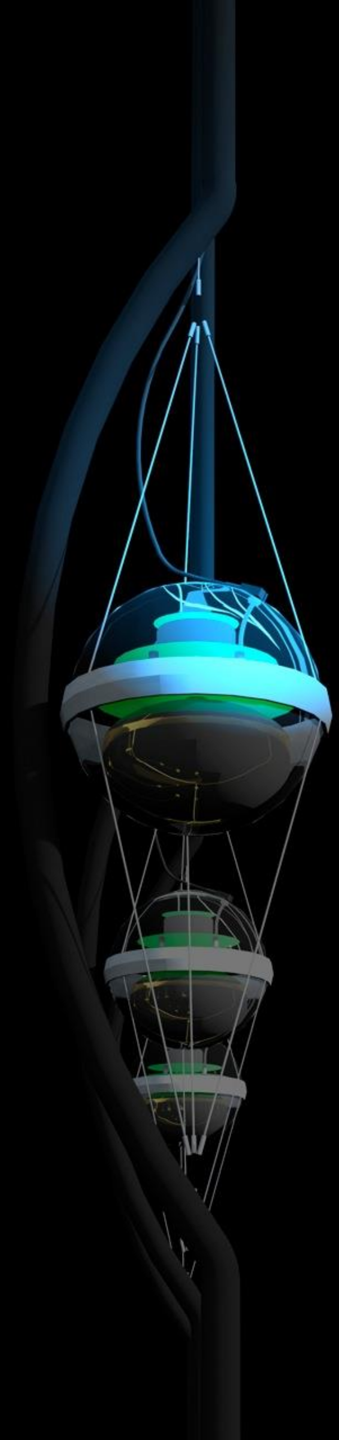
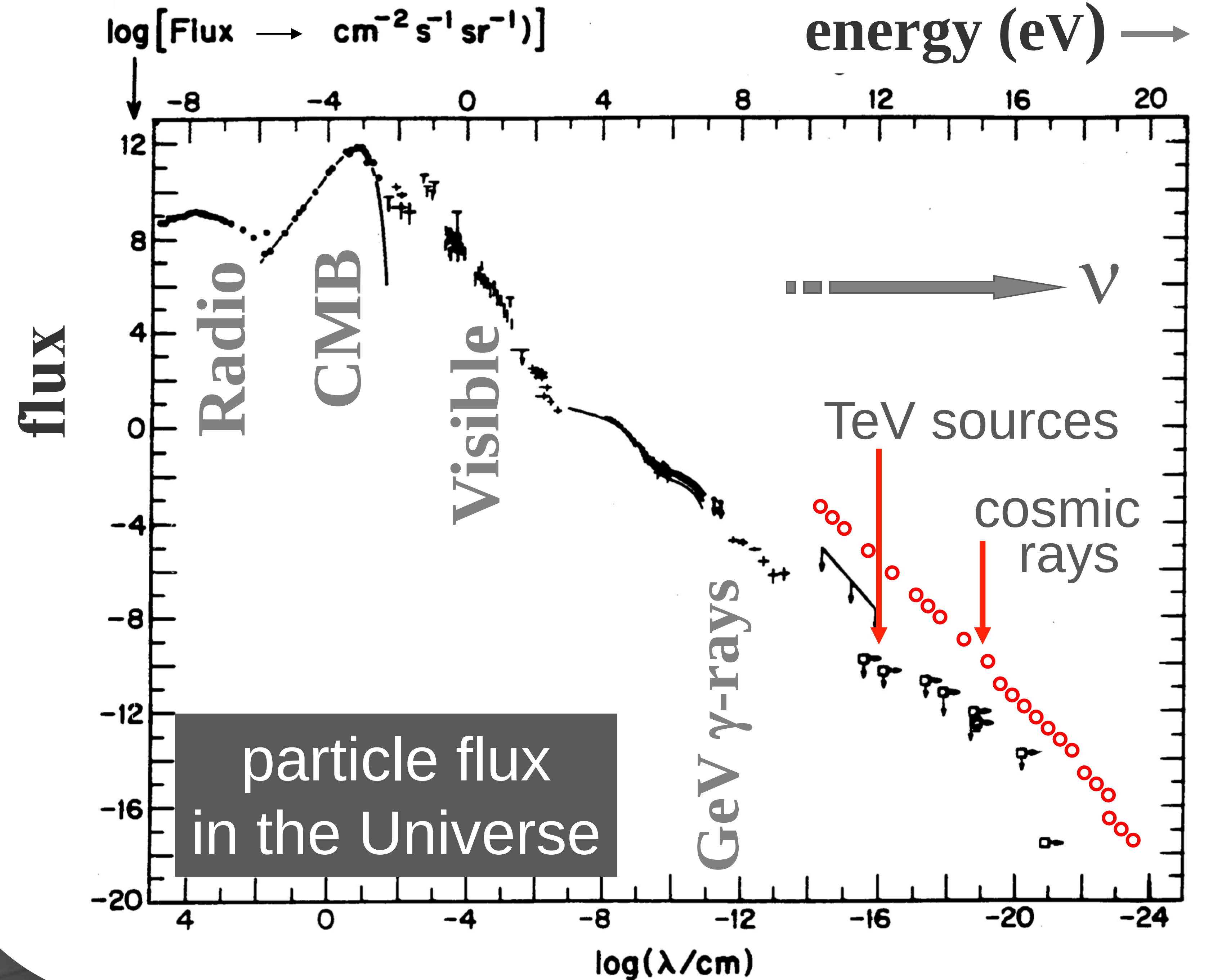


IceCube

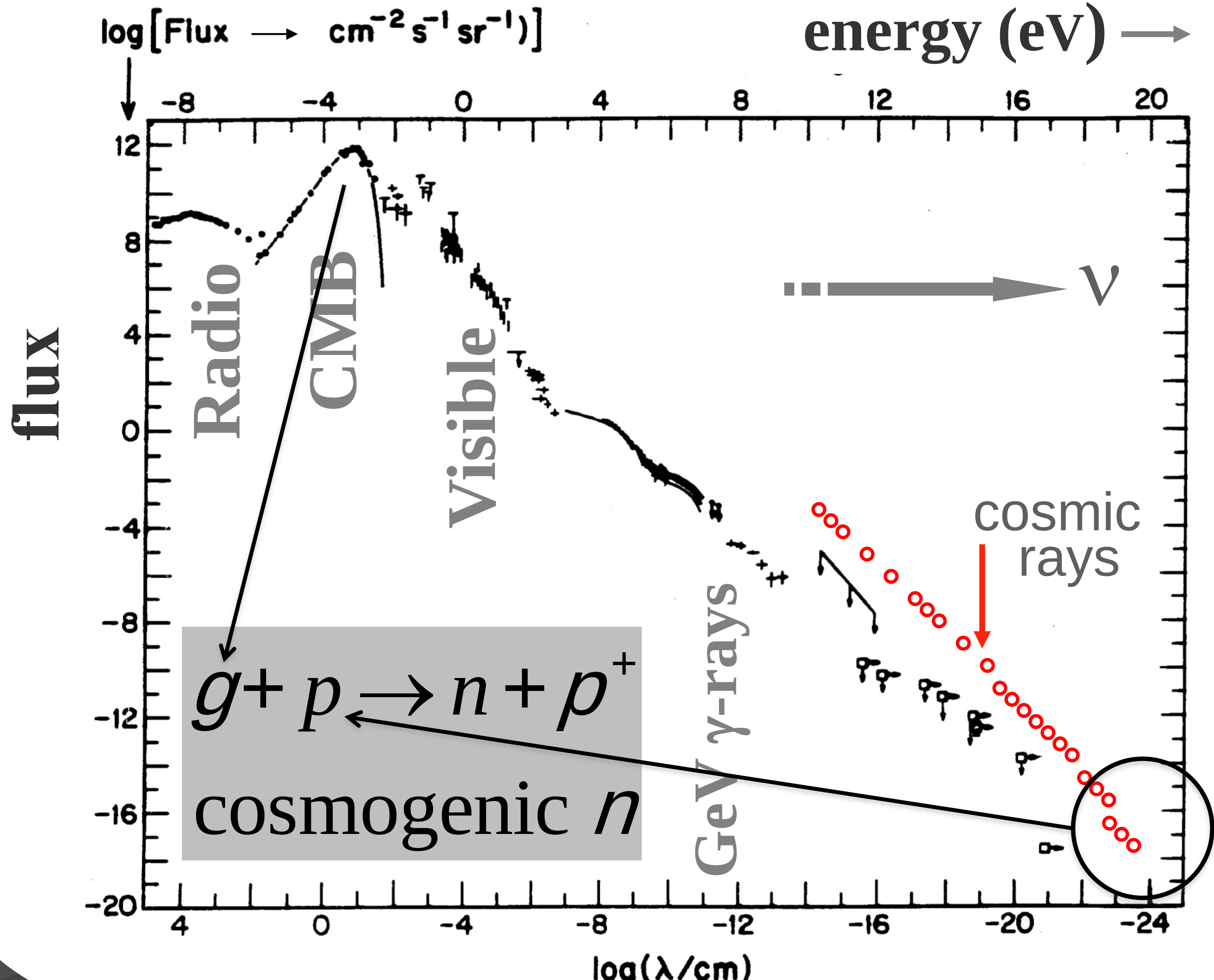
francis halzen

- cosmogenic neutrinos
- the energetics of cosmic ray sources
- neutrinos associated with cosmic rays
- a cubic kilometer detector
- evidence for extraterrestrial neutrinos
- conclusions

IceCube.wisc.edu



log[Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (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)



log[Flux → cm⁻² s⁻¹ sr⁻¹)]
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flux
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CMB
Visible
GeV γ-rays
ν
cosmic rays
$g + p \rightarrow n + p^{+}$
cosmogenic n
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

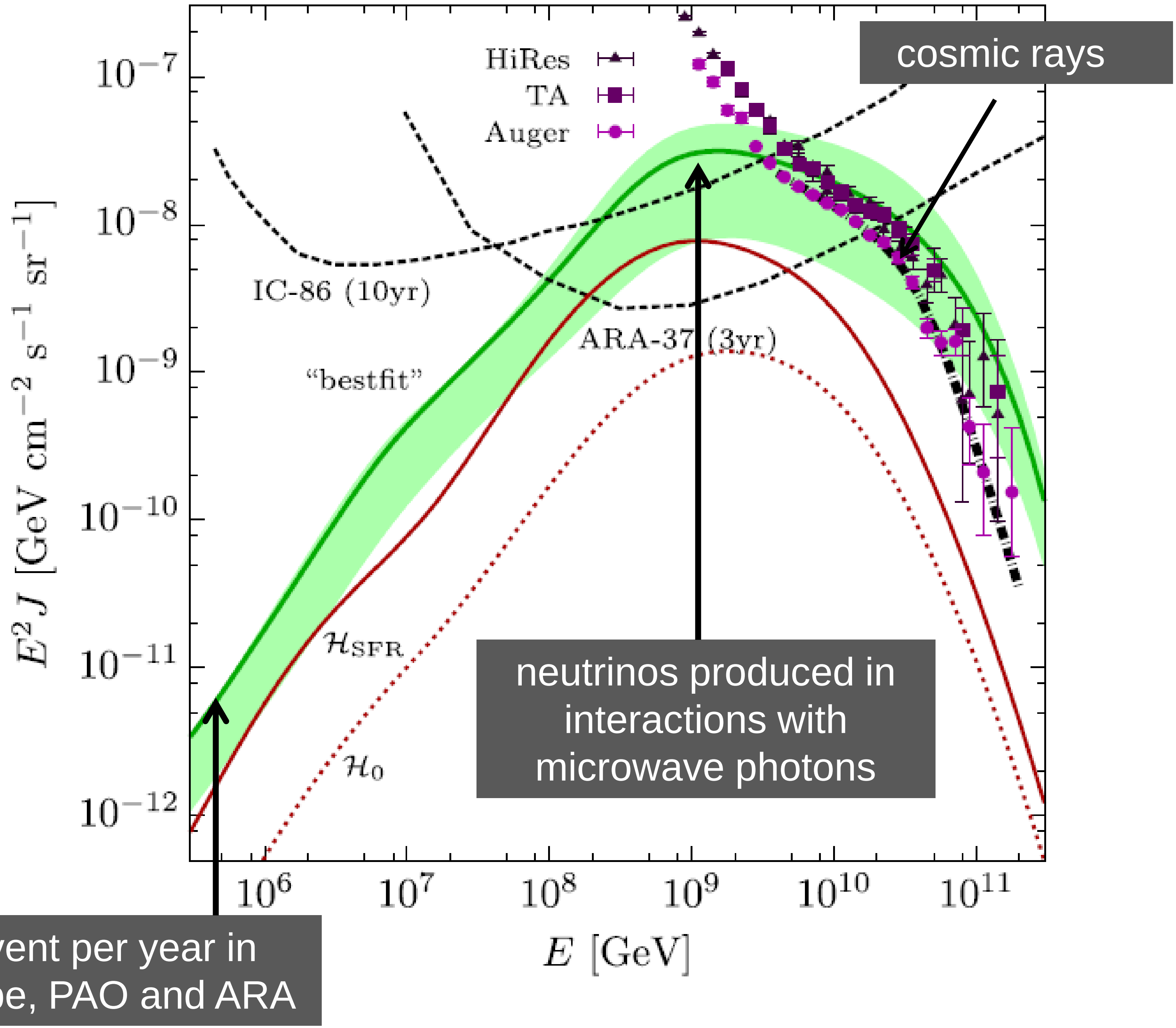
cosmic rays interact with the microwave background

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

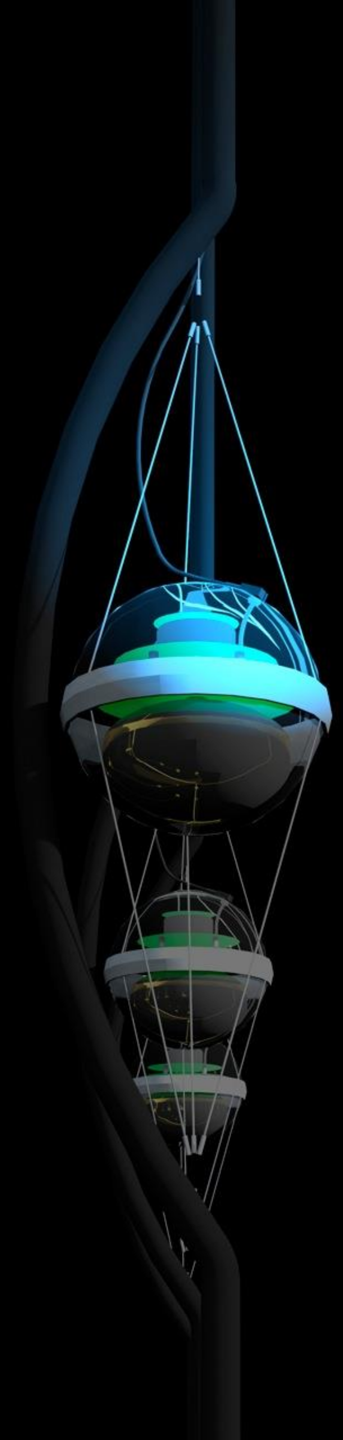
cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

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

1 event per cubic kilometer per year ...but it points at its source!



cosmic rays
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
neutrinos produced in interactions with microwave photons
~1 event per year in IceCube, PAO and ARA
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}



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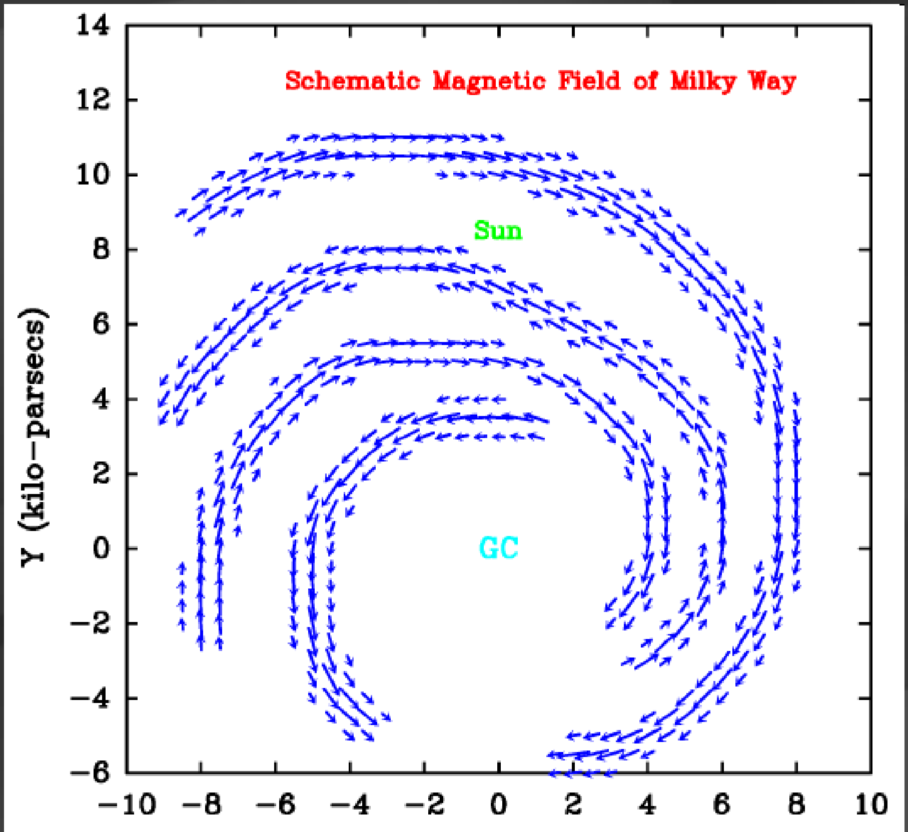
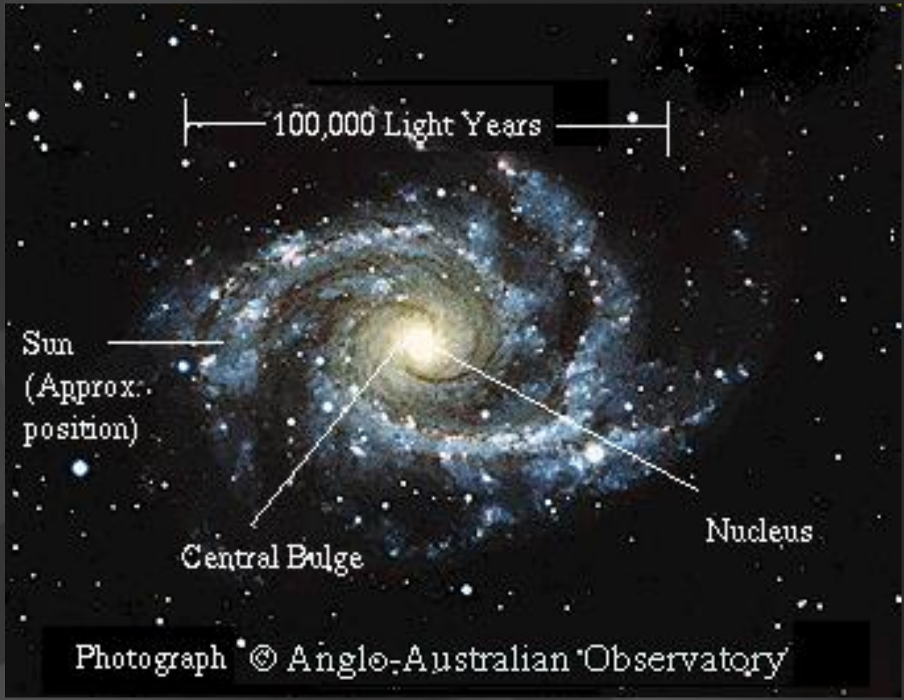
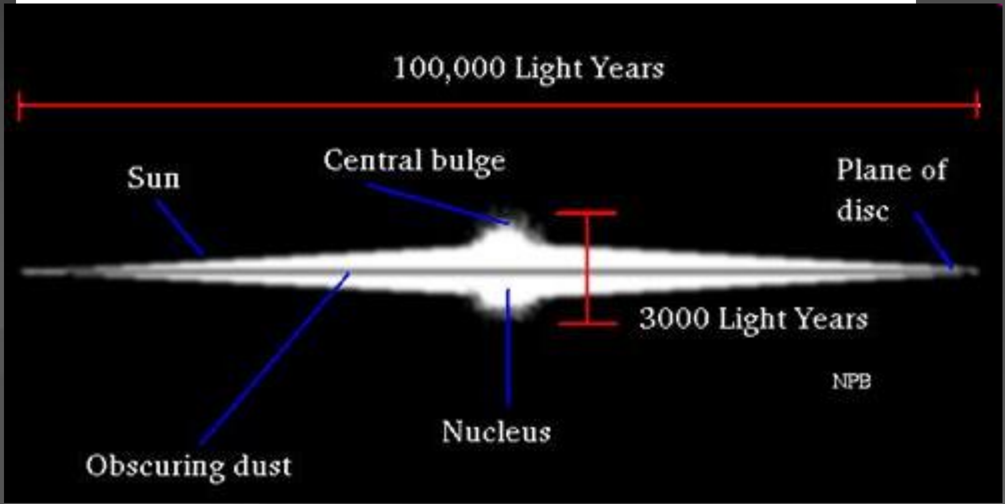
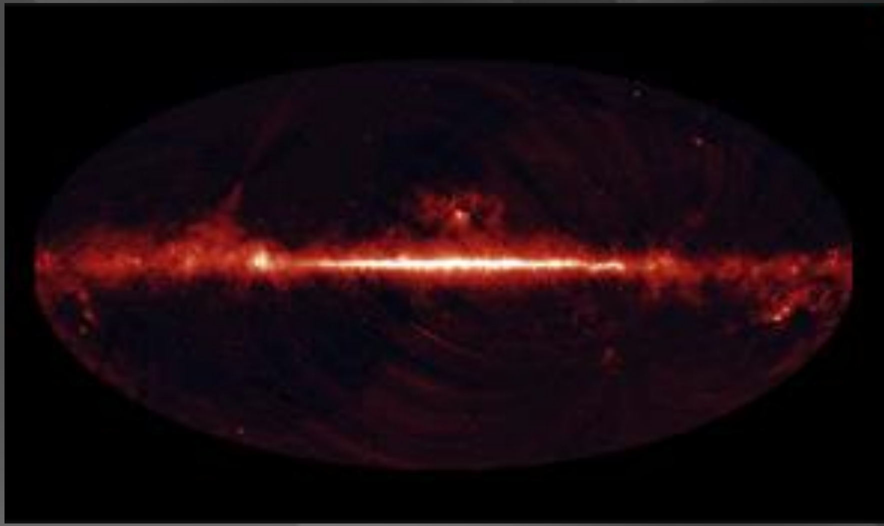
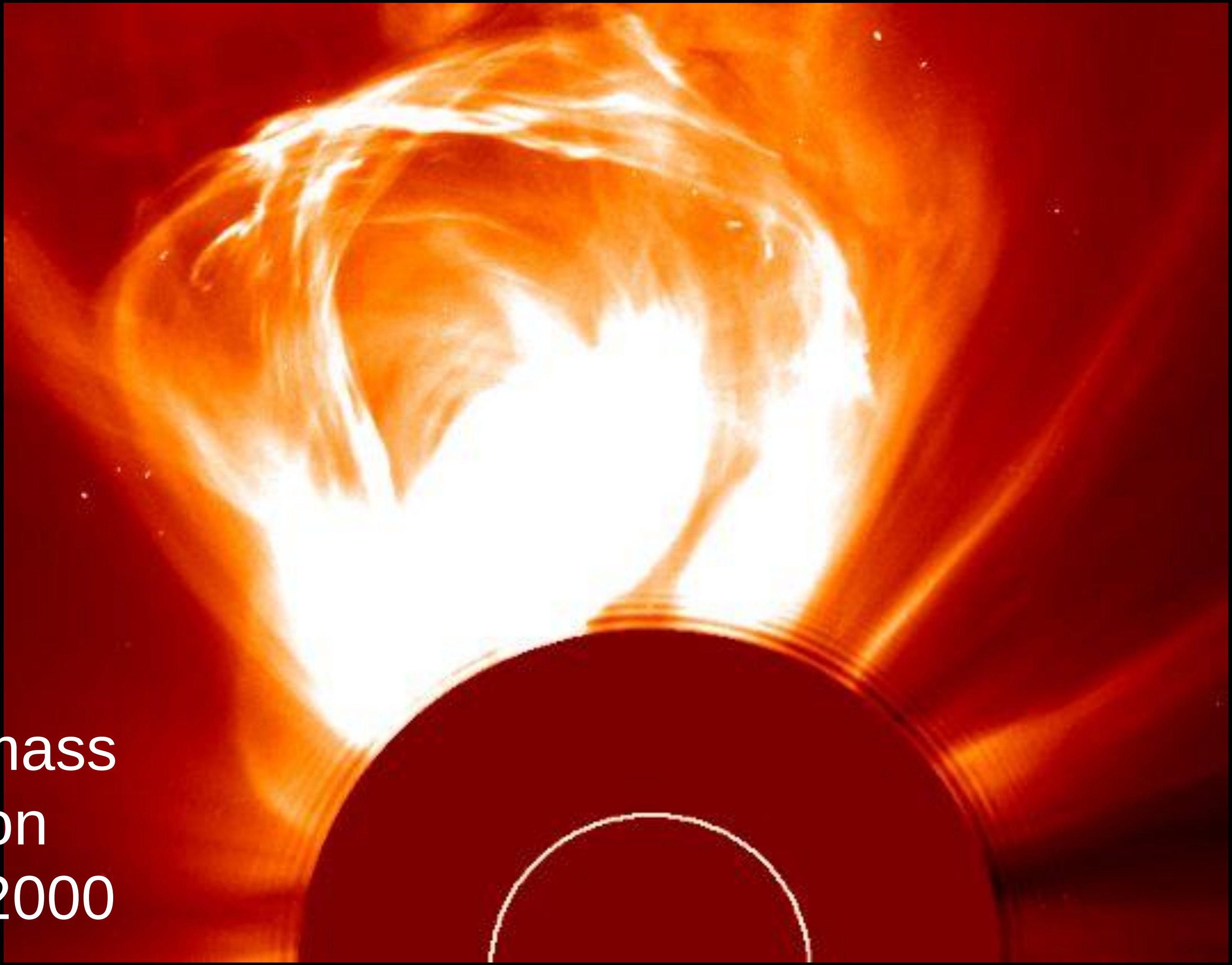

Schematic Magnetic Field of Milky Way
Sun
GC
Y (kilo−parsecs)
14
12
10
8
6
4
2
0
−2
−4
−6
−10
−8
−6
−4
−2
0
2
4
6
8
10


100,000 Light Years
Sun
(Approx.
position)
Central Bulge
Nucleus
Photograph © Anglo-Australian Observatory


100,000 Light Years
Sun
Central bulge
Plane of
disc
3000 Light Years
NPB
Nucleus
Obscuring dust



the sun constructs an accelerator



coronal mass ejection
09 Mar 2000

Hillas formula :

- accelerator must contain the particles

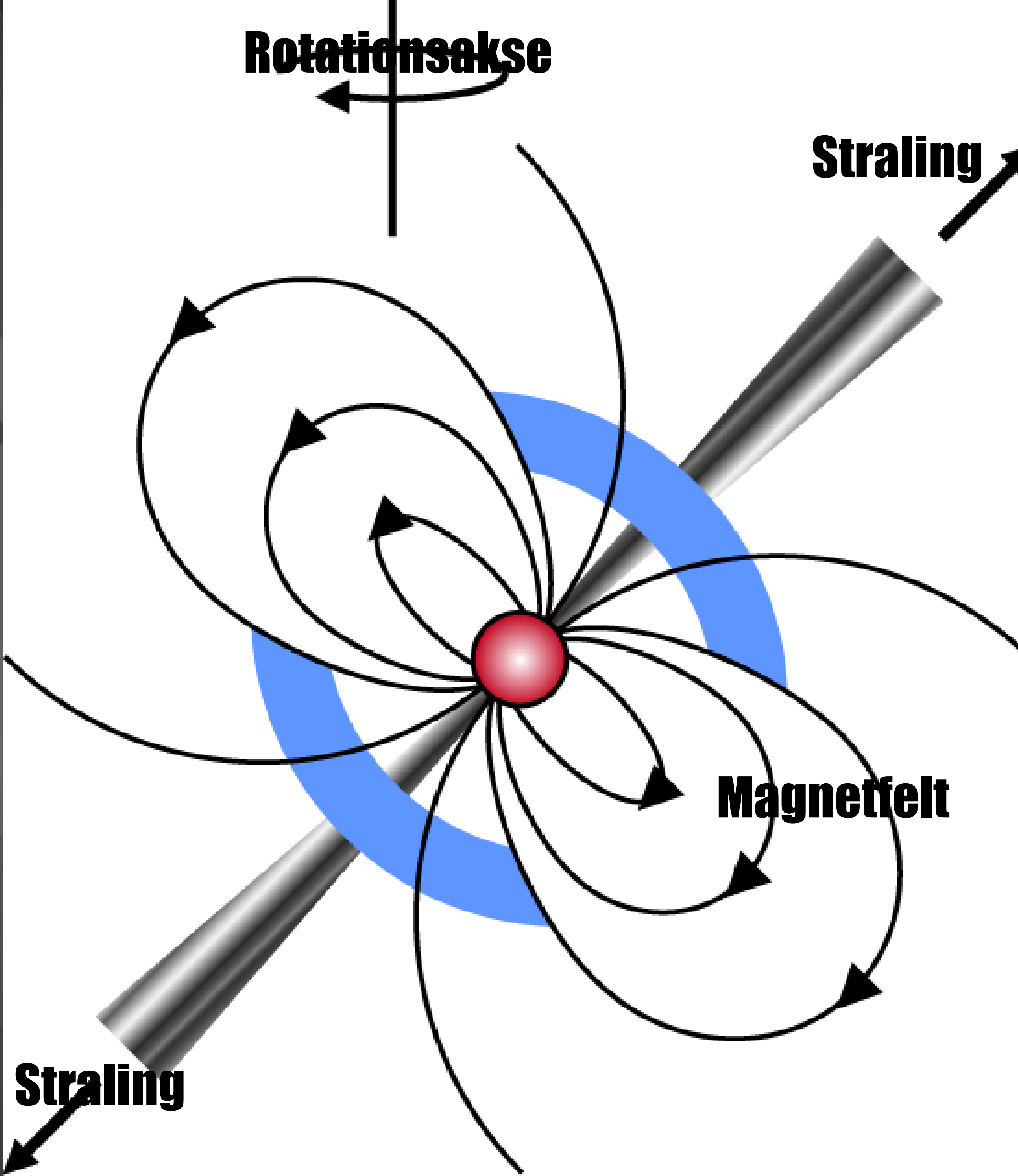
$$R_{gyro} \left(= \frac{E}{\mathrm{v} qB}\right) \leq R$$

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

- dimensional analysis, difficult to satisfy

pulsar

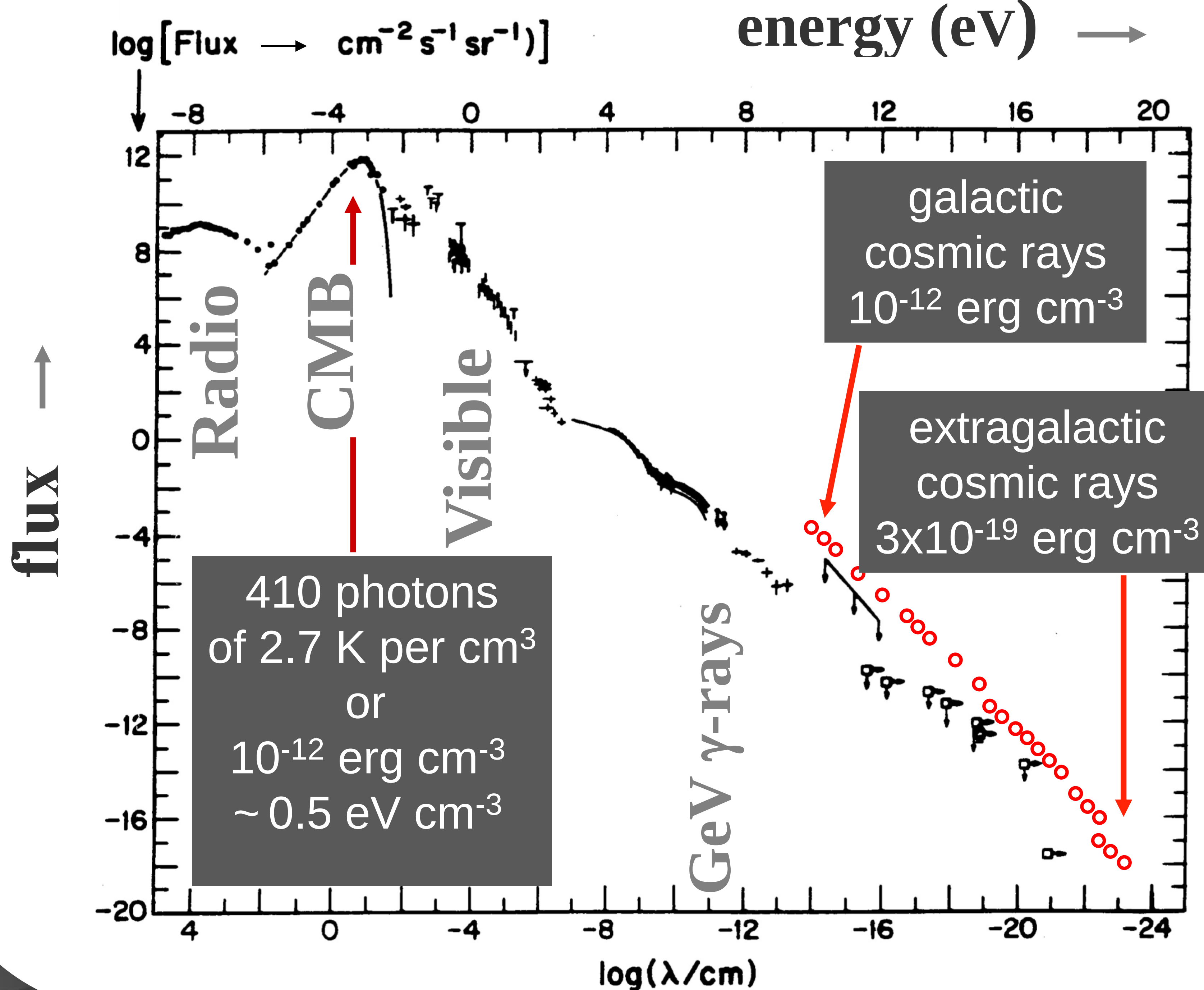
$$v \rightarrow \frac{2\pi R}{T}$$



$$E(eV) = B(Tesla)\ R(m)\ \frac{2\pi R}{T}$$

	ms-pulsar	*Fermilab*
R	10 km	km
B	10^8 Tesla	Tesla
T^{-1}	10^3	10^5 (#rev/s)
E	**10^7 TeV**	10^{12} eV = 1 TeV !

still a very open problem…



energy (eV)
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0
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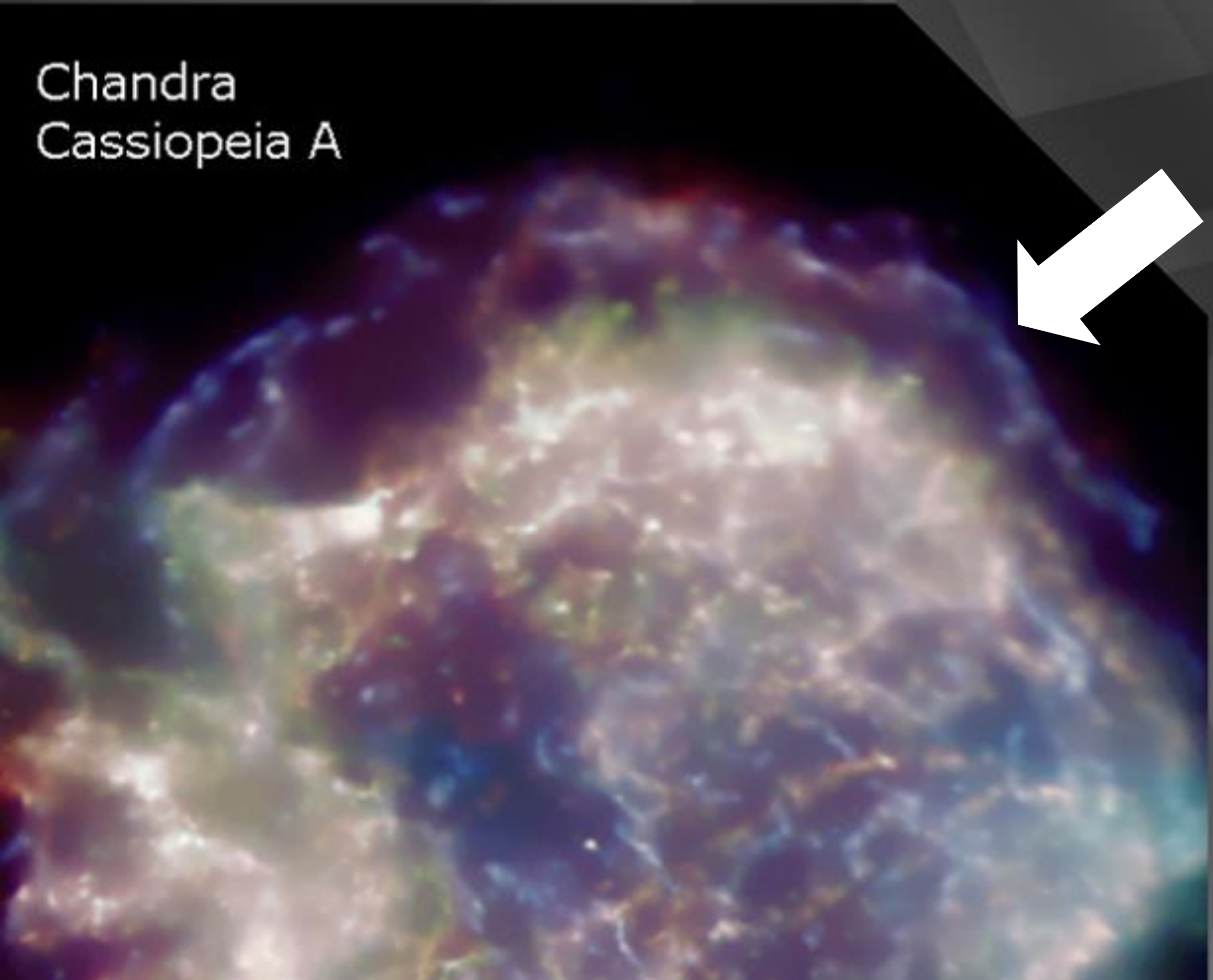
-12
-16
-20
-24
log(λ/cm)
flux
Radio
CMB
Visible
GeV γ-rays
galactic cosmic rays 10^{-12} erg cm^{-3}
extragalactic cosmic rays 3×10^{-19} erg cm^{-3}
410 photons of 2.7 K per cm^3 or 10^{-12} erg cm^{-3} ~ 0.5 eV cm^{-3}

supernova remnants

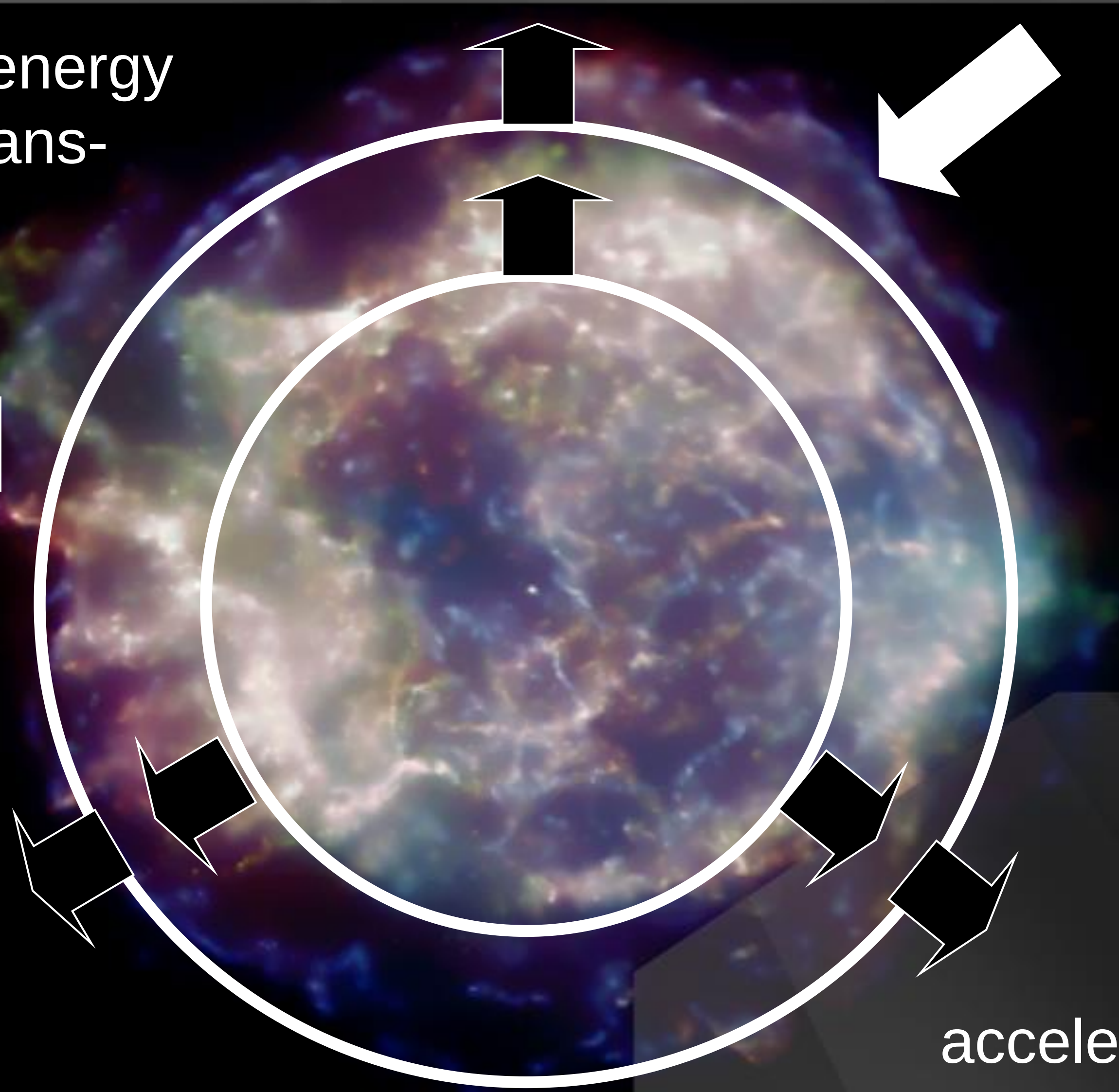


cassiopeia A supernova remnant in X-rays

gravitational energy released is trans-formed into acceleration

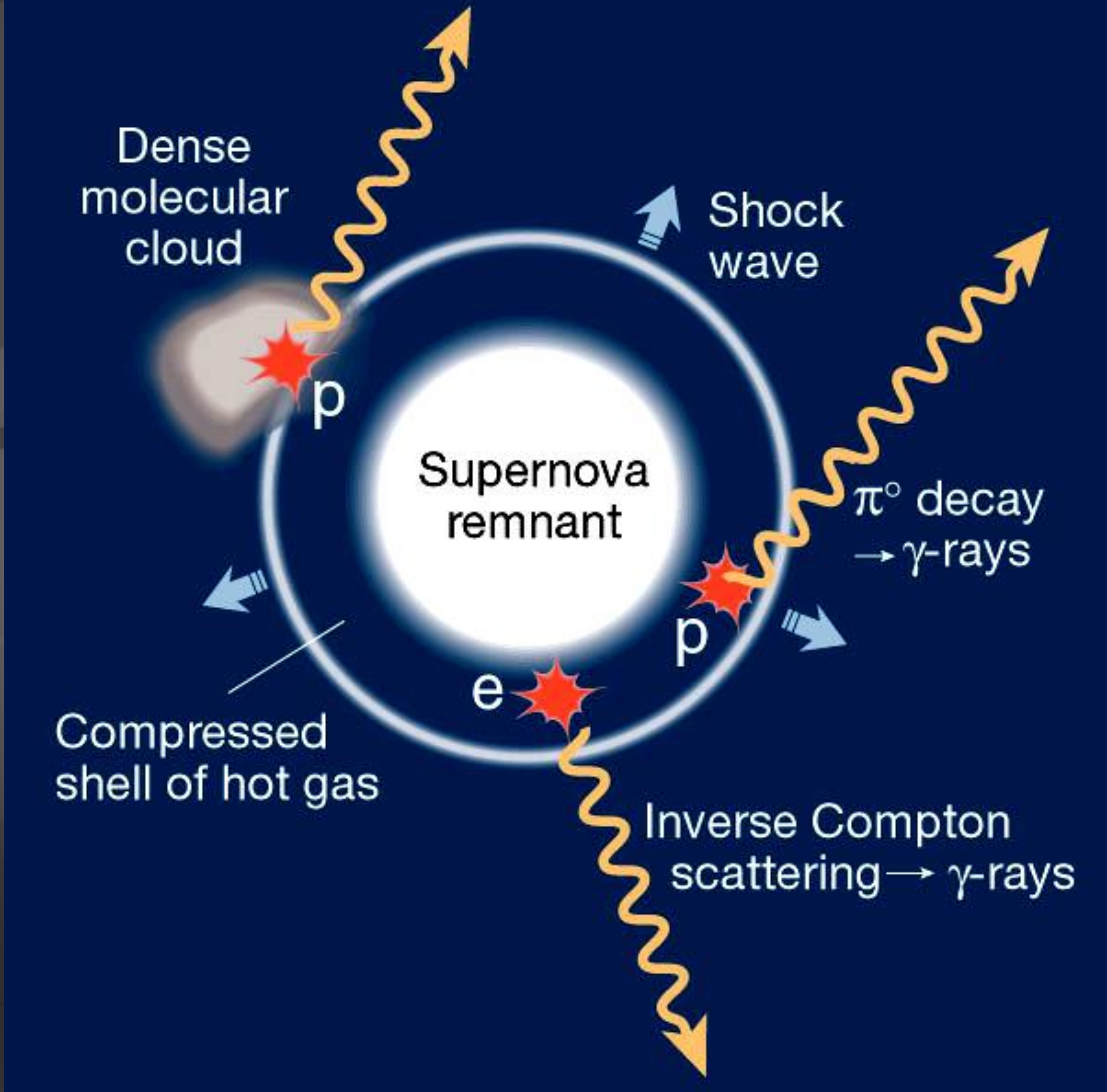
→

E^{-2} spectrum



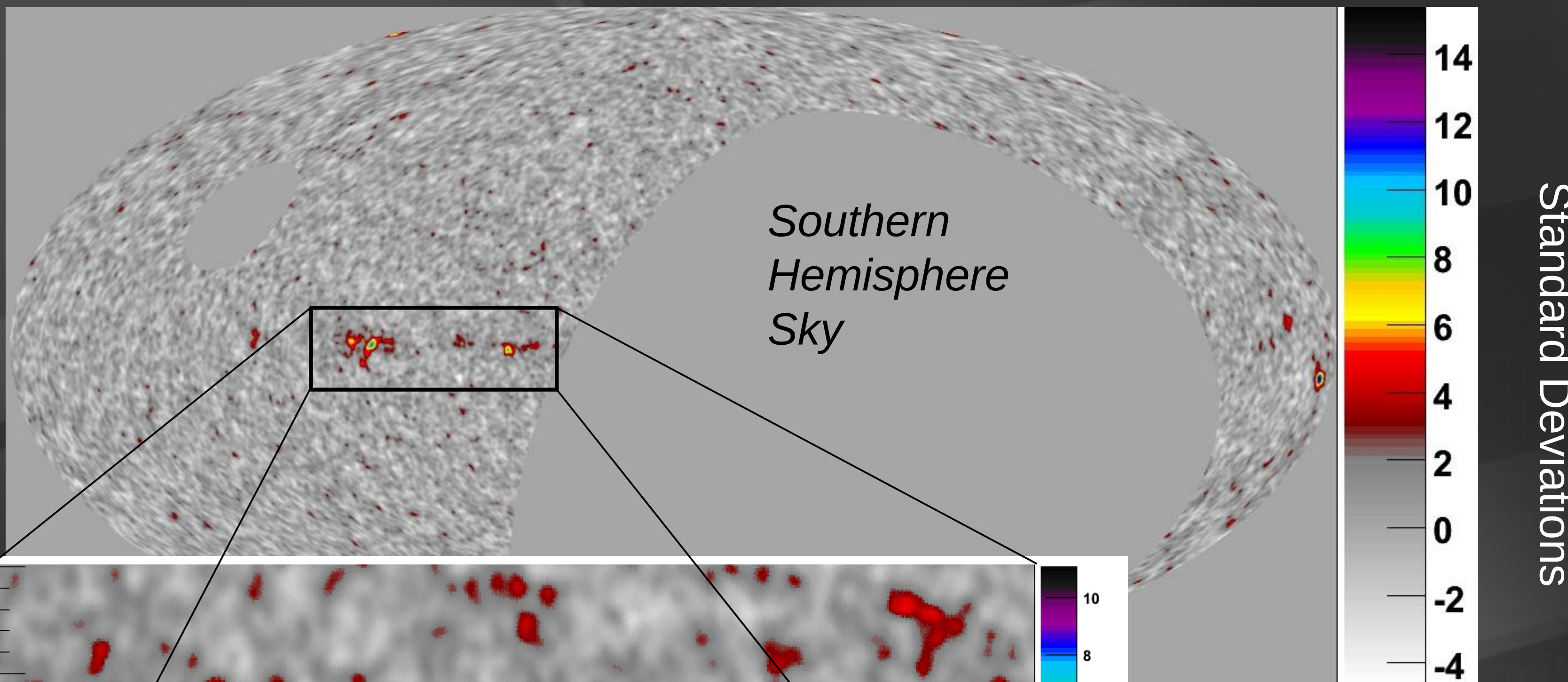
acceleration when particles cross high B-fields neutrinos from supernova remnants :

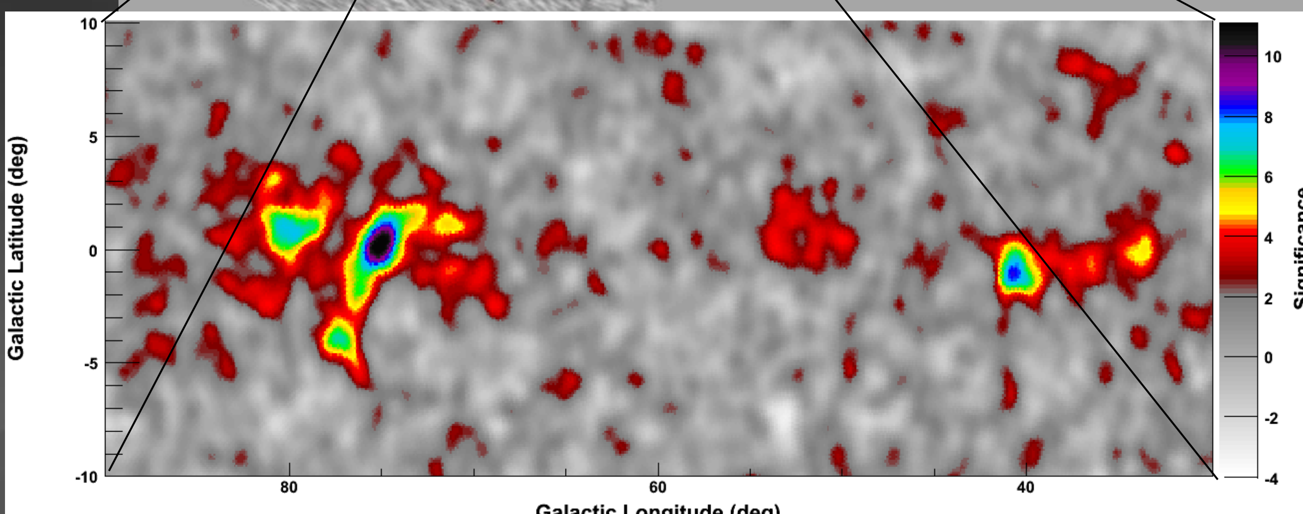
molecular clouds in star-forming regions where super-nova explode: beam dumps!

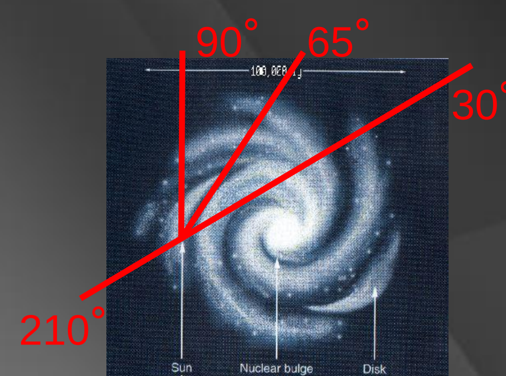


Galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions







milagro

neutral pions

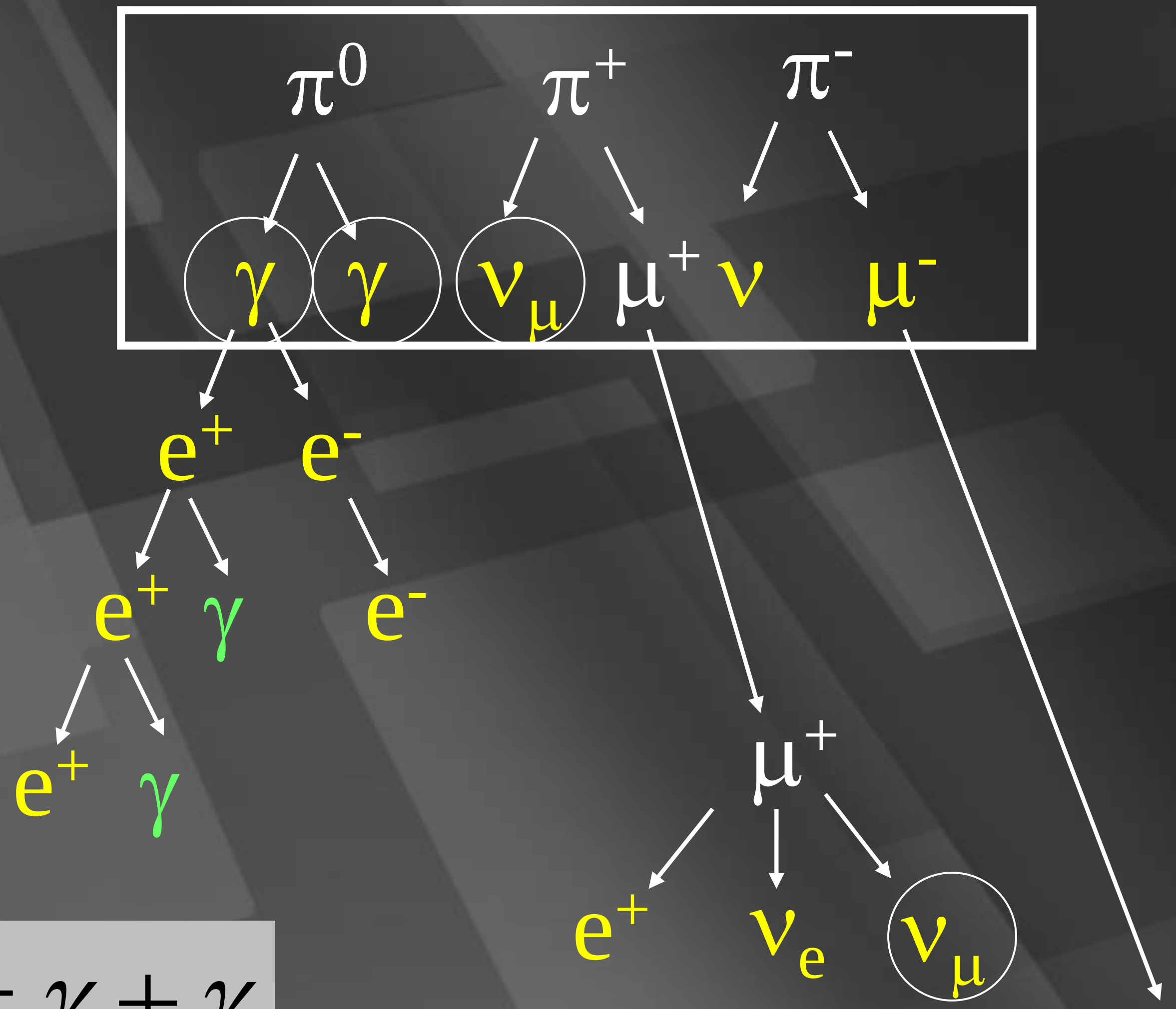
are observed as

gamma rays

charged pions

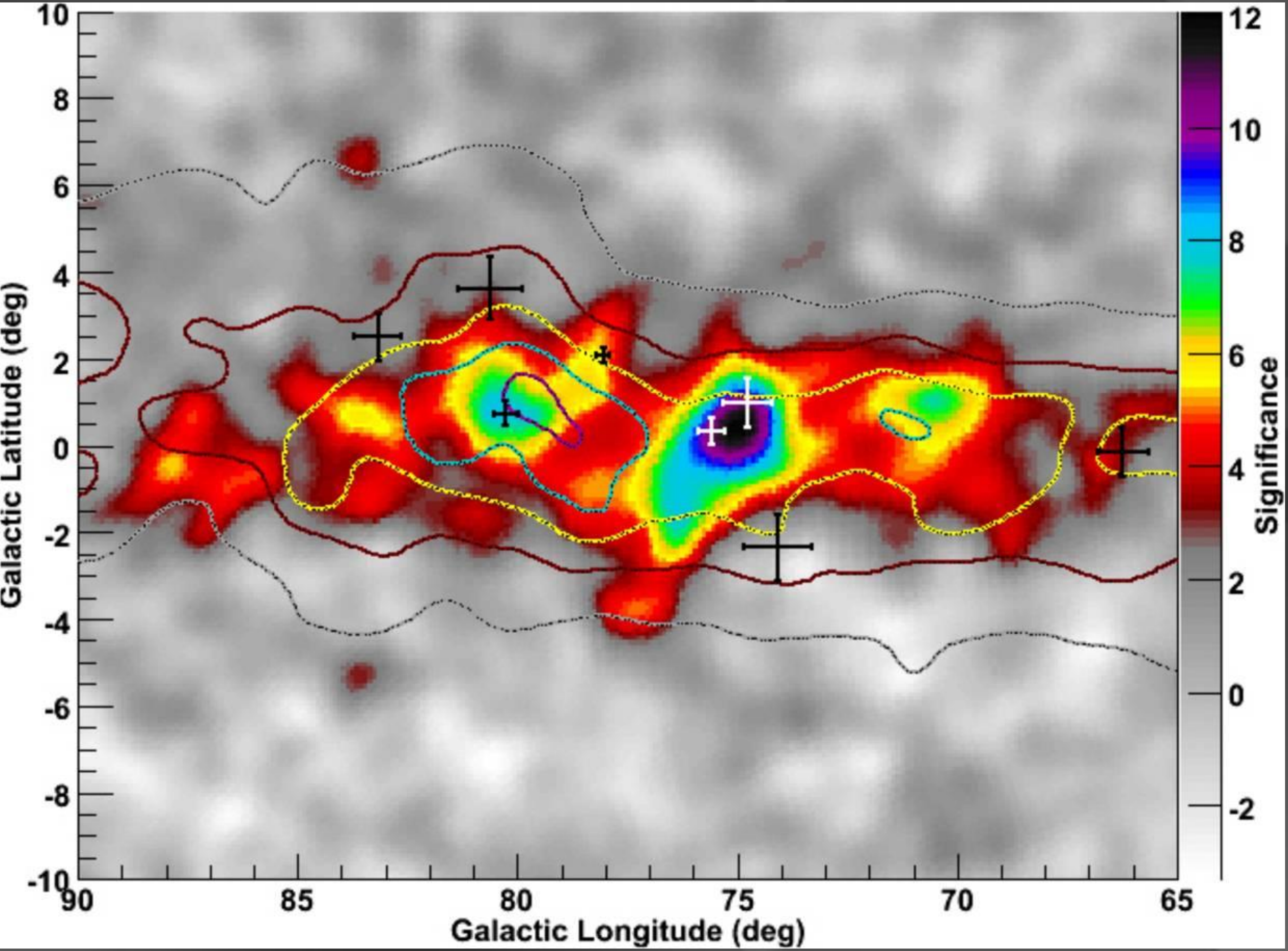
are observed as

neutrinos



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

Cygnus region : Milagro



translation of
TeV gamma rays
into
TeV neutrinos :

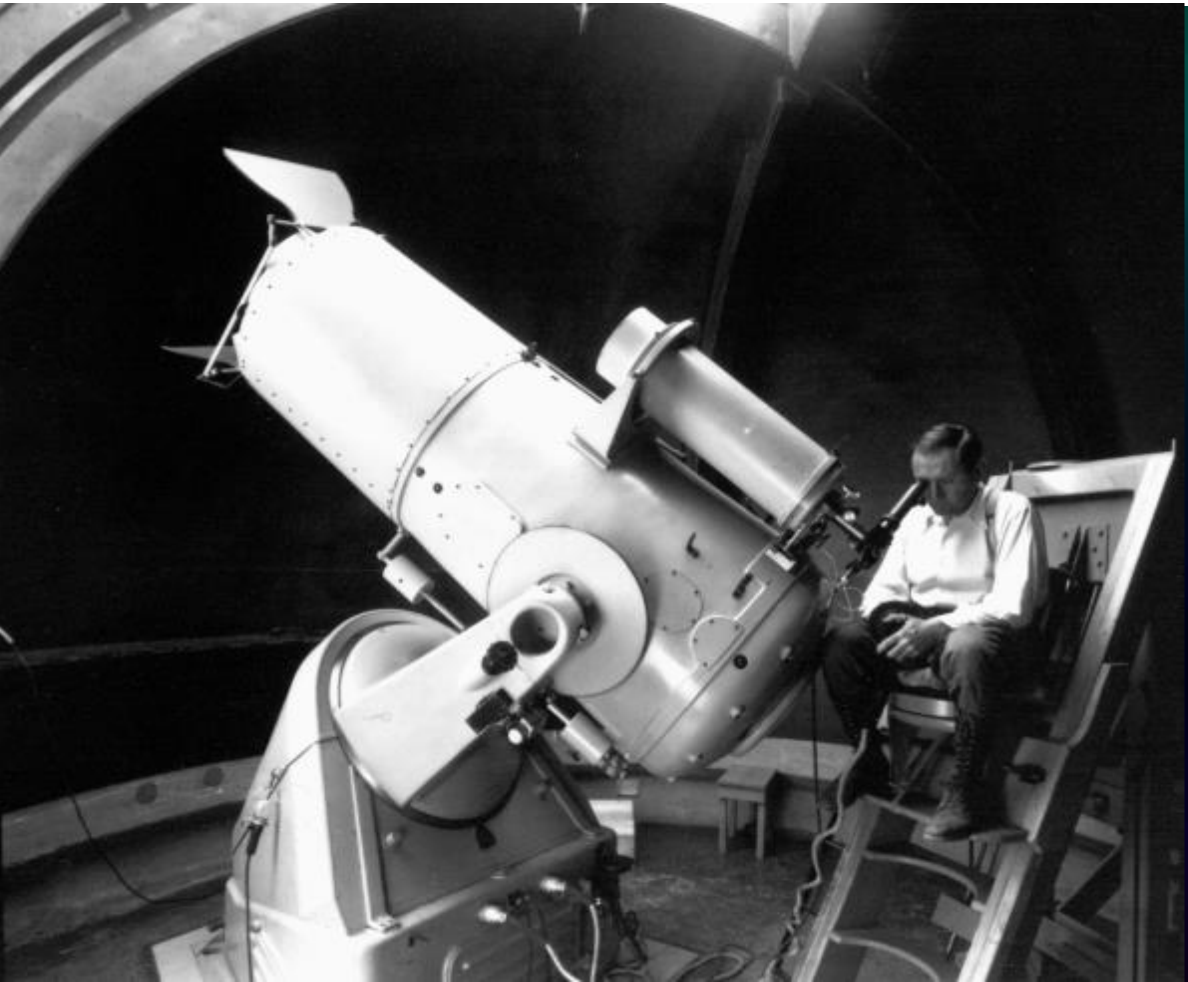
3 ± 1 ν per year in IceCube per source

ON SUPER-NOVAE

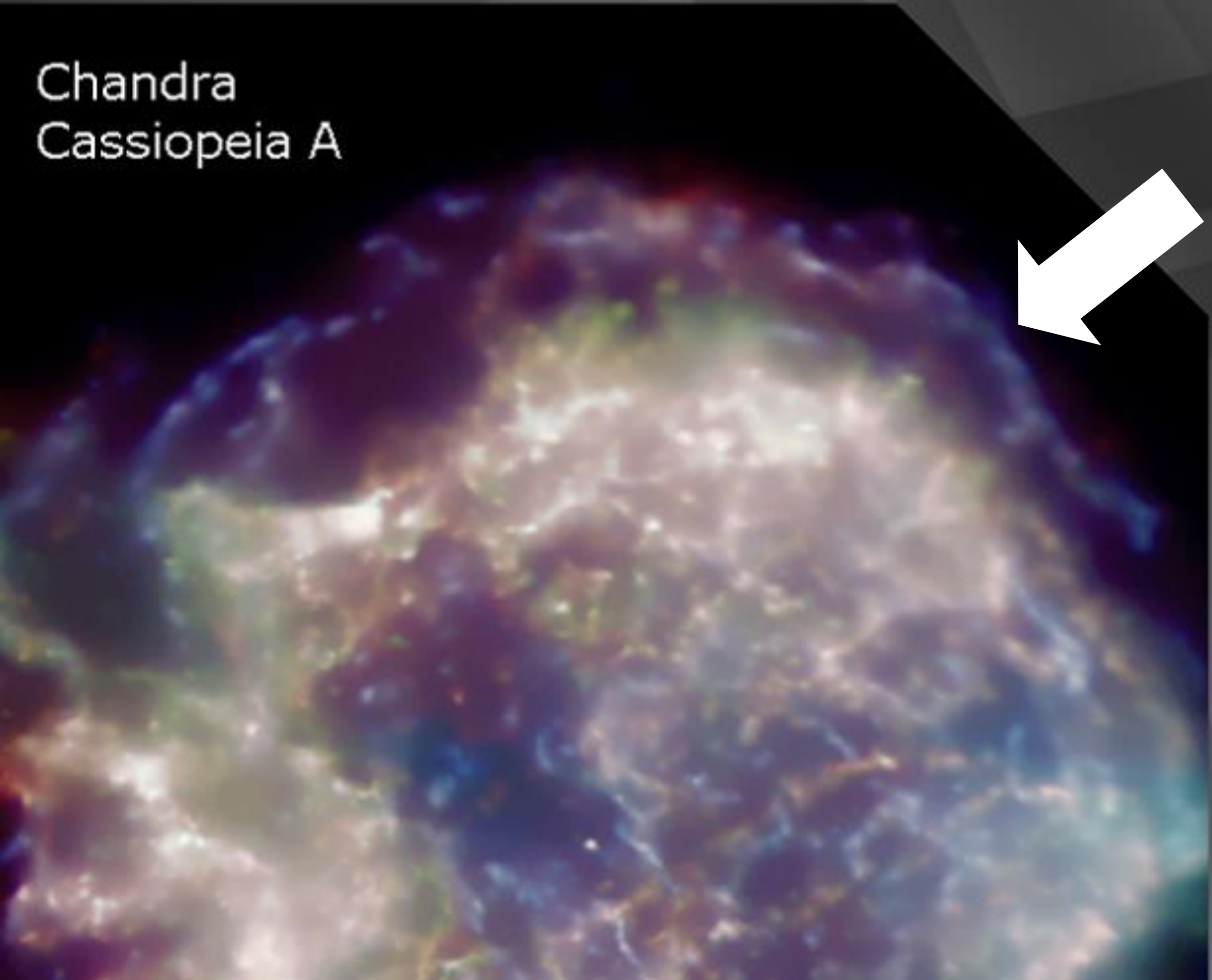
By W. Baade and F. Zwicky

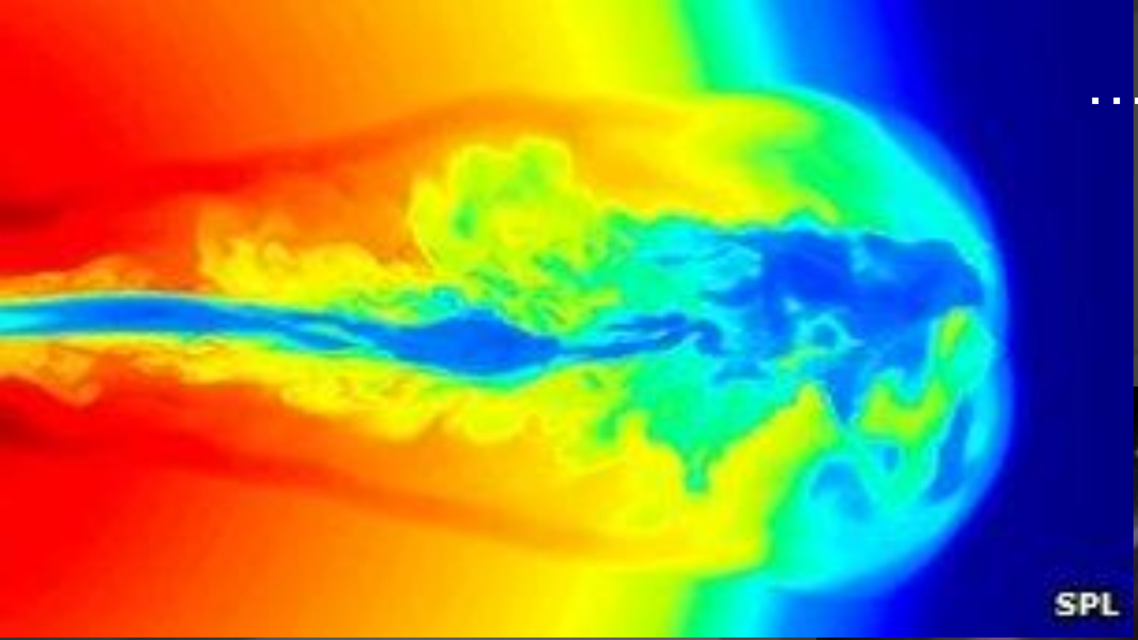
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934



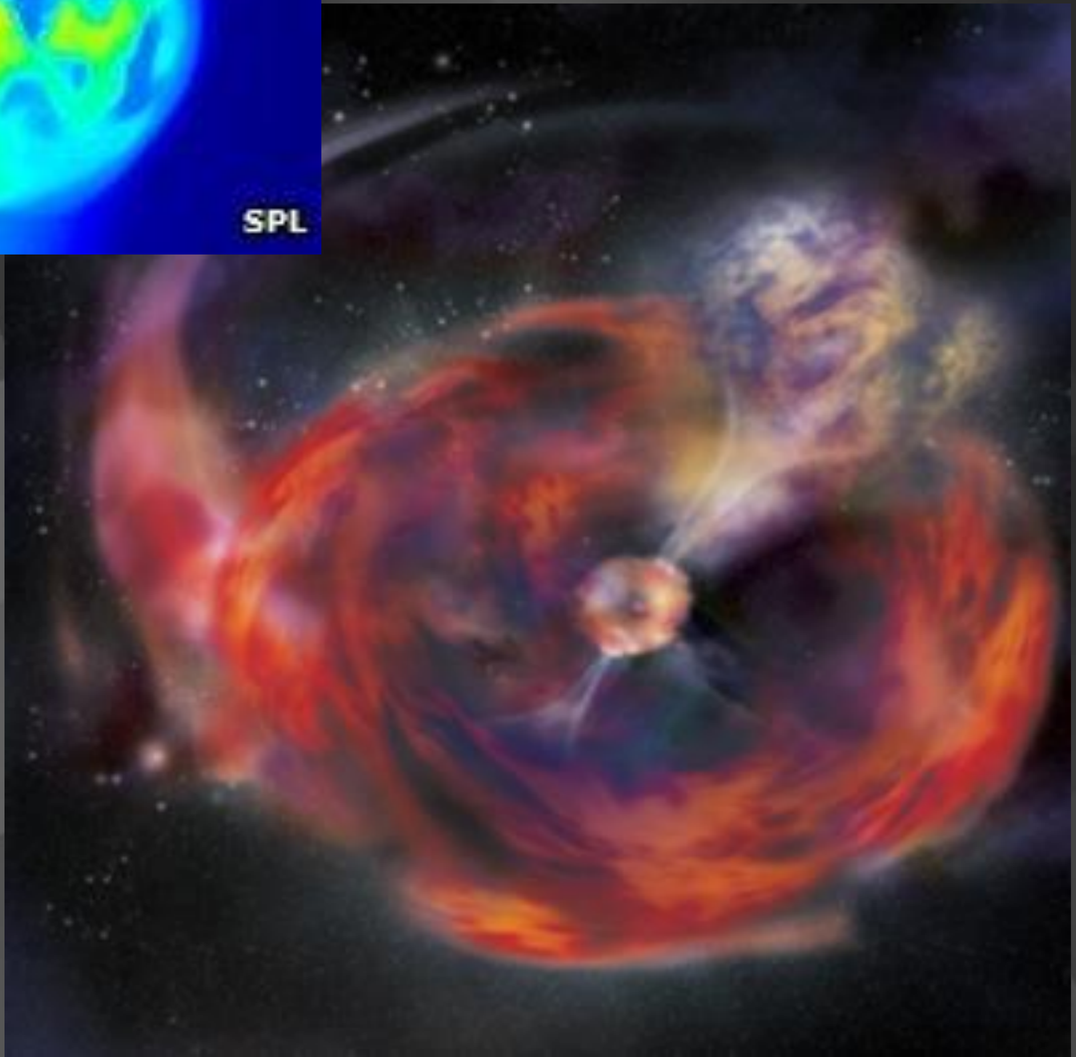
supernova remnants



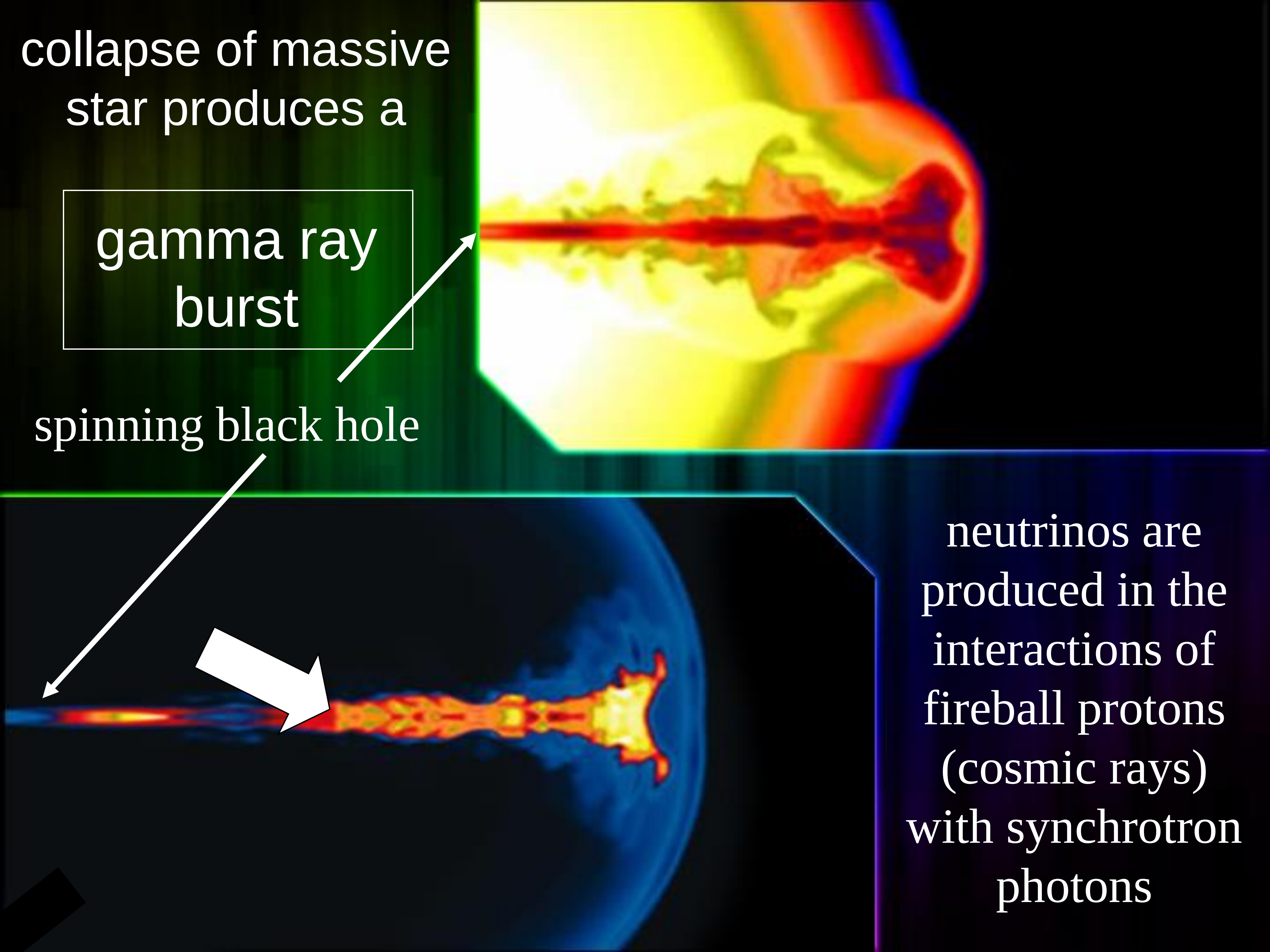


…and if the star collapses to a black hole…

gamma ray burst



- ✓ happens in seconds not thousands of year
- ✓ beamed along the spin axis of the black hole
- ✓ simulation not image


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

GRB fireball model

decays to PeV neutrino

↑

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

↓

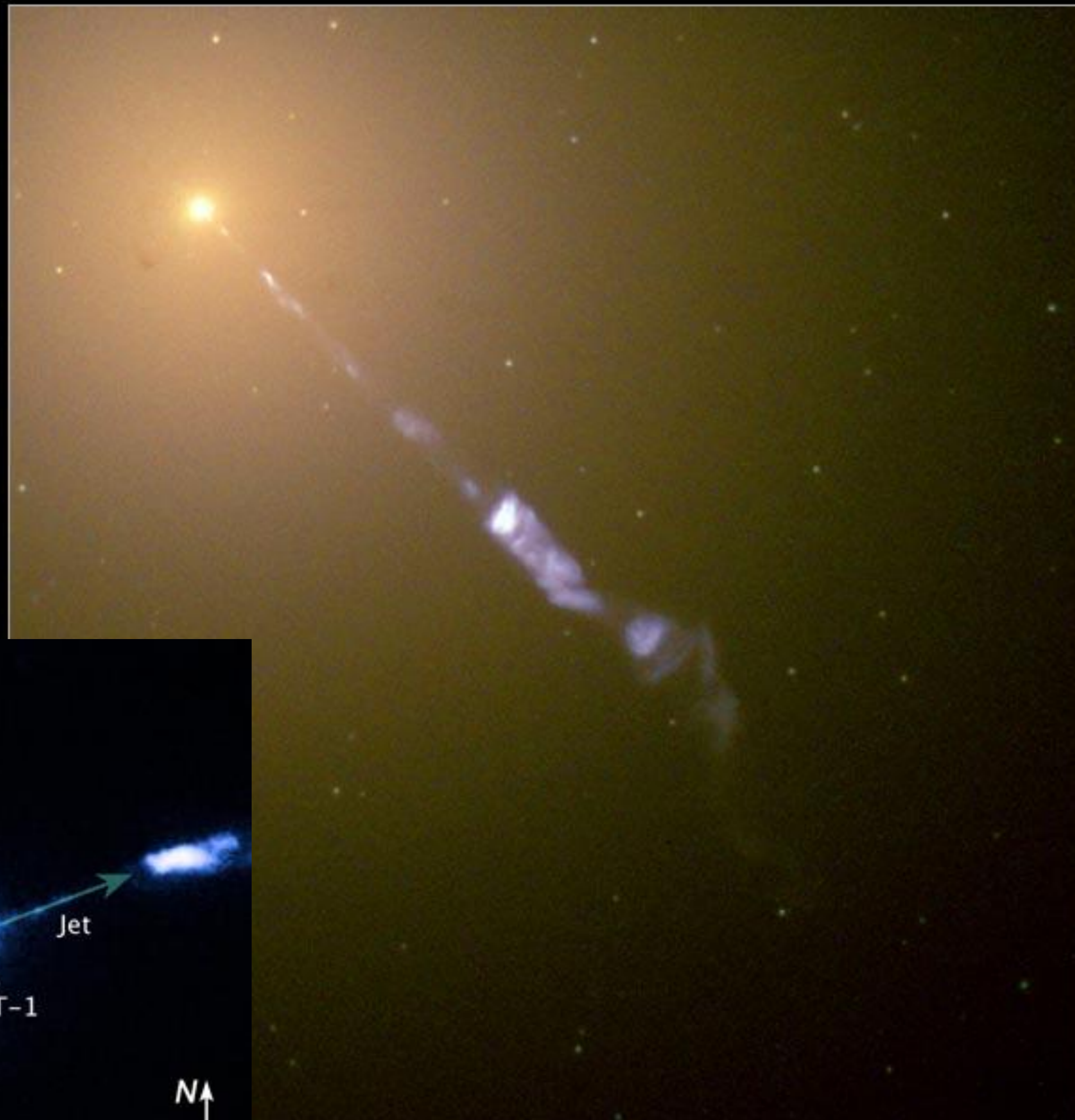
decays to cosmic ray

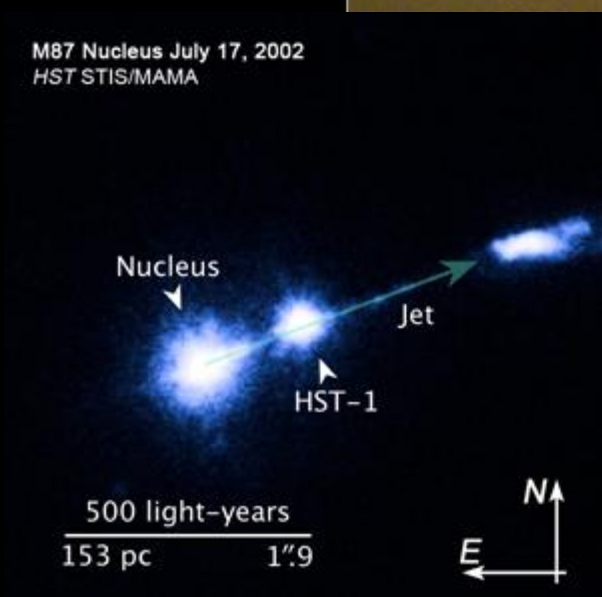
- one neutrino per cosmic ray observed
- ruled out by IceCube

active galaxy

particle flows near
supermassive
black hole

The M87 Jet

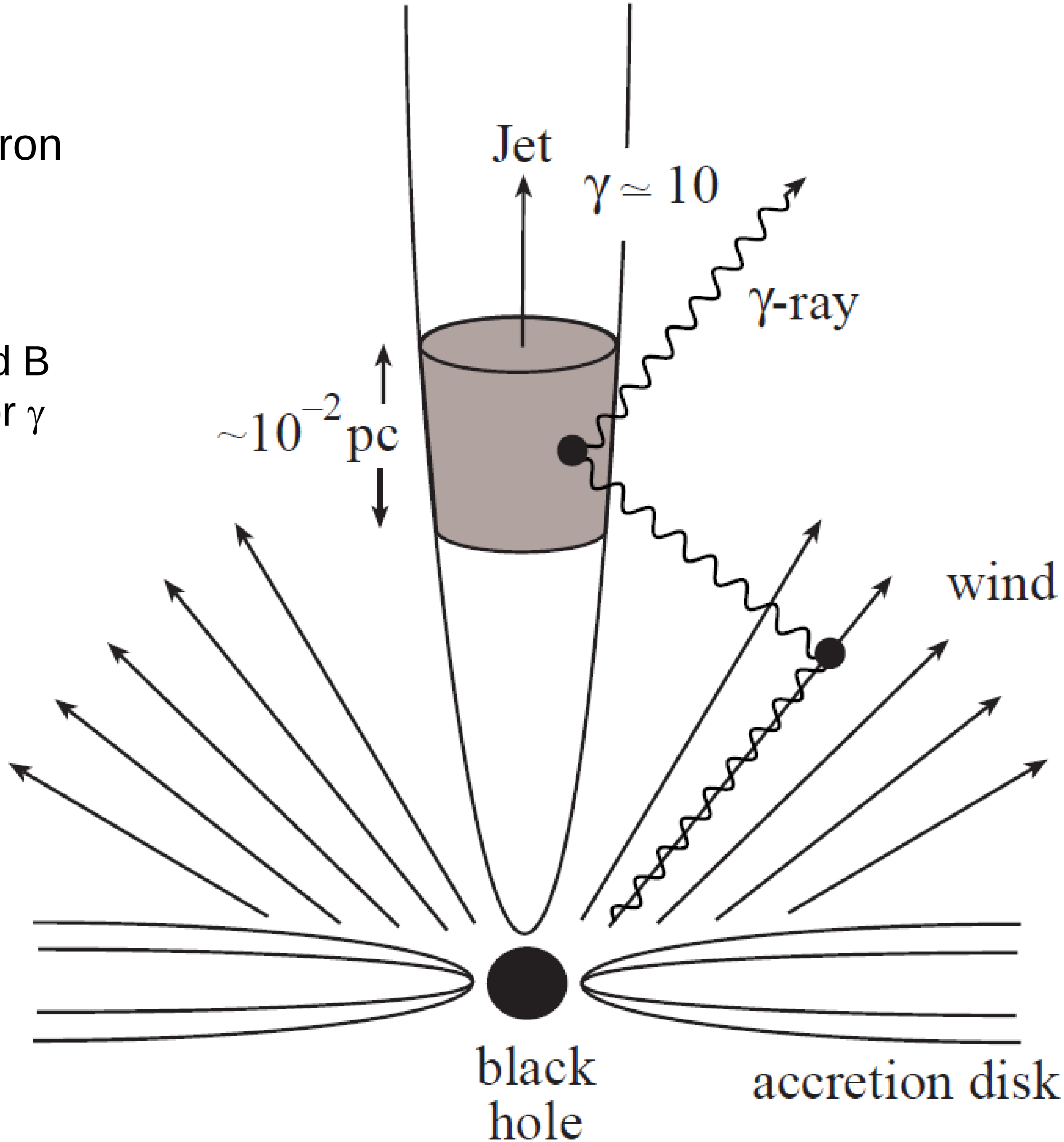




Hubble Heritage

parameters:
energy electron beam:

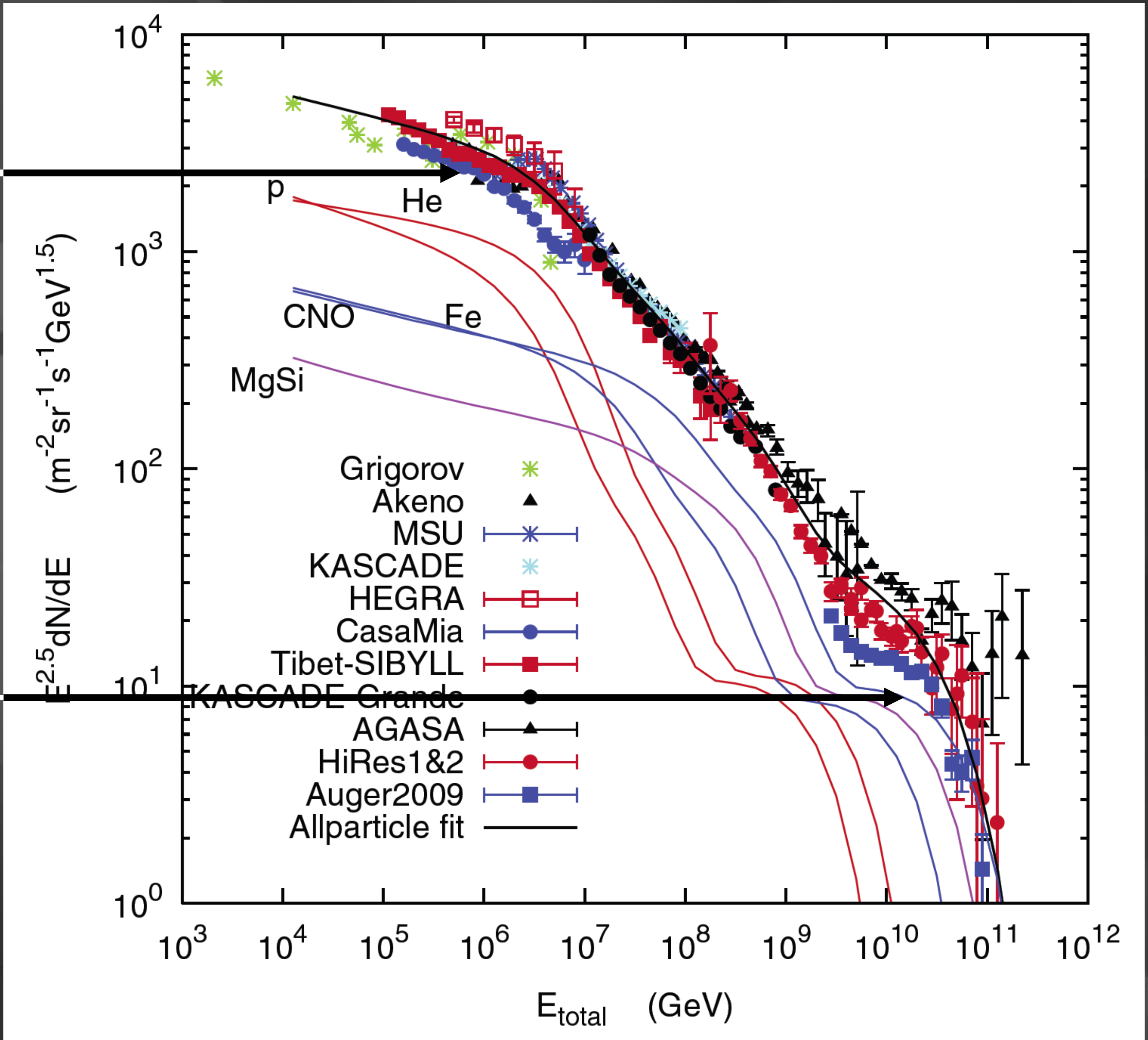
γ_e^{max}
magnetic field B
Doppler factor γ



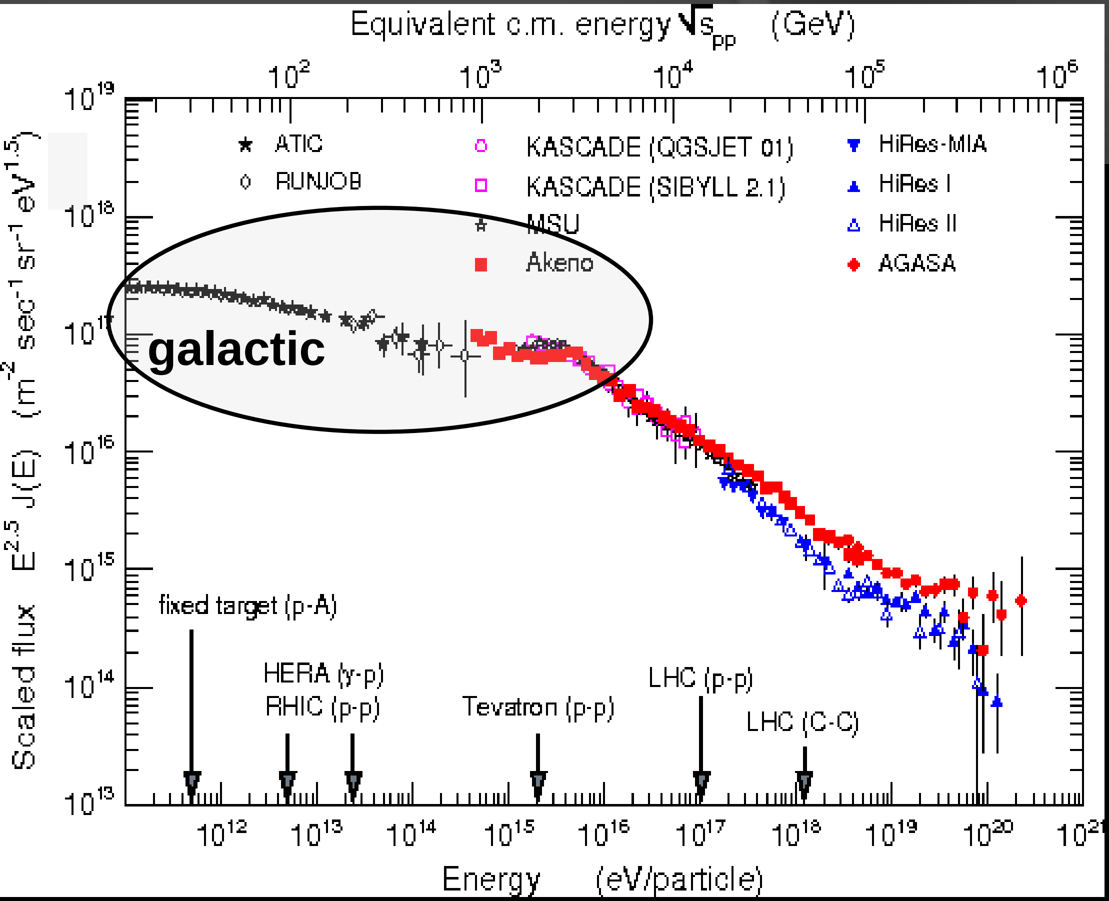
sources accommodating the observed energy budget

Galactic: supernova remnants?

extragalactic:
- gamma ray bursts??
- active galaxies?



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!

flux of extragalactic cosmic rays

ankle → one 10^{19} eV particle per km squared per year per sr

$$E^2 \frac{dN}{dE} = \frac{10^{19}\, eV}{(10^{10}\, cm^2)(3\times 10^7 \,\mathrm{sec})\; sr}$$

cosmic accelerator E^{-2}

$$= 3\times 10^{-11}\, TeV\, cm^{-2}\, \mathrm{sec}^{-1}\, sr^{-1}$$

total flux = velocity x density

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

$$\rho_E = \frac{4\pi}{c} \int \frac{3\times 10^{-11}}{E}\, dE\, \frac{TeV}{cm^3}$$

$$= \cdots \log \frac{E_{\max}}{E_{\min}} \cong 10^{-19}\, \frac{TeV}{cm^3}$$

$$1TeV \cong 1.6\, erg$$

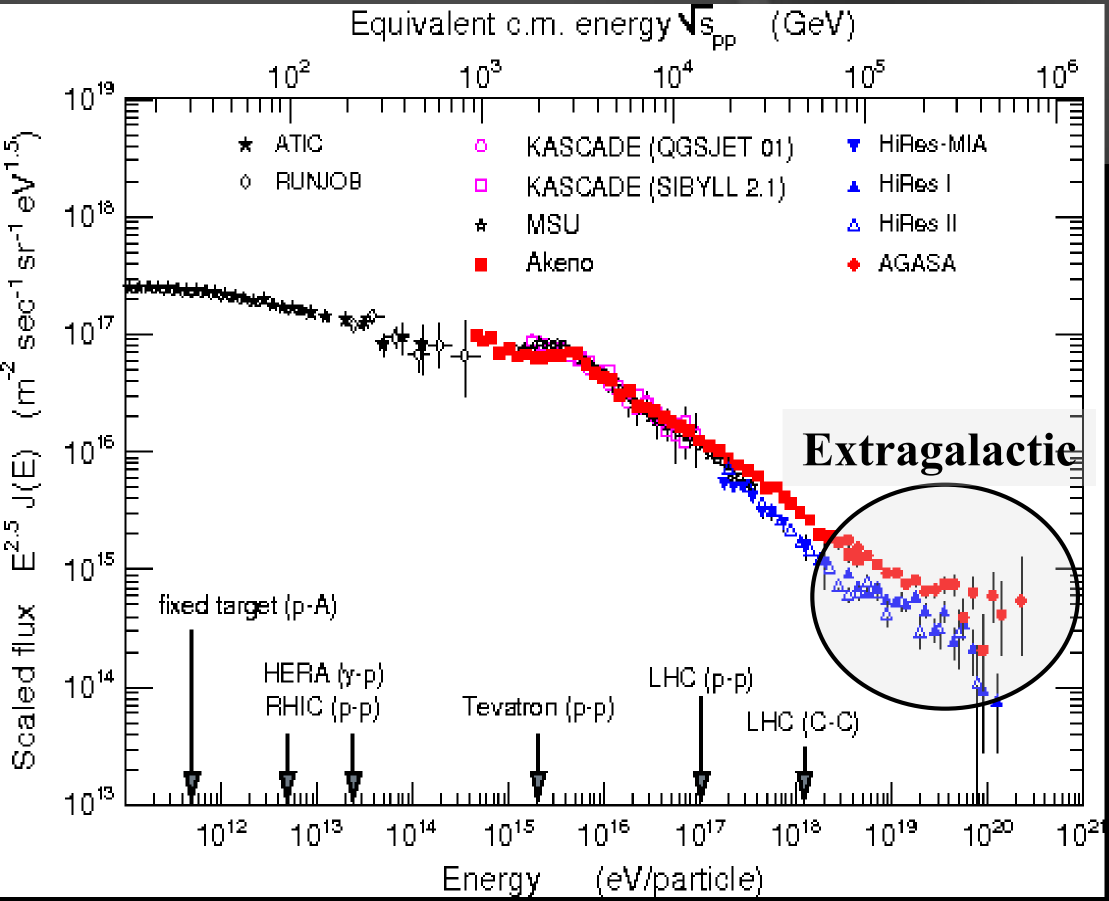
300 GRB per Gigaparsec^3 per year
for 10^{10} years (Hubble time)

$$2 \times 10^{51} erg \times \frac{300}{Gpc^3\ yr} \times 10^{10} yr = 3 \times 10^{-19} \frac{erg}{cm^3}$$

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

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

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

$\sim 10^{-19}$ erg / cm^3

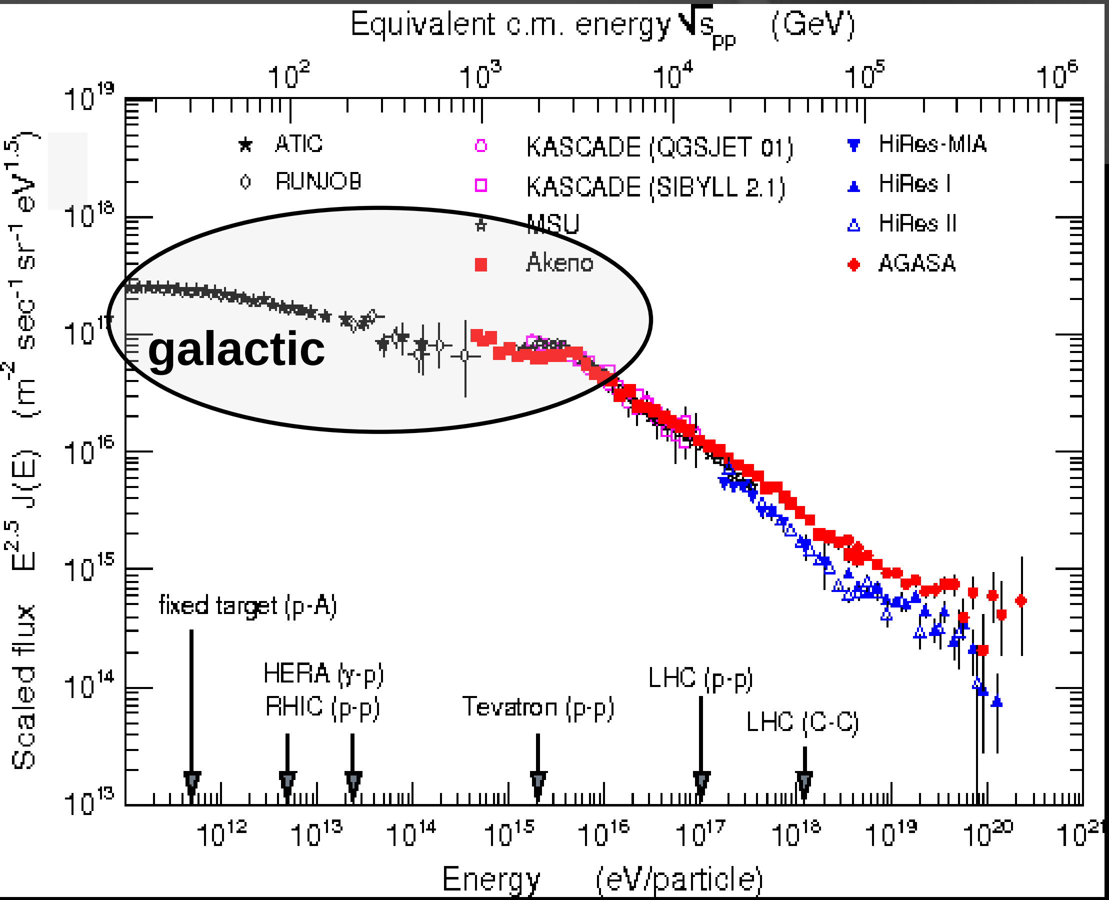
Gamma-Ray Bursts:

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

$\sim 10^{-19}$ erg / cm^3

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

Cosmic Rays & SNRs



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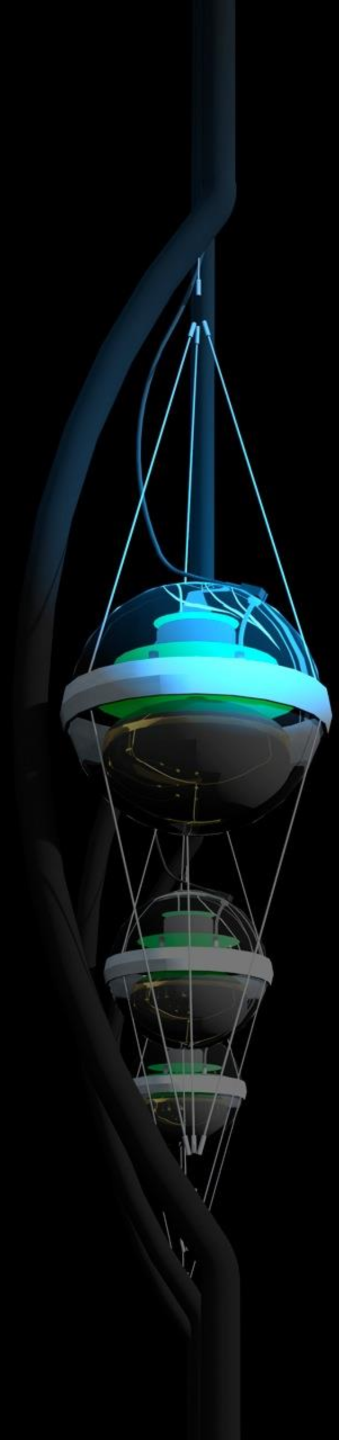

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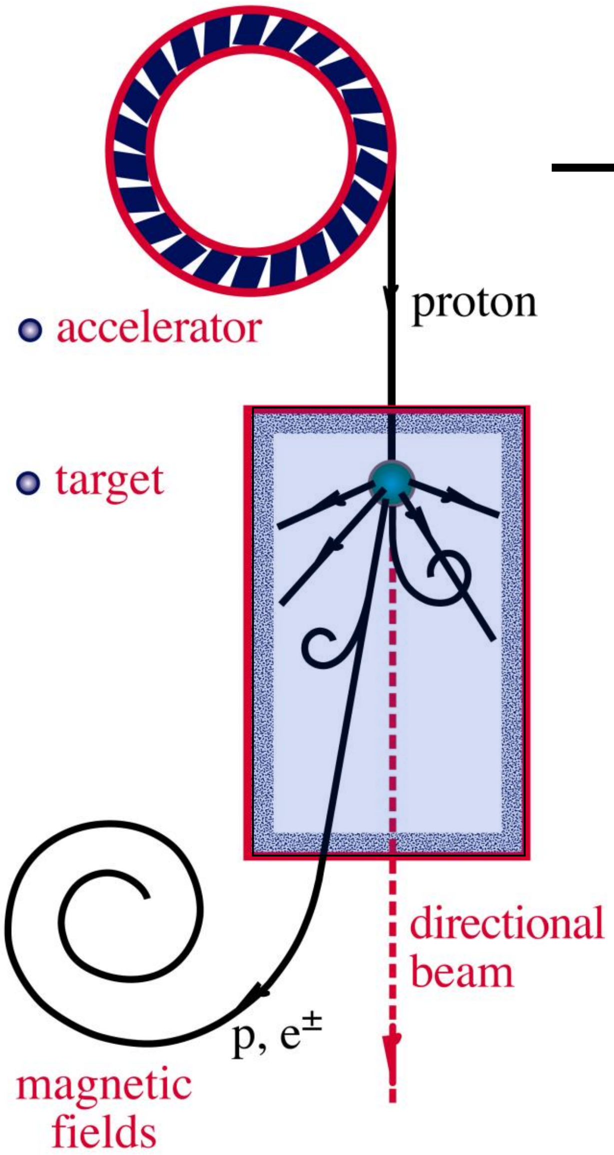
ν and γ beams : heaven and earth



black hole

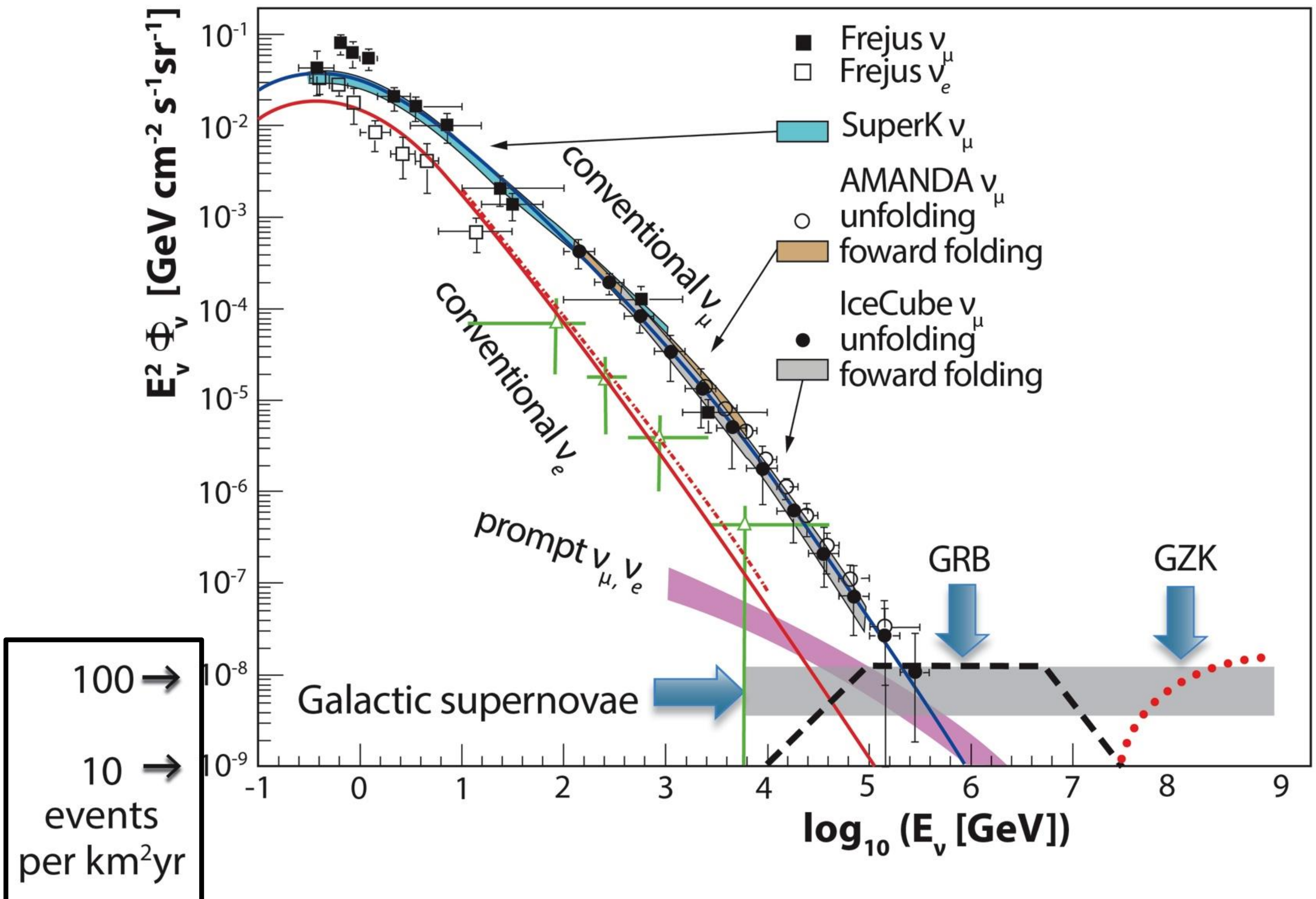
radiation and dust

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

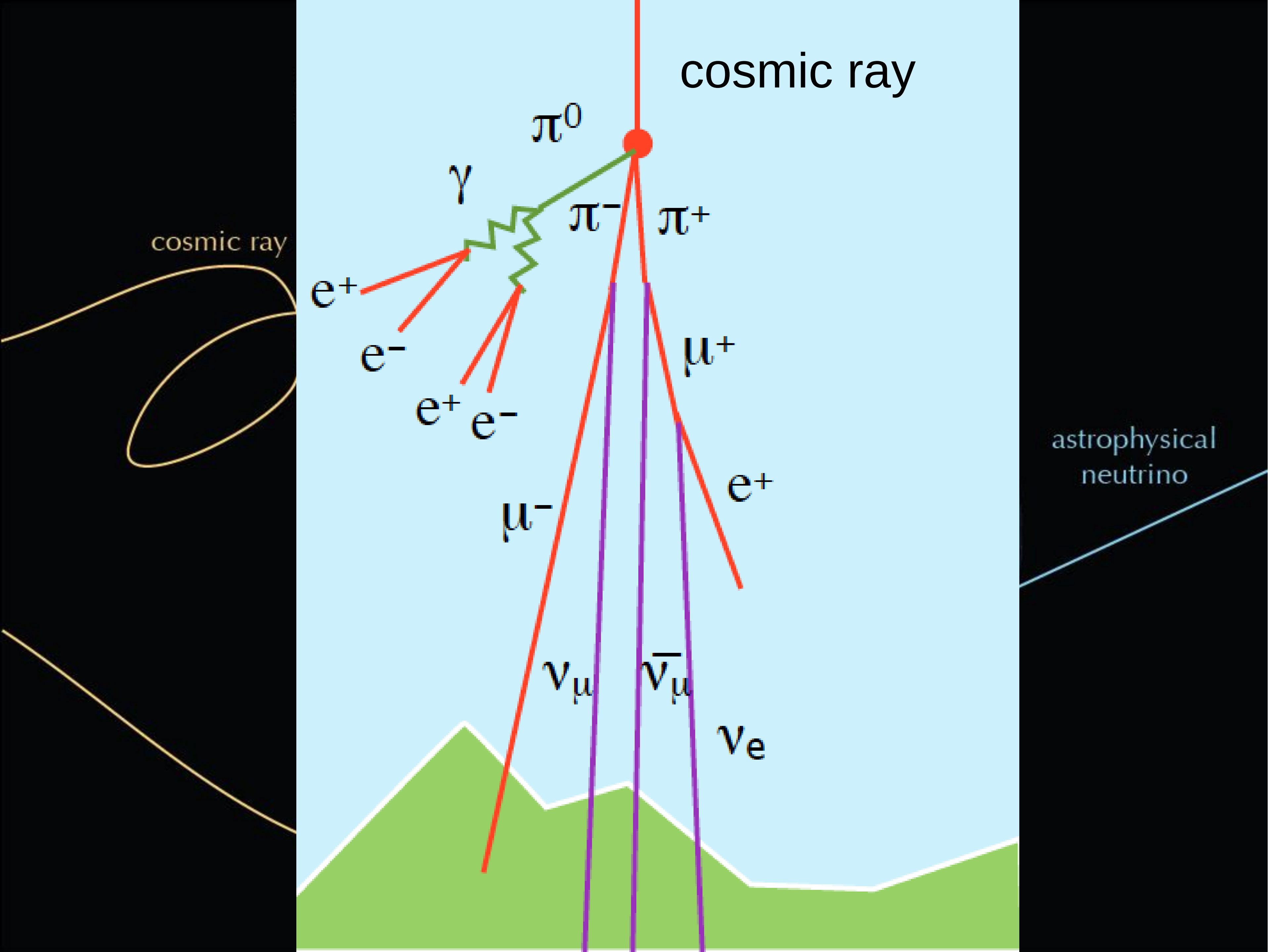
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

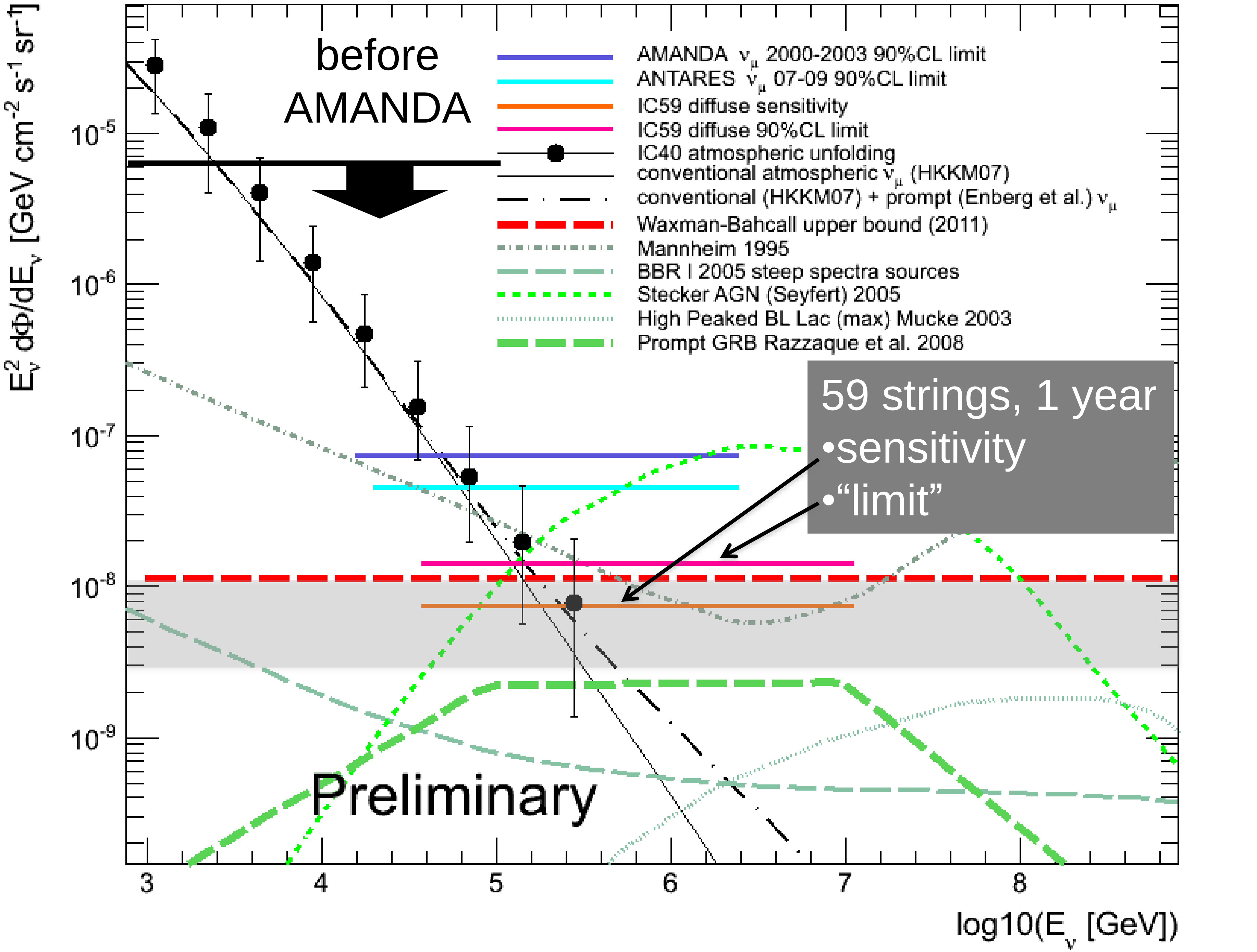
~ cosmic ray + gamma



$$F_{n} \text{ o } \frac{dN}{dE} » \frac{1}{E^{2}}$$

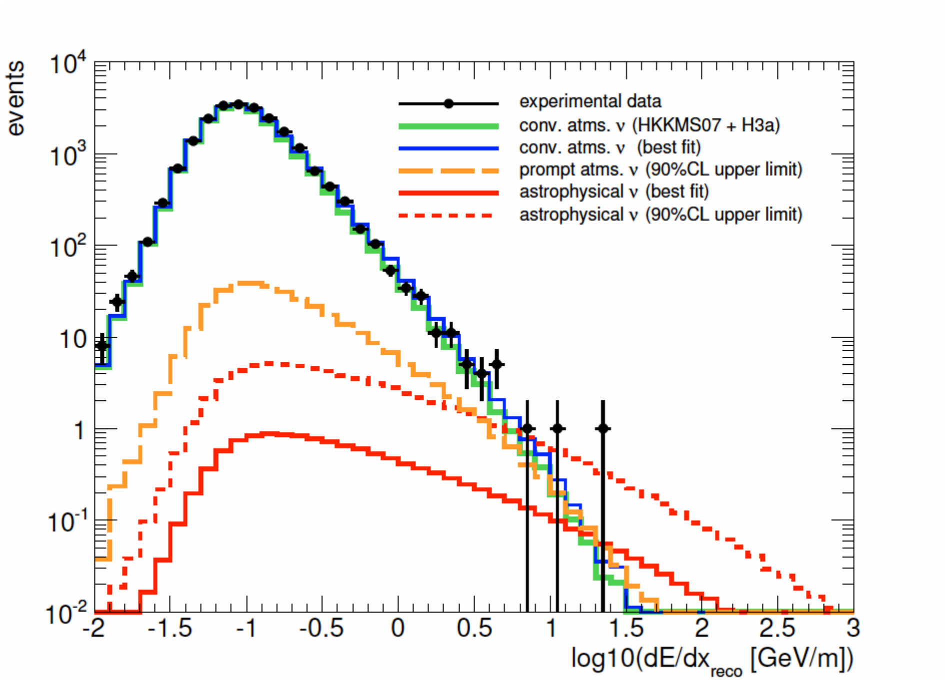


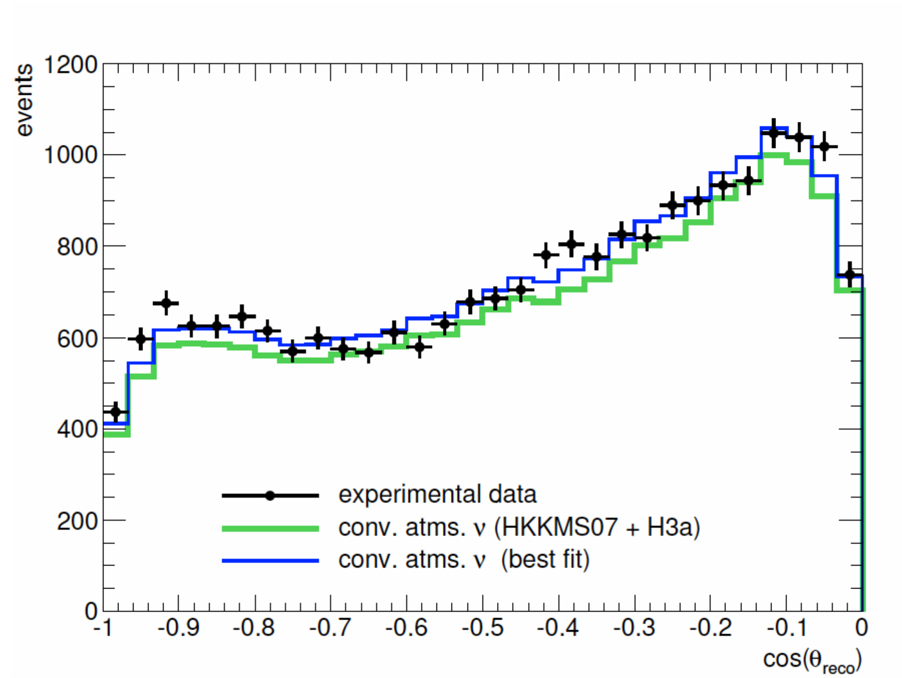
cosmic ray
π0
γ
π−
π+
cosmic ray
e+
e−
e+
e−
μ+
astrophysical
neutrino
e+
μ−
νμ
ν̄μ
νe



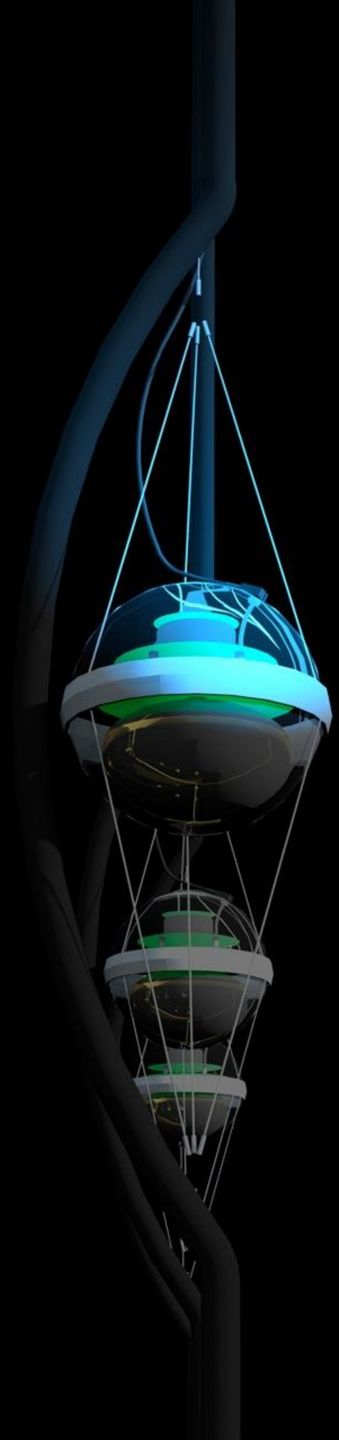
before AMANDA
AMANDA ν_μ 2000-2003 90%CL limit
ANTARES ν_μ 07-09 90%CL limit
IC59 diffuse sensitivity
IC59 diffuse 90%CL limit
IC40 atmospheric unfolding
conventional atmospheric ν_μ (HKKM07)
conventional (HKKM07) + prompt (Enberg et al.) ν_μ
Waxman-Bahcall upper bound (2011)
Mannheim 1995
BBR I 2005 steep spectra sources
Stecker AGN (Seyfert) 2005
High Peaked BL Lac (max) Mucke 2003
Prompt GRB Razzaque et al. 2008
59 strings, 1 year
•sensitivity
•"limit"
Preliminary
$E_\nu^2\, d\Phi/dE_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
3
4
5
6
7
8
log10(E_ν [GeV])

IceCube 59: the last limit ?





Sterile neutrinos? More about neutrino physics later



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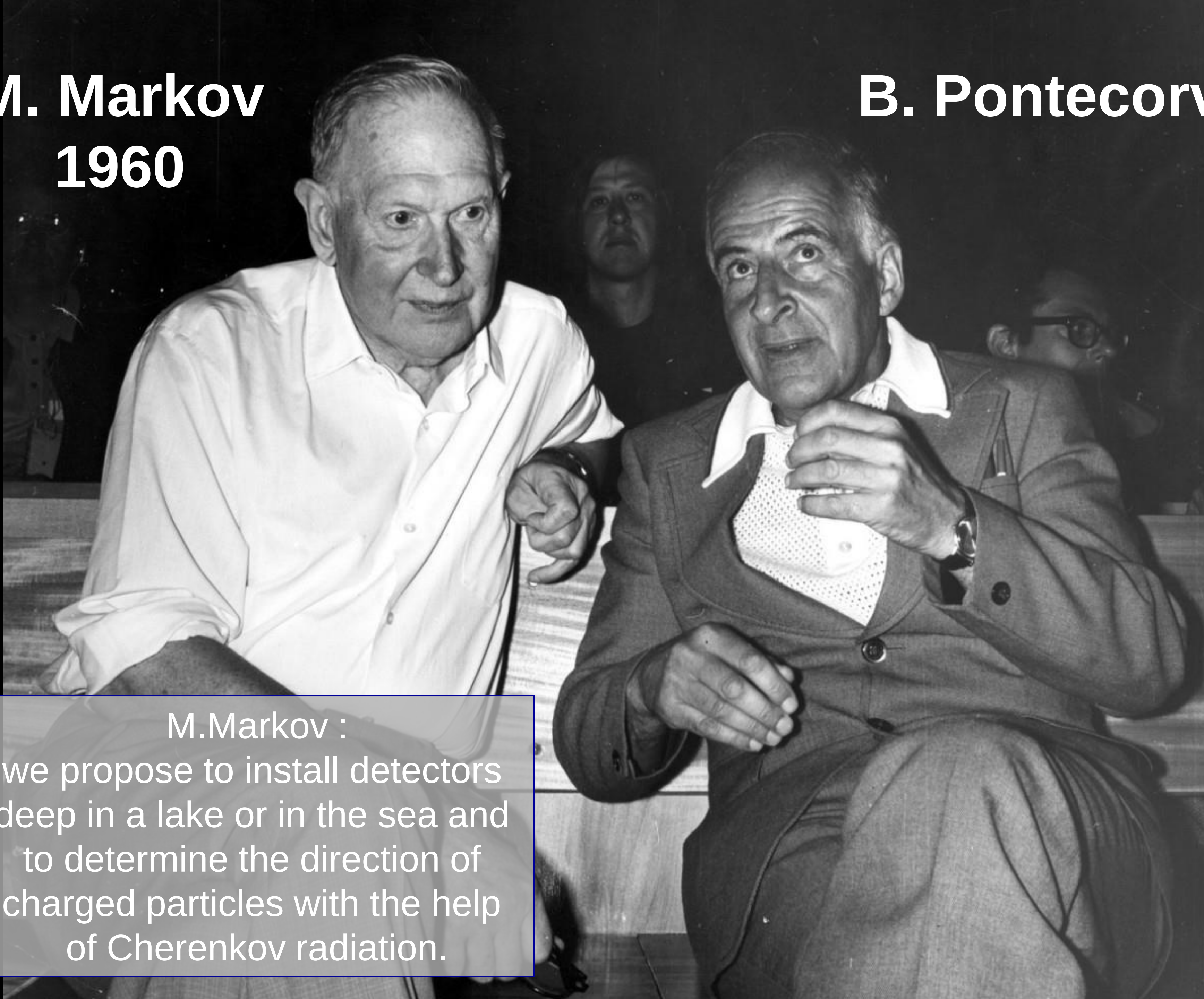
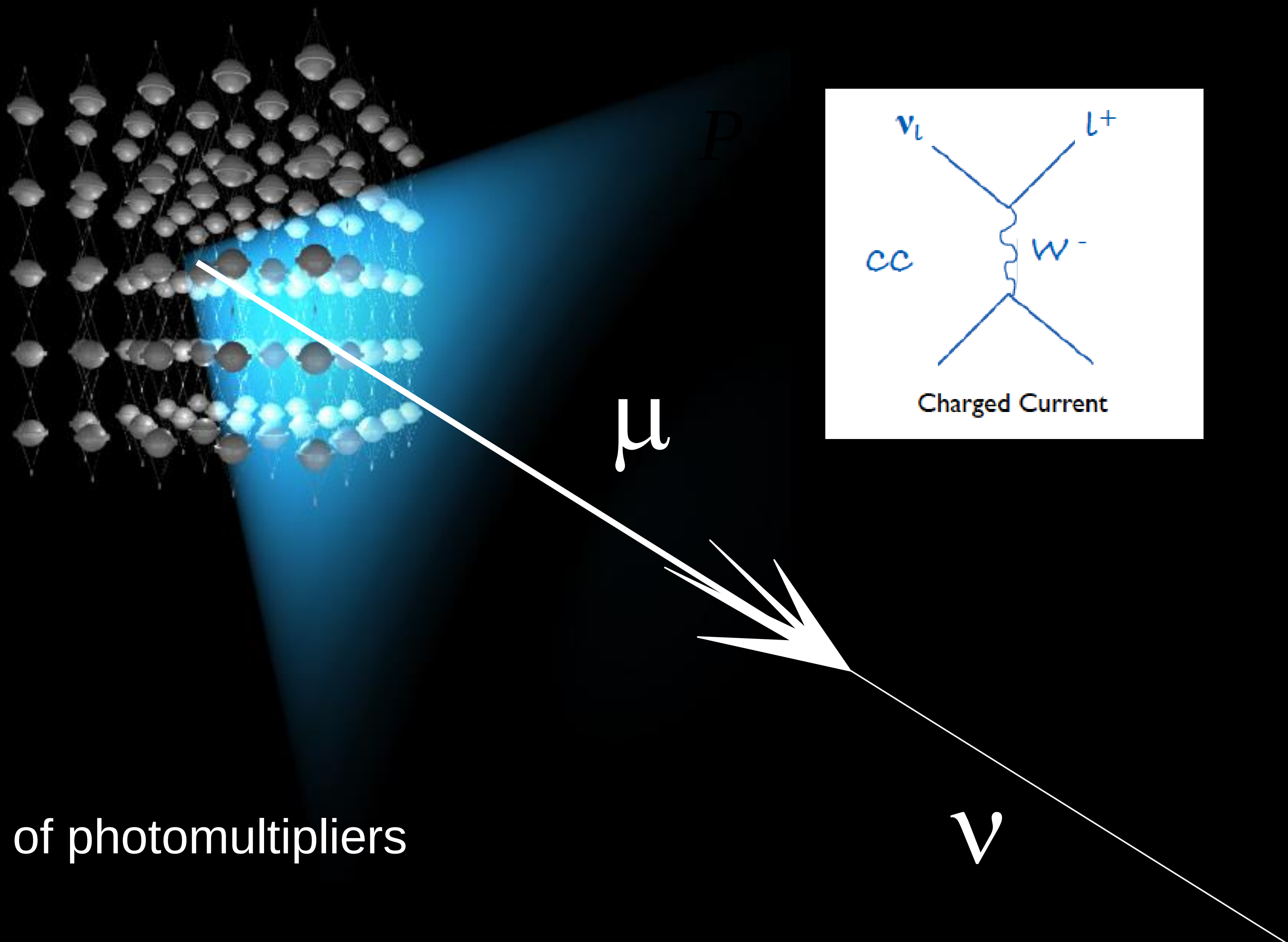


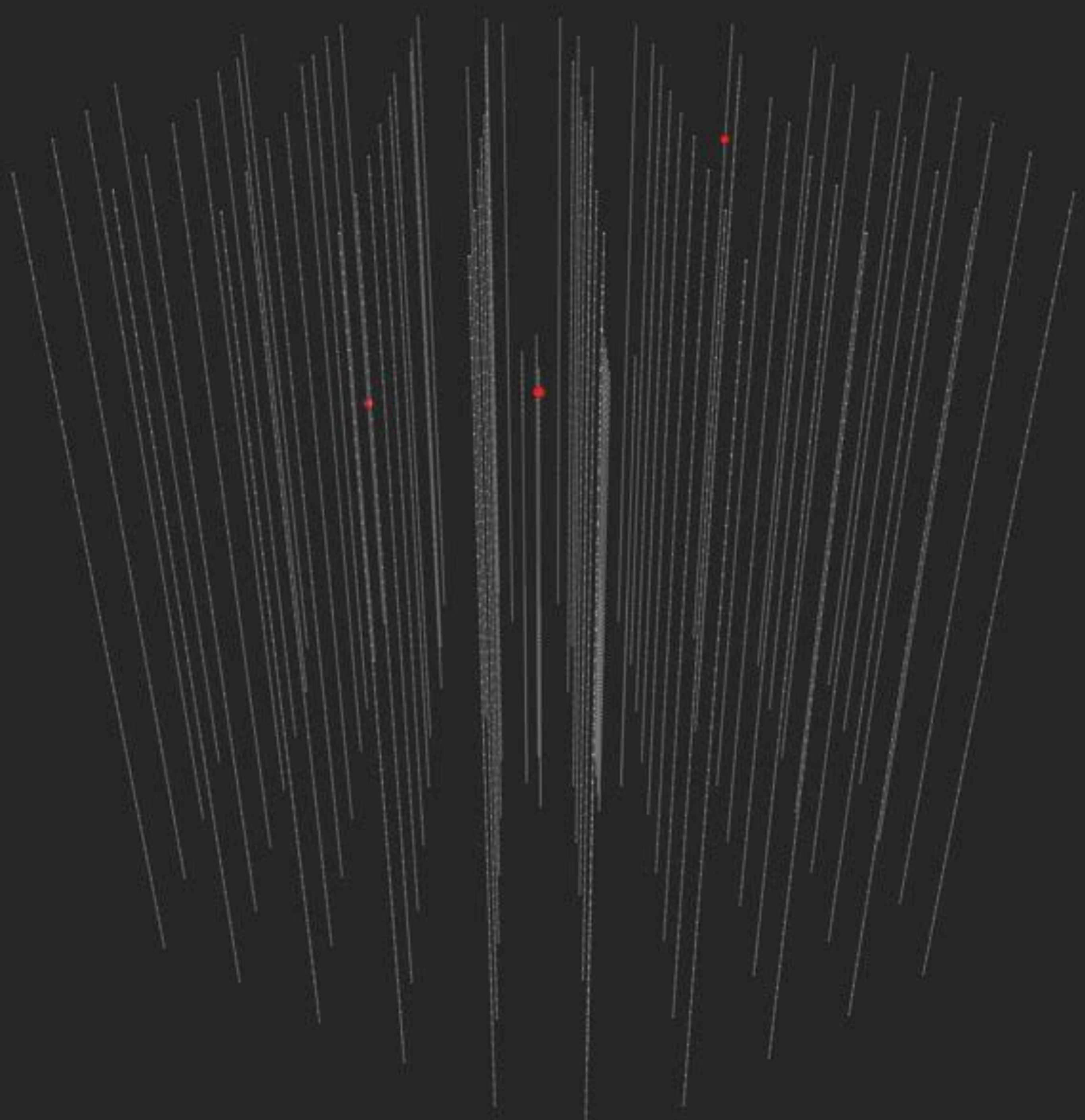
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

- shielded and optically transparent medium

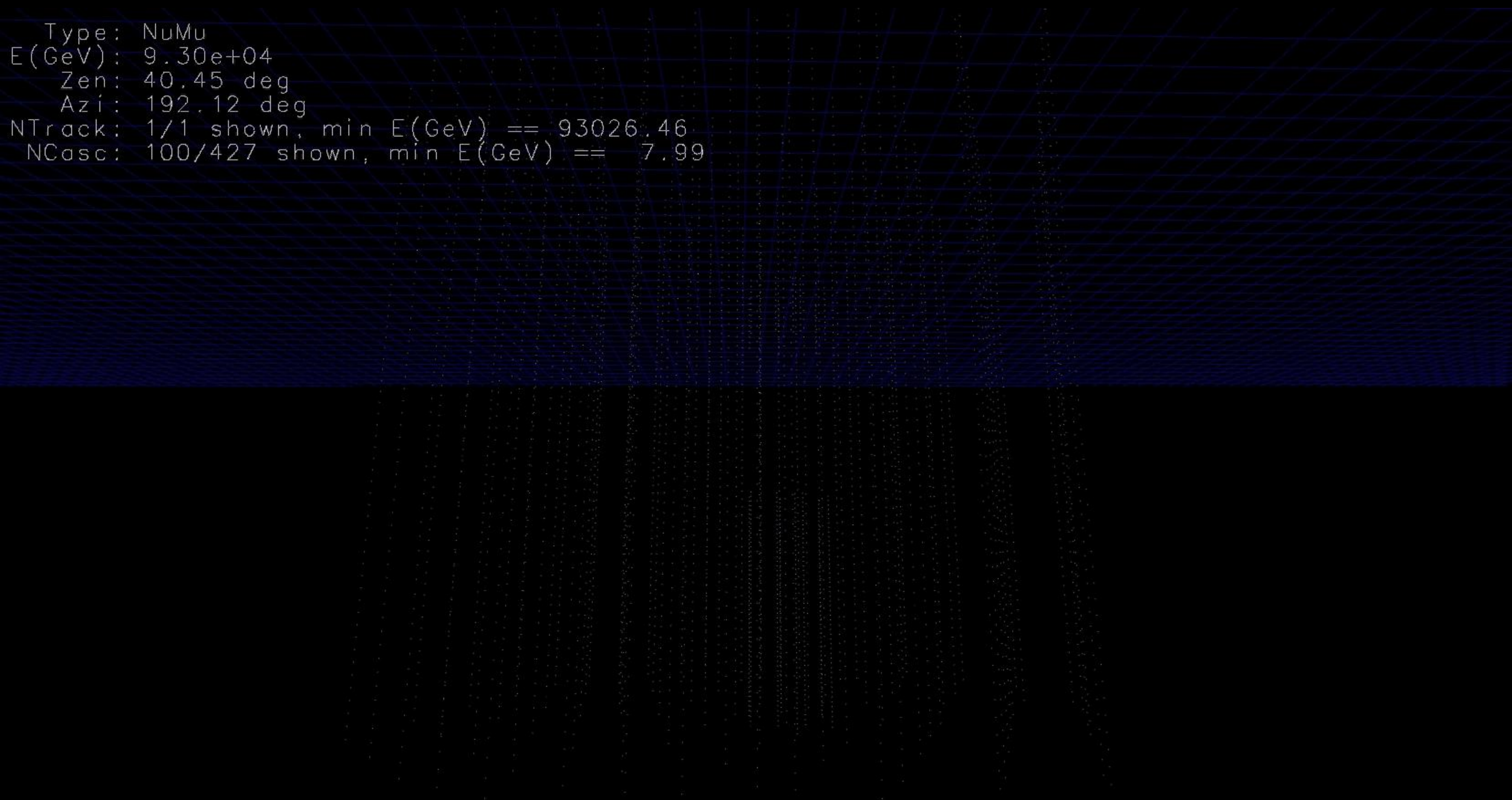


- lattice of photomultipliers

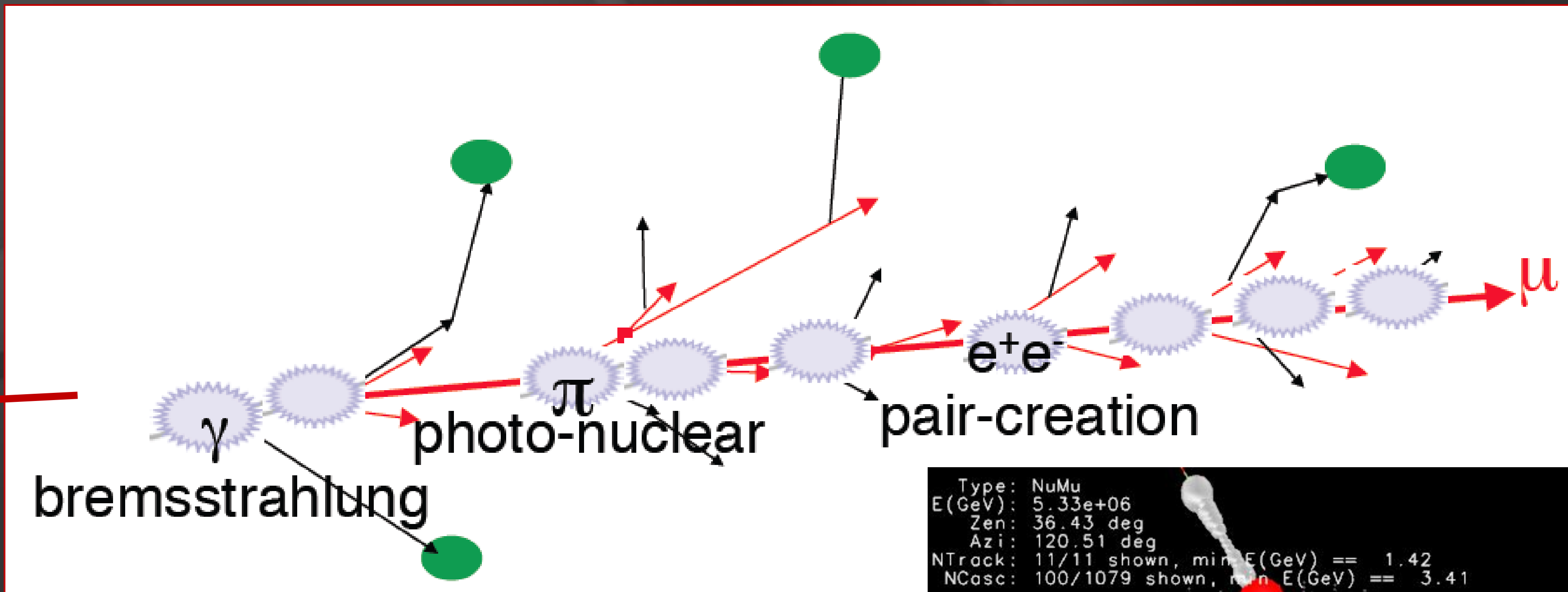
photomultiplier tube

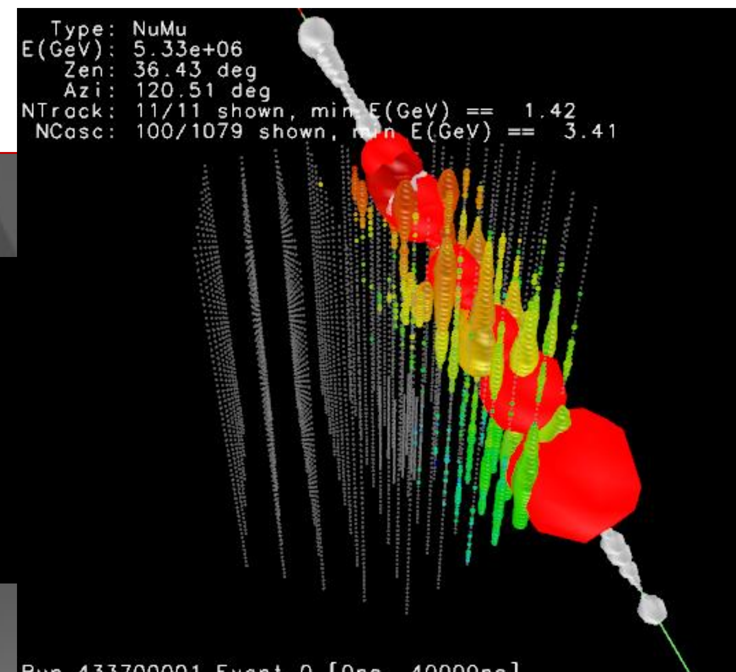


93 TeV muon

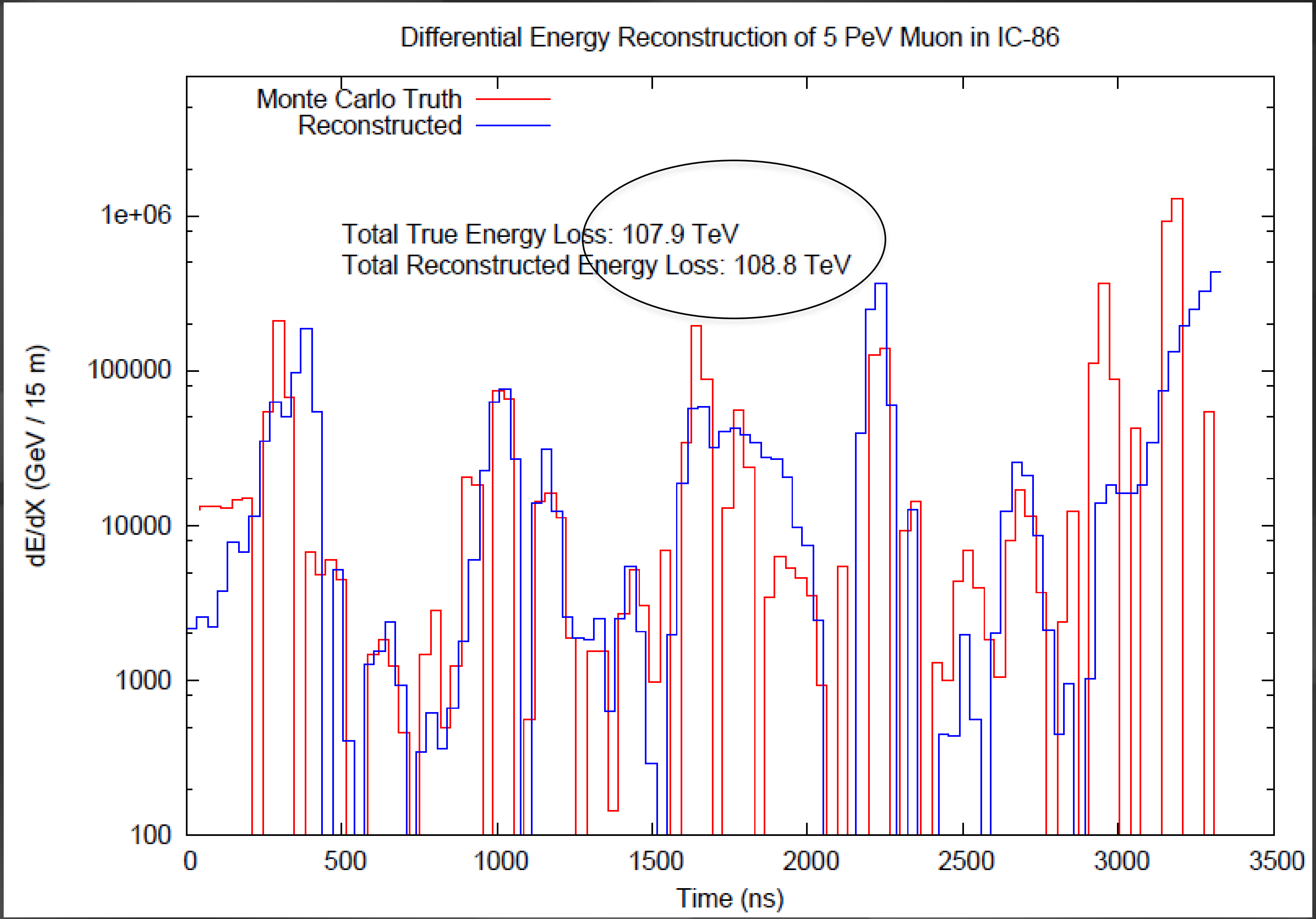

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)



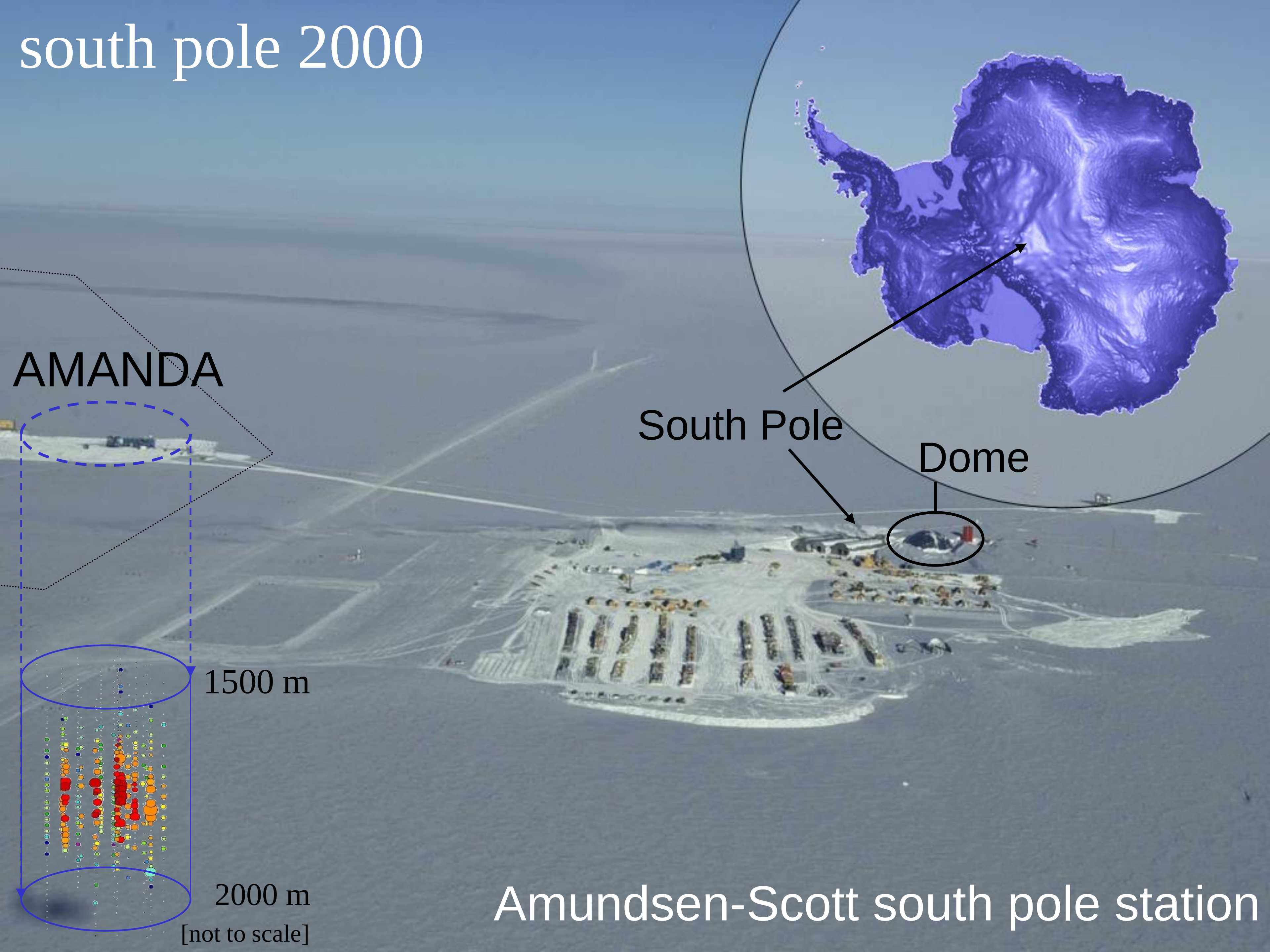


convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



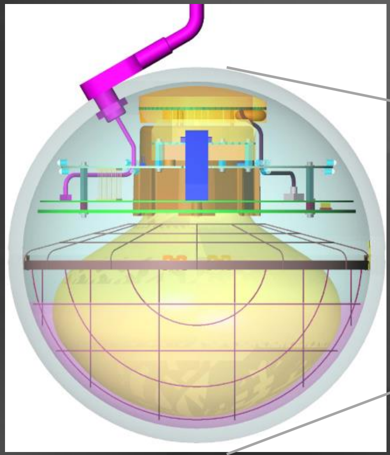
improving angular and energy resolution


why did it take so long ?

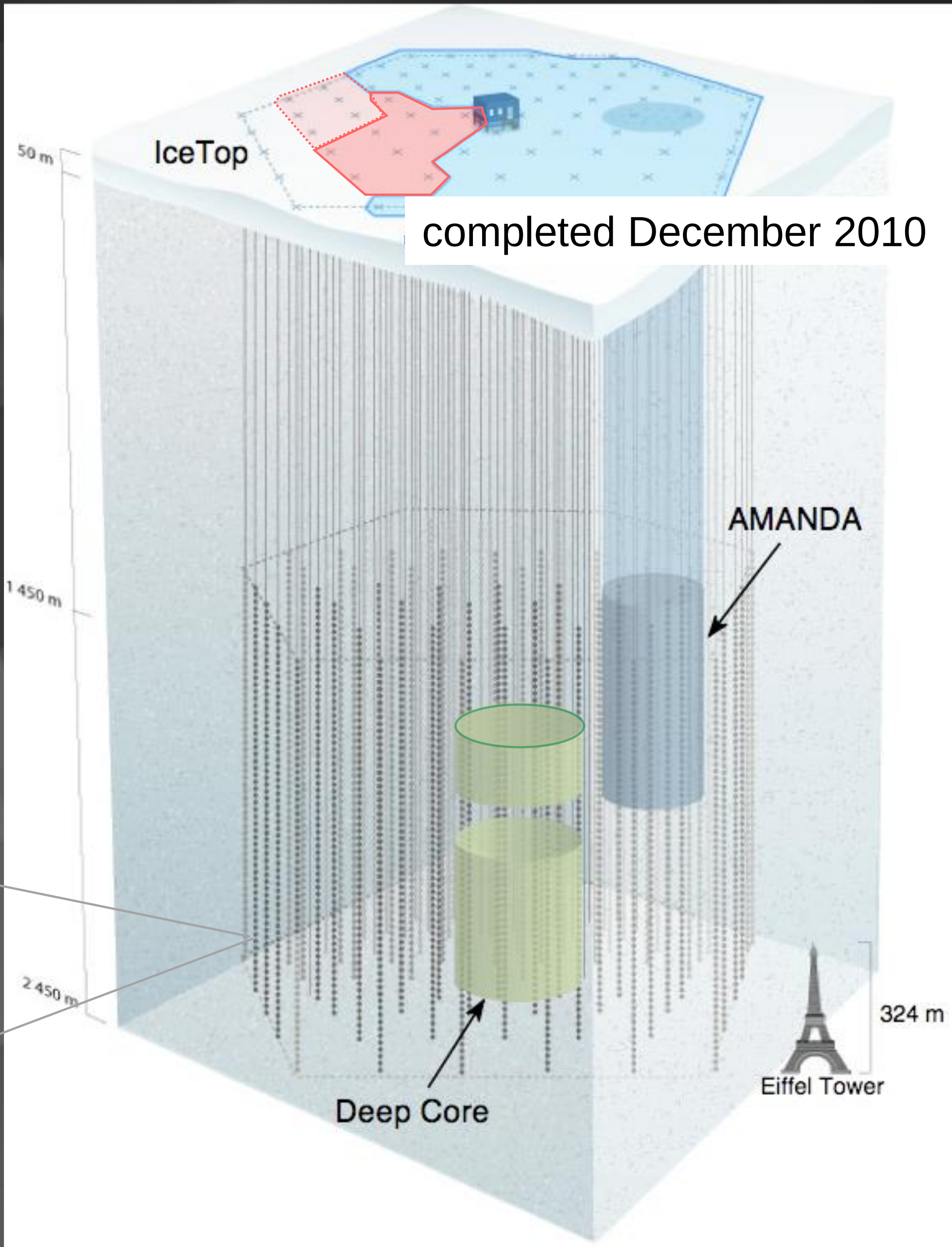

south pole 2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott south pole station

IceCube / Deep Core

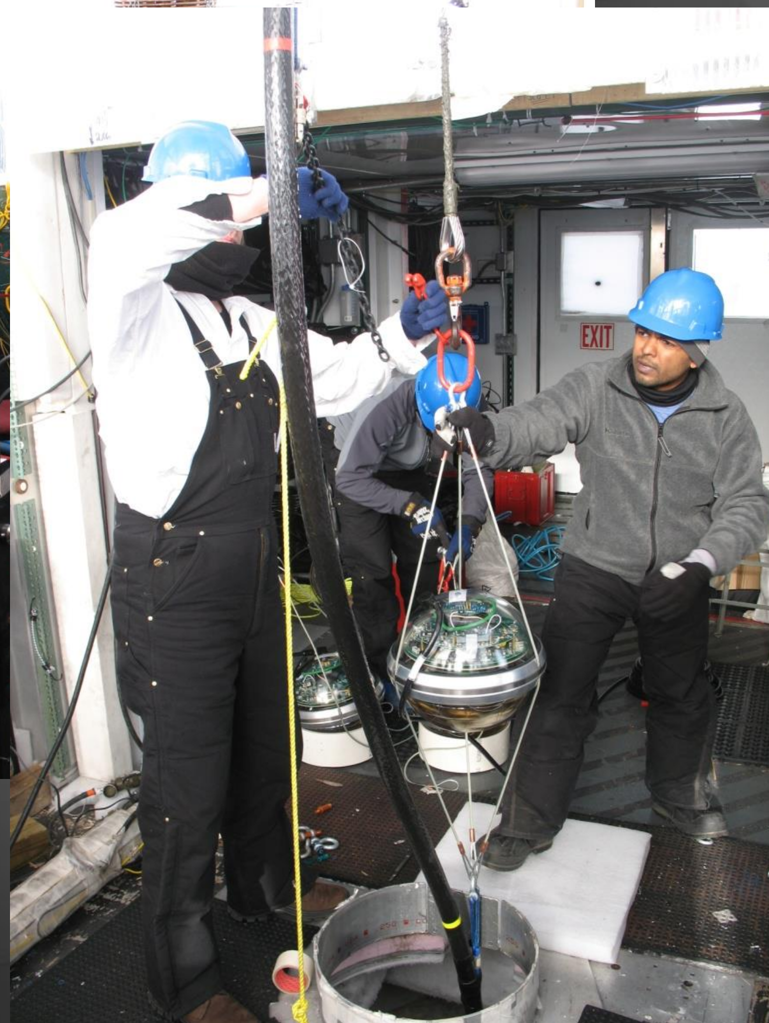
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
  < 0.3 degree off line
  for muons
  (10~15 degrees for showers)
- < 15% energy resolution



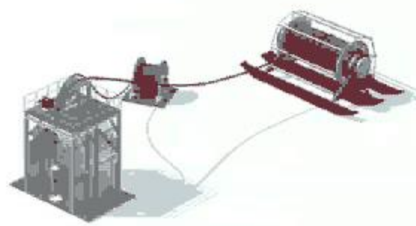
Digital Optical Module (DOM)

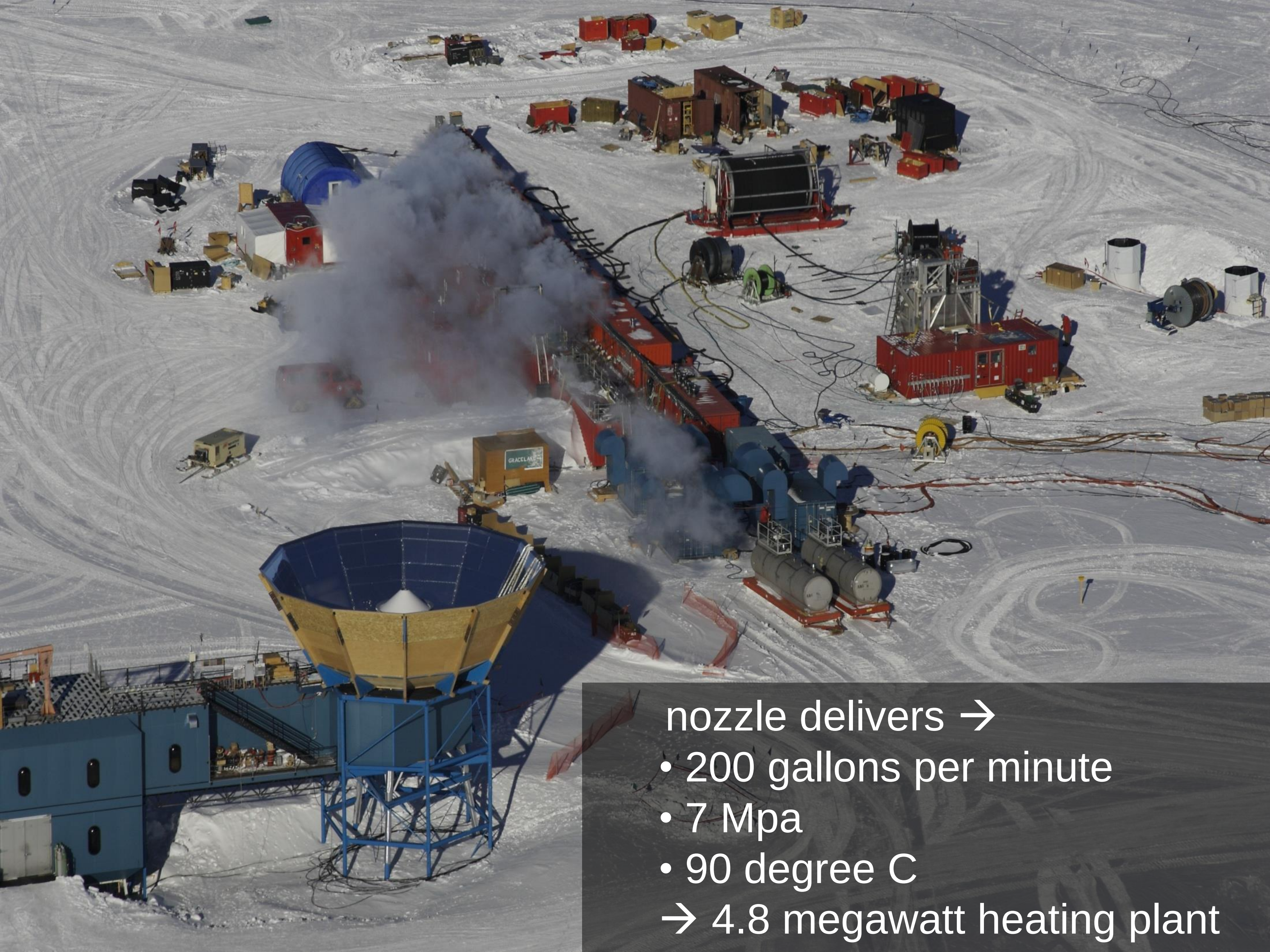


drilling and deployment

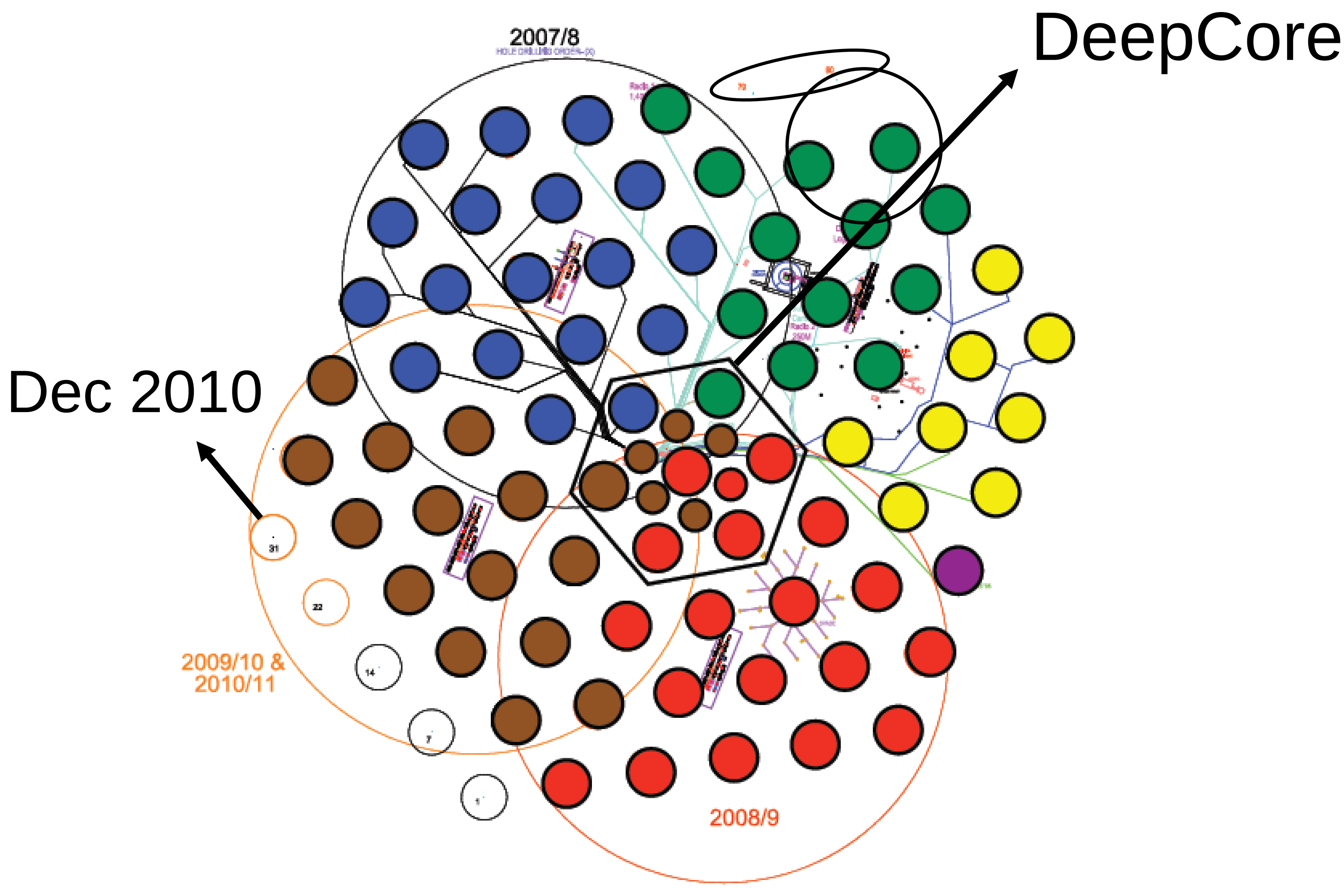


2 days per hole
3.5 cm/second

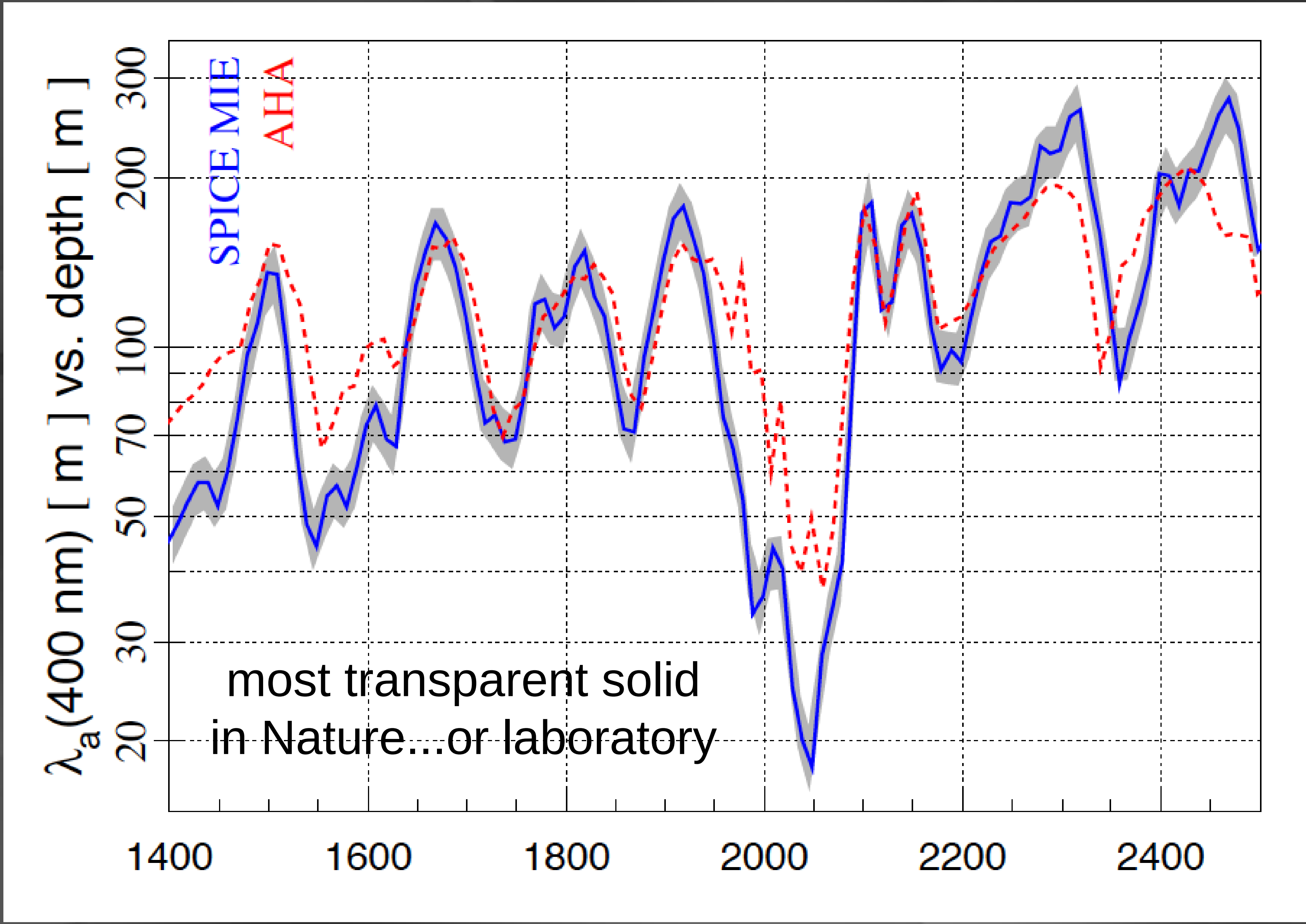



nozzle delivers →
• 200 gallons per minute
• 7 Mpa
• 90 degree C
→ 4.8 megawatt heating plant

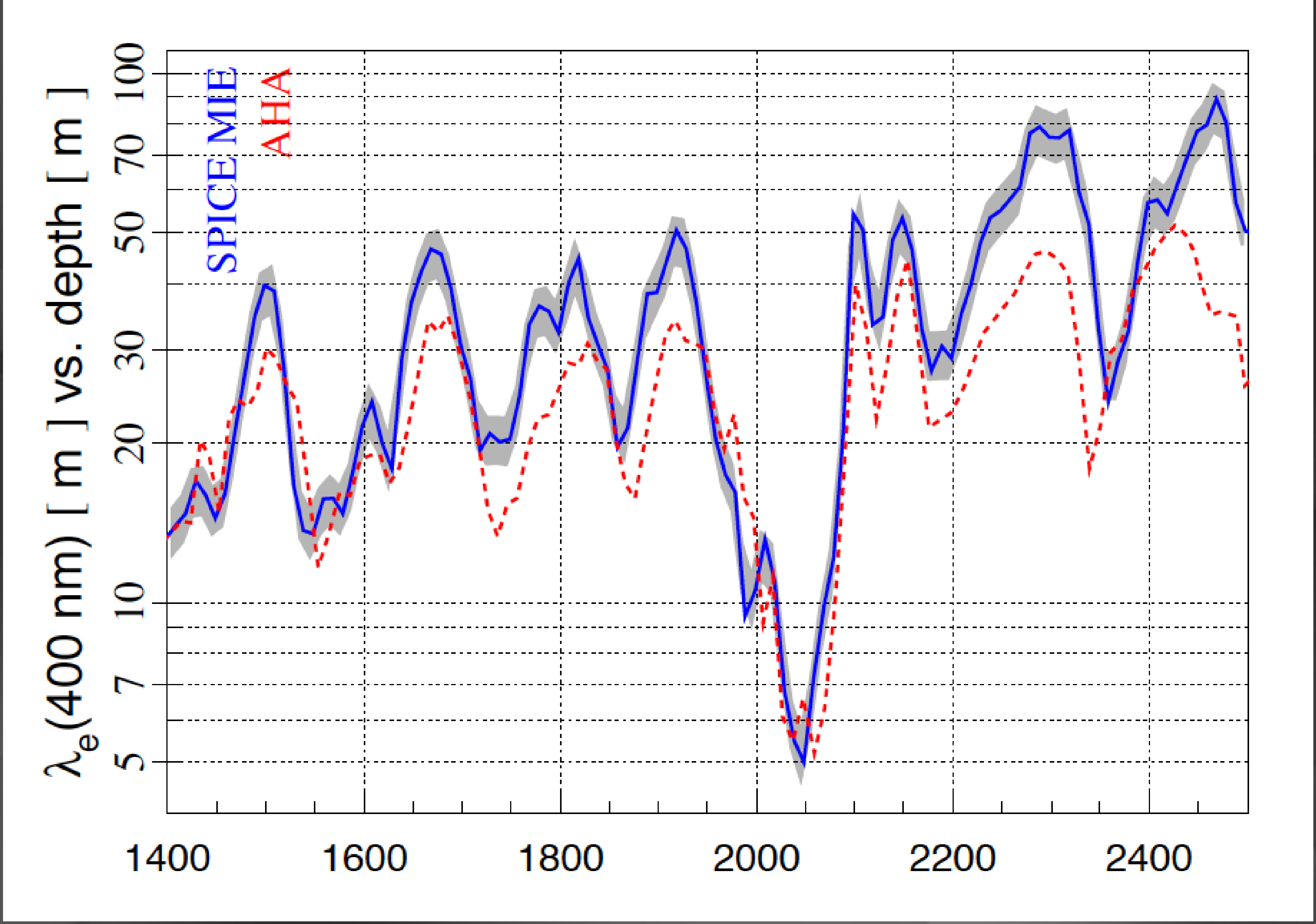
January 20, 2010

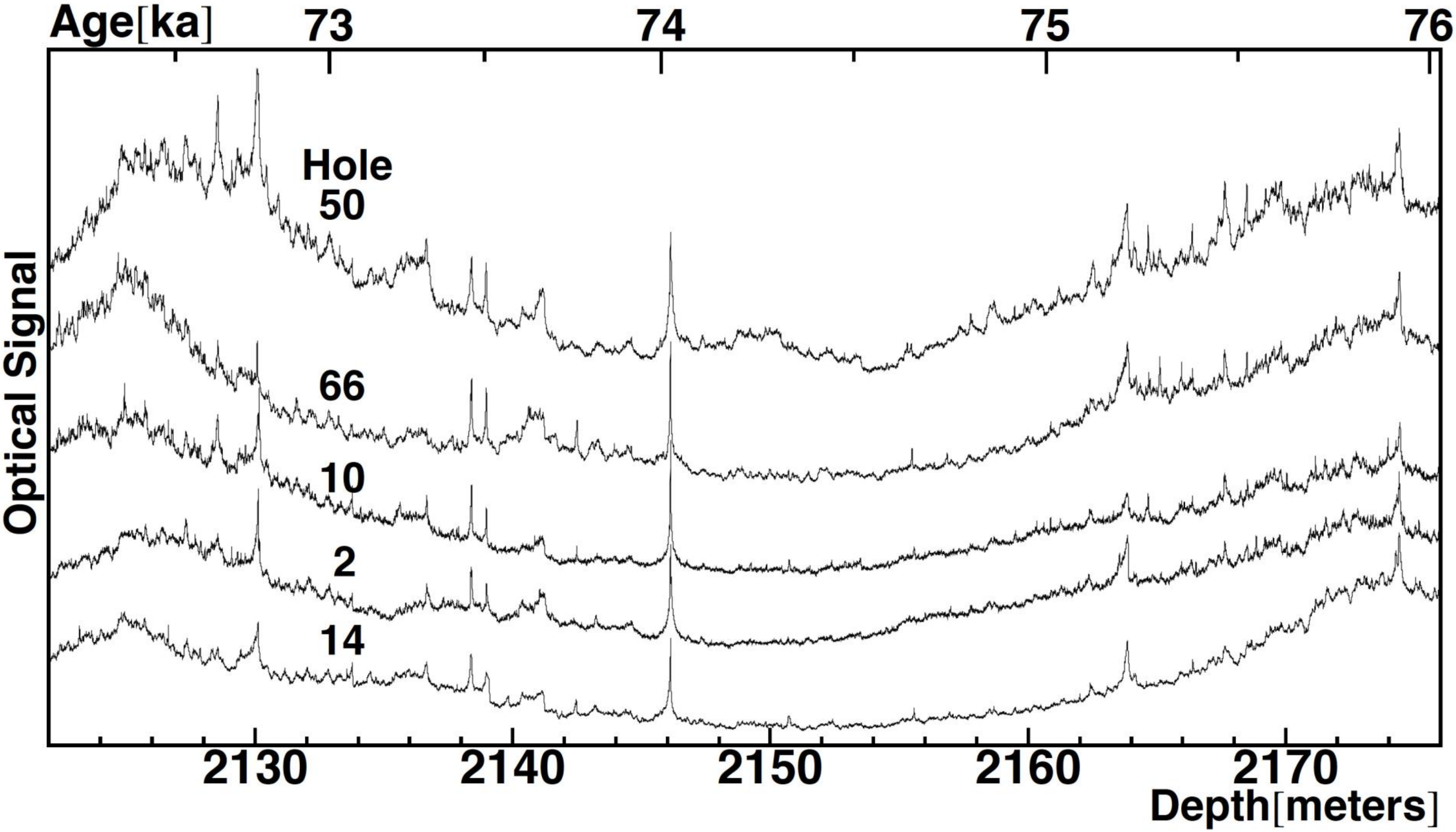


absorption length ← 220m →



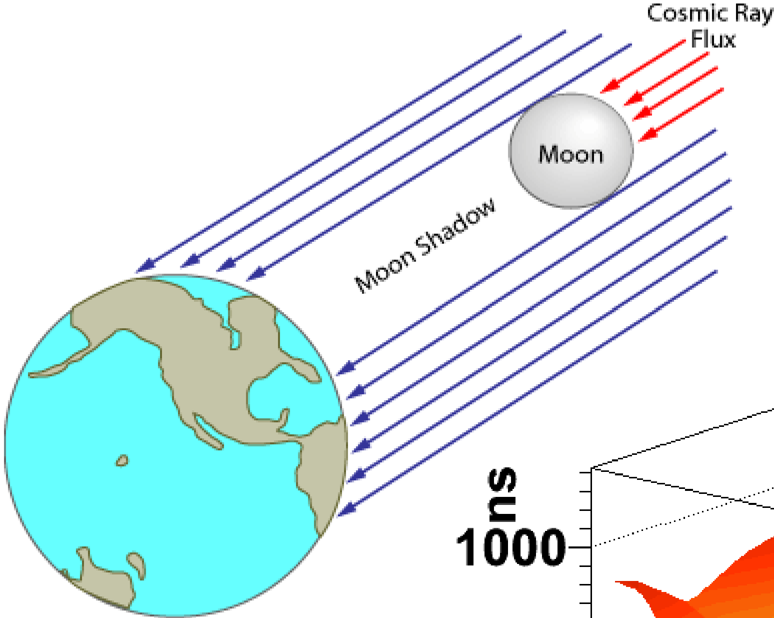
scattering length ← 47m →

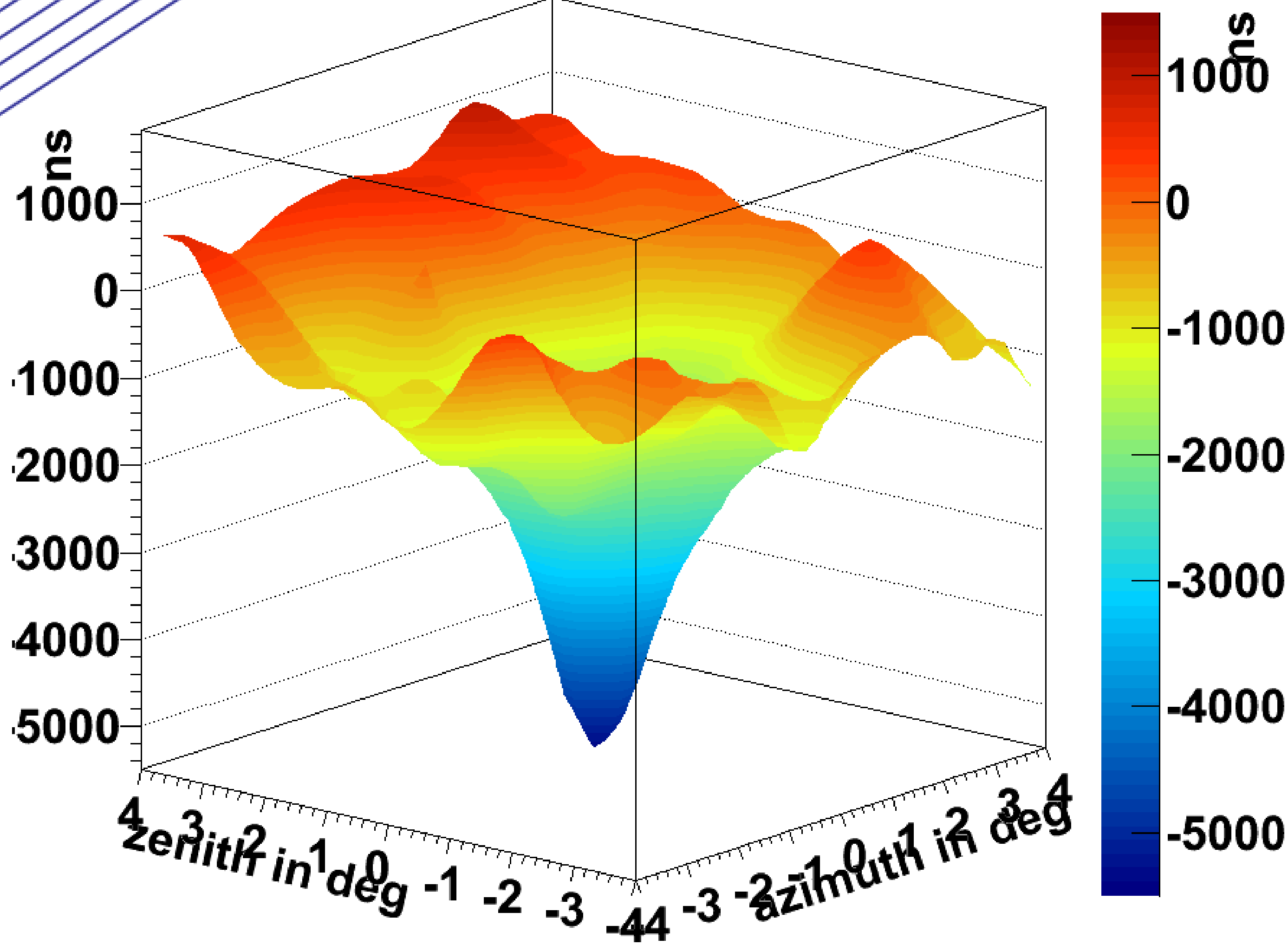




Age[ka]
73
74
75
76
Hole
50
66
10
2
14
Optical Signal
2130
2140
2150
2160
2170
Depth[meters]

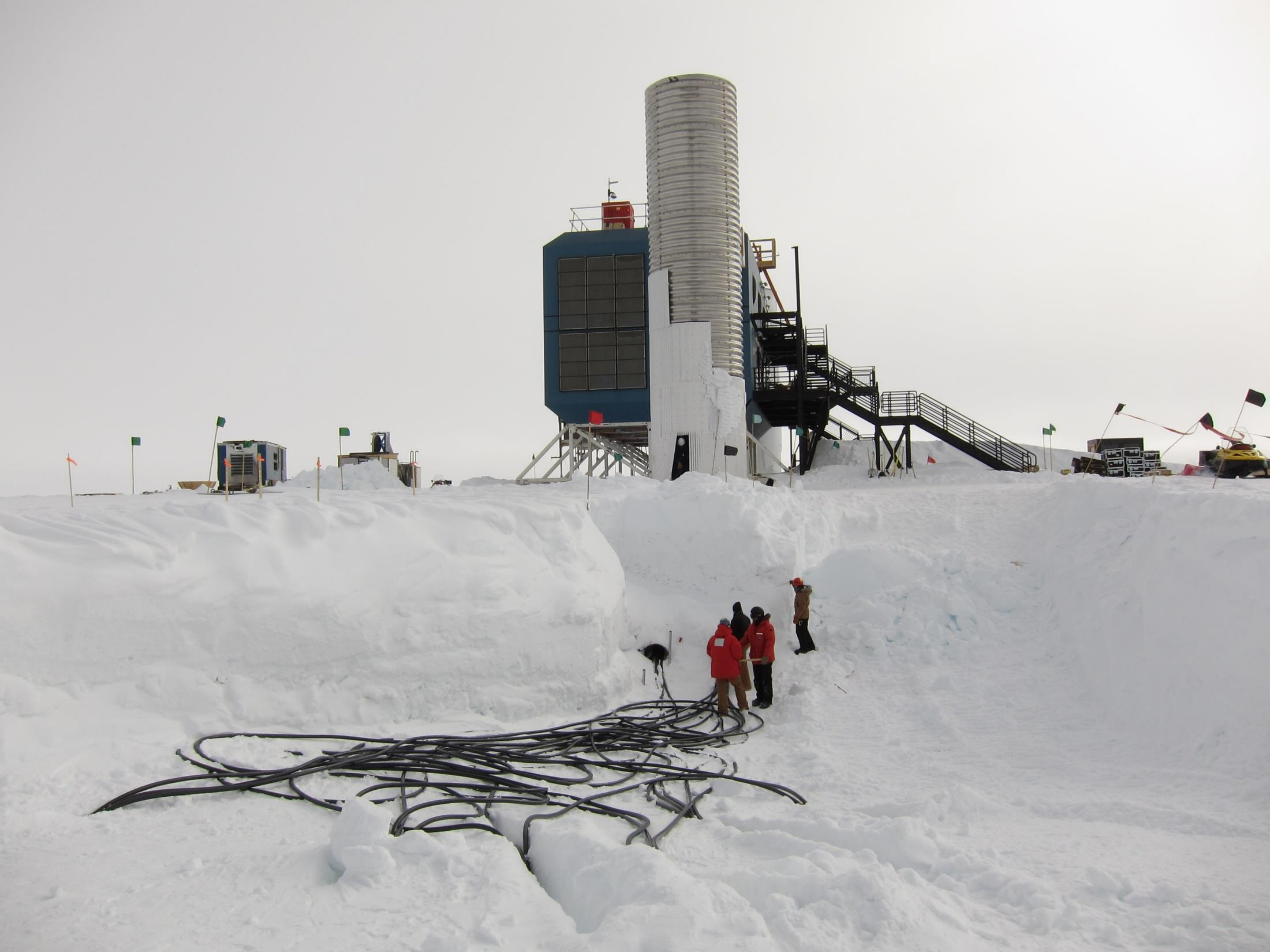
moon shadow





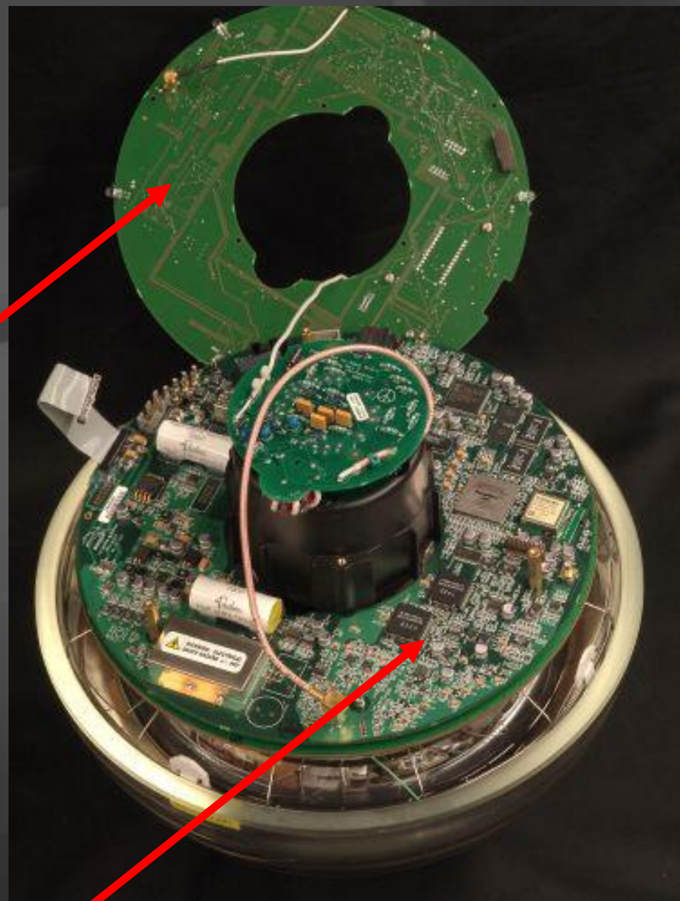
$> 10\sigma$

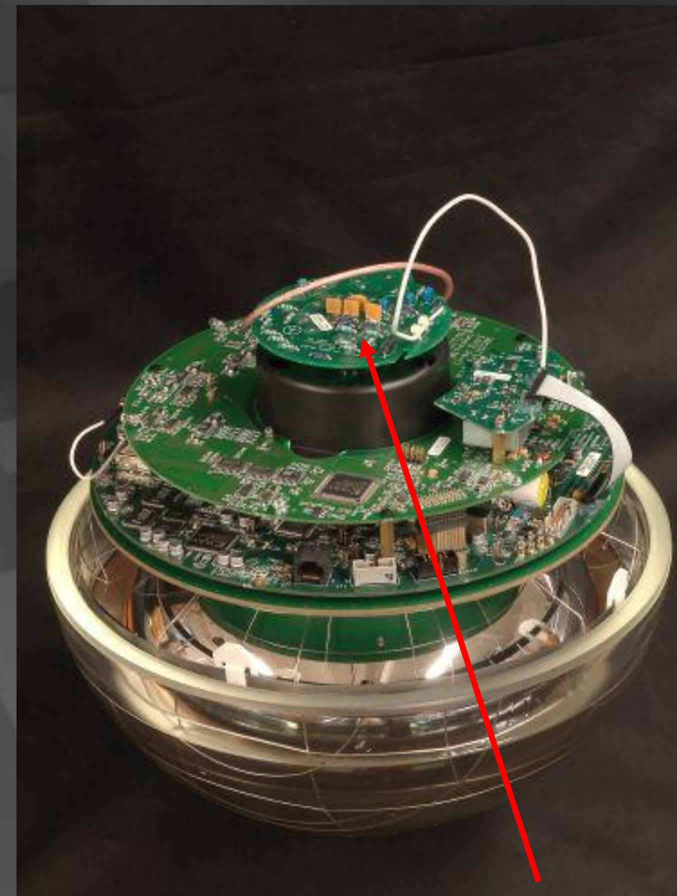
< 1 deg



architecture of independent DOMs

LED flasher board

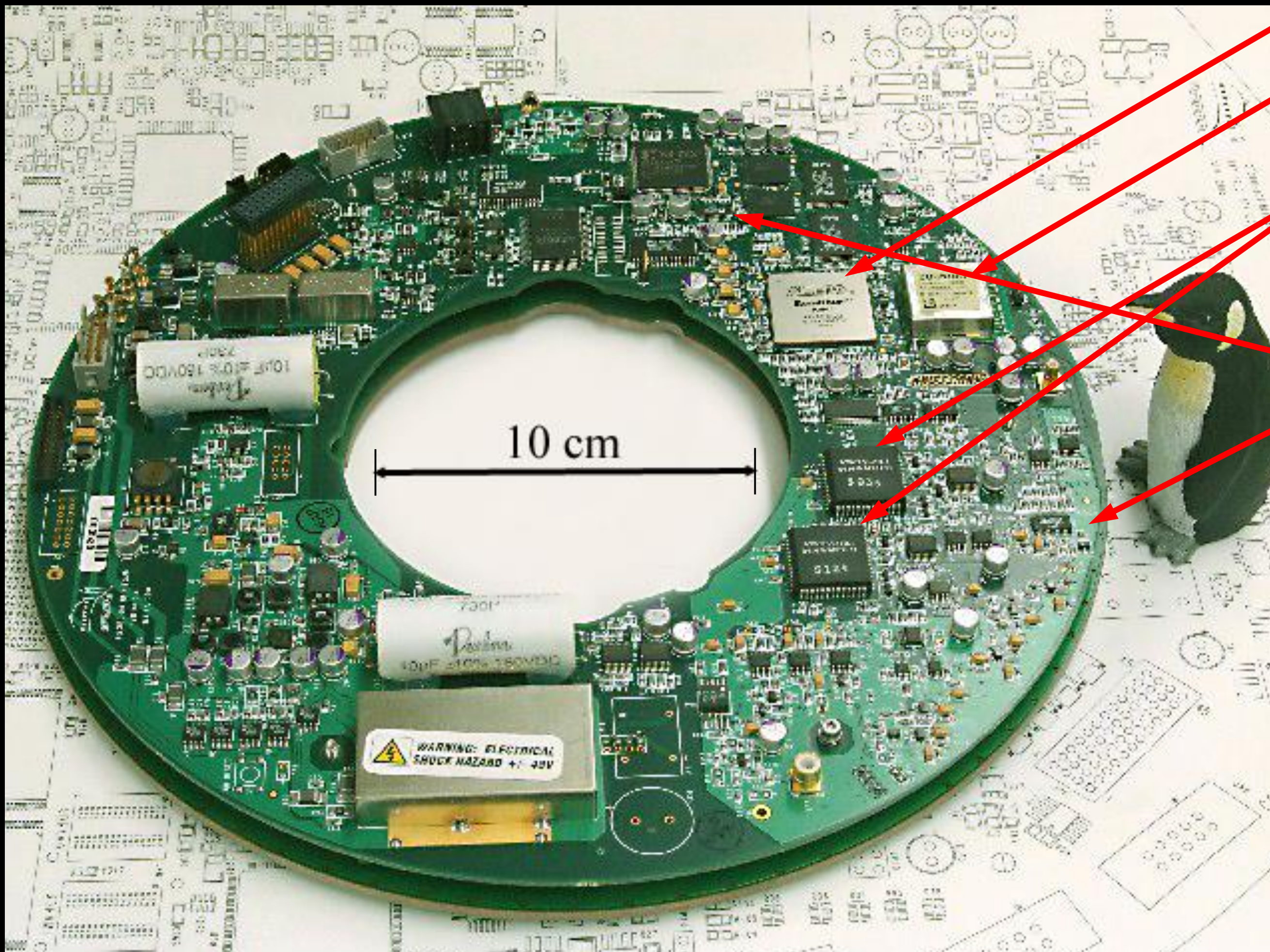




main board

HV board

Digital Optical Module Mainboard



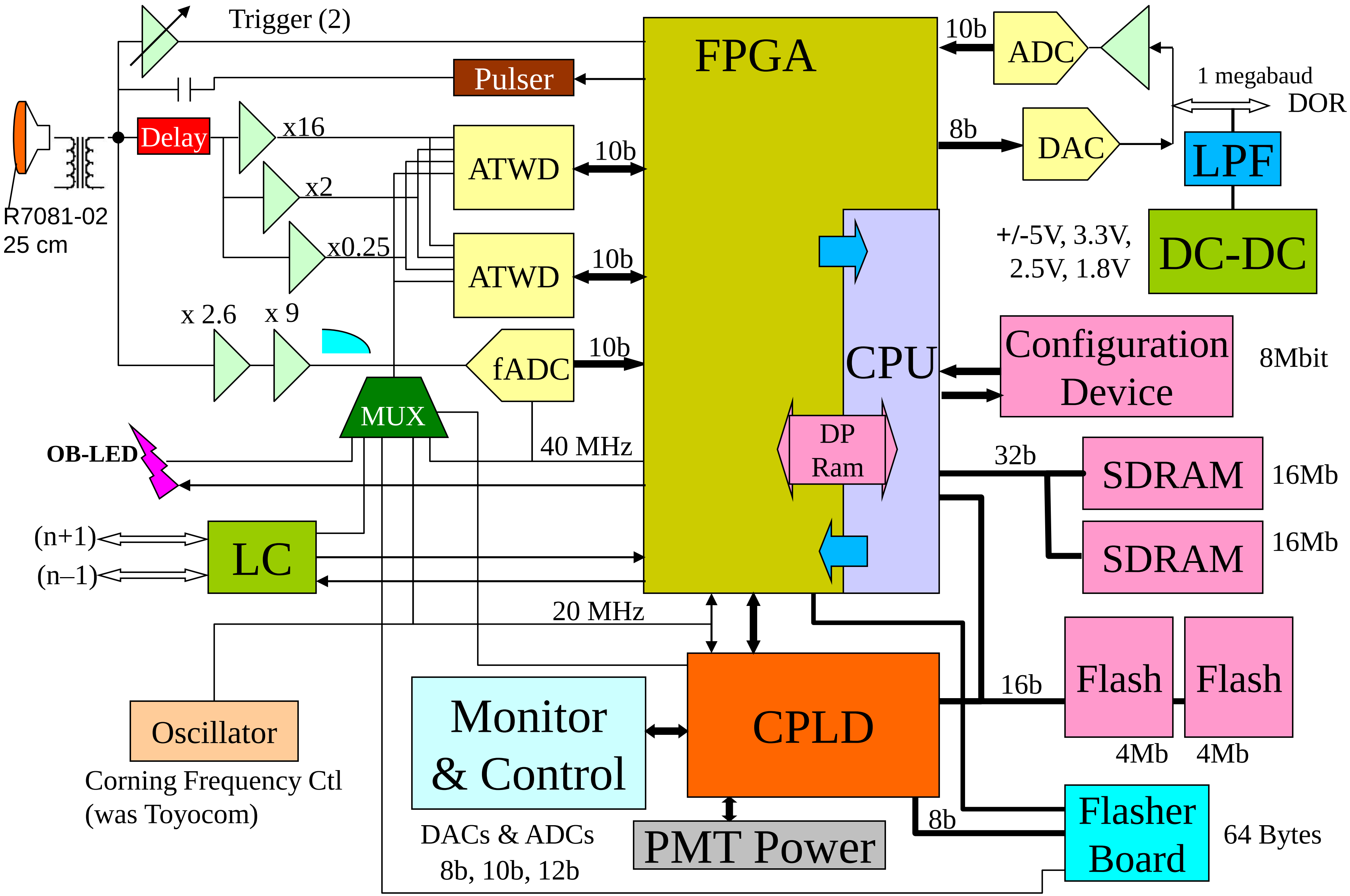
CPU+FPGA

20 MHz osc

2 ATWDs

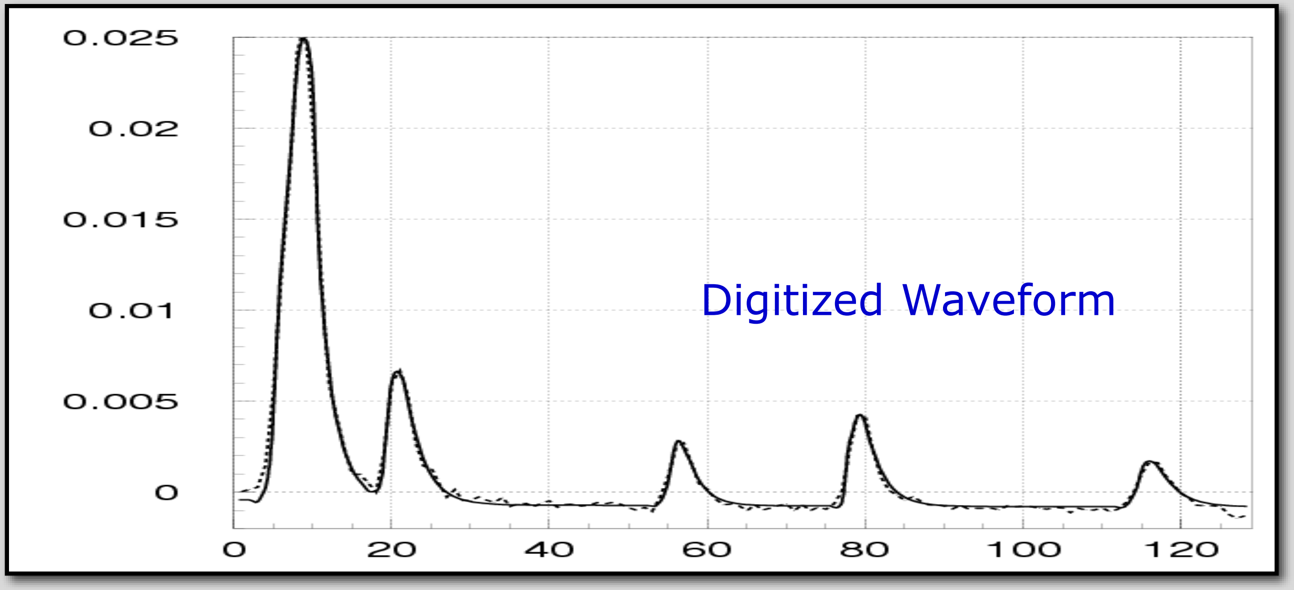
Fast ADC: waveform and COMM

DOM MB Block diagram



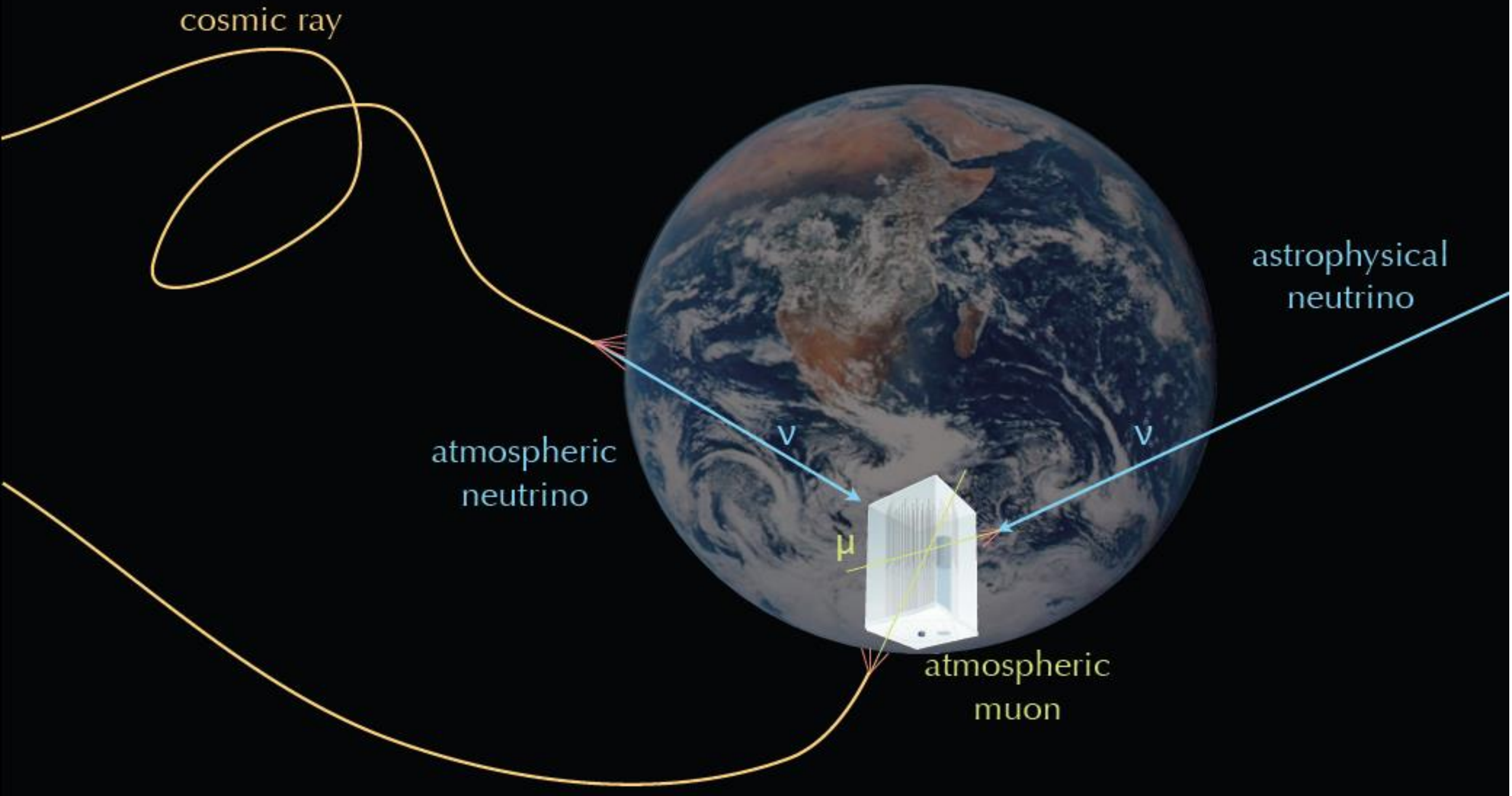
Digital Optical Module (DOM)

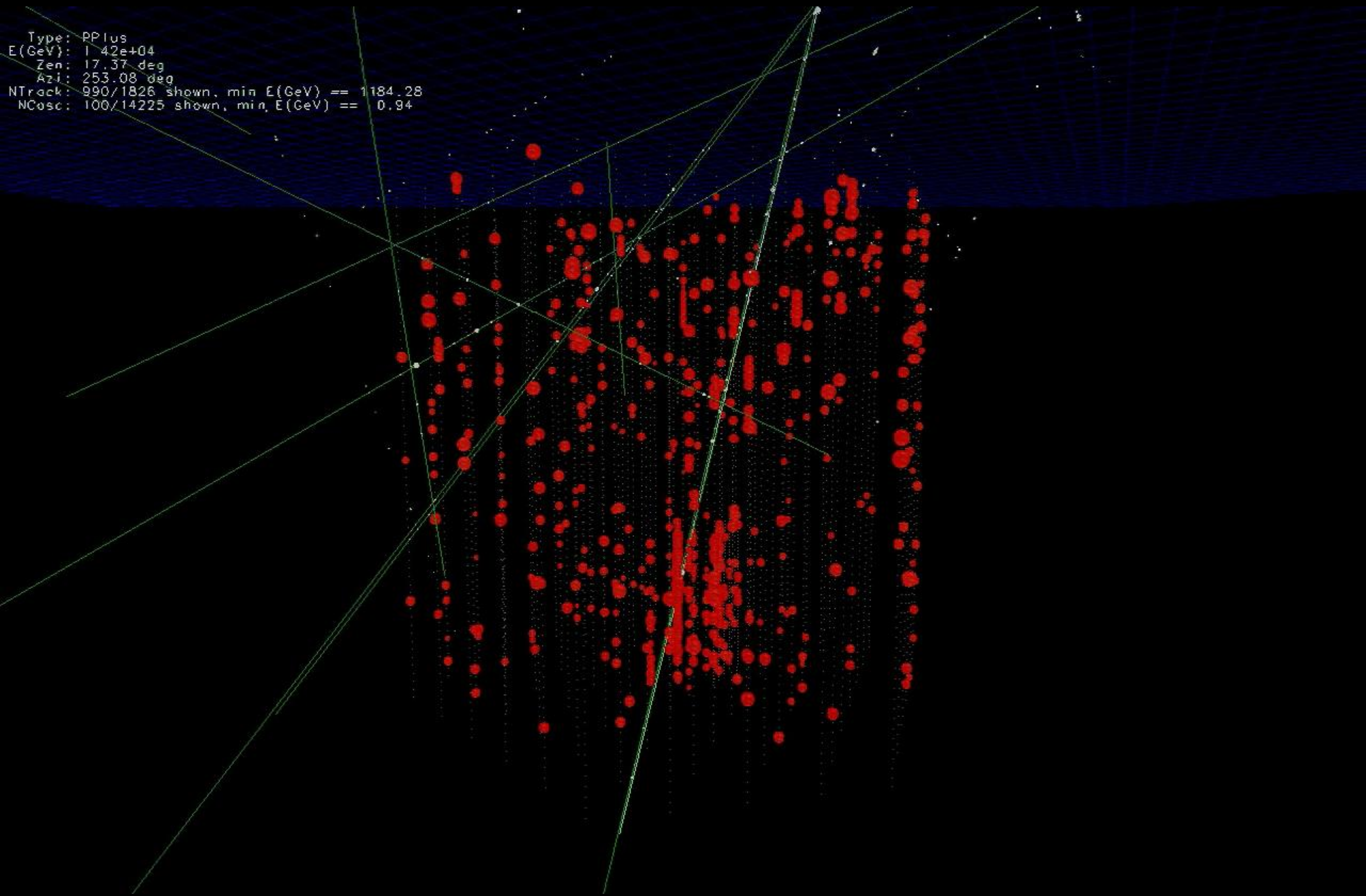
… each DOM independently collects light signals like this…



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

Signals and Backgrounds




Type: PPlus
E(GeV): 1 42e+04
Zen: 17.37 deg
Azi: 253.08 deg
NTrack: 990/1826 shown, min E(GeV) == 1184.28
NCosc: 100/14225 shown, min E(GeV) == 0.94

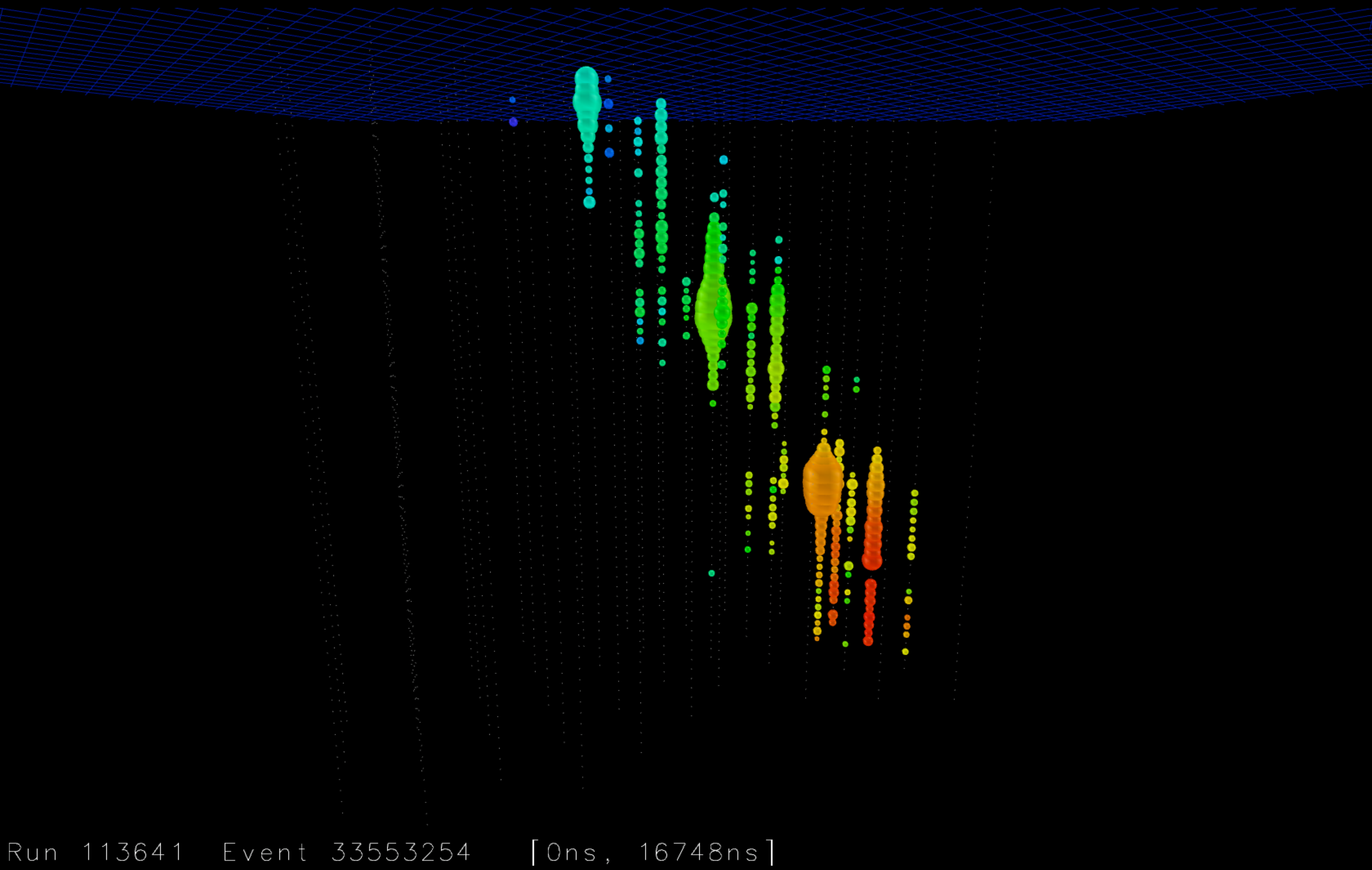
… you looked at 10msec of data !

muons detected per year:

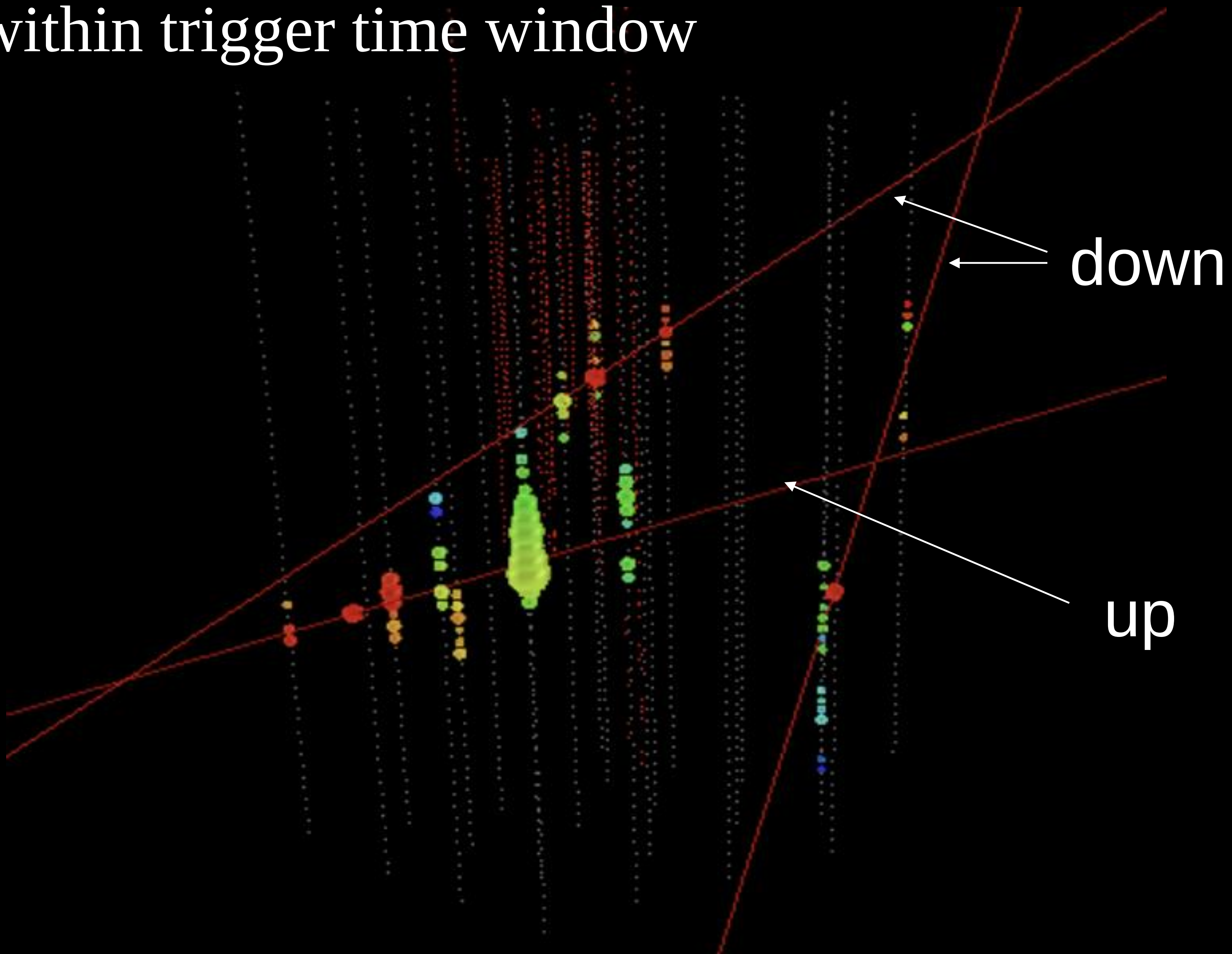
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^{5}$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 2700 per second

** 1 every 6 minutes

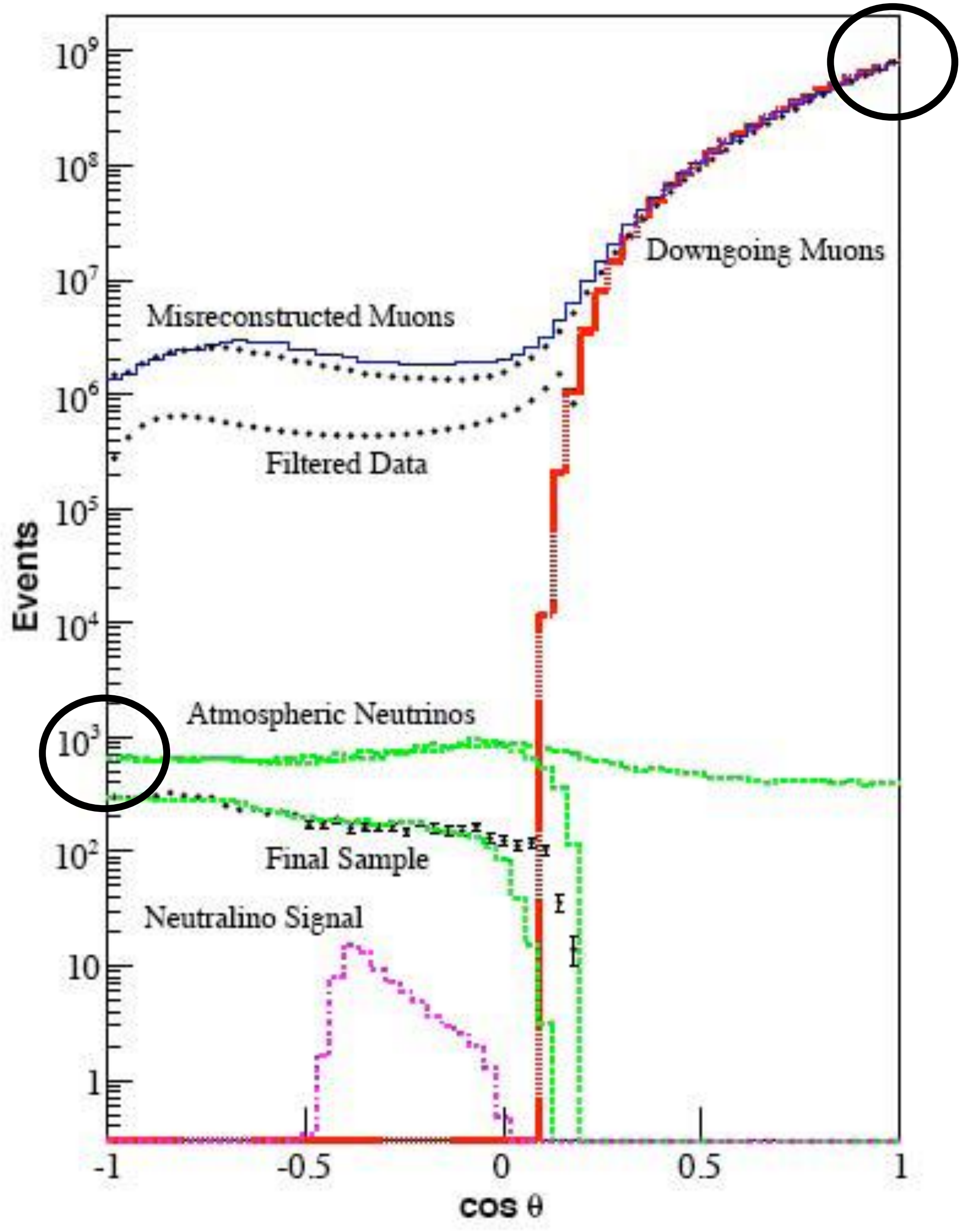

Run 113641 Event 33553254 [0ns, 16748ns]

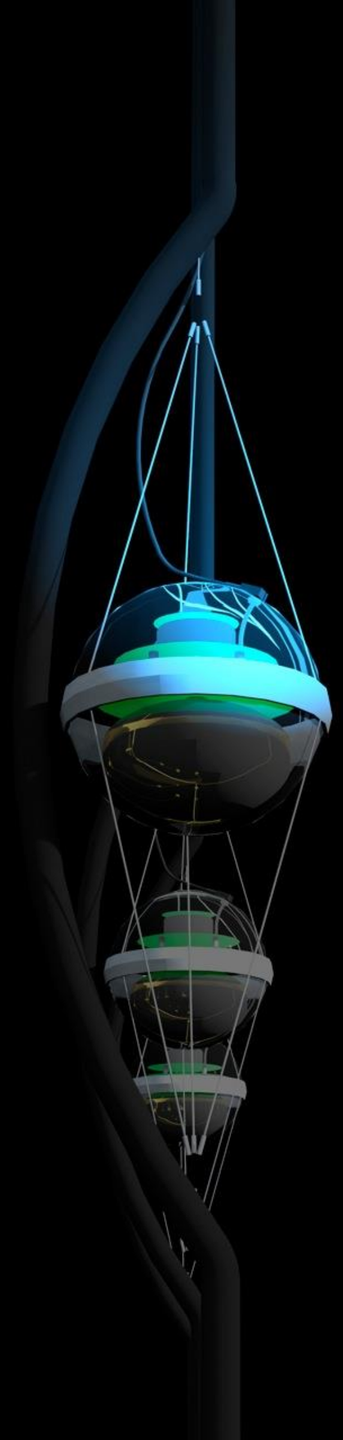
within trigger time window



quality cuts:

•direct hits
•track length
•smoothness
•…



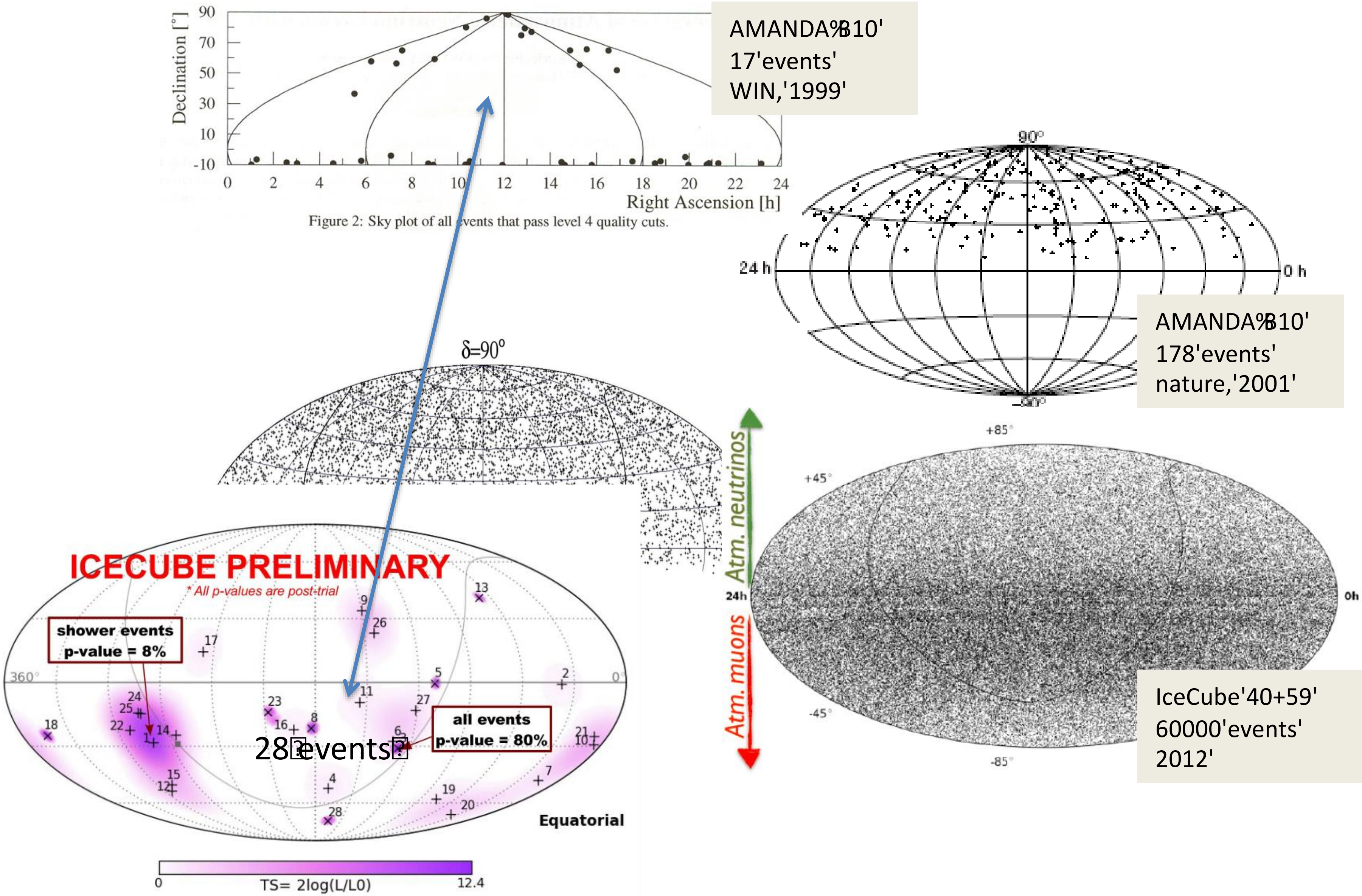


IceCube
francis halzen

- cosmogenic neutrinos
- the energetics of cosmic ray sources
- neutrinos associated with cosmic rays
- a cubic kilometer detector
- evidence for extraterrestrial neutrinos
- conclusions

IceCube.wisc.edu

Neutrino Skymaps

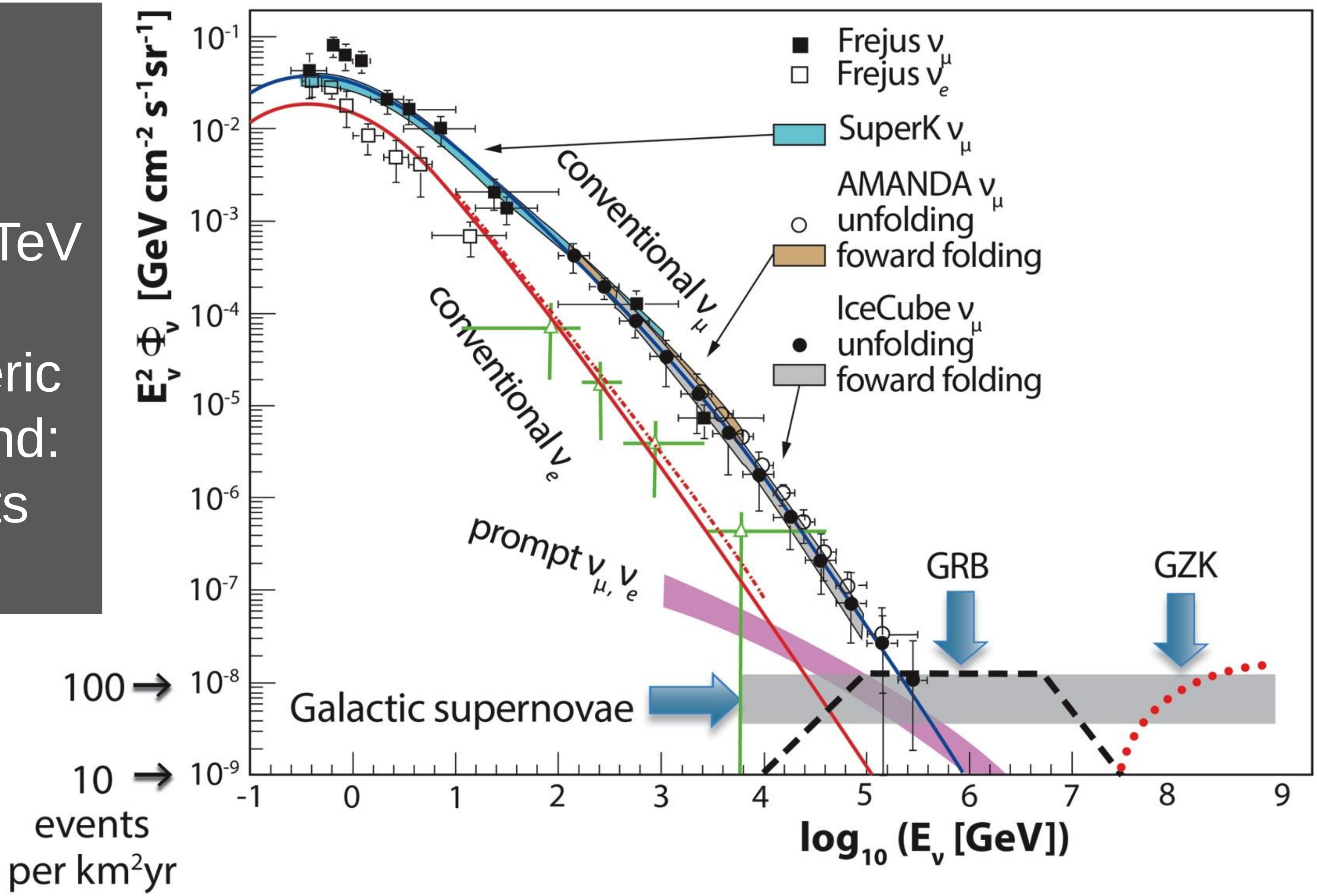


AMANDA-B10
17 events
WIN, 1999

AMANDA-B10
178 events
nature, 2001

IceCube 40+59
60000 events
2012

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



atmospheric

cosmic

cosmic rays interact with the microwave background

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

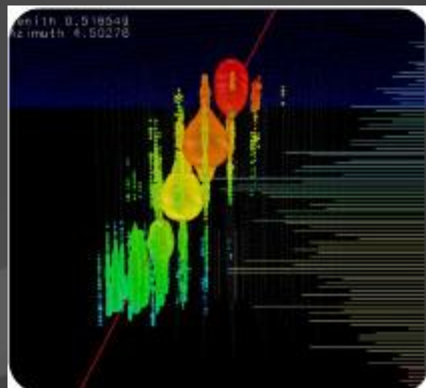
cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

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

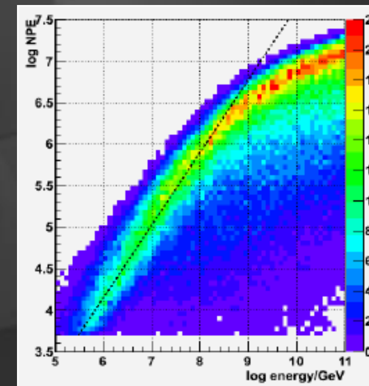
1 event per cubic kilometer per year

...but it points at its source

GZK neutrinos: > 41,000 photons near the horizon

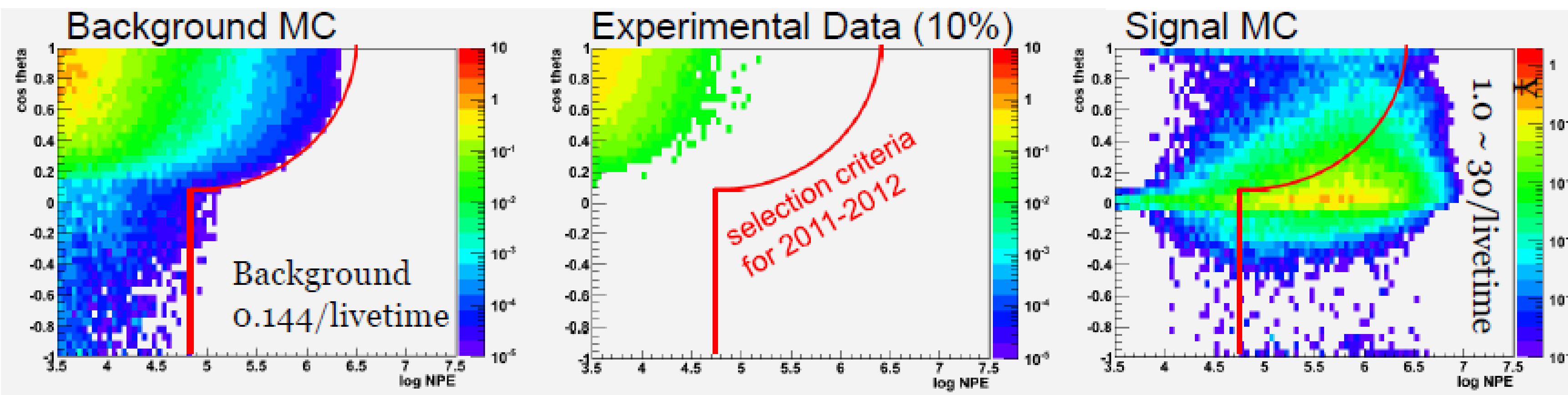


number of channels > 300

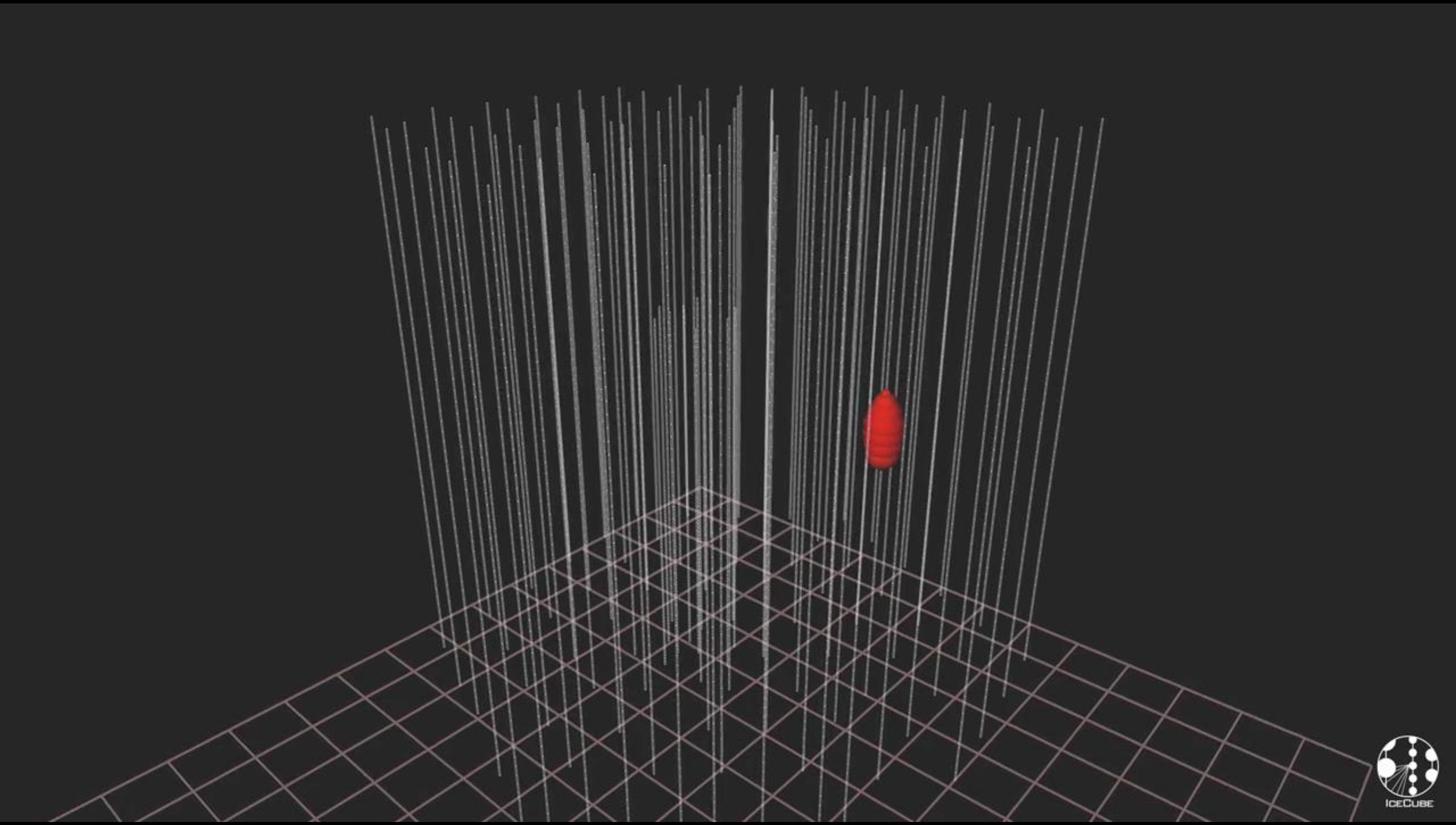


Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

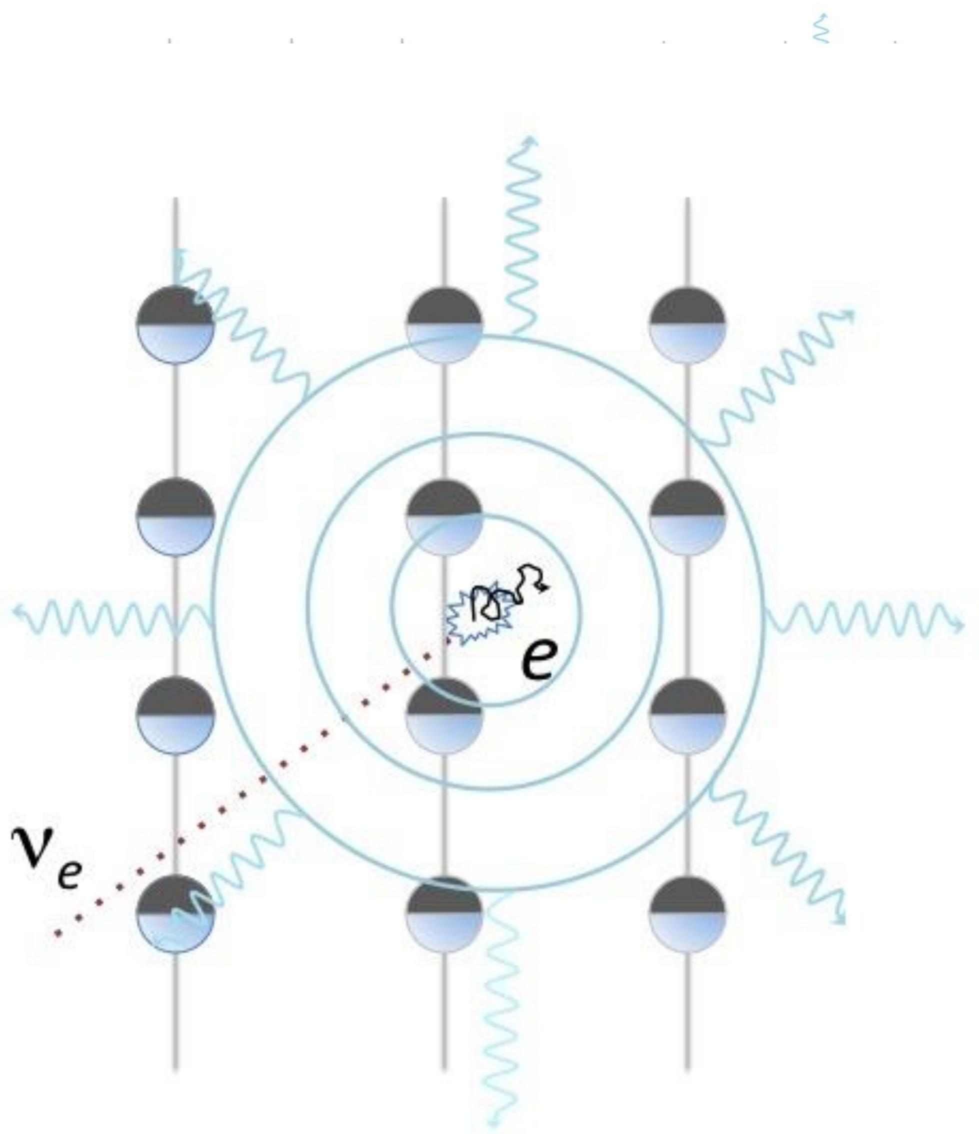
- Optimization based MC and MC verification based on 10% experimental 'burn' sample

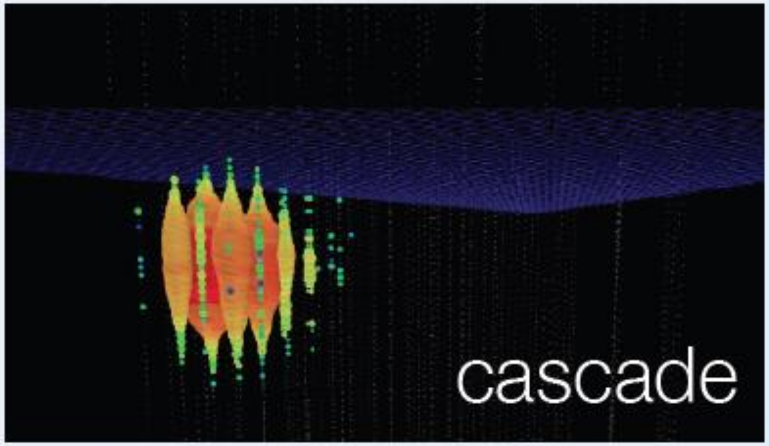


unblinding: 2 events in the signal region


IceCube

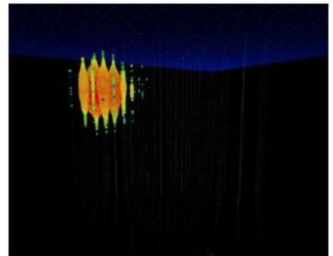
tracks and showers

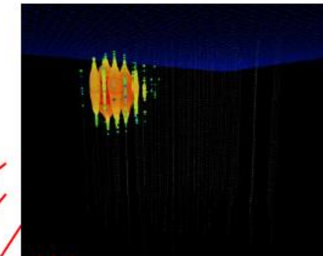




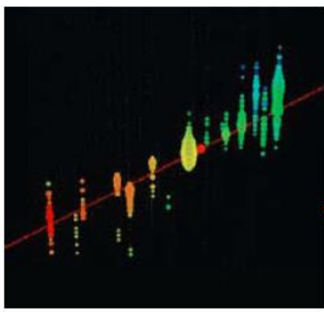
mostly showers ✓

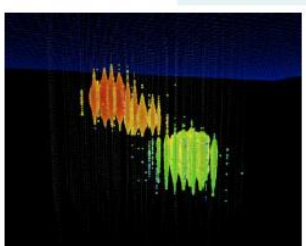
PeV showers:
•volume ~ 5 m^3
•isotropic after 25~ 50 m

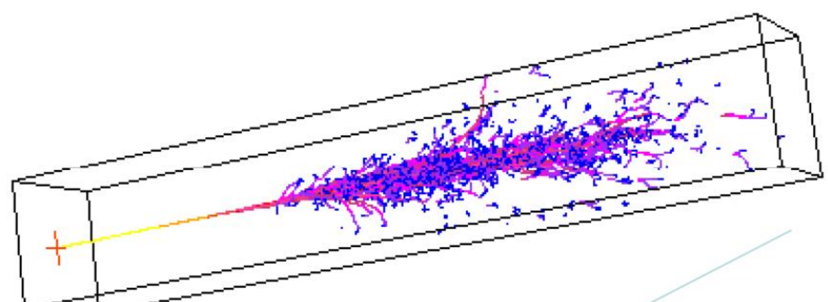


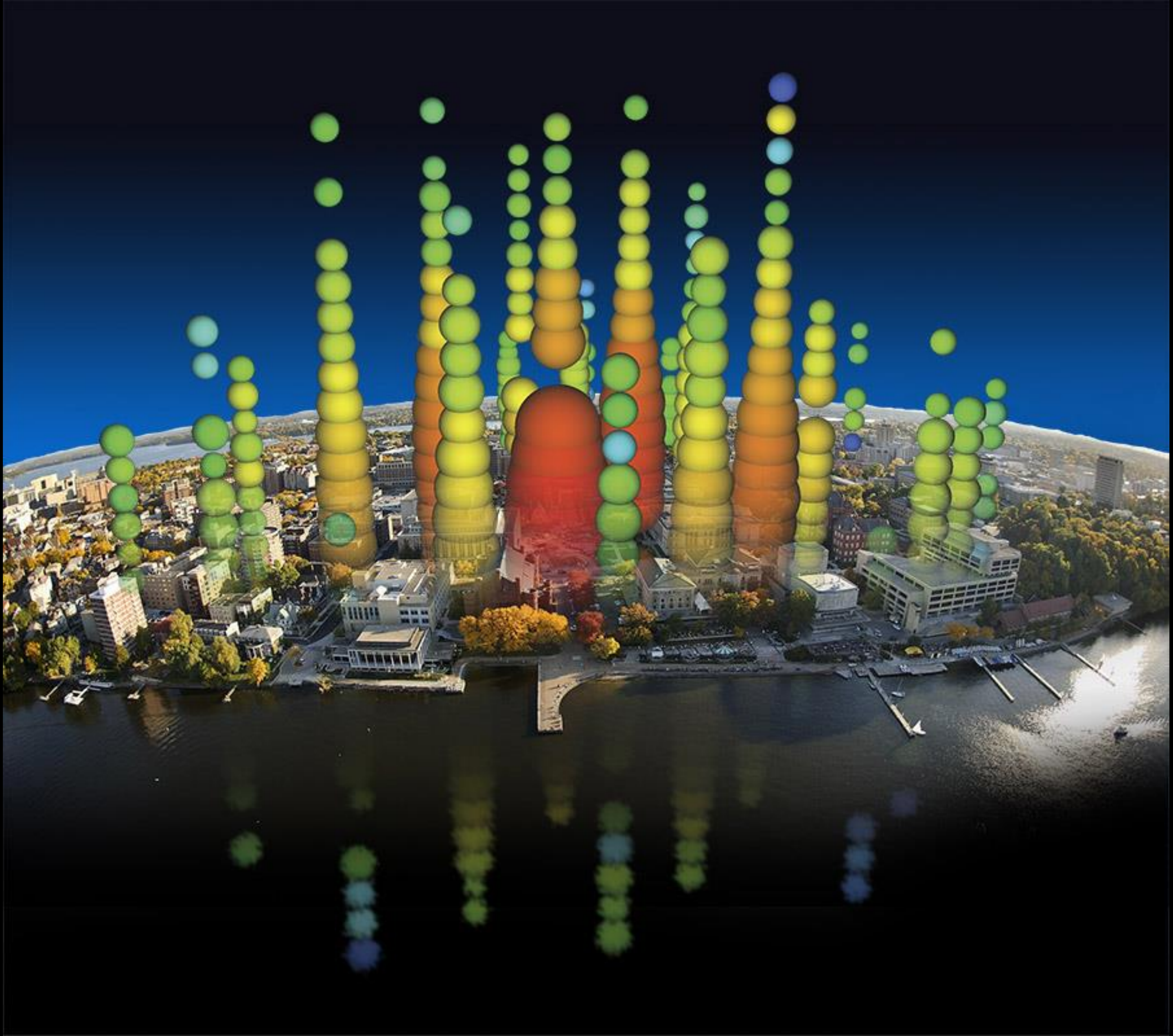


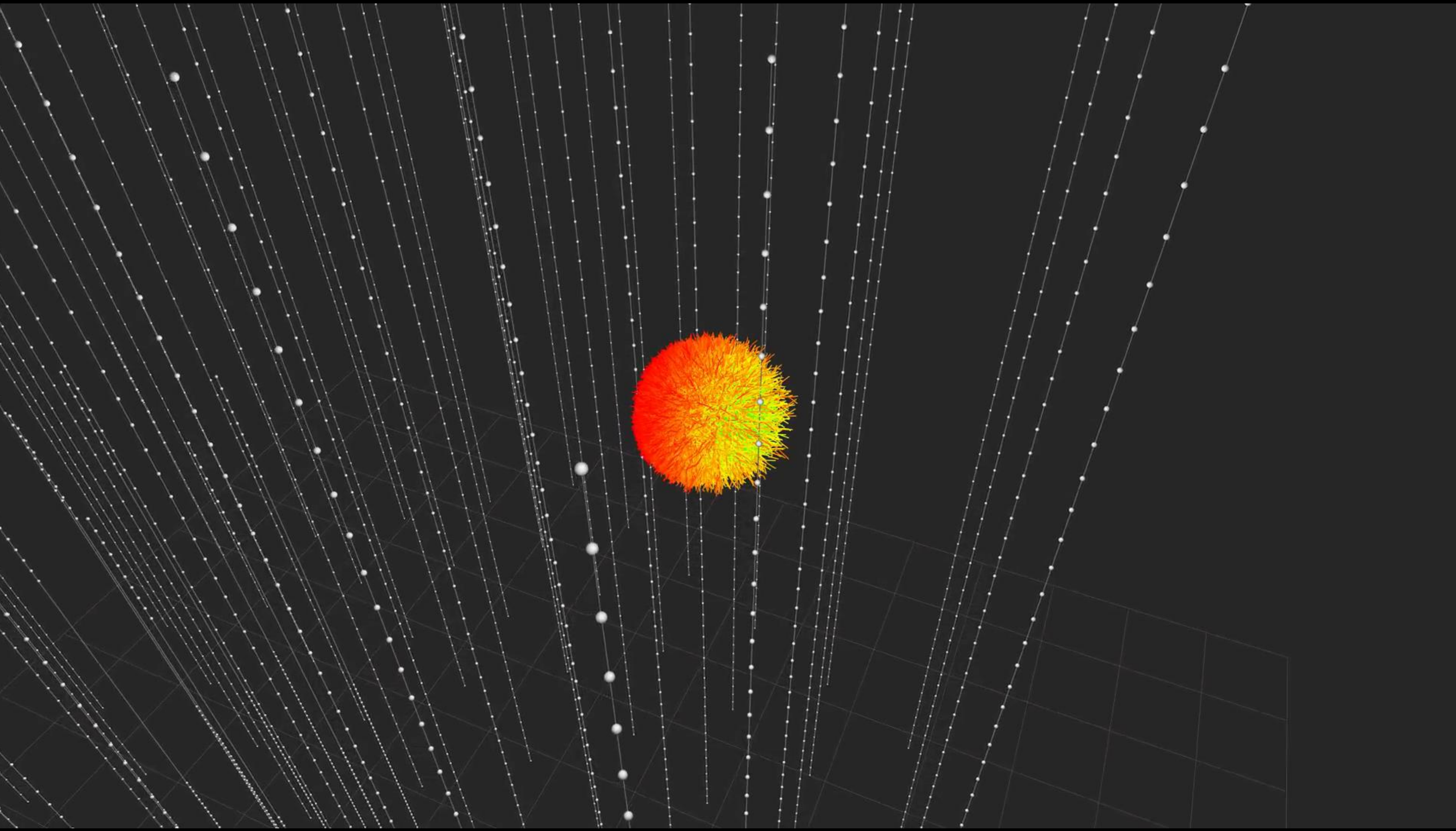
	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$

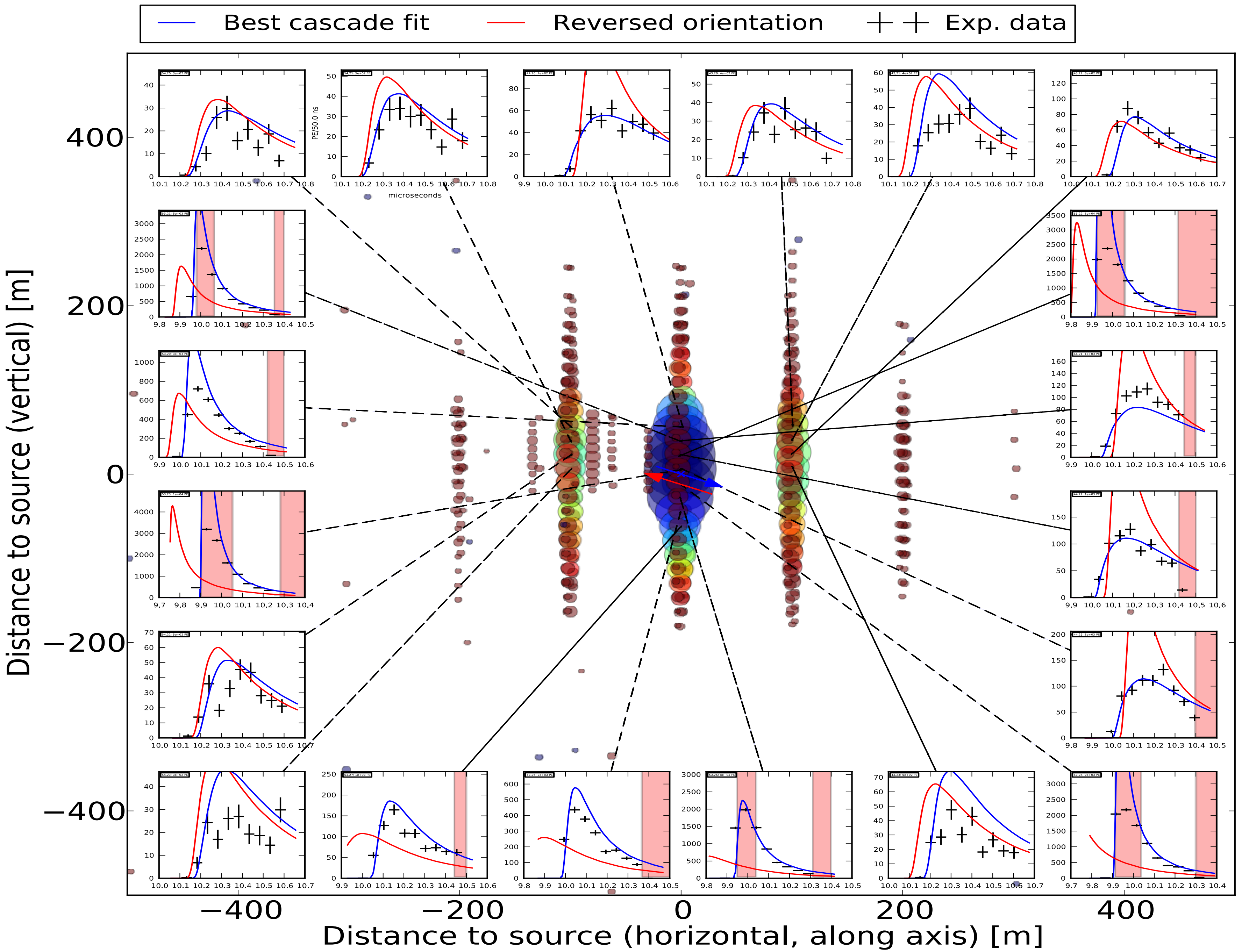




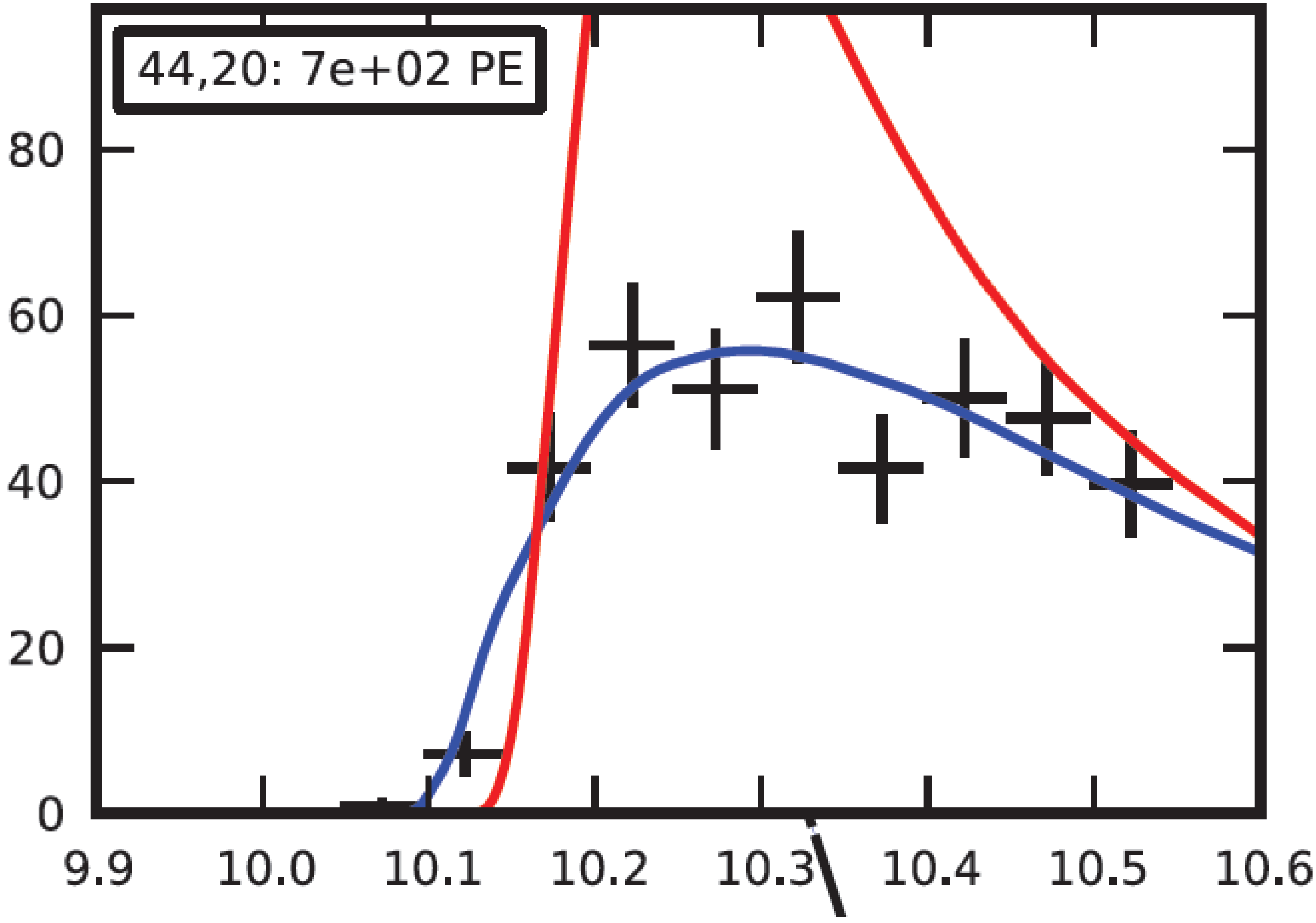




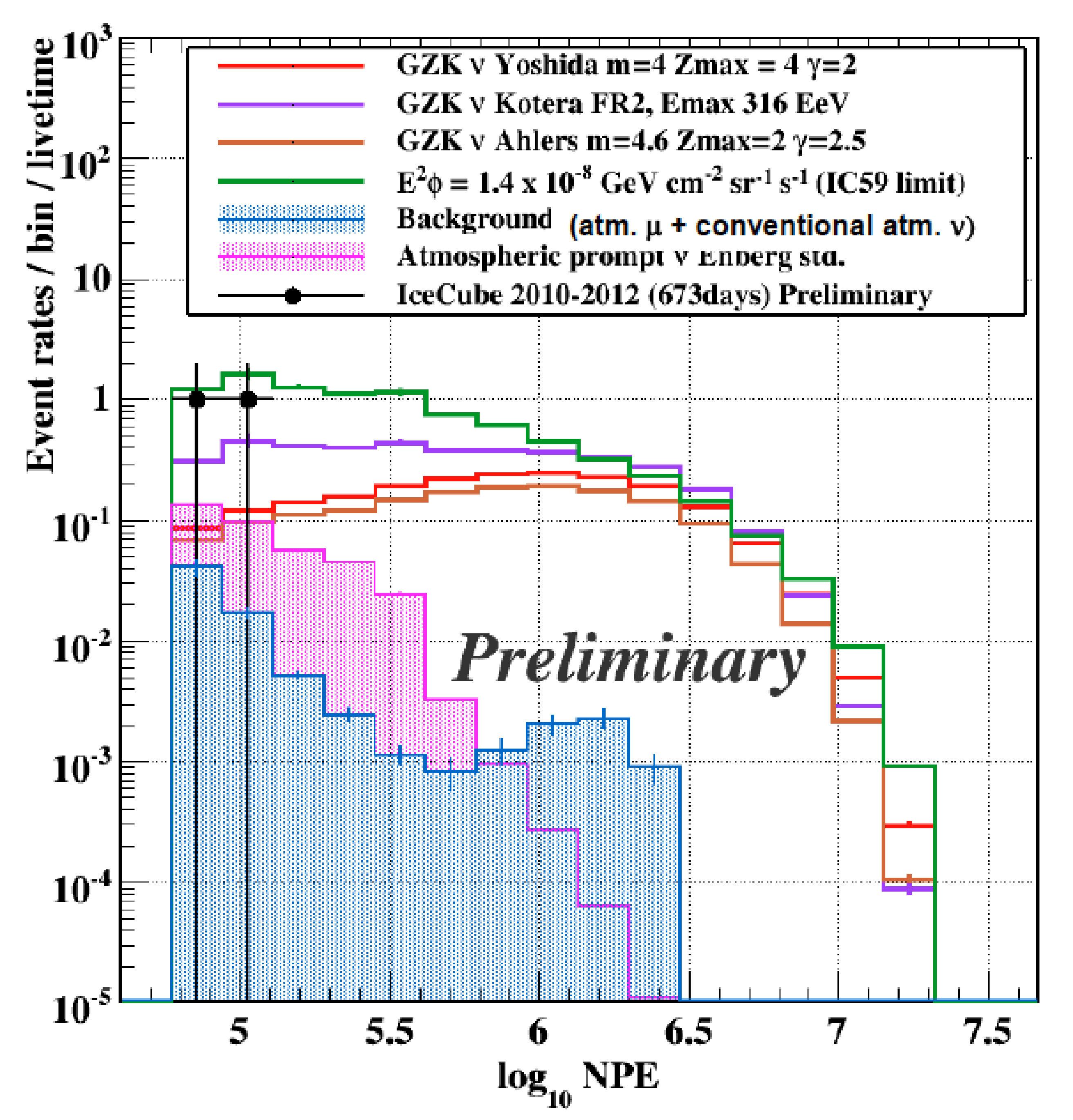



Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds
400
200
0
−200
−400

digital optical module 44 on string 20 only



Blue: best-fit direction, red: reversed direction



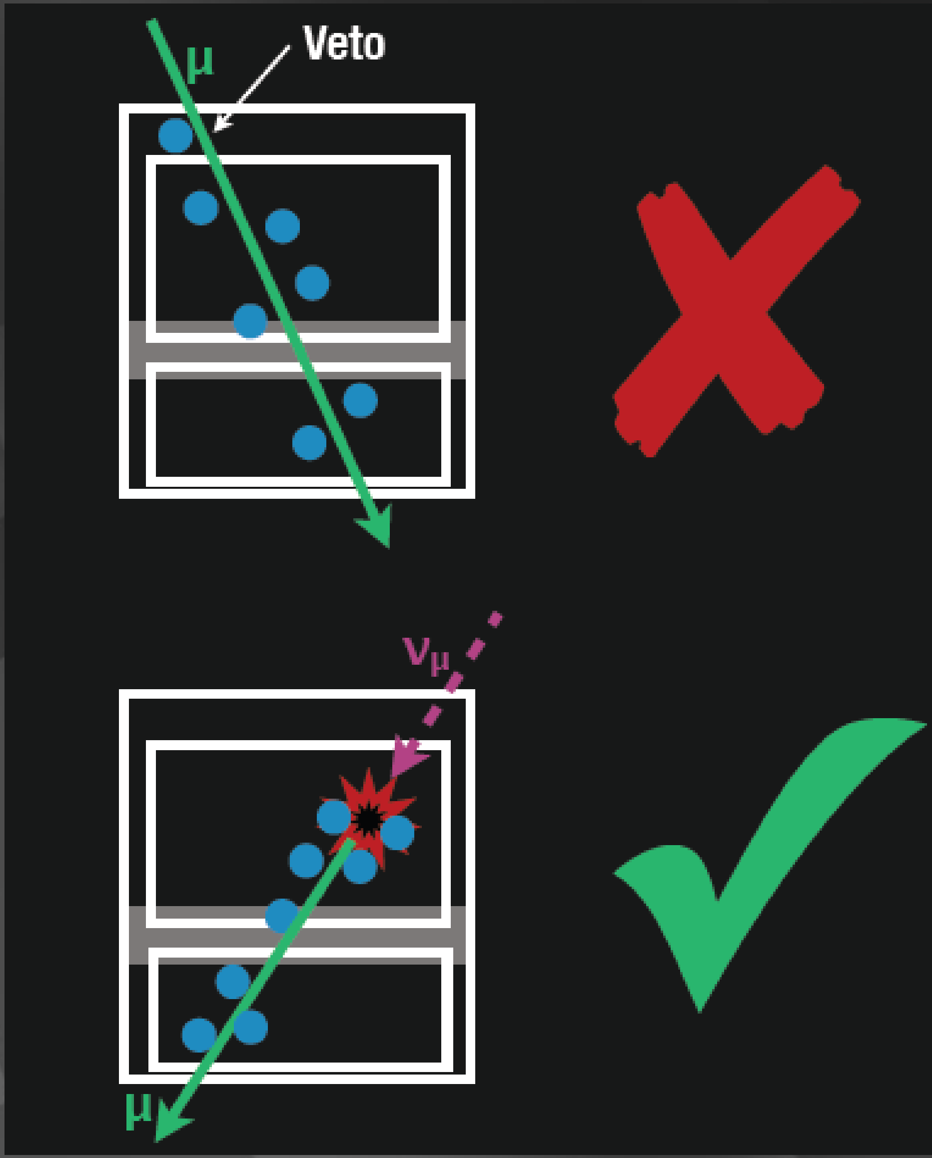
- energy

1,041 TeV
1,141 TeV
(15% resolution)

- not atmospheric: probability of no accompanying muon is 10^{-3} per event

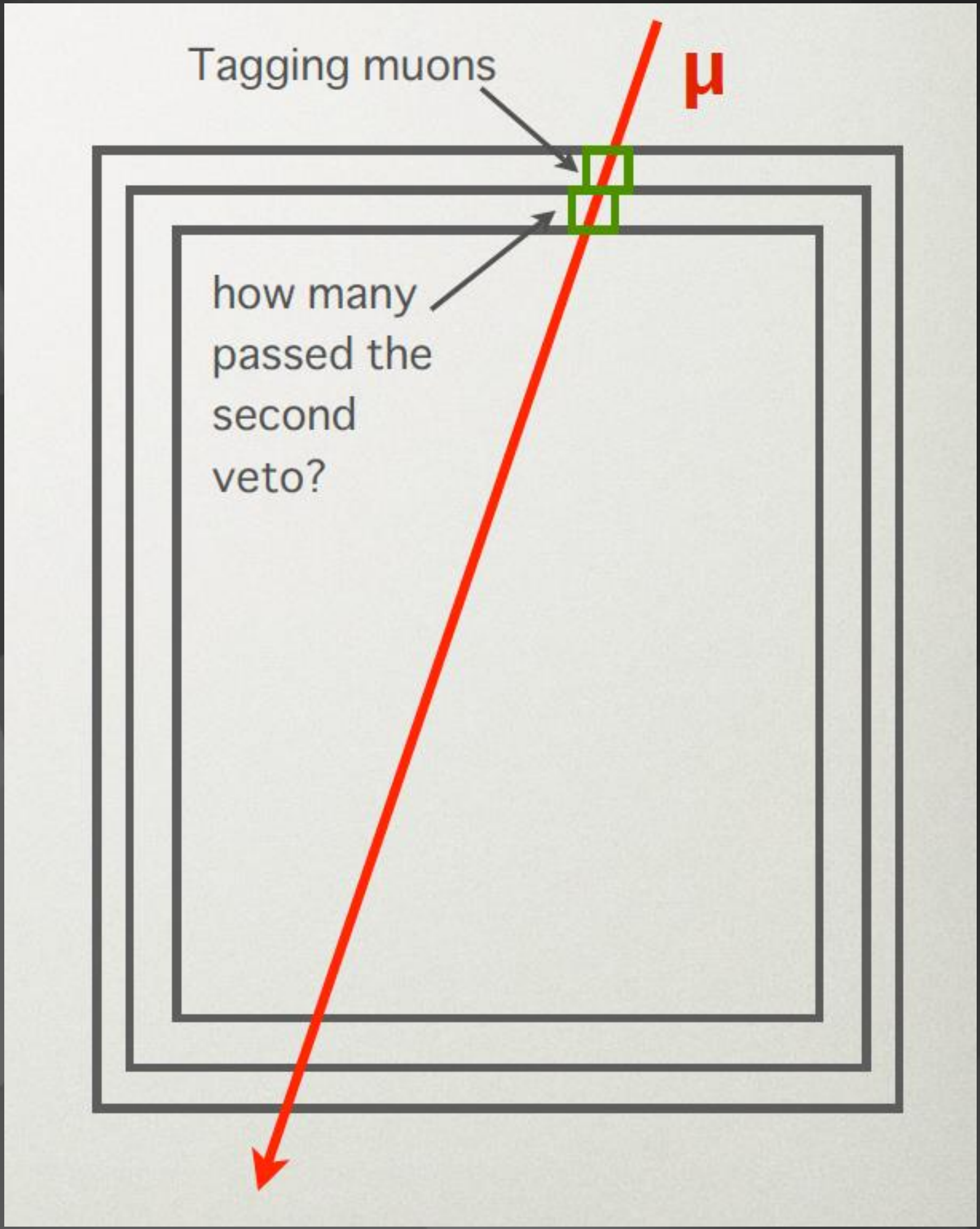
→ flux at present level of diffuse limit

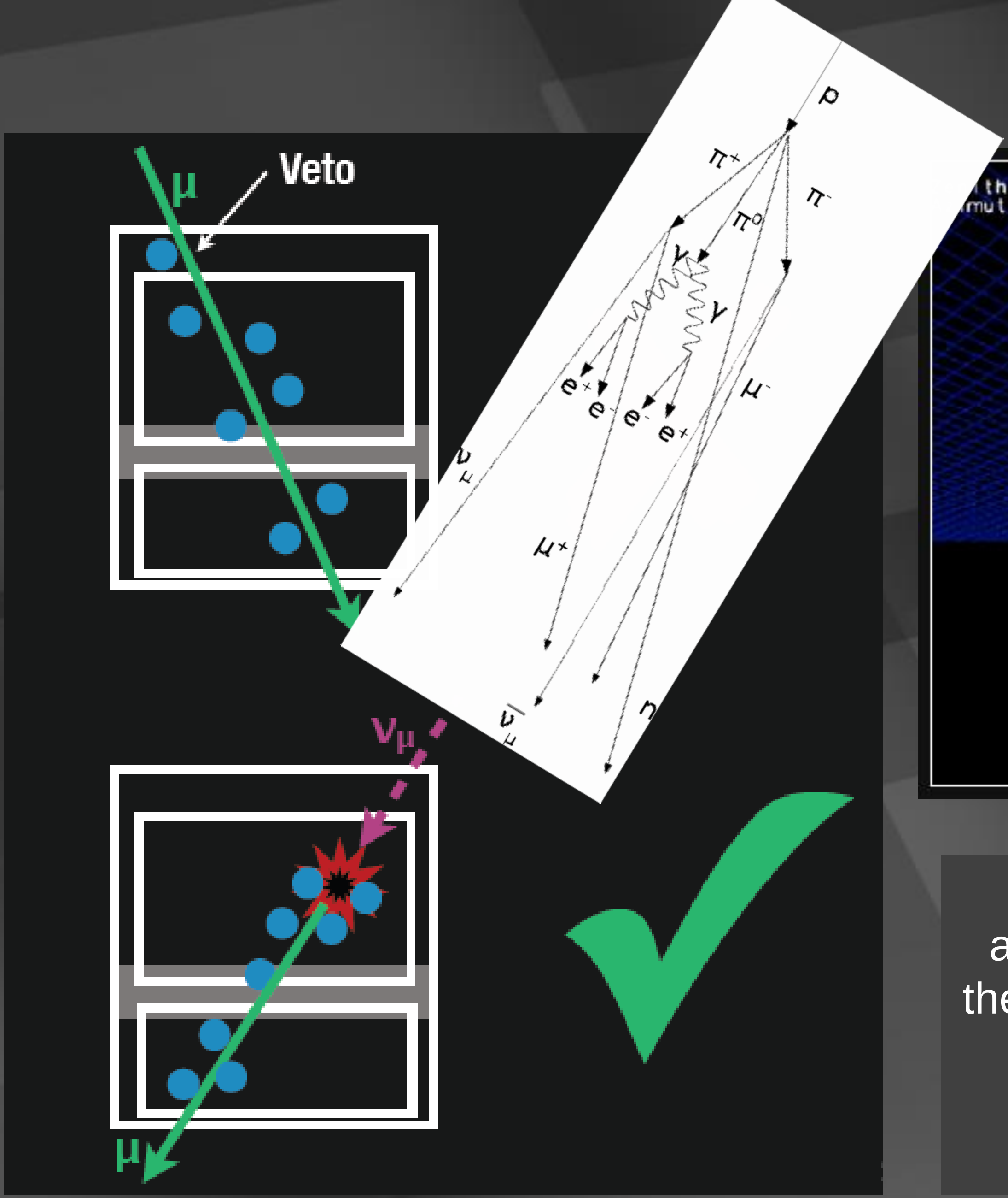
- find more contained events (420 Mton)
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

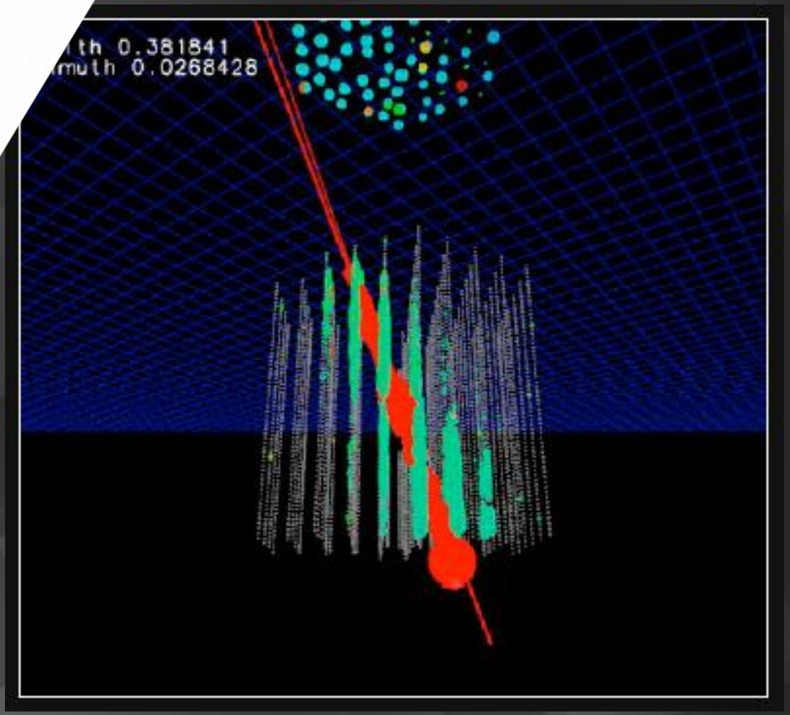


loss in statistics is compensated by event definition veto efficiency by two layer anticoincidence measurement:

tag muons in the veto region and see what fraction is vetoed by the layer of detectors below; *no simulation*



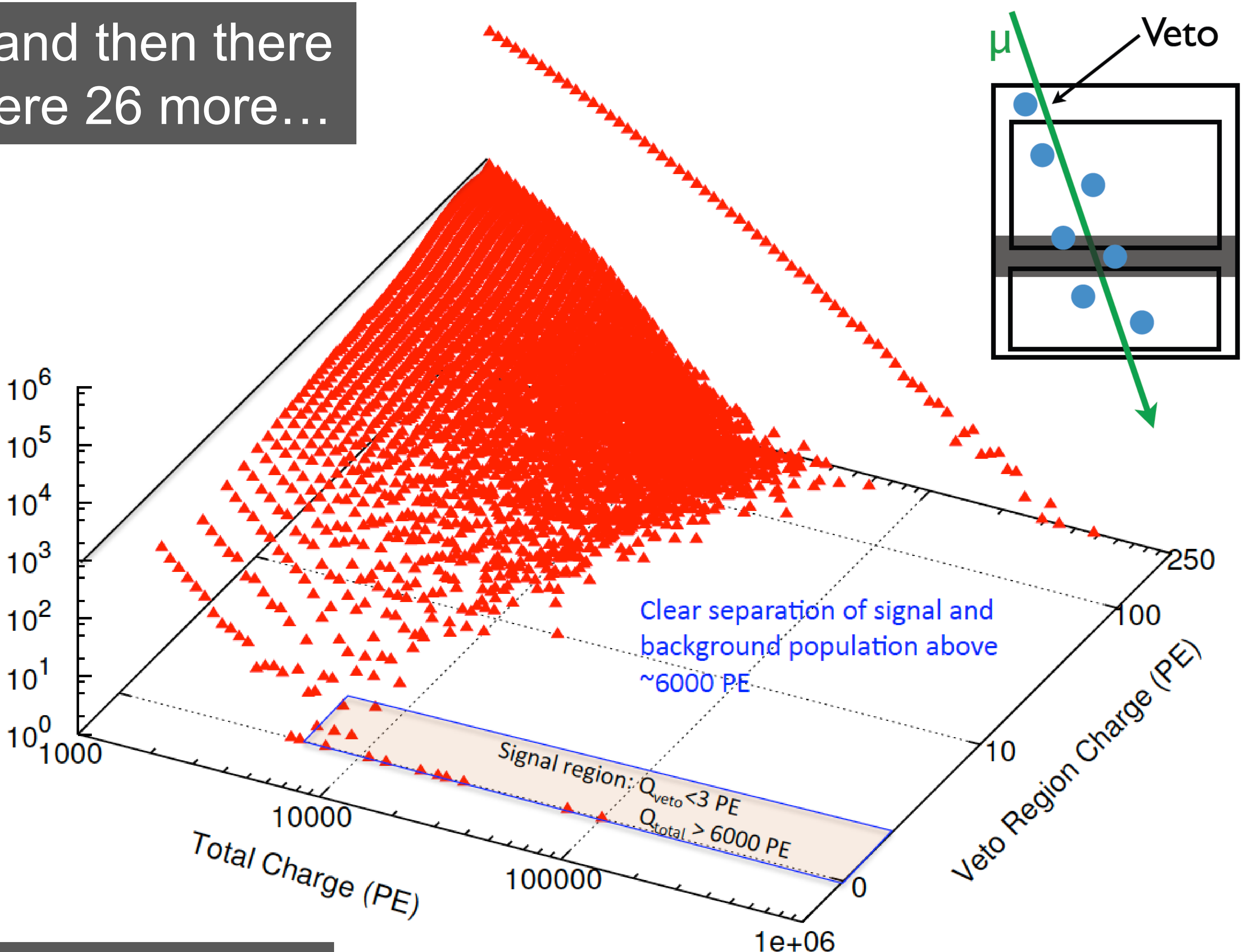




atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

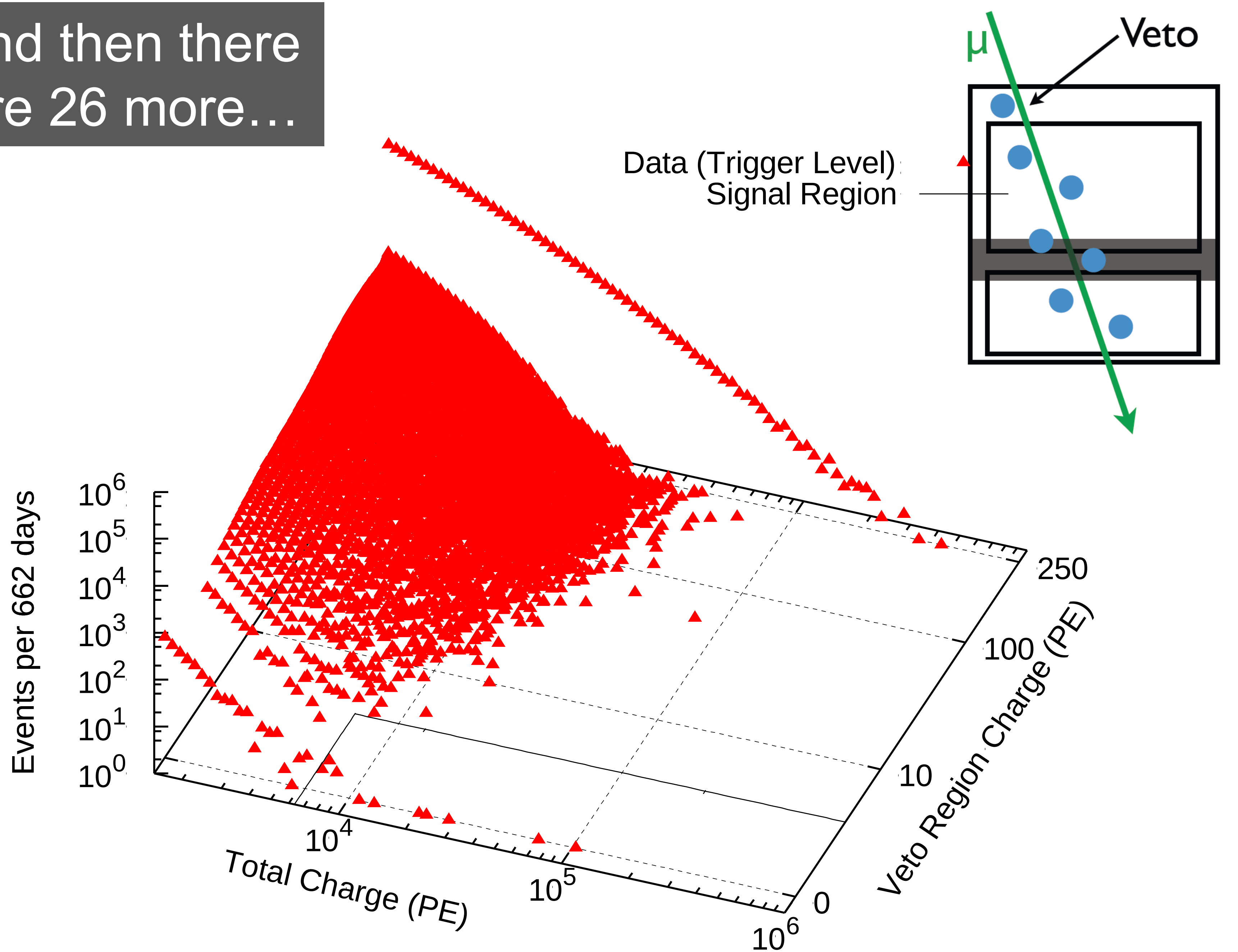
(no signals in IceTop)

…and then there were 26 more…



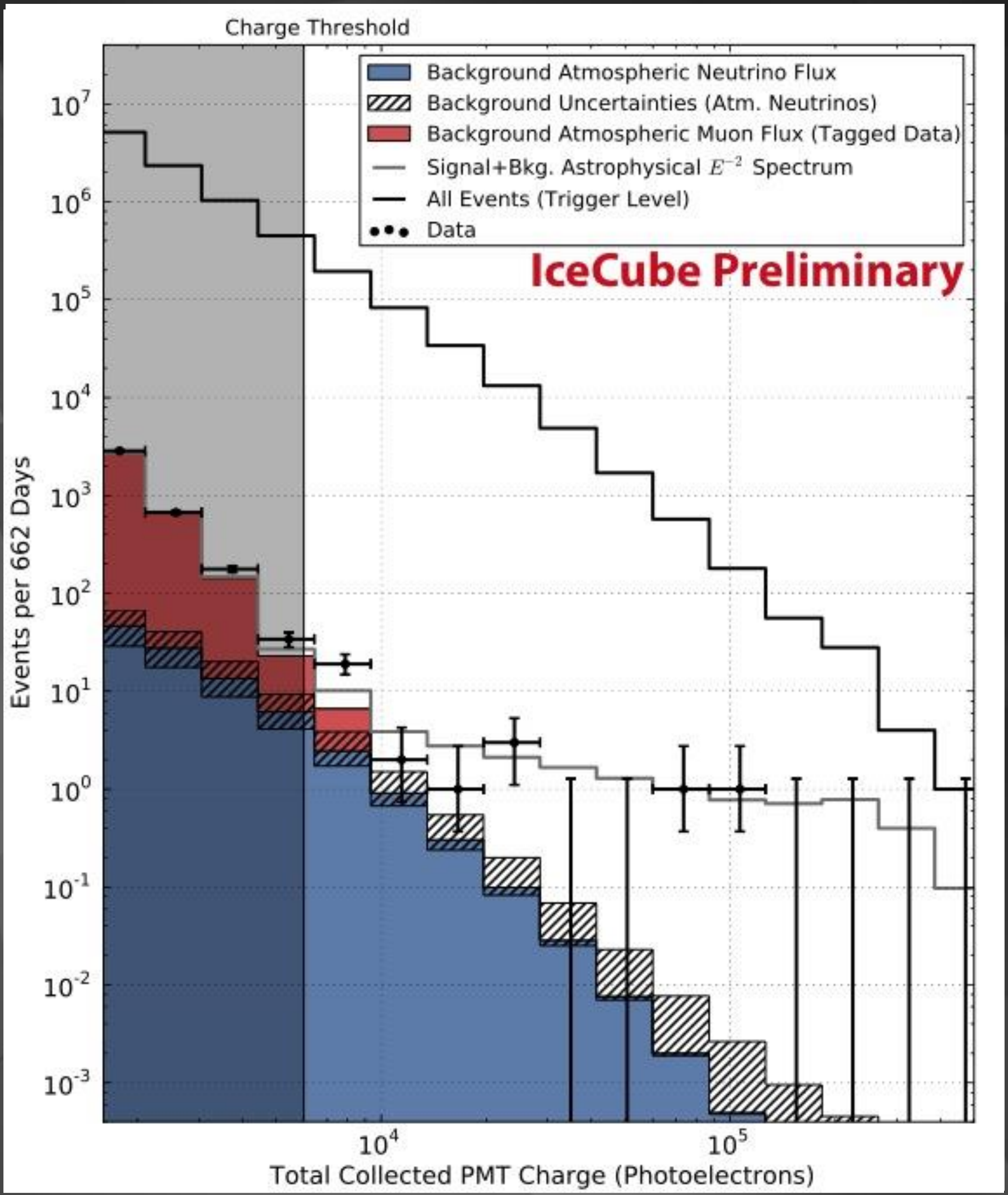
data: 86 strings one year

…and then there were 26 more…



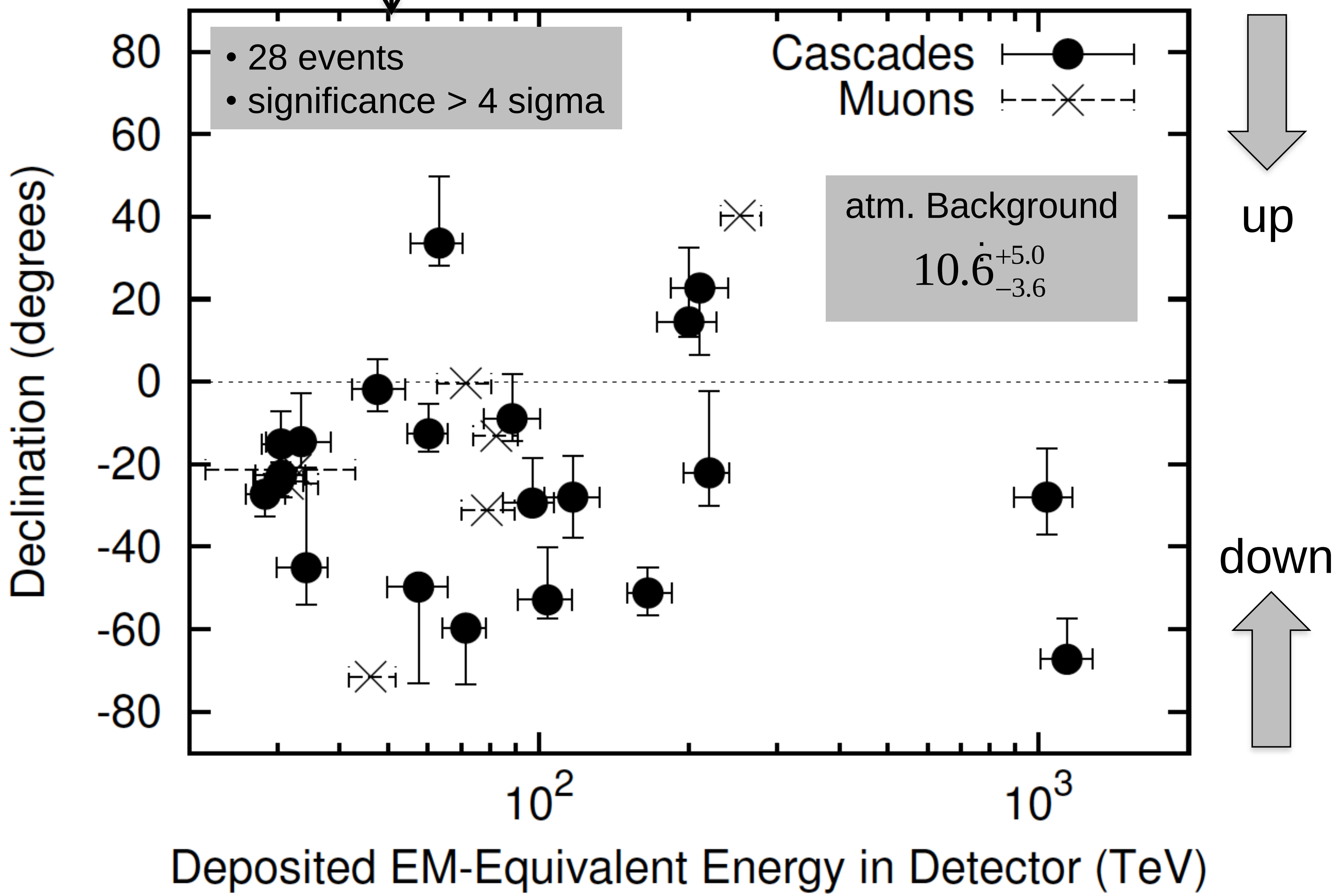
data: 86 strings one year

total charge collected by PMTs of events with interaction inside the detector

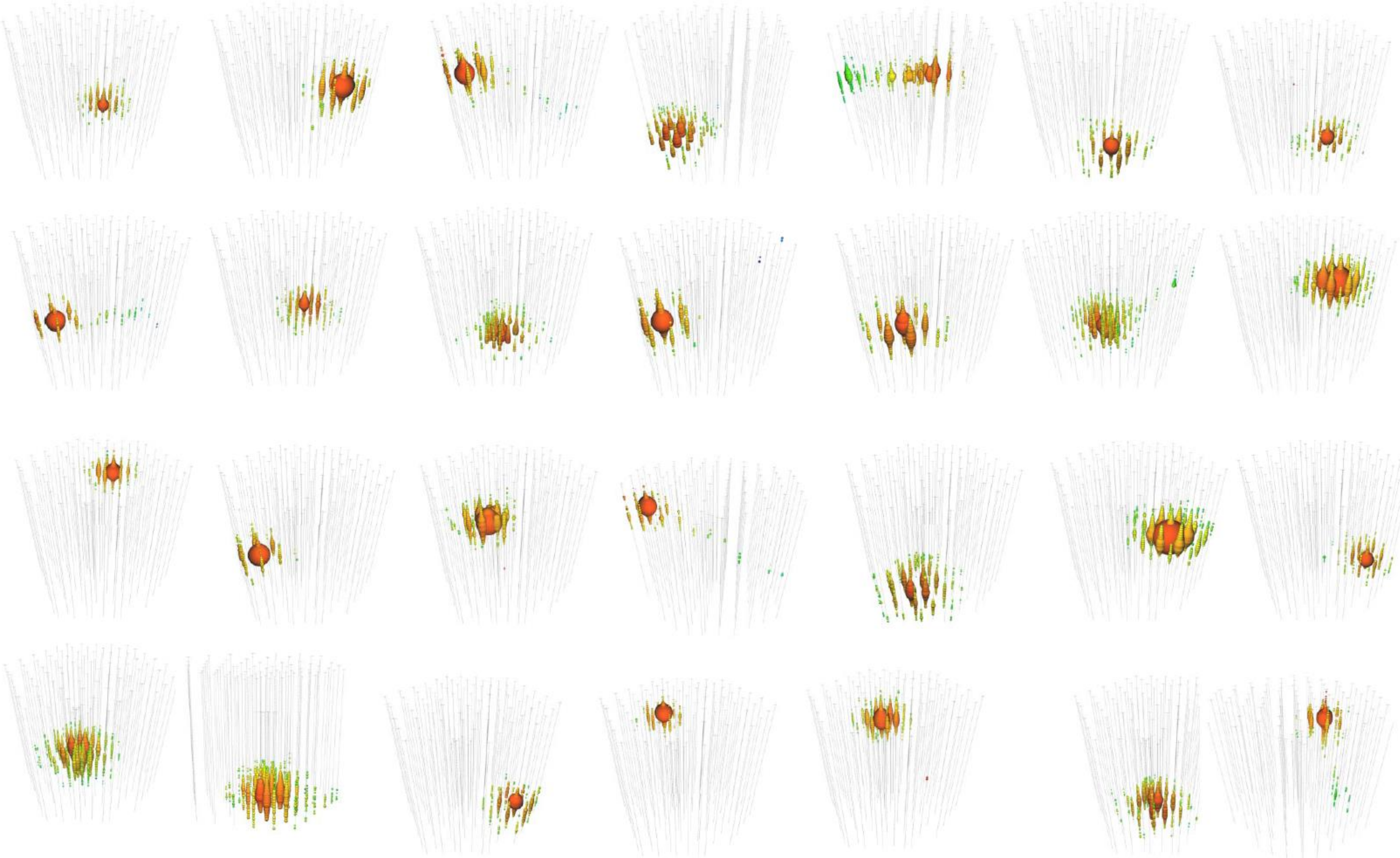


preliminary

> 100 TeV (50 em equivalent): 18 events

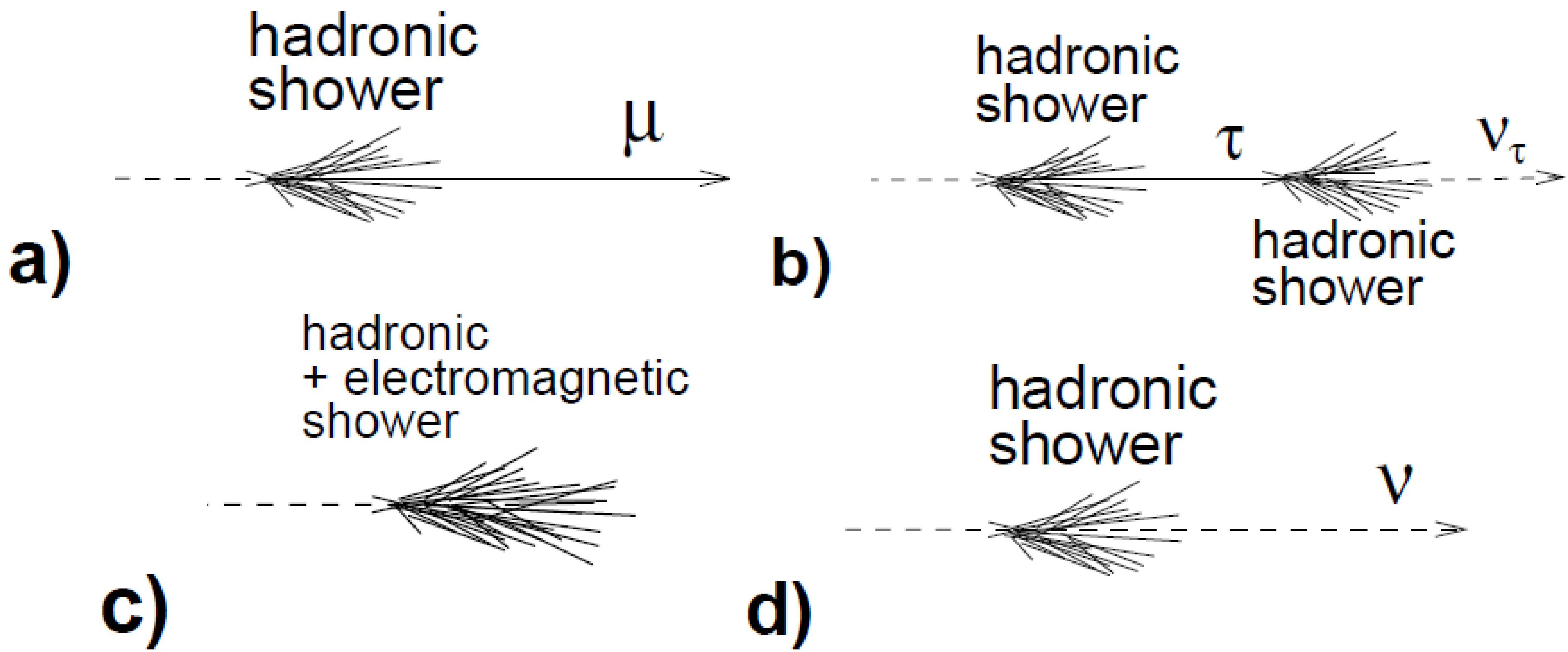


26 more: 19 showers and 7 muon tracks

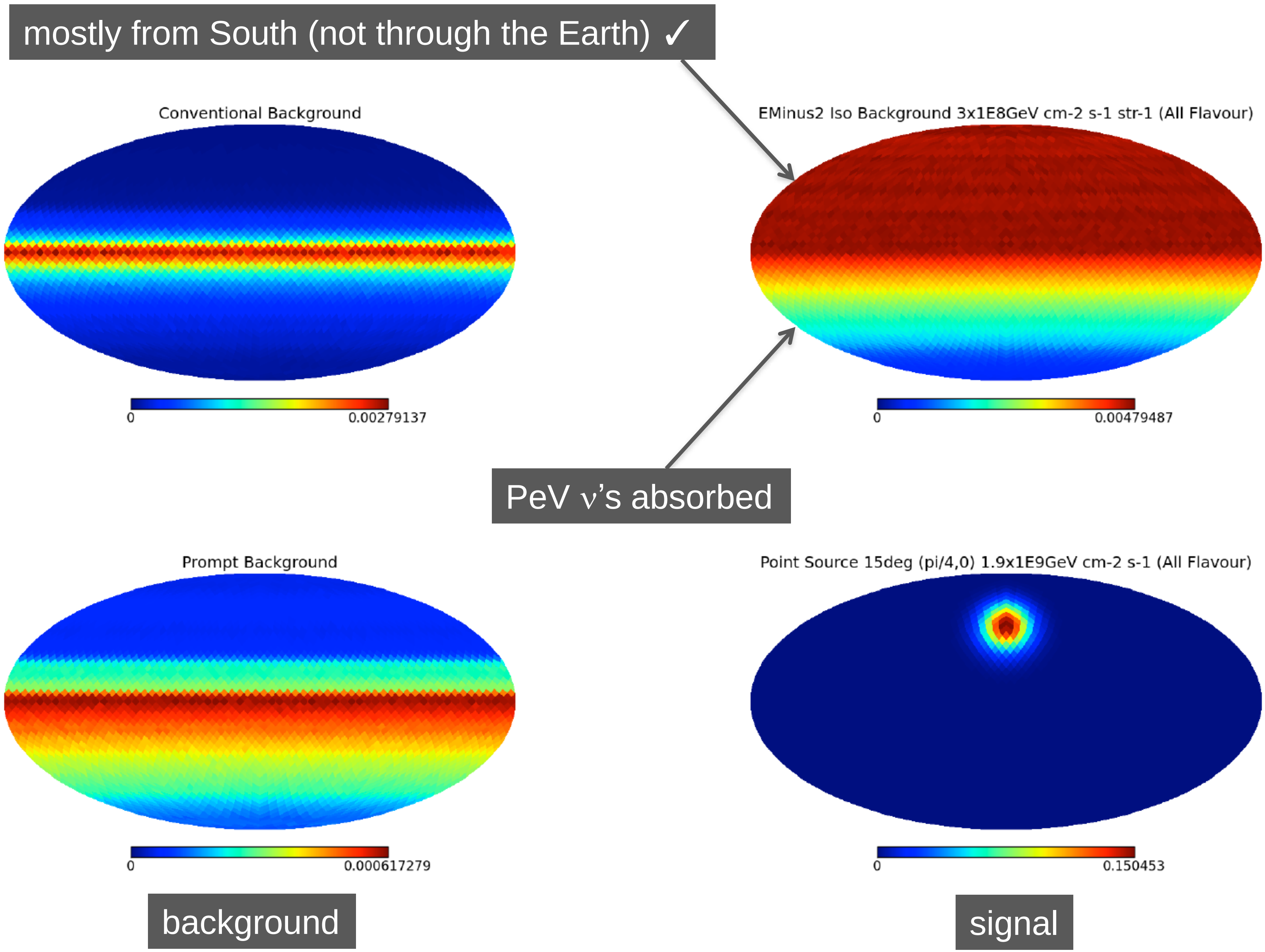


too few ν_μ ?
no, in an all flavor search ν_μ tracks are rare

$$\text{length of } t \text{ track} = 50\text{m}\,´\,\frac{E_n}{\text{PeV}}$$



a muon track is relatively rare


mostly from South (not through the Earth) ✓
Conventional Background
0
0.00279137
EMinus2 Iso Background 3x1E8GeV cm-2 s-1 str-1 (All Flavour)
0
0.00479487
PeV ν's absorbed
Prompt Background
0
0.000617279
Point Source 15deg (pi/4,0) 1.9x1E9GeV cm-2 s-1 (All Flavour)
0
0.150453
background
signal

too many from the northern hemisphere?
no, events have properties of a cosmic flux

atmospheric background:

- mostly from North (through the Earth, insufficient target to produce neutrinos from the South)
- mostly muons (muon neutrinos and cosmic ray muons from the South)

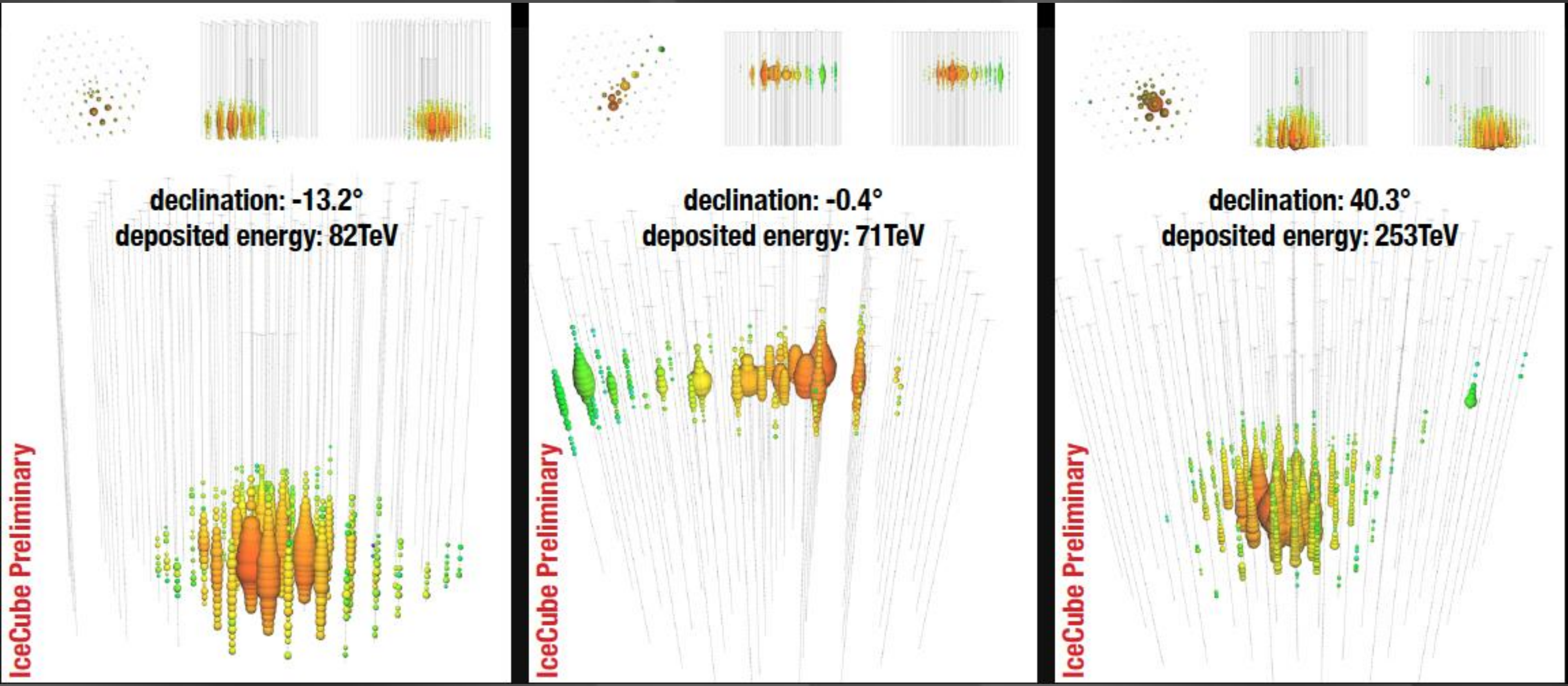
cosmic flux:

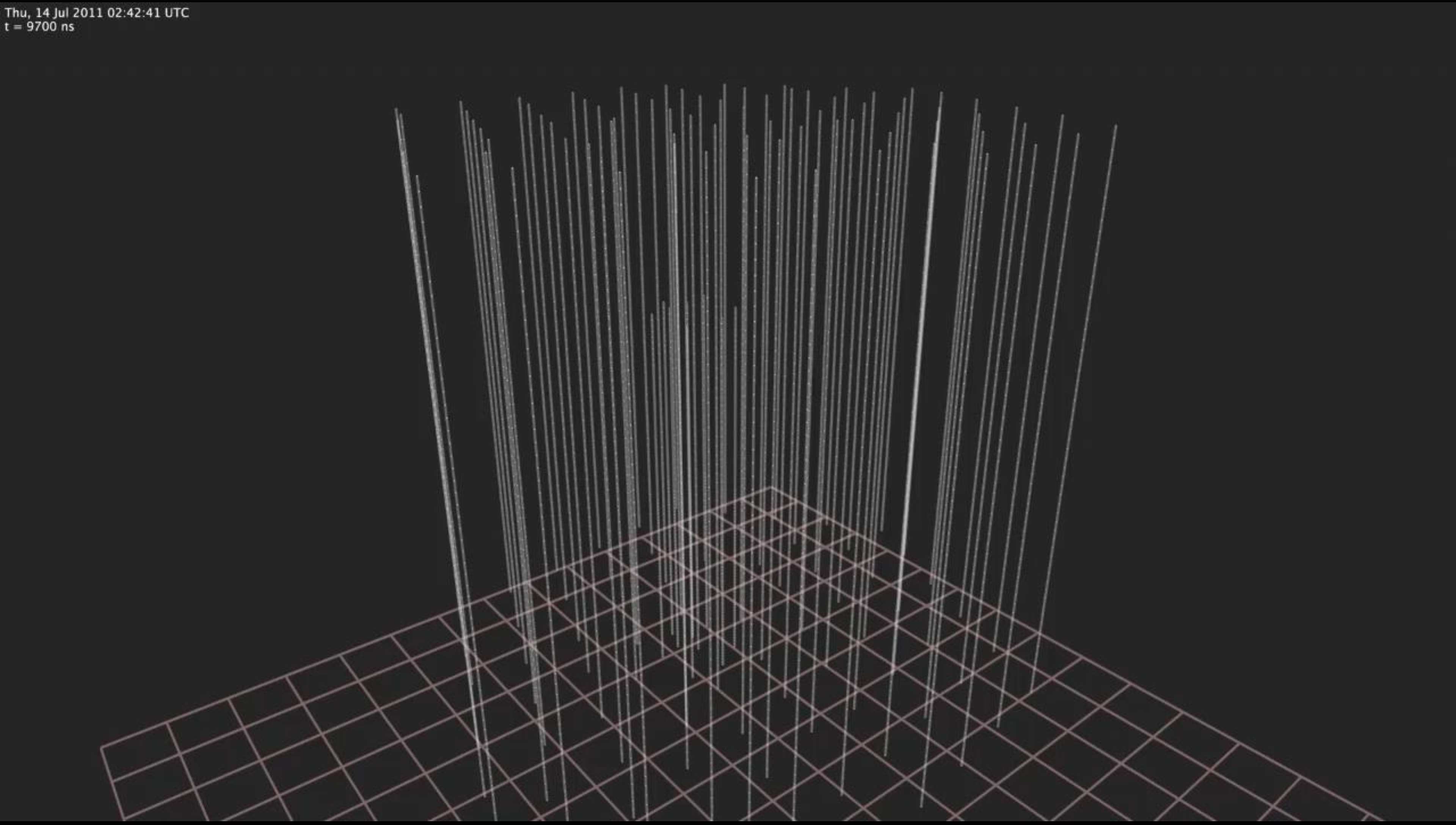
- mostly from the South (PeV neutrinos absorbed by the Earth)
- mostly showers (1:1:1 flavor composition and only CC muon neutrinos produce a track)

not neutrinos from production and prompt decay of charmed particles in the atmosphere

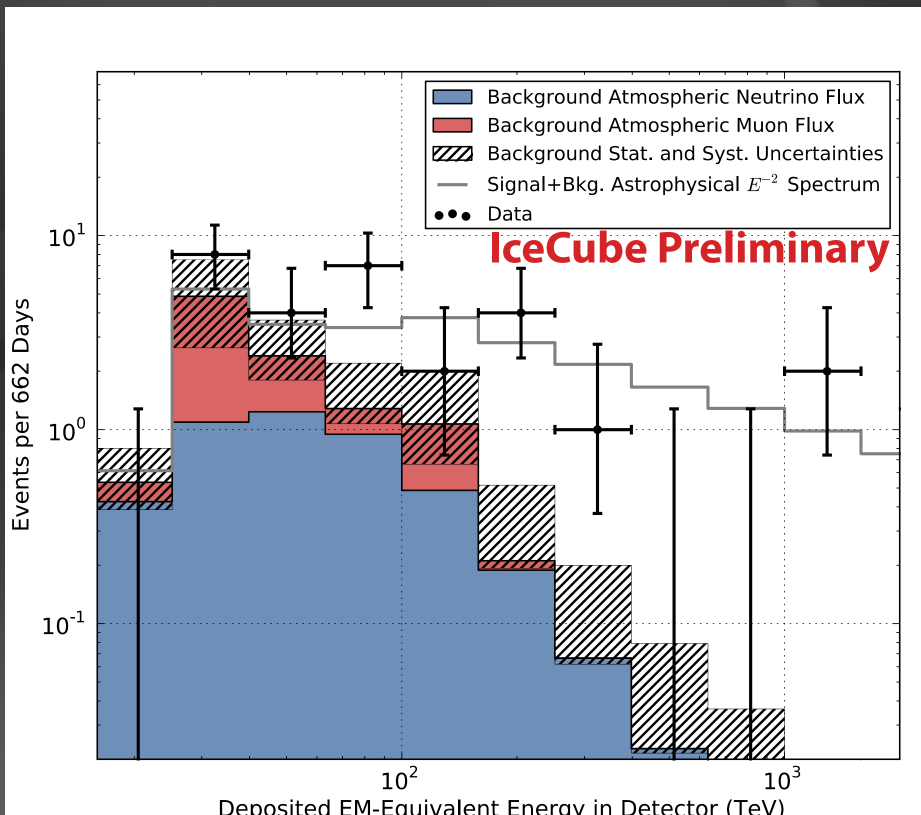
- IceCube data do not fit the energy dependence required by a charm signal.
- same for the zenith angle dependence.
- rate required to explain the data exceeds our own experimental limit by more than a factor of 2.
- level of charm background allowed by the data (actually, no evidence yet) is consistent with expectations.
- no evidence for the air shower that would have produced the charmed particle (no muons!).

some interesting events

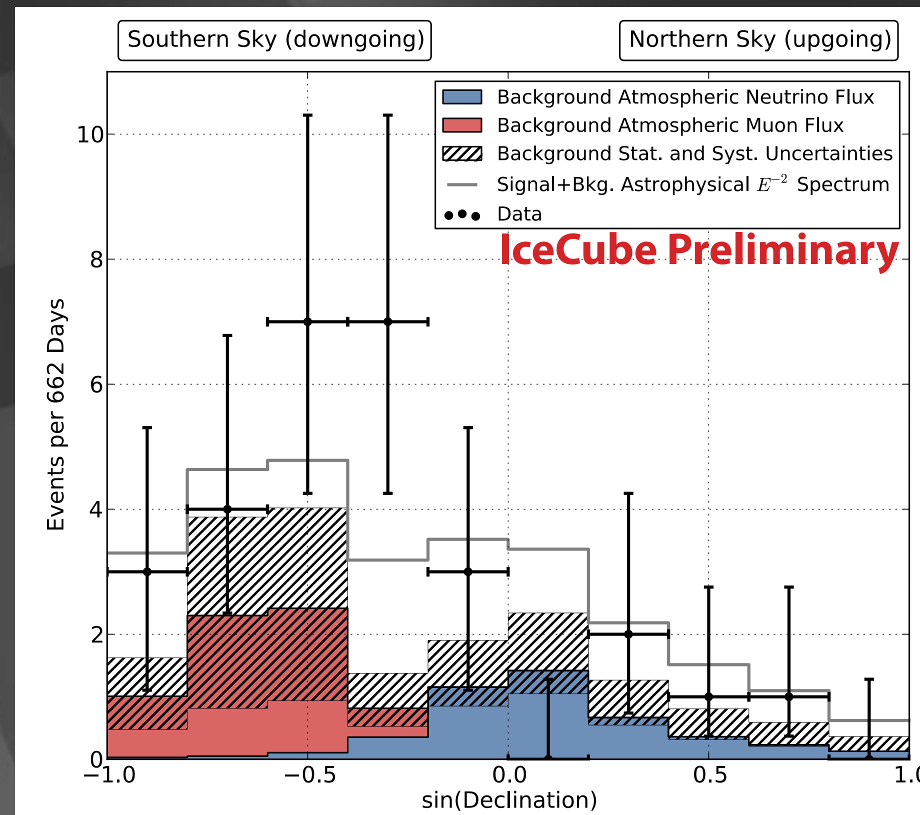



Thu, 14 Jul 2011 02:42:41 UTC
t = 9700 ns

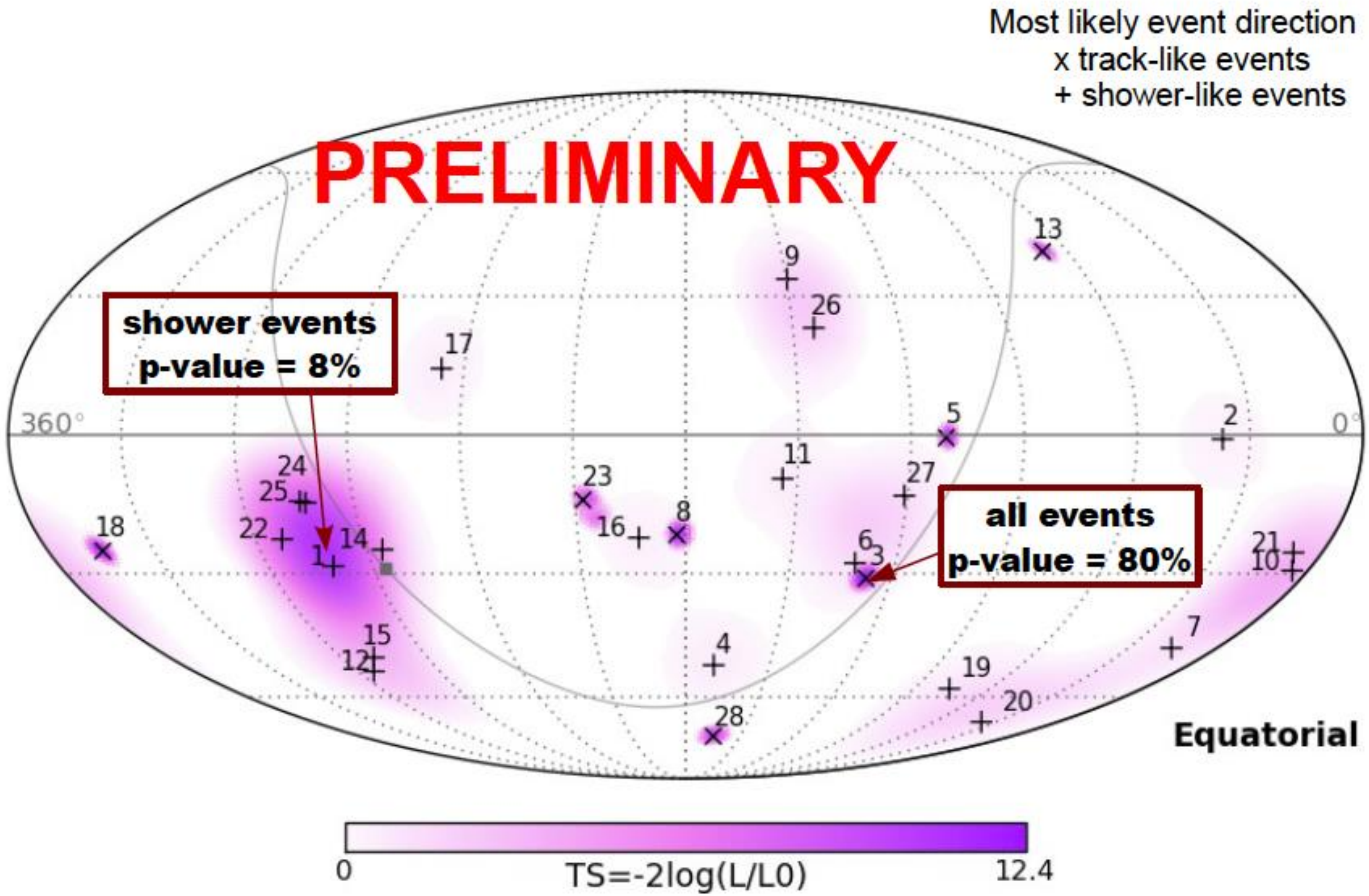
atmospheric muon (blue) + neutrino (red) background
+ astrophysical $E^2\Phi(E) = (3.6 \pm 1.2) \cdot 10^{-8}\ \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$



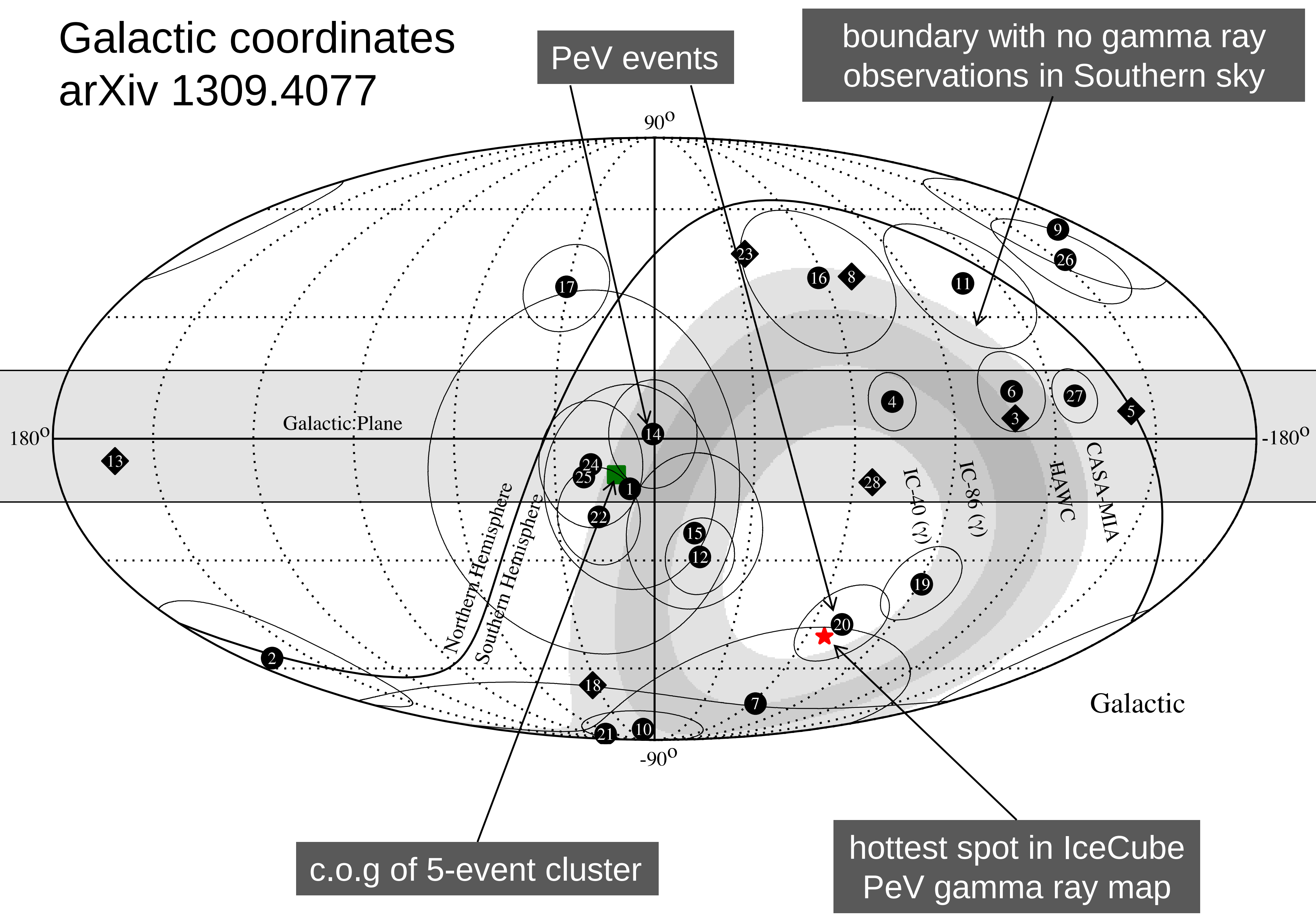
energy deposited in the detector



zenith angle

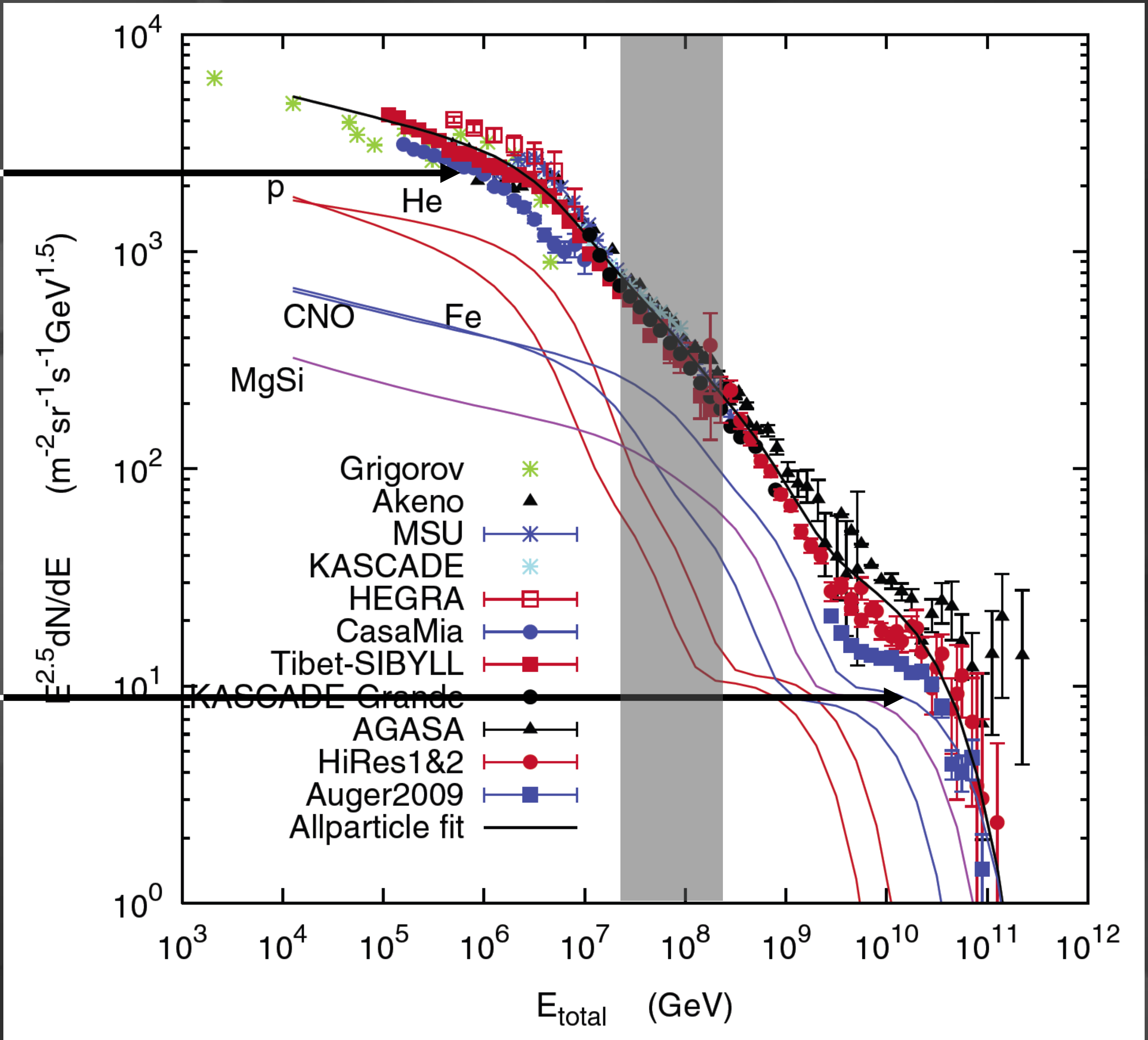


Most likely event direction
x track-like events
+ shower-like events
PRELIMINARY
shower events
p-value = 8%
all events
p-value = 80%
360°
0°
Equatorial
0
TS=-2log(L/L0)
12.4


Galactic coordinates
arXiv 1309.4077
PeV events
boundary with no gamma ray observations in Southern sky
90°
-90°
180°
-180°
Galactic Plane
Northern Hemisphere
Southern Hemisphere
IC-40 (γ)
IC-86 (γ)
HAWC
CASA-MIA
Galactic
c.o.g of 5-event cluster
hottest spot in IceCube PeV gamma ray map

sources accommodating the observed energy budget

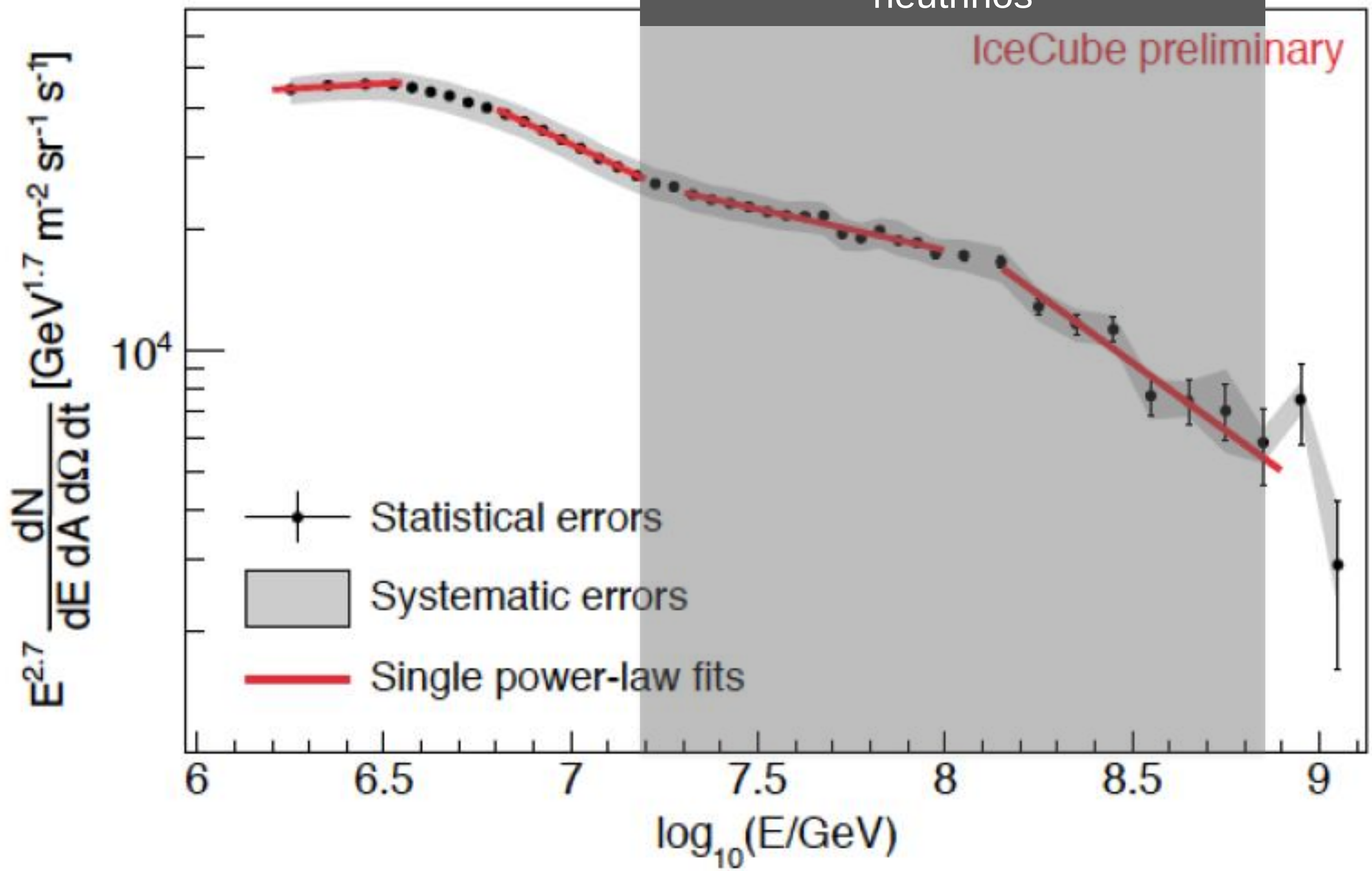
Galactic: supernova remnants?



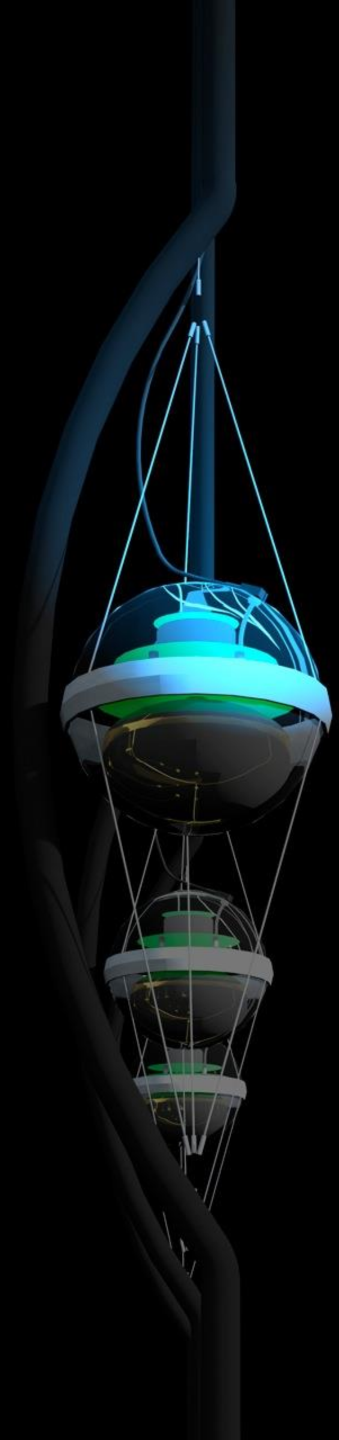
extragalactic:

- gamma ray bursts??
- active galaxies?

the energy range of cosmic accelerators producing PeV neutrinos



Galactic or extragalactic?



conclusions

•first evidence for cosmic neutrinos

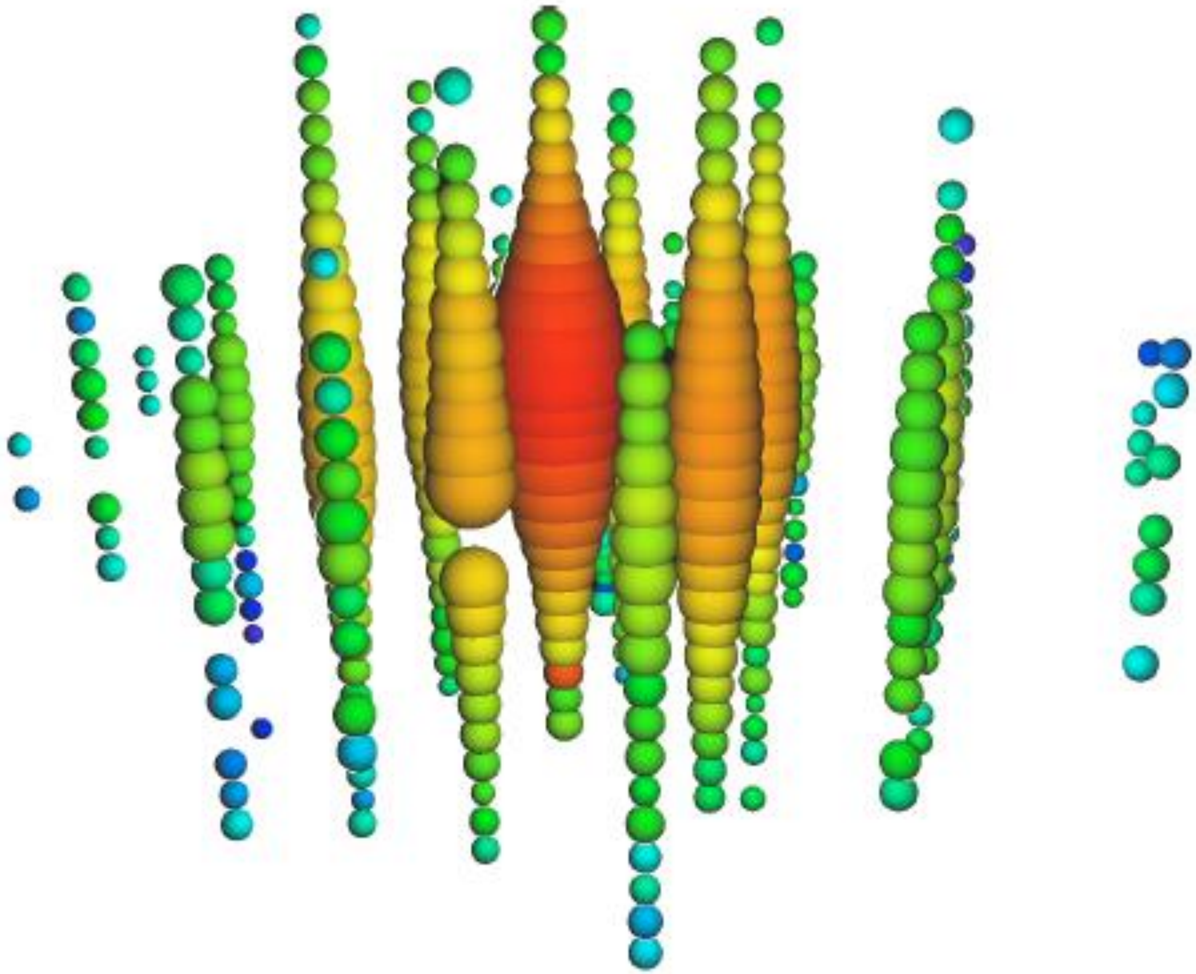
•origin not revealed yet, but…

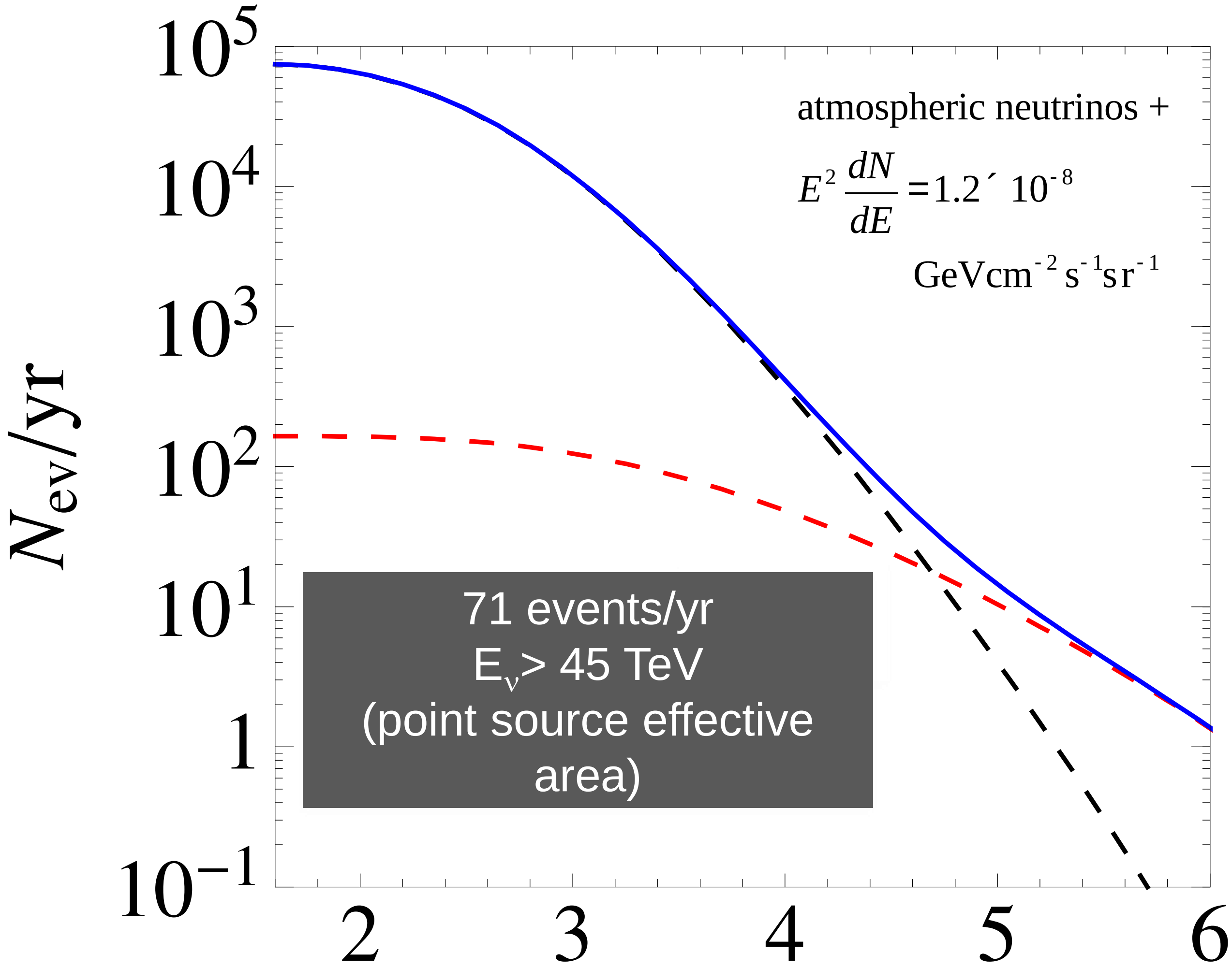
•one more year of data ready for unblinding, more being taken

•better and different (more ν_μ) analyses soon

IceCube.wisc.edu

10% of data taken during year 2 of IceCube unblinded

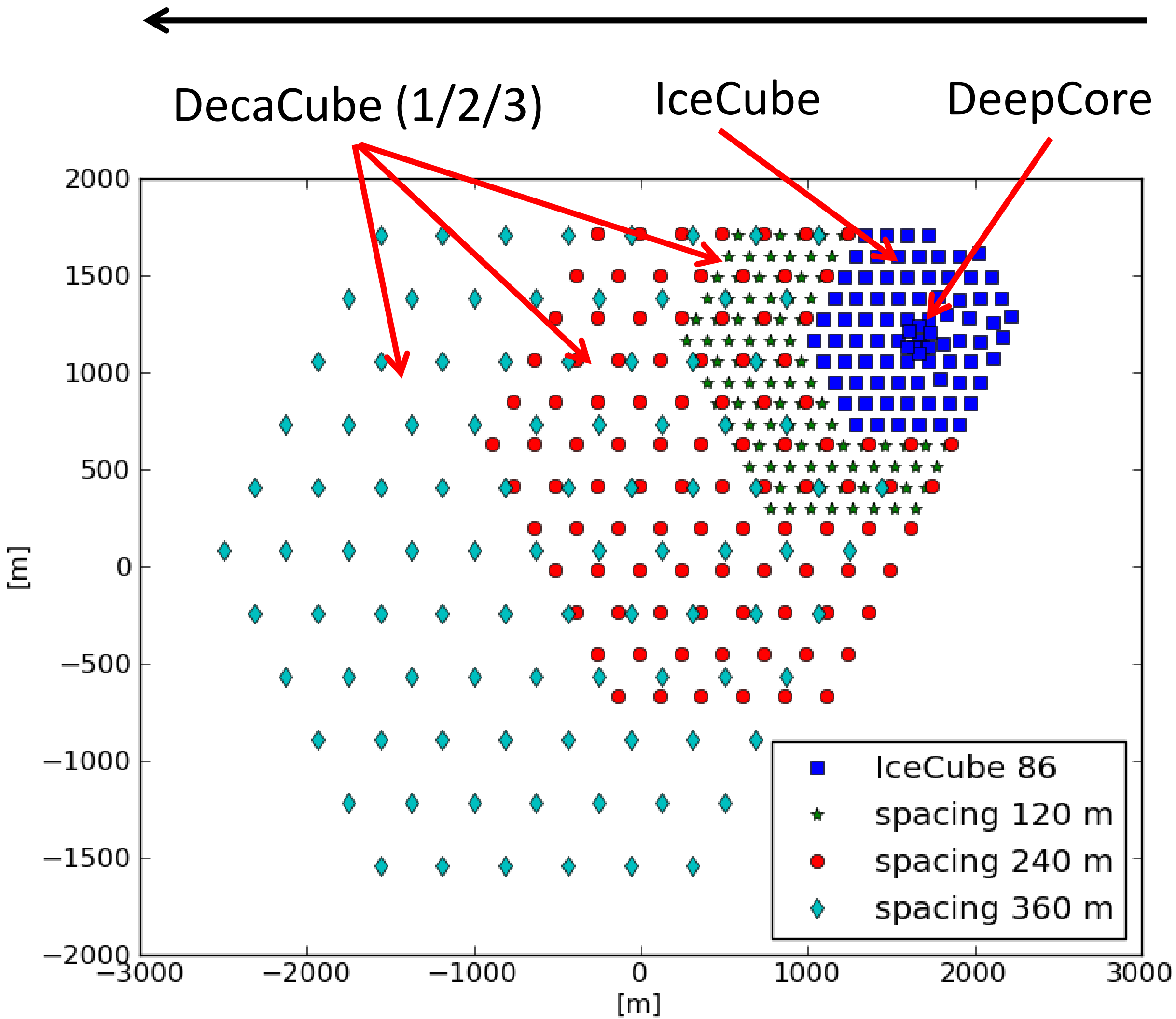




energy of the muon inside the detector (GeV)

V. Niro et al.

increase in threshold not important
(in the region where atmospheric background dominates)



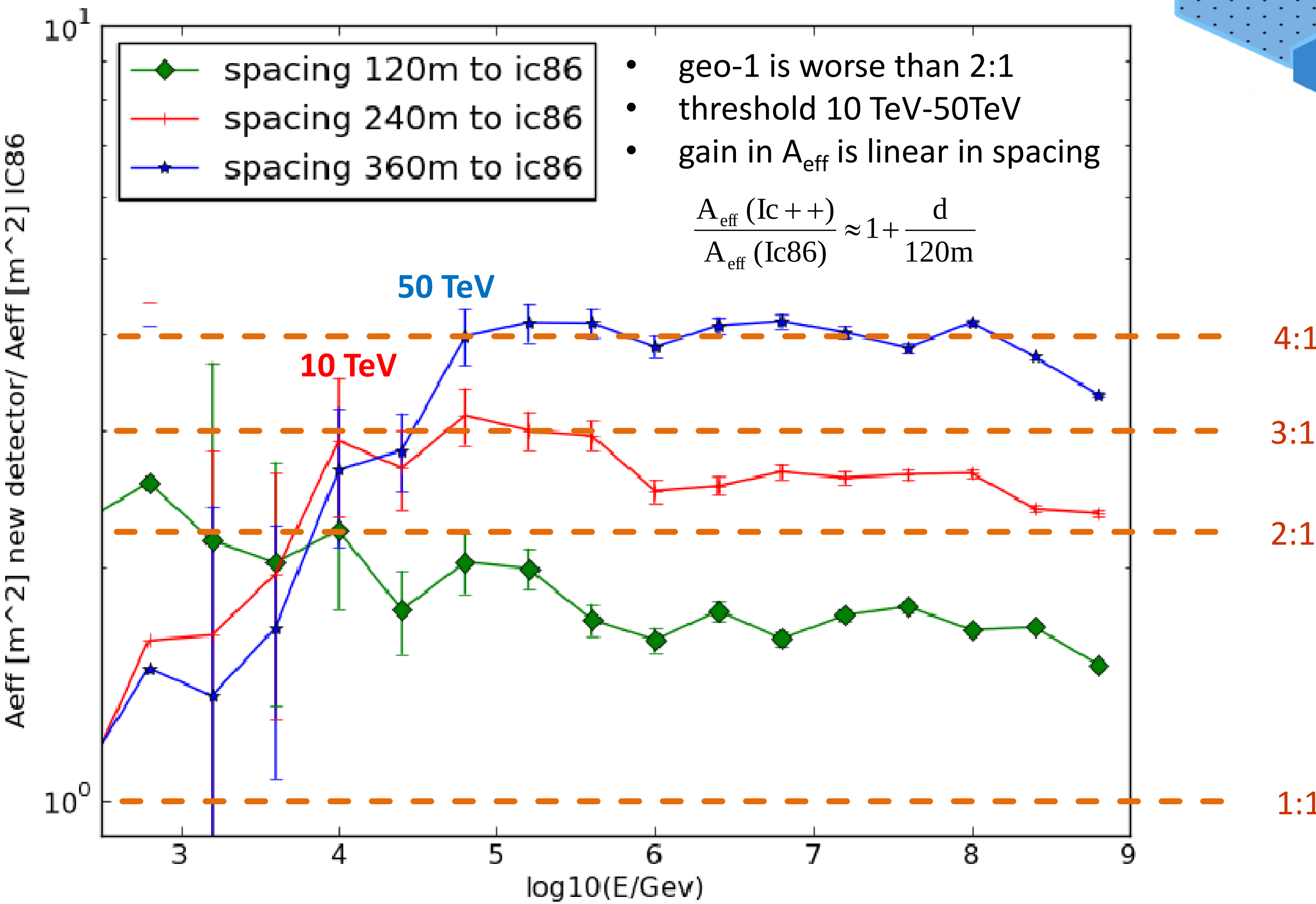
Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

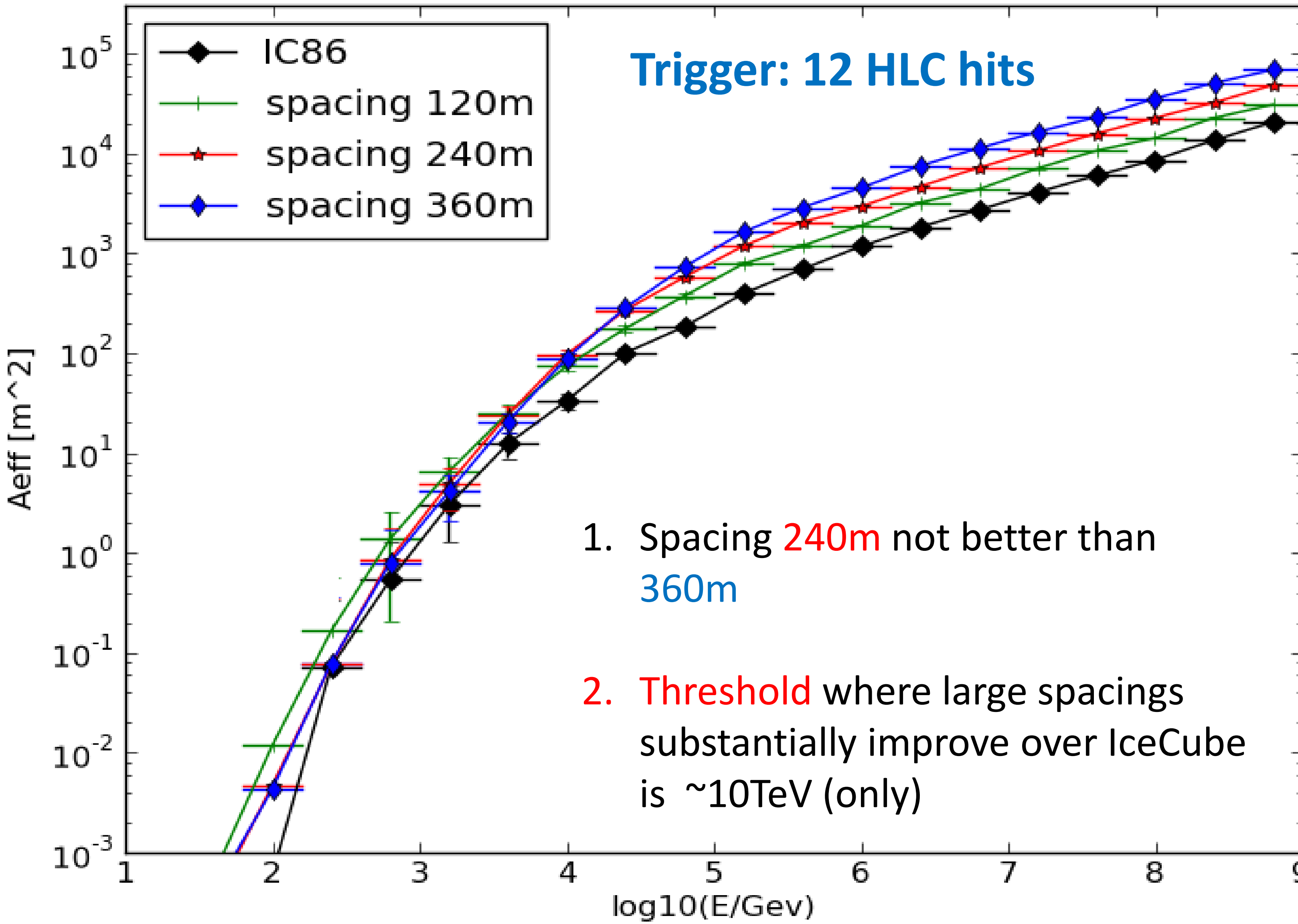
Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)

= 12,6 km³

Improvement Factor w.r. IceCube-86



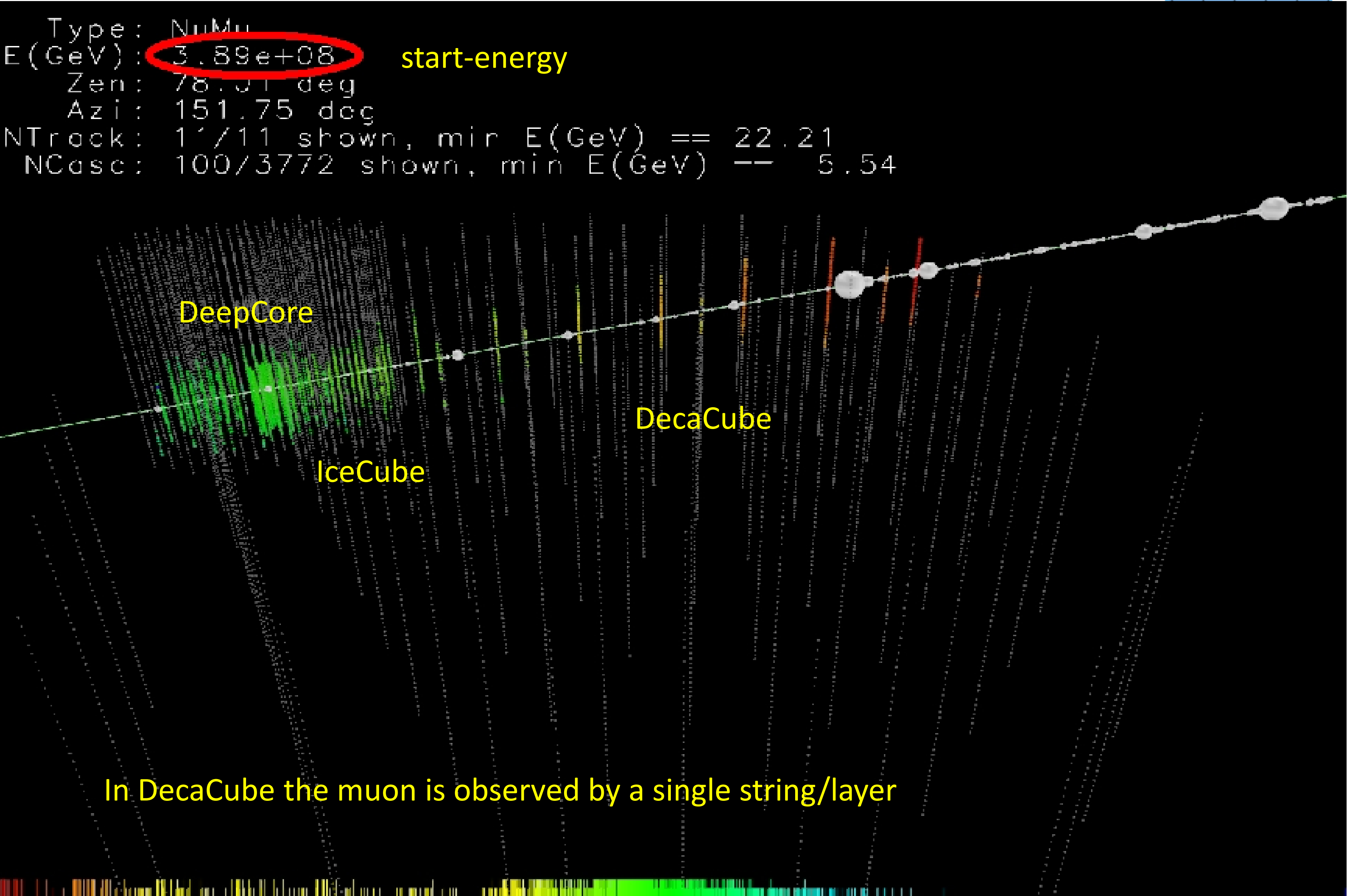
Effective Area on trigger level



1. Spacing 240m not better than 360m

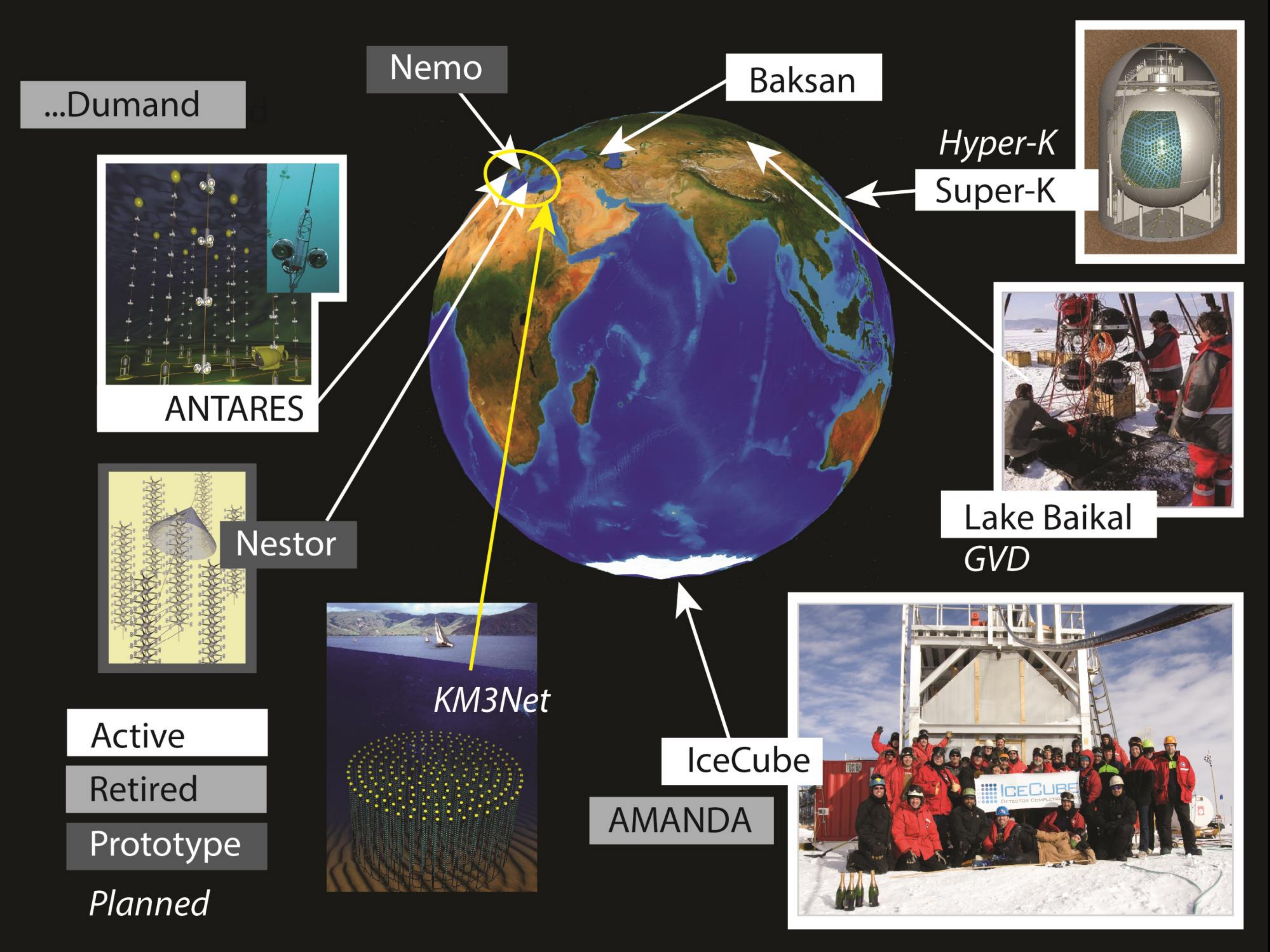
2. Threshold where large spacings substantially improve over IceCube is ~10TeV (only)

Spacing 3: 360m



In DecaCube the muon is observed by a single string/layer

IceCube & PINGU collaborations



...Dumand
Nemo
Baksan
Hyper-K
Super-K
ANTARES
Lake Baikal
GVD
Nestor
KM3Net
IceCube
AMANDA
Active
Retired
Prototype
Planned