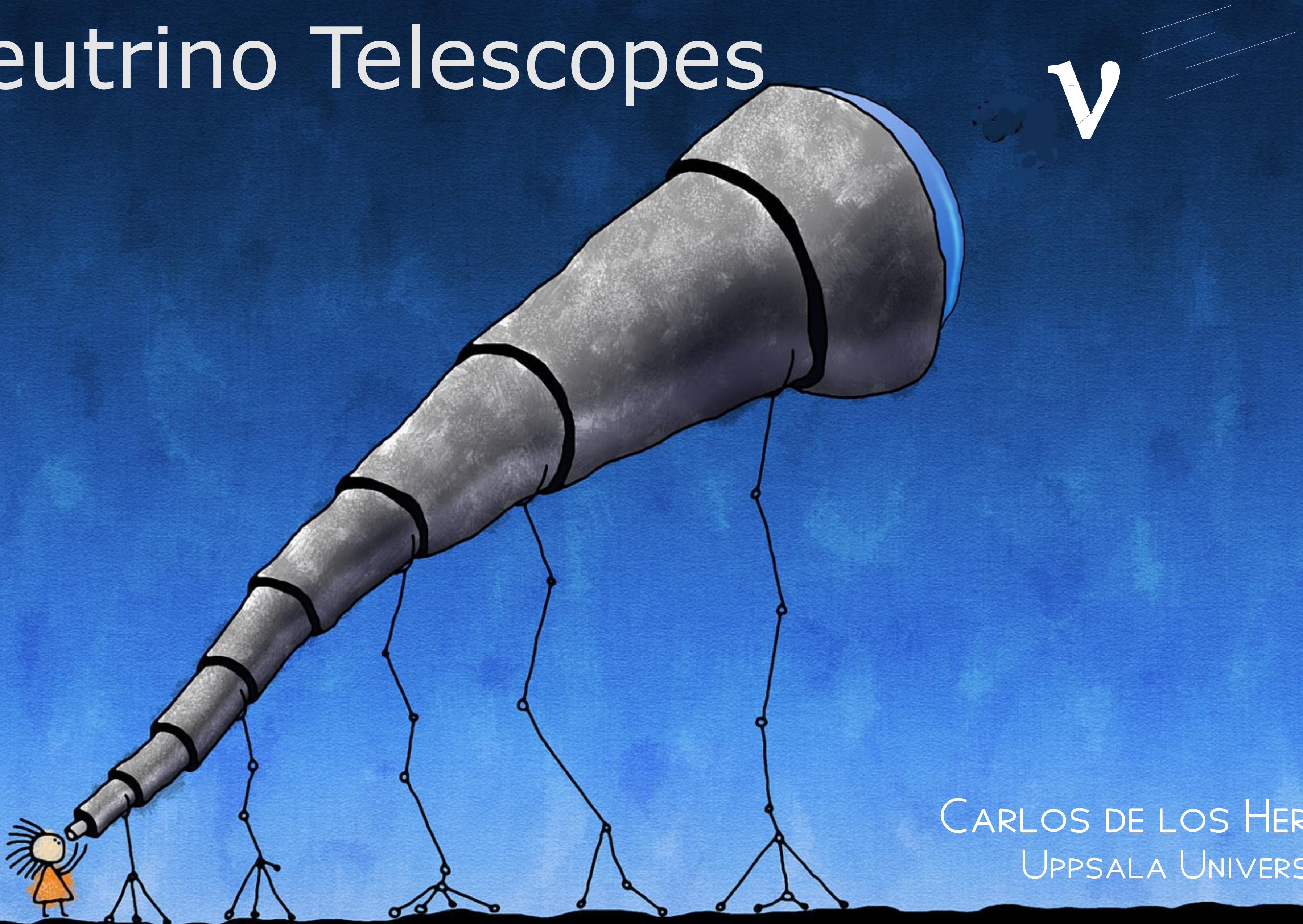
Lecture 1: Neutrino Telescopes



Carlos de los Heros
Uppsala University

ISAPP Summer School “The Multiwavelength Universe”
Belgirate, July 21-30, 2014

- why neutrino astronomy?
- detection techniques
- current projects

Since this is a school, I will focus more on the technical aspects and analysis methods, rather than giving a review of the latest results

aim of this lecture:

at the end of the lecture you should be able to construct and operate

your own neutrino telescope, and know what kind of physics to do with it

I will concentrate in high-energy neutrino telescopes, ie, will not cover underground detectors like SuperKamiokande, which also have sensitivity to some of the physics I will mention

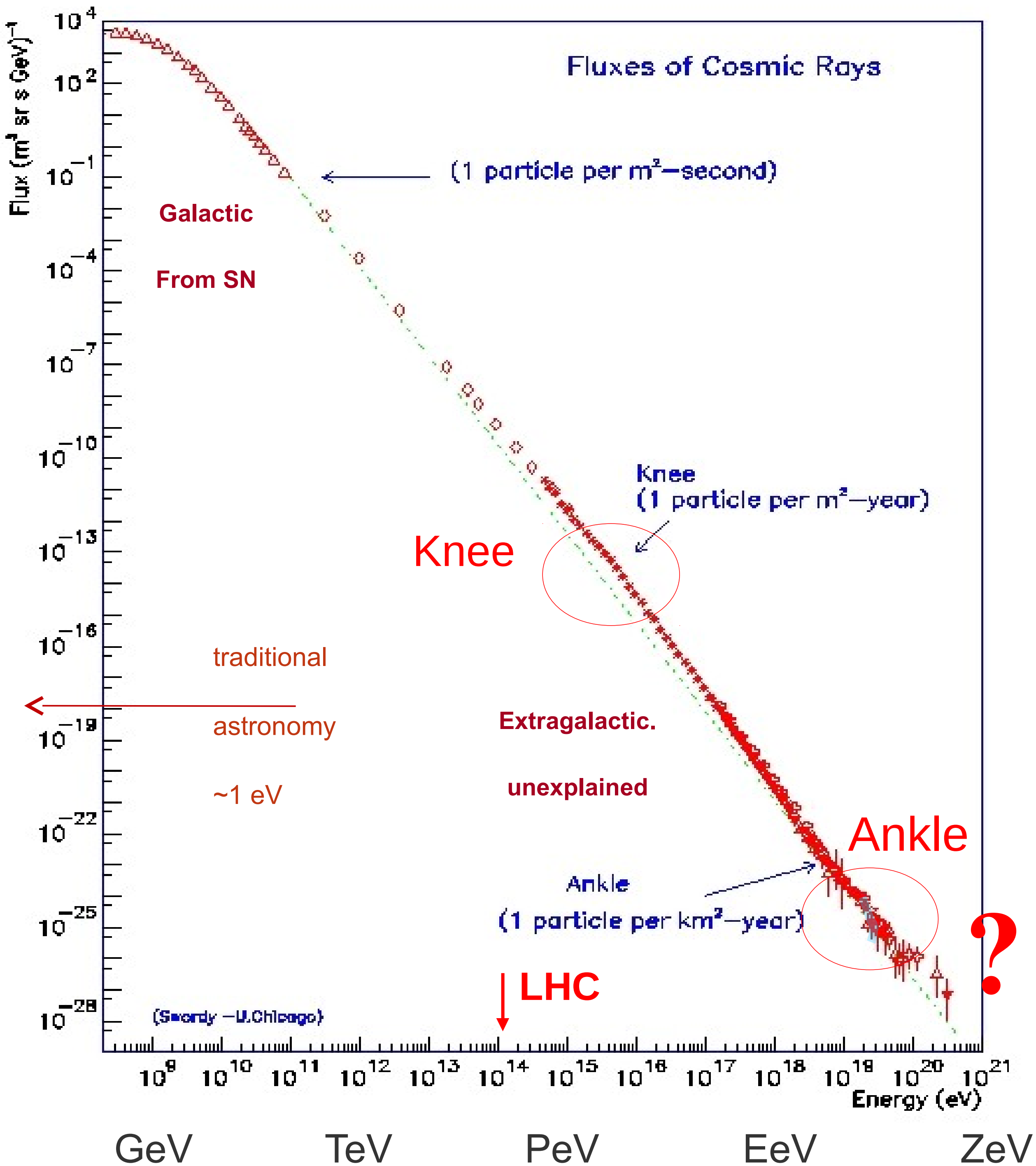
I will mainly show results from IceCube to keep the talk short (and because I am a member of the collaboration)

Results on the topics I will touch upon exist of course for the other projects I will mention (ANTARES, Baikal). See the recent summer conferences for the latest results from them:

Neutrino 2014, http://neutrino2014.bu.edu/

TeVPA/IDM, http://indico.cern.ch/event/278032/

the cosmic ray spectrum



Today we know CR’s are p’s, γ’s and heavier nuclei

CR’s detected at extremely high energies

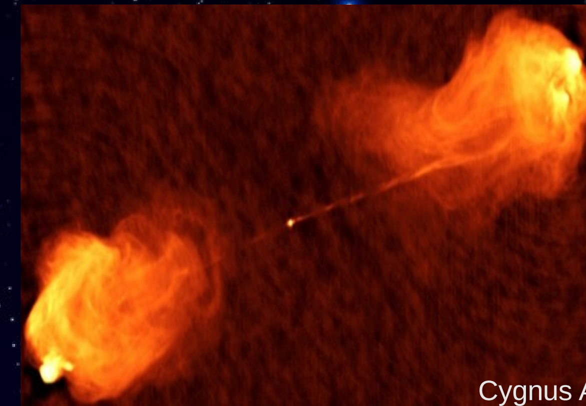
Sources: where do we expect them from?

Sources should also produce neutrinos (undetected so far **?**)

How?:

→ **neutrino telescopes**

aim of neutrino telescopes: neutrino astronomy

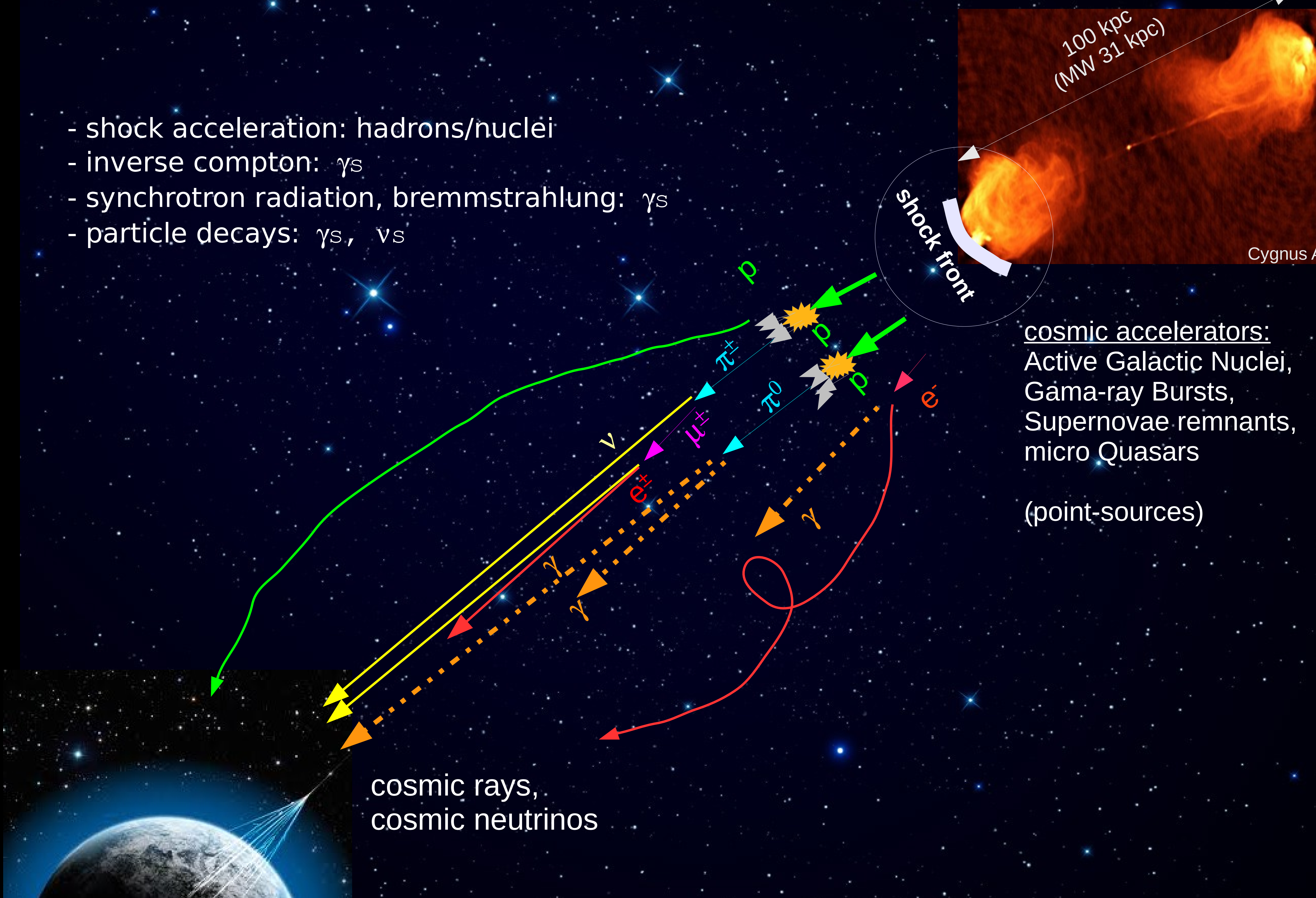


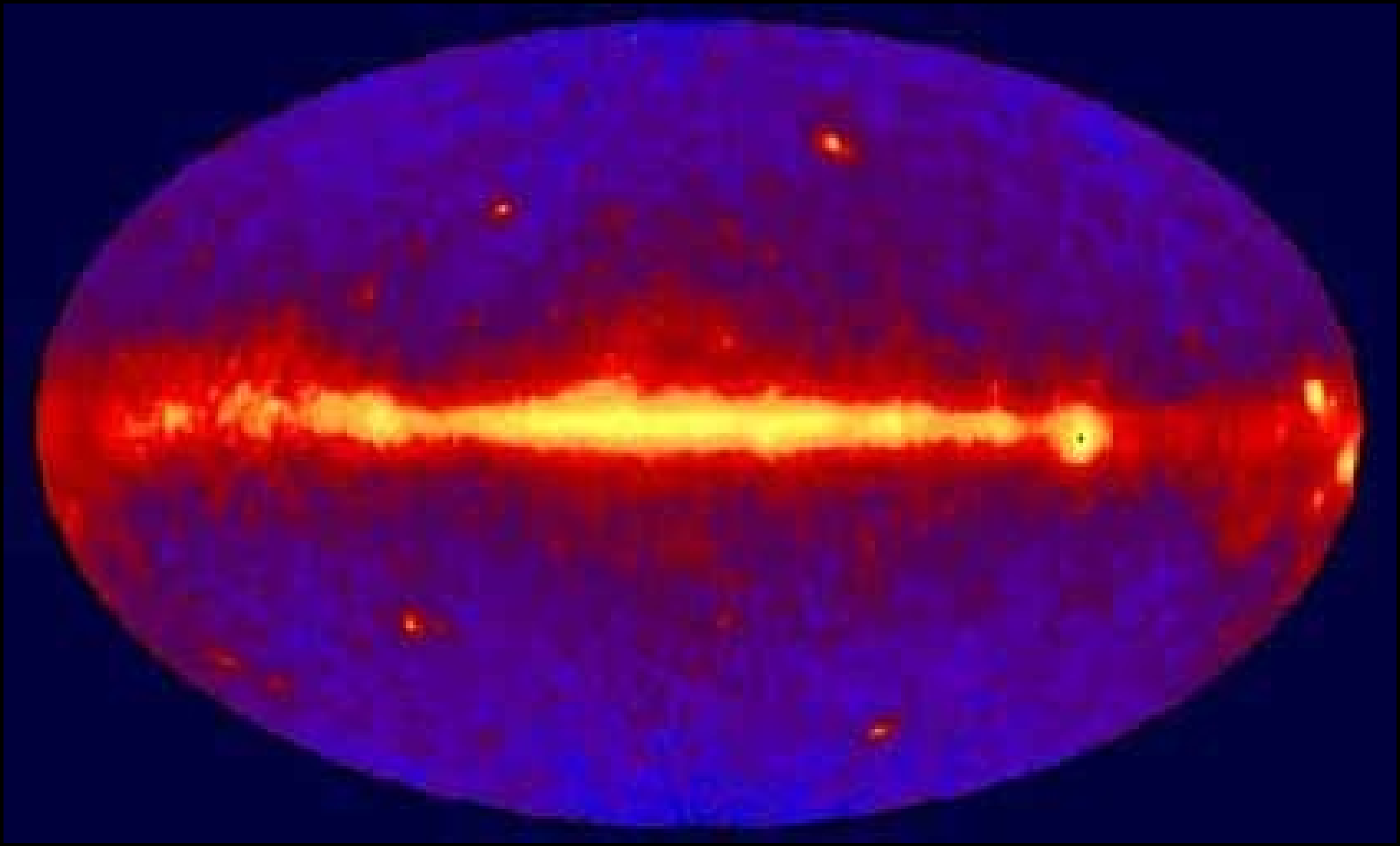
cosmic accelerators:
Active Galactic Nuclei,
Gama-ray Bursts,
Supernovae remnants,
micro Quasars

(point-source searches)

particle production in cosmic accelerators

- shock acceleration: hadrons/nuclei
- inverse compton: γs
- synchrotron radiation, bremmstrahlung: γs
- particle decays: γs , νs





γ ray sky (Fermi.LAT)

even if individual sources are too faint, one could expect a diffuse high-energy neutrino flux from the contribution of all unidentified sources

(all-sky searches)

-Astroparticle physics studies the cosmos through these ‘signatures’:
hadrons (p/nuclei), **leptons** (e+,e-), **photons and neutrinos:**

- protons are charged → deflected by intergalactic magnetic fields

(only very high energy CR’s, E>10^{18} eV, useful for astronomy: they can point)

- **γ**’s easily absorbed by intervening matter
- **ν**’s extremely difficult to detect (only weak interaction)

Detectors:

- p/nuclei, e's: Air shower arrays (surface), satellites (space)
- **γ**’s, e's: Cherenkov telescopes (surface), satellites (space)
- **ν’s: neutrino ‘telescopes’** (underground/underwater)

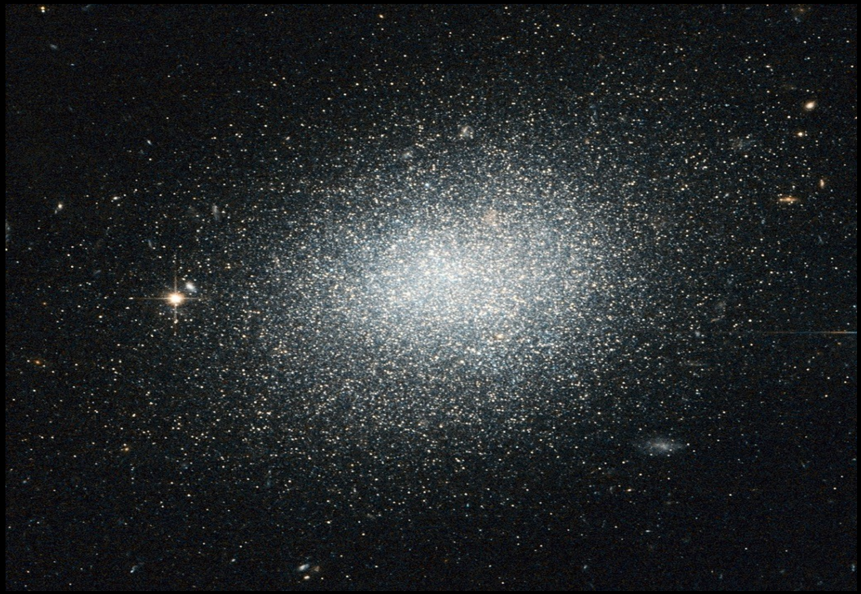
today's topic

other physics with neutrino telescopes

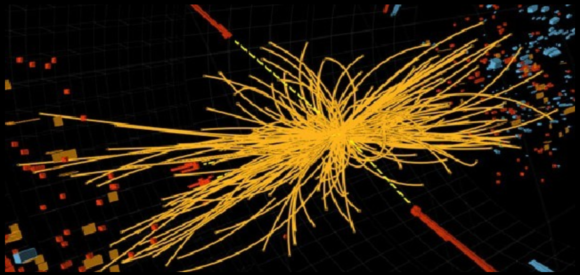
low-energy (MeV) neutrinos from
Supernovae explosions

(no pointing)

other physics with neutrino telescopes



neutrinos from
dark matter annihilations
(tomorrow's lecture)



particle physics:
neutrino properties
monopole/nuclearite searches,
fundamental laws...
(not covered this time)

Reminder:

In modern particle accelerators we collide counter-rotating particles, ie, $p_{beam} = - p_{target}$. That is, the CM system

(b=beam,

t=target)

$$\boldsymbol{P_b} = \left(E_b, \vec{p}_b\right)$$

$$\boldsymbol{P_t} = \left(E_t, \vec{p}_t\right)$$

$$s = \left(\boldsymbol{P_b} + \boldsymbol{P_t}\right)^2 = \left(E_b + E_t, \underbrace{\vec{p}_b + \vec{p}_t}_{=0 \; since \; \vec{p}_t = -\vec{p}_b},\right)^2 = \left(E_b + E_t\right)^2 = E_{CM}^2$$

In the lab frame (rest frame of the target particle), most usual case in detection of astrophysical processes:

$$\boldsymbol{P_b} = \left(E_b, \vec{p}_b\right)$$

$$\boldsymbol{P_t} = \left(m_t, \vec{0}\right)$$

$$s = \left(\boldsymbol{P_b} + \boldsymbol{P_t}\right)^2 = \left(E_b + m_t, \vec{p}_b\right)^2 = \left(E_b + m_t\right)^2 - p_b^2 =$$
$$= E_b^2 + m_t^2 + 2 E_b m_t - p_b^2 = m_b^2 + m_t^2 + 2 E_b m_t = E_{CM}^2$$

$$\boxed{\rightarrow E_{cm} \propto \sqrt{E_b}}$$

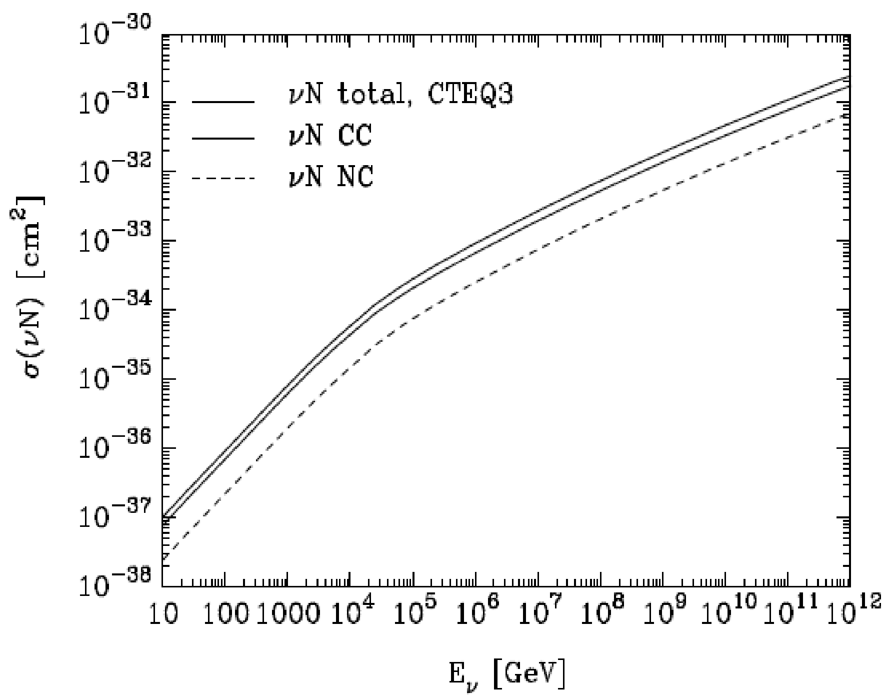
R. Ghandi *et al*, Astropart. Phys. 5, 81 (1996); J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84, 1307, 2012

$$\sigma^{CC}_{\nu_\mu N} = 0.677\times10^{-38}\,cm^2\left(\frac{E_\nu}{1\,GeV}\right) \qquad for\ E_\nu \lesssim TeV$$

$$\sigma^{CC}_{\nu_\mu N} = 5.53\times10^{-36}\,cm^2\left(\frac{E_\nu}{1\,GeV}\right)^{0.363} \qquad for\ E_\nu \gtrsim PeV$$

$$\sigma^{NC}_{\nu_\mu N} = 0.28\times10^{-38}\,cm^2\left(\frac{E_\nu}{1\,GeV}\right) \qquad for\ E_\nu \lesssim TeV$$

$$\sigma^{NC}_{\nu_\mu N} = 2.31\times10^{-36}\,cm^2\left(\frac{E_\nu}{1\,GeV}\right)^{0.363} \qquad for\ E_\nu \gtrsim PeV$$



example:

interaction length of a ν_μ of energy E GeV

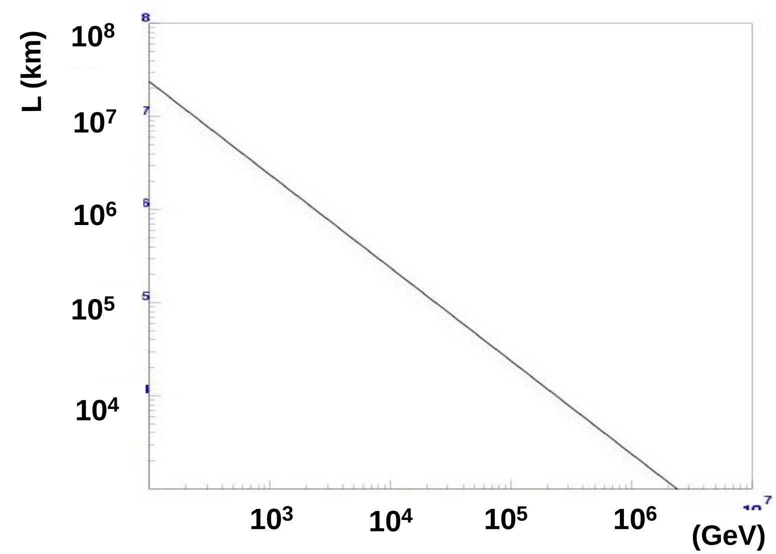
$$P = \sigma N_A \rho L \qquad [cm^2\ nucl^{-1}]\ [nucl\ gr^{-1}]\ [gr\ cm^{-3}]\ [cm]$$

$$L = \frac{P}{\sigma N_A \rho} = \frac{1}{\sigma N_A \rho} = \frac{1}{0.7\times10^{-38}\,E\ N_A\ \rho}$$

$$L = \frac{1}{0.7\times10^{-38}\,E\ \ 6.022\times10^{23}\ \ 1} =$$

$$= \frac{1}{4.21\times10^{-15}\,E/GeV}\ cm$$

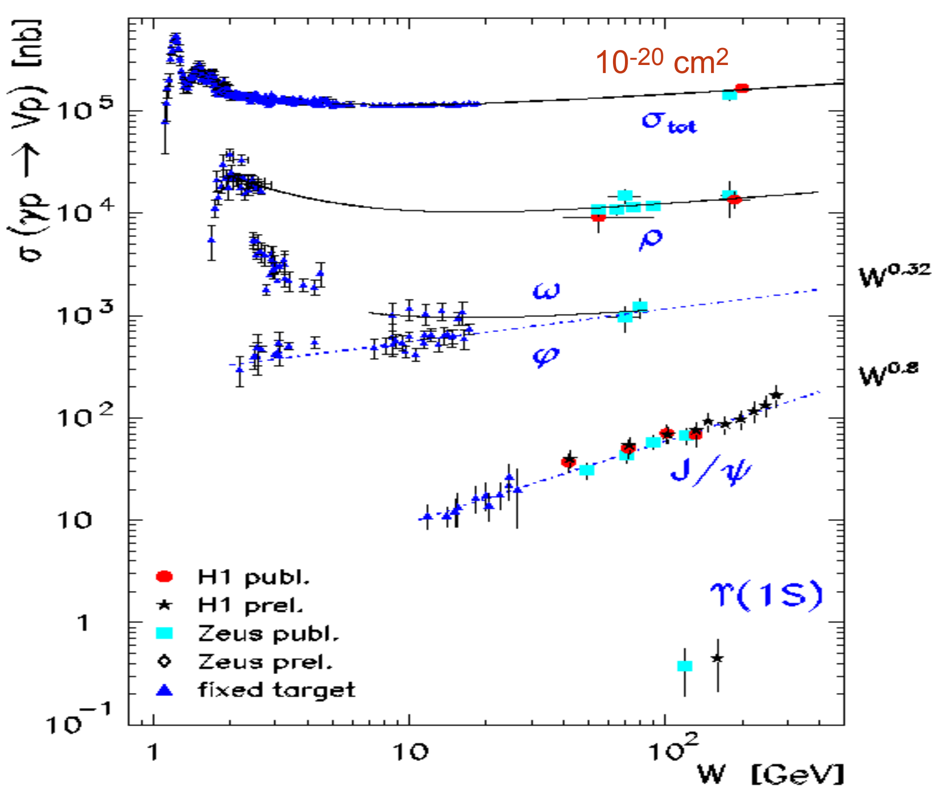
$$= \frac{2.37\times10^{9}}{E/GeV}\ km$$

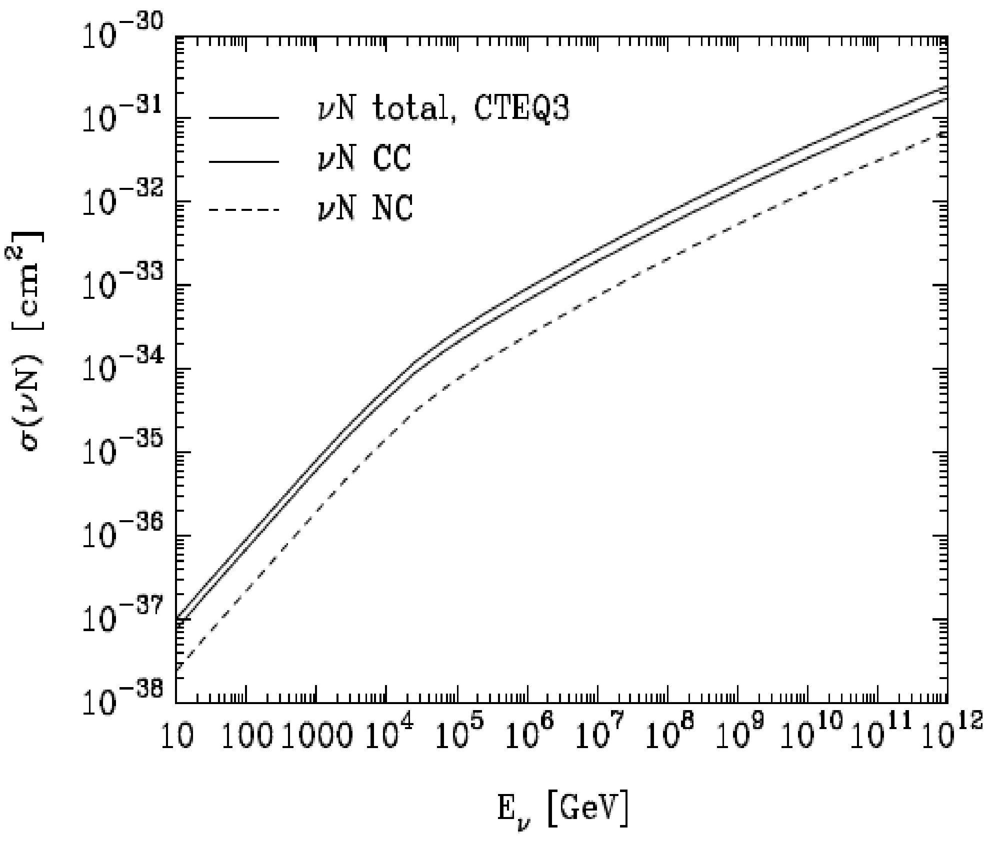


reminder: neutrino Xsection with matter

R. Ghandi *et al*, Astropart. Phys. 5, 81 (1996); J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84, 1307, 2012

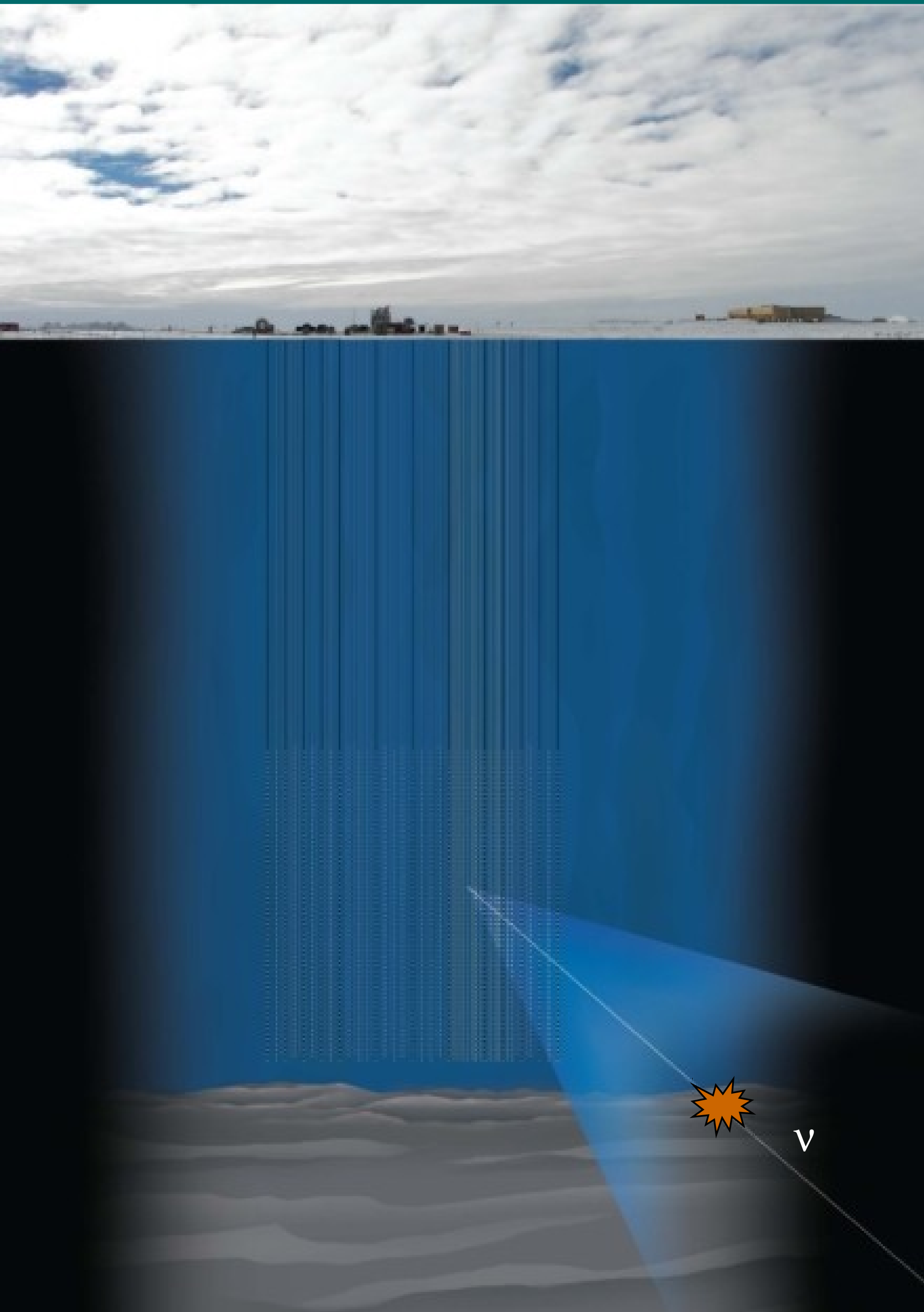
compare: γ+p Xsection

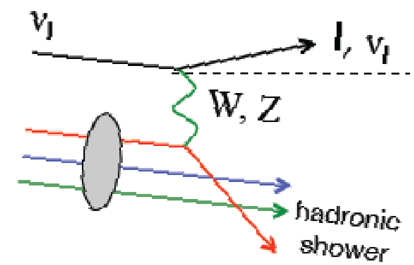




(1 barn =10^{-24} cm^2 1 nanobarn =10^{-33} cm^2)

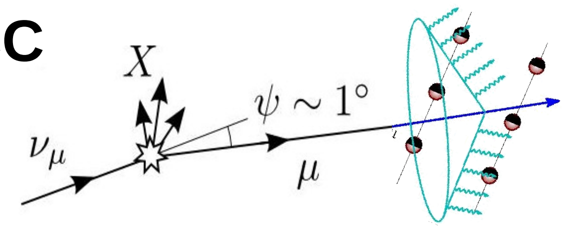
neutrino detection principle



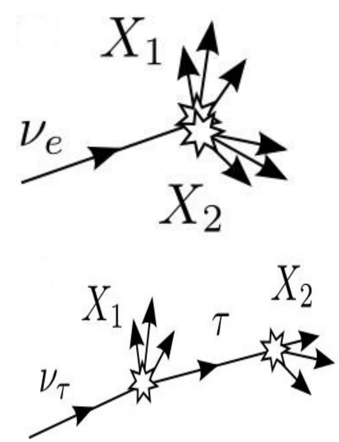


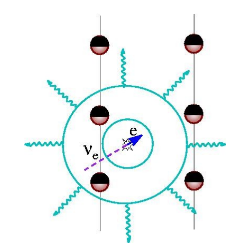
Detect Cherenkov light of interaction products

CC



μ tracks >100m @ E>100 GeV

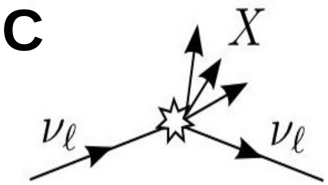




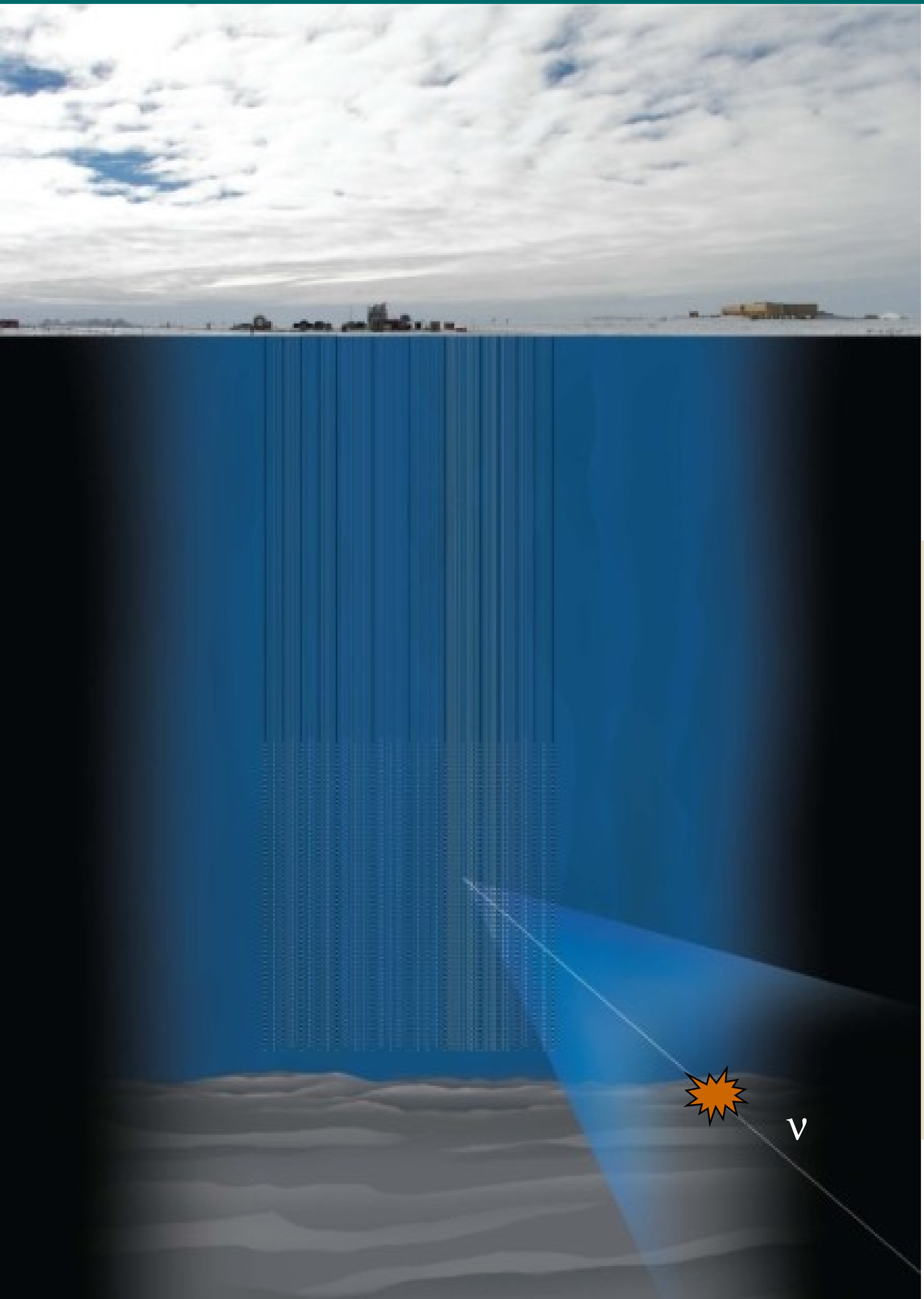
e^{+-} :electromagnetic shower

τ^{+-} : hadronic shower

NC



neutrino detection principle



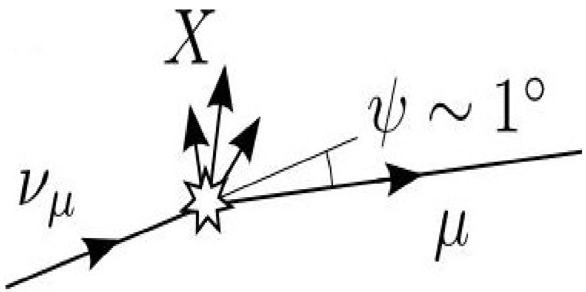
Array of optical modules in a transparent medium to detect the light emitted by relativistic secondaries produced in charged-current ν-nucleon interactions

Need ns timing resolution

Need HUGE volumes (tiny Xsects & fluxes)

neutrino detection principle

CC ν_μ



$$\sqrt{\langle \psi^2_{\nu\mu} \rangle} \propto \sqrt{m_p / E_\nu}$$

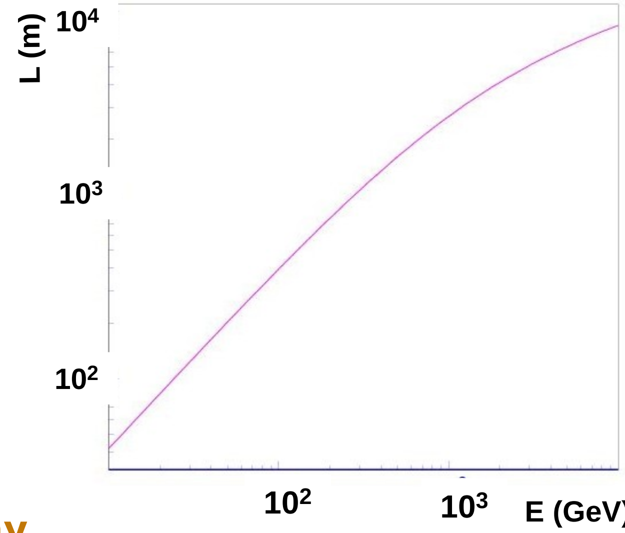
for $E\nu \gtrsim$ TeV, $\theta_{\nu\mu} \lesssim 1^\circ$

muon range in ice/water with continuous energy losses:

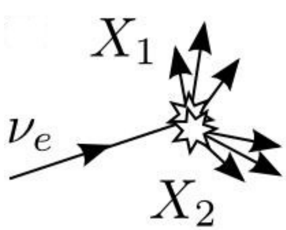
$$L_\mu = \frac{1}{b} \log\left(b\left(\frac{E_\mu}{a}\right) + 1 \right)$$

a, *b* material dependent constants

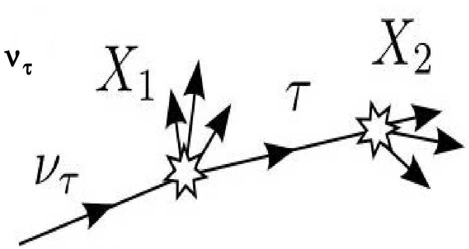
- possible to point, ie, possible to do astronomy



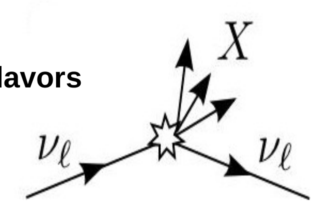
CC ν_e



CC ν_τ



NC all flavors

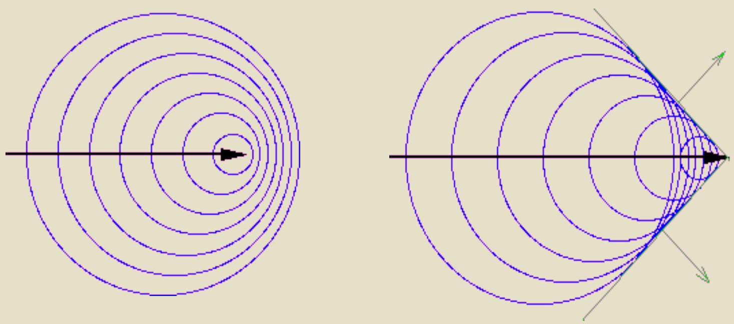


- e, τ, immediately loose energy through radiative processes → deposit energy in a localized region around the interaction point

- worst pointing. No lever arm to reconstruct tracks

- better energy estimation through amount of light deposited in the detector

Cherenkov emission



v<c/n   *v>c/n*

Emission of light by relativistic charged particles traversing a medium at a higher speed than the speed of light in the medium, *c/n*. The radiation is emitted at a characteristic angle

$$\cos\theta = \frac{1}{\beta n}$$

and it appears above a critical velocity $\beta > 1/n$, ($\cos\theta$ must be ≤ 1) which depends on the medium. For the most common case of relativistic particles, $\beta \approx c$, $\cos\theta = 1/n$.

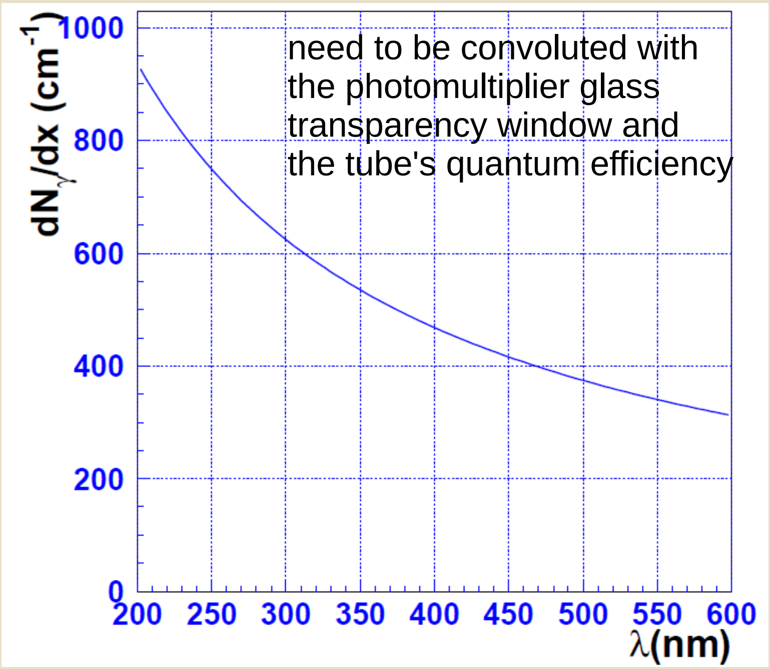
Atoms in the vicinity of the particle become polarized and emit coherent radiation when returning to the equilibrium state

The number of photons emitted per unit length and wavelength is (α is the EM constant)

$$\frac{dN^2}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

typical wavelengths of emission are ultraviolet-blue

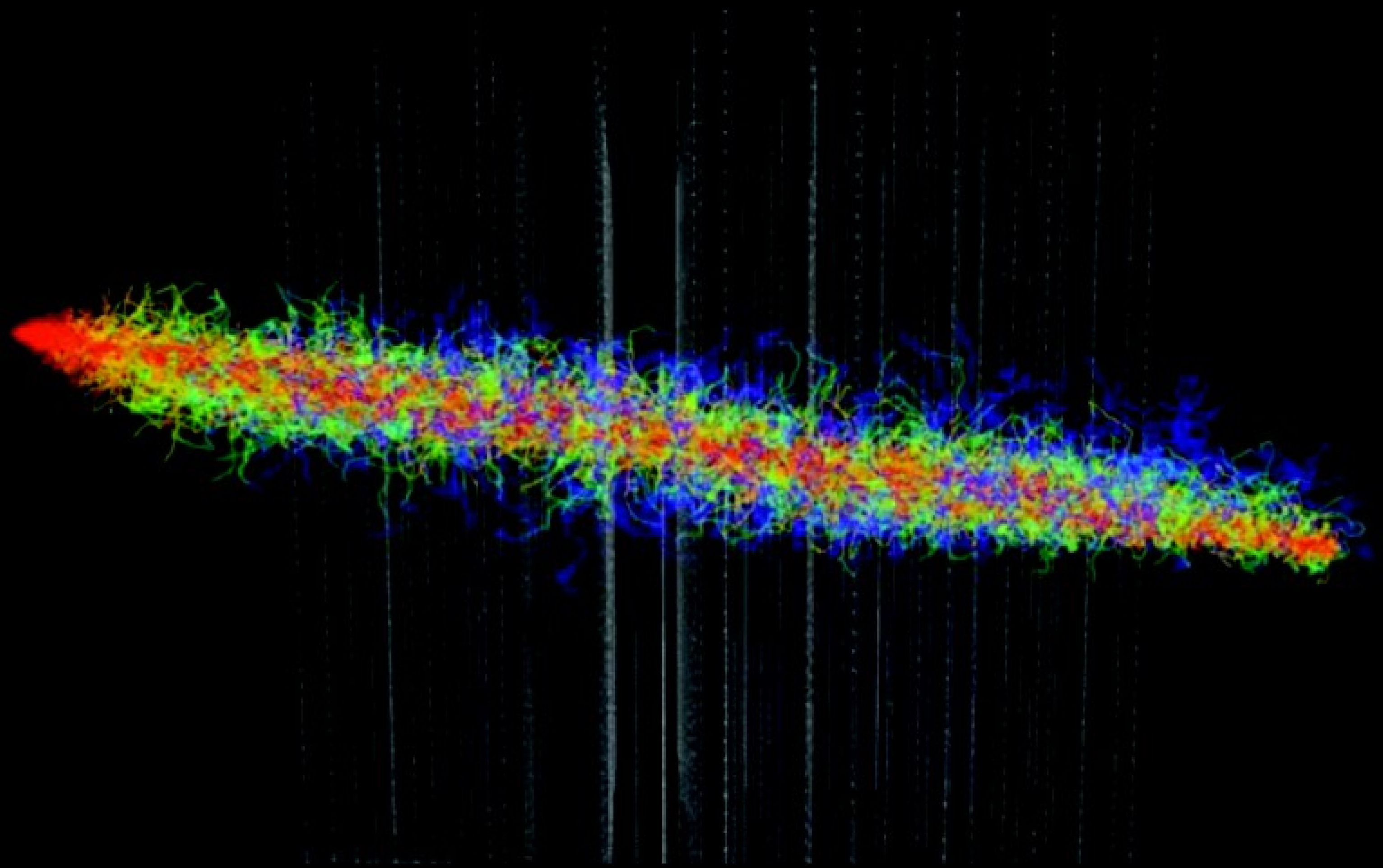
$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \text{ photons/cm}$$



~ 150 photons/cm in water for the relevant λ range.

Note that it is not the particle that emits the radiation, but the material. The particle does not loose energy through Cherenkov radiation and therefore the effect can be used over large distances

Cherenkov emission



simulation of the Cherenkov light emitted by a muon in ice

red: earlier photons -----> blue: late photons

(with respect to the muon track)

range/lifetime of a 1 TeV muon

$$E^2 = p^2c^2 + m^2c^4 \qquad (E = 1\ \text{TeV},\ m = 105\text{MeV}/c^2)$$

$$E \approx pc = mc\gamma v = mc\frac{v}{\sqrt{1-v^2/c^2}} = mc^2\frac{\beta}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{E/mc^2}{\sqrt{1+E^2/m^2c^4}} \qquad \text{for } E = 10^6 \text{ MeV}, \quad \beta = 0.999999994$$

$$t' = \frac{t}{\sqrt{1-\beta^2}}$$

for $\beta = 0.999999994$, $\quad t' = 10^4 t = 10^4 \text{x} 2.2\times10^{-6} s = 0.022 s$

$$v = 0.999999994c \Rightarrow v \approx 3\times10^8 m/s$$

$$L = v \times t \approx 10^3 km$$

no energy losses taken into account ! Just time dilation

range/lifetime of a 1 TeV tau

$$E^2 = p^2c^2 + m^2c^4 \qquad (E = 1\,\text{TeV},\, m = 1.78\,\text{GeV}/c^2)$$

$$E \approx pc = mc\gamma v = mc\frac{v}{\sqrt{1 - v^2/c^2}} = mc^2\frac{\beta}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{E/mc^2}{\sqrt{1 + E^2/m^2c^4}} \qquad \text{for } E = 10^3\ \text{GeV}, \quad \beta = 0.99999841$$

$$t' = \frac{t}{\sqrt{1-\beta^2}}$$

for $\beta = 0.999998$, $\quad t' = 561t = 561\text{x}290\text{x}10^{-15}s = 1.63\text{x}10^{-10}s$

$$v = 0.999998c \Rightarrow v \approx 3\text{x}10^8 m/s$$

$$L = v\text{x}t \approx 0.05m$$

no energy losses taken into account ! Just time dilation

energy loss of secondaries in detector medium

what about energy losses? We are talking of HUGE detectors compared with traditional particle physics detectors

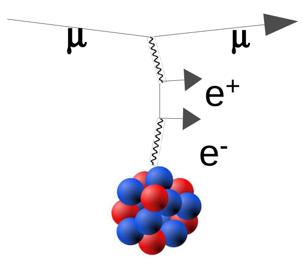
$$-dE/dx = \alpha(E) + \beta(E)E$$

α and β material-dependent constants

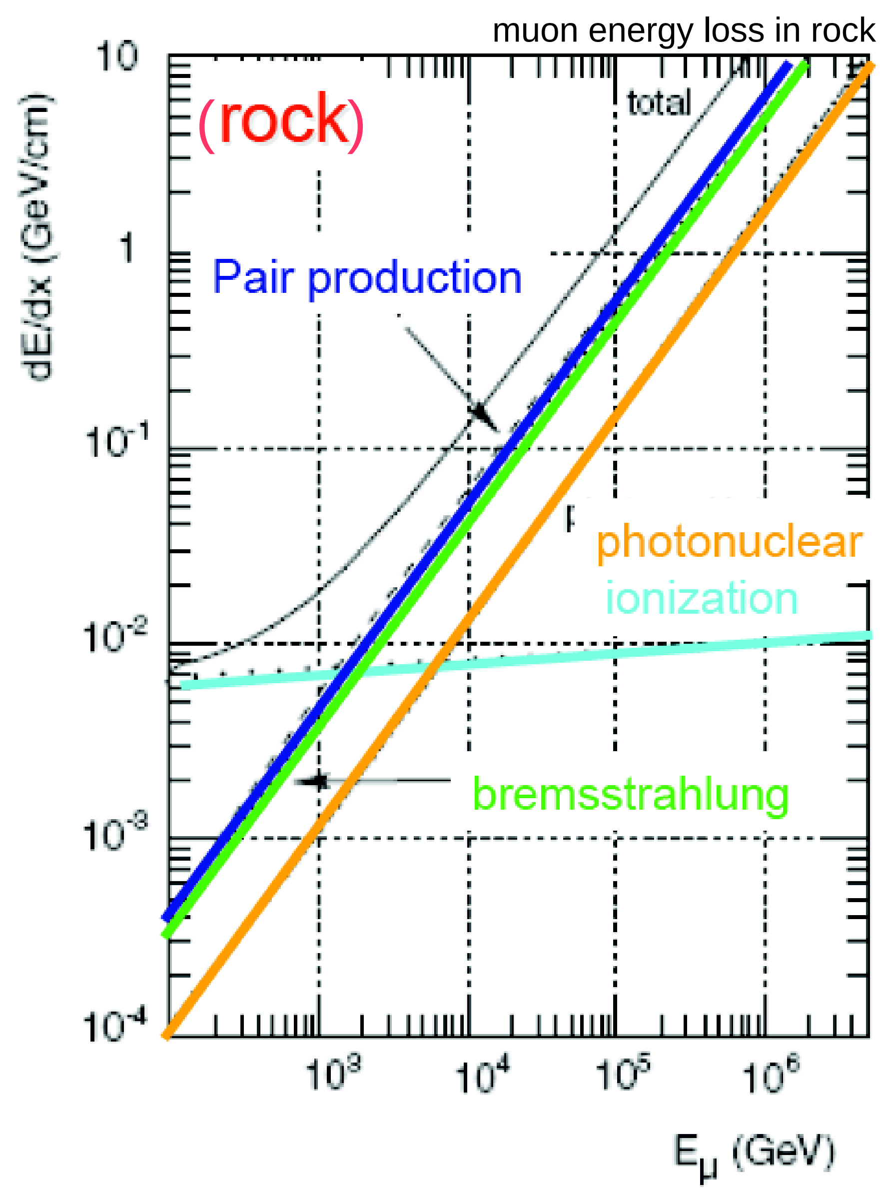
ionization: $\propto$ 1/m

photonuclear: inelastic interaction of muons with nuclei

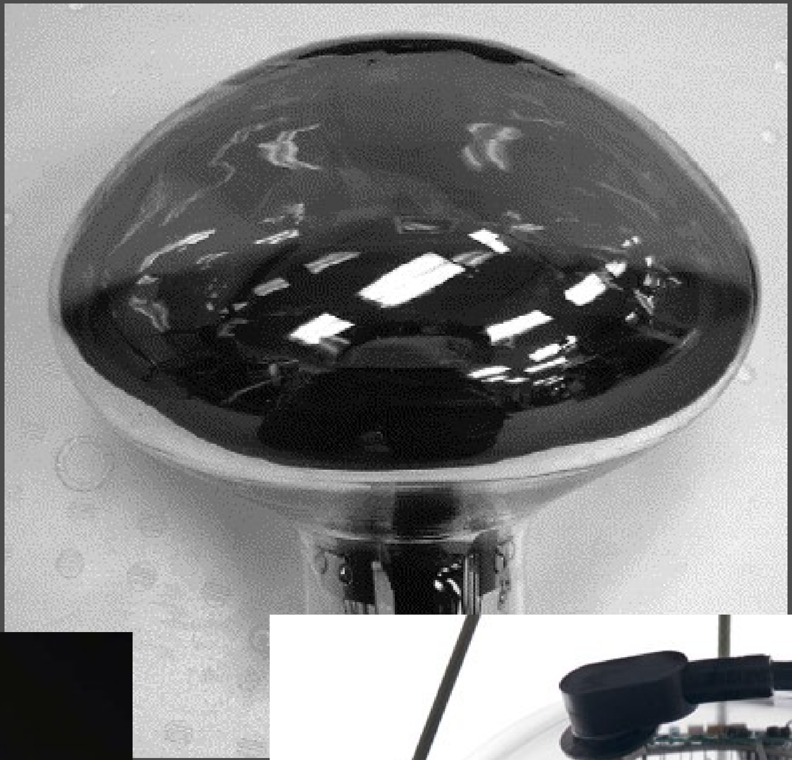
pair production:



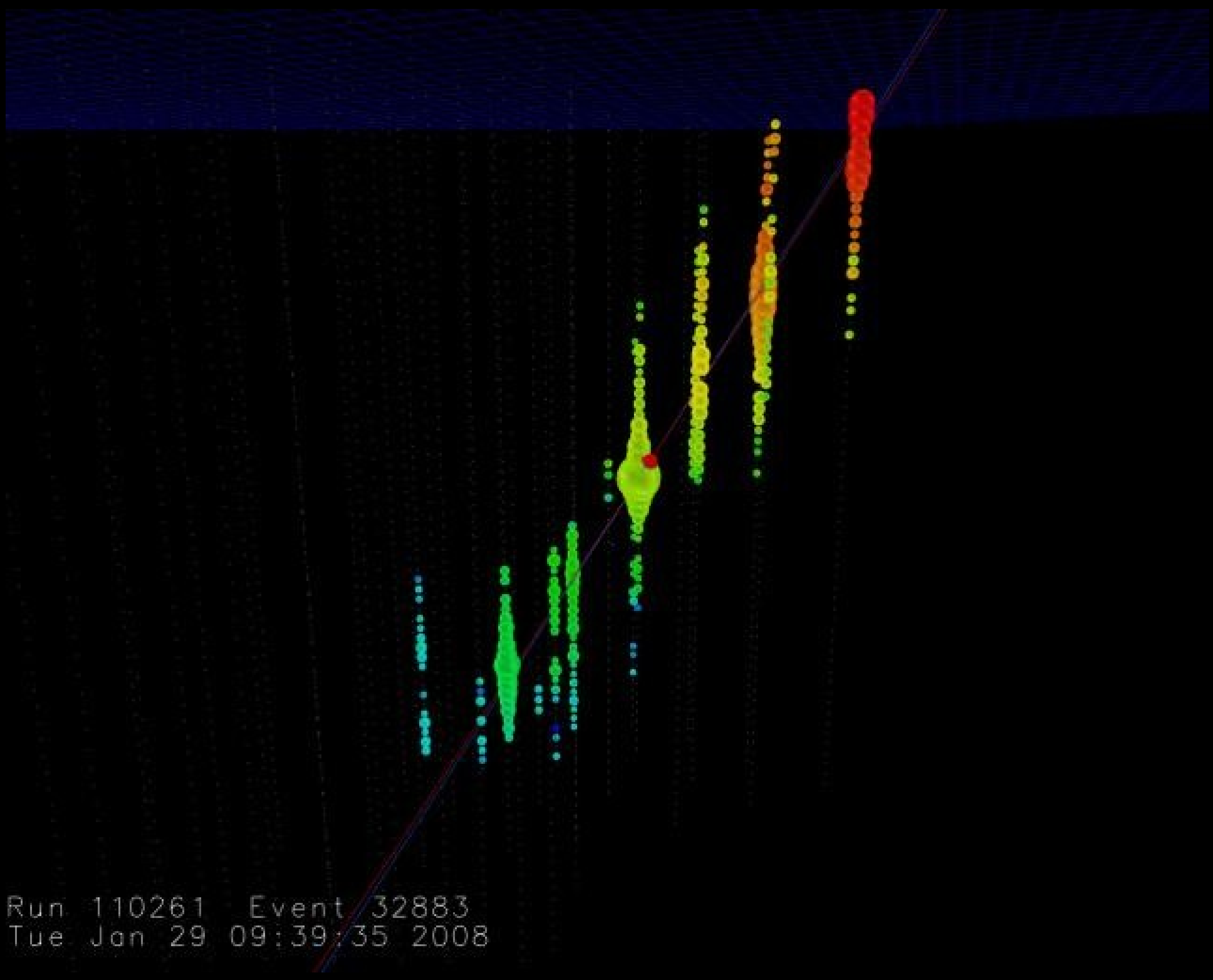
bremsstrahlung: radiation emitted by an a(de)celerated particle when interacting with the EM field of nuclei in a material, $\propto 1/m^2$



Chrenkov light detection: optical modules



Cherenkov emission



a muon as recorded in IceCube

red: earlier photons -----> blue: late photons

(with respect to the trigger time)

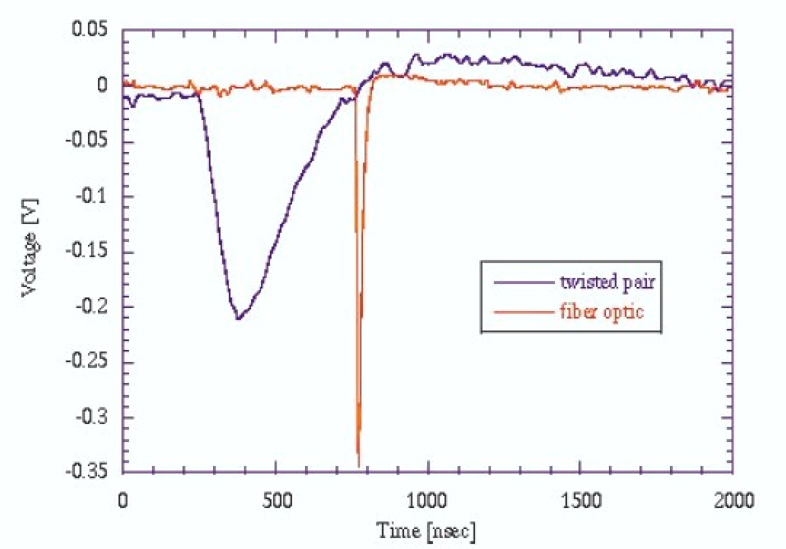
need ns resolution in order to be able to reconstruct muon direction.

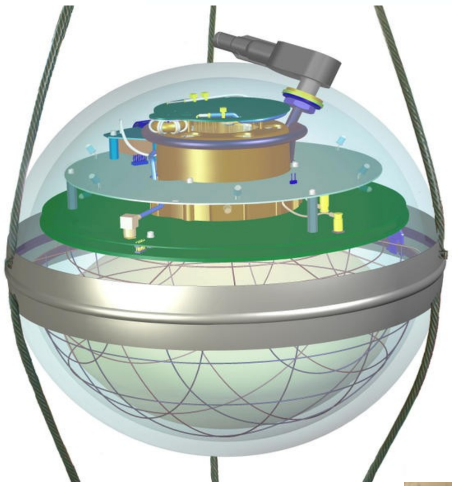
Fiber optics provide the desired signal resolution. But:

- expensive for big detectors (~km^3 instrumented volume)
- not reliable in the extreme conditions of cold/pressure

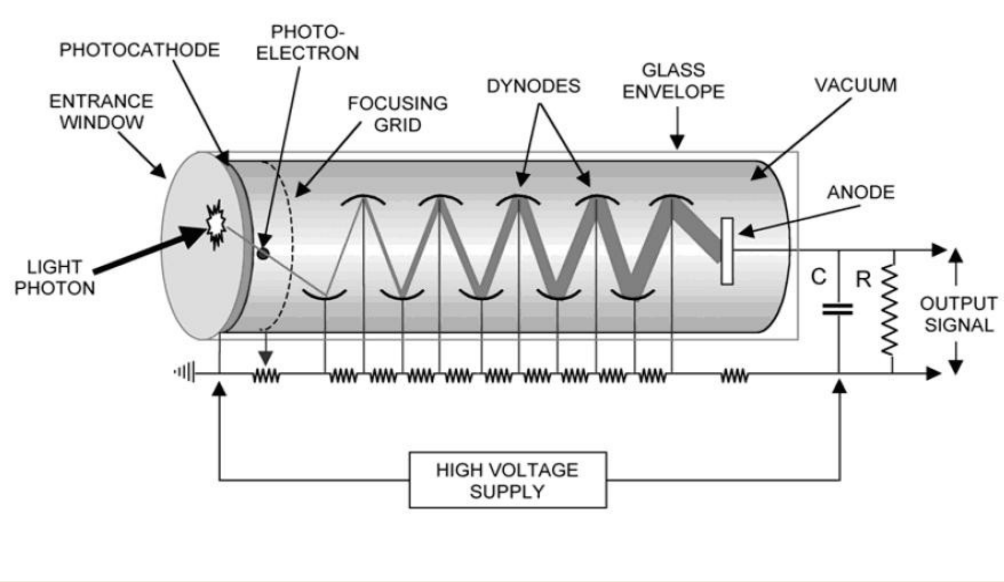
Copper cables: Robust but signal is delayed in the ~km long path to the data center

→ modern neutrino telescope designs digitize the PMT signal in-situ and send the resulting bit sequence to the computers in the lab in the surface.





collecting light: the photomultiplier tube



A 'reverse lightbulb' : light → electrical pulse

Based on the photoelectric effect:

incident photons eject electrons from a sensitive material deposited on the entrance window

The electrons are accelerated in steps through HV-separated secondary cathodes (dynodes), where the incoming electron ejects more electrons. Dynodes are made of materials with easy secondary electron emission (BeO, Mg-O-Cs, Sb-K-Cs ...)

Operational voltage: several hundred to few thousand V

The whole chain can reach amplification factors of 10^8

→ a measurable electrical pulse is produced: *O*(few hundred) mV and few ns wide.

<u>Advantage</u>: PMTs are sensitive to individual photons!

Not all incident photons will cause electron emission

→ Quantum efficiency: N_e/N_γ Usually ~20%

Performance determined by window transparency

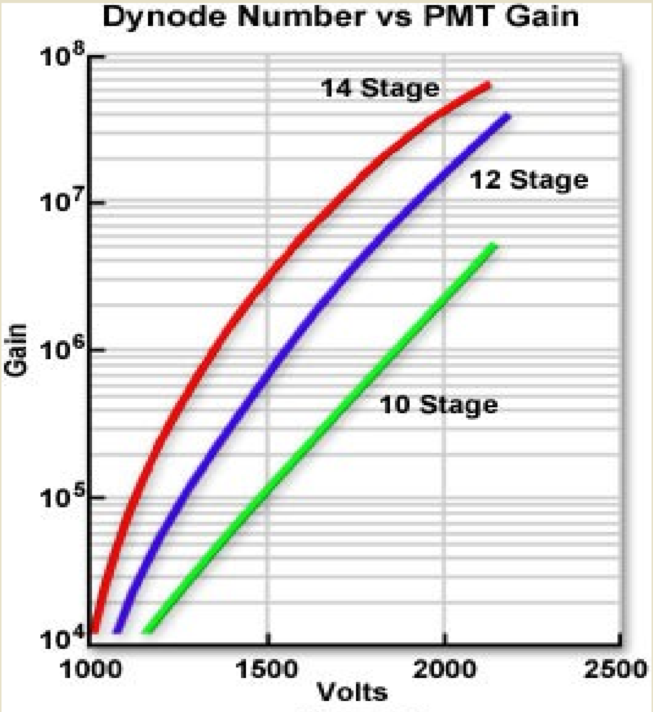
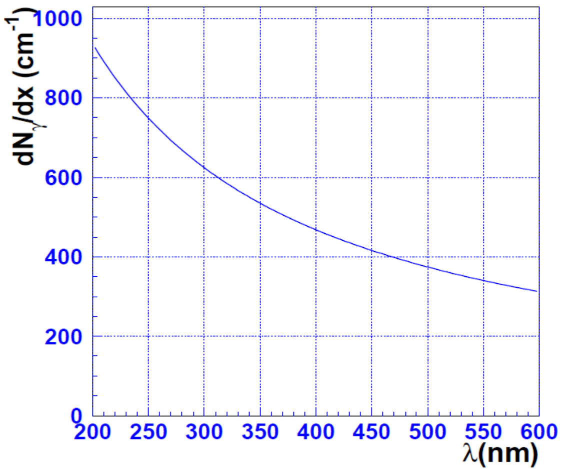
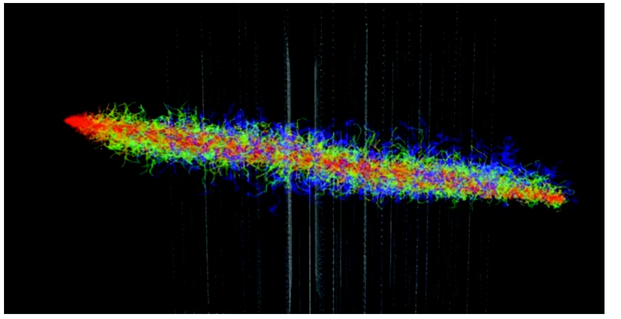


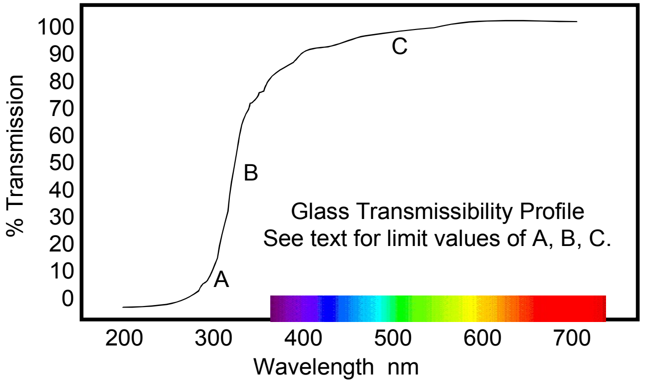
Figure 1

physics vs technology: what you get and what you see

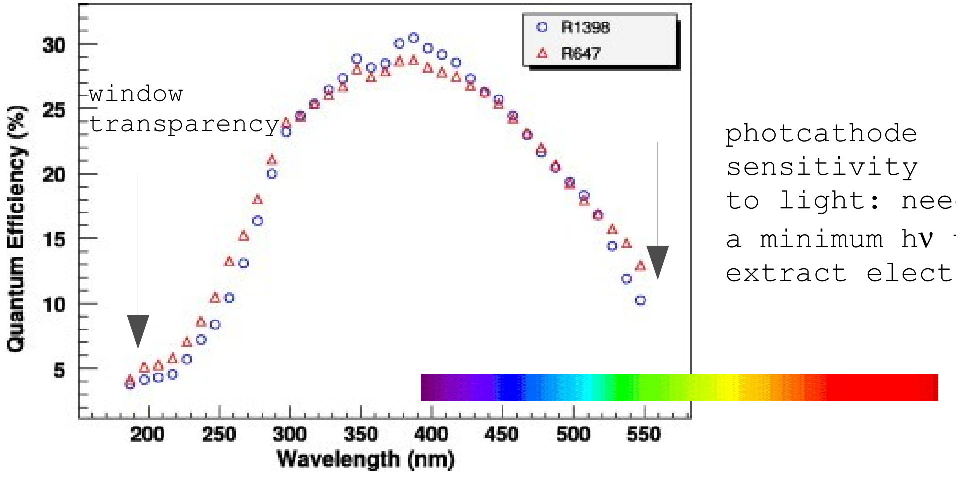




Cherenkov emission: continuous as a function of 1/λ



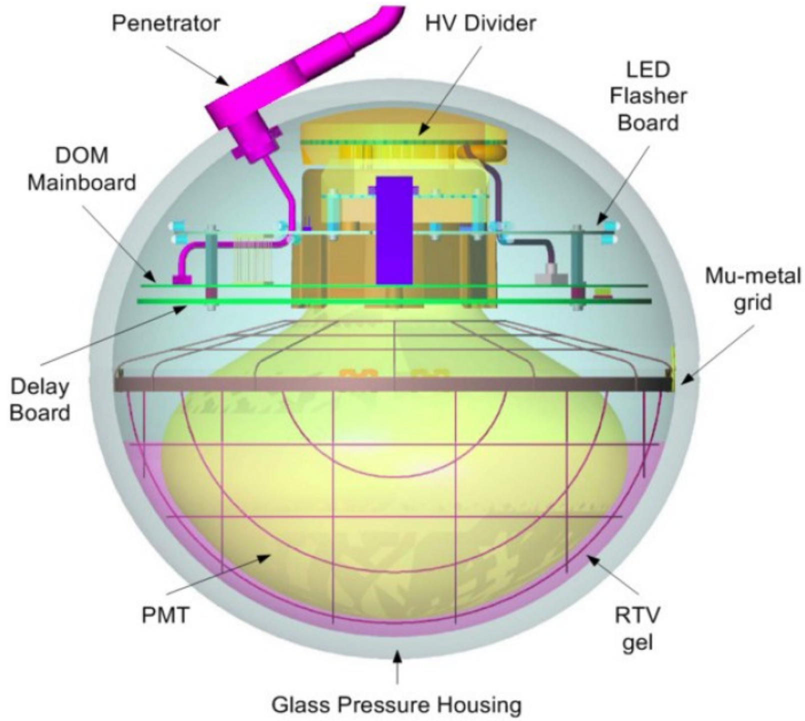
lower wavelengths cut-off by OM protective glass transparency



photcathode sensitivity to light: need a minimum hν to extract electron

higher wavelengths cut-off by photomultiplier tube efficiency

Chrenkov light detection: example, IceCube optical modules



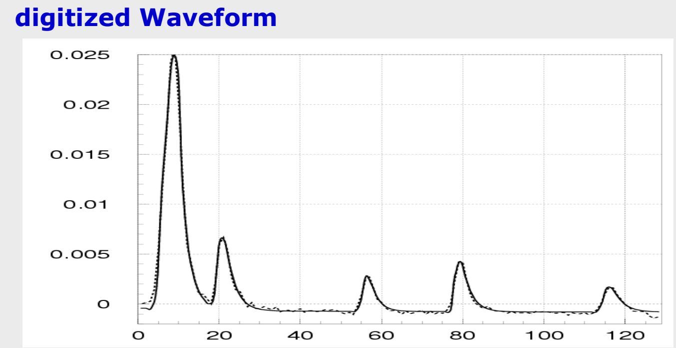
- **PMT**: Hamamatsu, 10''

-**Digitizers**:

ATWD: 3 channels. Sampling 300MHz, capture 400 ns

FADC: sampling 40 MHz, capture 6.4 µs

Dynamic range 500pe/15 nsec, 25000 pe/6.4 µs



- **Flasher board**:

12 controllable LEDs at 0° or 45° for calibration purposes

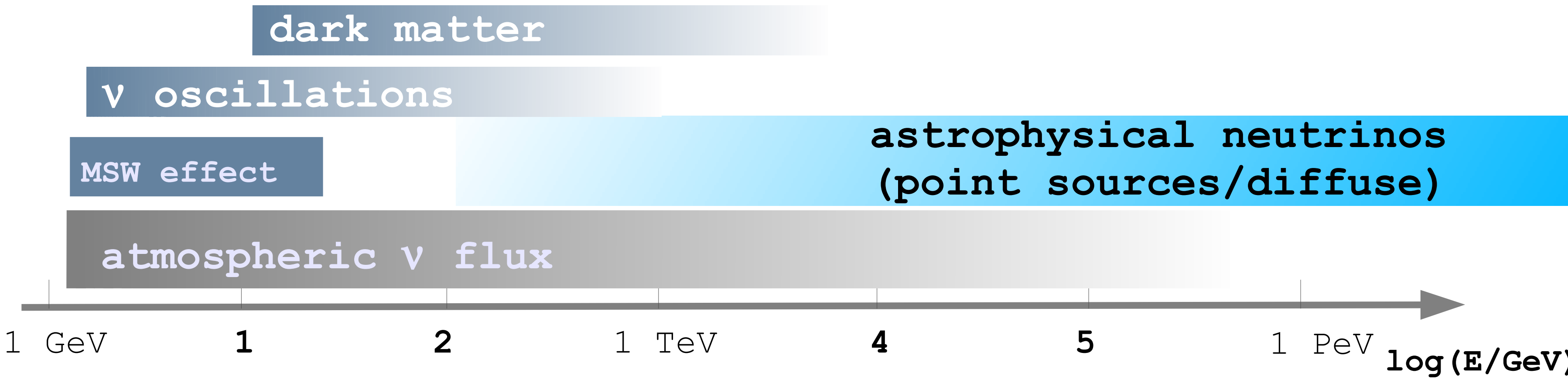
- Dark Noise rate ~ 400 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns
- Power consumption: 3W

Clock stability: 10-10 ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec with 2 ns precision

the projects

the projects

neutrino telescopes are multipurpose...



... multi-flavour detectors

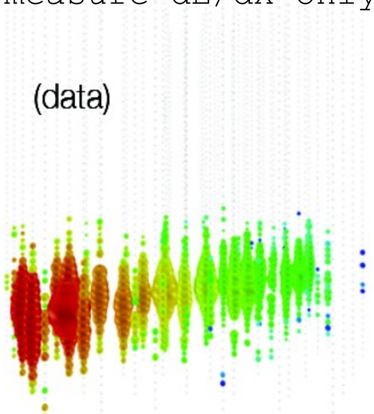
neutrino event signatures (IceCube examples):

tracks:

ν_μ CC

angular resolution ~ 1°

can measure dE/dX only



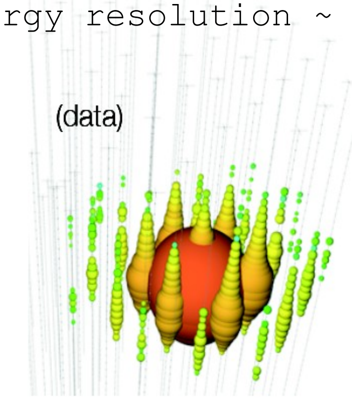
cascades:

ν_e, ν_τ CC

all flavours NC

angular resolution ≥ 10°

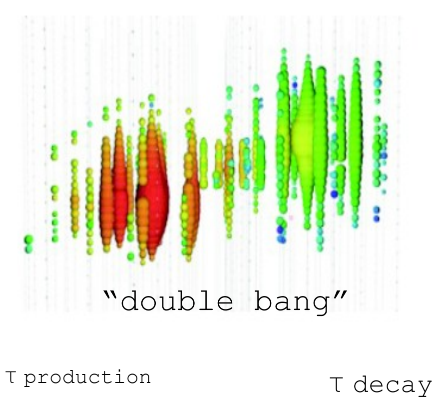
energy resolution ~ 15%



Tau neutrino, CC

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

(simulation)



event reconstruction by Cherenkov light timing:
array of optical modules with ~1ns resolution

→ optical properties of the medium of prime importance

	absorption length	scattering length
South Pole ice (IceCube)	**110 m (@ 400nm)**	**20 m (@ 400nm)**
Lake Baikal	**25 m (@ 480nm)**	**59 m (@ 480nm)**
Mediterranean (ANTARES/KM3NET)	**~60 m (@ 470nm)**	**100-300 m (@ 470nm)**

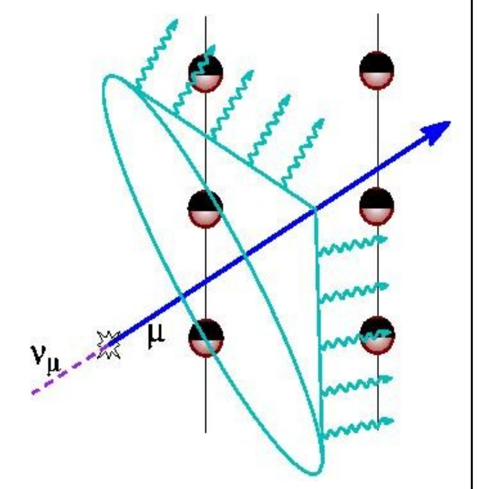
longer absorption length → larger effective volume

longer scattering length → better timing, (ie pointing resolution)

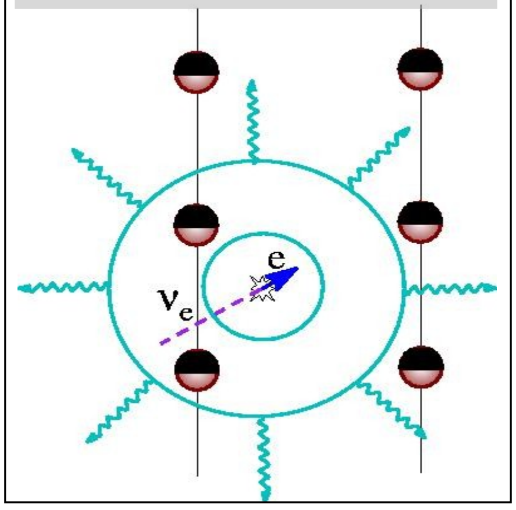
neutrino astronomy possible since $\Theta_{\mu\nu} \approx 0.7° \cdot (E_\nu / \mathrm{TeV})^{-0.7}$

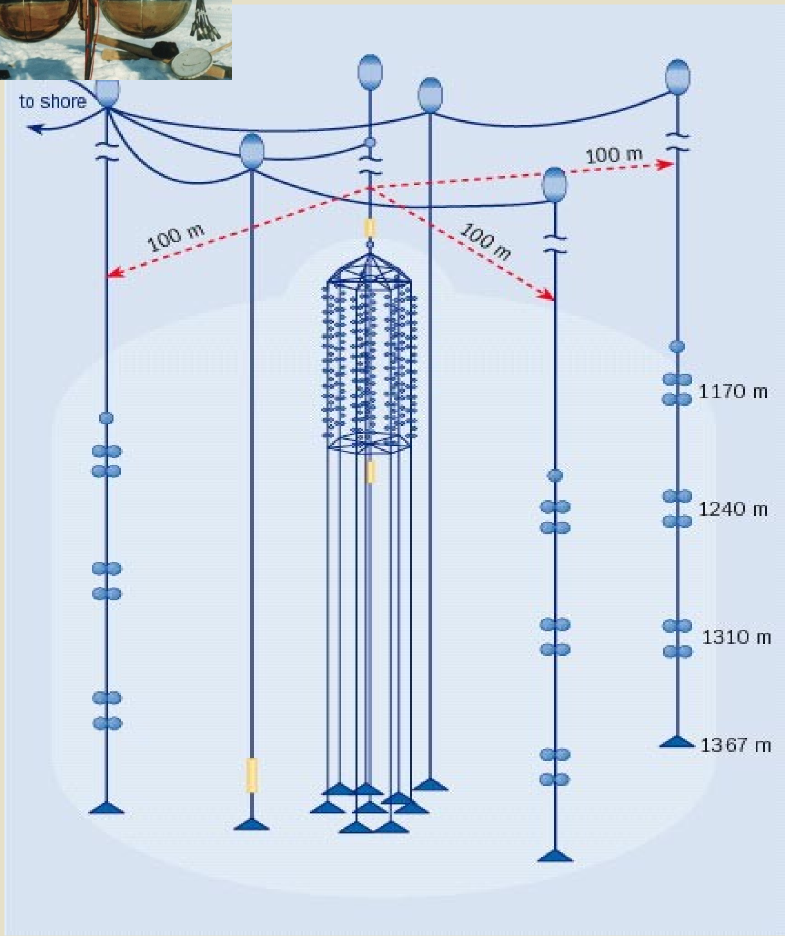
signatures

***O*(km) long muon tracks**



***O*(10m) cascades, ν_e ν_τ neutral current**





NT-200

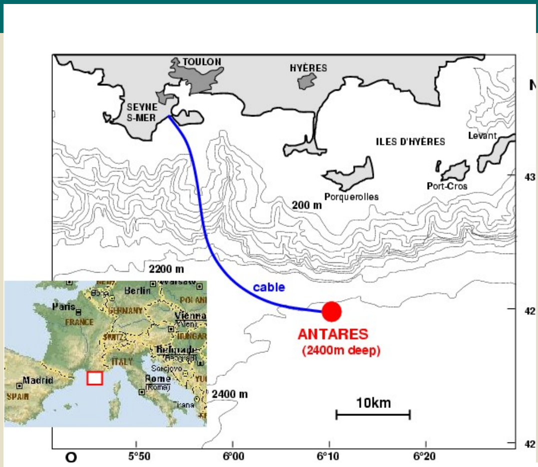
- 8 strings with 192 optical modules
- 72 m height, 1070 m depth
- μ effective area >2000 m^2 (E_μ>1 TeV)
- Running since 1998

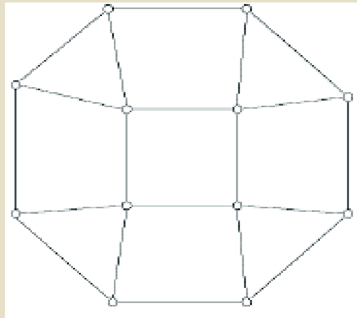
NT-200+

- **commisioned April 9, 2005.**
- 3 new strings, 200 m height
- 1 new bright Laser for time calibration

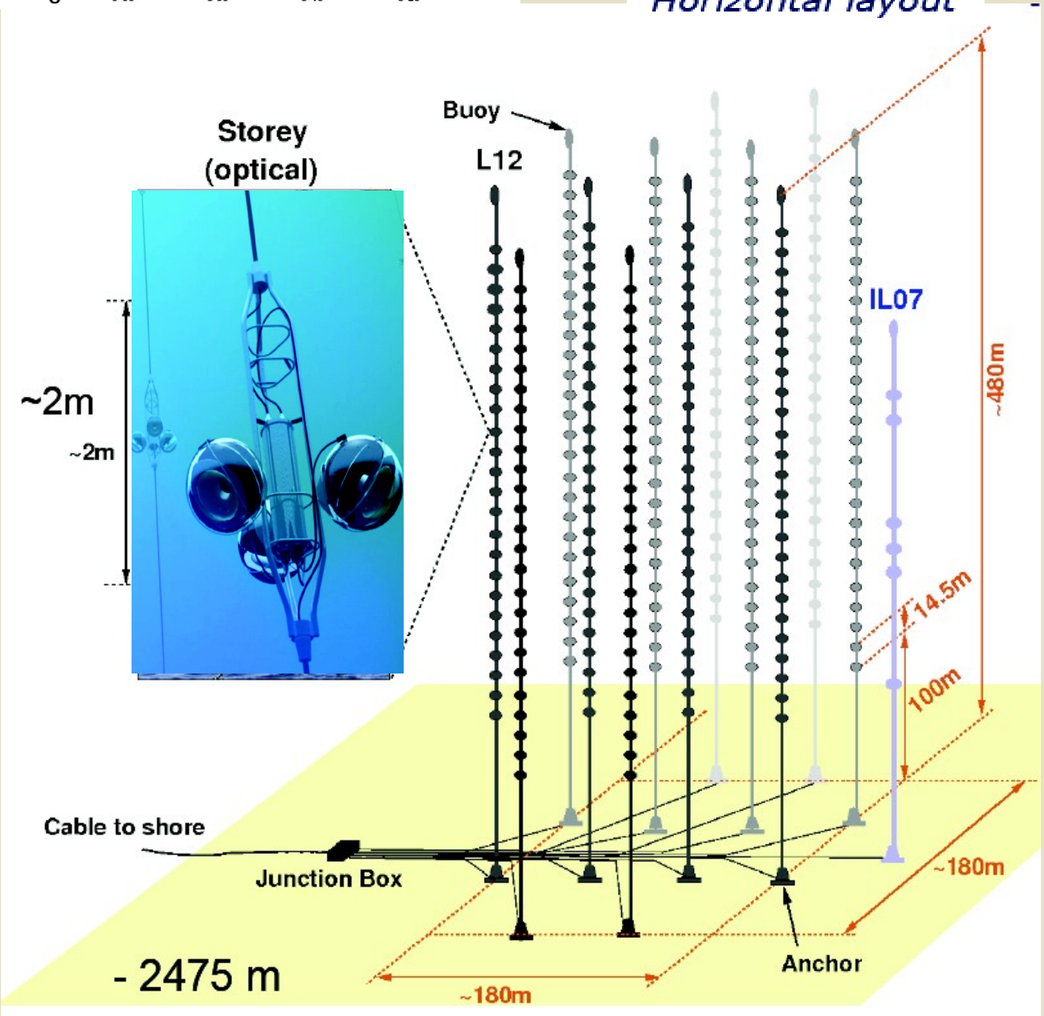
- new DAQ
- 2 new 4km cables to shore

the ANTARES neutrino telescope





Horizontal layout



2.5 Km deep in the Mediterranean

12 lines

25 ‘storeys’ with 3 OMs each

350 m long strings (active height)

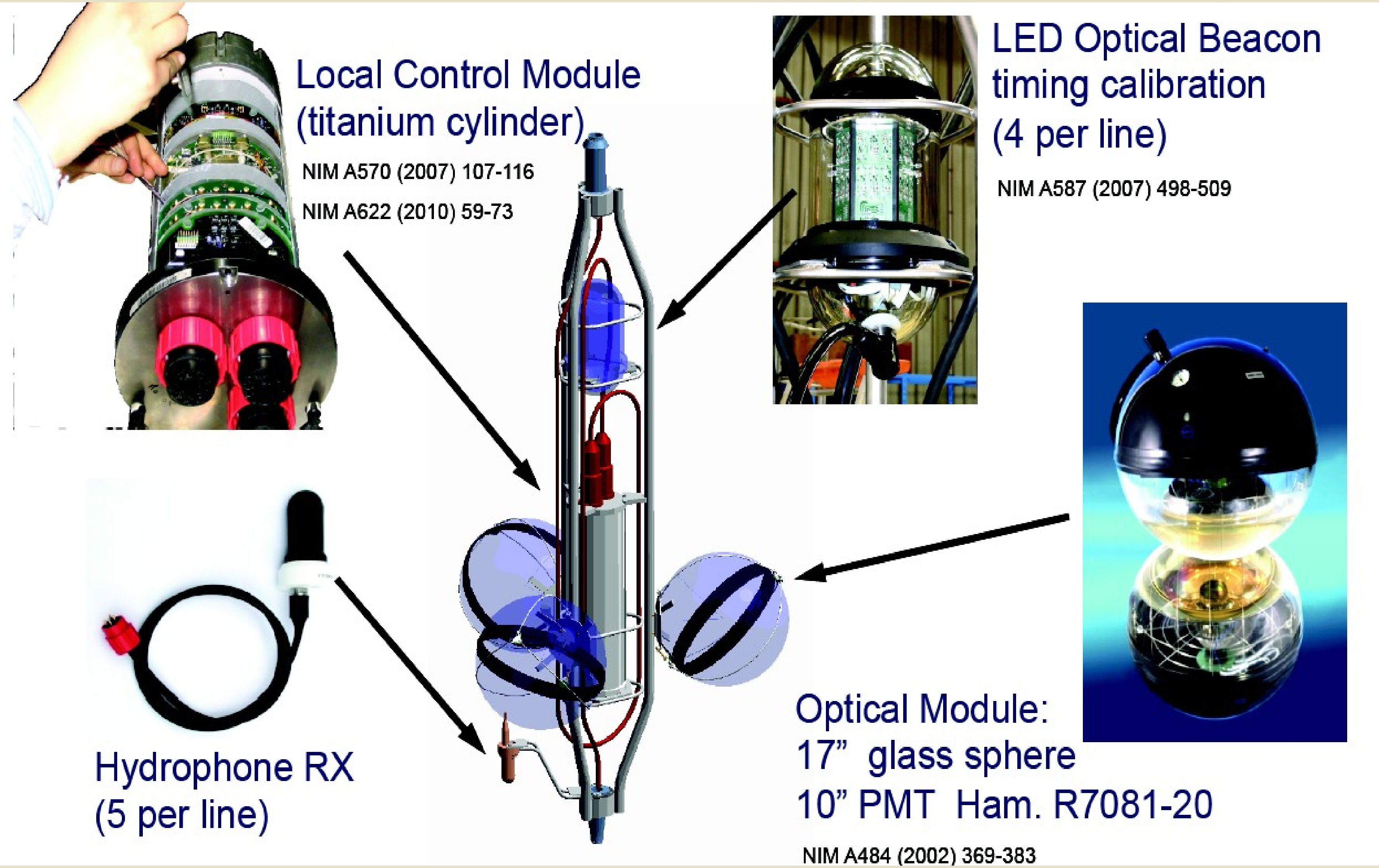
~70 m inter-string separation

14.5 m vertical storey separation

0.04 km^3 instrumented volume

effective area ~ 1m^2@ 30 TeV

median angular resolution ~0.4^o


Local Control Module
(titanium cylinder)
NIM A570 (2007) 107-116
NIM A622 (2010) 59-73
LED Optical Beacon
timing calibration
(4 per line)
NIM A587 (2007) 498-509
Hydrophone RX
(5 per line)
Optical Module:
17" glass sphere
10" PMT Ham. R7081-20
NIM A484 (2002) 369-383

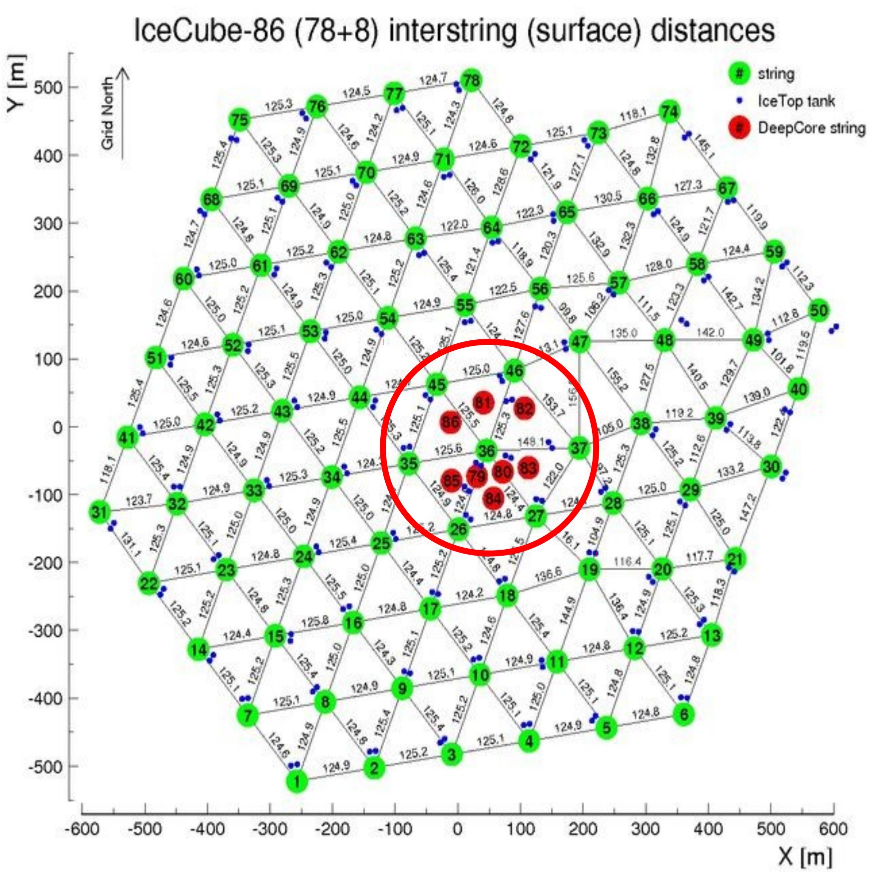
(from T. Eberl)

86 strings, 5160 optical modules

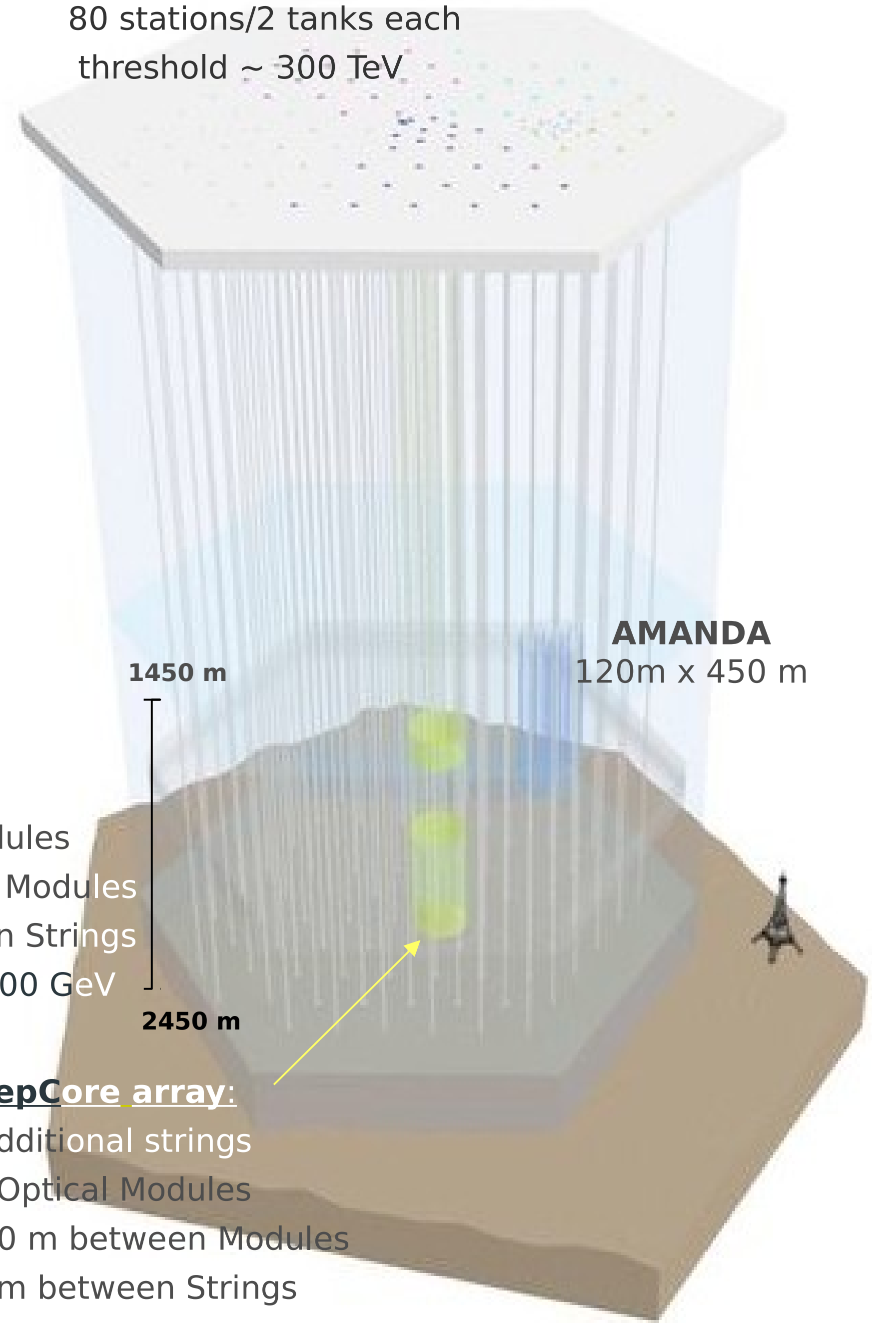
86 ice tanks on the surface

~ 50 GeV energy threshold

~ 1º angular resolution

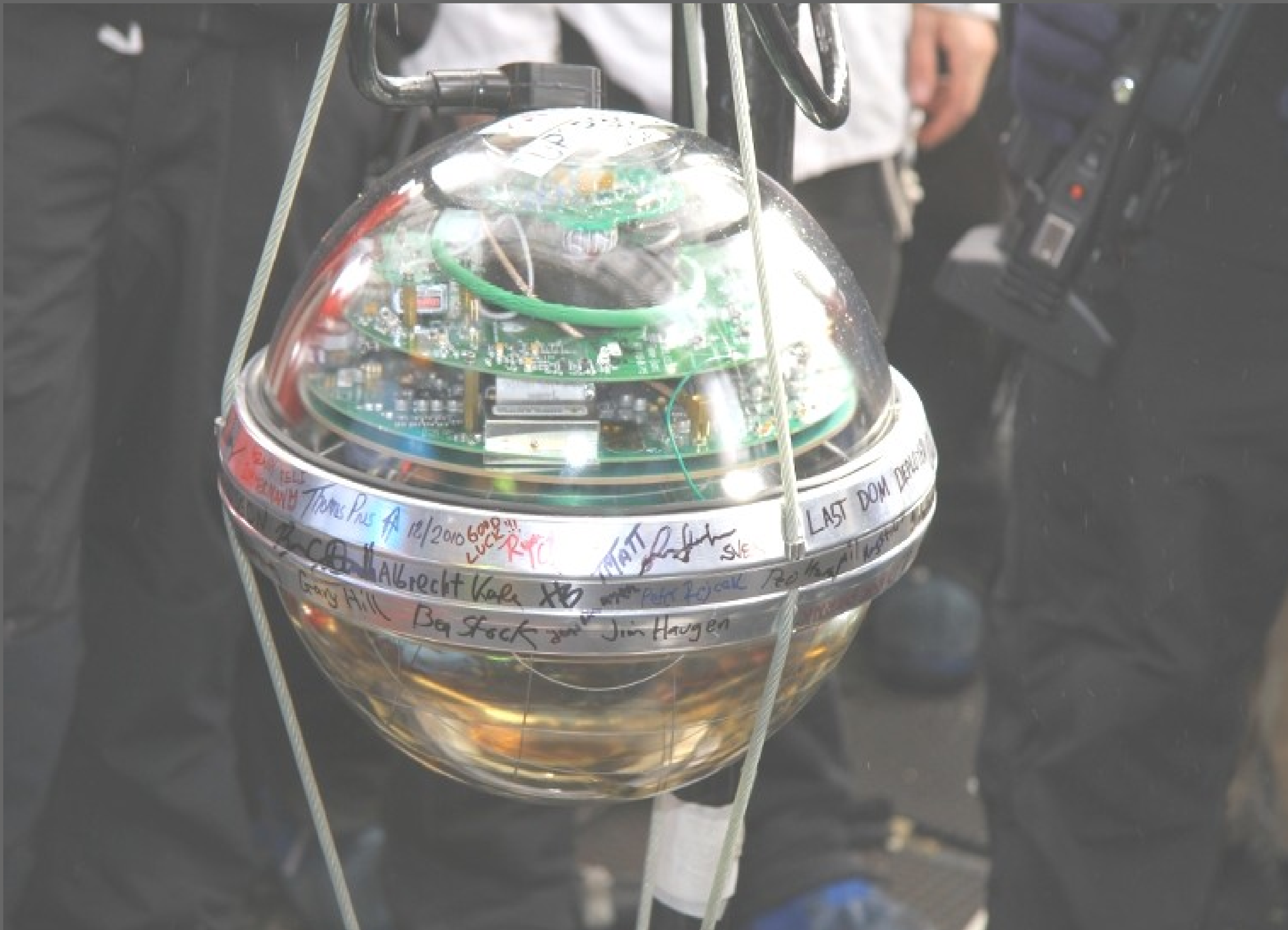


IceTop: Air shower detector
80 stations/2 tanks each
threshold ~ 300 TeV



InIce array:
80 Strings
60 Optical Modules
17 m between Modules
125 m between Strings
ν threshold ≲100 GeV

DeepCore array:
6 additional strings
60 Optical Modules
7/10 m between Modules
72 m between Strings
ν threshold ~10 GeV


LAST DOM
12/2010
GOOD LUCK!!!
Albrecht Karle
Gary Hill
Jim Haugen
MATT

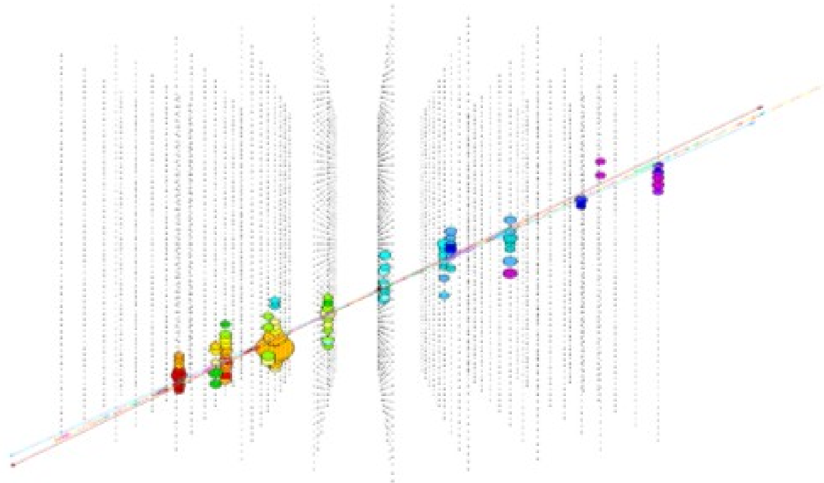


Figure 13: A 10-TeV muon track in IceCube.

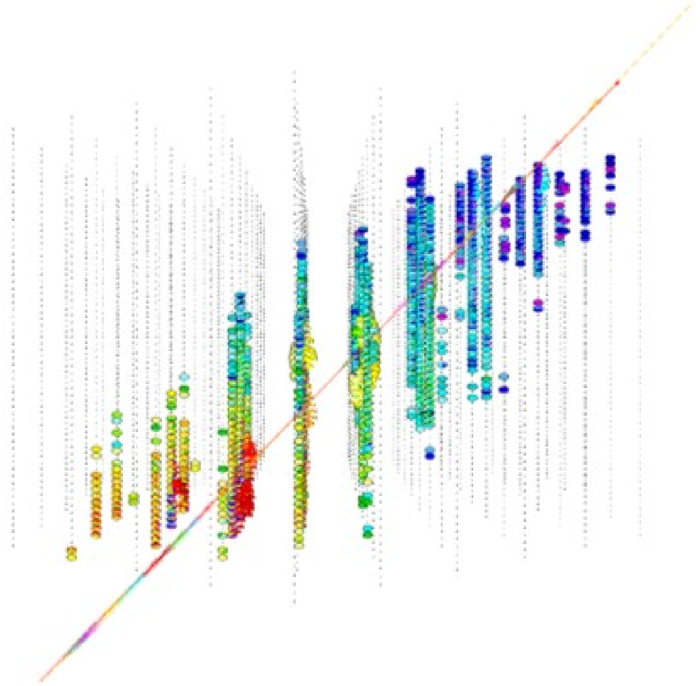


Figure 14: A 6-PeV muon track in IceCube.

Neutrino telescopes do not have a fixed (hit or miss) collection area.

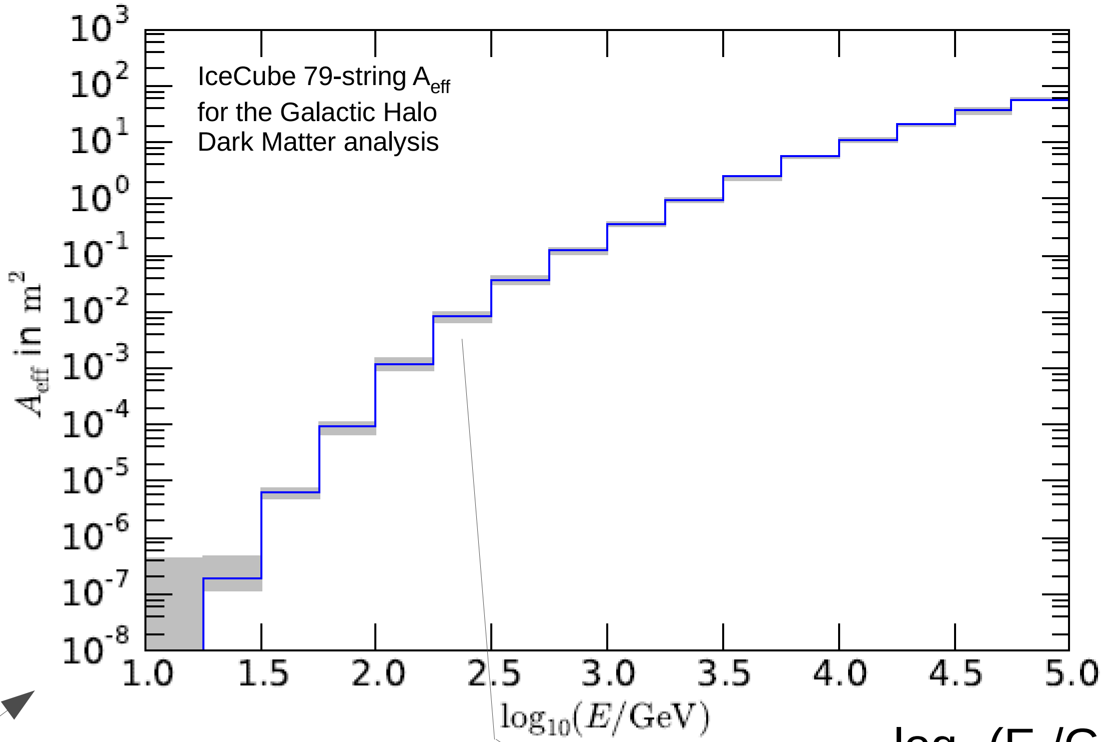
The efficiency to detect a neutrino of a given energy E_ν is characterized by the effective area of the detector, which represents the equivalent area of a detector with 100% detection efficiency

$$A_{eff}(E_\nu) = \frac{N_{det}}{N_{gen}} \times A_{gen}$$

which **can only be obtained by Monte Carlo simulations**. N_{gen} is the number of events generated in Monte Carlo, distributed over an area A_{gen}, which covers the detector geometrically, and N_{det} is the number of surviving events after a given analysis.

→ There is no a unique effective area of a neutrino telescope!
It depends on the analysis

neutrino effective area (m^2)



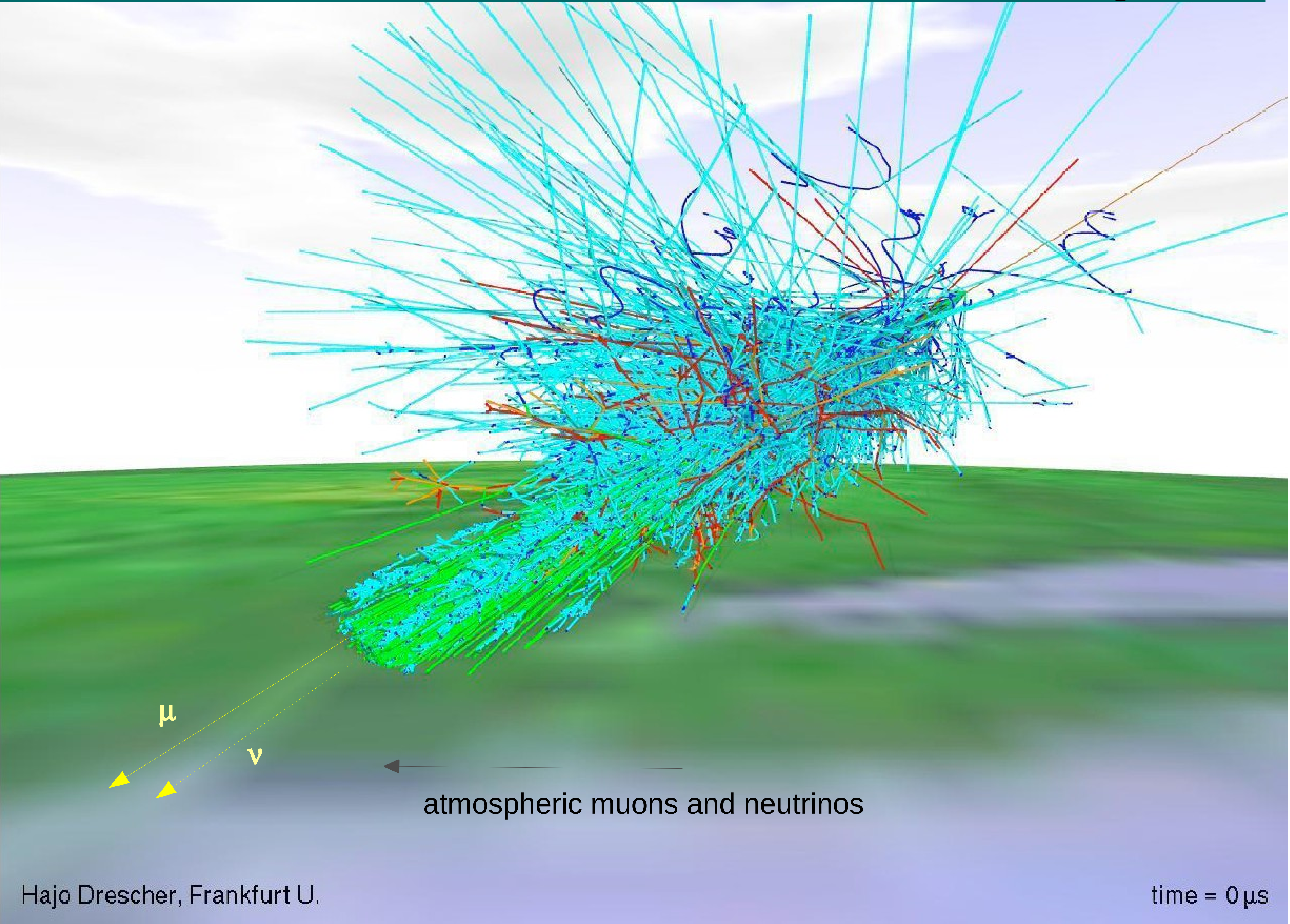
$\log_{10}(E_\nu/\mathrm{GeV})$

note the scale!

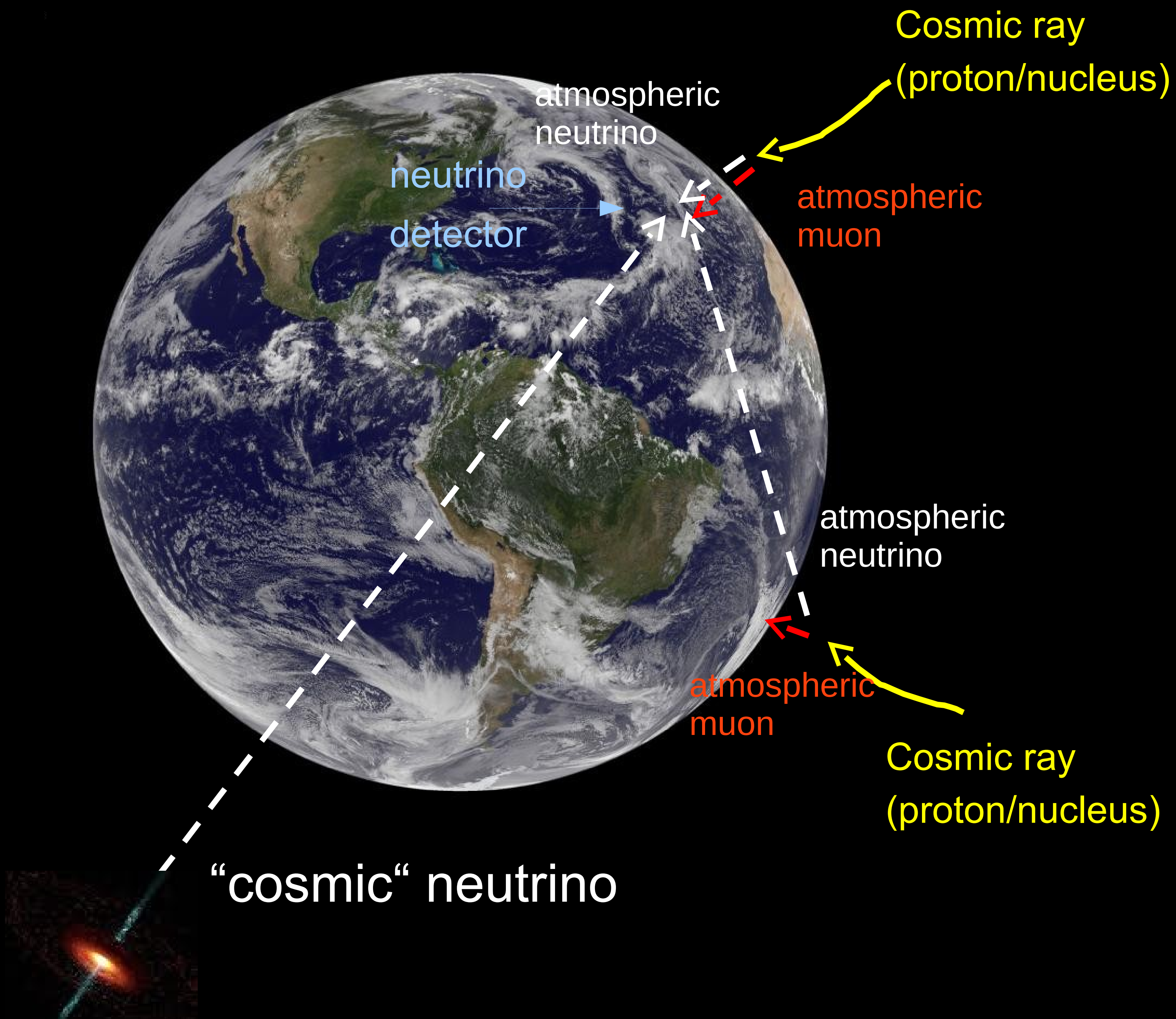
Galileo's telescope, ~21 cm^2

the physics

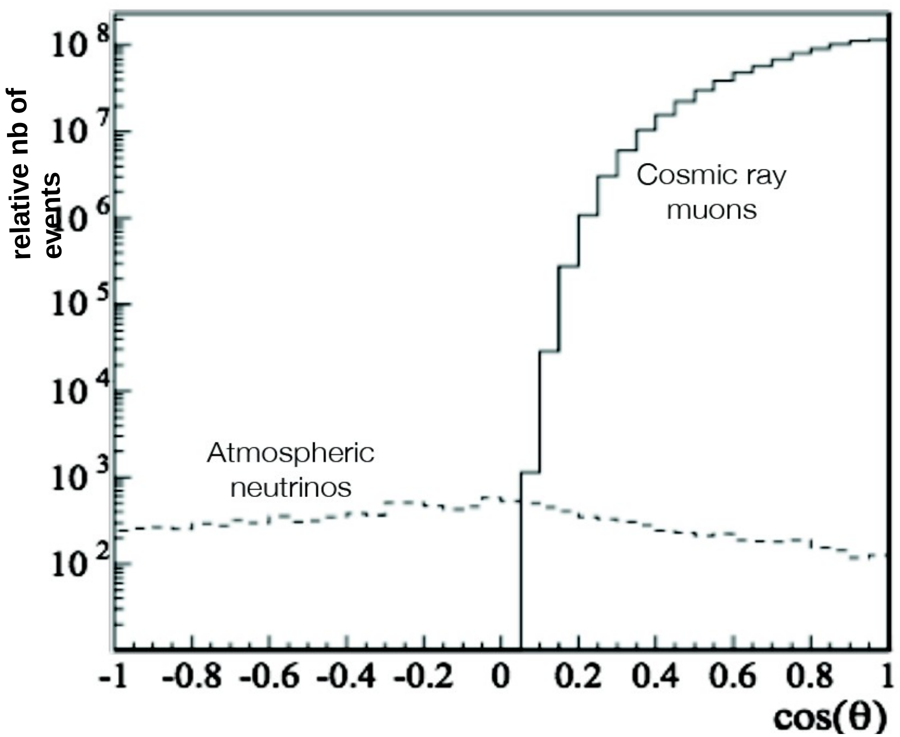
backgrounds


μ
ν
atmospheric muons and neutrinos
Hajo Drescher, Frankfurt U.
time = 0 μs

some terminology



backgrounds

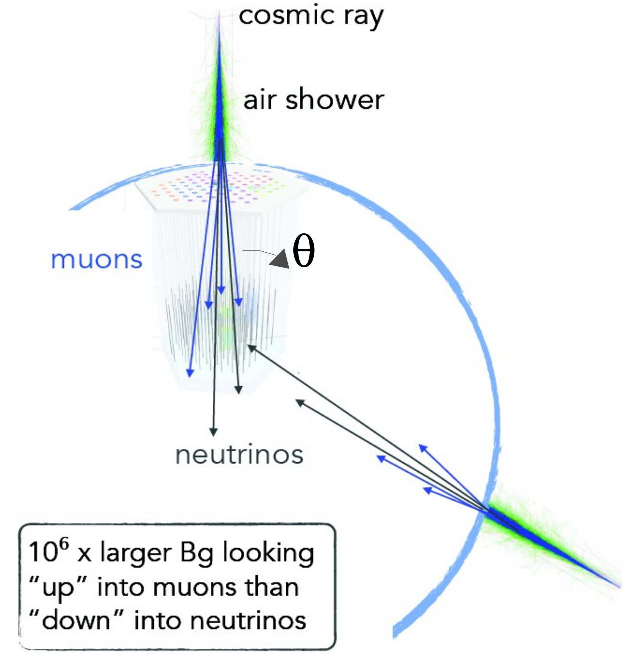


below the horizon
(upgoing tracks)

Earth has filtered
all cosmic ray products
except neutrinos

above the horizon
(downgoing tracks)

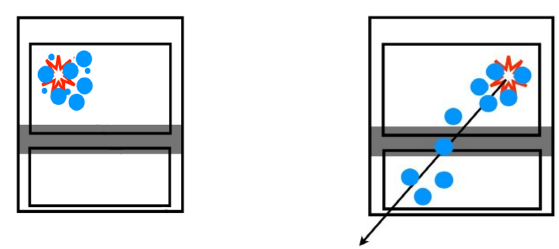
High energetic muons
can penetrate km in
water or ice



<u>To identify ν's:</u>

a) use Earth as a filter, ie, look for upgoing tracks, cos(θ)<0

b) define "starting tracks" in the detector. Use any angle



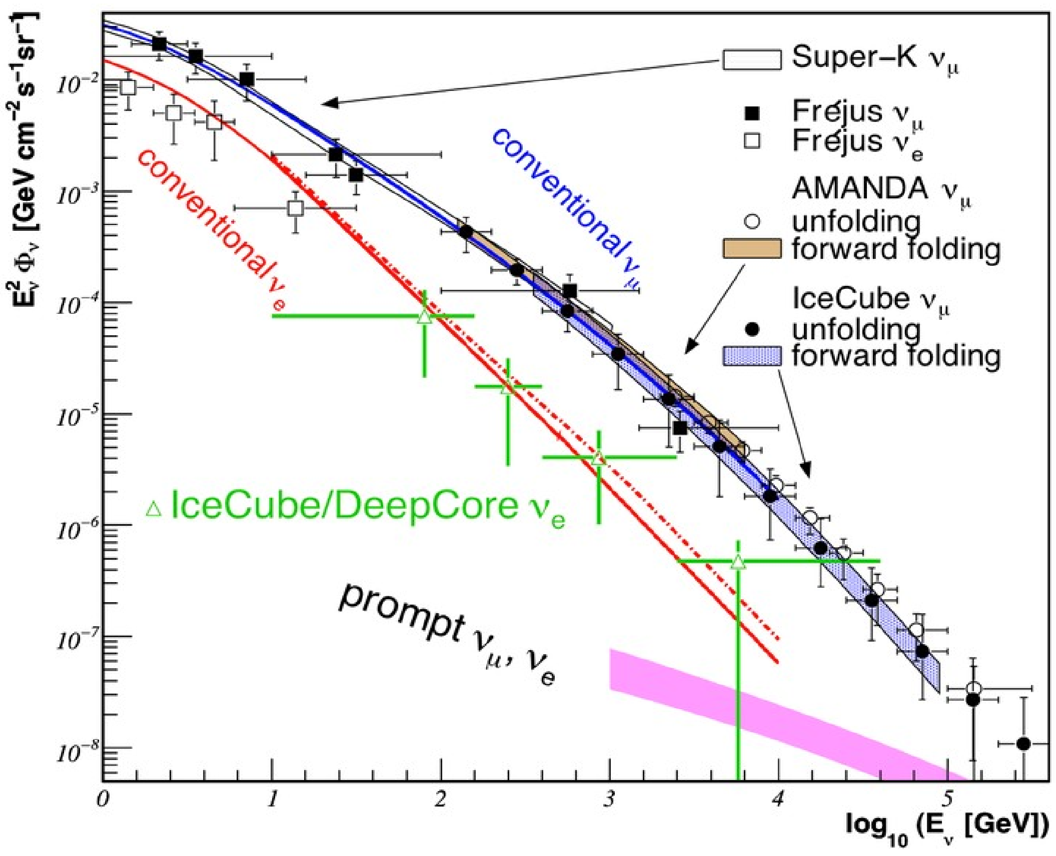
$$CR + N \rightarrow \pi's + X$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

expected flavour ratio:

$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$



measurements agree with predictions based on
the cosmic ray flux and neutrino production physics

atmospheric neutrinos: the prompt component

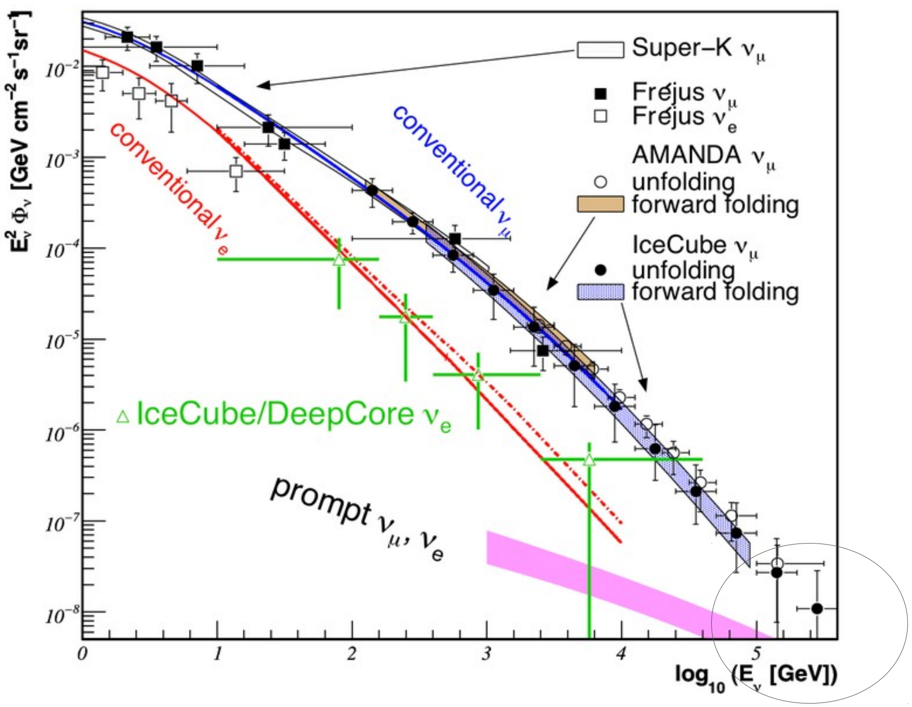
standard: from π/k decays

$$CR + N \rightarrow \pi's + X$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

but: π/K are long lived. They loose energy in the atmosphere before decaying.
Resulting ν's are low-energy



prompt: from charm decays

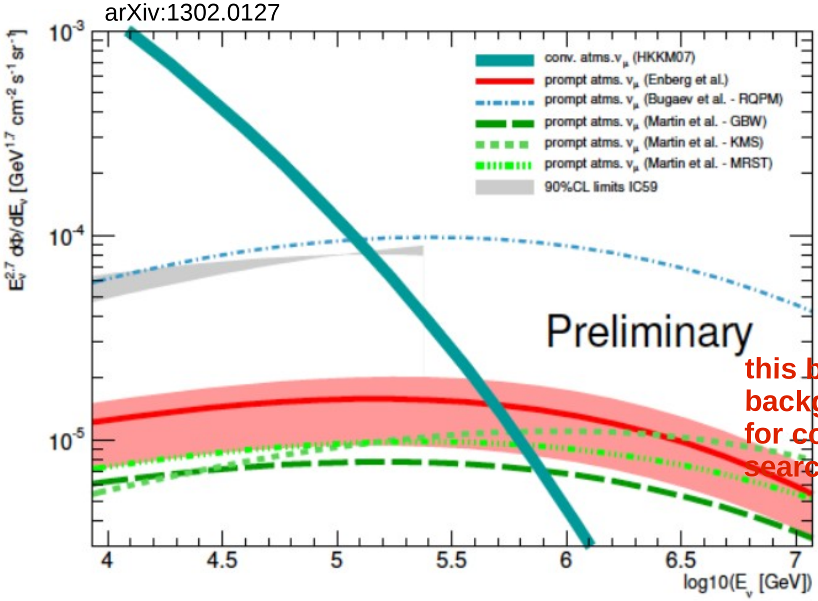
$$CR + N \rightarrow D^{0,+,-} + X$$

Hadrons containing heavy quarks, c or b, are extremely short lived, cτ ~ μm.
They decay before they have time to loose energy in the atmosphere.
Produced neutrinos have higher energies

But: Calculation of charm production needs knowledge of parton distribution functions at low Bjorken x, much smaller than provided by colliders (cosmic rays have energies much higher than any man-made accelerator), and non-perturbative QCD calculations

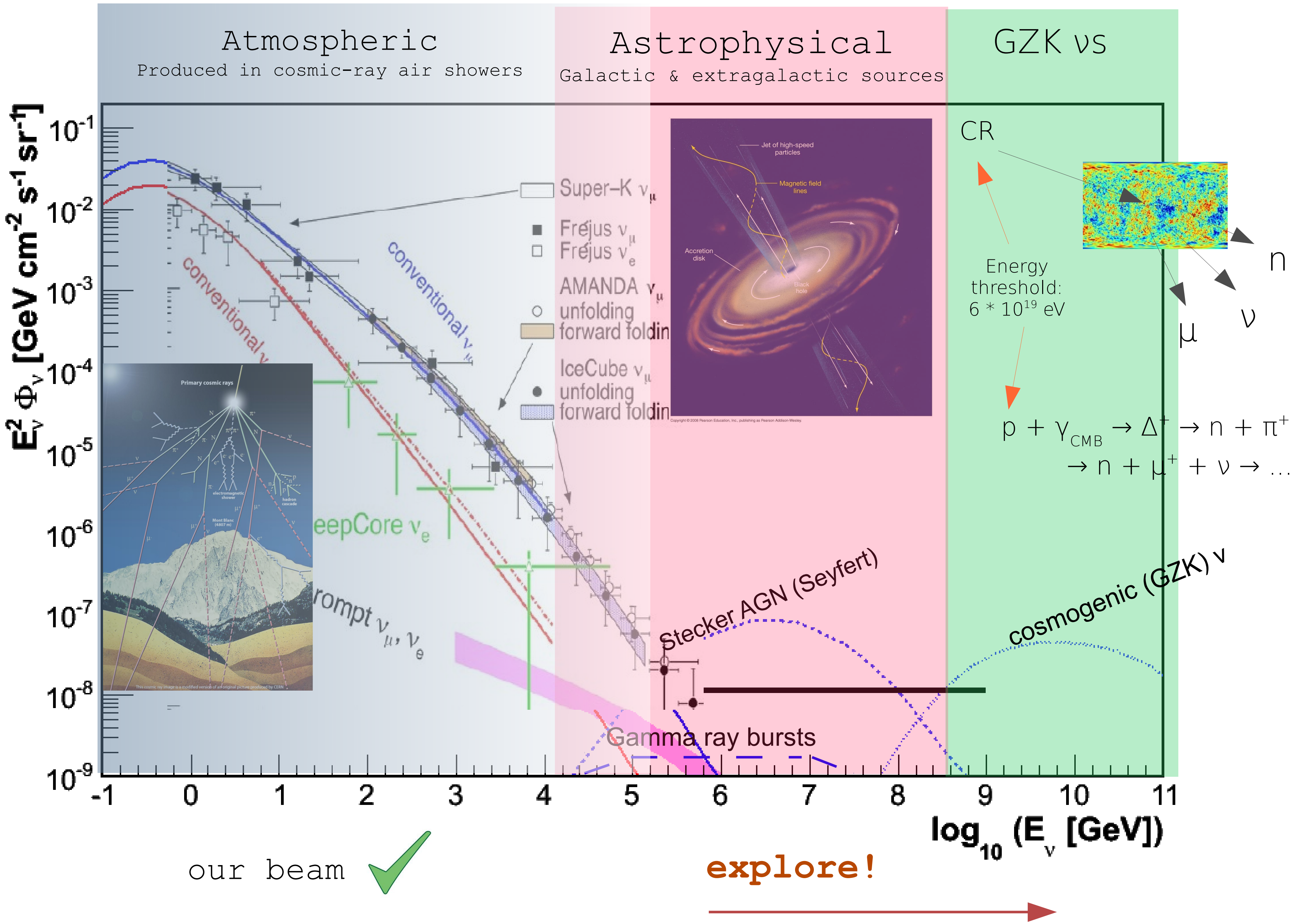
–> predicted flux has huge uncertainties

arXiv:1302.0127



this becomes the background for cosmic neutrino searches!!

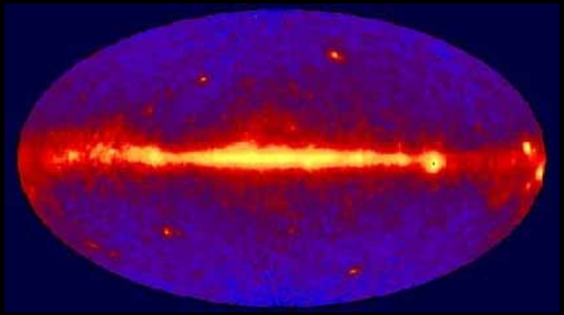
beyond atmospheric neutrinos: cosmic signals in neutrino telescopes



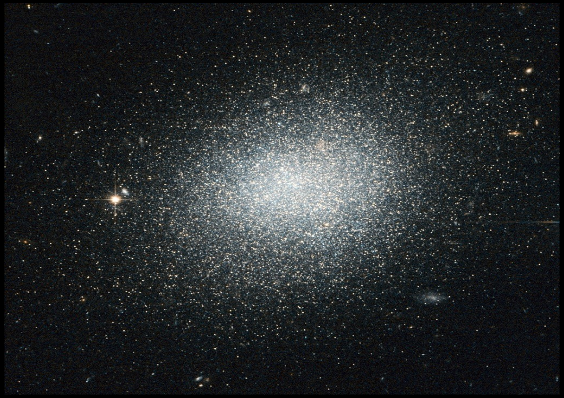
recap: sources of cosmic neutrinos

cosmic accelerators
(point-source searches)

Supernovae



diffuse neutrino flux
(all-sky searches)



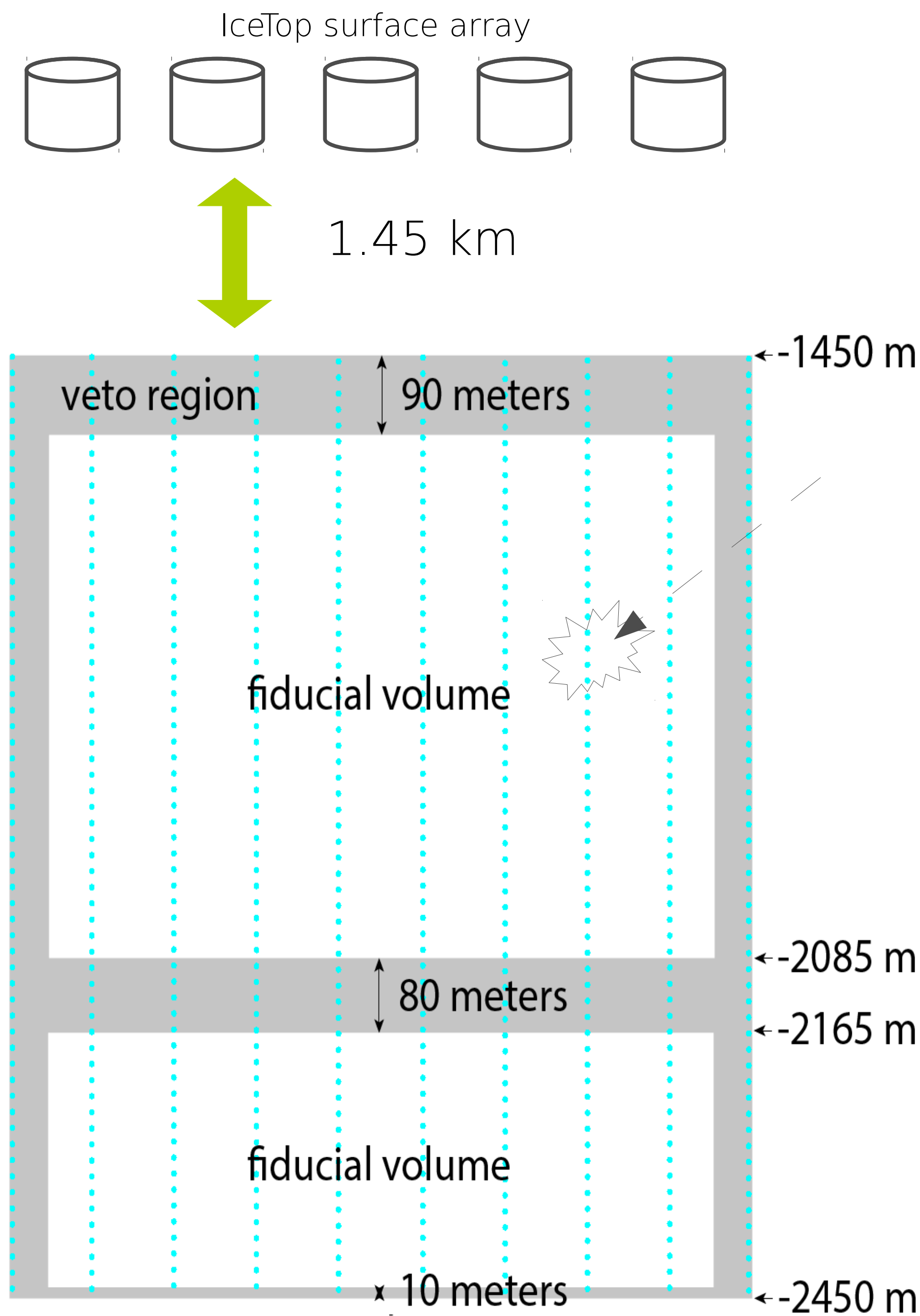
dark matter
(tomorrow's lecture)

cosmic rays

Take advantage of completed, i.e. big, detector to define a veto:
- top 5 layers of modules (=90 m)
- bottom layer of modules (=10 m)
- outer layer of strings

- for atms. μ
→ reject tracks entering the detector from outside

- for atms. ν
→ accompanied by air showers with muons
(detectable when coming from the Southern hemisphere)



Try to lower the threshold to ~50 TeV

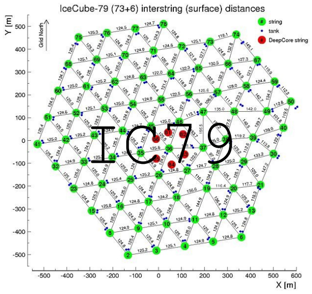
Requirements:
All-sky
(in particular Southern-sky) acceptance of HE events

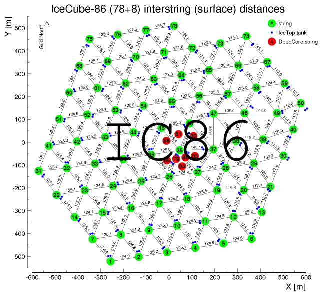
Challenge:
Atmospheric ν and μ background

Strategy:
Look for starting events in the detector

→ these must be neutrinos!!!

Data samples   May 2010 – June 2013





Expected background:

Atmospheric μ background

Determined from experimental data:
Define a second veto layer and tag events, which pass the first layer

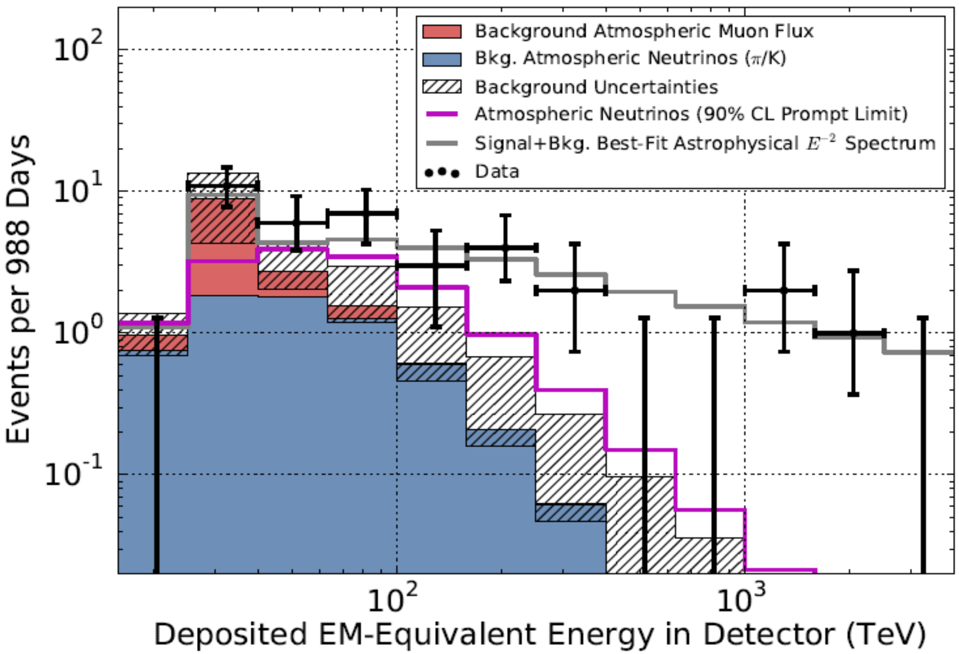
8.4 ± 4.2

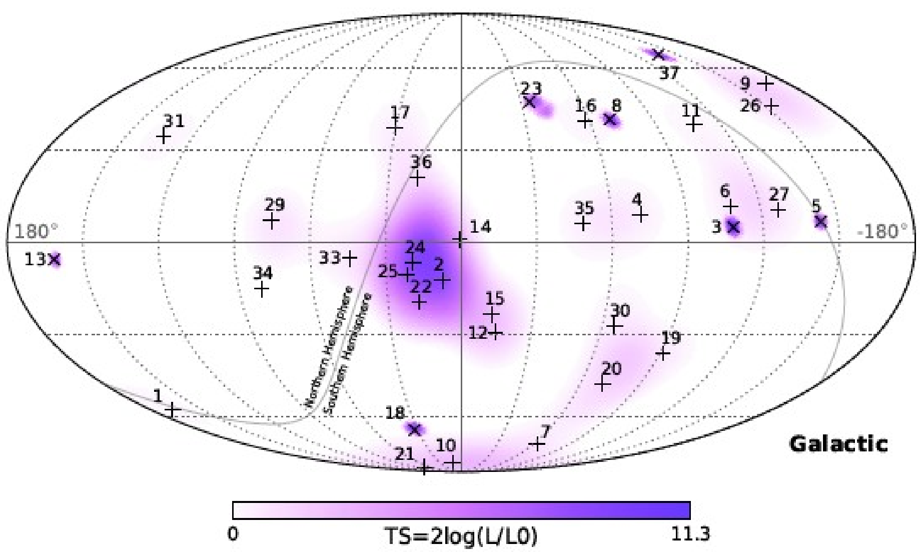
Atmospheric ν background

Based on MC simulation and previous IceCube measurements

$6.6^{+5.9}_{-1.6}$

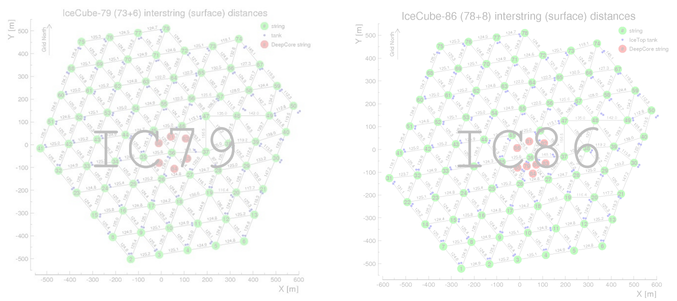
<u>observed events:</u> 37





5.7σ deviation from expected atmospheric ν spectrum

Data samples   May 2010 - June 2013



Expected background:

Atmospheric μ back...

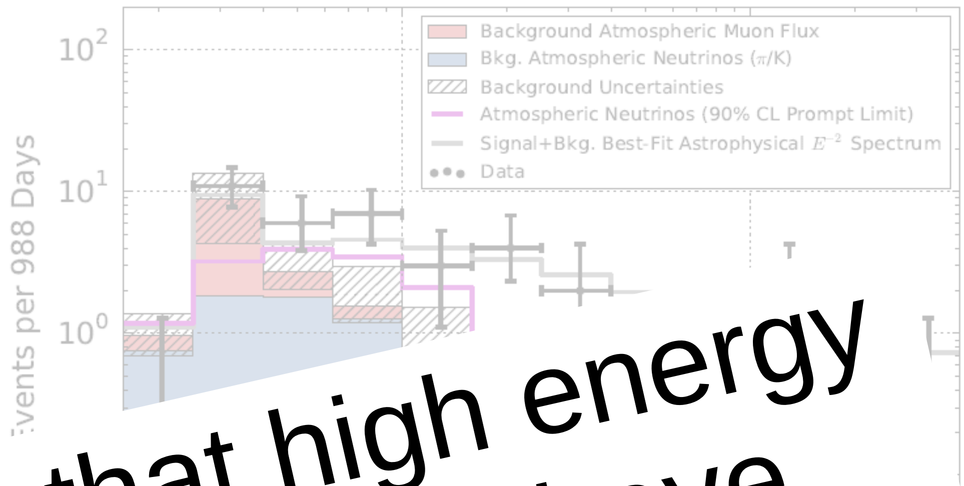
Determ...

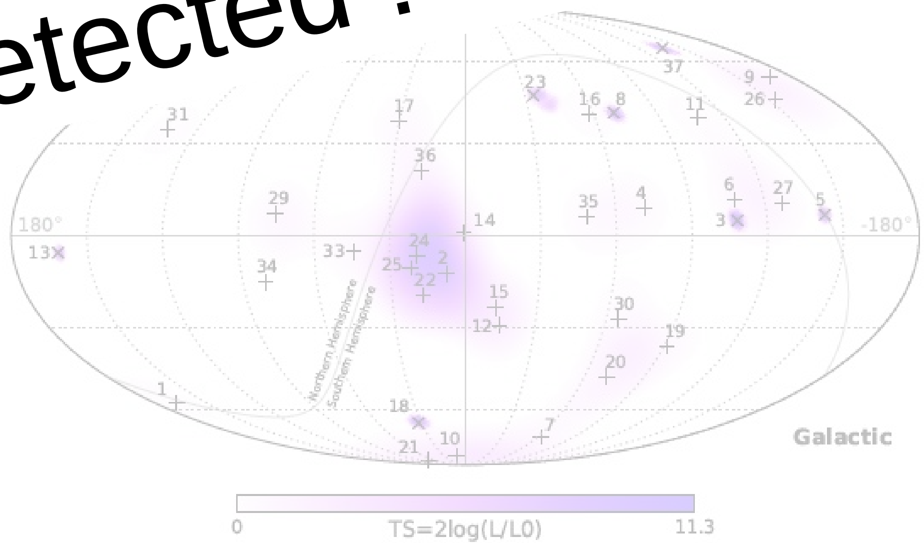
At... ...ground

Bas... on MC simulation and previous IceCube measurements

$6.6^{+5.9}_{-1.6}$

observed events: 37



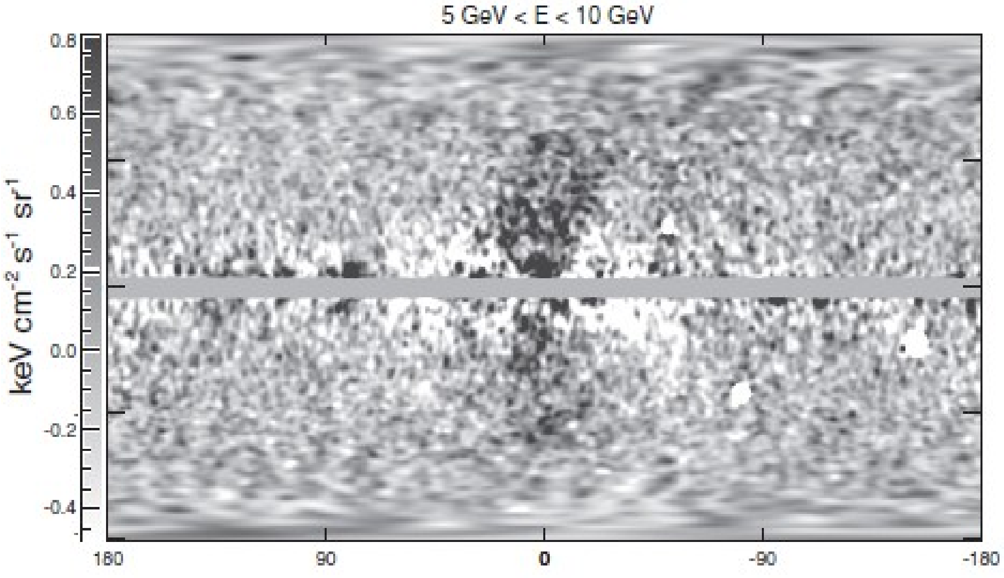


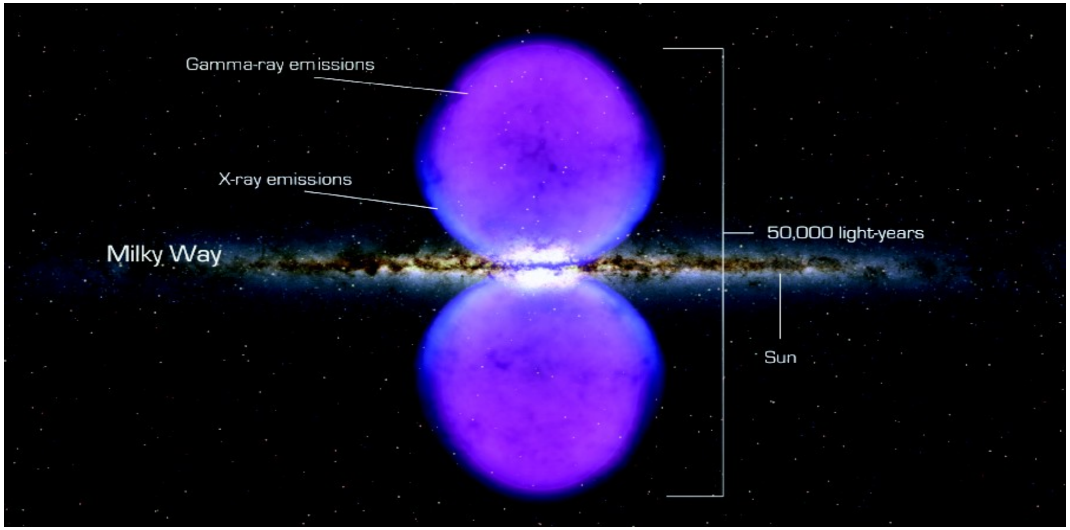
5.7σ deviation from expected atmospheric ν spectrum

this is the first time that high energy neutrinos of cosmic origin have been detected !

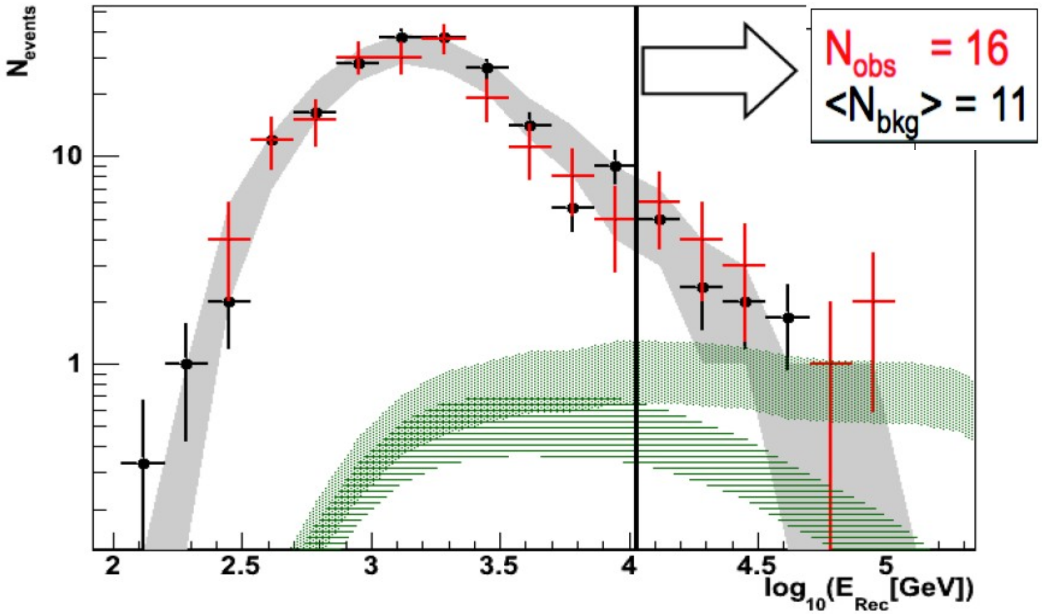
Fermi bubbles: excess of γ and x-rays in extended regions (bubbles) perpendicular to the Galactic Center (Su, Slatyer, Finkbeiner, ApJ. 724, 1044 (2010))

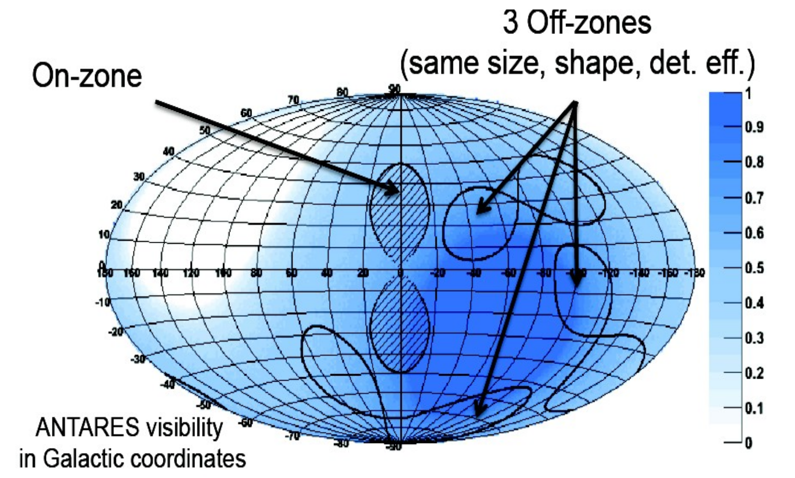
Neutrinos can be produced if hadronic processes involved (Crcker&Aharonian, PRL 106, 101 (2011))





other diffuse neutrino searches: ANTARES Fermi bubbles



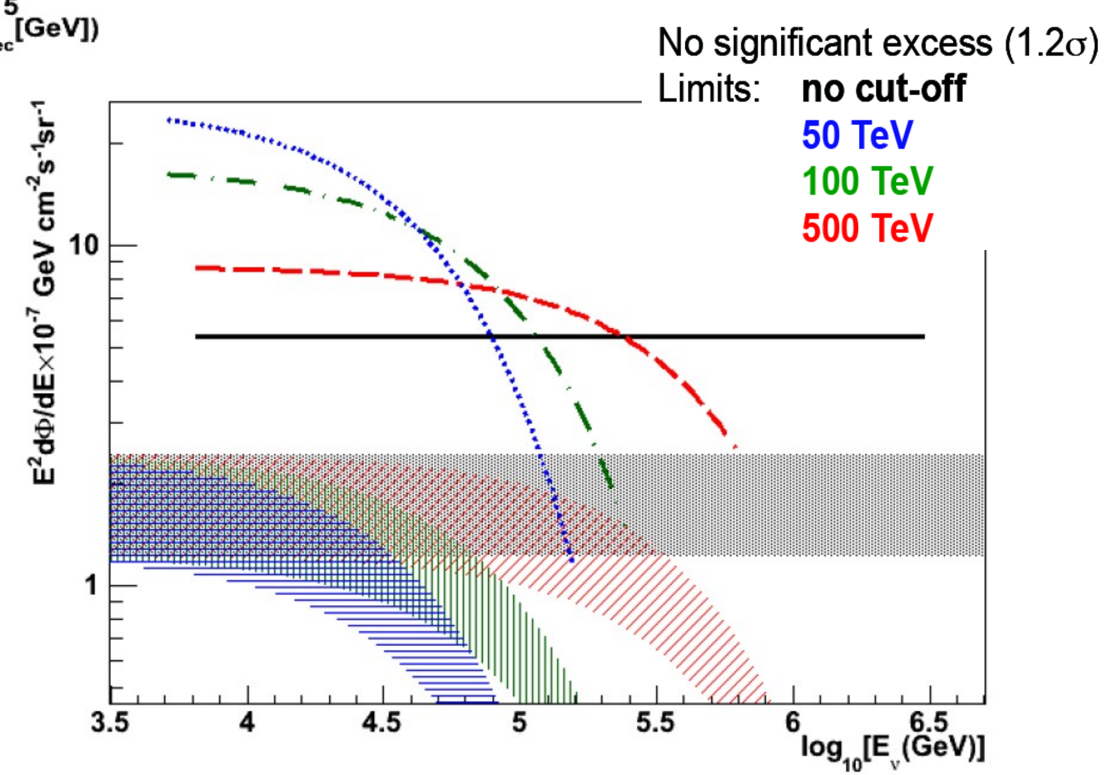


on-source

off-source average

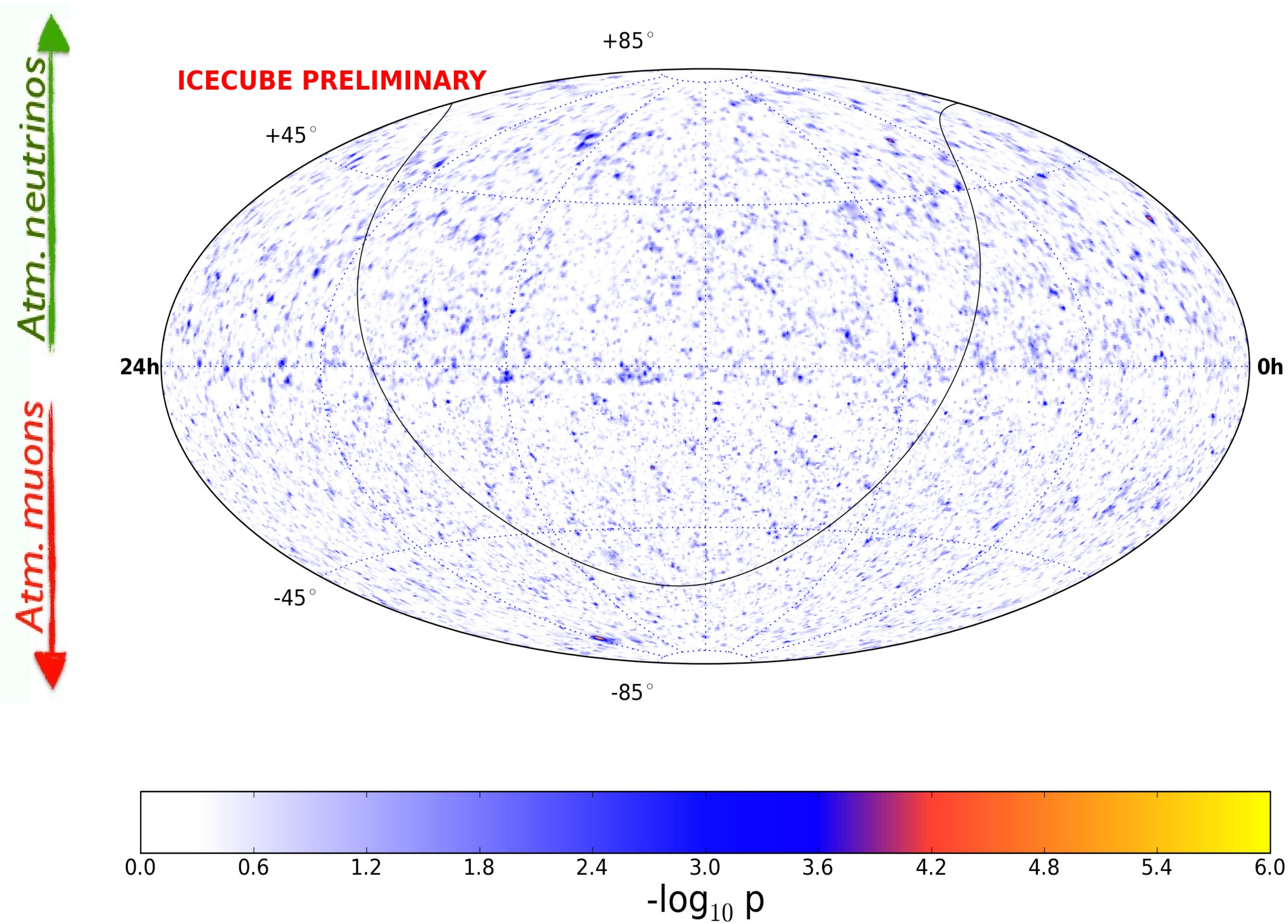
expected signal

(no cut-off, 50 TeV cut-off)



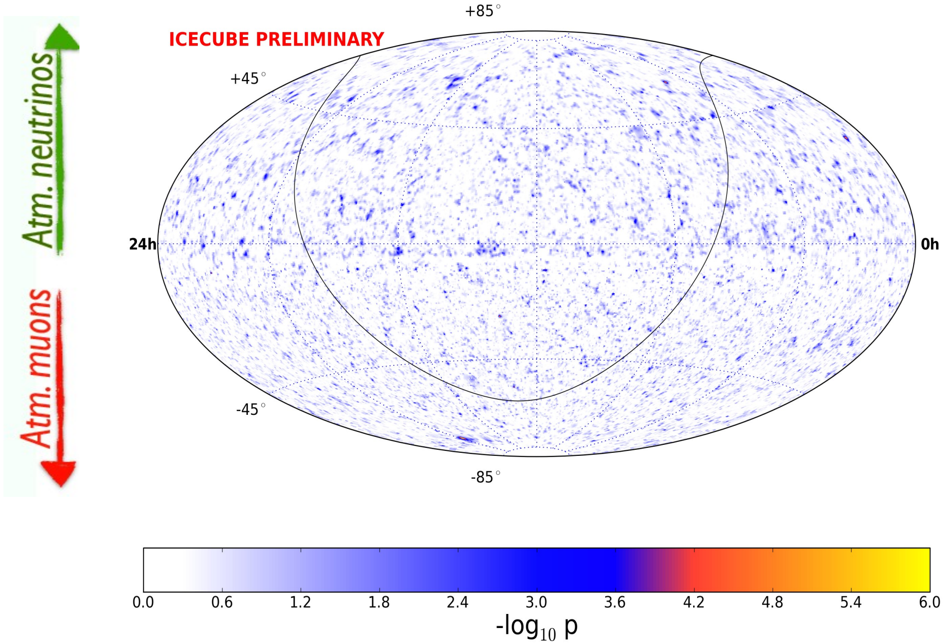
4-year (IC40+IC59+IC79+IC86-I) neutrino sky.

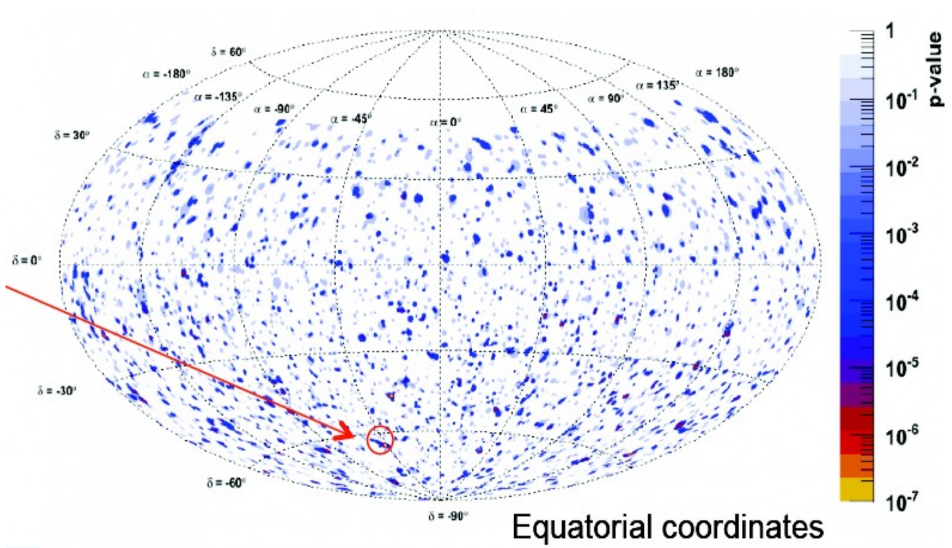
total livetime 1371.7 d
total number of events: 178000 upgoing
216000 downgoing (atm muons)



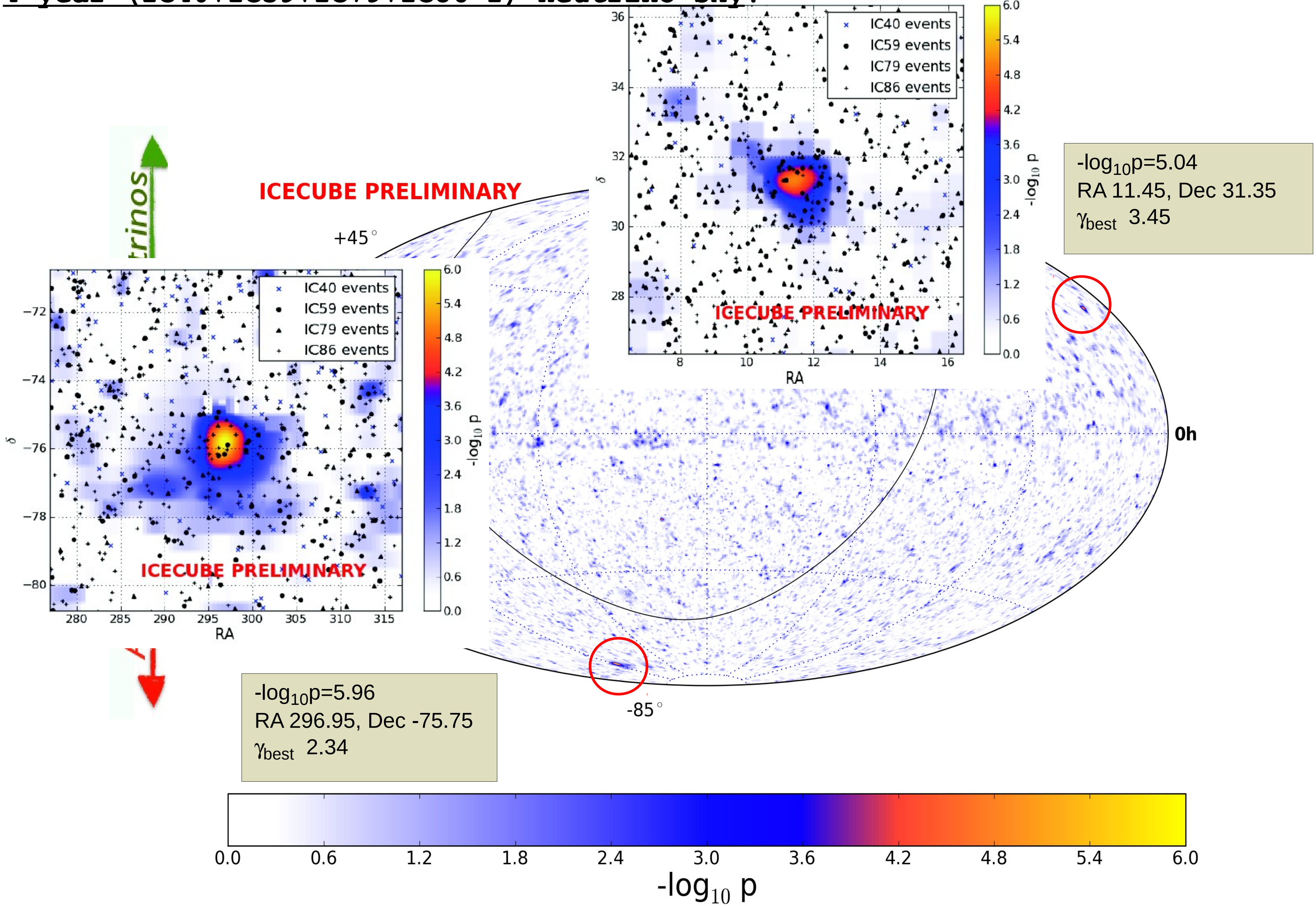
<u>4-year (IC40+IC59+IC79+IC86-I) neutrino sky</u>.
total livetime 1371.7 d
total number of events:
178000 upgoing
216000 downgoing (atm muons)

<u>5-year ANTARES neutrino sky</u>.
total livetime 1338 d
total number of events: 5515 upgoing



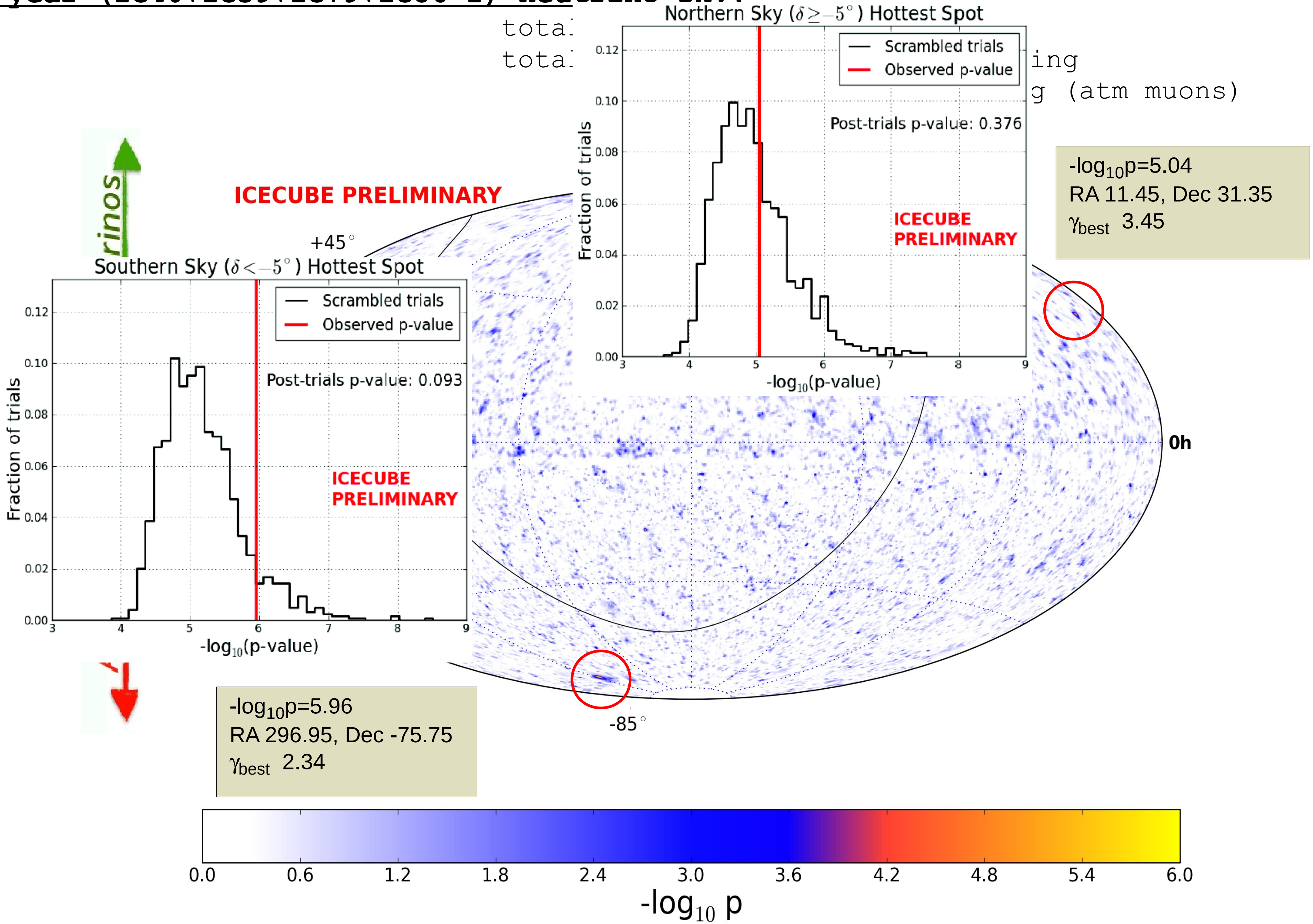


4-year (IC40+IC59+IC79+IC86-I) neutrino sky.

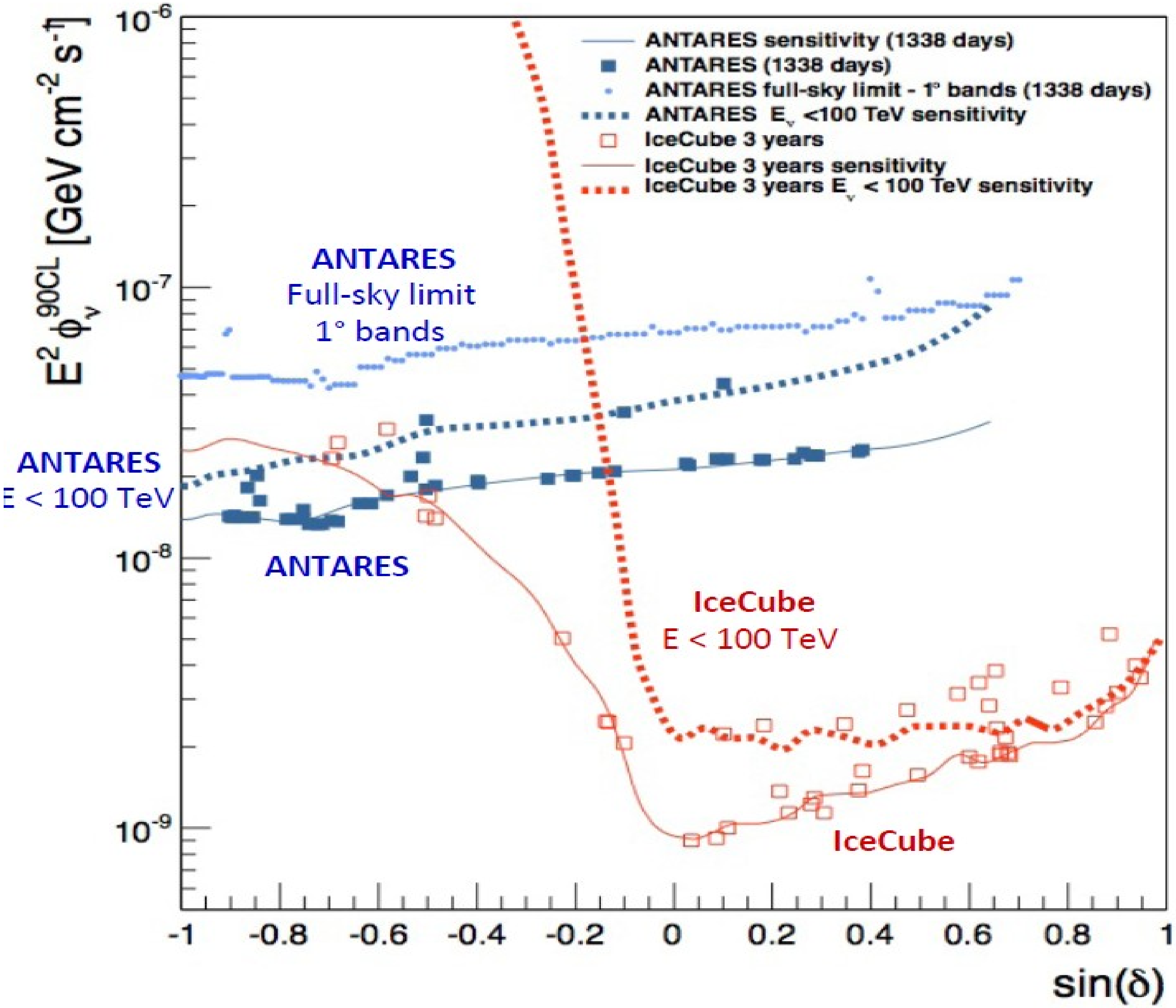


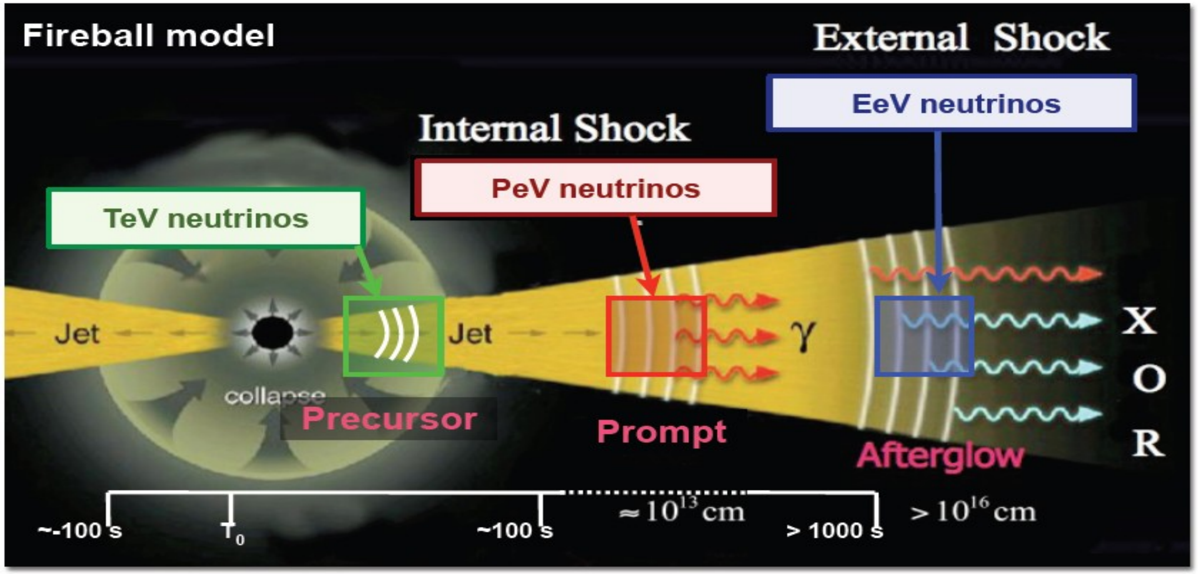
4-year (IC40+IC59+IC79+IC86-I) neutrino sky.

tota
tota ... ing
g (atm muons)



Lacking a positive signal, the different collaborations have set limits on the neutrino flux from a selection of potential sources





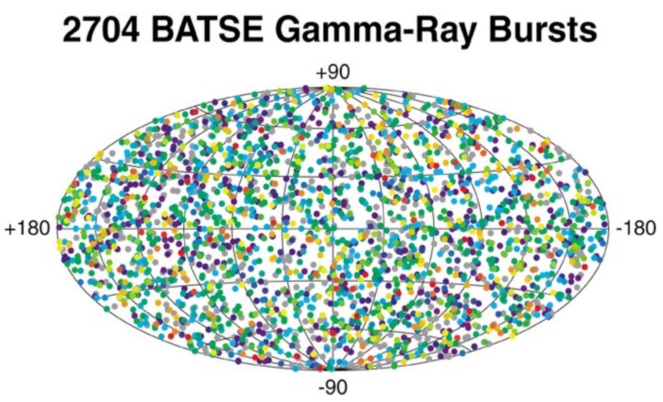
Time and position of the bursts taken from satellite data

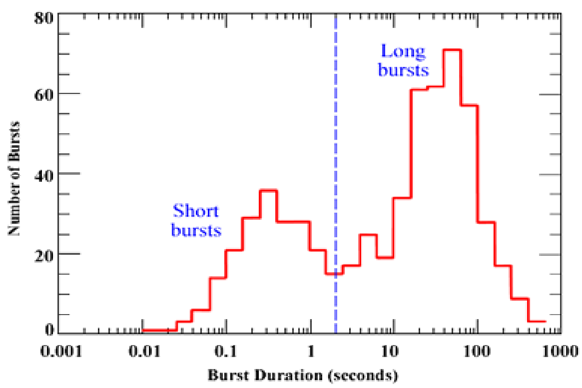
→ low background analysis due to both space and time coincidence search!

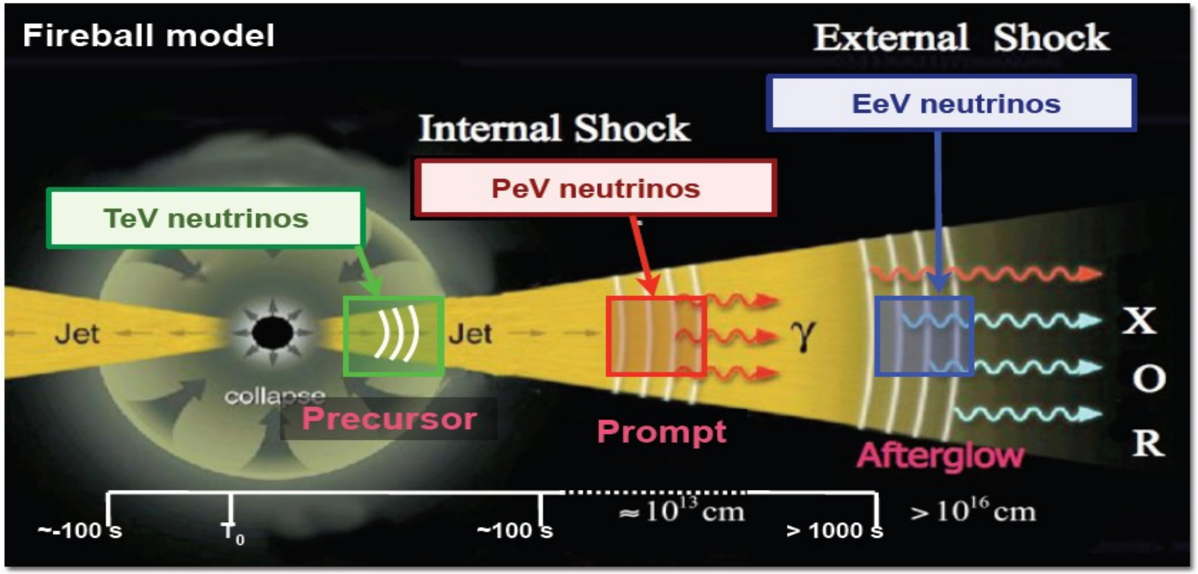
fireball protons interact with remnant of the star

fireball protons and photons interact & produce neutrinos which can escape

afterglow protons interact with inter-stellar medium

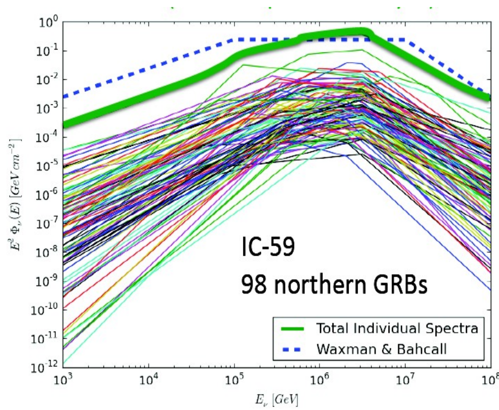






2008-09 data (40-string)
117 GRBs in northern sky

2009-10 data (59-string)
95 GRBs in northern sky
85 GRBs in southern sky



Results:

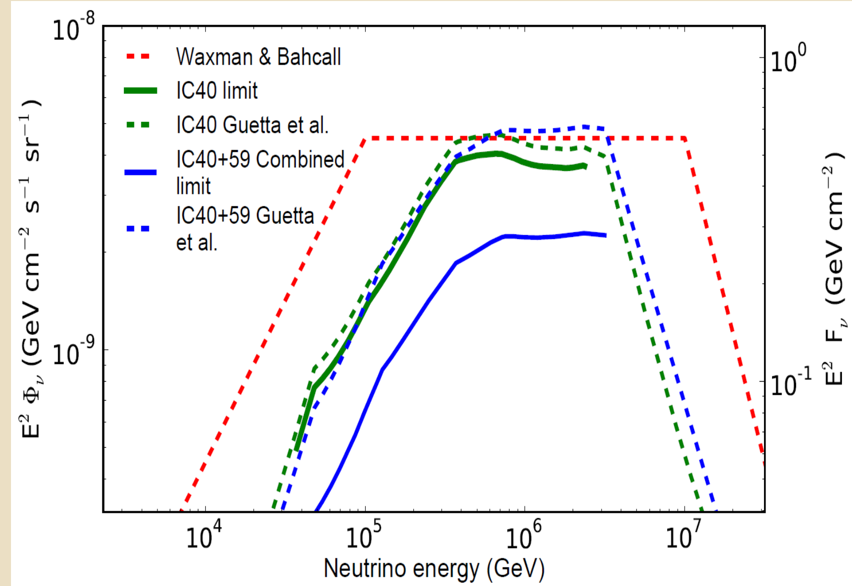
0 events observed

5.2 events expected (Guetta et al.)

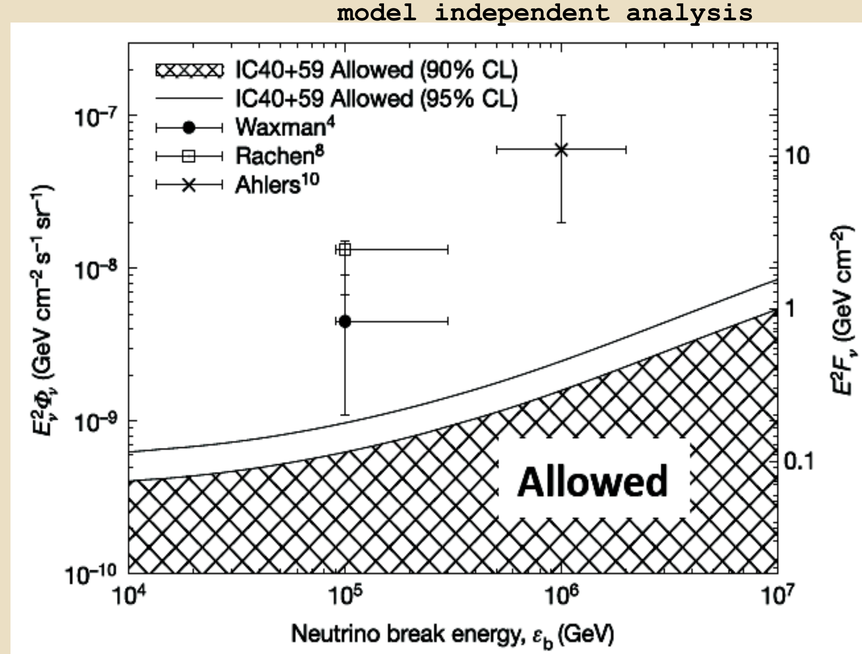
model disfavored at > 3σ

→ revisit theory
Some models strongly excluded already

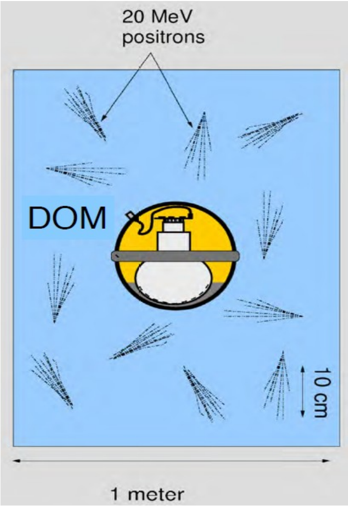
model dependent analysis



model independent analysis



on the other side of the spectrum: neutrinos from SN explosions



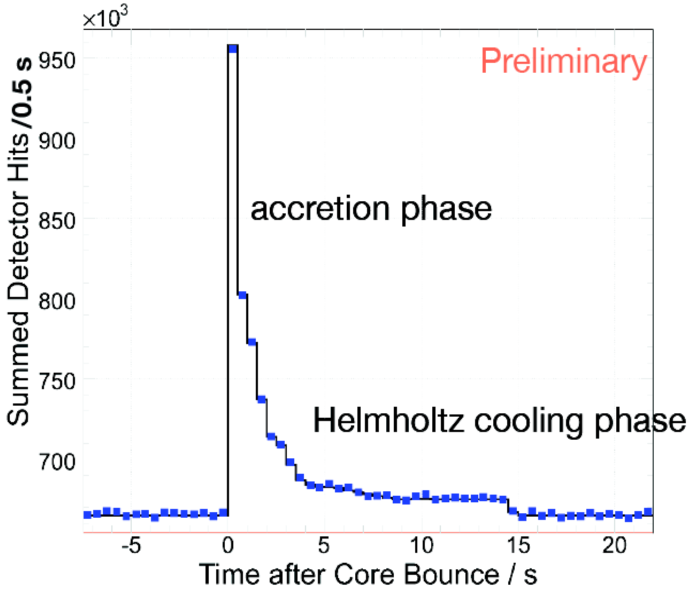
Main detection: inverse β-decay, $\bar{\nu}_e + p \rightarrow n + e^+$

e^+ tracks about 5 cm in ice

Expect ~10^7 low E (~10 MeV) ν's from a SN@10 kpc

→ A nearby Supernova will illuminate uniformly the ice during a very shot time due to the Cherenkov radiation of the positrons produced in the huge amount of neutrino interactions

→ Translates into a collective rate increase, 10^5 'hits'/15 s expected



Disadvantage: no pointing. Need correlation with optical detectors for identification in the sky

- Neutrino telescopes aim at studying the high energy universe
- I hope I have convinced you that this is fun
- IceCube has discovered an excess of neutrinos at energies >50 TeV which is incompatible with known atmospheric neutrino production and it is considered the discovery of high energy cosmic neutrinos
- Individual sources still need to be identified
- KM3NET in the Mediterranean and the IceCube extension at the South Pole being planned to gather more statistics
- Neutrino telescopes also used for particle-physics related topics
- We are in a discovery era!