Recent Results from IceCube



Jon Dumm

OKC Colloquium

05 Feb 2015

Stockholm University

Oskar Klein centre

IceCube

- What is ICECUBE?

IceCube

- What is Ice Cube?

IceCube

- What is IceCube?

IceCube

Google

IceCube

ice cube
icecube **neutrino**
ice cube movies
ice cube tray

About 30,600,000 results (0.33 seconds)

Showing results for ***ice cube***
Search instead for IceCube

Ice Cube - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/**Ice_Cube** ▾ Wikipedia ▾
O'Shea Jackson (born June 15, 1969), better known by his stage name **Ice Cube**, is an American rapper, record producer, actor, screenwriter, film producer, and ...
Ice Cube discography - AmeriKKKa's Most Wanted - I Am the West - The Predator

Ice Cube - IMDb
www.imdb.com/name/nm0001084/ ▾ Internet Movie Database ▾
Ice Cube was born in South Central Los Angeles, to Doris (Benjamin), a custodian and hospital clerk, and Hosea Jackson, a UCLA groundskeeper. He first ...

Ice Cube (@icecube) | Twitter
https://twitter.com/**icecube** ▾
1277 tweets • 270 photos/videos • 1.98M followers. "CAPTION THIS! http://t.co/cT9kx7MVtr"

Ice Cube
www.**icecube**.com/ ▾
Subscribe to my YouTube channel. **Cube** Vision. Sign Up For Newsletter. Visit Store. Email. --Verify Age--, I am under 13 years of age, I am 13 years of age of ...

IceCube Neutrino Observatory
https://**icecube**.wisc.edu/ ▾ IceCube Neutrino Observatory ▾
IceCube is a particle detector at the South Pole that records the interactions of a nearly massless subatomic particle called the neutrino. **IceCube** searches for ...



Ice Cube

Rapper

O'Shea Jackson, better known by his stage name Ice Cube, is an American rapper, record producer, actor, screenwriter, film producer, and director. He began his career as a member of the hip-hop group C.I.A. and later joined N.W.A. Wikipedia

Born: June 15, 1969 (age 45), Baldwin Hills, Los Angeles, California, United States

Full name: O'Shea Jackson

Spouse: Kimberly Woodruff (m. 1992)

Children: Darrel Jackson, OMG, Shareef Jackson, Deja Jackson, Karima Jackson

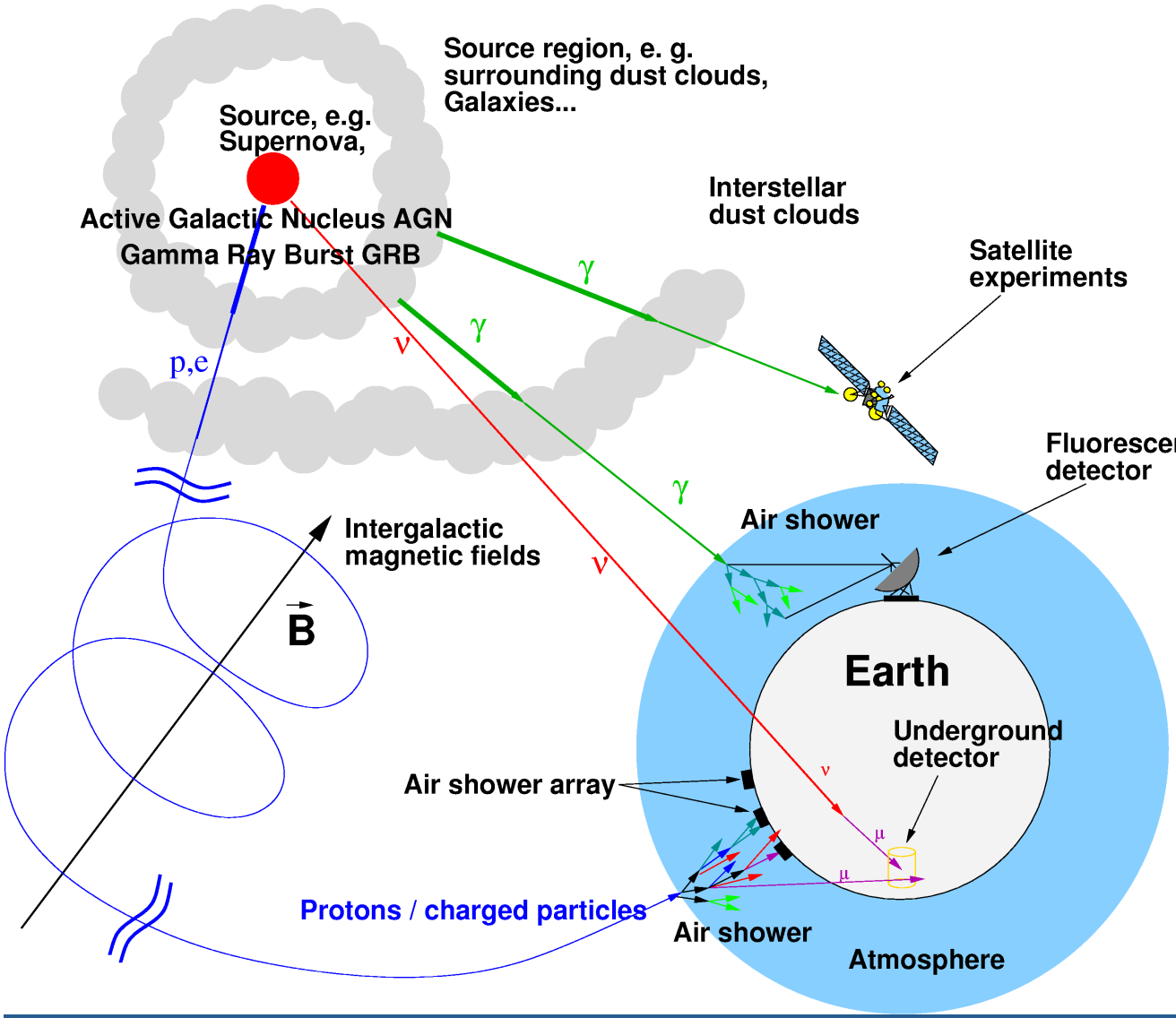
Albums: AmeriKKKa's Most Wanted, I Am the West, The Predator, More

Profiles

Outline

- Neutrino Detection and IceCube
- IceCube science variety show
- The diffuse flux
- Model interpretations
- An IceCube expansion

Neutrinos as Cosmic Messengers



γ *Photons:* easily absorbed by CMB and IR/O backgrounds.

p *Protons:* deflected by magnetic fields.

ν *Neutrinos:* not deflected. Low cross-section.

Why Expect HE Neutrinos?

Extraordinary particle accelerators **somewhere**, but still **poorly identified** after more than a century

- Supernova remnants?
- Active galactic nuclei?
- Gamma ray bursts?
- Other?

Cosmic ray interactions with matter and photons produce:

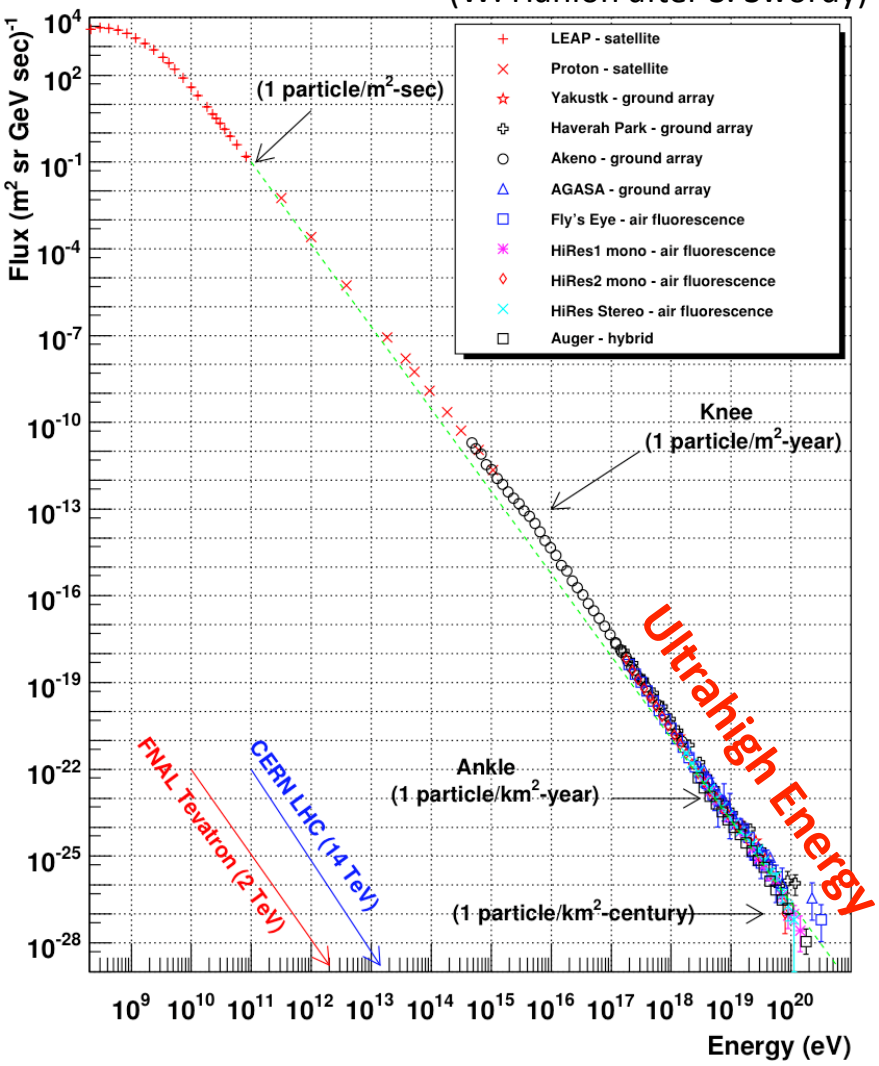
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

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

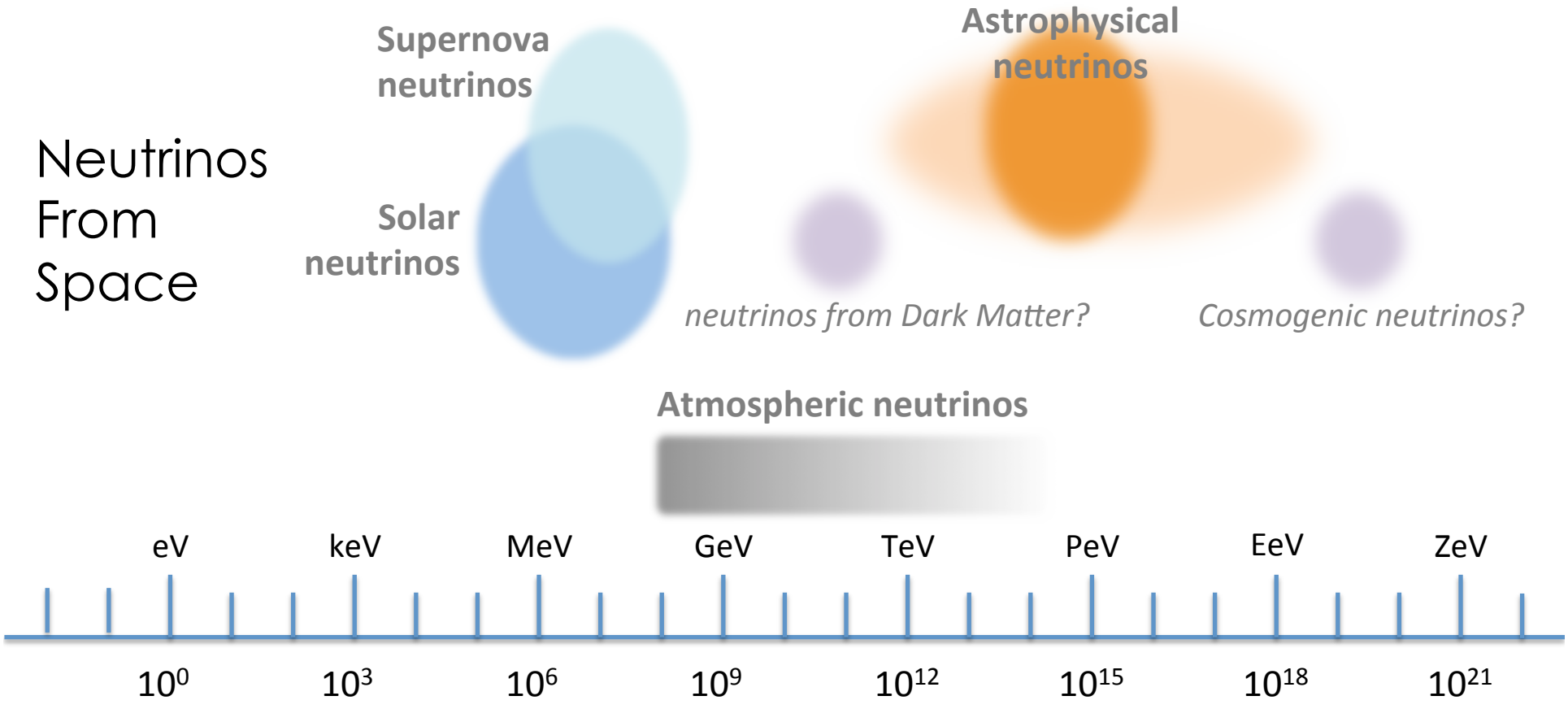
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(W. Hanlon after S. Swordy)



HE Neutrino Astro - Context

Neutrinos From Space



HE Neutrino Astro - Context

Neutrinos From Space

Supernova neutrinos

Solar neutrinos

Astrophysical neutrinos

neutrinos from Dark Matter?

Cosmogenic neutrinos?

Atmospheric neutrinos

eV keV MeV GeV TeV PeV EeV ZeV

10^0 10^3 10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21}

Ultraviolet

Optical

X-ray

Gamma-ray

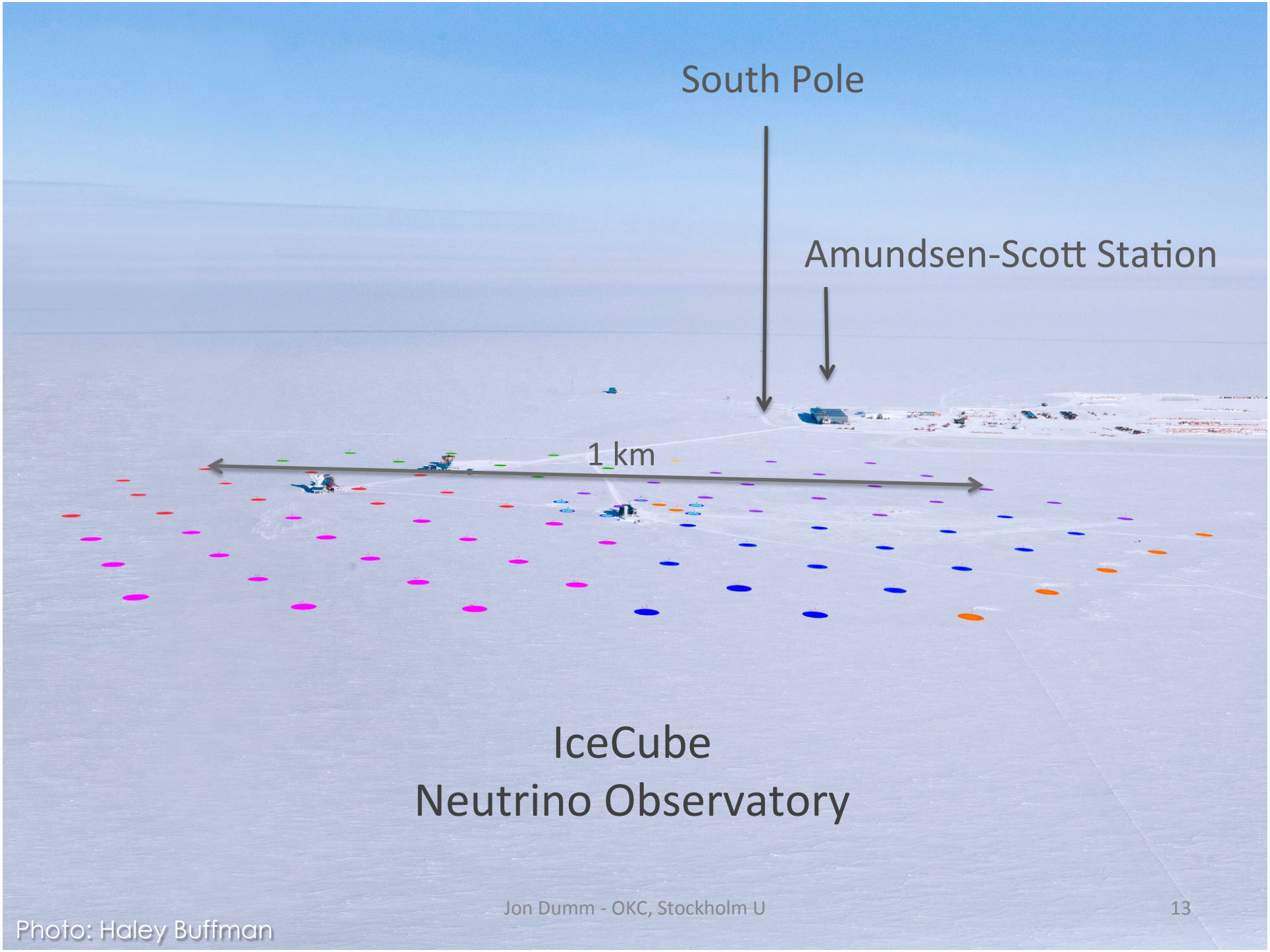
Photons From Space

The IceCube Collaboration





Photo: Haley Buffman



IceCube
Neutrino Observatory

Photo: Haley Buffman

IceCube Neutrino Observatory

86 strings

60 Optical Modules per string

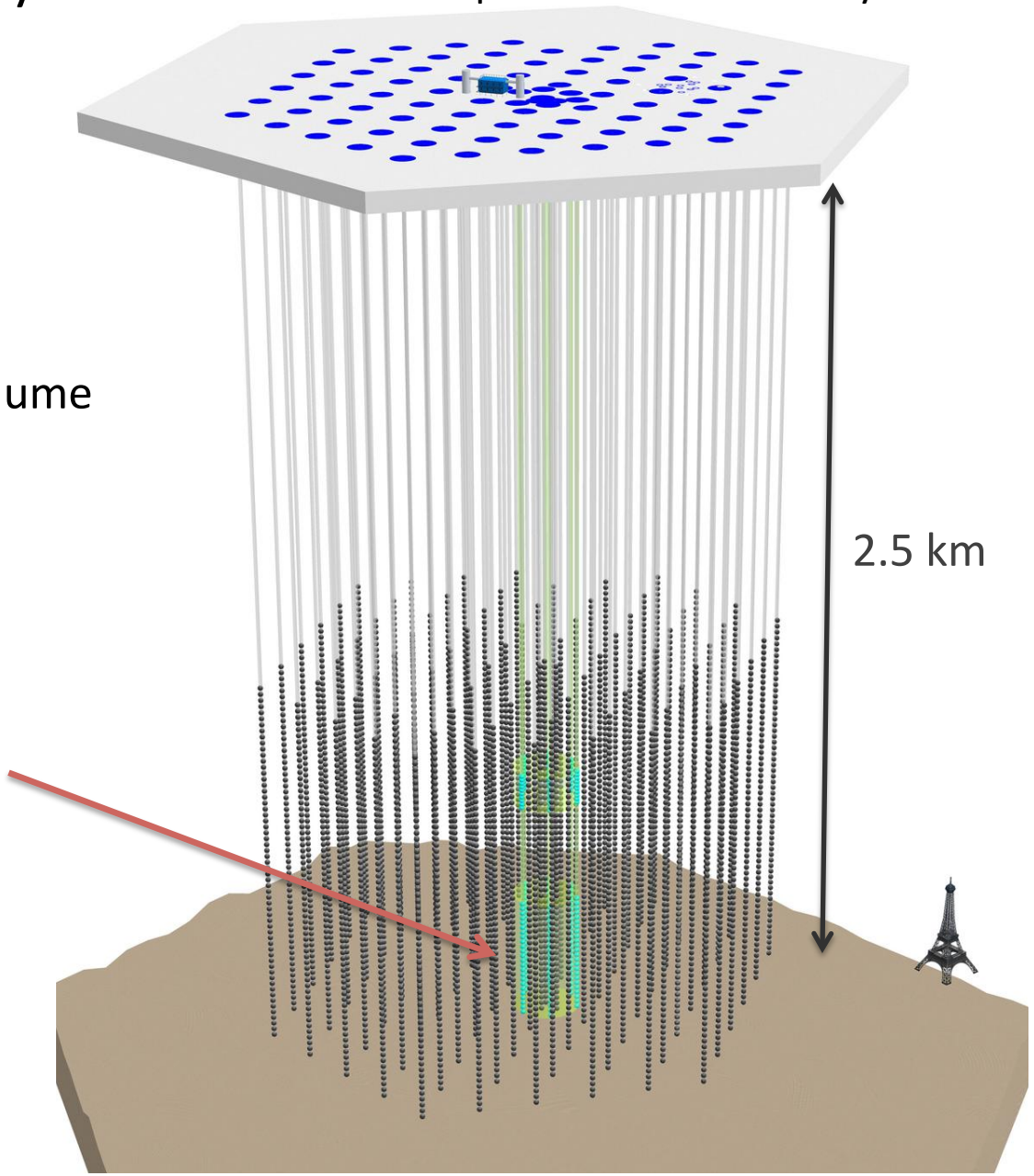
5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

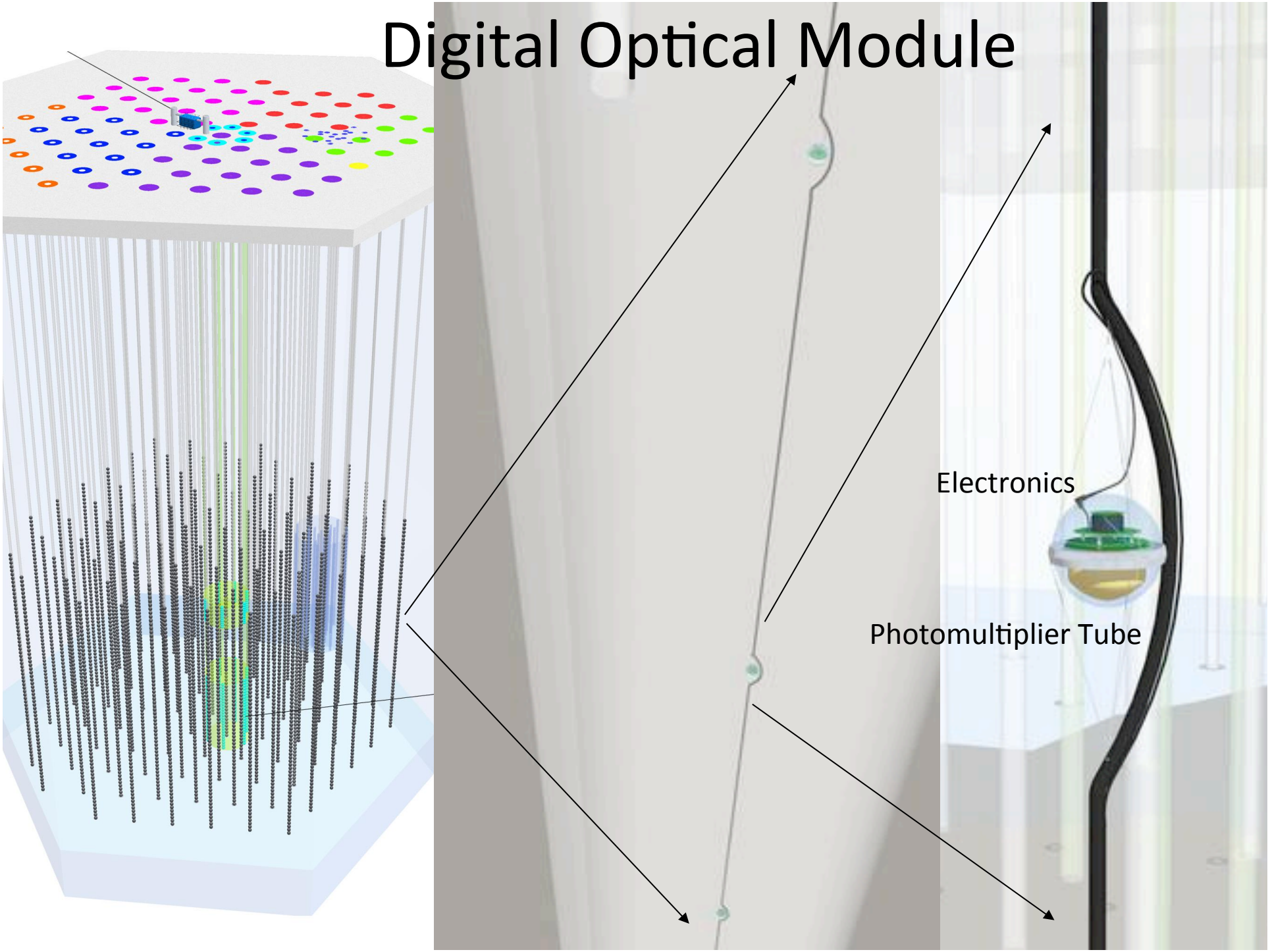
Began full operations May 2011

DeepCore
Low-energy Extension

Dark Matter,
Neutrino Oscillations



Digital Optical Module



D.O.M.

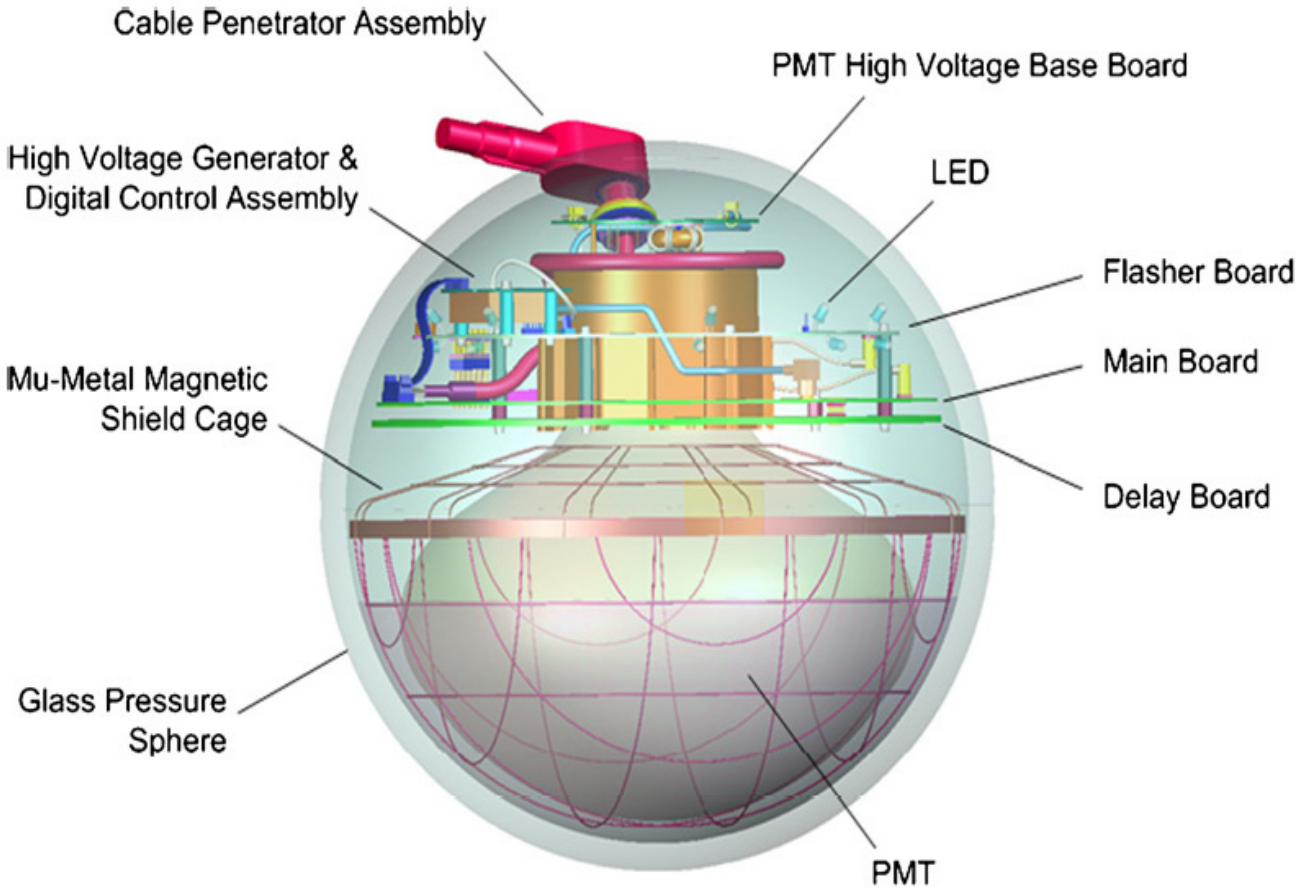
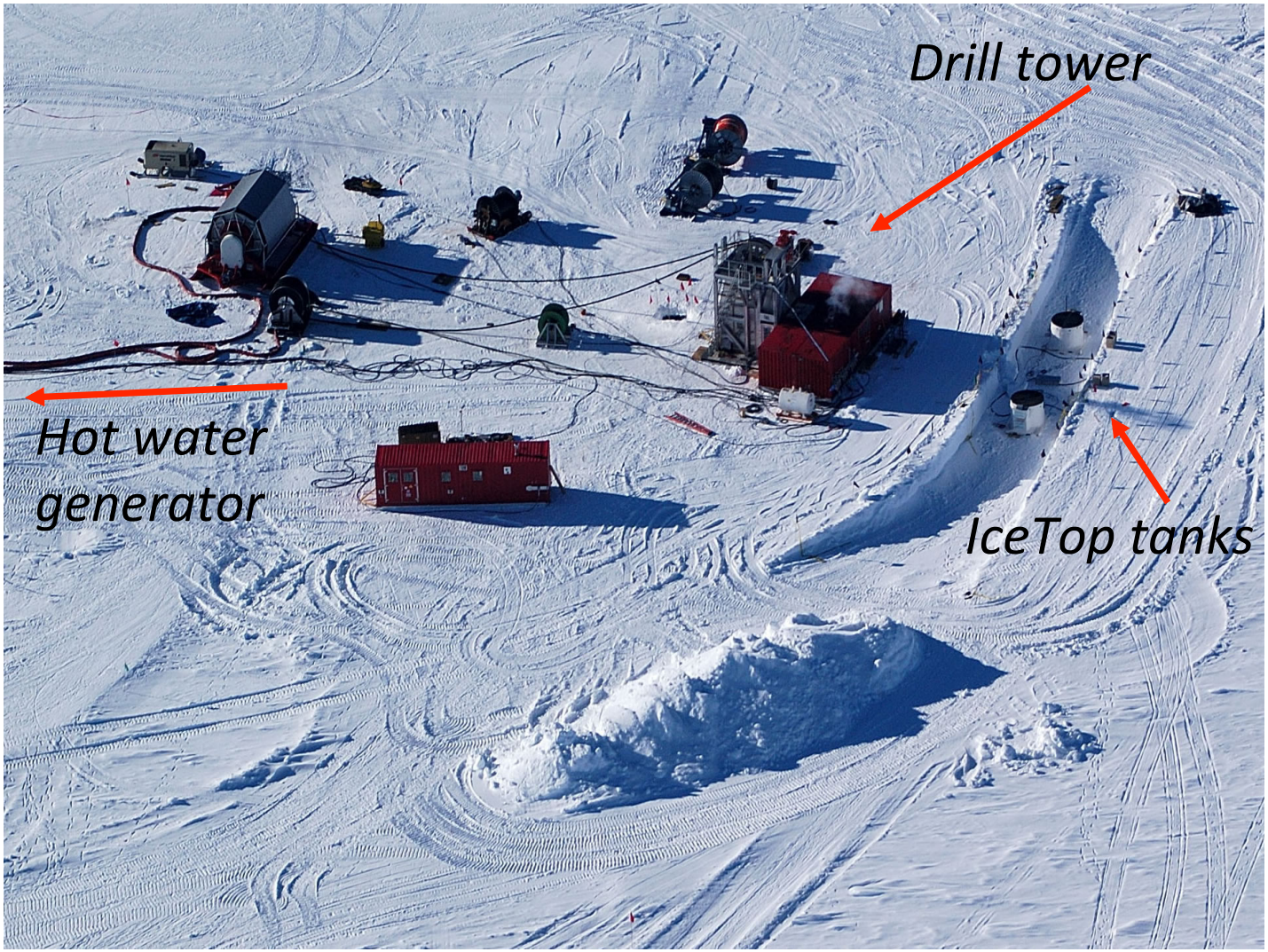


Fig. 3. A schematic view of an IceCube digital optical module.

Drilling Site

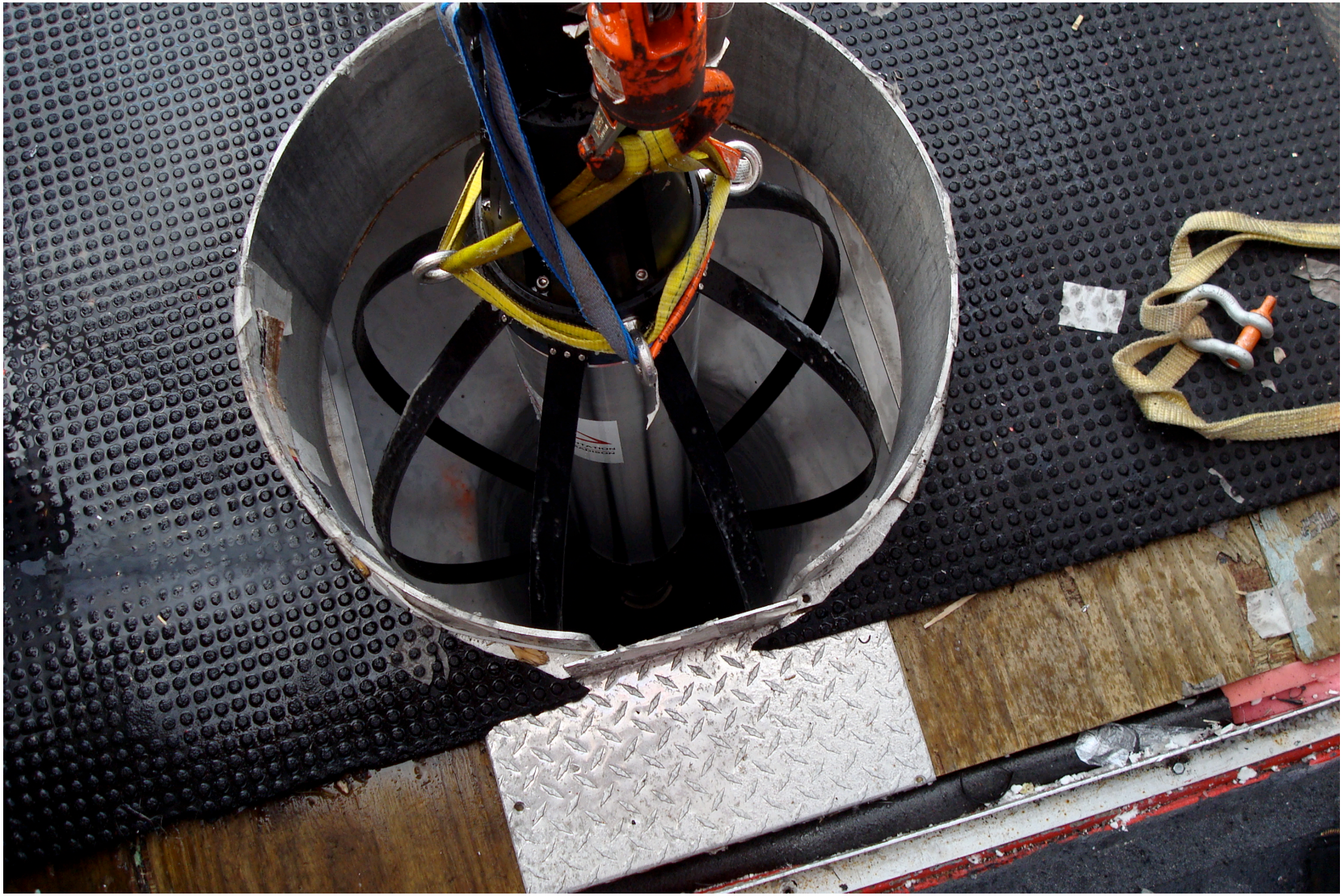


Drill Baby Drill!



- IceCube takes advantage of unique South Pole site
  - Existing logistical infrastructure
  - 2.8-km thick ice sheet
    - Serves as target and Cherenkov radiator
  - Relative ease of deployment with hot water drill
- Optical properties of ice are amazing
  - Measured in situ and in comparison to ice cores from nearby sites
  - absorption length ~**100—200** m
  - Low noise environment
- Detector is performing great
  - ~99% duty cycle
  - ~98% DOMs operating

Drill Baby Drill!



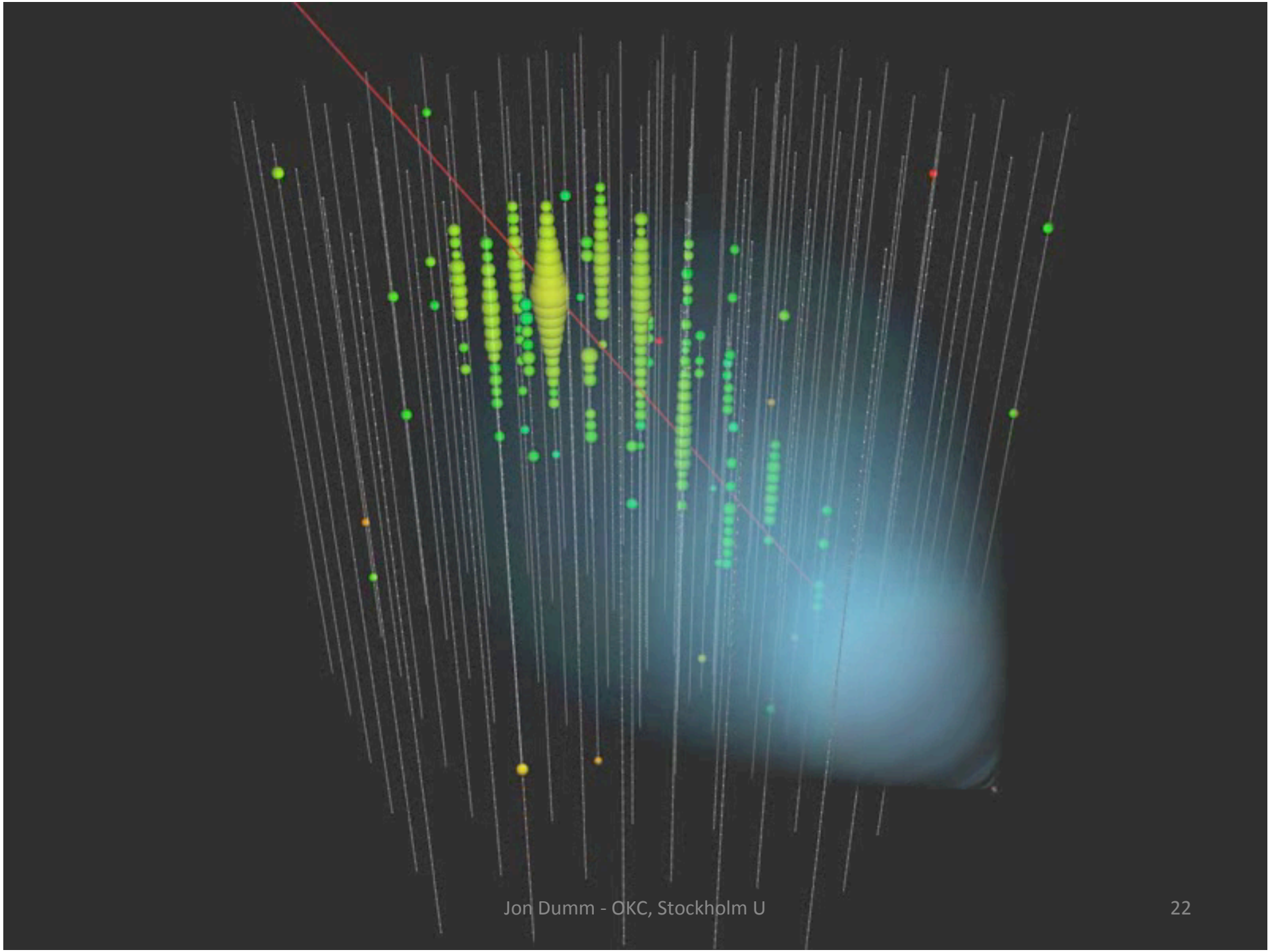
Drill Baby Drill!

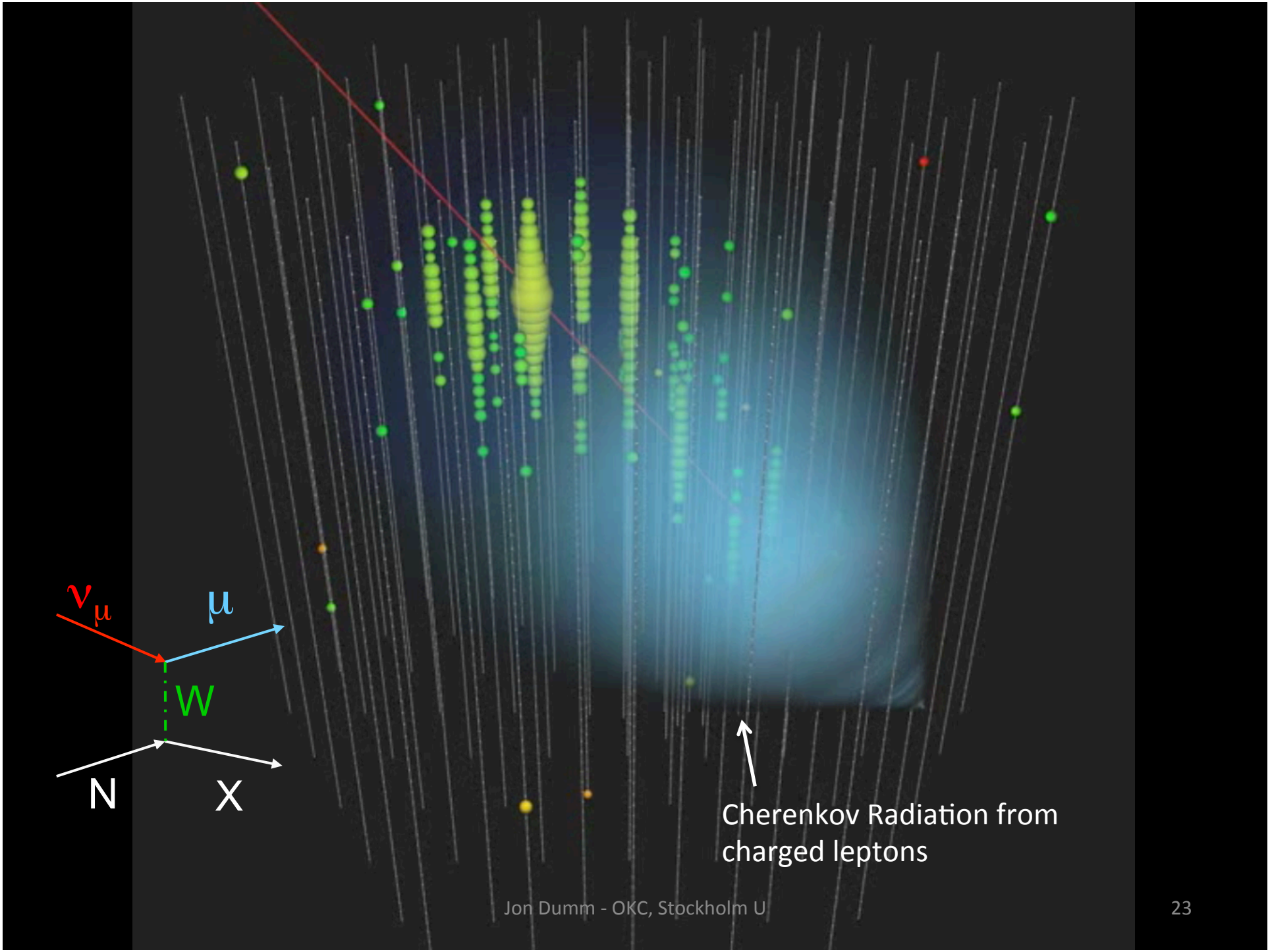


In Comparison...

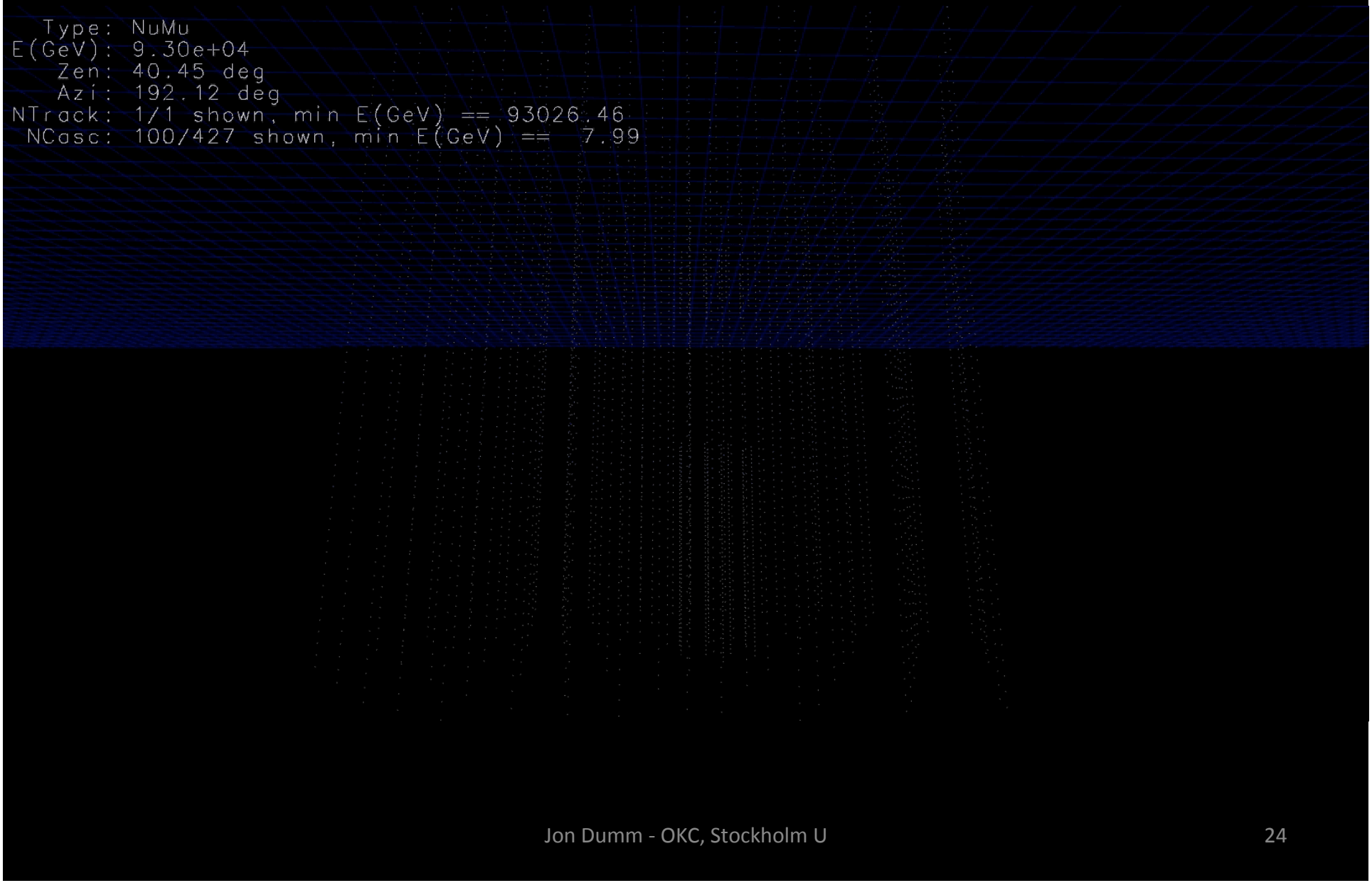
- South Pole more convenient than Mt. Etna!
- SLN site of a ASTRI/CTA prototype array



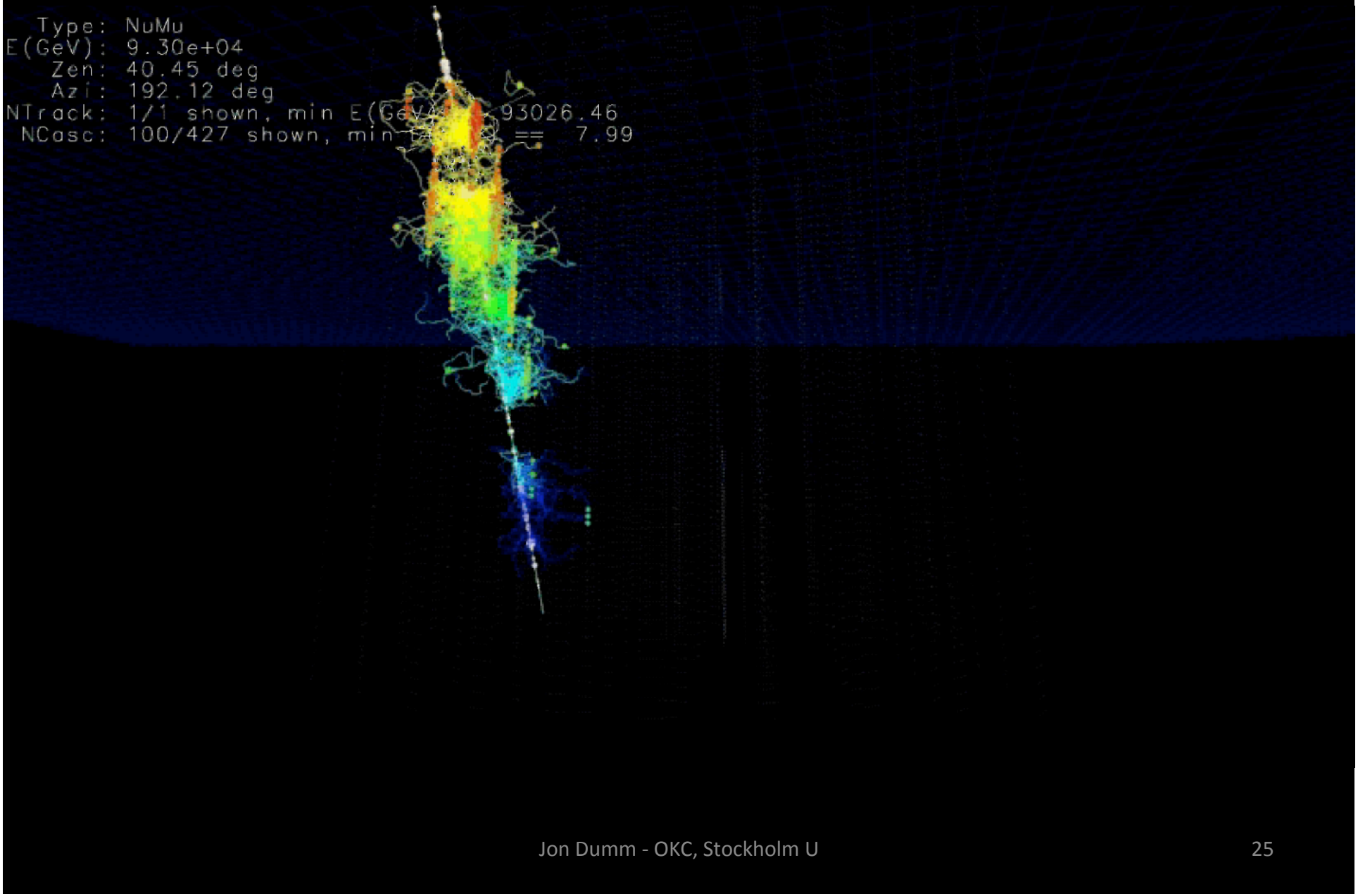



ν_μ
μ
W
N
X
Cherenkov Radiation from
charged leptons

93 TeV muon


Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

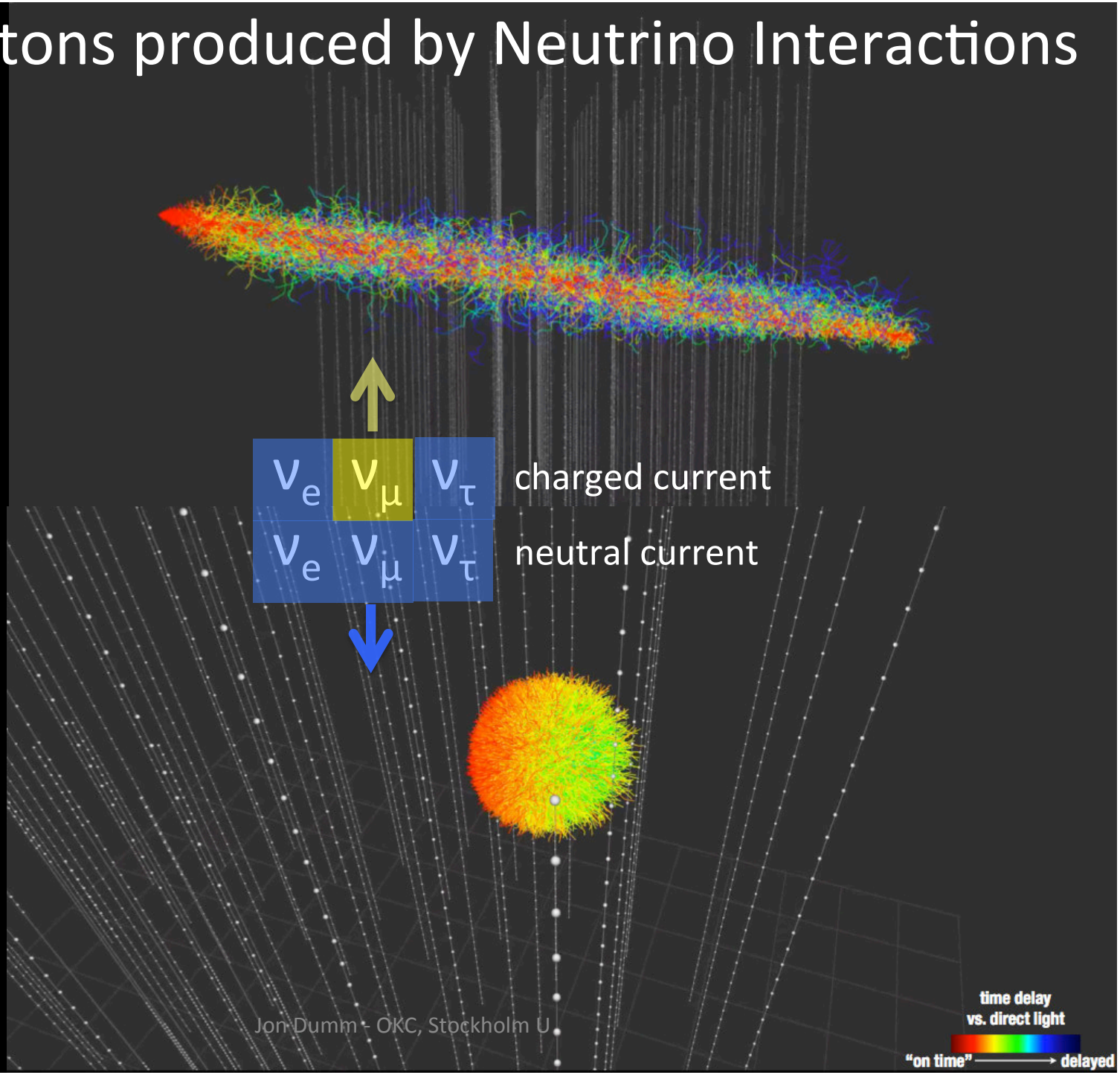
93 TeV muon


Type: NuMu
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Zen: 40.45 deg
Azi: 192.12 deg
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Photons produced by Neutrino Interactions

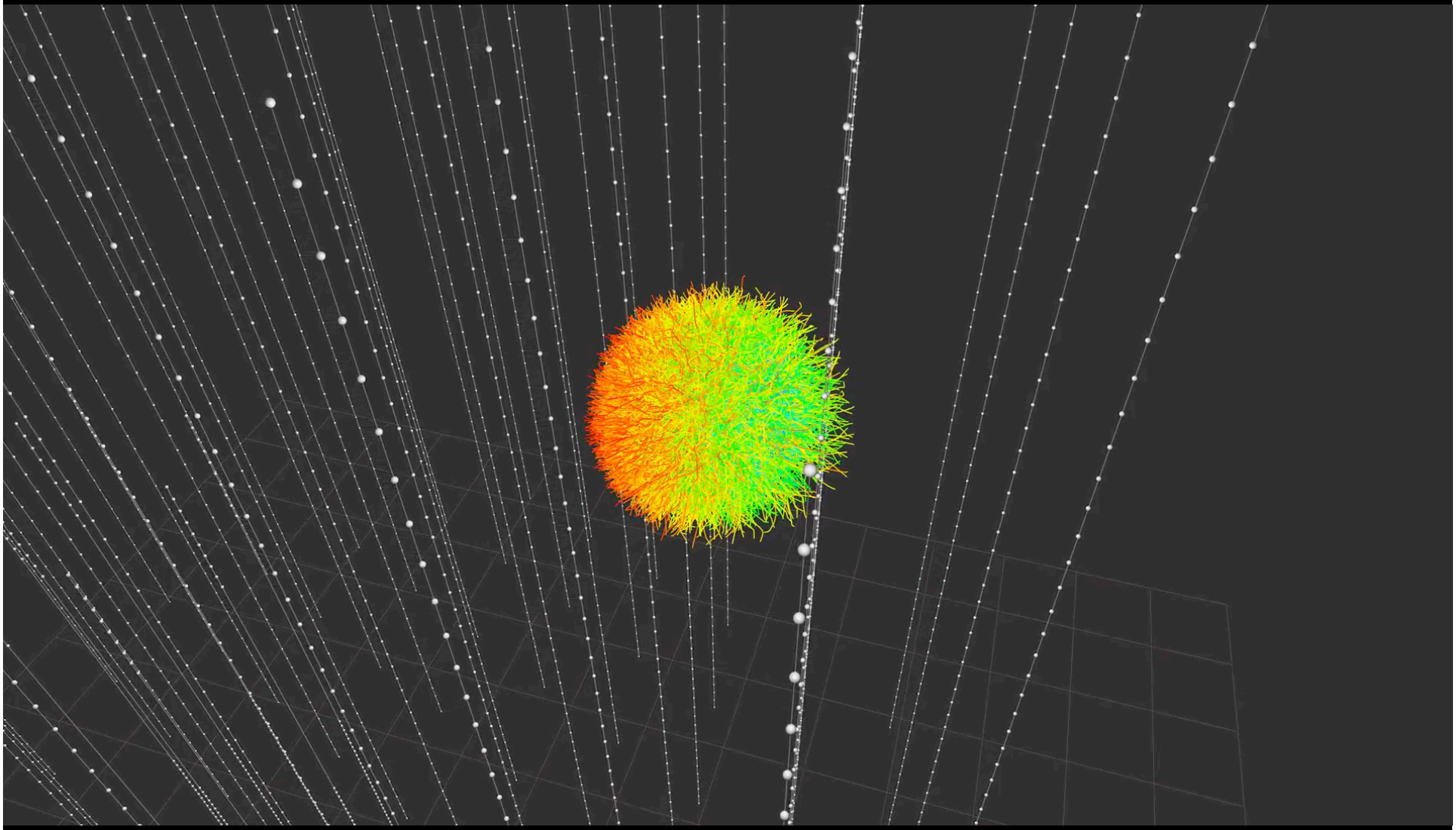
Track topology
(e.g. induced by muon neutrino)

Good pointing, 0.1° - 1°
Lower bound on energy



Cascade topology
(e.g. induced by electron neutrino)

Good energy resolution, 15%
Some pointing, 10° - 15°



IceCube Triggers Per Year

~ 100 000 000 000 triggered events – mostly muons from cosmic rays above ice

~ 100 000 neutrino events – mostly from cosmic ray air showers

~ 100 astrophysical neutrinos – that we estimate so far…

One person's background is another's signal...

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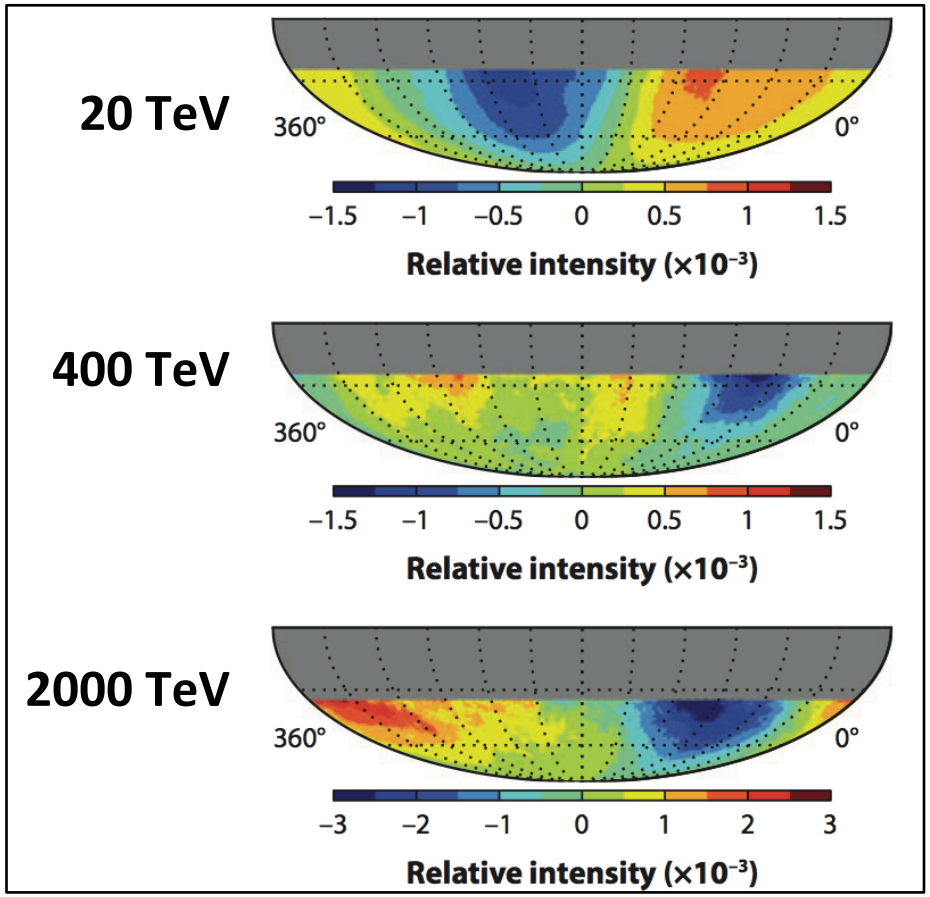
Cosmic Ray Anisotropy

Measured with

- IceCube events (20 TeV, 400 TeV)
- IceTop events (2000 TeV)

Large scale structure changes dramatically with energy

Gaisser & Halzen, Annu. Rev. Nucl. Part. Sci. 2014. 64:4.1–4.23
ApJL 718:L194 (2010);
ApJ 746:33 (2012); ApJ 765:55 (2013)



IceCube Triggers Per Year

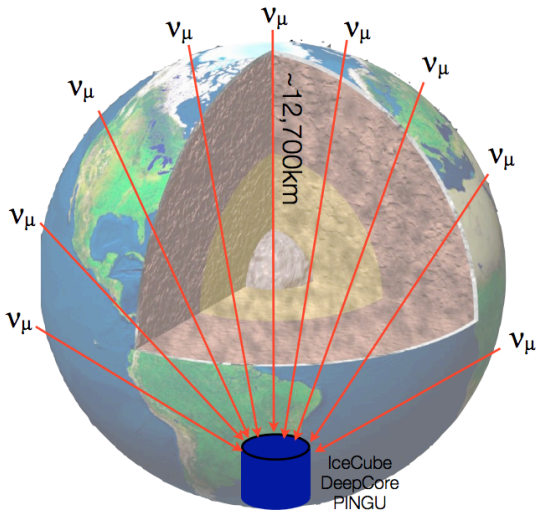
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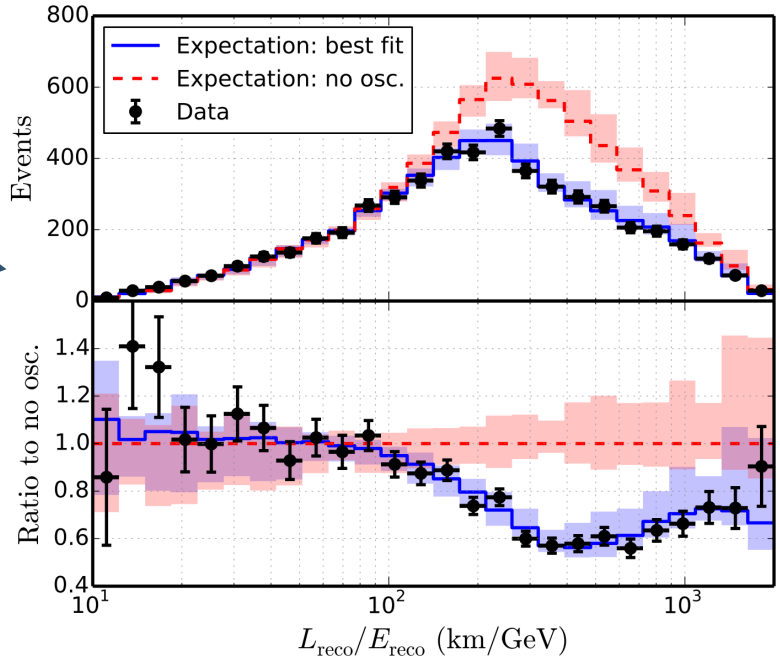
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~ 100 astrophysical neutrinos – that we estimate so far…

Measurement of **Neutrino Oscillation** parameters (IceCube-DeepCore)

L/E shown for illustration: Full analysis performed with 2D representation





IceCube Triggers Per Year

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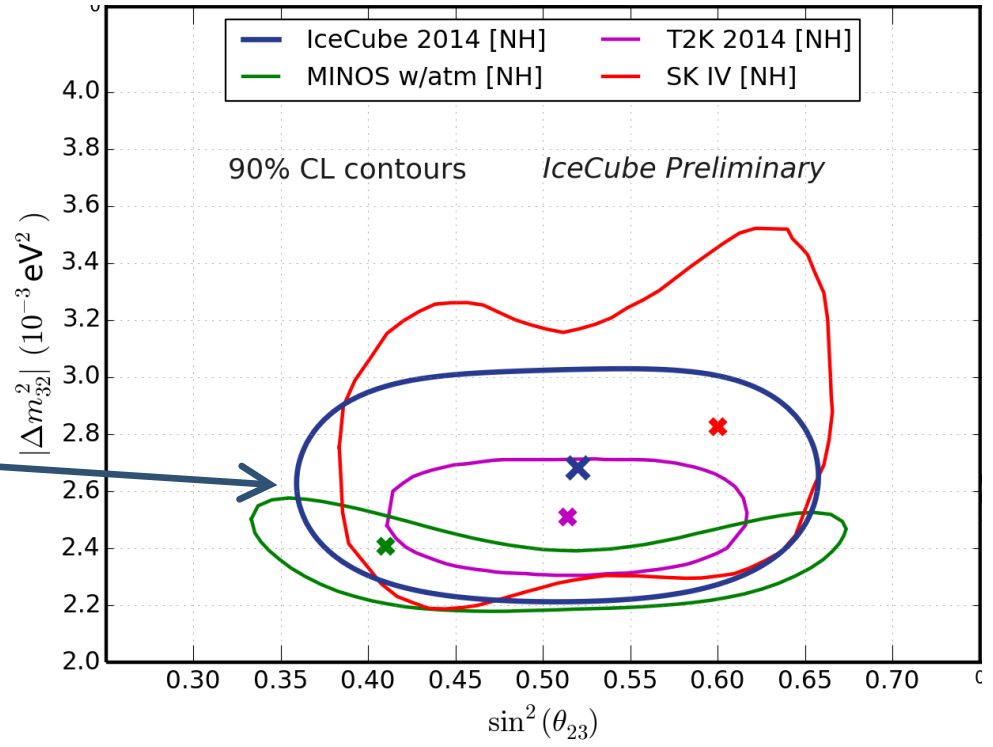
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Measurement of **Neutrino Oscillation** parameters (IceCube-DeepCore)

1-year analysis: PRL **111**, 081801 (2013)

3-year analysis: preliminary (arXiv:1410.7227)

Pathway to future **PINGU** low-energy extension detector for precision measurements and determination of **Neutrino Mass Hierarchy**



IceCube Triggers Per Year

~ 100 000 000 000 triggered events – mostly muons from cosmic rays above ice

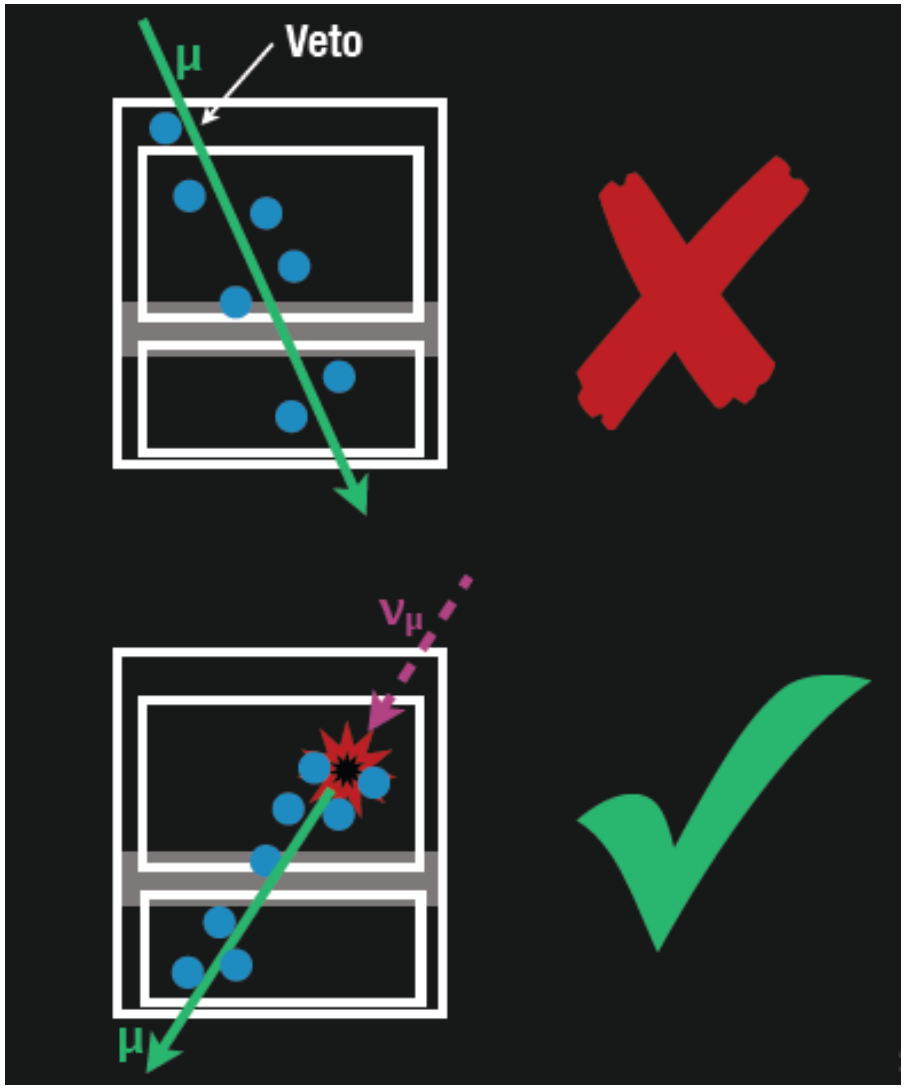
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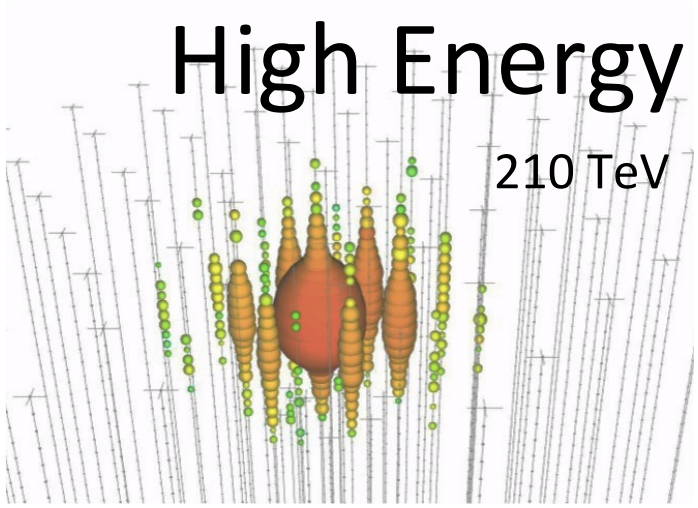
- Many techniques to pick out these few most interesting events...
  - High Energy Starting Event (HESE) analysis
    - mostly sensitive to 'cascades'
  - Muon neutrino diffuse analysis
    - only sensitive to muon 'tracks'
  - Point source analysis
    - Source class scenarios

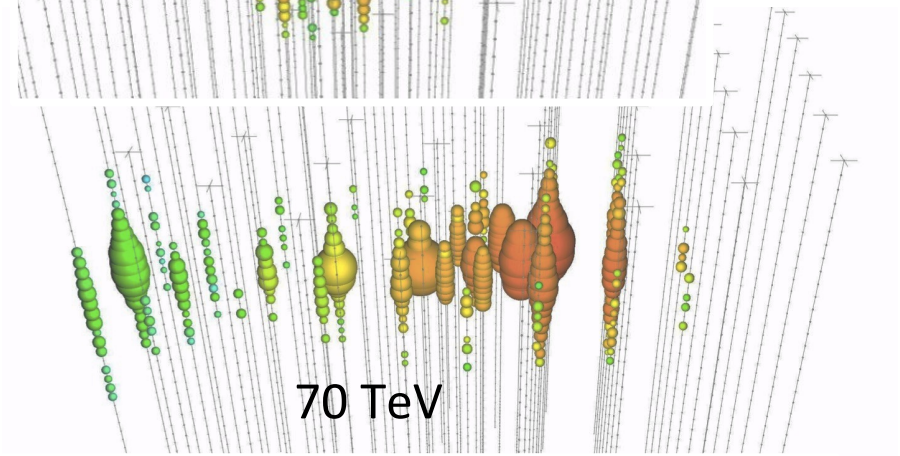
High Energy Starting Events

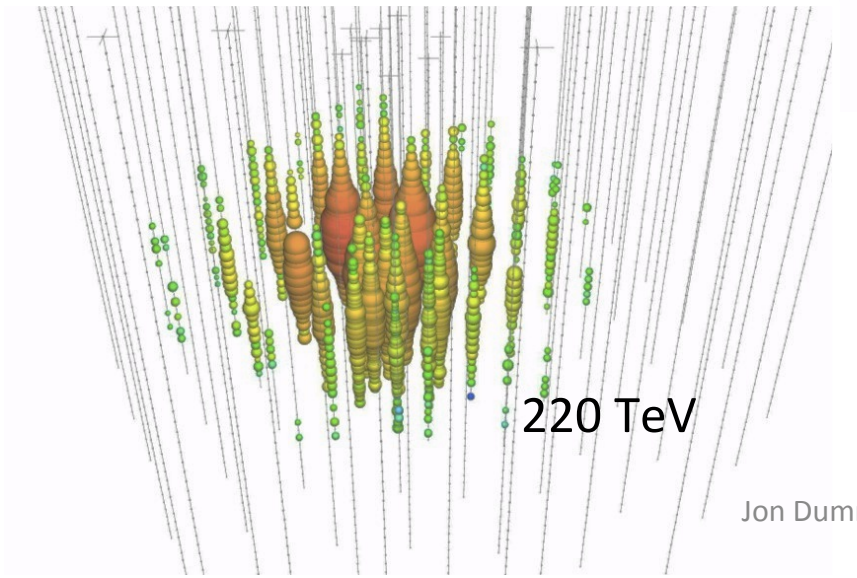
- Two simple cuts
  - Contained (420 Mton)
  - Bright (6000 p.e.)
- Good calorimetry
- Complete sky coverage
  - atm. nu self-veto
- Dominated by cascades
  - Some good tracks too
- High event quality
  - despite low event counts

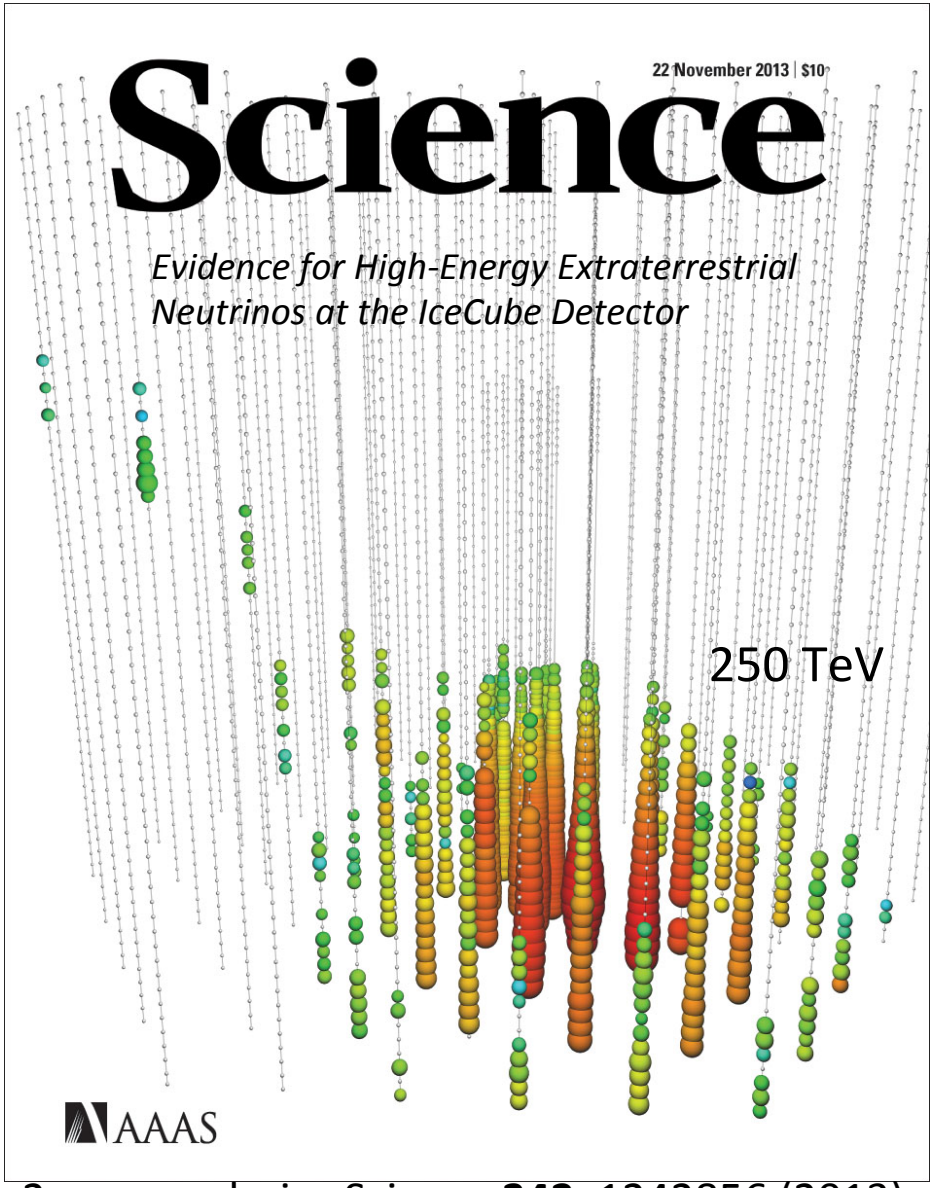


High Energy Starting Event Analysis









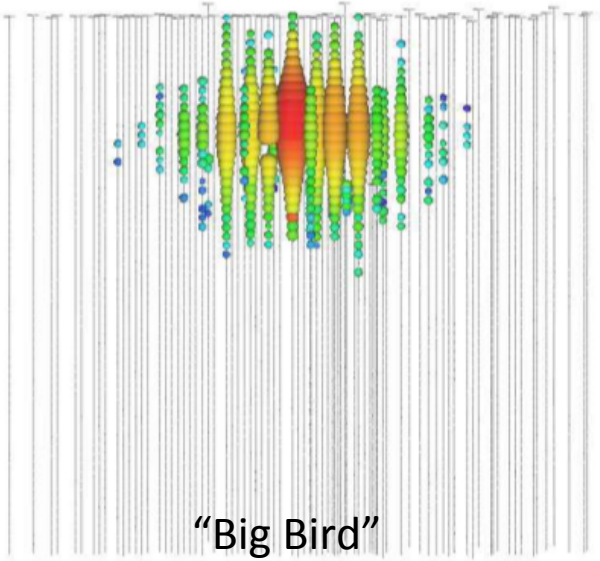
2-year analysis: Science **342**, 1242856 (2013)

High Energy Starting Event Analysis

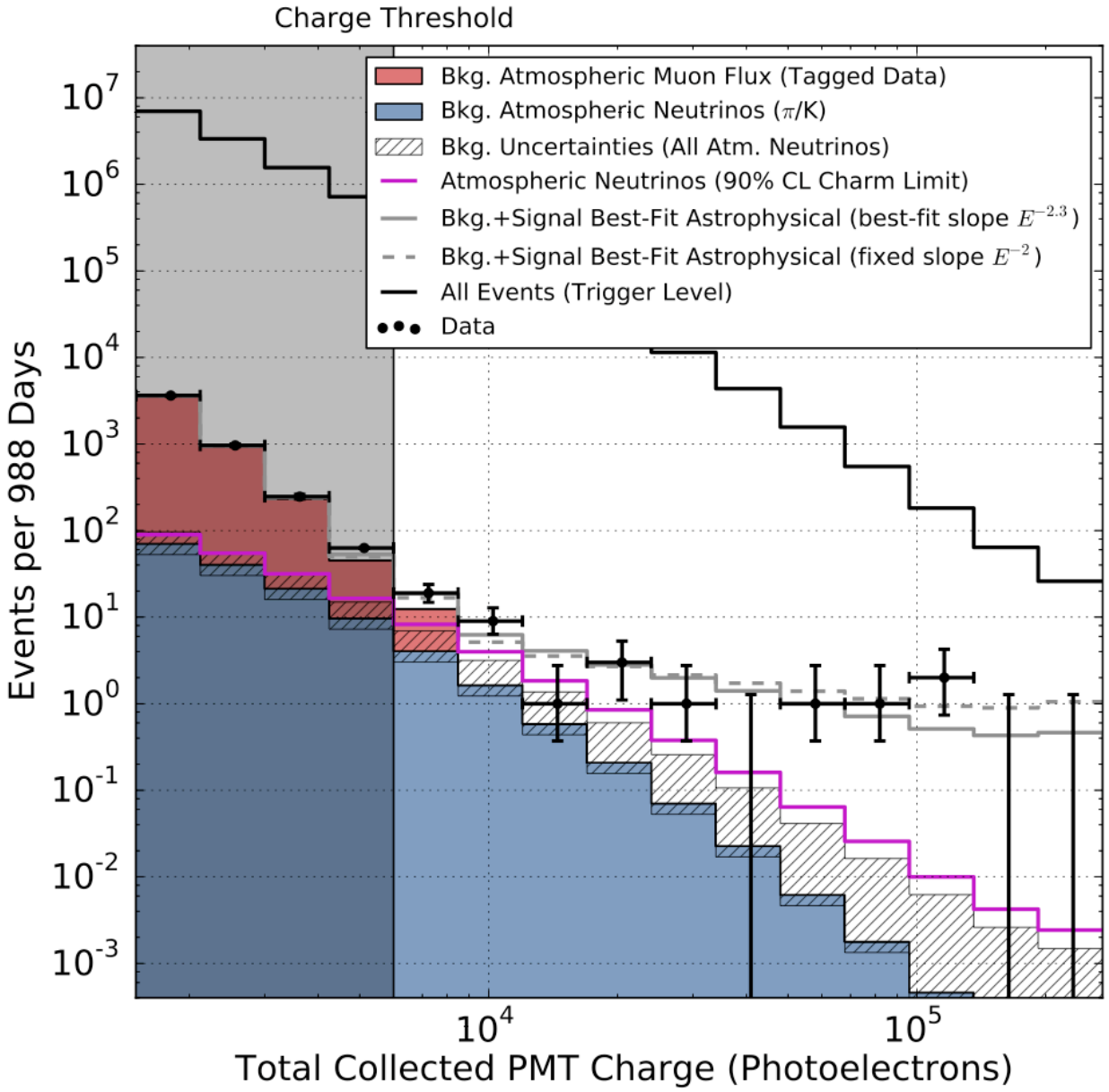
3-Year Analysis
PRL **113**, 101101 (2014)

36 events & **5.7 σ**
(~1/2 expected to be background)

Three > PeV events seen in three years, including a 2-PeV neutrino



"Big Bird"



High Energy Starting Event Analysis

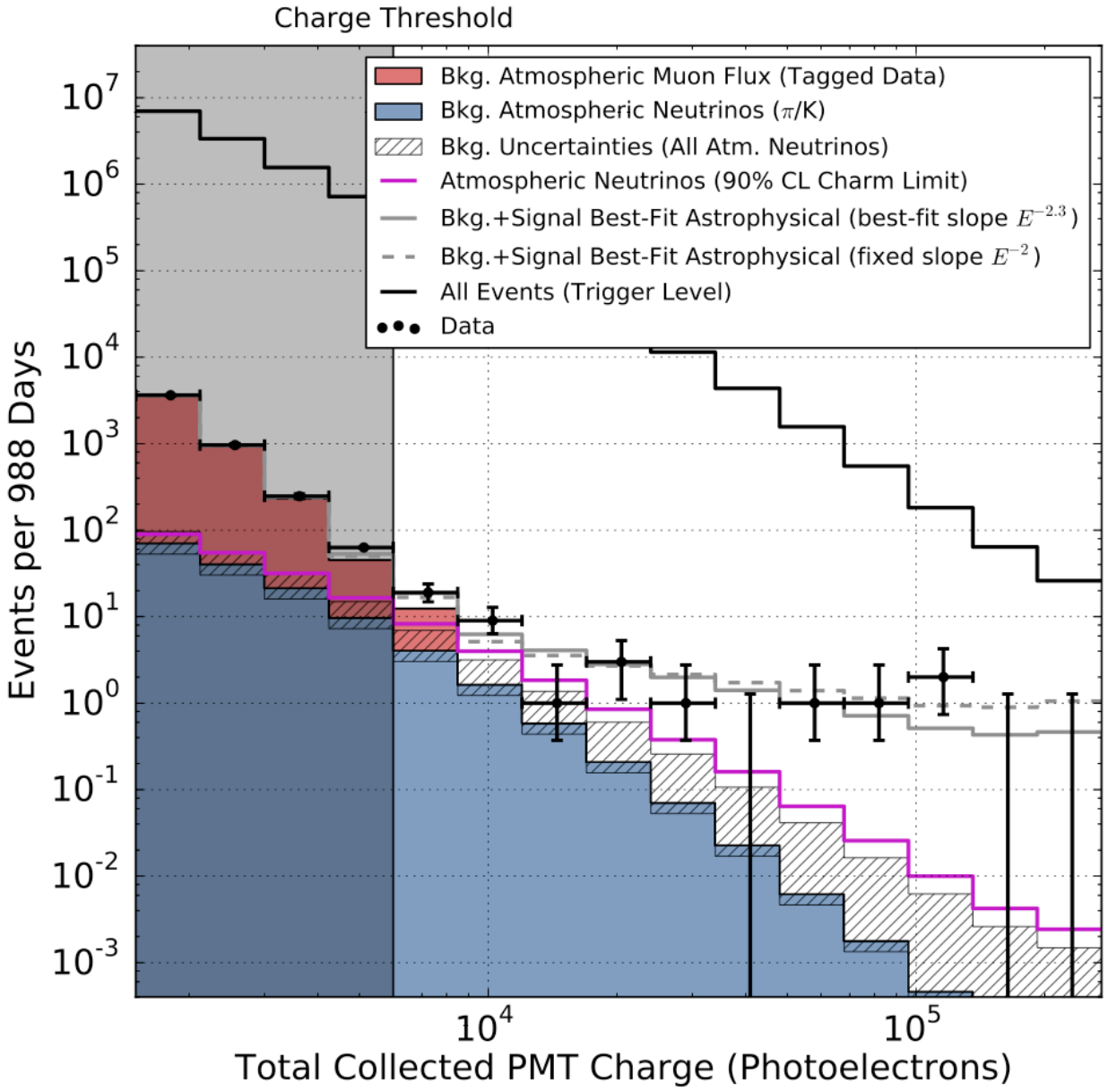
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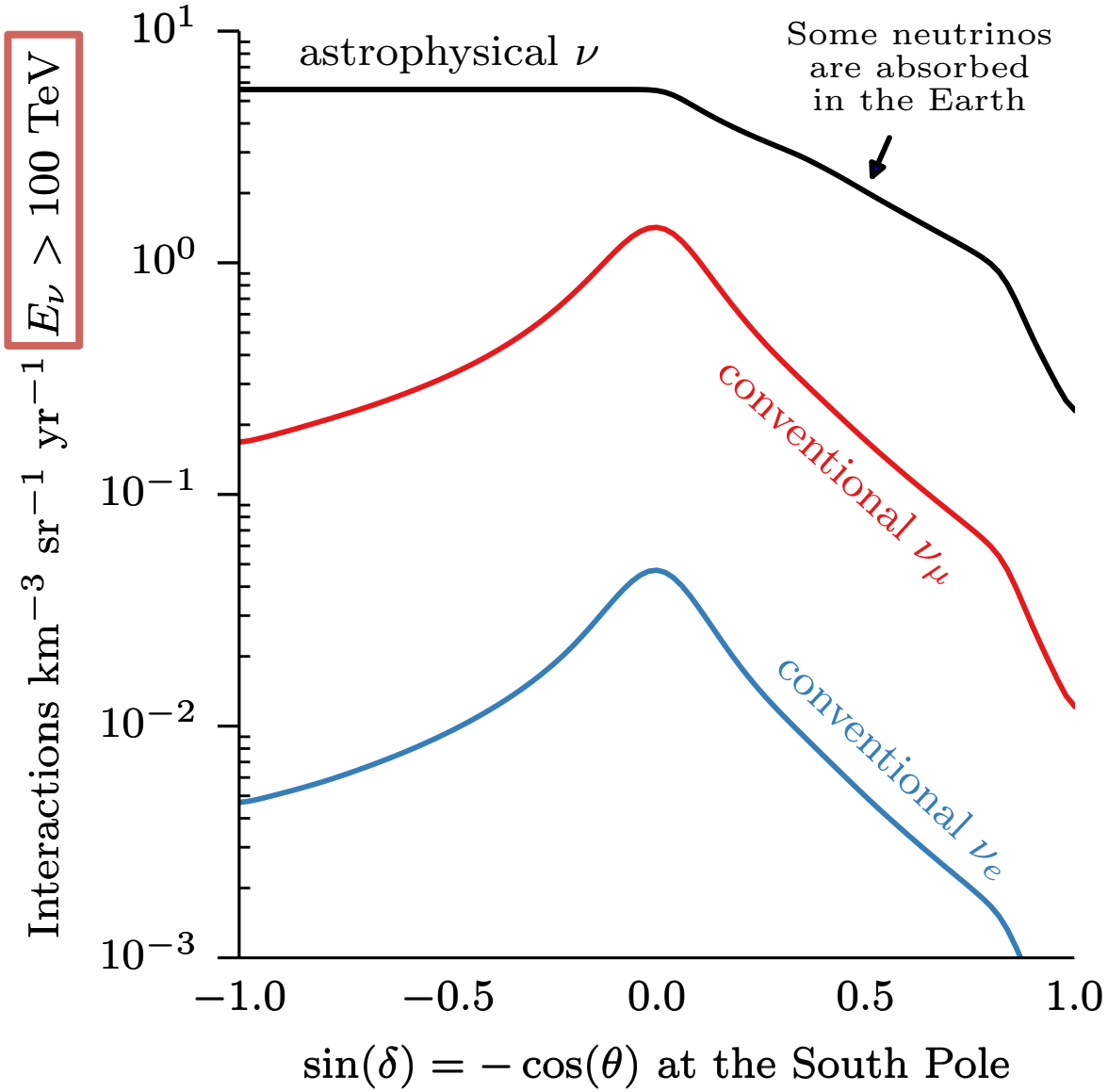
Three > PeV events seen in three years, including a 2-PeV neutrino

Astrophysical component fit depends on
- **number**,
- **energy**, and
- **direction**

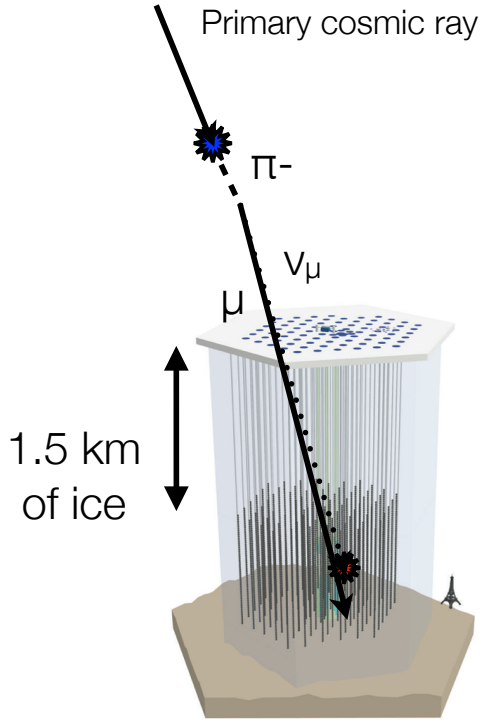
Shape of signal and background different for both energy (shown here) and zenith angle



Atmospheric Neutrino Self-veto



An active muon veto removes down-going atmospheric neutrinos.

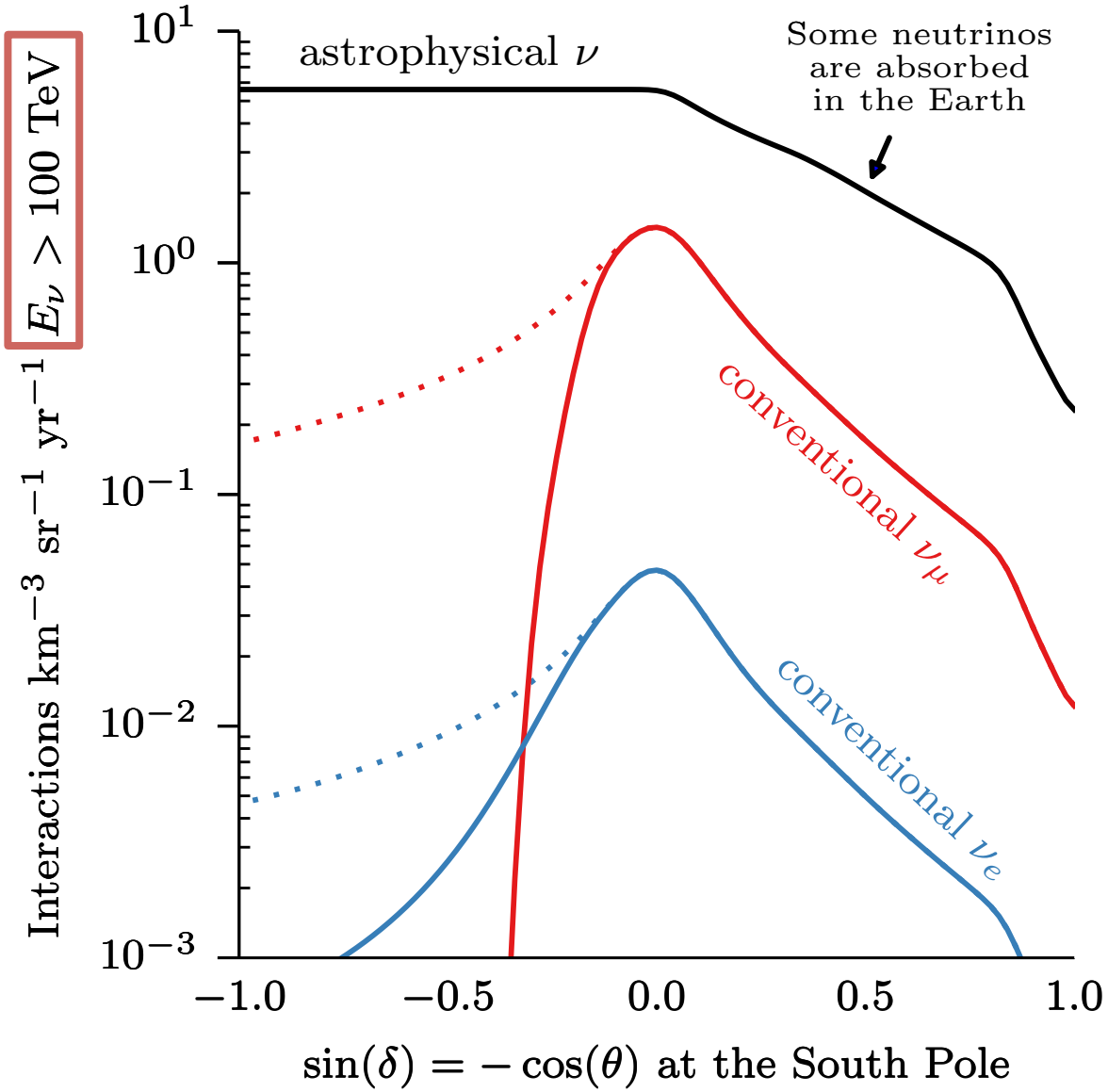


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

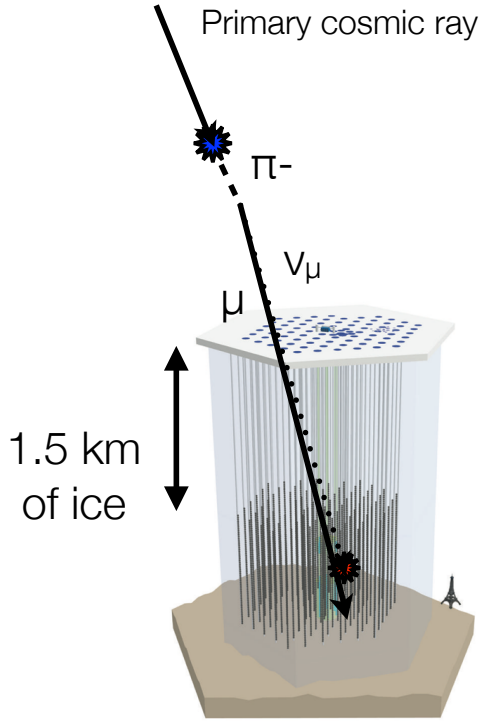
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Adapted from slides by Jakob van Santen

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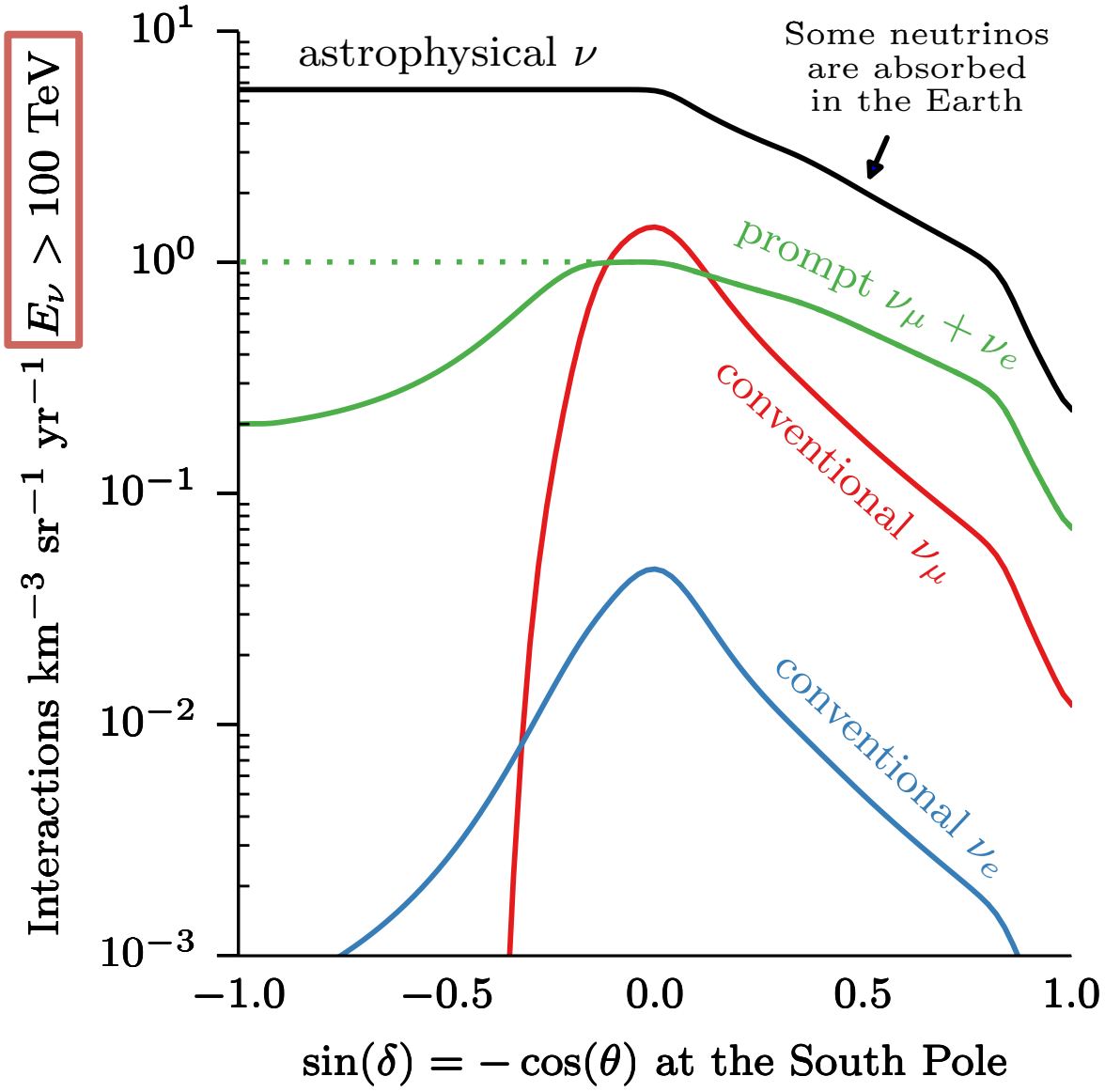


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

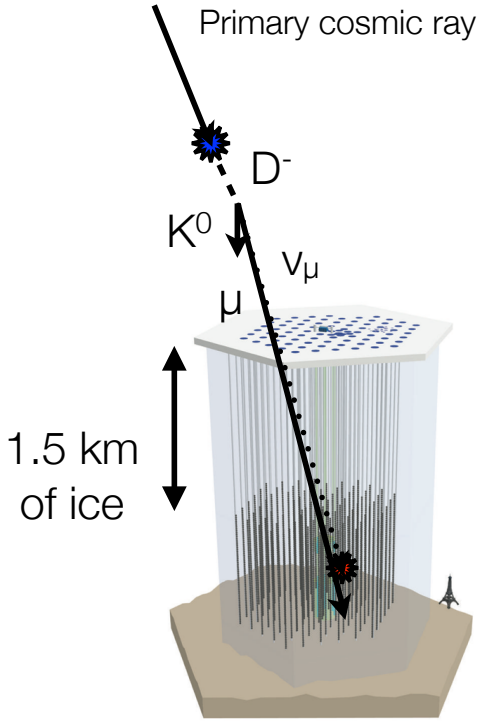
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Adapted from slides by Jakob van Santen

Atmospheric Neutrino Self-veto



Prompt atmospheric neutrinos are vetoed, too.

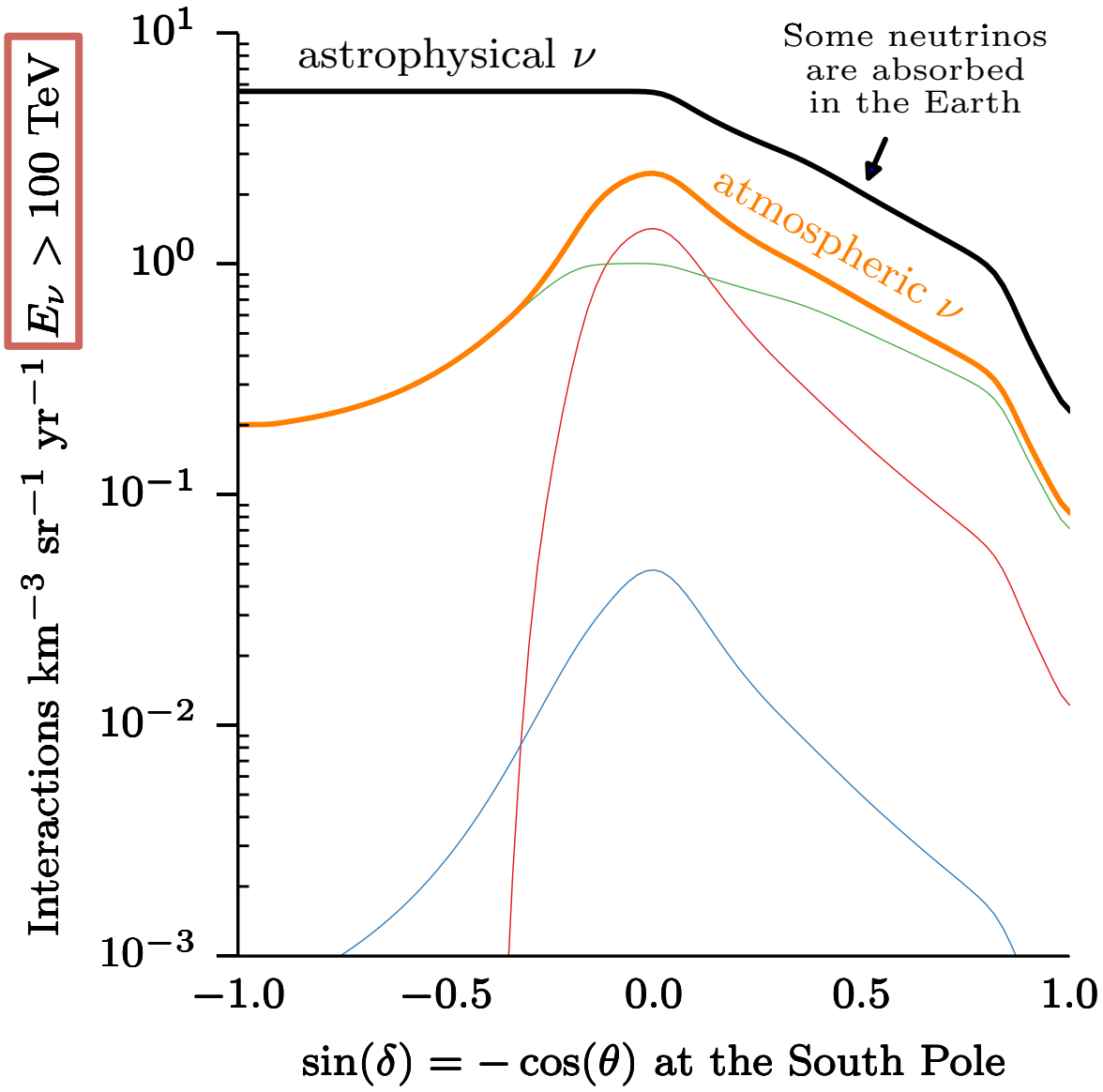


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

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Atmospheric Neutrino Self-veto



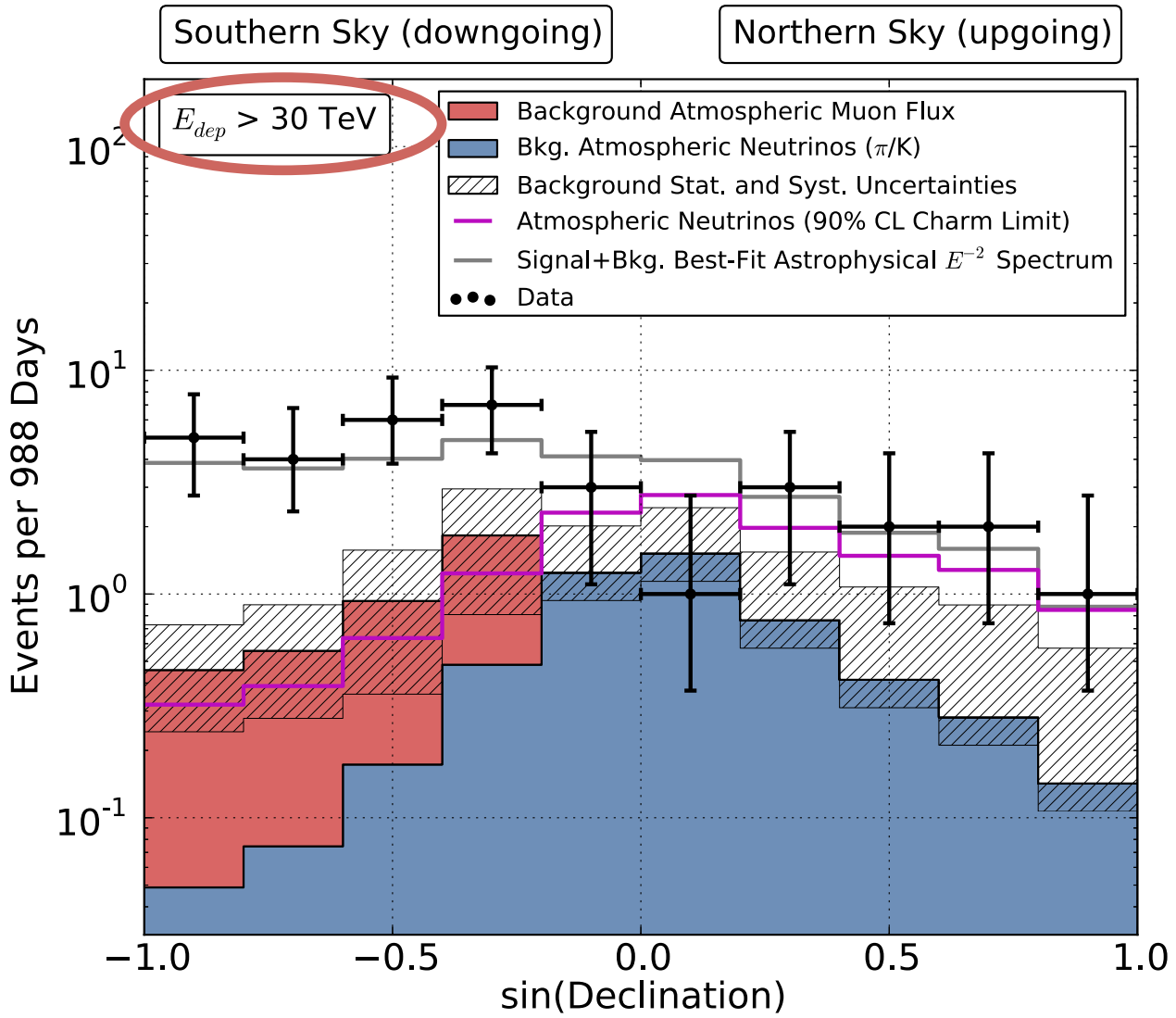
The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

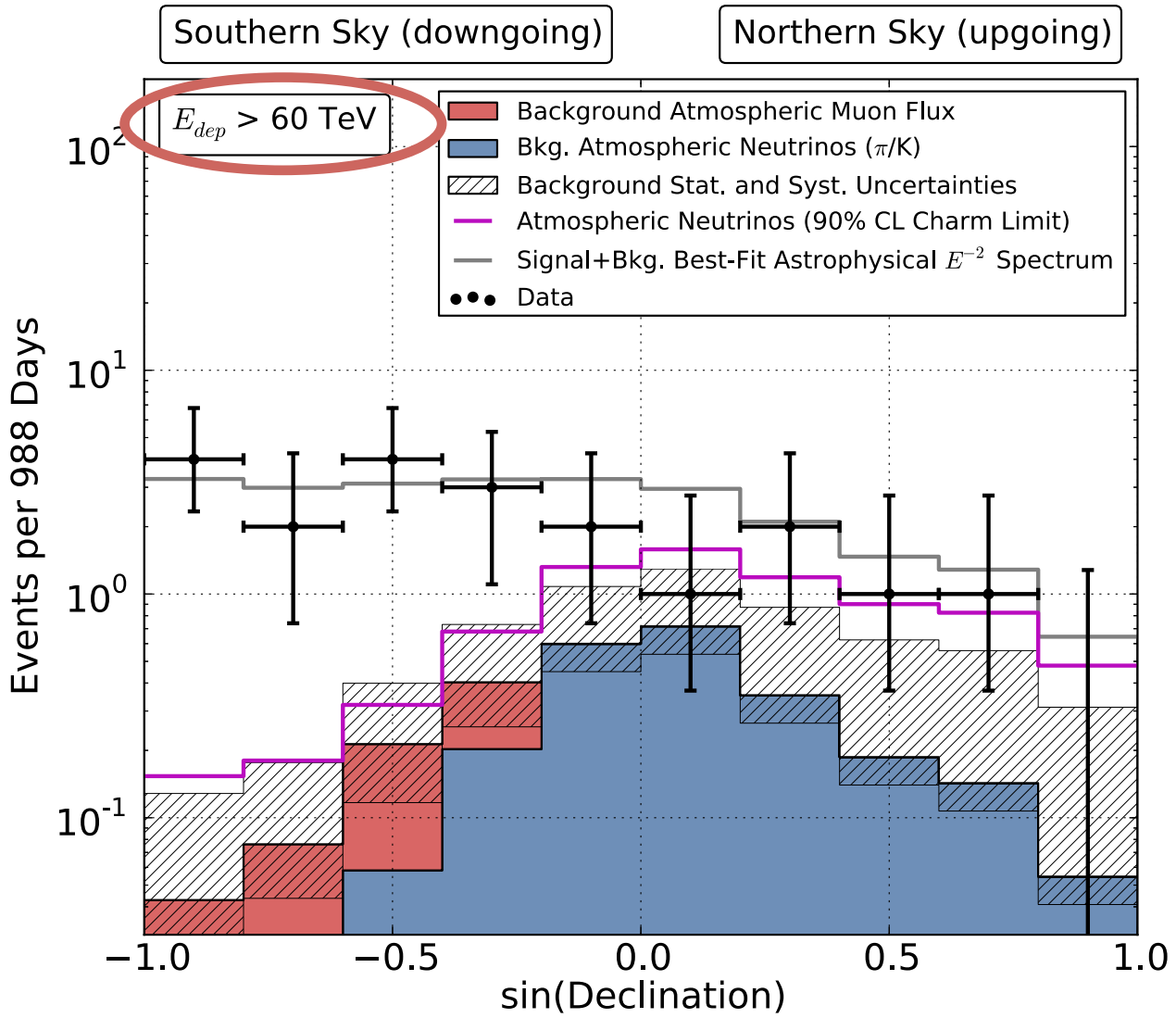
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

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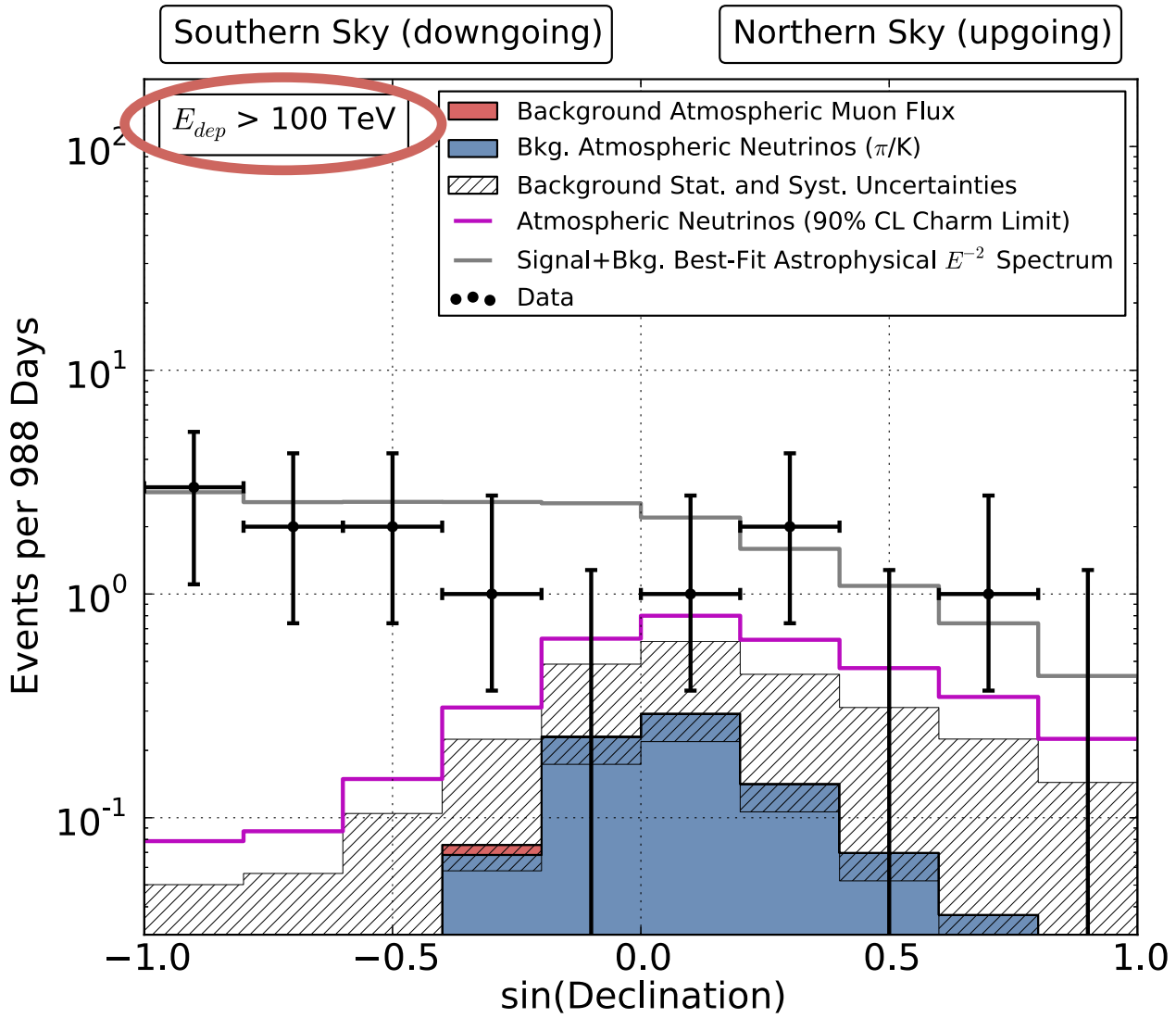
3-Year
High Energy
Starting Event
Analysis



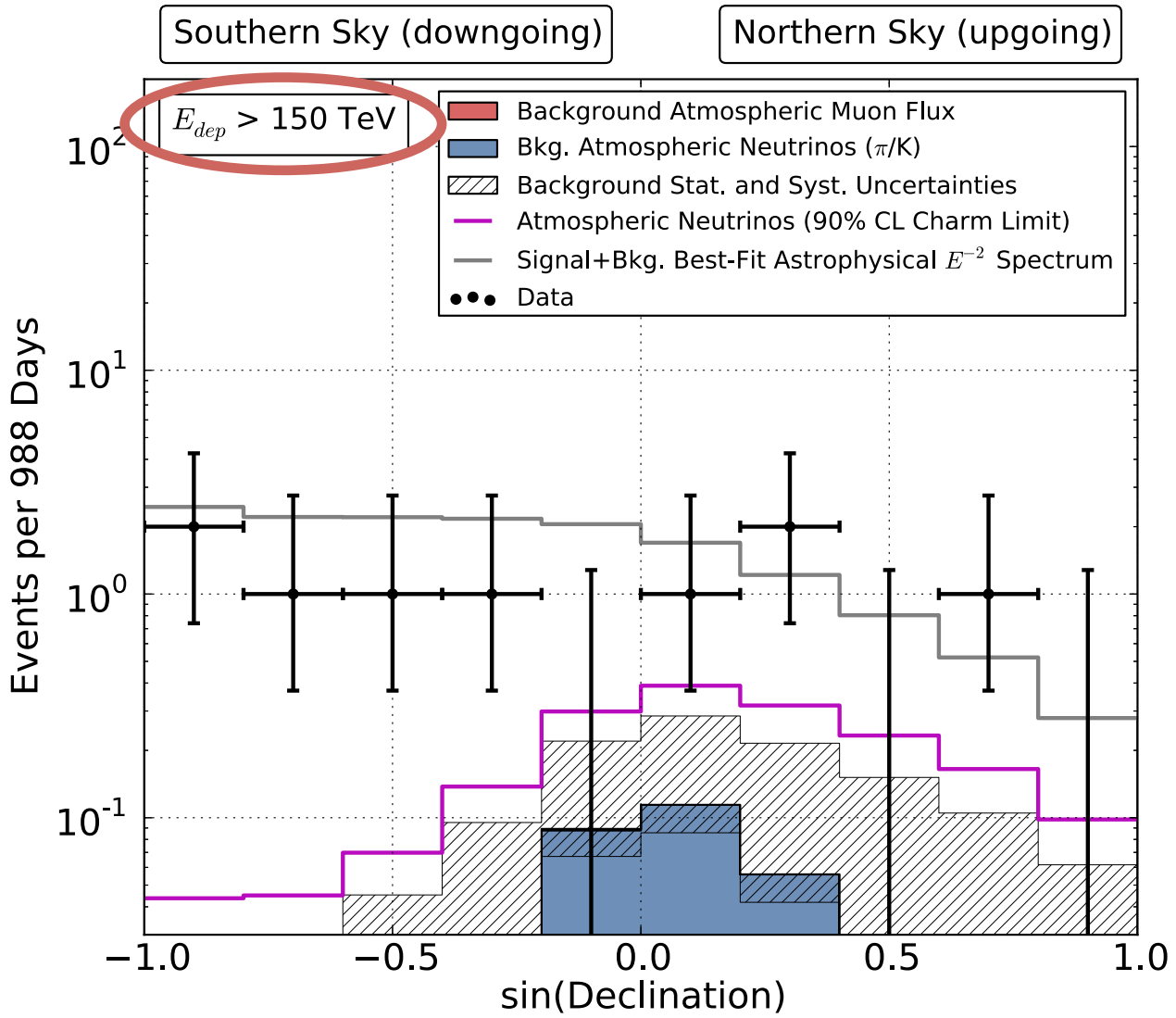
3-Year
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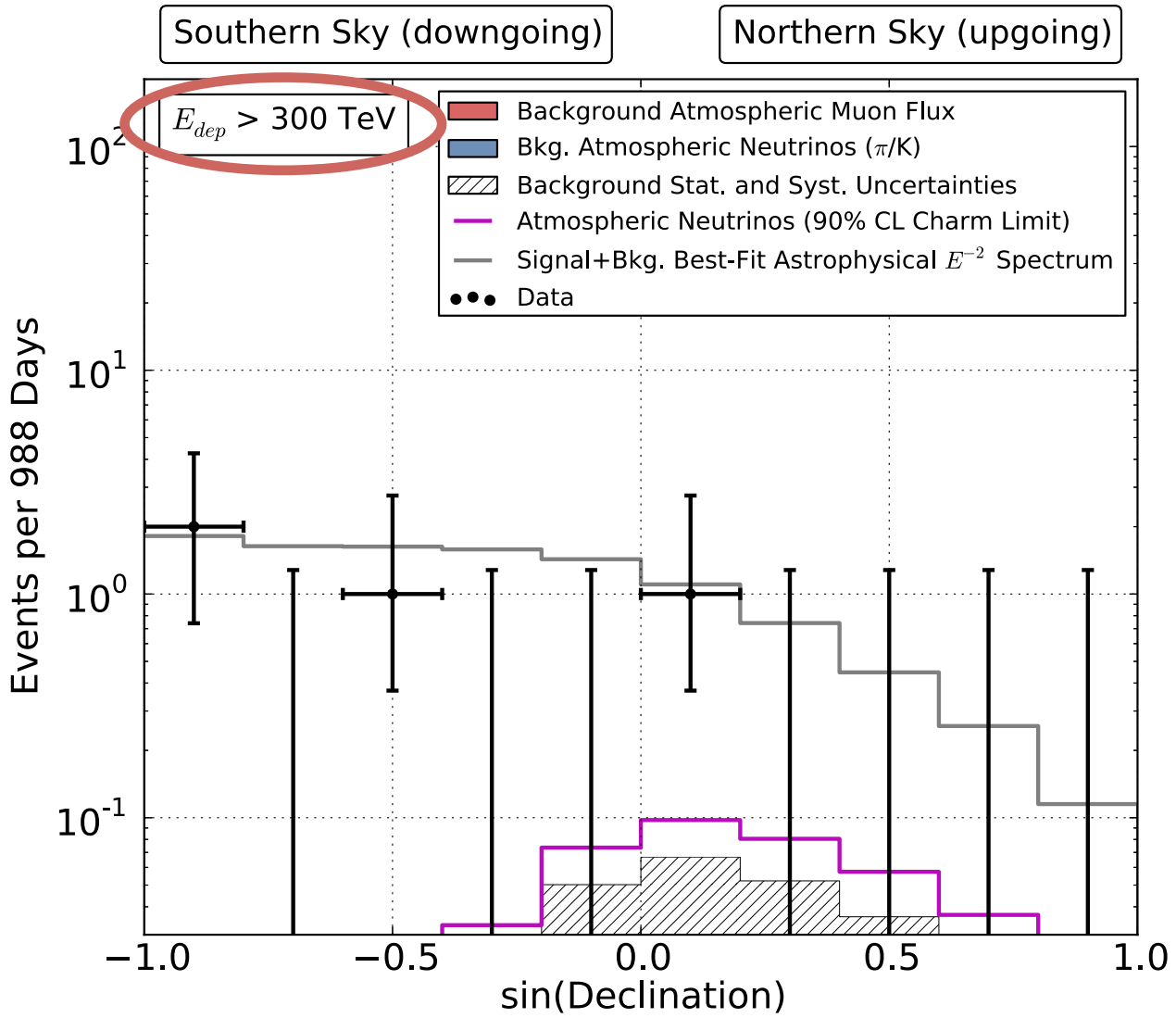
3-Year
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3-Year
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3-Year
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Starting Event
Analysis



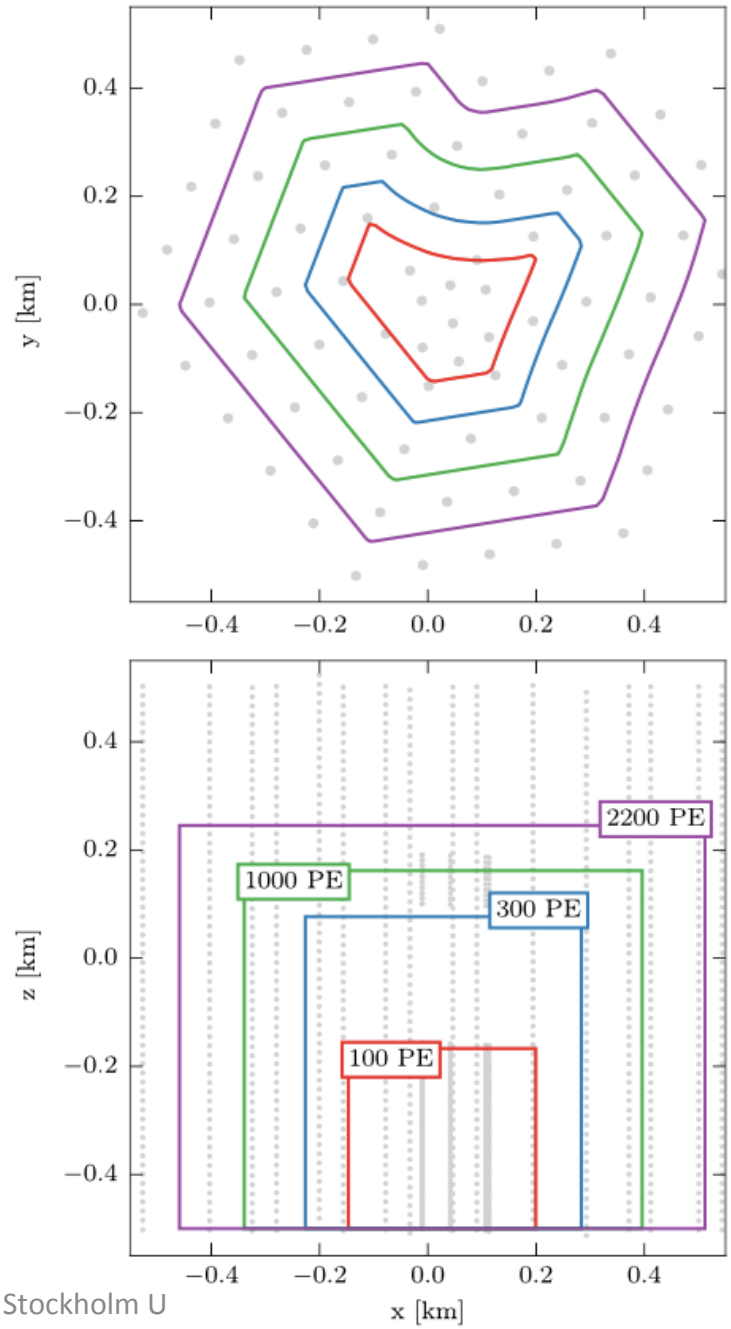
More sophisticated analysis published this fall: PRD 91:022001 (2014)

Nested layers of vetoes

Series of lower energy thresholds

388 events selected in 2 years of data

87 ± 14 astrophysical neutrinos



High Energy Starting Event Analysis

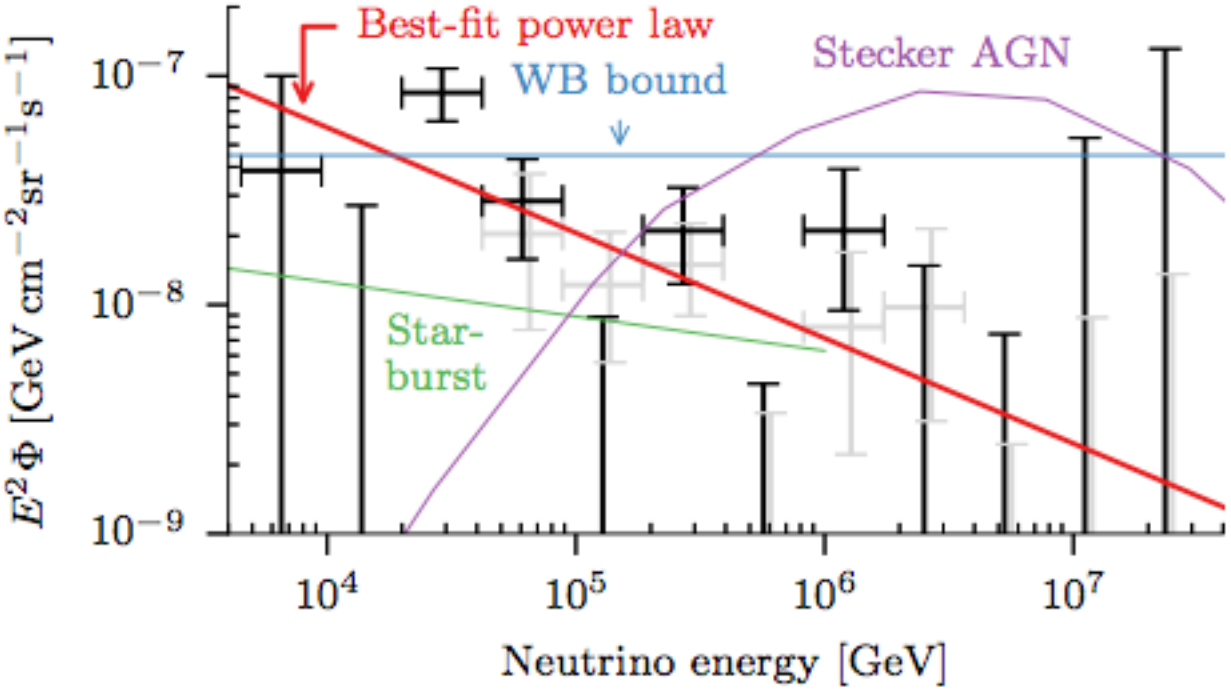
Latest spectral results: [arXiv:1410.1749]

$$\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} \left(E_\nu/10^5 \text{ GeV}\right)^{-2.46\pm0.12} \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$$

Assuming an unbroken power law, standard expectation of **E^{-2} disfavored at 99% CL**

Atmospheric charmed-meson cross section limited to **< 1.52 x ERS** (benchmark) 90% CL

ERS ref: R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008)



Muon Neutrino Diffuse Analysis

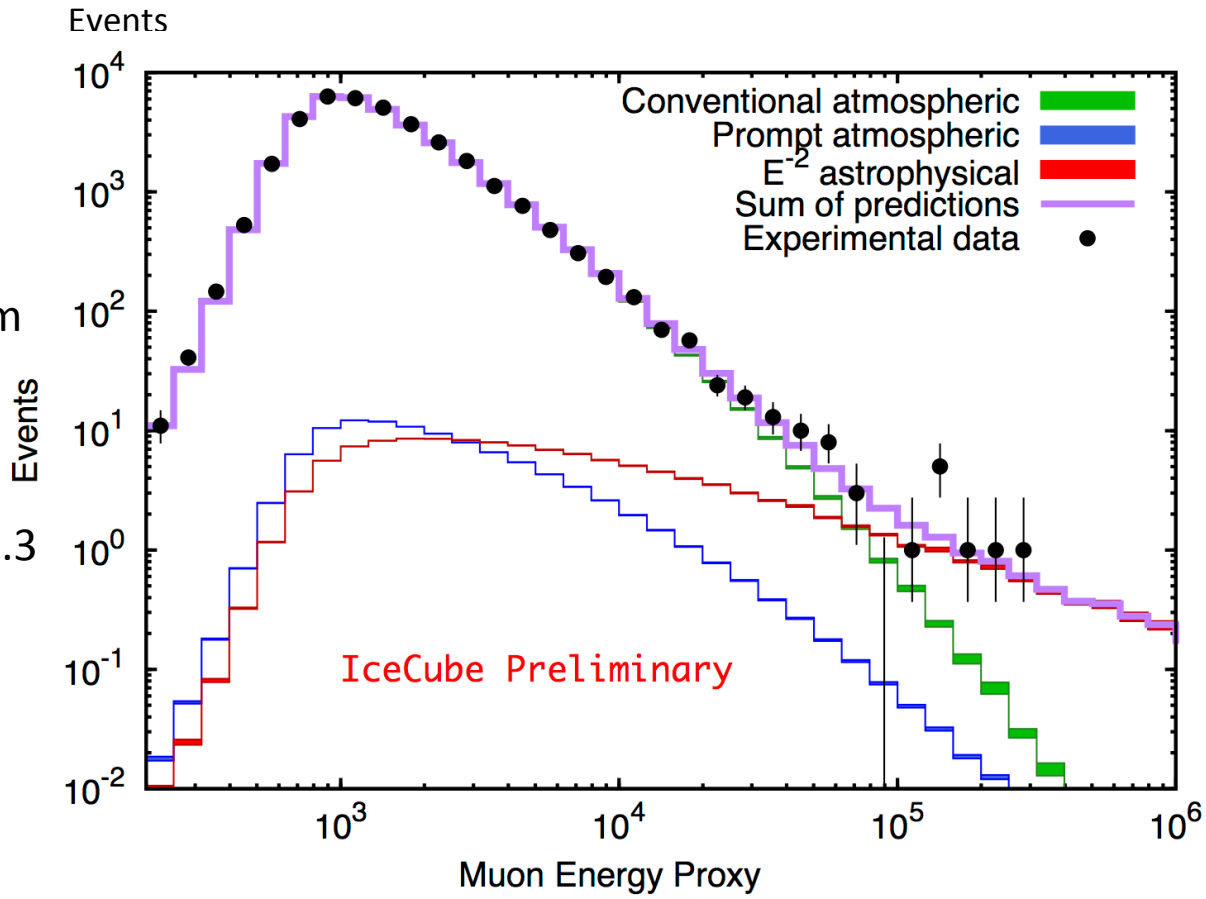
Complementary analysis to Starting Event analysis

Northern sky – allow events to enter from **outside** detector, use Earth as filter against muons from cosmic rays

Good pointing: ~ 0.5°
$\log_{10}$ muon energy resolution ~ 0.3 (at energies ~ 100 TeV)

35 000 events in 2-year analysis

Estimated 99.9% pure muon neutrino sample



Energy estimate for the muon track.
Only lower-bound on neutrino energy
(interacted before reaching detector)

Muon Neutrino Diffuse Analysis

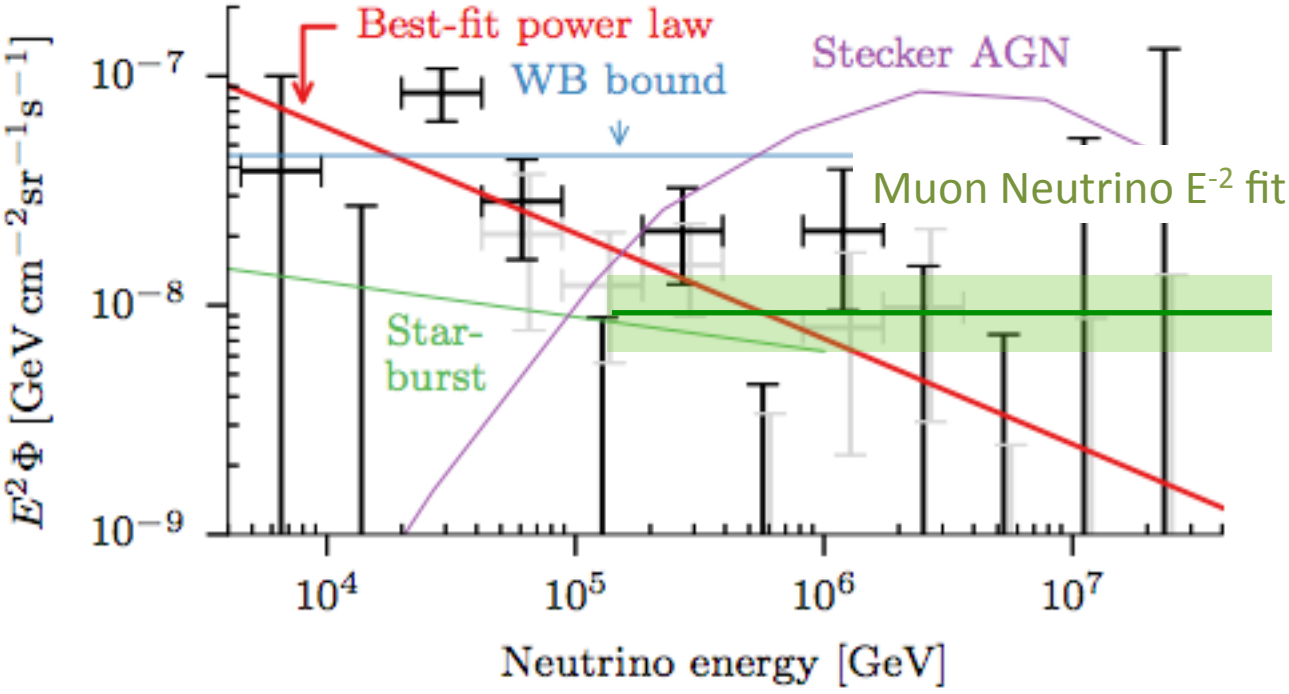
Best fit for E^{-2} astrophysical spectrum is:

$0.96 \pm 0.35 \times 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

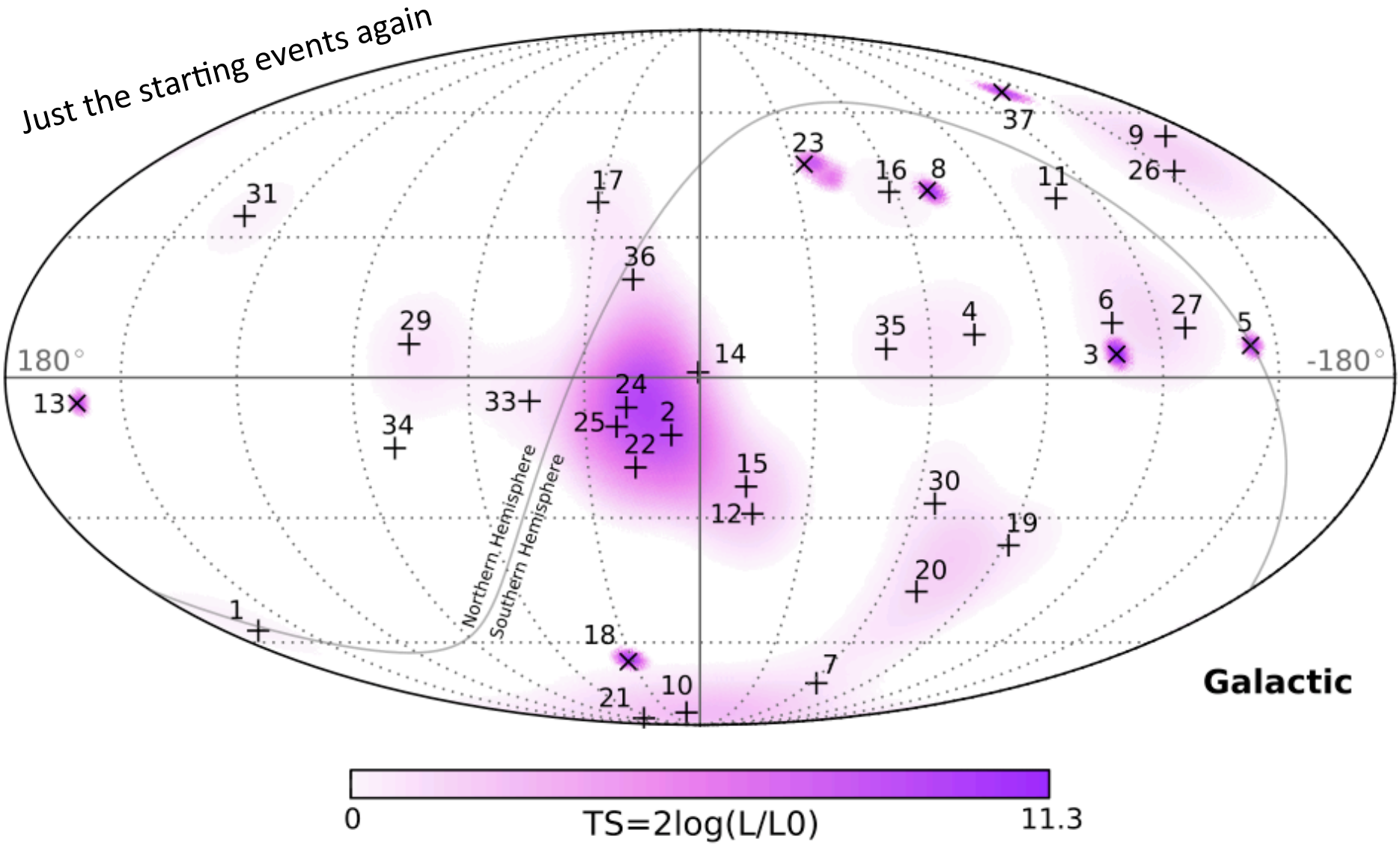
3.9σ evidence of astrophysical flux

(nearly) **independent** of starting track analysis

Strengthens evidence that flux is **all-flavor** and **all-sky**



High Energy Starting Event **PS** Analysis



- No significant clustering: Several variations on point-source hypotheses performed

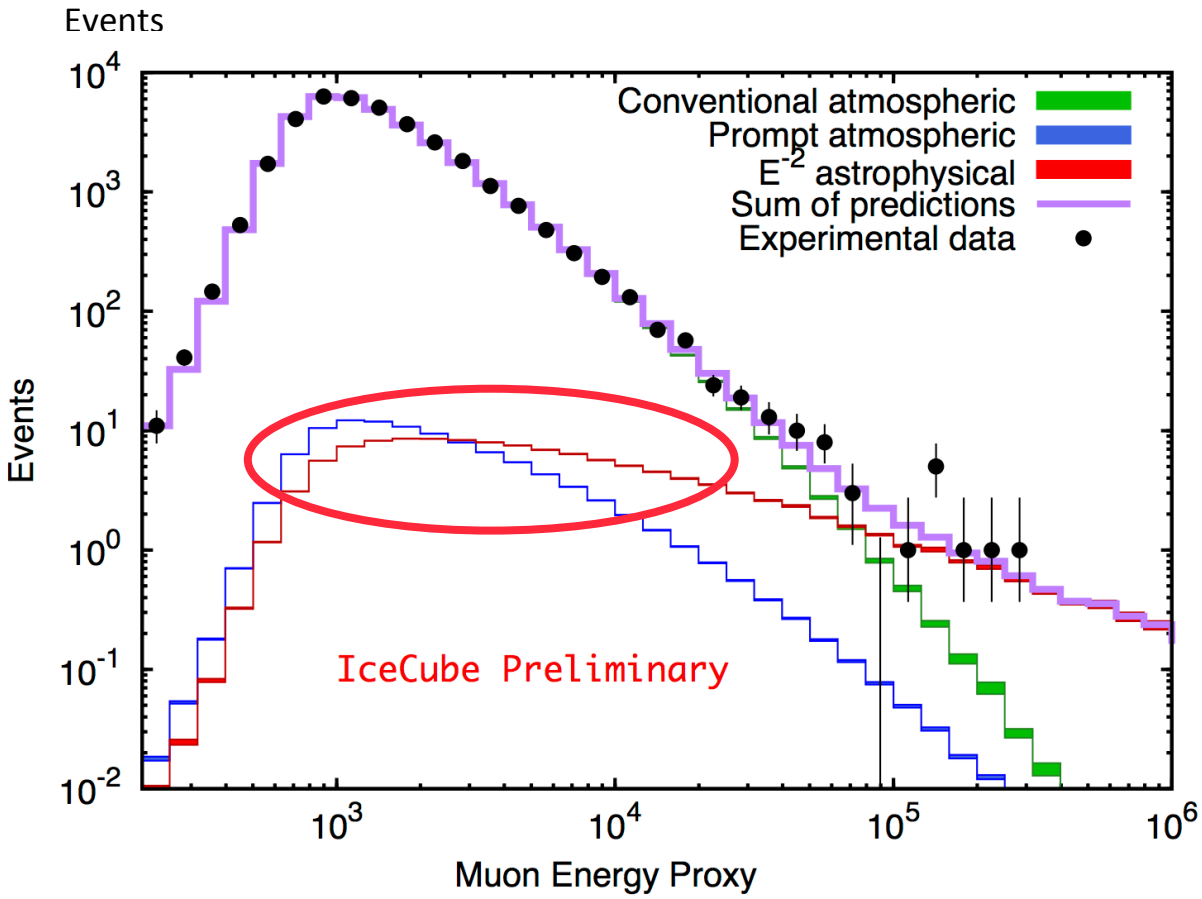
Muon Neutrino Diffuse Analysis

Diffuse analysis measures the tip of the iceberg

E^{-2} flux implies there are ~ 100 astrophysical muon neutrino events in sample at lower energies…

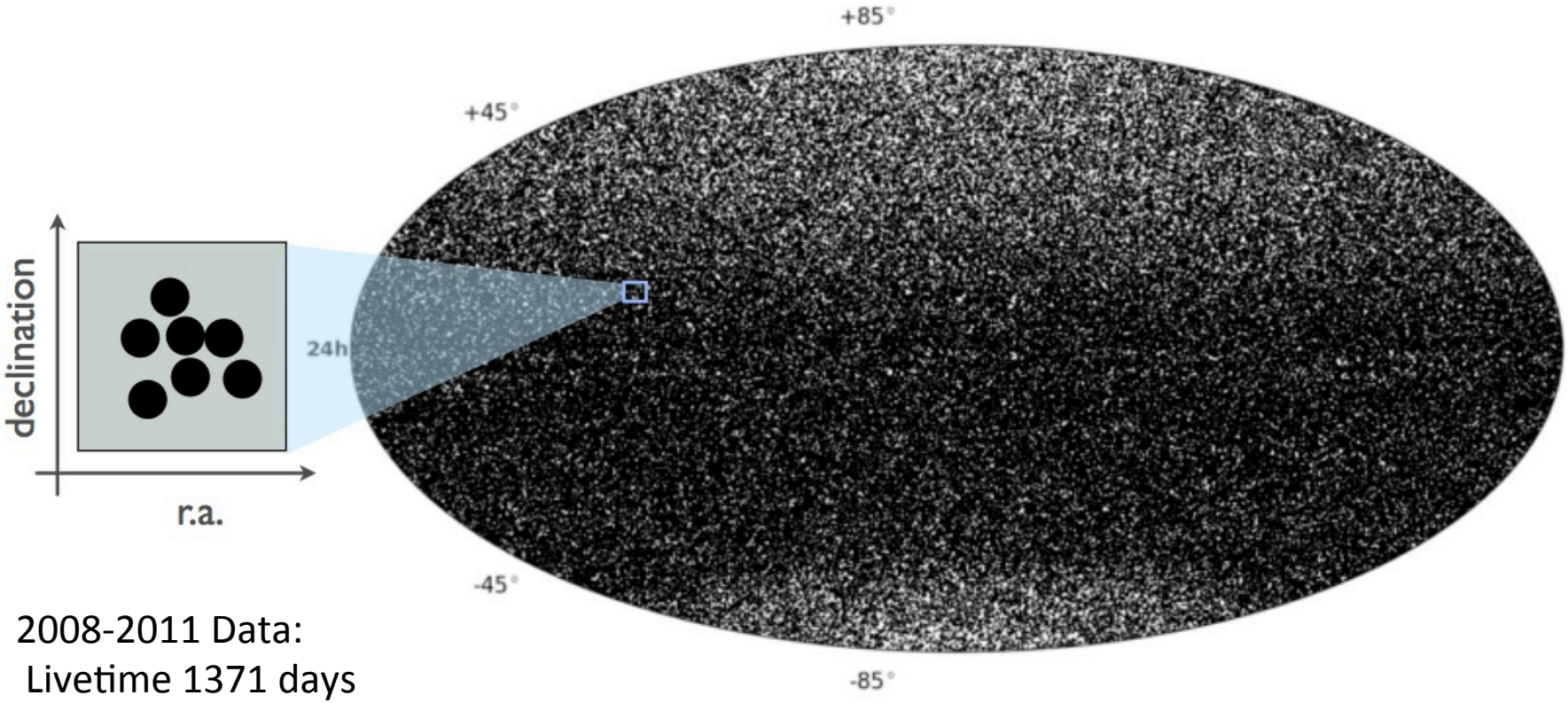
or much more, if spectrum is softer than E^{-2}

These events are nearly hidden in diffuse analysis, but can stand out in point source analysis



Energy estimate for the muon track.
Only lower-bound on neutrino energy
(interacted before reaching detector)

Muon Neutrino Point Source Analysis



2008-2011 Data:
Livetime 1371 days

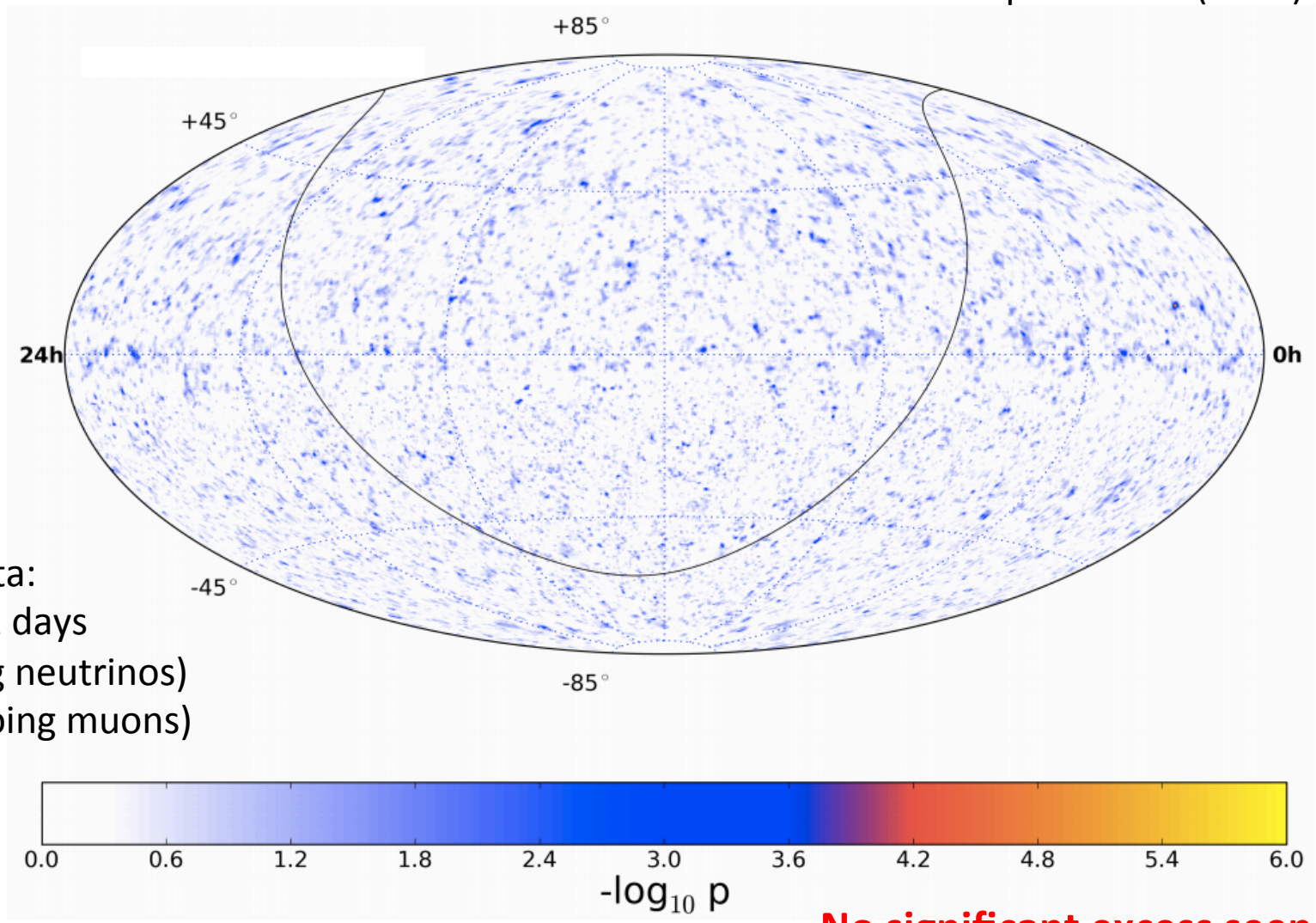
178 000 upgoing neutrinos

216 000 downgoing CR muons

Perform a search looking for significant clustering of events above random background expectation (unbinned maximum likelihood analysis)

Muon Neutrino Point Source Analysis

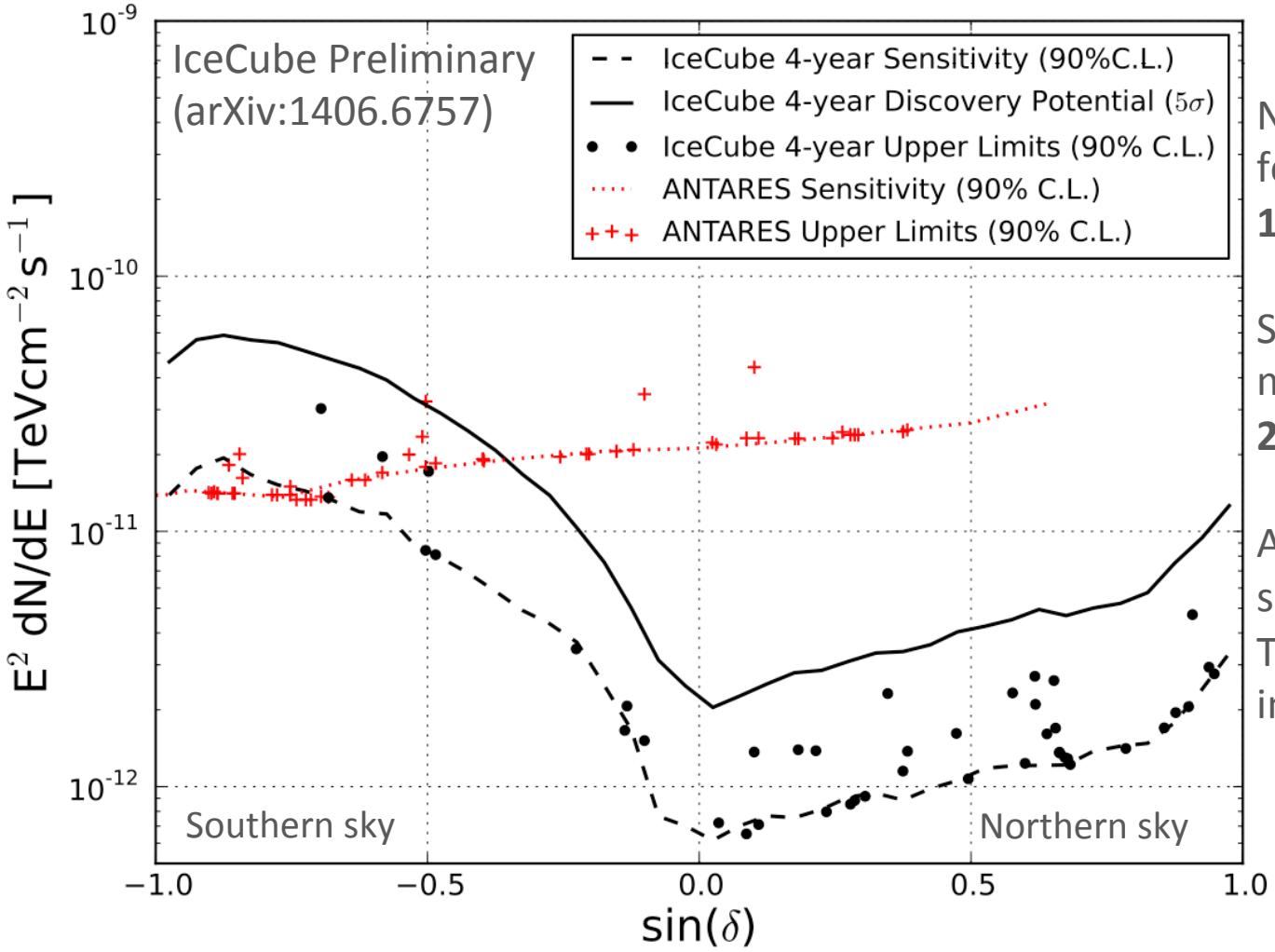
ApJ 796:109 (2014)



2008-2011 Data:
Livetime 1371 days
178k (upgoing neutrinos)
216k (downgoing muons)

No significant excess seen

Muon Neutrino Point Source Analysis

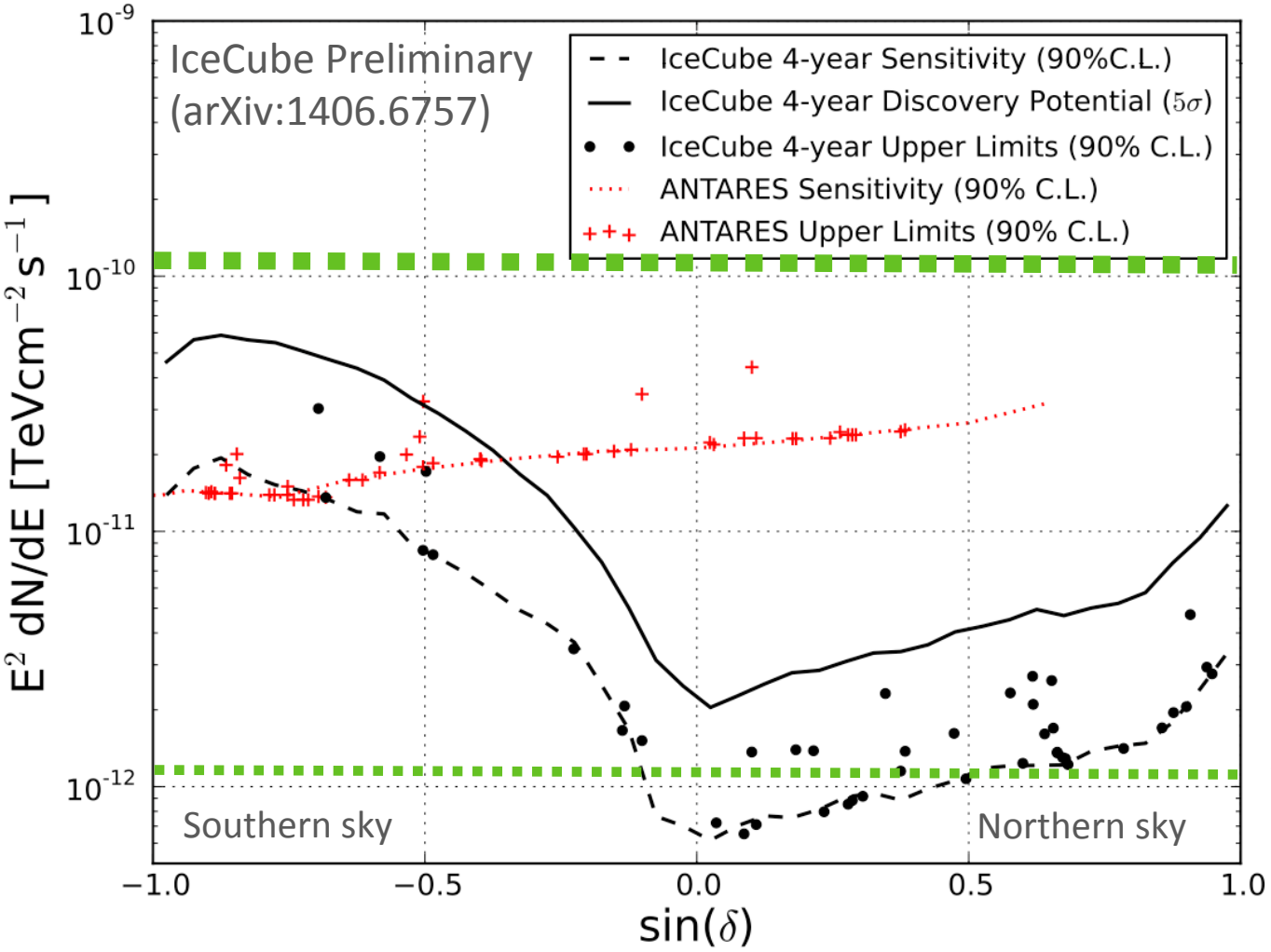


Northern Sky sensitive for TeV – PeV:
178k upgoing neutrinos

Southern Sky sensitive mainly > PeV:
216k downgoing muons

ANTARES sensitive to TeV – PeV in both skies

Muon Neutrino Point Source Analysis



Point-source equivalent flux if the diffuse flux came from:

one point in the sky

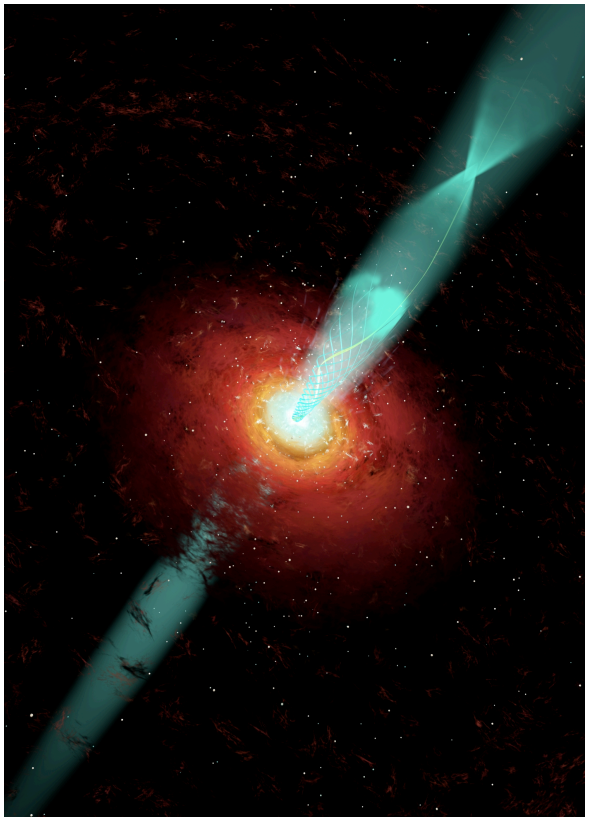
100 points in the sky

Population studies with Stacking Searches:

1000 points in the sky

Blazars Scenario

- Lacking a clear source association
  - The sources are numerous
  - We can speculate that they are quite distant
- Blazars are active galactic nuclei (AGN) with jets directed along our line of sight
  - Powered by accretion onto supermassive black holes
  - Particle acceleration occurs somewhere in the jet
- Great candidates for ultra-high energy cosmic ray production
  - Great neutrino source candidate
- Detected readily in gamma rays
  - Can be modeled with purely leptonic processes
  - Can also be explained with mixed leptohadronic processes

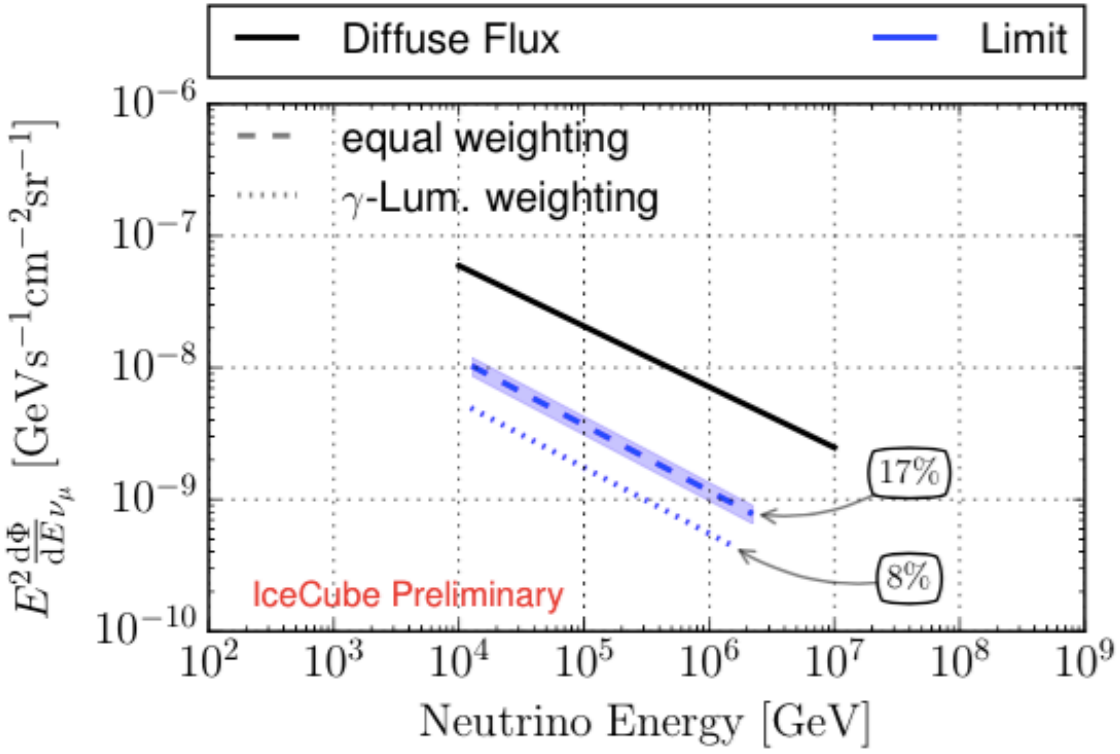


Ajello et al.
arXiv:1501.05301v1

Blazar Stacking

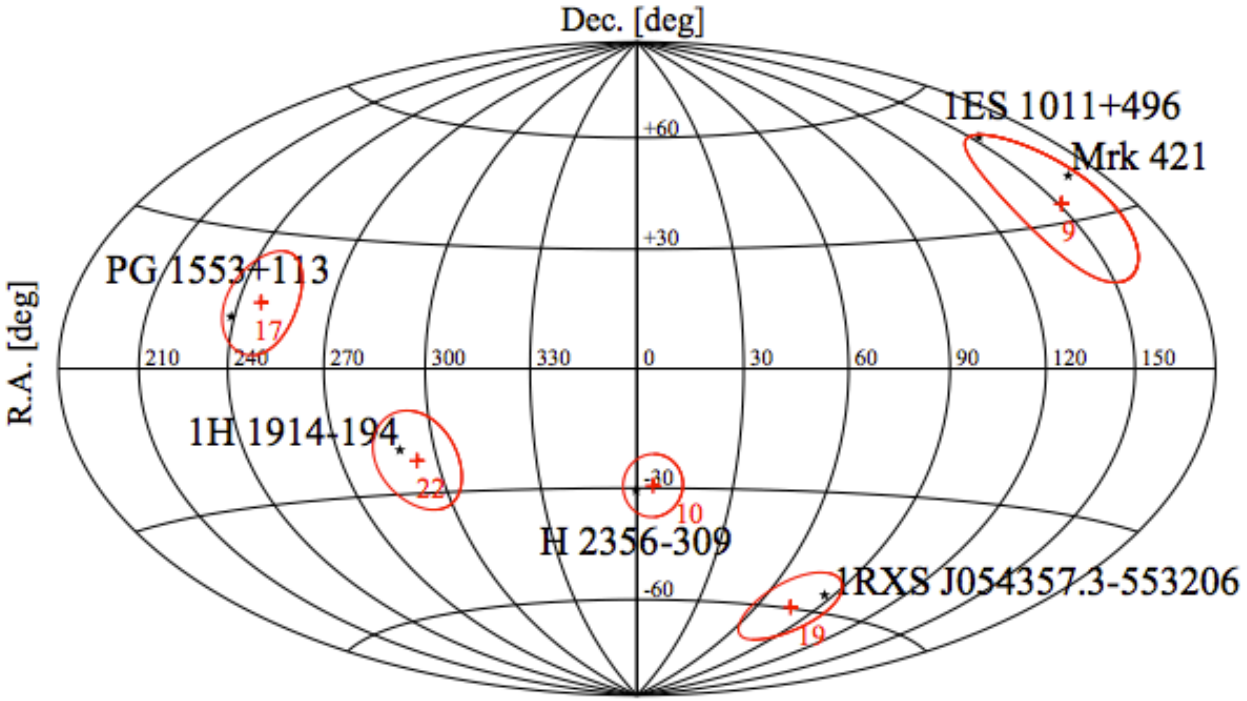
- We performed stacked searches for neutrinos from known blazars
  - Fermi LAT catalog of 862 blazars
- No significant excess observed in IceCube stacked search
- Total flux upper limit is well below measured diffuse neutrino flux
- Sub-categories by presence of emission lines
  - FSRQs
  - BL Lacs
    - classified based on emission peak frequency
    - Low-, Intermediate-, and **High-synchrotron-peaked**

Glüsenkamp, RICAP 2014 Proceedings



HSP Associations?

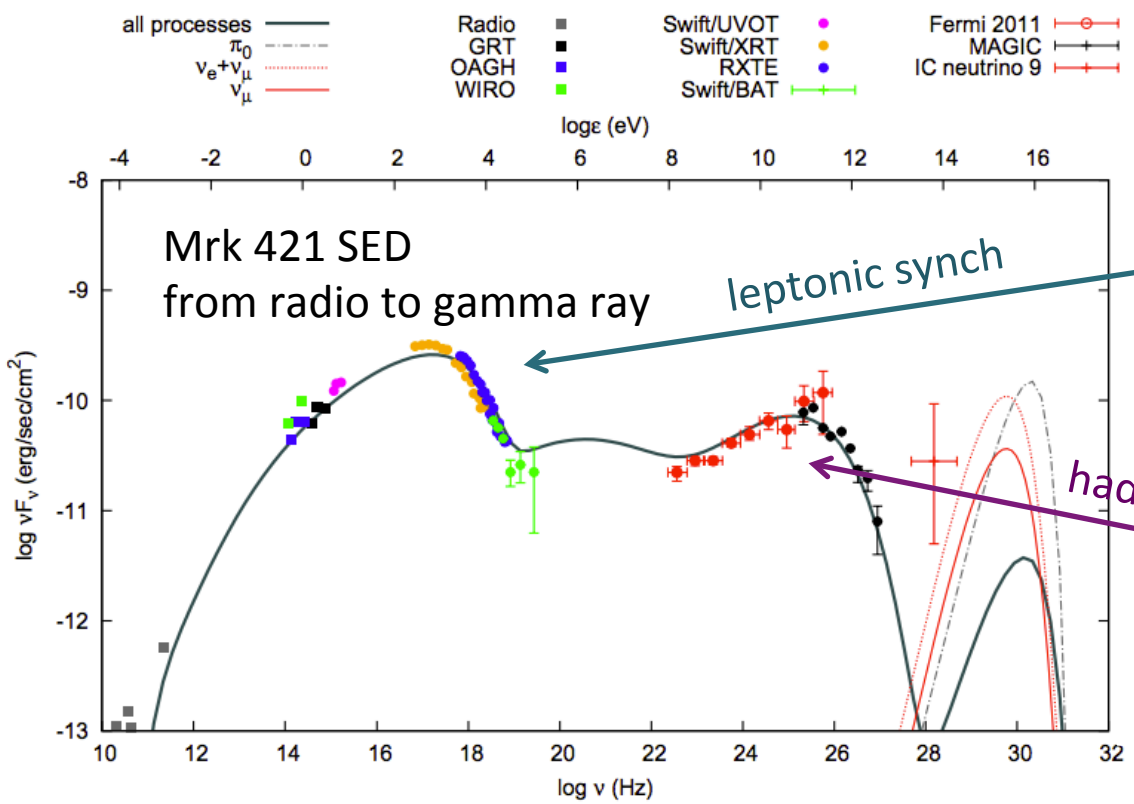
- Despite strict limits on blazar contribution to the diffuse flux, there is renewed interest in hadronic modeling of HSP blazars
  - Due to both **stretching** of leptonic model parameters and observed **association** with high energy starting events
  - If spectrum does not extend down as a power law, may circumvent limit calculation assumptions
  - Recall: ~15° ang. res. for cascades
  - HSPs peak at the highest observed gamma-ray energies, so a natural candidate for the PeV events

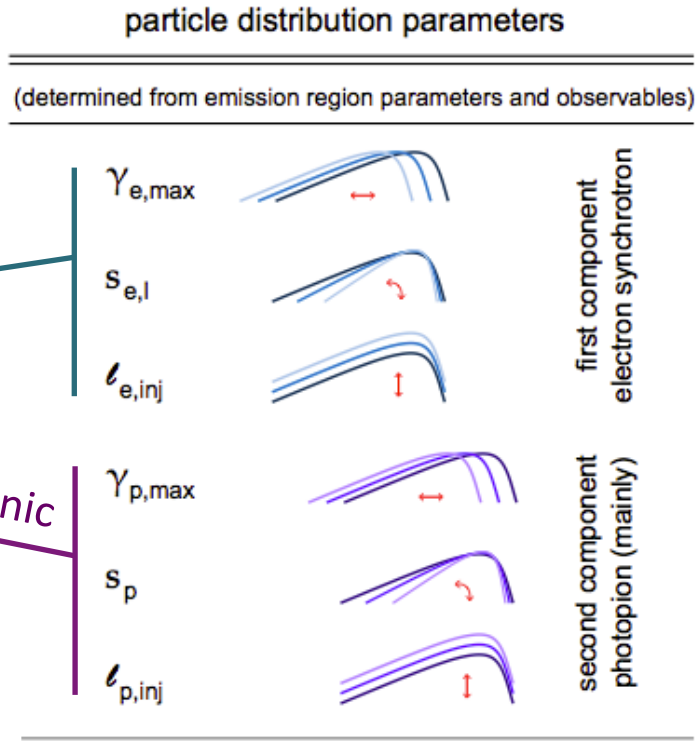


Associations of five HE starting neutrinos with HSP BL Lacs are suggestive but not significant

Blazar Modeling

- Simplified model, agnostic about mechanism of acceleration
  - Assumes power law injections of electrons and protons into region with turbulent magnetic and possibly photon fields
  - Many free parameters

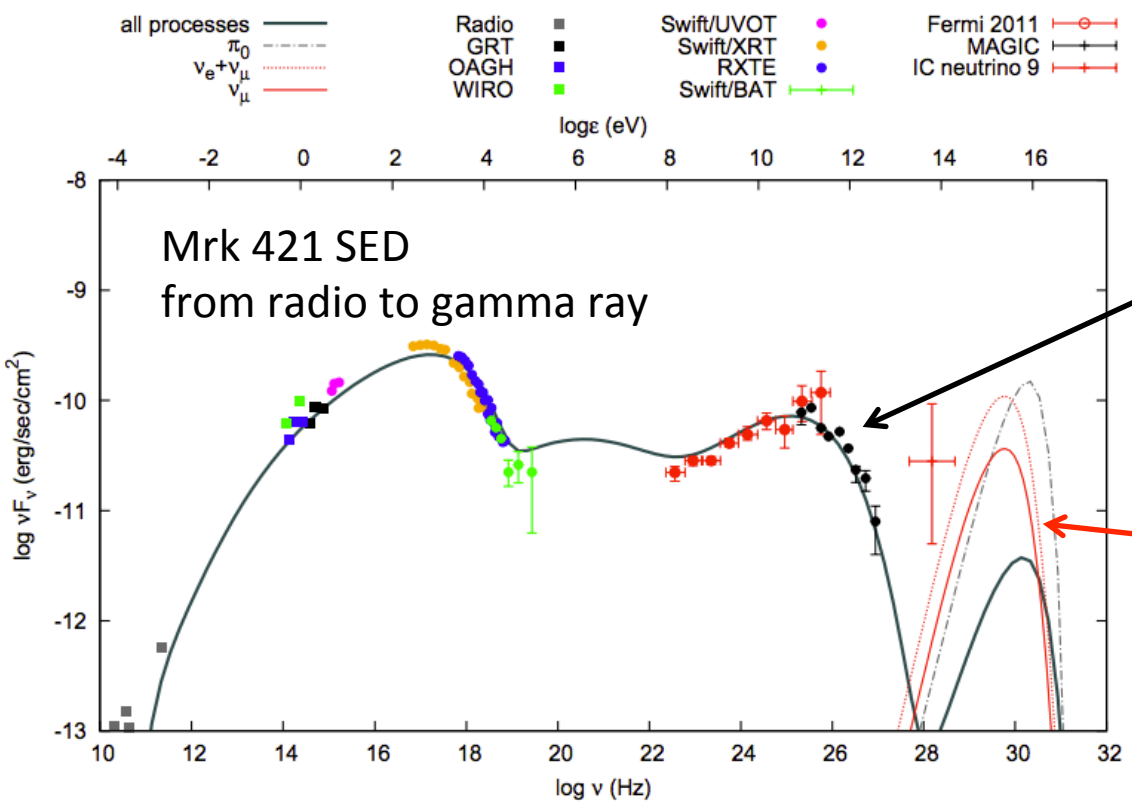




arXiv:1501.07115v1
Petropoulou et al., 2015

Blazar Modeling

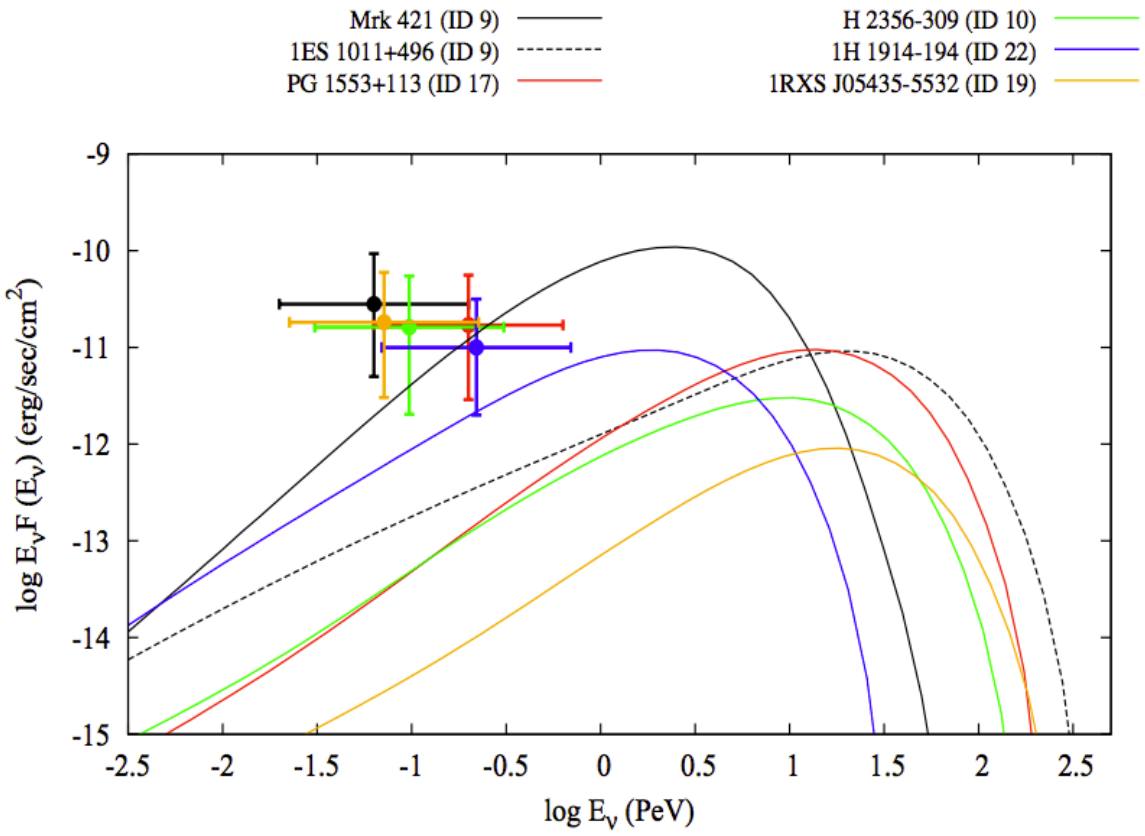
- Simplified model, agnostic about mechanism of acceleration
  - Assumes power law injections of electrons and protons into region with turbulent magnetic and possibly photon fields
  - Many free parameters



- High energy peak from hadrons, but choice in dominant emission mechanism
  - π^0 decay
  - p synchrotron
  - **π-decay product (μ,e) synchrotron**
- Choosing the latter gives a sharp neutrino peak
  - No extension as power law down to lower energy

arXiv:1501.07115v1
Petropoulou et al., 2015

Predictions for All Assoc. Blazars



- Five out of six associated HSP Blazars allow neutrino flux predictions with ~3 σ of IceCube flux
- While association is not significant, certainly an interesting source class candidate

arXiv:1501.07115v1
Petropoulou et al., 2015

Starburst Scenario



Starburst Scenario

- Candidate: Starburst galaxies
  - High star formation rates -> Lots of supernovae -> Lots of cosmic ray acceleration
  - Lots of target material (high interstellar gas density)
  - Both factors lead to efficient neutrino production through pp interactions and subsequent pion decay

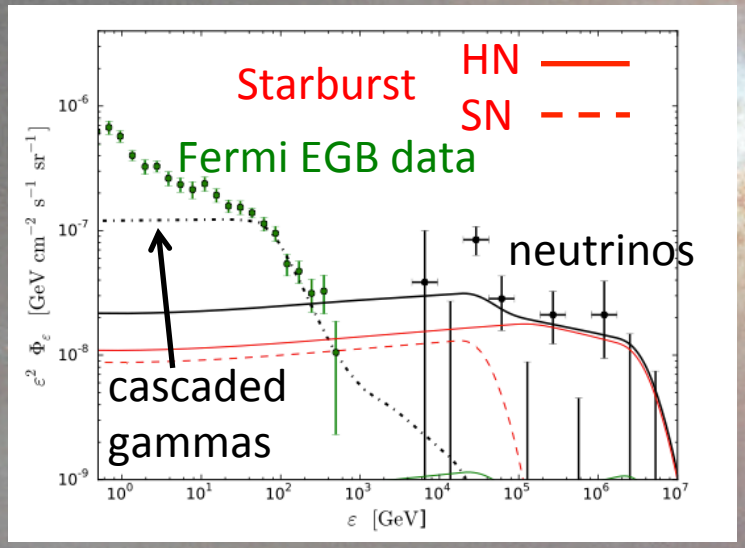
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

M82 - HST

Starburst Scenario

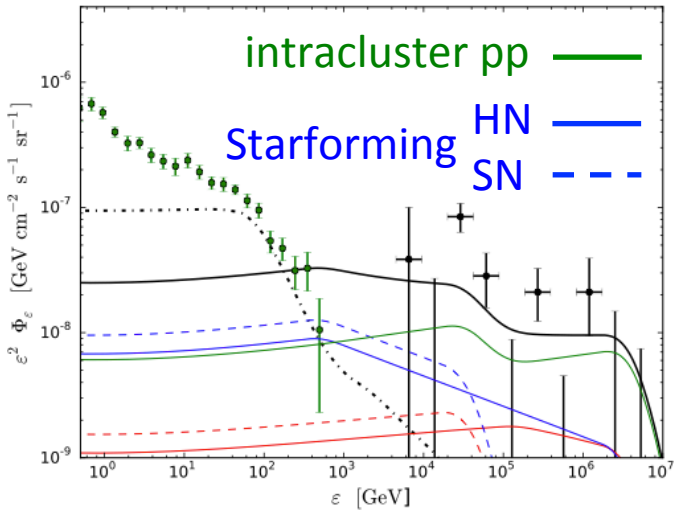
Senno et al 2015
arXiv:1501.04934v1

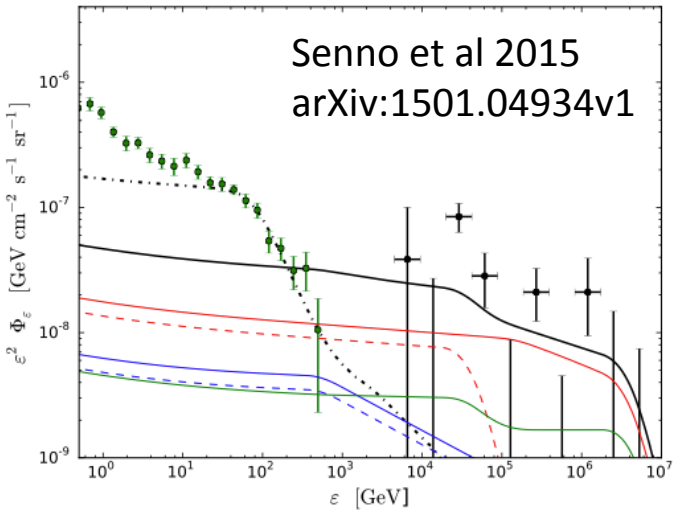
- Recent paper explores the link between supernovae and hypernovae in starburst/starforming galaxies
  - Case shown where starbursts dominate neutrino production
- PeV neutrino production implies PeV photon production, which cascade down to lower energies (GeV)!

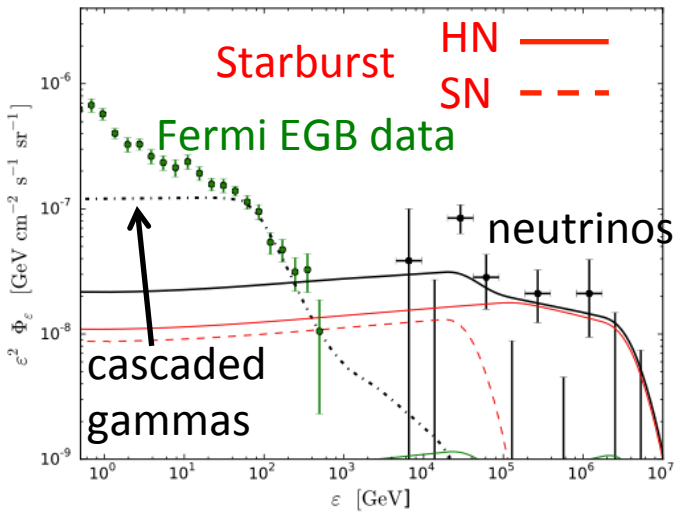


$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$
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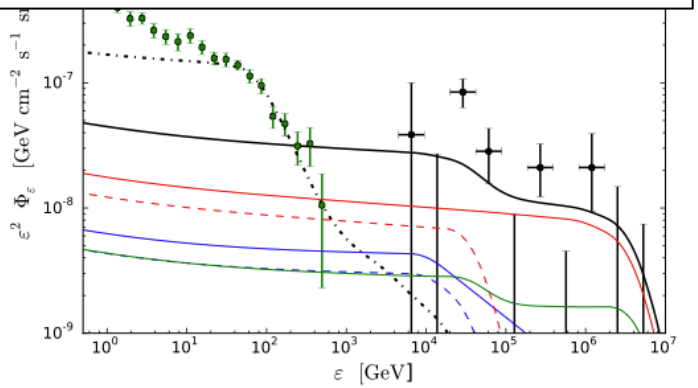
(Large Parameter Space)

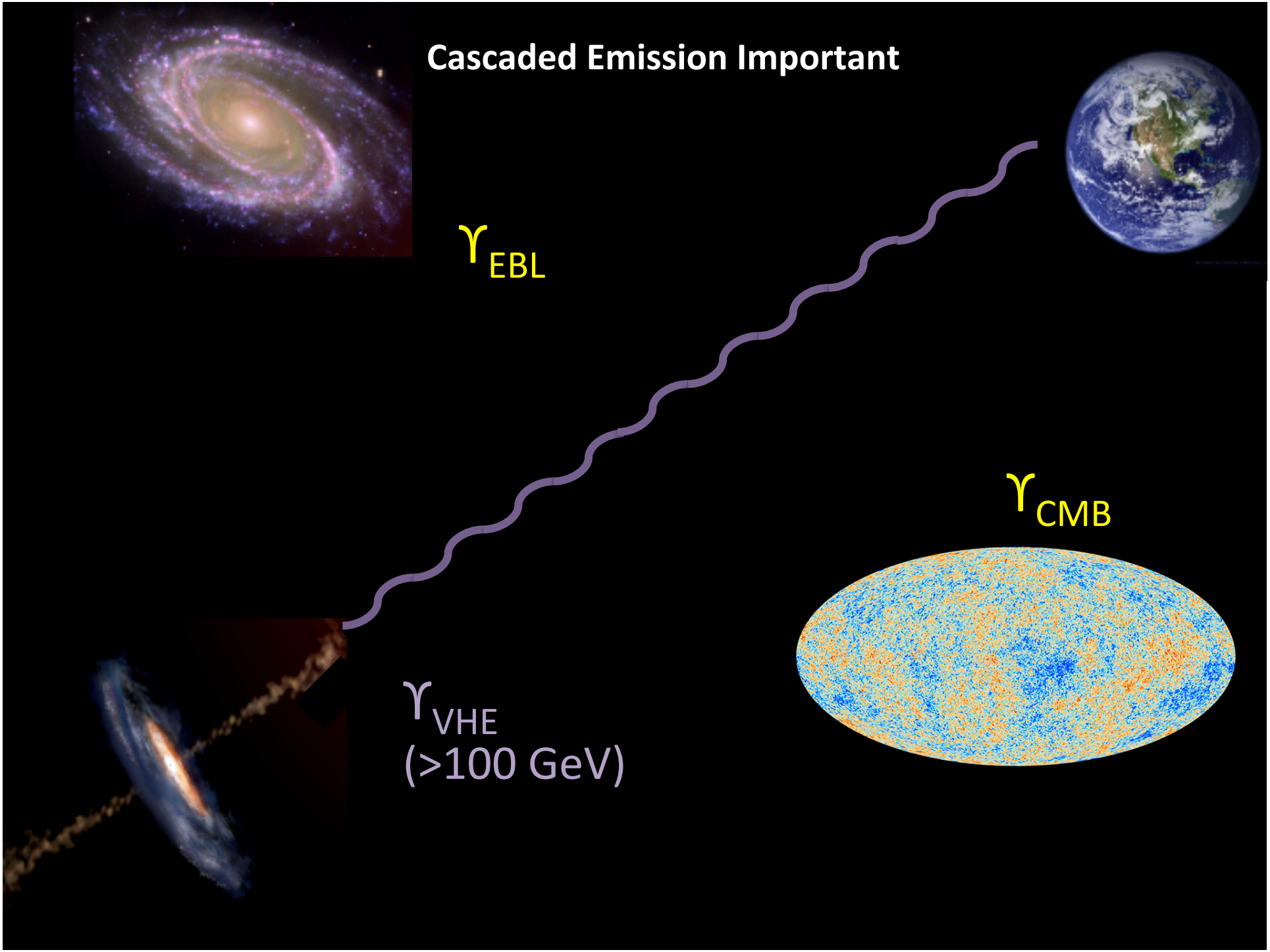


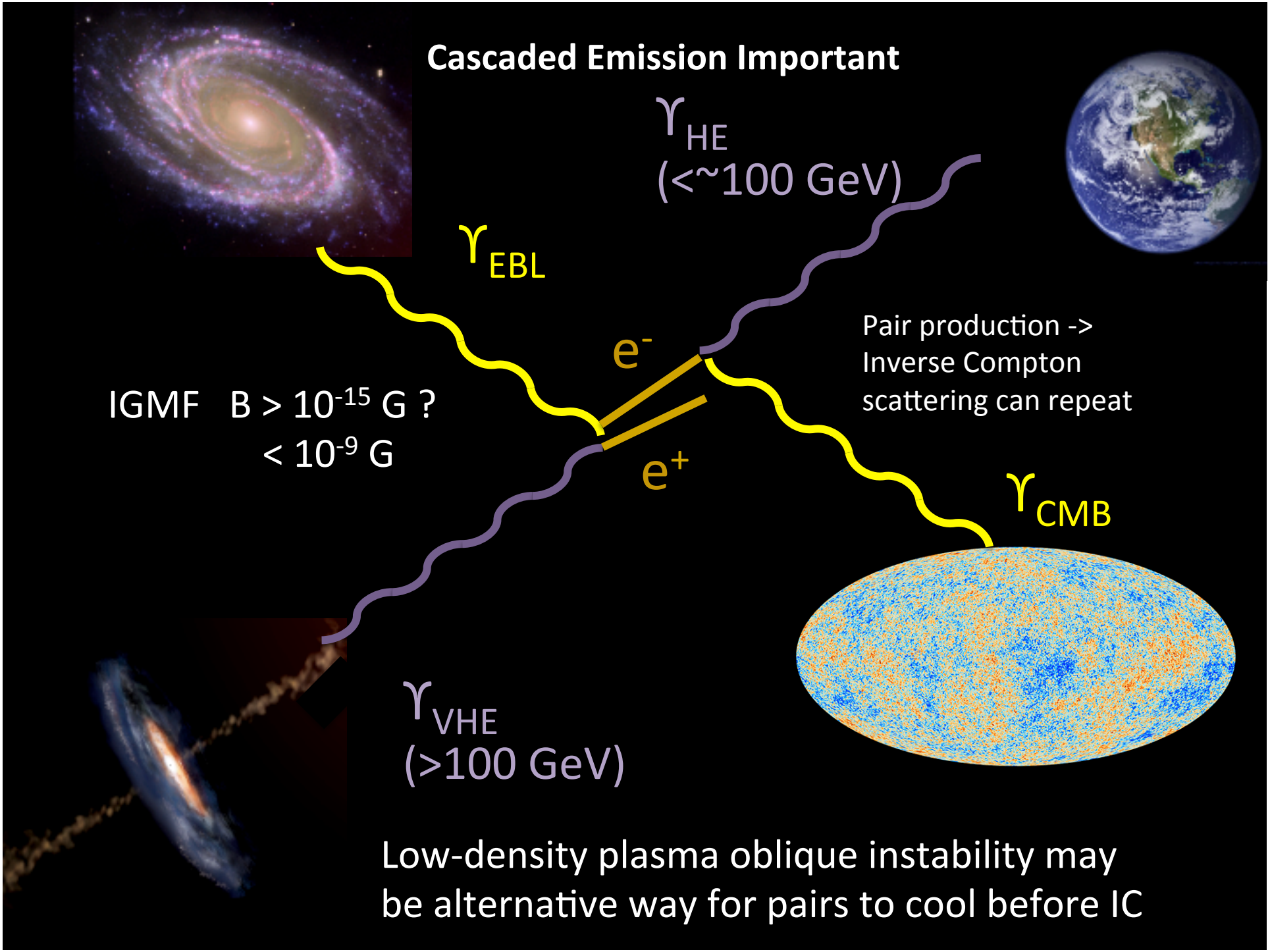




Testing:
- -CR diffusion coefficients
- -CR spectral indices
- -Source population contributions



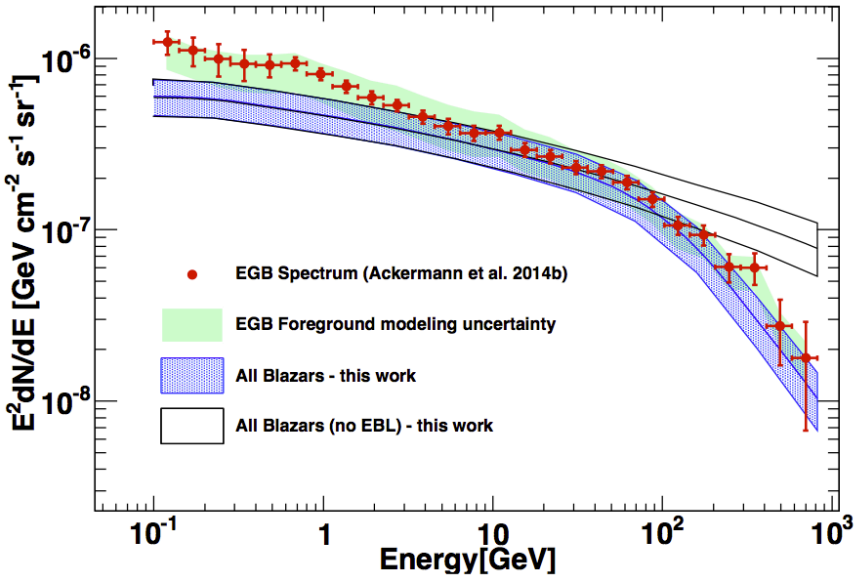

Cascaded Emission Important
γ_{EBL}
γ_{CMB}
γ_{VHE}
(>100 GeV)


Cascaded Emission Important
γ HE (<~100 GeV)
γ EBL
e-
e+
Pair production -> Inverse Compton scattering can repeat
IGMF B > 10-15 G ? < 10-9 G
γ CMB
γ VHE (>100 GeV)
Low-density plasma oblique instability may be alternative way for pairs to cool before IC

Cascaded Emission Important

- Starburst scenario implies most (or all) of Fermi's >~100 GeV extragalactic gamma-ray background are from reprocessed PeV gamma rays

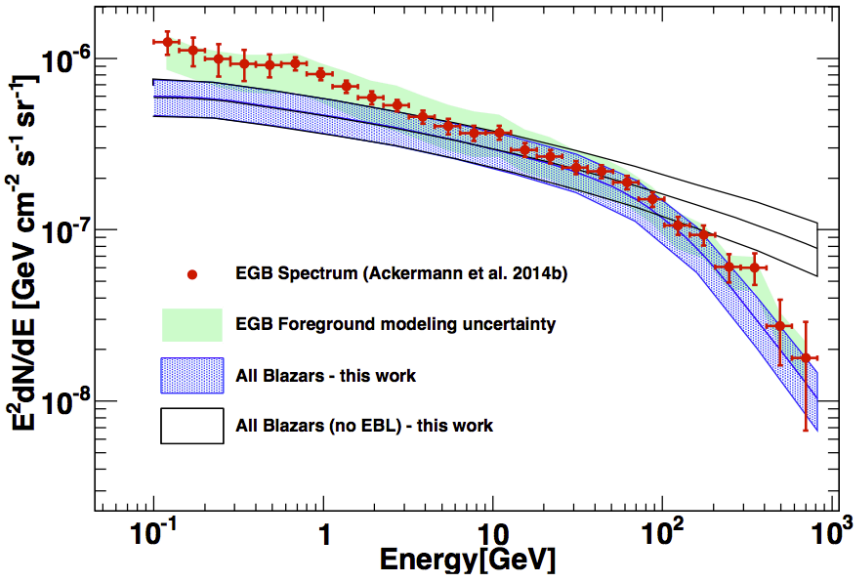
- Recent publication already makes the claim that all the >100 GeV EGB is from blazars
  - Detailed prediction of gamma rays, integrating over all blazars
  - Enough confidence to set competitive limits on the Dark Matter annihilation cross section
  - Perhaps the gamma rays from blazars and IceCube's neutrinos have same origin

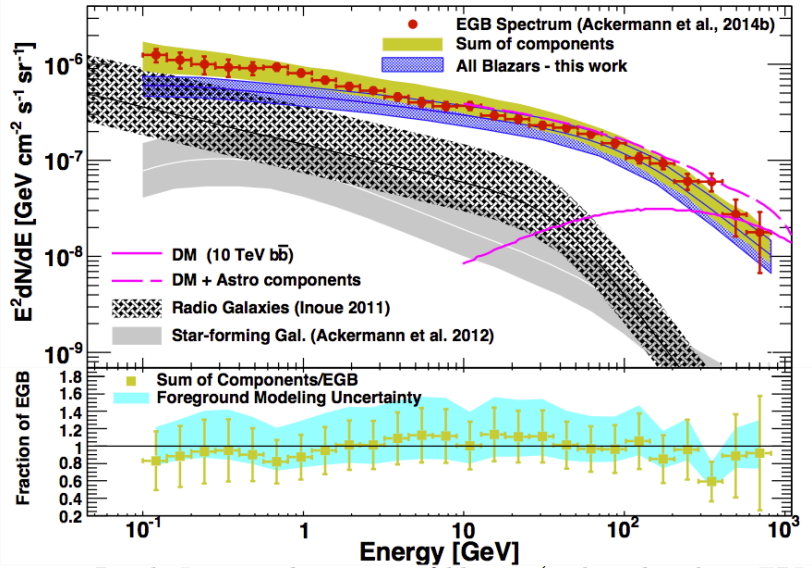


Cascaded Emission Important

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Ajello et al. arXiv:1501.05301v1

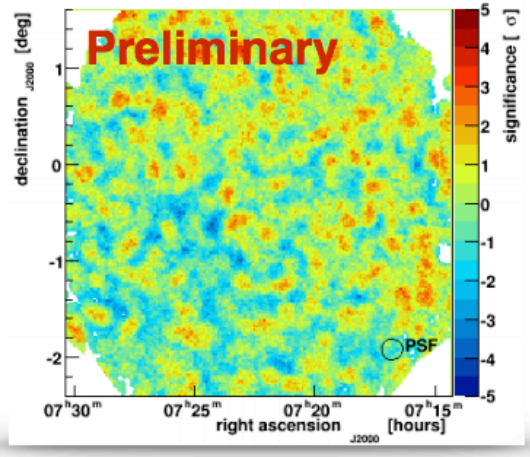
MWL Followup



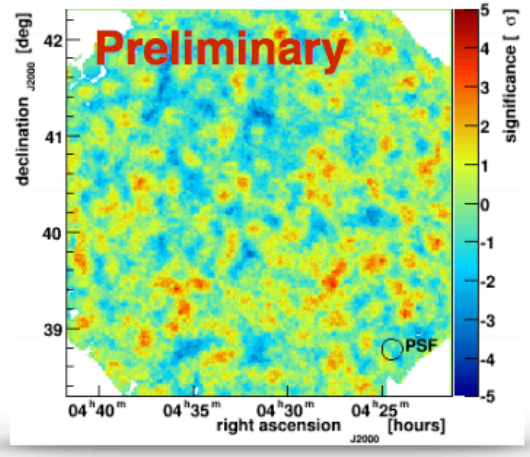
MoUs with IACTS: VERITAS, MAGIC, H.E.S.S. to share information between collaborations

Optical followup for transients also in place

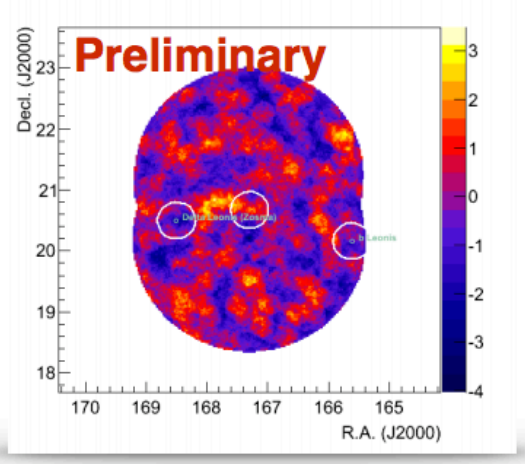
- VERITAS (100 GeV – ~30 TeV) observing track-like events, 1—2% Crab limits



Event 5

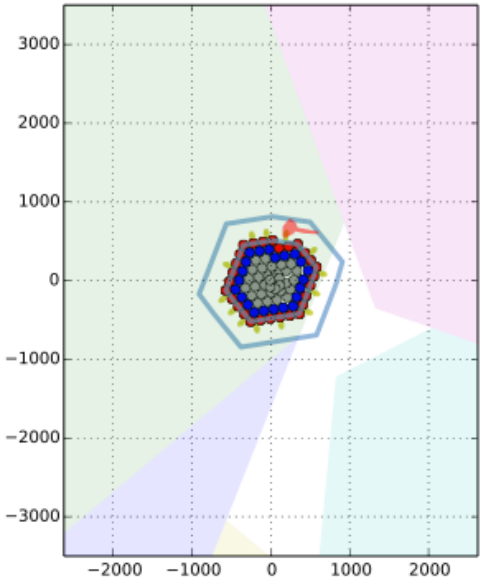


Event 13

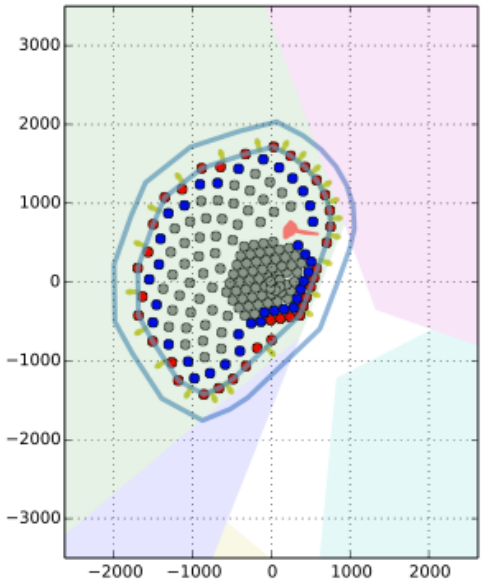


Event 37

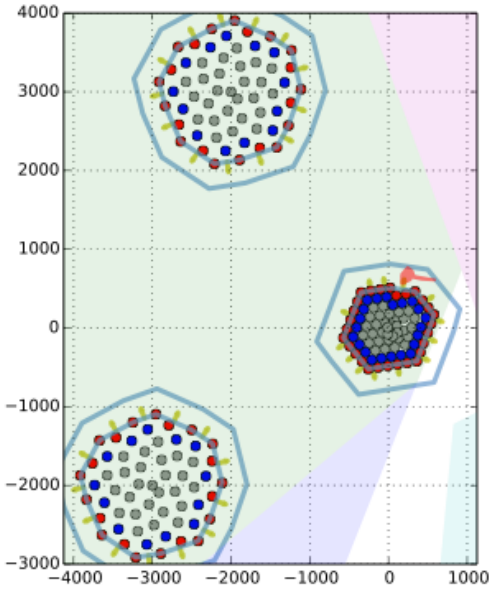
strings: IC86 spacing: ~125m



strings: IC86+96 spacing: ~240m



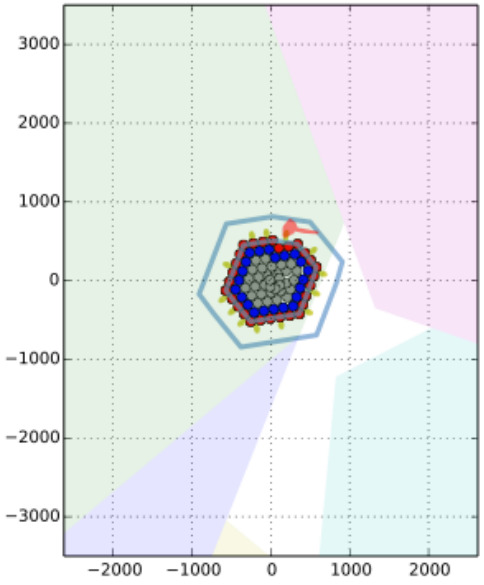
strings: IC86+2x60 spacing: ~240m



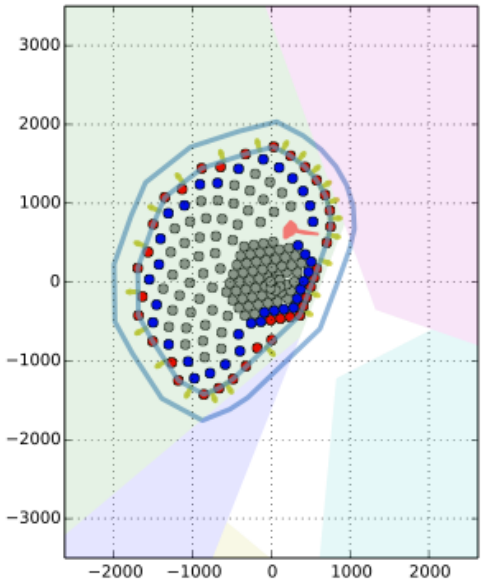
Future High Energy Extension

InIce Strings

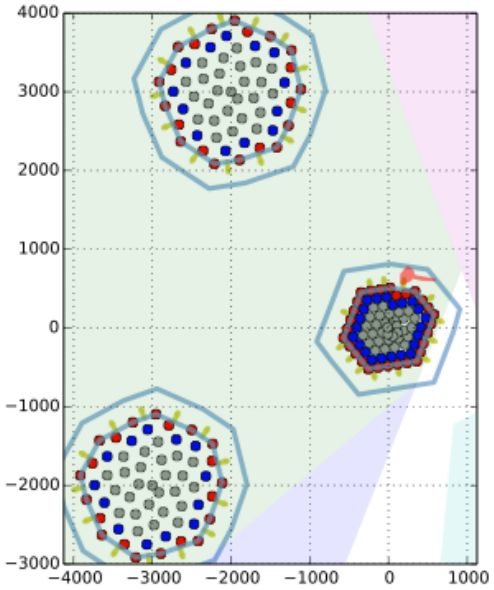
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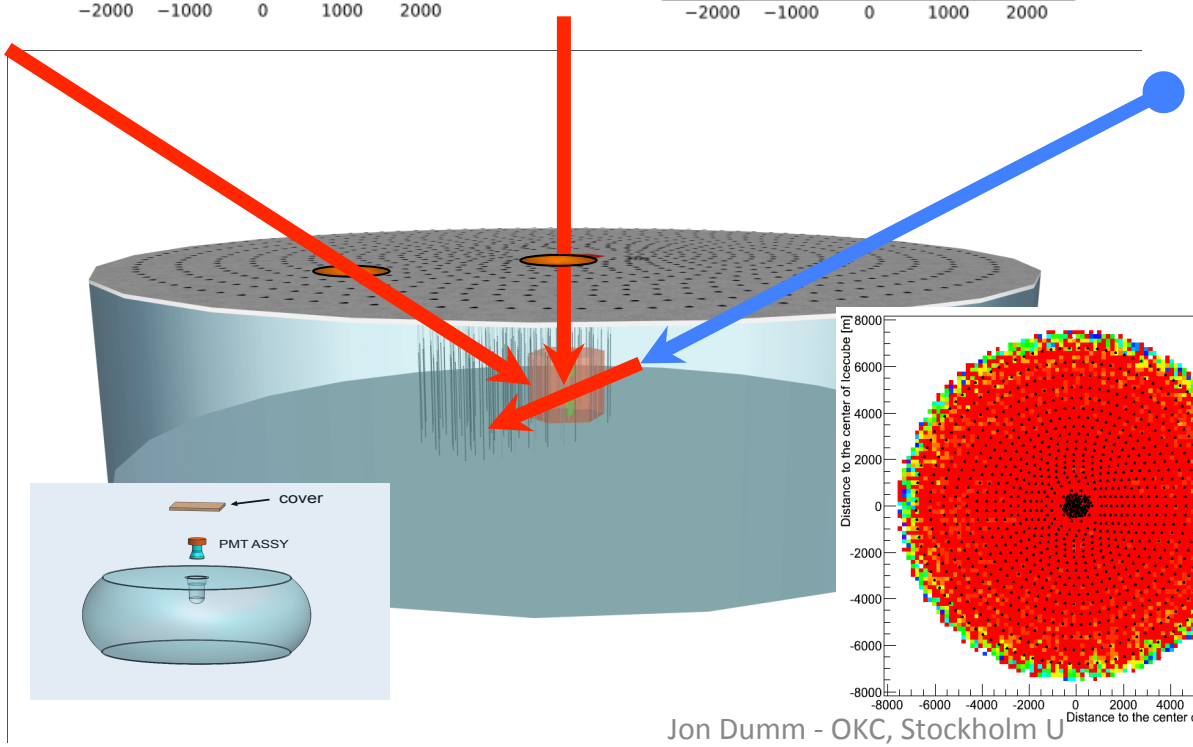


strings: IC86+96 spacing: ~240m



strings: IC86+2x60 spacing: ~240m

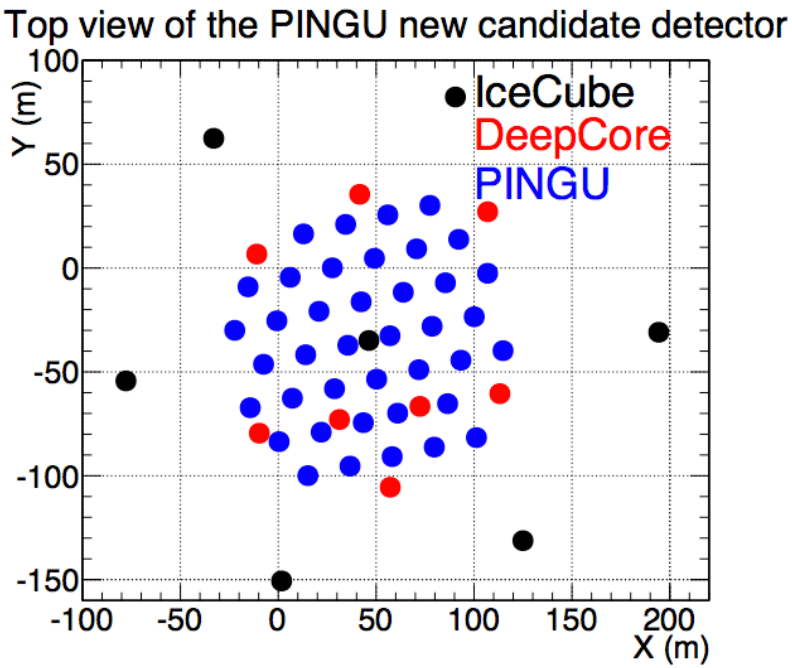




Future High Energy Extension

InIce Strings
+
Surface Veto

PINGU





- PINGU infill would push the energy threshold down to a few GeV
- Opens possibility for measure **neutrino mass hierarchy** and atm **tau neutrino appearance**
- PINGU itself could be a pathfinder for an even larger infill array for neutrino physics

Conclusions

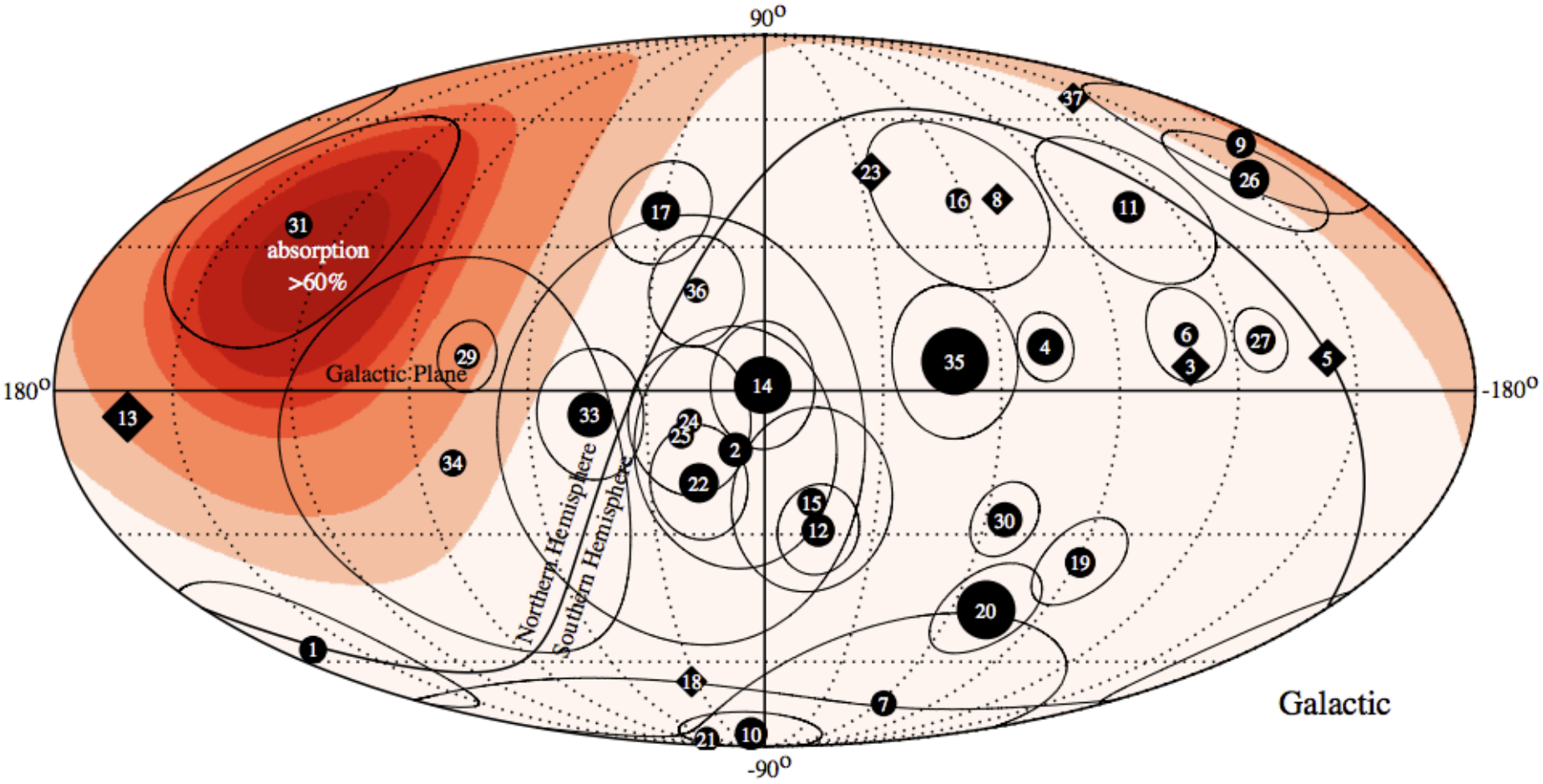
- IceCube discovered a HE astrophysical neutrino flux up to 2 PeV by searching for starting (contained) events
  - Recent confirmation in through-going muon analysis
- Origins of this flux remain elusive
  - Consistent with isotropy and 1:1:1 flavor ratio
  - Ongoing work to use source catalogs to associate or exclude various source classes
  - The next year or two could be very exciting
- Pure starburst or blazar scenarios viable
  - But perhaps more complicated, mixed or exotic
- A next-generation detector with 5—10 x IceCube volume and a dense sub-array is a very real possibility
  - Cost of large, sparse volume comparable to original IceCube budget
  - Still tuning physics goals

IceCube-Gen2: arXiv:1412.5106v2

- Thanks for your attention!

Backup Slides

Skymap with Absorption



Ice Properties

