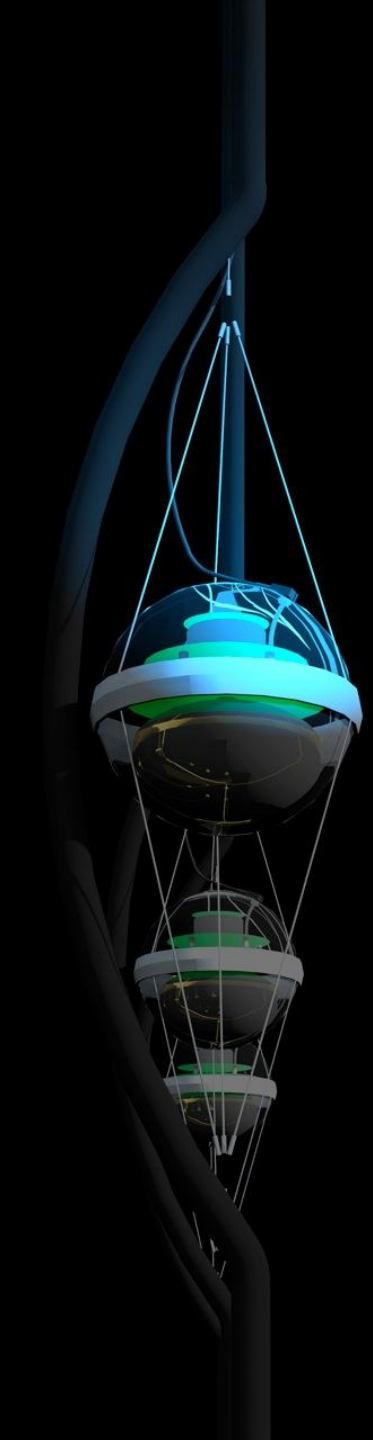
neutrino "astronomy"

francis halzen
university of wisconsin
http://icecube.wisc.edu



- introduction
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- neutrino physics
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

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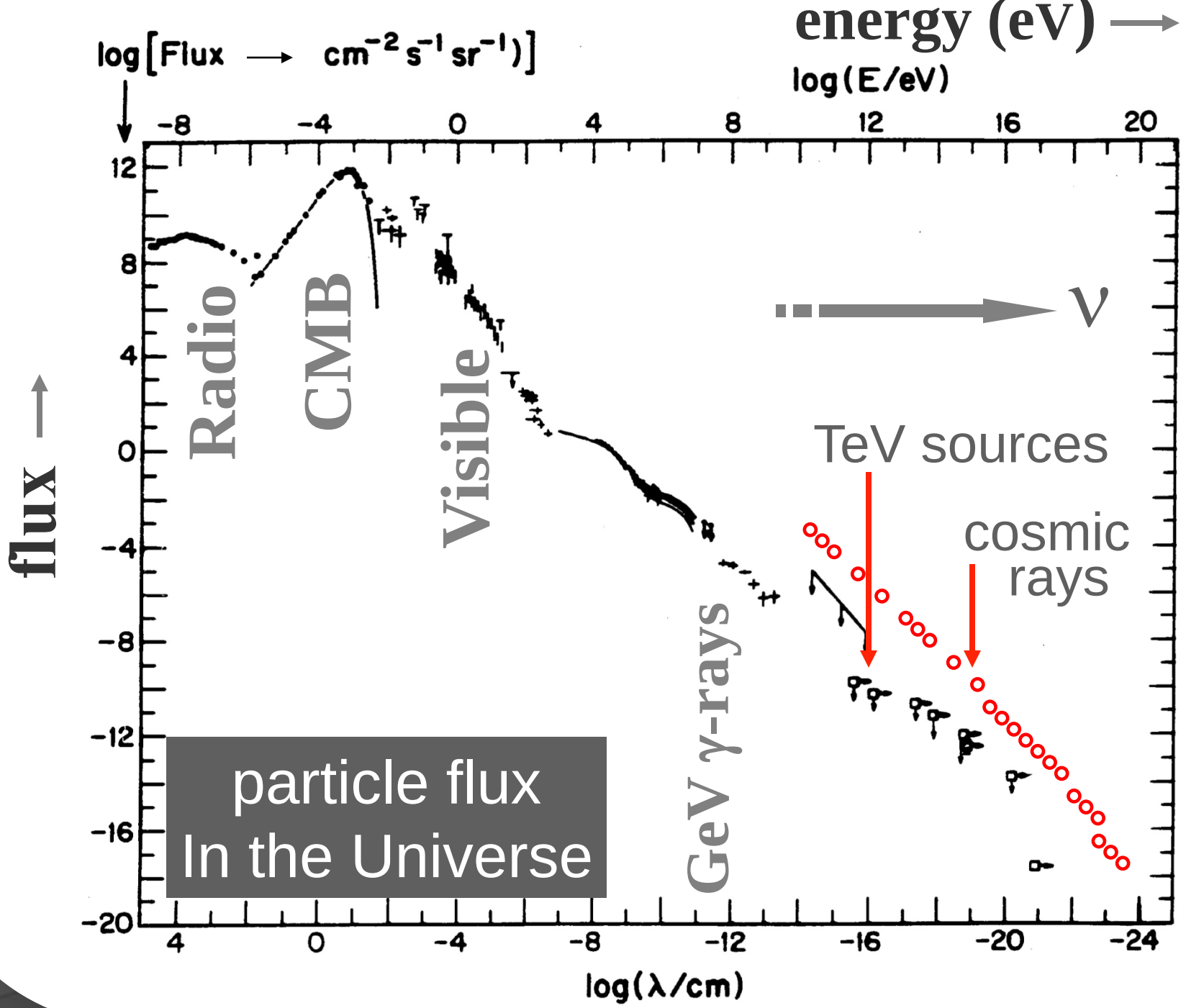

energy (eV) →
log[Flux → cm⁻² s⁻¹ sr⁻¹)]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux →
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources
cosmic
rays
particle flux
In the Universe
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

cosmic rays interact with the microwave background

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

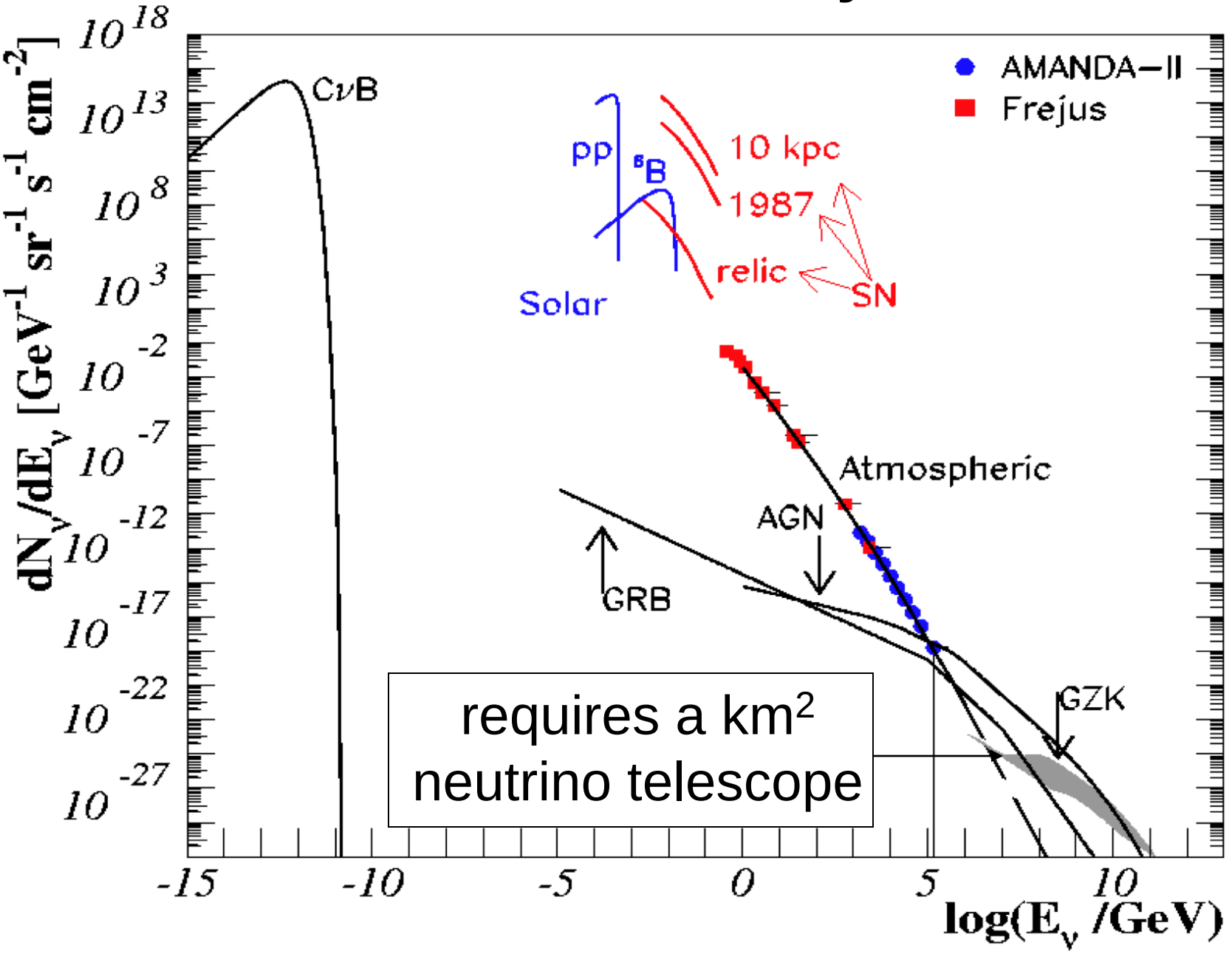
cosmic rays disappear, neutrinos appear

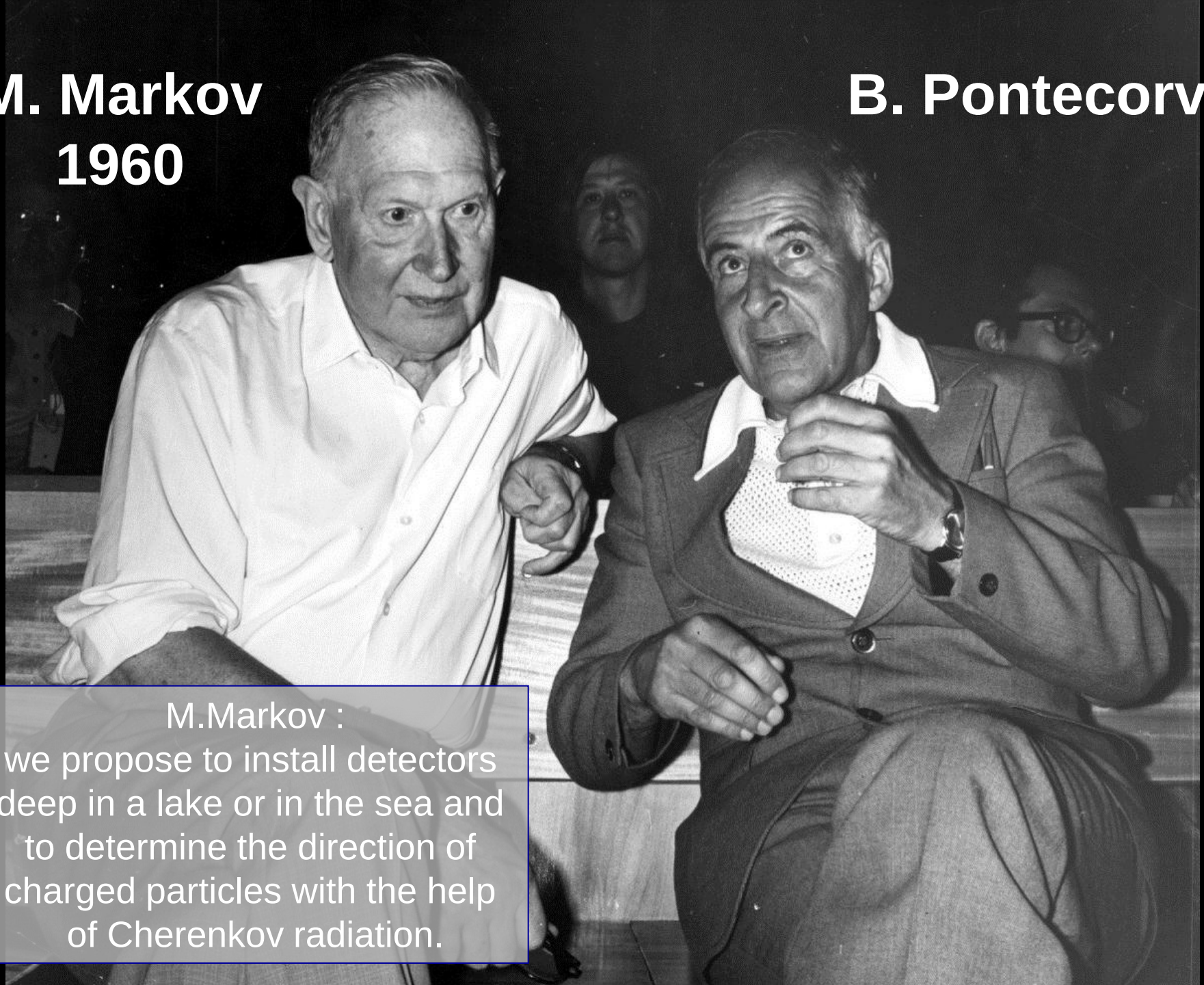
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

$$E_{\upsilon} \geq 2 \times 10^{6} TeV$$

~1 event per cubed kilometer per year

neutrino sky



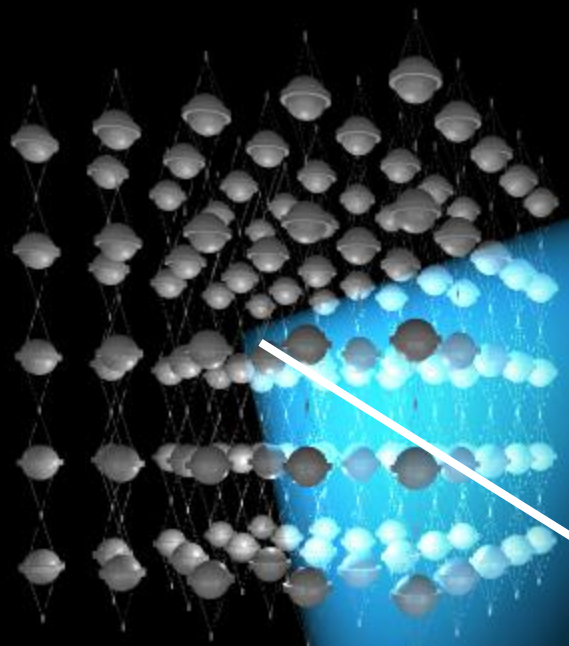


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

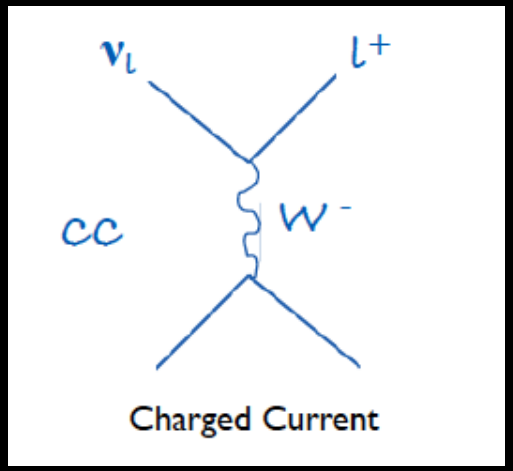
photomultiplier tube

- shielded and optically transparent medium

$$P_{\mu\to\nu} = \frac{\lambda_\mu}{\lambda_\nu} = n\sigma_\nu R_\mu$$



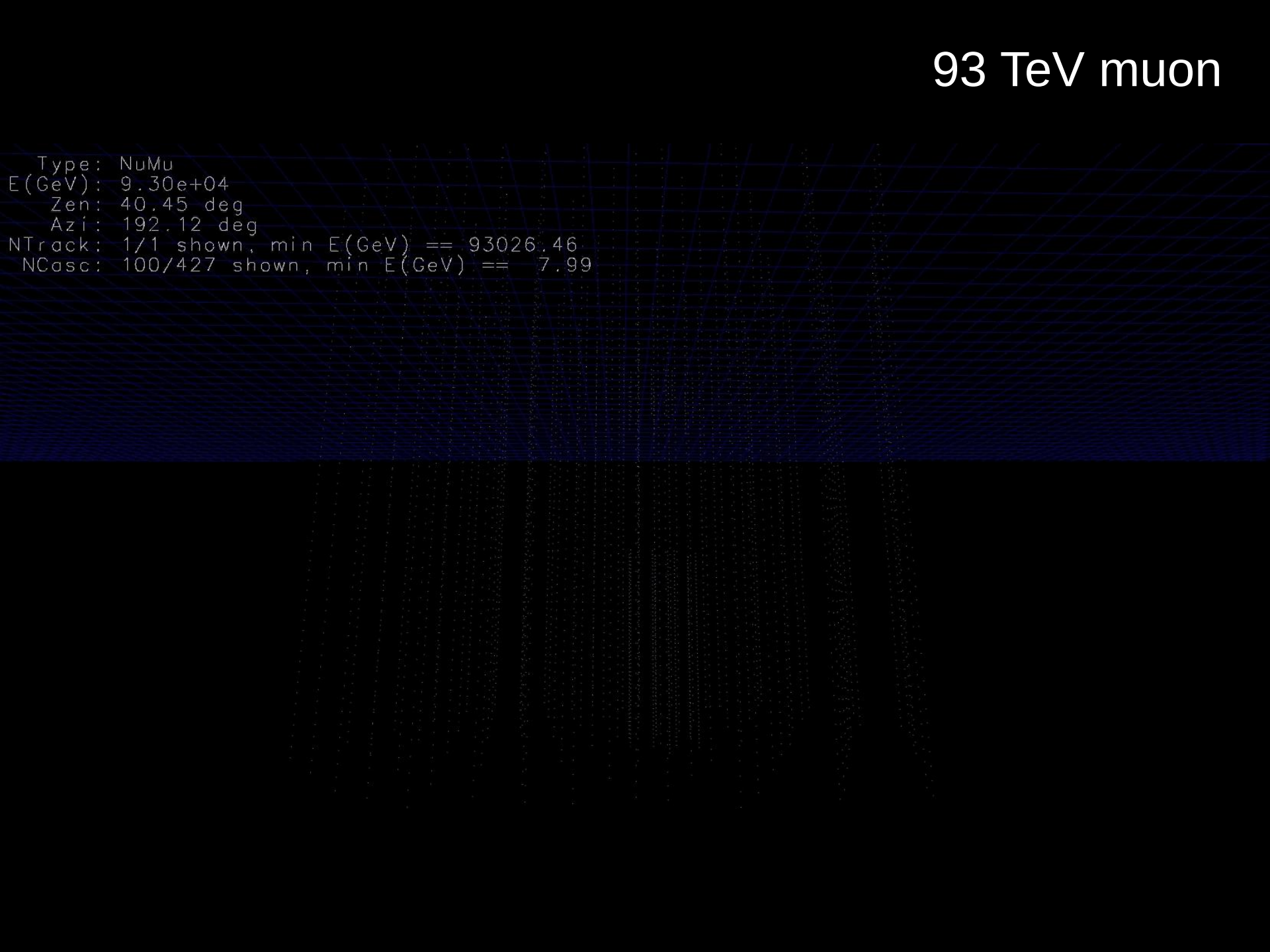
μ



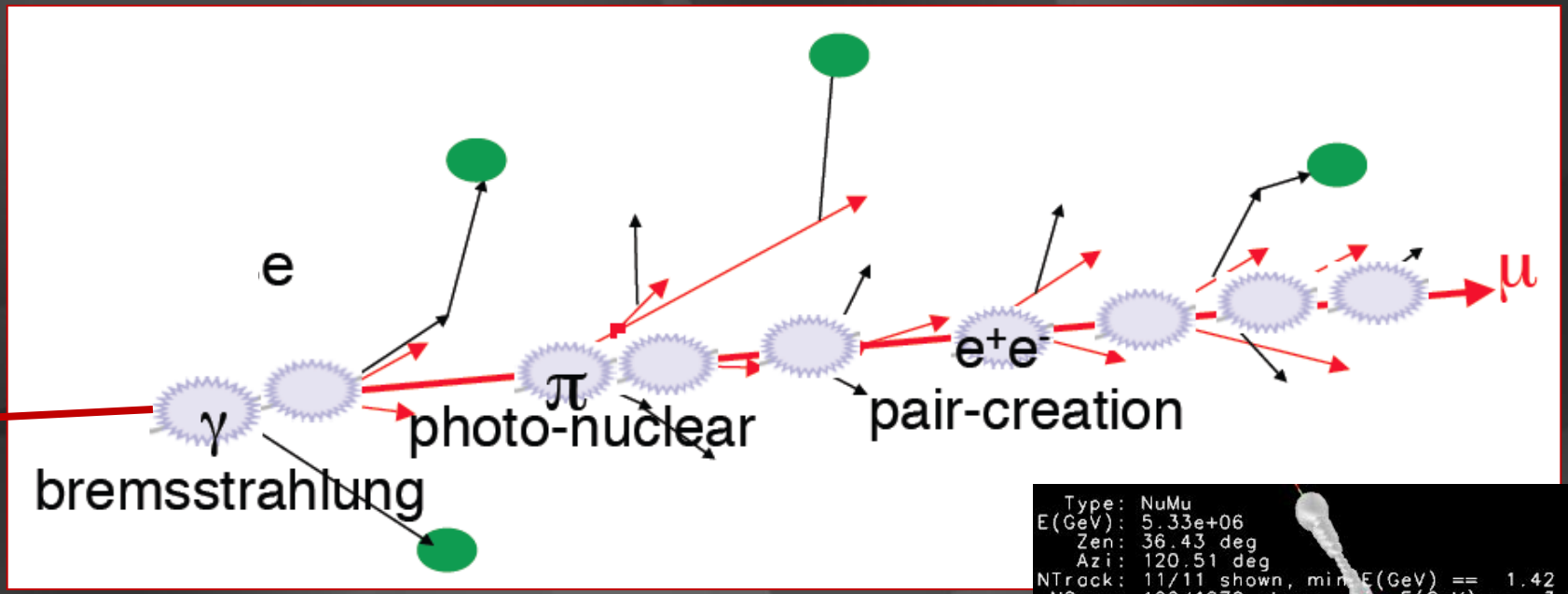
ν

- lattice of photomultipliers

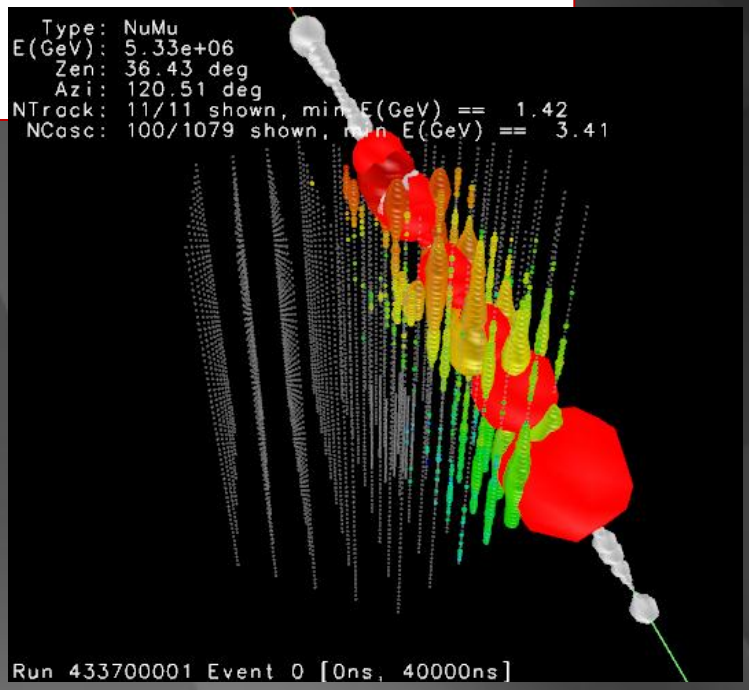
93 TeV muon


Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)



convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

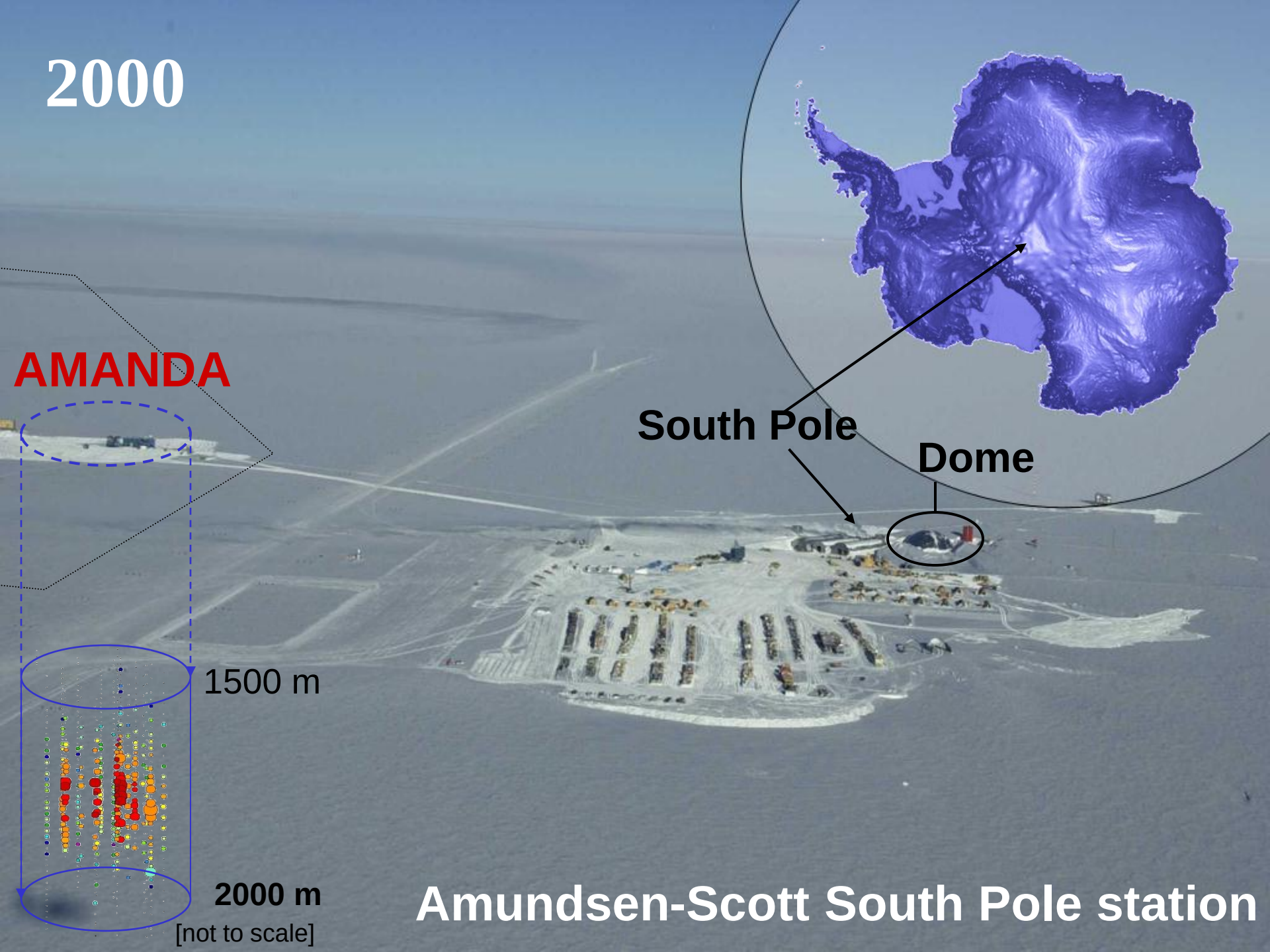


Hawaii 1987: DUMAND test string

ANTARES Lake Baikal:

proof of concept for KM3NeT

why did it take so long ?

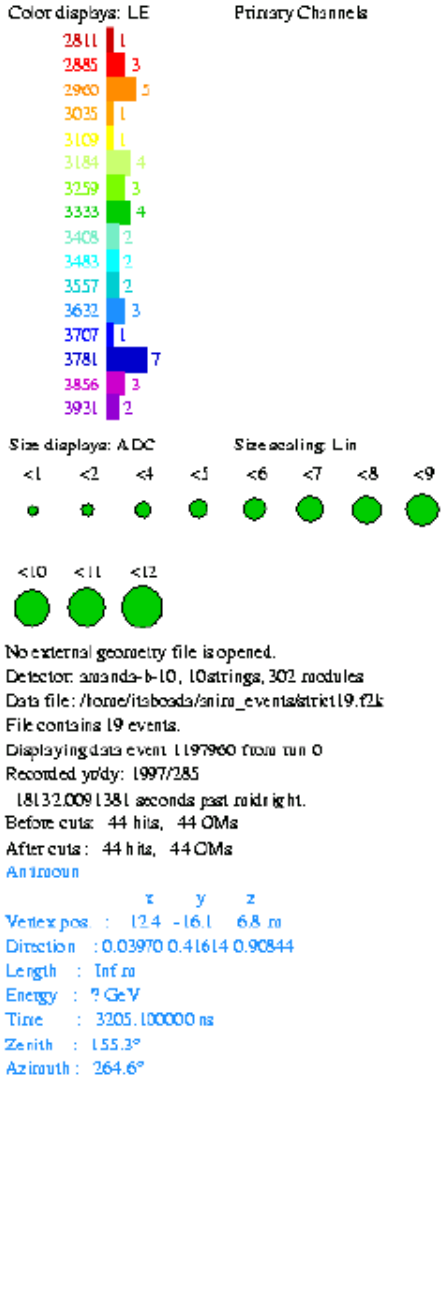

2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

AMANDA event: muon neutrino

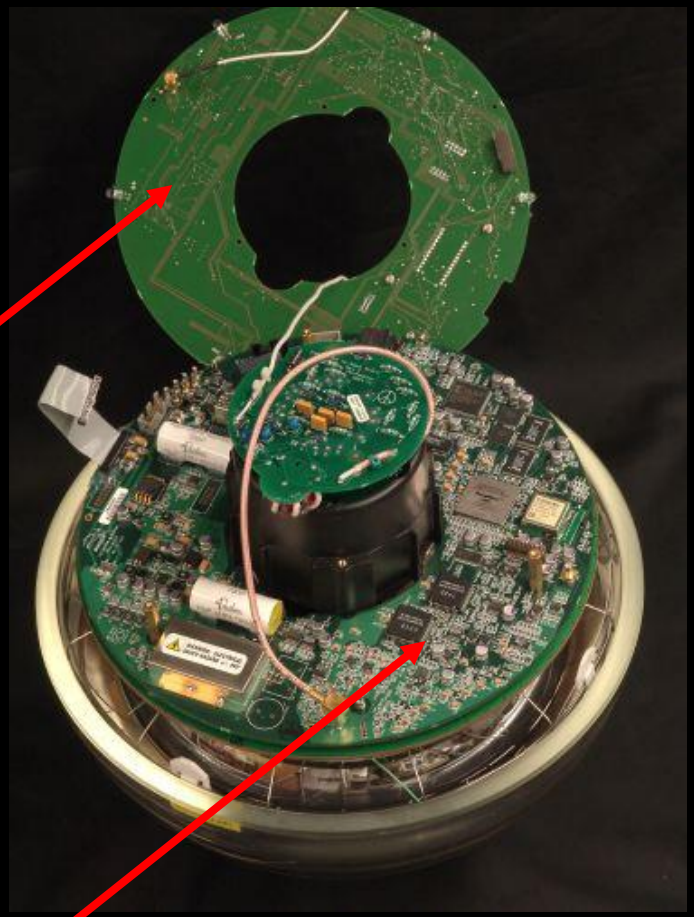
neutrino interaction creates muon track

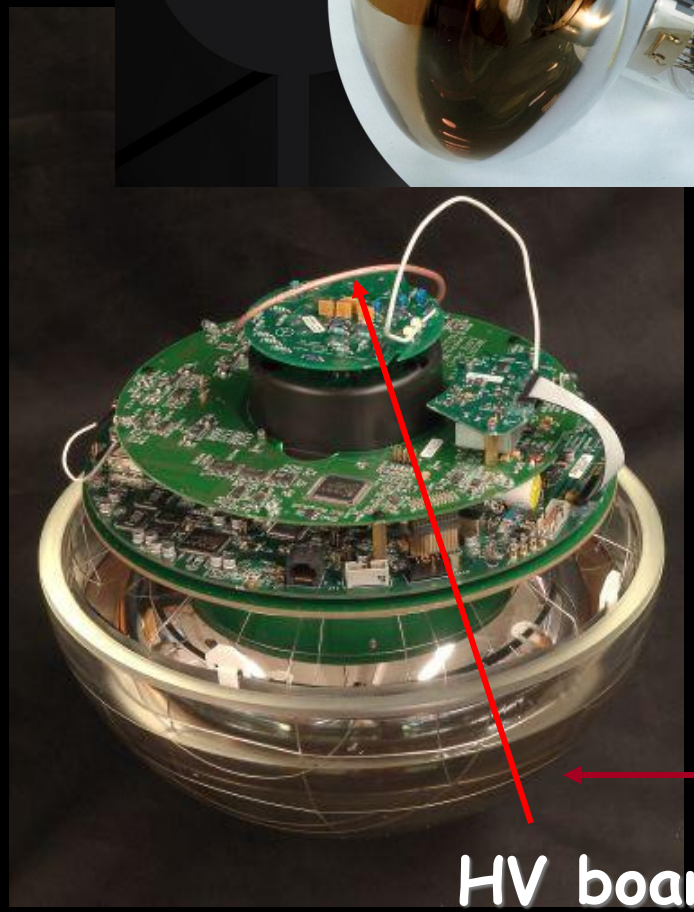
$\nu_\mu + p \rightarrow \mu + \ldots$

analog signal after 2 km… not pretty



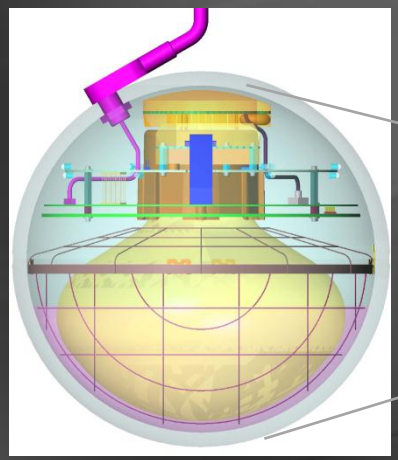
architecture of independent DOMs



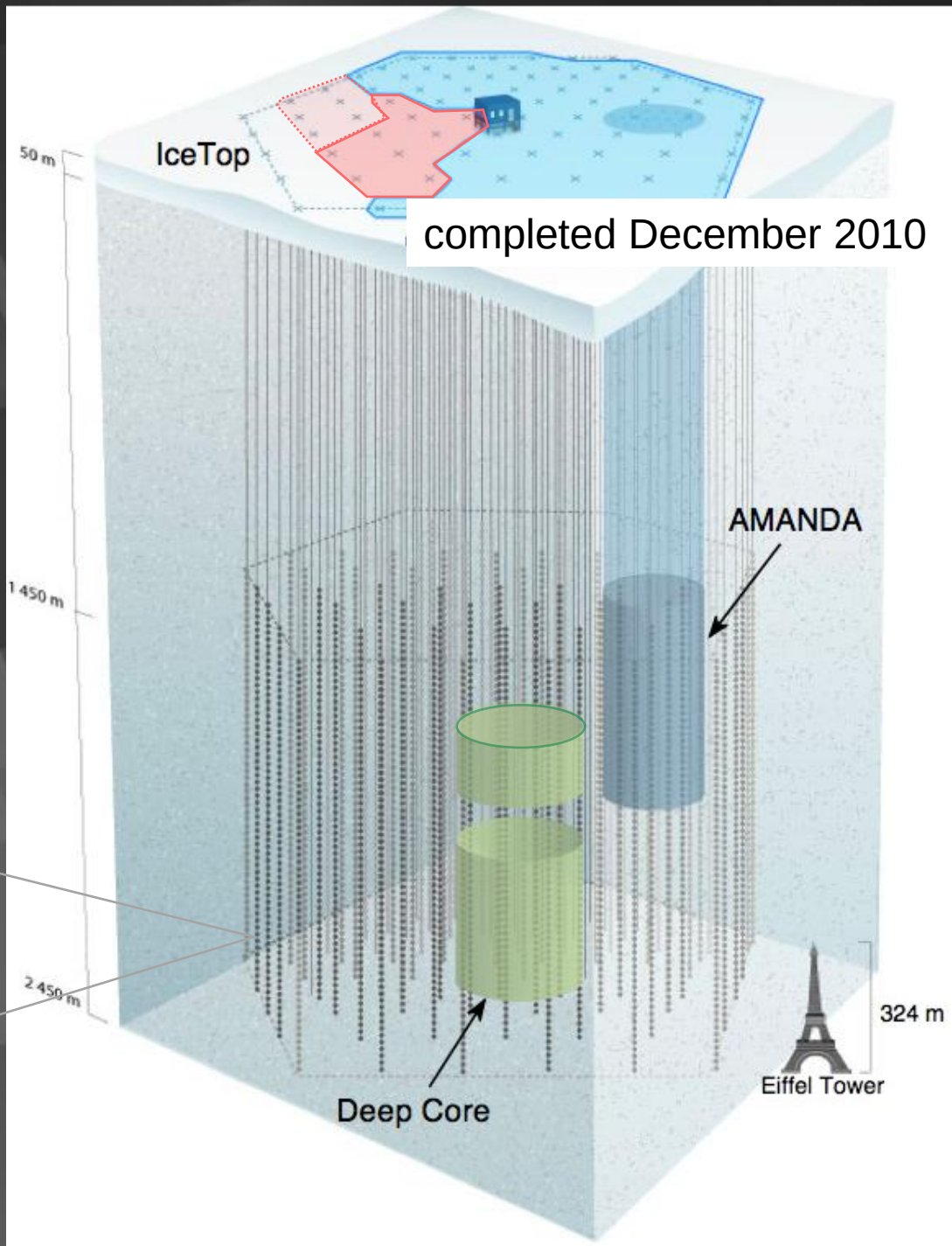


IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- detects > 200 neutrino-induced muons and ~ 2 x10^8 cosmic ray muons per day



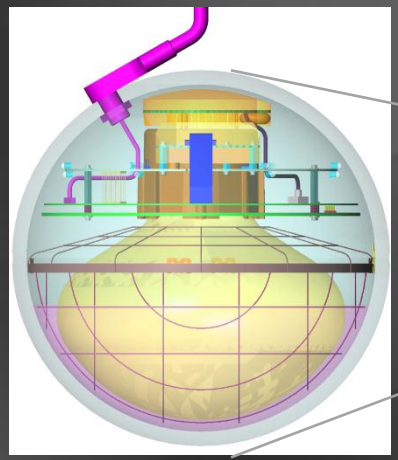
Digital Optical Module (DOM)



completed December 2010

IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- ~ 0.5 degree on-line
  < 0.2 degree off line
- < 30% energy resolution



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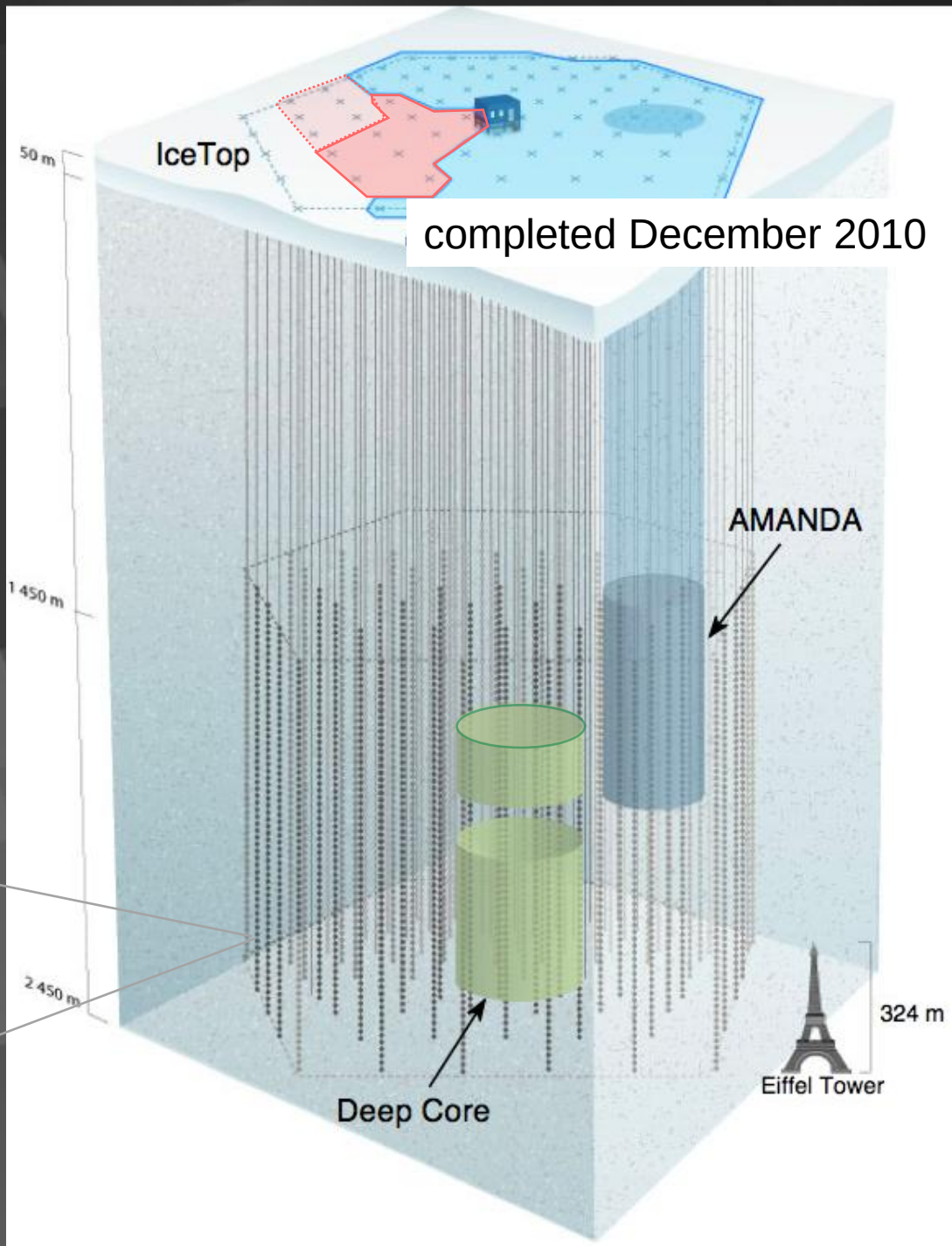
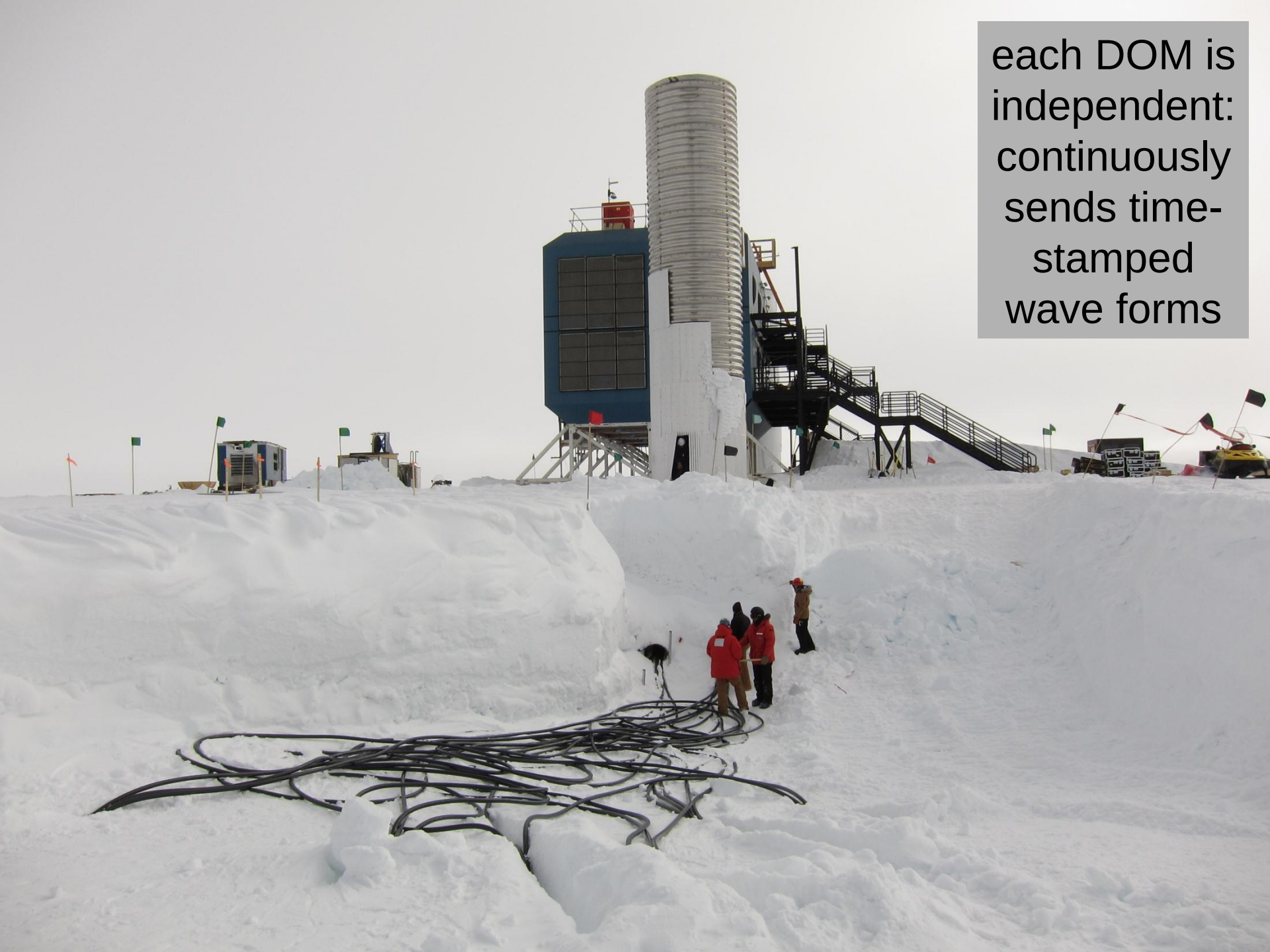
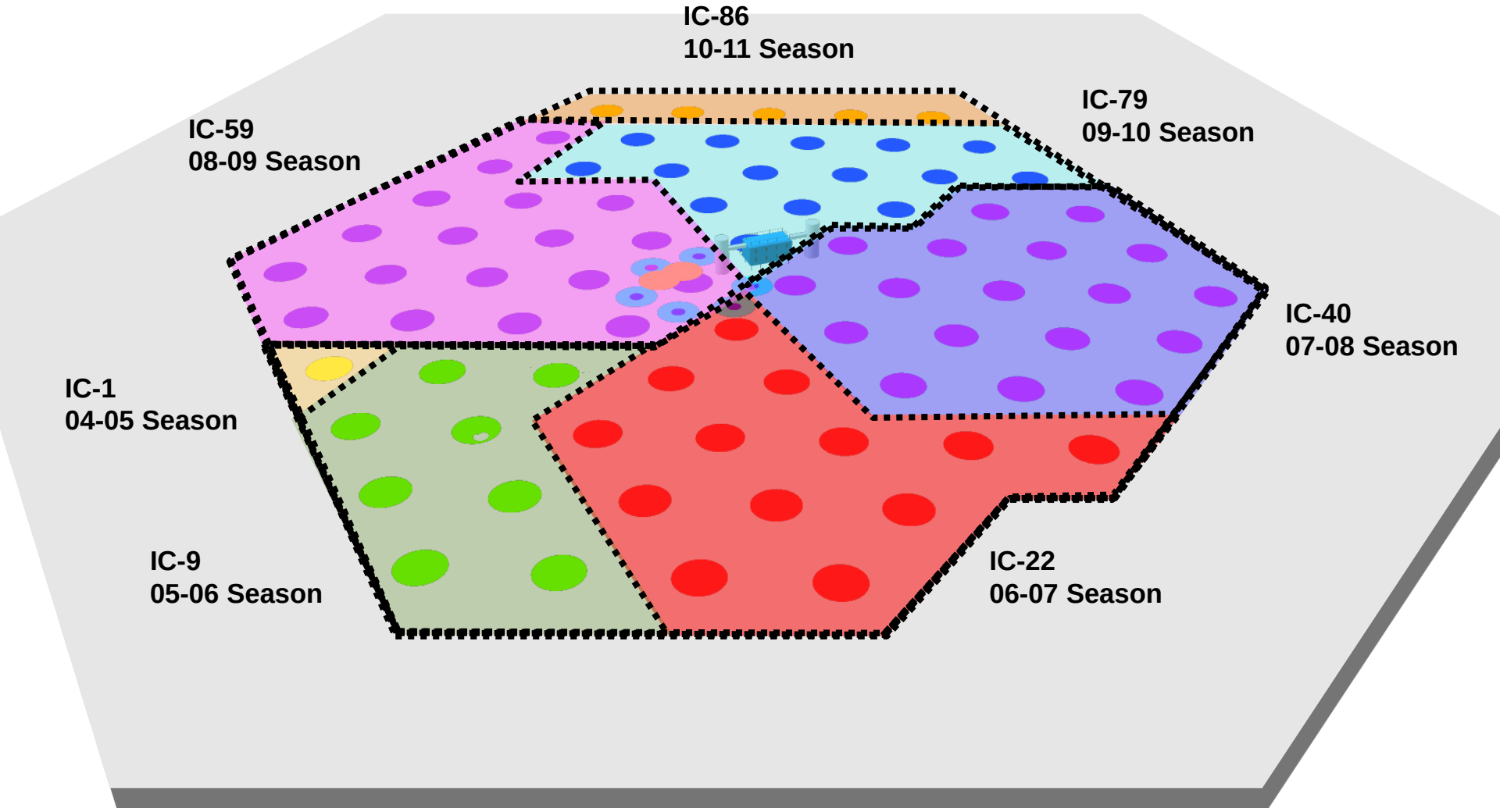


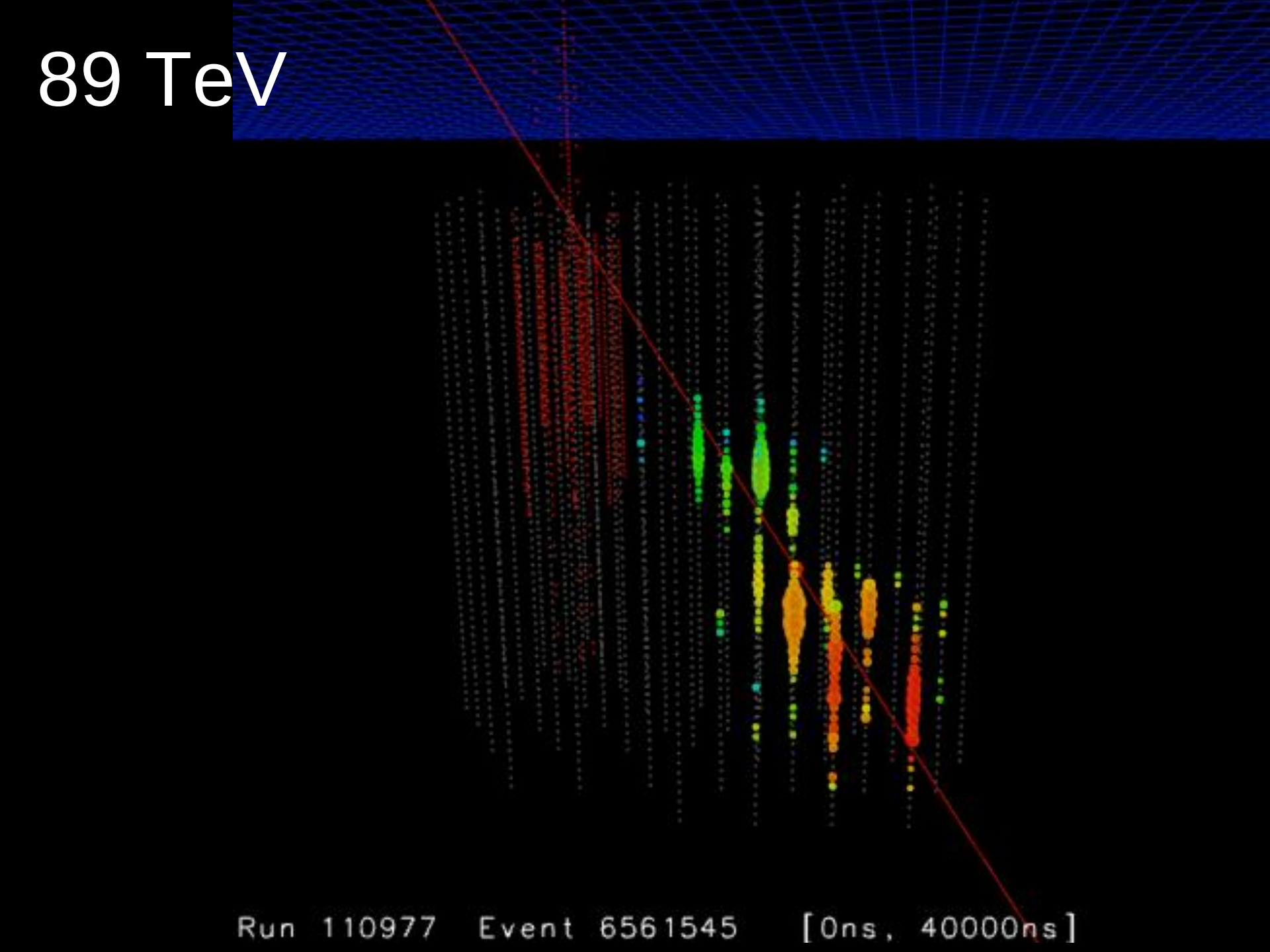
completed December 2010

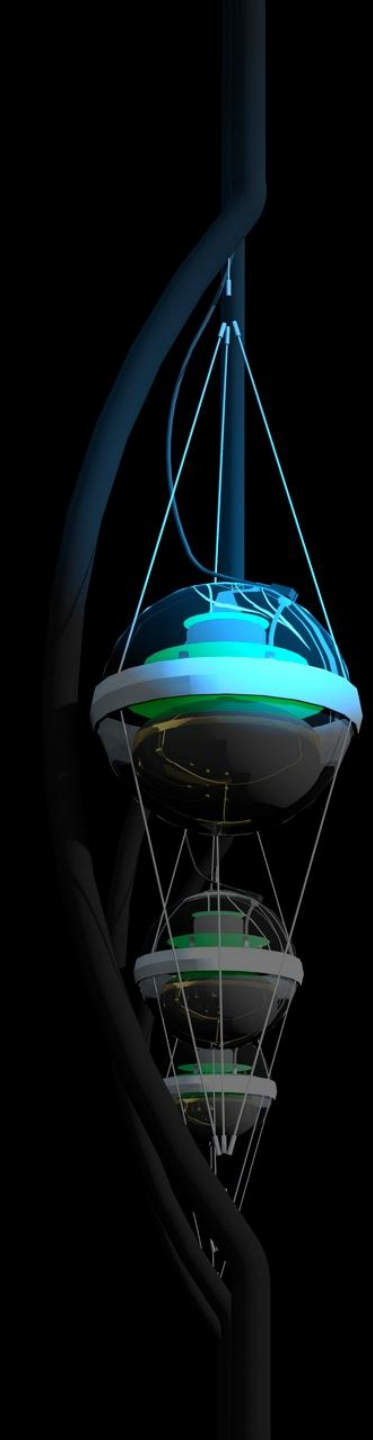

each DOM is independent: continuously sends time-stamped wave forms

completed December 18, 2010



89 TeV





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- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons

- search for the sources of the Galactic cosmic rays

- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

dark matter

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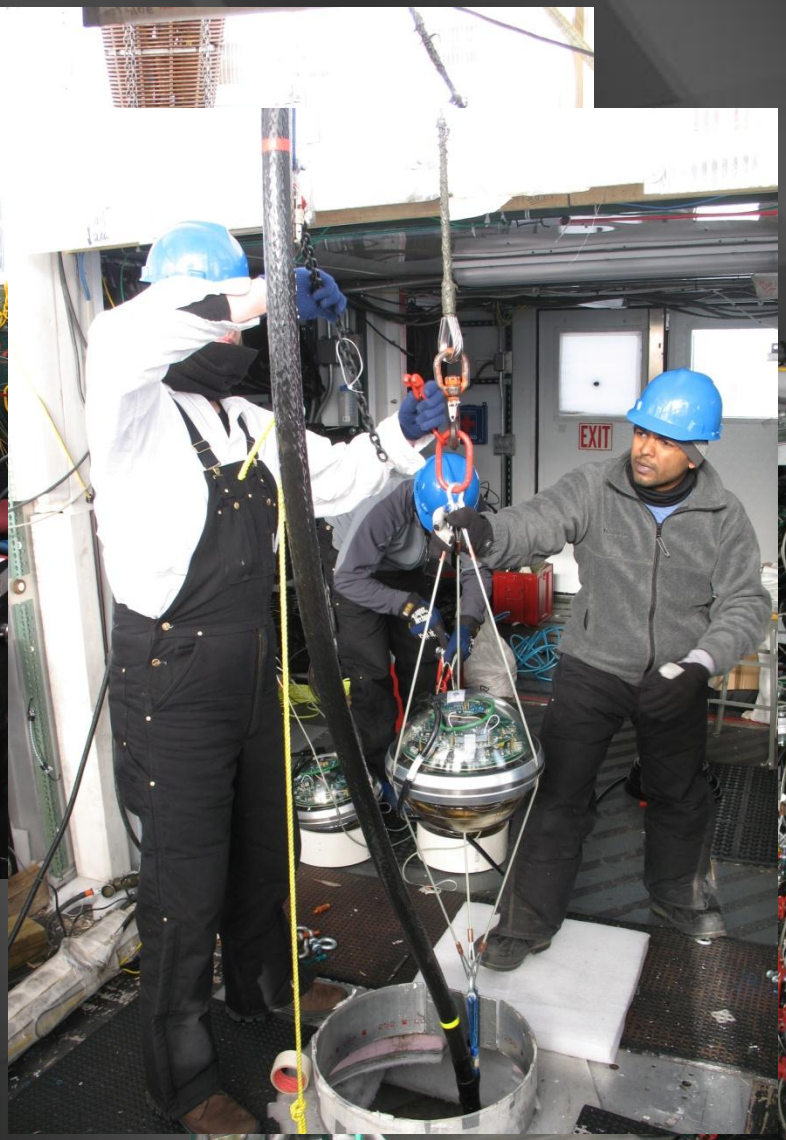
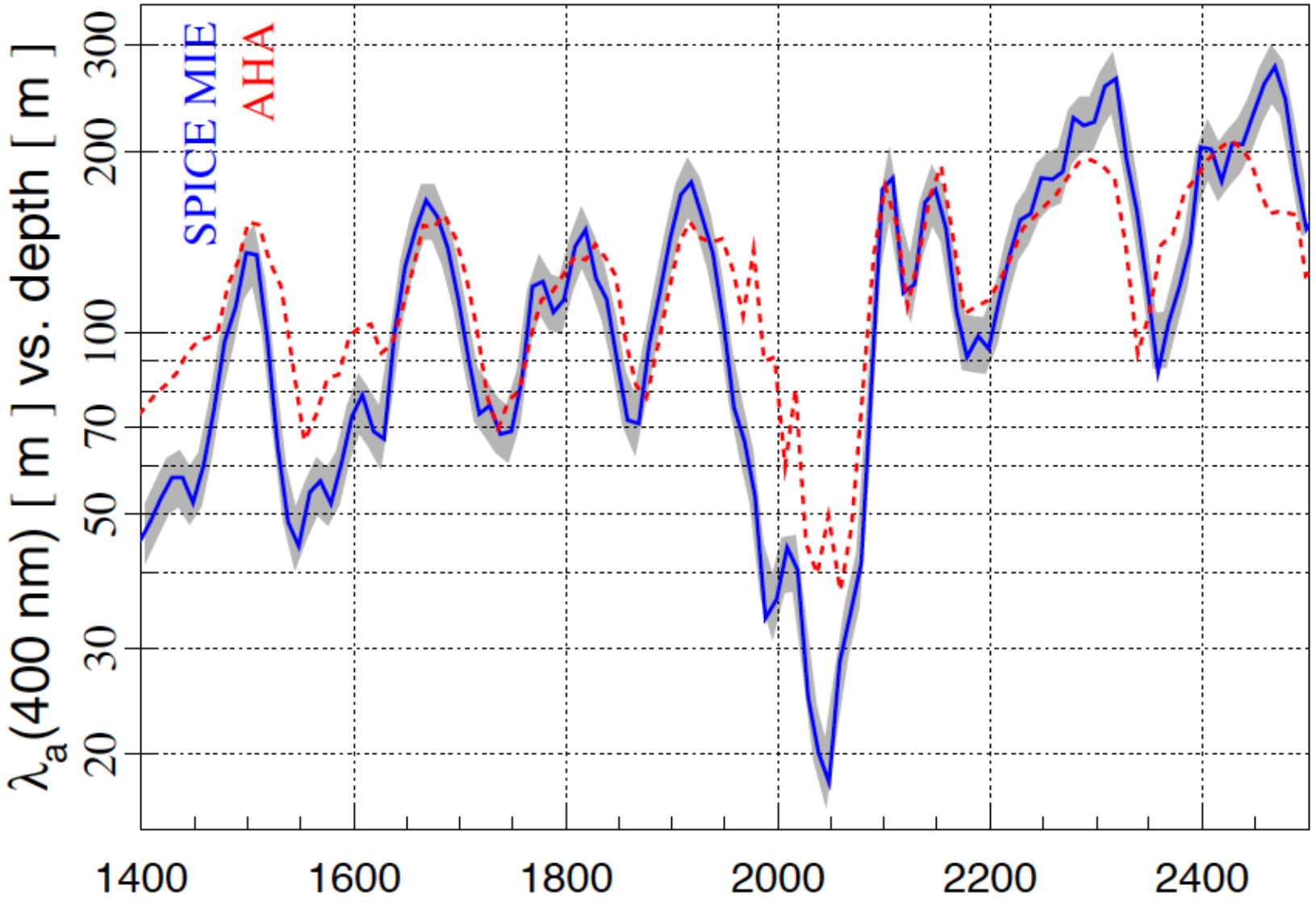
drilling and deployment

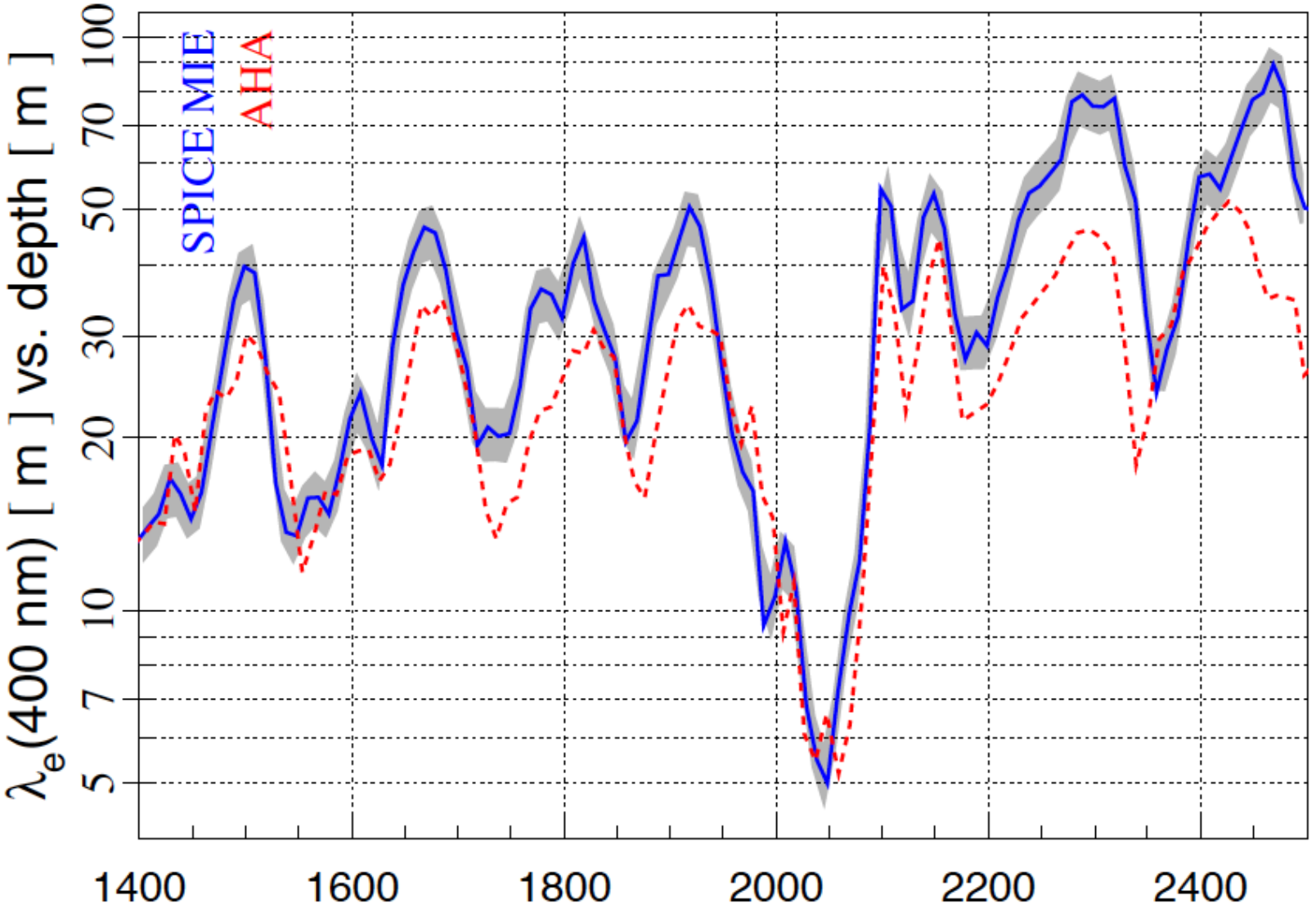
drill and install 60 DOMs in less than 2 days

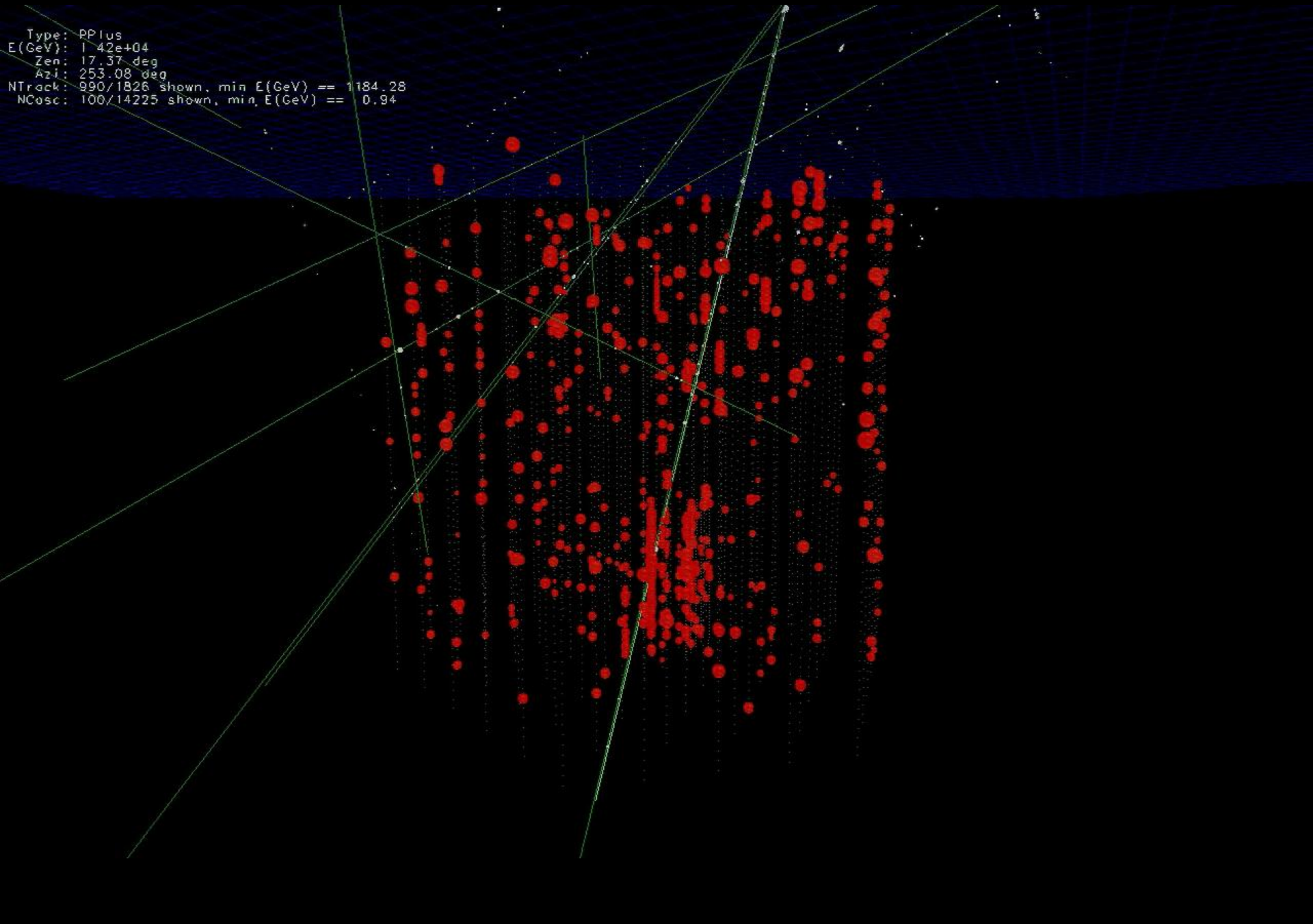


absorption length ← 220m →



scattering length ← 47m →



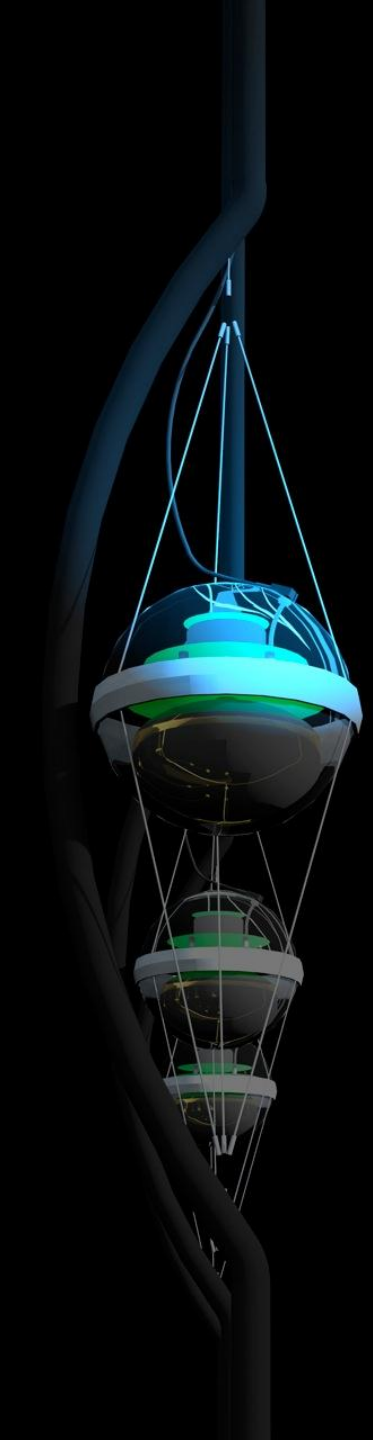

Type: PPlus
E(GeV): 1.42e+04
Zen: 17.37 deg
Azi: 253.08 deg
NTrack: 990/1826 shown, min E(GeV) == 1184.28
NCasc: 100/14225 shown, min E(GeV) == 0.94

… you looked at 10msec of data !

muons detected per year:

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

* 2700 per second ** 1 every 6 minutes



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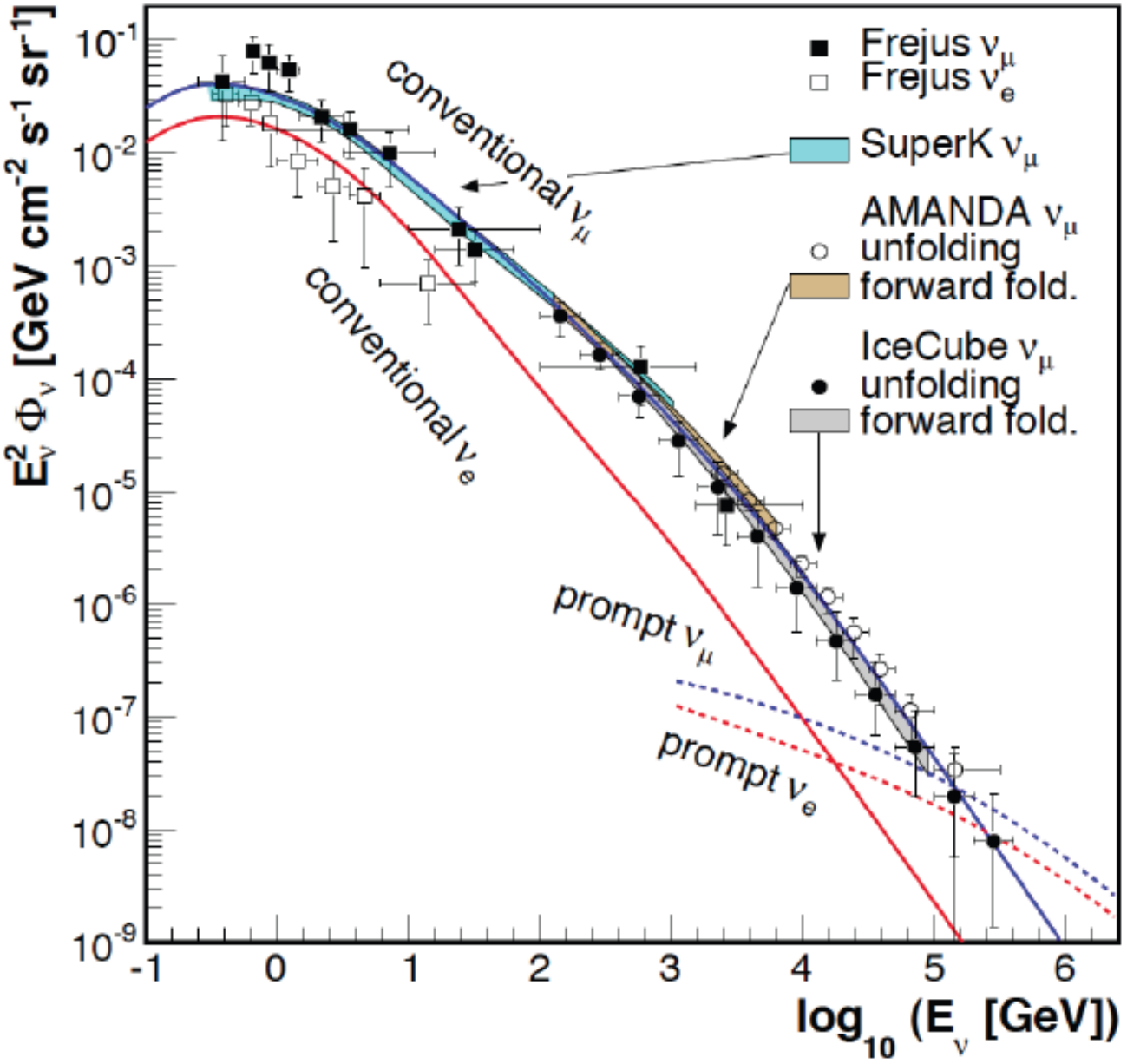
IceCube.wisc.edu

… on to IceCube science

we measure the flux of atmospheric muons and neutrinos at higher energies and with better statistics than previous experiments. Any deviations from what is expected is new neutrino physics or new astrophysics. We just look for surprises.

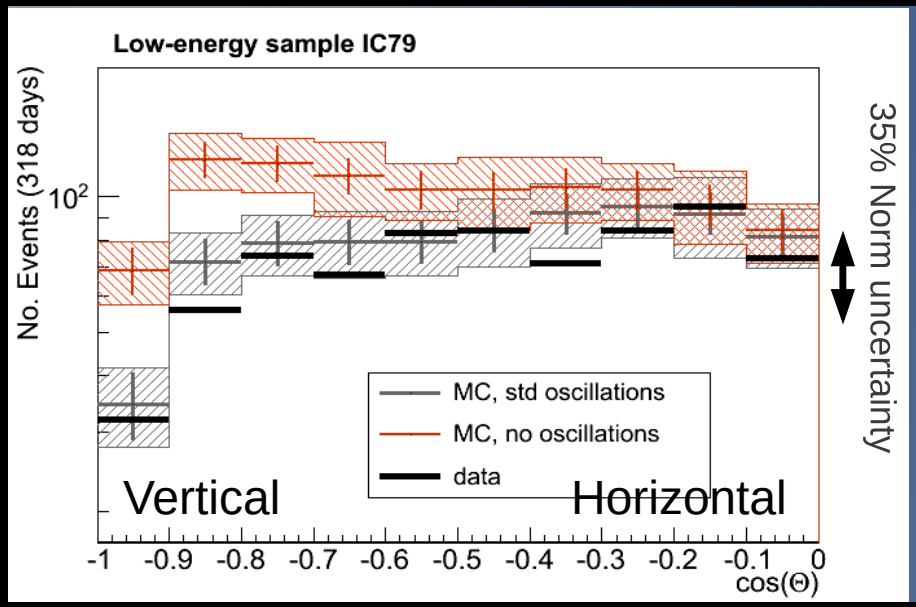
cosmic neutrinos:

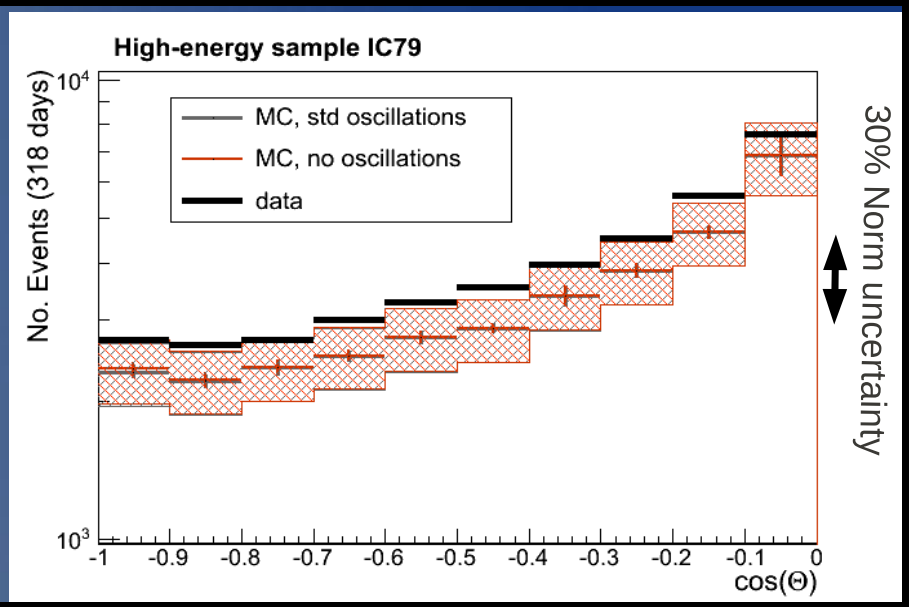
energy: >> 100 TeV

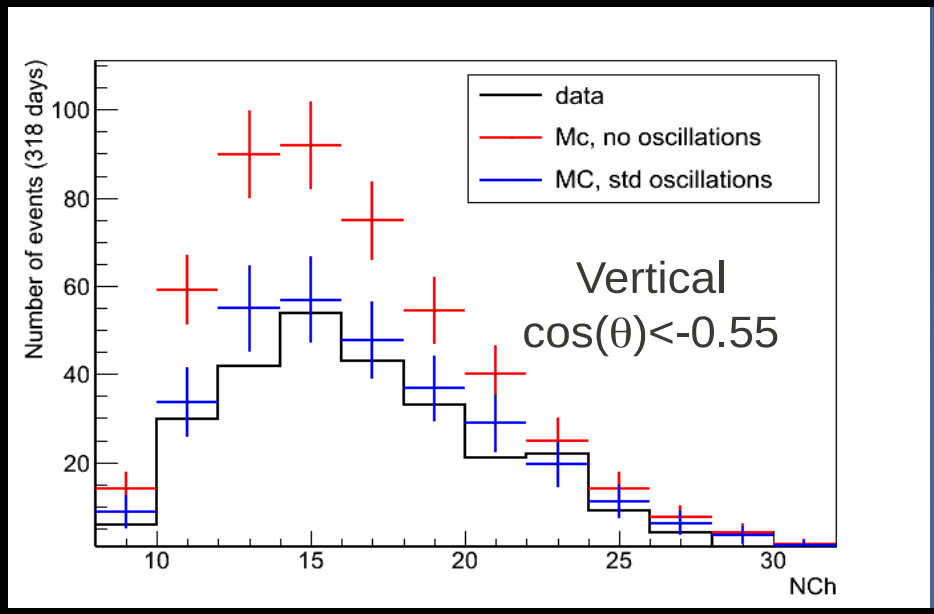


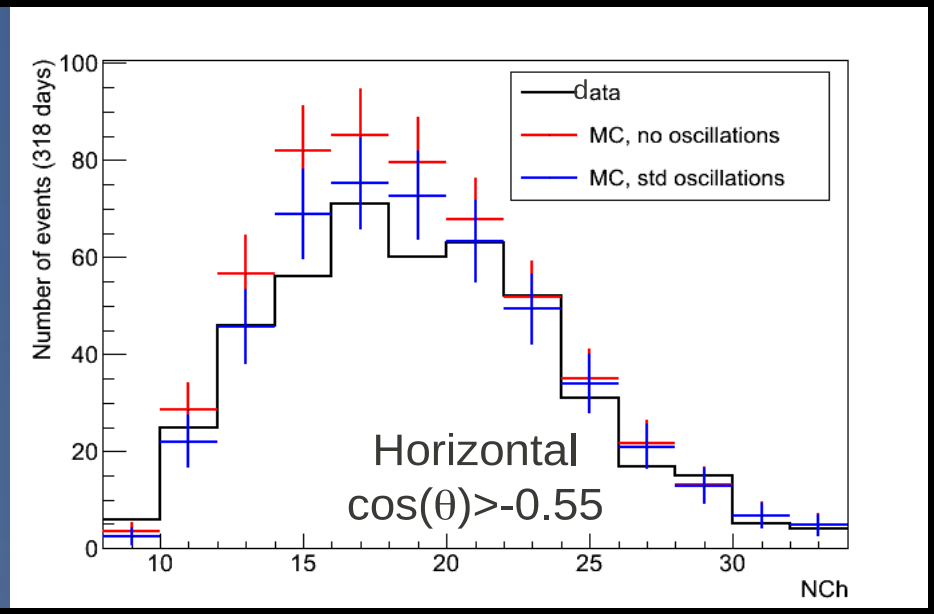
atmospheric neutrino spectrum to ~100 TeV

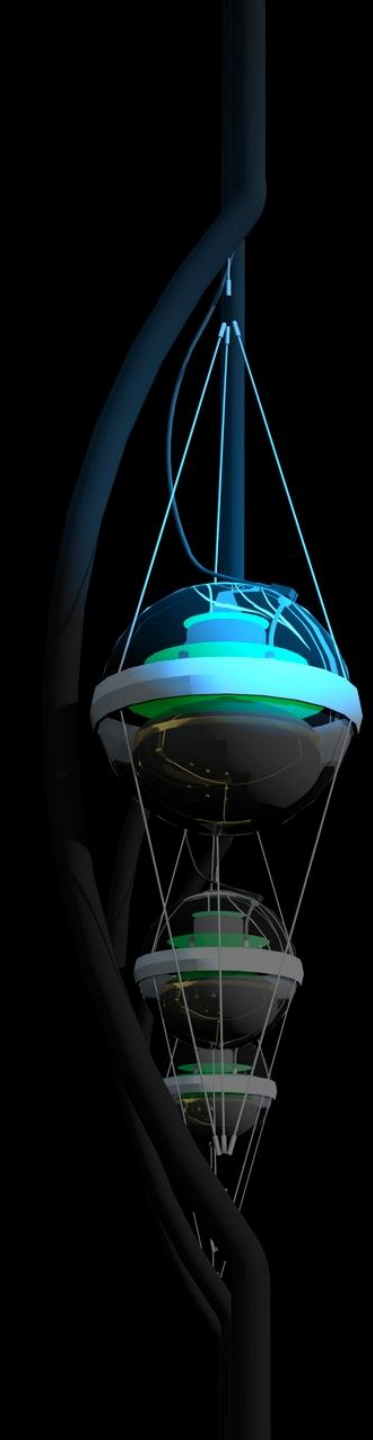
oscillations in DeepCore [energy ~30 GeV; 5.6 sigma]











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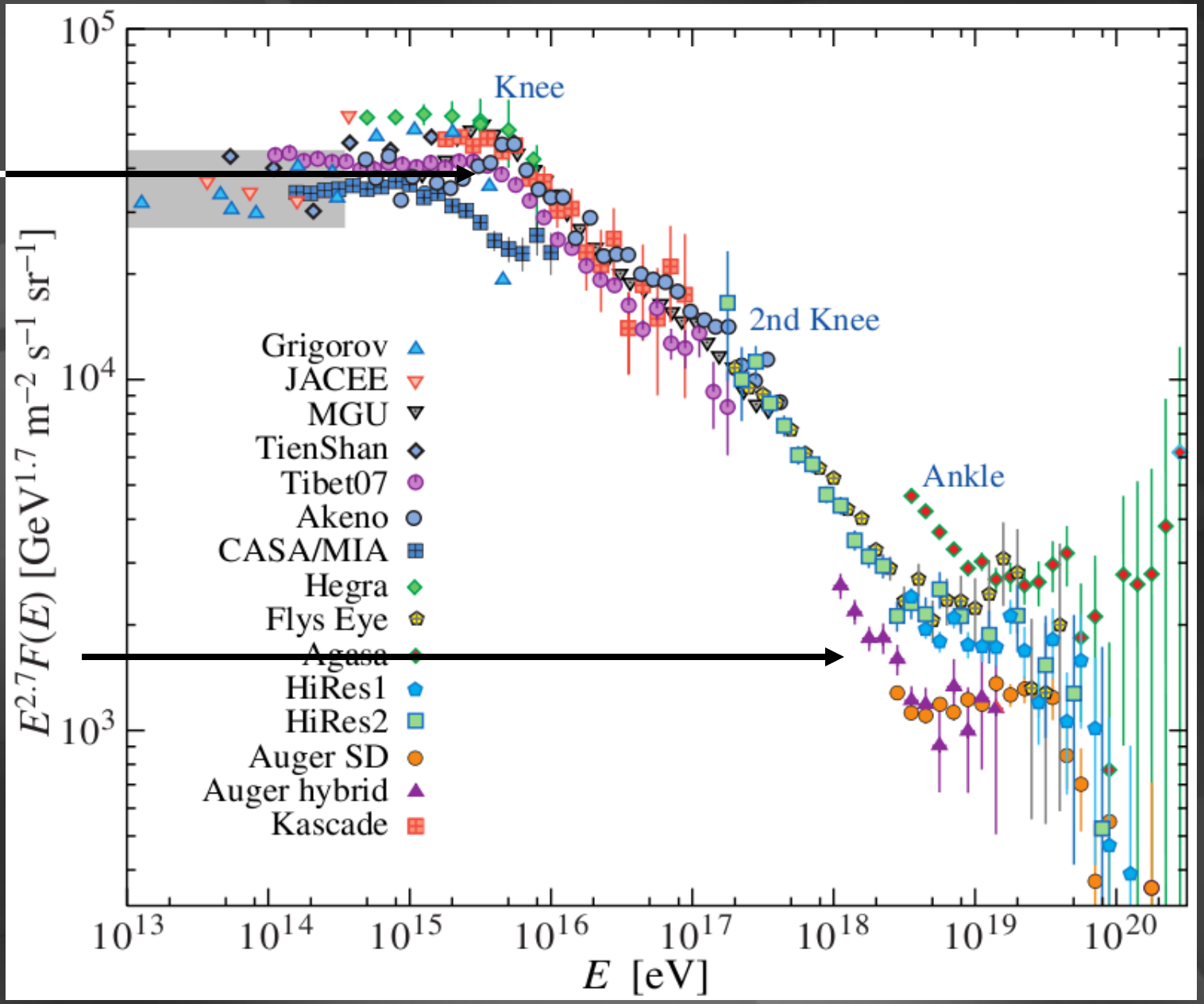
sources accommodating the observed energy budget

Galactic: supernova remnants?

extragalactic: gamma ray bursts? active galaxies?



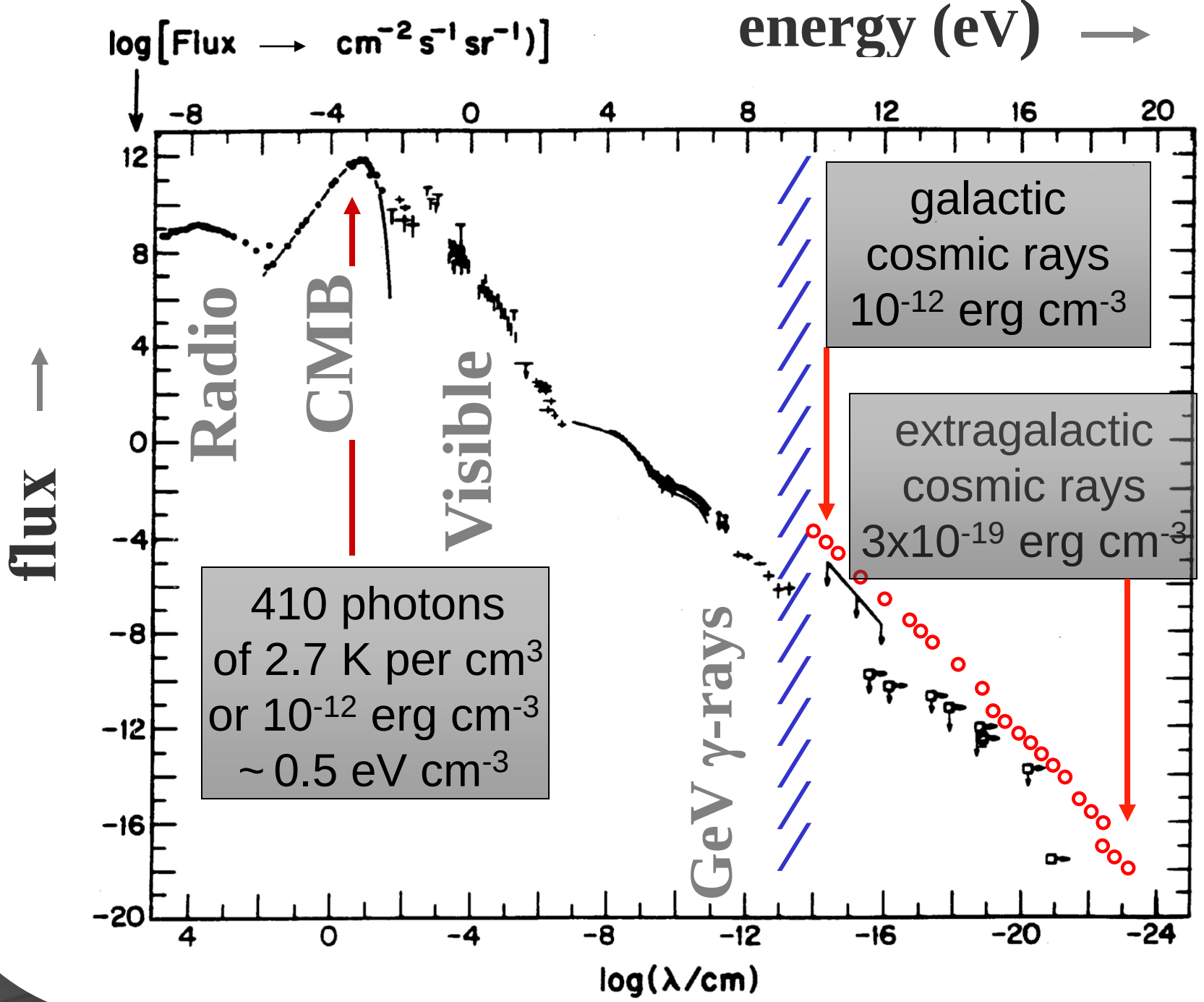
Hillas formula :

- accelerator must contain the particles

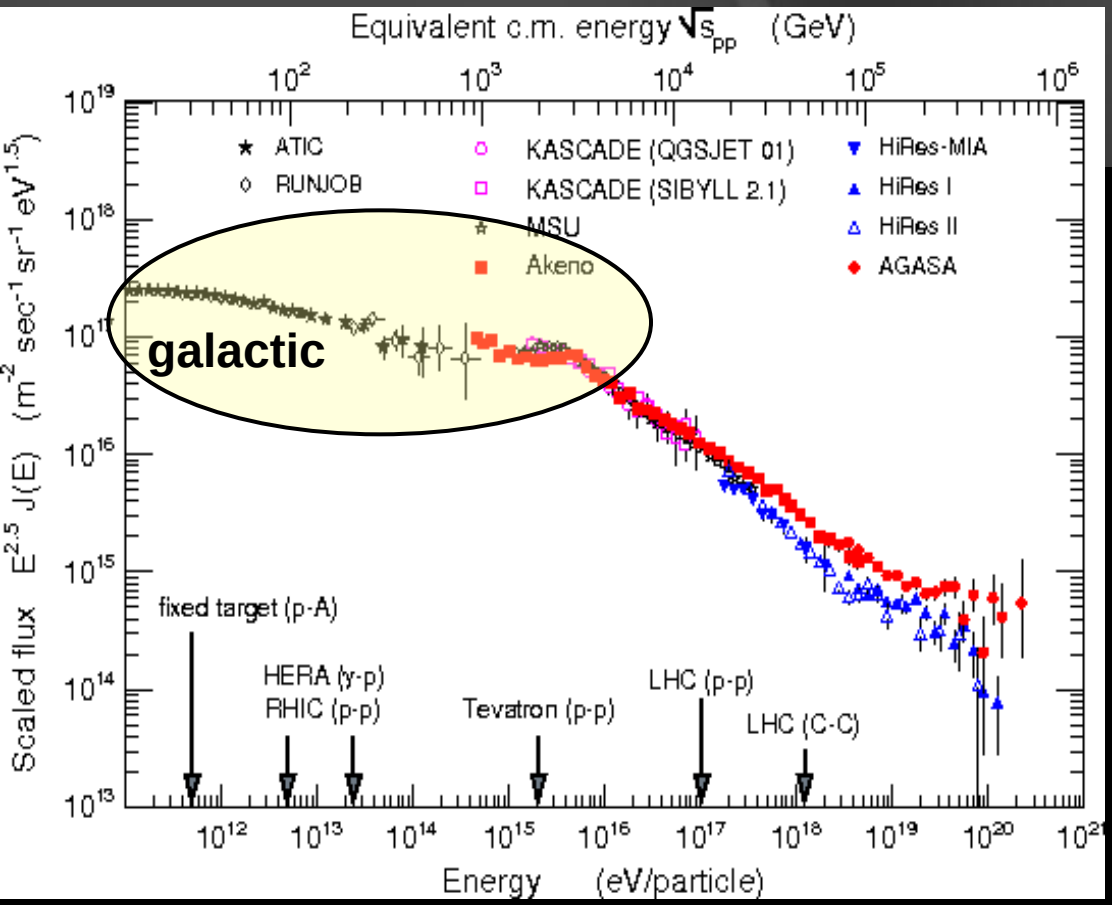
$$R_{gyro}\left(=\frac{E}{vqB}\right)\leq R$$

$$\boxed{E \leq v\, qBR}$$

- dimensional analysis, difficult to satisfy


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux →
Radio
CMB
Visible
GeV γ-rays
galactic cosmic rays 10-12 erg cm-3
extragalactic cosmic rays 3x10-19 erg cm-3
410 photons of 2.7 K per cm3 or 10-12 erg cm-3 ~ 0.5 eV cm-3
log(λ/cm)

Cosmic Rays & SNRs



observed energy density of galactic CR:

$\sim 10^{-12}$ erg/cm^3

supernova remnants:

10^{50} ergs every 30 years

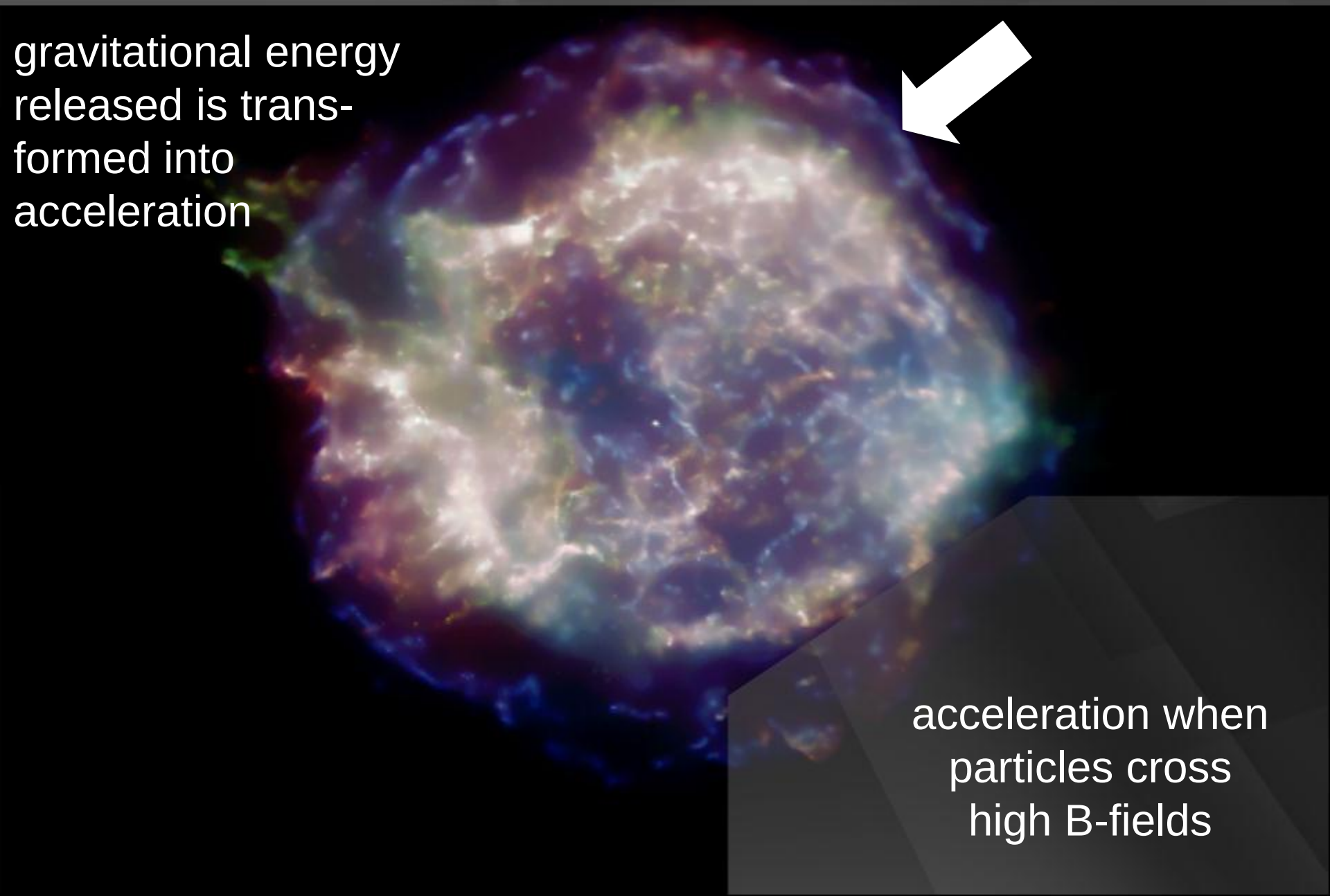
$\sim 10^{-12}$ erg/cm^3

for steady state of CR with lifetime 10^6 years

SNRs provide the environment and energy to explain the galactic cosmic rays!

cassiopeia A supernova remnant in X-rays

gravitational energy released is trans-formed into acceleration



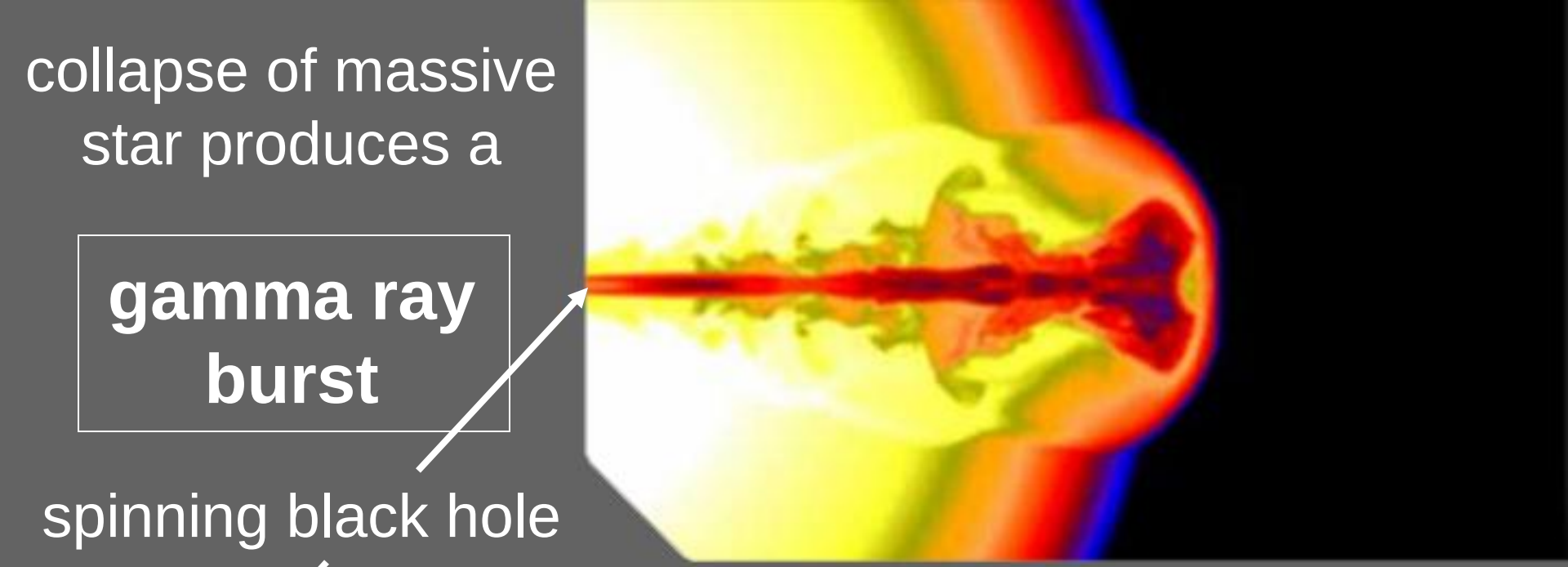
acceleration when particles cross high B-fields

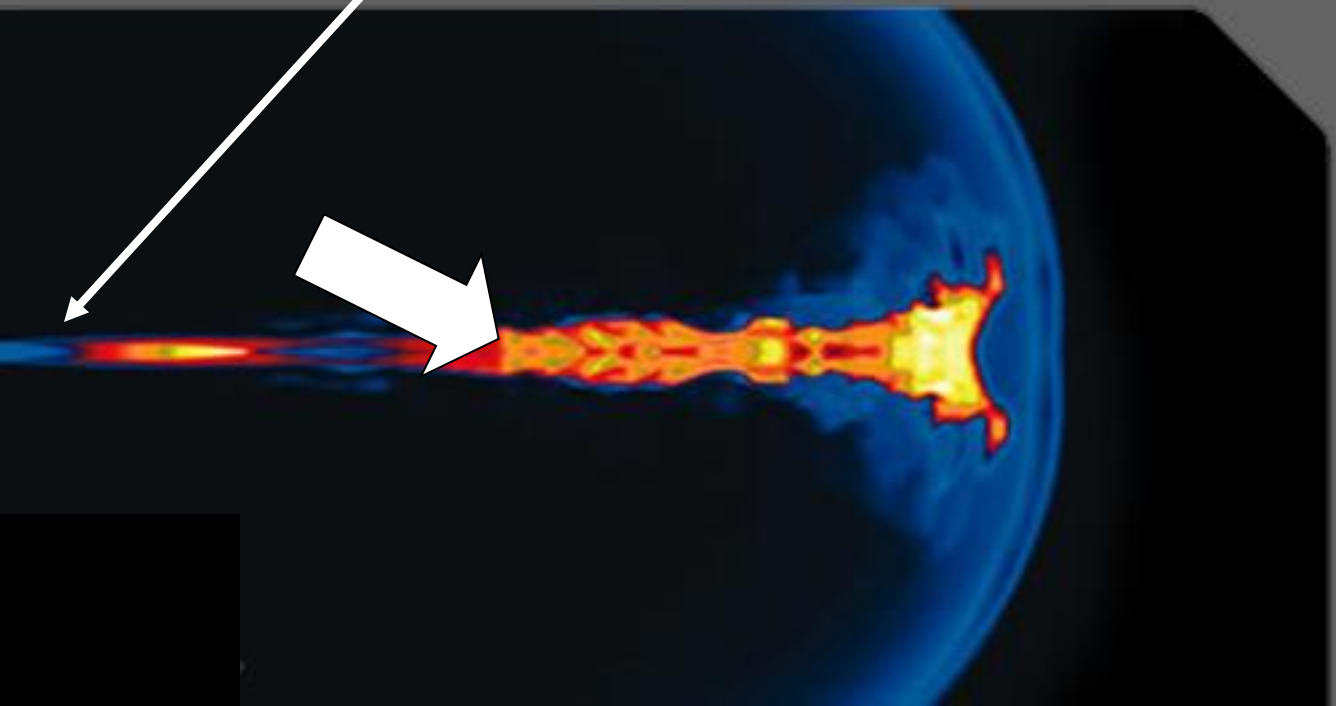
and if the star collapses to a black hole …

collapse of massive star produces a

gamma ray burst

spinning black hole



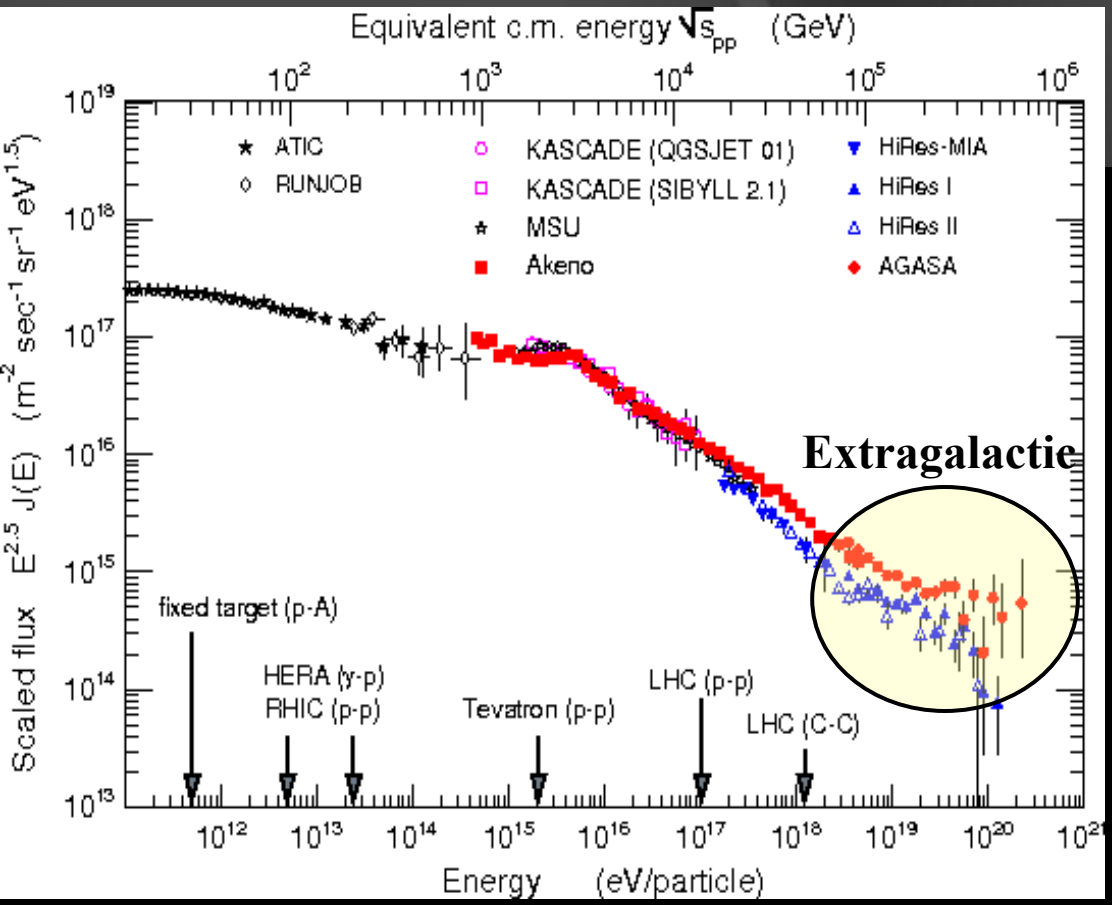


shocks produced in the outflow of the spinning black hole: electrons (and protons ?)

and if the star collapses to a black hole …

→ happens in seconds not thousands of years
→ beamed not spherical
→ simulation not image

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

~ 10^{-19} erg / cm^3

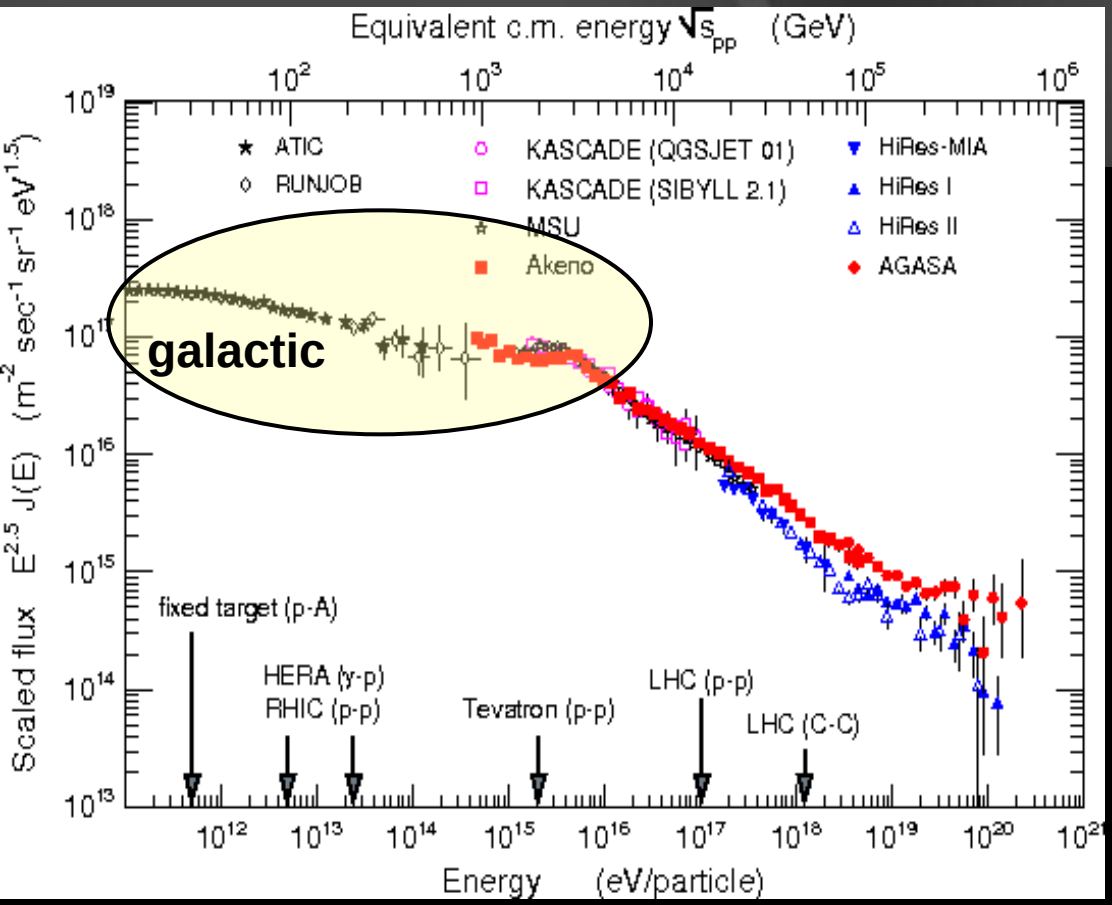
Gamma-Ray Bursts:

2×10^{51} ergs x 300/Gpc^3 x 10^{10} yr

~ 10^{-19} erg / cm^3

GRBs provide environment and energy to explain the extragalactic cosmic rays!

Cosmic Rays & SNRs



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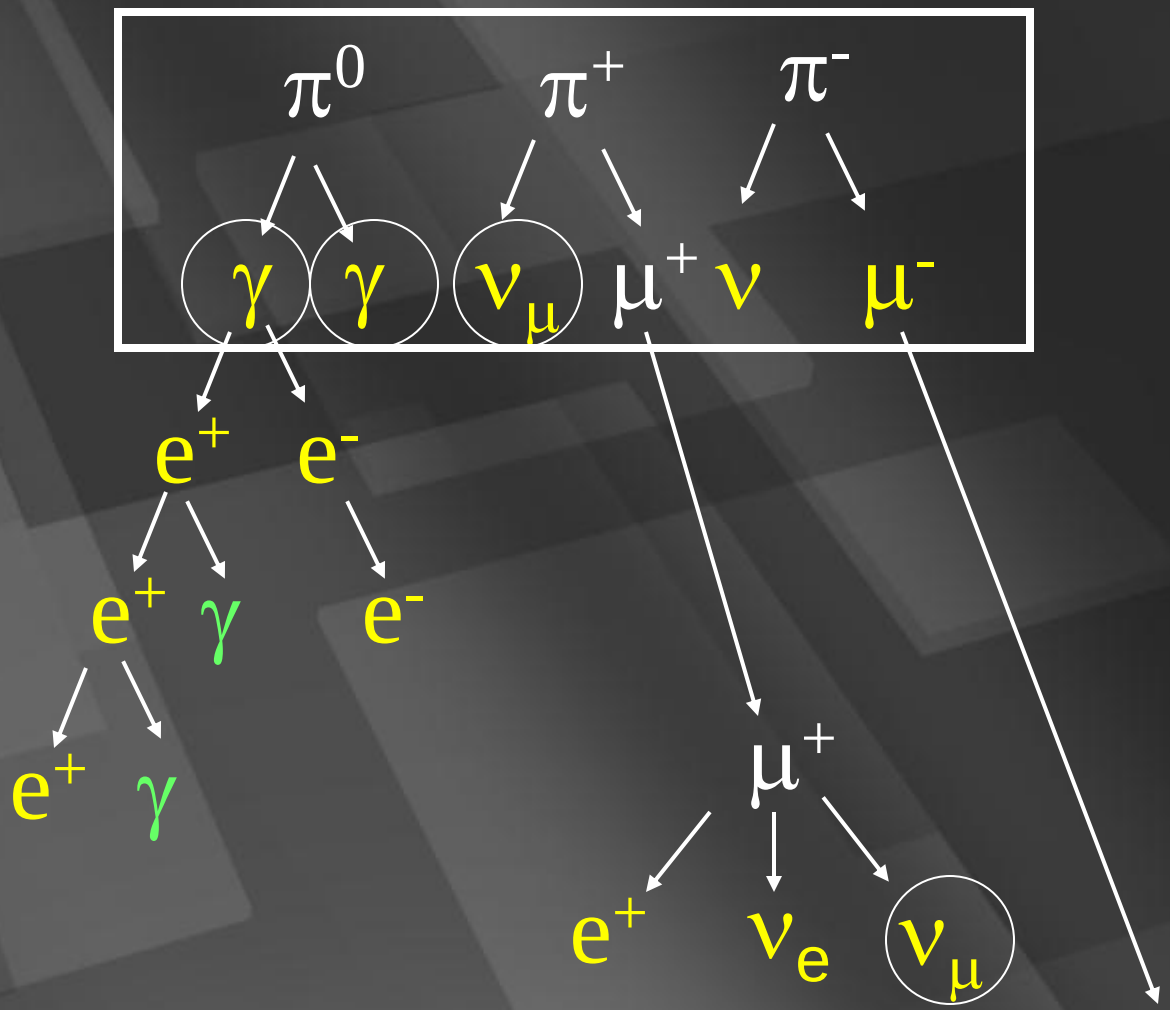
enter ν-astronomy: neutrinos trace cosmic rays

- neutral pions are observed as gamma rays
- charged pions are observed as neutrinos

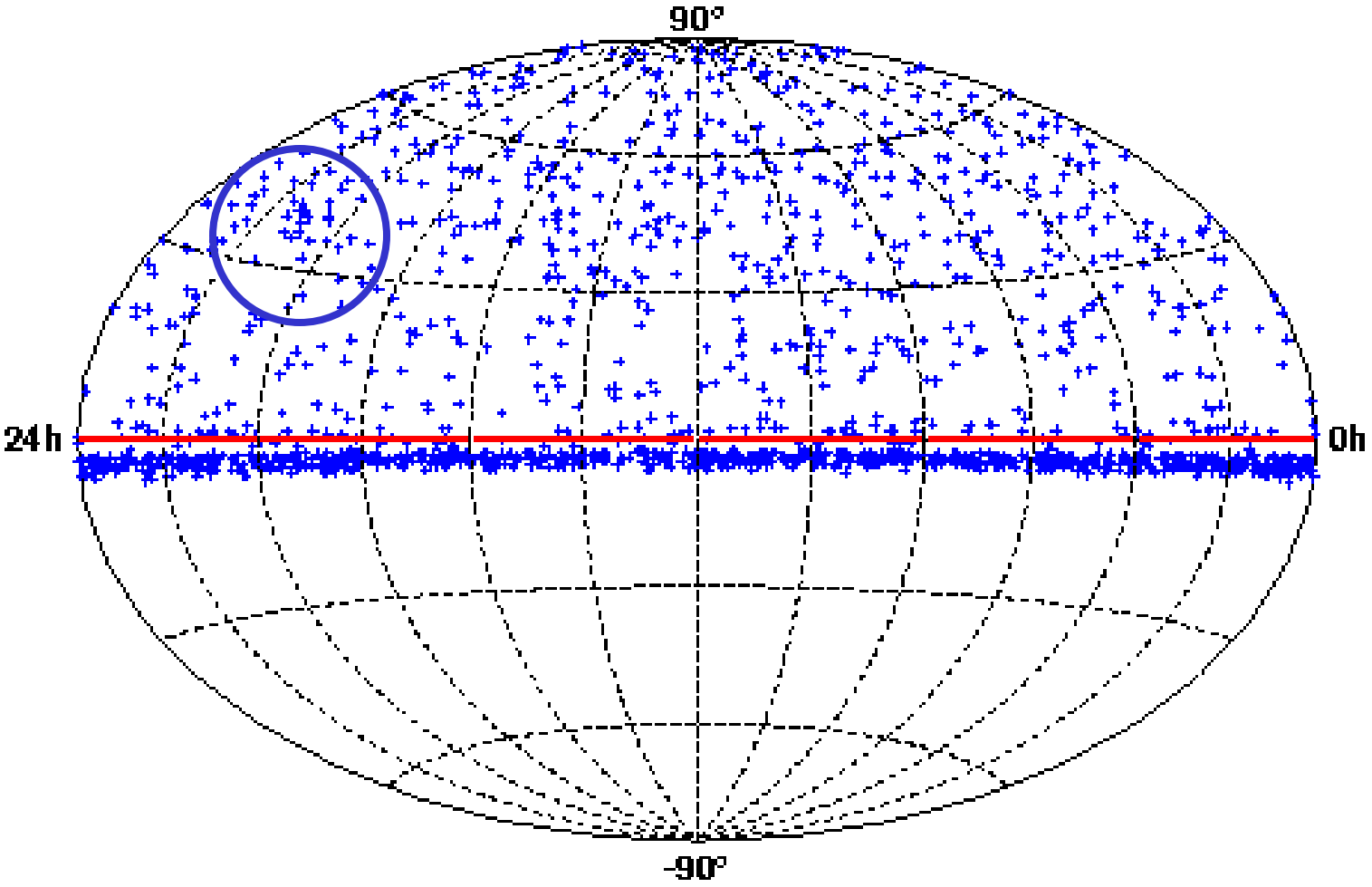


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

early astronomy

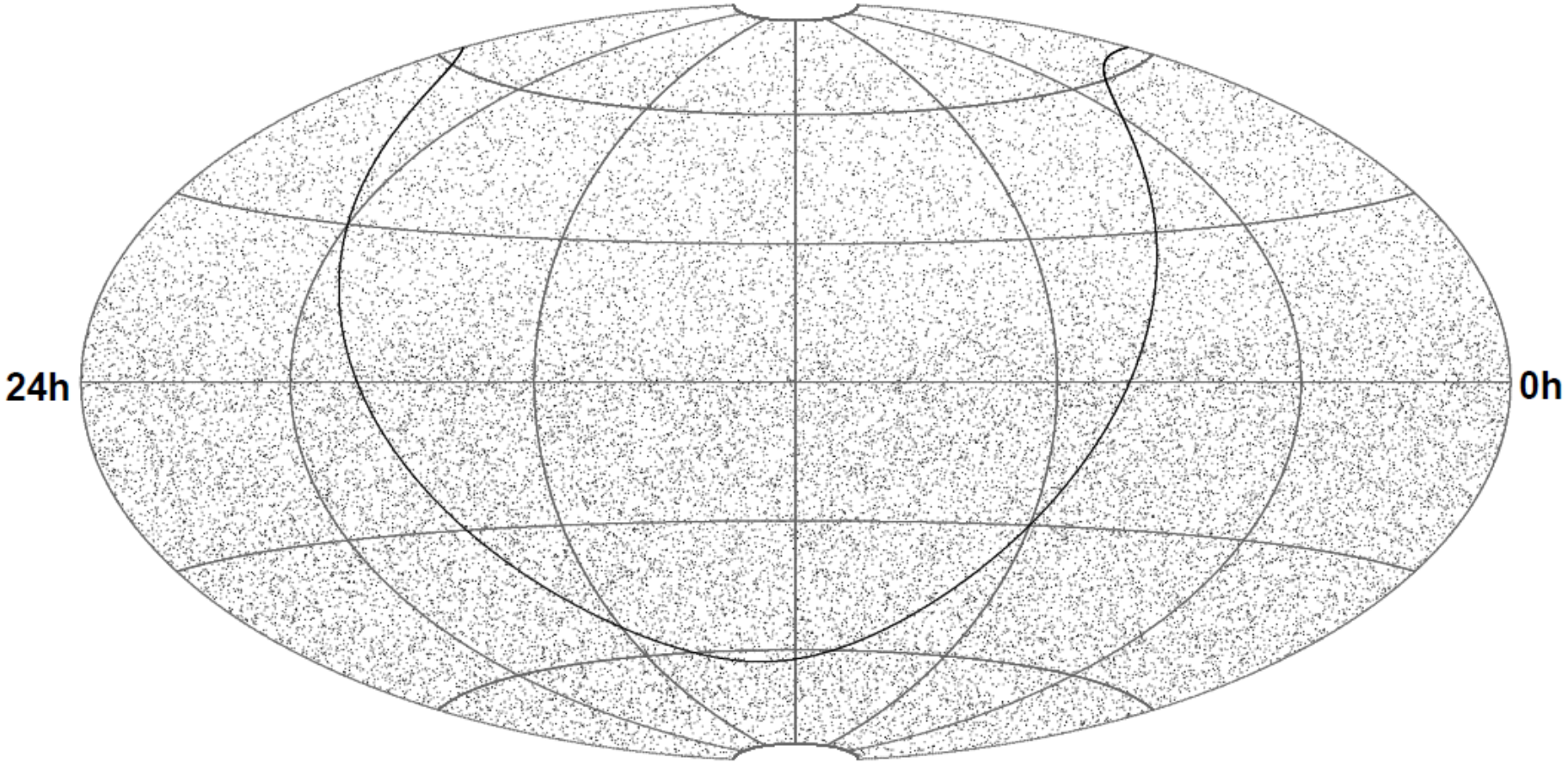
AMANDA 2000

directions of ~ 600 neutrinos



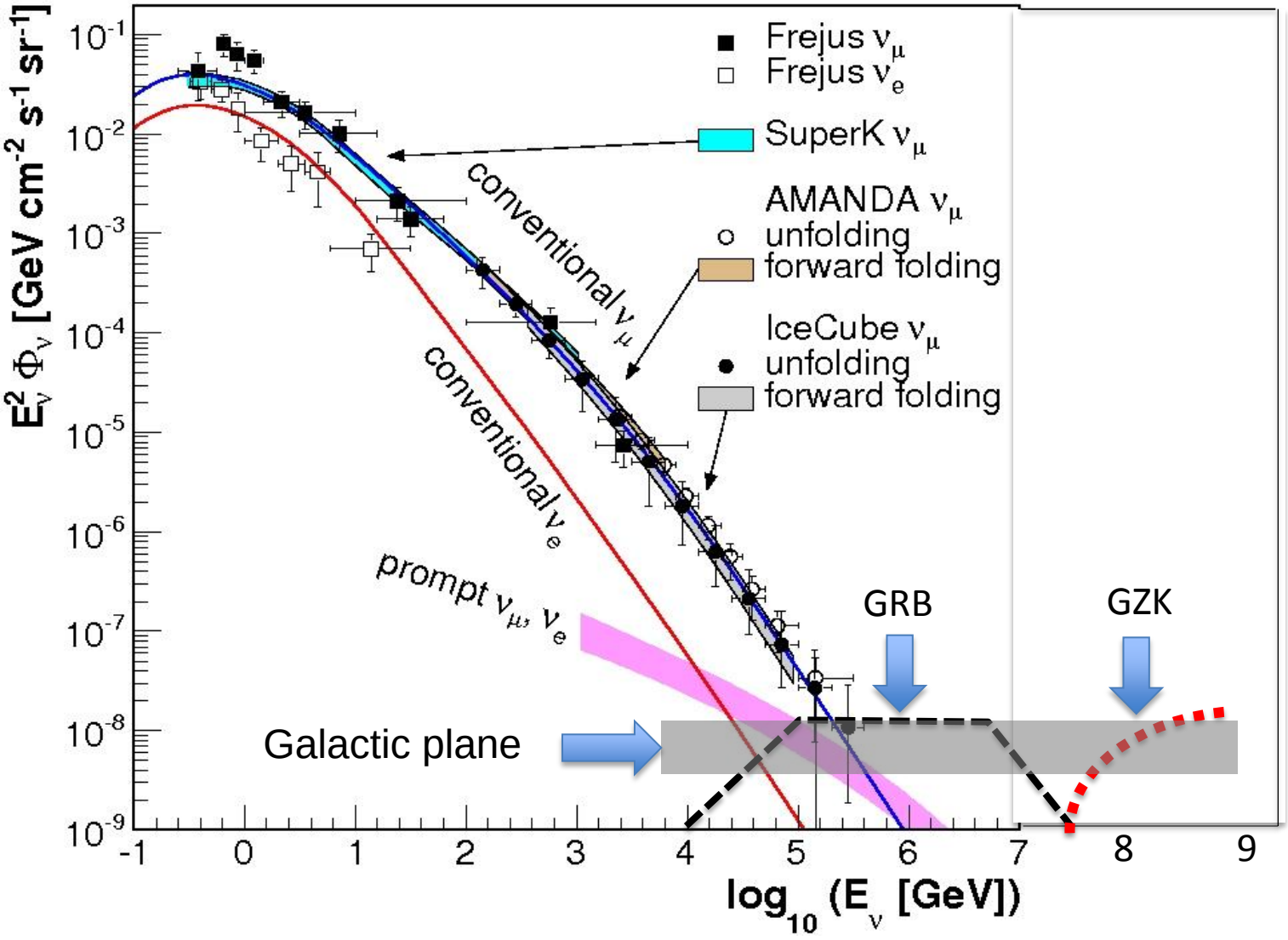
IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos



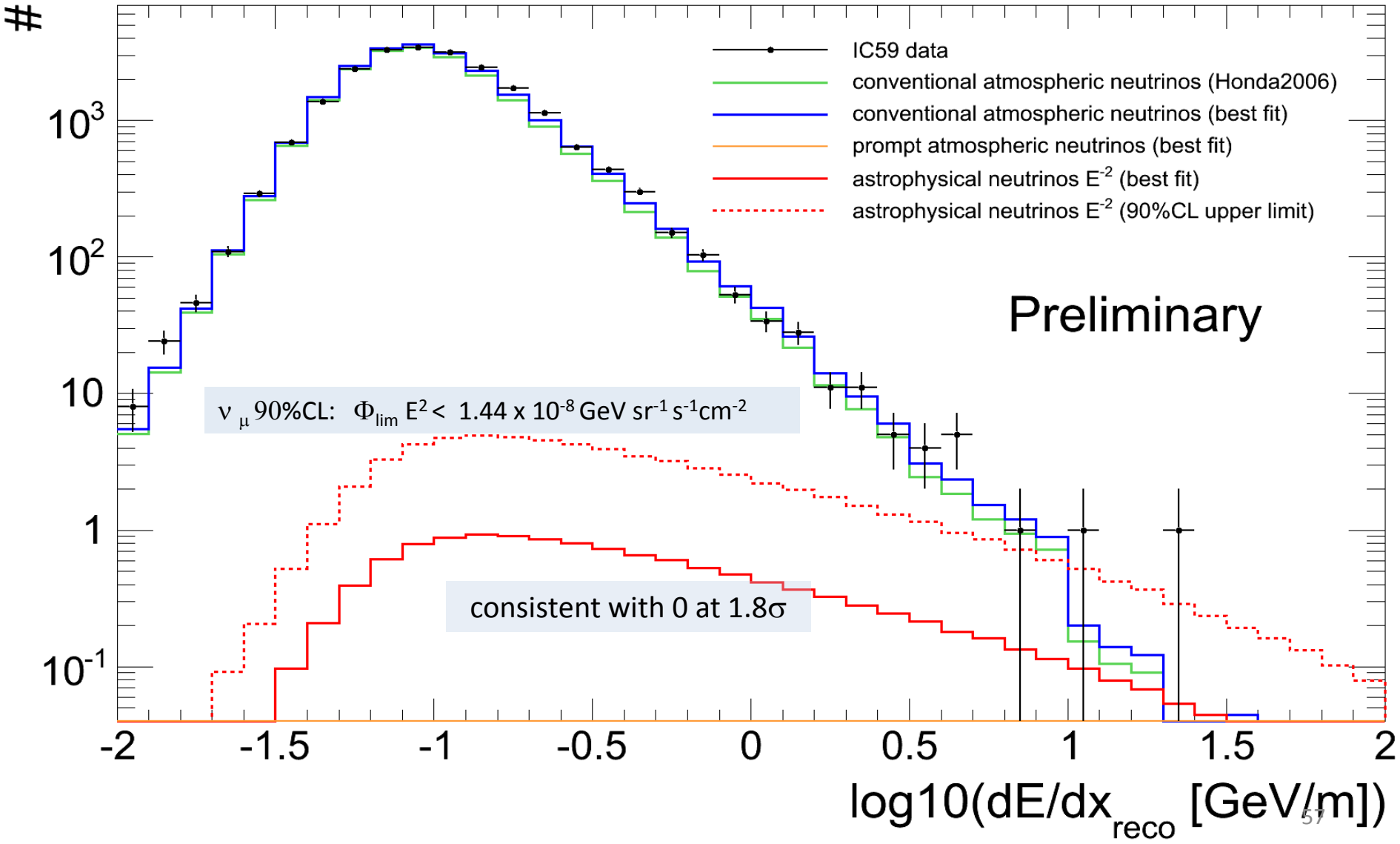
search for
- clustering
- high energy (>> 100 TeV)

southern sky: 23151 muons

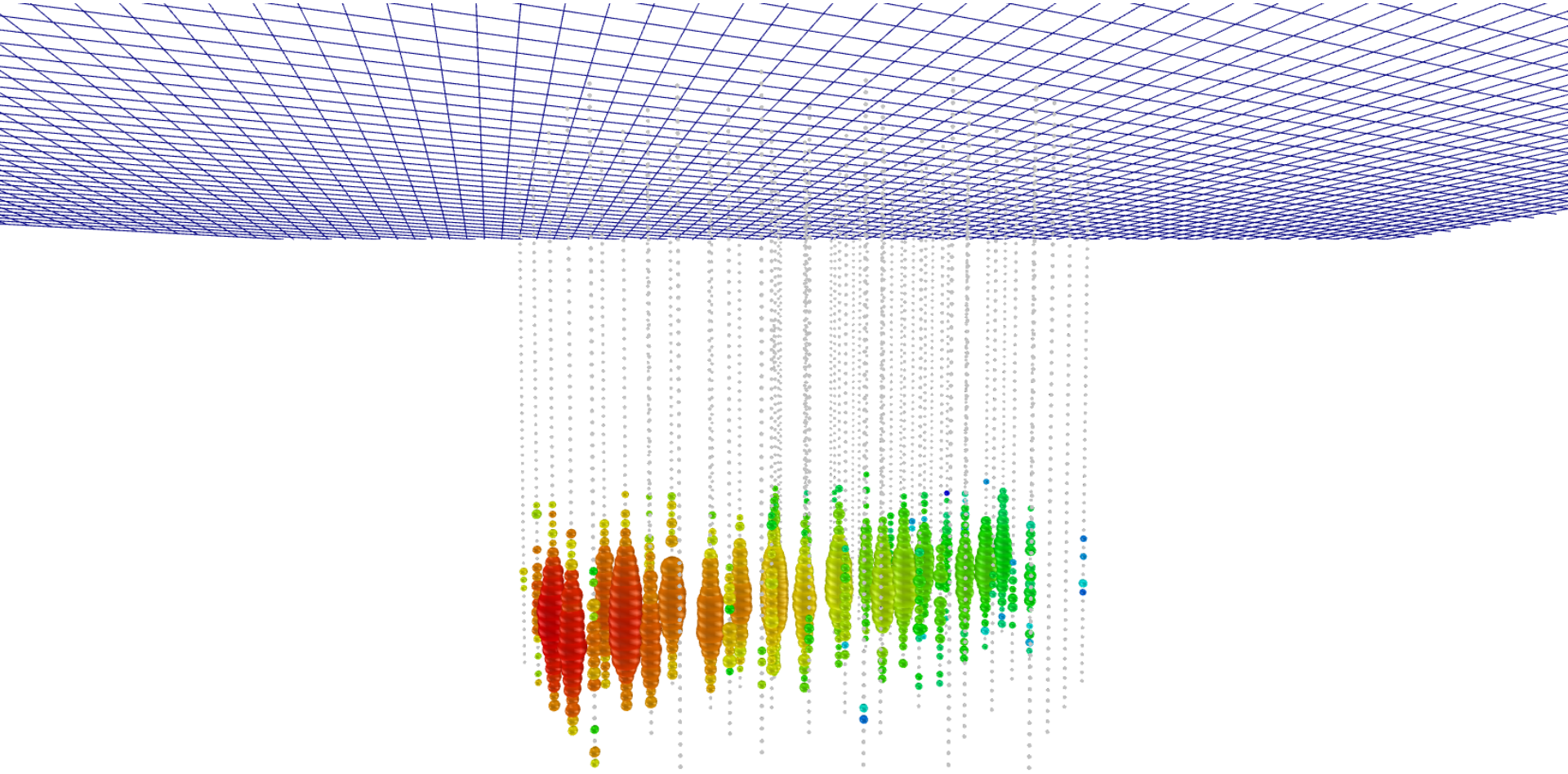

$E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-1
0
1
2
3
4
5
6
7
8
9
$\log_{10}(E_\nu$ [GeV])
Frejus ν_μ
Frejus ν_e
SuperK ν_μ
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
GRB
GZK
Galactic plane

IC59: diffuse ν_μ fit to data

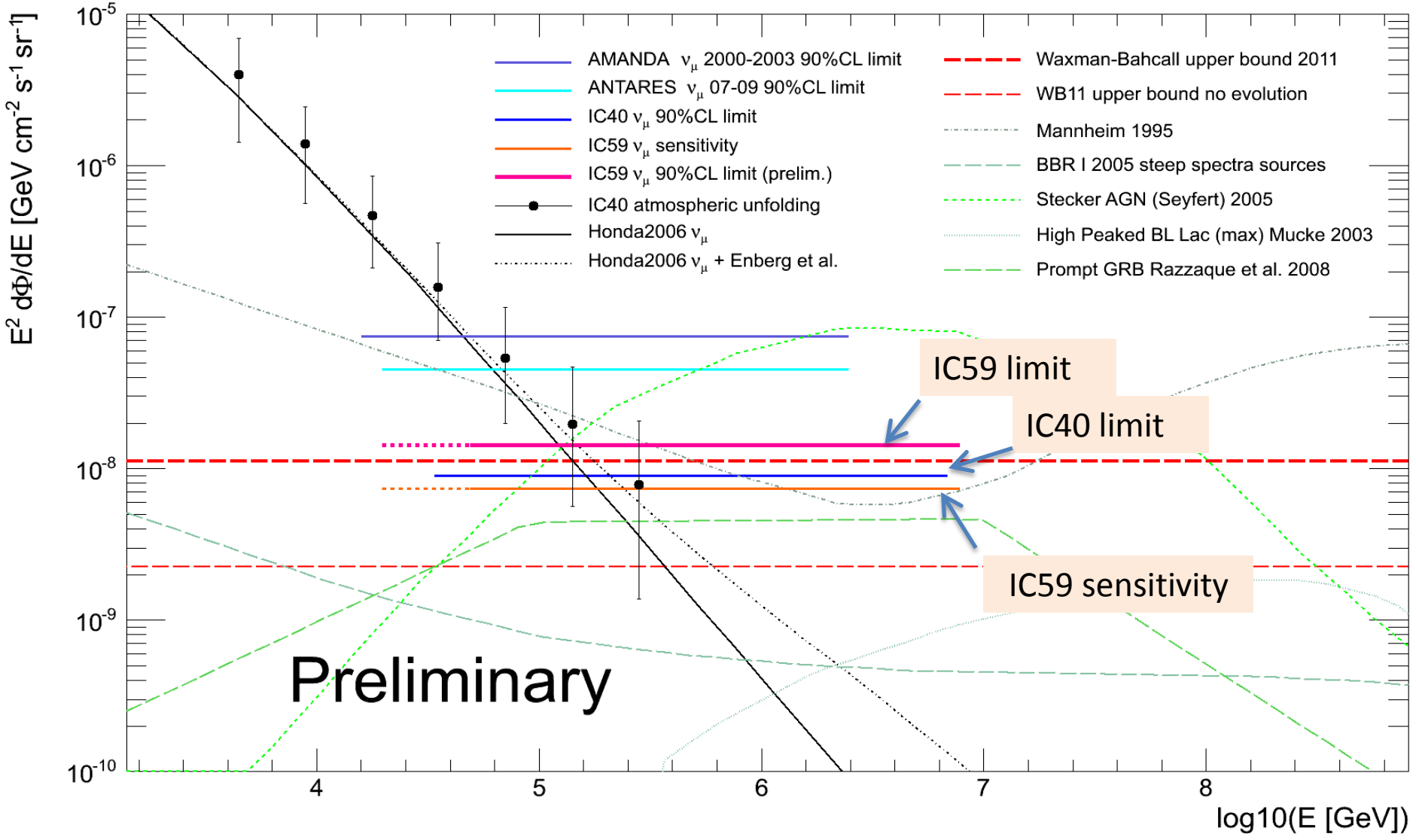
livetime: 348 days events: 21943



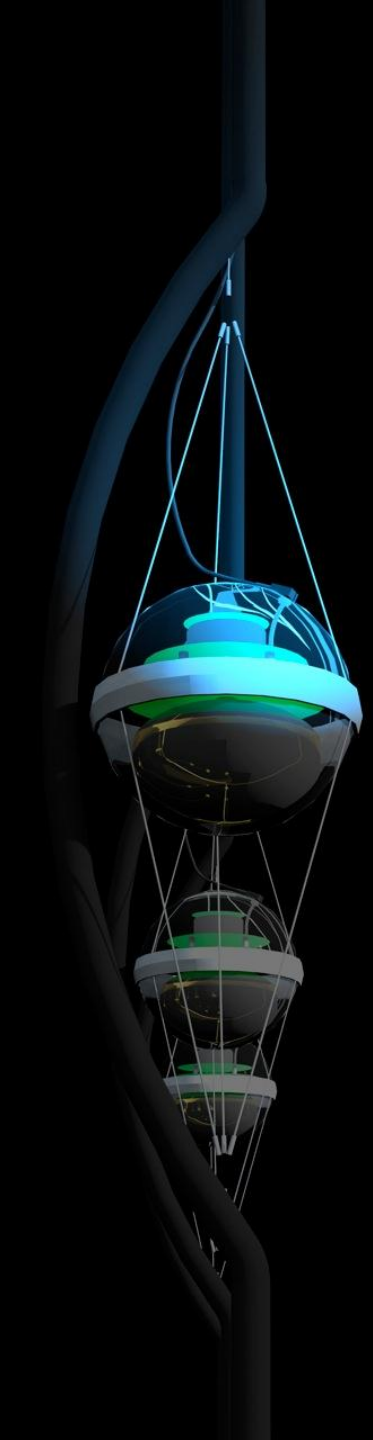
highest energy event



diffuse flux limit



- nothing seen
- nothing expected
- this is just the beginning…



- introduction
- we built a km^3 neutrino detector → 3 challenges:
  - drilling
  - optics of ice
  - atmospheric muons
- neutrino physics
- search for the sources of the Galactic cosmic rays
- search for the extragalactic cosmic rays
  - gamma ray bursts
  - active galaxies

IceCube.wisc.edu

Galactic cosmic rays :

must produce pionic γ-rays in interactions with hydrogen in Galactic plane (1 proton cm^{-3})

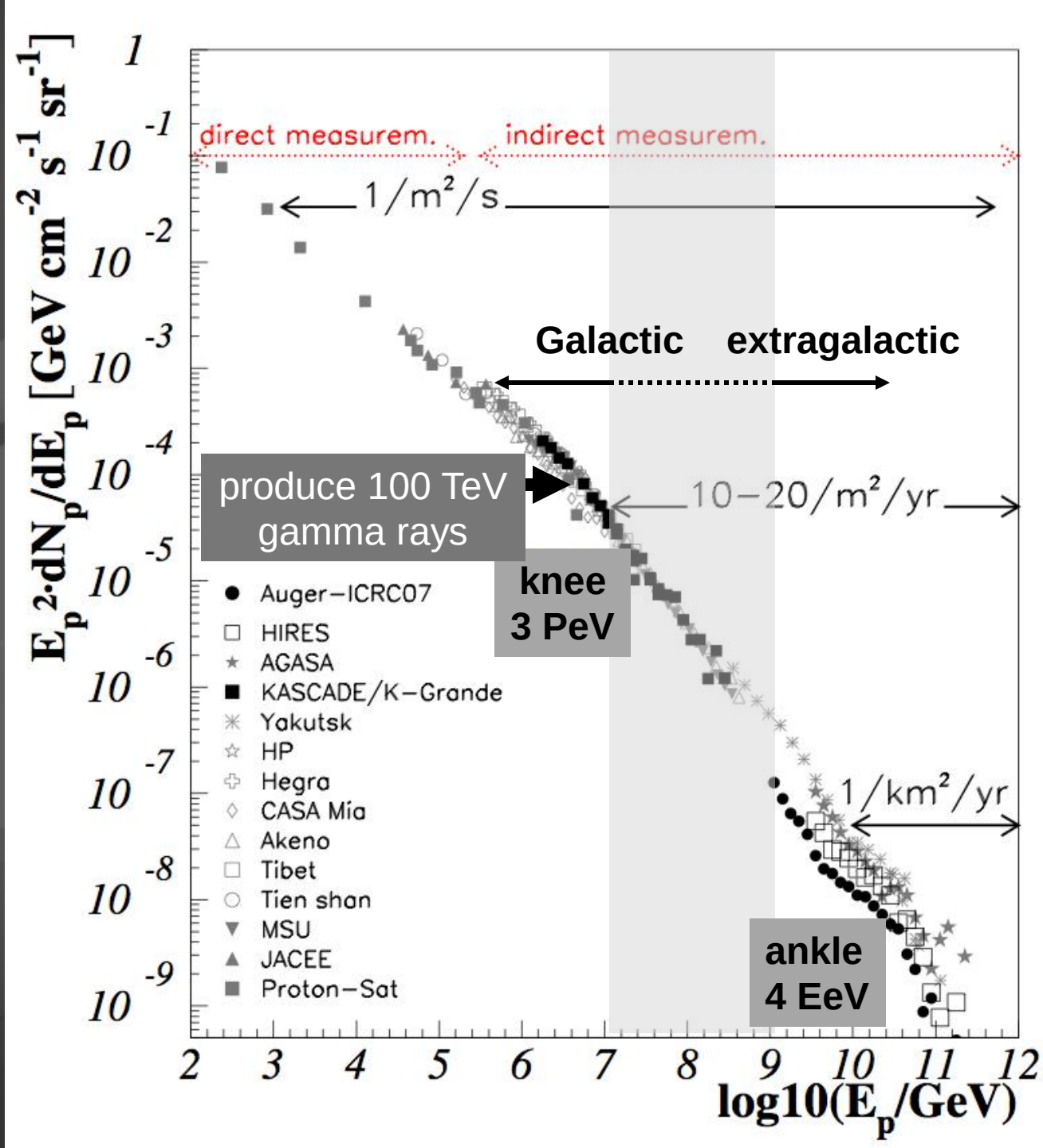
↓

cr + p → pions

$\pi^0 \rightarrow \gamma\gamma$

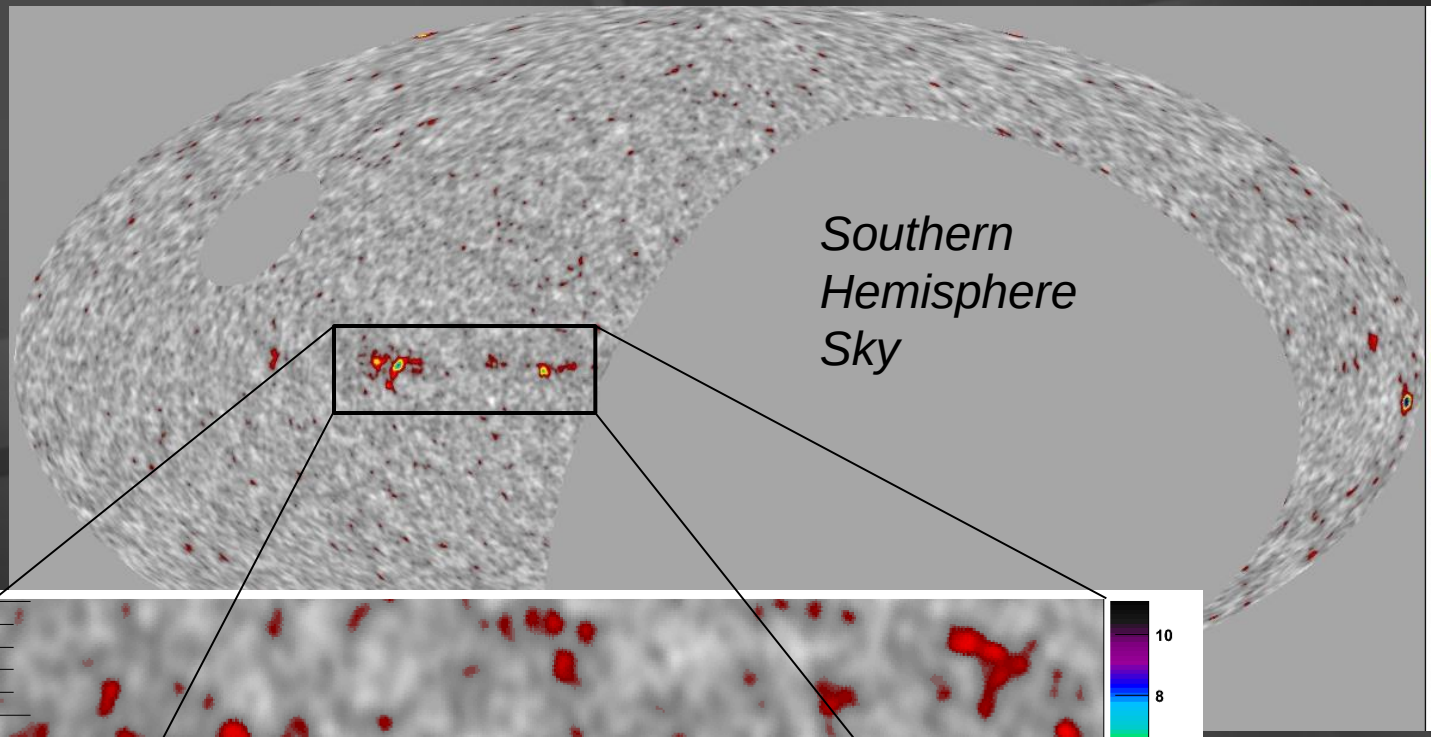
↓

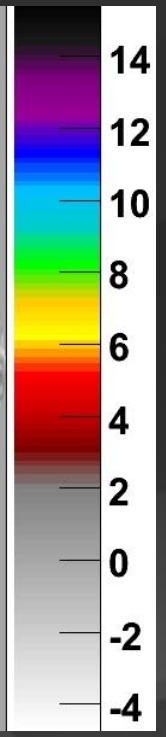
trace cosmic rays

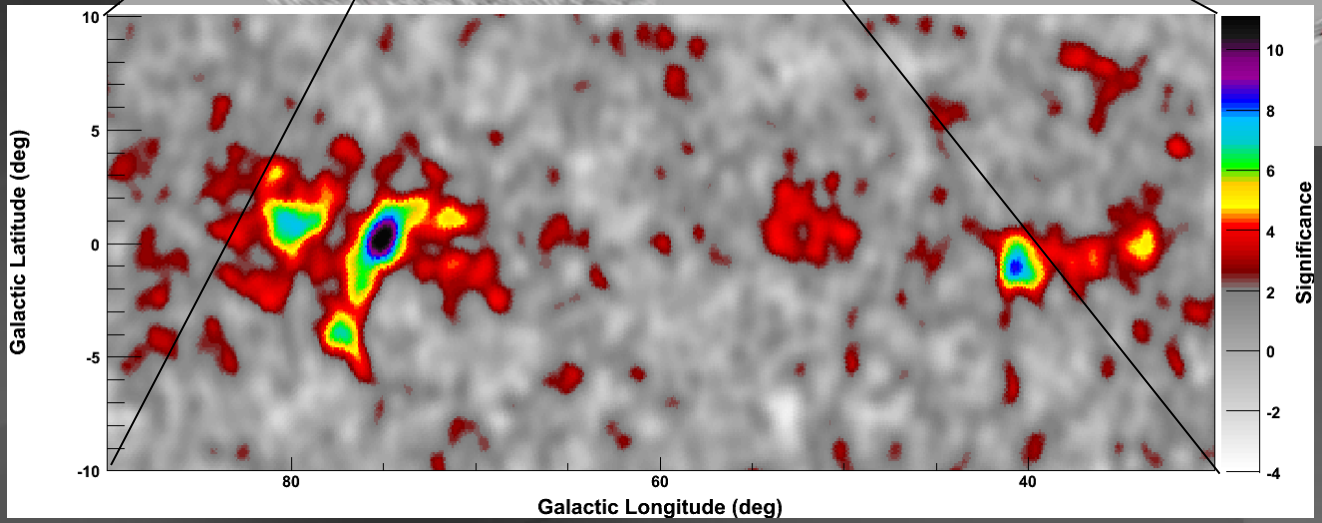


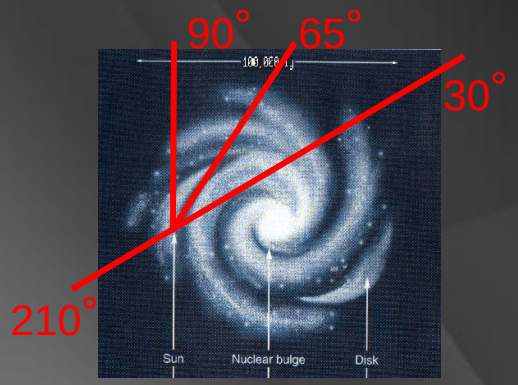
Galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions





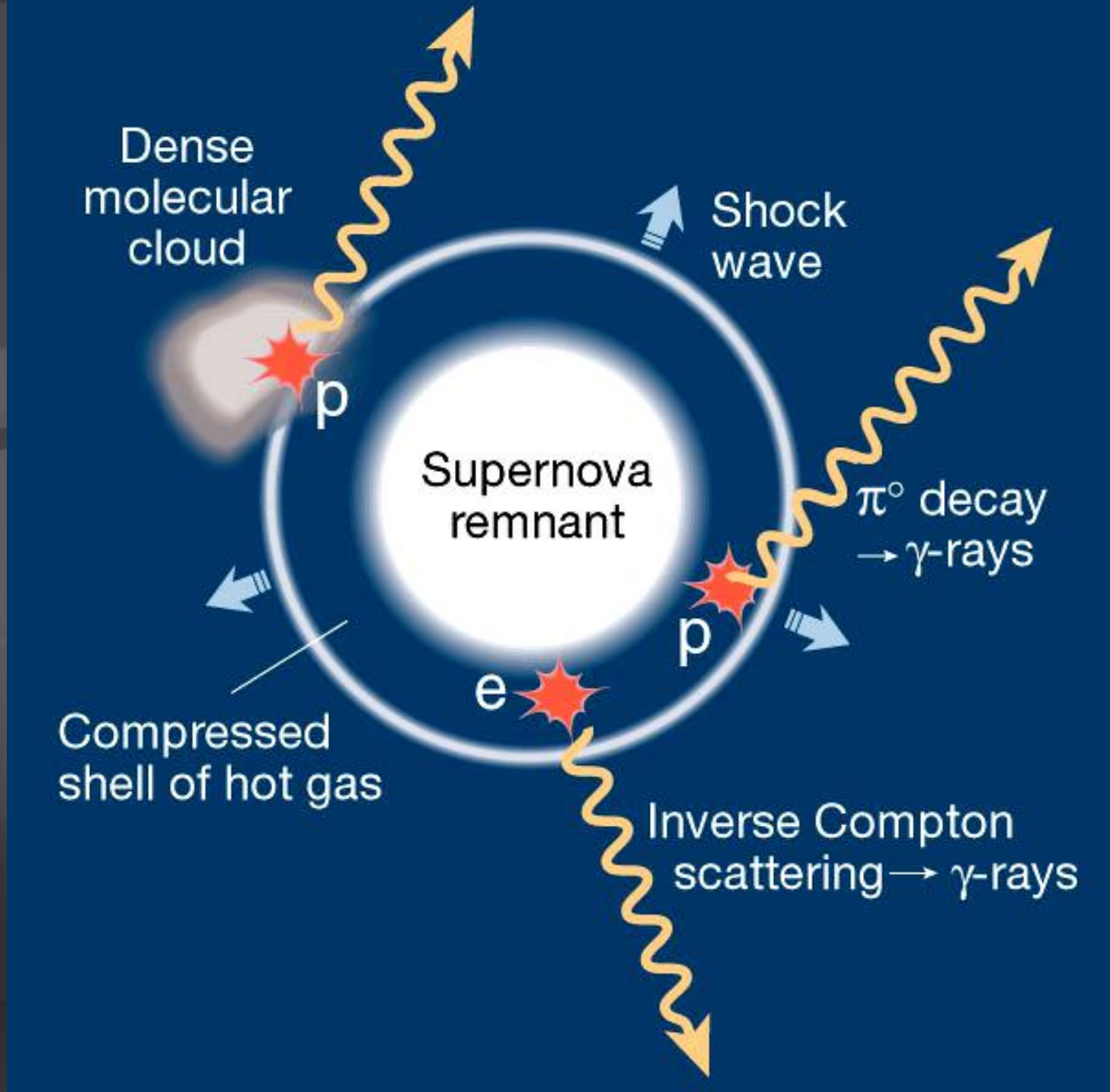




milagro

neutrinos from supernova remnants :

molecular clouds as beam dumps



neutral pions

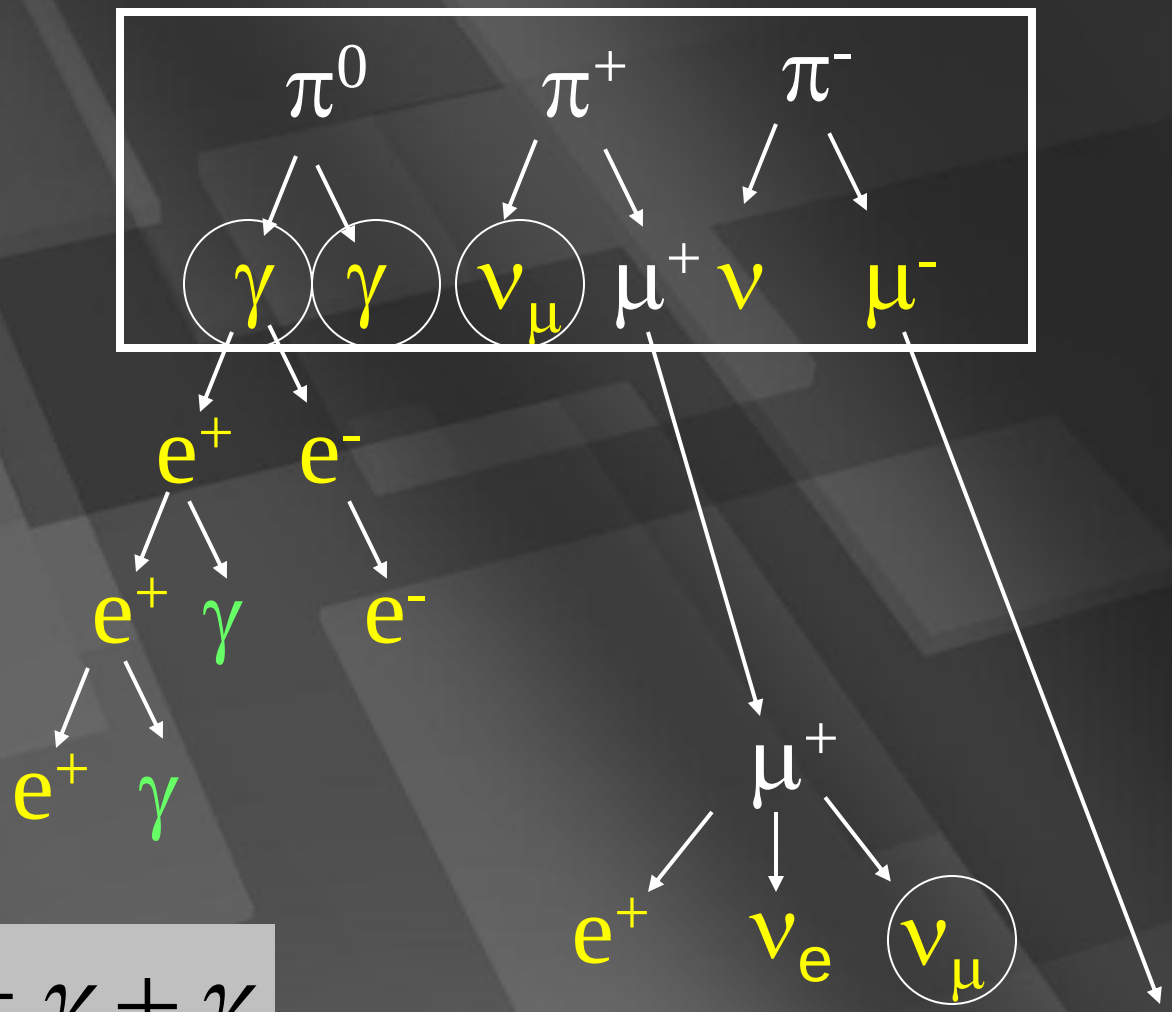
are observed as

gamma rays

charged pions

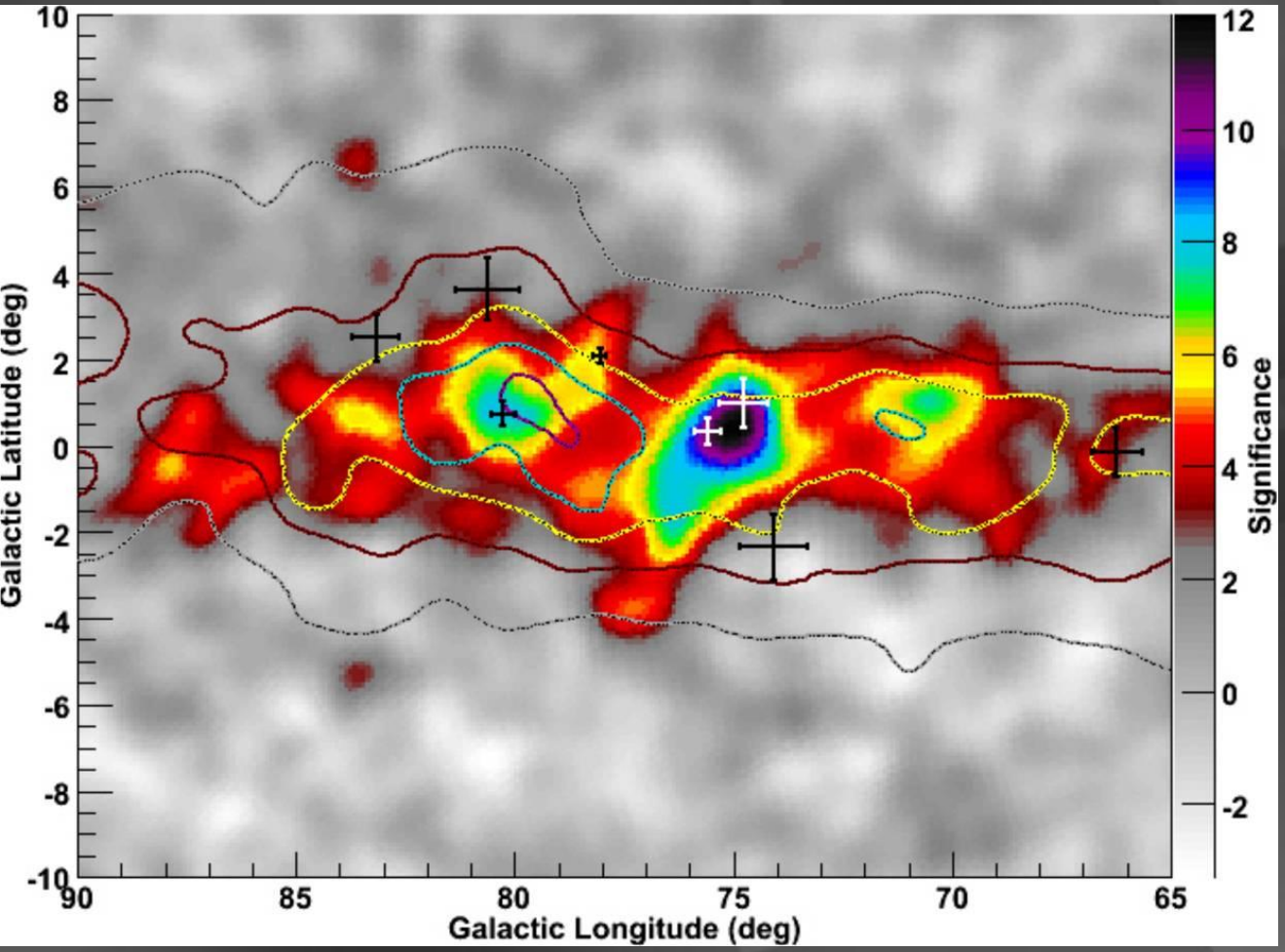
are observed as

neutrinos



$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

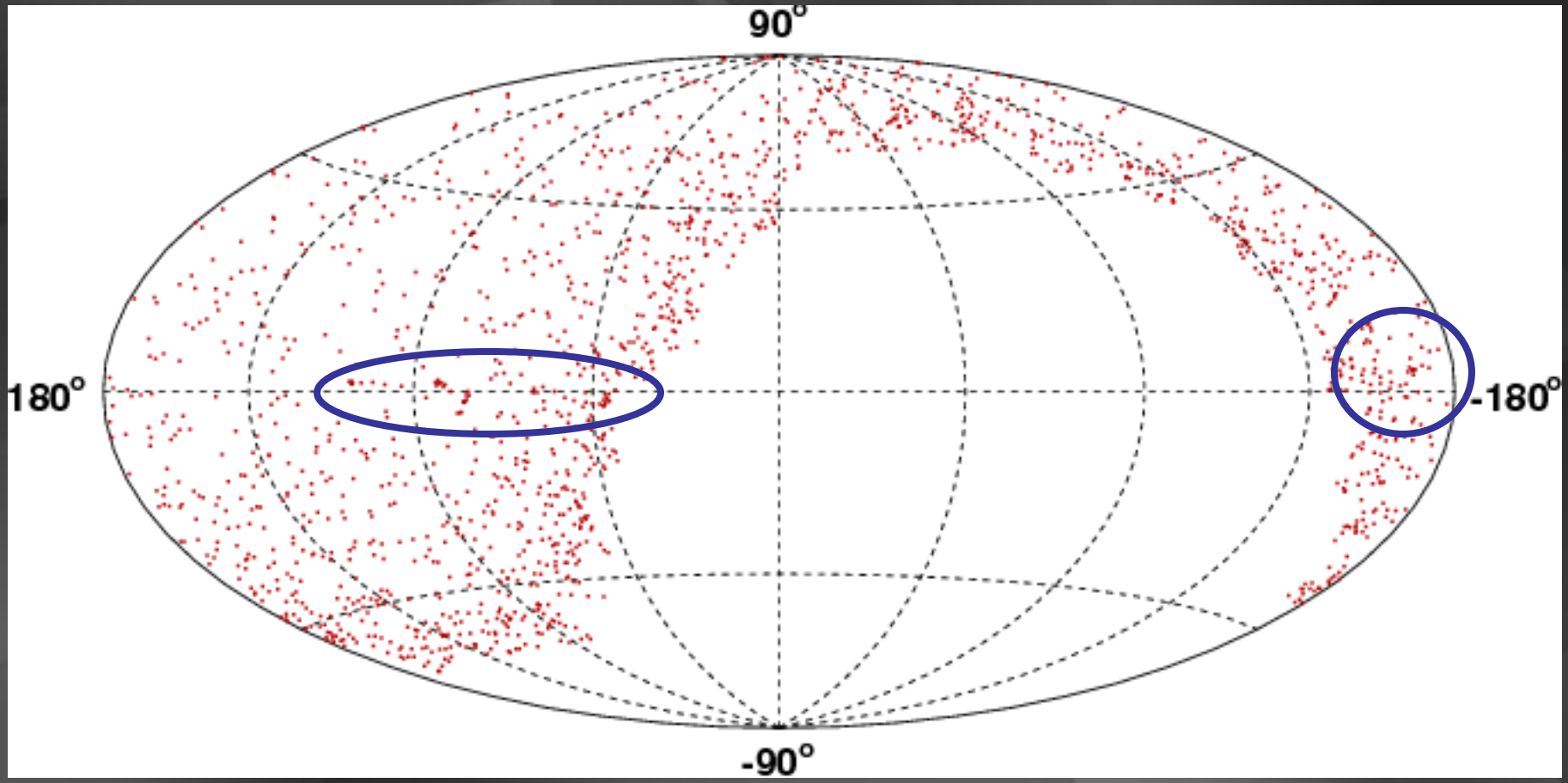
Cygnus region : Milagro



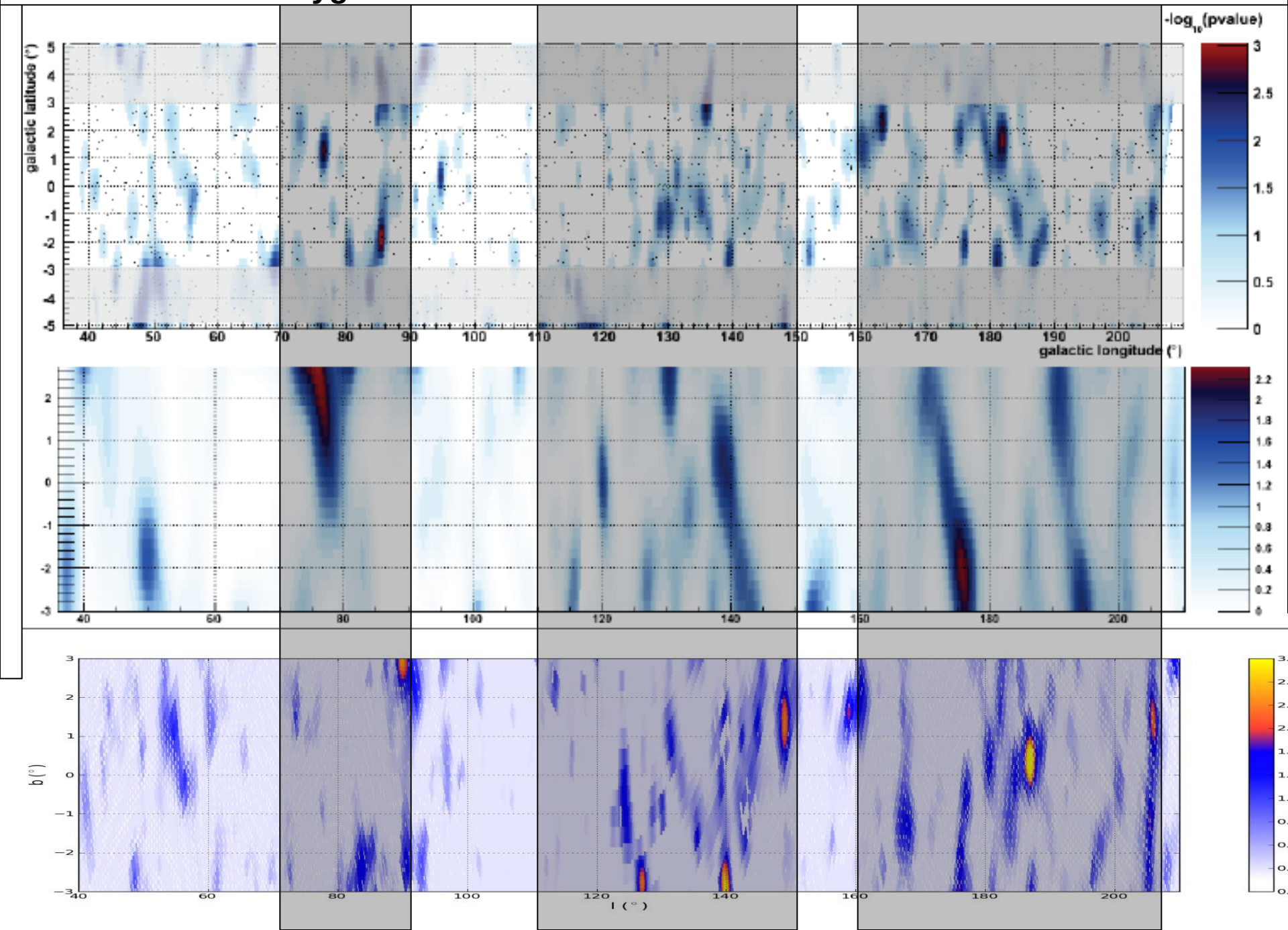
translation of
TeV gamma rays
into
TeV neutrinos :

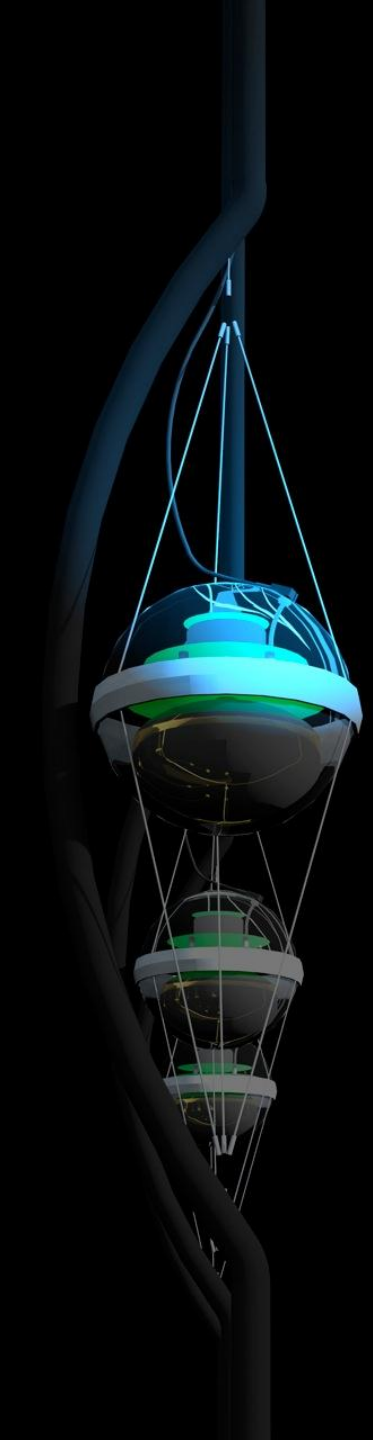
3 ± 1 ν per year in IceCube per source

5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV



Cygnus ← → Perseus arm





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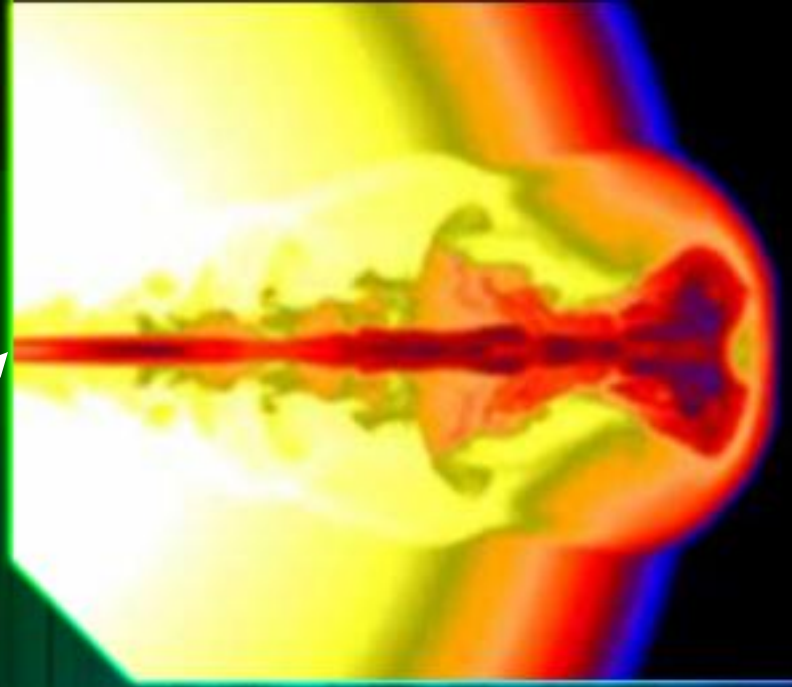
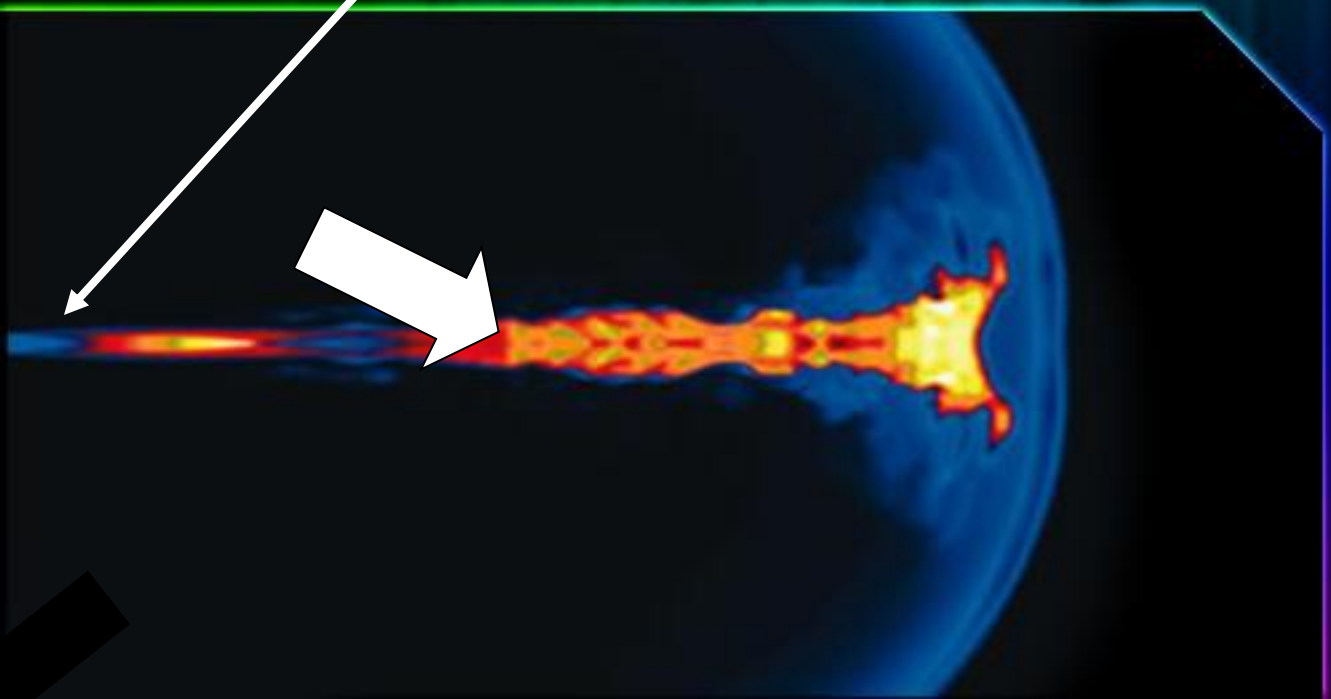
collapse of massive star produces a

gamma ray burst



spinning black hole



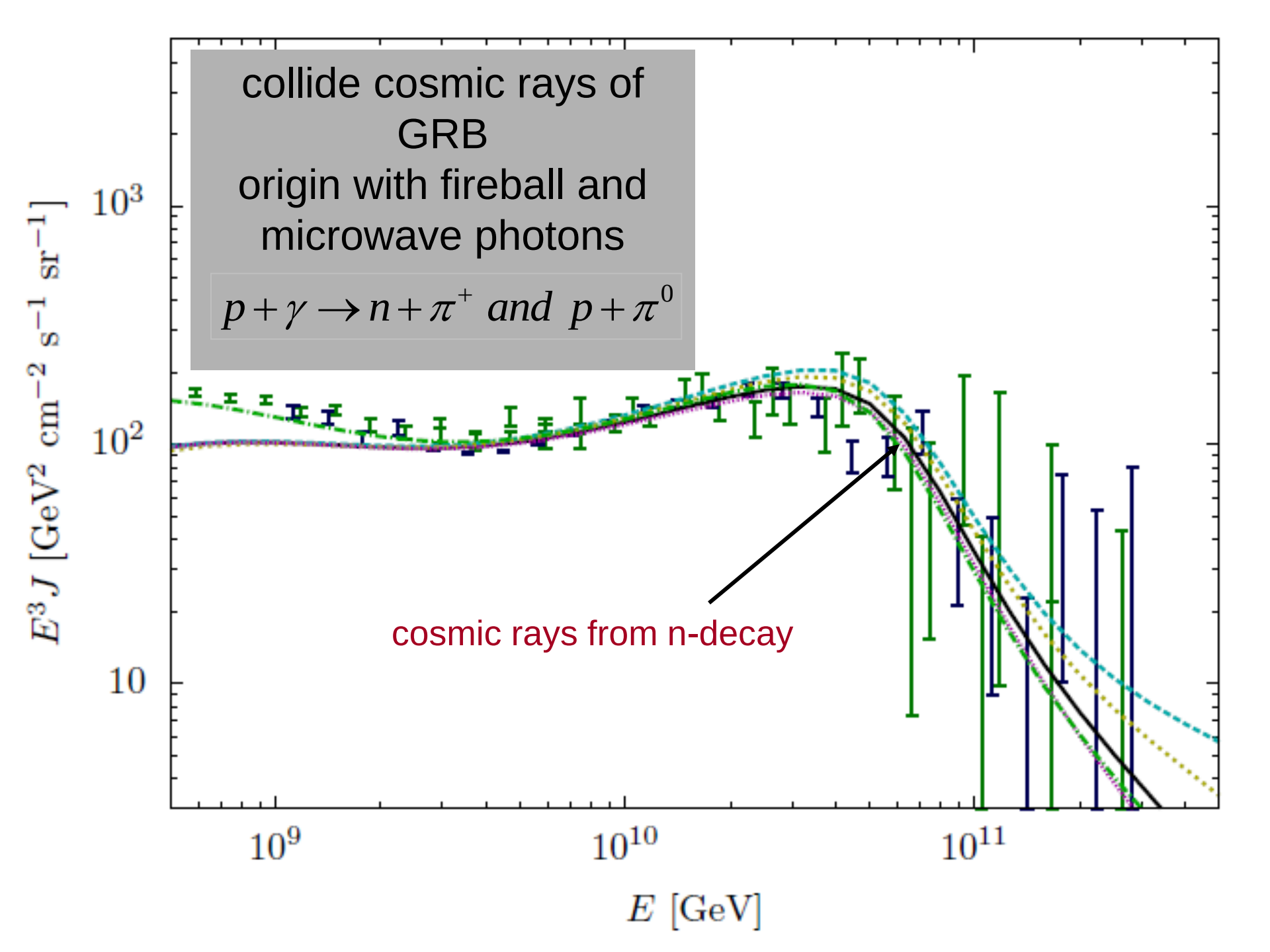
neutrinos are produced in the interactions of fireball protons (cosmic rays) with synchrotron photons

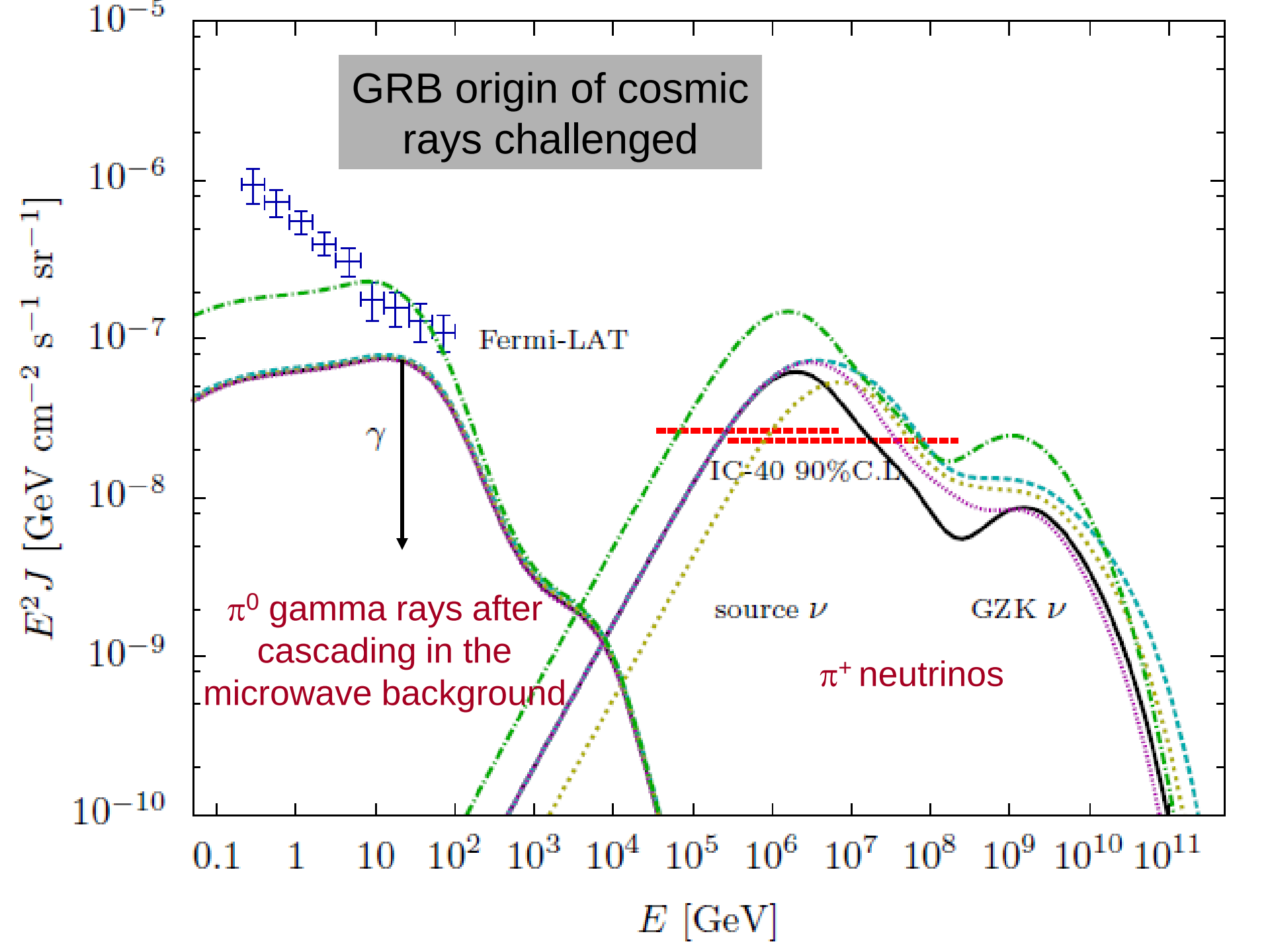
decays to PeV neutrino

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

decays to cosmic ray

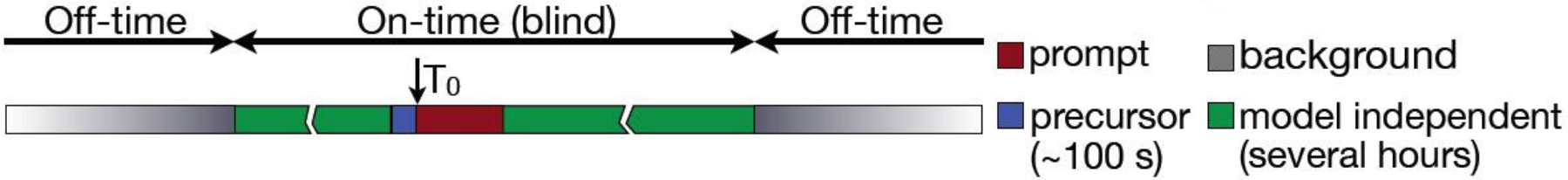
GRB: one neutrino per cosmic ray observed


collide cosmic rays of GRB origin with fireball and microwave photons
$p+\gamma \rightarrow n+\pi^+$ and $p+\pi^0$
cosmic rays from n-decay
$E^3 J$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
10^3
10^2
10
10^9
10^{10}
10^{11}
E [GeV]


GRB origin of cosmic rays challenged
Fermi-LAT
γ
IC-40 90%C.L.
source ν
GZK ν
π+ neutrinos
π0 gamma rays after cascading in the microwave background
E² J [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0.1
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

Search for GRB in coincidence with FERMI and SWIFT alerts

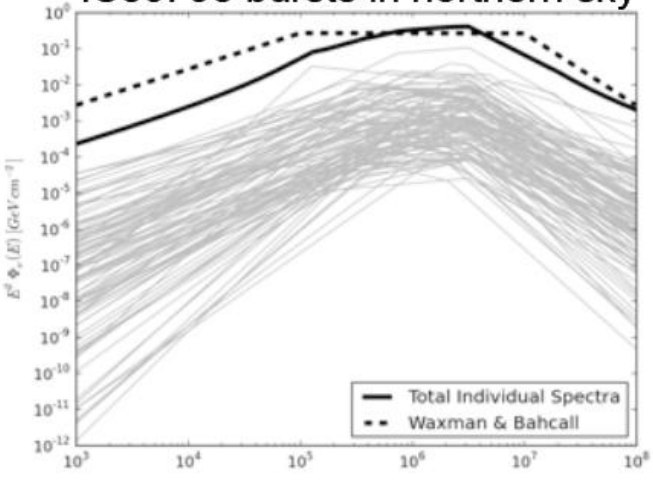
- Using satellite information (time and direction, GCN)

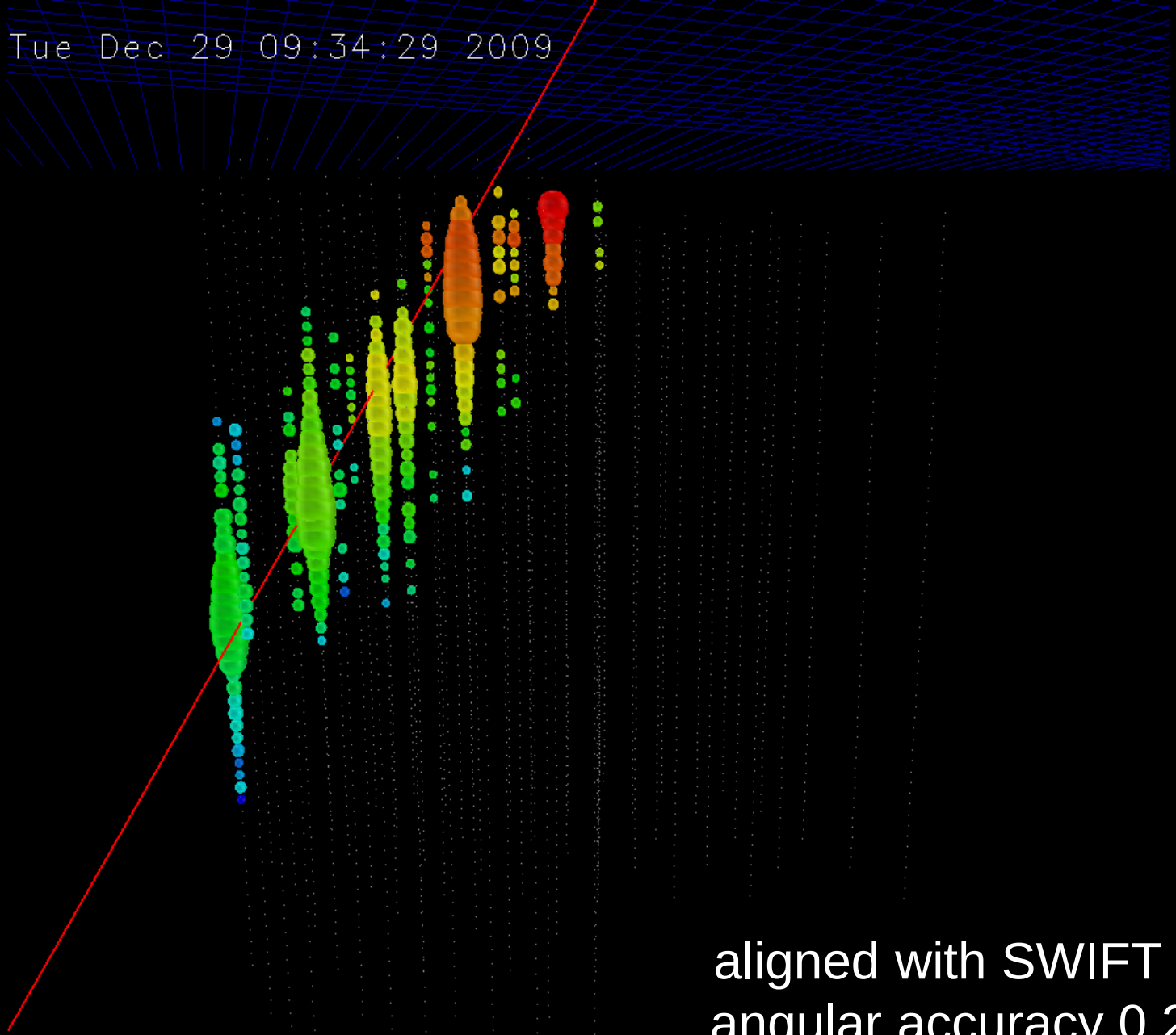


very low background → 1 event can be significant !

- 98 bursts (northern sky) observed with IceCube 59 strings
- Individual modeling of neutrino fluxes (fireball model)

IC59: 98 bursts in northern sky

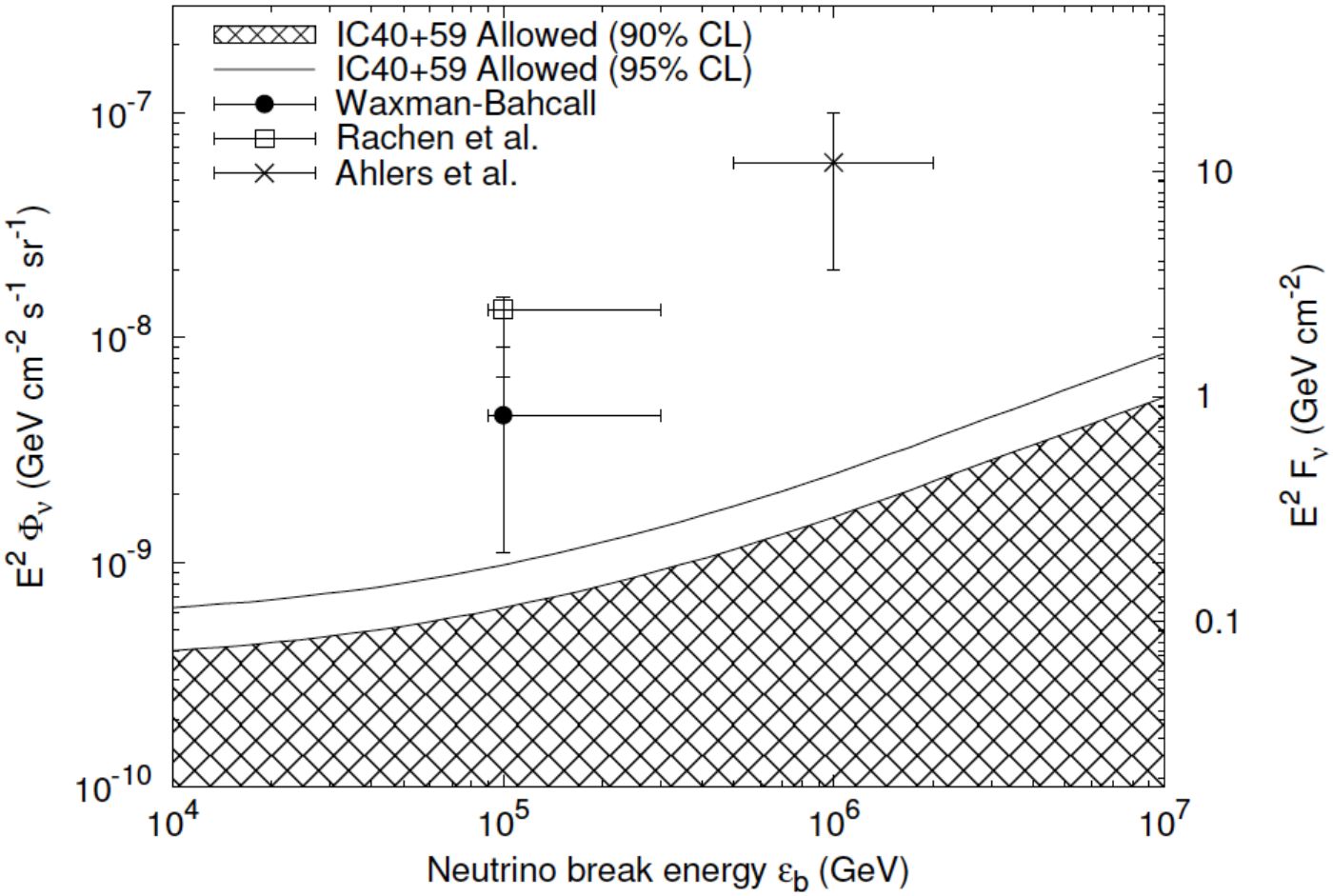


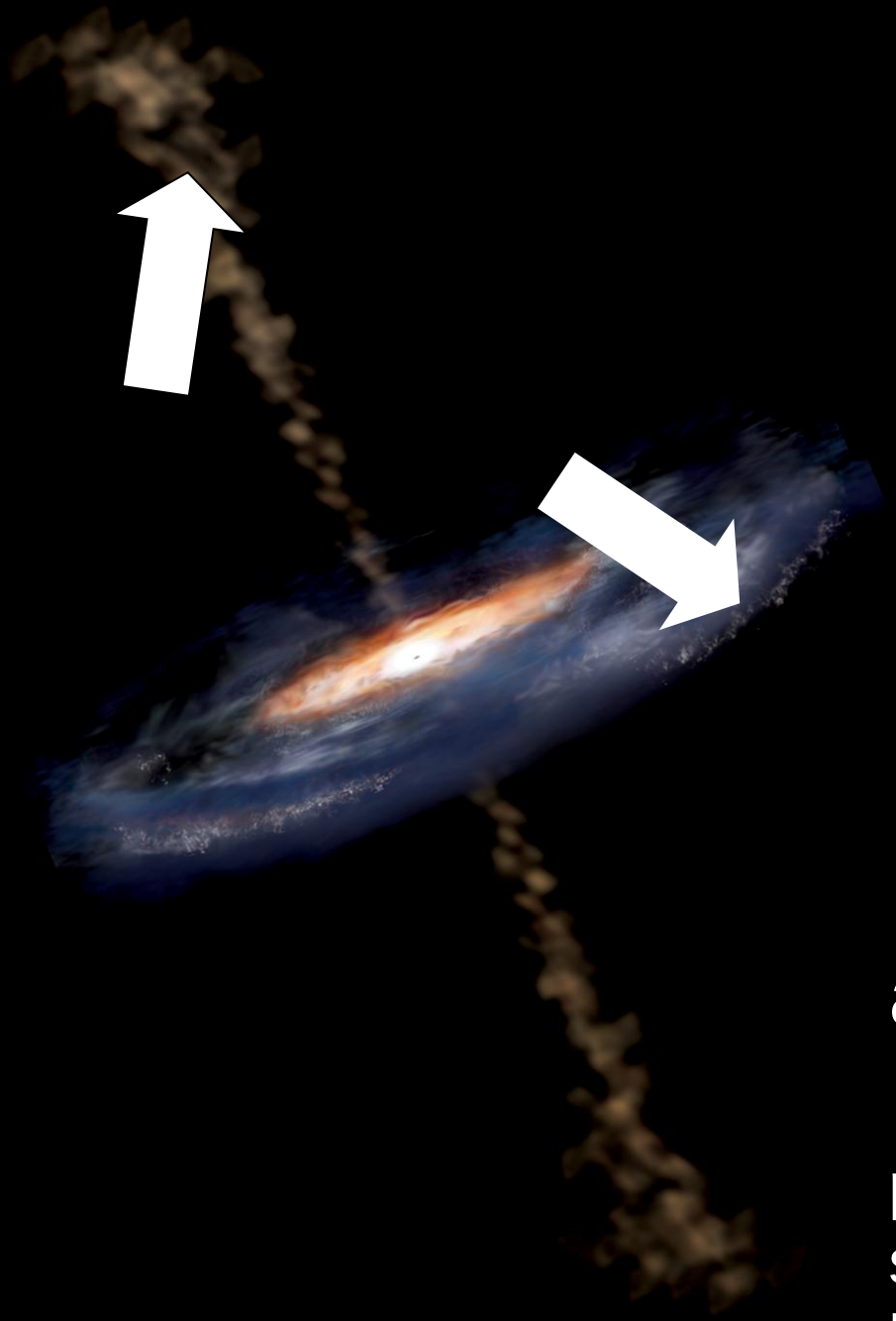


aligned with SWIFT GRB
angular accuracy 0.2 deg
energy 109 TeV

GRB on probation

Model	Predicted ν	Fractional Upper Limit
Reference Fireball (CR-normalized)	$\gtrsim 84$	0.04
Waxman 2003 (CR-normalized)	27	0.11
Guetta et al. (γ-normalized)	14	0.21

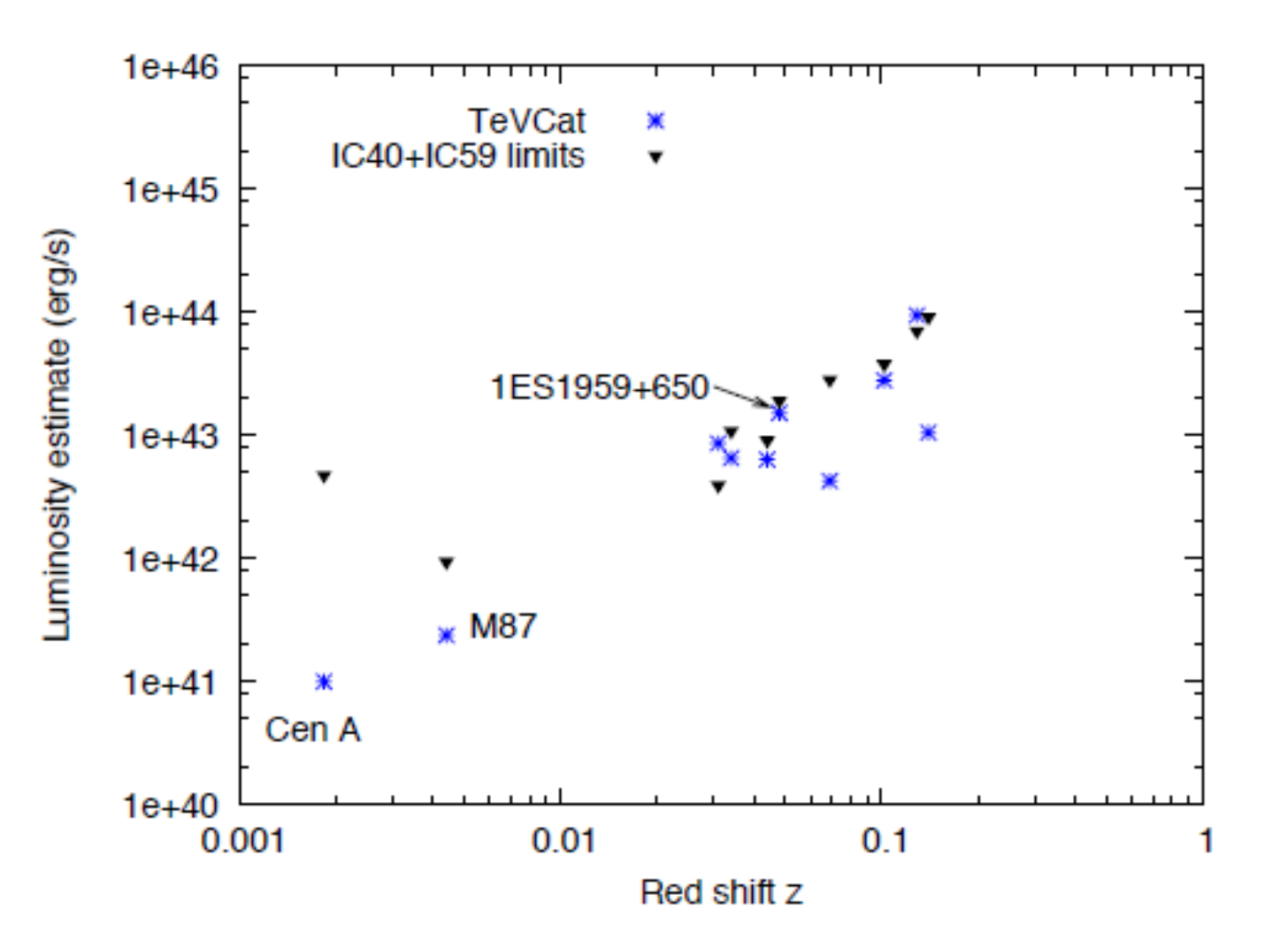




active galaxy

particle flows near supermassive black hole

with 59 strings IceCube limits matched TeV photon flux



this is also the case for Galactic supernova remnants

cosmic rays interact with the microwave background

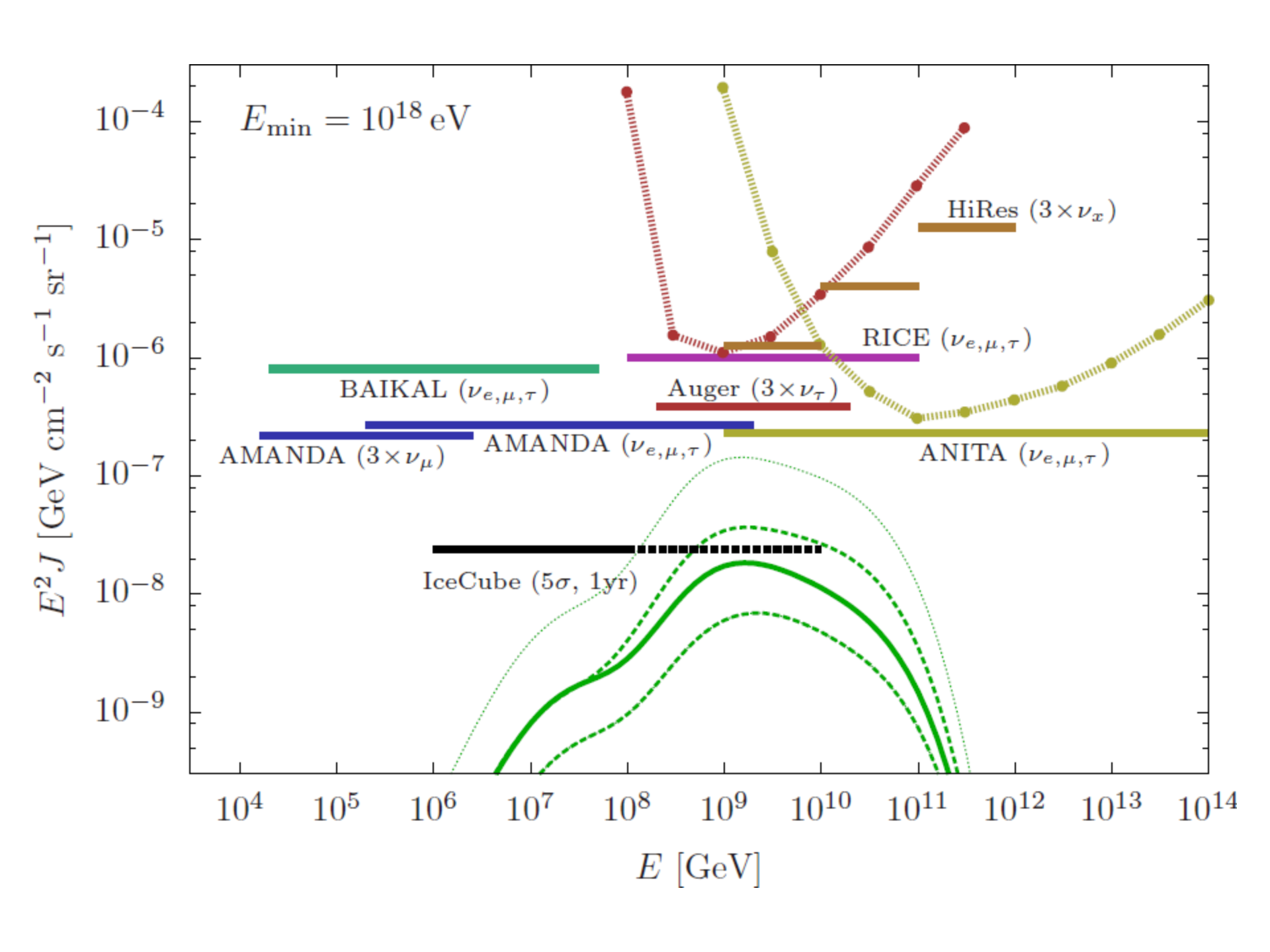
$$p + \gamma \rightarrow n + \pi^{+} \ and \ \ p + \pi^{0}$$

cosmic rays disappear, neutrinos appear

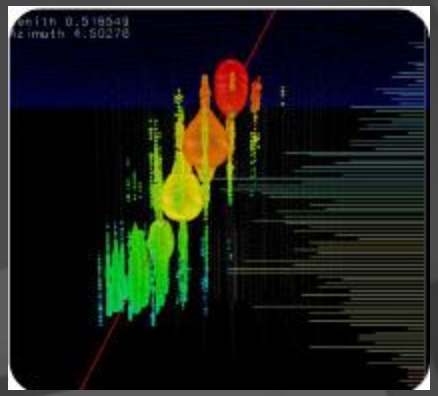
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

$$E_{\upsilon} \geq 2 \times 10^{6} TeV$$

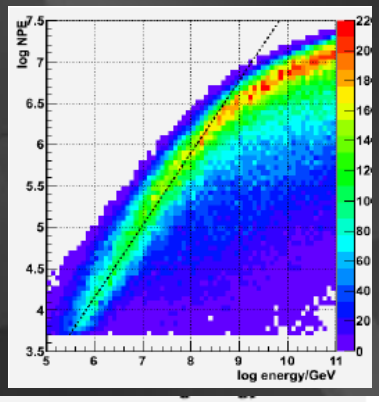
~1 event per cubed kilometer per year


$E_{\rm min} = 10^{18}\,{\rm eV}$
HiRes $(3\times\nu_x)$
RICE $(\nu_{e,\mu,\tau})$
BAIKAL $(\nu_{e,\mu,\tau})$
Auger $(3\times\nu_\tau)$
AMANDA $(3\times\nu_\mu)$
AMANDA $(\nu_{e,\mu,\tau})$
ANITA $(\nu_{e,\mu,\tau})$
IceCube $(5\sigma,\,1{\rm yr})$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

GZK neutrinos: > 41,000 photons near the horizon

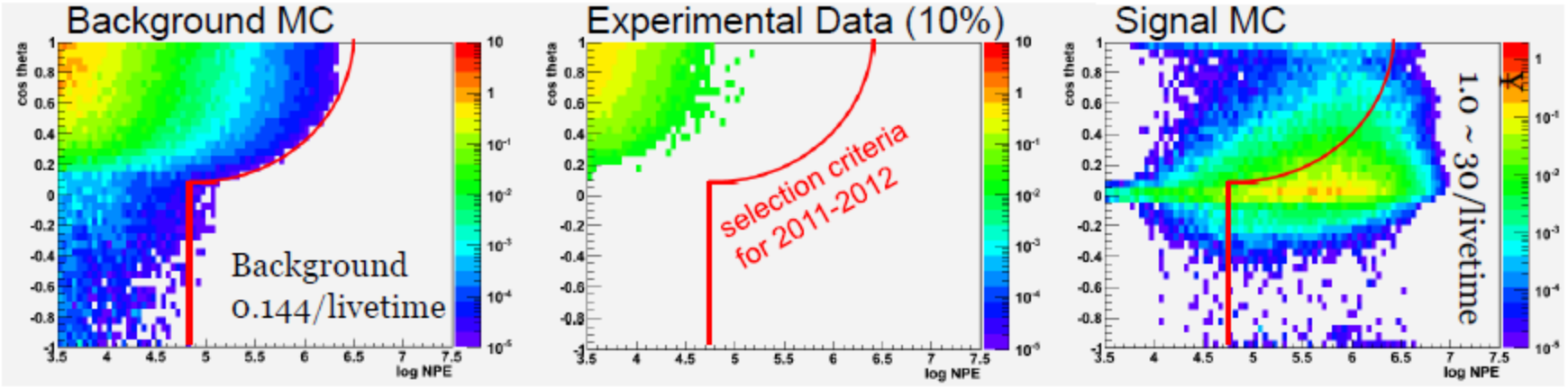


number of channels > 300

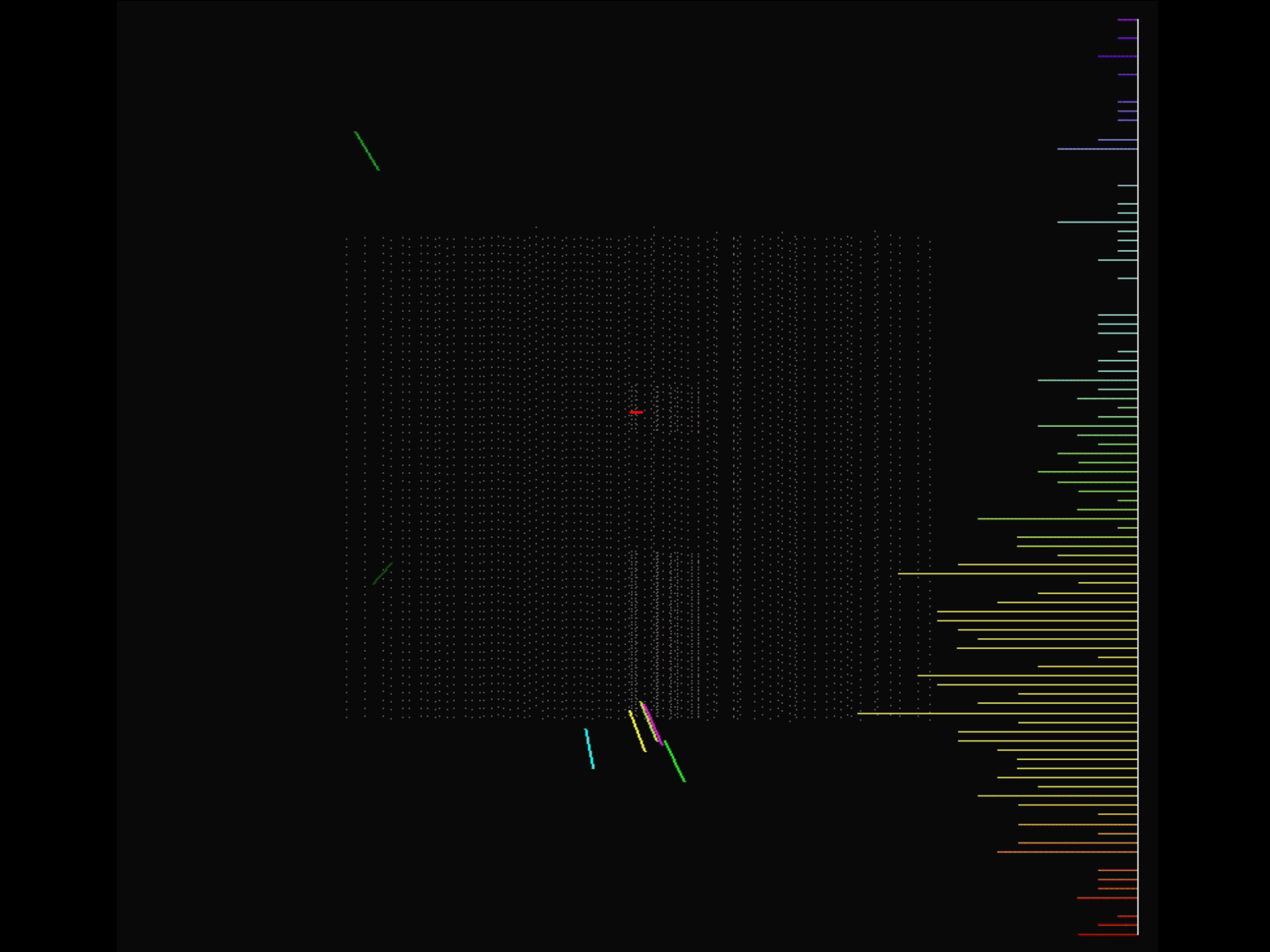


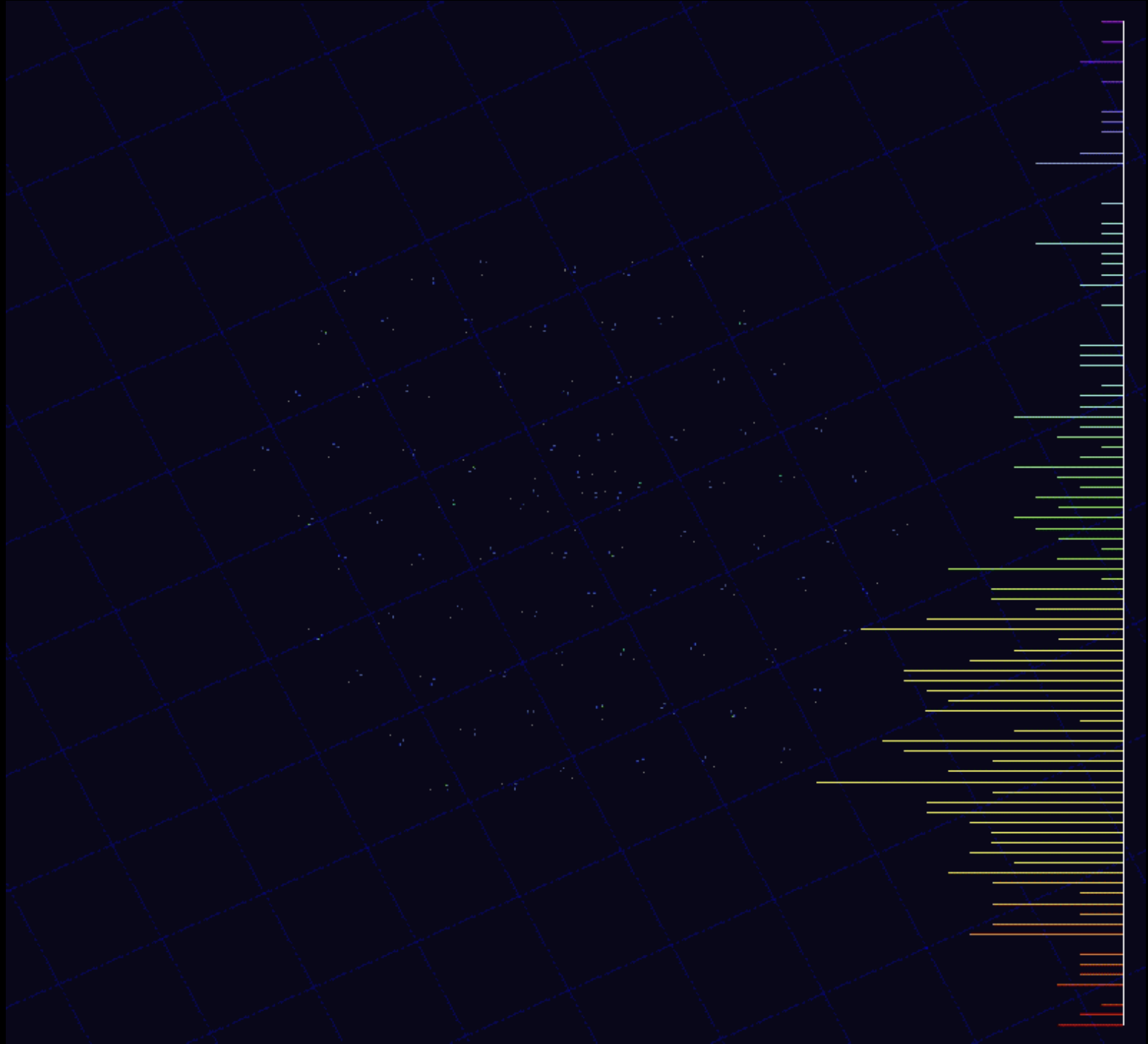
Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

- Optimization based MC and MC verification based on 10% experimental 'burn' sample

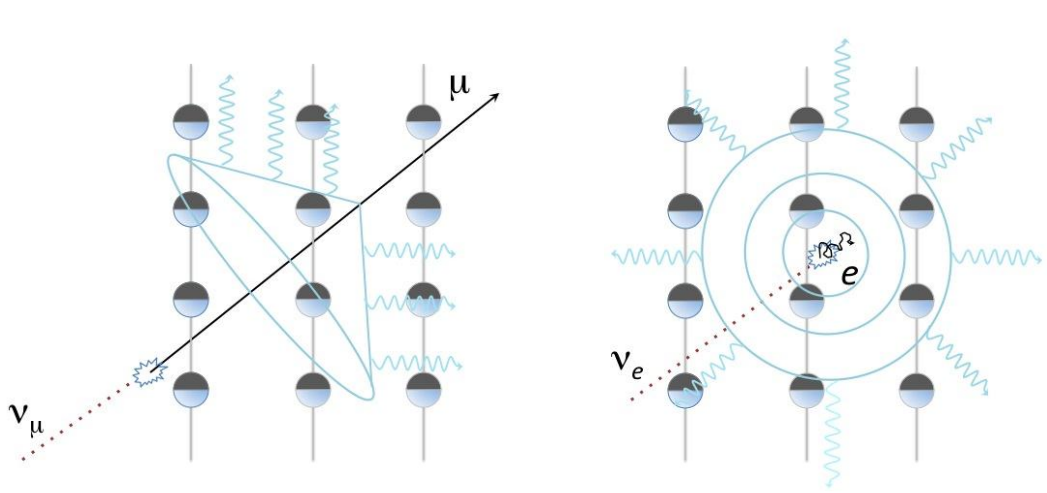


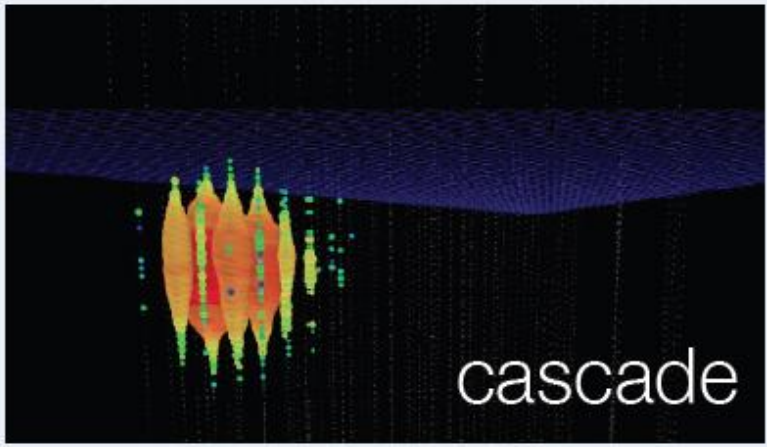
unblinding: 2 events in the signal region

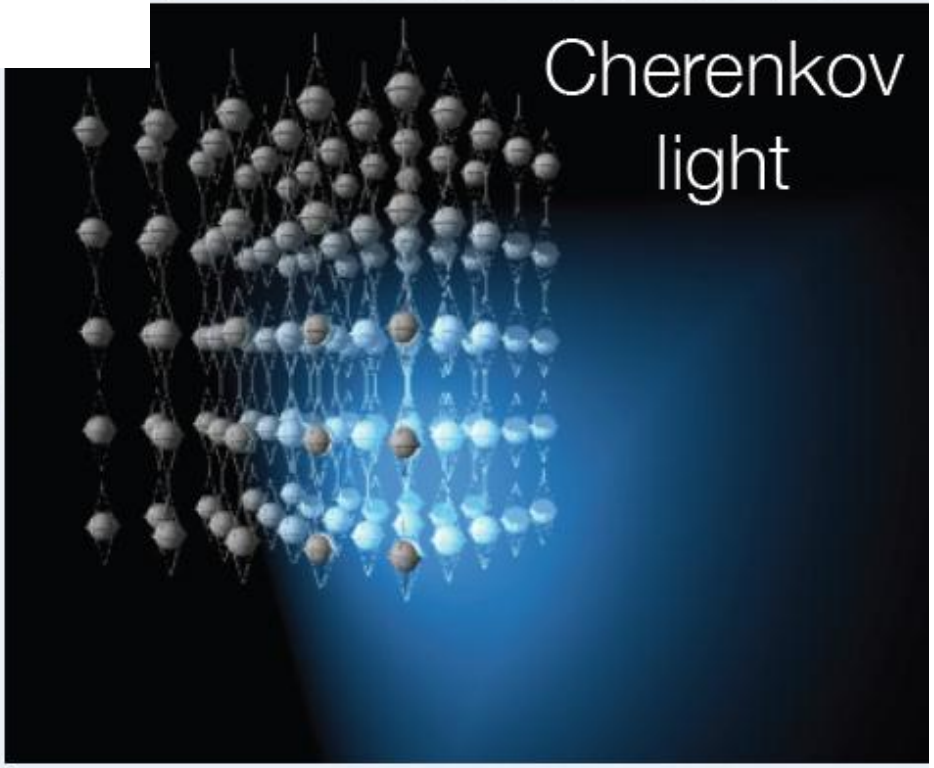


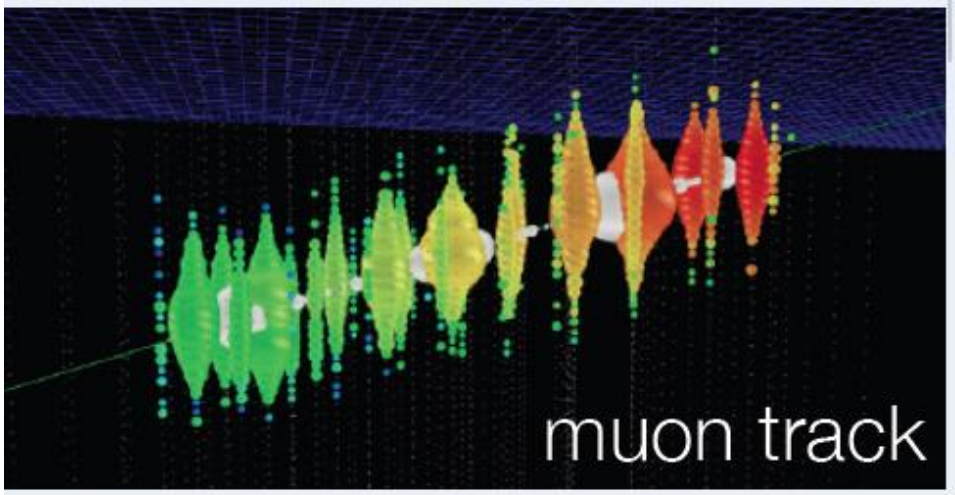


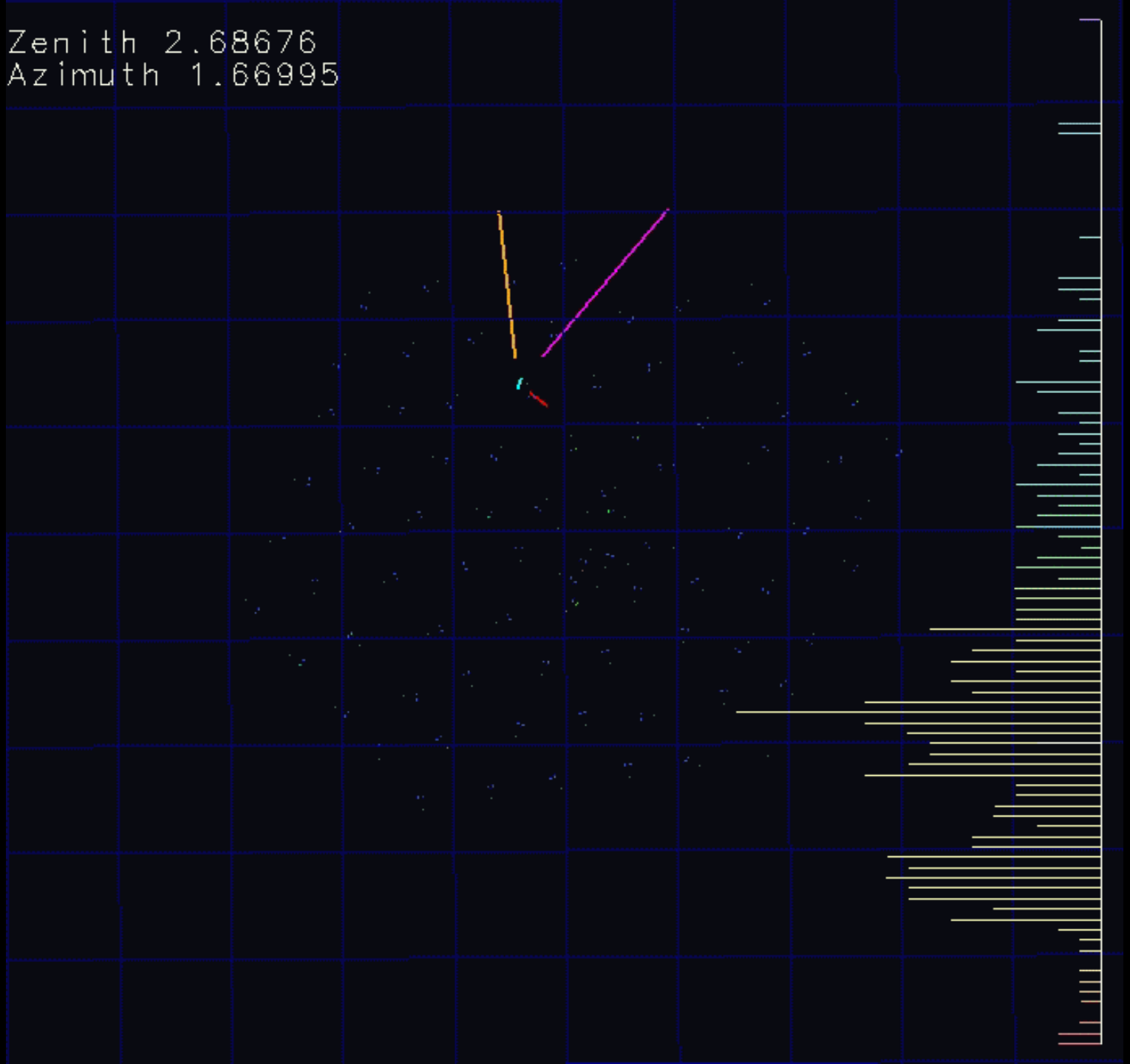
tracks and showers

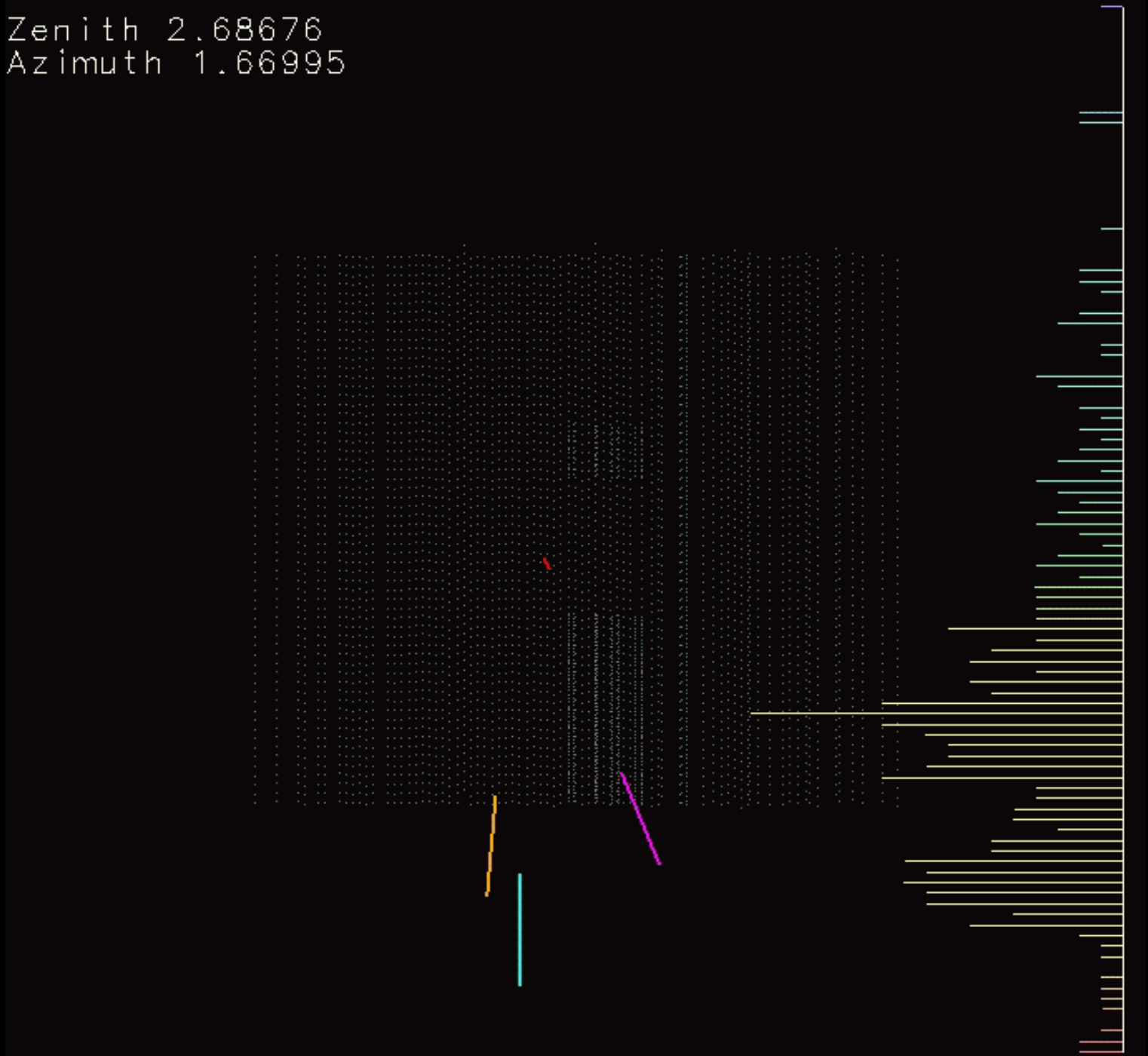









Zenith 2.68676
Azimuth 1.66995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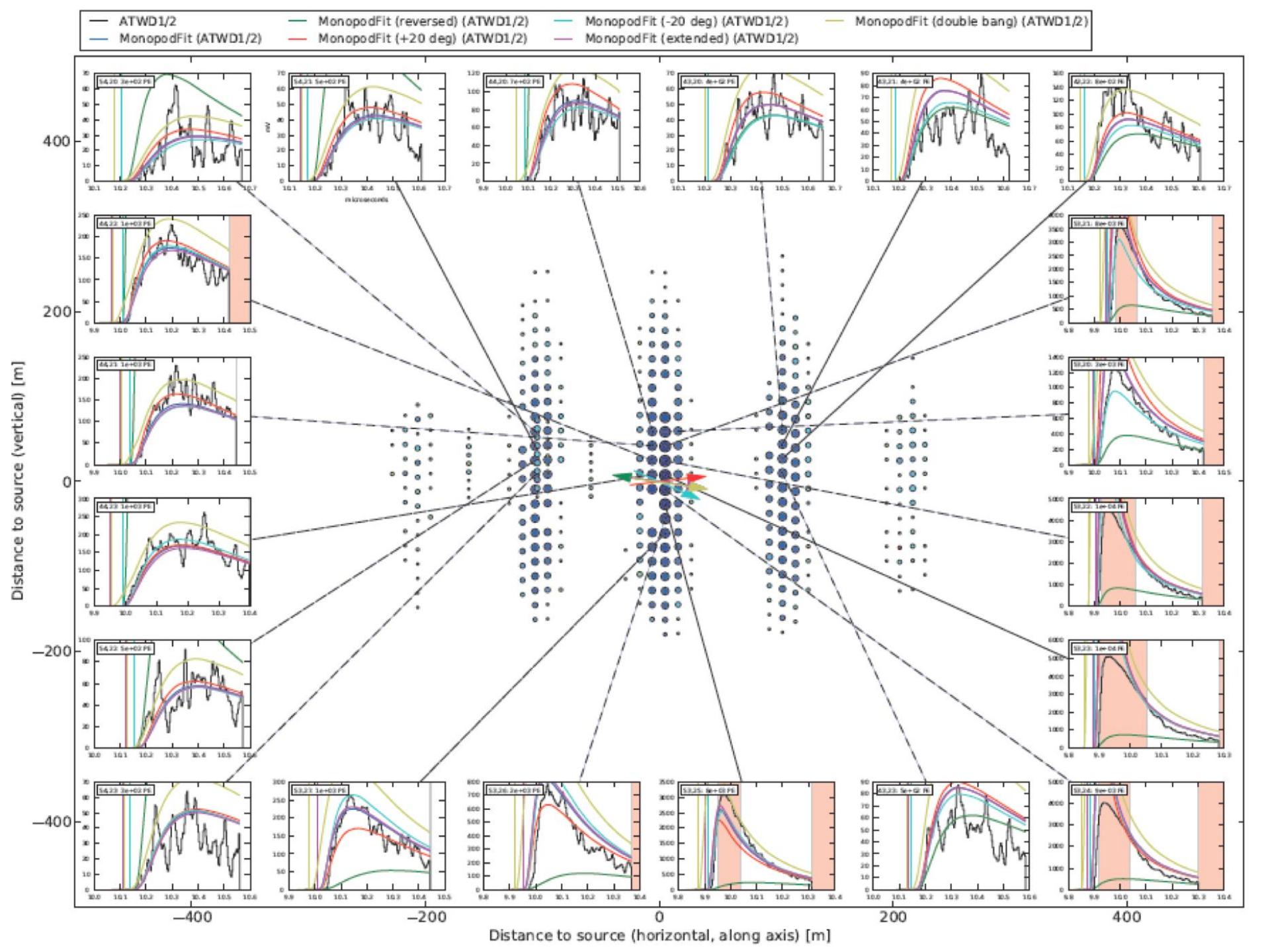
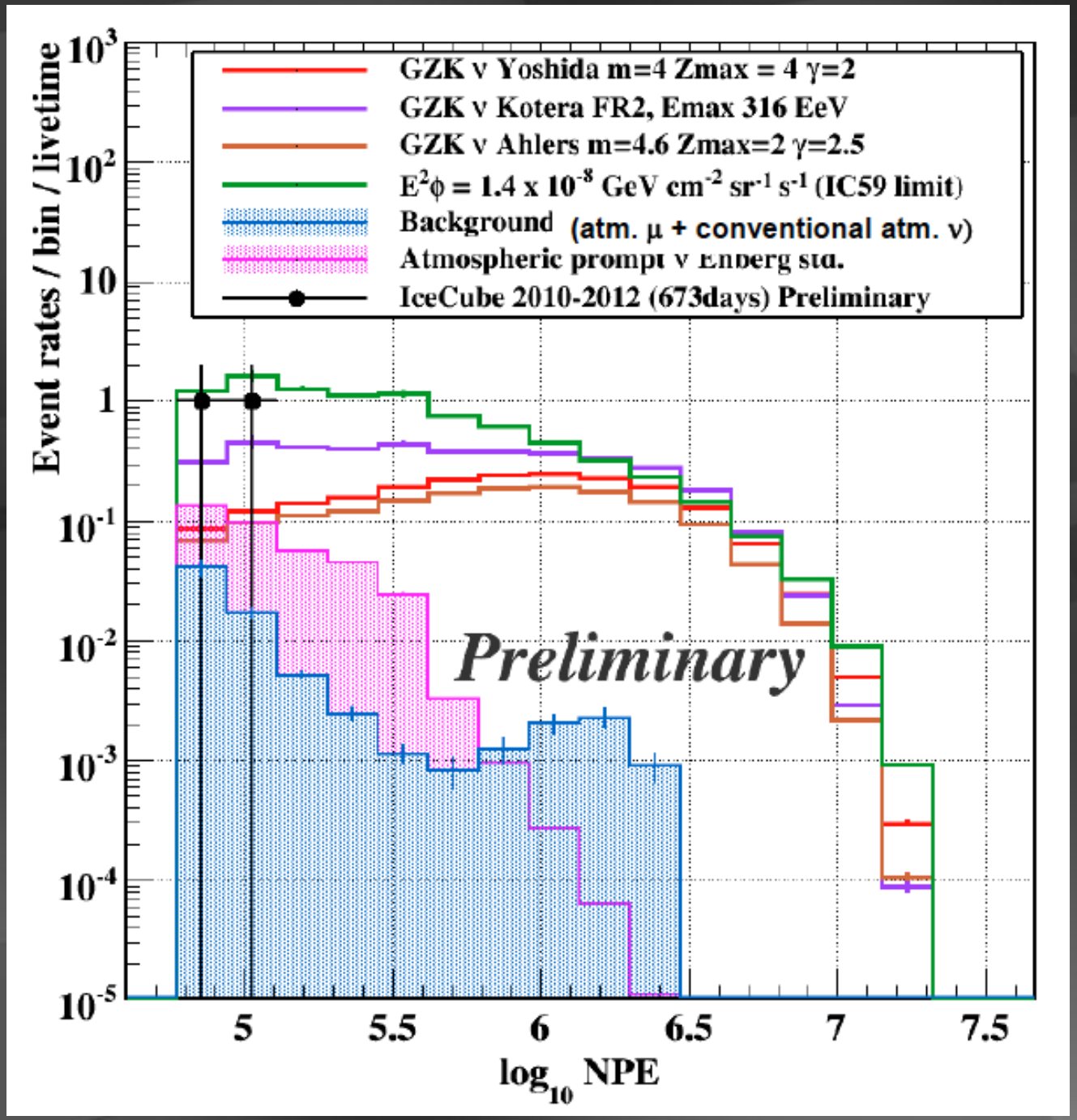

ATWD1/2
MonopodFit (ATWD1/2)
MonopodFit (reversed) (ATWD1/2)
MonopodFit (+20 deg) (ATWD1/2)
MonopodFit (-20 deg) (ATWD1/2)
MonopodFit (extended) (ATWD1/2)
MonopodFit (double bang) (ATWD1/2)
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400



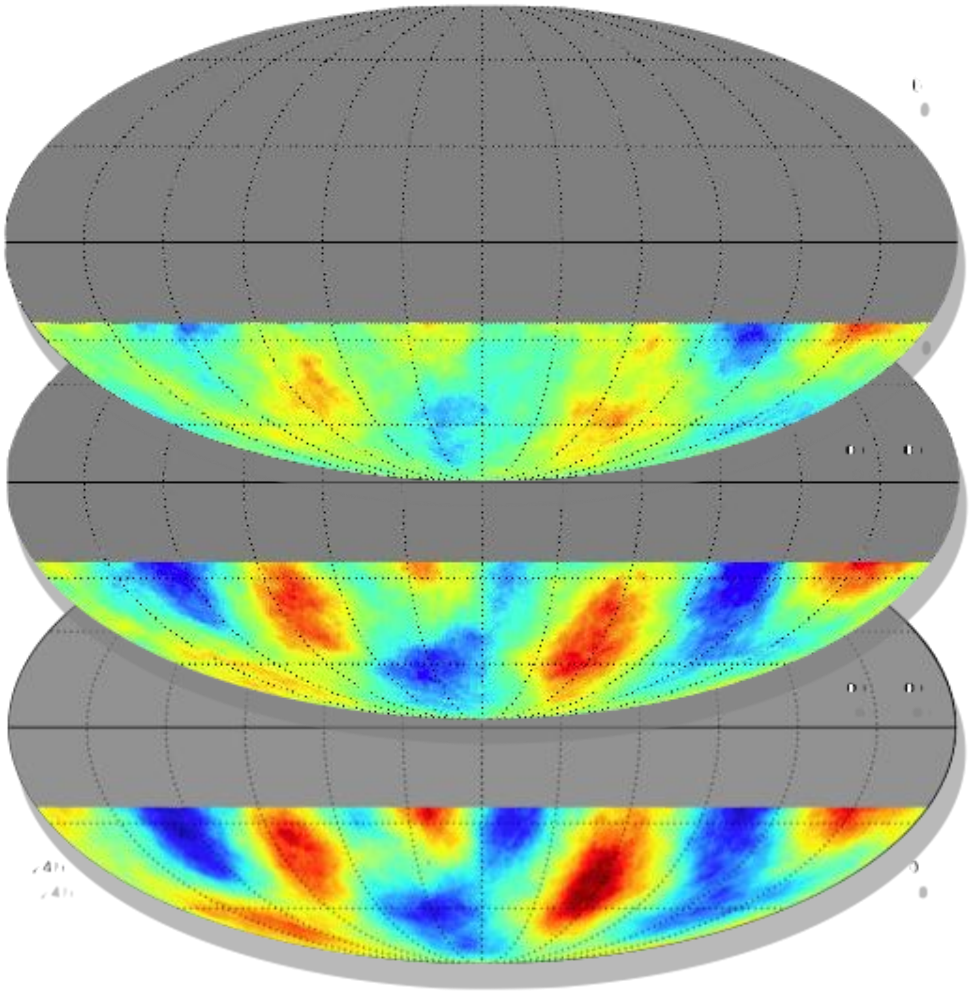
- PeV energy
- cascade
- downgoing
- not atmospheric

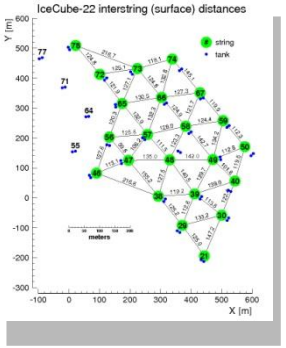
→ flux at present level of diffuse limit

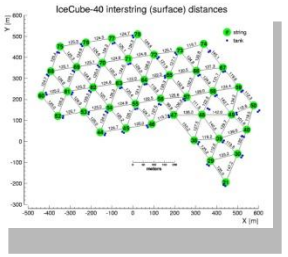
→ largest bkgd: atmospheric charm
< 0.2 events

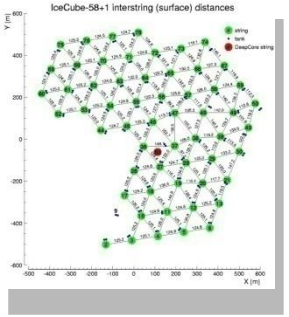
muon astronomy

IC22 and IC40 : muon astronomy (!)

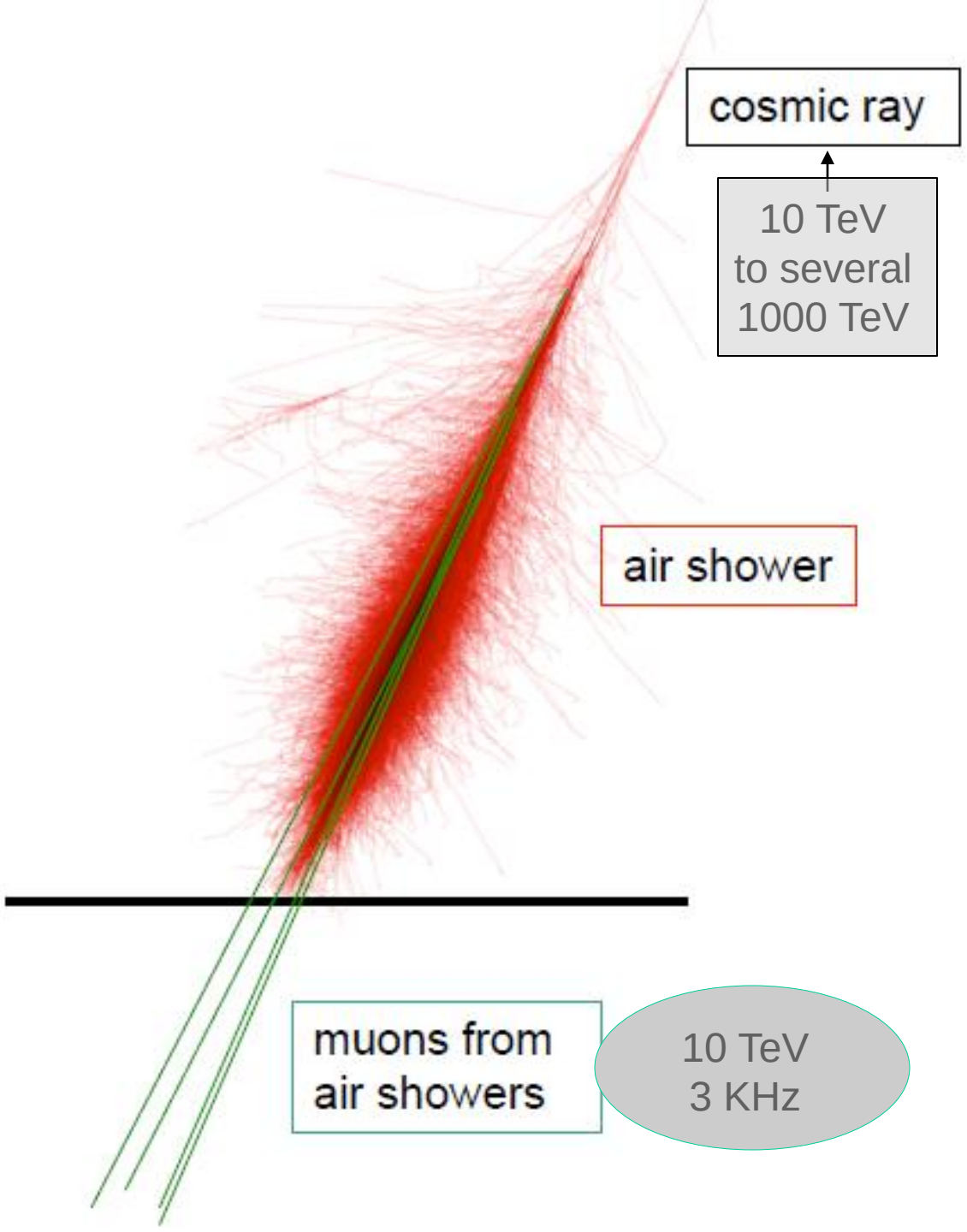








Different geometries, same structure



cosmic rays in IceCube

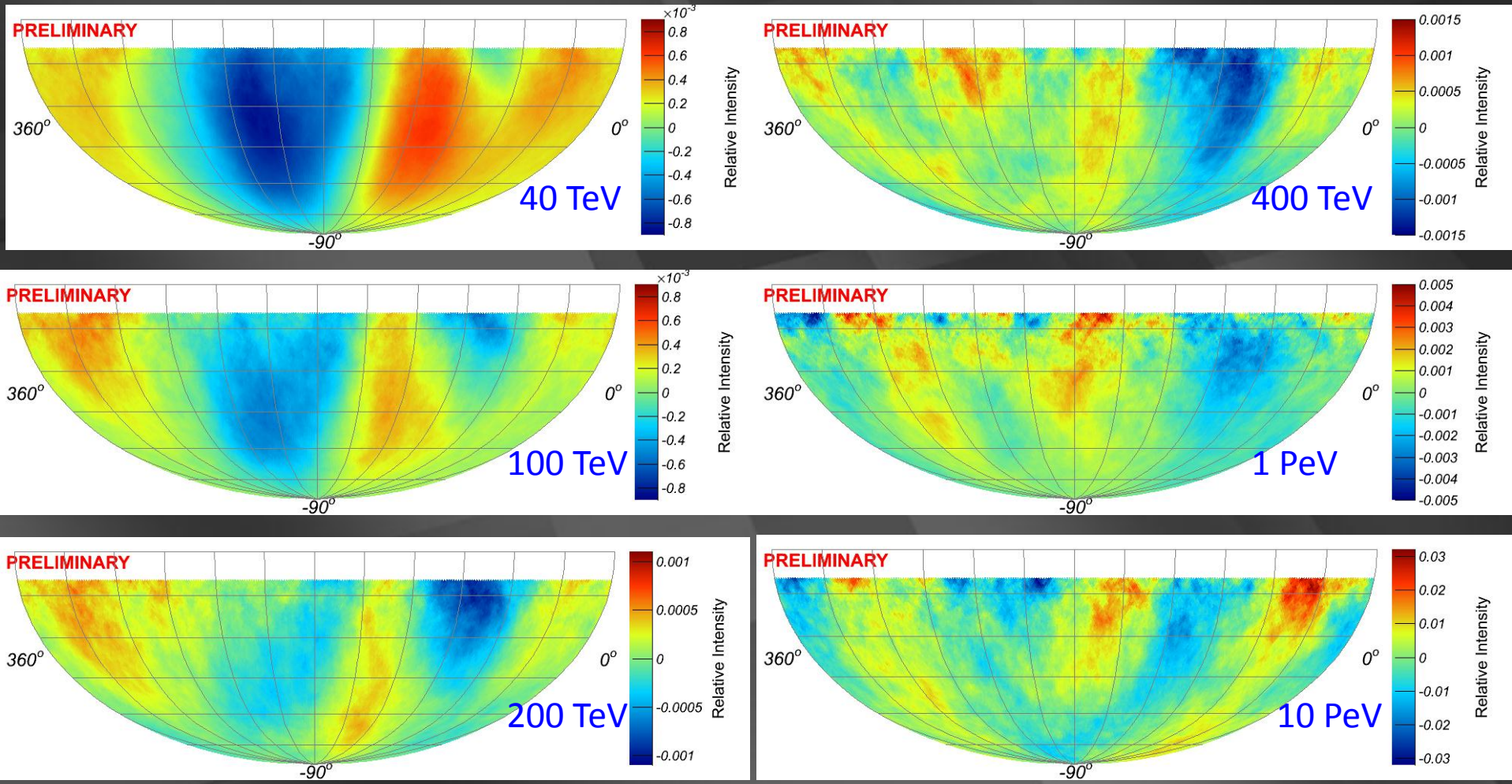
- we map the highest energy Galactic cosmic rays, but…
- their gyroradius is < 1 pc in microgauss magnetic field
- closest sources > 100 pc

should not point!

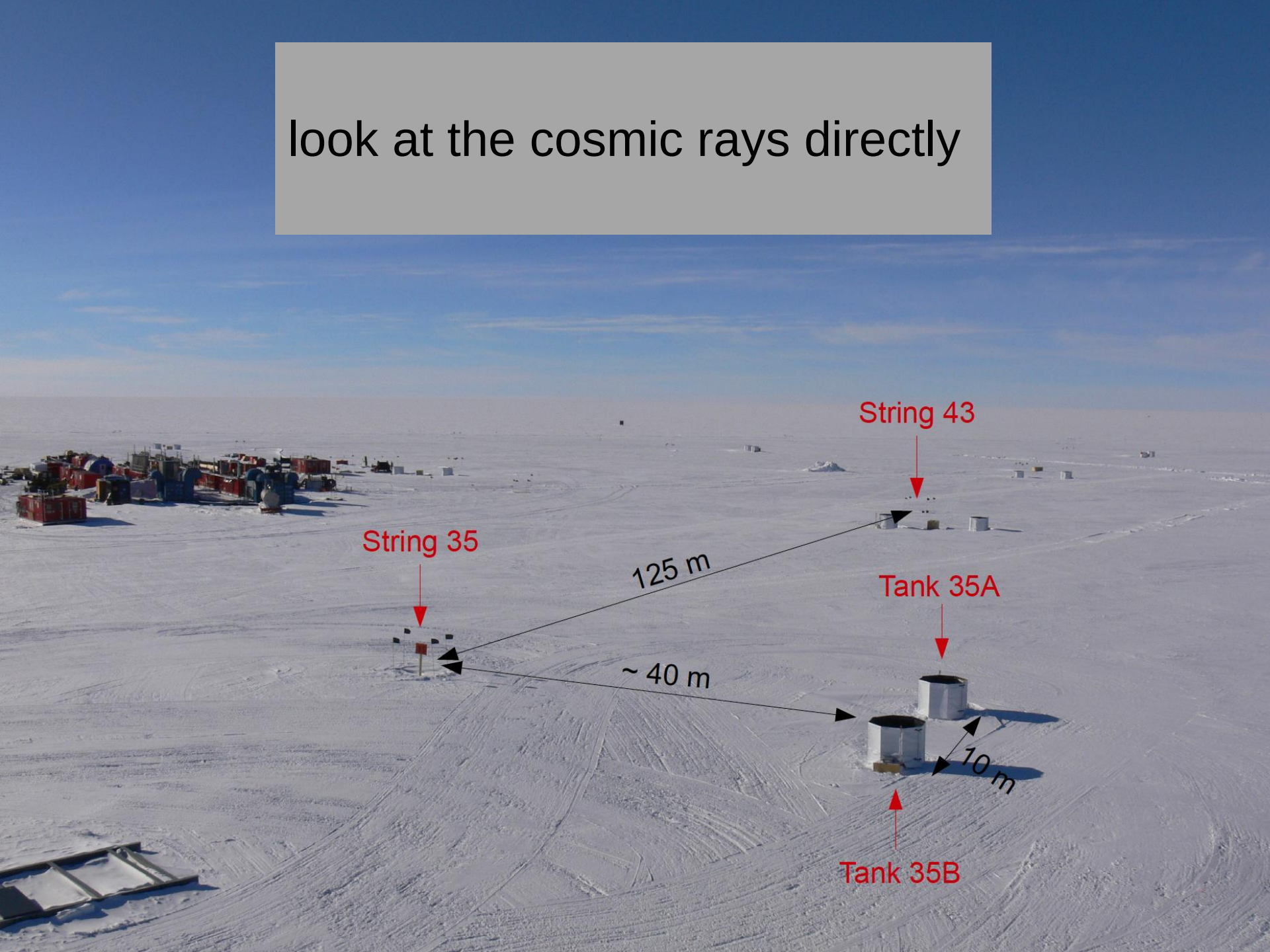
→ that's why we look for neutrinos!

IceCube 79 → energy dependence of anisotropy

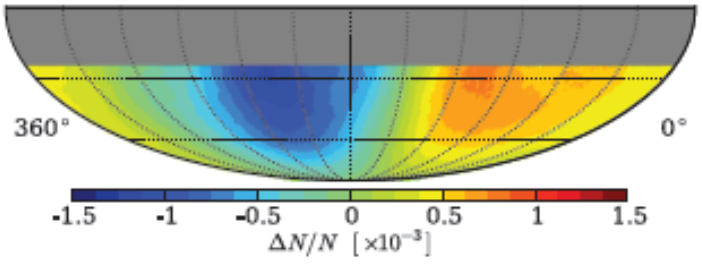
- non-diffusive effects in propagation of the particles?
- nearby supernova remnant(s)?

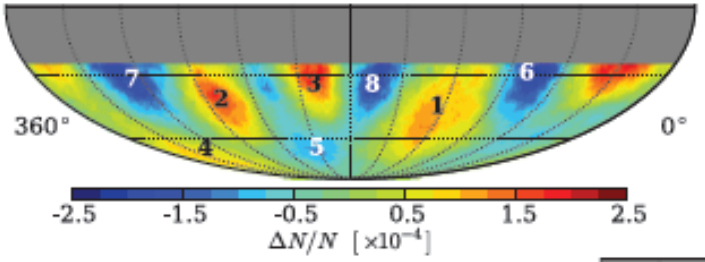


look at the cosmic rays directly



20 TeV

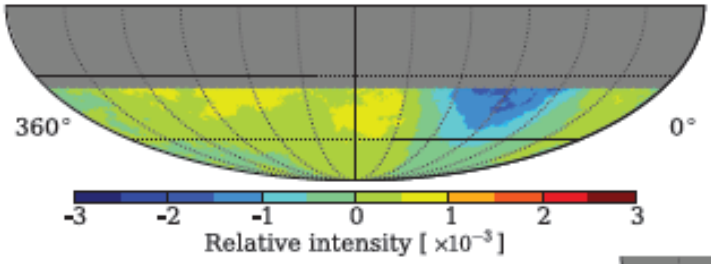




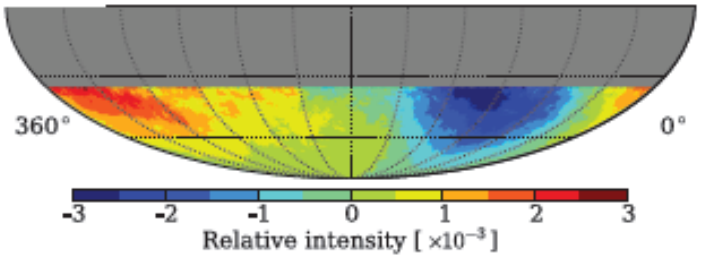
- Anisotropy changes in phase and amplitude with energy.

energy

400 TeV

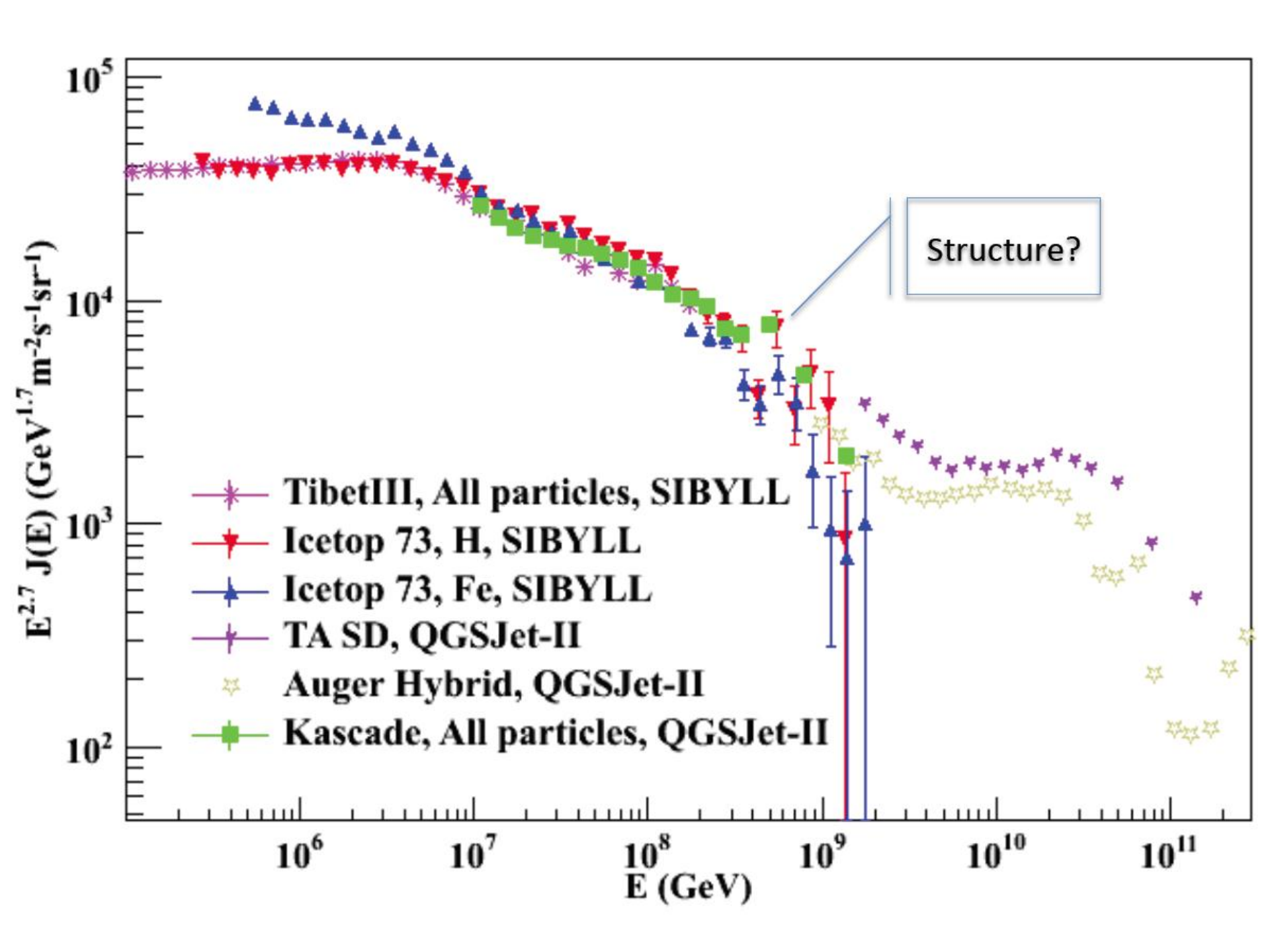


2 PeV



IceCube
ApJ 718 (2010) L194
ApJ 740 (2012) 16

IceCube/IceTop
ApJ 746 (2012) 33

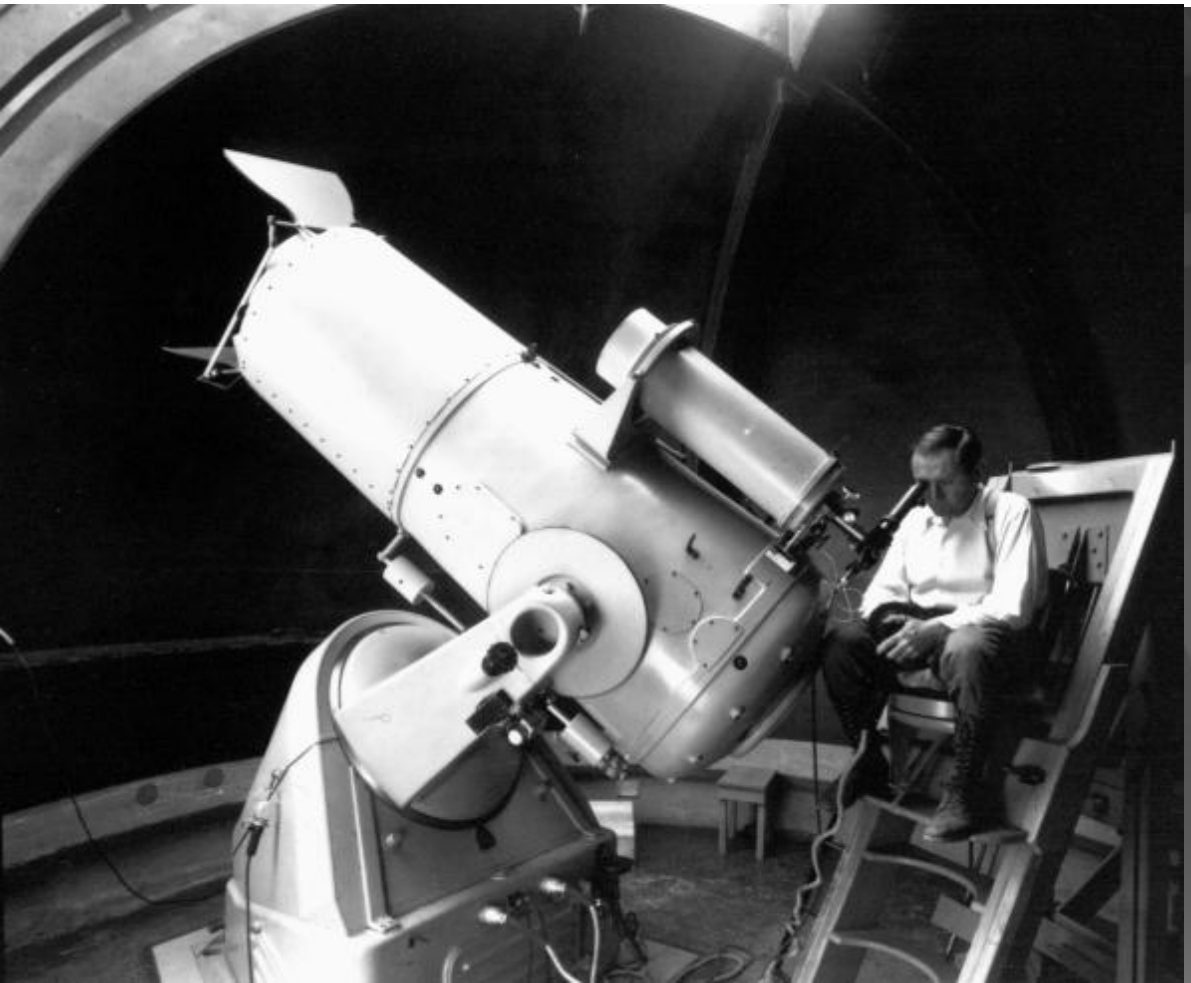

Structure?
TibetIII, All particles, SIBYLL
Icetop 73, H, SIBYLL
Icetop 73, Fe, SIBYLL
TA SD, QGSJet-II
Auger Hybrid, QGSJet-II
Kascade, All particles, QGSJet-II
$E^{2.7}$ J(E) ($GeV^{1.7} m^{-2} s^{-1} sr^{-1}$)
E (GeV)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

ON SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934



conclusions

- Hess 1912…. and still no conclusion
- the instrumentation is in place …
- … supernova remnants, cosmogenic ν and GRB are in very close range !
- first 86-string unblinding: two >PeV events

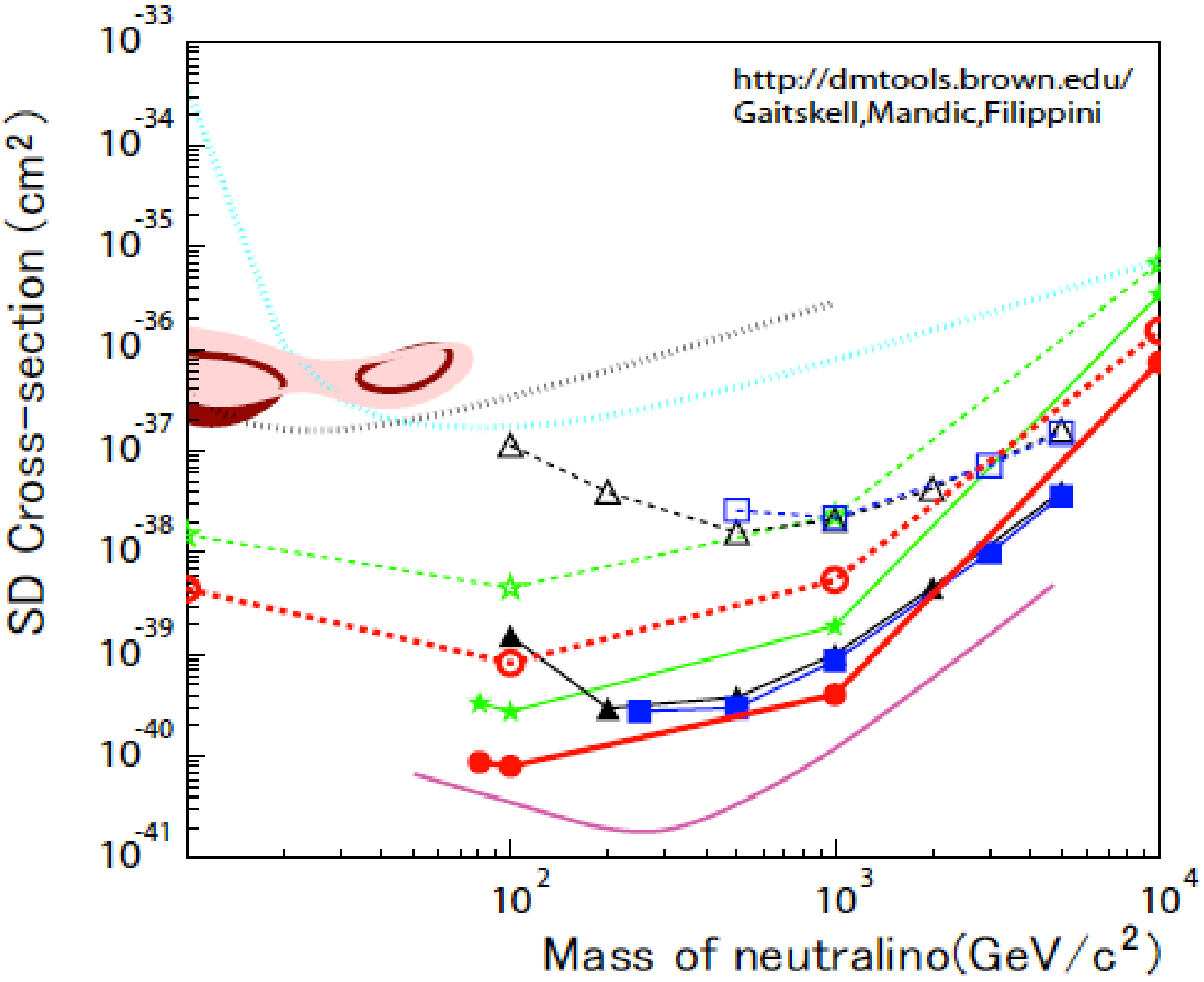
The IceCube Collaboration

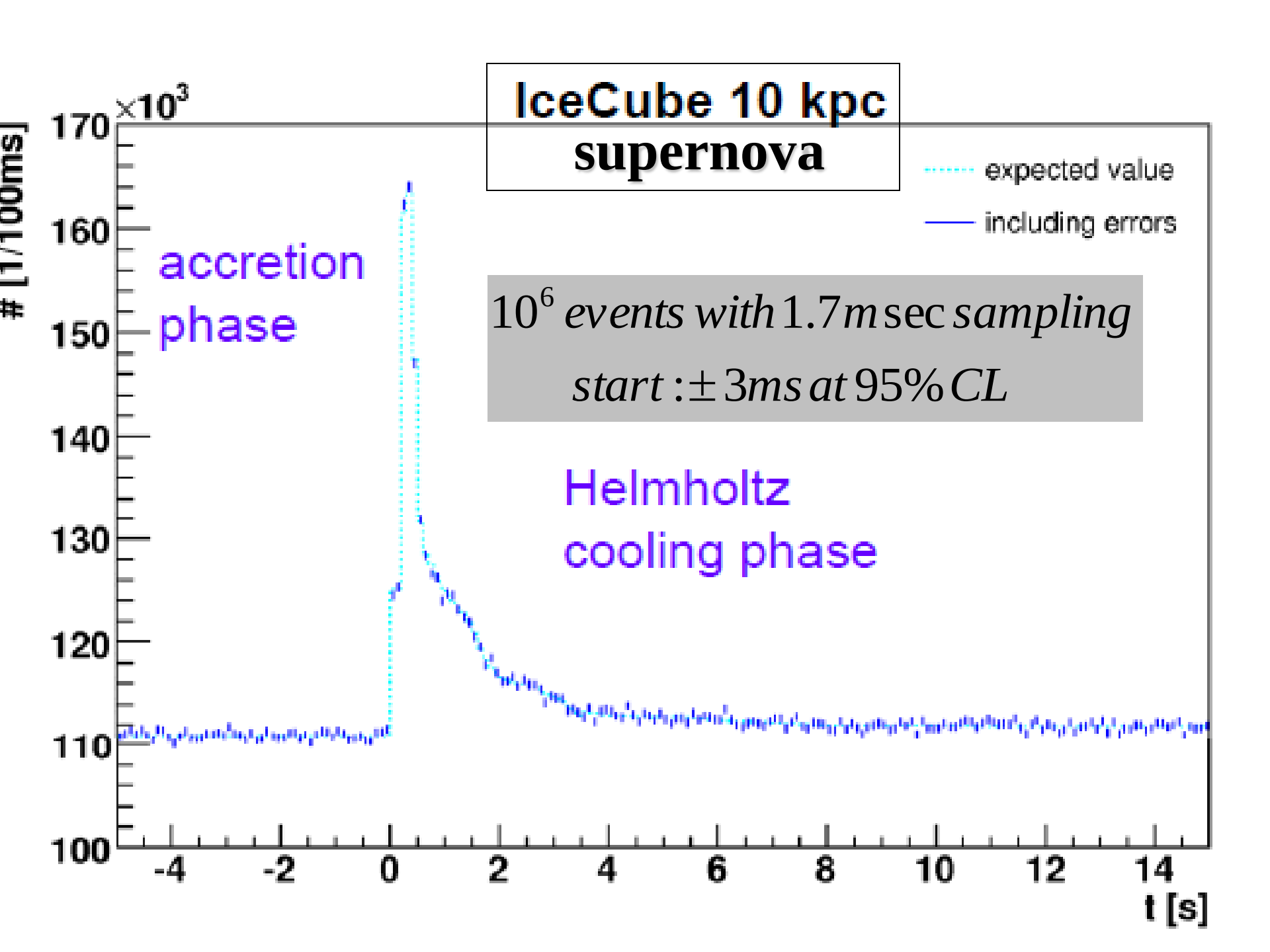
39 Institutions
~220 collaborators

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)
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)

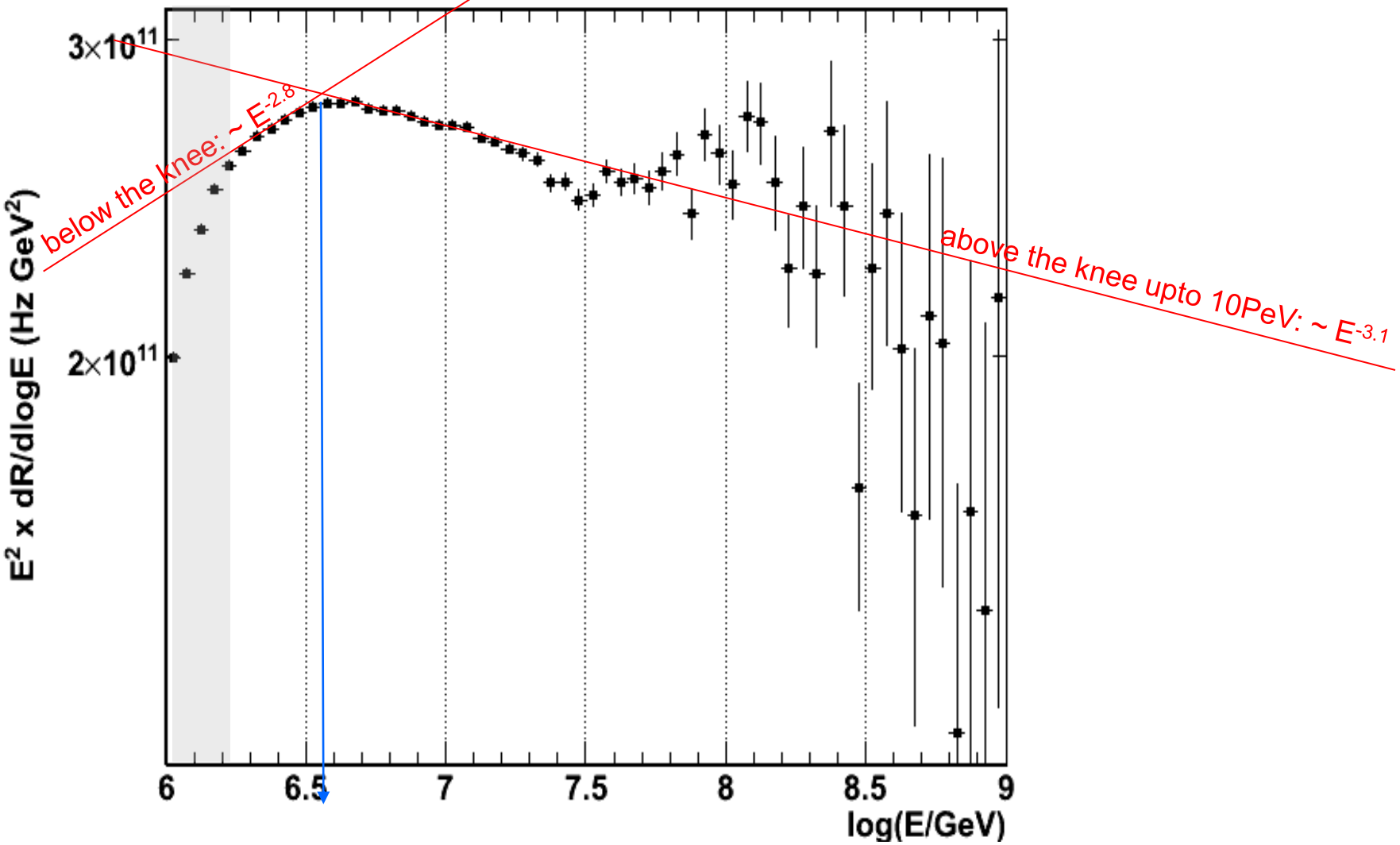

AMANDA
DESY 1995


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
SD Cross−section (cm²)
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10²
10³
10⁴
Mass of neutralino(GeV/c²)


IceCube 10 kpc
supernova
expected value
including errors
accretion
phase
10^6 events with 1.7msec sampling
start : ± 3ms at 95% CL
Helmholtz
cooling phase
[1/100ms]
×10^3
170
160
150
140
130
120
110
100
-4
-2
0
2
4
6
8
10
12
14
t [s]

11 months of IceTop-73 Data June 15 2010 – May 13 2011

nearby sources stick out at the end of the cosmic ray flux?



total flux = velocity x density

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

energy density is the key !

$$1\, TeV = 1.6\, erg$$

total flux = velocity x density

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

energy density is the key !

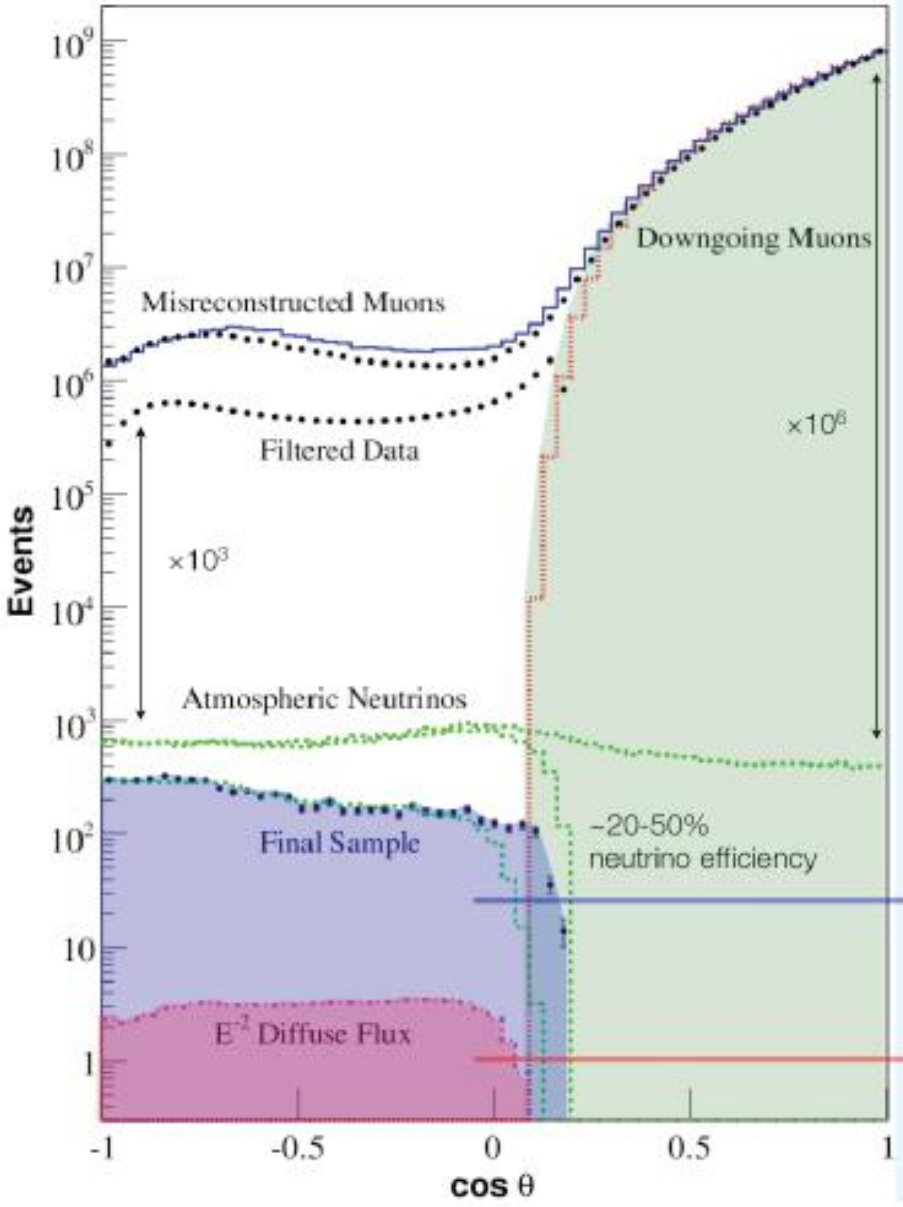
$$1\, TeV = 1.6\, erg$$

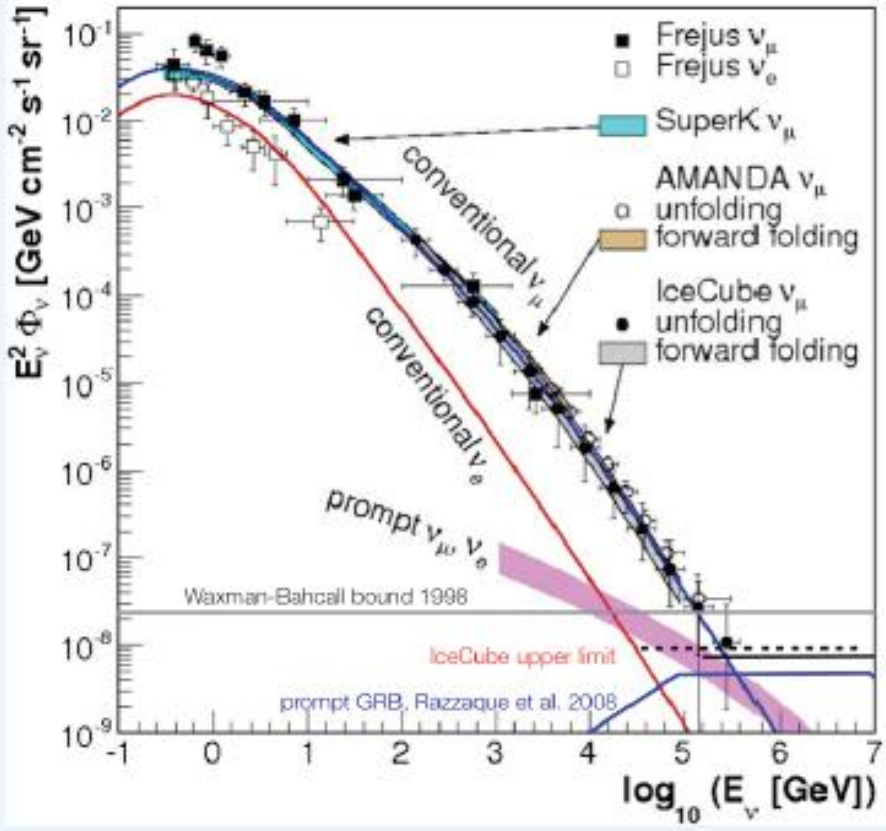
300 GRB per Gigaparsec^3 per year for 10^{10} years (Hubble time)

$$2\times10^{52} erg \times \frac{300}{Gpc^3\ yr} \times 10^{10}\ yr = 3\times10^{-19}\ \frac{erg}{cm^3}$$

- correct cosmology: same answer
- Fermi: photon (electron) energy less than this ?

$$1 Gpc^3 = 2.9\times10^{82} cm^3 \qquad Hubble\ time = 10^{10}\ years$$





atmospheric neutrinos

extra-terrestrial neutrinos