Cosmic Signals in the Antarctic Ice

The IceCube Neutrino Observatory

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What I want to tell you:

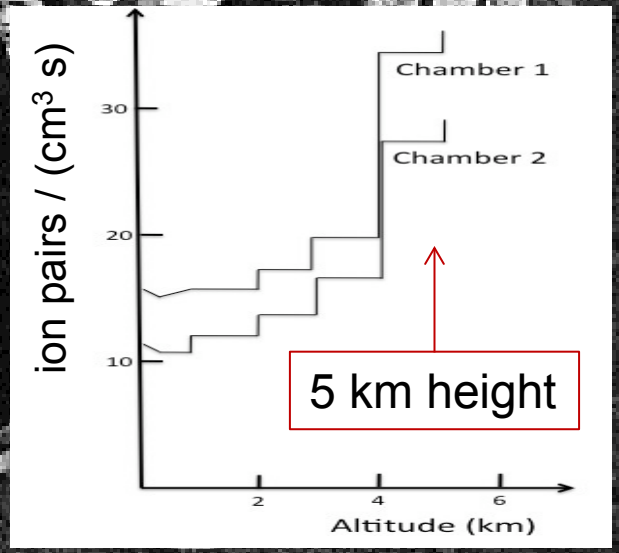
- Cosmic rays (CR)
- How to measure cosmic rays
- What we know and don‘t know about CR
- Neutrinos as messengers of cosmic accelerators
- Neutrino Observatory IceCube
- The IceCube Muppet Show ....
- Do not talk about
  e.g. exotic searches (wimps, …)

Cosmic Rays

100 years after their discovery not yet understood

faster discharge
of an electrometer
with increasing height

Viktor Hess 1912



interpreted due to radiation
from space: **“Höhenstrahlung”**

Zwicky's proposal for the CR Origin

In Los Angeles Times, Jan. 1934

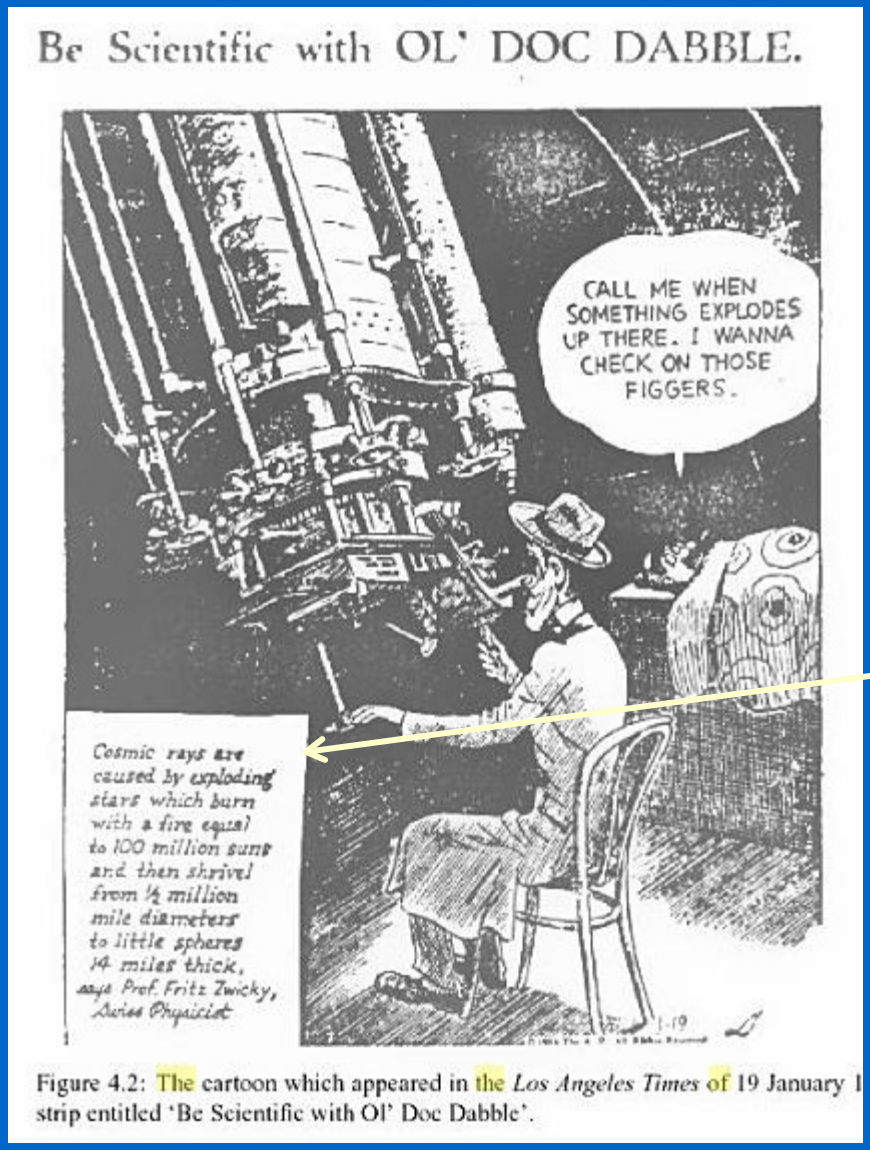
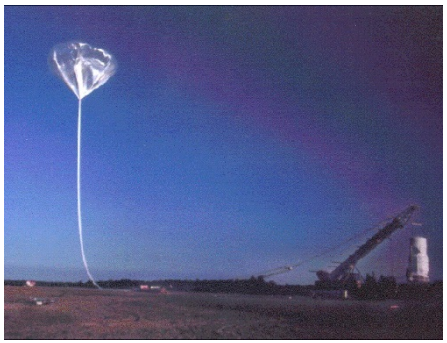


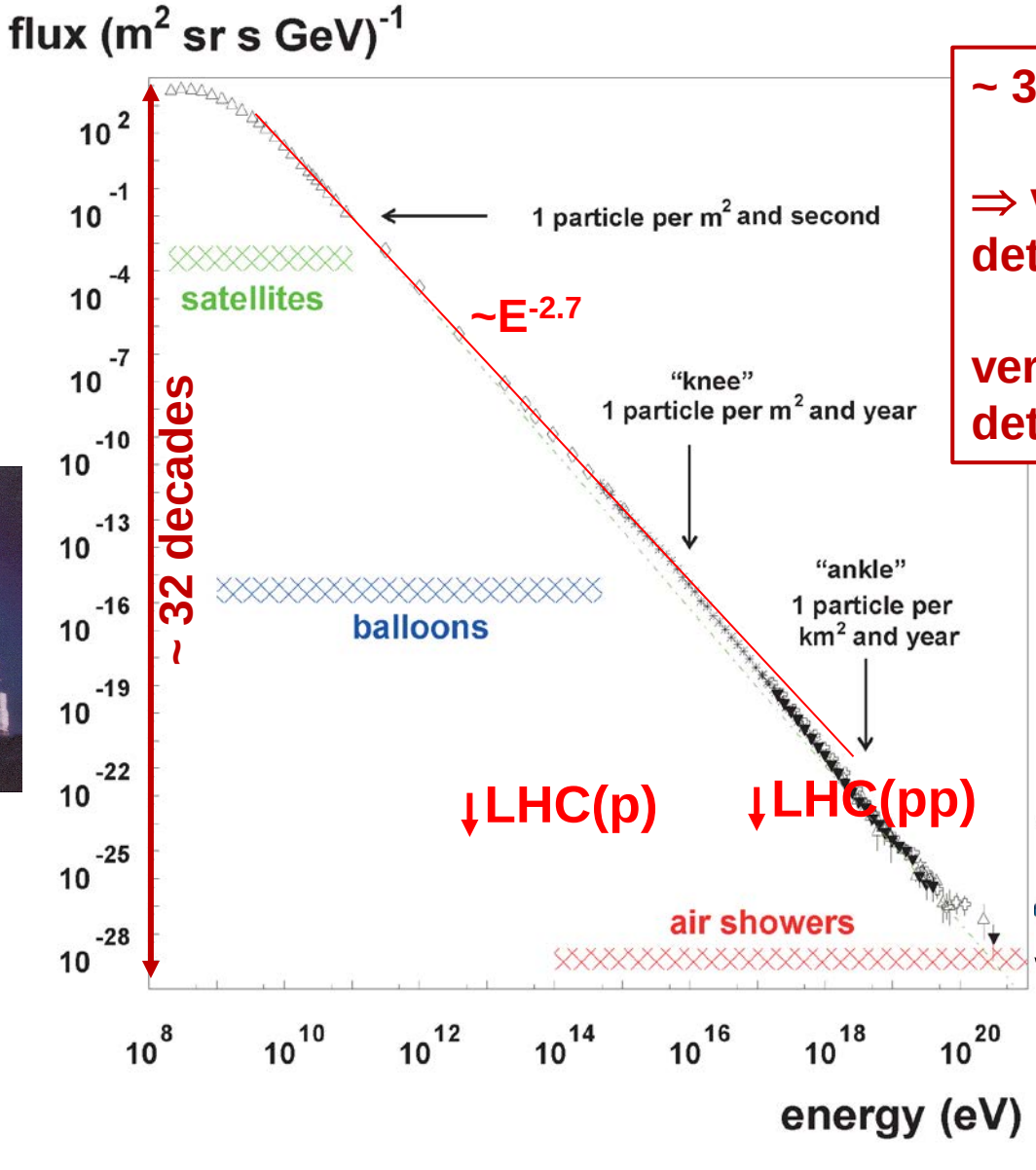
Figure 4.2: The cartoon which appeared in the *Los Angeles Times* of 19 January 1 strip entitled 'Be Scientific with Ol' Doc Dabble'.

"Cosmic rays are caused by exploding stars which burn with a fire equal to 100 million suns and then shrivel from ½ million mile diameters to little spheres 14 miles thick.", says Fritz Zwicky, Swiss Physicist.

… since then we are trying to prove it

Cosmic Ray Spectrum

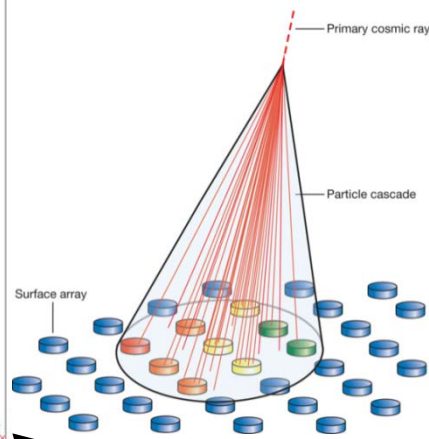




~ 32 decades

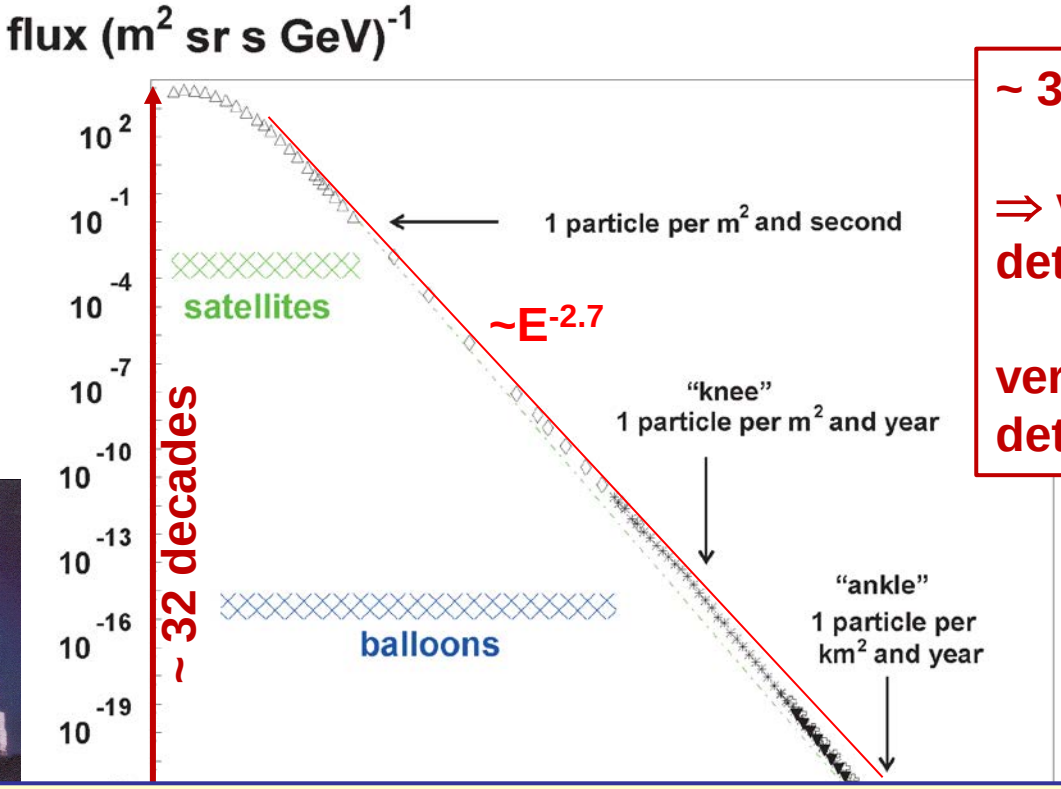
⇒ very different detection methods

very different detector sizes



cut-off?

Cosmic Ray Spectrum



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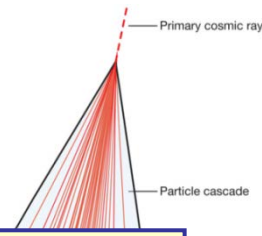
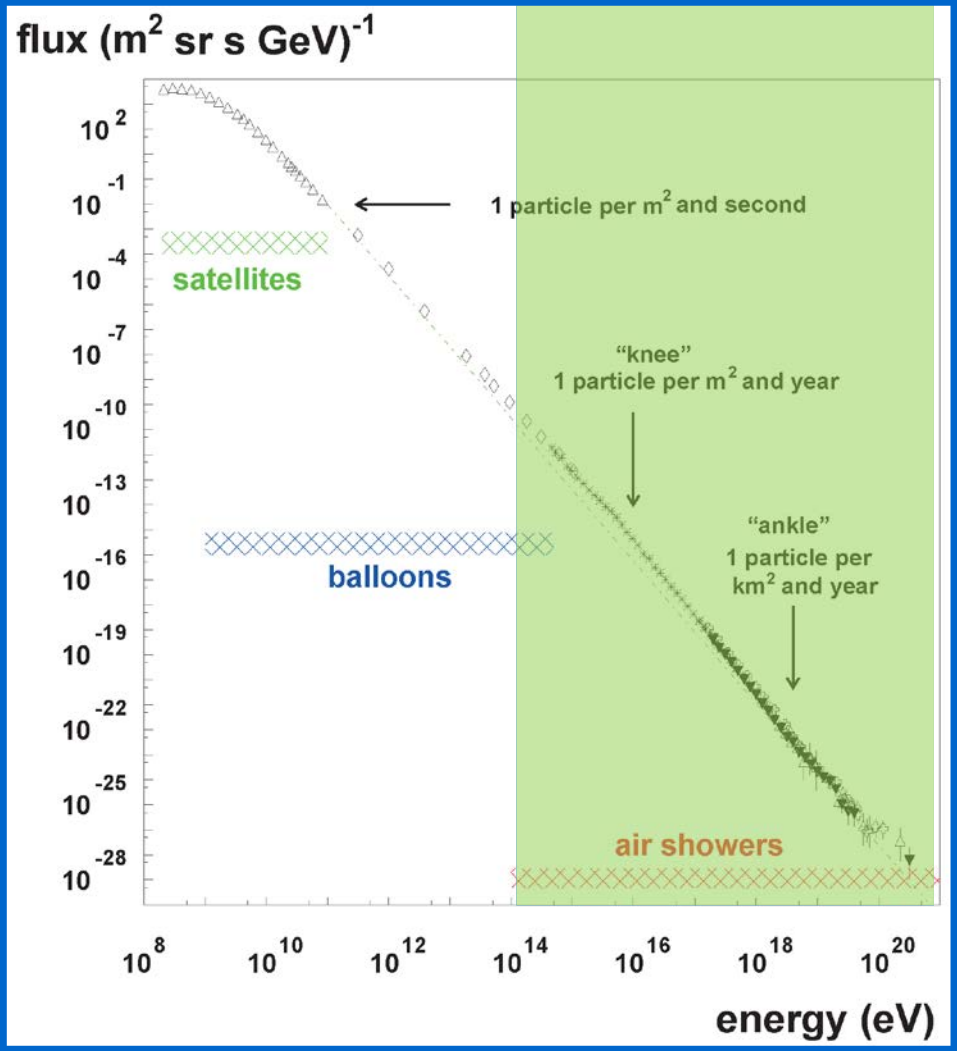


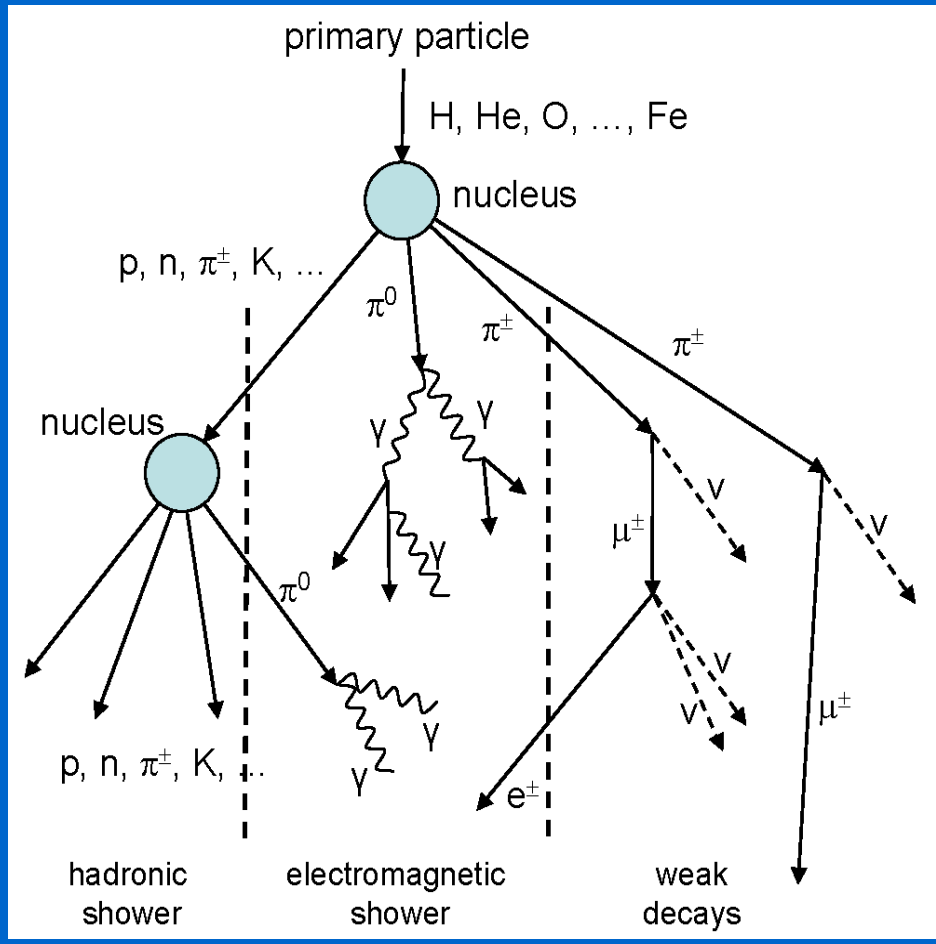
Where and how are the highest energies produced???

What is the elemental composition?

Galactic and/or extragalactic?

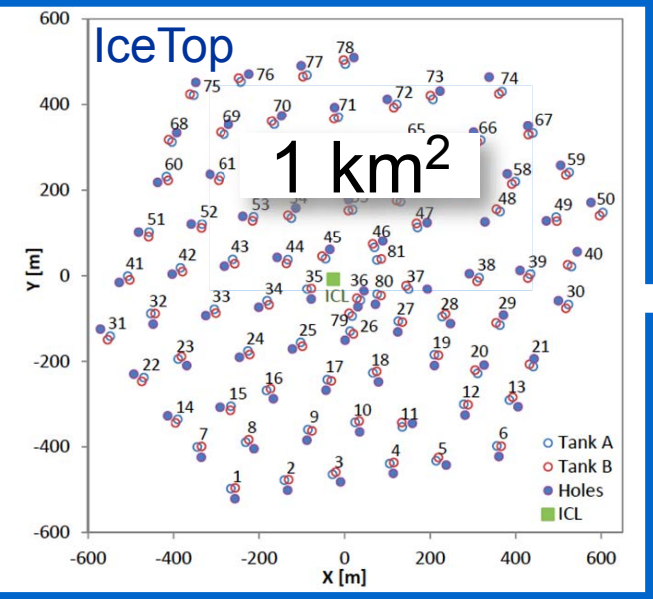
Extensive Air Showers

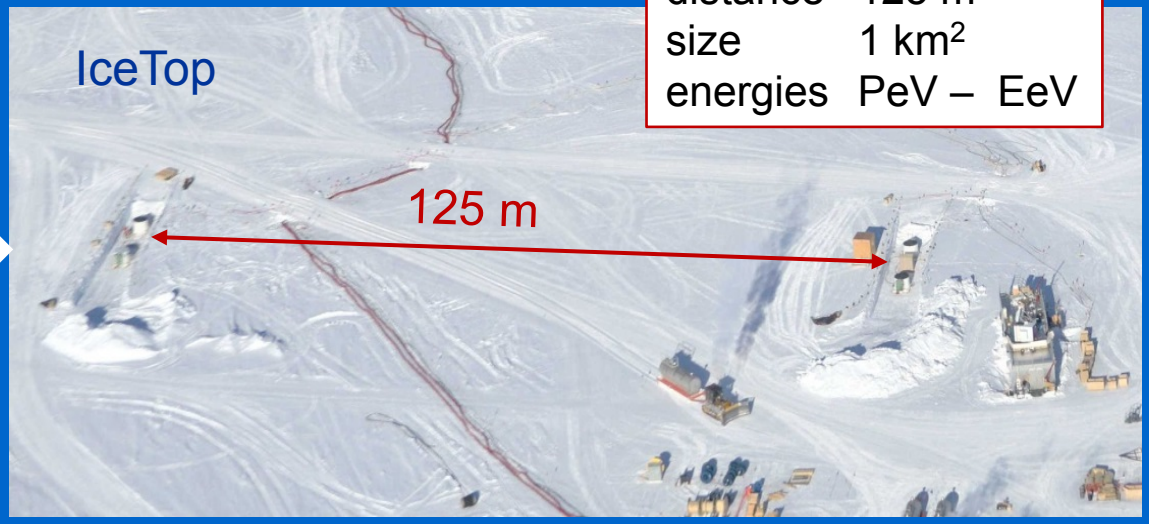




Use the atmosphere as calorimeter

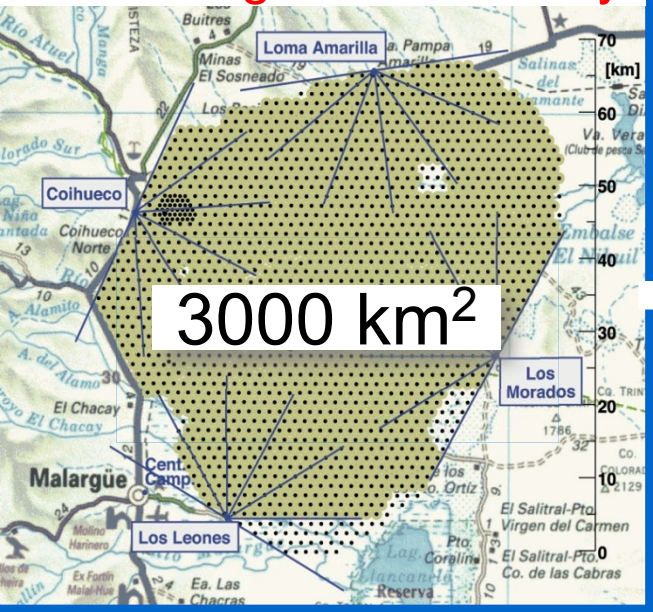
Air Shower Detectors

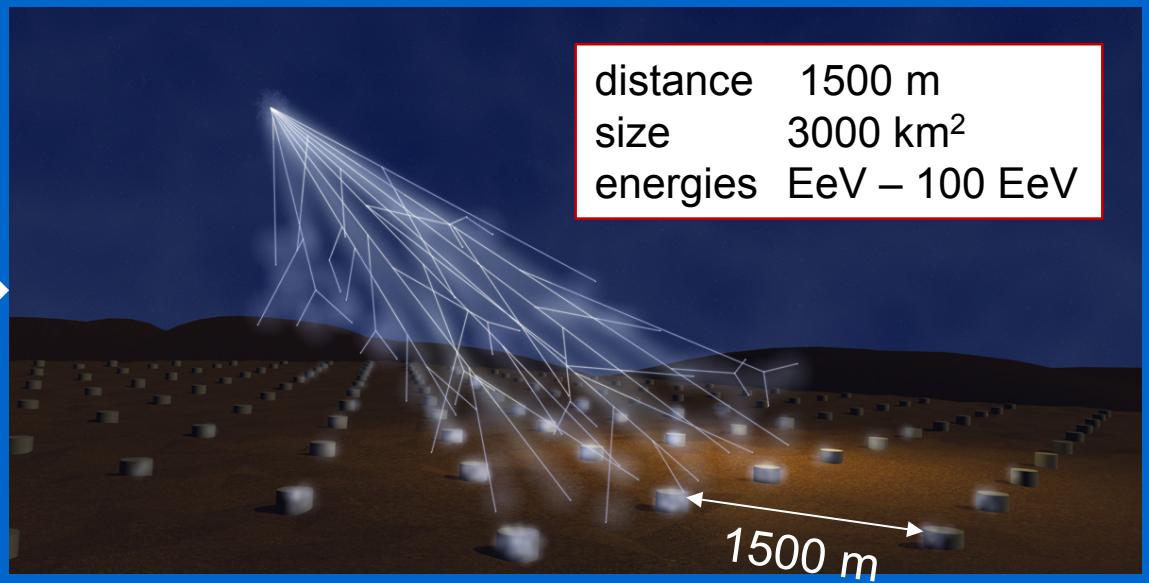




distance 125 m
size 1 km²
energies PeV – EeV

Pierre Auger Observatory

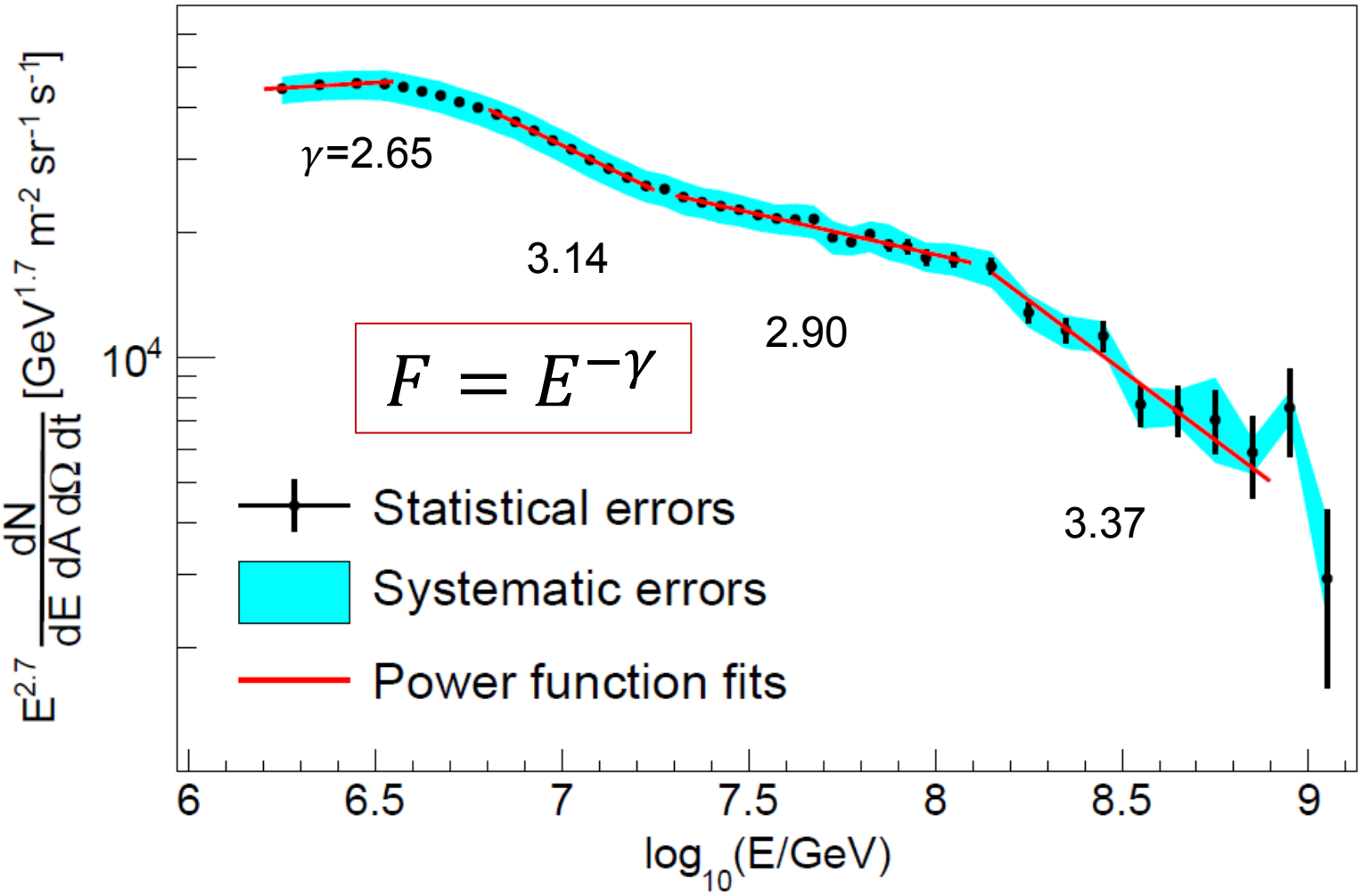




distance 1500 m
size 3000 km²
energies EeV – 100 EeV

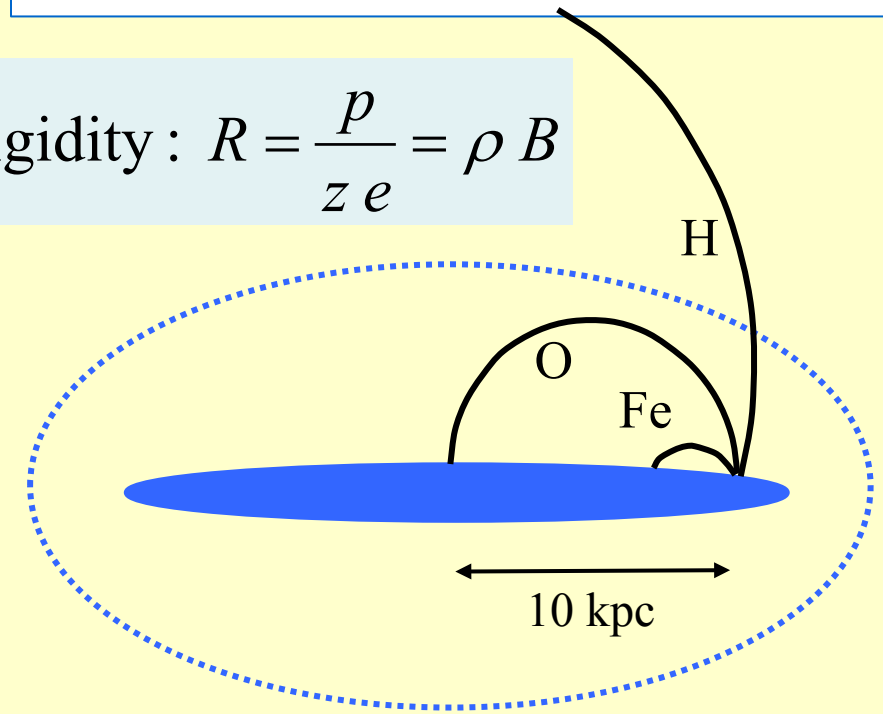
PeV to EeV

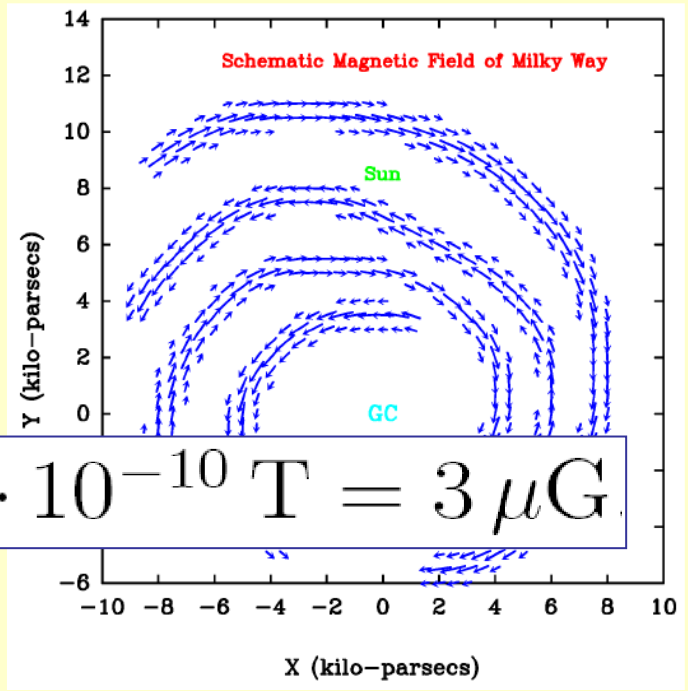
The fine structure in the spectrum
M.G. Aartsen et al, Physical Review D88 (2013) 042004!



Confinement in the Galaxy

$$\text{Rigidity}: \; R = \frac{p}{z\,e} = \rho\, B$$





$$3 \cdot 10^{-10}\,\mathrm{T} = 3\,\mu\mathrm{G}$$

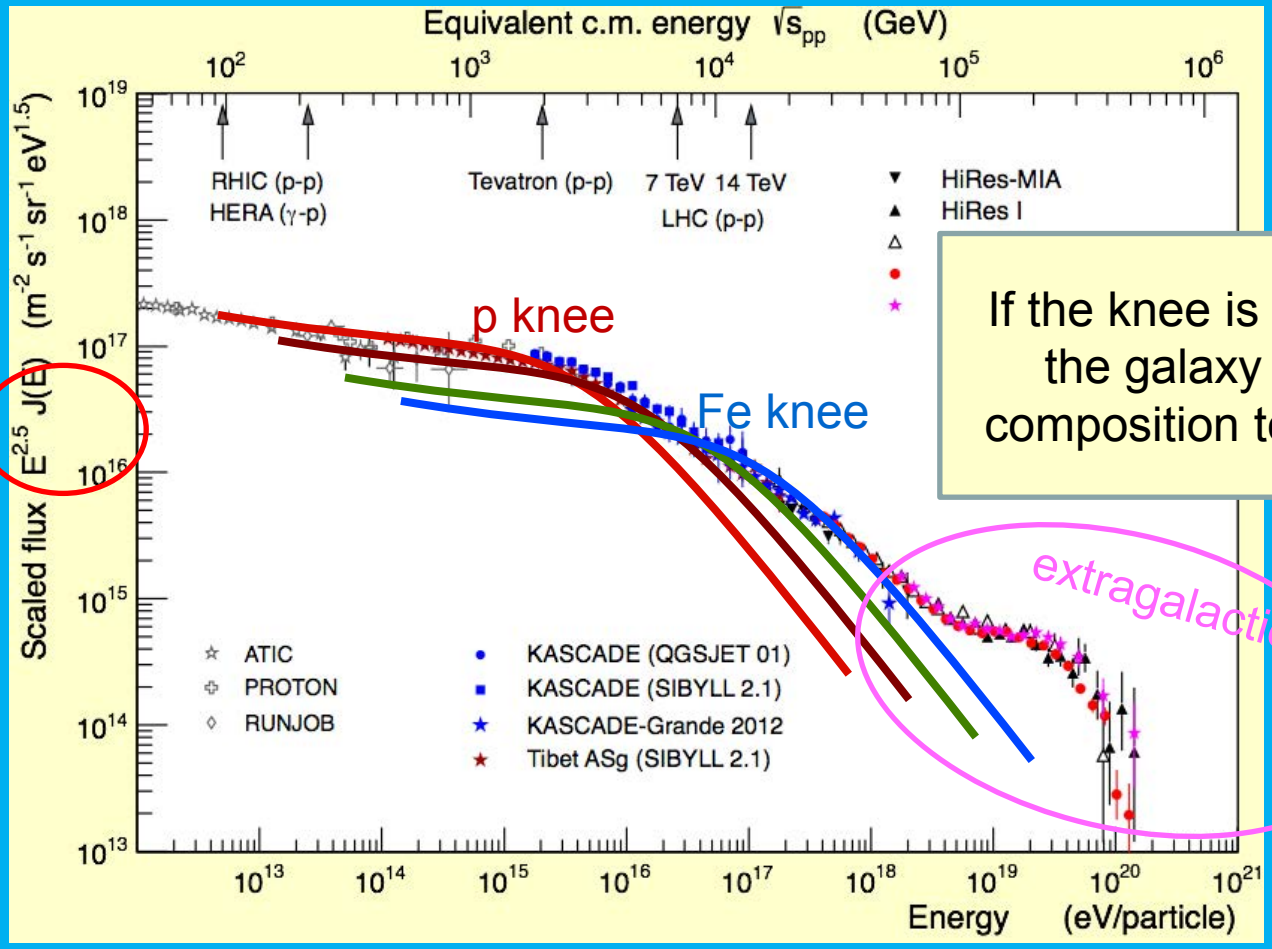
$$E_{max} \sim Z \;\Rightarrow\; E_{max}(\mathrm{Fe}) \approx 26\, E_{max}(\mathrm{H})$$

CR in galaxy: mean lifetime 10^7 years

Energy has to be refueled.

Where, how?

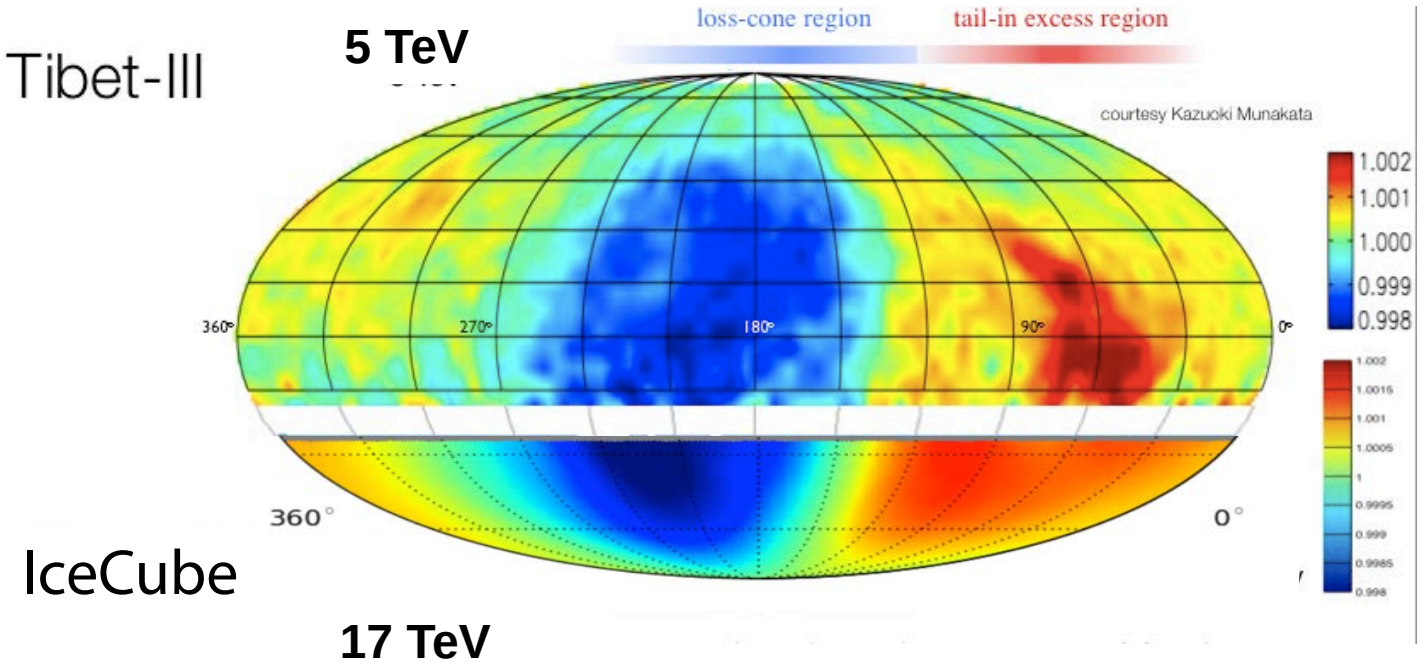
Origin and Physics of the knee(s)



If the knee is due to the diffusion out of the galaxy we expect a change in composition towards heavier elements

spectrum below the knee: well known by direct measurements; above the knee: indirect measurements via air showers, difficult

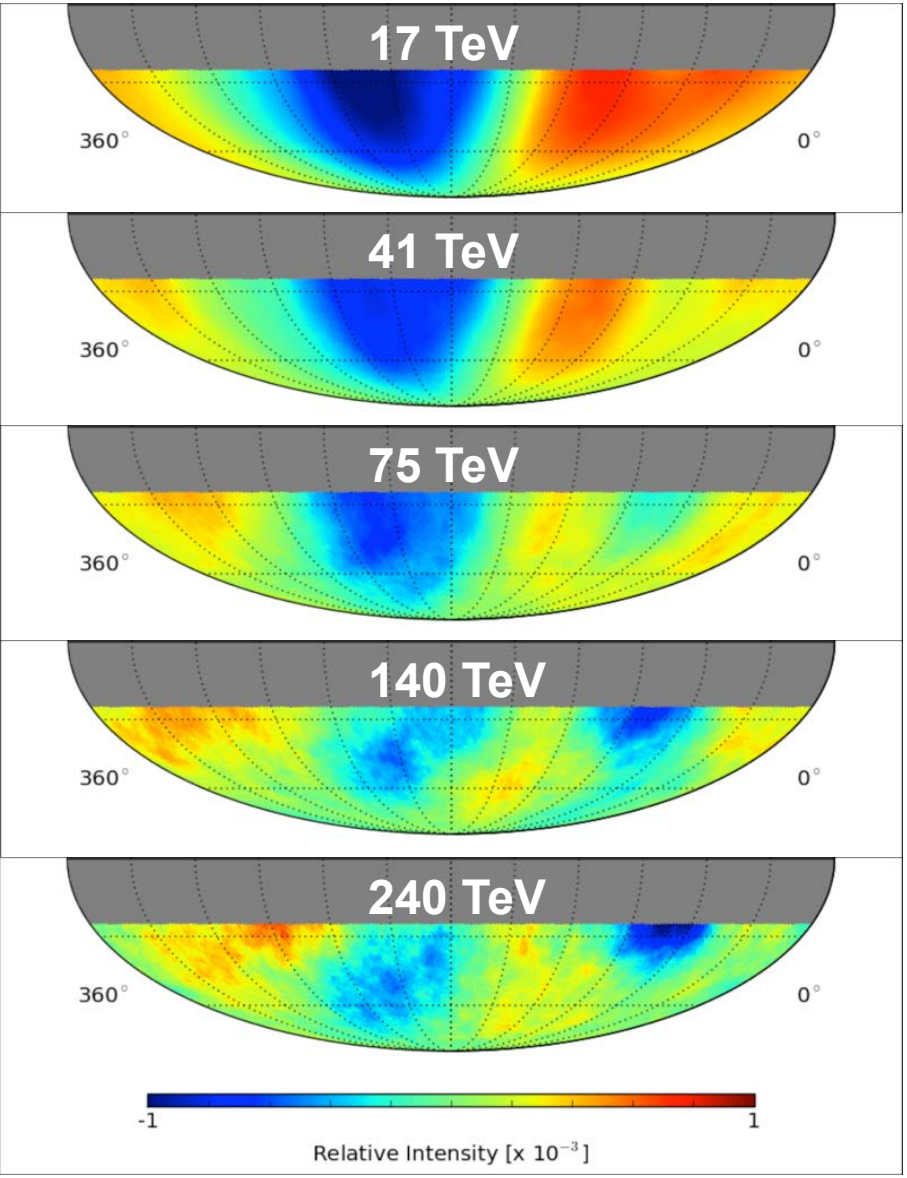
Cosmic Ray Anisotropy

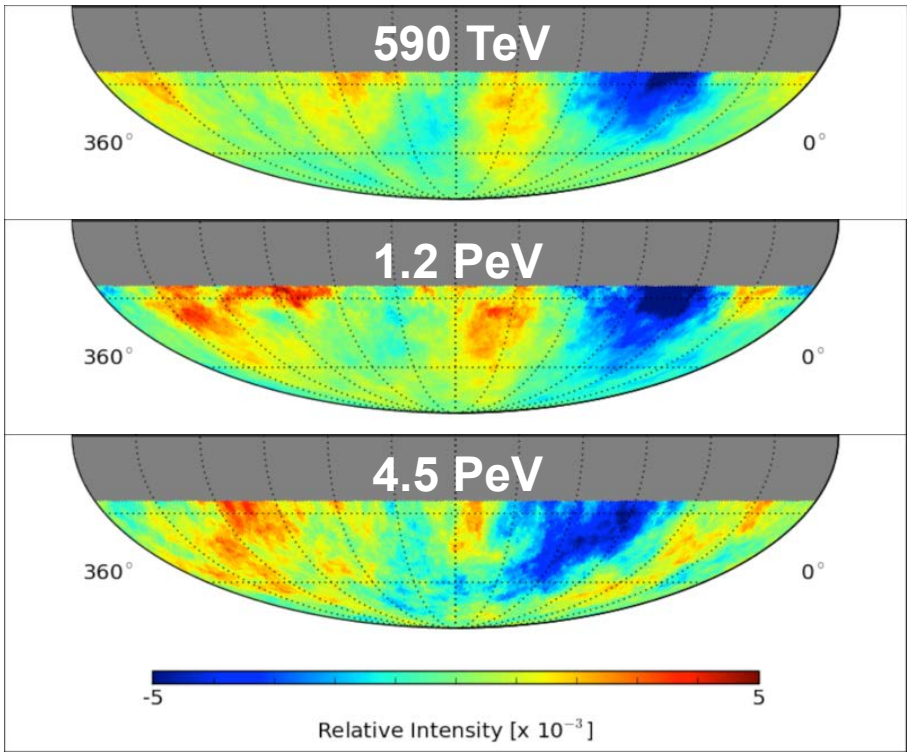


The orientation of the dipole moment does **not** correspond to the relative motion (~200 km/s) in the Galaxy (Compton-Getting effect)

Diffusive transport in galactic magnetic field from nearby sources?

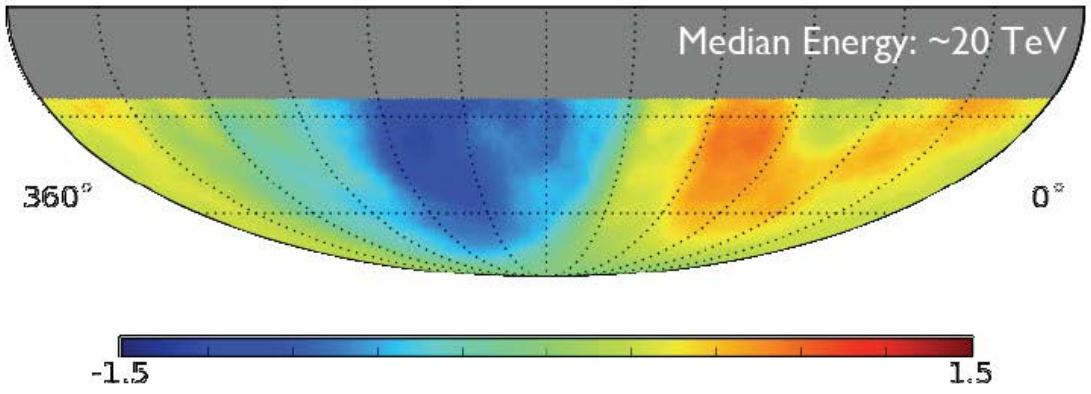
Energy Dependence of CR Anisotropy



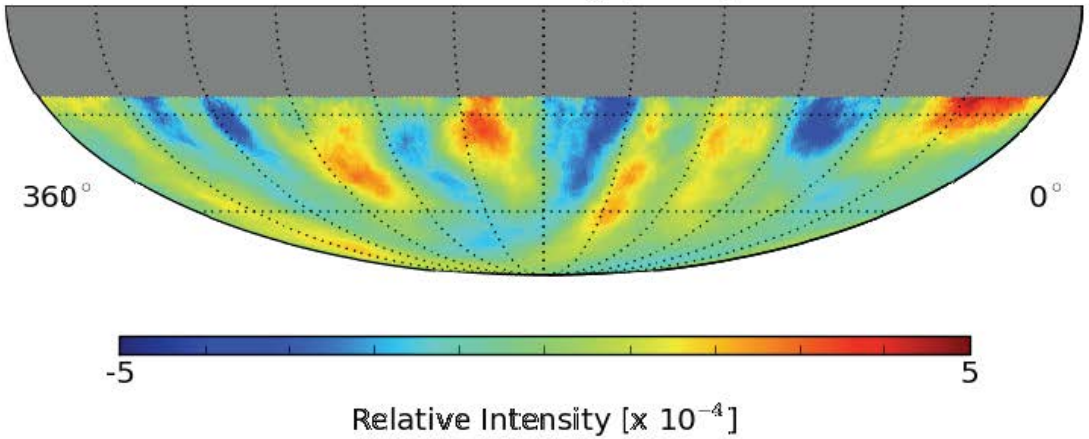


- Anisotropy changes in position, size
- Above 400 TeV there's indication of an increase in strength.

Large and Small Scale Anisotropies



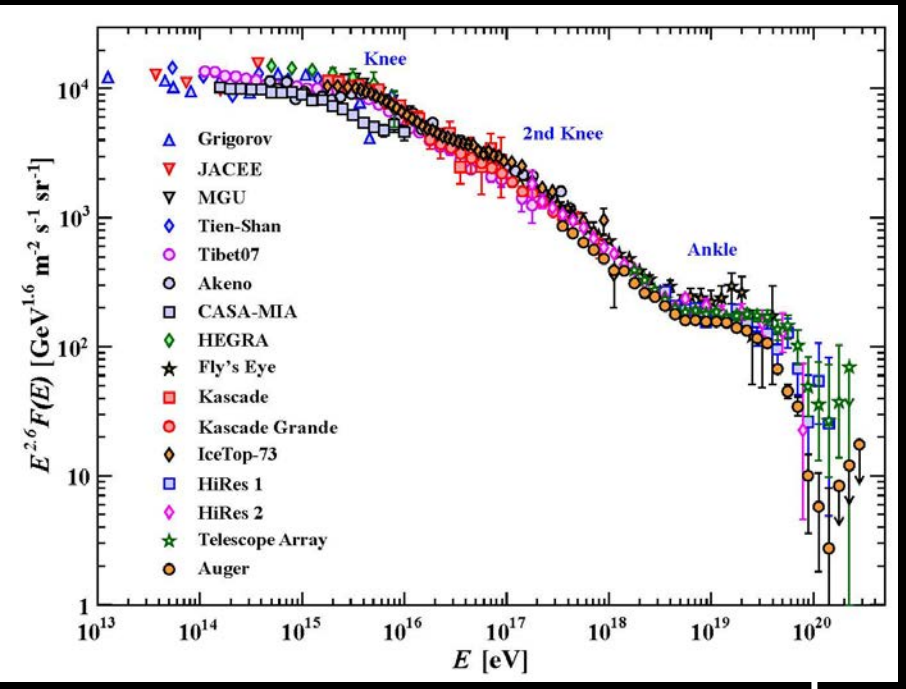
- Relative Intensity
- 5° smoothing



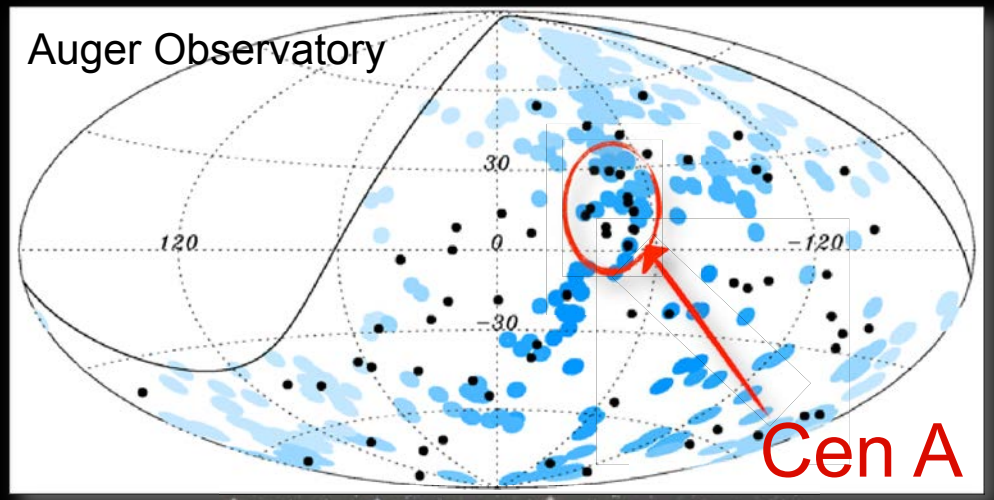
- Dipole/quadrupole fit residual map
- Relative Intensity
- 5° smoothing

diffusive transport from nearby sources?
observed small scale (10°) structures ⇒ few pc distance

UHECR Results



cut-off at 10^{20} eV
definitely observed



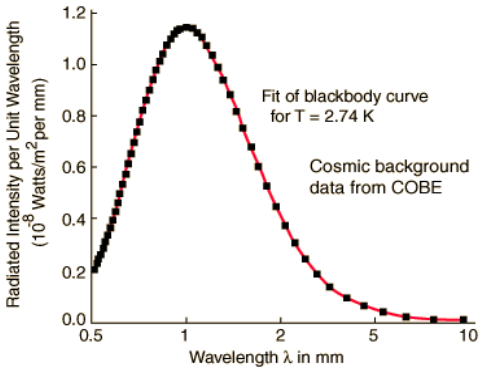
direction correlation with AGN?

GZK or source power limited?

(GZK = Greisen-Zatsepin-Kuzmin)

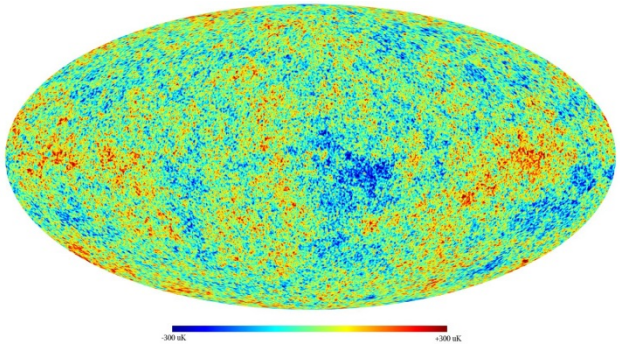
28/84 = 33%
isotropic background = 21%
→ <1 % chance probability

Cosmic Rays, CMB Photons and Neutrinos



Cosmic Microwave Background (CMB):

perfect blackbody at 2.74 K



Greisen-Kuzmin-Zatsepin (GZK) Cut-Off

$$\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} \rightarrow n\,\mu\nu \\ p\,\pi^{0} \rightarrow p\,\gamma\gamma \end{matrix}$$

CMB 2.7 K $\rightarrow$ threshold $E_p \approx 4\times10^{19}$ eV

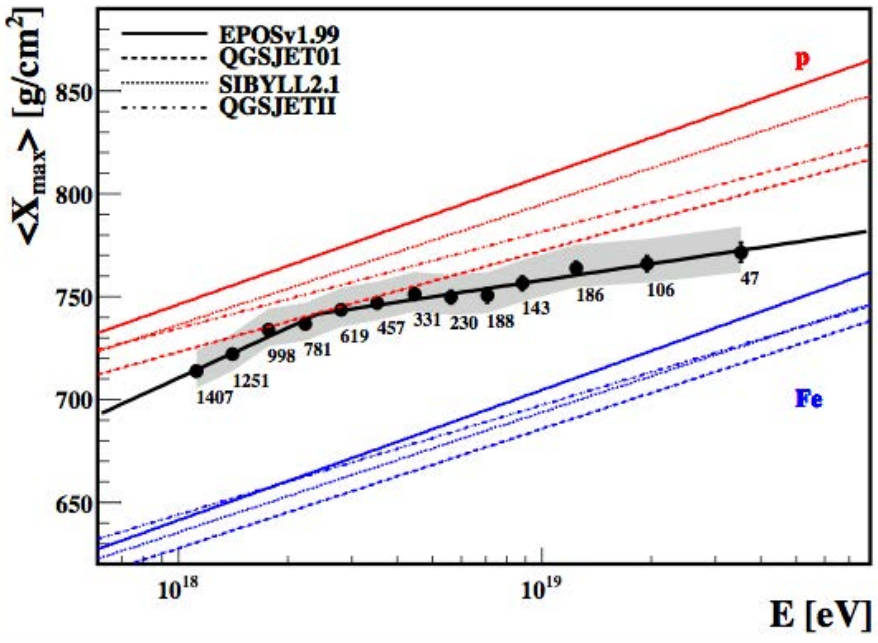
"GZK horizon" ~160 Mly

Nature of the Cutoff?

Is this the "GZK cutoff"?
Energy loss by collison with CMB photons?

Or do accelerators run out of steam?
⇒ composition becomes heavier → Fe

Auger: X_{max} with florescence detectors



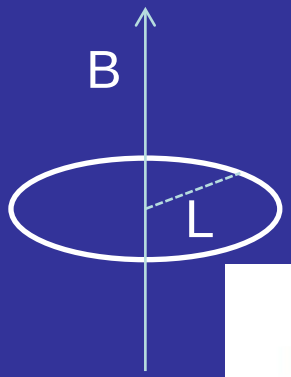
data suggest change of composition from light to heavy

Not GZK cutoff?

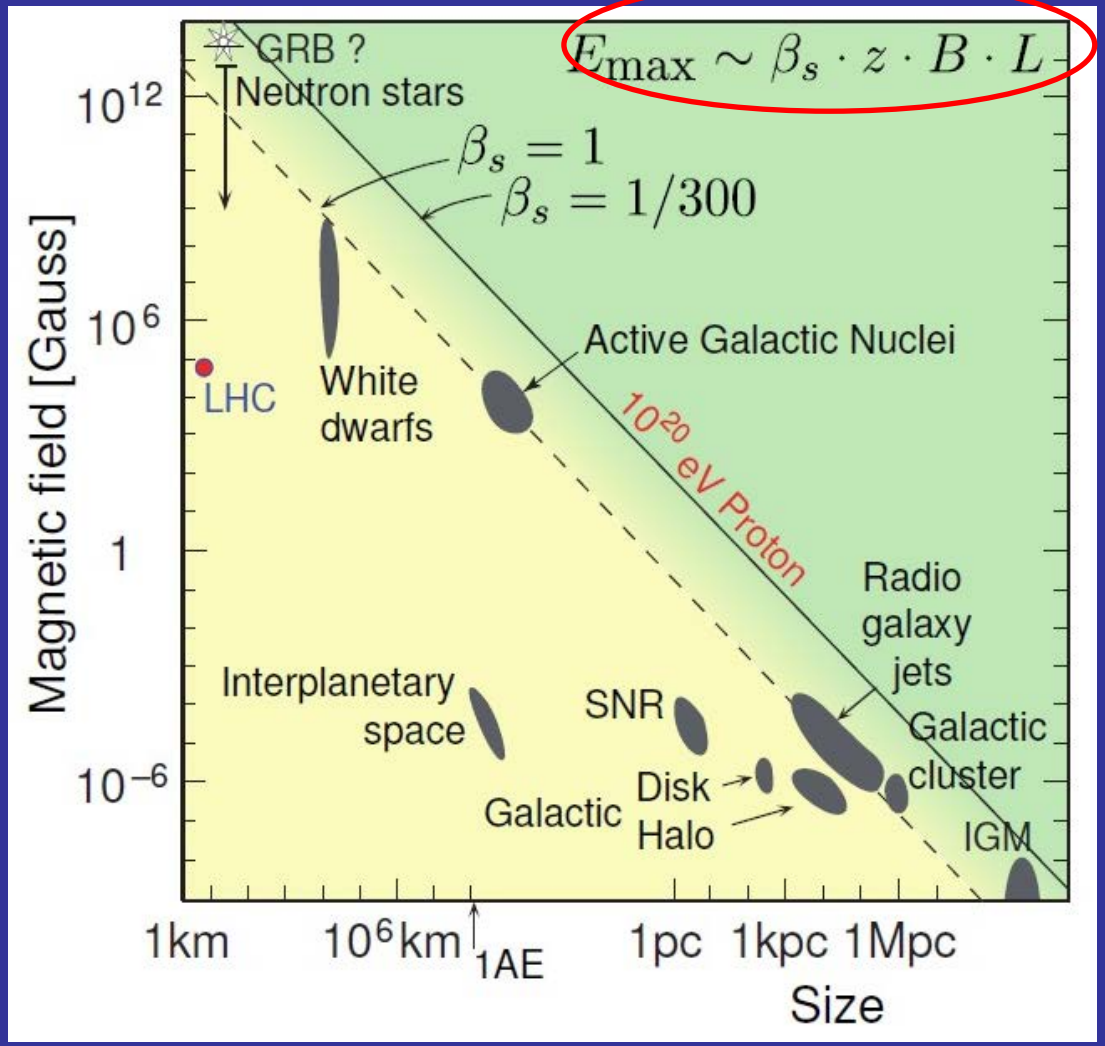
Clarification from other messengers?

Are there GZK neutrinos?

Where could particles possibly be accelerated? Hillas diagram

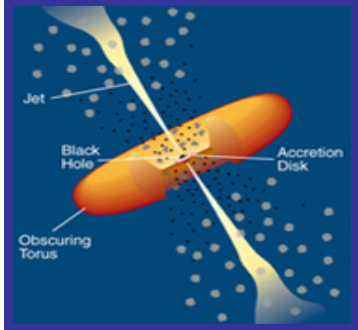


$E_{max} \approx 10^{18}$ eV z β_s (L / kpc) (B / μG)



supernova remnants (SNR)

gamma ray bursts (GRB)



active galactic nuclei (AGN)

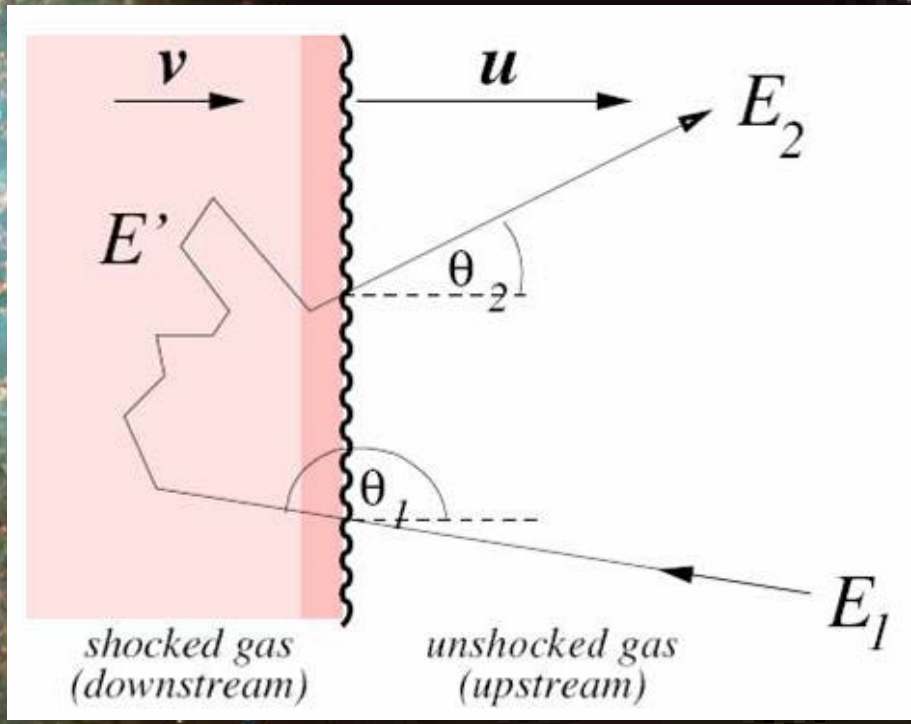
black holes

Cosmic Accelerators

Supernova Remnants (SNR)

Crab Nebula (explosion 1054)

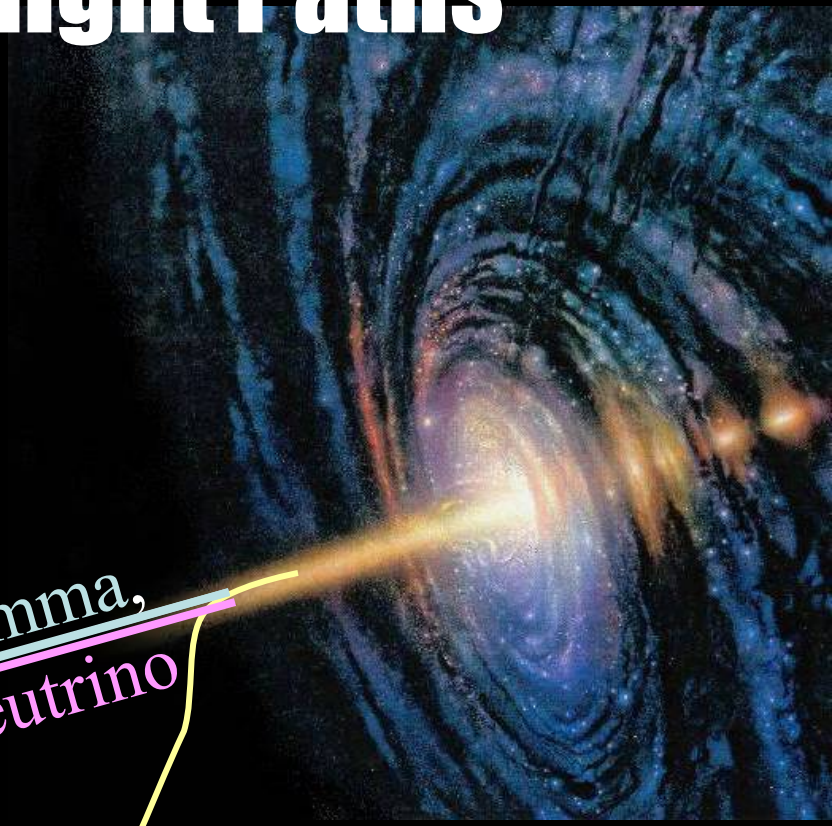
Fermi acceleration at shock front

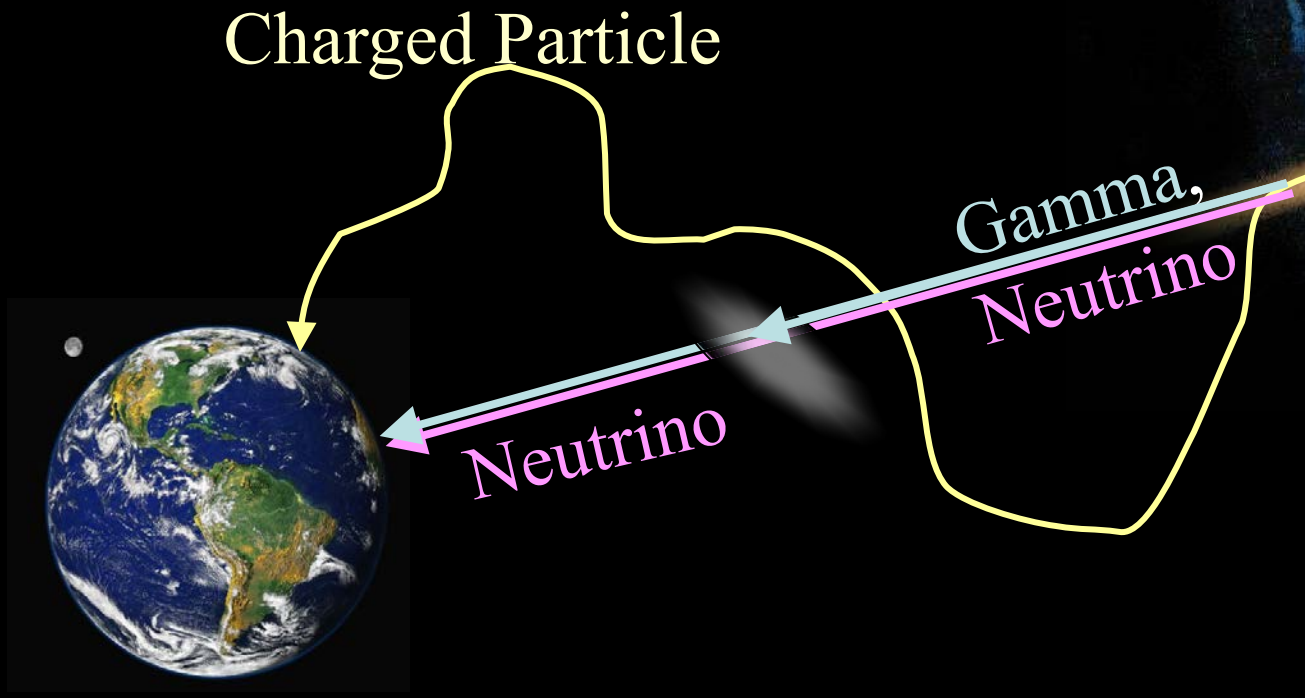


1 % of the energy of all SN explosions can explain energy density of cosmic rays in galaxy (~ 0.5 MeV/m^3)

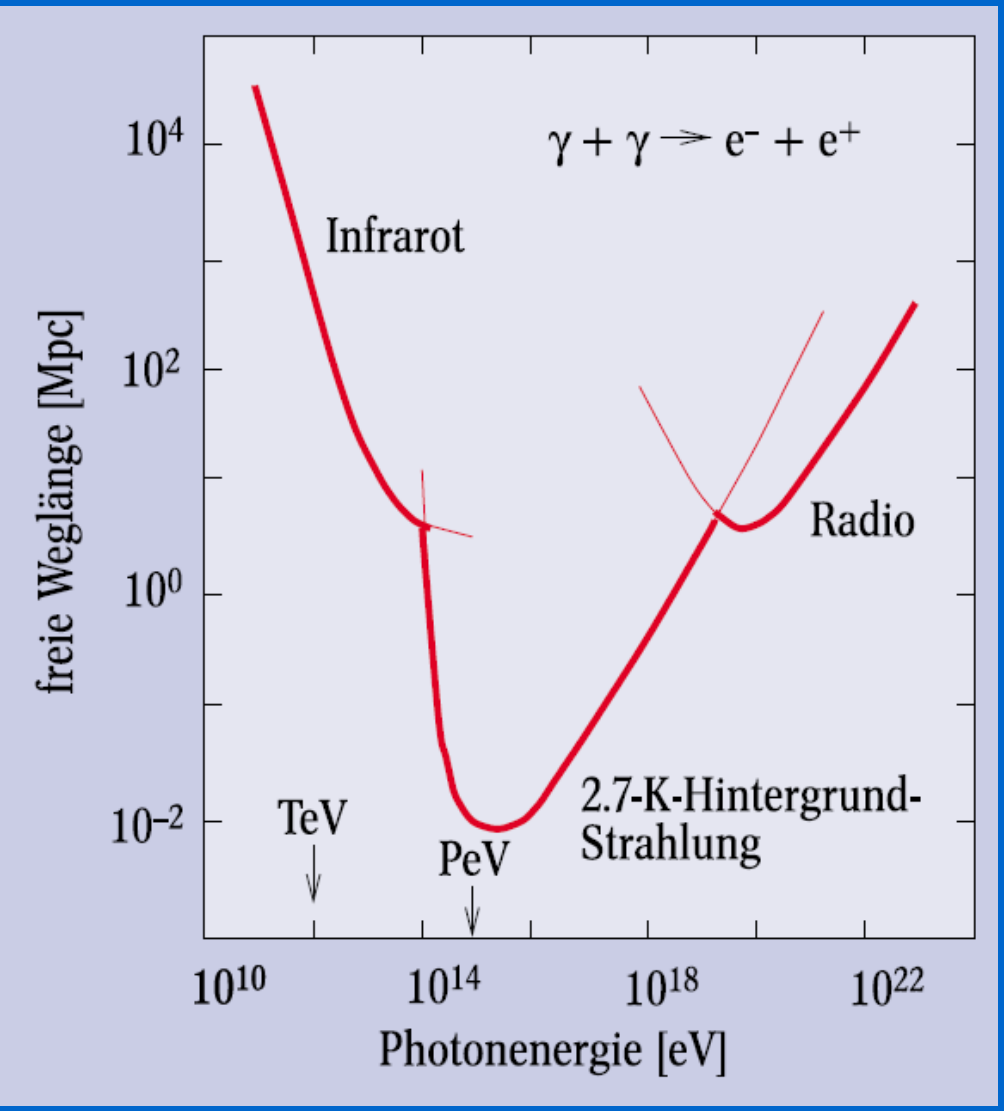
However: No SNR has been clearly pinned down as source

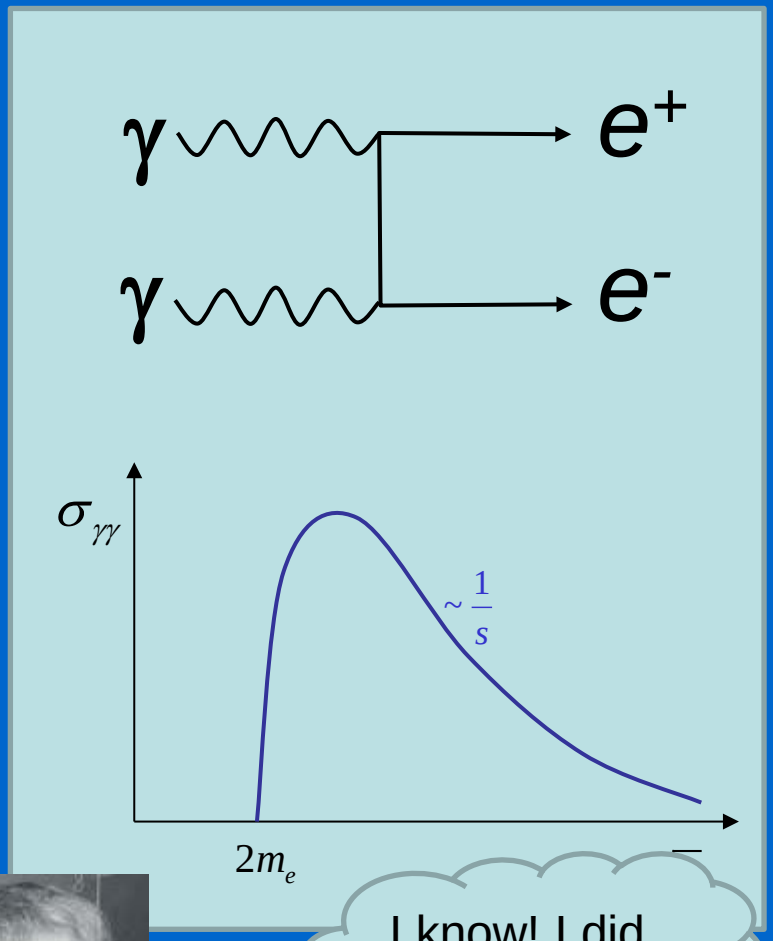
Twisted and Straight Paths





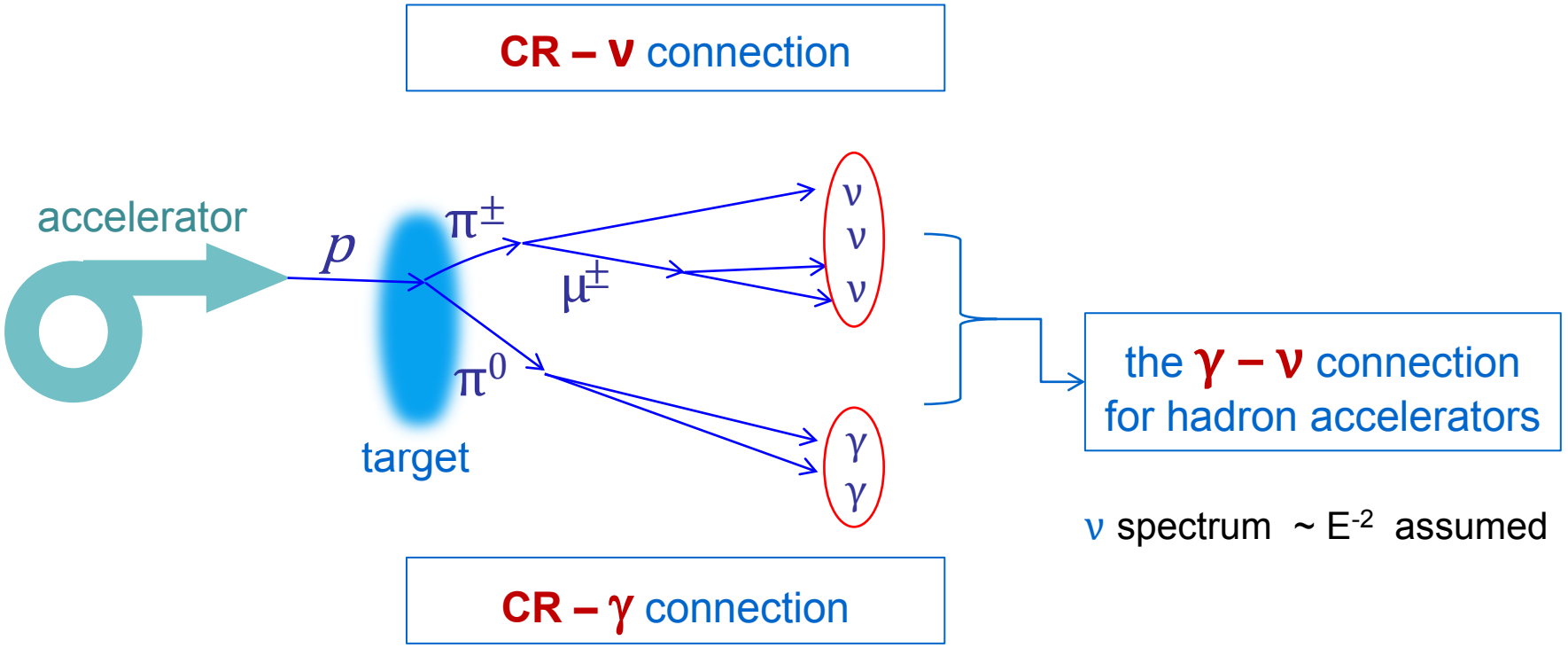
Absorption of γ's by γ γ -> e^+e^-



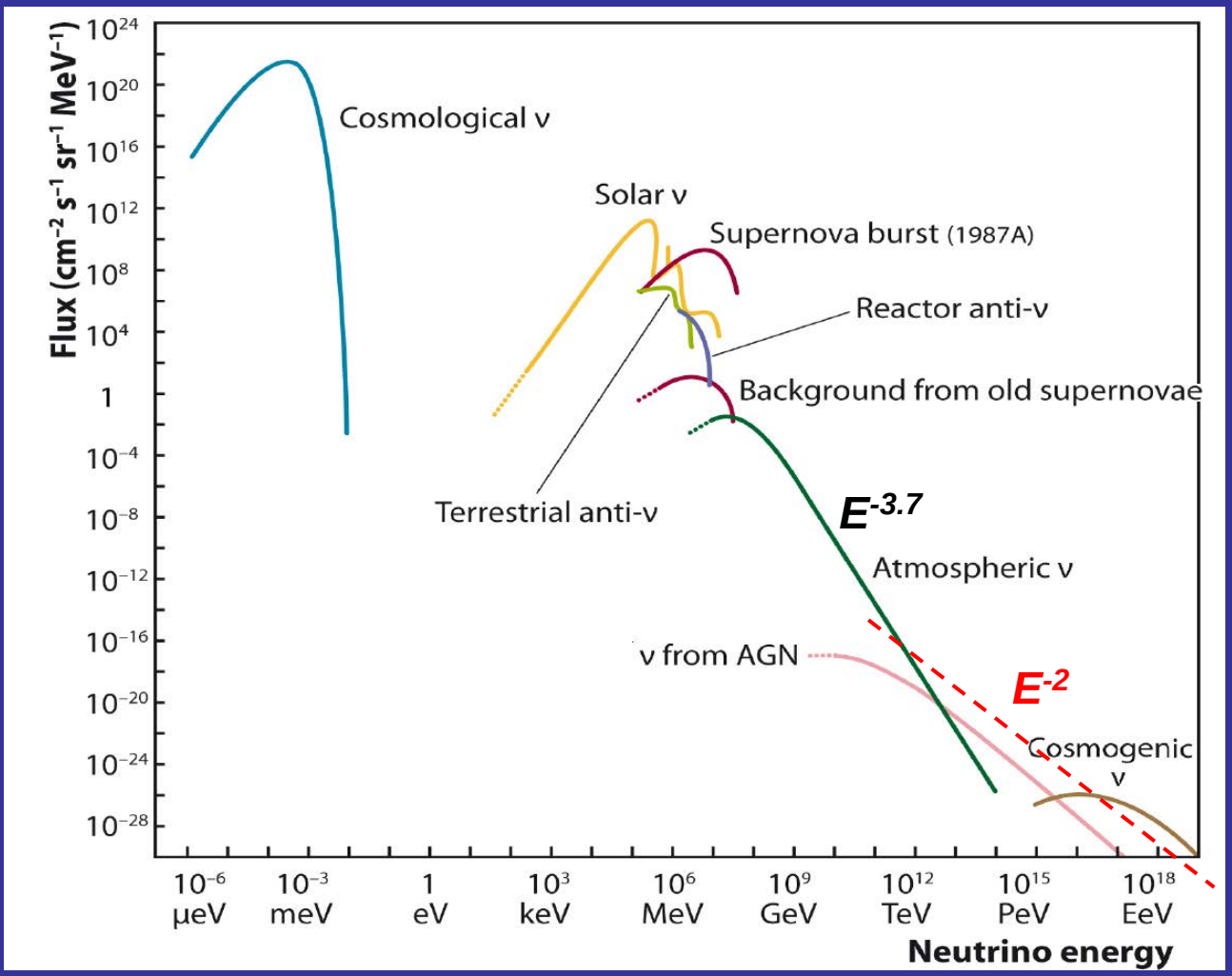


I know! I did
γ γ → *hadrons*

Cosmic Rays, Gammas and Neutrinos



Neutrino fluxes



Cosmic neutrinos should have a hard spectrum

$F \sim E^{-2}$

atmospheric ν

$F \sim E^{-3.7}$

How to detect cosmic high energy neutrinos?

quite difficult

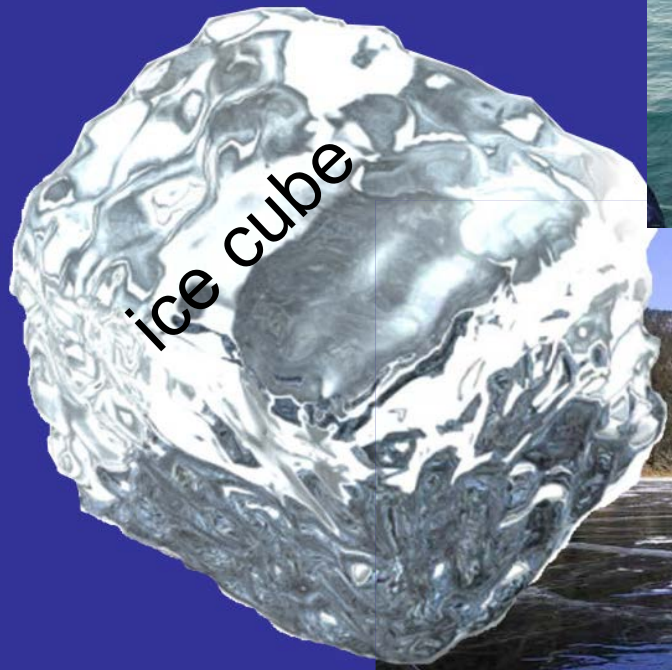
Absorption small → detection probability small

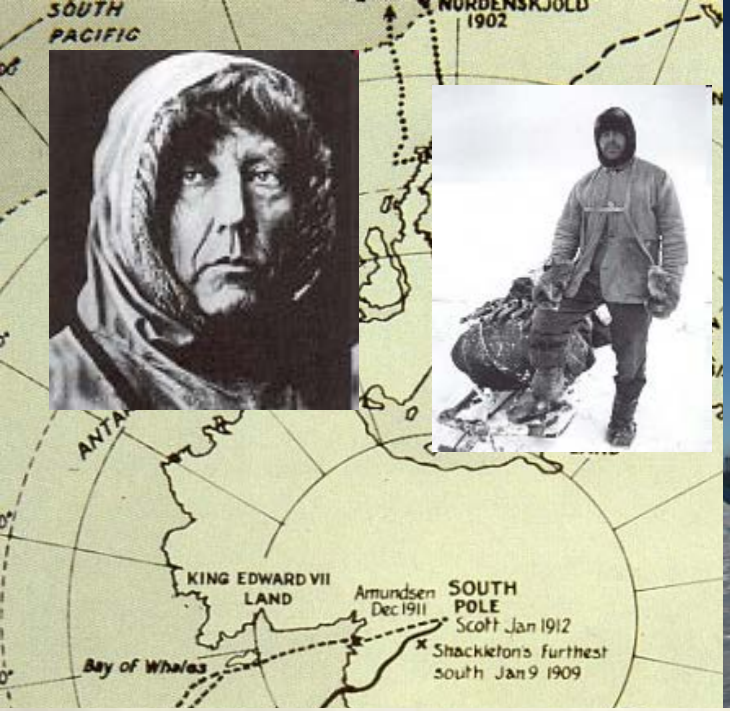
⇒ **large target volume**

Most efficient:
Cherenkov light from charged **ν** products

⇒ **transparent**

⇒ **water** or **ice**




SOUTH PACIFIC
NORDENSKJOLD 1902
KING EDWARD VII LAND
Amundsen Dec 1911
SOUTH POLE
Scott Jan 1912
Shackletons furthest south Jan 9 1909
Bay of Whales


GEOGRAPHIC SOUTH POLE
ROALD AMUNDSEN
ROBERT F. SCOTT

Approaching the Pole these Days

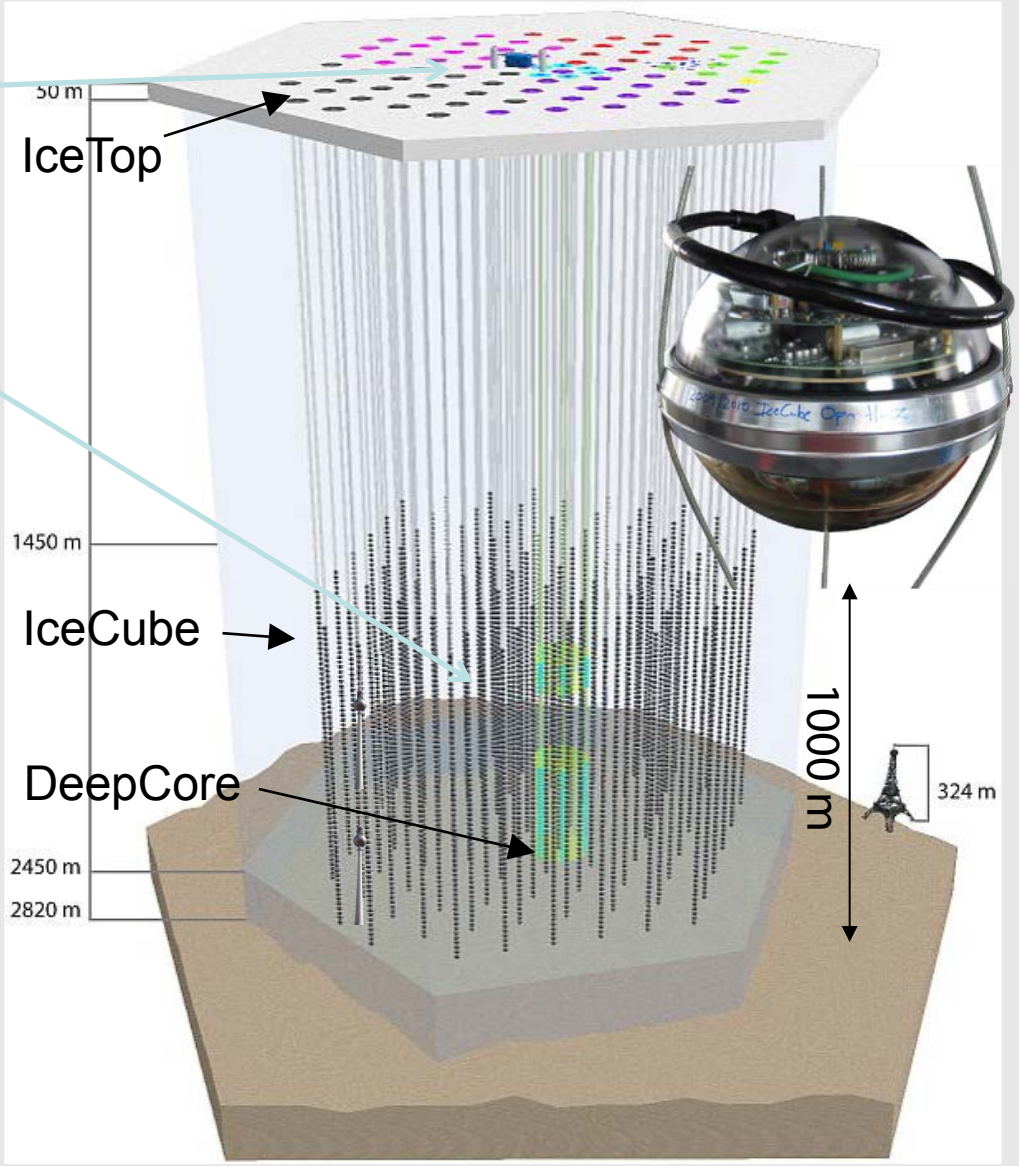
Arriving at Pole

IceCube Neutrino Observatory

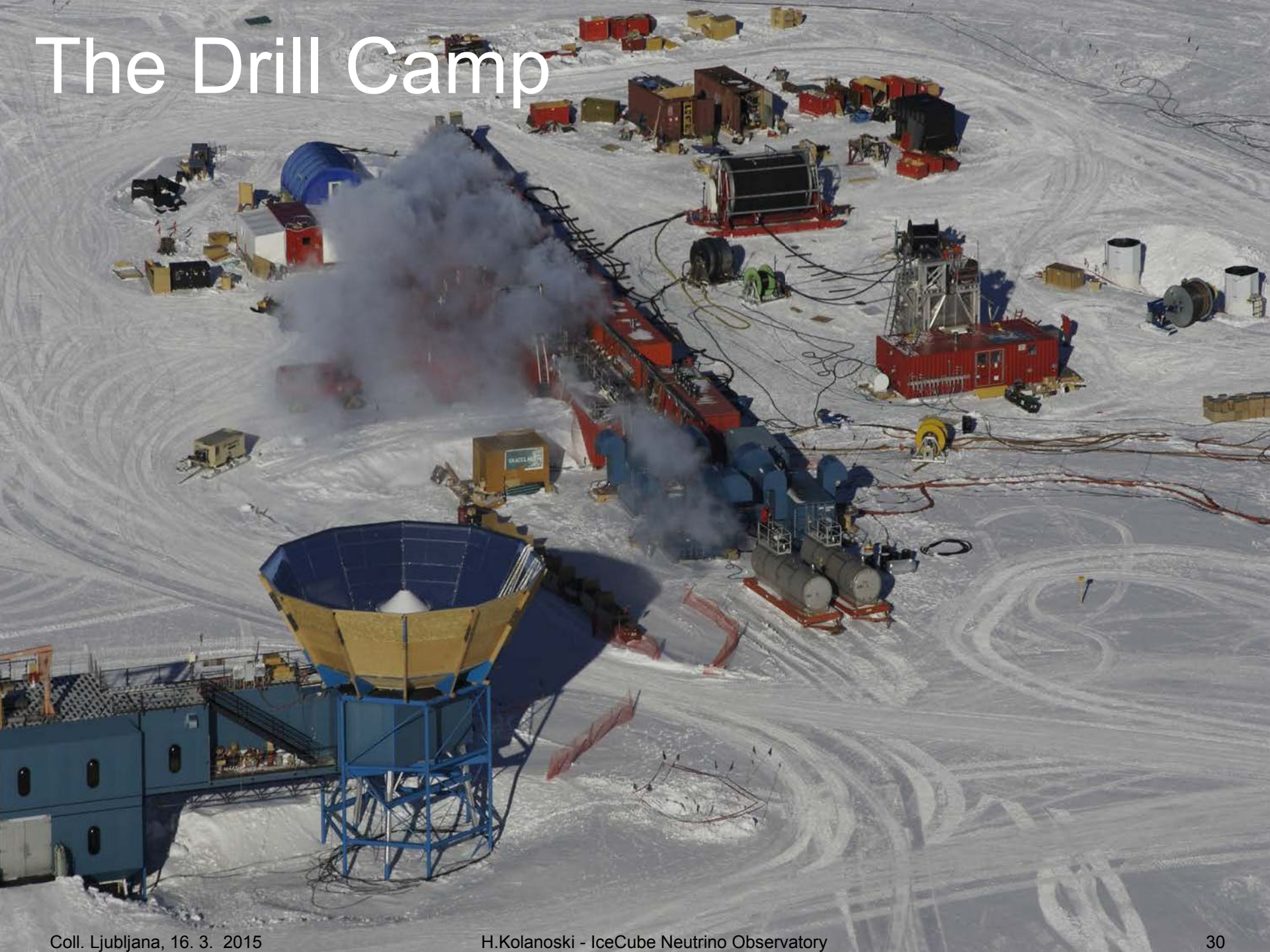
air shower array

neutrino telescope

- 86 Strings, 2450 m deep
- 5160 Optical Modules
- Instrumented: 1 km^3
- IceTop: 1 km^2
- Installation: 2005-2011



The Drill Camp



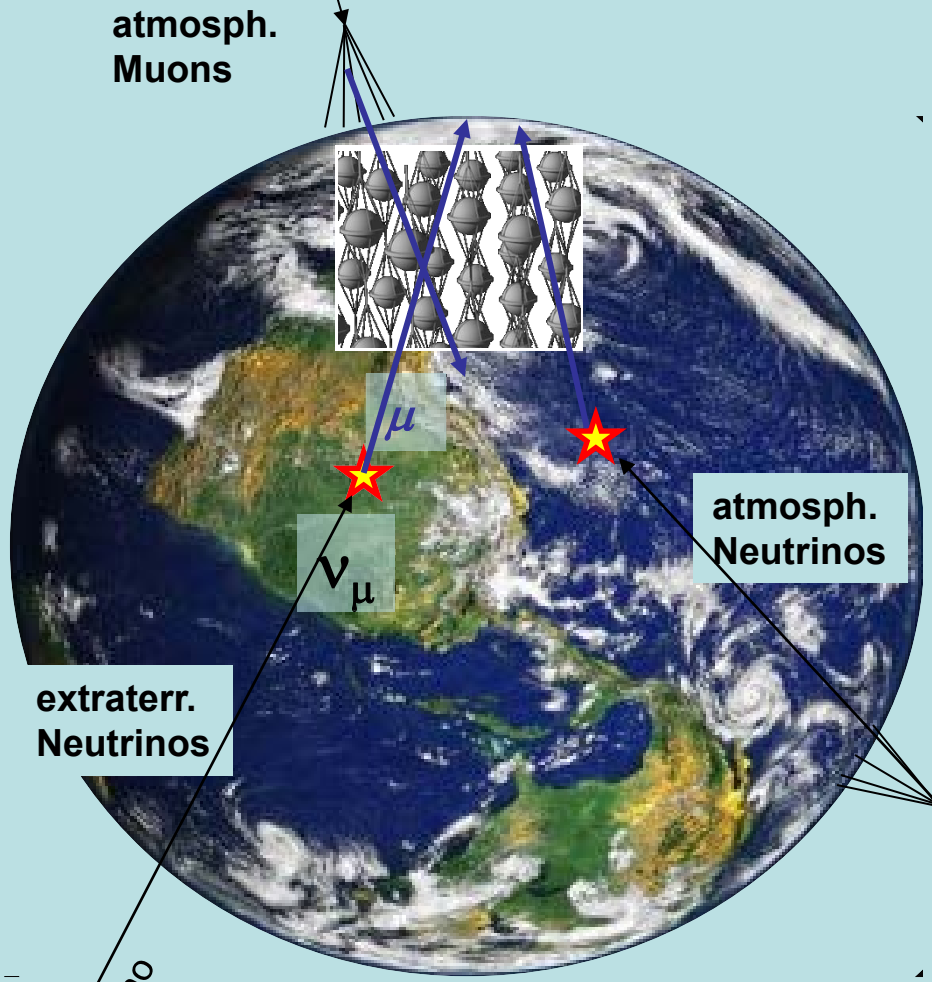

.... 2450 m deep


.. what you see
down there

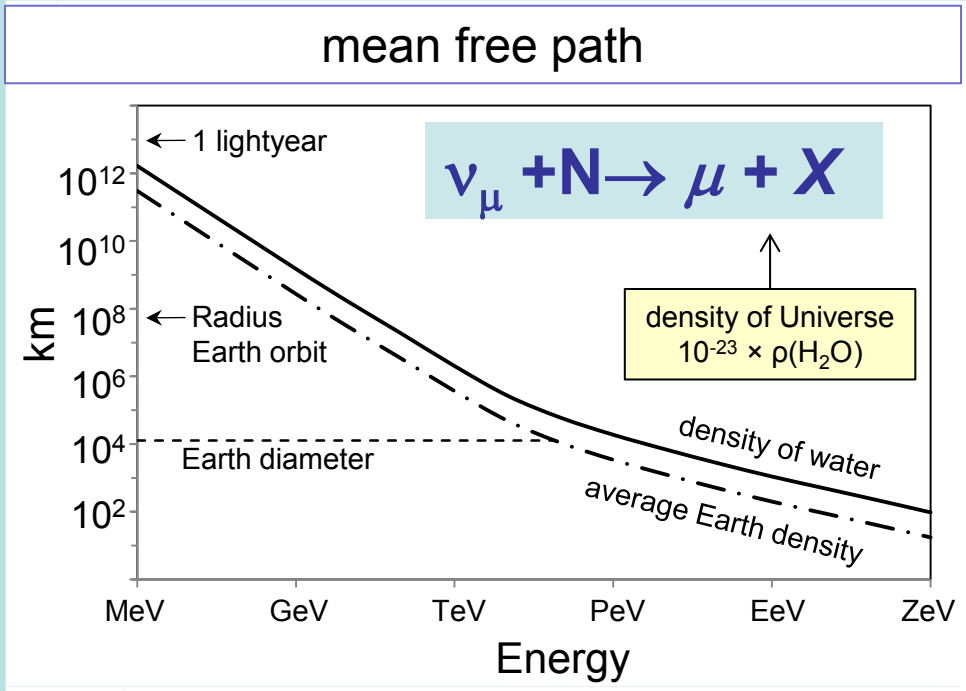
When the Season is over

The Last Flight at the End of the Season

Detection of High Energy Neutrinos



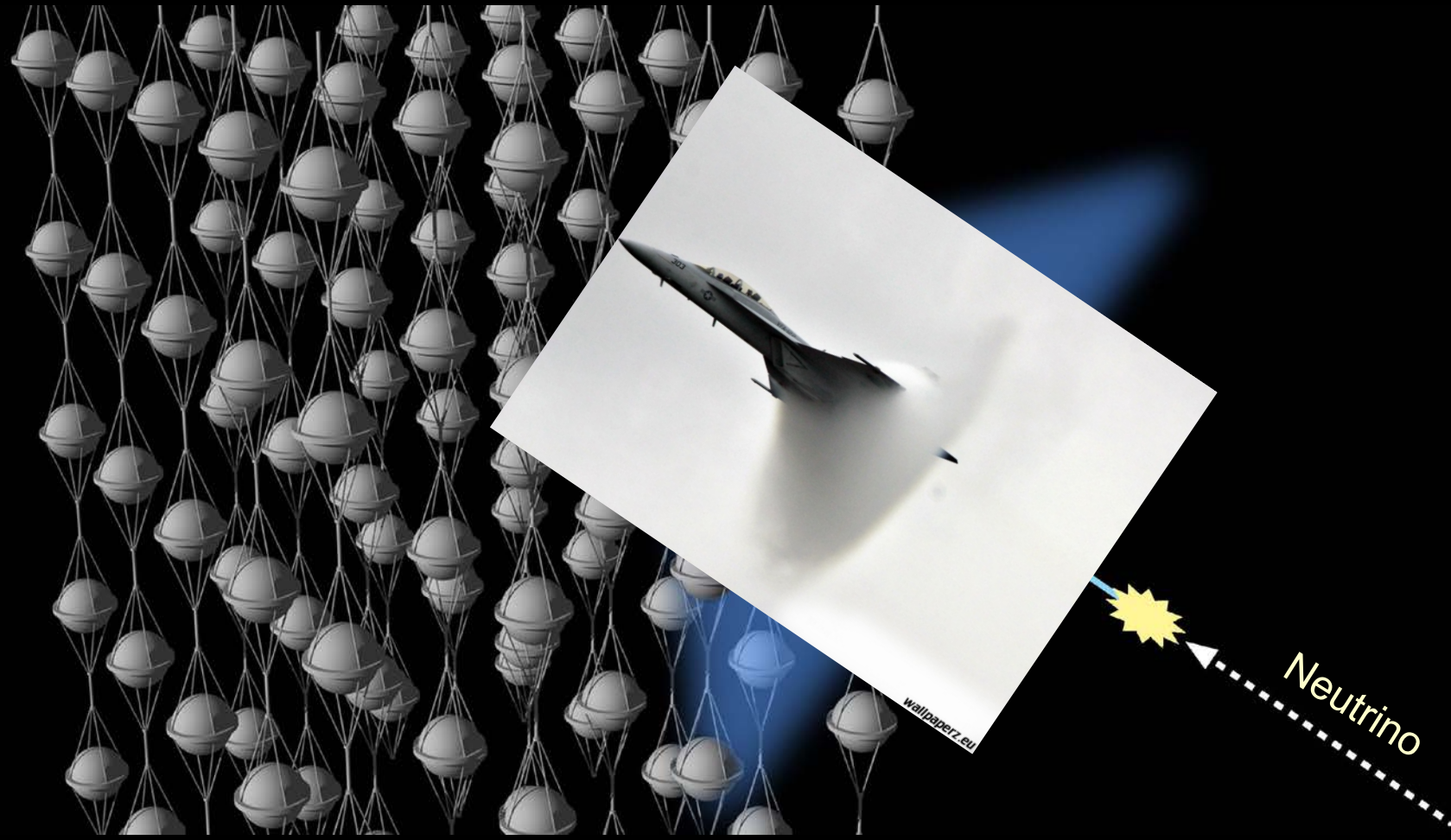
Earth as filter

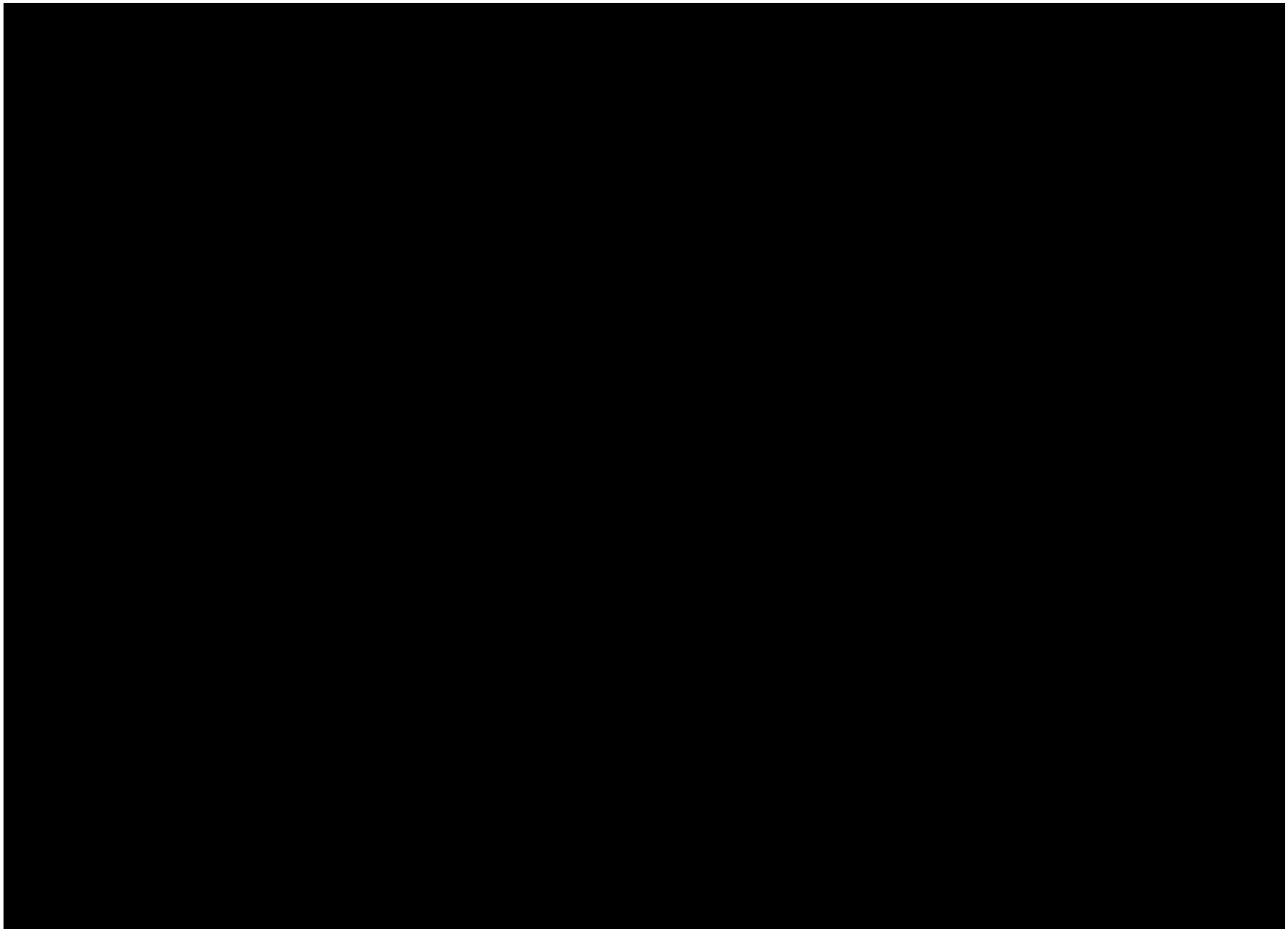


even for neutrinos the Earth becomes opaque above about 1 PeV

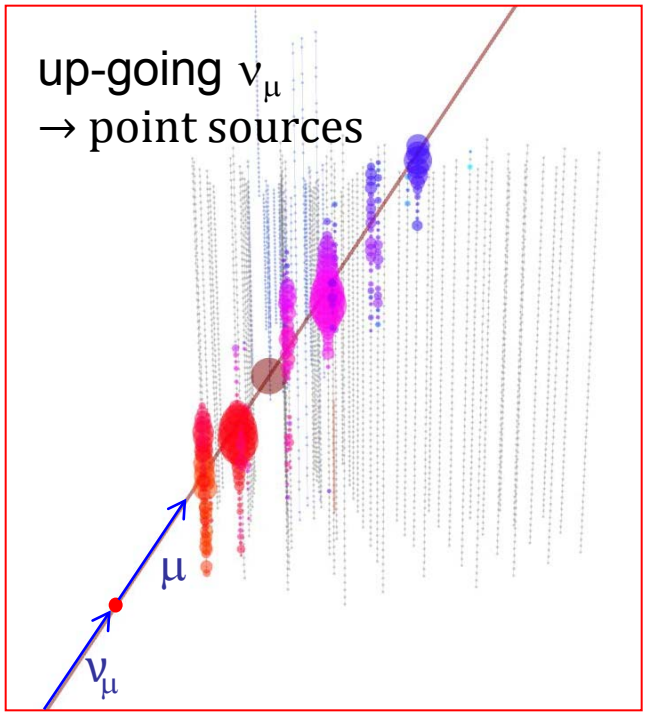
⇒ look **upward** – atm. background becomes less

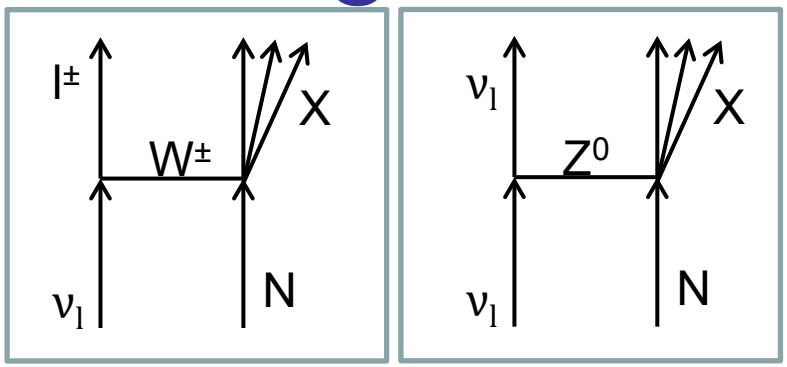
Detecting a Neutrino



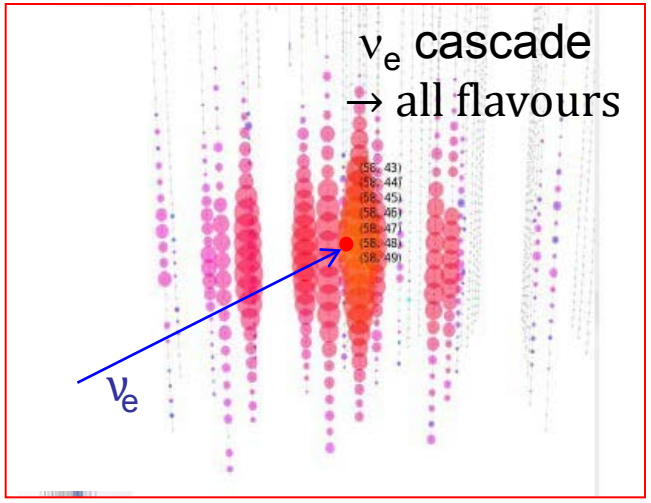


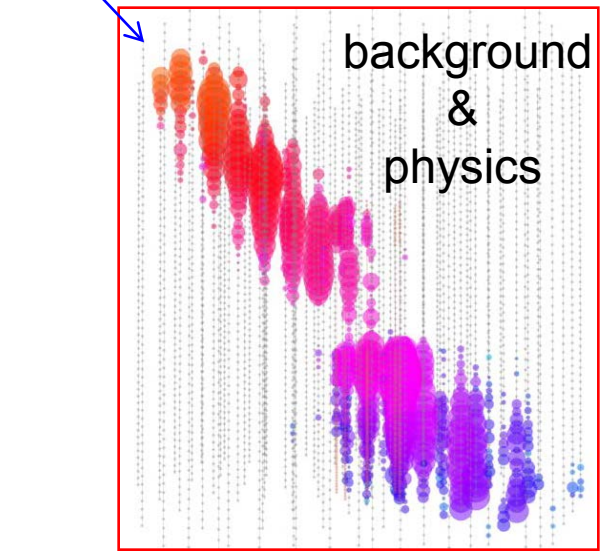
Particle Signatures

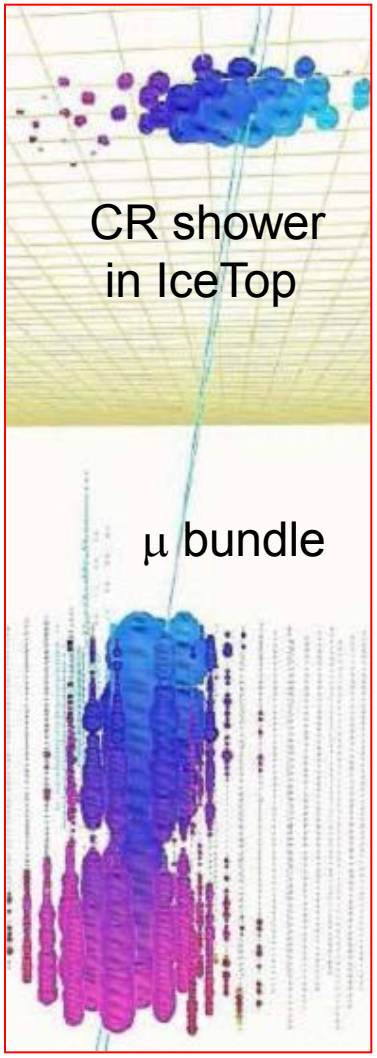




- muon tracks
- em + had. shower

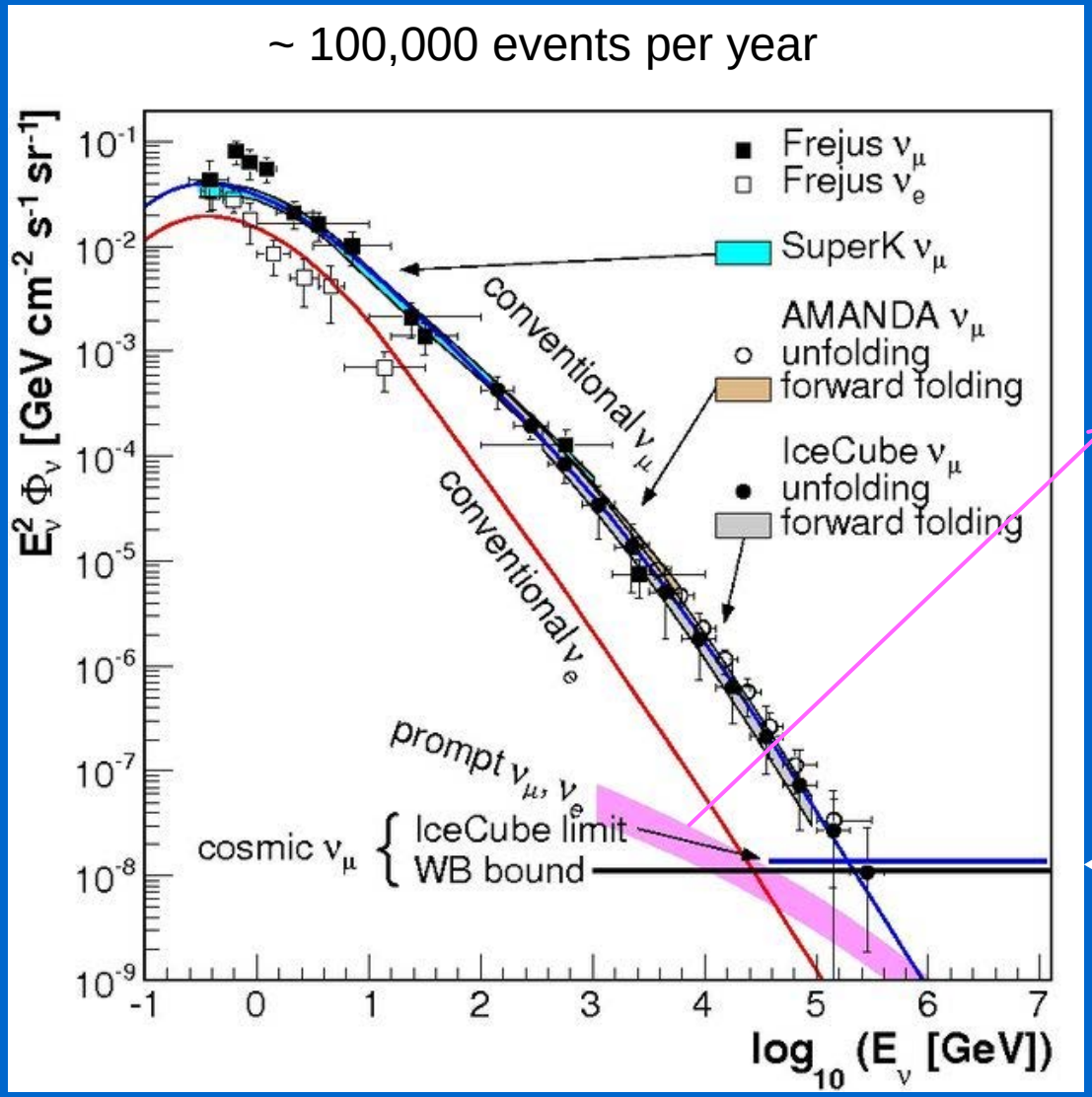






Search for Diffuse Astrophysical Neutrino Flux Background: Atmospheric Neutrinos

~ 100,000 events per year



"prompt" ν's:

from (semi-) leptonic decays of heavy hadrons (mainly charm).

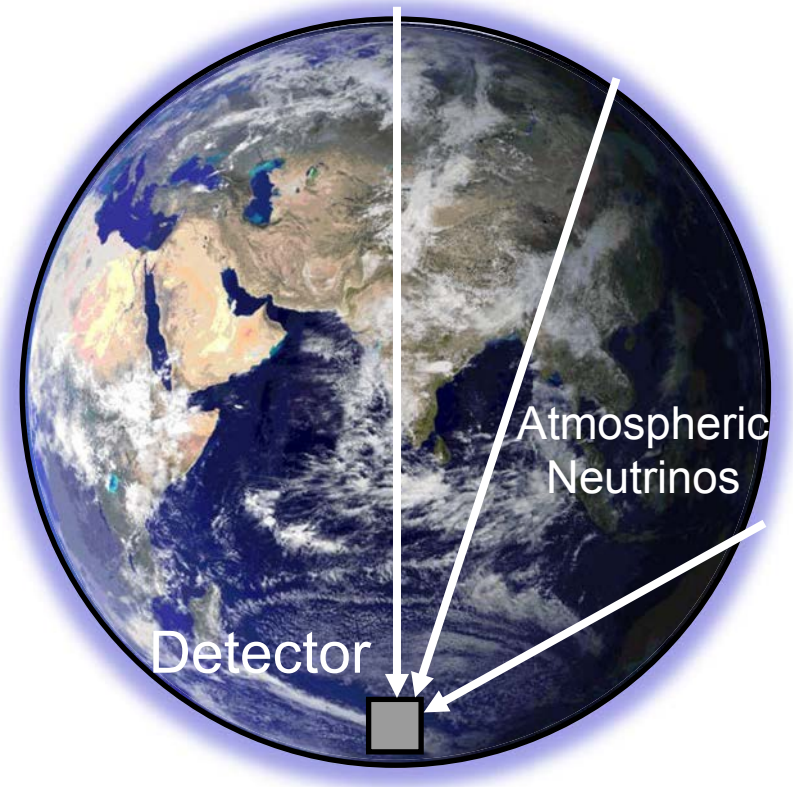
Flatter spectrum than "conventional" ν's
$\Rightarrow$ large uncertainty for astro-ν's

IceCube has now constrained to ~ ERS model (Enberg et al.)

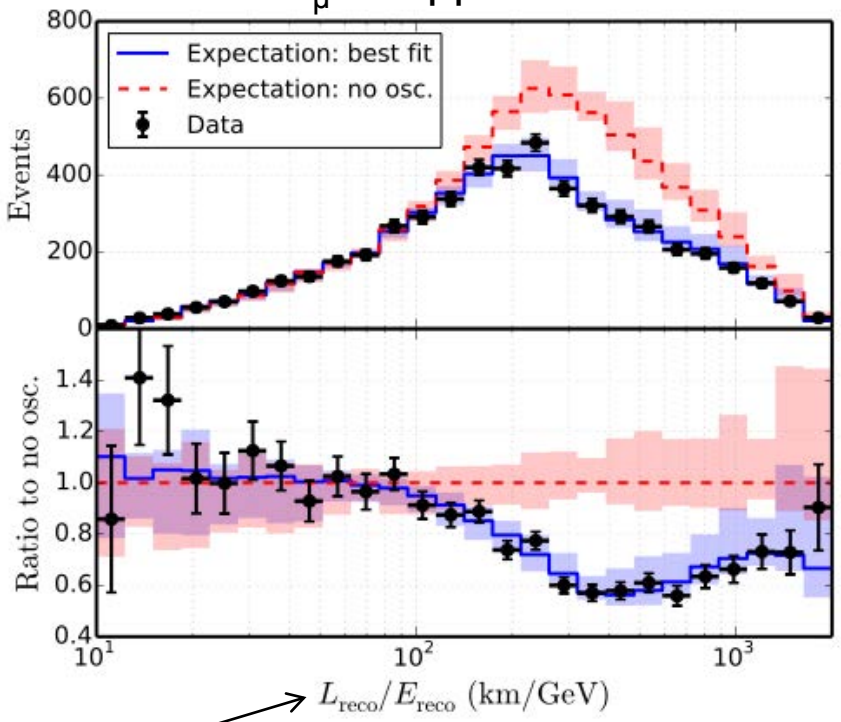
E^{-2} astrophysical?

Atmos. ν's: background for one – Signal for the other

Neutrino Oscillation



ν_μ disappearence



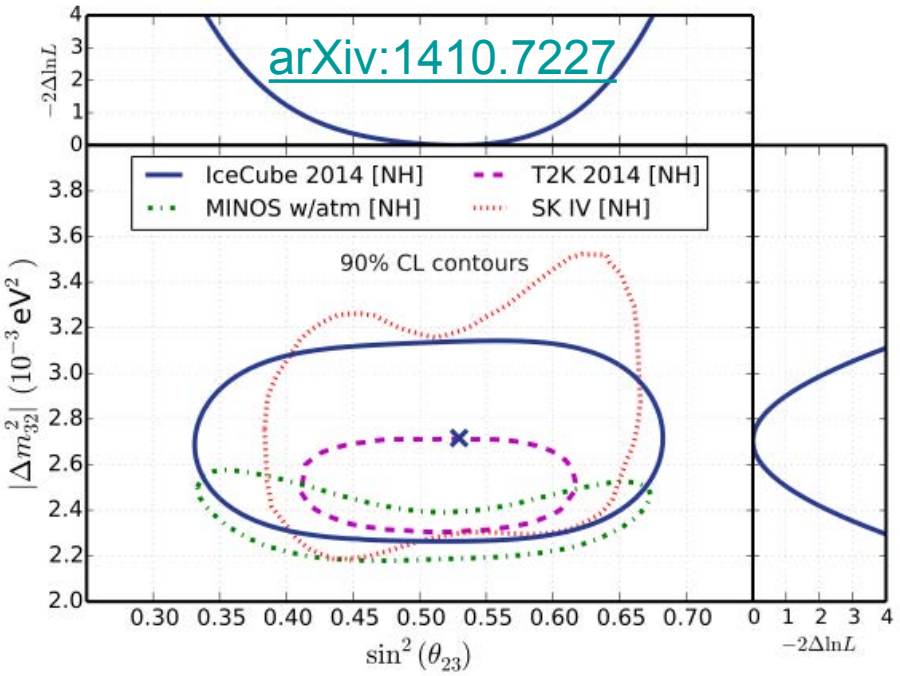
Different direction = different pass length

$E_\nu \approx 10 – 100$ GeV in DeepCore

Survival probability in the 2ν scheme

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4 E_\nu}\right)$$

Neutrino Oscillation

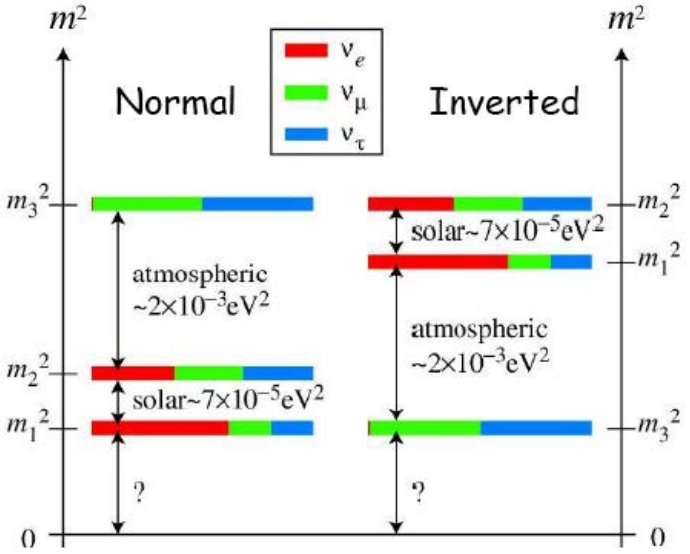


Disappearance atmospheric ν_μ with 3 years of data (for the normal hierarchy):

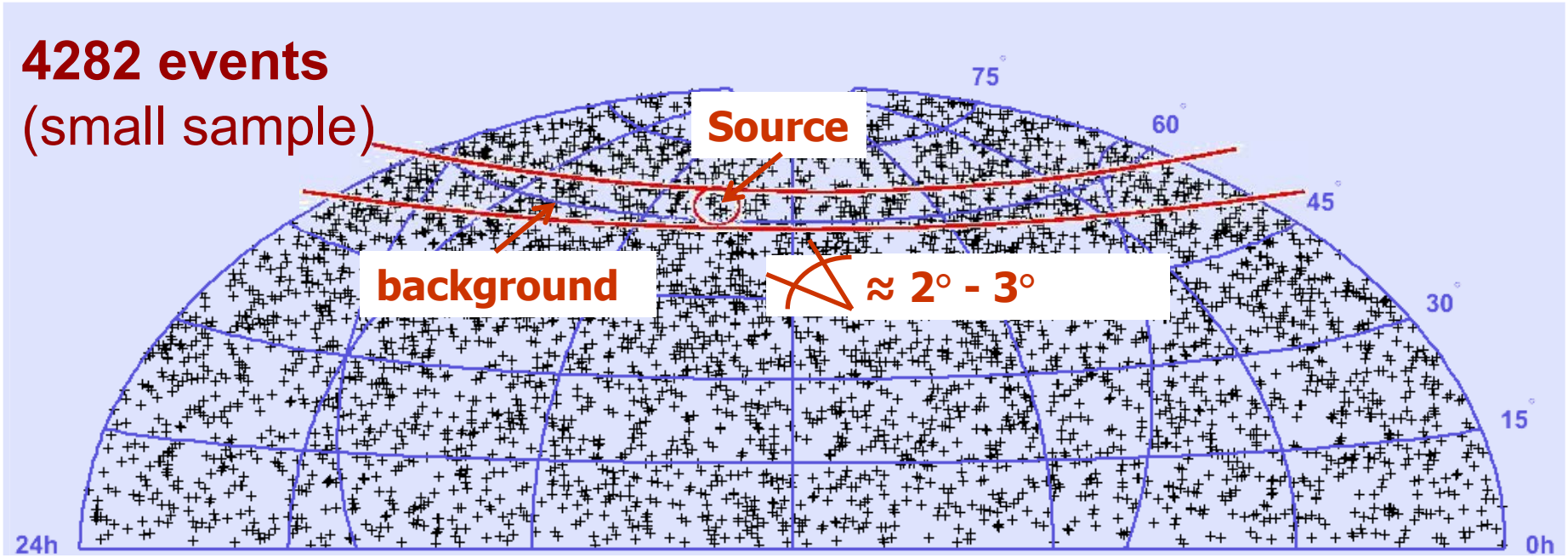
$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$

$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$

Ultimate goal:
measure **mass hierarchy** with a densely instrumented extension:
PINGU



Search for Pointsources: The Method



- background: atmospheric ν
- Search for event excess within **2° - 3°**

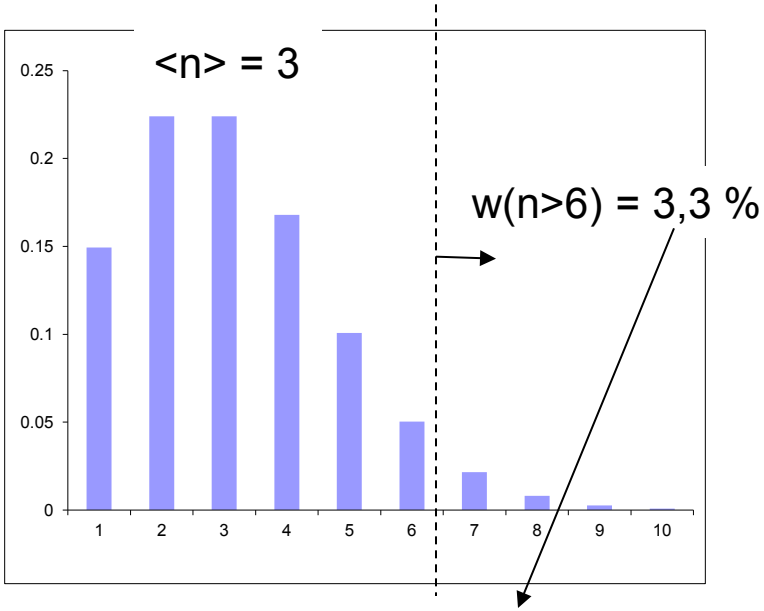
  - **somewhere in the Northern sky**
  - **from list of candidate sources**

The Statistics Problem

If you search long enough you will for sure get an excess at some point

"I only believe in statistics that I doctored myself"

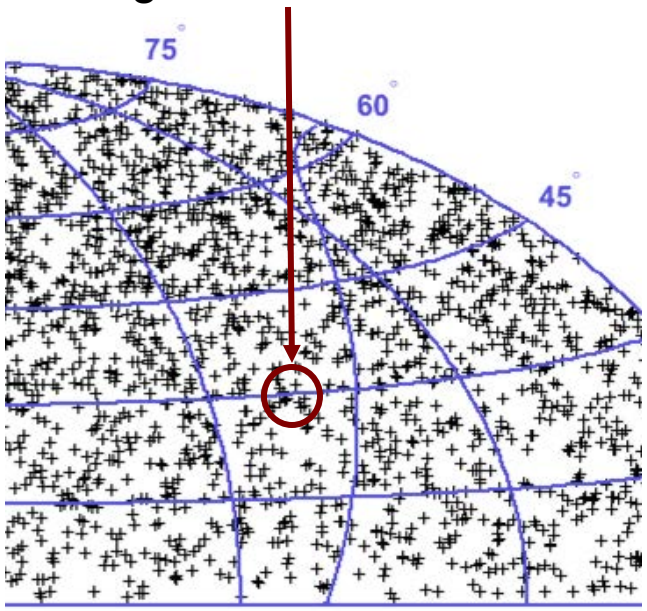
Winston Churchill



Already for about 30 search windows the probability to see 7 or more events in any window is about 60% for background only.

Example:

Expect 3 events background in a search window, but see 7. How significant is this?

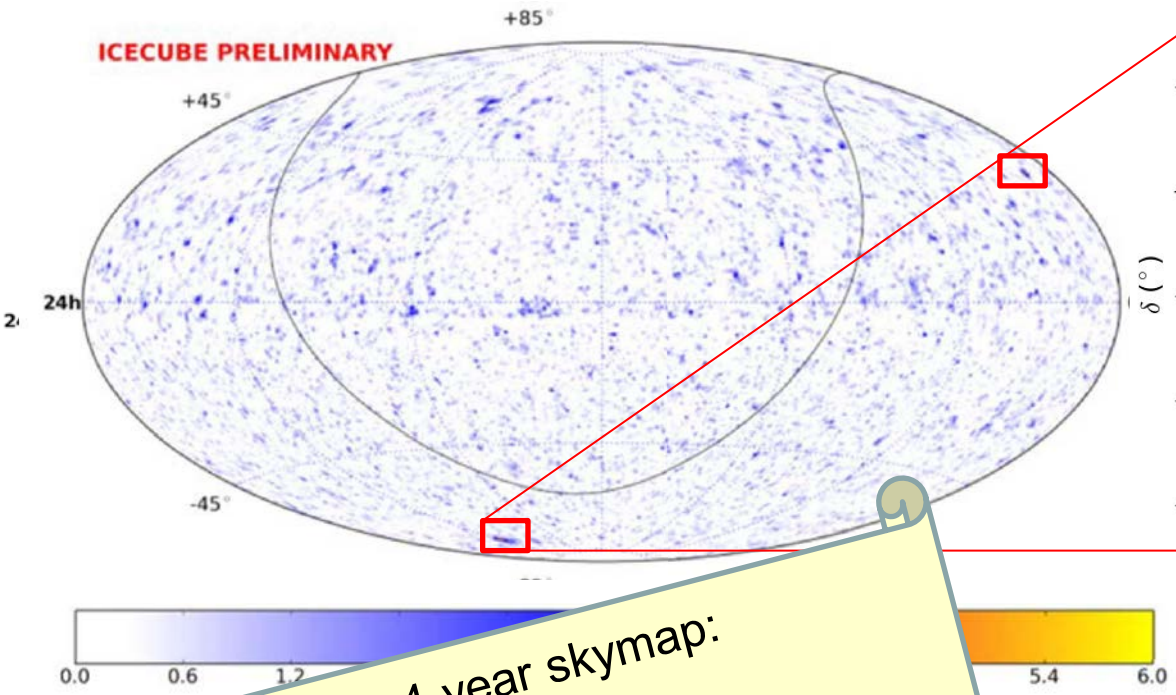


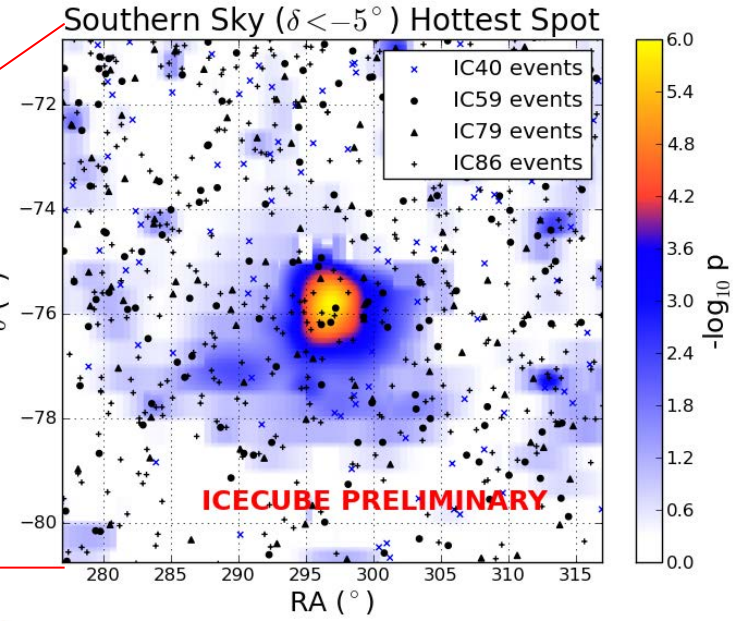
Significance is determined by ~10000-fold

simulation of measurement

Point Source Search 2008-2011

IC86+79+59+49





The 4-year skymap:

No significant signal

(9.3% chance to be backgr.)

spot in South:

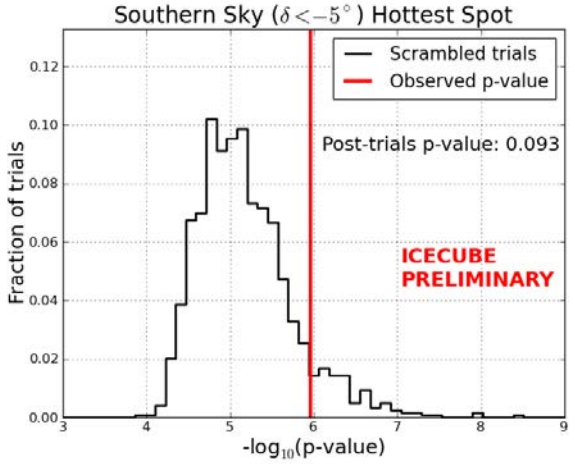
p-value* ≈ 10^{-6} (pre-trial)

Ra: 296.95 Dec: -75.75

N_s=16.16 γ=2.34

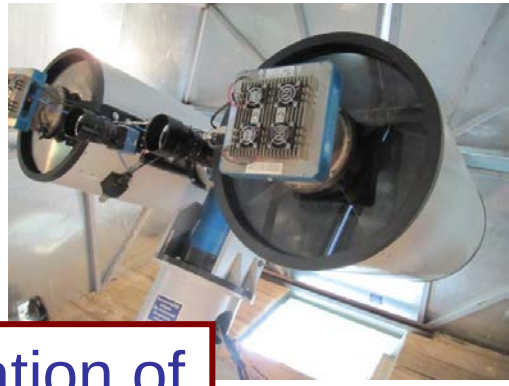
p-value* ~ 9.3% (post-trial)

*p-value for background only

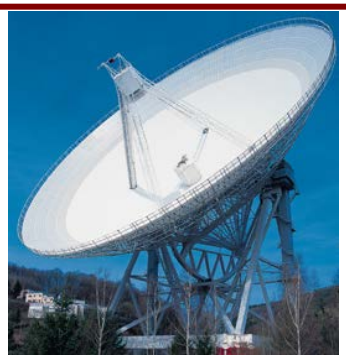


Improving Statistical Significance

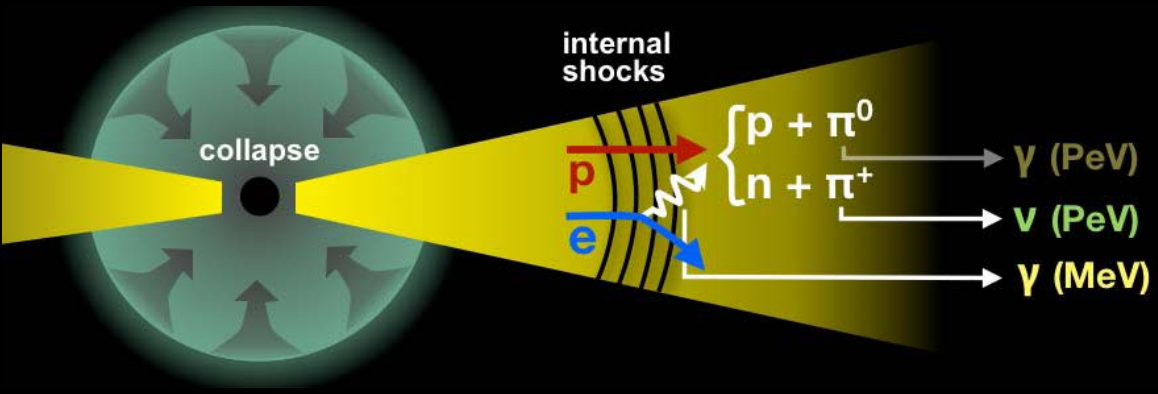
- pre-defined source positions
- pre-defined time-window
- „stacking“ of pre-defined sources



„Pre-Definition“ with **„multi-messenger“** information of optical, gamma, X-ray, radio telescopes …

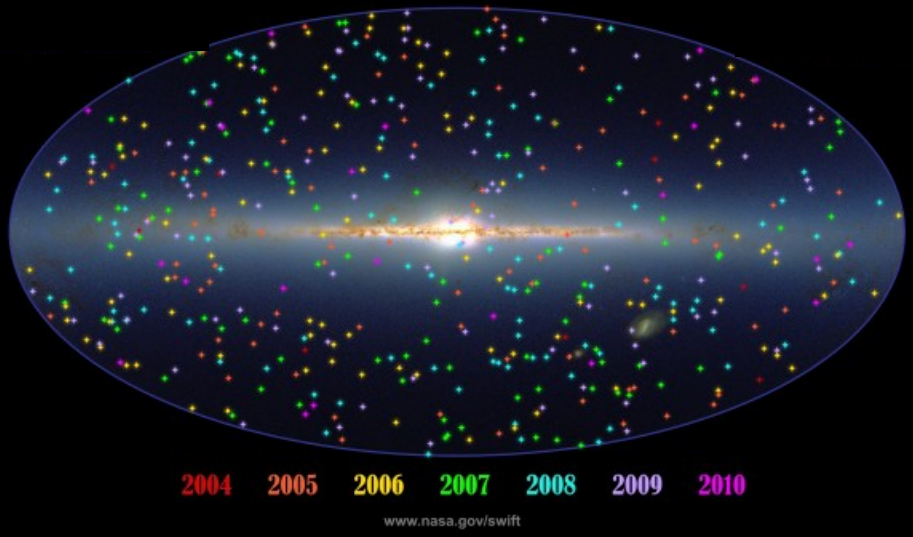


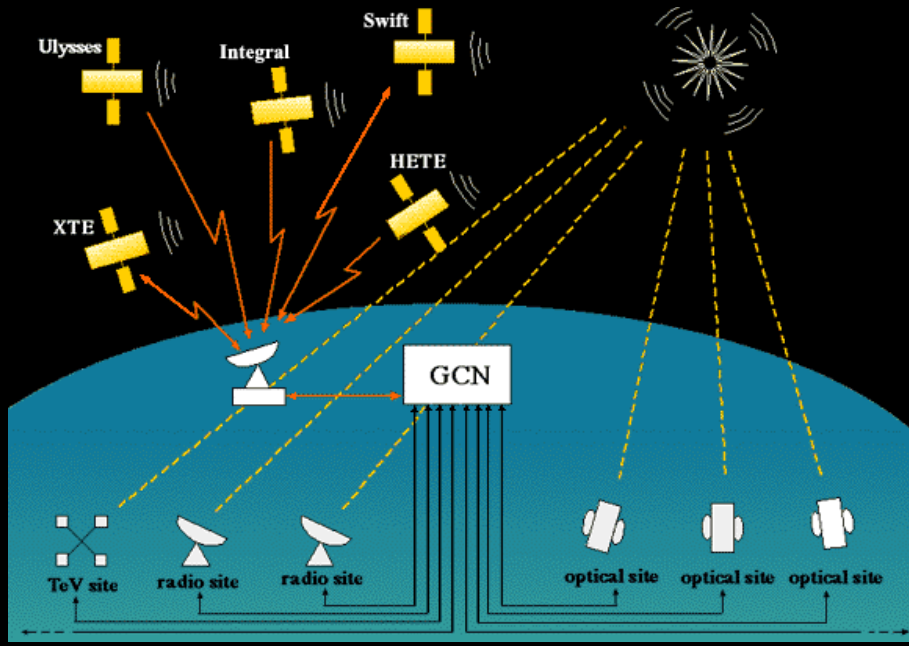
Gamma-ray bursts (GRB)



- Intense flashes of gamma rays
- Duration some seconds
- highly-relativistic jet (‘fireball’)

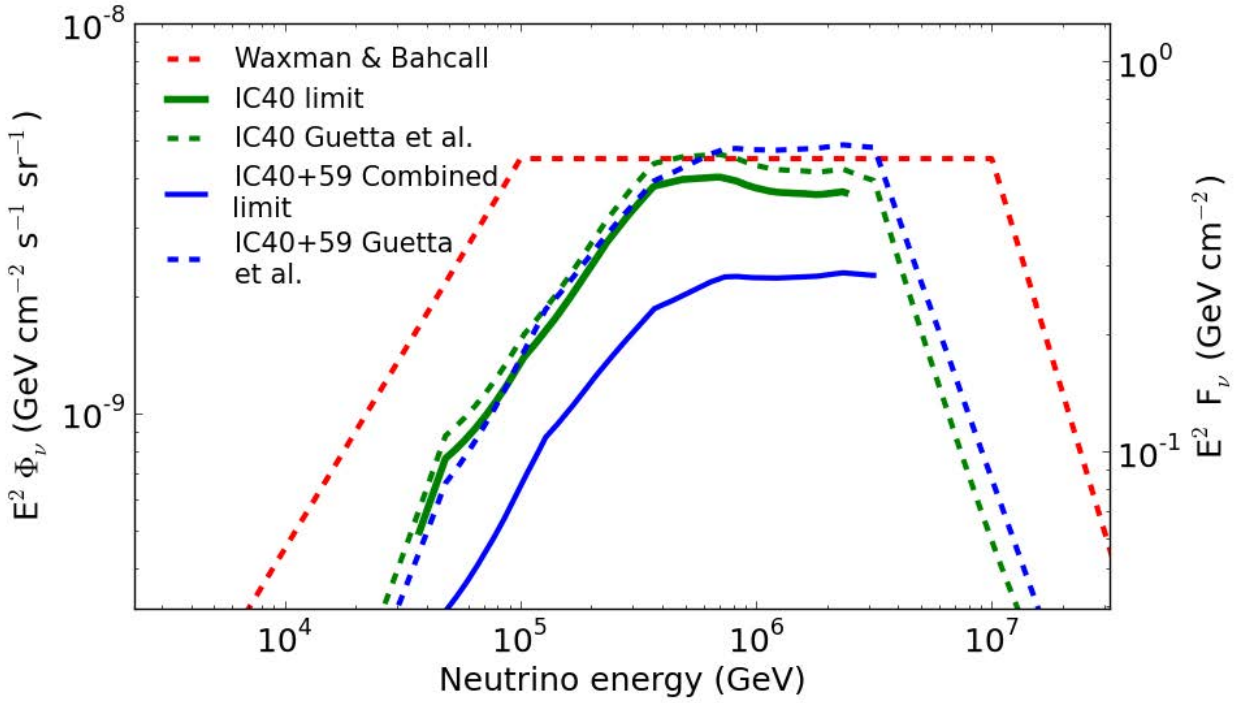
Search for neutrinos which are in time and direction consistent with GRB





GCN: The Gamma-ray Coordinates Network

Are GRBs the main sources of Cosmic Rays?



225 GRB ... no coincidences observed

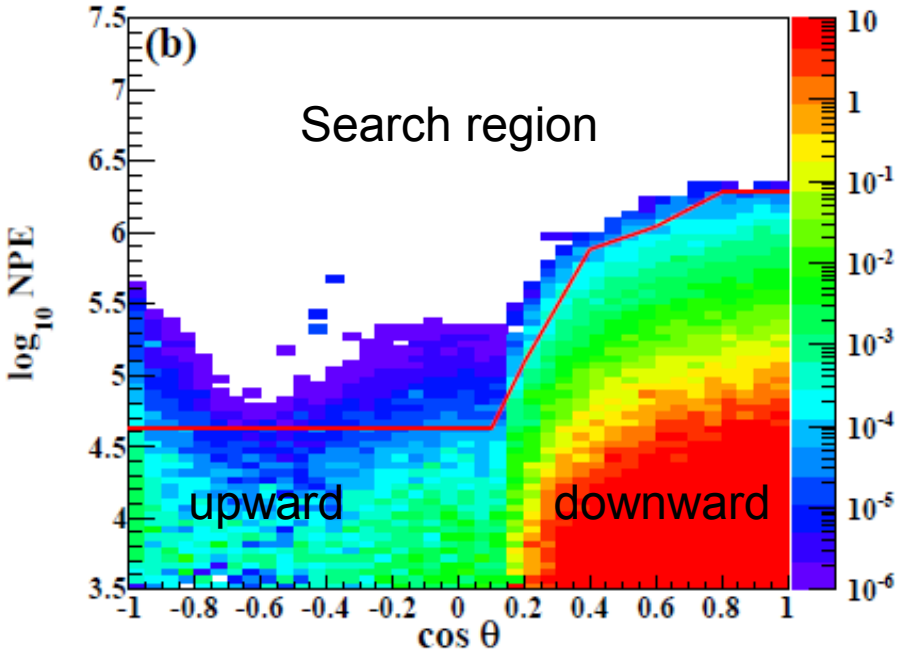
Standard Fireball Models excluded [Nature 484 (2012) 351]

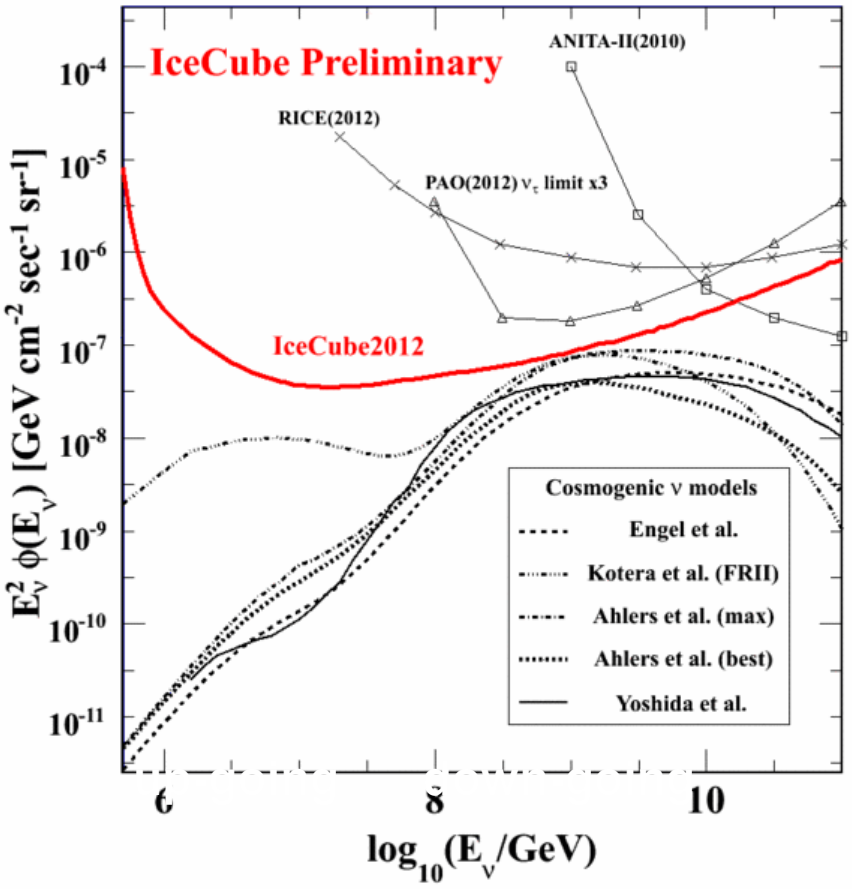
Extremly High Energy (EHE) Neutrinos

GZK $\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} & \rightarrow n\,\mu\nu \\ p\,\pi^{0} & \rightarrow p\,\gamma\gamma \end{matrix}$ threshold ~ 5×10^{19} eV

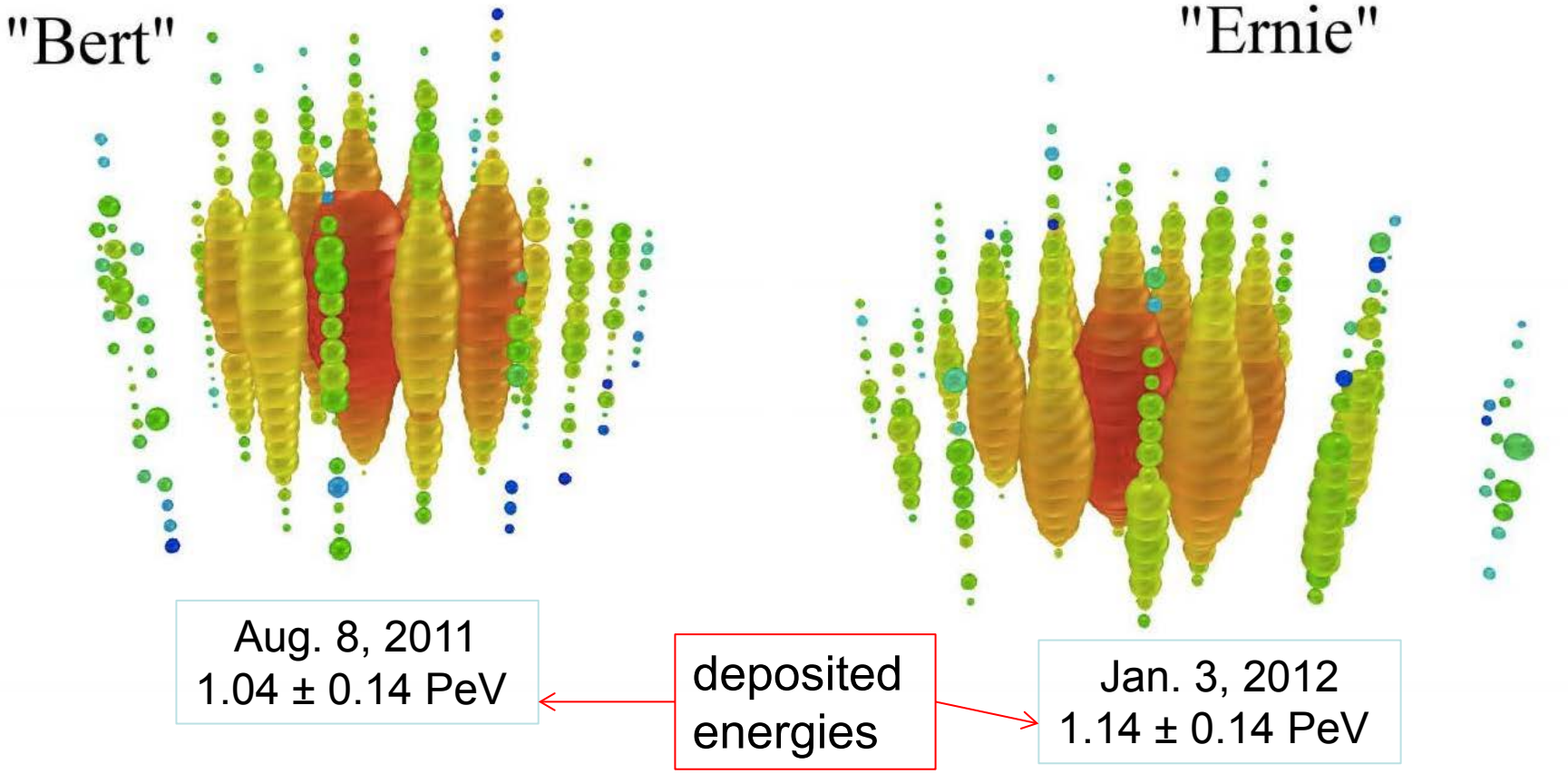
Search for high number of Cherenkov photons = NPE

θ = zenith angle



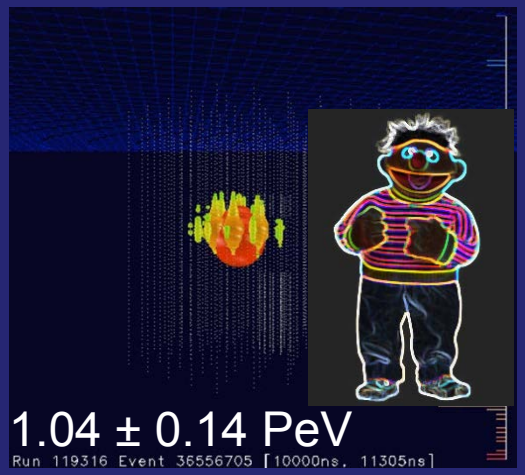


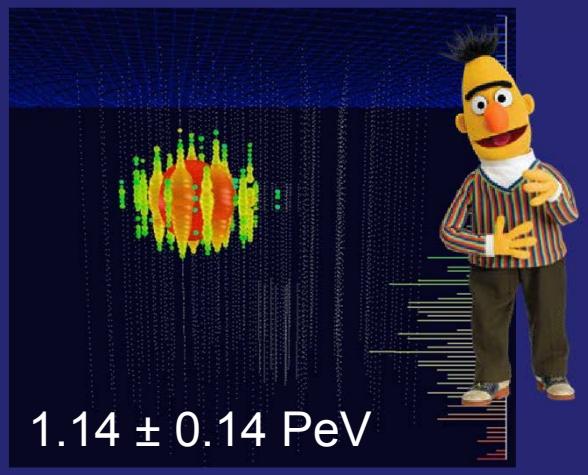
Search for cosmogenic neutrinos with 2010-2012 data.



- Two shower type events found in 616 days of IceCube observations.
- Neutrino energies could be higher than deposited energies, if neutral current interaction.

The Muppet Show





A theoreticians view (Francis Halzen, IceCube PI) :

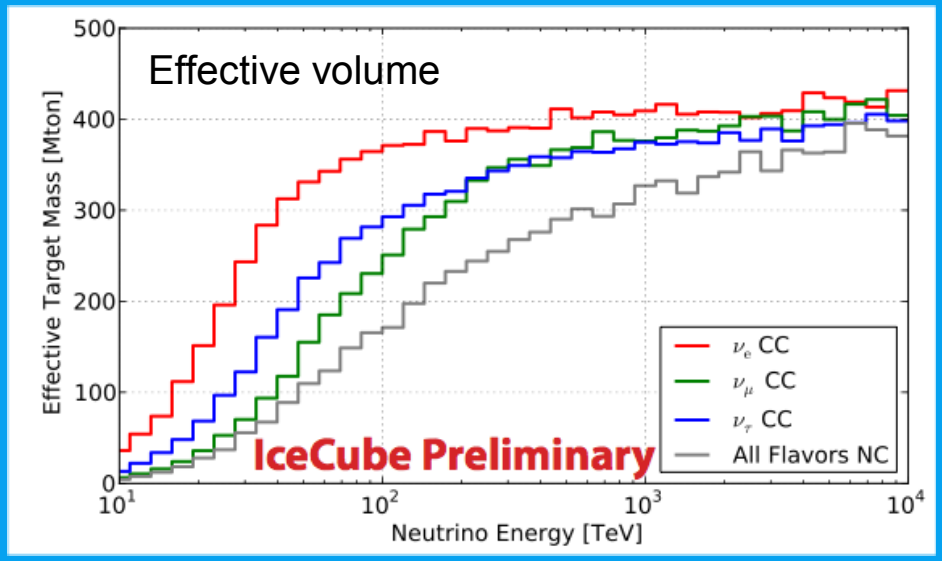
A detection of 1 neutrino is interesting …

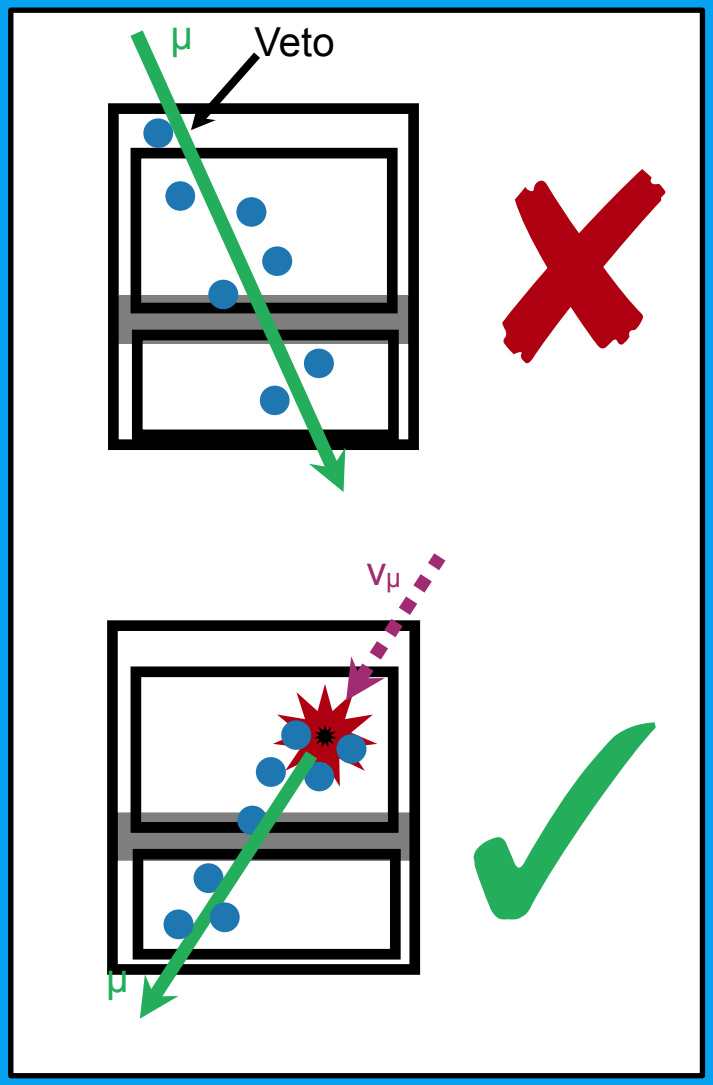
2 is evidence …

… and 3 is a spectrum!

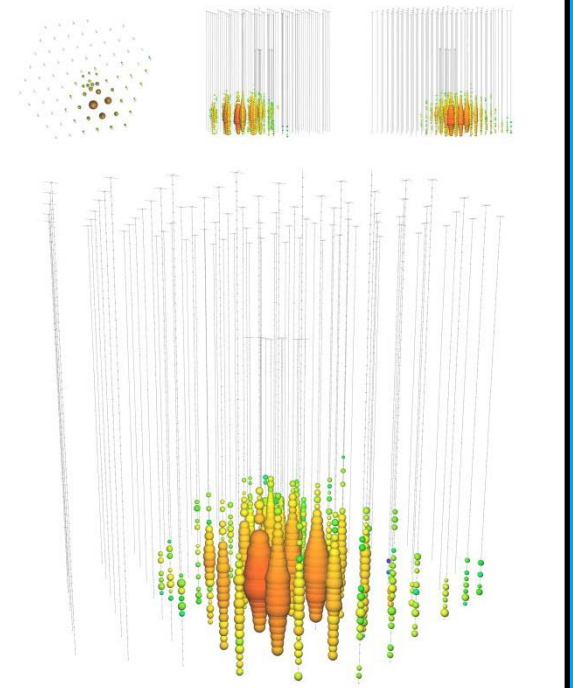
Follow-up Search for contained and semi-contained events

- find contained events below the energy threshold of the “Bert-and-Ernie” analysis
  - same dataset, 662 days of livetime
- Use outer IceCube layers as incoming track veto
  - Additional atmospheric muon veto
  - Sensitive to all flavors in region above ~ 60TeV
  - Muon background can be estimated from data

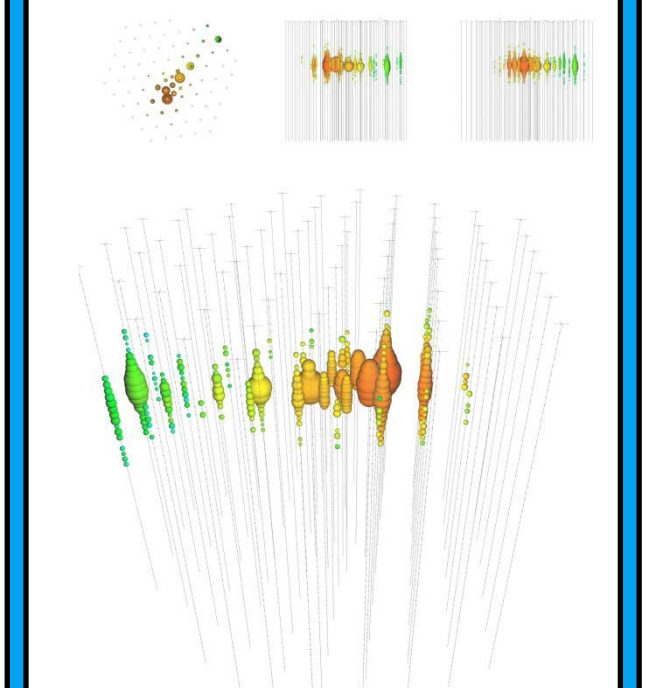




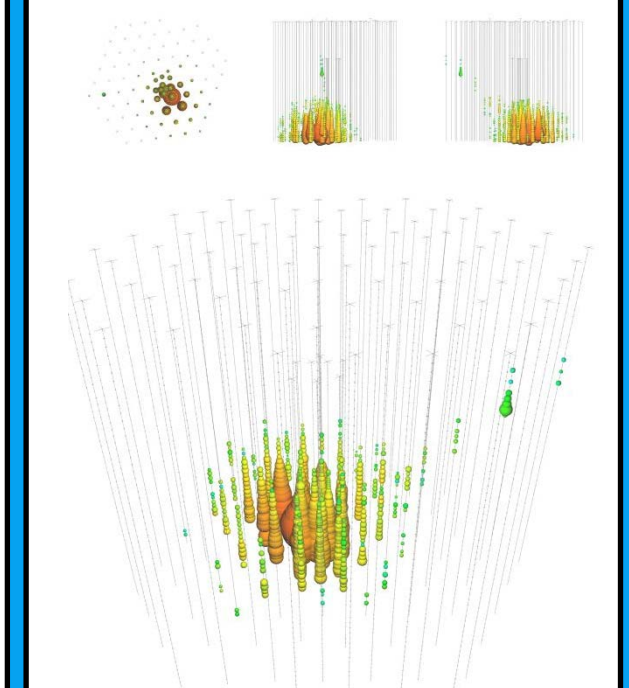
Some example events



declination: -13.2°
deposited energy: 82TeV

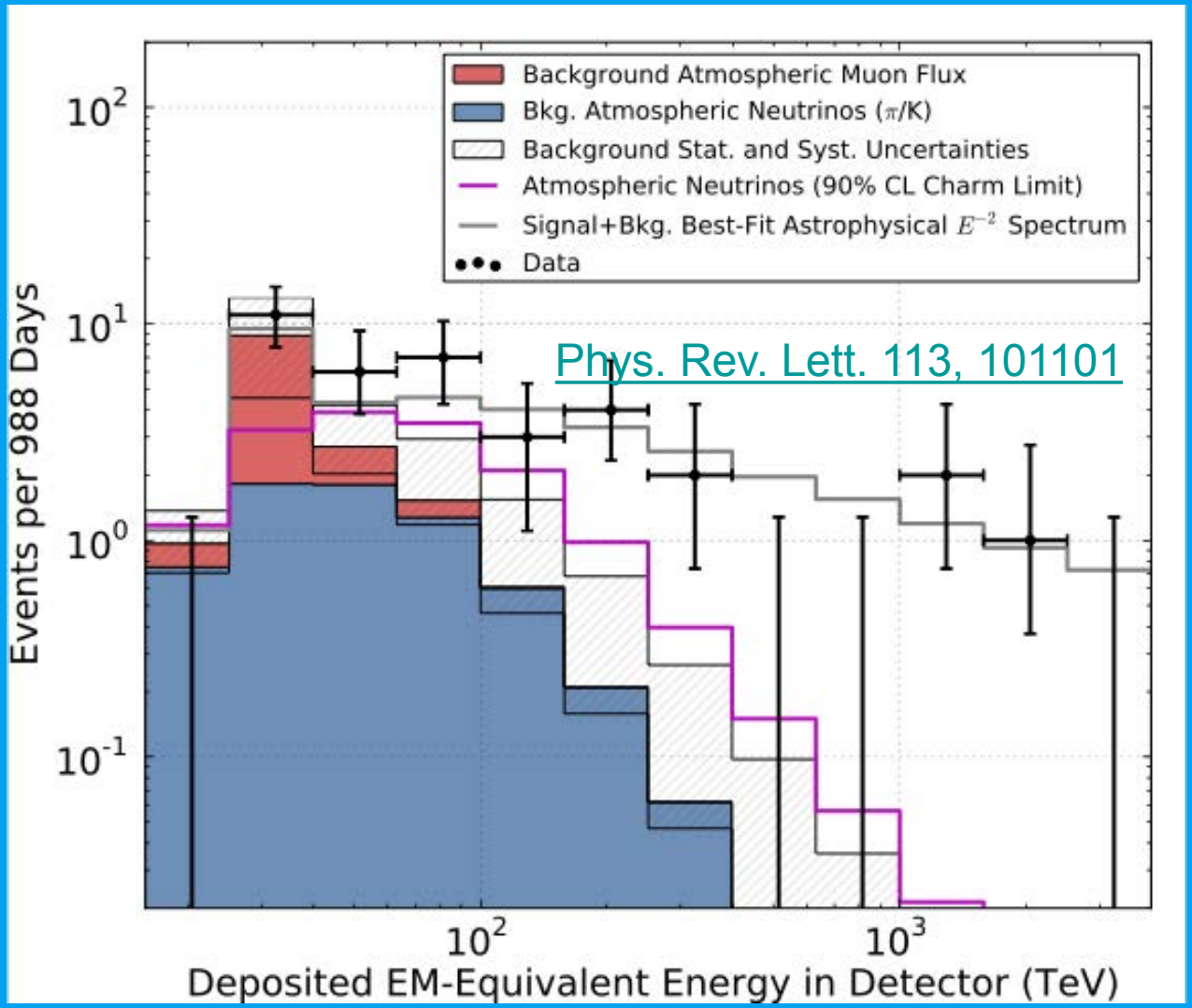


declination: -0.4°
deposited energy: 71TeV



declination: 40.3°
deposited energy: 253TeV

Excess of HE Starting Tracks



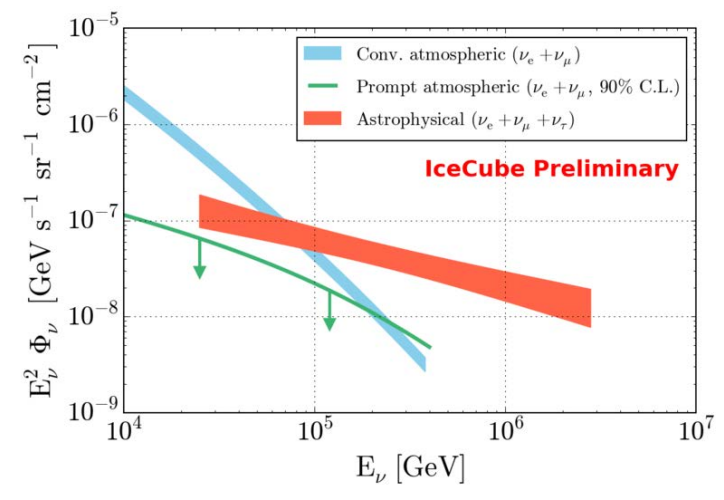
Significance about 5.7 σ

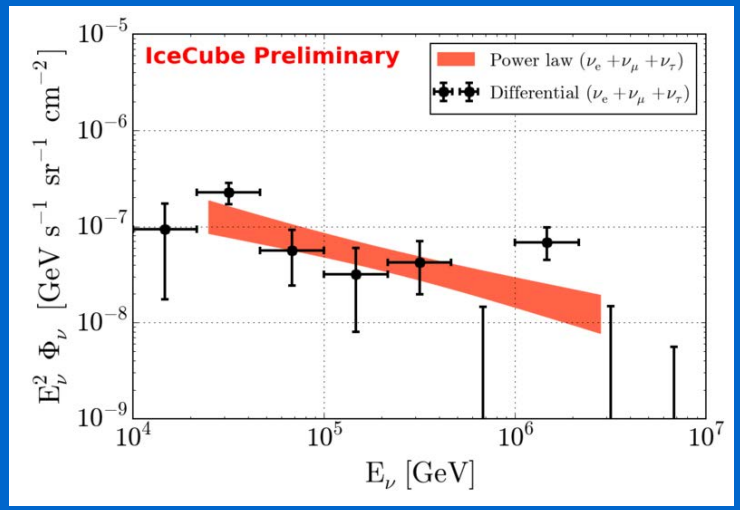
First observation of astrophysical flux of high energy neutrinos

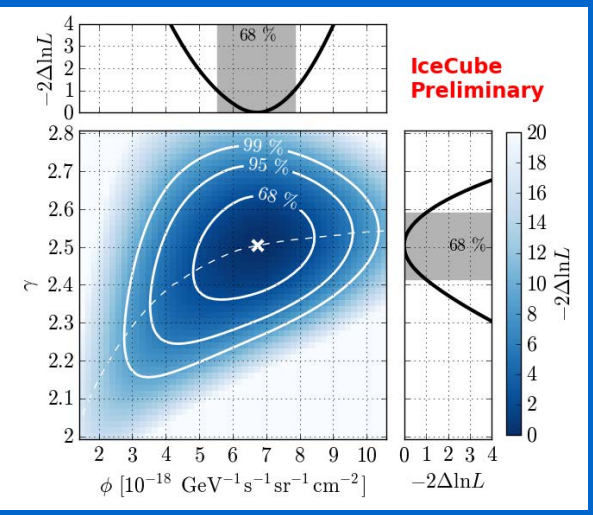
Starting events depositing >60 TeV using 3 years of data, events up to ~2 PeV

Global Fit to 6 Different Measurements

Simplest model: flux $\Phi_\nu = \phi \cdot \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$ and flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$







Results:

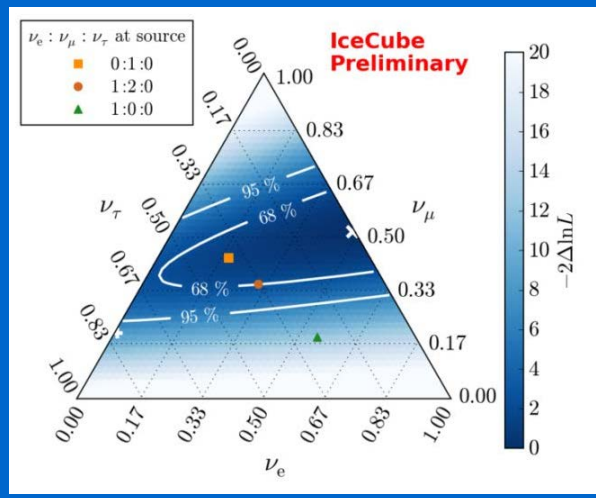
$$\gamma = 2.50 \pm 0.09$$

$$\phi = (6.7^{+1.1}_{-1.2}) \cdot 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}$$

Flavor ratio compatible with

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

„prompt“ < 2 × ERS

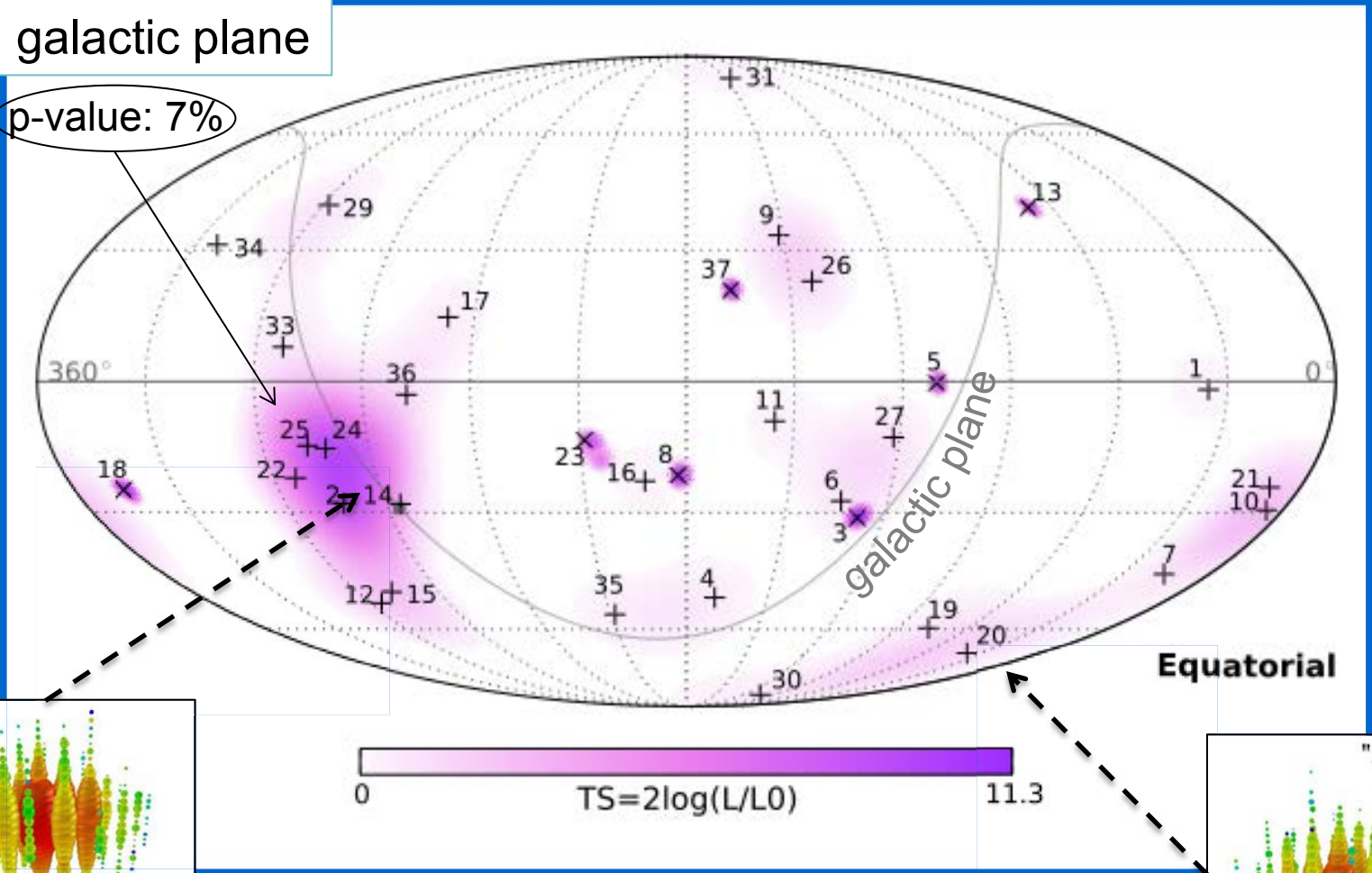


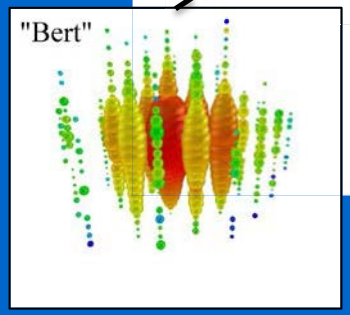
Skymap

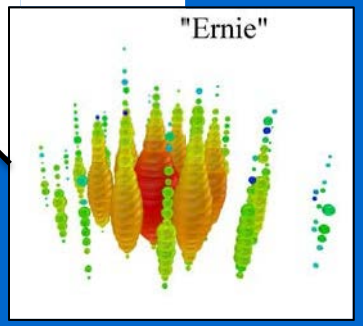
equatorial coordinates

no significant correlation with galactic plane

p-value: 7%

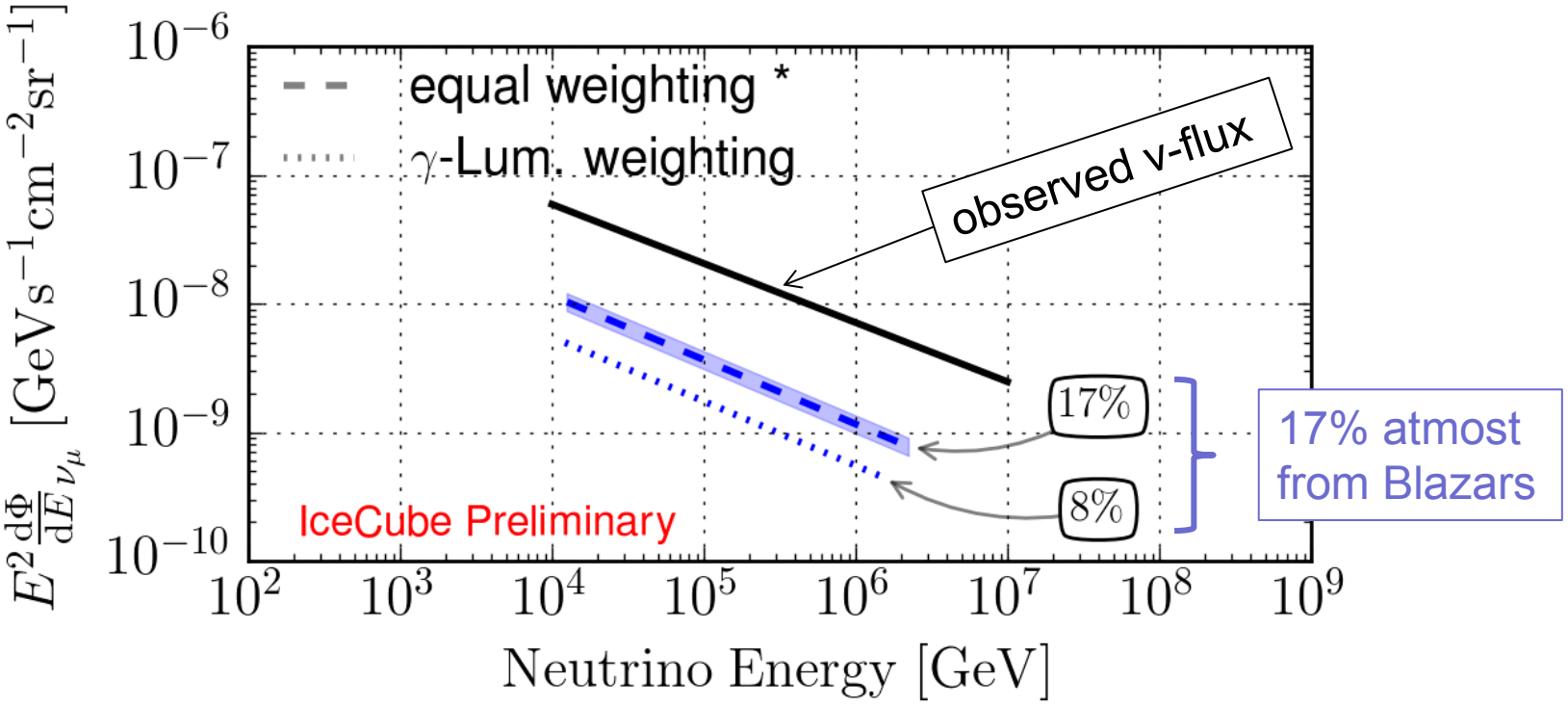






Blazars or GRB as Sources?

Compare directions of the high energy ν_μ
with directions of Blazars observed by
Fermi Satellite at high γ luminosity



17% atmost from Blazars

Even more stringent for GRB:
from analysis of 506 GRBs in four years it was found that no more than 1% of the high energy neutrinos could come from GRB

1% atmost from GRBs


Anything new down there?
Quite interesting. Let's keep looking
Illustrated by Guy Billou

CONCLUSION

?

„Alles Wissen und alle Vermehrung unseres Wissens endet nicht mit einem Schlußpunkt, sondern mit Fragezeichen“

Hermann Hesse .

… imagine Sisyphos to be happy

»… il faut imaginer Sisyphe heureux« A.Camus


The End

The IceCube Collaboration

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)
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Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)