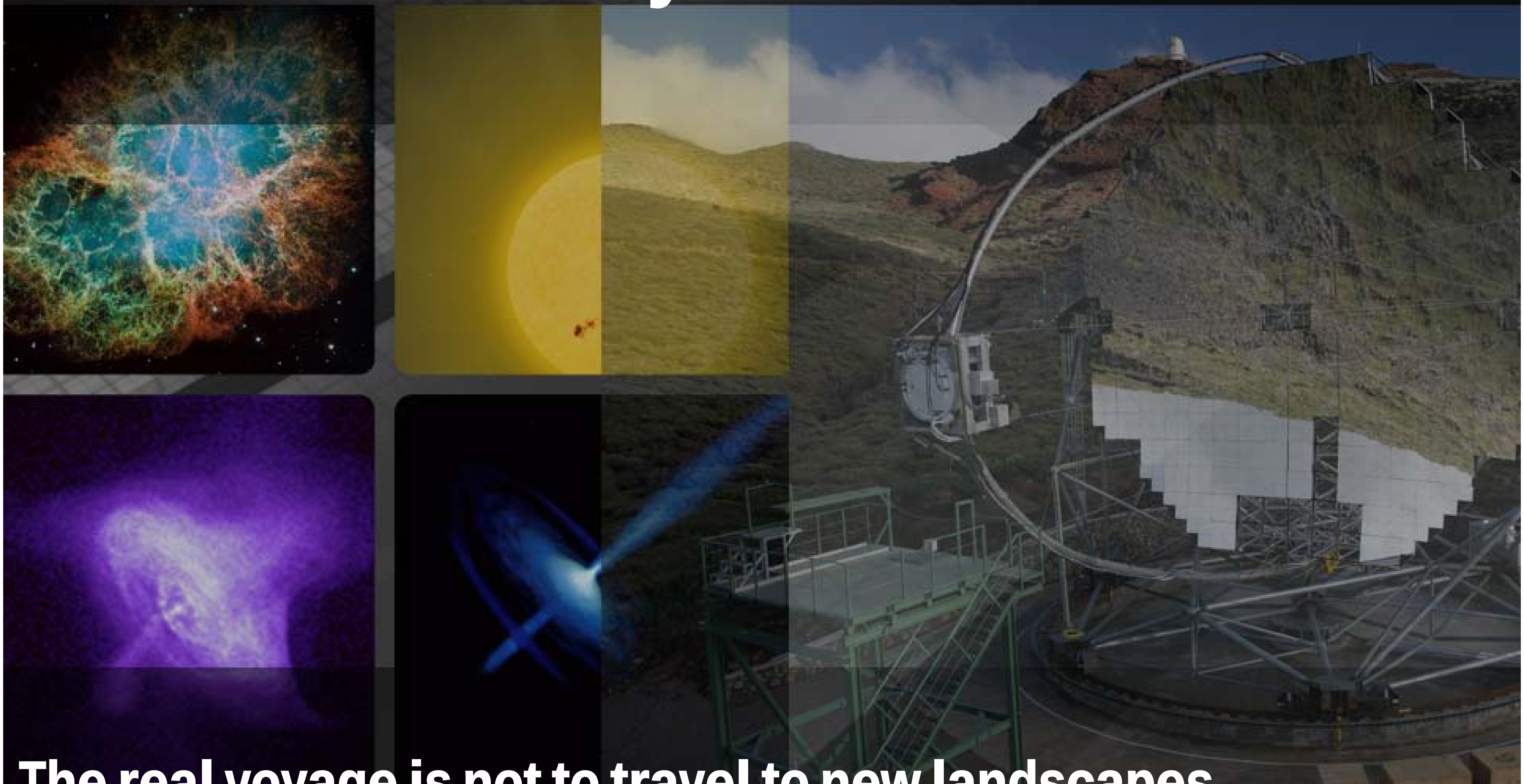
neutrino astronomy

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



The real voyage is not to travel to new landscapes,
but to see with new eyes. . .

Marcel Proust

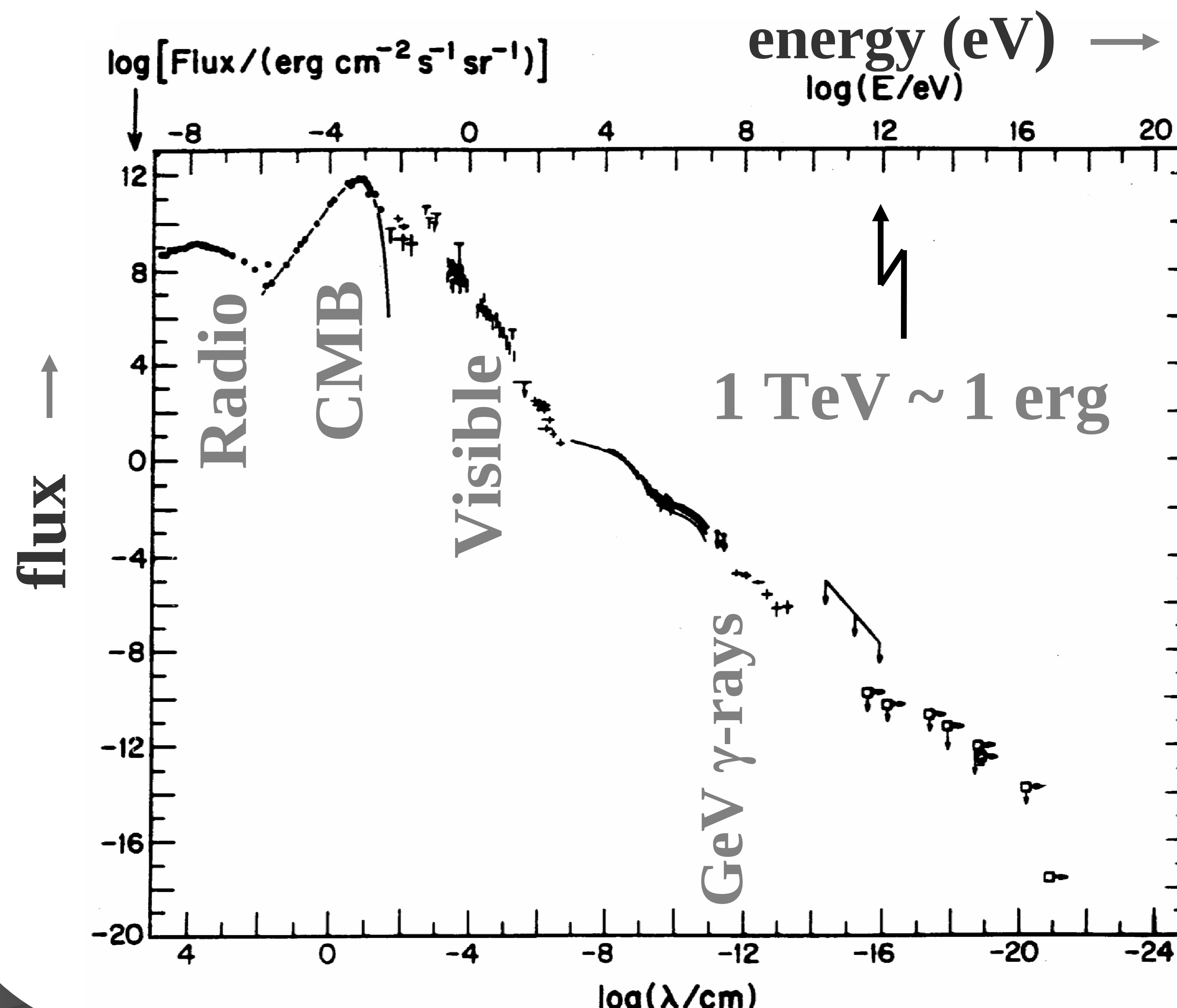
icebound neutrinos

francis halzen

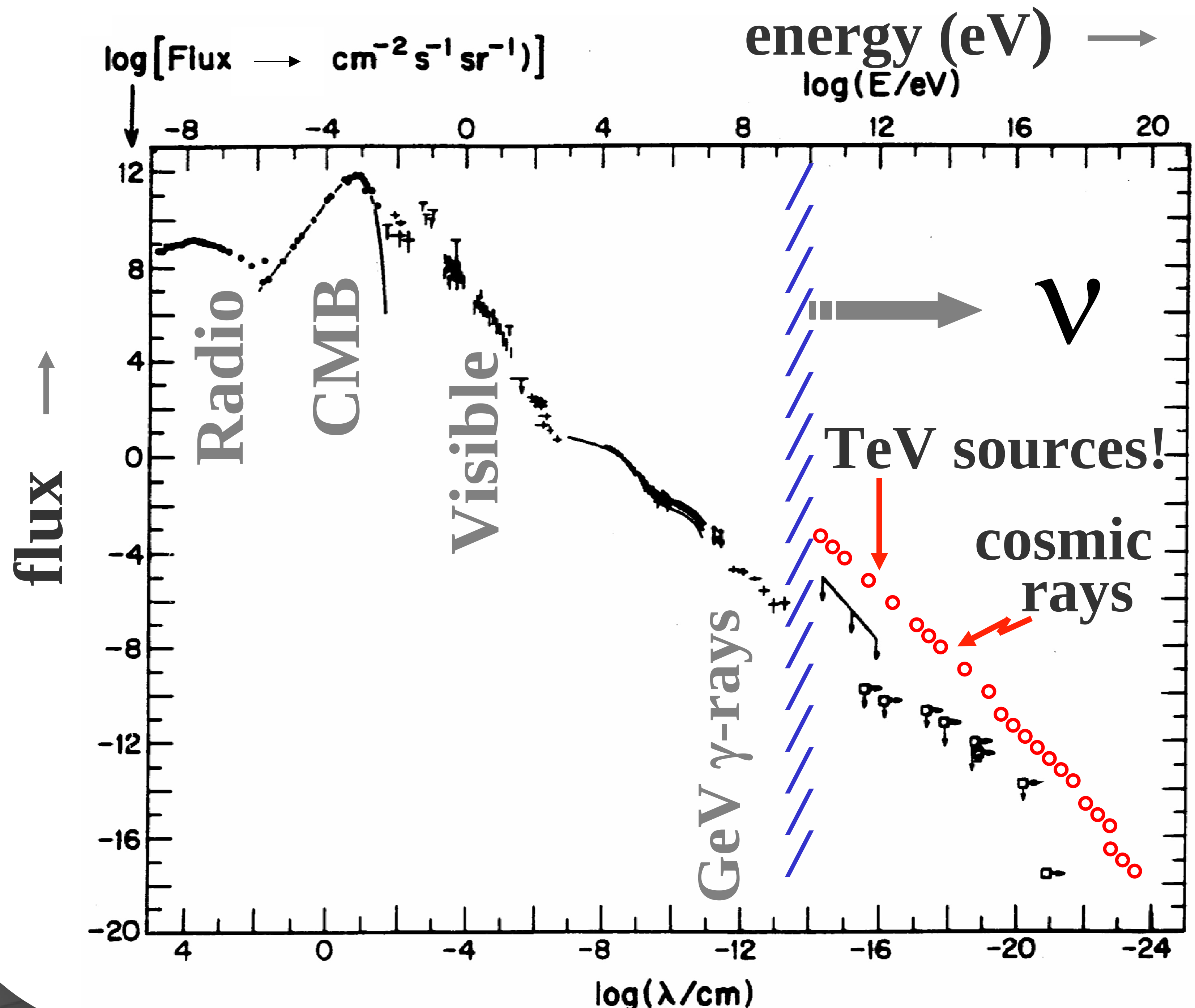
University of Wisconsin
http://icecube.wisc.edu

menu

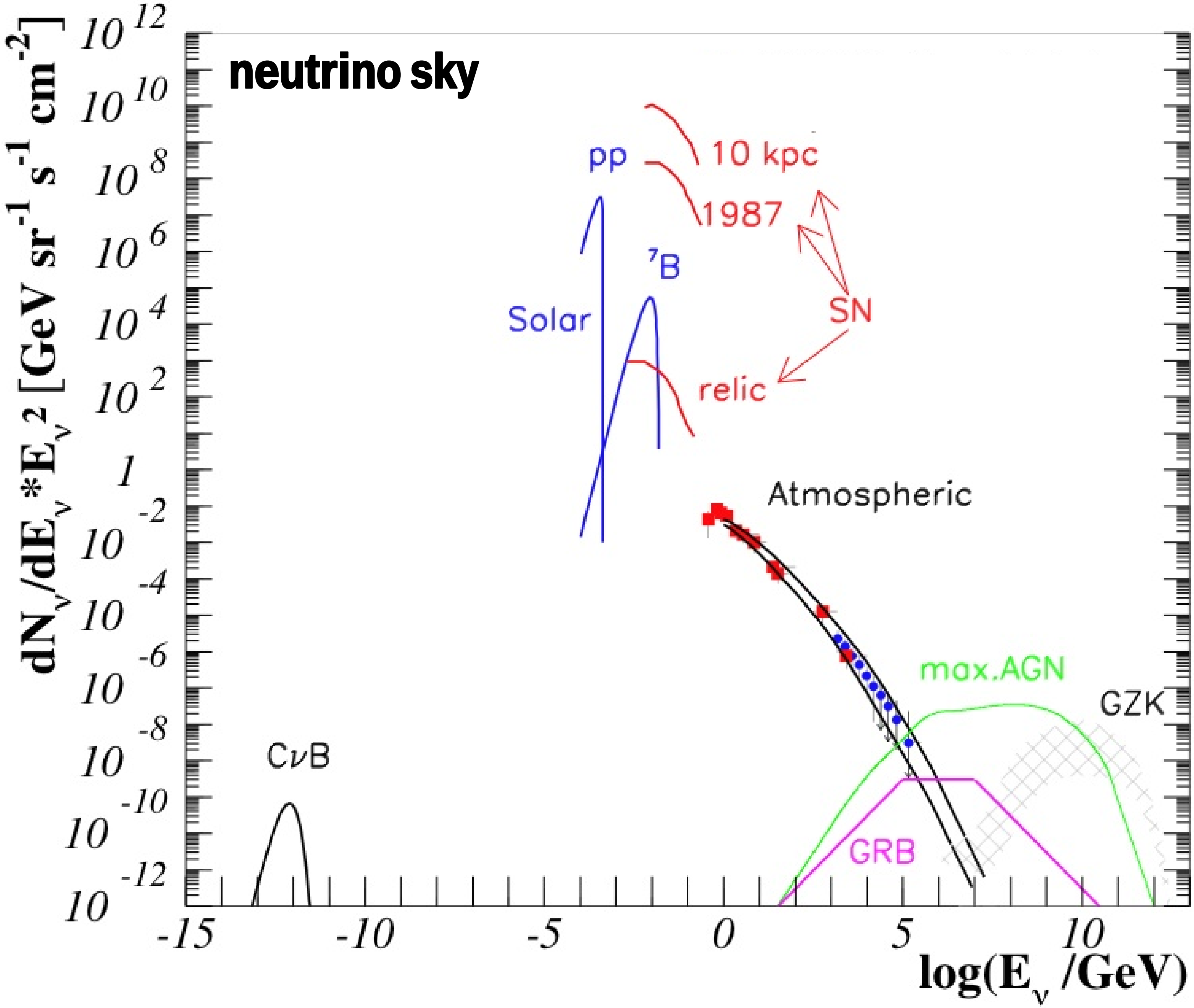
- introduction : it’s the technology
- cosmic neutrinos associated with cosmic rays
- cosmic neutrinos associated with TeV gamma rays
- progress through technology : first generation neutrino telescopes Antares and Amanda
- kilometer-scale neutrino detectors… now
- particle physics
- conclusions



energy (eV)
log(E/eV)
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
flux
Radio
CMB
Visible
GeV γ-rays
1 TeV ~ 1 erg
log(λ/cm)

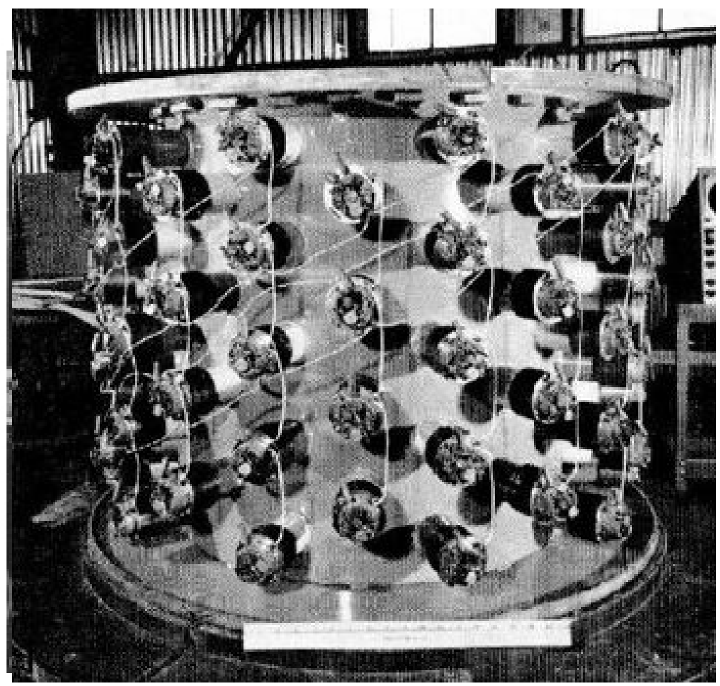


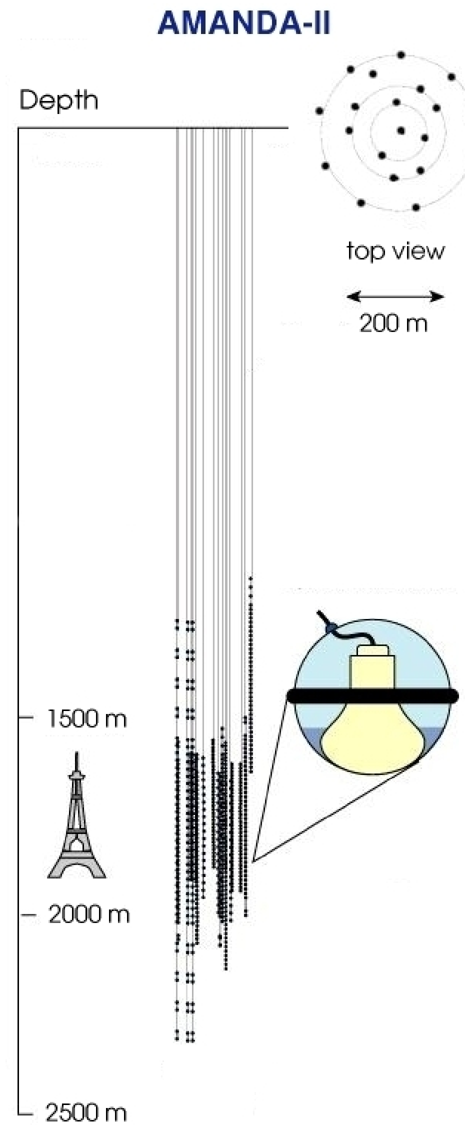
energy (eV)
log(E/eV)
log[Flux → cm^{-2} s^{-1} sr^{-1})]
flux
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources!
cosmic rays
log(λ/cm)



neutrino sky
pp
10 kpc
1987
7B
SN
Solar
relic
Atmospheric
max.AGN
GZK
CνB
GRB
dNν/dEν *Eν 2 [GeV sr-1 s-1 cm-2]
10 12
10 10
10 8
10 6
10 4
10 2
1
10 -2
10 -4
10 -6
10 -8
10 -10
10 -12
-15
-10
-5
0
5
10
log(Eν /GeV)

Requires Kilometer-Scale Neutrino Detectors





	favorite sources	possible science
*****	Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
***	GRB (successful and failed)	Sources of cosmic rays Test of Lorenz invariance Planck scale physics, quantum decoherence
**	AGN	Sources of cosmic rays
*	Starburst Galaxies	
****	Supernova remnants also, microquasars, magnetars, PWNe, binaries, unidentified EGRET sources, plane of the galaxy	Sources of galactic cosmic rays
****	Cosmic rays interacting with microwave photons	Identify sources of cosmic rays Neutrino cross section at EeV energy
	Dark Matter	Annihilation in the sun, mostly spin-dependent
*****	Cosmic rays interacting with the sun	Background to WIMP search
*****	Supernova explosion	Deleptonization, TeV emission, hierarchy, $\sin\theta_{13}$

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particle physics

Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
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astrophysics

Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
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fundamental symmetries

Atmospheric (~100,000 per year, up to 1000 TeV, charm ?)	Oscillations New neutrino interactions Tests of relativity and equivalence principle
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…. anything not on the previous 4 slides

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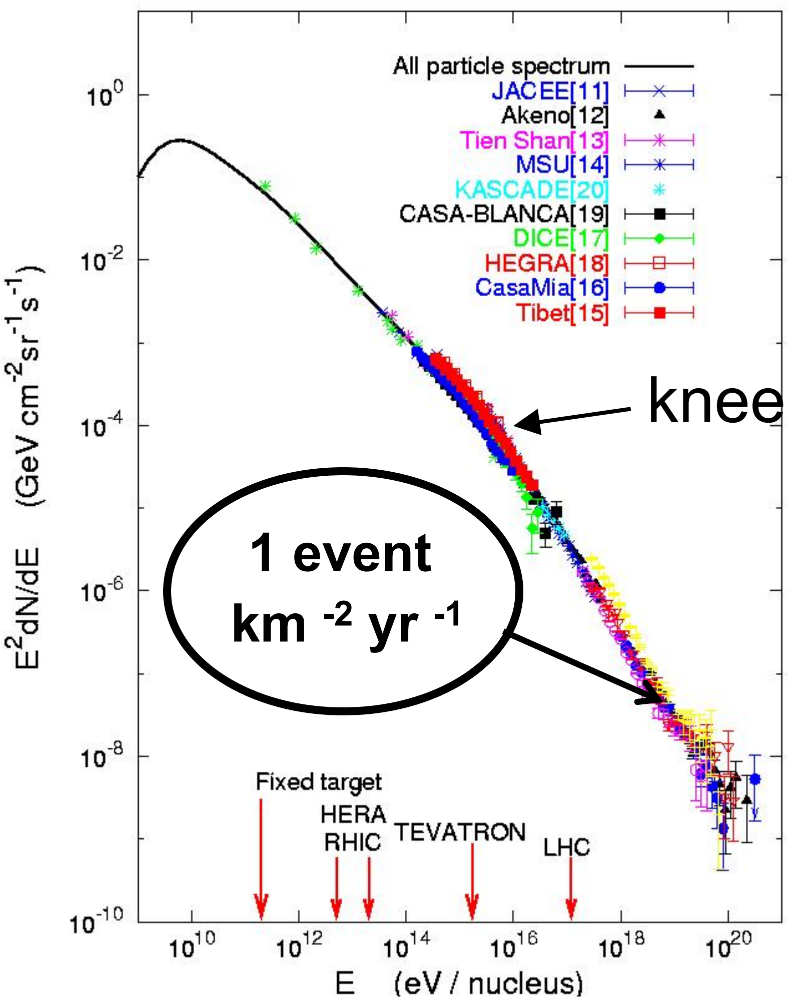
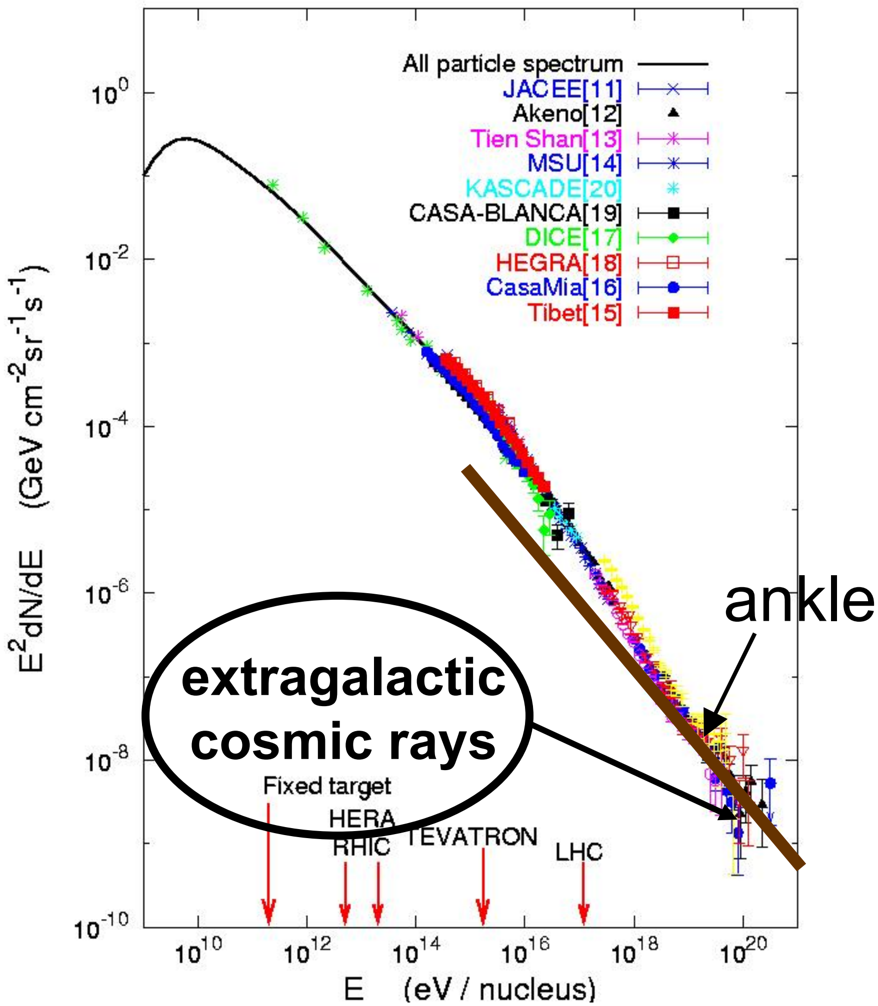
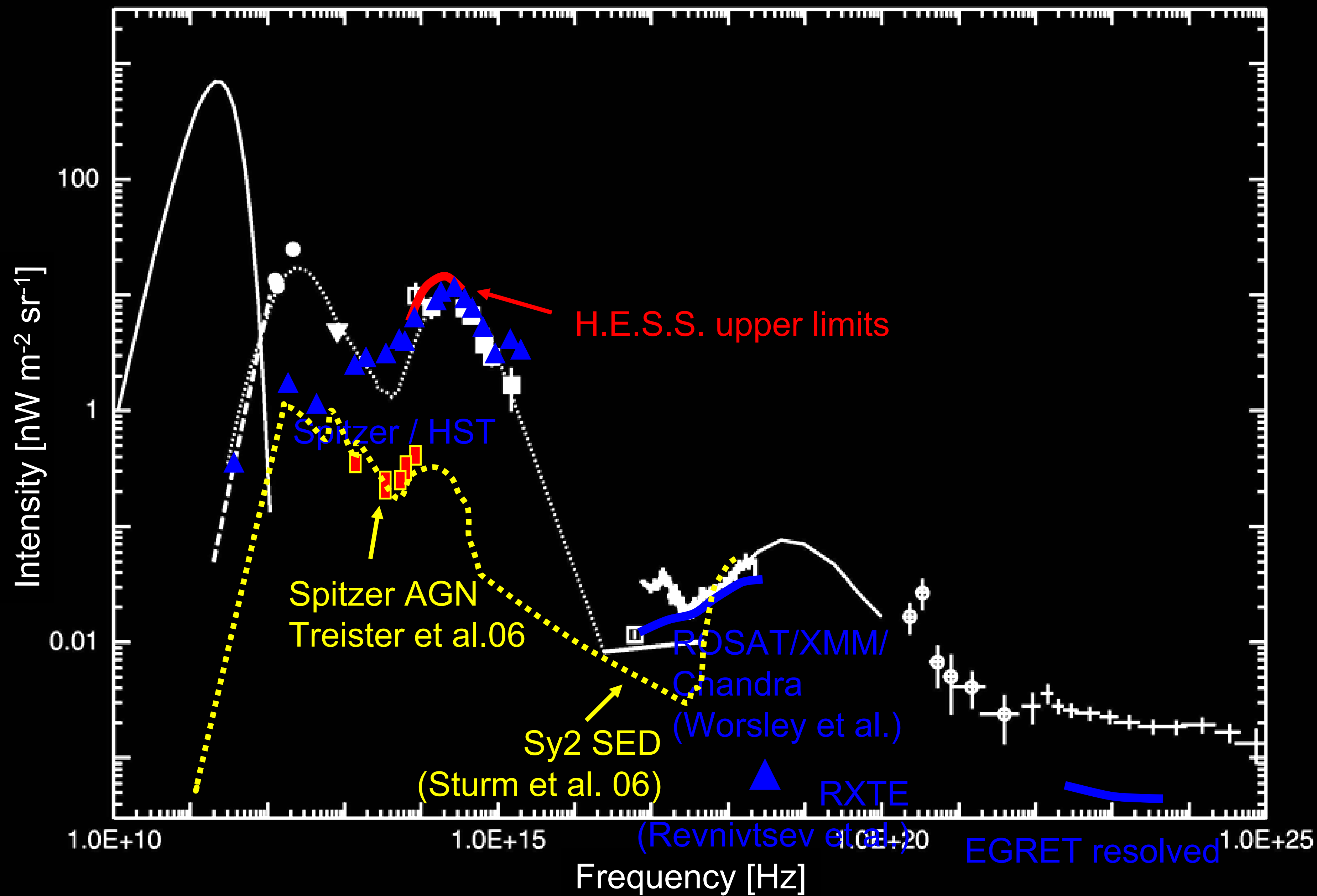
galactic and extragalactic cosmic rays





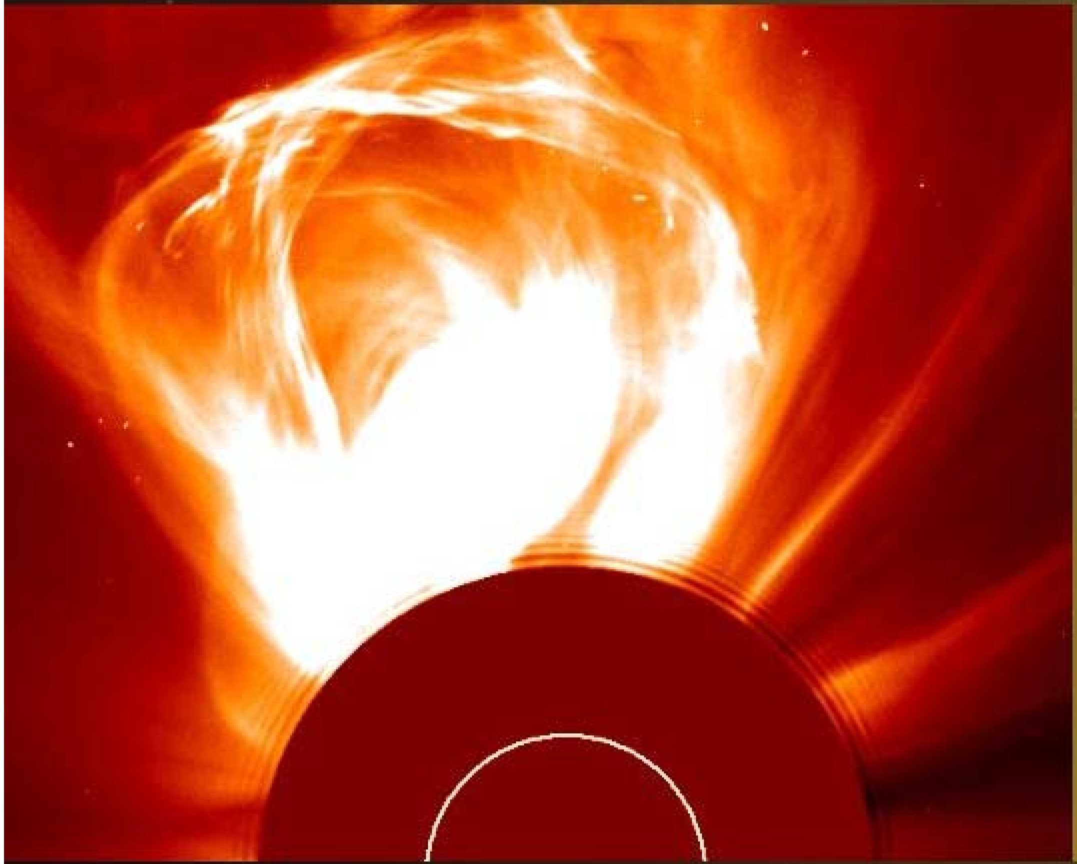
photon energy distribution



energy, not particle flux is the key !

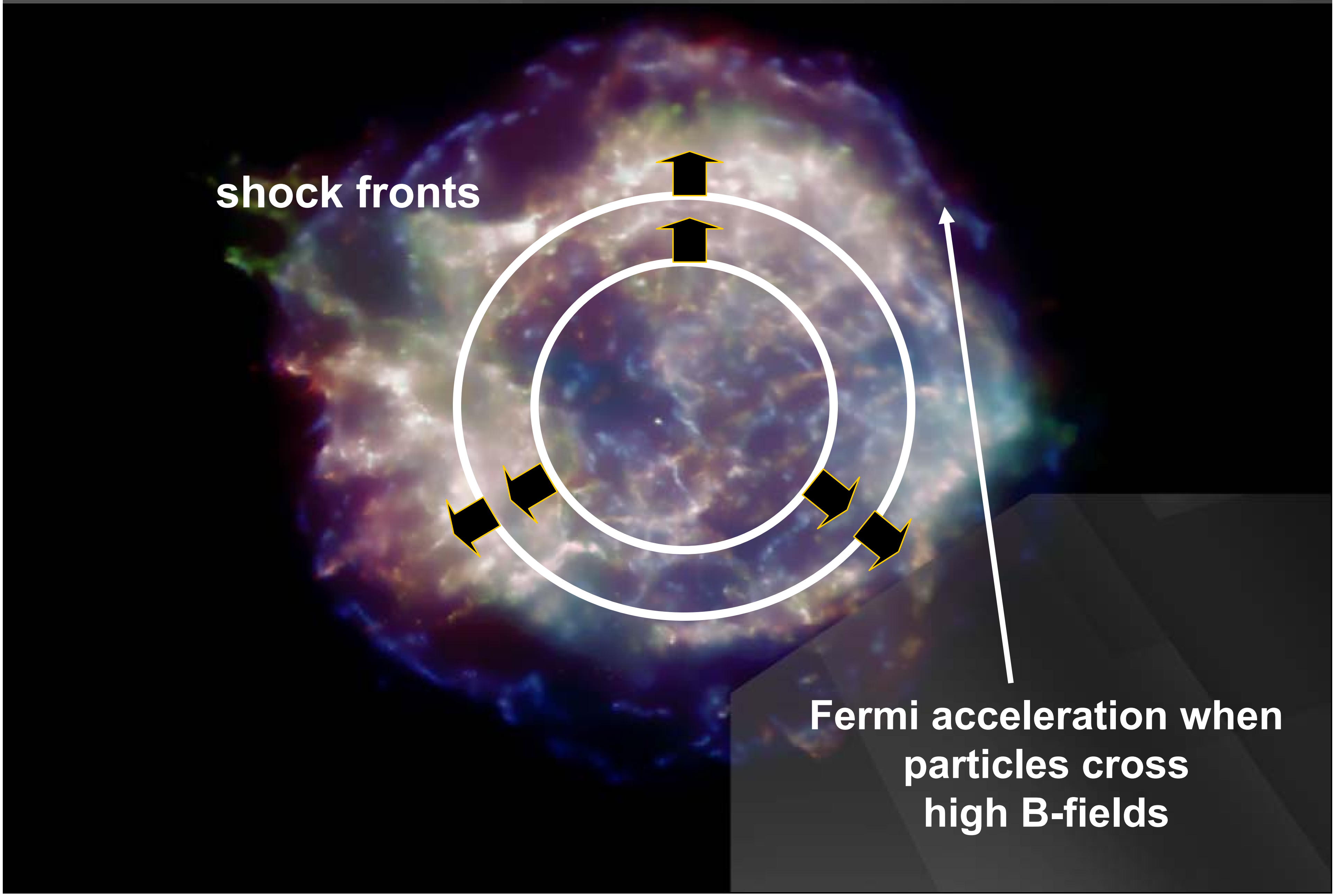
galactic cosmic rays

solar flare shock acceleration

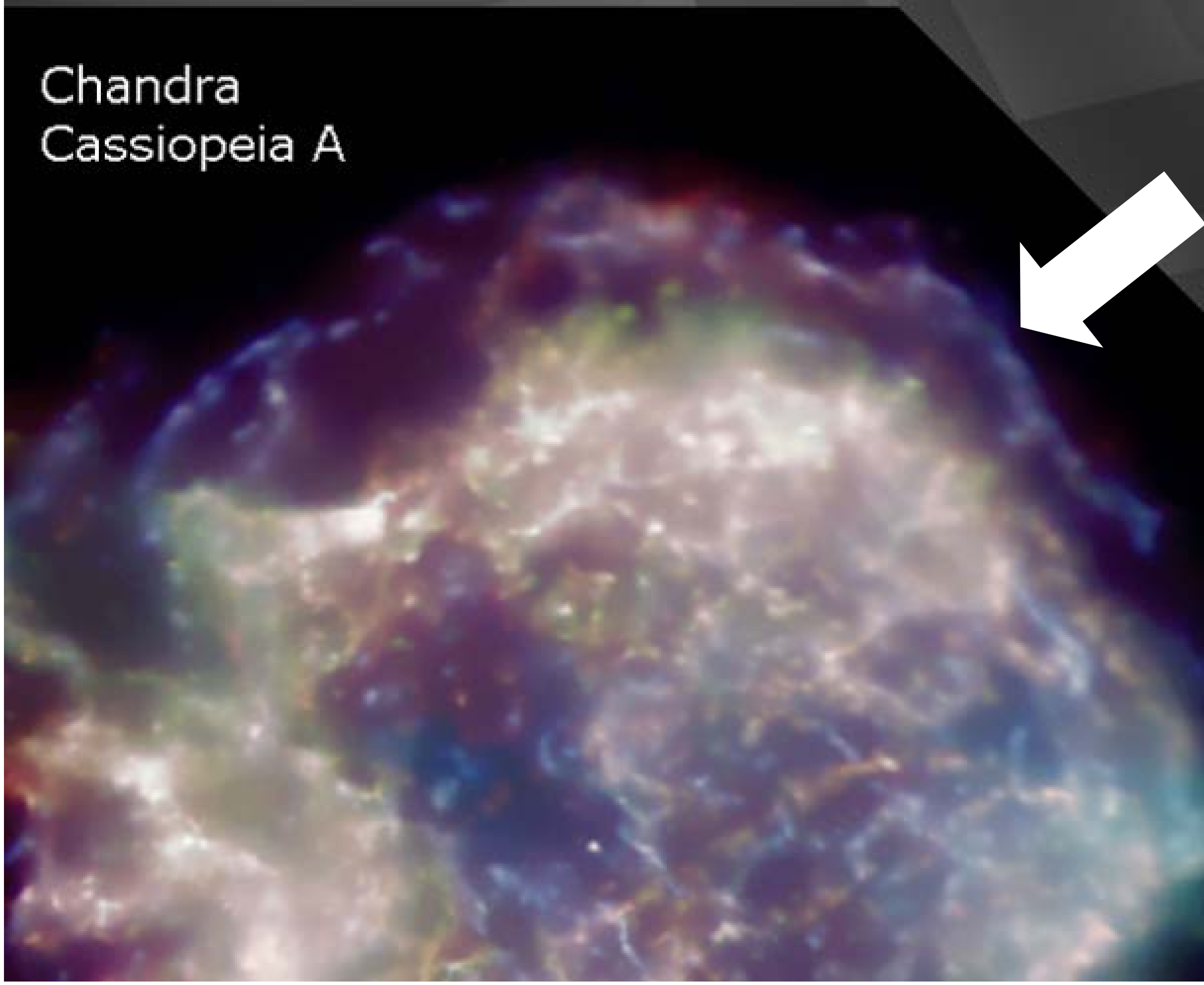


coronal
mass
ejection
→
10 GeV
particles

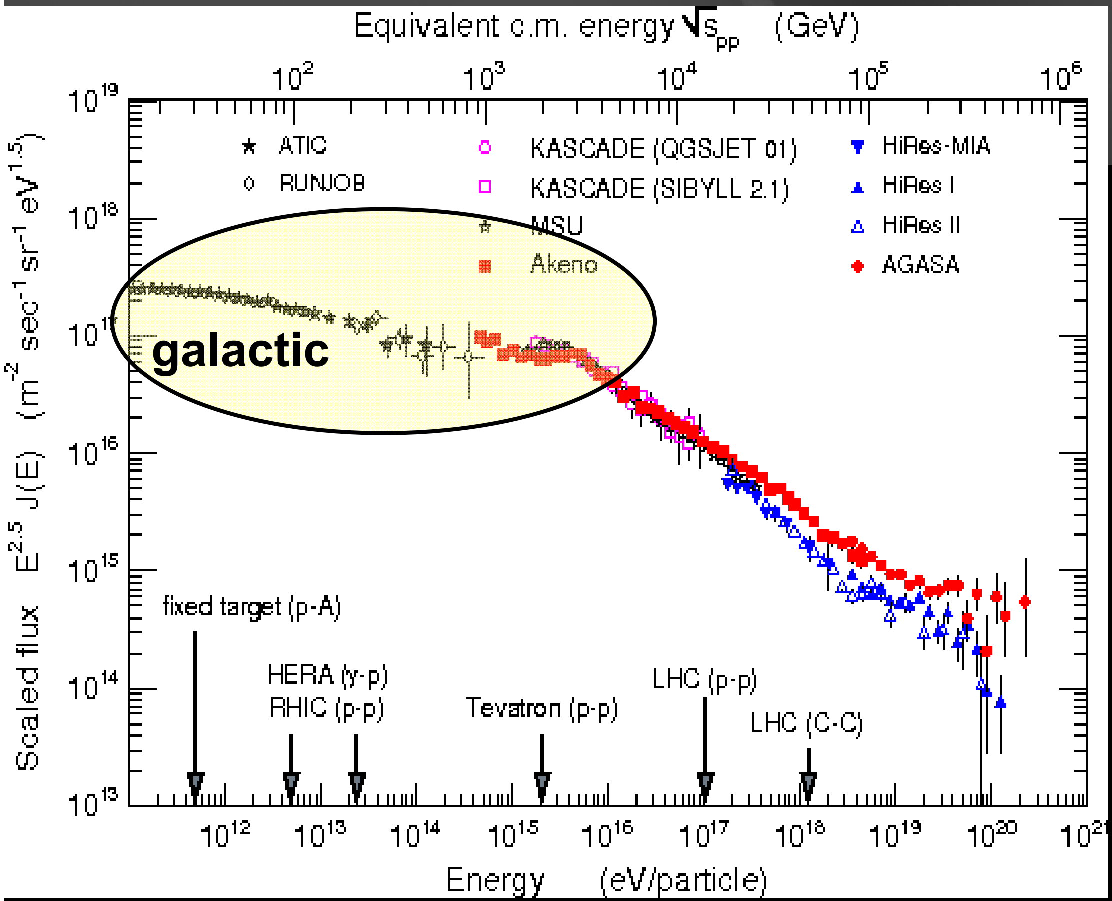
Cas A supernova remnant in X-rays



large magnetic field



Cosmic Rays & SNRs



observed energy density of galactic CR:

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

supernova remnants:

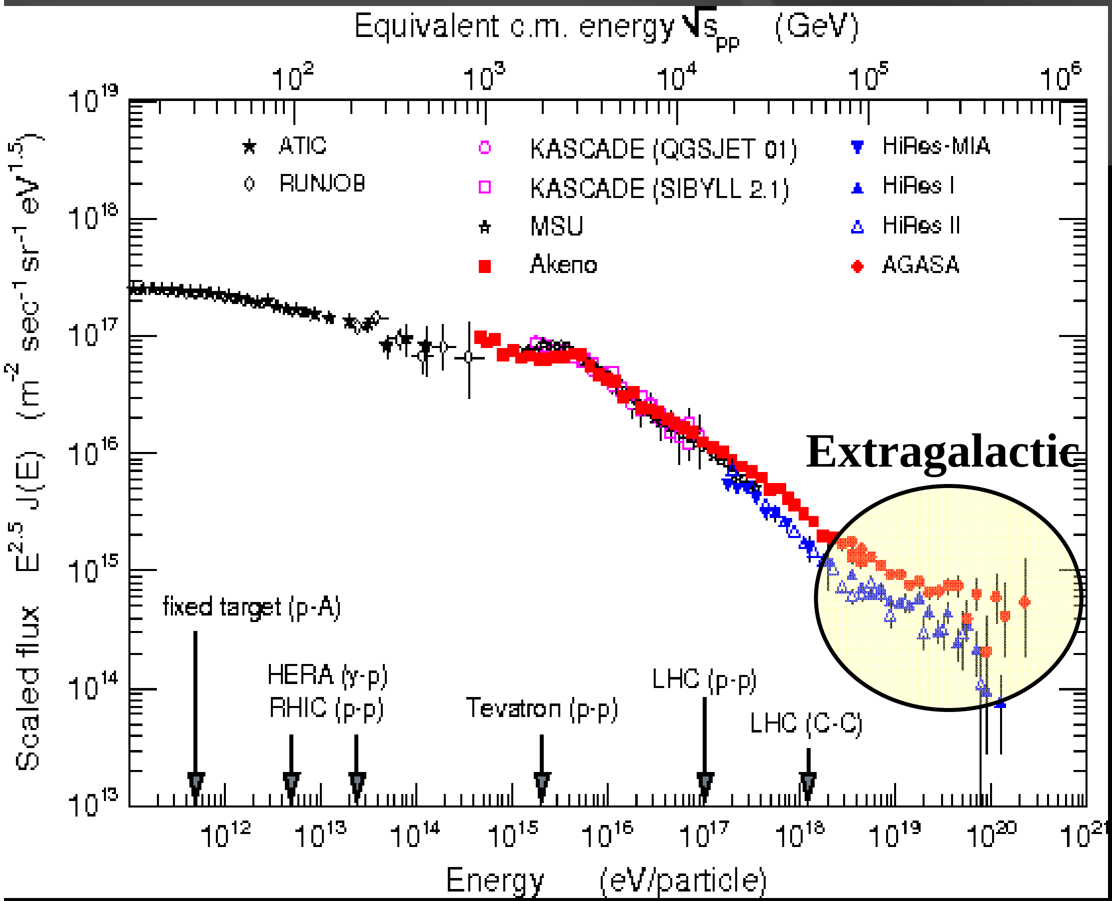
10^{50} ergs every 30 years

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

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

extragalactic cosmic rays

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

$\sim 10^{44}$ ergs/yr/Mpc^3

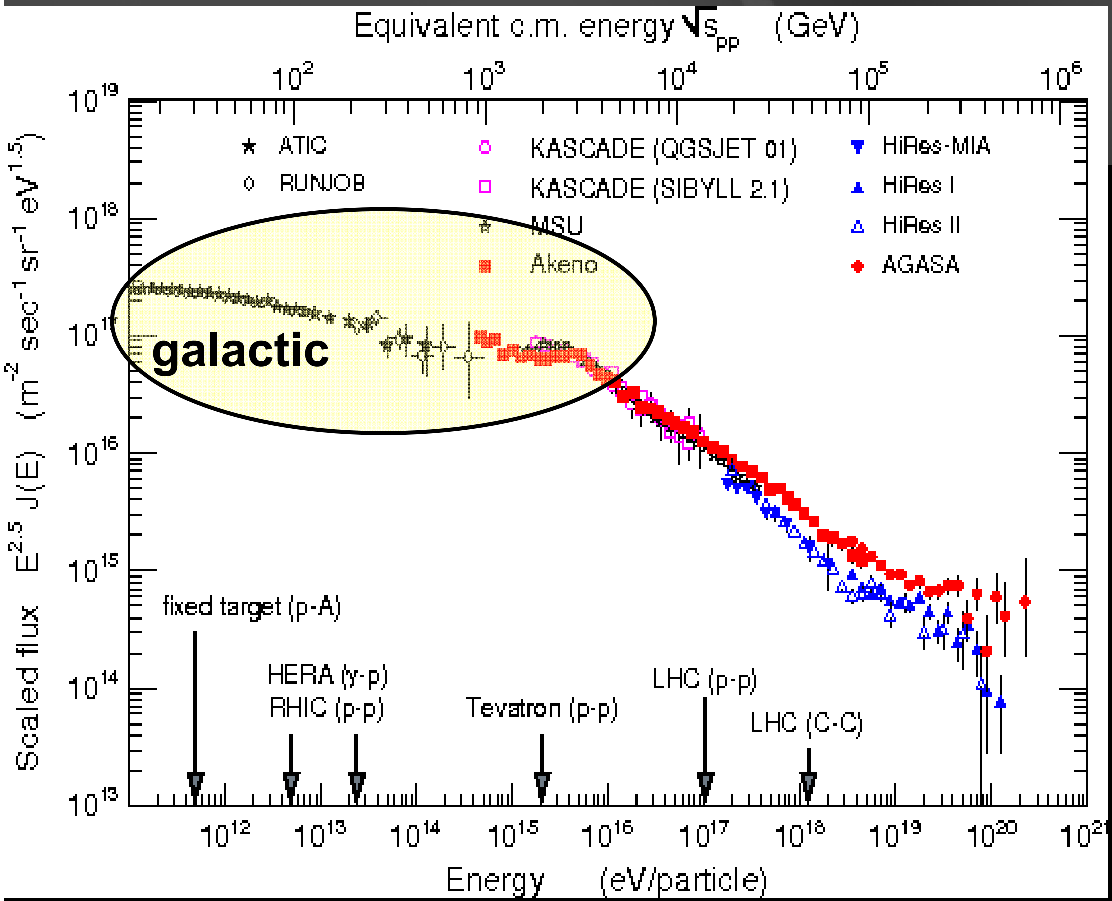
Gamma-Ray Bursts:

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

$\sim 10^{44}$ ergs/yr/Mpc^3

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

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

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

→ energy in extra-galactic cosmic rays

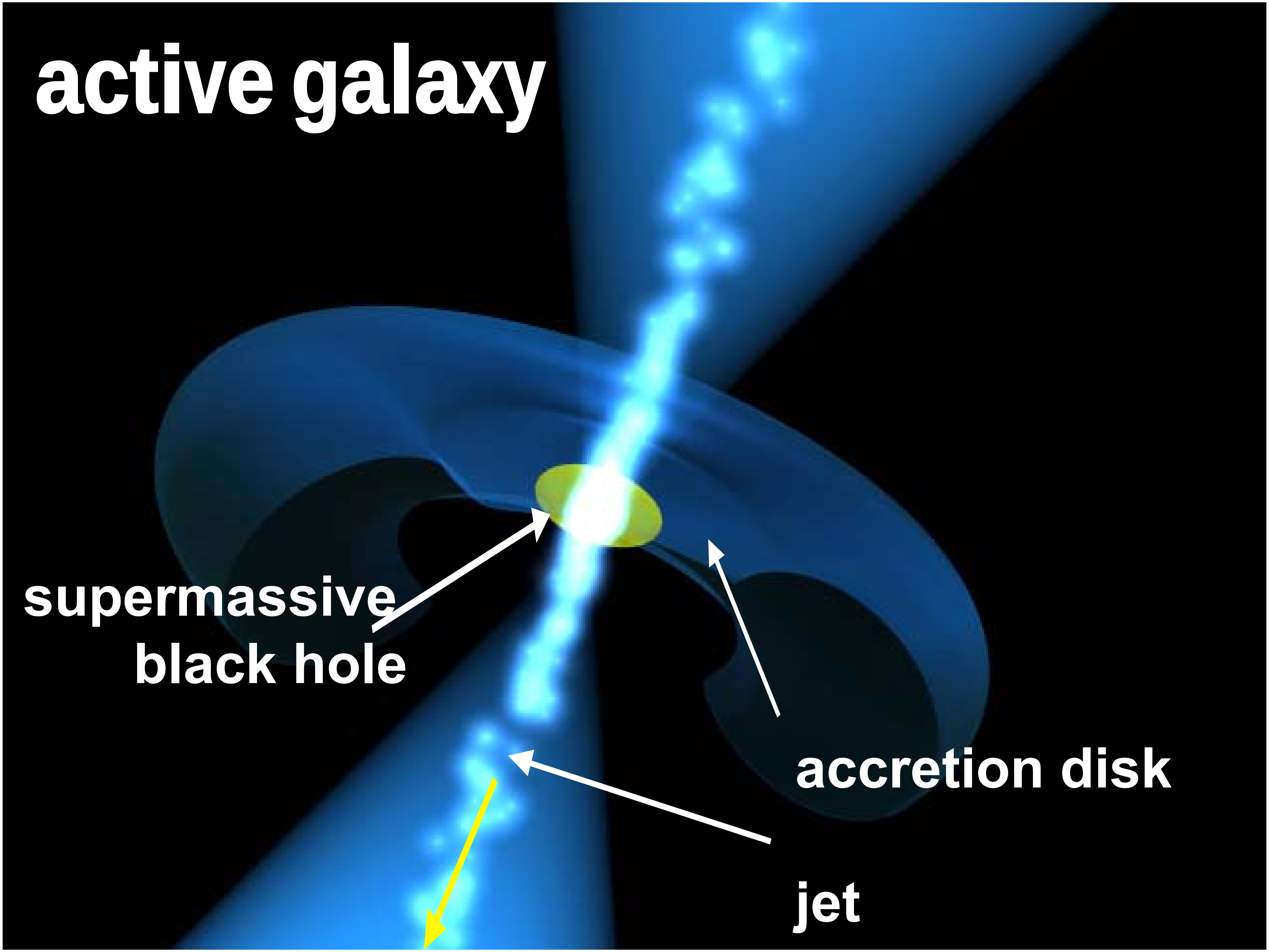
~ 3×10^{-19} erg/cm^3 or

~ 10^{44} erg/yr per (Mpc)^3 for 10^{10} years

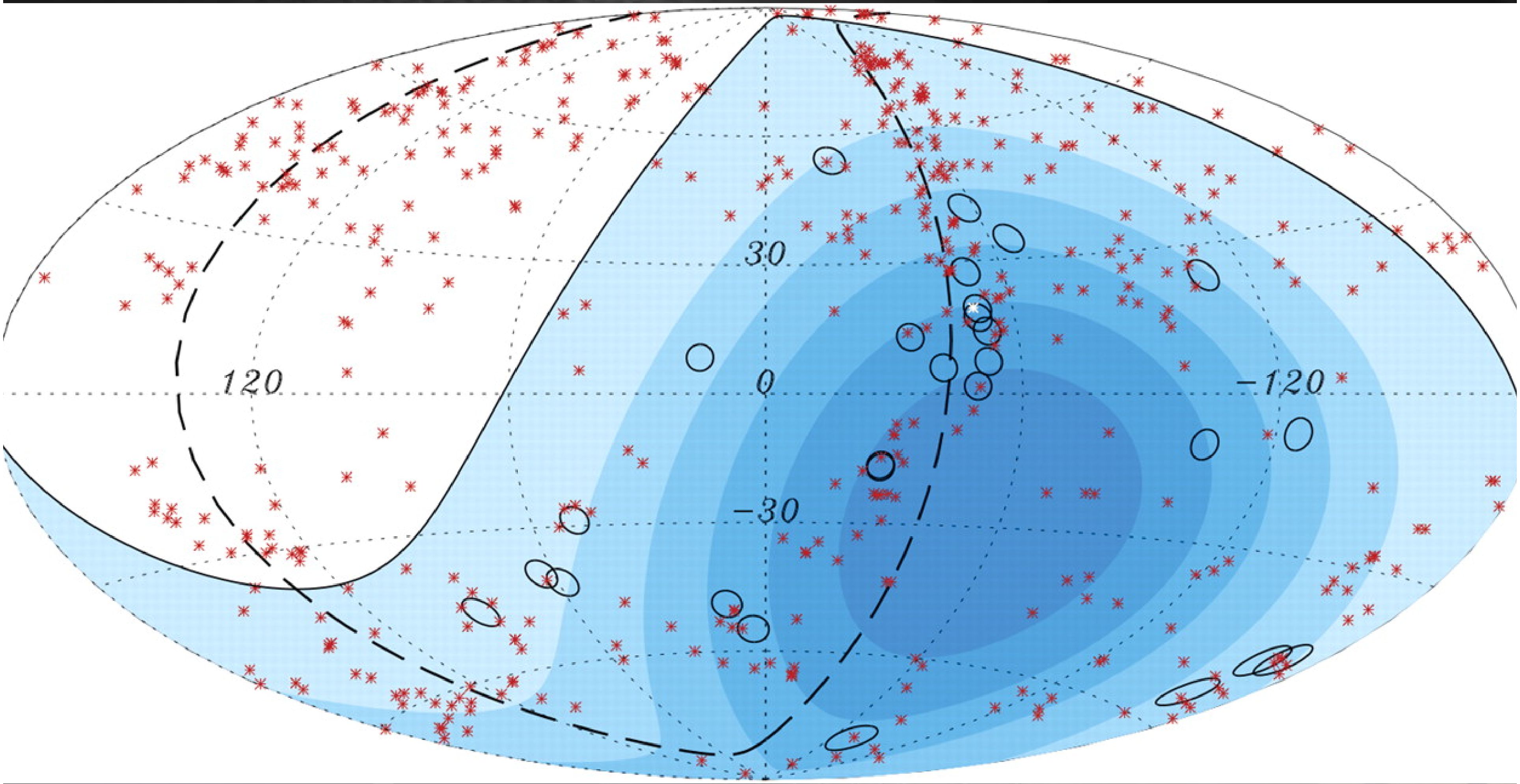
3×10^{44} erg/s per active galaxy !!!

2×10^{51} erg per gamma ray burst

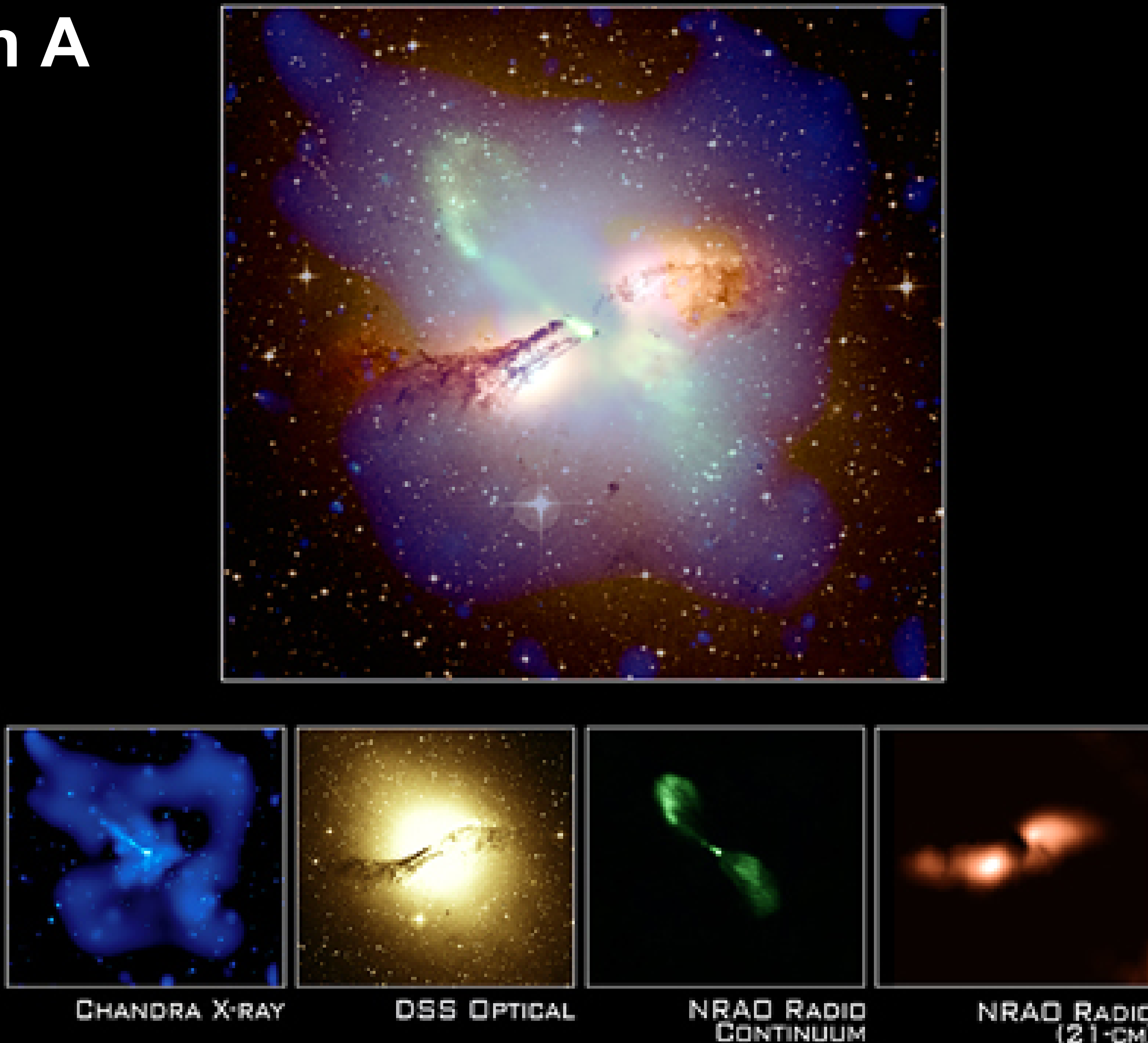
→ energy in cosmic rays ~ equal to the energy in light !


active galaxy
supermassive black hole
accretion disk
jet

Auger: the sources revealed



Cen A


CHANDRA X-RAY
DSS OPTICAL
NRAO RADIO CONTINUUM
NRAO RADIO (21-CM)

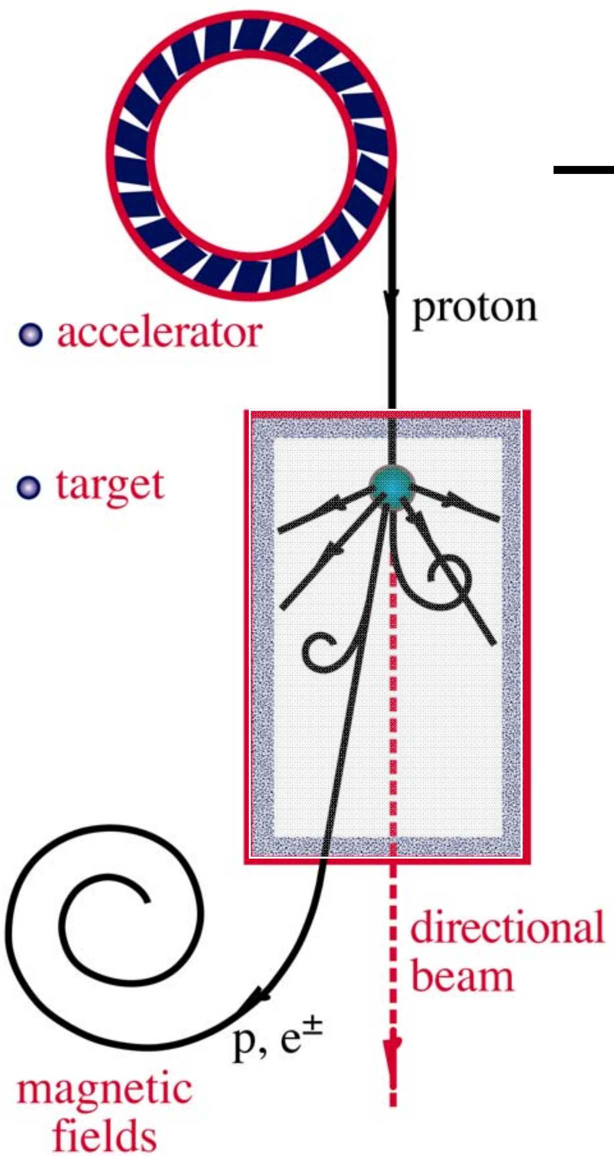
general energetics may be understood,
but accelerating particles to
energies in excess of

> 1000 TeV in galactic and

> 10^8 TeV for extragalactic

sources remains a challenge

NEUTRINO BEAMS: HEAVEN & EARTH



Black Hole

Radiation Enveloping Black Hole

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

→ energy in extra-galactic cosmic ray

~ 3×10^{-19} erg/cm^3 or
~ 10^{44} erg/yr per (Mpc)^3 for 10^{10} years

3×10^{44} erg/s per active galaxy
2×10^{52} erg per gamma ray burst

energy in→

cosmic rays ~ photons ~ neutrinos

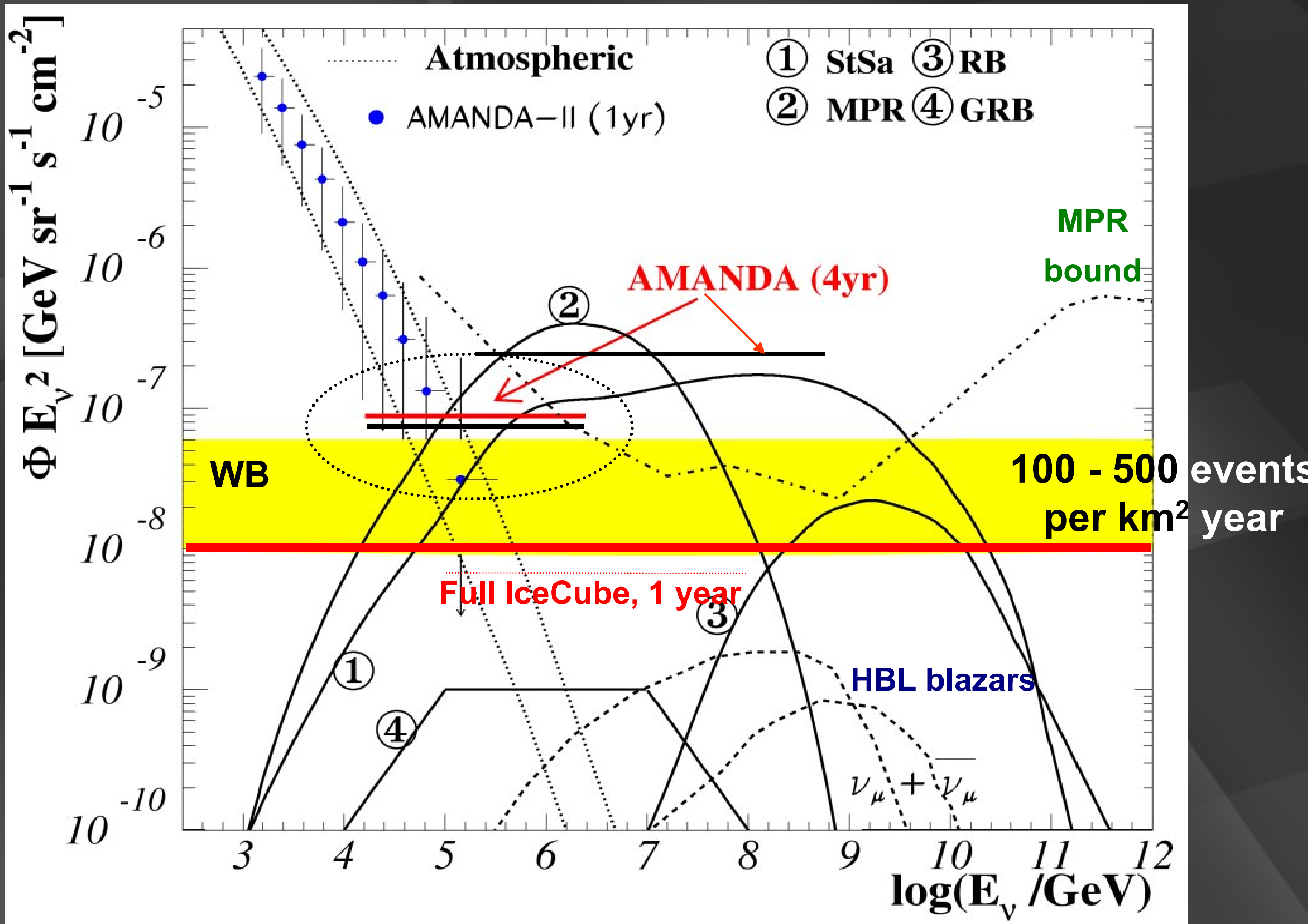
flux of neutrinos is roughly equal to the flux of extra-galactic cosmic rays

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

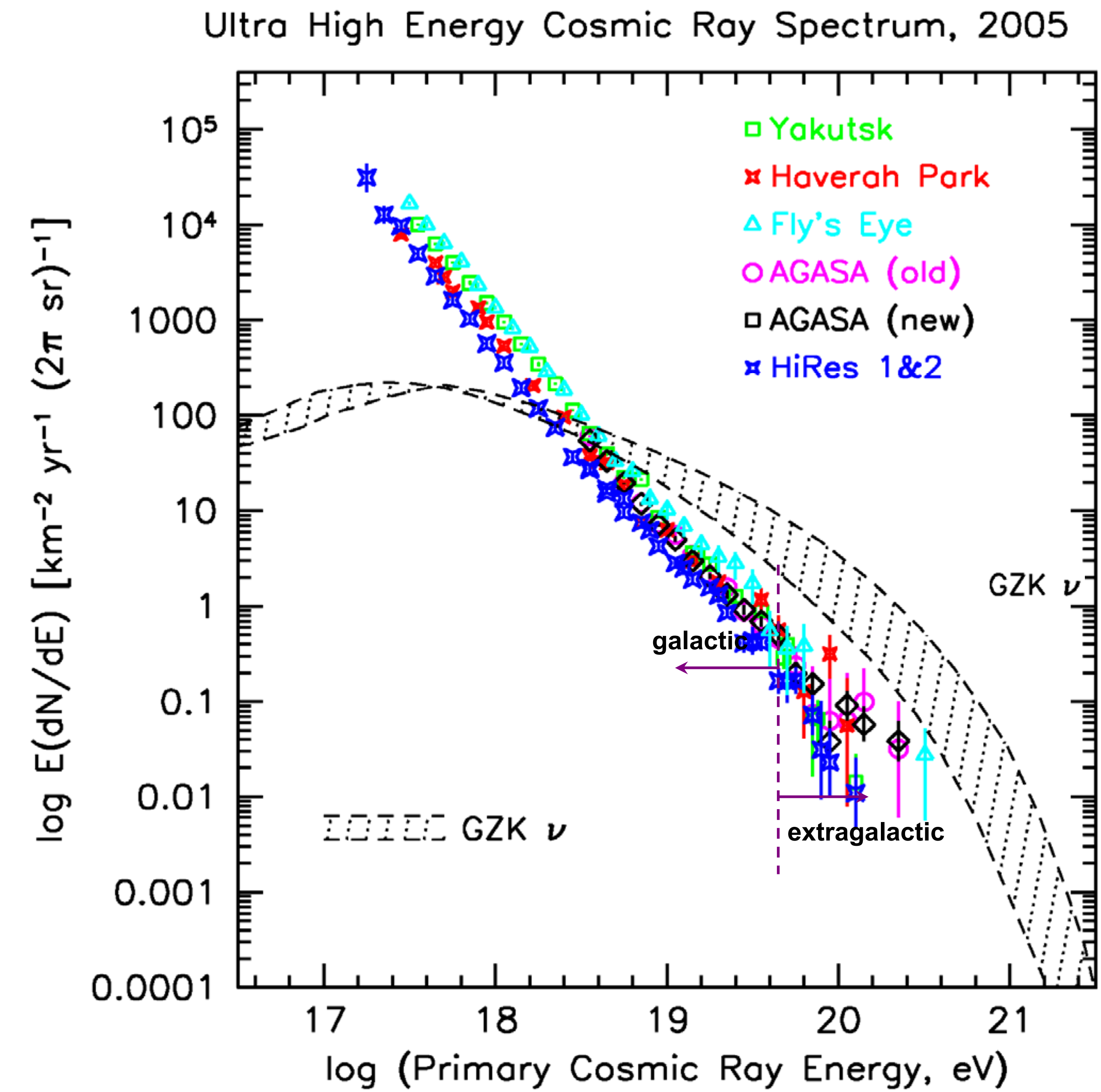
$$E^2 \frac{dN}{dE} = \frac{10^{19}\, eV}{(10^{10}\, cm^2)(3 \times 10^7\ sec)\ sr}$$

$$= 3 \times 10^{-8}\ GeV\ cm^{-2}\ sec^{-1}\ sr^{-1}$$

diffuse muon neutrino flux



neutrinos from GZK interactions



cosmic rays interact with the microwave background

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

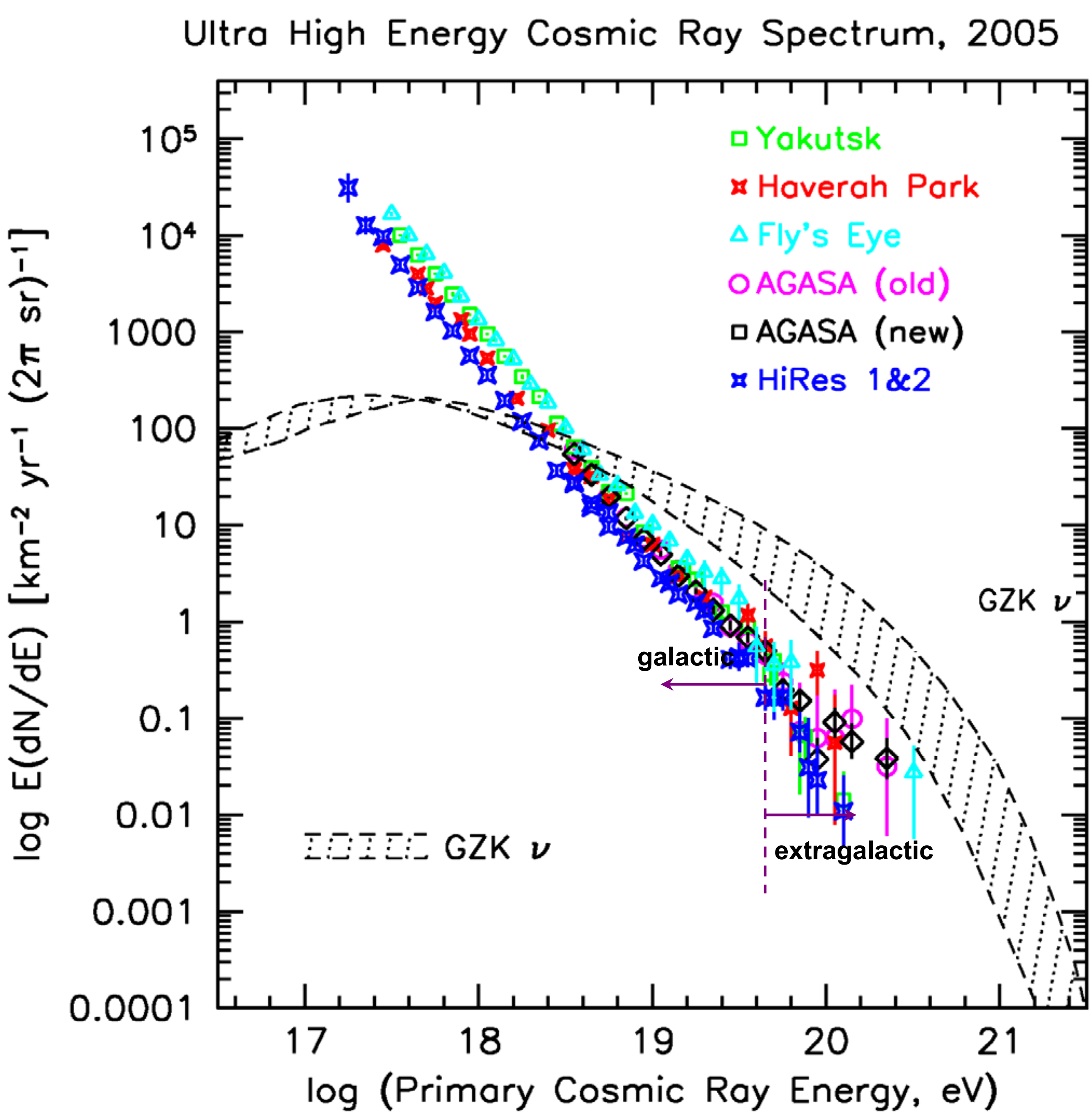
cosmic rays disappear, neutrinos appear

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

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

~ 1 event per kilometer squared per year

neutrinos from GZK interactions



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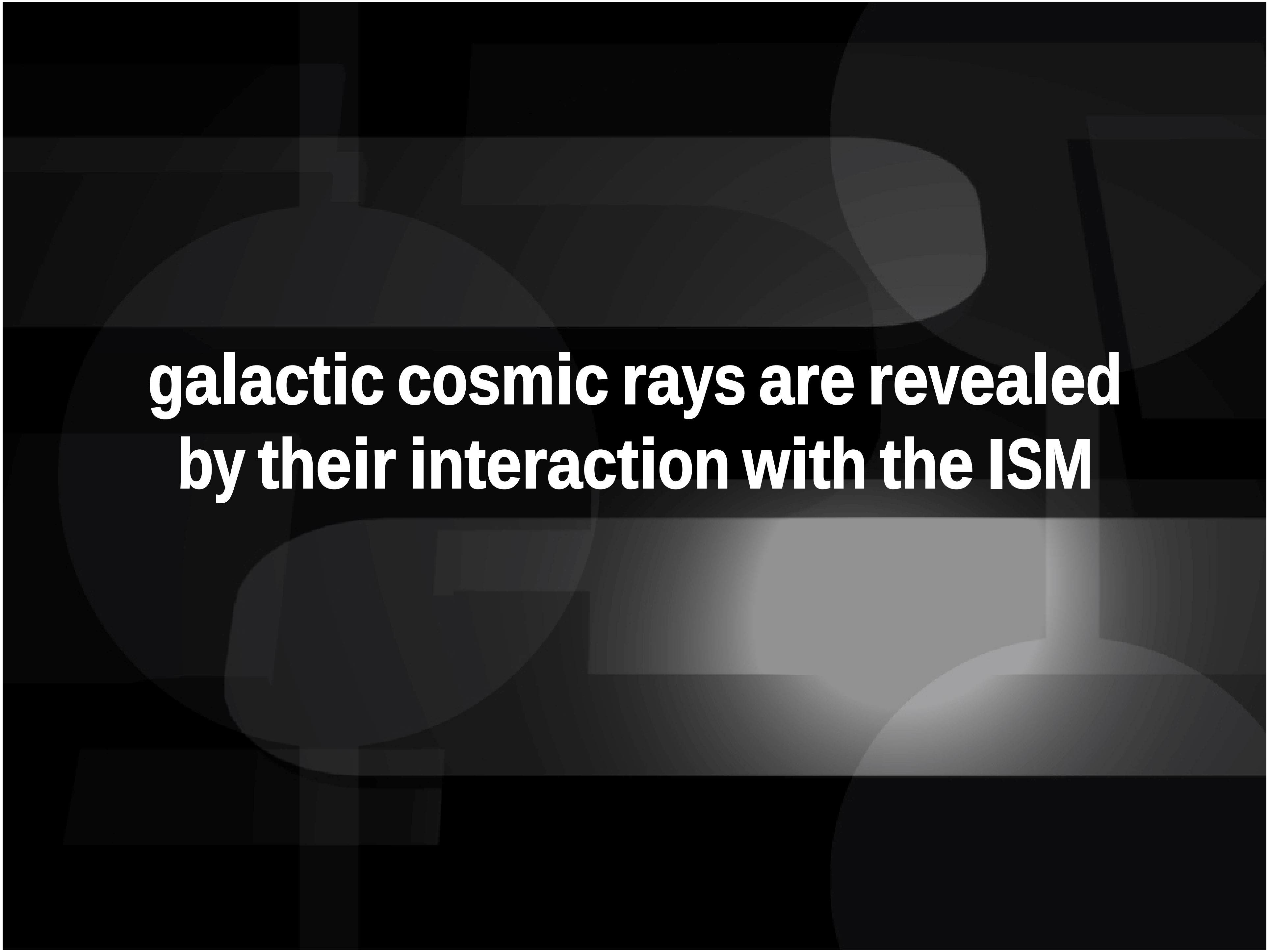
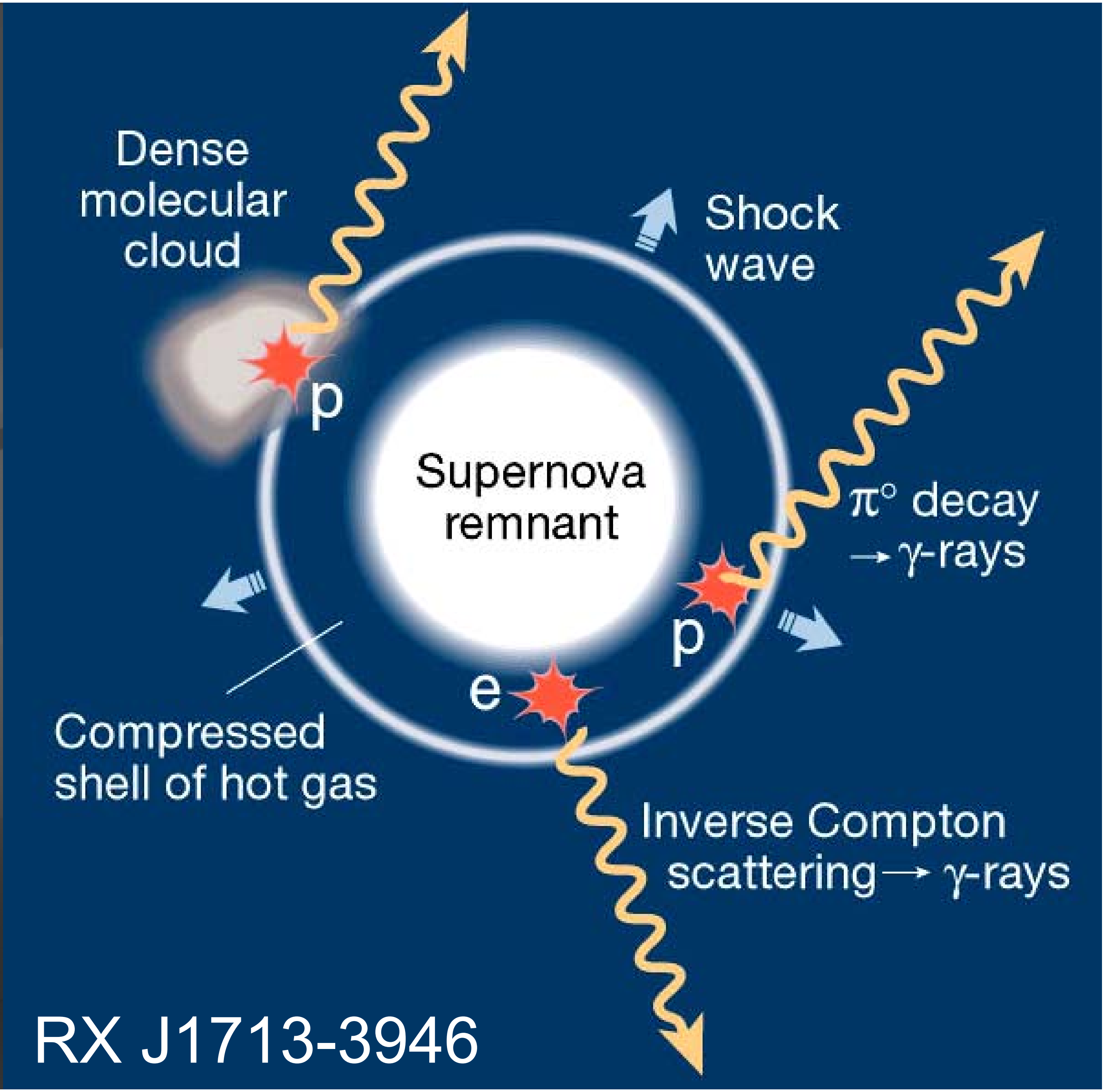
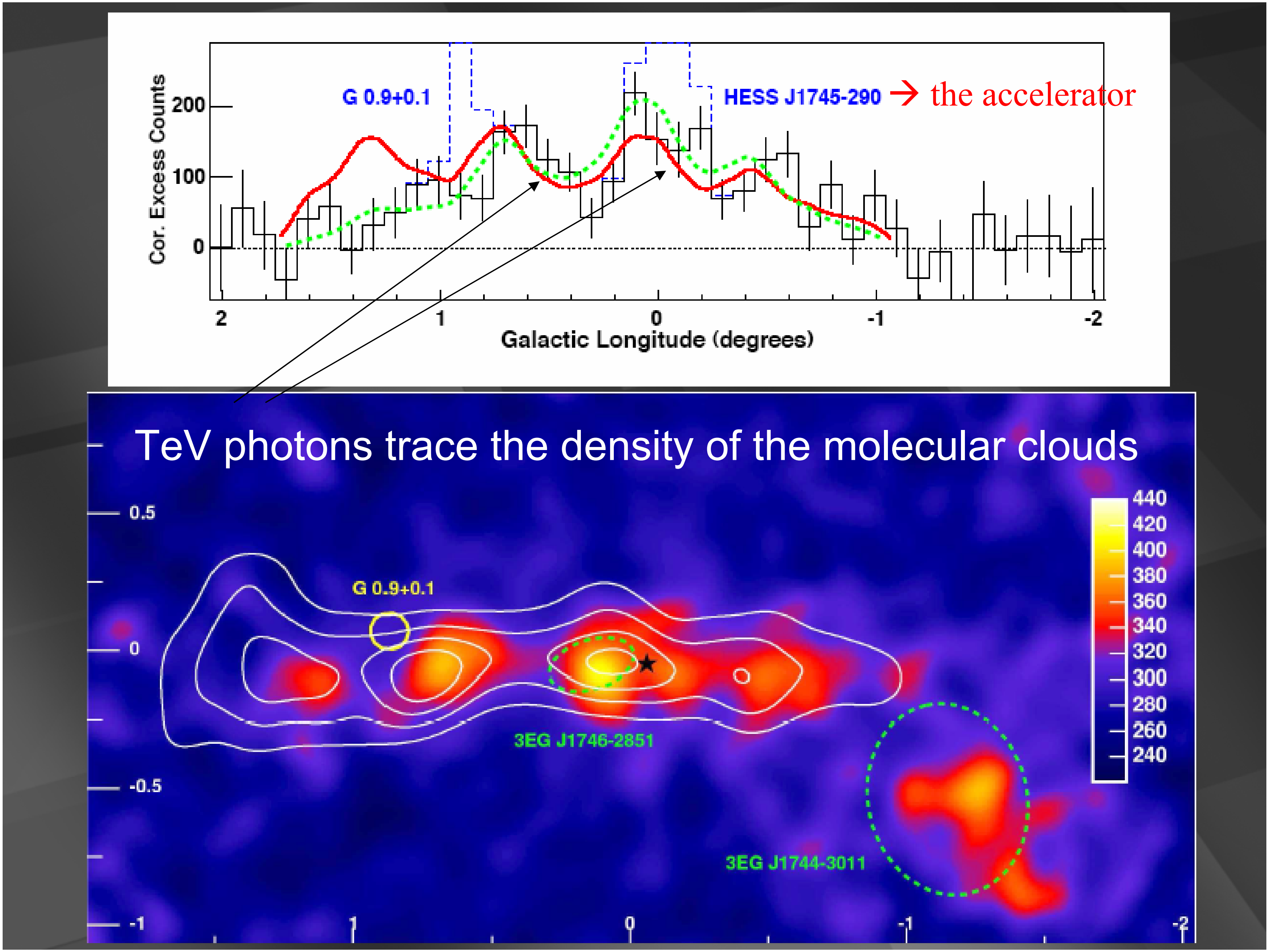

galactic cosmic rays are revealed
by their interaction with the ISM

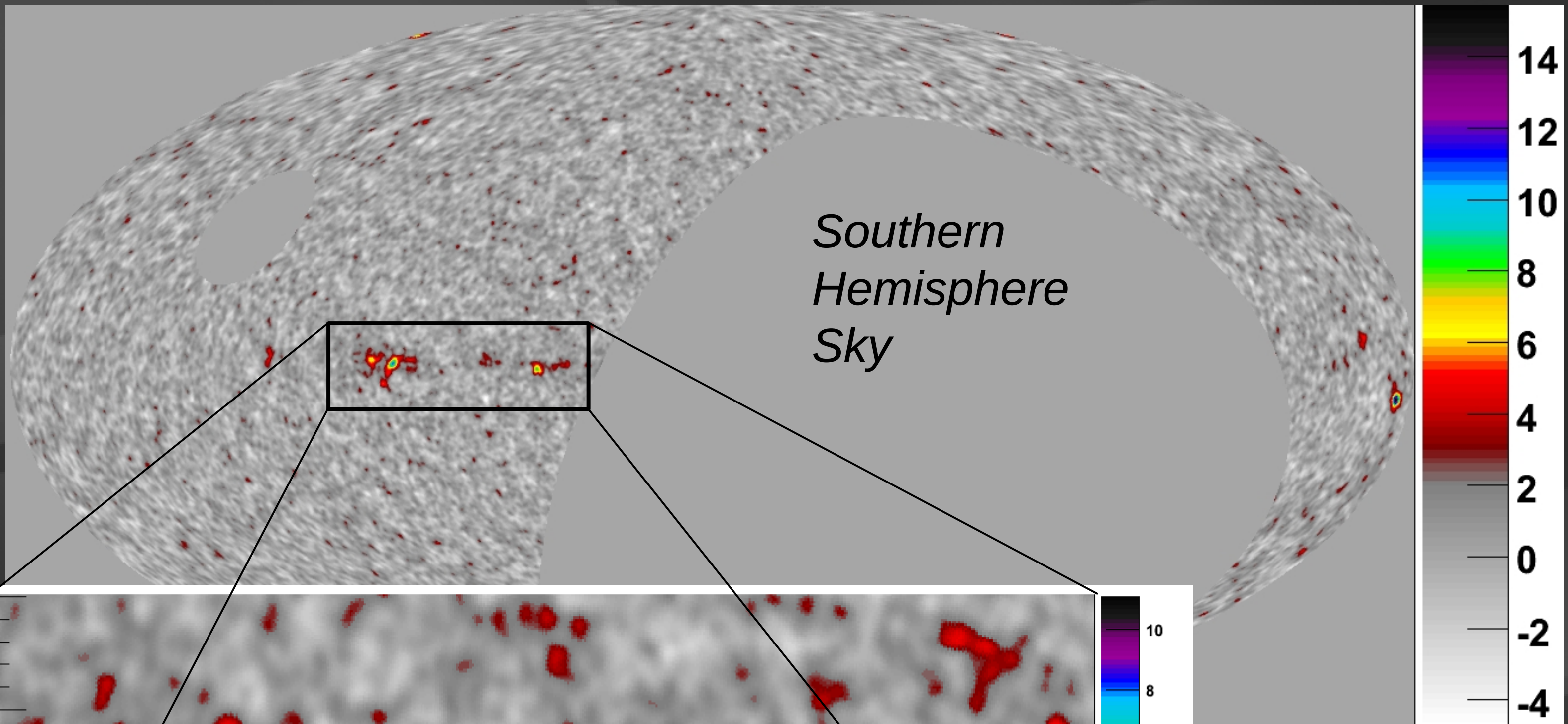
supernova beam dump

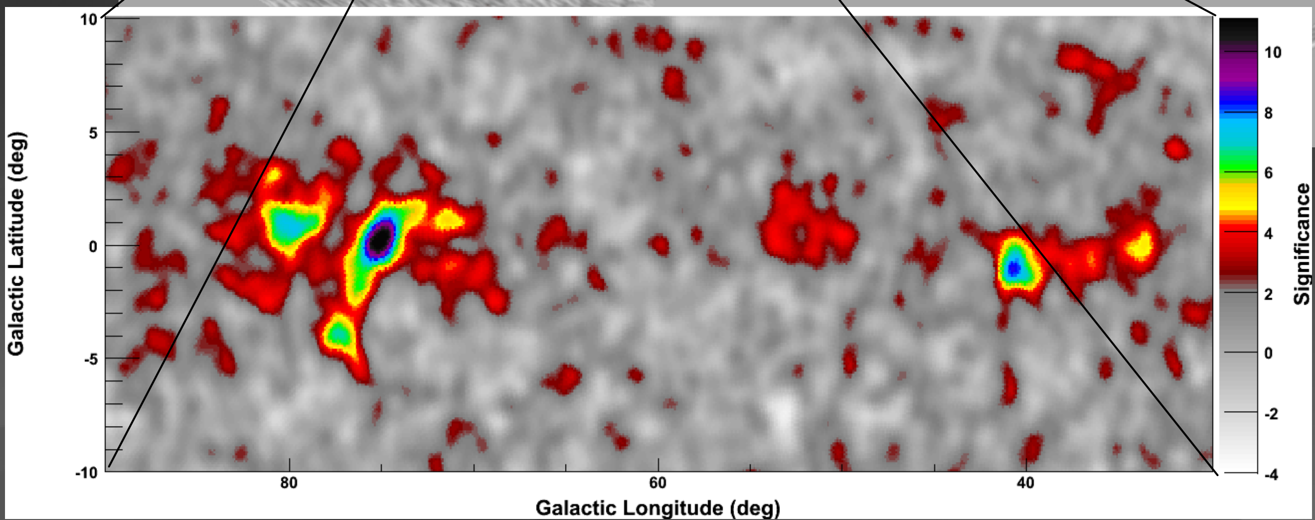


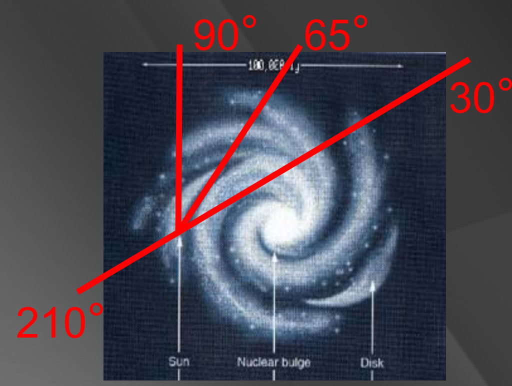
RX J1713-3946


G 0.9+0.1
HESS J1745-290
→ the accelerator
Cor. Excess Counts
200
100
0
2
1
0
-1
-2
Galactic Longitude (degrees)
TeV photons trace the density of the molecular clouds
0.5
0
-0.5
-1
G 0.9+0.1
3EG J1746-2851
3EG J1744-3011
440
420
400
380
360
340
320
300
280
260
240
1
0
-1
-2

galactic plane







neutral pions

are observed as

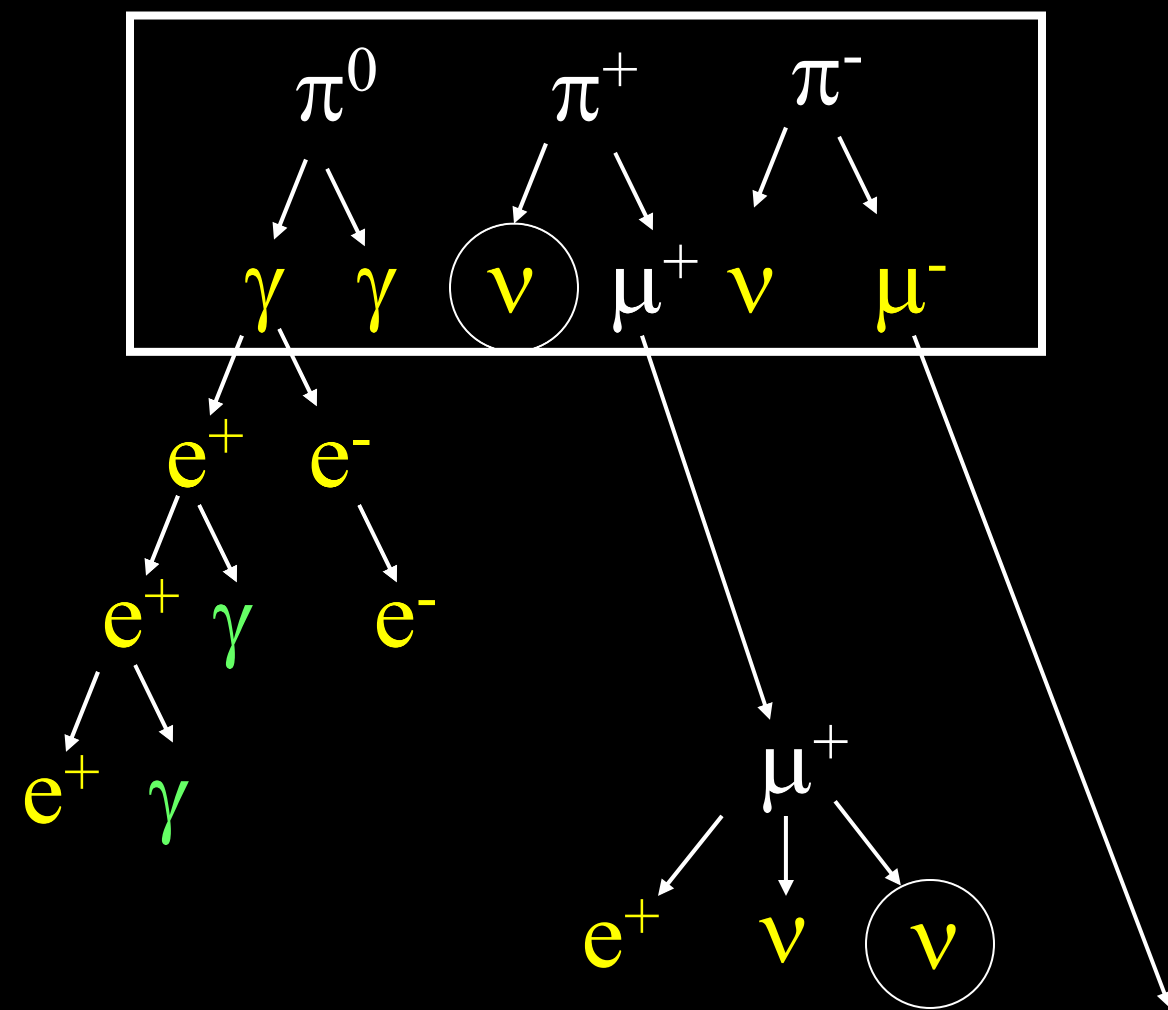
gamma rays

charged pions

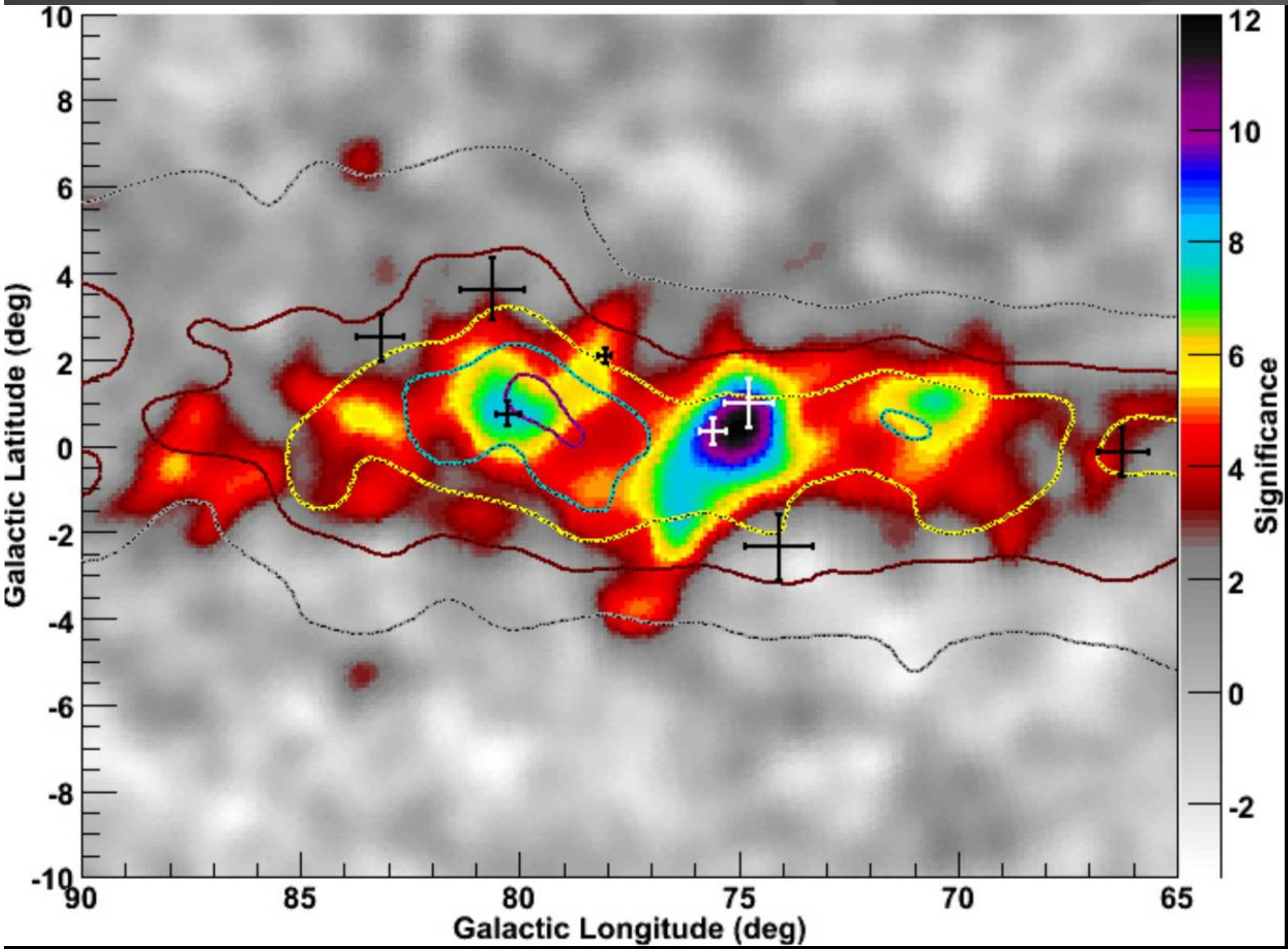
are observed as

neutrinos

$$\nu_\mu \sim \gamma / 2$$



cygnus region : Milagro and Tibet



Milagro

contours are pion model with no sources

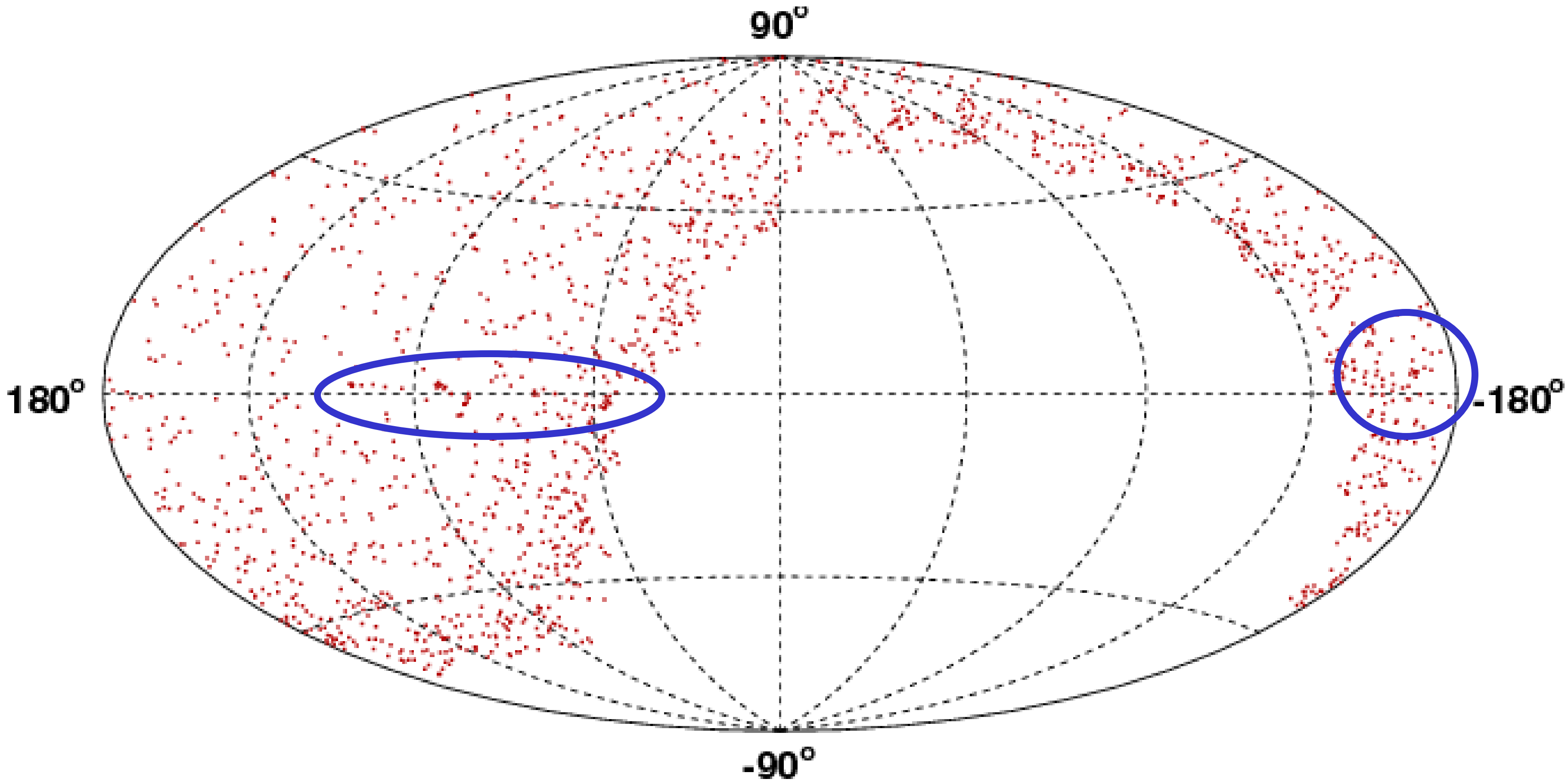
crosses are EGRET unidentified sources

TeV/matter correlation

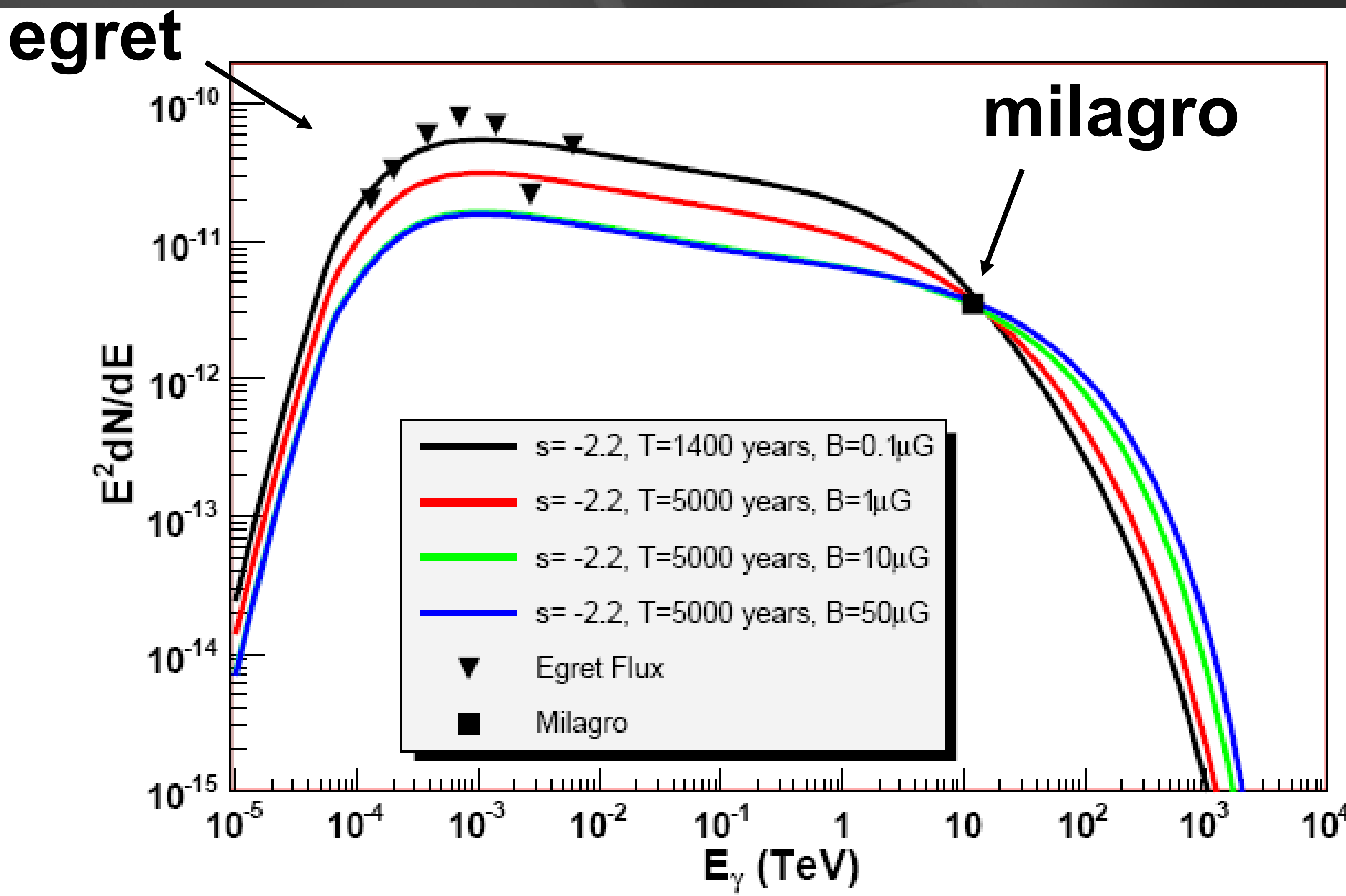
chance noncorrelation
1.5×10^{-6}

3 ± 1 ν per year in IceCube per source

IceCube image of our galaxy



1000 models ... same ν-rate



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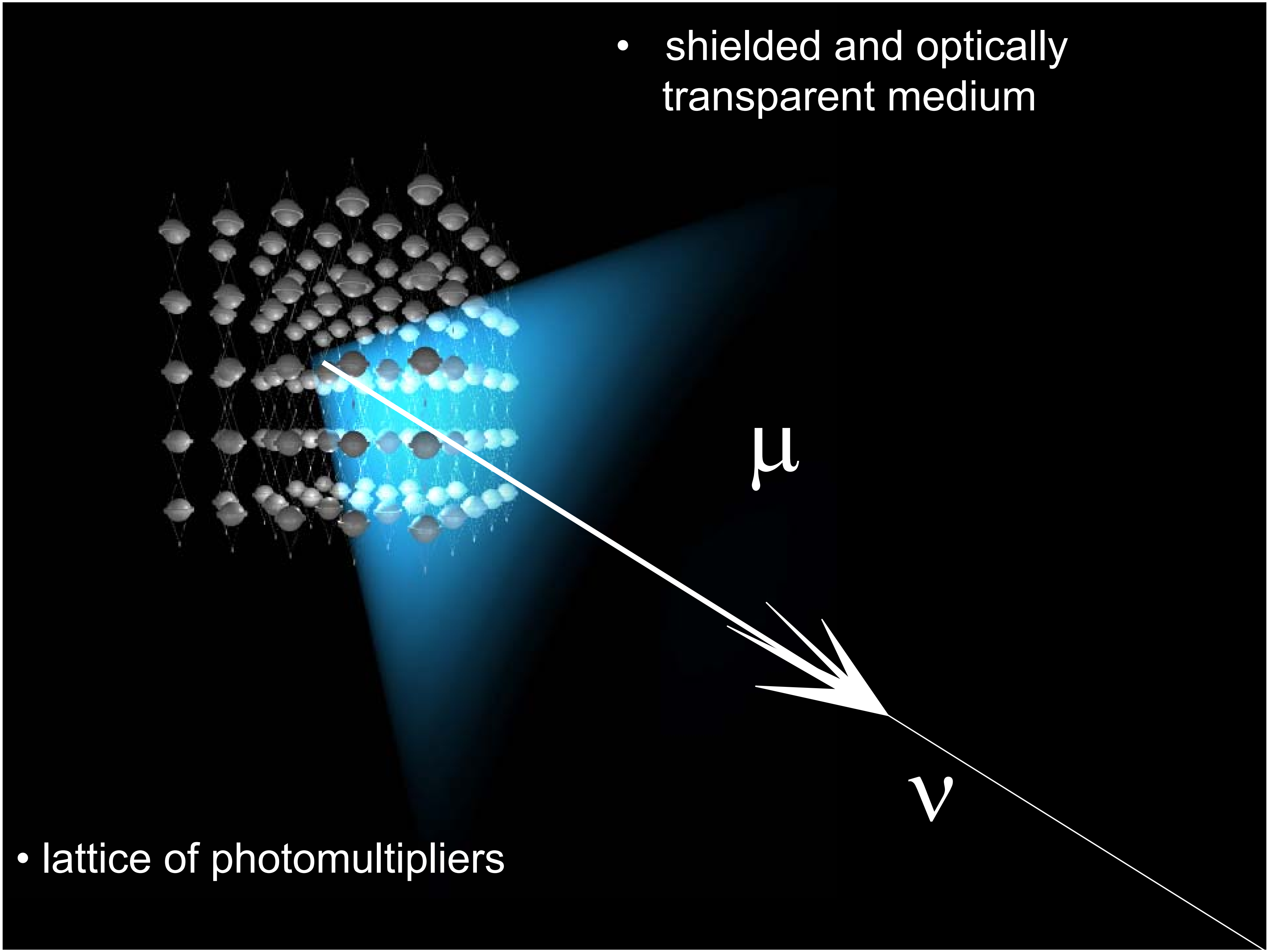
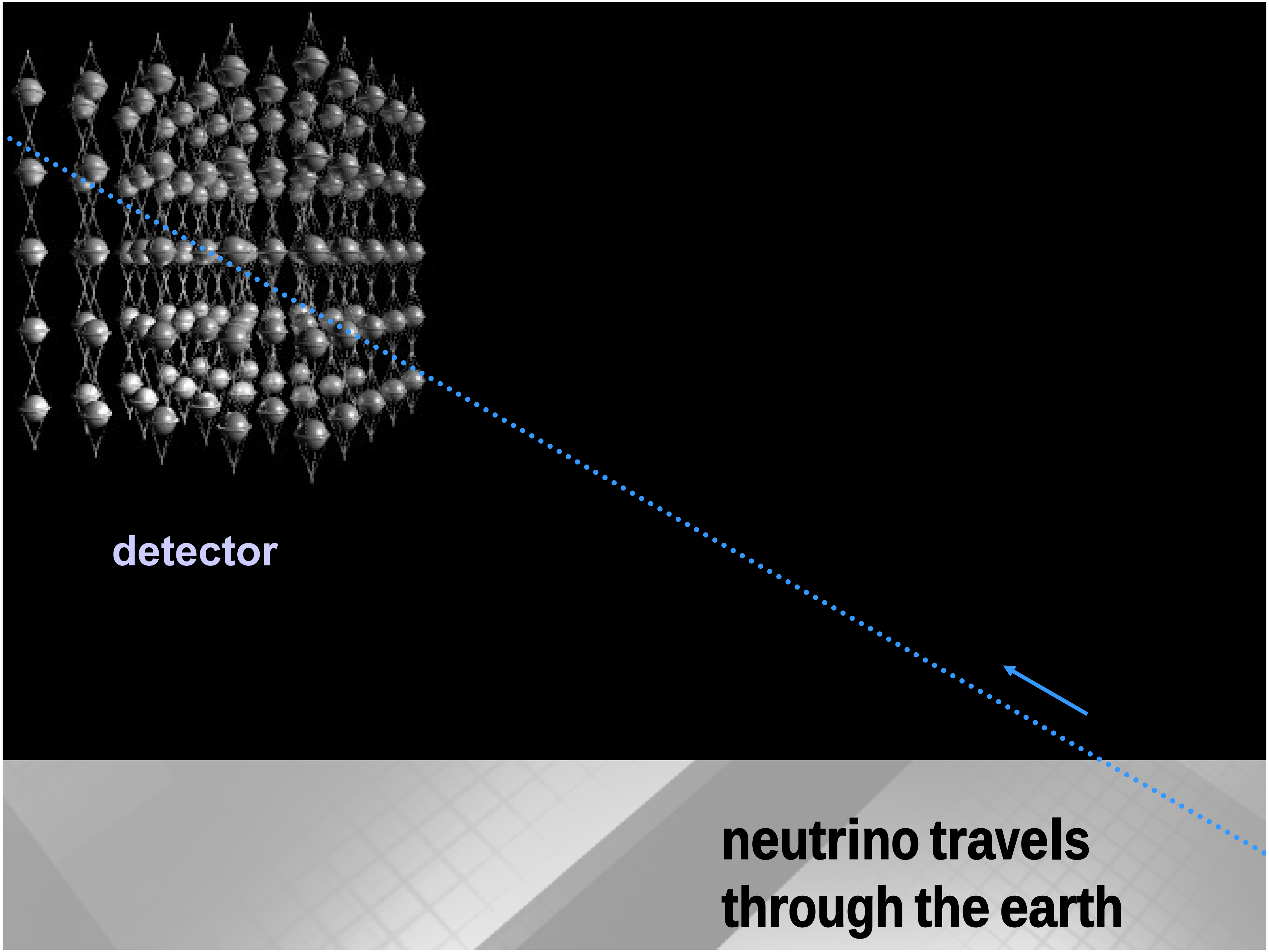
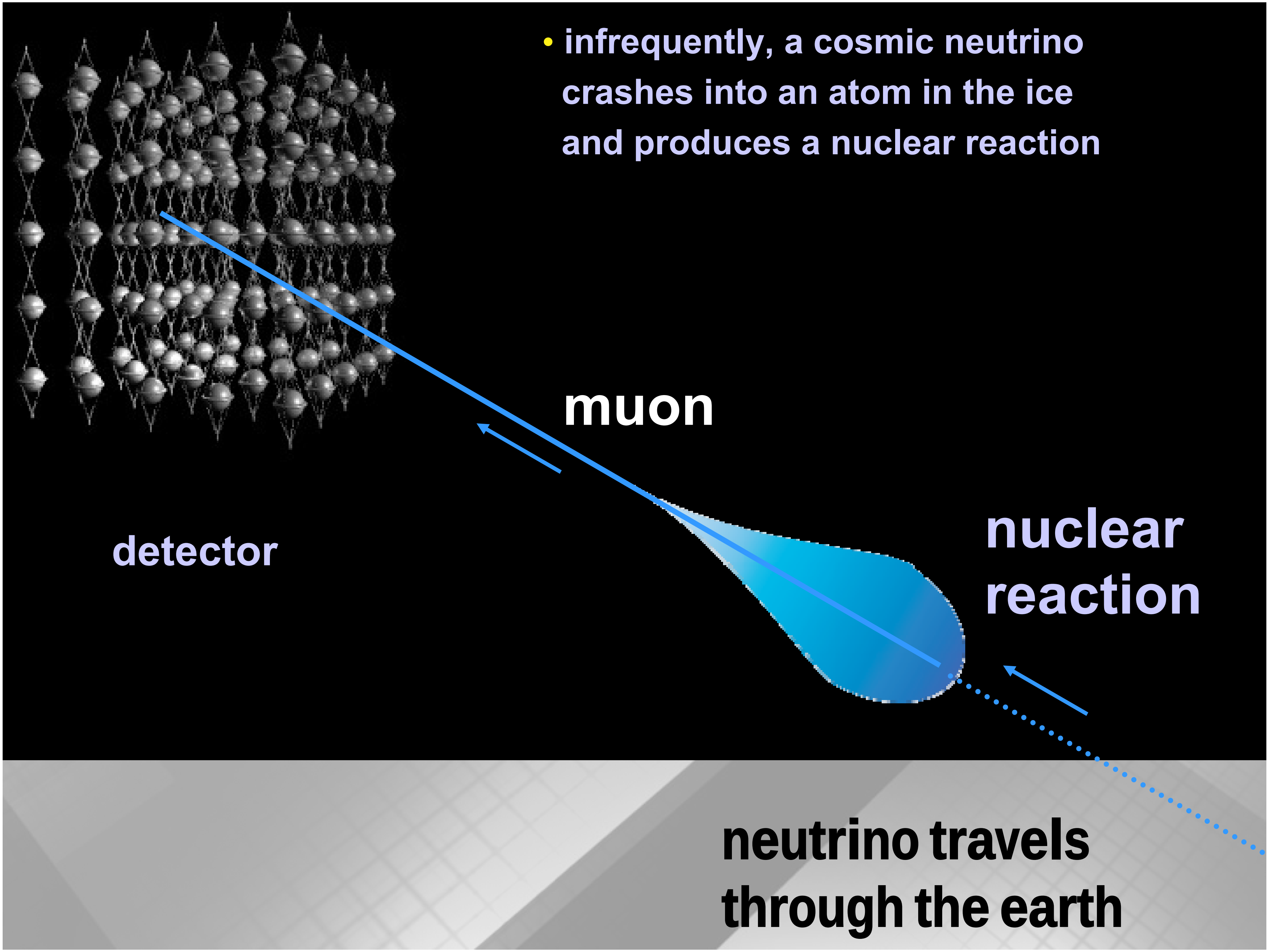
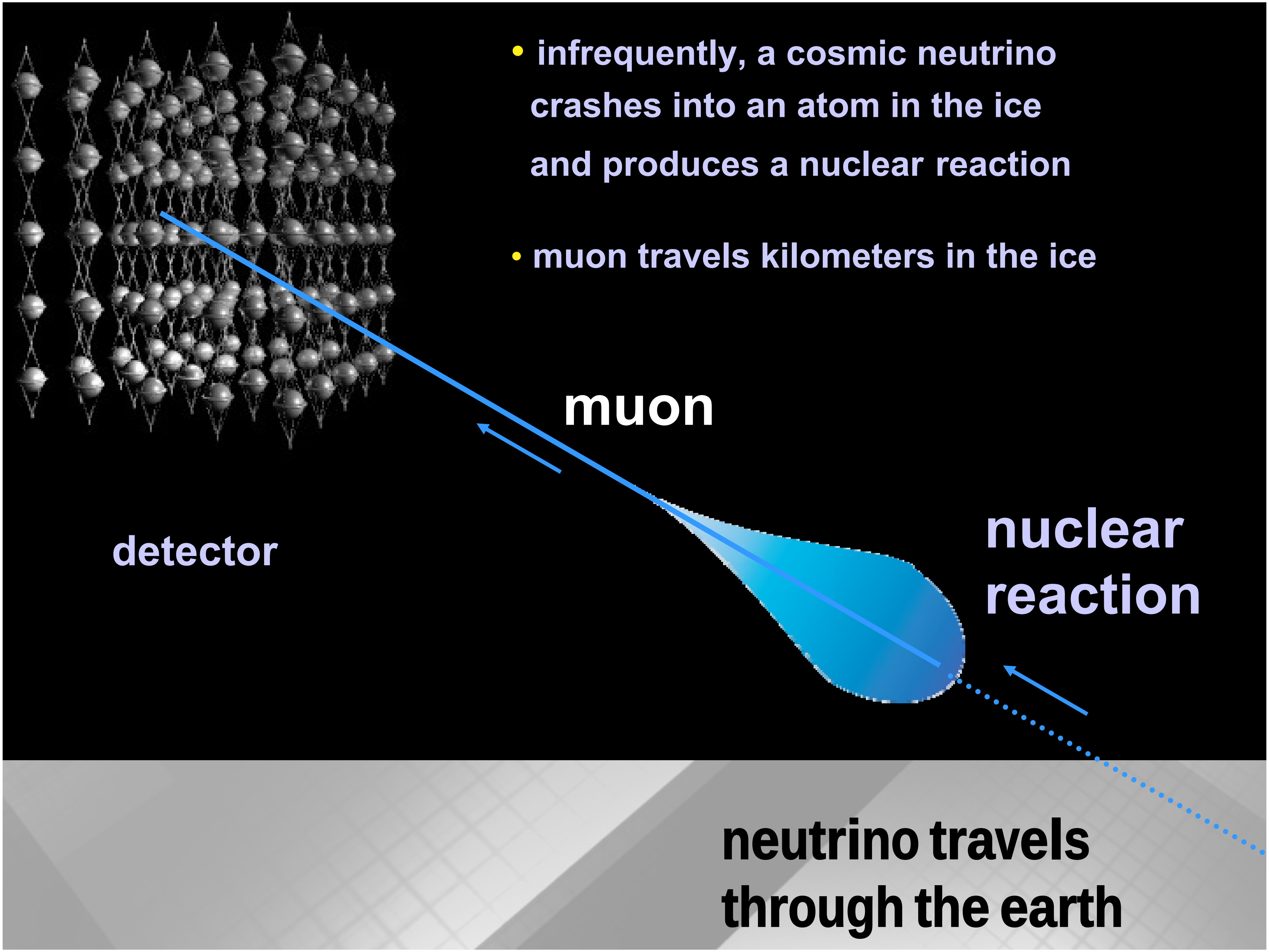
cosmic neutrinos: how ?

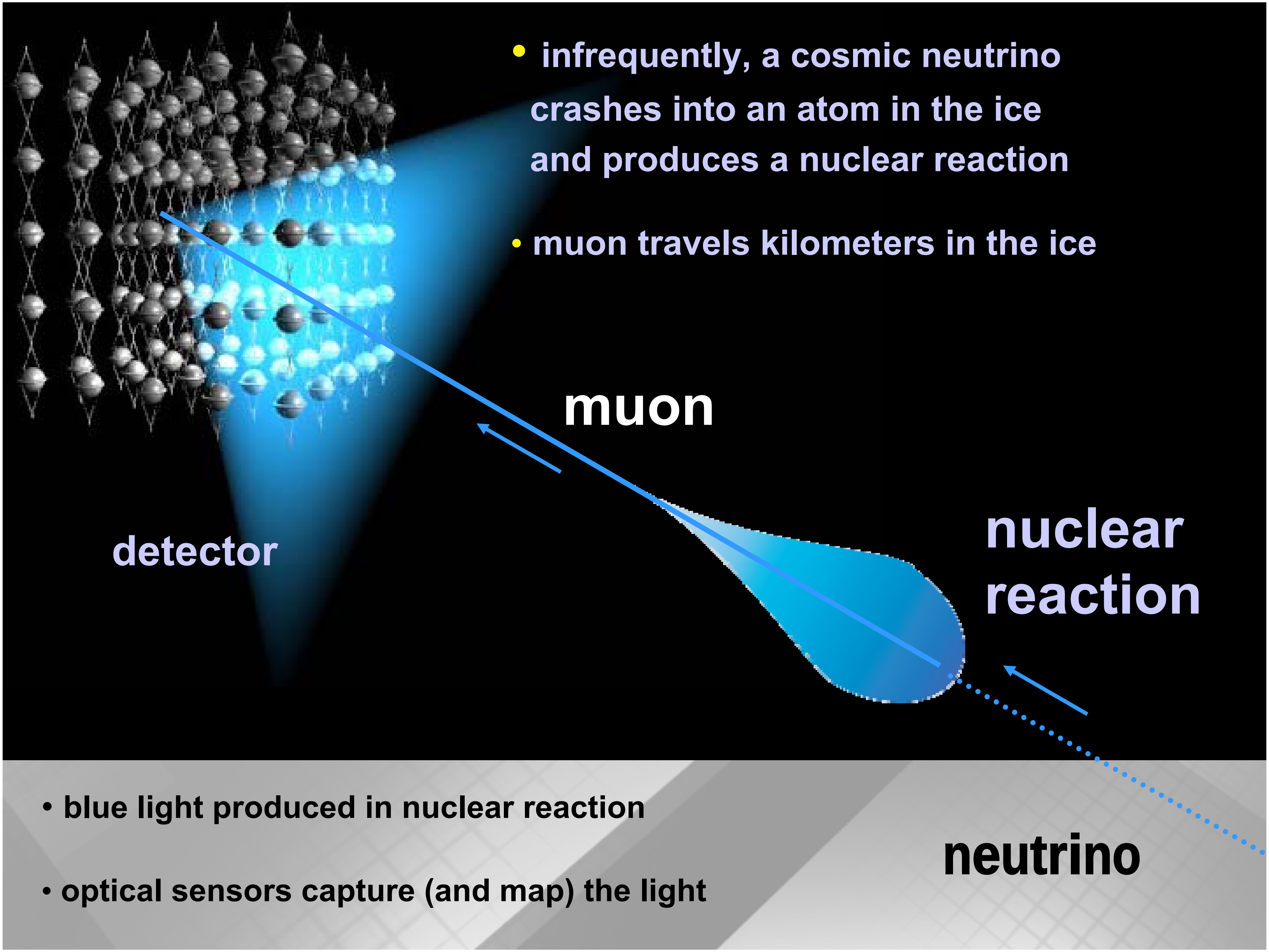

• shielded and optically transparent medium
μ
ν
• lattice of photomultipliers

Photomultiplier Tube


detector
neutrino travels
through the earth


• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
muon
detector
nuclear reaction
neutrino travels through the earth

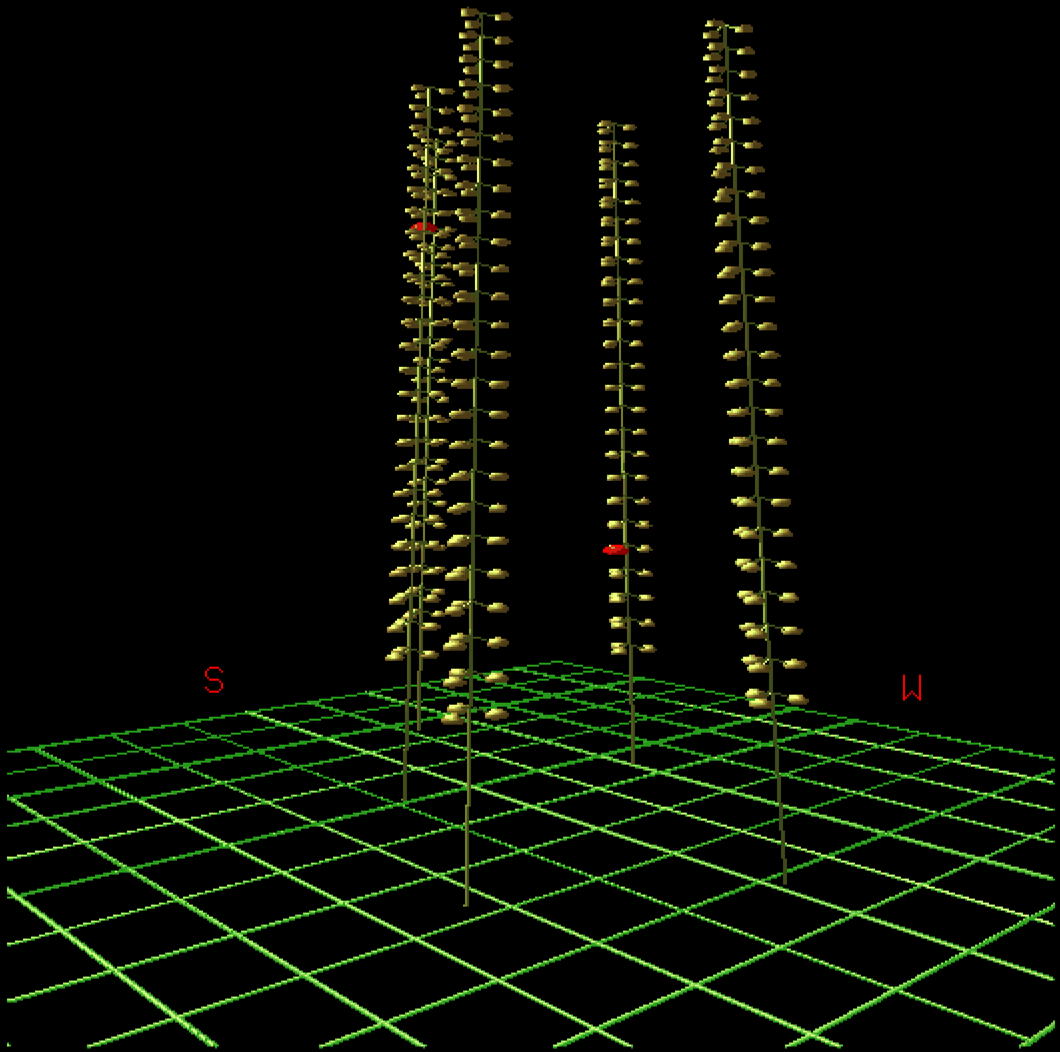

• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
• muon travels kilometers in the ice
muon
detector
nuclear reaction
neutrino travels through the earth


• infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
• muon travels kilometers in the ice
muon
detector
nuclear reaction
• blue light produced in nuclear reaction
• optical sensors capture (and map) the light
neutrino

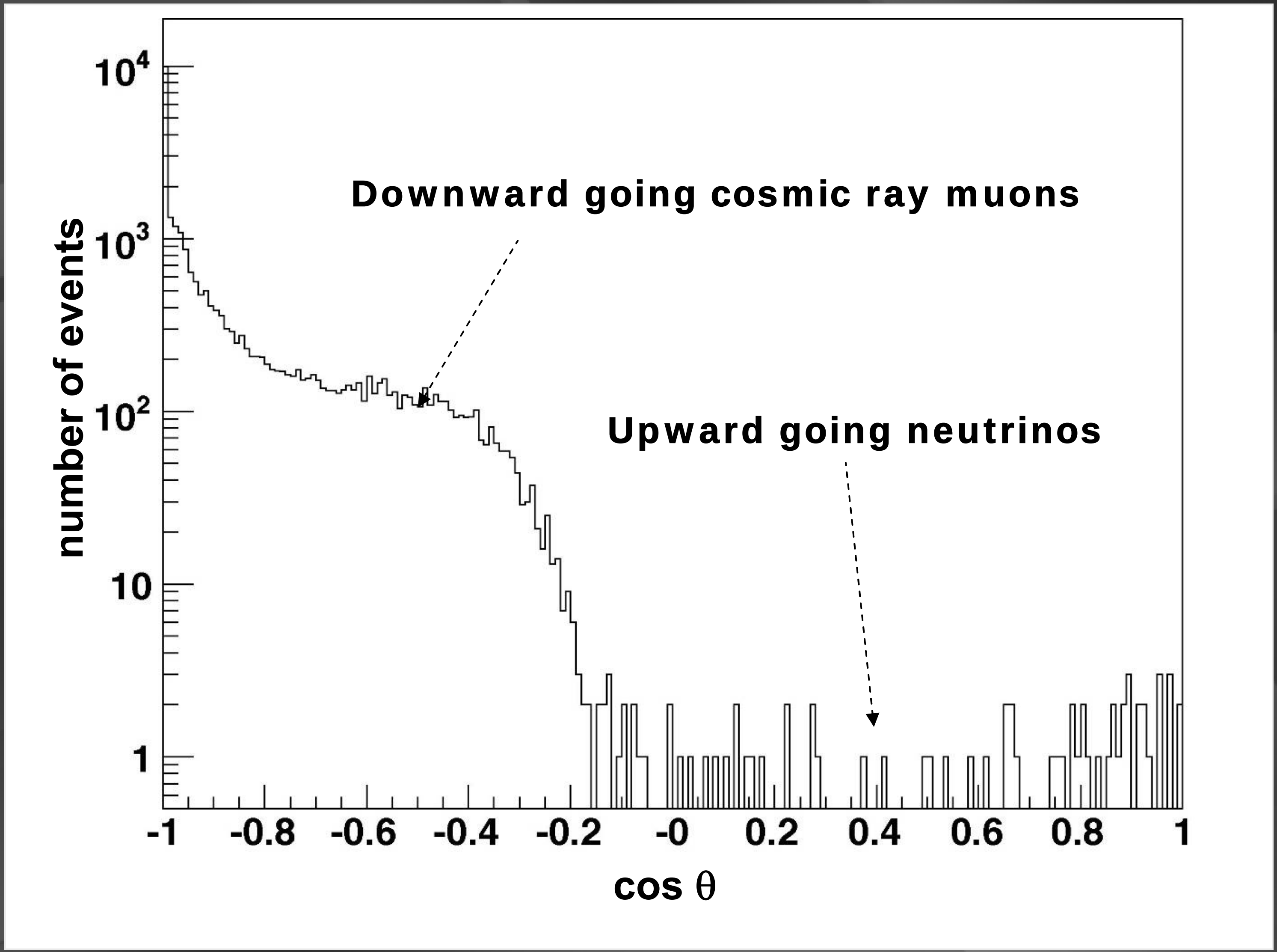
ANTARES

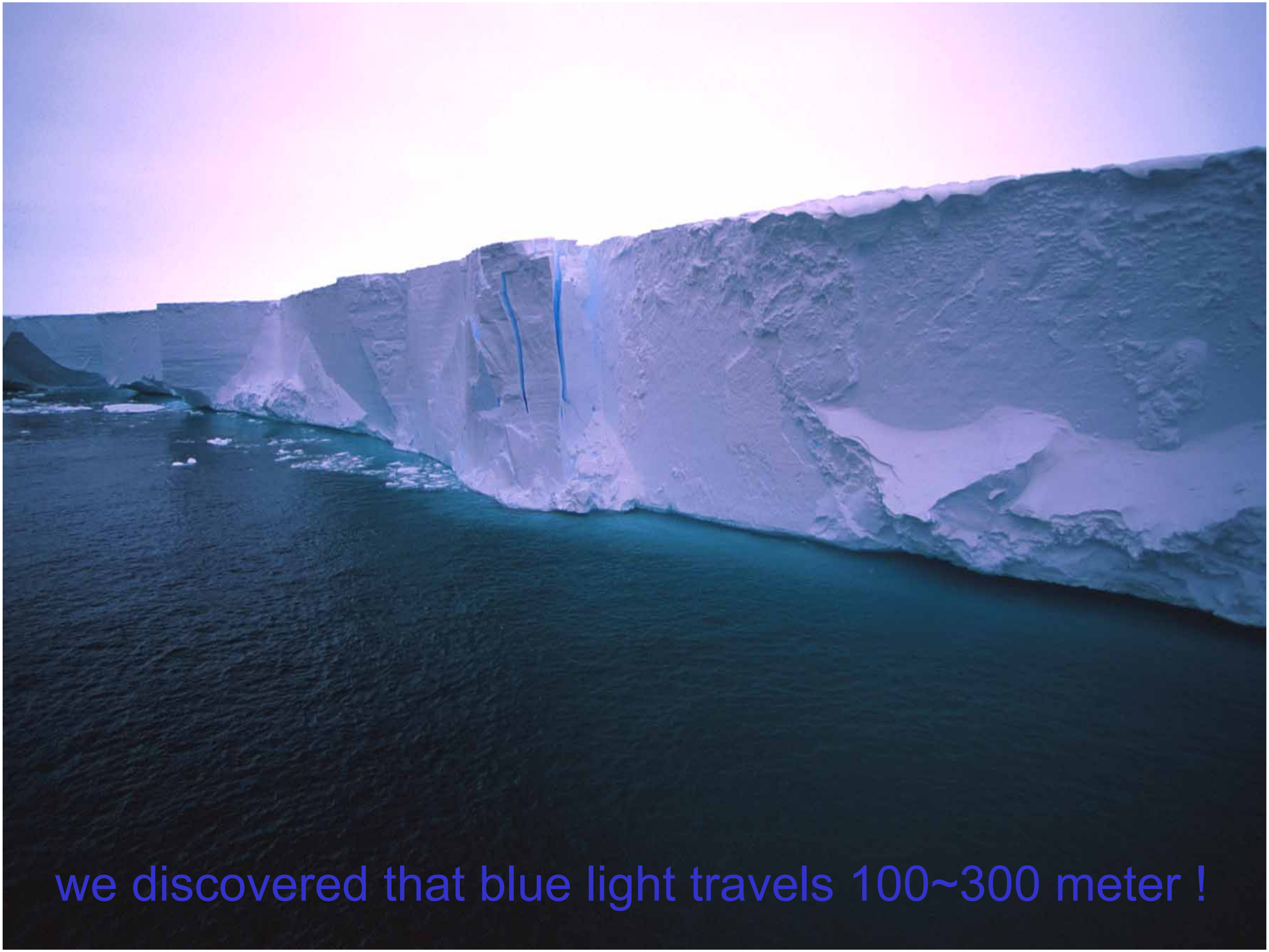
10 out of 12 strings deployed

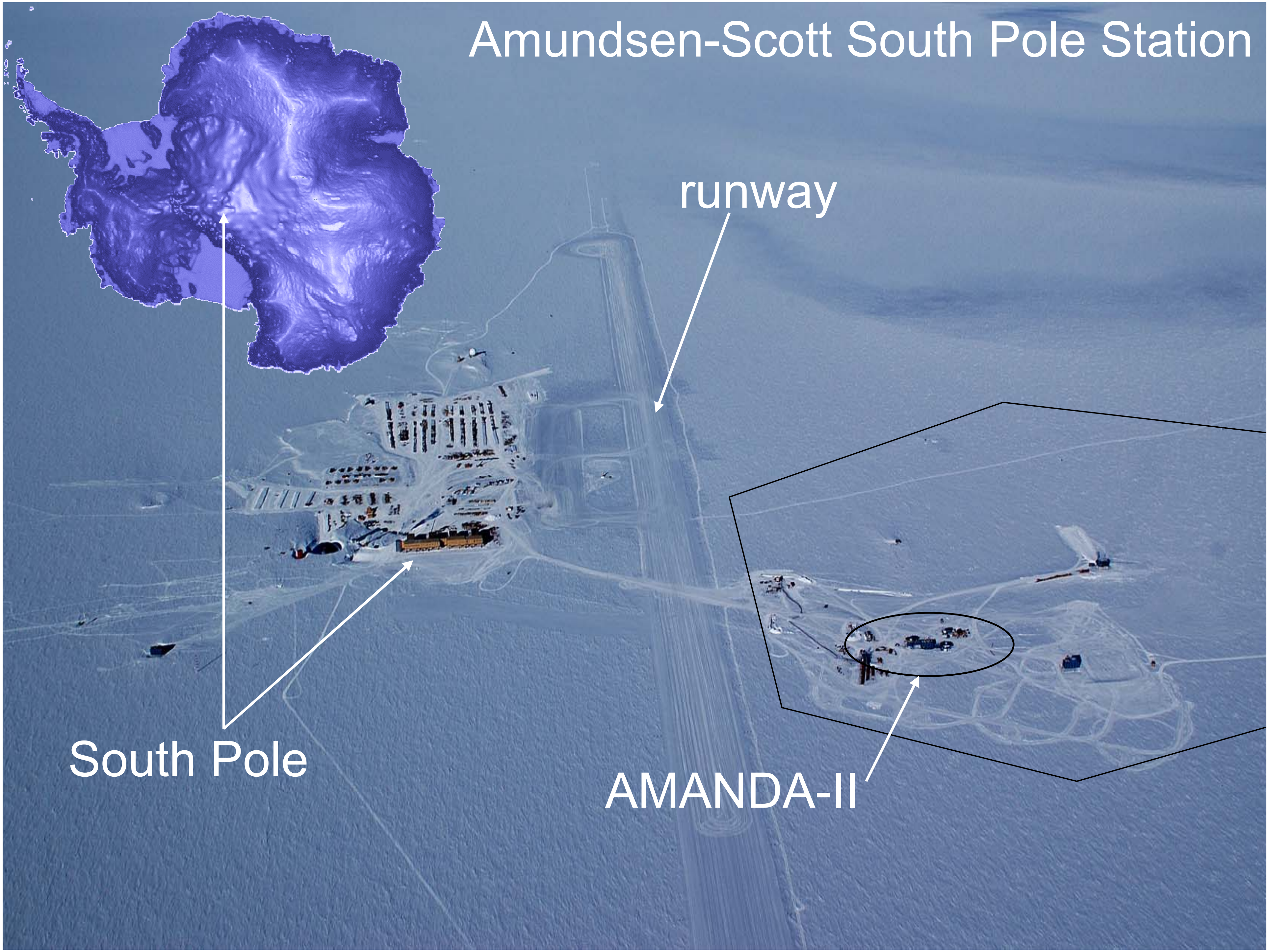
antares



antares neutrino candidates

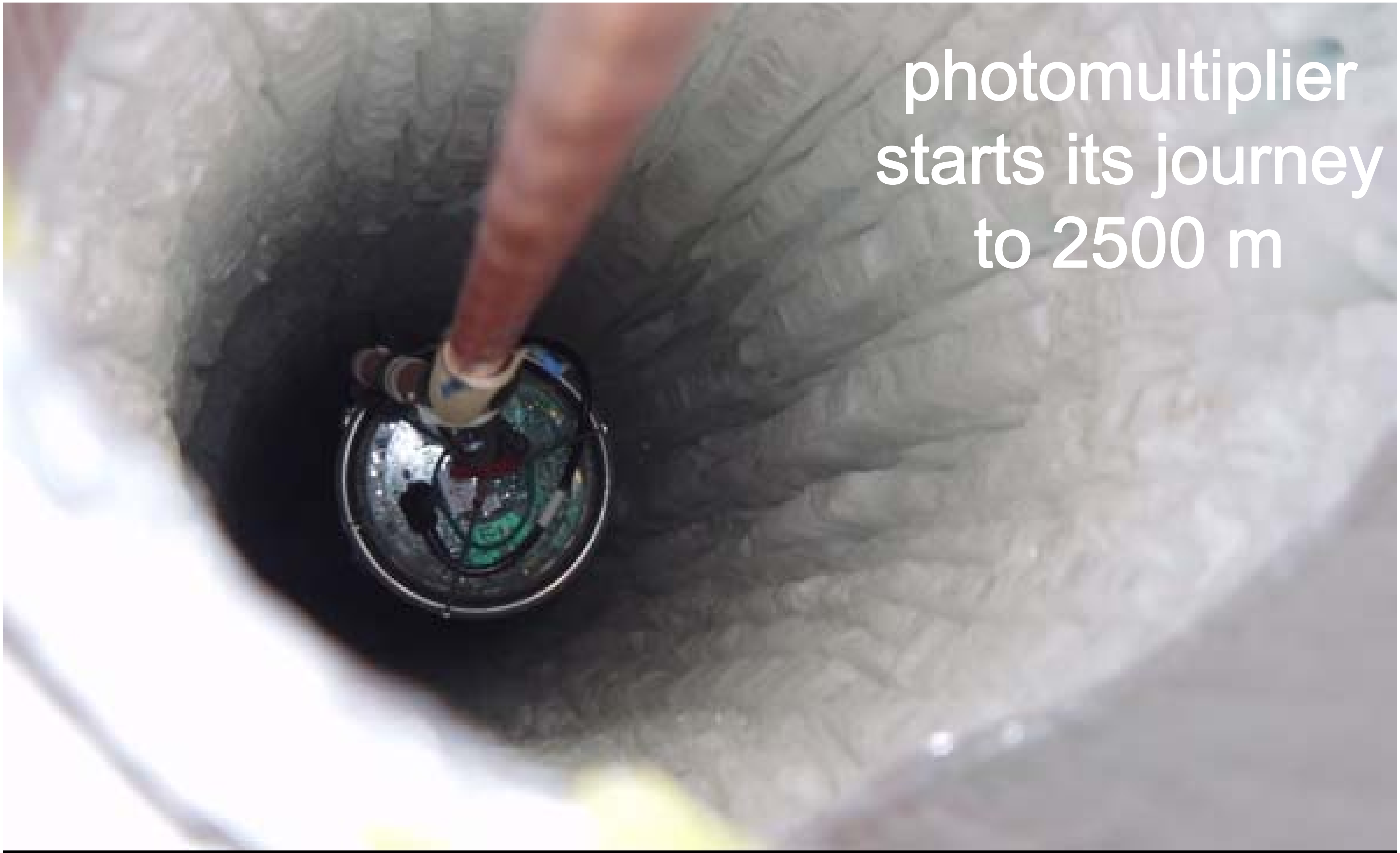



we discovered that blue light travels 100~300 meter !

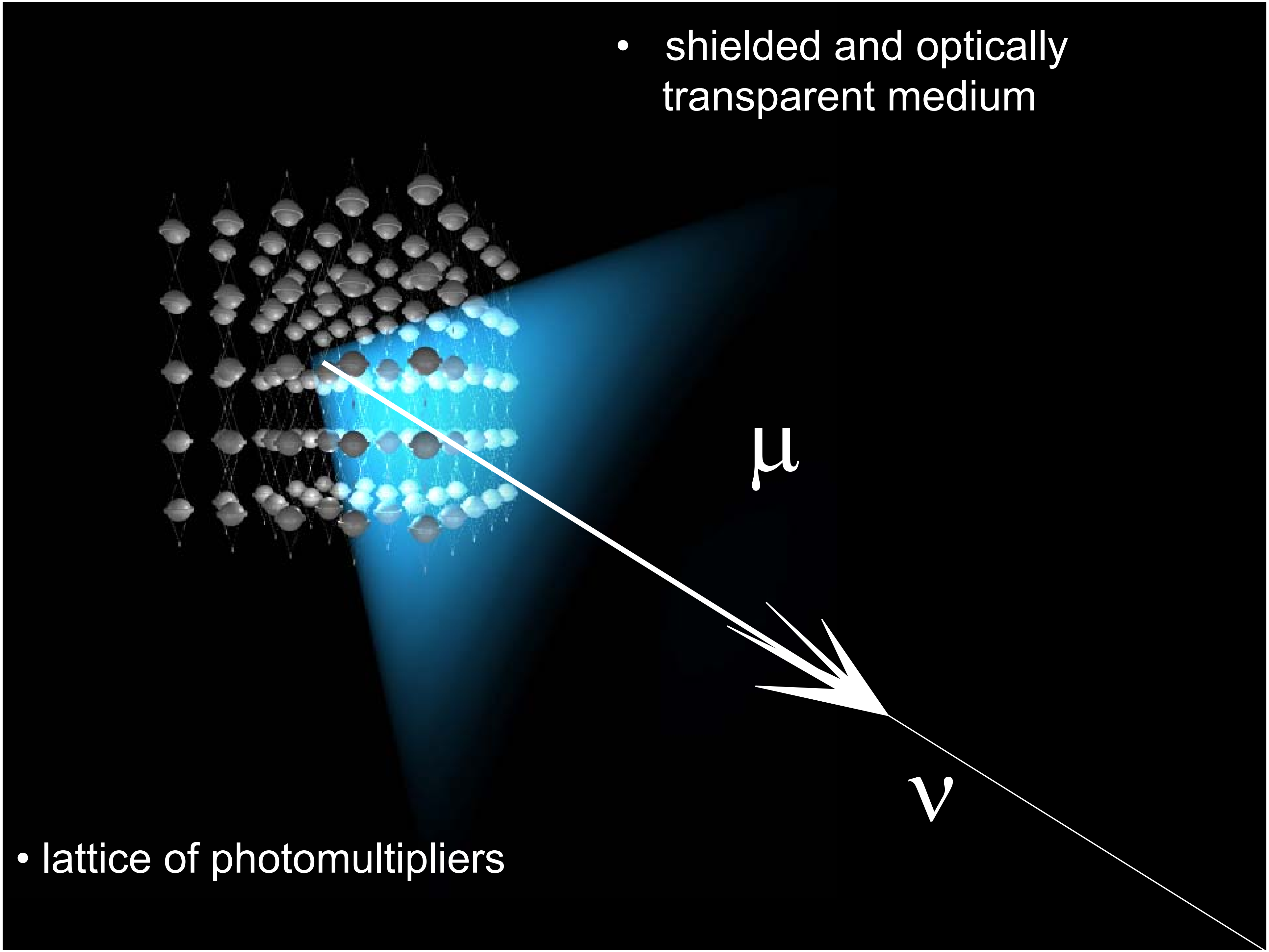


Amundsen-Scott South Pole Station
runway
South Pole
AMANDA-II

new South Pole station



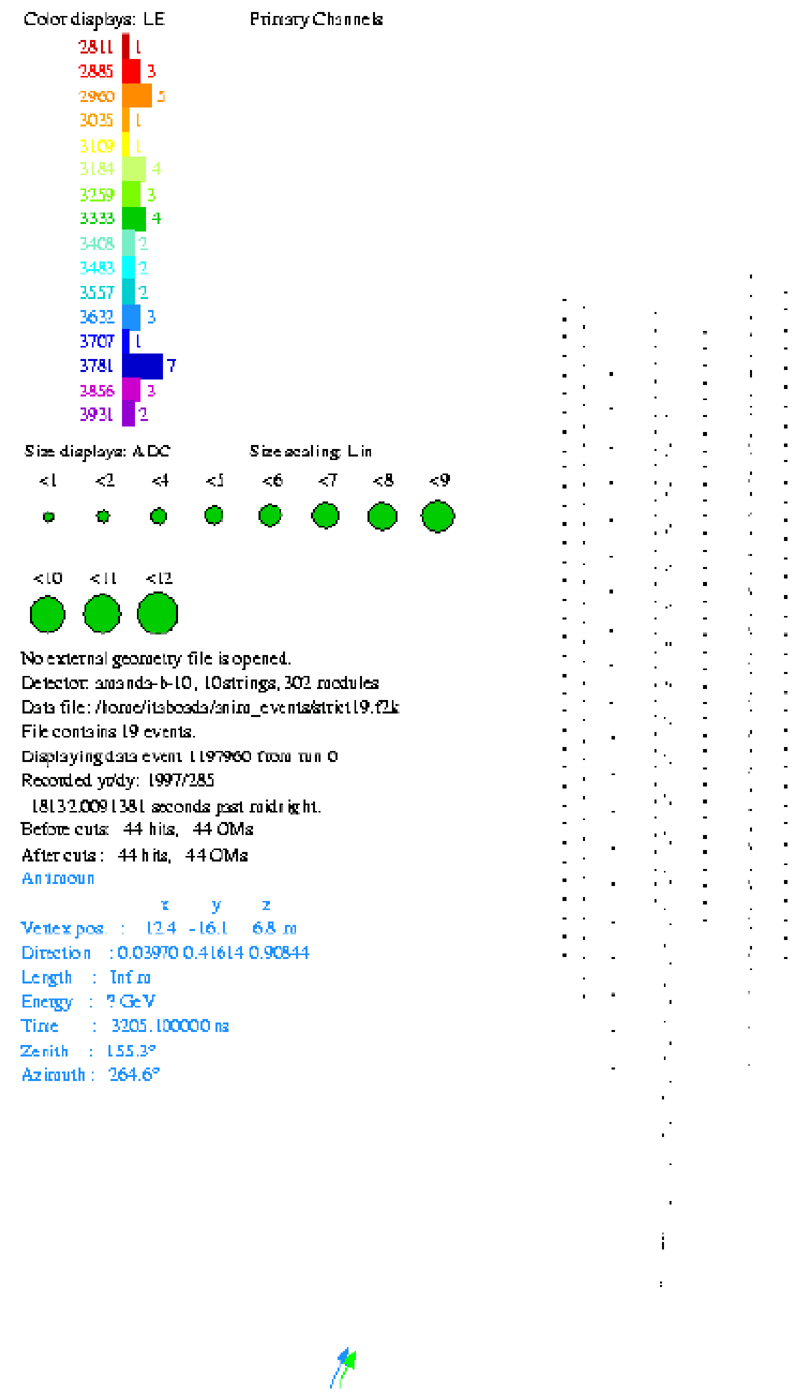
the project will eventually transform
a billion tons of ice into a particle physics detector


• shielded and optically transparent medium
μ
ν
• lattice of photomultipliers

AMANDA Event Signatures: Muons

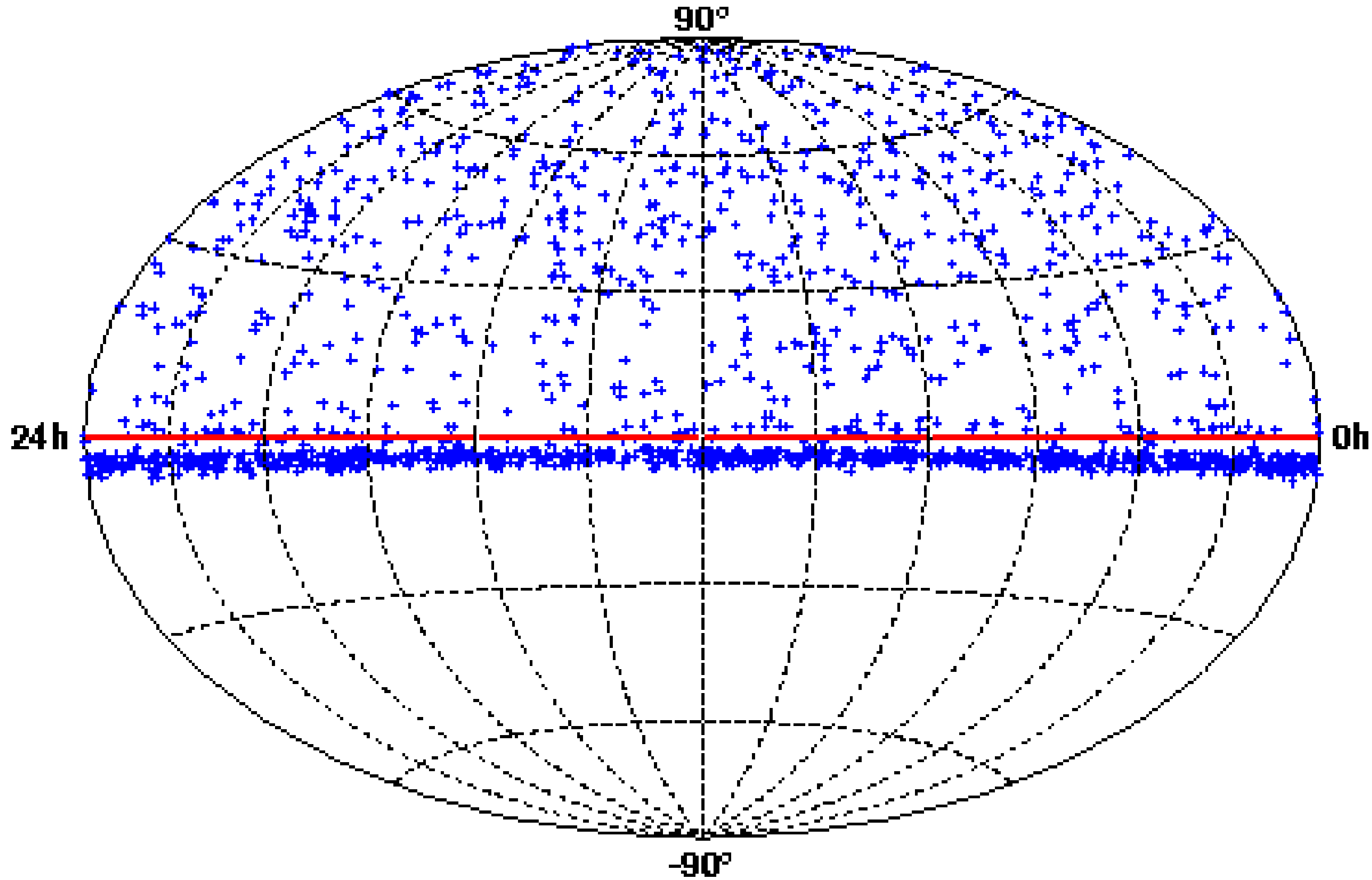
muon neutrino interaction → track

$$\nu_\mu + N \rightarrow \mu + X$$



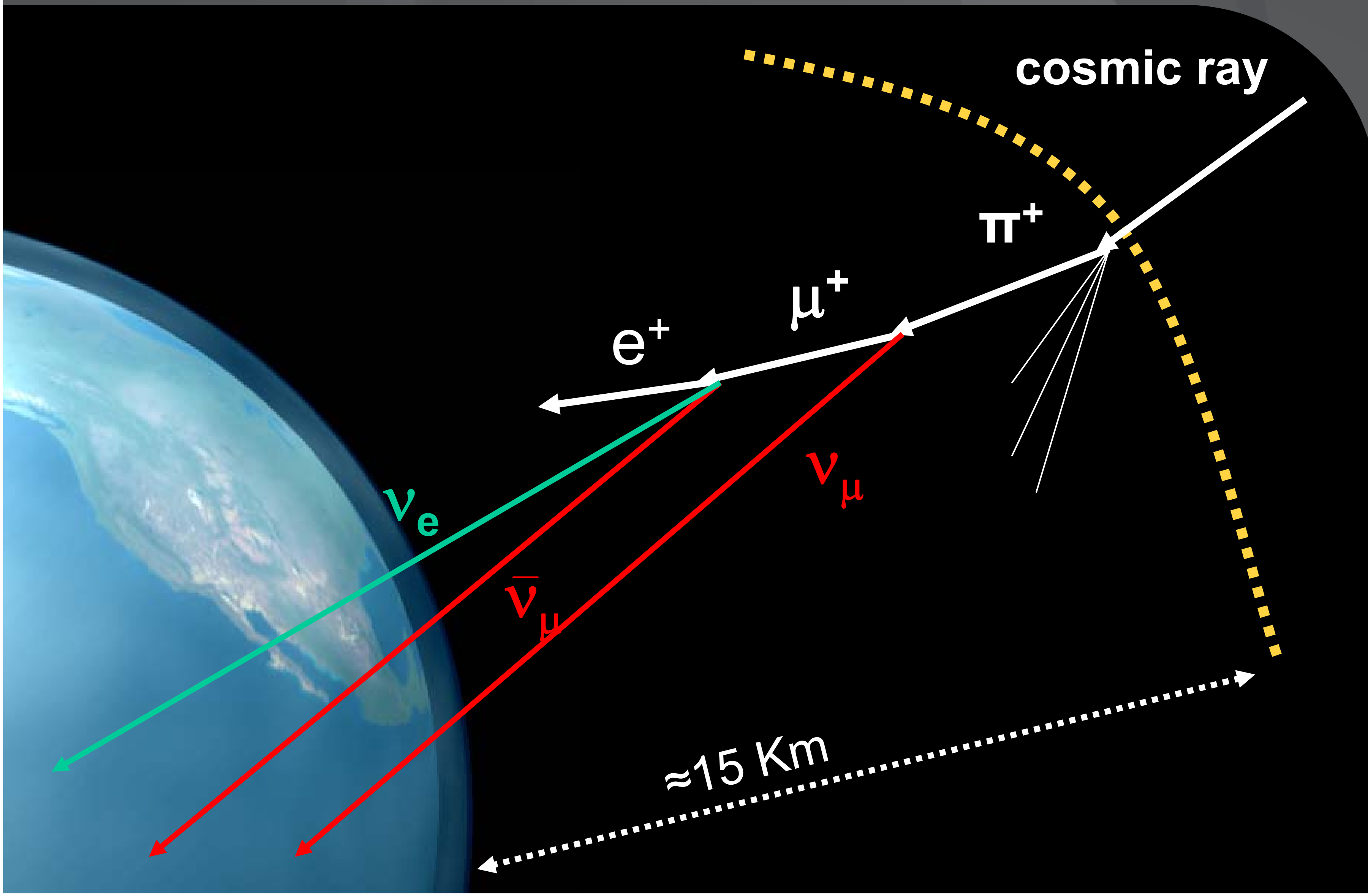
AMANDA II 2000

1555 Events

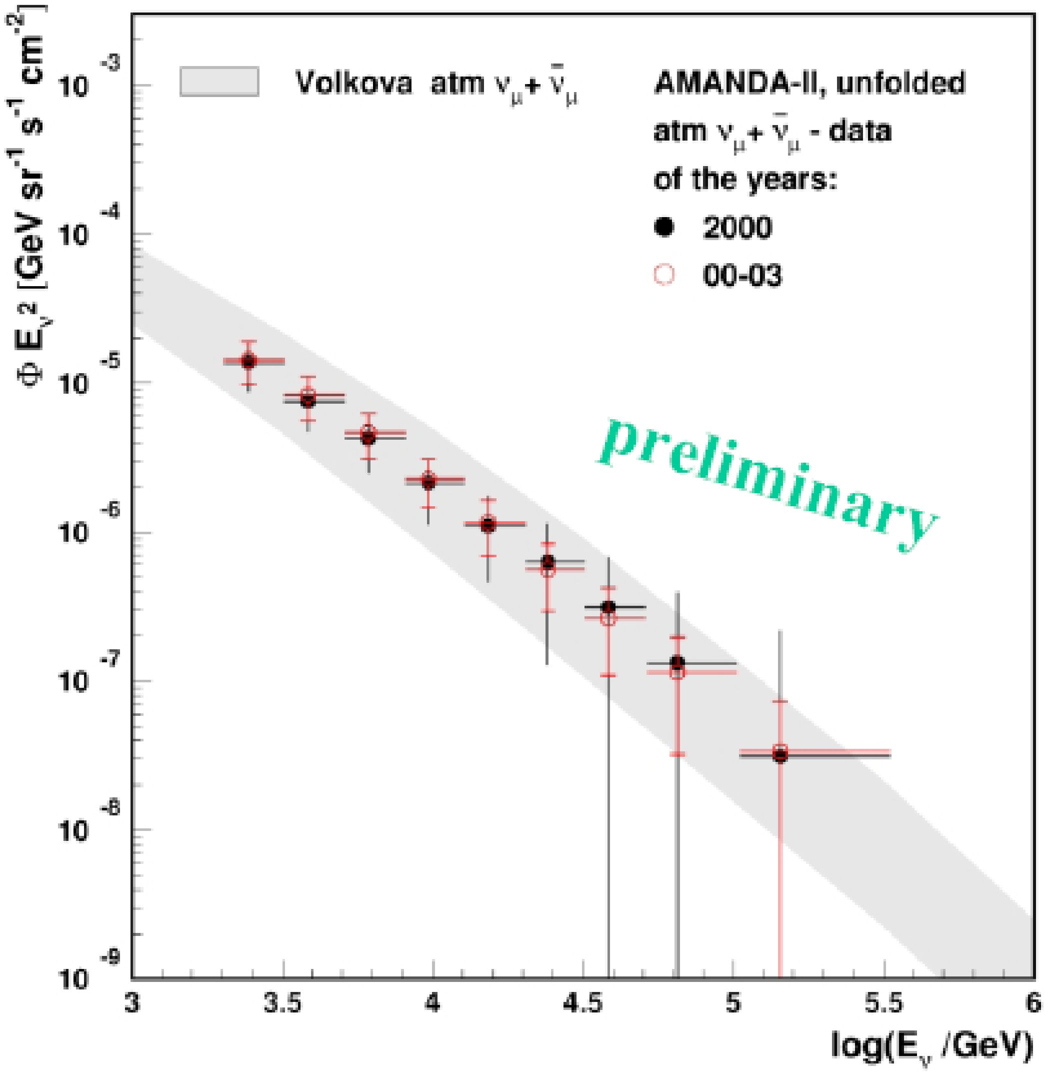


AMANDA: proof of concept

atmospheric neutrinos

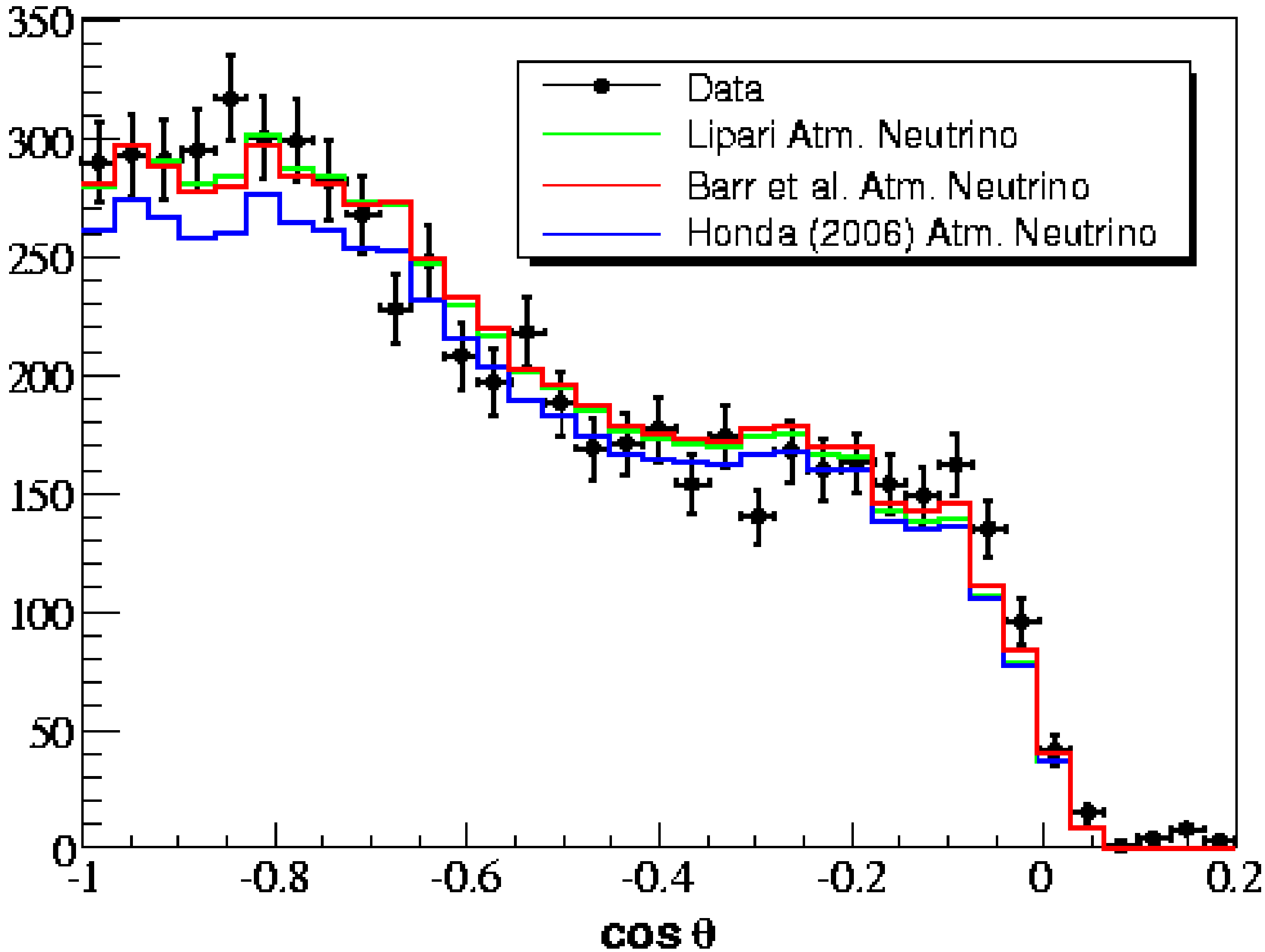


atmospheric neutrinos up to 100 TeV



detector measures the atmospheric neutrino flux predicted: method validated

AMANDA: final sample for atmospheric ν's (6163 events)

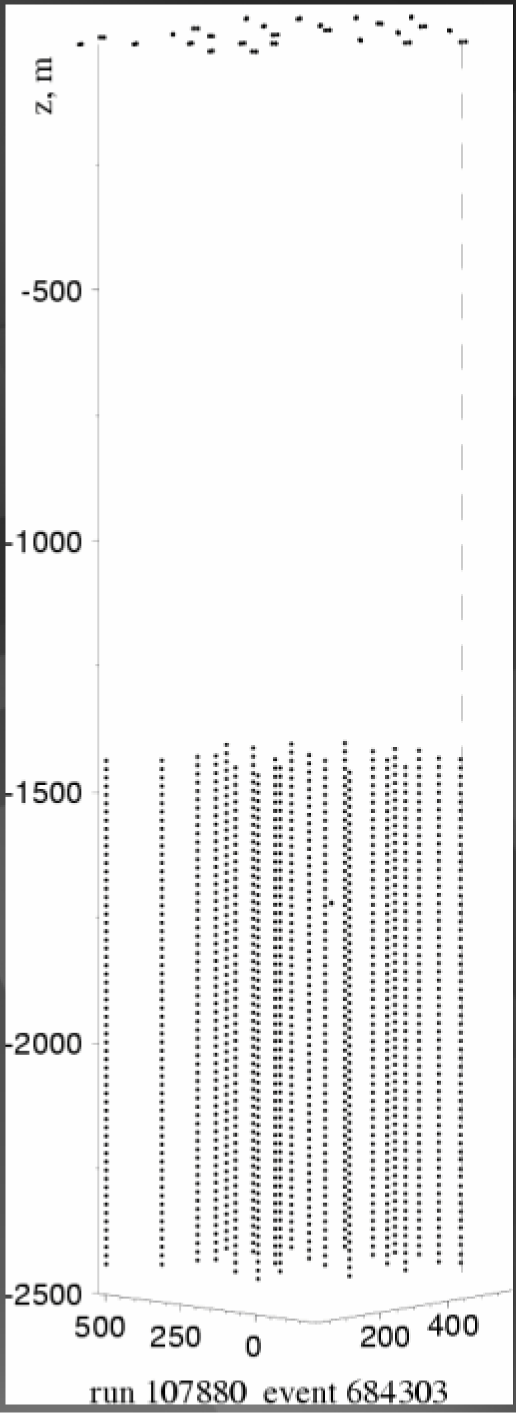


background:
downgoing cosmic
ray muons

600 per second

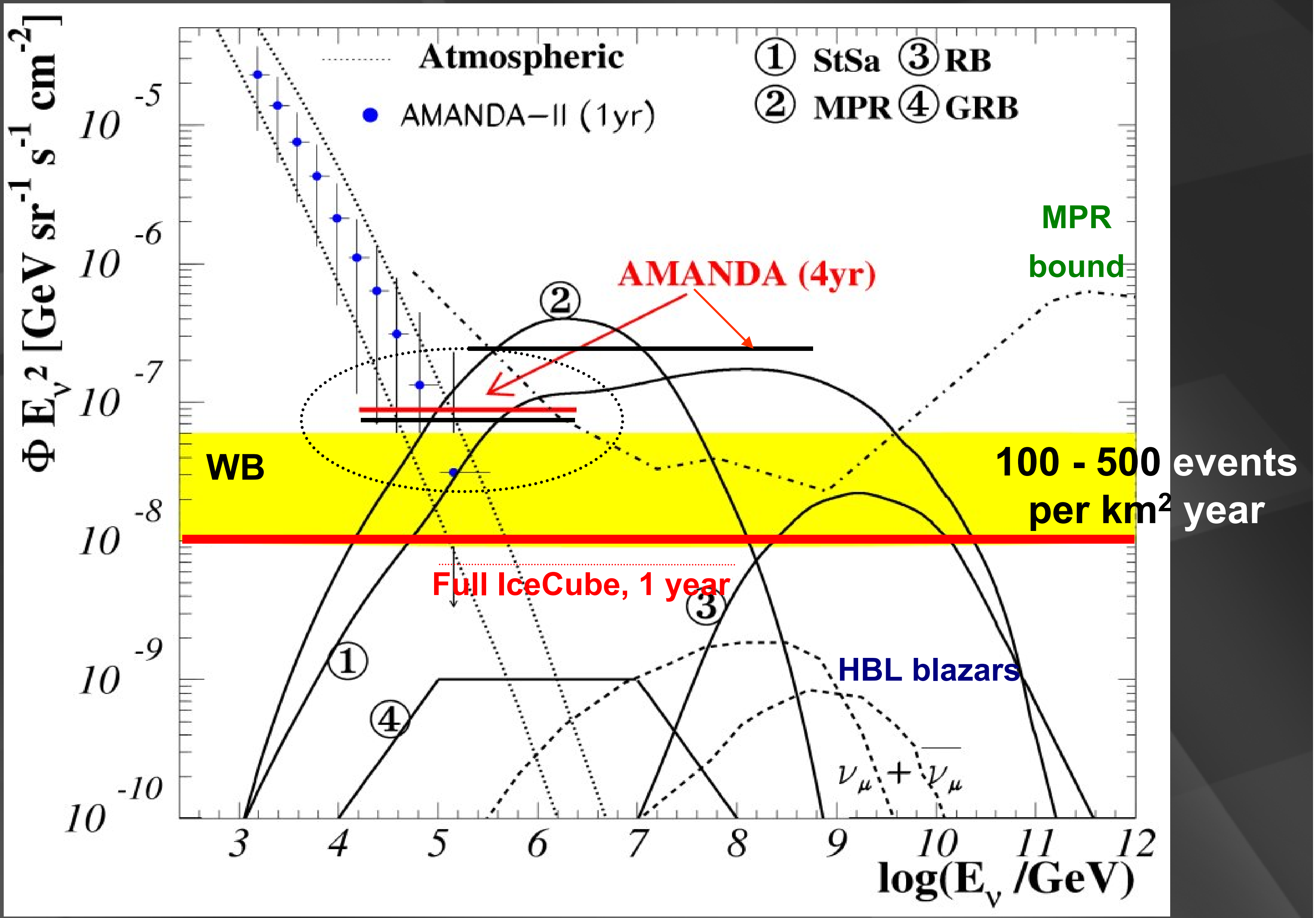
signal:
upgoing muons
initiated by
neutrinos

1 per hour



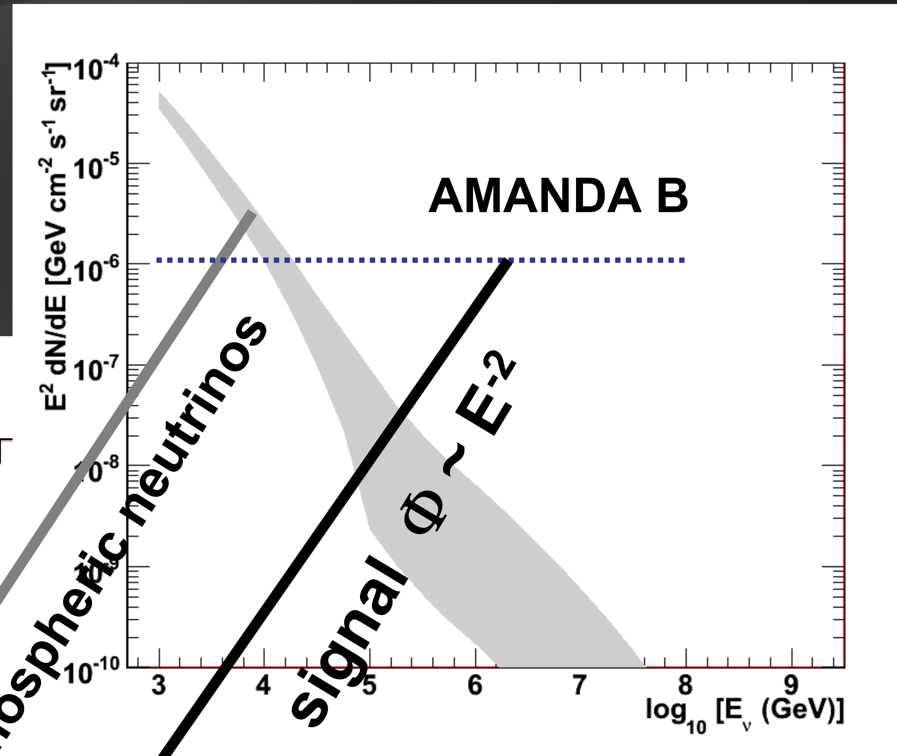
science

diffuse muon neutrino flux

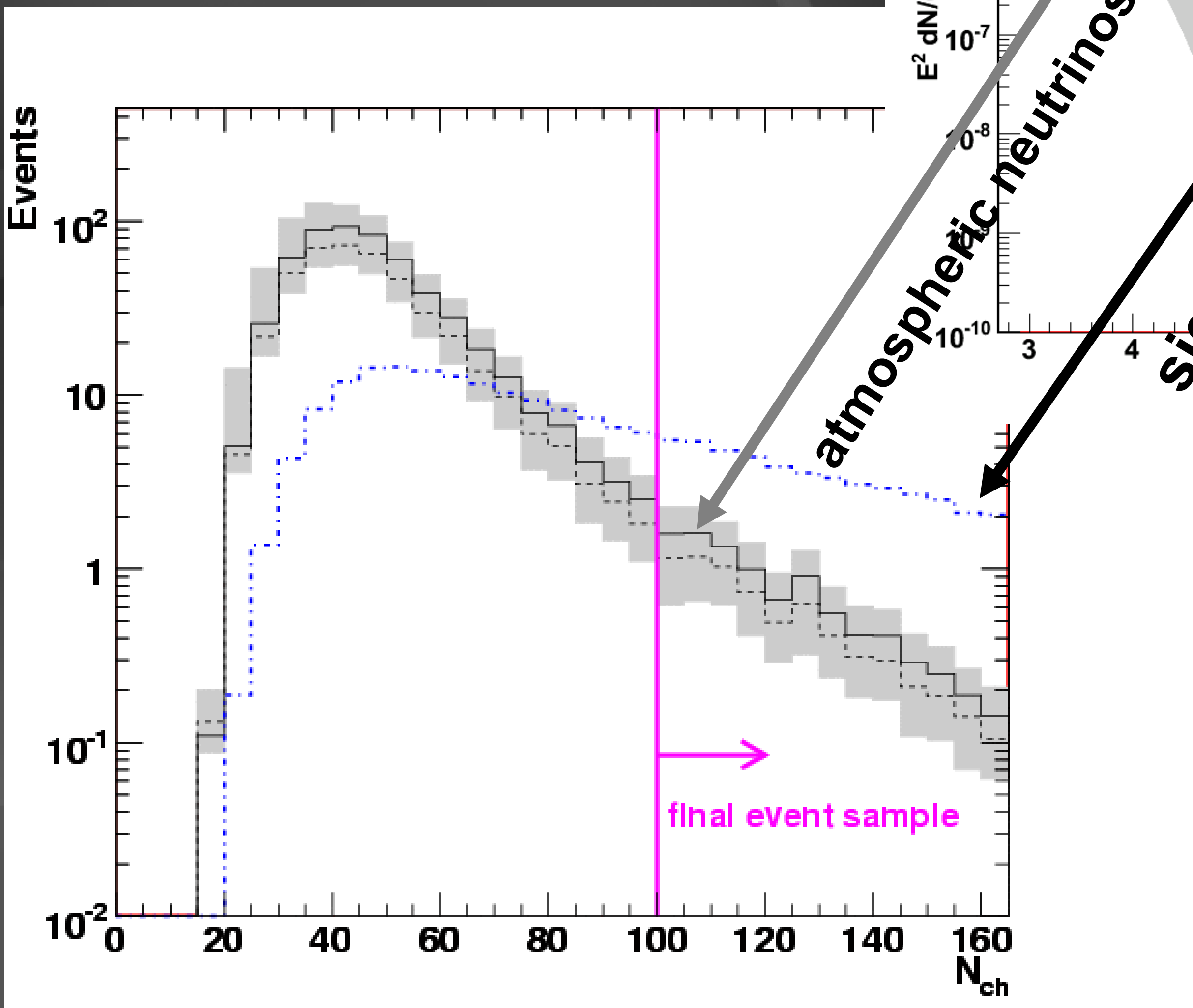


AMANDA II

flux

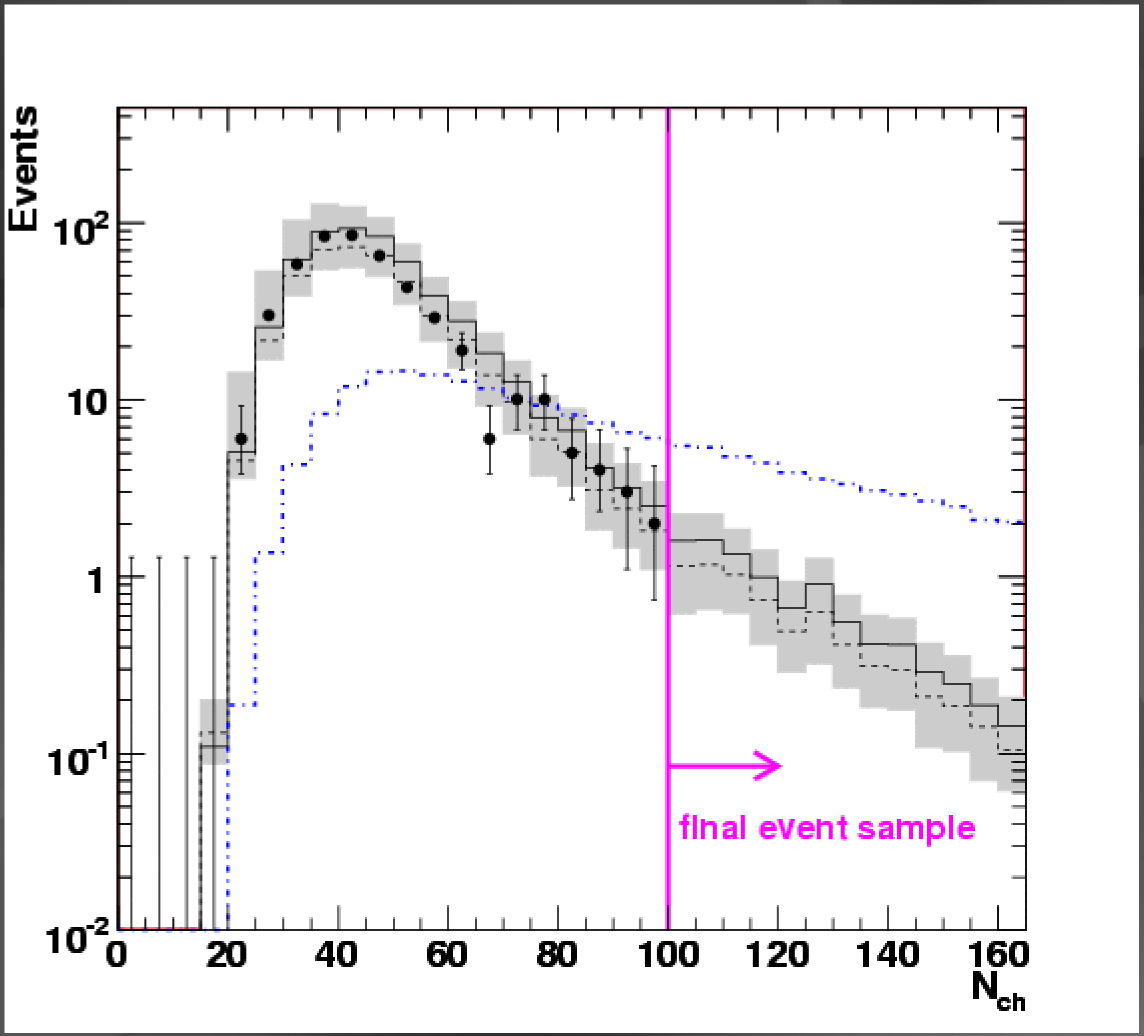


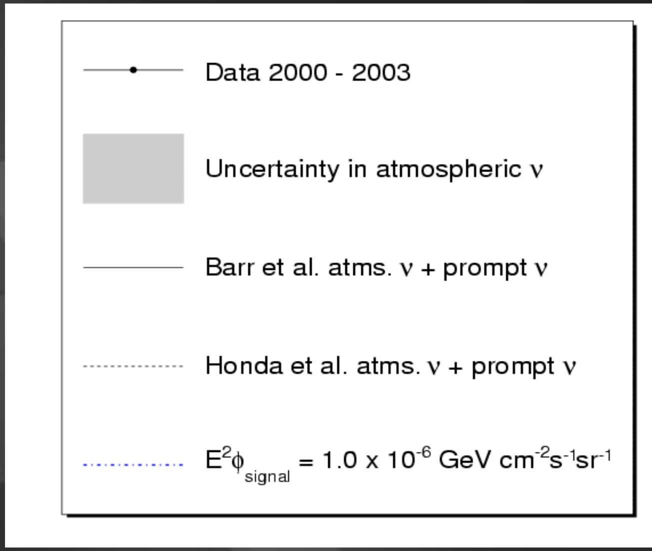
events predicted



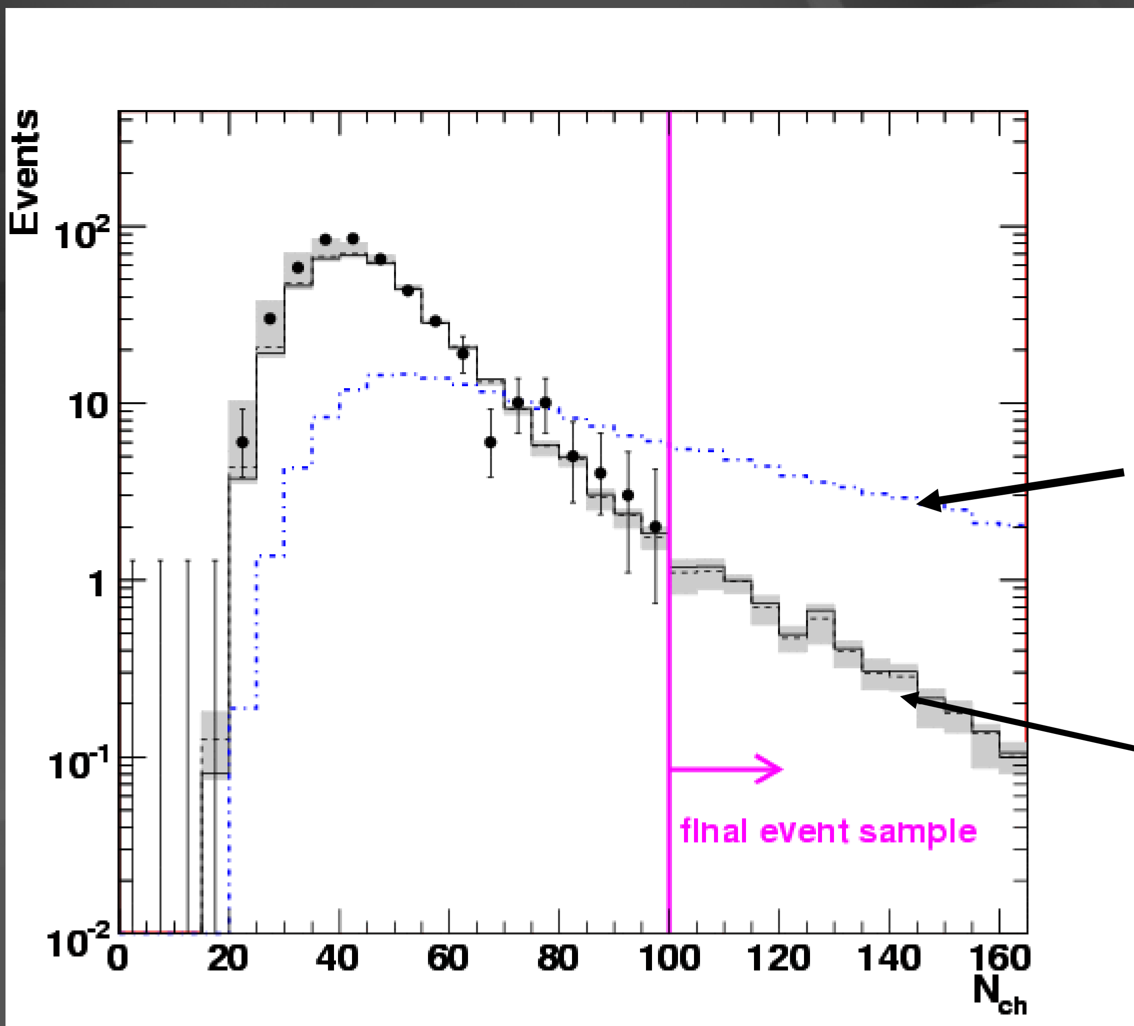
energy $\longrightarrow$ $N_{channel}$

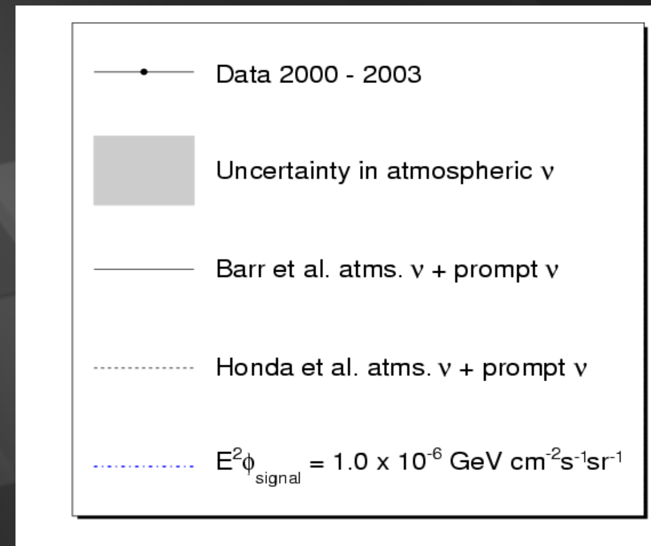
low energy data is compared to the simulation





the simulation is scaled so that the number of low energy events predicted matches the low energy data





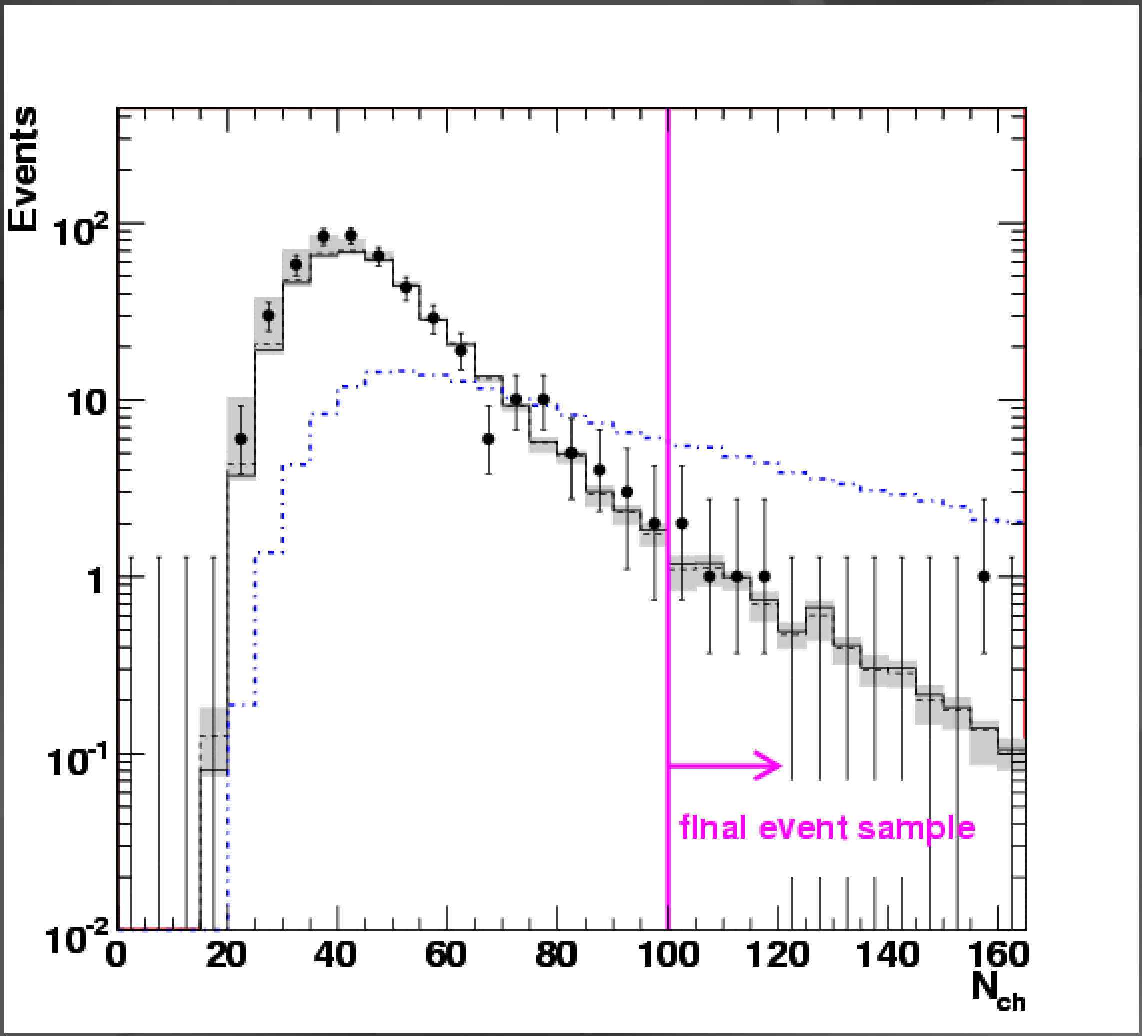
$E^2\phi_{signal} = 1.0 \times 10^{-6}$ GeV cm^{-2}s^{-1}sr^{-1}

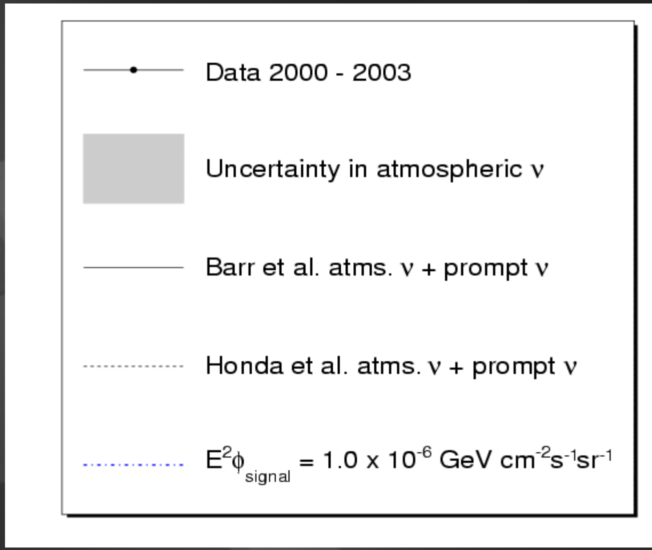
66.7 events

bkgd = 7.0 (6.1-8.3) events

high energy data set is unblinded

the number of high energy (N_{ch}>100) data events is counted and compared to the background simulation.

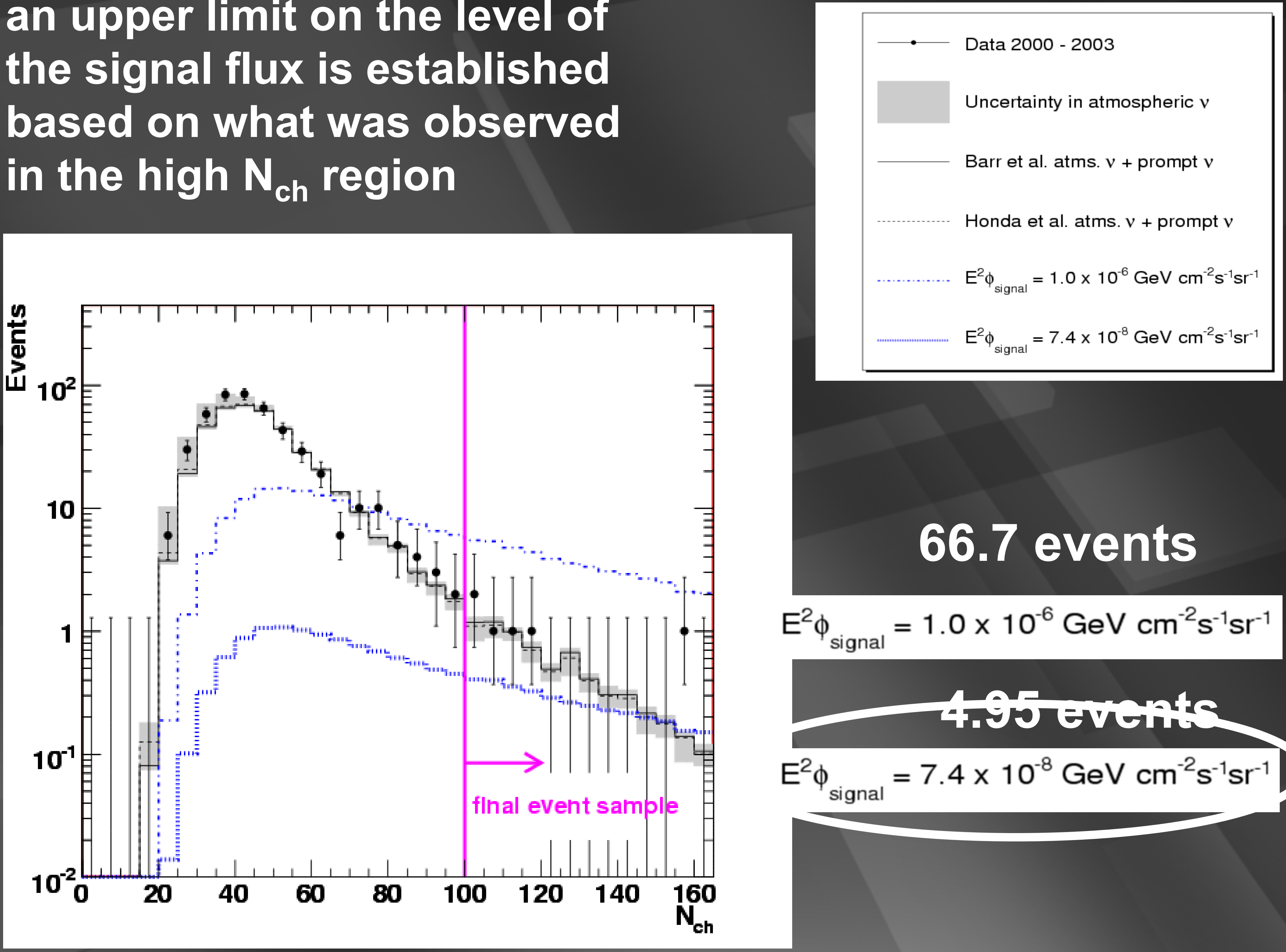




average background predicted = 7.0

6 data events observed

an upper limit on the level of the signal flux is established based on what was observed in the high N_{ch} region



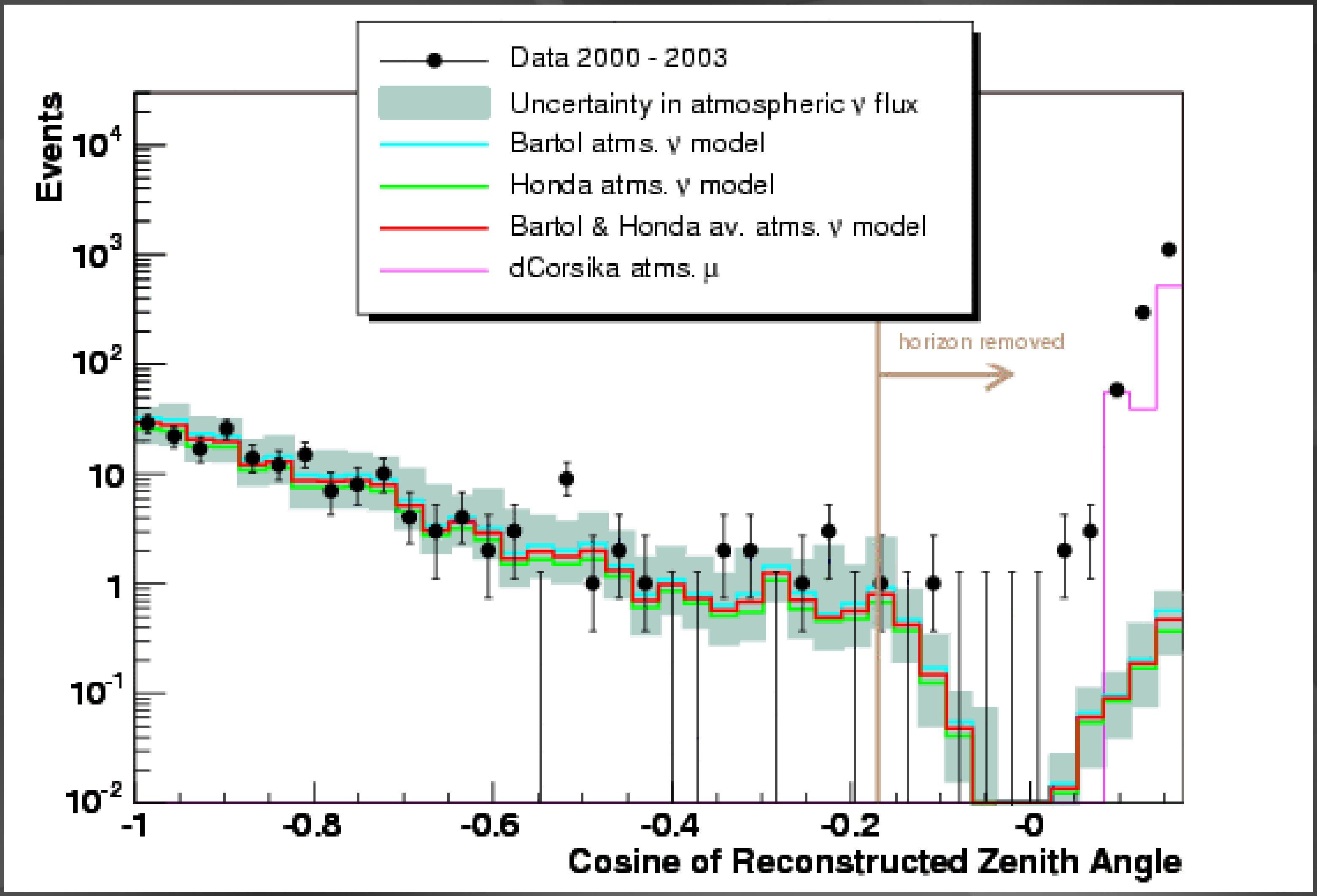
66.7 events

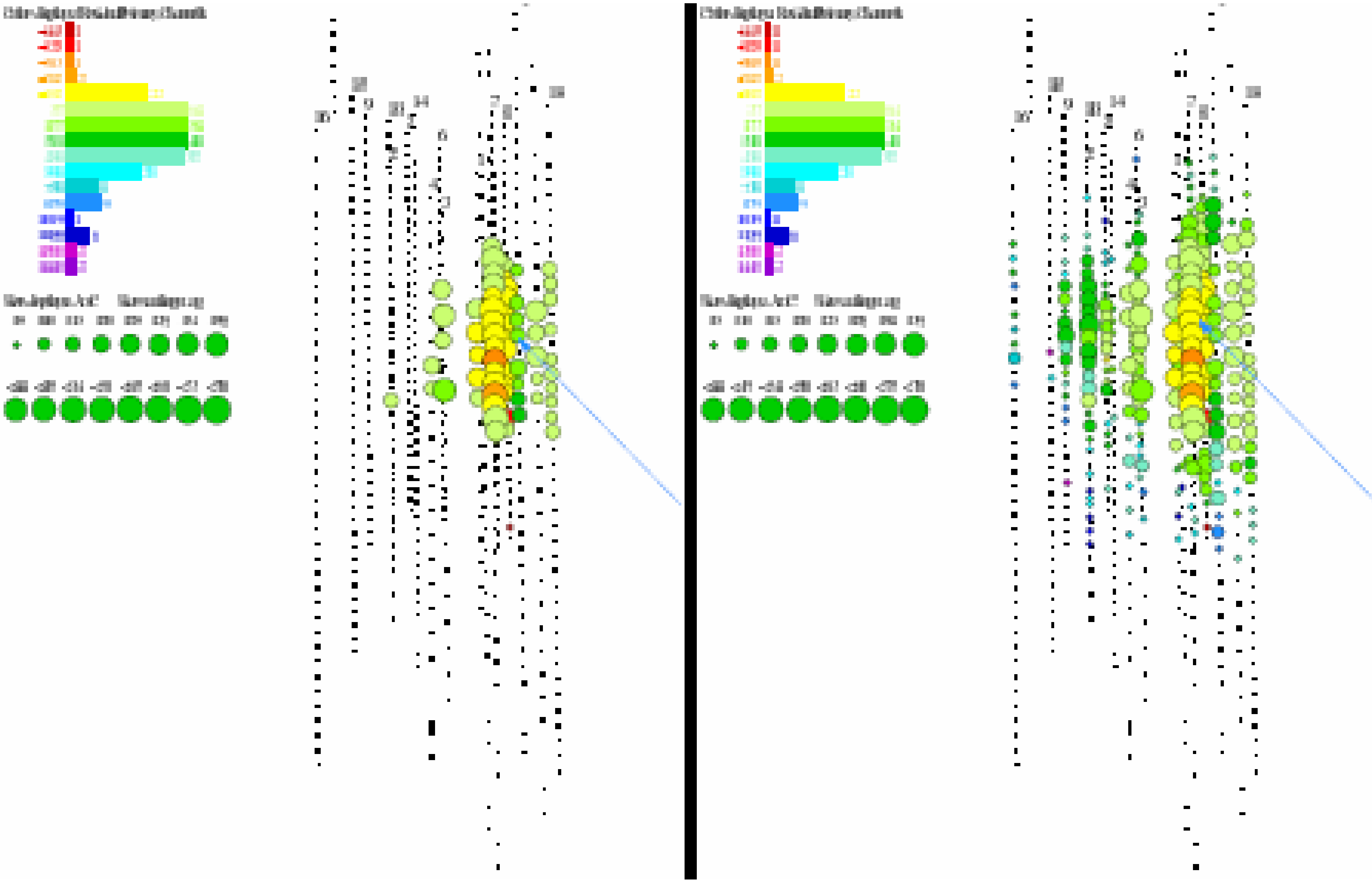
$E^2\phi_{signal} = 1.0 \times 10^{-6}$ GeV $cm^{-2}s^{-1}sr^{-1}$

4.95 events

$E^2\phi_{signal} = 7.4 \times 10^{-8}$ GeV $cm^{-2}s^{-1}sr^{-1}$

clean upgoing neutrino sample of atmospheric ν's:
no evidence for cosmic diffuse flux
– any point sources, extra high energy events, bursts ?



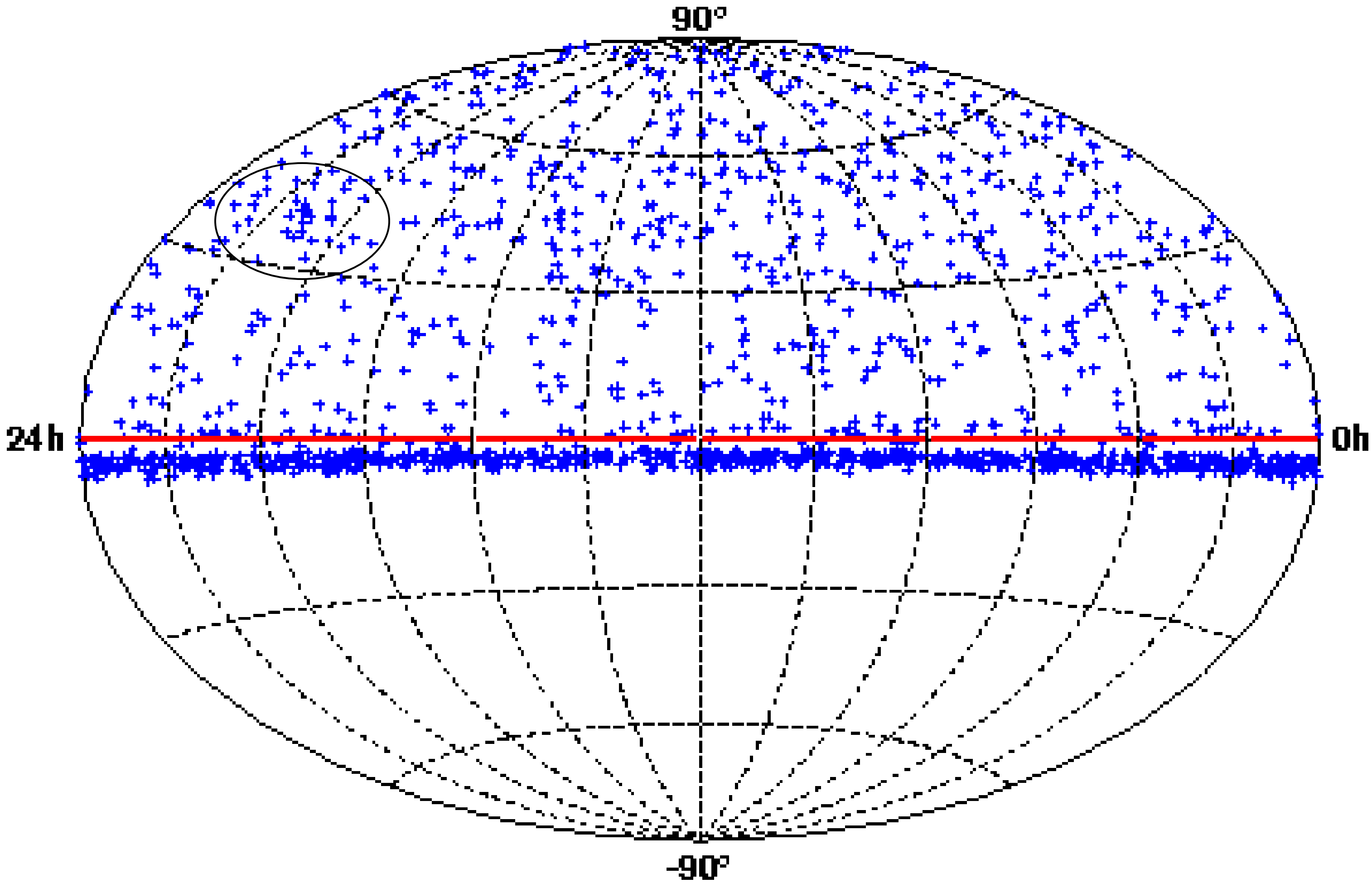


number of channels = 349

point sources and bursts

AMANDA II 2000

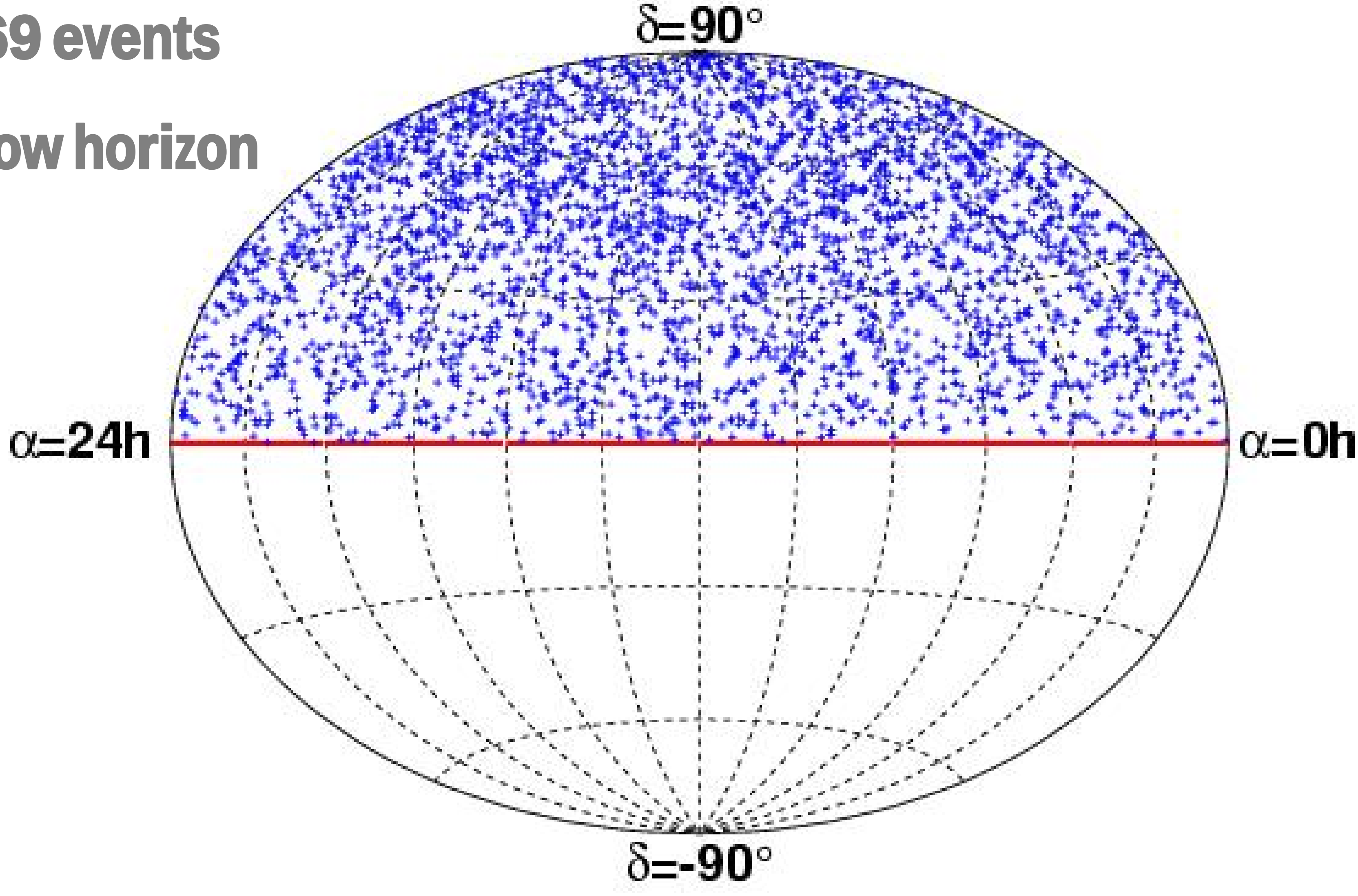
1555 Events

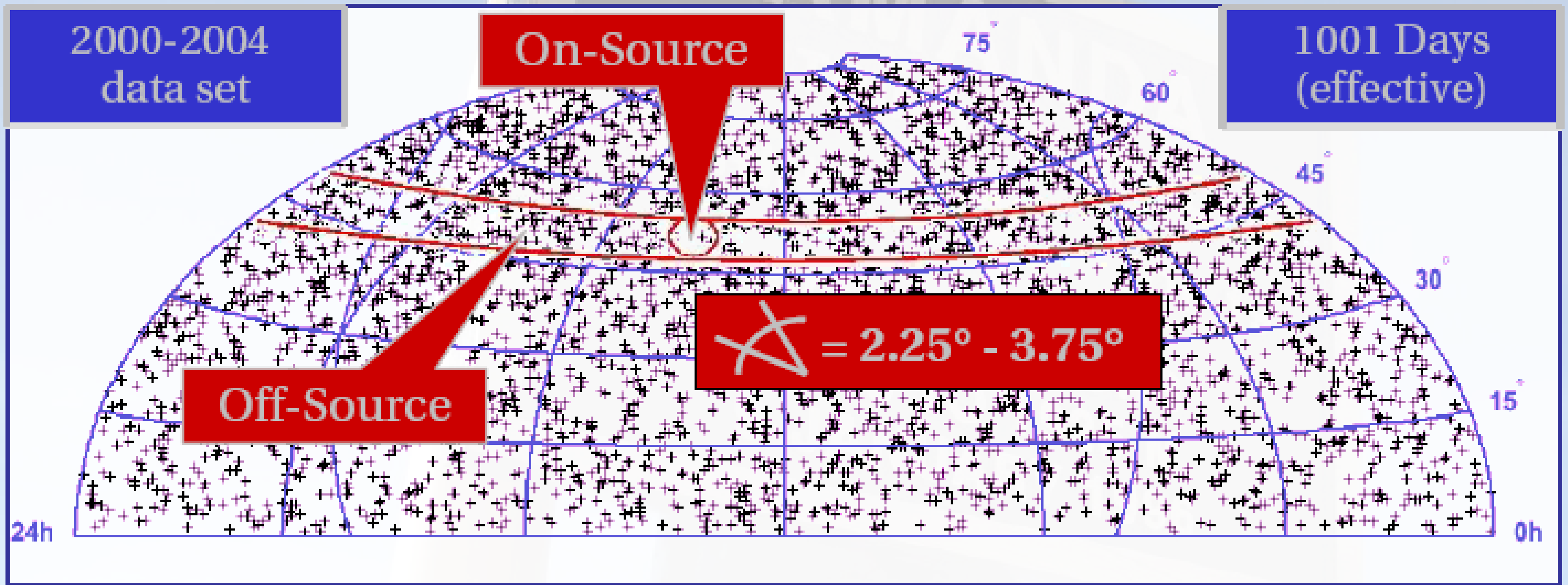


AMANDA skyplot 2000-2003

3369 events

below horizon

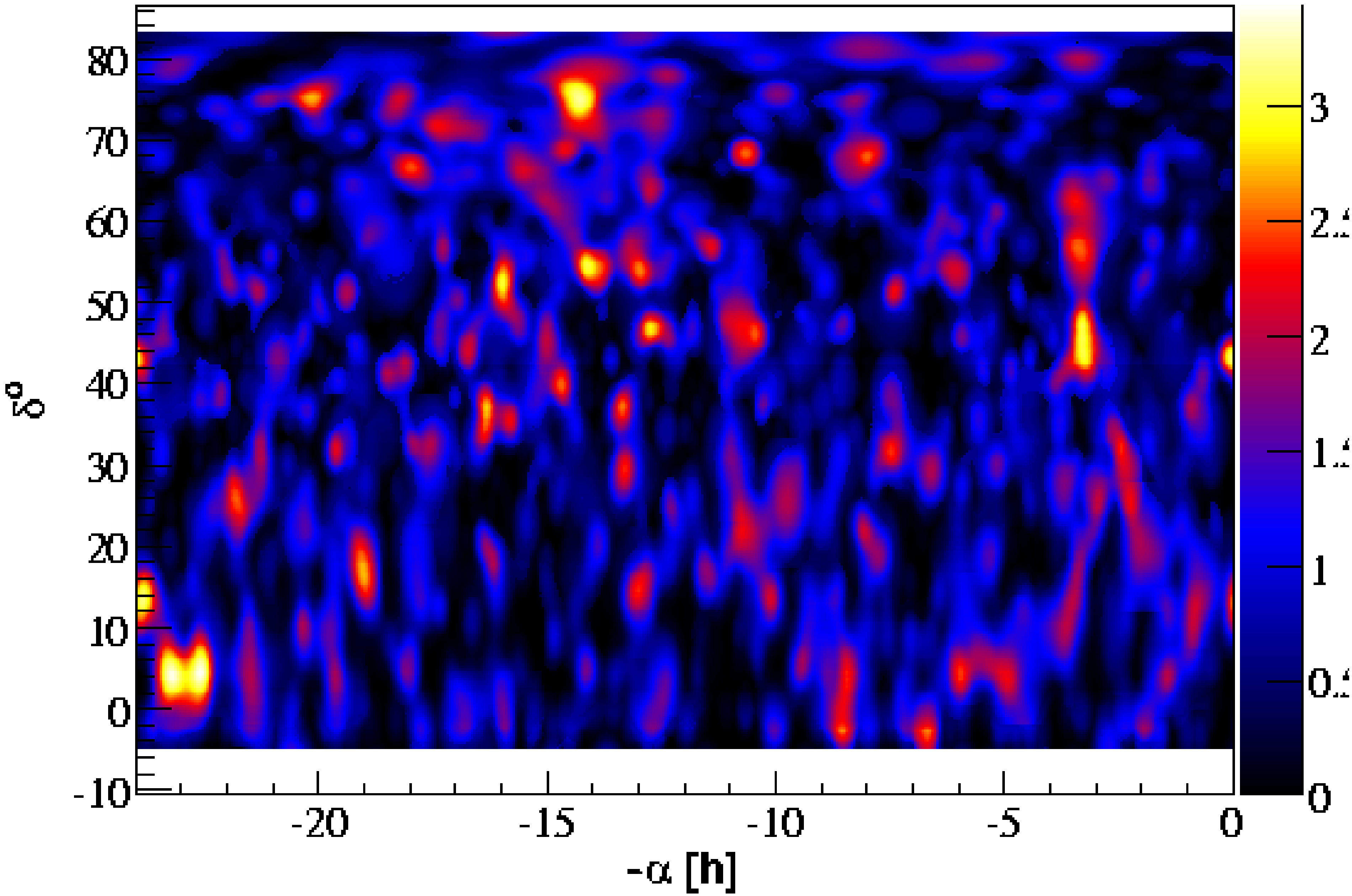




Source: M. Ackermann, DESY Zeuthen

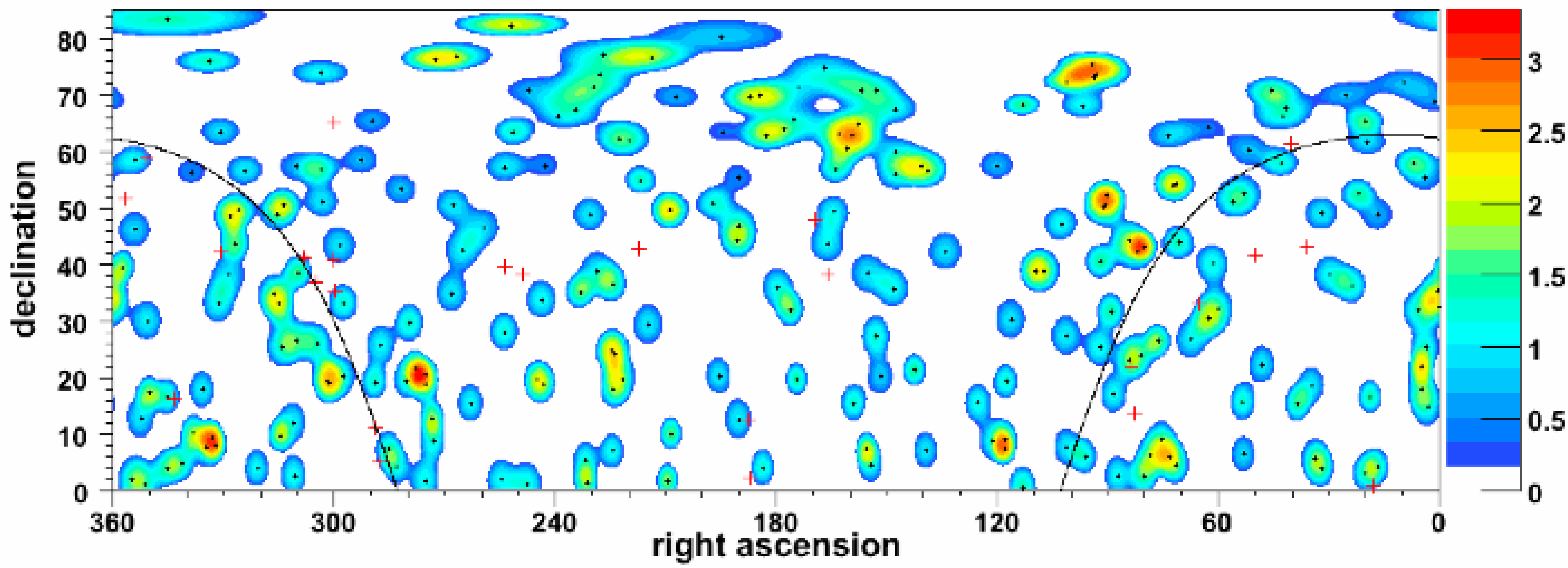
Neutrino-Data Set:	4282 Events
MC (atm. ν):	3627 – 4912 Events

search for point sources 5 year data



seven year data soon: unbinned analysis

first IceCube sky



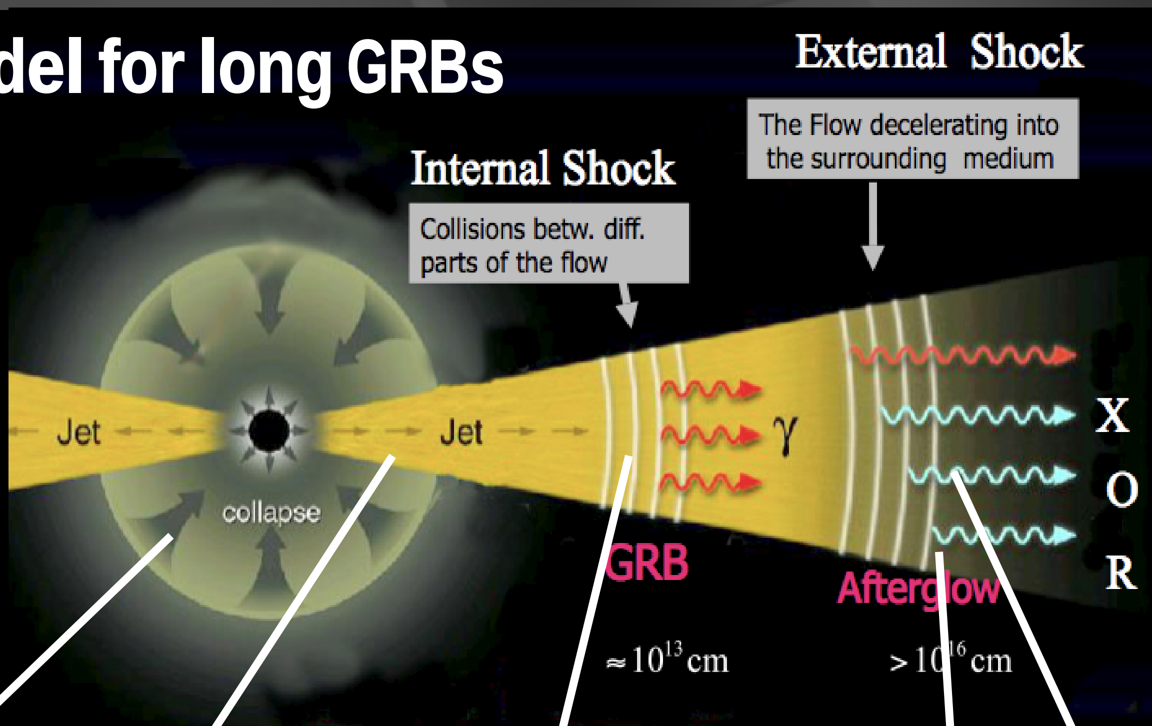
search for clusters of events in the Northern sky

	Source	Events observed/ background (2000-2004)	Excess parameter -log10 P	Flux upper limit (15% sys, 7% stat) Φ_0 @ 90% CL [10^{-7} GeV cm^{-2}s^{-1}] for $\Phi = \Phi_0 E^{-2}$	
				$\Phi_0(\nu_\mu)$	$\Phi_0(\nu_\mu+\nu_\tau)$ (1:1)
AGN	Markarian 421	**6 / 7.37**	0.13	0.42	0.74
AGN	Markarian501	**8 / 6.39**	0.51	0.85	1.47
AGN	1ES1959+650	**5 / 4.77**	0.29	0.78	1.35
AGN	M87	**6 / 6.08**	0.25	0.49	0.87
AGN	3C273	**8 / 4.72**	0.98	1.00	1.80
Microquasar	SS433	**4 / 6.14**	0.06	0.27	0.48
Microquasar	LSI +61 303	**5 / 4.81**	0.28	0.74	1.26
Microquasar	Cygnus X-1	**8 / 7.01**	0.39	0.77	1.32
Microquasar	Cygnus X-3	**7 / 6.48**	0.50	0.68	1.18
SNR	Cassiopeia A	**5 / 6.00**	0.15	0.51	0.89
SNR	Crab Nebula	**10 / 6.74**	0.84	1.02	1.78

- 32 sources selected to reduce **trial factor**

GRB as sources of high-energy neutrinos

Fireball model for long GRBs



PeV neutrinos from internal shock

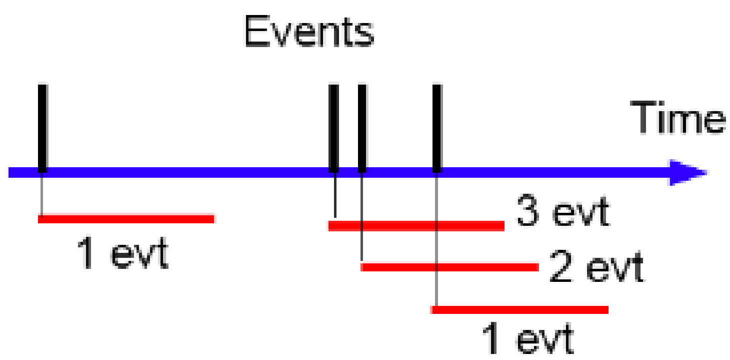
MeV neutrinos at collapse

EeV neutrinos from external shocks

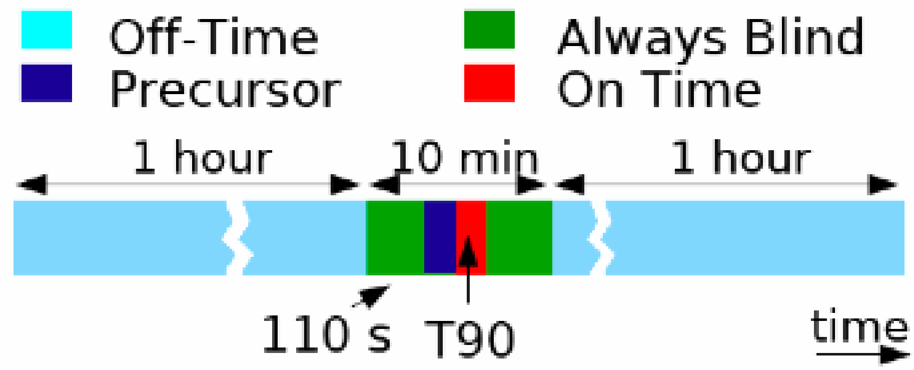
TeV neutrinos from inside the star

PeV-EeV neutrinos from flares

GRB/transient search strategies

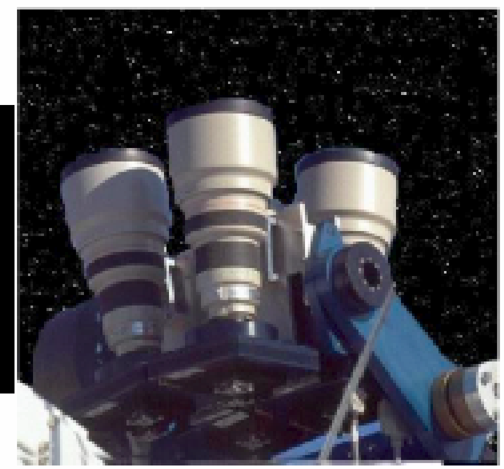


Rolling Search



Satellite Triggered Search

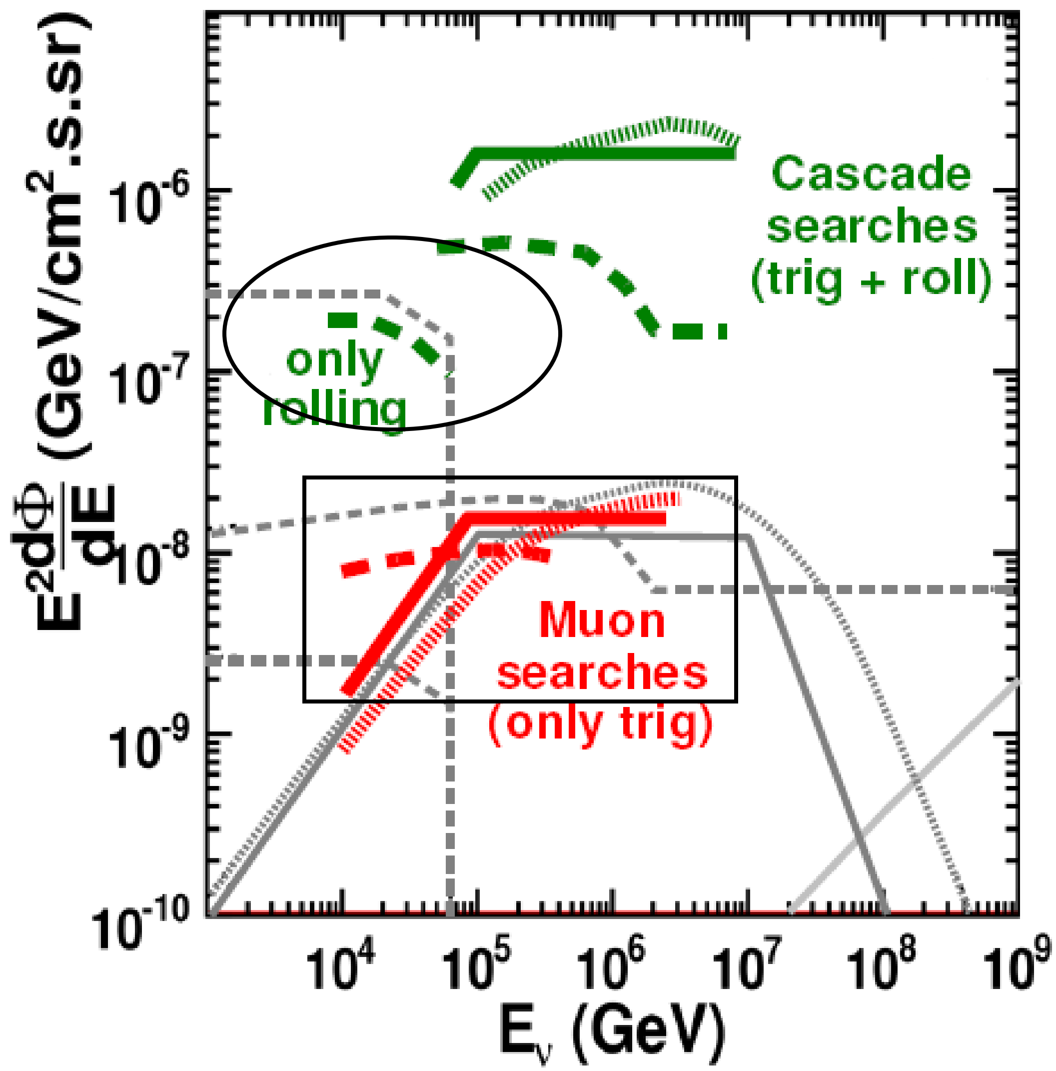
time and directional correlation reduces background and increases sensitivity

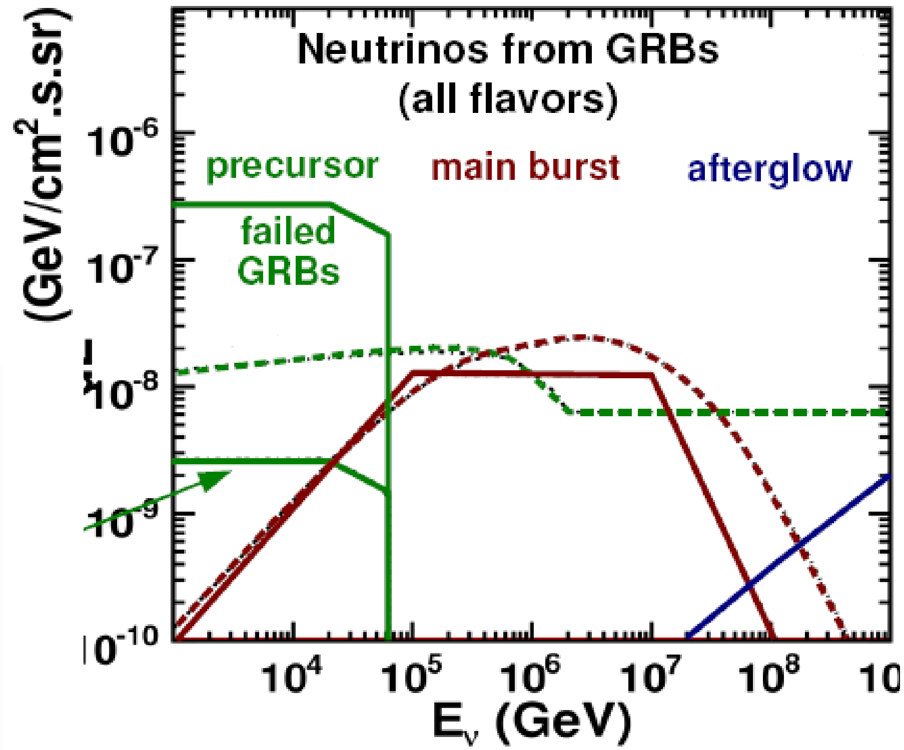


Optical Follow-up

420 GRB searched

multiplied with E² !



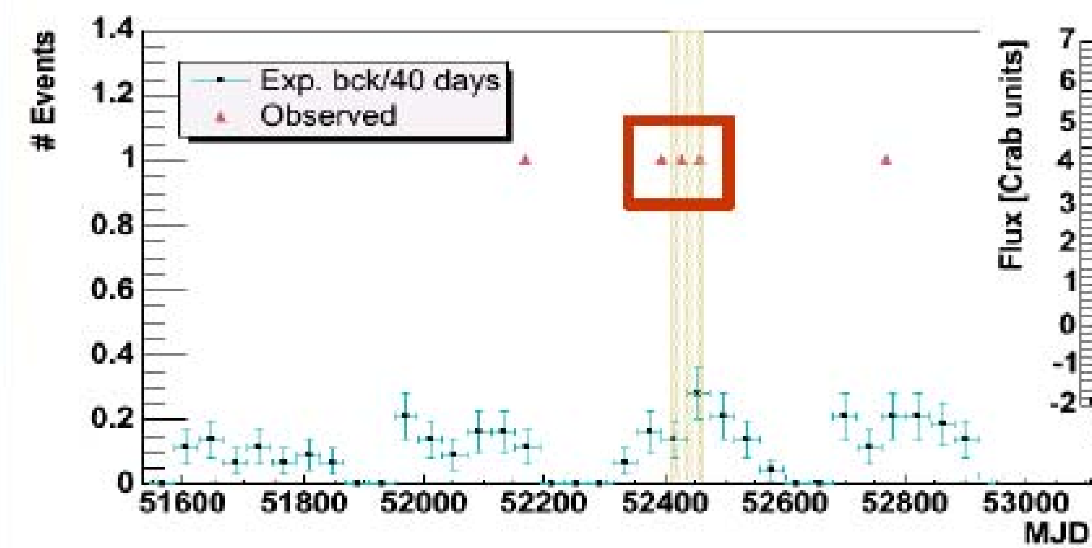


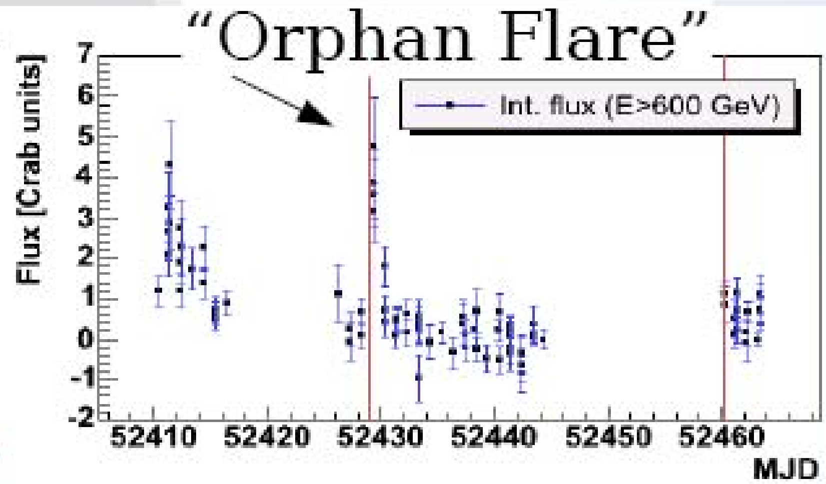
- AMANDA starts to exclude models
- IceCube will reach 70 times the instrumented volume in 2009

multiwavelength campaign

1ES 1959:

- 5 Events from 2000 to 2003, 3.7 expected
- Three of those events took place within 66 days, partially overlapping with period of strong VHE emissions
- One event coincident with “orphan flare” (low x-ray flux, strong TeV flux)



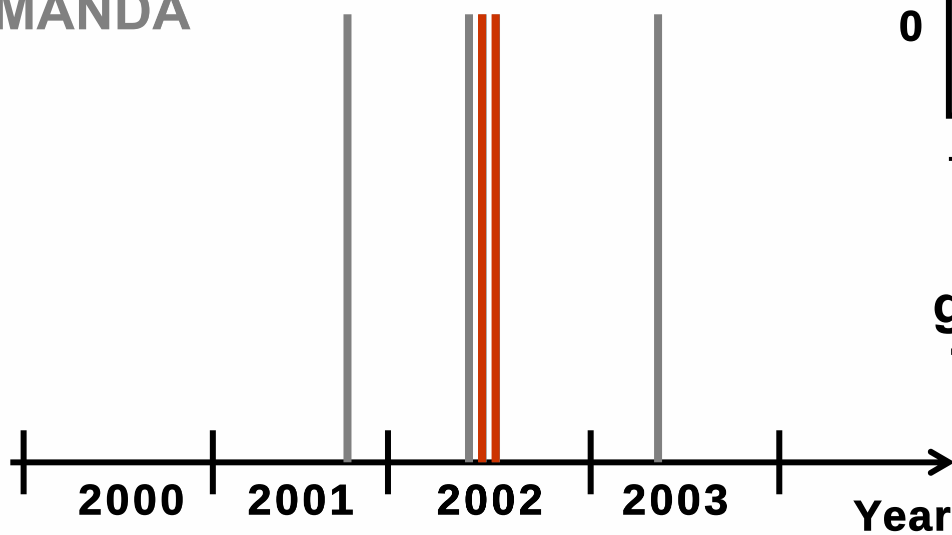


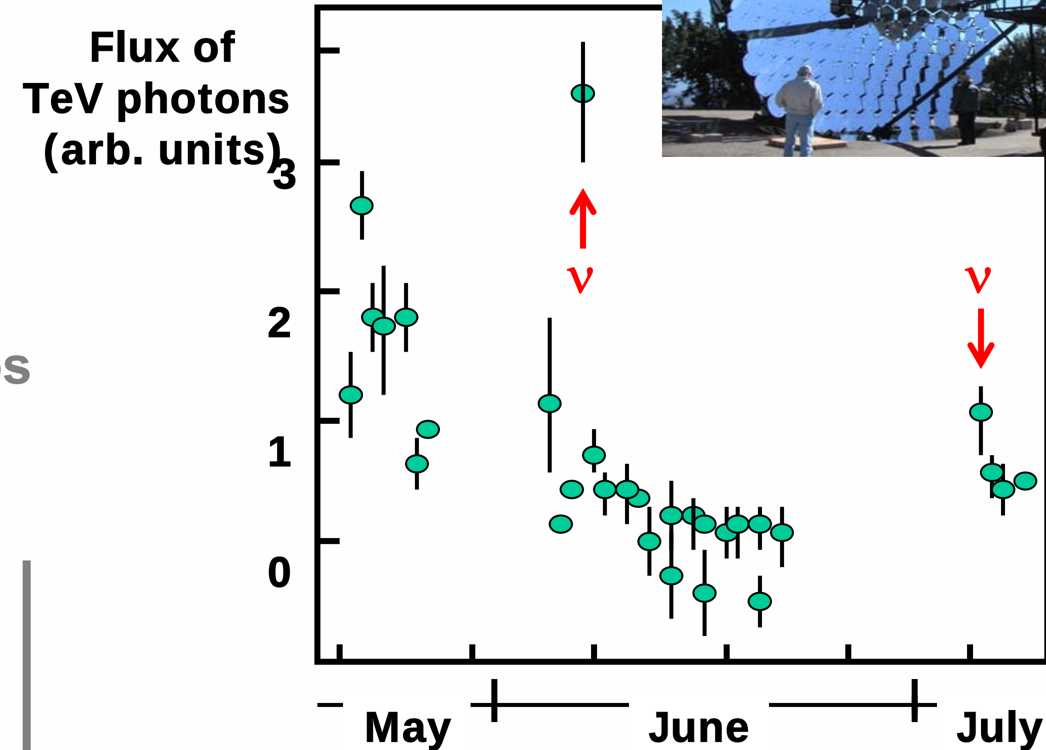
Events within 2.25° of 1ES 1059

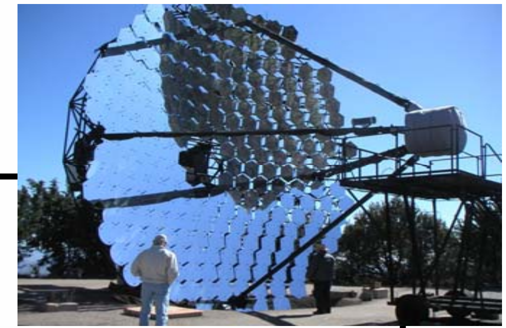
Whipple-Data [Holder et al 2003]

need a larger detector

Arrival time of the neutrinos from the direction of ES1959+650 detected by AMANDA







gamma-rays detected by TeV gamma telescopes

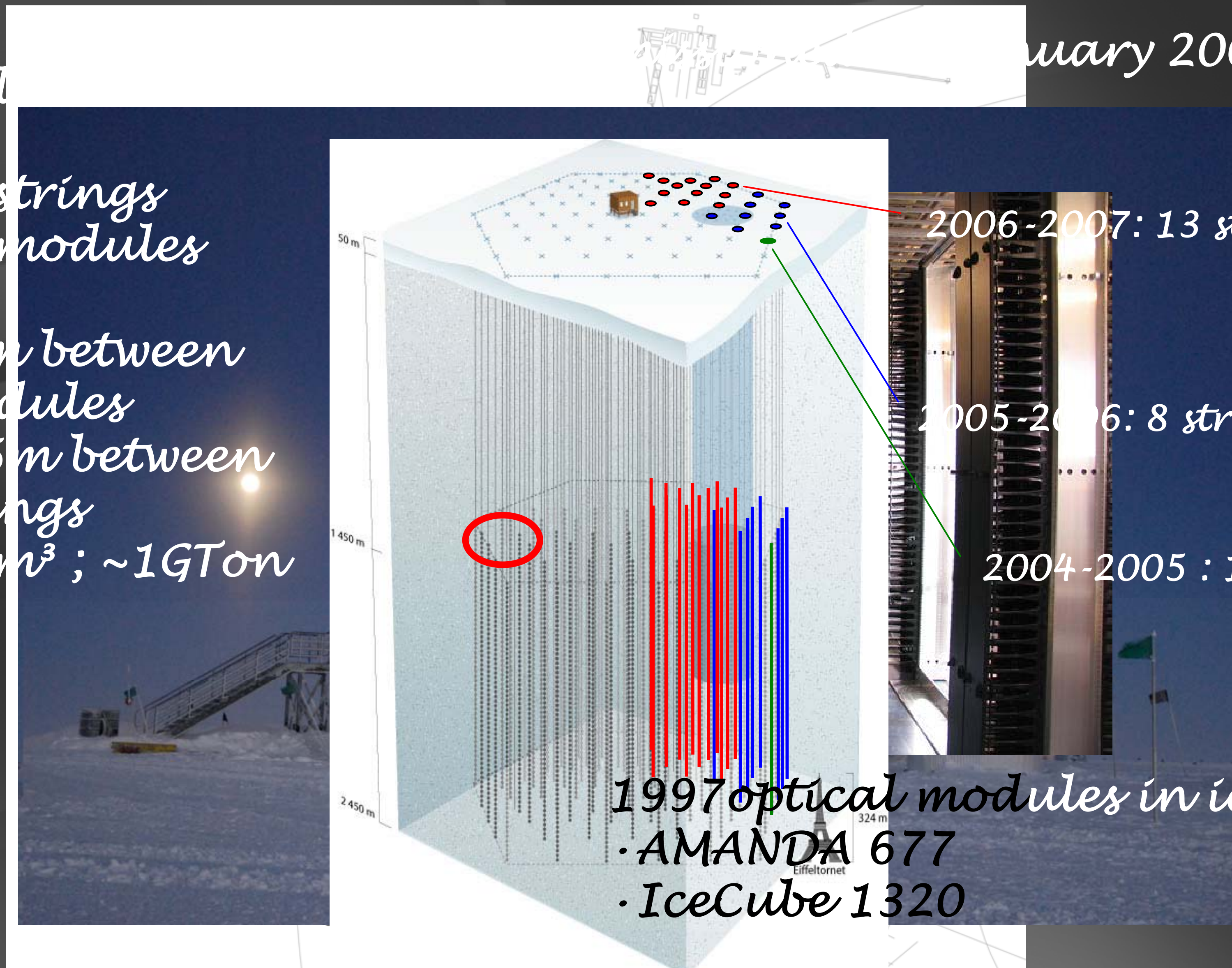
menu

- introduction : it's the technology
- cosmic neutrinos associated with cosmic rays
- cosmic neutrinos associated with TeV gamma rays
- progress through technology : first generation neutrino telescopes Antares and Amanda
- kilometer-scale neutrino detectors… now
- particle physics
- conclusions

IceCube deployments

Compl … uary 2007

- 80 strings 60 modules each
- 17m between modules
- 125m between strings
- 1 km³ ; ~1GTon



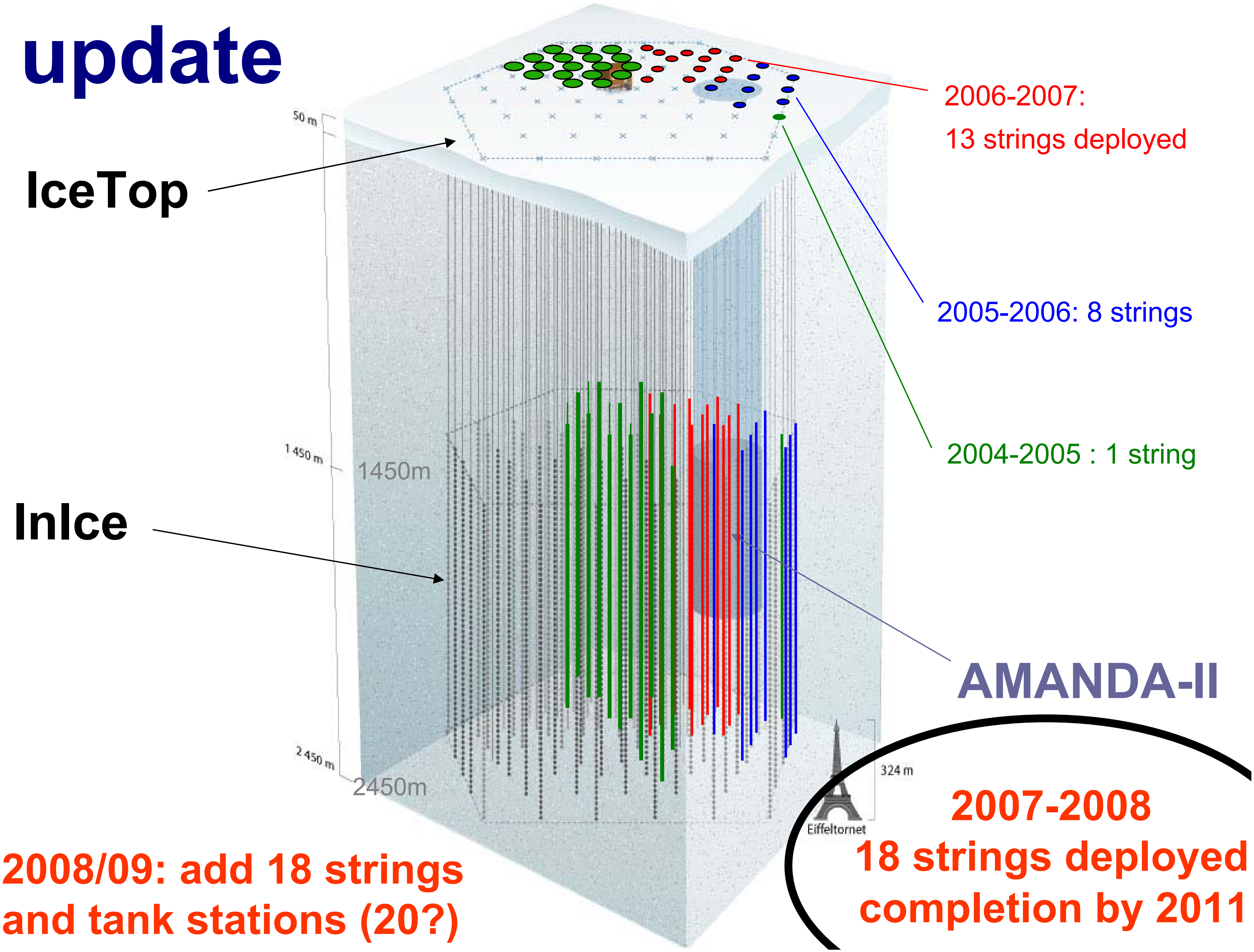
2006-2007: 13 strings

2005-2006: 8 strings

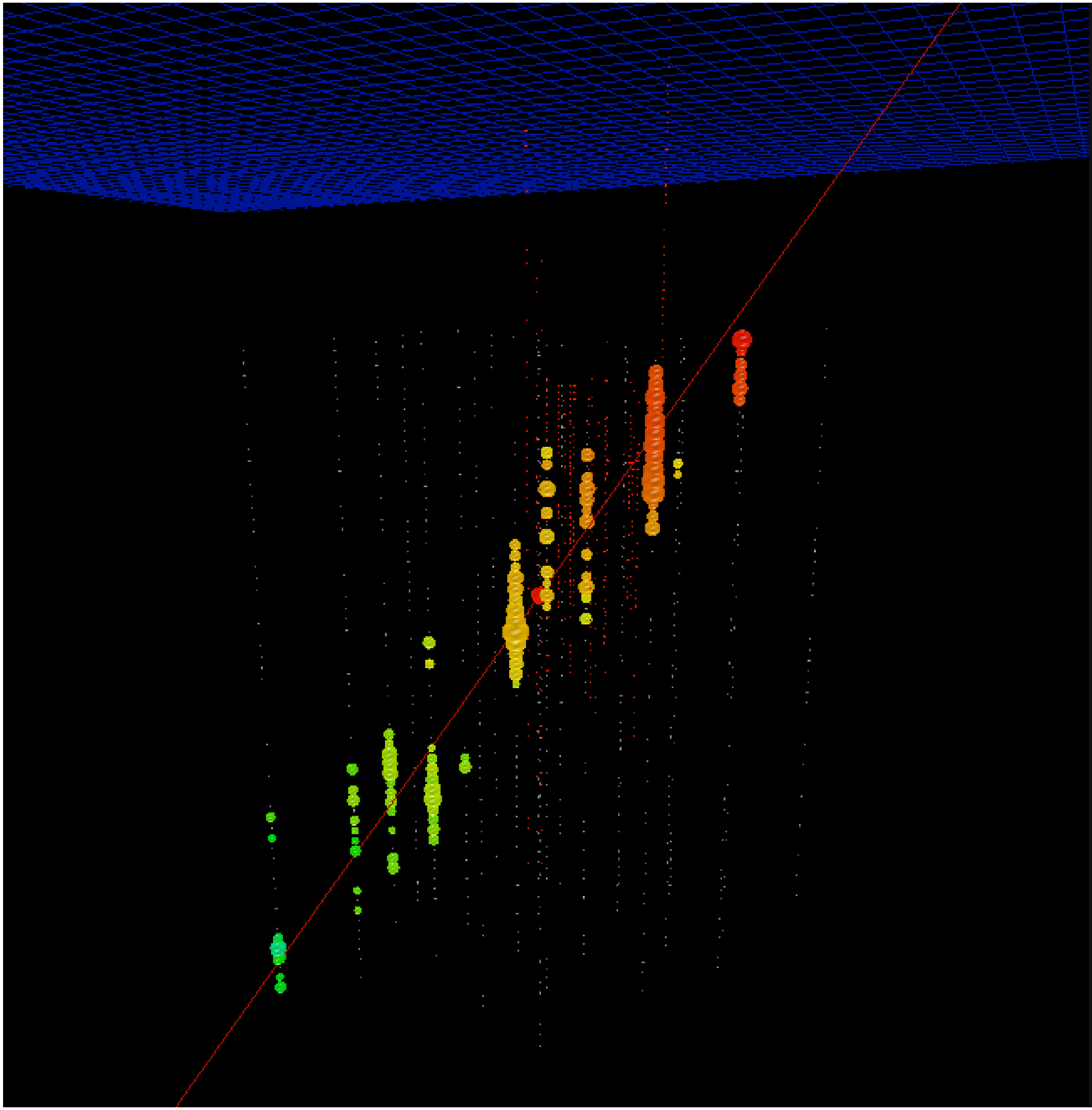
2004-2005 : 1 string

1997 optical modules in ice:
- AMANDA 677
- IceCube 1320

update



2008/09: add 18 strings
and tank stations (20?)



IceCube event

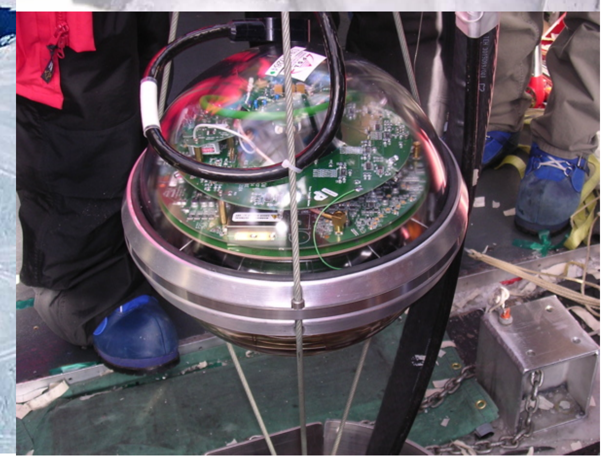
22 strings

AMANDA and IceCube

AMANDA	IceCube
2 megawatt drilling	4.8 megawatt drilling
Analog signals to surface	In-ice signal digitization
ADC/TDC	Full Waveform recording
Saturation for multiple p.e. signals	Larger dynamic range
1 ms deadtime	No deadtime
Hardware Trigger	Software Trigger
Depth ~ 1500-2000m	Depth 1450-2450 m
String spacing Vertical: 10-20 m Horizontal: 55-75 m	String Spacing Vertical: 17 m Horizontal: 125 m
Instrumented Volume .015 km^3	Instrumented Volume ~ 1 km^3

IceCube is both larger and technologically superior

IceCube construction

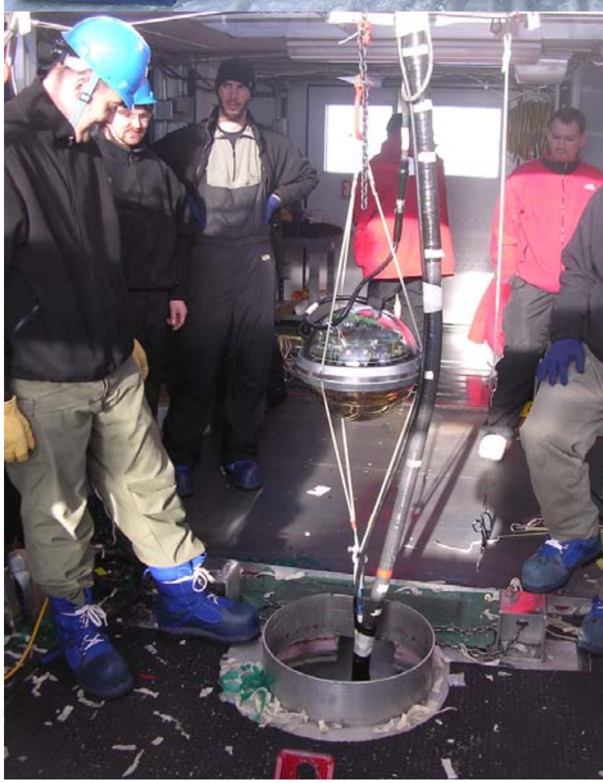


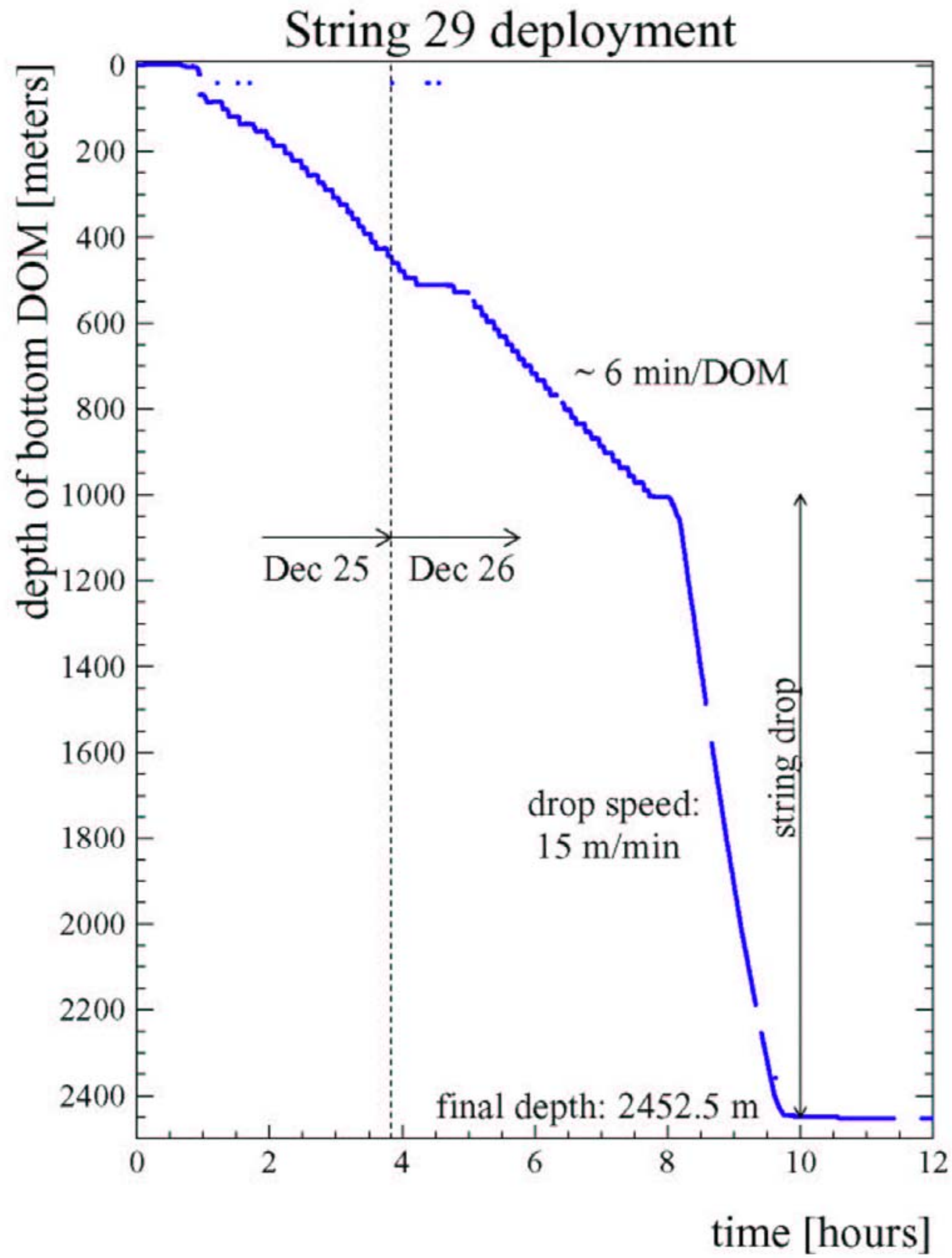
- 1 million pounds of cargo
- C-130 planes: > 50 flights

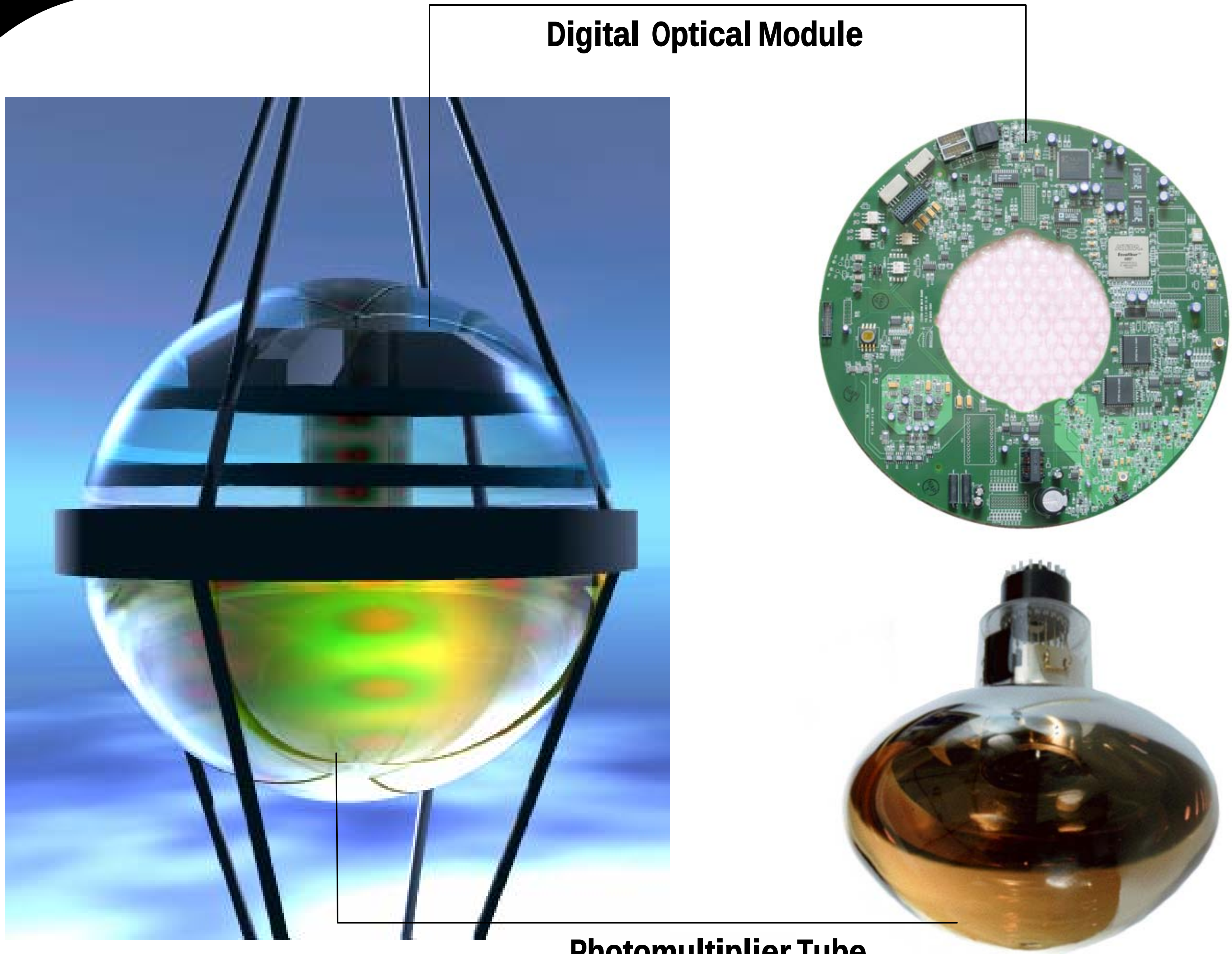

5 megawatt power plant

one of 21 drill modules arrive in antarctica

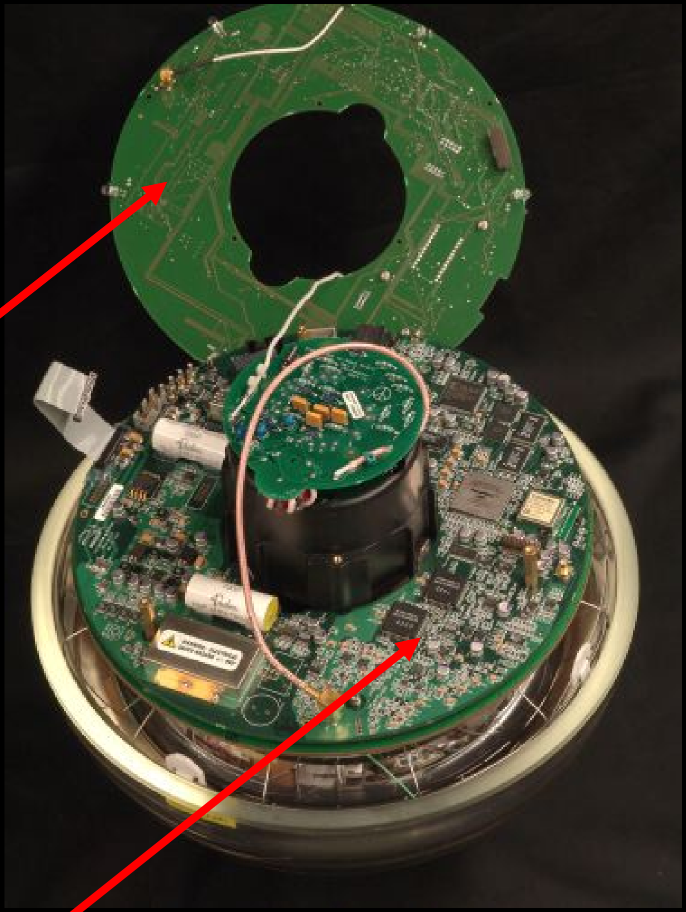
String cable 2500 m   Weight ~6 tons

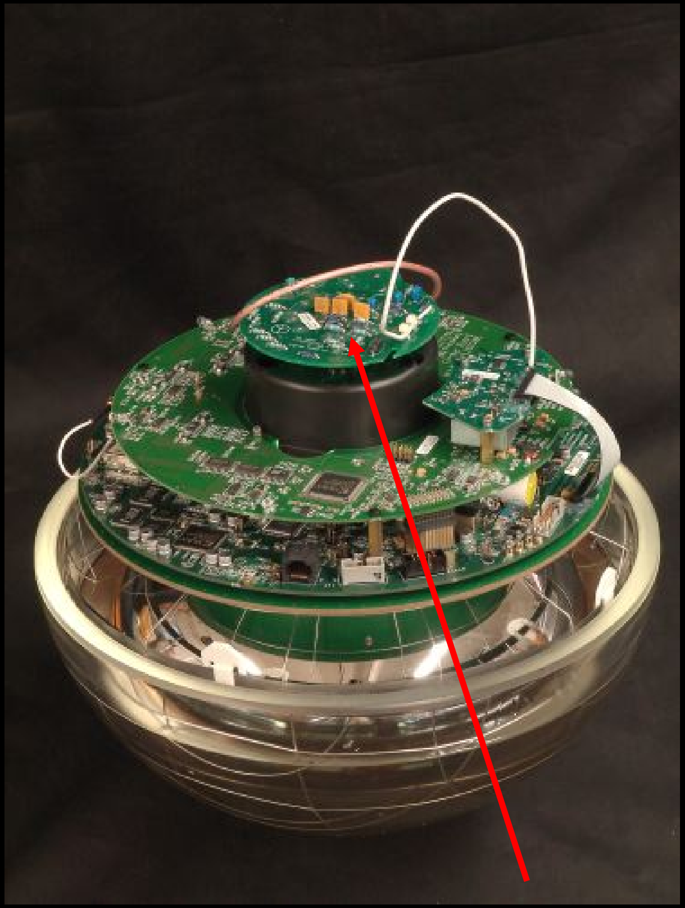





Digital Optical Module
Photomultiplier Tube

Digital Optical Module



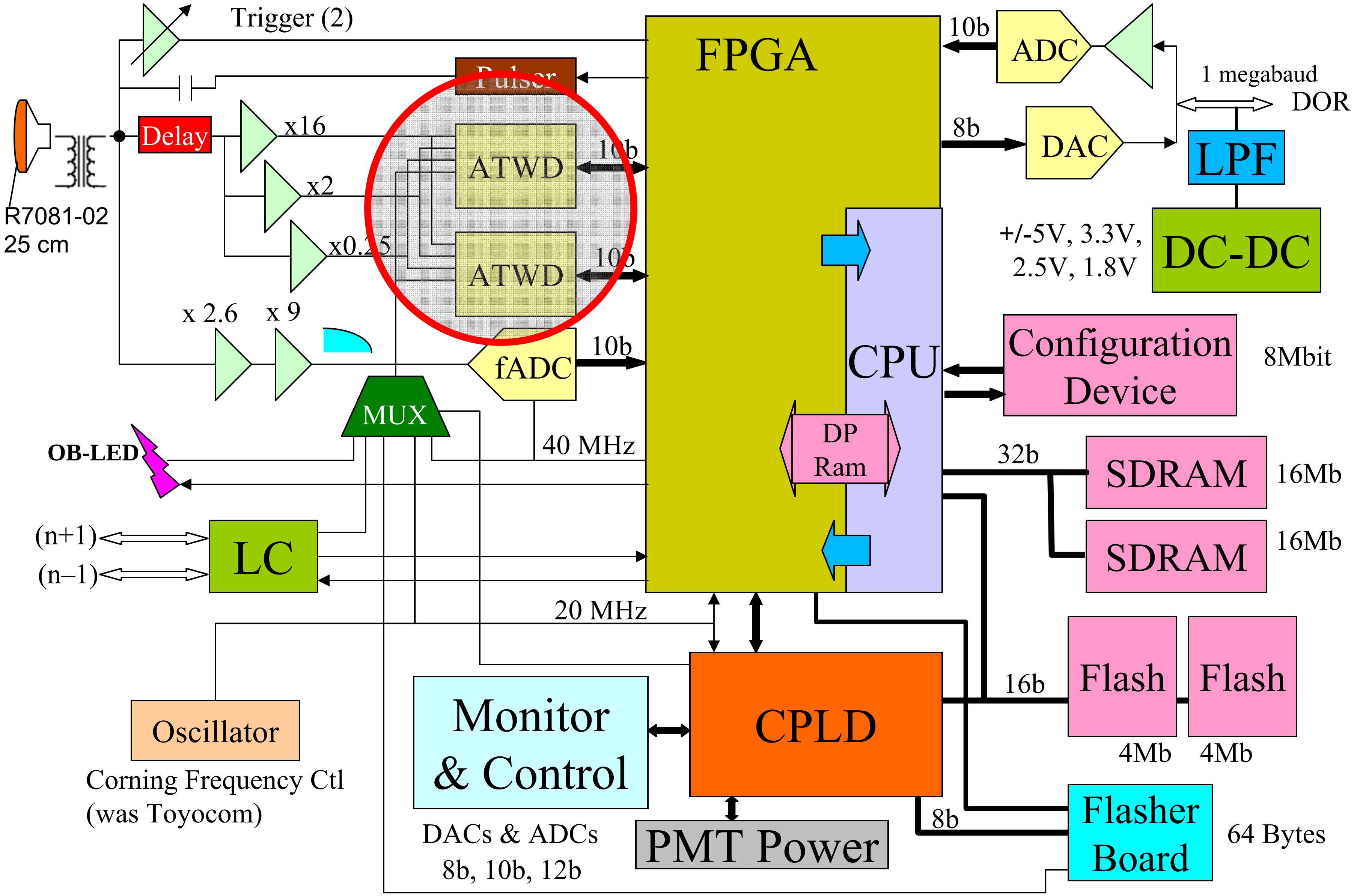


LED flasher board

main board

HV board

DOM MB Block diagram



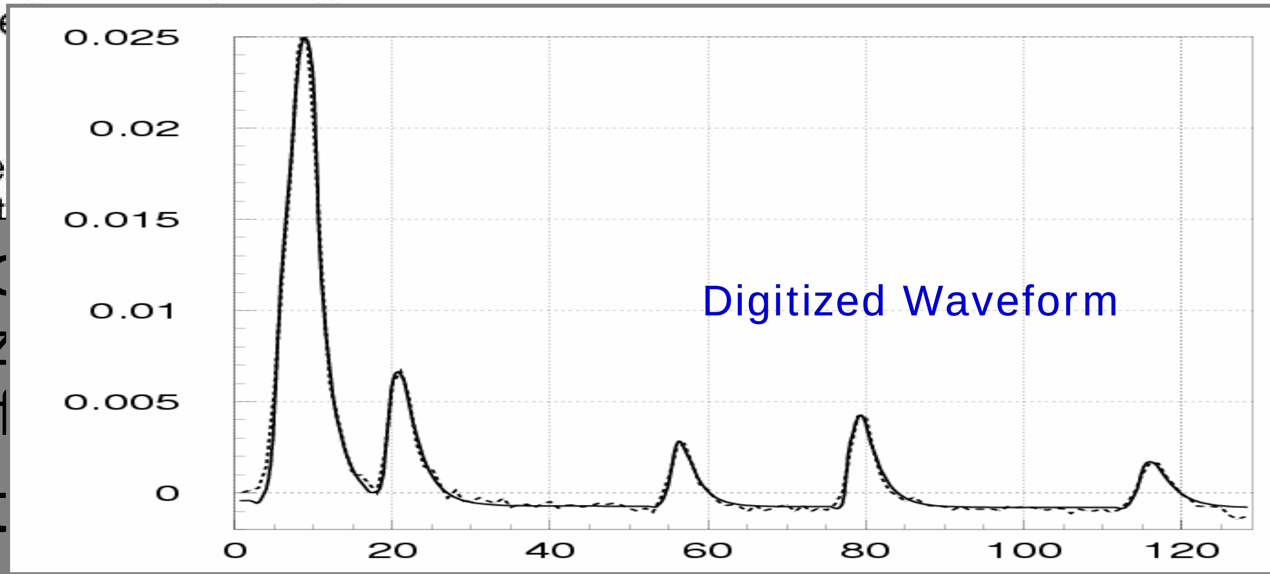
The Digital Optical Module (DOM)

Cable

High Voltage

Digital Cont

- Onboard c
  - 300 MHz
  - 40 MHz f
- Absolute t
- Dynamic range ~1000 p.e./10 ns
- Deadtime < 1%
- Noise rate ~700 Hz (260 Hz w/ artif. deadtime)
- Failure rate < 1%



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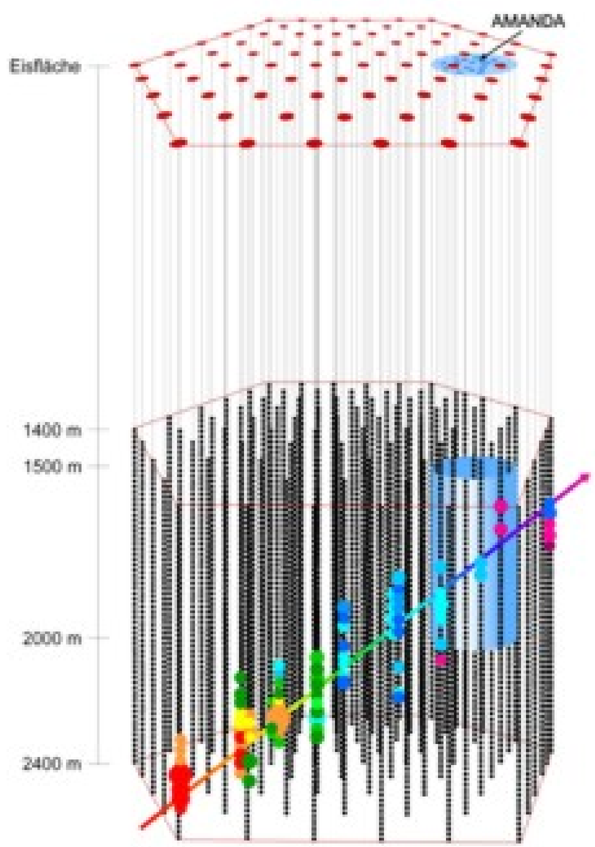
IceCube



• in the next 10 years IceCube will observe

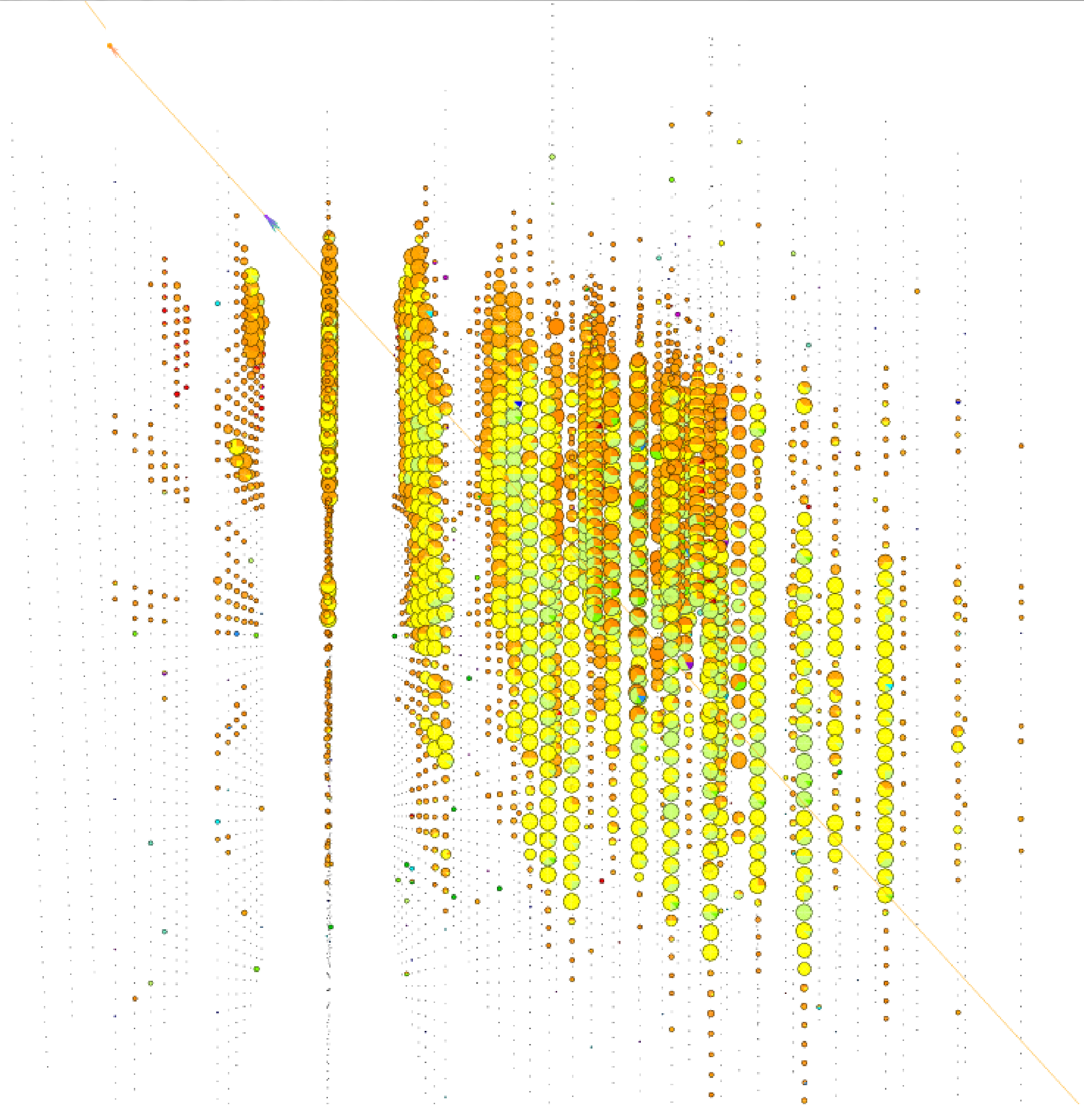
$\sim 10^6$ neutrinos with energies 0.1—1,000 TeV

• guaranteed: made in the interactions of cosmic rays with the Earth's atmosphere

• with m~0.01 eV and E~100 TeV the Lorenz factor of the neutrino is

$$\gamma = \frac{E_\nu}{m_\nu} \approx 10^{16}$$

GZK event: cosmic ray + cmb photon → 10 EeV neutrino



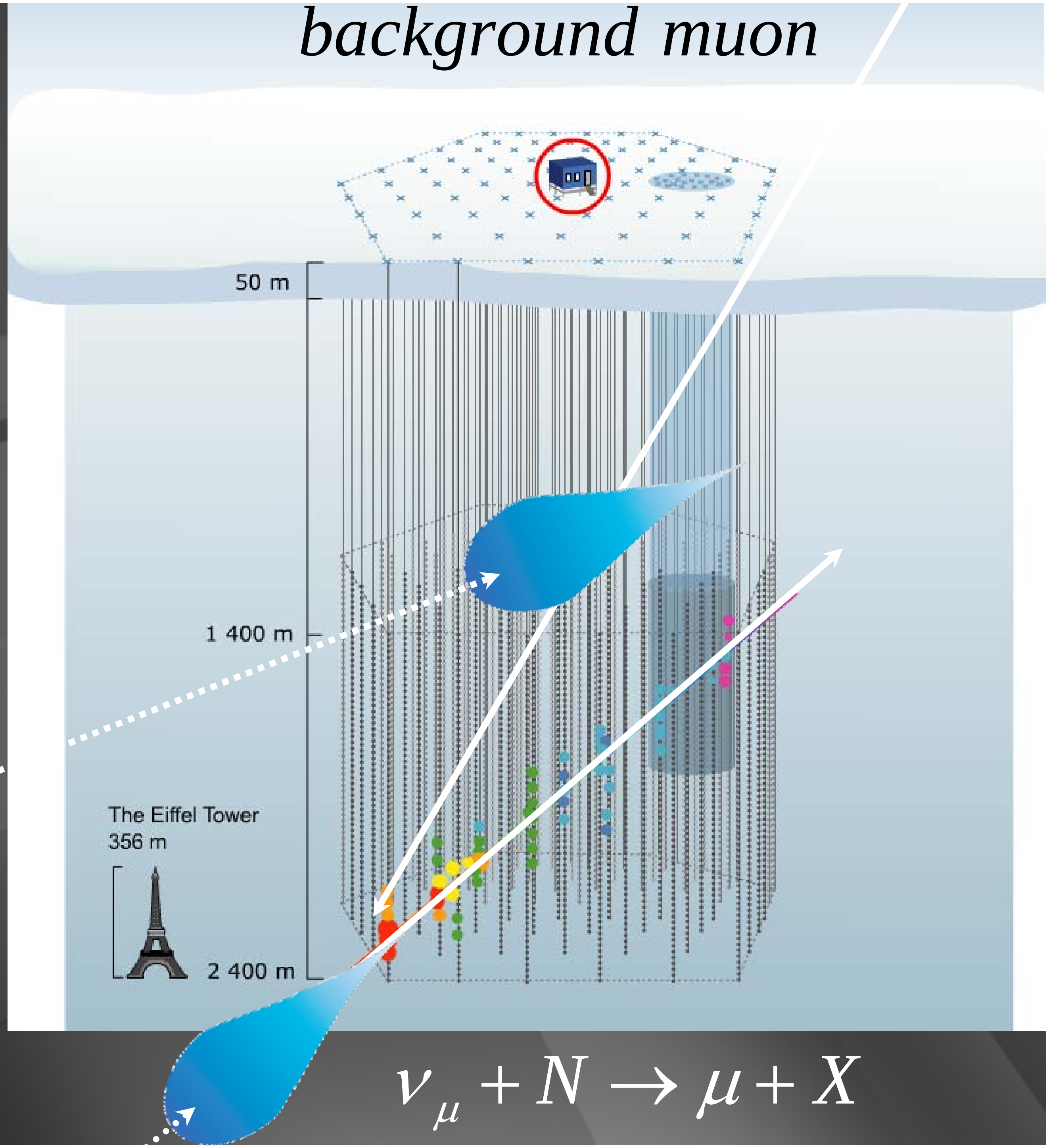
Direction:

Reconstruction of Cerenkov cone

Energy:

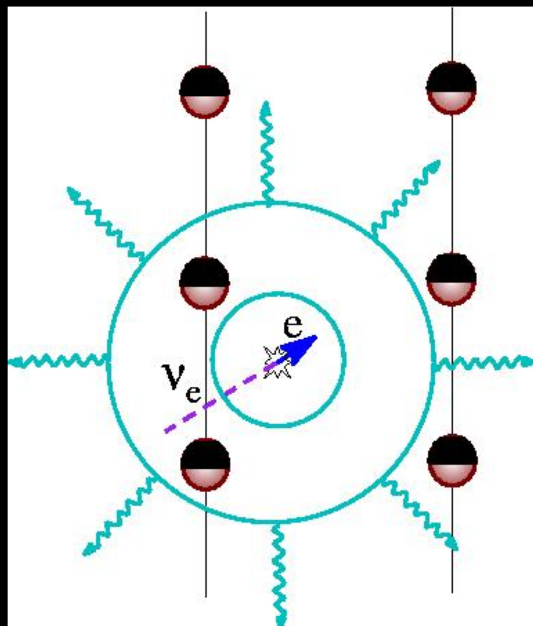
Counting of modules that see photons

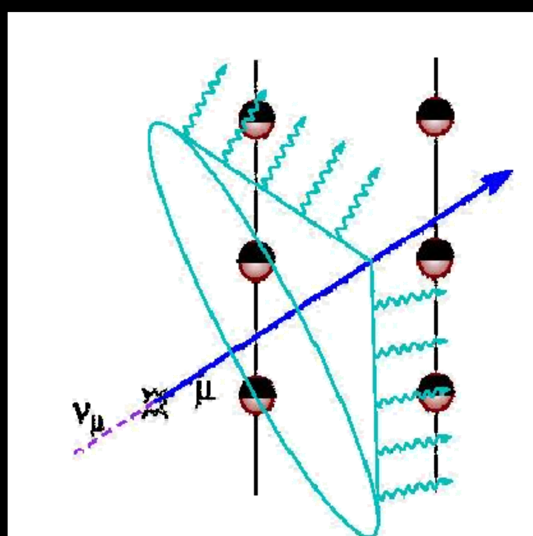
$$\nu_e + N \rightarrow e + X$$



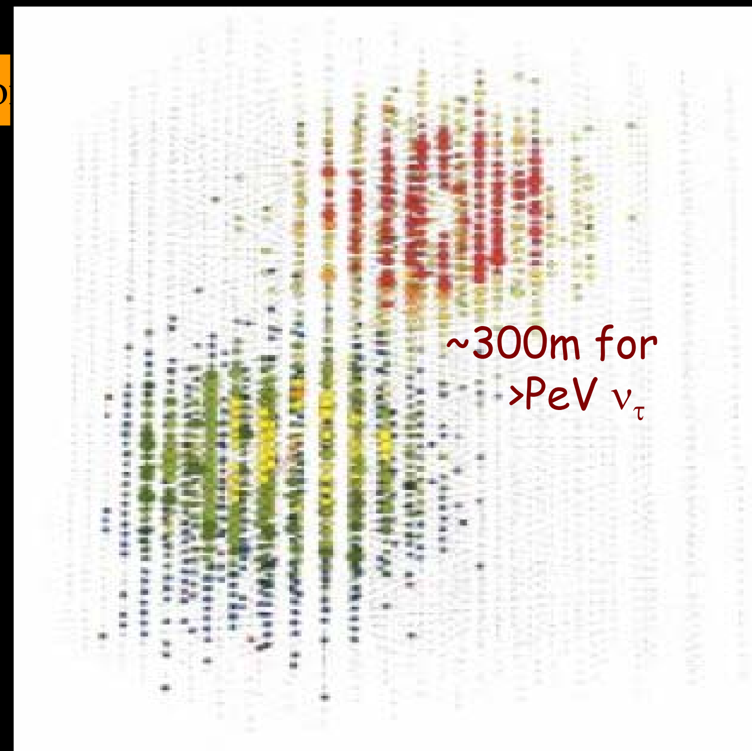
$$\nu_\mu + N \rightarrow \mu + X$$

neutrino flavor



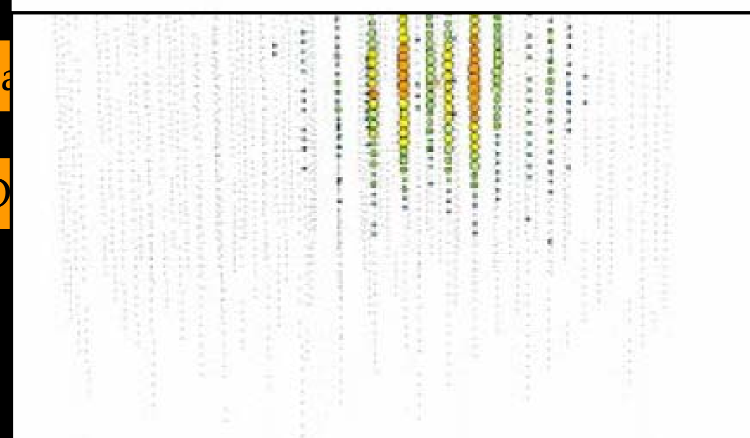


Po



Tra

“D

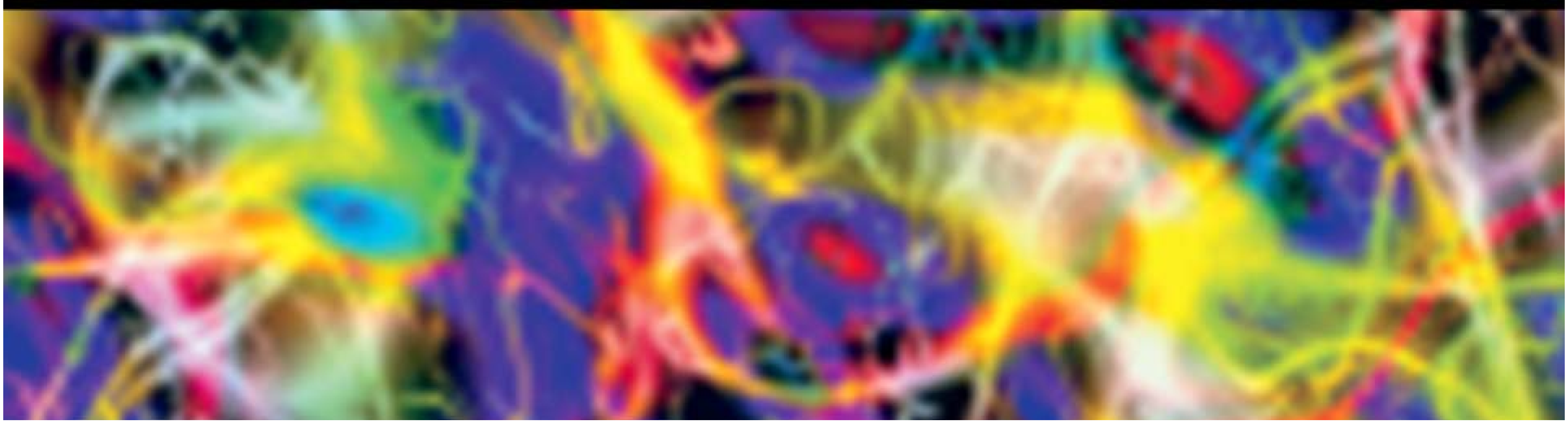


IceCube : particle physics with one million atmospheric neutrinos

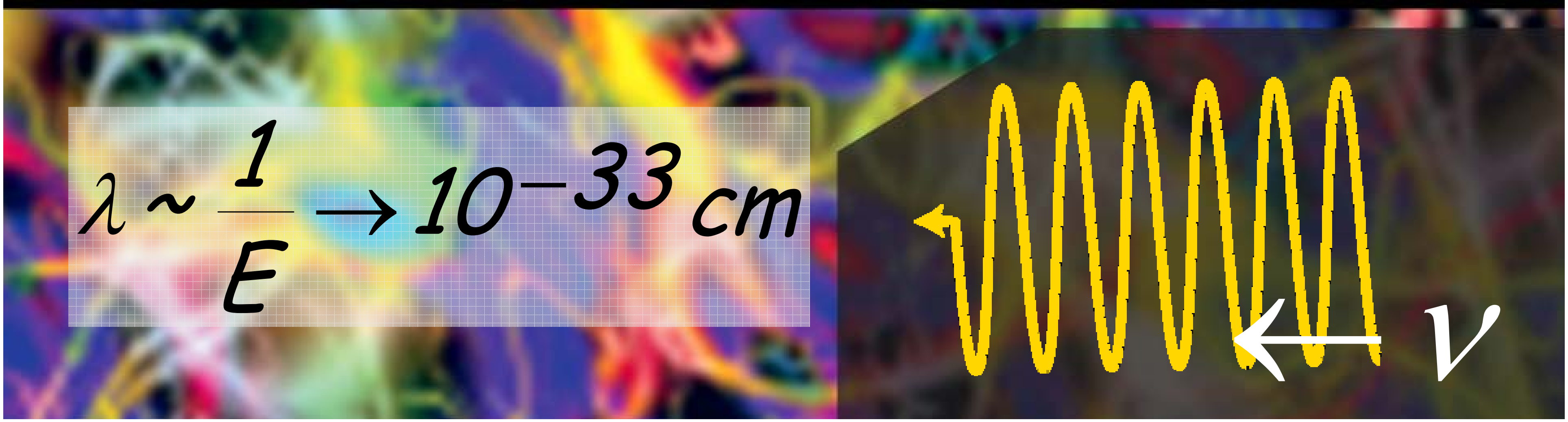
- **Astronomy:**
- **new window on the Universe**

- **Physics:**
- **measurement of the high-energy neutrino cross section**
- **gravity, quantum decoherence**
- **physics beyond 3-flavor oscillations**
- **test special and general relativity with new precision**
- **search for magnetic monopoles**
- **search for neutralino (or other) dark matter**
- **search for topological defects and cosmological remnants**
- **search for non-standard model neutrino interactions**
- **Planck scale physics with GRBs**
- **…**

quantized space: matter where the geometry is activated



quantized space: matter where the geometry is activated



neutrino "astronomy"

violation of Lorentz invariance may be a tool to study Planck scale physics

→ interaction with Planck mass particles distort spacetime

→ Planck scale vacuum fluctuations probed by high energy neutrinos

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{\varsigma M_{Planck}}\right)^n \pm \ldots$$

modification to dispersion relation leads to an energy dependent speed of light.

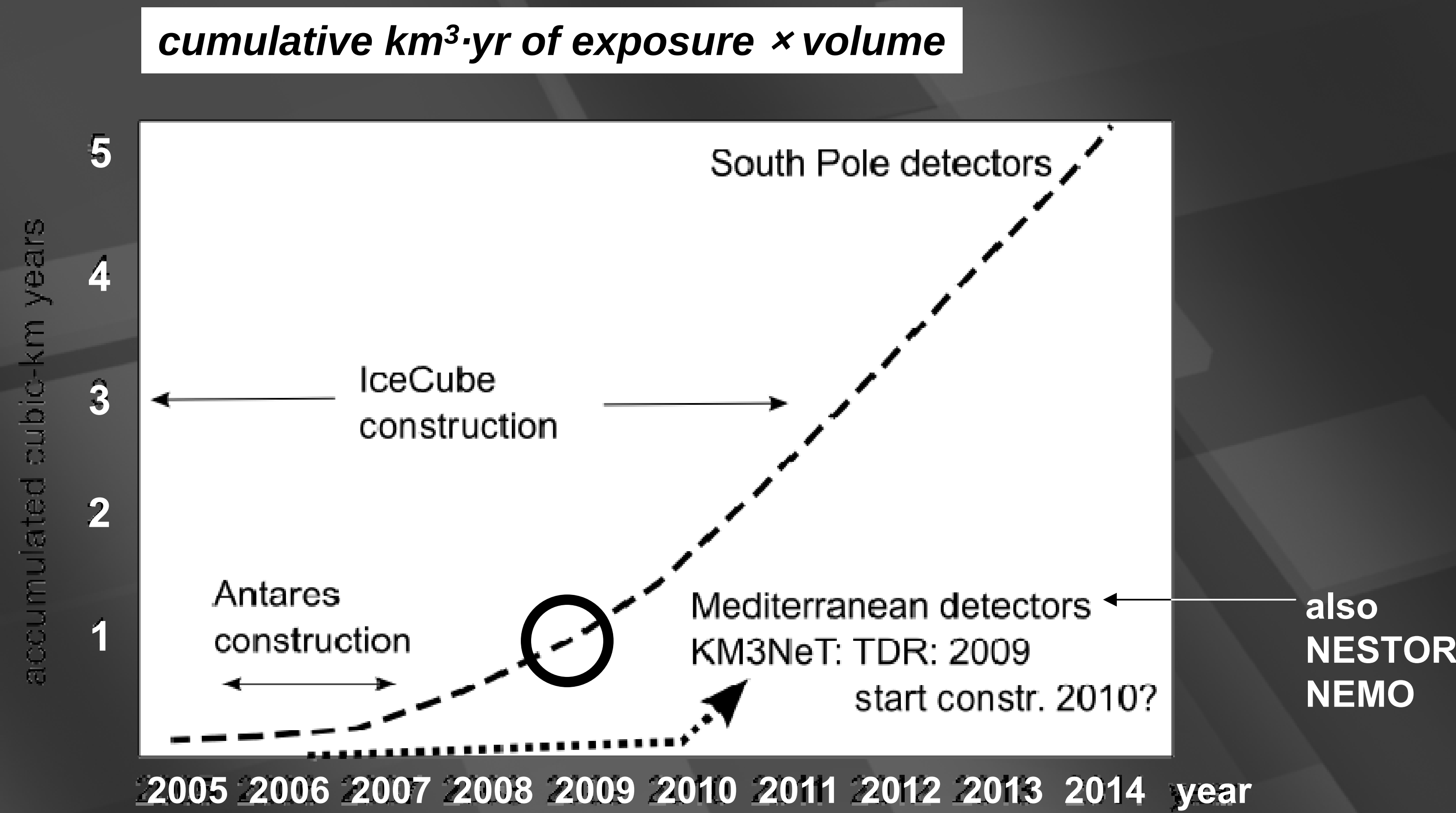
sensitivity to Planck scale !

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

$$\Delta t \approx \frac{1+n}{2}\left(\frac{d}{c}\right)\left(\frac{E_\nu}{\varsigma M_{Planck}}\right)^n$$

from a source at a distance d; for instance a GRB.

stay tuned: IceCube integrated volume



- ☞ 1 km^3·yr reached 2 years *before* detector is completed
- ☞ close to 4 km^3·yr at the beginning of 2^{nd} year of full array operation

looking ahead ...

- technology delivered !
- a km squared year data by 08~09
- data from completed Antares detector → KM3NET
- radio and acoustic detectors

AMANDA

IceCube string and IceTop station deployed 01/05

IceCube string and IceTop station deployed 12/05 – 01/06

IceTop station only 2006

IceCube string and IceTop station to be deployed 12/06 – 01/07

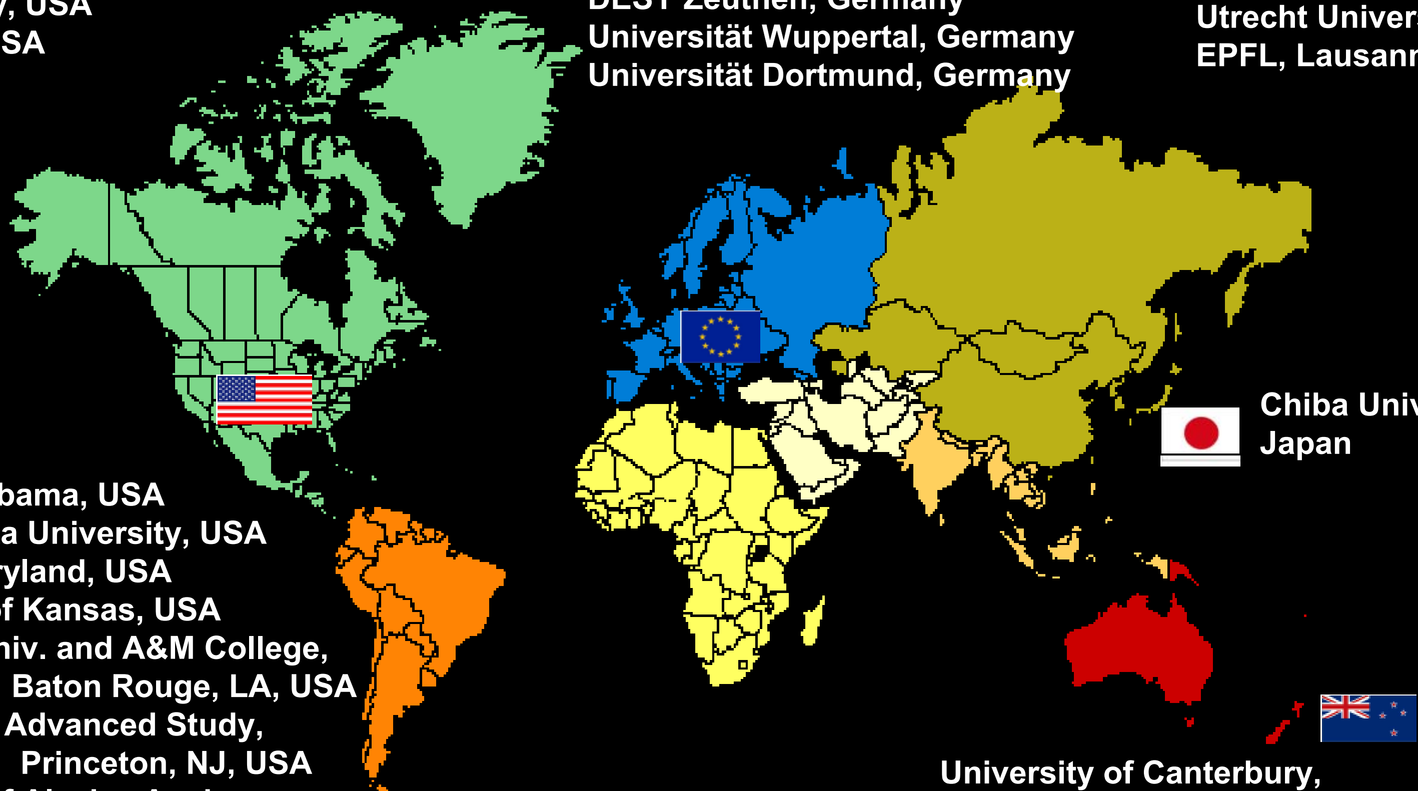
- 604 DOMs deployed to date
- Want to achieve steady state of 14 strings / season.

IceCube Collaboration

Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands
EPFL, Lausanne, Switserland



Chiba University, Japan

Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
Institute for Advanced Study, Princeton, NJ, USA
University of Alaska, Anchorage

University of Canterbury, Christchurch, New Zealand

IceCube Collaboration

Bartol Research Inst, Univ of Delaware, USA

Pennsylvania State University, USA

University of Wisconsin-Madison, USA

University of Wisconsin-River Falls, USA

LBNL, Berkeley, USA

UC Berkeley, USA

UC Irvine, USA

Univ. of Alabama, USA

Clark-Atlanta University, USA

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Universität Wuppertal, Germany

EPFL, Lausanne, Switzerland

Humboldt Universität, Germany

MPI, Heidelberg

Uppsala Universitet, Sweden

Stockholm Universitet, Sweden

Kalmar Universitet, Sweden

Imperial College, London, UK

University of Oxford, UK

Utrecht University, Netherlands

Universität Dortmund, Germany

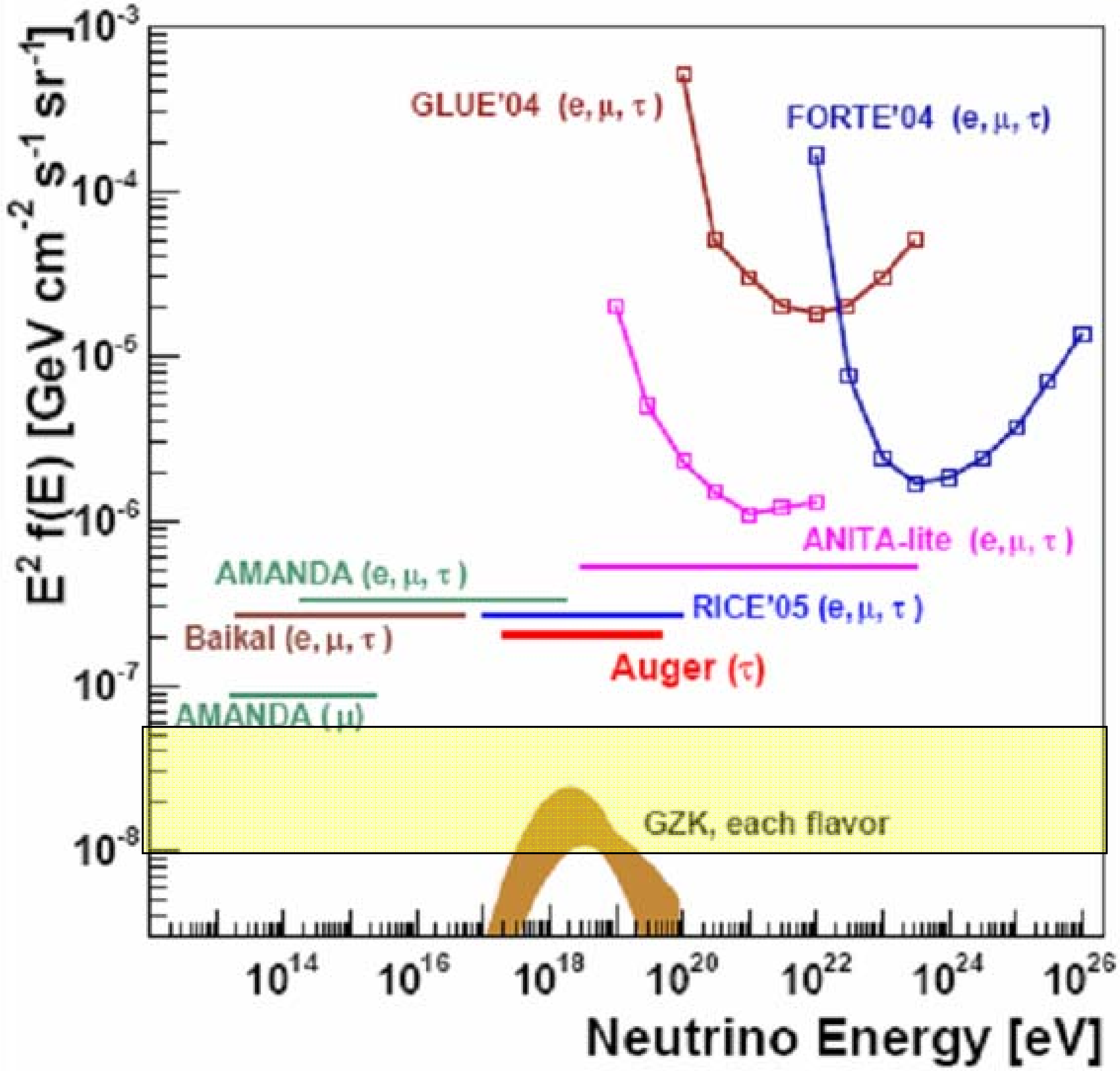
University of Canterbury, Christchurch, New Zealand

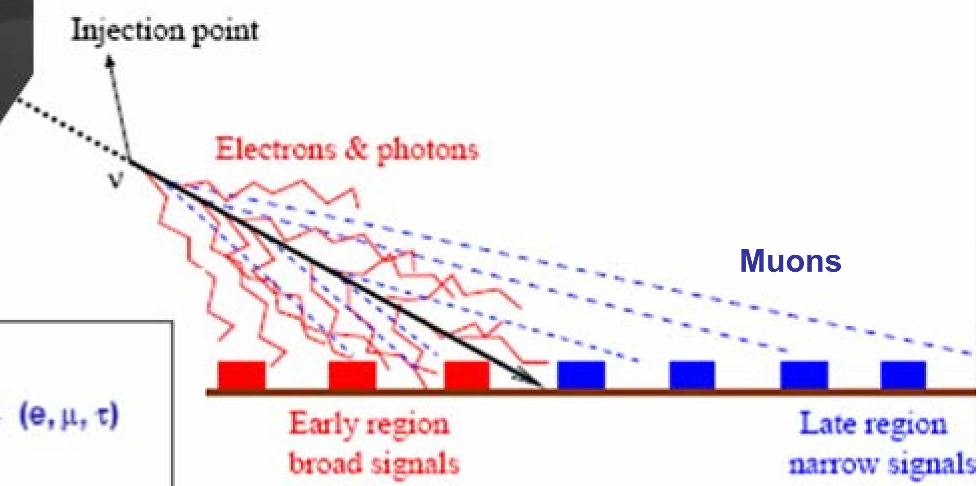
Chiba University, Japan

overflow

novel detection methods:
radio, acoustic and horizontal showers

neutrinos from the interactions that create the GZK feature in the cosmic ray spectrum


GLUE'04 (e, μ, τ)
FORTE'04 (e, μ, τ)
ANITA-lite (e, μ, τ)
AMANDA (e, μ, τ)
RICE'05 (e, μ, τ)
Baikal (e, μ, τ)
Auger (τ)
AMANDA (μ)
GZK, each flavor
E² f(E) [GeV cm⁻² s⁻¹ sr⁻¹]
Neutrino Energy [eV]


Injection point
Electrons & photons
ν
Muons
Early region
broad signals
Late region
narrow signals

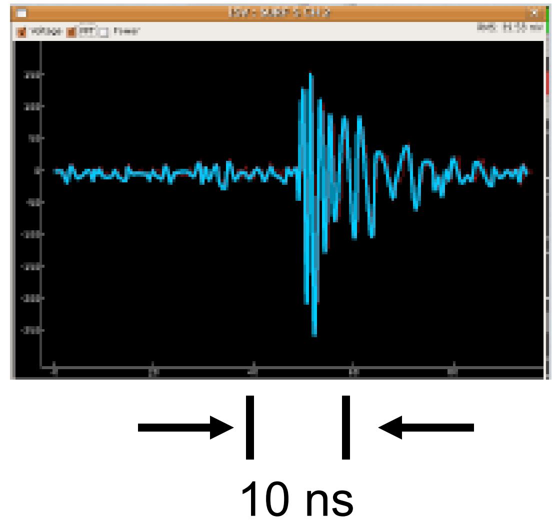
Gurgen Askaryan (1962)

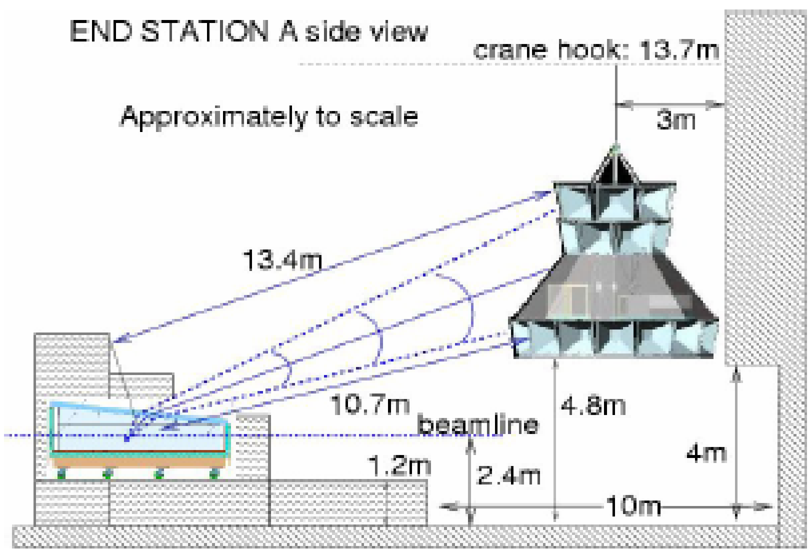
radio emission from neutrino induced showers

→
Cherenkov power is not proportional to frequency because
of coherence at MHz to GHz wavelengths
→
showers (photons and pairs) are not electrically neutral

confirmed by calculation and experiment in 1990s

SLAC T486 (Jul'06): Askaryan on ice



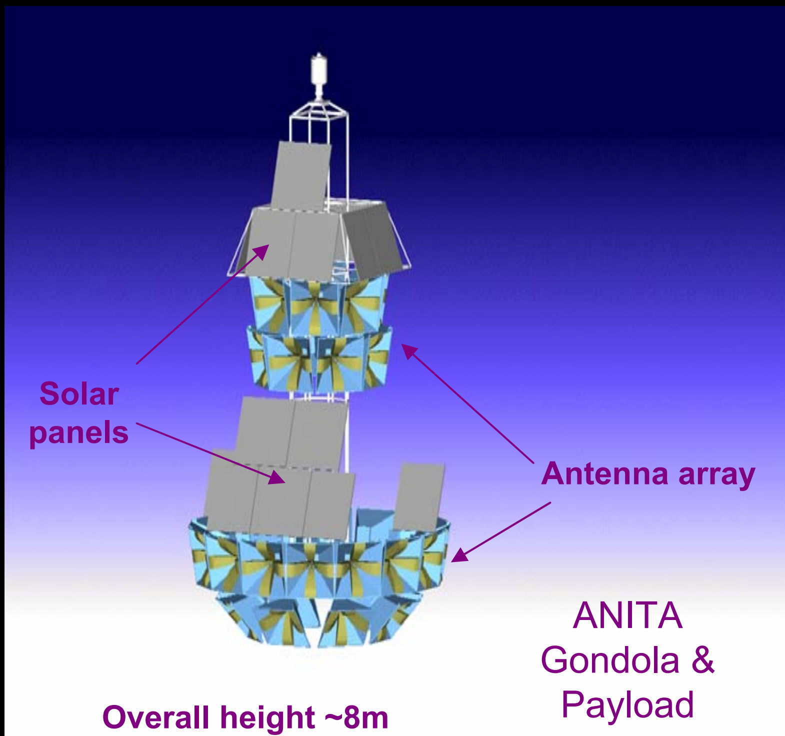


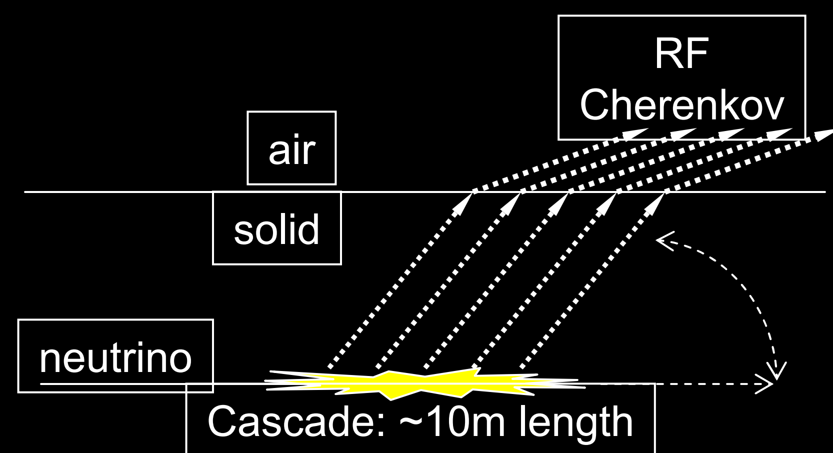
- Opportunity to test the effect in a medium relevant to several current and future experiments: ANITA, RICE, etc.

- 12-tons of ice + ANITA + End Station A + SLAC beam = Ideal ANITA calibration + comprehensive validation of Askaryan

Antarctic Impulsive Transient Antenna Experiment

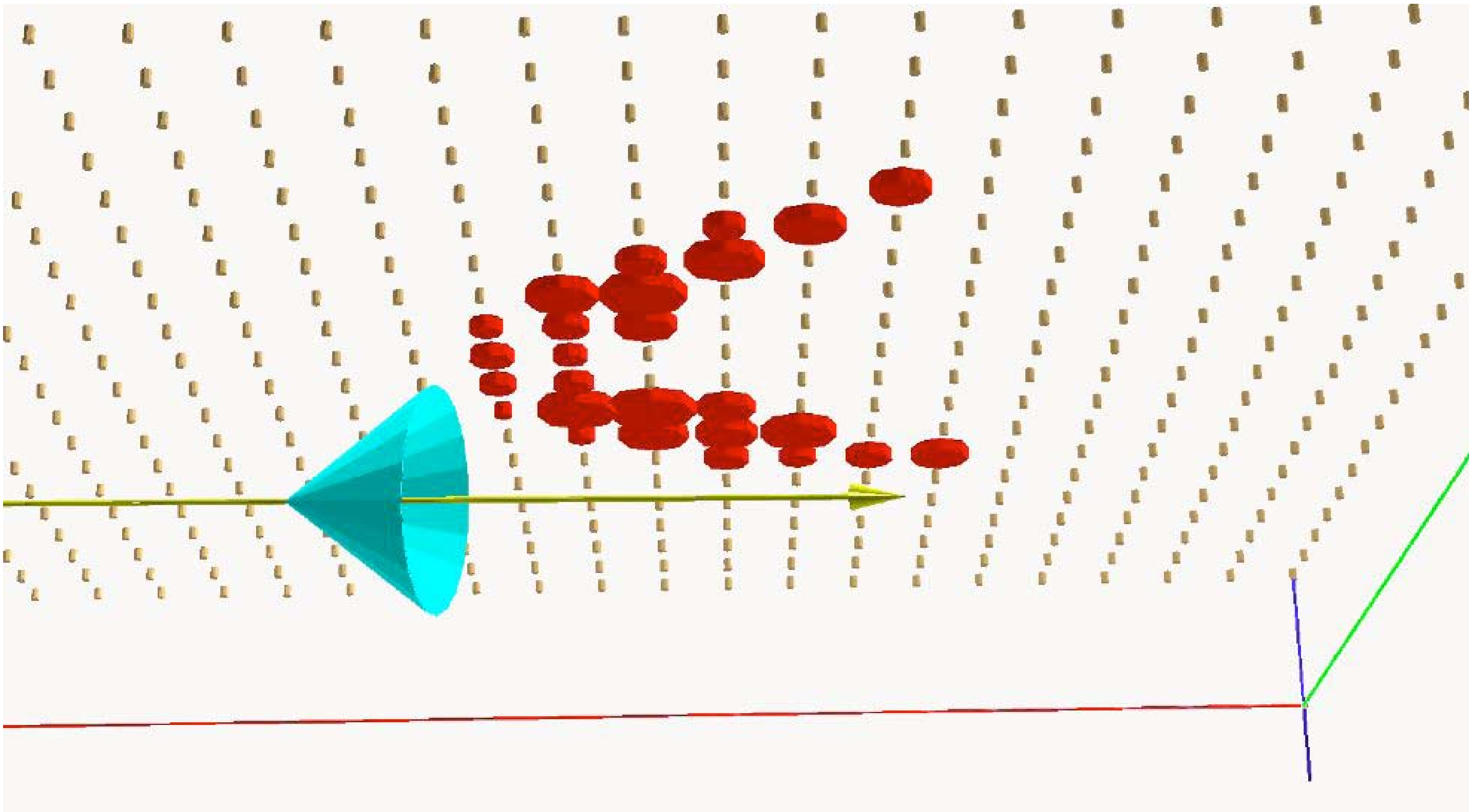
ANITA





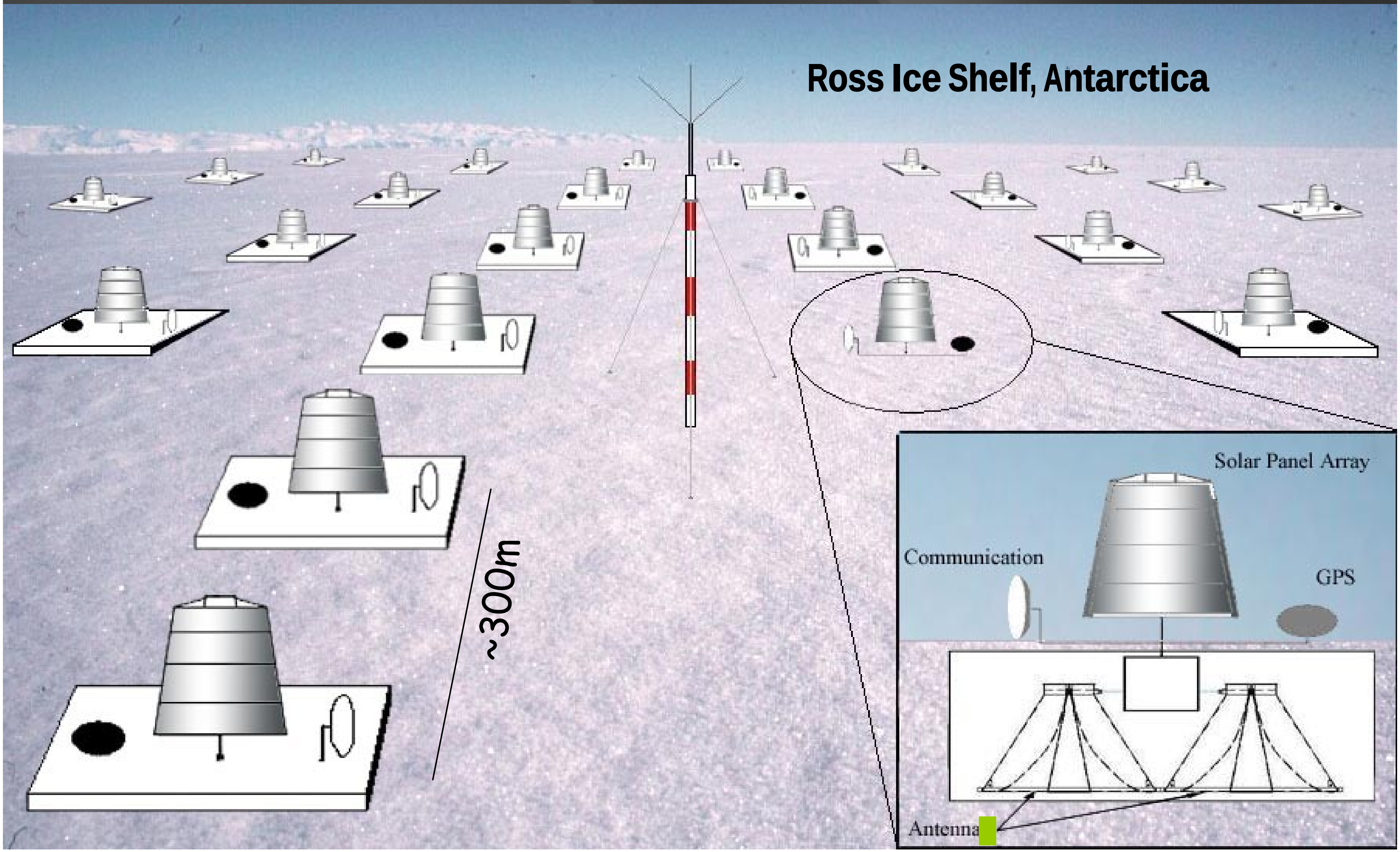
searching for GZK neutrinos with radio detection in Antarctic ice

in-ice view of radio detection

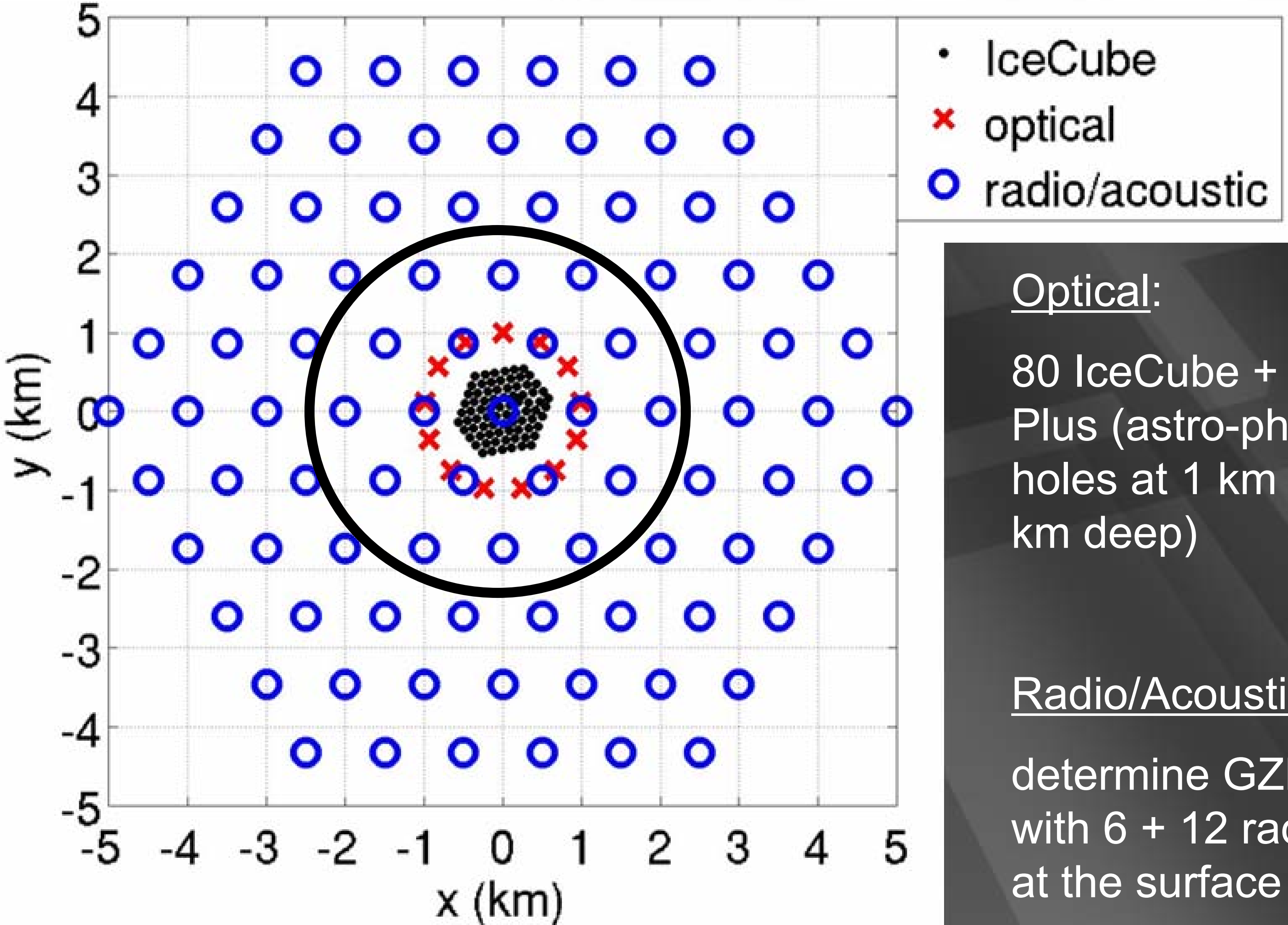


ARIANNA concept

100 x 100 station array



staged IceCube enhancements



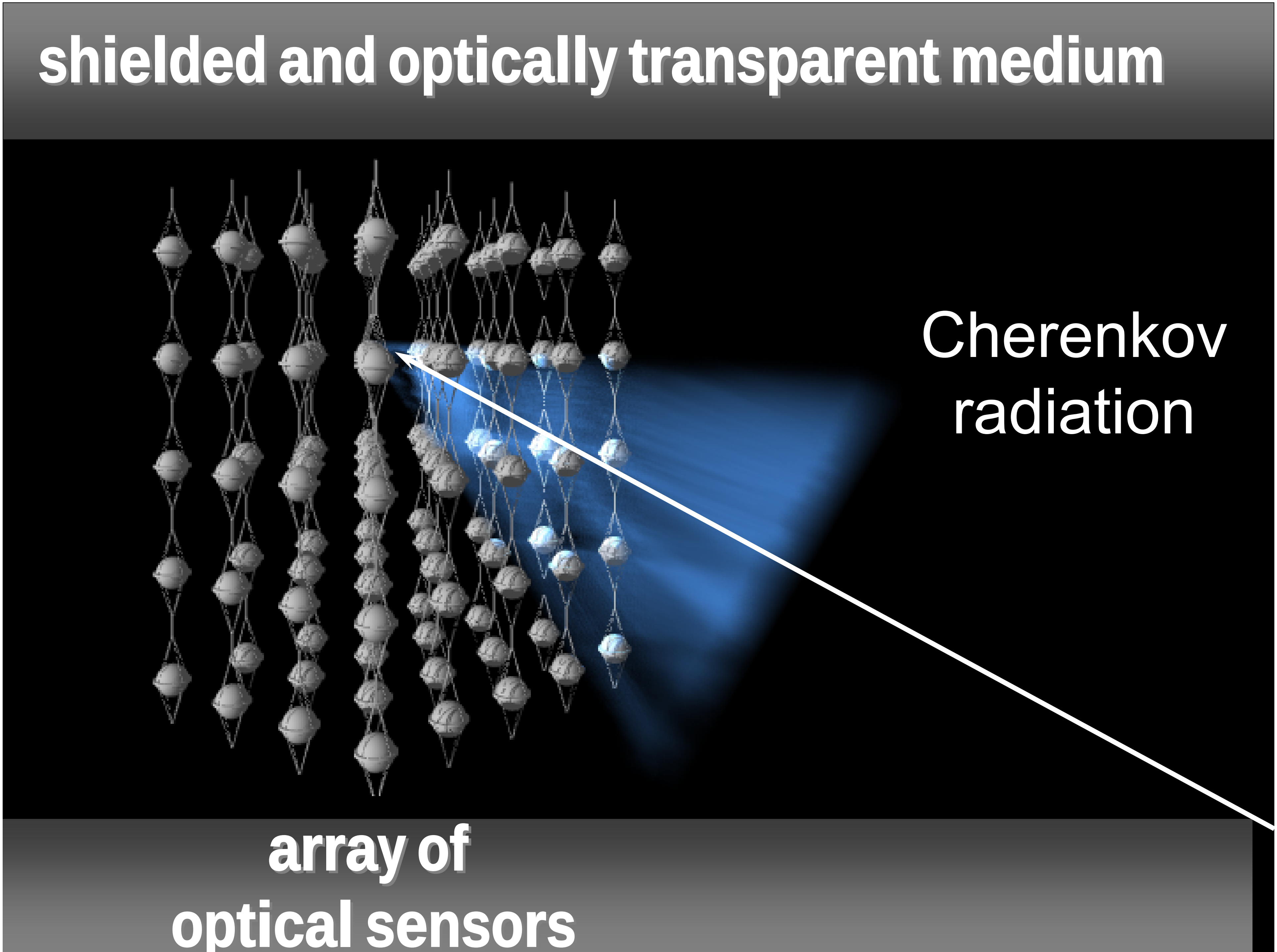
Optical:

80 IceCube + 13 IceCube-Plus (astro-ph/0310152) holes at 1 km radius (2.5 km deep)

Radio/Acoustic:

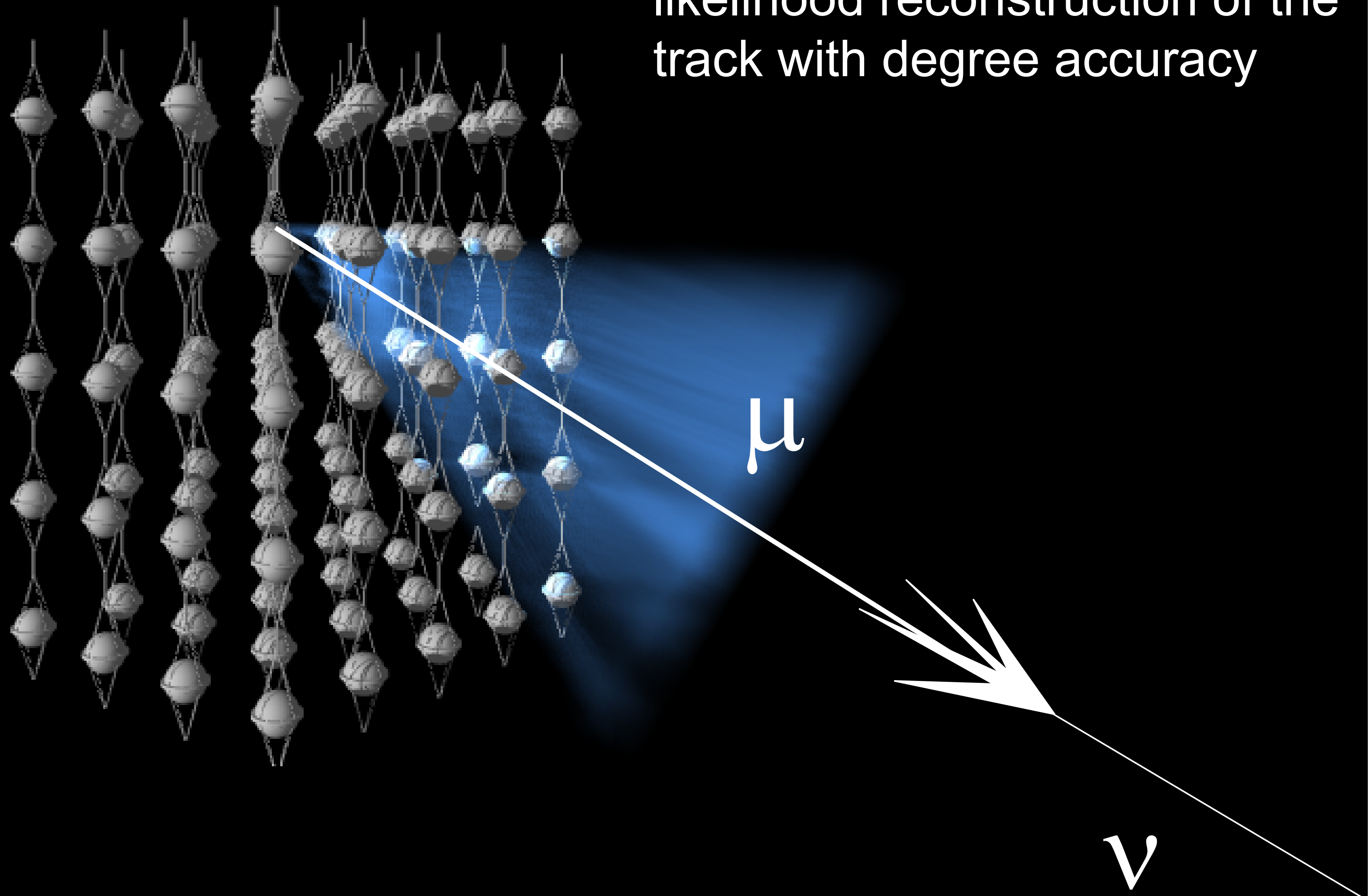
determine GZK event rates with 6 + 12 radio detectors at the surface or at depth

calibration with IceCube!


shielded and optically transparent medium
Cherenkov
radiation
array of
optical sensors

detection

- nanosecond timing allows likelihood reconstruction of the track with degree accuracy

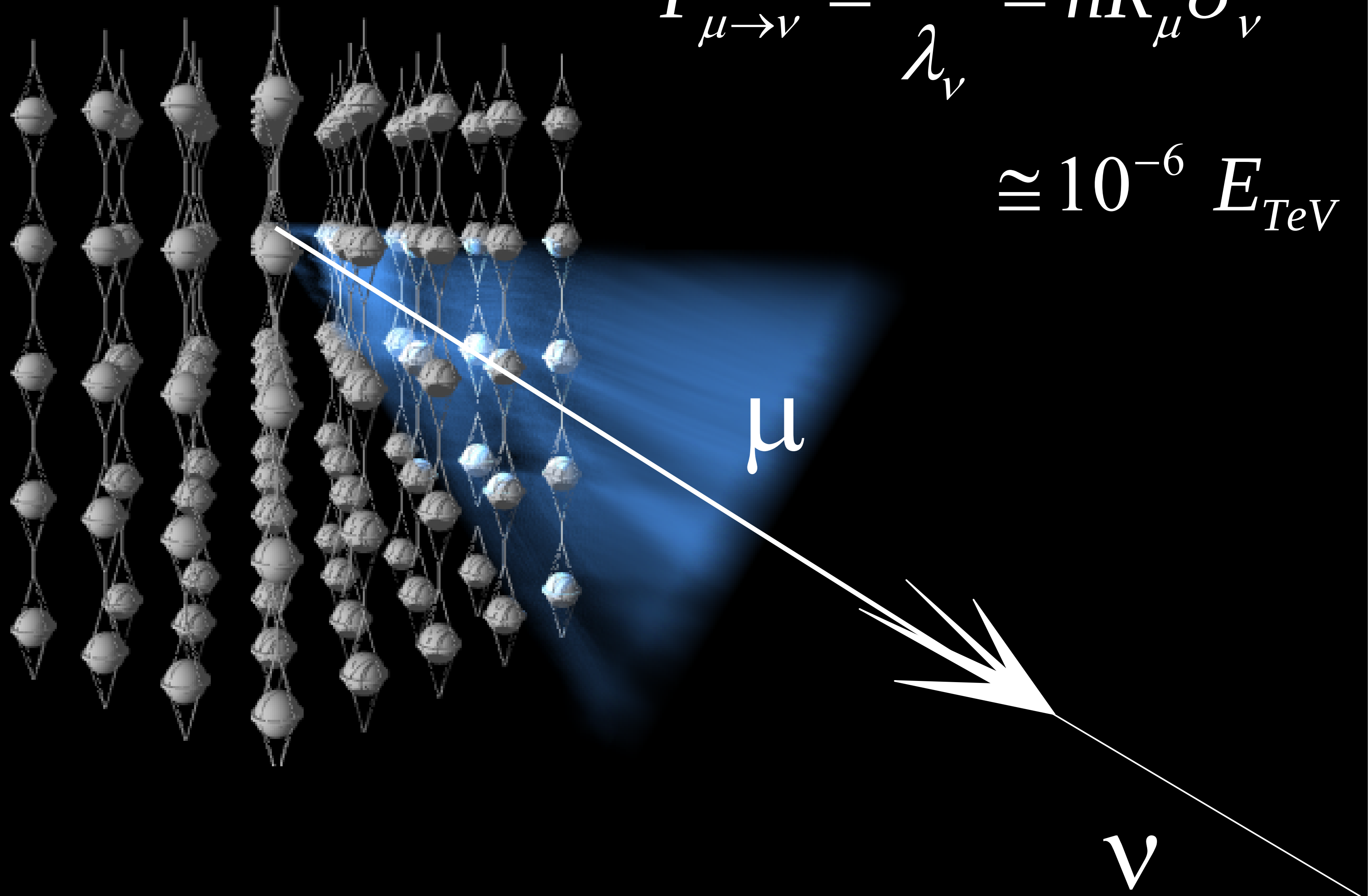


- photon counts reflect energy of the muon that loses energy catastrophically (bremsstrahlung,…)

detection method

$$P_{\mu\rightarrow\nu} = \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu\sigma_\nu$$

$$\cong 10^{-6}\ E_{TeV}$$



unfortunately, detecting a neutrino is difficult !

deep core

Goal: identify contained, sub-TeV events for WIMP searches, atmospheric ν, …

- Replace AMANDA with IceCube digital optical modules
- European funding for new DOMs