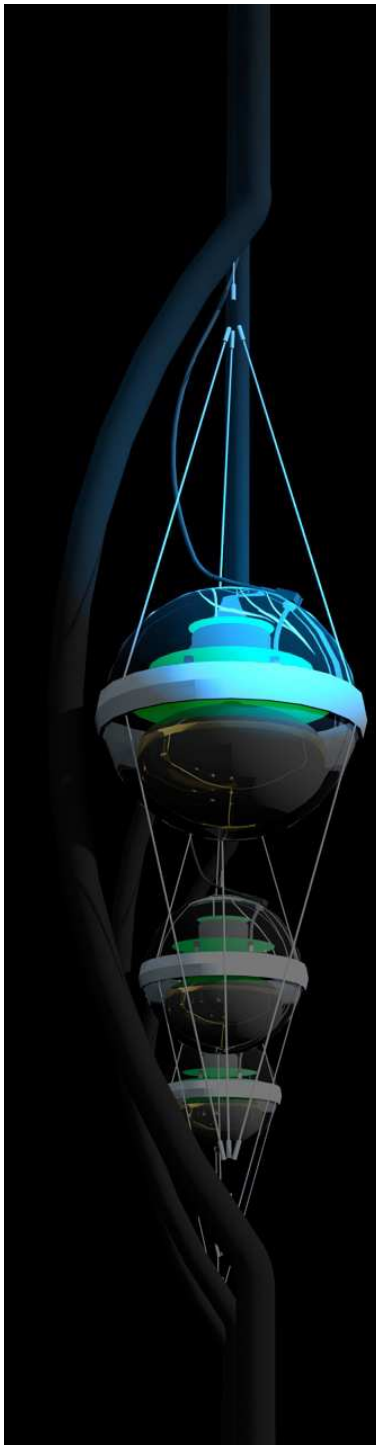
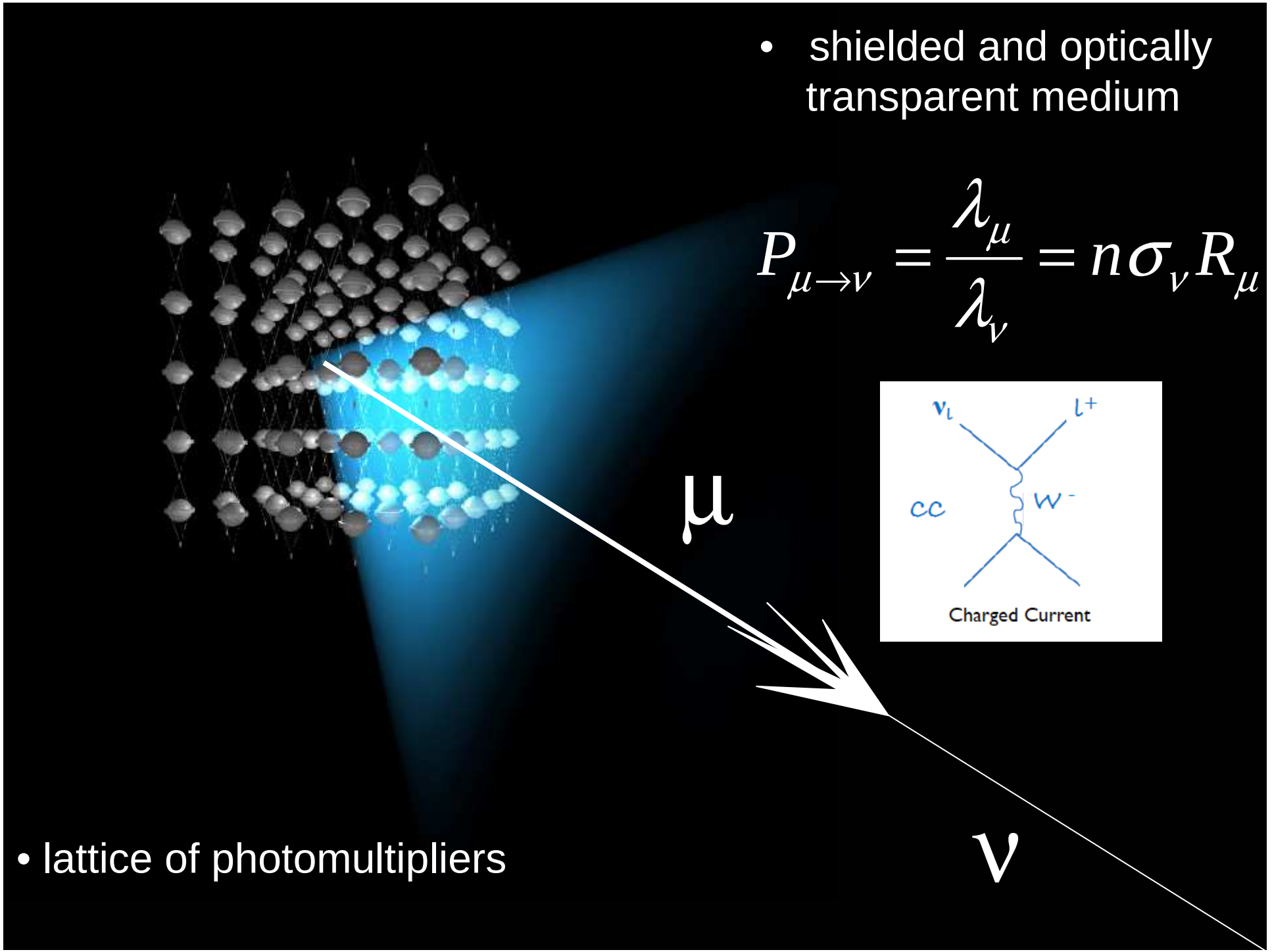


NOW 2012

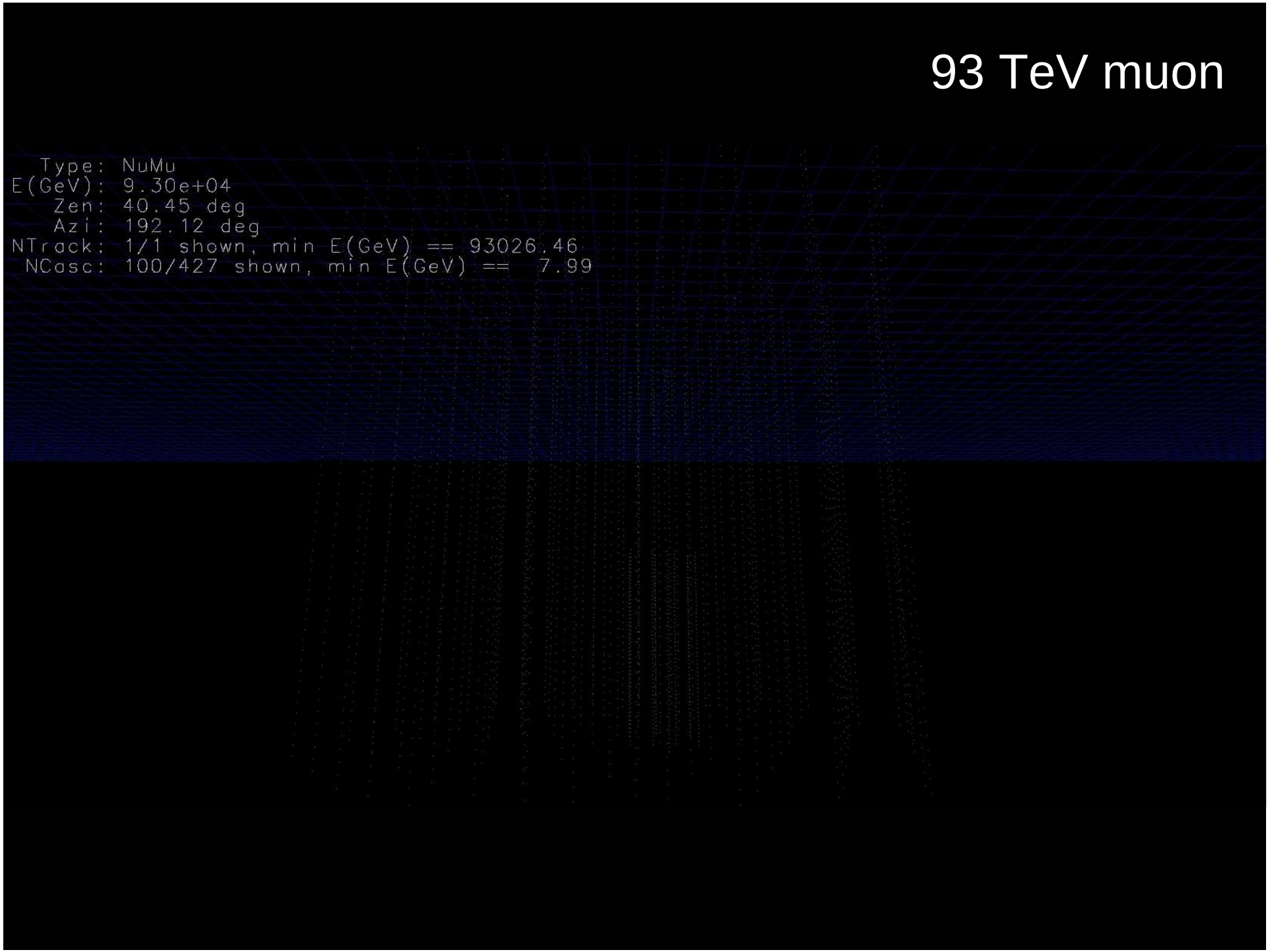
- IceCube
- atmospheric and cosmic neutrinos
- the search for the sources of the Galactic and extragalactic cosmic rays

IceCube.wisc.edu

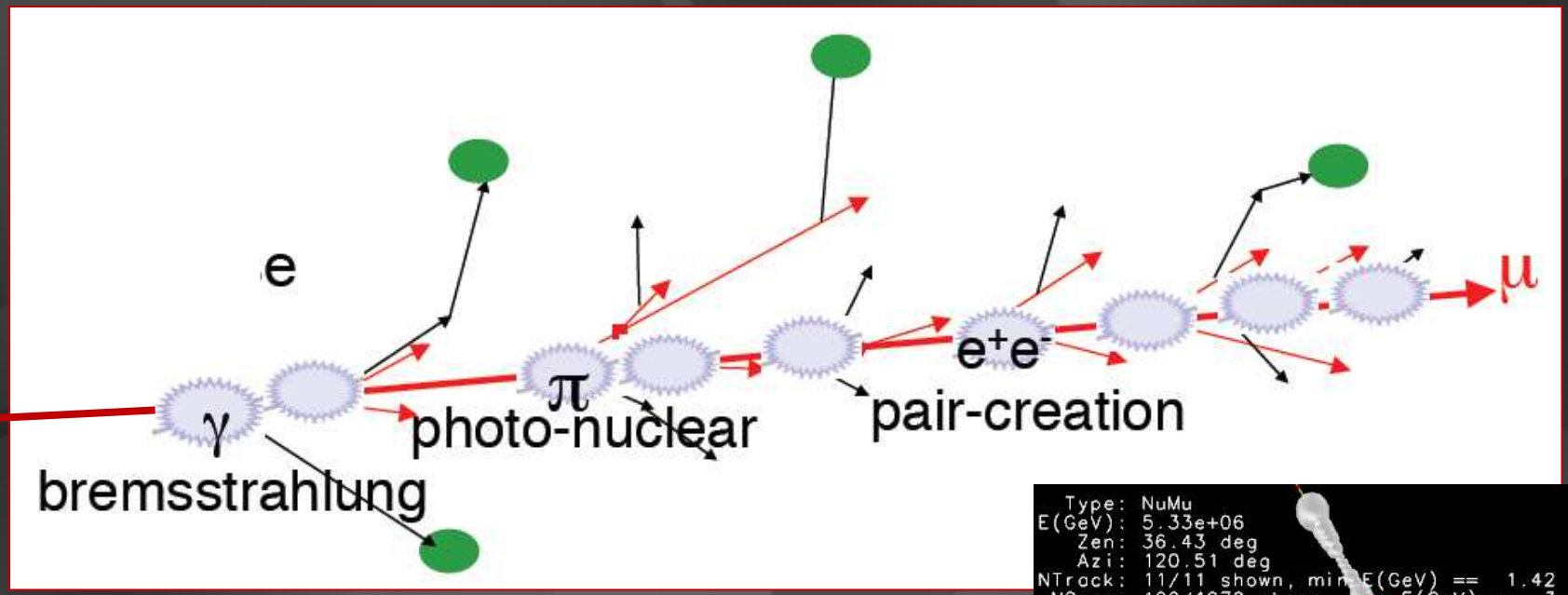

• shielded and optically transparent medium
$P_{\mu\to\nu} = \frac{\lambda_\mu}{\lambda_\nu} = n\sigma_\nu R_\mu$
ν_l
l^+
cc
W^-
Charged Current
μ
ν
• lattice of photomultipliers

photomultiplier tube

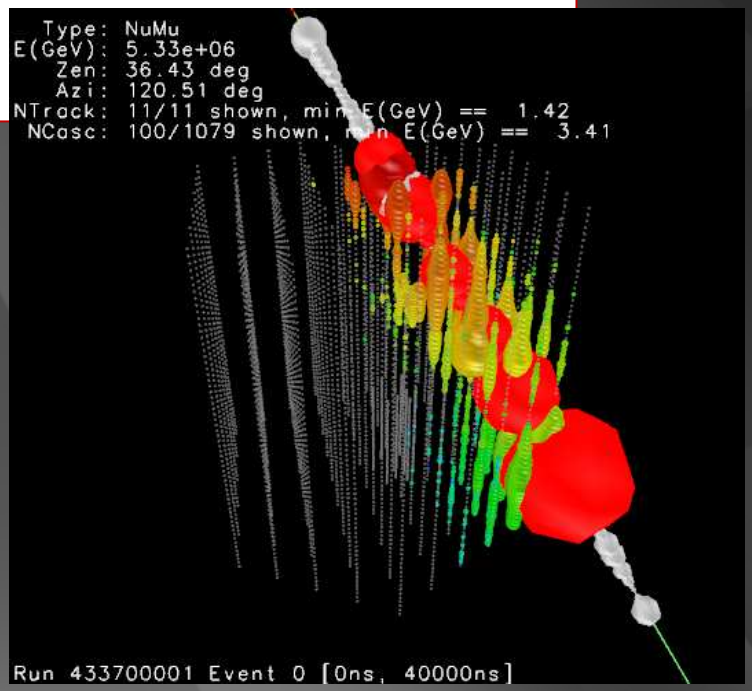
93 TeV muon

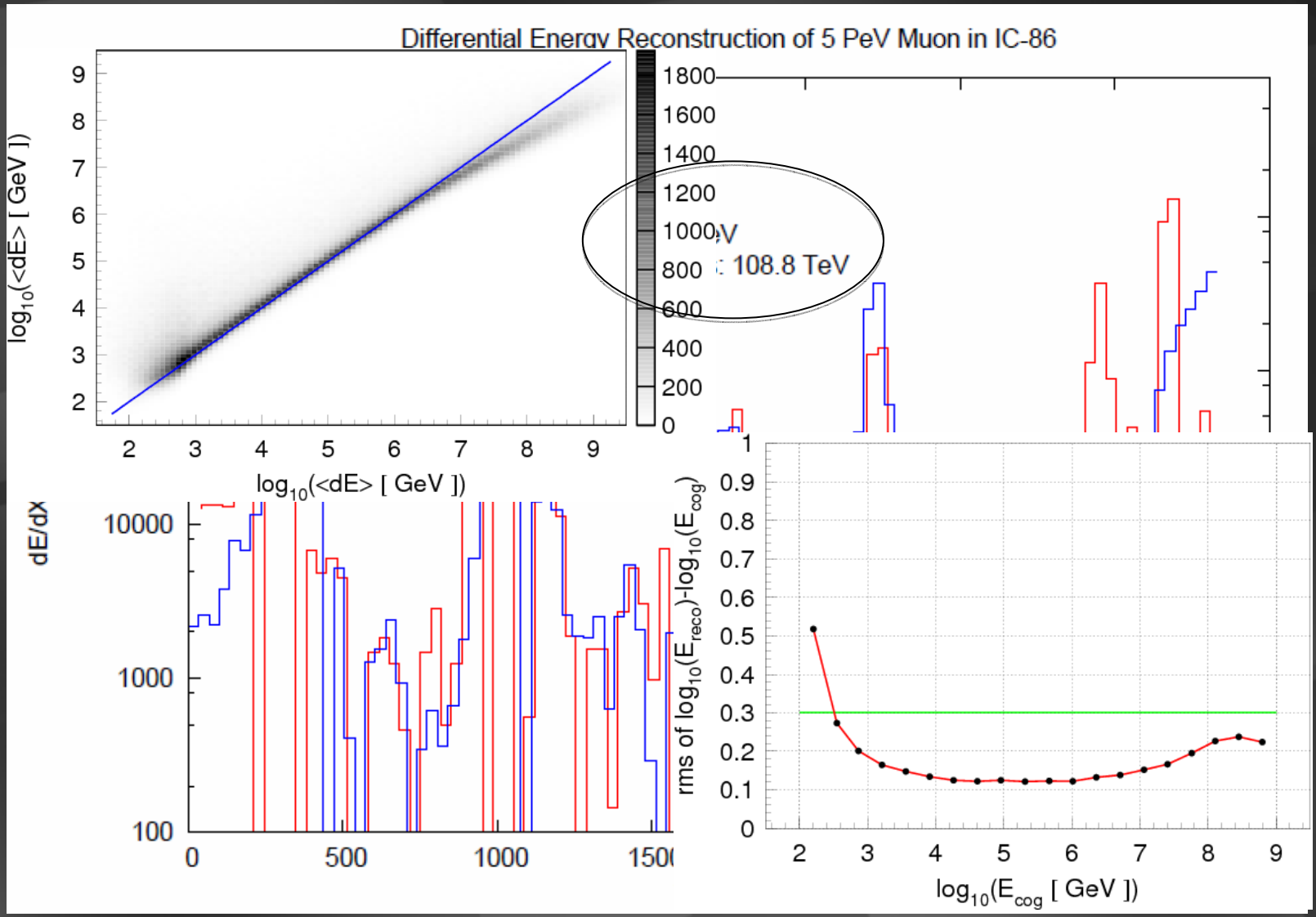

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

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, …)

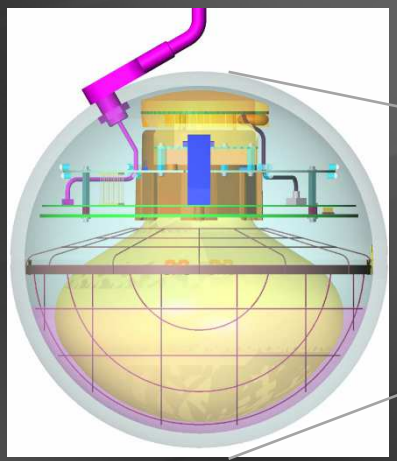




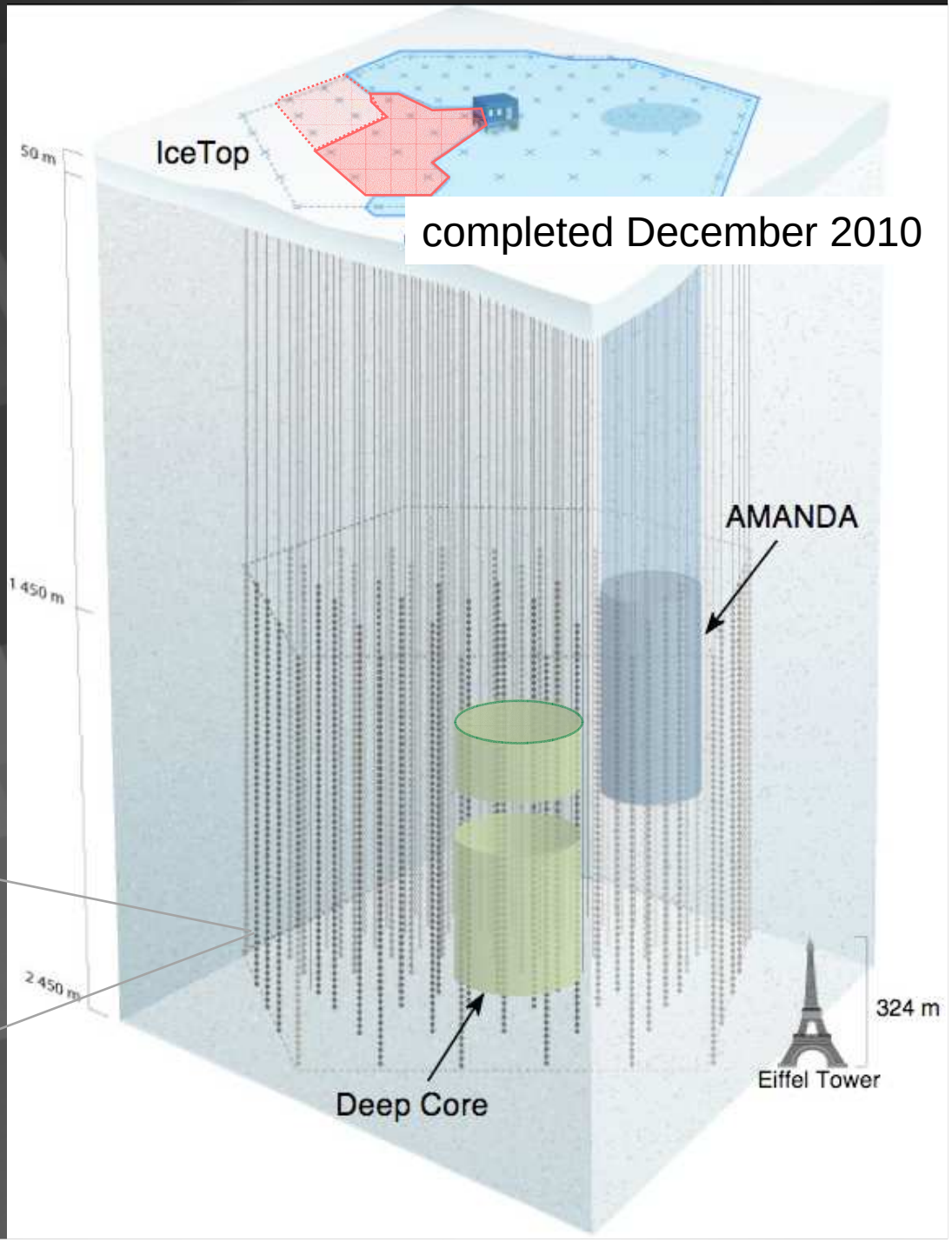
improving angular and energy resolution

IceCube / Deep Core

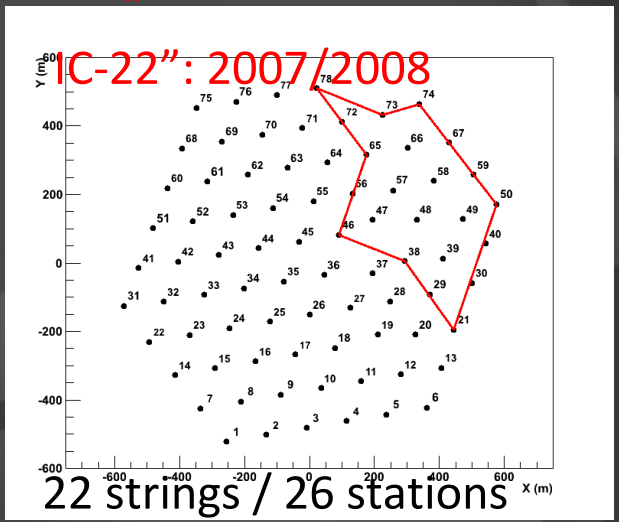
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
  < 0.2 degree off line
- < 30% energy resolution

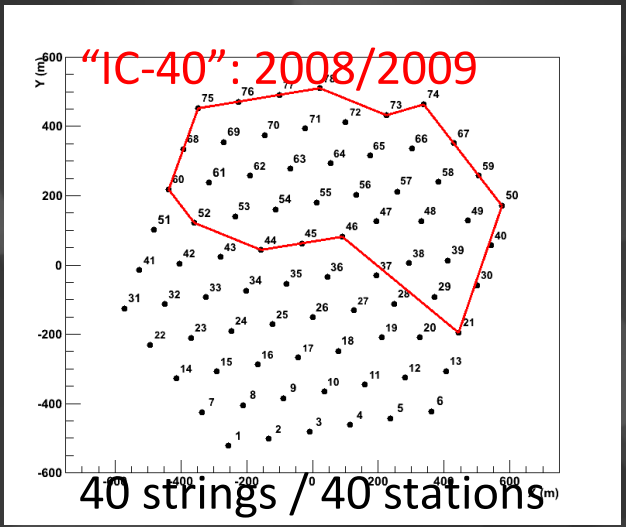


Digital Optical Module (DOM)

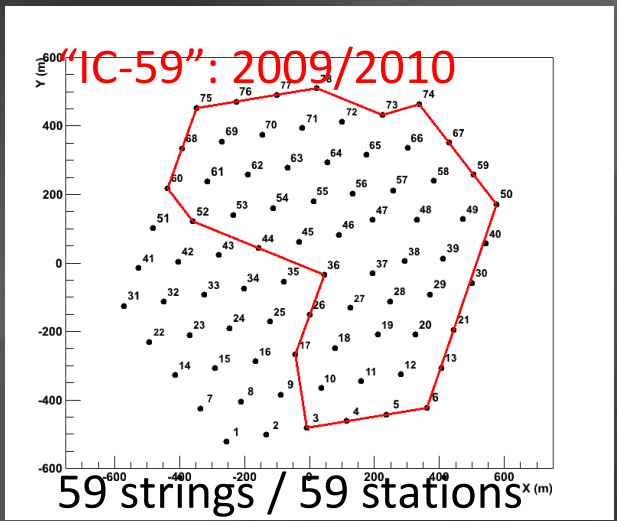


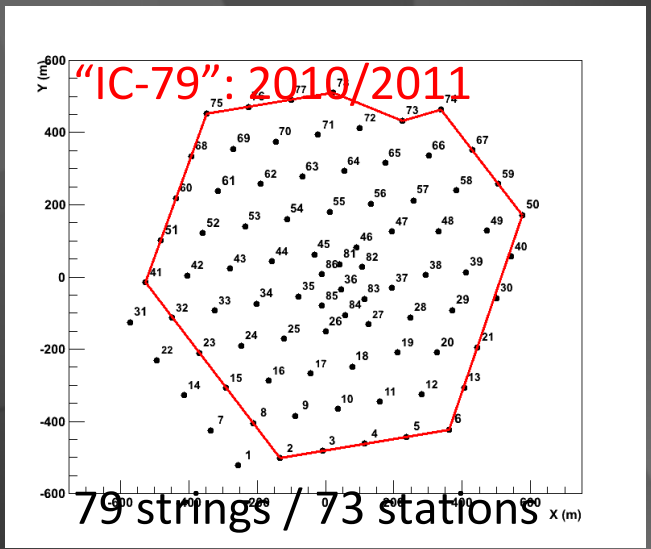
construction of IceCube, year by year…

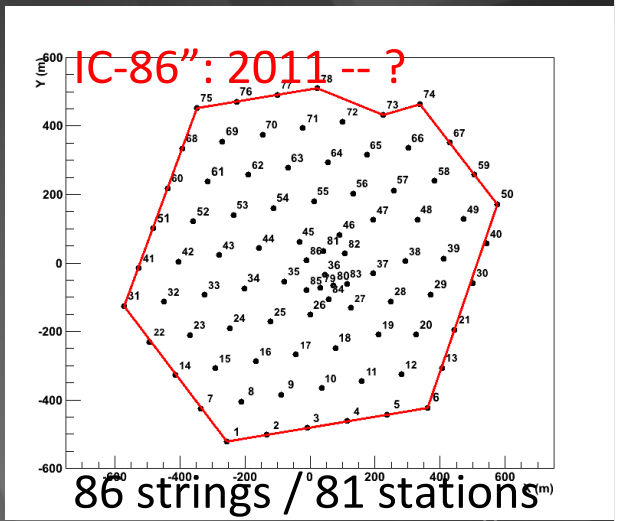




construction completed: Dec 2010.
Fully operational (all strings): May 2011

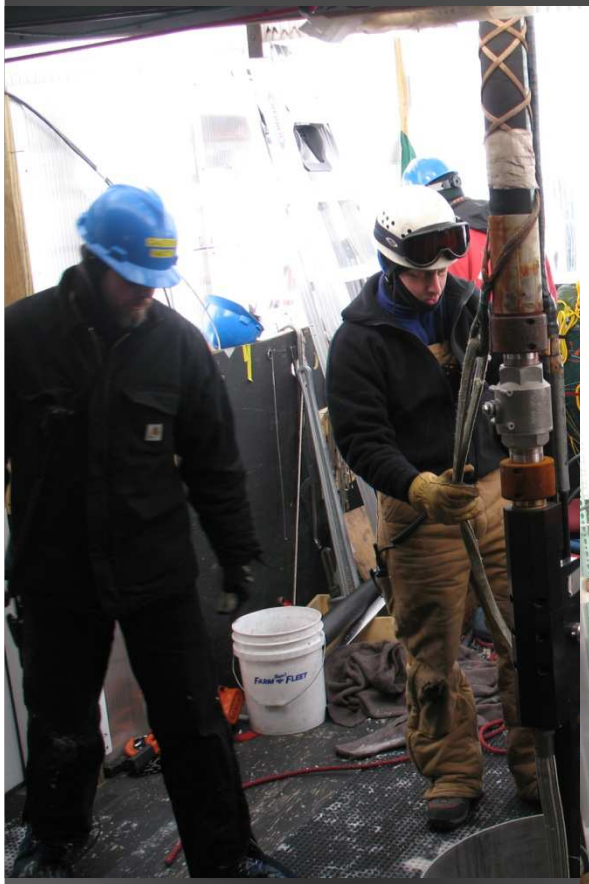






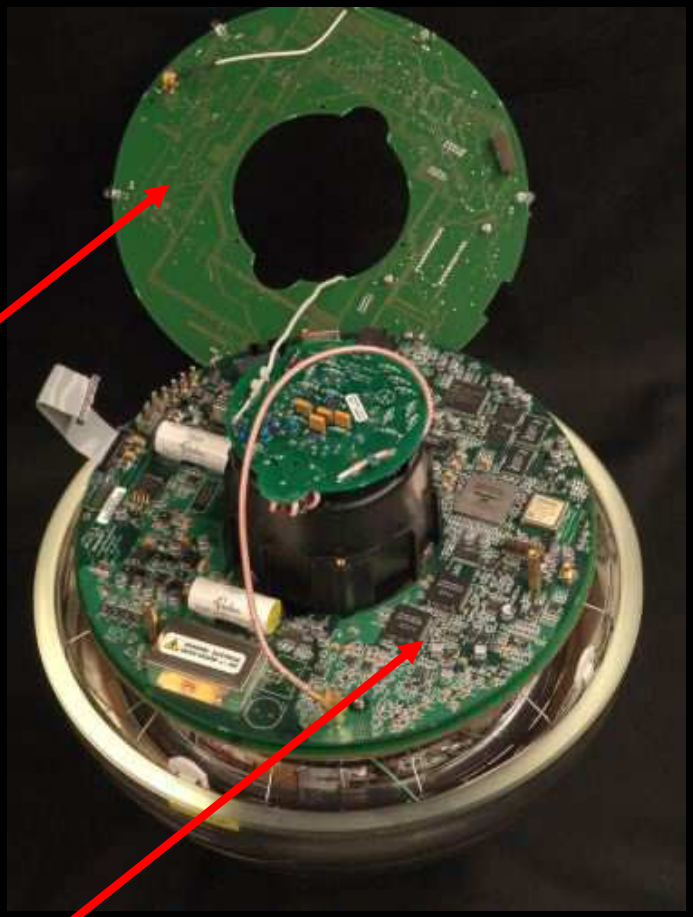
drilling and deployment

drill and install 60 DOMs in less than 2 days



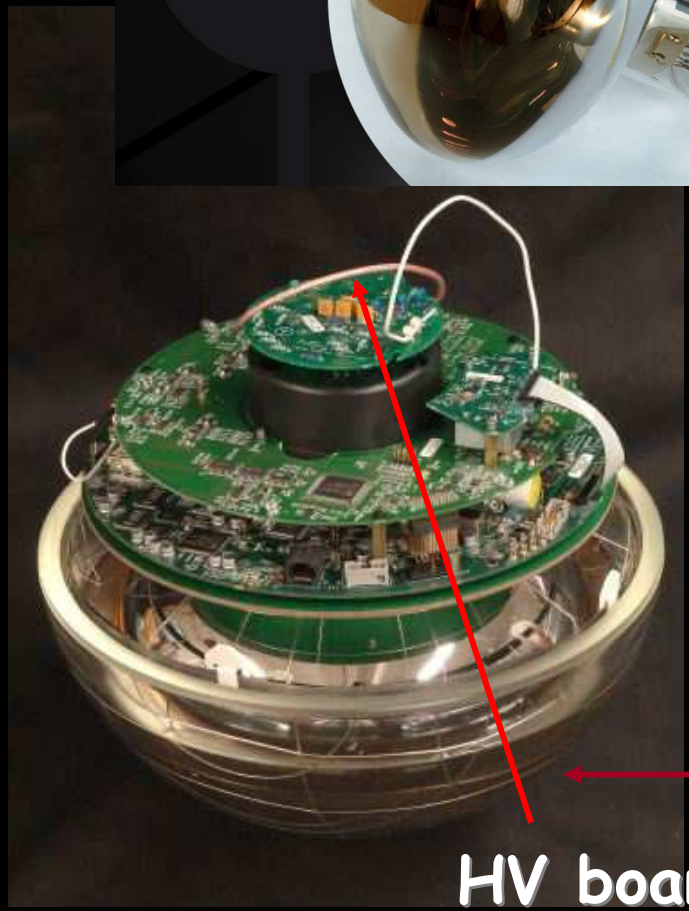
architecture of independent DOMs

10 inch pmt



LED flasher board

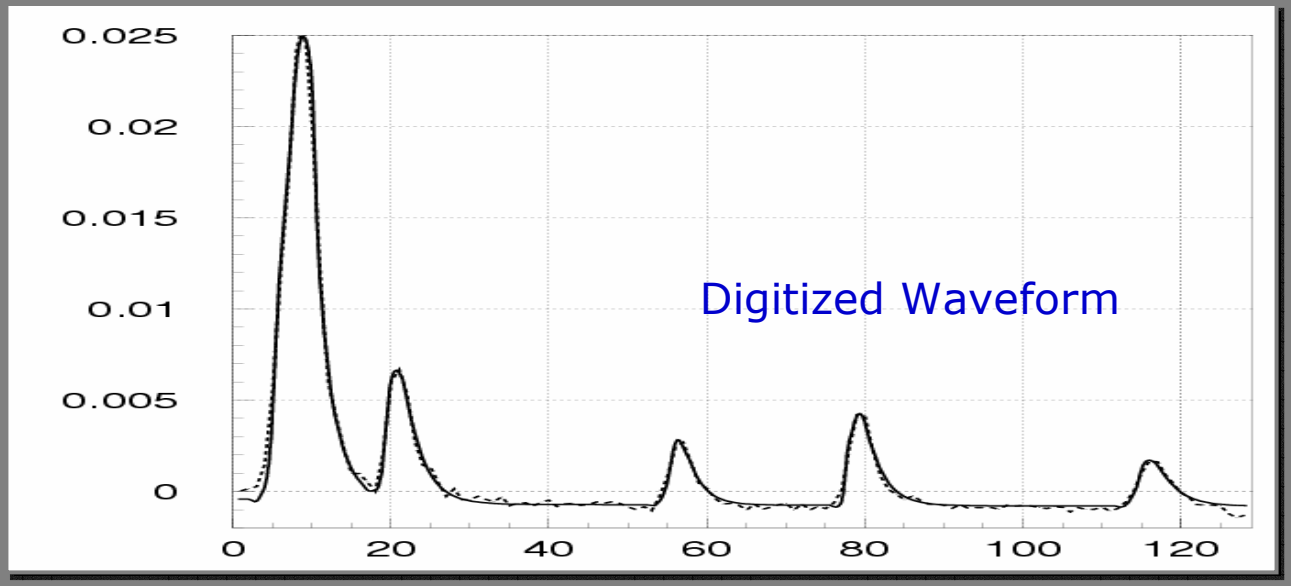
main board



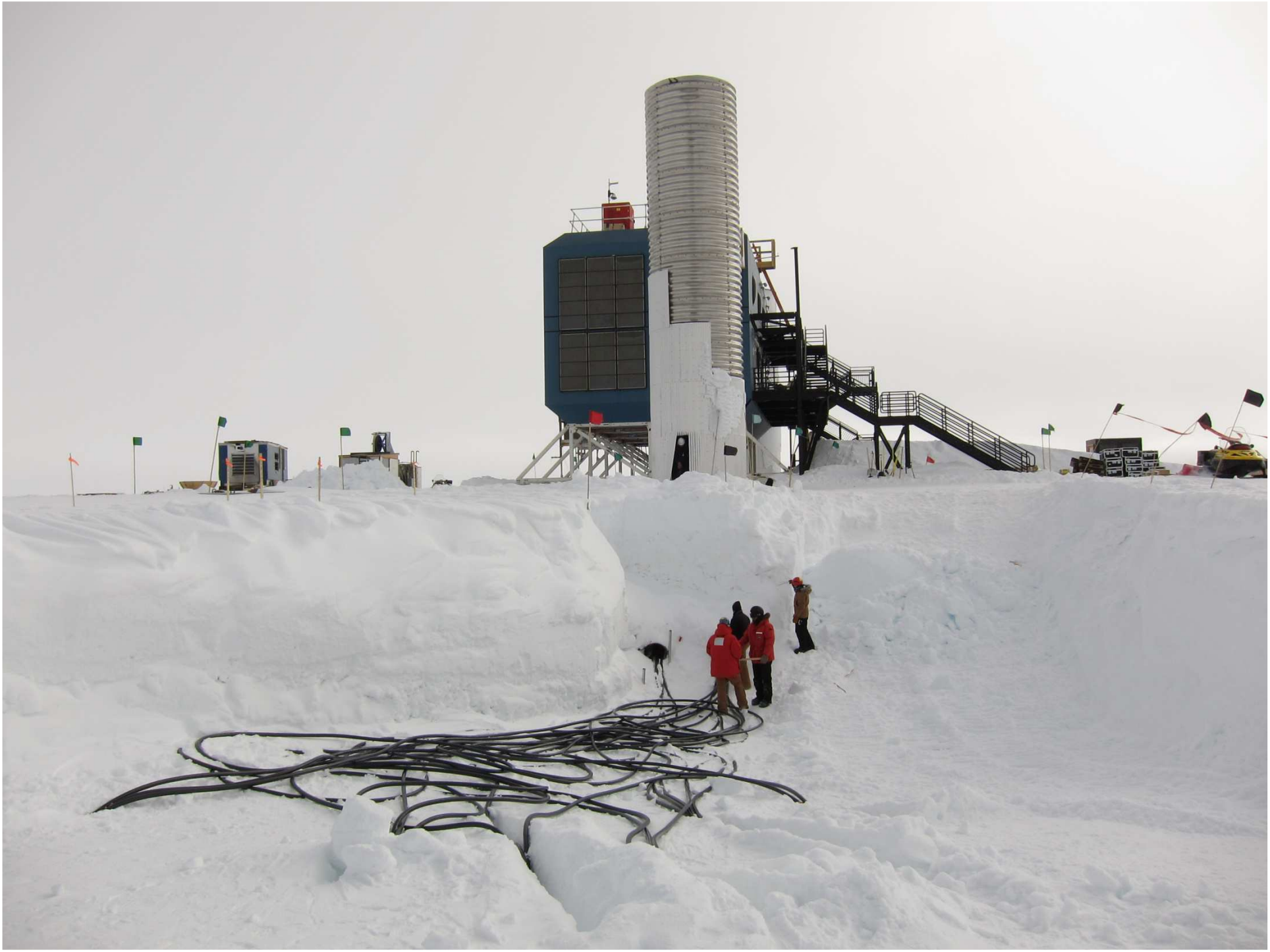
HV board

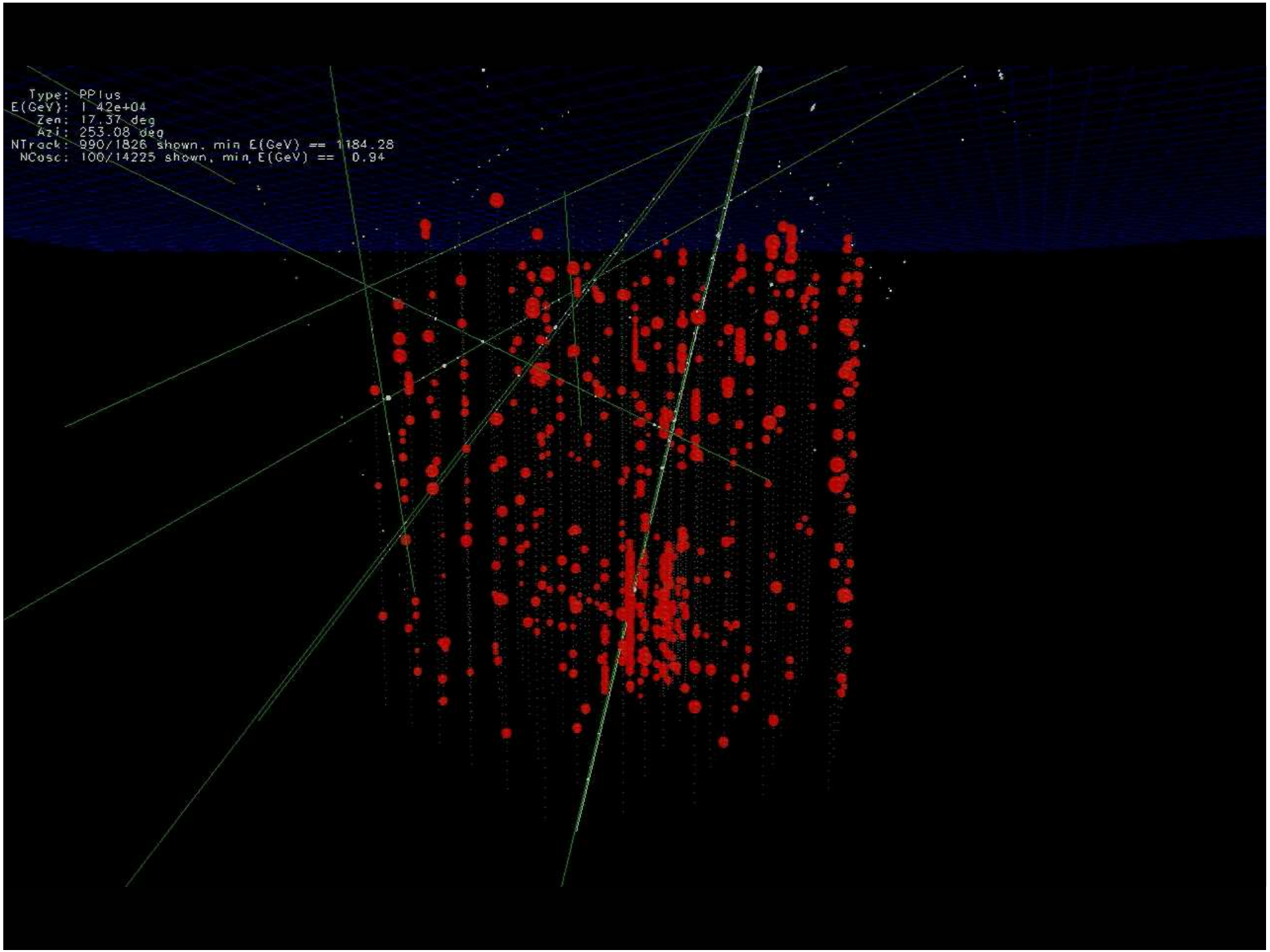
Digital Optical Module (DOM)

… 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 neutrino events…




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

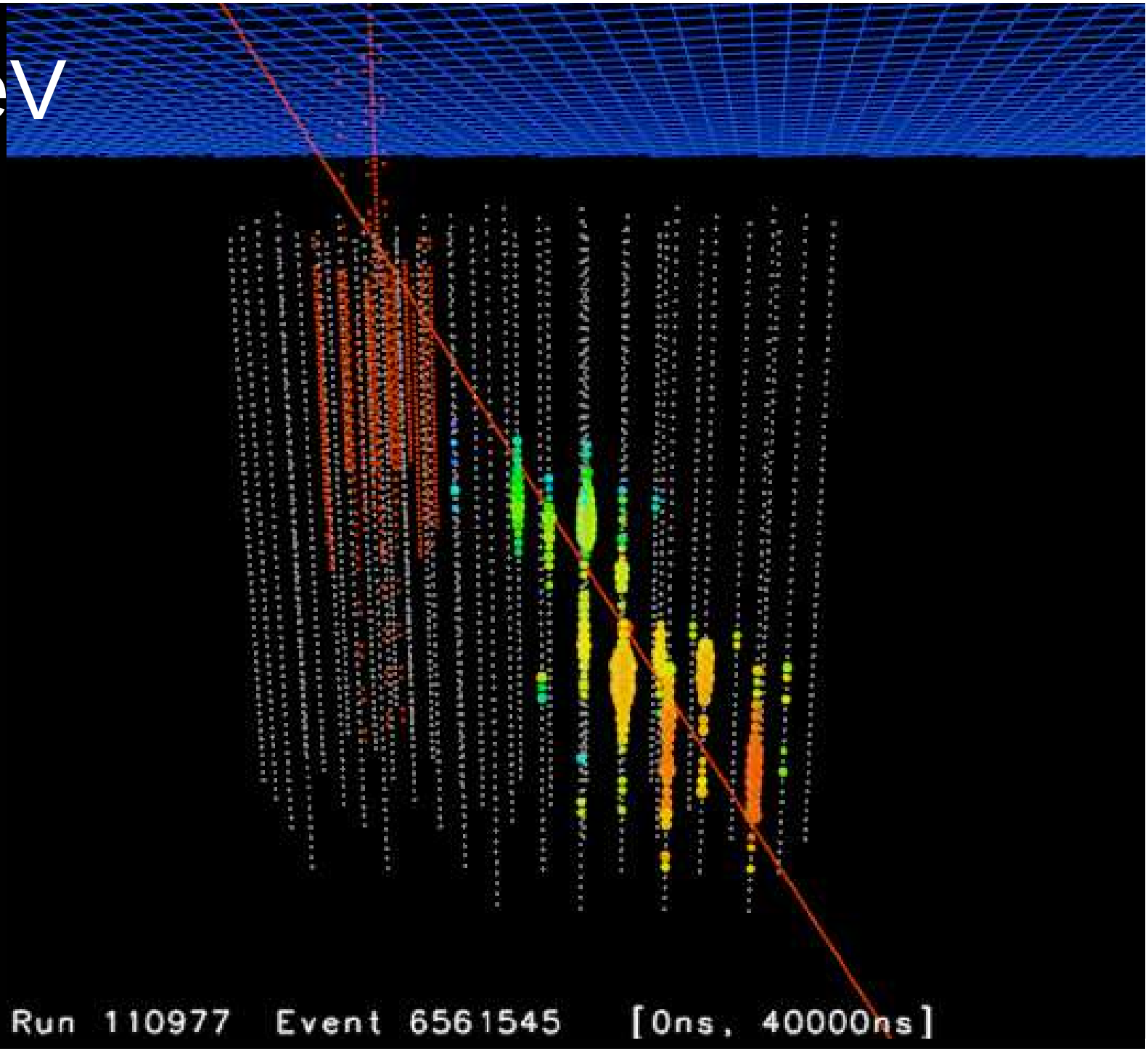
… you looked at 10 msec of data !

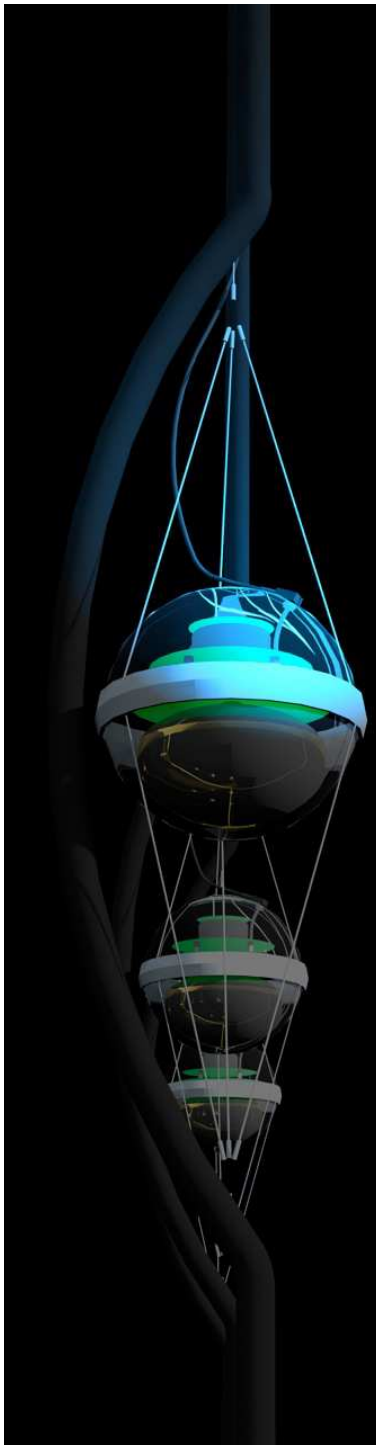
muons detected per year:

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

* 3000 per second ** 1 every 6 minutes

89 TeV





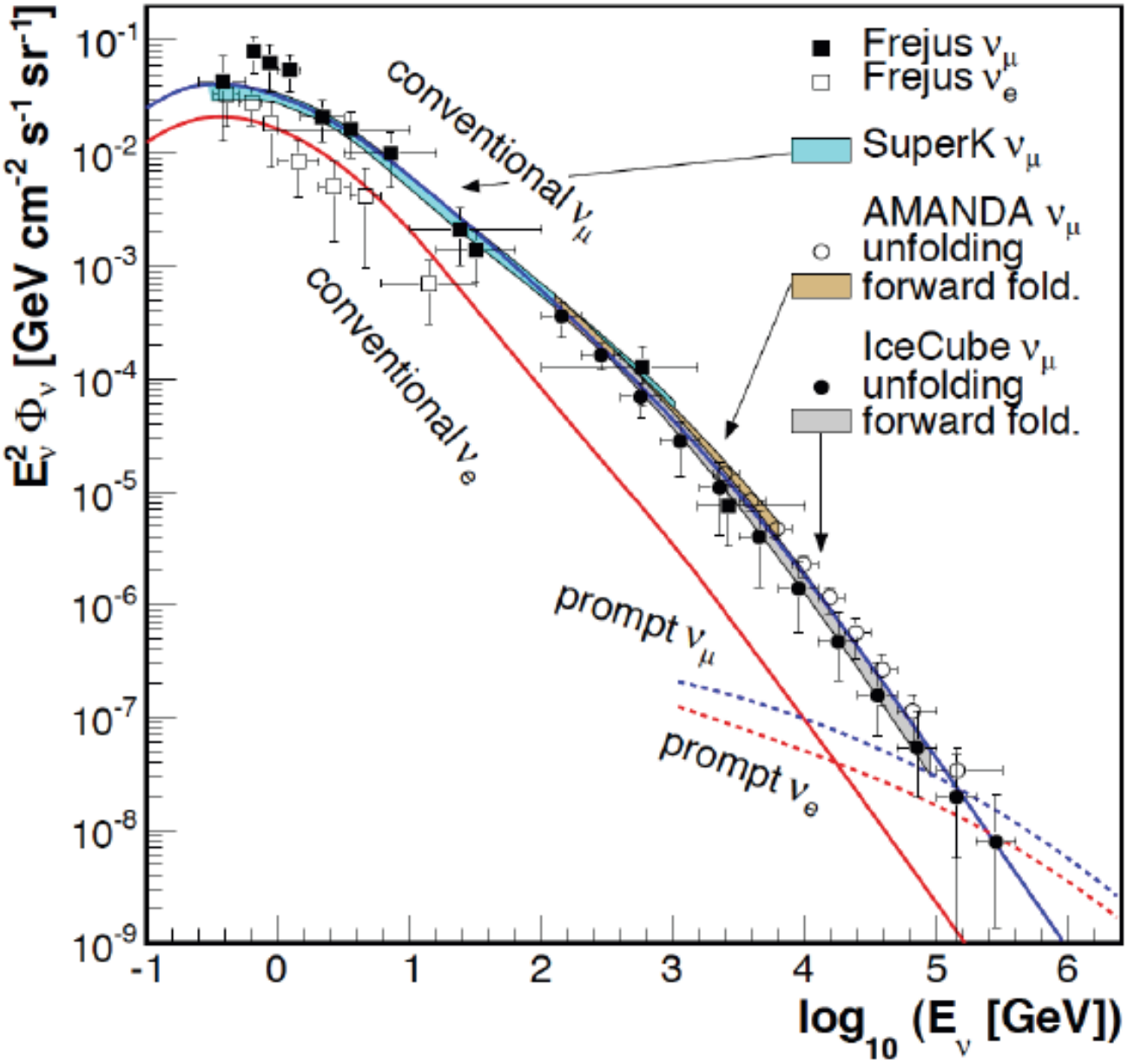
NOW 2012

- IceCube
- atmospheric and cosmic neutrinos
- the search for the sources of the Galactic and extragalactic cosmic rays

IceCube.wisc.edu

cosmic neutrinos:

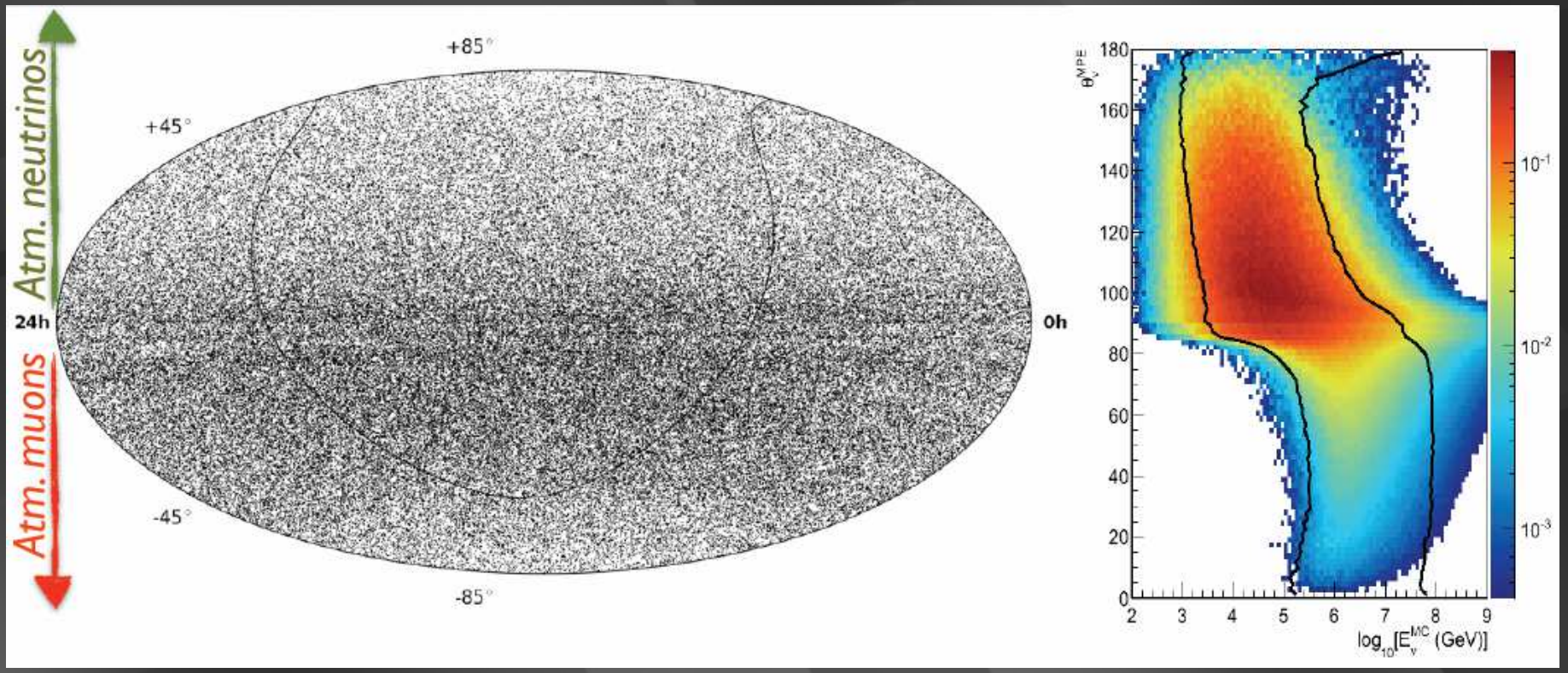
energy:
>> 100 TeV



atmospheric neutrino spectrum to >100 TeV

IceCube 40 + 59 strings out of 86

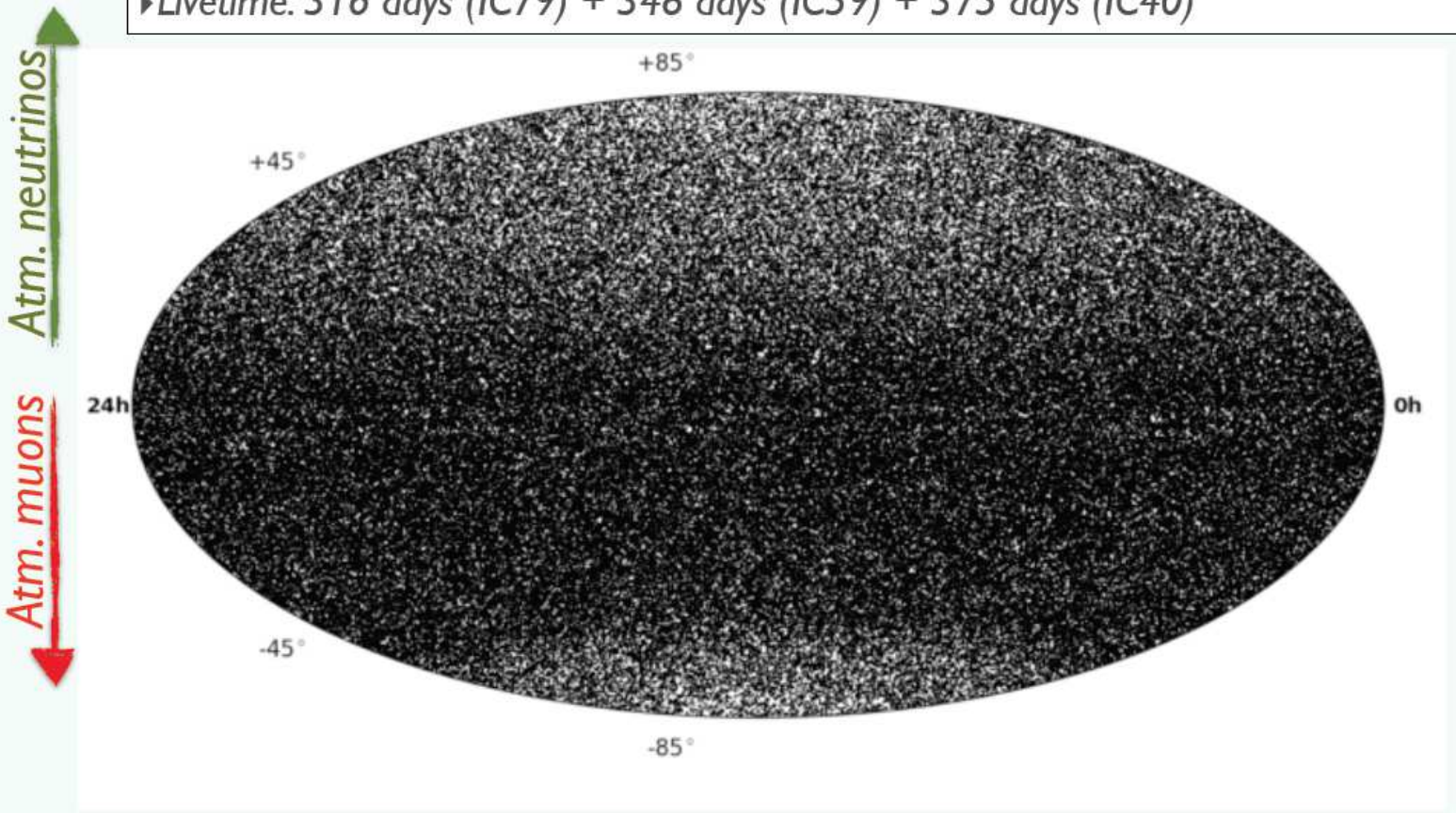
43339 neutrinos



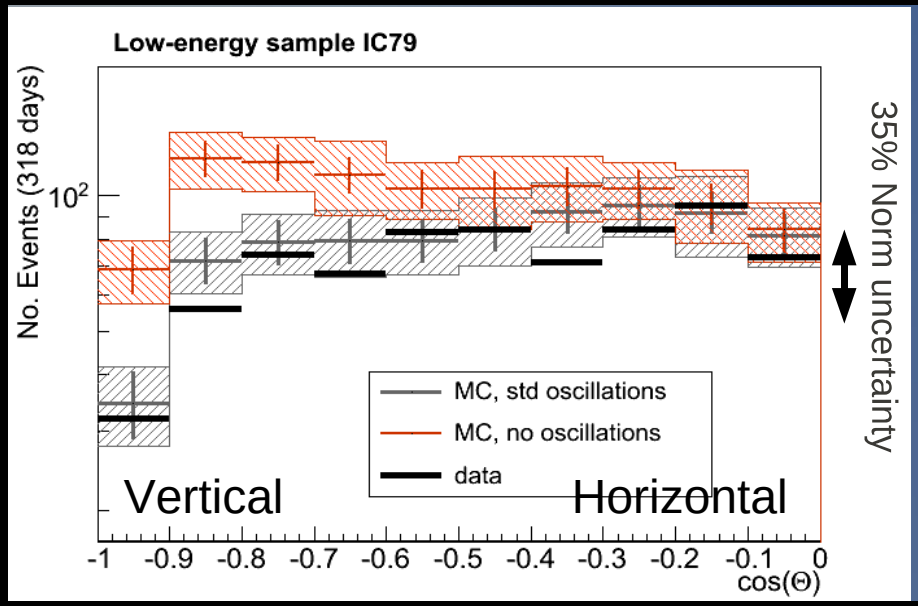
64230 muons

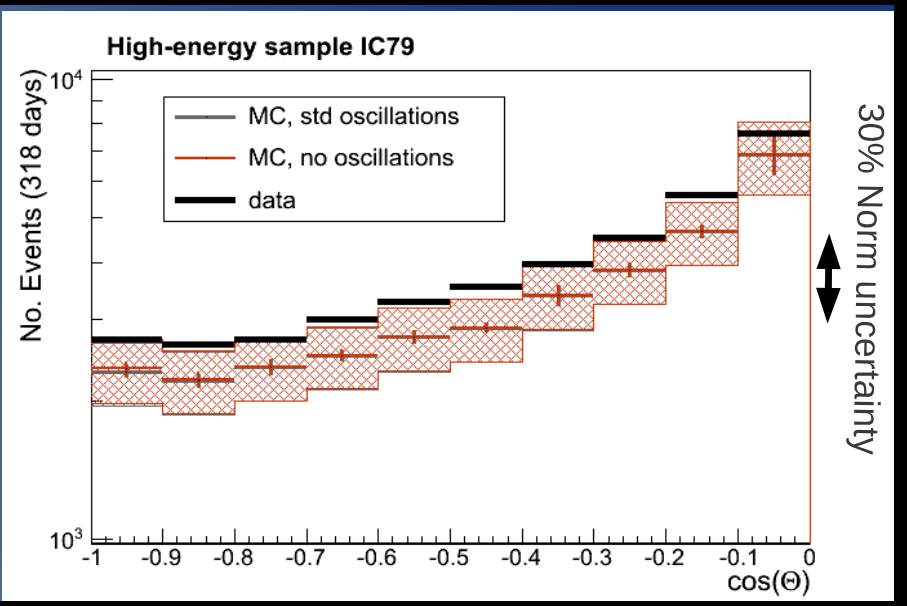
+IC79 SKYMAP

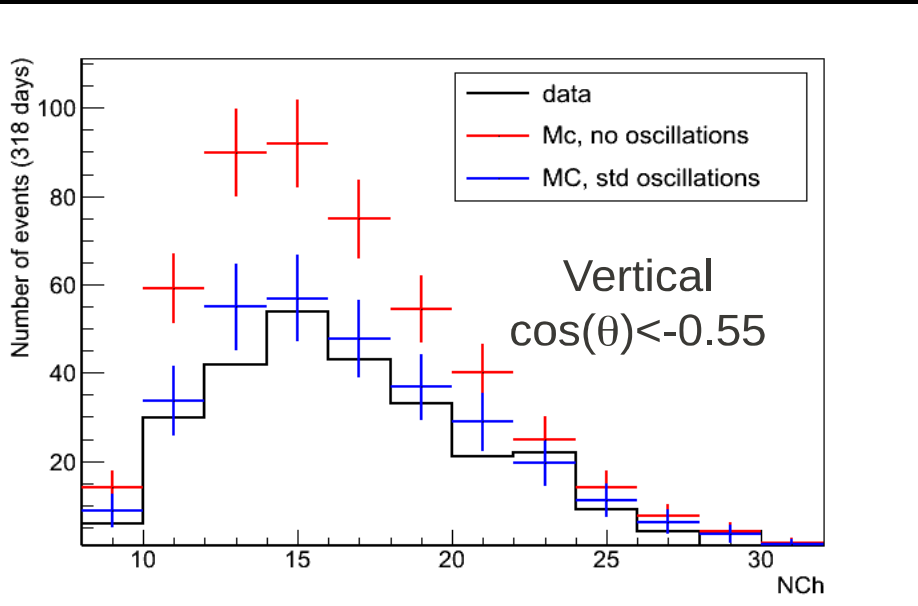
- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*

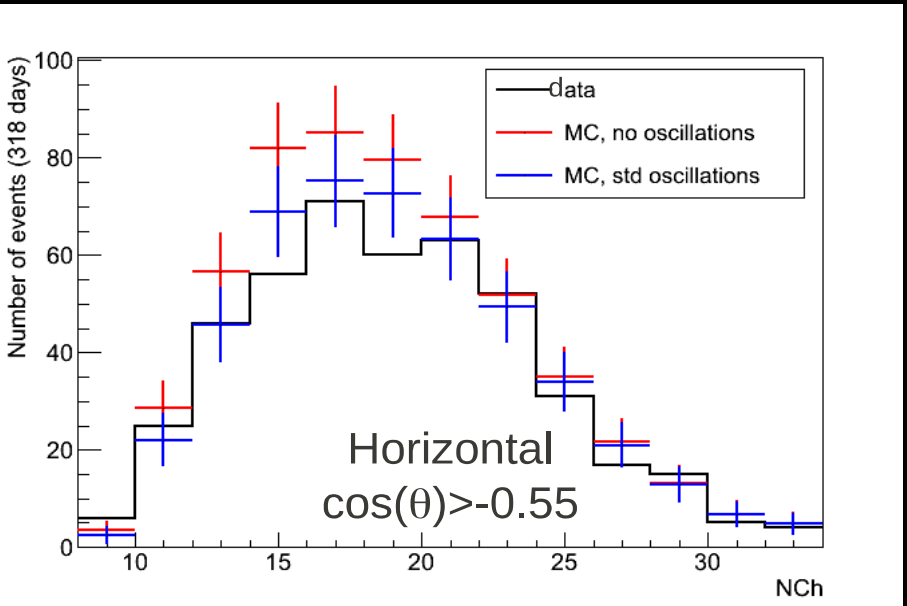


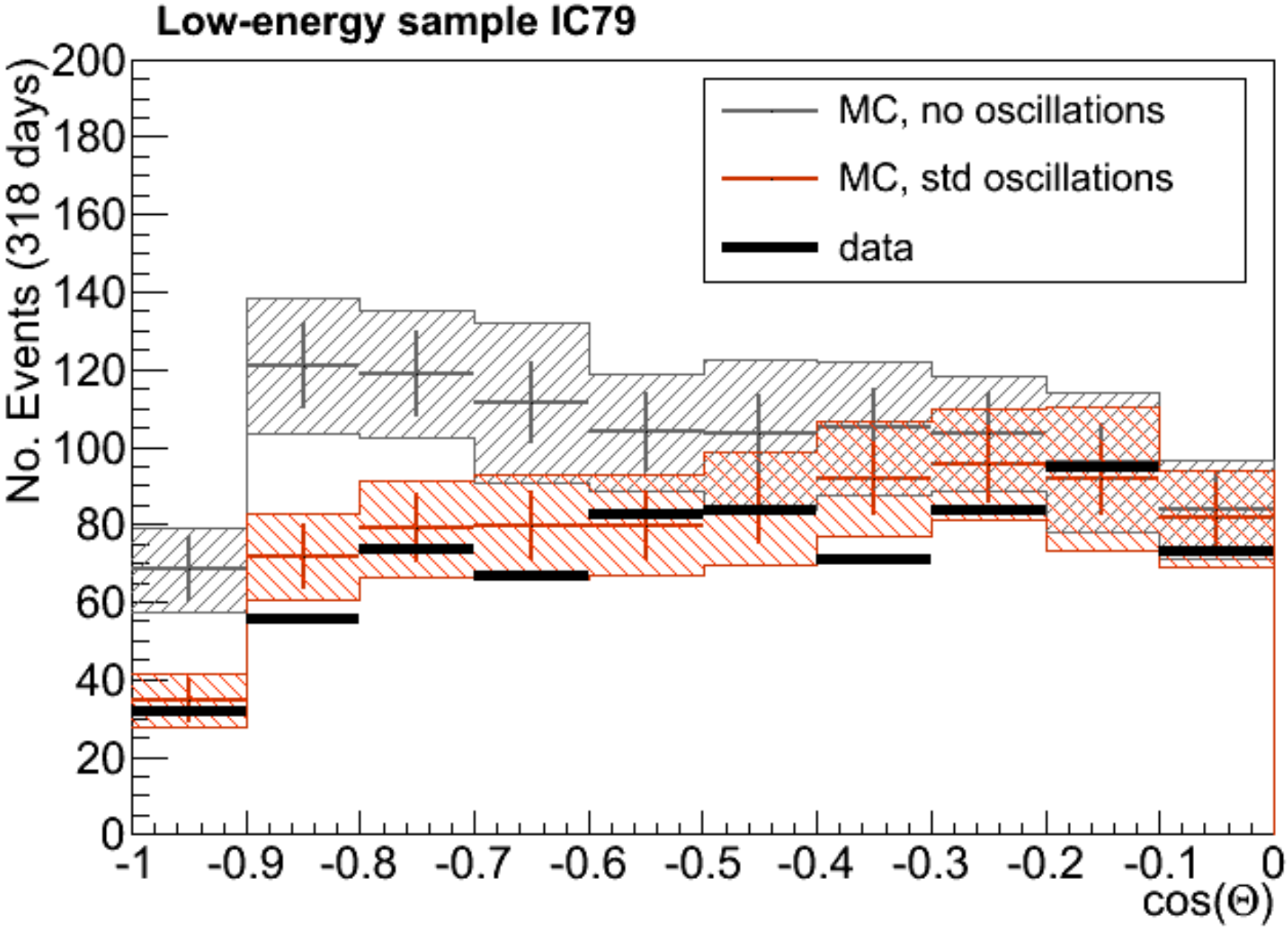
oscillations in DeepCore [5.6 sigma] Andreas Gross



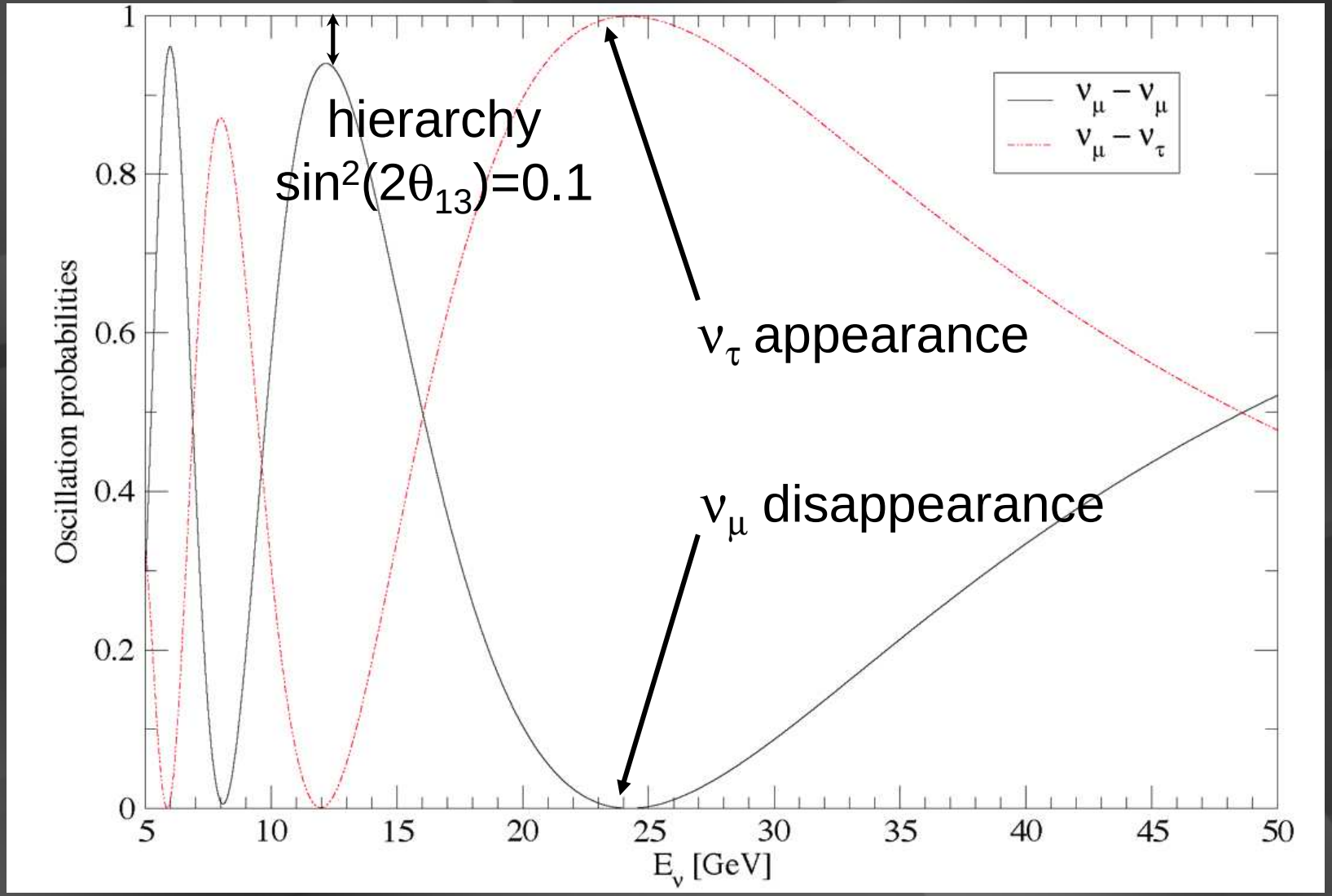






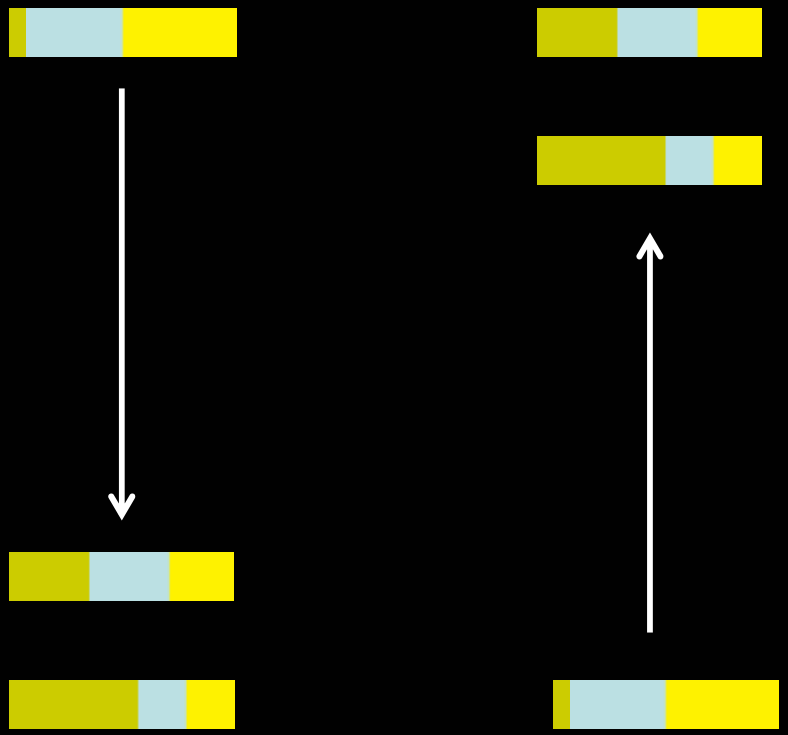

Low-energy sample IC79
No. Events (318 days)
200
180
160
140
120
100
80
60
40
20
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
cos(Θ)
MC, no oscillations
MC, std oscillations
data

neutrino oscillations in Deep Core



resonance in effective θ_{13} angle traversing the Earth diameter at 10 GeV

hierarchy: sign Δ_{13}?



~ 10 GeV : hierarchy revealed by
“large” matter effects in the Earth

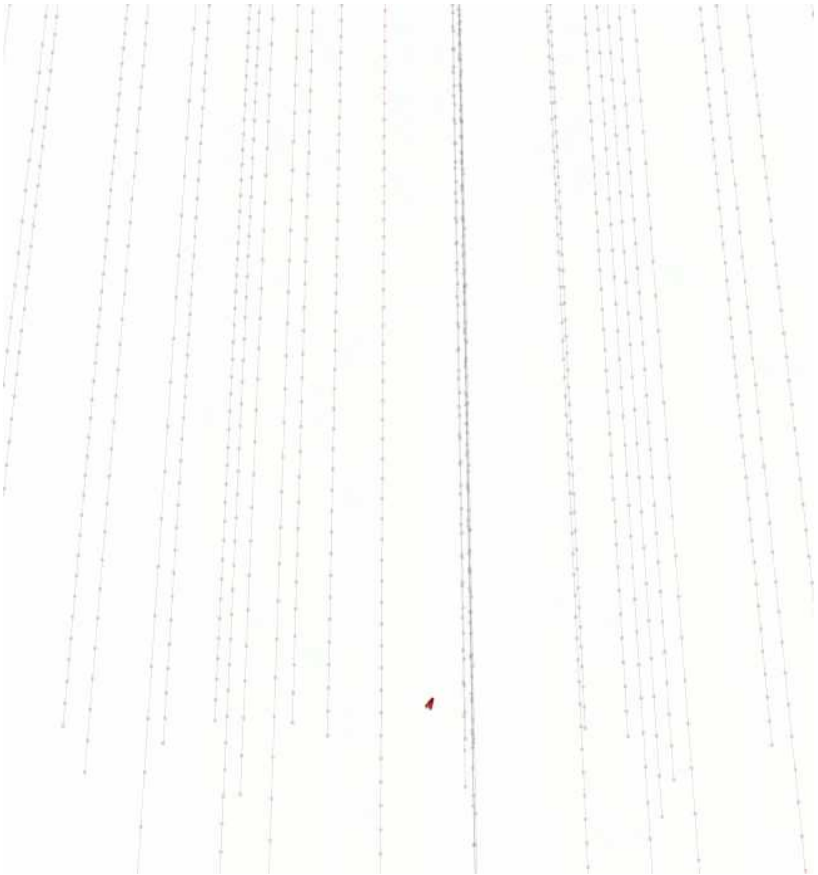
$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2G_F n_e}}{\Delta_{13}}\right]}$$

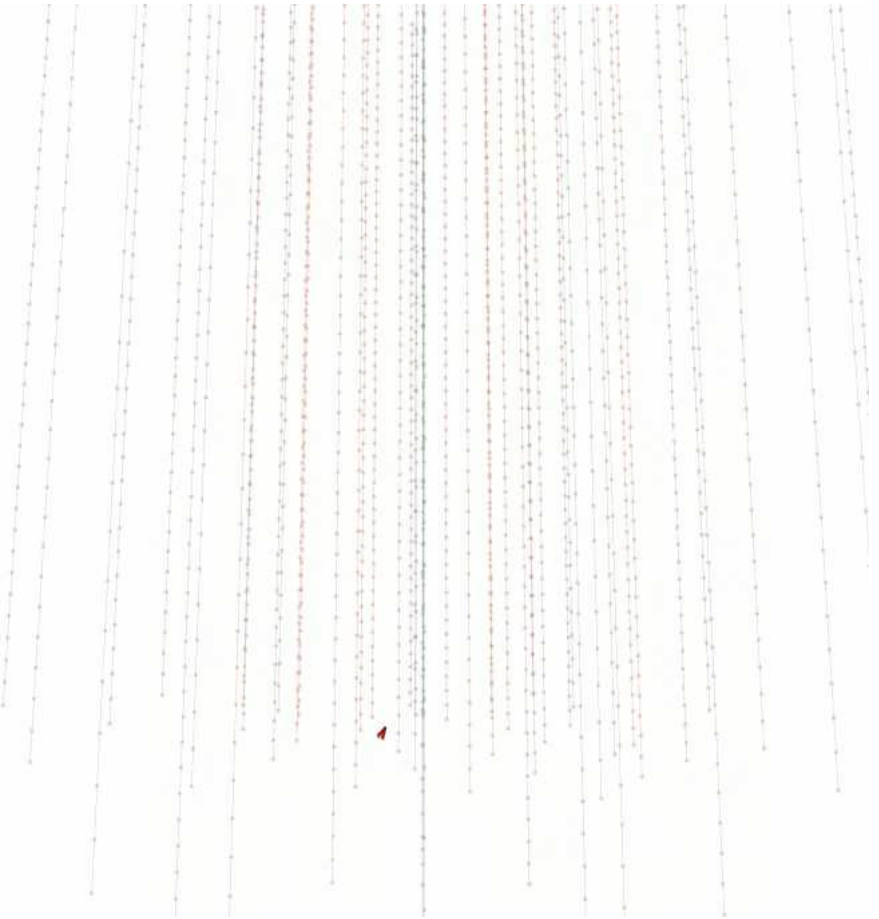
(mostly) neutrino + antineutrino -

sign Δ_{13} : hierarchy !

DeepCore (+6 strings):11 hits

PINGU (+20 strings): 83 hits





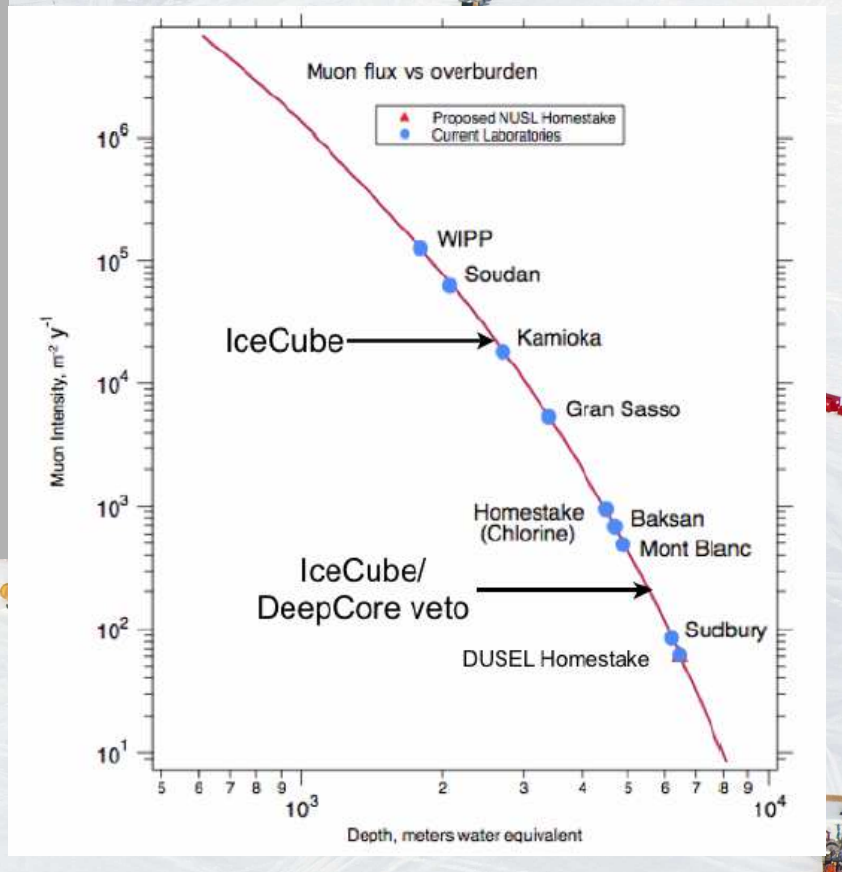
8 GeV muon-neutrino

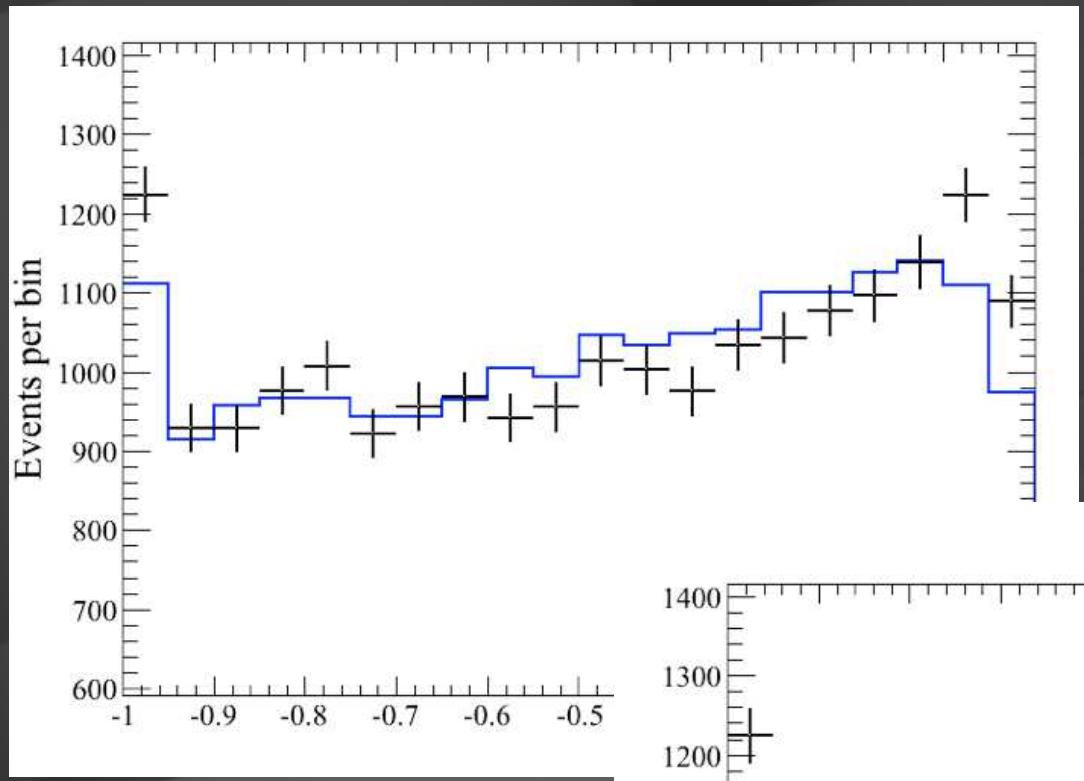
IceCube drilling to best low background site on Earth:

→ radio-pure ice
→ no seasonal variations (temperature, humidity,…)
→ shielded from cosmic rays by IceCube veto

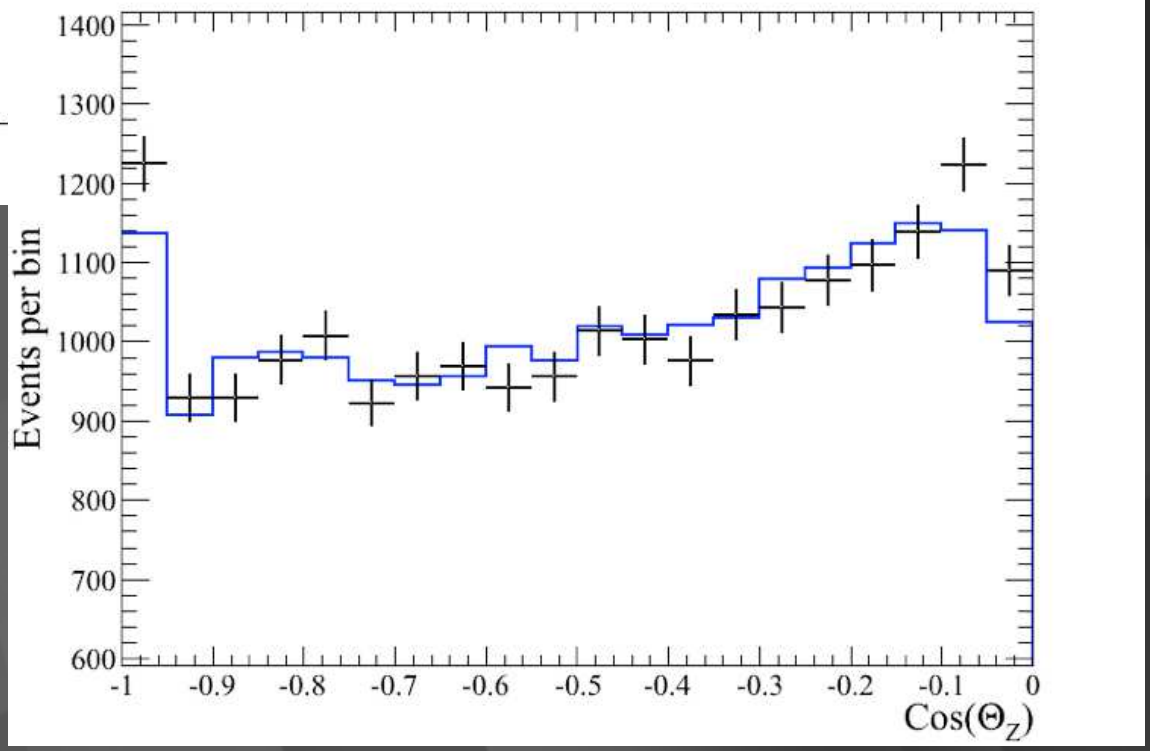
• DM-ice, DeepCore upgrades

• $1.25M per string of 60 ten inch PMTs (data to your pc, includes logistics)





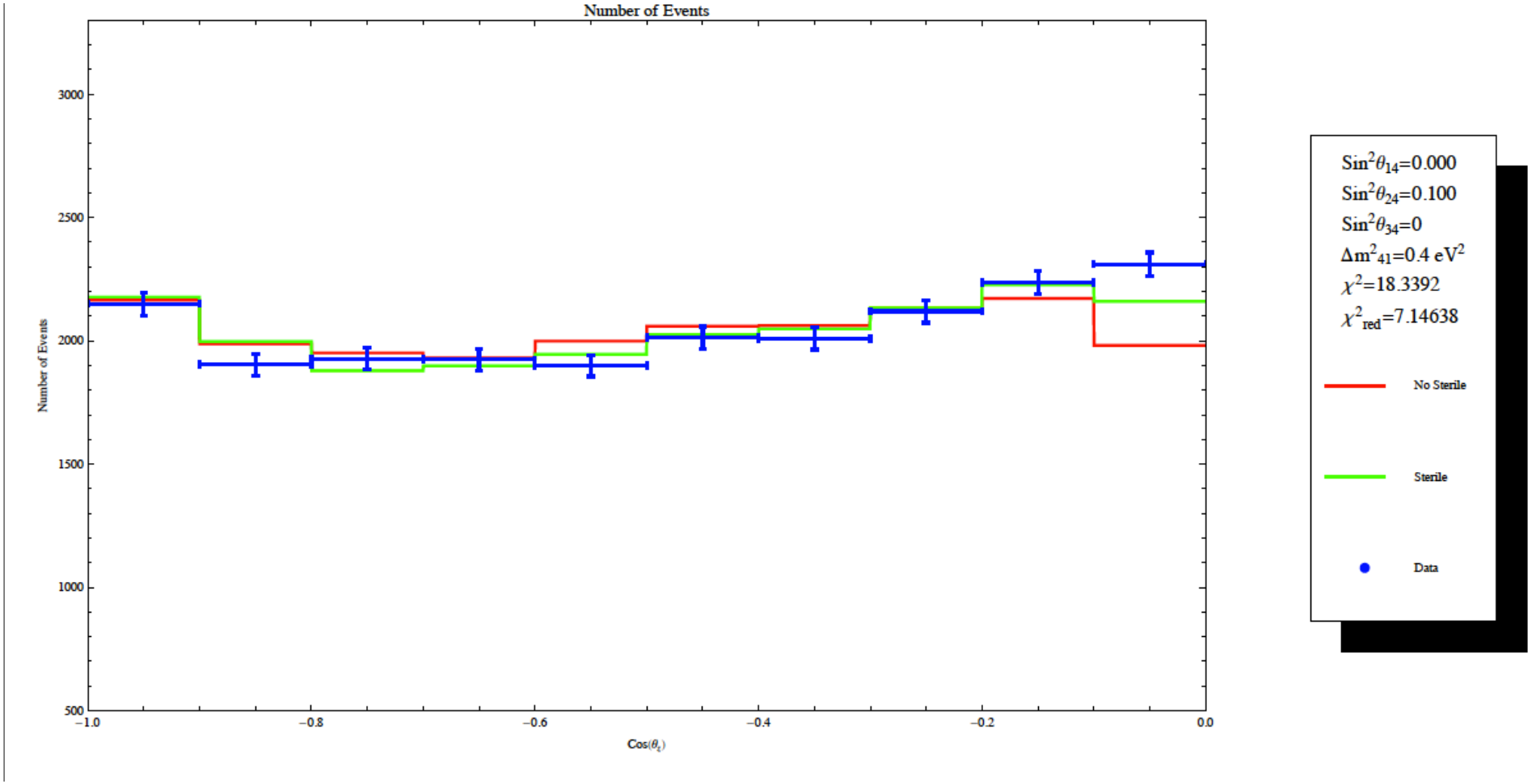
3



3+1

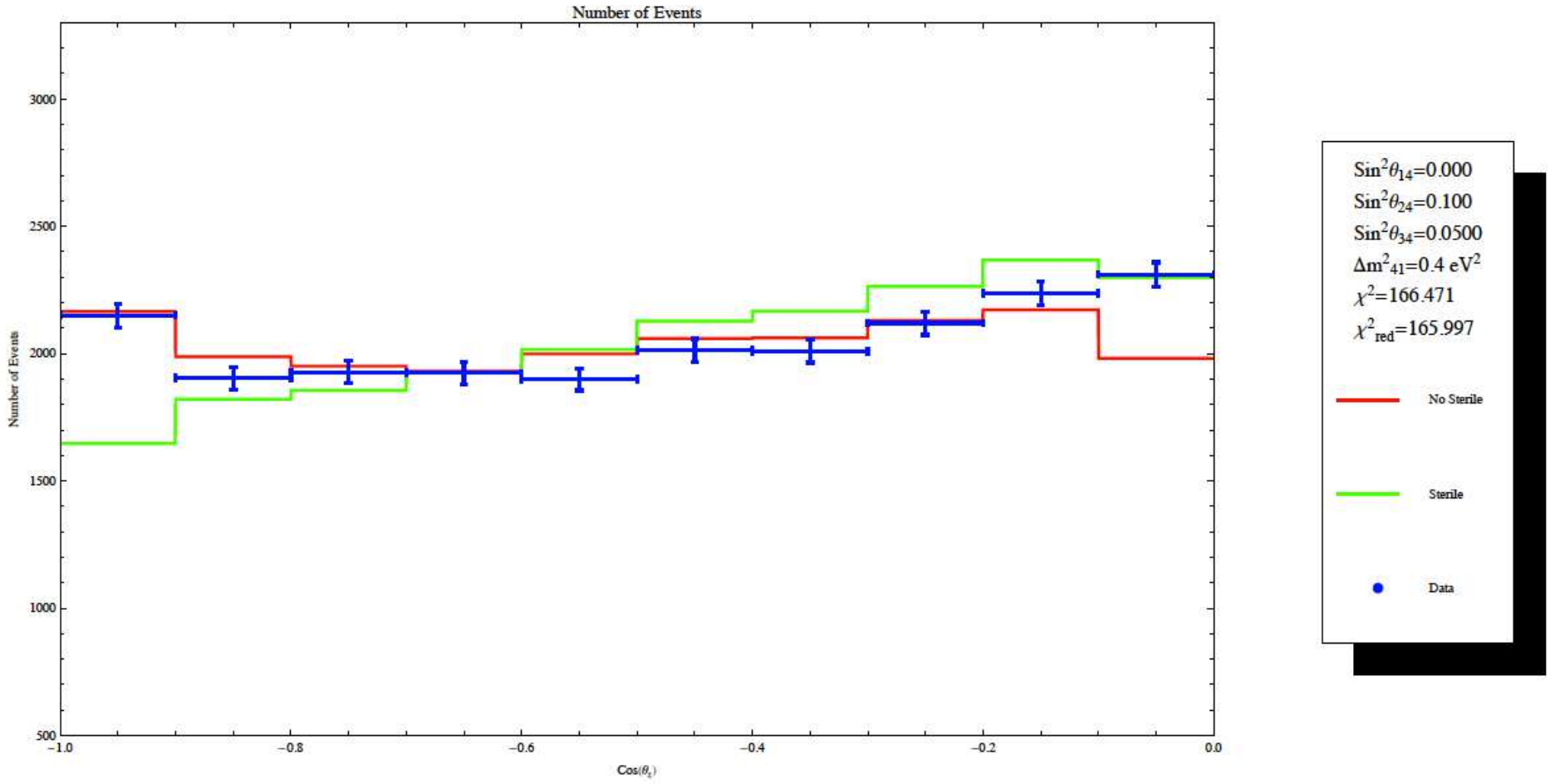
matter effect
of eV sterile ν's ?

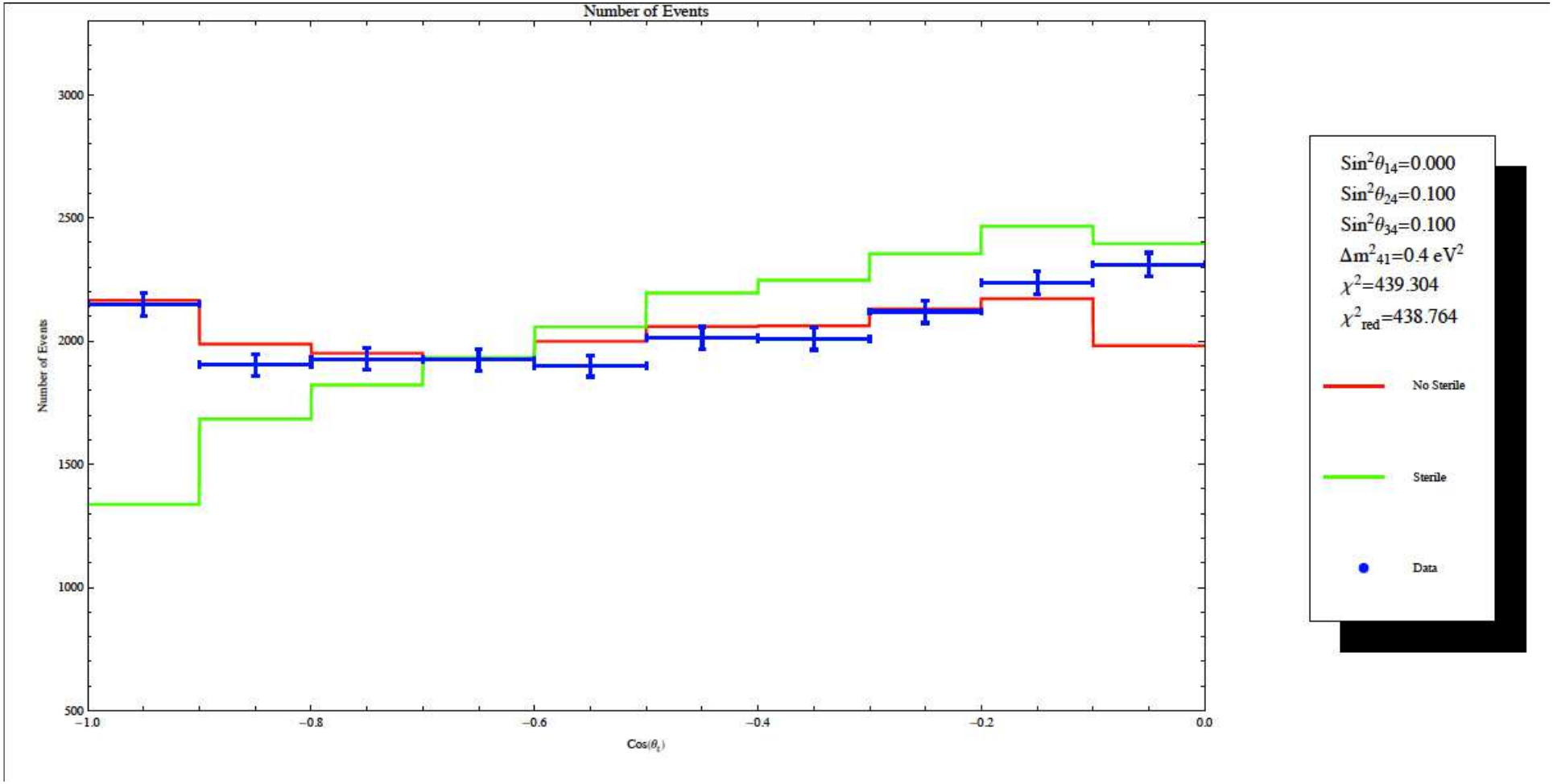
number of nu-mu events versus cosθ in IceCube 40

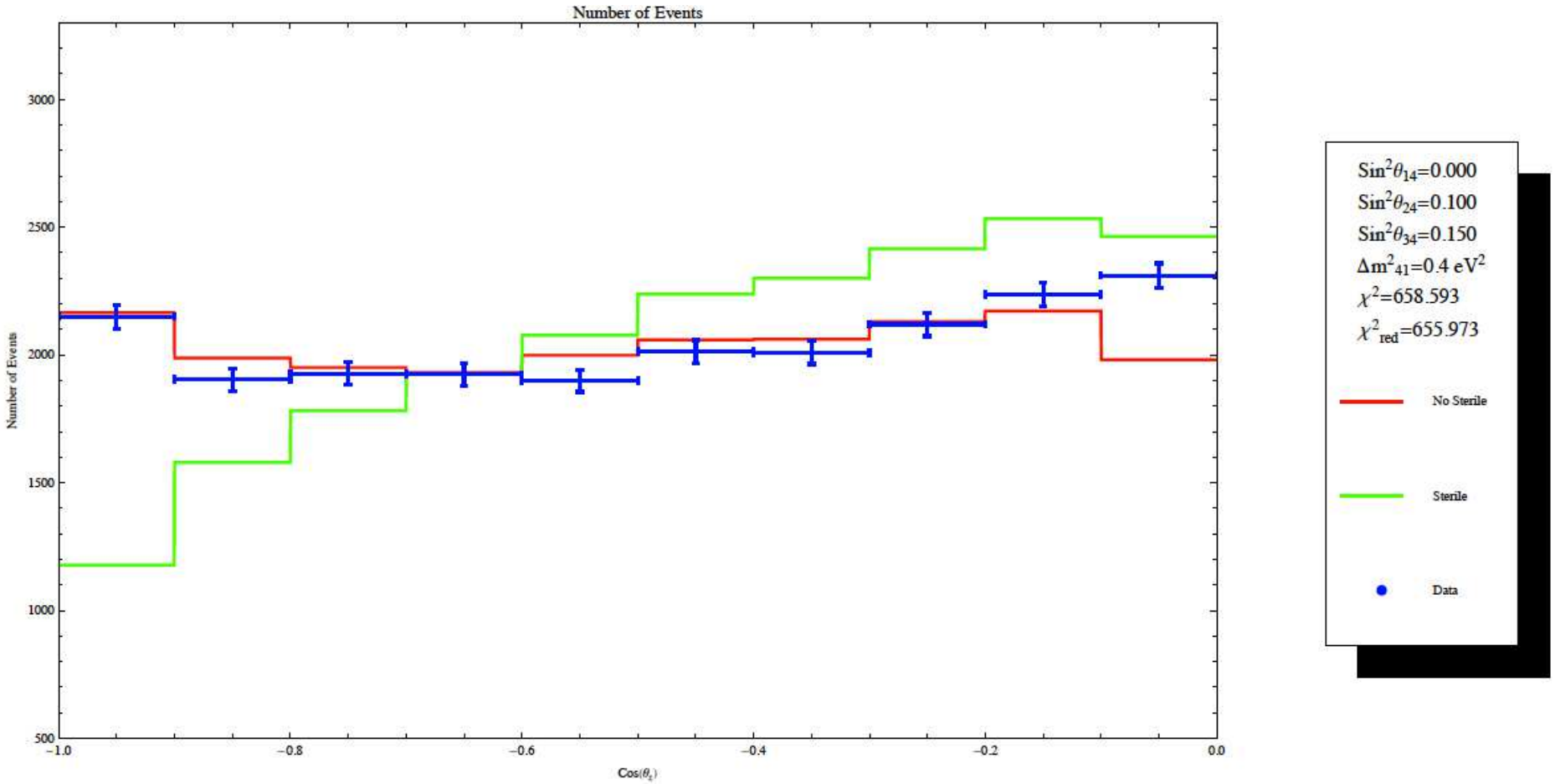


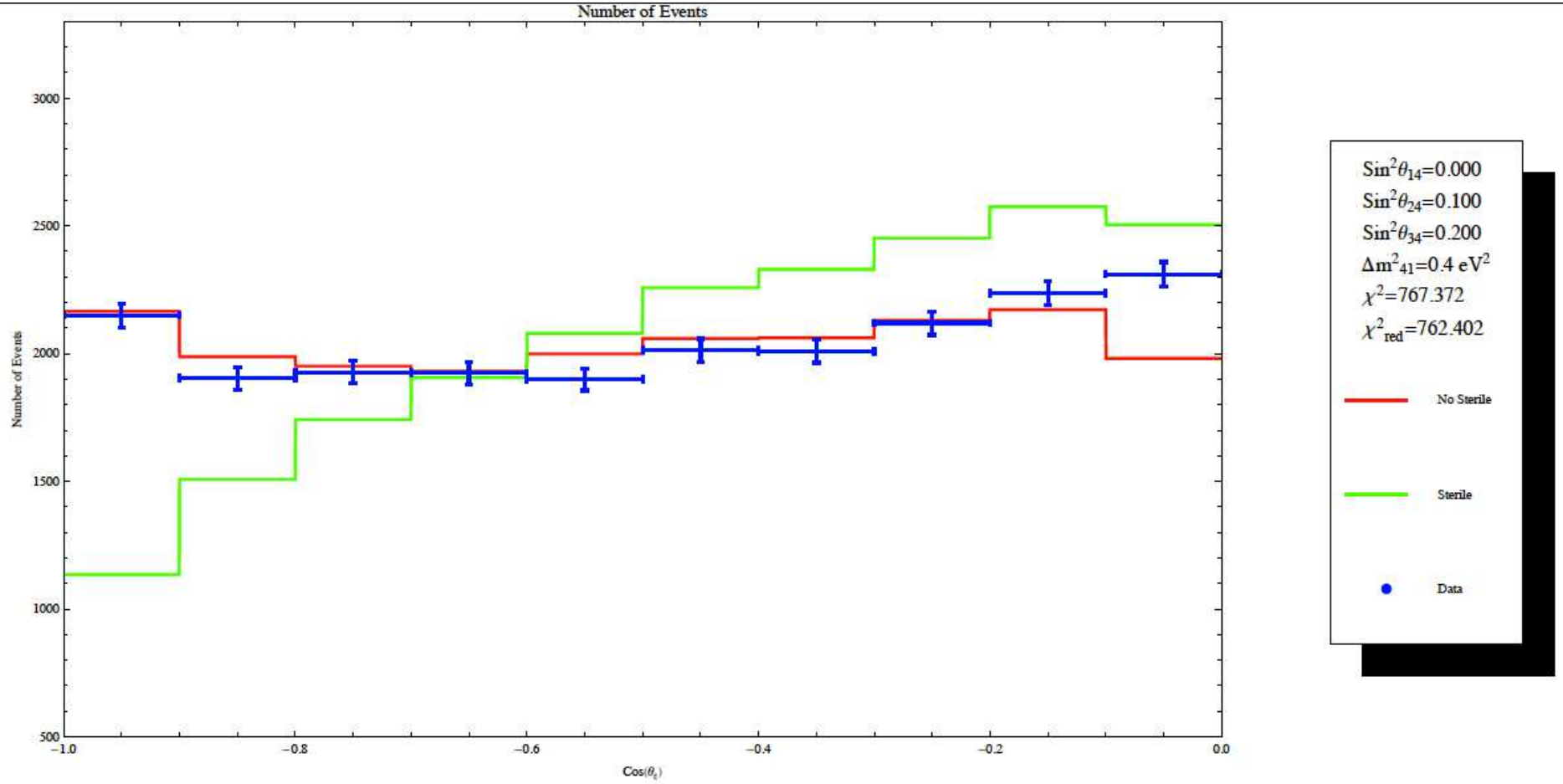
$\Delta m^2 = 0.4\ eV^2$ and $\sin^2\theta_{34} = 0 \rightarrow 0.5$

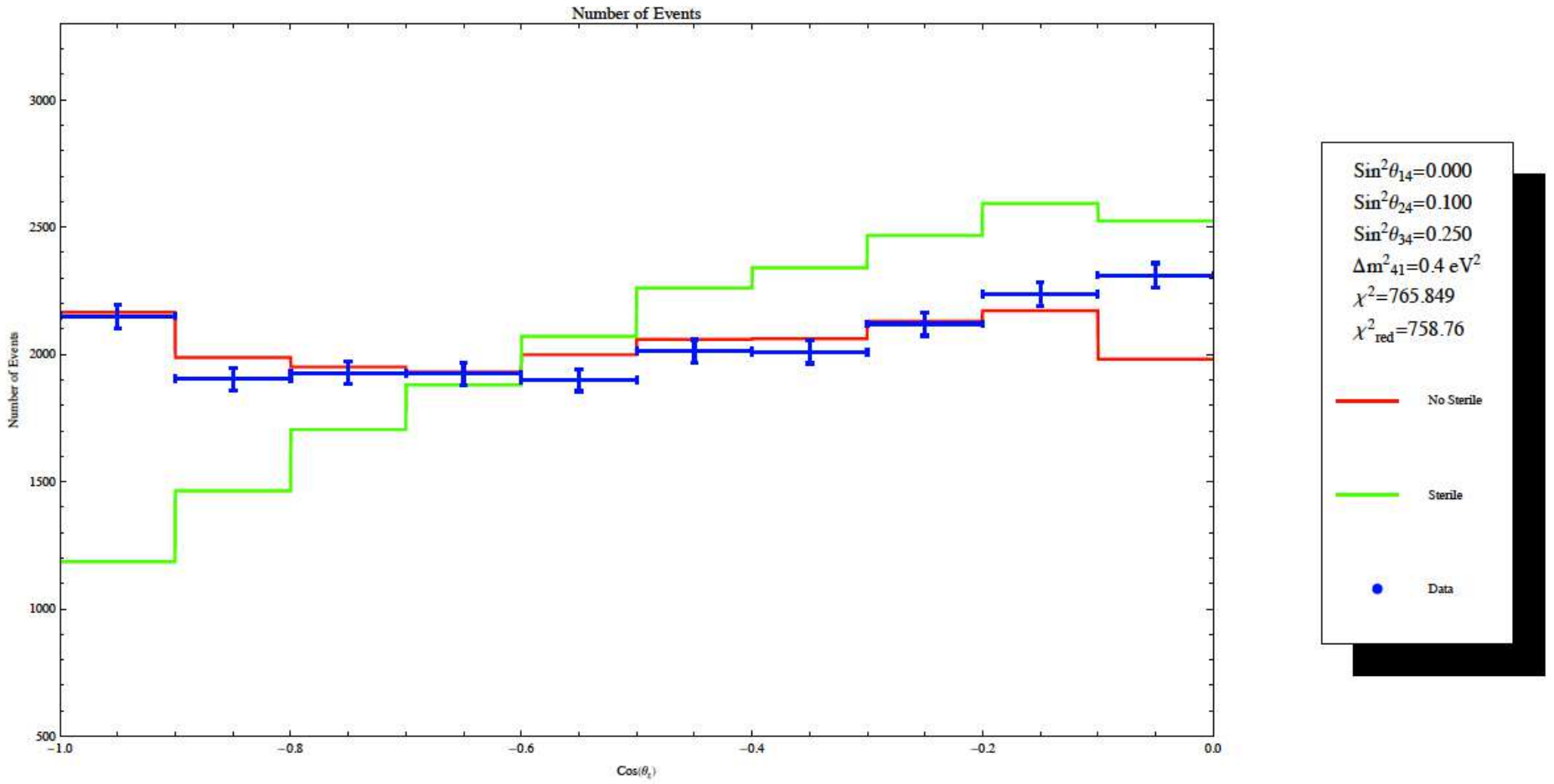
Arman Esmaili

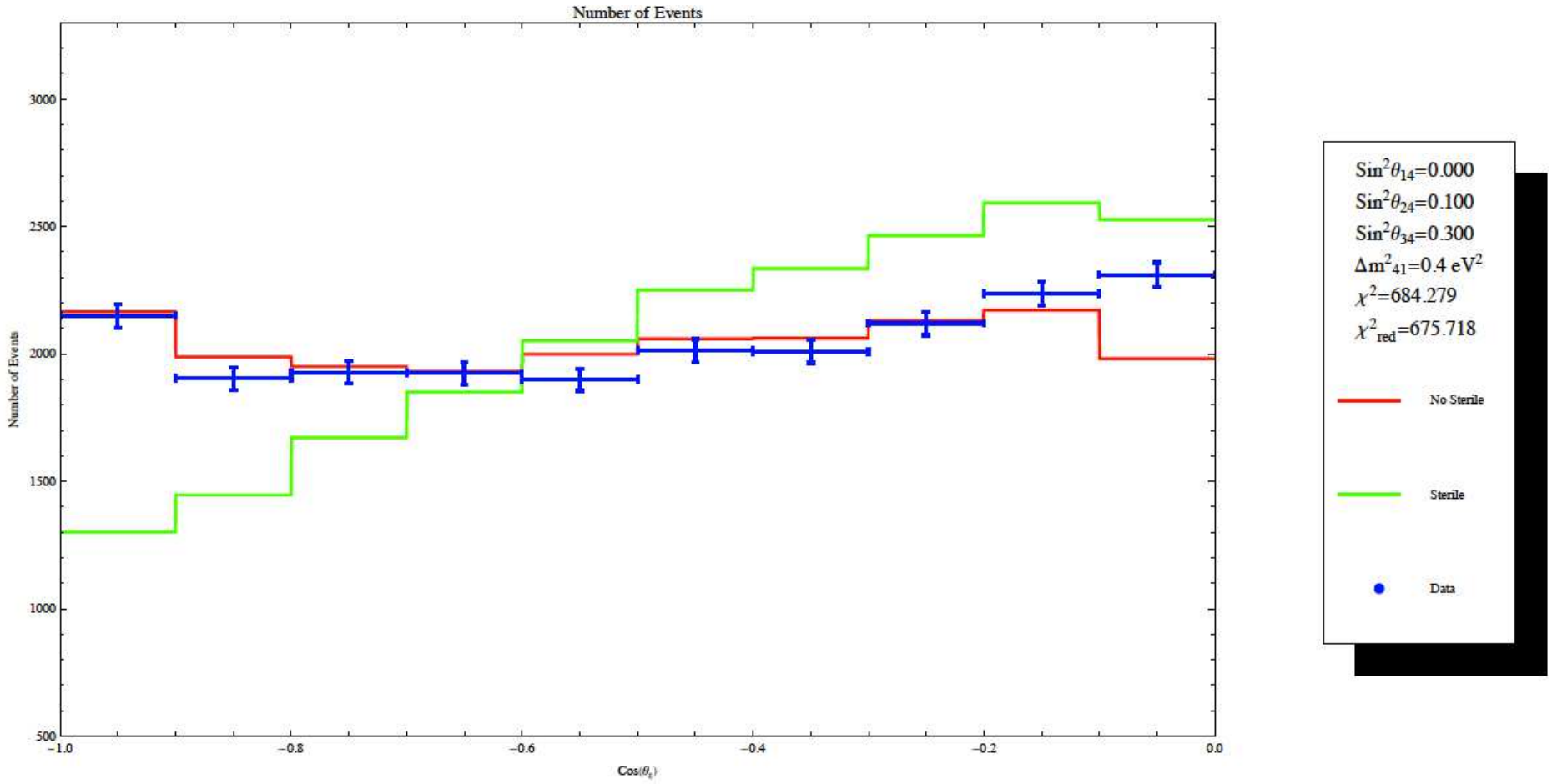

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.0500
Δm²41=0.4 eV²
χ²=166.471
χ²red=165.997
No Sterile
Sterile
Data

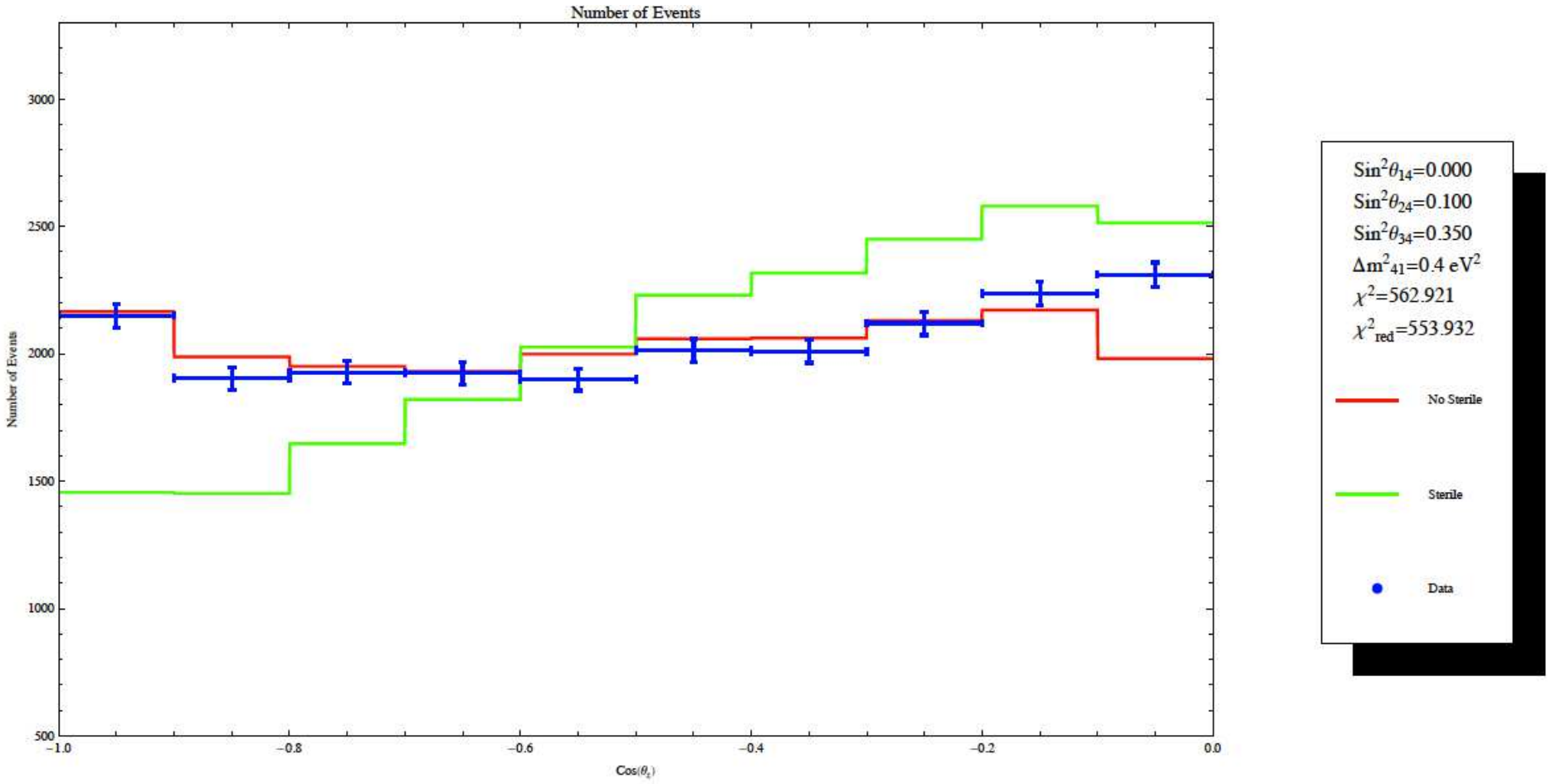

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_z)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.100
Δm²41=0.4 eV²
χ²=439.304
χ²red=438.764
No Sterile
Sterile
Data

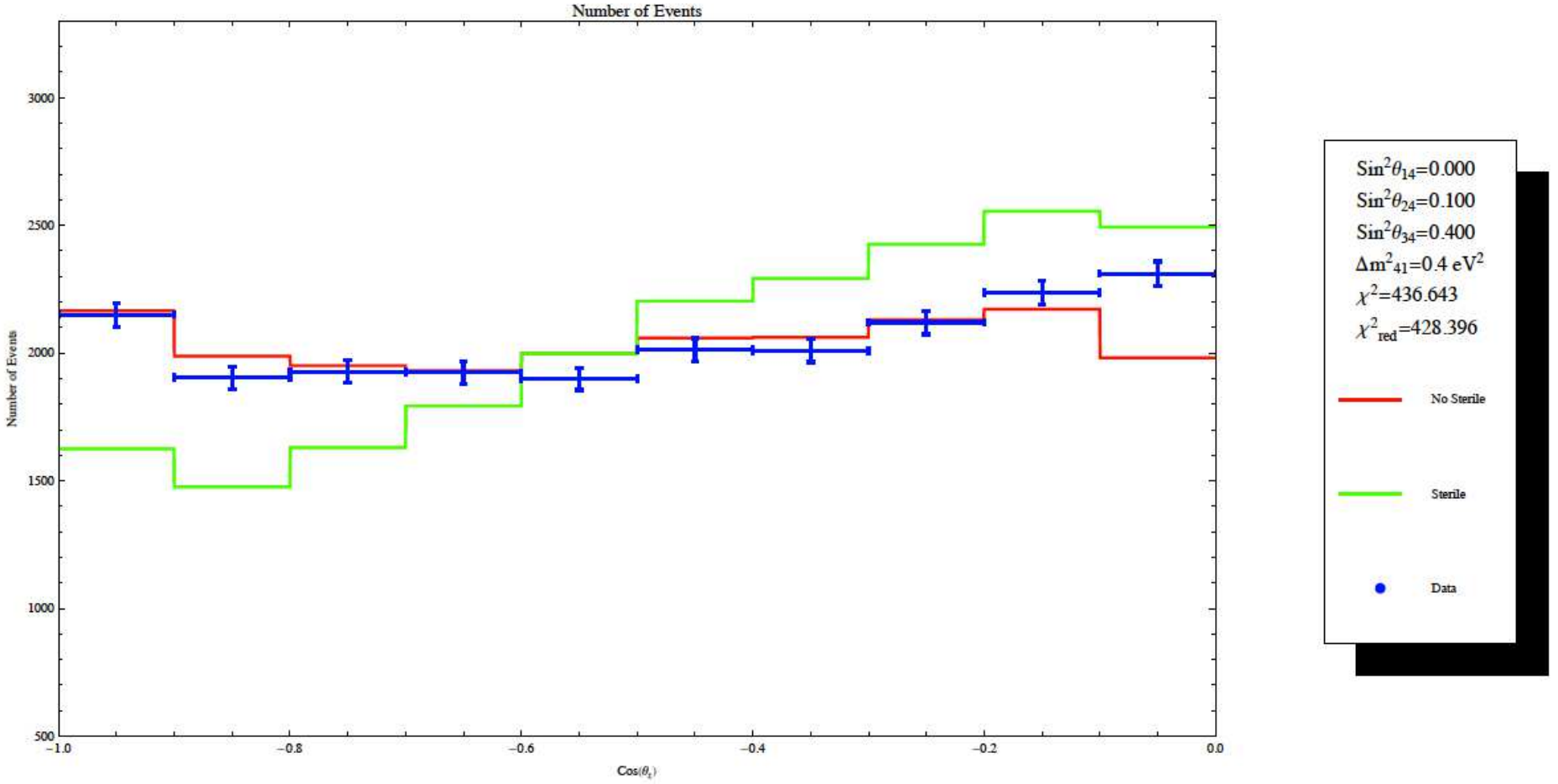

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_z)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.150
Δm²41=0.4 eV²
χ²=658.593
χ²red=655.973
No Sterile
Sterile
Data

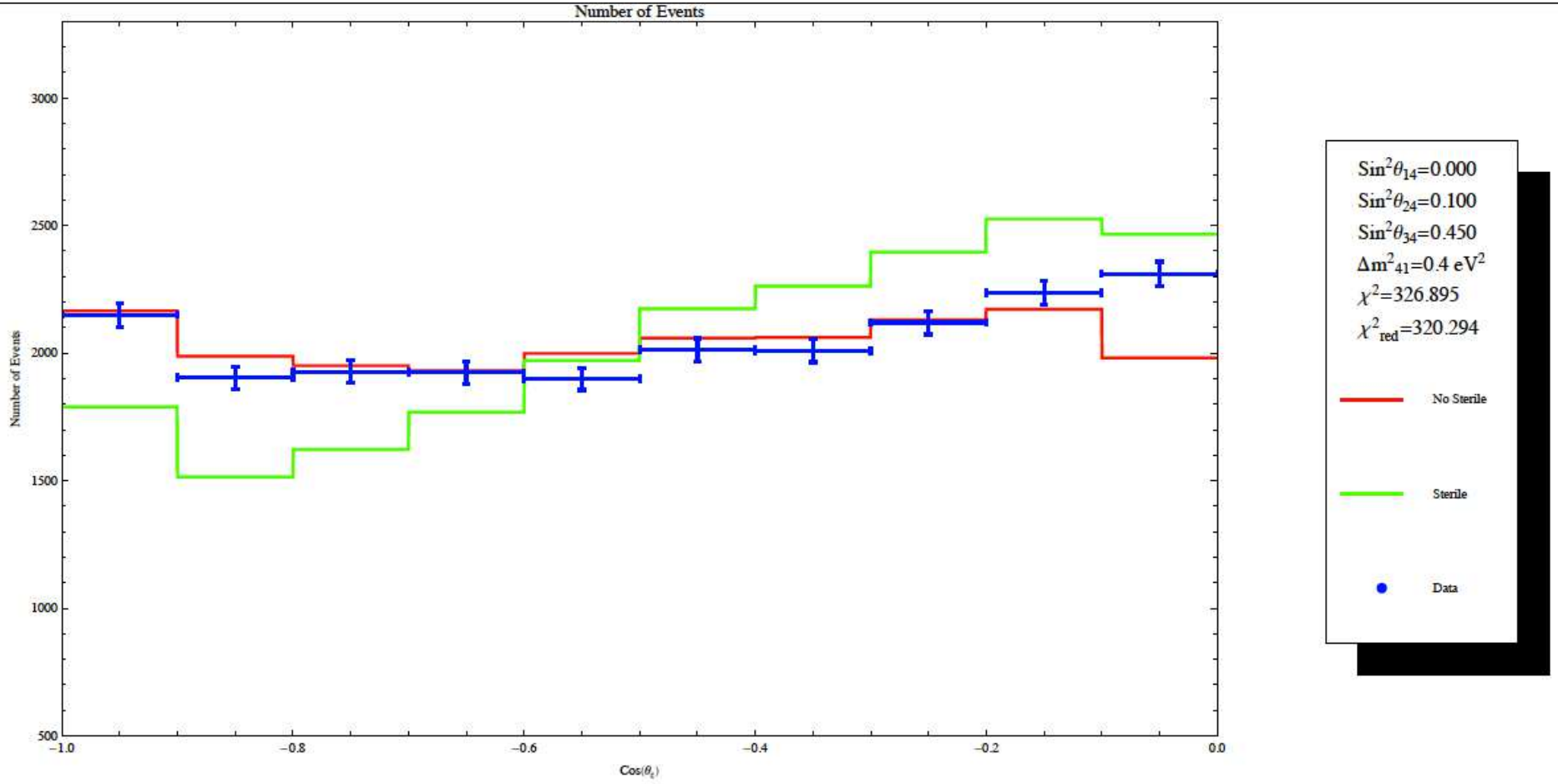

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.200
Δm²41=0.4 eV²
χ²=767.372
χ²red=762.402
No Sterile
Sterile
Data

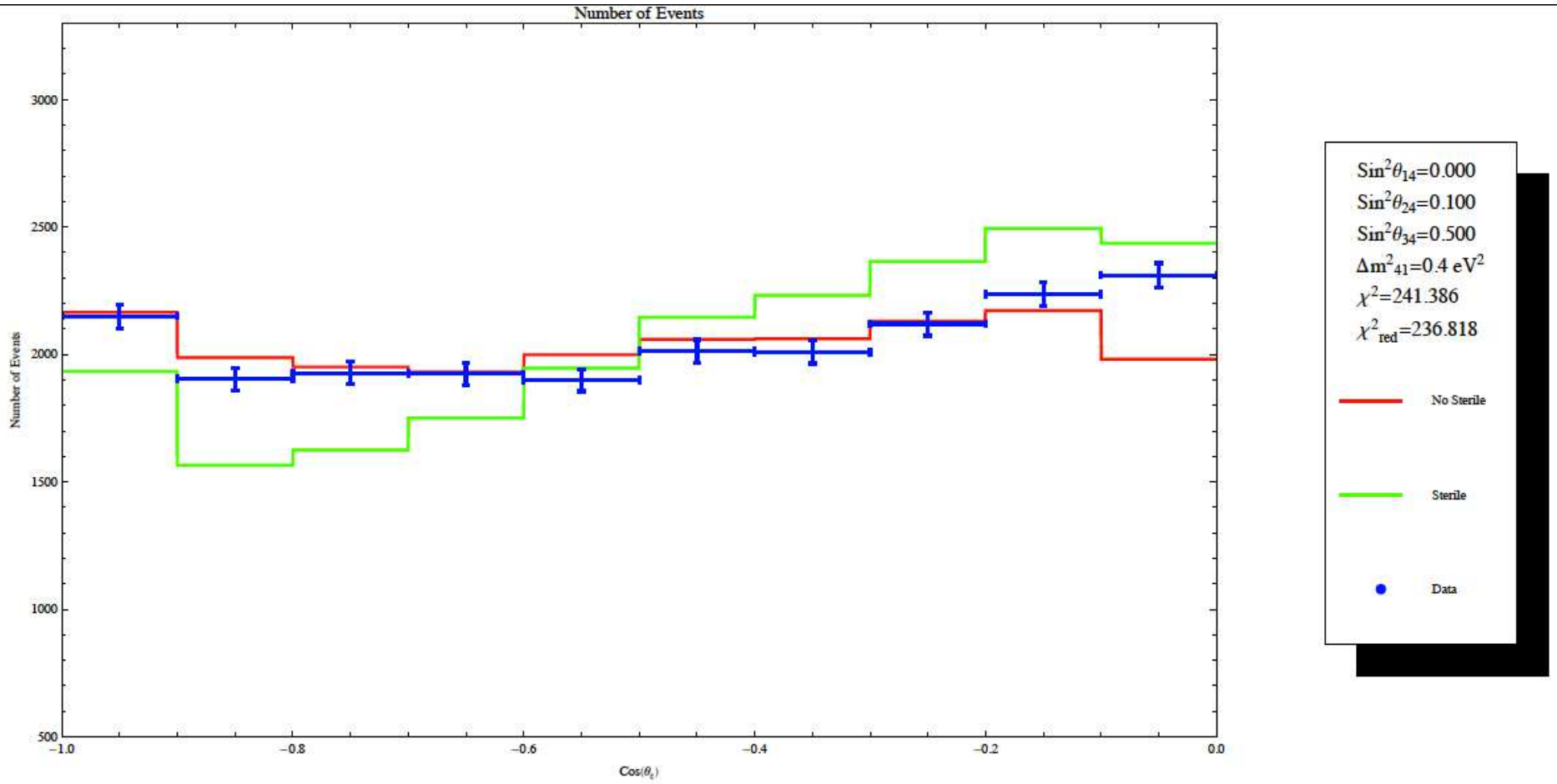

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.250
Δm²41=0.4 eV²
χ²=765.849
χ²red=758.76
No Sterile
Sterile
Data

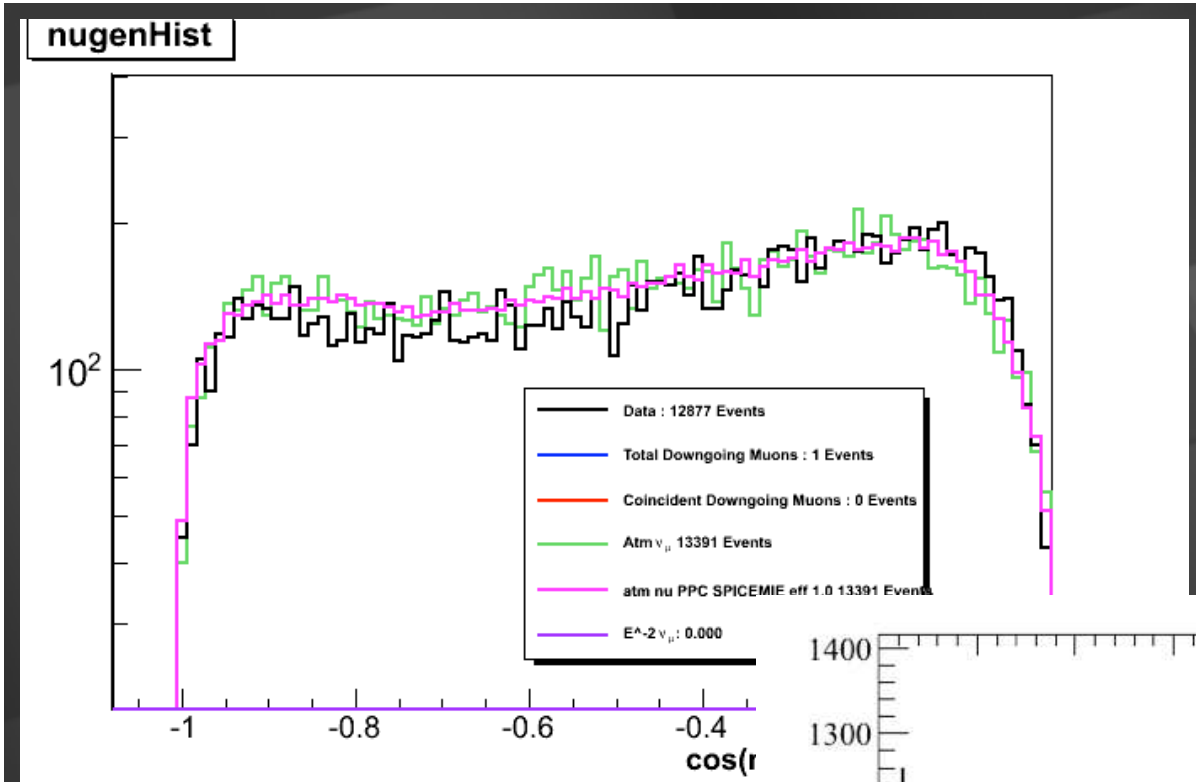

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.300
Δm²41=0.4 eV²
χ²=684.279
χ²red=675.718
No Sterile
Sterile
Data


Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.350
Δm²41=0.4 eV²
χ²=562.921
χ²red=553.932
No Sterile
Sterile
Data

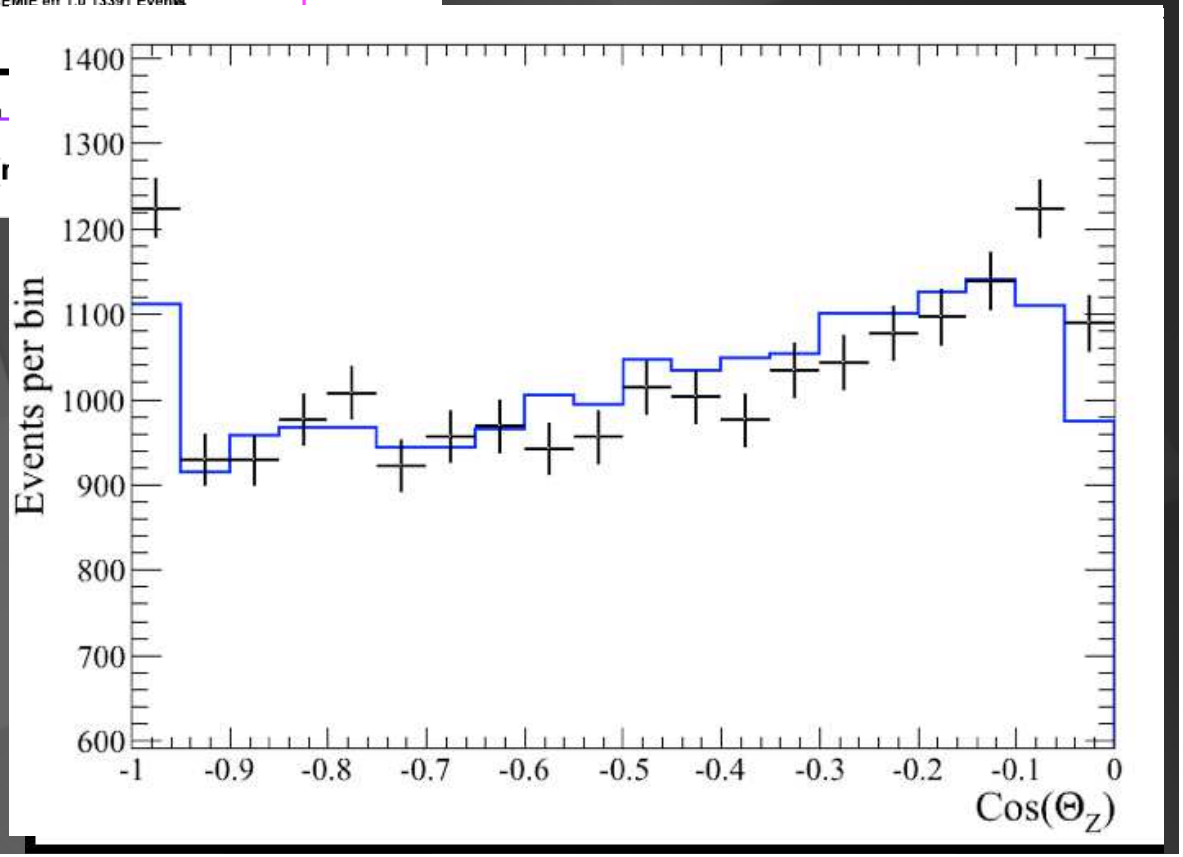

Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.400
Δm²41=0.4 eV²
χ²=436.643
χ²red=428.396
No Sterile
Sterile
Data


Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θz)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.450
Δm²41=0.4 eV²
χ²=326.895
χ²red=320.294
No Sterile
Sterile
Data


Number of Events
Number of Events
3000
2500
2000
1500
1000
500
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Cos(θ_ℓ)
Sin²θ14=0.000
Sin²θ24=0.100
Sin²θ34=0.500
Δm²41=0.4 eV²
χ²=241.386
χ²red=236.818
No Sterile
Sterile
Data

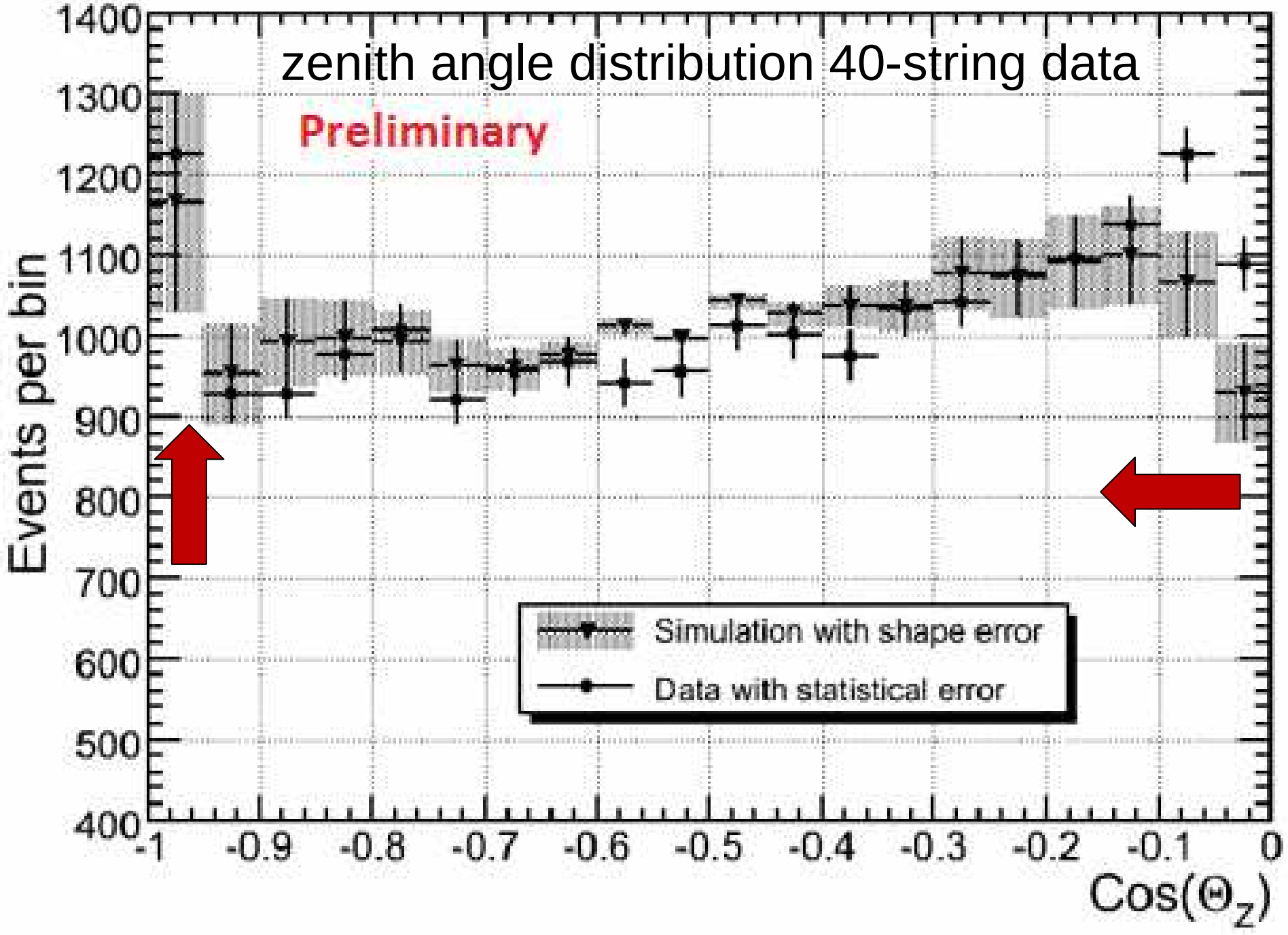


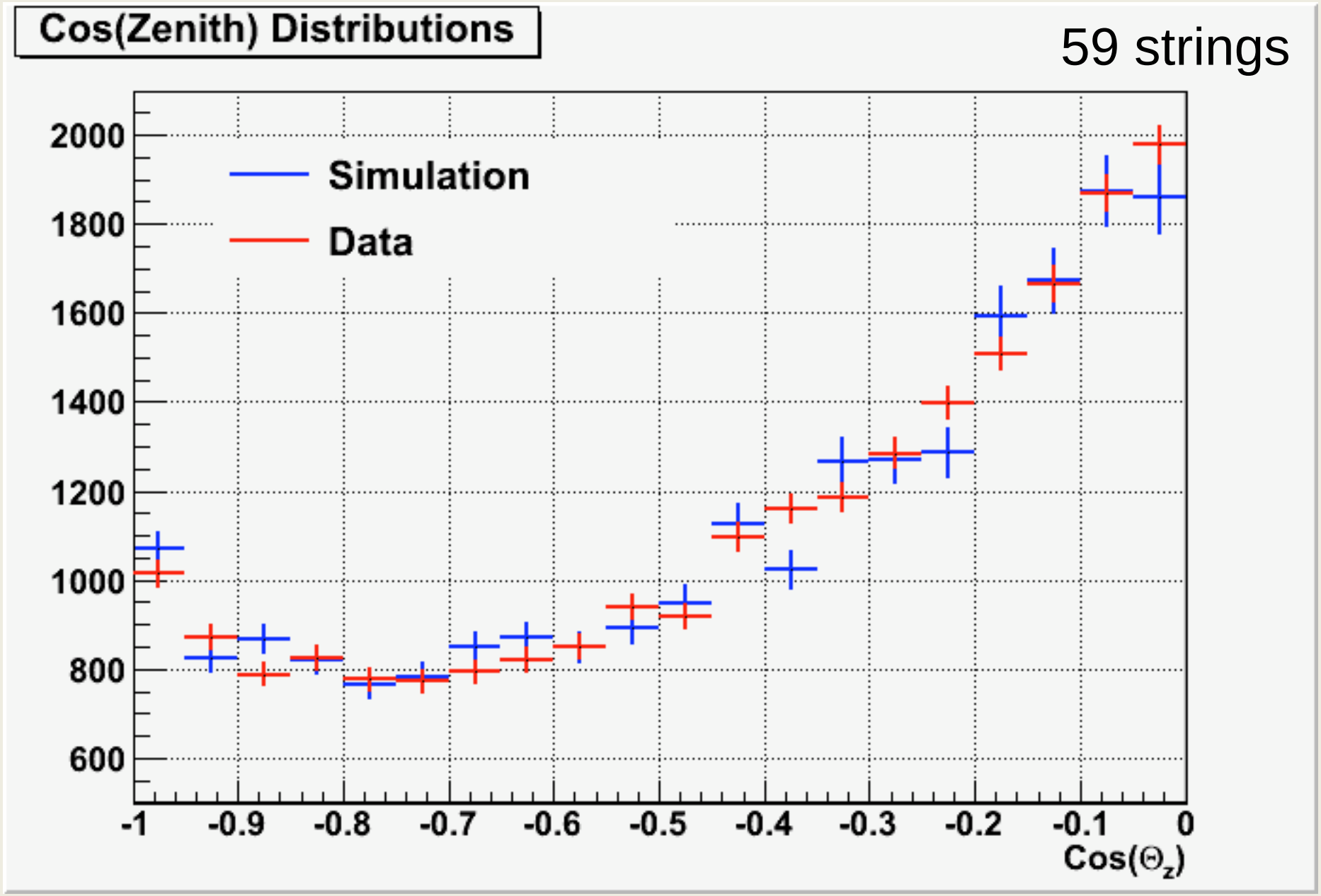
zenith angle
two analyses

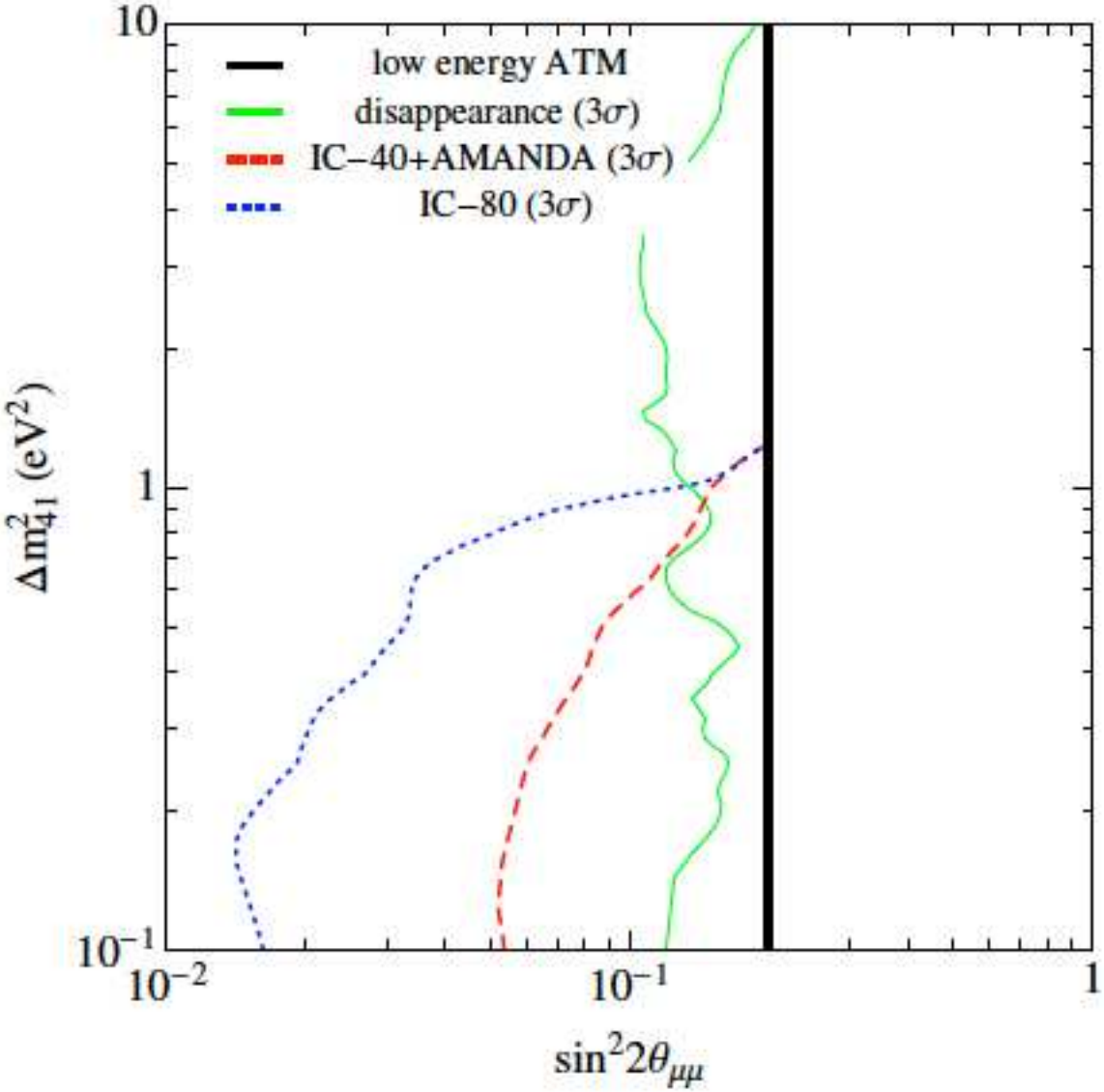


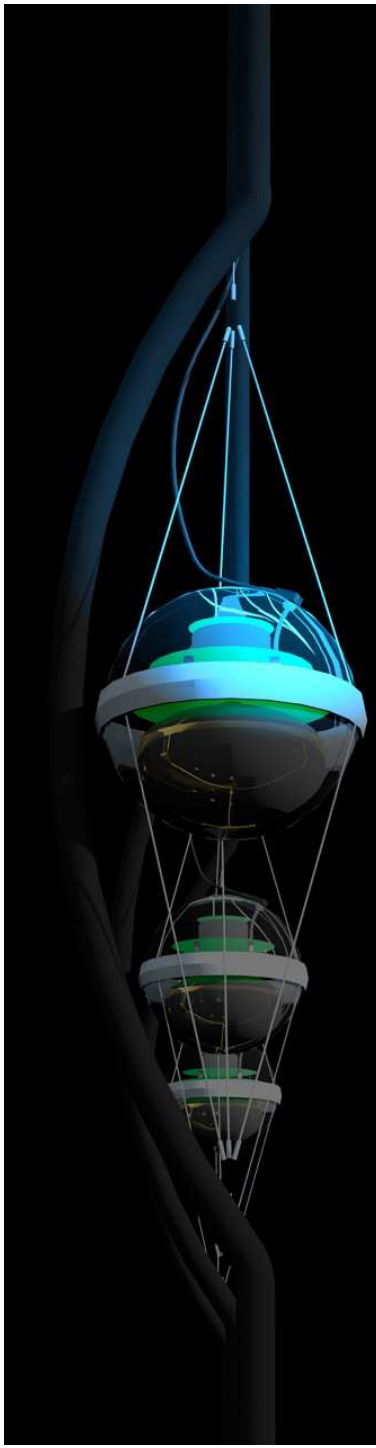
SYSTEMATICS !!!

- K/π ratio
- zenith acceptance of modules
- ice
- CR flux,composition [IceTop helps]


zenith angle distribution 40-string data
Preliminary
Events per bin
1400
1300
1200
1100
1000
900
800
700
600
500
400
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cos(Θz)
Simulation with shape error
Data with statistical error


Cos(Zenith) Distributions
59 strings
Simulation
Data
2000
1800
1600
1400
1200
1000
800
600
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cos(Θz)


low energy ATM
disappearance (3σ)
IC−40+AMANDA (3σ)
IC−80 (3σ)
10
1
10^{-1}
10^{-2}
10^{-1}
1
Δm^2_{41} (eV^2)
$\sin^2 2\theta_{\mu\mu}$



NOW 2012

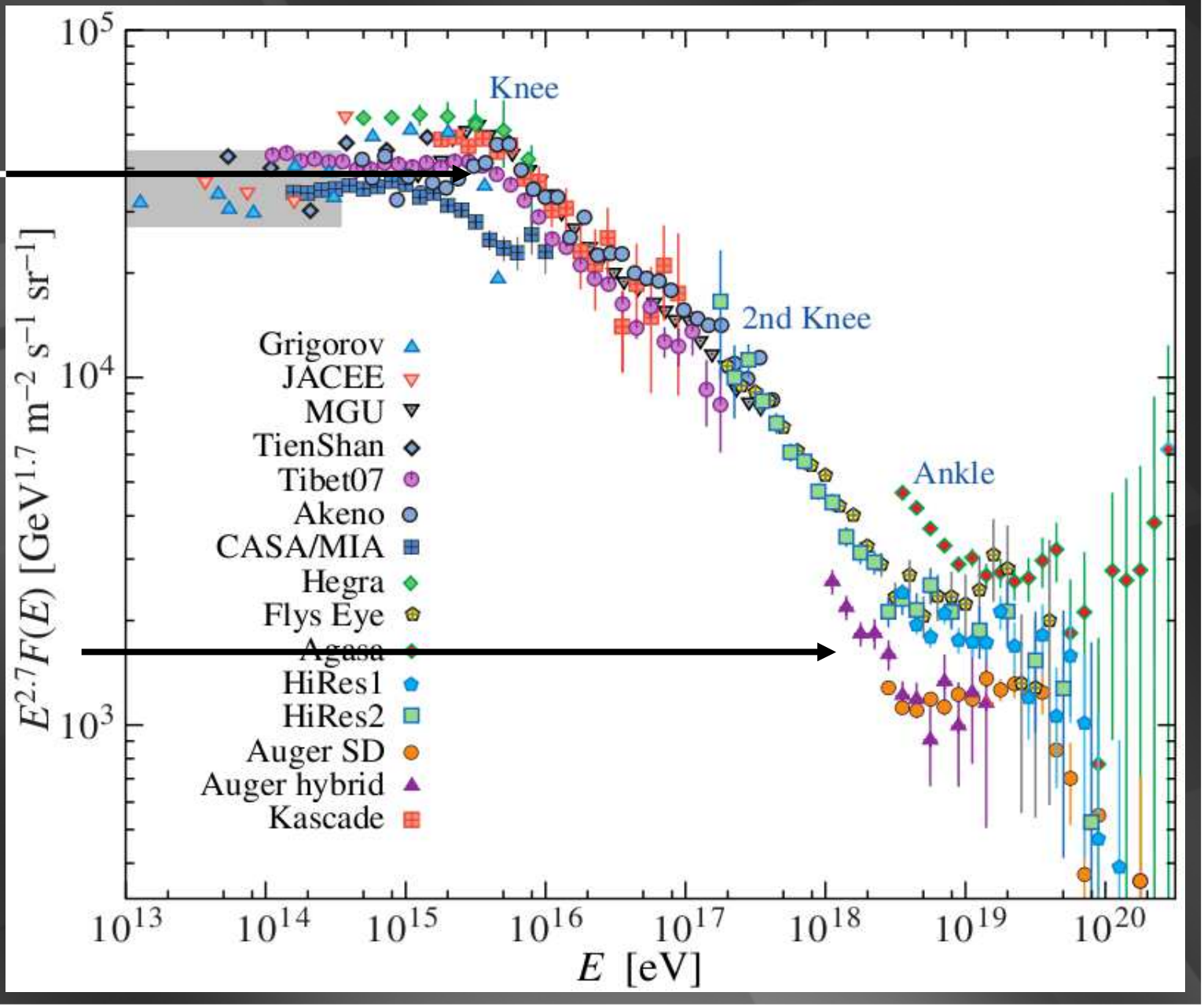
- IceCube
- atmospheric and cosmic neutrinos
- the search for the sources of the Galactic and extragalactic cosmic rays

IceCube.wisc.edu

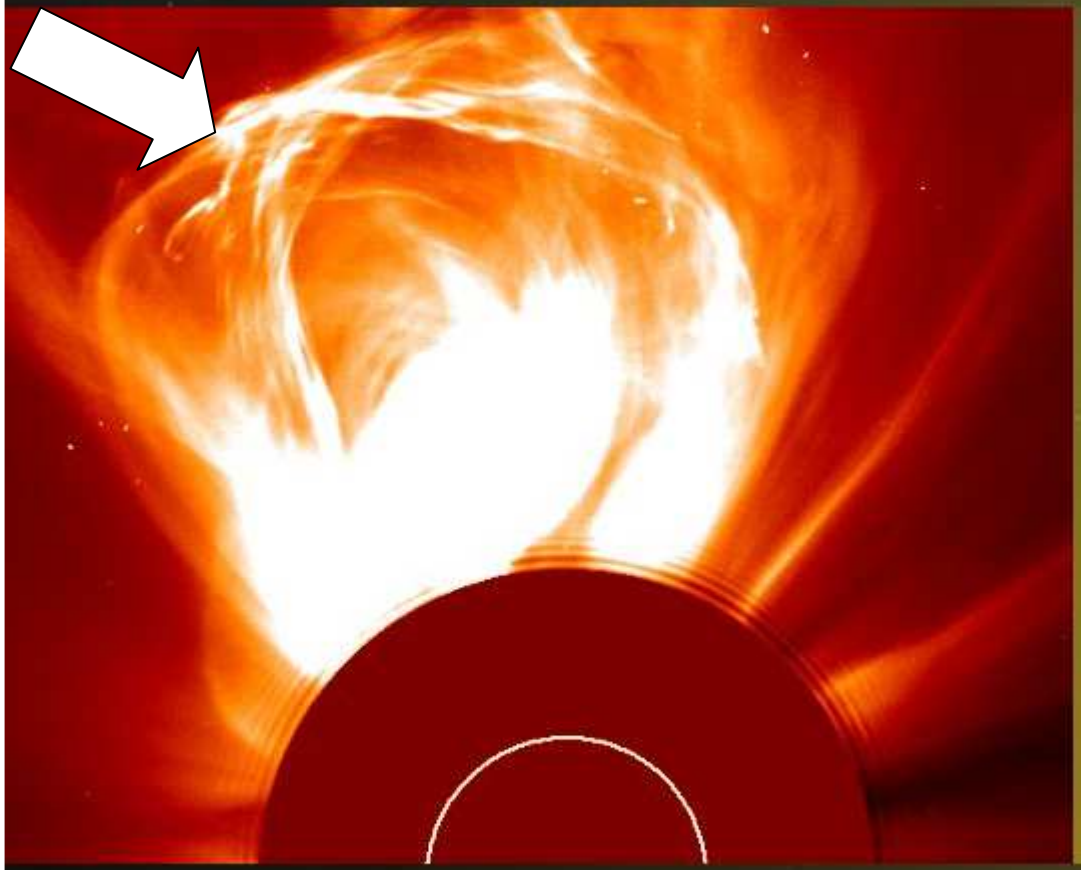
sources accommodating the observed energy budget

Galactic: supernova remnants?

extragalactic: gamma ray bursts? active galaxies?



shock acceleration (solar flare)



coronal
mass
ejection
→
10 GeV
particles

flows of charged particles result in large B-fields

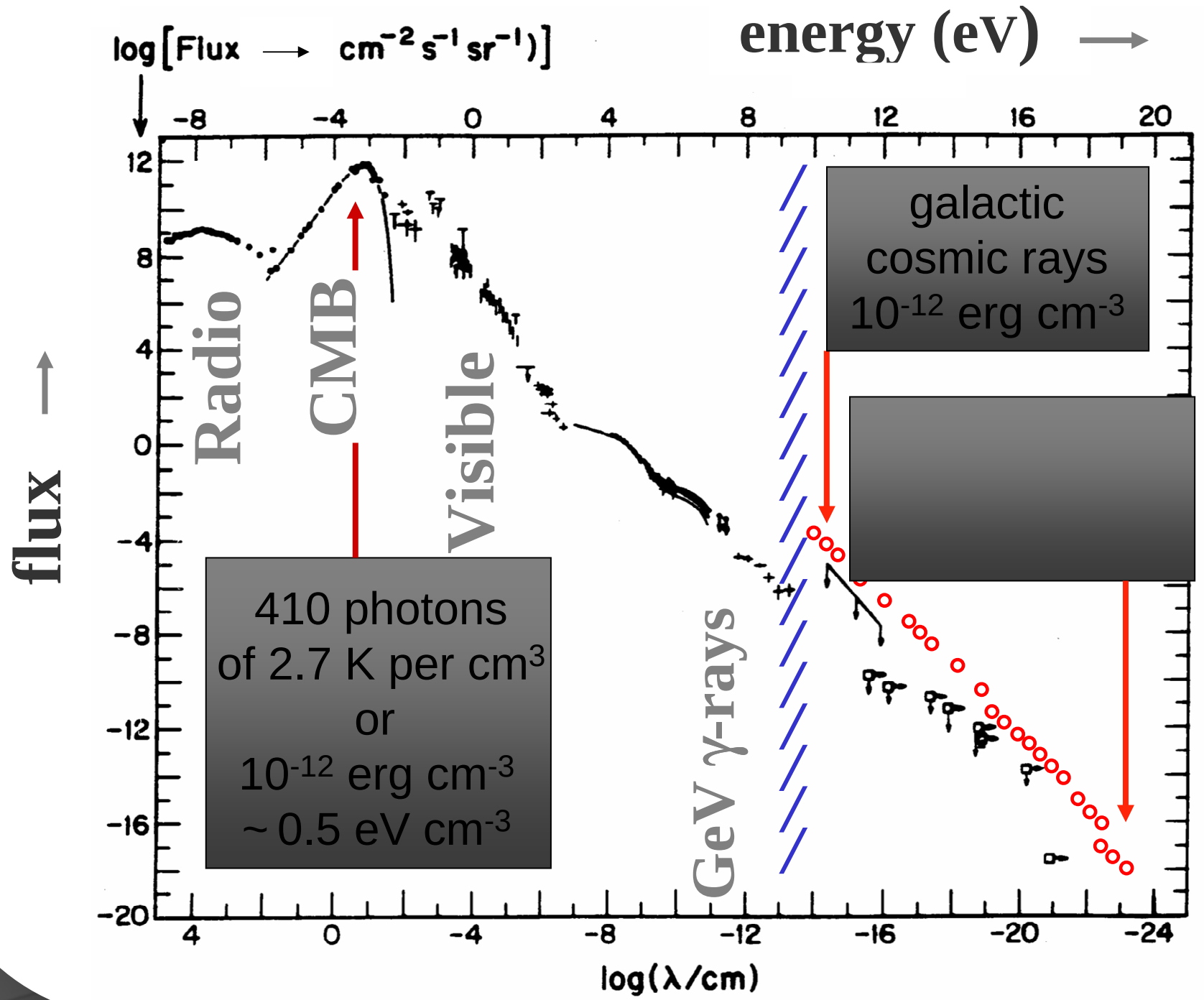
Hillas formula :

- accelerator must contain the particles

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

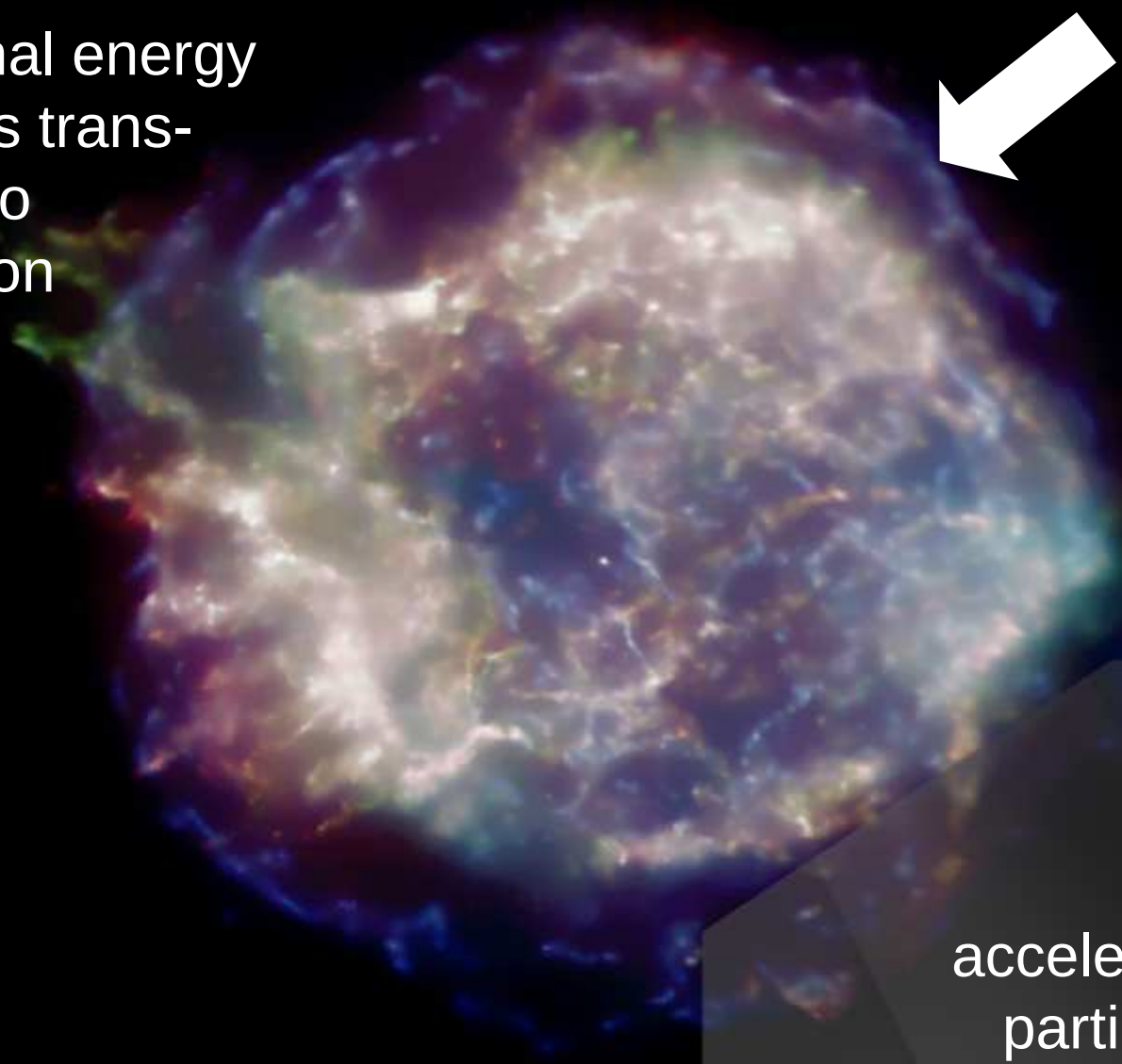
$$\boxed{E \leq \mathrm{v}\, qBR}$$

- dimensional analysis, difficult to satisfy


energy (eV)
log [Flux → cm⁻² s⁻¹ sr⁻¹)]
flux
Radio
CMB
Visible
GeV γ-rays
galactic
cosmic rays
10⁻¹² 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)

cassiopeia A supernova remnant in X-rays

gravitational energy released is trans-formed into acceleration

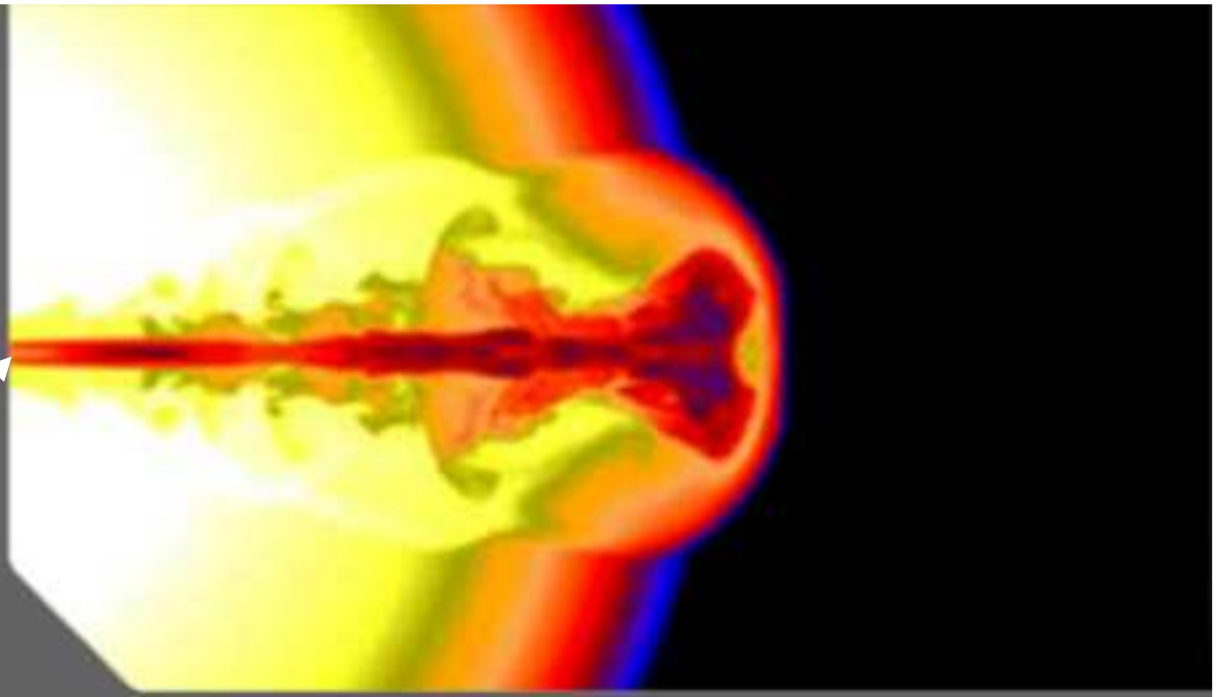


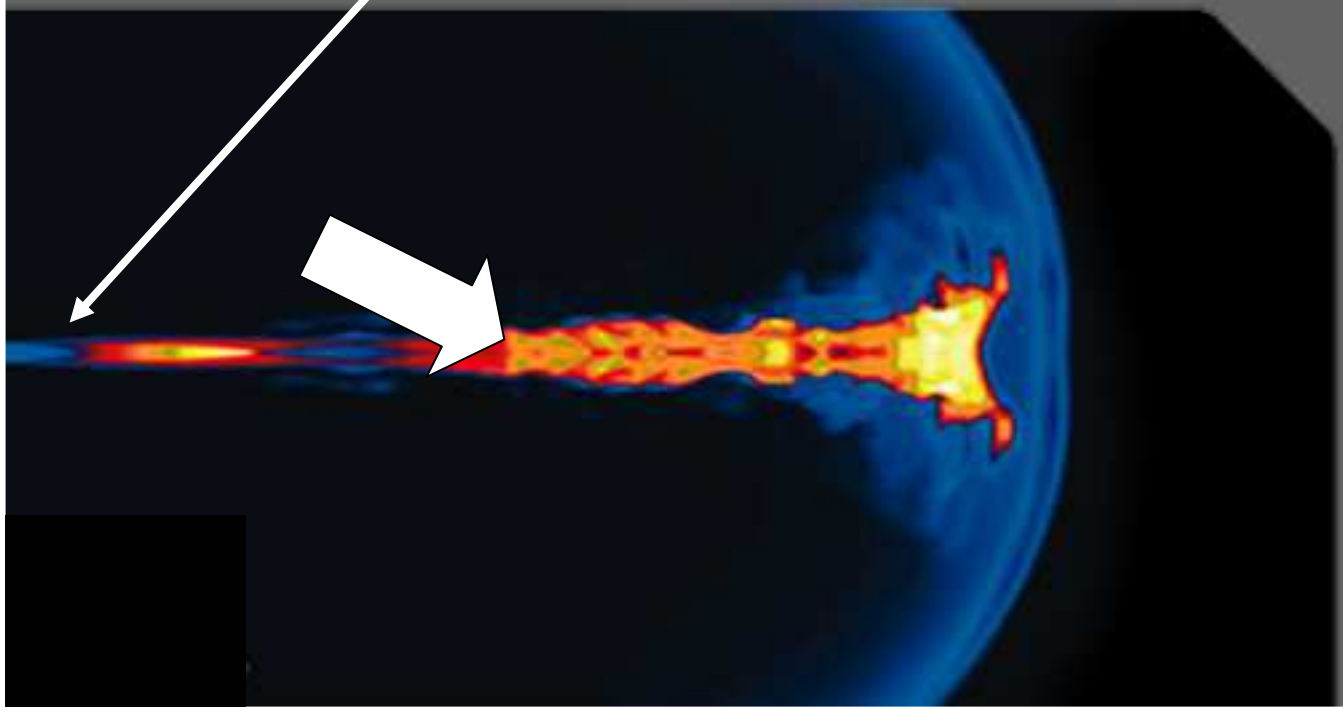
acceleration when particles cross high B-fields

collapse of massive star produces a

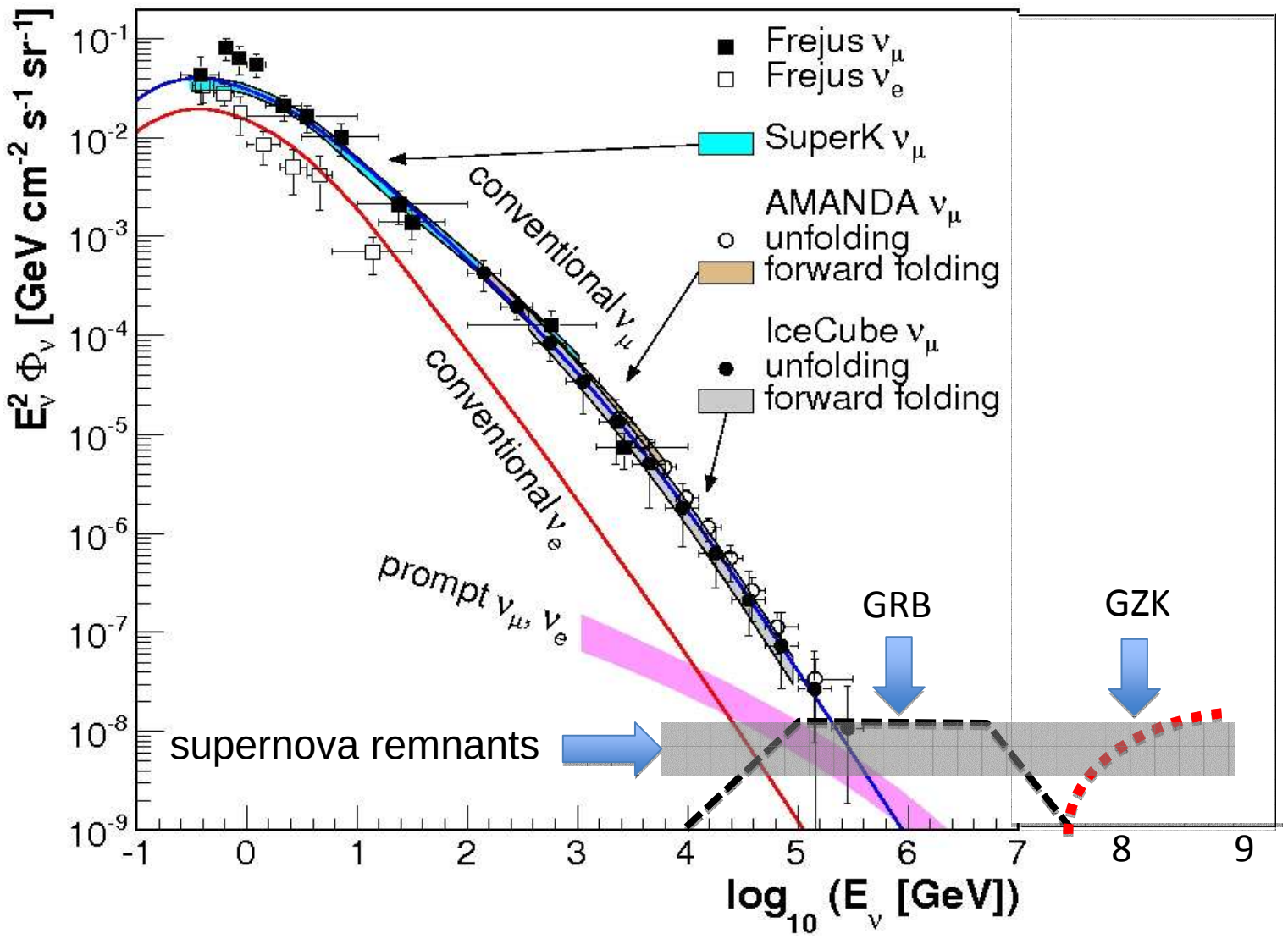
gamma ray burst

spinning black hole

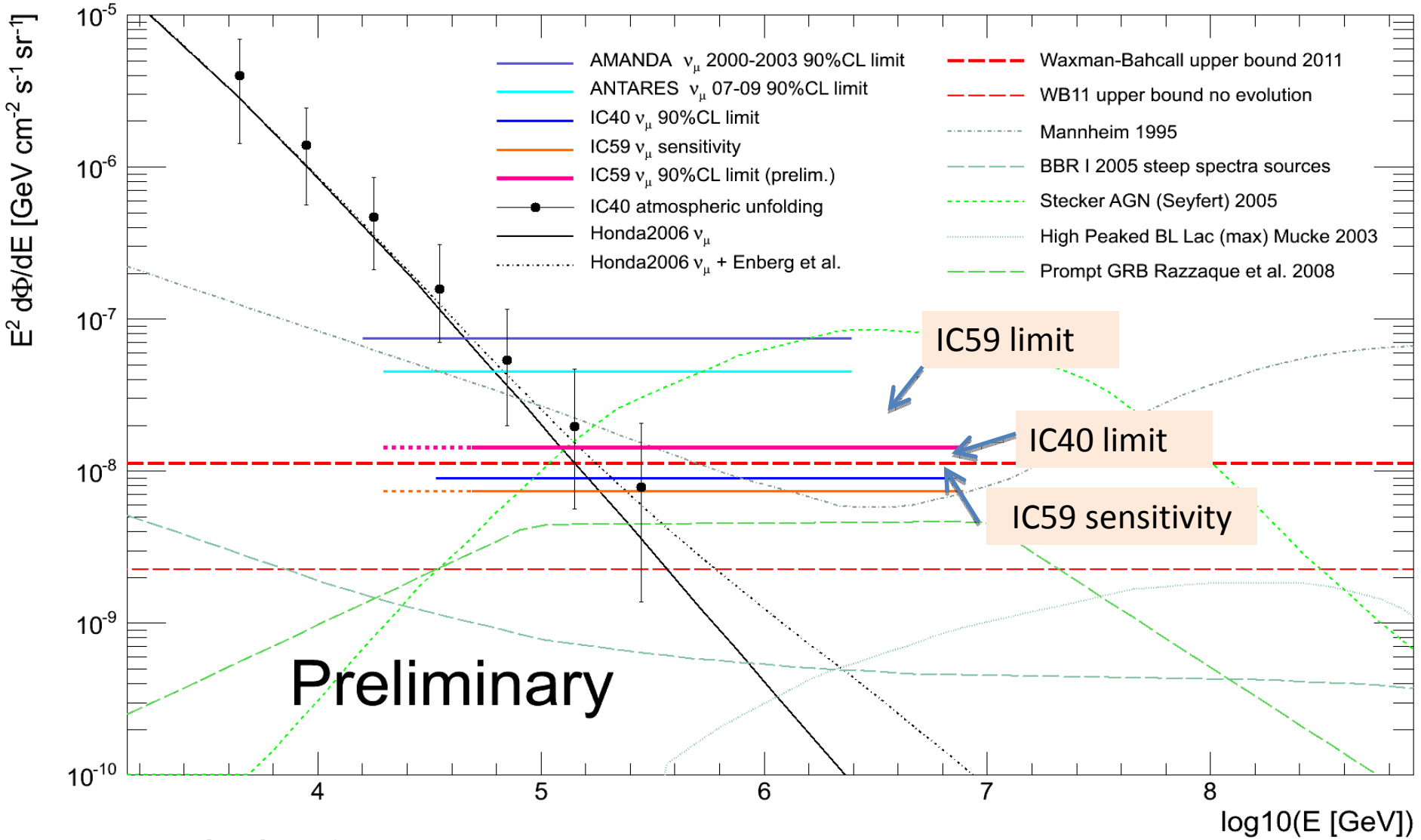




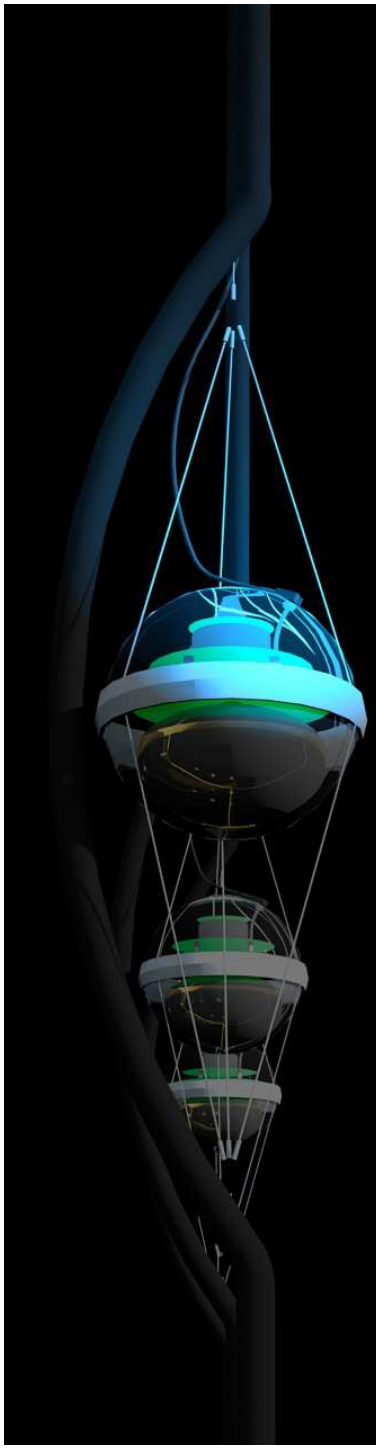
shocks produced in the outflow of the spinning black hole: electrons (and protons ?)


$E_\nu^2 \Phi_\nu$ [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
supernova remnants

diffuse flux limit



Anne Schukraft



NOW 2012

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- the search for the sources of the Galactic and extragalactic cosmic rays

IceCube.wisc.edu

cosmic rays interact with the microwave background

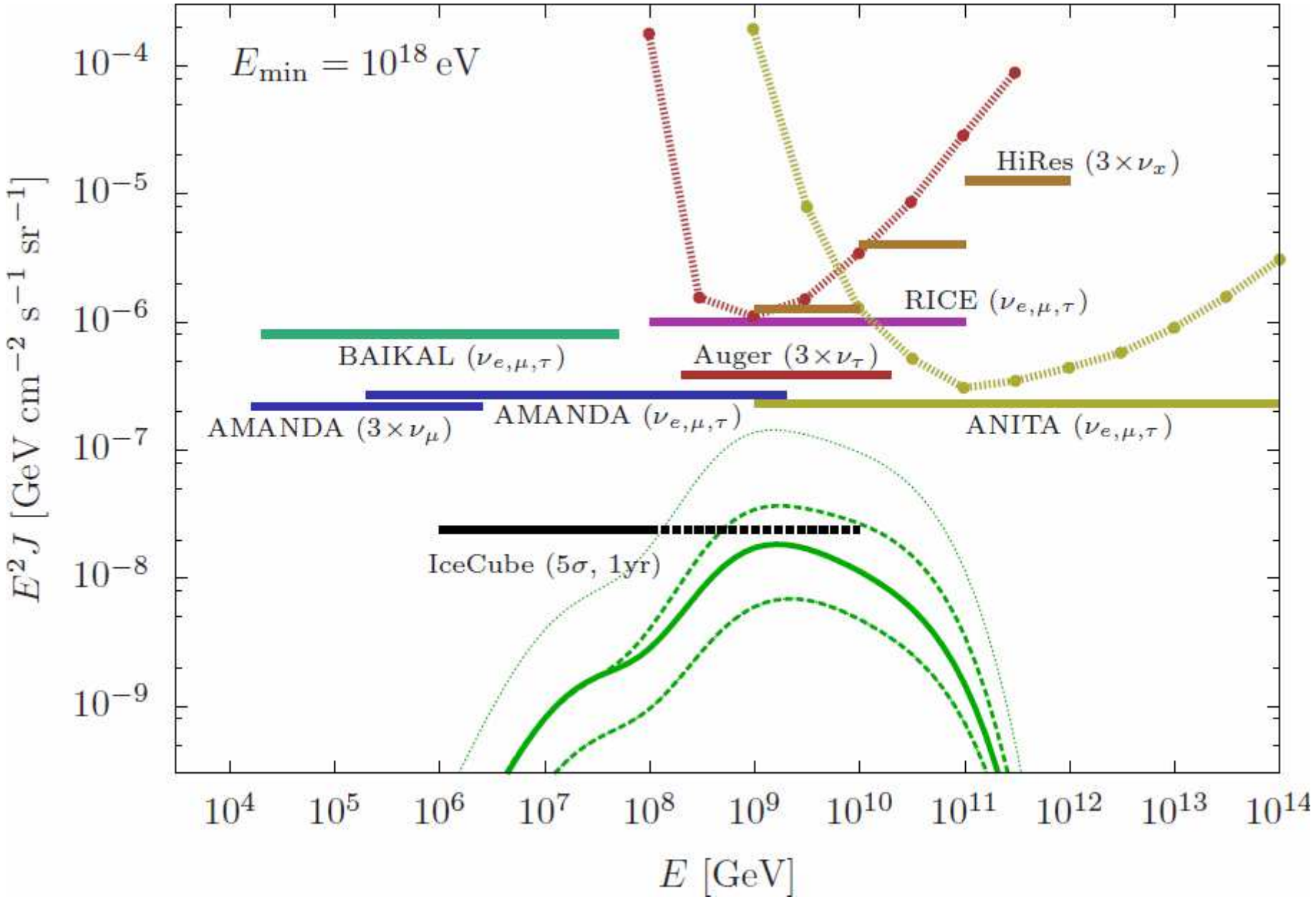
$$p + \gamma \rightarrow n + \pi^{+} \ and \ \ p + \pi^{0}$$

cosmic rays disappear, neutrinos appear

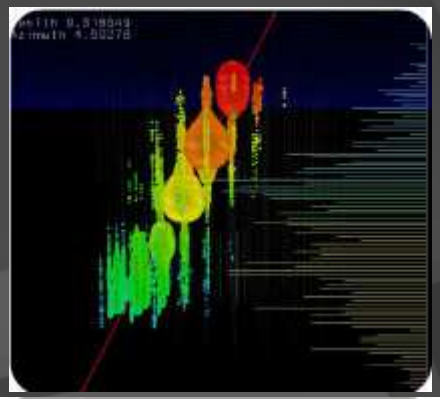
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

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

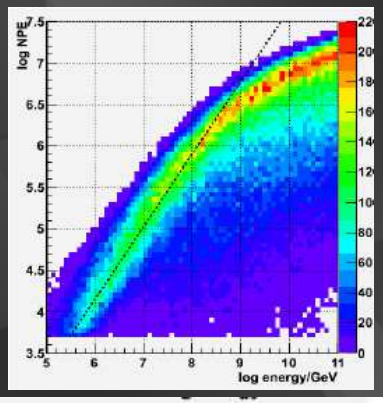
~1 event per cubed kilometer per year


$E_{\rm min} = 10^{18}\,{\rm eV}$
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 $(5\sigma,\ 1{\rm yr})$
$E^2 J\ [{\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}]$
$E\ [{\rm GeV}]$
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

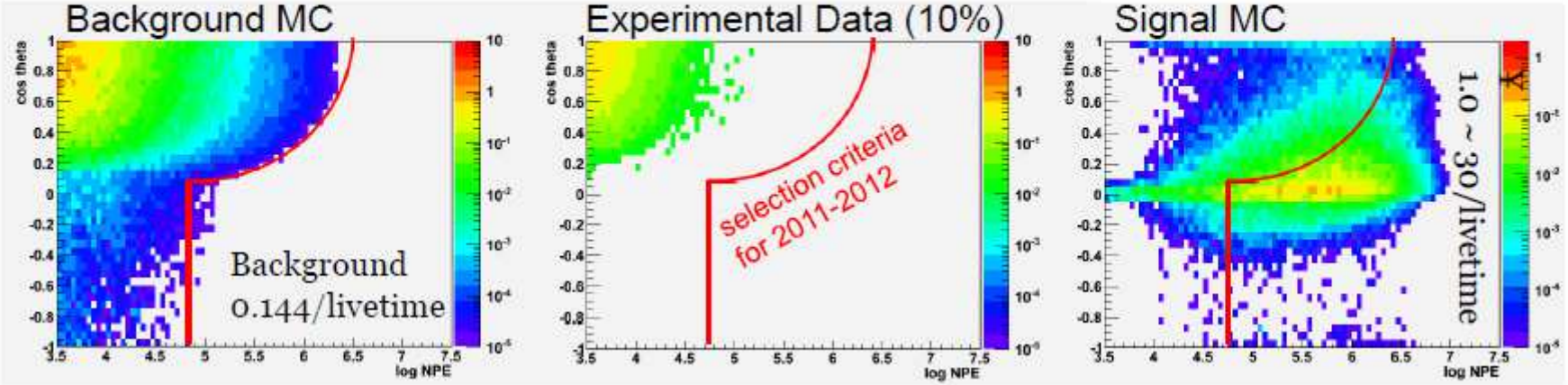


number of channels > 300

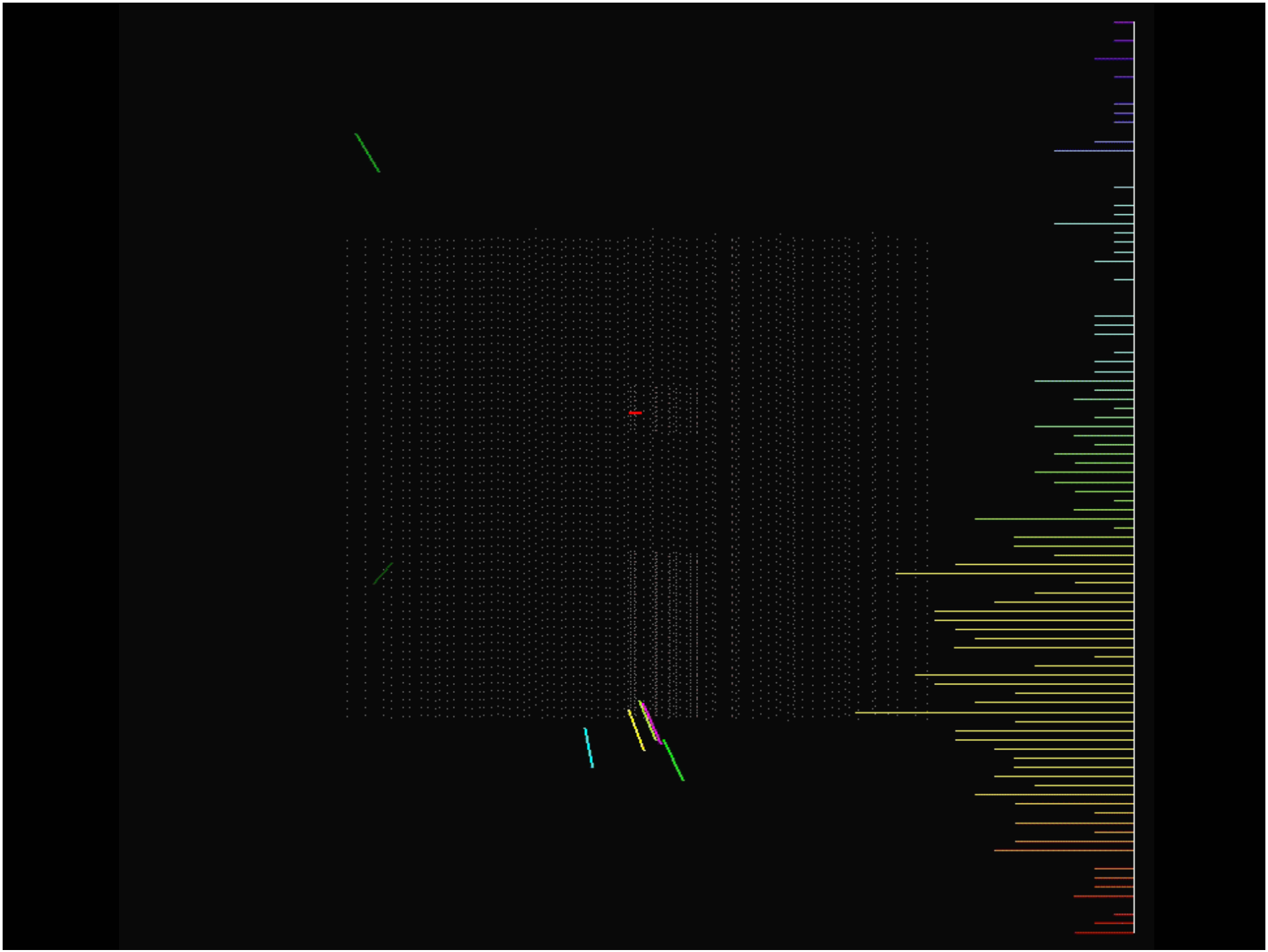


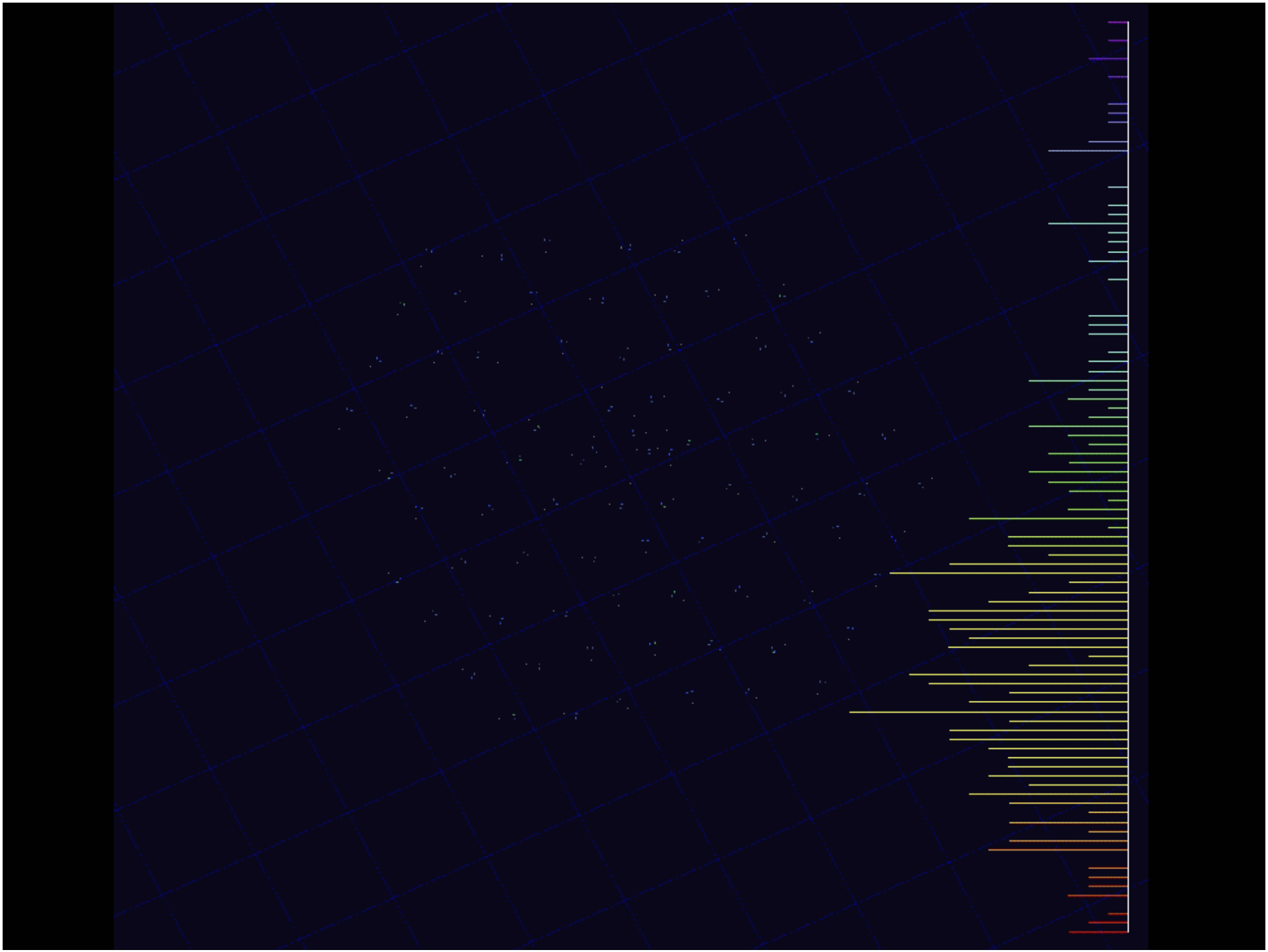
Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

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

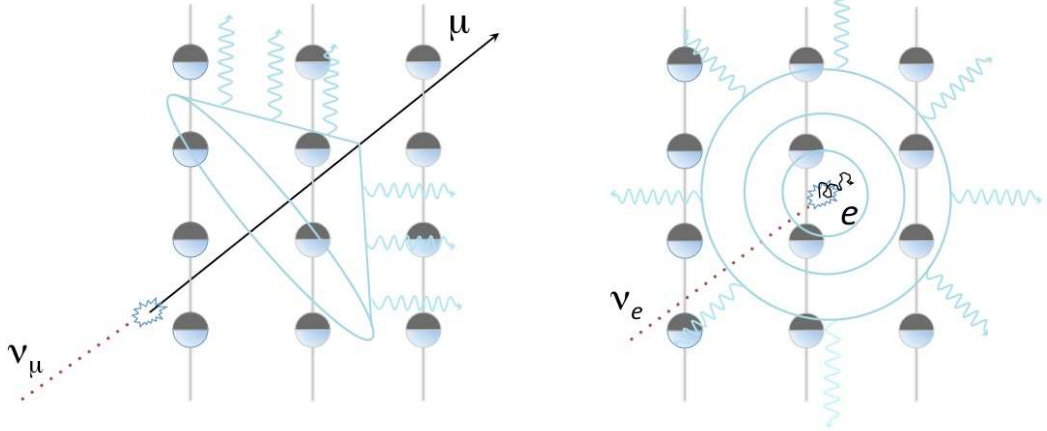


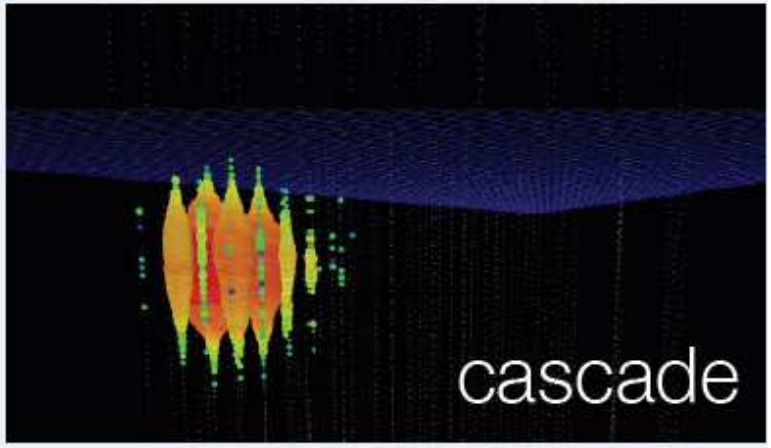
unblinding: 2 events in the signal region

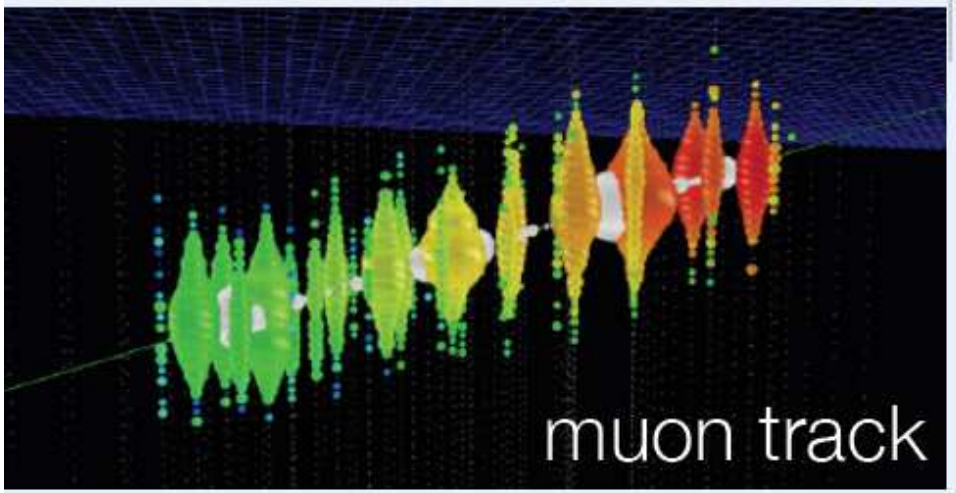


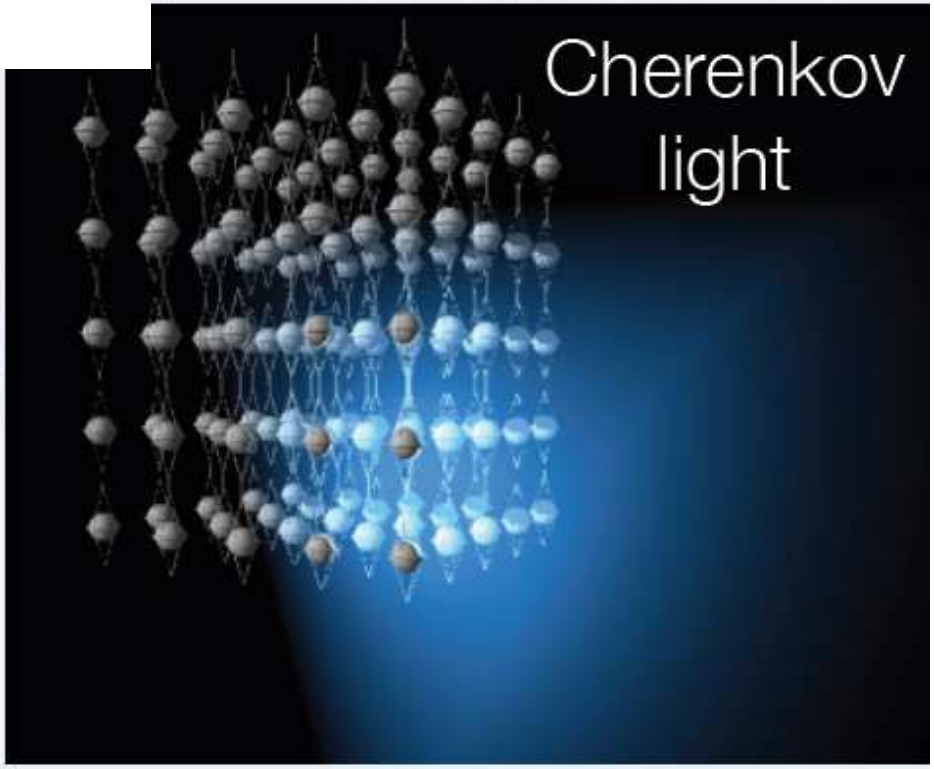


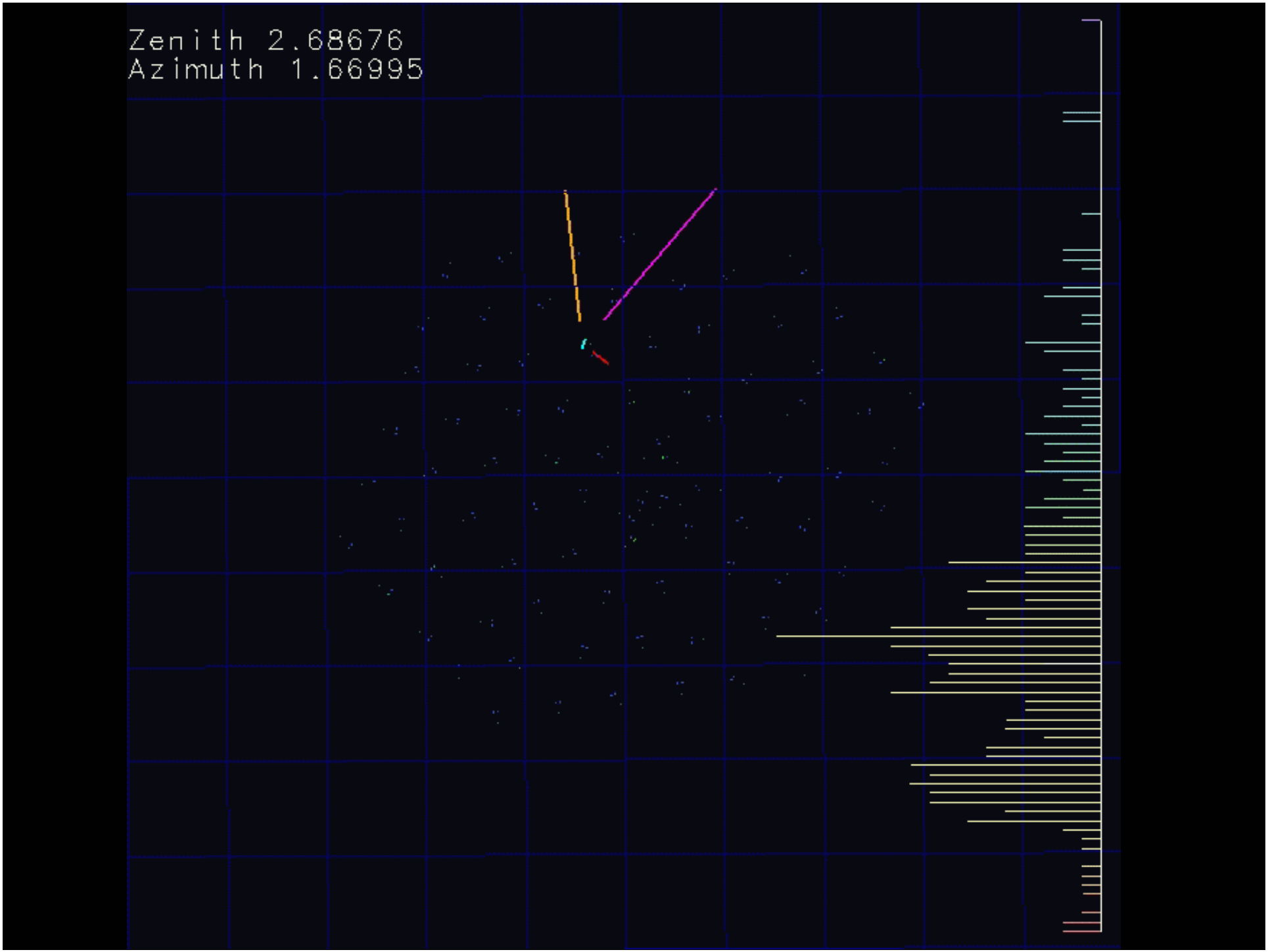
tracks and showers

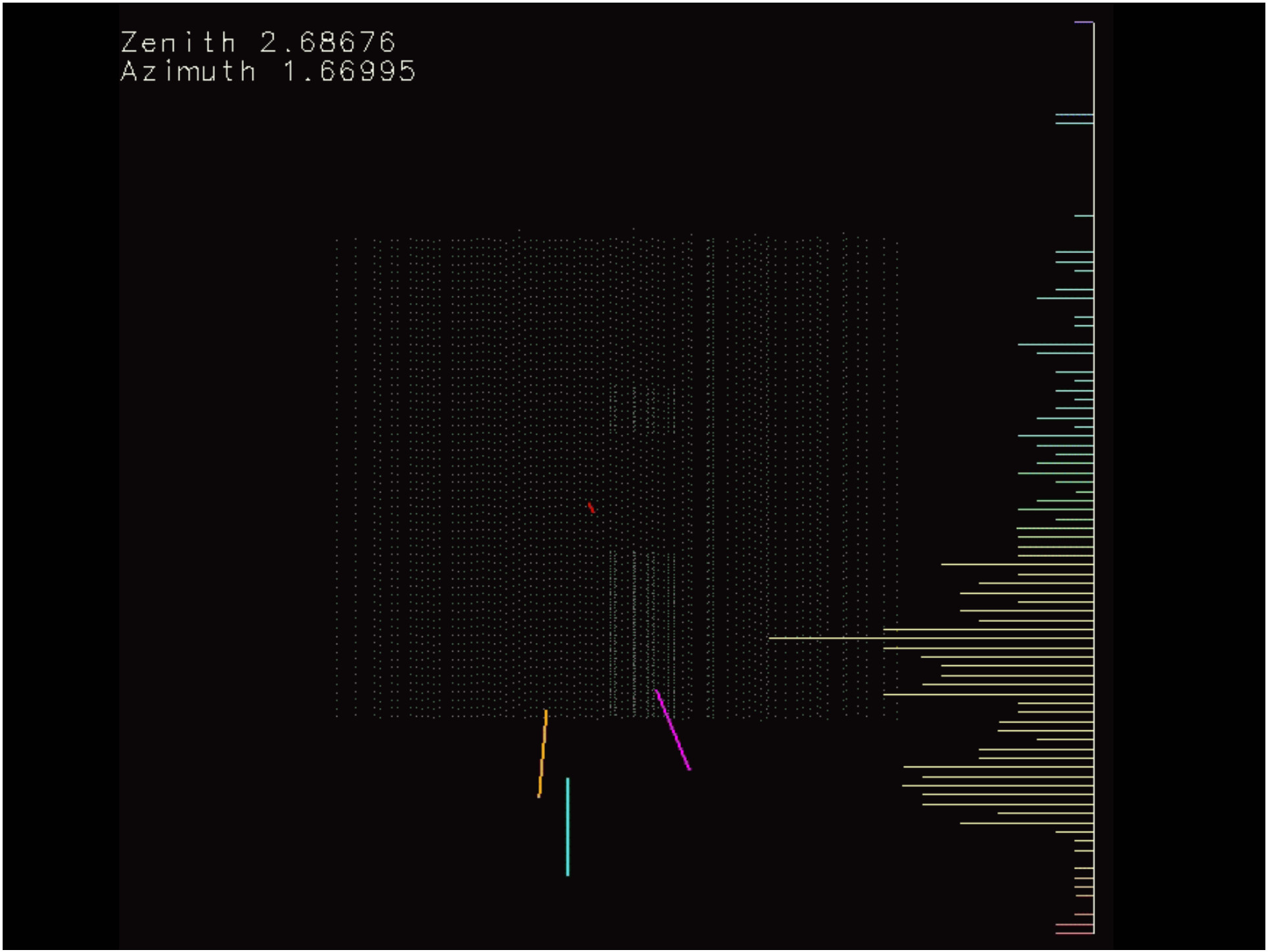


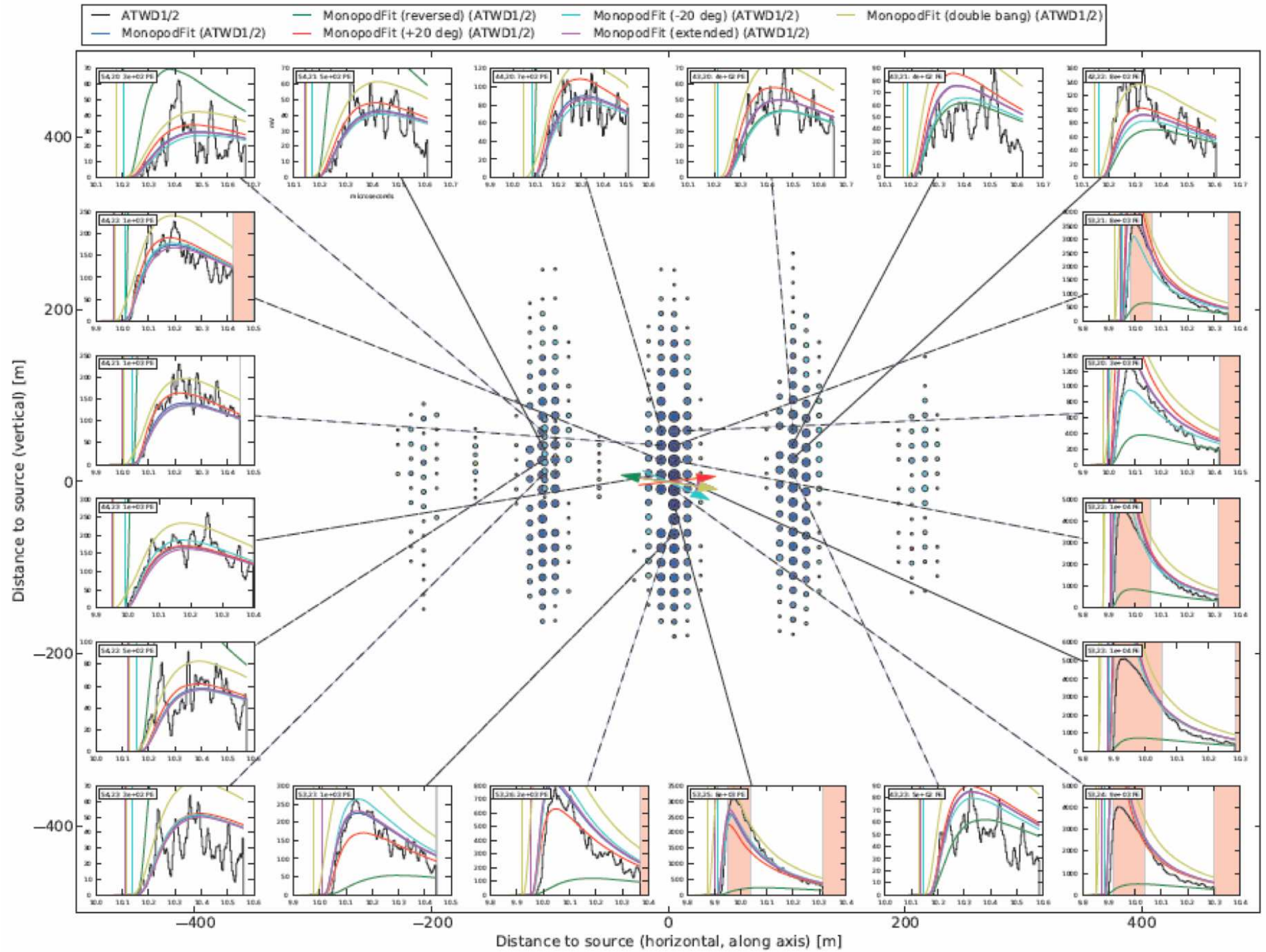


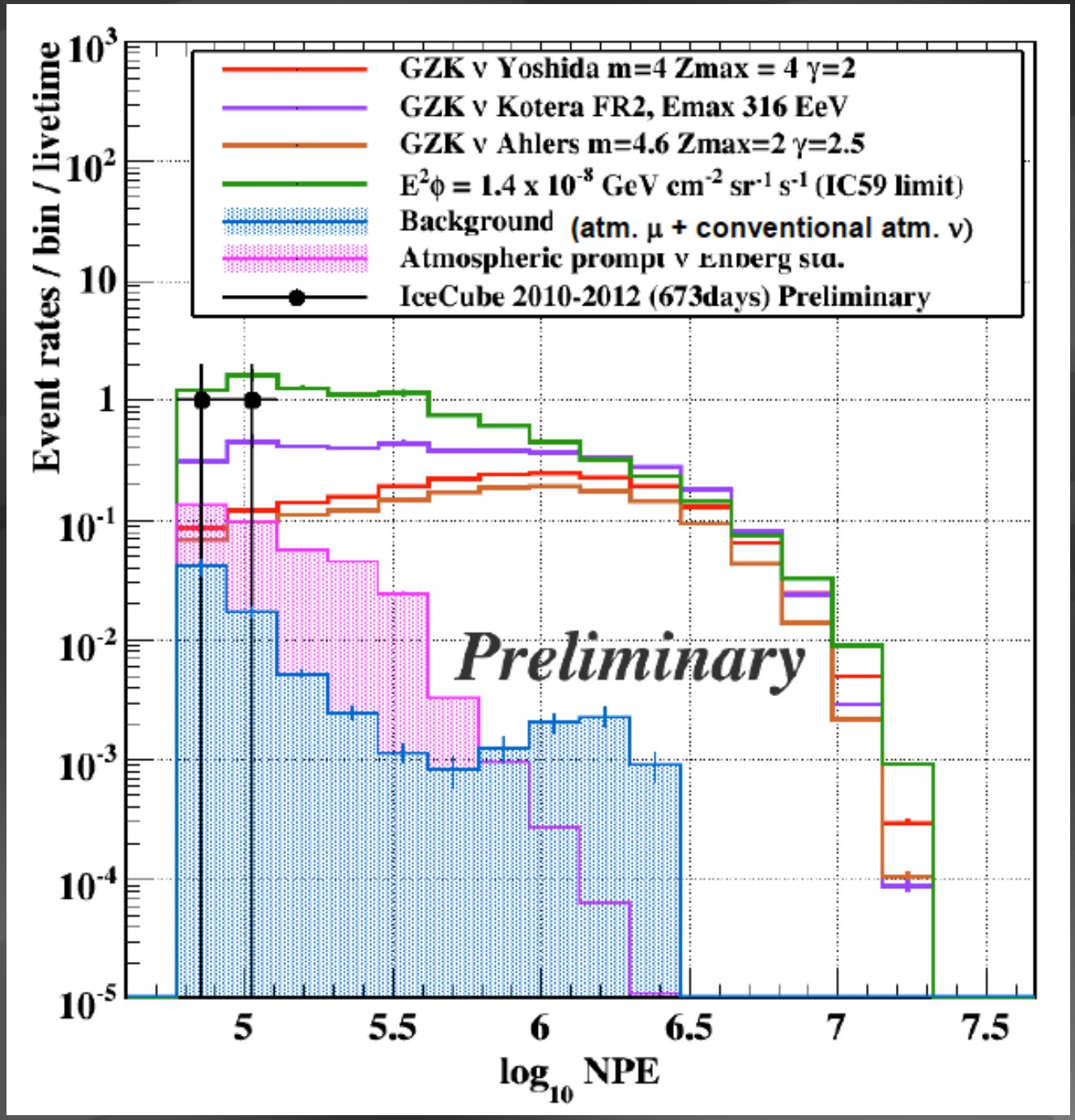





Zenith 2.68676
Azimuth 1.66995


Zenith 2.68676
Azimuth 1.66995


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

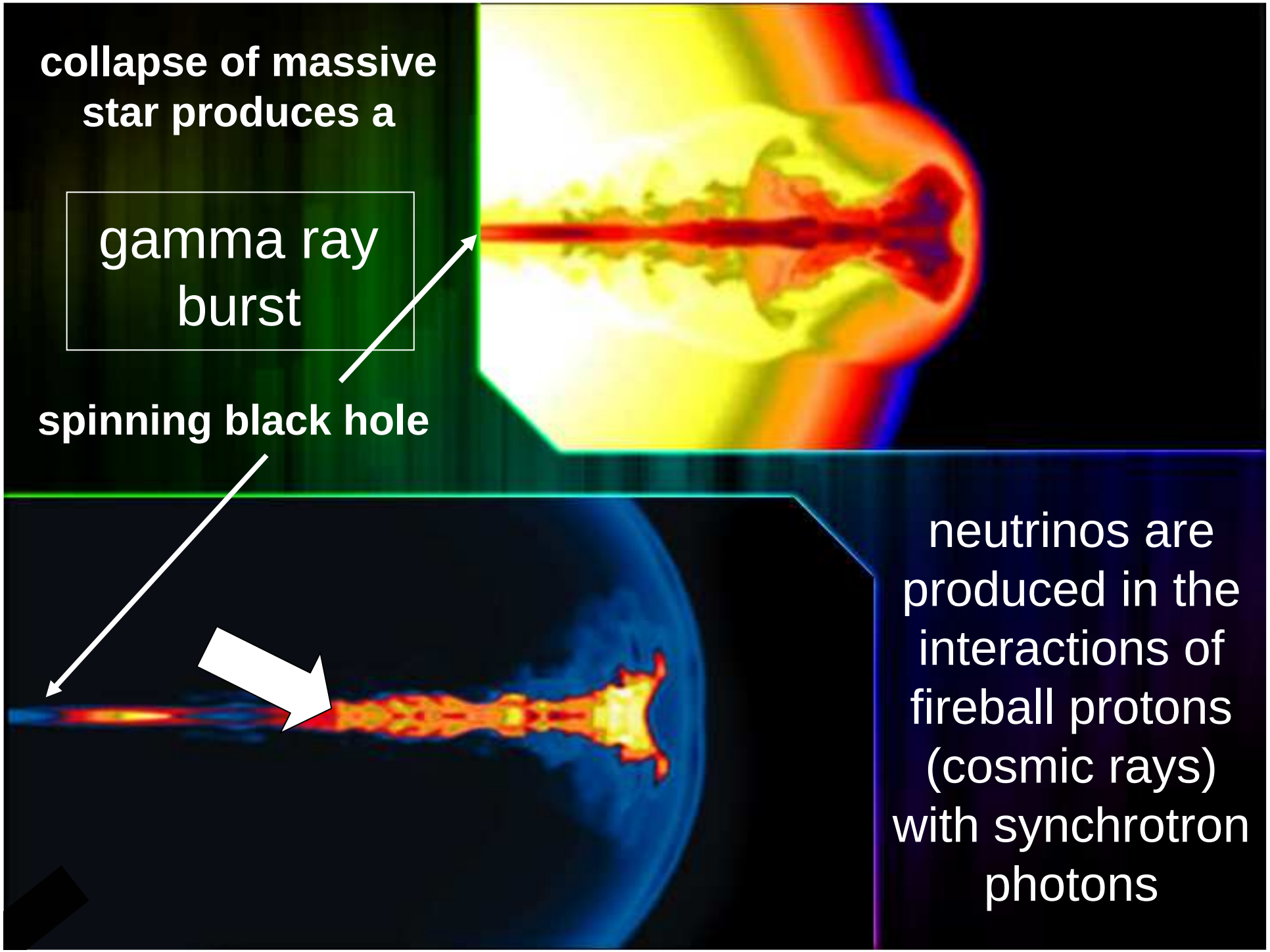


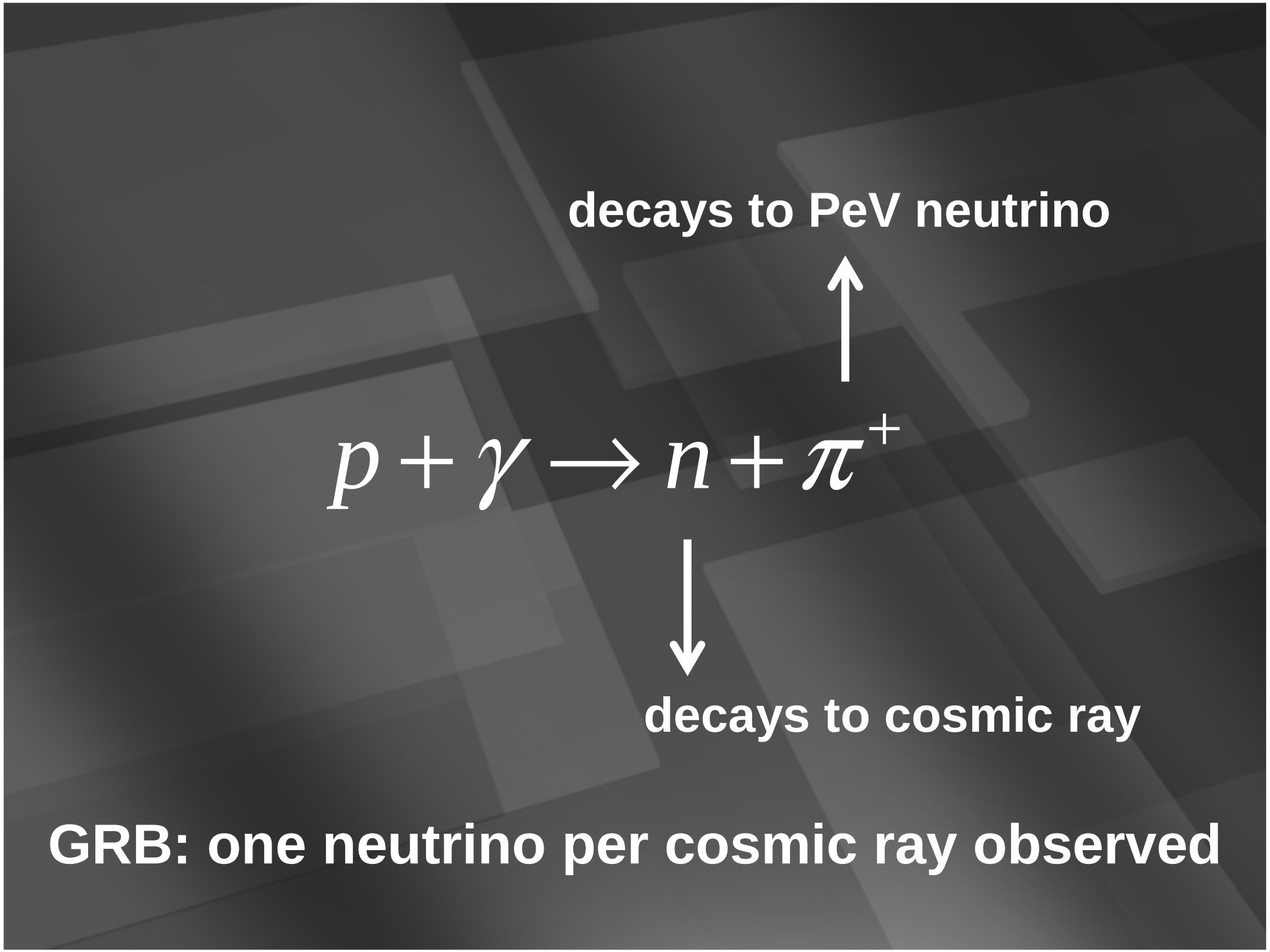
1.1 and 1.3 PeV
< 35% systematic error

directions soon

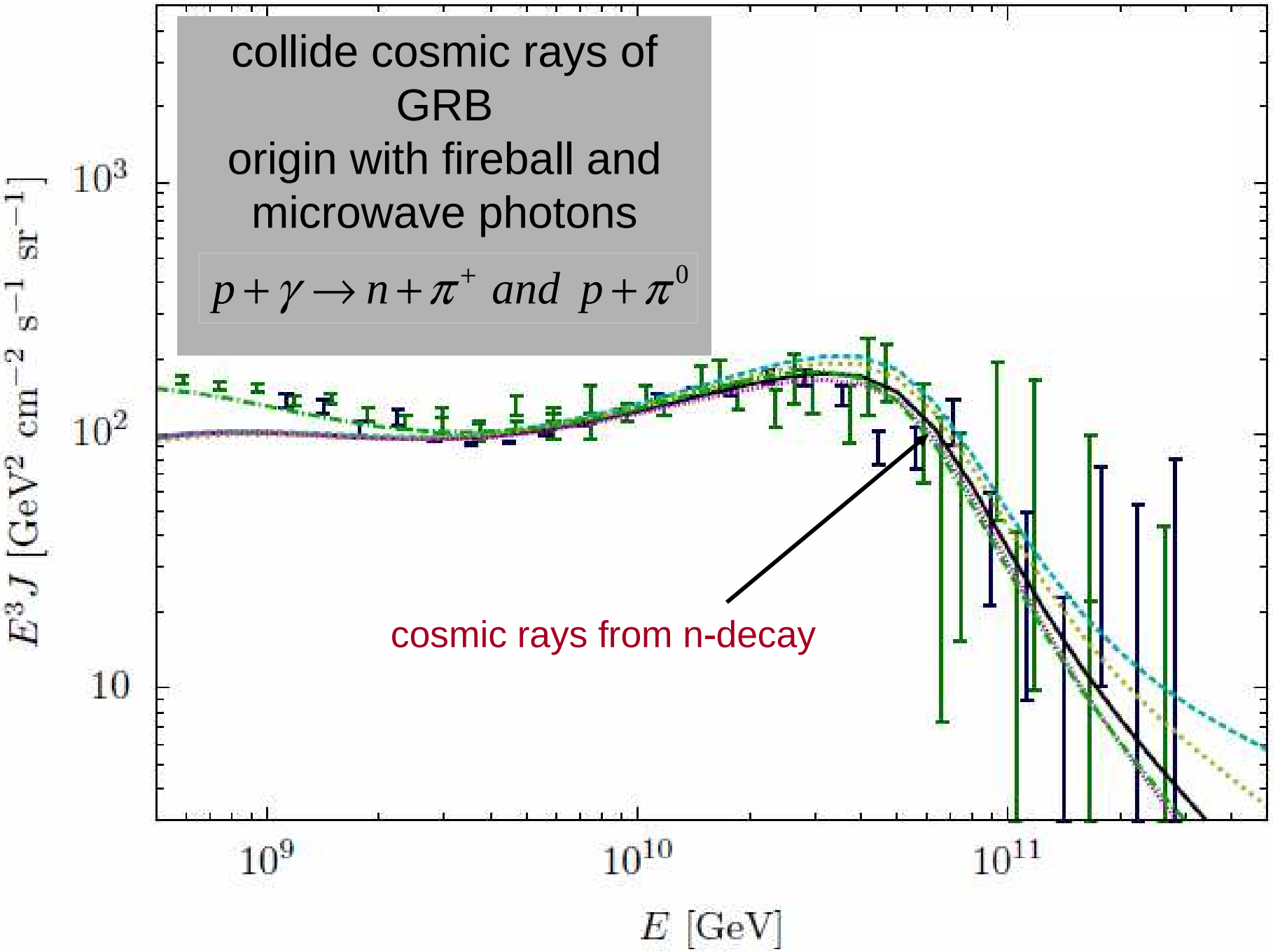
flux at present level of diffuse limit

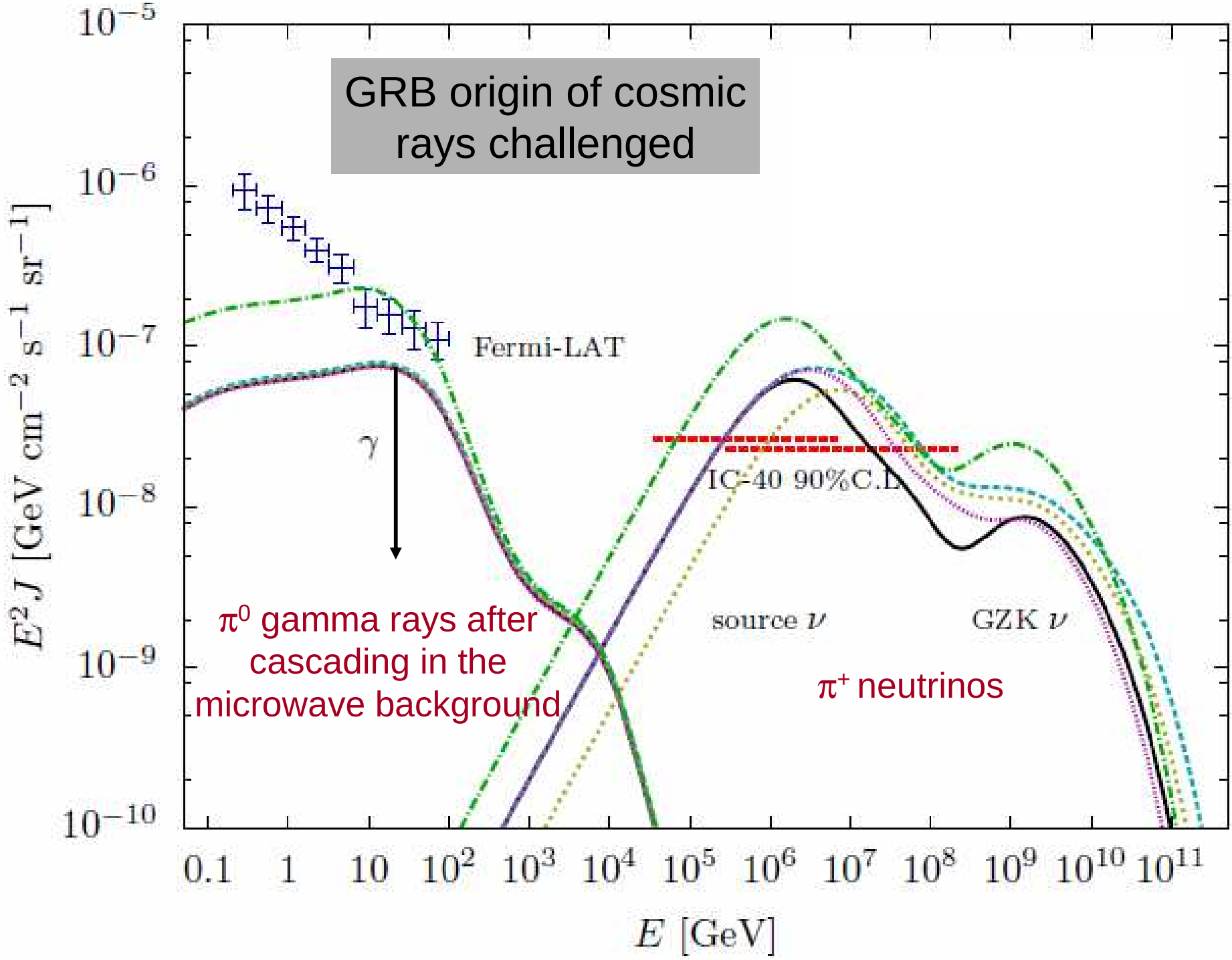
largest bkgd: atmospheric charm
< 0.2 evts
no air shower


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

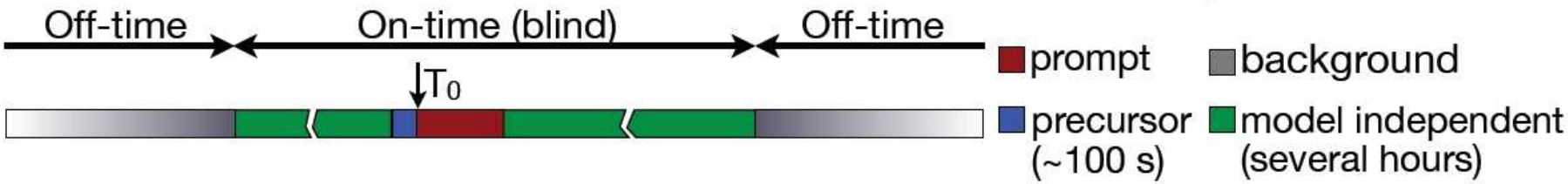


GRB: one neutrino per cosmic ray observed


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]

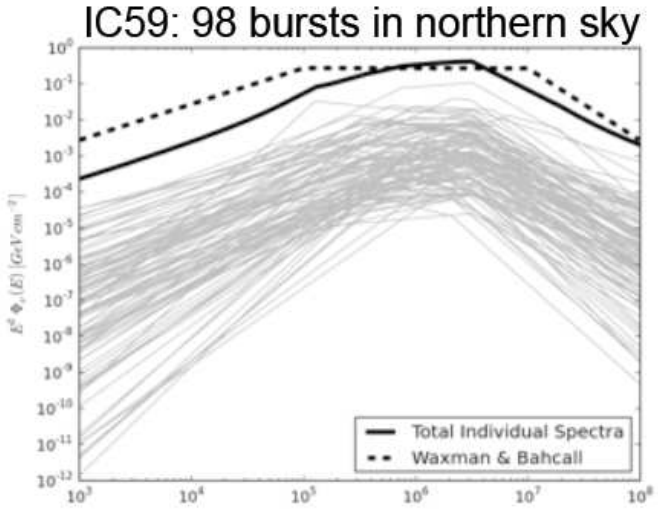

GRB origin of cosmic rays challenged
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
Fermi-LAT
γ
IC-40 90%C.L.
source ν
GZK ν
π^0 gamma rays after cascading in the microwave background
π^+ neutrinos
0.1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
E [GeV]

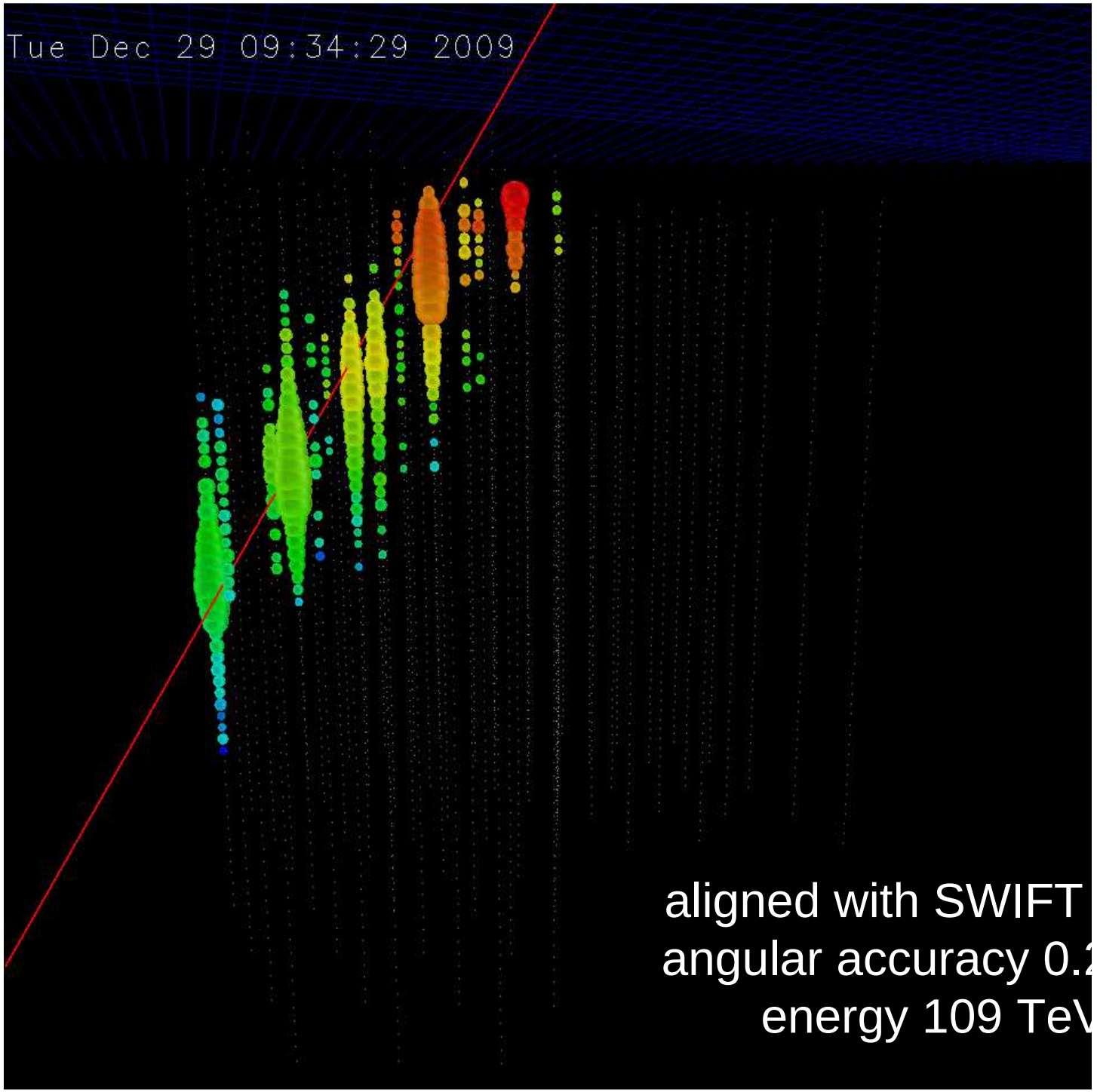
- Using satellite information (time and direction, GCN)



very low background → 1 event can be significant !

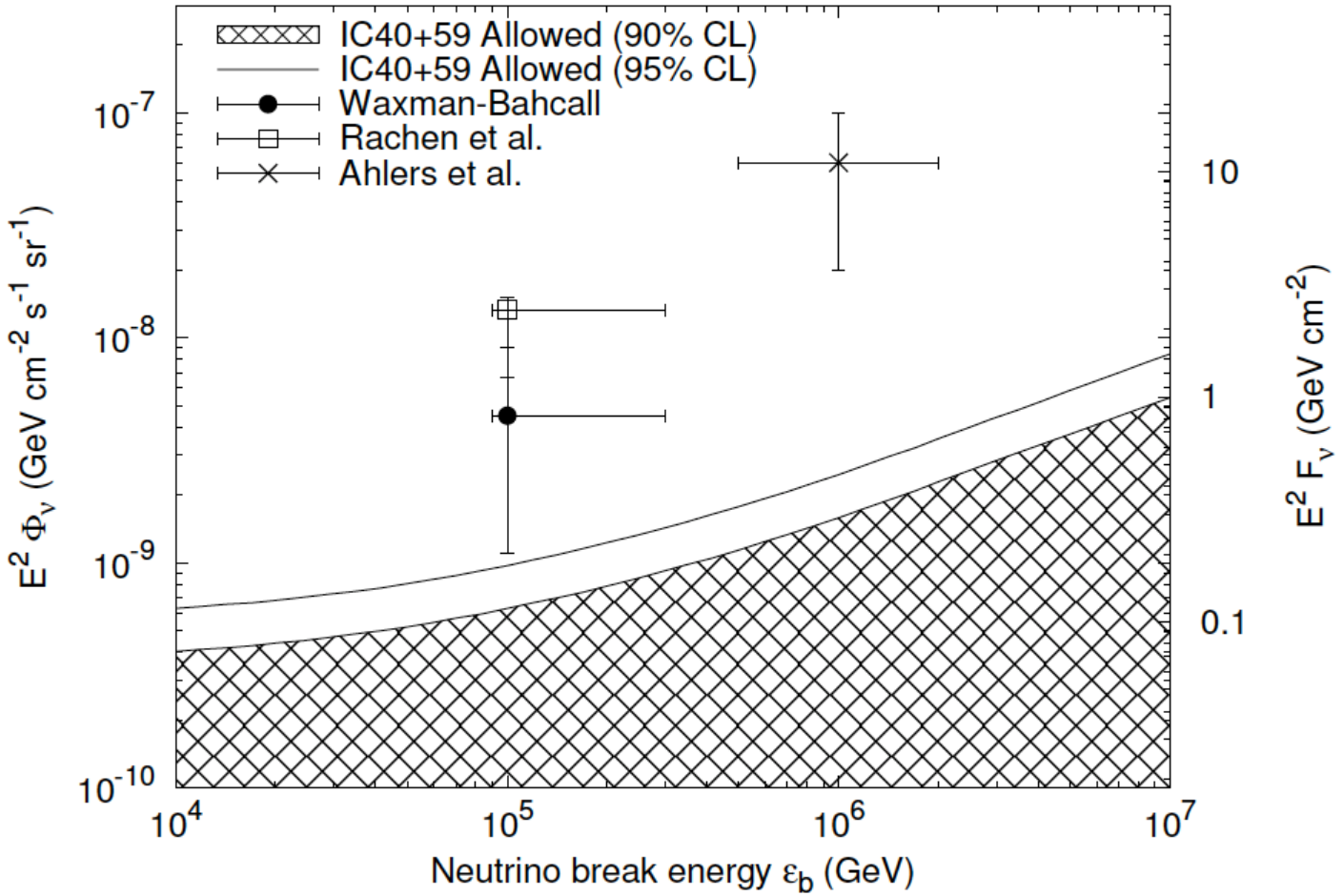
- 98 bursts (northern sky) observed with IceCube 59 strings
- Individual modeling of neutrino fluxes (fireball model)

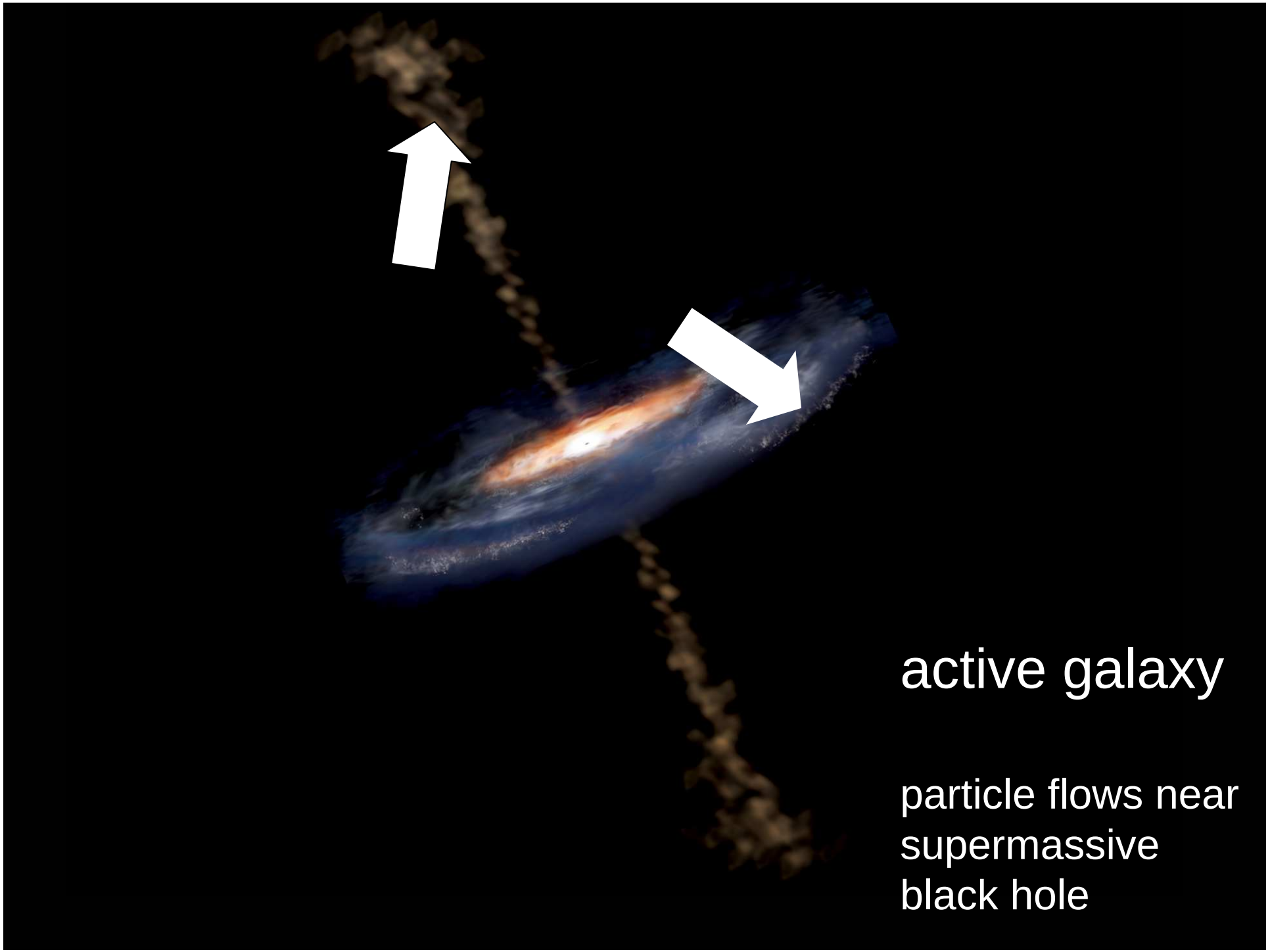


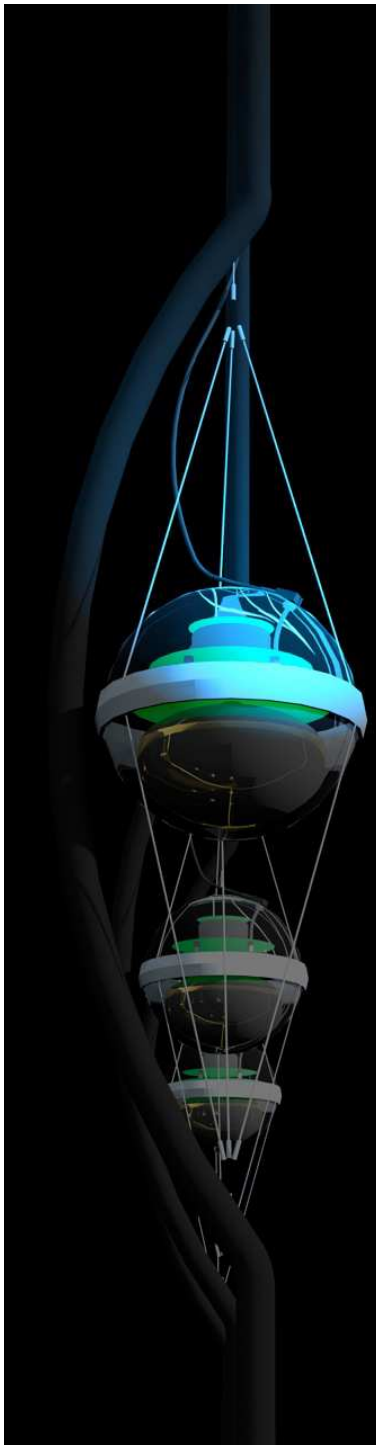

Tue Dec 29 09:34:29 2009
aligned with SWIFT
angular accuracy 0.2
energy 109 TeV

GRB on probation

Model	Predicted ν	Fractional Upper Limit
Reference Fireball (CR-normalized)	$\gtrapprox 84$	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



NOW 2012

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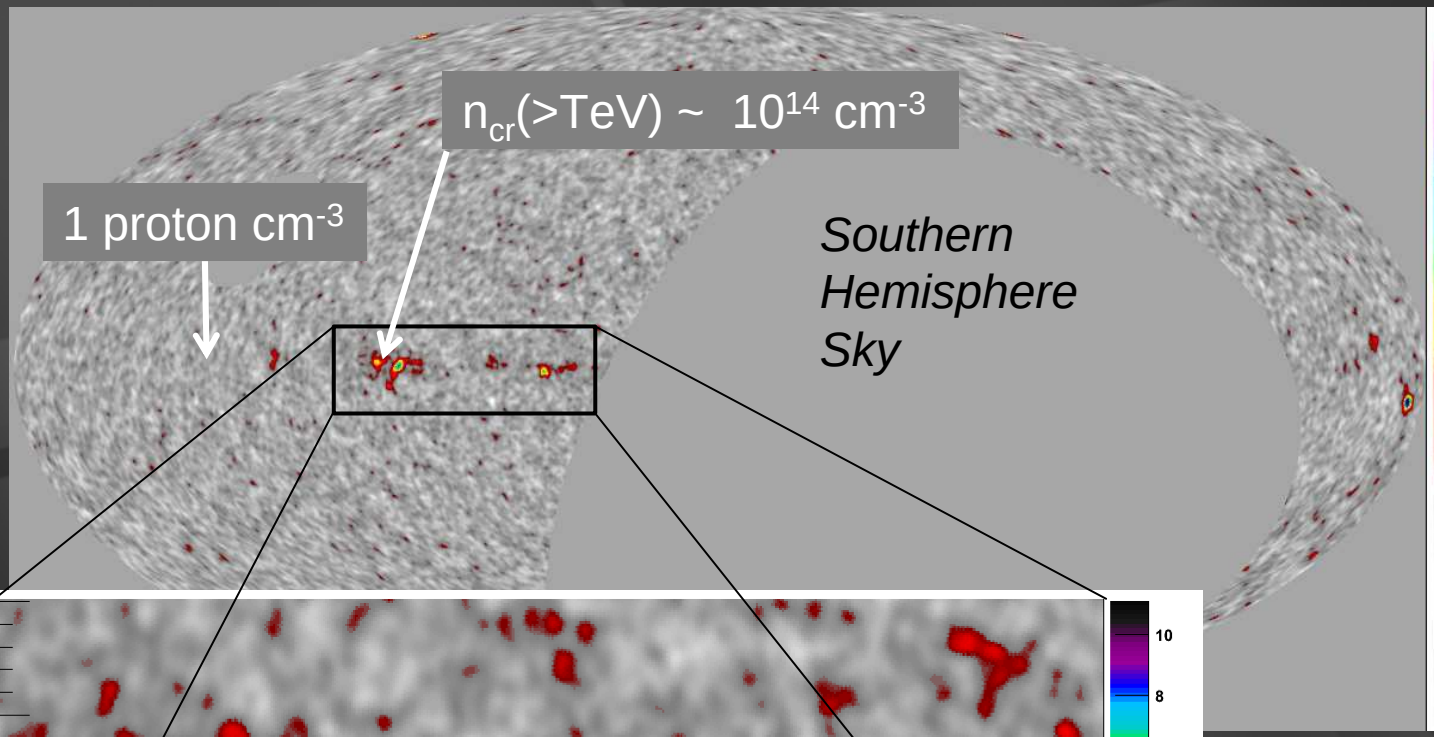
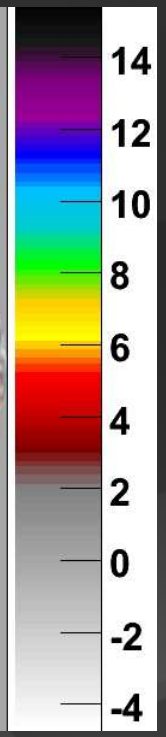
- the search for the sources of the Galactic and extragalactic cosmic rays

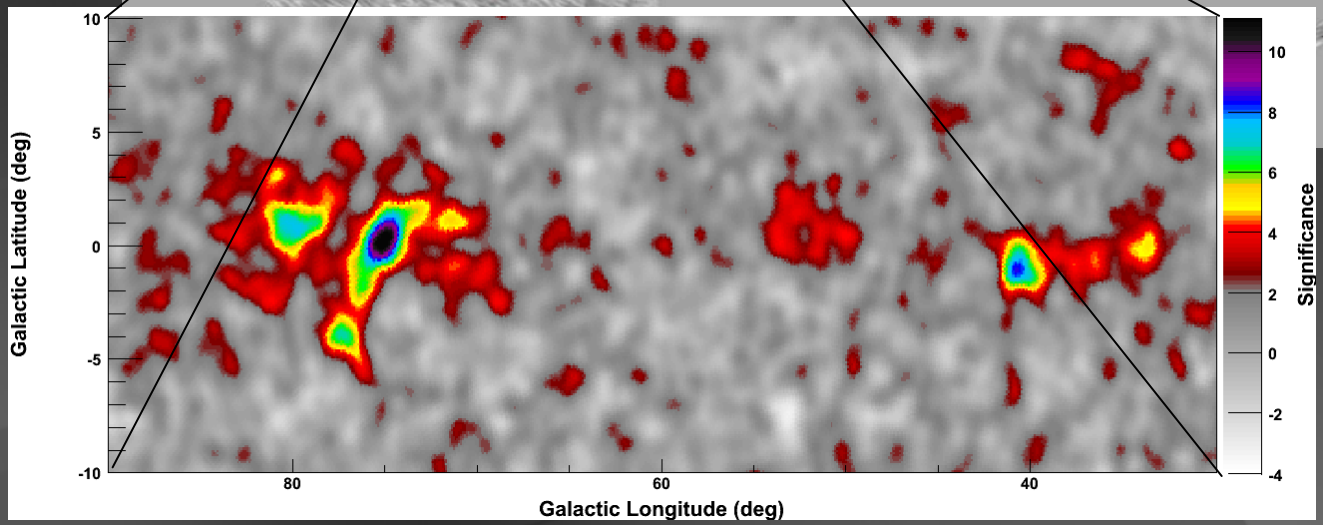
IceCube.wisc.edu

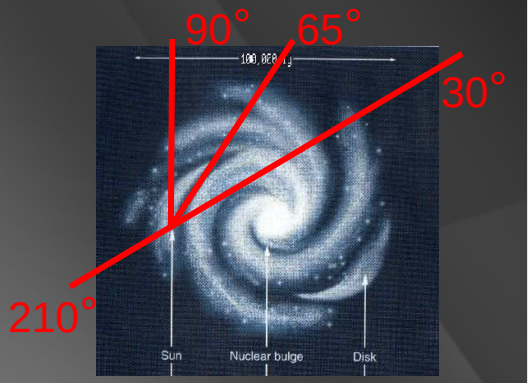
Galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions





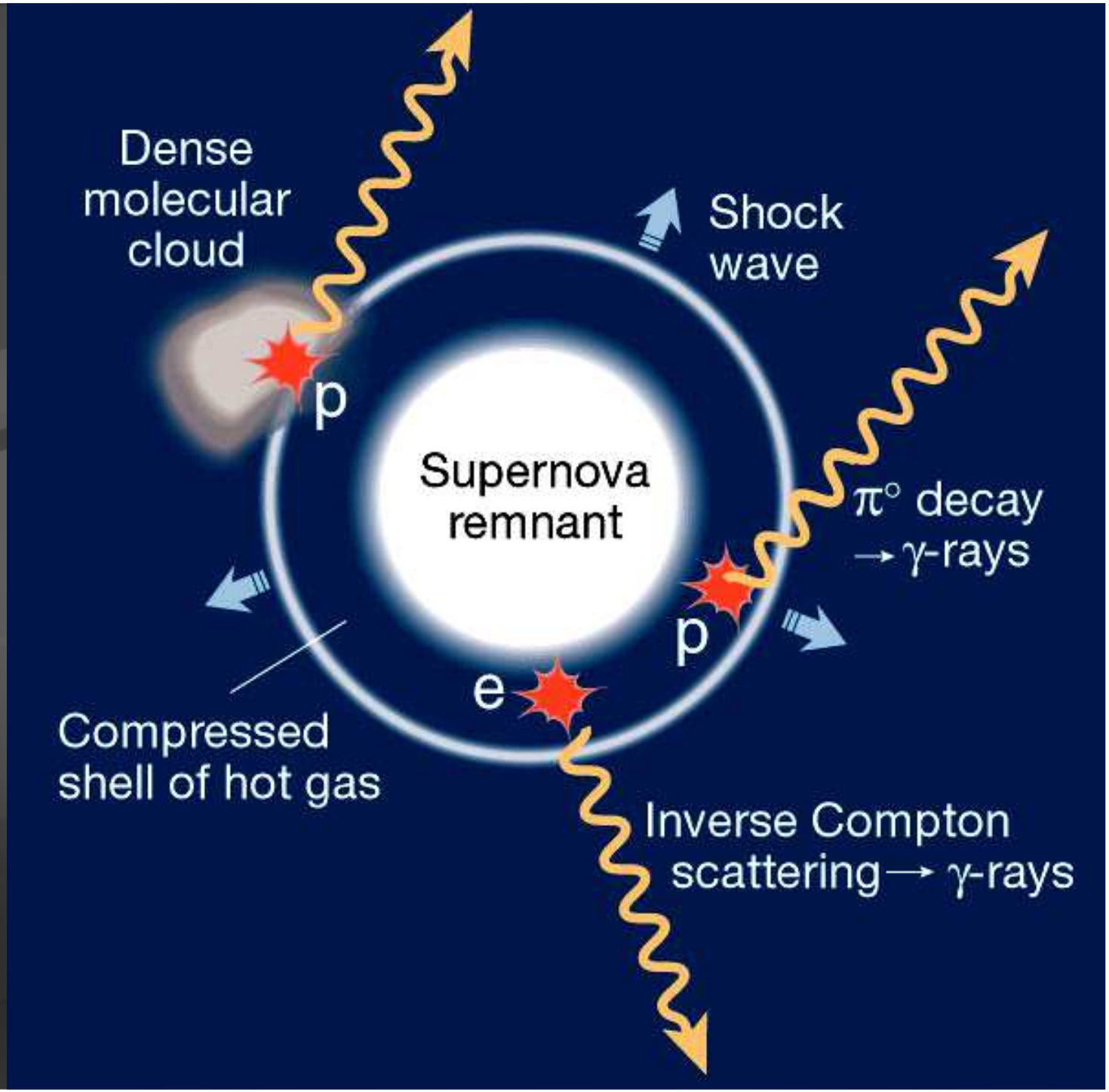




milagro

neutrinos from supernova remnants :

molecular clouds as beam dumps



neutral pions

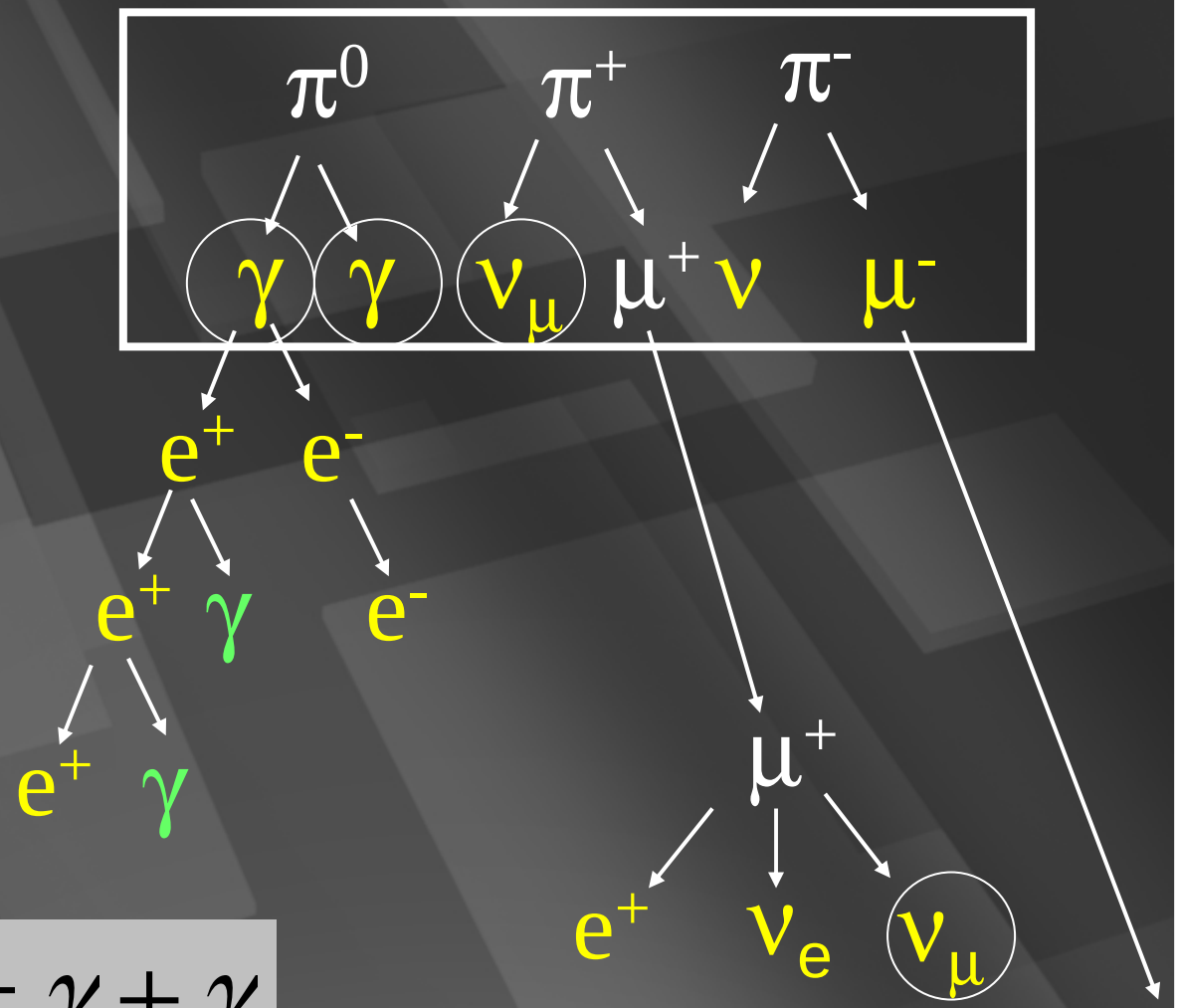
are observed as

gamma rays

charged pions

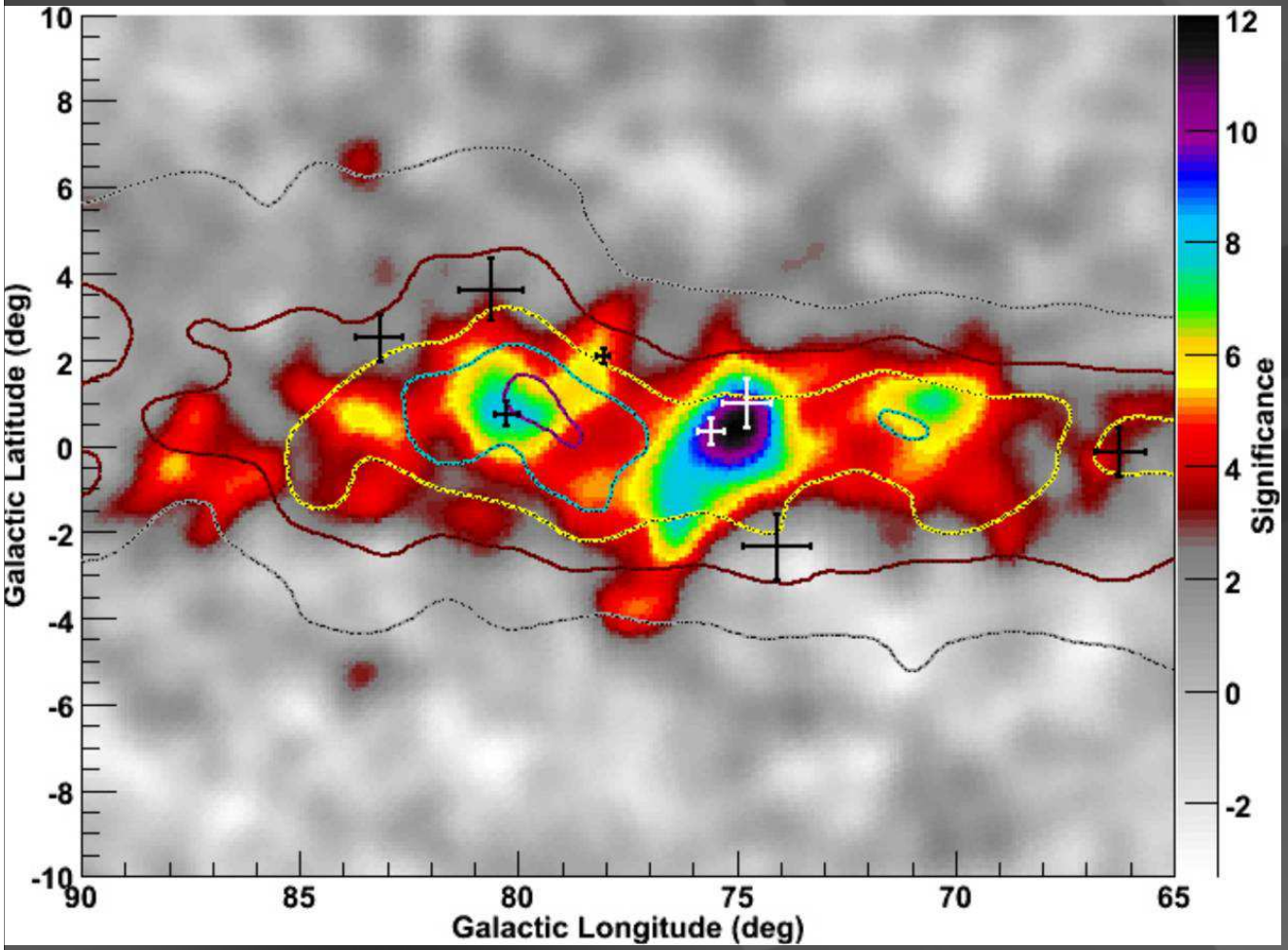
are observed as

neutrinos



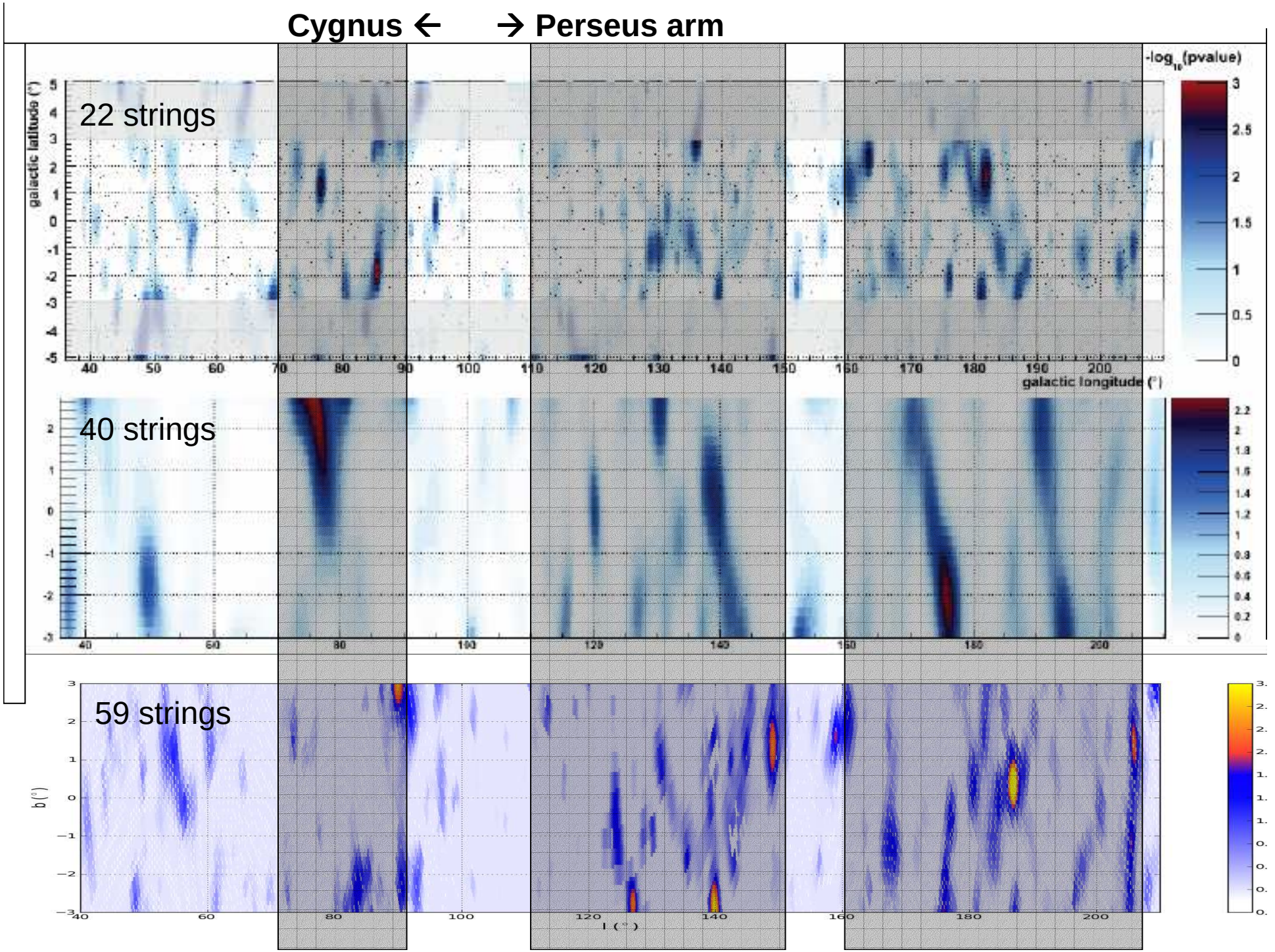
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

Cygnus region : Milagro

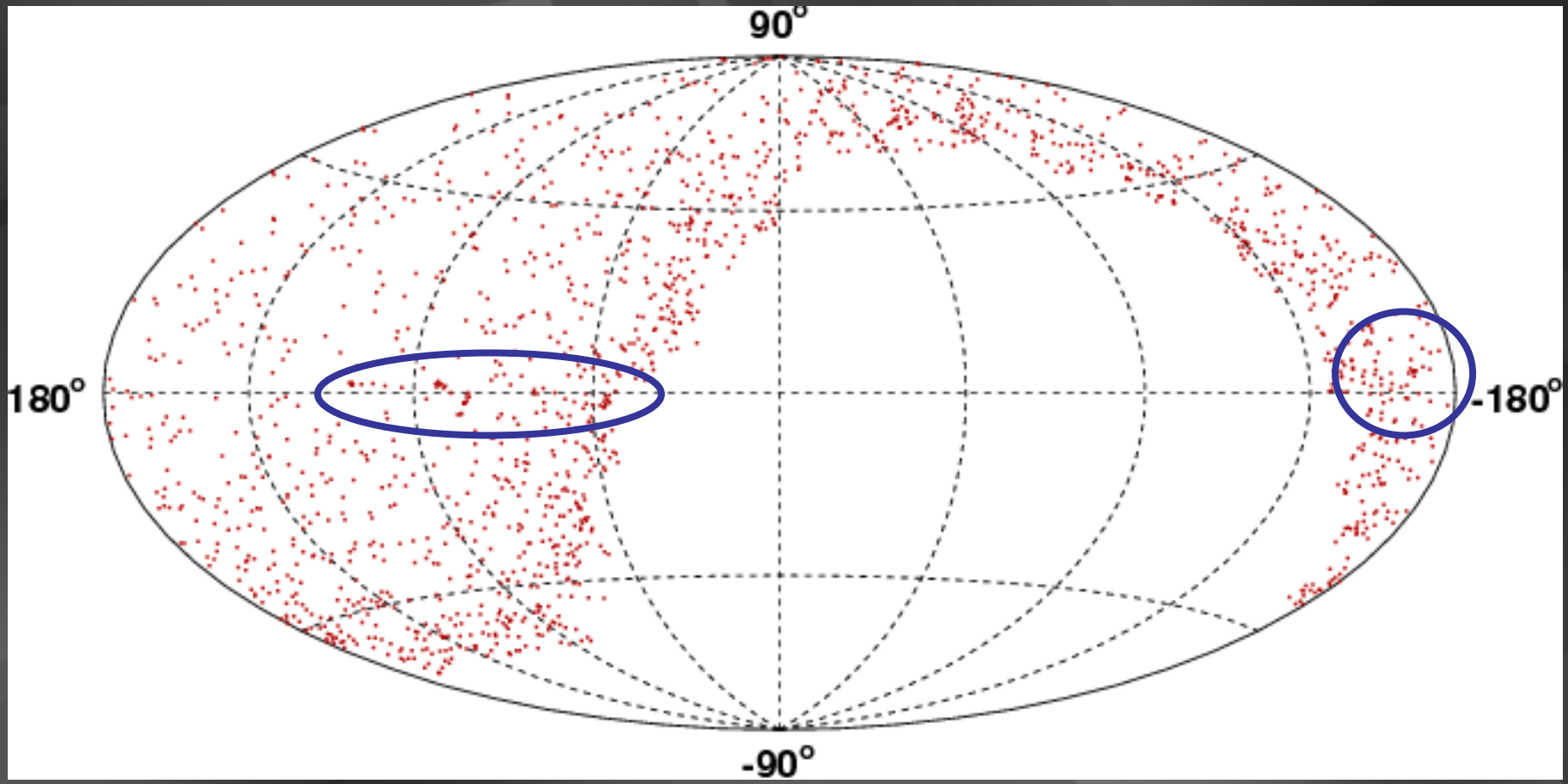


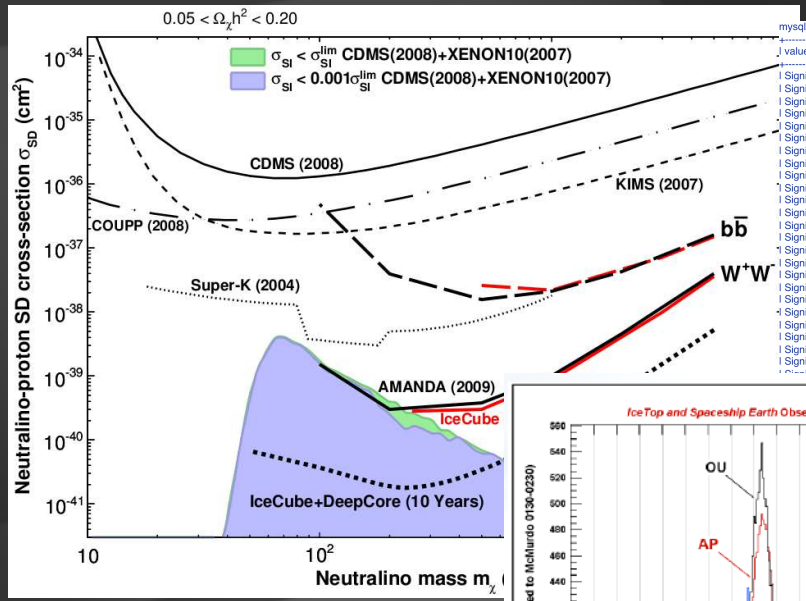
translation of
TeV gamma rays
into
TeV neutrinos :

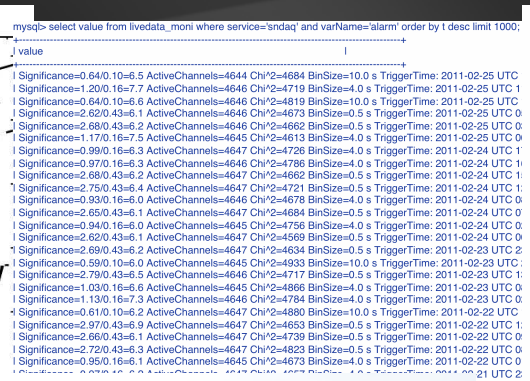
3 ± 1 ν per year in IceCube per source

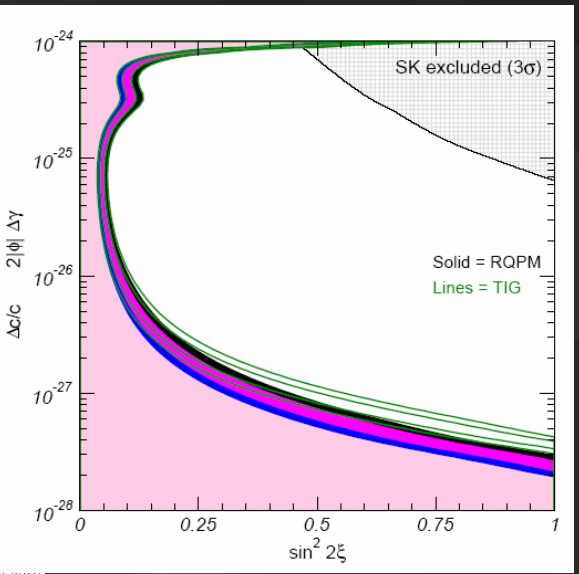

Cygnus ←
→ Perseus arm
22 strings
40 strings
59 strings
galactic latitude (°)
galactic longitude (°)
-log10(pvalue)
b (°)
l (°)

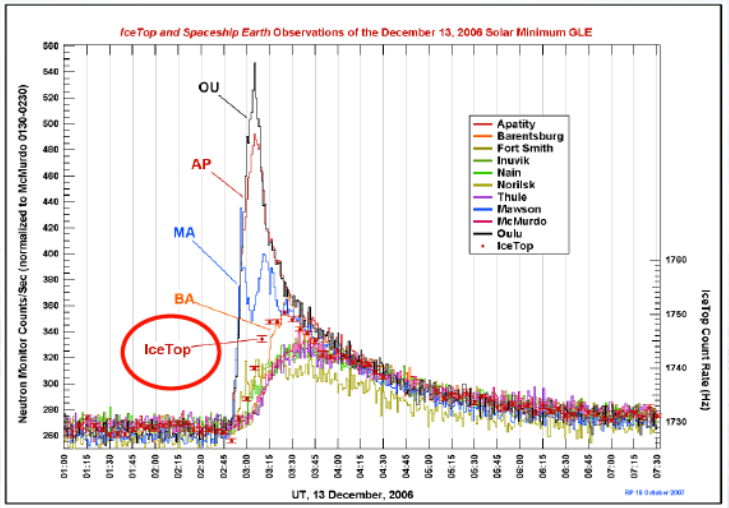
5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV

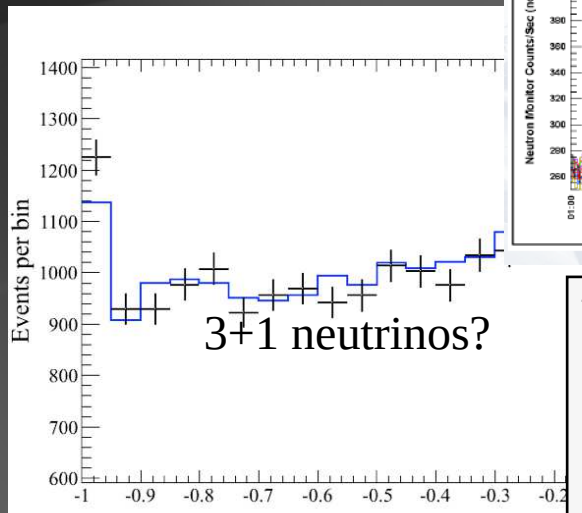


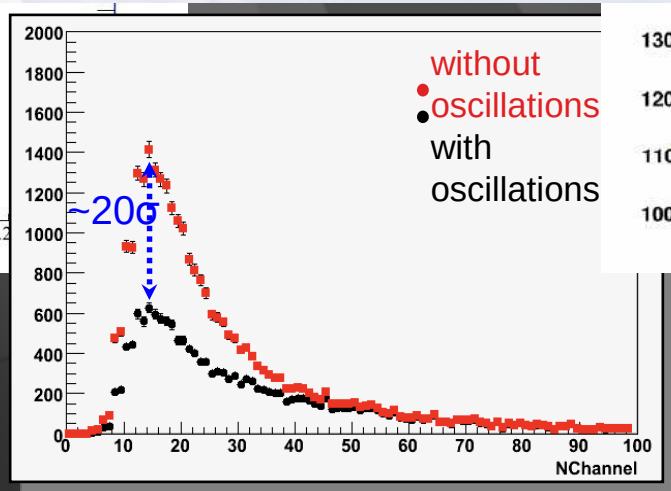


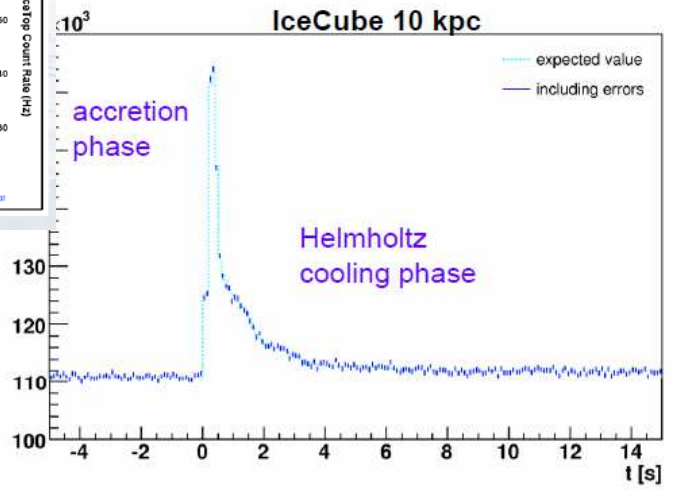












IceCube

science

conclusions

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- the instrumentation is in place …
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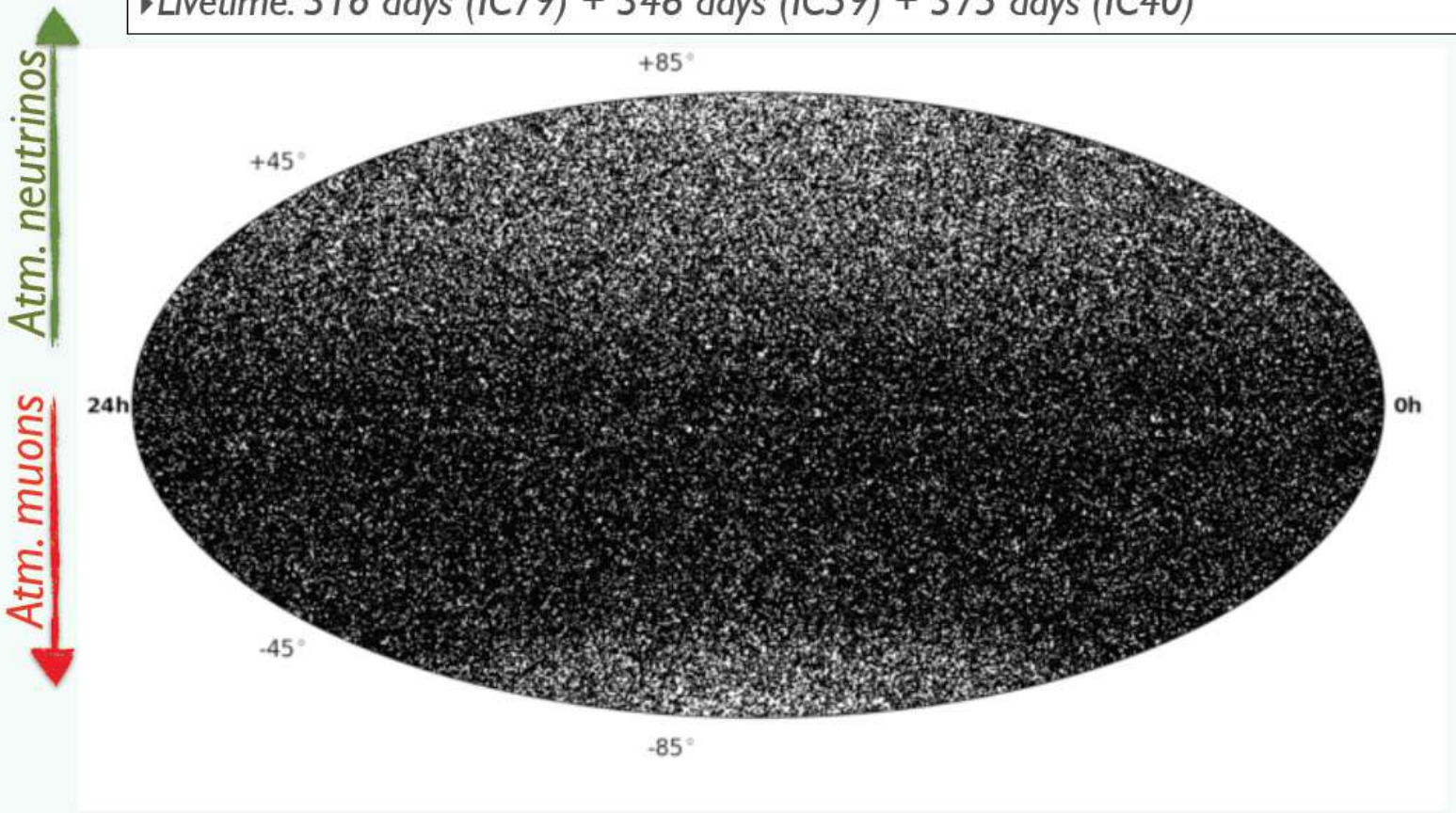
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

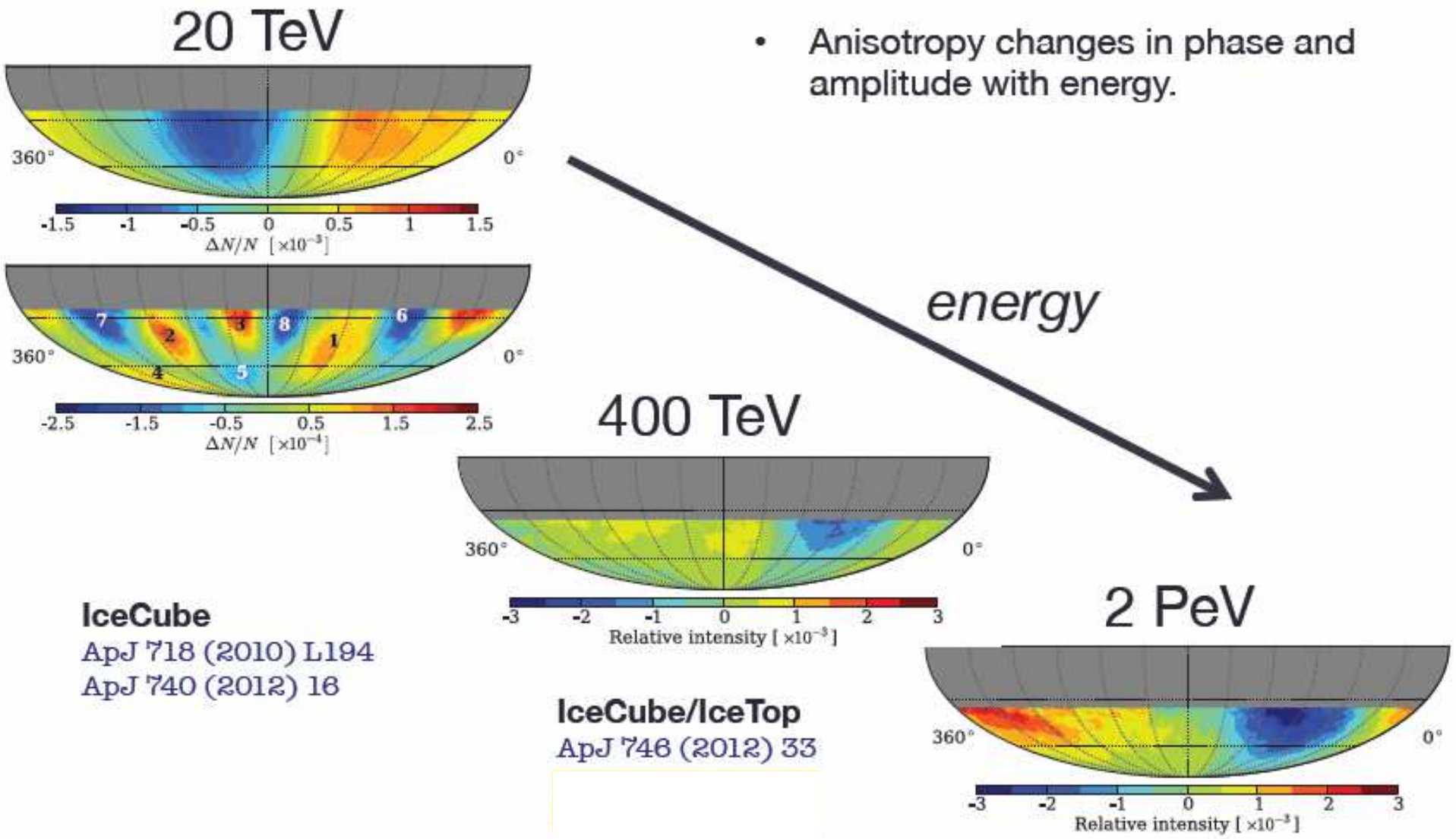
muon astronomy

+IC79 SKYMAP

- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*



muon astronomy: nearby Galactic source(s)?

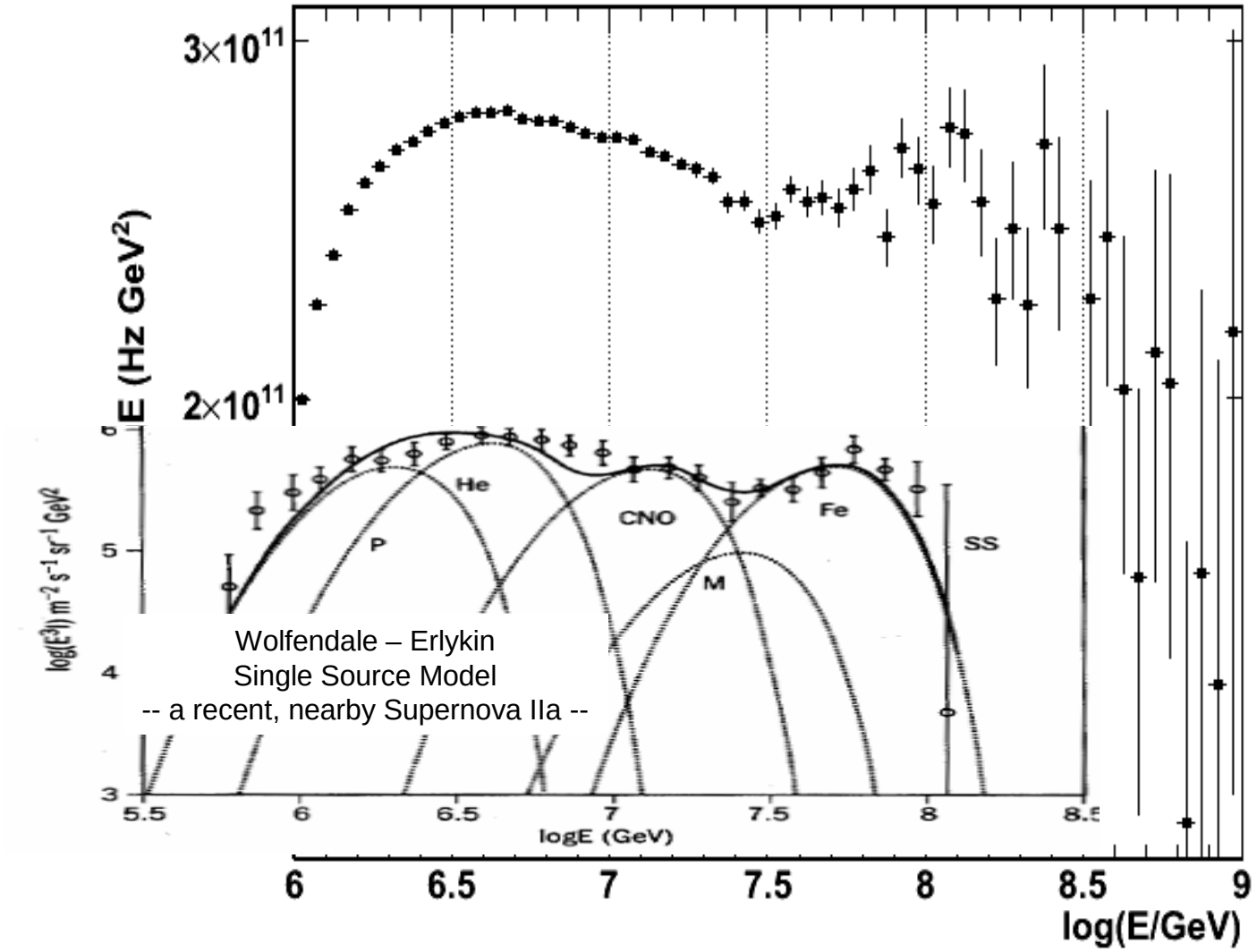


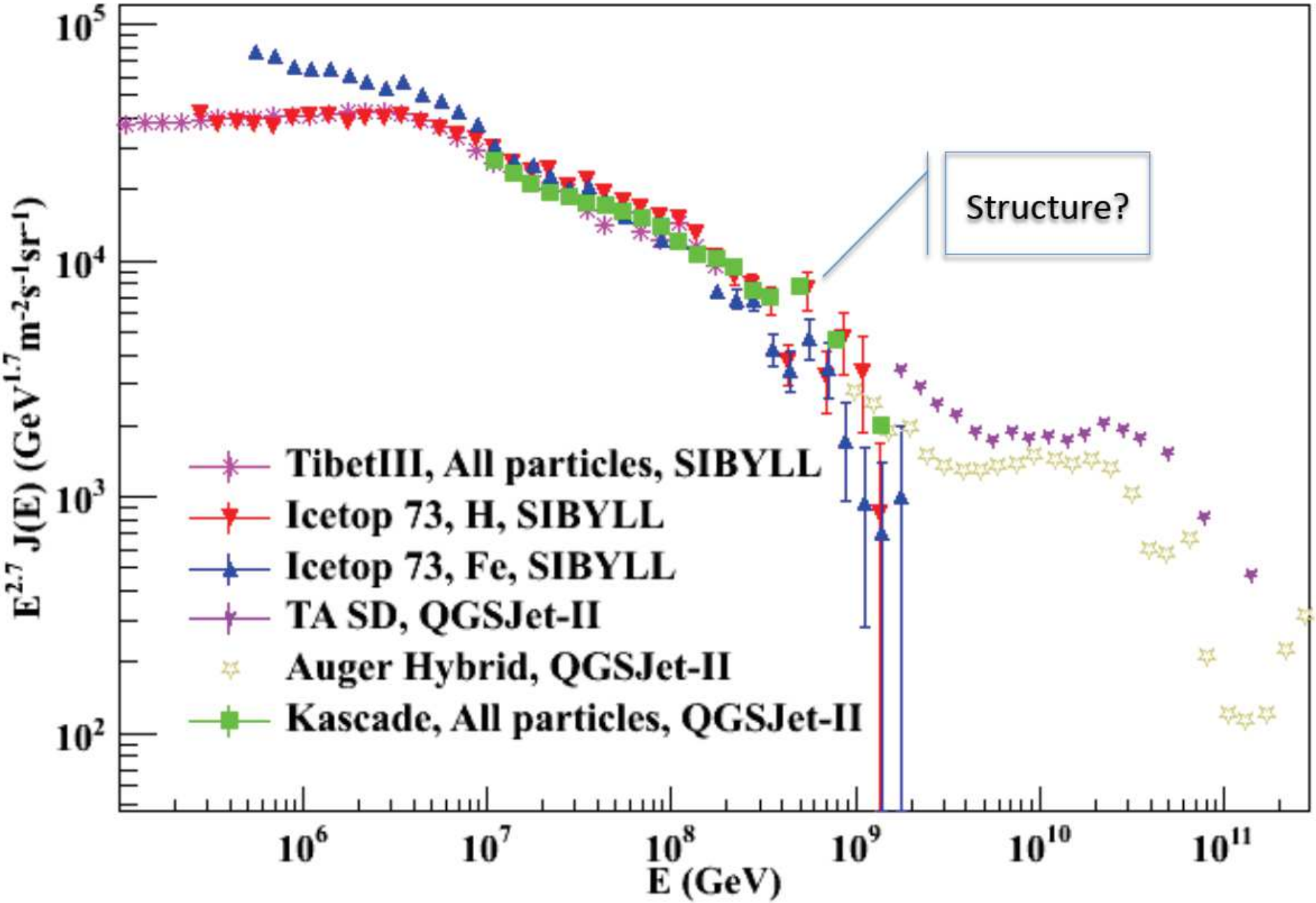
IceCube
ApJ 718 (2010) L194
ApJ 740 (2012) 16

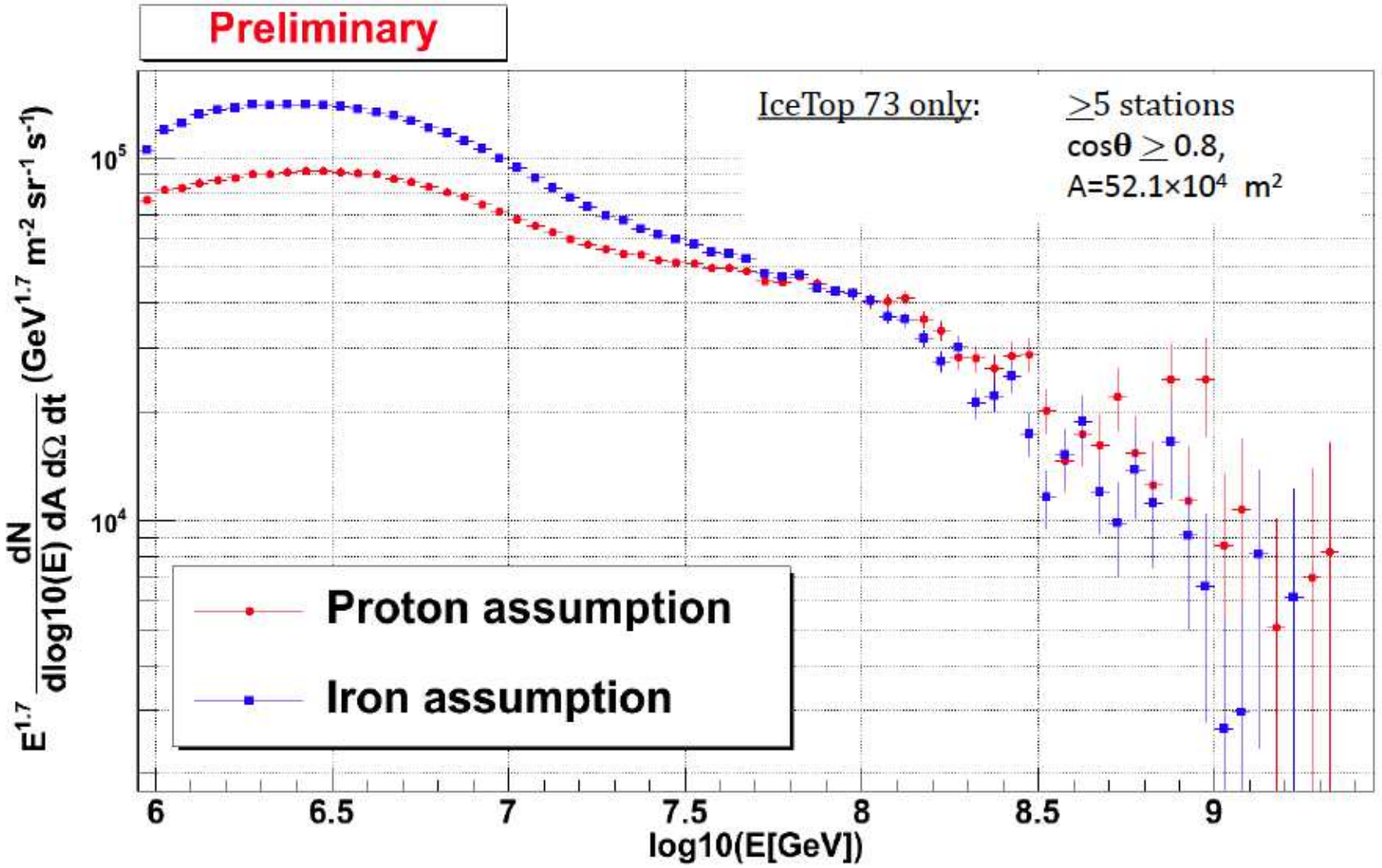
IceCube/IceTop
ApJ 746 (2012) 33

“diffusive” picture of nearby Galactic source(s)

the rare high energy particles at the end of the spectrum are produced by the closest source




10^5
10^4
10^3
10^2
$E^{2.7}$ J(E) (GeV$^{1.7}$m^{-2}s^{-1}sr^{-1})
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
10^6
10^7
10^8
10^9
10^{10}
10^{11}
E (GeV)

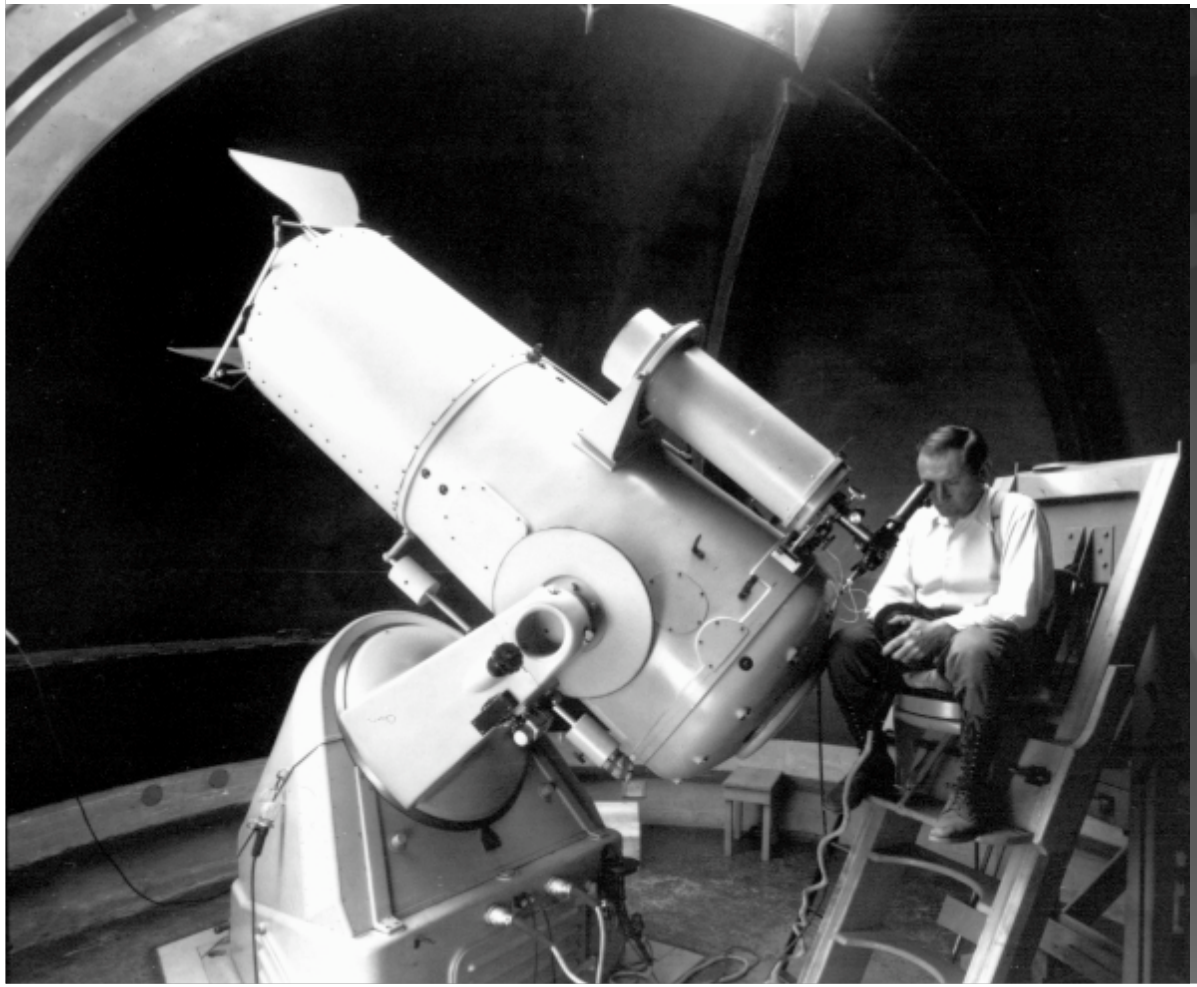

Preliminary
IceTop 73 only:
≥5 stations
cosθ ≥ 0.8,
A=52.1×10⁴ m²
Proton assumption
Iron assumption
E^1.7 dN / dlog10(E) dA dΩ dt (GeV^1.7 m^-2 sr^-1 s^-1)
log10(E[GeV])

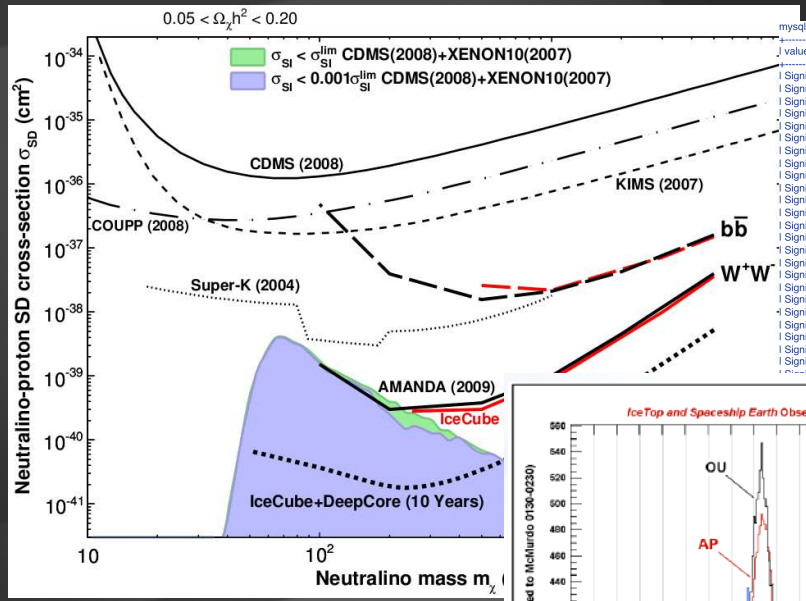
ON SUPER-NOVAE

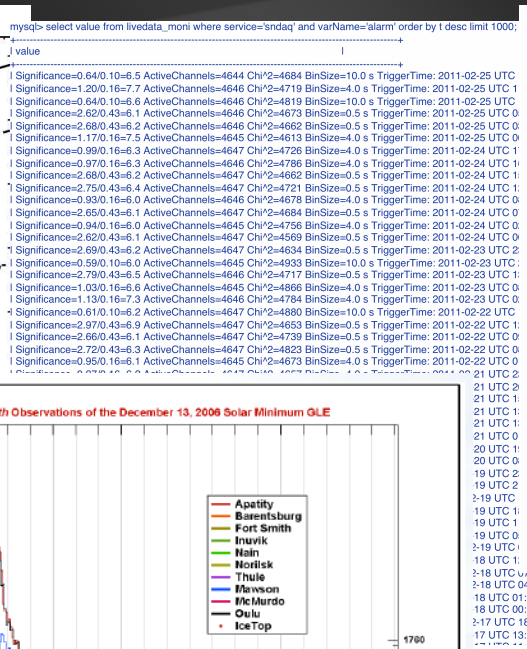
By W. Baade and F. Zwicky

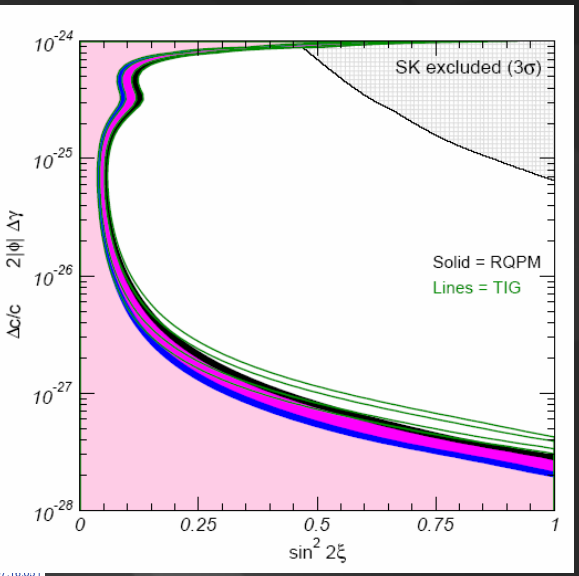
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

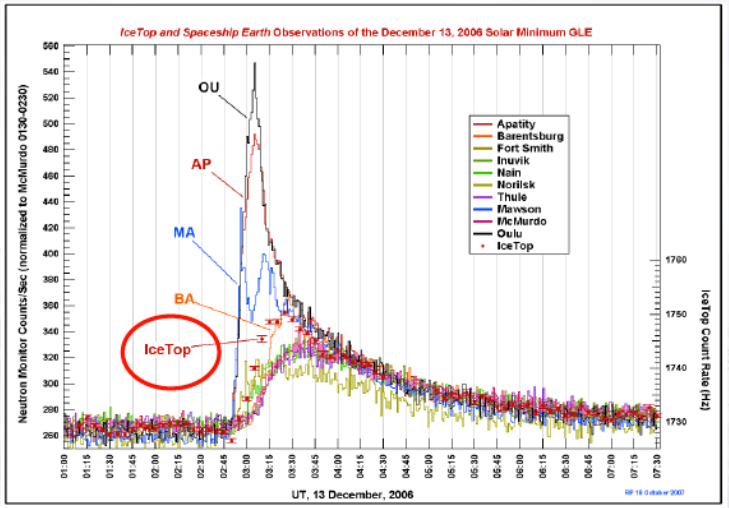
Communicated March 19, 1934

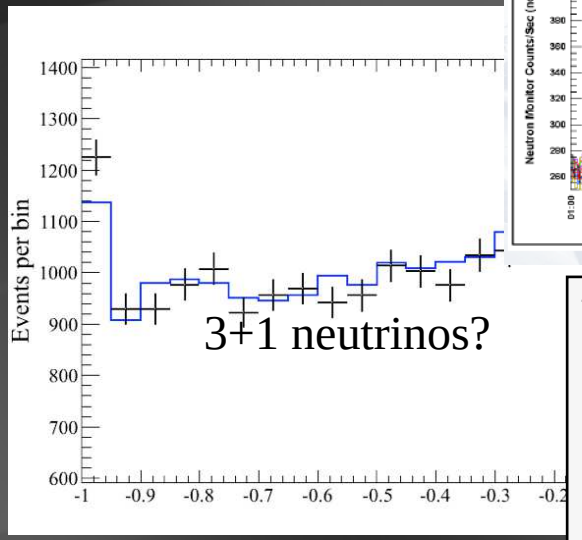


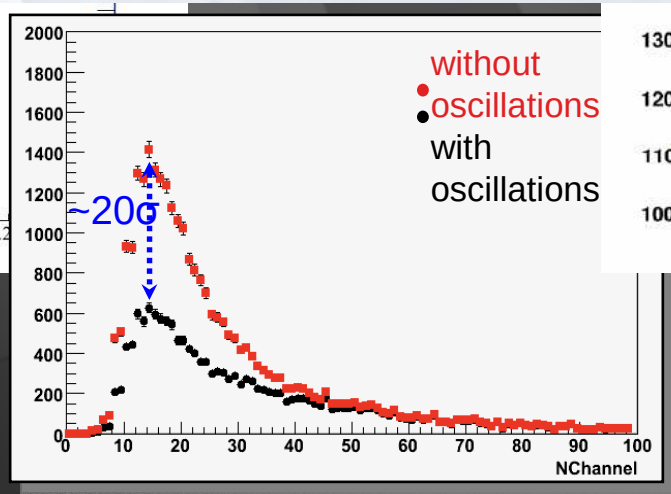


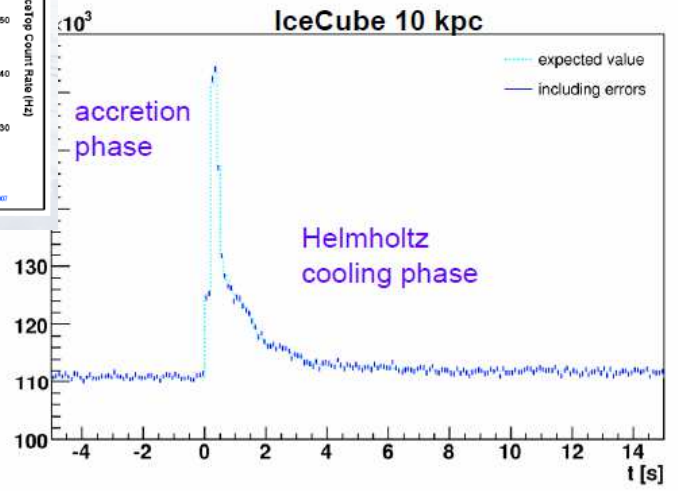












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Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)