Highlights on Neutrino Astronomy

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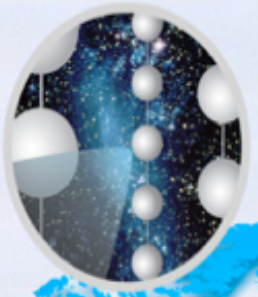
OUTLINE

- The IceCube Observatory
- Fundamental Physics:
  - Dark Matter
  - Neutrino properties
- The future of Neutrino Telescopes
- The cosmic diffuse neutrino signal in IceCube
- The TeV messengers
- 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!

The `eyes' of IceCube

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

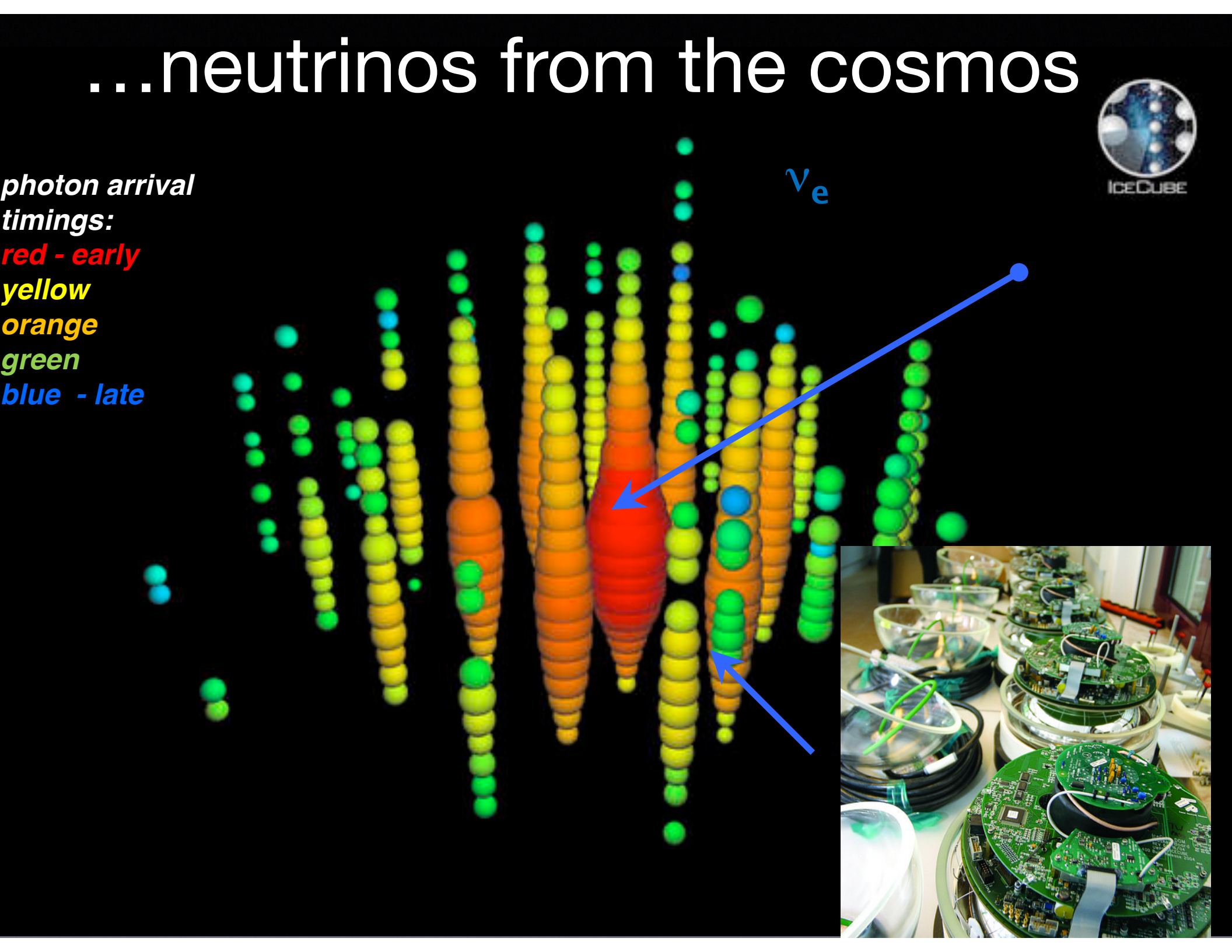
Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal

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)

…neutrinos from the cosmos



Main Physics Themes

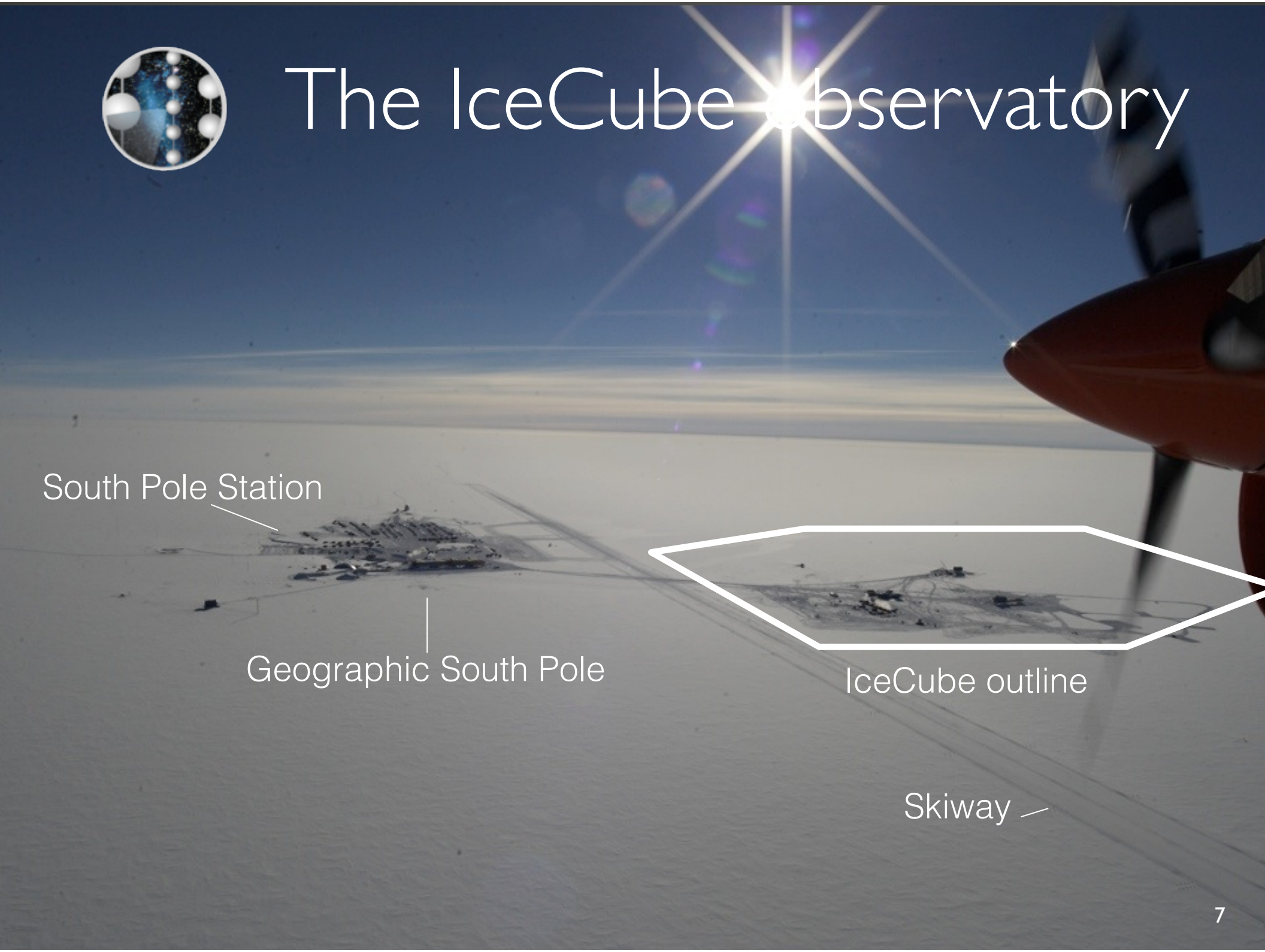
Theme 1: Cosmic Particle Acceleration

- ***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

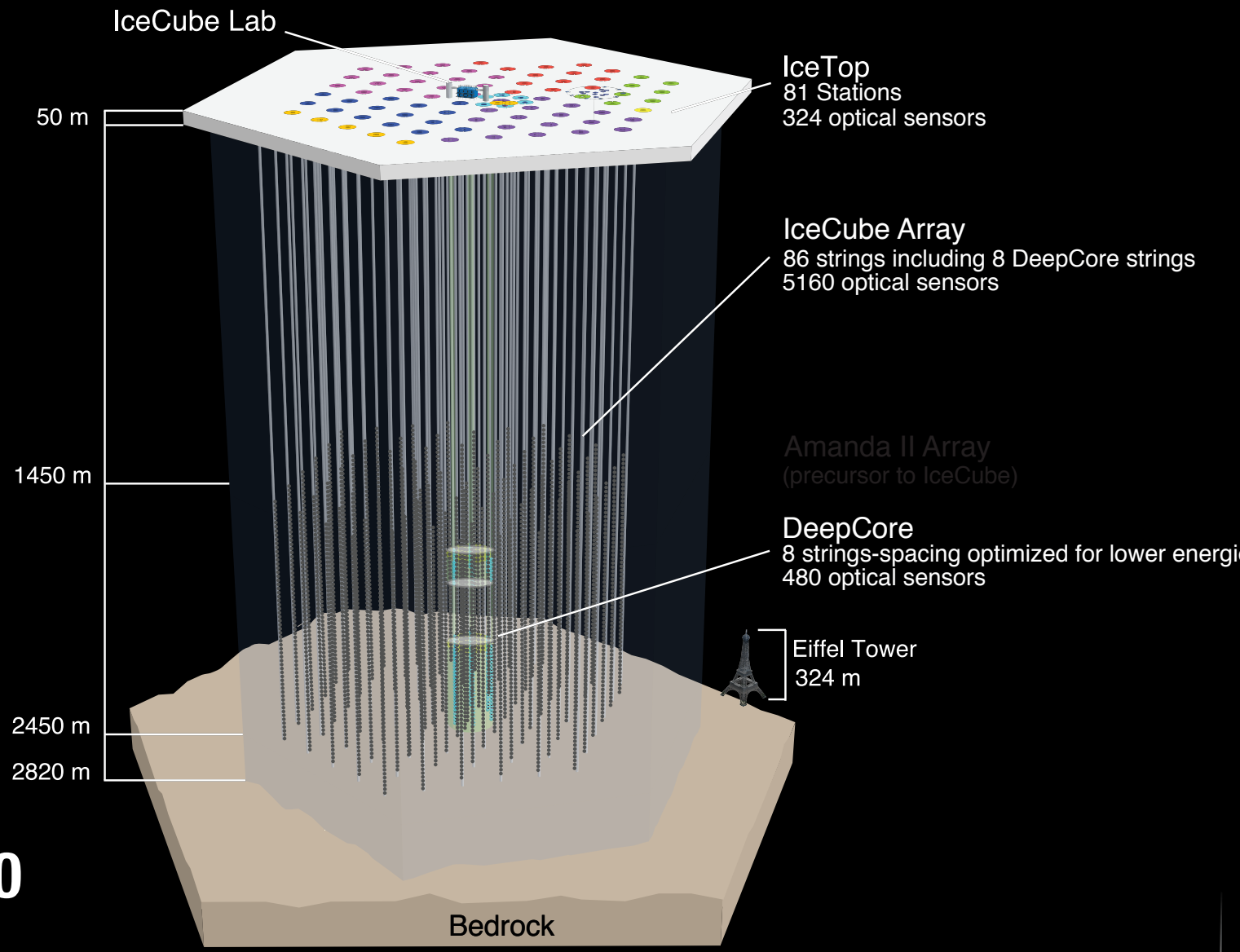
- *what is the nature of **dark matter** and where it is located?*
- *Neutrino oscillations and hadronic interactions (kaons, charm)*
- *Is the speed of light a constant for high energy neutrinos (VLI)*

The IceCube Observatory



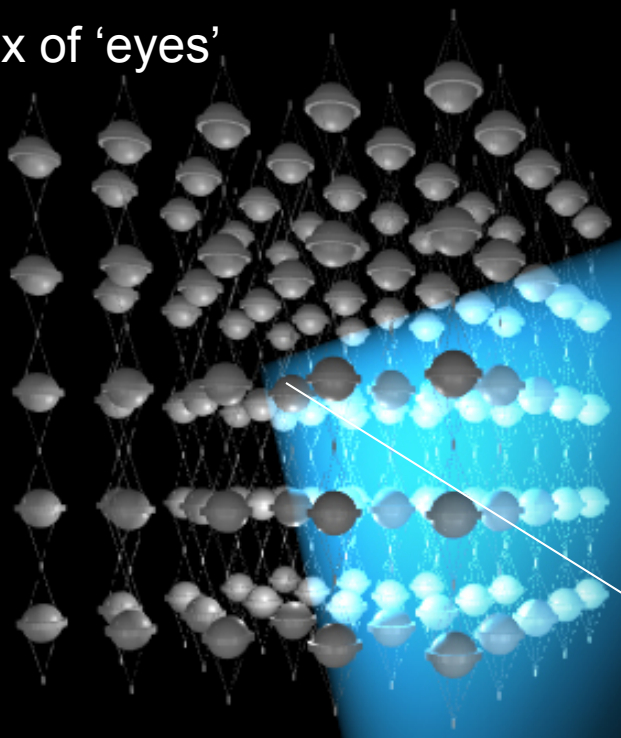
The IceCube Observatory

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



Deep ice is a dark transparent medium

3D matrix of ‘eyes’



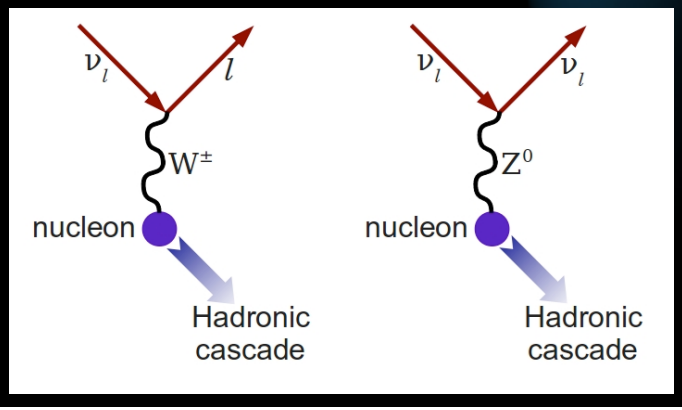
1 every million events interacts producing a detectable muon

41deg

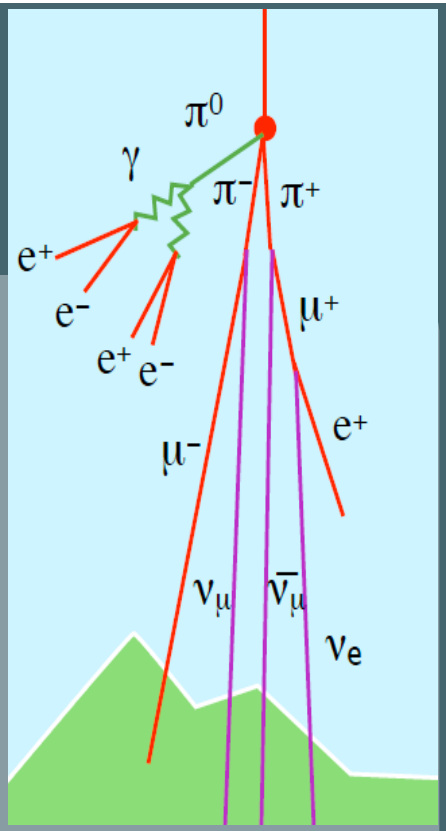
muon β~1

interaction

neutrino



Neutrino Signal and Background



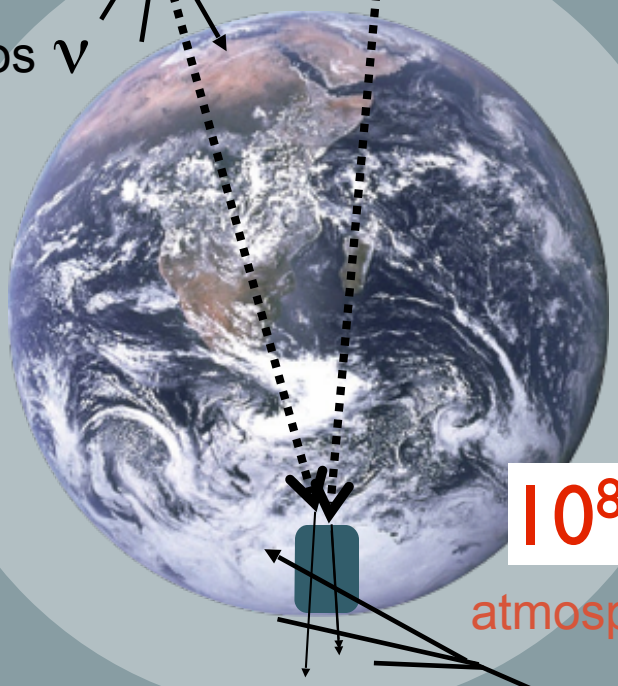
cosmic ray

signal ν

200 neutrino events/day**

Northern Sky

atmos ν



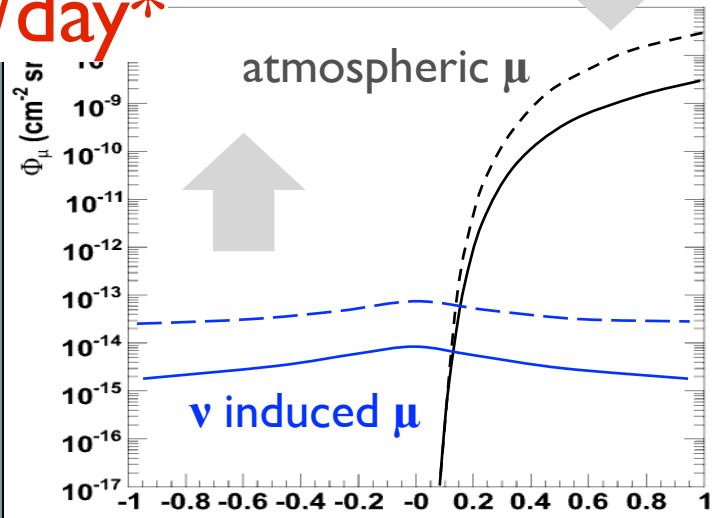
* IceCube trigger rate

**IceCube analysis level/day

atmospheric background

10^8 muon events/day*

atmospheric μ

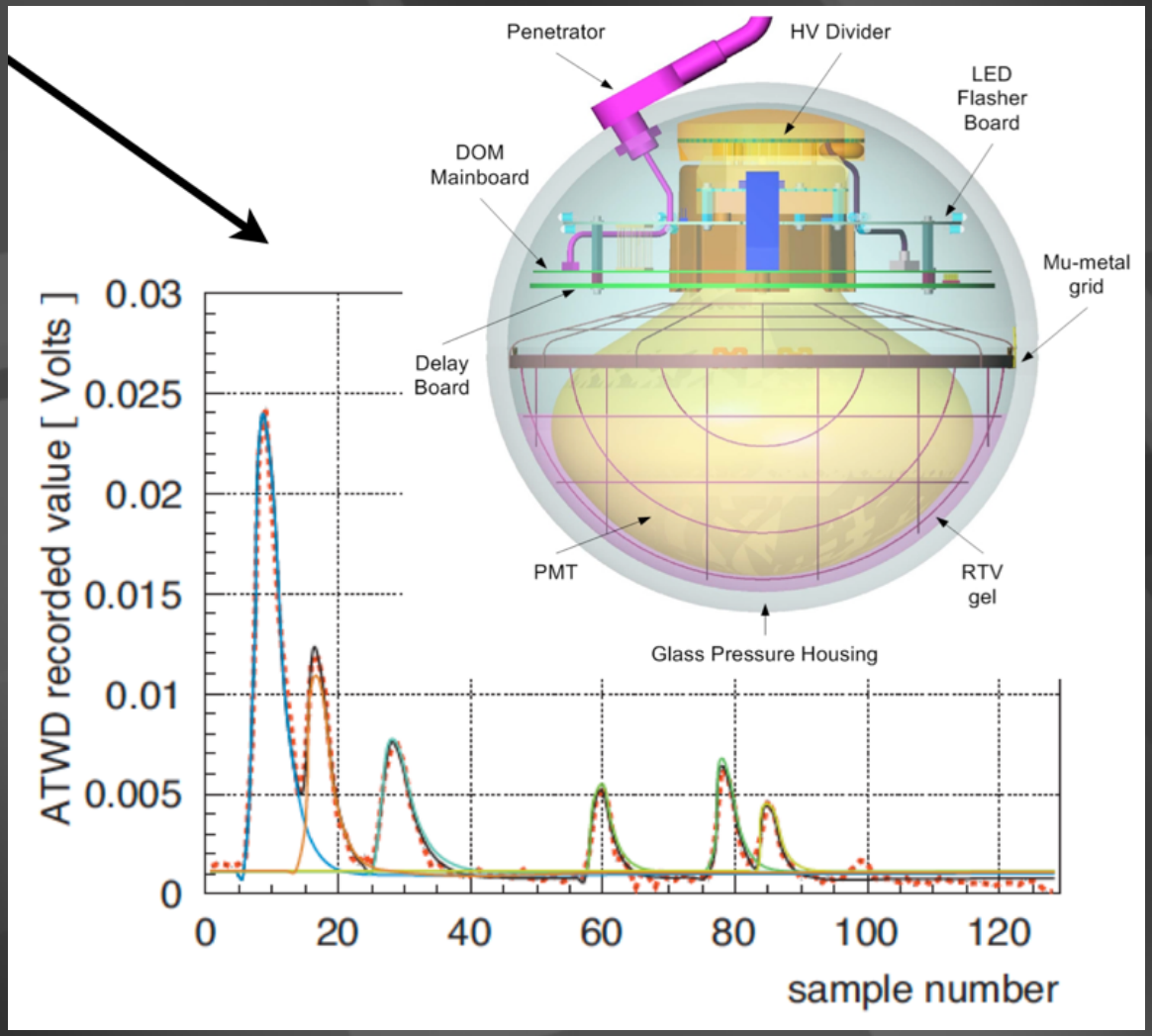


atmospheric μ

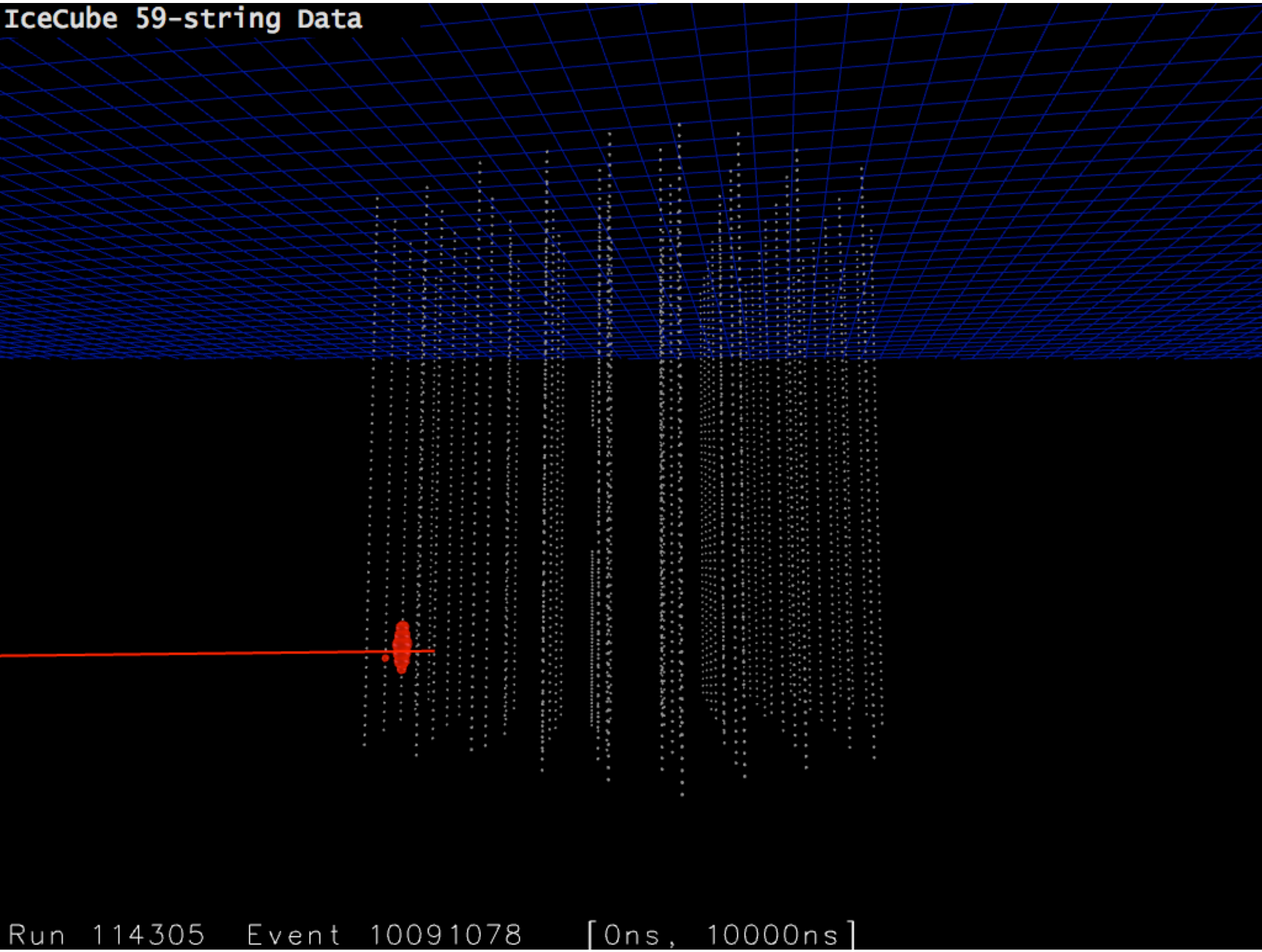
cosmic ray

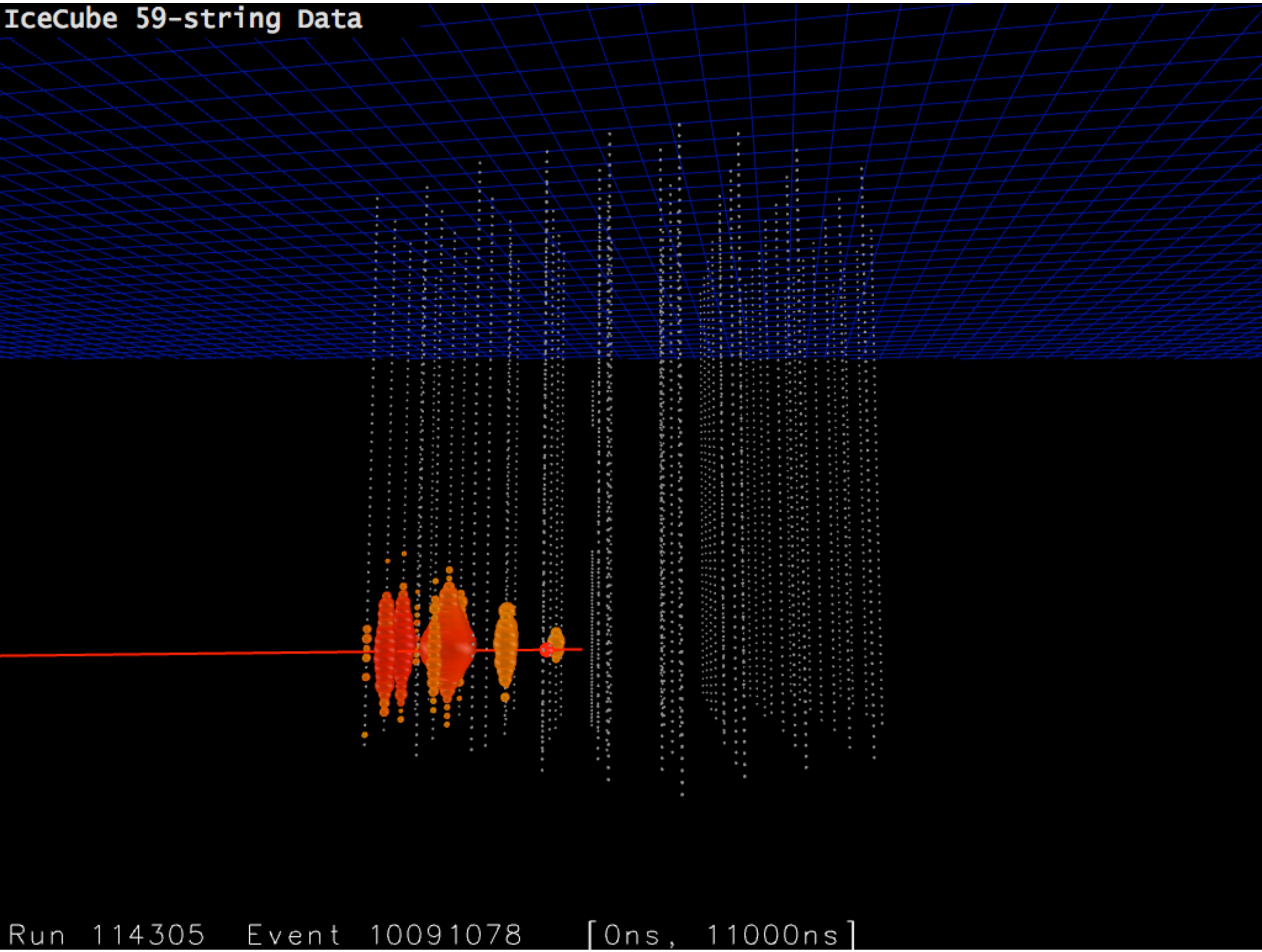
Southern Sky

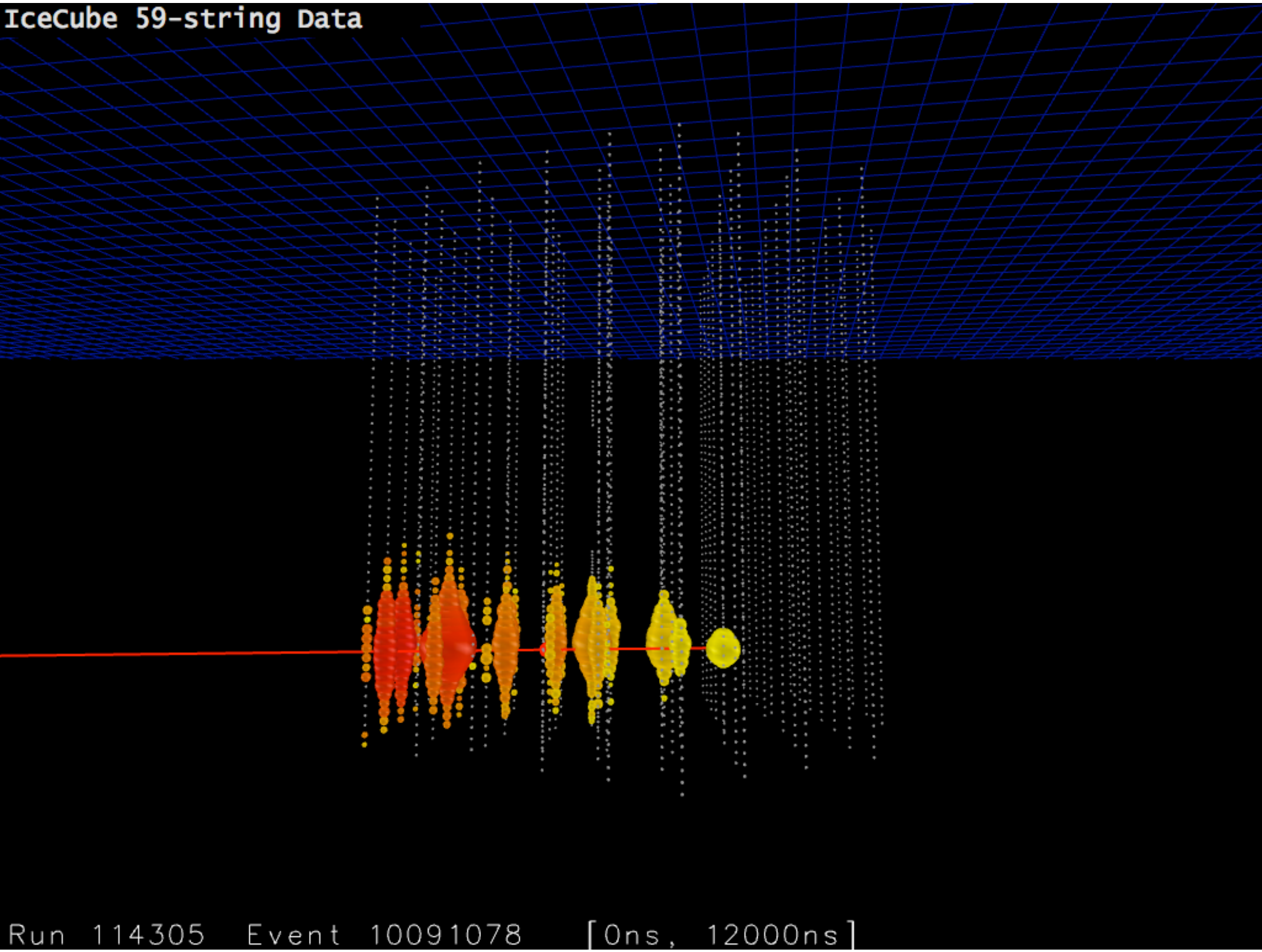
… each Digital Optical Module independently collects light signals like this, digitizes them,

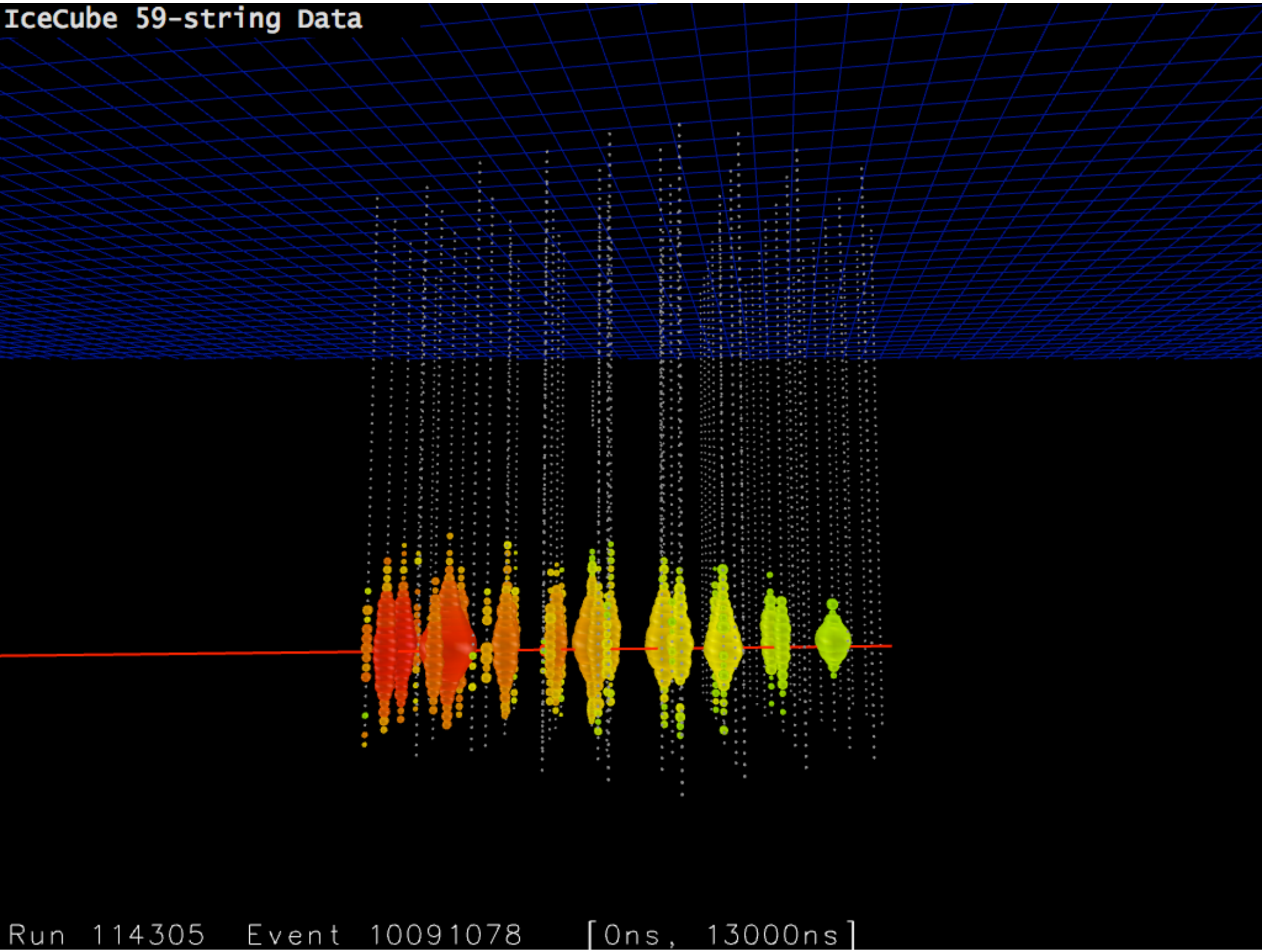


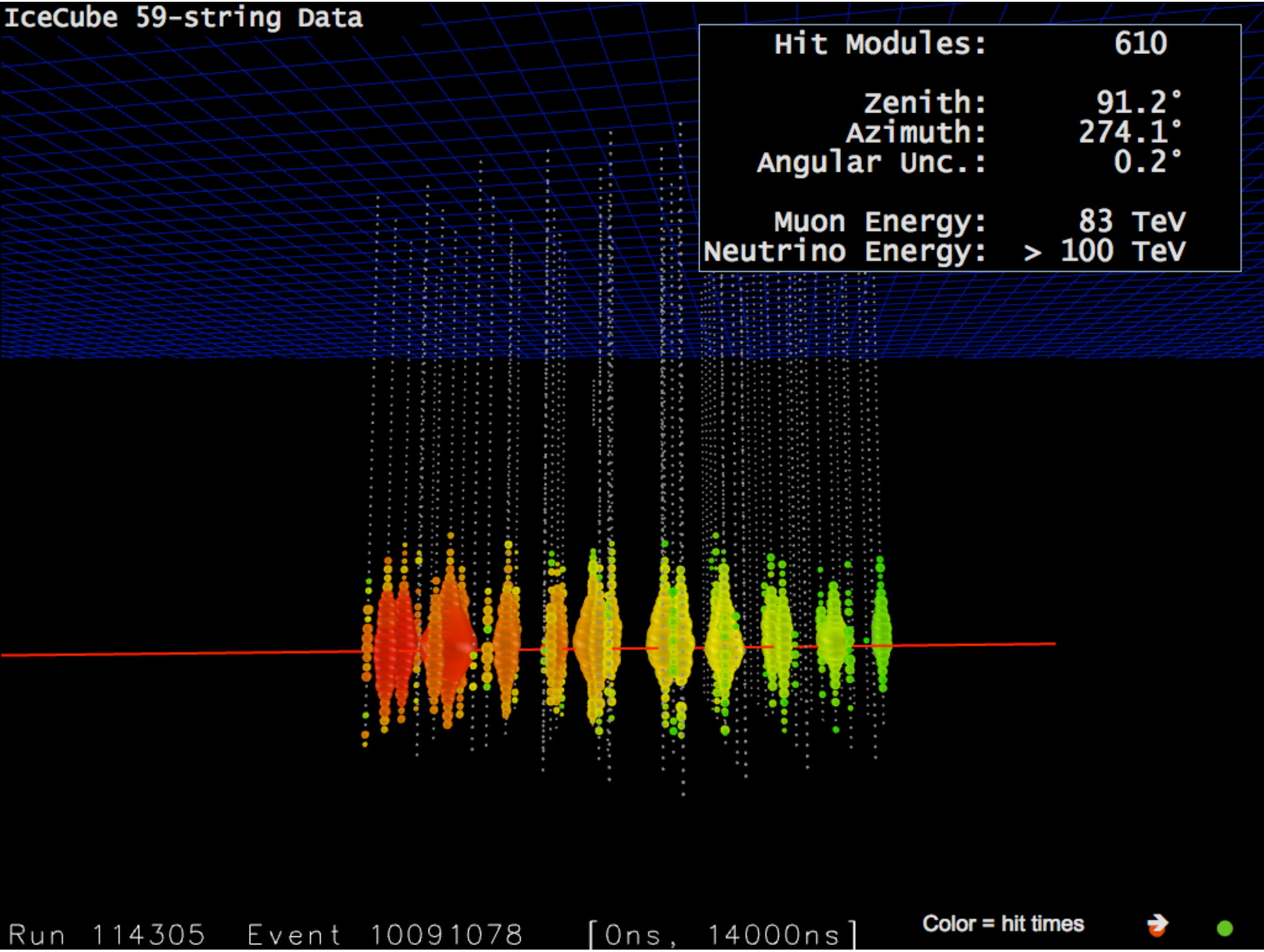
…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…


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

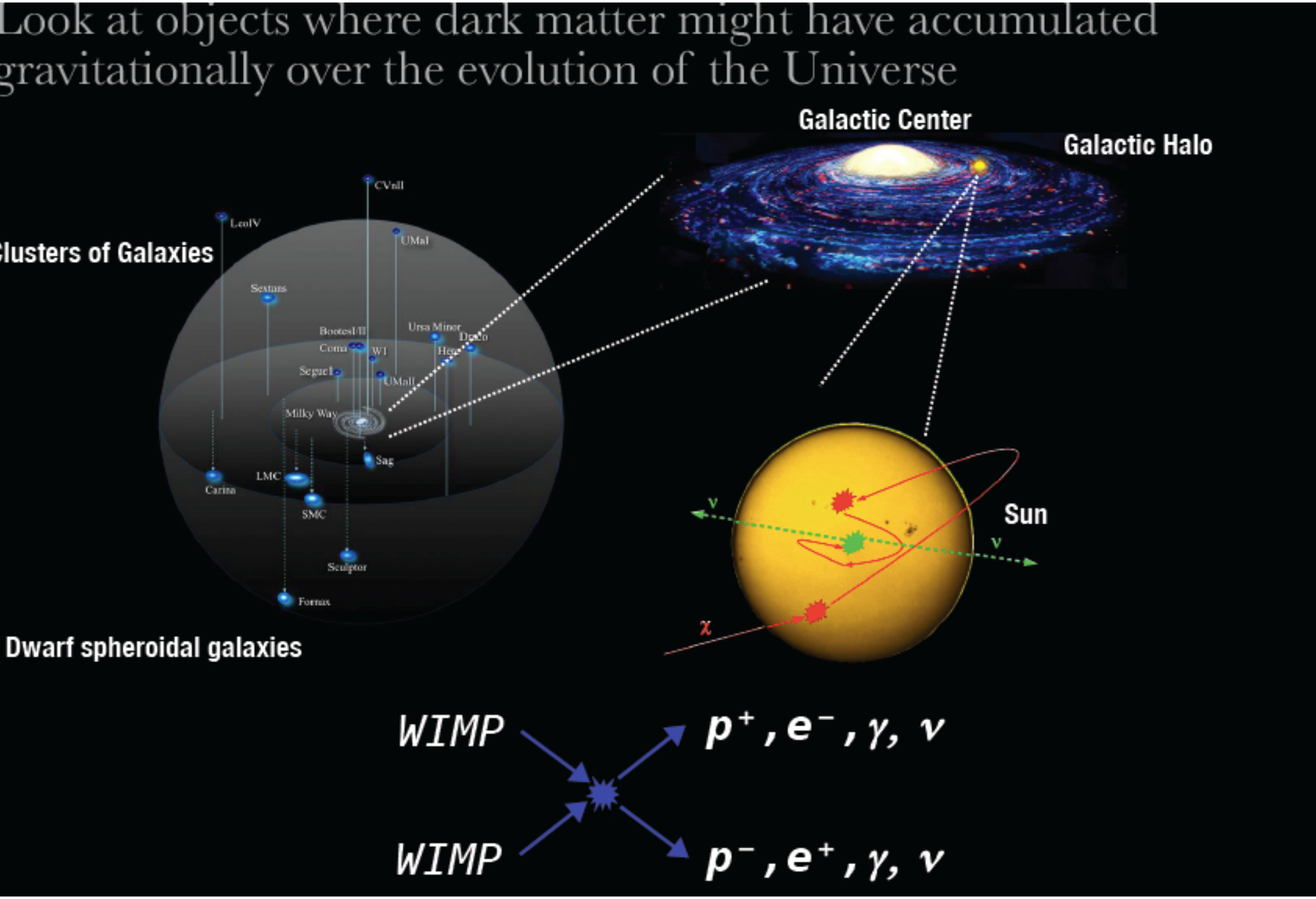

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 11000ns]


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

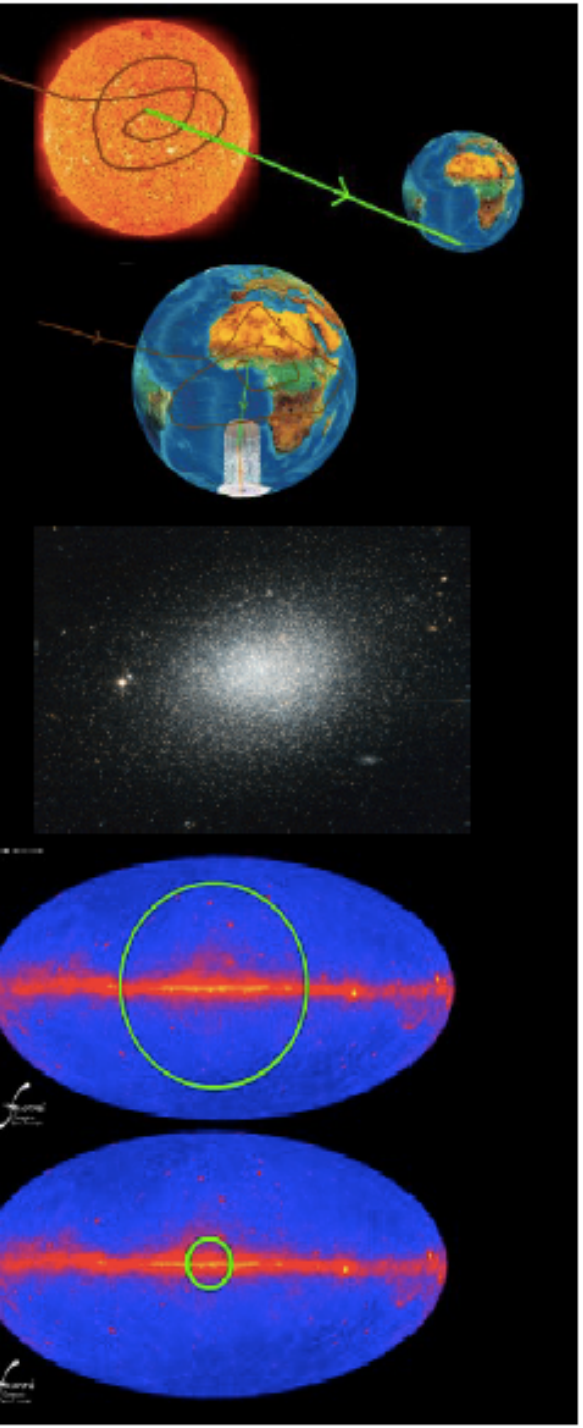

IceCube 59-string Data
Run 114305 Event 10091078 [0ns, 13000ns]


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

Indirect Searches for Dark Matter



Dark Matter Searches in IceCube



Sun

Earth

probes $\sigma^{SD}_{\chi\text{-}N}$, $\sigma^{SI}_{\chi\text{-}N}$

- complementary to direct detection
- different systematic uncertainties
  - hadronic (not nuclear)
  - density averaged
  - can benefit from co-rotating disk

dwarves & distant halos

Galactic Halo

Galactic Center

probes $\langle \sigma_A \, v \rangle$

- complementary to searches with other messangers (γ, CRs...)
- shared astrophysical systematic uncertainties (halo profiles...)

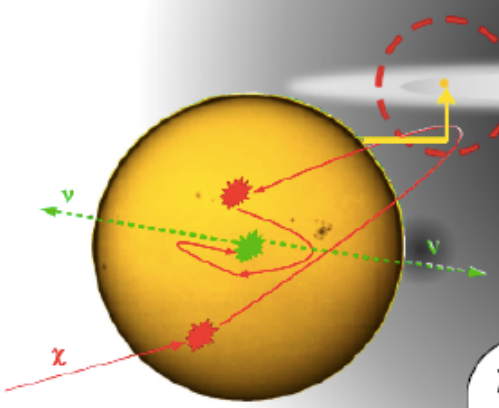
IceCube searches for neutrinos from accumulations of WIMPs

Dwarf spheroidal Galaxies:
→ IceCube-59 limits

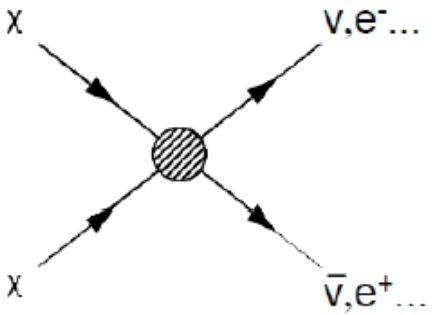
Clusters of Galaxies:
→ IceCube-59 limits
(arXiv:1210.3557 2012)

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* ($b\bar{b}$)

Various Potential Dark Matter Signals

Various analyses looking at different source distributions

Galactic Halo:

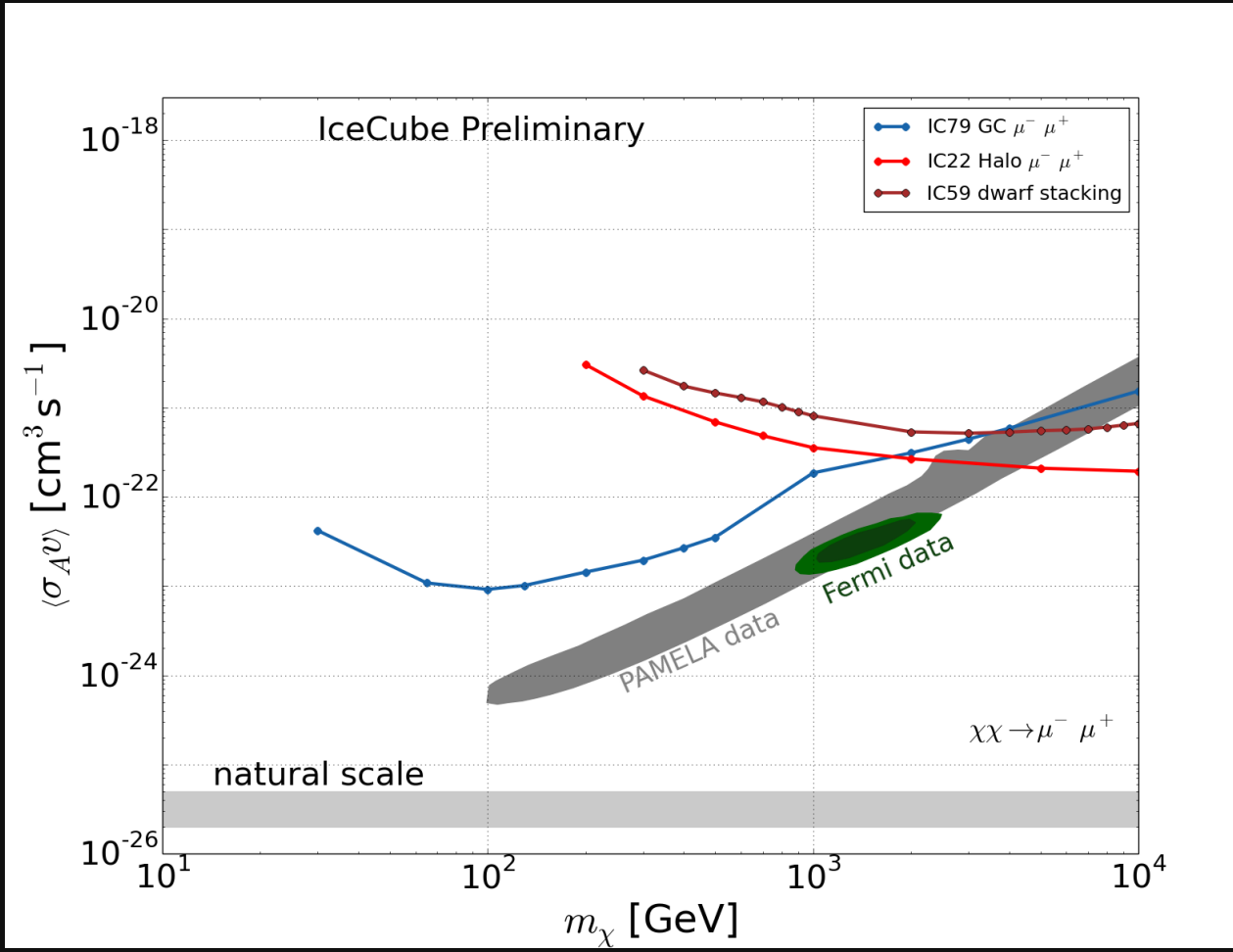
- IC22 PRD 8 (2011) 022004

Galactic Center:

- IC79 in preparation

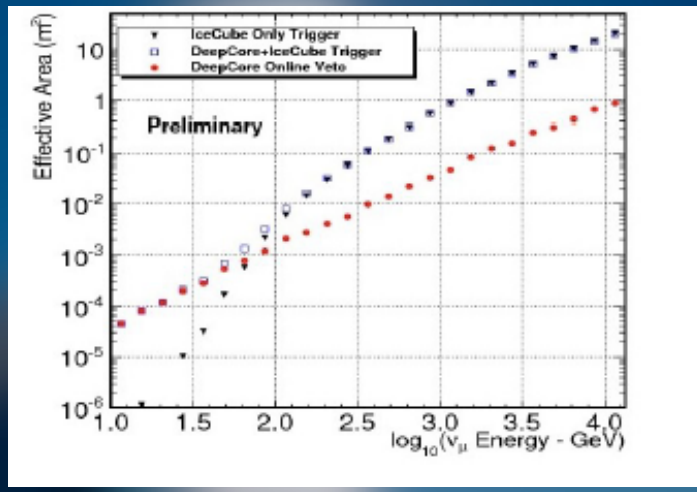
Dwarf spheroids:

- IC59 PRD 88 (2013) 122001

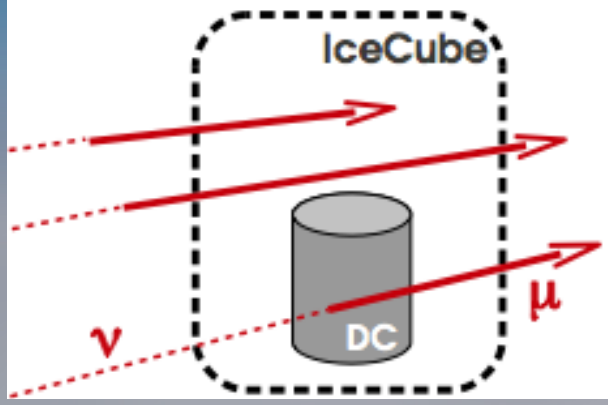


Neutrinos from WIMP annihilations in the Sun

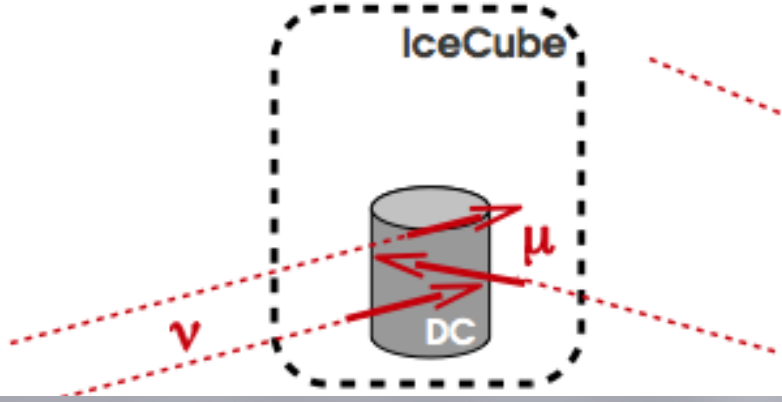
- Sun is a down-going source during austral summer
- Sun is an up-going source during austral winter



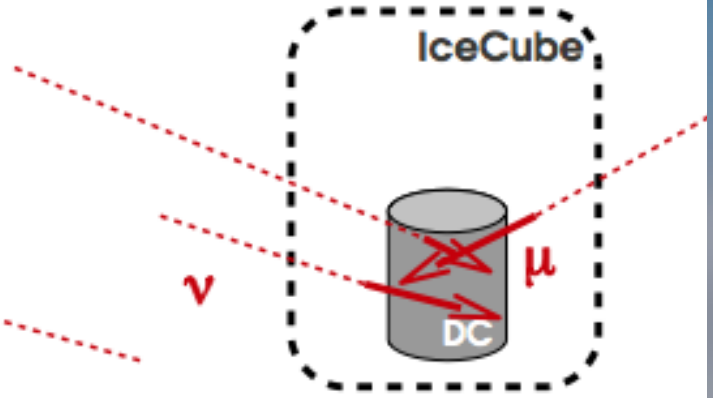
- ***Up-going*** (1)
- No containment



- ***Up-going*** (2)
- strong containment

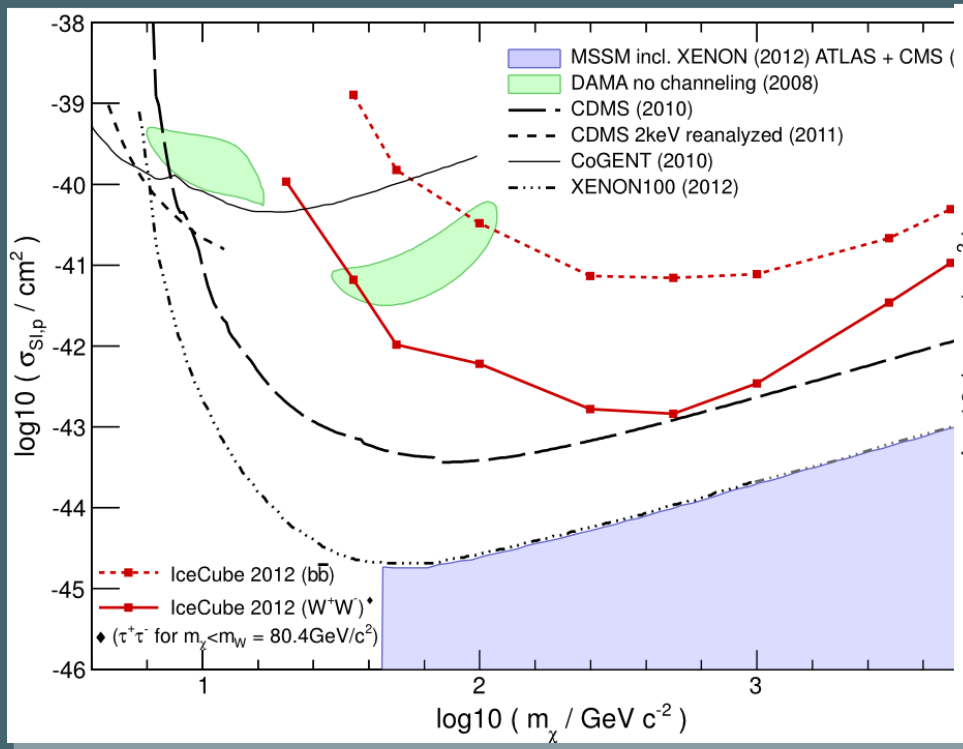


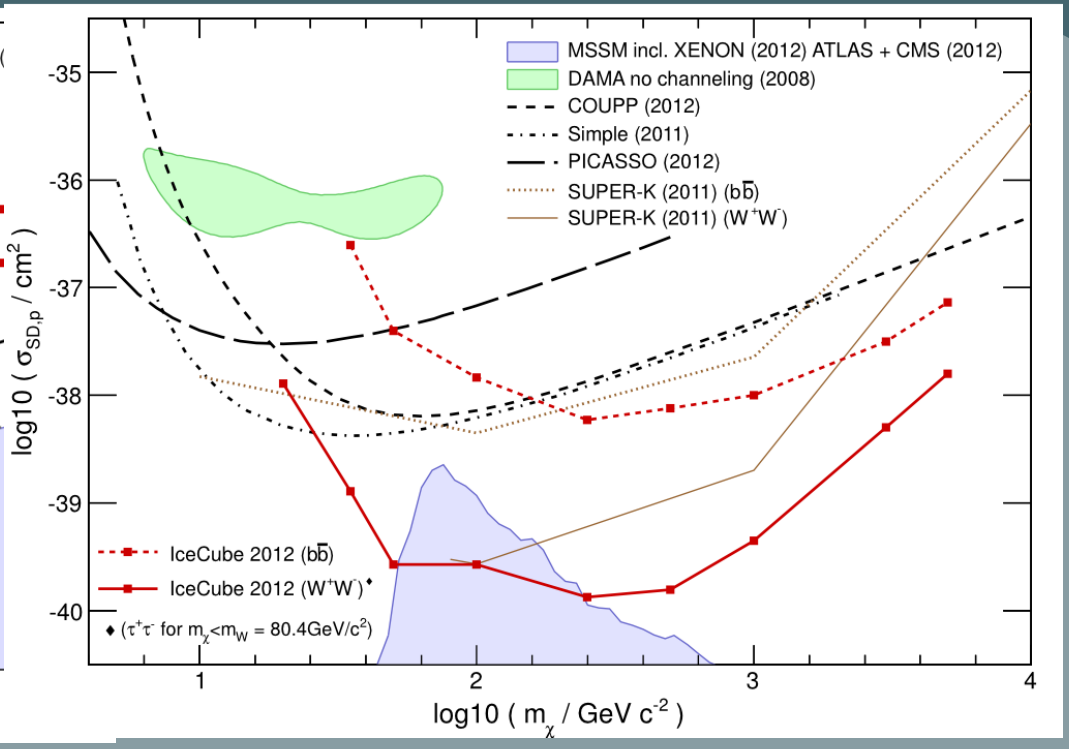
- ***Down-going*** (3)
- strong containment



317 days of livetime, down to neutrino energies of ~10GeV!

Neutrinos from WIMP annihilations in the Sun





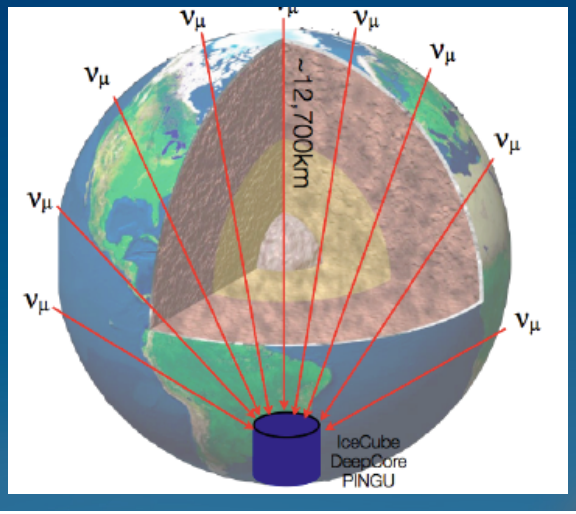
90% CL χ-p cross-section (spin-independent)

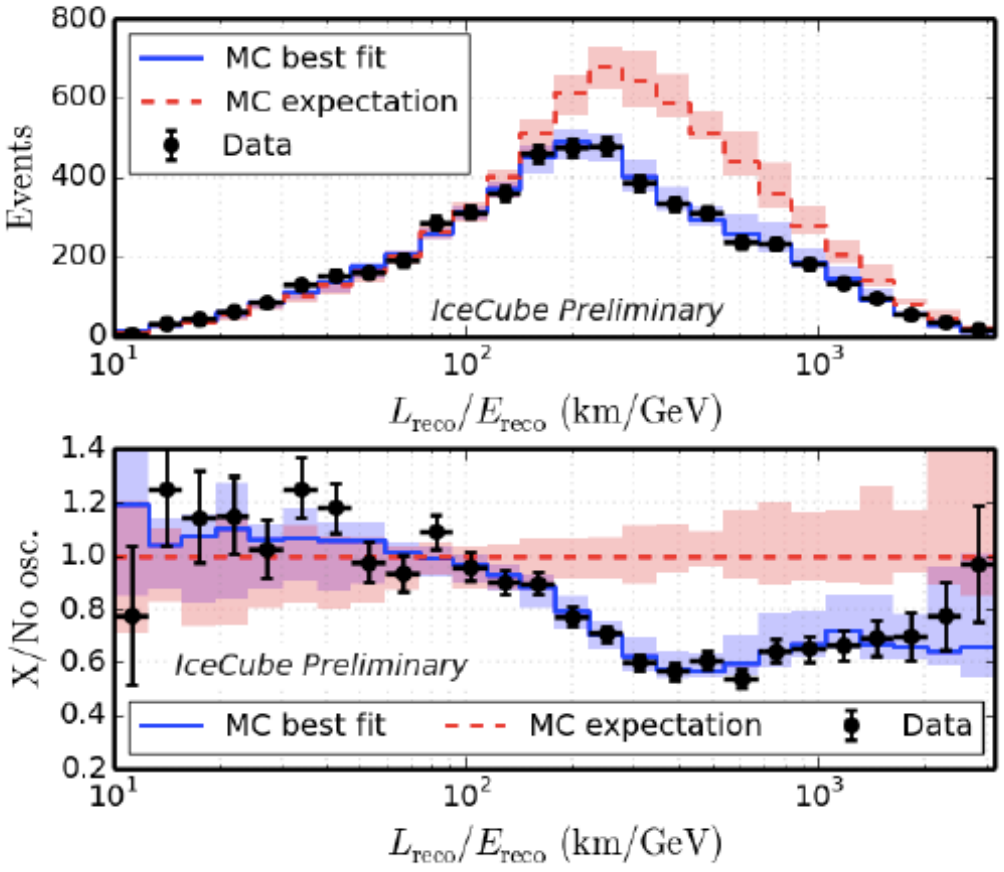
90% CL χ-p cross-section (spin-dependent)

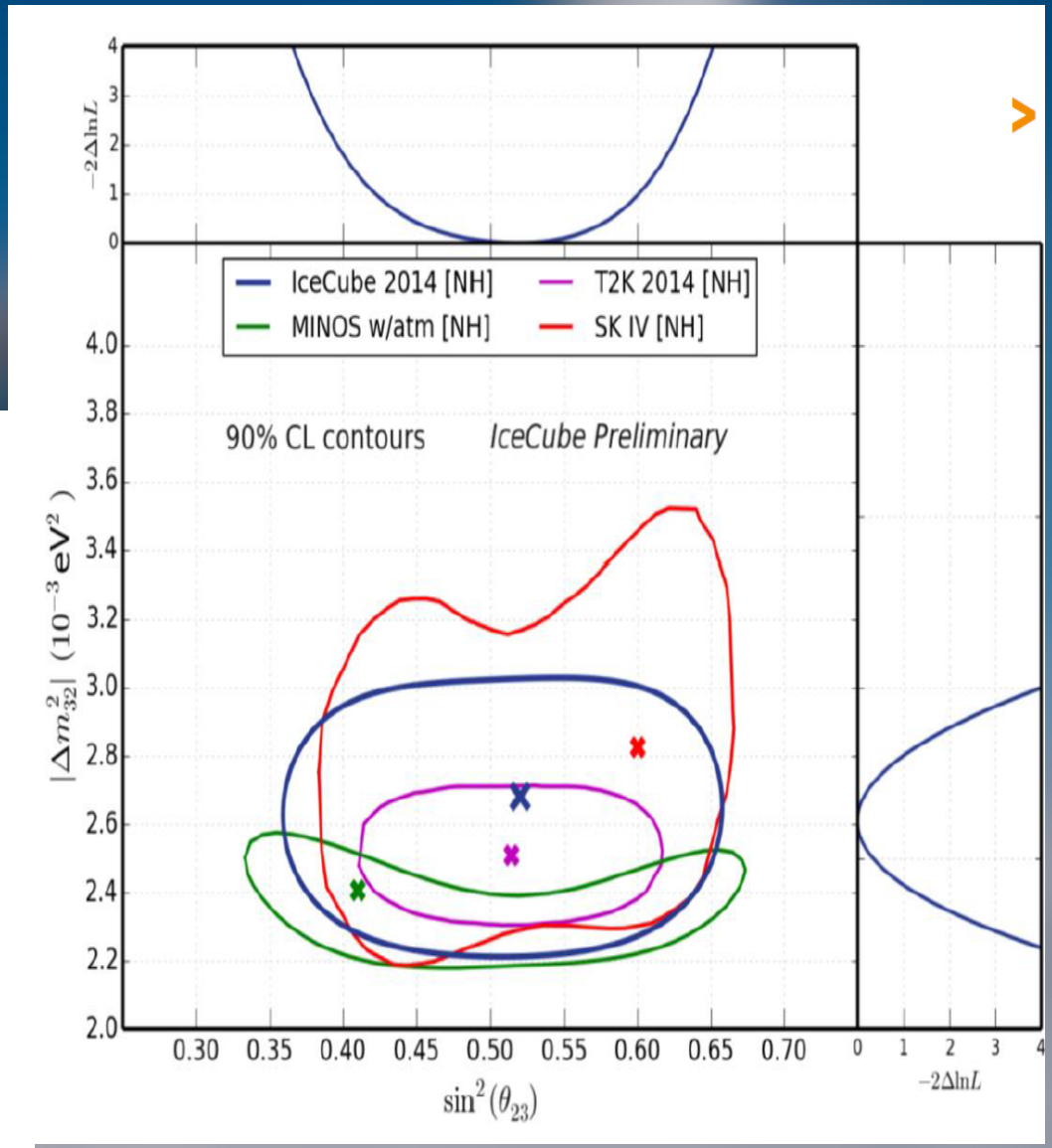
- Assume : Capture and annihilation have reached equilibrium in the Sun -> Set limits on WIMP-nucleon scattering cross section
- Translation into Direct detection parameter almost model indepdent
- Most stringent SD cross-section limit for most models

IceCube, PRL 110 (2013) 131302

Neutrino Oscillations with IceCube



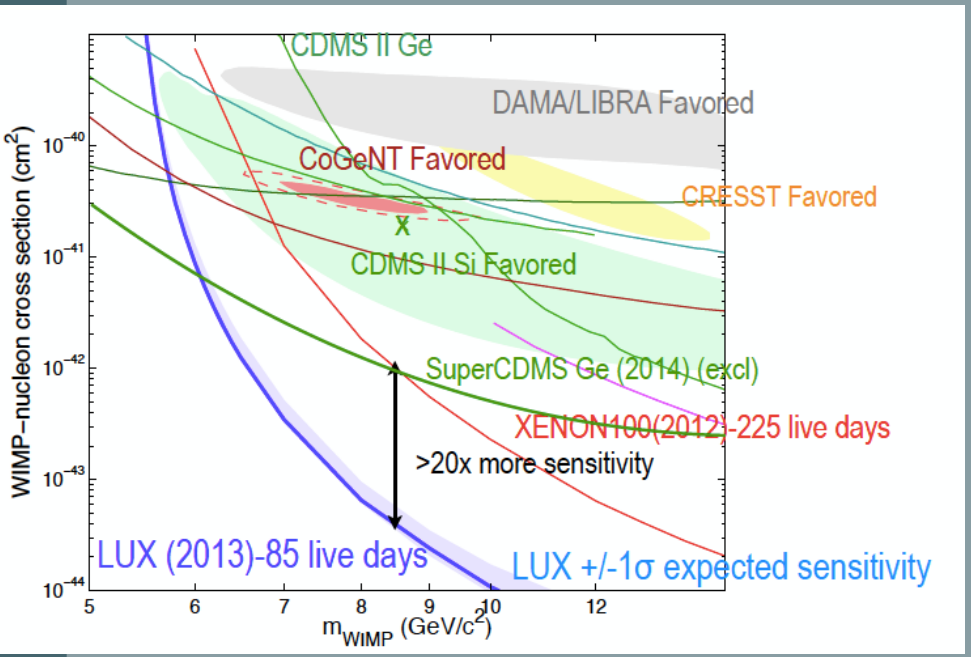


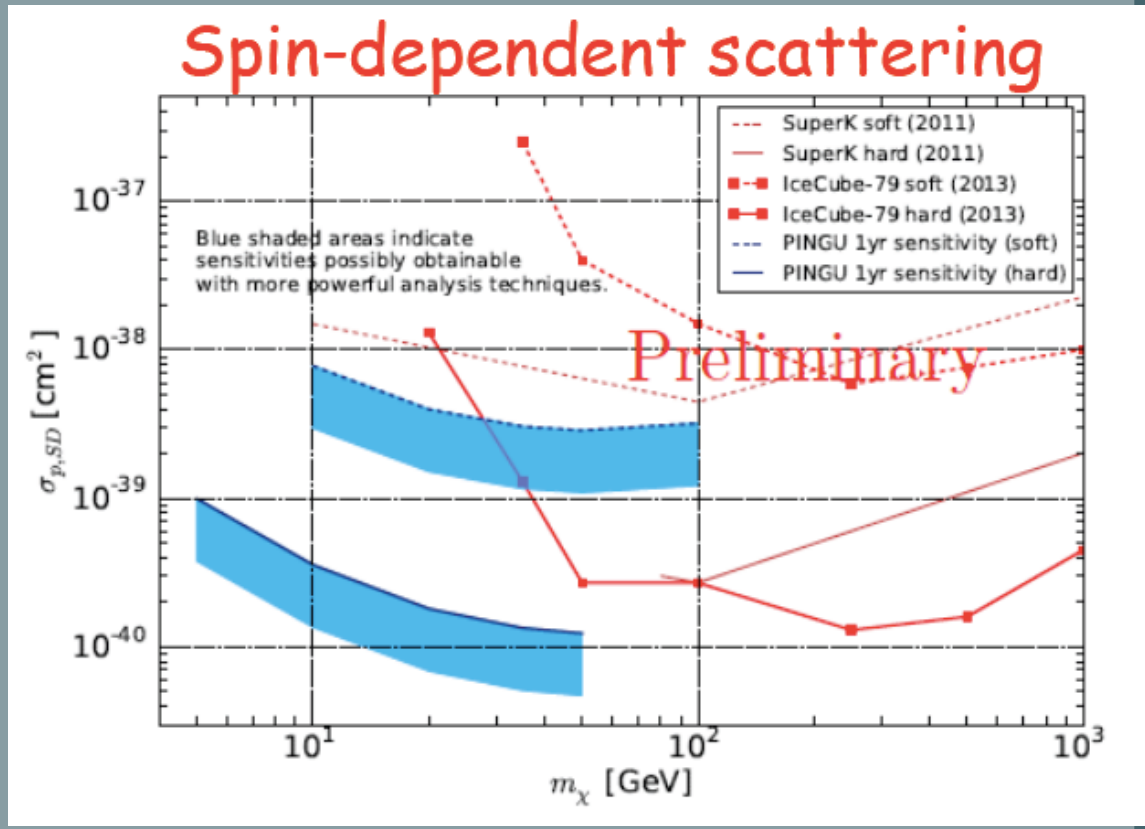


The FUTURE

PINGU

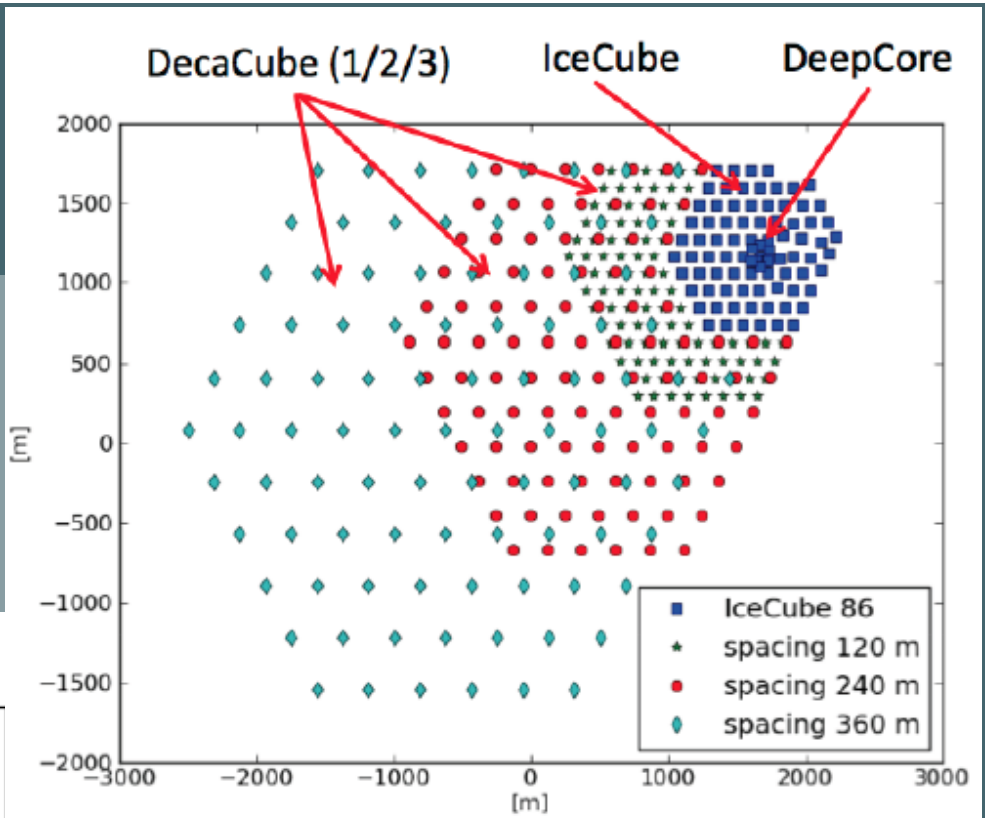
Further in-fill of deep core.
Lower the energy threshold few GeV
Oscillations and Neutrino Mass Hierarchy
Dark Matter

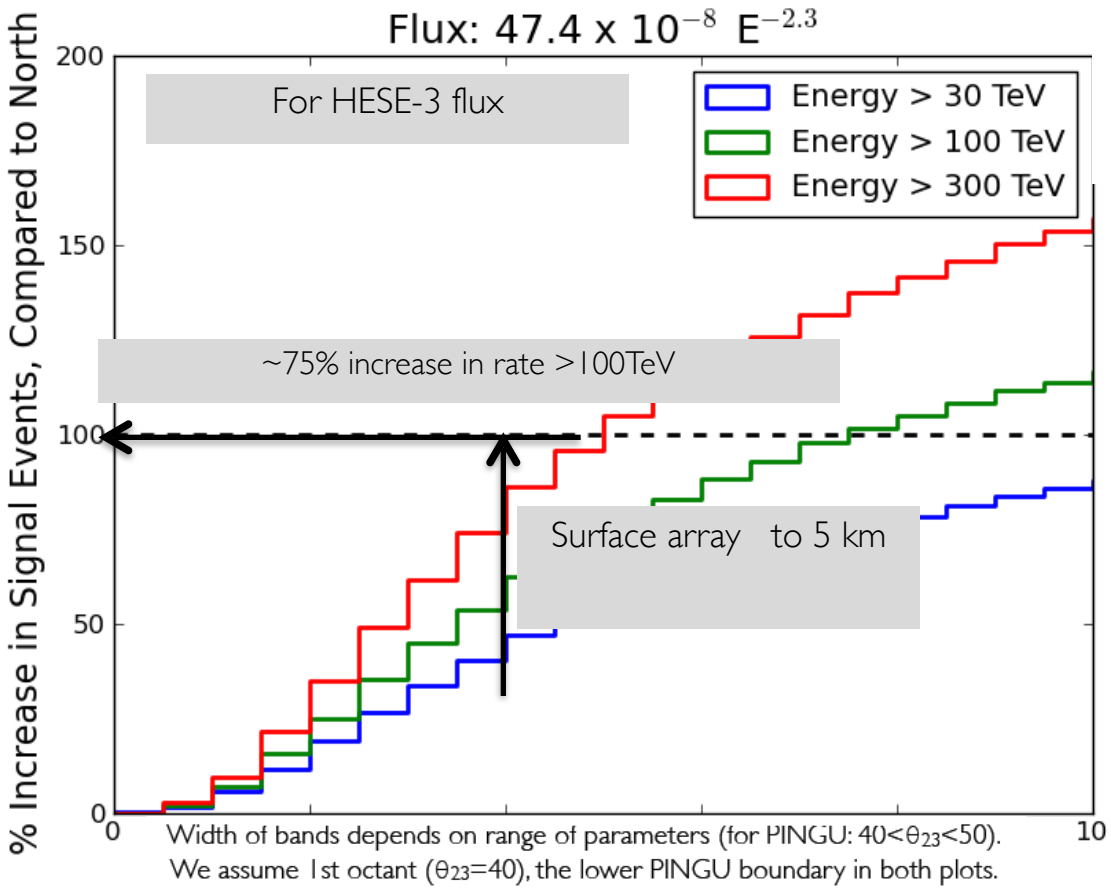




The Future (contd)

An extended surface array would increase veto coverage of IceCube





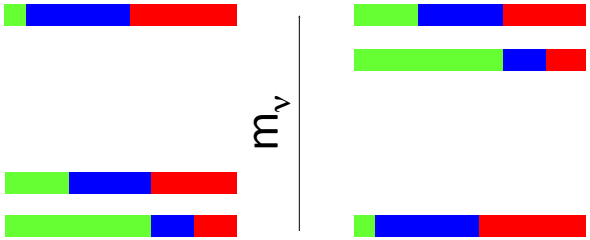
Spacing 1 (120m): IceCube
(1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

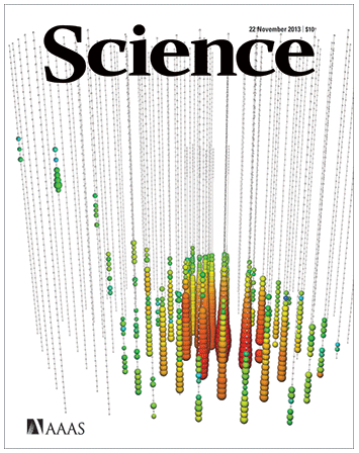
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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

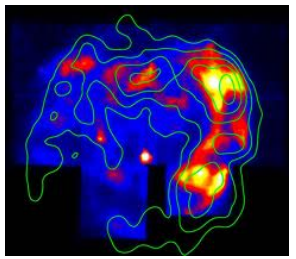
KM3NeT outlook

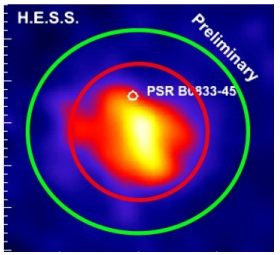
Neutrino physics



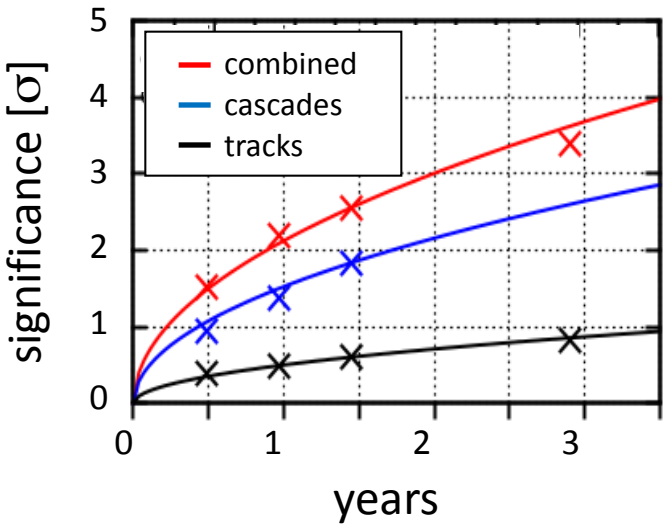


Neutrino astronomy

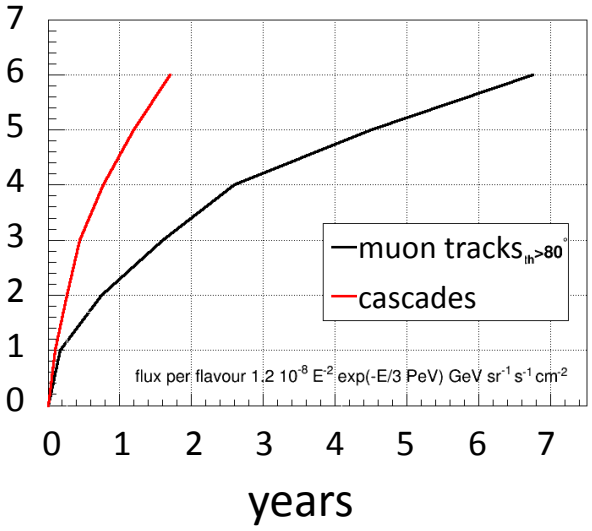




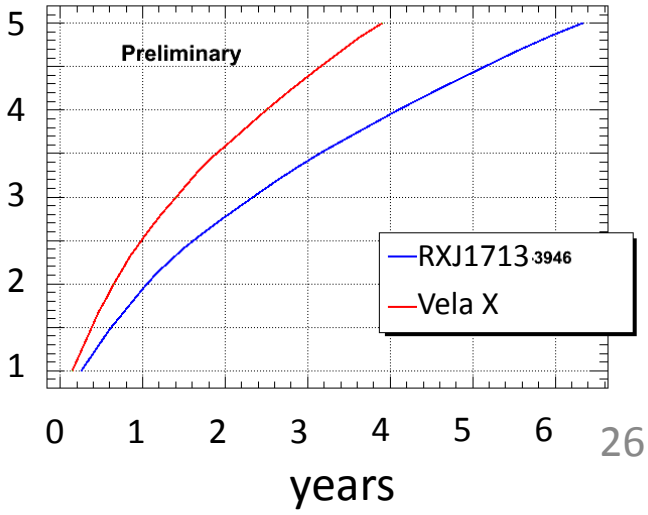
ORCA
+40 M€



Phase-1.5
+50–60 M€

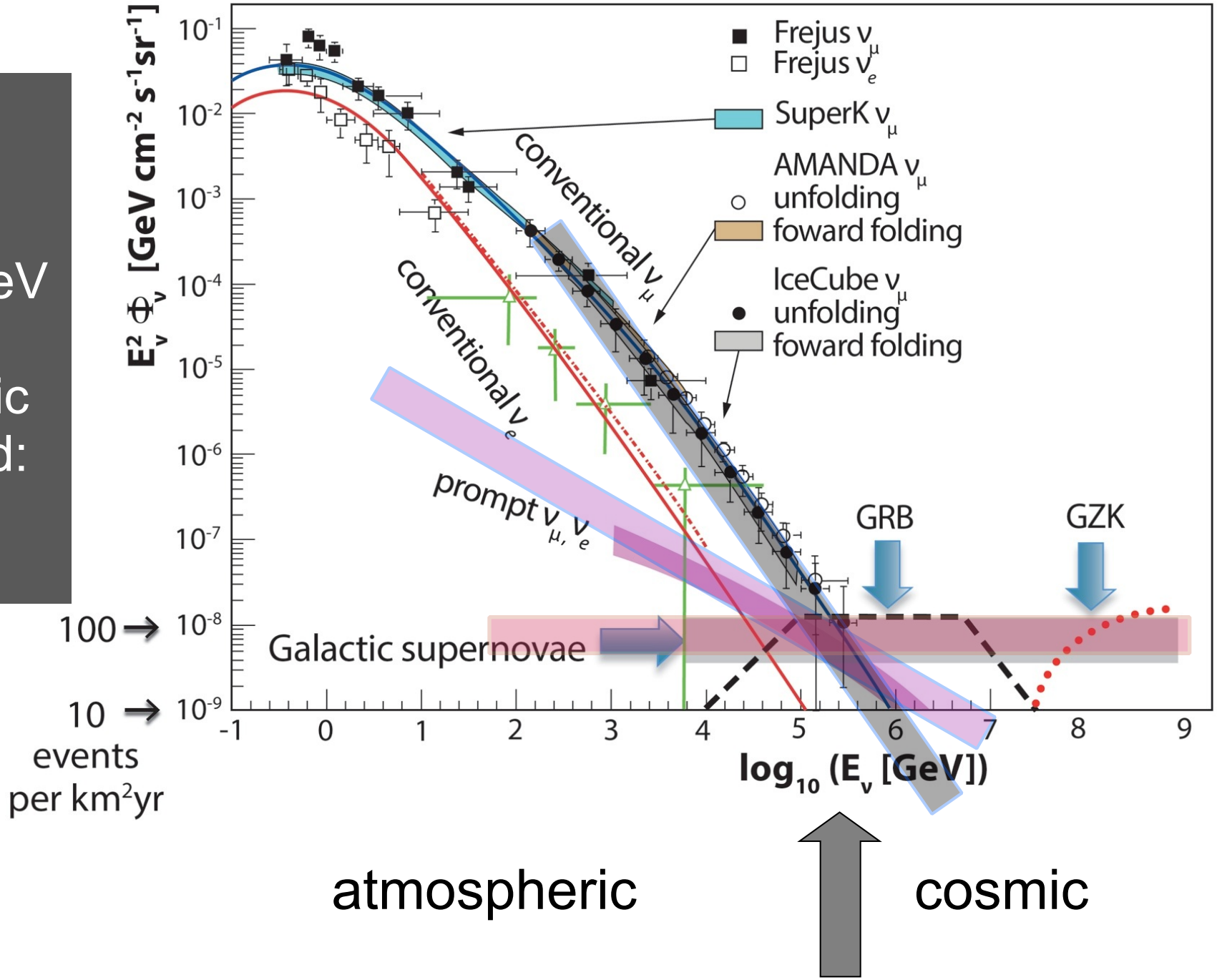


Phase-2
+130–170 M€



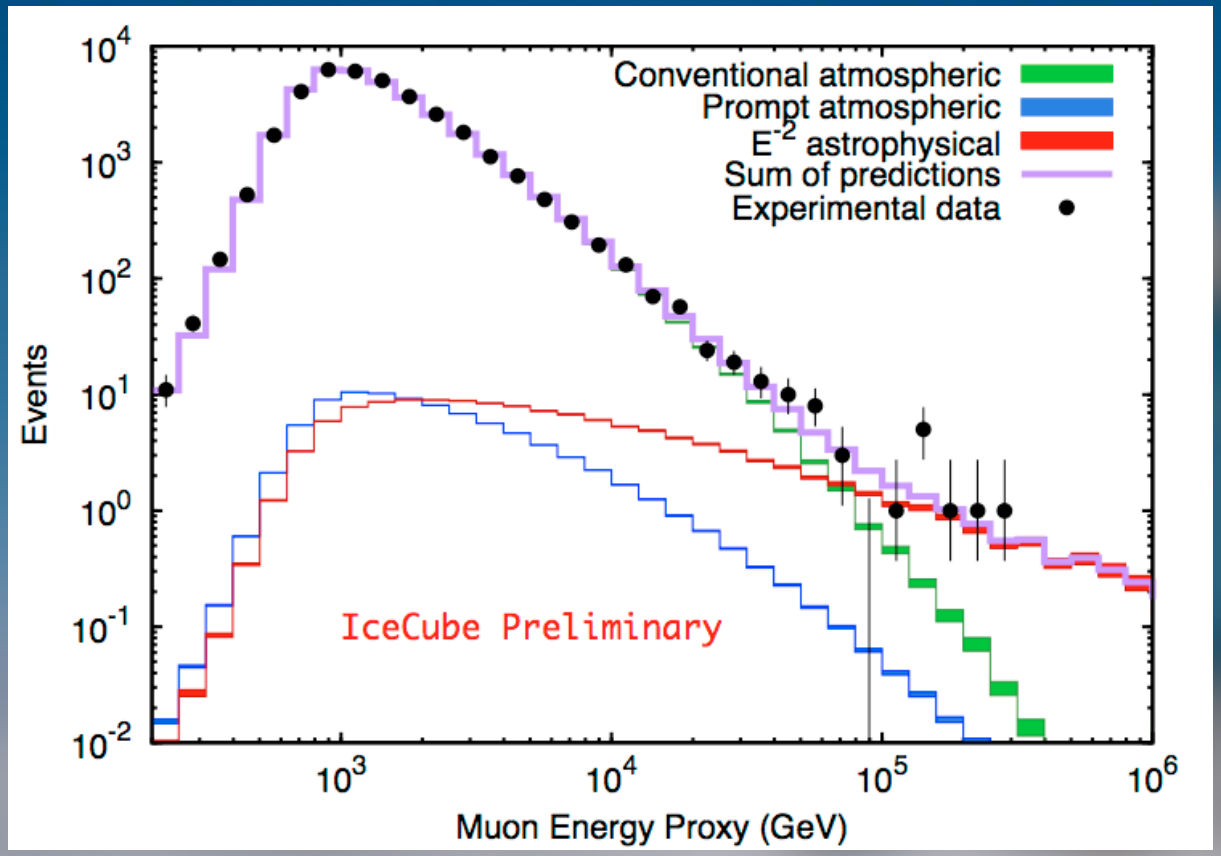
Diffuse Fluxes of Neutrinos

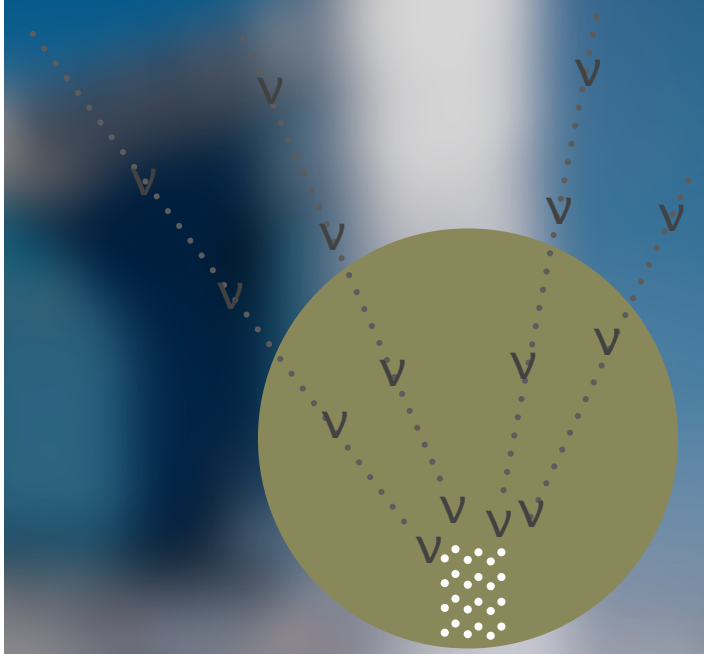
- cosmic neutrinos: energy
  > 100 TeV
- atmospheric background: 1~2 events per year



Evidence : Upgoing Muons in IceCube 79 and 86-I

Standard through going-muon diffuse analysis



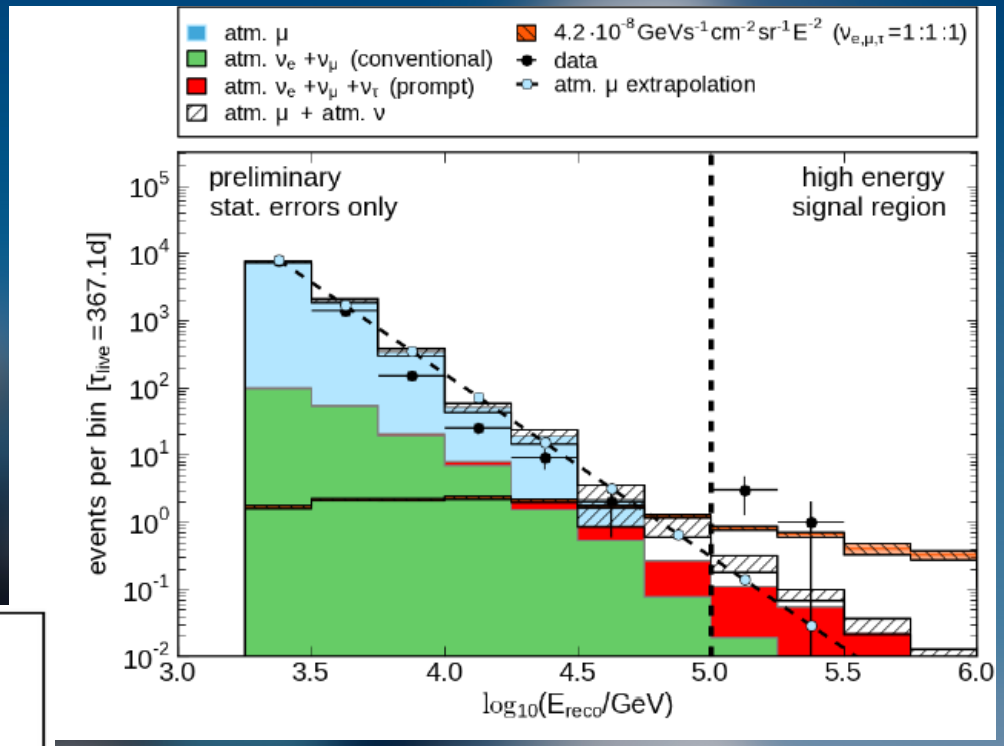


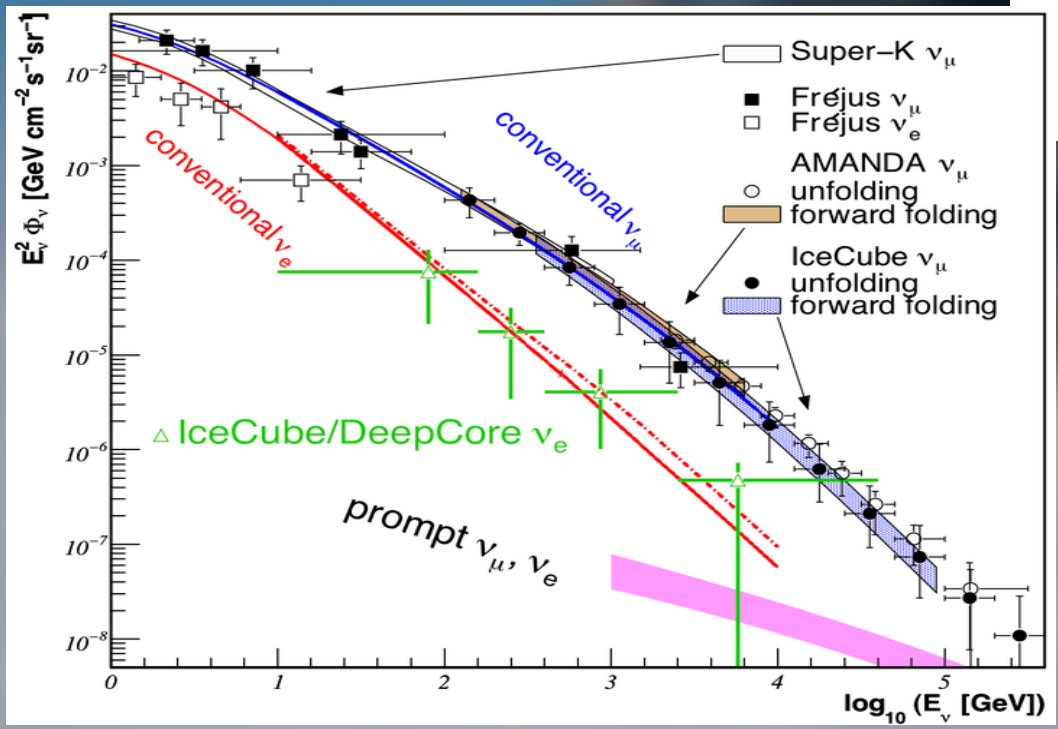
- The best-fit astrophysical flux: $1.01 \times 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$
- The bkg-only hypothesis is disfavored: **3.9σ , 659 d**

Some Hints : 1. Cascades in IceCube 40

IceCube 40 Cascades

Bkg only hyp disfavored at: **2.4σ**



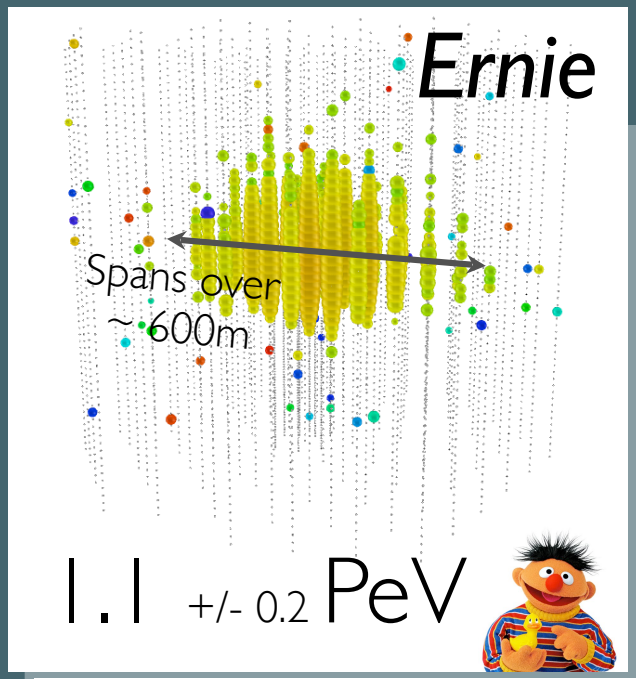


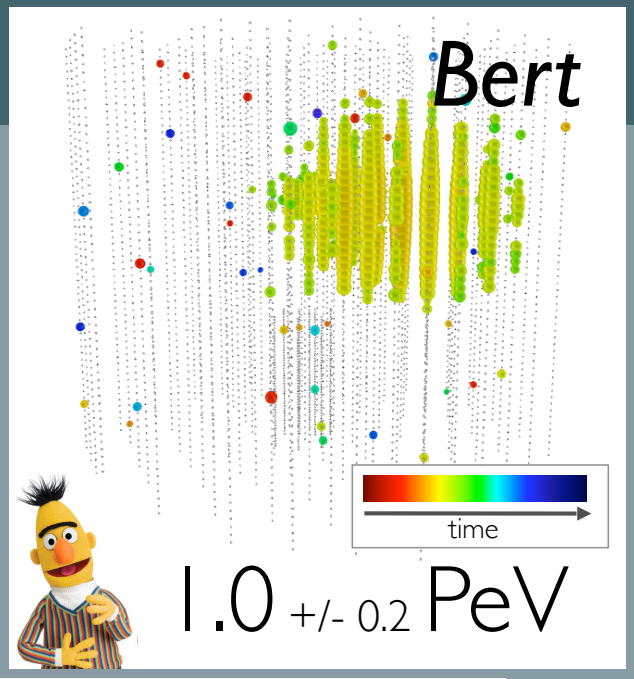
Other Measurements :

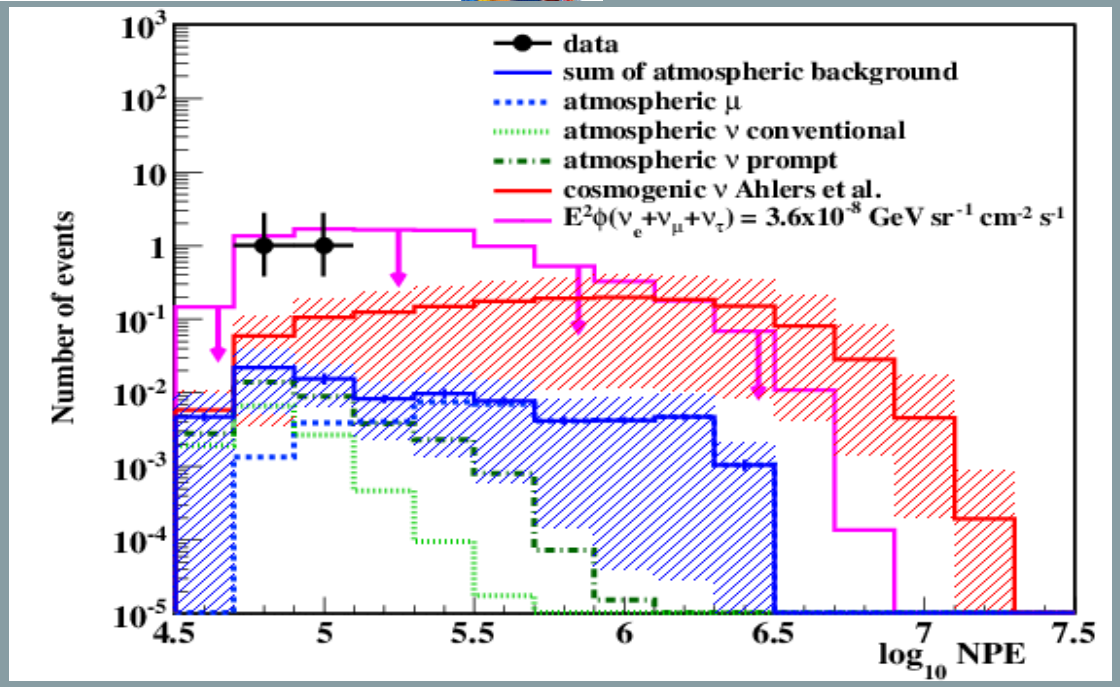
Atmospheric ν_e and ν_μ fluxes

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

Some Hints: 3. PeV Neutrinos







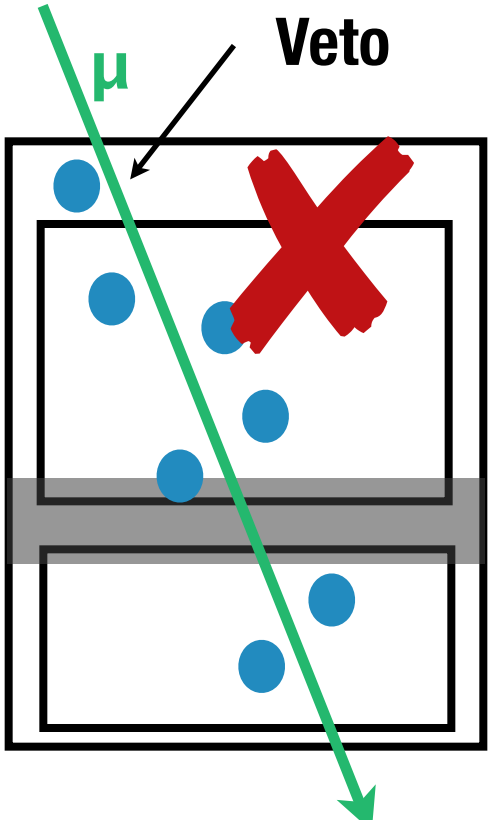
- Two very interesting cascade events found in IceCube (IC79/IC86)
- Analysis targeting much higher energy all flavor neutrinos (related to GZK cutoff)
- Expected background: 0.08 ± 0.05
- Significance: **2.8σ**

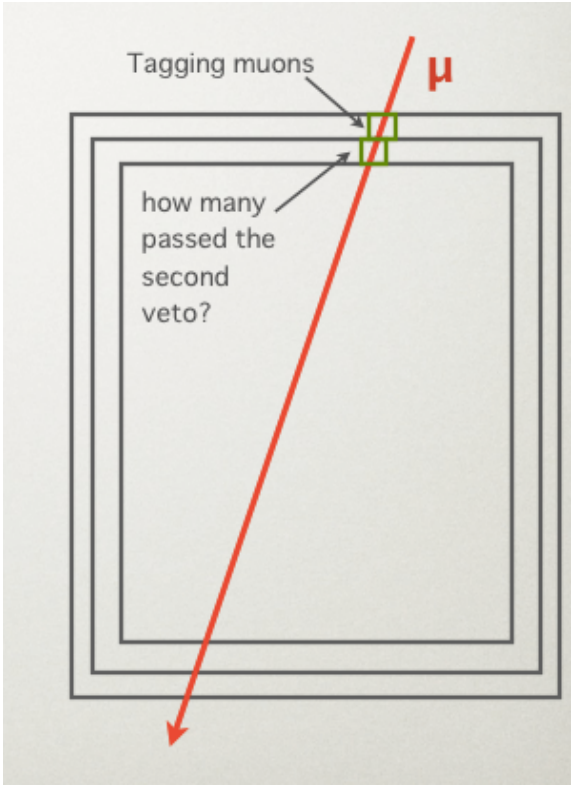
Too low in energy for GZK
Too high in energy for atmospheric

IceCUbe PRL111 (2013)

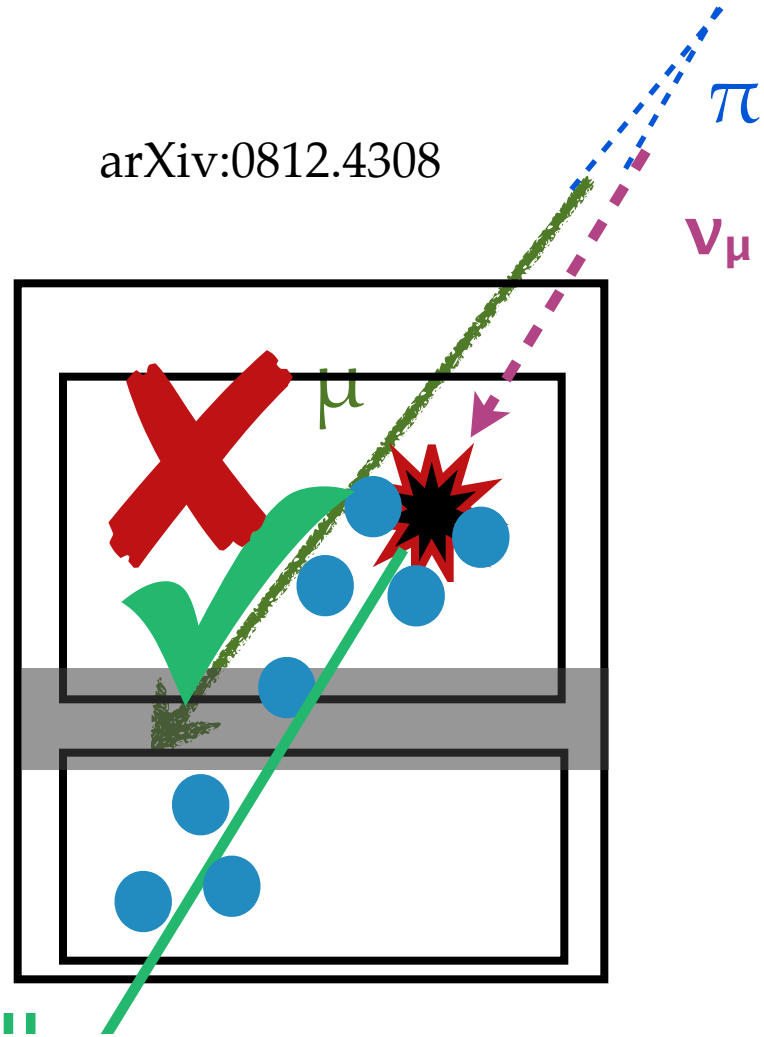
Vetoes

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

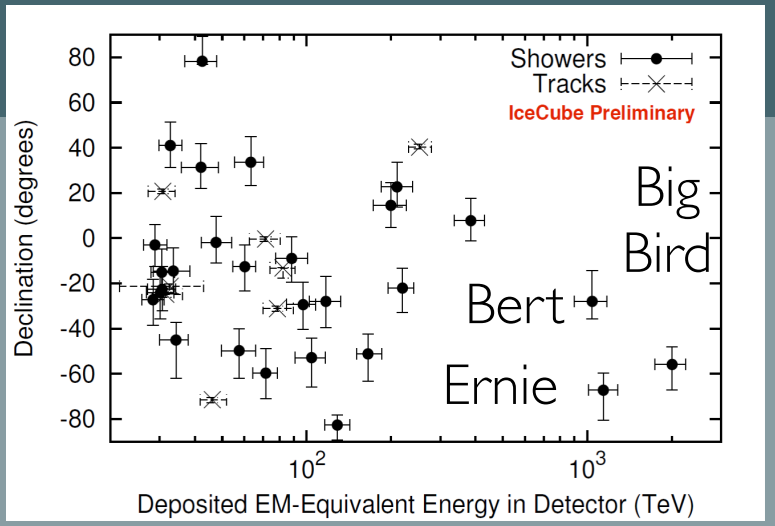




arXiv:0812.4308



High Energy Starting Events (HESE): 3 YEARS
37 EVENTS



up-going down-going

9 track-like events

1° ang. resolution

Muon takes some energy away

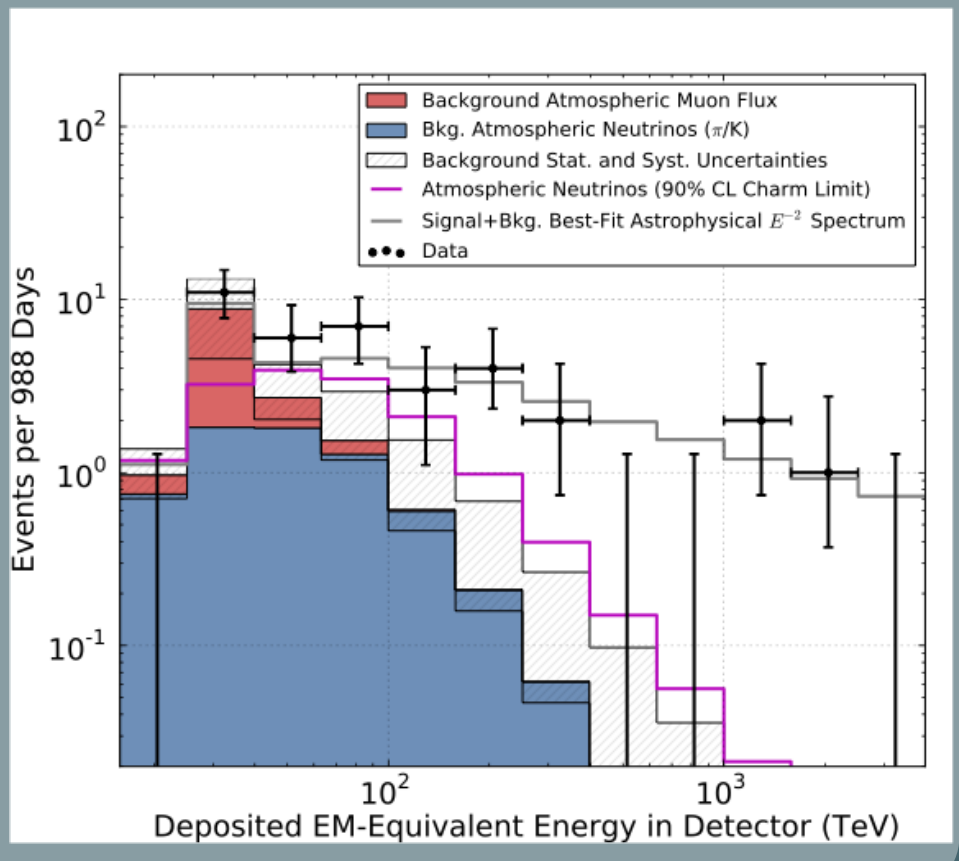
28 cascade-like events

10° – 45° ang. resolution

15% visible energy resolution

Estimated background:

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



5.7σ full likelihood fit of all components

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

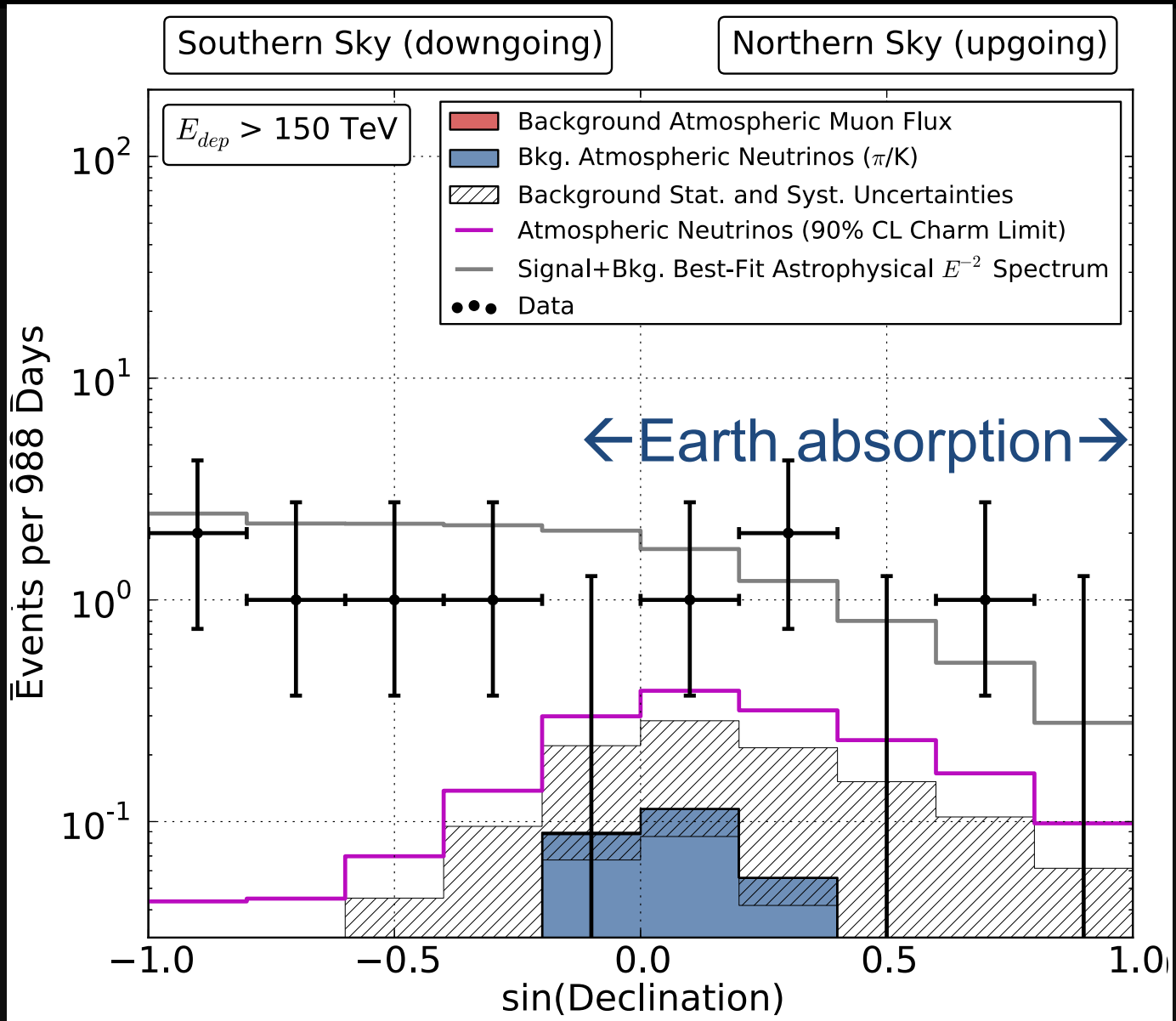
IceCube arXiv:1405.5303

Declination Distribution

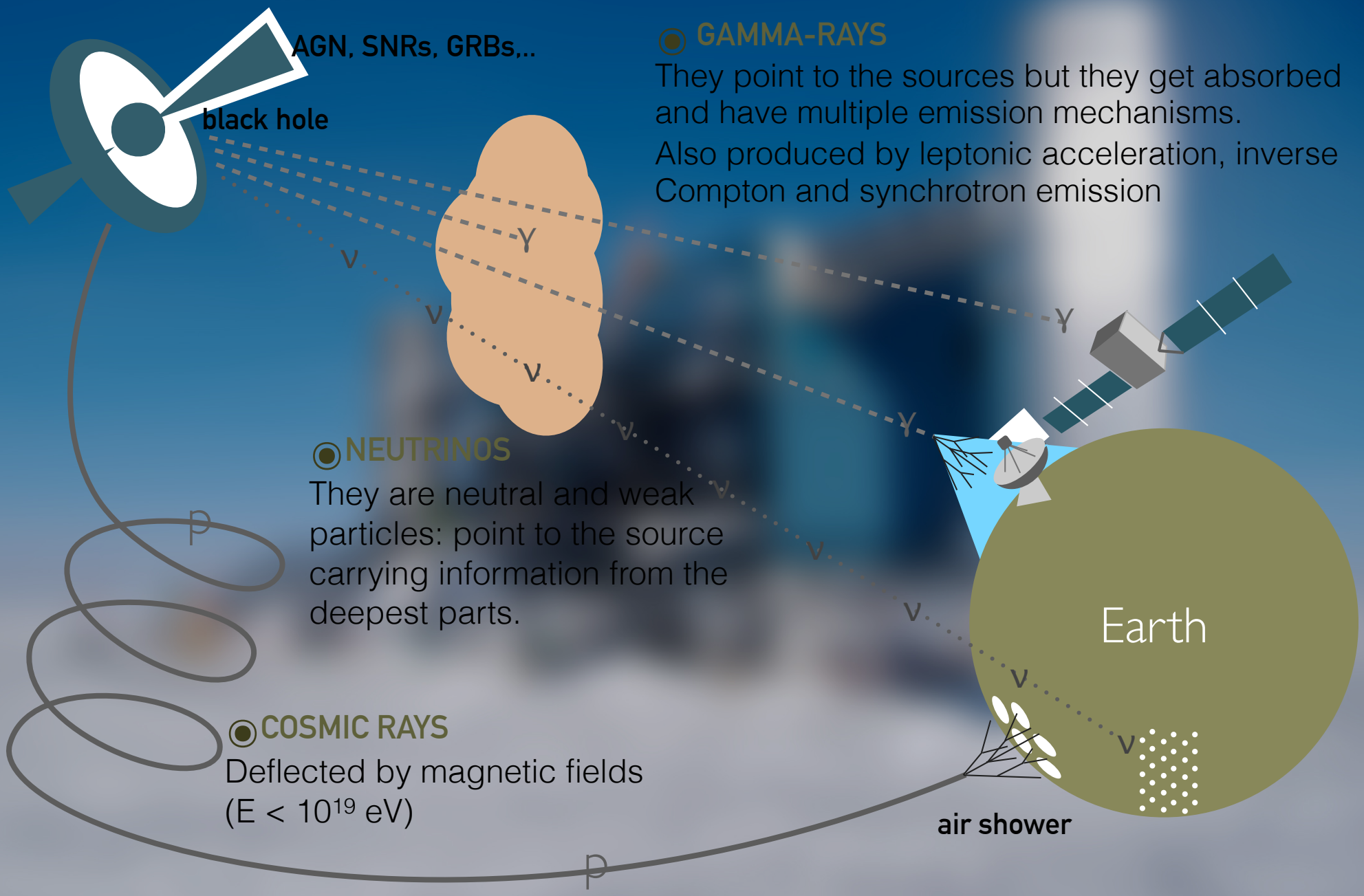
Or: "zenith Distribution" because we are at the South Pole

Compatible with isotropic flux

upgoing events absorbed in Earth



Multi-Messenger approach



GAMMA-RAYS

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

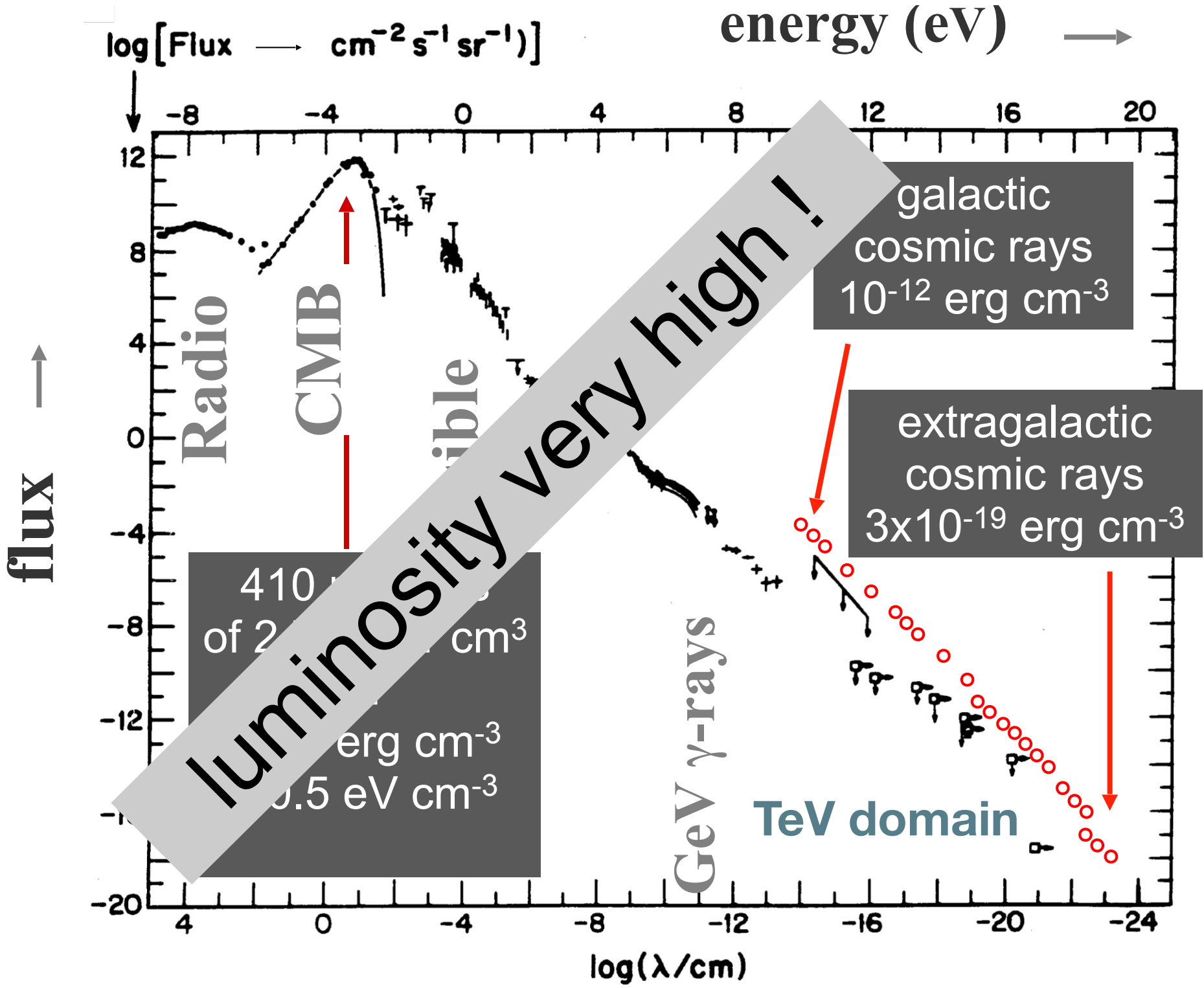
Also produced by leptonic acceleration, inverse Compton and synchrotron emission

NEUTRINOS

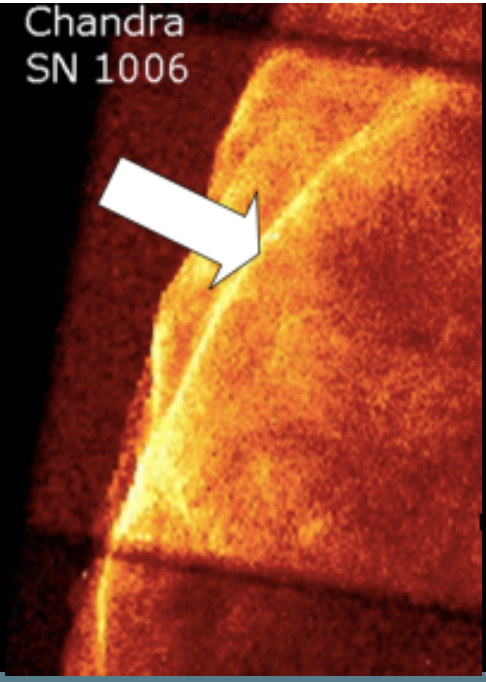
They are neutral and weak particles: point to the source carrying information from the deepest parts.

COSMIC RAYS

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

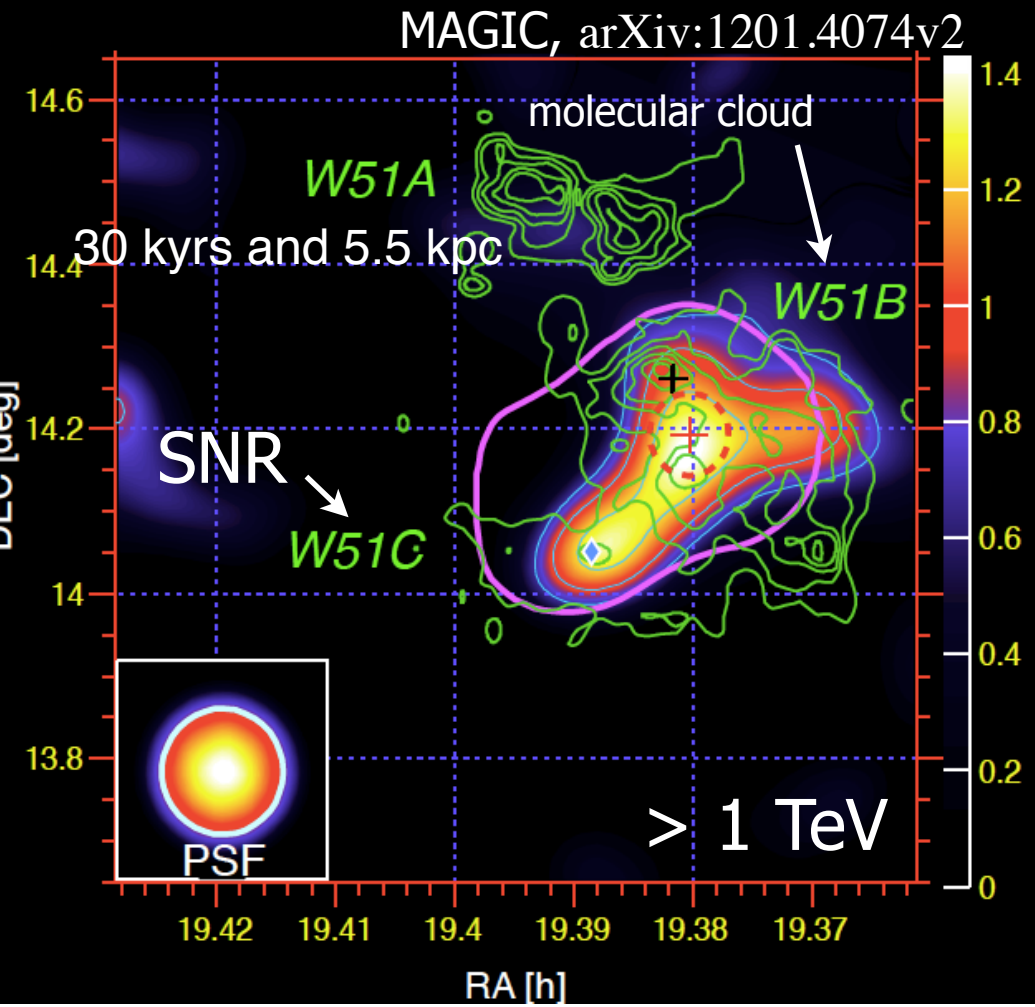

energy (eV)
log [Flux → cm⁻² s⁻¹ sr⁻¹)]
flux →
log(λ/cm)
Radio
CMB
GeV γ-rays
TeV domain
galactic cosmic rays 10⁻¹² erg cm⁻³
extragalactic cosmic rays 3x10⁻¹⁹ erg cm⁻³
luminosity very high !

Supernova Remnants in the TeV

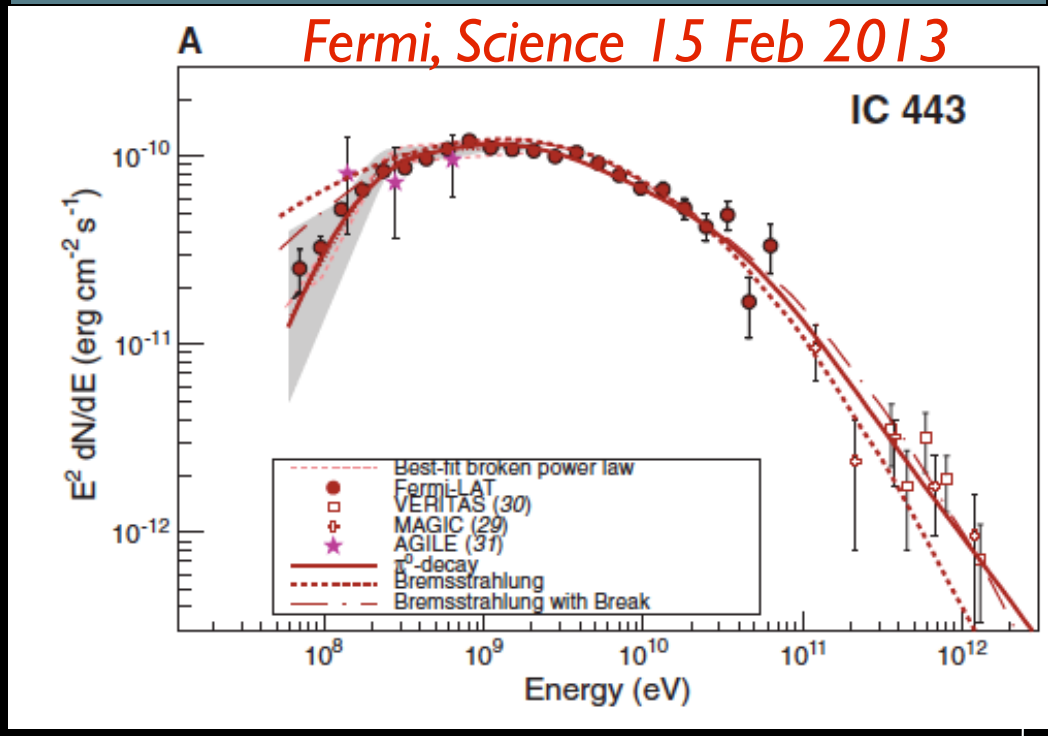


? $E_{max} = Z \times 100$ TeV < E_{knee} ?

Indirect evidence of protons: clouds.

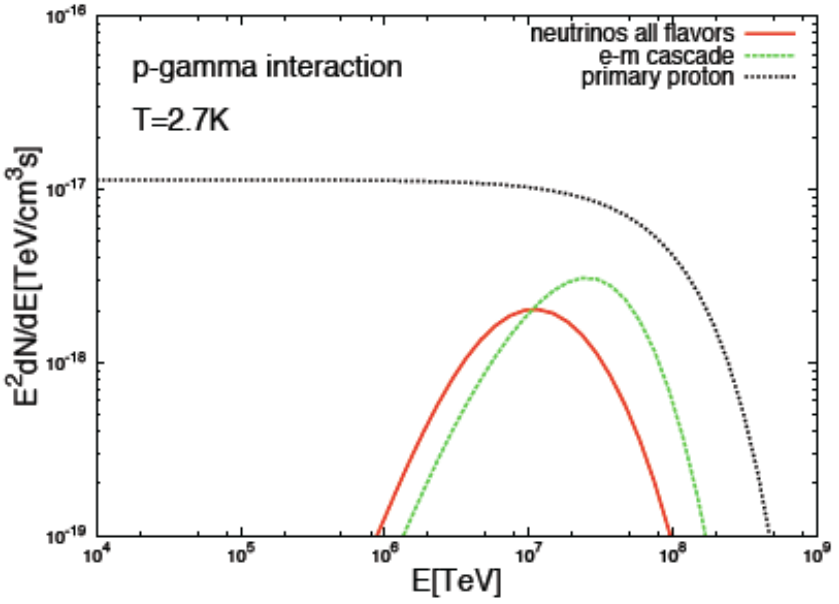


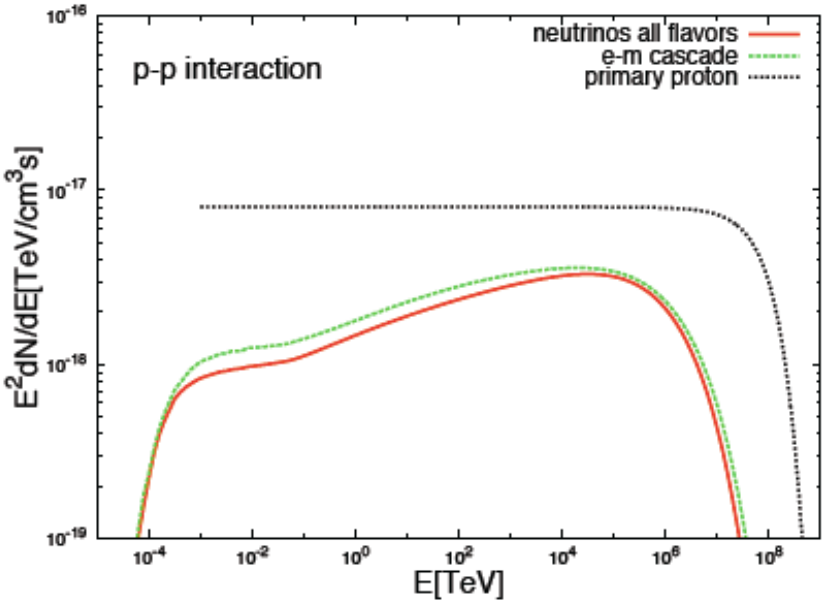
Fit of spectra prefer GeV pions (Fermi Agile)



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

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

or p + p

TeV gamma rays

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

Cosmic rays?

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

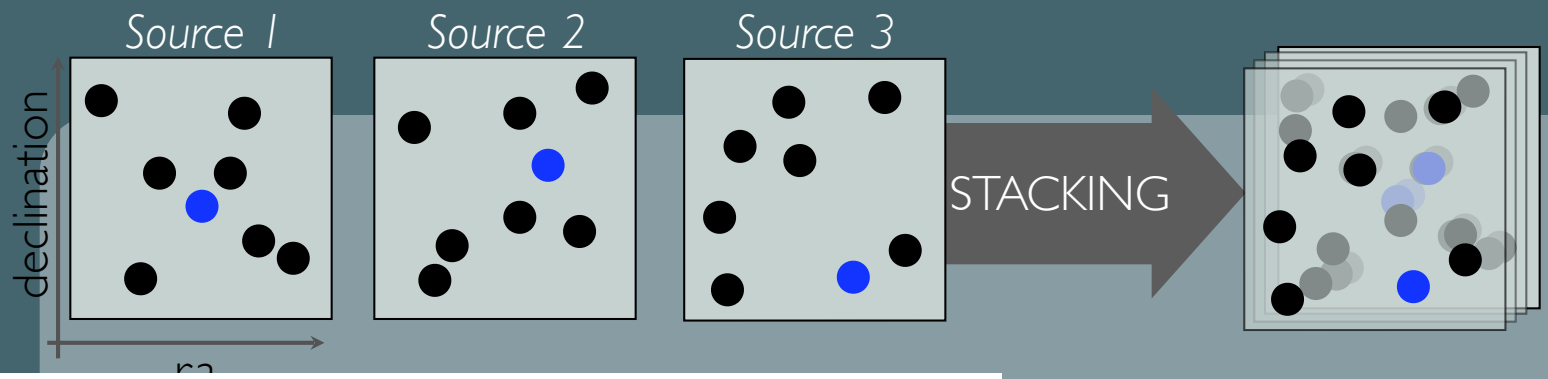
TeV neutrinos

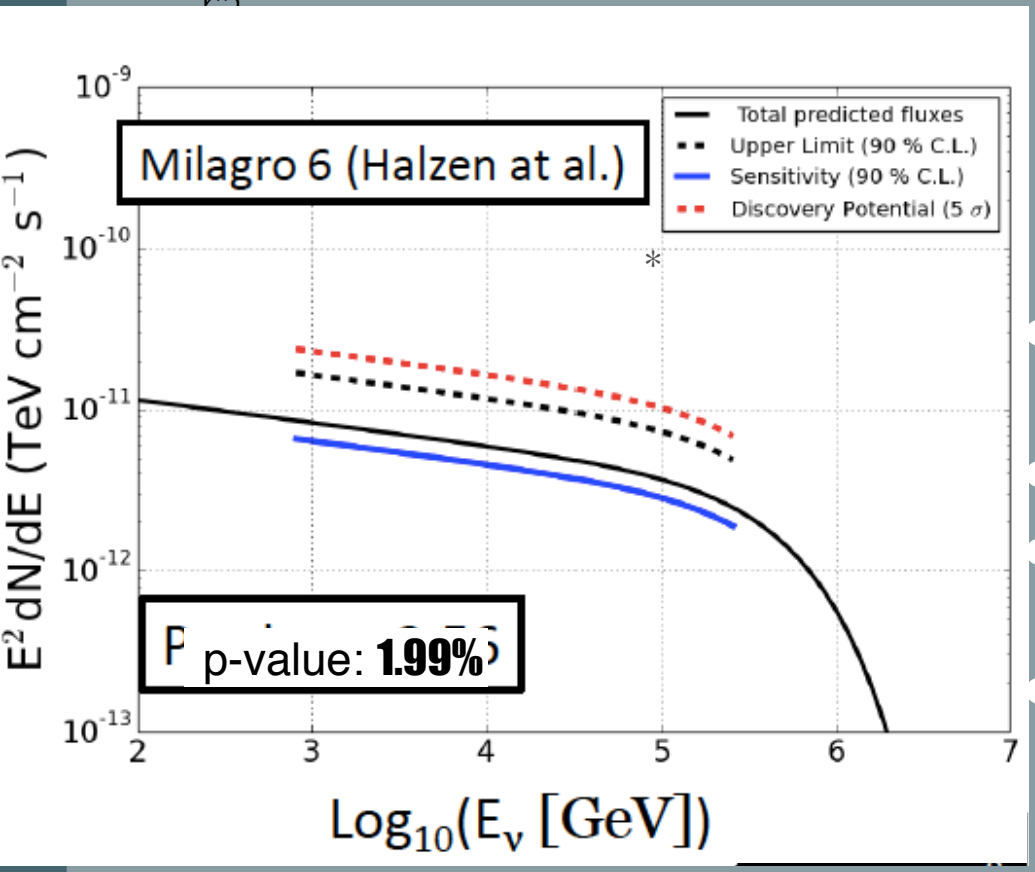
at the source: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 :$

- Oscillations of the neutrino flavor:

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

Cygnus region in neutrinos



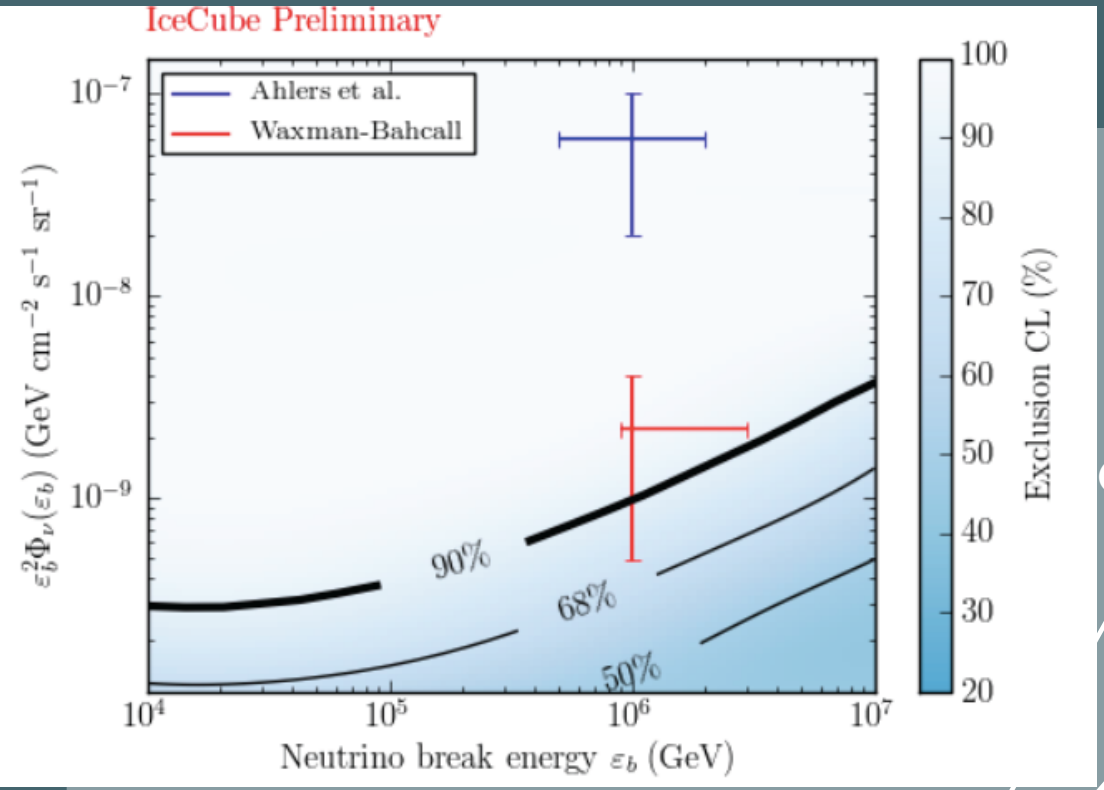


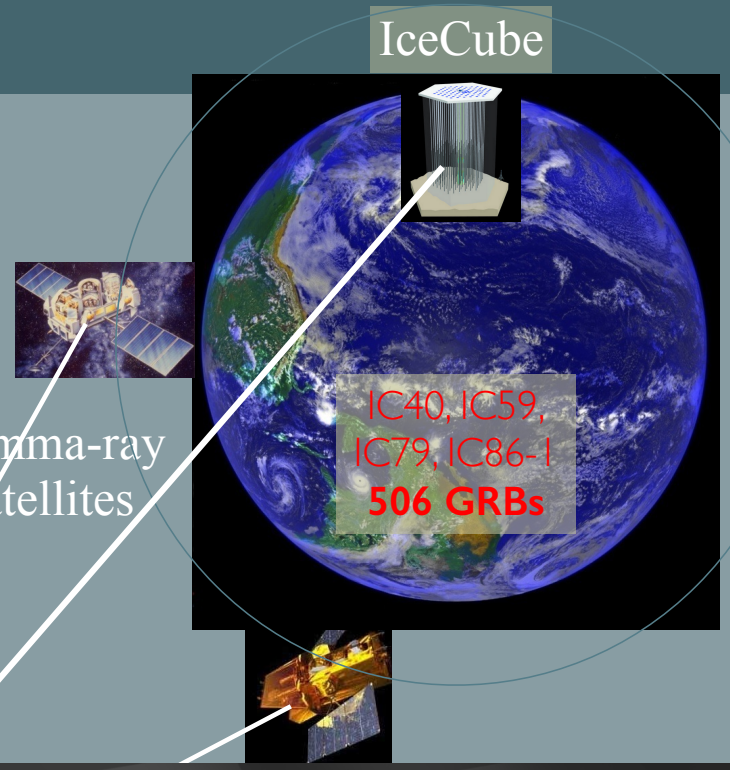
Most Significant Deviation

- 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)

Neutrinos coincident with GRBs?





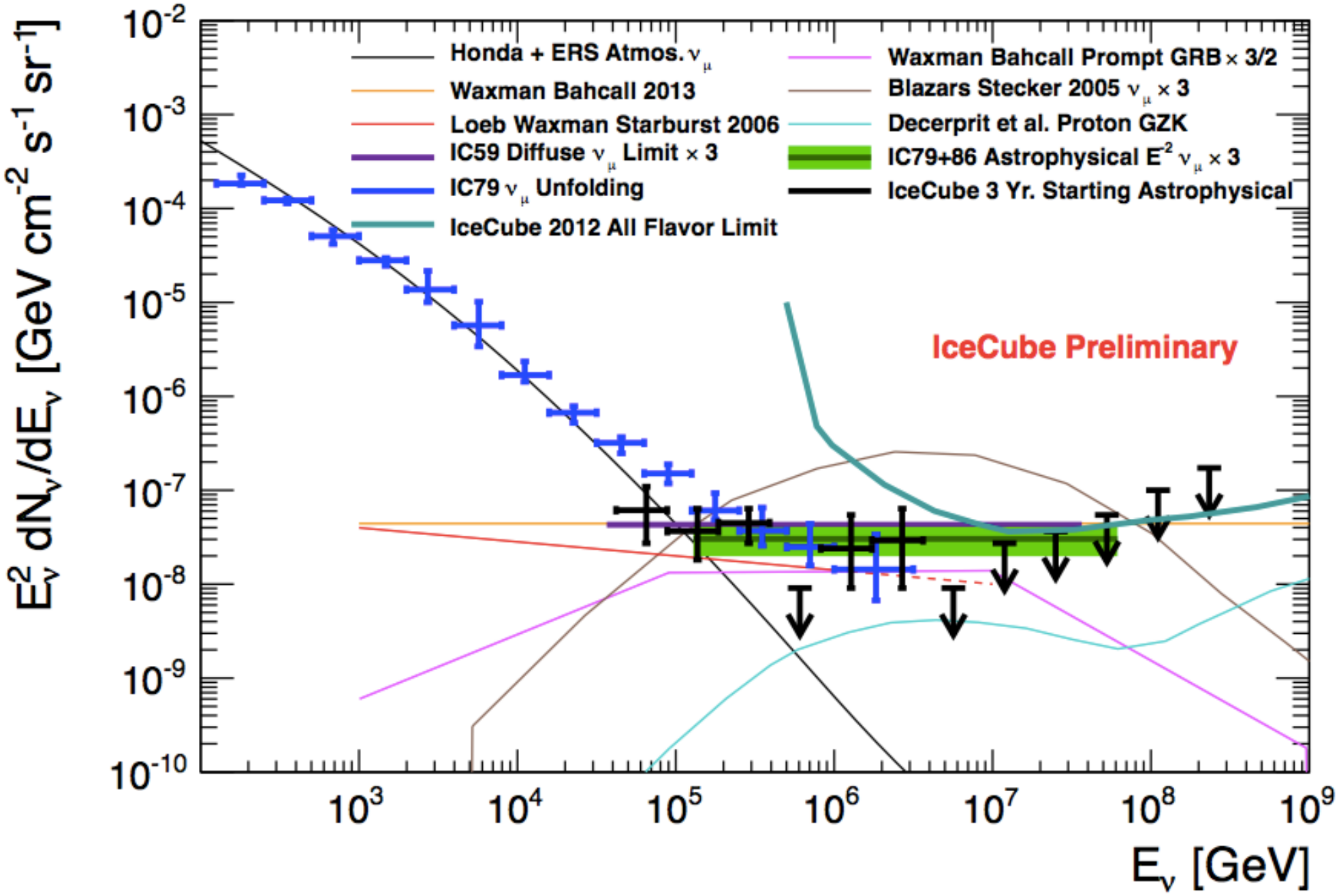
GRB: one neutrino per cosmic ray observed disfavored by IceCube

decays to a PeV neutrino

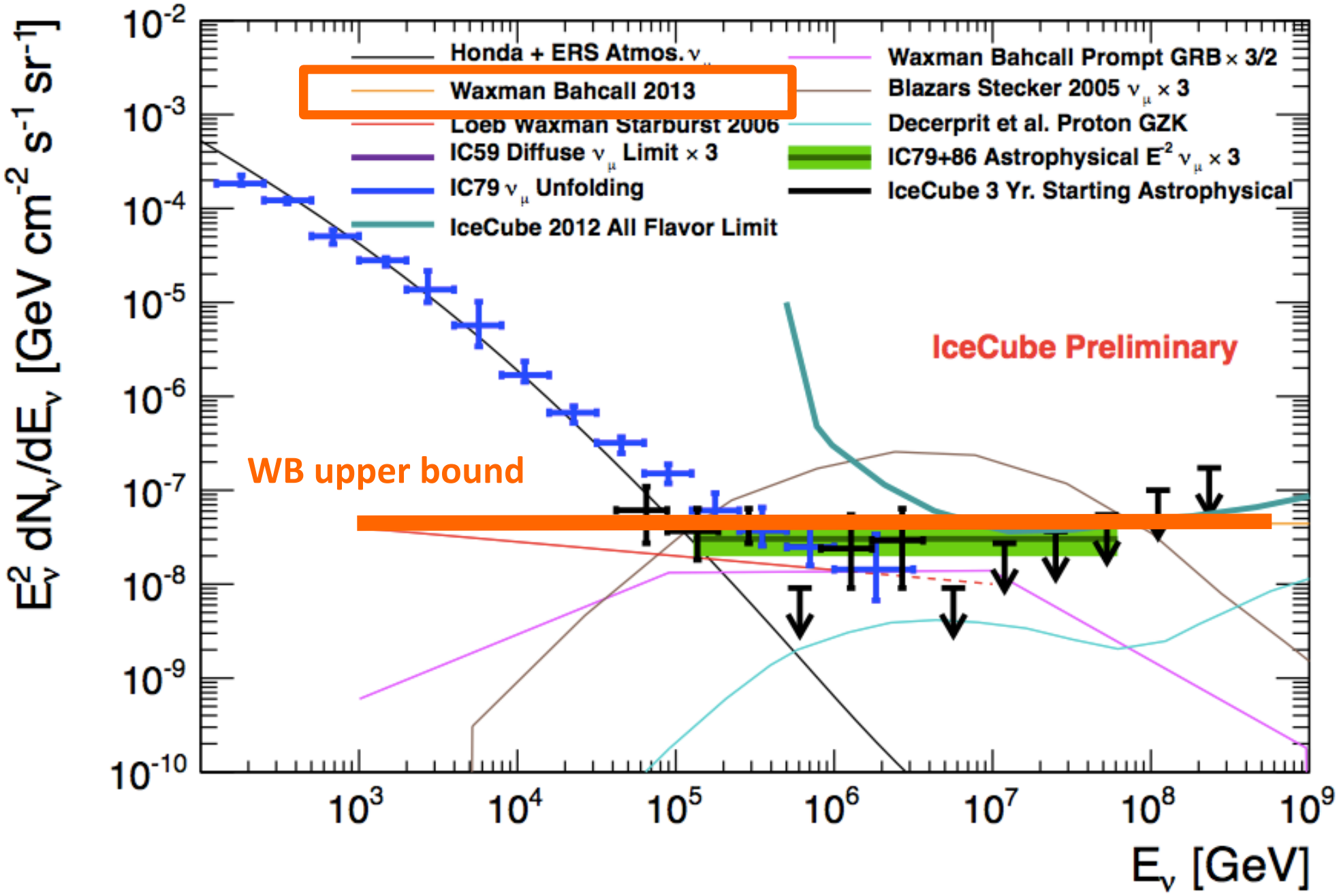
$$p + \gamma \rightarrow n + \pi^+$$

decays to cosmic ray

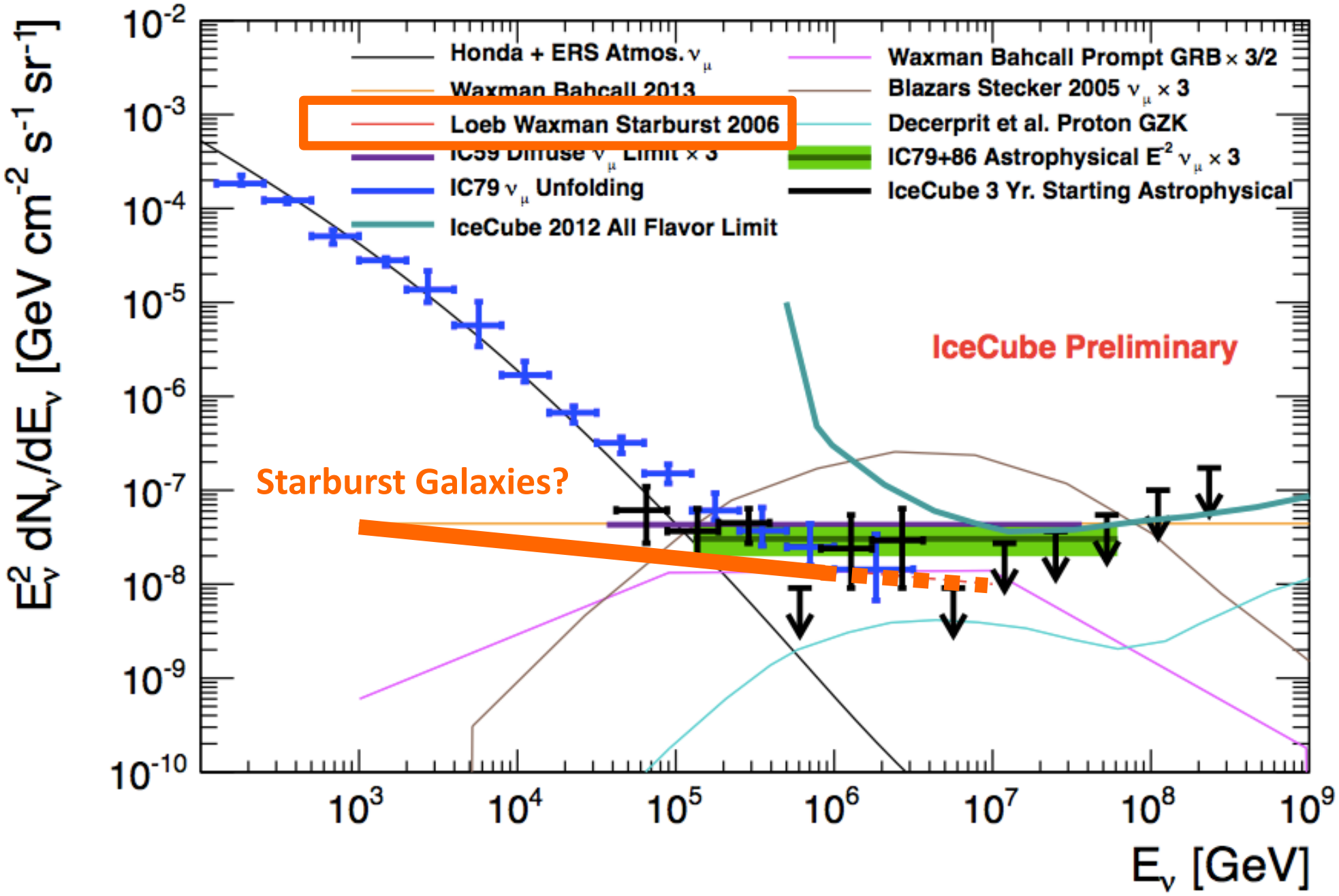
Diffuse fluxes



Diffuse fluxes

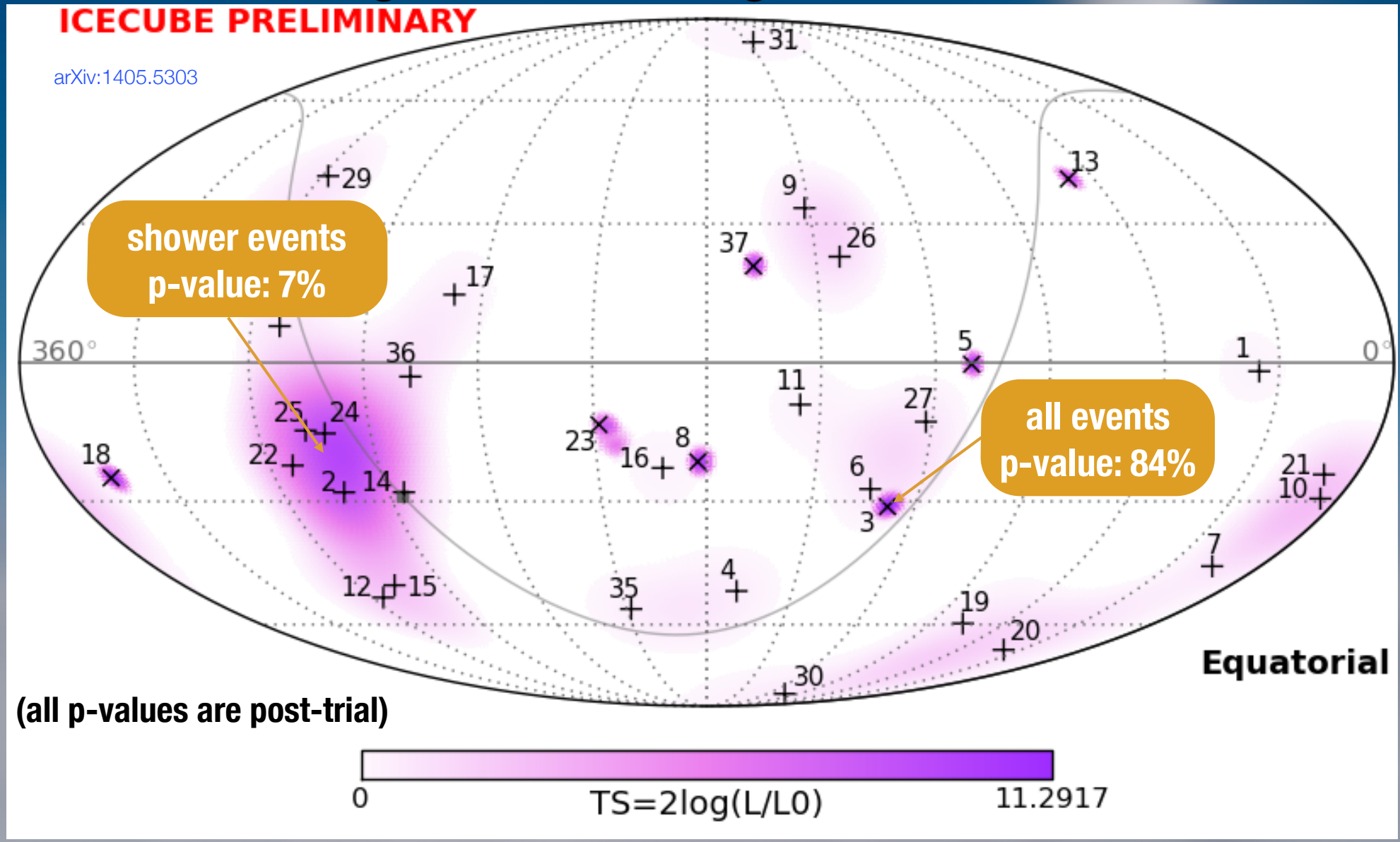


Diffuse fluxes



Where do the HESE come from?

No significant clustering observed 3 years



Conclusions

We fit a E^{-2} - like spectrum at the level of the expected upper bound on cosmic neutrinos from measured CRs
Neutrinos play a relevant role for DM searches

Thank You for your attention