icebound neutrinos

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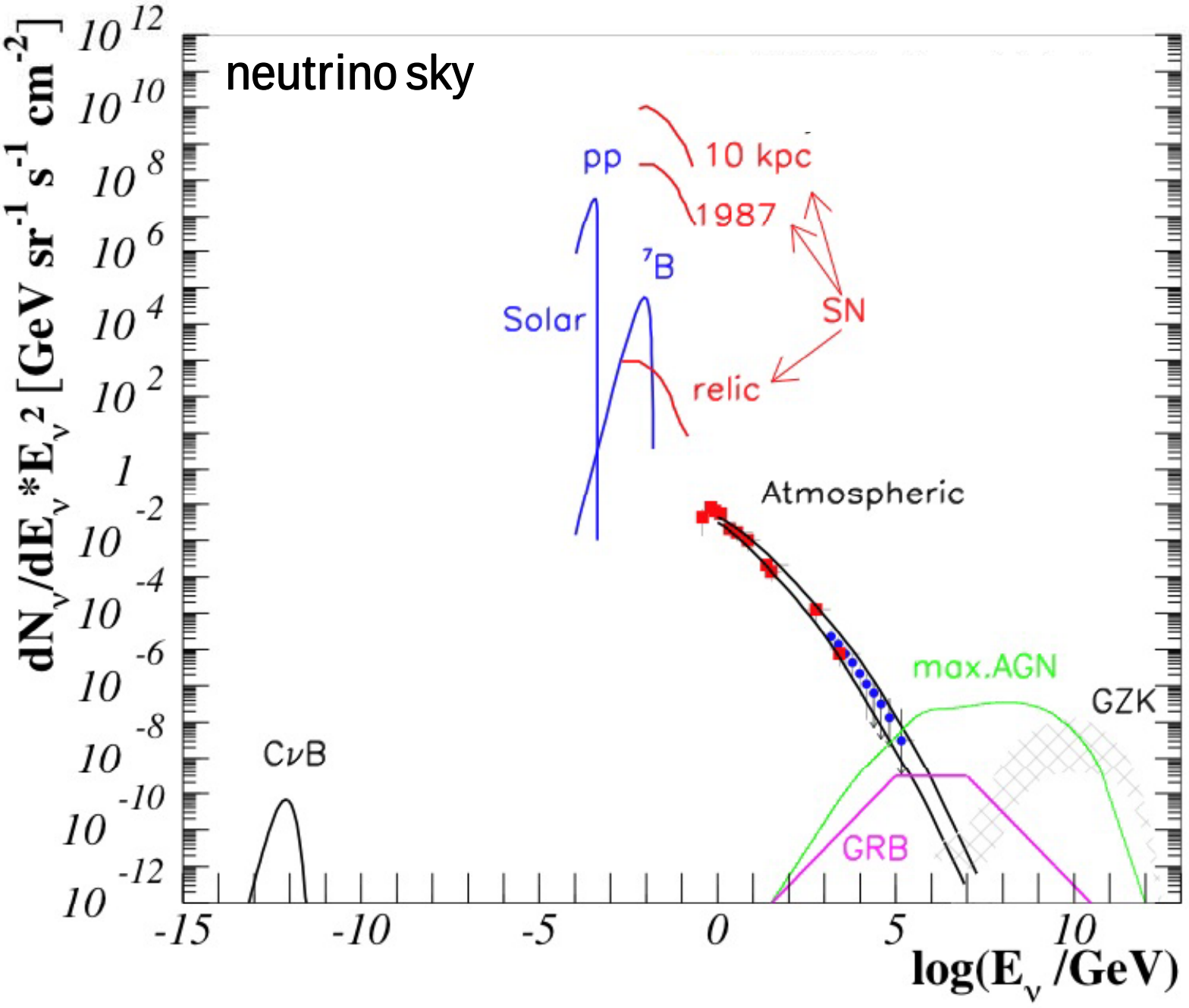
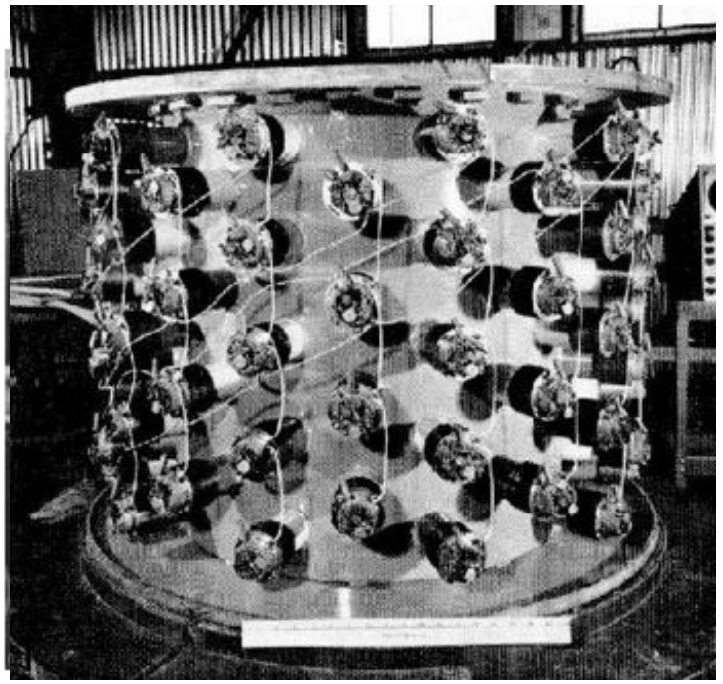
http://icecube.wisc.edu

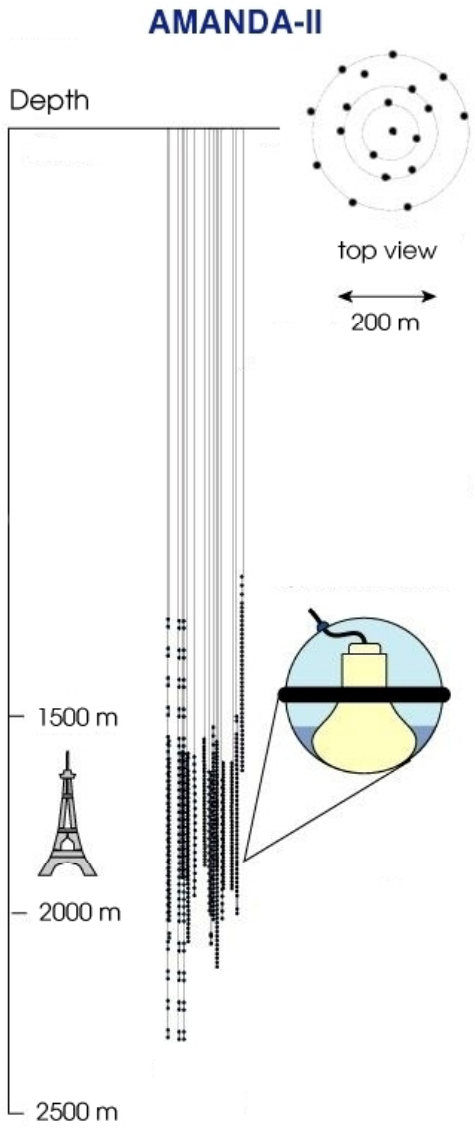
menu

- **it’s the technology!**
- **cosmic neutrinos associated with**
  - **Galactic cosmic rays**
  - **extragalactic cosmic rays**
- **particle physics with atmospheric and supernova neutrinos**
- **conclusions**


neutrino sky
pp
10 kpc
1987
SN
Solar
^{7}B
relic
Atmospheric
max.AGN
GZK
GRB
CνB
$dN_\nu/dE_\nu * E_\nu^2$ [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)

Requires Kilometer-Scale Neutrino Detectors



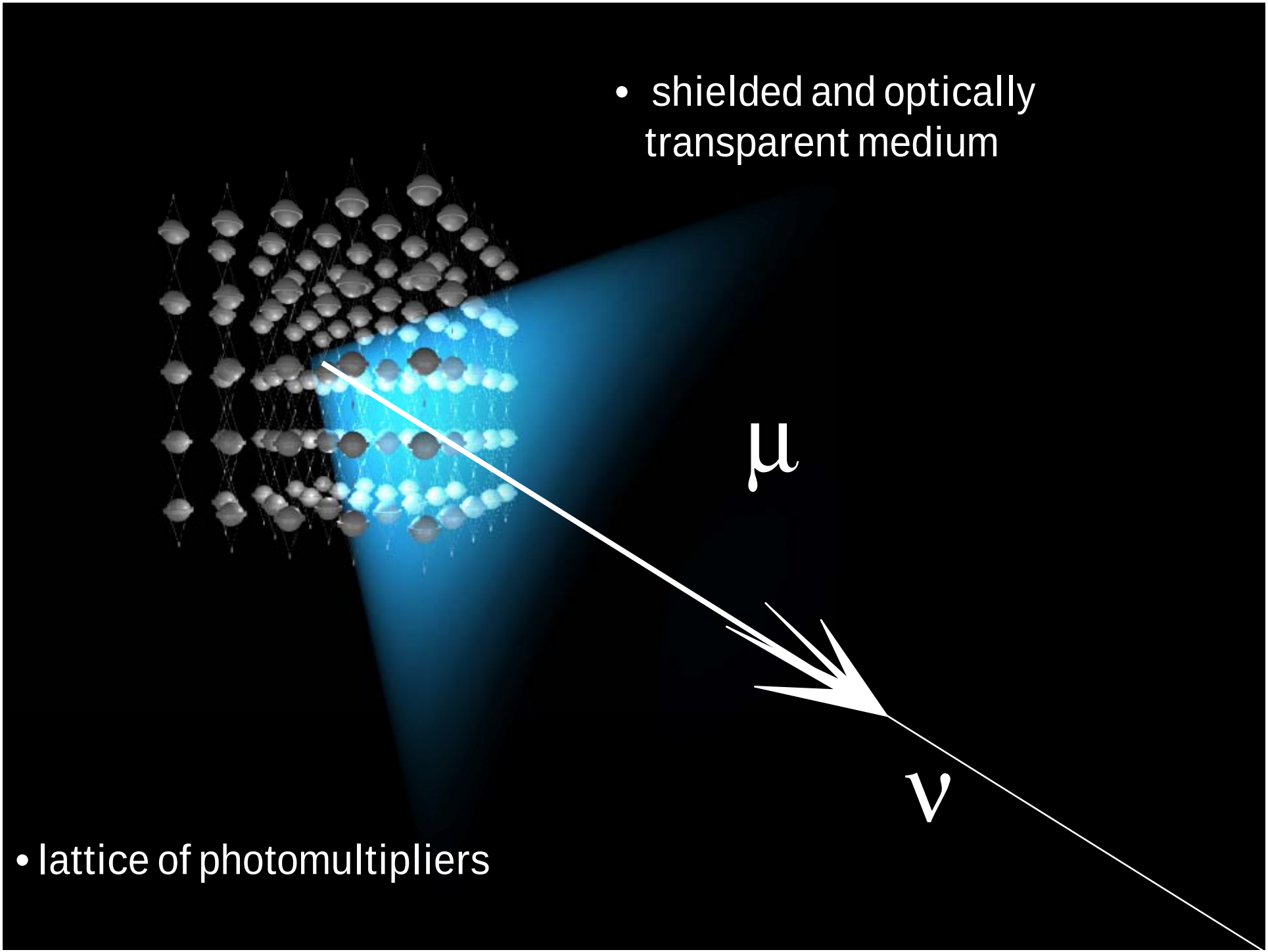


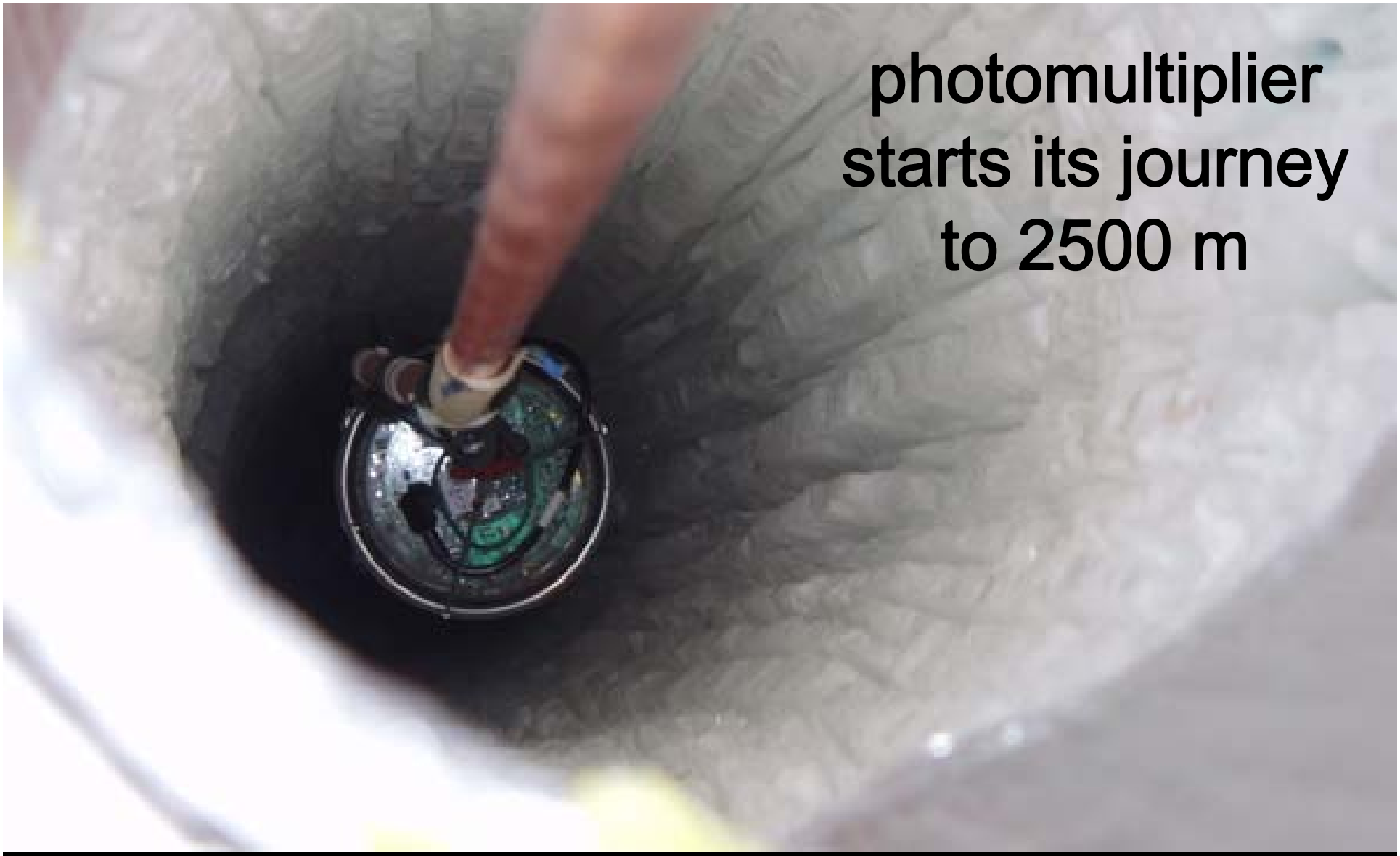
ANTARES

completed

1.3 neutrinos/day

with 5 strings


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

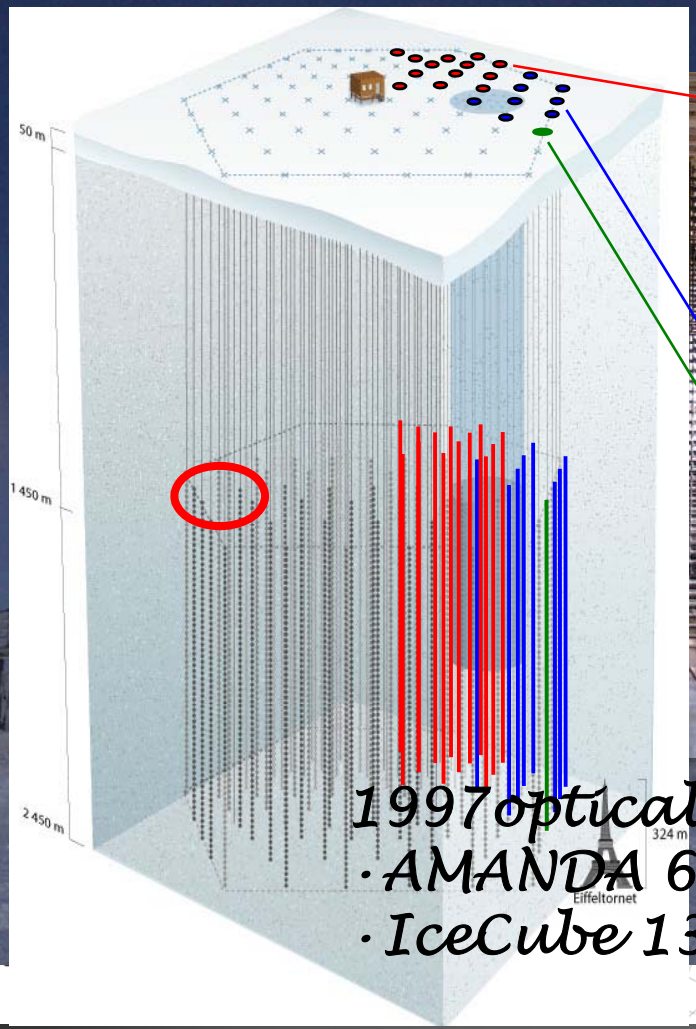


IceCube will transform a billion tons of ice into a particle physics detector with 4800 photomultipliers

second generation detectors : IceCube

Compl…uary 2007

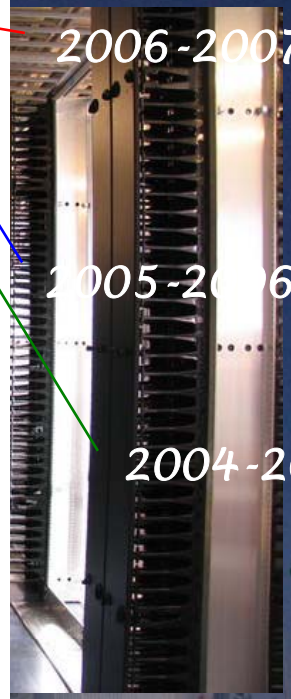
- 80 strings
  60 modules
each
- 17m between modules
- 125m between strings
- 1 km³ ; ~1GTon



2006-2007: 13 strings

2005-2006: 8 strings

2004-2005 : 1 string



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

2007-2008:
18 strings

2006-2007:
13 Strings

2005-2006: 8 Strings

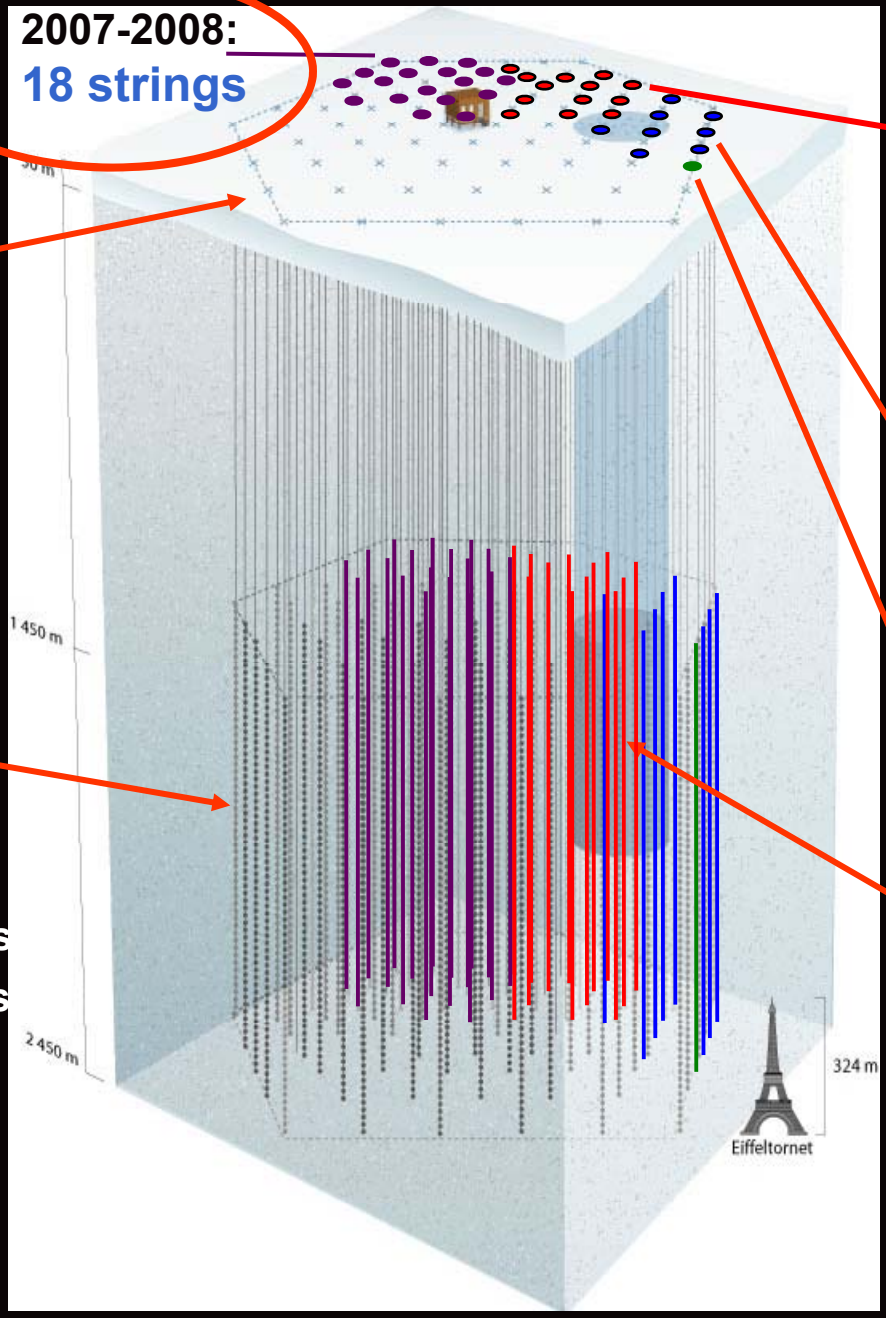
2004-2005 : 1 String

IceTop

Air shower detetor
threshold ~ 300 TeV

InIce

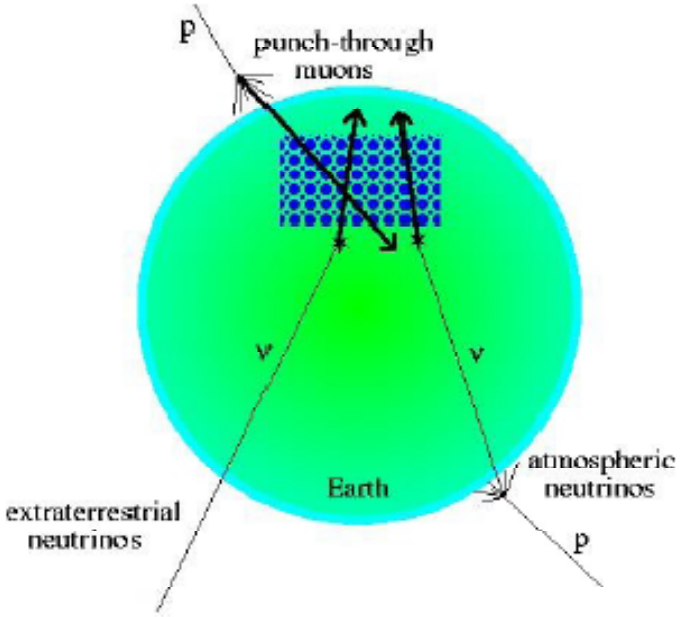
70-80 Strings ,
60 Optical Modules
17 m between Modules
125 m between Strings



AMANDA

19 Strings
677 Modules

the challenge: reject background of downgoing muons

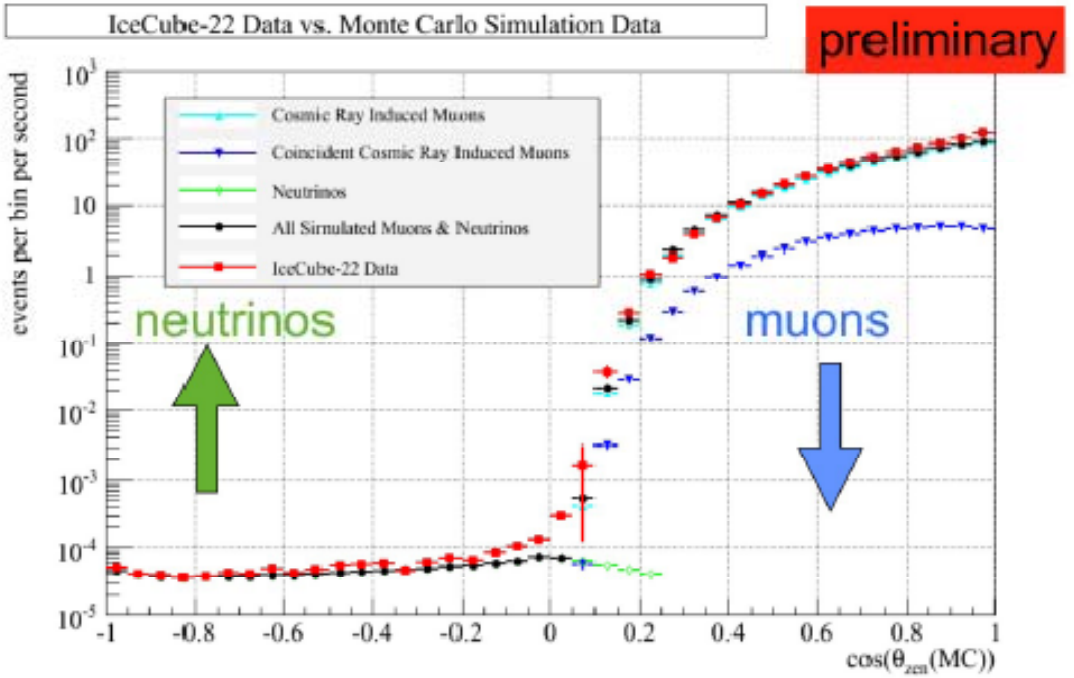


Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40*	1200 Hz	110 / day
IC80*	1650 Hz	220 / day

AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr

Step 1: Remove background of downgoing muons

Step 2: Isolate extraterrestrial events from "irreducible" background of atmospheric neutrinos

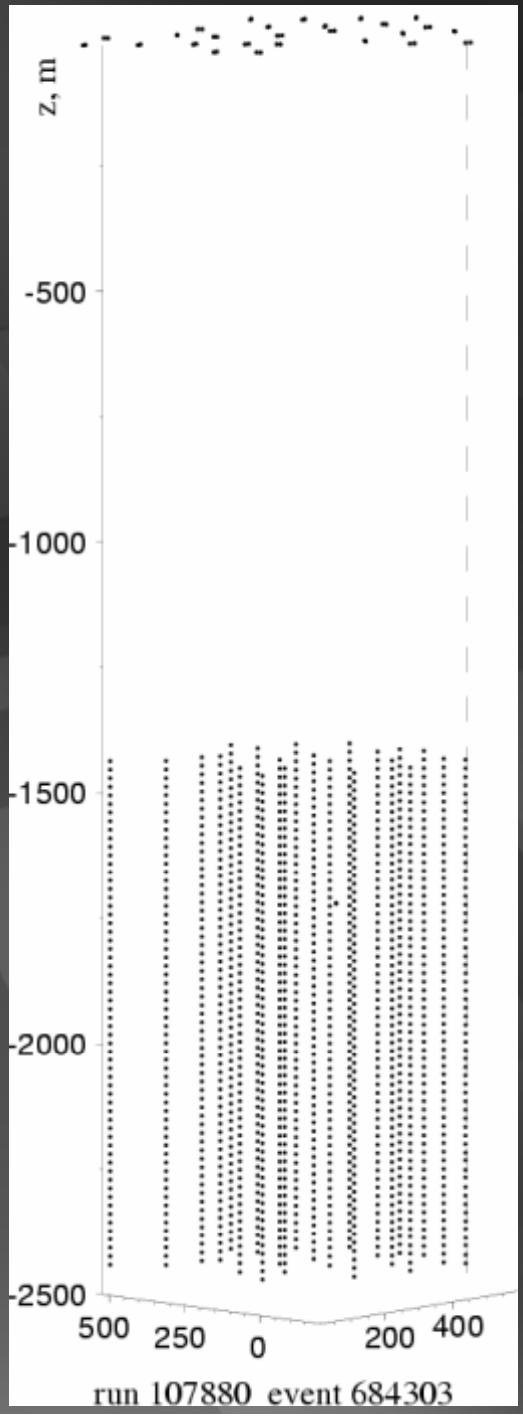


background:
downgoing cosmic ray muons

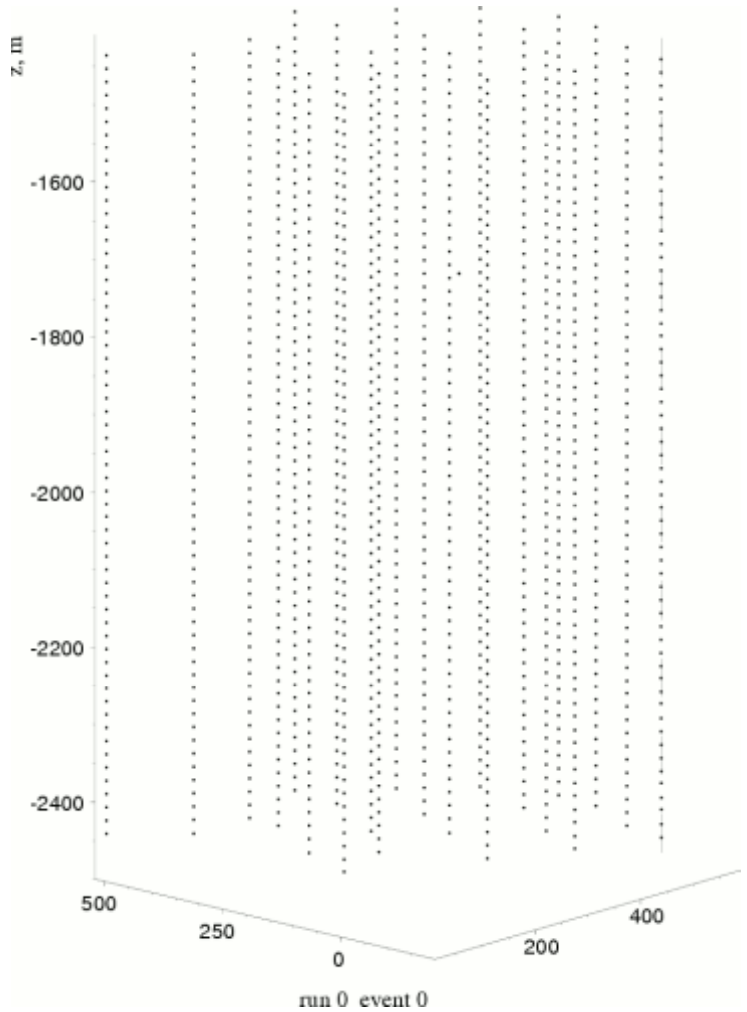
~ 1500 per second

signal:
upgoing muons initiated by neutrinos

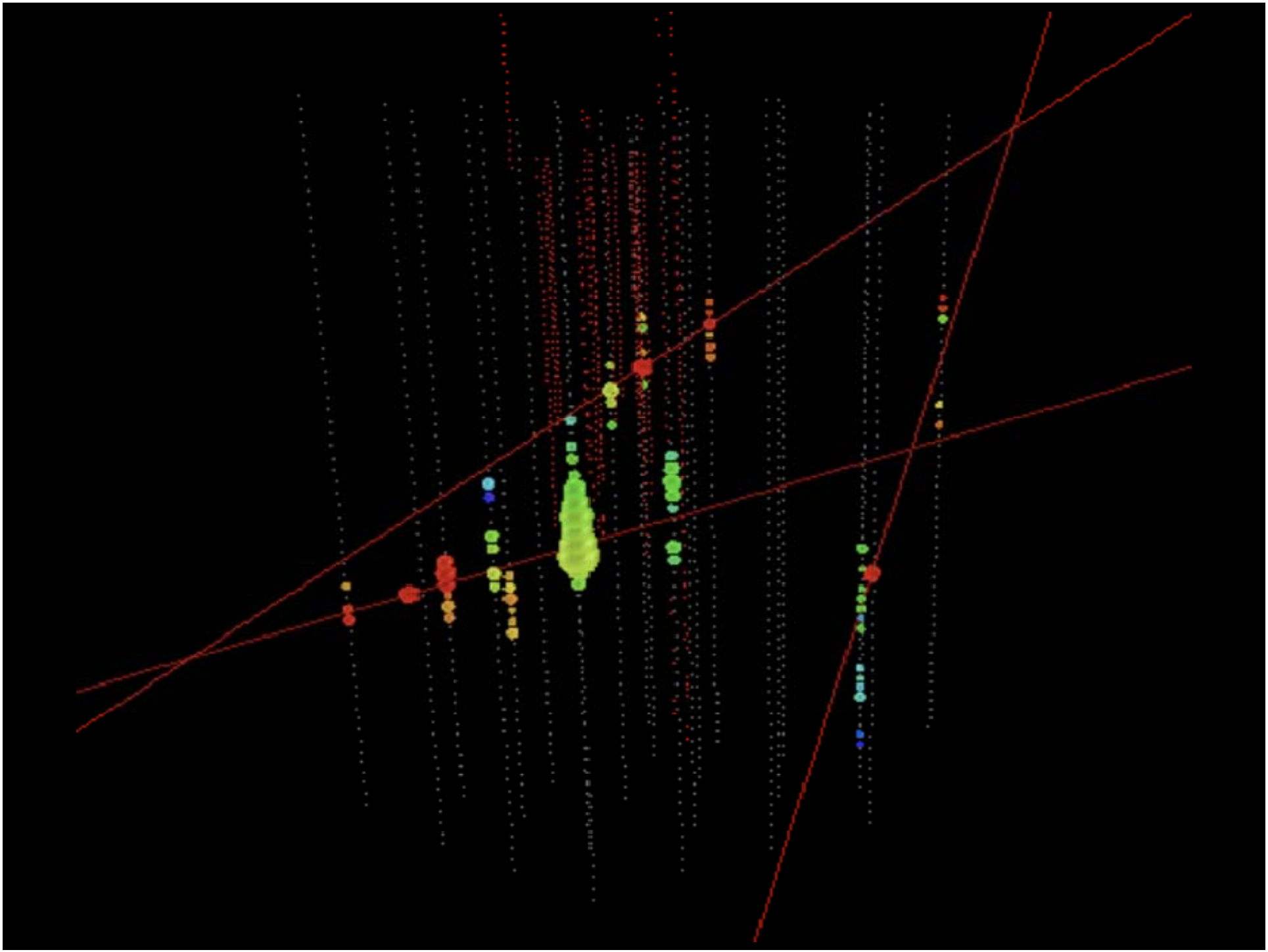
~ 240 per day



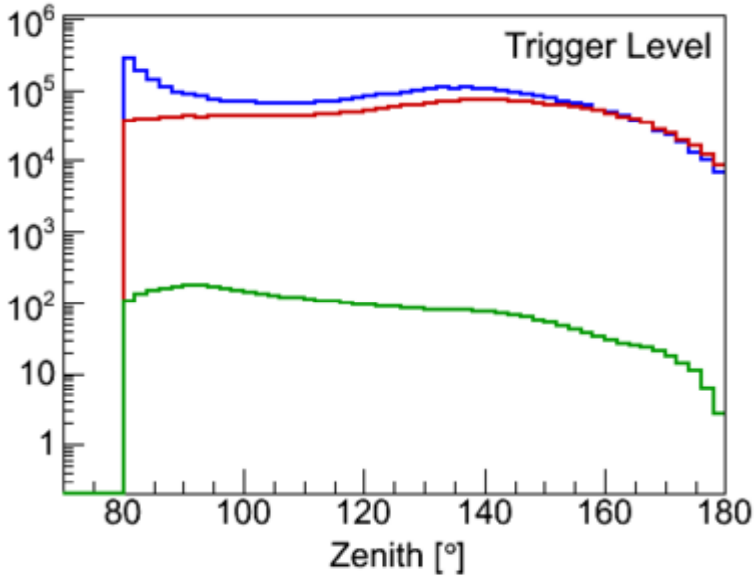
1500 Hz: only one in 10^6 muon tracks is produced by a neutrino

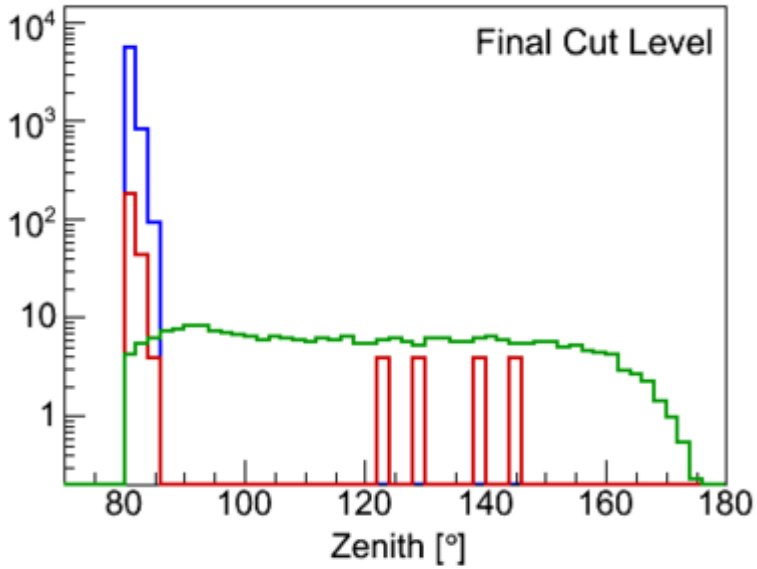


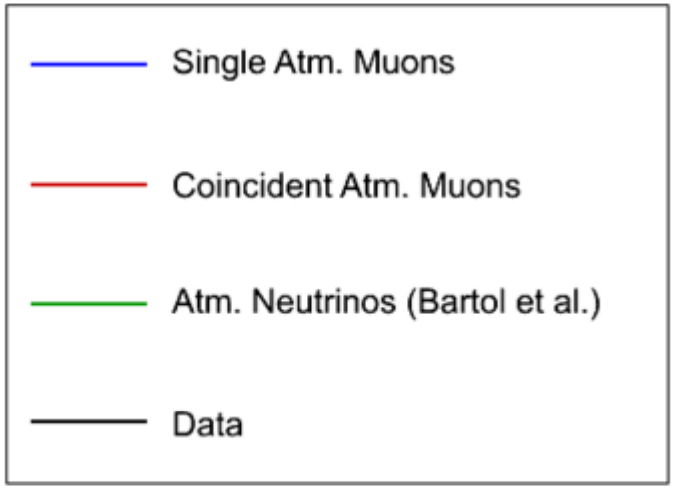
IceCube 22

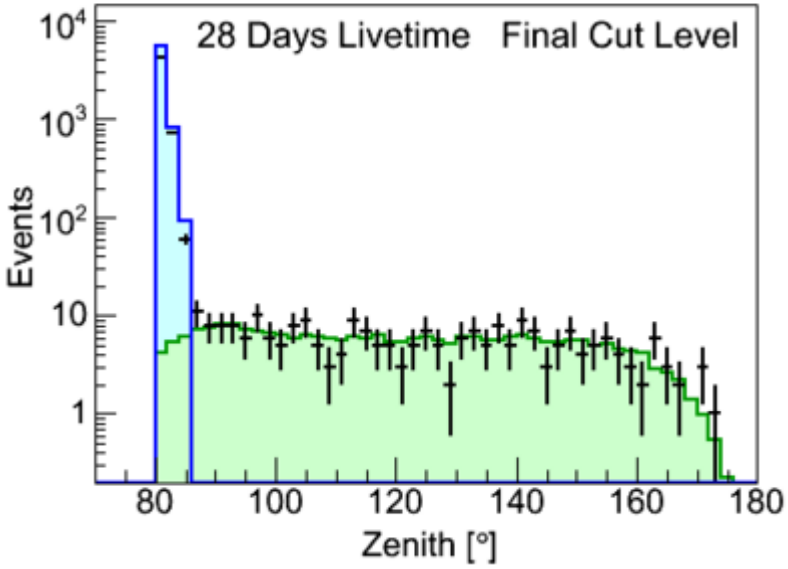


IceCube (1/2) turns the corner at the horizon

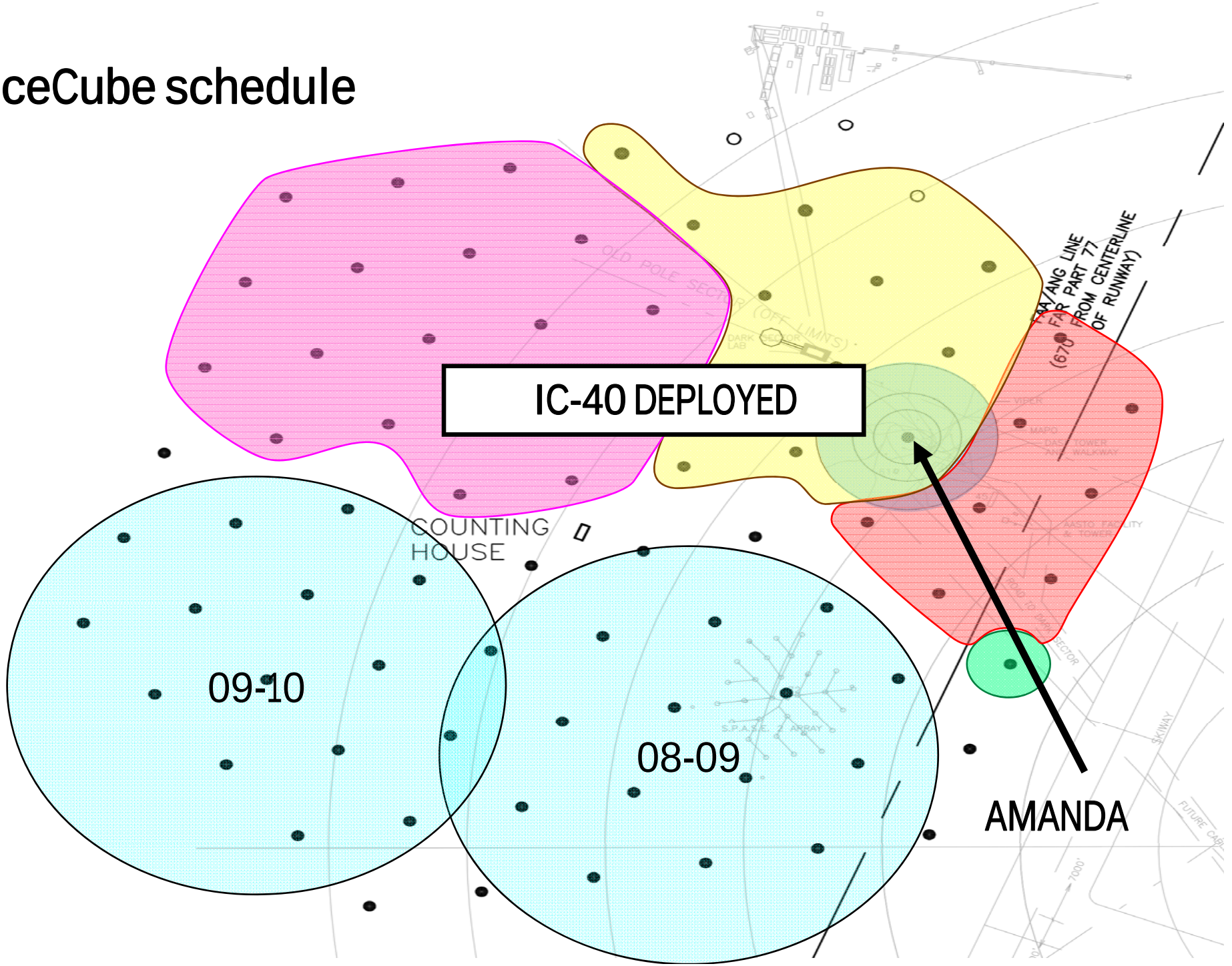




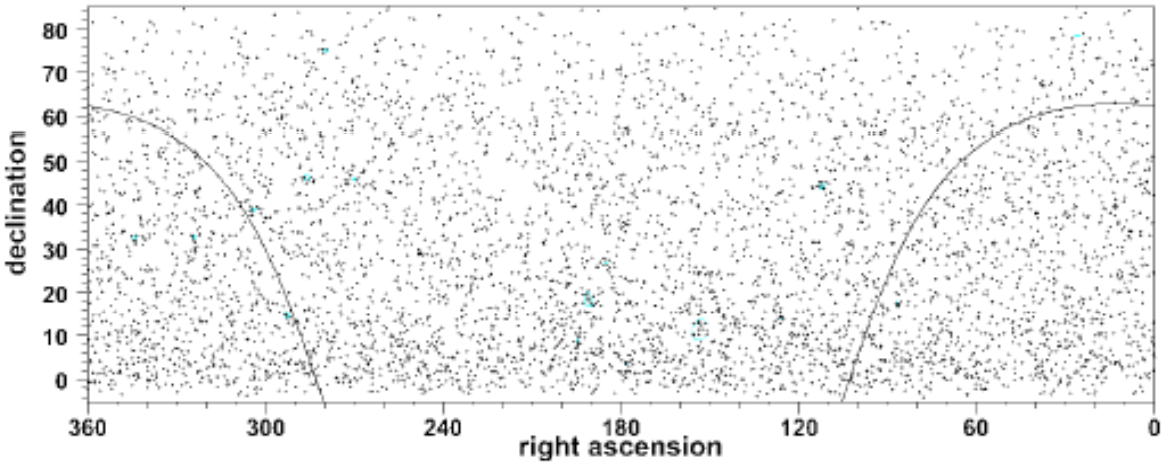




IceCube schedule



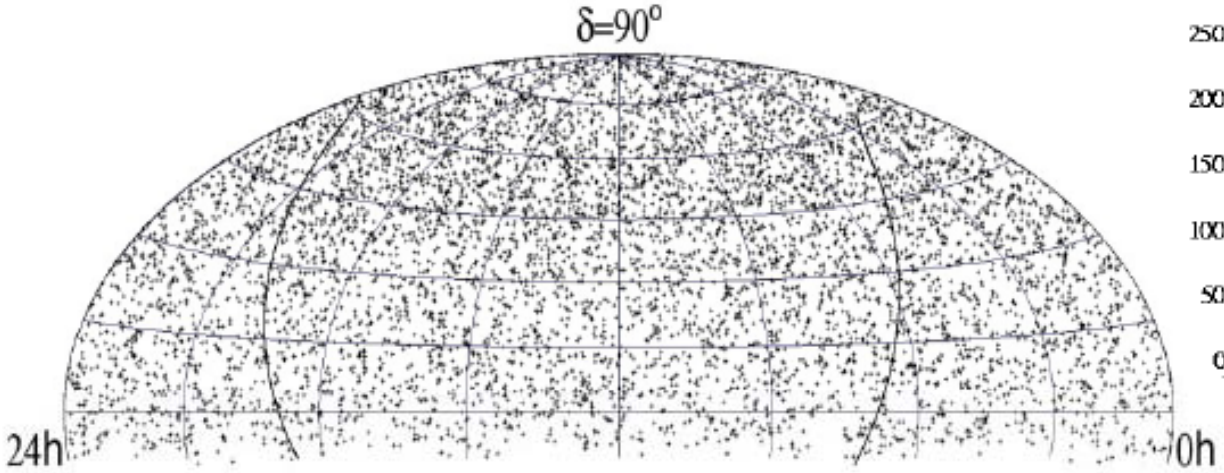
neutrinos: IceCube 22 > AMANDA (3.8 years)

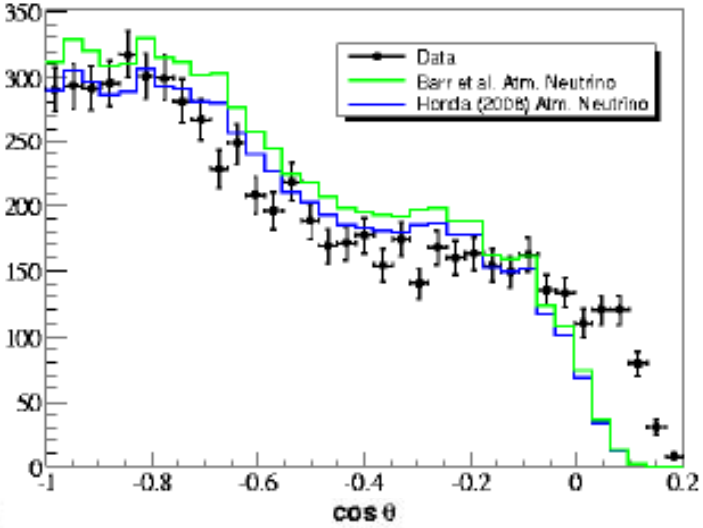


IceCube 22 String:

5114 neutrino candidates
in 276 days livetime

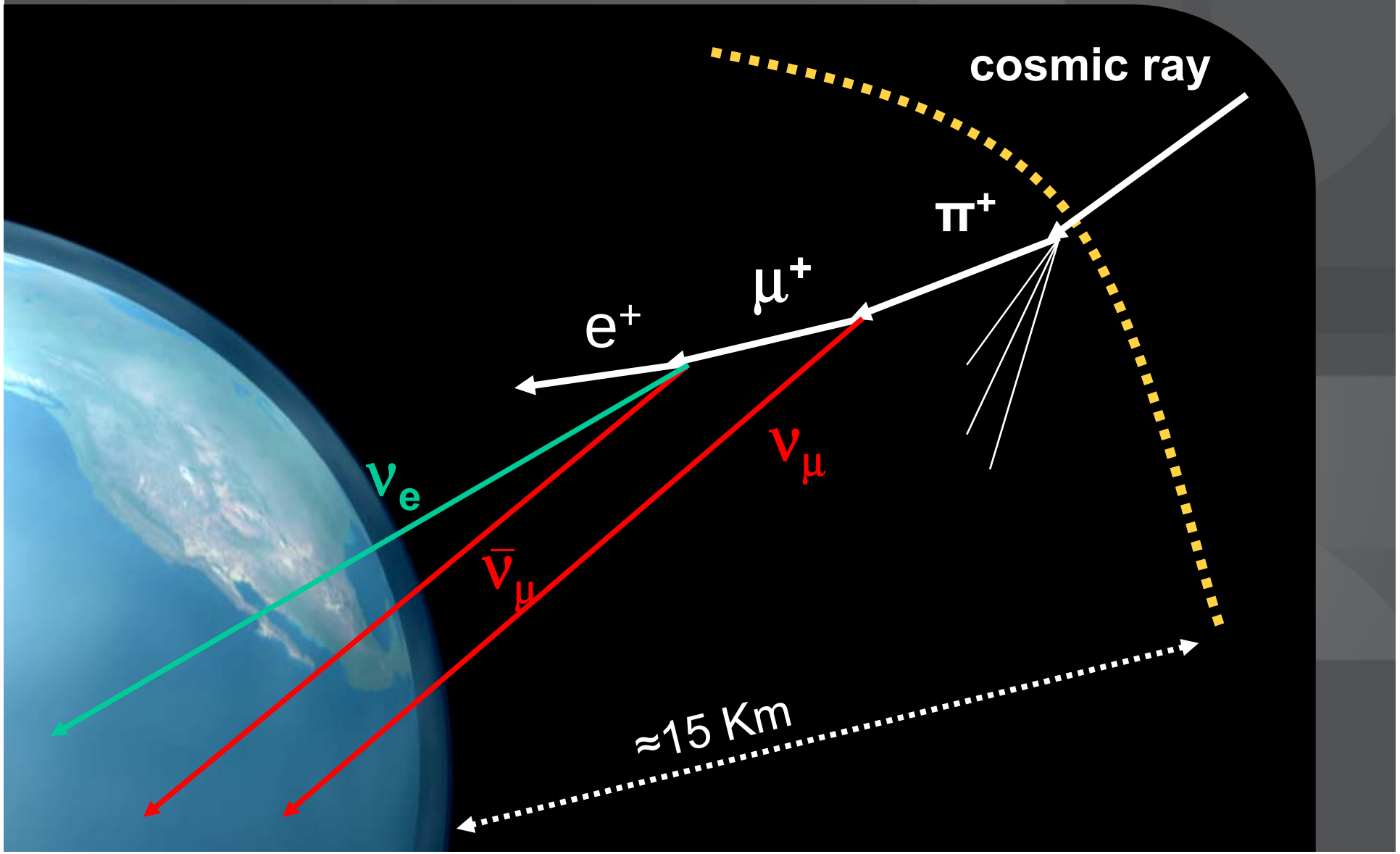
AMANDA: 6595 ν candidates in 3.8 live-years



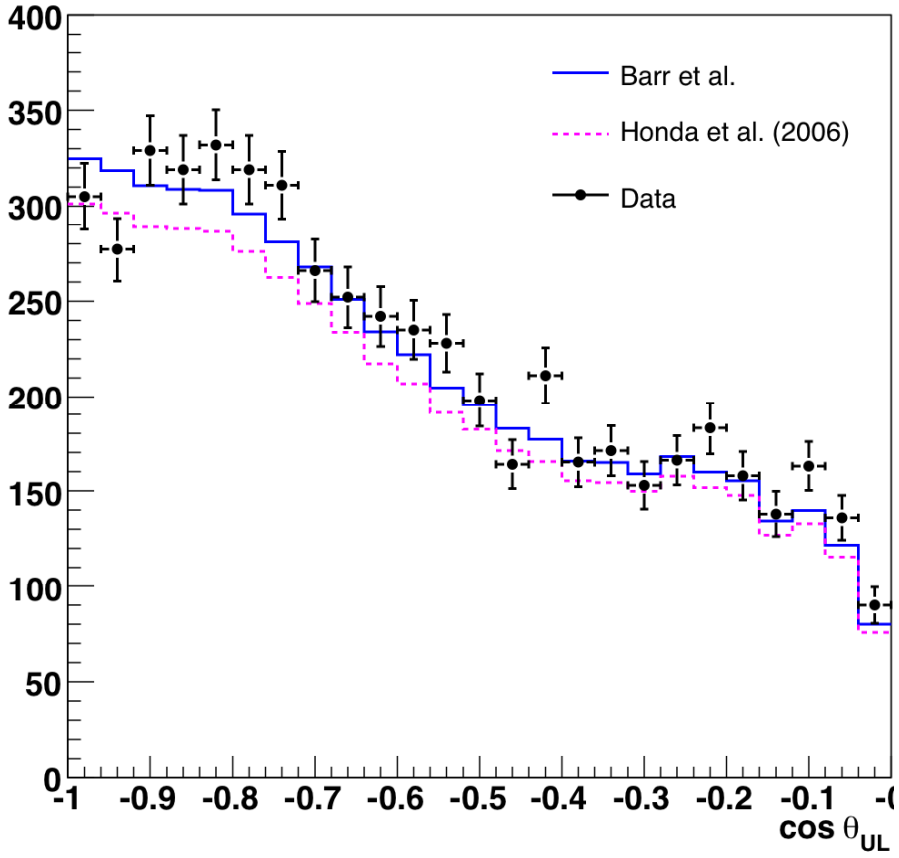


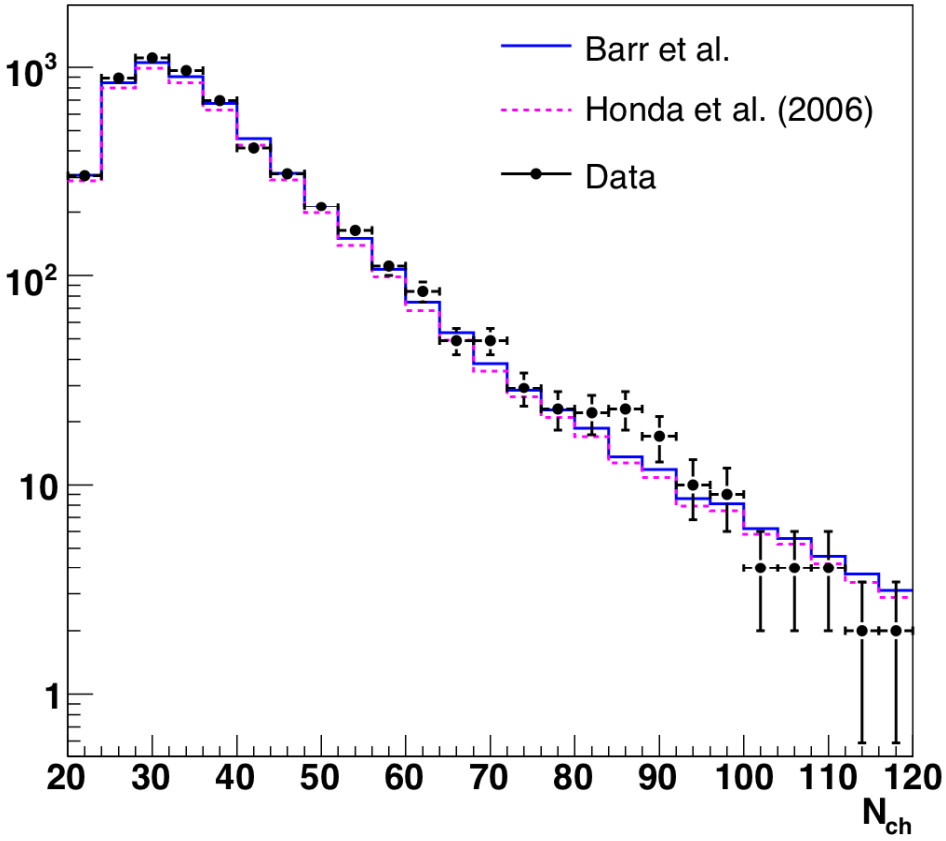
AMANDA: proof of concept

atmospheric neutrinos : science/calibration



atmospheric neutrino spectrum

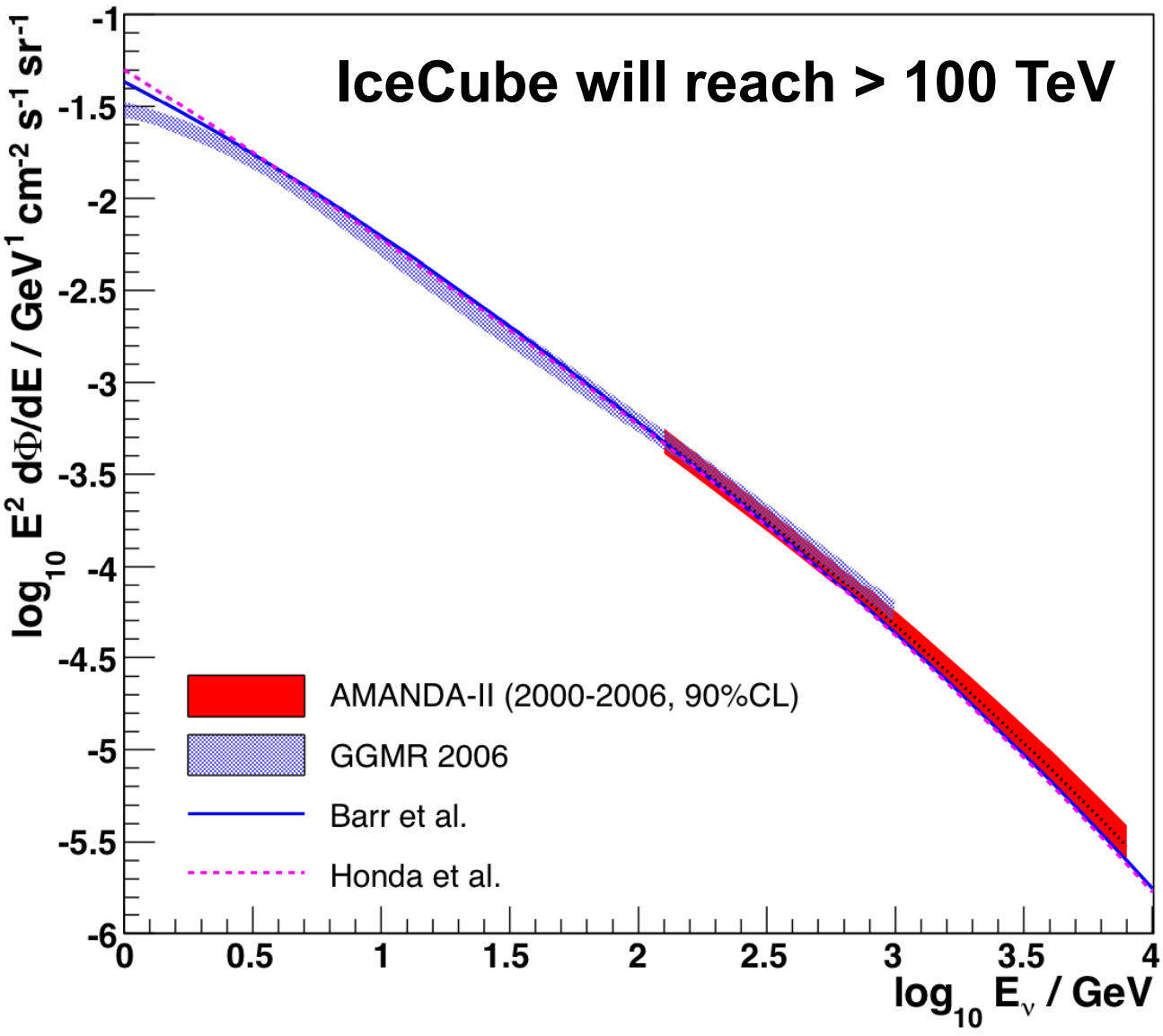




zenith angle

number of PMT

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



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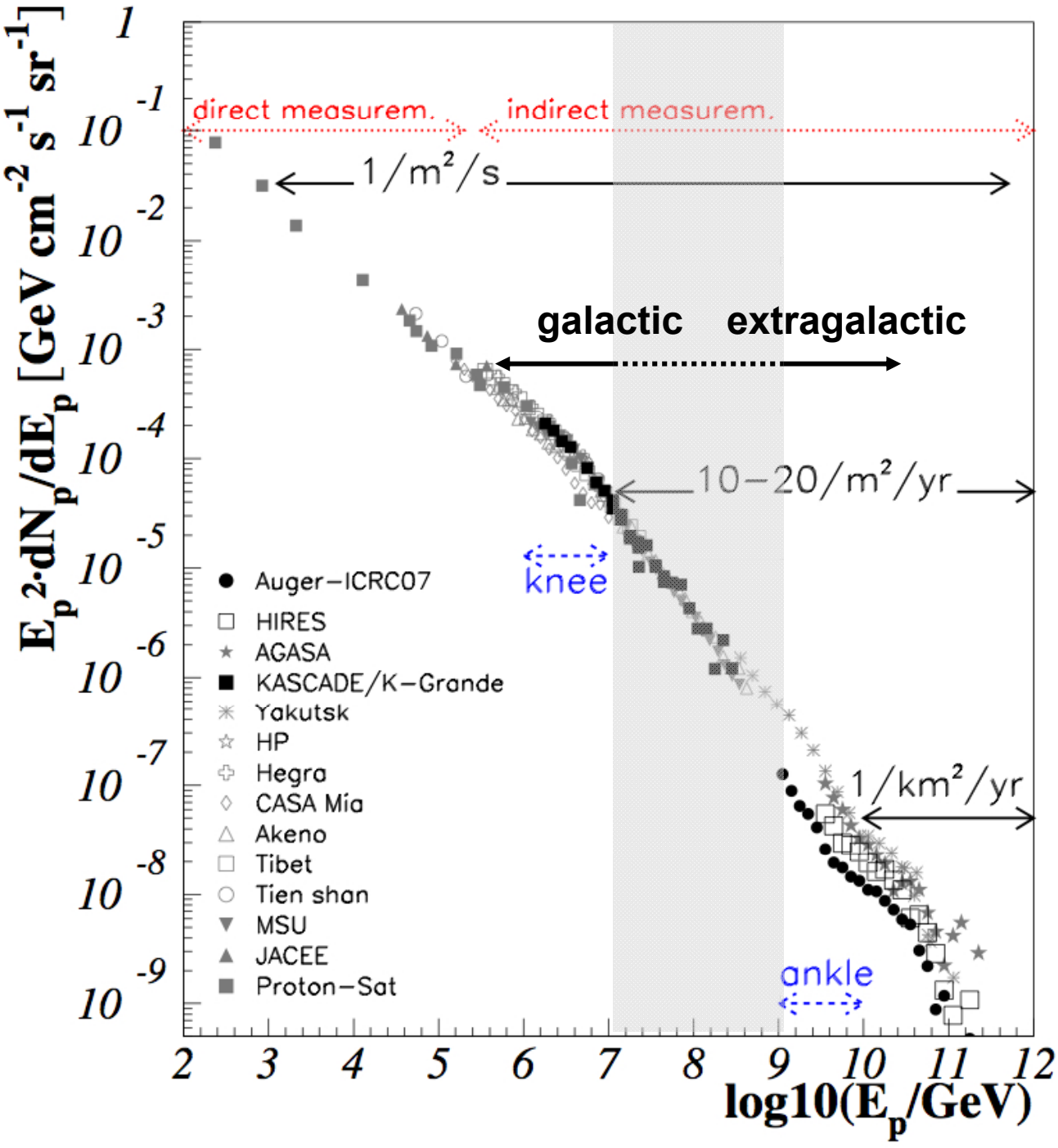
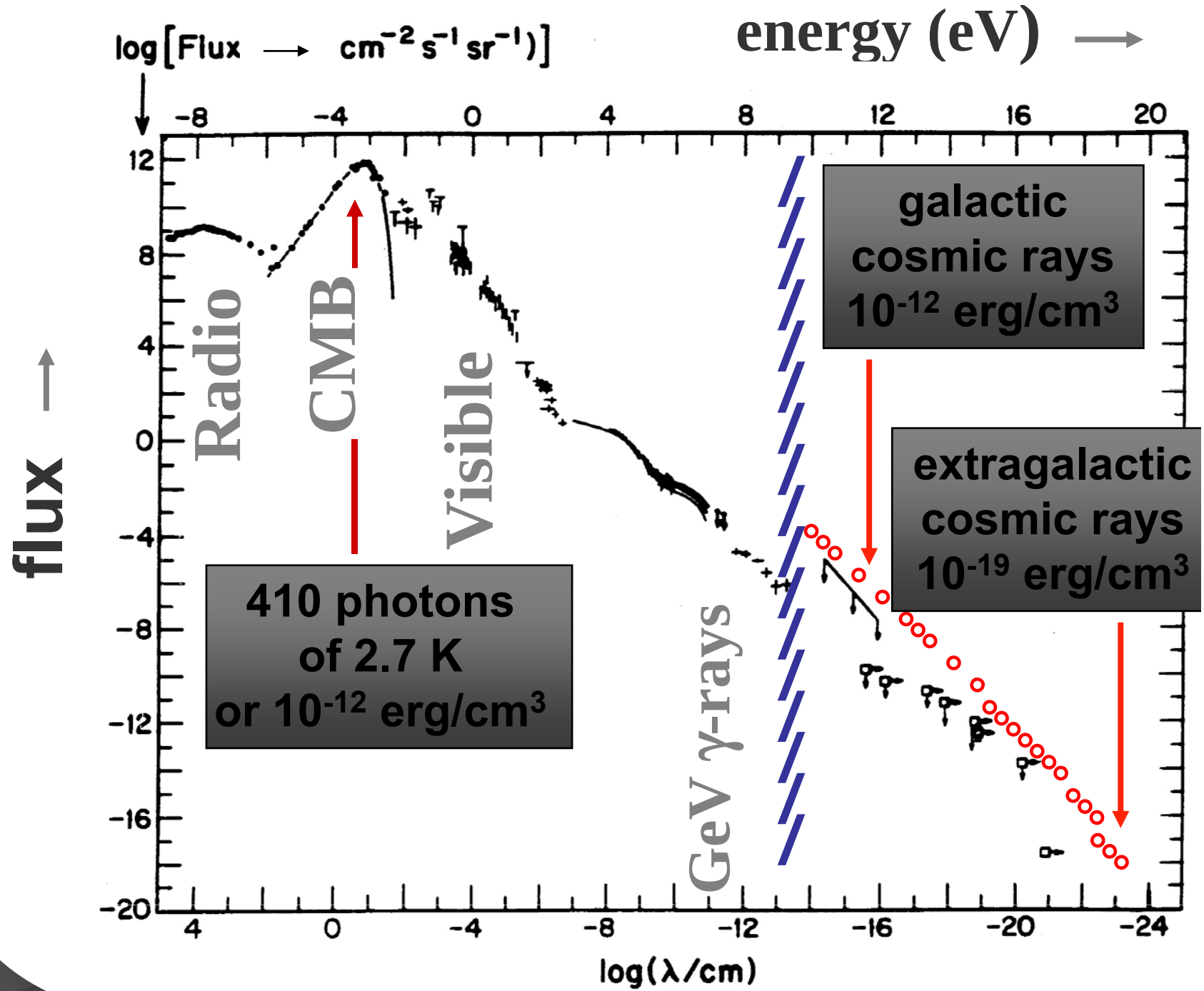
galactic and extragalactic cosmic rays




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

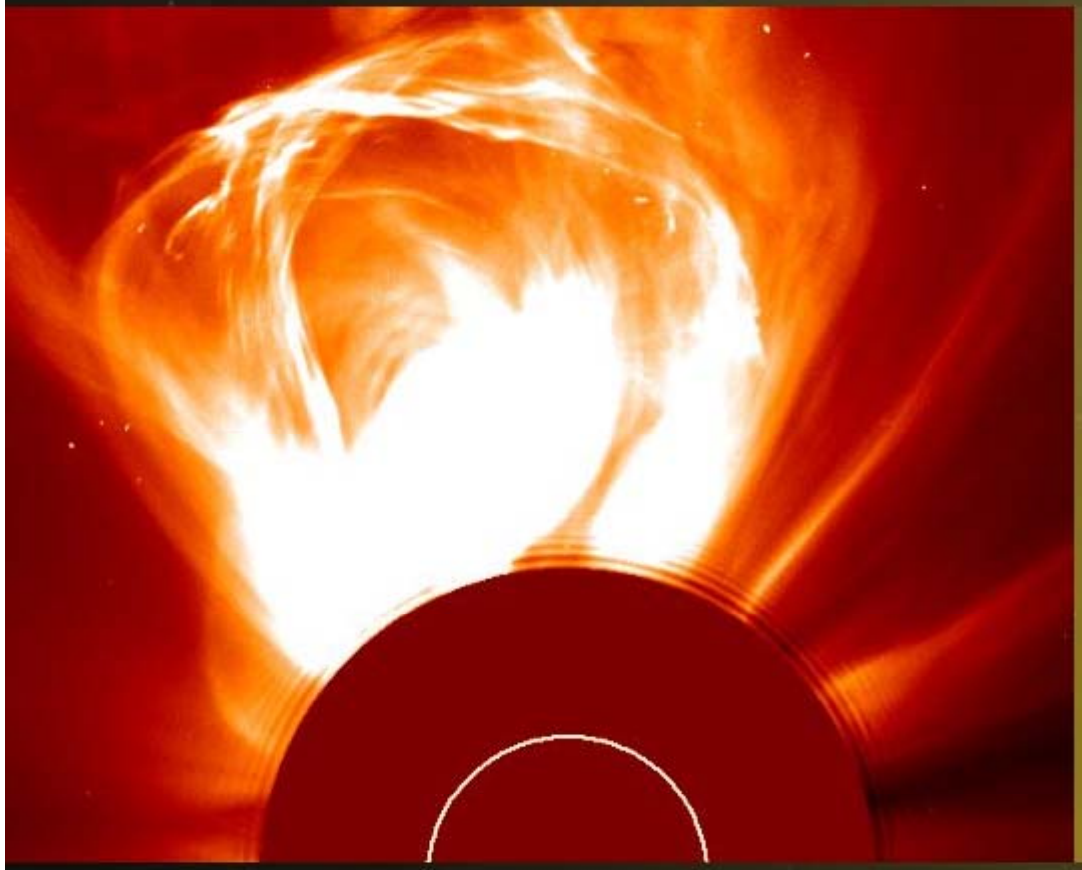
total flux = velocity x density :

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

it's the energy density,
not the particle flux !

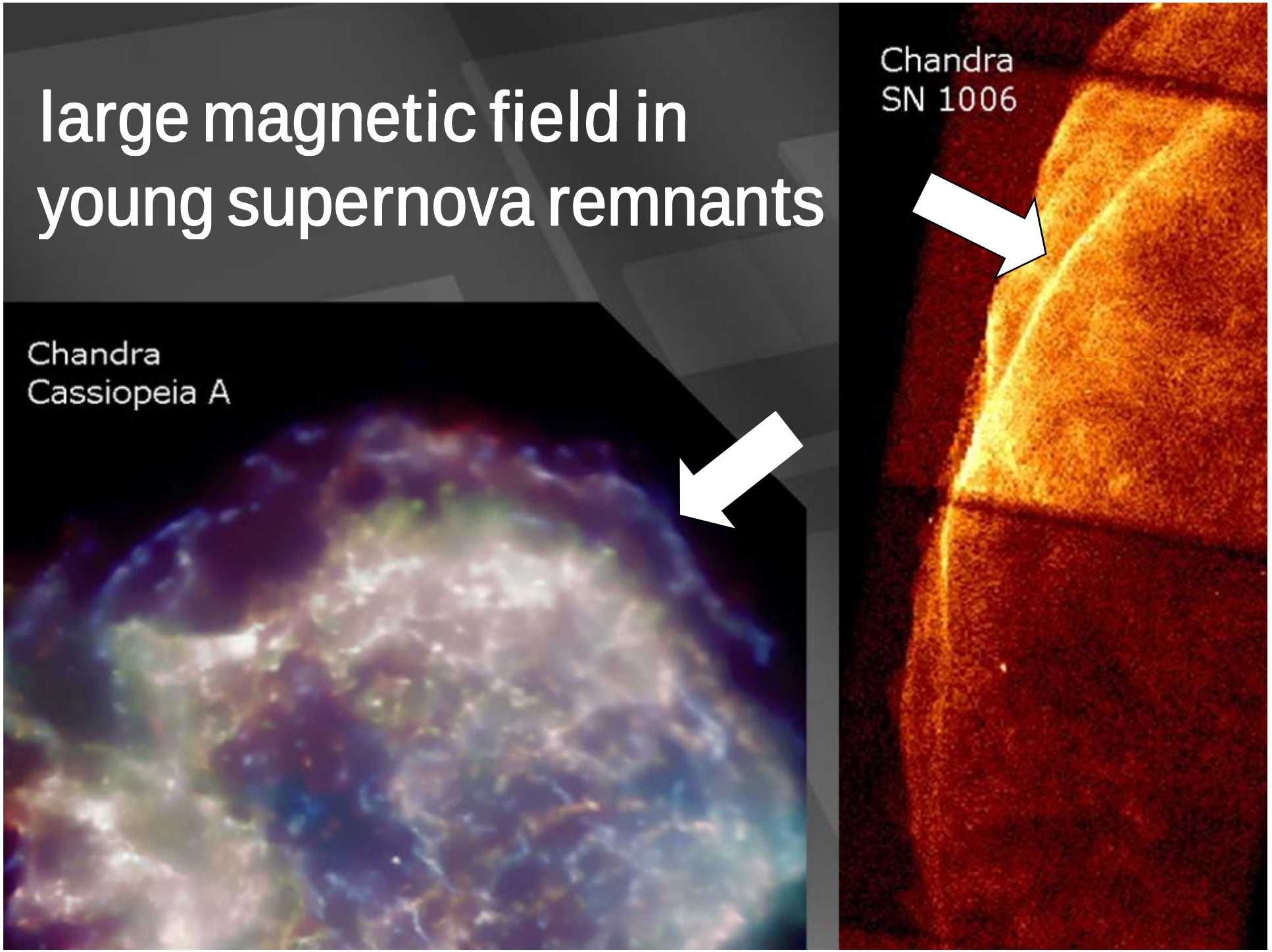
galactic galactic cosmic rays

shock acceleration (solar flare)

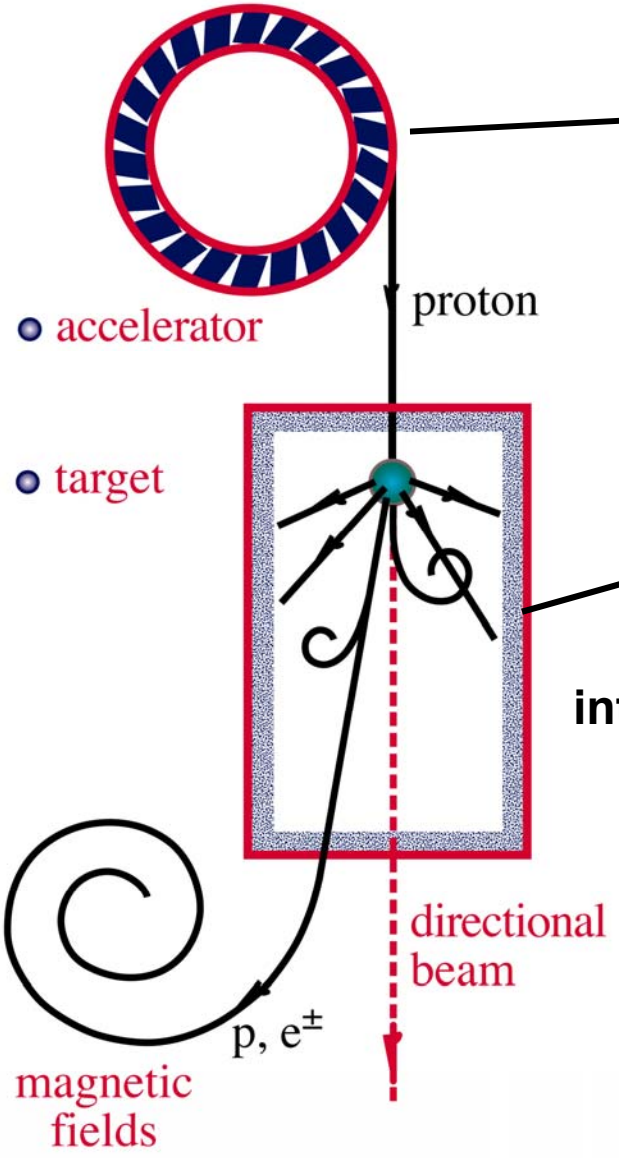


coronal
mass
ejection
→
10 GeV
particles

large magnetic field in young supernova remnants

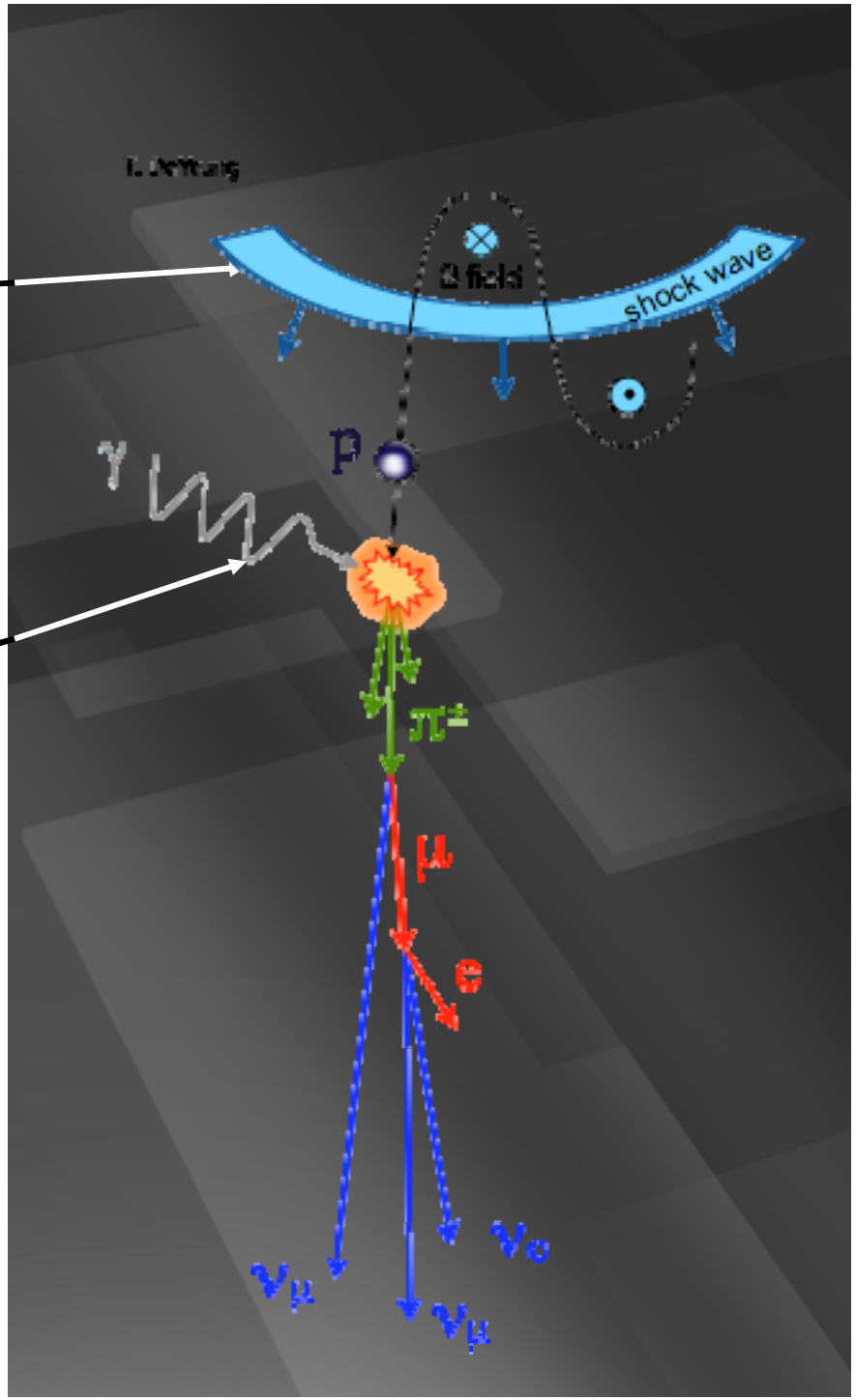


ν and γ beams : heaven and earth

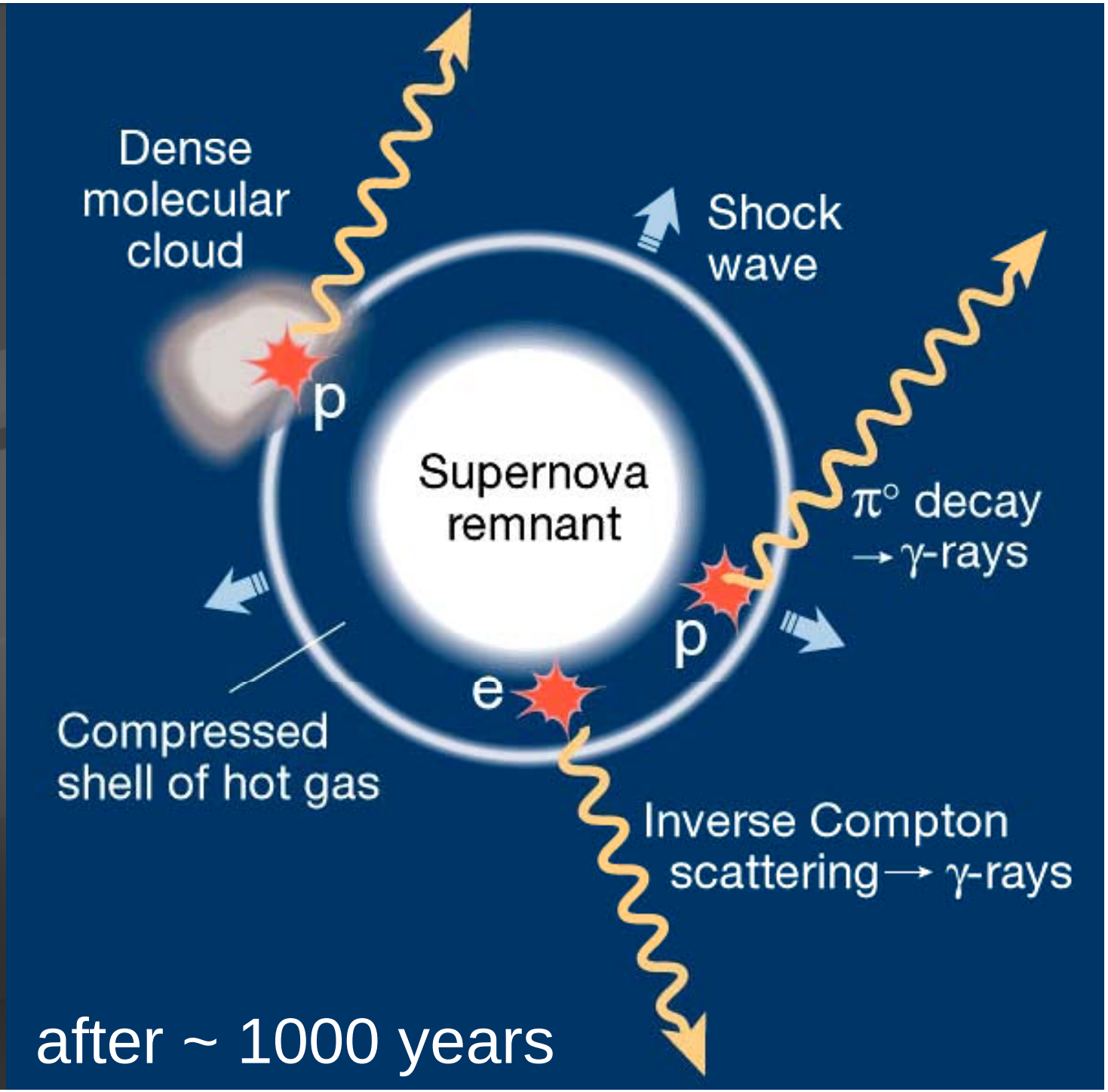


radiation or

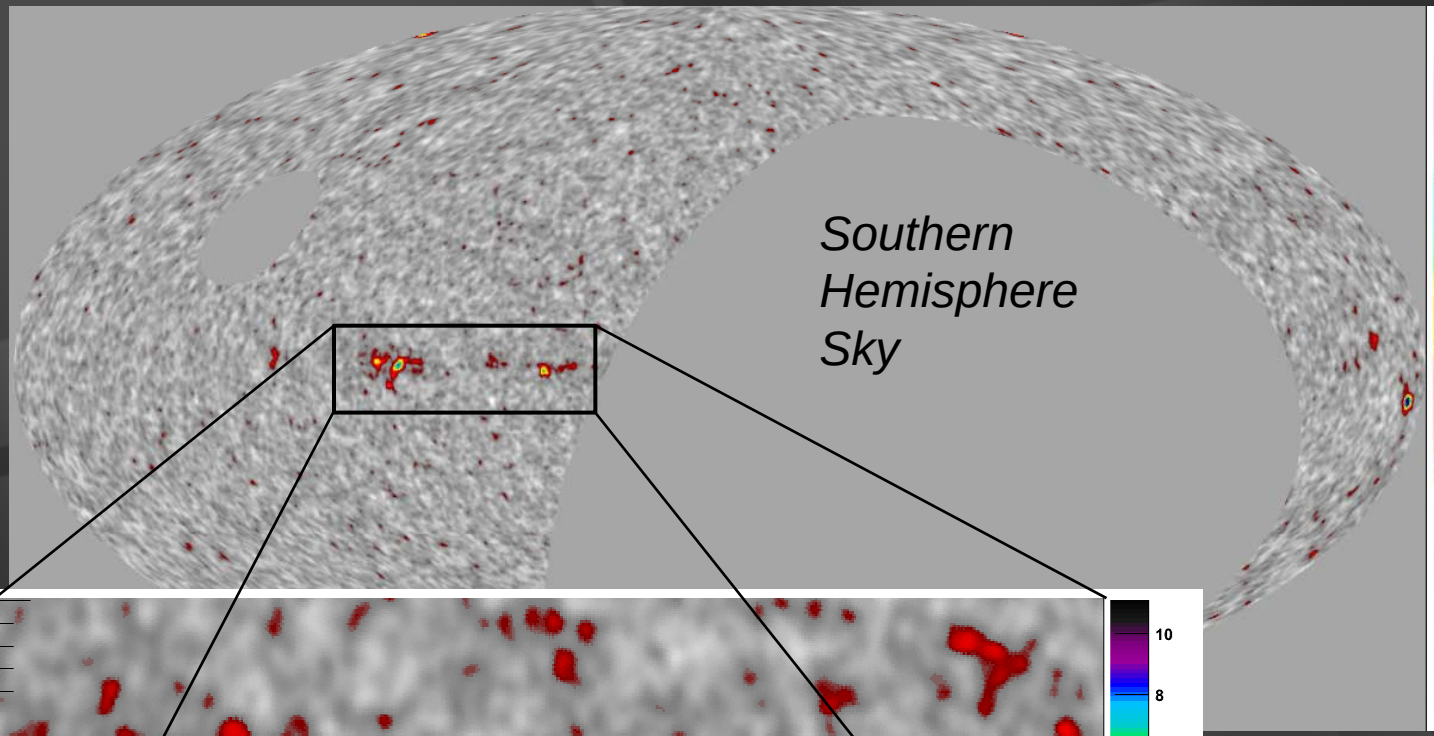
hydrogen in interstellar medium

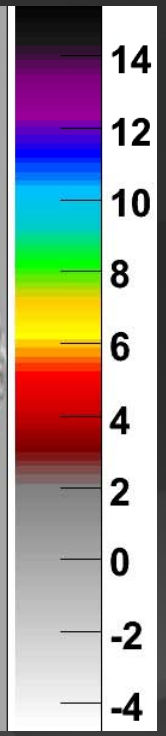


supernova beam dump → molecular clouds

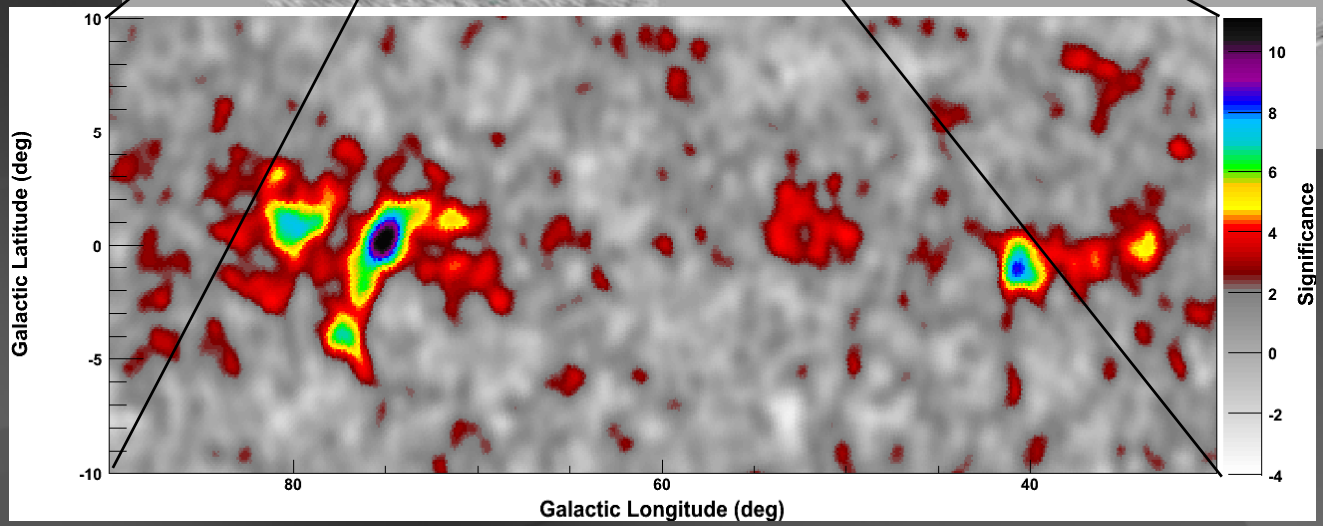


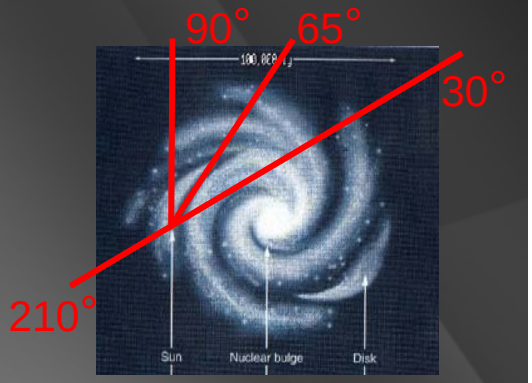
galactic plane at 10 TeV (milagro)





Standard Deviations

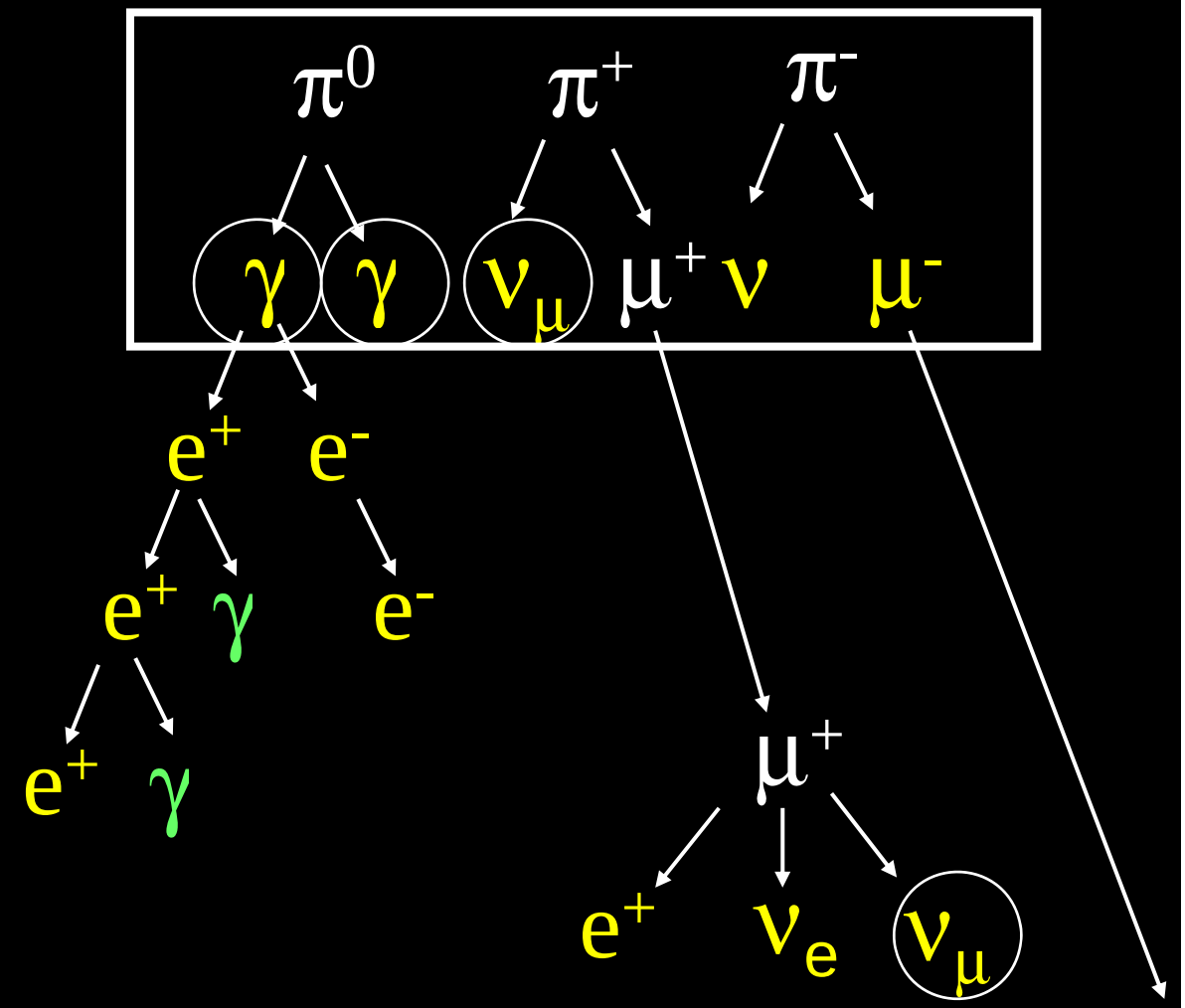


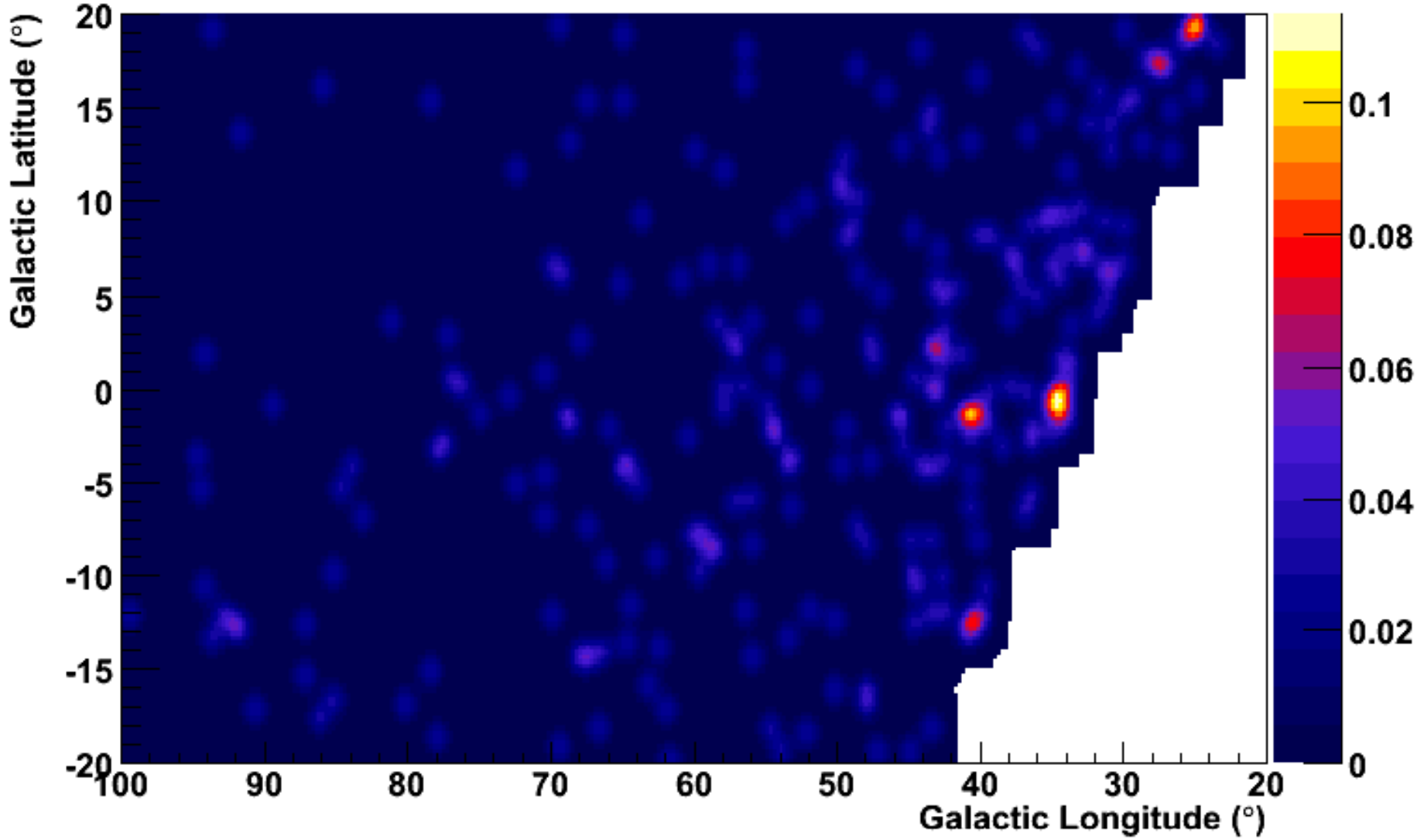


neutral pions
are observed
as
gamma rays

charged pions
are observed
as
neutrinos

$\nu_\mu \sim 2\gamma$





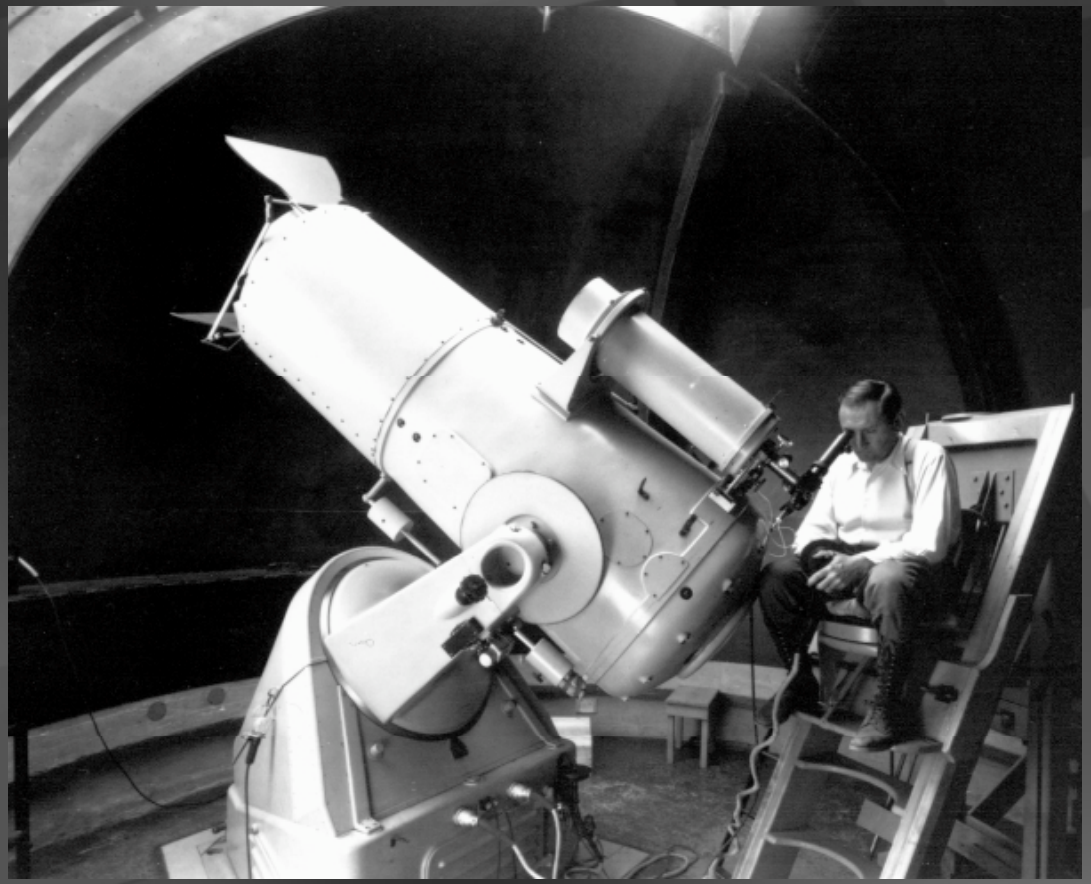
IceCube 5 years (E > 40 TeV)

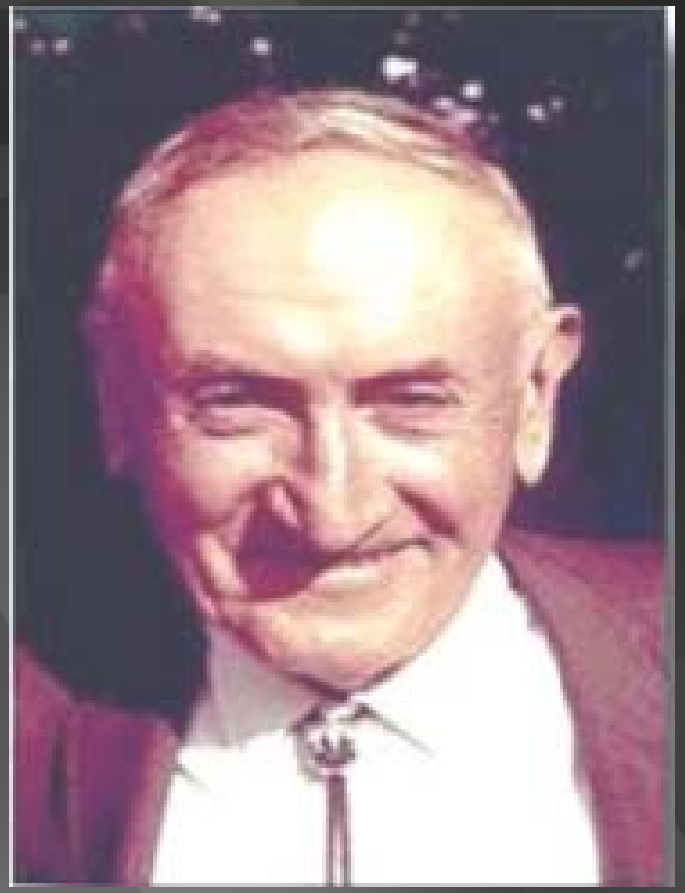
ON SUPER-NOVAE

By W. Baade and F. Zwicky

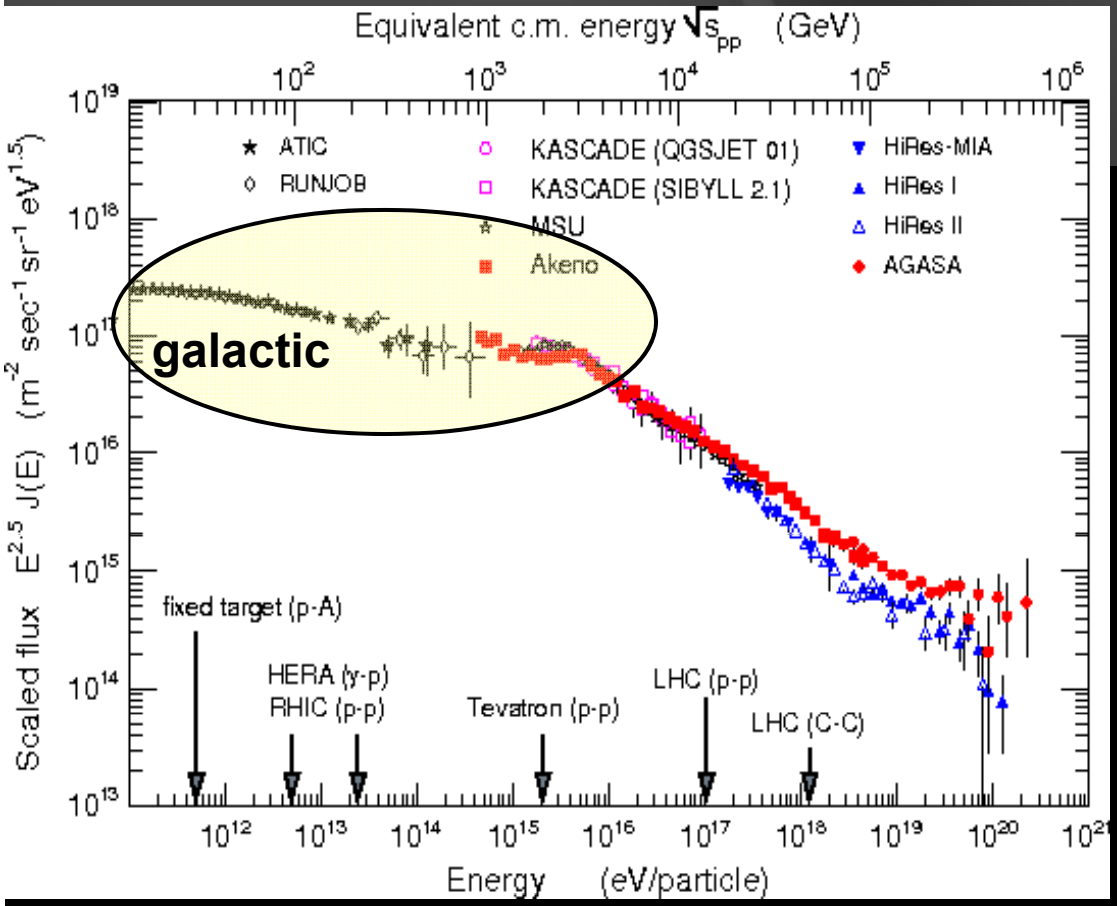
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934





Cosmic Rays & SNRs



observed energy density of galactic CR:

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

supernova remnants:

10^{50} ergs every 30 years

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

for steady state of CR with lifetime 10^6 years

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

extragalactic galactic cosmic rays

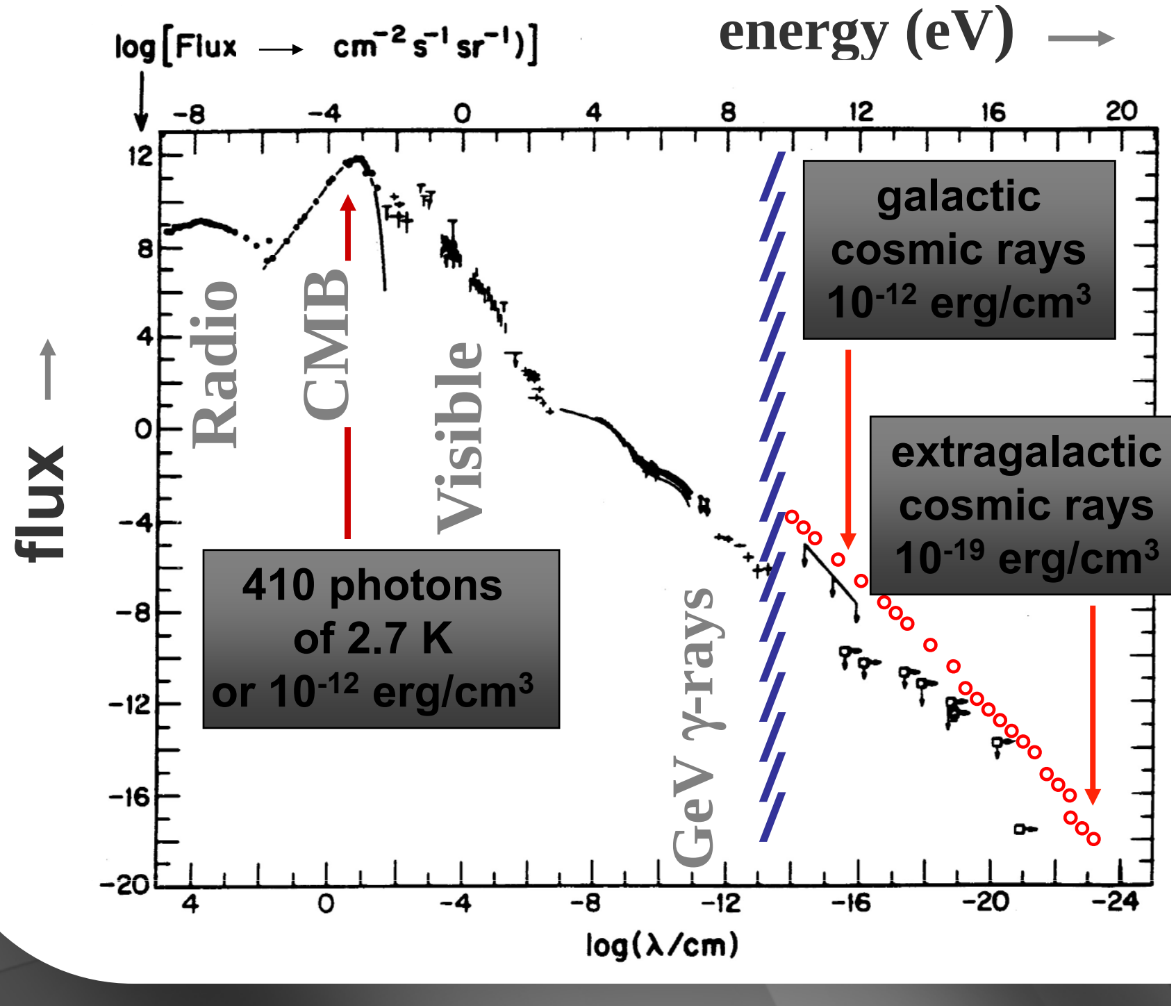
accelerators ?

- gamma ray bursts:

  like supernova remnants but the star collapses to a black hole and the radiation is released in seconds, not a thousand years

- active galaxies:

  particle flows associated with supermassive black holes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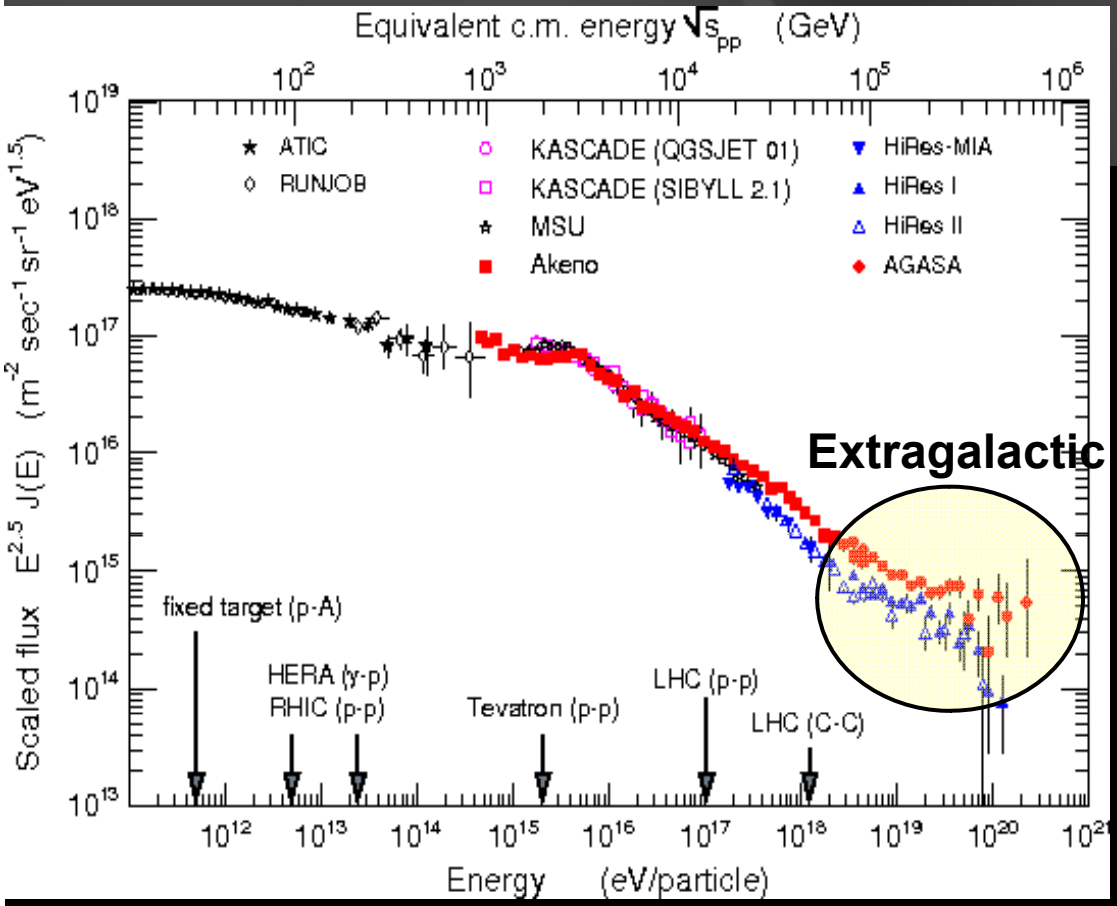
Cosmic Rays & GRBs



observed energy density of extragalactic CR:

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

Gamma-Ray Bursts:
10^{52} ergs x 300/Gpc^3
x 10^{10} yr

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

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

→ energy in extra-galactic cosmic rays is ~ 3×10^{-19} erg/cm^3

3×10^{44} erg/s per active galaxy

2×10^{52} erg per gamma ray burst

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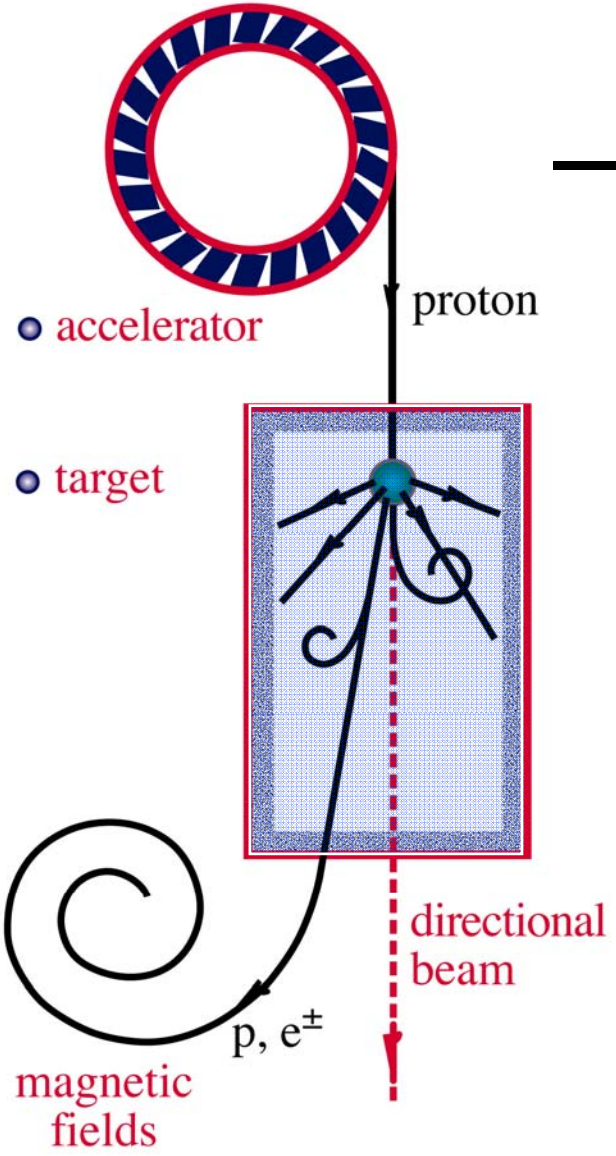
energy in

cosmic rays ~ photons ~ neutrinos

ν and γ beams : heaven and earth



Black Hole

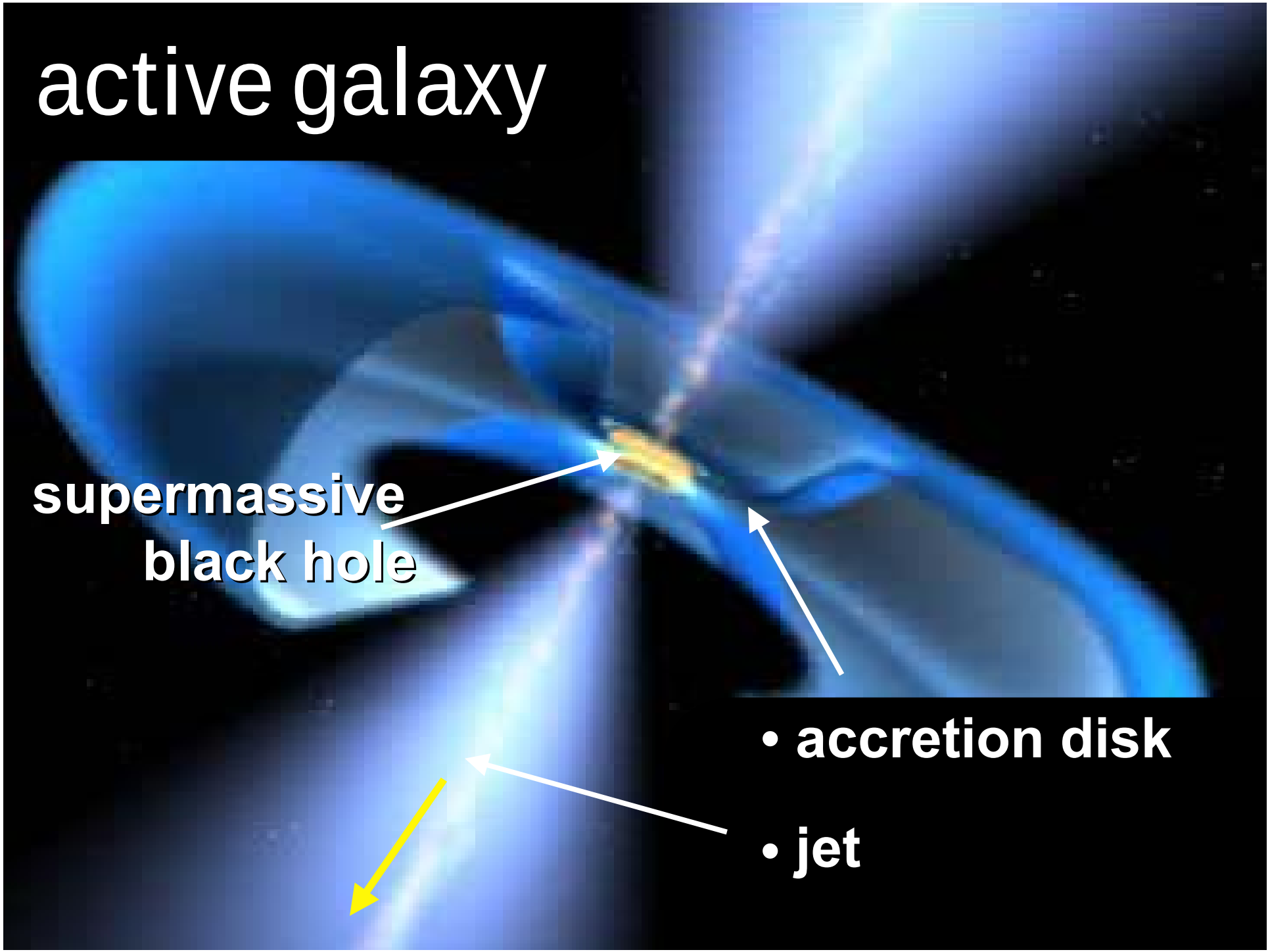
Radiation
Enveloping
Black Hole

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

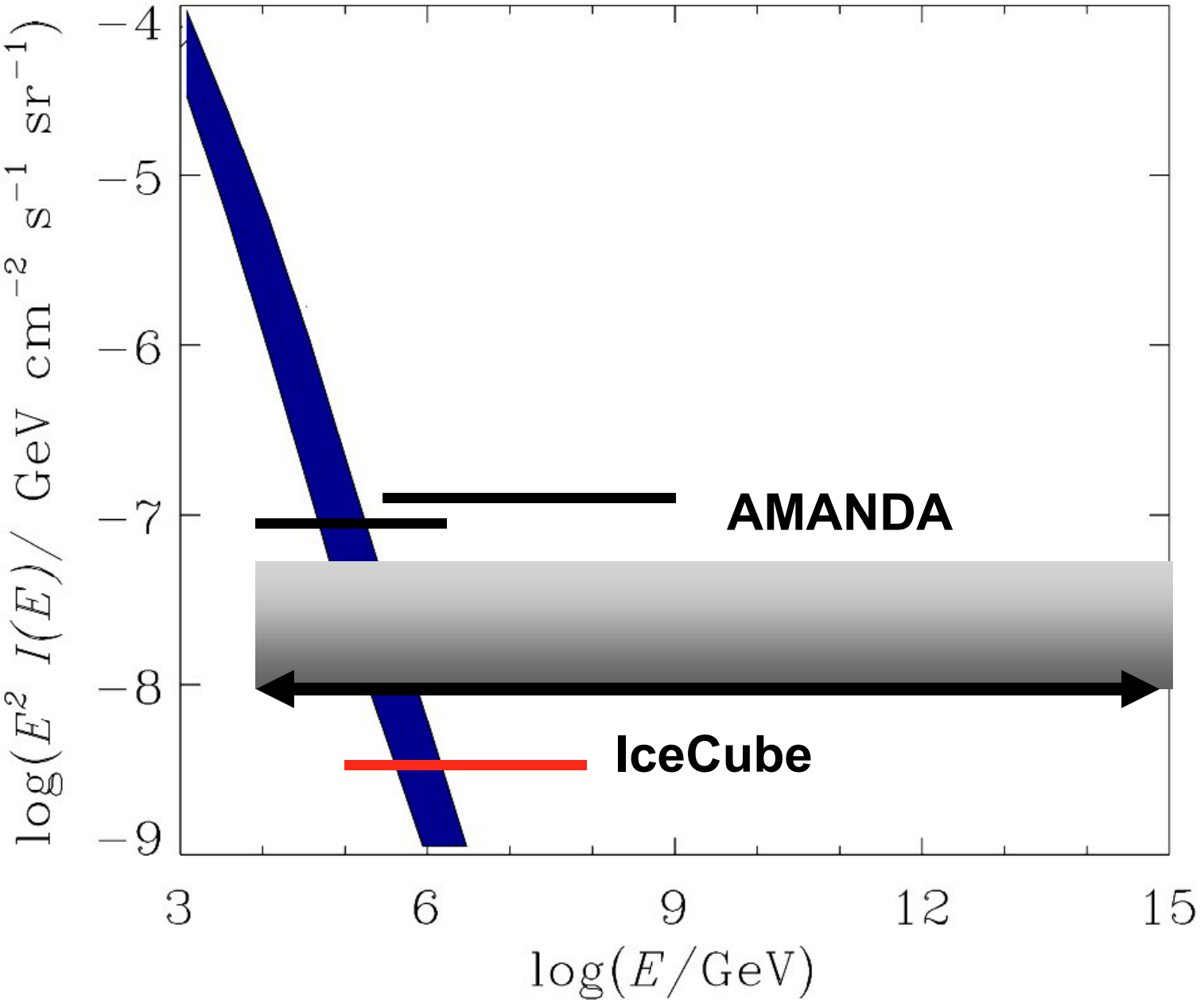
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

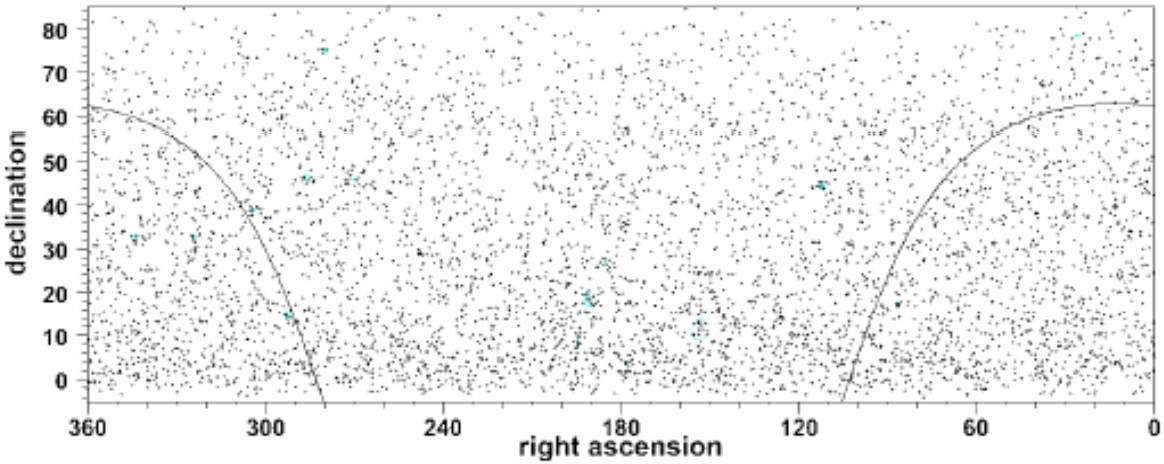

active galaxy
supermassive
black hole
• accretion disk
• jet

neutrinos associated with extragalactic cosmic rays



cosmic rays : evidence ?

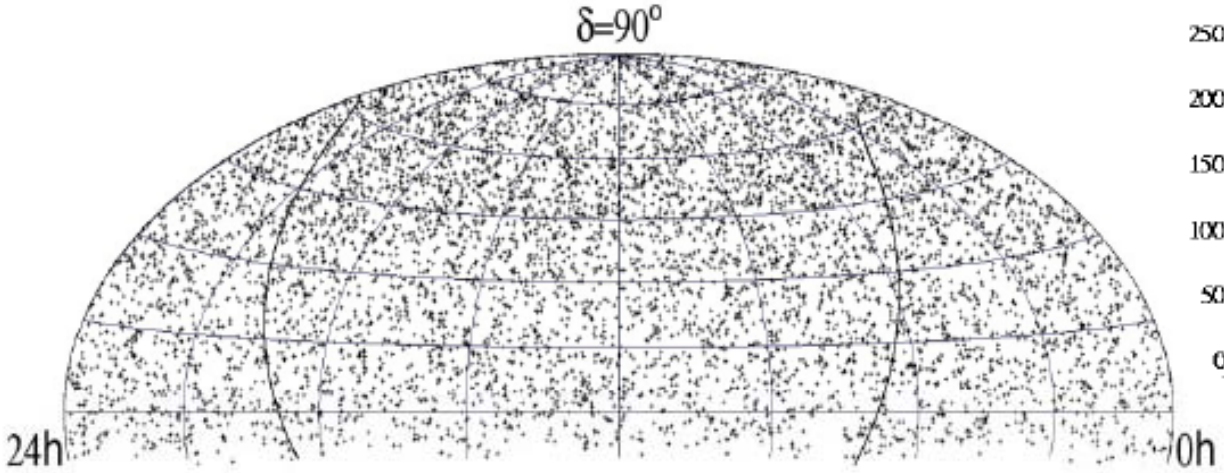
neutrinos: IceCube 22 > AMANDA (3.8 years)

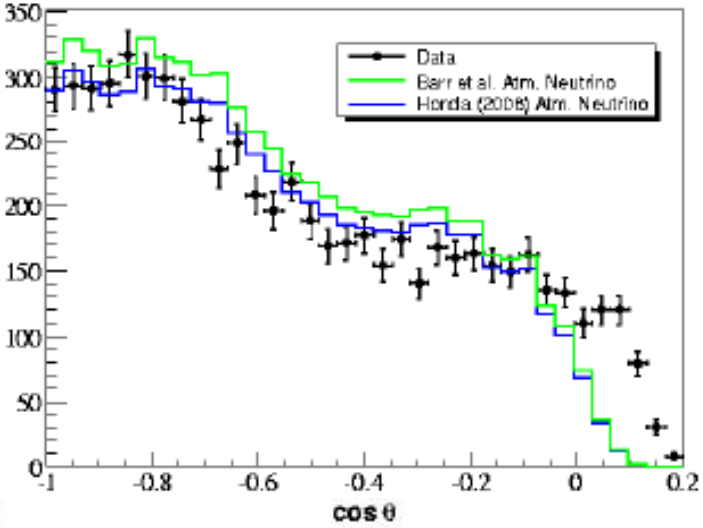


IceCube 22 String:

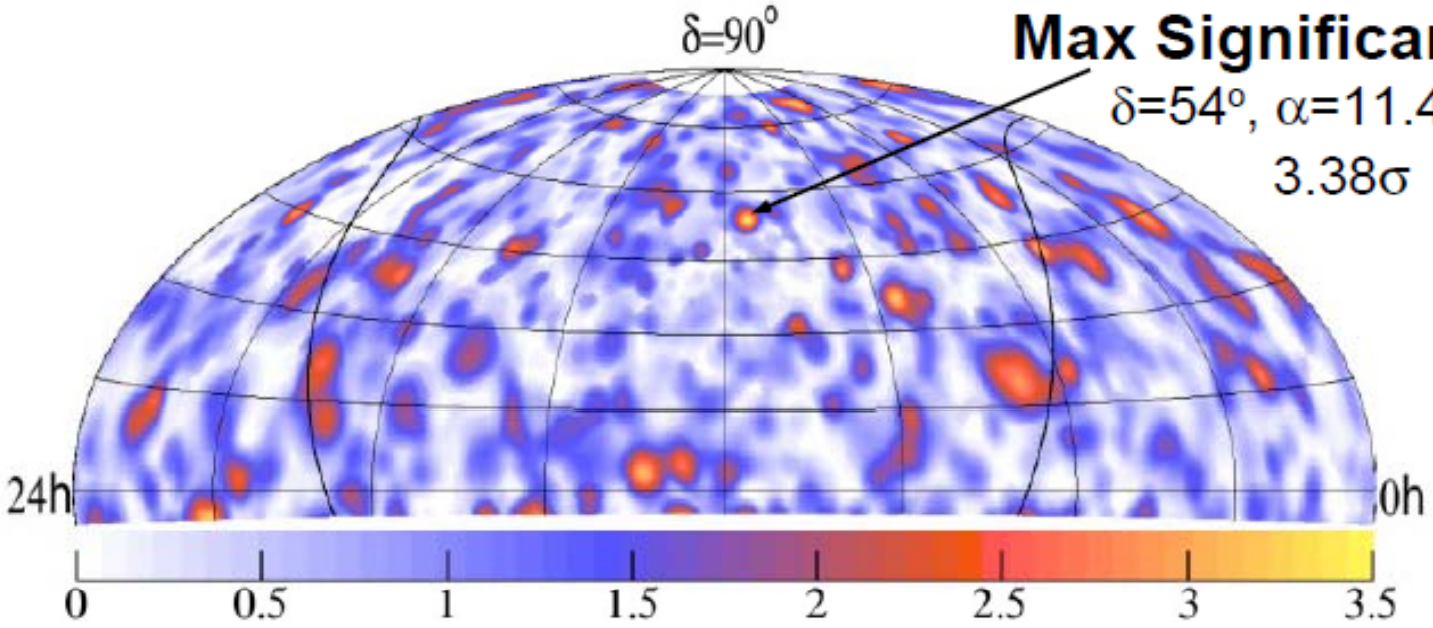
5114 neutrino candidates
in 276 days livetime

AMANDA: 6595 ν candidates in 3.8 live-years





AMANDA All-Sky Search



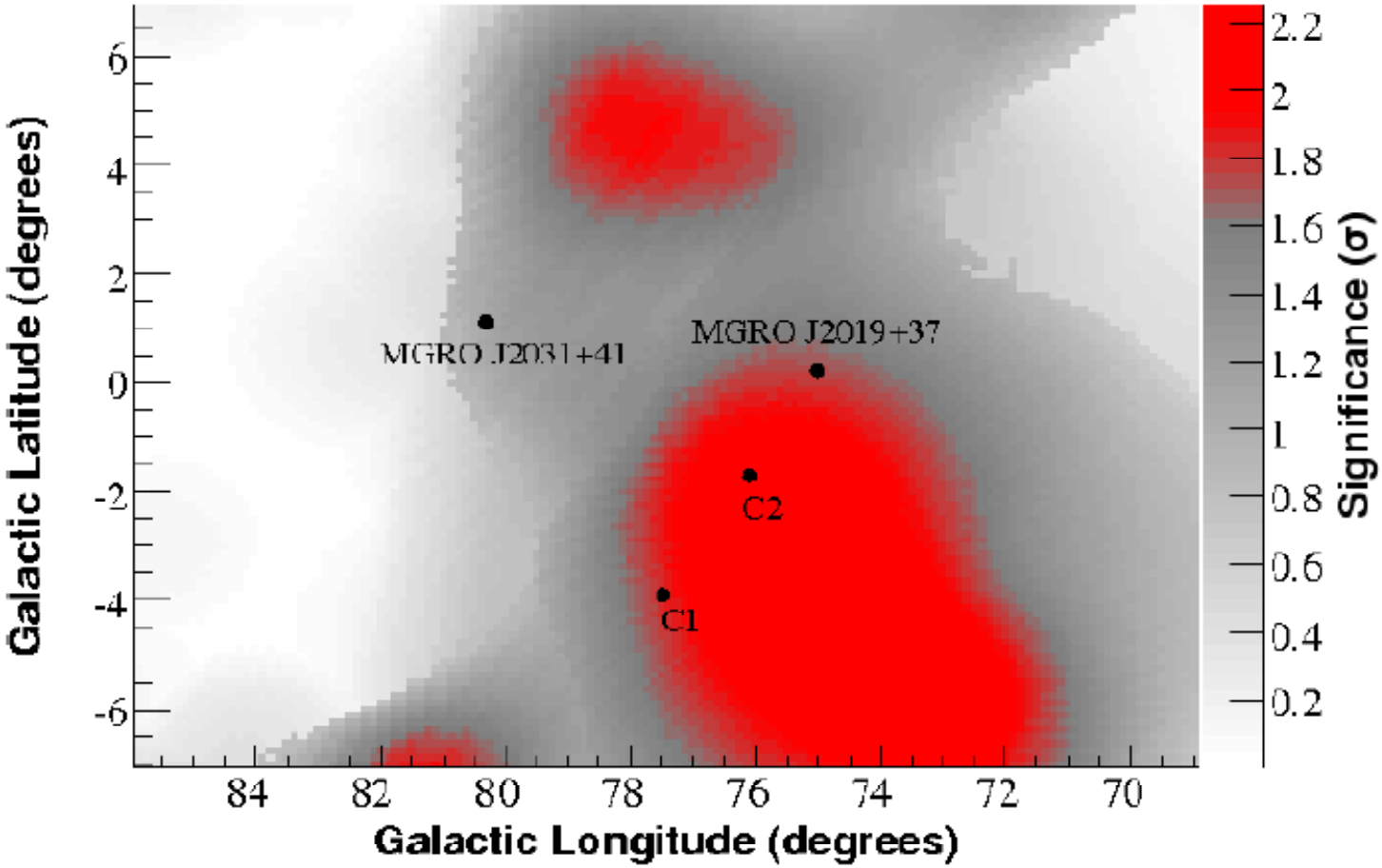
95 of 100 data sets randomized in RA have a significance ≥ 3.38σ

Source	μ_{90}	P-value
Crab	9.27	0.10
MGRO J2019+37	9.67	0.077
Mrk 421	2.54	0.82
Mrk 501	7.28	0.22
LS I +61 303	14.74	0.03
Geminga	12.77	0.0086

$E^2\Phi < \mu 90 * 10^{-11}$ TeV cm^{-2} s^{-1}

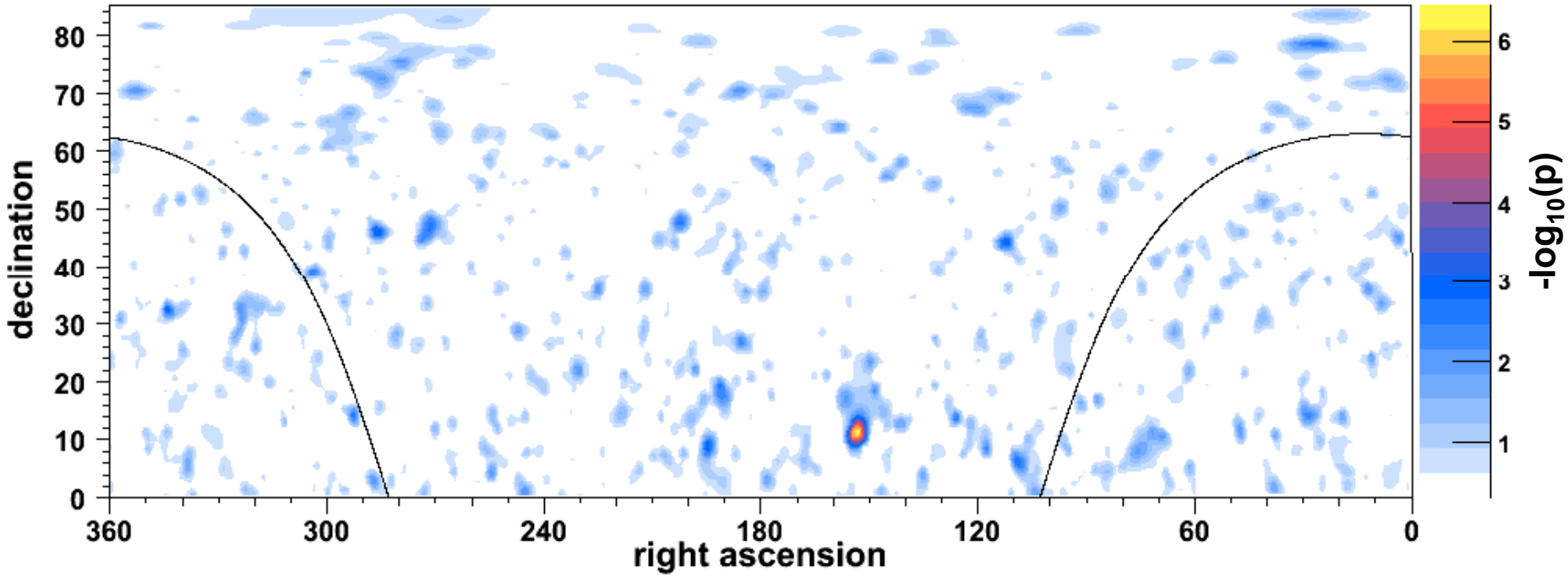
The probability of obtaining p ≤ 0.0086 for at least one of the 26 sources is 20%

The Cygnus Region



AMANDA 3.8 years

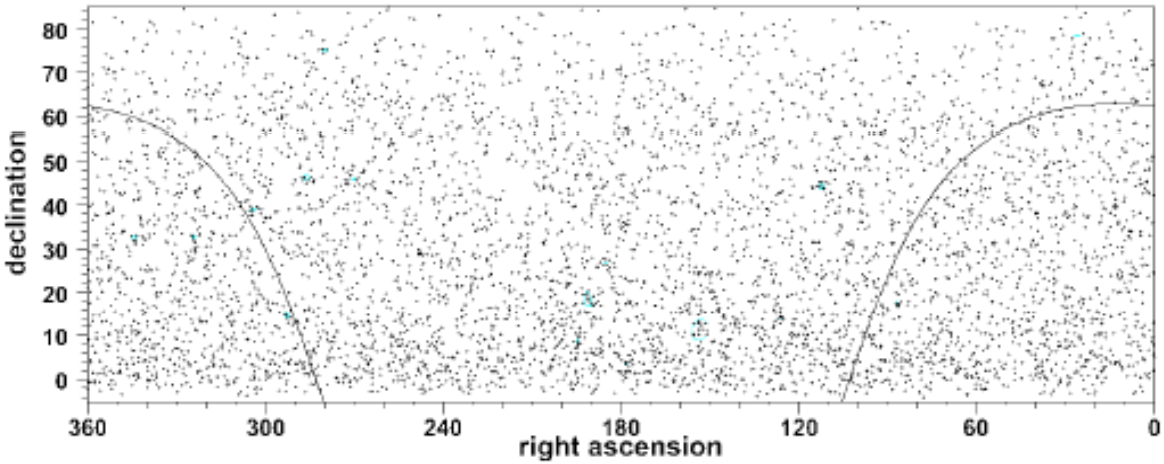
IC22 (255 days) all-sky results (unblinded)



the hottest spot location is: Ra 153.5 , Dec 11.5
estimated number of events = 7.7 estimated gamma = 1.65

pre-trials: $-\log_{10}$(p-value) : 6.14 (4.8 sigma)

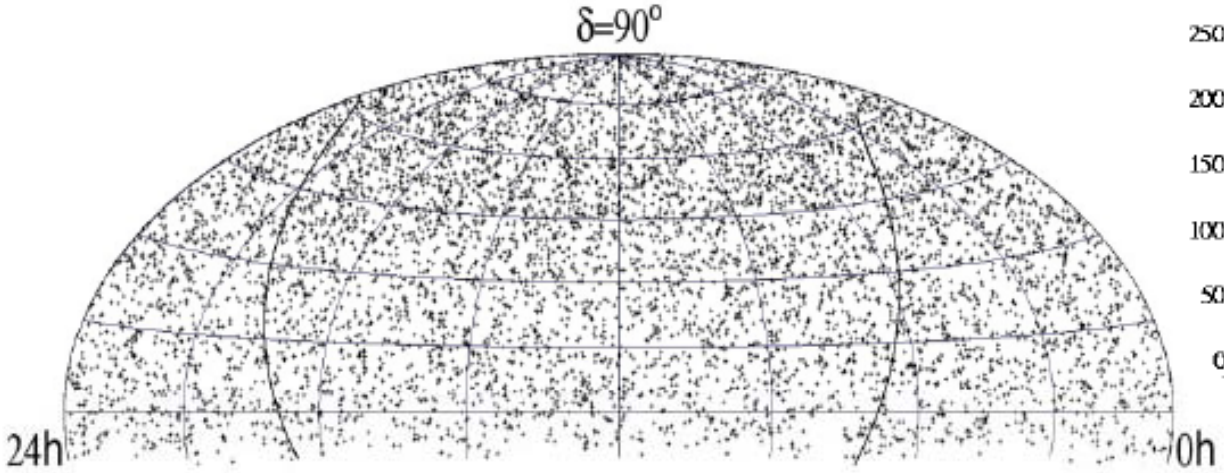
neutrinos: IceCube 22 > AMANDA (3.8 years)

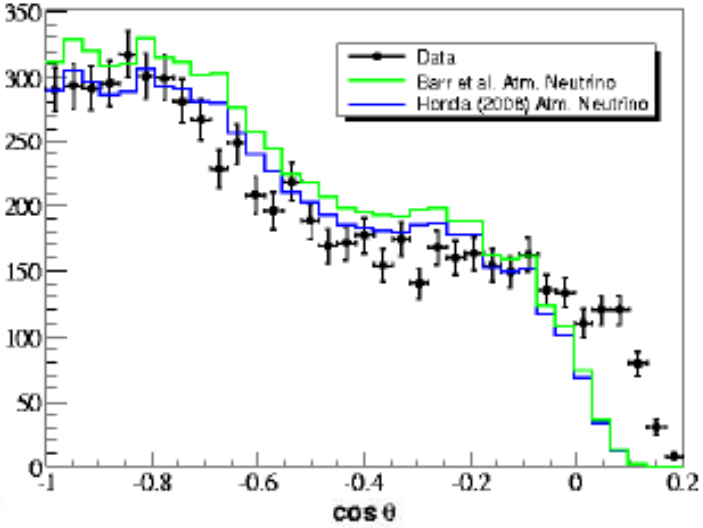


IceCube 22 String:

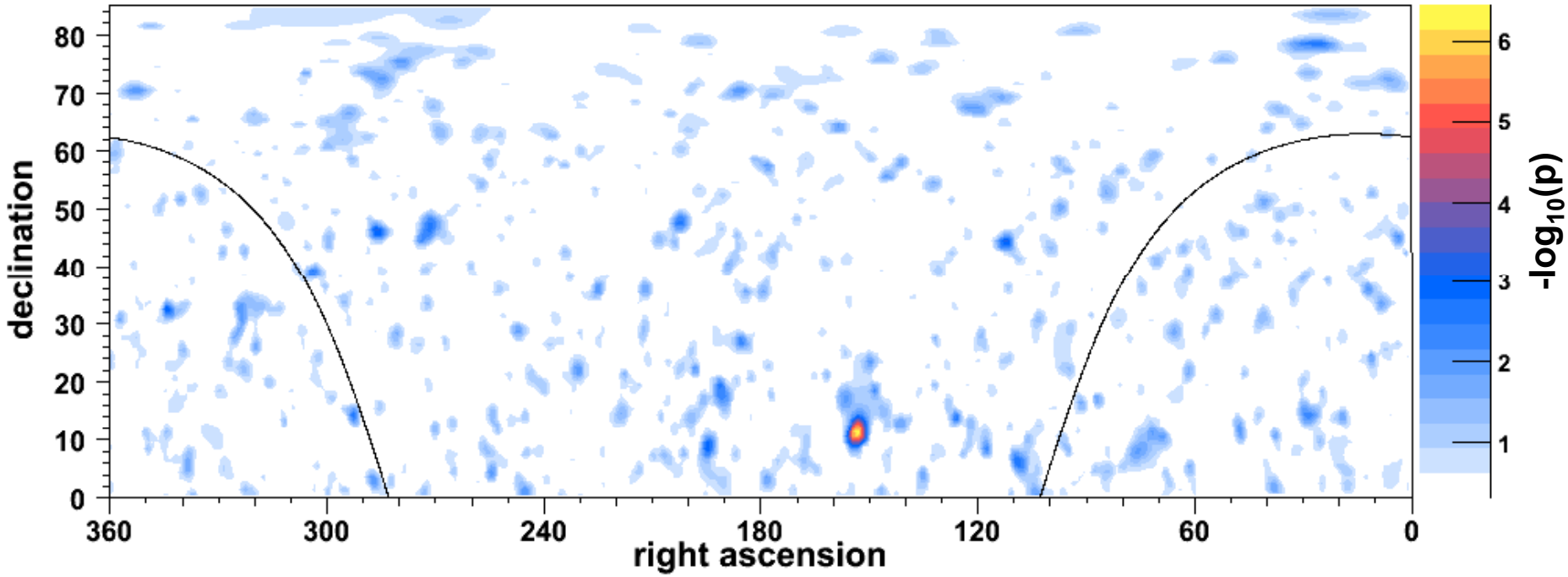
5114 neutrino candidates
in 276 days livetime

AMANDA: 6595 ν candidates in 3.8 live-years





IC22 (255 days) all-sky results (unblinded)



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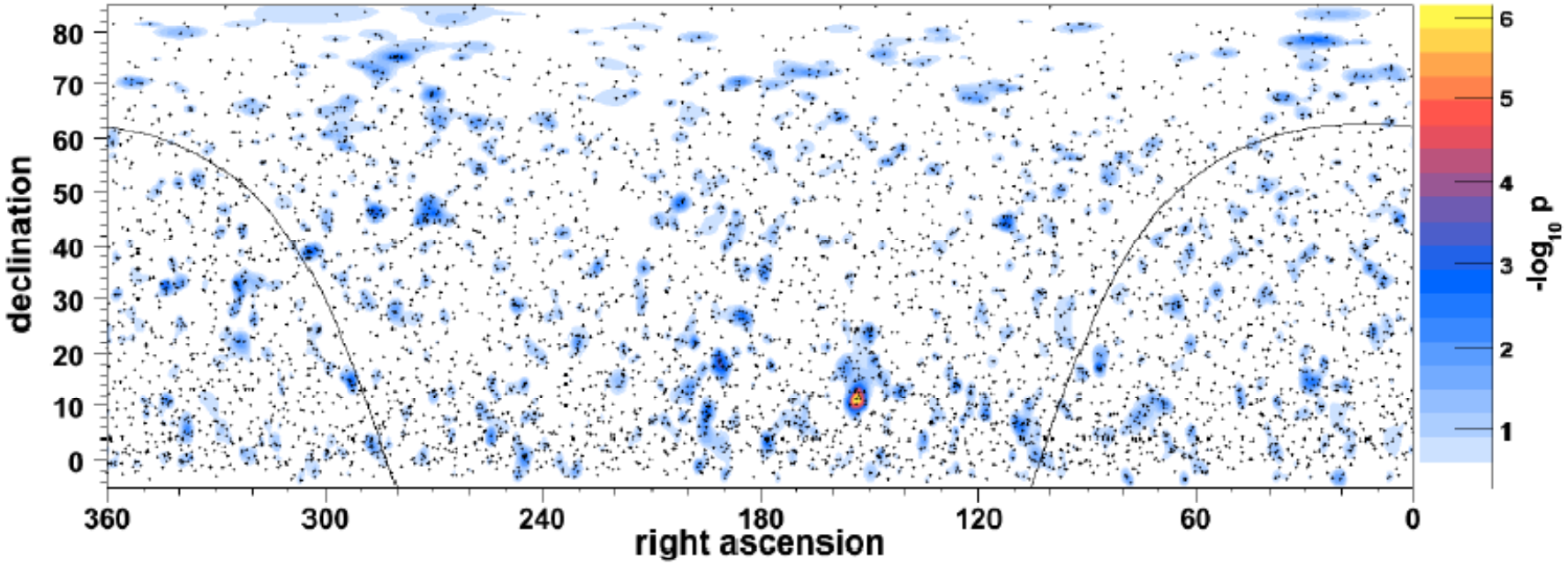
IceCube 22 String



the hottest spot location is: Ra 153.5 , Dec 11.5
estimated number of events = 7.7 estimated gamma = 1.65

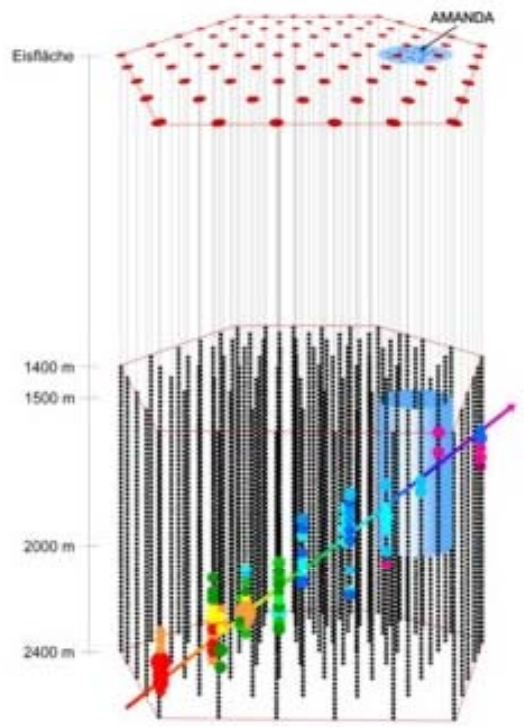
pre-trials: $-\log_{10}$(p-value) : 6.14 (4.8 sigma)

post-trials p-value of analysis is ~ 1.34% (2.2 sigma)

menu

- **it's the technology!**
- **cosmic neutrinos associated with**
  - **Galactic cosmic rays**
  - **extragalactic cosmic rays**
- **particle physics with atmospheric and supernova neutrinos**
- **conclusions**

IceCube



• in the next 10 years IceCube will observe

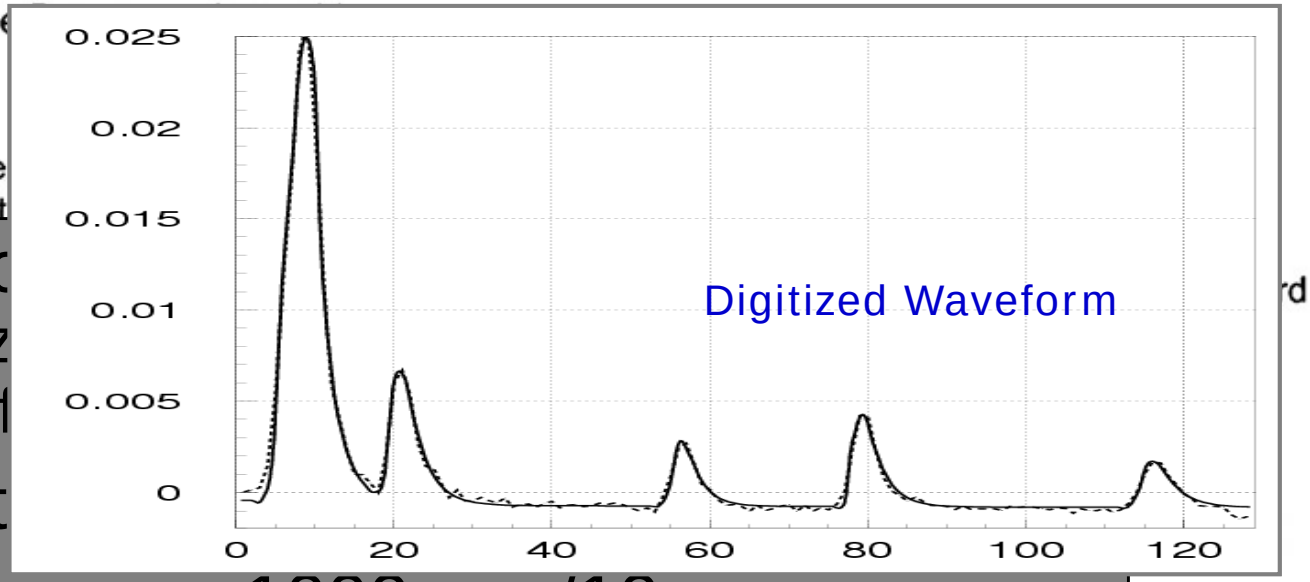
~ 10^6 neutrinos with energies 0.1—1,000 TeV

• 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

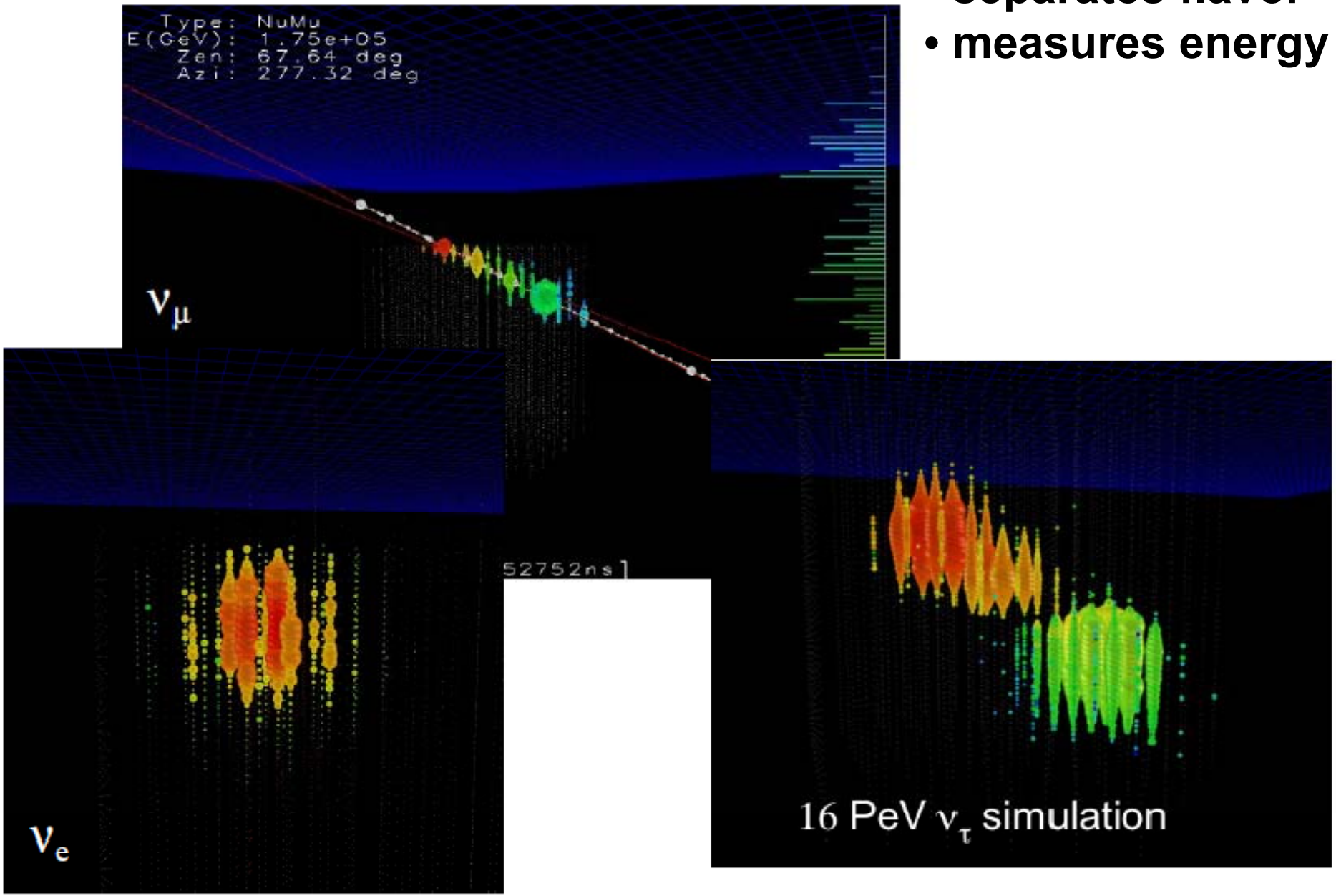
$$\gamma = \frac{E_\nu}{m_\nu} \approx 10^{16}$$

The Digital Optical Module (DOM)



- Onboard d
  - 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%

- **separates flavor**
- **measures energy**

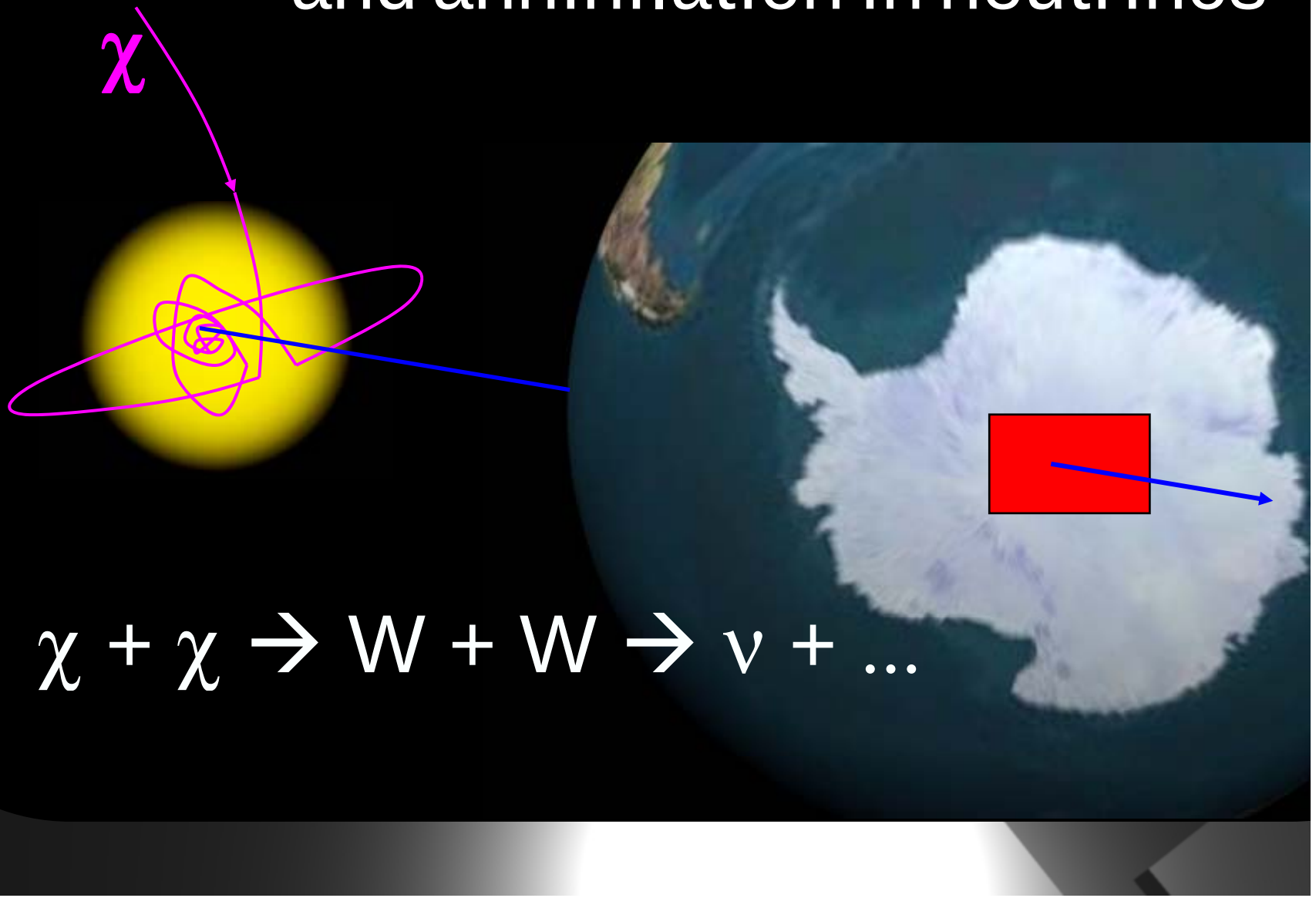


IceCube : particle physics with one million atmospheric neutrinos

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

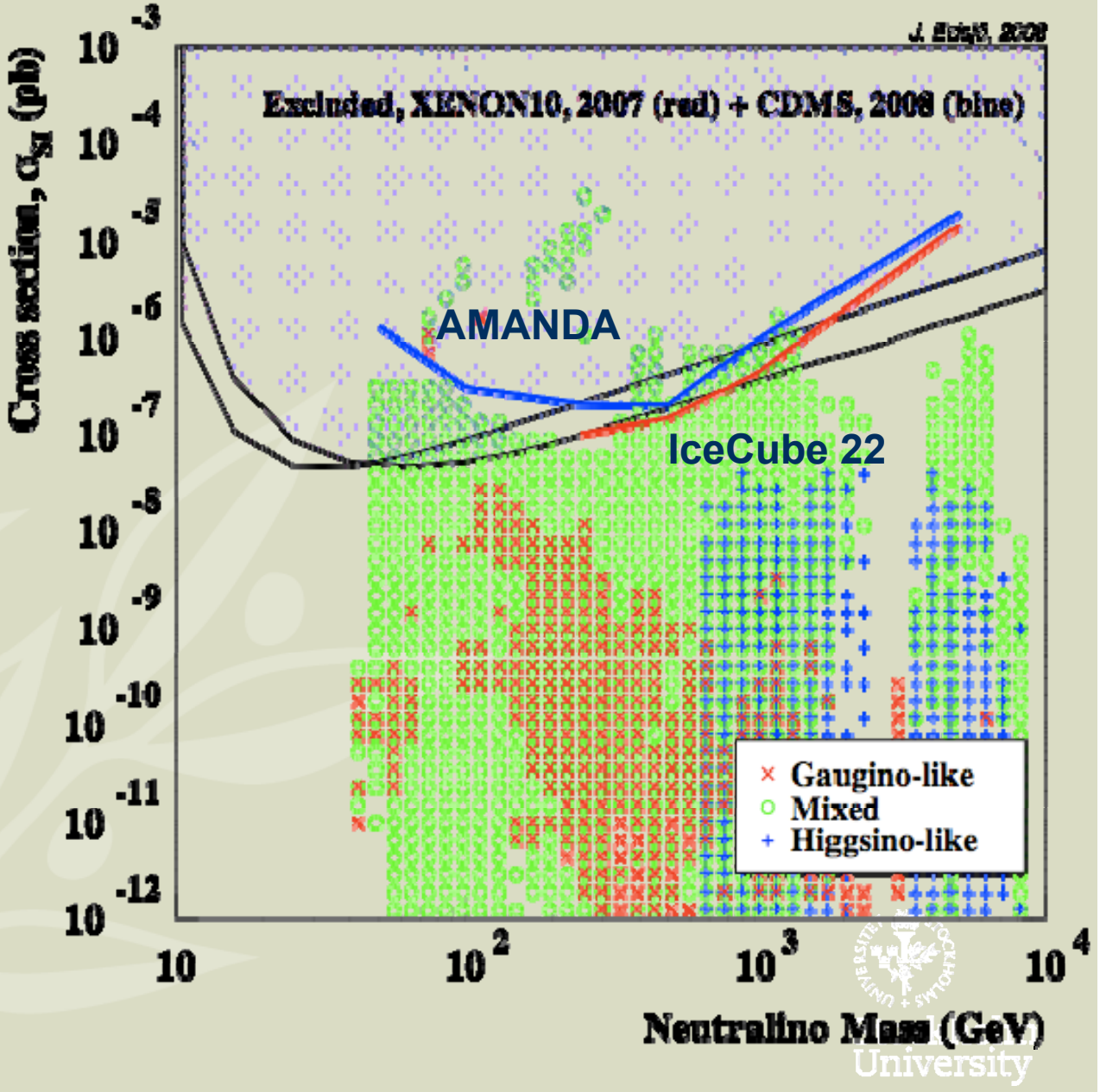
- Physics:
- **measurement of the high-energy neutrino cross section**
- **gravity, quantum decoherence**
- **physics beyond 3-flavor oscillations**
- **test special and general relativity with new precision**
- **search for magnetic monopoles**
- **search for neutralino (or other) dark matter**
- **search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

WIMP capture in the sun and annihilation in neutrinos

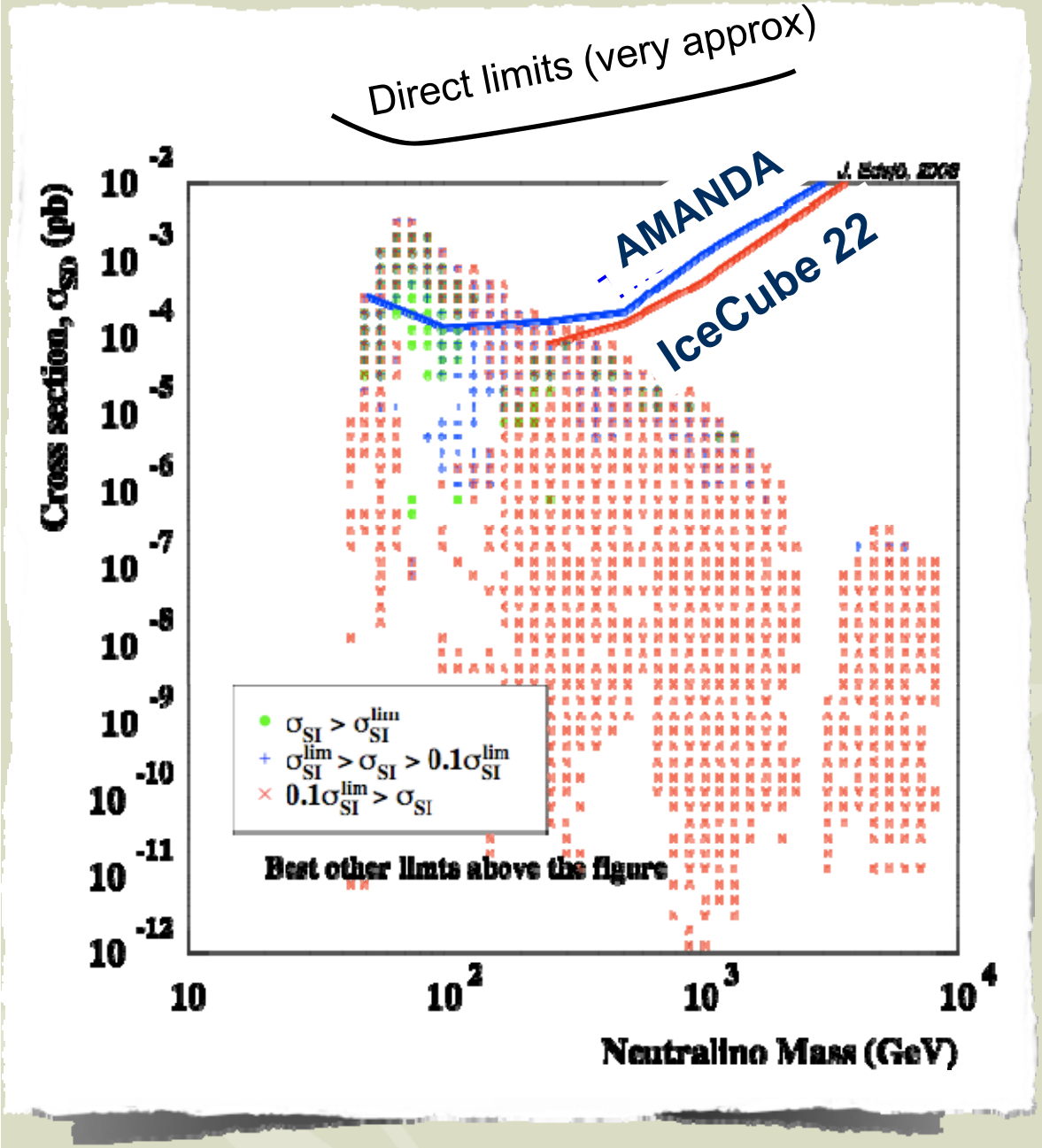


$\chi + \chi \rightarrow W + W \rightarrow \nu + \ldots$

spin-independent scattering



spin dependent scattering



Stockholm University

atmospheric neutrino physics

- TeV physics and above : new physics
- > 10 TeV : observation of core-mantle transition from neutrino absorption in the Earth
- ~ 10 GeV : hierarchy from matter effects in the Earth near first absorption dip
- 2 megaton detector for MeV neutrinos from a galactic supernova (observe deleptonization)

new physics with atmospheric neutrinos

$$\mathbf{H}_{\pm} \equiv \frac{\Delta m^2}{4E}\mathbf{U}_\theta \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_\theta^\dagger + \sigma_n^{\pm}\frac{\Delta\delta_n E^n}{2}\mathbf{U}_{\xi_n}\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}\mathbf{U}_{\xi_n}^\dagger ,$$

For Violation of Equivalence Principle

$$\Delta\delta_1 = 2|\phi|(\gamma_1 - \gamma_2) \equiv 2|\phi|\Delta\gamma , \qquad \sigma_1^+ = \sigma_1^- .$$

For Violation of Lorentz Invariance:

$$\Delta\delta_1 = (c_1 - c_2) \equiv \Delta v , \qquad \sigma_1^+ = \sigma_1^- .$$

For Coupling to a space-time torsion field

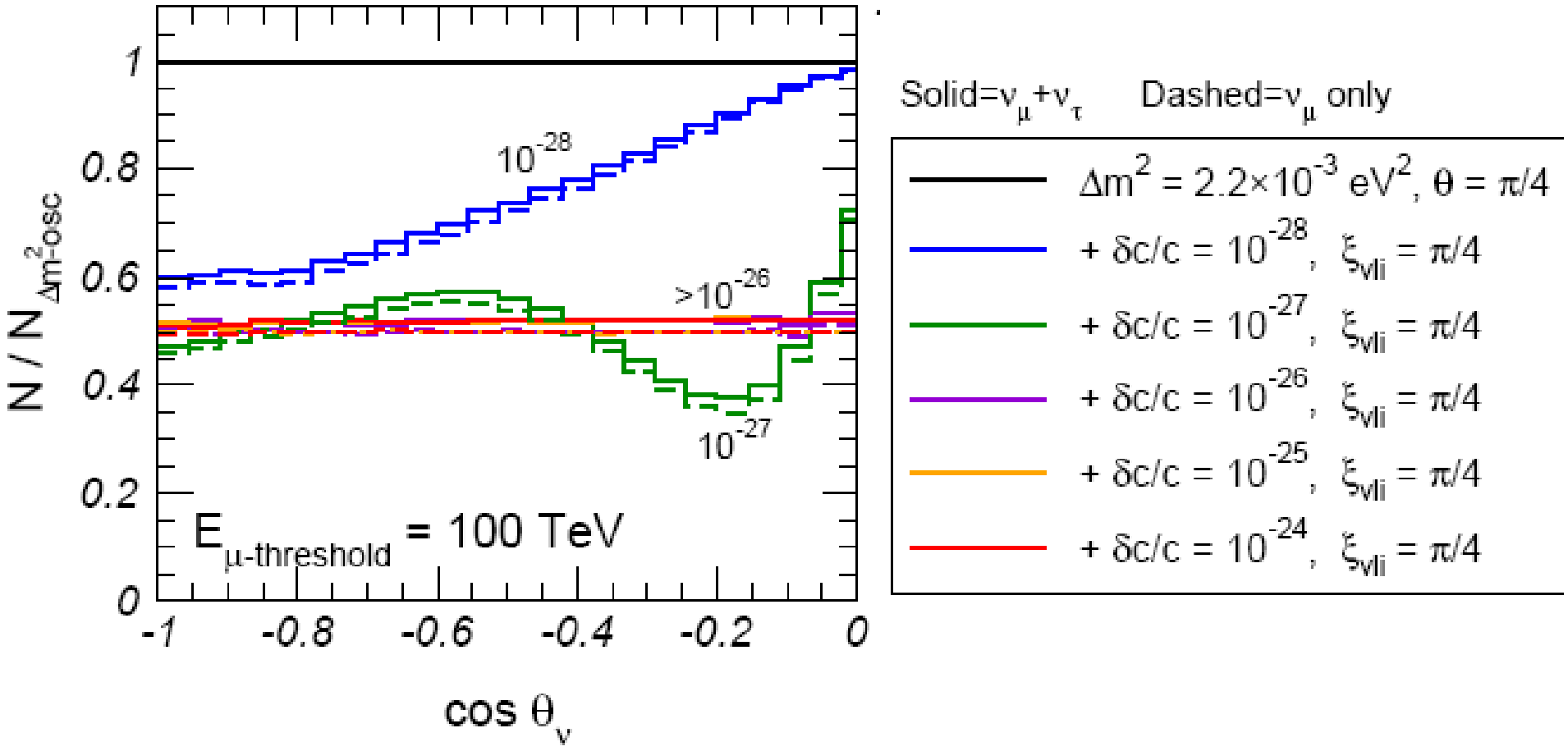
$$\Delta\delta_0 = Q(k_1 - k_2) \equiv Q\,\Delta k , \qquad \sigma_0^+ = \sigma_0^- .$$

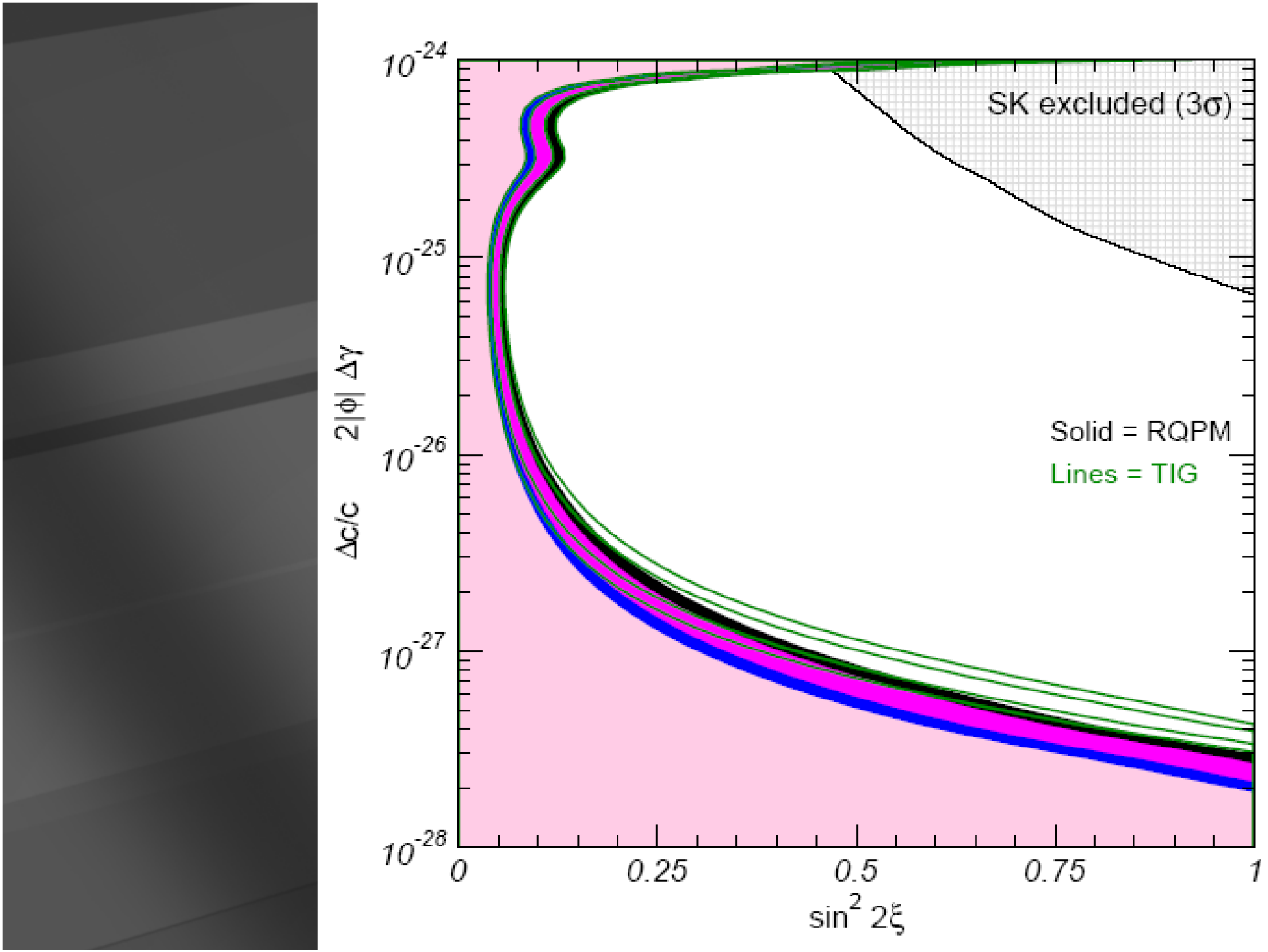
For Violation of Lorentz Invariance via CPT violation

$$\Delta\delta_0 = b_1 - b_2 \equiv \Delta b , \qquad \sigma_0^+ = -\sigma_0^-$$

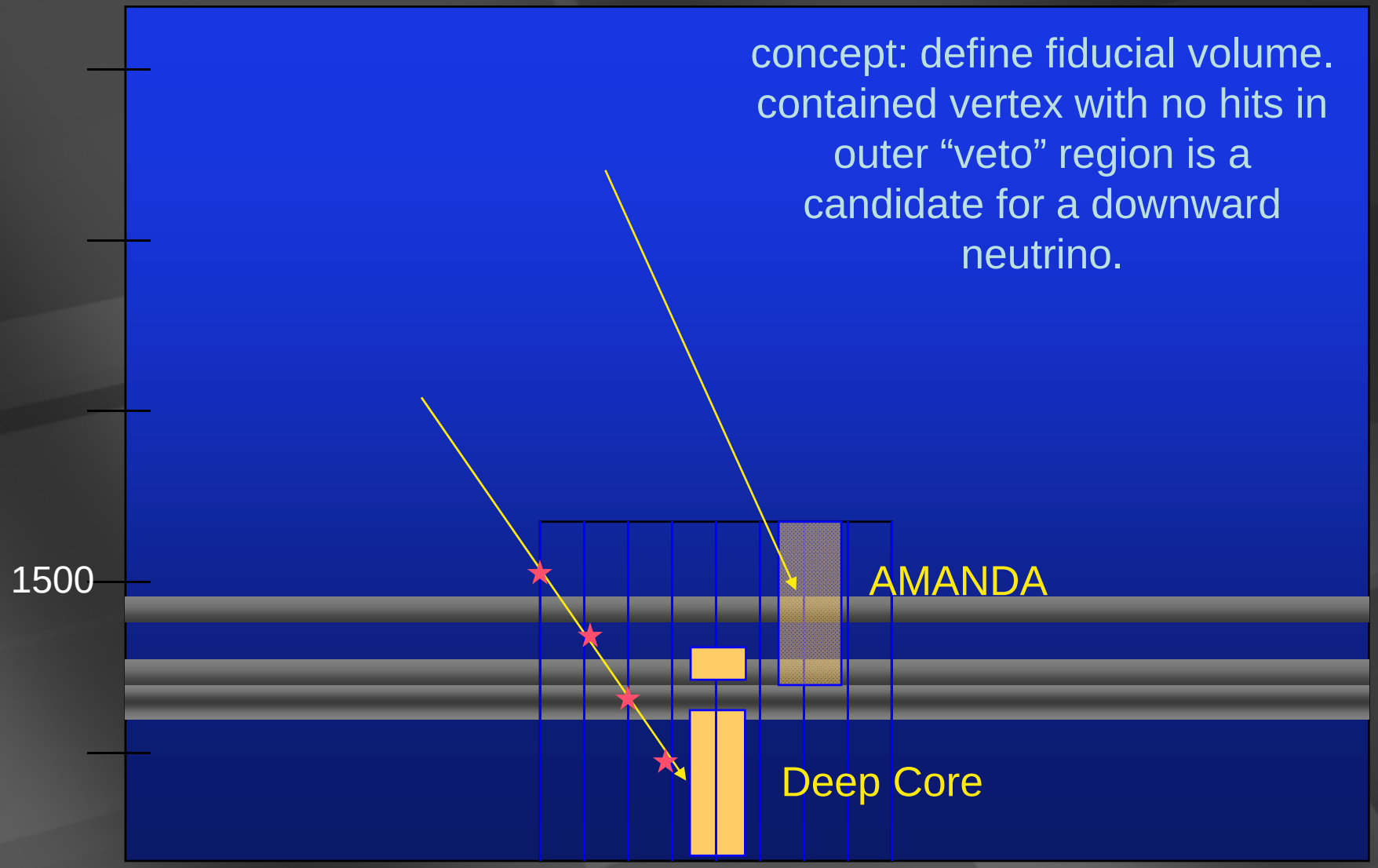
For NSNI

$$\Delta\delta_0 = 2\sqrt{2}\,G_F\,N_f(\vec{r})\sqrt{\varepsilon_{\mu\tau}^2 + \frac{(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})^2}{4}} \qquad \sin^2 2\xi = \frac{\varepsilon_{\mu\tau}}{\sqrt{\varepsilon_{\mu\tau}^2 + \frac{(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})^2}{4}}} \qquad \sigma_0^+ = -\sigma_0^-$$


Solid=$\nu_\mu+\nu_\tau$ Dashed=ν_μ only
$\Delta m^2 = 2.2\times10^{-3}$ eV^2, $\theta = \pi/4$
+ $\delta c/c = 10^{-28}$, $\xi_{vli} = \pi/4$
+ $\delta c/c = 10^{-27}$, $\xi_{vli} = \pi/4$
+ $\delta c/c = 10^{-26}$, $\xi_{vli} = \pi/4$
+ $\delta c/c = 10^{-25}$, $\xi_{vli} = \pi/4$
+ $\delta c/c = 10^{-24}$, $\xi_{vli} = \pi/4$
10^{-28}
$>10^{-26}$
10^{-27}
$E_{\mu\text{-threshold}}$ = 100 TeV
$N / N_{\Delta m^2\text{-osc}}$
cos θ_ν
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0


SK excluded (3σ)
Solid = RQPM
Lines = TIG
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
$\Delta c/c \quad 2|\phi|\,\Delta\gamma$
0
0.25
0.5
0.75
1
$\sin^2 2\xi$

low energy core for IceCube



$$n_{strings} \times height \times \left(\pi\, \lambda^2_{scatt}\right) \approx ten\ Mton$$

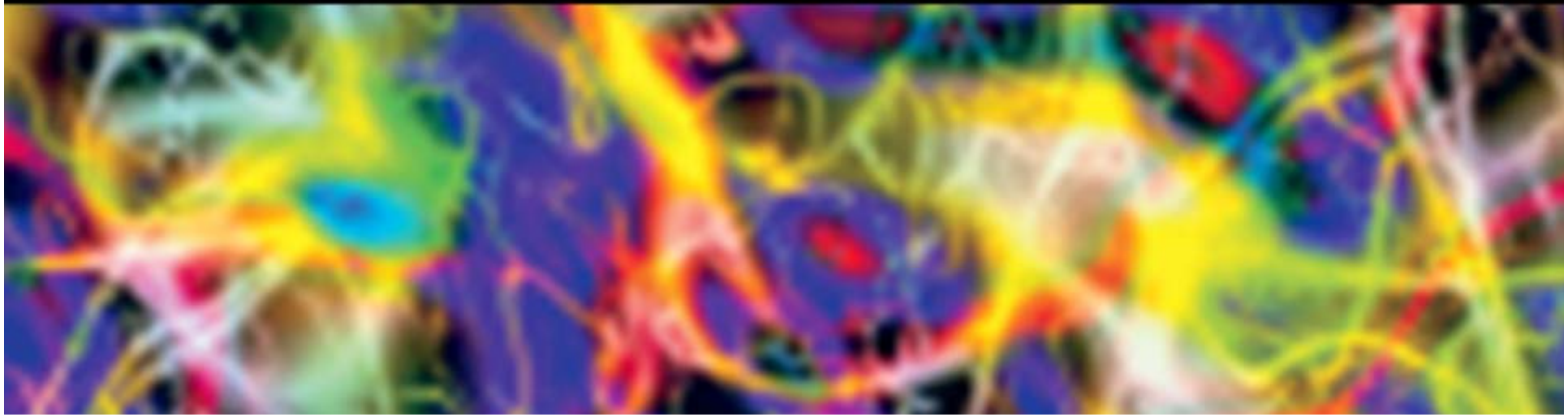
~ 10 GeV : hierarchy from matter effects in the Earth near first absorption dip

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(\cos 2\theta_{13} \pm \frac{\sqrt{2G_F}\, N_e}{\Delta_{13}} \right)^2}$$

(mostly) neutrino + antineutrino -

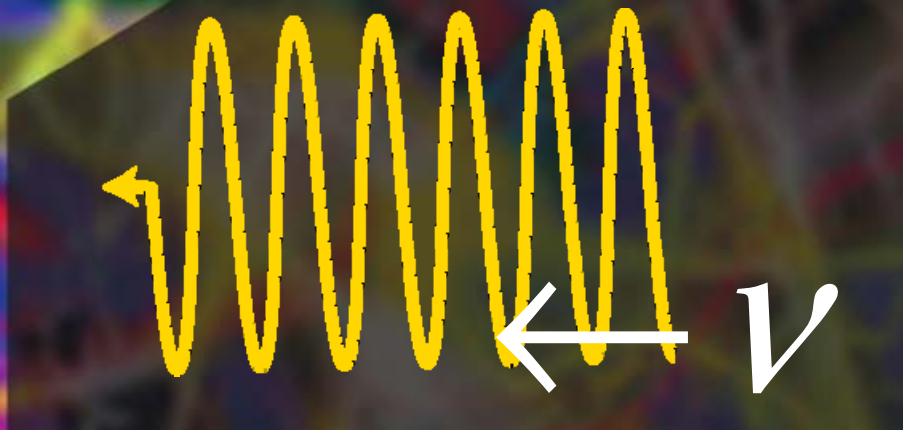
sign Δ_{13} : hierarchy !

quantized space: matter where the geometry is activated



quantized space: matter where the geometry is activated

$$\lambda \sim \frac{1}{E} \rightarrow 10^{-33}\,cm$$



Lorentz violation from Planck scale

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

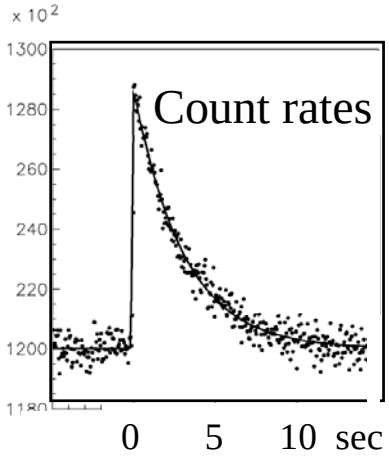
$$\Delta t \approx \frac{1+n}{2}\left(\frac{d}{c}\right)\left(\frac{E_\nu}{\varsigma M_{Planck}}\right)^n$$

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

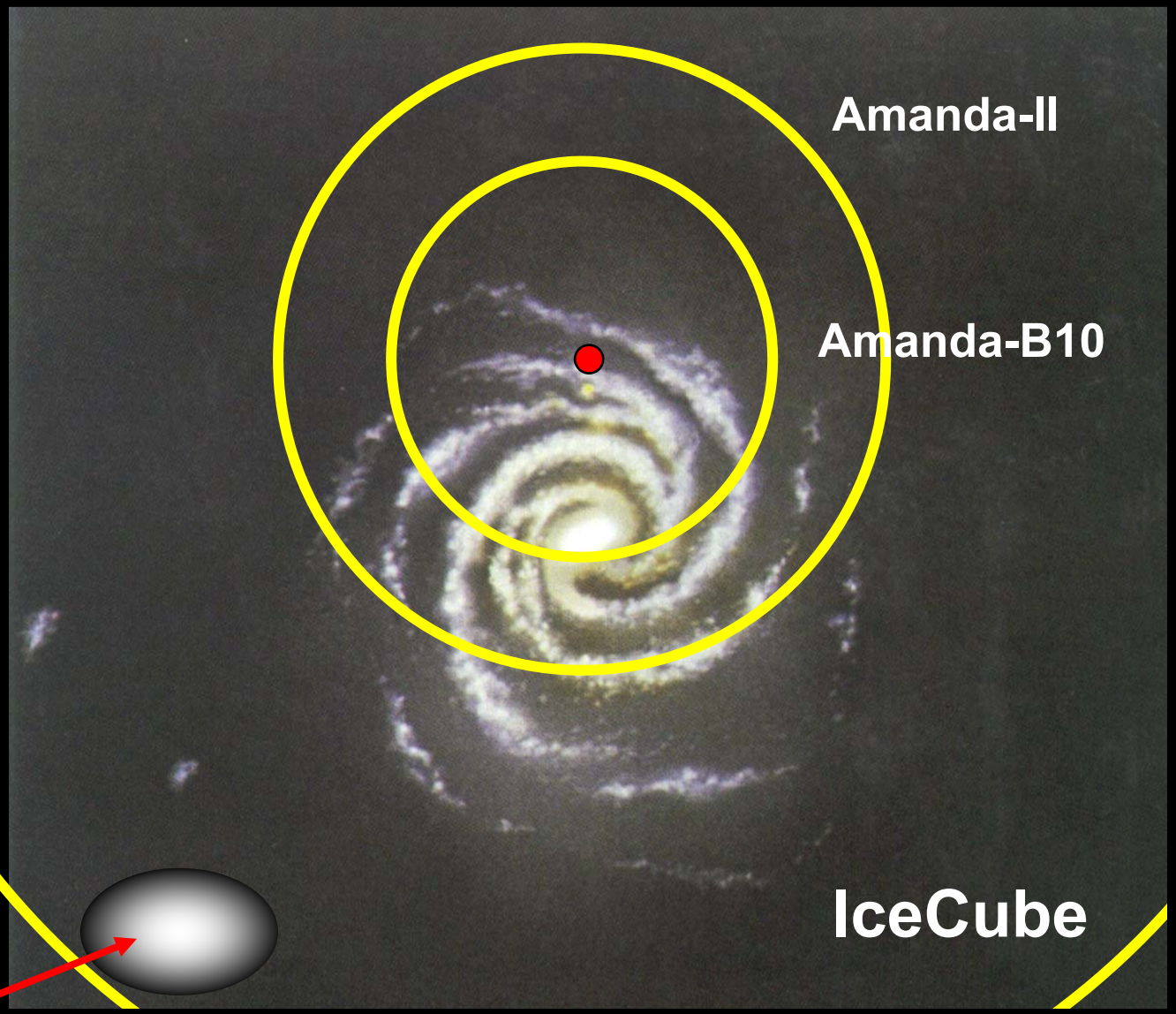
Supernova Monitor

B10:
60% of Galaxy

A-II:
95% of Galaxy



IceCube:
up to LMC



10^6 events in millisecond bins from 8 kpc

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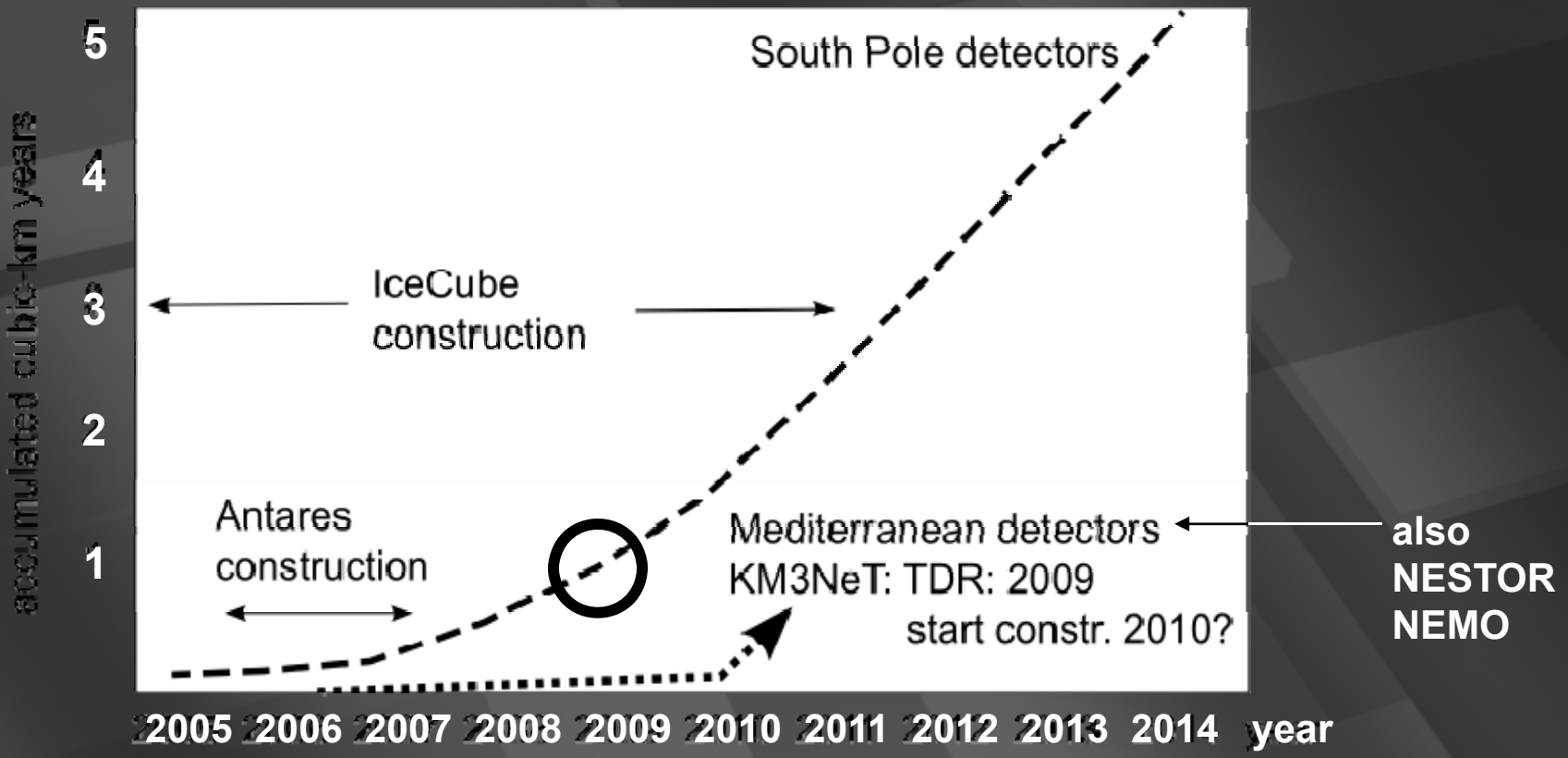
stay tuned: IceCube integrated volume

cumulative km³·yr of exposure × volume



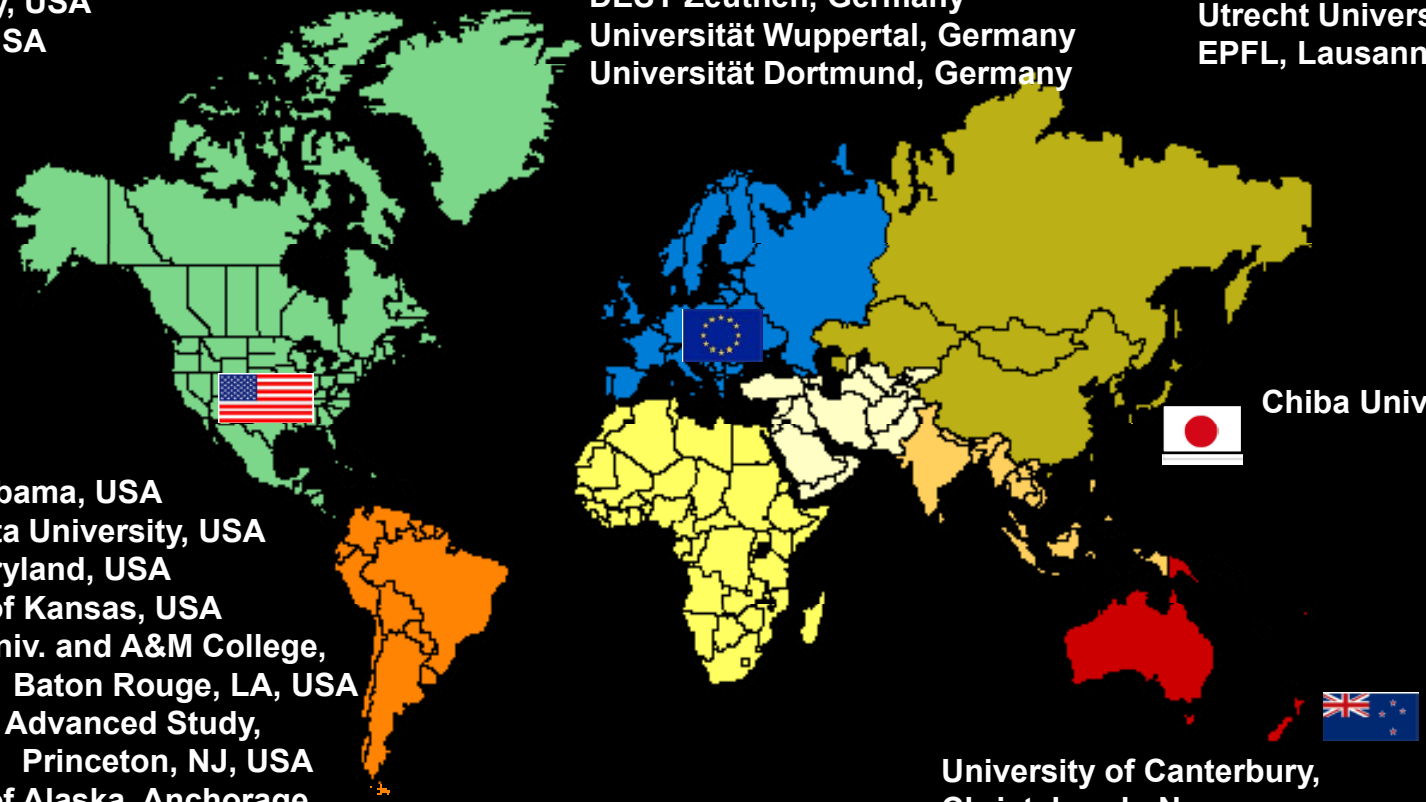
- 1 km³·yr reached 2 years *before* detector is completed
- close to 4 km³·yr at the beginning of 2nd year of full array operation

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