Particle Astrophysics with IceCube and HAWC

PENNSTATE

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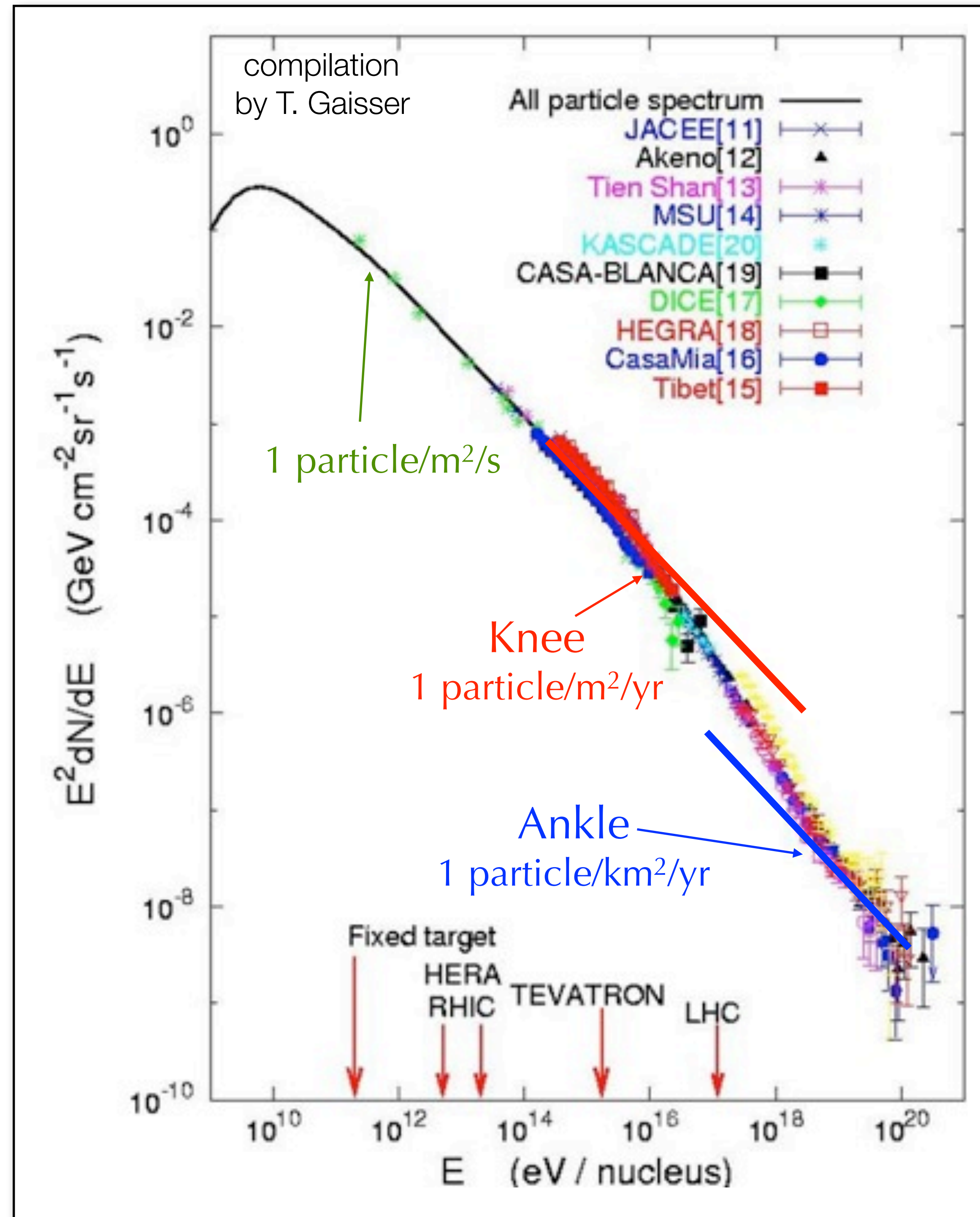
Physics Department Colloquium
Pennsylvania State University
November 3, 2011

Cosmic Rays and Particle Astrophysics

- Radiation of cosmic origin first established in 1912
  - Hess carries electroscopes to 5000 m altitude (!) in a balloon
- Where do they come from?
  - Charged particles, so they don't point back to their sources
  - Clues from spectrum, composition
  - How are they accelerated?
  - Can we learn new physics by understanding their sources?
- What can we learn about the fundamental properties of the particles themselves?



Outline

- Particle Astrophysics 101
- Probing Astrophysical Sources: Gamma Ray Bursts
  - Recent Observations
  - Prospects for HAWC
- Studying Astrophysical Particles: Atmospheric Neutrinos
  - Observation of Electron Neutrinos with IceCube DeepCore
  - Prospects for Measuring Tau Neutrino Appearance
  - Future Prospects: PINGU and MICA

The IceCube Collaboration

University of Alabama
University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
Bartol Research Inst., University of Delaware
Georgia Institute of Technology
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Ohio State University
Pennsylvania State University
Southern University and A&M College
State University of New York at Stony Brook
University of Wisconsin, Madison
University of Wisconsin, River Falls

RWTH Aachen
Ruhr-Universität Bochum
Universität Bonn
DESY, Zeuthen
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
BUGH Wuppertal

Stockholms Universitet
Uppsala Universitet

Vrije Universiteit Brussel
Université Libre de Bruxelles
Universiteit Gent
Université de Mons

University of Alberta

Chiba University

University of Canterbury

University of Adelaide

EPF Lausanne
Université de Genève

Oxford University

University of the West Indies, Barbados

The HAWC Collaboration

University of Maryland
Los Alamos National Laboratory
University of Alabama
University of California, Irvine
University of California, Santa Cruz
Colorado State University
George Mason University
Georgia Institute of Technology
Goddard Space Flight Center
Harvey Mudd College
Michigan State University
Michigan Technological University
University of New Hampshire
University of New Mexico
Pennsylvania State University
University of Utah
University of Wisconsin, Madison

Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
Universidad Autónoma de Chiapas
Universidad de Guadalajara
Universidad de Guanajuato
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y Estúdios Avanzados (CINVESTAV)
Benemérita Universidad de Puebla

Penn State Folks

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Graduate Students

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Undergraduates

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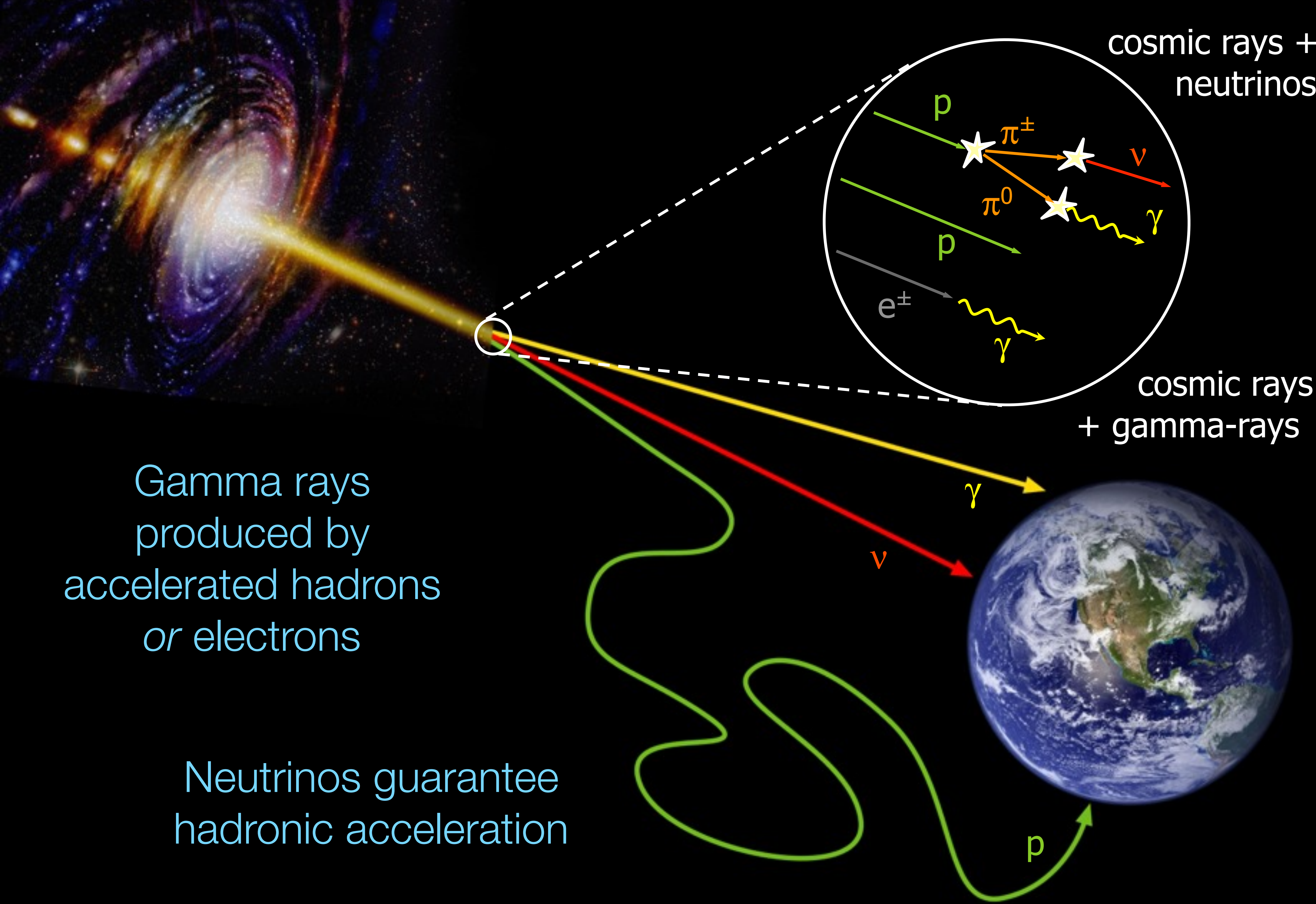
Multimessenger Astrophysics

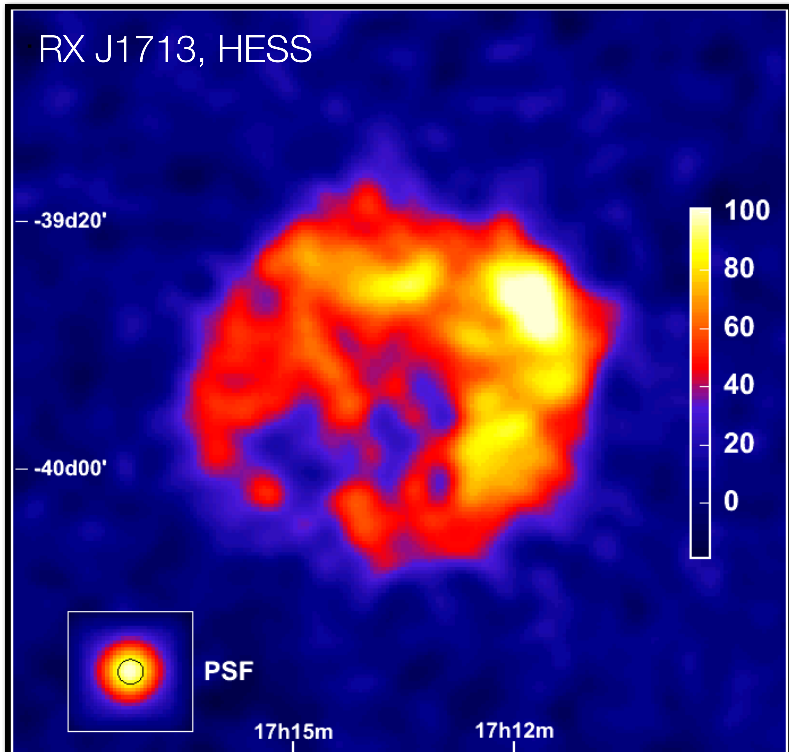


Gamma rays produced by accelerated hadrons *or* electrons

Neutrinos guarantee hadronic acceleration

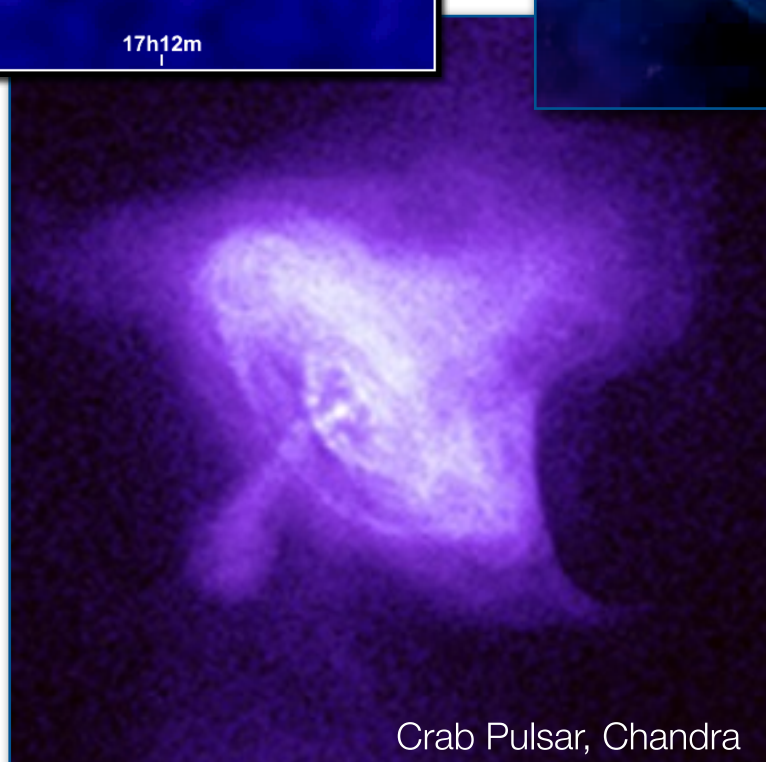
Astrophysical Accelerators

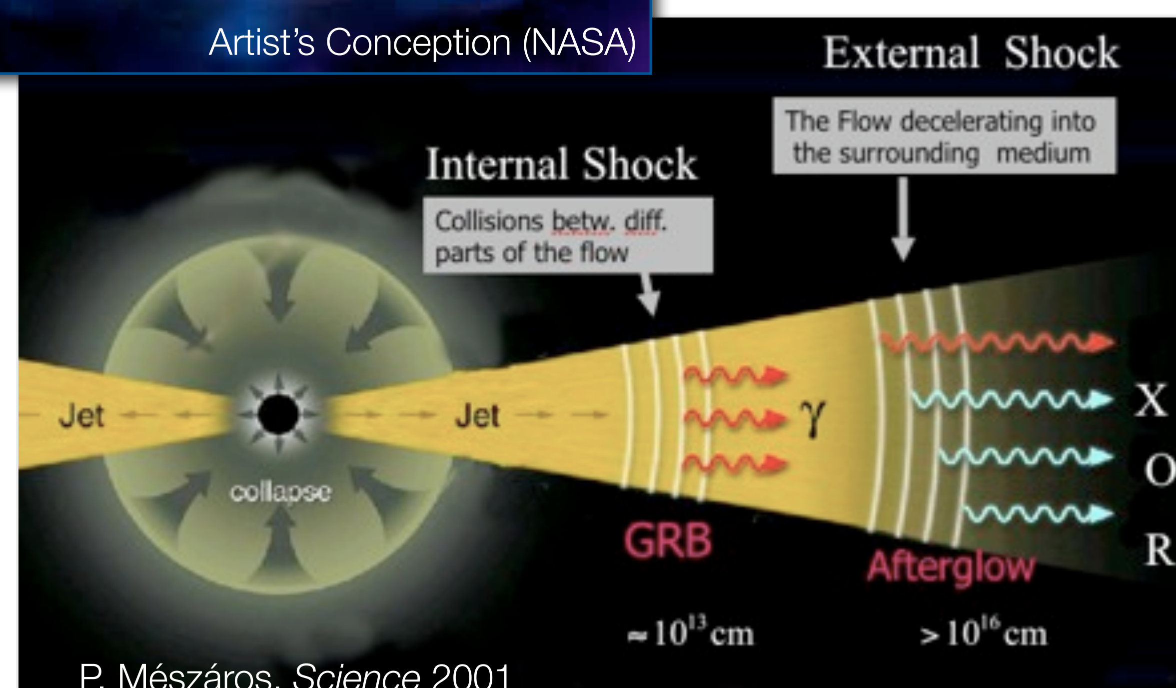
AGN



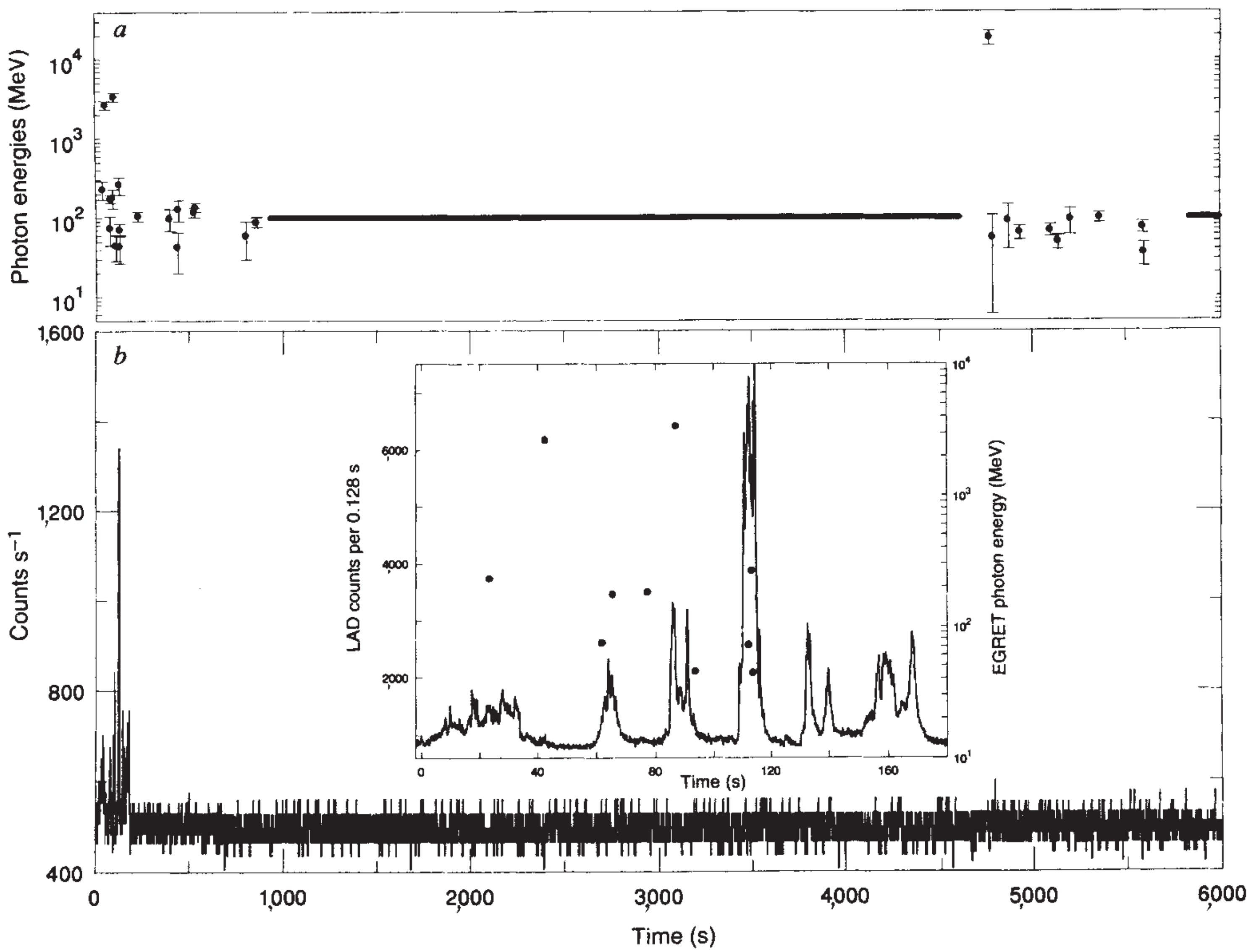
GRBs

SNRs & PWN

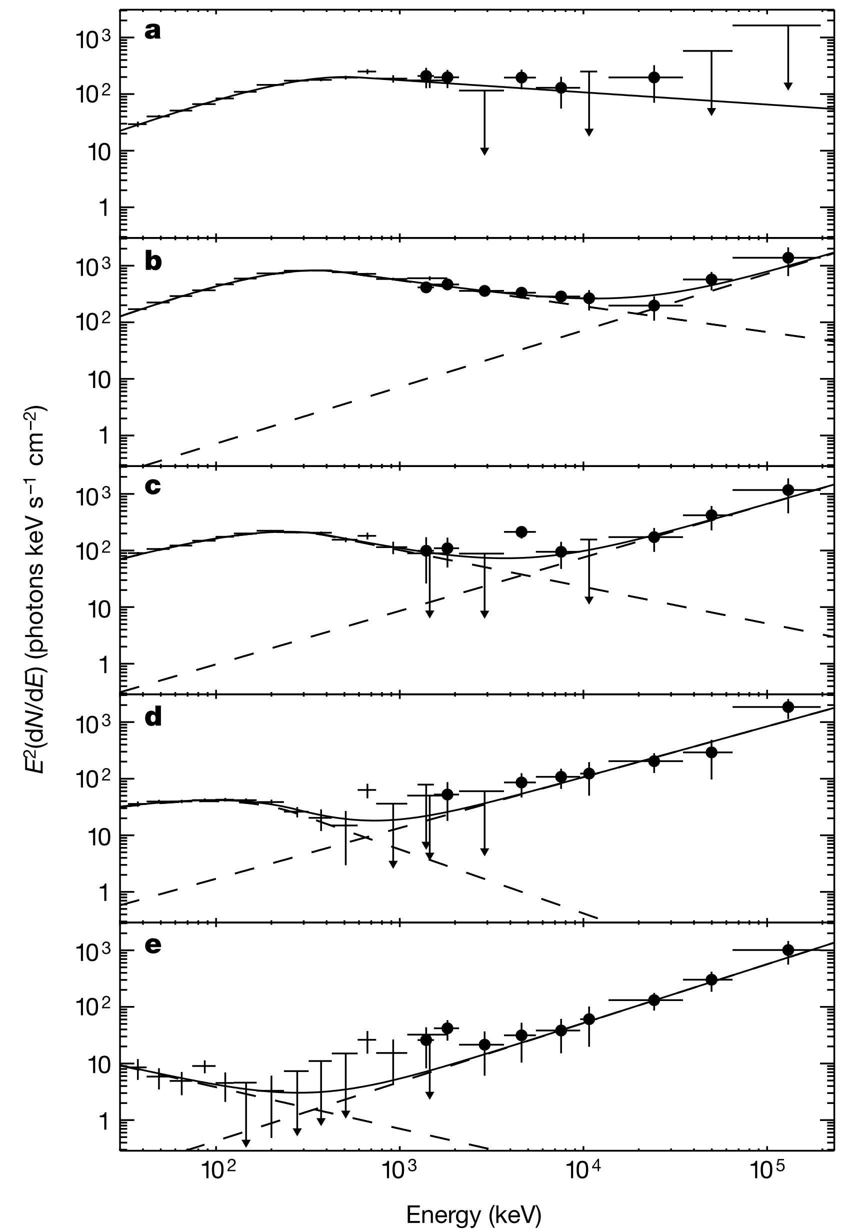




A Slow, High Energy Emission Component?



EGRET: Hurley et al., Nature 1994



EGRET: González et al., Nature 2003

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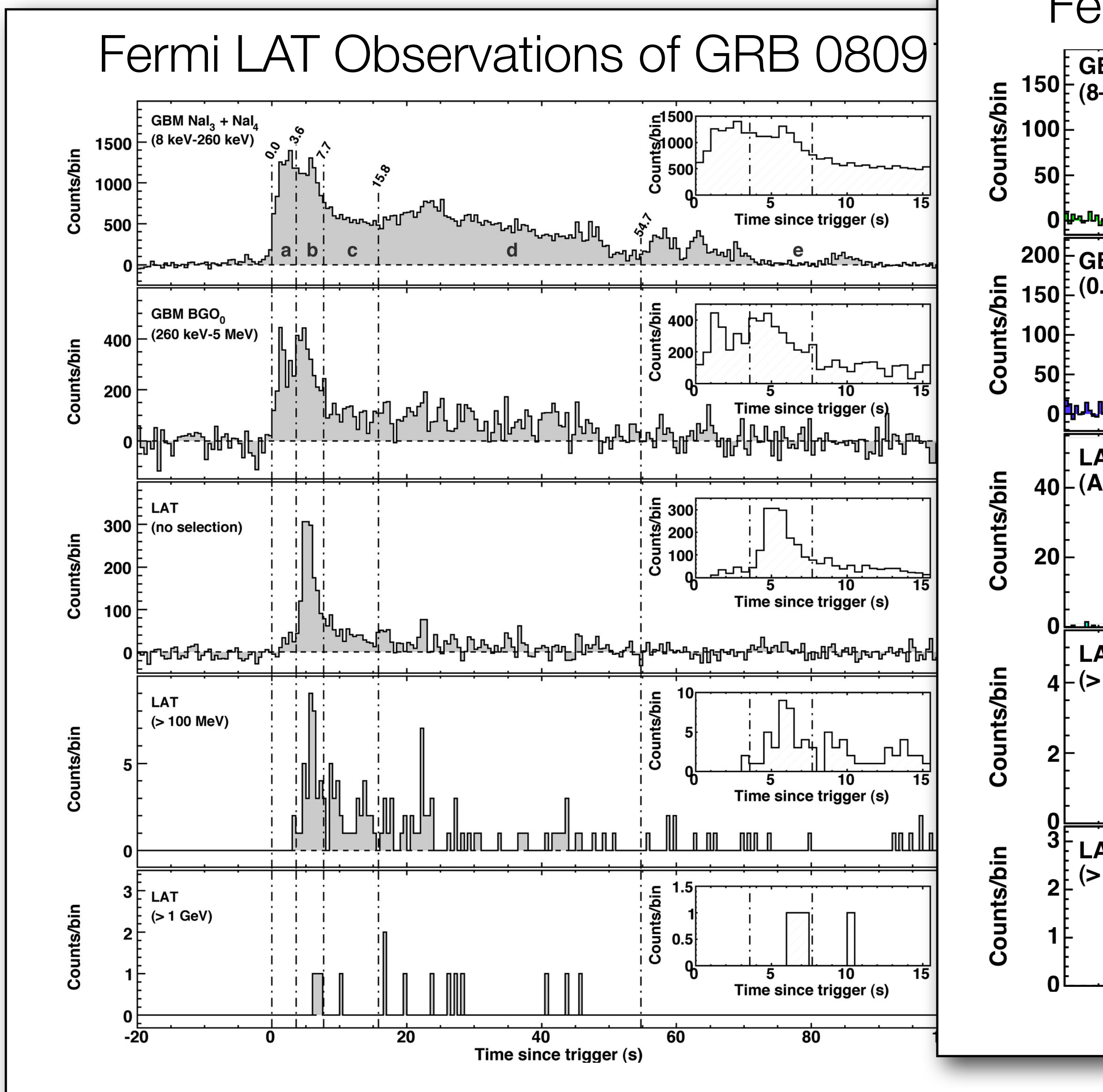

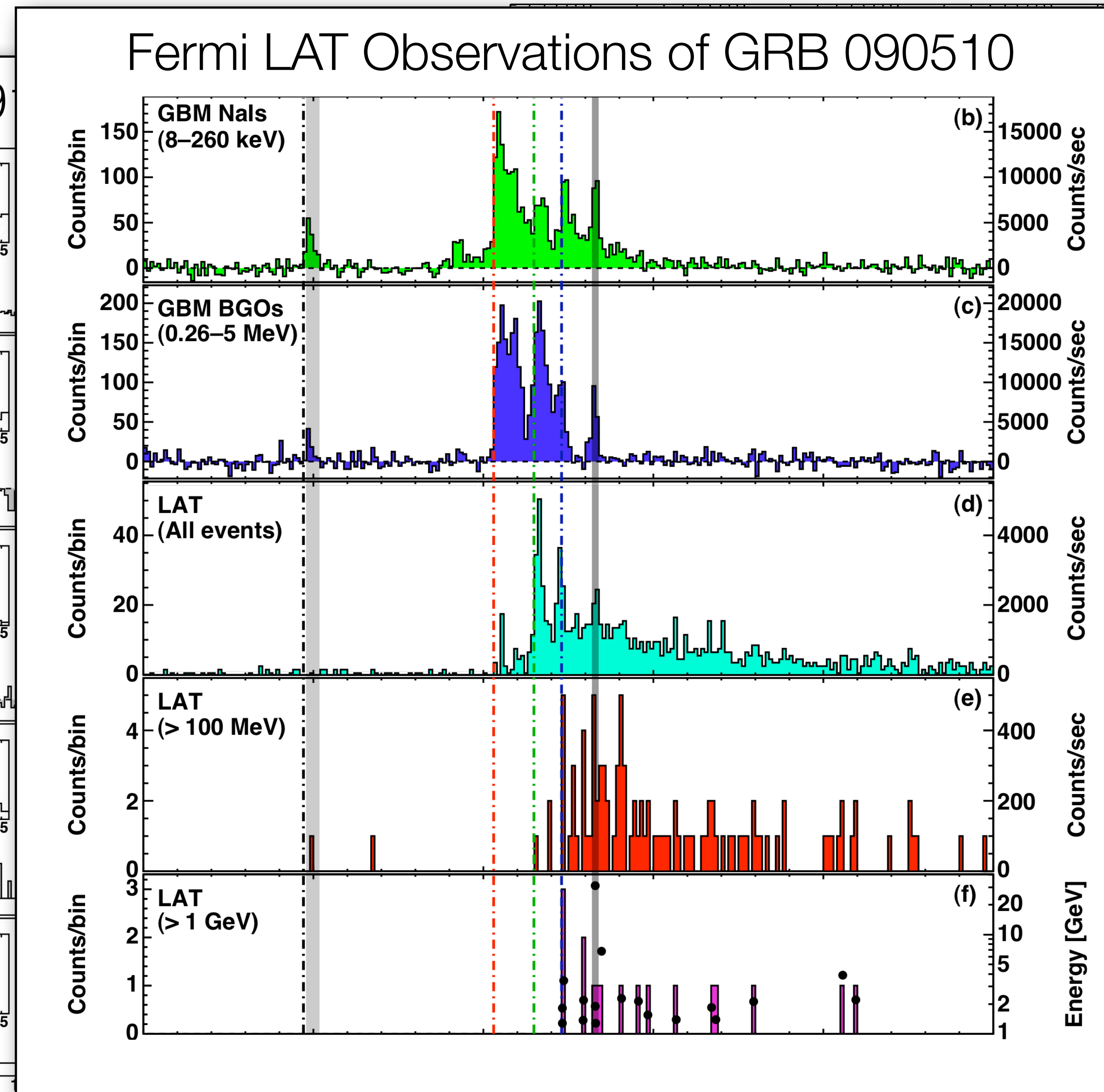

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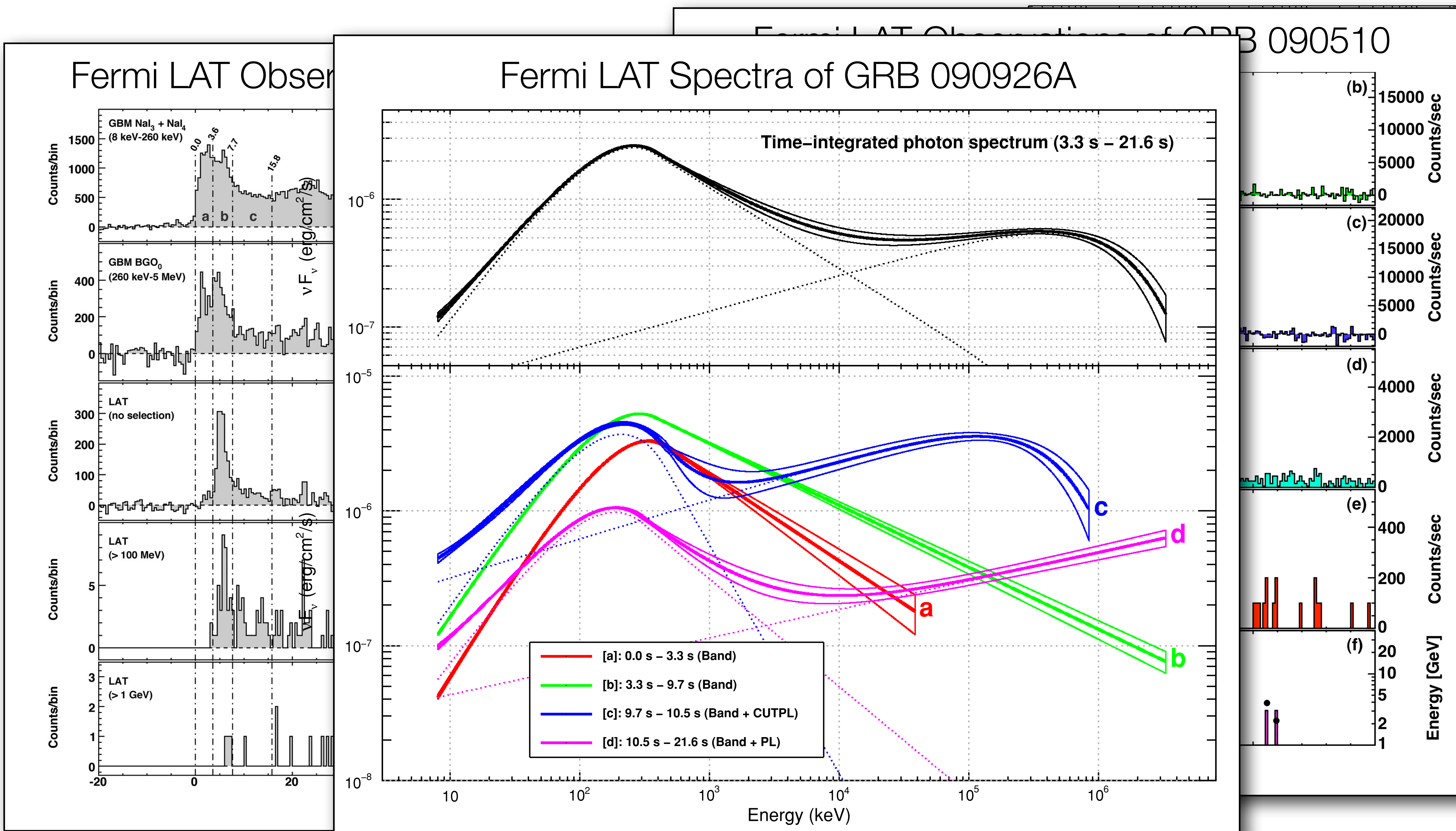

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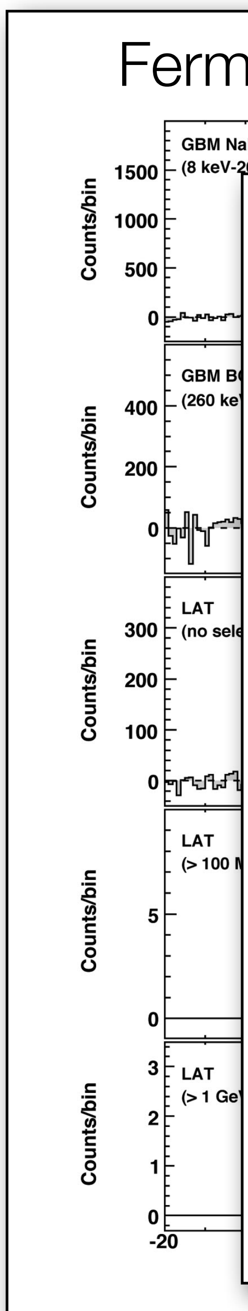
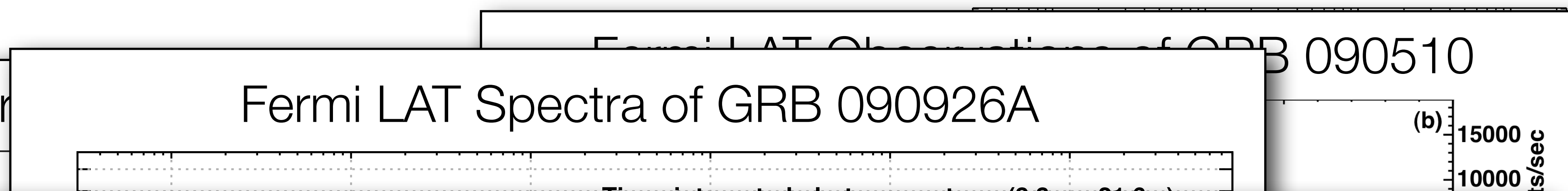
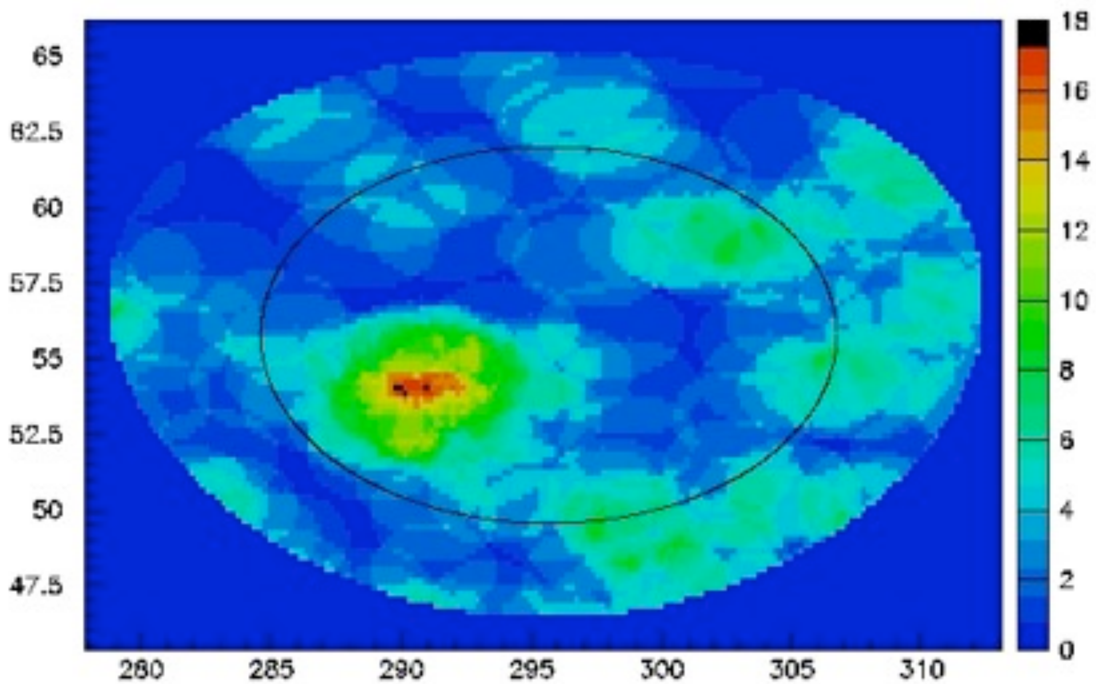
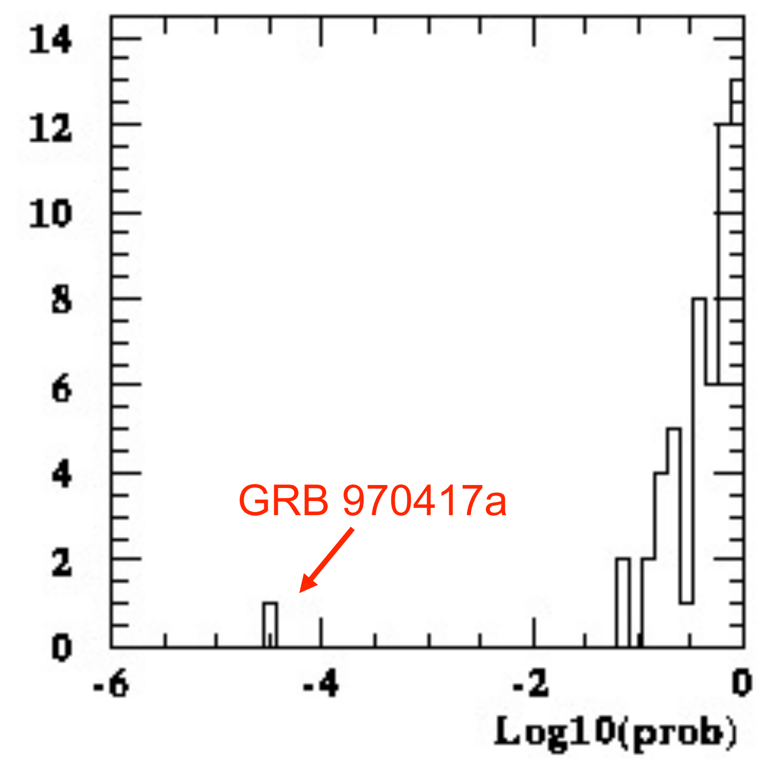


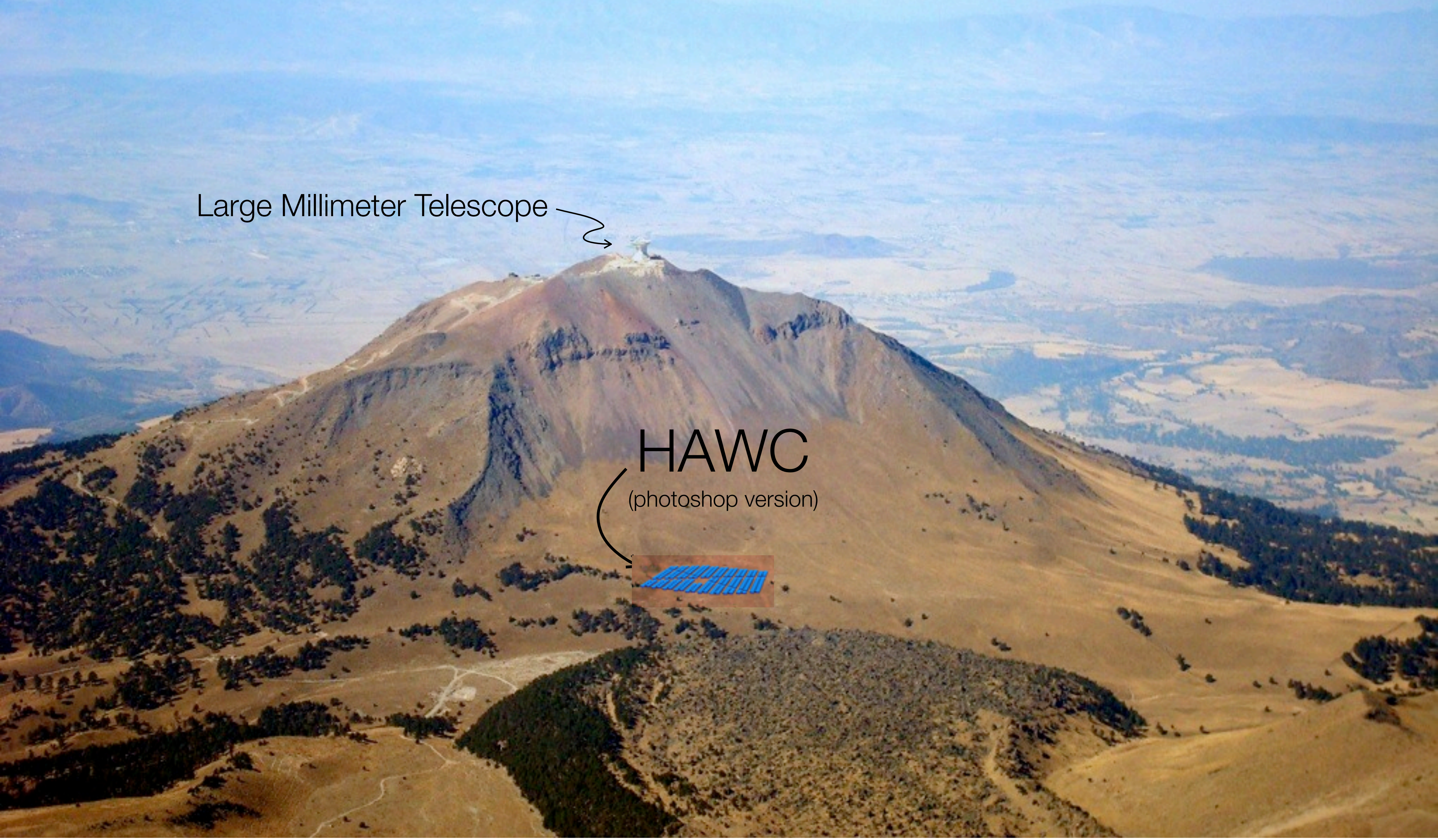






One of 54 GRBs observed by Milagrito
18 events seen on a background of 3.3
chance probability (post-trials) of 1.7×10^{-3} (2.9σ)
if real, TeV fluence > 10x keV fluence

Milagro: Atkins et al., 2000

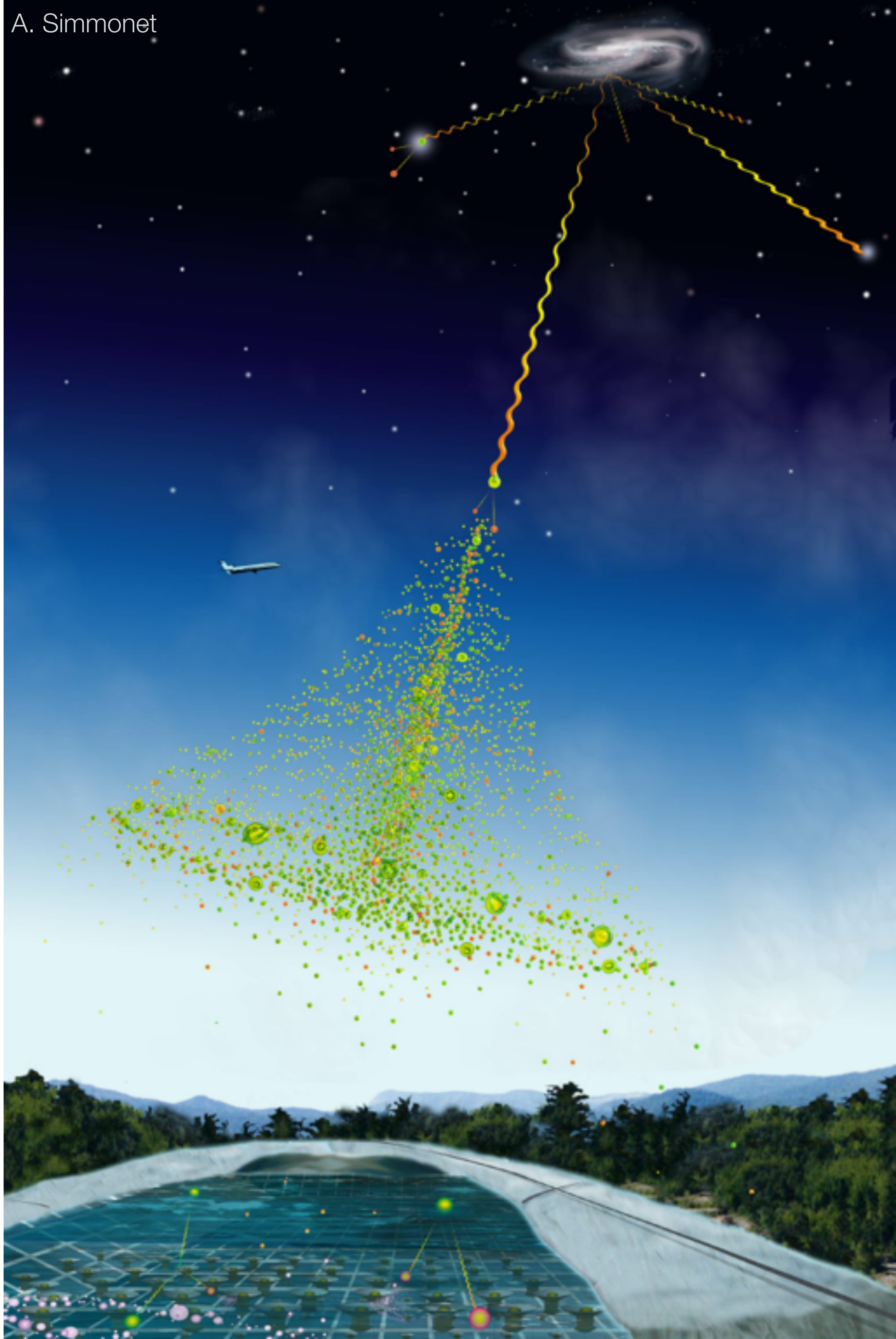


HAWC

Pico de Orizaba, altitude 4100 m, latitude 18º 59’ N
Two hours drive from Puebla, four from Mexico City
Site of Large Millimeter Telescope (existing infrastructure)

The HAWC Gamma Ray Observatory

- Gamma ray interacts in the atmosphere, forms a particle cascade
    - Particles produce Cherenkov light in water at ground level
- Reconstruct direction from timing of PMT hits across the detector
- Views the entire overhead sky, day and night, in all weather
    - Field of view ~2 sr, typical duty factor >95%
- Most triggers come from cosmic rays, gamma rays a small minority

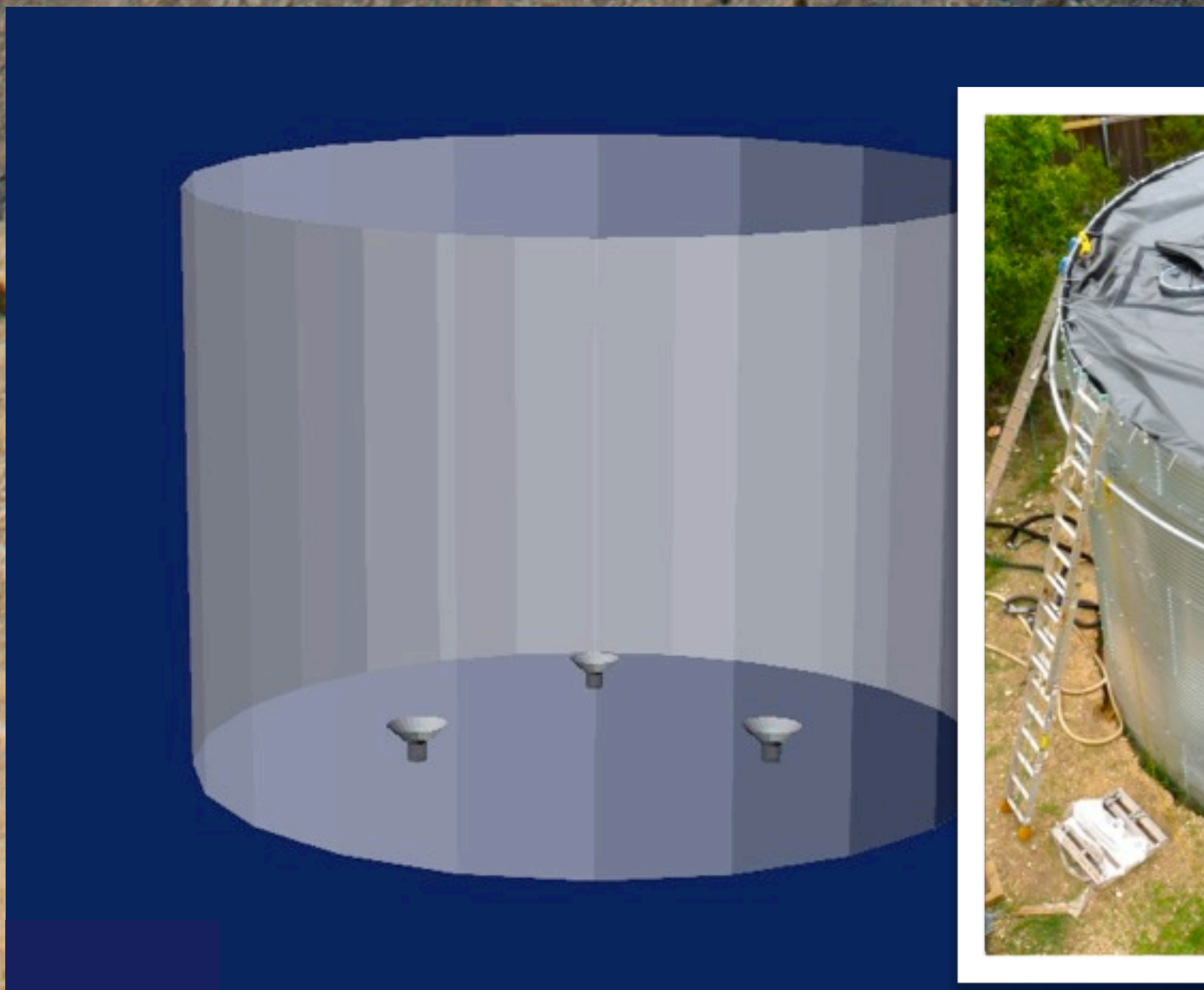


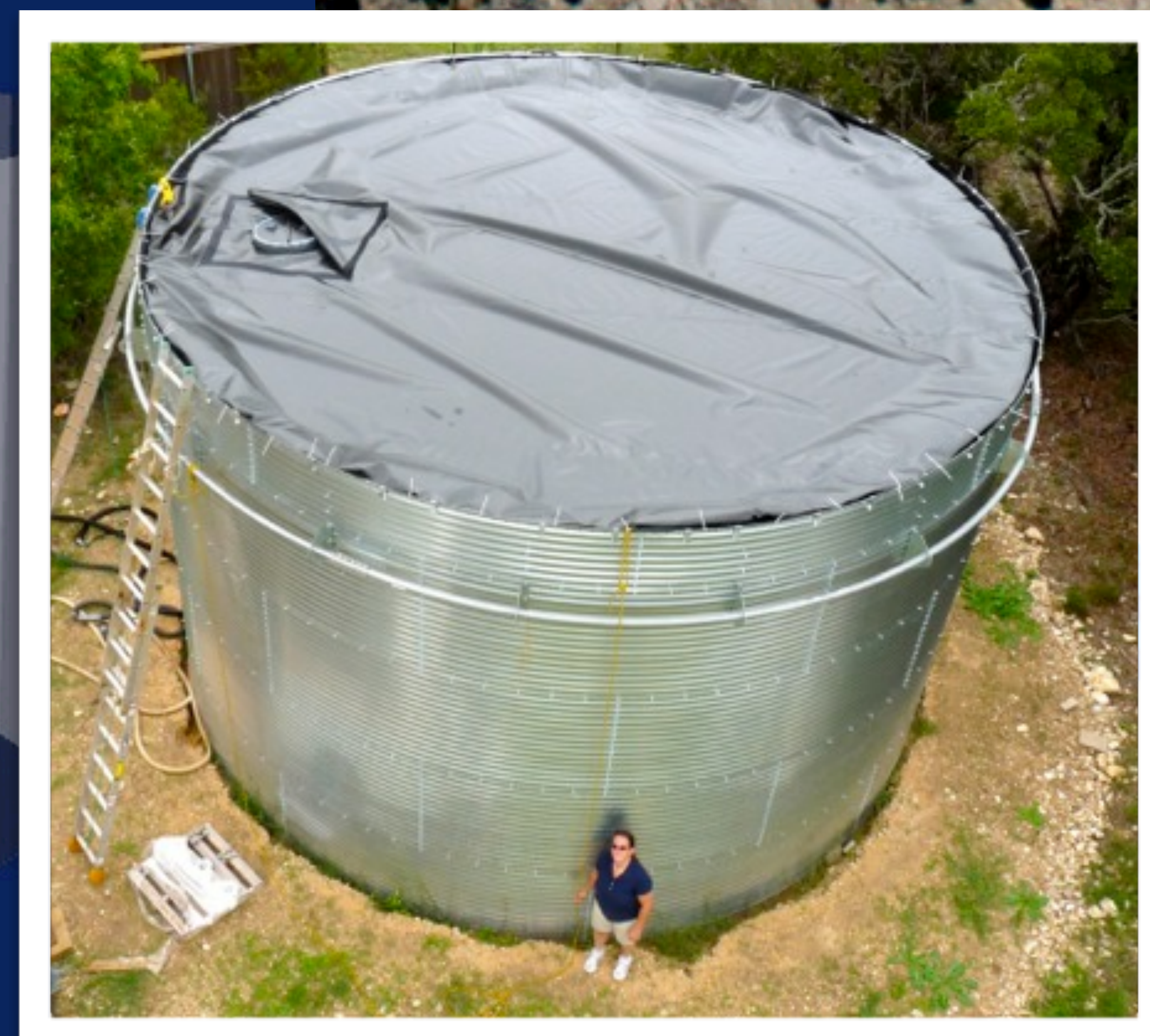

300 Water Cherenkov Detectors
7.2 m diameter x 4.3 m tall, containing 4 PMTs
20,000 m^2 area, 60% active Cherenkov volume
VAMOS
engineering array
Future site of HAWC

300 Water Cherenkov Detectors

7.2 m diameter x 4.3 m tall, containing 4 PMTs

20,000 m^2 area, 60% active Cherenkov volume





300 Water Cherenkov Detectors

7.2 m diameter x 4.3 m tall, containing 4 PMTs

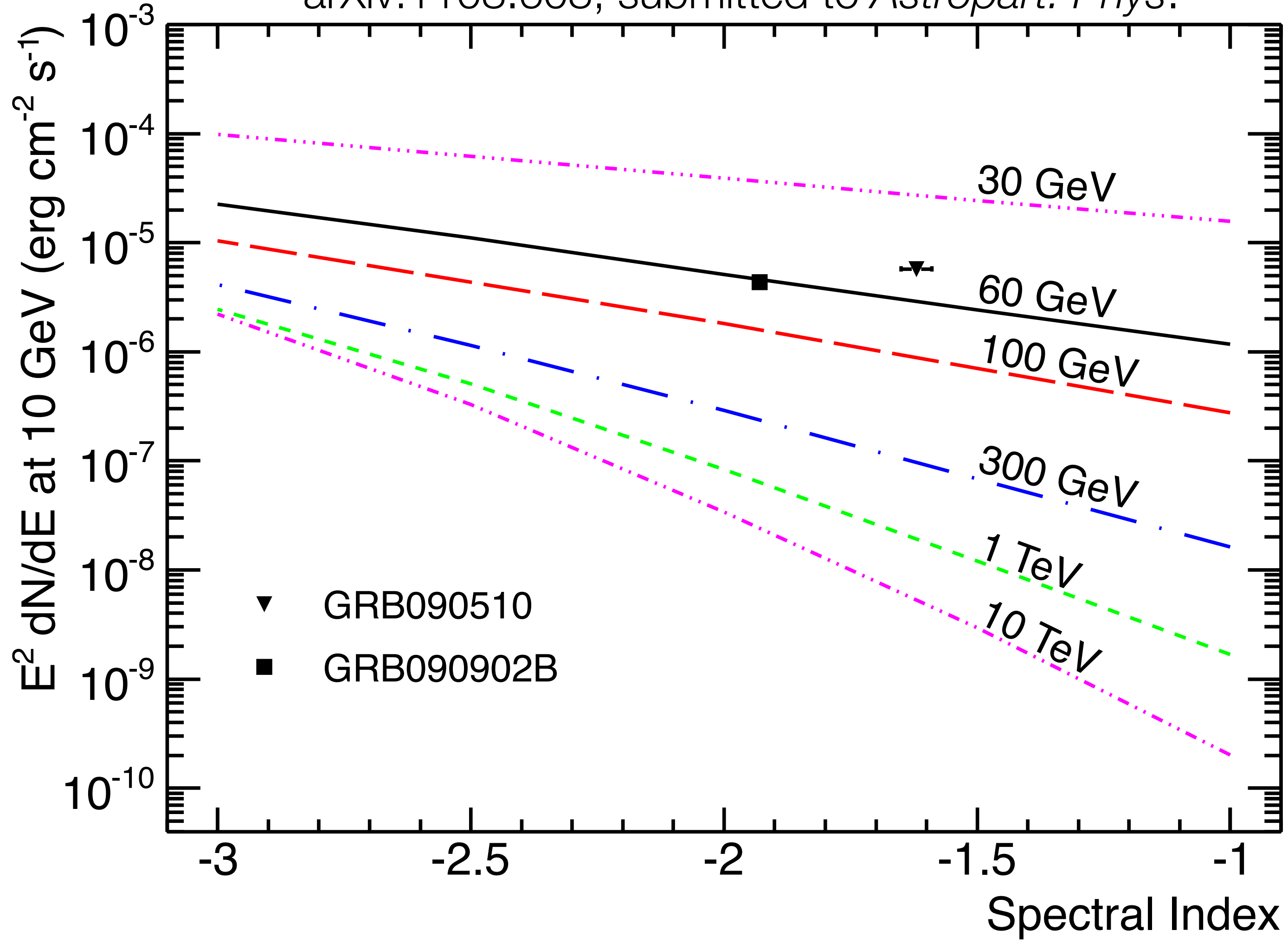
20,000 m^2 area, 60% active Cherenkov volume

HAWC Sensitivity to GRBs

D. Zaborov, K. Sparks

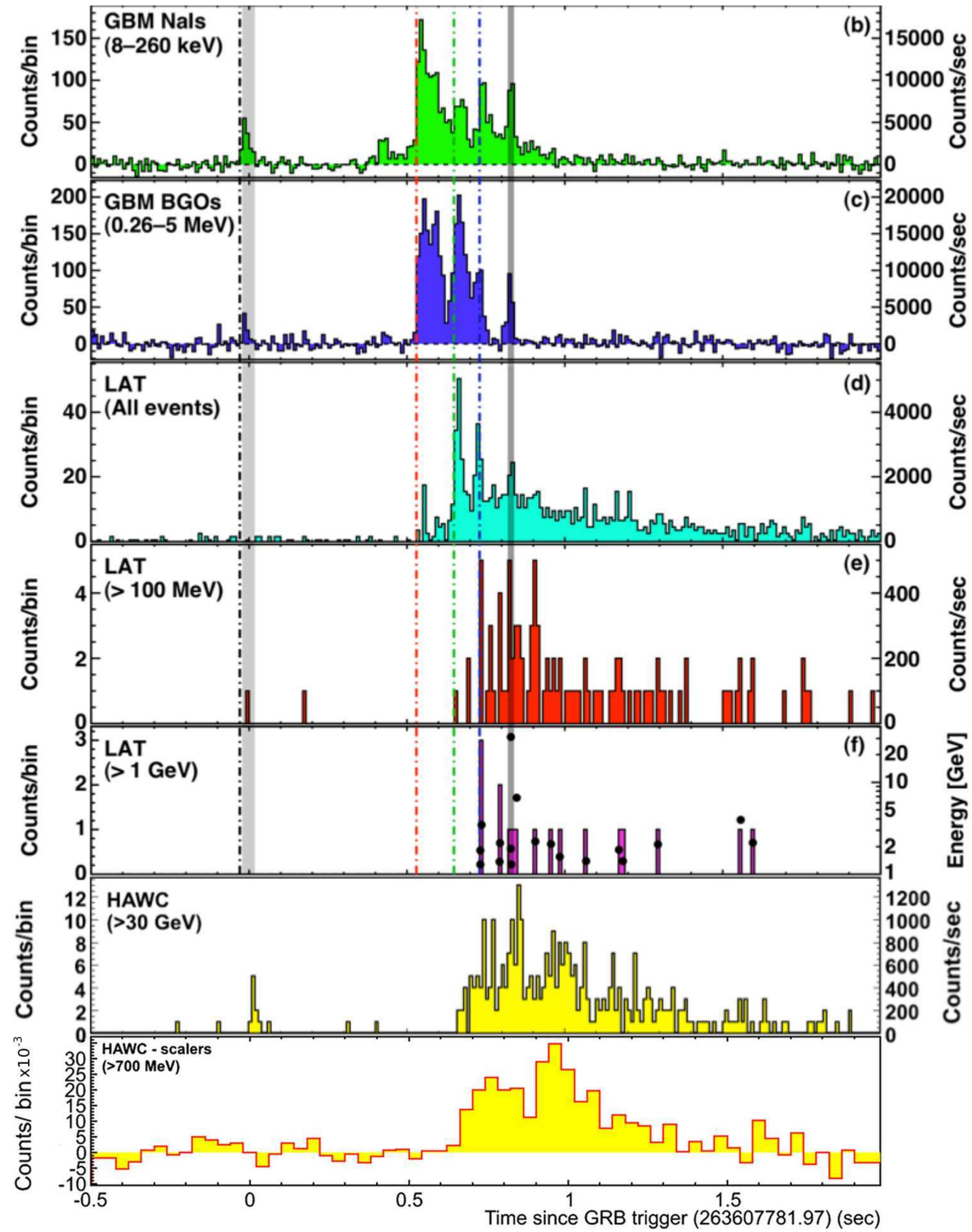
- HAWC will probe GRB emission above Fermi LAT energies
  - Effective area a rising function of gamma ray energy
  - Extragalactic background light absorbs high energy γ rays, depending on source redshift
  - Detection depends on GRB spectrum, cutoff energy (intrinsic or due to EBL)
- Brightest GRBs likely observable, based on high energy LAT photons
  - A 4th PMT added to each tank, will further increase sensitivity

A. U. Abeysekara et al. (HAWC Collaboration), arXiv:1108.603, submitted to *Astropart. Phys*.



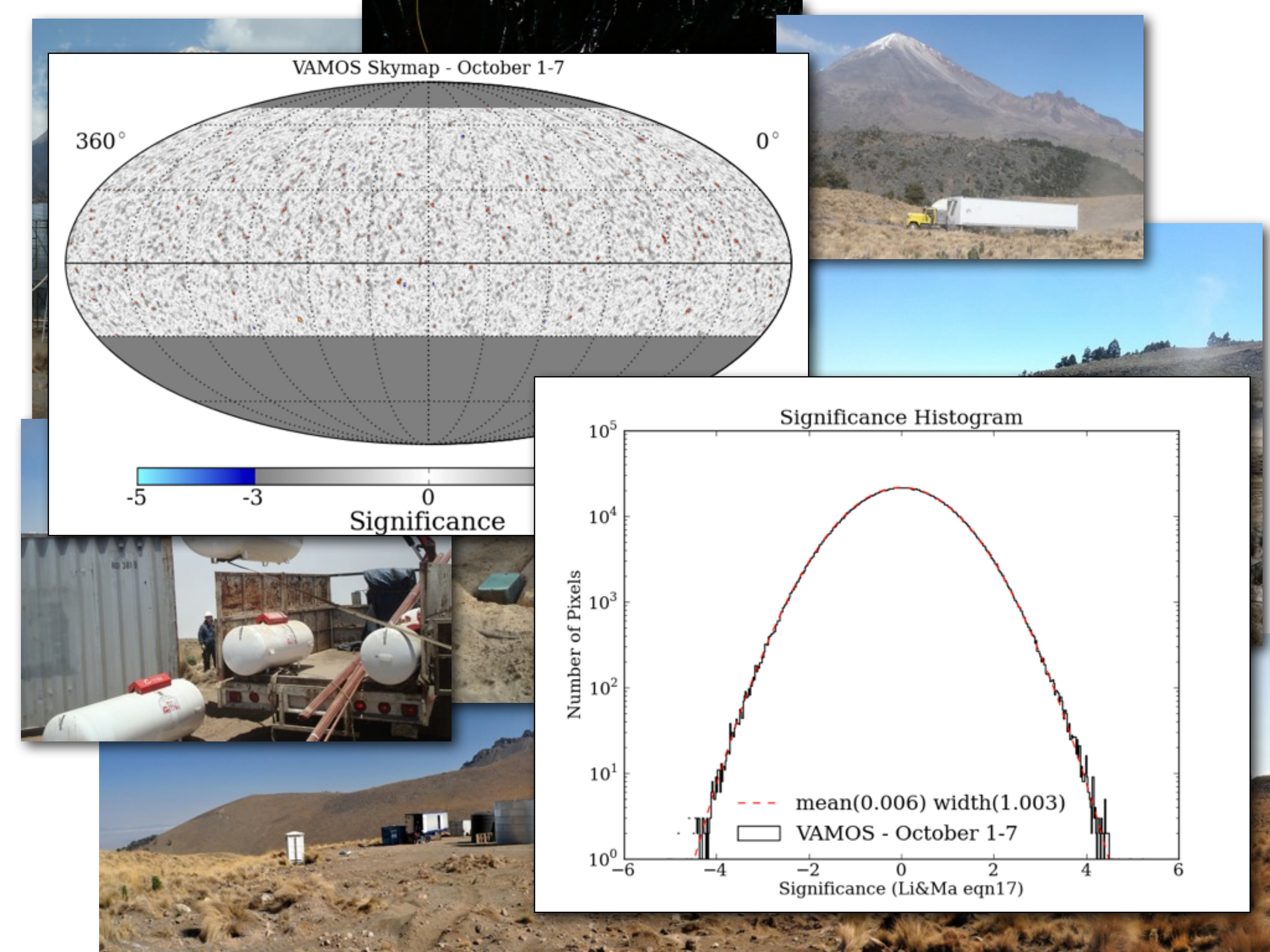
Simulated HAWC GRB Light Curve

- GRB 090510 (z = 0.9) observed by Fermi in GBM and LAT
- Simulated HAWC response assuming extension of spectrum with LAT index
  - EBL absorption and cosmic ray background included
- Expect ~200 events above 30 GeV if spectrum extends to EBL
- Around 10 events observed by HAWC even if cut off at energy of highest photon observed by Fermi

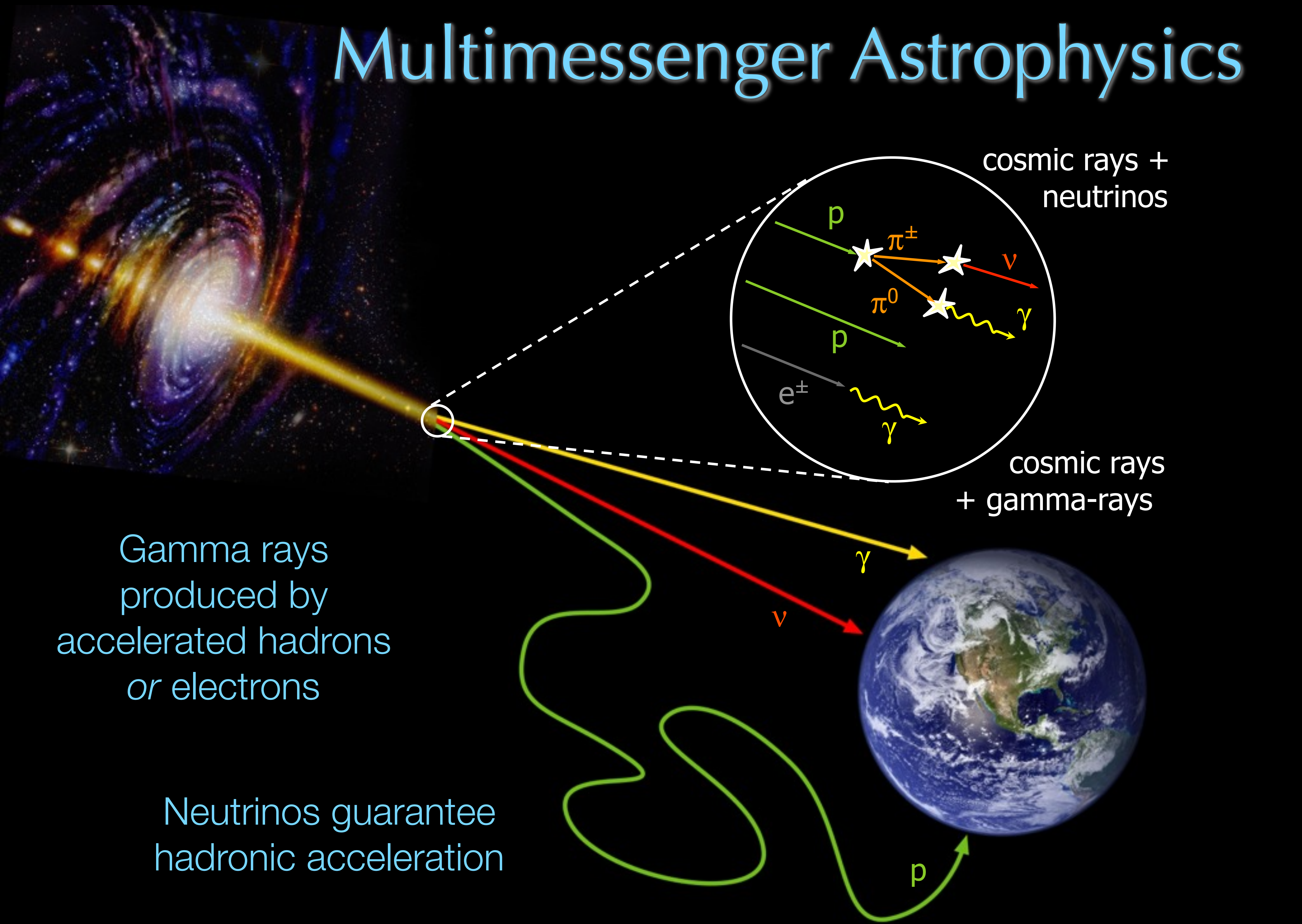


HAWC Construction Schedule

- Construction began February 2011
- Fall 2012: 30 Tanks
  - Sensitivity comparable to Milagro
- Summer 2013: 100 Tanks
  - Begin continuous operations in Fall 2013
- Fall 2014: 300 Tanks (construction complete)


VAMOS Skymap - October 1-7
360°
0°
-5
-3
0
Significance
Significance Histogram
Number of Pixels
10^0
10^1
10^2
10^3
10^4
10^5
−6
−4
−2
0
2
4
6
mean(0.006) width(1.003)
VAMOS - October 1-7
Significance (Li&Ma eqn17)

Multimessenger Astrophysics



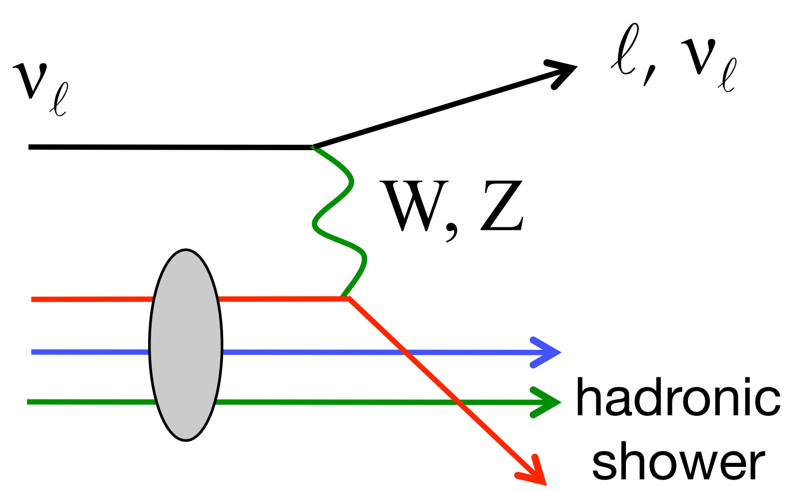
Gamma rays produced by accelerated hadrons *or* electrons

Neutrinos guarantee hadronic acceleration

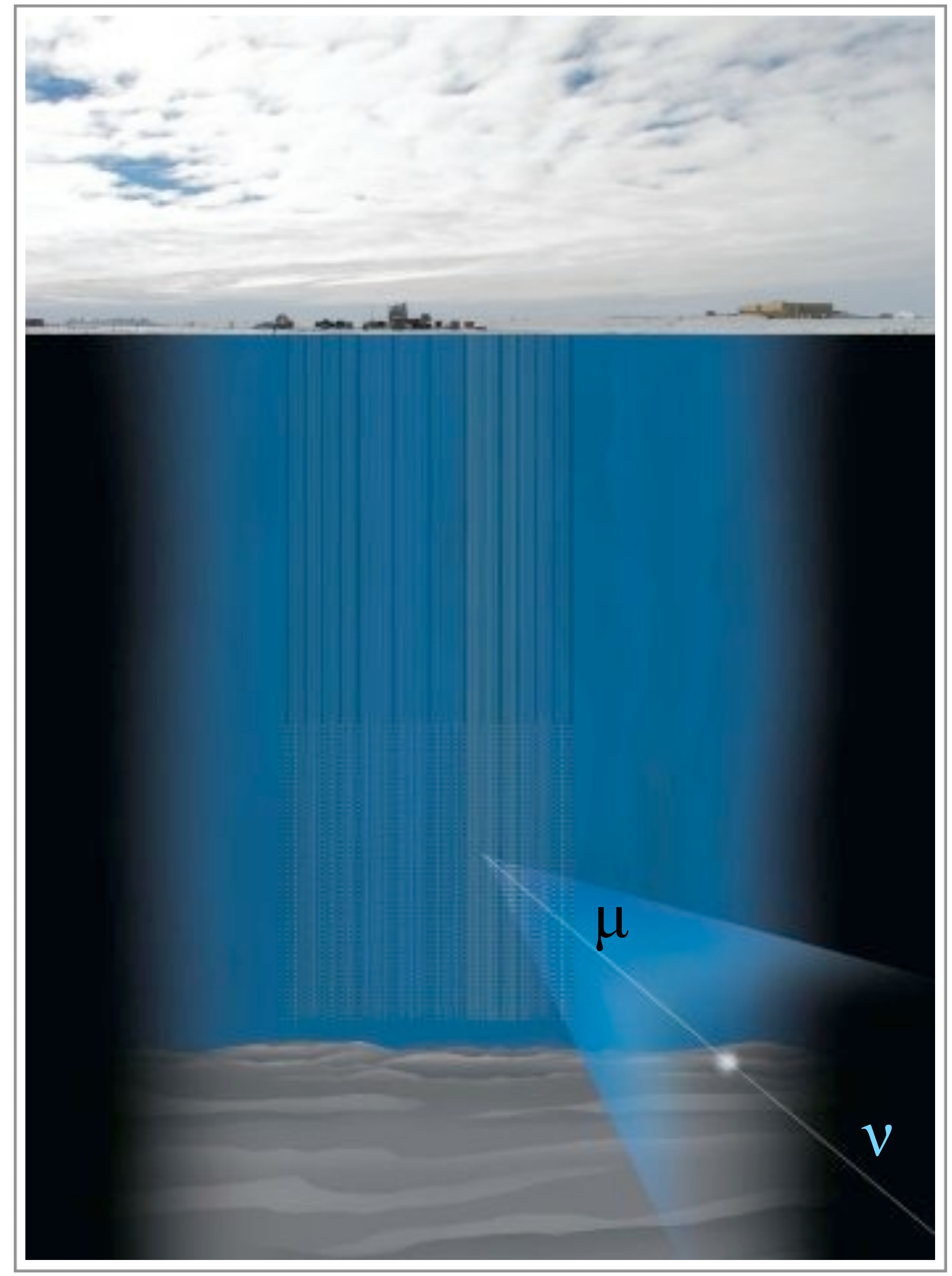
High Energy Neutrino Telescopes

- Need a big piece of transparent material (cubic kilometers)

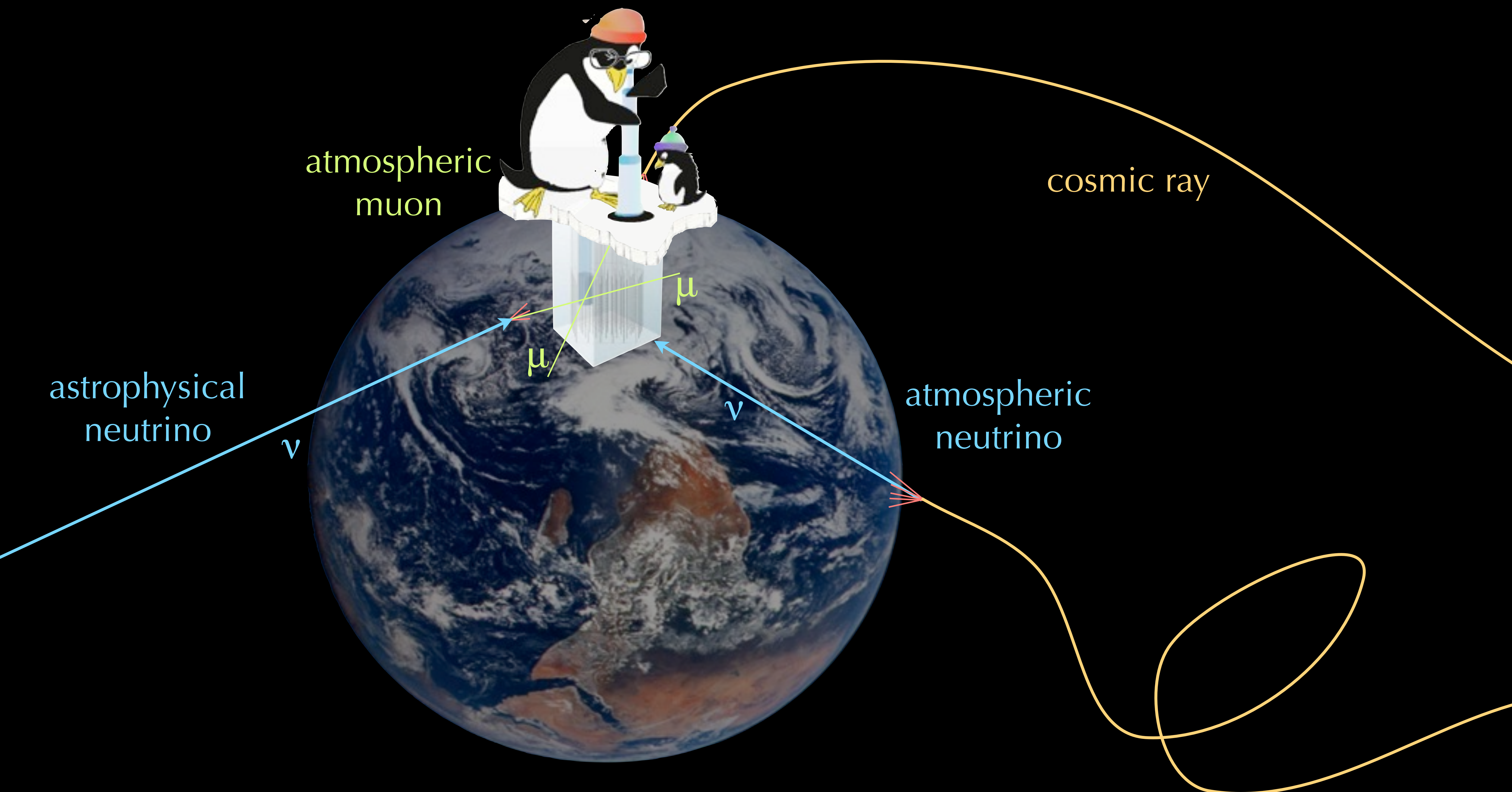
- Neutrinos interact in or near the detector



  - Cherenkov radiation detected by 3D array of optical sensors (OMs)
  - $\mathcal{O}$(km) muon tracks from ν_μ CC
  - $\mathcal{O}$(few m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC

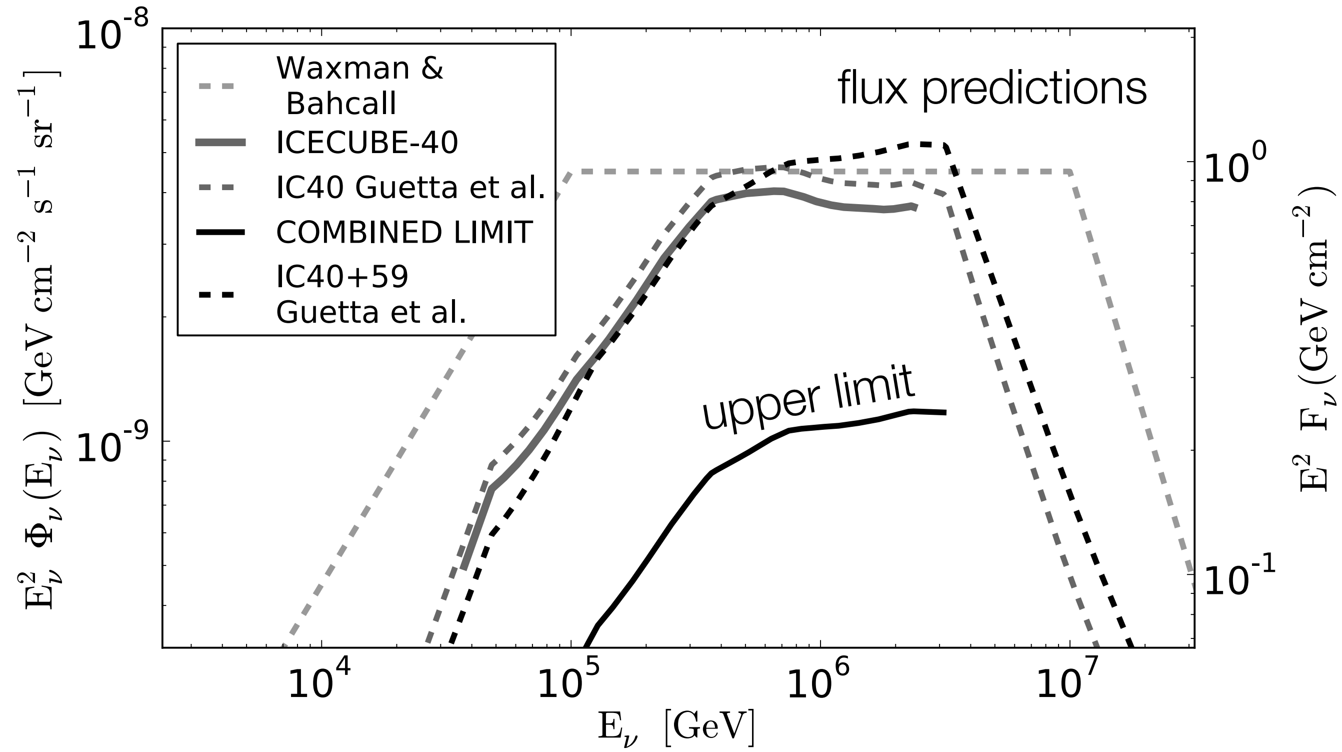


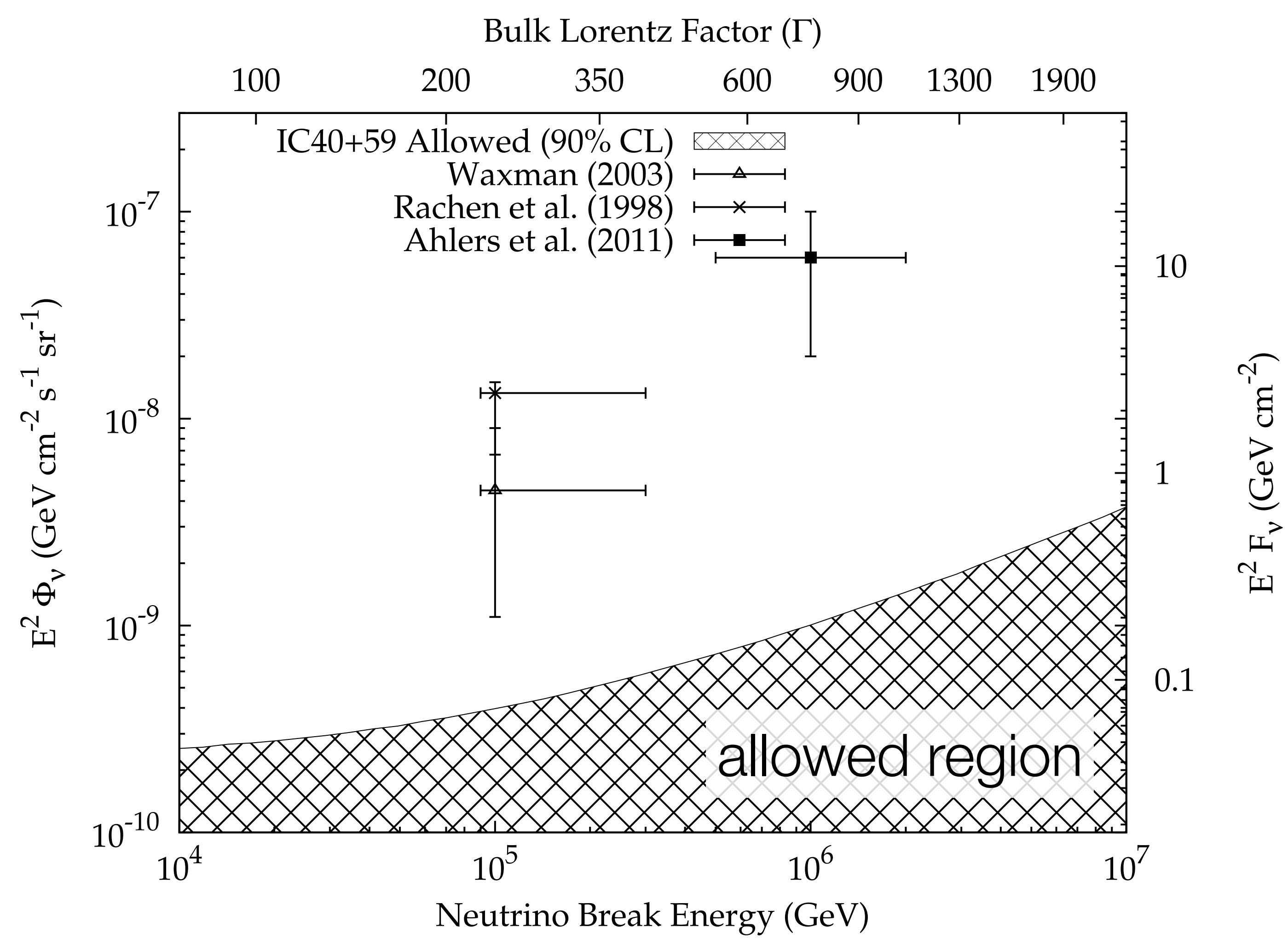
Neutrino Telescopes



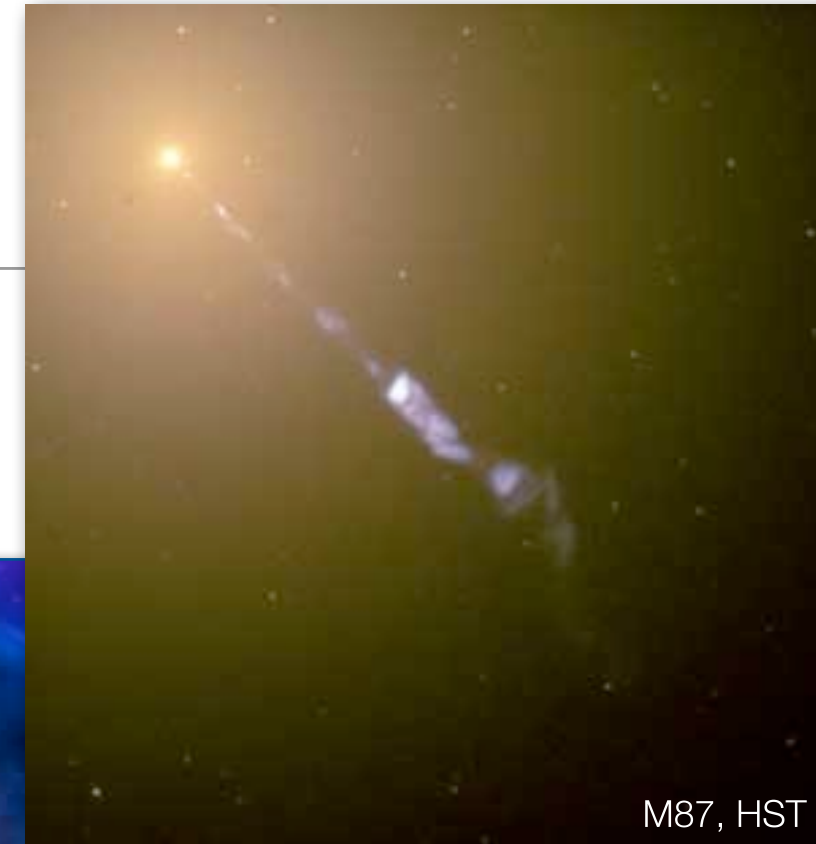
IceCube Search for Neutrinos from GRBs

- IceCube has searched for neutrinos in coincidence with 300 GRBs recorded 2008 – 2010
  - 40 and 59 string configurations
- No neutrinos observed in coincidence with these GRBs
  - Upper limits at approximately 20% the predicted flux, if GRBs are the (sole) sources of the observed UHE cosmic rays
- Somewhat dependent on modeling of GRBs, but limits are already constraining – and will improve over the next few years



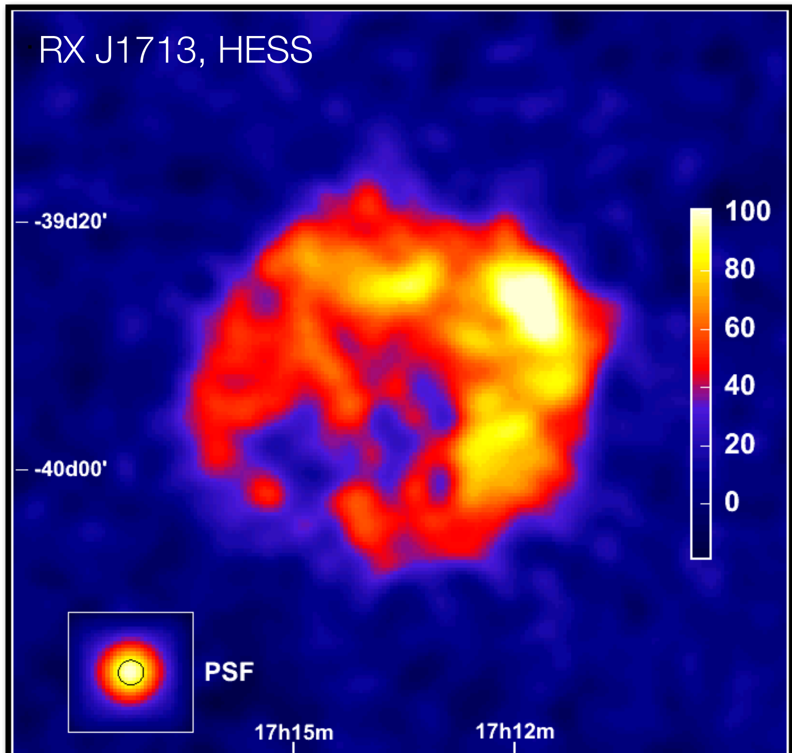


Astrophysical Accelerators



M87, HST

AGN

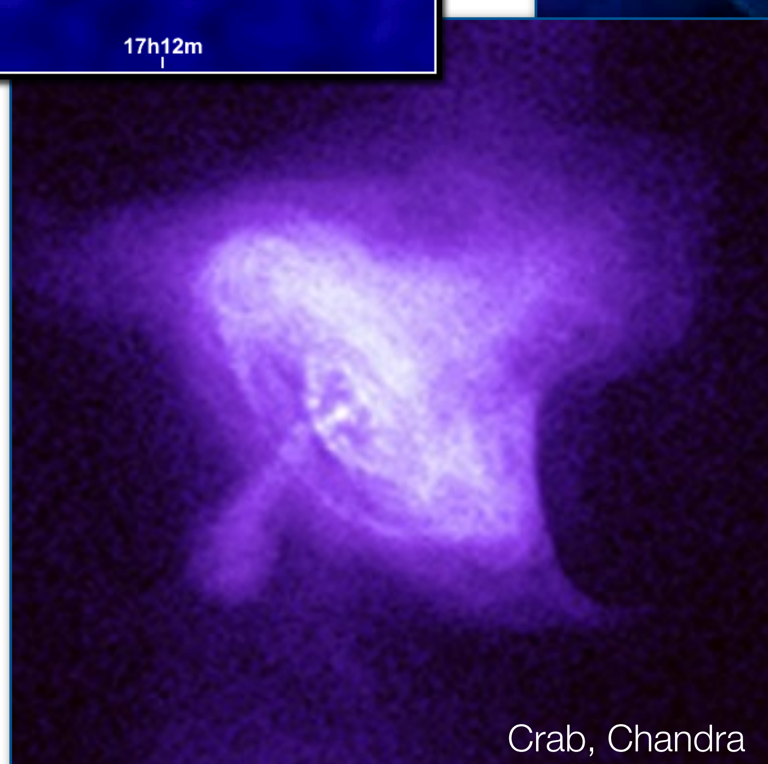


RX J1713, HESS

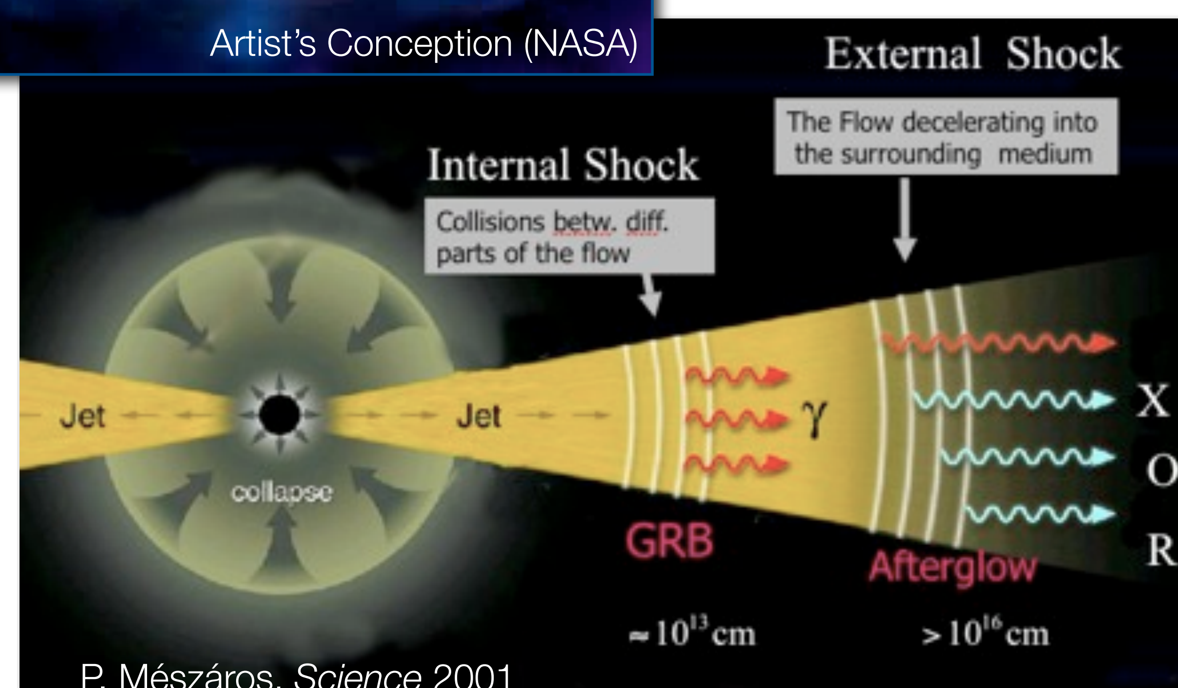
Artist's Conception (NASA)

GRBs

SNRs & PWN

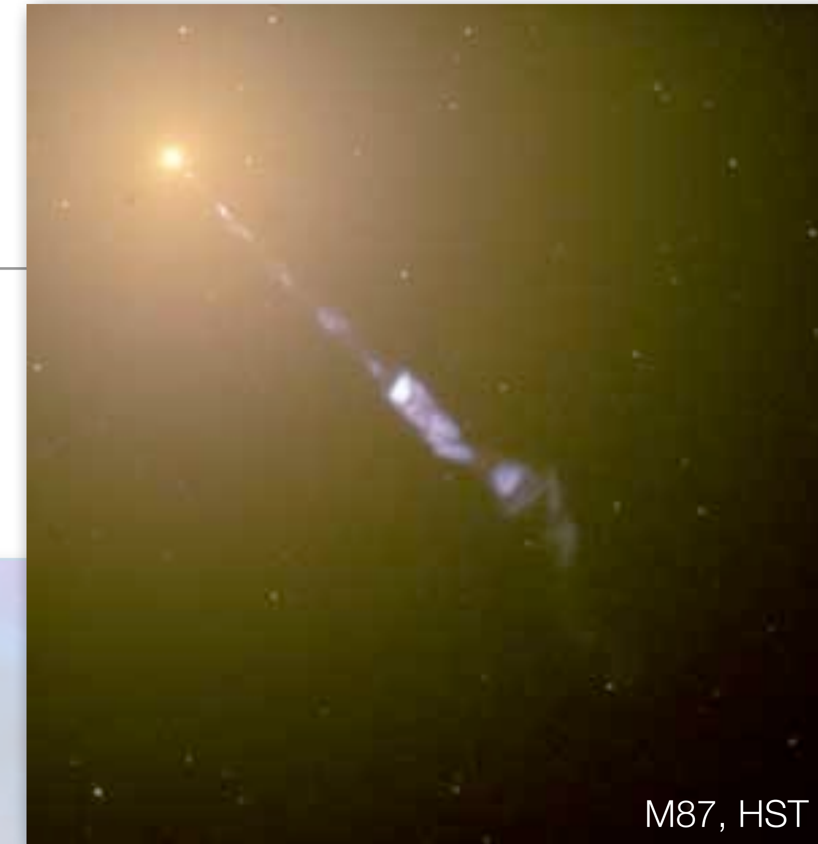


Crab, Chandra



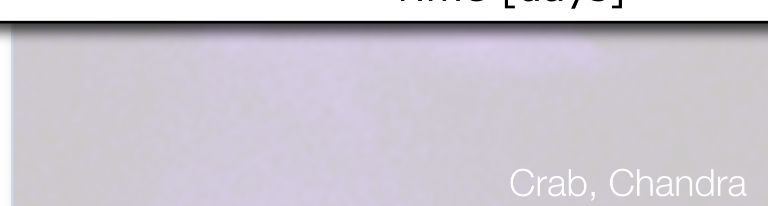
P. Mészáros, *Science* 2001

Astrophysical Accelerators

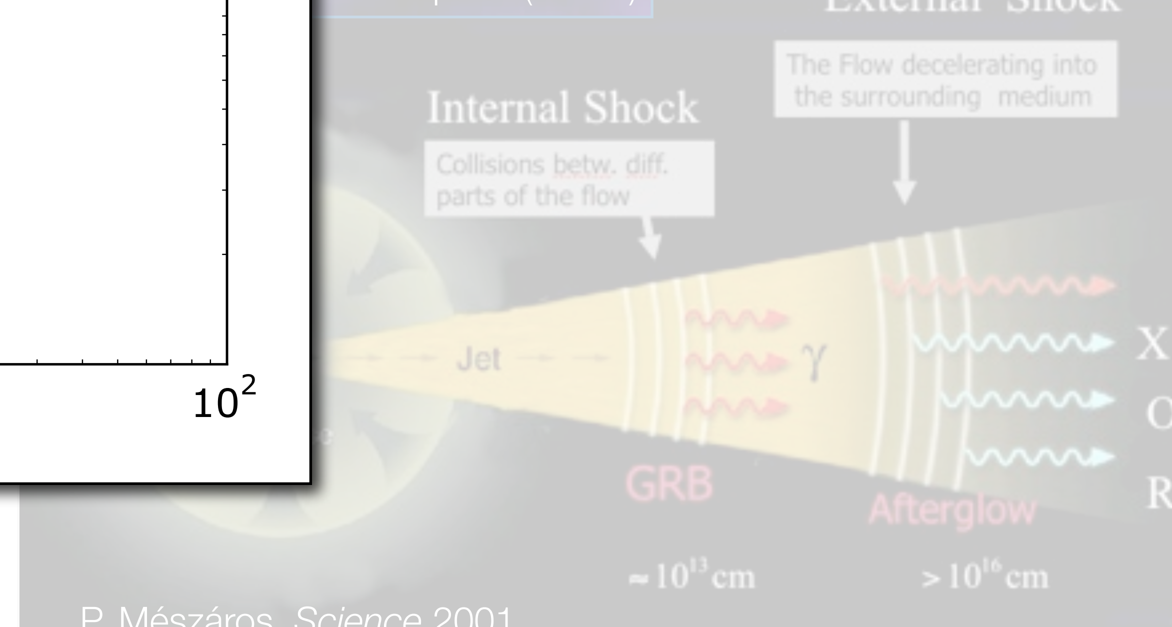


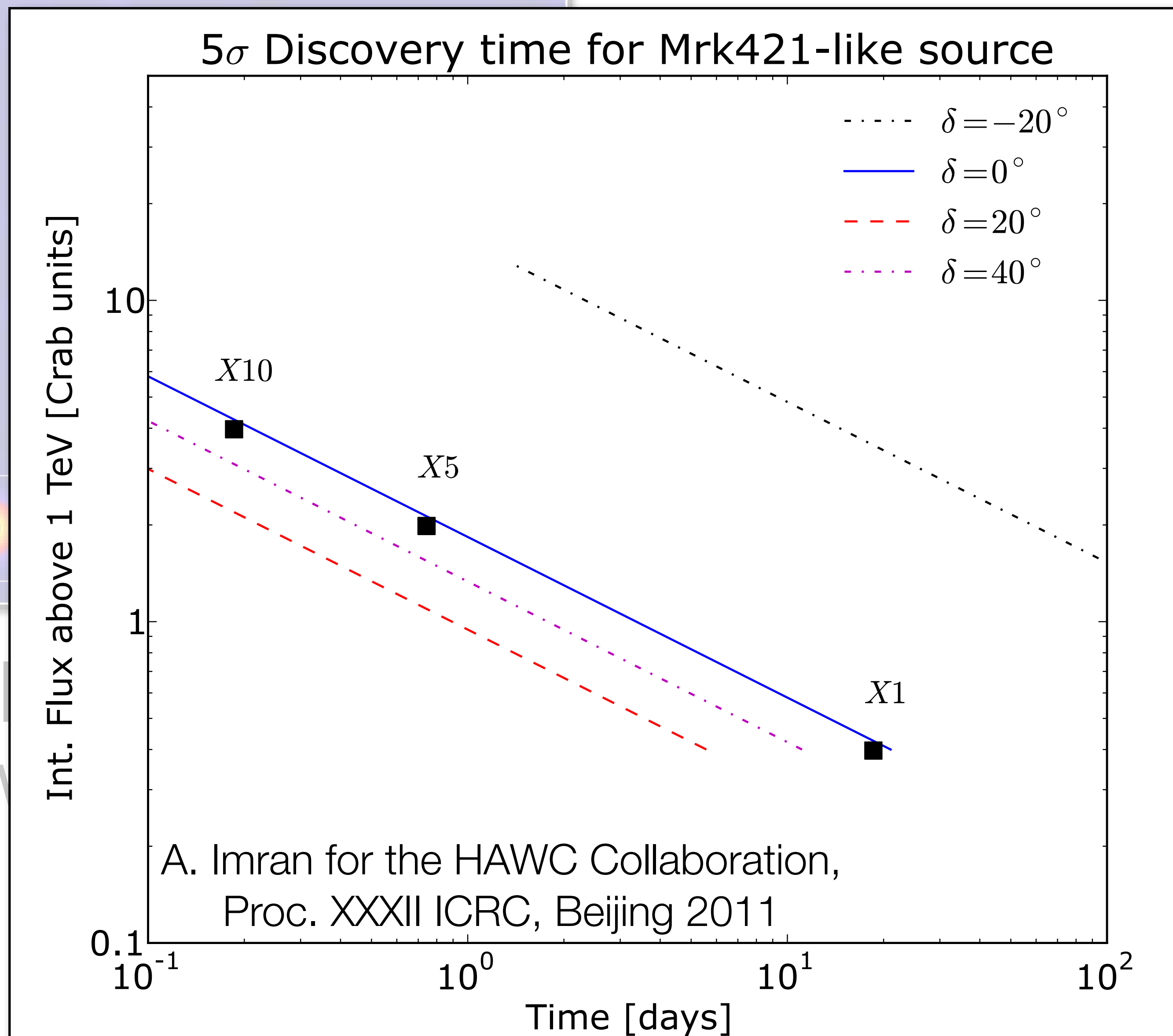
AGN

SNI
PV

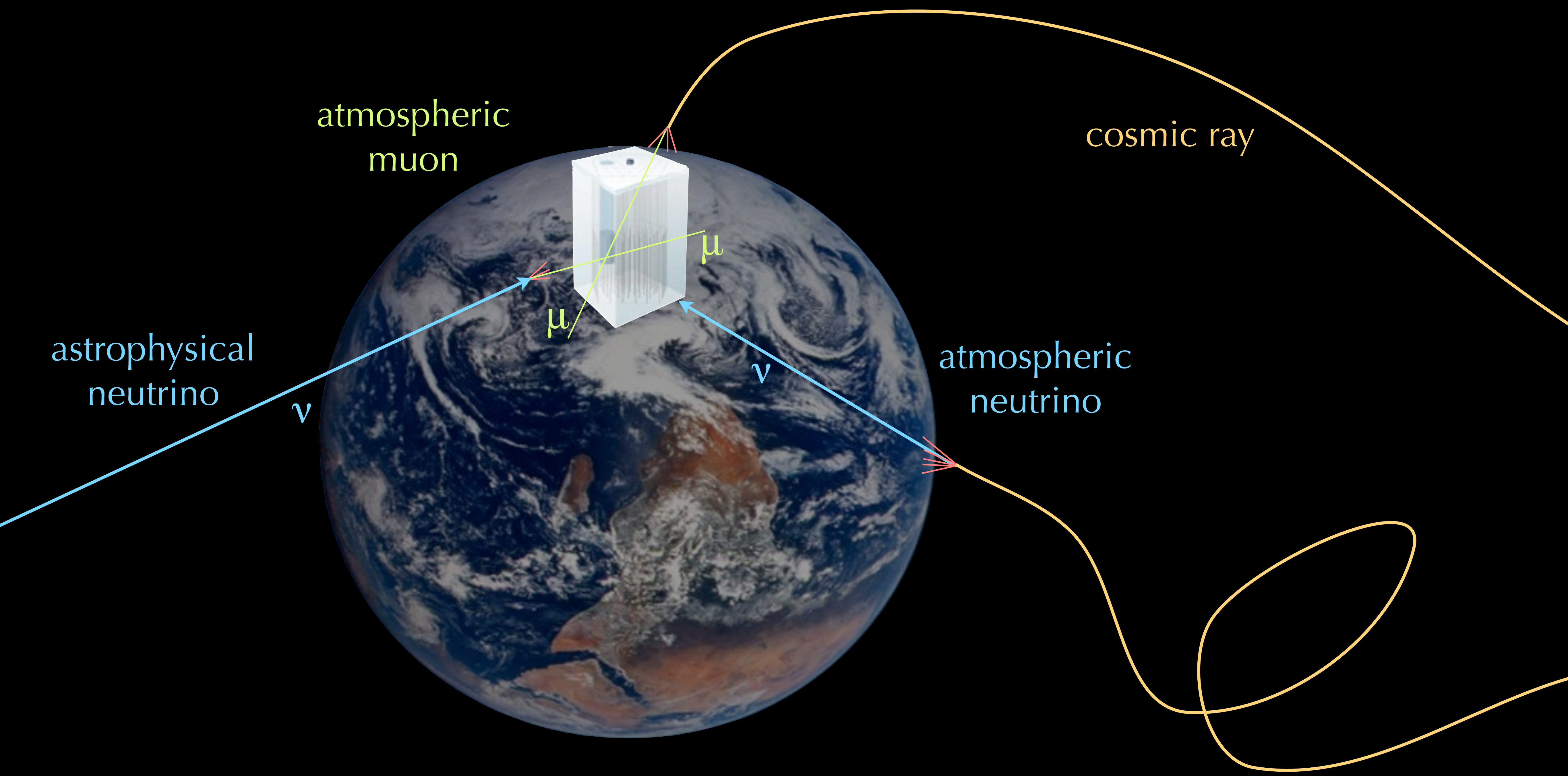


GRBs



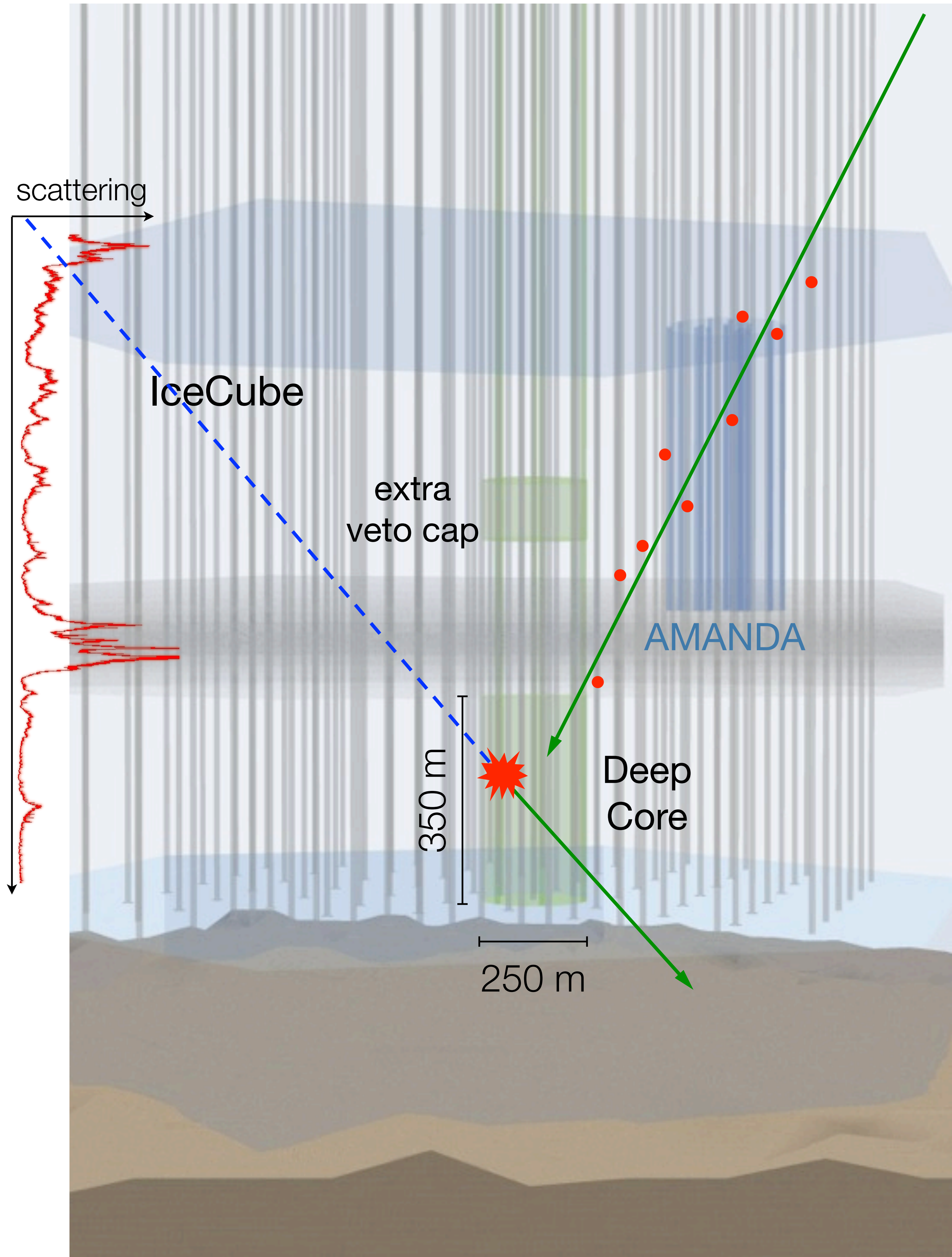


Neutrino Telescopes



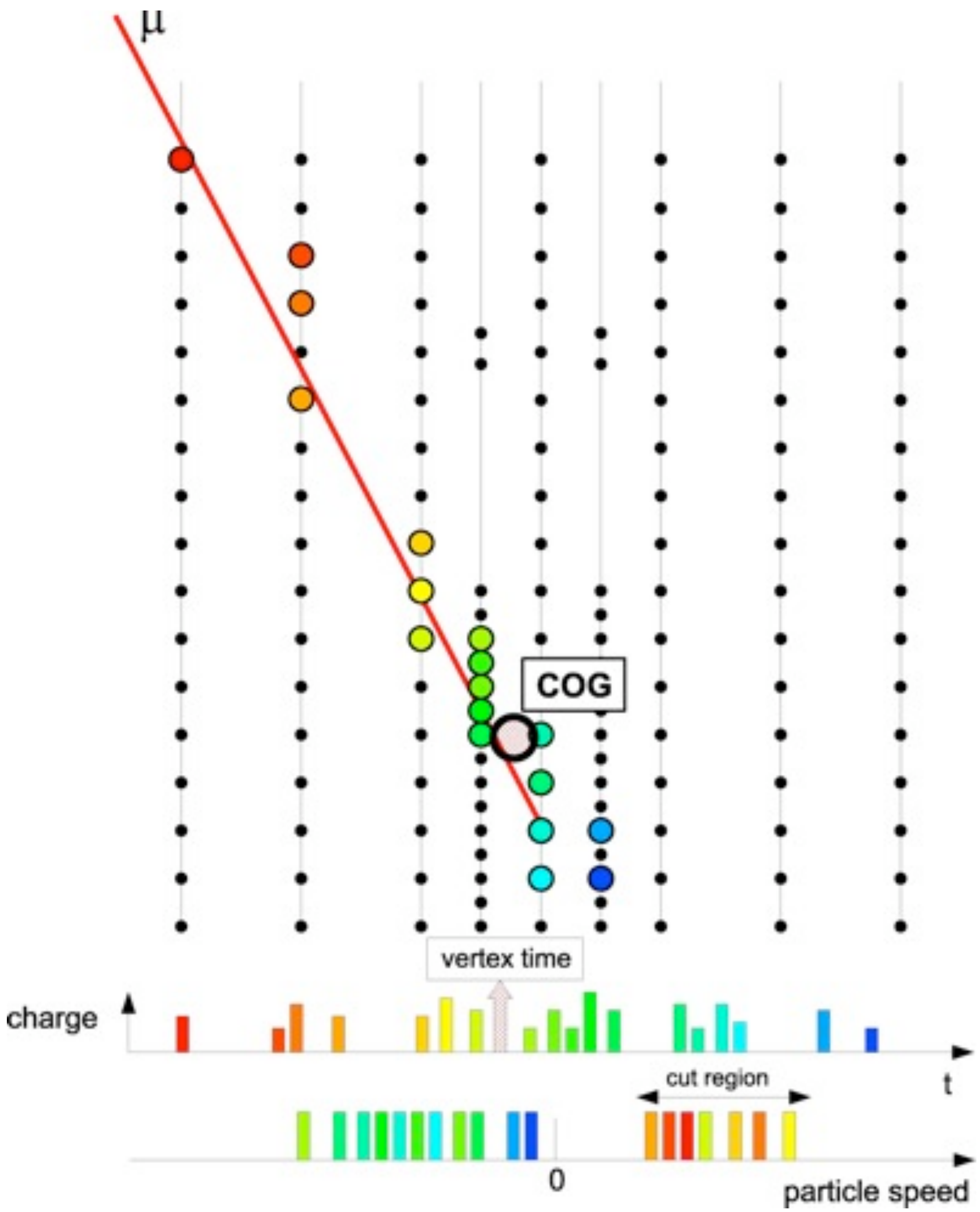
IceCube DeepCore

- A more densely instrumented region at the bottom center of IceCube
  - Eight special strings plus 12 nearest standard strings
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx 50$ m
- IceCube provides an active veto against cosmic ray muon background (around 10^6 times atmospheric neutrino rate)

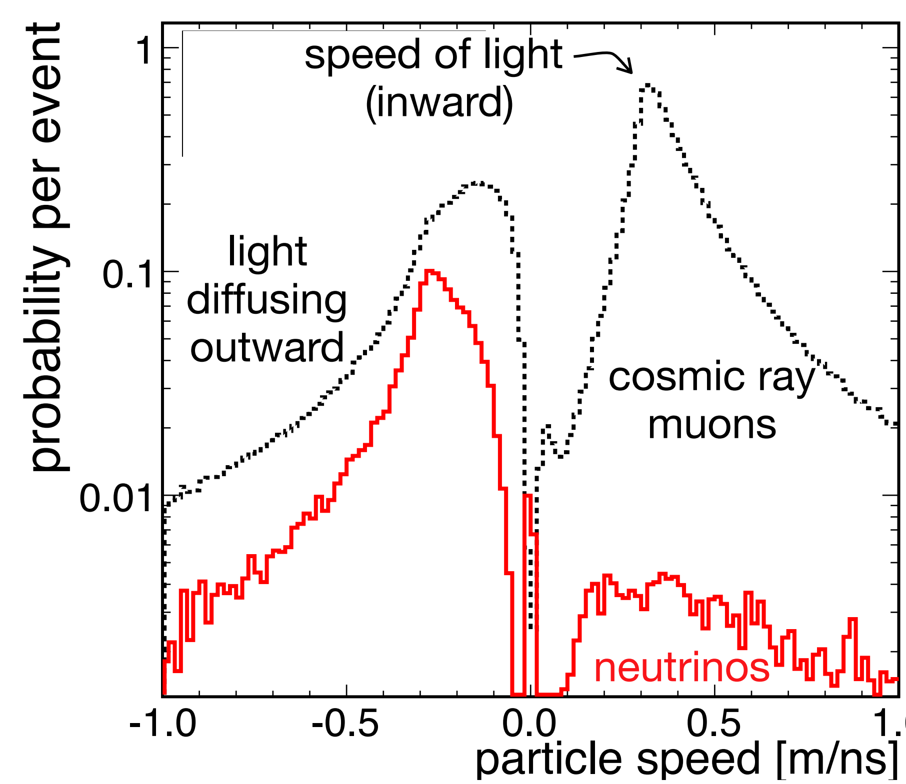


Vetoing Atmospheric Muons

D. Grant, L. Bradley



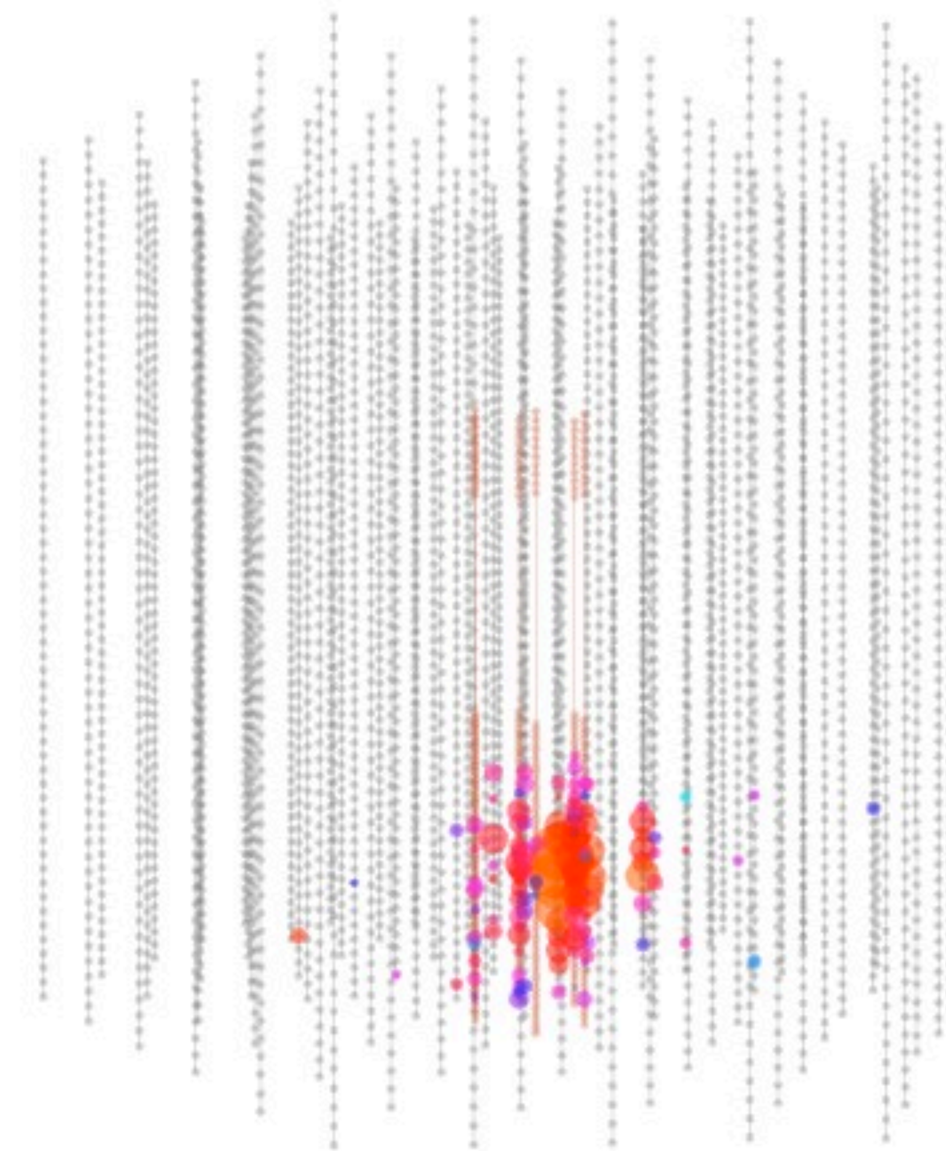
- Look for hits in veto region consistent with speed-of-light travel time to hits in DeepCore
  - Achieves 8 x 10^{-3} rejection of cosmic ray muon background with 99% efficiency for neutrinos interacting within DeepCore
  - More sophisticated versions used offline



Atmospheric Cascades with IceCube

C. H. Ha

- First detection of neutrino cascades ($\nu_e + \nu_\mu$ NC) in a neutrino telescope
  - Previous searches have turned up a half-dozen candidates, consistent with cosmic ray muon background
- Use DeepCore with IceCube veto to reduce background
  - Reduced fiducial volume OK given high atmospheric flux
  - Use machine learning tools, maximum likelihood fits to identify cascades
  - Dominant background to cascades is atmospheric ν_μ CC with short μ tracks

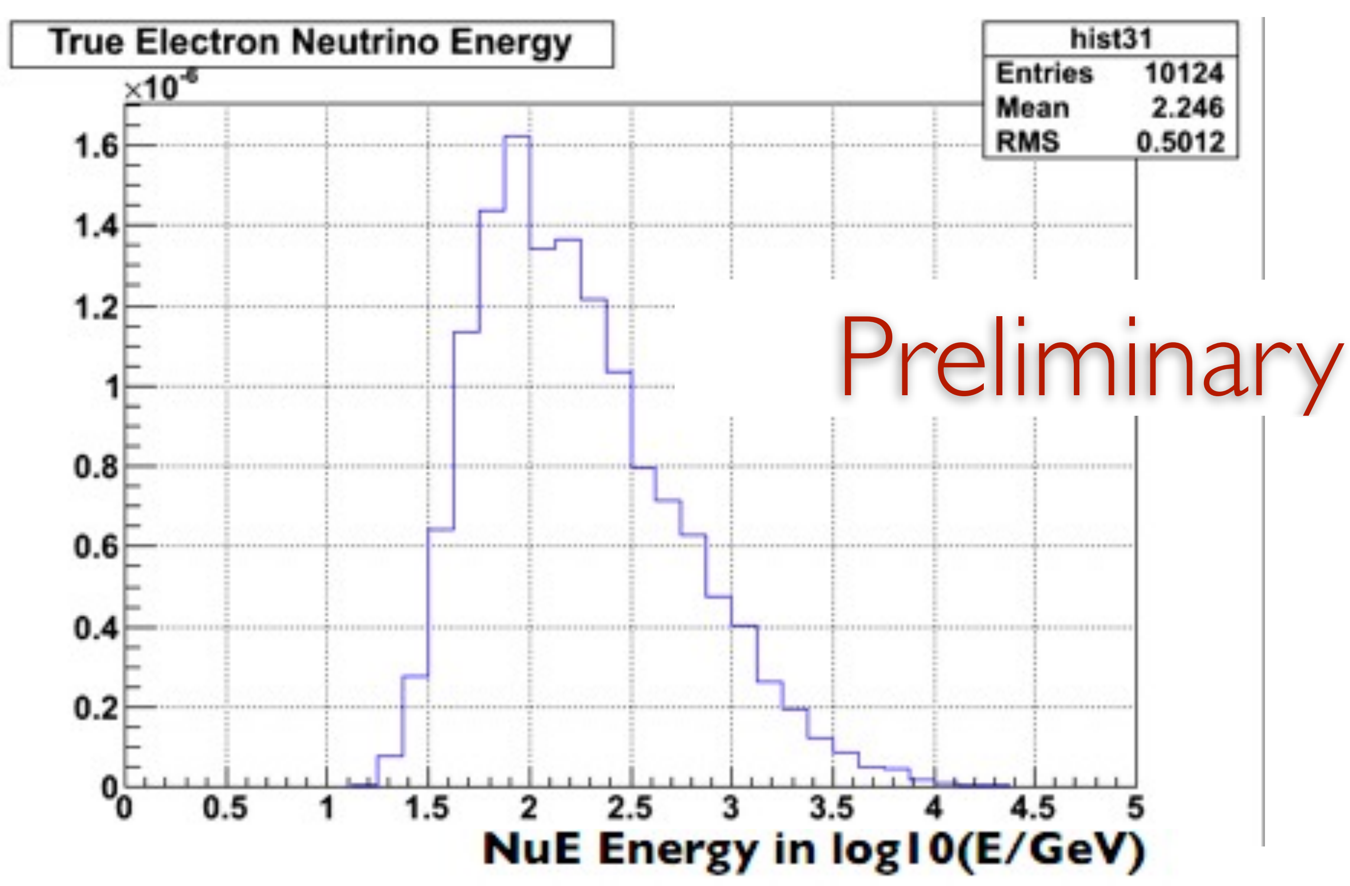


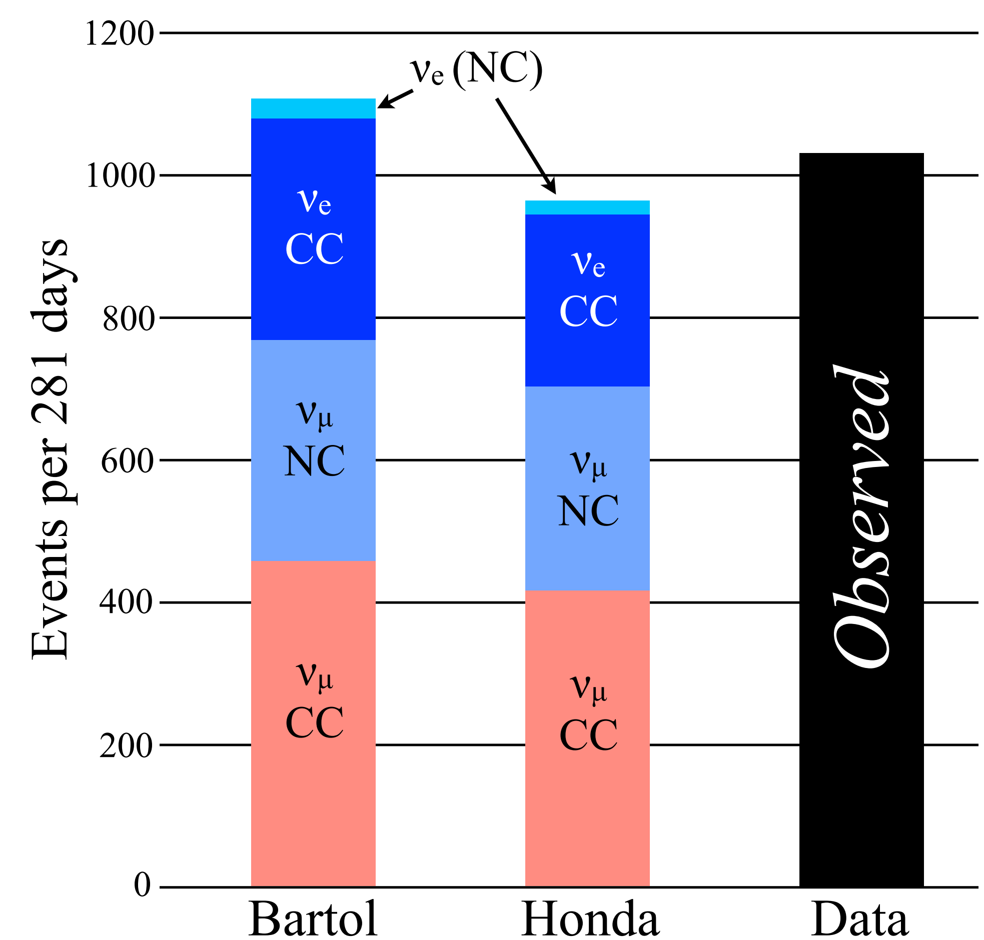
Run = 116100
Event ID = 13022869
2010/06/28

Observation of Atmospheric Cascades

C. H. Ha

- Data set of 1029 events from 2010, ~60% real cascades
  - Atmospheric muon background being assessed, but contribution small
  - Potential to discriminate between leading atmospheric neutrino models
  - Mean energy ~180 GeV, not sensitive to oscillations with this sample

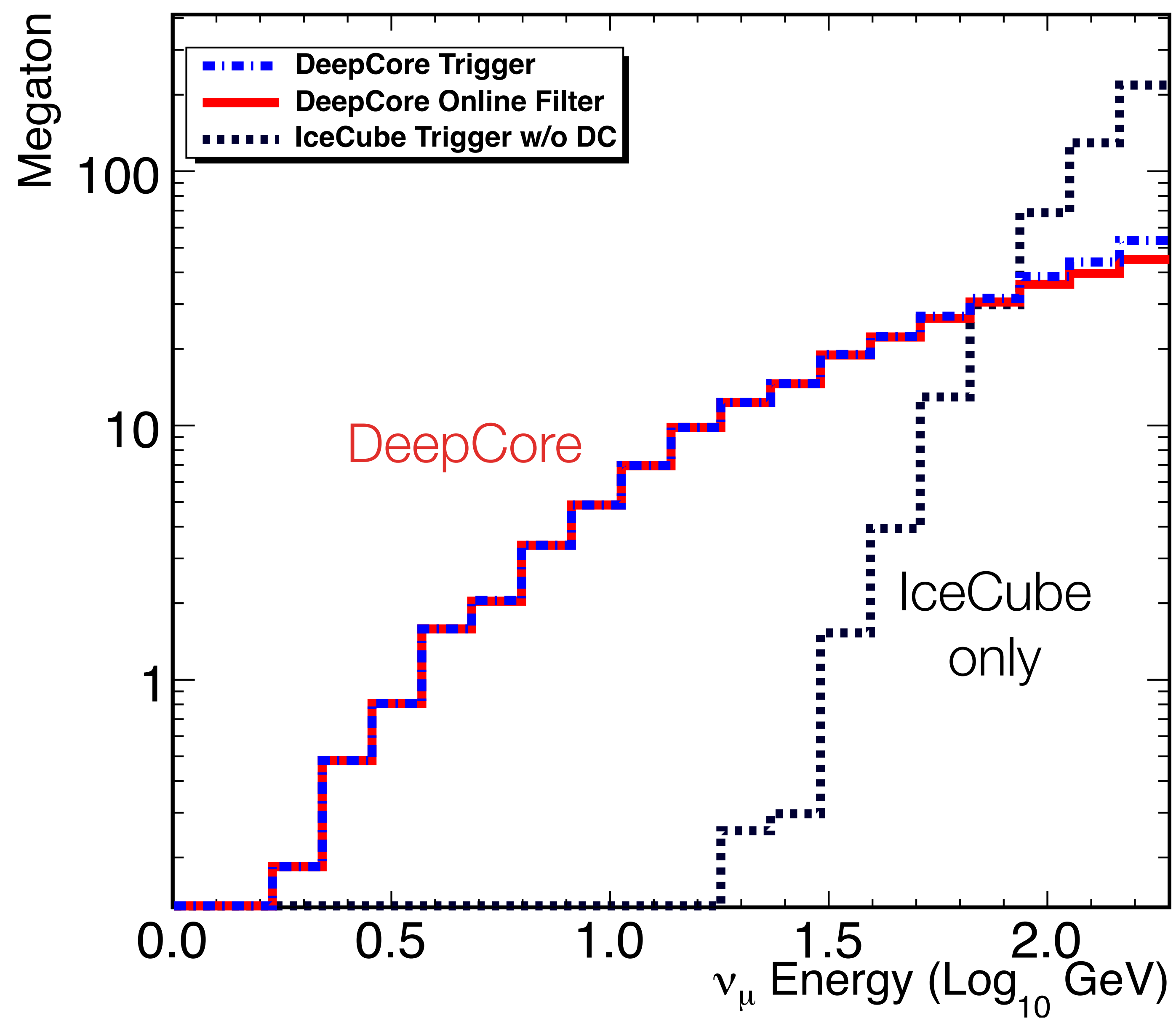




Atmospheric Neutrinos in DeepCore

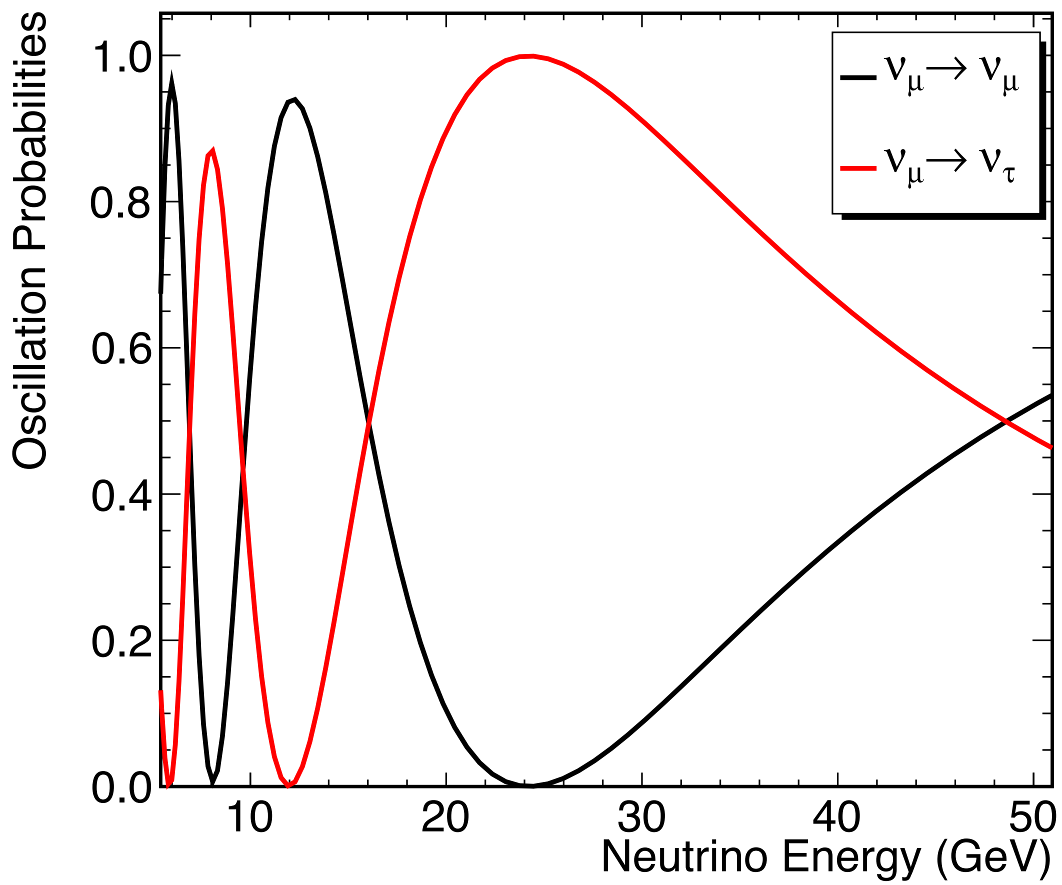
- DeepCore greatly expands IceCube's sensitivity to low energy neutrinos (<100 GeV)
  - The atmospheric neutrino spectrum follows $dN/dE \sim E_\nu^{-3.7}$
- 30 MTon detector with ~10 GeV threshold
  - The lower threshold leads to much higher neutrino event rates than in IceCube
- $\mathcal{O}(10^5)$ atmospheric neutrinos triggered / year

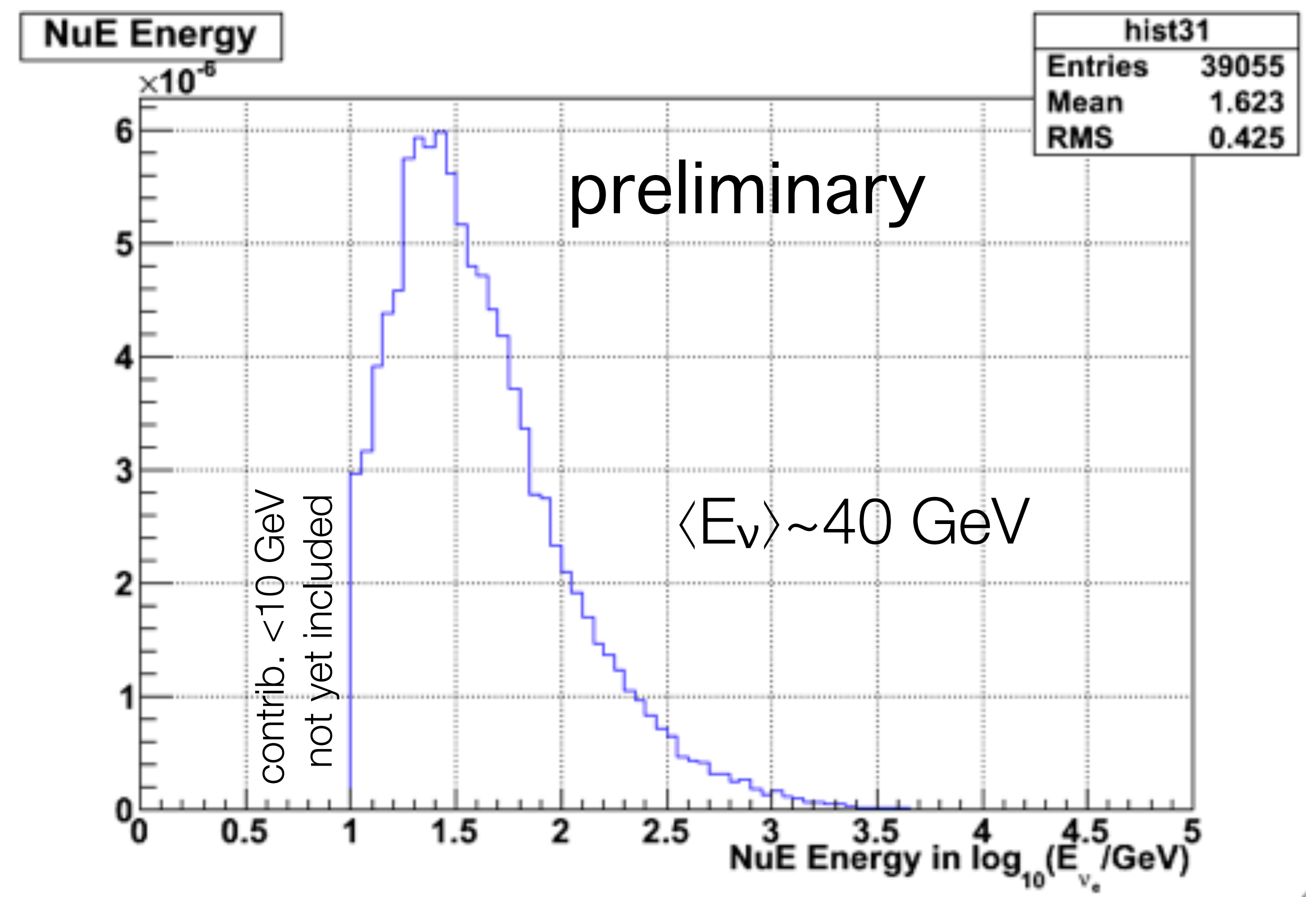
J. Koskinen



Neutrino Oscillations with DeepCore

C. H. Ha, J. Koskinen

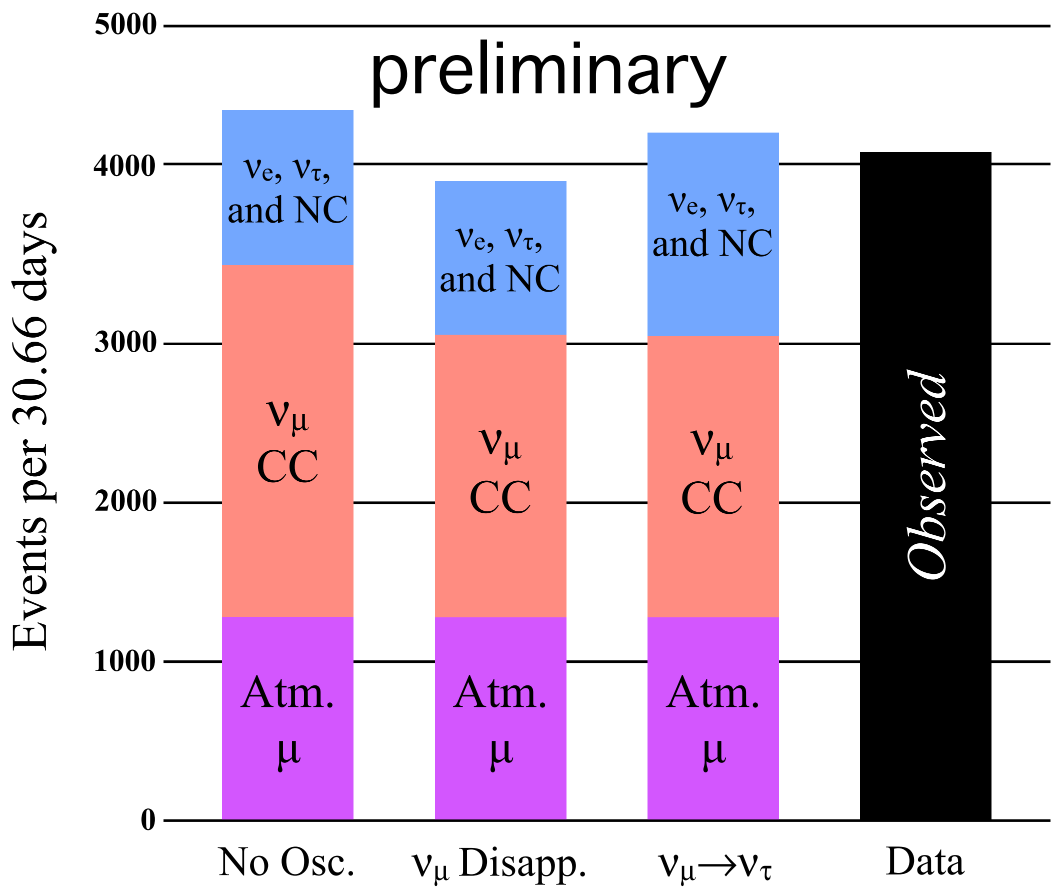


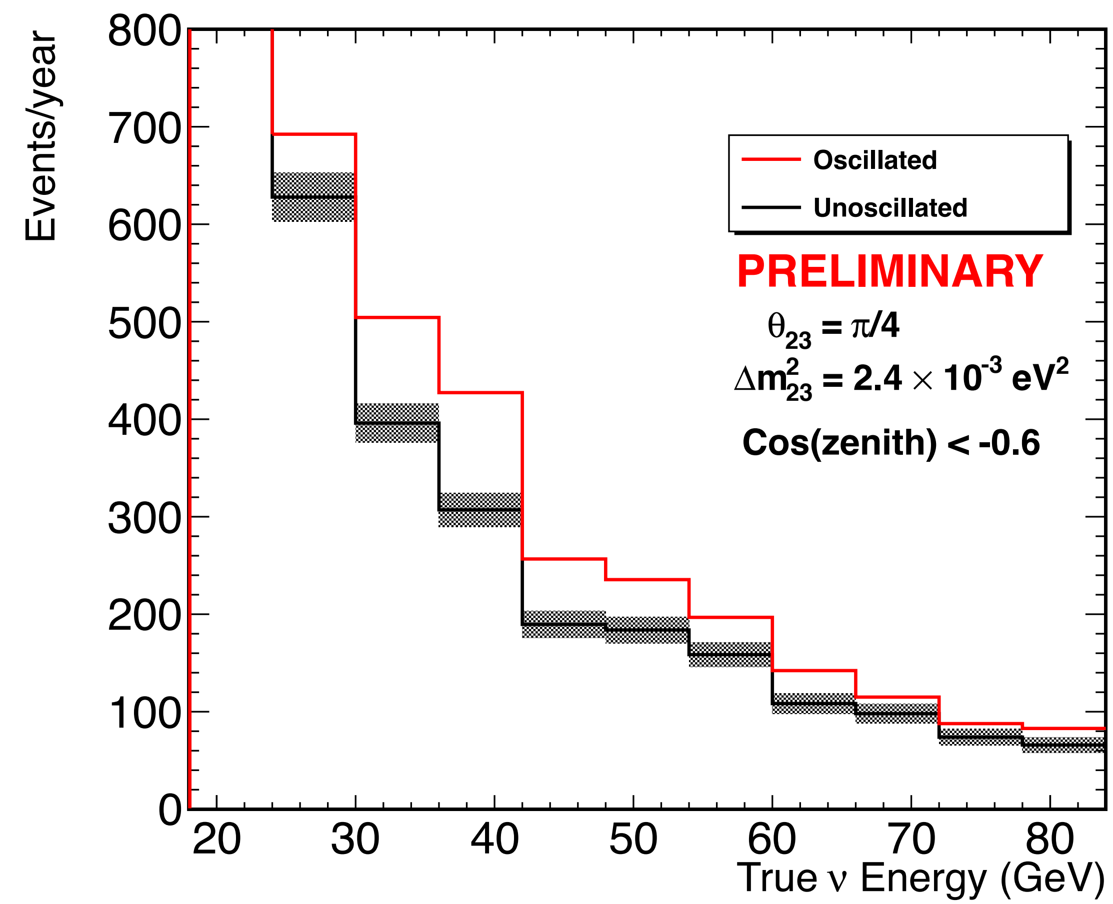


- Energy threshold of first analysis high due to final particle ID cuts
- Alternate sample trades higher background for reduced threshold
  - Measurement of tau neutrino appearance appears possible (a first!)
  - Requires detailed understanding of systematics – work in progress

Measuring Tau Neutrino Appearance

C. H. Ha, J. Koskinen





- First step: measure neutrino rates, infer tau neutrino contribution
  - Approximately 15σ statistical observation in 2010 data set (plus syst.)
- Then work toward observing distortion of the cascade spectrum
  - Improve precision and reduce background by adding reconstruction info

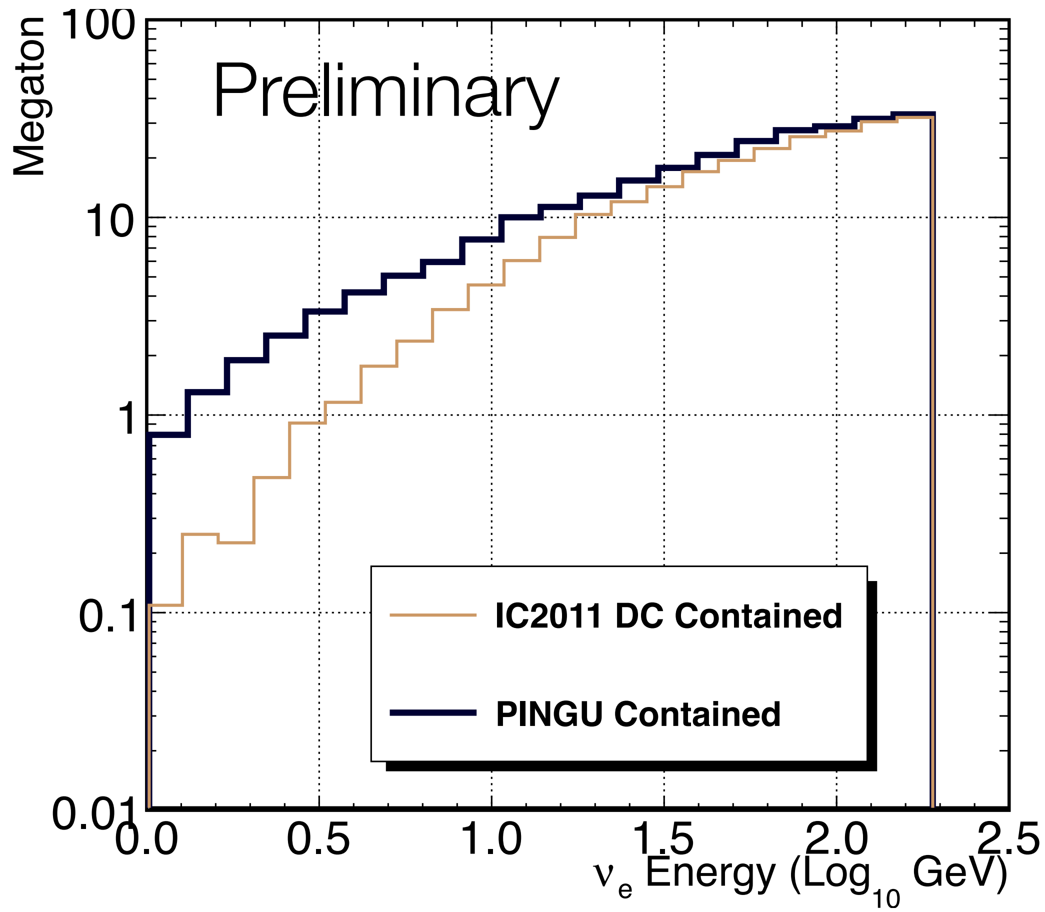
Toward Precision Physics in Ice

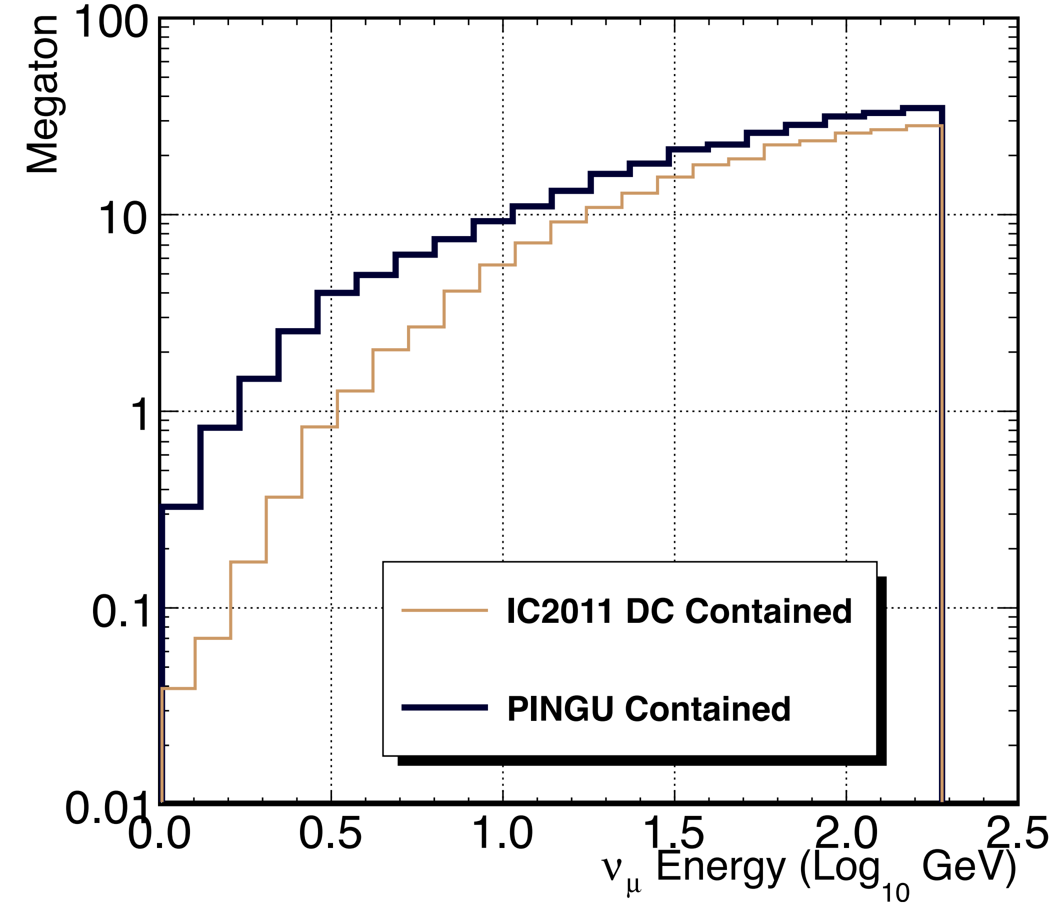
J. Koskinen, D. Grant

- First stage: PINGU
  - Add ~20 further infill strings to DeepCore, extend energy reach to ~1 GeV
  - Improved sensitivity to DeepCore physics, and test bed for next stage
  - Use mostly standard IceCube technology, include some R&D toward new types of photodetectors
  - Include additional calibration devices with an eye toward few-% systematics
- Thinking big: MICA
  - Using new photon detection technology, can we build a detector that can reconstruct Cherenkov rings for events well below 1 GeV?
  - PINGU physics topics, plus proton decay, extragalactic supernova neutrinos
  - At least comparable in scope to IceCube, but in a much smaller volume

PINGU Performance

J. Koskinen, R. Wasserman



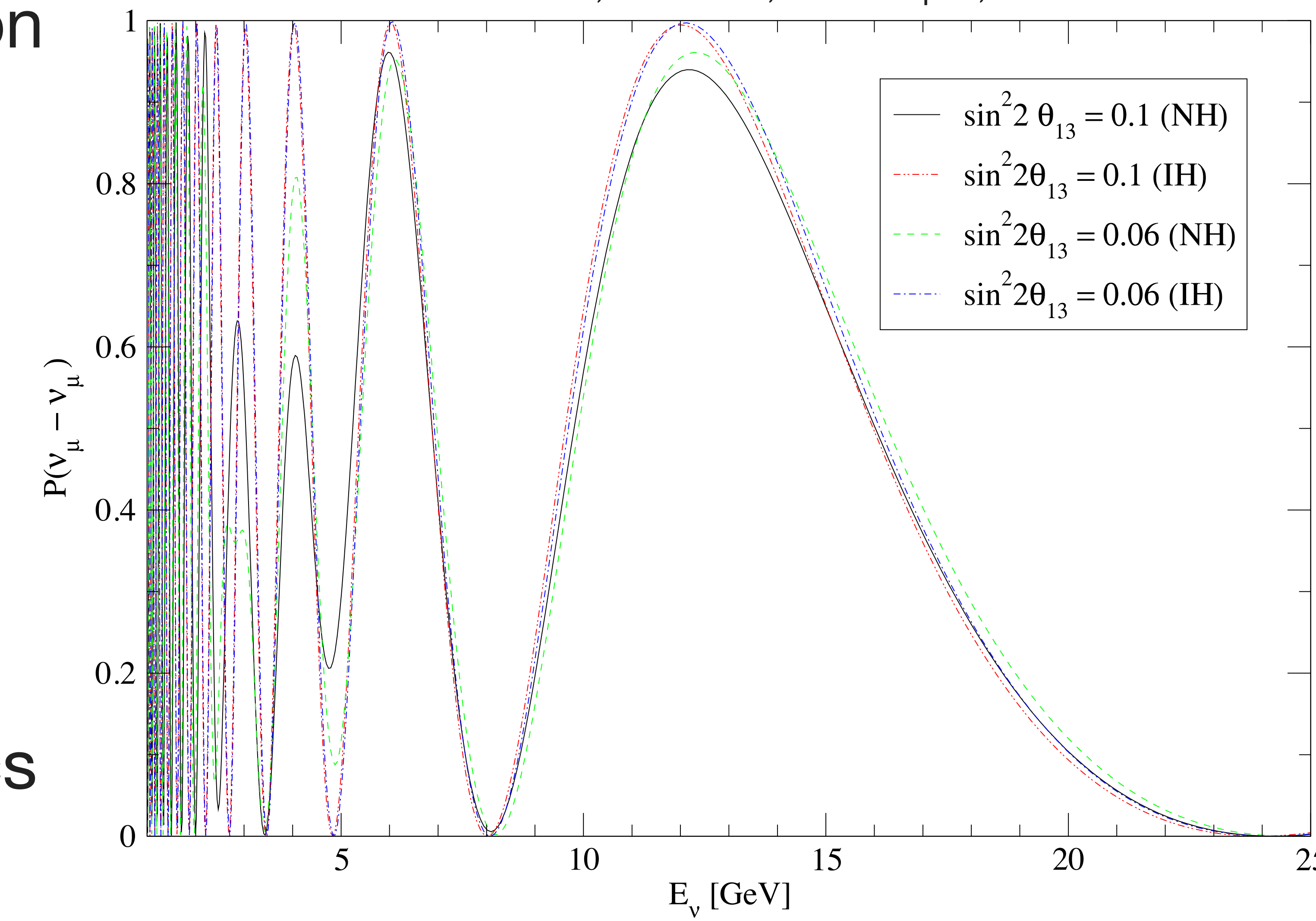


- Increased effective volume for energies below ~15 GeV
- Several megatons effective volume at a few GeV
- Does not include analysis efficiencies, reconstruction precision
  - Absolute scale lower, but larger relative improvement over DeepCore

PINGU Neutrino Physics

- Sensitivity to 2nd oscillation peak/trough, and lower?
  - Measuring full minimum and 2nd peak would improve extraction of Δm_{23}^2 and $\sin^2(2\theta_{23})$ in a very large data set
- Limited by systematic uncertainties, not statistics
  - Will include a robust calibration program to refine understanding of systematics

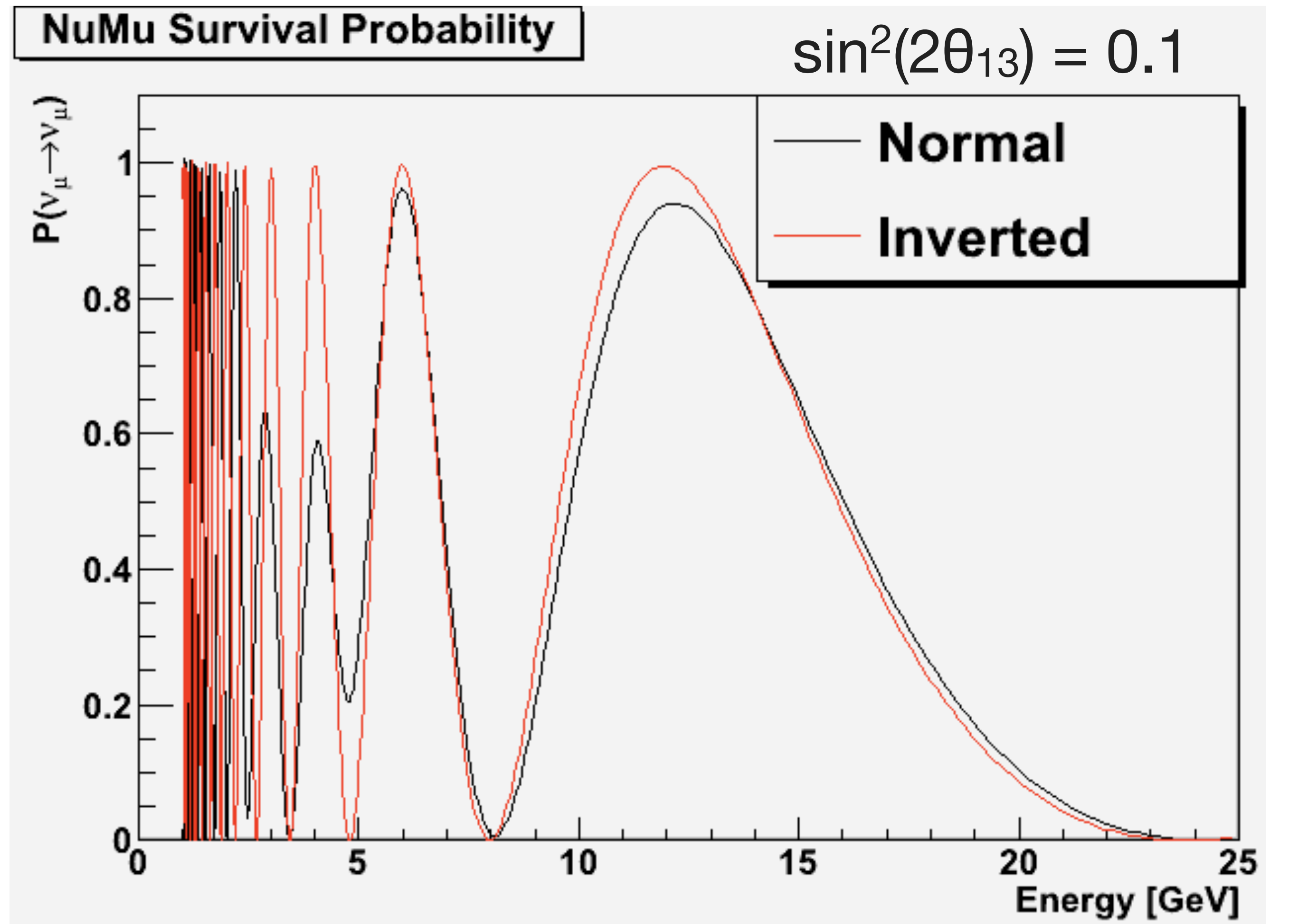
Mena, Mocioiu, Razzaque, arXiv:0803.3044

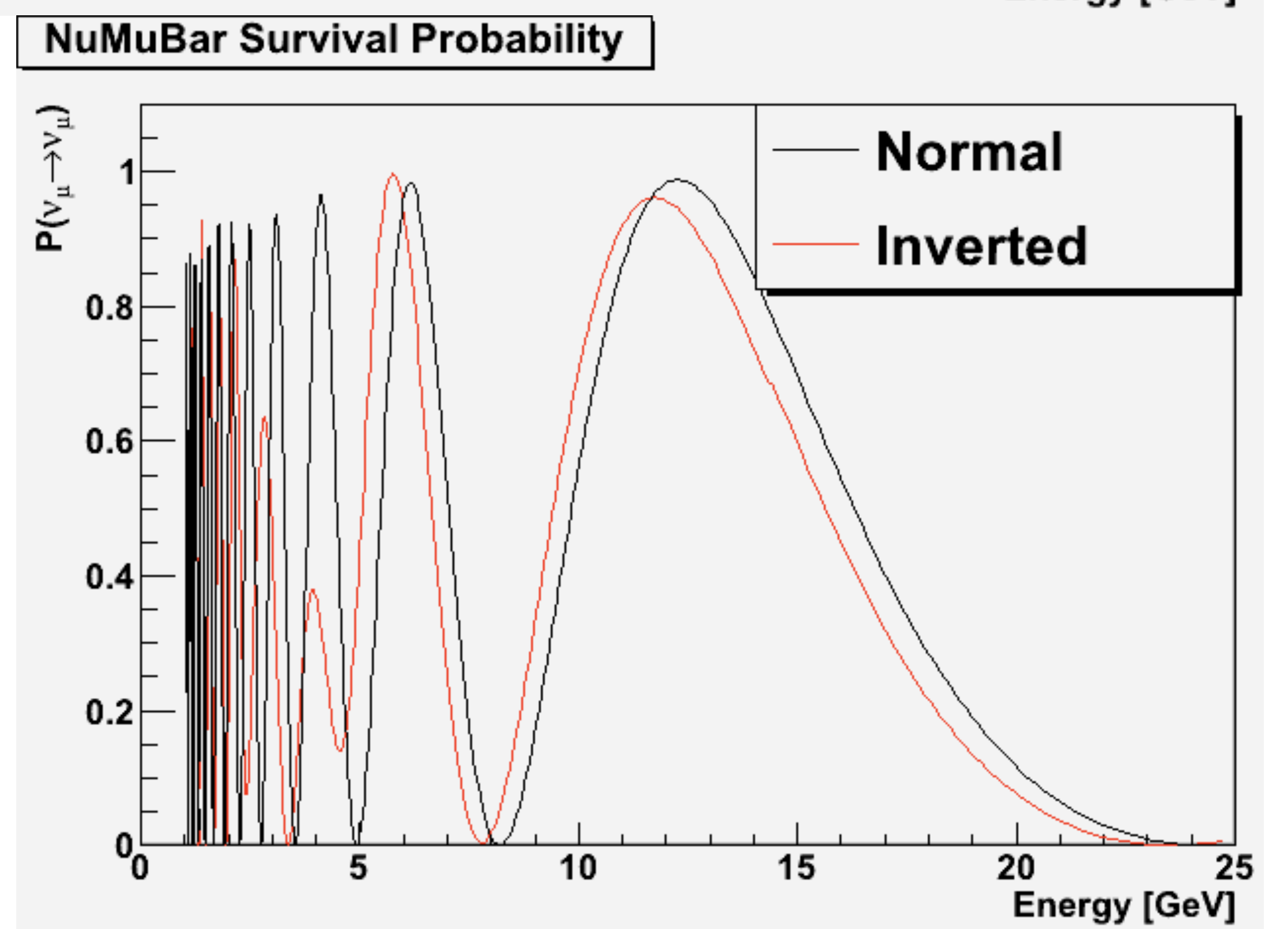


Probing the Neutrino Mass Hierarchy?

- Possible sensitivity to neutrino mass hierarchy via matter effects if θ_{13} is large
  - Exploit asymmetries in ν / $\bar{\nu}$ cross section, kinematics
  - Effect is largest at energies of a few GeV (for neutrinos crossing the Earth's core)
  - Control of systematics crucial
- Recent results from T2K suggest that nature may have been kind to us by giving us a large θ_{13}

$\sin^2(2\theta_{13}) = 0.1$



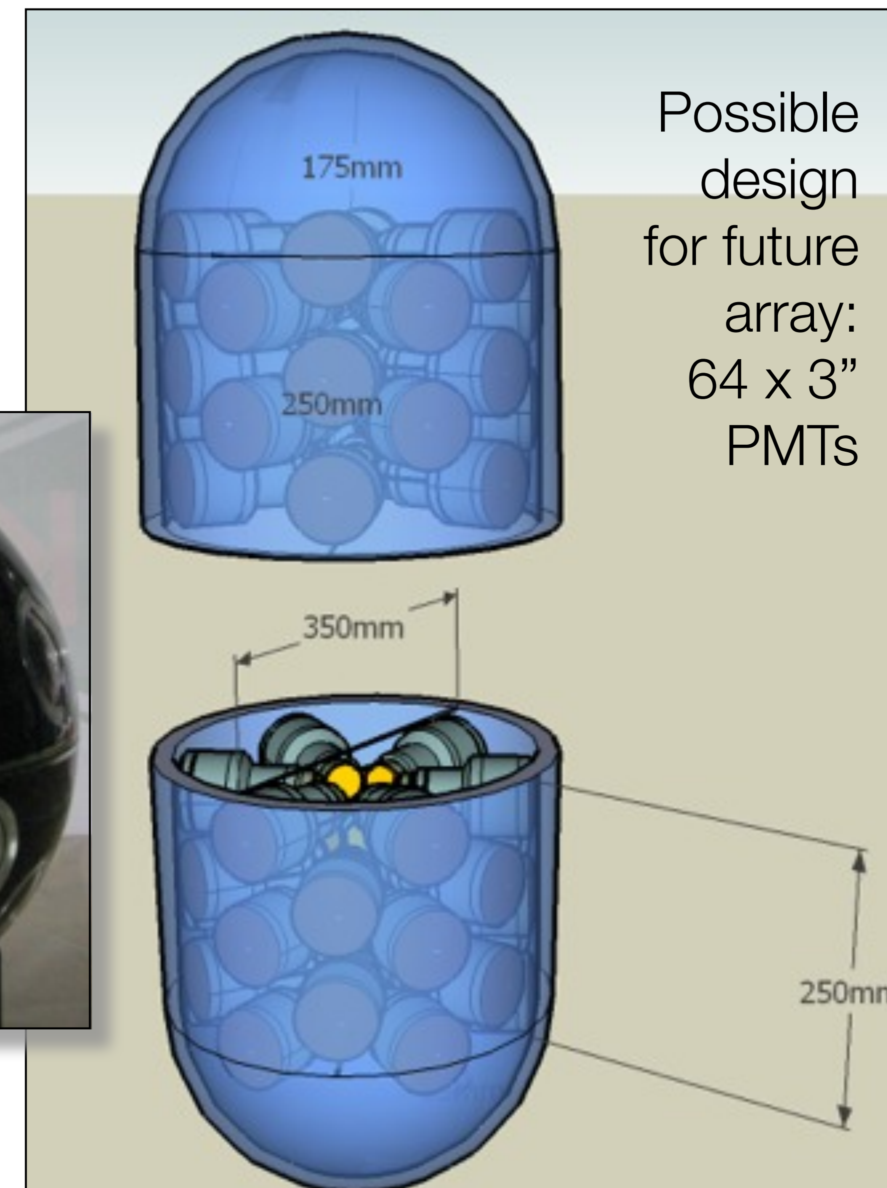


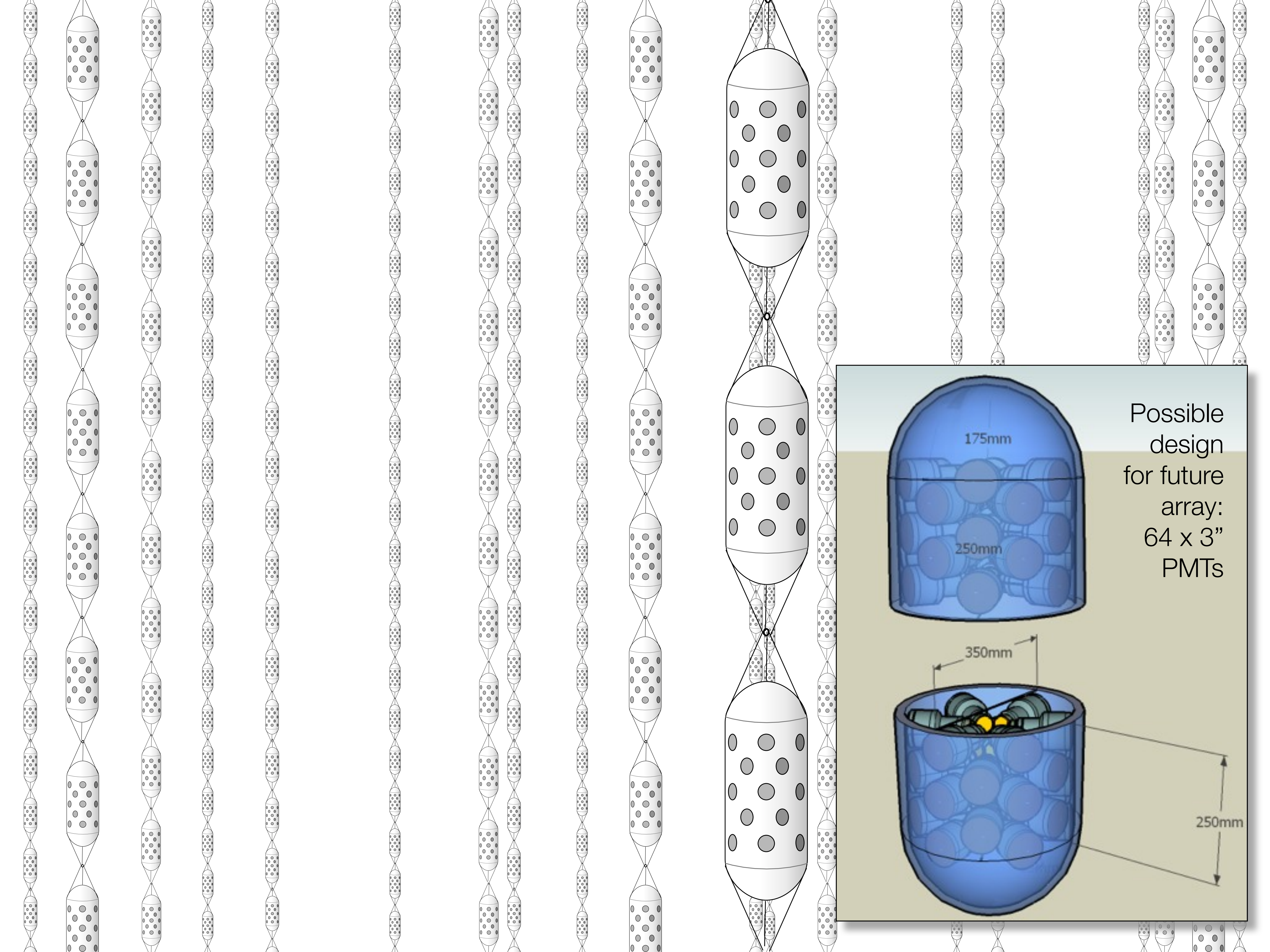
Beyond PINGU: A Megaton Ice Cherenkov Array

- Underground detectors such as Super-K, SNO, et al. have made tremendous contributions to particle physics, but are approaching the limits of feasible detector size
  - Physics reach determined by photocathode coverage, radiopurity, optical quality of the medium
  - Costs driven primarily by photocathode coverage, purification, and civil engineering – and the latter is coming to dominate
- Ice offers one great advantage: the medium is the support structure
  - Installation costs low (on the scale of a next-generation detector)
  - Deep ice has reasonably good optical quality, very high radiopurity
  - But the maximum density of instrumentation is determined by installation procedure, and the optical properties must be assessed *in situ*

R&D: Multi-PMT Digital Optical Module

- Based on a KM3NeT design
- Glass cylinder containing 64 3” PMTs and associated electronics
  - About 5x the photocathode area of a standard IceCube 10” PMT
  - Module diameter similar to IceCube DOMs, single connector
- Might enable Cherenkov ring imaging in the ice
  - Feasible to build a multi-MTon detector in ice with an energy threshold of 10’s of MeV?
- R&D beginning now




Possible design for future array: 64 x 3” PMTs
175mm
250mm
350mm
250mm

MICA Physics Goals

- Proton decay
  - Studying sensitivity to $p \rightarrow \pi^0 + e^+$ channel
  - Requires energy threshold of ~100's of MeV
  - Background limited – depends on energy resolution, particle (ring) ID
- Supernova neutrinos
  - Only 2±1 core collapse SNe per century in the Milky Way
  - Need to reach well beyond our galaxy to get statistical sample of supernovae observed in neutrinos – requires multi-MTon effective volume
  - Background levels may be too high for a ~10 MeV threshold for individual events, but still allow observations of a burst of neutrinos
- Plus improvements for dark matter, neutrino physics compared to PINGU and DeepCore

Summary

- An exciting time in particle astrophysics!
- IceCube now complete, HAWC under construction
  - DeepCore array in place, first results appearing
- We are learning a lot about gamma ray bursts
  - Interesting things going on at high energy (how high?)
  - But where are the neutrinos?
- IceCube with DeepCore has great potential as a laboratory for neutrino physics
  - Studies of neutrino oscillations with world’s largest neutrino data sets
  - How far can we go with this idea?