Neutrino Astronomy at its sunrise

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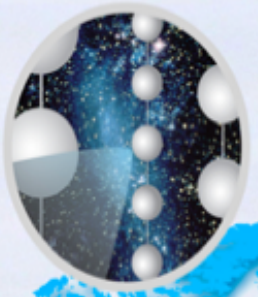
OUTLINE

- The TeV Universe and its messengers
- The cosmic diffuse neutrino signal
- What are the neutrino sources?
- Fundamental Physics:
  - Dark Matter
  - Neutrino Oscillations
- The future of IceCube
- Conclusions

Most of the presented results are obtained by a great team of people capable of leaving forever a sign of their explorations in the South Pole ice!

http://icecube.wisc.edu/gallery



The IceCube Collaboration

10 countries, 40 institutions, ~260 collaborators

http://icecube.wisc.edu

University of Alberta

Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls

Chiba University
Sungkyunkwan University
University of Oxford
Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel
University of Adelaide
University of Canterbury

Stockholm University
Uppsala Universitet

Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal

Ecole Polytechnique Fédérale de Lausanne
University of Geneva

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

53 years to take snapshots of…

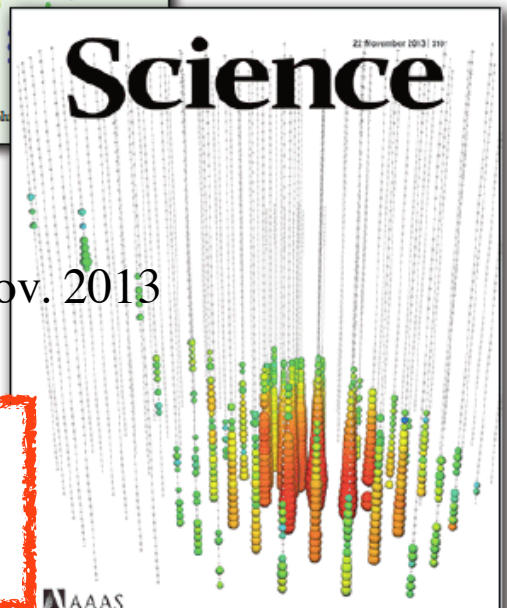
Ann.Rev.Nucl.Sci 10 (1960) 63

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

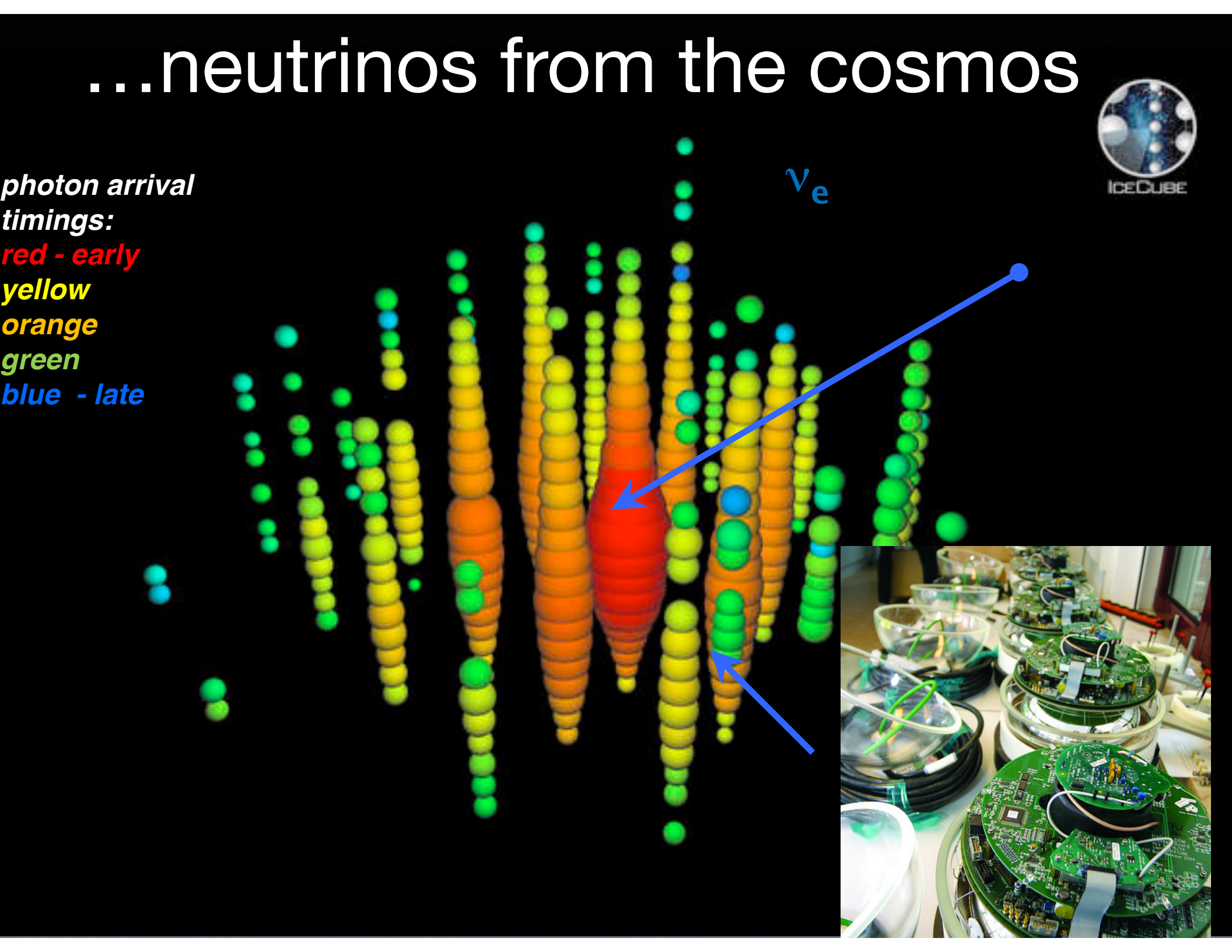
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward



Science 342, Nov. 2013

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

…neutrinos from the cosmos



Main Physics Themes

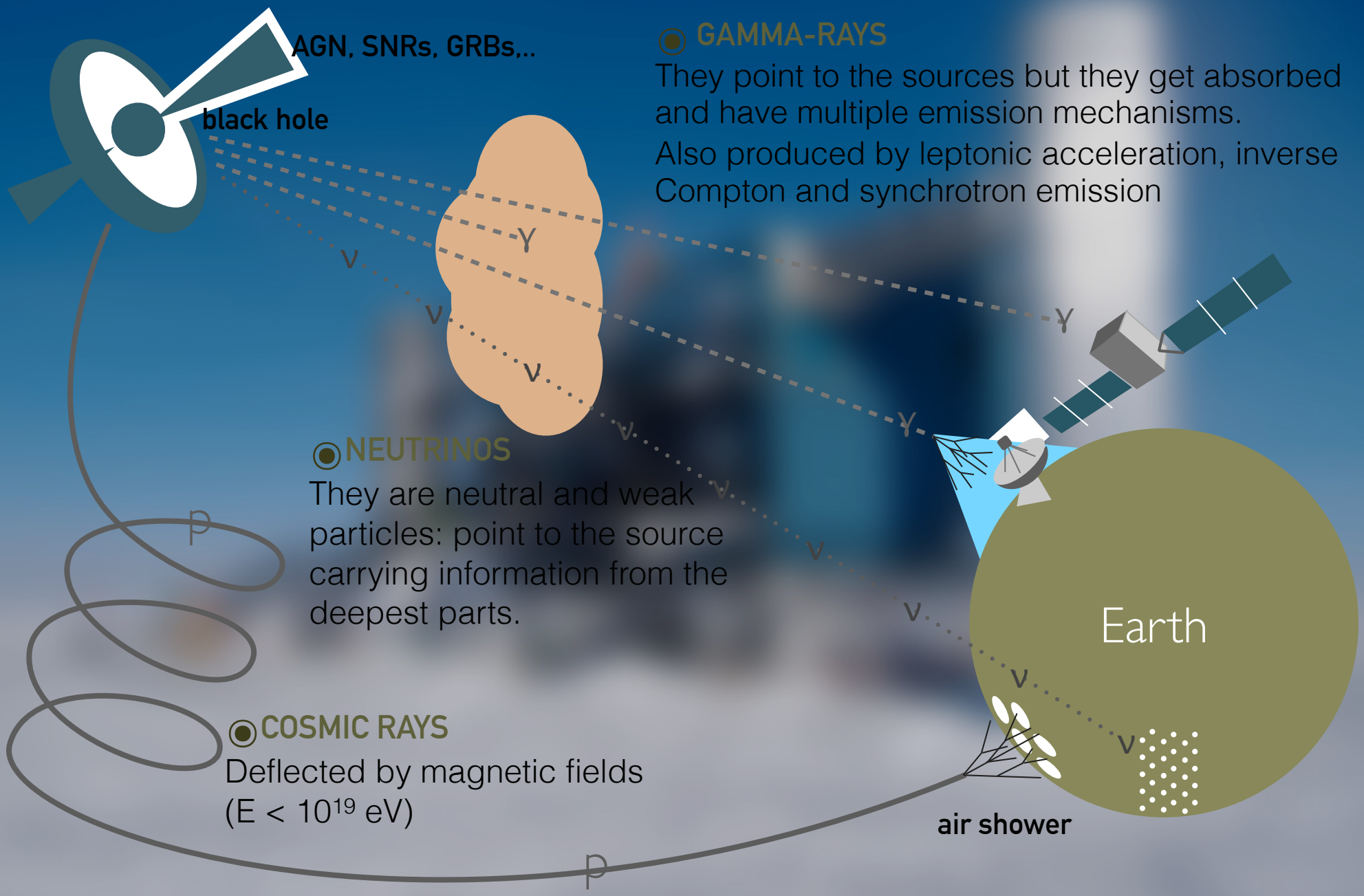
Theme 1: Cosmic Particle Acceleration

- ***what are the sources of the huge luminosity we observ in photons and cosmic rays?***
- ***how do the accelerators work? gamma-ray bursts, bla holes, SNRs***
- *magnetic fields in the local environment and in sources*

Theme 2: Fundamental Physics

- *what is the nature of **dark matter** and where it is located?*
- *Neutrino oscillations and hadronic interactions (kaons, charm)*
- *Is the speed of light a constant for high energy neutrinos (VLI)*

Multi-Messenger approach



GAMMA-RAYS

They point to the sources but they get absorbed and have multiple emission mechanisms.

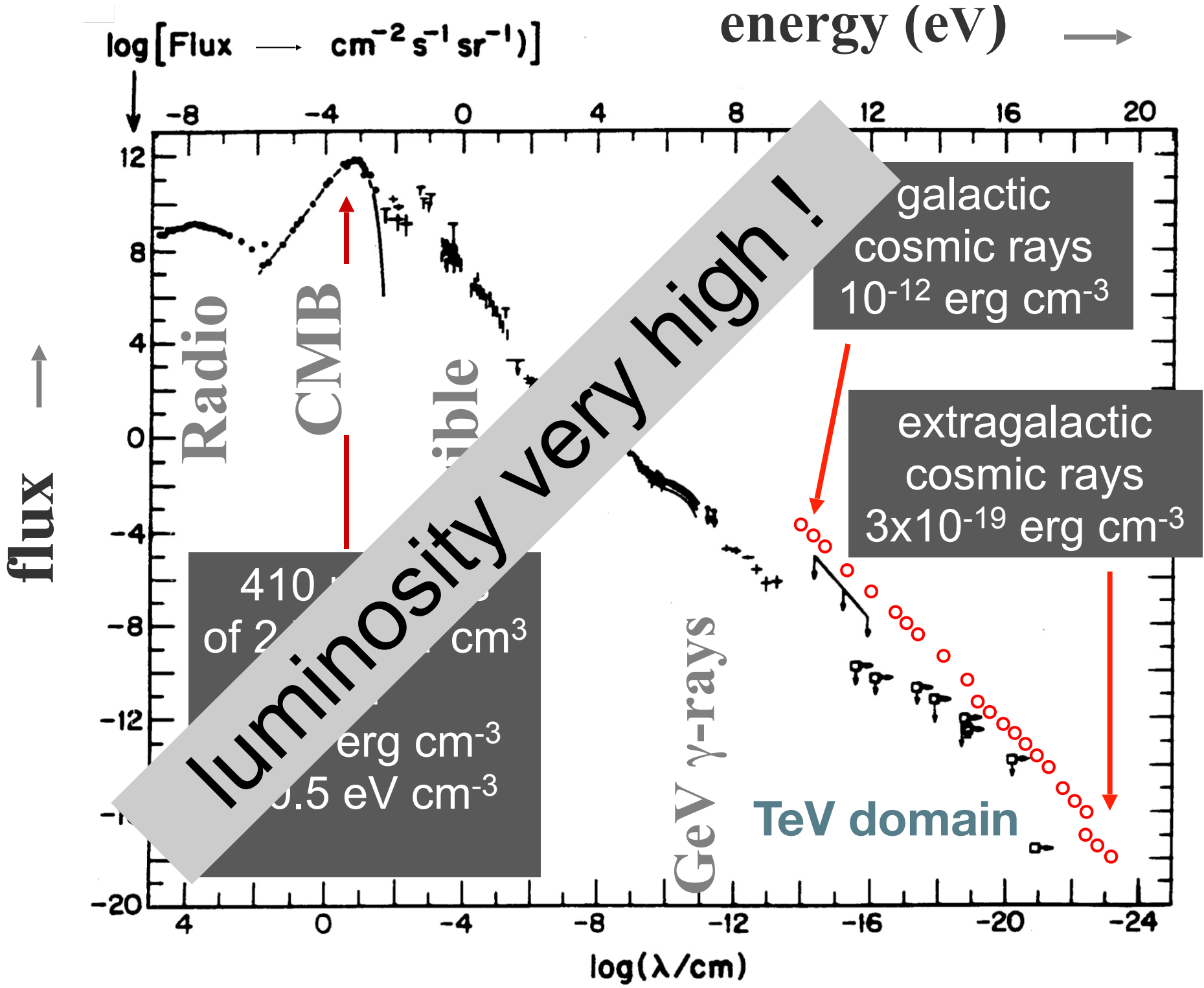
Also produced by leptonic acceleration, inverse Compton and synchrotron emission

NEUTRINOS

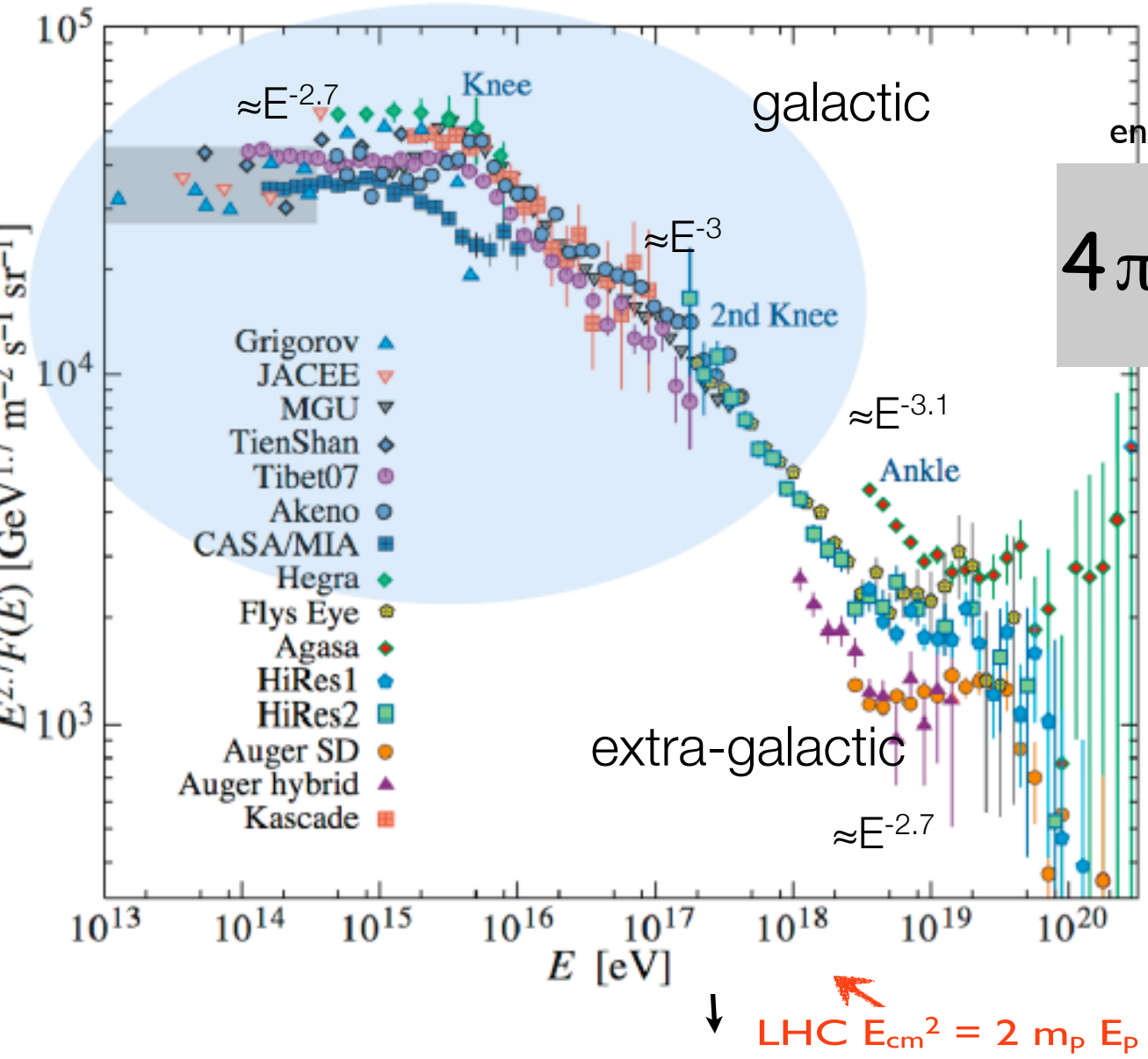
They are neutral and weak particles: point to the source carrying information from the deepest parts.

COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)

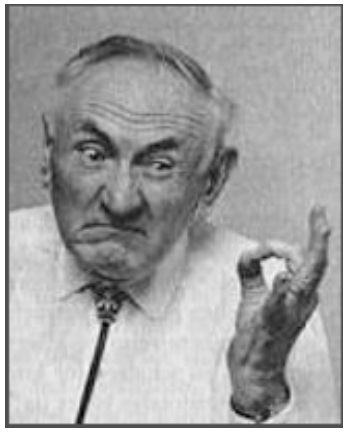

energy (eV)
log [Flux → cm⁻² s⁻¹ sr⁻¹)]
flux →
log(λ/cm)
Radio
CMB
GeV γ-rays
TeV domain
galactic cosmic rays 10⁻¹² erg cm⁻³
extragalactic cosmic rays 3x10⁻¹⁹ erg cm⁻³
luminosity very high !

Cosmic Ray Spectrum



energy density flux = velocity x density

$$4\pi \int dE \left(E \frac{dN}{dE} \right) = c\, \rho_E$$

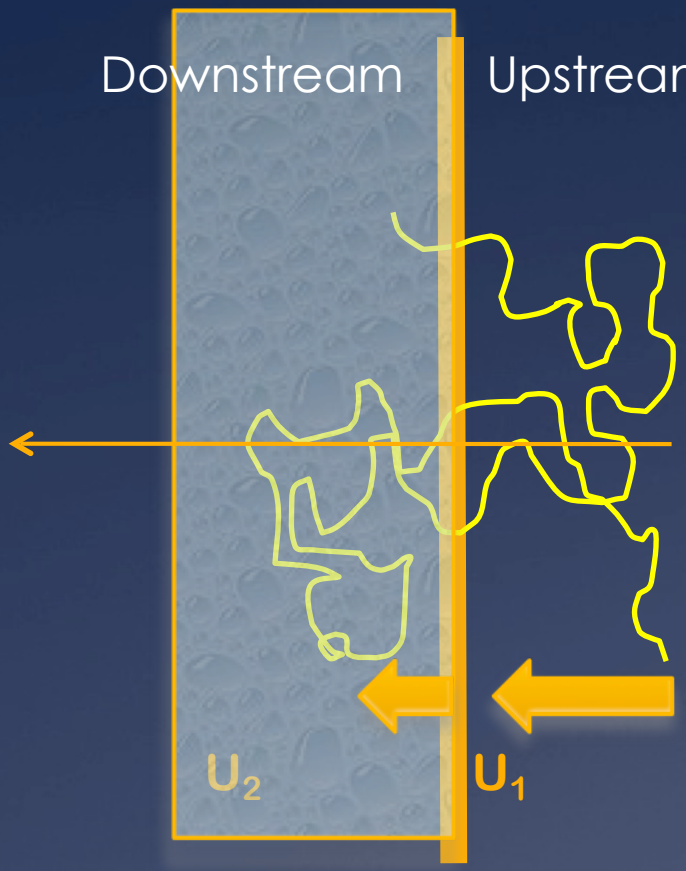


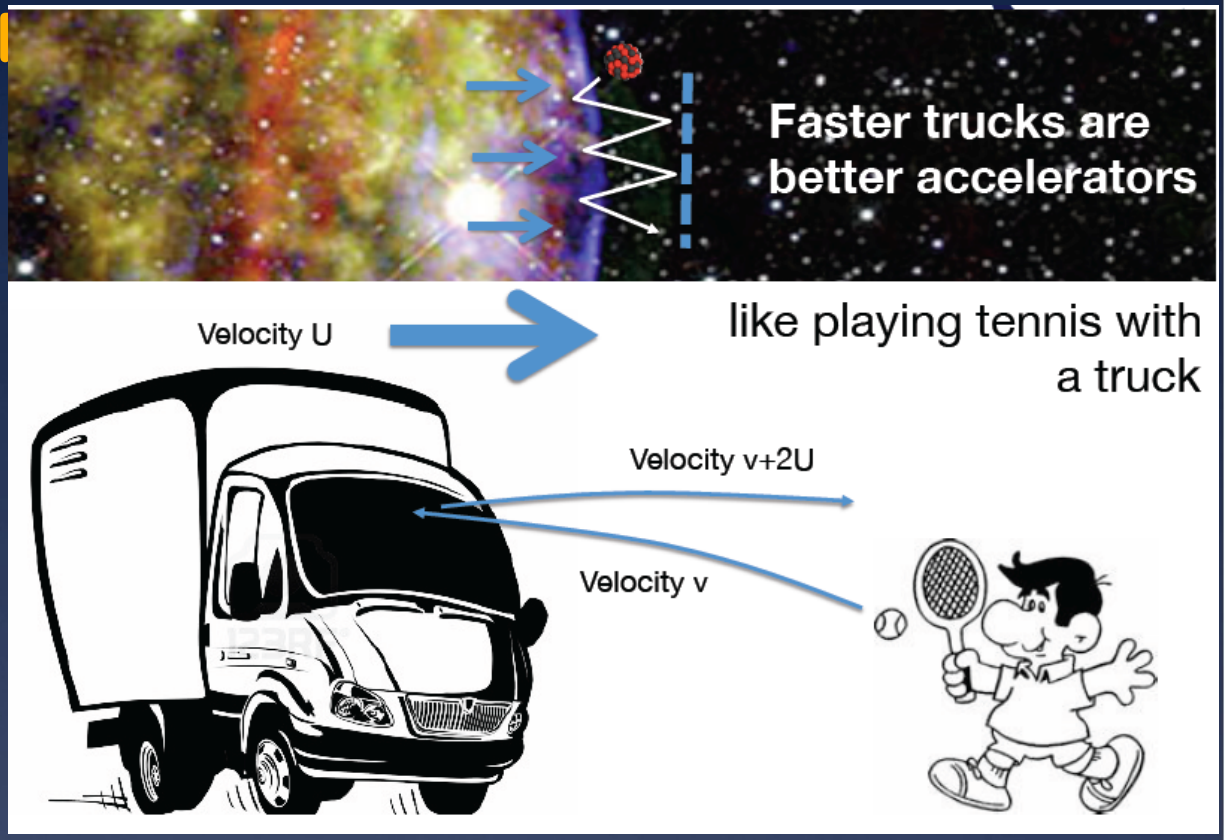
The Supernova Paradigm (Zwicky, 1934)

10^{51} erg/3 galactic SN per century power = 10% of SN kinetic energy provided to the environment through ejecta

The first order I

SHOCK FRONT

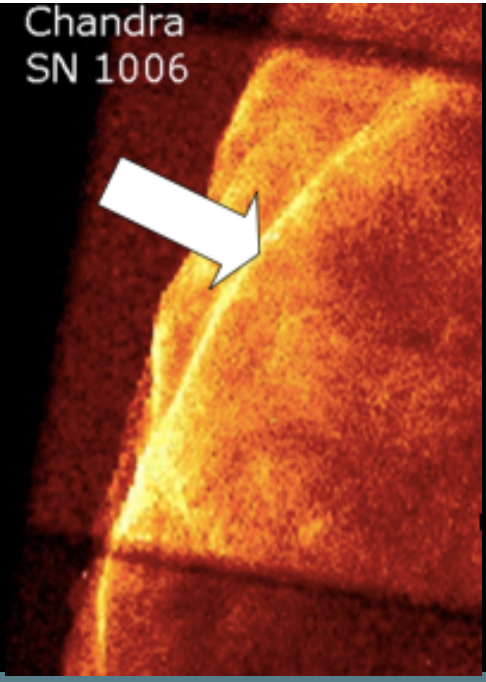




DIFFUSION BACK and FORTH the shock => particle speed increase 3/4U
PARTICLES ARE ACCELERATED TO A POWER LAW SPECTRUM

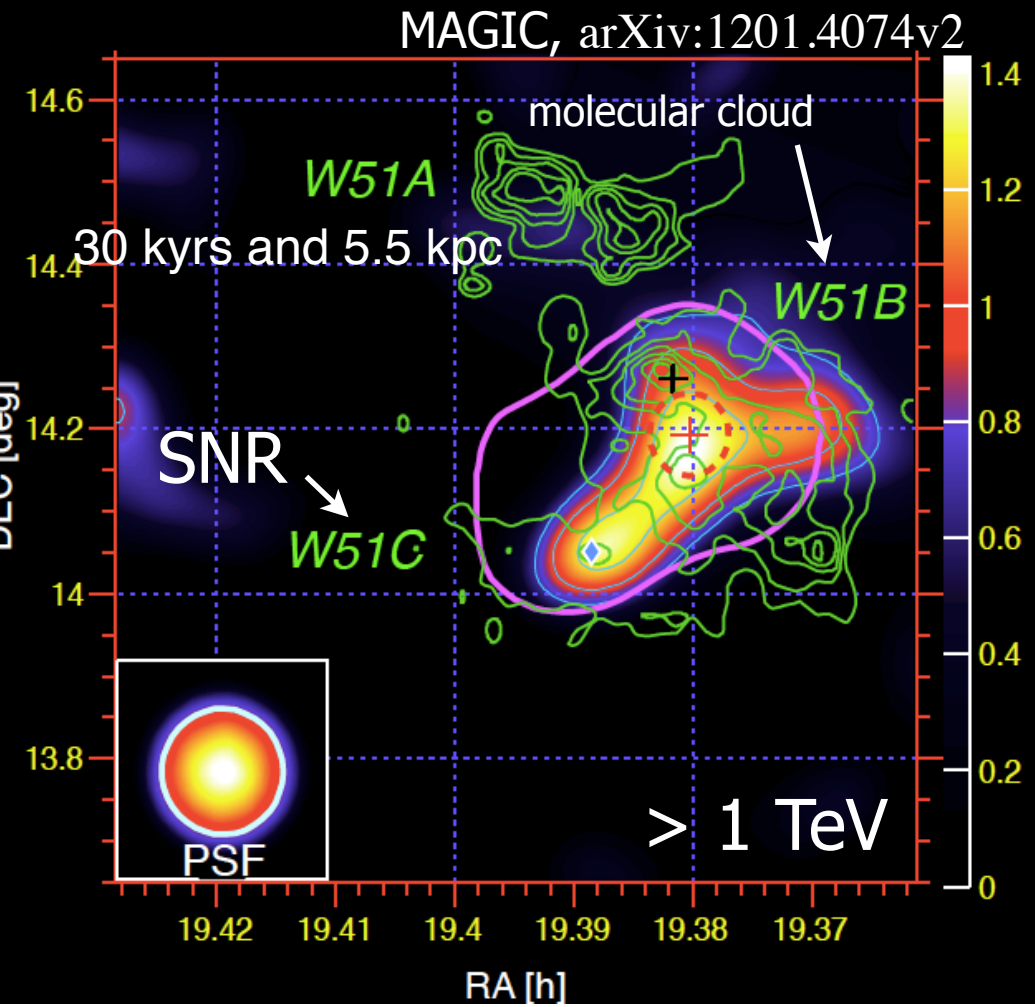
FOR STRONG SHOCKS: E^{-2}
SPECTRUM SLOPE DEPENDS ON THE COMPRESSION RATIO $\rho_2/\rho_1 = U_1/U_2 = 4$

Supernova Remnants in the TeV

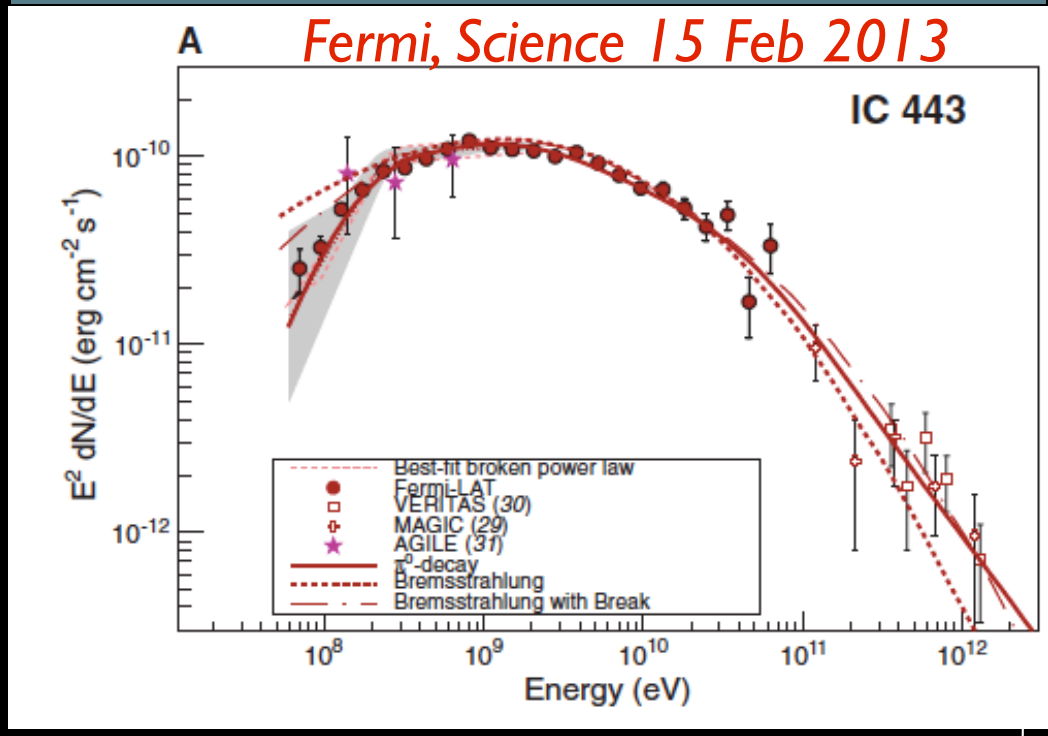


? $E_{max} = Z \times 100$ TeV < E_{knee} ?

Indirect evidence of protons: clouds.

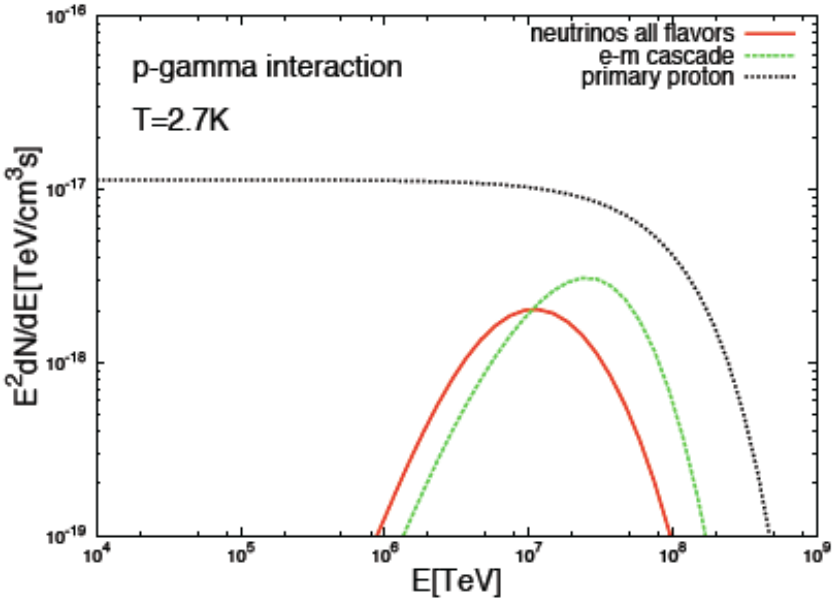


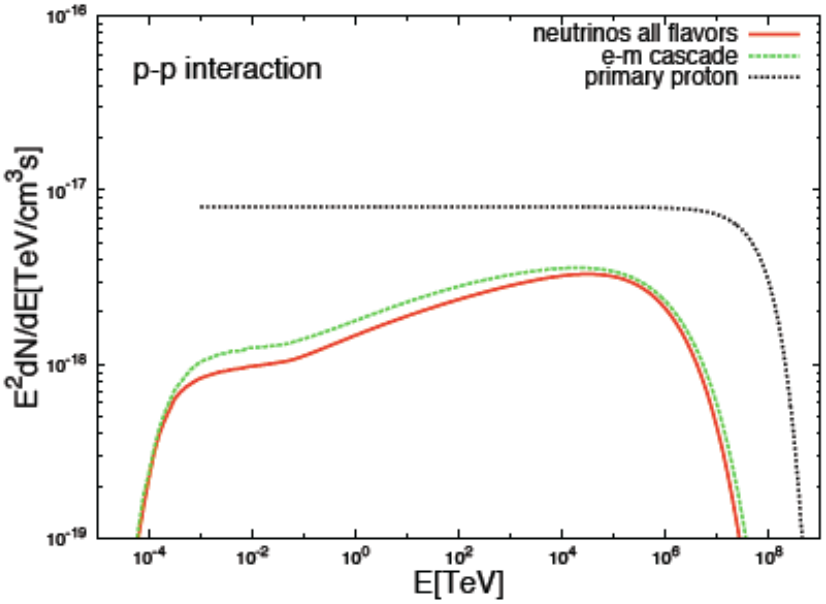
Fit of spectra prefer GeV pions (Fermi Agile)



The gamma-ray liaison

$$\frac{dN_p}{dE_p} \propto E_p^{-2} exp\left(-E_p/10^{20} eV\right)$$





Kelner et al. 2006 and 2008

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

$$\hookrightarrow \gamma + \gamma + p$$

TeV gamma rays

or p + p

$$\rightarrow \pi^+ + n$$

Cosmic rays?

$$\hookrightarrow \mu^+ + \nu_\mu + n$$

$$\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n$$

TeV neutrinos

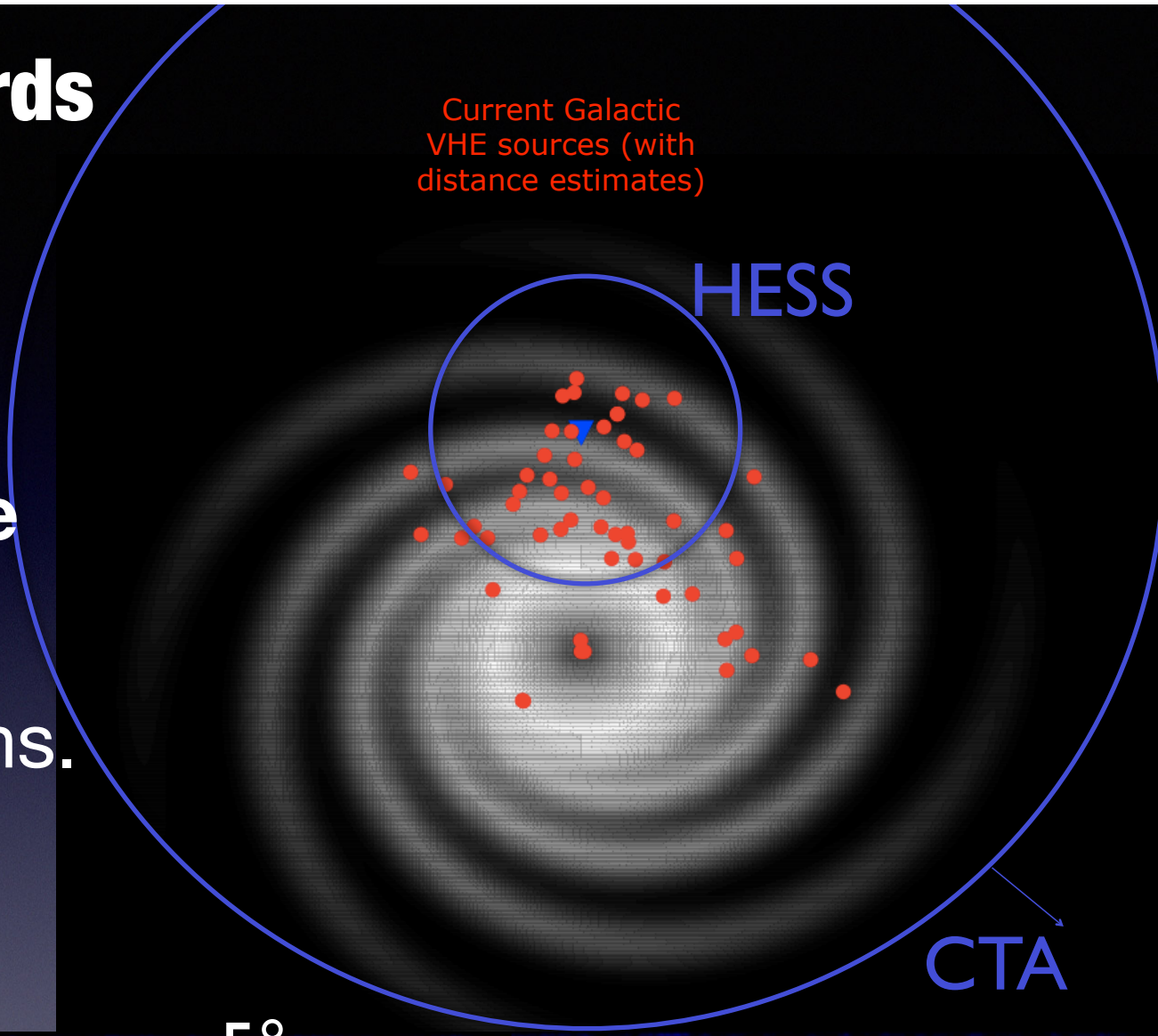
at the source: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 :$

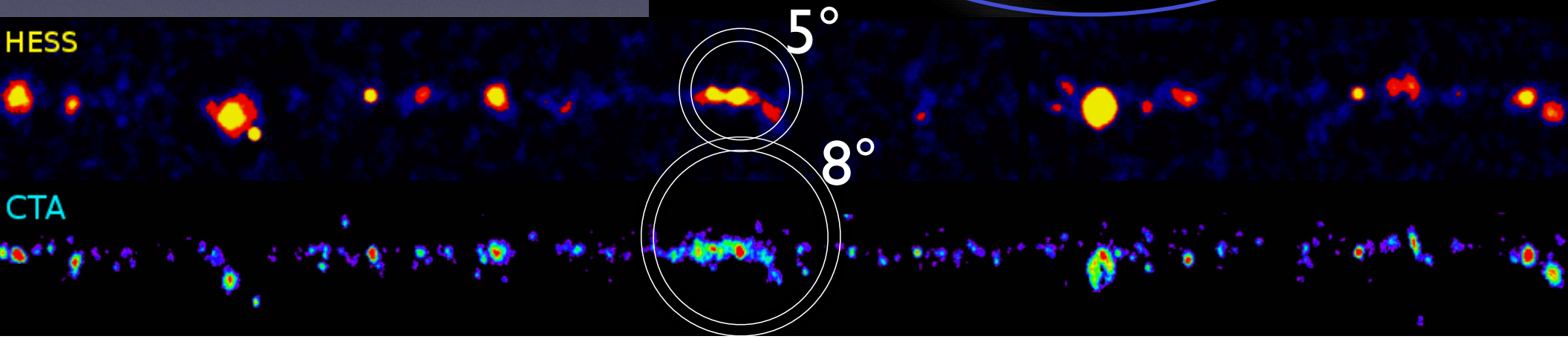
- Oscillations of the neutrino flavor:

at Earth: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 :$

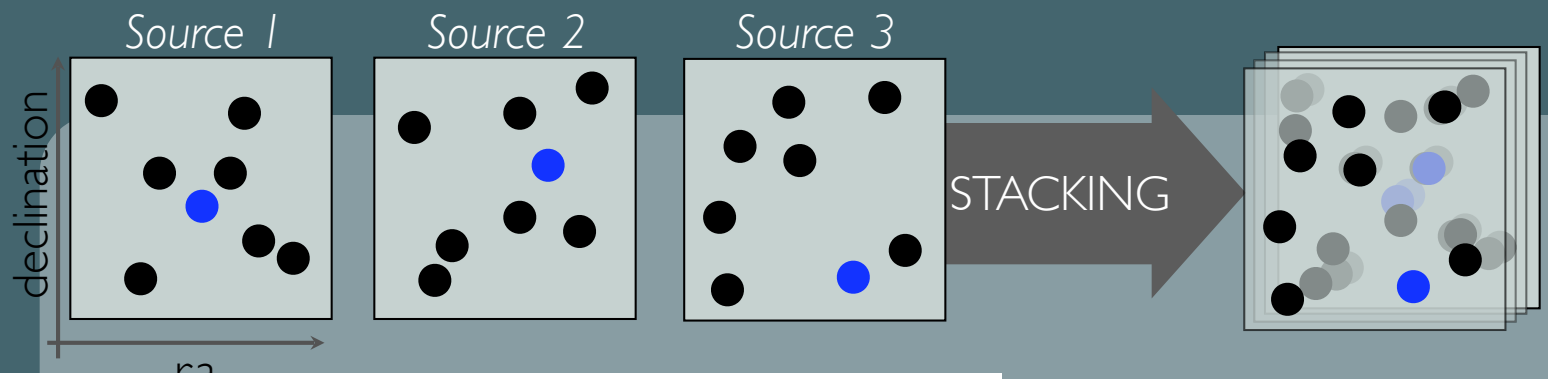
Gamma-rays towards precision era

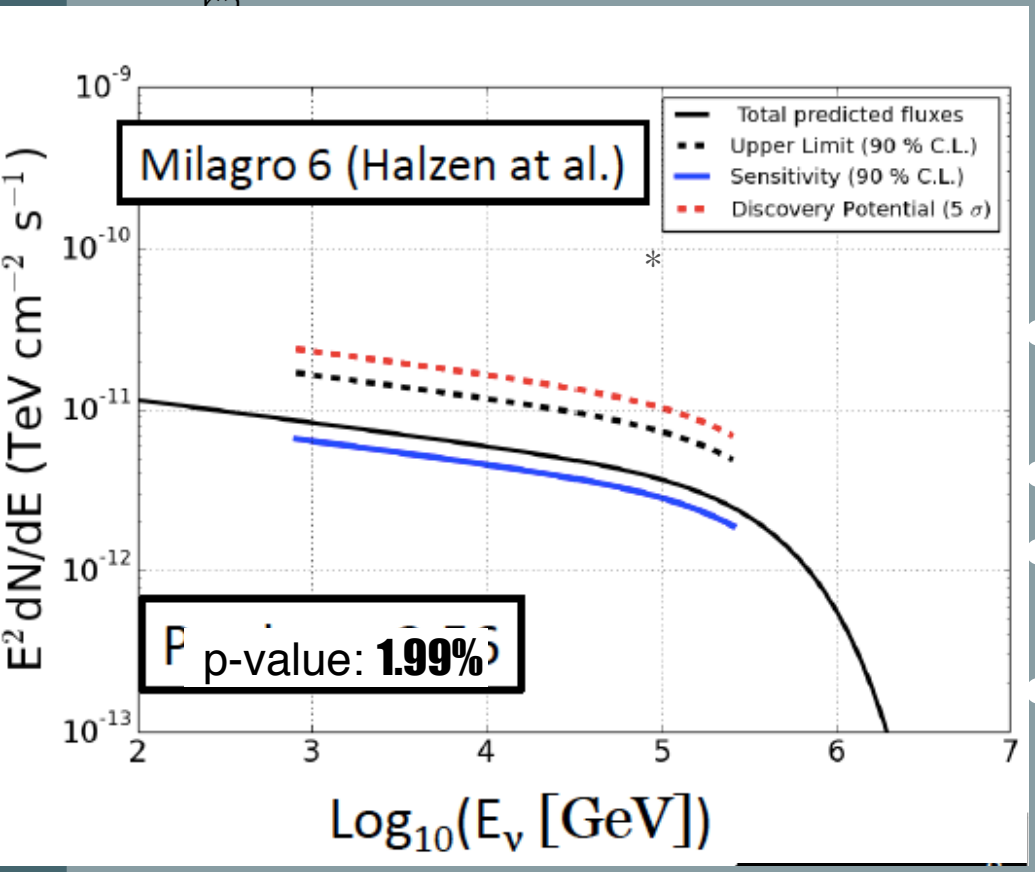
- CTA will see **whole** Galaxy
- ➡ Field of view + sens.
- Survey speed ~300×HESS





Cygnus region in neutrinos





Most Significant Deviation

- 6 TeV associations with supernova remnants based on **Milagro observations**.
- p-value of 2% *a posteriori* in IC40.
- Evolved from under-fluctuation in IC59 and 20% in IC59+IC79.
- p-value in IC86+IC79+IC59: 1.99%

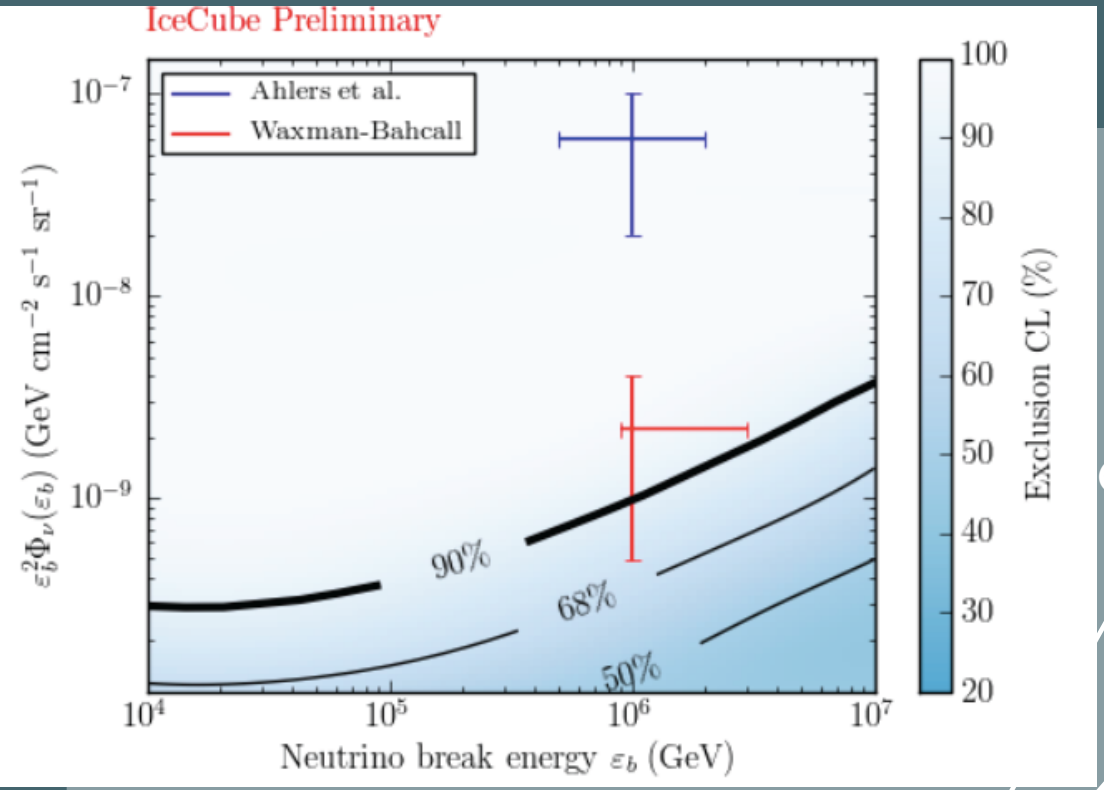
*F. Halzen, A. Kappes and A. O'Murchadha (Phys. Rev. D78:063004, 2008)

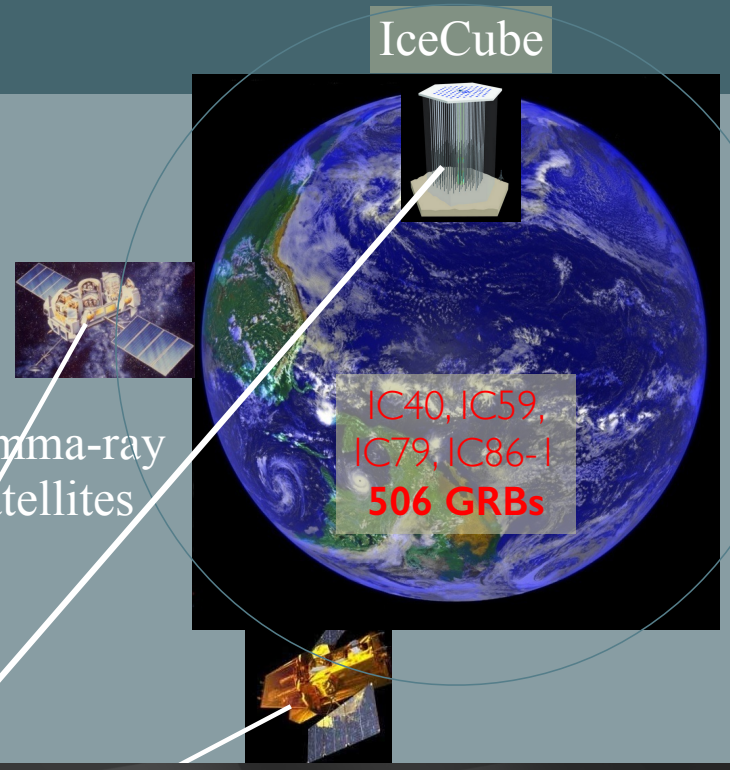
…and if the star collapses to a black hole…

gamma ray burst

- ✓ happens in seconds not thousands of year
- ✓ beamed along the spin axis of the black hole
- ✓ ? IceCube, Nature 2011

Neutrinos coincident with GRBs?





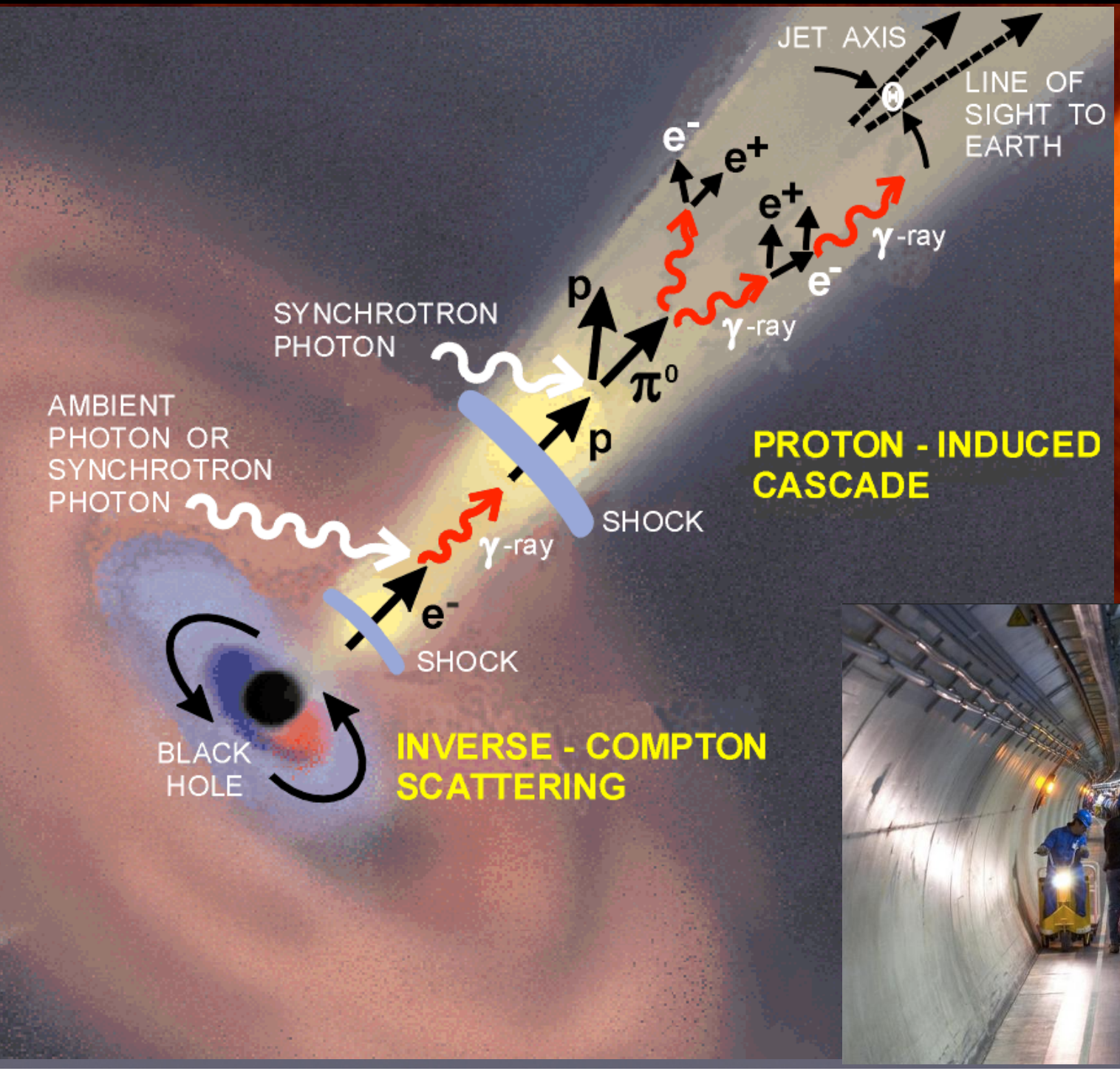
GRB: one neutrino per cosmic ray observed disfavored by IceCube

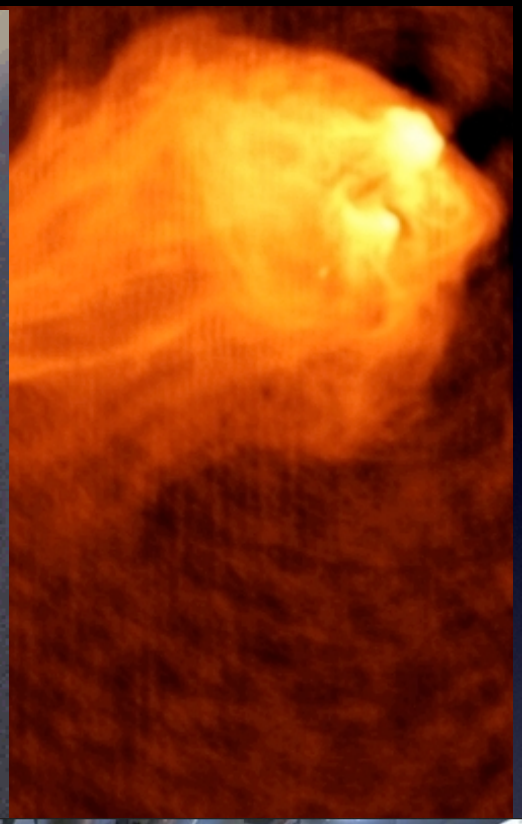
decays to a PeV neutrino

$$p + \gamma \rightarrow n + \pi^+$$

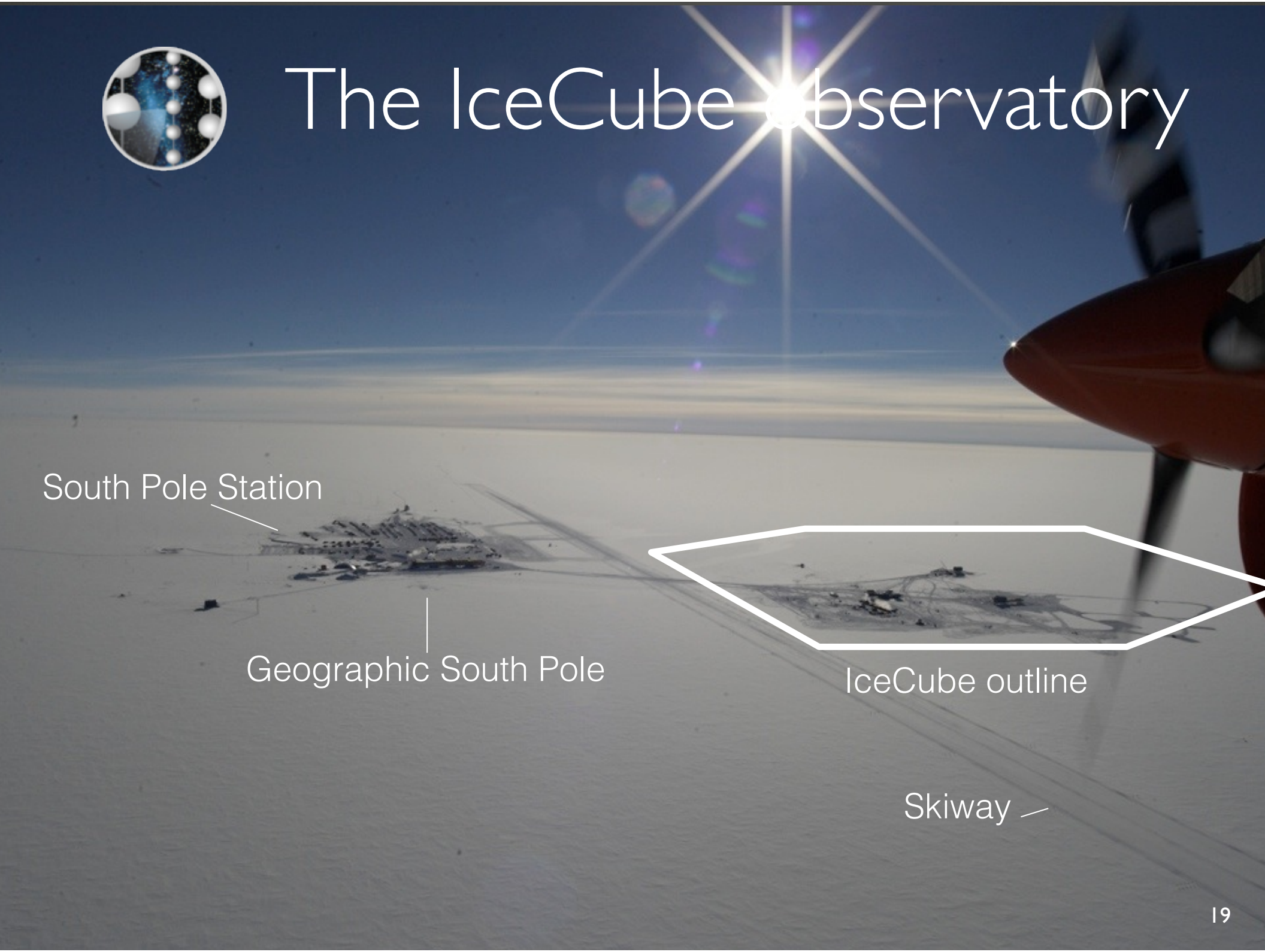
decays to cosmic ray

AGN jets


JET AXIS
LINE OF SIGHT TO EARTH
θ
e-
e+
e+
e-
γ-ray
γ-ray
p
π0
p
SYNCHROTRON PHOTON
AMBIENT PHOTON OR SYNCHROTRON PHOTON
γ-ray
e-
SHOCK
SHOCK
PROTON - INDUCED CASCADE
BLACK HOLE
INVERSE - COMPTON SCATTERING

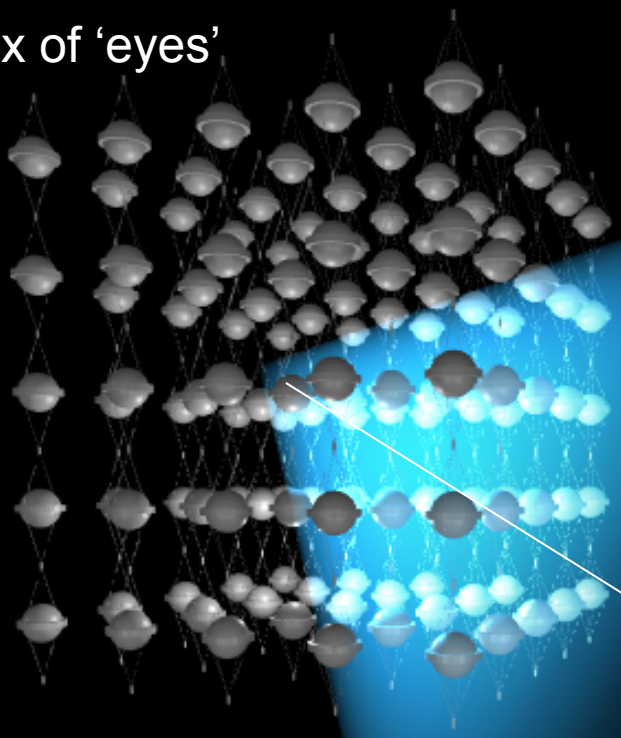


The IceCube Observatory



Deep ice is a dark transparent medium

3D matrix of ‘eyes’



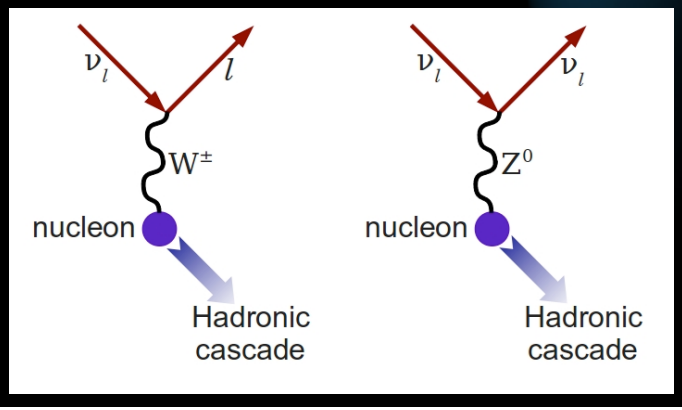
1 every million events interacts producing a detectable muon

41deg

muon β~1

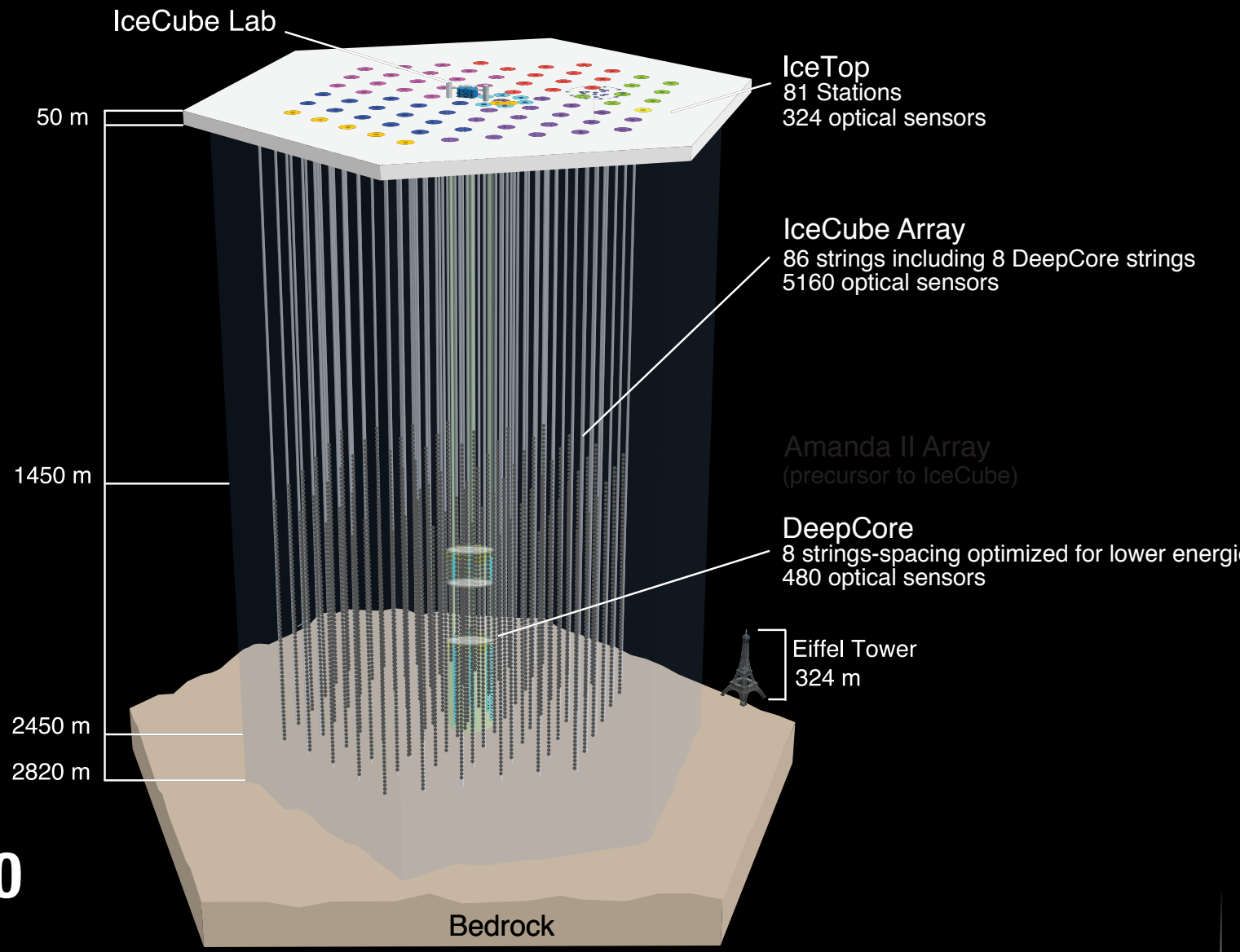
interaction

neutrino

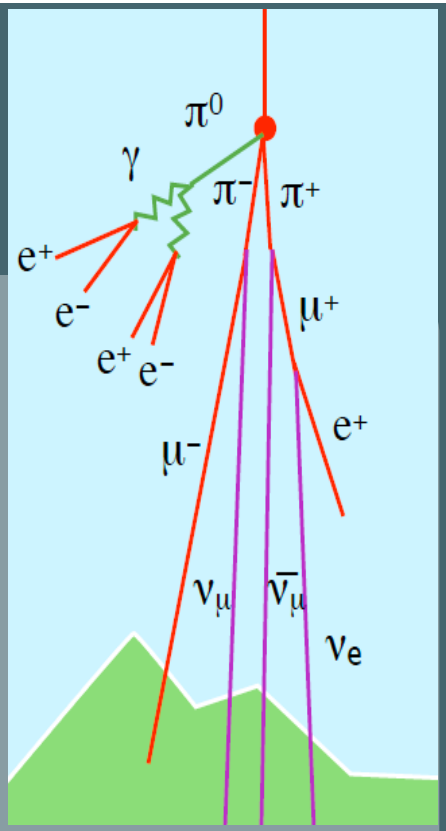


The IceCube Observatory

- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 125 m string spacing
- Completed 2010



Neutrino Signal and Background



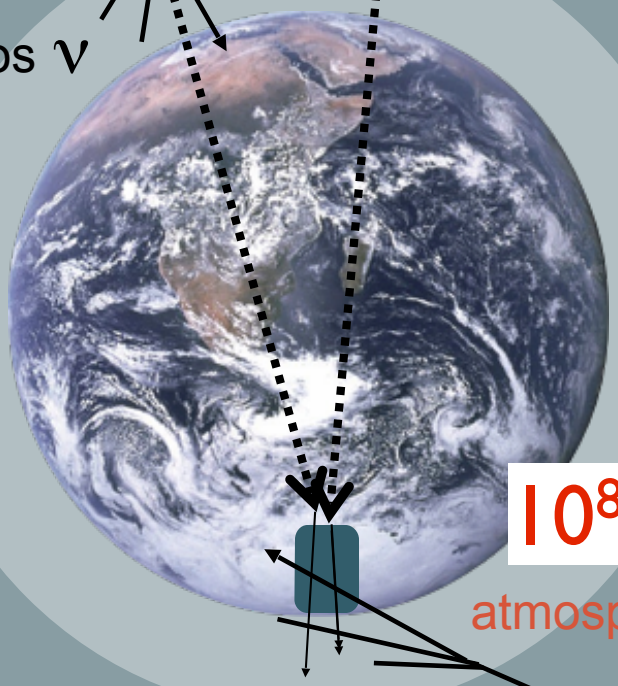
cosmic ray

signal ν

200 neutrino events/day**

Northern Sky

atmos ν



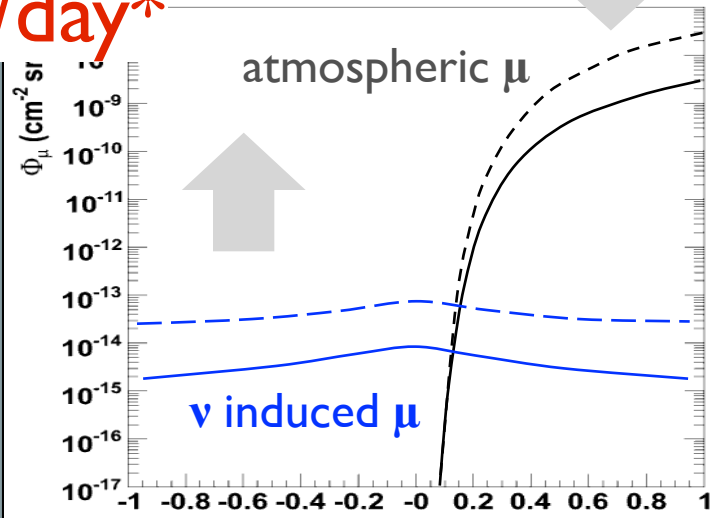
* IceCube trigger rate

**IceCube analysis level/day

atmospheric background

10^8 muon events/day*

atmospheric μ

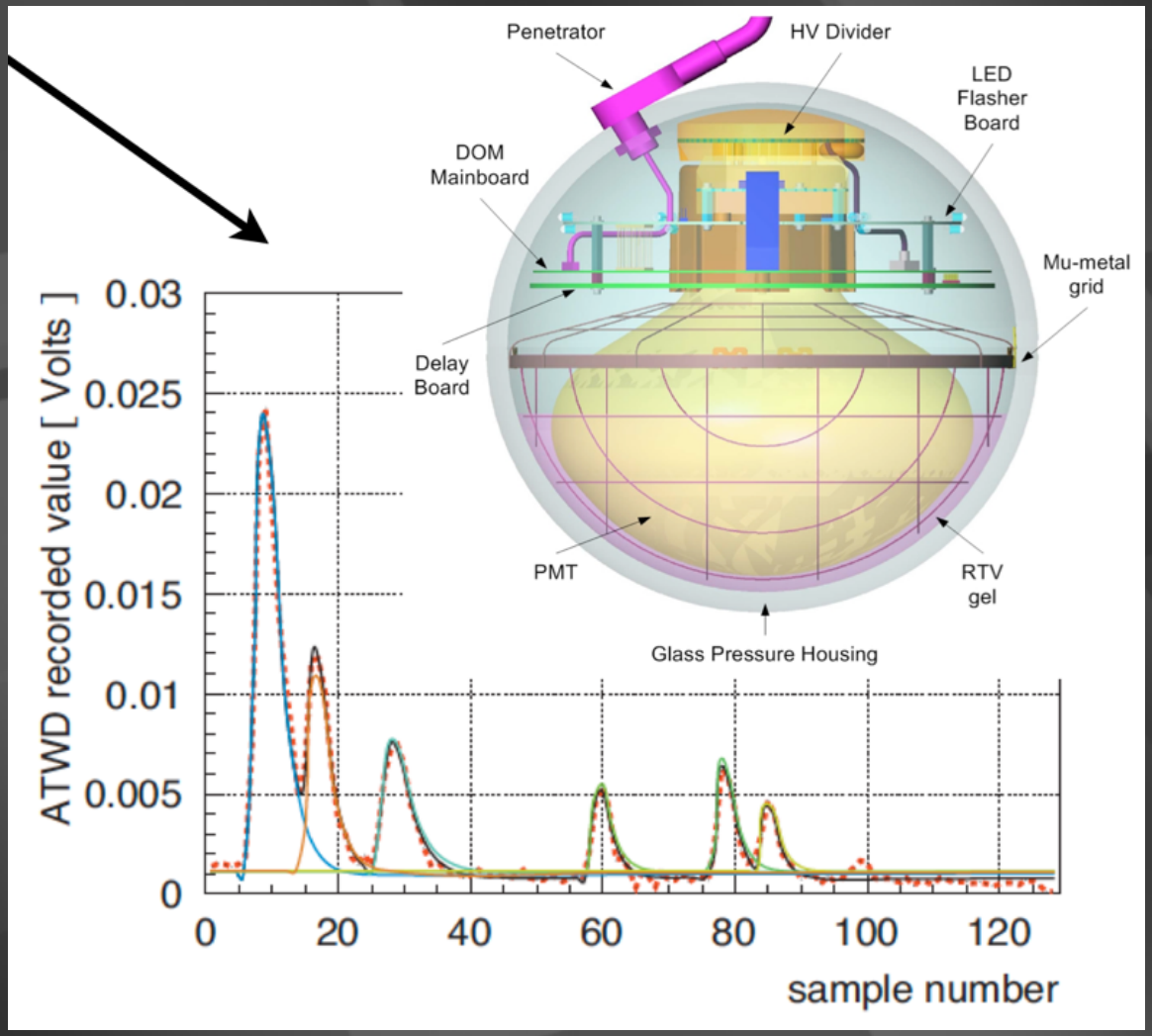


atmospheric μ

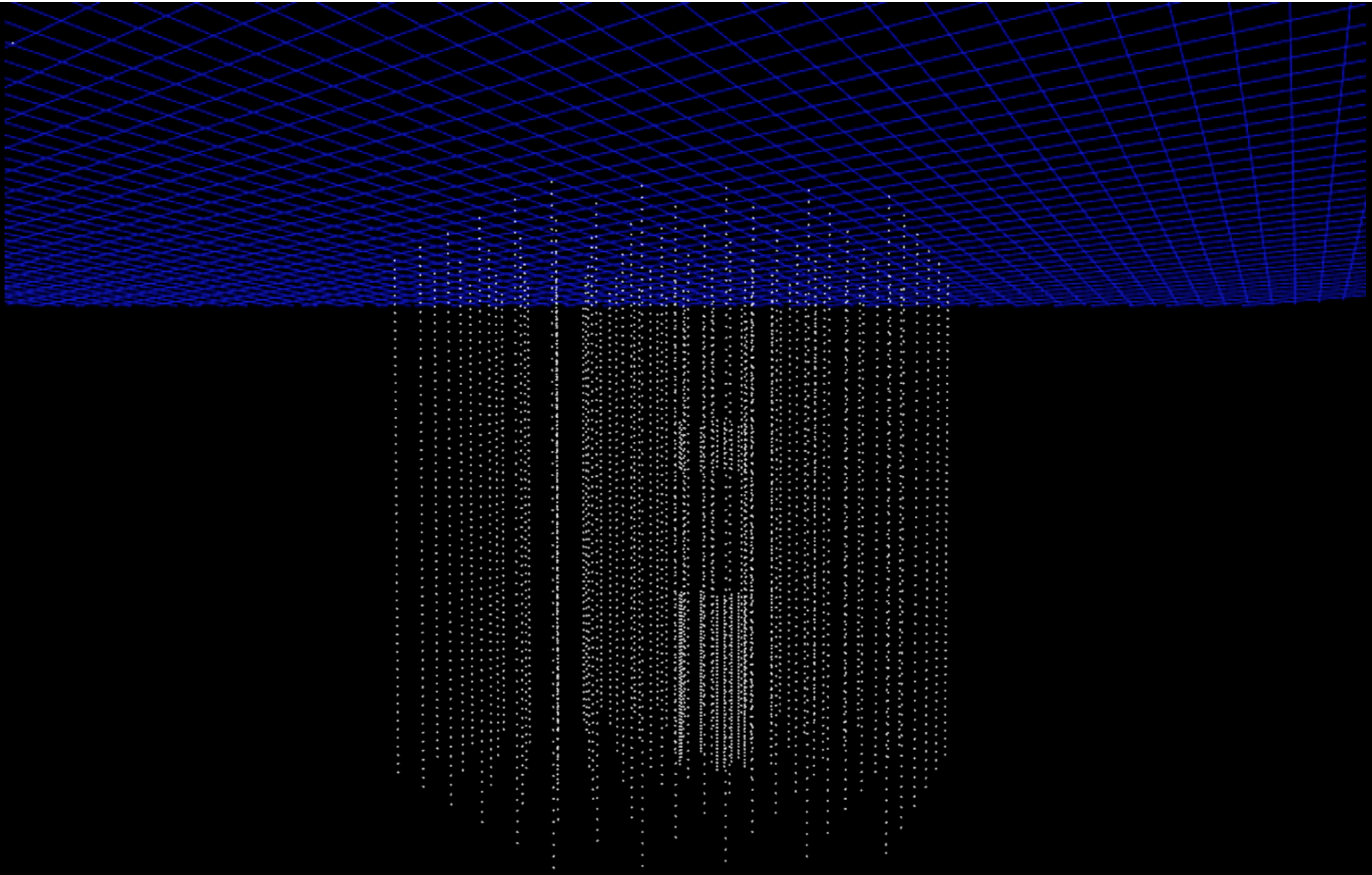
cosmic ray

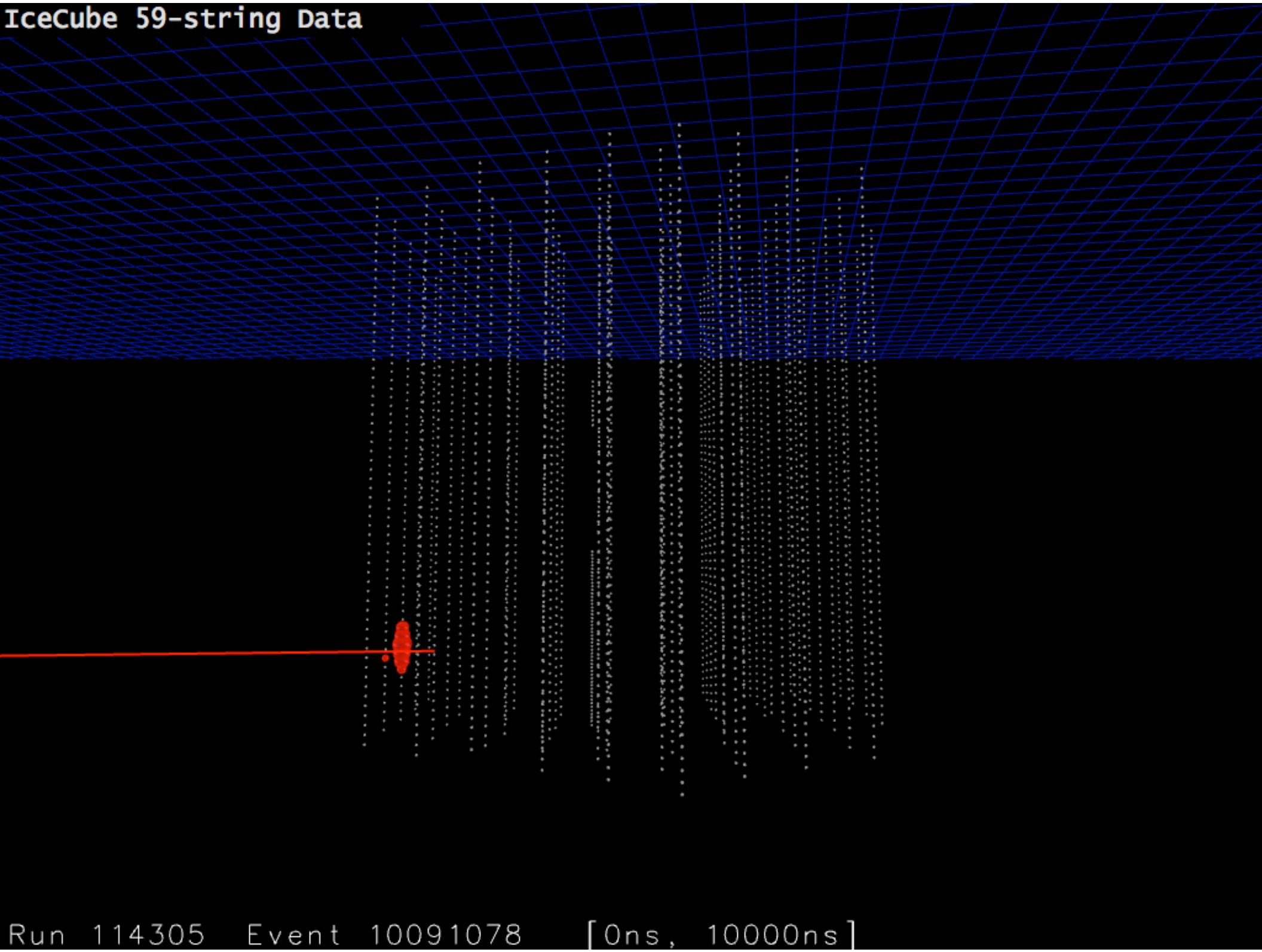
Southern Sky

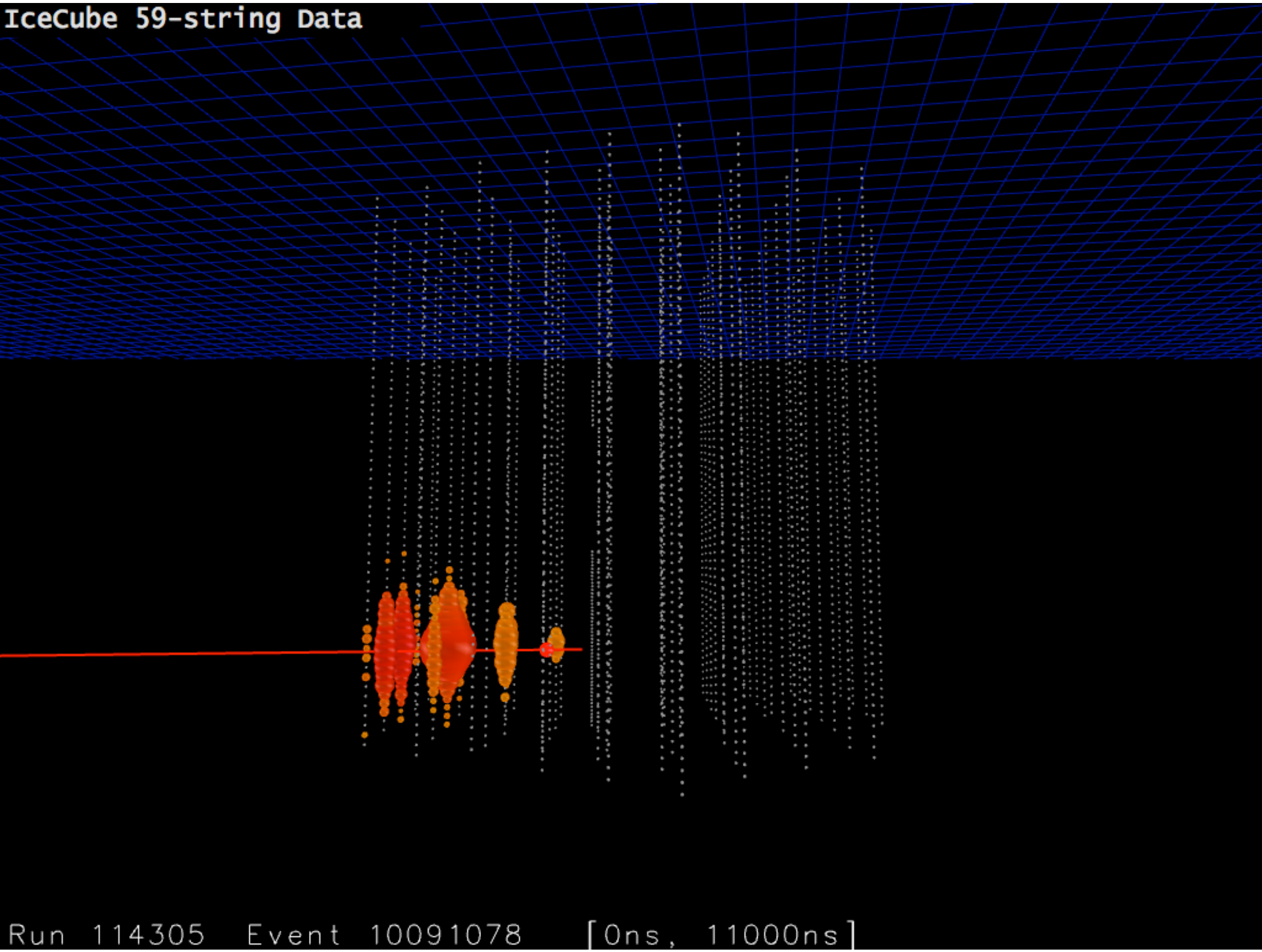
… each Digital Optical Module independently collects light signals like this, digitizes them,



…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…


you looked at 10 ms of data!


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 10000ns]


IceCube 59-string Data
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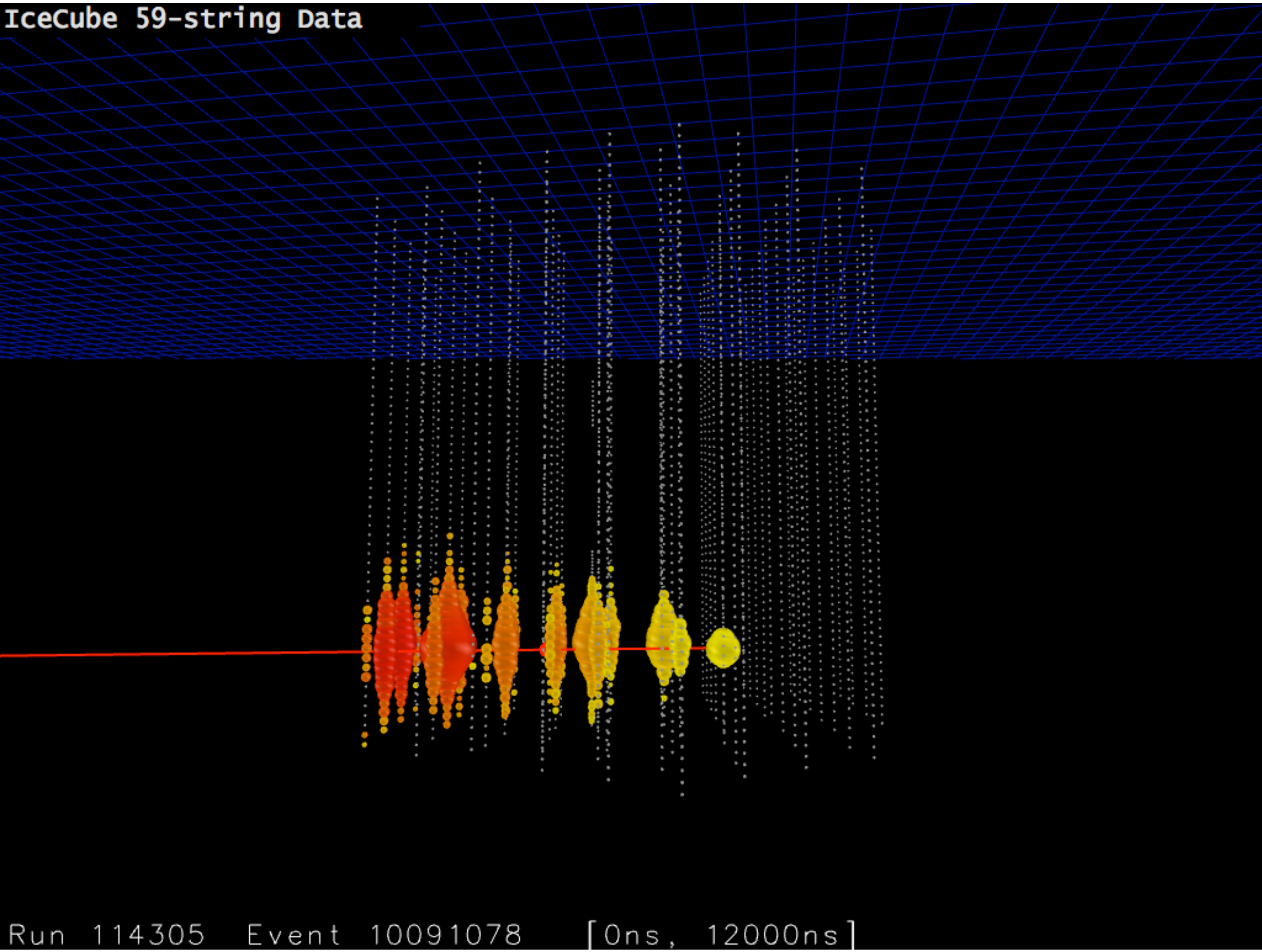
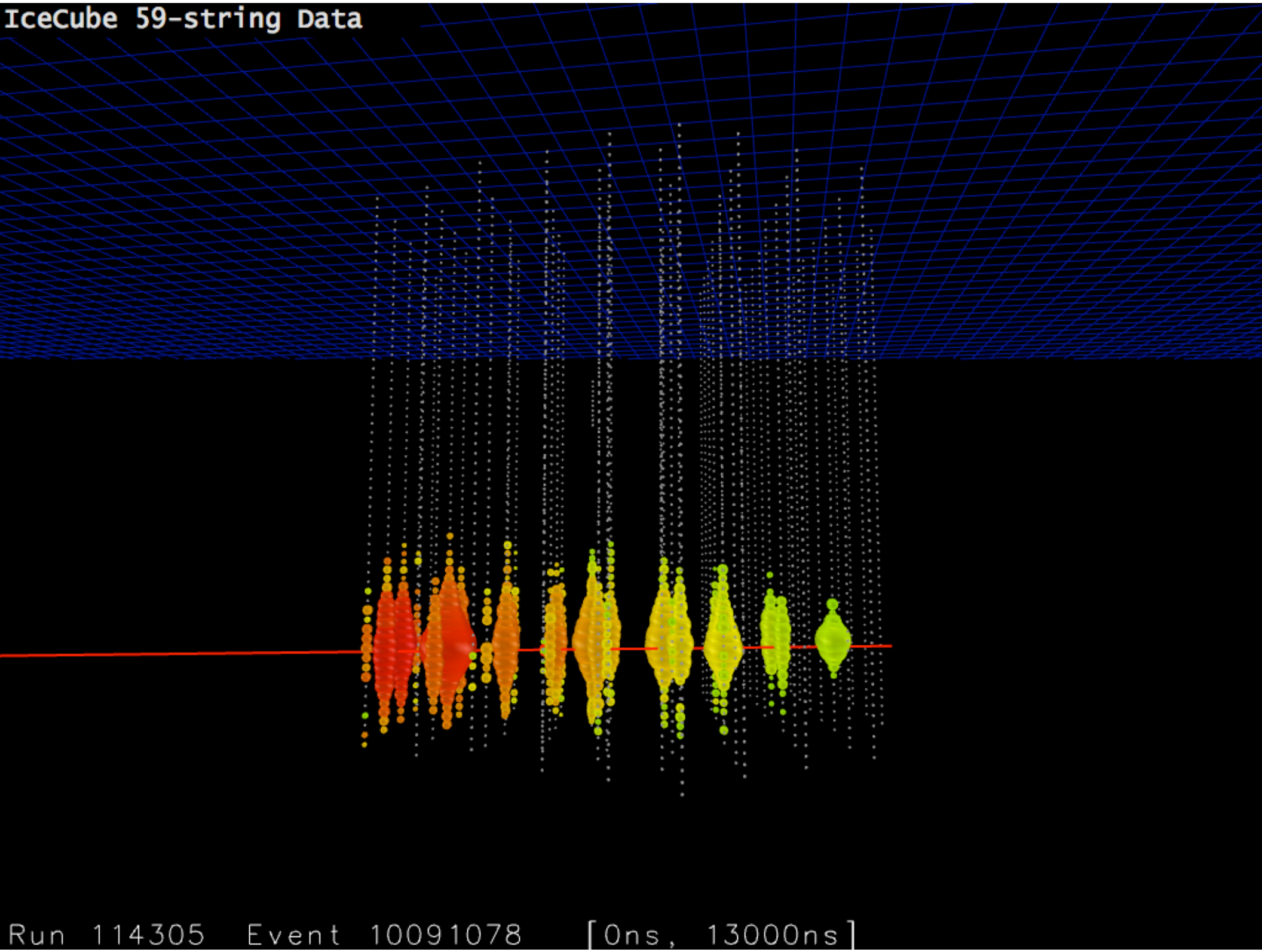
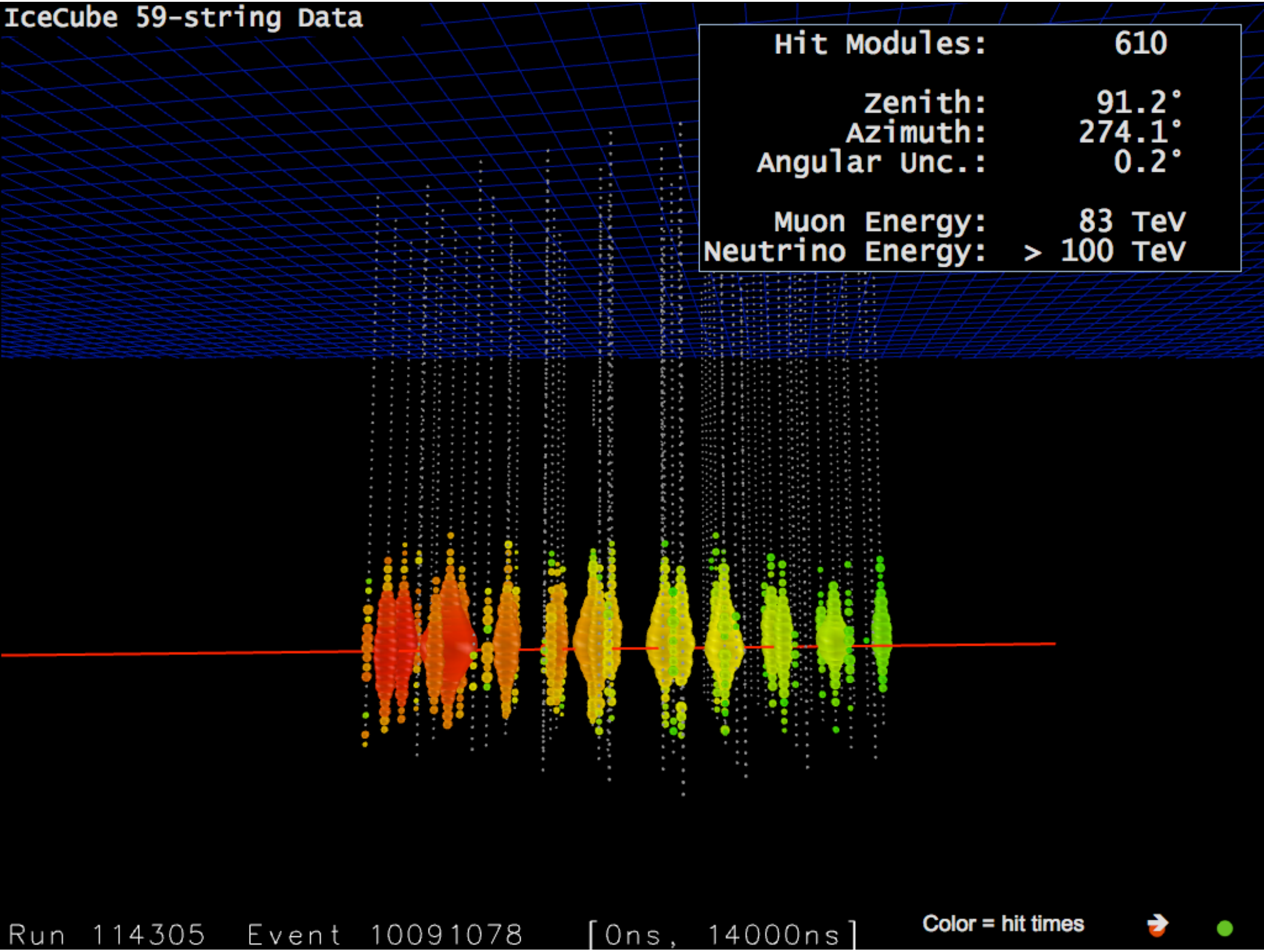
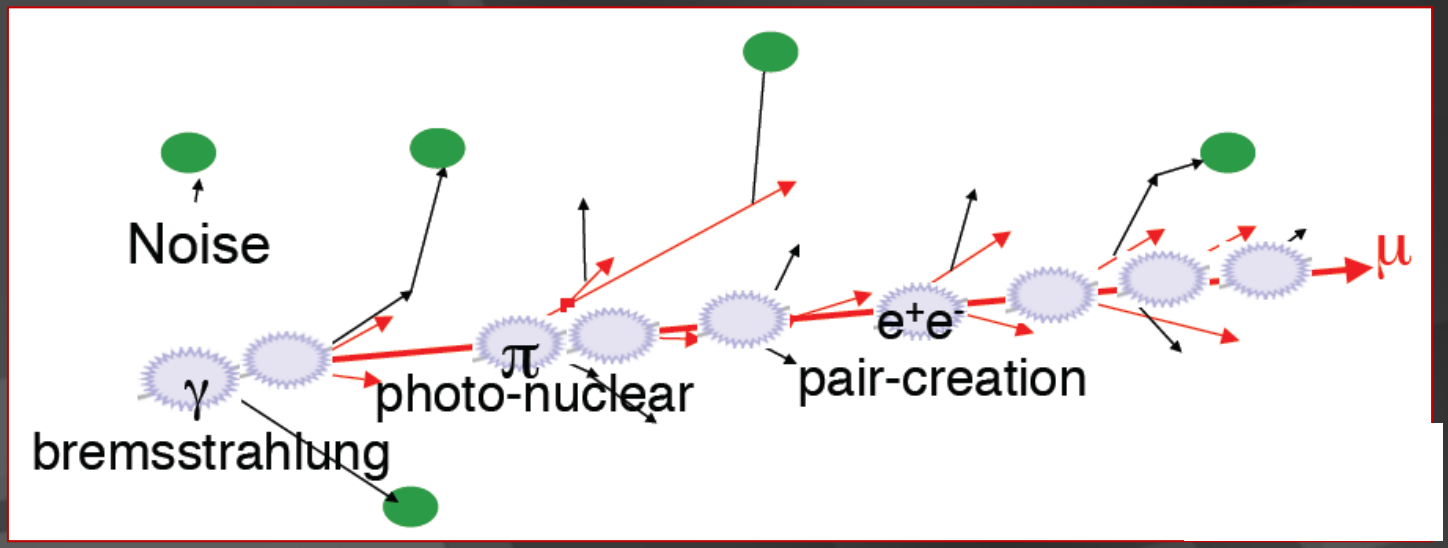

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 12000ns]


IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 13000ns]

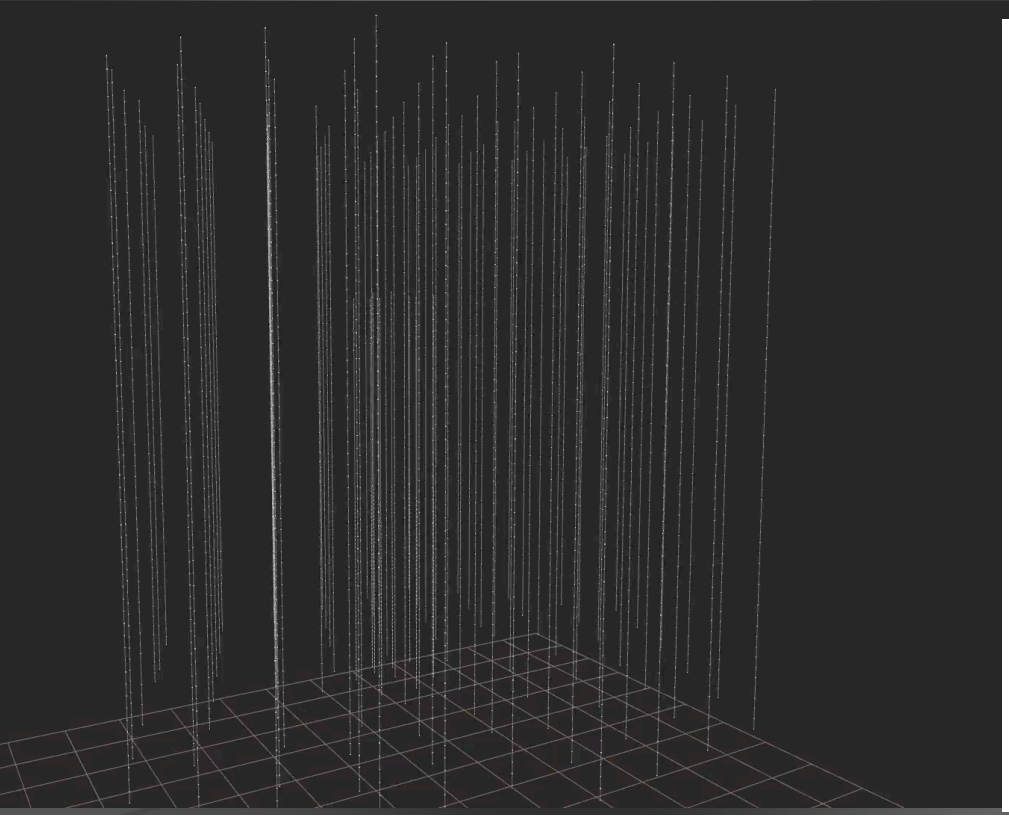

IceCube 59-string Data
Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV
Run 114305 Event 10091078 [0ns, 14000ns]
Color = hit times

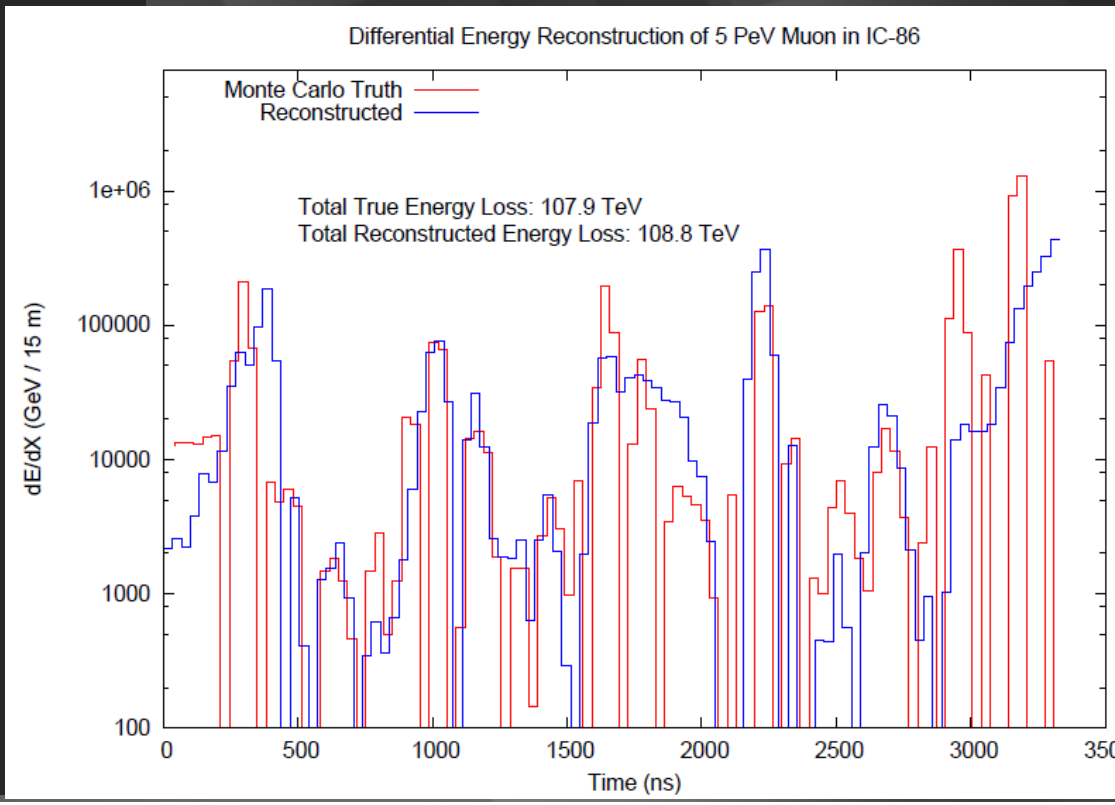
Milestone 1: improve energy measurement



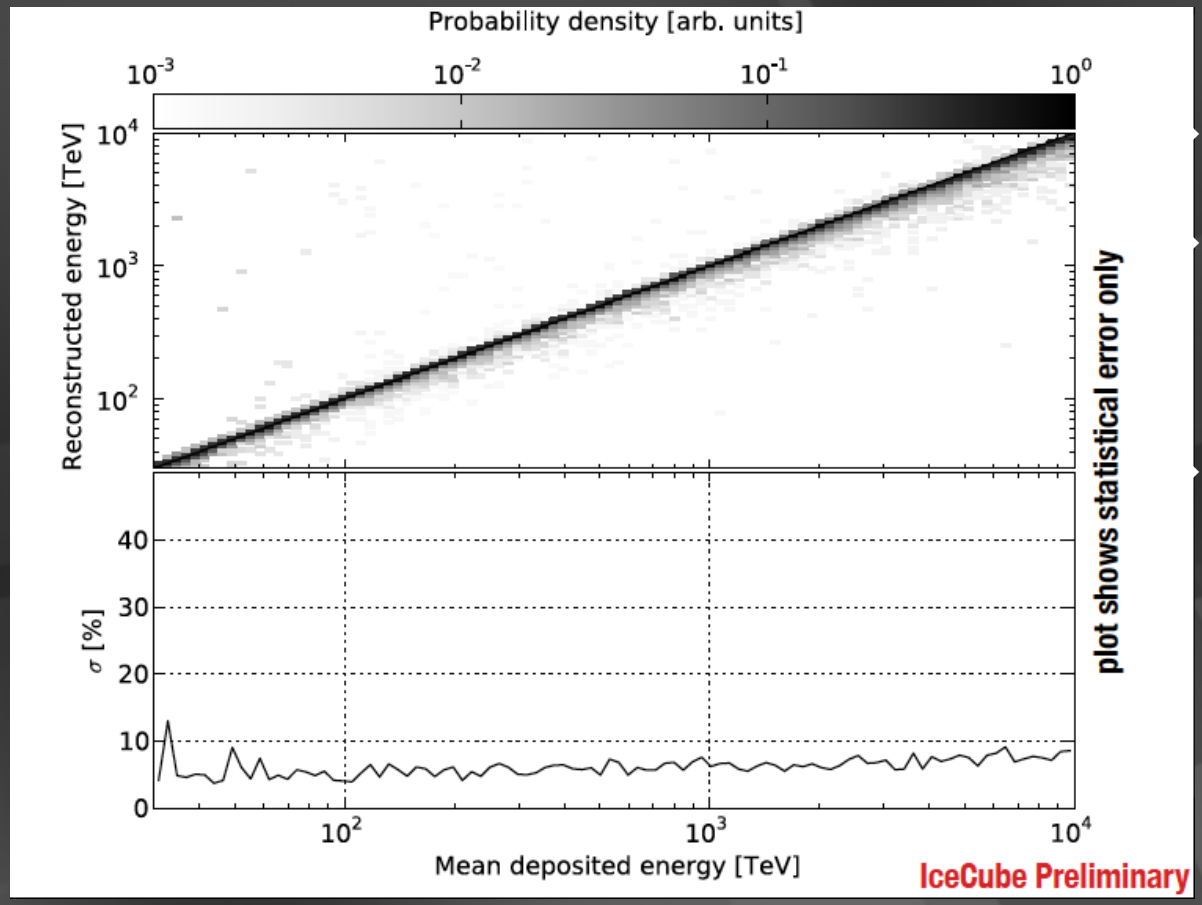
- **Muon visible Energy res: ≈ 20%**

measure at single photons

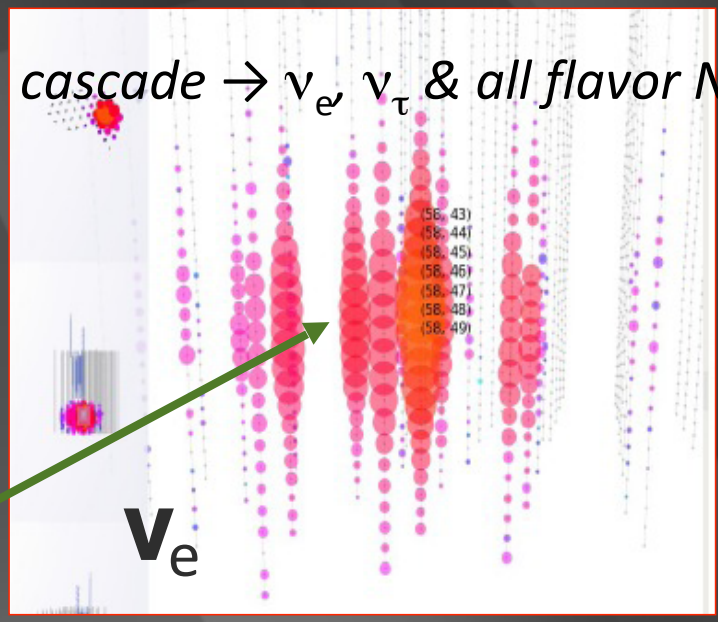




Milestone 2: improve cascade measurement

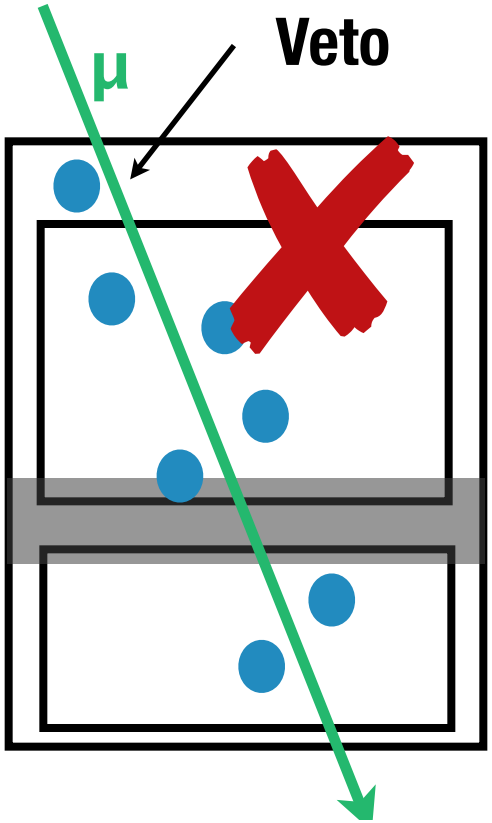


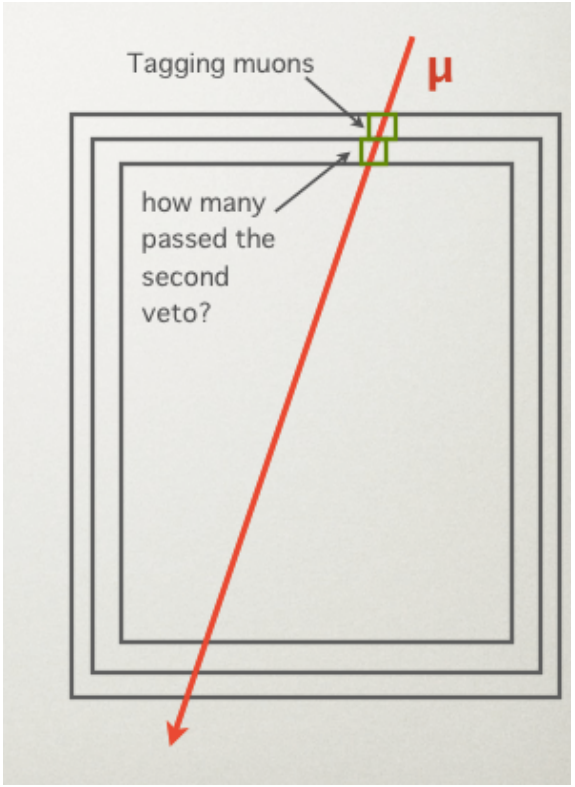
- **Cascade Angular resolution: ≈ 10-15%**
- **Cascade Energy resolution: better than ≈ 10%(measured with in-ice calibration laser)**
- **Modeling of photon transport in ice (measured with in-ice calibration LEDs and other devices (dust logger, ...)**



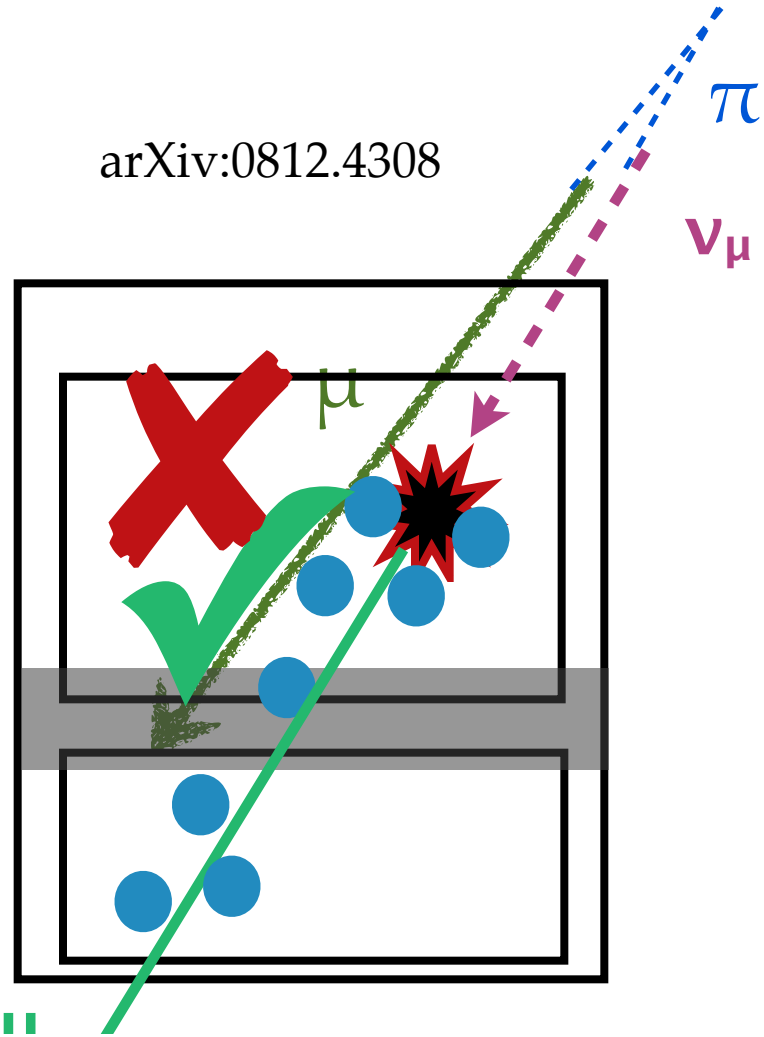
Milestone 3: improve cascade measurement

Muon Veto efficiency tagged on data 6 ± 3.4 muons per 2 years

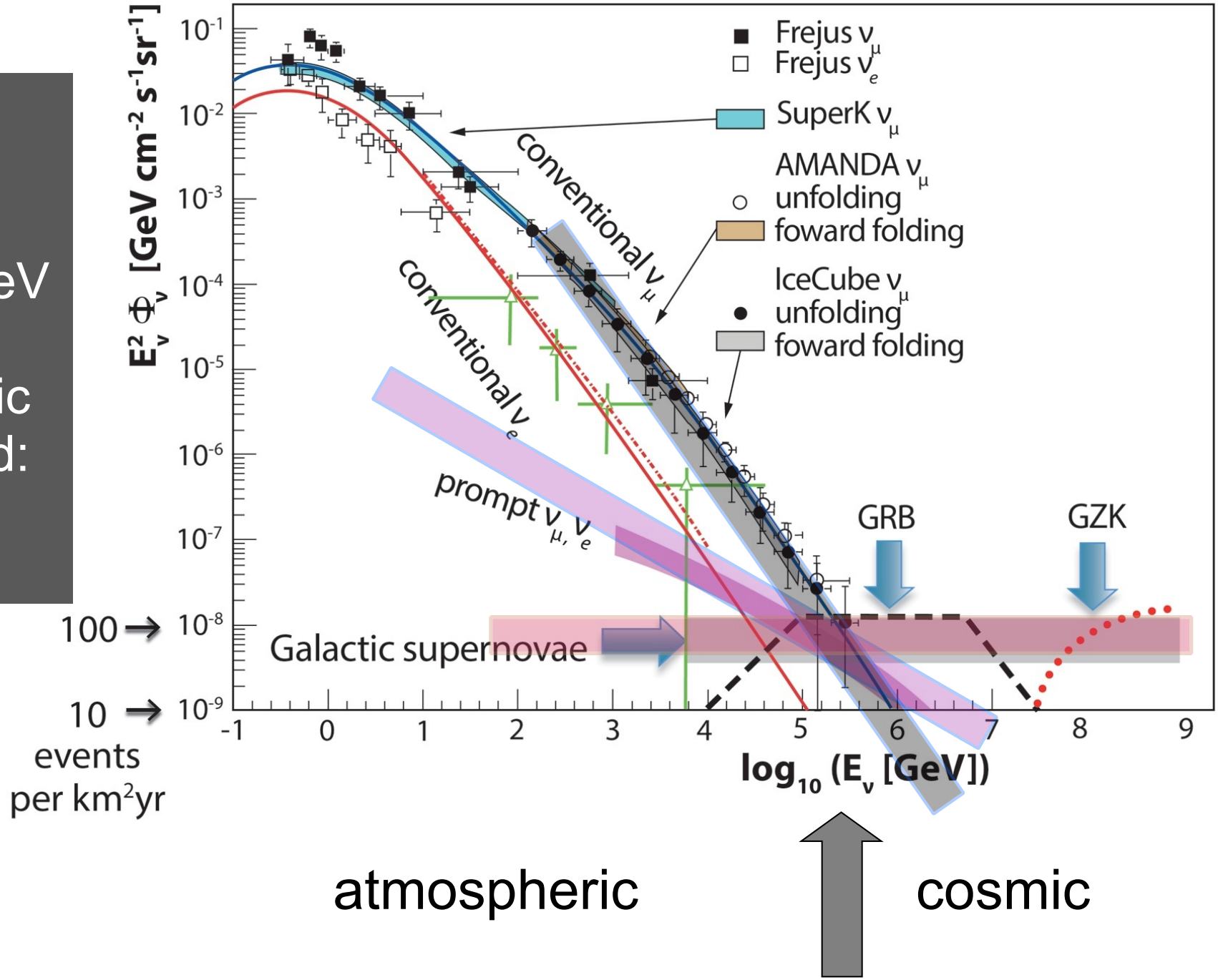




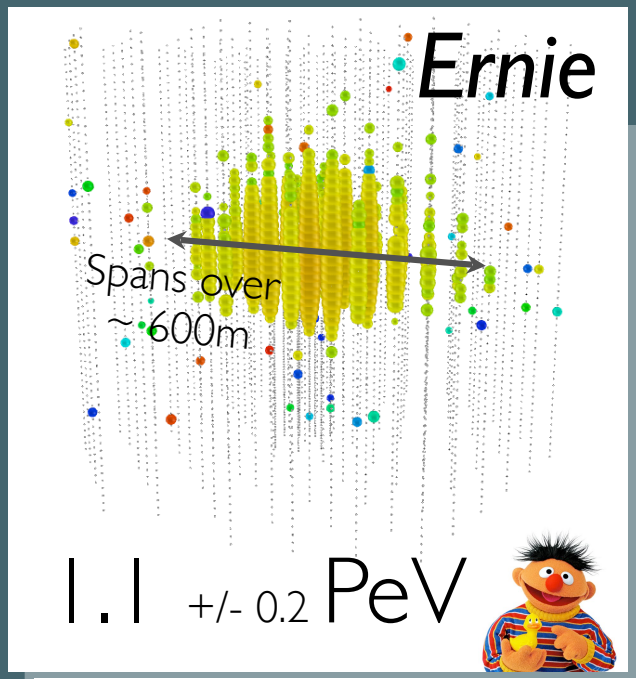
arXiv:0812.4308

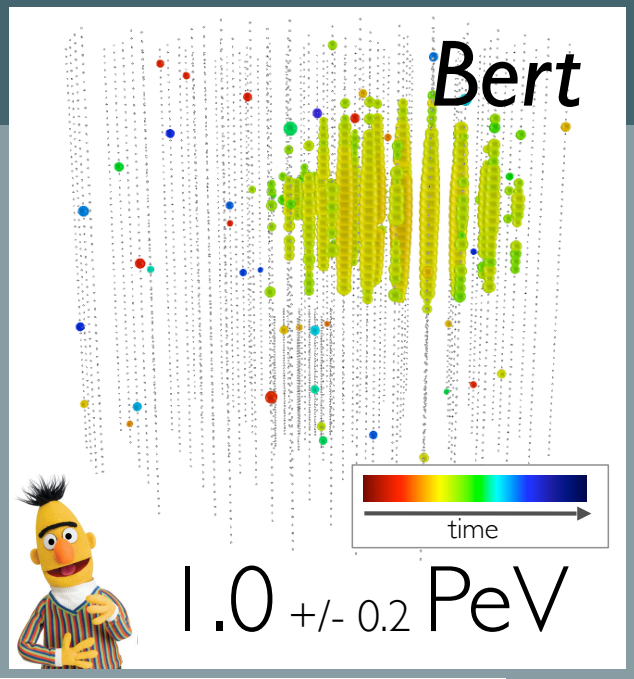


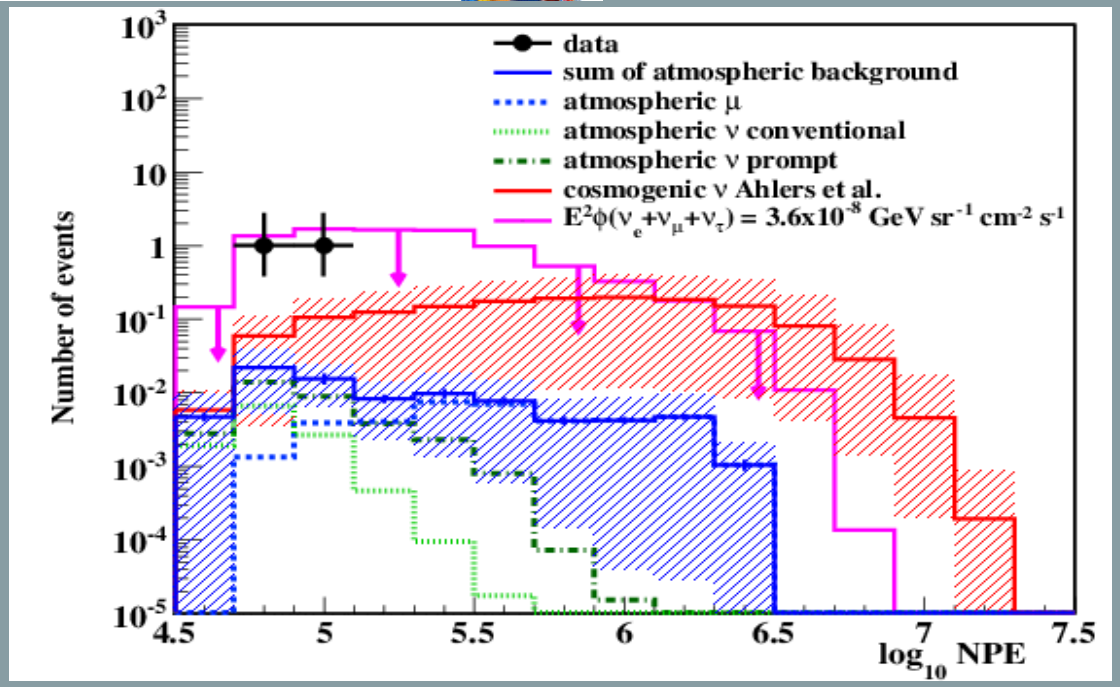
- cosmic neutrinos: energy
  > 100 TeV
- atmospheric background: 1~2 events per year



Some Hints: 3. PeV Neutrinos







- Two very interesting cascade events found in IceCube (IC79/IC86)
- Analysis targeting much higher energy all flavor neutrinos (related to GZK cutoff)
- Expected background: 0.08 ± 0.05
- Significance: **2.8σ**

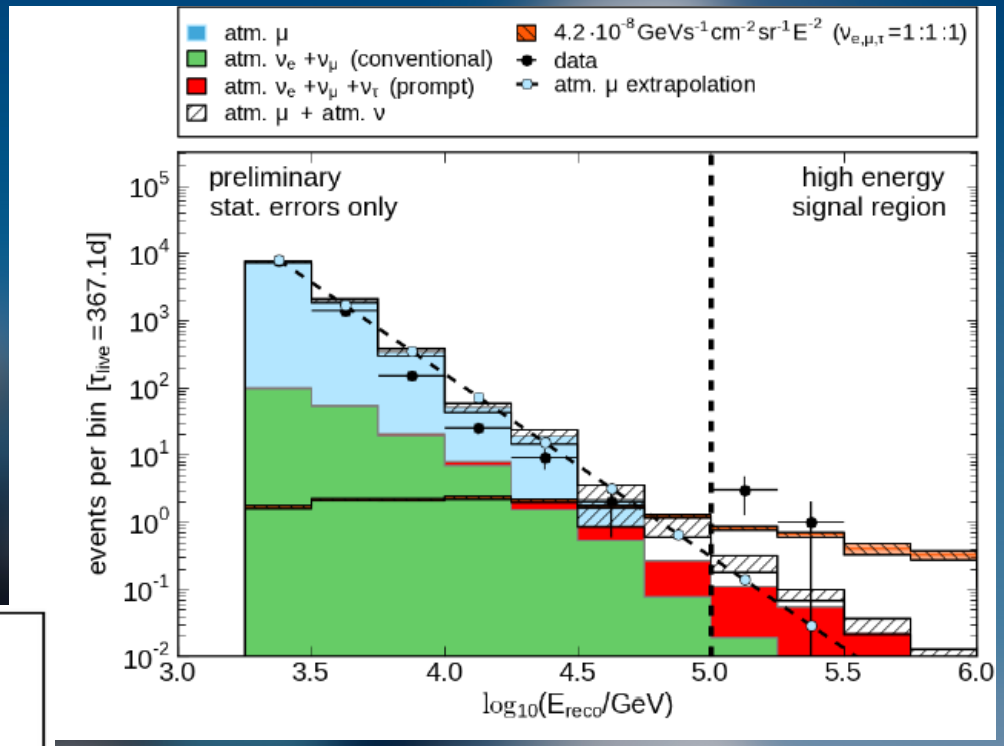
Too low in energy for GZK
Too high in energy for atmospheric

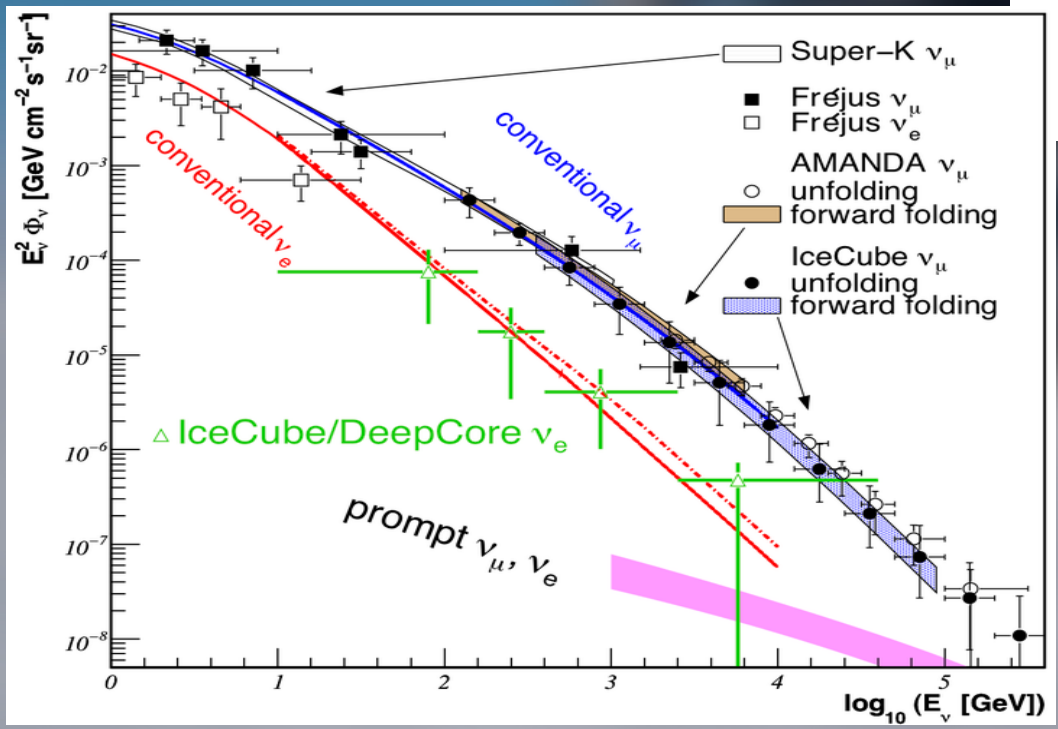
IceCUbe PRL111 (2013)

Some Hints : 1. Cascades in IceCube 40

IceCube 40 Cascades

Bkg only hyp disfavored at: **2.4σ**





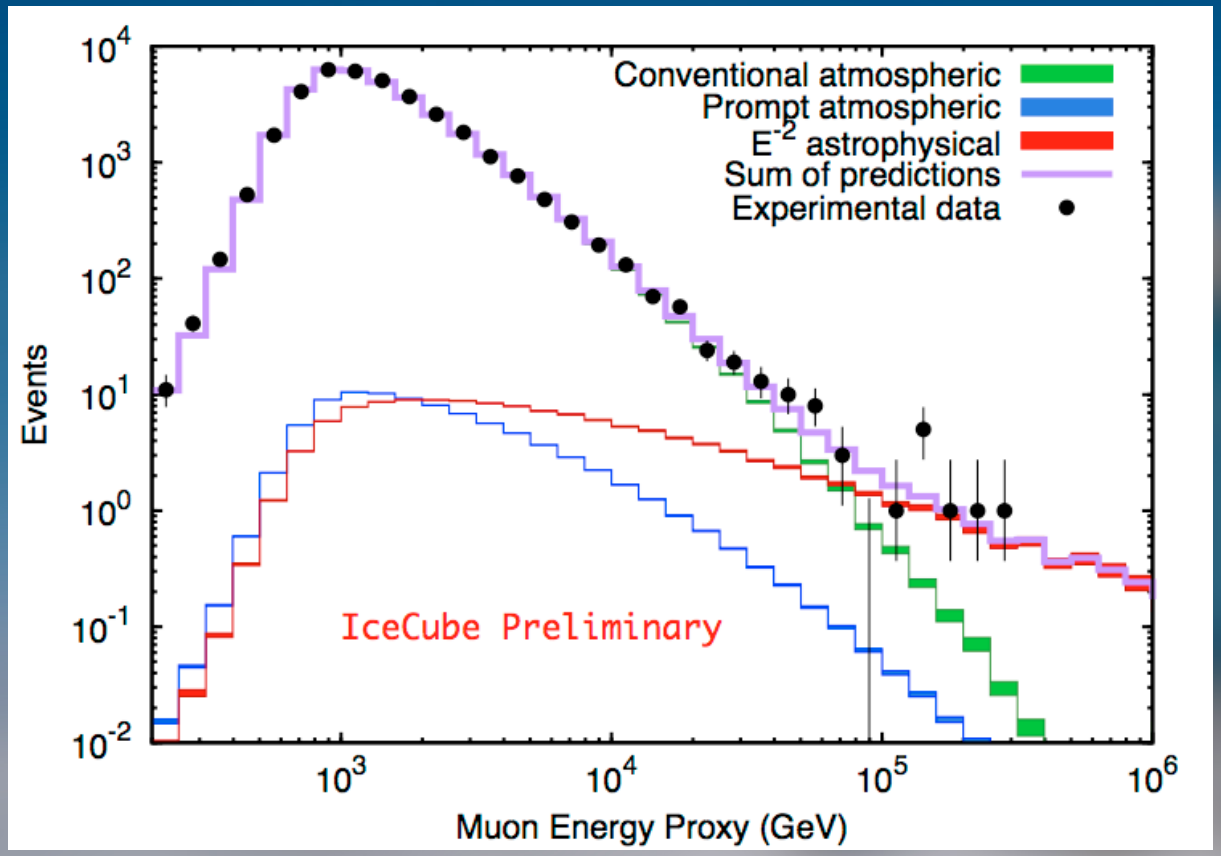
Other Measurements :

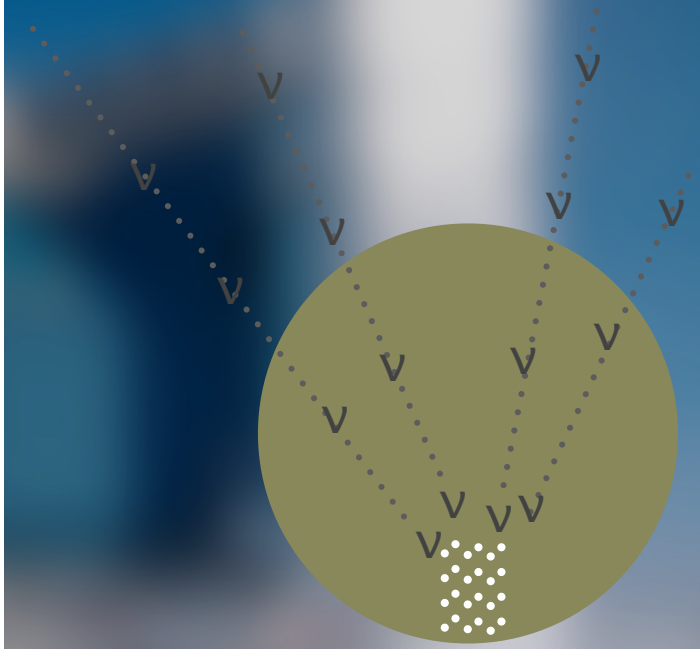
Atmospheric ν_e and ν_μ fluxes

Phys. Rev. Lett. 110,151105 (2013) and
Phys. Rev. D 83, 012001 (2011)

Evidence : Upgoing Muons in IceCube 79 and 86-I

Standard through going-muon diffuse analysis





- The best-fit astrophysical flux: $1.01 \times 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$
- The bkg-only hypothesis is disfavored: **3.9σ , 659 d**

High Energy Starting Events (HESE): 3 YEARS

37 EVENTS

9 track-like events

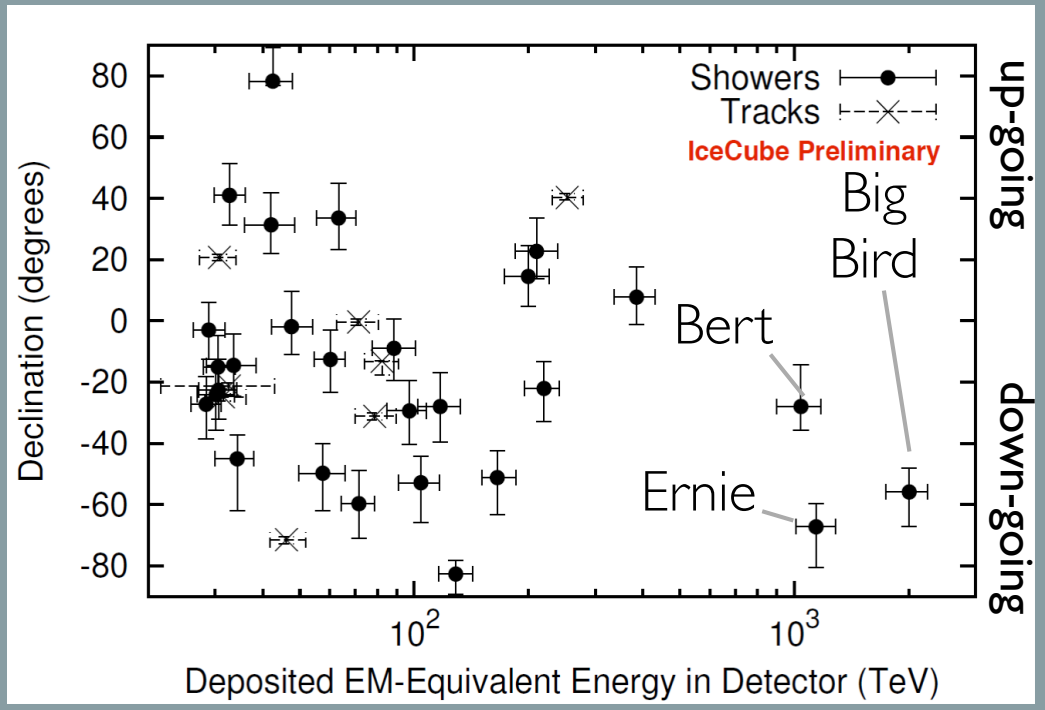
1° ang. resolution

Muon takes some energy away

28 cascade-like events

10° – 45° ang. resolution

15% visible energy resolution



Estimated background:

- $6.6^{+5.9}_{-1.6}$ atm. neutrinos
- 8.4±4.2 atm. muons

4.8σ

combining with 2.8σ from GZK results (35 + 2 events)

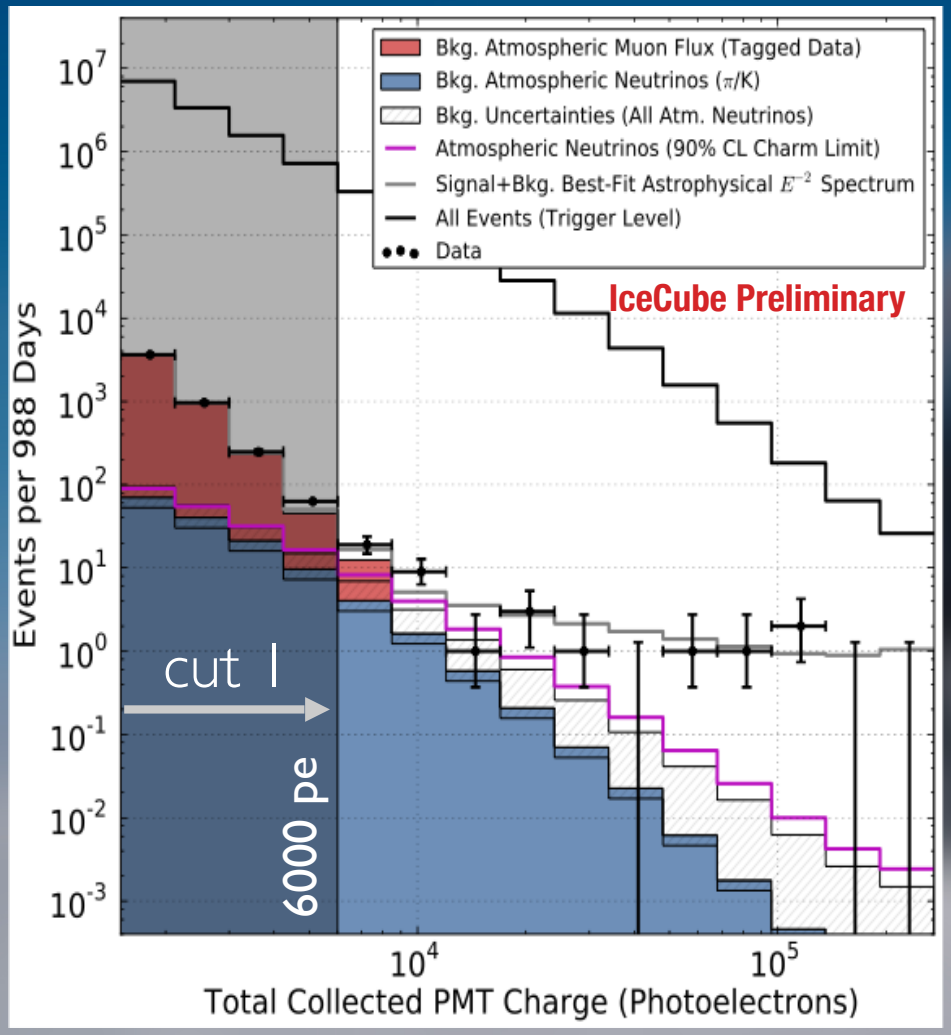
5.7σ

full likelihood fit of all components (36 + 1 events)

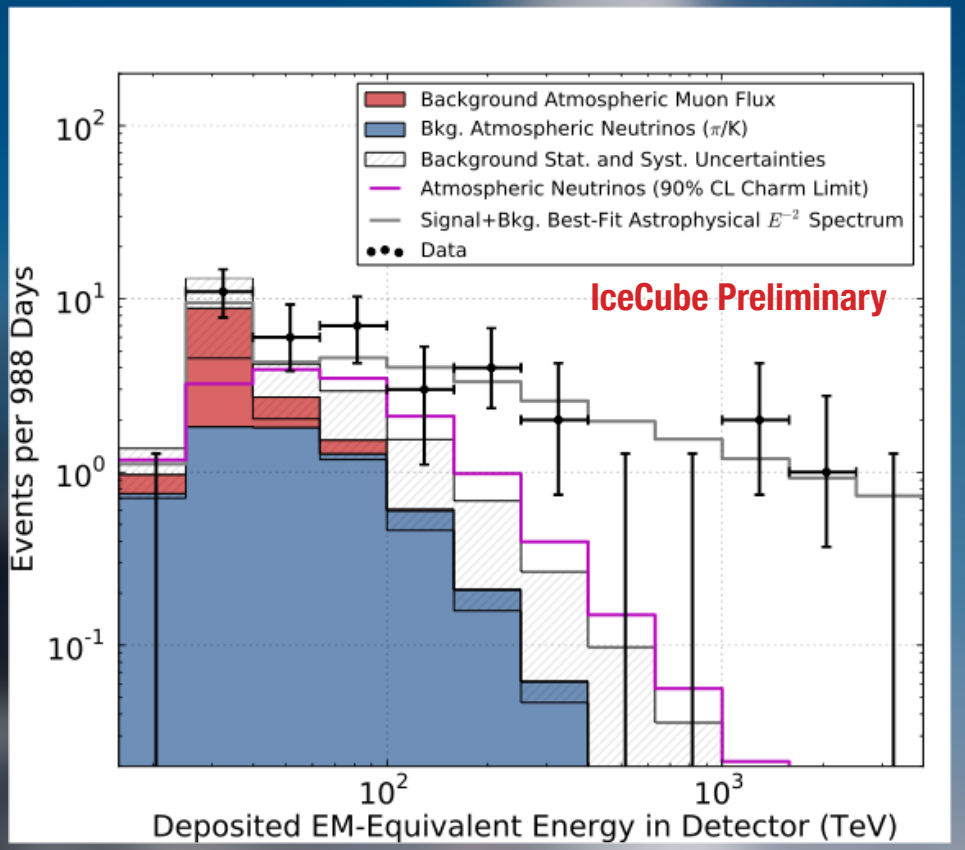
IceCube arXiv:1405.5303

Charge and Energy Distribution

Charge



Energy



Harder than any expected atmospheric background. Best fit (per flavor):

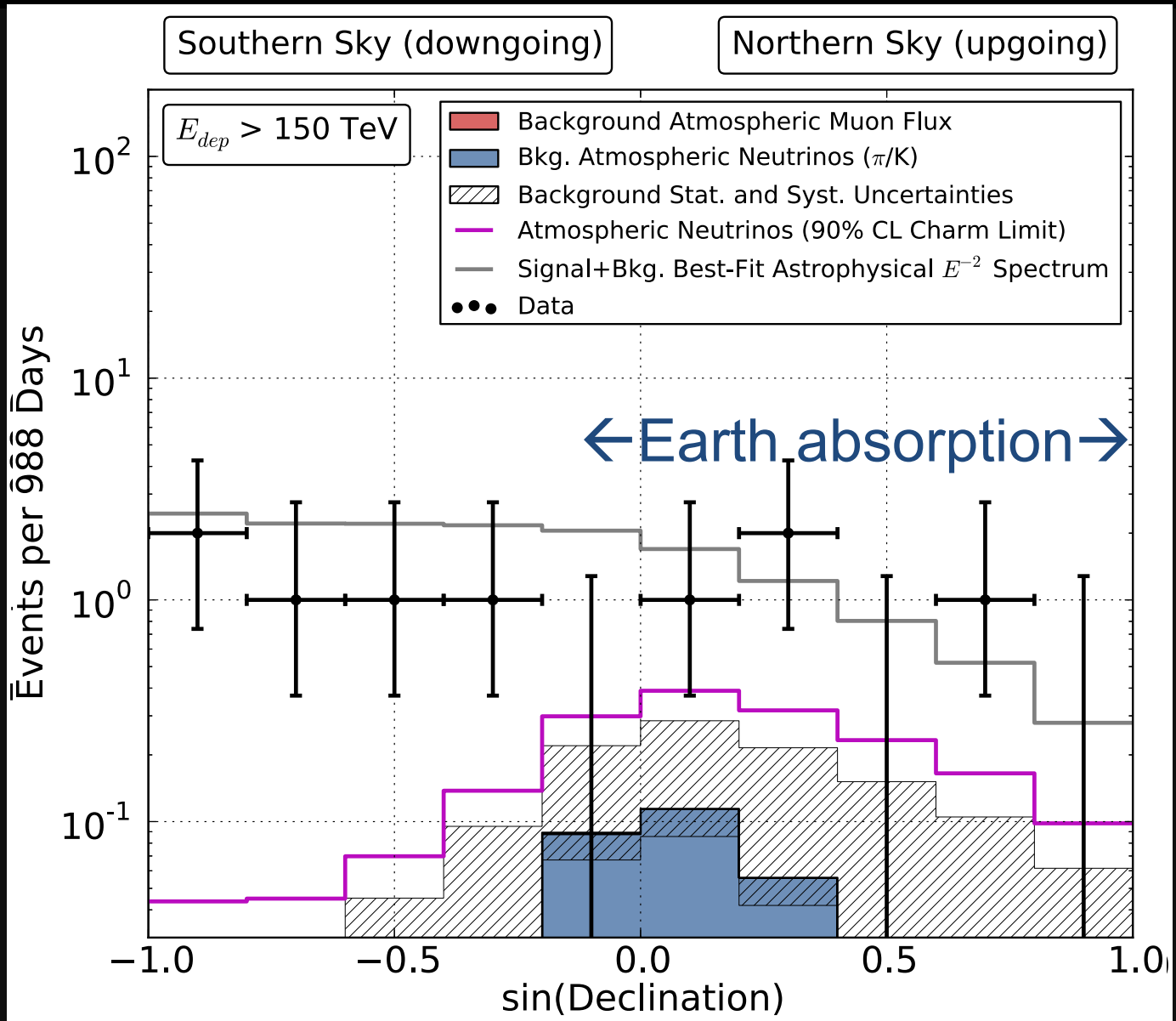
$$0.95 \pm 0.3 \times 10^{-8}\ E^{-2}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

Declination Distribution

Or: "zenith Distribution" because we are at the South Pole

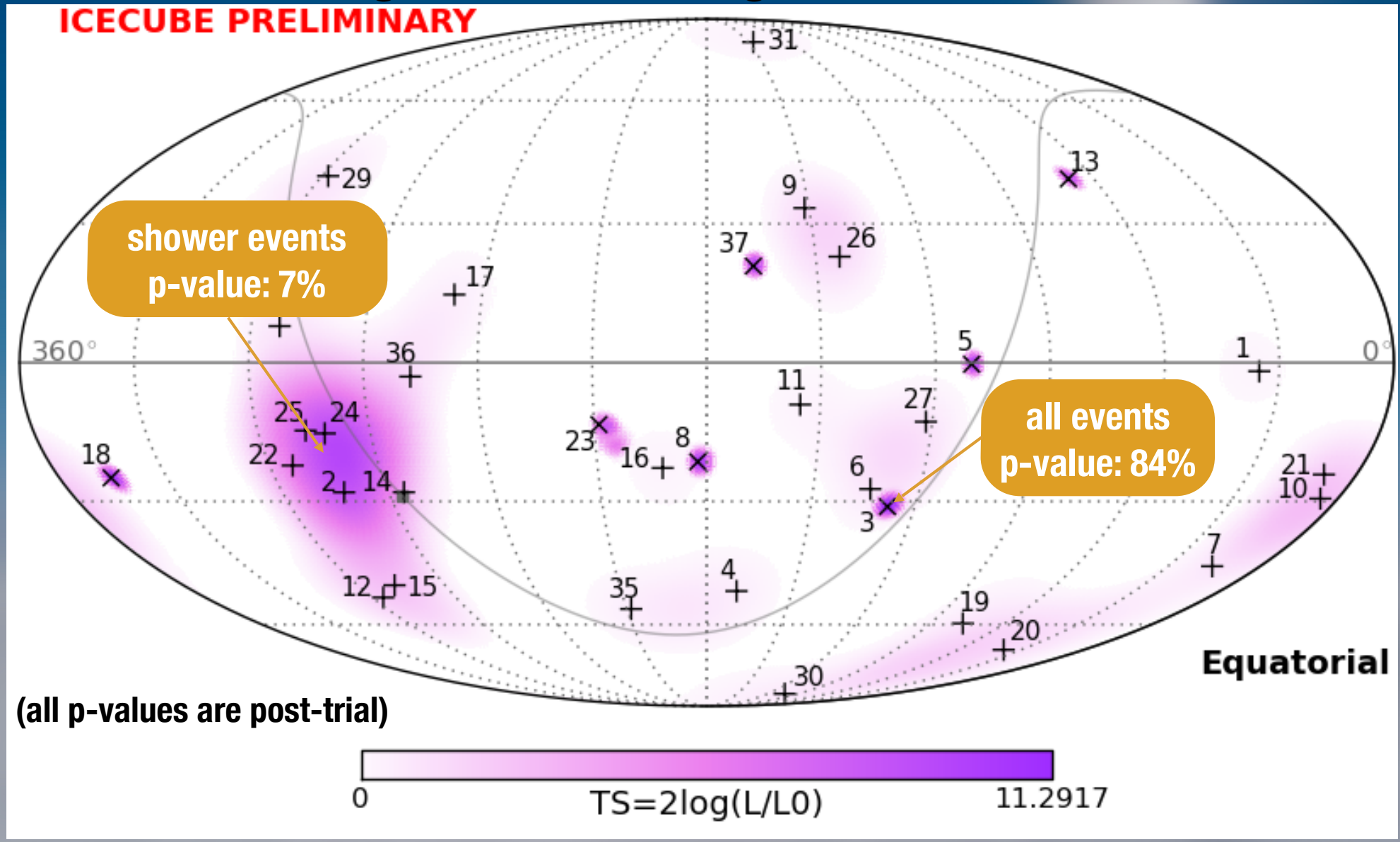
Compatible with isotropic flux

upgoing events absorbed in Earth



Where do the HESE come from?

No significant clustering observed 3 years

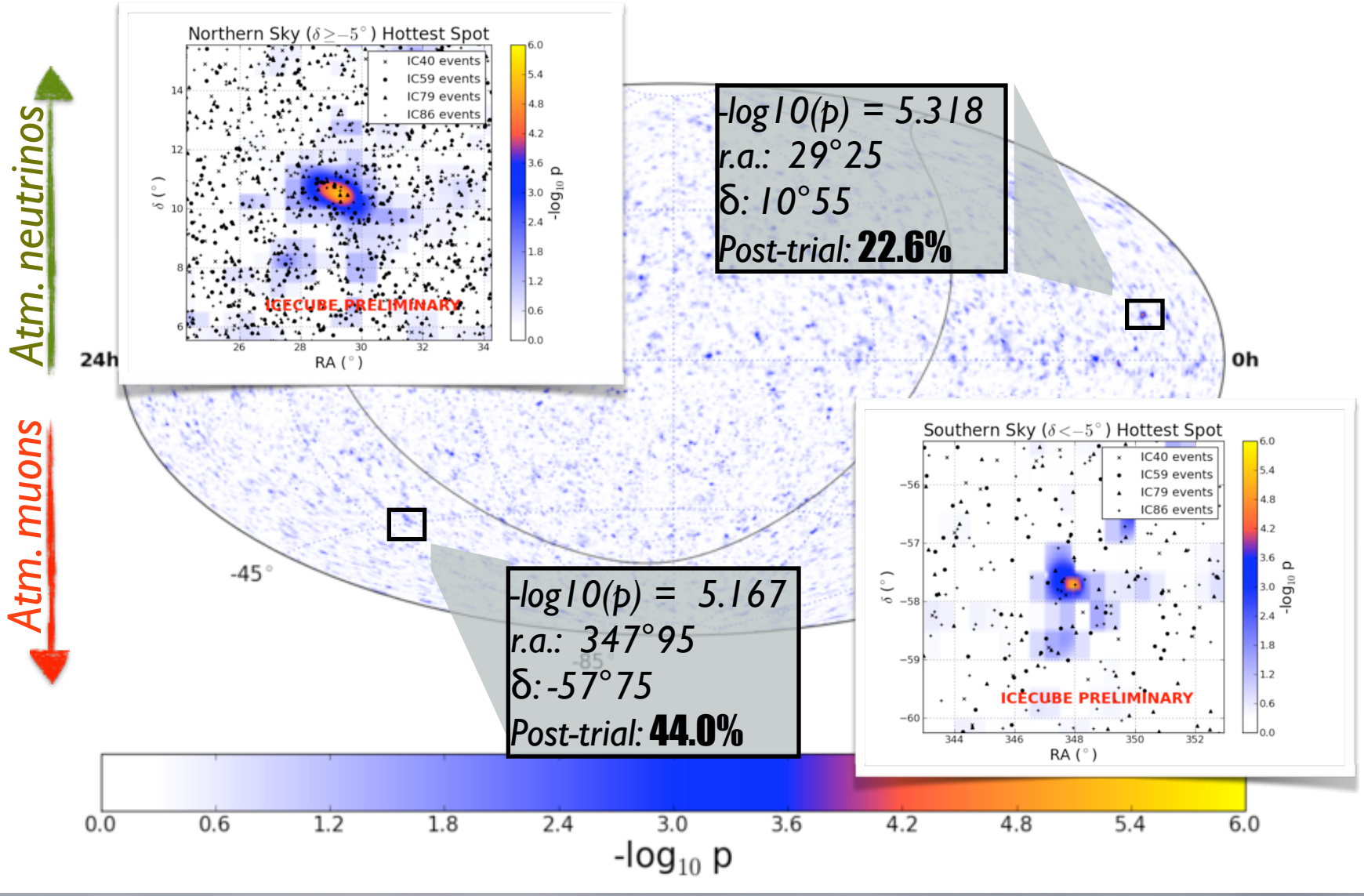


Do these events correlate in direction with PAO and TA UHECR events? Analyses in progress.

Point Source Search Skymap

4 years

- Total events: **394,000** (178k upgoing + 216k downgoing)
- Livetime: **1371 days**



paper submitted today to ApJ

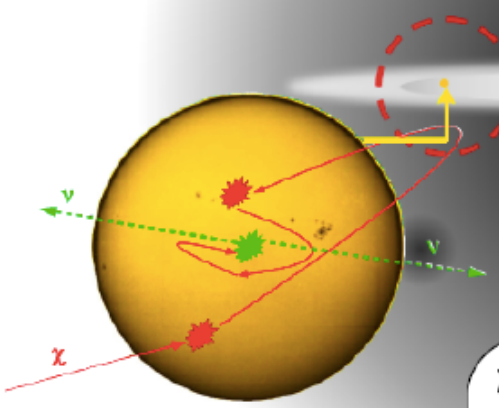
IceCube searches for neutrinos from accumulations of WIMPs

Dwarf spheroidal Galaxies:
→ IceCube-59 limits

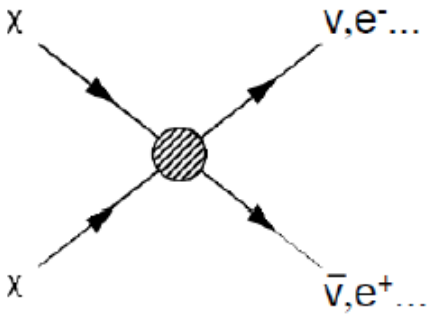
Clusters of Galaxies:
→ IceCube-59 limits
(arXiv:1210.3557 2012)

Galactic Halo:
→ IceCube-22 limits
(PRD 84 (2011) 022004)
→ IceCube-79 limits

Galactic Center:
→ IceCube-40 limits
(arXiv:1210.3557 2012)
→ IceCube-79 sens

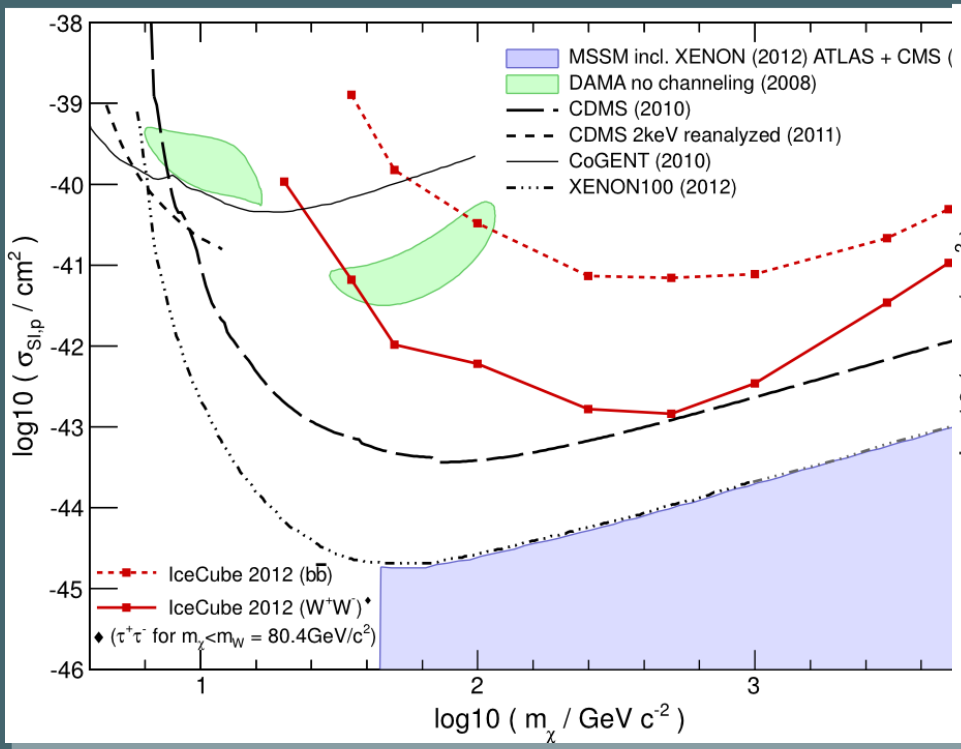


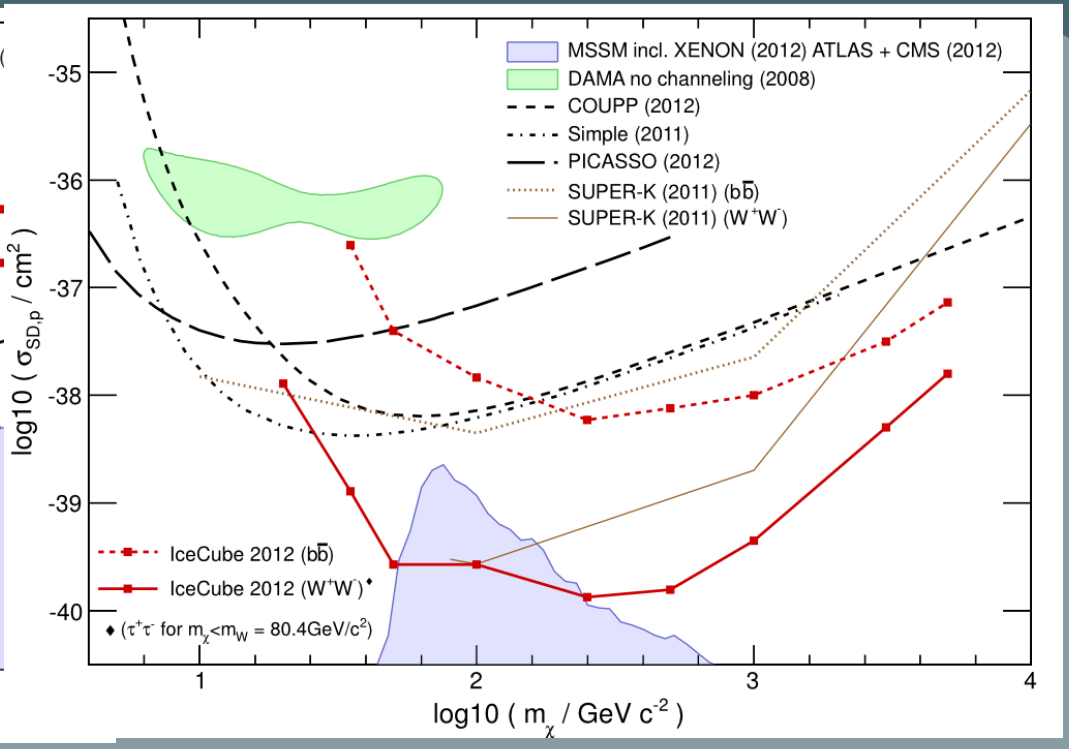
Local sources (Sun & Earth):
→ IceCube-79 limits
(PRL 110 (2013) 131302)
→ Specific models & Global fits
(JCAP 11 (2012) 057)



- Searching for DM-annihilations is in low energy regime for IceCube. (~10 GeV-TeV)
- Consider "extrema" to bracket possible neutrino spectrum. e.g. *hard* (W^+W^-) and *soft* ($b\bar{b}$)

Neutrinos from WIMP annihilations in the Sun





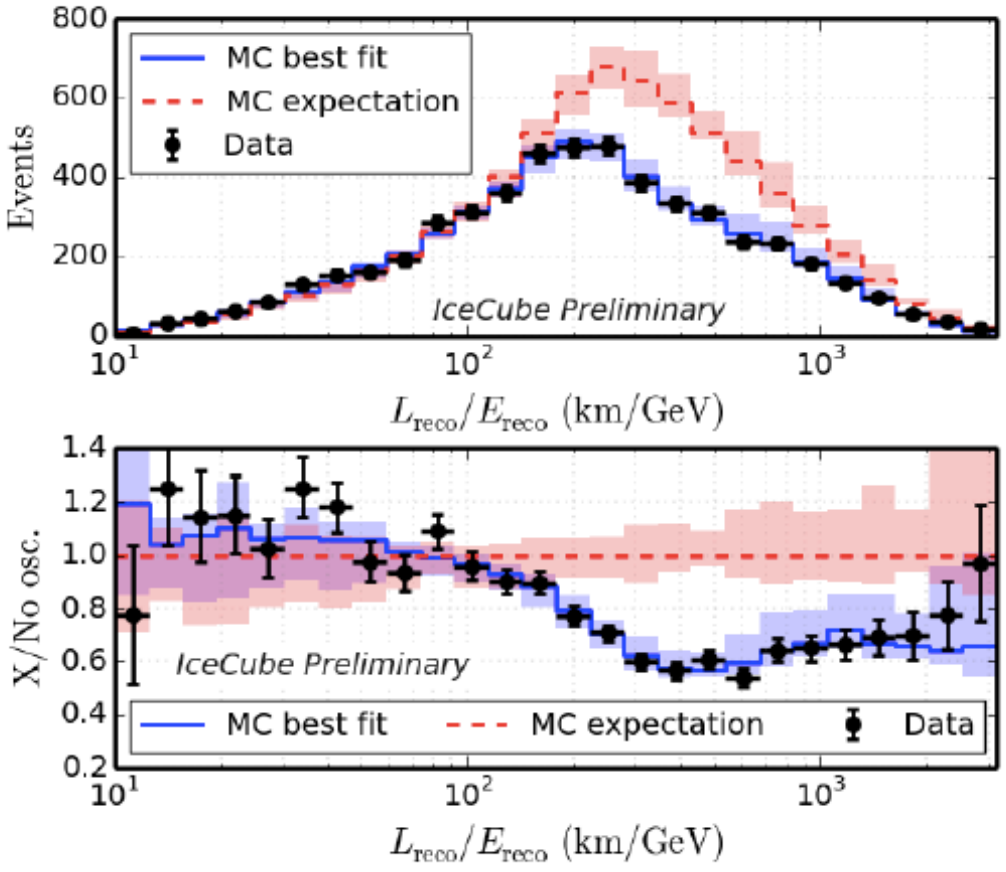
90% CL χ-p cross-section (spin-independent)

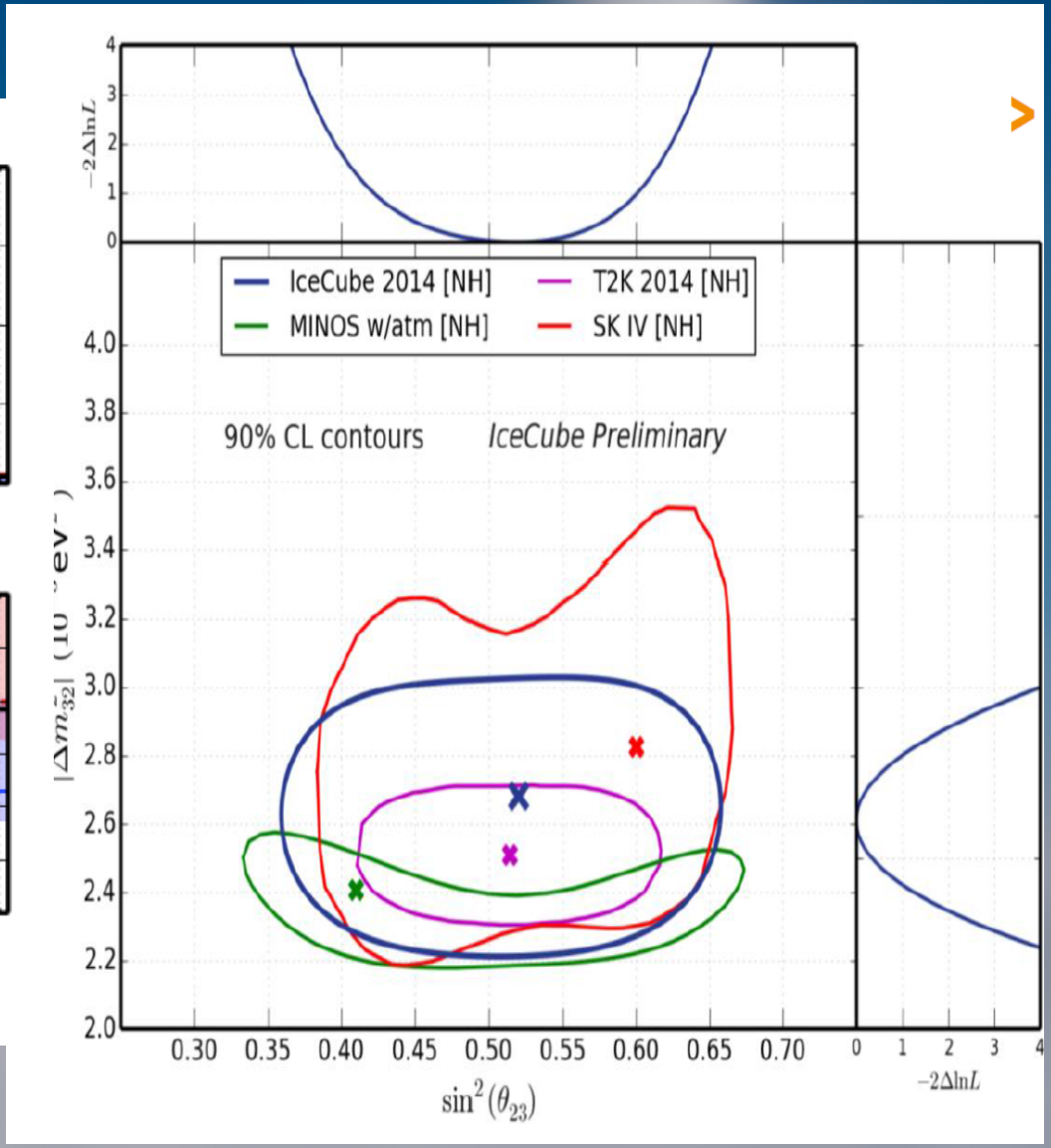
90% CL χ-p cross-section (spin-dependent)

- Assume : Capture and annihilation have reached equilibrium in the Sun -> Set limits on WIMP-nucleon scattering cross section
- Translation into Direct detection parameter almost model indepdent
- Most stringent SD cross-section limit for most models

IceCube, PRL 110 (2013) 131302

Neutrino Oscillations

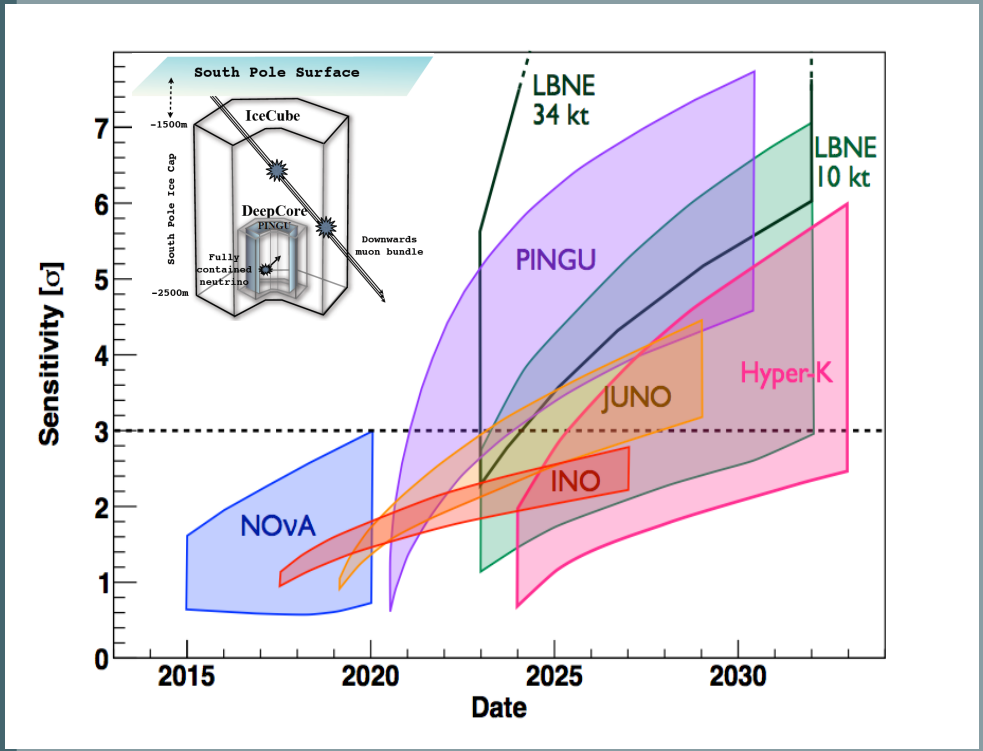


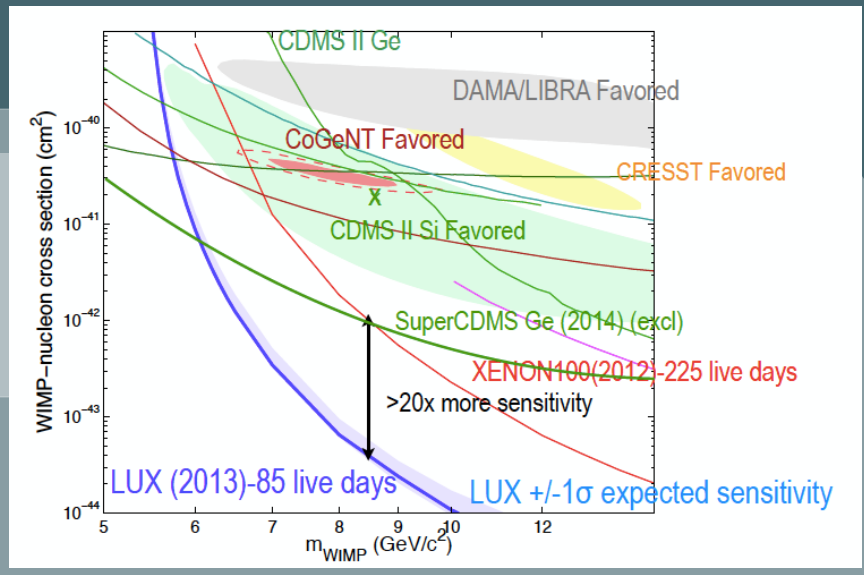


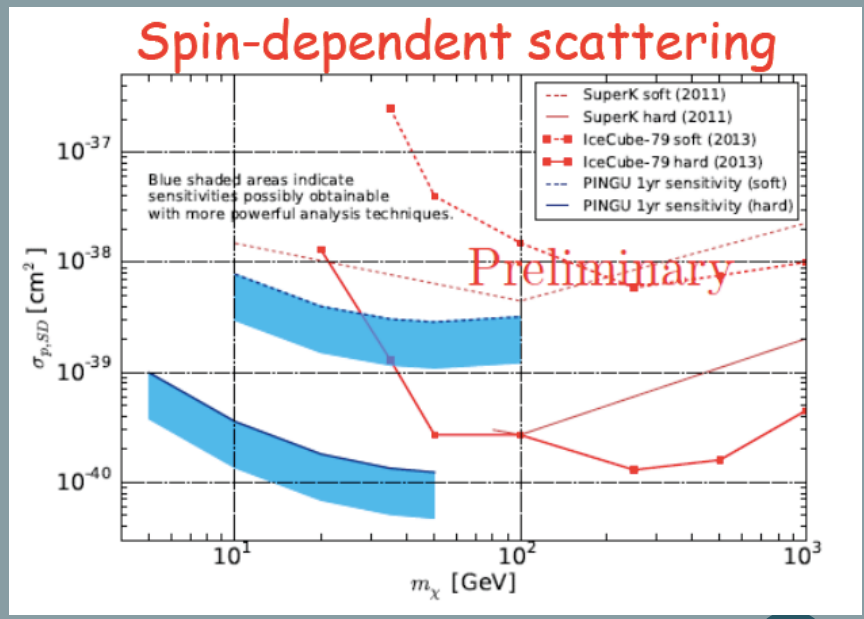
The FUTURE

PINGU

Further in-fill of deep core.
Lower the energy threshold few GeV
Oscillations and Neutrino Mass Hierarchy
Dark Matter



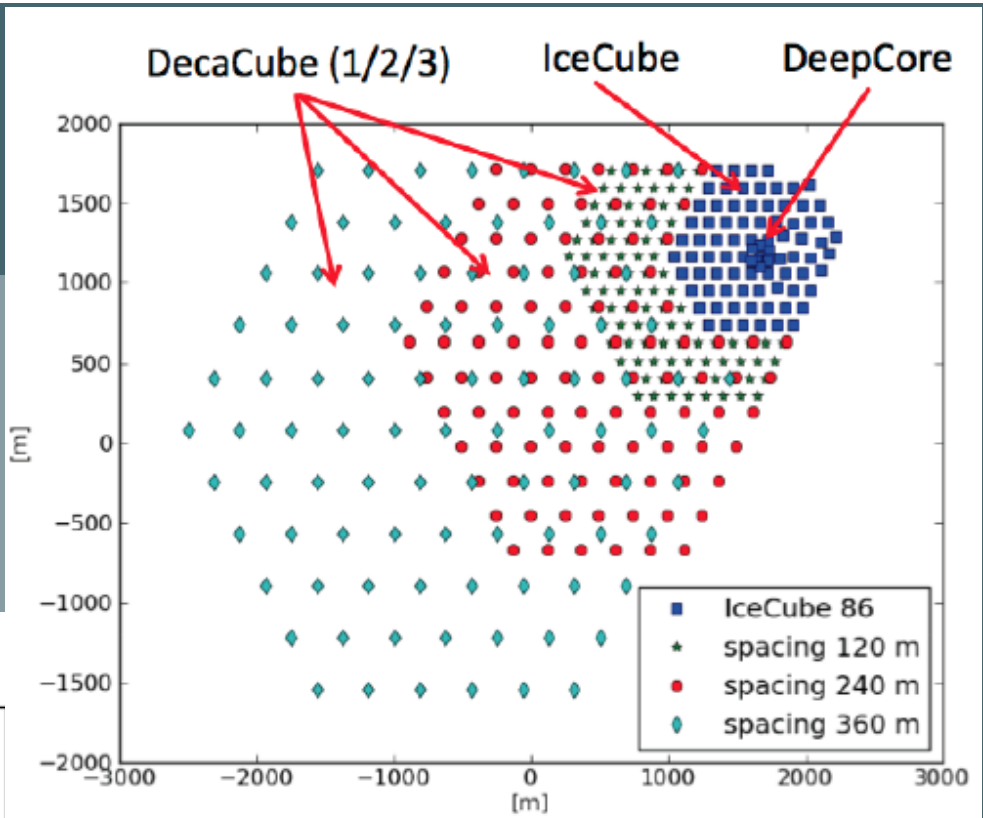


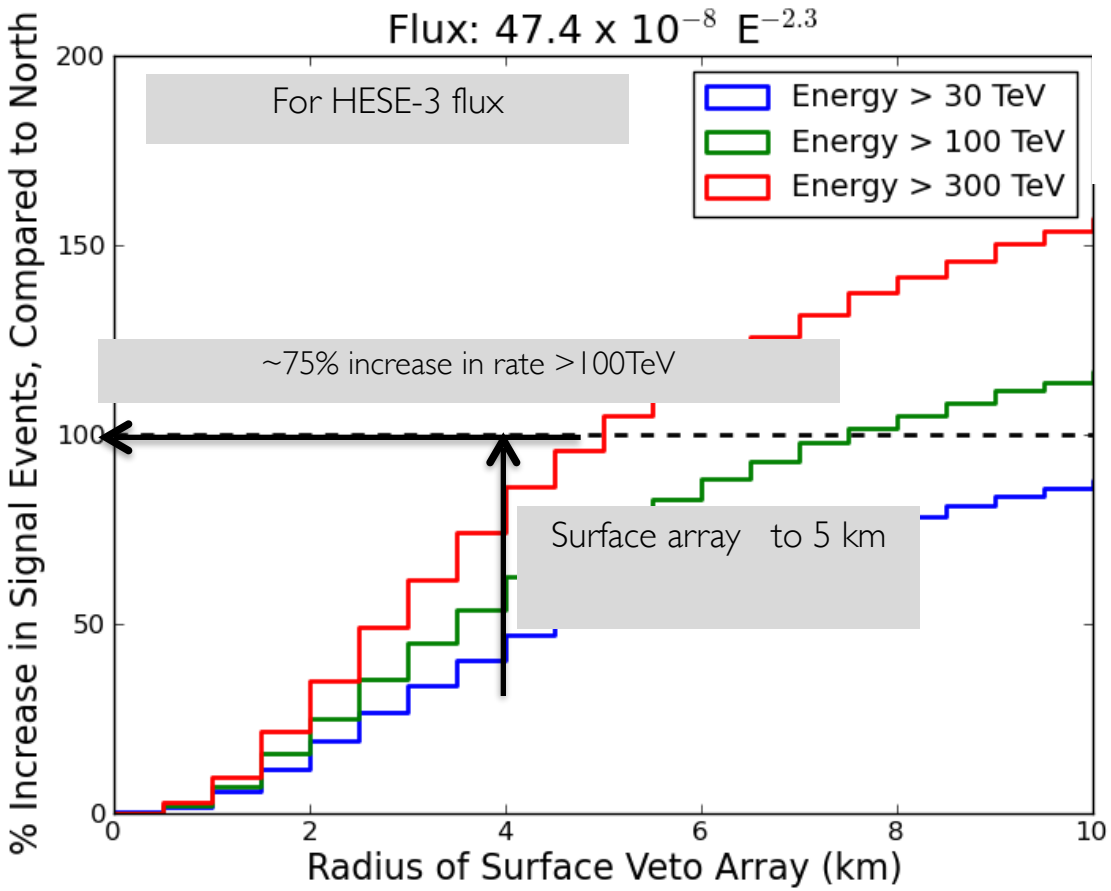


Width of bands depends on range of parameters (for PINGU: $40<\theta_{23}<50$).
We assume 1st octant ($\theta_{23}=40$), the lower PINGU boundary in both plots.

The Future (contd)

An extended surface array would increase the angular IceTop veto coverage





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