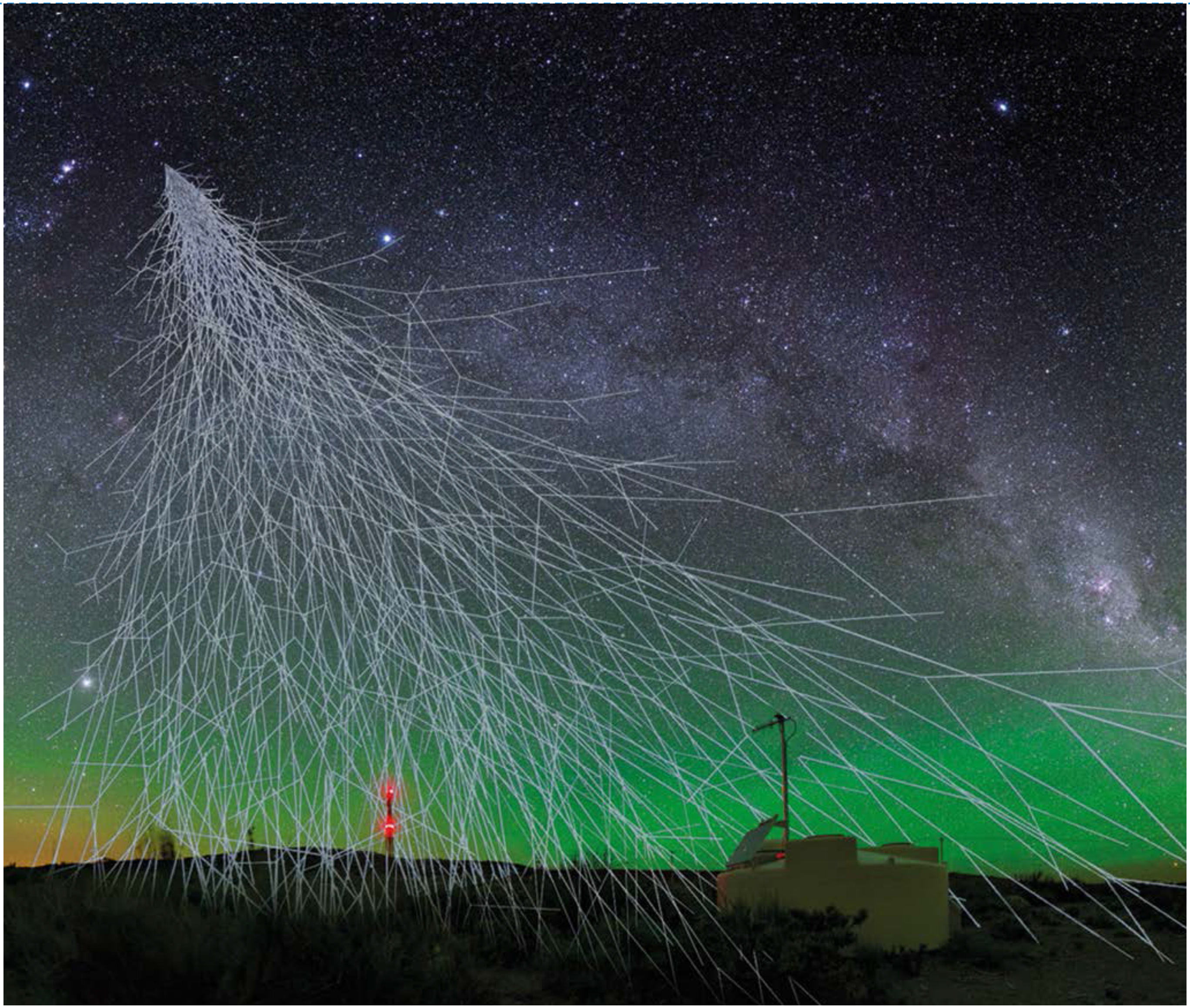
Introduction to Astroparticle Physics

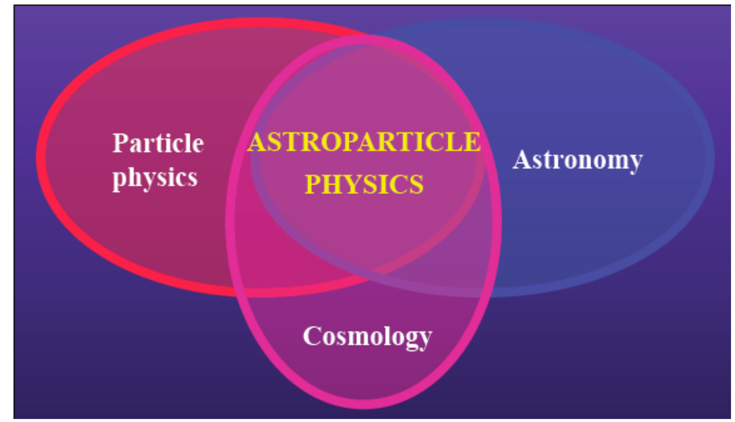


Nikola Godinović, University of Split – FESB

Astroparticle physics

What dose it explore?

- The most violent Universe
- The earliest Universe
- Invisible Universe



How does it?

- Telescopes/detector of very high energy cosmic and gamma rays
- Neutrino detector
- Gravity wave detector

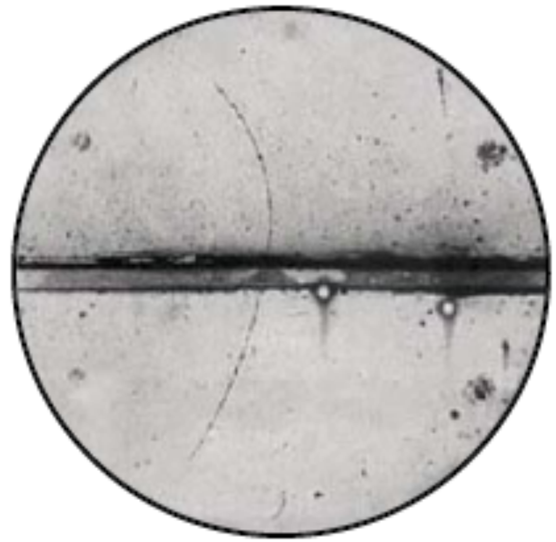
Use techniques from Particle Physics to advance Astronomy

Use input from Particle Physics to explain Universe, and particles from outer space to advance Particle Physics

Cosmic Ray discovered in 1912

August 1912: Victor Hess after his highest balloon flight. Hess' discovery of cosmic rays was acknowledged with the 1936 Nobel Prize in Physics.

1932 positron discovered



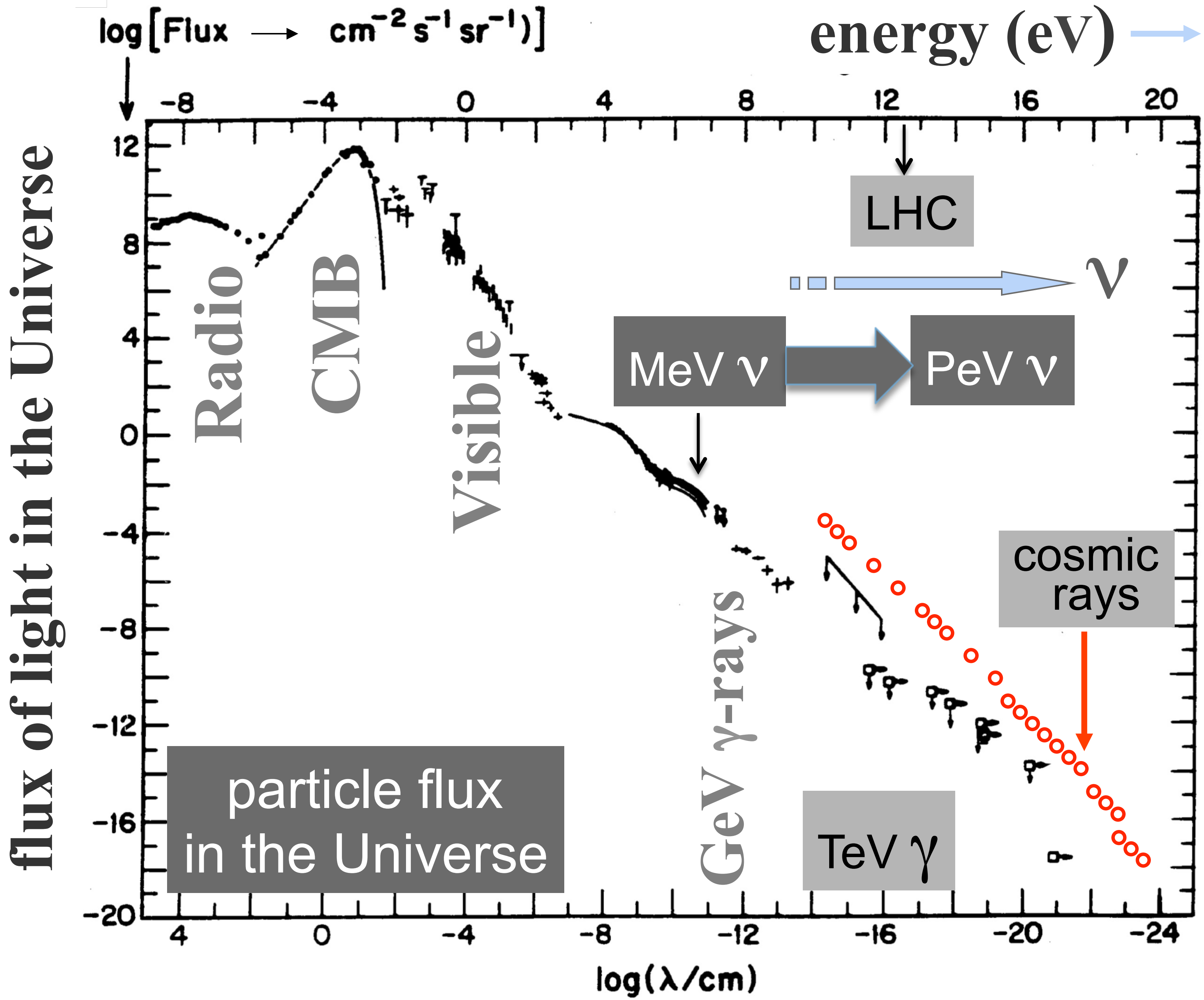
One of the first positron tracks in a cloud chamber, recorded by Carl D. Anderson in 1932.

1937 - muon discovered
1947 - pion discovered
1956 –antineutrino discovered
Until early 1950's CR main resource for discovering new particles.

Important milestones in astroparticle physics

- **1912:** Victor Hess climbs to 5200 metres in a balloon and demonstrates the existen of radiation coming from the sky.
- **1930:** Pierre Auger discovers particle showers, which come from the collisions between cosmic rays and particles of the atmosphere.
- **1932:** Carl Anderson discovers the positron; the first antiparticle.
- **1937:** For the first time, muons are observed in the tracks of a particle shower in a bubble chamber.
- **1956:** Frederick Reines & Clyde Cowan bring the neutrinos to the fore.
- **1965:** Arno Penzias & Robert Wilson discover the Cosmic Microwave Background.
- **1987:** Neutrino emissions by Supernova SN 1987A confirm theories about the origin of elements.
- **1989:** The first source of high-energy gamma rays is discovered.
- **1992:** The COBE satellite discovers the anisotropy of the Cosmic Microwave Background.
- **1998:** Cosmic neutrinos reveal the oscillatory nature of these particles.

- 2015 Gravitacijski valovi

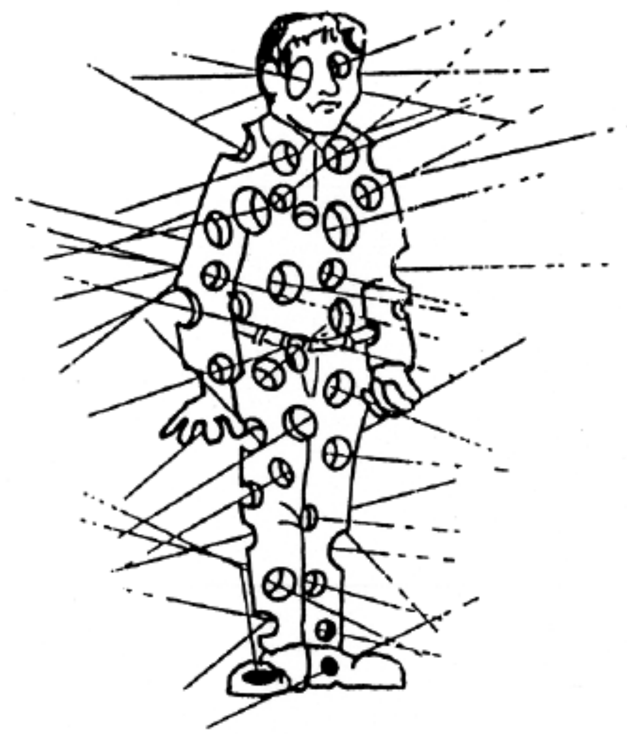


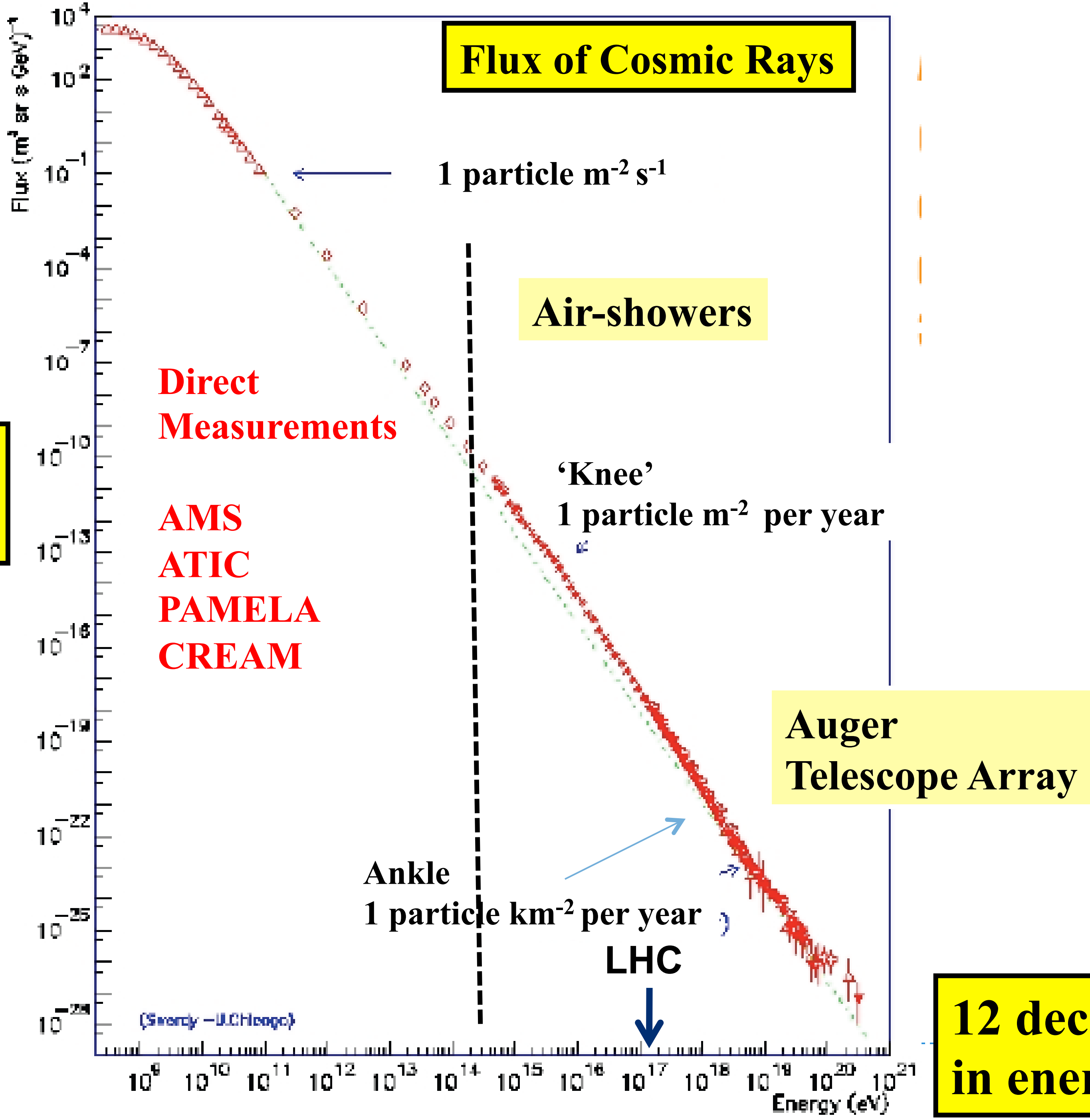
log[Flux → cm−2 s−1 sr−1)]
energy (eV)
flux of light in the Universe
Radio
CMB
Visible
GeV γ-rays
LHC
ν
MeV ν
PeV ν
cosmic rays
TeV γ
particle flux in the Universe
log(λ/cm)

Cosmic ray

Cosmic ray

- Cosmic ray are constantly impinging on earth
- About 100 000 cosmic ray is going through your body in an hour.
- When CR hit the chip they could change it memory state.
- Could dammage humman cells.

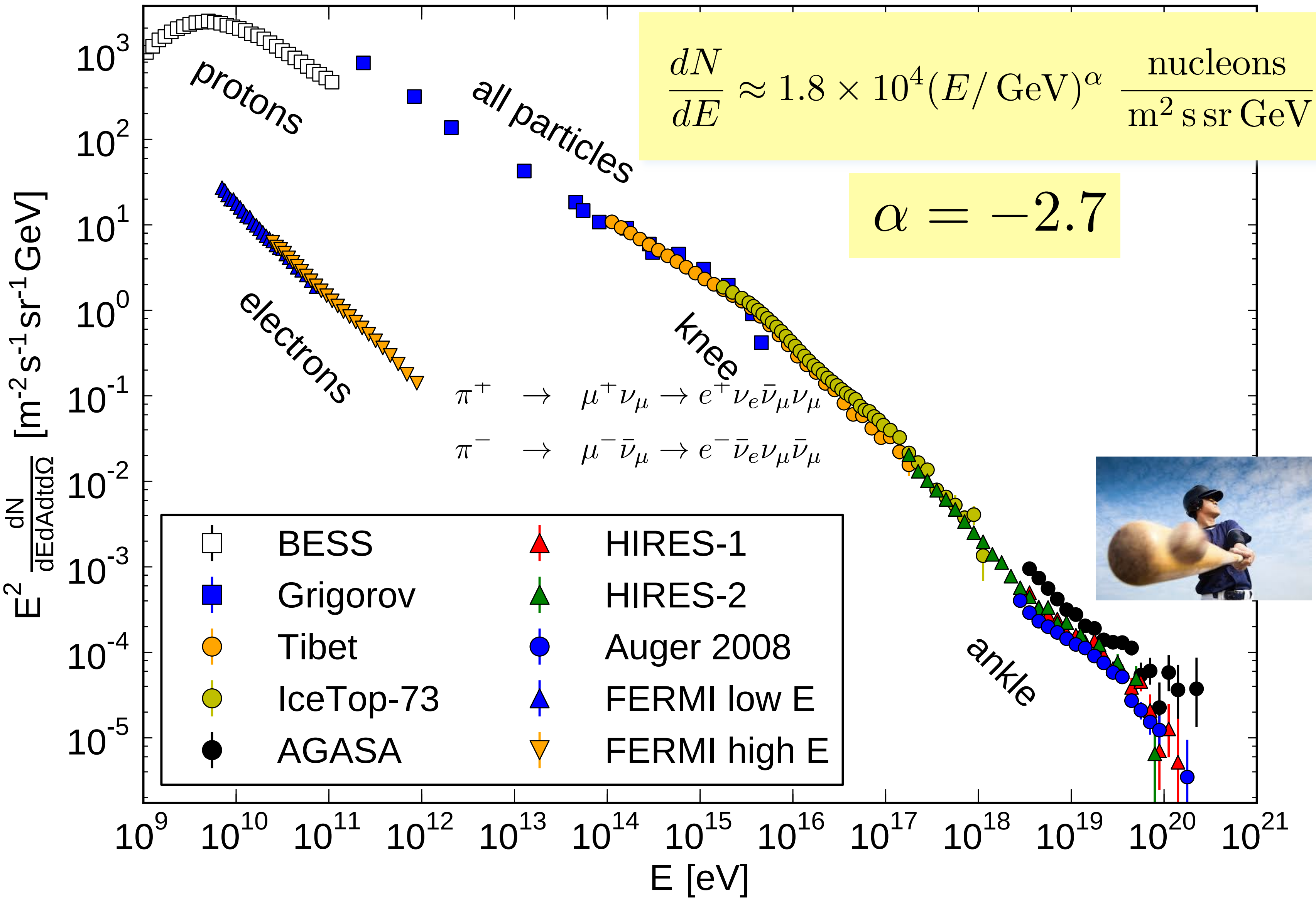




32 decades in intensity

12 decades in energy

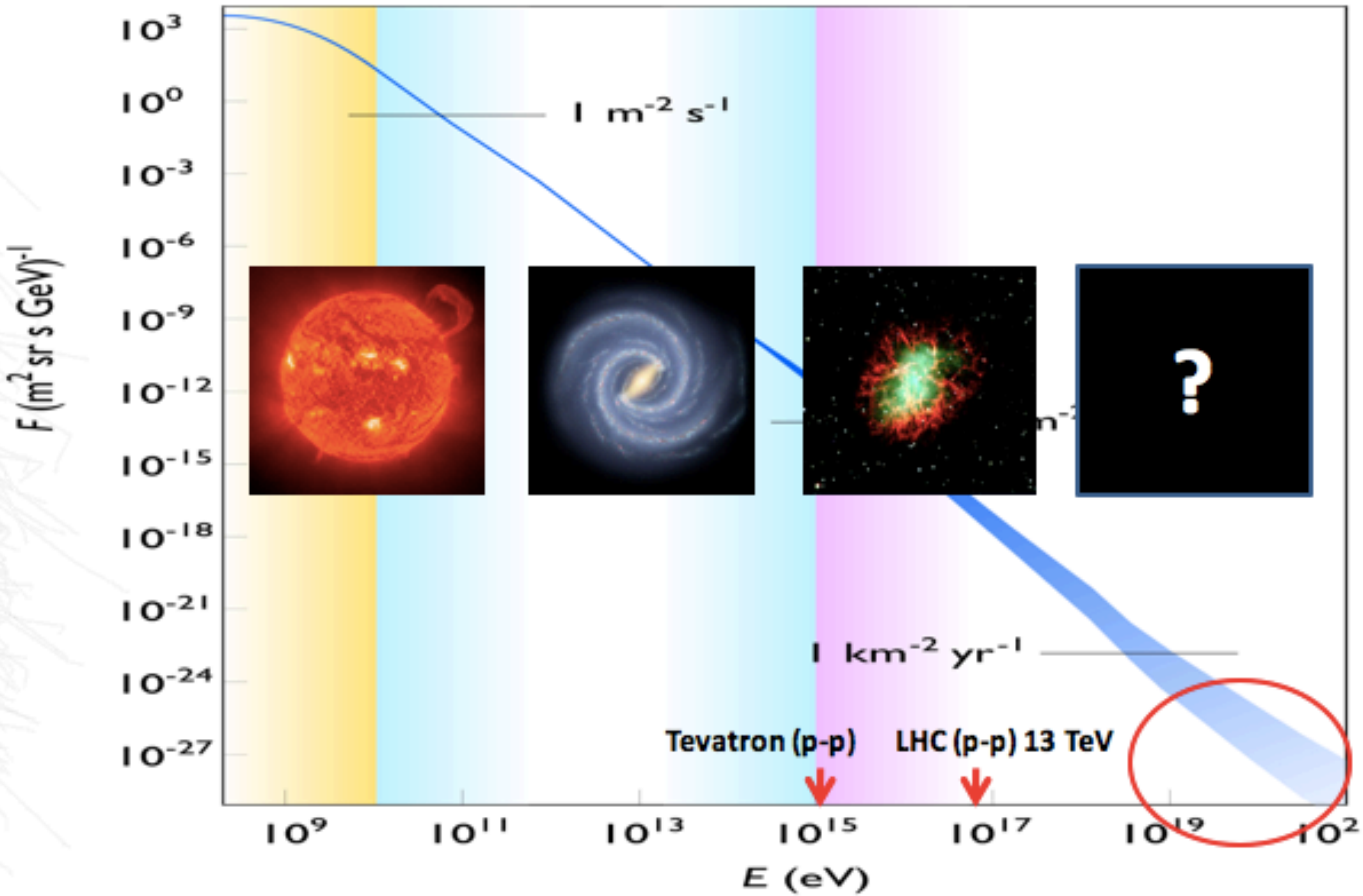
Cosmic Ray Spectrum



$$\frac{dN}{dE} \approx 1.8 \times 10^4 (E/\,\mathrm{GeV})^{\alpha} \; \frac{\mathrm{nucleons}}{\mathrm{m^2\,s\,sr\,GeV}}$$

$$\alpha = -2.7$$

Cosmic ray energy spectrum



Does the Cosmic Ray Energy Spectrum terminate?

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

$$\gamma_{2.7\,K} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \text{ or } p + \pi^{o}$$

and

$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

(1Mpc=3.3 x10^{6} l.y.)

- **Sources must lie within ~ 100 Mpc at 100 EeV**
  - **Note that neutrinos - of different energies – come from the decay of π^{+} and n**
  - **Photons from decay of π^{o}**

Acceleration mechanism

What is the origin of cosmic ray

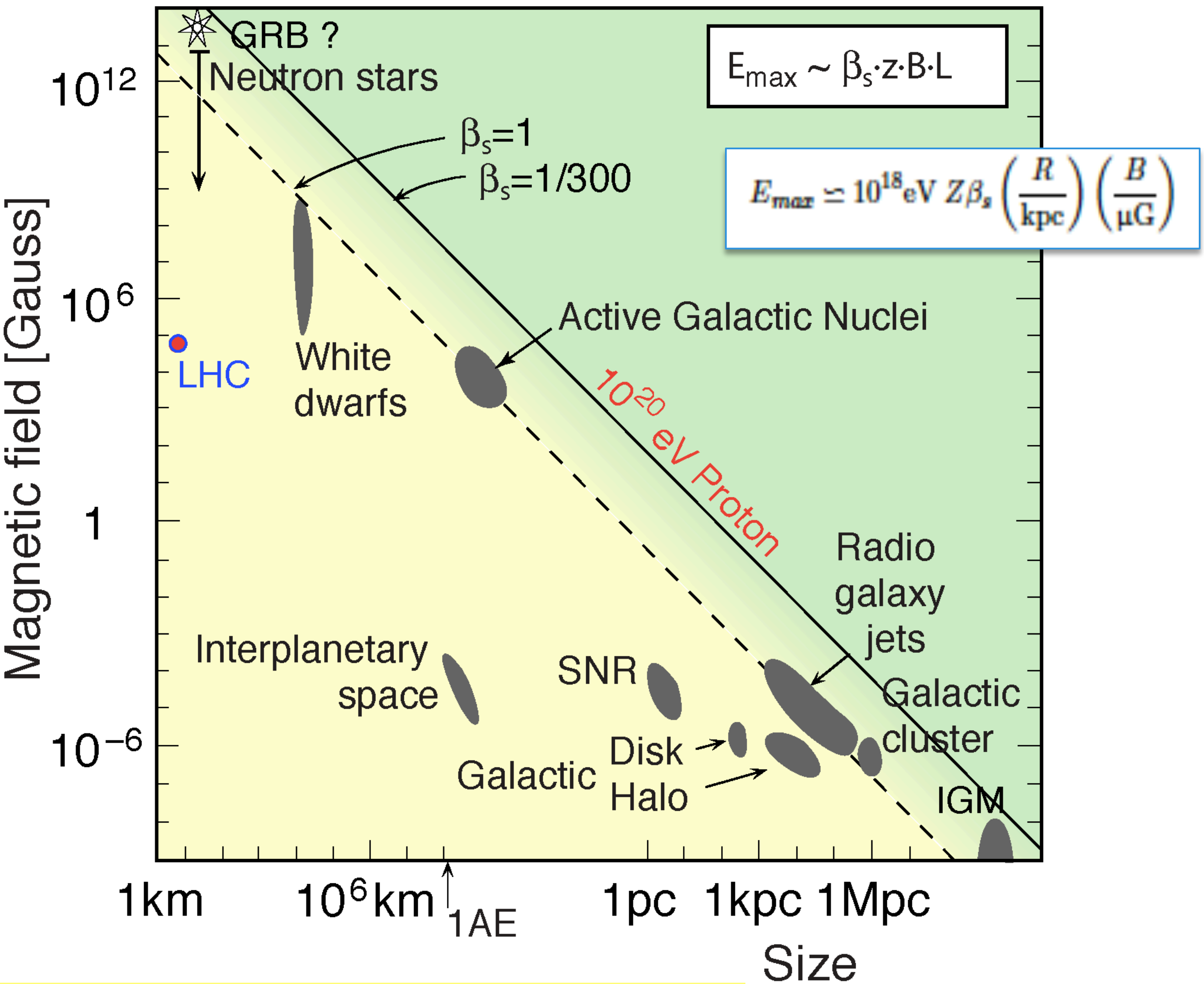
- **Bottom up scenario**
  - Very energetic protons and nuclei are decay products of very heavy particles
- **Top down scenario**
  - Acceleration within region of intense magnetic field
- **General constrains on the cosmic accelerators:**
  - **geometry:** the accelerated particle should be maintained within the object during the acceleration;
  - **power**: the source should be able to provide the necessary energy for the accelerated particles;
  - **radiation losses:** within the accelerating field the energy gained by a particle should be no less than its radiation energy loss;
  - **interaction losses:** the energy lost by a particle due to its interaction with other particles should not be greater than its energy gain;
  - **emissivity**: the density and power of sources must be enough to account for the observed flux;
  - **coexisting radiation:** the accompanying photon and neutrino flux, and the low-energy cosmic-ray flux, should not be greater than the observed fluxes (this constraint must be satisfied by the flux from a single source and by the diffuse flux).

Basic concept about accelerations

$$\frac{d}{dt}(\gamma m \vec{v}) = q(\vec{E} + \vec{v} \times \vec{B})$$

- In most object, static electric field can not exists since the media are high conductive.
- Acceleration could be due to non-stationary electric filed, for example electromagnetic wave of very high energy density or due to magnetic filed
- Magnetic filed confine a charge particle in acceleration region.

Hillas plot



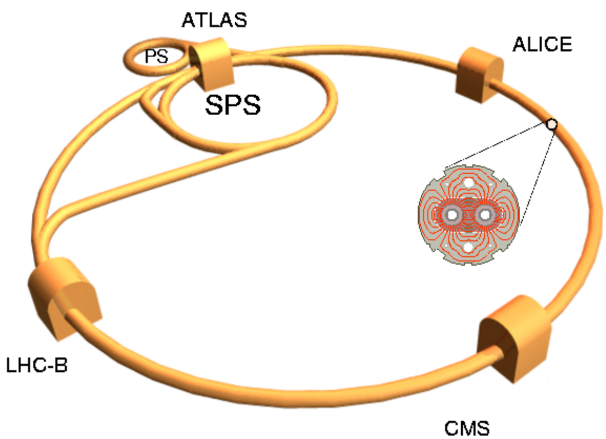
(Larmor radius) $r_L < r_a$ (accelerator size)

Hillas criteria: $E_{max} = \gamma ZeBR$

Particle Acceleration

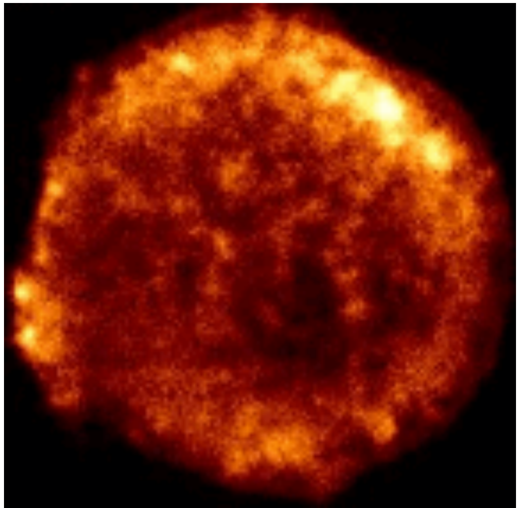
$E \propto BR$

Large Hadron Collider



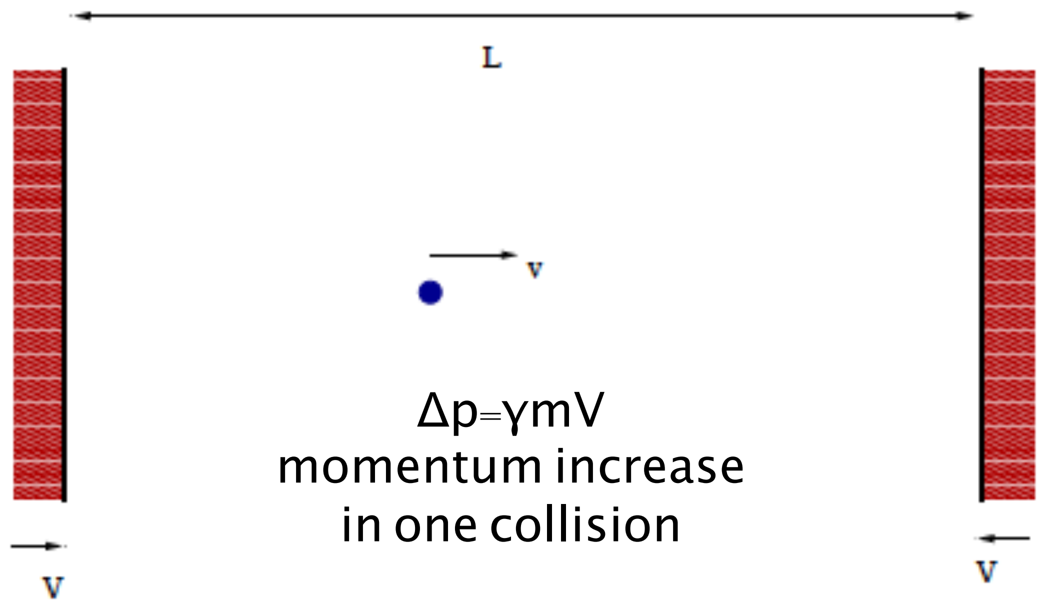
$R \sim 3\,\text{km},\ B \sim 9\,\text{T} \quad \Rightarrow E \sim 10\ \text{TeV}$

SuperNova Remnant



$R \sim 10^{15}\text{km},\ B \sim 10^{-10}\text{T} \quad \Rightarrow E \sim 1000\ \text{TeV}$

First order Fermi acceleration – simple concept



Δp=γmV
momentum increase
in one collision

$$\frac{dE}{dt} = \text{Rate of collisions} \times \text{energy change per collision}$$

$$\Delta E = \Delta pc = \gamma m V c \longrightarrow \frac{dE}{dt} \approx \frac{v}{L} \times \gamma m V c$$

$$v = c. \longrightarrow \approx \frac{\gamma m c^2 V}{L}$$

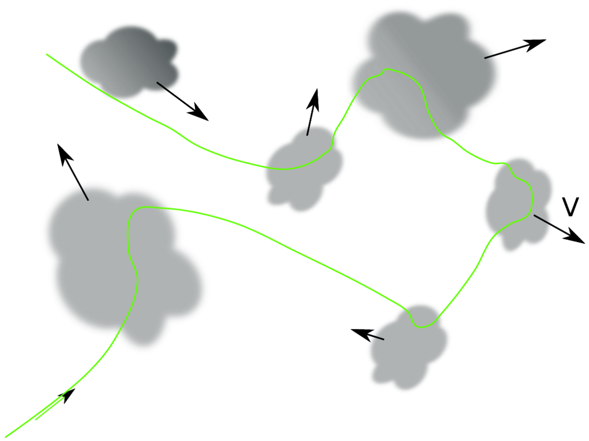
$$\approx \frac{EV}{L}$$

$$\frac{dE}{dt} = \frac{E}{\tau}$$

Particle energy will
increase exponentialy

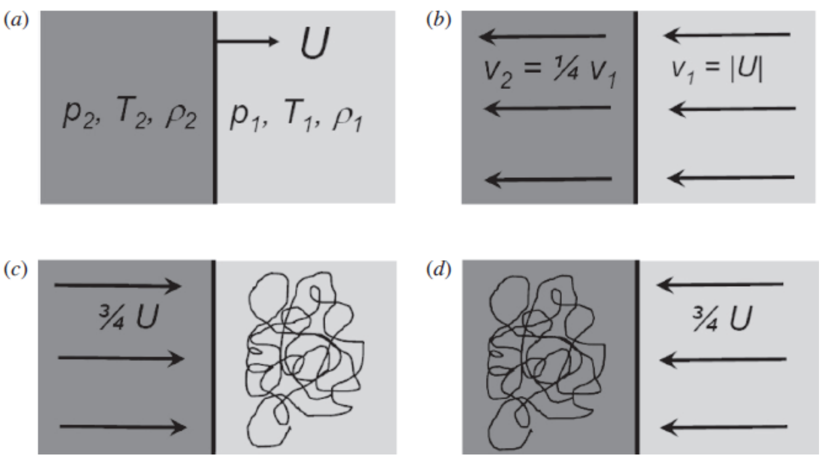
Fermi acceleration (1949)

Second order Fermi acceleration



$$\frac{\Delta E}{E} \sim \left(\frac{V}{c}\right)^2$$

First order Fermi acceleration

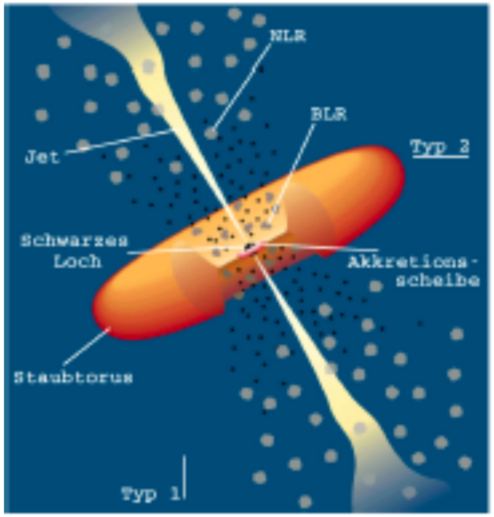


$$\frac{\Delta E}{E} \sim \left(\frac{V}{c}\right)$$

$$\frac{dN(E)}{dE} \sim E^{-2}$$

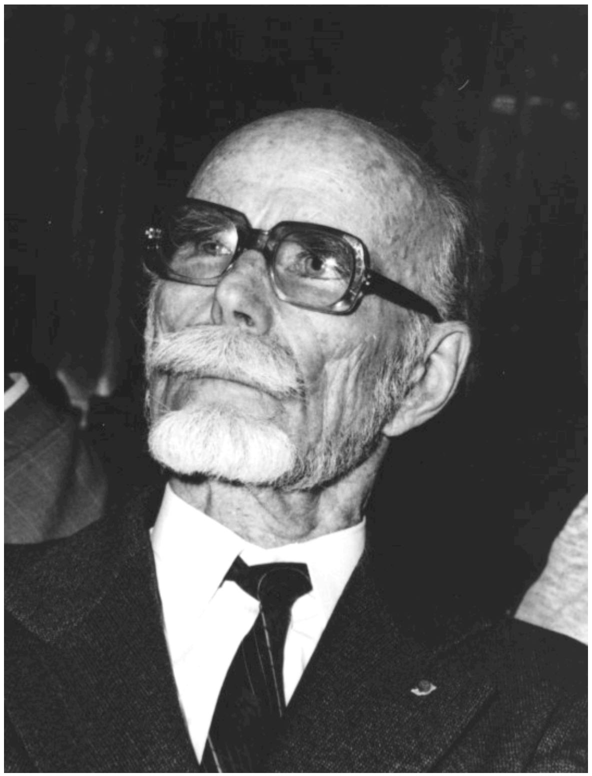
Where first order Fermi acceleration could exist

- Shock wave from SN remnant has life time of about several 10^4 -10^5 years, $v_s=10^6$ m/s
- SNR able to accelerate particle up to 1000 TeV
- SNR are confirmed as main galactic accelerator of Cosmic Ray.
- AGN - origin of extra galactic cosmic ray



Detection of cosmic rays

Extensive Air Showers (EAS)



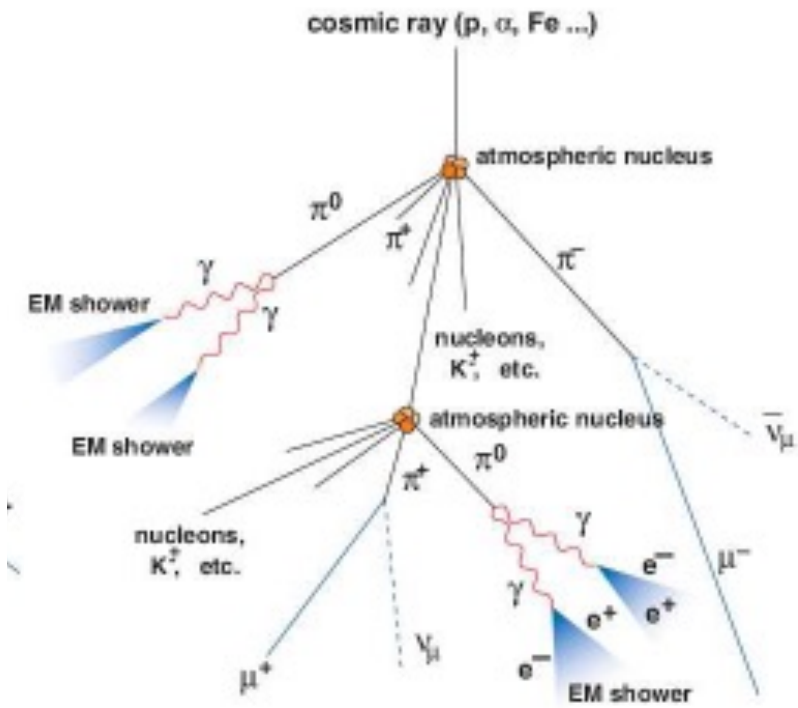
- Discovered in 1938 by Pierre Auger. Main processes:
- Electromagnetic showers:
  - $\gamma \longrightarrow e^+ e^-$ (pair production)
  - $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)
- Hadronic showers:
  - CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - $\pi^\circ \longrightarrow \gamma\,\gamma \longrightarrow$ e.m. showers

Hadron-initiated showers

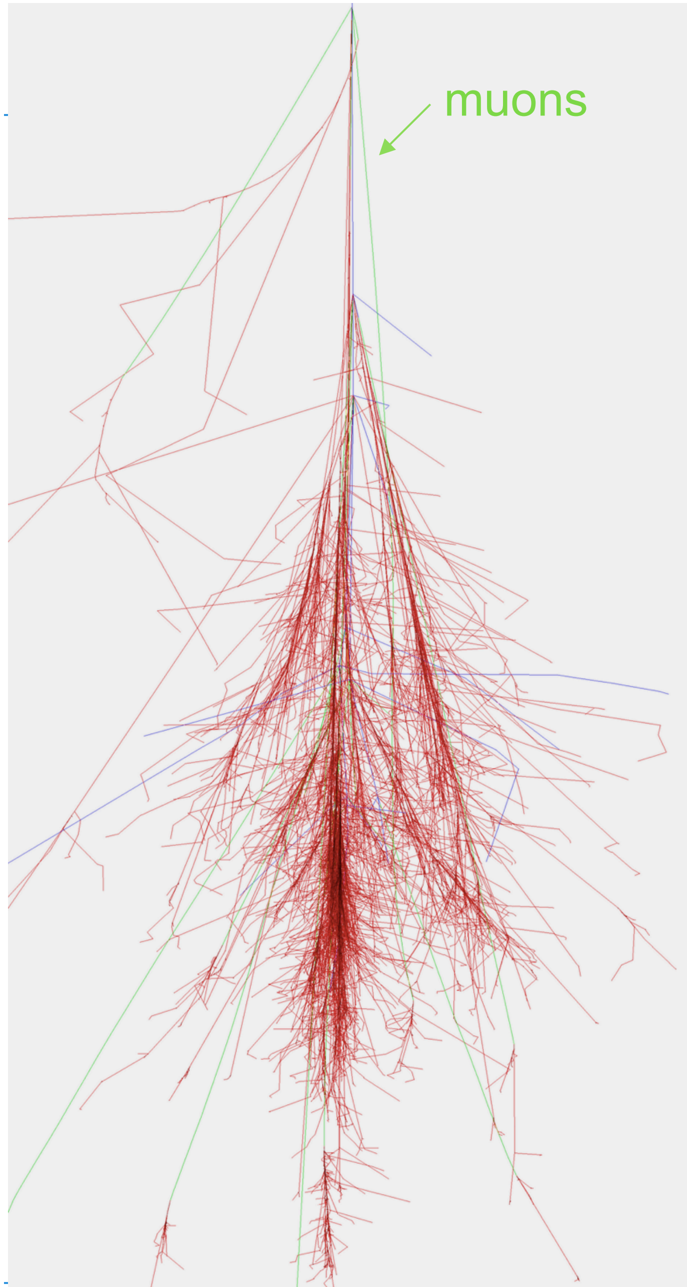
- After the first interaction, the nucleonic component of the showers goes on interacting until

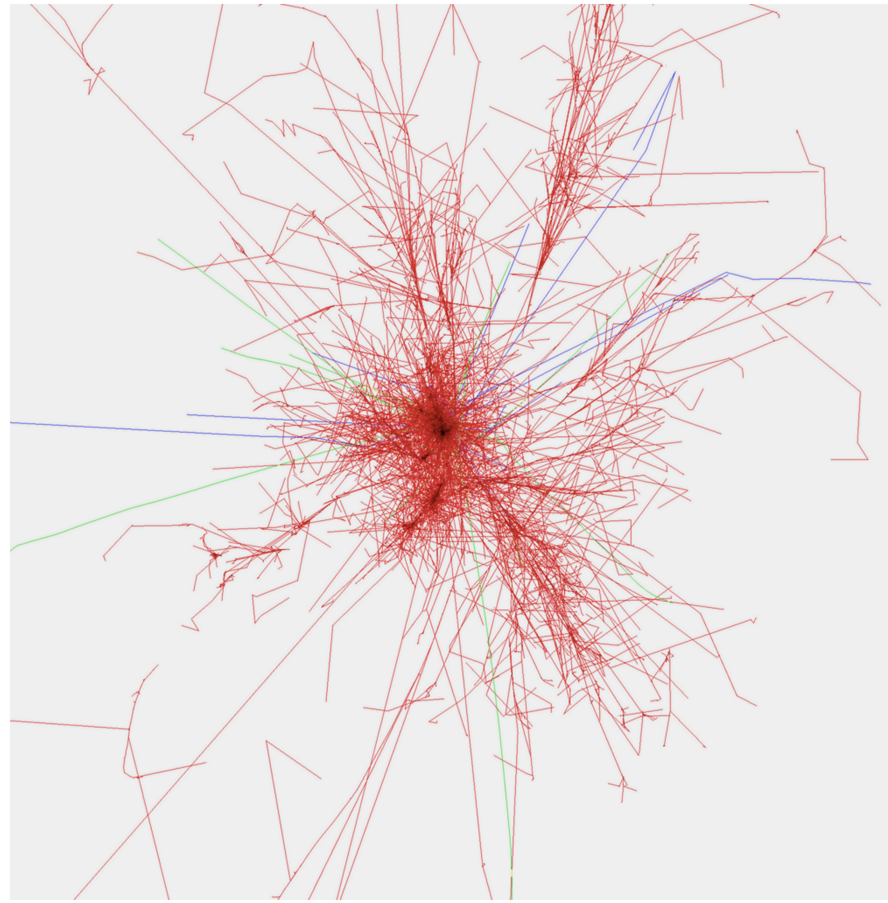
  $\langle E/A \rangle < E_c$ = 1 GeV (pion production threshold)

- Simple model: “superposition” ⇒ nucleus behaves as A nucleons of energy E_0 / A :
  - $X_{max} \propto \ln [E_0 / (A E_C)]$: for a given E_0 , showers initiated by heavy nuclei develop higher in the atmosphere



Simulated proton 100 GeV



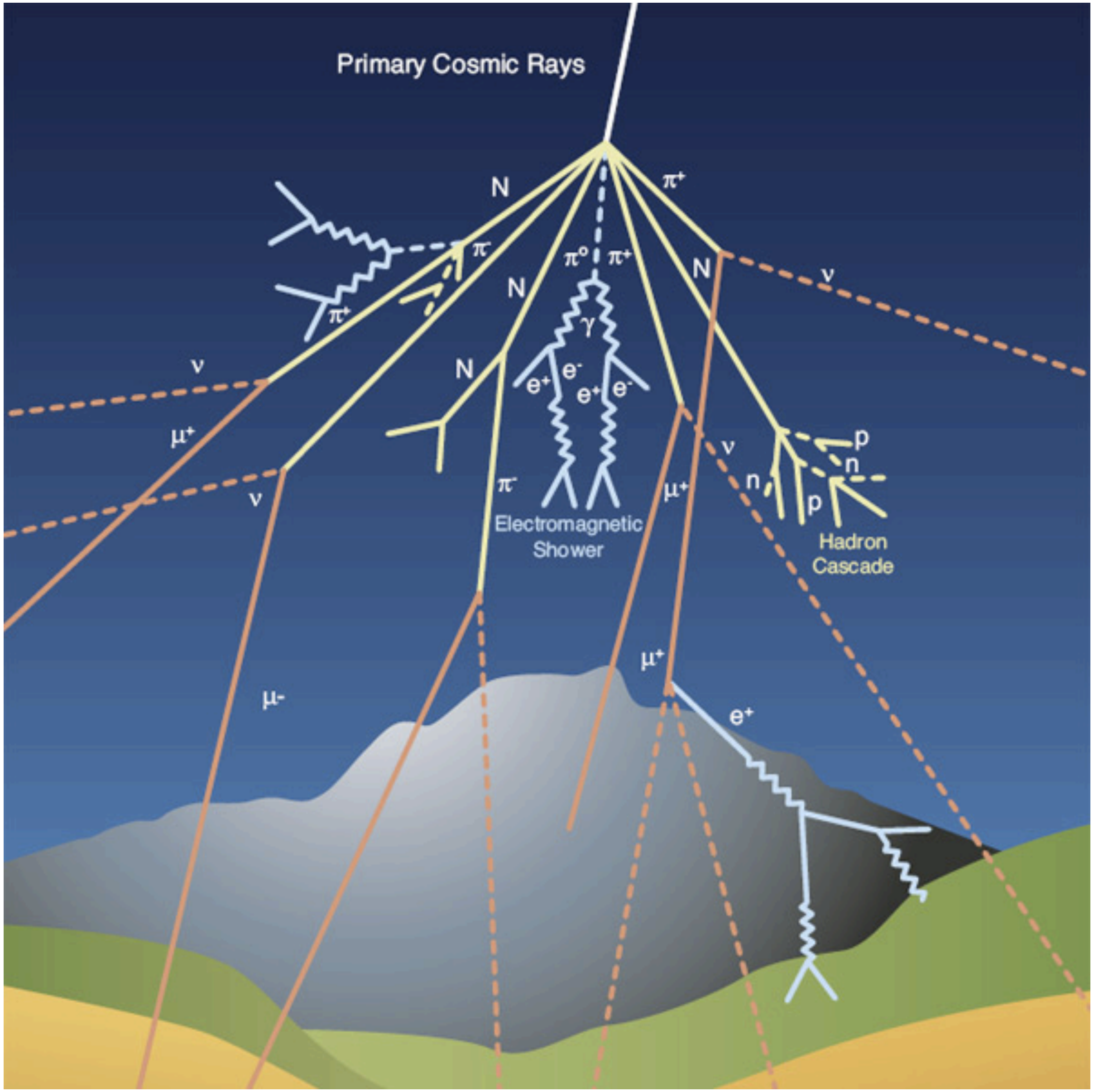


Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Hadron-initiated showers

- Muons, resulting mainly from charged pions, have a half-life of 2.2 μs in their own reference frame $\Rightarrow$ many arrive at the ground before decaying (and account for 75% of all secondary CRs detected at sea level)
- Neutral pions decay (most often) in 2 γ, resulting in EM subshowers at some angle w.r.t. the shower axis (carrying in average 1/3 of E_0)
- Detailed study requires a full Monte Carlo simulation

Cosmic ray shower



Current Observatories of Ultrahigh Energy Cosmic Rays

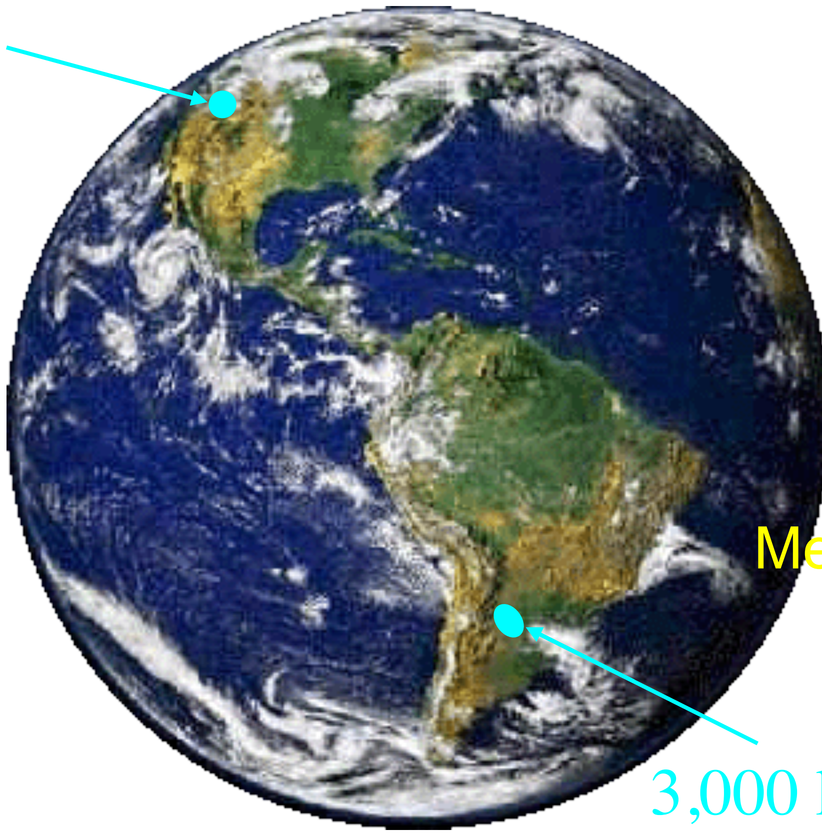
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



Pierre Auger Observatory

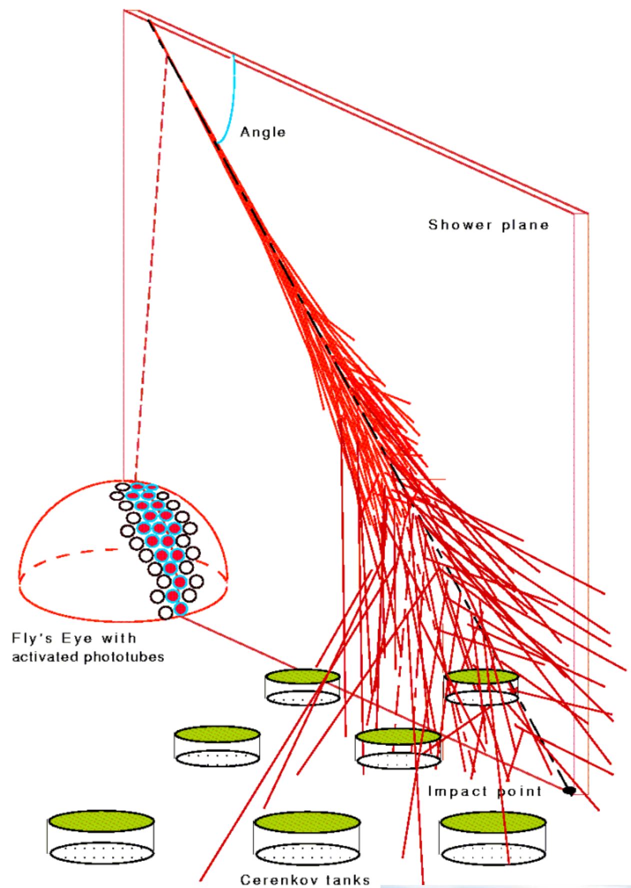
Mendoza, Argentina

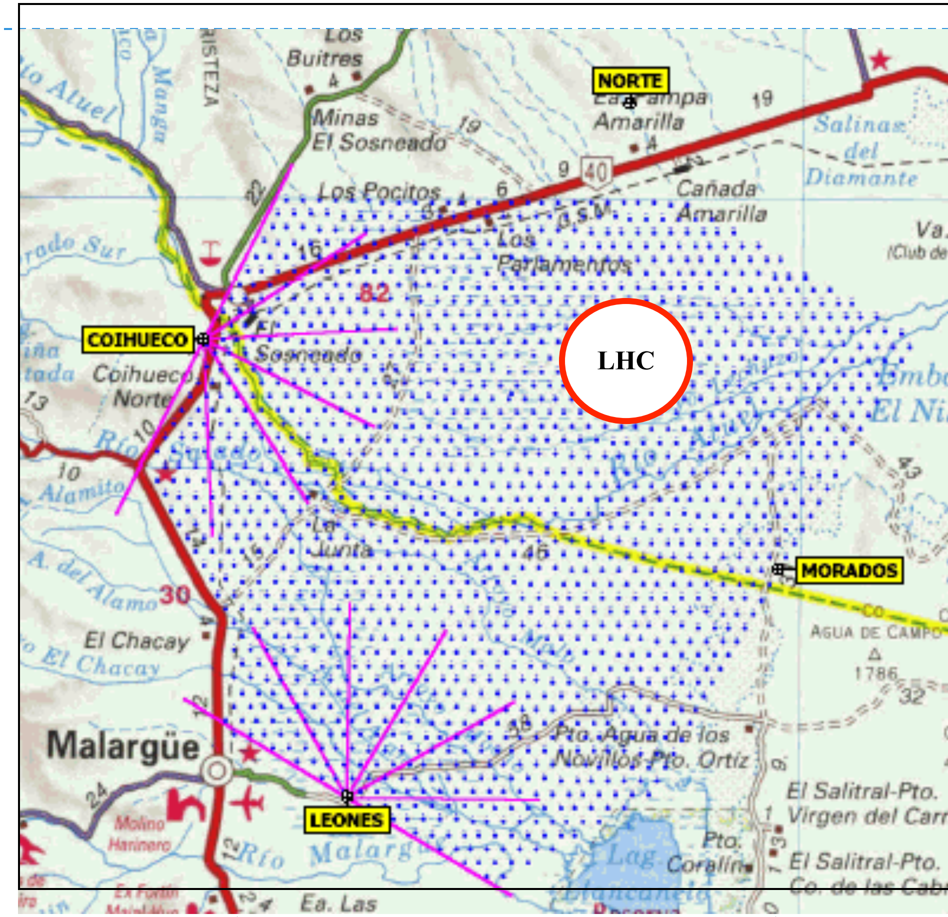
(19 country collaboration)

3,000 km^2 array

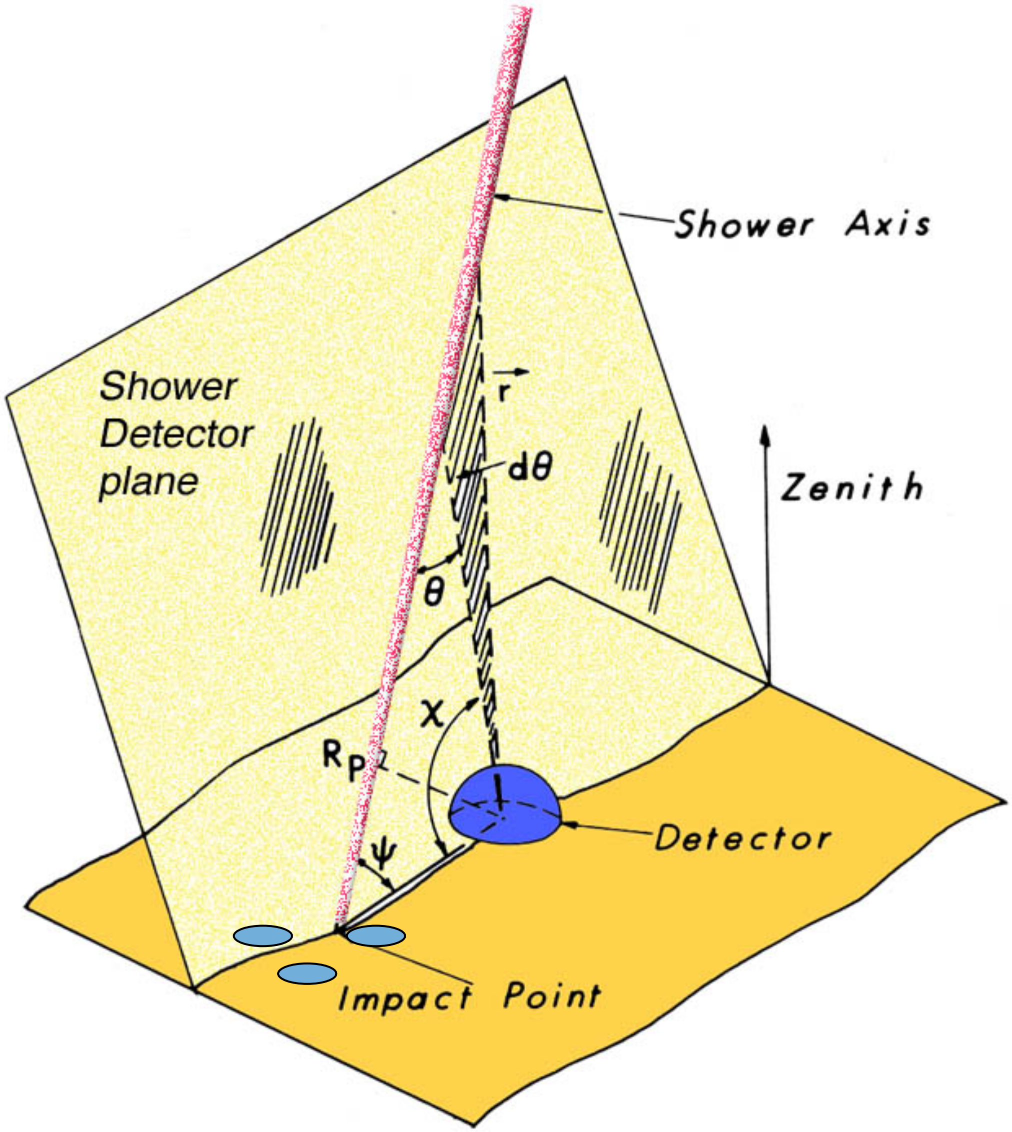
4 fluorescence telescopes

Pierre Auger Observatory (PAO)





65 km



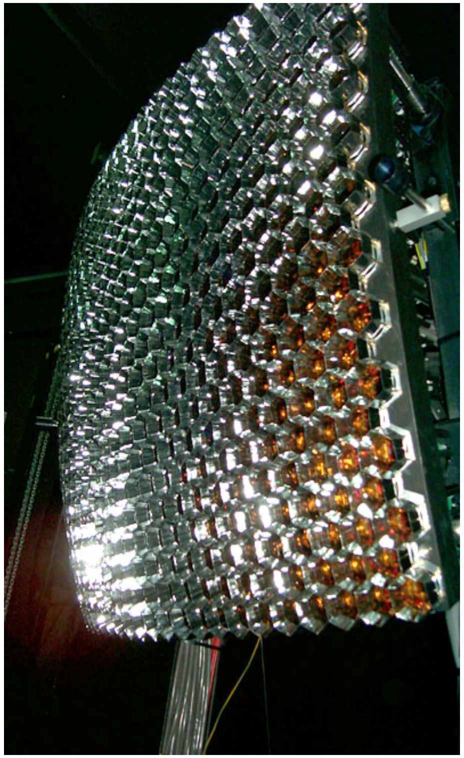
Important feature of the hybrid approach

Precise shower geometry

Essential step towards high quality energy and X_{max} resolution

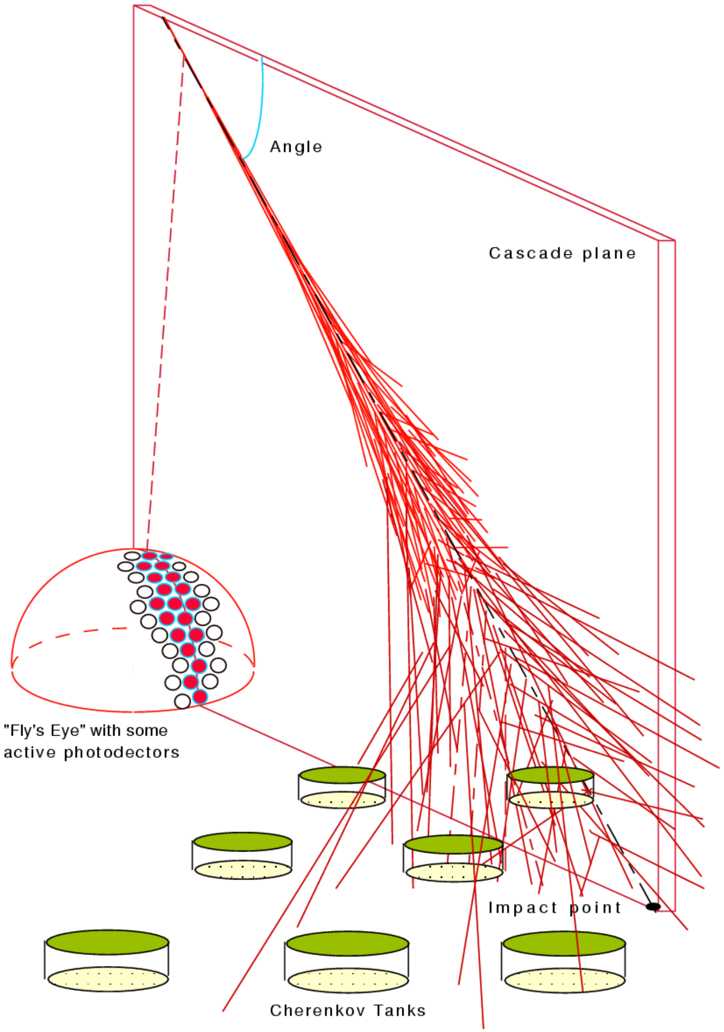
Times at angles, χ , are key to finding R_p

PAO – Principle of detection



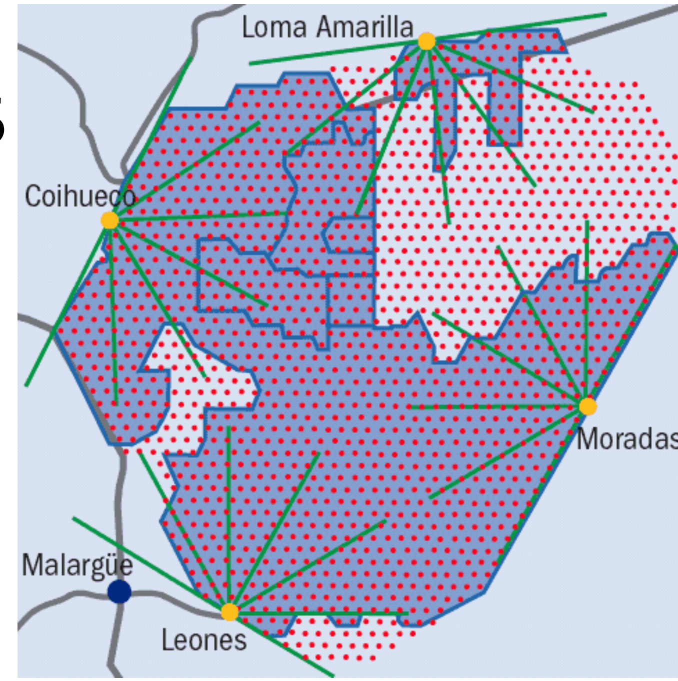
Camera with 440 PMTs

(Photonis XP 3062)

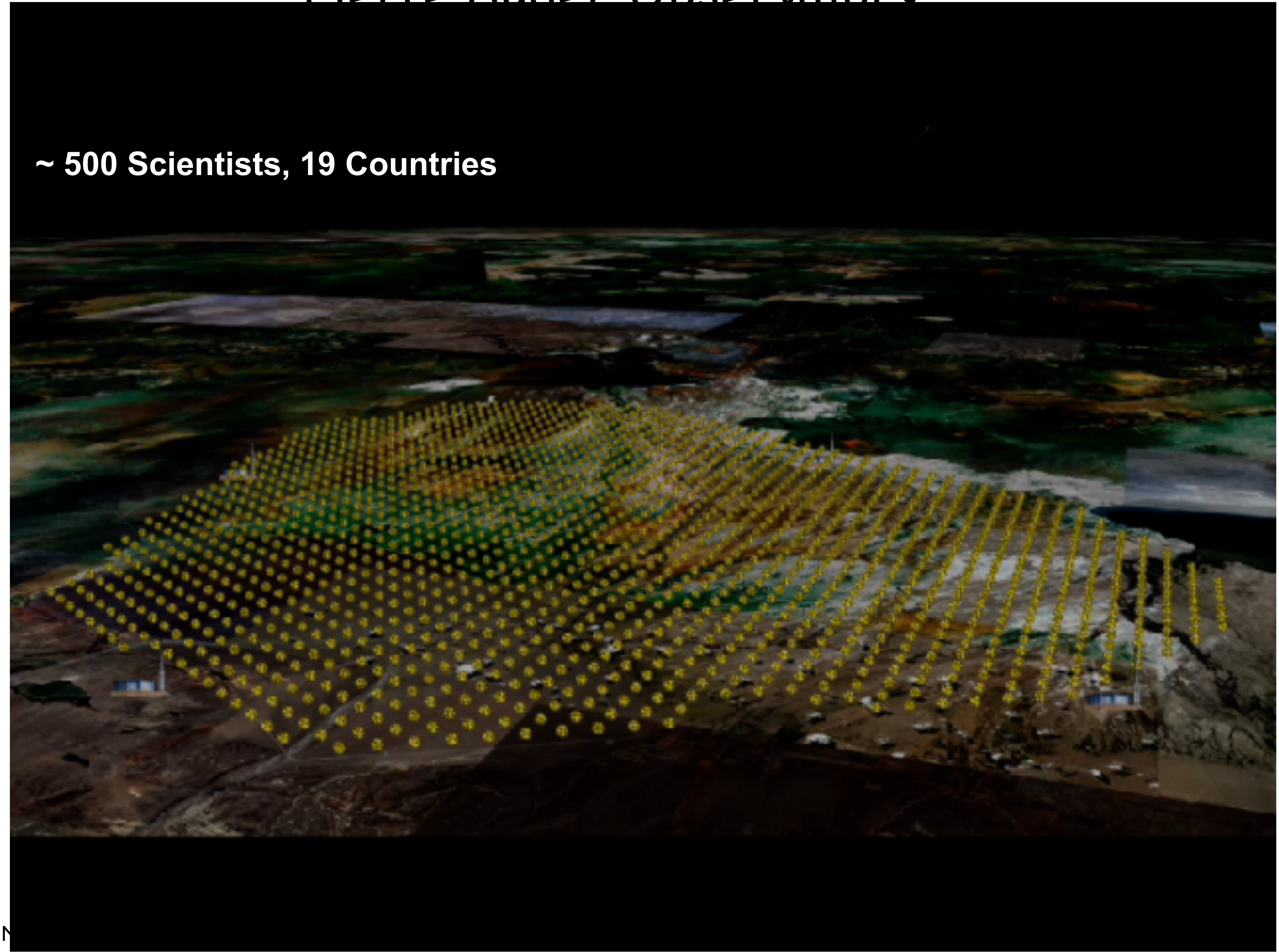


Pierre Auger(PAO) Observatory (UHE-EHE)

- 1660 water ČD at a distance of 1,5 km distributed over the area of 3000 km² – measure lateral profile EAS.
- 24 special telescopes record UV light (300-400 nm) emitted by excited nitrogen atoms in the atmosphere – measure longitudinal profile of EAS.



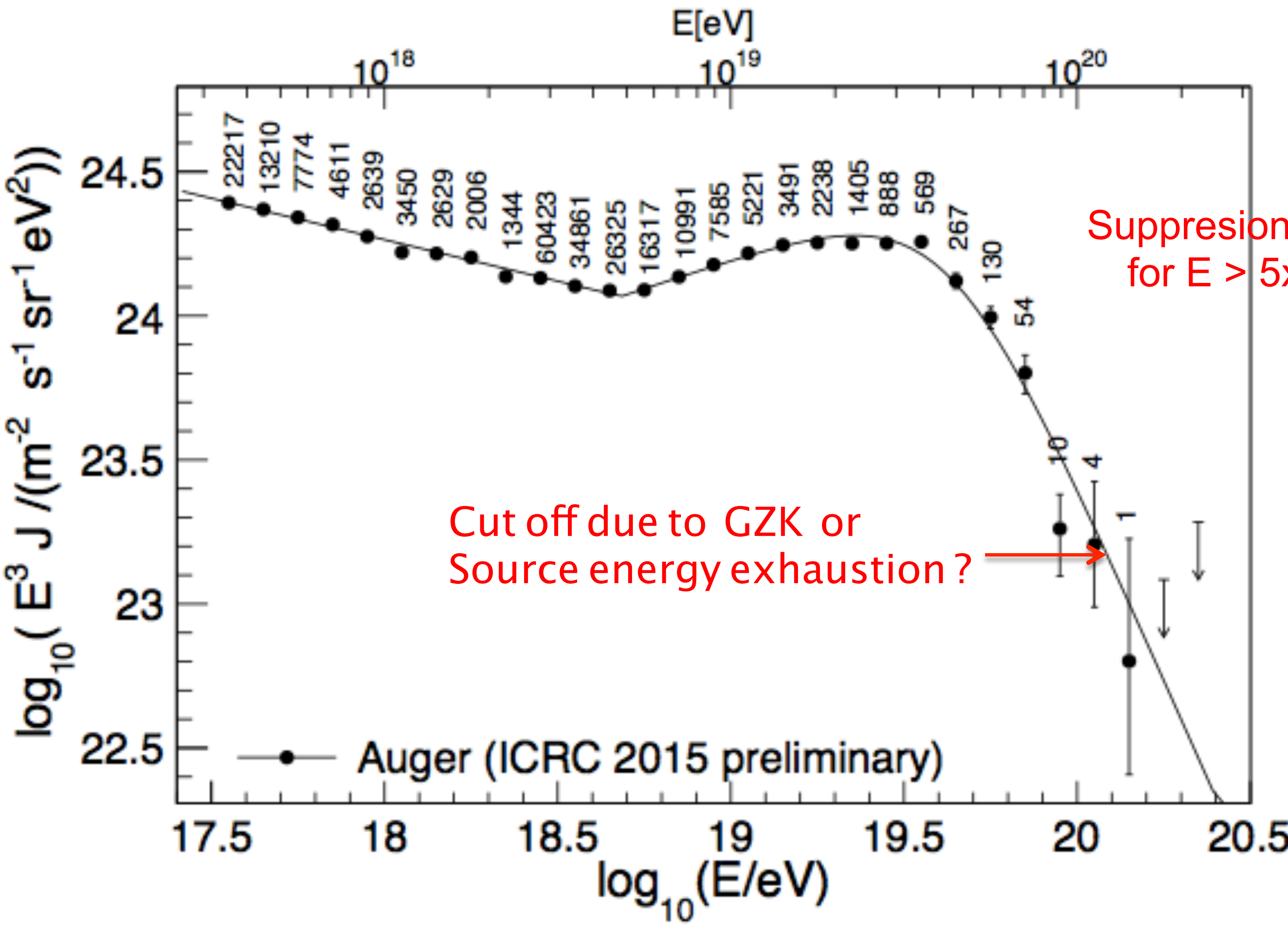
Pierre Auger Observatory



N

PAO results

I. Valiño for the Pierre Auger Coll., Proc. 34th ICRC (2015)



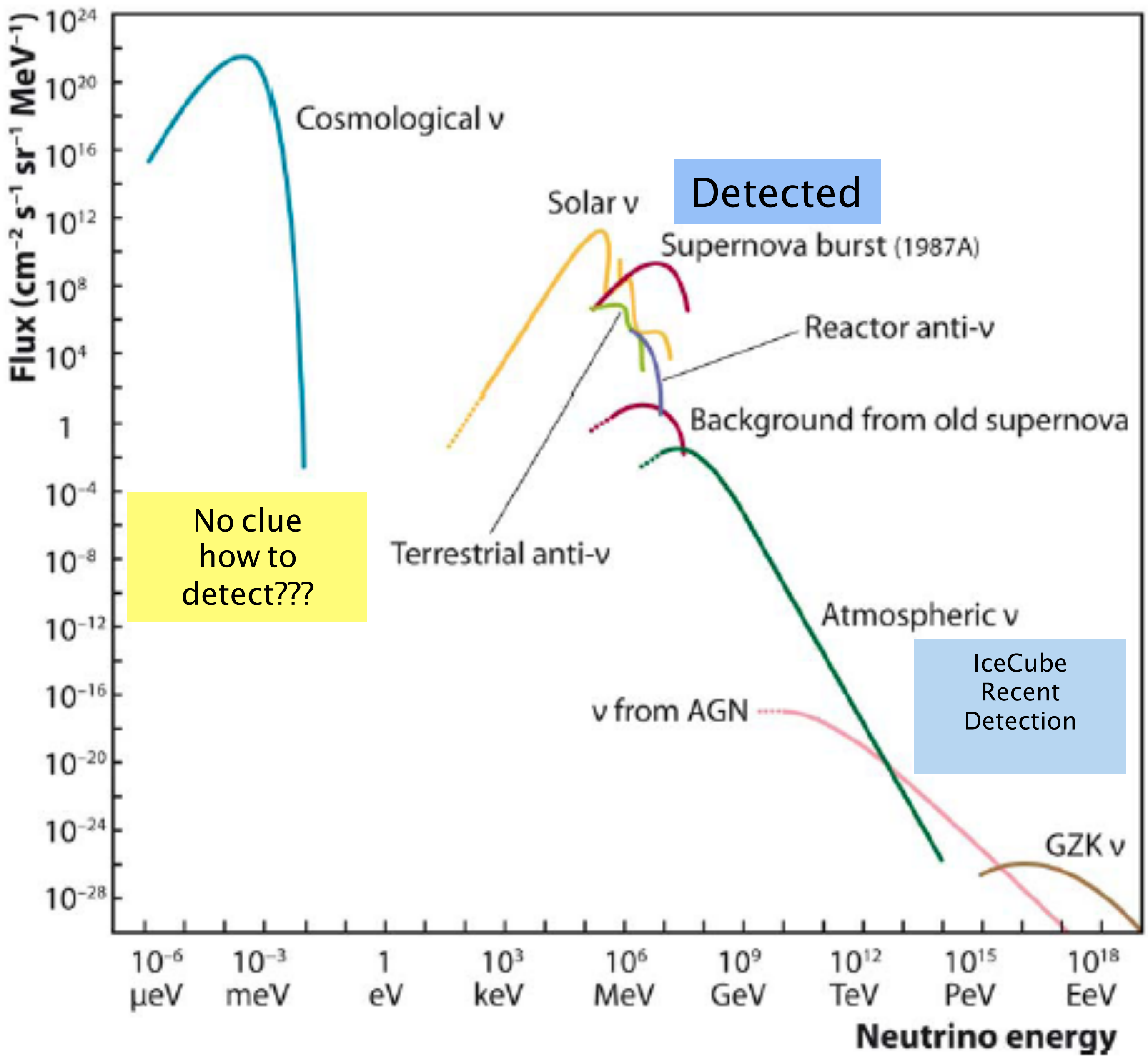
To understand the spectrum features it is essetial to understand the composition of UHE CR

PAO - summary

- PAO – study ultra high energy Universe and particle physics at the highest energies ($\sqrt{s}$=57 TeV)
- GZK – like suppresion established
- Complex primary mass compositions scenario
- Current hadronic interaction model not able to describe consistently the air shower observables
- Upgrade: AUGER PRIME & AERA – measure independently the e.m. nnd muonic componnet on the ground as well as radiation emitted in the frequency range 30-80 MHz by air-shower electons and positrons deflected in the Earth magnetic filed

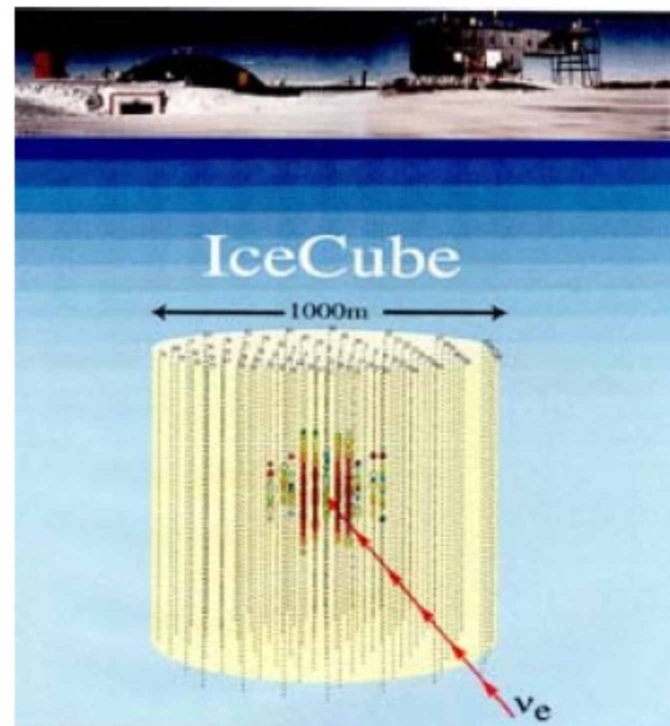
Neutrino astronomy

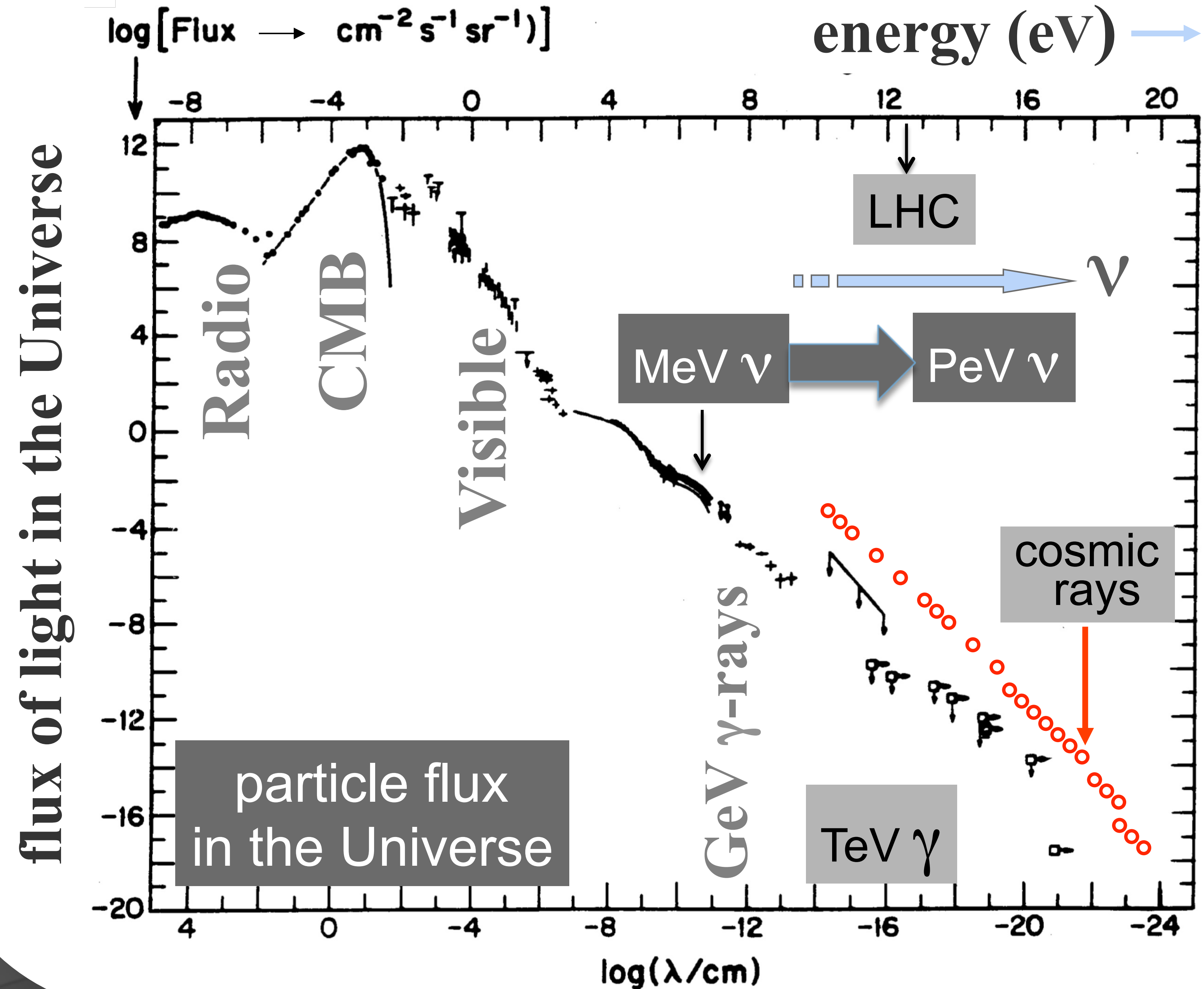
Neutrino spectrum



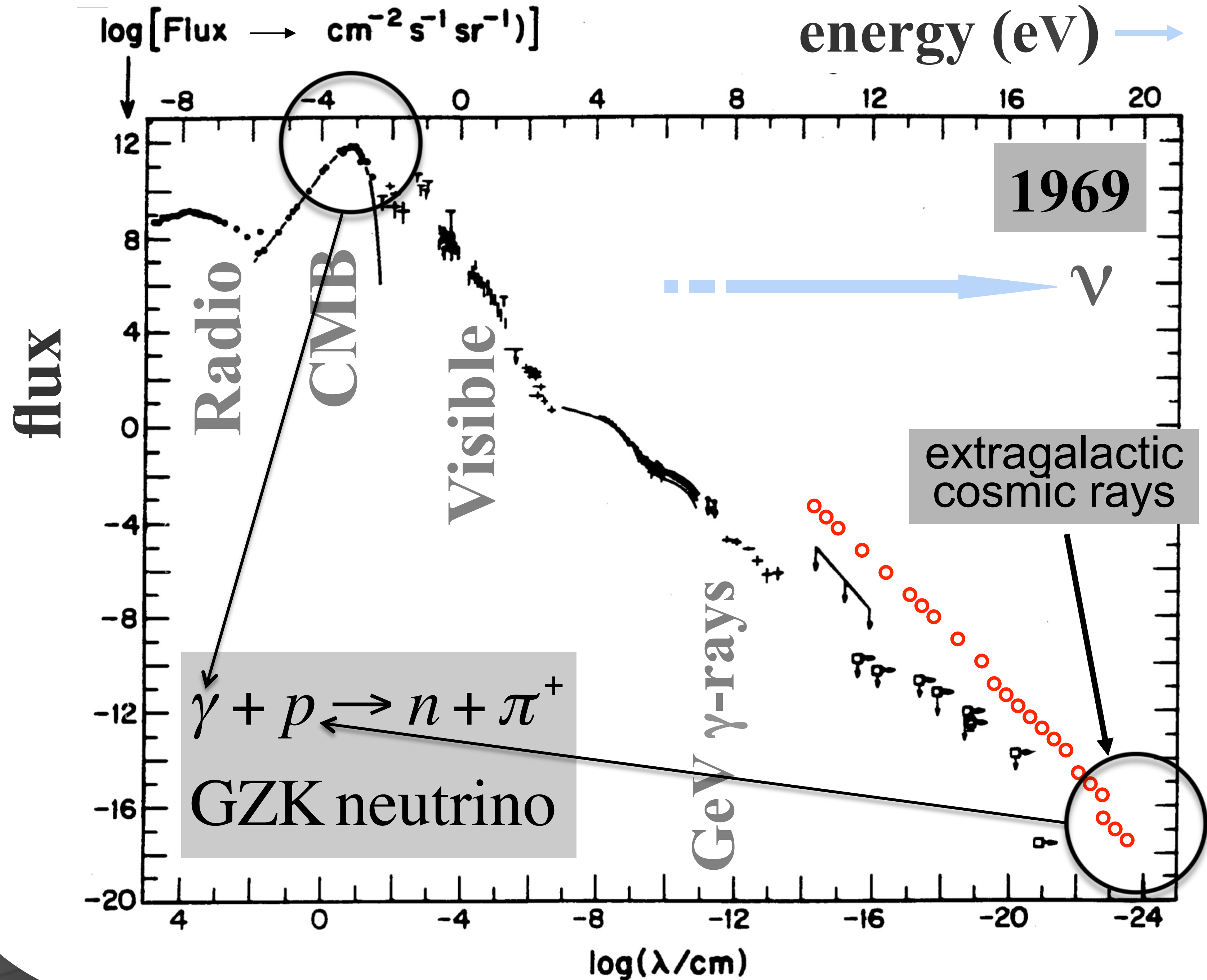
Neutrino astronomy

- Neutrinos are elementary particles of very small mass (SuperKamiokande 1998).
- Intergalactic gas, dust and magnetic filed does not affect neutrinos.
- Neutrinos are ideal messenger from the region of the Universe unreachable by electromagnetic spectrum
- Universe is full of relic neutrinos of very low energy (400 neutrinos/m^3 at 1.9 K) generated 2 seconds after Bing Bang-a, passing through 50 l.y. thick lead.
- It will be wonderful to detect this neutrinos !?
- Neutrino detectors need a huge volume.
- Neutrino oscillation impose a lower limit on the heaviest neutrino mass of about 0.05 eV. Neutrino contribute at least 0.1% to cosmic matter





log[Flux → cm−2 s−1 sr−1)]
energy (eV)
flux of light in the Universe
LHC
ν
MeV ν
PeV ν
Radio
CMB
Visible
GeV γ-rays
cosmic rays
TeV γ
particle flux
in the Universe
log(λ/cm)



log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
4
8
12
16
20
1969
ν
flux
Radio
CMB
Visible
GeV γ-rays
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^+$
GZK neutrino
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+} \ \ and \ \ p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

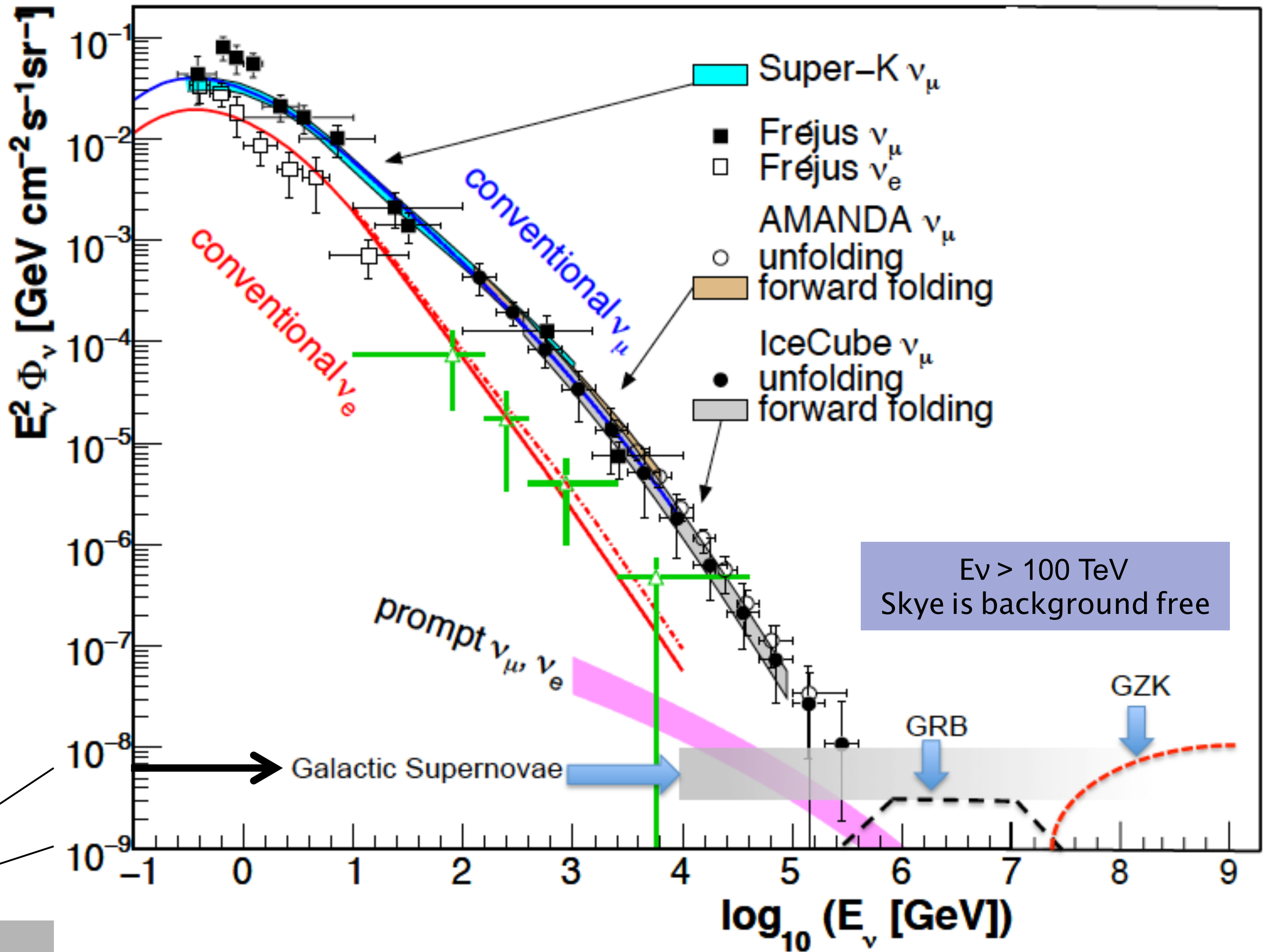
...but it points at its source!

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$$dN/dE \sim E^{-2}$$

10—100 events per year for fully efficient 1 km^3 detector



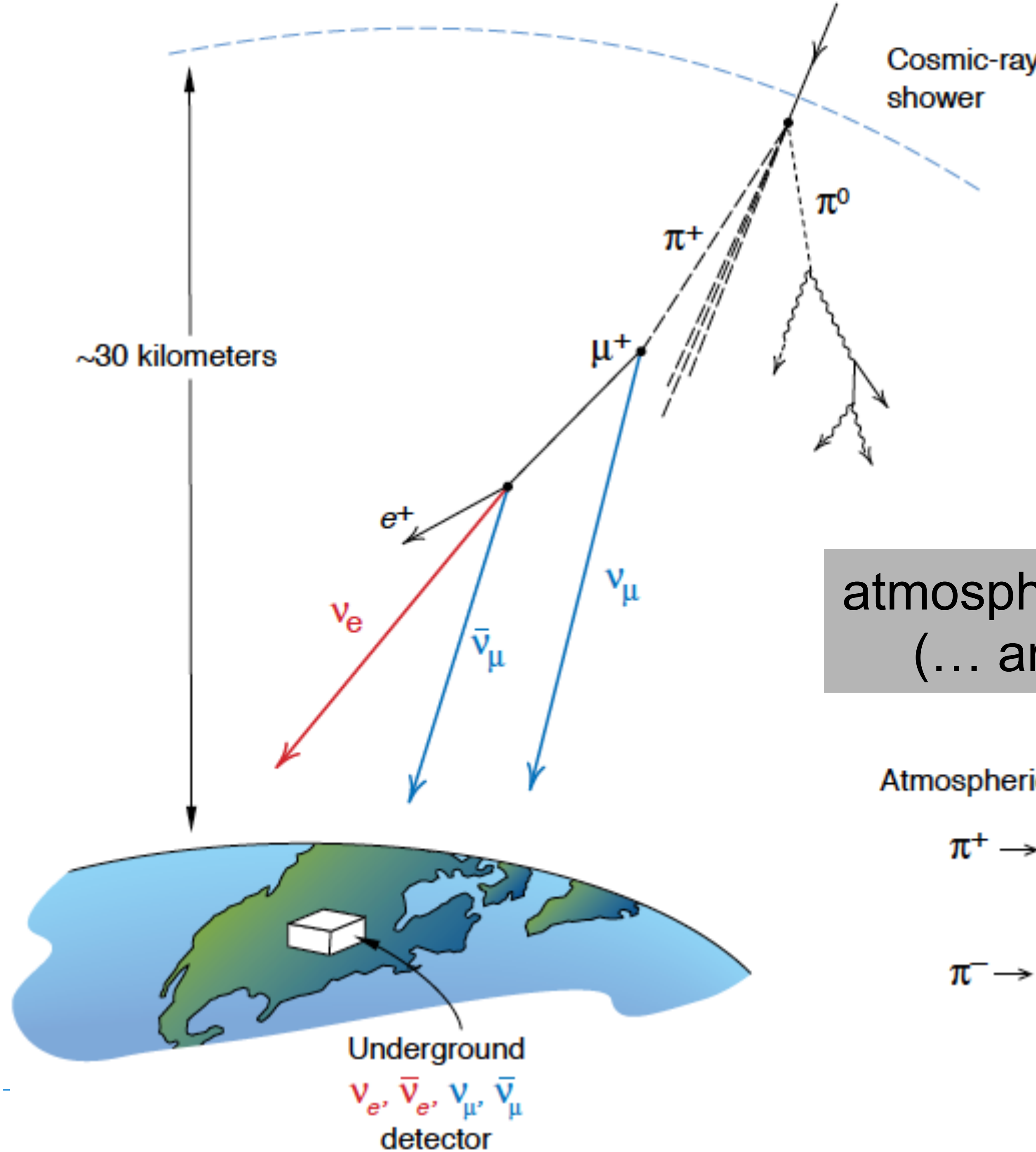
Prediction of neurtino fulx

atmospheric

cosmic

100 TeV

atmospheric neutrinos (… and muons!)

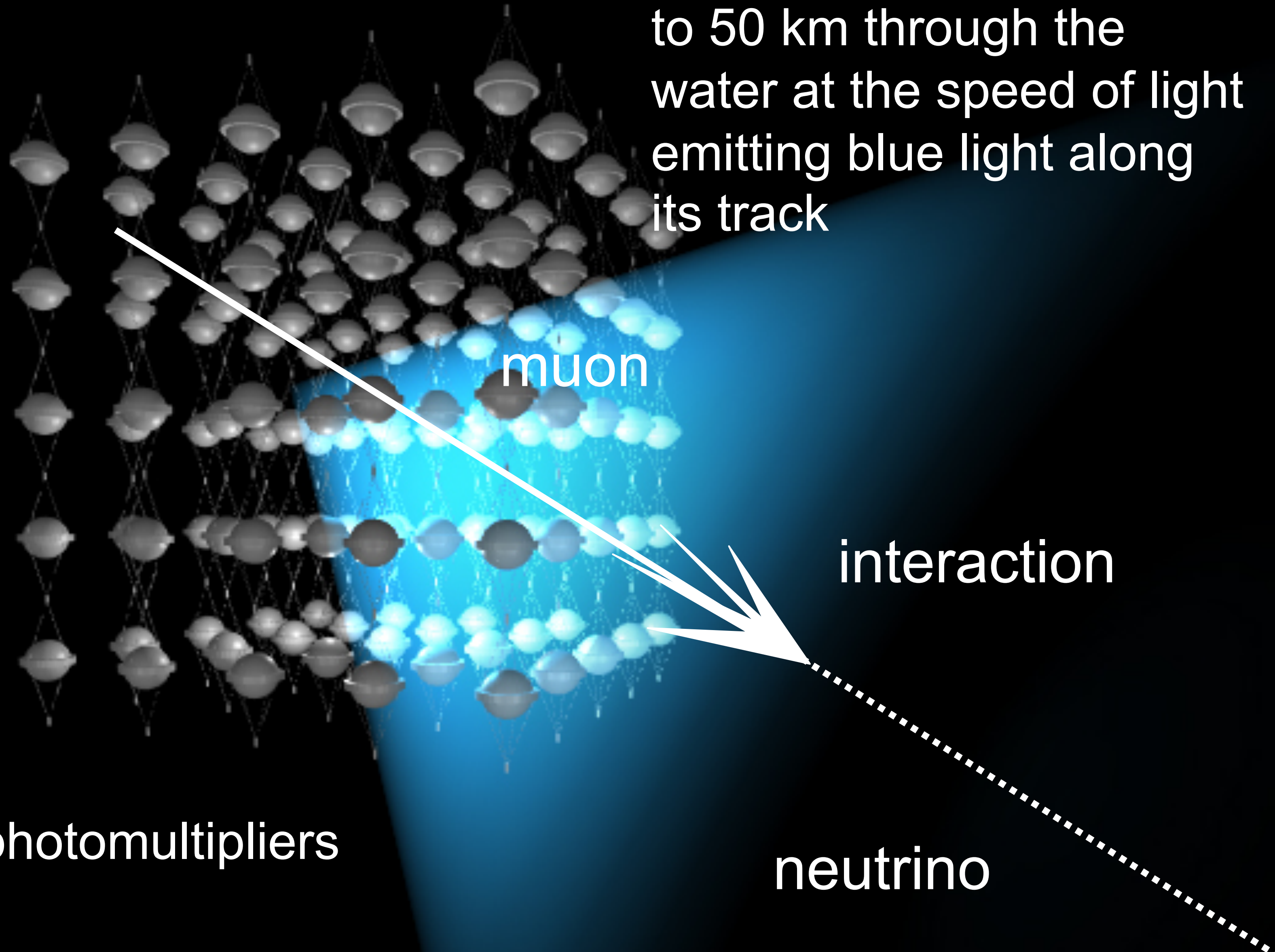


Atmospheric neutrino source

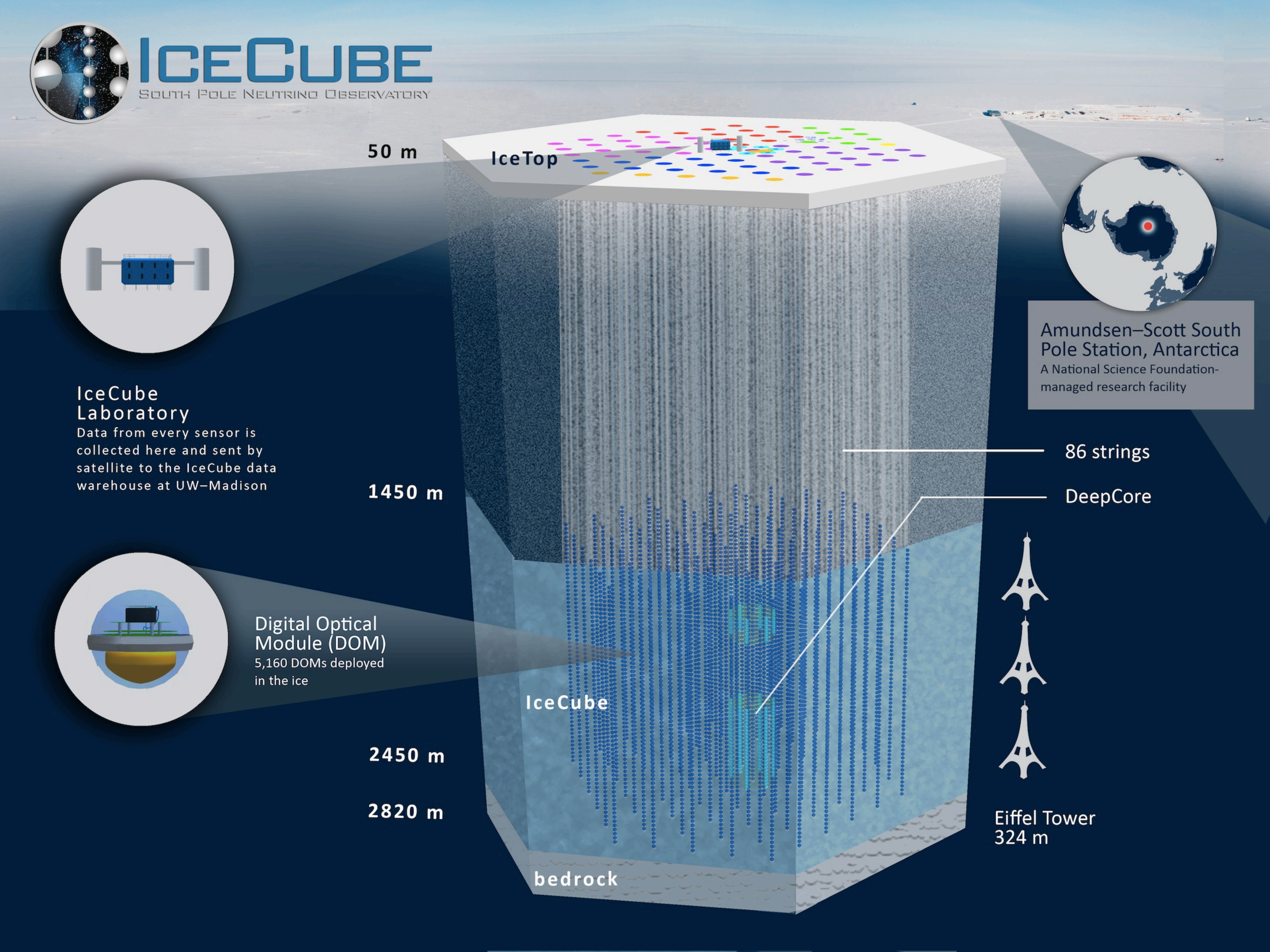
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

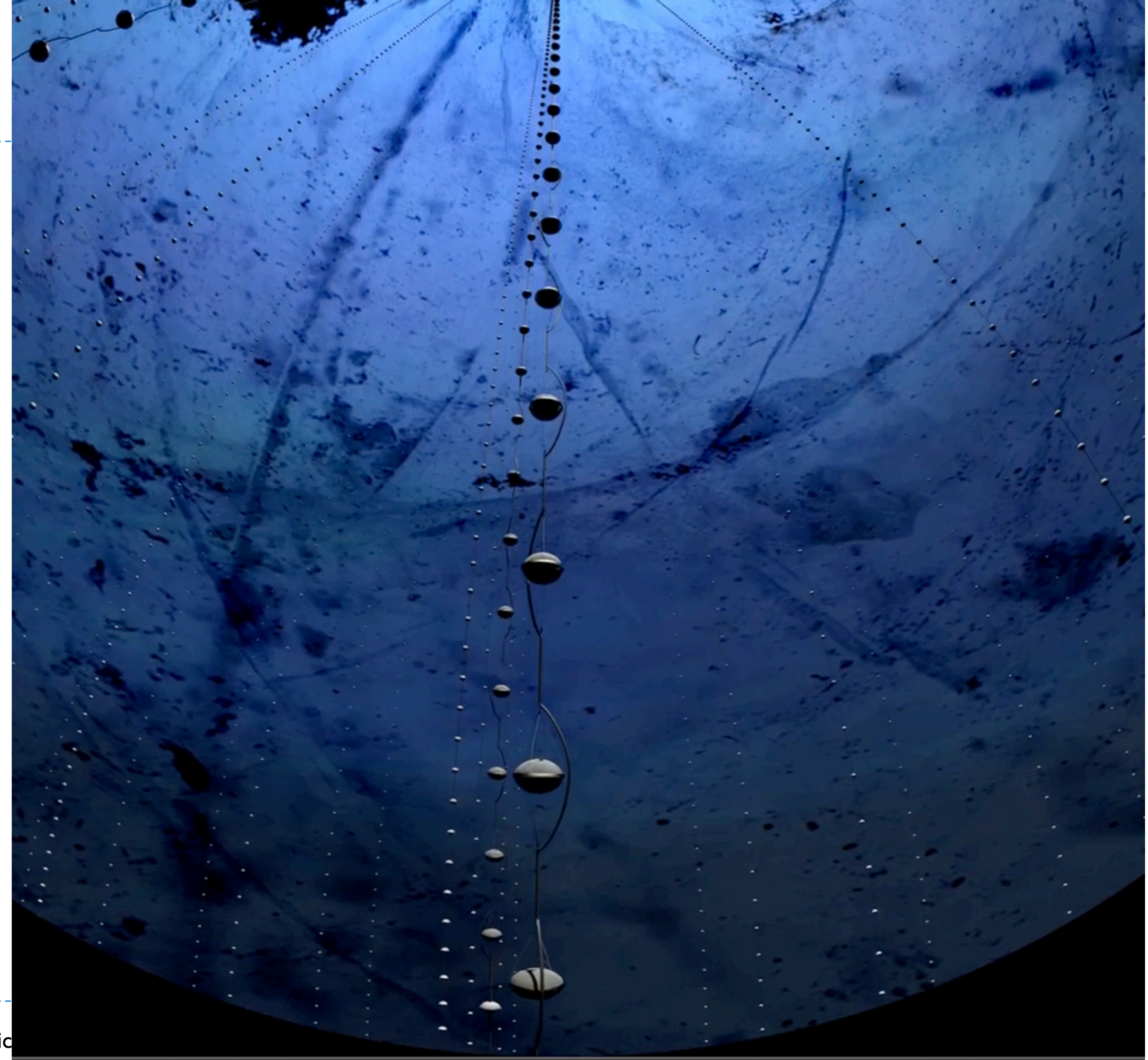
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

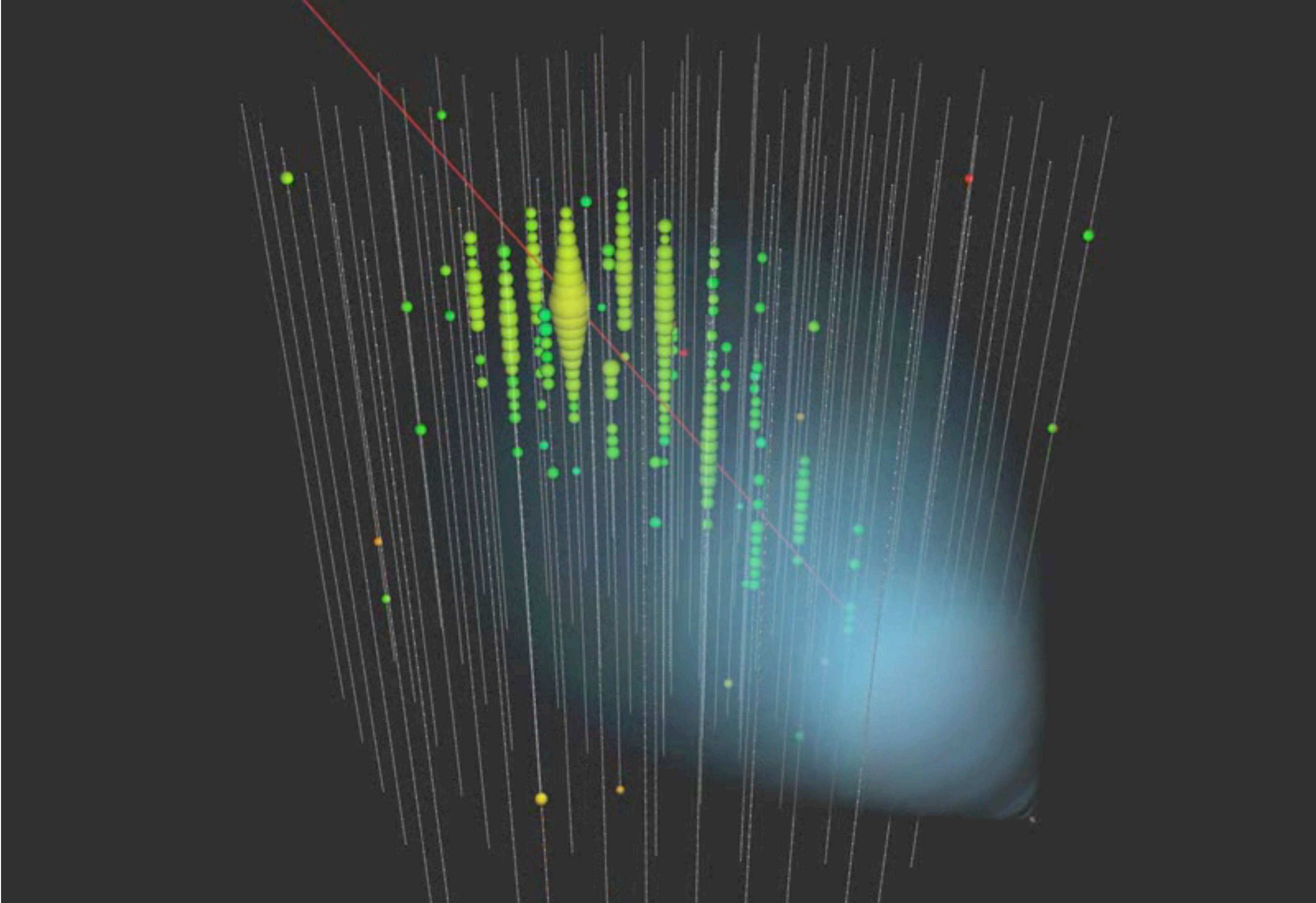


- lattice of photomultipliers


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube
Laboratory
Data from every sensor is
collected here and sent by
satellite to the IceCube data
warehouse at UW–Madison
Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility
86 strings
DeepCore
1450 m
Digital Optical
Module (DOM)
5,160 DOMs deployed
in the ice
IceCube
2450 m
2820 m
bedrock
Eiffel Tower
324 m



photomultiplier tube -10 inch

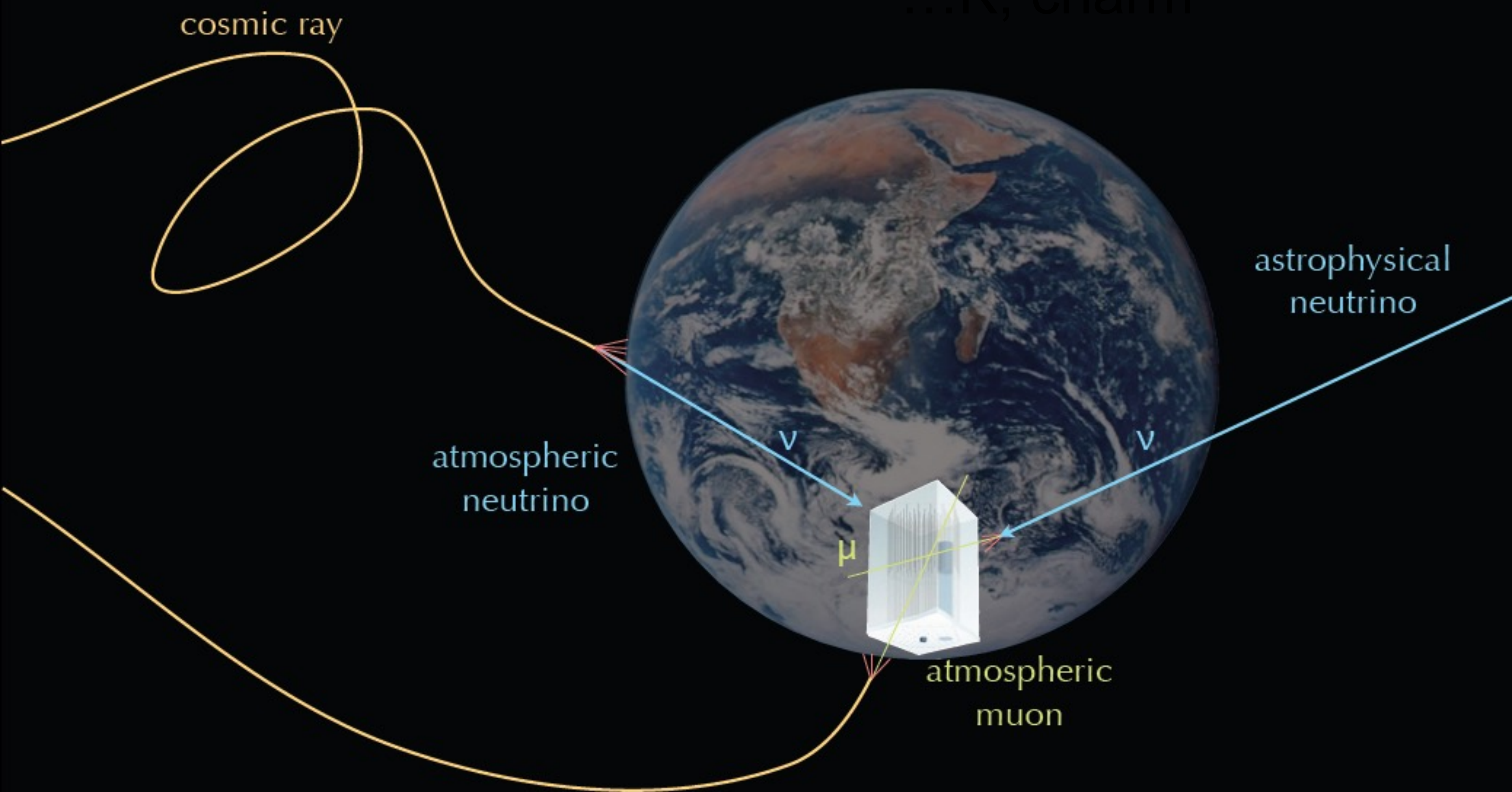


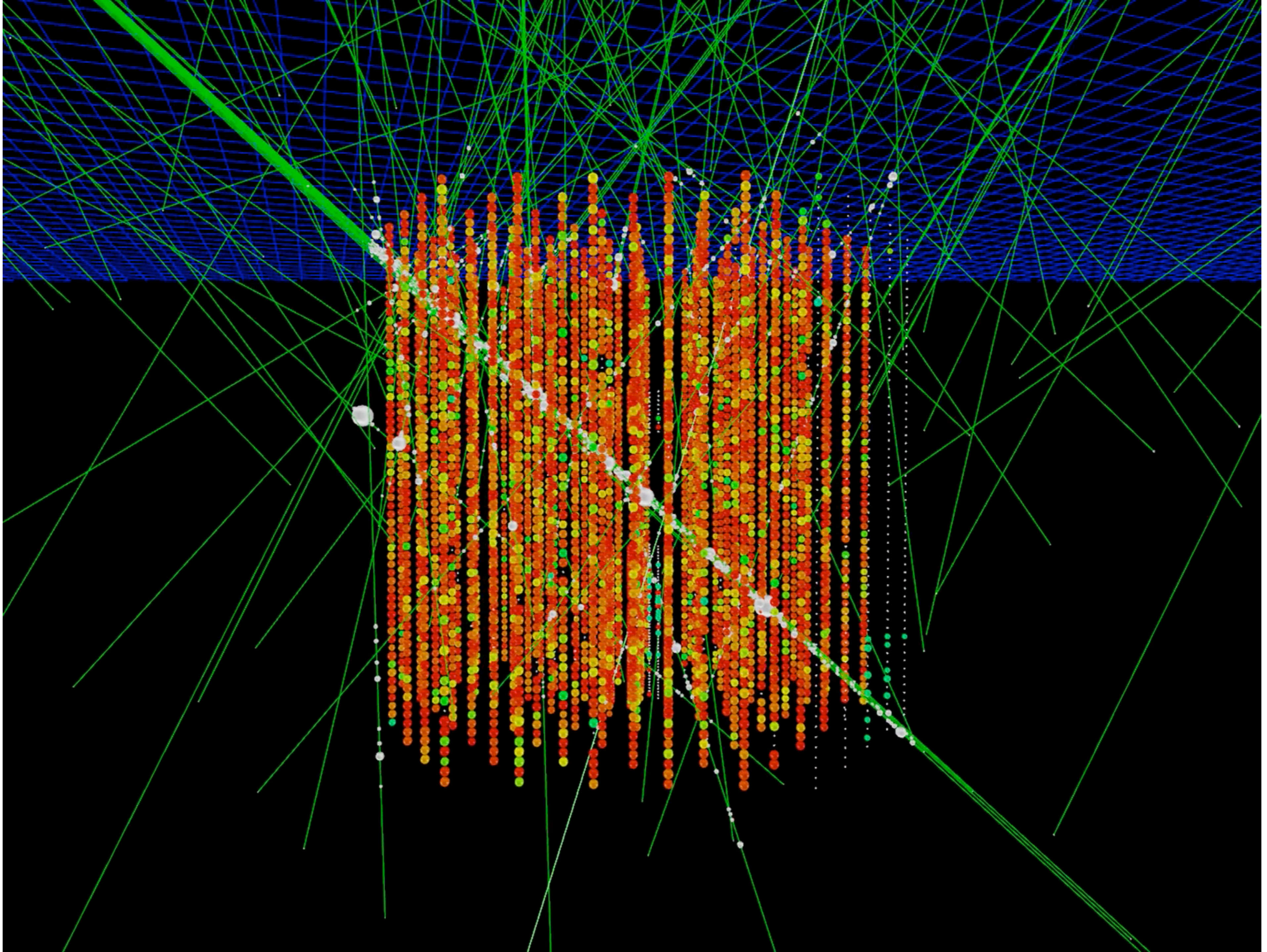
muon track: time is color; number of photons is energy

Signals and Backgrounds

cosmic ray

...K, charm





… you looked at 10msec of data !

muons detected per year:

• atmospheric*	μ	~ 10^{11}
• atmospheric**	$\nu \rightarrow \mu$	~ 10^{5}
• cosmic	$\nu \rightarrow \mu$	~ 10

* 3000 per second

** 1 every 6 minutes

Events in IceCube

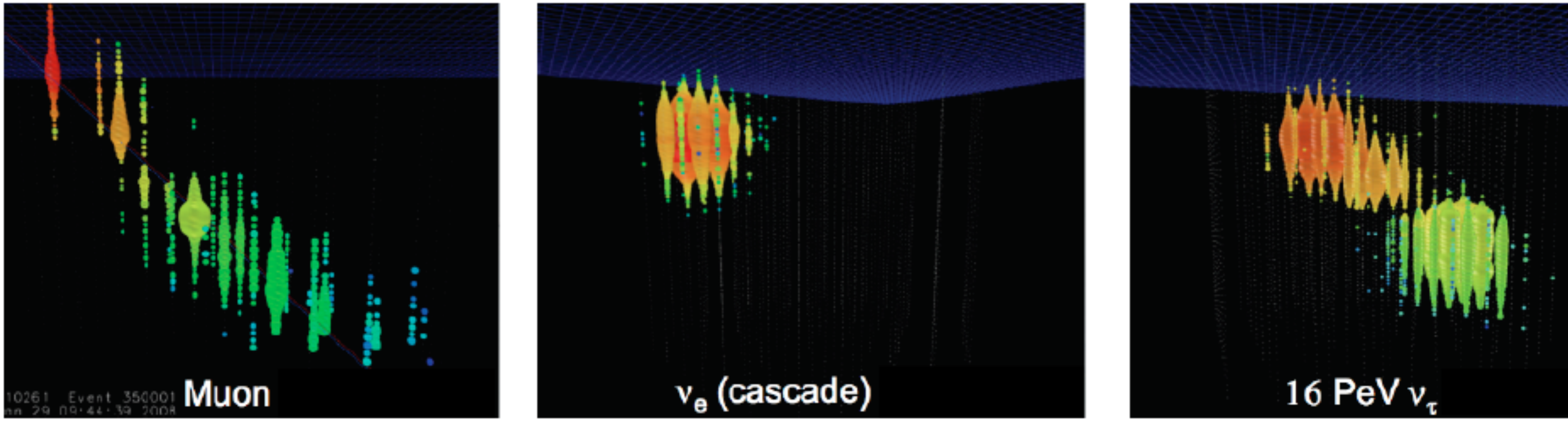
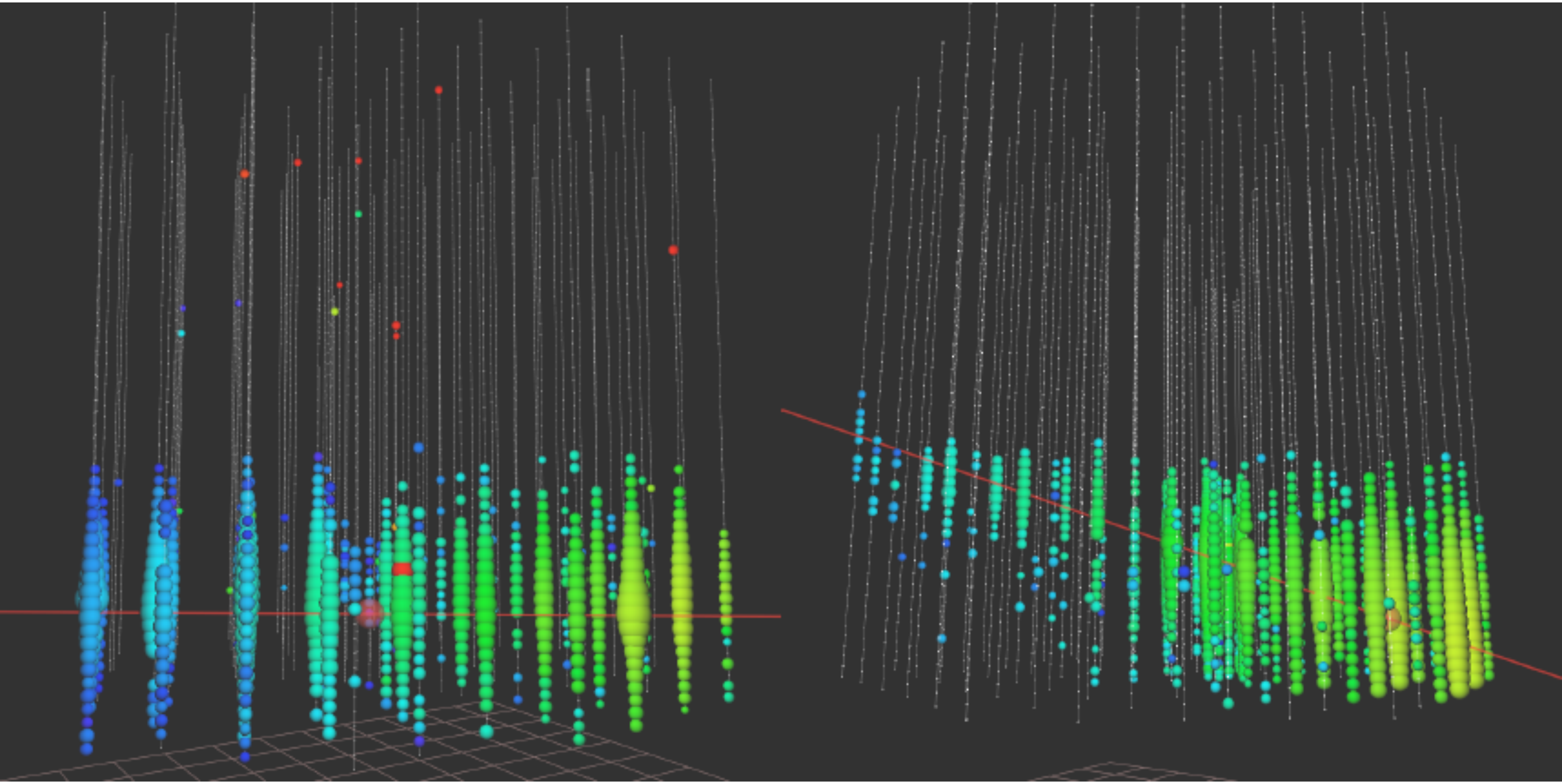


Figure 4: Simulated events in the IceCube detector, visualized using the IceCube event display, showing the 3 typical topologies discussed in Sec 3. The shading represents the time sequence of the hits. The size of the dots corresponds to the number of photoelectrons detected by the individual photomultipliers. From left to right: a muon event of 100 TeV, a cascade event induced by a 100 TeV ν_e, and a double bang event induced by a 16 PeV ν_τ.

Highest energy muon energy observed: 560 TeV
→ PeV energy neutrino



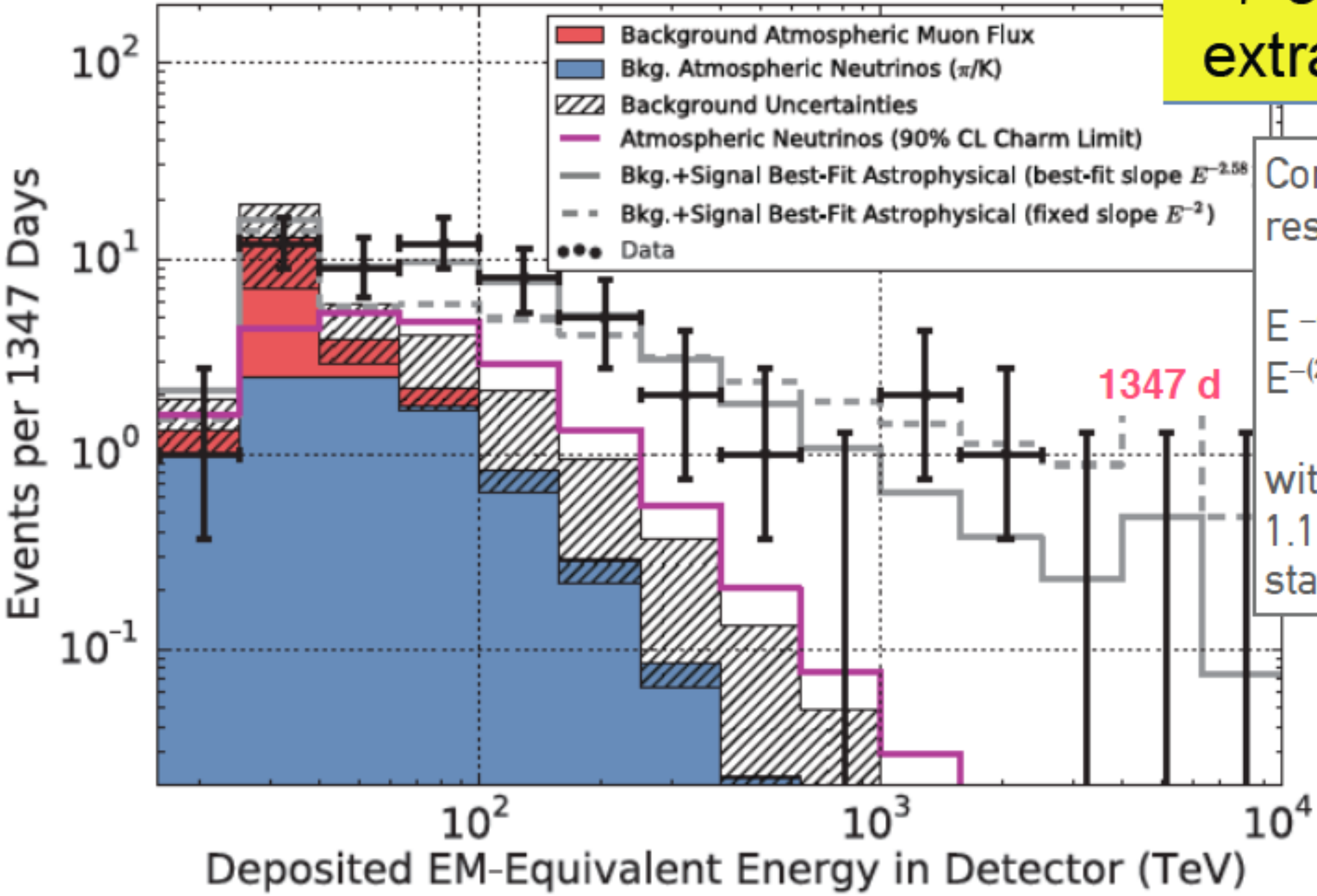
Photons are timed with 2 ns precision allowing direction reconstruction with 10^o precision

Four years of data

54 events of which 2 are evident background events. Background: 12.6 ± 5.1 atmospheric muon events + Atmospheric prompt component estimated using a previously set limit on atmospheric neutrinos with 59 strings: $9.0_{-2.2}^{+8.0}$

- Flux assuming E^{-2}: ~1.0 x $10^{-8} E^{-2}$ [/GeV/cm^2/s/sr]
- Best fit spectral index: -2.56

~7 σ evidence for extra-terrestrial ν



Compared to the all-sky result, the fit prefers

$E^{-(2.0 \pm 0.4)}$ in the northern sky
$E^{-(2.56 \pm 0.12)}$ in the southern sky

with a significance of 1.1 σ (p = 13%). Probably a statistical fluctuation.

ICRC2015
arXiv:1510.05223

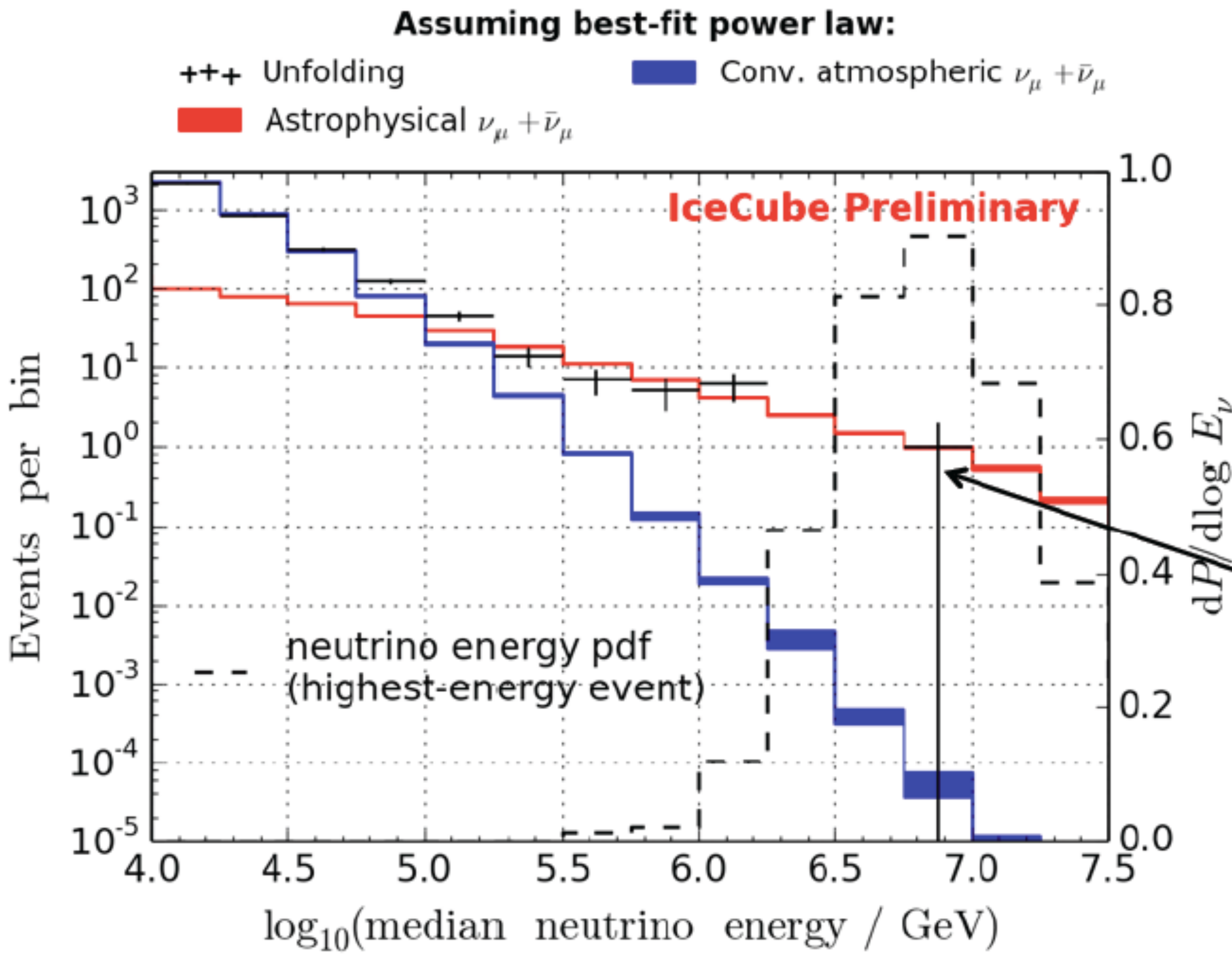
Four years of data

Best fit astrophysical spectral index of γ = 2.13 ± 0.13

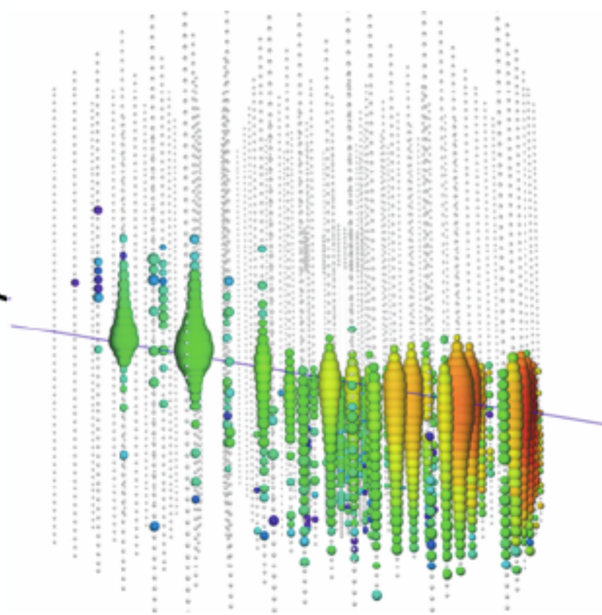
$(0.90^{+0.30}_{-0.27}) \times 10^{-18}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$

191 TeV and 8.3 PeV

ICECUBE



5.6 sigma detection of astrophysical neutrinos with through-going muons analysis

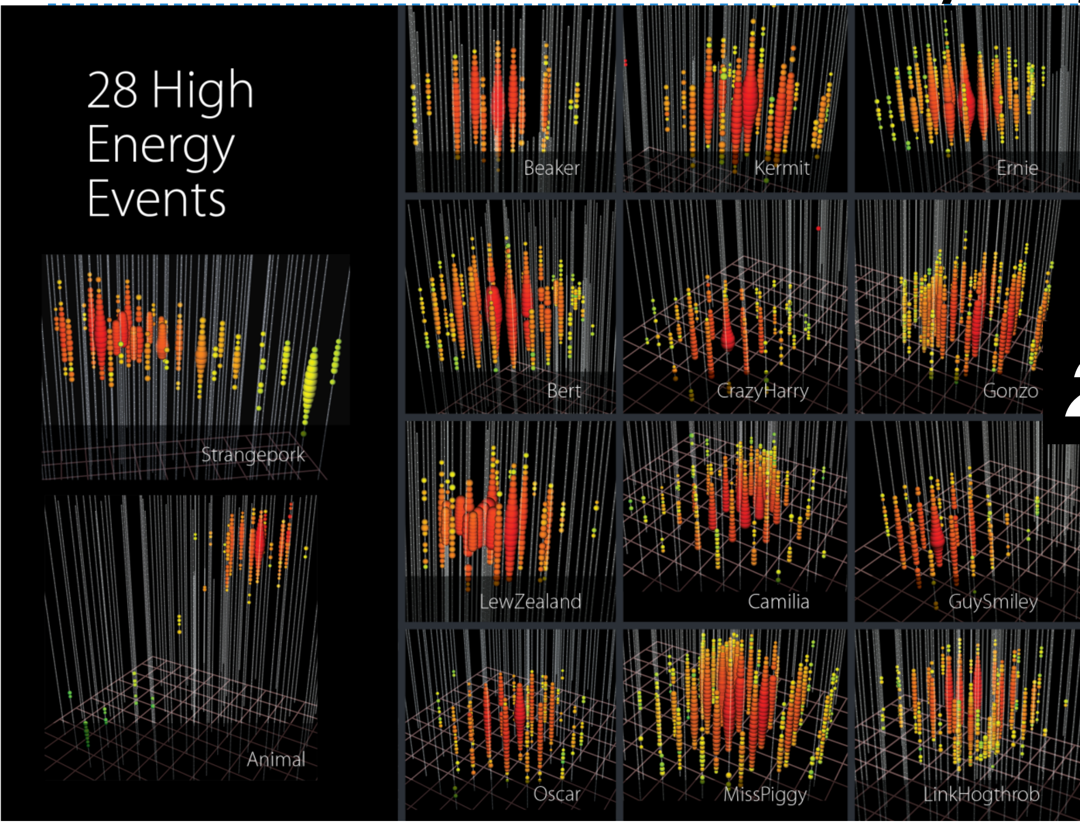


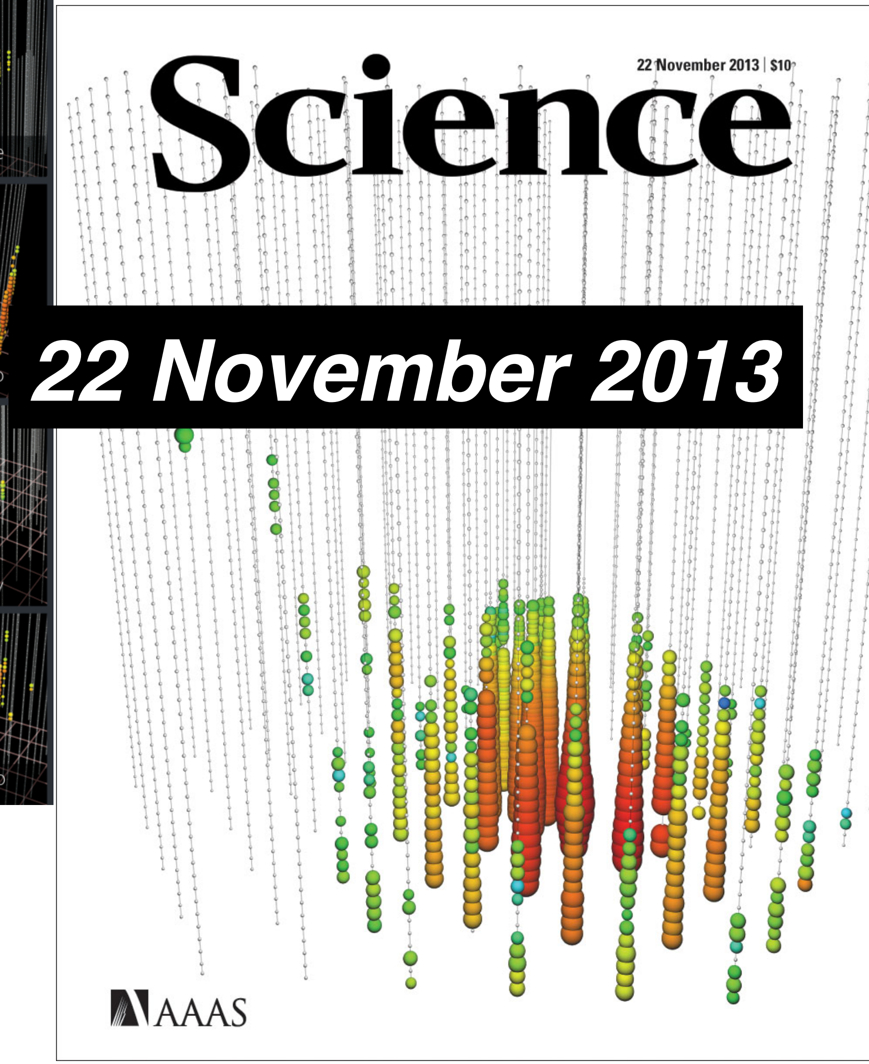
Deposited energy: 2.6±0.3 PeV

arXiv:1607.08006

6 year $\nu_\mu \rightarrow \mu$ analysis

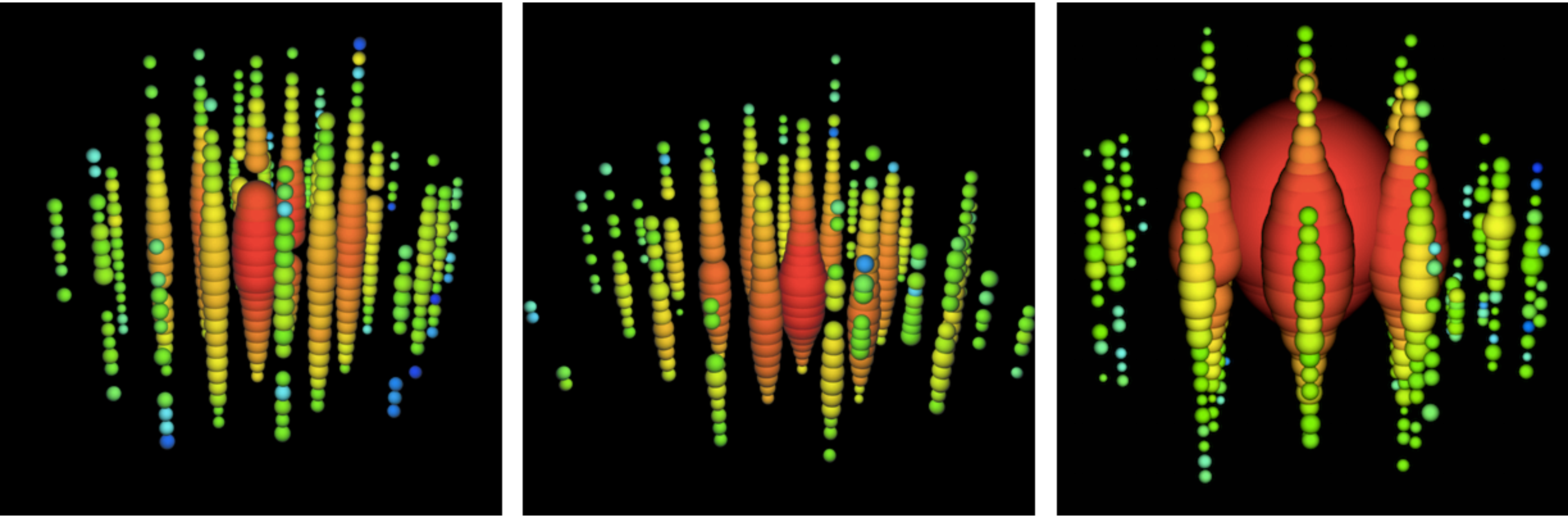
Evidence for very high energy neutrinos





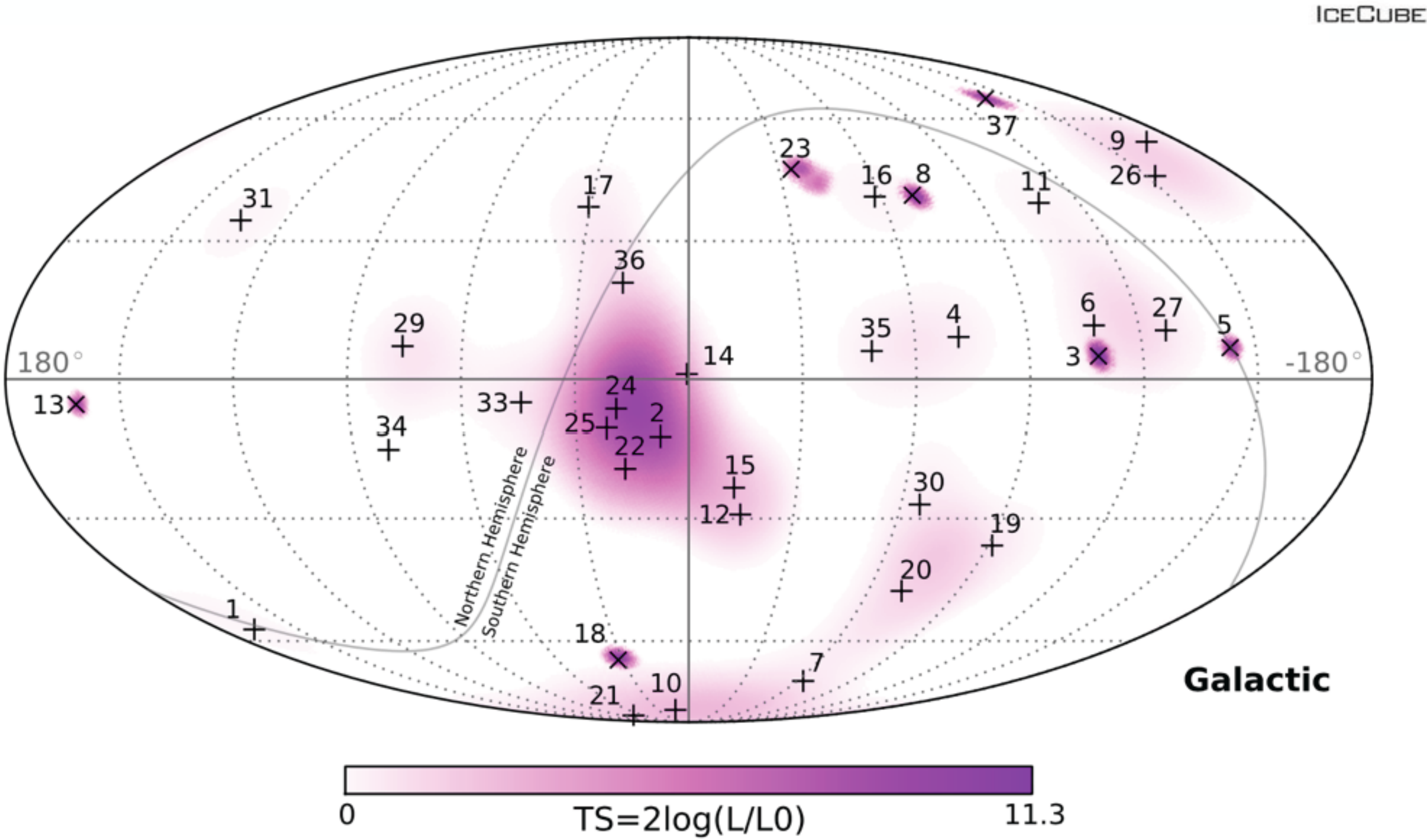
“We observed 28 neutrino candidate events (two previously reported), substantially more than the 10.6 $^{+5}_{-3.6}$ expected from atmospheric backgrounds, and ranging in energy from 30 to 1200 TeV. With the current level of statistics, we did not observe significant clustering of these events in time or space, preventing the identification of their sources at this time.”

PeV neutrinos



IceCube has detected the highest energy neutrinos ever recorded, with energies reaching above 2 PeV. From left to right, Bert, Ernie and Big Bird, with energies of 1.0, 1.1 and 2.2 PeV.

Sky map of 54 High Energy Events



Clustering of events test did not yield significant evidence

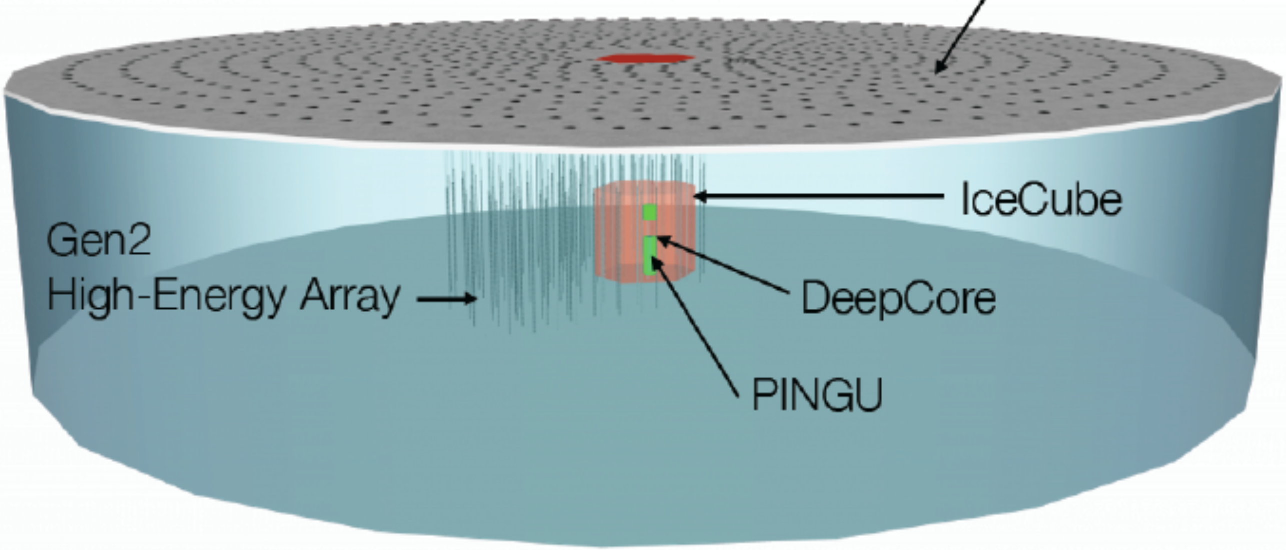
Ice Cube results

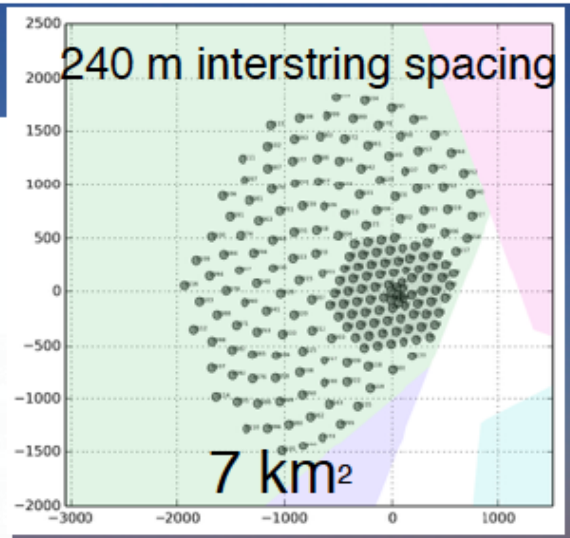
- A flux of neutrinos was observed from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos
- Hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe
- Gamma ray sources: predict neutrinos. We are close to identifying point sources

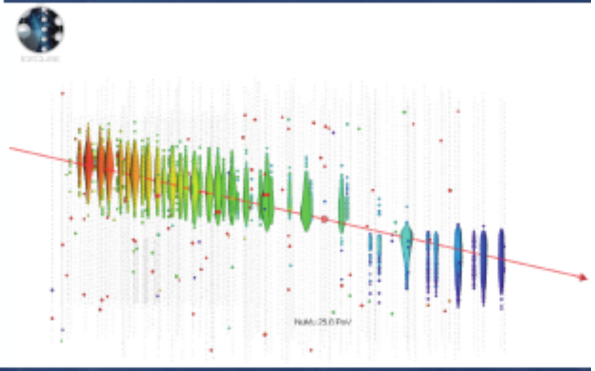
FUTURE OUTLOOK

Multi-component observatory:

- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU







- ~120 new strings, 80 DOMs per string, instrumented over 1.25 km
- ~10 x IC volume for contained event analysis above 200 TeV

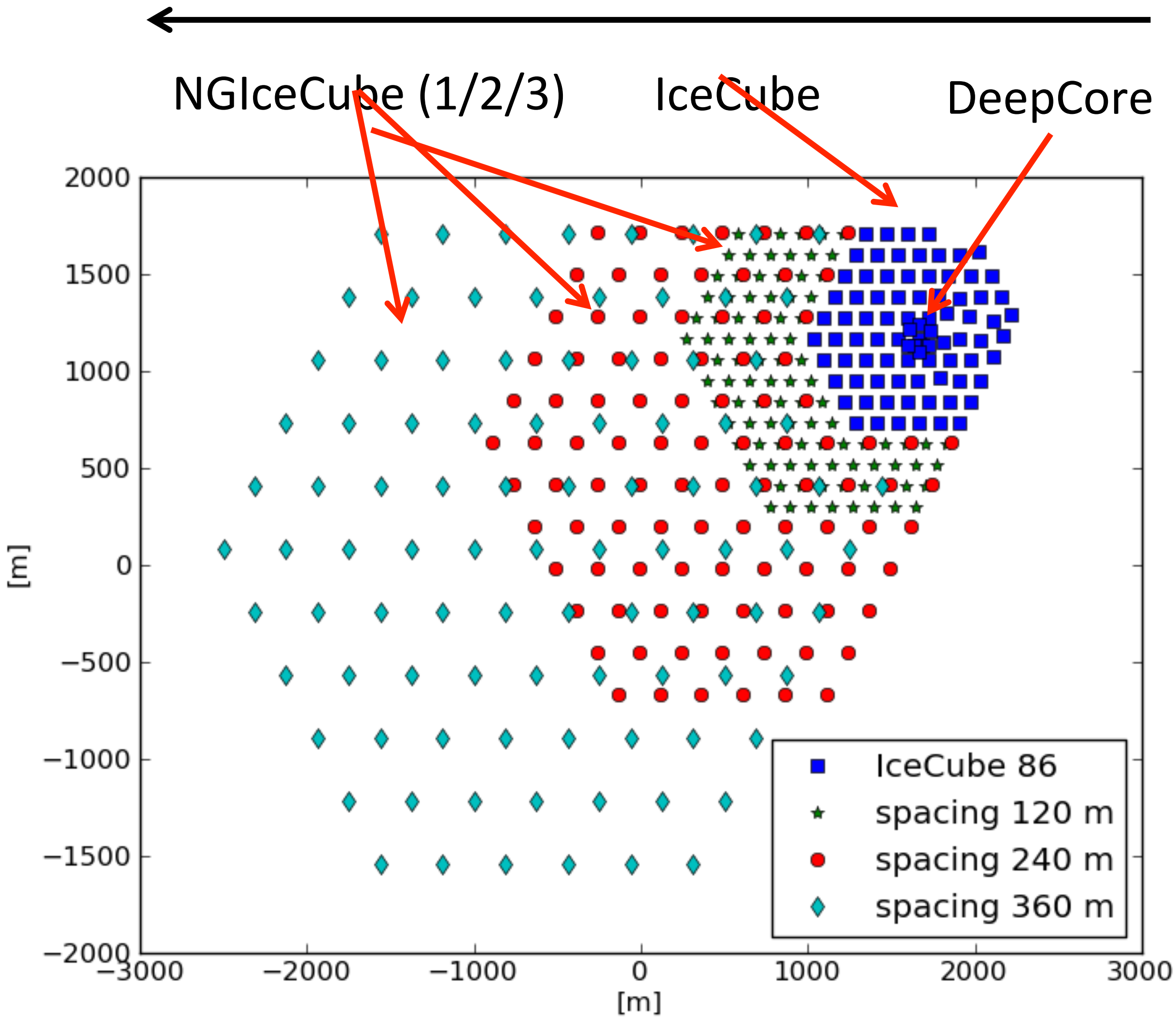
Enjoy a splendid aurora from our winter overs K. Krueger & M. van Rossem!

https://vimeo.com/163213110#collections

- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years
- need 1,000 events vs 100 now
- discovery instrument → astronomical telescope

measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

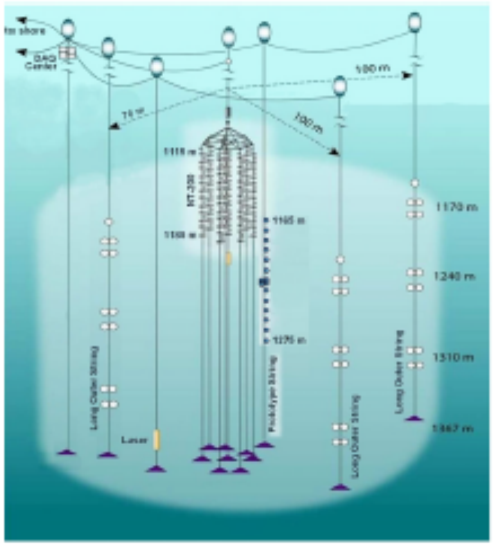


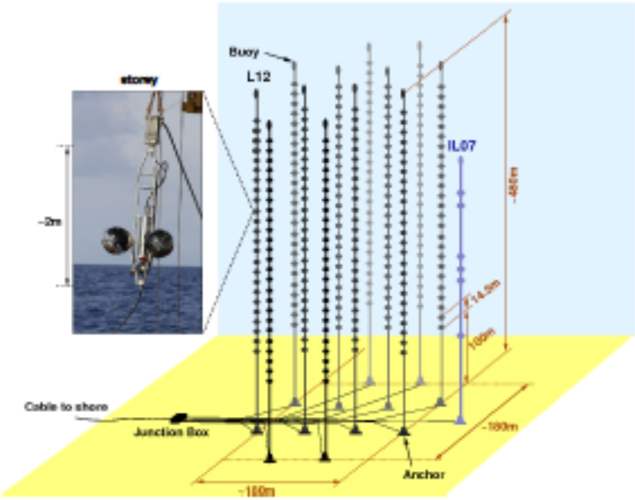
Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

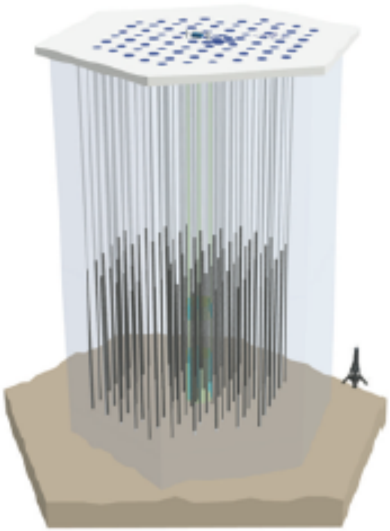
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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

NT-200+ | ANTARES | IceCube







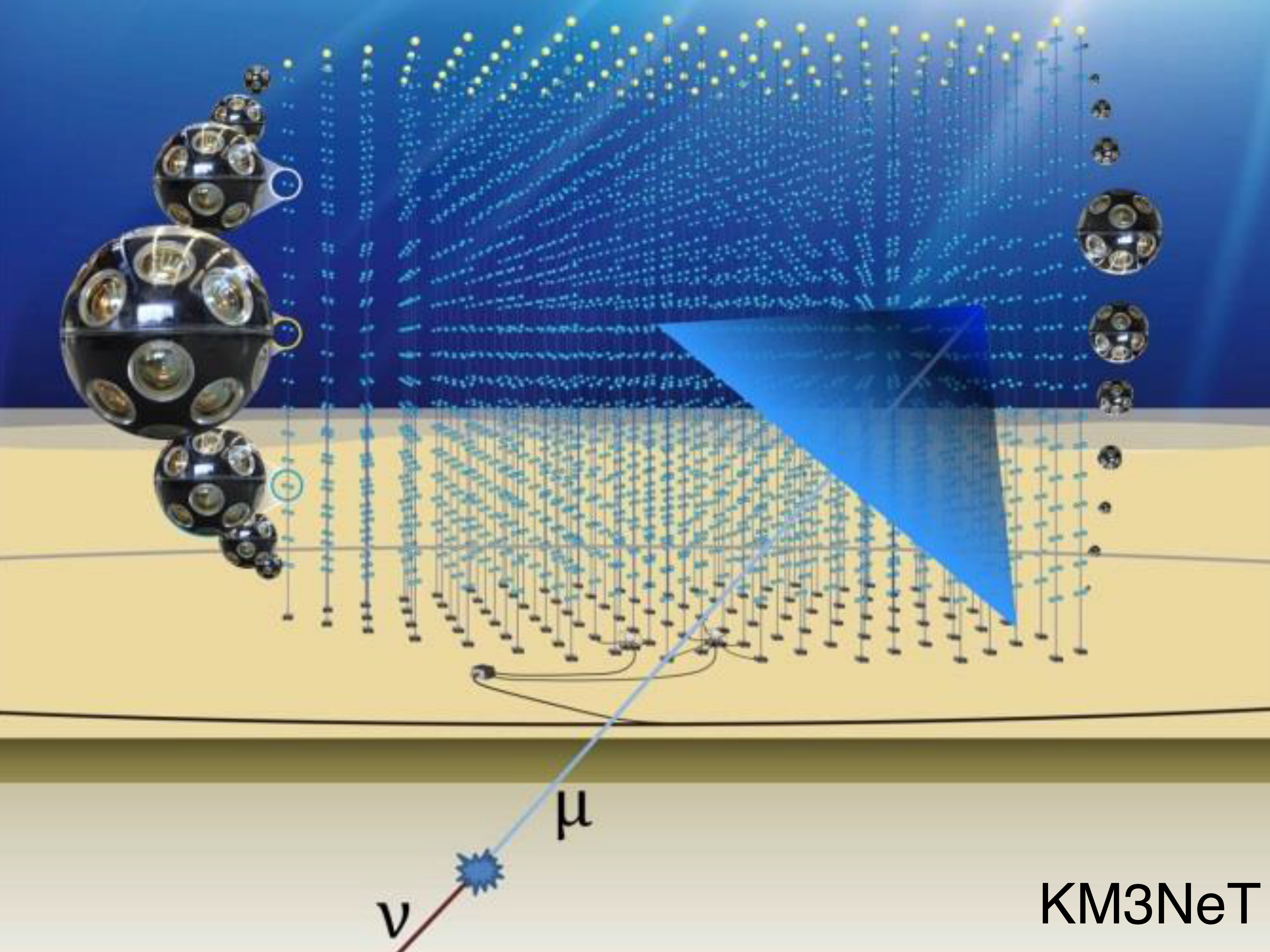
- Lake Baikal
- 1/2000 km^3
- 228 PMTs

- Mediterranean Sea
- 1/100 km^3
- 885 PMTs

- South Pole glacier
- 1 km^3
- 5160 PMTs

Larger, sparser → higher energies

future: < 100 m (lower threshold) 250m (high energy)


μ
ν
KM3NeT

KM3net – neutrino telescope

- KM3NeT, a future European deep-sea research infrastructure, will host a neutrino telescope with a volume of several cubic kilometres at the bottom of the Mediterranean sea that will open a new window on the Universe.
- The telescope will search for neutrinos from distant astrophysical sources like gamma ray burst, supernovae or colliding stars and will be a powerful tool in the search for dark matter in the Universe.
- An array of thousands of optical sensors will detect the faint light in the deep sea from charged particles originating from collisions of the neutrinos and the Earth.
- The facility will also house instrumentation from Earth and Sea sciences for long term and on-line monitoring of the deep sea environment and the sea bottom at depth of several kilometres.

KM3NeT

KM3NeT expands May 2014

On May 7, a prototype of the KM3NeT detection unit consisting of a string with three optical modules has been deployed at a depth of 3500 metres, 100 kilometres off the coast of Portopalo di Capo Passero, Italy. Following the successful deployment of the first optical module off the coast of Toulon, France in April 2013, the construction of the KM3NeT research infrastructure also progresses at the Italian site in the Mediterranean Sea.

About KM3NeT:

KM3NeT is a large international effort with a challenging and compelling objective: The discovery of neutrino sources in the Universe. Neutrinos are sub-atomic particles, well known for their reluctance to be detected. A discovery of a neutrino source provides for identification and understanding of astrophysical particle accelerators. The KM3NeT research infrastructure will be shared by a multitude of other sciences, making continuous and long-term measurements in the area of oceanography, geophysics, and marine biological sciences possible. The KM3NeT collaboration has about 240 members from 40 European institutes and Universities.

On May 7, a prototype of the KM3NeT detection unit consisting of a string with three optical modules has been deployed at a depth of 3500 metres, 100 kilometres off the coast of Portopalo di Capo Passero, Italy. Each optical module consists of a 17" glass sphere, equipped with 31 ultra-fast sensors that can detect light at the quantum level, electronics for the digitisation of the signals and fibre optics to transmit the data to shore. The complete KM3NeT research infrastructure will consist of about 12,000 such modules distributed in the Mediterranean Sea off the coasts of France, Italy and Greece, and covering several cubic kilometres of deep-sea water.

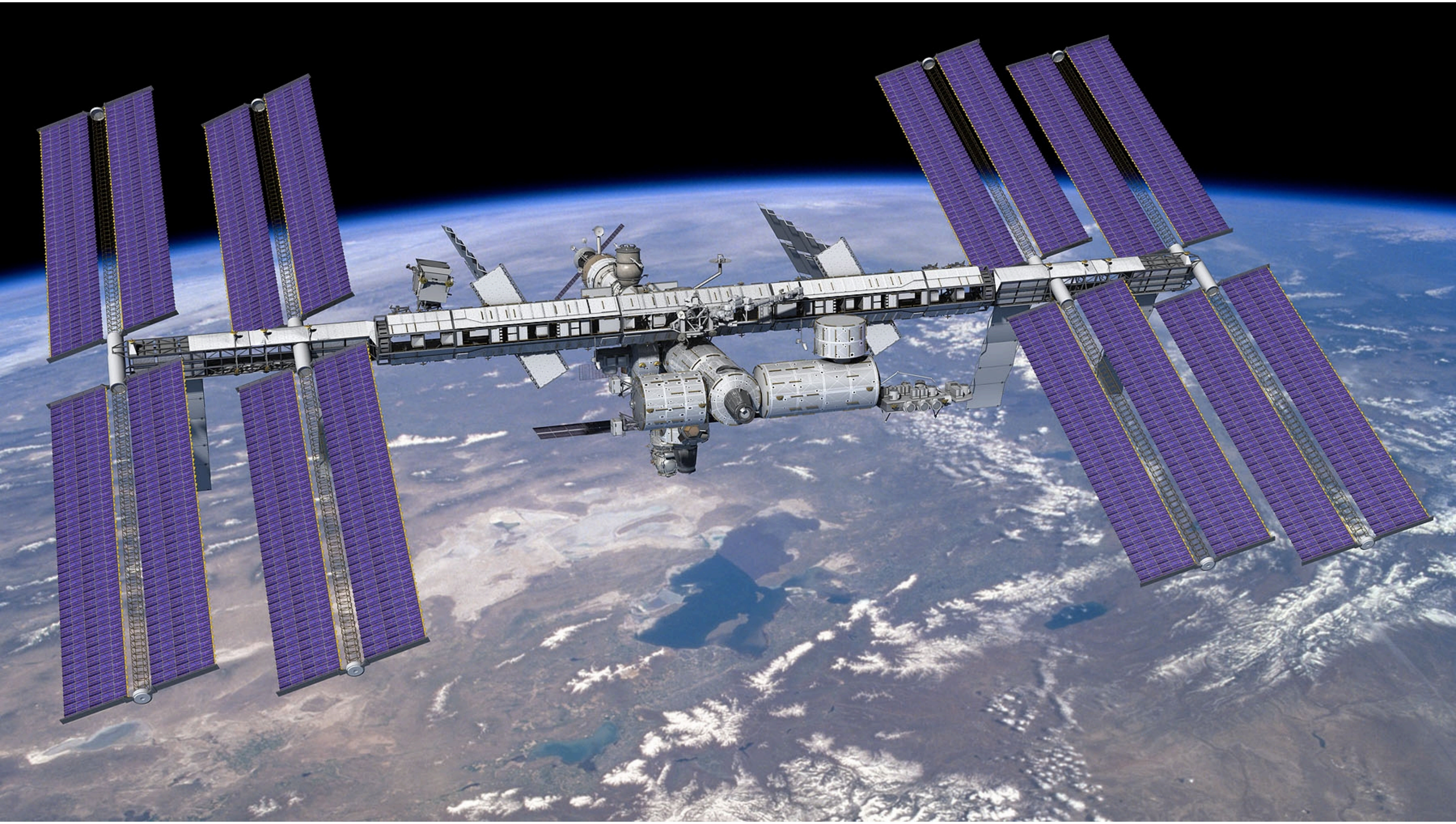
Following the successful deployment of the first optical module off the coast of Toulon, France in April 2013, the construction of the KM3NeT research infrastructure also progresses at the Italian site in the Mediterranean Sea. The construction will continue through several phases. The completion of the first phase is expected by the end of 2016. Plans for a next phase exist which is aimed at a measurement of the signal of high-energy neutrinos from the cosmos that has recently been reported by the IceCube collaboration.

More information:

KM3NeT web page: http://www.km3net.org/
Spokesperson: Prof. dr. M. de Jong (Nikhef & Leiden University) - e-mail.

Dark matter search

Antimatter sepctometer (AMS)



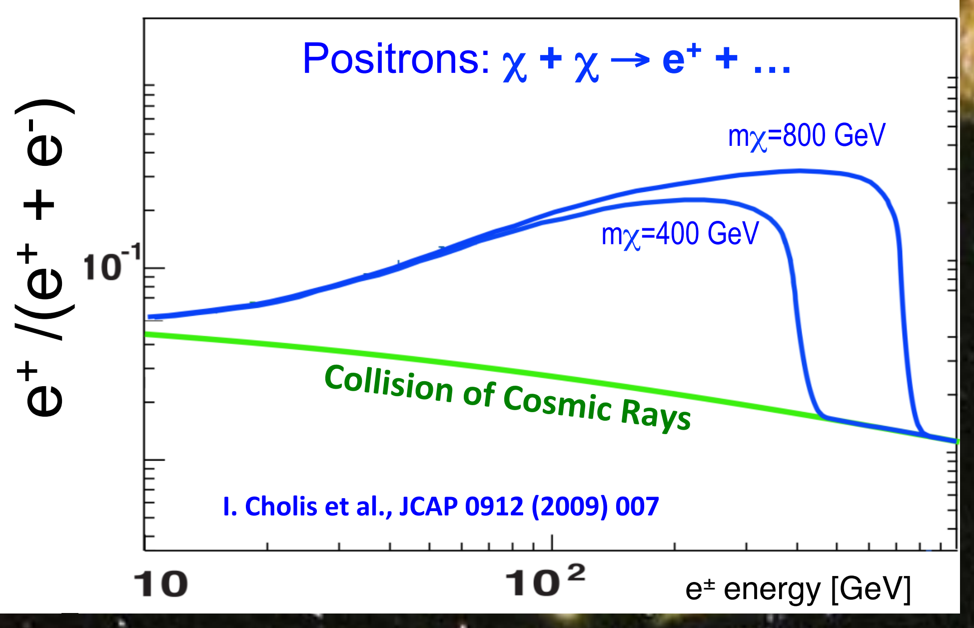
In its first four years on orbit, AMS has collected more than 60 billion cosmic ray events (electrons, positrons, protons, antiprotons, and nuclei of helium, lithium, boron, carbon, oxygen, ...) up to multi-TeV energies.

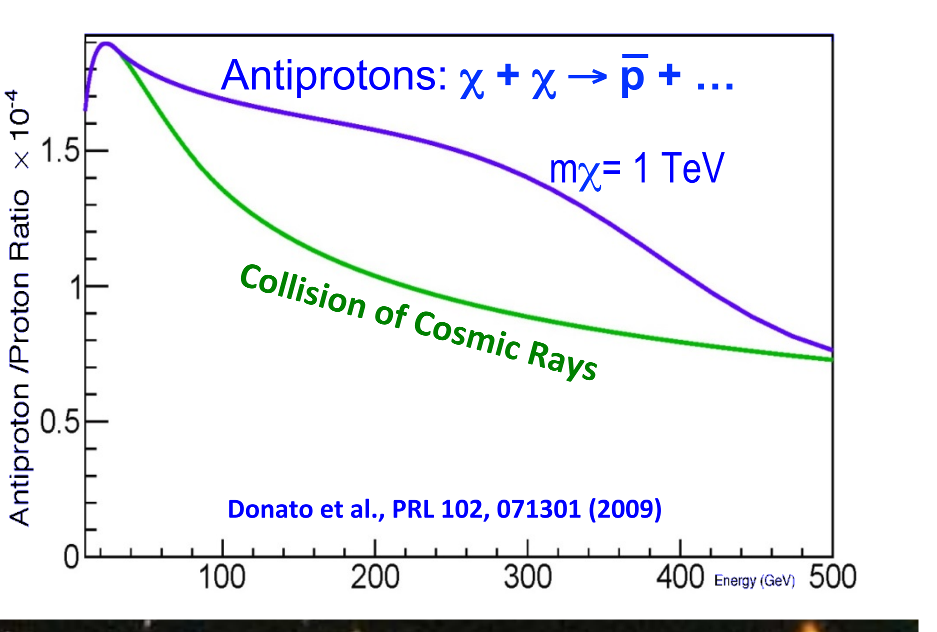
The Origin of Dark Matter

~ 90% of Matter in the Universe is not visible and is called Dark Matter

Collision of “ordinary” Cosmic Rays produce e+, $\bar{p}$..

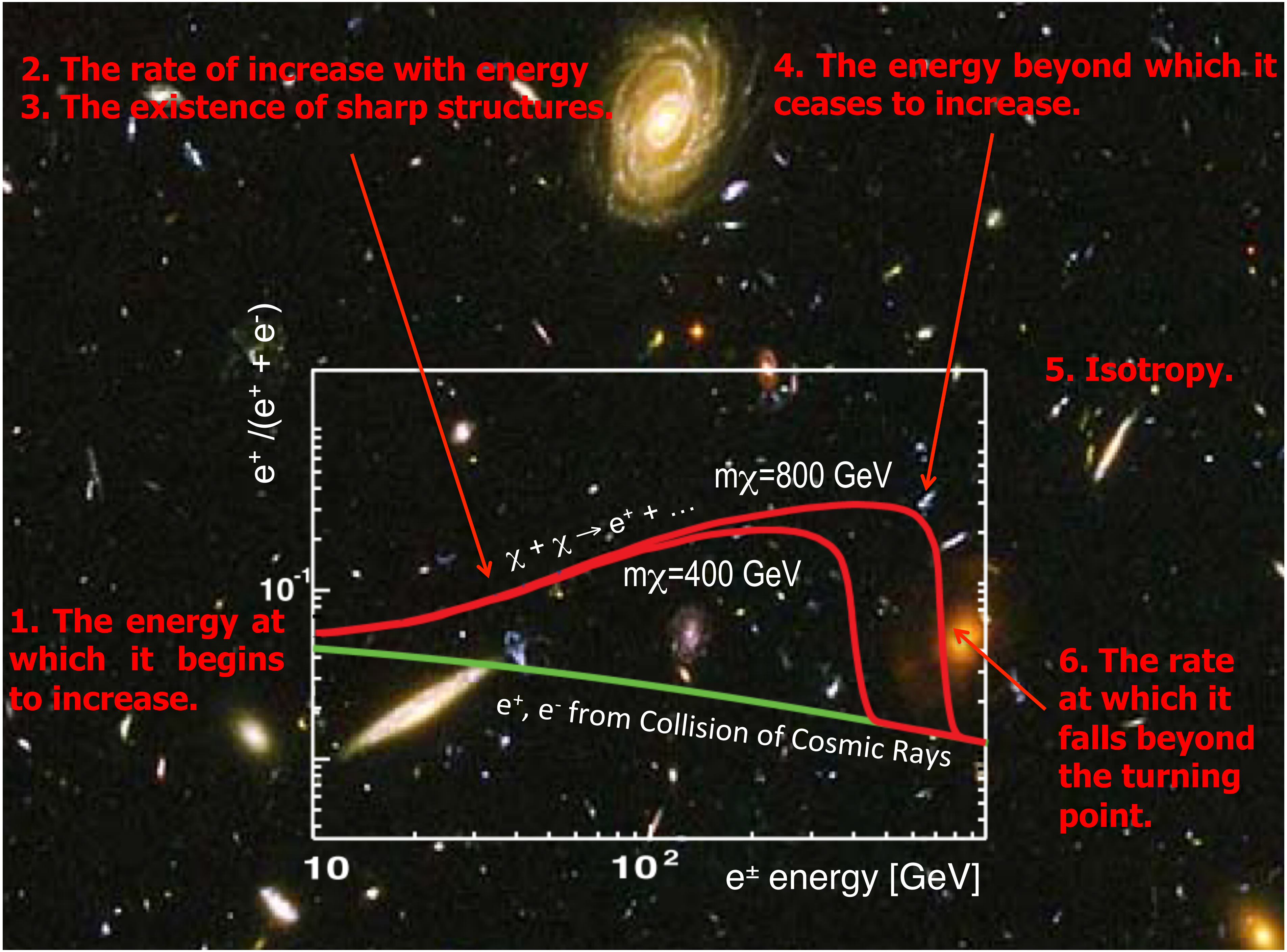
Collisions of Dark Matter (neutralinos, χ) will produce additional e+, $\bar{p}$, …





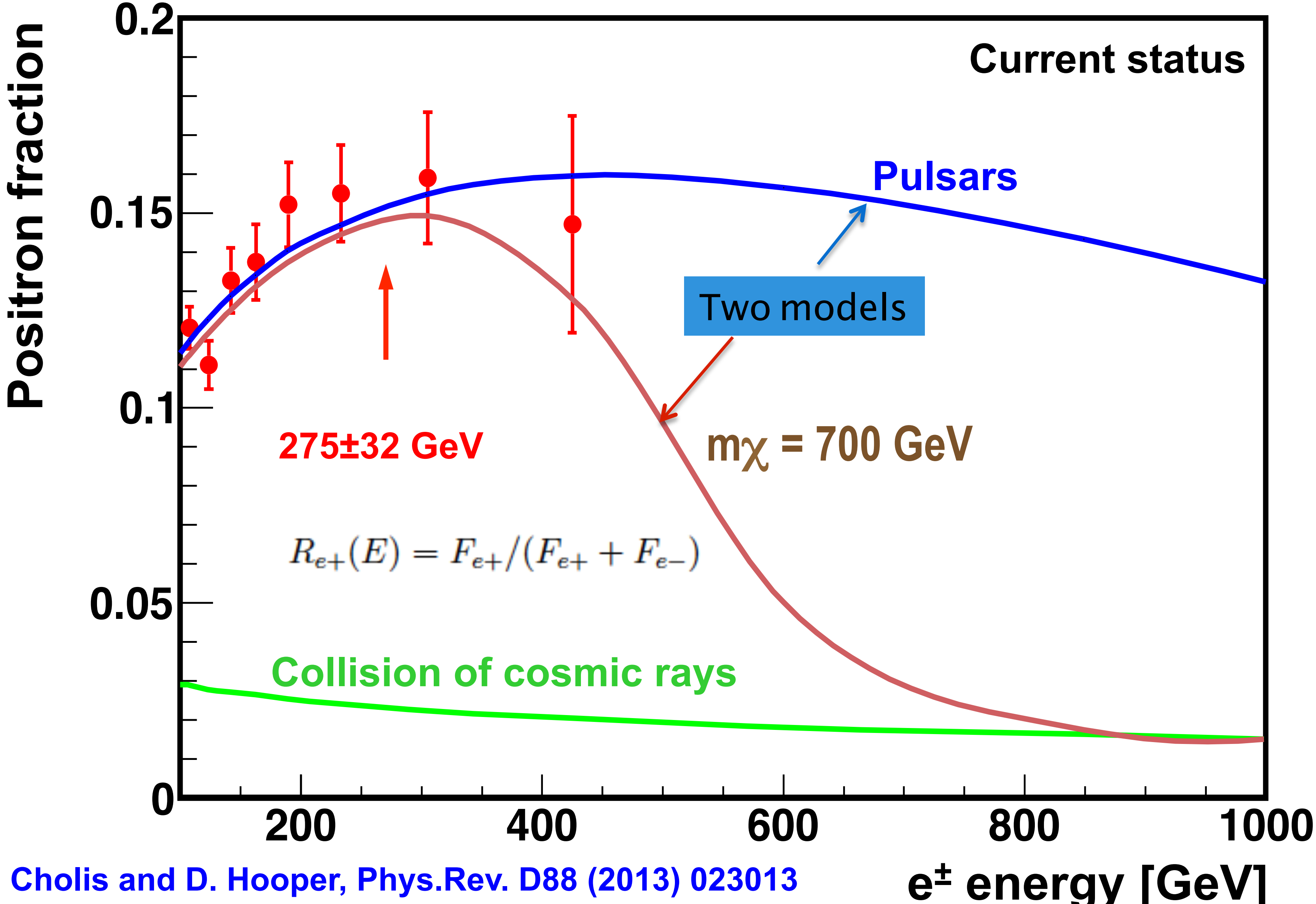
To identify the Dark Matter signal:

- Measurements of e^+, e^-, antiproton
- Precise knowledge of cosmic ray fluxes (p, He, C, ..
- Propagation and acceleration …



2. The rate of increase with energy
3. The existence of sharp structures.
4. The energy beyond which it ceases to increase.
5. Isotropy.
1. The energy at which it begins to increase.
6. The rate at which it falls beyond the turning point.
$e^+/(e^+ + e^-)$
$m\chi$=800 GeV
$m\chi$=400 GeV
$\chi + \chi \rightarrow e^+ + \ldots$
10^{-1}
e^+, e^- from Collision of Cosmic Rays
10
10^2
$e^{\pm}$ energy [GeV]

(vi) The expected rate at which it falls beyond the turning point.



I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
J. Kopp, Phys. Rev. D 88 (2013) 076013

AMS2 results

- Positron fraction is measured from 0.5 to 500 GeV:
- Steadily increases from 10 to ~250 GeV, no fine structures;
- At 275±32 GeV the slope crosses zero, i.e the fraction reaches its max;
- The positron to electron ratio is consistent with isotropy at the 95% *C.L*
- Exact behavior of the positron fraction at high energies requires more statistics.
- The AMS results on the positron fraction, the electron spectrum, the positron spectrum, and the combined electron plus positron spectrum are consistent with dark matter collisions and cannot be explained by existing models of the collision of ordinary cosmic rays. There are many new models showing that the results may be explained by new astrophysical sources (such as pulsars) or new acceleration and propagation mechanisms (such as supernova remnants).
- The antiproton to proton ratio stays constant from 20 GeV to 450 GeV kinetic energy. This behavior cannot be explained by secondary production of antiprotons from ordinary cosmic ray collisions. Nor can the excess of antiprotons be easily explained from pulsar origin.

Final remark

- Particle physics started as astroparticle physics and it is coming back … EHE particle comes for free from space, make use of them

- Advance of technology and understanding of elementary particle physics allow us to study the most violent process in the universe which are inaccessible in the laboratory

Falënderim