: higher threshold → 10 to 50 TeV
-> larger spacing



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

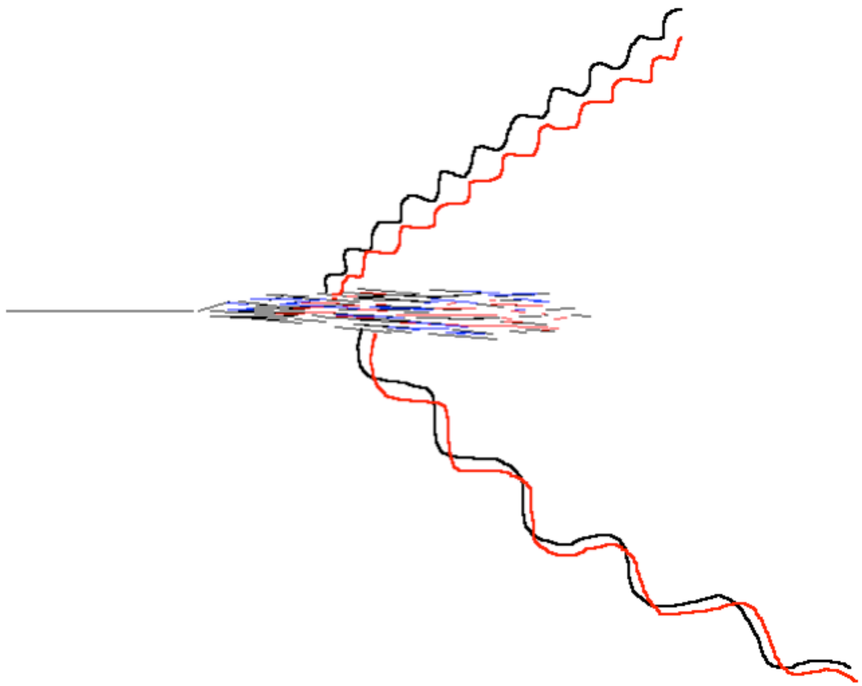
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

IceCube Upgrade Plans

- Add an additional 95 strings with 3x spacing
  - Increase area by ~12
- Expand IceTop to get background free downgoing flux
- The goal is:
  - To get ~100 contained vertex events above 1 PeV
  - To get ~1000 muon events with angular res. ~1^{o}
  - Precision energy spectrum
  - Tau neutrinos must show up, flavor ratios tell about accelerators particle physics, cross-sections, unexpected
  - Expand point source search in PeV to EeV range
  - GZK neutrino searches of radio detectors above 10^{17}eV
- Another NSF MREFC
  - ~\$270M - ~\$200M from US

GZK Neutrinos with Radio

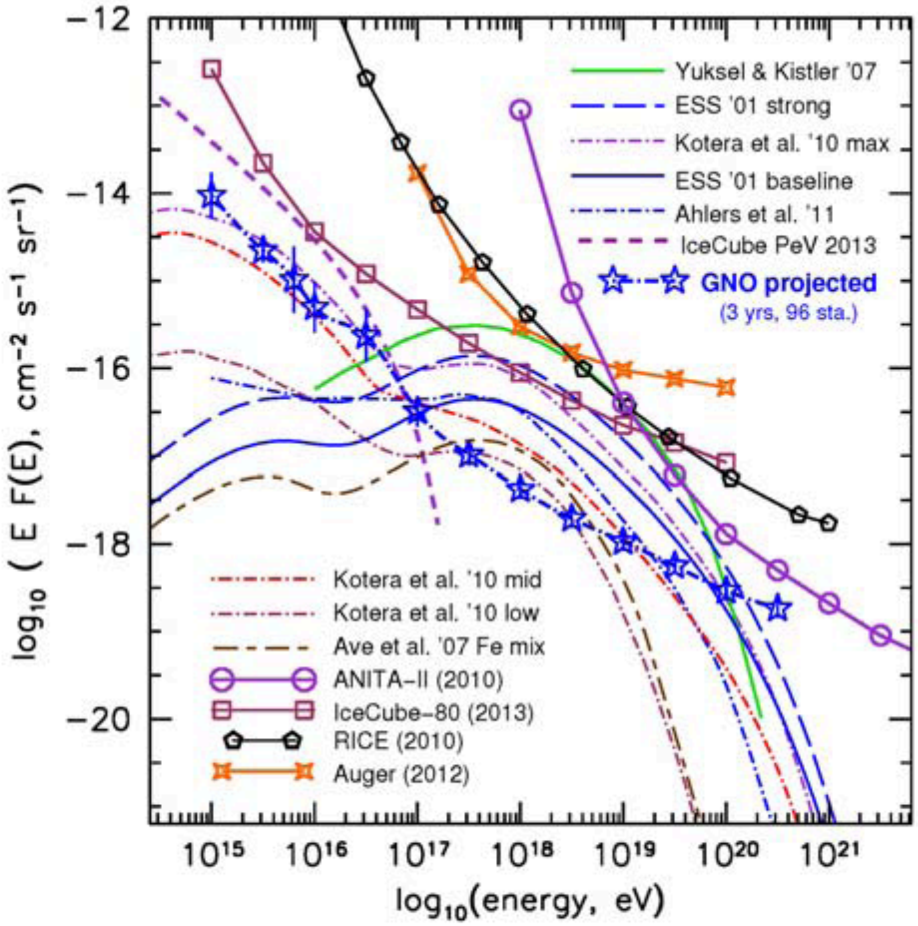


Radio Experiments in Ice

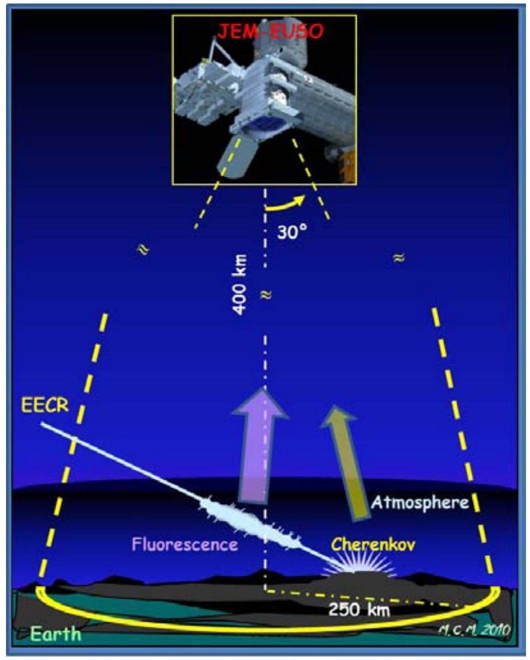
- A number of promising GZK radio experiments
- The GZK ν flux can give a measurement of ν nucleon cross section at well above LHC
- ANITA – Balloon-borne detector – large area – high threshold
  - Several flights – high energy showers, but no neutrinos
  - Another flight planned
- ARIANNA - 1,000 station array on the Ross Ice Shelf
  - 3 stations installed in 2012 – 4 more planned, but delayed
- ARA – 37 Station array at South Pole
  - 3 stations installed - 5-7 more proposed
- Greenland Neutrino Observatory
  - deploy first station Summer 2014
- Experiments are in the ~$15M-$25M

(including international contributions)

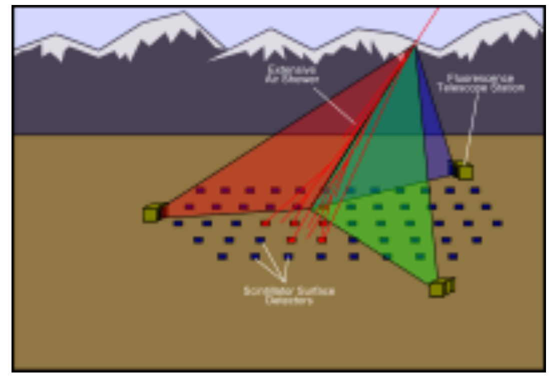
- First gen. detectors
  - Measure the flux
  - Explore GZK mechanism
  - Angular res ~5^o
- Later build an observatory-class instrument



Auger

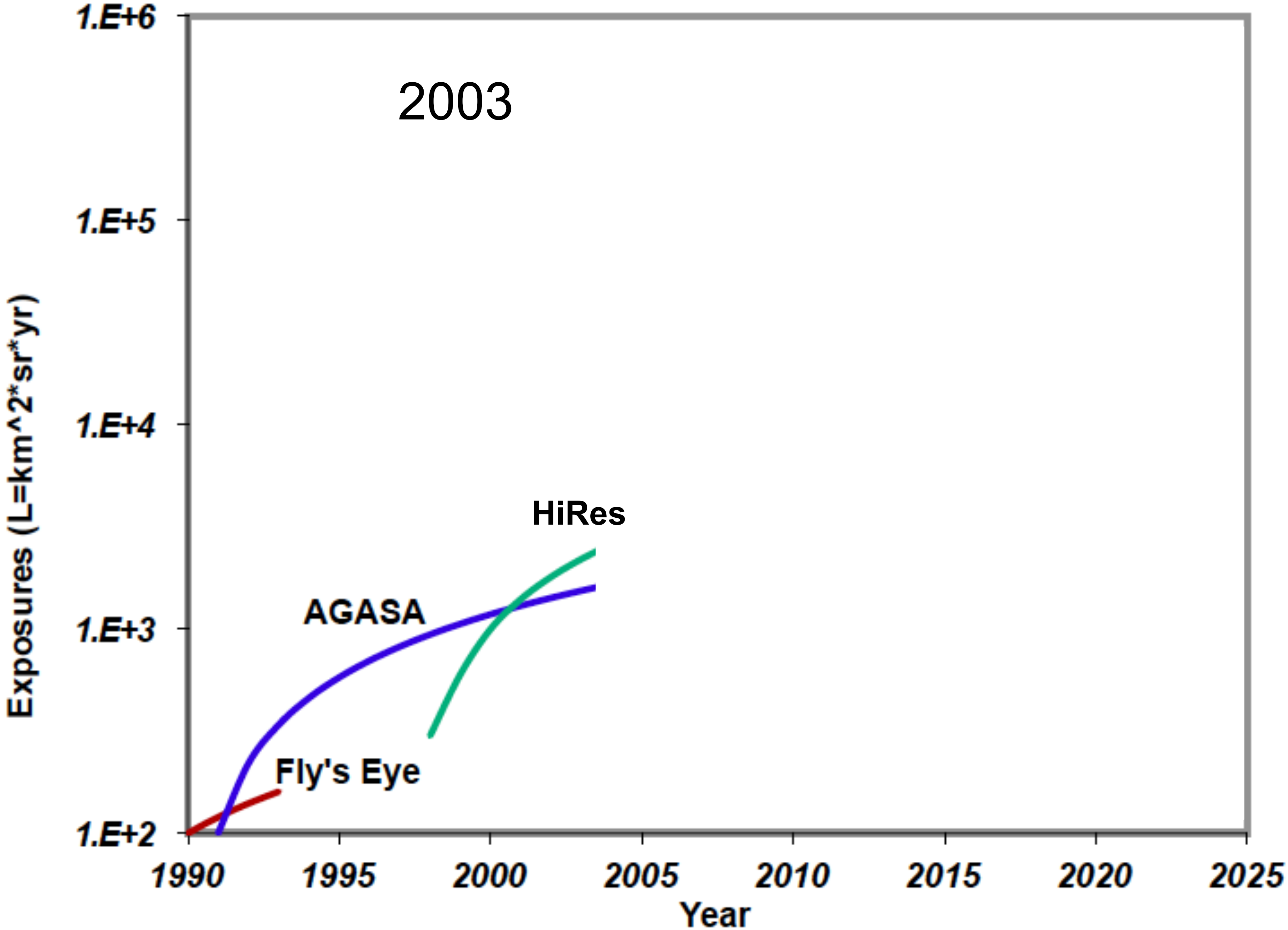


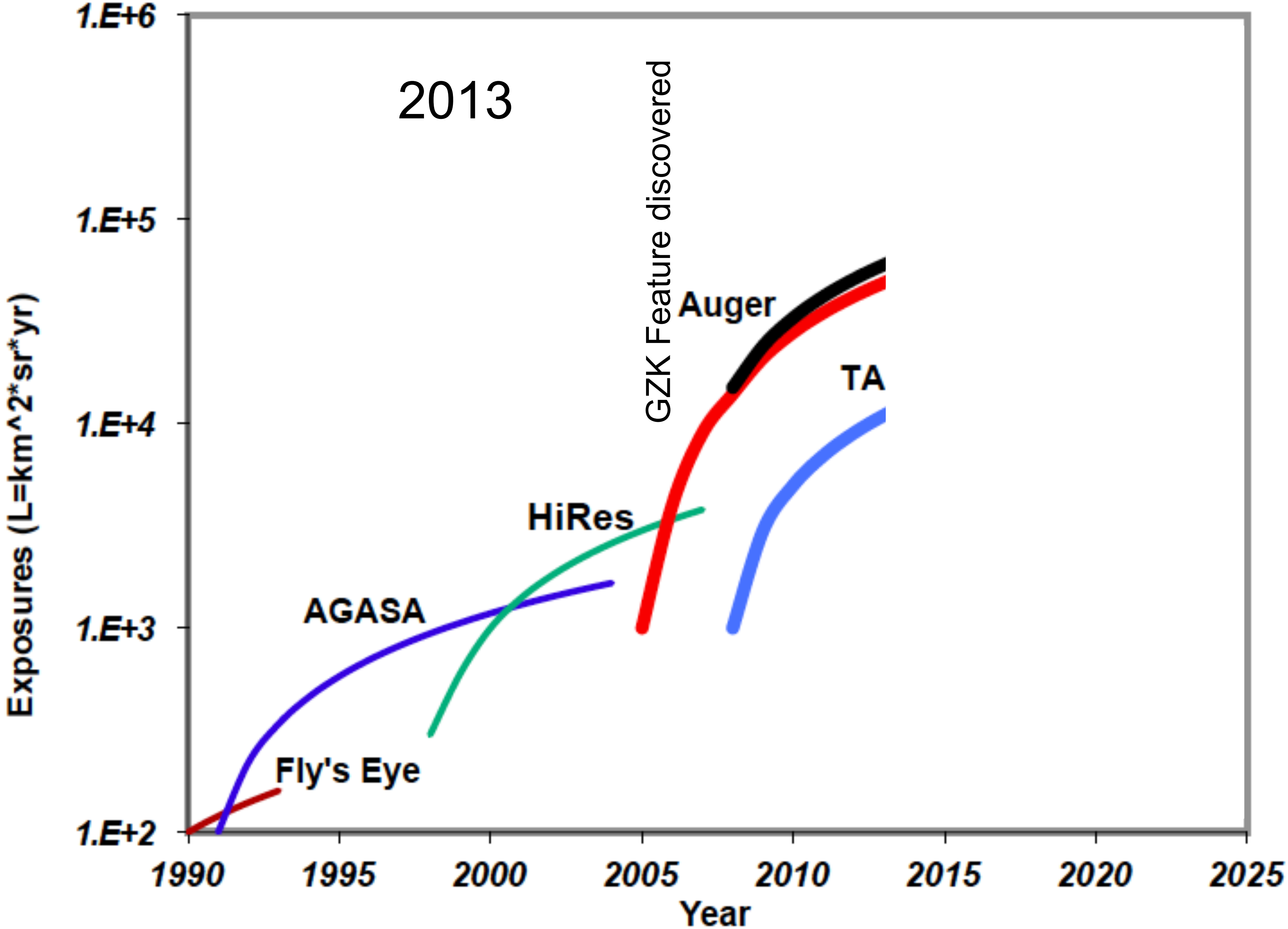
JEM –EUSO



Telescope Array

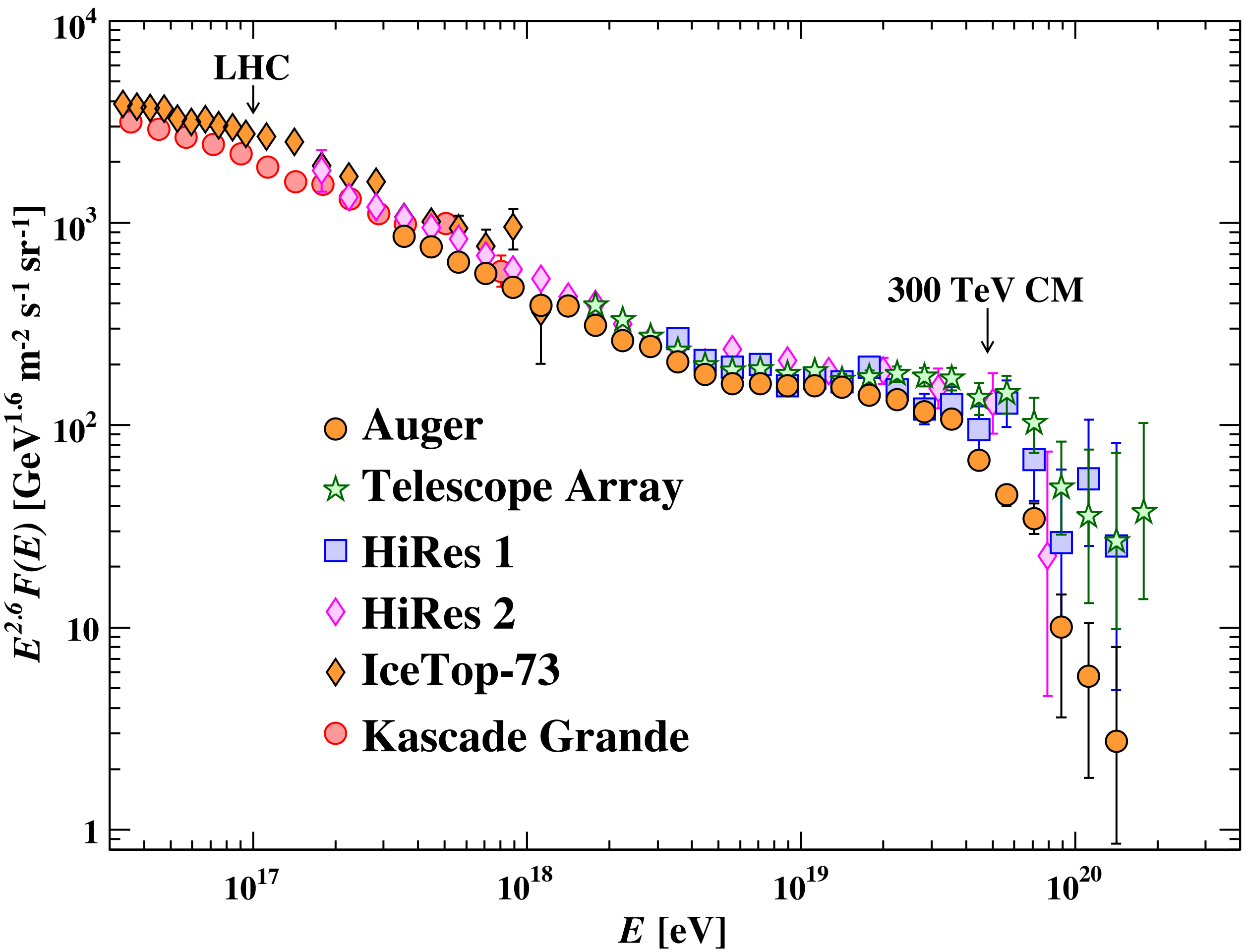
UHE COSMIC RAYS


2003
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
HiRes
AGASA
Fly's Eye
1990
1995
2000
2005
2010
2015
2020
2025
Year

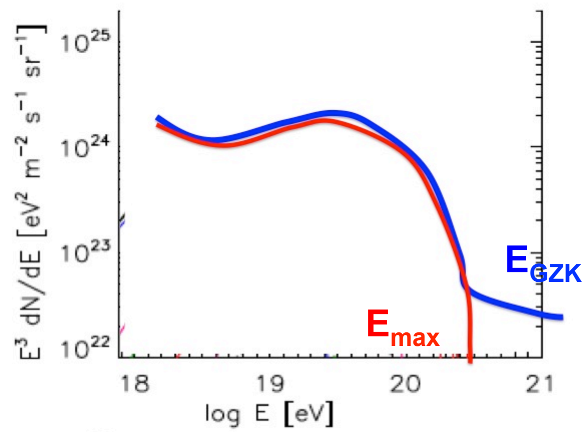


2013
GZK Feature discovered
Auger
TA
HiRes
AGASA
Fly's Eye
Exposures (L=km^2*sr*yr)
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
1990
1995
2000
2005
2010
2015
2020
2025
Year

Flux suppression at the highest energies

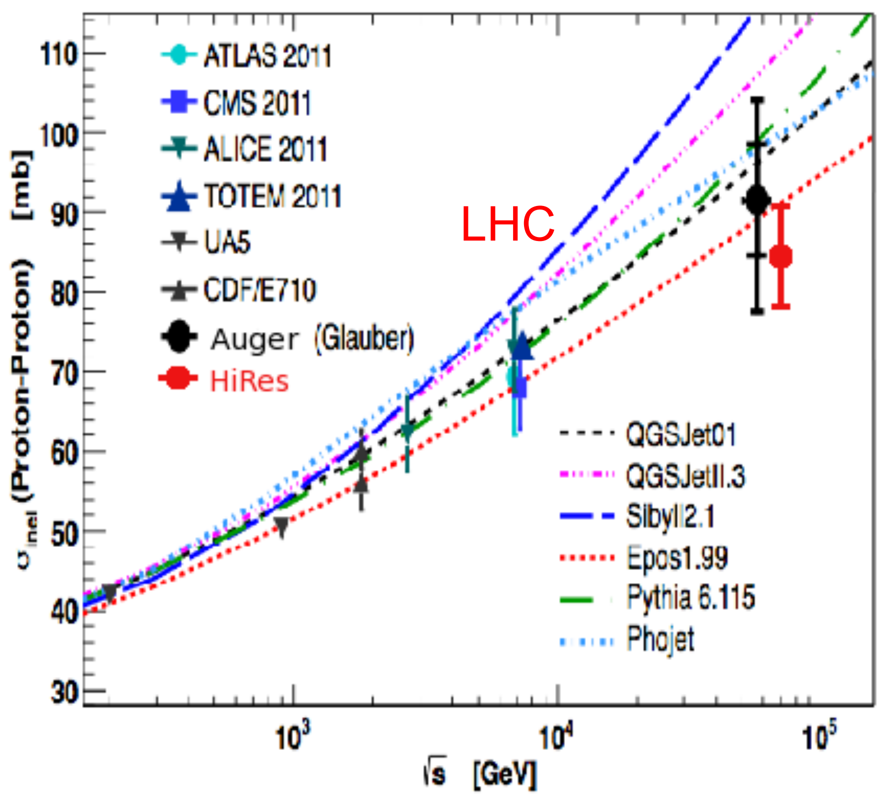


What is the origin of the flux suppression?



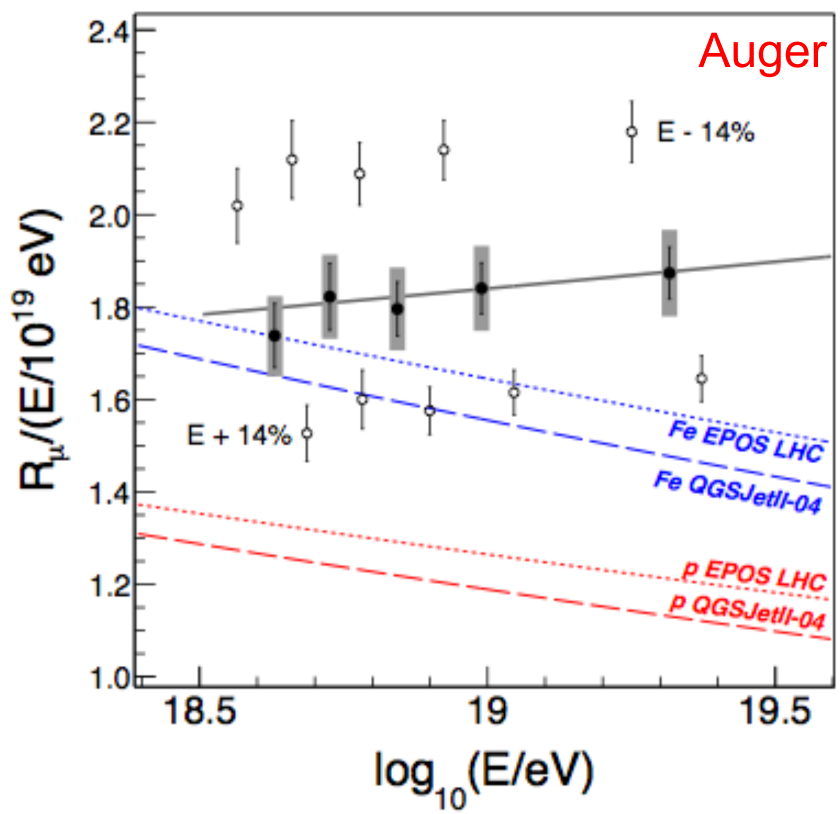
GZK (i.e. interaction with CMB) or maximum acceleration energy?

Explore particle interactions above 20 TeV CM



p-p cross section at 57 TeV CM

Inclined showers dominated by muons

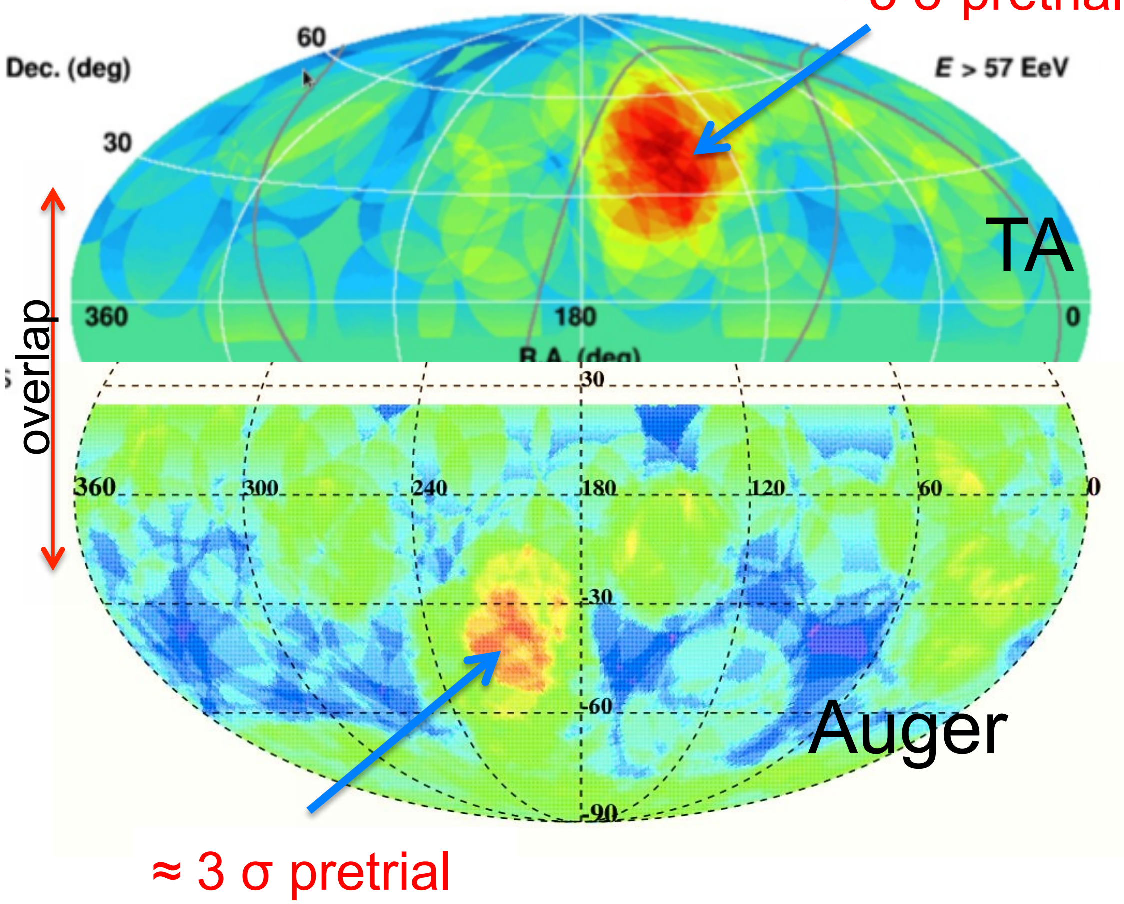


More muons than predicted by hadronic models

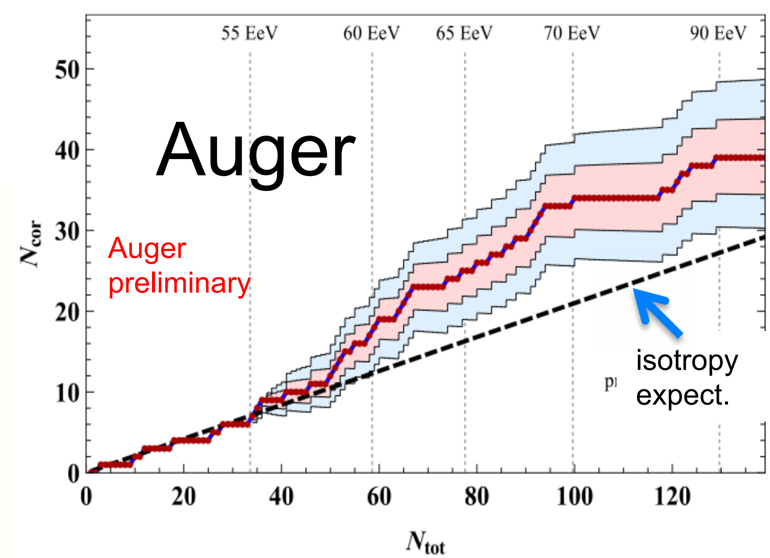
Origin of UHE Cosmic Rays?

Evidence for Comic Ray Anisotropy above 5.7x 10^{19} eV in the North and South - Still statistically limited – but it will be clear in a few years

E > 5.7x 10^{19} eV   20º smoothing

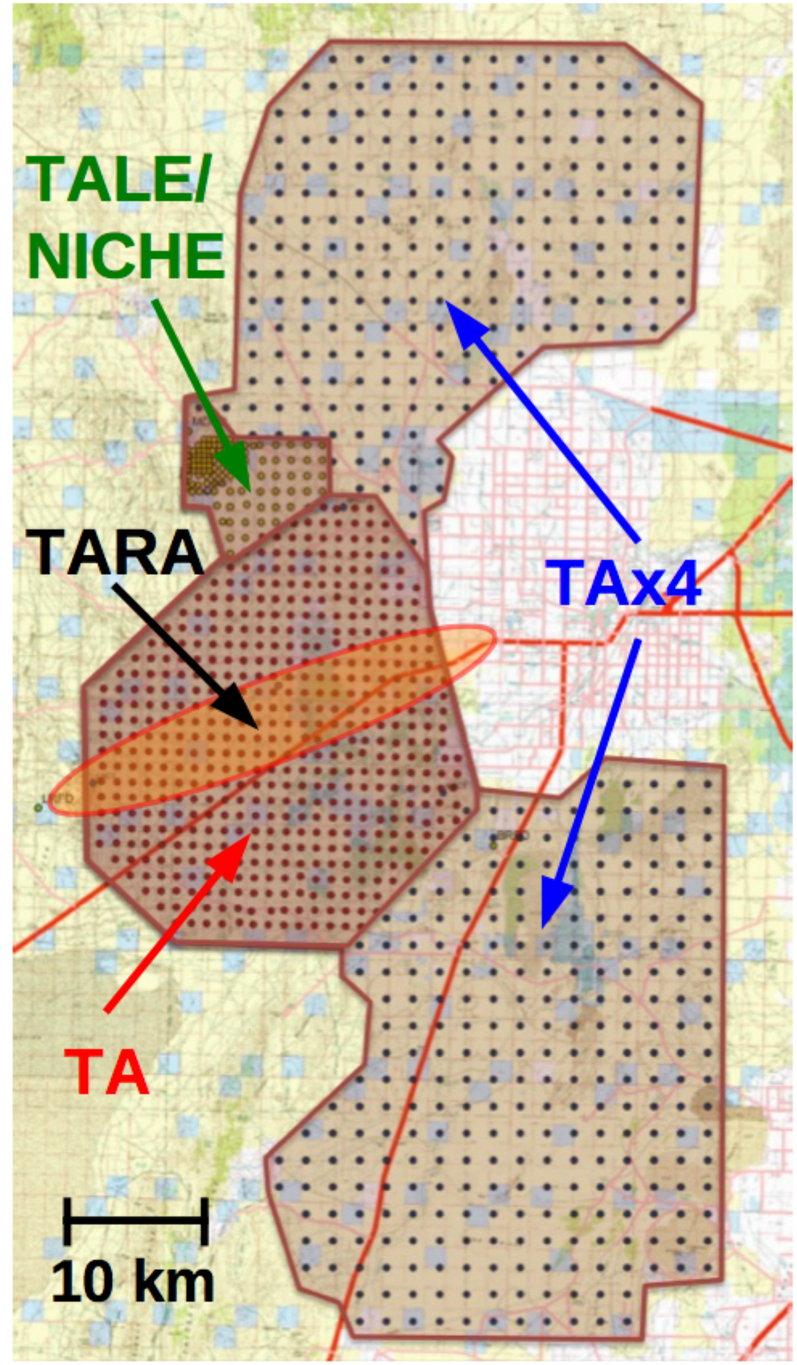


# of events correlating with AGN, ordered in energy (integral plot)



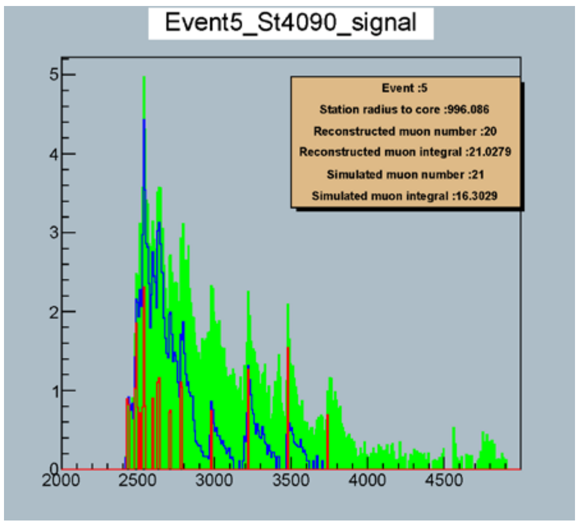
Telescope Array Expansion

- **Telescope Array** (700 km²)
  - 507 Surface Detectors; 1.2 km grid.
  - 3 Fluorescence Detectors
- **TALE** (Low-Energy Extension)
  - 100 SD infill array
  - High elevation angle FD
  - Commissioning in progress
- **TARA** Radar R&D
  - 8 MW ERP transmitter at 54 MHz
  - 250 Ms/s VHF receiver
- **TA x 4** (3,000 km²)
  - 500 new SDs; 2 km grid (Japan, $5M)
  - 1 new FD (US NSF, $1M)
  - Anisotropy: 20 TA years by 2019
- Non Imaging Cherenkov Array **NICHE**
  - TA/TALE 3×10^{16} – 3×10^{20} eV
  - NICHE 10^{15} – 10^{18} eV
  - 85 Cherenkov light collectors
  - Observe shower from 1st interaction
  - Calibrate NICHE with TALE



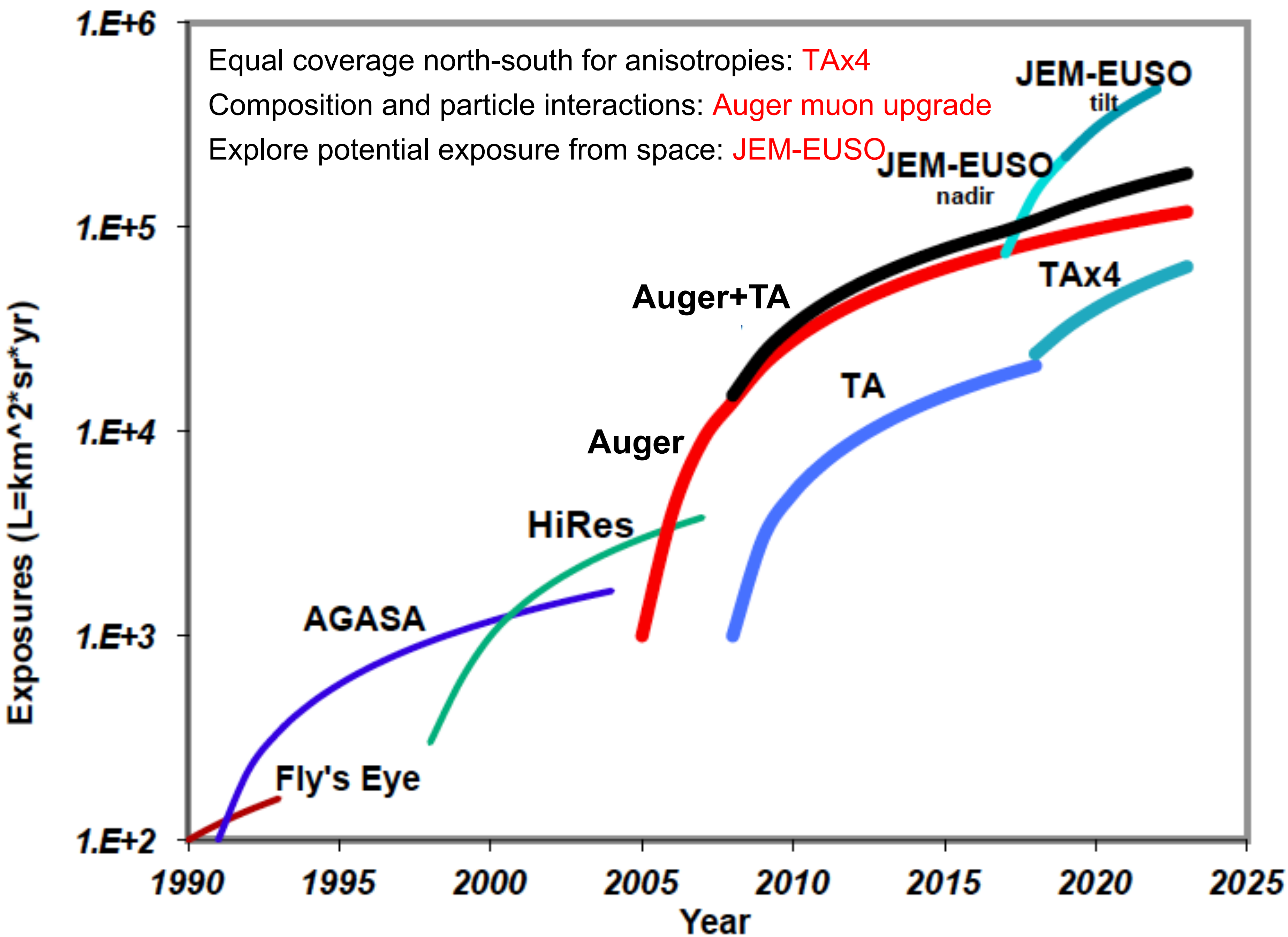
Pierre Auger Observatory Upgrades: Designs

Target: ***Better measurement of muons***
- ***Accelerator maximum*** *heavier nuclei at high energy*
- ***Photon, neutrino identification***
- ***Proton identification:*** *astronomy* - ***Hadron physics***



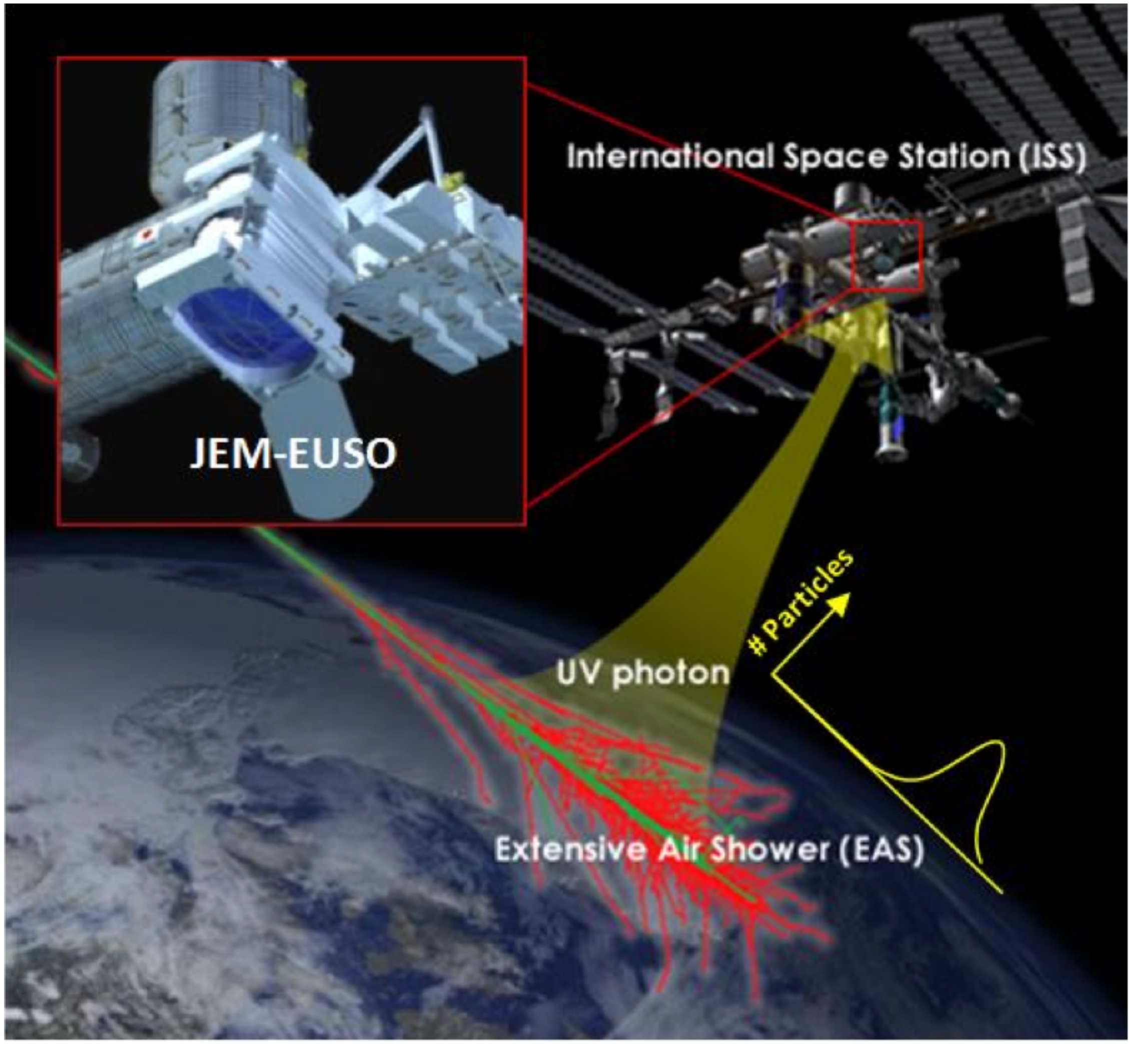
1. **Faster electronics** – distinguish muon spikes in SD traces
2. **Additional muon detectors** – scintillators, RPCs
3. **Modified SD** – segmented tanks

In the next decade, Auger will roughly triple its present data set: obtaining **event-by-event** composition measurements will be an **order-of-magnitude** increase in that kind of data.



Equal coverage north-south for anisotropies: TAx4
Composition and particle interactions: Auger muon upgrade
Explore potential exposure from space: JEM-EUSO
JEM-EUSO
tilt
JEM-EUSO
nadir
TAx4
Auger+TA
TA
Auger
HiRes
AGASA
Fly's Eye
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year

JEM-EUSO Mission



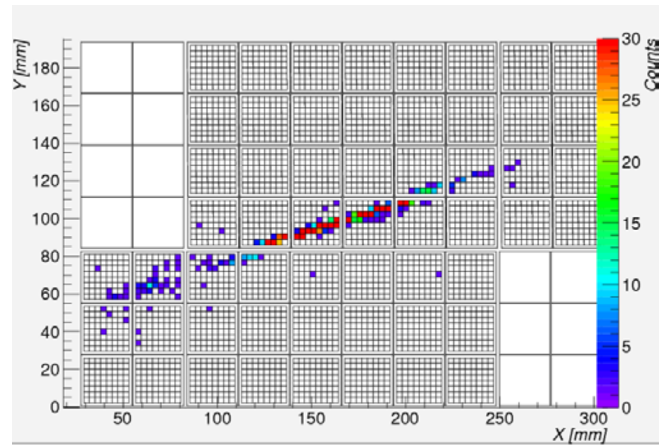
Extreme Universe Space Observatory (EUSO) at the Japanese Experiment Module (JEM) on the ISS

14 Country Collaboration to build 60 deg FOV UV telescope w/ 4.5 m^2 focal surface of 0.3 million pixels MAPMTs monitoring 130,000 km^2

JEM-EUSO

Pioneer mission to study of UHECR from Space

~10x increase exposure over full sky to discover the nearby sources of UHECRs



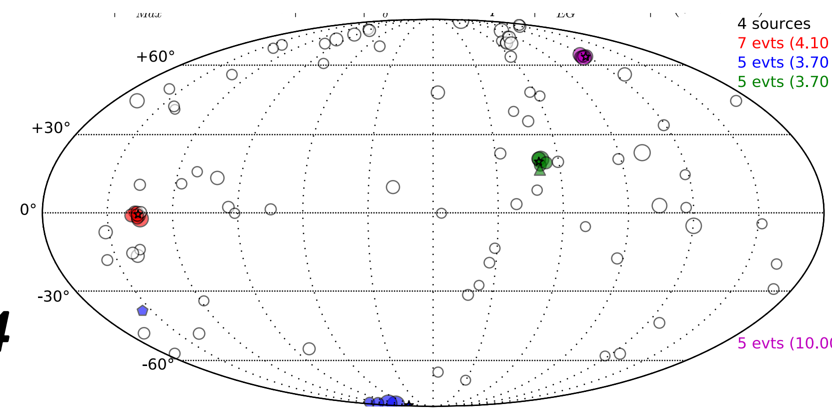
NASA approved US participation

in JAXA led mission (A/O Spring 2014)

DOE/NSF requests:

R&D on SiPM focal Surface

US trigger group



Prototypes:

EUSO@TA deployment Spring 2014,

EUSO-Balloon launch CNES in Fall 2014

Mini-EUSO deployment ISS 2014-2015

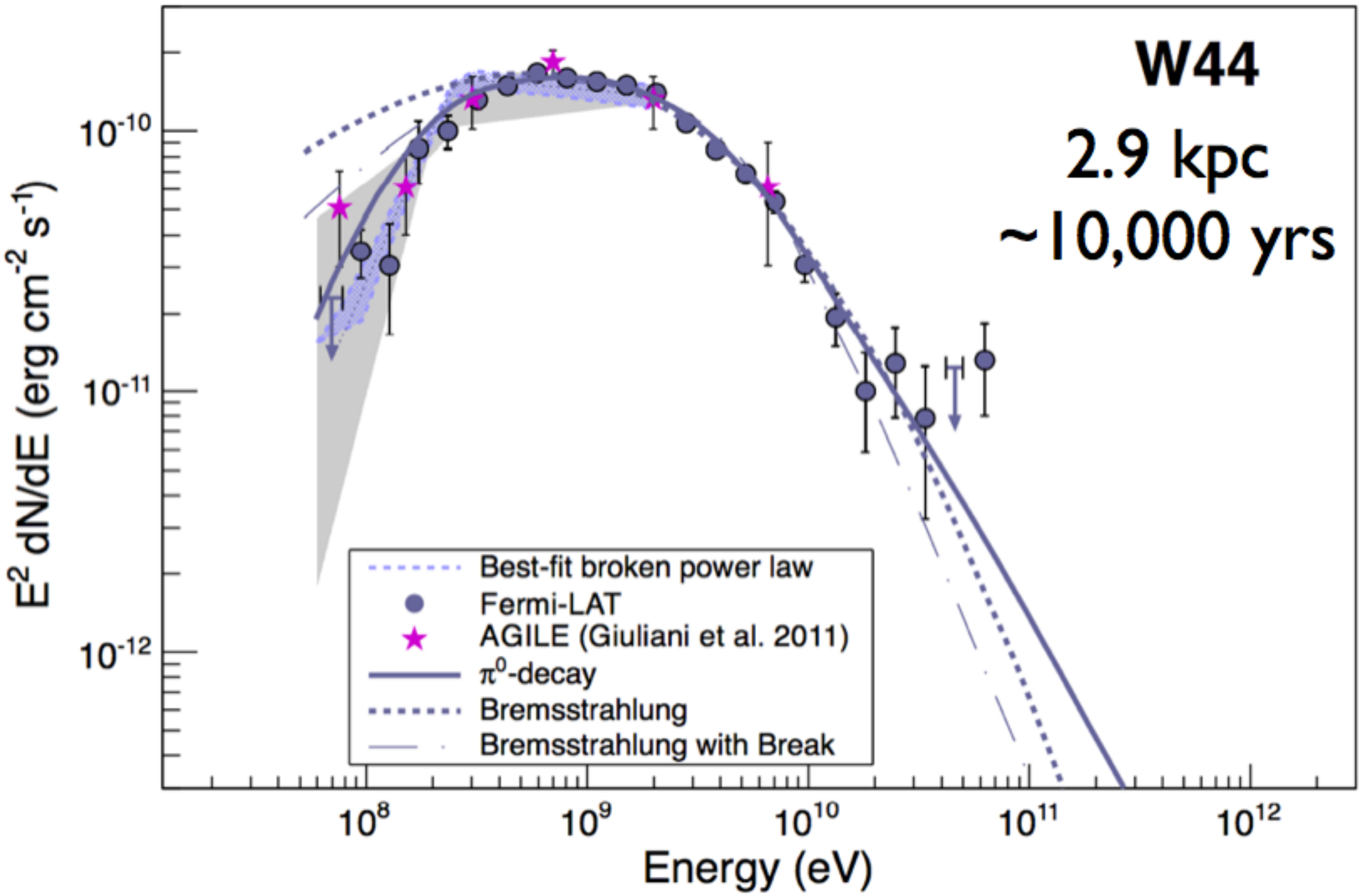
Project	Total Cost	US Portion	New Construction
HAWC (Construction)	$14M	$7M NSF, DOE	
HAWC Operations	$1.4M/yr	$1M/yr NSF, DOE	
HAWC Upgrade	$3M	$0.5M NSF	2015
IceCube (Construction)	$270M	$230M (MREFC)	
IceCube Operations	*~$7.5M/yr*	*$6.5M/yr NSF*	
IC3 Upgrades	~$270M	$200M (MREFC)	2015-16
Radio	~$15-25M		2015-16

Project	Total Cost	US Portion	New Construction
Auger (Construction)	$53M	$11M	
Auger Operations	*$2M/yr*	*$0.4M/yr*	
Auger Upgrade	$10M	$2M - NSF	2015
TA (Construction)	$18M	$3M - NSF	
TA Operations	*$2M/yr*	*$1M/yr- NSF*	
TA Upgrades	$7M	$1M -NSF	2014
JEM/EUSO	$150M (payload)	$4.5M - NASA $2M – NSF $2M - DOE	2015

Summary

- The US has a strong and vibrant program in Cosmic Particles
  - Exciting new results are rapidly emerging
  - Probing important questions in Astrophysics and Particle Physics
- The US with support from NSF and DOE have lead the development of the field
  - They have helped design and/or build all the major instruments
  - They provided an excellent training ground for students/post-docs to work on design, construction and analysis of an experiment
- The US has an opportunity to leverage large international support with a modest US contribution to retain a leading role in the science
  - P5 should encourage this investment

BACKUP MATERIALS



W44
2.9 kpc
~10,000 yrs
E2 dN/dE (erg cm-2 s-1)
Energy (eV)
Best-fit broken power law
Fermi-LAT
AGILE (Giuliani et al. 2011)
π0-decay
Bremsstrahlung
Bremsstrahlung with Break

Lorentz Invariance Violation

- Theories of quantum gravity typically define a minimum length scale, usually the Planck length, 1.6x10^{-33} cm (or 1.2x10^{19} GeV)
- This is a violation of Lorentz invariance
- LIV can lead to a vacuum dispersion relation - an energy dependent speed of light
- Gamma ray bursts and AGN flares provide an excellent probe of LIV

$$p^2c^2 = E^2\left(1 \pm \xi_1 \frac{E}{M_{QG}} \pm \xi_2 \left(\frac{E}{M_{QG}}\right)^2 + \ldots\right)$$

$$v_l \approx c\left(1 - \xi_1 \frac{E}{M_{QG}}\right)$$

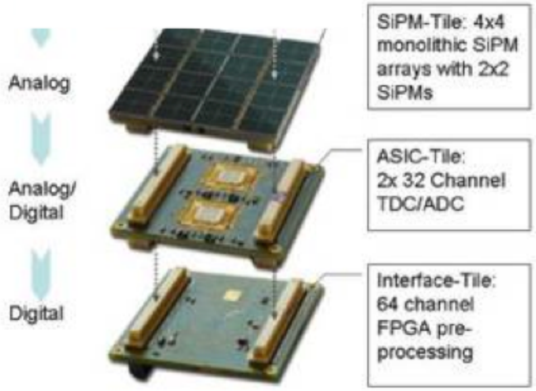
$$v_q \approx c\left(1 - \xi_2 \frac{E^2}{M_{LIV}^2}\right)$$

JEM-EUSO Mission Plans

- Almost all parts of JEM-EUSO have been prototyped and are being tested.
- EUSO-Balloon Test 2014 w/helicopter calibrated flasher
- Integration and launch in 2017
- 3 years mission operations with a plan to extend the mission an additional 2 years.
- Funding
  - Anticipated Requests (NSF-DOE)
  - SiPM Research From DOE
  - Trigger Studies from NSF

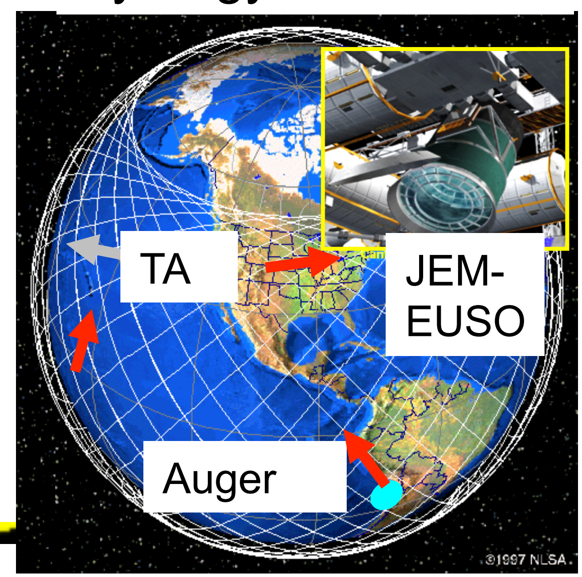
R&D Activities

Silicon PMs



'Lightweight' Fluorescence (FAST)

Synergy w/ **Lasers**



Radio Techniques

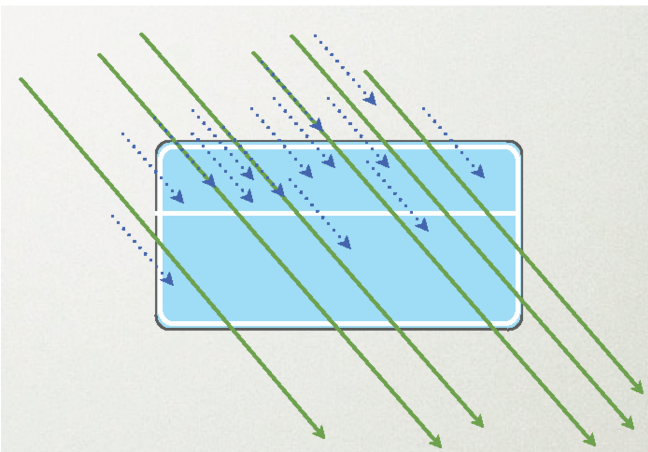
Radar Techniques

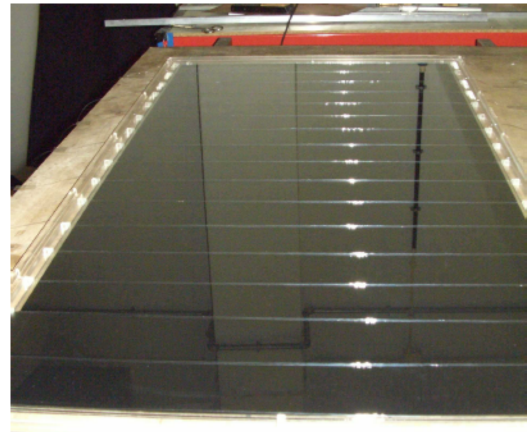
J Goodman

Pierre Auger Observatory Upgrades: Status

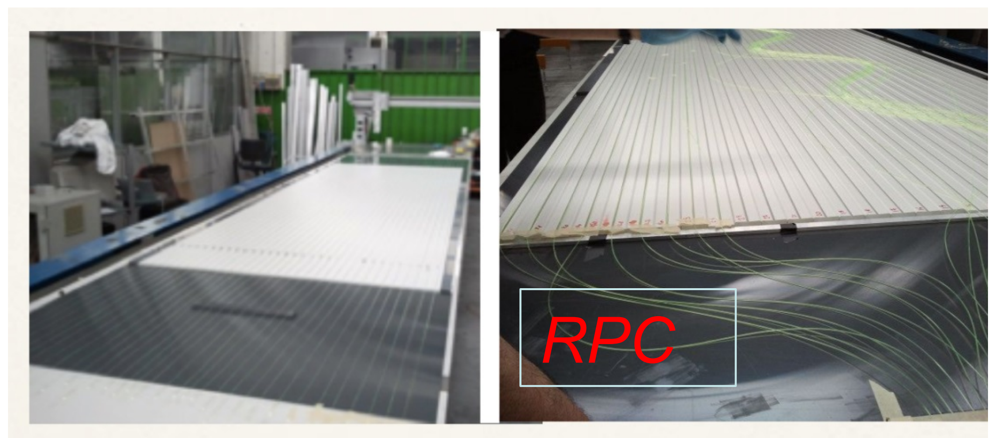
PIERRE AUGER OBSERVATORY

Prototypes of detector designs underway



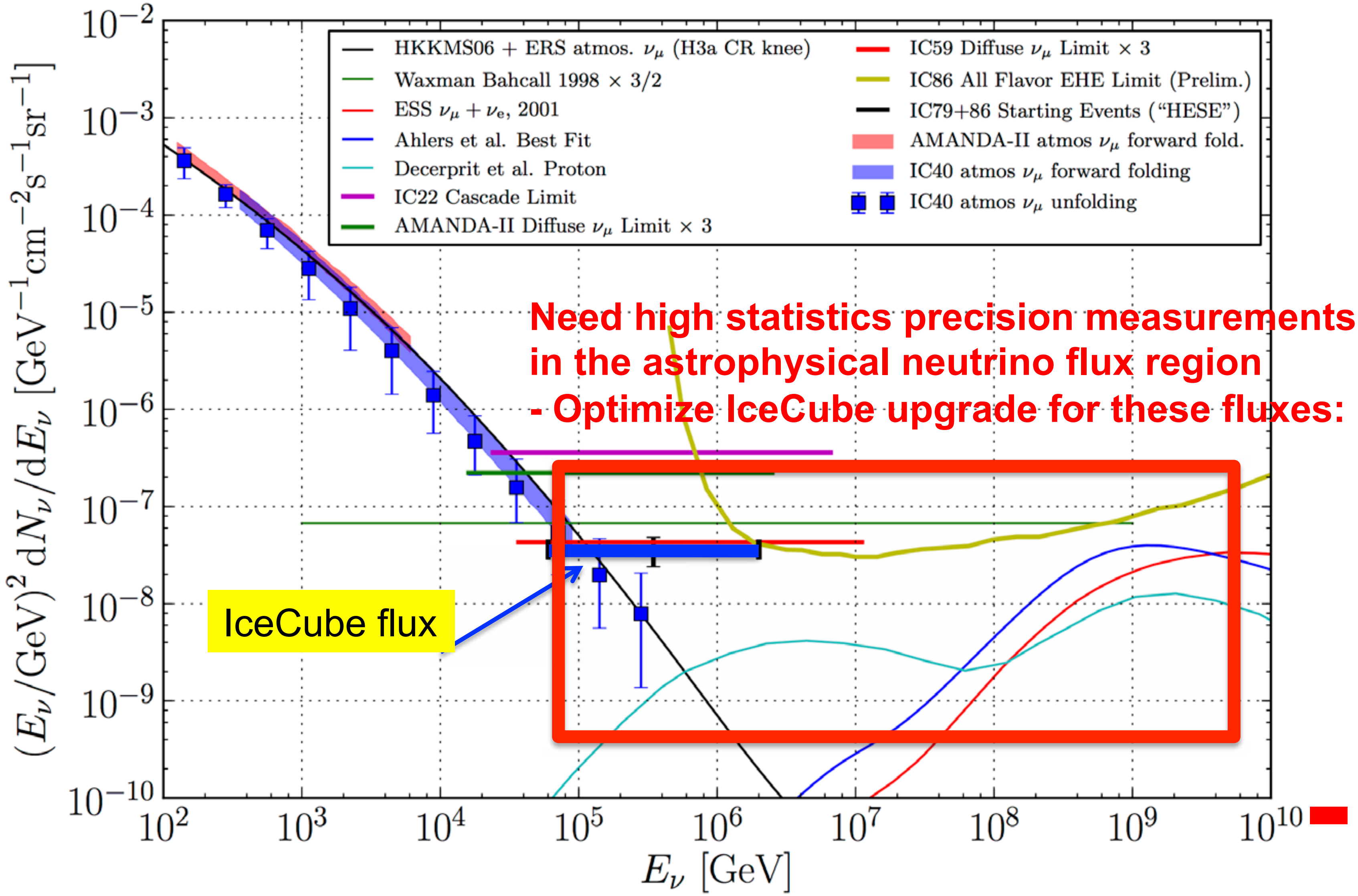


Scintillators

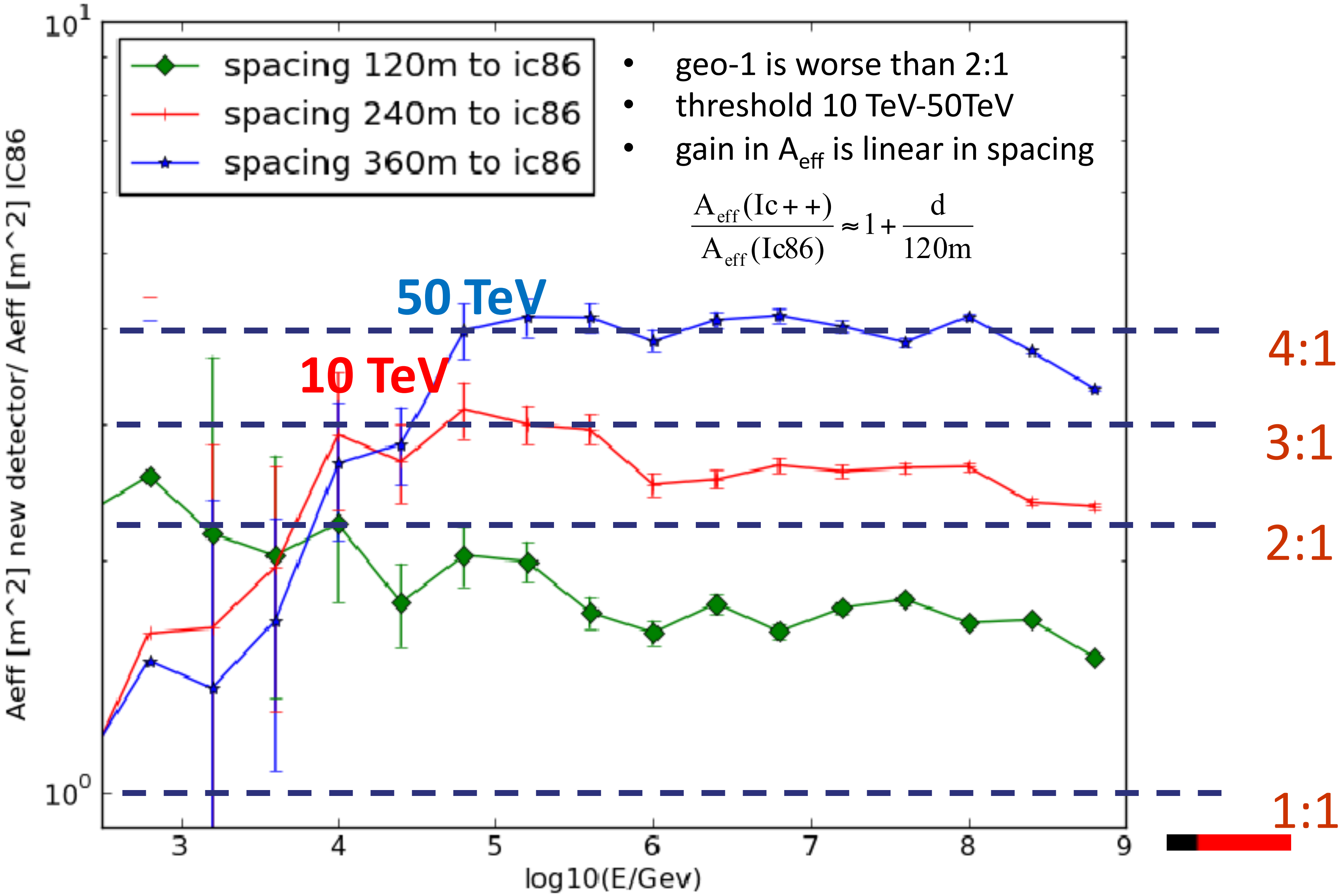


Cost Target: 20% of investment ($10-12M US)
US Contribution at MRI scale

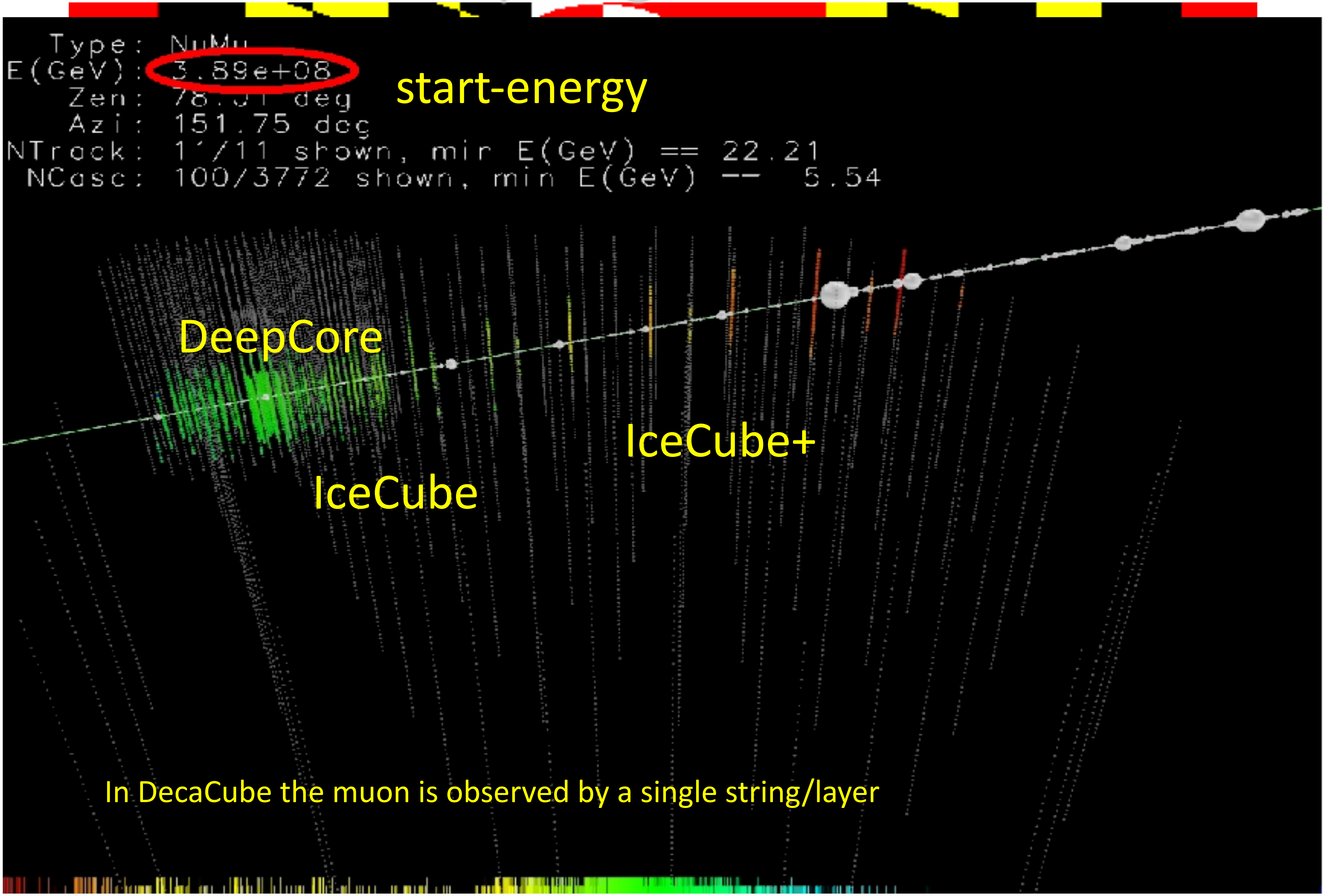
Study Cosmogenic Neutrinos



Improvement Factor w.r.t. IceCube-86

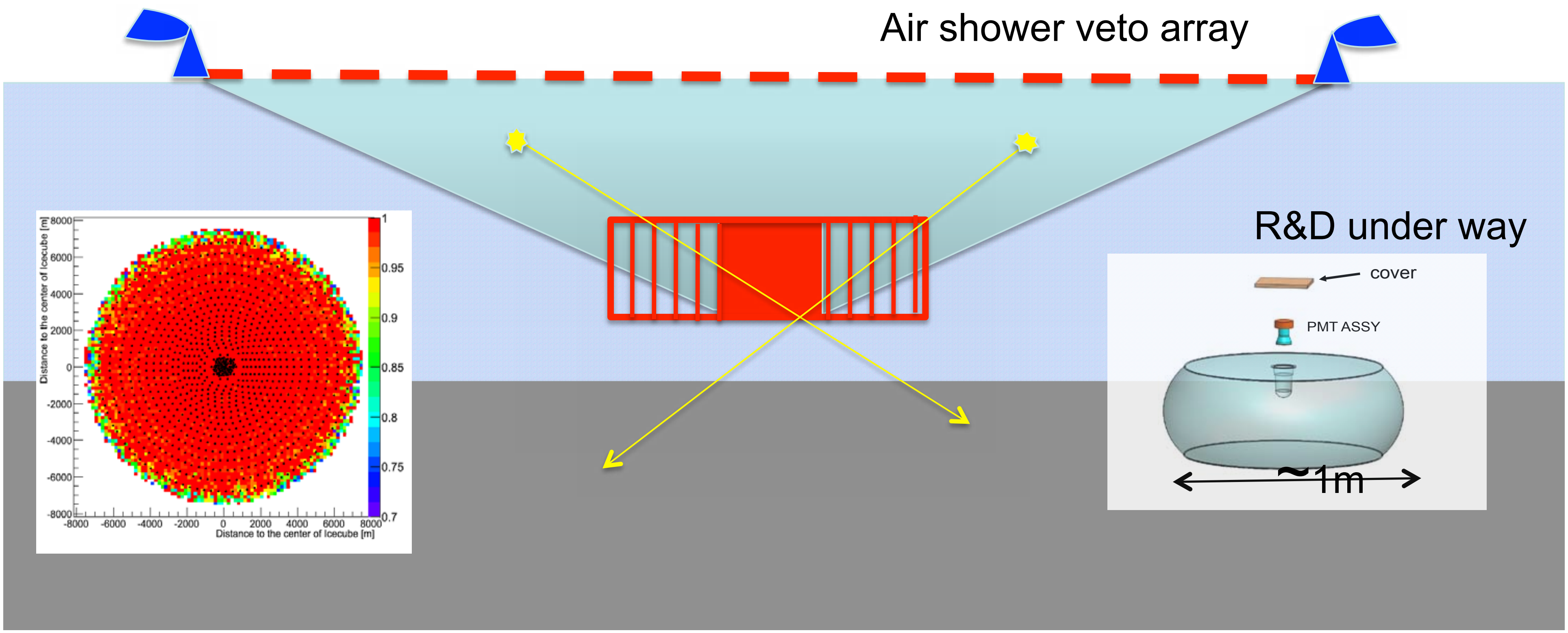


Spacing 3: 360m



Expand surface veto

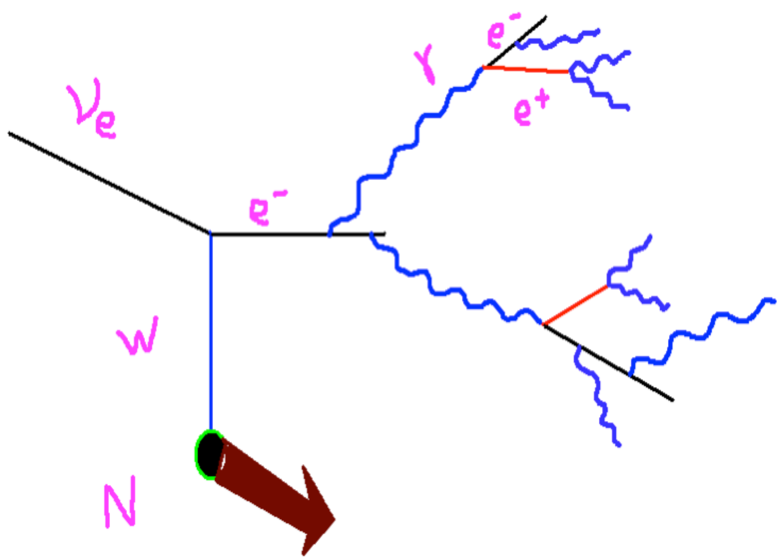
- Surface veto above 1 PeV can reject atmospheric muon and neutrino background.
- Expanded IceCube will gain background free effective volume
- Build a bigger detector with a full surface veto, 100 km^2, for 3 – 5 sr background free muon neutrino detection



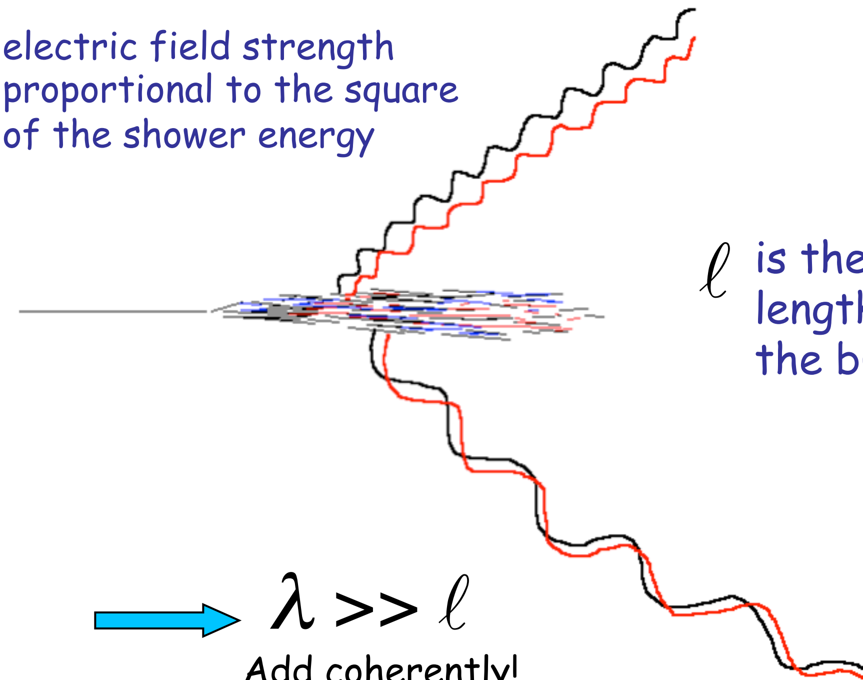
Coherent Radio from EM Shower

aka the "Askaryan effect"

charge asymmetry in particle shower development- combined effects of positron annihilation and Compton scattering on atomic electrons result in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → wavelengths shorter than the bunch length suffer from destructive interference



electric field strength proportional to the square of the shower energy

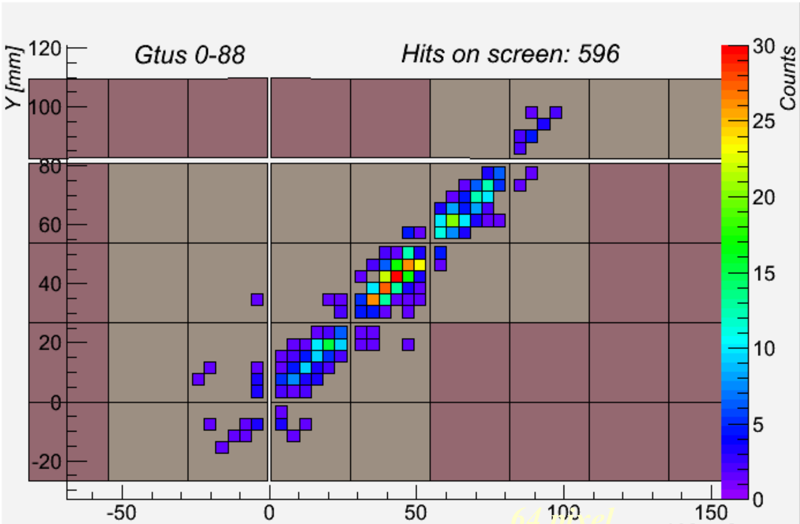


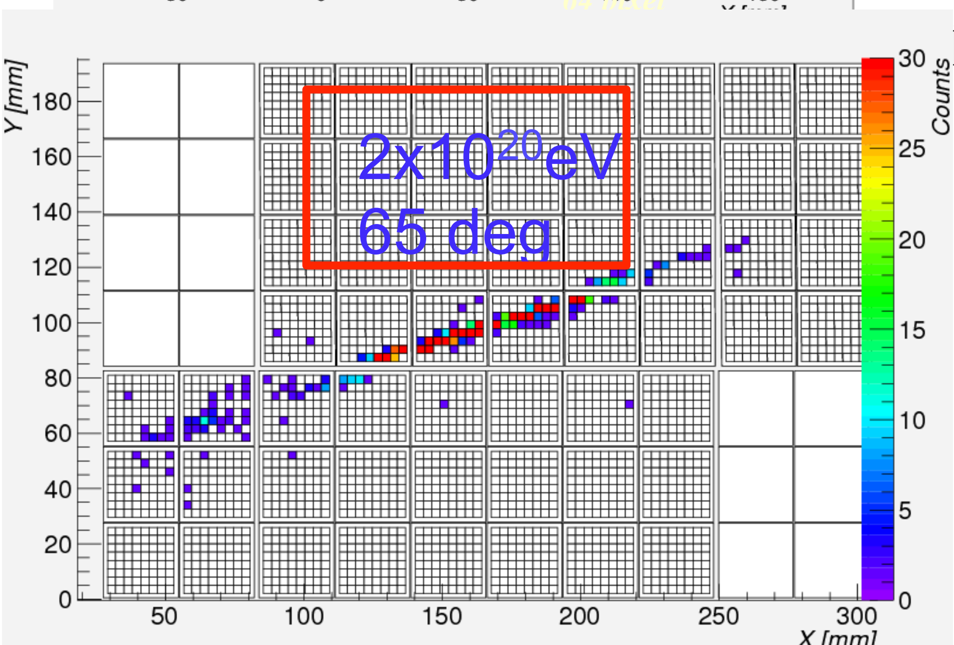
ℓ is the length of the bunch

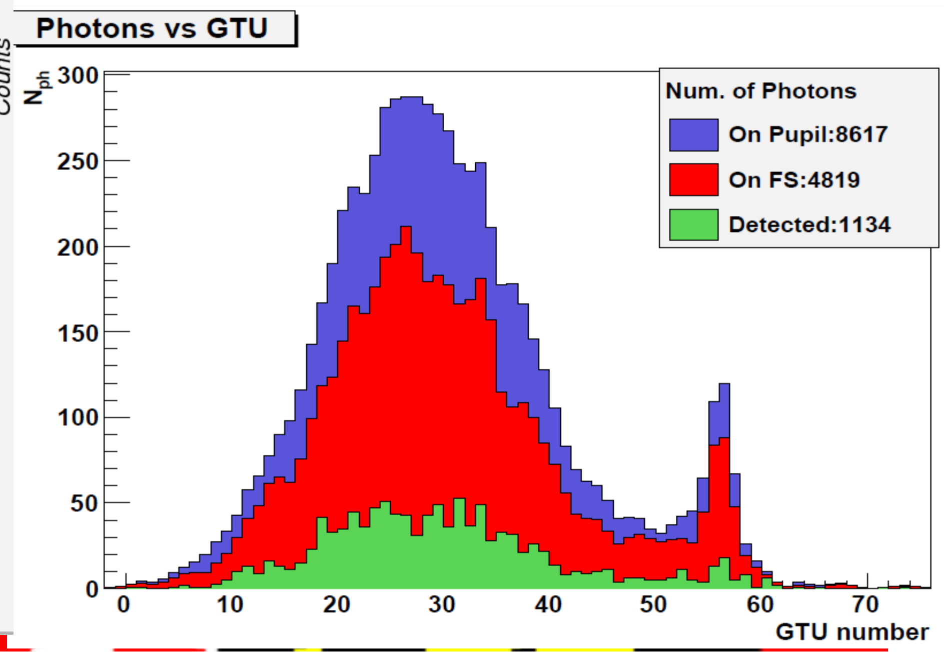
→ $\lambda >> \ell$

Add coherently!

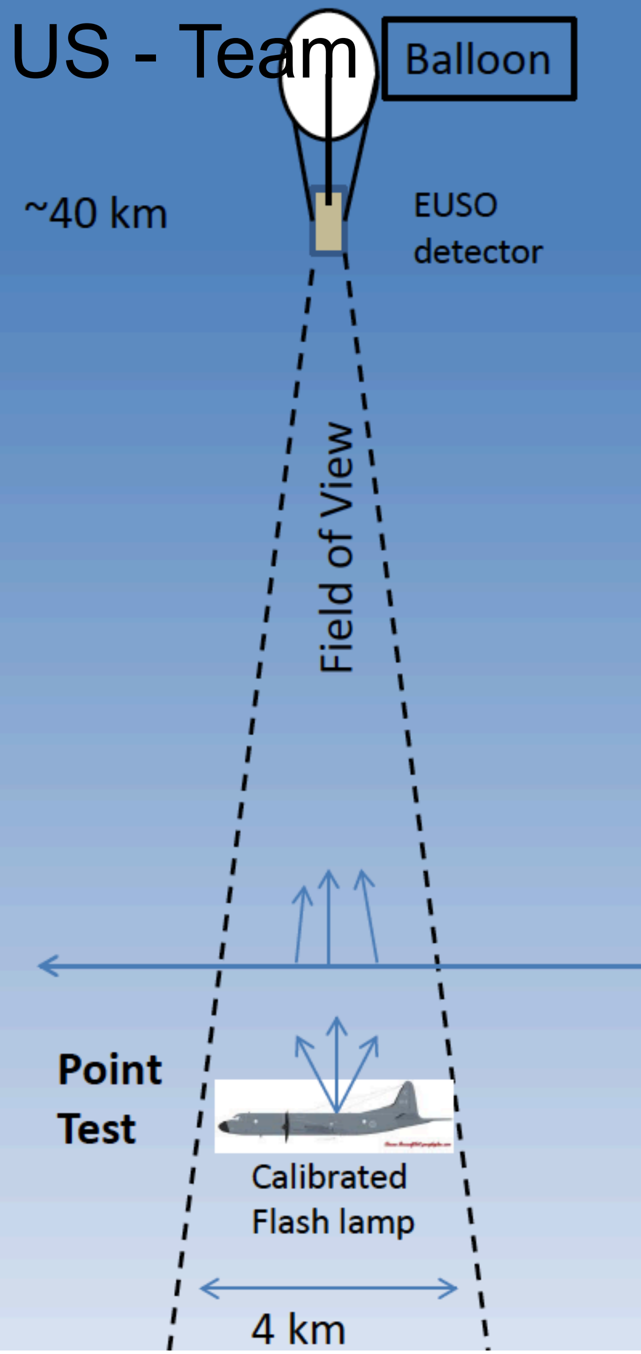
JEM-EUSO


Gtus 0-88
Hits on screen: 596
Y [mm]
Counts
64 pixel


$2x10^{20}eV$
65 deg
Y [mm]
X [mm]
Counts


Photons vs GTU
N_{ph}
Num. of Photons
On Pupil:8617
On FS:4819
Detected:1134
GTU number

US - Team



Testing EUSO-Balloon

Fly one aircraft equipped with
two types of calibrated pulsed UV light sources.

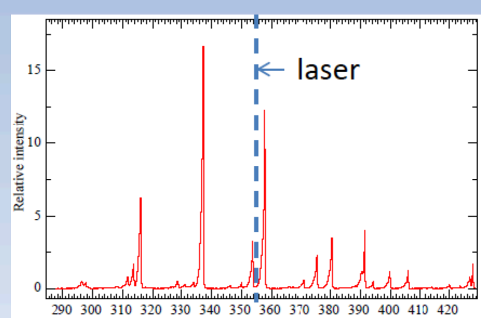
Point Test: Fly airplane in field of view and fire **flash lamp**. Light travels directly from lamp to detector

Track Test: Fly airplane outside field of view and shoot a UV pulsed **laser** across field of view. Light scatters out of the beam to the detector.
(5 mJ Laser ~100 EeV Cosmic Ray)

Fly aircraft at altitudes between 1-5 km.

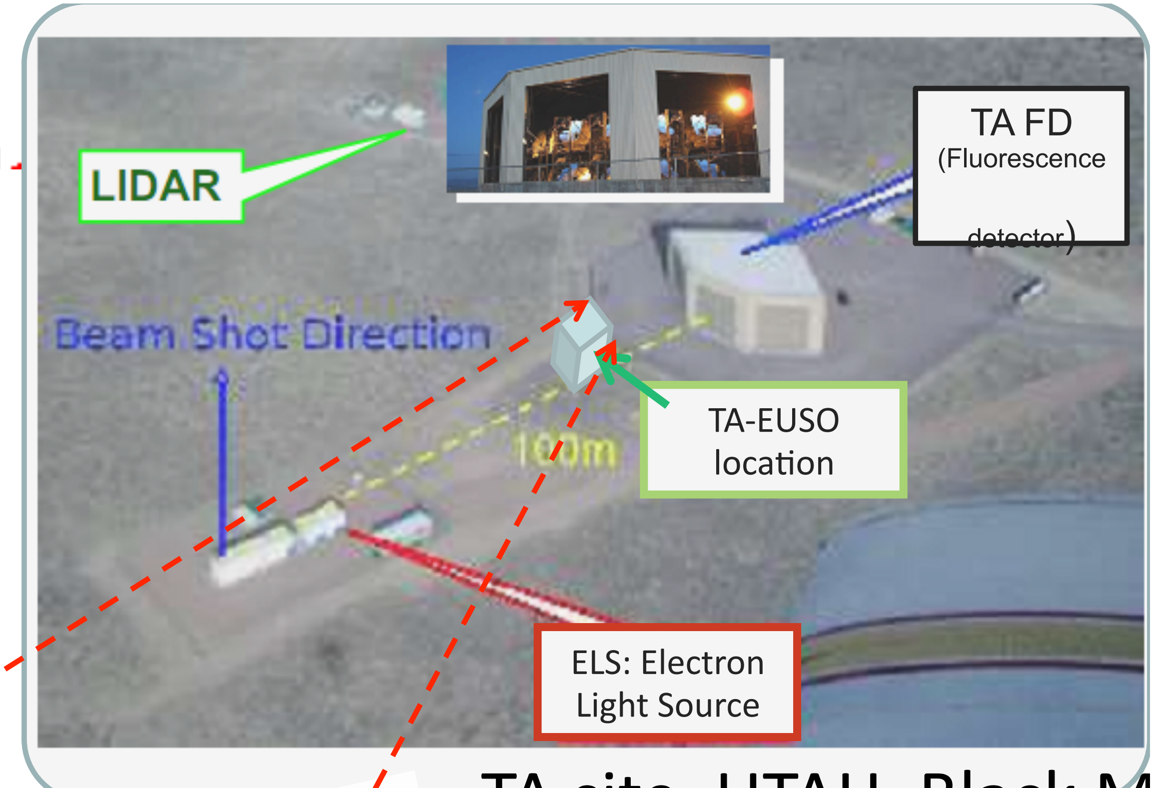
Calibrated UV laser

Track Test

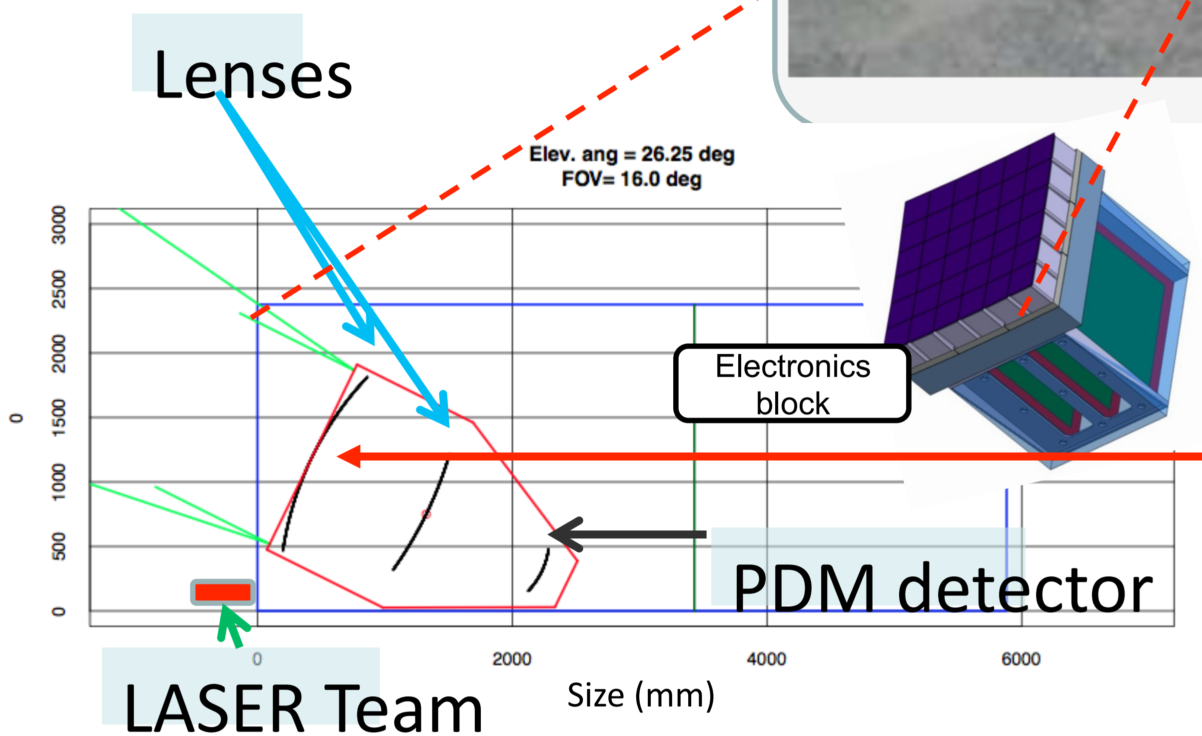


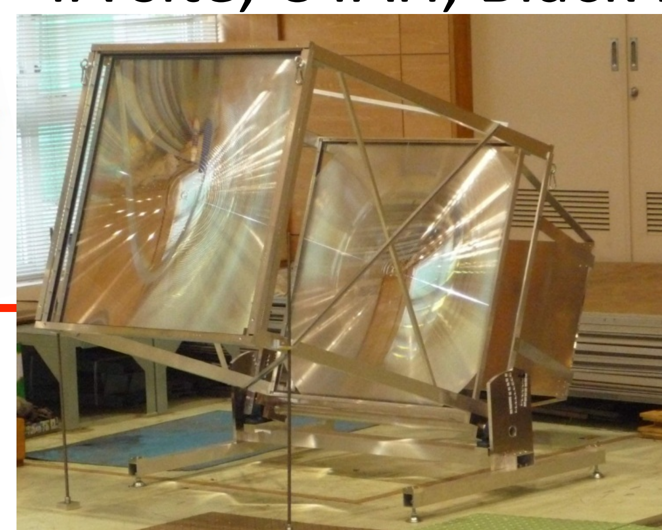
TA-EUSO

GROUND-EUSO
Detector at Telescope Array site



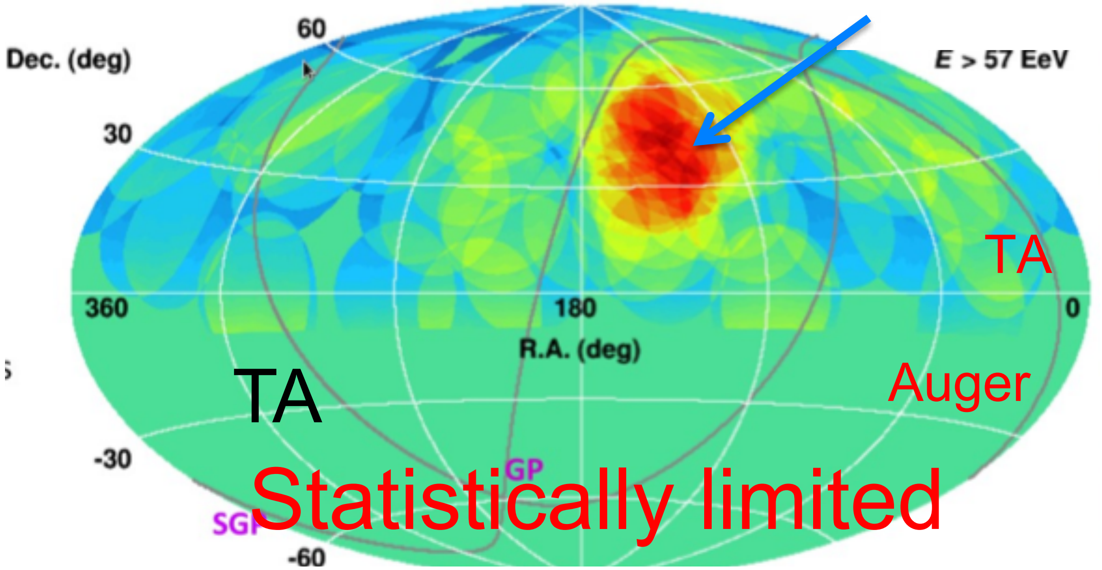
TA site, UTAH, Black M



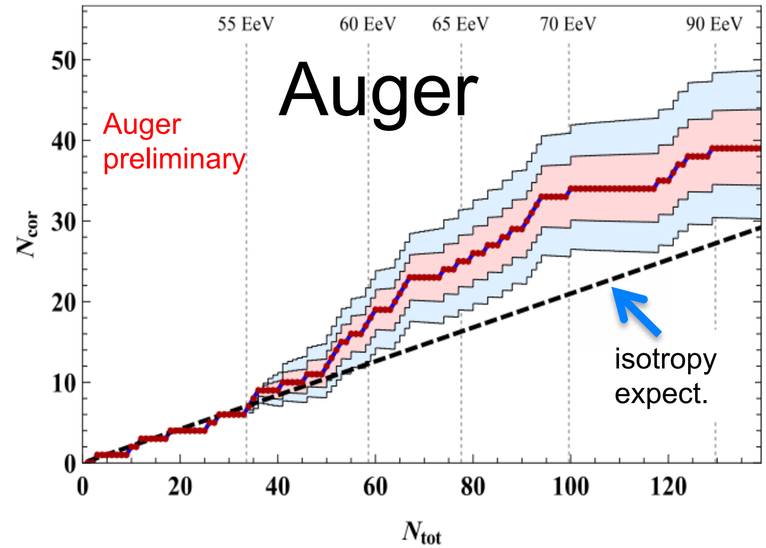


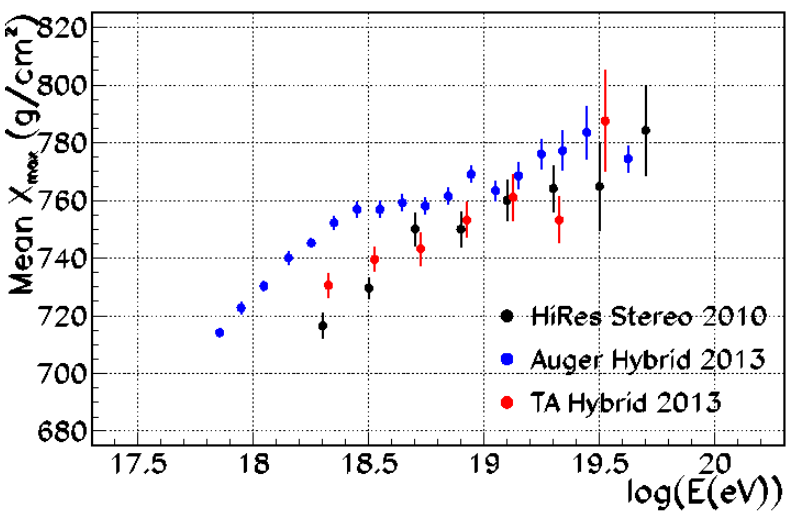
Origin of UHE Cosmic Rays?

$E > 5.7 \times 10^{19}$ eV 20^{o} smoothing   5 σ pretrial



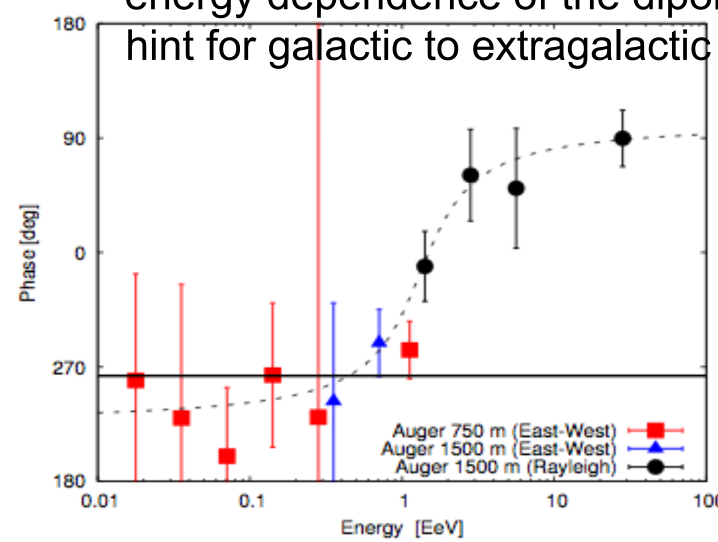
# of events correlating with AGN, ordered in energy (integral plot)





X_{max} measurements impact understanding of compostion (or interaction)

energy dependence of the dipole phase: hint for galactic to extragalactic transition



12/3/13

Telescope Array Expansion

NICHE

- Non-Imaging CHErenkov Array
- Going lower than TALE:
  - TA/TALE: $3\times10^{16} - 3\times10^{20}$ eV
  - NICHE: $10^{15} - 10^{18}$ eV
- 85 Cherenkov light collectors
- 3" PMT with Winston cone
- Observe shower from first interaction
- Calibrate NICHE Cherenkov X_{max} with TALE fluorescence X_{max}