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

Marcel Proust

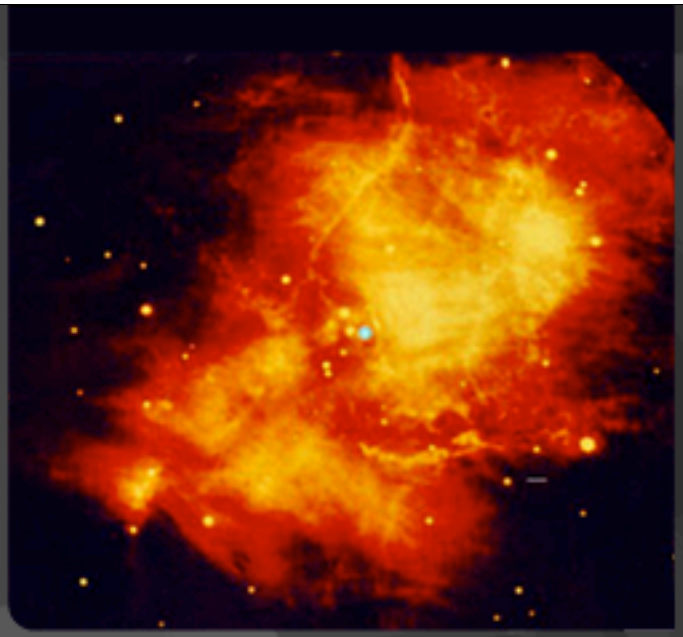
icebound neutrinos

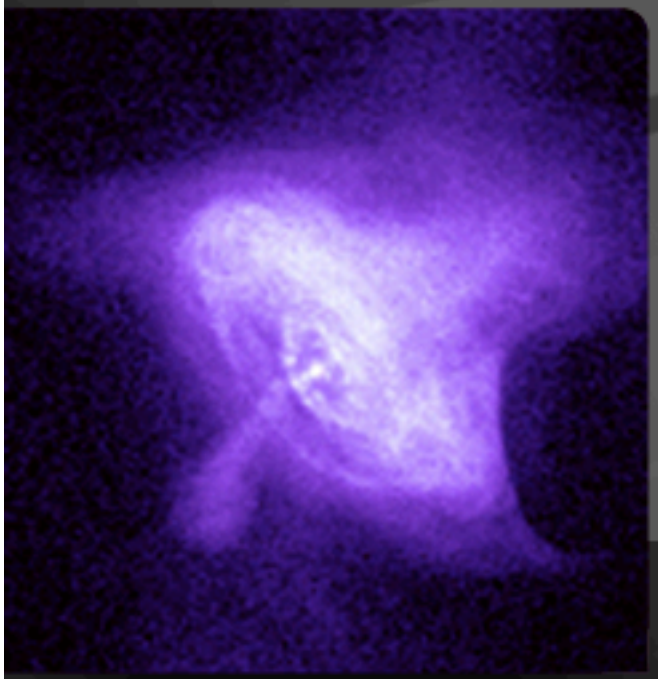
Francis Halzen

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

neutrinos from the cosmos

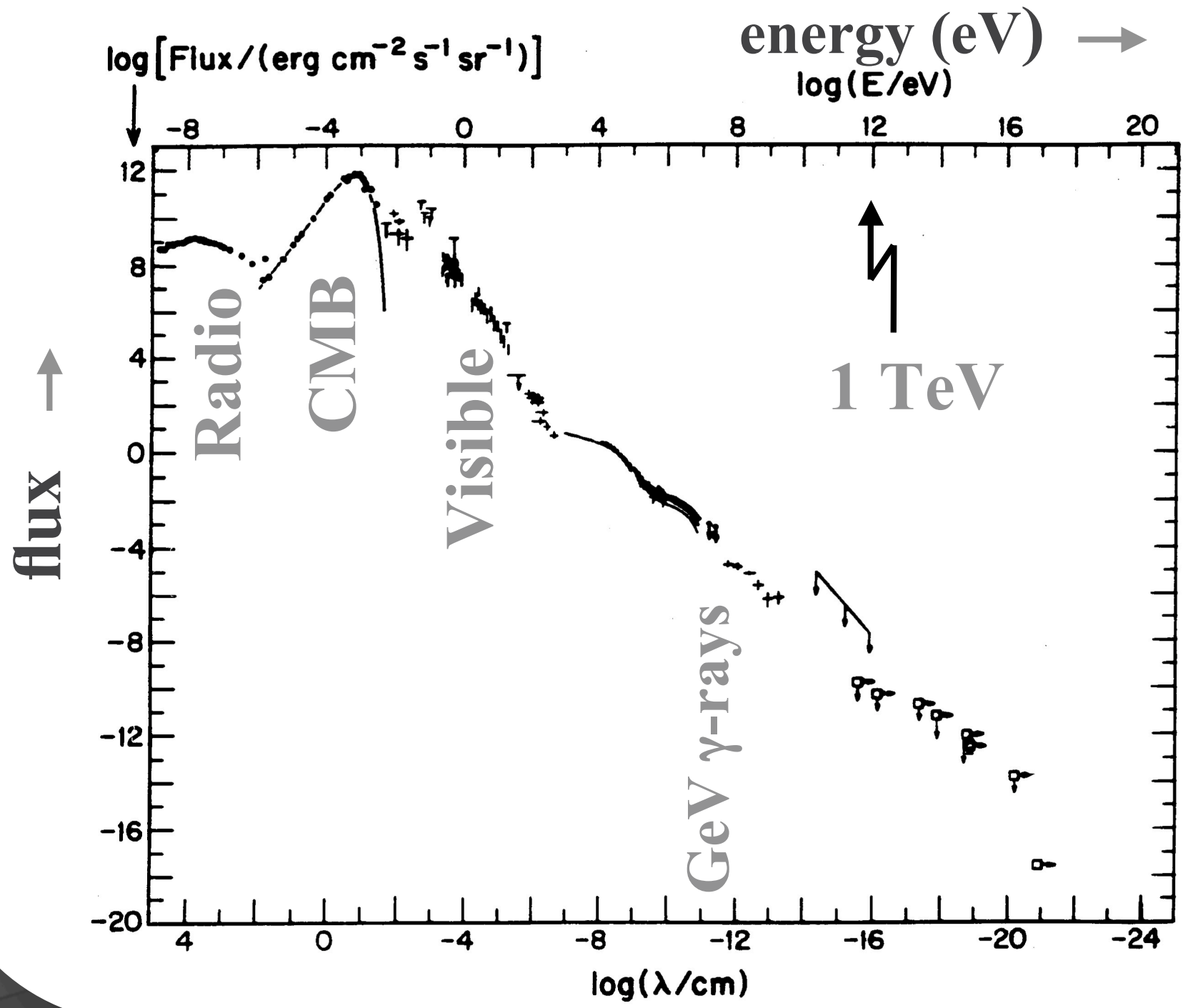
- neutrino astronomy
- the extreme universe
  → cosmic rays and TeV photons
  → also neutrinos
- kilometer-scale detectors
  → AMANDA
  → IceCube
- also particle physics





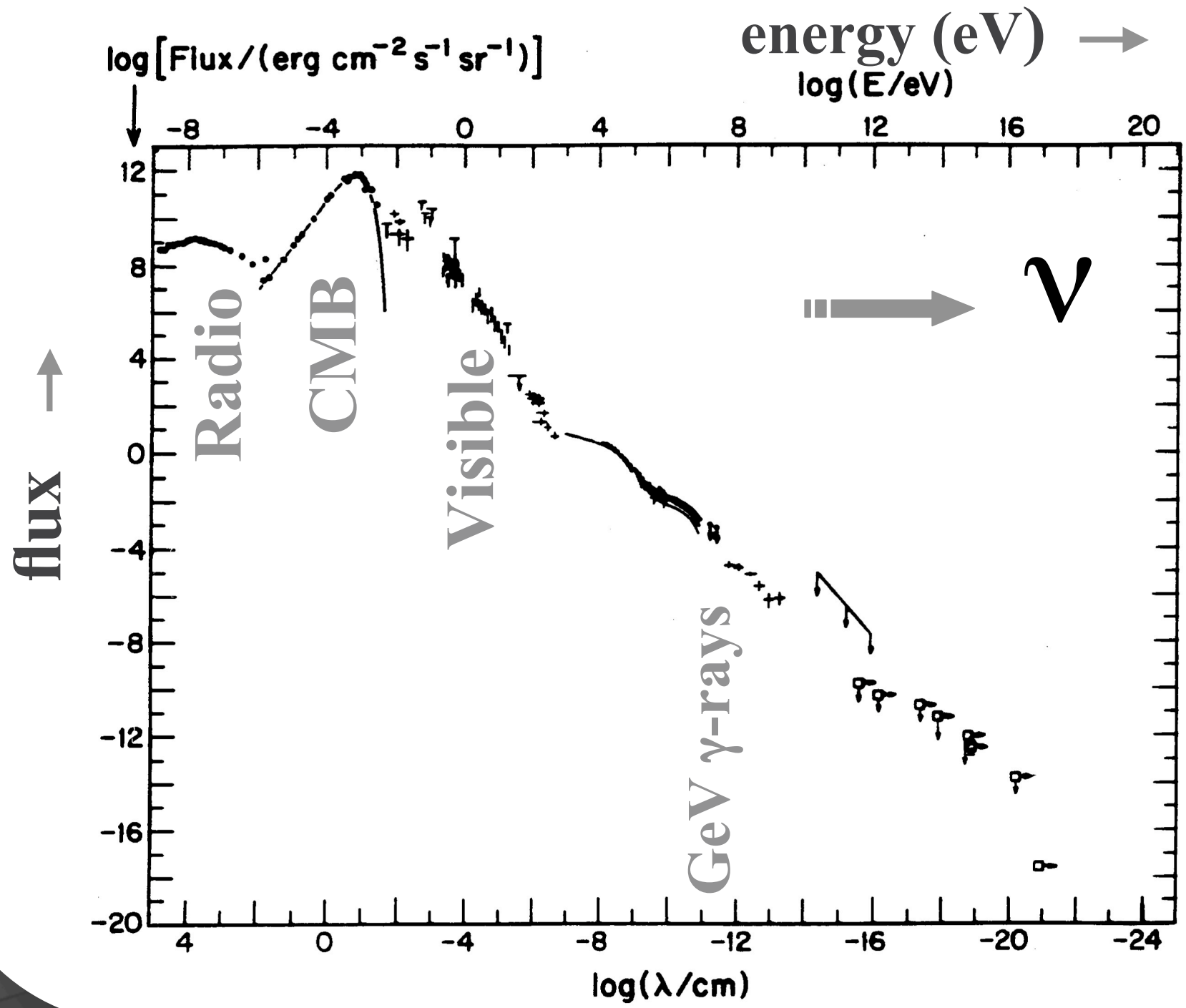
neutrinos ?

Crab supernova remnant


energy (eV)
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
1 TeV
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

with 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background

$$\gamma + \gamma_{\mathrm{CMB}} \longrightarrow e^+ + e^-$$


energy (eV)
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-8
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16
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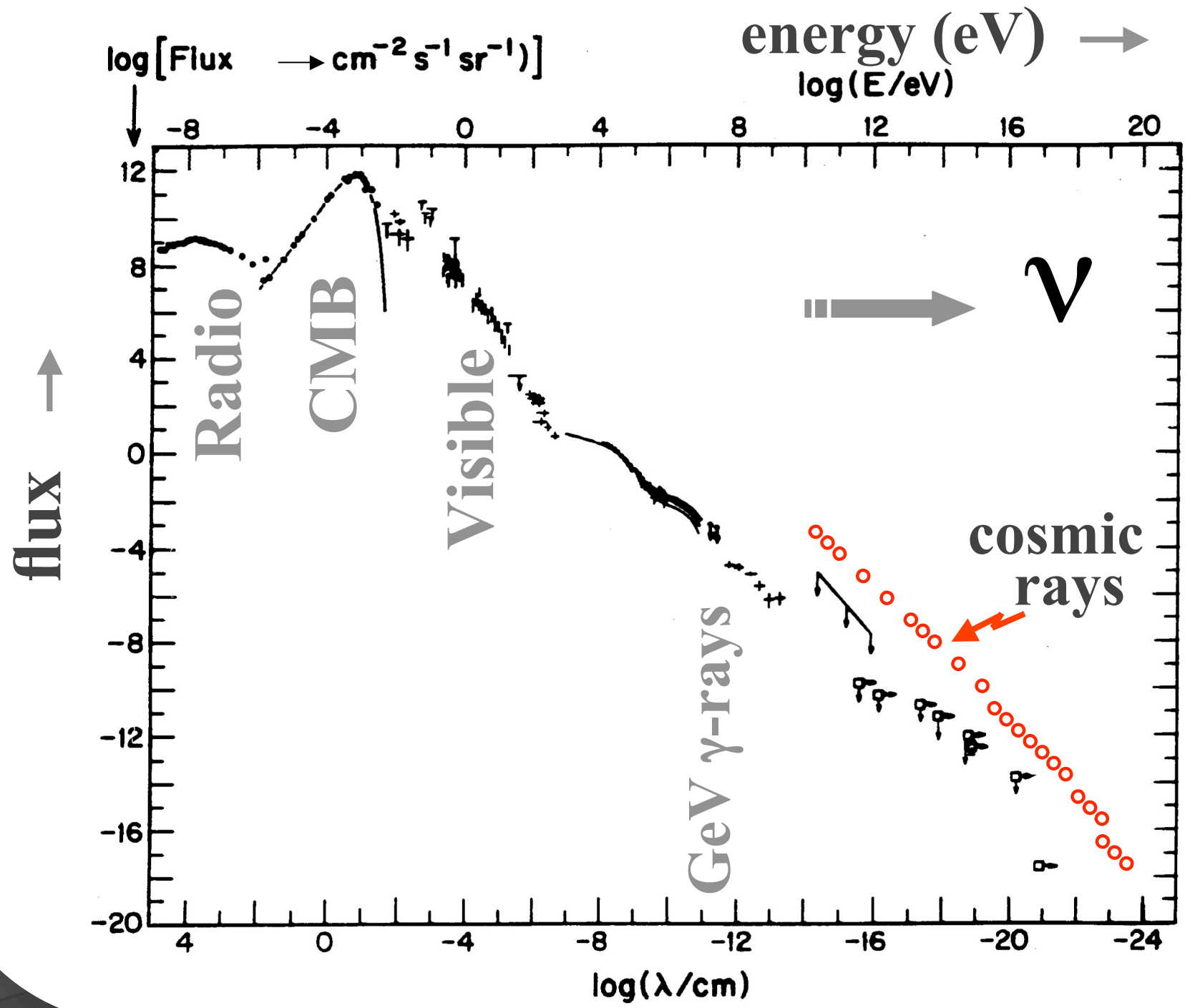
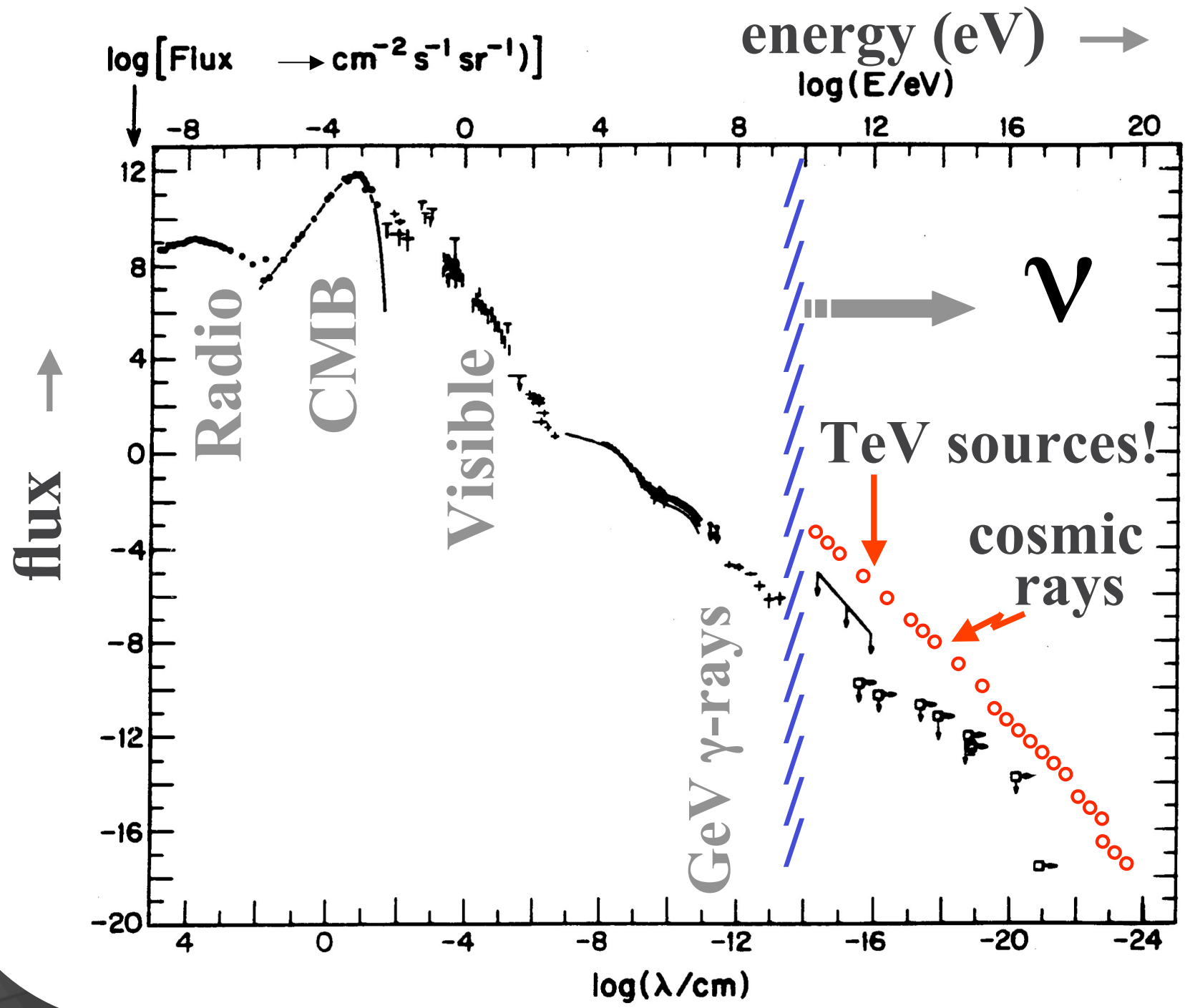
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
ν
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

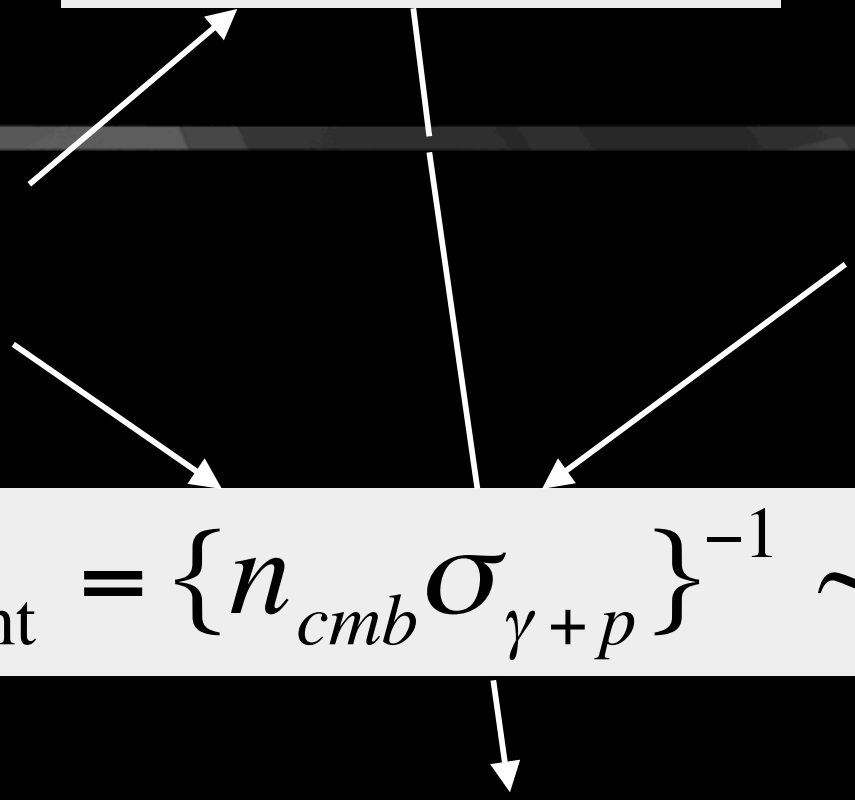

log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux →
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)


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

neutrinos from GZK interactions

cosmic rays interact with the microwave background

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



$$\lambda_{\mathrm{int}} = \{ n_{cmb} \sigma_{\gamma + p} \}^{-1} \sim 10\, Mpc$$

cosmic rays interact with the microwave background

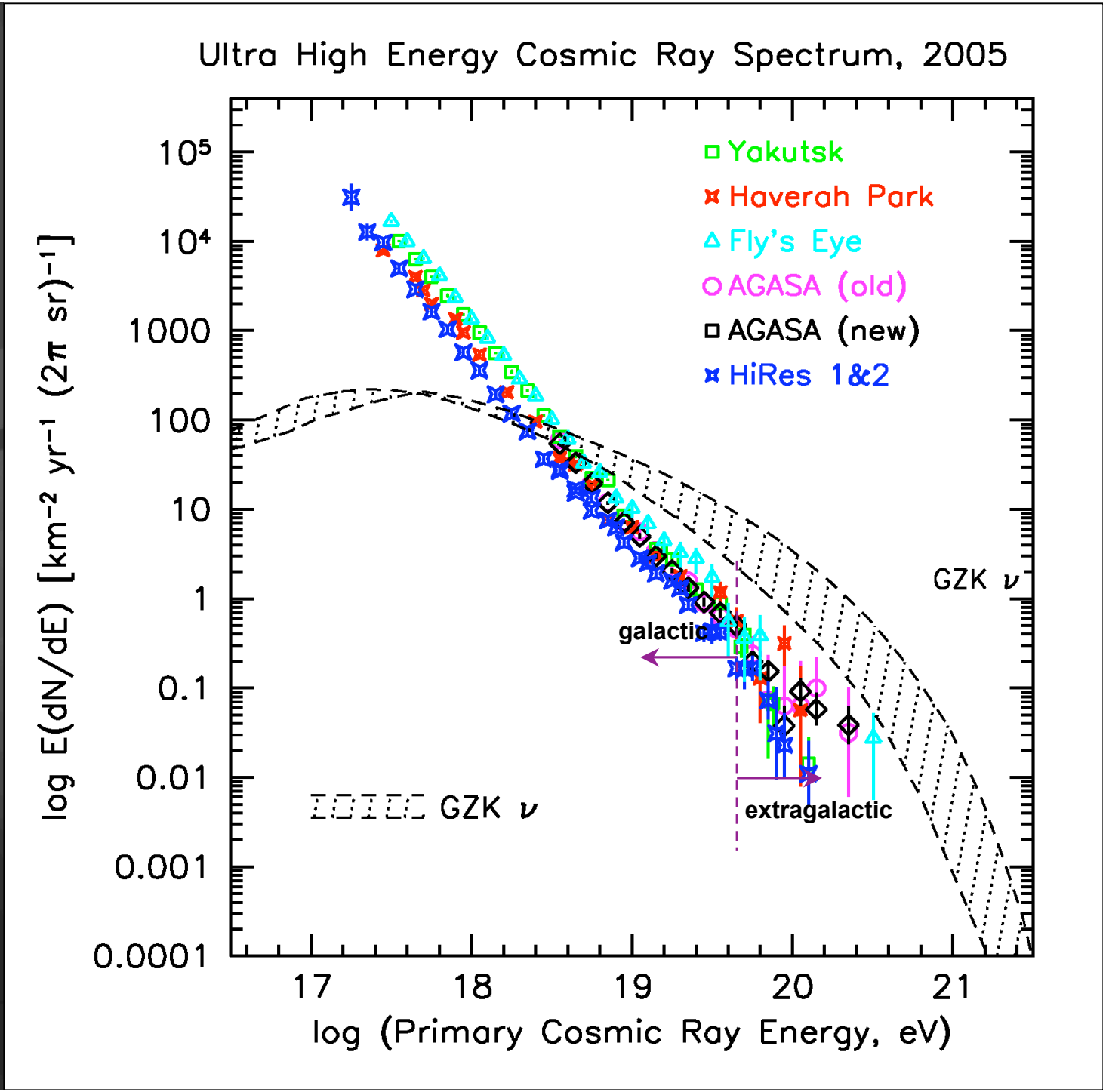
$$p + \gamma \rightarrow n + \pi^{+}$$

cosmic rays disappear, neutrinos appear

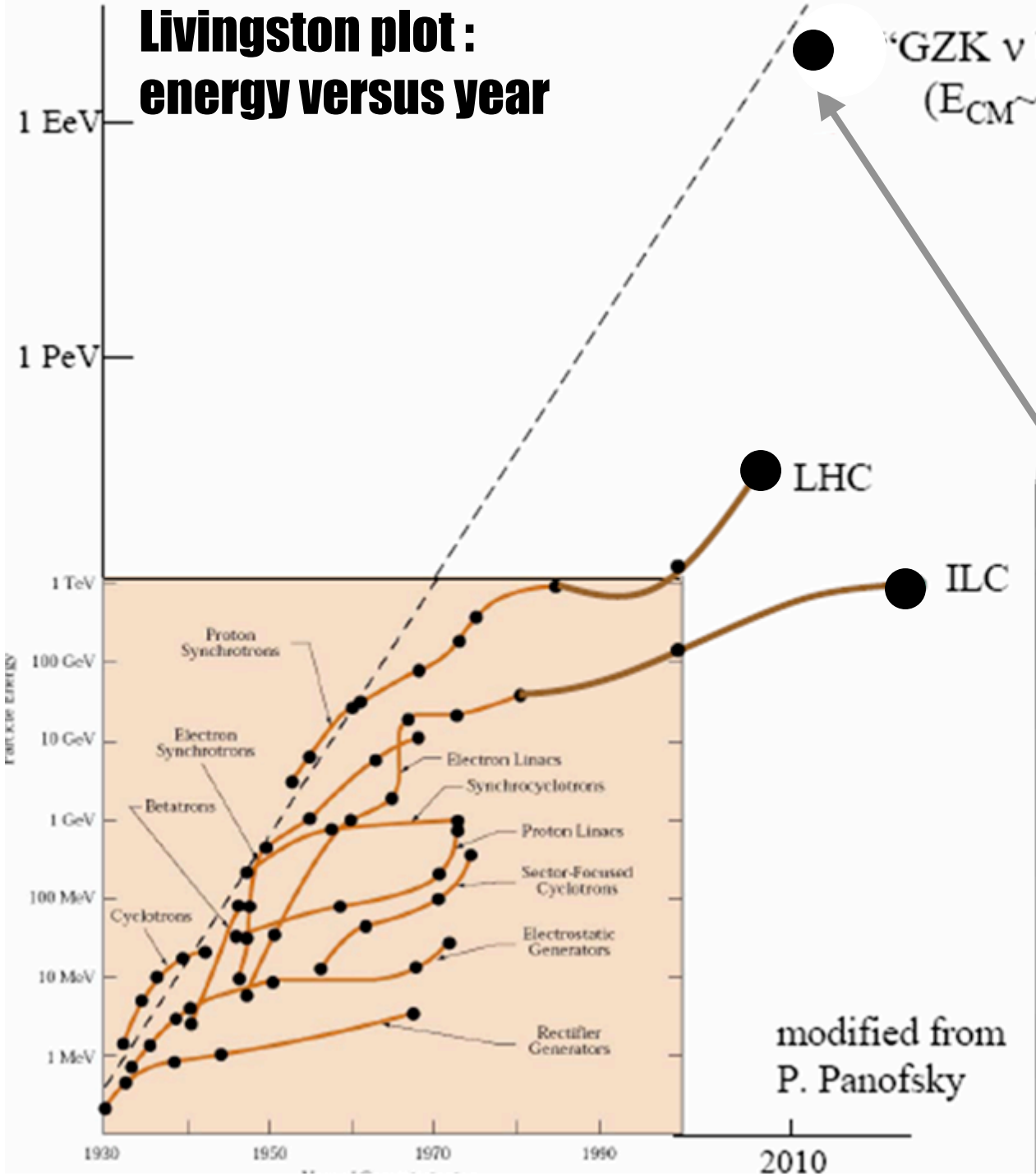
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

~ 1 event per kilometer squared per year

neutrinos from GZK interactions



Livingston plot : energy versus year

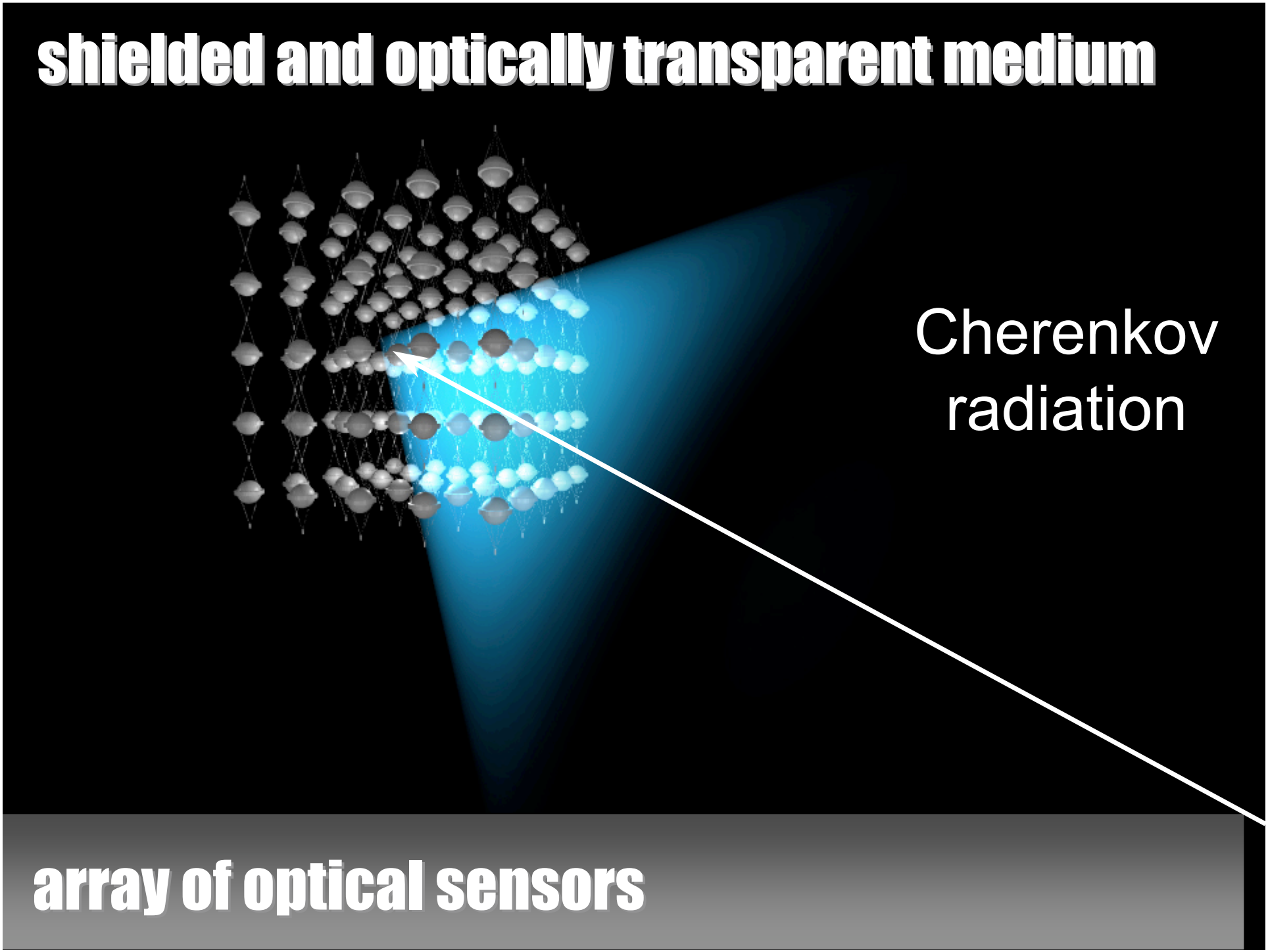


- ~ 1 event per year in IceCube
- radio/acoustic domain
- measure the neutrino cross section

new window on the Universe ?
expect surprises

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

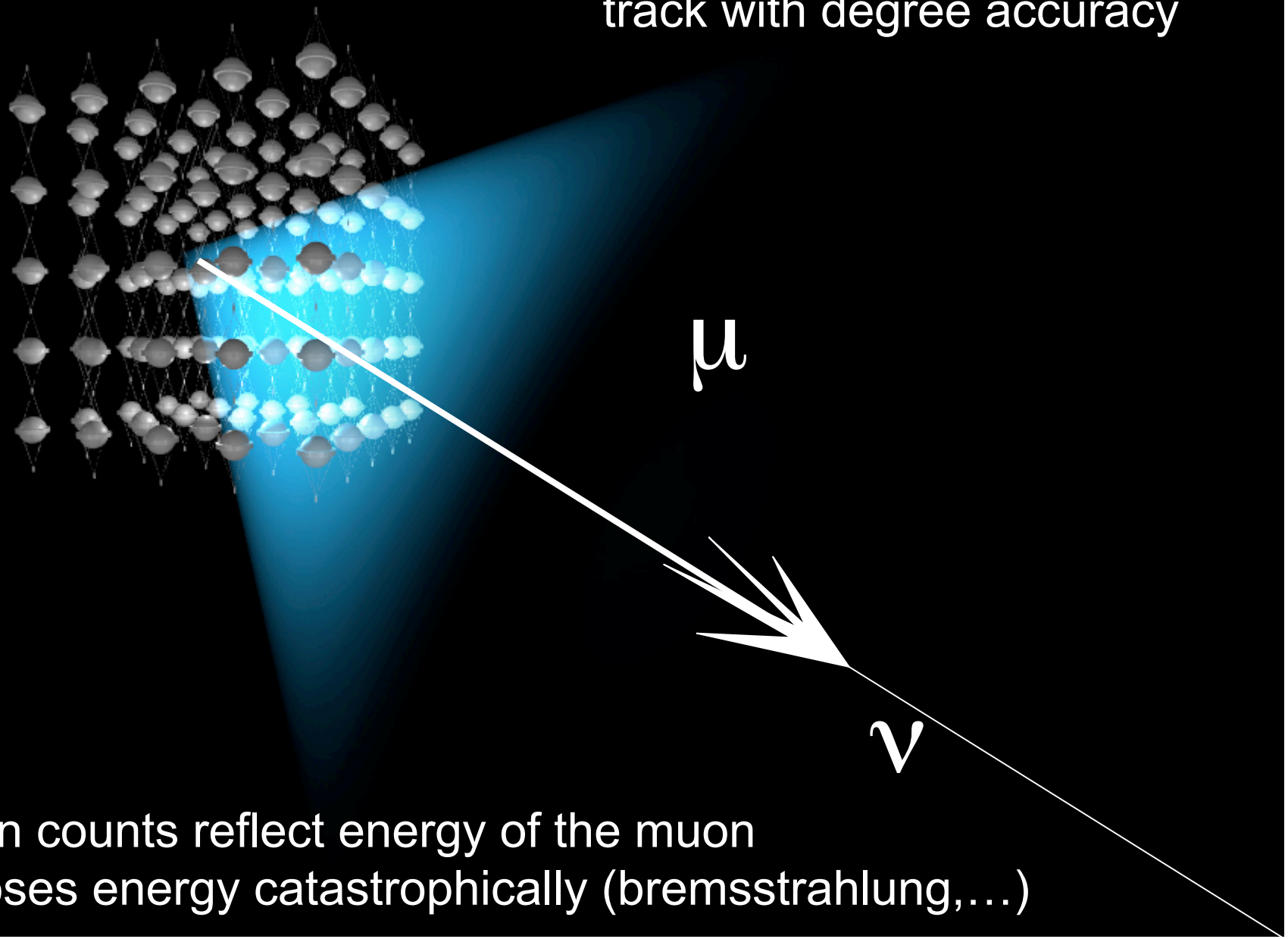
cosmic neutrinos: how ?


shielded and optically transparent medium
Cherenkov radiation
array of optical sensors

Photomultiplier Tube

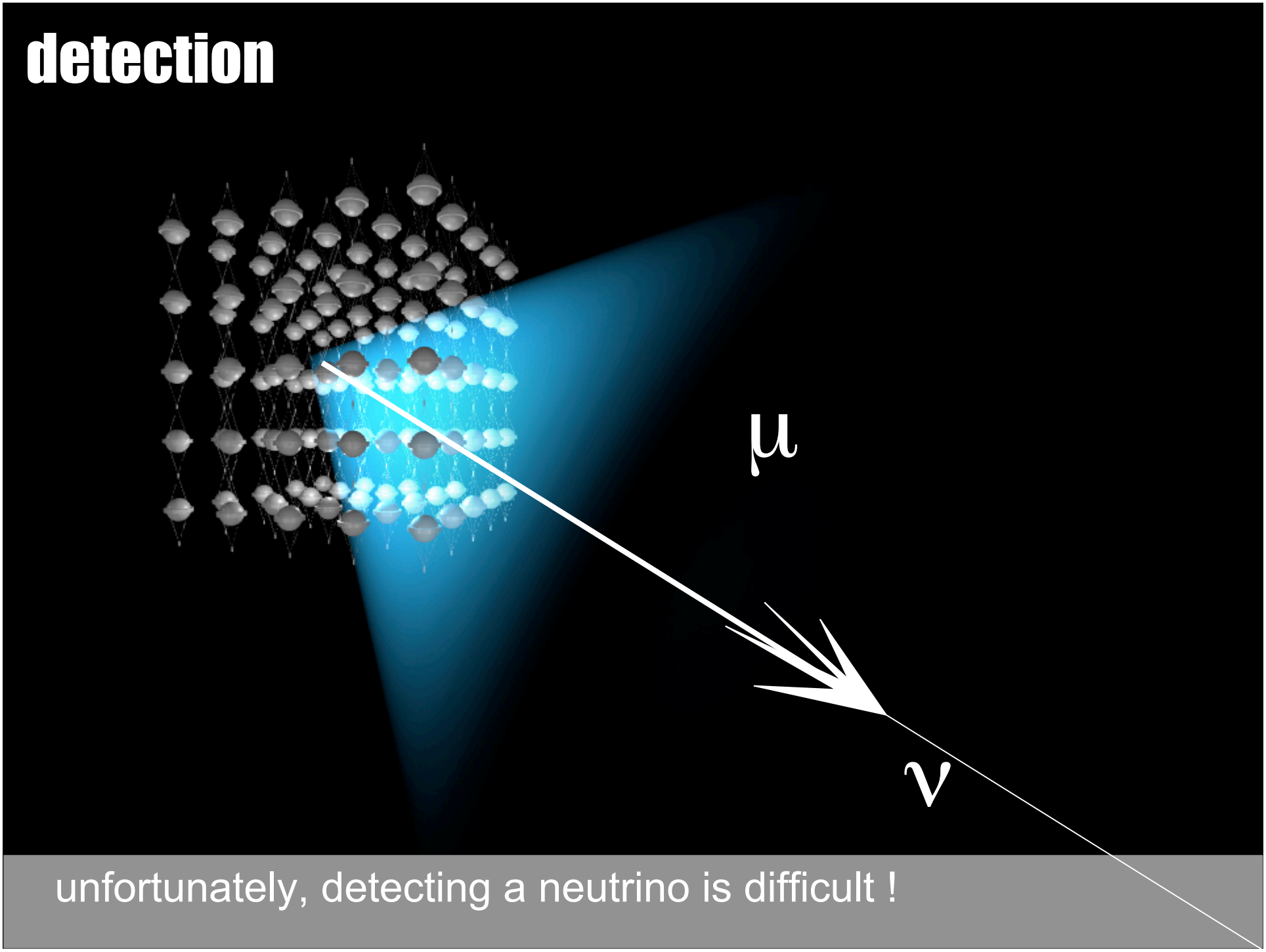
detection

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



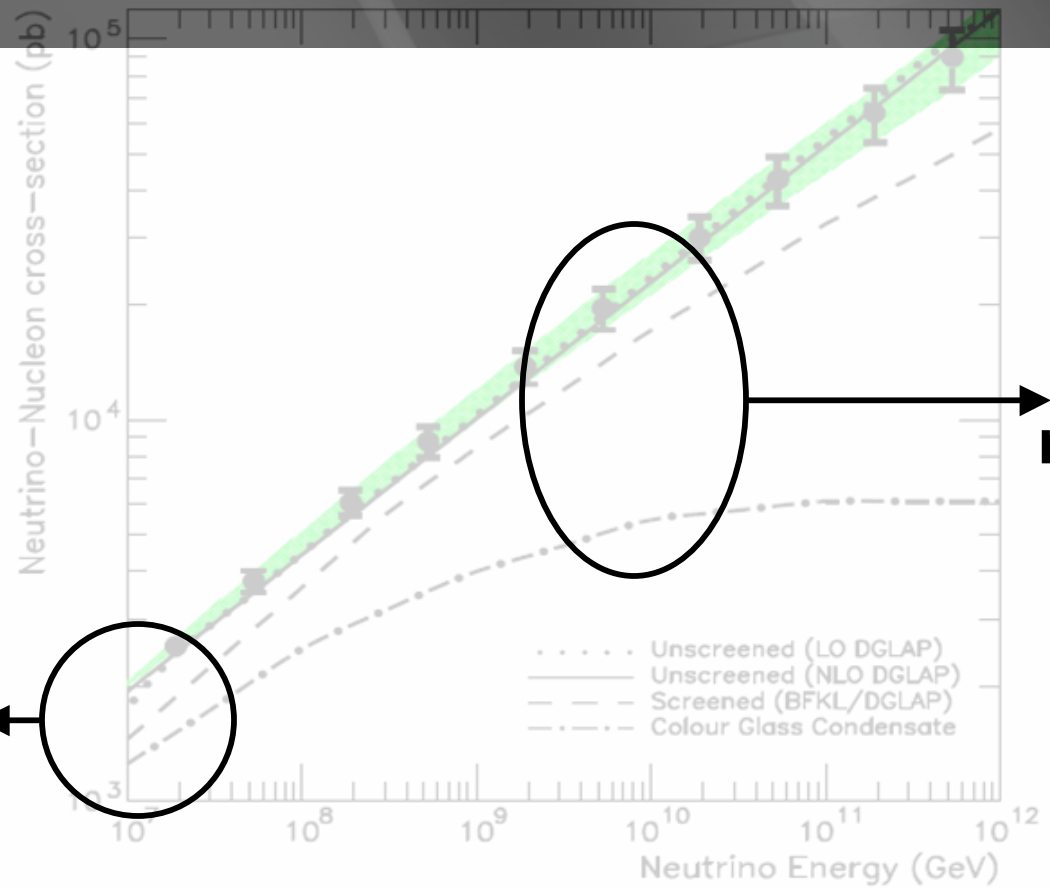
- photon counts reflect energy of the muon that loses energy catastrophically (bremsstrahlung,…)

detection



unfortunately, detecting a neutrino is difficult !

neutrino cross-section at 10^{18} eV ?

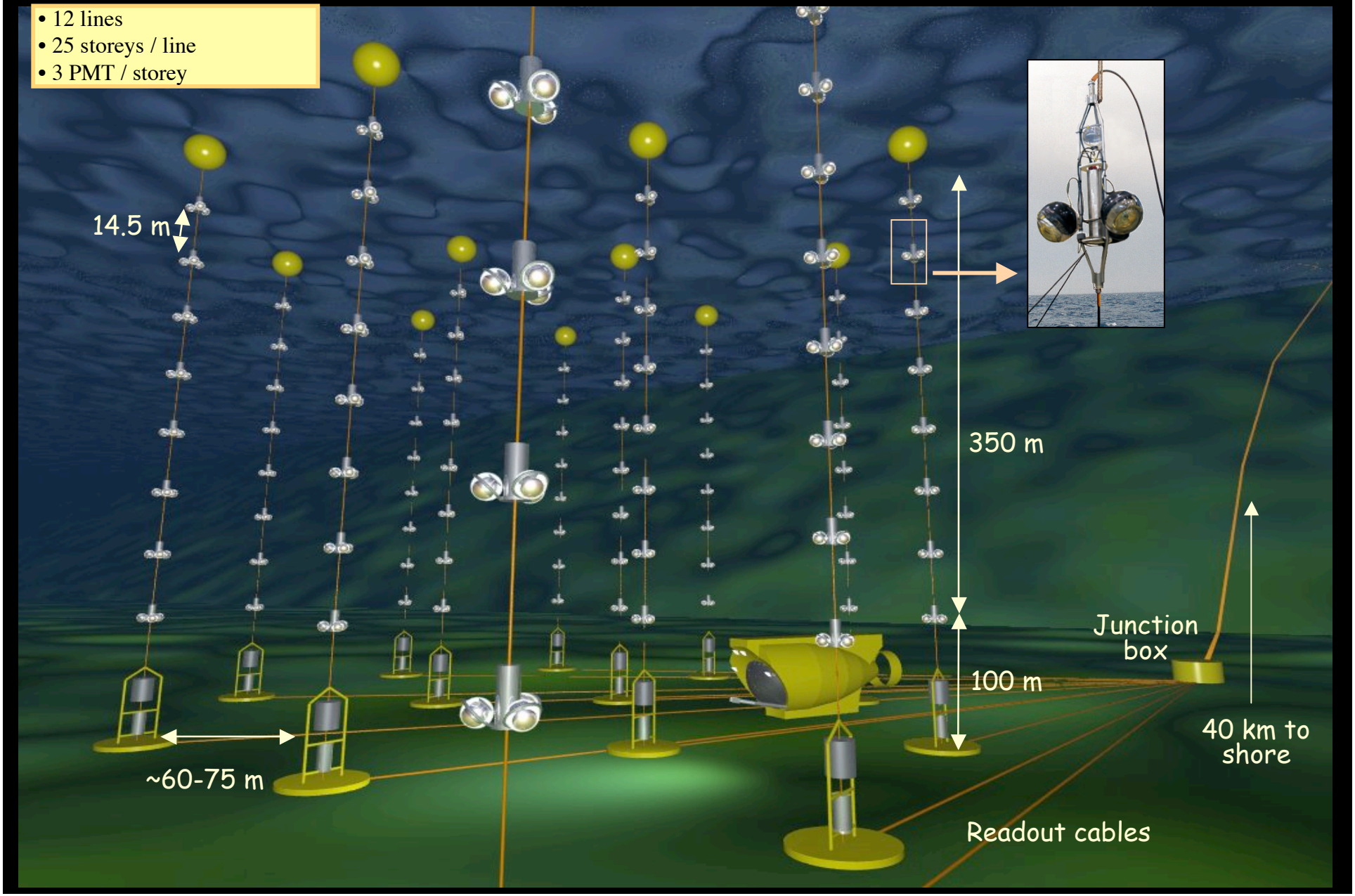


order of magnitude at 10^{20} eV

better than factor 2 at 10^{16} eV

flux itself is ambiguous because of spectrum and evolution of the unknown sources

from DUMAND to ANTARES (via lake Baikal)



how big a detector ?
the highest energy particles

Nature's Accelerators ?

protons > 10^8

TeV

photons > 10^2

how big a detector (ctd) ?
extragalactic cosmic rays

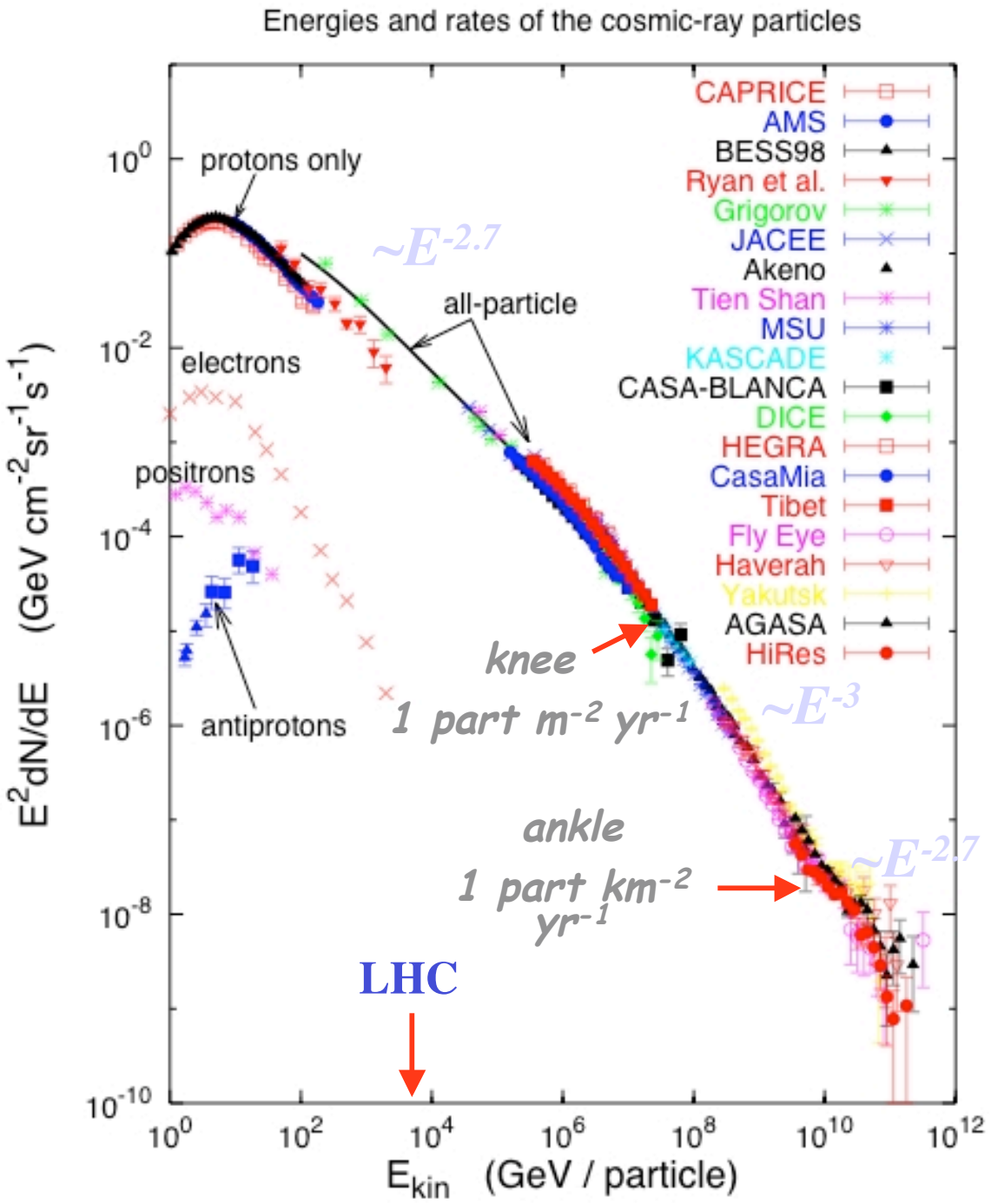
cosmic rays*

Nature accelerates particles 10^7 times the energy of LHC !

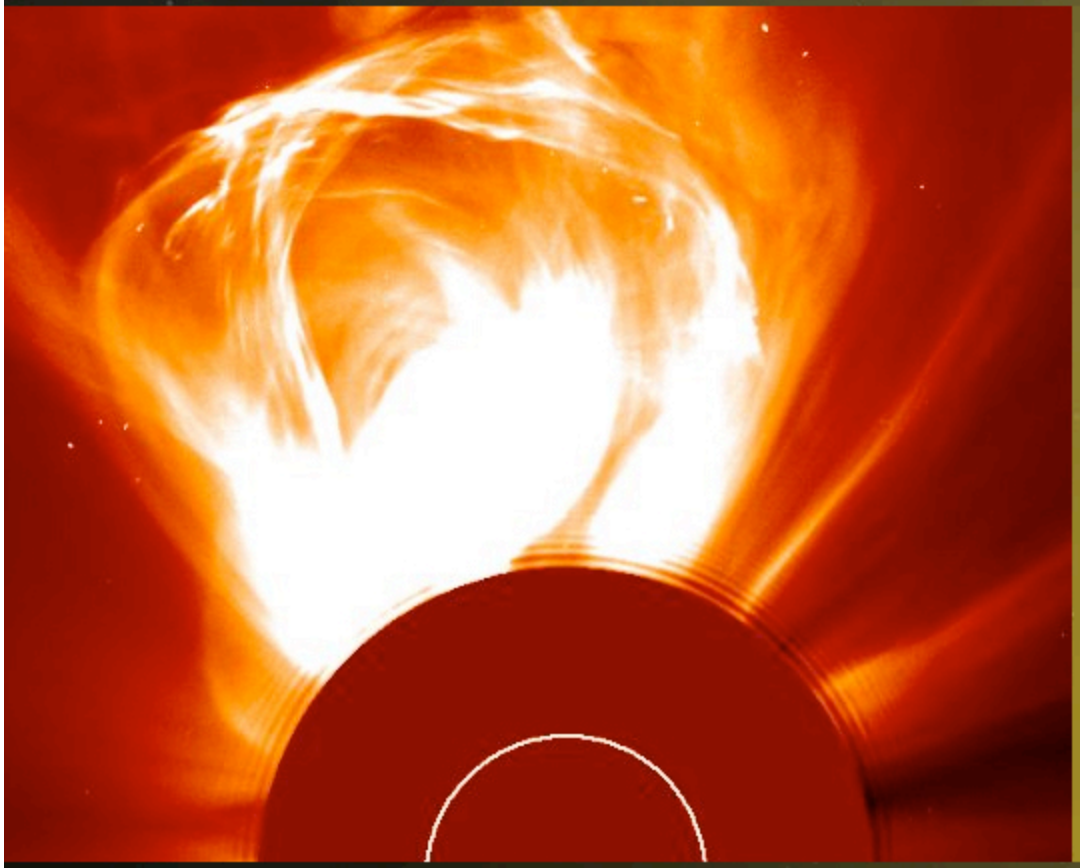
where?

how?

*do not point at their sources



shock acceleration : solar flares to black holes



coronal
mass
ejection
→
10 GeV
particles

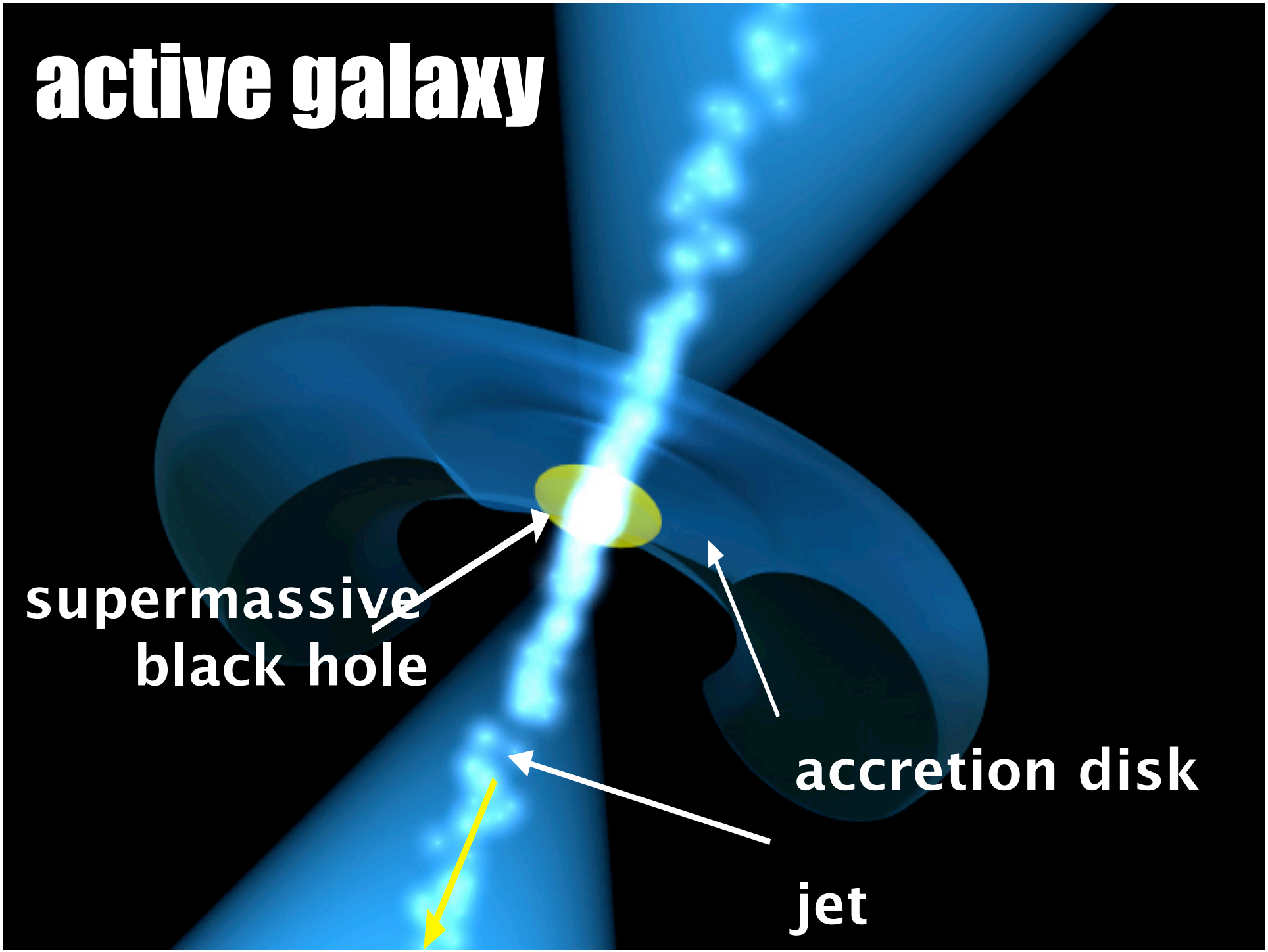
acceleration to 10^{21} eV ?

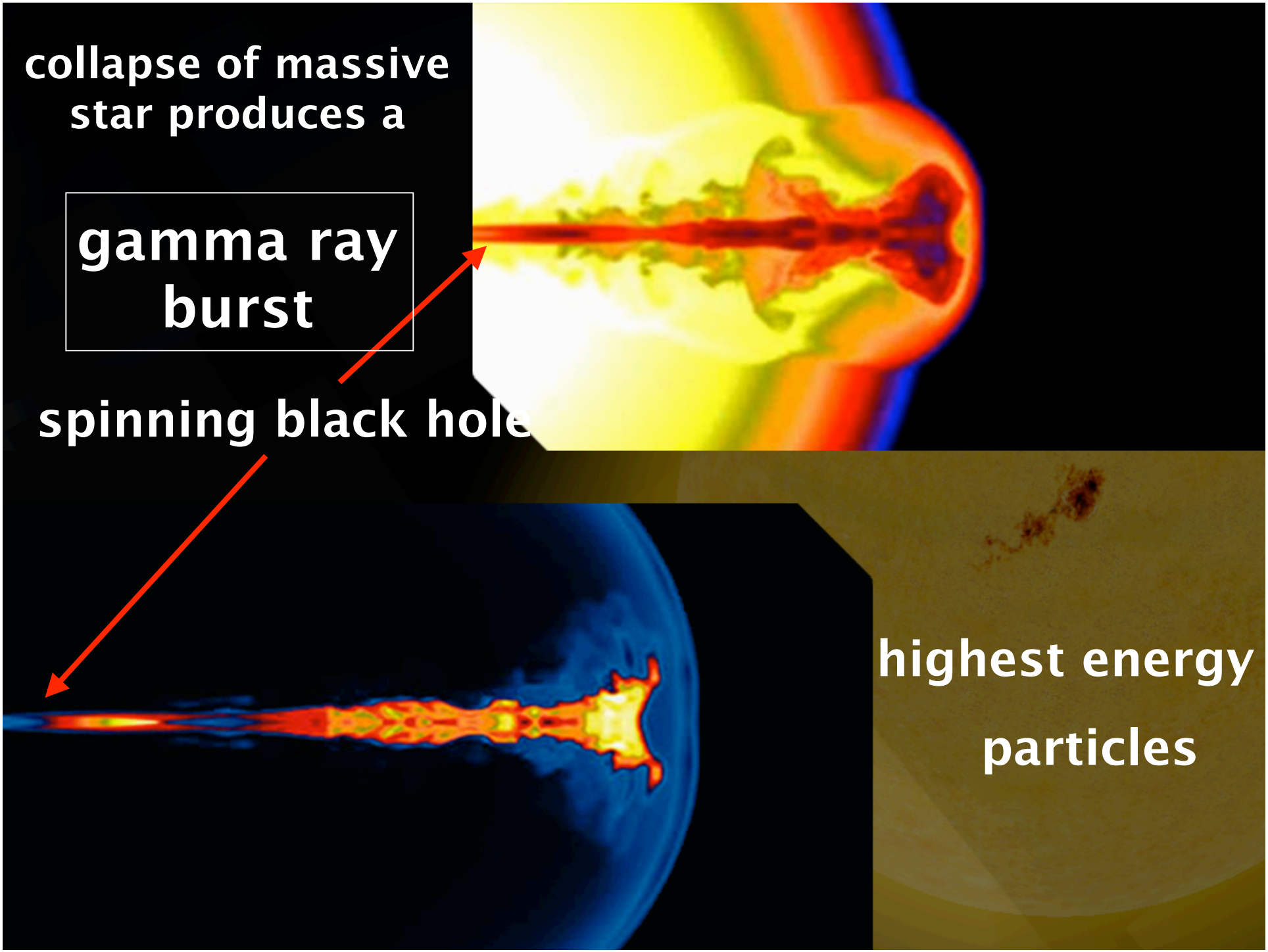
$\sim 10^2$ *Joules*

$\sim 0.01\ M_{GUT}$

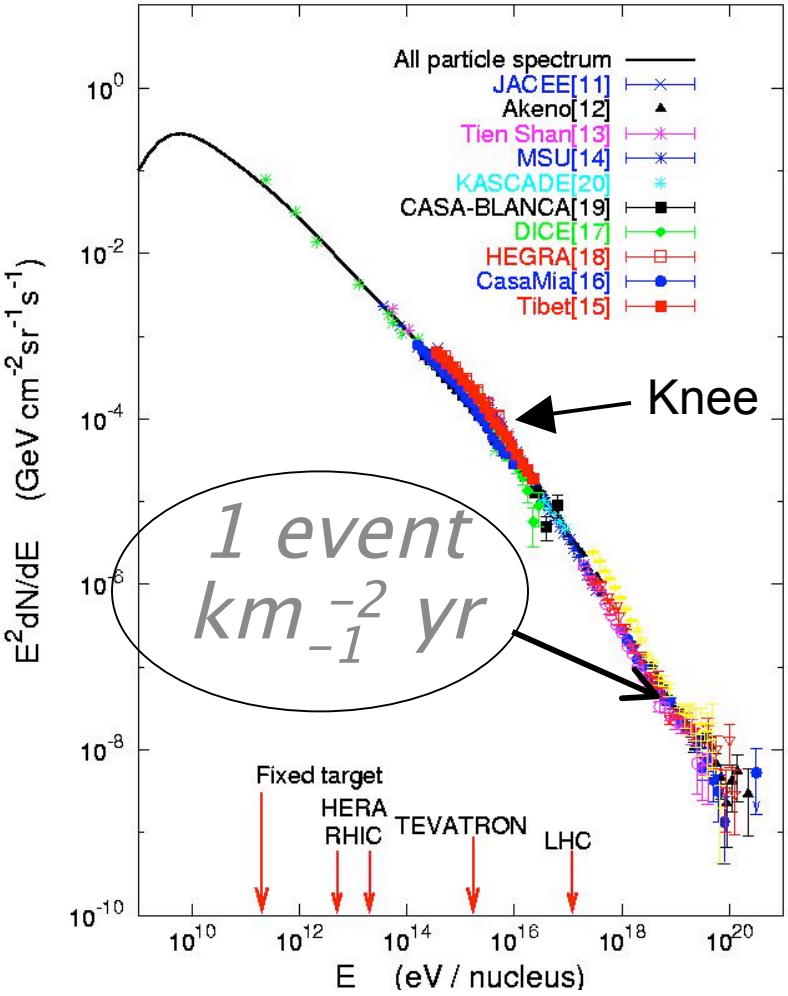
dense regions with exceptional gravitational force creating relativis flows of charged particles, e.g.

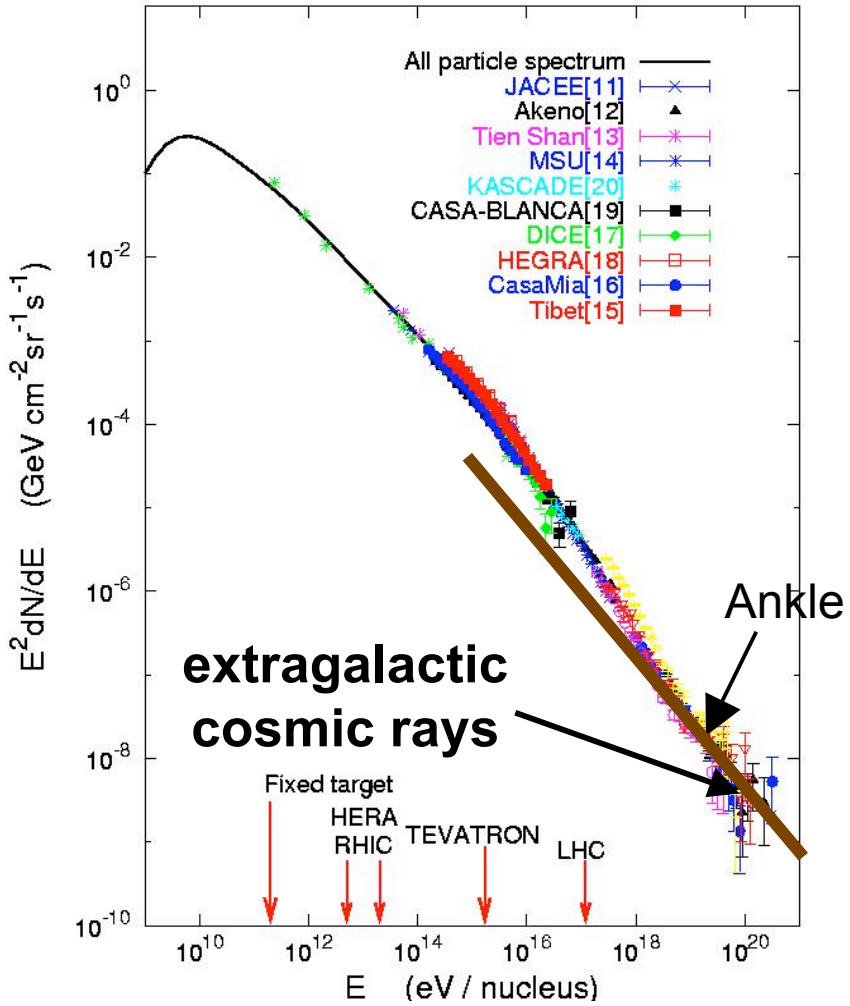
- *dense cores of exploding stars*
- *supermassive black holes*
- *merging galaxies*


active galaxy
supermassive
black hole
accretion disk
jet


collapse of massive star produces a
gamma ray burst
spinning black hole
highest energy particles

galactic and extragalactic cosmic rays





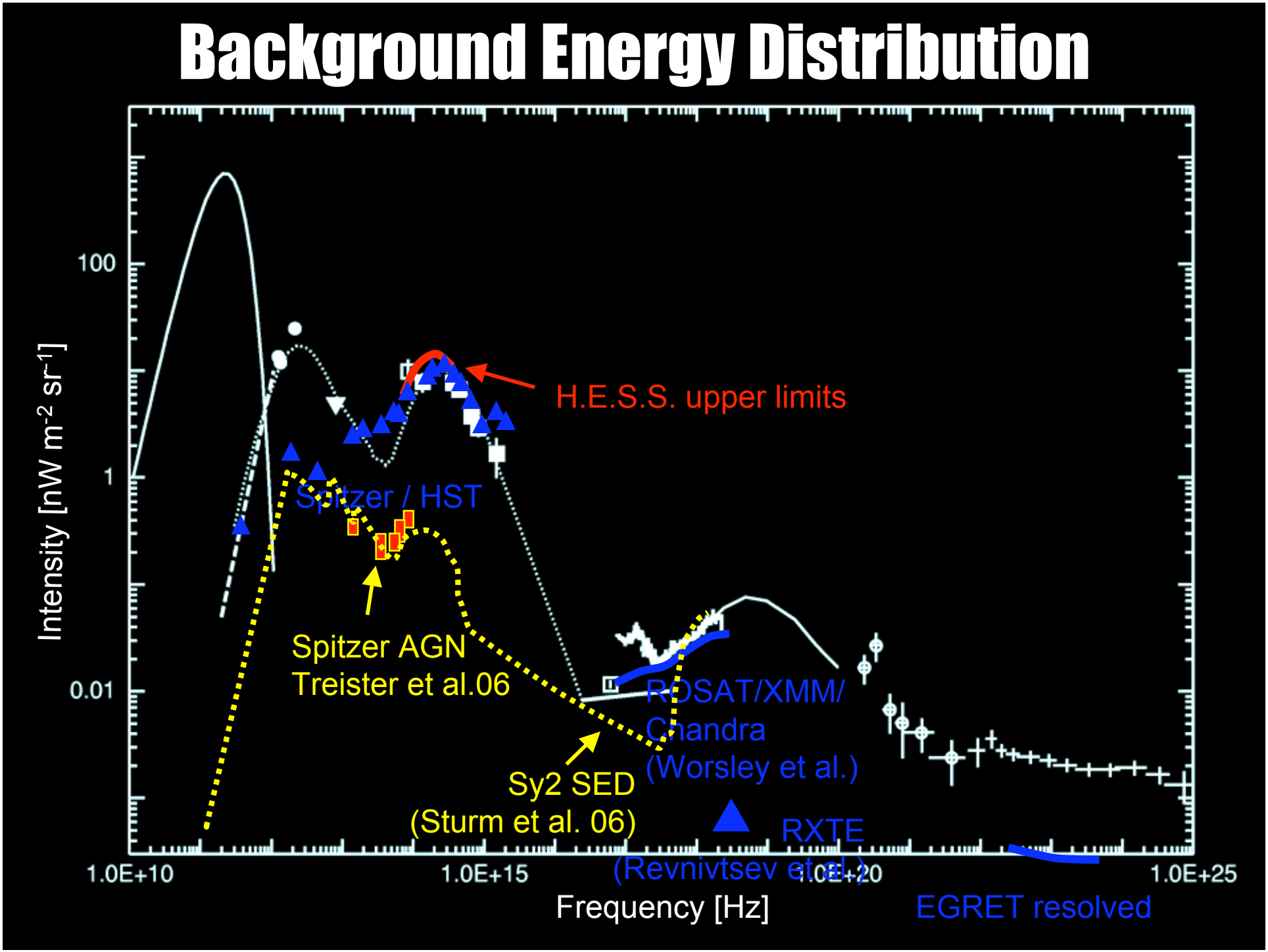
total flux = velocity x density :

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

$$\rho_E = \frac{4\pi}{c} \int \frac{3 \times 10^{-8}}{E} dE \; \frac{GeV}{cm^3}$$

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

Background Energy Distribution



>>> 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^{39} erg/s per galaxy

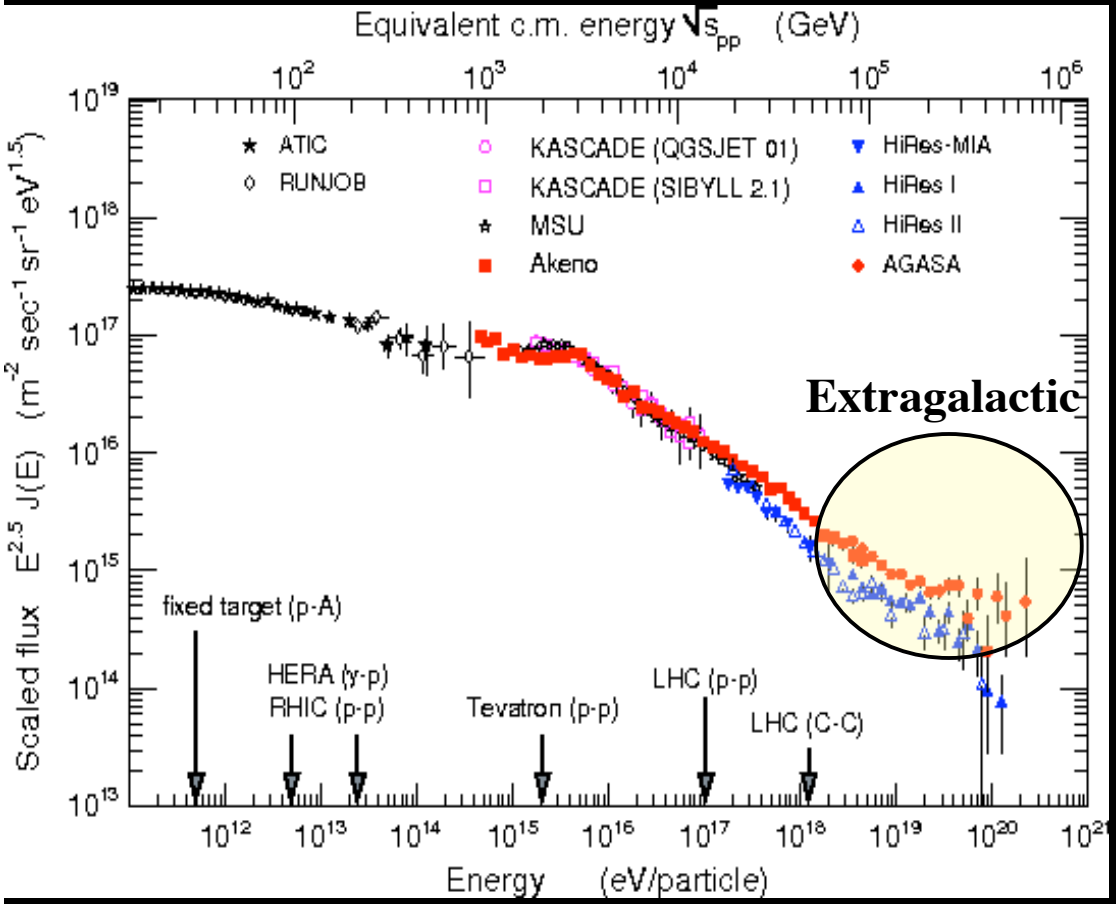
3×10^{44} erg/s per active galaxy

2×10^{52} erg per gamma ray burst

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

1 TeV = 1.6 erg

Cosmic Rays & GRBs



energy density of extragalactic CR:

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

Gamma-Ray Bursts:

$\rho_{GRBs} \sim 10^{51}$ ergs x 300/yr/Gpc^3

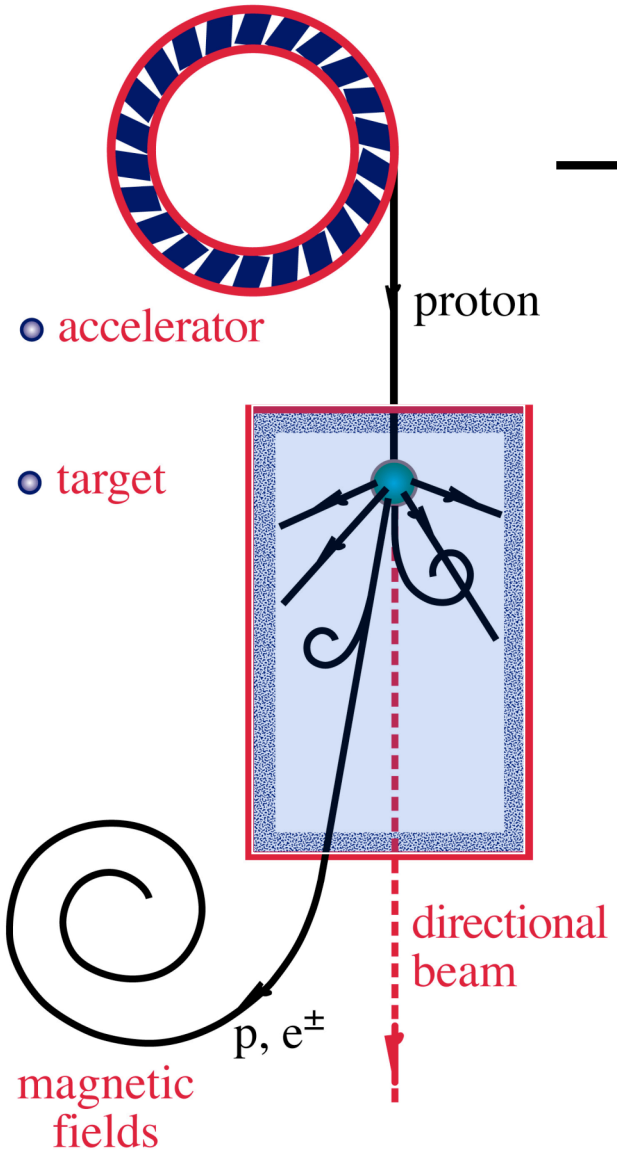
$\sim 10^{44}$ ergs/yr/Mpc^3

GRBs could provide environment

and energy to explain the highest

energy cosmic rays!

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 rays:**

~ 3×10^{-19} erg/cm^3 or

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

3×10^{39} erg/s per galaxy

3×10^{44} erg/s per active galaxy

2×10^{52} erg per gamma ray burst

→ **energy in**

cosmic rays ~ photons ~ neutrinos

flux of extra-galactic cosmic rays

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

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

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

cosmic sources →

cosmic rays ~ photons ~ neutrinos

agrees with observations !

10~1000 neutrinos per kilometer square year

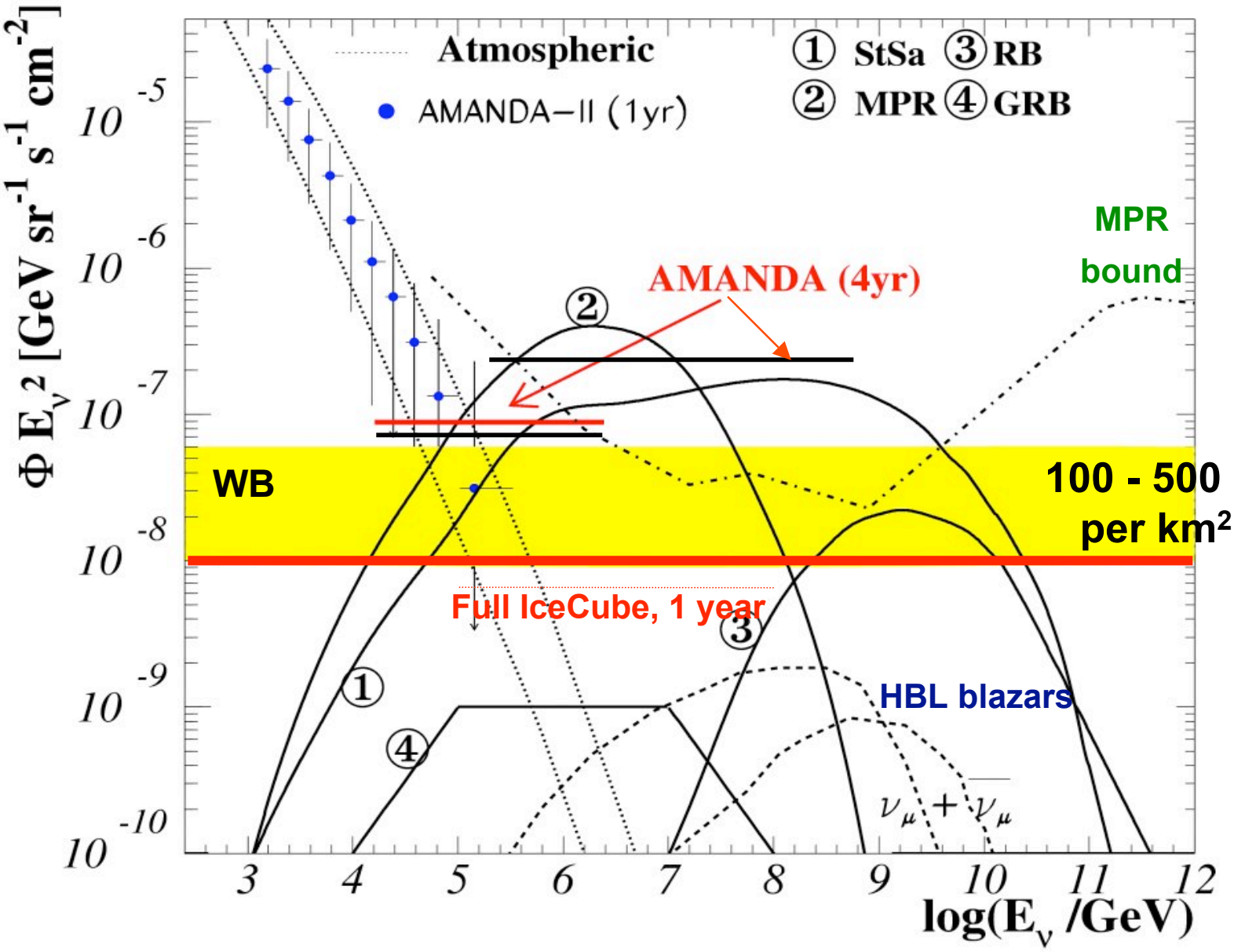
John Bahcall

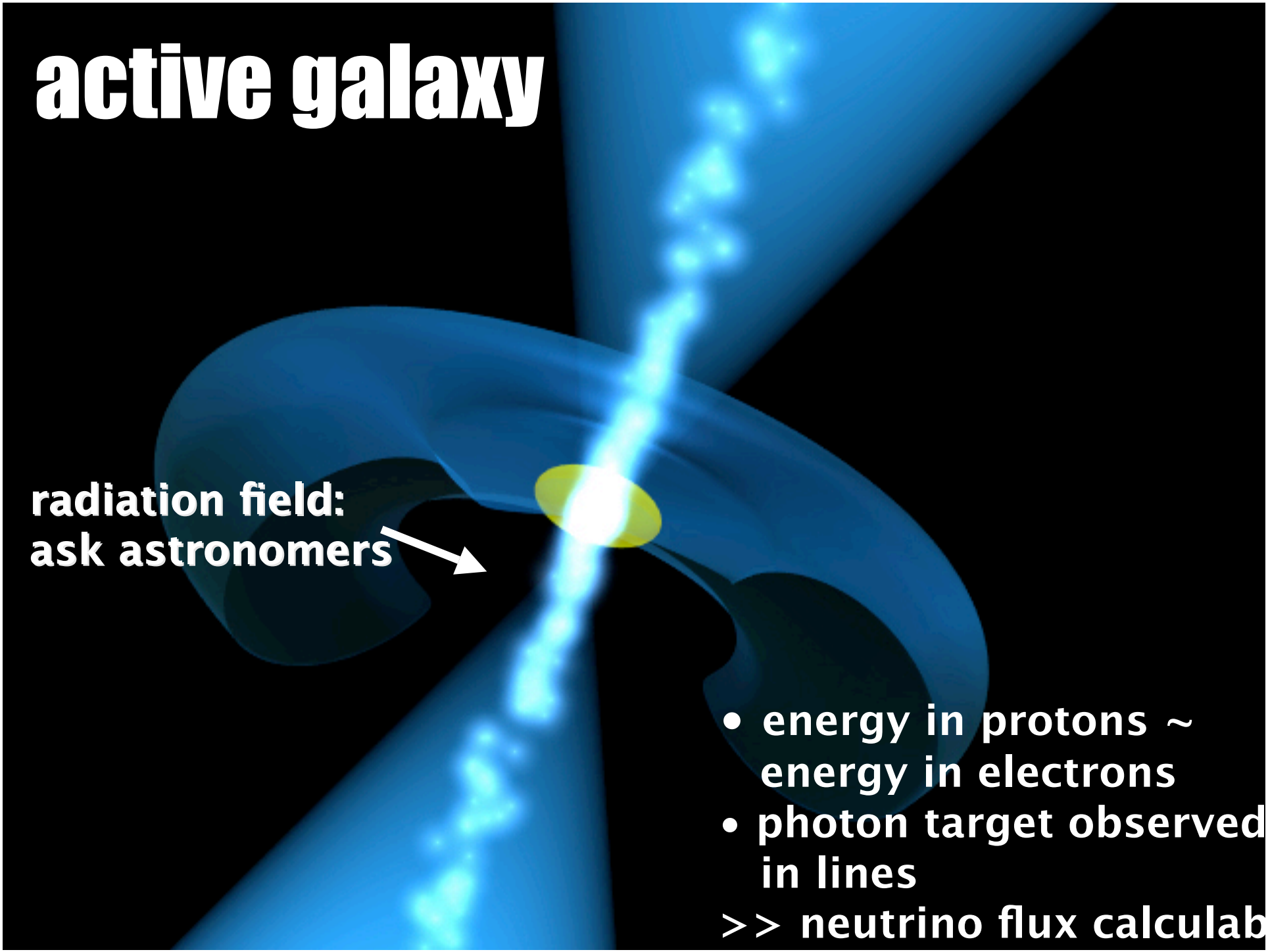
- **events per km2 year:**

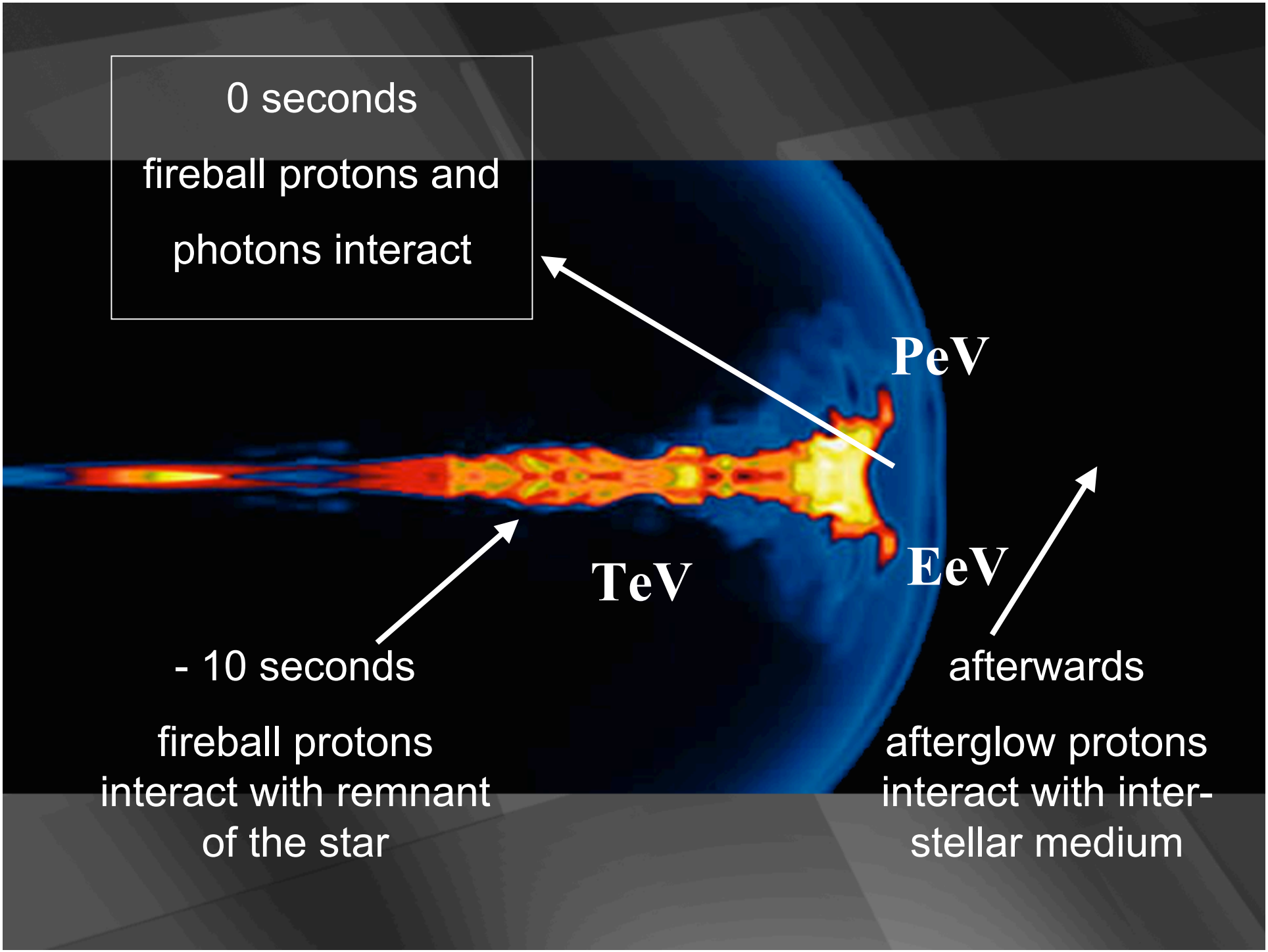
$$N = 2\pi \times area \times time \times \int \frac{dN}{dE} P_{\nu \to \mu}\, dE$$

$$N \cong 80 \times \log \frac{E_{\nu\, max}}{E_{\nu\, min}} \cong 500\ events$$

Diffuse muon neutrino flux




active galaxy
radiation field:
ask astronomers
• energy in protons ~
energy in electrons
• photon target observed
in lines
>> neutrino flux calculab


0 seconds
fireball protons and
photons interact
PeV
TeV
EeV
- 10 seconds
fireball protons
interact with remnant
of the star
afterwards
afterglow protons
interact with inter-
stellar medium

what's the problem ?

Hillas formula

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

$$E \leq qBR$$

$$\boxed{E \leq c\ qBR}$$

Cosmic Accelerators

$$E \sim q\, vBR$$

$$R \sim GM/c^2$$

energy

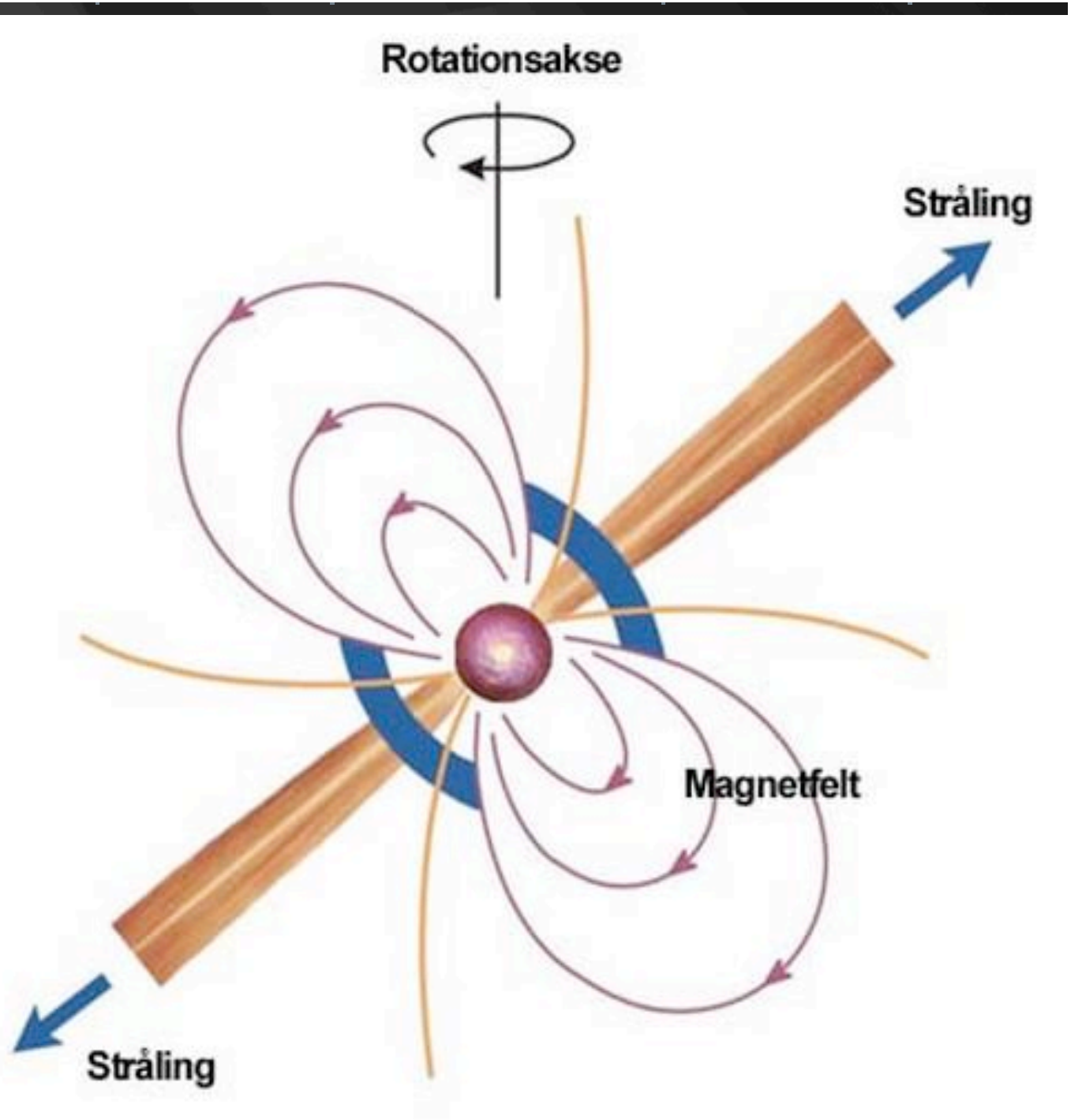
magnetic field

$$E \sim BR^2/T$$

period

pulsar

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



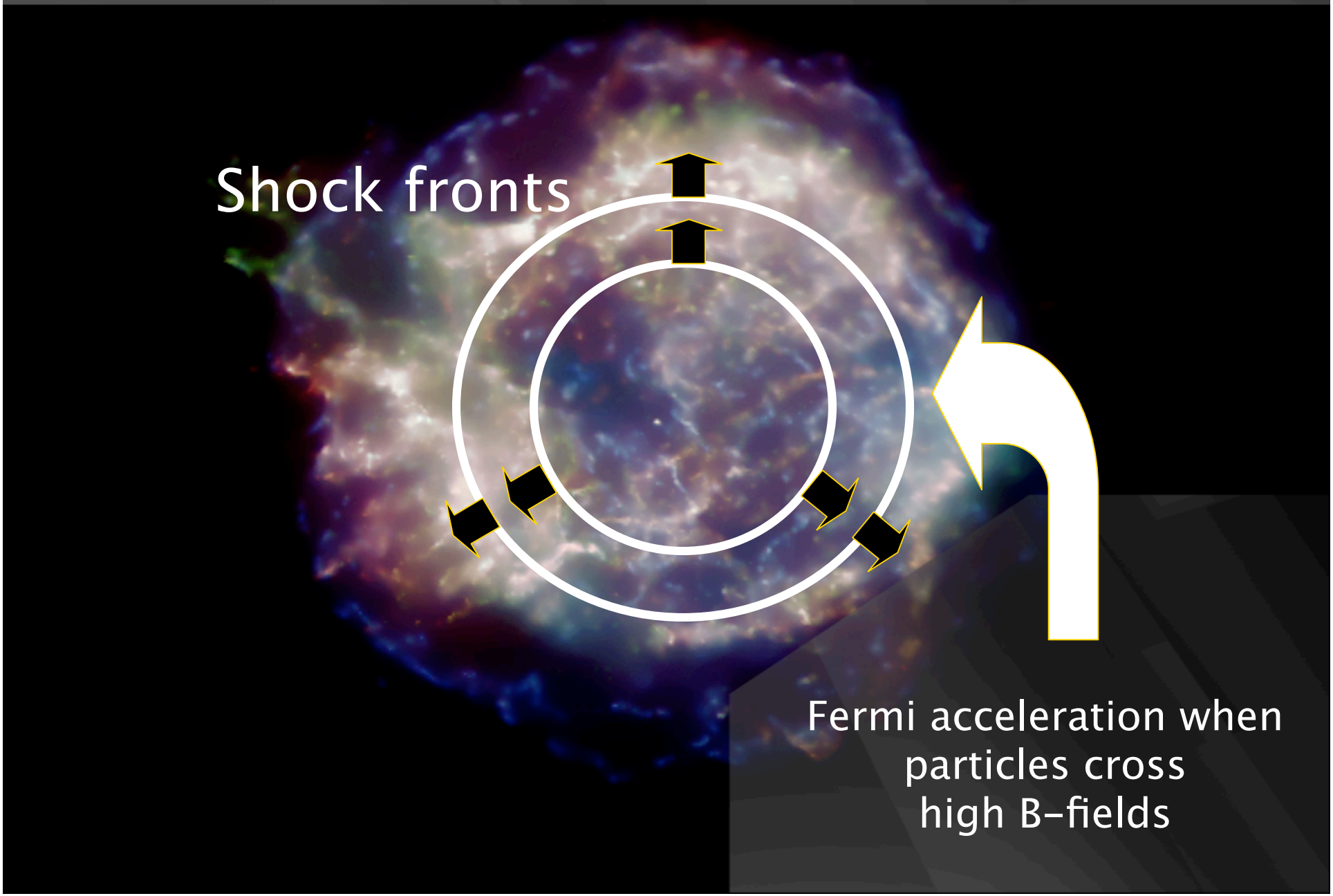
$$E\,(\mathrm{eV}) = B\,(\mathrm{Tesla})\,R^2\,(\mathrm{m})\,\frac{2\pi}{T}$$

	ms-pulsar	Fermilab
R	10 km	few km
B	10^8 T	few T
T^{-1}	10^3	10^5 (#revs^{-1})
E	10^7 TeV	$\sim 10^{12}$ eV = 1 TeV !

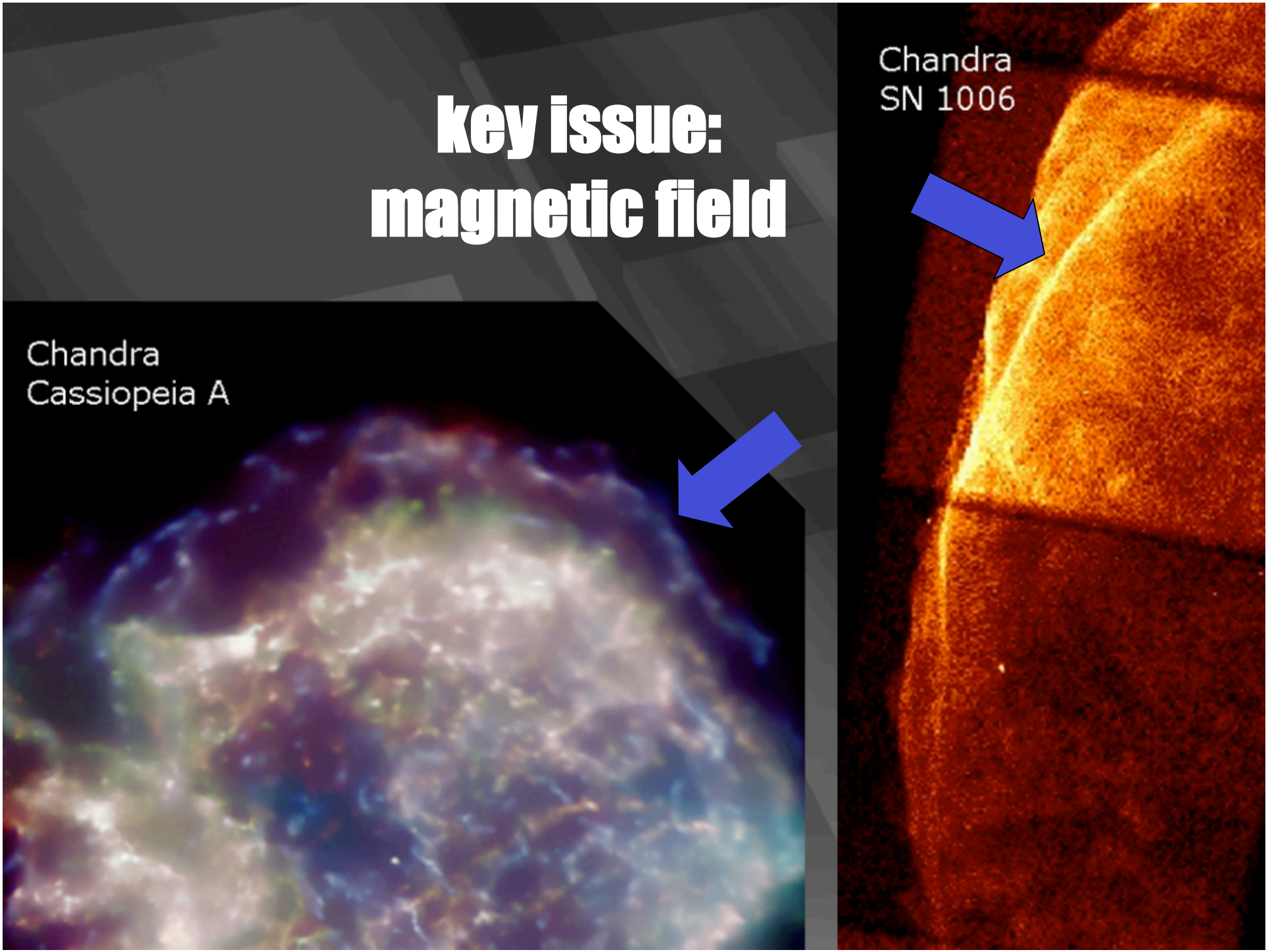
Georges Lemaitre believed that cosmic rays where primordial radiation from the Big Bang

how big a detector (ctd) ?
galactic cosmic rays and supernovae

Cas A supernova remnant in X-rays



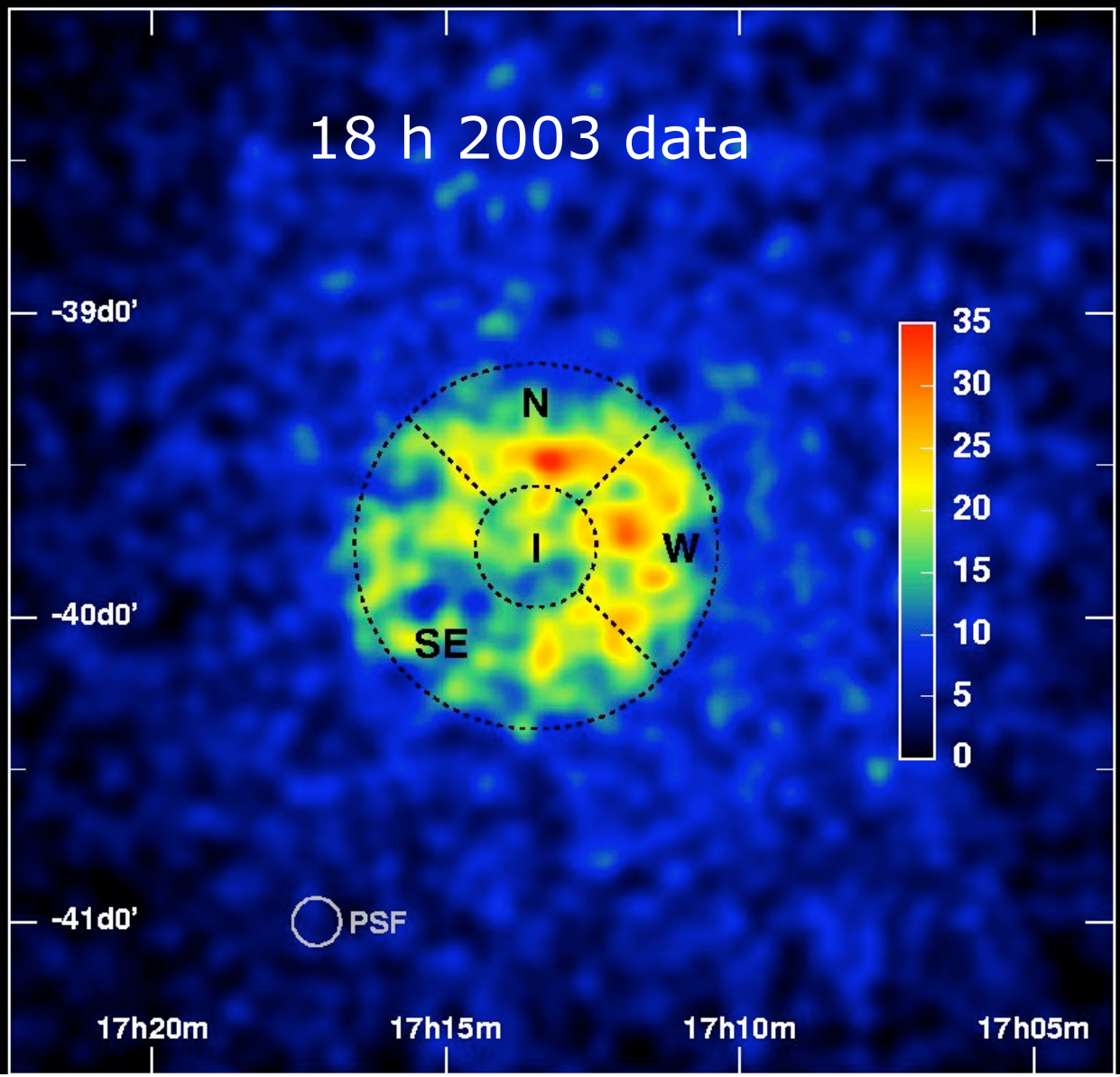
key issue: magnetic field



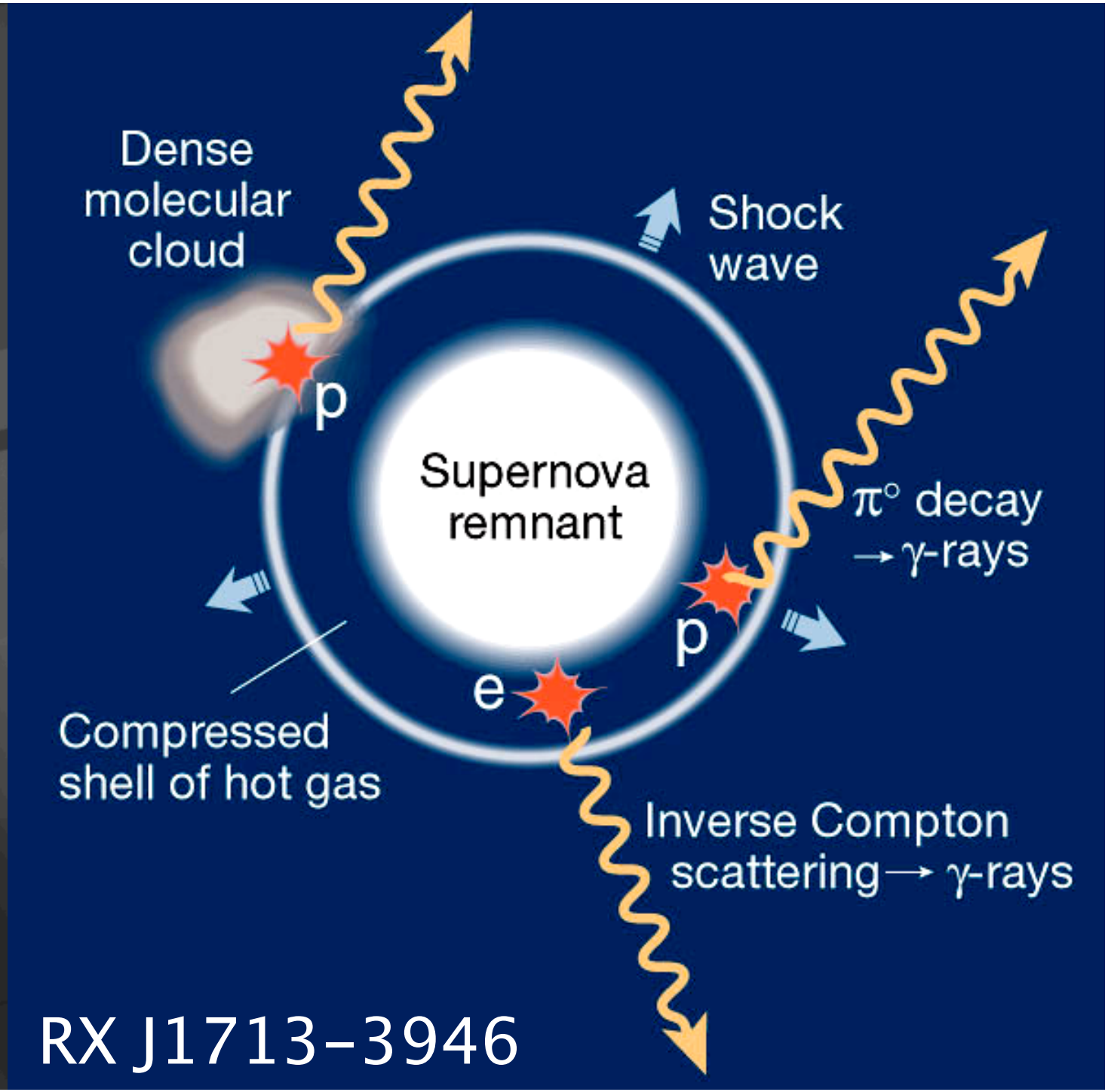
HESS: RX J1713 Spectrum

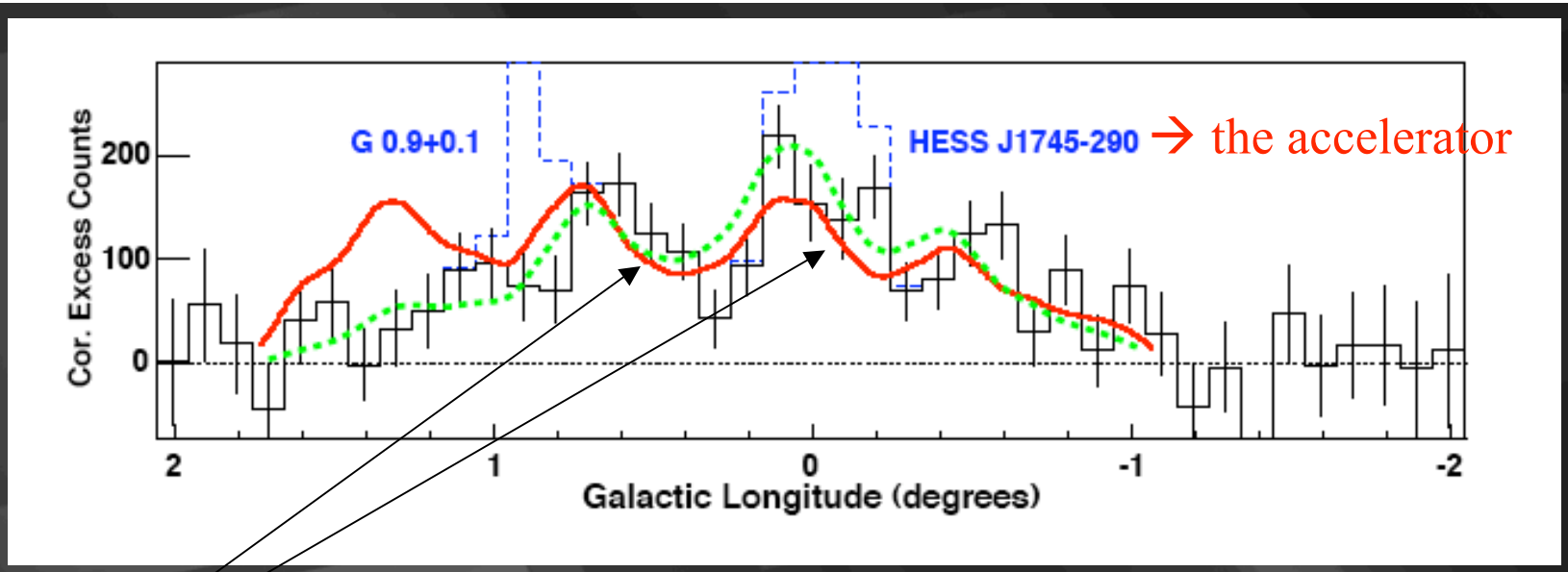
1 ~ 10 neutrinos per km^2 year

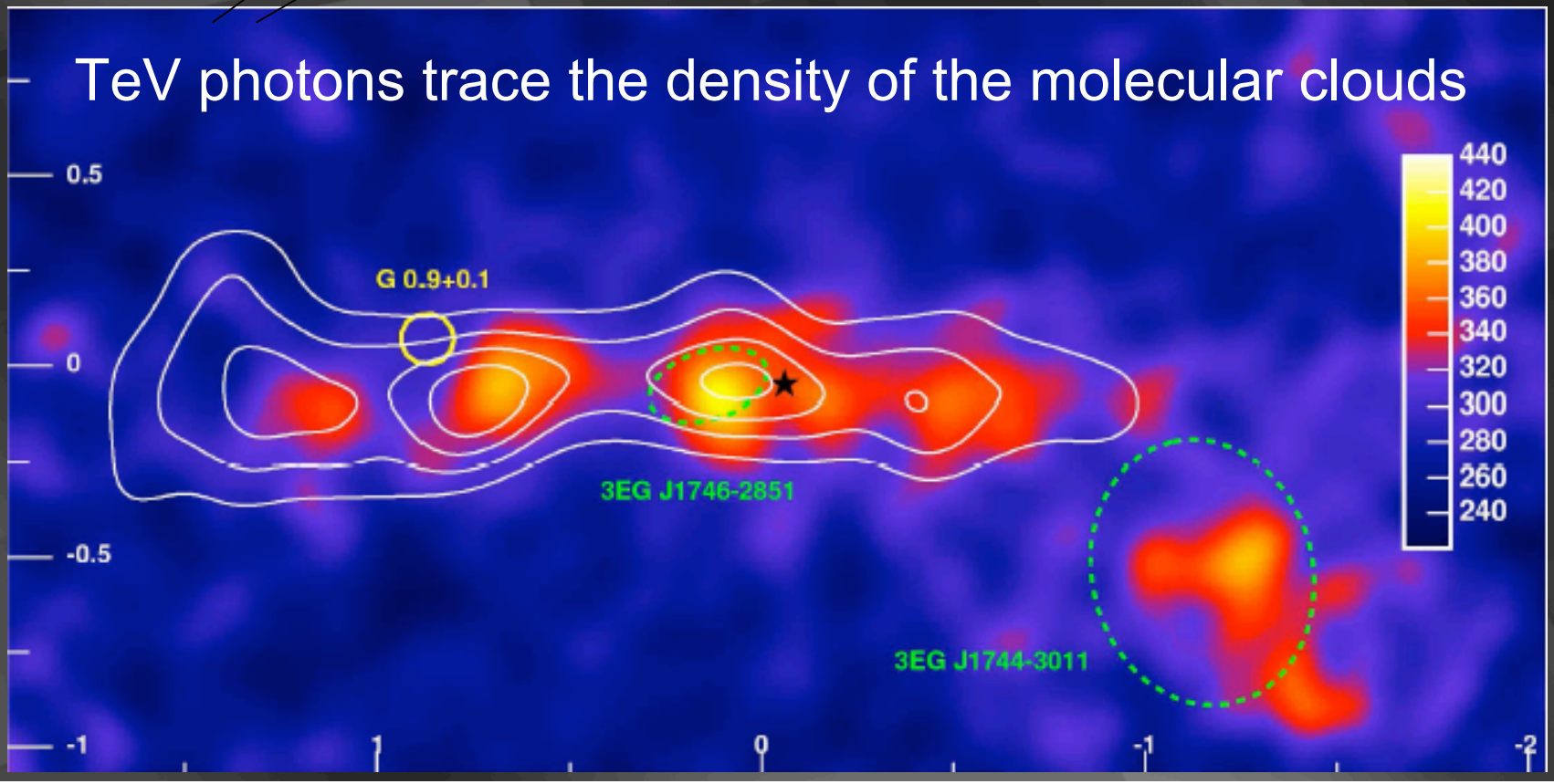
KM3NeT



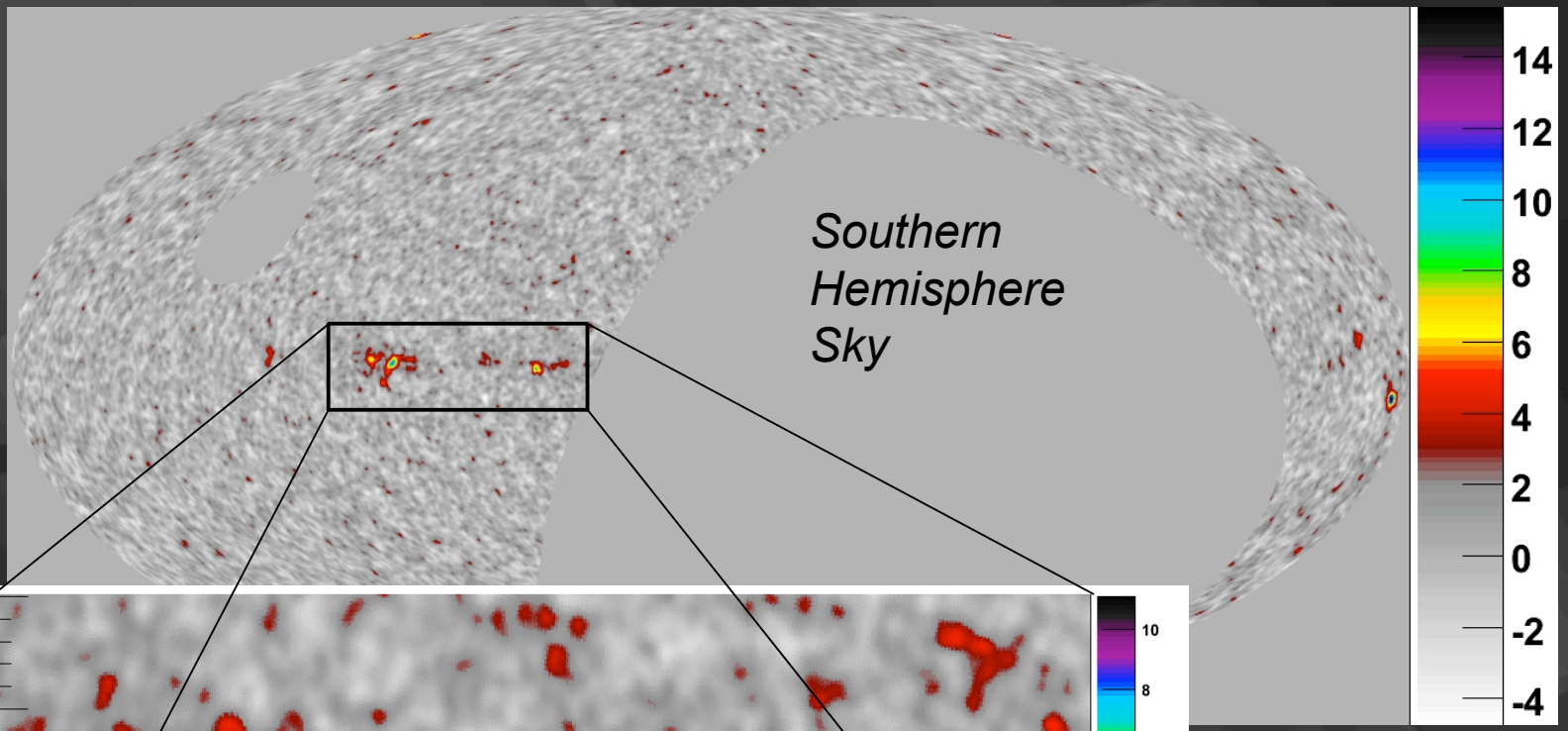
supernova beam dump

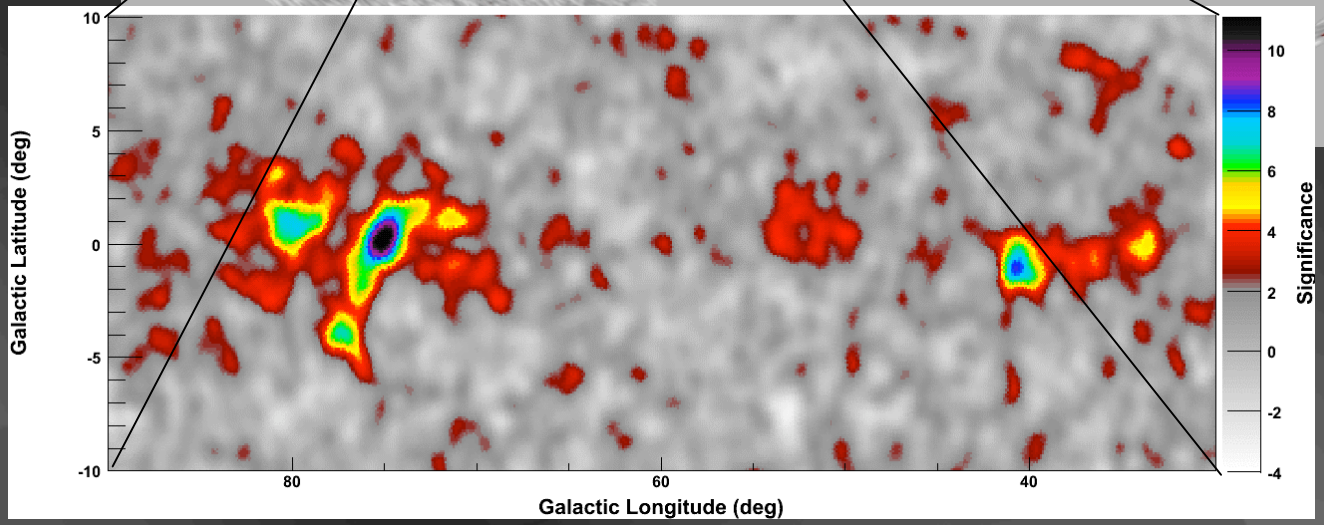


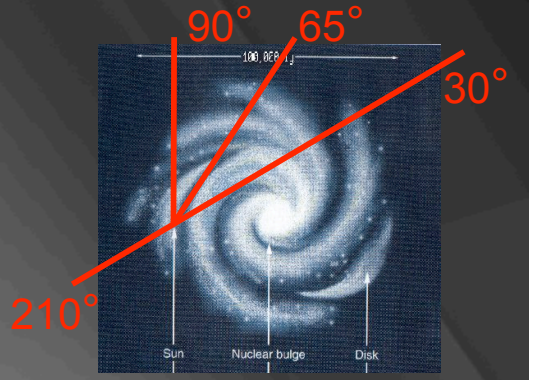

G 0.9+0.1
HESS J1745-290 → the accelerator
Cor. Excess Counts
200
100
0
2
1
0
-1
-2
Galactic Longitude (degrees)


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

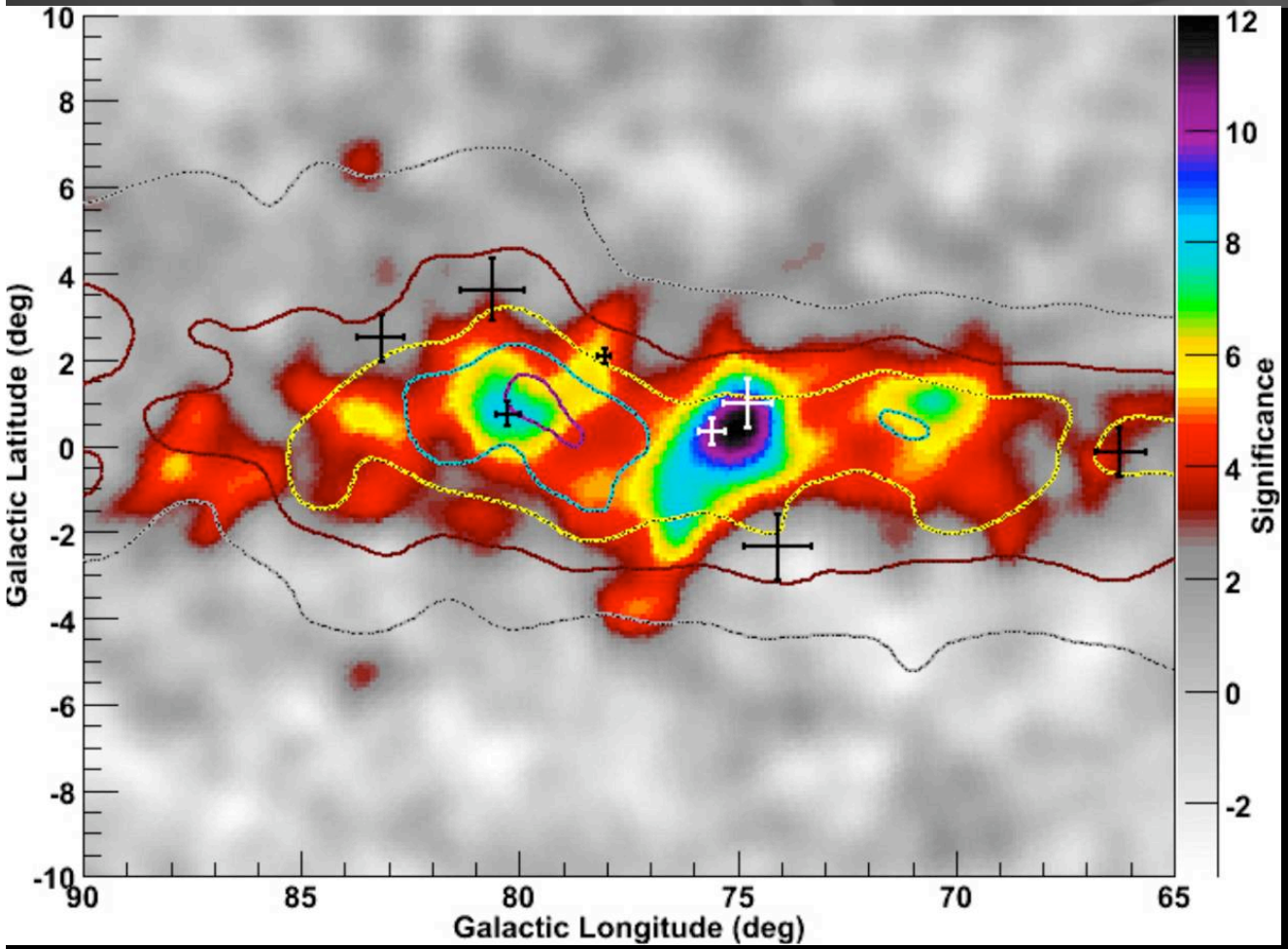
galactic plane







cygnus region : Milagro and Tibet



Milagro

contours are pion model with no sources

crosses are EGRET unidentified sources

TeV/matter correlation good

chance noncorrelation 1.5×10^{-6}

2~4 neutrinos in IceCube per source

γ, ν flux of galactic cosmic rays

a SNR at d = 1 kpc transfers W = 10^{50} erg
to cosmic rays interacting with molecular clouds
with density n = 1 cm^{-3}

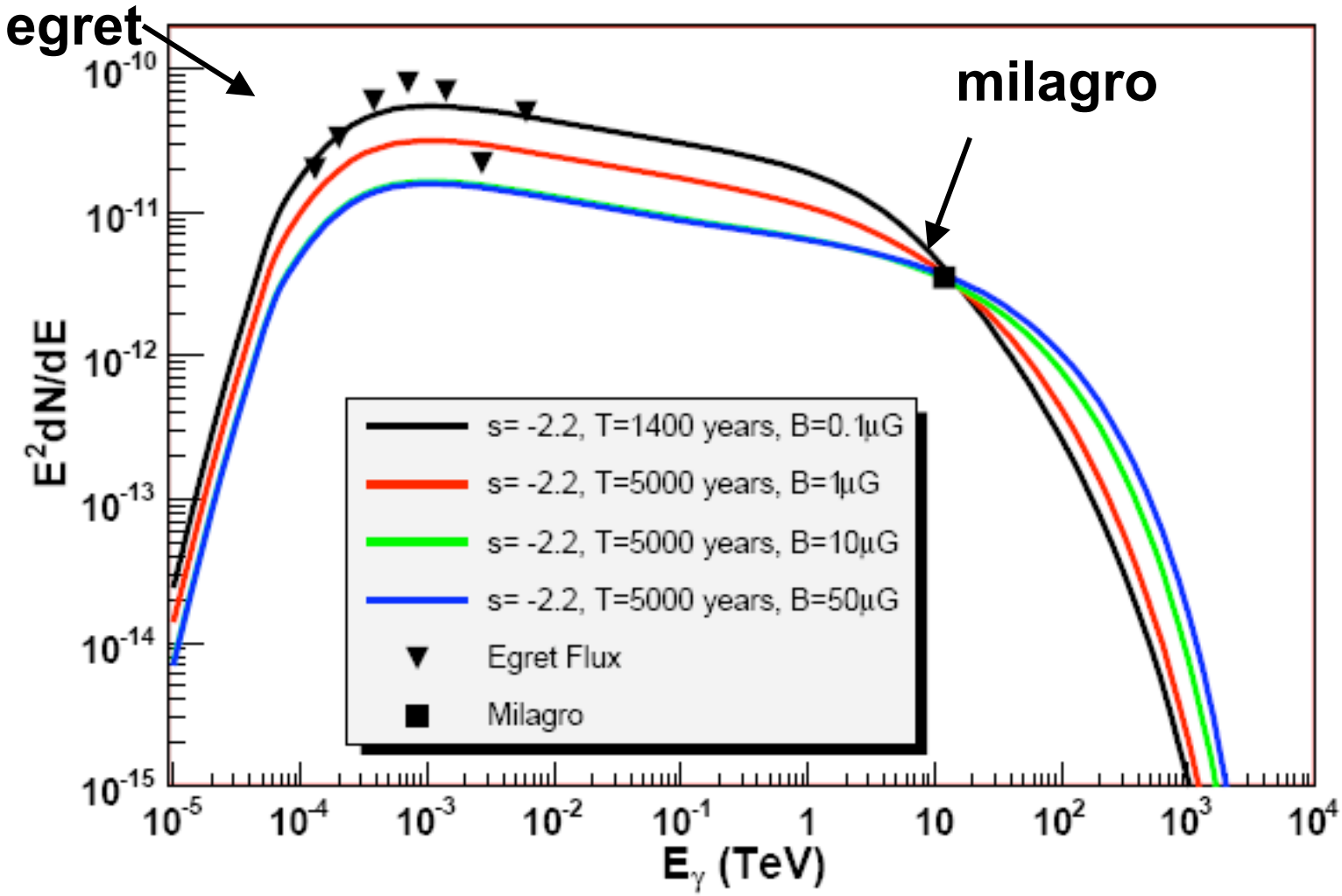
$$E\frac{dN_\gamma}{dE}(>1\,TeV) =$$

$$= 10^{-11}\,\frac{ph}{cm^2 s}\,\frac{W}{10^{50}\,erg}\,\frac{n}{1 cm^3}\left(\frac{d}{1 kpc}\right)^{-2}$$

2 SN per century supply the observed density of galactic cosmic rays

e.g. RX J1713.7-3946

1000 models … same ν-rate



neutral pions

are observed as

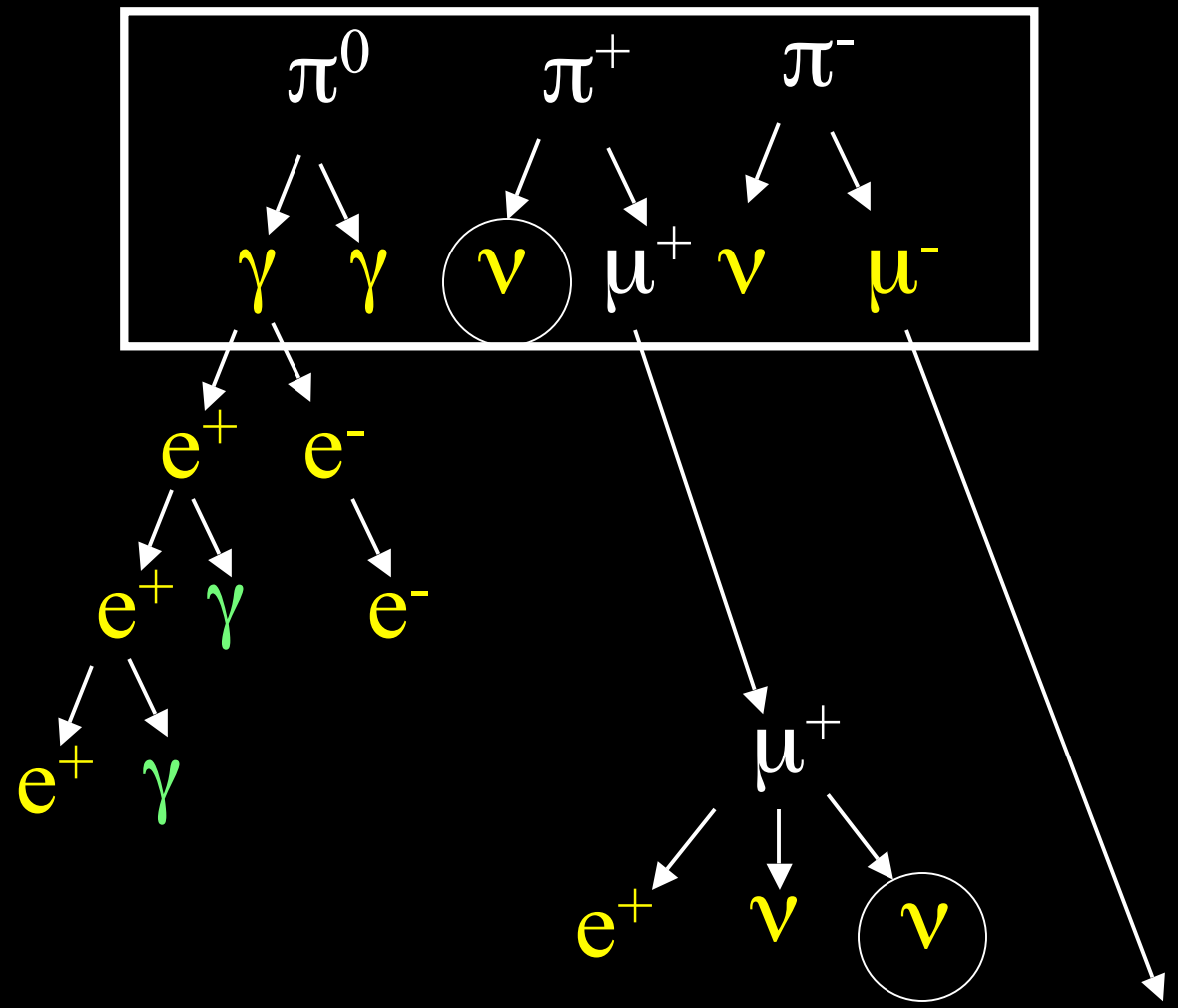
gamma rays

charged pions

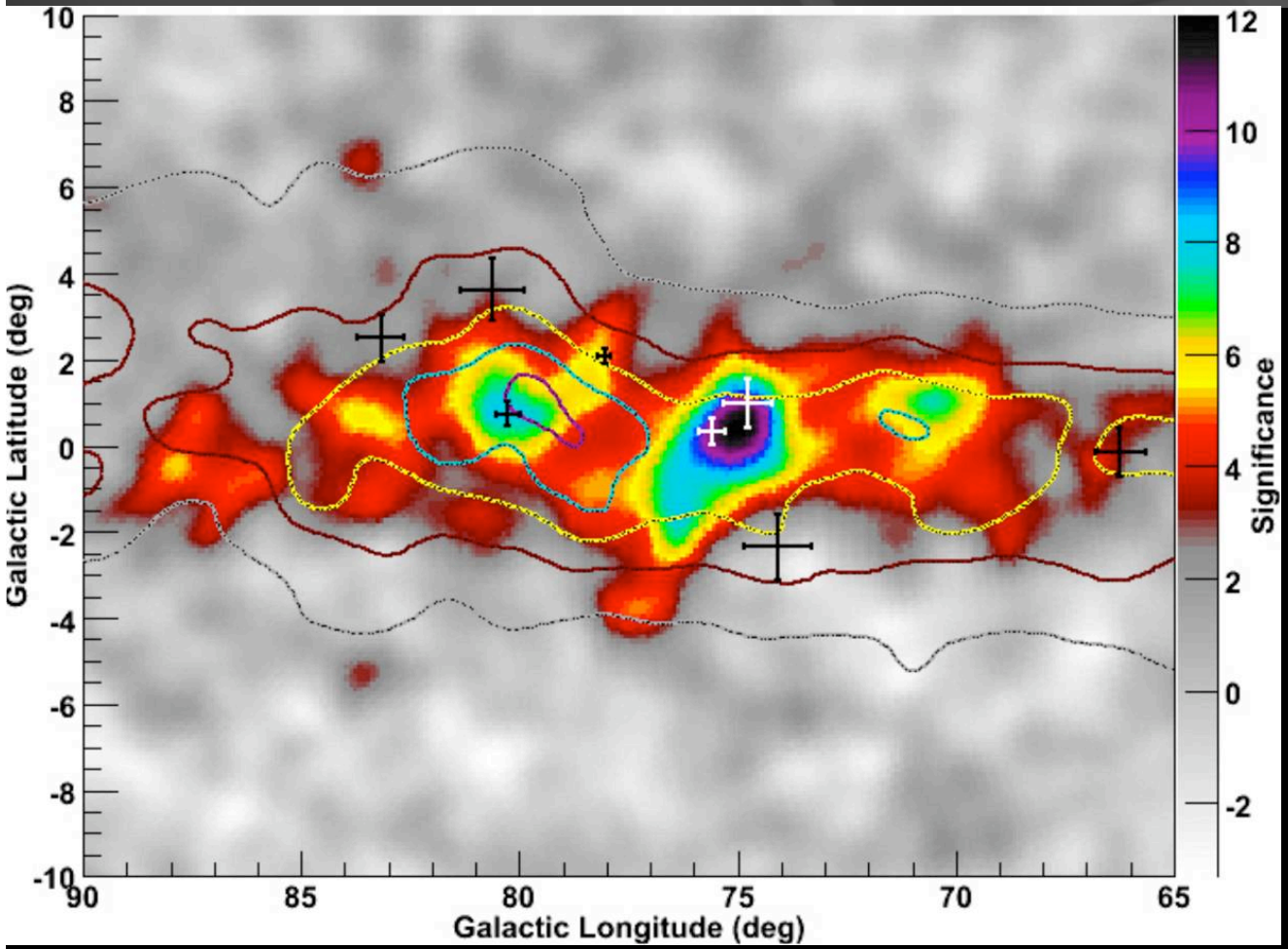
are observed as

neutrinos

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



cygnus region : Milagro and Tibet



Milagro

contours are pion model with no sources

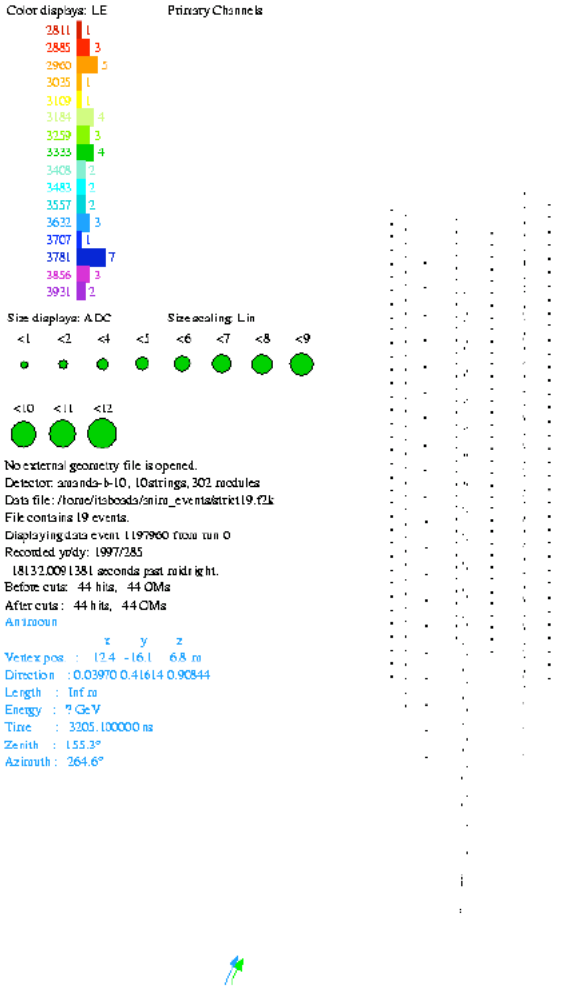
crosses are EGRET unidentified sources

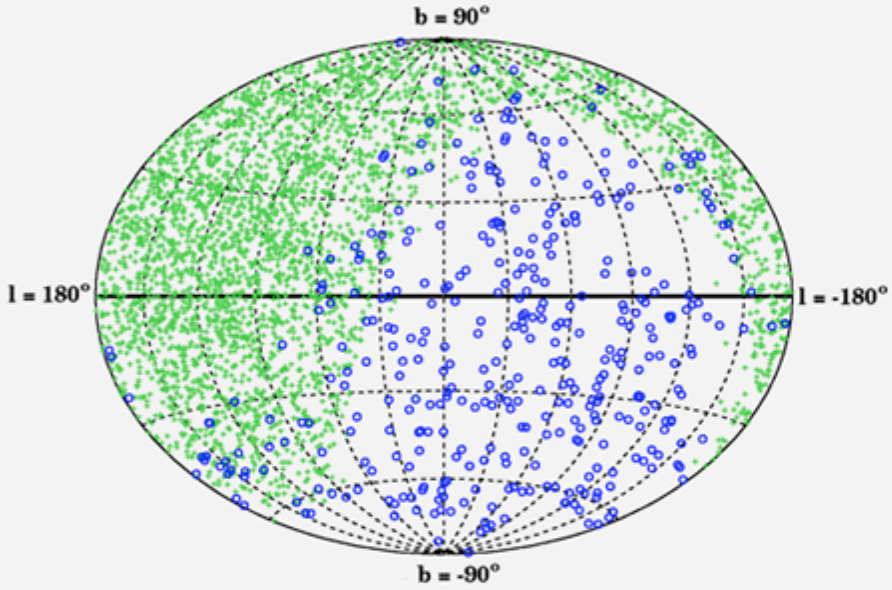
TeV/matter correlation good

chance noncorrelation 1.5×10^{-6}

2~4 neutrinos in IceCube per source

Skyplot AMANDA and Baikal

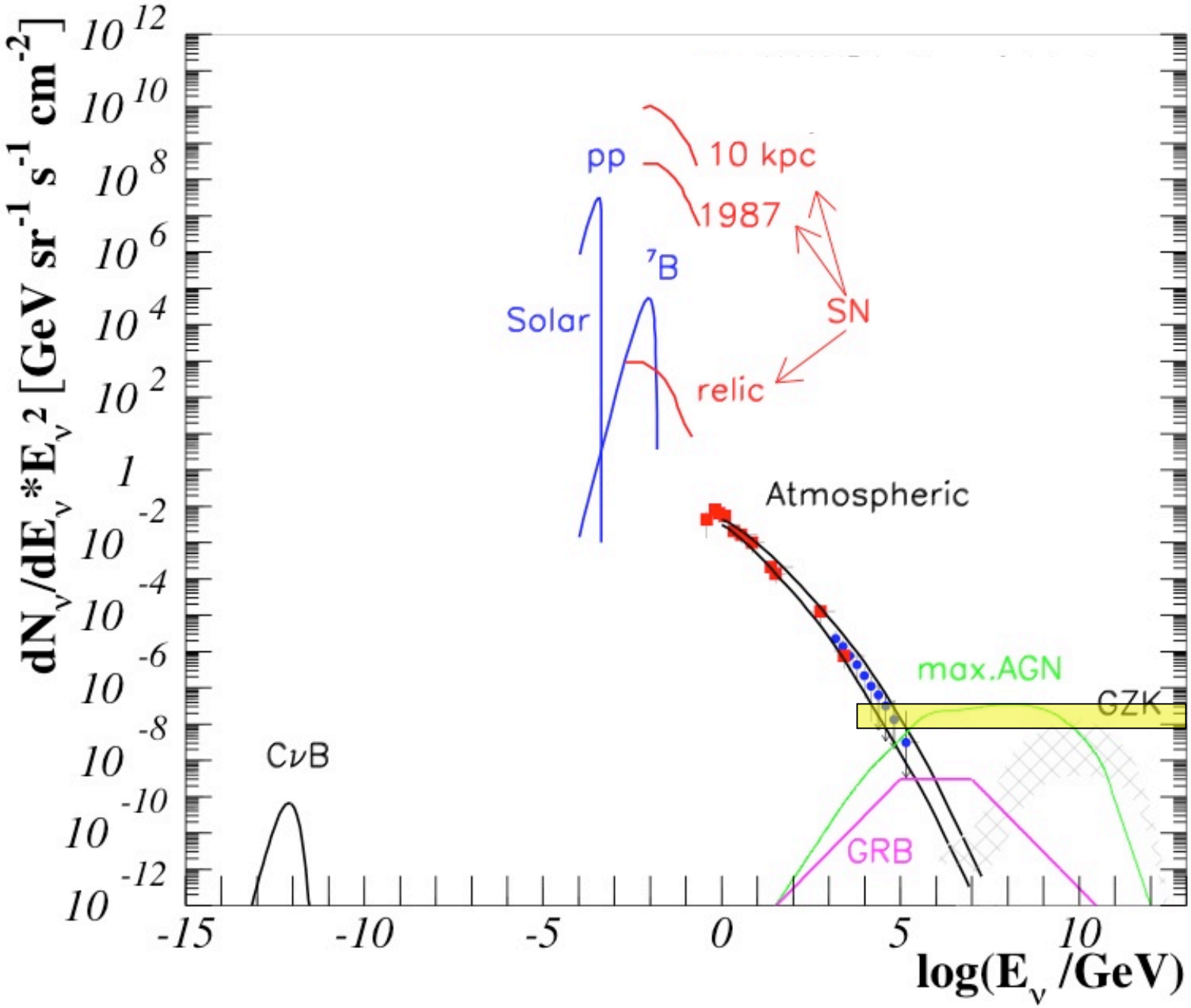




AMANDA:2000-2003, Baikal: 1998-2002
galactic coordinates

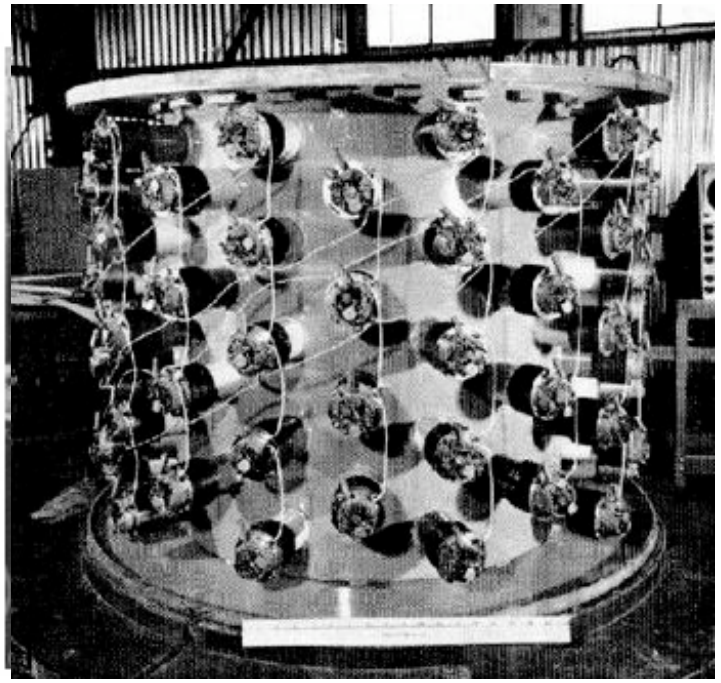
$$\nu_\mu + N \rightarrow \mu + X$$

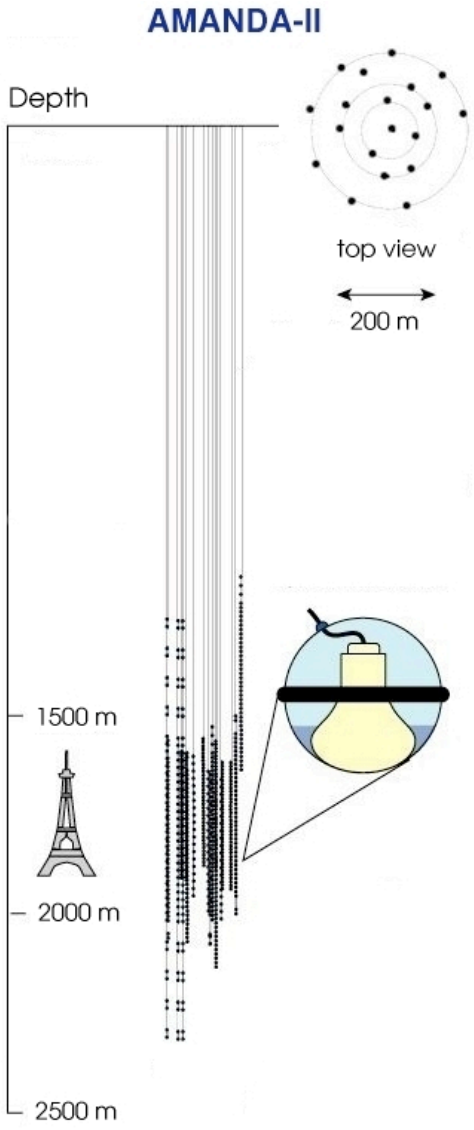
a one billion ton neutrino detector ?



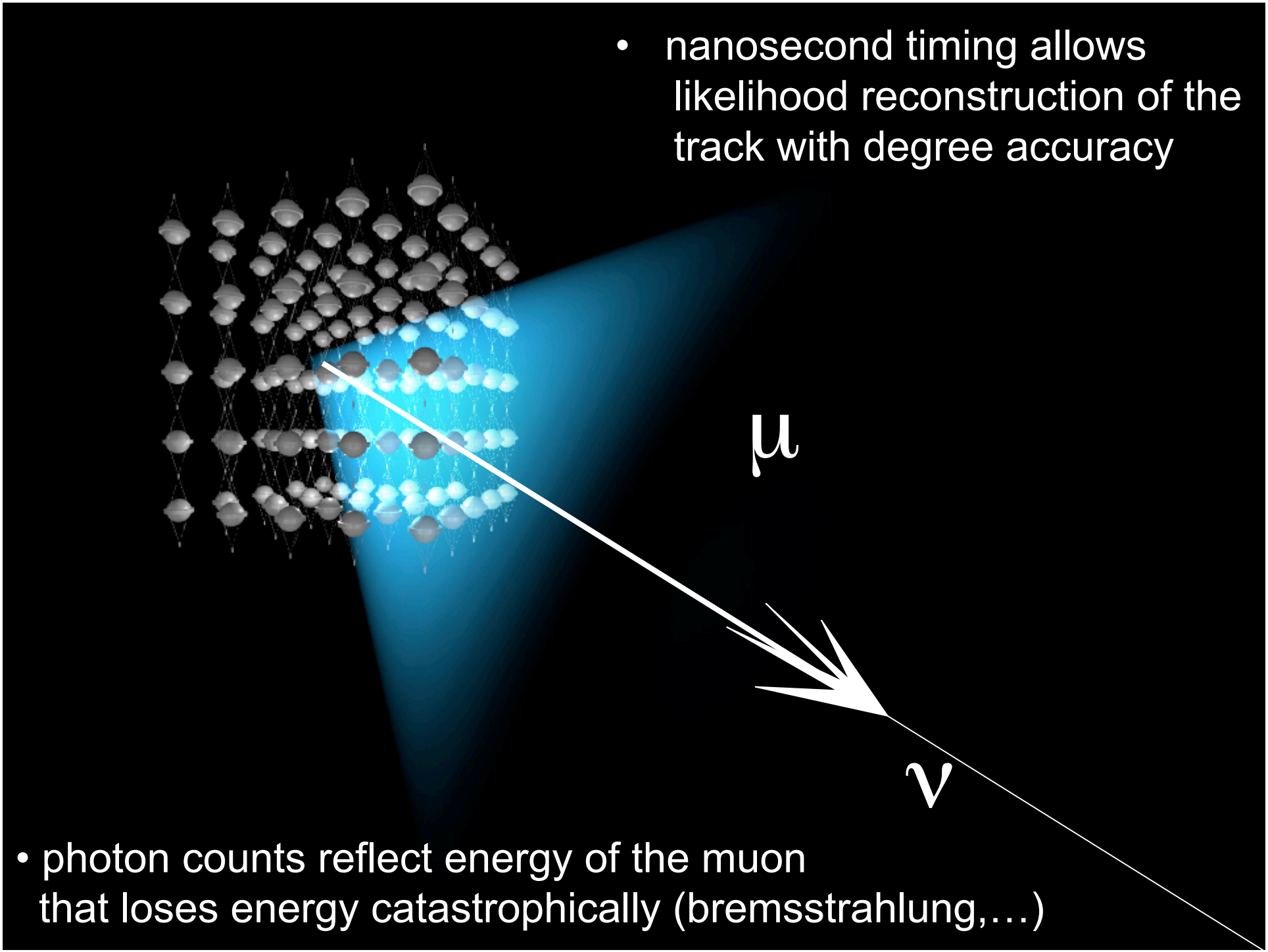
$dN_\nu/dE_\nu * E_\nu^2$ [GeV sr^{-1} s^{-1} cm^{-2}]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
-15
-10
-5
0
5
10
log(E_ν /GeV)
pp
10 kpc
1987
^{7}B
Solar
SN
relic
Atmospheric
max.AGN
GZK
CνB
GRB

requires kilometer-scale neutrino detectors





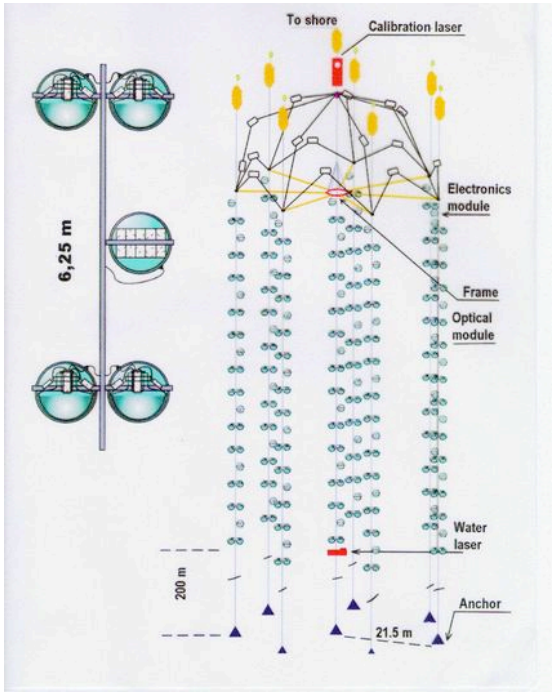
SuperKamiokande in the Japanese alps


• nanosecond timing allows likelihood reconstruction of the track with degree accuracy
μ
ν
• photon counts reflect energy of the muon that loses energy catastrophically (bremsstrahlung,…)

first generation detectors: AMANDA and Antares

northern hemisphere detectors

Baikal NT200

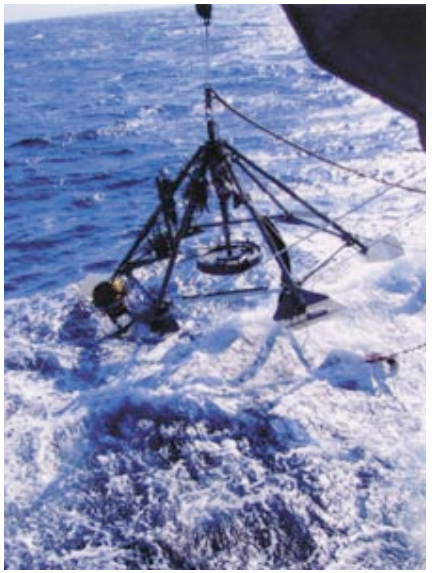


1100 m deep
data taking since 1998
new: 3 distant strings

Antares

March 17, 2003
2 strings connected
2400 m deep
completion: start 2006

Nestor

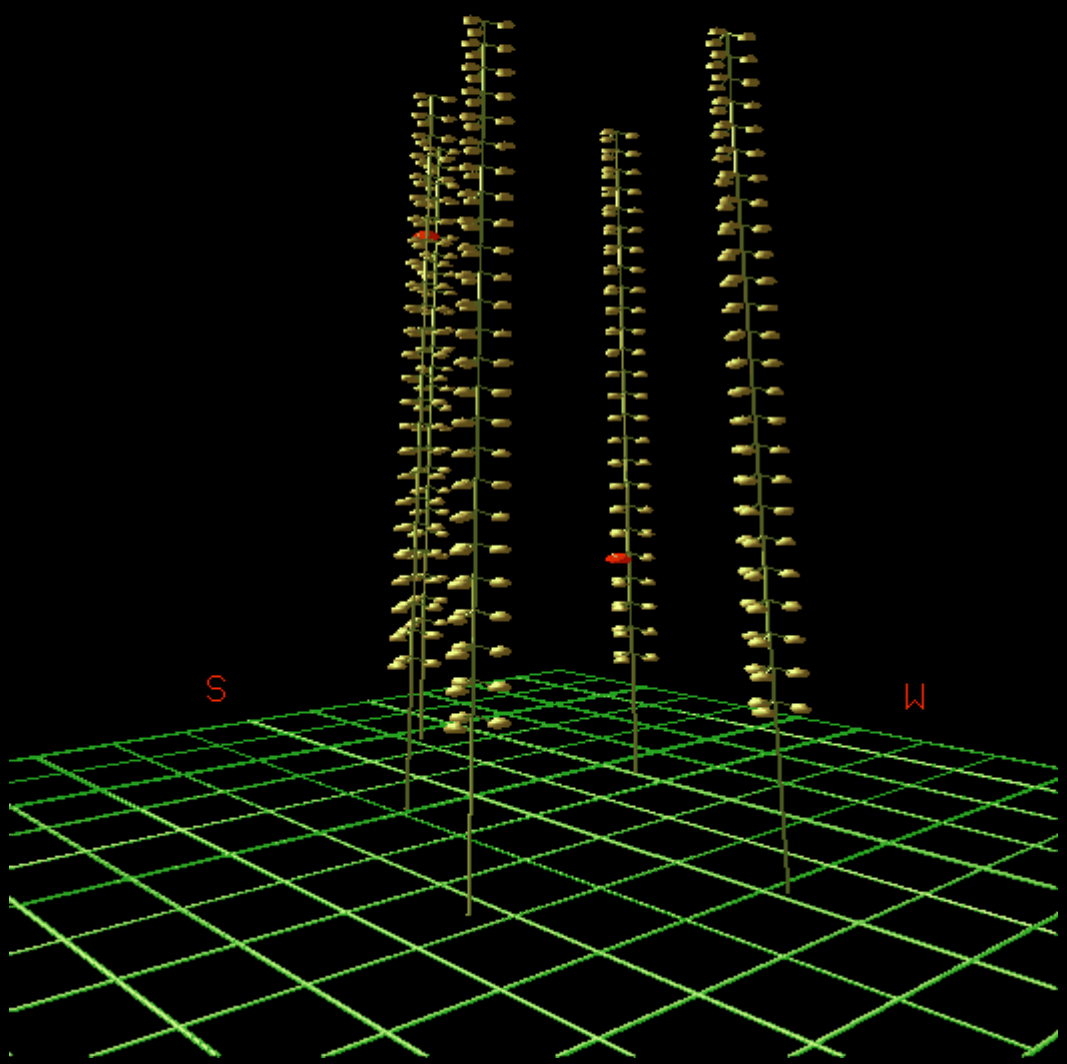


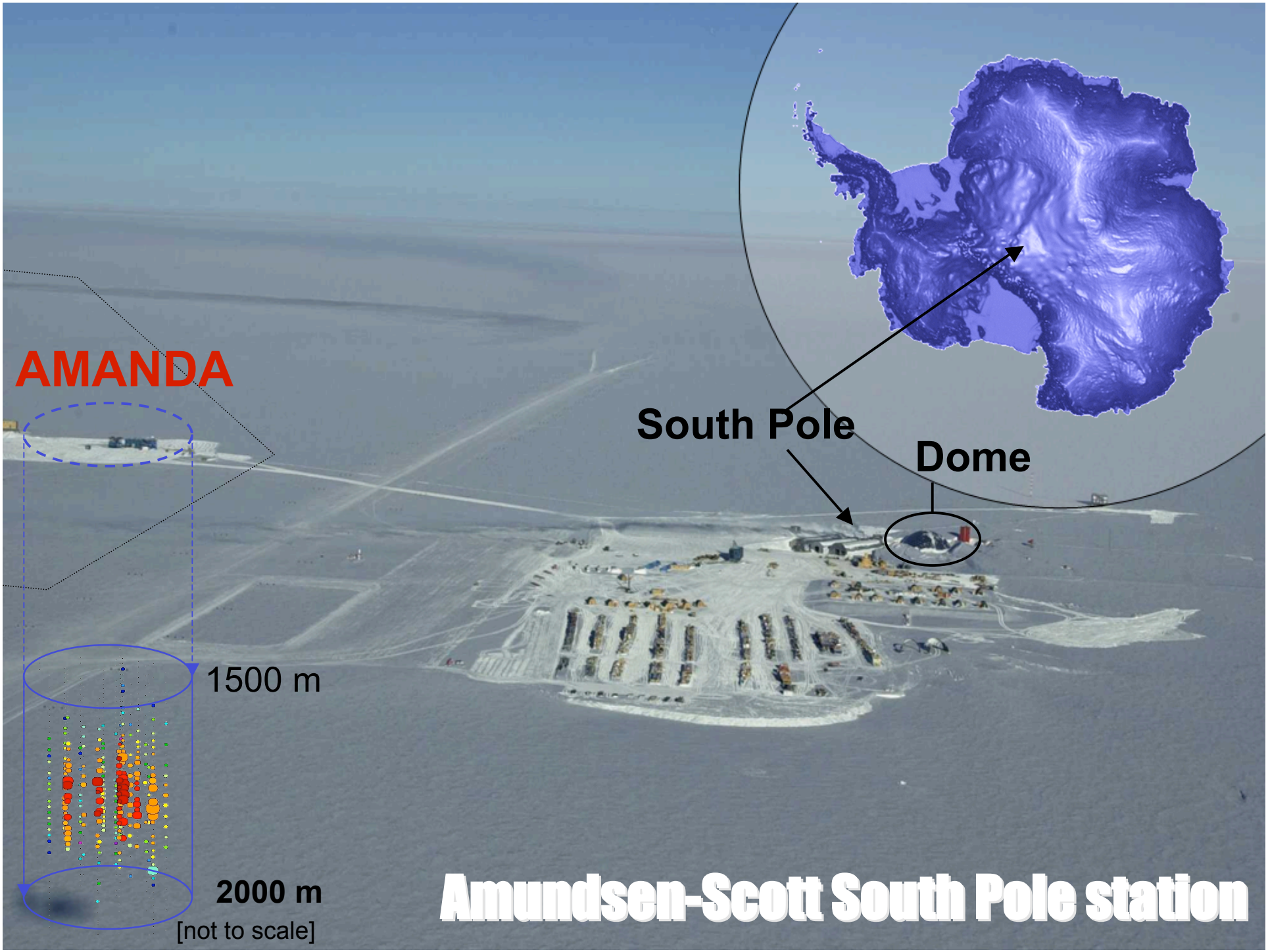
March 29, 2003
1 of 12 floors deployed
4000 m deep
completion: 2006

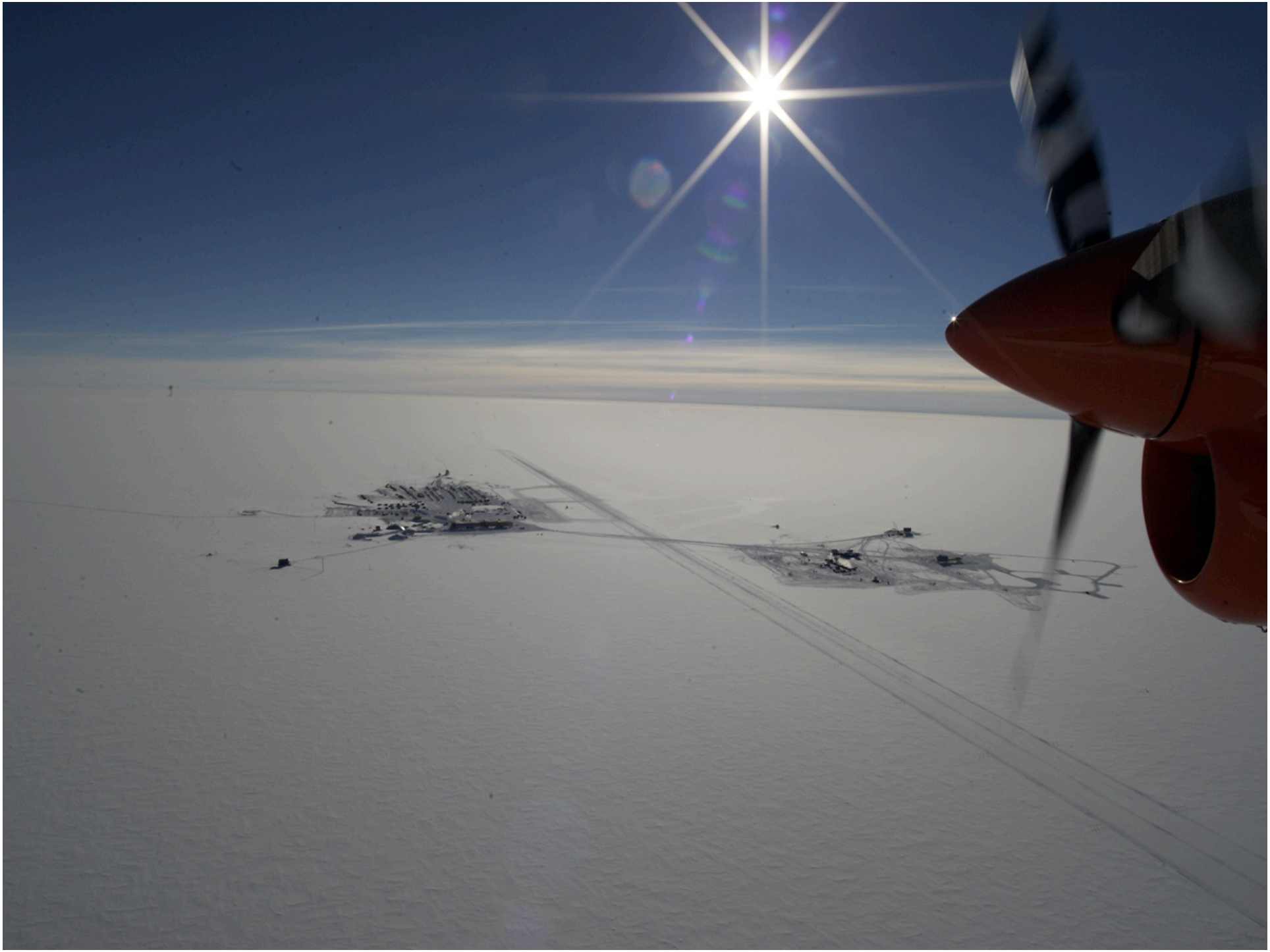
ANTARES

7 strings
completed 07

antares




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

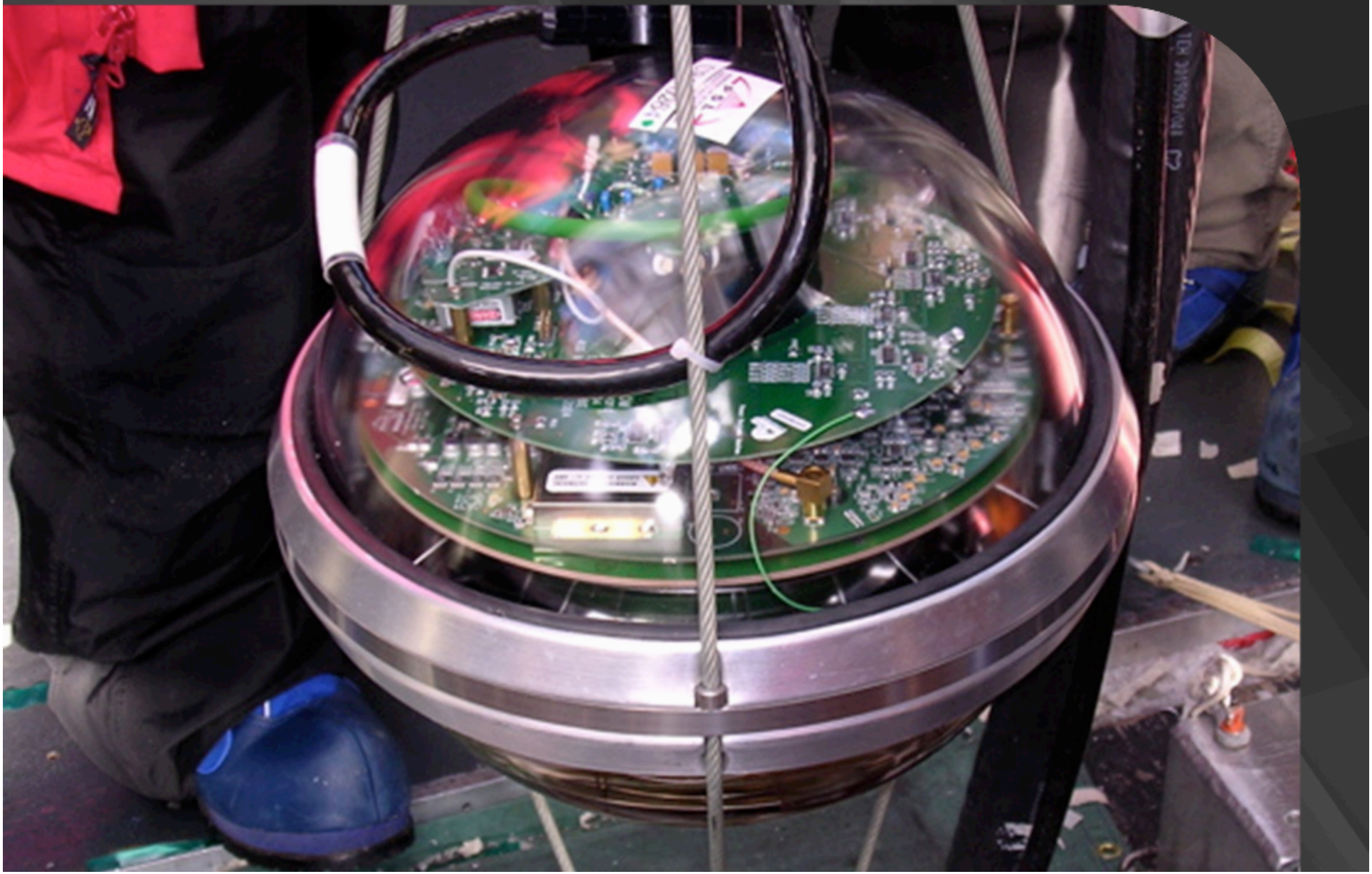


Building AMANDA

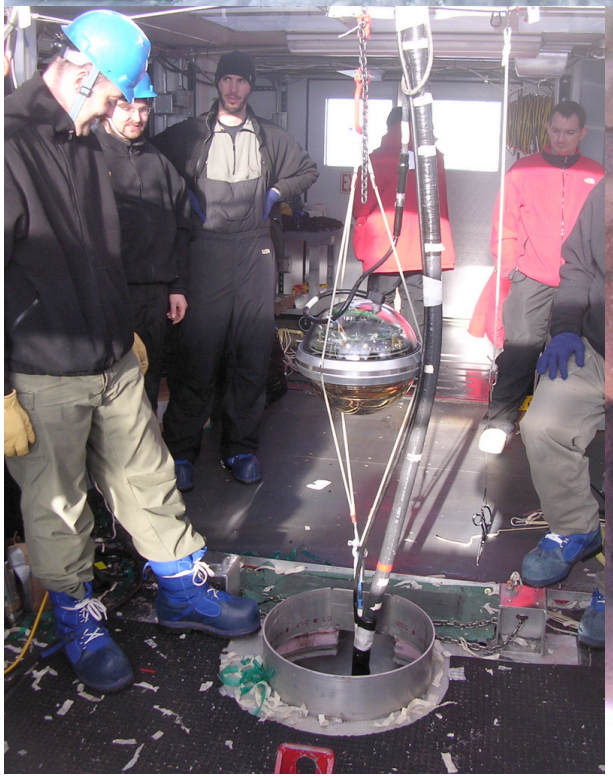
Drilling Holes with Hot Water

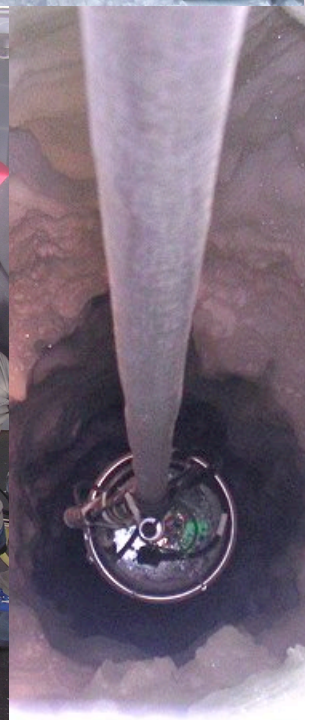
The Optical Module

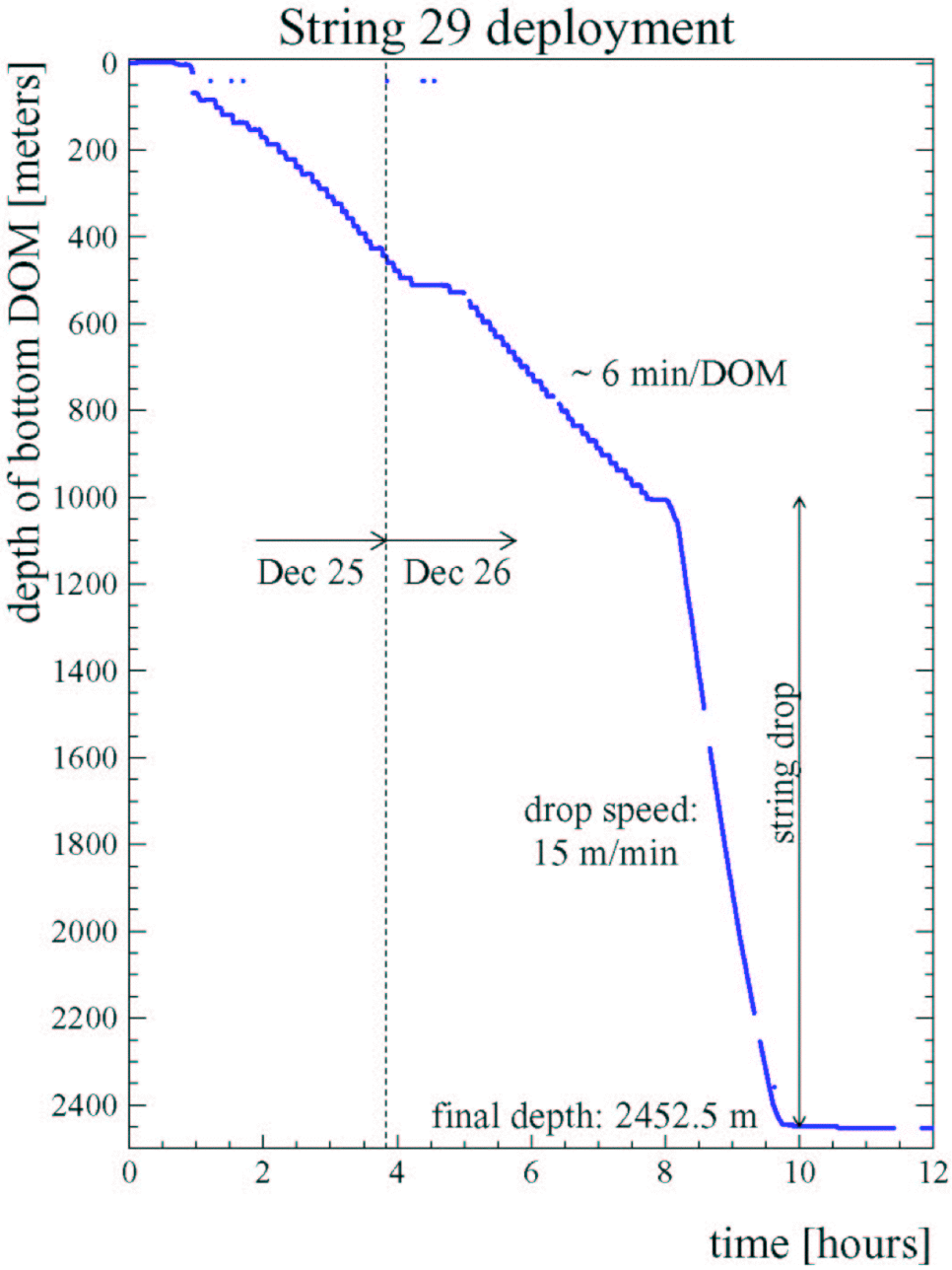
optical sensor

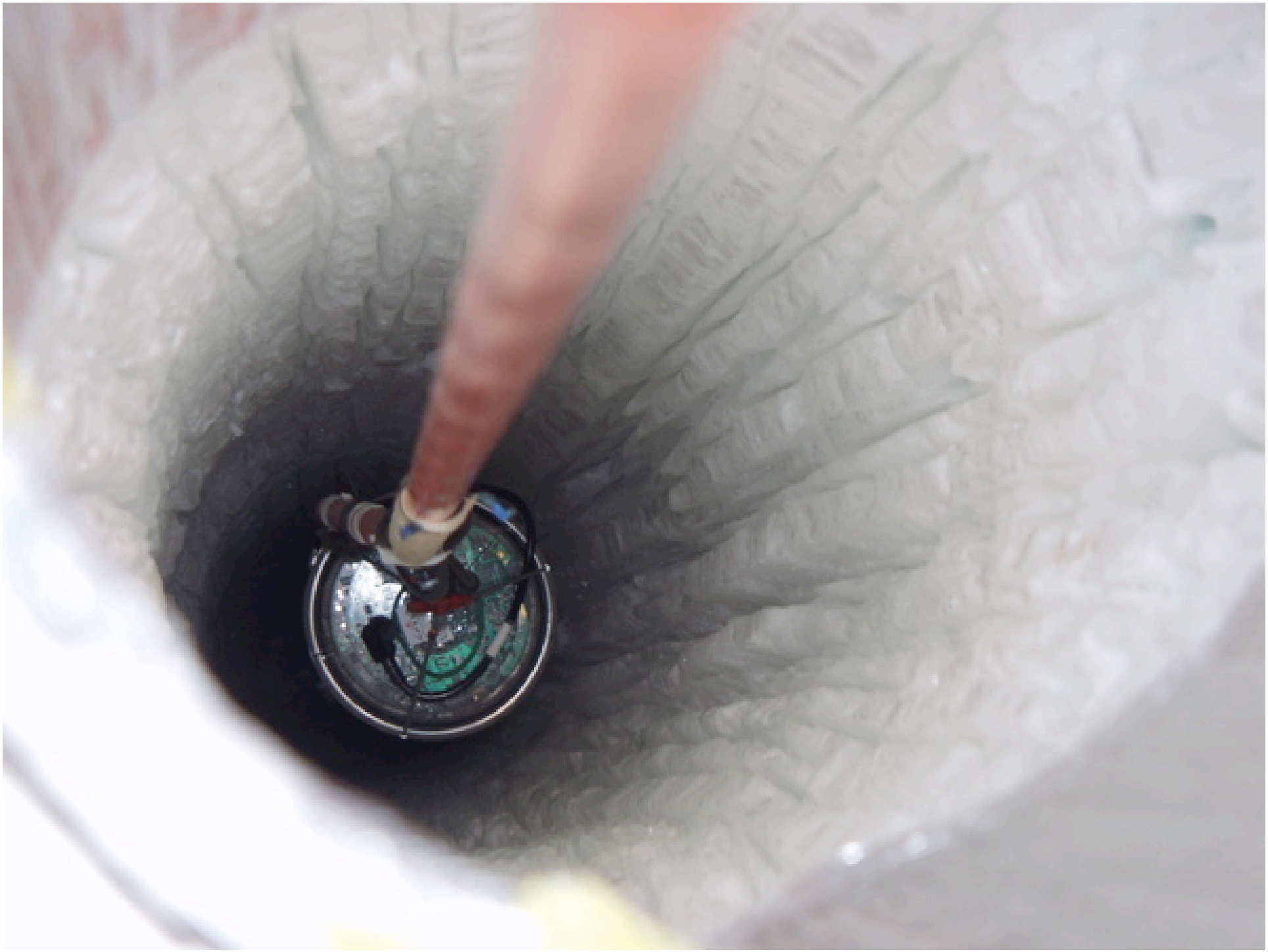


String cable 2500 m Weight ~6 tons

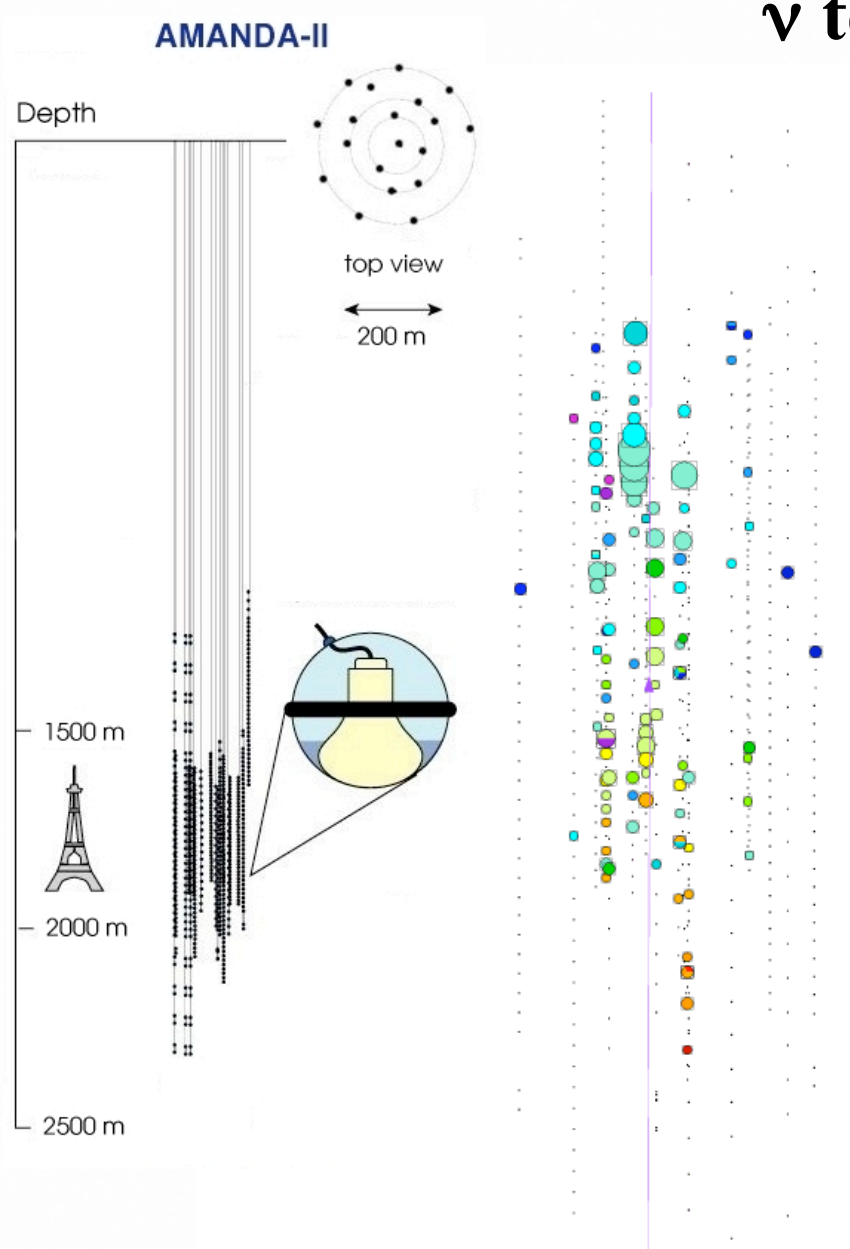




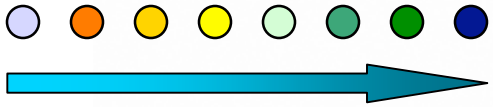




ν telescope : AMANDA event



energy deposited in OM

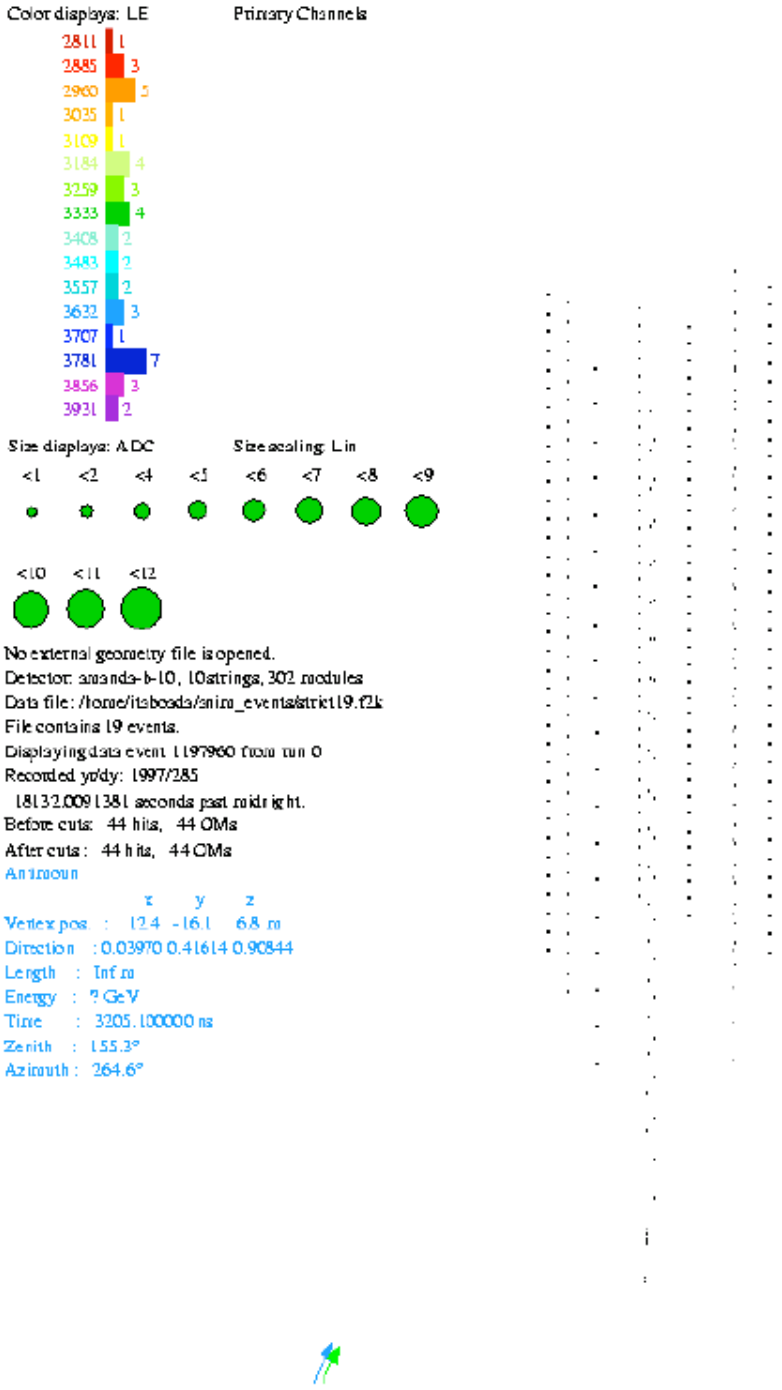


time recorded on OM

AMANDA Event Signatures: Muons

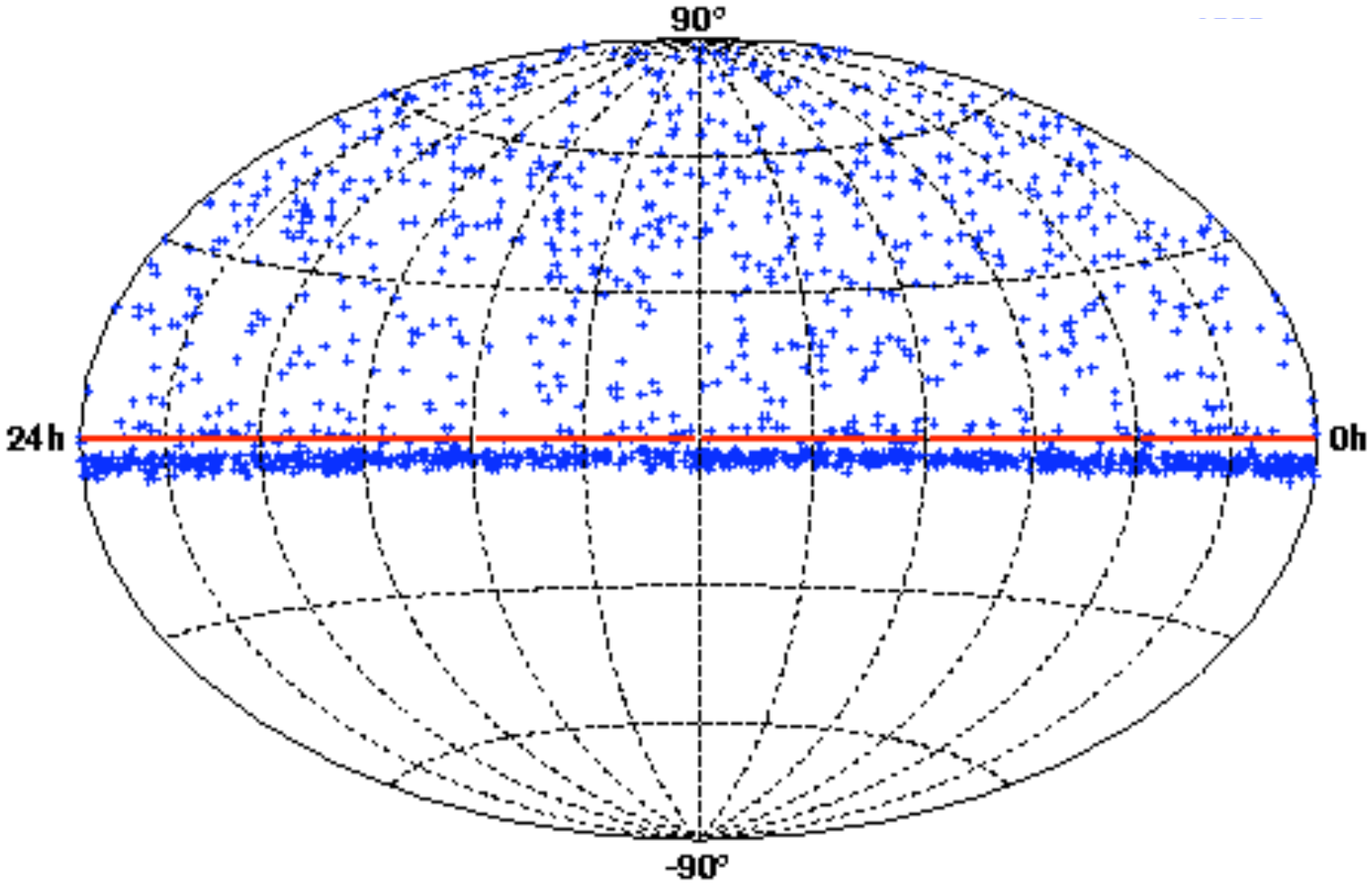
muon neutrino interaction → track

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

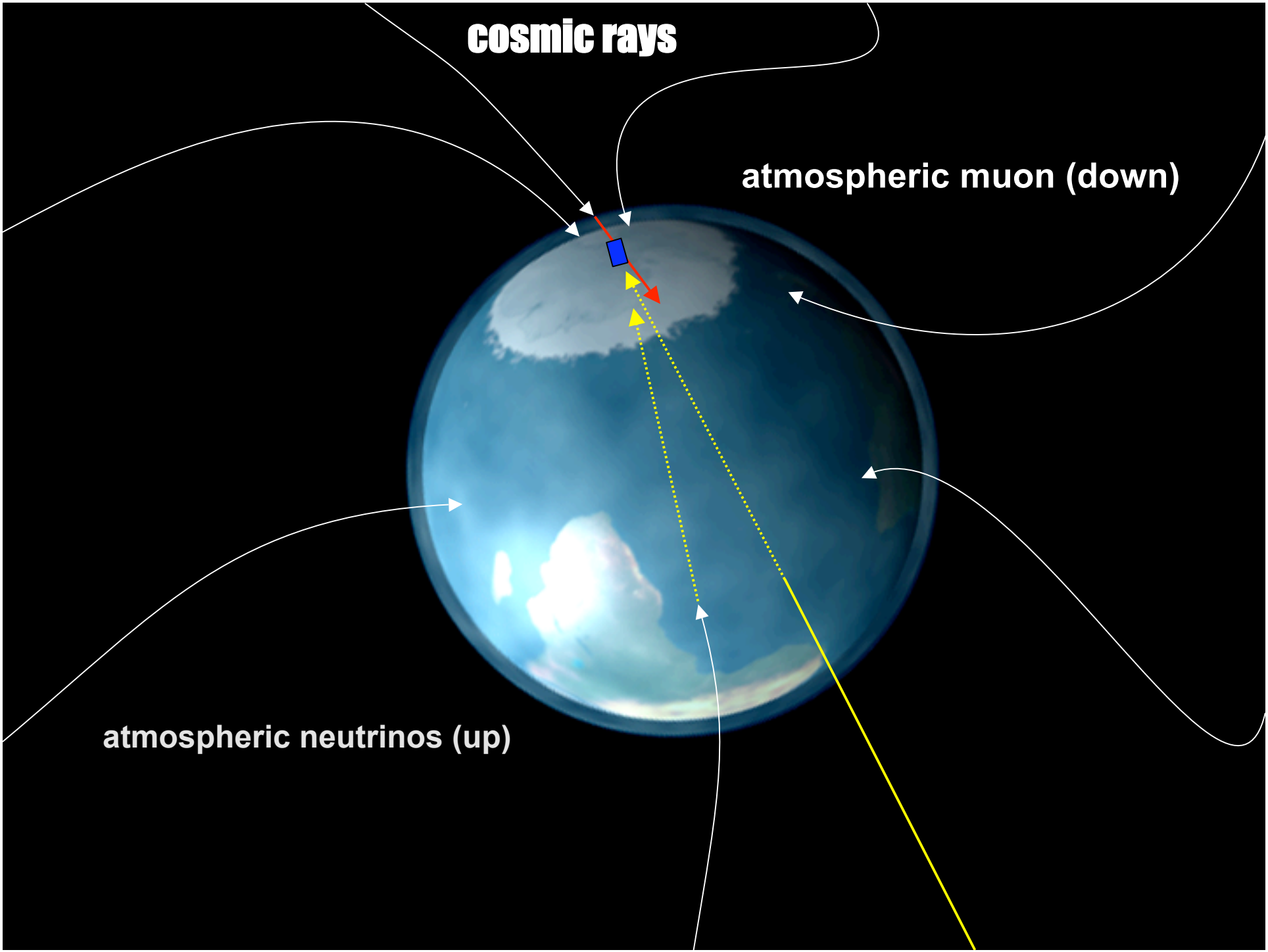


AMANDA II 2000

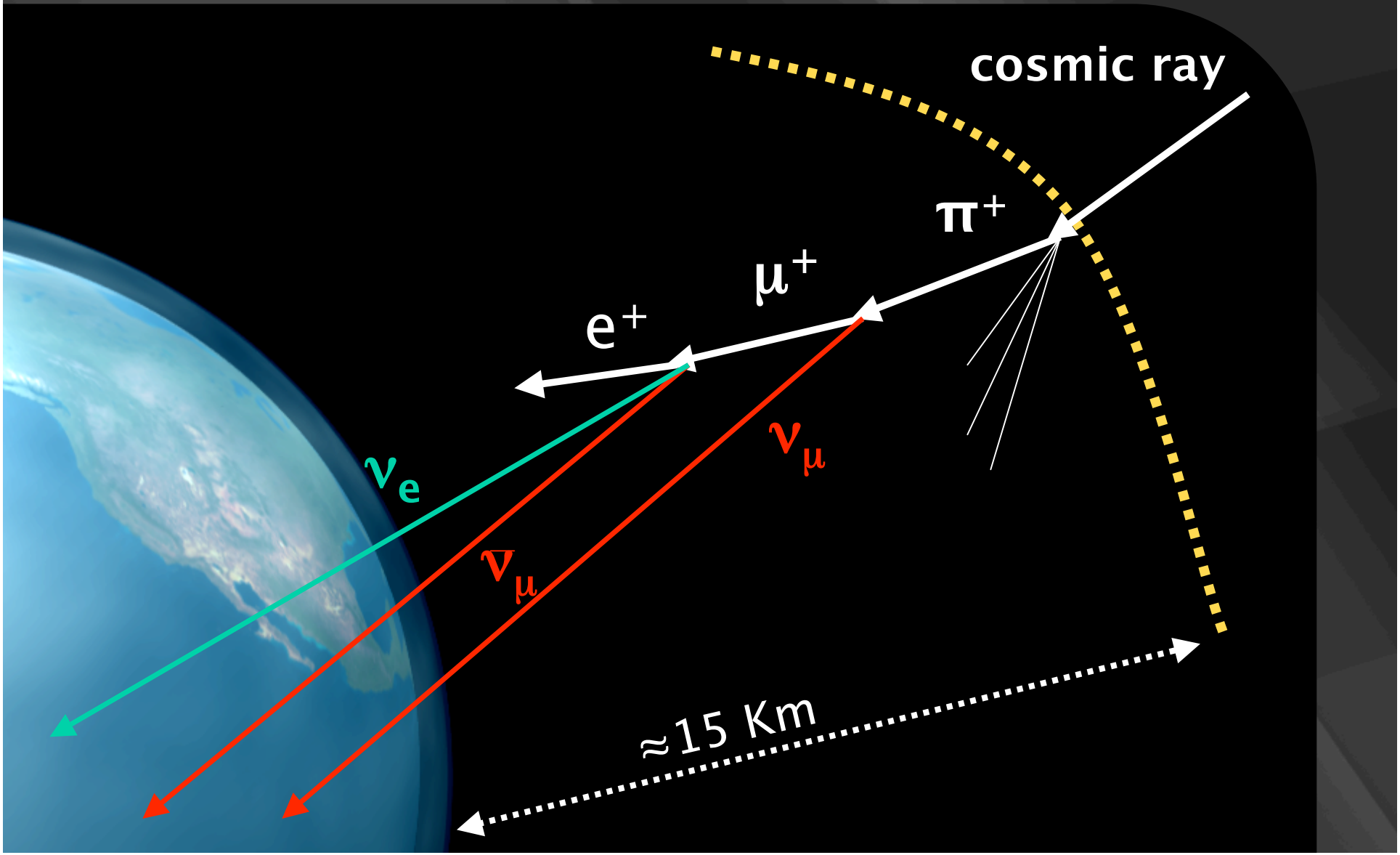
1555 Events



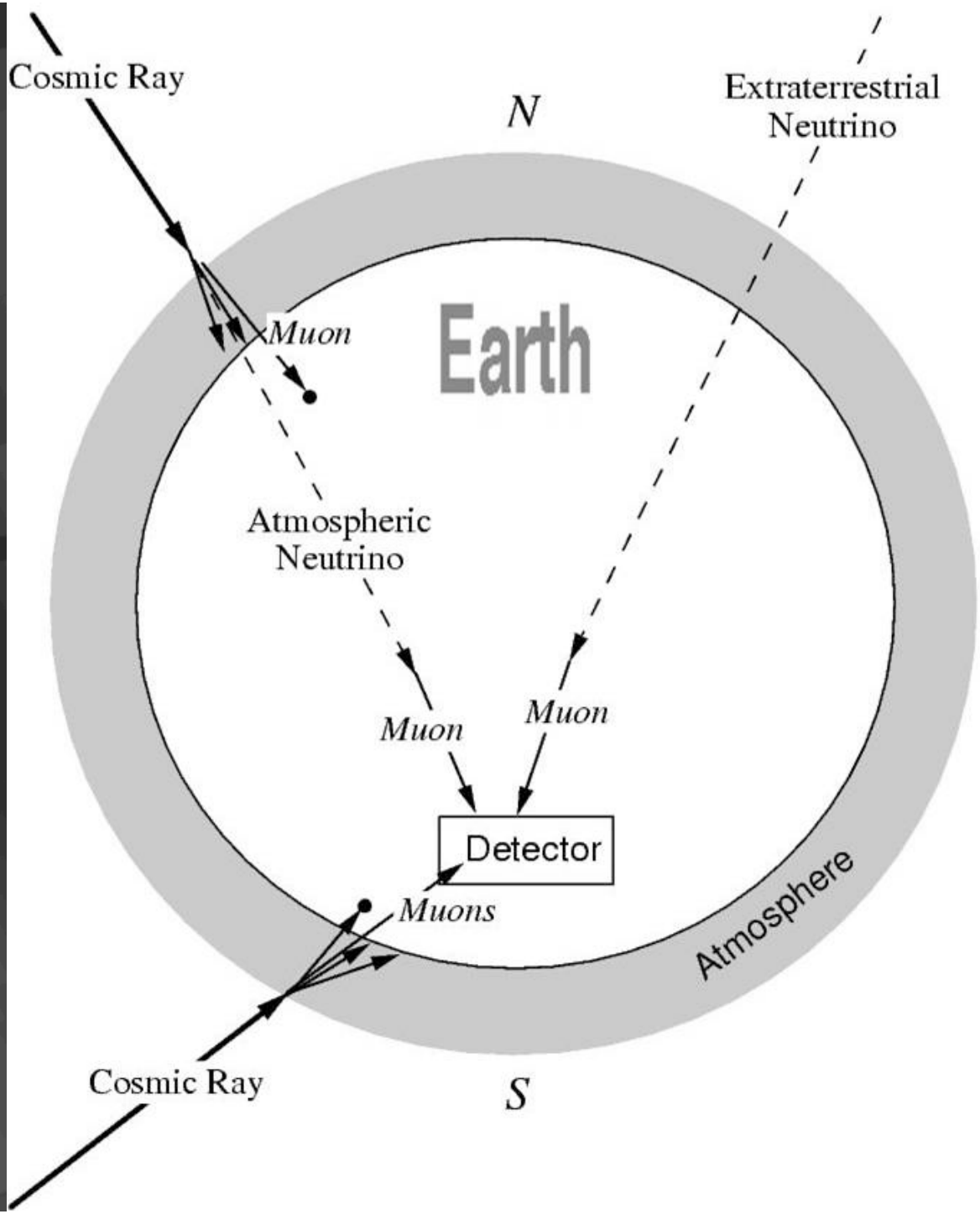
AMANDA: proof of concept


cosmic rays
atmospheric muon (down)
atmospheric neutrinos (up)

atmospheric muons and neutrinos

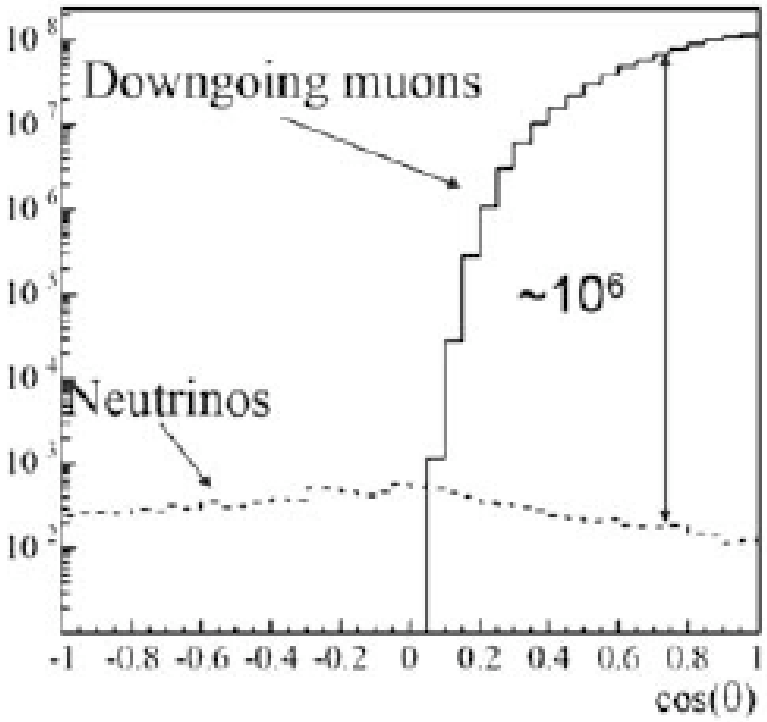


the challenge

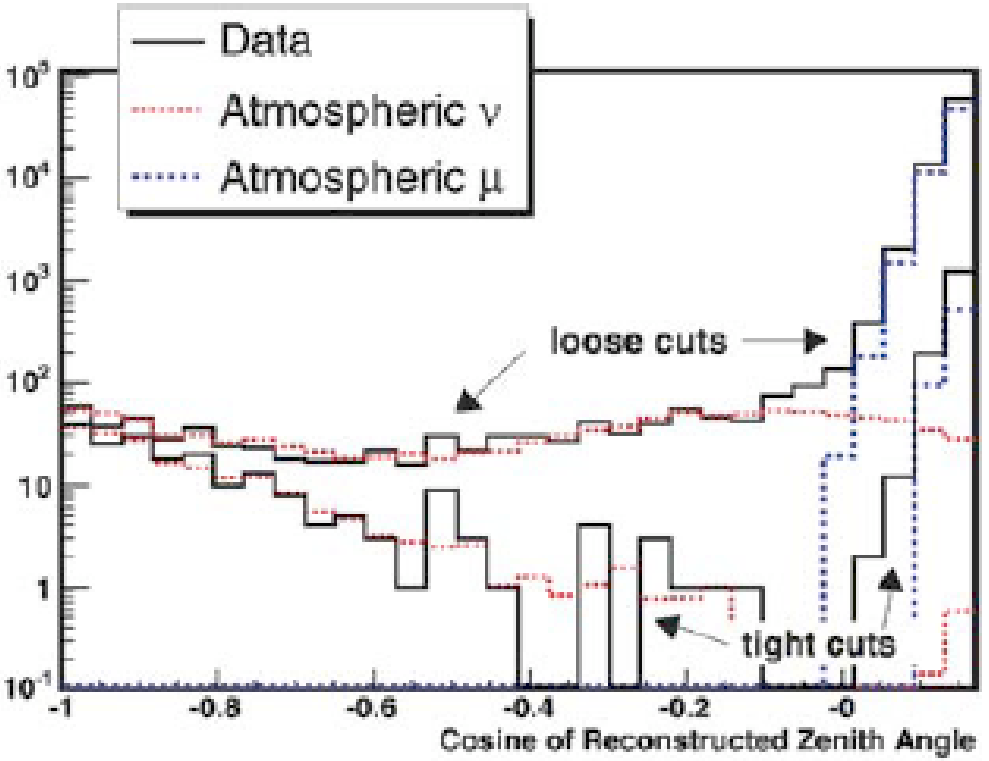


challenge :

- 100 Hz detector rate
- << one reconstruction mistake in one million tra
- understand ice as Cherenkov medium

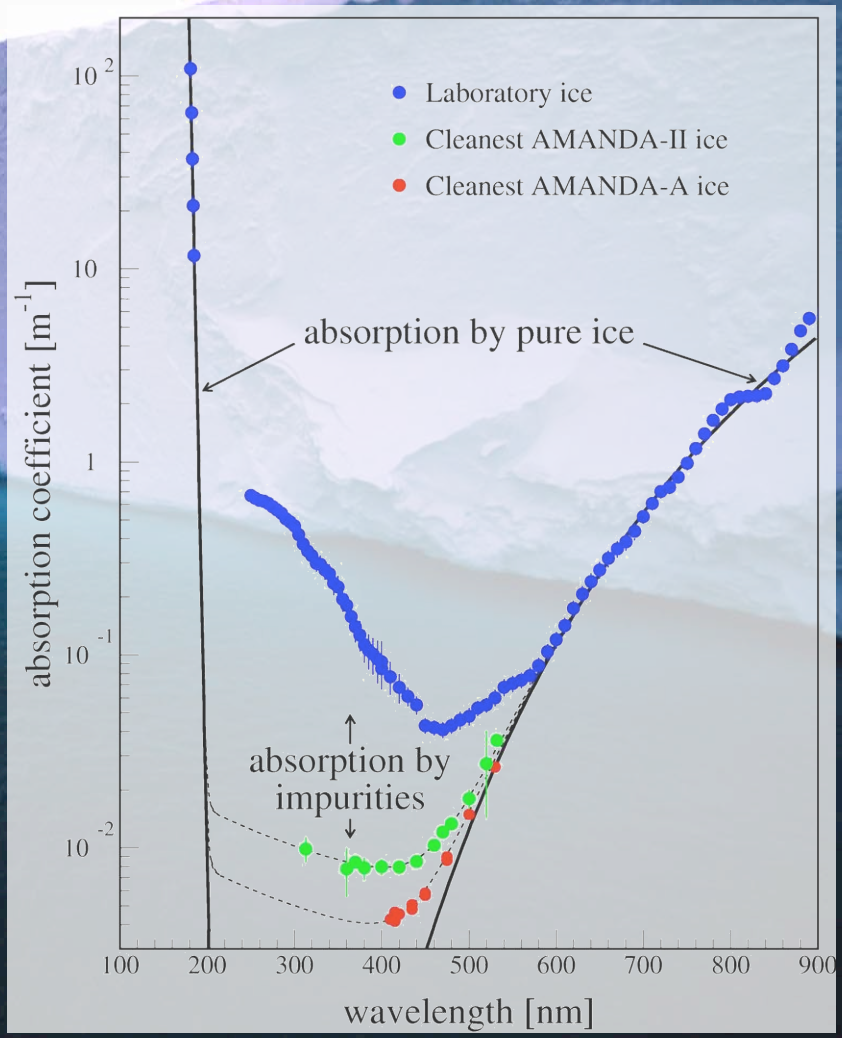


(a)

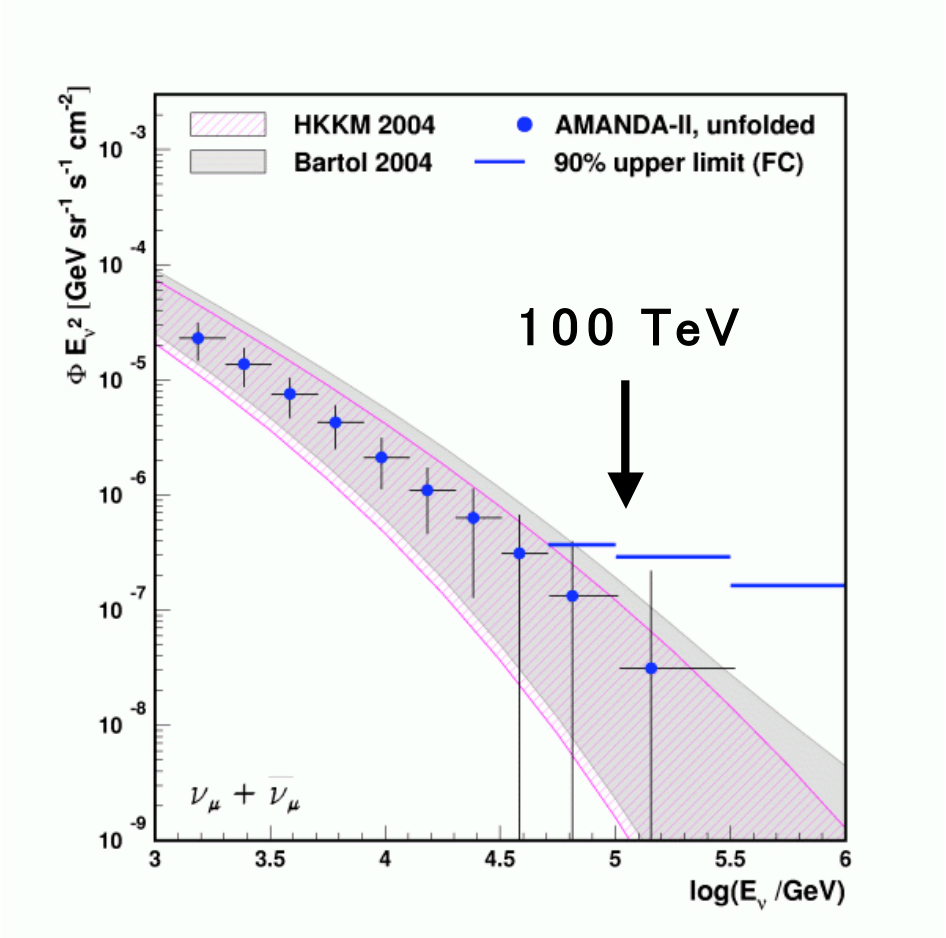


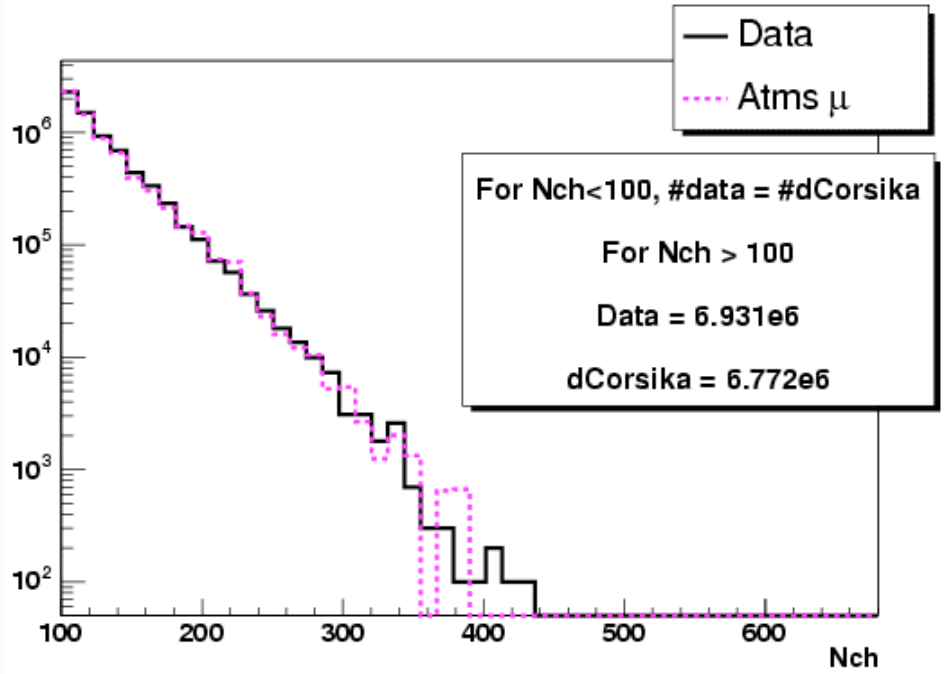
(b)

Ice quality


Laboratory ice
Cleanest AMANDA-II ice
Cleanest AMANDA-A ice
absorption by pure ice
absorption by impurities
absorption coefficient [m^{-1}]
wavelength [nm]
10^{2}
10
1
10^{-1}
10^{-2}
100
200
300
400
500
600
700
800
900

calibration on cosmic ray neutrinos and muons

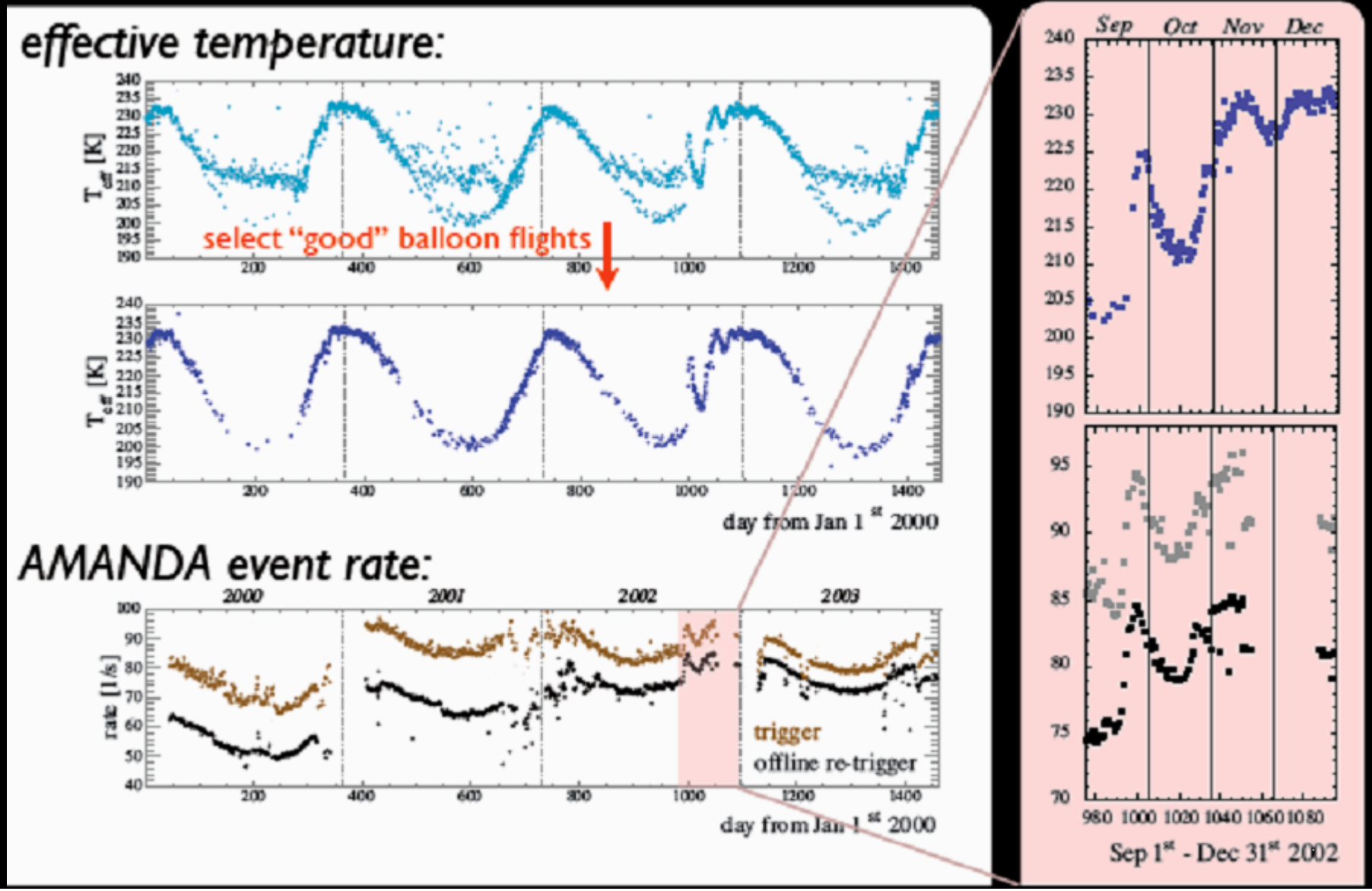




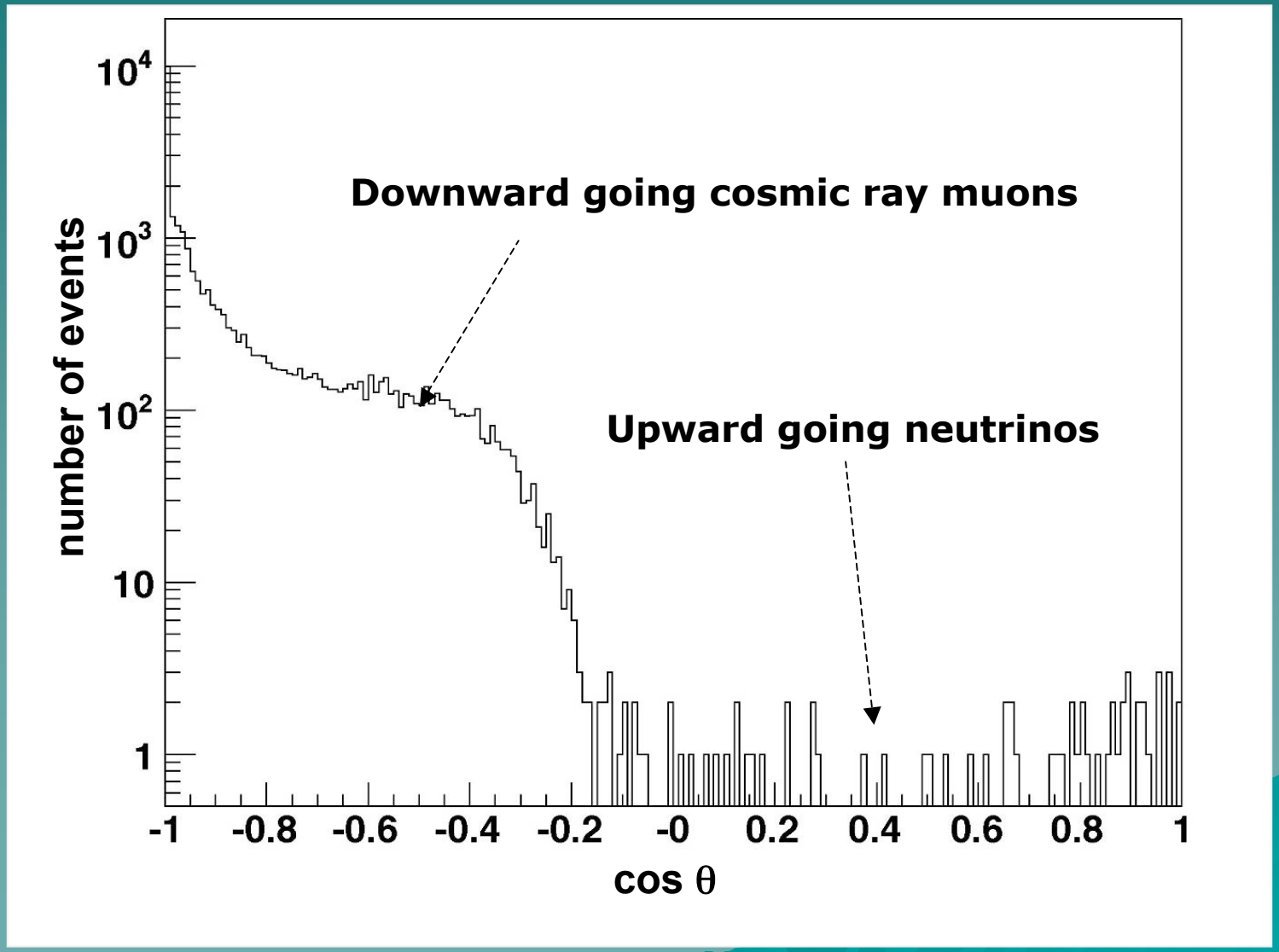
inverted analysis: use atmospheric muons to benchmark MC

· atmospheric ν_μ spectrum

Effective Atmospheric Temperature Over The South Pole



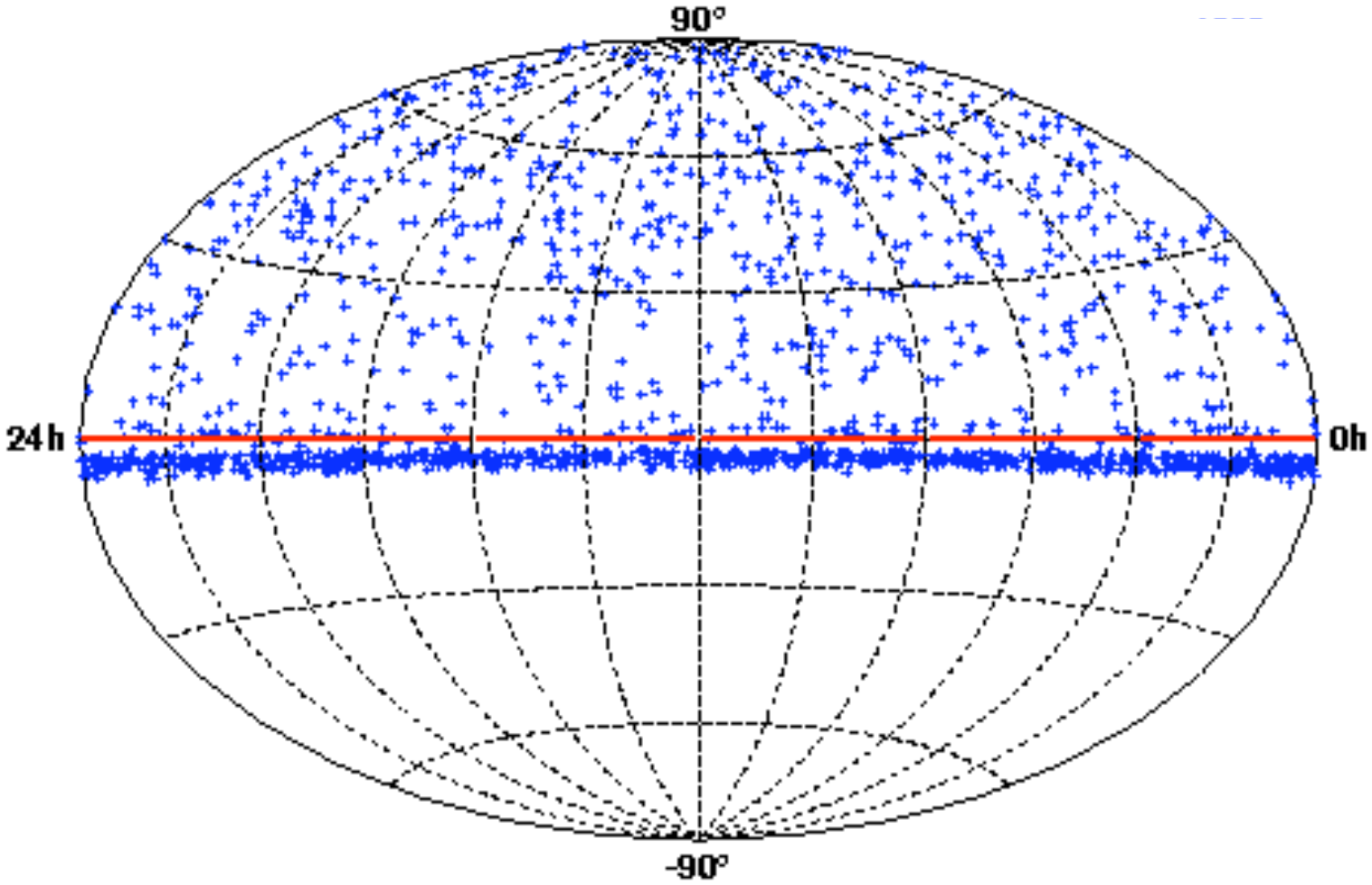
antares zenith angle distribution



AMANDA science

AMANDA II 2000

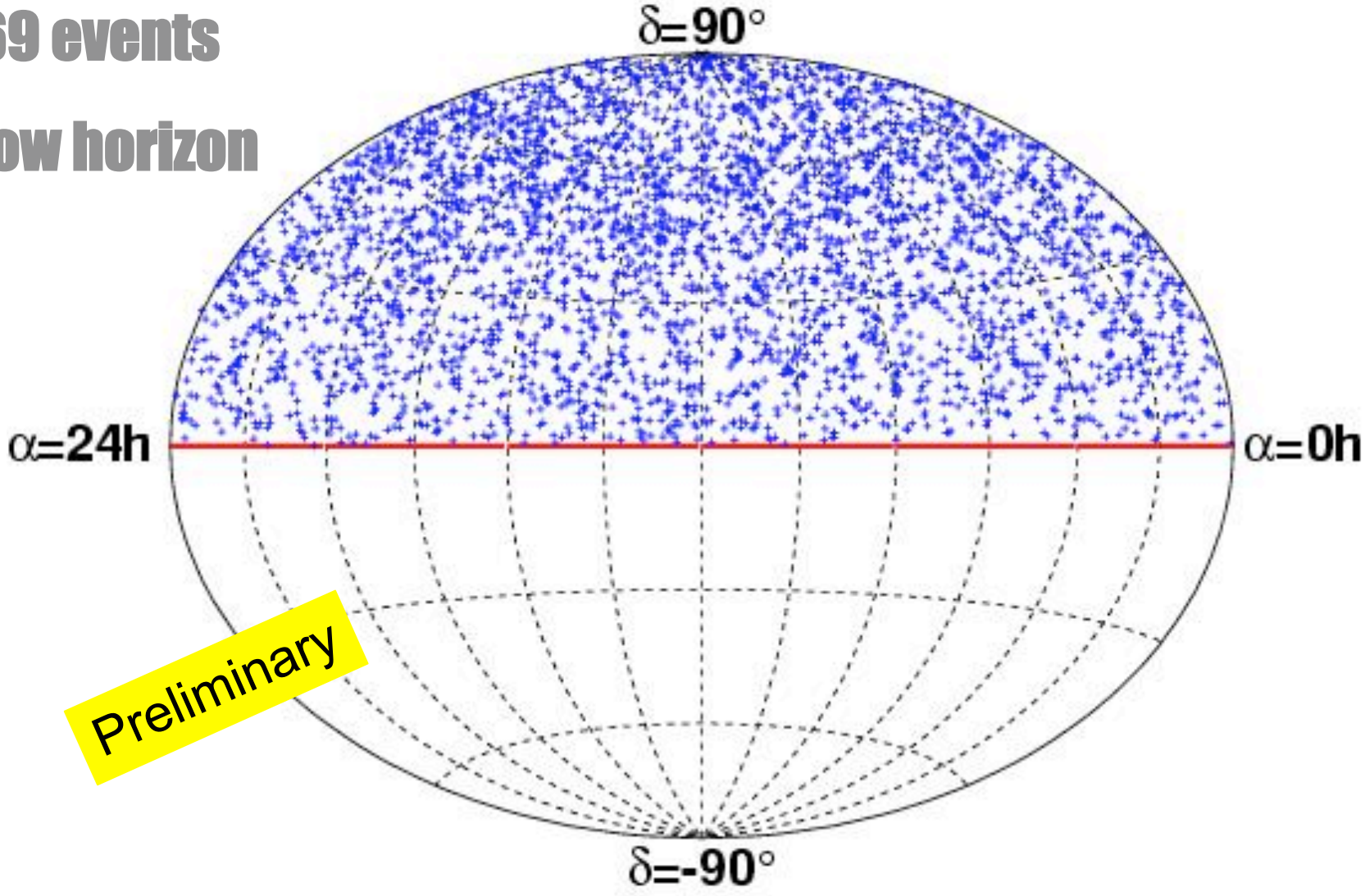
1555 Events



AMANDA skyplot 2000-2003

3369 events

below horizon



search for clusters of events in the Northern sky

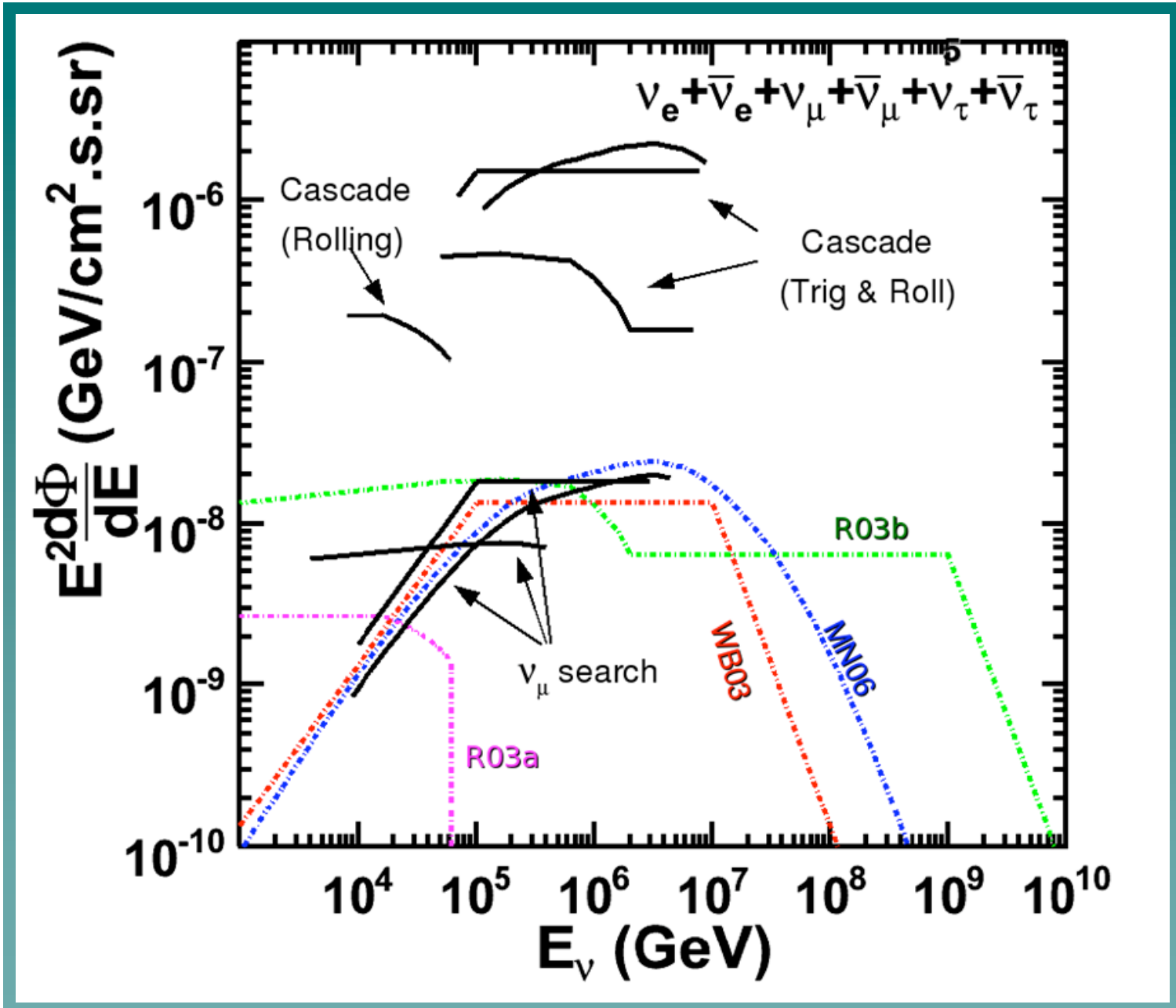
Sensitivity Φ_ν/Φ_γ **~2** for 200 days of "high-state" and spectral results from HEGRA

Crab Nebula: MC probability to obtain an entry with at least this excess significance is **64%**

Source	Nr. of ν events (4 years)	Expected backgr. (4 years)	Flux Upper Limit $\Phi_{90\%}(E_\nu>10\ \text{GeV})$ $[10^{-8}\text{cm}^{-2}\text{s}^{-1}]$
Markarian 421	6	5.58	0.68
1ES1959+650	5	3.71	0.38
SS433	2	4.50	0.21
Cygnus X-3	***6***	***5.04***	0.77
Cygnus X-1	4	5.21	0.40
Crab Nebula	10	5.36	1.25

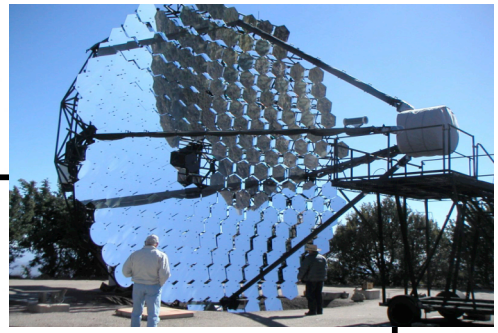
… out of **33** sources

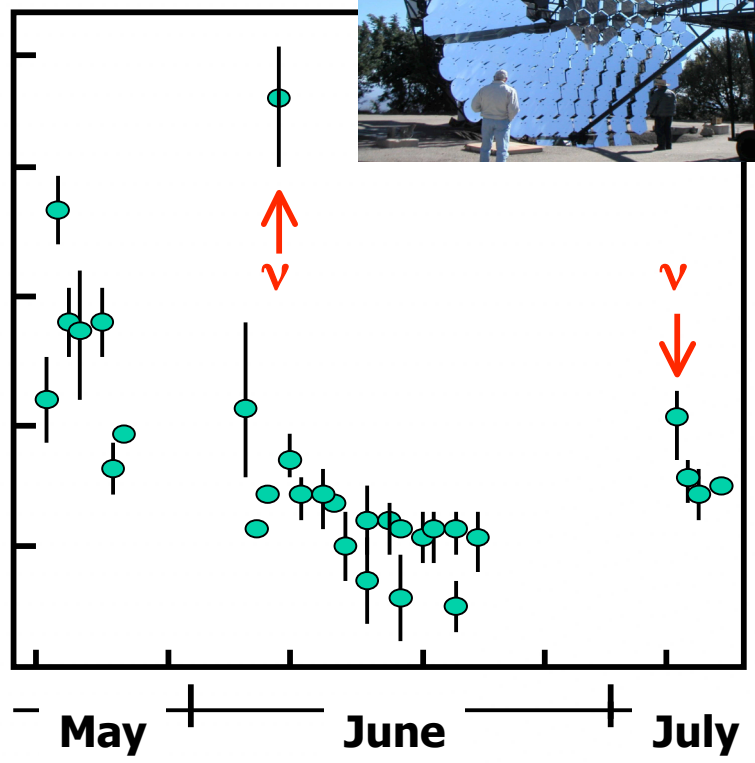
GRB



other methods yield increased sensitivity

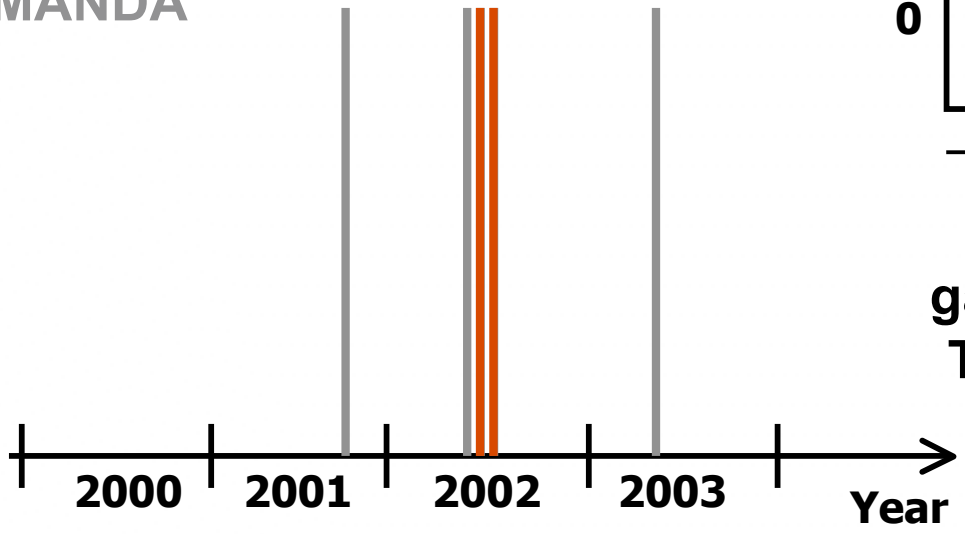
need a larger detector





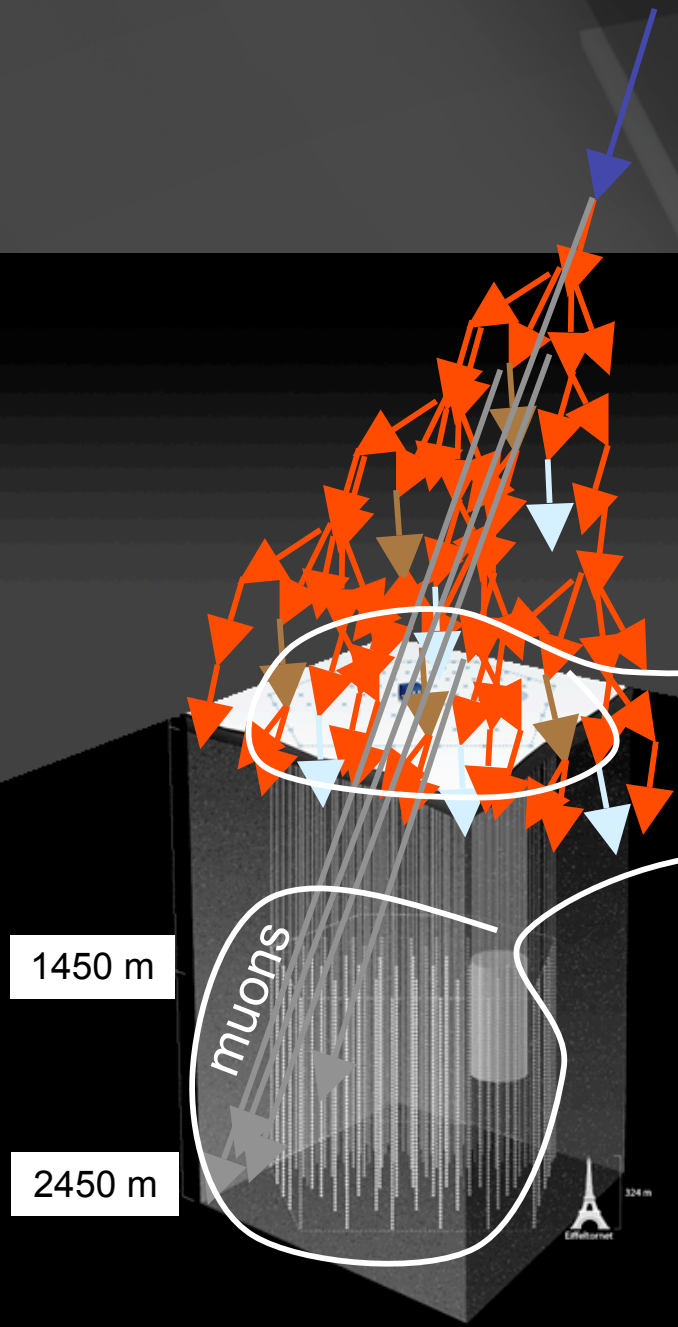
gamma-rays detected by
TeV gamma telescopes

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



icecube

IceCube/IceTop



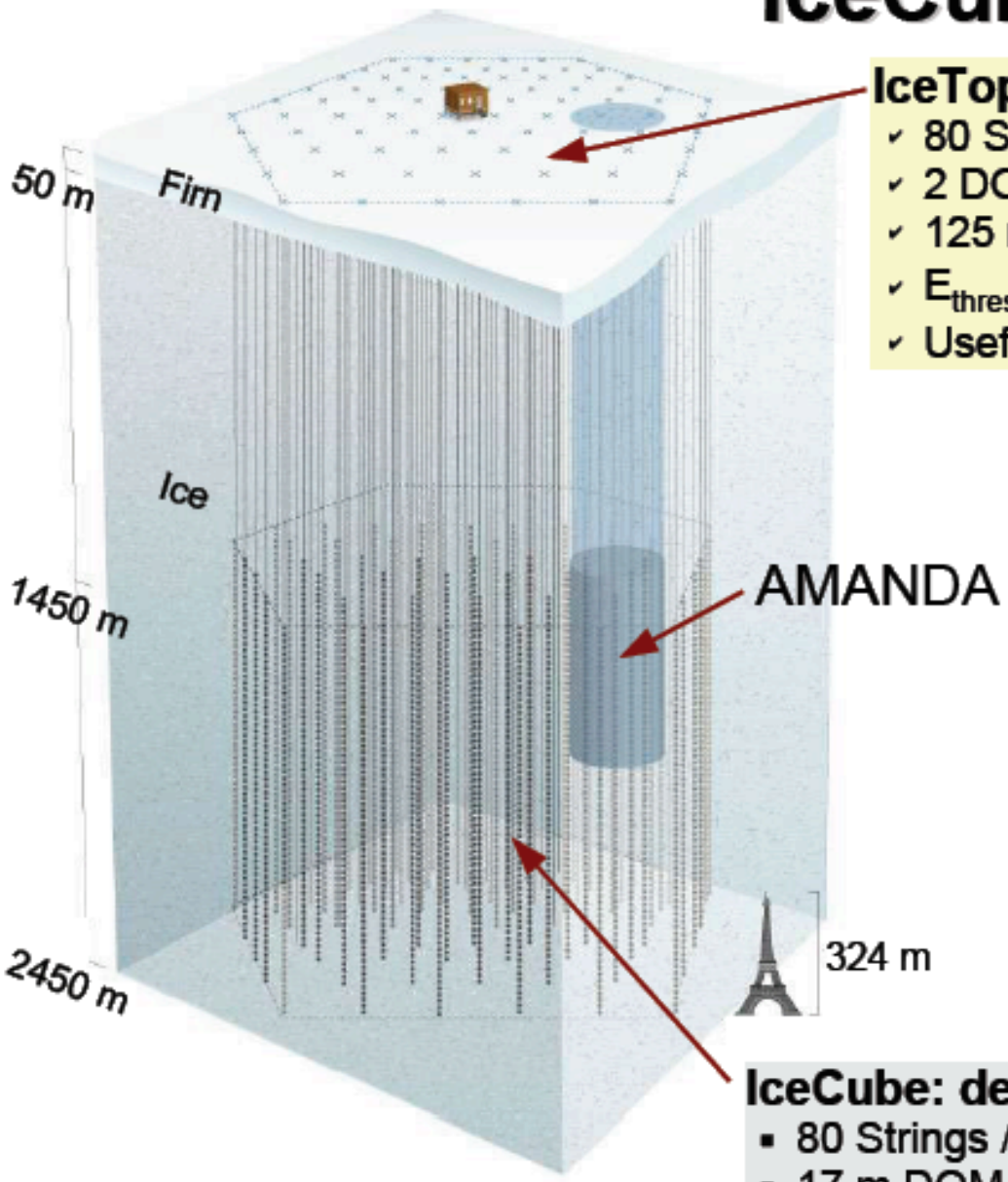
IceTop:

- 80 Stations à 2 Ice-Č-Tanks
  → **Last year: 16 stations**
- 2830 m altitude
- 125 m spacing
- $3 \cdot 10^{14} < E < 10^{18}$ eV
- $A_{tot} \sim 1\ km^2$
  → **Last year ~ 0.13 km²**

IceCube Strings:

- 4800 DOMs
- Muon bundle detector
- $E_{muon} >$ TeV

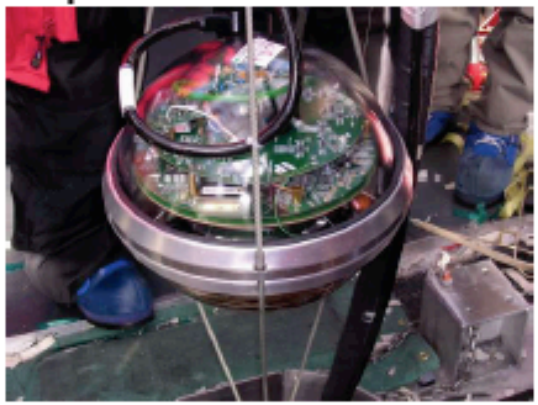
IceCube



IceTop: air shower array

- 80 Stations / 2 Tanks each
- 2 DOMs each per tank
- 125 m grid, 1 km^2 at 690 g/cm^2
- E_{thres} ~ 300 TeV for ≥ 4 stations
- Useful rate up to ~EeV

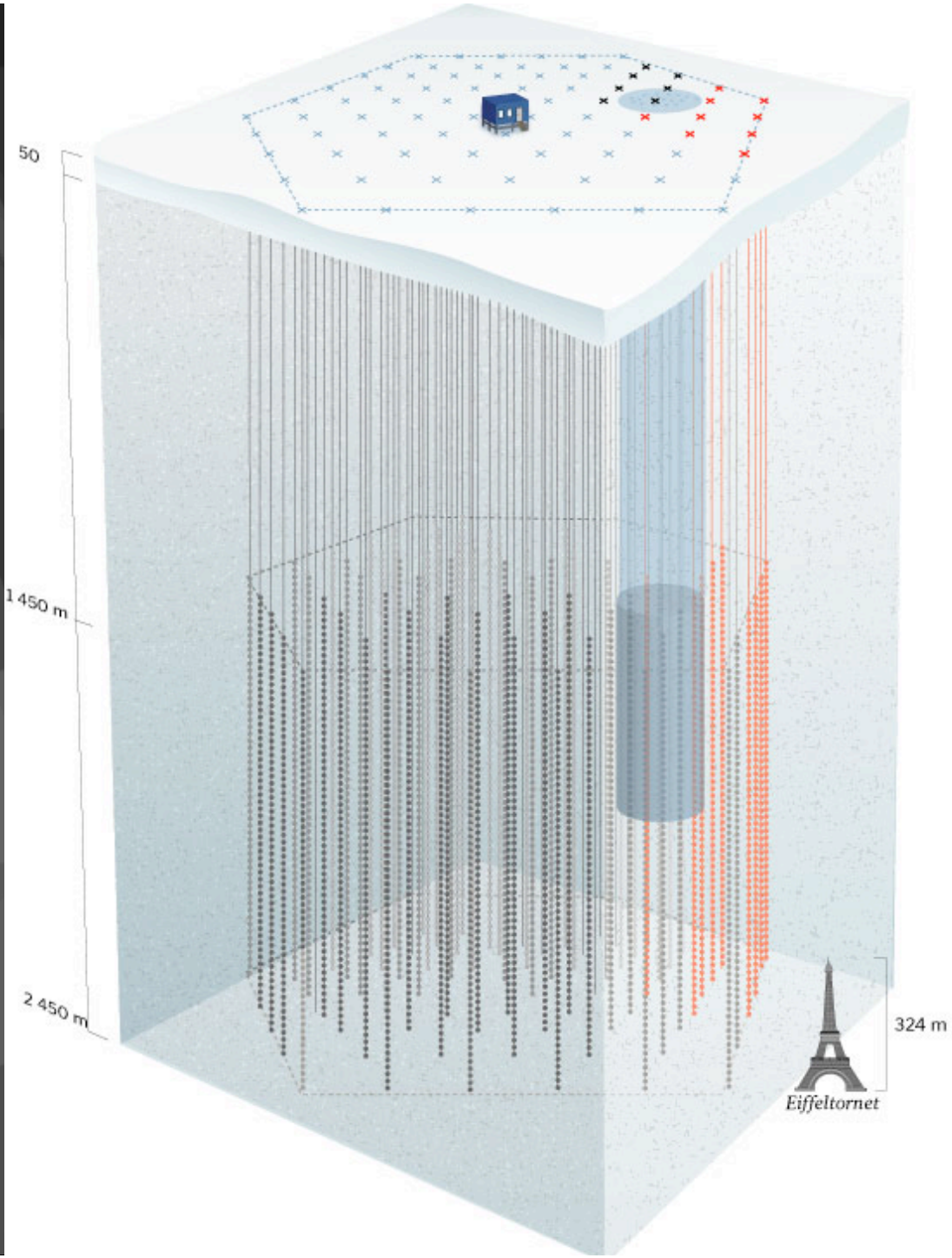
Digital **O**ptical **M**odule

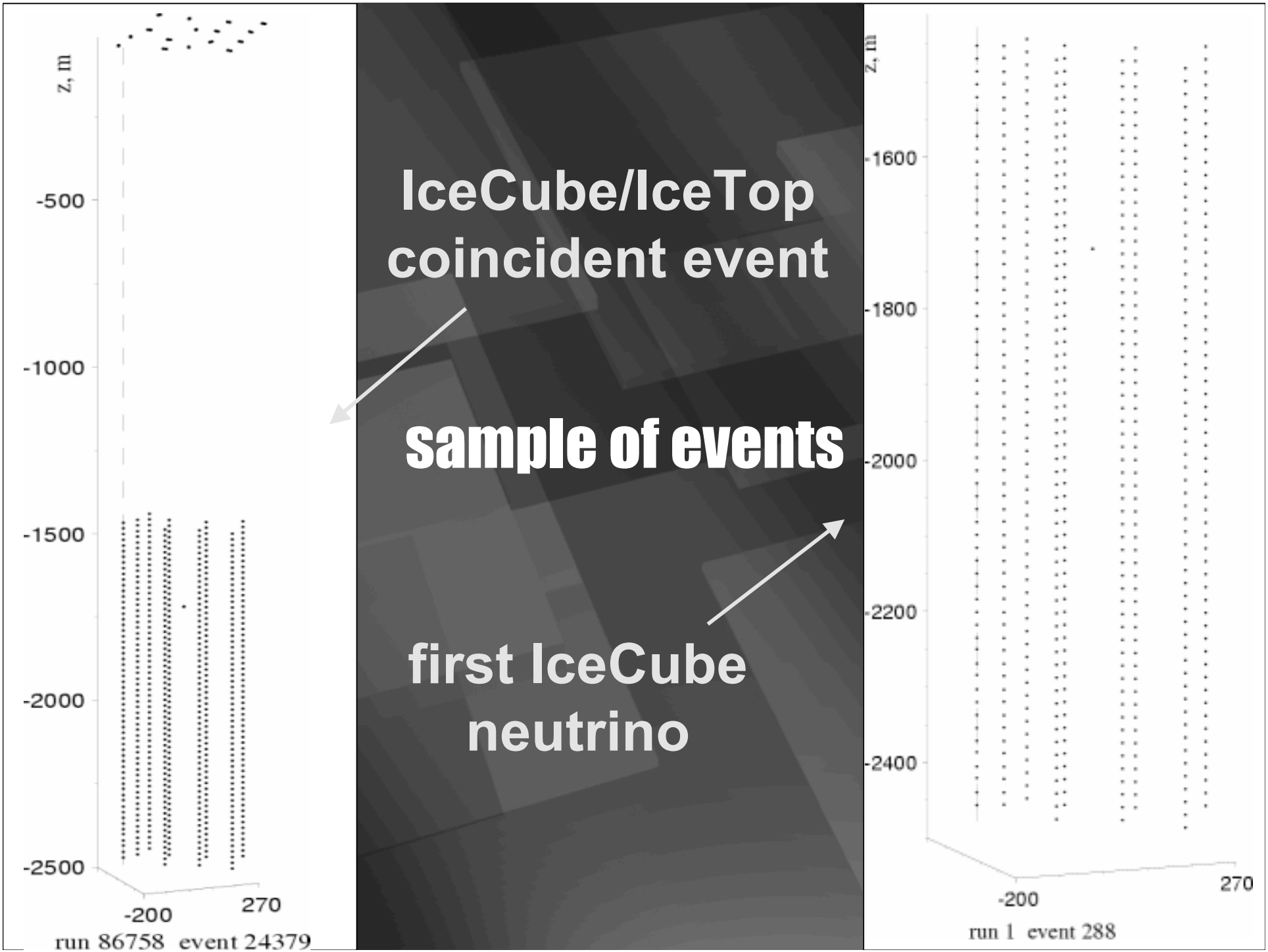


IceCube: deep ice array

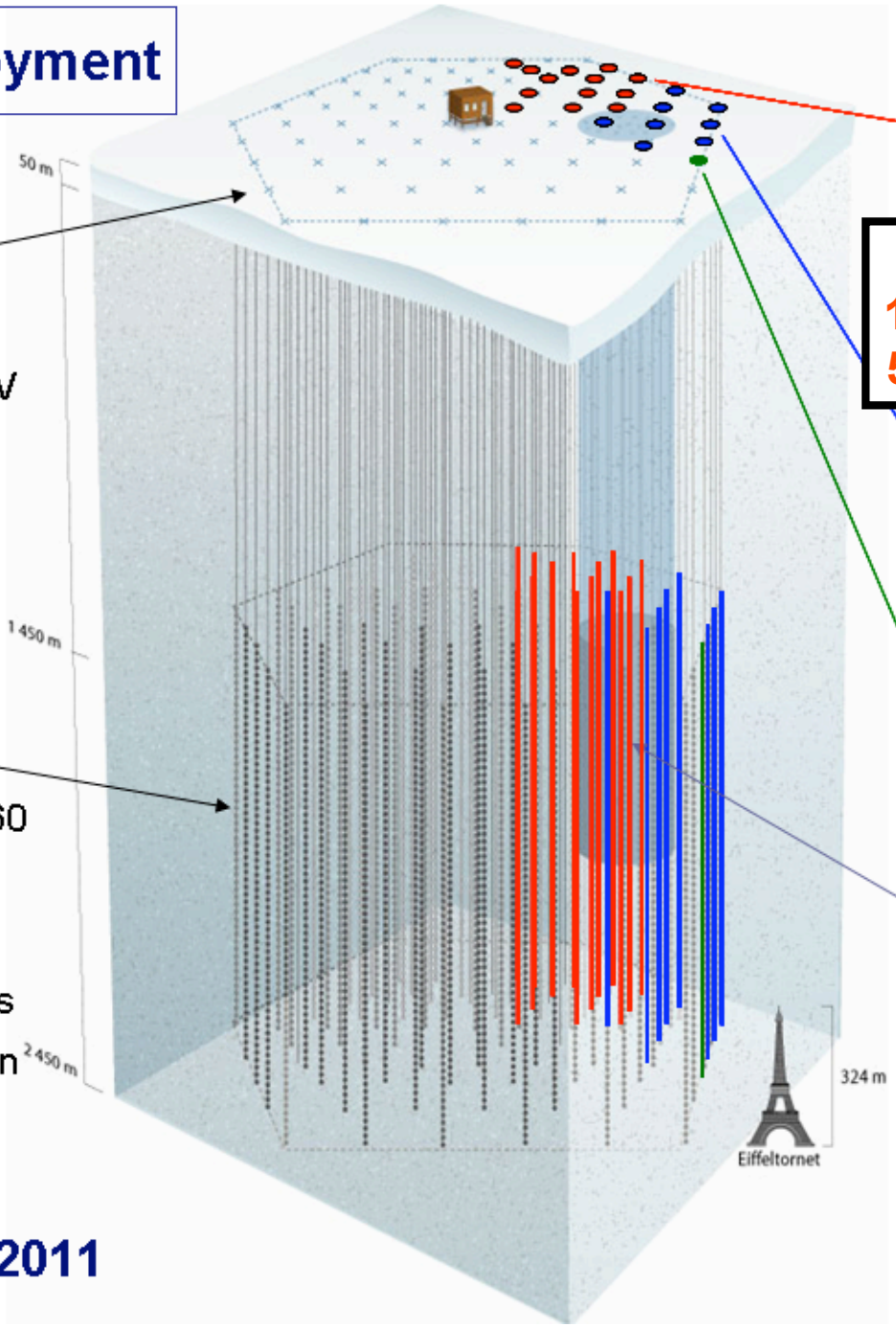
- 80 Strings / 60 DOMs each
- 17 m DOM spacing
- 125 m between strings
- 1 km^3 instrumented

IceCube February 2006




z, m
-500
-1000
-1500
-2000
-2500
-200
270
run 86758 event 24379
IceCube/IceTop
coincident event
sample of events
first IceCube
neutrino
z, m
-1600
-1800
-2000
-2200
-2400
-200
270
run 1 event 288

IceCube Deployment



IceTop

Air shower detector

Threshold ~ 300 TeV

InIce

planned 80 strings of 60 optical modules each

17 m between modules

125 m string separation

2006-2007:

13 strings deployed

22 strings
1320 digital modules
52 surface detectors

2005-2006: 8 strings

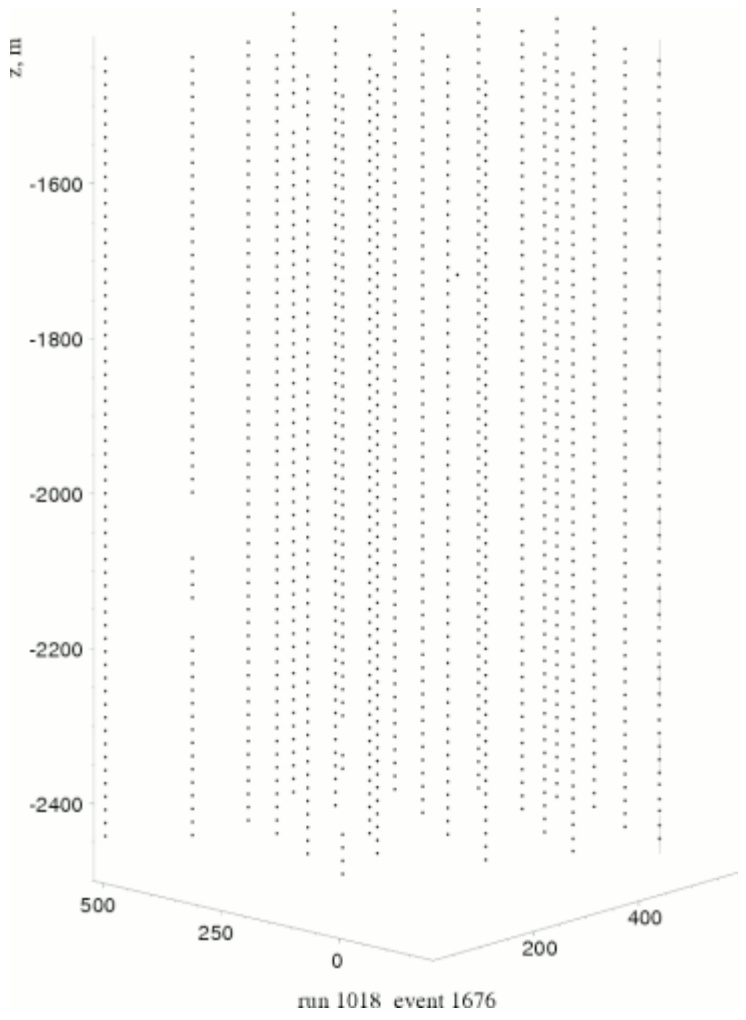
2004-2005 : 1 string

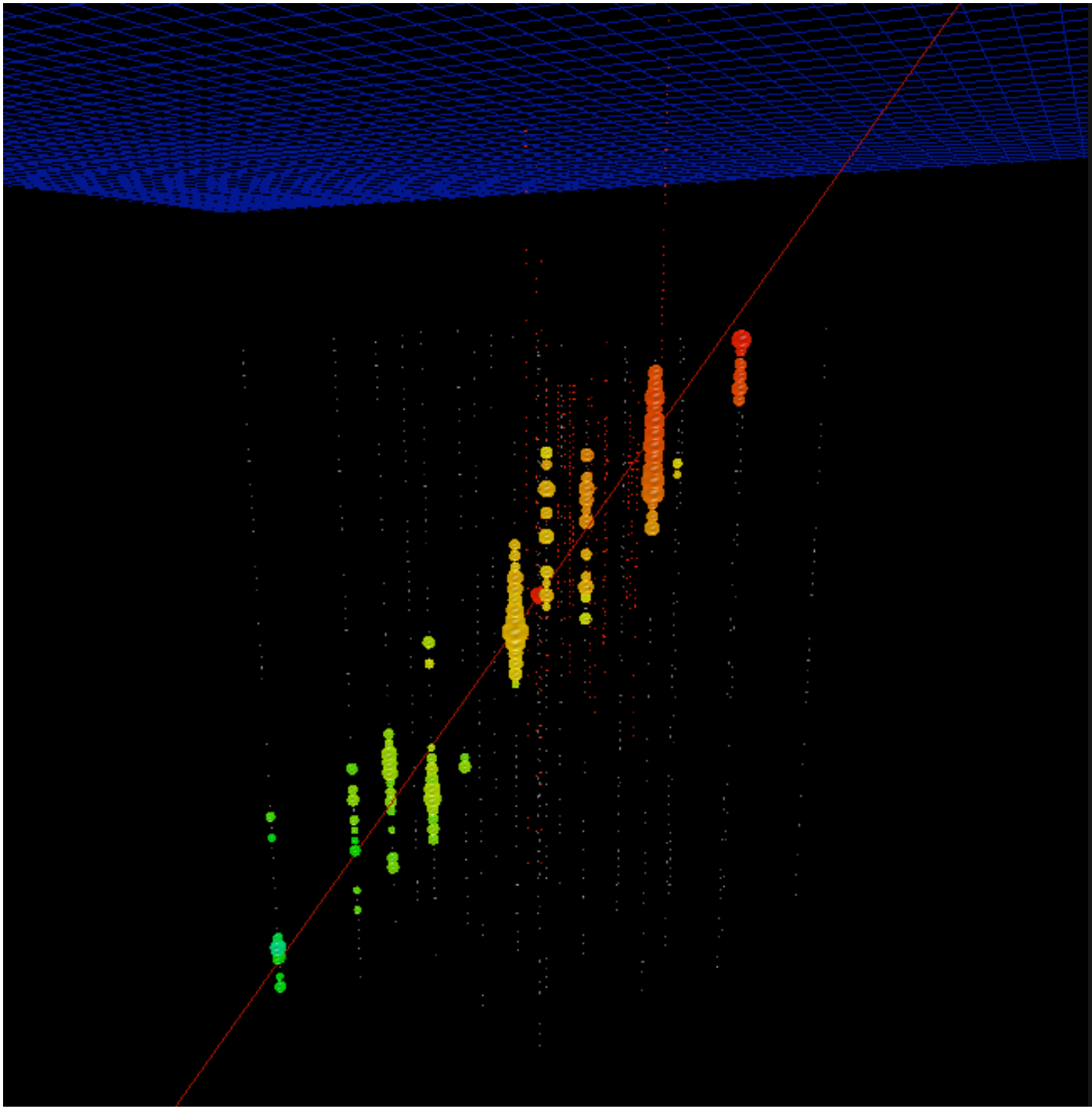
First data in 2005
first upgoing muon:
July 18, 2005

AMANDA
19 strings
677 modules

Completion by 2011

IceCube/Amanda ~ 2000 modules





IceCube event

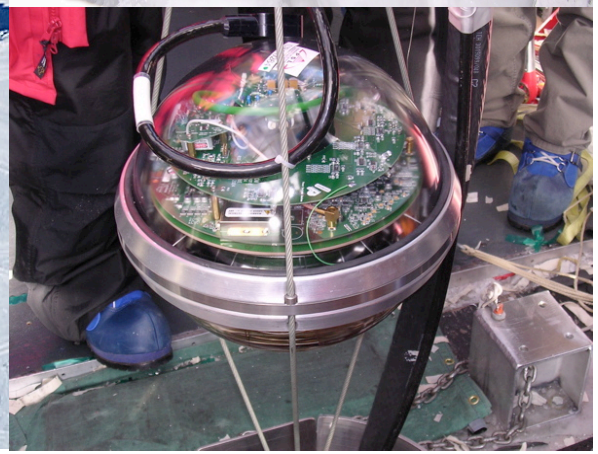
22 strings

AMANDA vs. 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

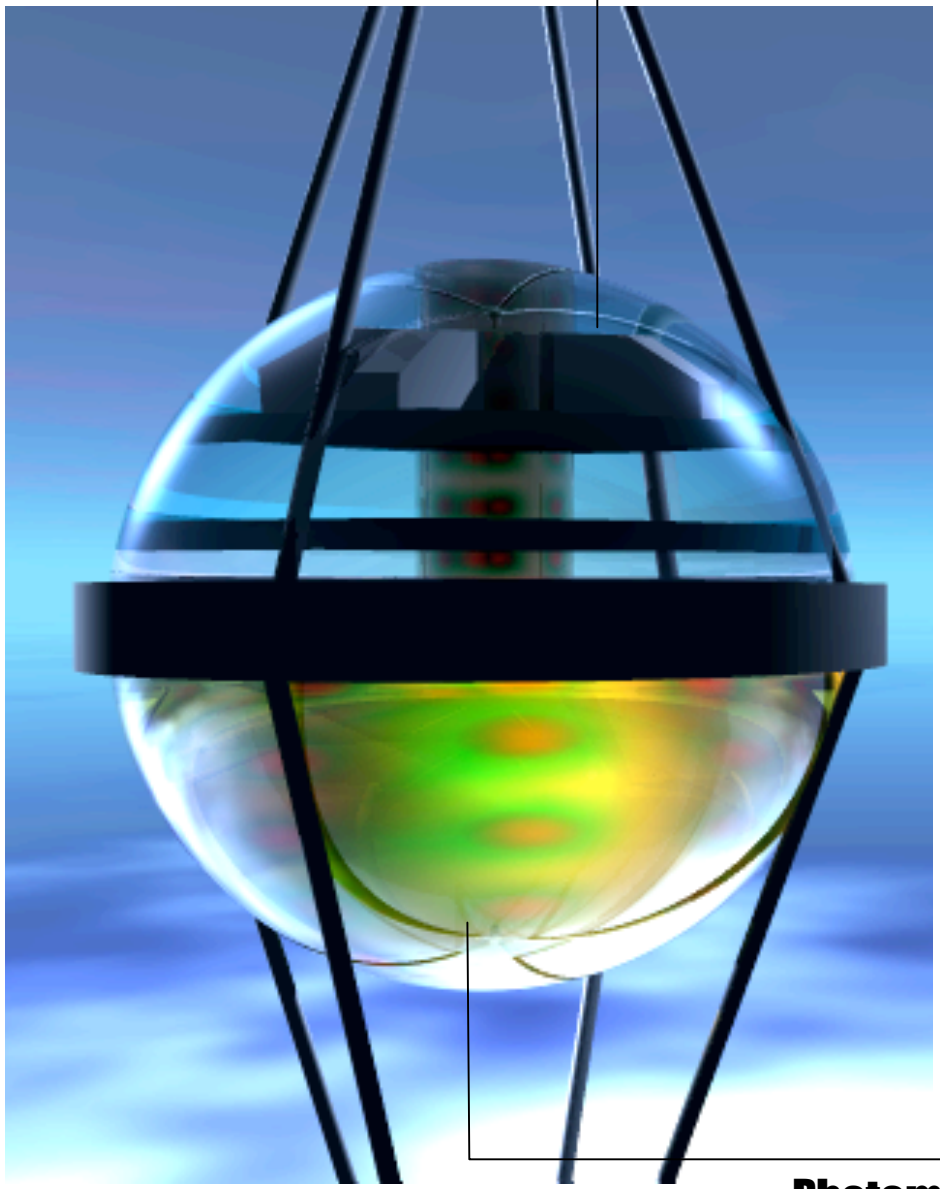
IceCube construction

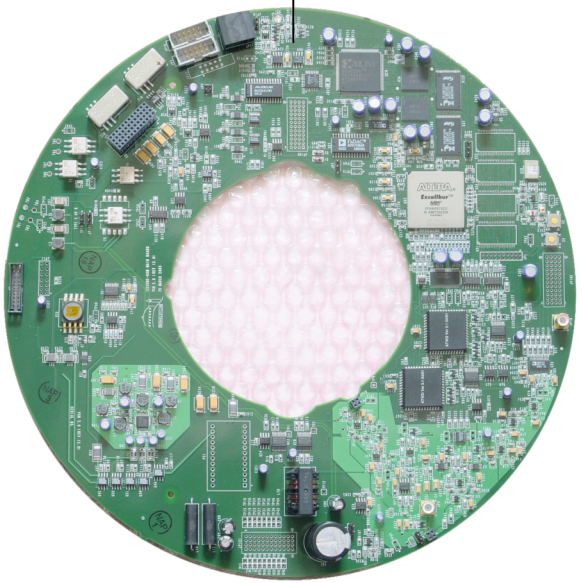


- 1 million pounds of cargo
- C-130 planes: > 50 flights

one of 21 drill modules arrive in antarctica

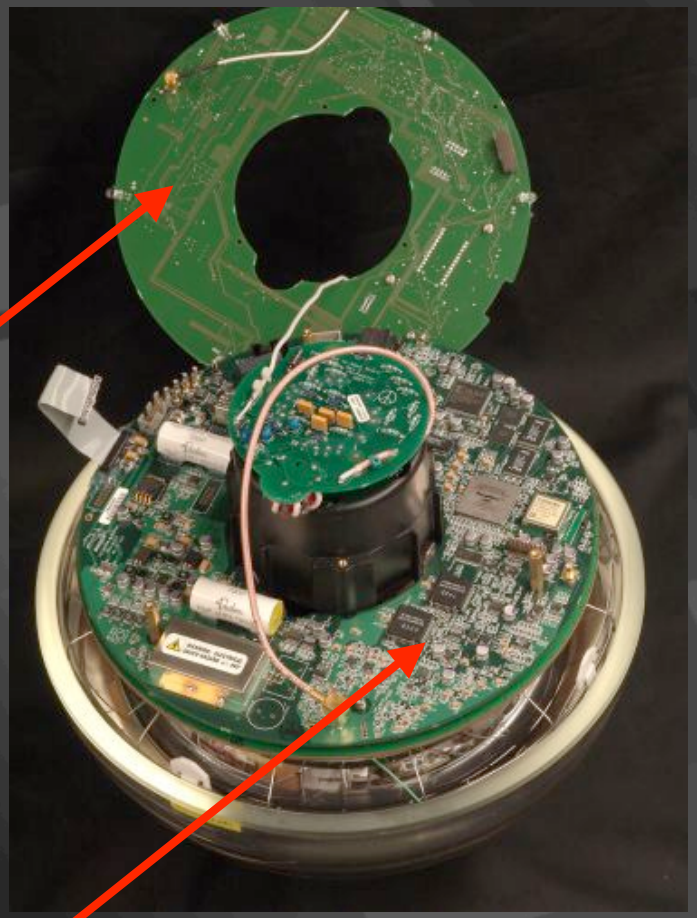
Digital Optical Module

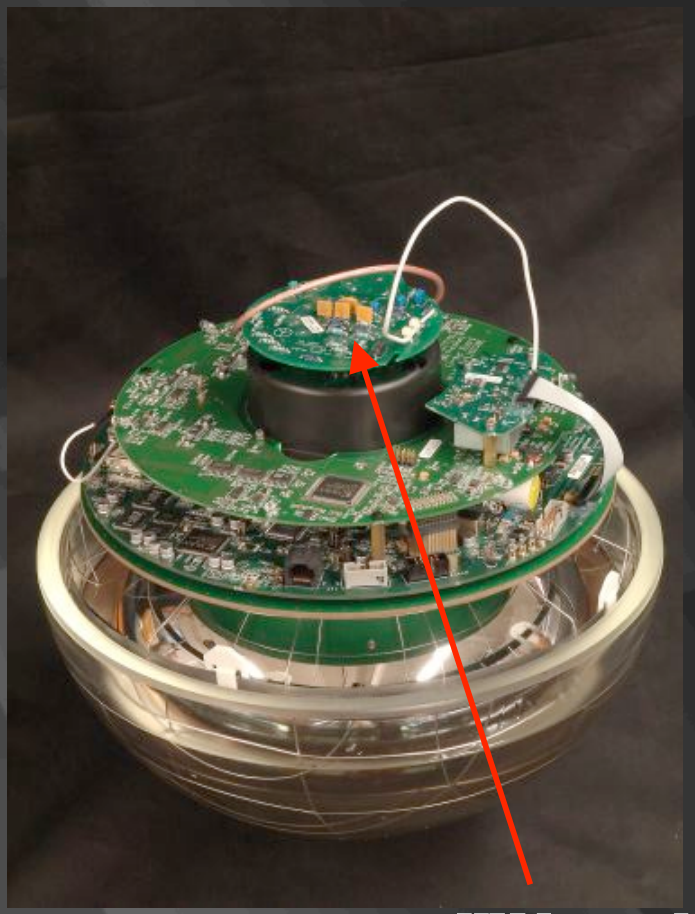




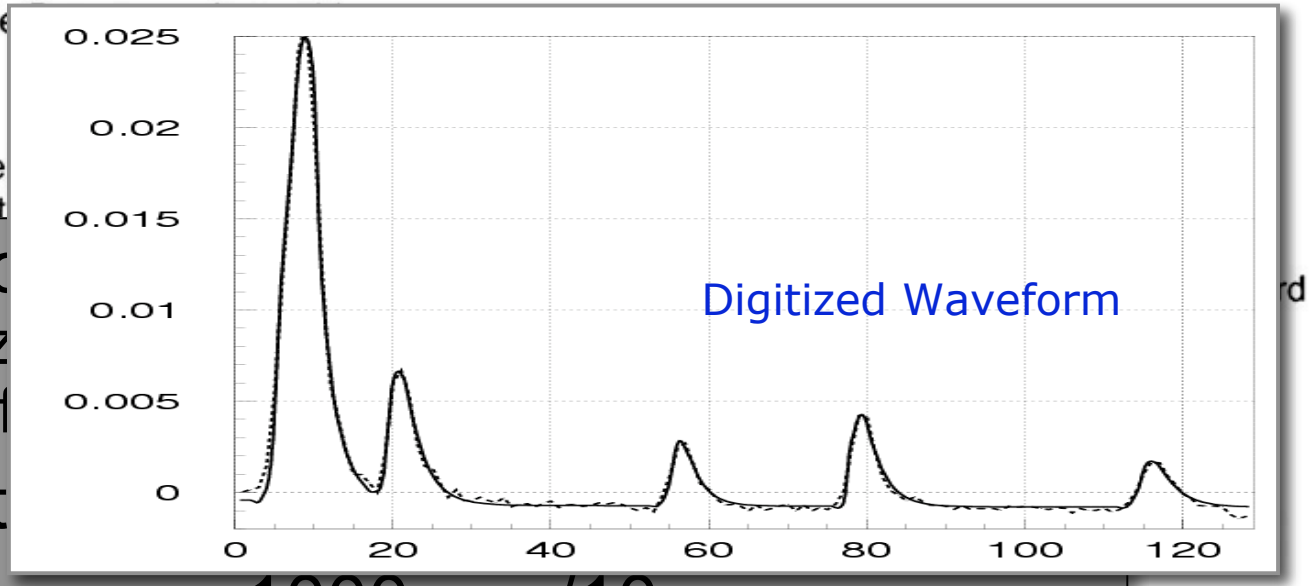
Photomultiplier Tube

Digital Optical Module



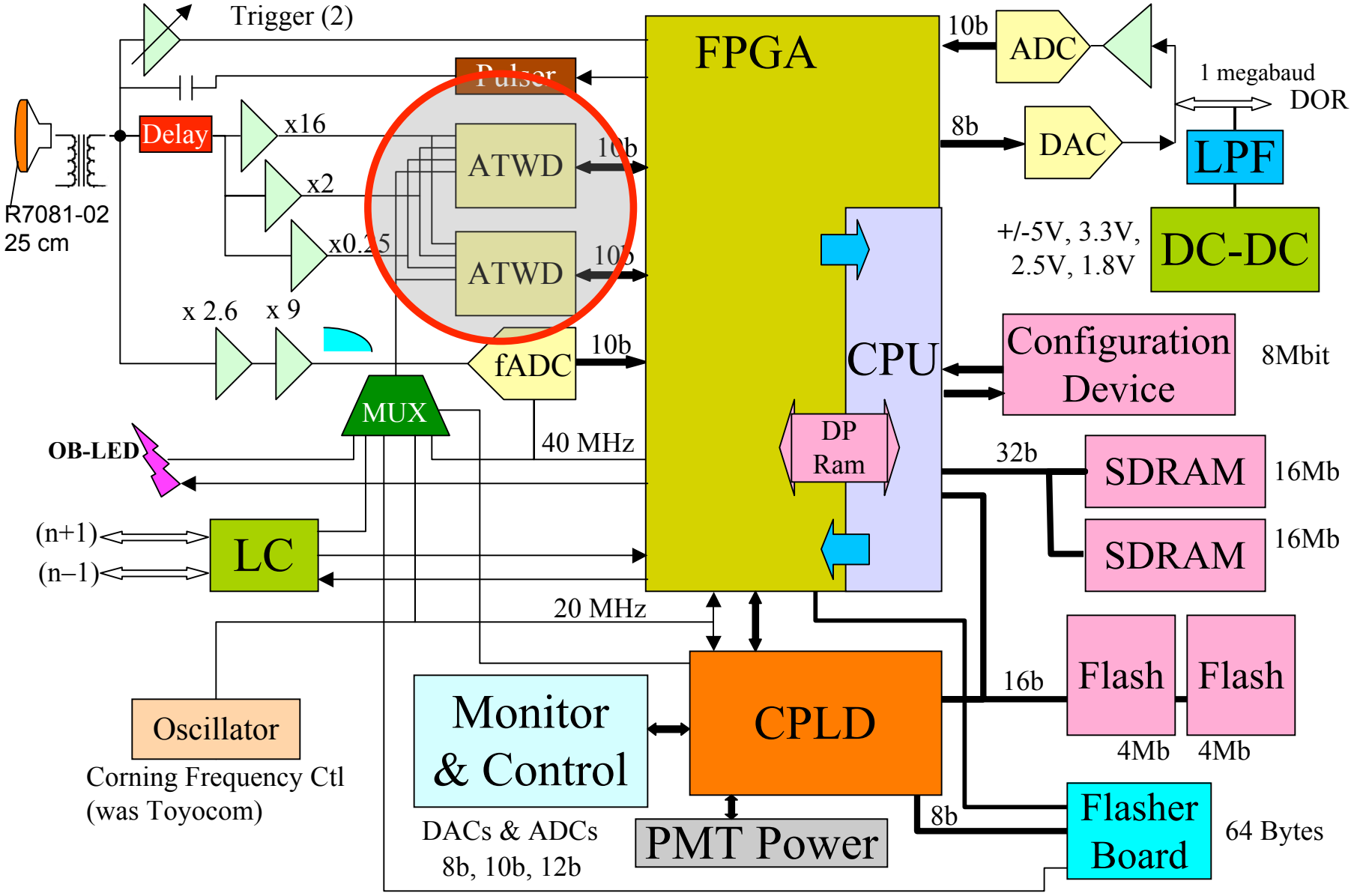


The Digital Optical Module (DOM)



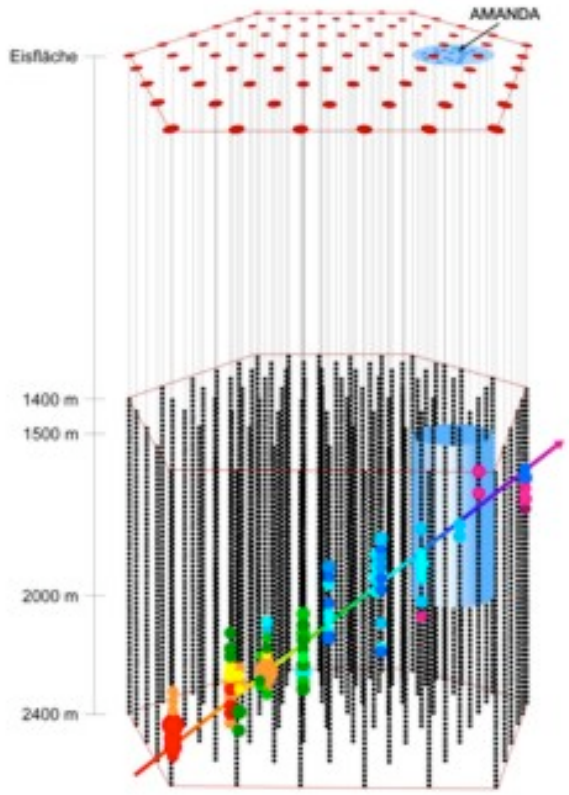
- Onboard d
  - 300 MHz
  - 40 MHz t
- Absolute t
- Dynamic range ~1000 p.e./10 ns
- Deadtime < 1%
- Noise rate ~700 Hz (260 Hz w/ artif. deadtime)
- Failure rate < 1%

DOM MB Block diagram



particle physics

IceCube



• in the next 10 years IceCube will observe

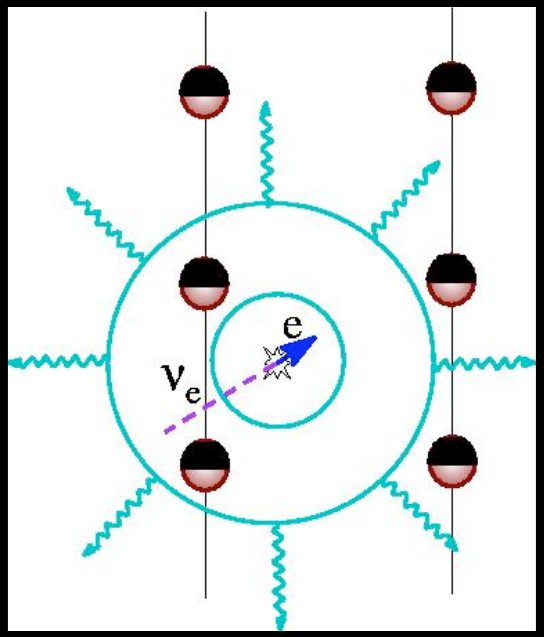
~ 10^6 neutrinos with energies 0.1—1,000 TeV
~ 10 neutrinos with energy > 10^6 TeV

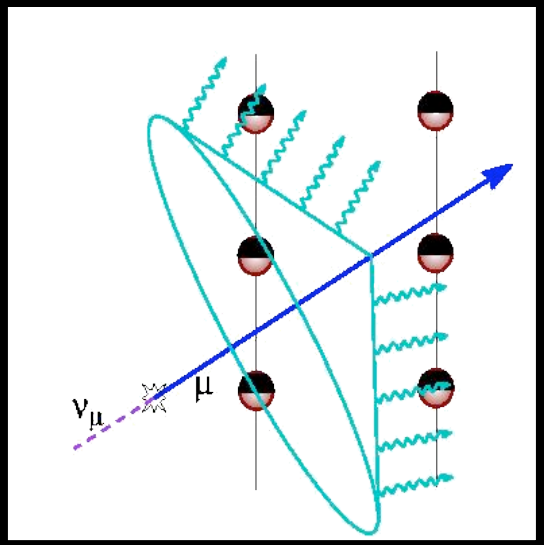
made in the interactions of cosmic rays with the Earth's atmosphere and microwave photons.

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

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

neutrino flavor





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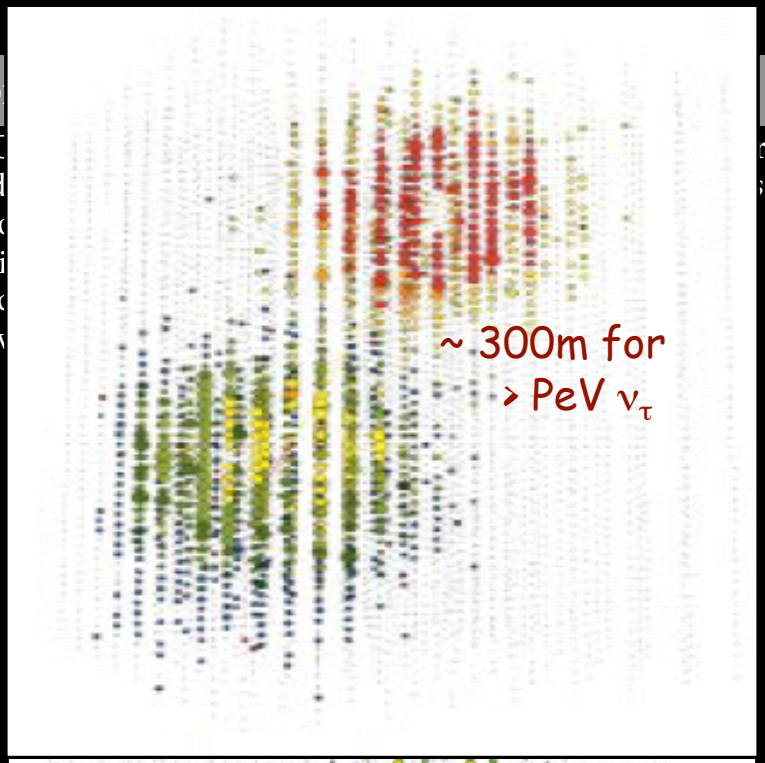

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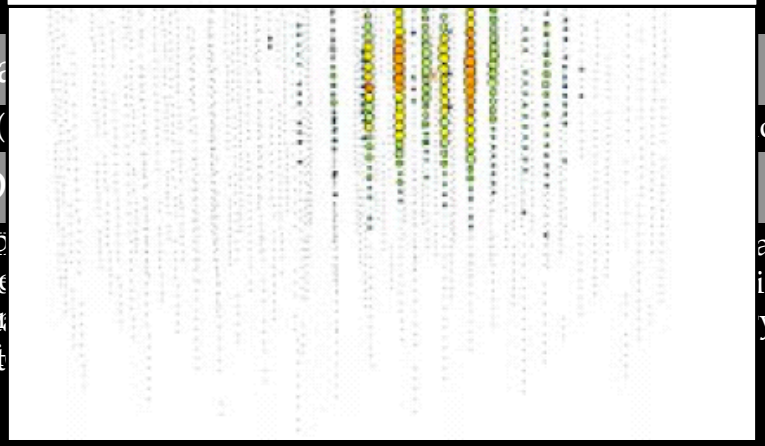
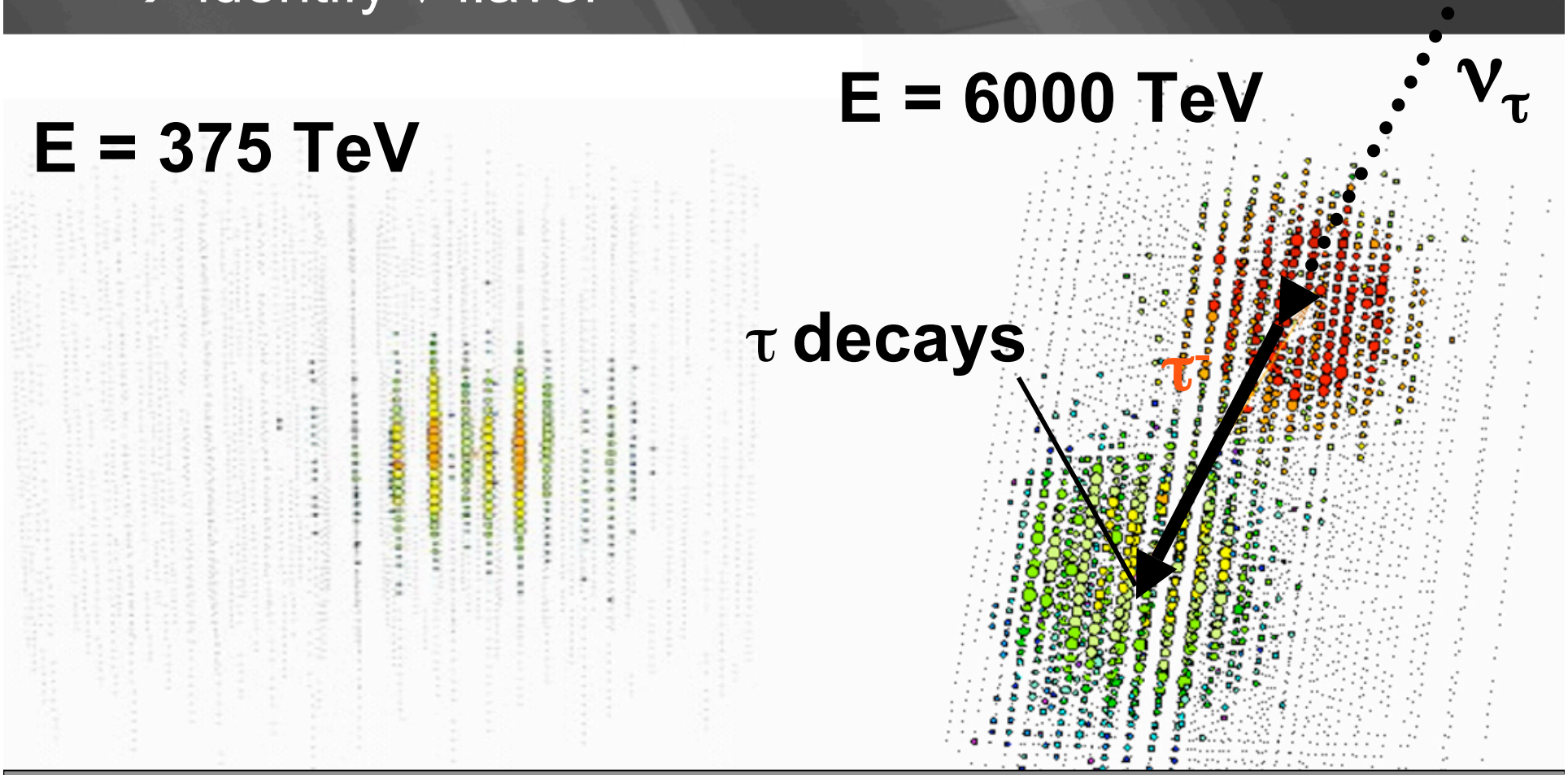


ν_e and ν_τ detection in IceCube

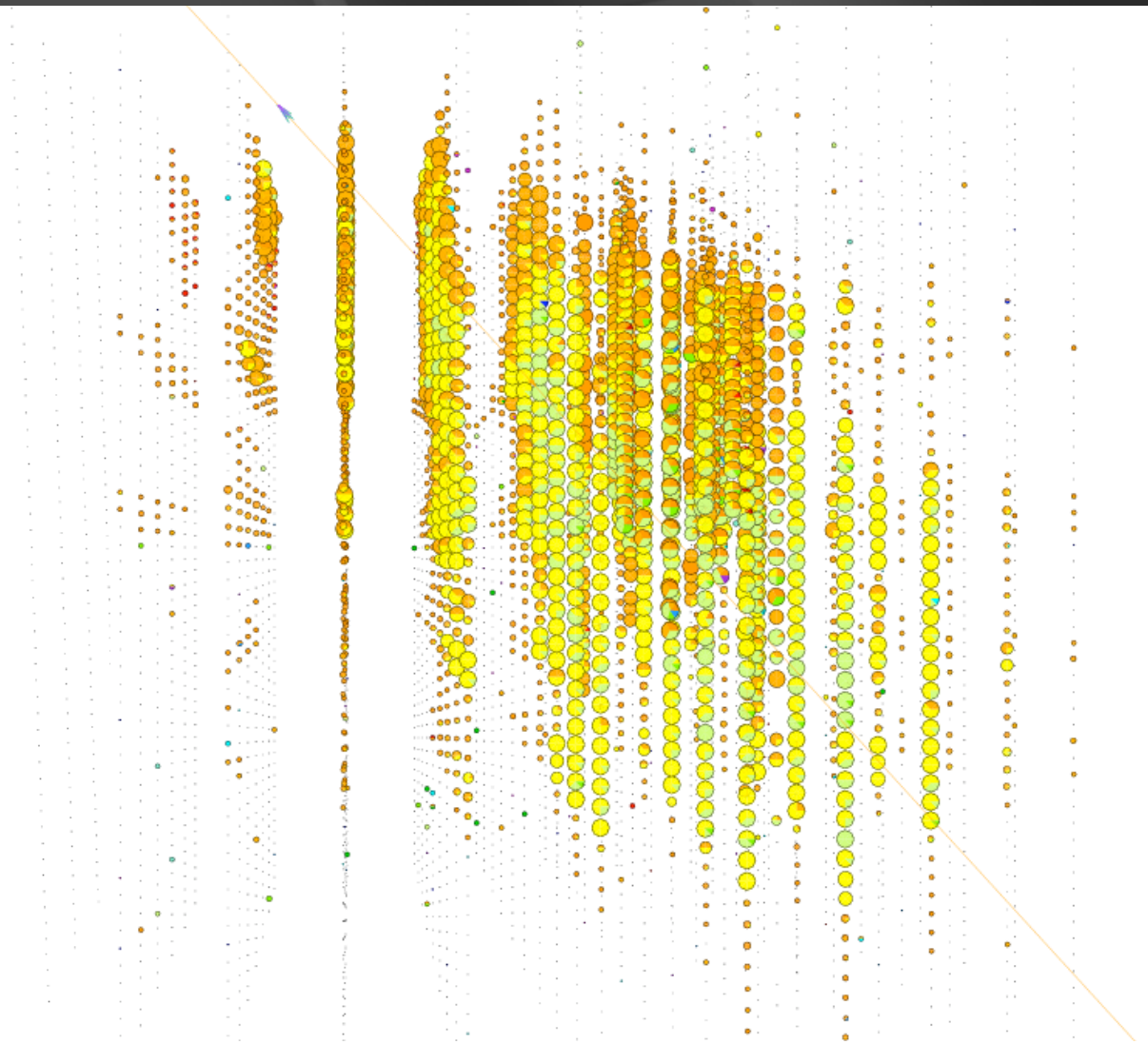
→ identify ν flavor



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

$\nu_\tau + N \rightarrow \tau^- + X$

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

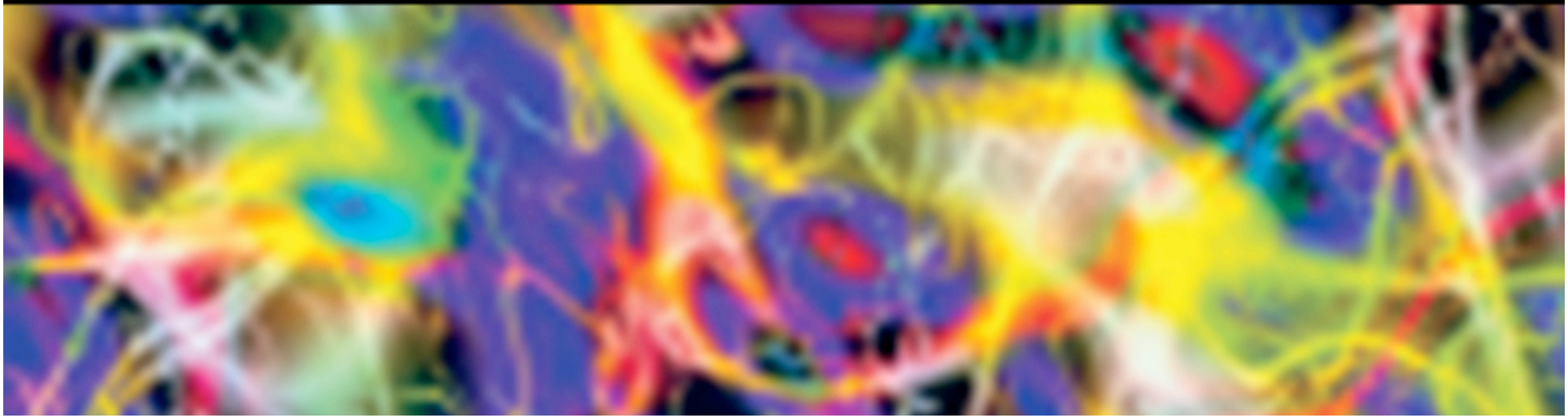


IceCube : particle physics with one million atmospheric neutrinos

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

- **Physics**:
- measurement of the high-energy neutrino cross section
- TeV-scale 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
- …

quantized space: like traveling through a crystal



quantized space: like traveling through a crystal

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

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

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

Lorentz violation: ΔE vs Δt

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

$$energy\ scale \cong \frac{d}{c}\frac{\Delta E}{\Delta t} \cong M_{Planck}$$

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

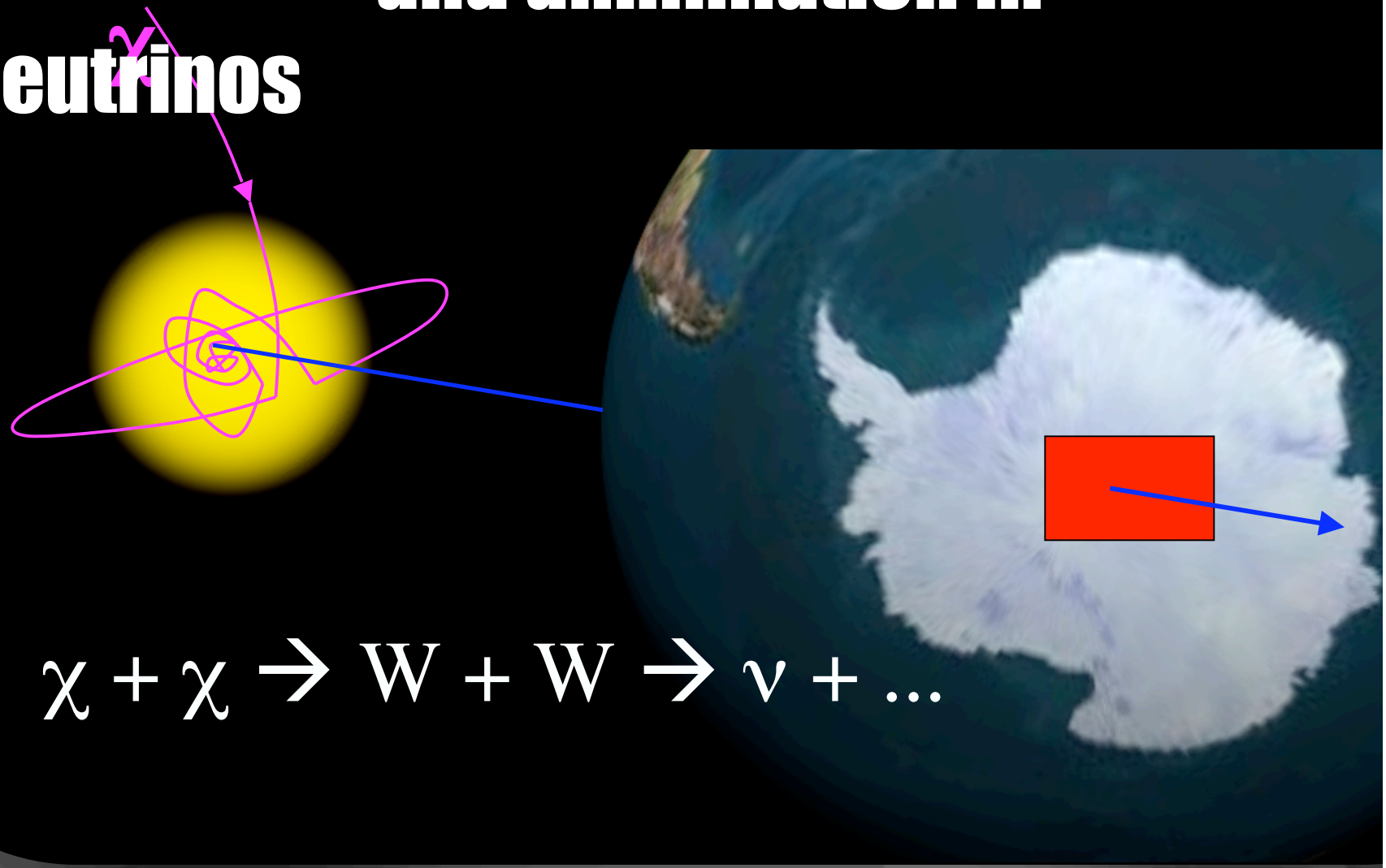
Lorentz violation: ΔE vs Δt

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.

WIMP capture in the sun and annihilation in neutrinos



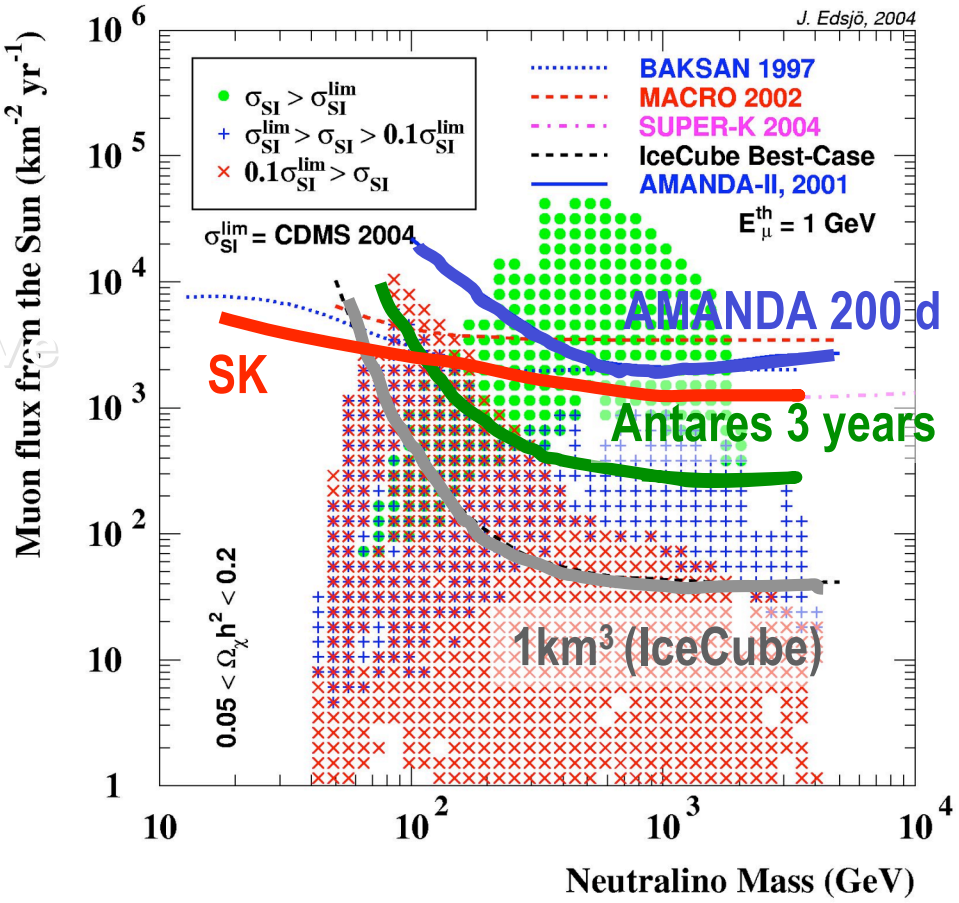
$$\chi + \chi \rightarrow W + W \rightarrow \nu + \ldots$$

wimp search

PRELIMINARY

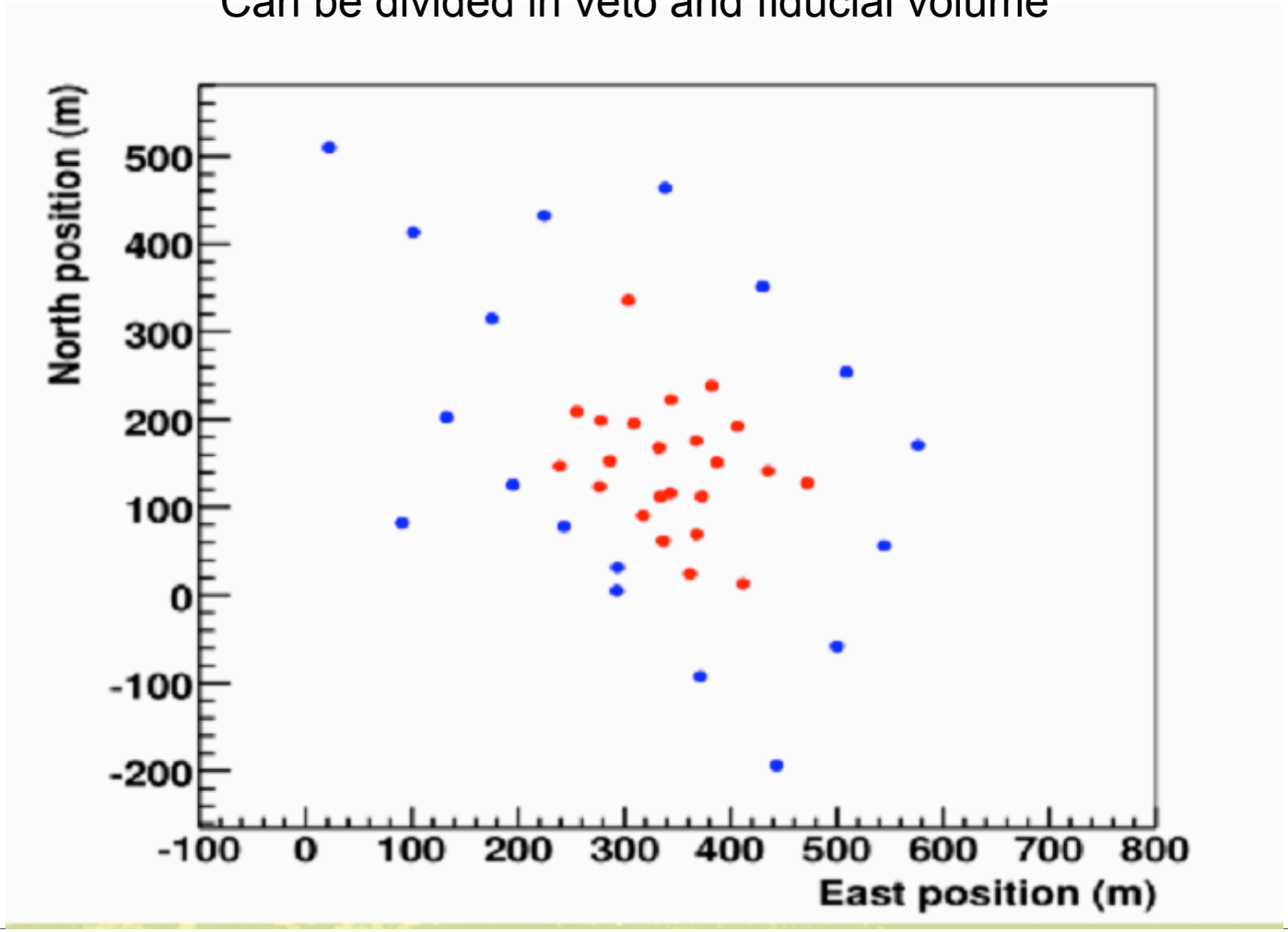
- solar neutrino flux ~ wimp cross section
- AMANDA (6 year) competitive with CDMS
- sensitive to spin dependent interactions

limits on muon flux from sun



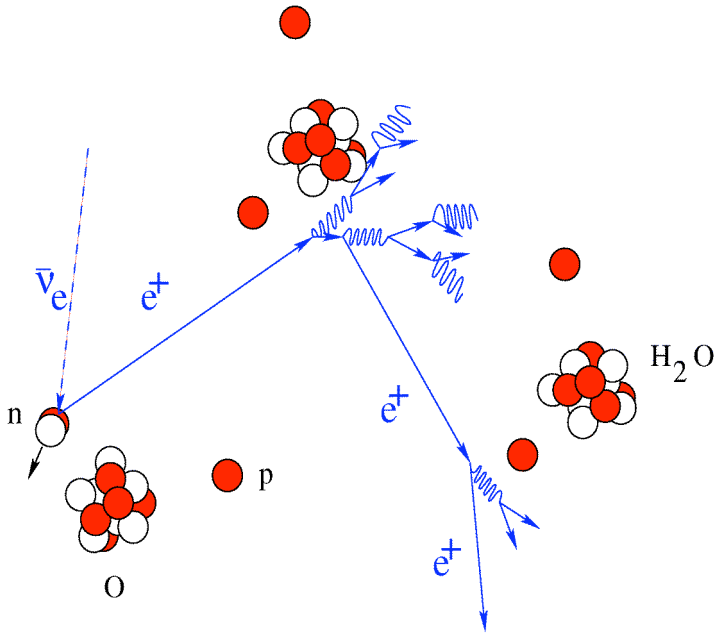
IceCube: the contained event detector

2007 detector: 22 IceCube strings + AMANDA
Can be divided in veto and fiducial volume

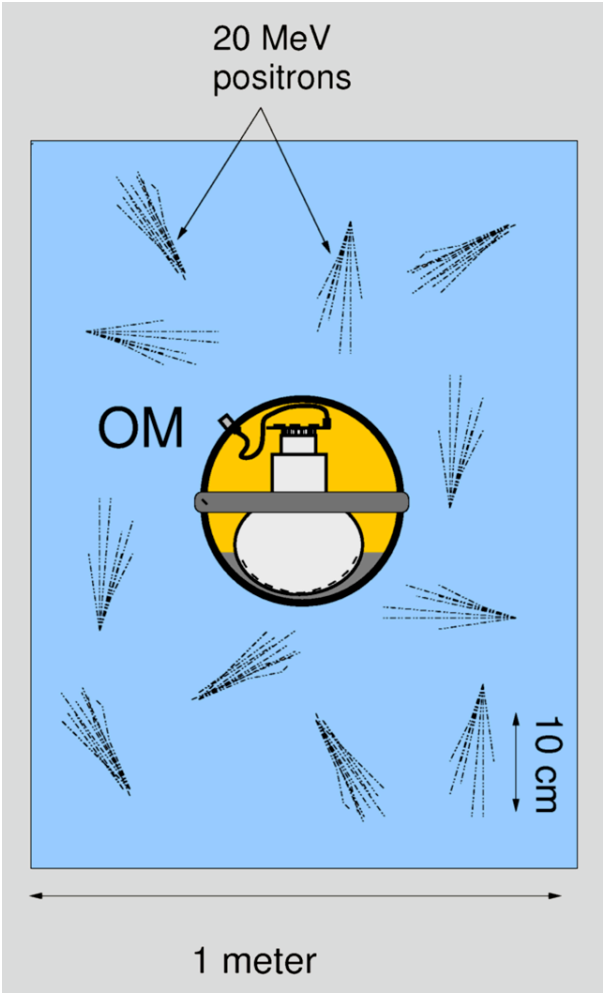


AMANDA/IceCube as MeV ν detector

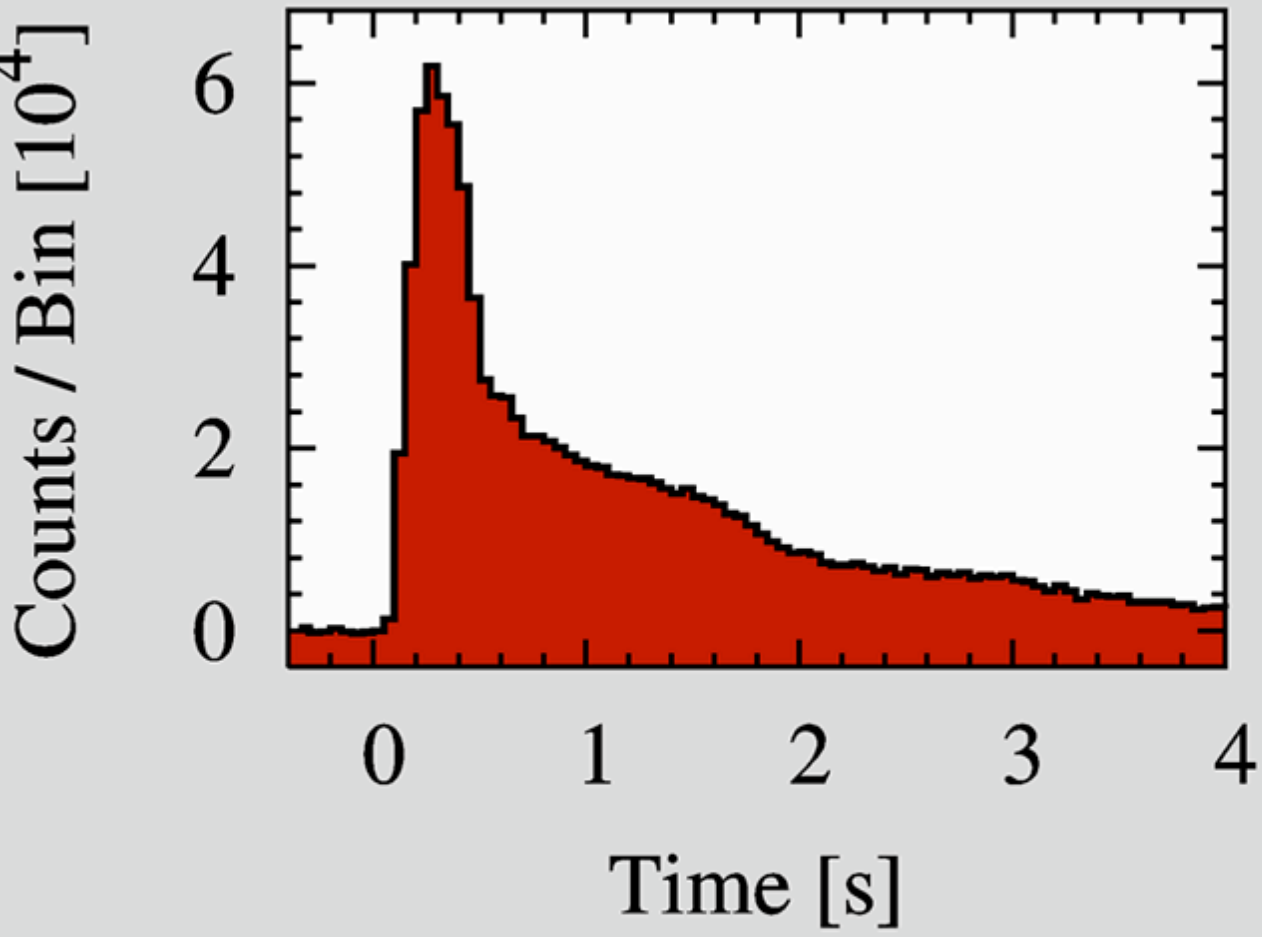
…first proposed by Halzen, Jacobsen & Zas, astro-ph/9512080



- ice uniformly illuminated
- detect correlated rate increase on top of PMT noise



AMANDA/IceCube as MeV ν detector



Disadvantage:

- ☞ no pointing
- ☞ intrinsic noise

Advantage:

- ☞ high statistics (0.25% stat. error)

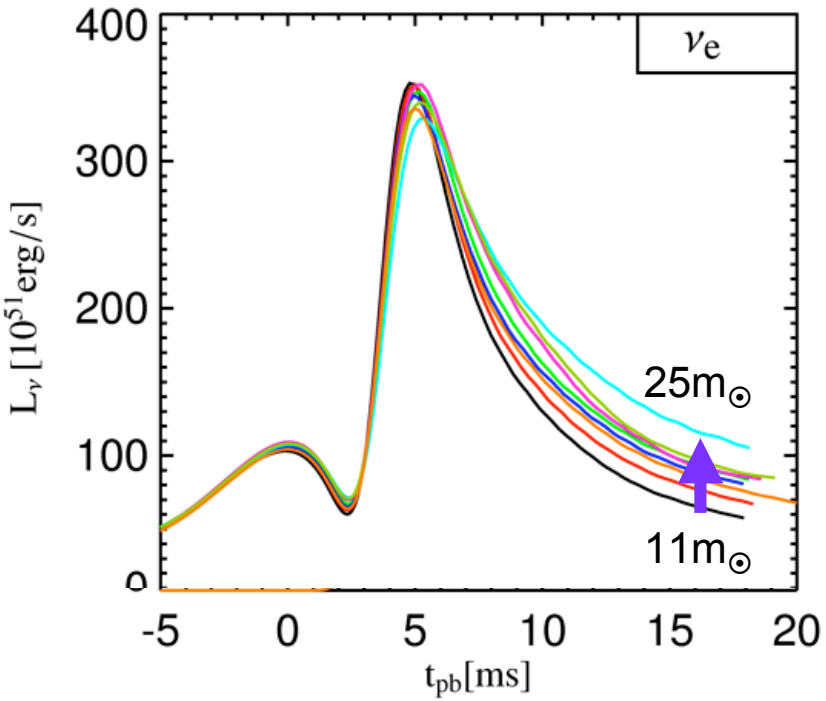
Good for fine time structures (noise low)!

Simulation based on a numerical Livermore model, normalized
To SN1987A at 10 kpc

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216
See also: Dighe, Keil & Raffelt, hep-ph/0303210

Neutronization Burst, a Standard Candle?

Kachelriess,Tomàs, Buras,Janka, Marek & Rampp,astro-ph/0412082



Peak rather independent of

- mass of star
- neutrino transport
- nuclear equation of state

Peak strongly dependent on

MSW effect in supernova

θ_{13}

neutrino mass hierarchy

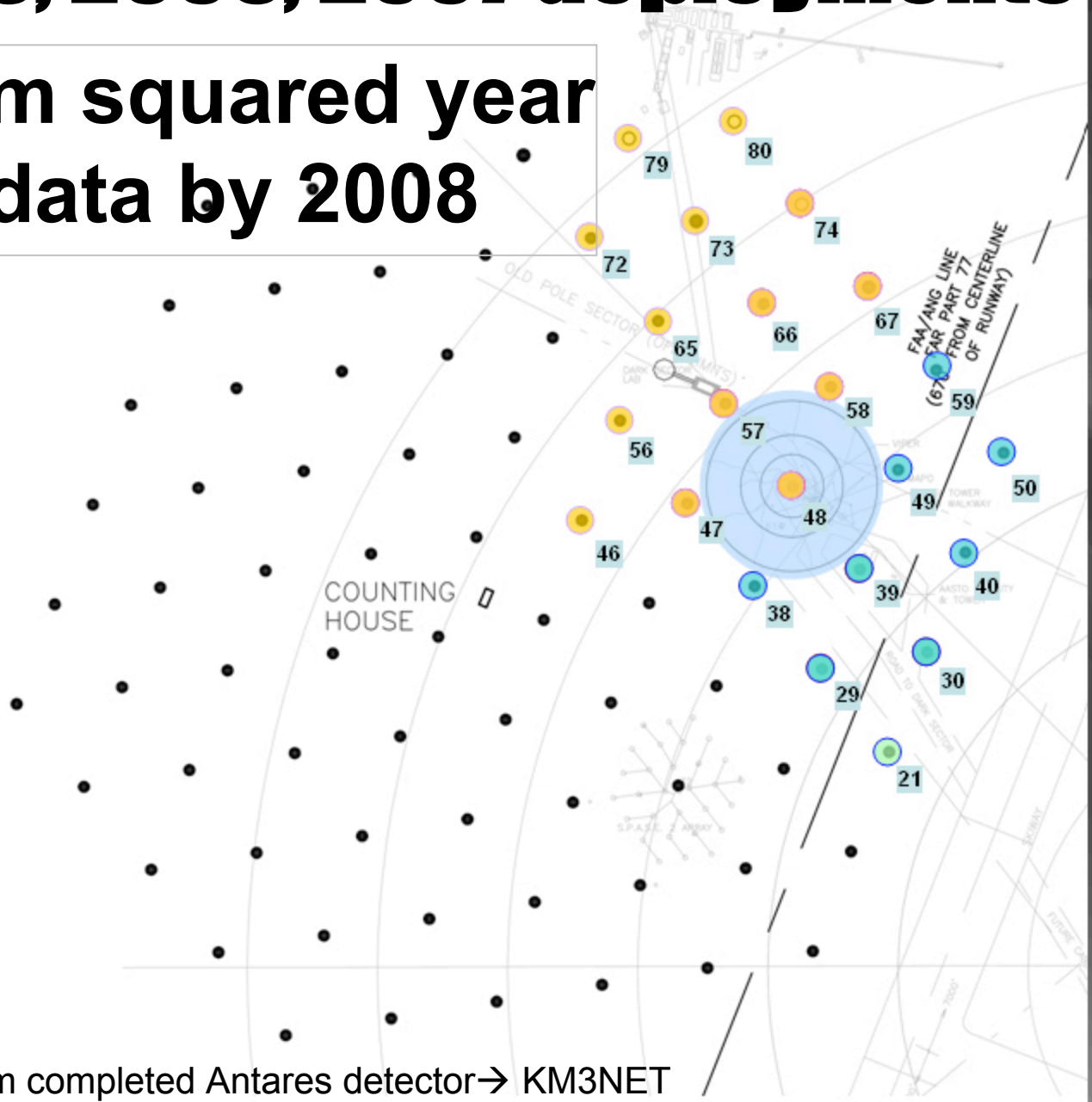
Else, if neutrino mixing matrix known:

excellent method to measure distance with <10% accuracy

Can IceCube see it?

2005, 2006, 2007 deployments

a km squared year data by 2008



AMANDA

IceCube string and IceTop station deployed 01/05

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

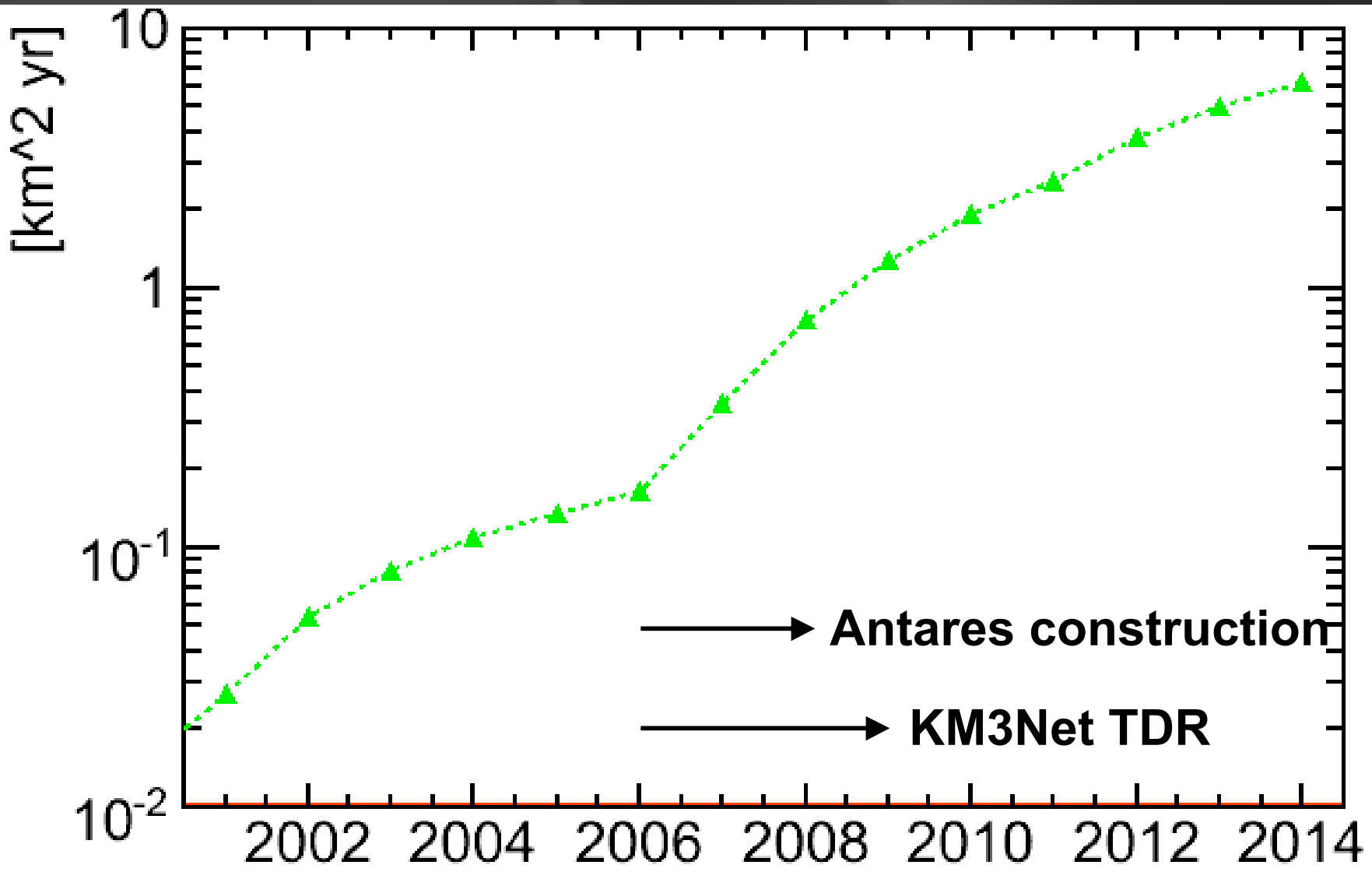
IceTop station only 2006

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.

Data from completed Antares detector→ KM3NET

IceCube
accumulated exposure at 100 TeV



effective telescope area at 100 TeV

- AMANDA ~ ANTARES ~ (1- 5) m^2
- IceCube 22 strings (now) ~ 30 m^2
- IceCube 80 strings (final) ~ 100 m^2

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

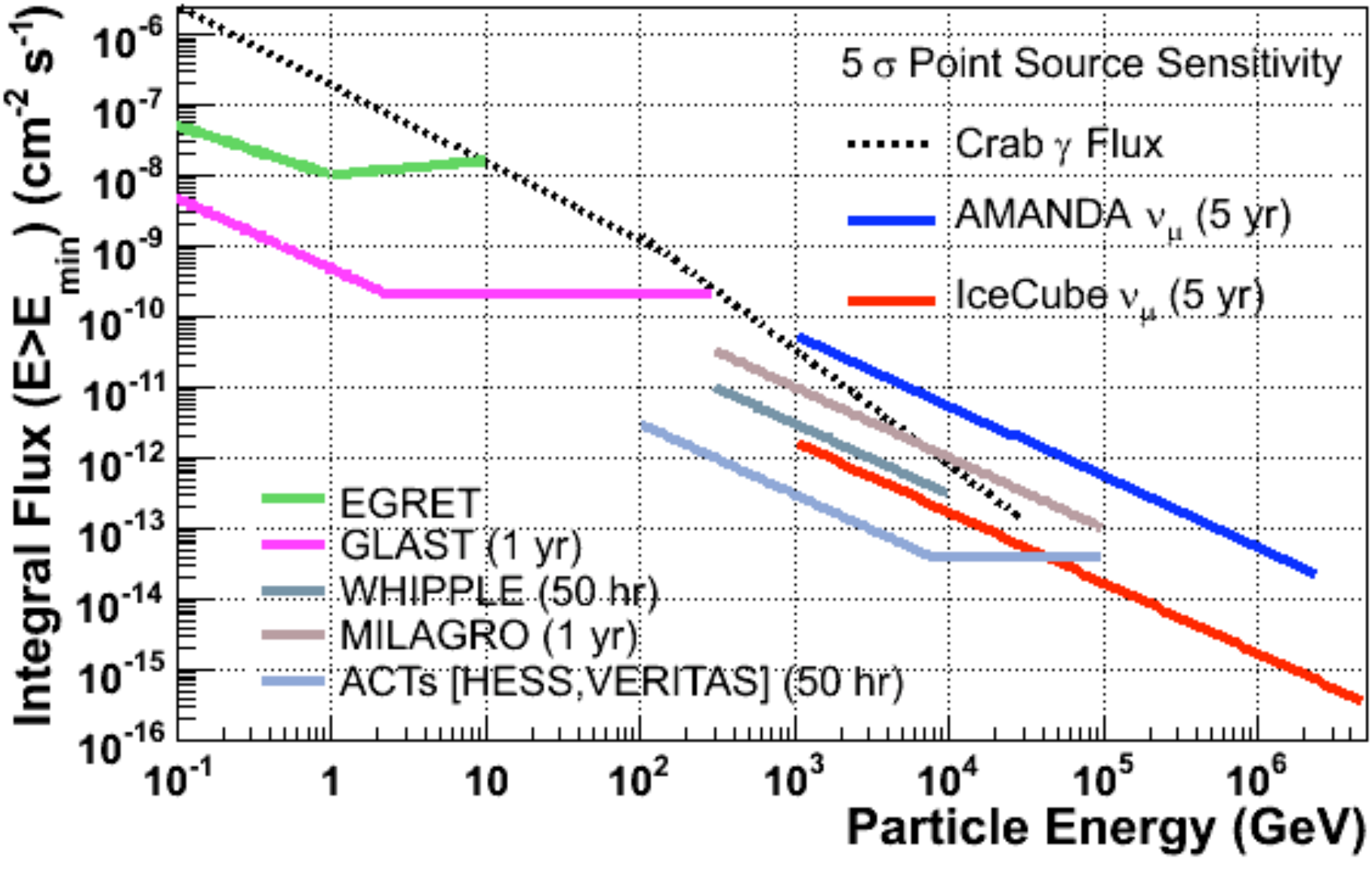
Humboldt Universität, Germany
Universität Dortmund, Germany
MPI, Heidelberg
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands

Chiba University, Japan

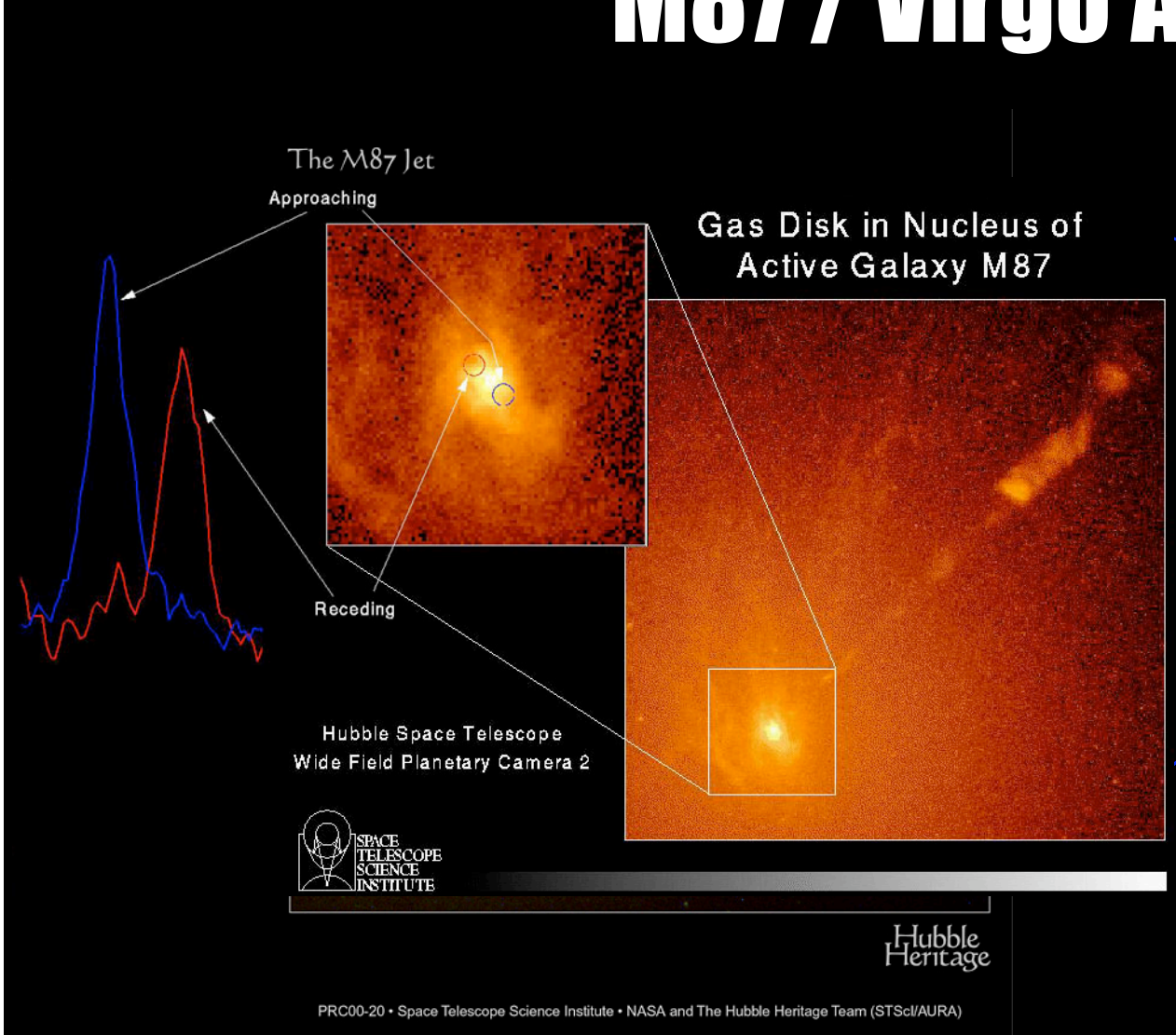
Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
Institute for Advanced Study, Princeton, NJ, USA
University of Alaska, Anchorage

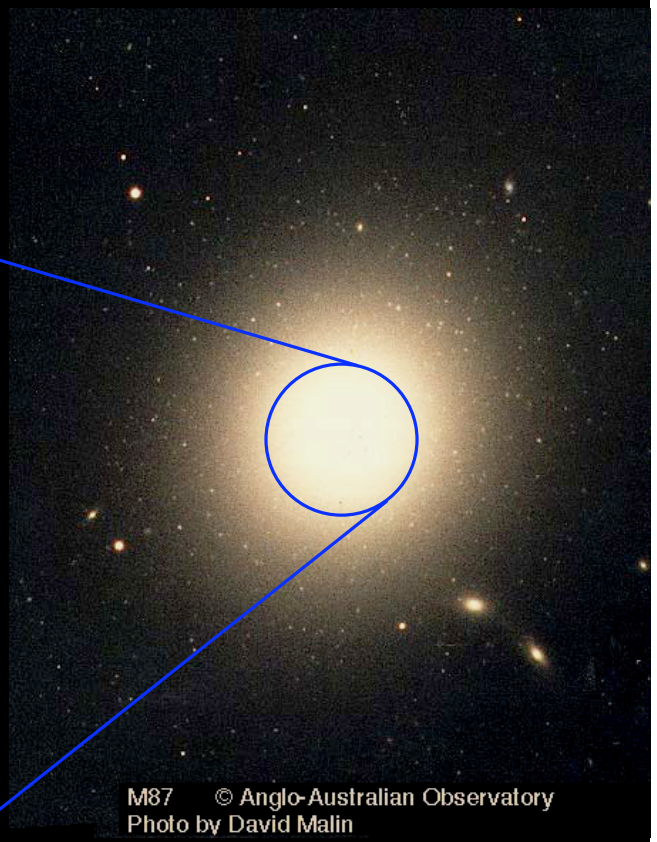
University of Canterbury, Christchurch, New Zealand

overflow

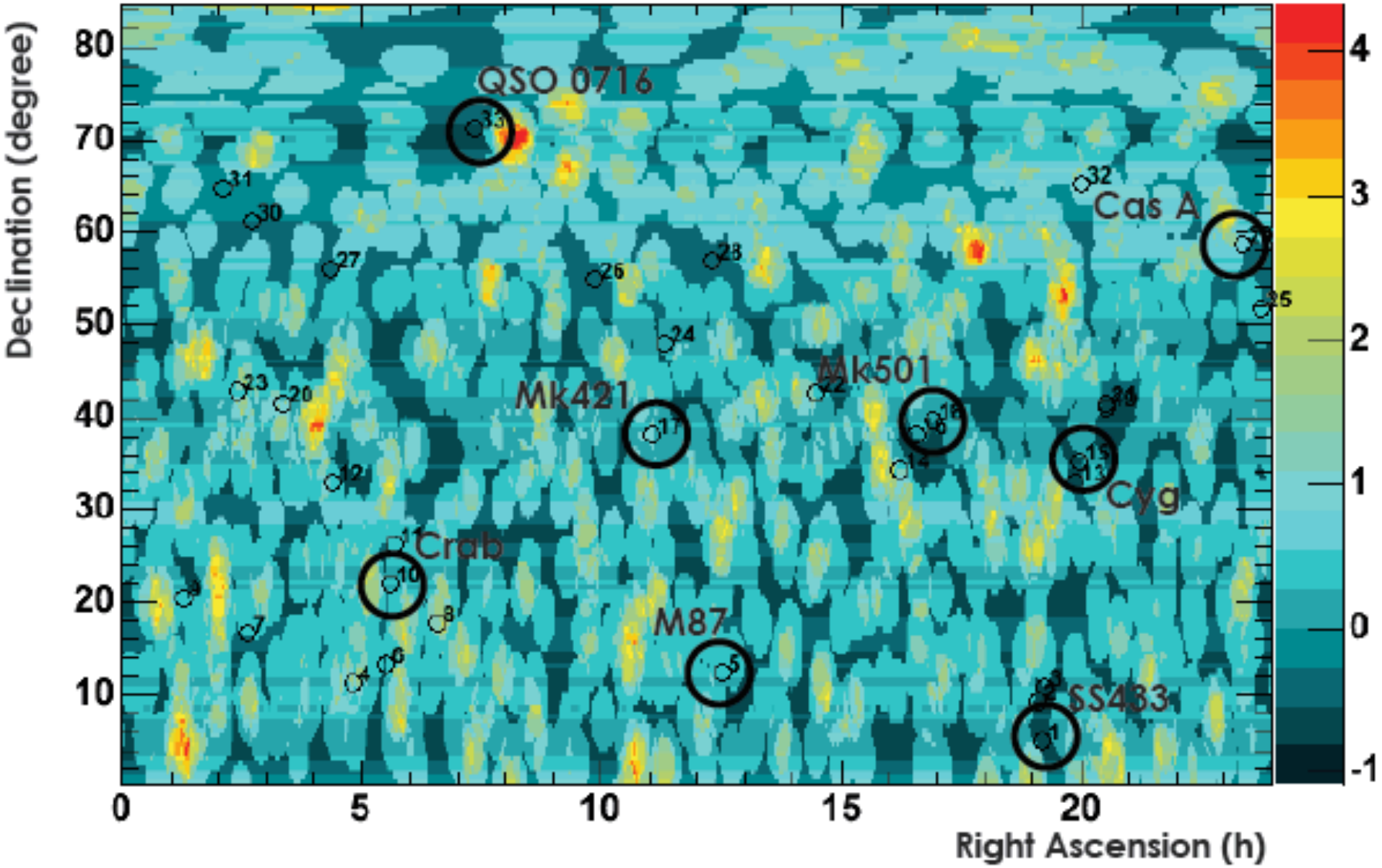

5 σ Point Source Sensitivity
Crab γ Flux
AMANDA ν_μ (5 yr)
IceCube ν_μ (5 yr)
EGRET
GLAST (1 yr)
WHIPPLE (50 hr)
MILAGRO (1 yr)
ACTs [HESS,VERITAS] (50 hr)
Integral Flux (E>E_min) (cm^-2 s^-1)
Particle Energy (GeV)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-1
1
10
10^2
10^3
10^4
10^5
10^6

M87 / Virgo A


The M87 Jet
Approaching
Receding
Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE TELESCOPE SCIENCE INSTITUTE
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

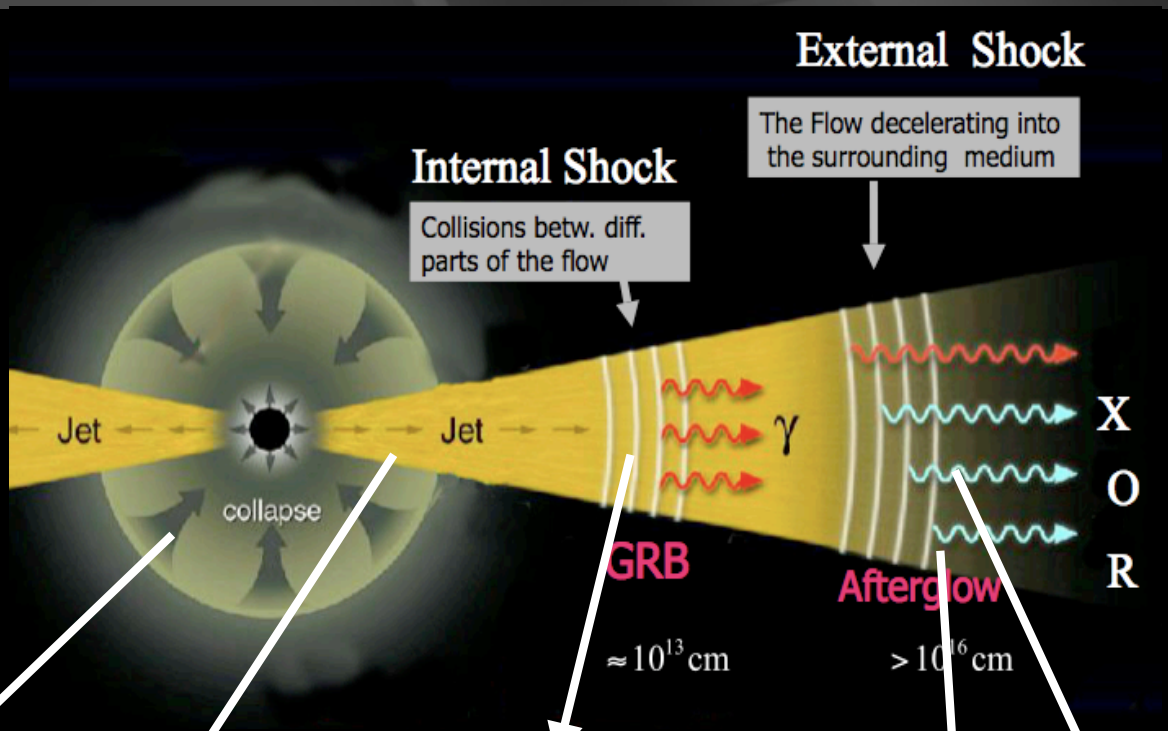

M87 © Anglo-Australian Observatory
Photo by David Malin

32 selected sources



GRBs as sources of high-energy neutrinos

Fireball model for long GRBs:



MeV neutrinos at collapse

TeV neutrinos from inside the star
[Meszaros & Waxman, 2001]
[Razzaque et al. 2003]

PeV neutrinos from internal shock

PeV-EeV neutrinos from flares

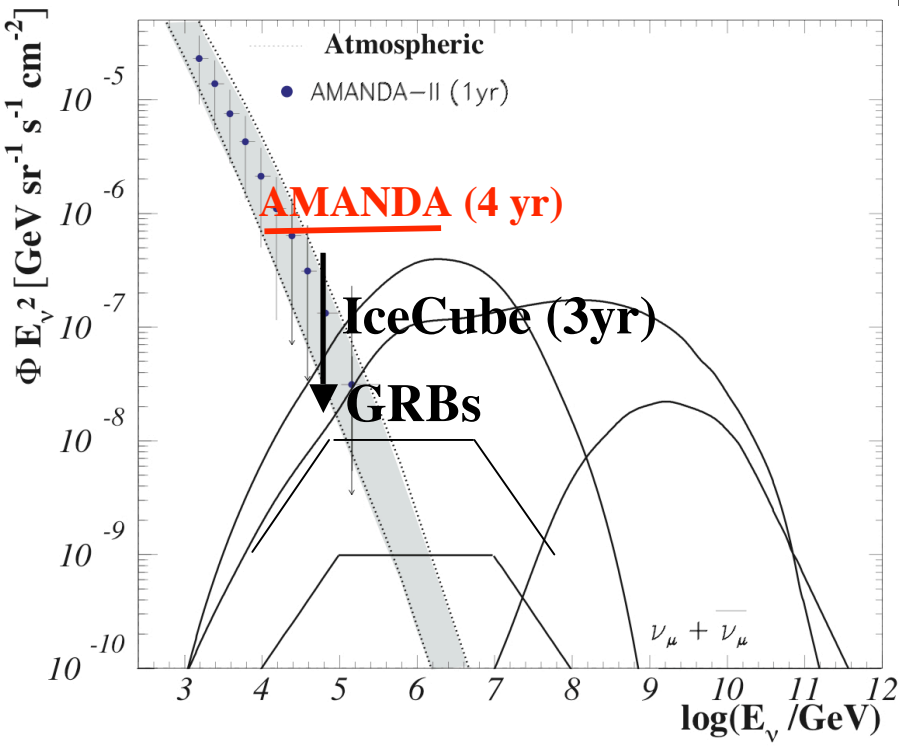
EeV neutrinos from externa shocks

GRB search with AMANDA

Besides T90 search →

- „Rolling search“ for excess events on short time scales.
- Individual bursts (e.g. GRB 030329).
- Search for ν_e, ν_τ (4π - sensitivity!).
- Search for isotropic flux from the cumulative signal of ALL GRBs.

diffuse neutrino flux



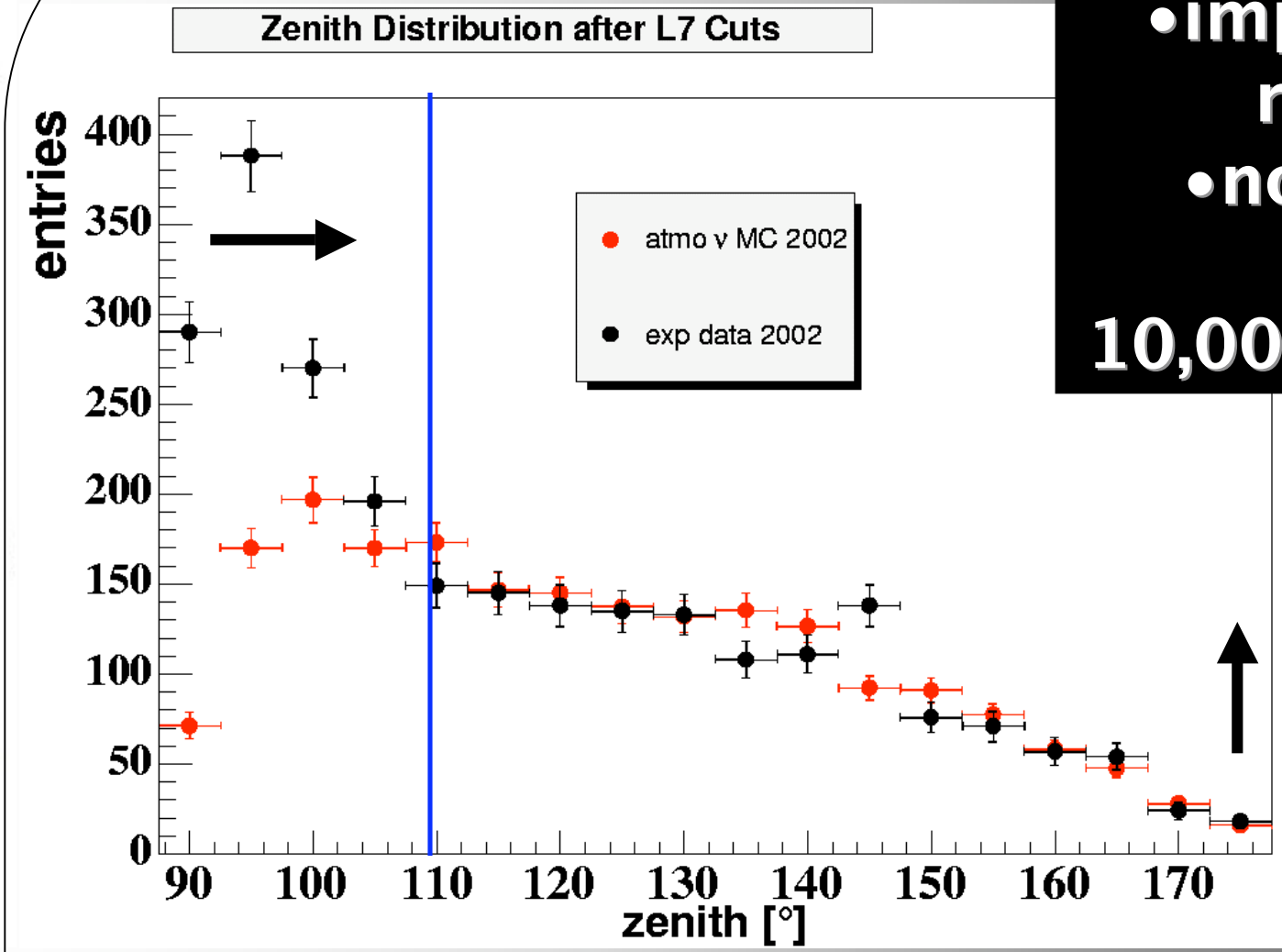
Optimized 2002 analysis

→10 events per day:

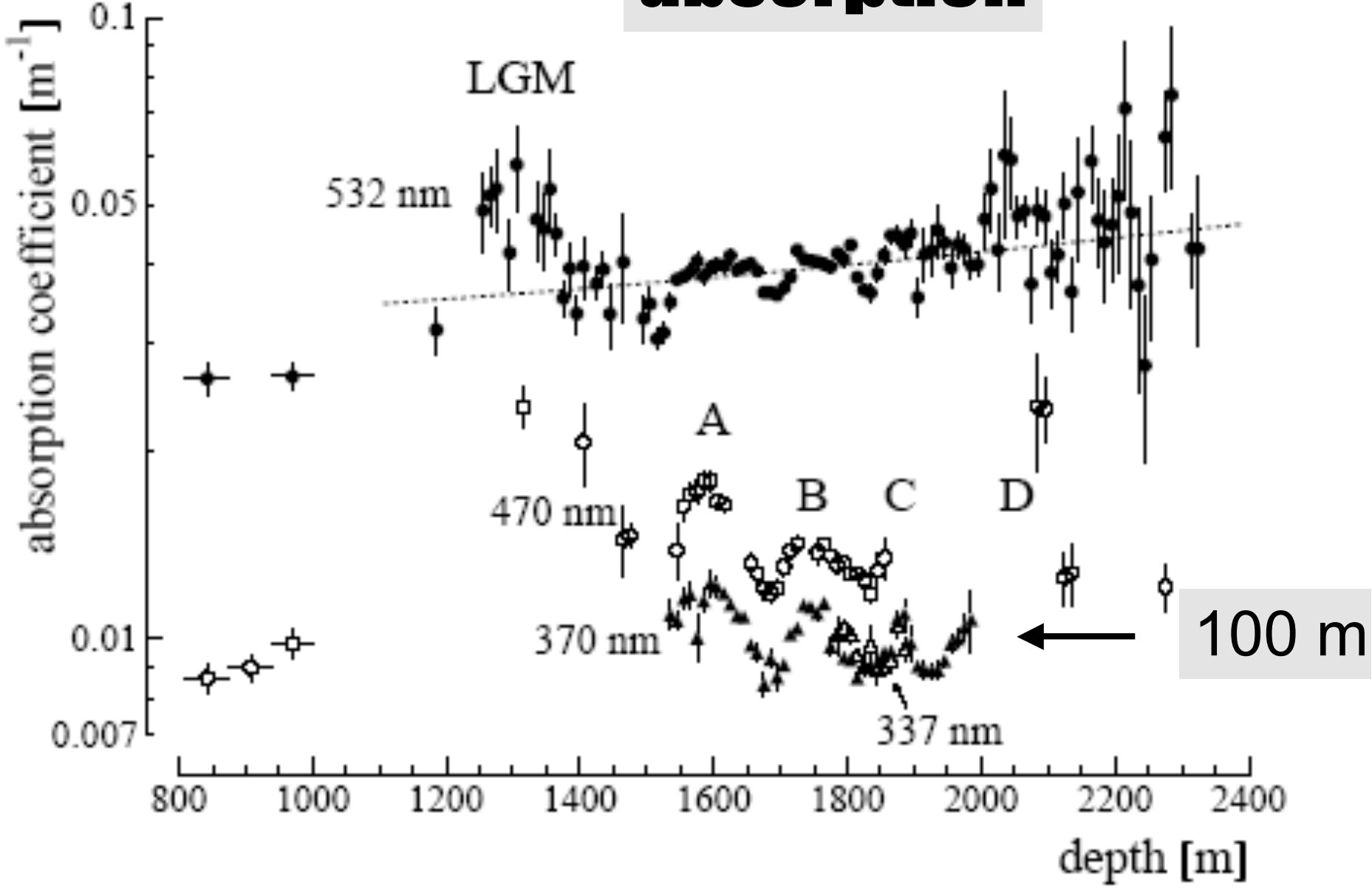
- improved reco
- no cuts

10,000 in 00–05

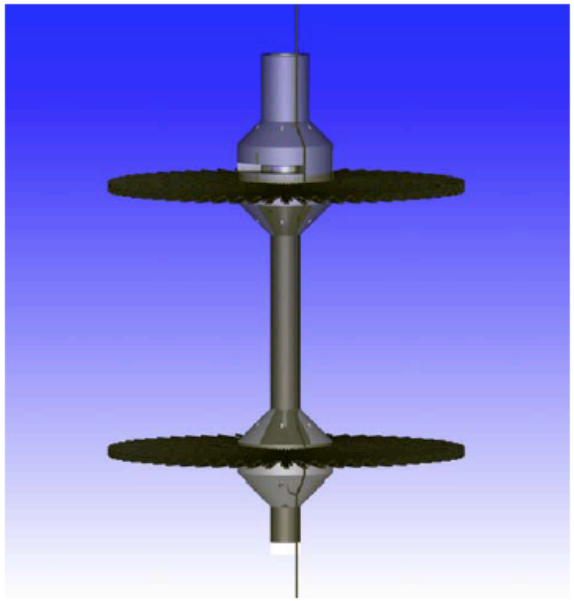
zenith distribution

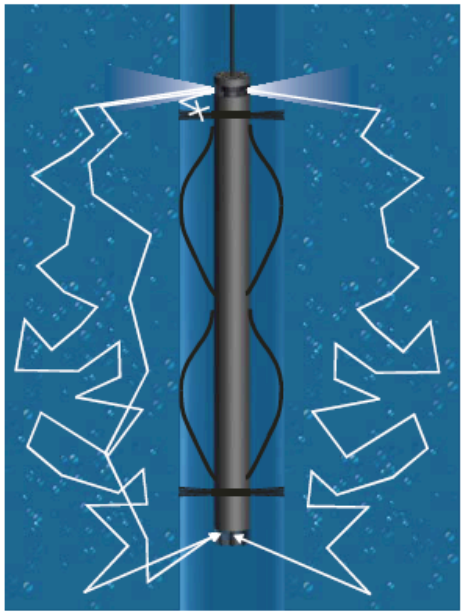


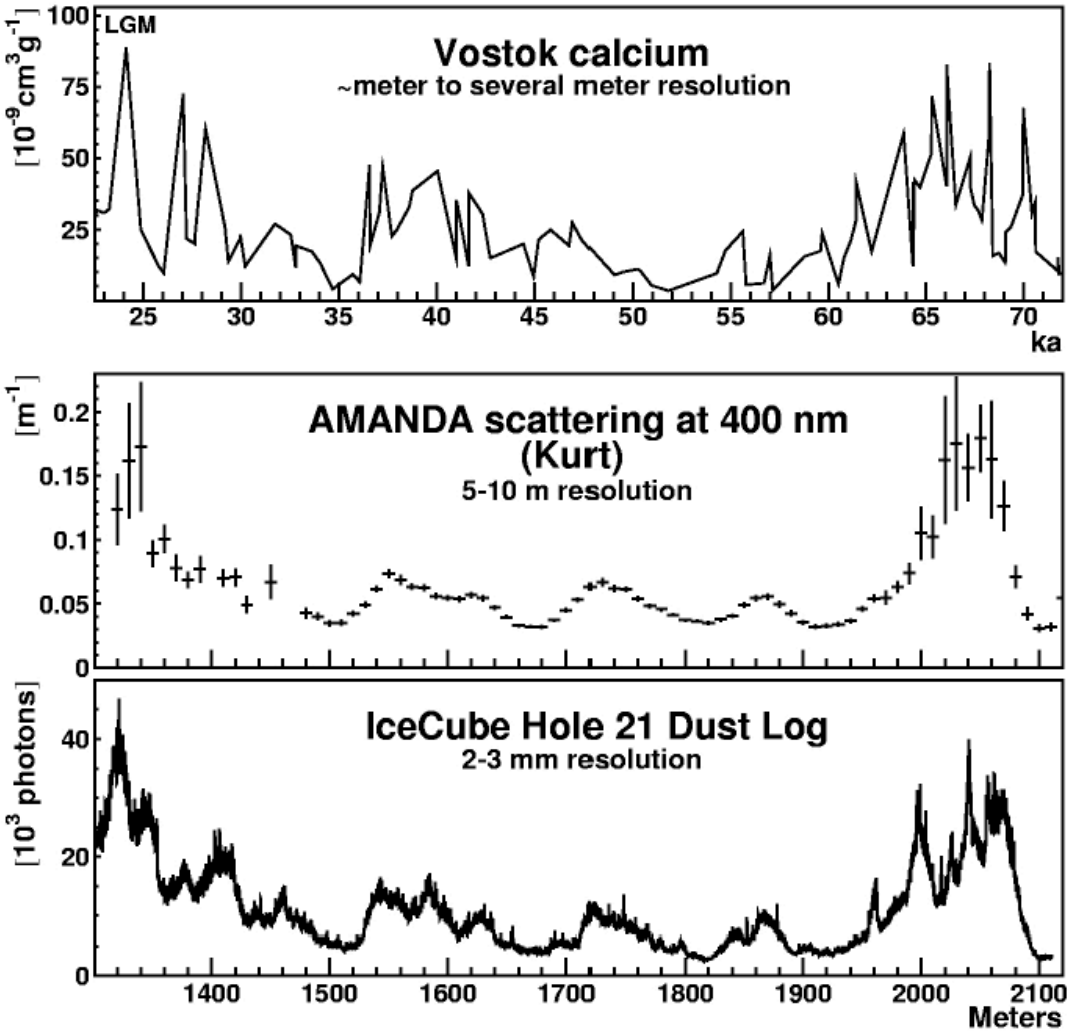
absorption


absorption coefficient [m^{-1}]
0.1
0.05
0.01
0.007
LGM
532 nm
470 nm
370 nm
337 nm
A
B
C
D
100 m
800
1000
1200
1400
1600
1800
2000
2200
2400
depth [m]

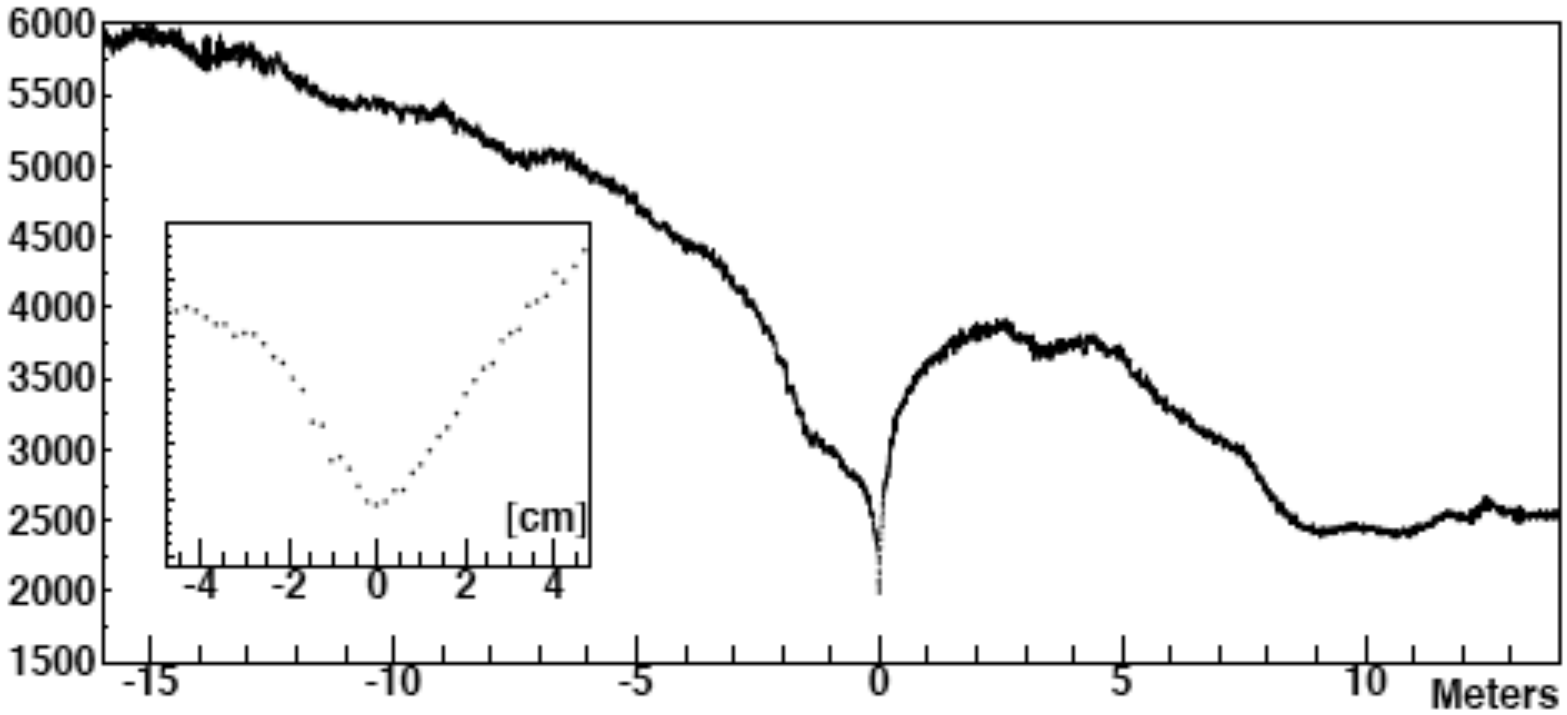
Glaciology with Light







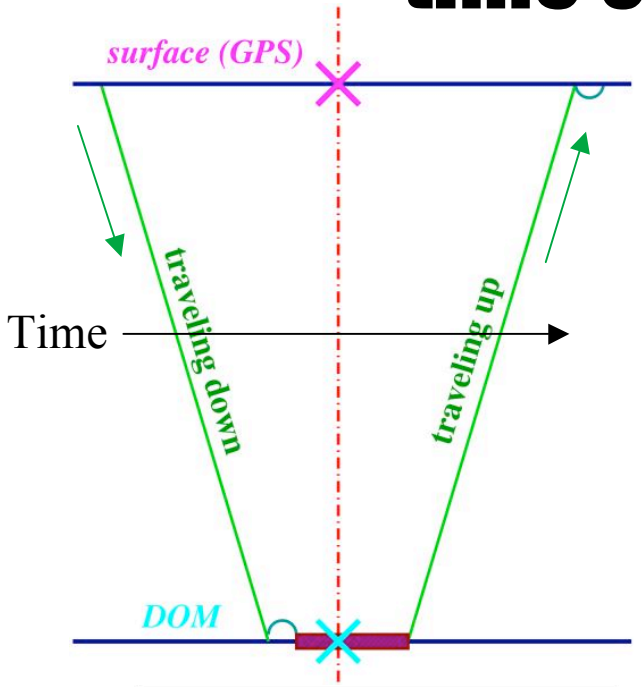
volcanic ash layer



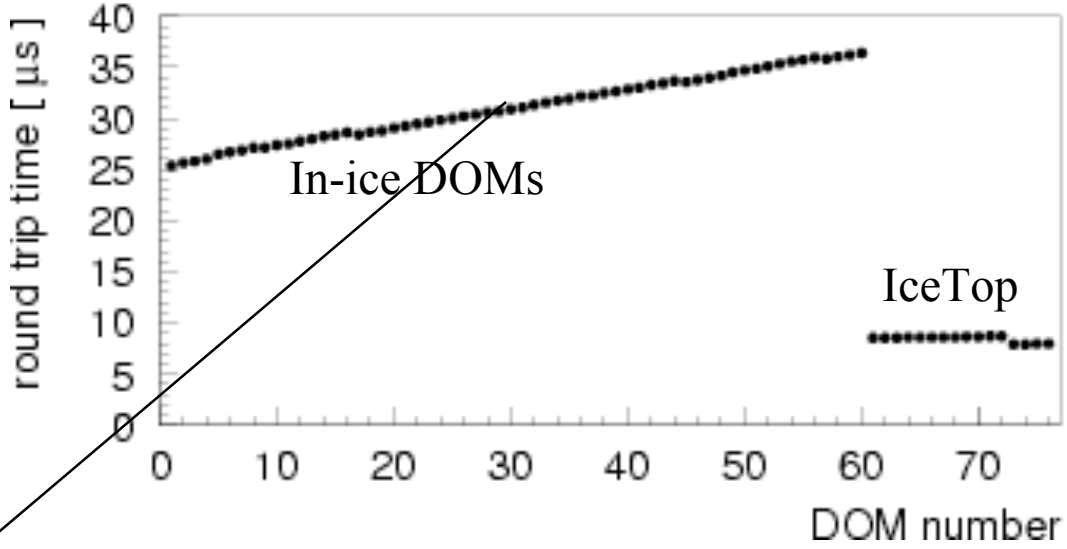
We were lucky!

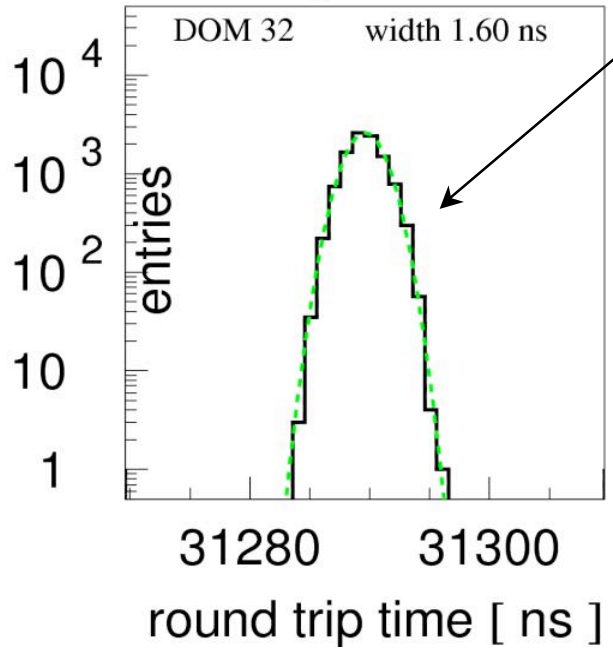
- Light travels more than 100 meters in the ultra-pure, sterile ice
- Scattering of the light is manageable
- We use the existing infrastructure of the National Science Foundation's South Pole Research Station
- Makes the construction of the ultimate kilometer-scale neutrino observatory

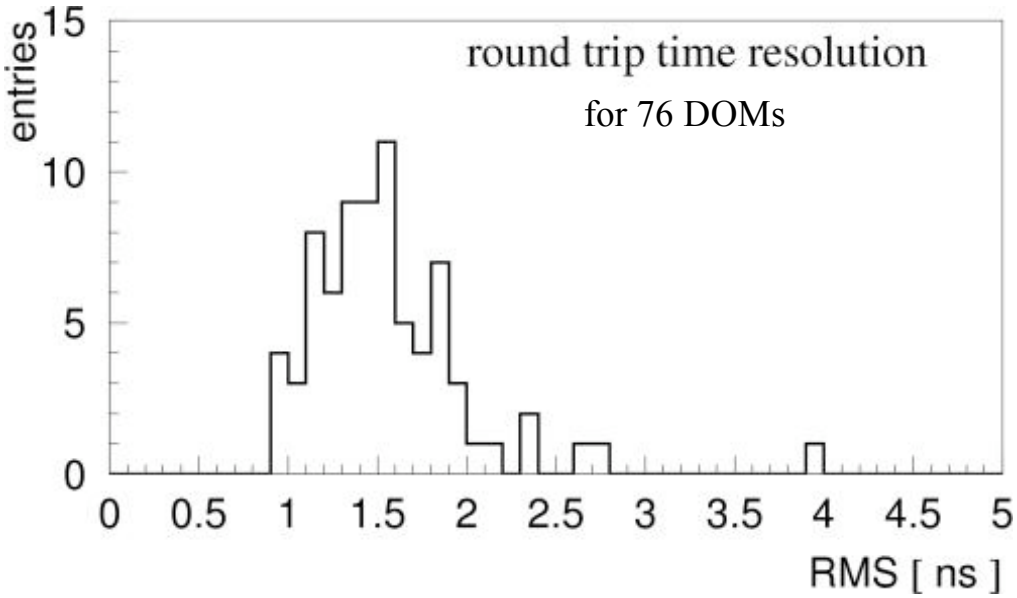
time calibration < 3 ns



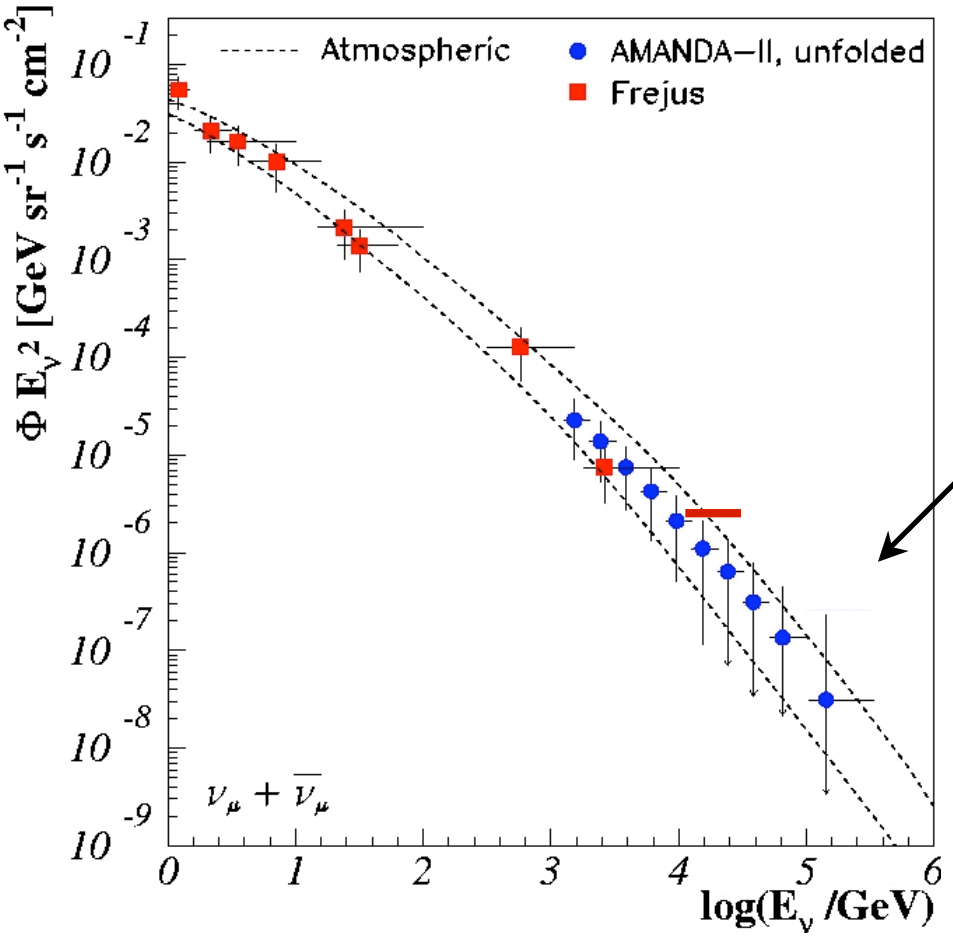
automatic, every few seconds







Atmospheric neutrinos

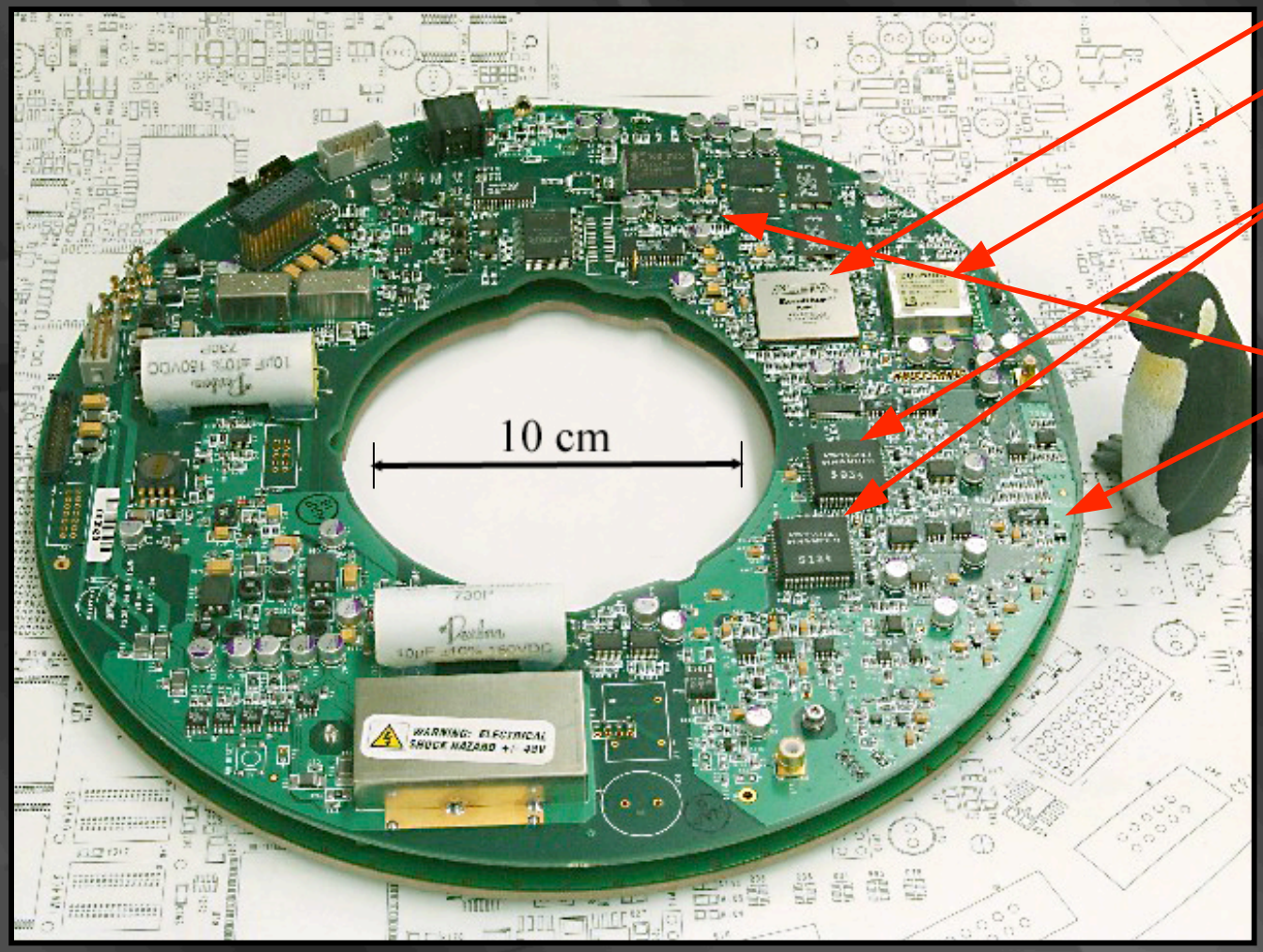


Limit on diffuse E^{-2} ν_μ flux (100-300 TeV):

$$E^2\Phi_{\nu_\mu}(E) < 2.6\cdot10^{-7}$$
$$\text{GeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

Includes 33% systematic uncertainty

Digital Optical Module Mainboard

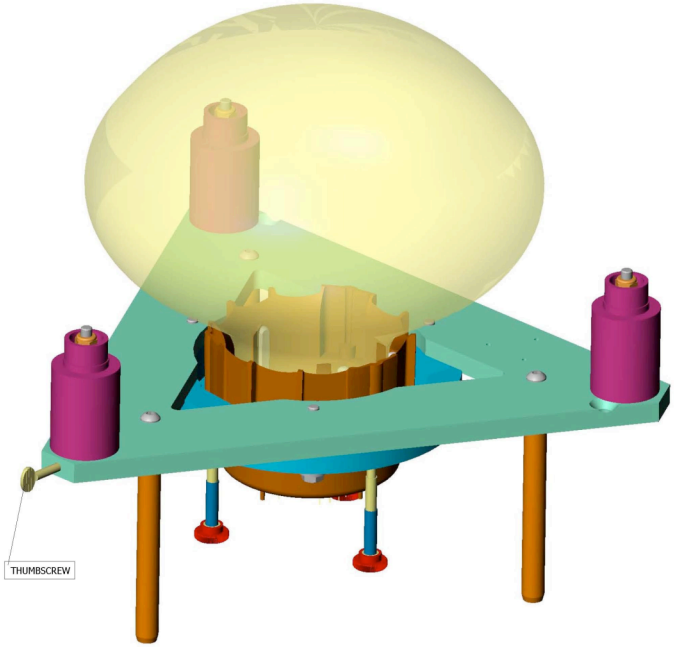


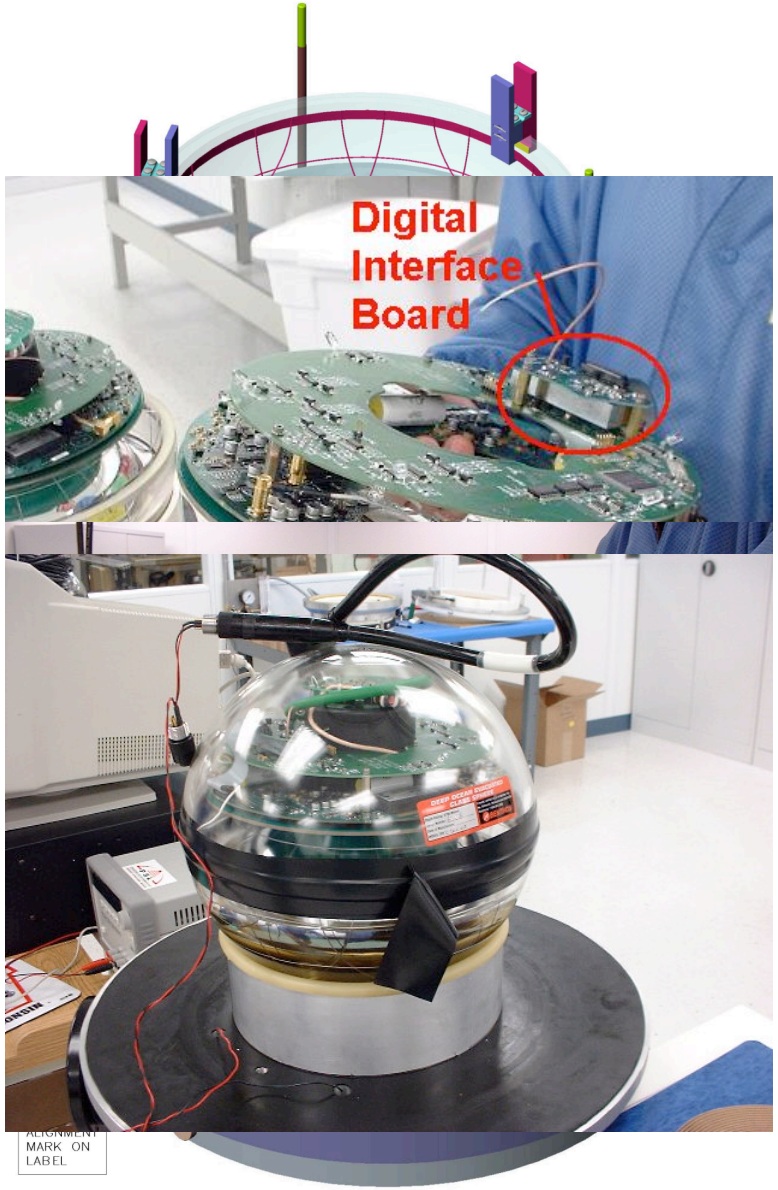
CPU+FPGA
20 MHz osc

2 ATWDs

Fast ADC:
waveform
and COMM

Mainboard design, fabrication and testing by
Lawrence Berkeley National Laboratory



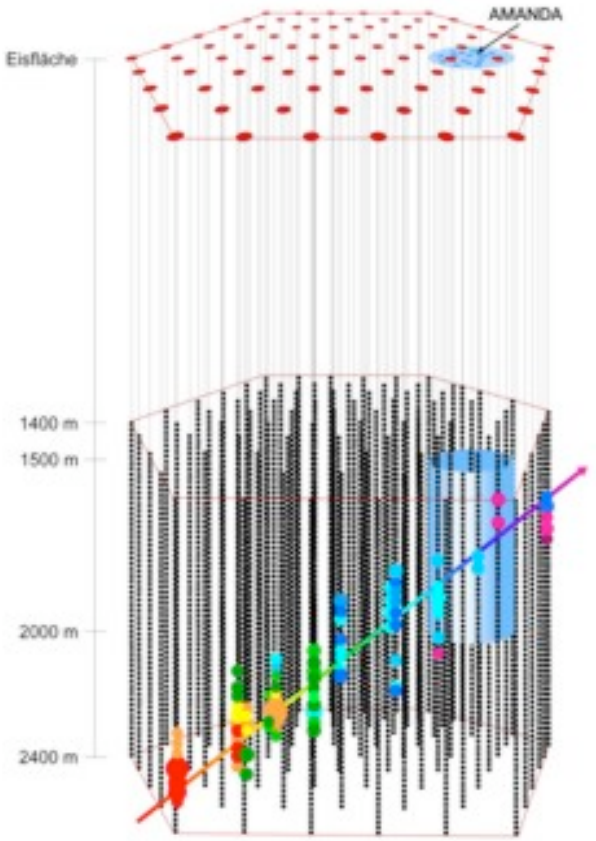


1. PMT prepared by gluing plastic collar to hold board s
2. E
gel – mechanical interface to PMT
3. I
p
4. E
5. T
r
6. S

DOMs Shipped to Pole

Year	# DOMs
2004	270
2005	701
2006	900

IceCube



• in the next 10 years IceCube will observe

~ 10^6 neutrinos with energies 0.1—1,000 TeV
~ 10 neutrinos with energy > 10^6 TeV

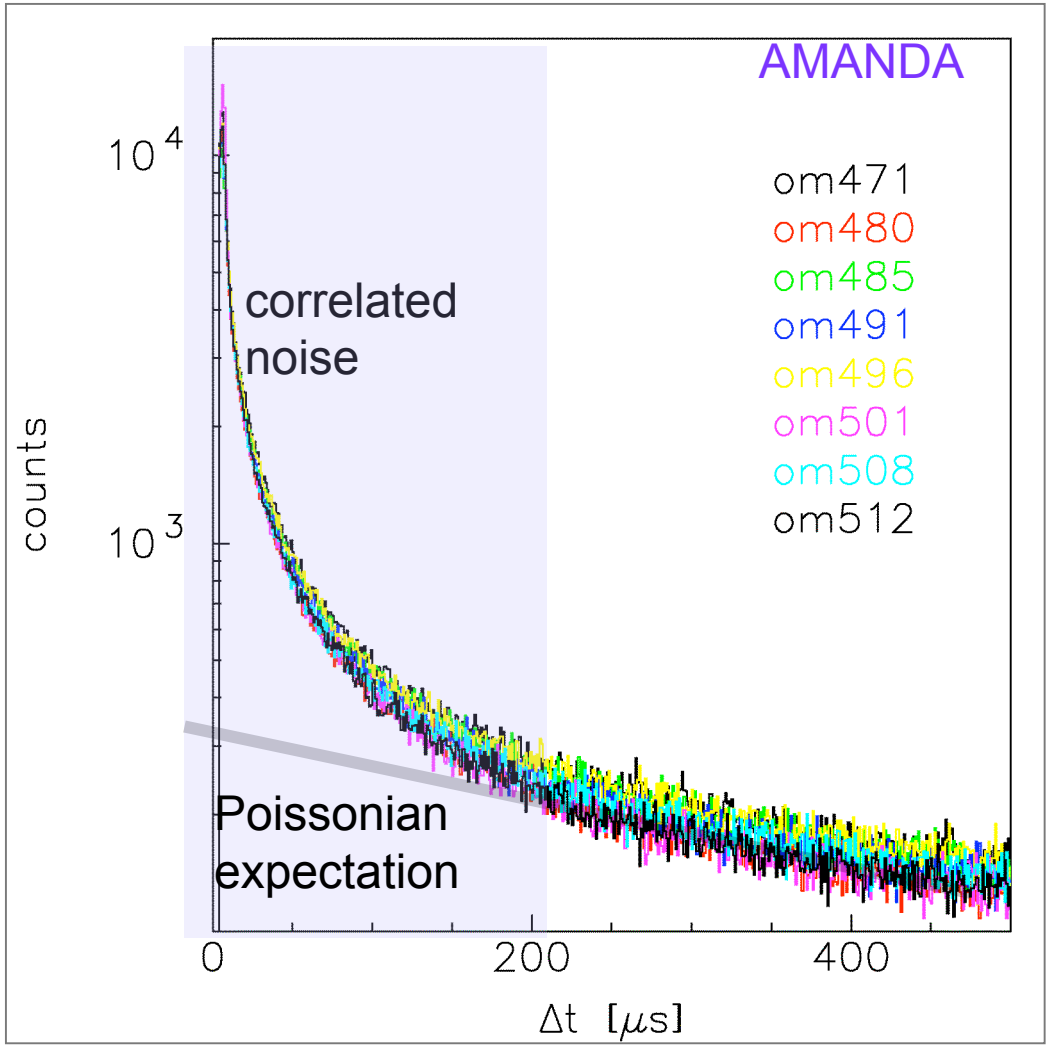
made in the interactions of cosmic rays with the Earth's atmosphere and microwave photons.

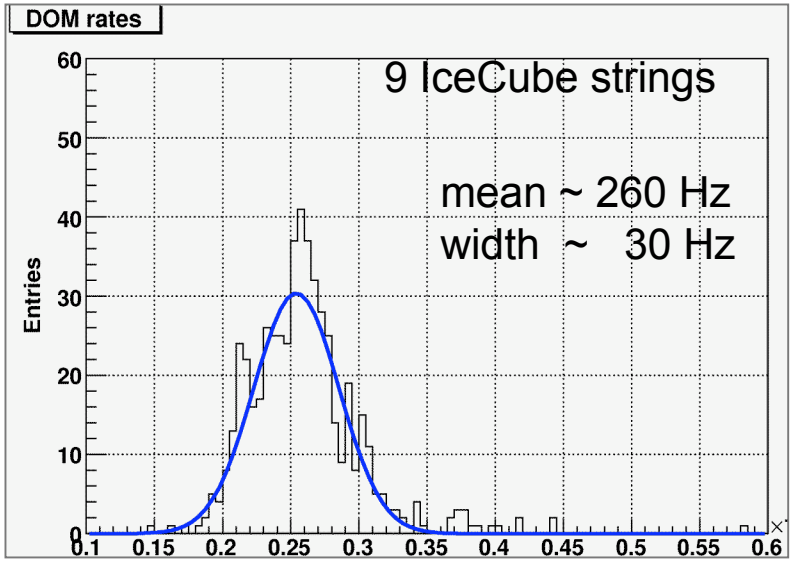
• with m~0.01 eV and E~100 TeV
the gamma factor of the neutrino is

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

DOM Noise

very low dark noise at low temperature



correlated noise due to radioactive decays producing fluorescence in glass

suppress with artificial deadtime O(200μs)