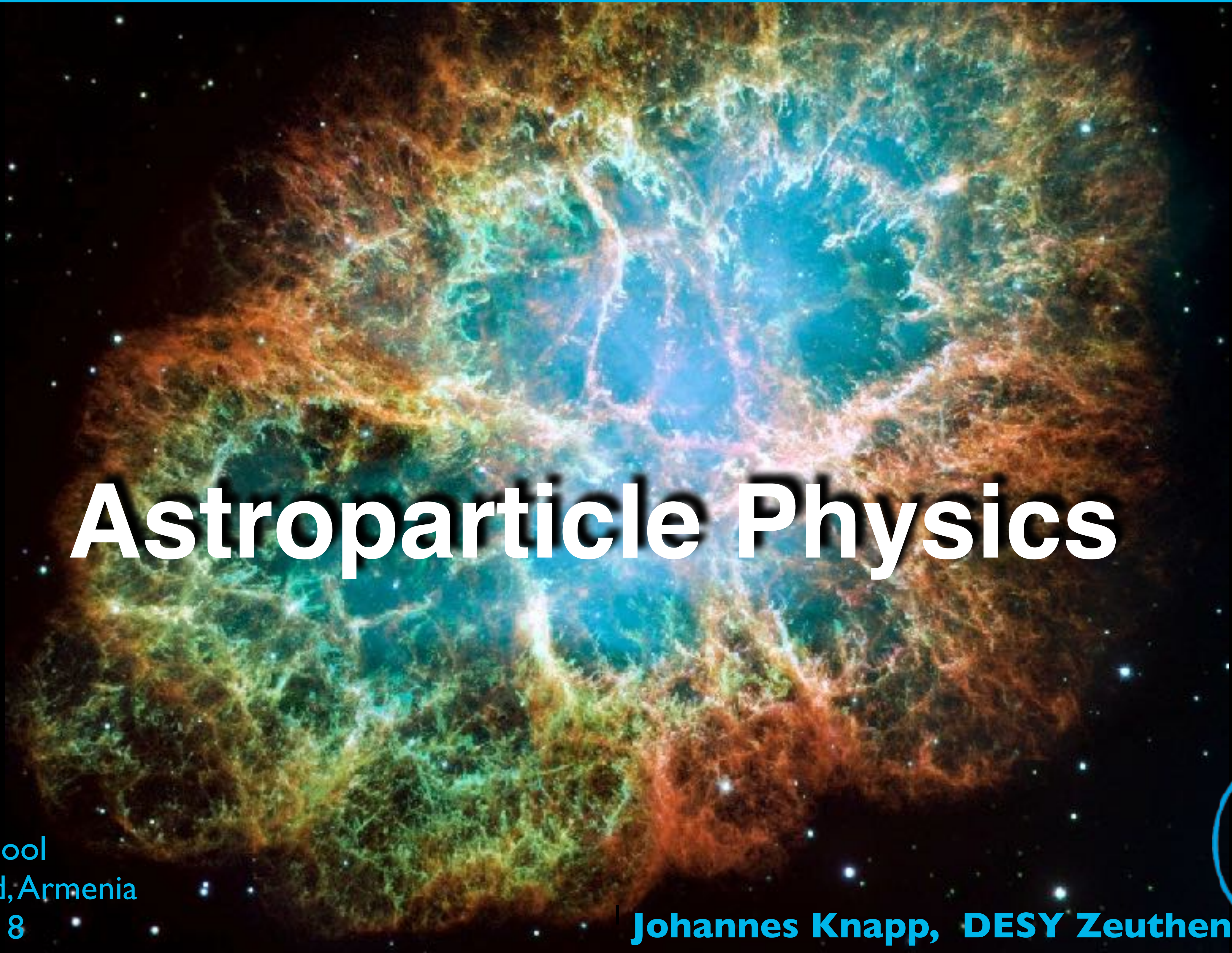
From Measurement to Discovery – The Scientific Method in Physics



Astroparticle Physics

Summer School
Nor Amberd, Armenia
5-8 June, 2018

Johannes Knapp, DESY Zeuthen

From Measurement to Discovery

My Plan for APP:

Discovery
Discovery

Lecture 1: Cosmic Rays: discovery, techniques, spectra & spectral features

Lecture 2: Neutrinos ν: neutrino hypothesis & detection, the solar model, solar neutrino problem, neutrino oscillations


Lecture 3: Neutrino astronomy: the idea, techniques atmospheric neutrinos, sources **Discovery**

Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes **very many discoveries**

From Measurement to Discovery

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Discovery

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Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes

very many discoveries

Much of this is what we call today "Astroparticle Physics"

3. Neutrino Astronomy

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Neutrinos

Strongly linked to cosmic rays,
complementary information.

point back
no absorption
very difficult to detect

The basic reactions: (weak interaction)

$\nu \neq \bar{\nu}$

$$n \longrightarrow p^+ + e^- + \bar{\nu}$$

in nuclear reactors neutron-rich fragments emerge from fission of neutron-rich Uranium which stabilise by neutron decay

$$p^+ \longrightarrow n + e^+ + \nu$$

in the Sun, 4 protons are fused into a ^4He (2p, 2n), i.e. 2 p are converted into 2 n

$$p^+ + e^- \longrightarrow n + \nu$$

in a supernova, protons and electrons merge into neutrons.

Neutrino properties:

leptons, connected to e, μ, τ : ν_e , ν_μ , ν_τ

has only weak interaction,

parity violation,

helicity: left-handed neutrinos, (spin anti-parallel to momentum)

right-handed anti-neutrinos (spin parallel to momentum)

Neutrino beams at accelerators:

Intense proton beam on target: creation of pions / kaons (±)

Selection of charge (+ or –) by magnetic field

Pions decay into muons + muon neutrinos

Muons decay into electrons + muon neutrinos + electron neutrinos

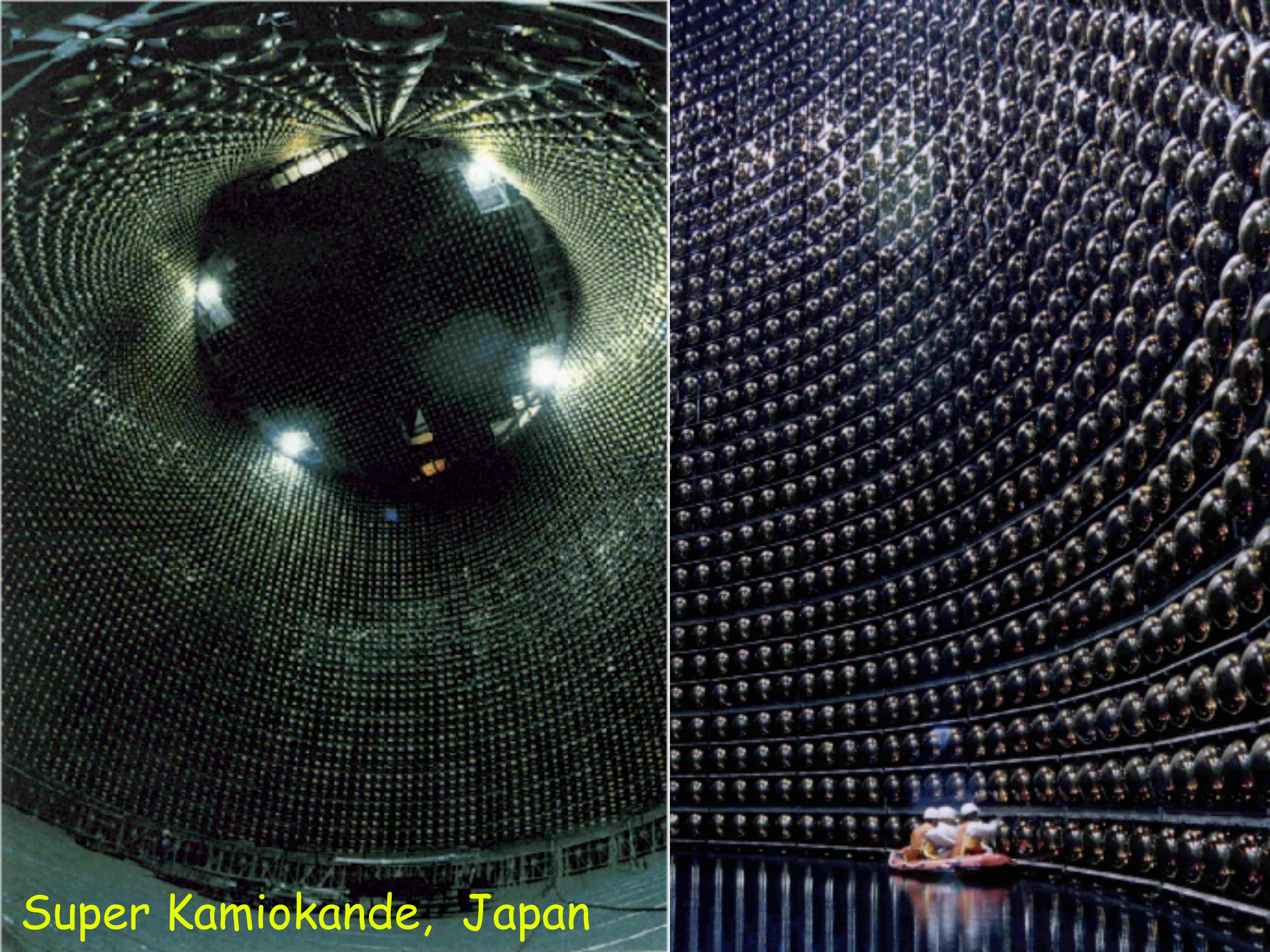
Flexible choice of neutrino type for downstream experiments.

charge current, neutral current interactions

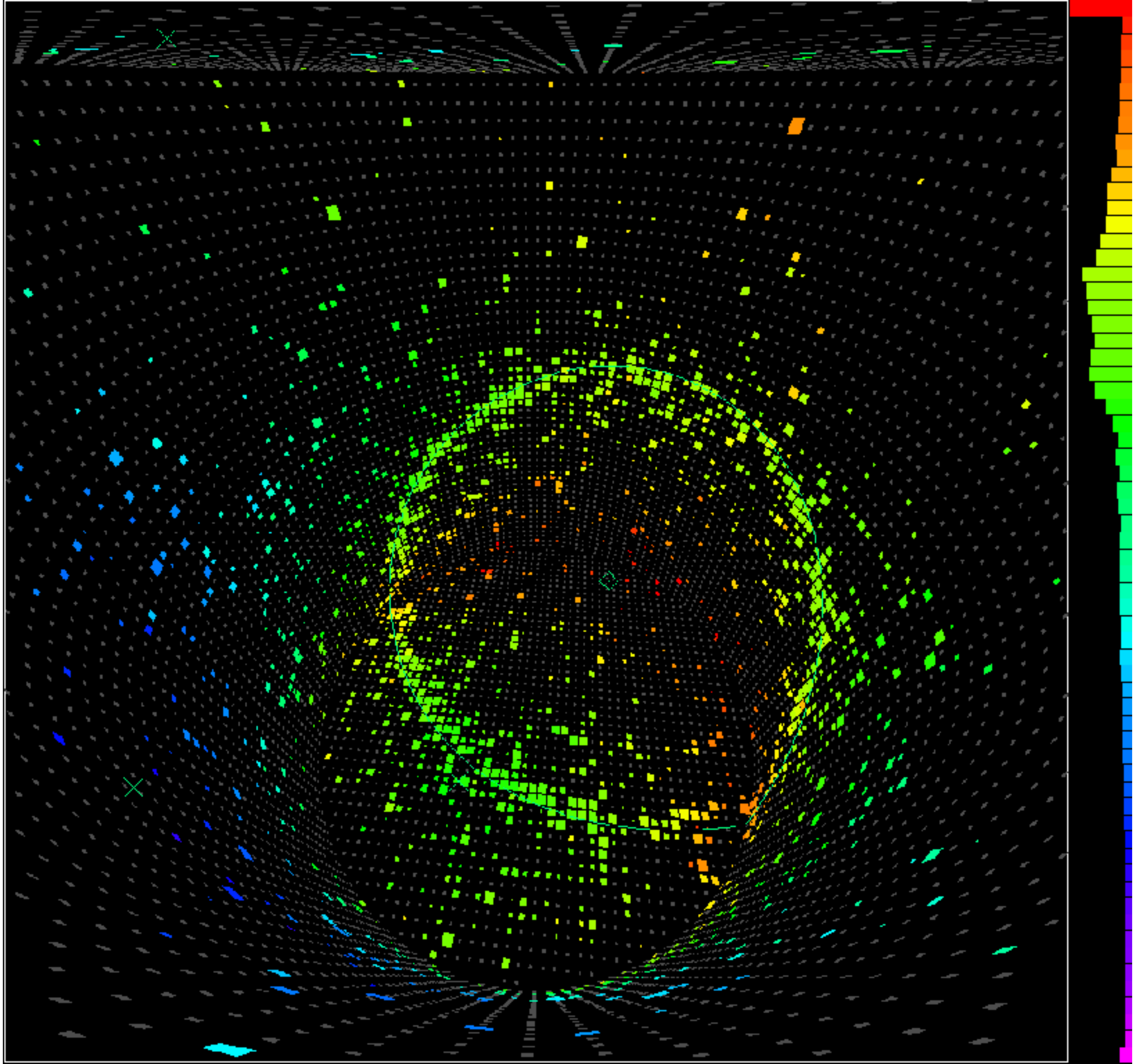
cross sections: $\approx 10^{-44}$ cm^2 x E_ν / MeV

tiny !!

Neutrinos can be detected and investigated !



Super Kamiokande, Japan



~~Are several experiments wrong ?~~
~~Is standard solar model wrong ?~~
~~Is nuclear physics wrong ?~~

ν oscillations ?

quantum effect,
if neutrinos have different masses

neutrinos “oscillate”: $\nu_e \longrightarrow \nu_\mu \longrightarrow \nu_e \longrightarrow \ldots.$

detection works only for ν_e

Neutrinos **do oscillate**
i.e they **have mass** !!

$m_1 \neq m_2 \neq m_3$
only (mass differences)^2 can be measured

mass states are a mixture of flavour states
flavour states are a mixture of mass states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle ,$$
$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle ,$$

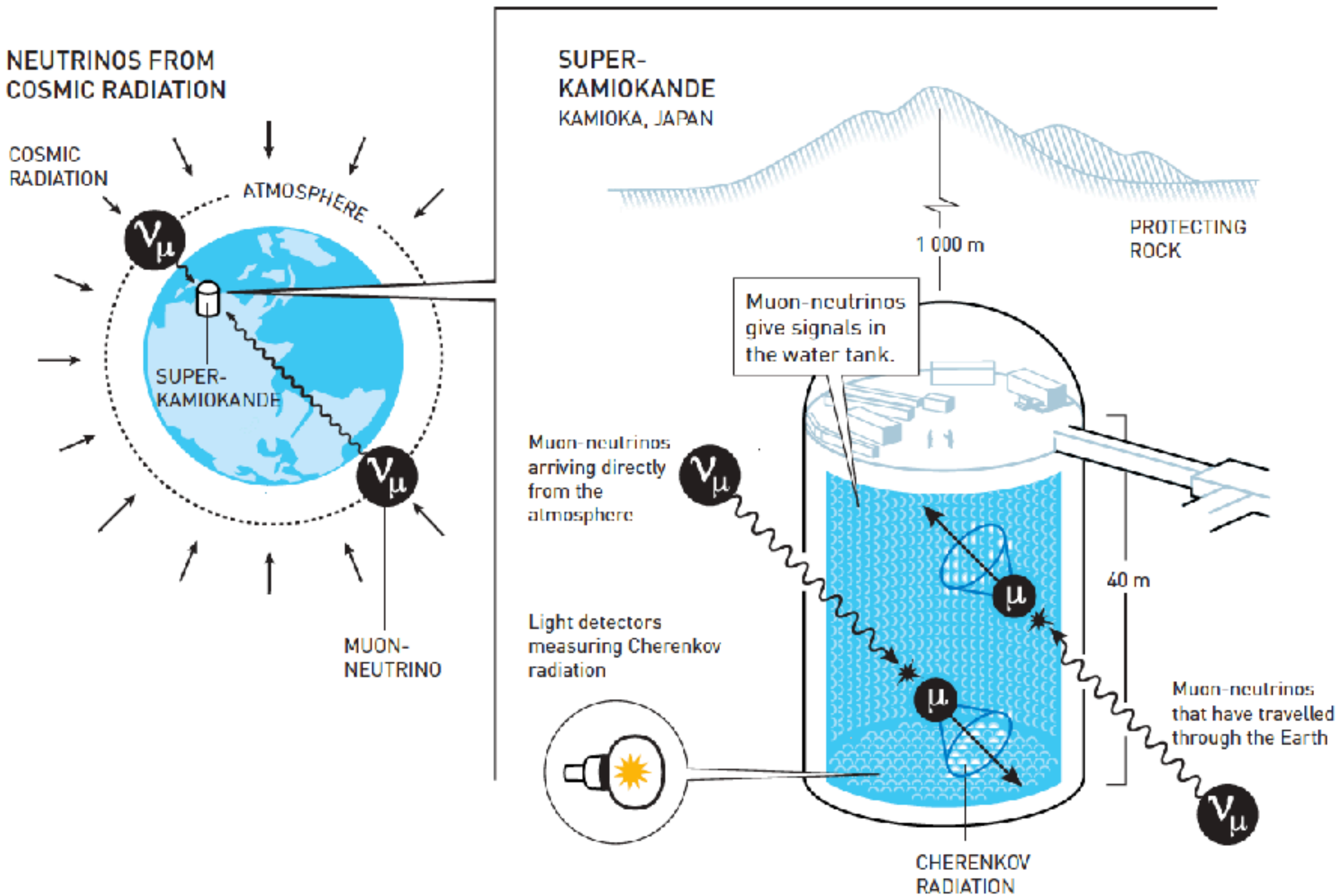
mixing angles to be determined experimentally

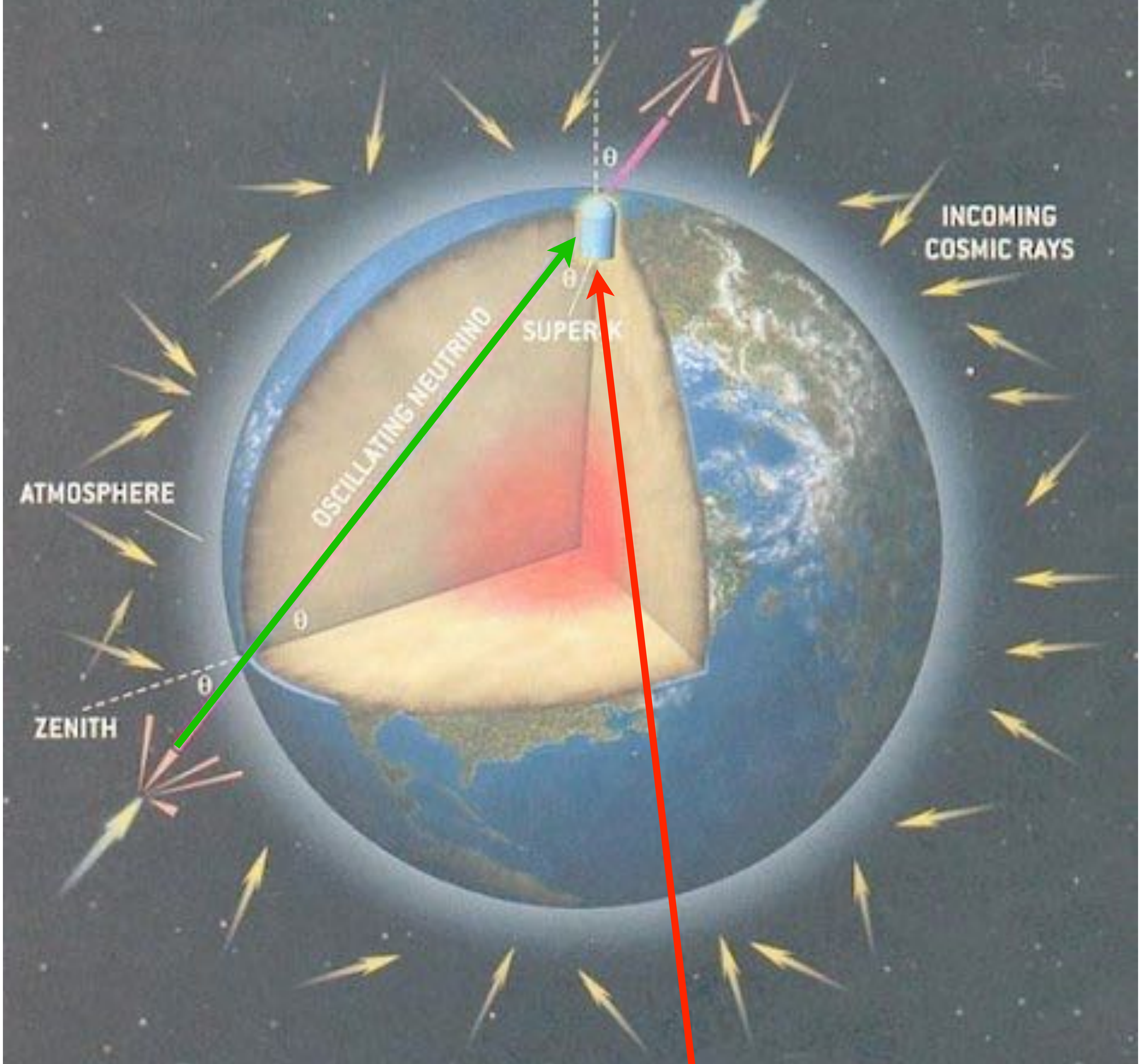
where

- $|\nu_\alpha\rangle$ is a neutrino with definite flavor α = e (electron), μ (muon) or τ (tauon),
- $|\nu_i\rangle$ is a neutrino with definite mass m_i, $i = 1, 2, 3$,

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

Atmospheric Neutrinos with Super-Kamiokande





atmospheric ν

astrophysical ν

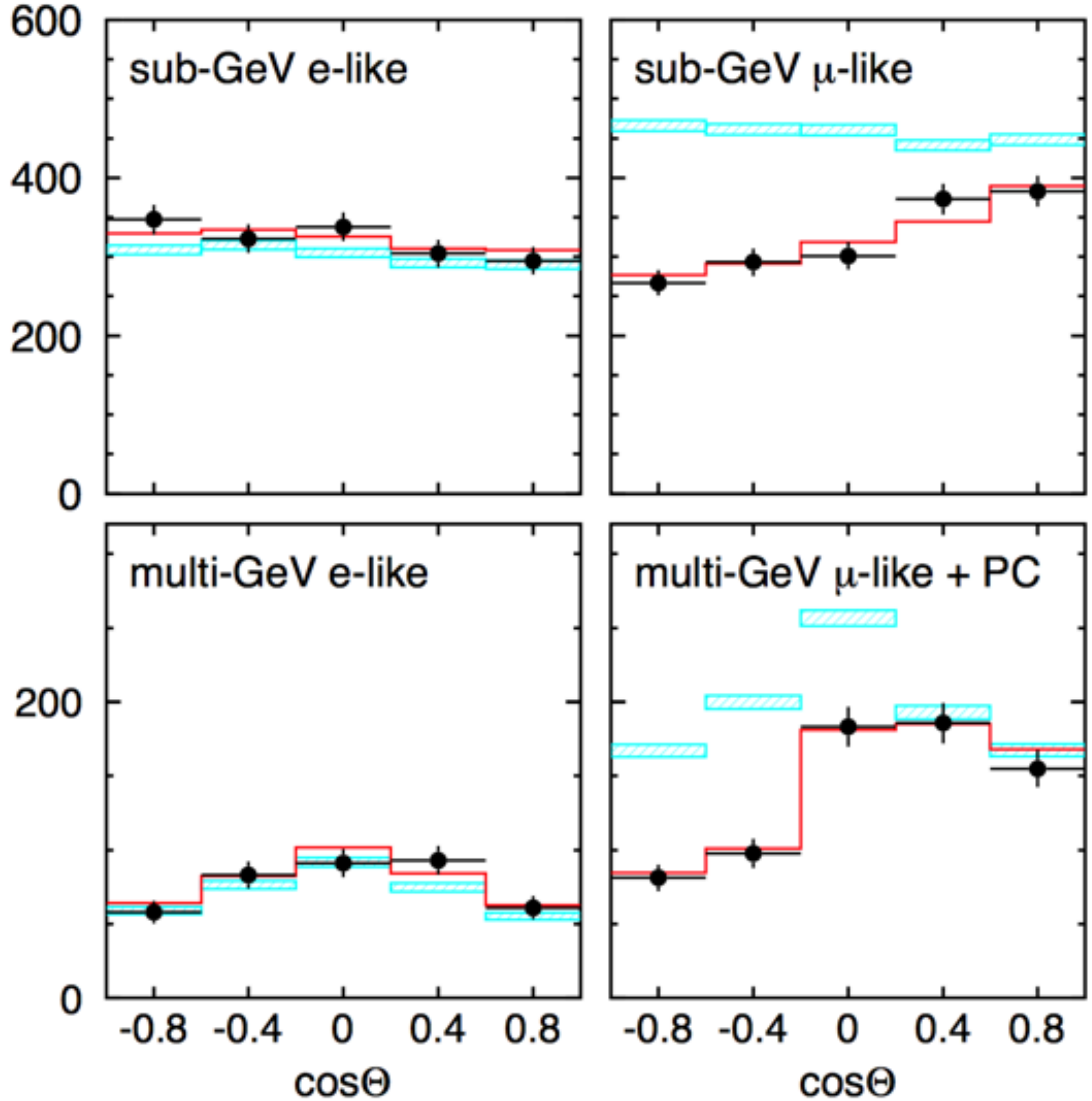


Figure 5: Zenith angle distributions of e-like and μ-like events in Super-Kamiokande with momenta above and below 1.33 GeV [52]. The boxes show the expectation assuming no oscillations, whereas the full drawn lines show the results of the best fit.

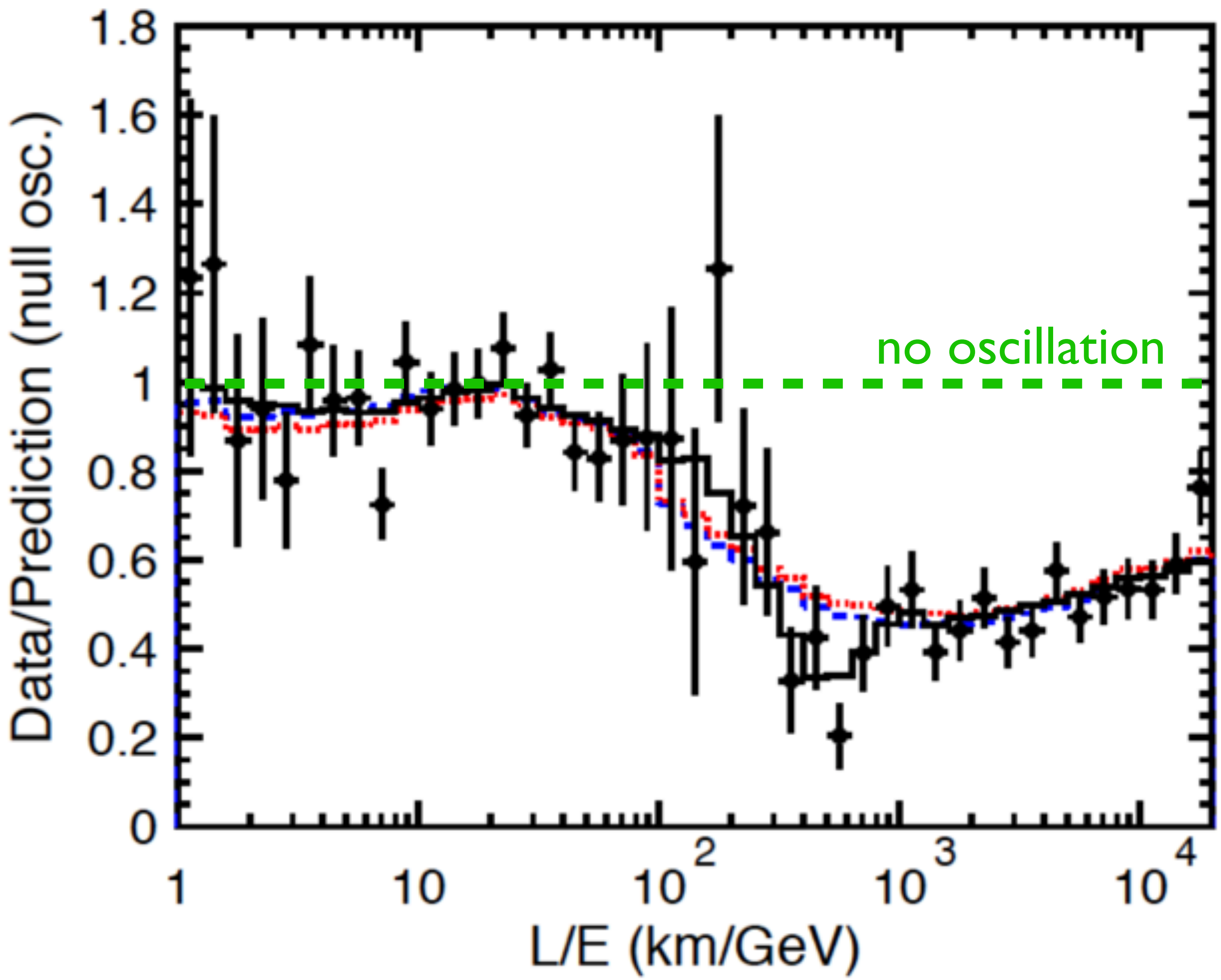


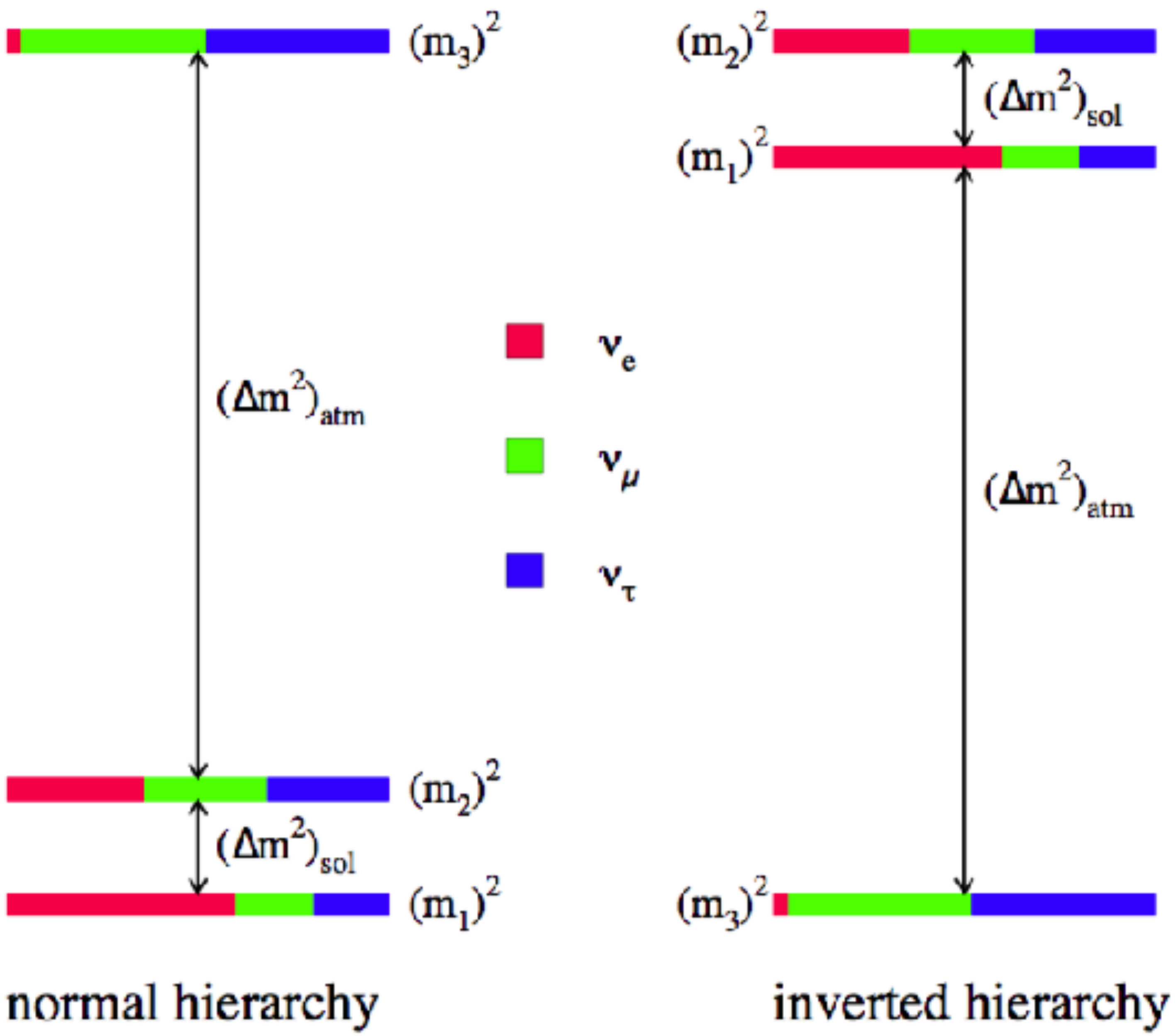
Figure 6: Ratio of data from Super-Kamiokande to Monte Carlo expectation assuming no oscillation, as a function of reconstructed L/E [53]. The black histogram is a fit to a two flavour oscillation hypothesis.

Neutrino mass hierarchy not yet clear

solar

$$|\Delta m_{21}^2| \cong 7.5 \times 10^{-5}\ \ \mathrm{eV}^2$$
$$|\Delta m_{31}^2| \cong 2.5 \times 10^{-3}\ \ \mathrm{eV}^2$$

atmospheric



Sun and SN 1987a show:

Neutrinos from

astrophysical objects

can be detected !

Energy scale:

the range of astroparticle physics

radio IR Visible light UV X rays γ rays

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

non-thermal processes

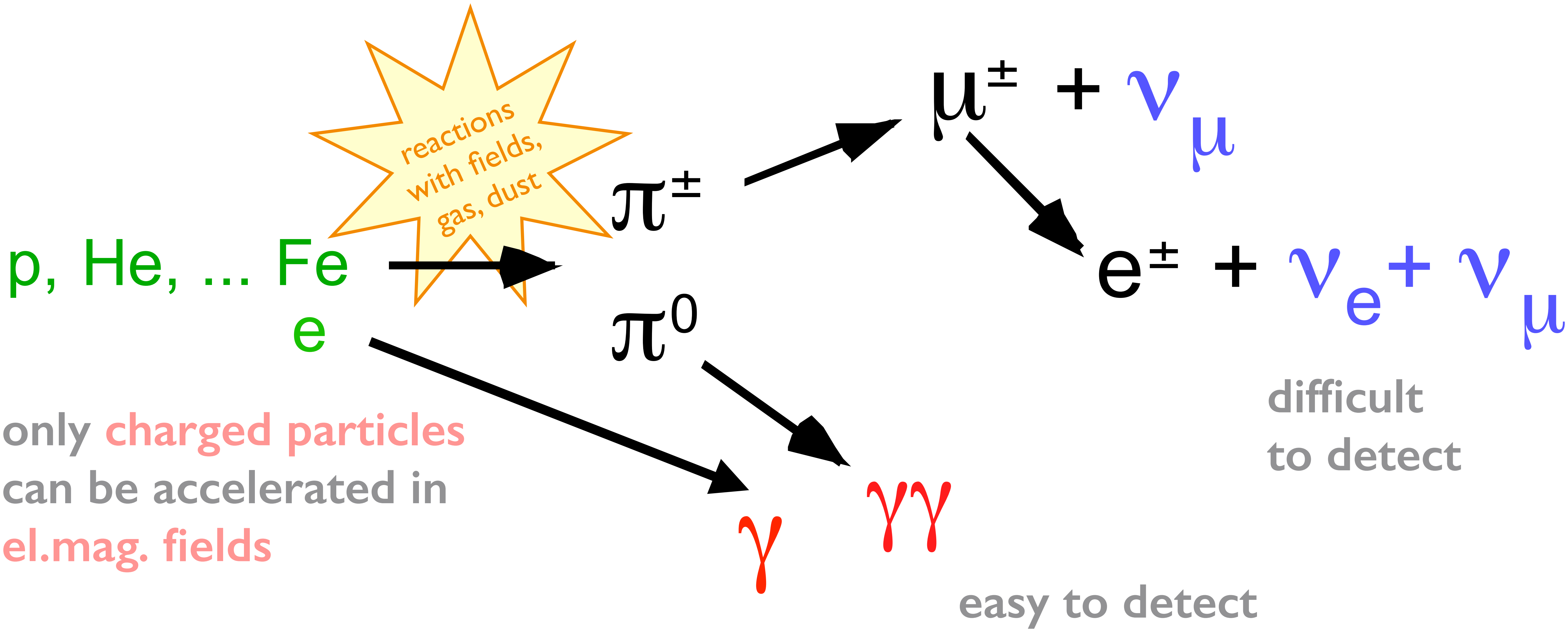
Photons: astronomy

charged: p, He, ... Fe, ... completely ionised nuclei

electrons

Neutrinos:

Cosmic rays, gamma rays and neutrinos come likely from the same sources



“multi-messenger astrophysics”

but gamma rays are currently the most “productive” messengers.

γ,ν

point back to sources (good for astronomy)
but serious backgrounds

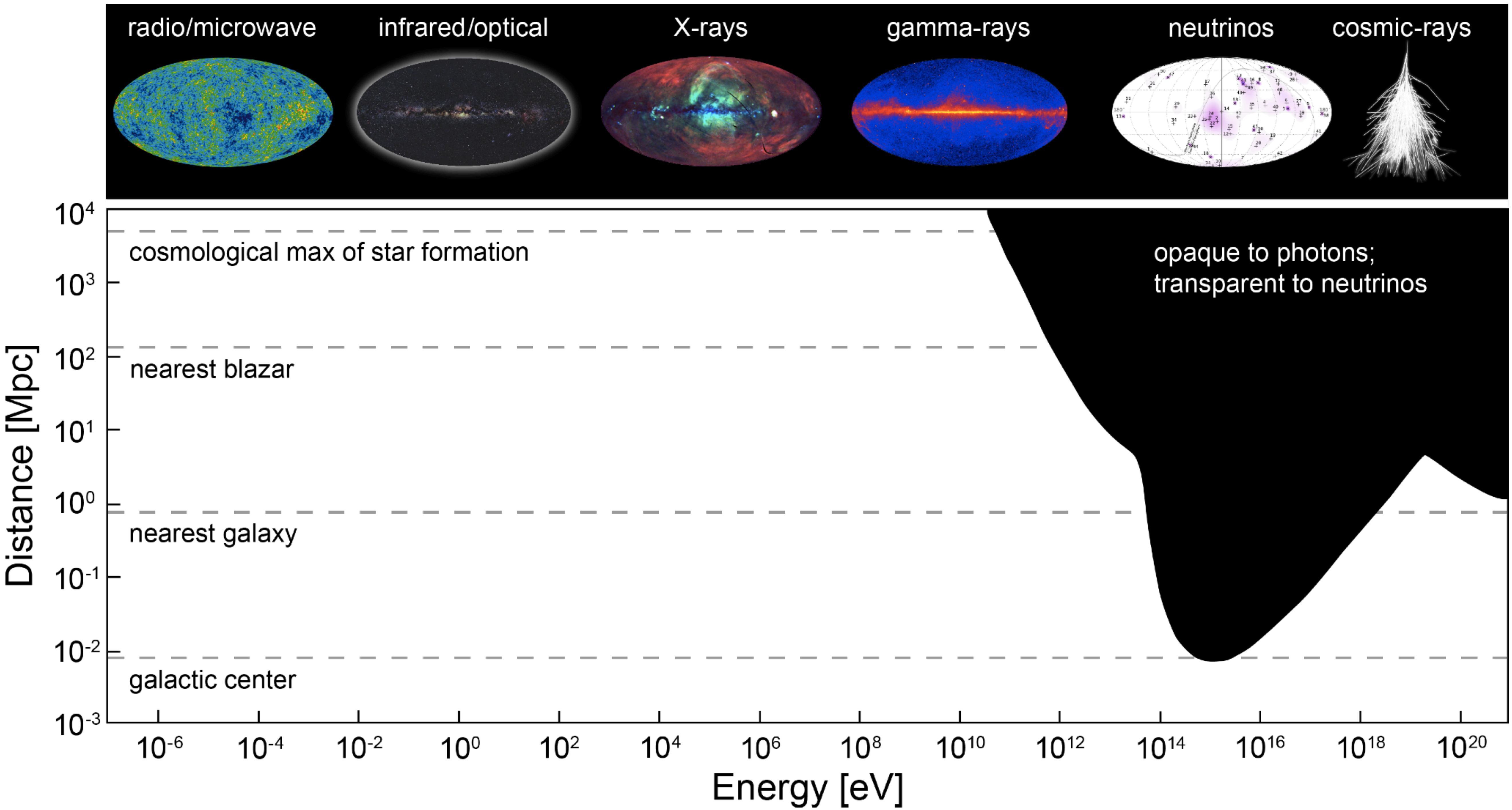
In a SN explosion, 99% of the energy released is in neutrinos!

There are many objects / events in the universe
that produce neutrinos.

They are very inert for reaction with matter,
i.e. they can reach us from dense areas where
no photon could escape (centre of stars, galaxies, …)

But most pass also the detector without interacting,
i.e. one needs huge detectors to capture a few neutrinos
much larger than earlier neutrino detectors.

The uniqueness of neutrinos



- Neutrinos allow us to peek **beyond the gamma-ray horizon**…
- … and into environments **opaque to electromagnetic radiation**.

km^3 sized detector needed …

Dumand: in the deep sea off Hawaii (1976 - 1995; unsuccessful)

NT200: in lake Baikal in Siberia (1988 -)

1994: first neutrinos detected

Antares & KM3Net: in the Mediterranean Sea (1999 -)

Amanda & IceCube: at the South Pole (1995 -)

2010: 1 km^3 instrumented !

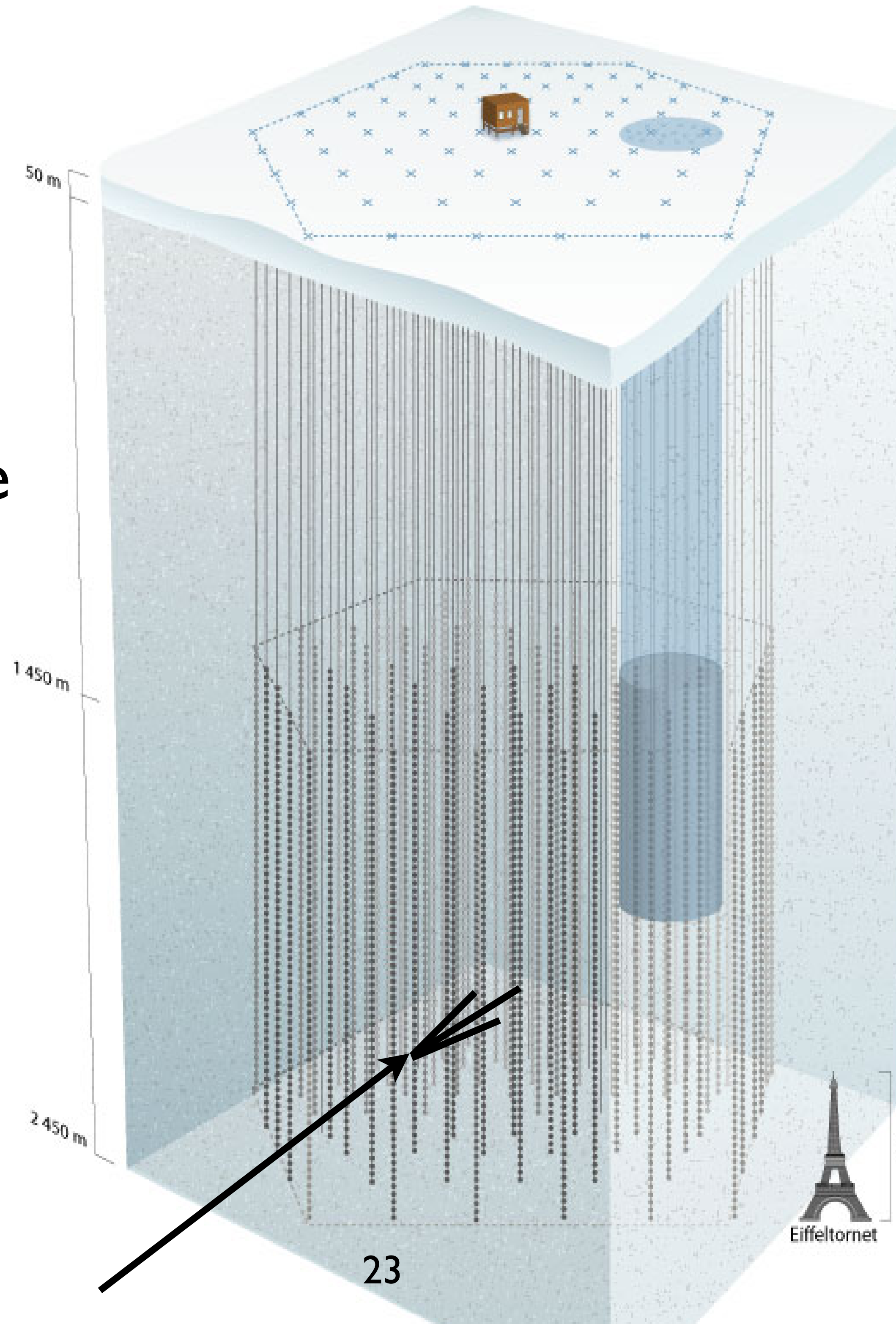
data taking ongoing

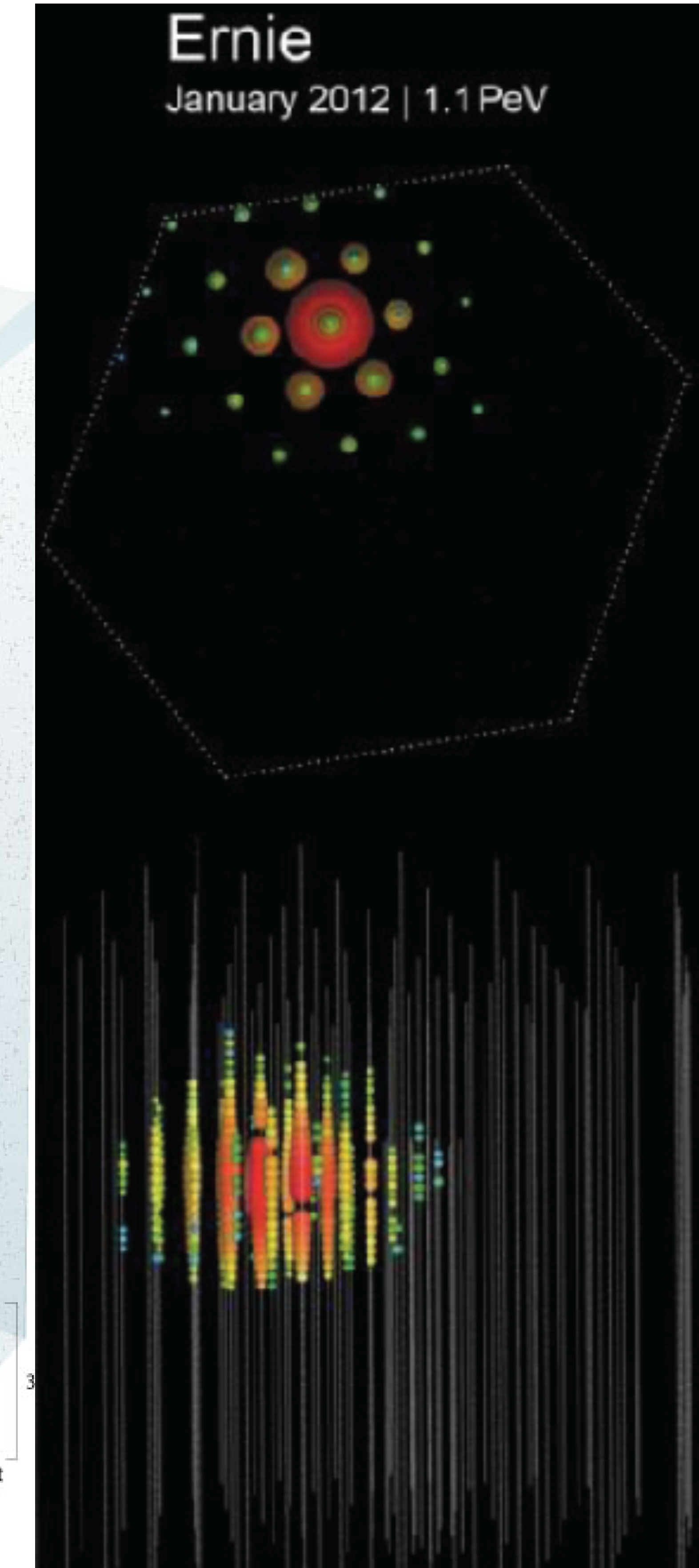
Large, natural volumes become part of the detectors:

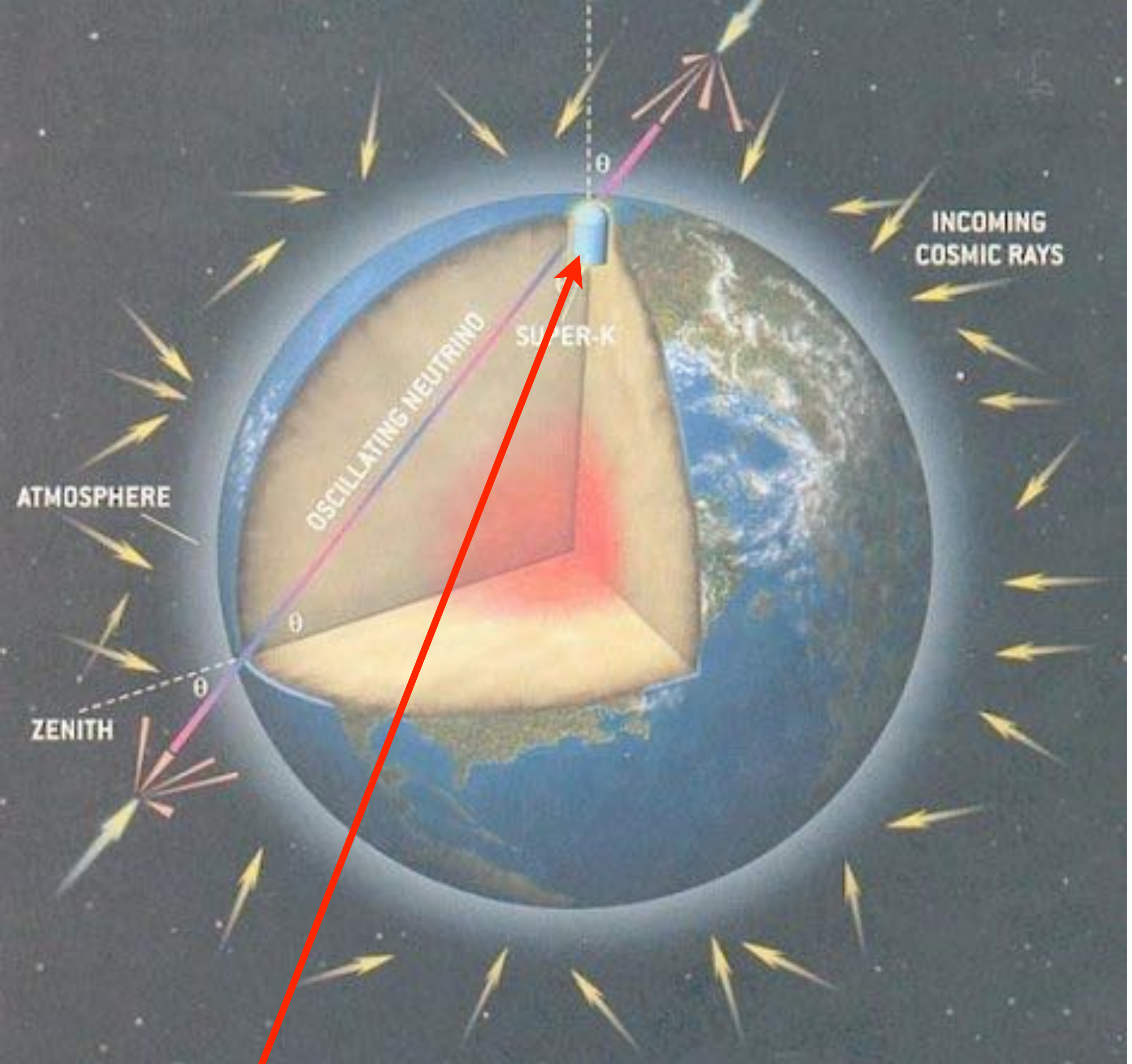
atmosphere,
ice shields,
oceans,
...

IceCube at the South Pole
1 km^3 5200 sensors,
~2 km deep in ice

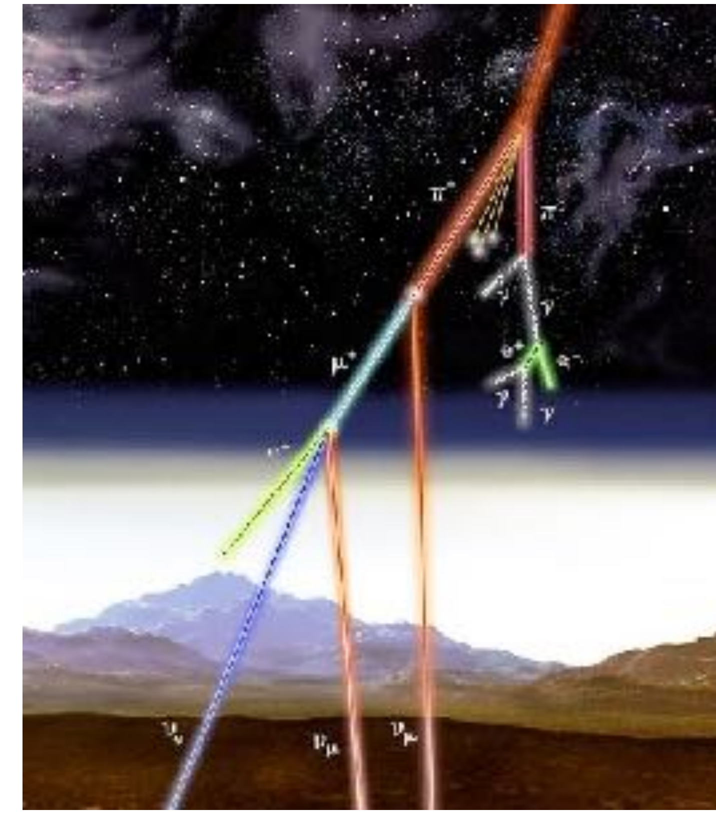
Neutrinos go through the earth.
(E ≈ 10^{11}–10^{15} eV)







astrophysical ν



How to tell apart astrophysical / atmospheric neutrinos?

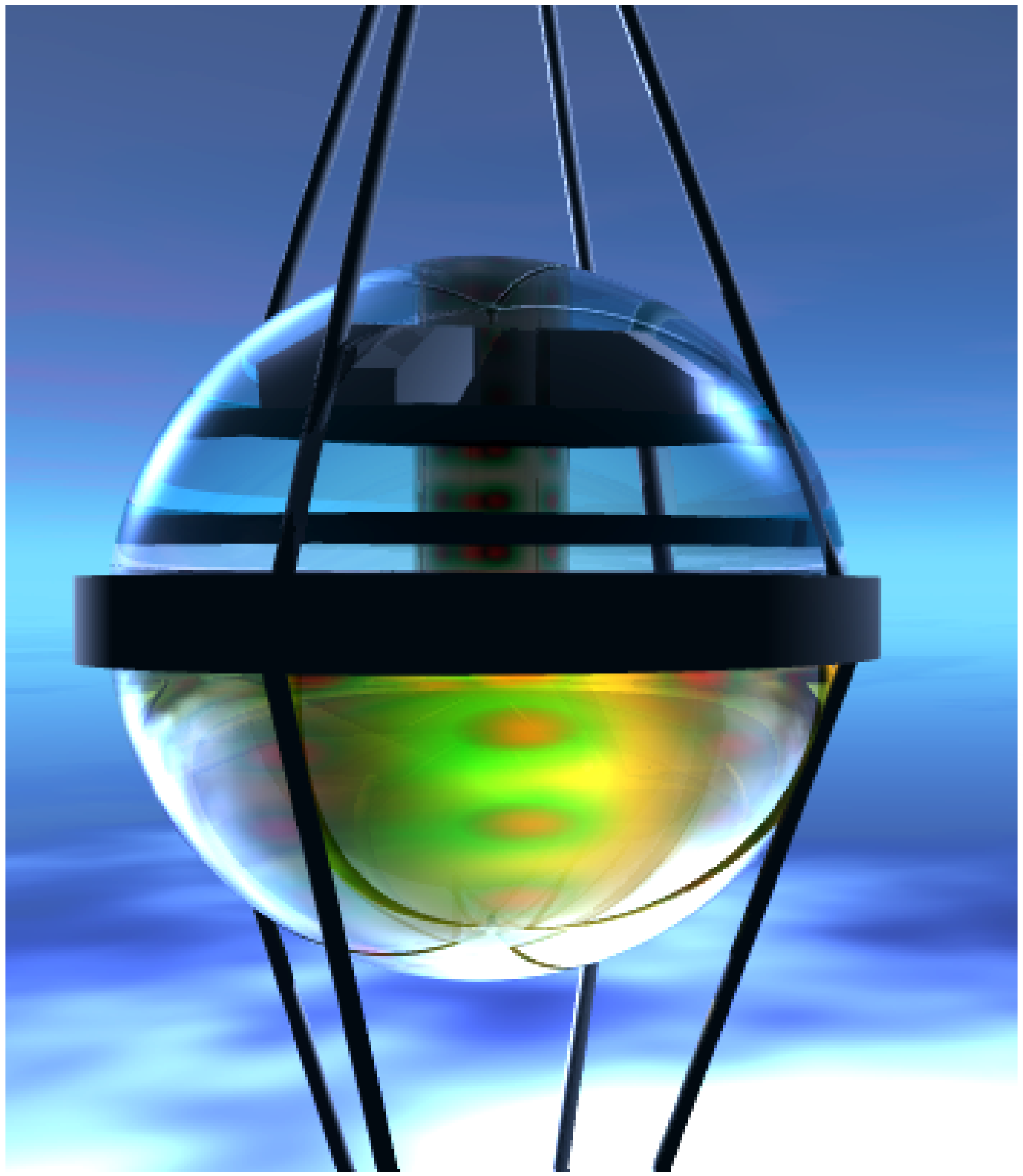
At energies > 10^{15} eV astrophysical ν are expected to dominate the atmospheric ones.

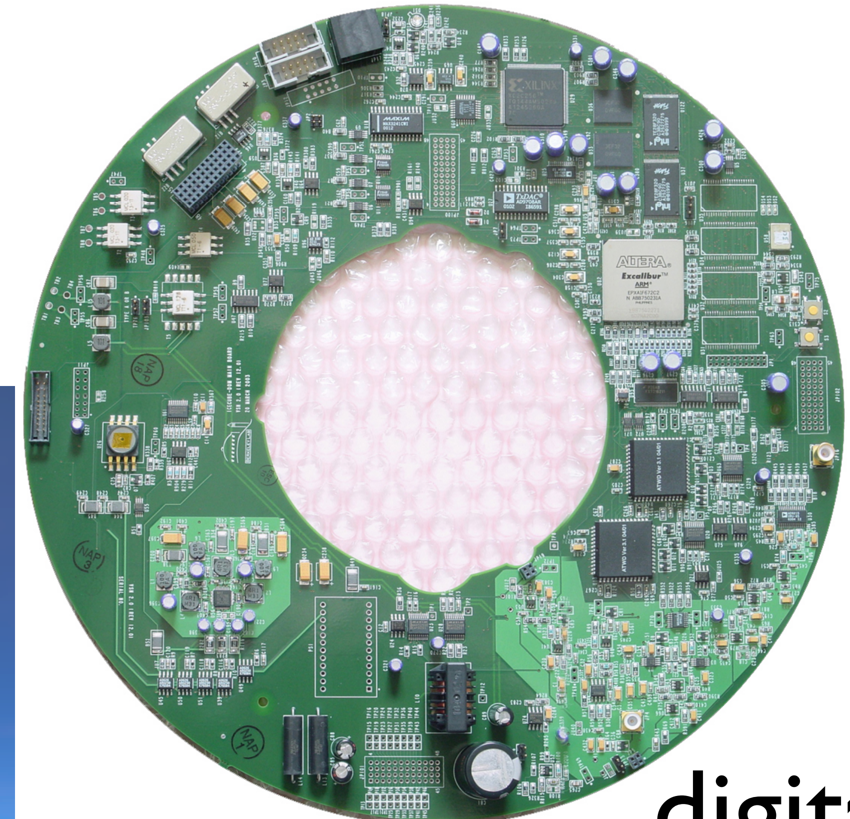
"coincident appearance"
"excess of events"

atmospheric ν:

CR air showers produce many νs.
(diffuse background)

optical module





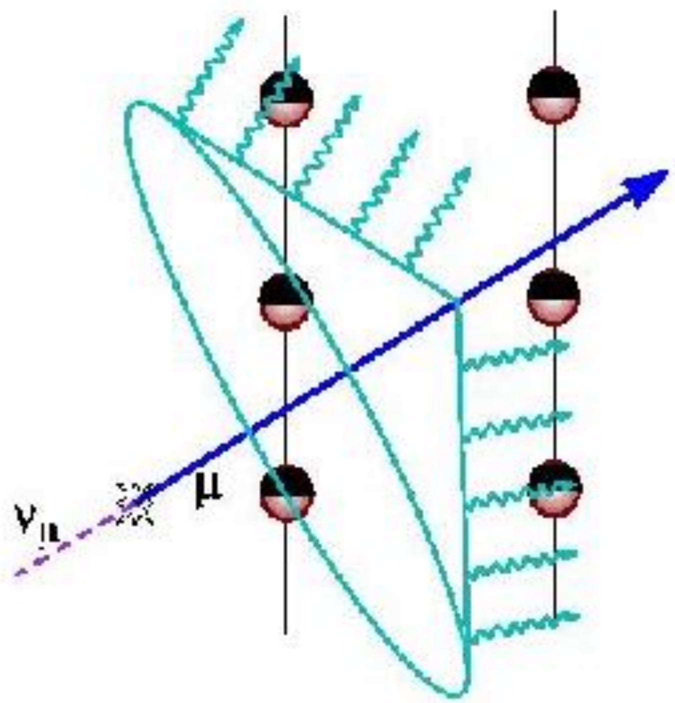
digital electronics

PMT

(Light sensors)

86 strings of 60 opt. modules each

Neutrinos create charged particles
which in turn produce Cherenkov light.

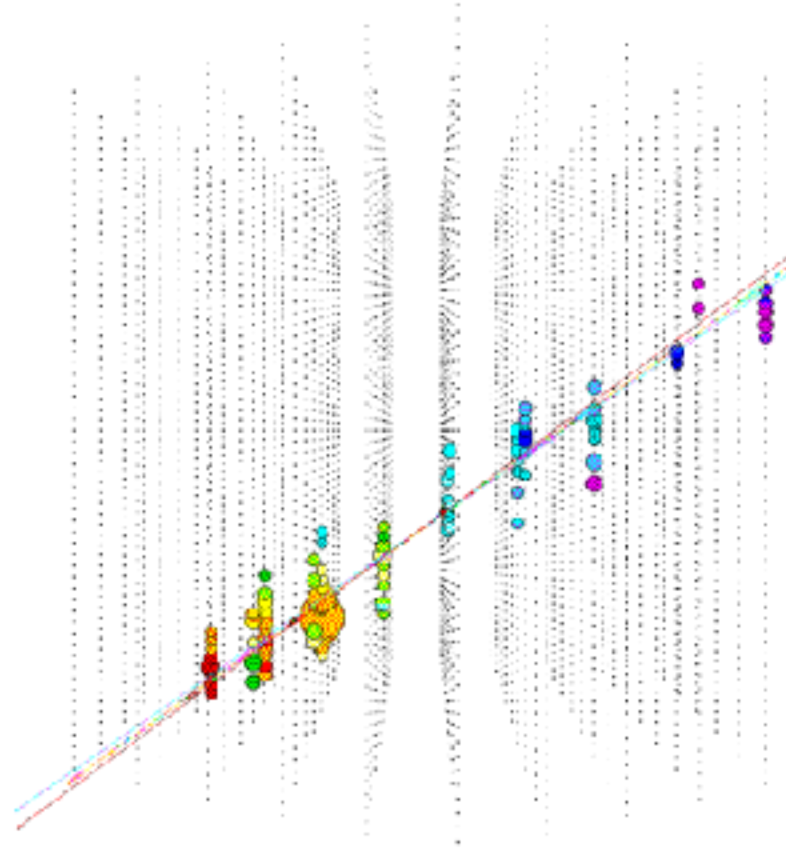


Muon-tracks

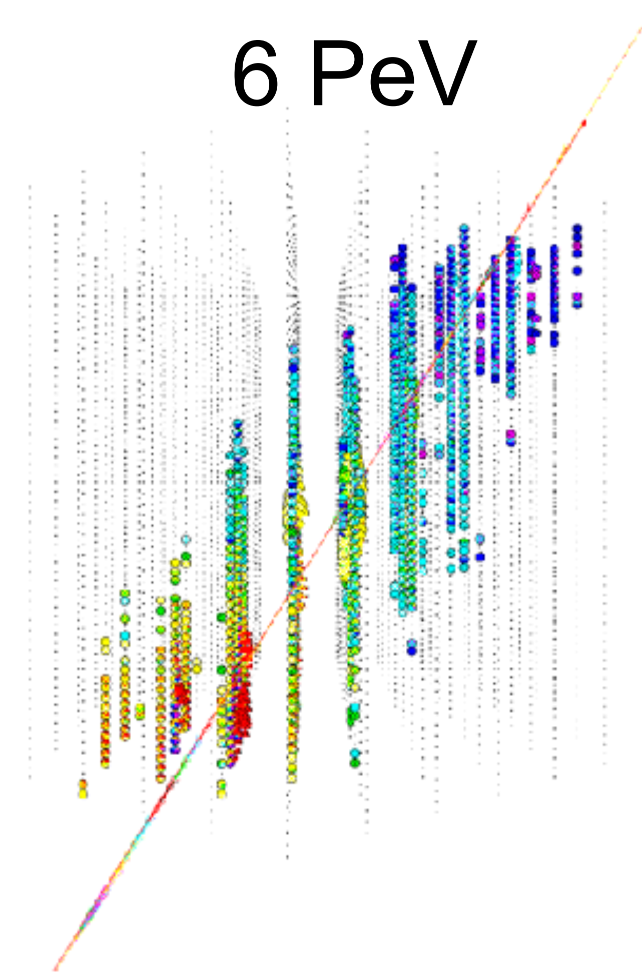
good pointing (<1 degree)

large event rates due to long muon tracks

10 TeV



6 PeV

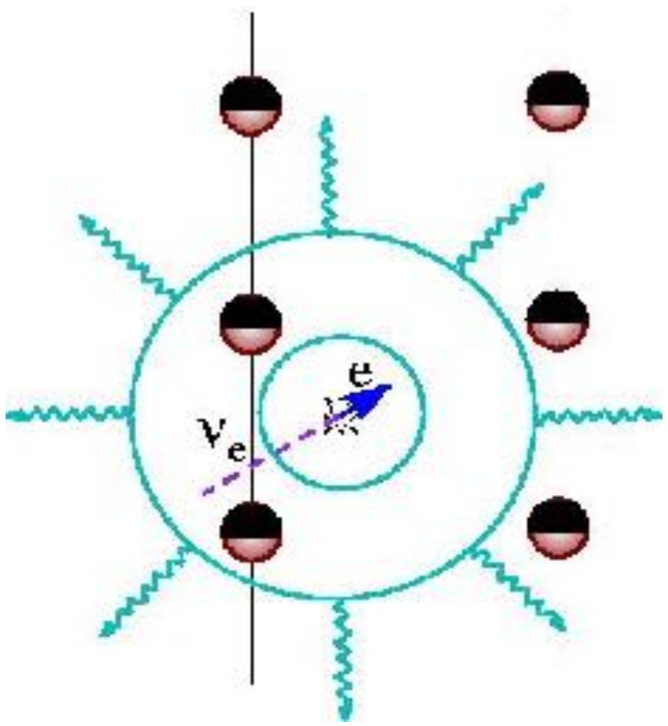


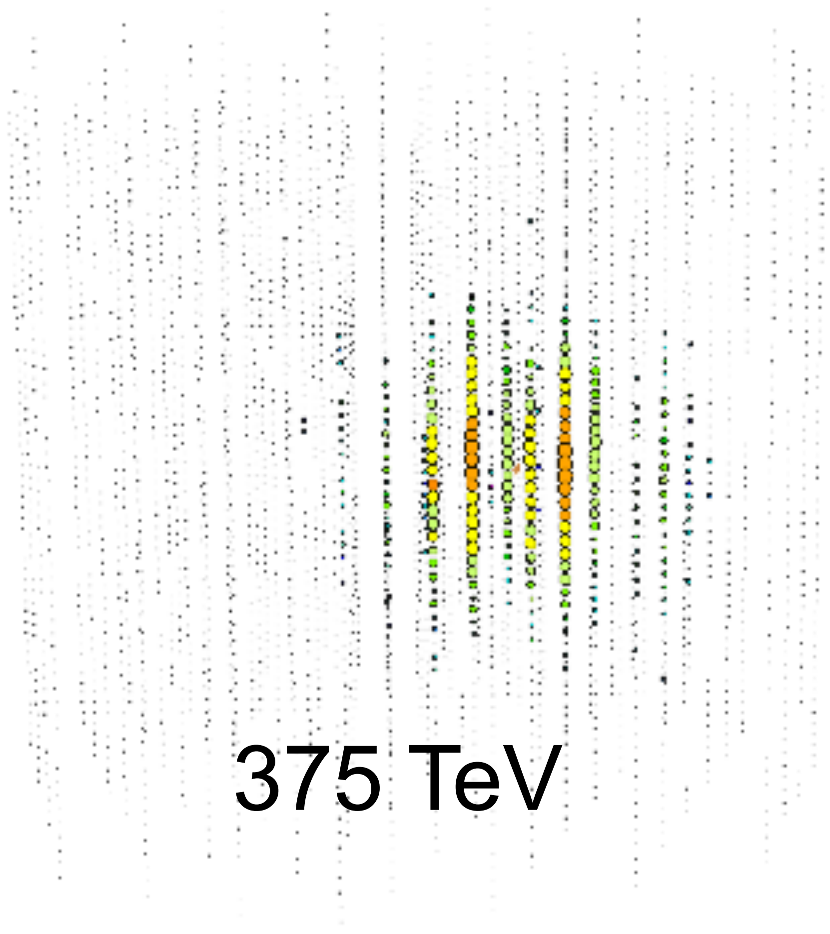
signature of ν_μ

Particle cascades

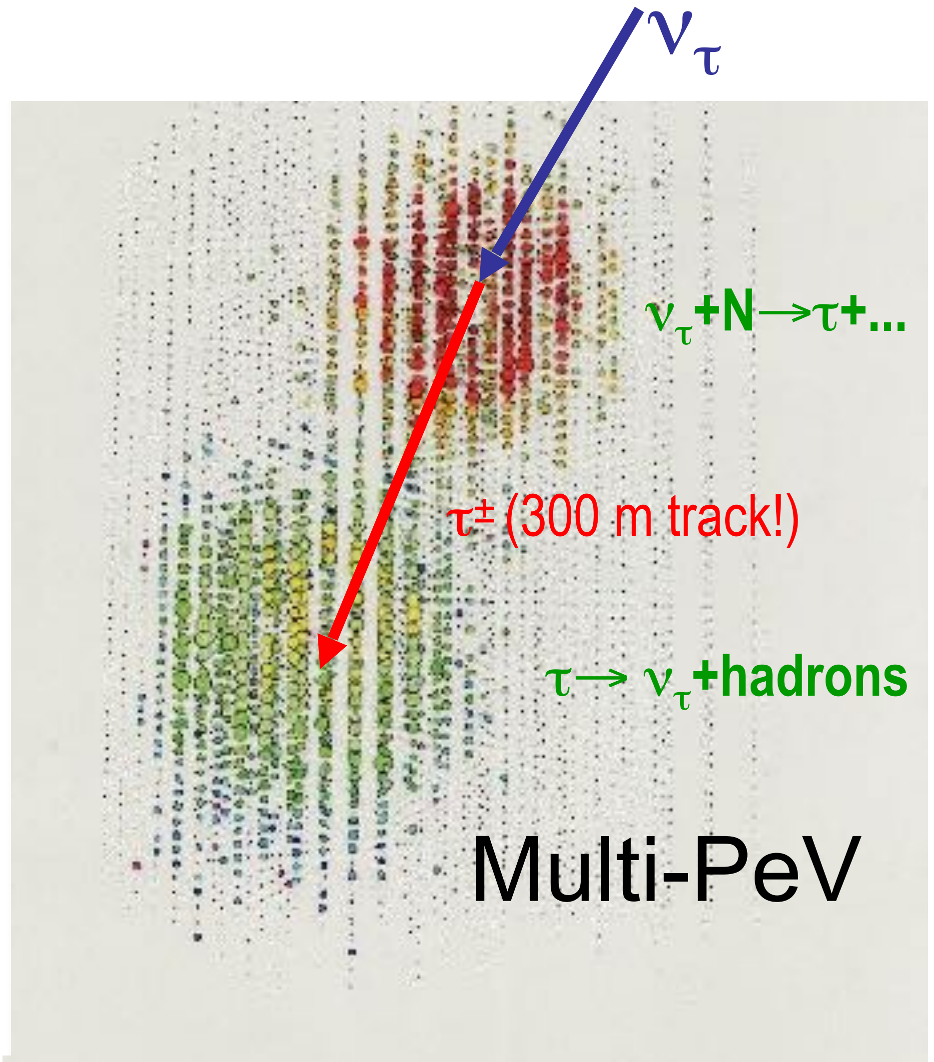
ν_e , ν_τ

good energy resolution,
little background





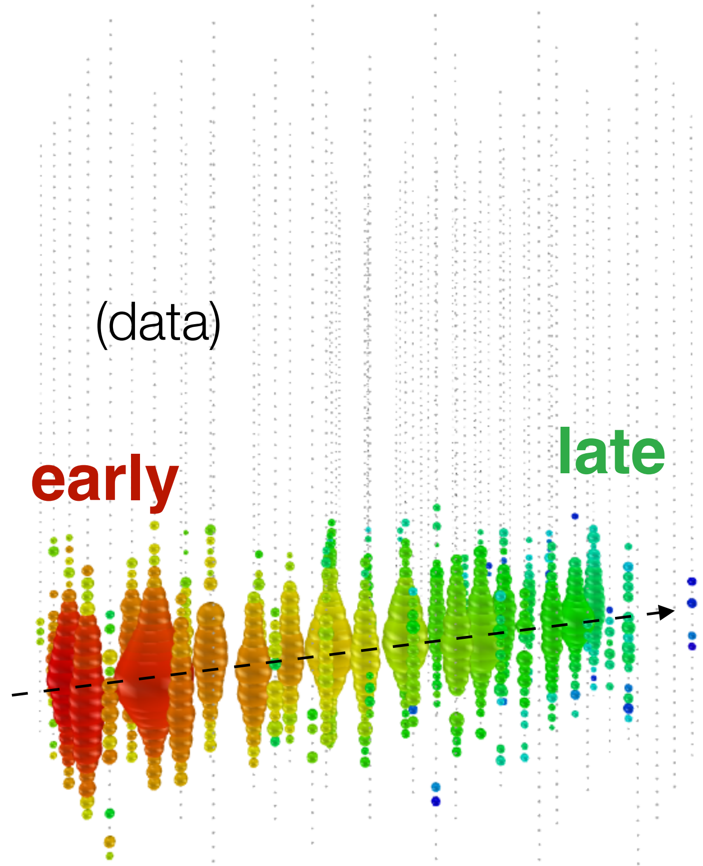
signature of ν_e



signature of ν_τ

Neutrino event types

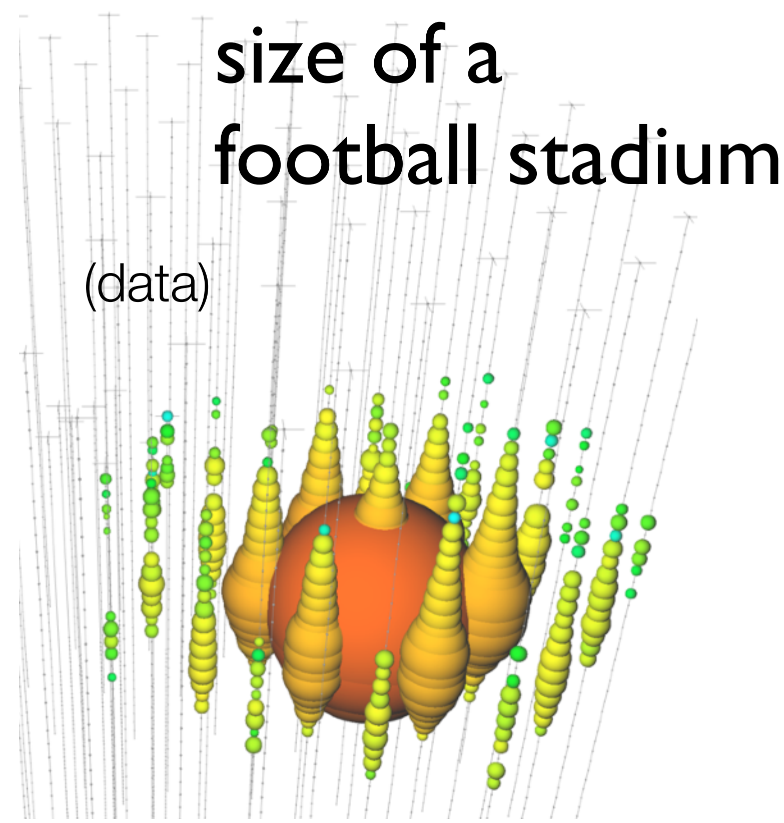
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

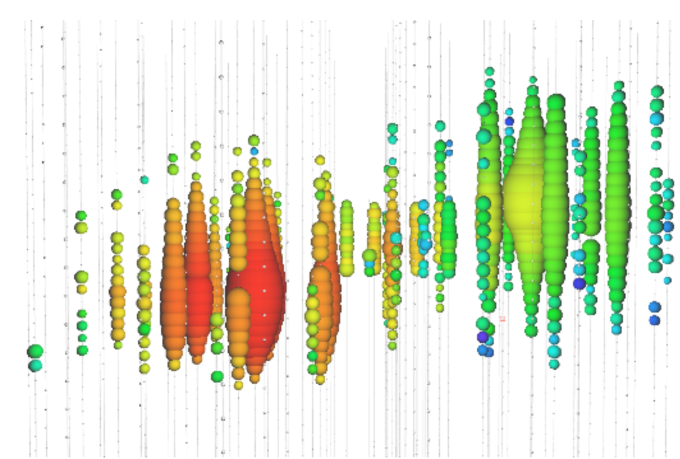


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

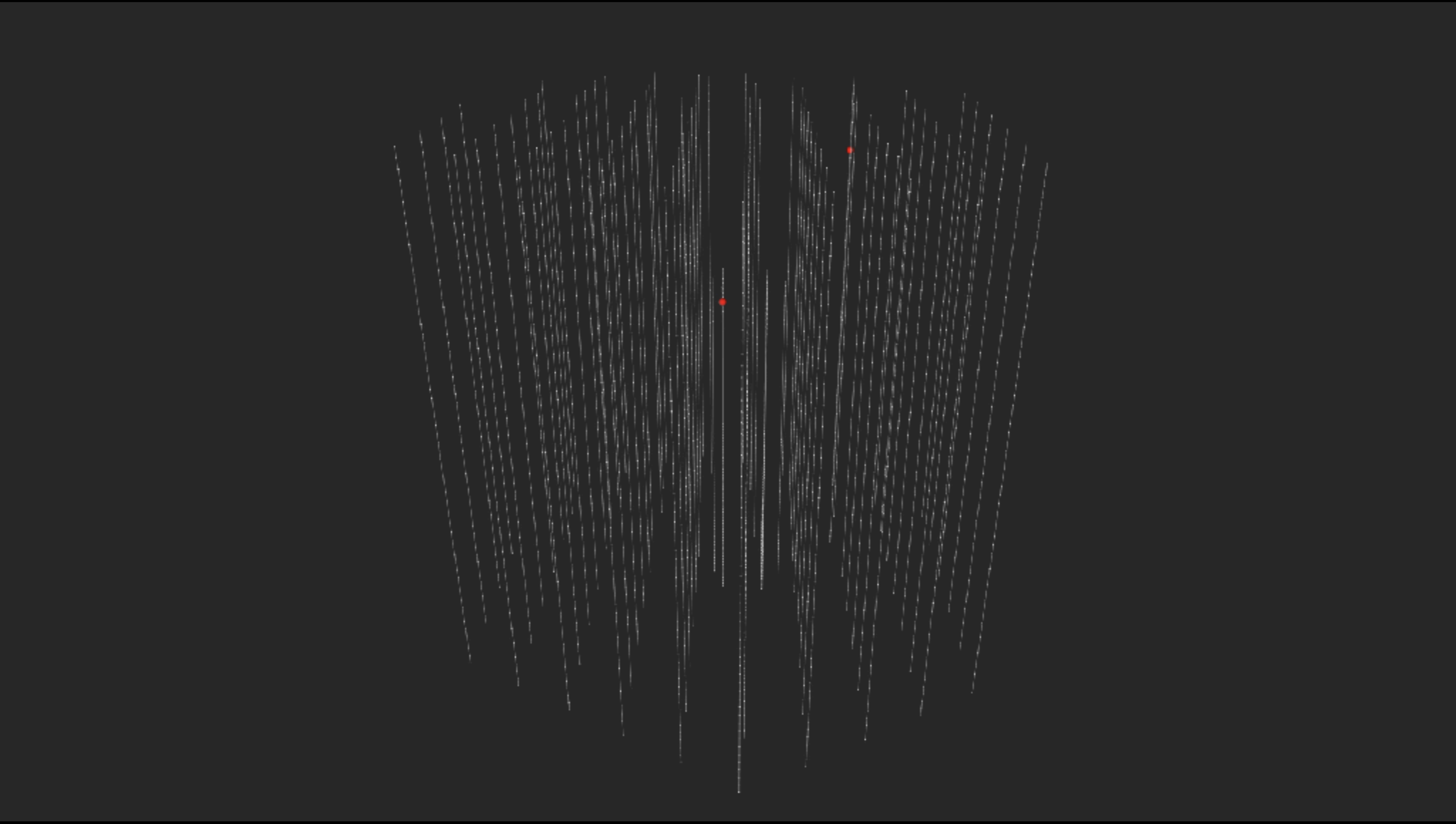
Charged-current ν_τ

(simulation)

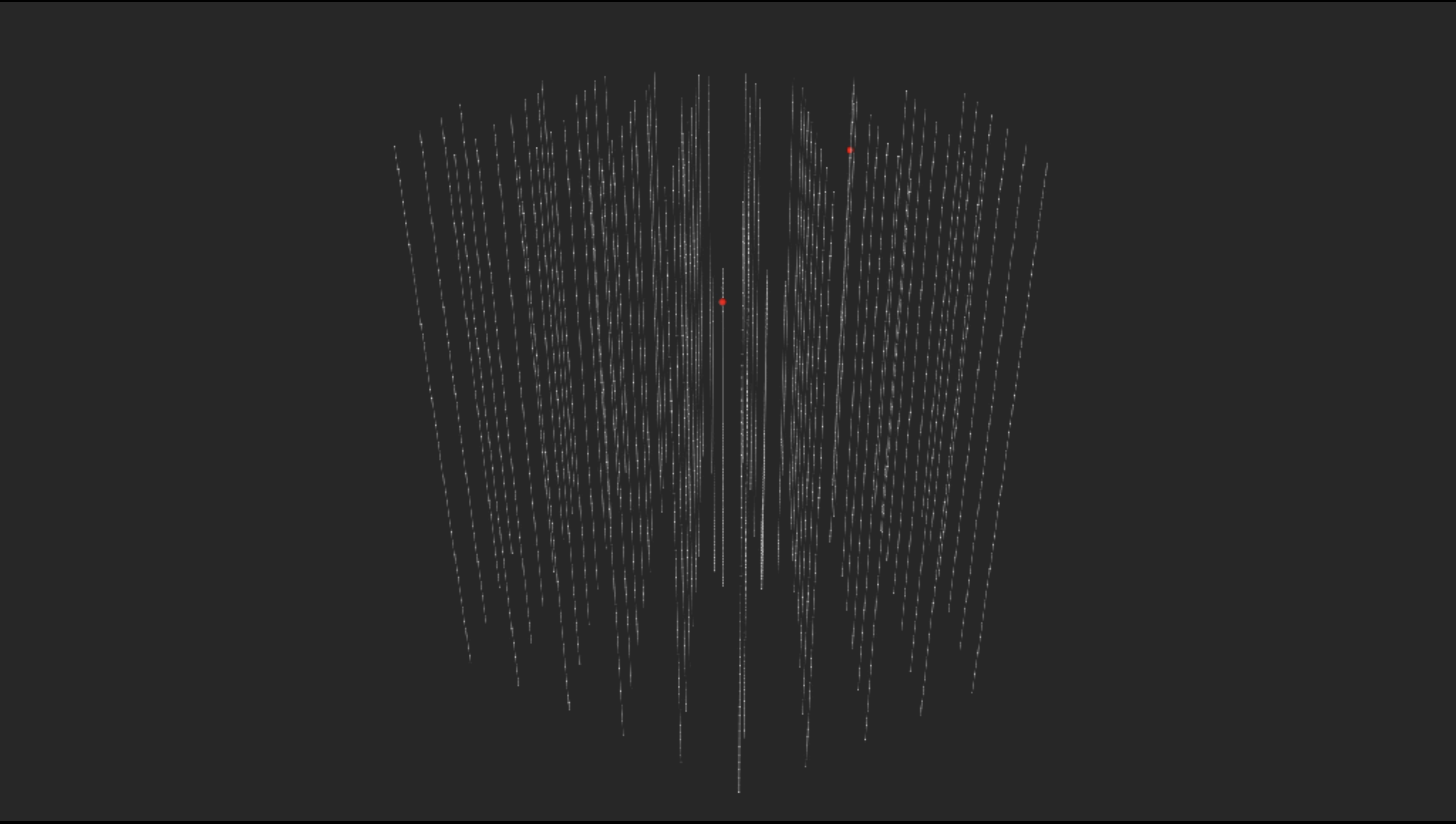


Double cascade

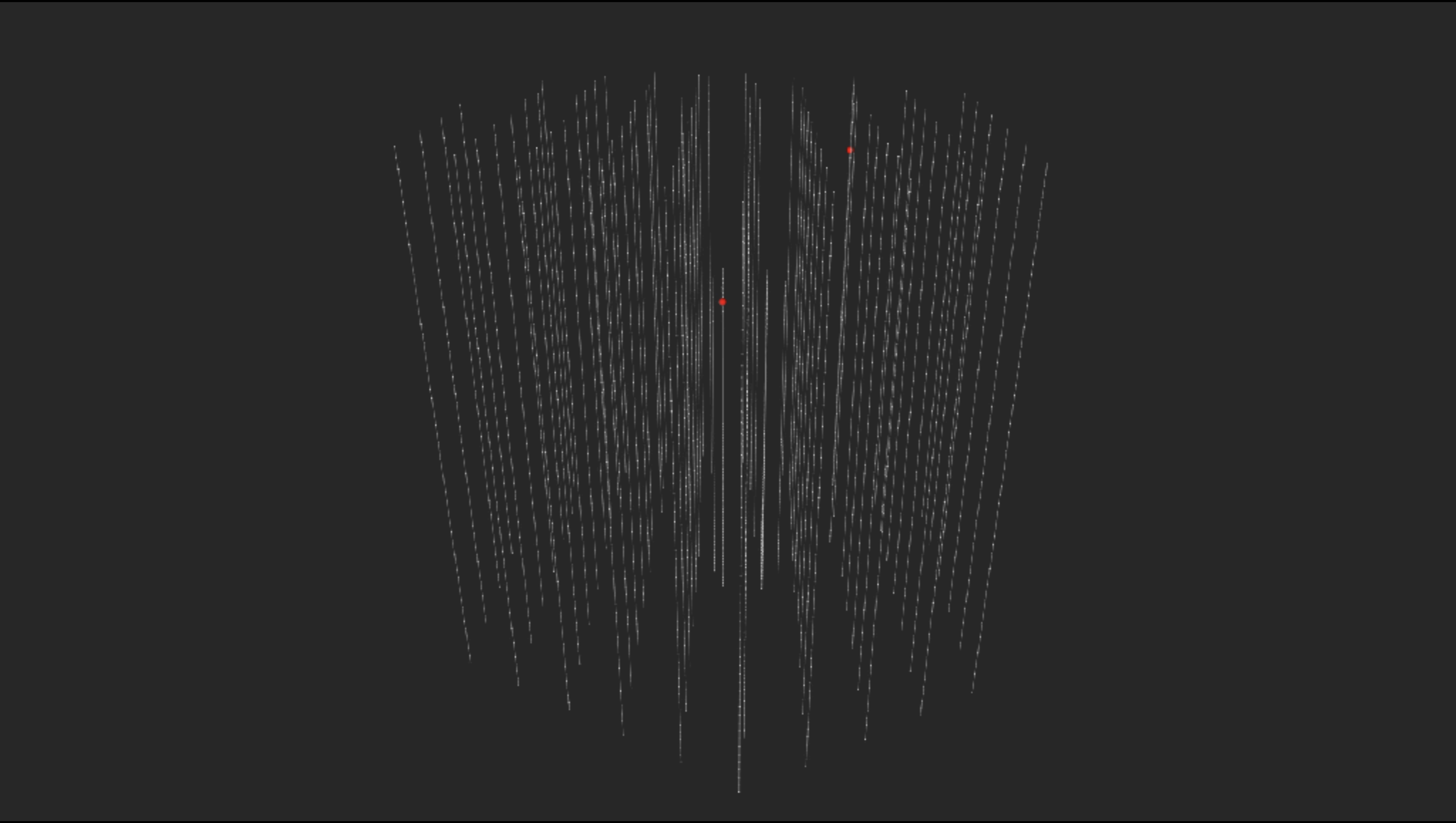
(resolvable above O(100) TeV deposited energy, 20 m τ decay length)



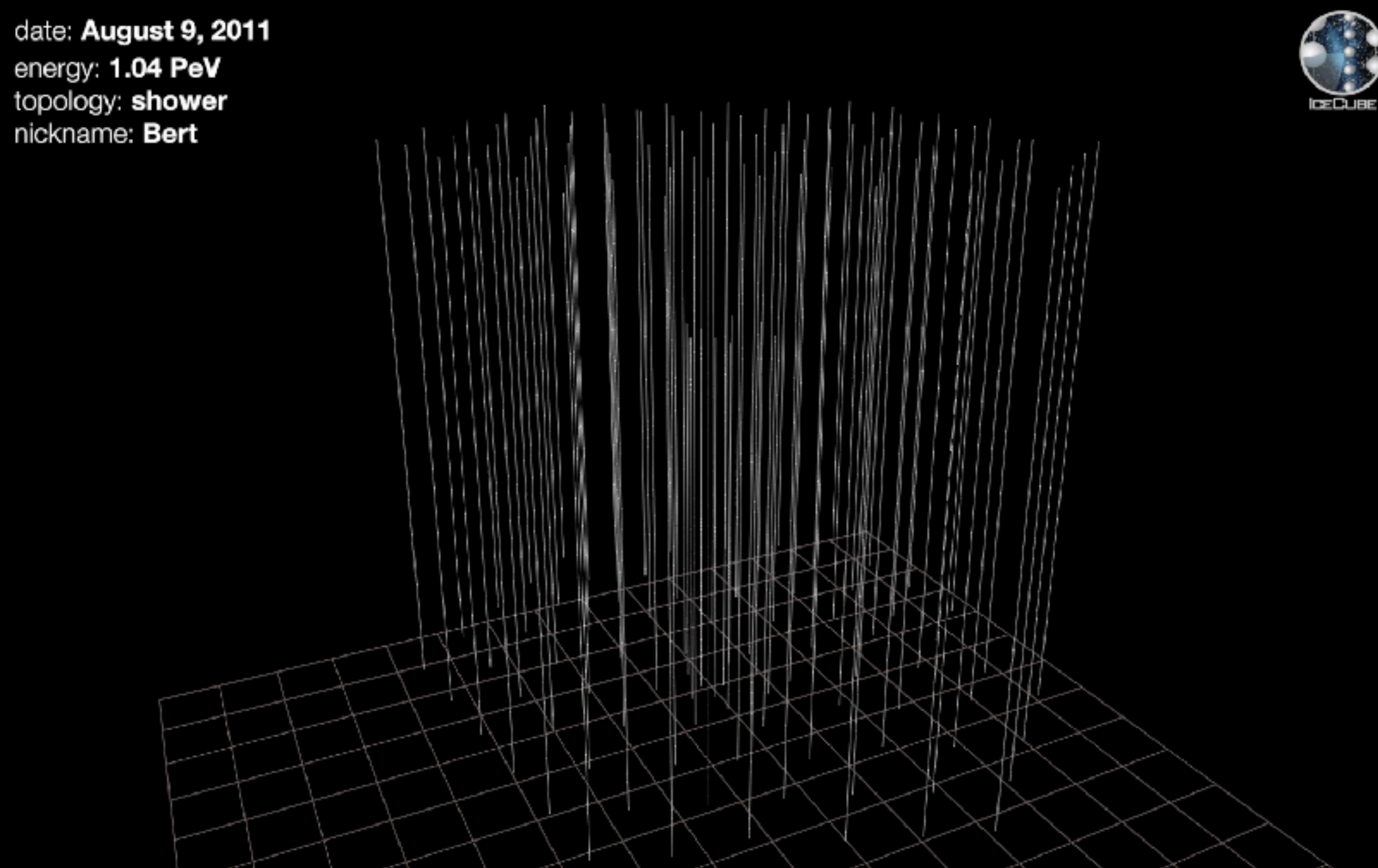
track-like



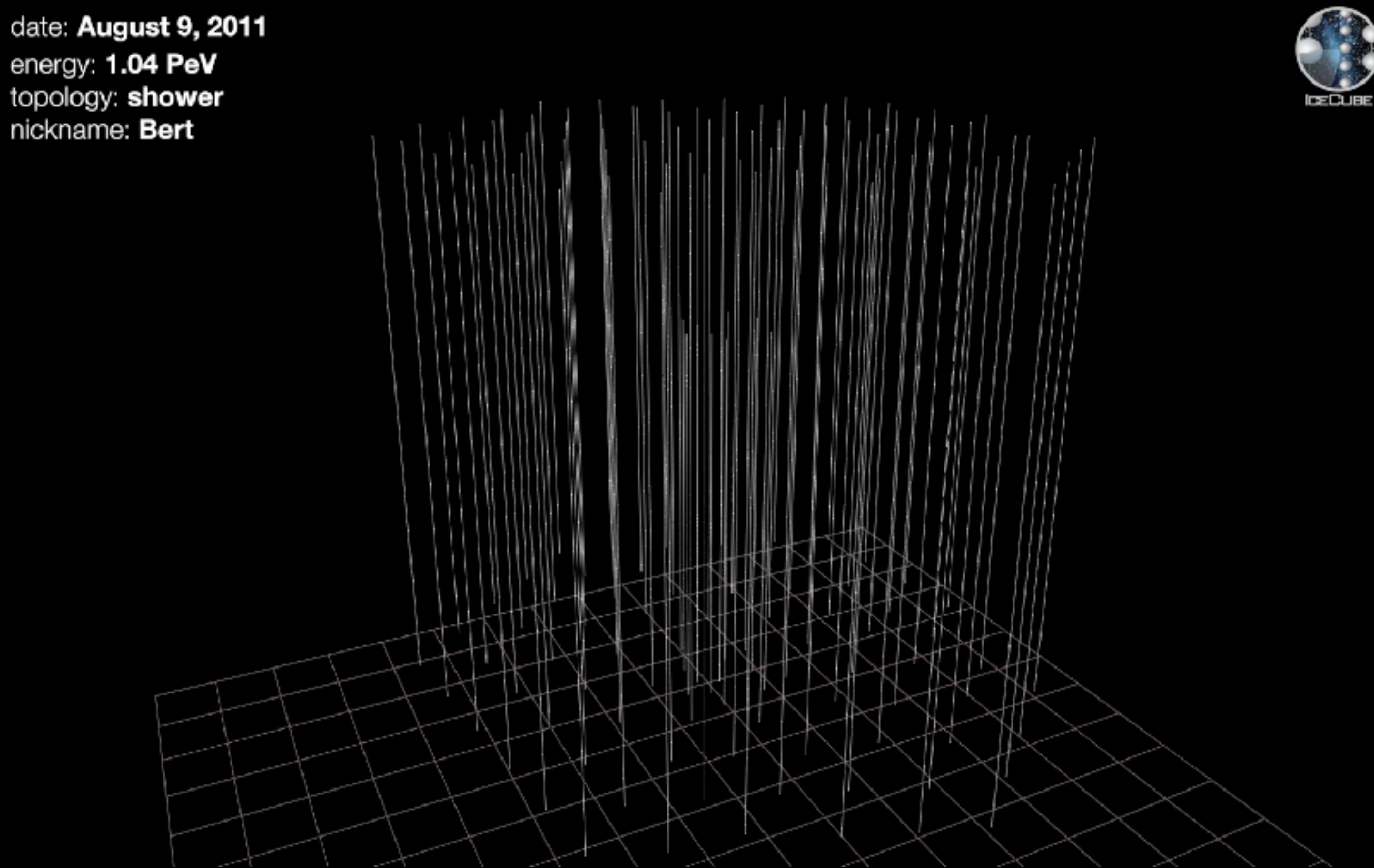
track-like



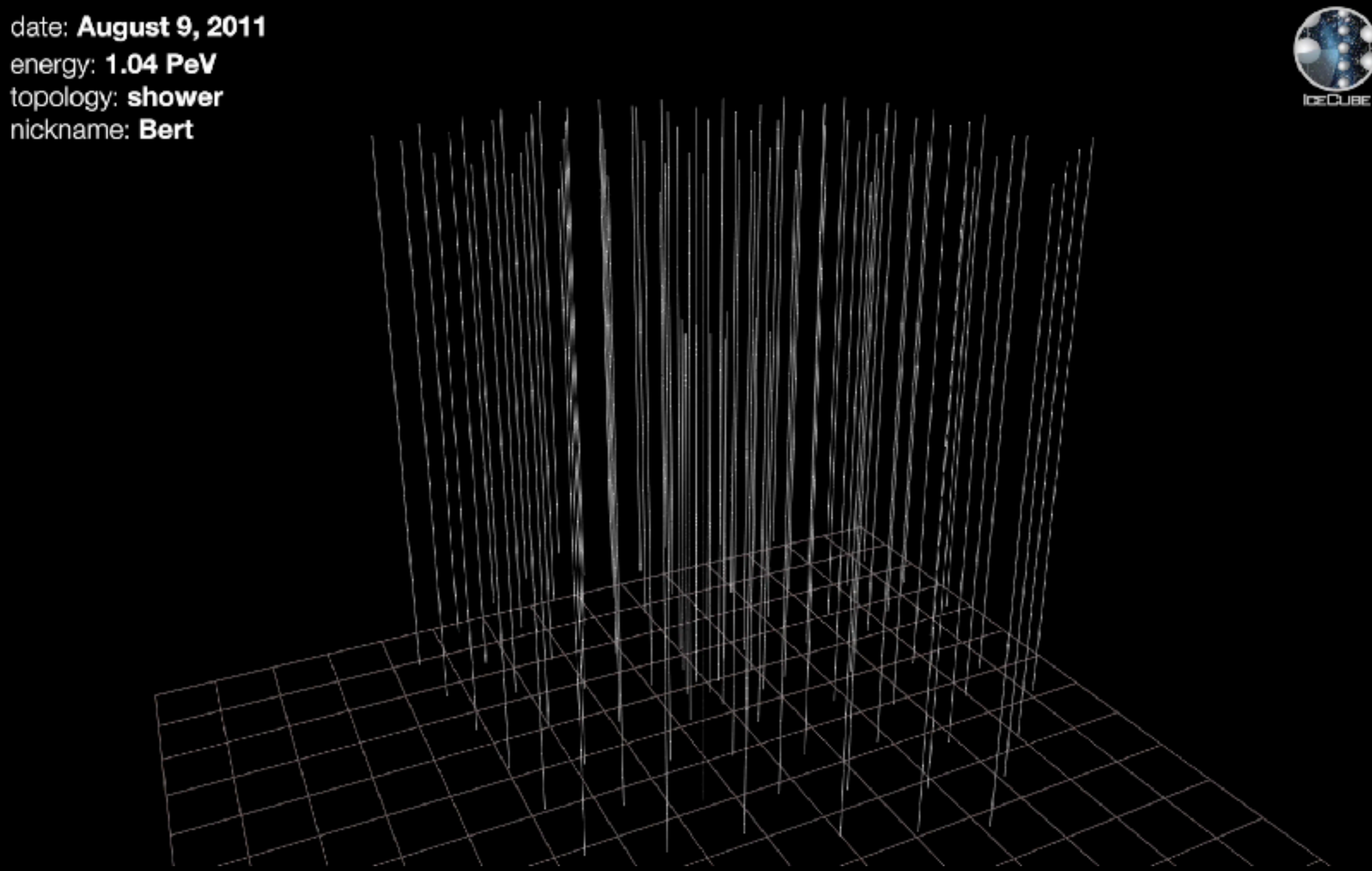
track-like



shower-like (data)



shower-like (data)

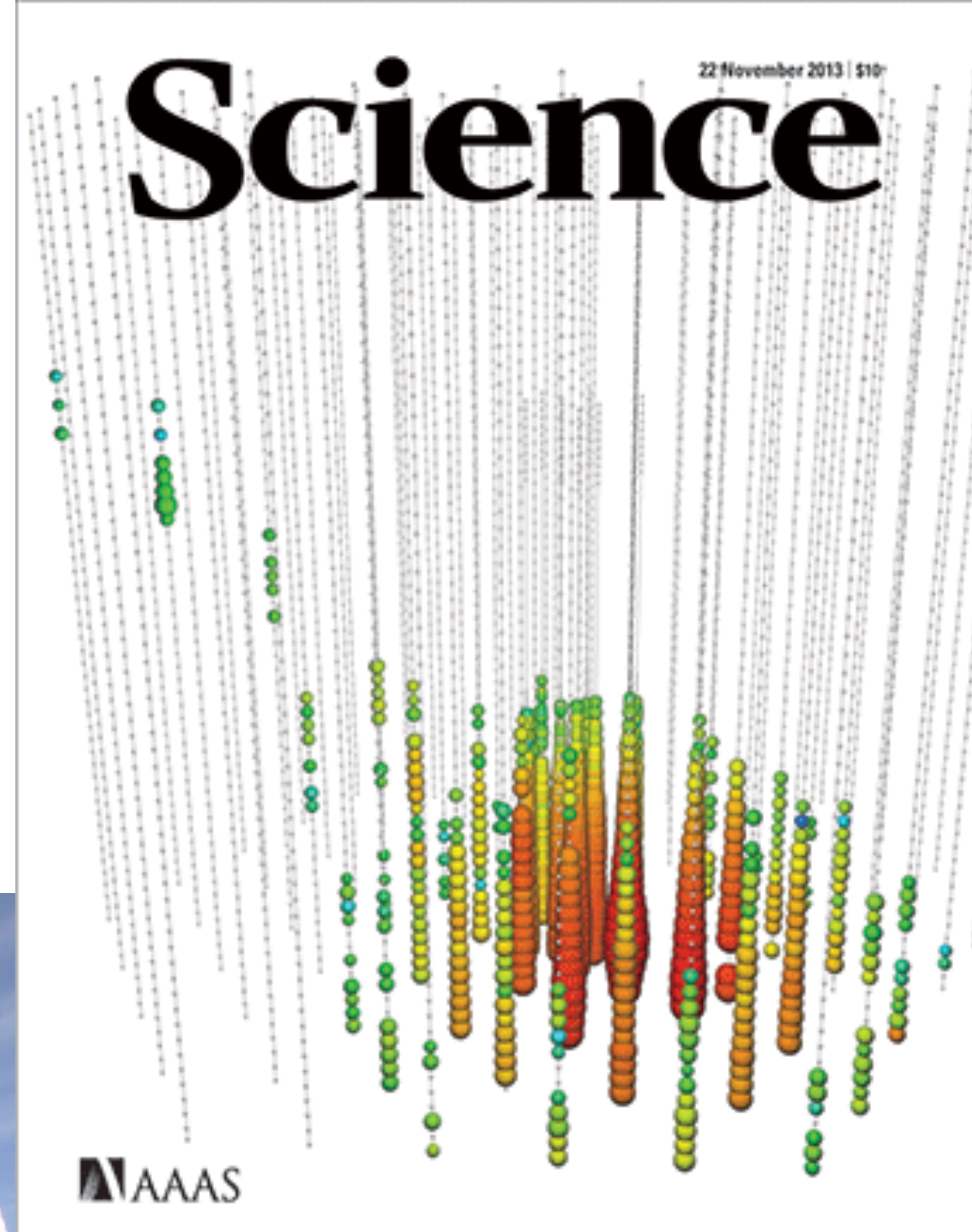


shower-like (data)

28 high-energy νs

Clear evidence for astrophysical origin

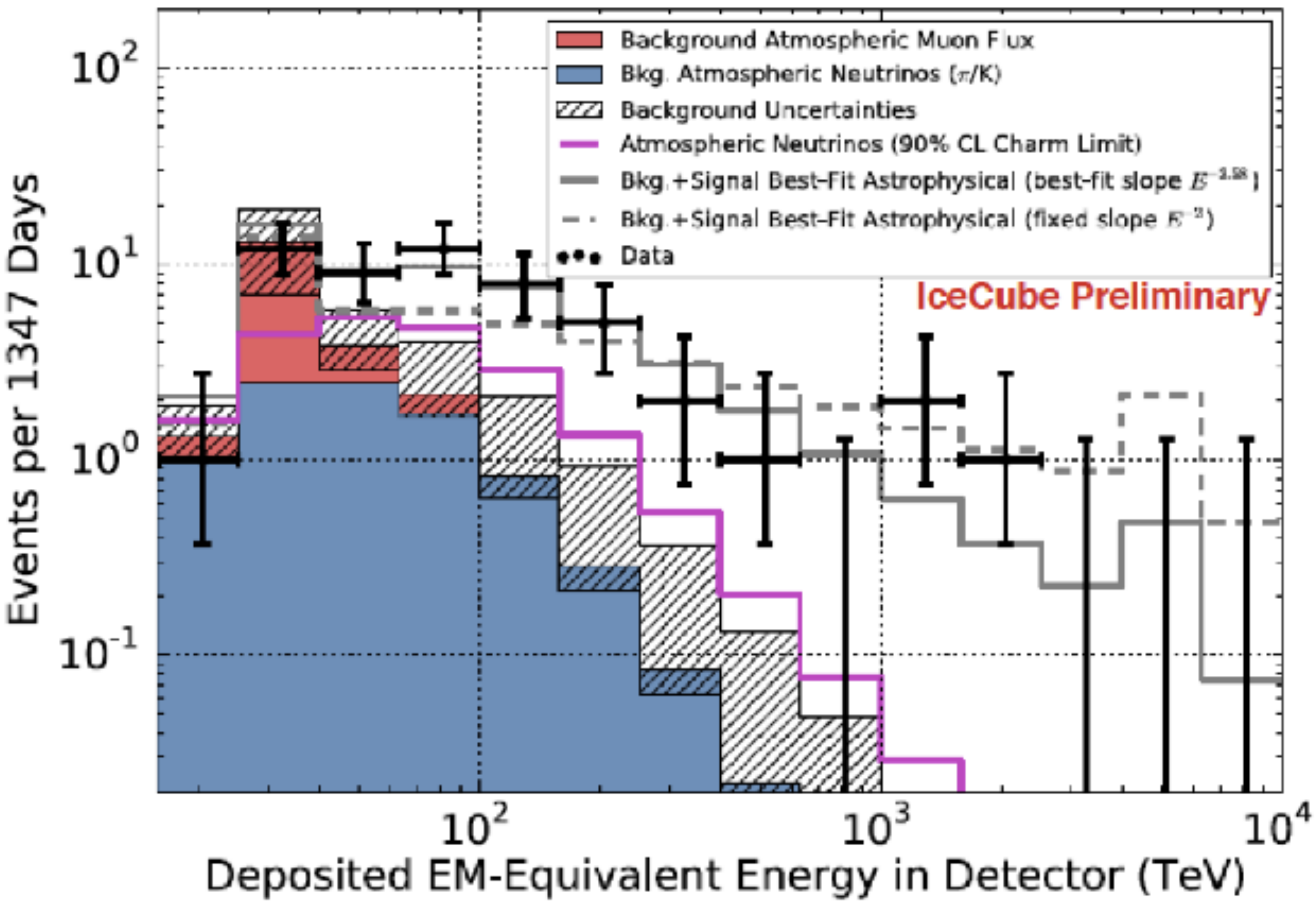
(>5σ)



Nov 2013

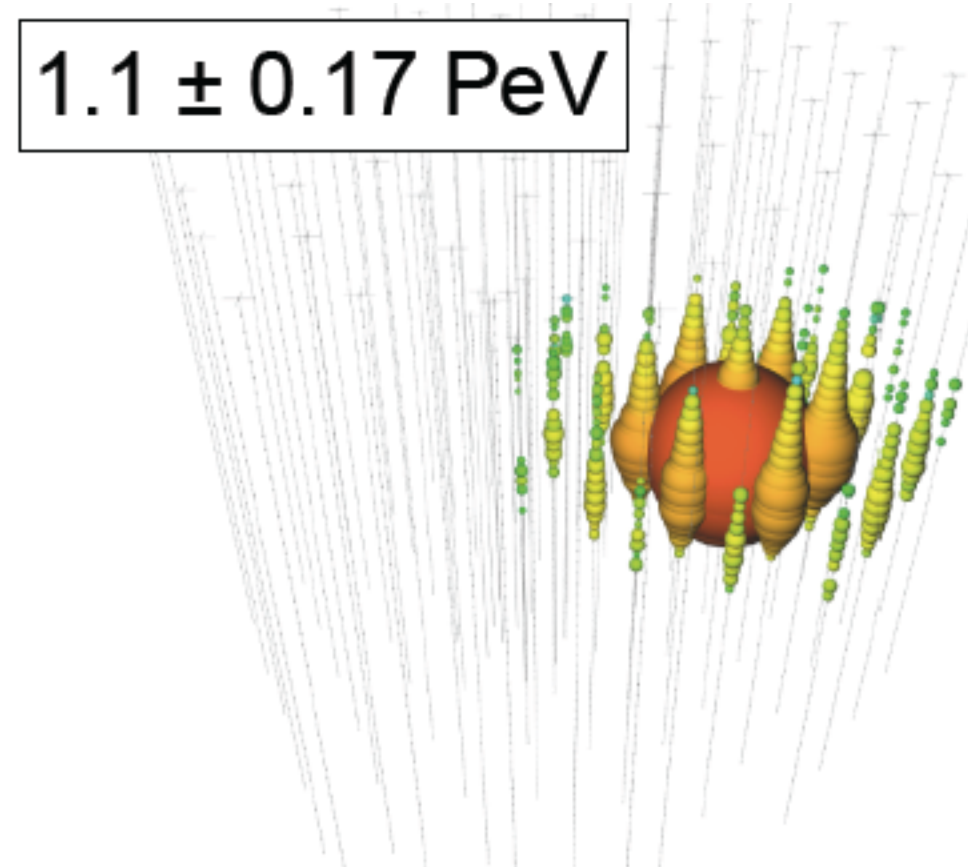
Spectrum

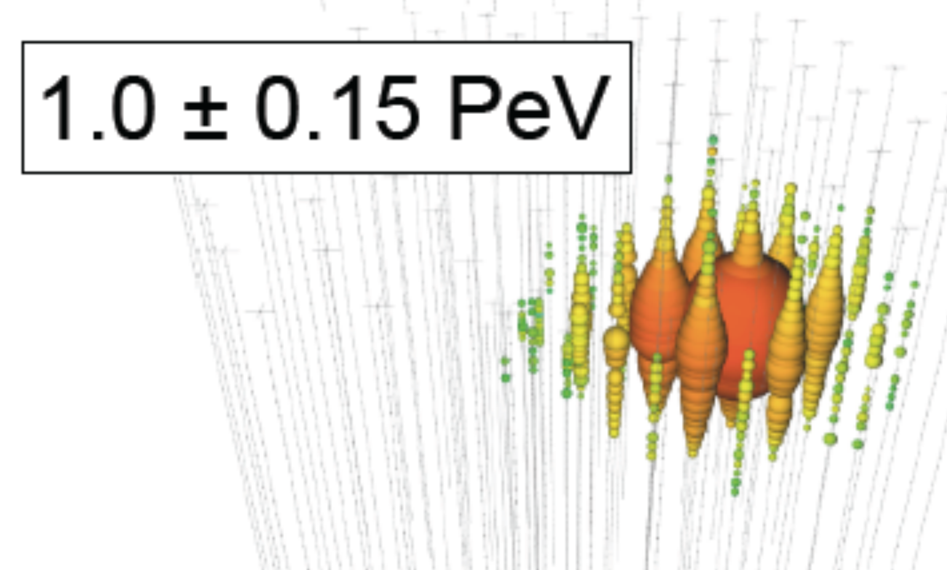
54 events observed,
20±6 expected from atmosphere

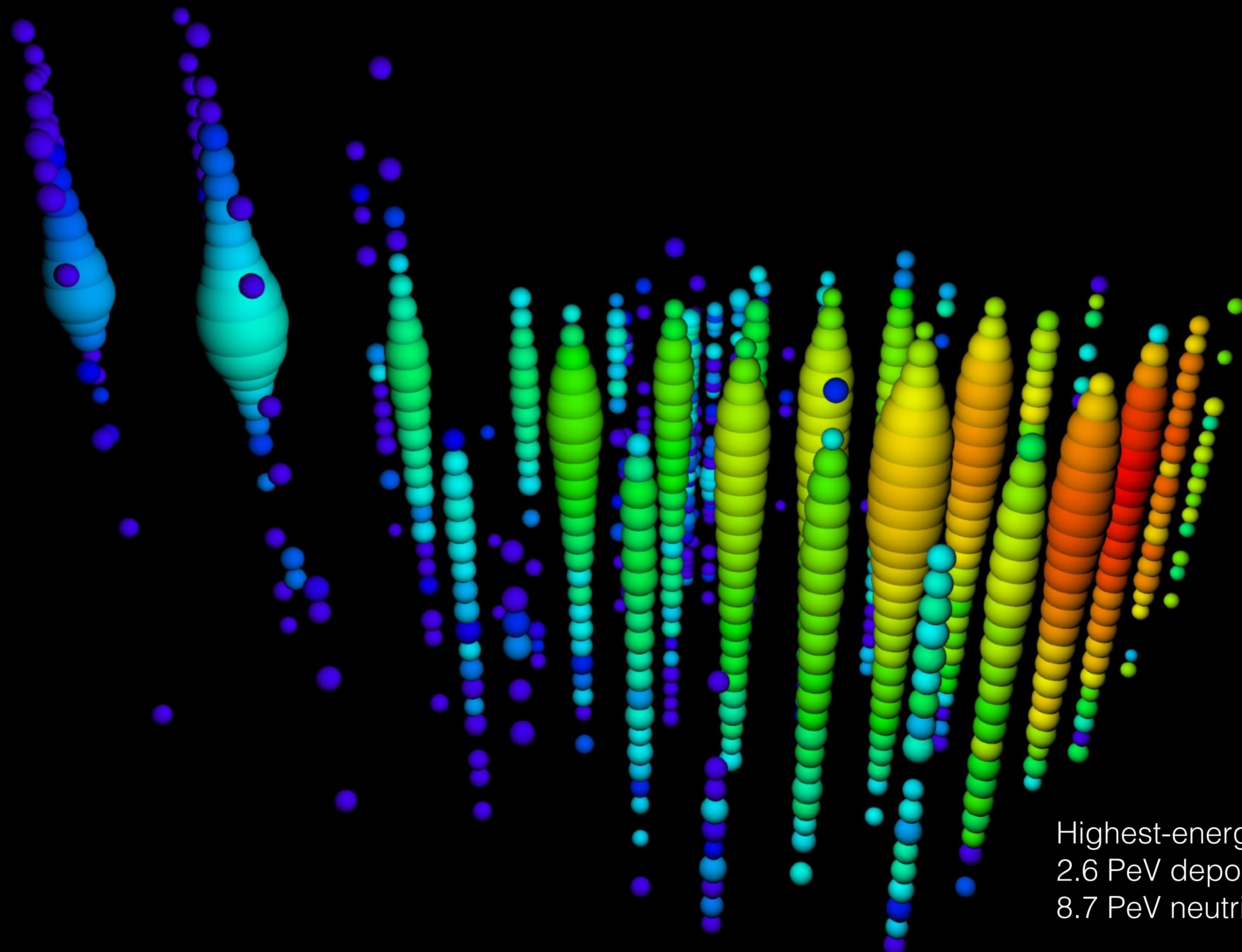


now: ~7 σ evidence for
extra-terrestrial ν

E ≥ 10^{15} eV





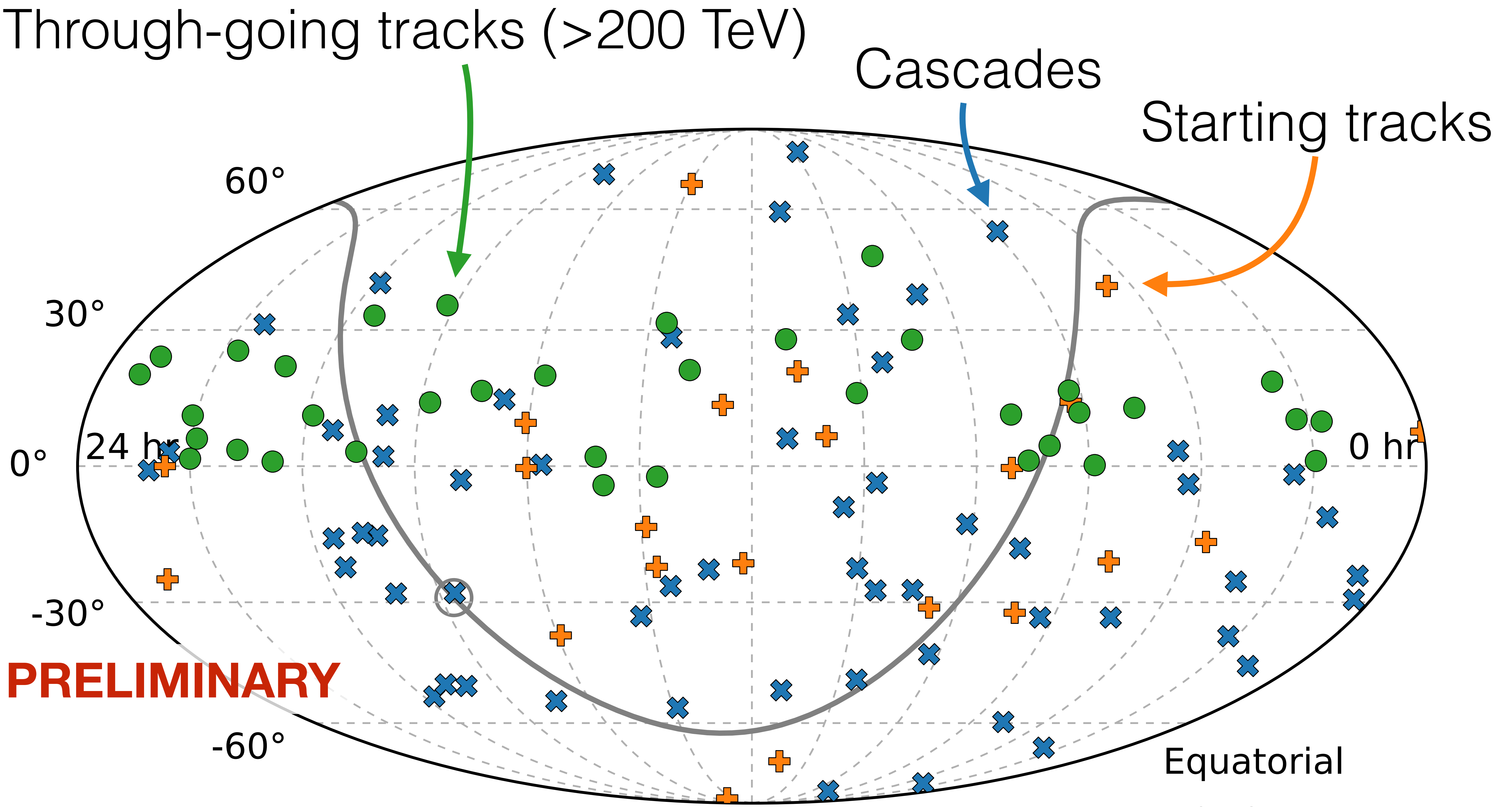


Highest-energy neutrino-induced muon
2.6 PeV deposited energy
8.7 PeV neutrino energy (median)

Astrophys.J. 833 (2016) no.1, 3

2013: The birth of Neutrino Astronomy

High-energy neutrinos on the sky



See C. Kopper, NU060

No evidence of clustering in high-energy neutrino directions (> 50% astrophysical).

… **must be largely extragalactic**

Each neutrino points back at its source.
(track like events: <1 deg precision)

Why don't we see a "strongest source" with more than a few neutrinos?

Perhaps, there are very many sources,
but with so low fluxes that most give us
0 neutrinos,
few give us one neutrino,
none gives us more than one.

Neutrinos reach us from the whole universe.
There are very many sources….

Not much to learn on sources, if on has an isotropic sky and no more than 1 neutrino per source.

Possible Sources?

Blazars (AGN): bright/powerful in gamma rays
predicted to are neutrino sources

GRBs: very bright in gamma rays, transient

… but comparison of neutrino positions with Blazars / GRBs
rules them out as major sources.

GRBs < 1% of IceCube neutrinos
Blazars < 27%

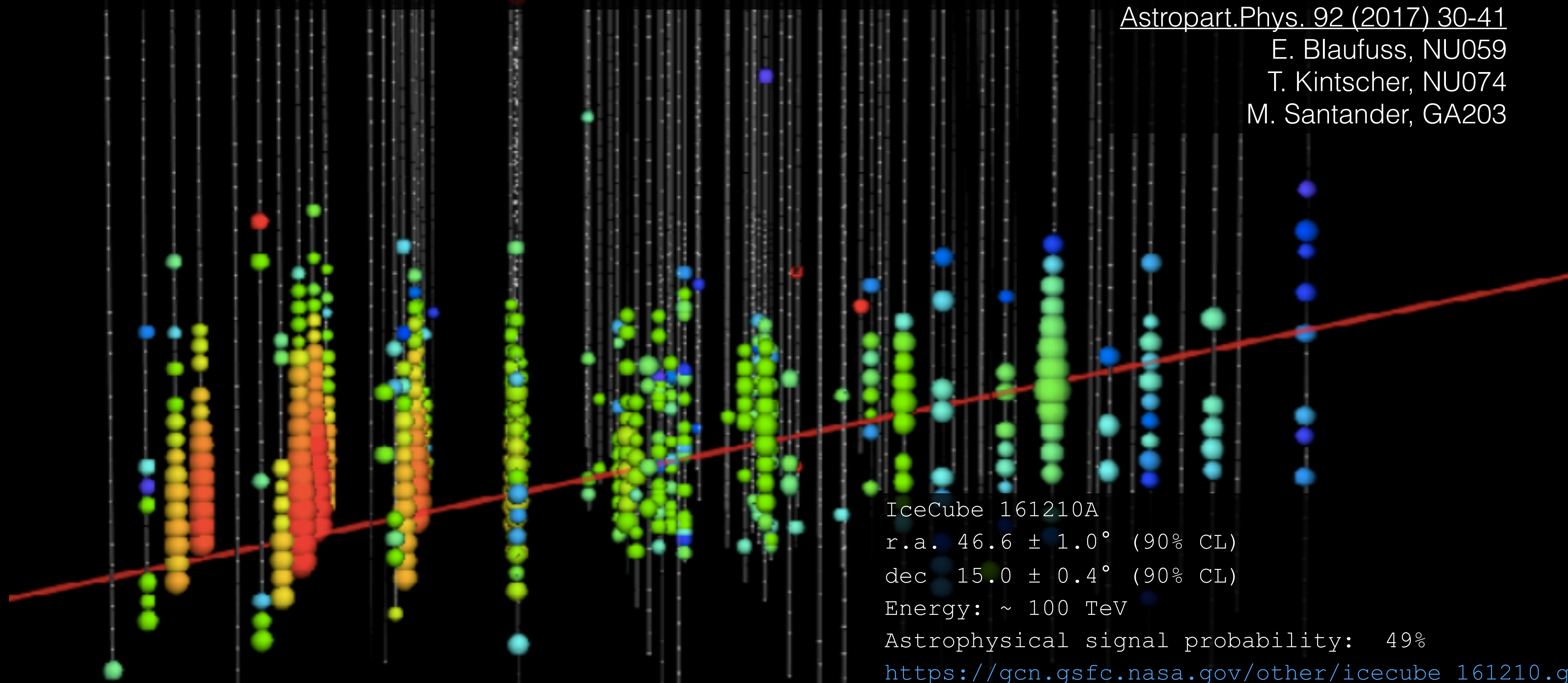
So, what are the source of the high-energy neutrinos???

Realtime alerts via GCN and AMON

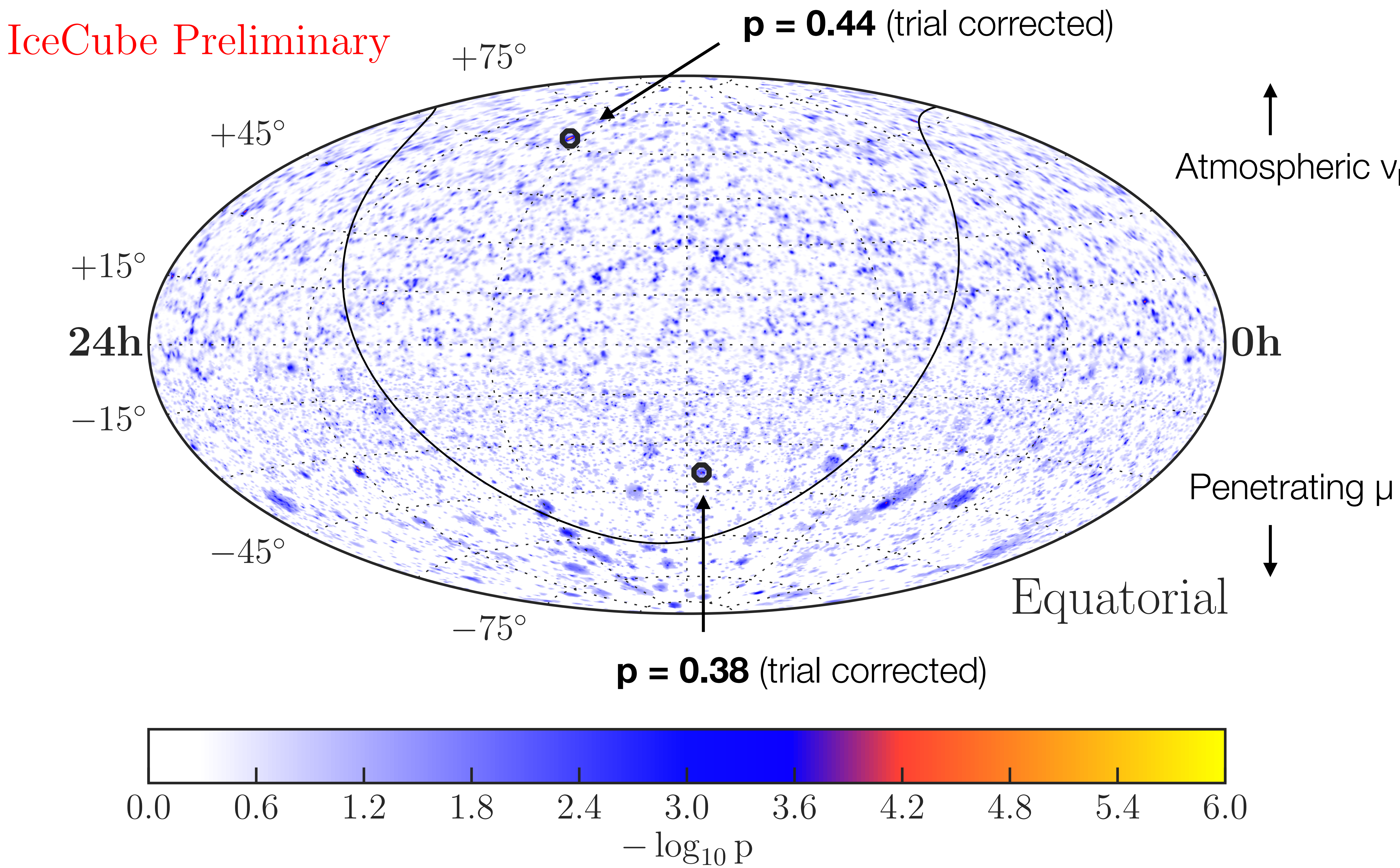
- Public alert stream running since April 2016 (9 events so far)
- Typical delay: < 1 min from trigger to public alert
- Many follow-ups reported for events with high signal probability:

  AGILE, ANTARES, FACT, Fermi-GBM, Fermi-LAT, HAWC, H.E.S.S., INTEGRAL, IPN, Konus-Wind, LCO, MAGIC, MASTER, Maxi/GSC, Pan-STARRS, PTF, Swift, VERITAS

Astropart.Phys. 92 (2017) 30-41
E. Blaufuss, NU059
T. Kintscher, NU074
M. Santander, GA203

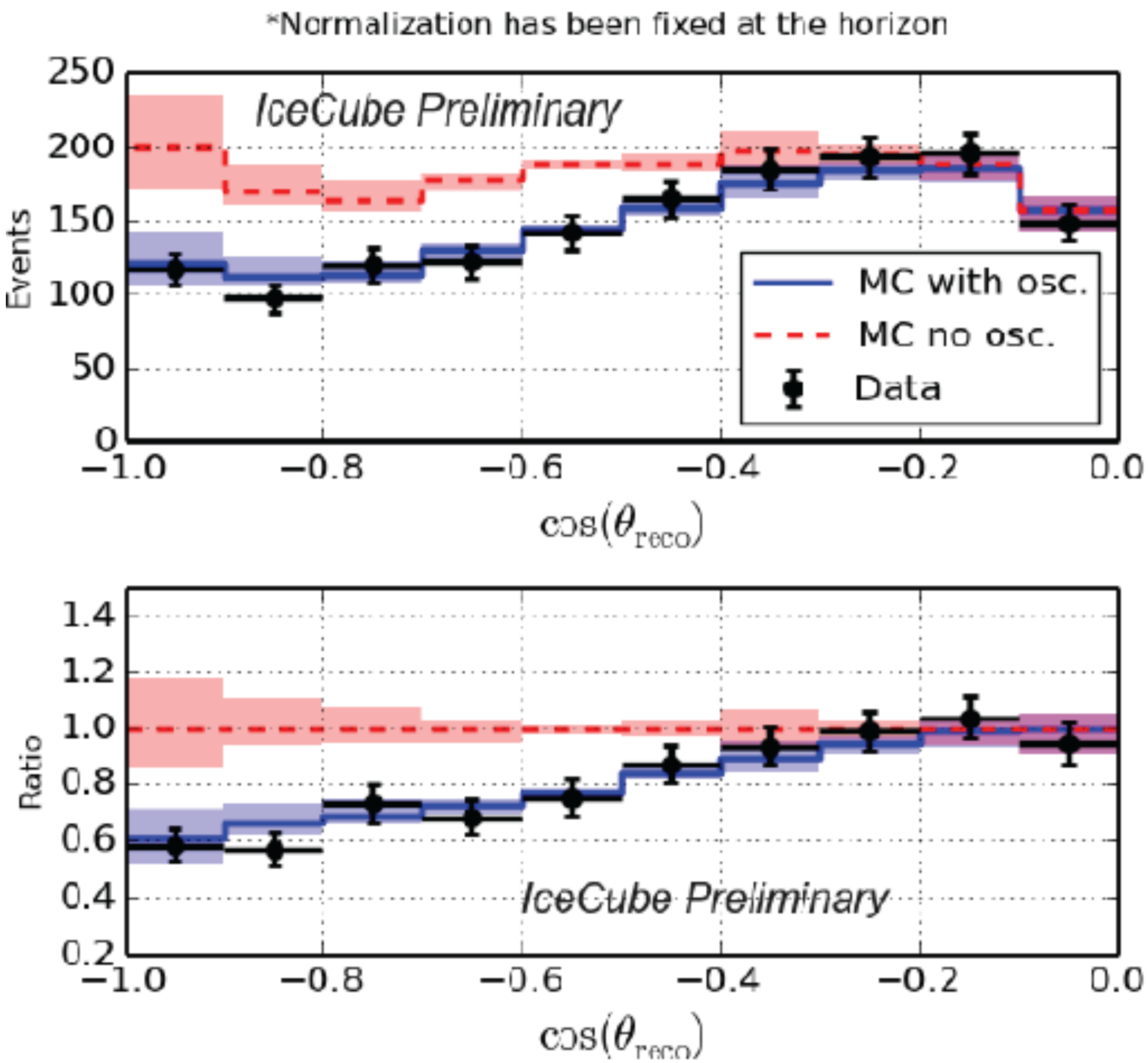


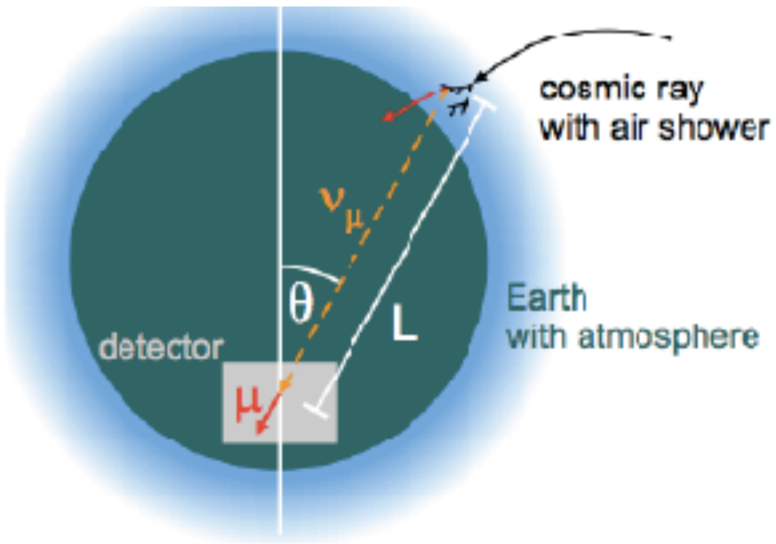
All-sky time-integrated point source search

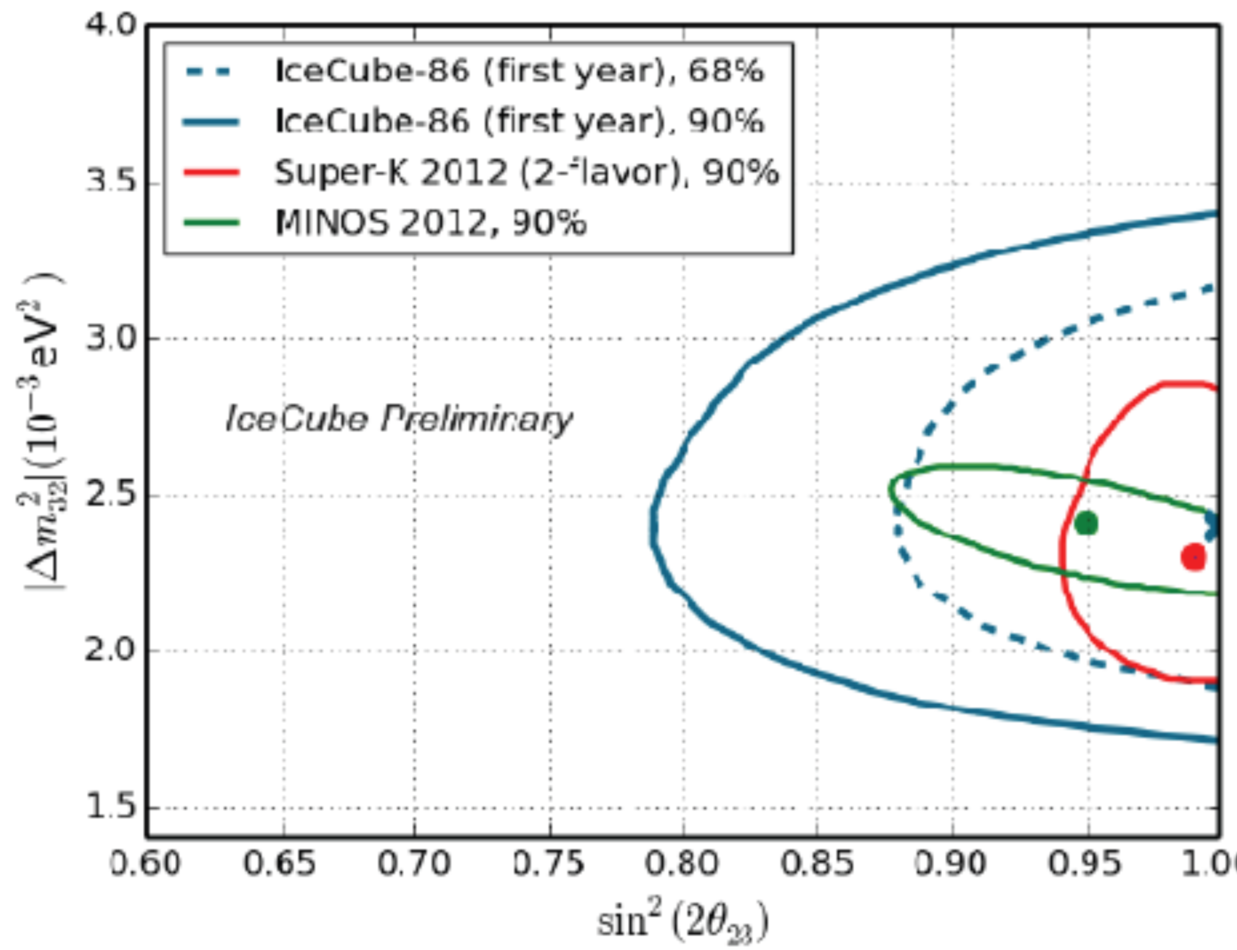


ApJ 835 (2017) 2, 151

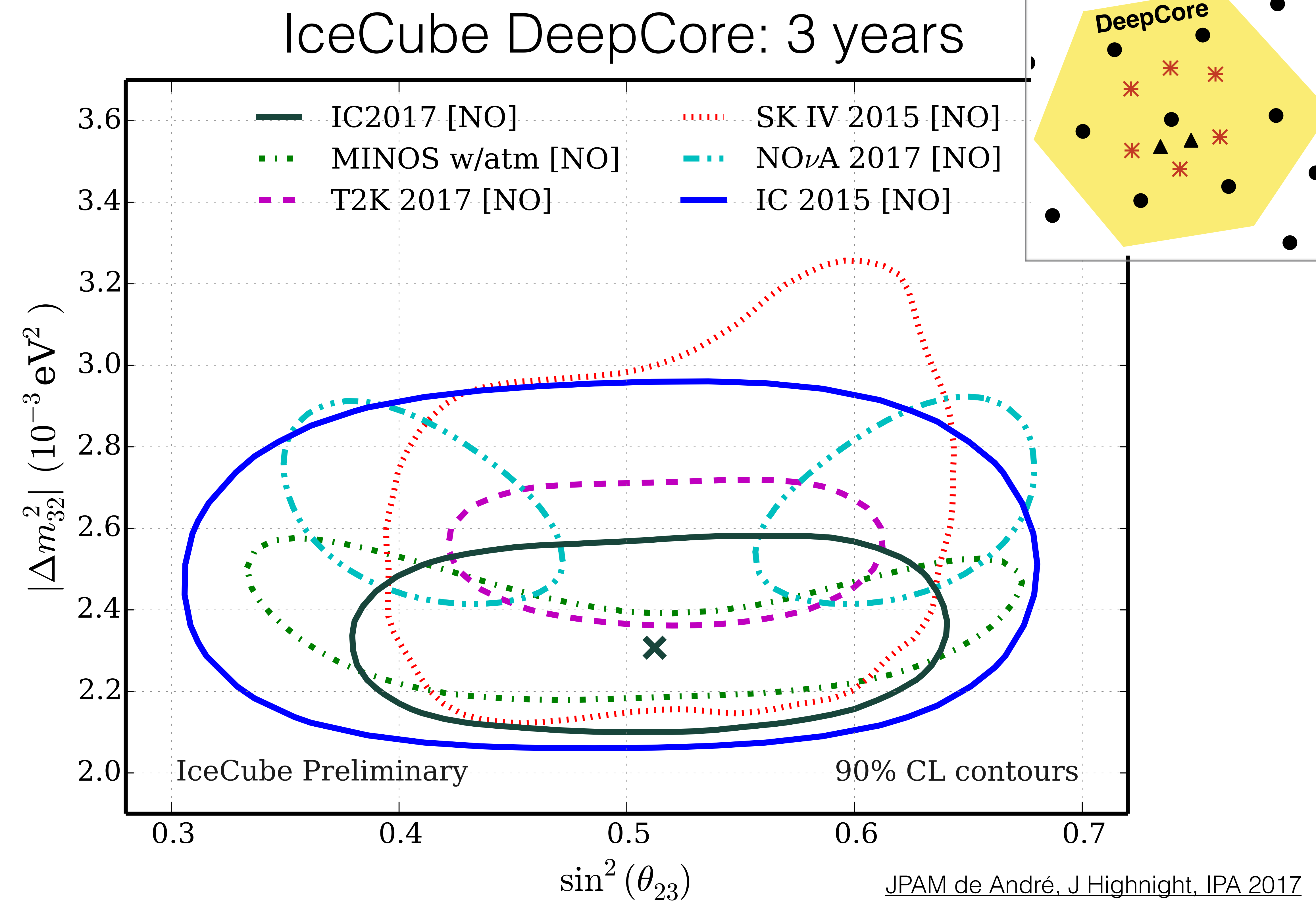
Neutrino properties (oscillations)







Phase 1 science: precision ν_μ disappearance



JPAM de André, J Highnight, IPA 2017

First determination of θ_{23} and Δm^2 with a neutrino telescope.

Can detectors be improved ?

larger detector volume

denser detector spacing for lower threshold and improved reconstruction

better veto for air shower events

Identify sources of IceCube's high-energy neutrinos

Find sources of the Ultra-High Energy Cosmic Rays

Improve multi-messenger alerting and analysis (Transients)

….

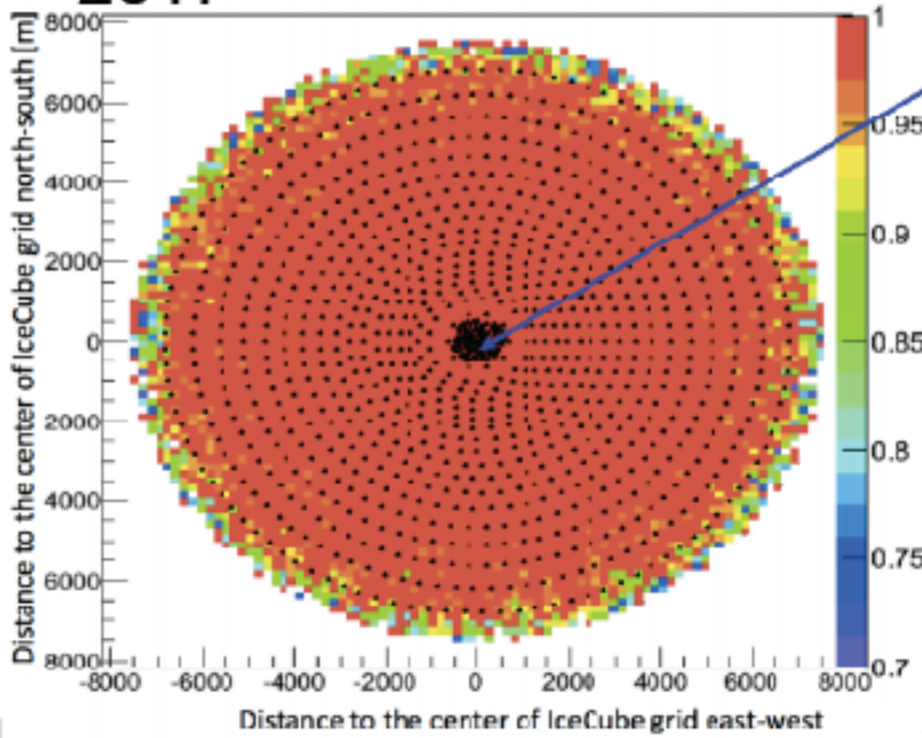
Beyond IceCube: Gen2

… a multi-purpose research infrastructure at the South Pole.

> 2017

Multi-km^2 Surface Detector

Atm. neutrino veto
CR physics

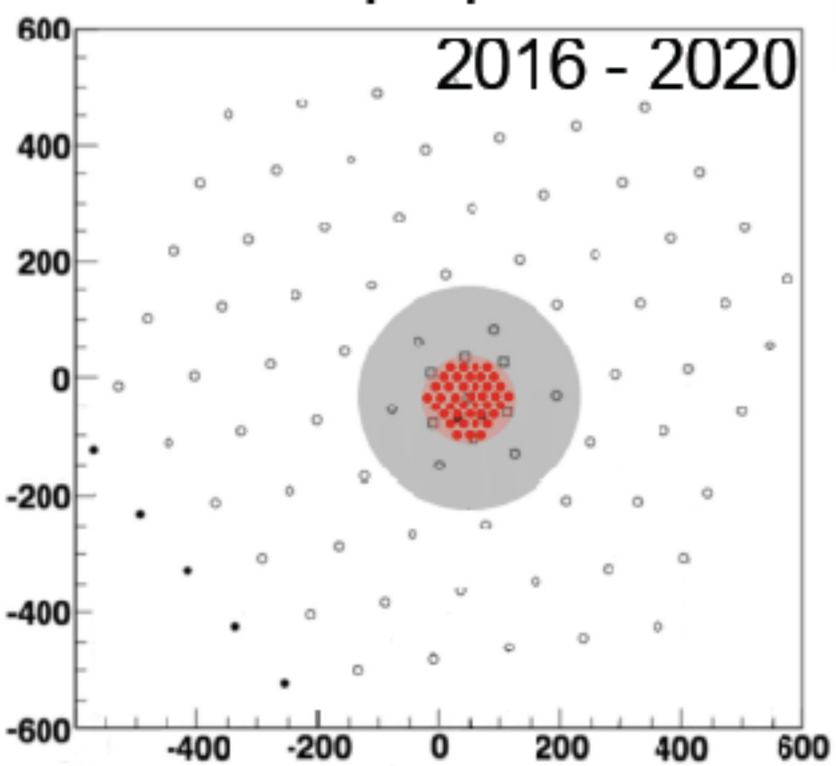


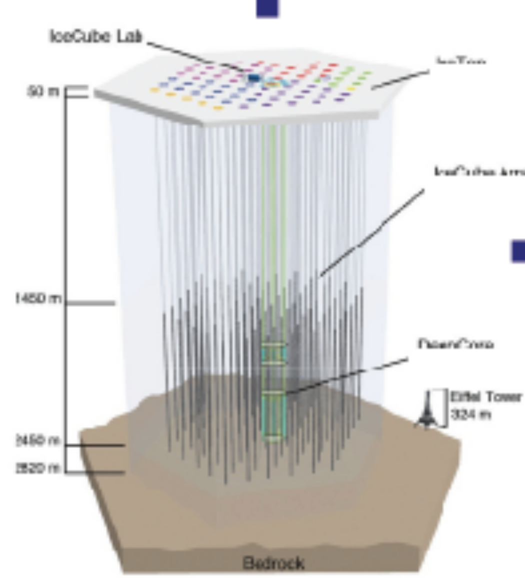
+ other…

PINGU

Neutrino properties

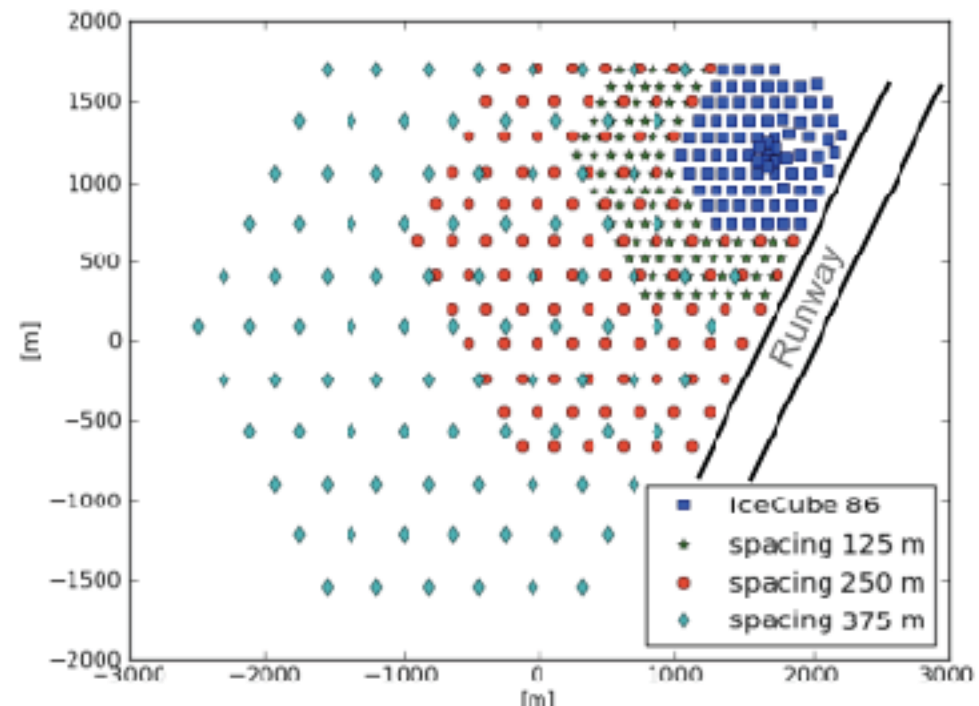
2016 - 2020





Multi-km^3 Neutrino Telescope

Neutrino astronomy



>2020

Beyond IceCube: Gen2

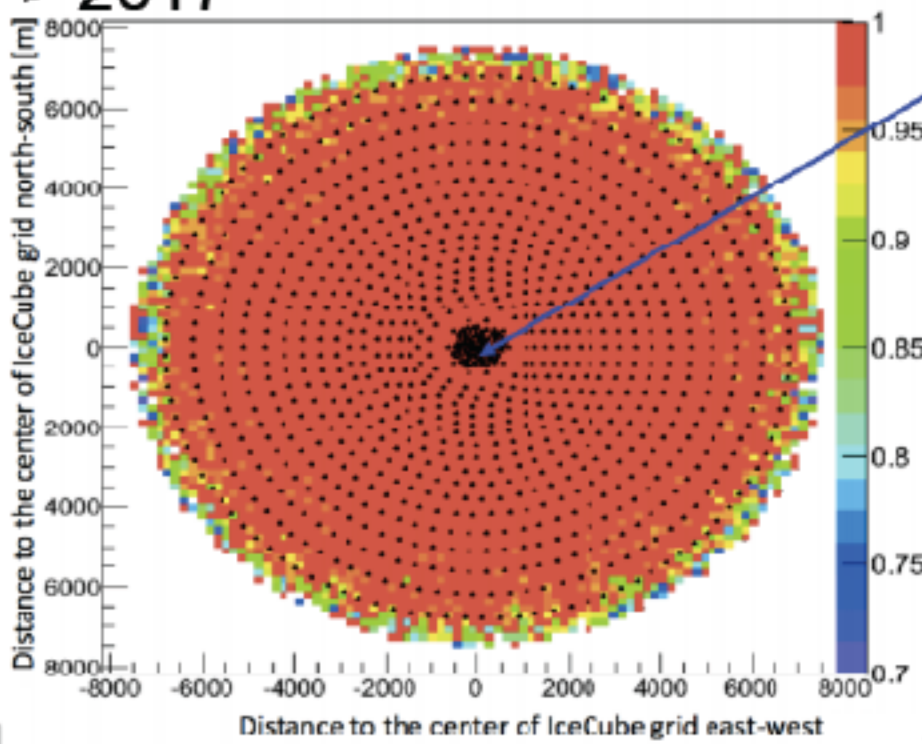
… a multi-purpose research infrastructure at the South Pole.

> 2017

Multi-km^2 Surface Detector

Atm. neutrino veto

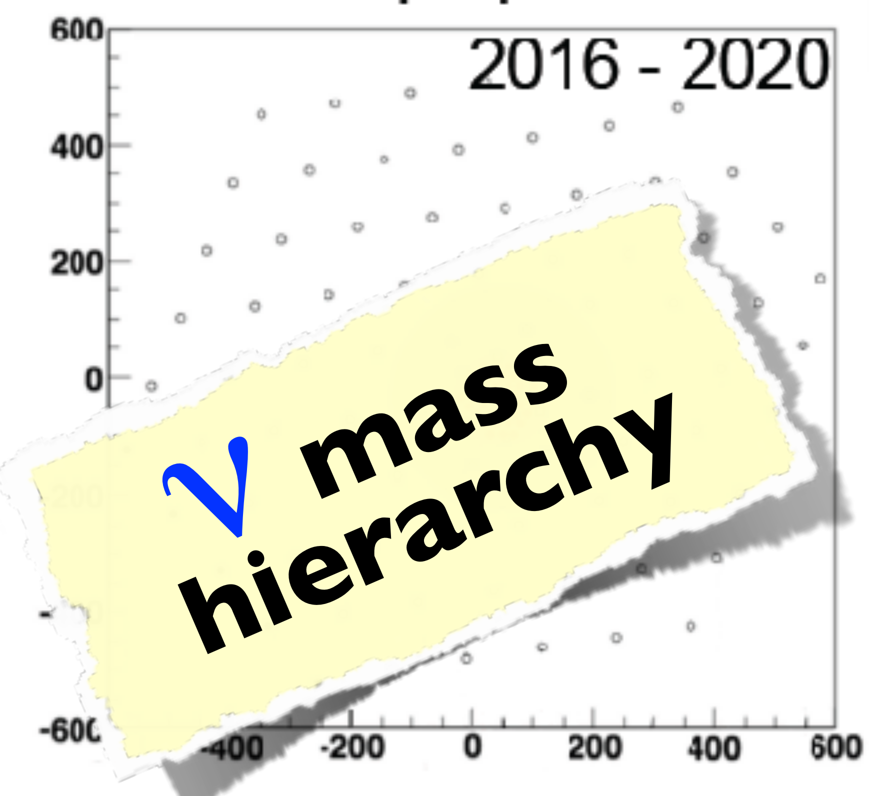
CR physics

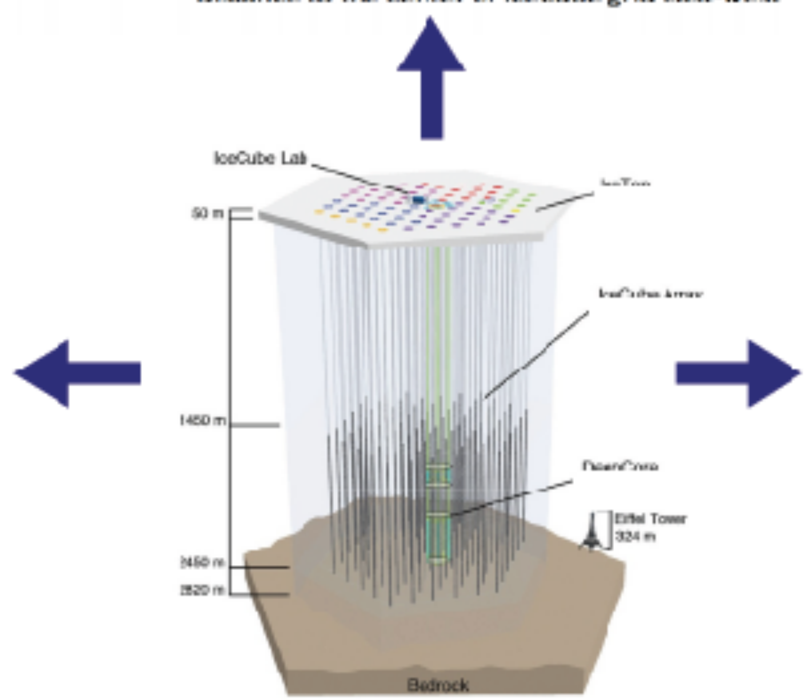


+ other…

PINGU

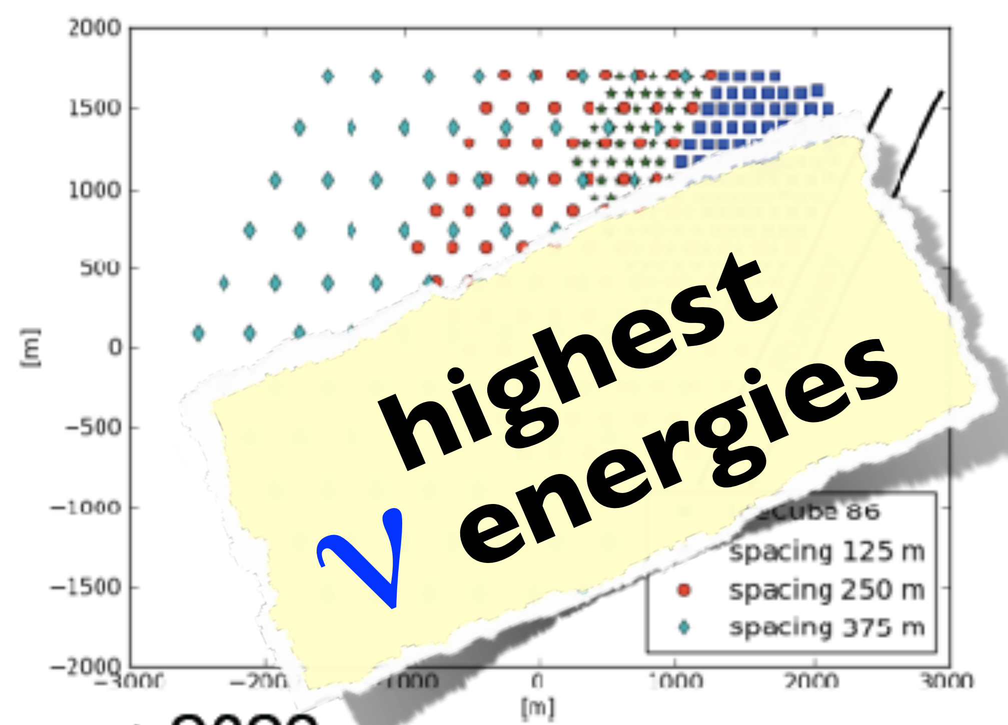
Neutrino properties





Multi-km^3 Neutrino Telescope

Neutrino astronomy



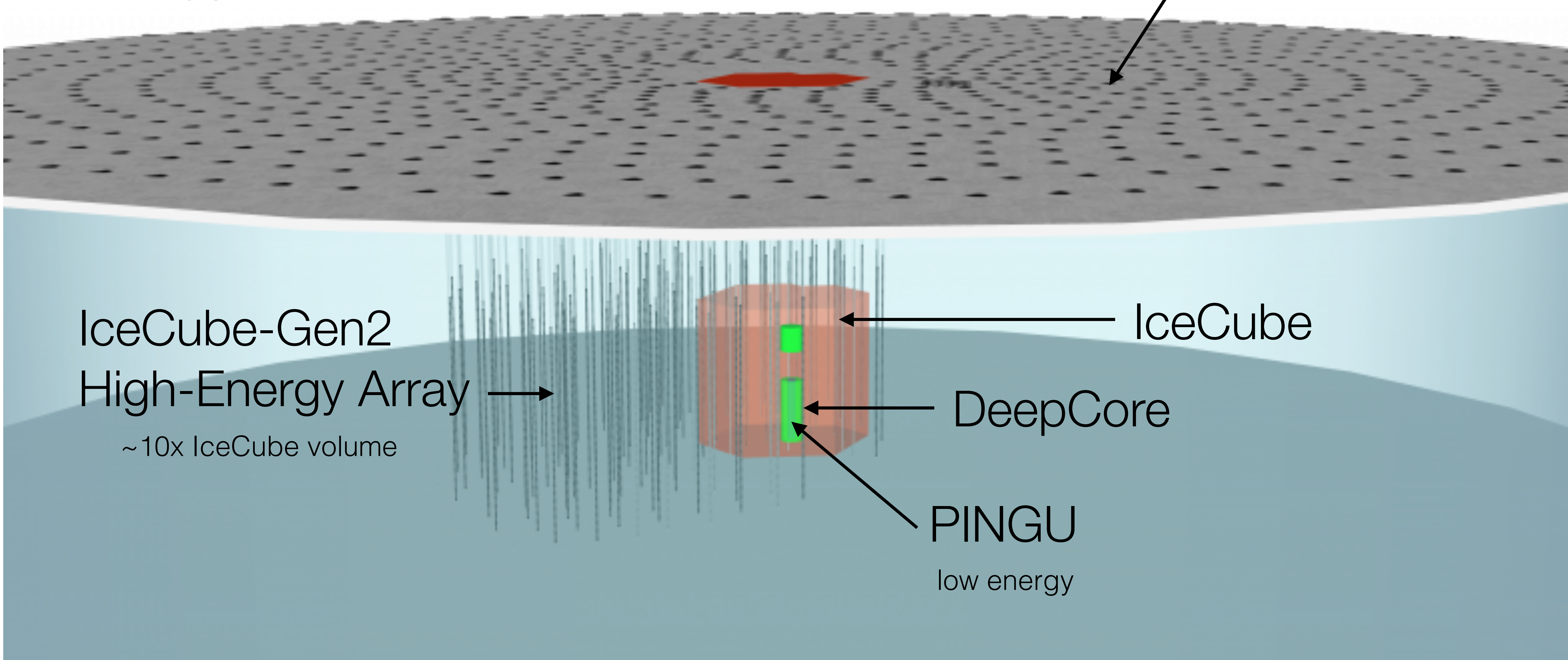
>2020

The IceCube-Gen2 facility

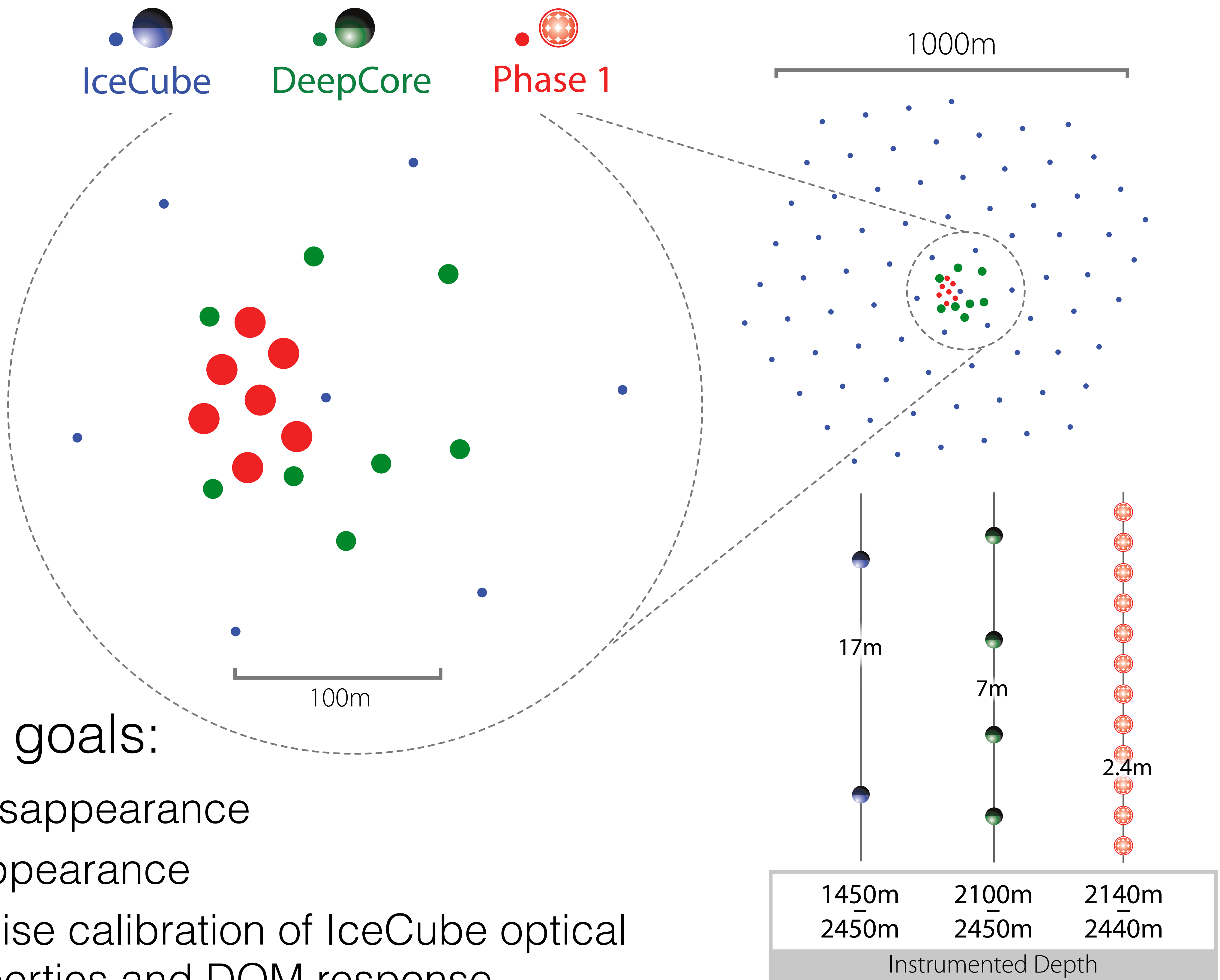
A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:

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



IceCube-Gen2 Phase 1



Science goals:

- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response

PINGU (Precision IceCube Next Generation Upgrade)

very dense core to be instrumented in Phase 1 of Gen2,
do oscillation studies down to few GeV

Clarify the neutrino mass hierarchy.

Summary Neutrinos

Neutrinos can be detected from astrophysical objects
(Sun, SN-explosion, other, …)

- SN explosions are rare, the next one in our galaxy is overdue
- we do see astrophysical neutrinos in the TeV to >PeV range; must come from hadronic interactions of cosmic rays
- we **do not see** (yet) a bright source
- we **do not know** what the sources are
  (not the most promising candidates)
- oscillation parameters measured at high energies
- it is still early days (only yr 6 after first discovery)
- plans for instrument upgrade / new instruments