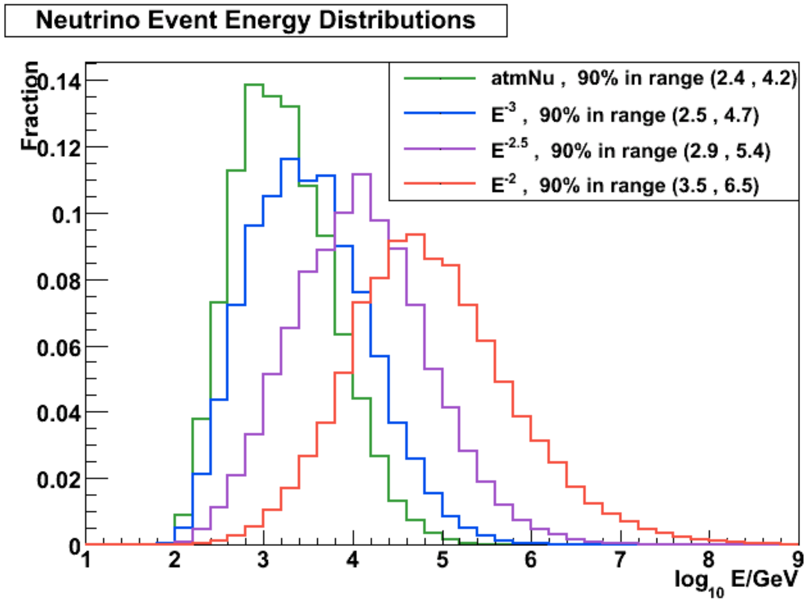
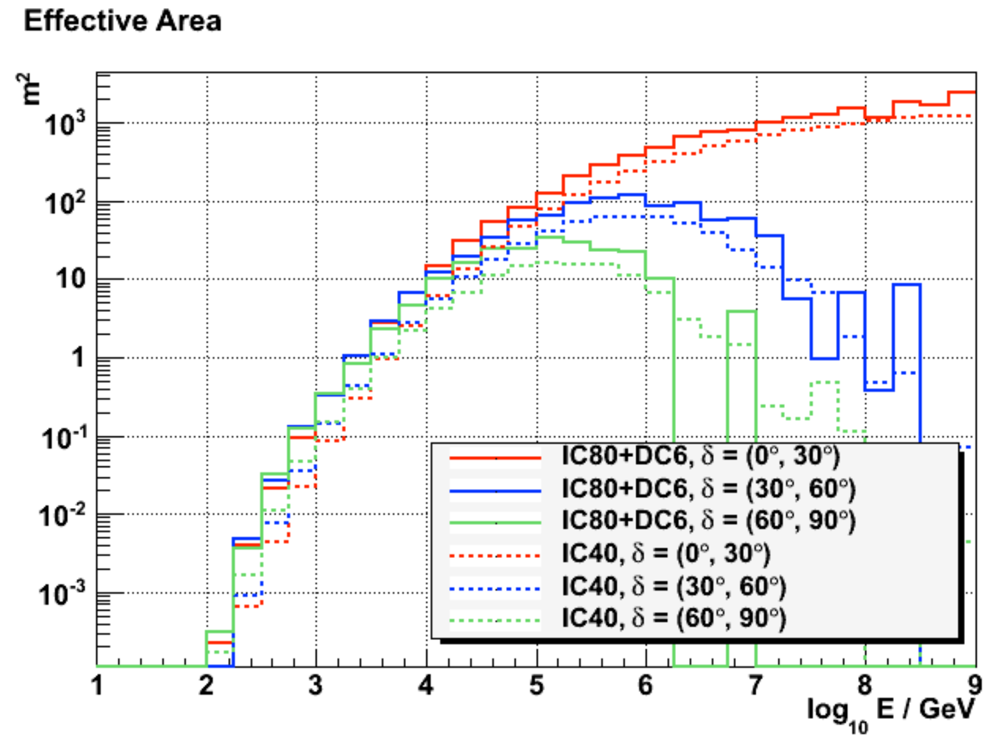
Neutrino Astronomy / Astro-physics

Today
- the propagation of messengers
- IceCube results and future

Niels Bohr Institute PhD School, 1 Aug. 2015

Effective Area





Neutrino-nucleon cross-section

Neutrinos flux model

$$N_\mu = \int V_{eff}(E_\nu,\theta_\nu,\phi_\nu)\,(\rho\, N_A)\,\sigma(E_\nu)\,\frac{d\Phi_\nu}{dE_\nu d\Omega_\nu}\,dE_\nu\, d\Omega_\nu$$

Target nucleon density

Shadowing effect

$$A^\nu_{eff} = V_{gen} \times \frac{N_{xxx}(E_\nu,\theta_\nu,\phi_\nu)}{N_{gen}(E_\nu,\theta_\nu,\phi_\nu)} \times (\rho\, N_A)\,\sigma(E_\nu) \times P_{earth}(E_\nu,\theta_\nu)$$

Event rate

$$P_{earth}(E_\nu,\theta_\nu) = e^{-N_A\,\sigma(E_\nu)\int \rho\, dl}$$

$$N_\mu = \int A^\nu_{eff}(E_\nu,\theta_\nu,\phi_\nu)\,\frac{d\Phi_\nu}{dE_\nu d\Omega_\nu}\,dE_\nu\, d\Omega_\nu$$

9

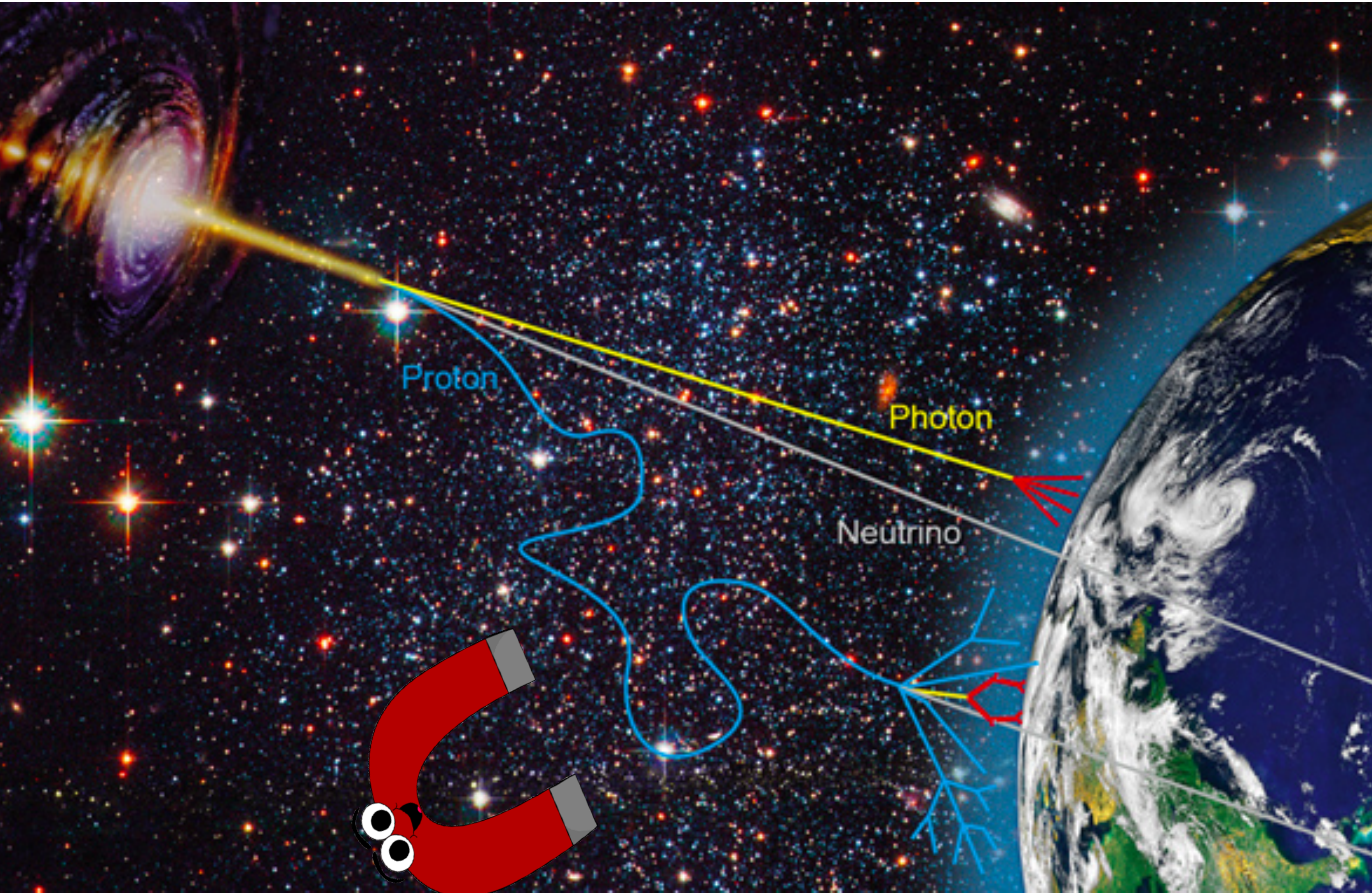
Gamma-neutrino connection at Earth (after oscillations)

$$\frac{dN_\nu}{dE} = \frac{1}{2}\frac{dN_\gamma}{dE} \text{ for p} - \text{p}$$

$$\frac{dN_\nu}{dE} = \frac{1}{8}\frac{dN_\gamma}{dE}\, for\, p - \gamma$$

Warning: we neglected absorption of photons

Multi-messenger astrophysics



Reminder: Mean free path

$$w = \text{interaction prob.} = \mathrm{w} = \mathrm{N\sigma dx}$$

σ = cross section
N= n. of target particles / volume

P(x) = prob. that a particle does not interact after traveling a distance x
P(x + dx) = prob that a particle has no interaction between x and x+dx = P(x+dx) = P(x) (1-wdx)

$$P(x+dx) = P(x) + \frac{dP}{dx}dx = P(x) - P(x)wdx$$

$$\frac{dP}{P} = -wdx \Rightarrow P(x) = P(0)e^{-wx}$$

P(0) = 1 it is sure that initially the particle did not interacts

$$\lambda = \frac{\int xP(x)dx}{\int P(x)dx} = \frac{1}{w} = \frac{1}{N\sigma}$$

Atomic number

Medium density

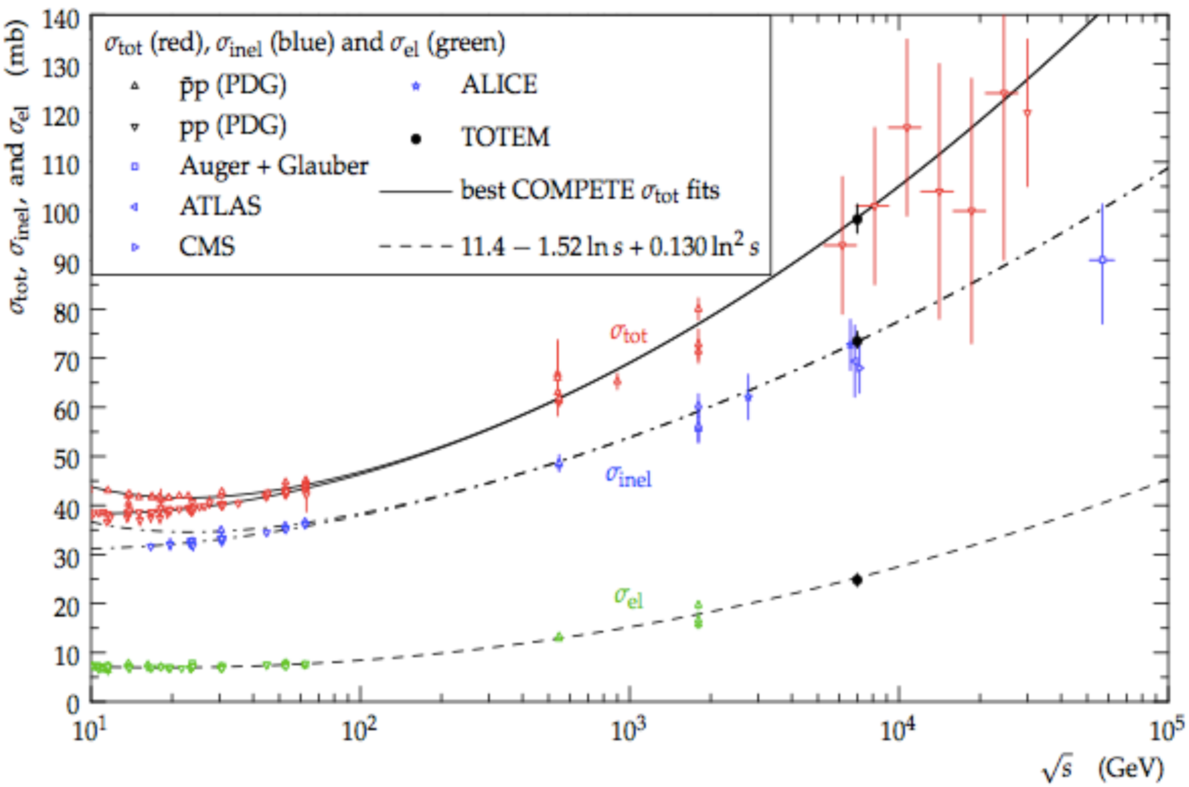
$$\lambda_I = \lambda\rho = \frac{\rho}{N_c\sigma} = \frac{Am_p}{\sigma}$$

in g/cm^2

Example: interaction length of CRs in the atmosphere

$$\lambda_I = \lambda\rho = \frac{\rho}{N_c\sigma} = \frac{Am_p}{\sigma}$$ in g/cm²

Total, inelastic and elastic (anti-)protons on proton cross section



At p∿10GeV/c $\sigma_{pp,inel}$ ∿40 mb

At 1 TeV $\sigma_{pp,inel}$ ~ 50 mb

(1mb = 10^{-27} cm²)

<$A_{atmosphere}$> = 14.5
(dominated by N)

$$\lambda_I = \frac{Am_p}{\sigma_{pAir}}$$

For a beam of A nucleons: $\sigma_{nucl} = \pi \cdot r_N^2 = \pi \cdot (r_o A^{1/3})^2 \cong 5\times 10^{-26} A^{2/3} \quad cm^2 = 50 \quad mb$ x $A^{2/3}$

```
For p-AIR: 14.5*1.67 x 10^-27kg /300 x 10^-27 cm^2 = 80 g/cm^2
For Fe-Air: 5 g/cm^2
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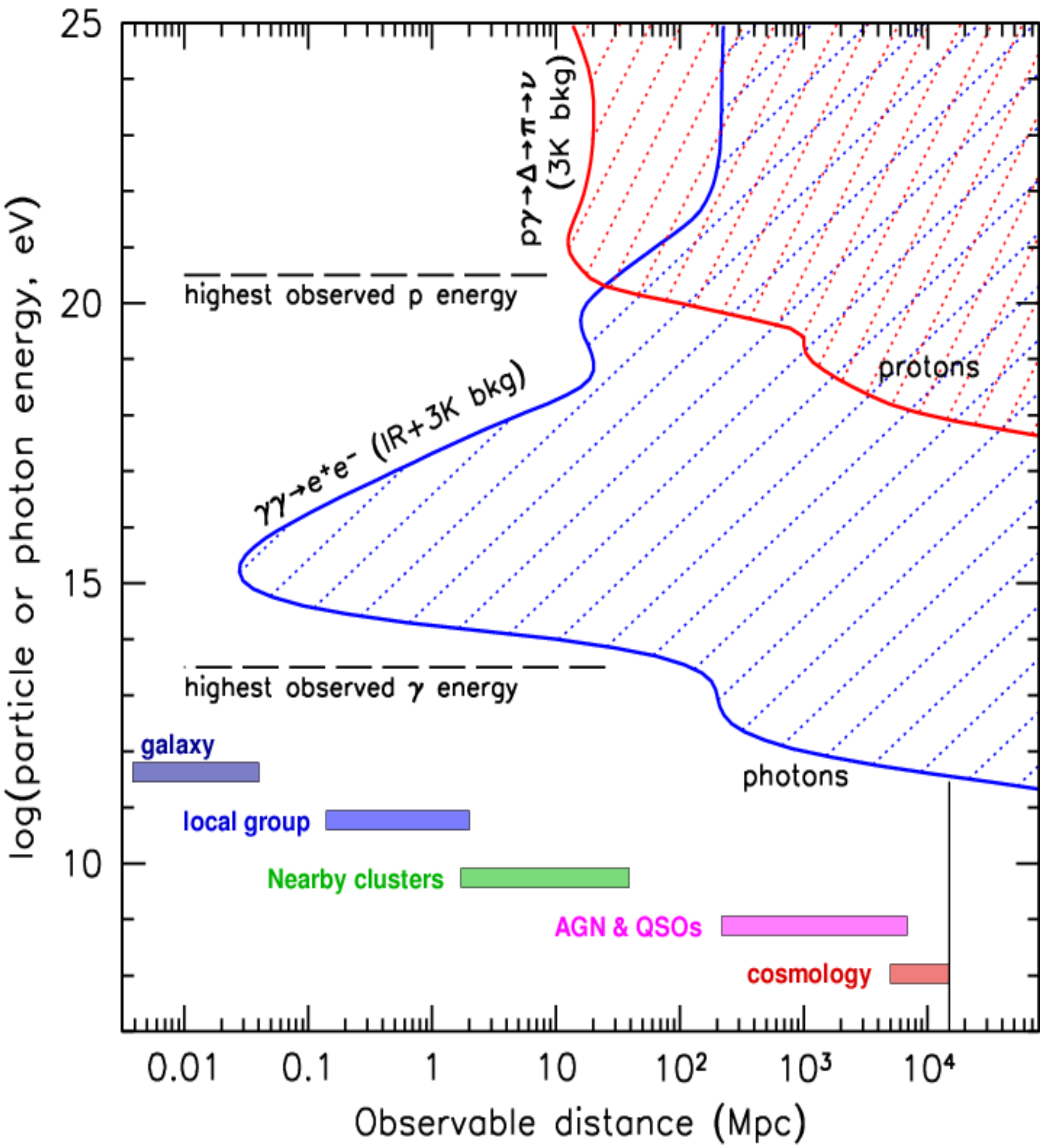
The multi-messenger's horizons



arxiv.org/pdf/0811.1160v2.pdf

Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \to \Delta^+ \to \pi^+ n$$

$$L_\gamma = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\mathrm{cm}^2 \times 400\mathrm{cm}^{-3}} \sim 10\ \mathrm{Mpc}$$

The neutrino horizon is comparable to t observable universe!

$$\bar\nu\nu_{1.95K} \to Z \to X$$

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4\times 10^{21}\left(\frac{1\mathrm{eV}}{m_\nu}\right)\mathrm{eV}$$

$$L_\nu = \frac{1}{\sigma_{res}\times n} = \frac{1}{5\times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

T. J. Weiler, Phys. Rev. Lett. **49**, 234 (1982)

The proton horizon

$$r_{\phi\pi}(E_{20}) \cong \frac{13.7 \exp[4/E_{20}]}{[1+4/E_{20}]} \text{ Mpc}$$

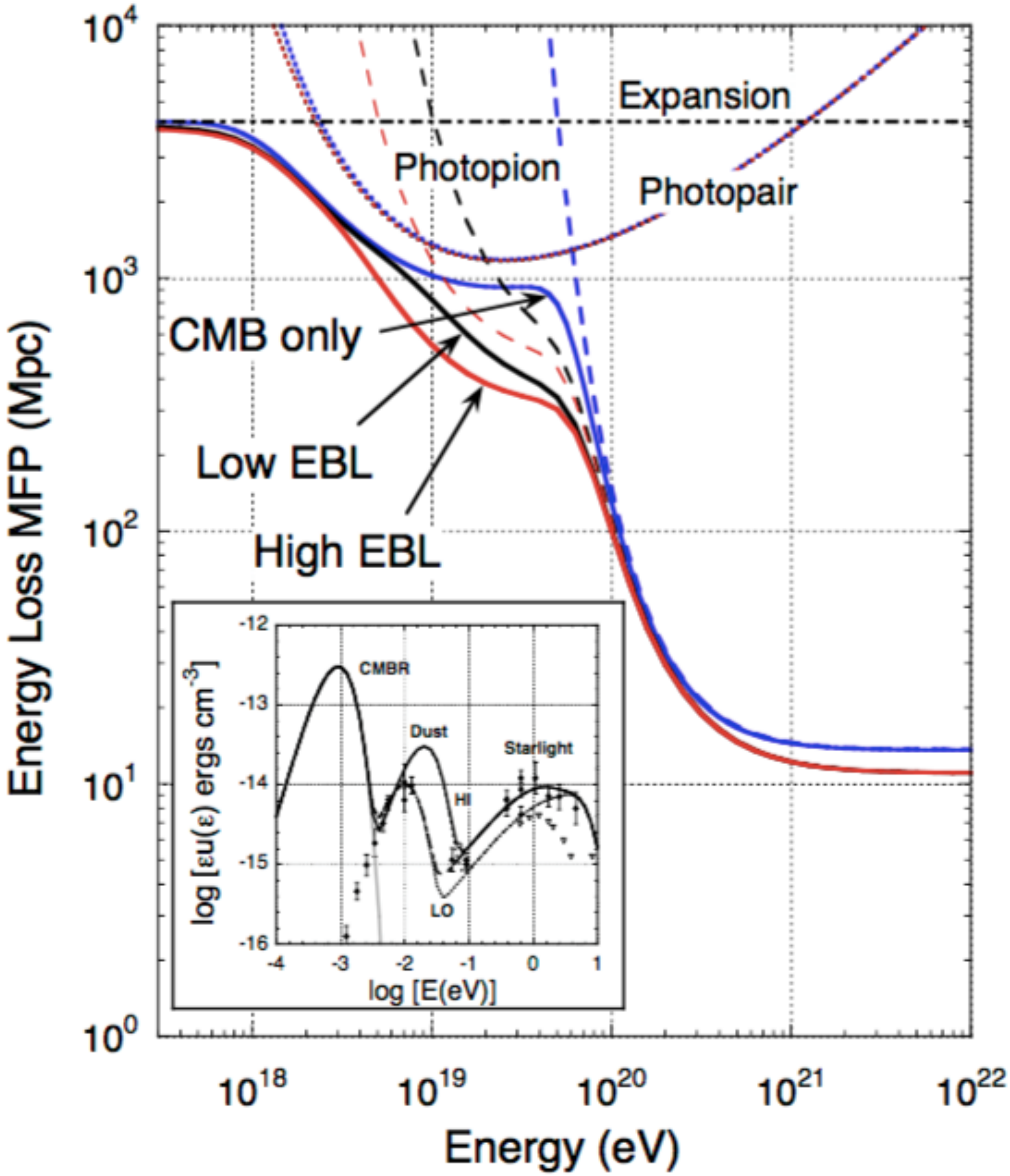
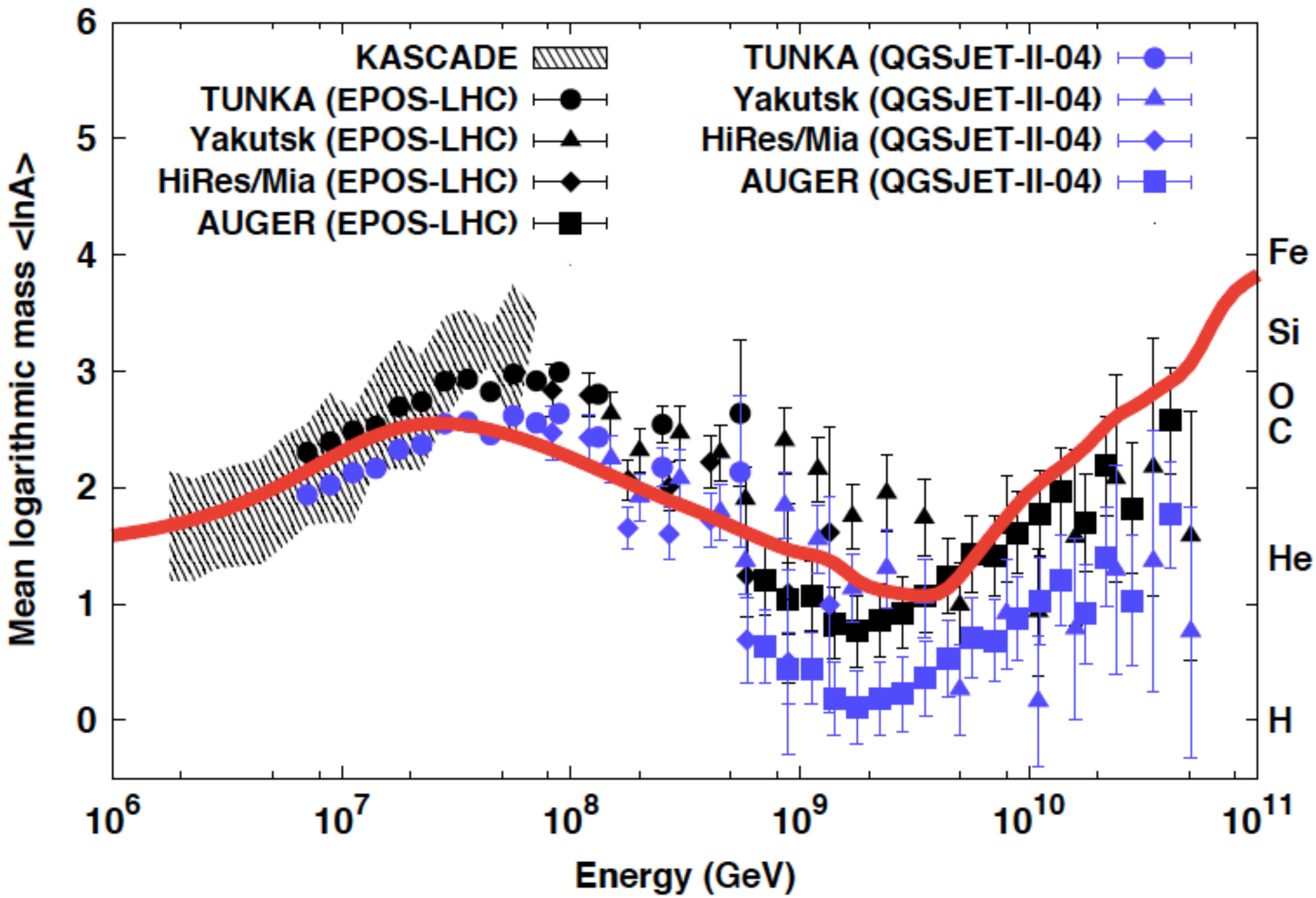


Figure 1. Mean-free paths for energy loss of UHECR protons in different model EBLs are shown by the solid curves, with photopair (dotted) and photopion (dashed) components shown separately. "CMB only" refers to total energy losses with CMB photons only, using eq. (4) for the energy-loss rate of protons due to photopion production. Inset: Measurements of the EBL at optical and infrared frequencies, including phenomenological fits to low-redshift EBL in terms of a superposition of modified blackbodies. A Hubble constant of 72 km s^{-1} Mpc^{-1} is used throughout.

What about neutrons? for a neutron of $E = 10^9$ GeV, $l_{decay} = \Upsilon c\tau = E/mc^2 \times c \times 886$ s $= 10^9$ GeV/1GeV x 3×10^8m/s x 886s = 2.66×10^{20} m x 3.24×10^{-20} kpc/m = 8.6 kpc

CR Composition



Deflection of CRs in B-field

$$mv^2/r = pv/r = ZevB/c$$

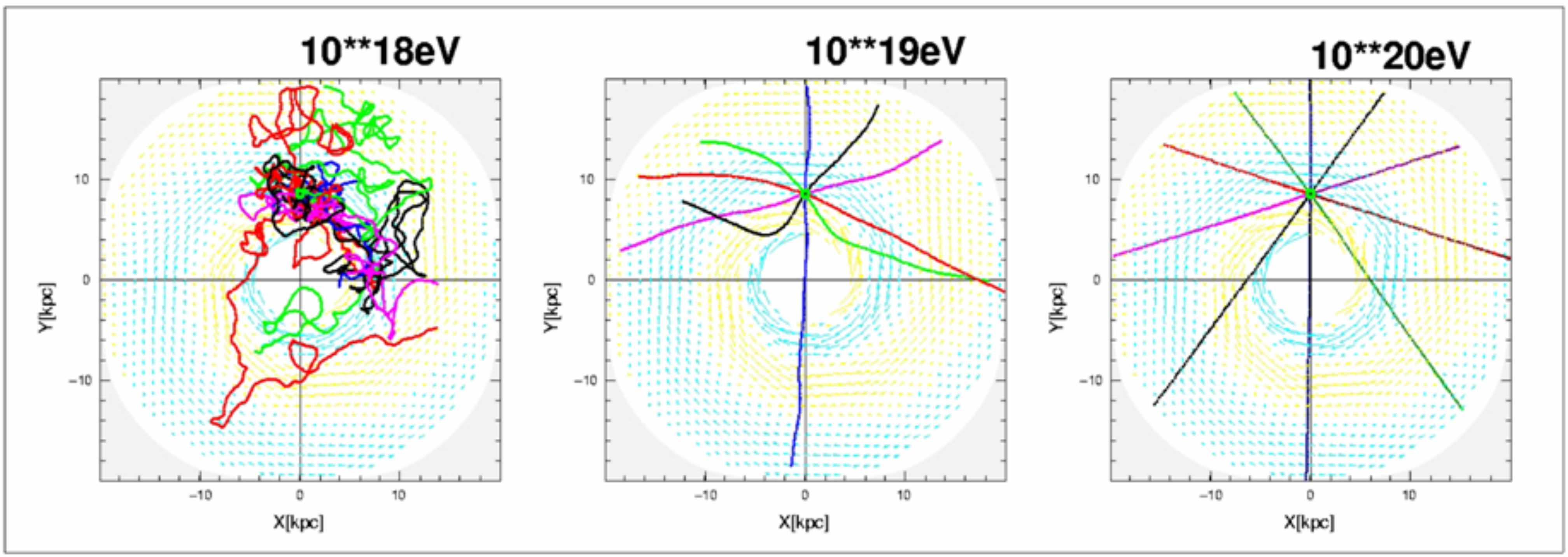
$$r = pc/ZeB$$

$$r(cm) = \frac{1}{300}\frac{E(eV)}{ZB(G)}$$

$$(10^{12}eV) = 10^{15}cm = 3\times10^{-4}pc$$

$$r = (10^{15}eV) = 10^{18}cm = 3\times10^{-1}pc$$

$$(10^{18}eV) = 10^{21}cm = 300\,pc$$



Deflection of CRs in B-field

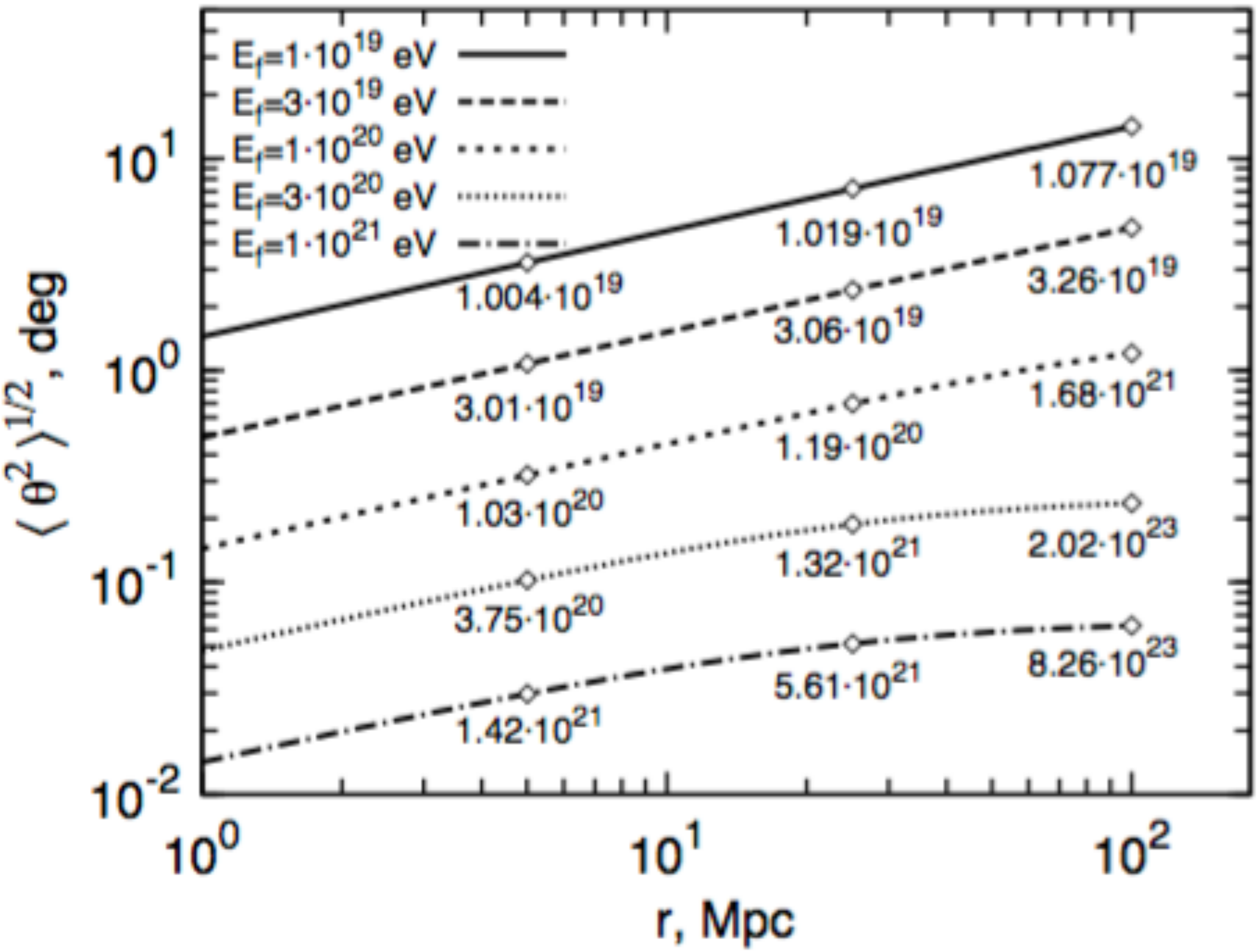
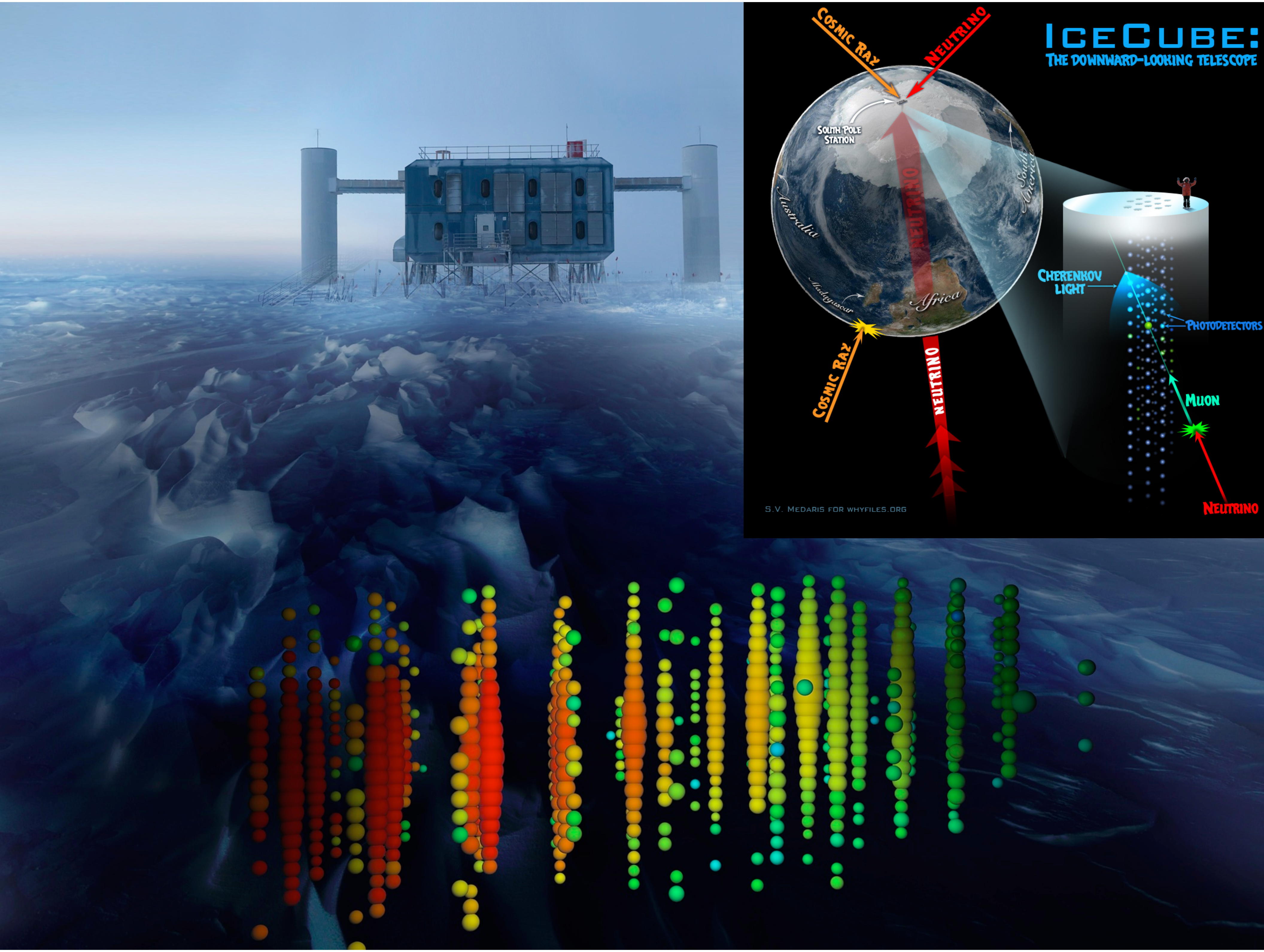
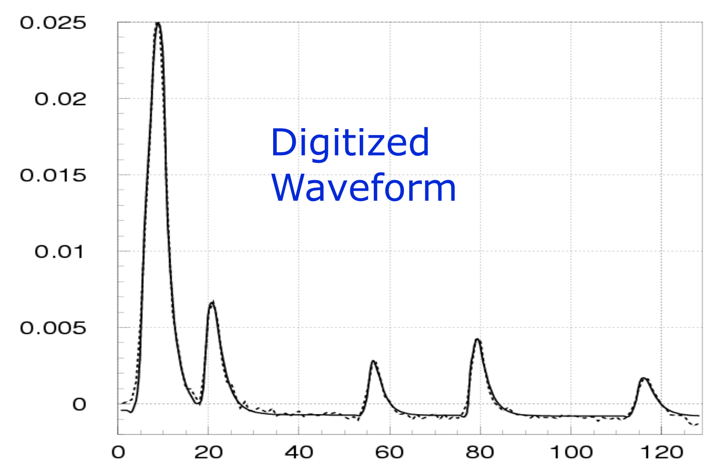


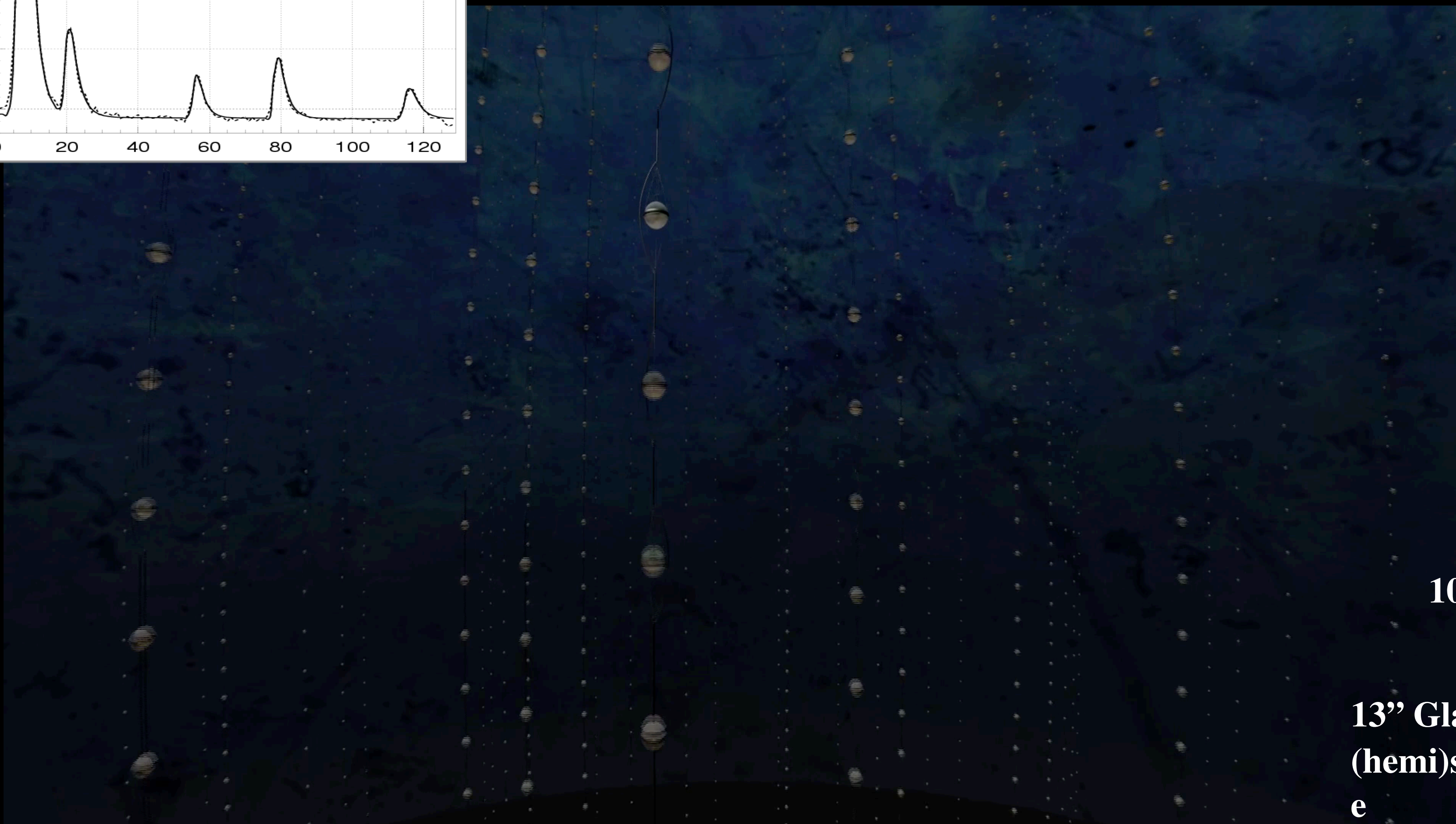
FIG. 2: The mean deflection angle of protons for the fixed *observed* energy E_f over the distance r. The numbers at the curves indicate the energies which proton had at the distance r from the observer.

Kelner, Aharonian, http://arxiv.org/pdf/1006.1045.pdf



ICECUBE:
THE DOWNWARD-LOOKING TELESCOPE
COSMIC RAY
NEUTRINO
SOUTH POLE STATION
Australia
South America
Madagascar
Africa
NEUTRINO
COSMIC RAY
NEUTRINO
CHERENKOV LIGHT
PHOTODETECTORS
MUON
NEUTRINO
S.V. MEDARIS FOR WHYFILES.ORG



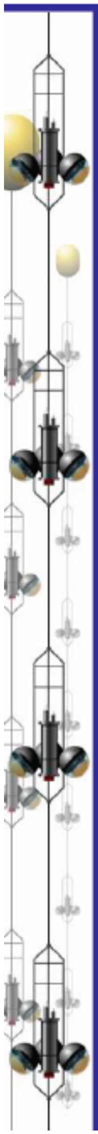


10” PMT

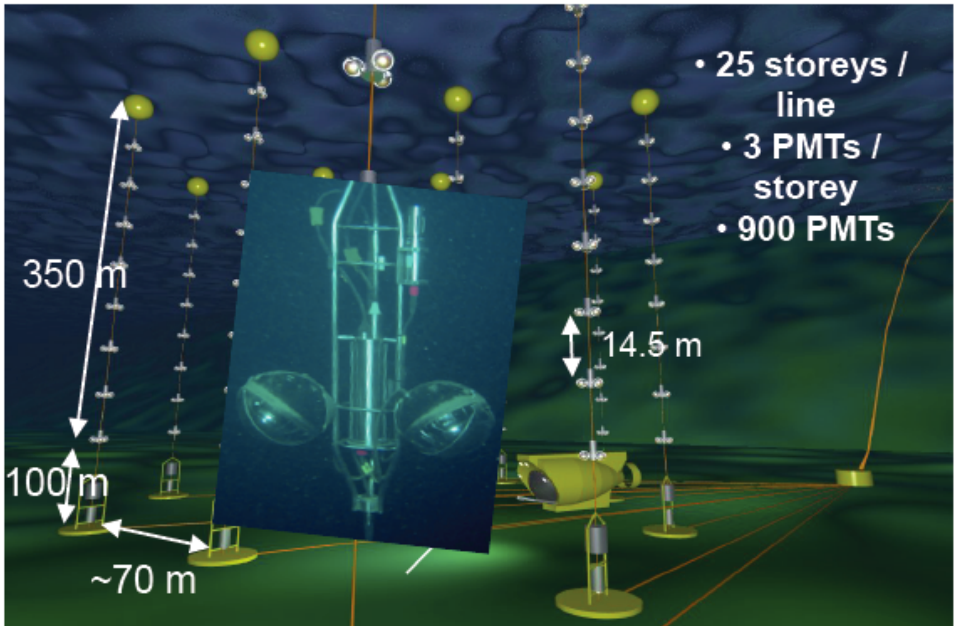
13” Glass (hemi)sphere

> 98.5% of DOMs in stable operation

Mediterranean Detectors



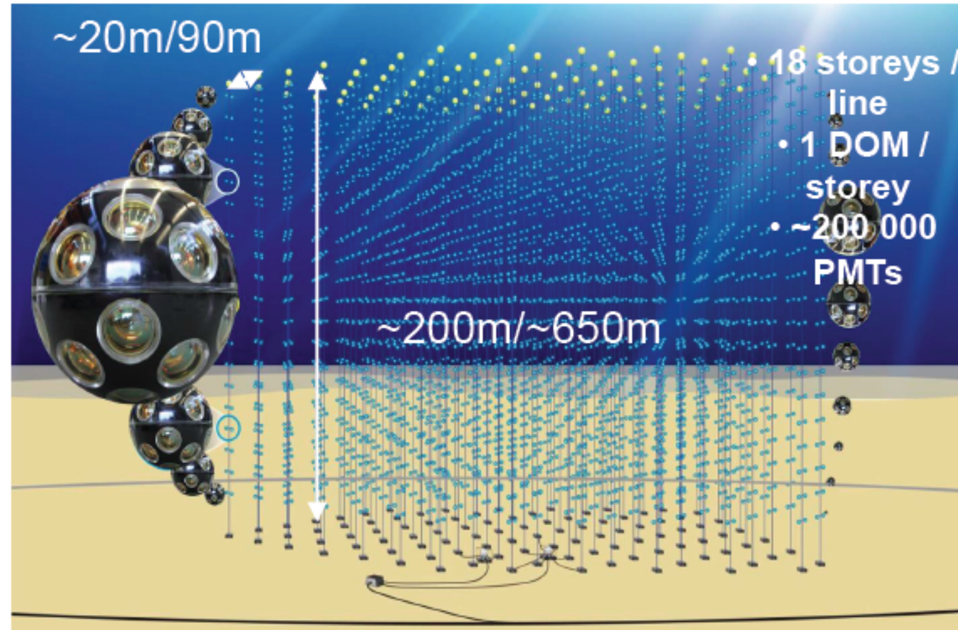
ANTARES Complete since 2008



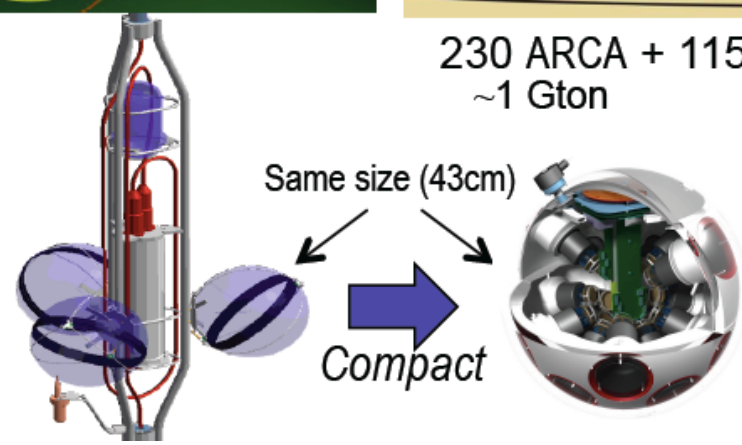
~10 Mton

12 lines
First Generation
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton



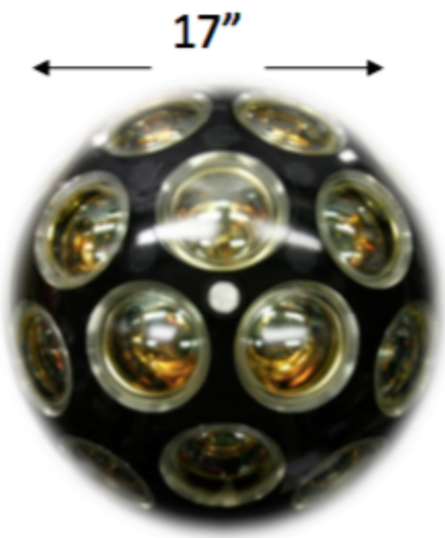
- DOM: 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

What technologies for the coming future?

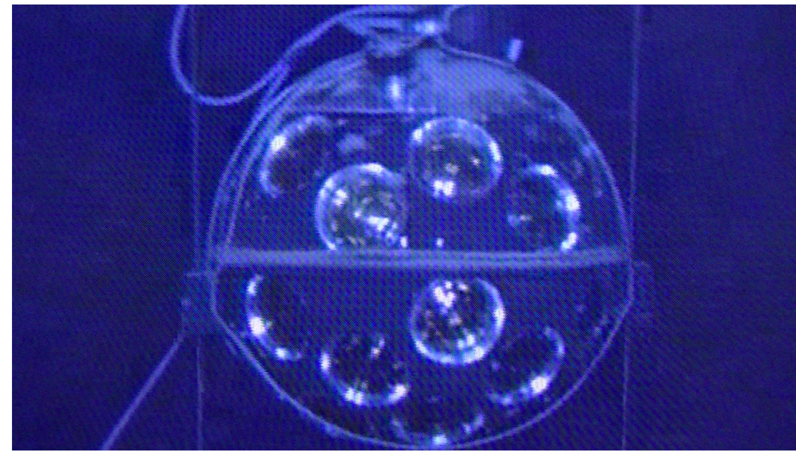
Best case scenario (NH and θ_{23}=48°) >5σ by mid 2021 (1.5 years)

Digital Optical Module



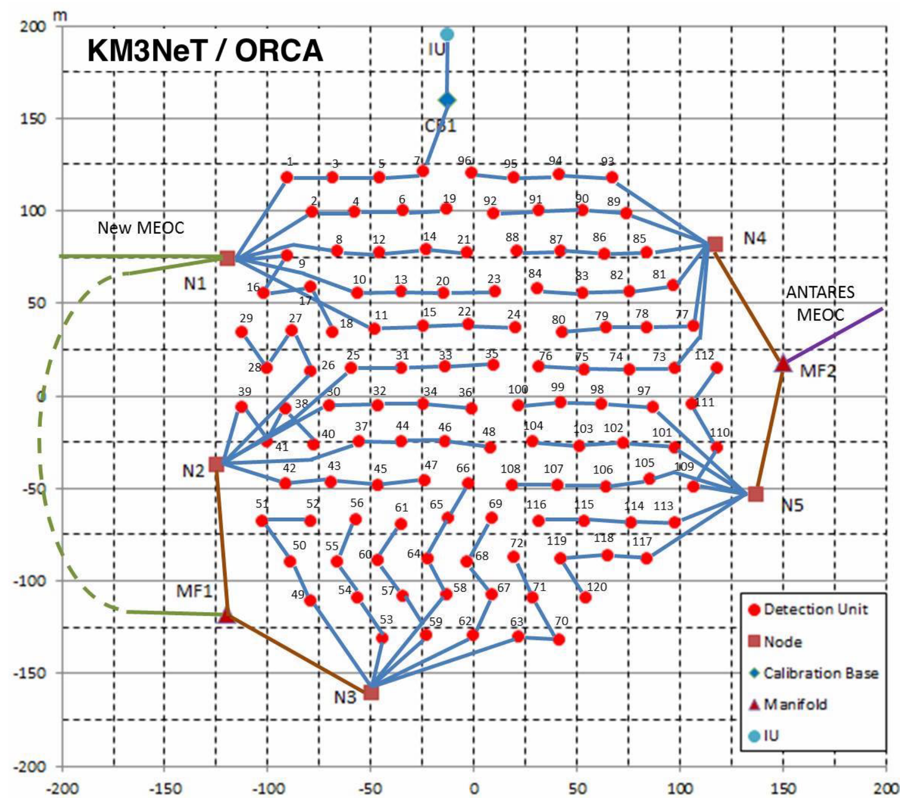
Power consumption
7 W (x 200’000 DOMs)
20% @ 470 nm and
28% @ 404 nm

TTS 4.5 ns (FWHM)
Gain 3 x 10^6

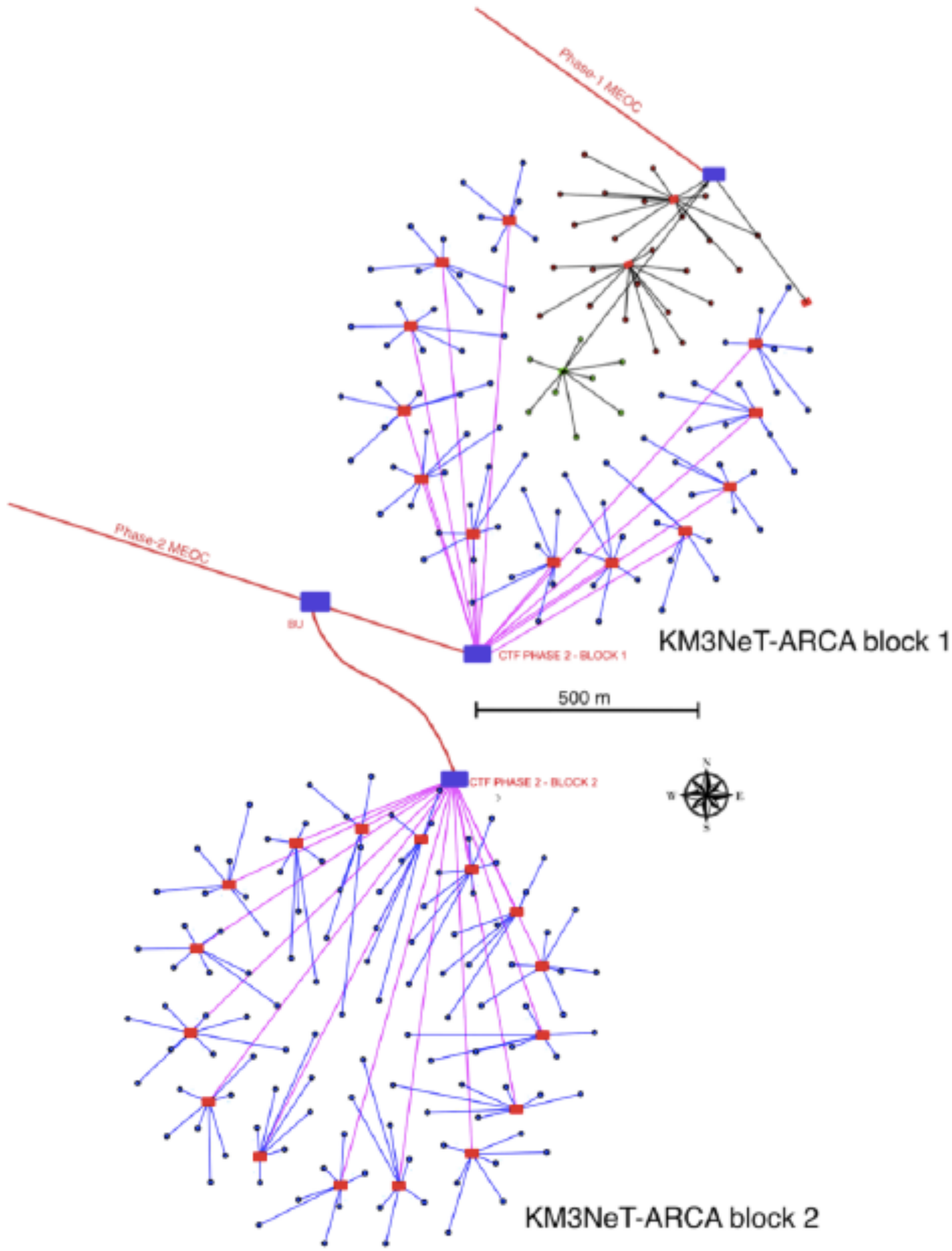


Each PMT has an individual low-power high-voltage base with integrated amplification and tuneable discrimination threshold.
The arrival time and the ToT of each PMT, are recorded by an individual TDC implemented in a FPGA.

- 31 x 3” PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Background rejection
- All data to shore

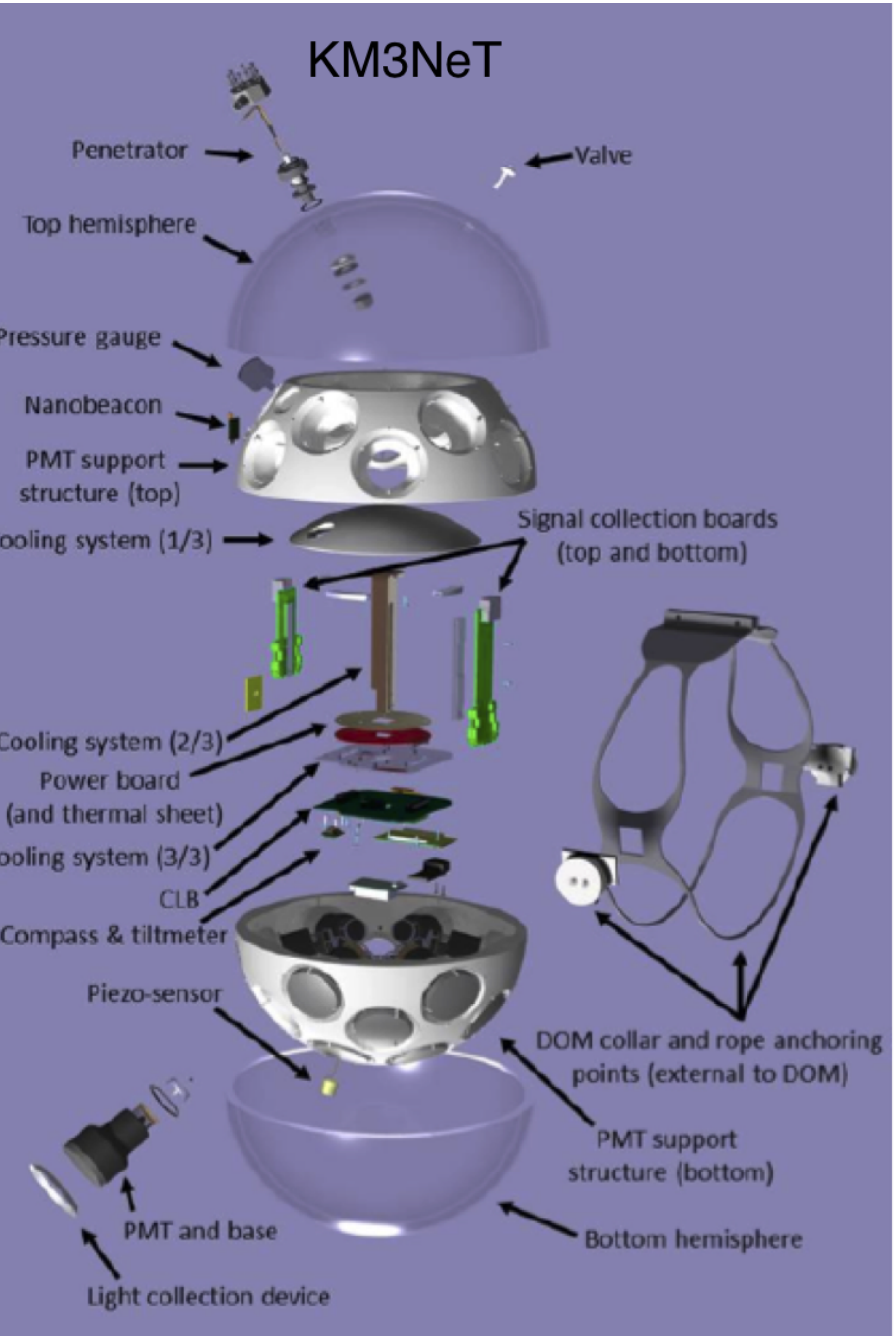


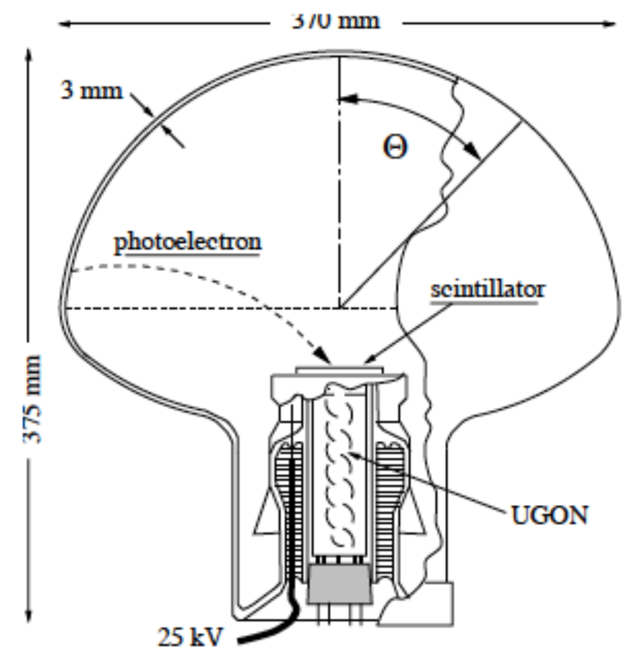
High energies ARCA



The russian idea (80ies): the quasar

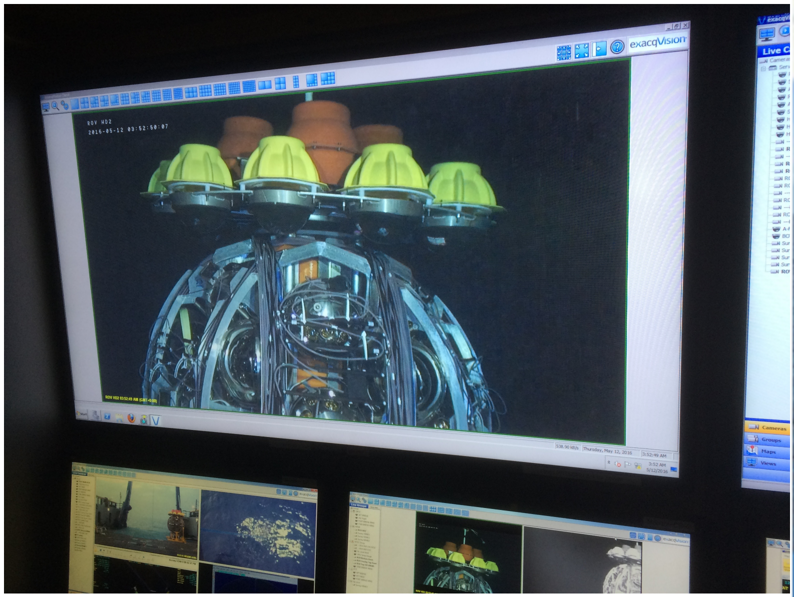
Spiering arXiv:1207.4952

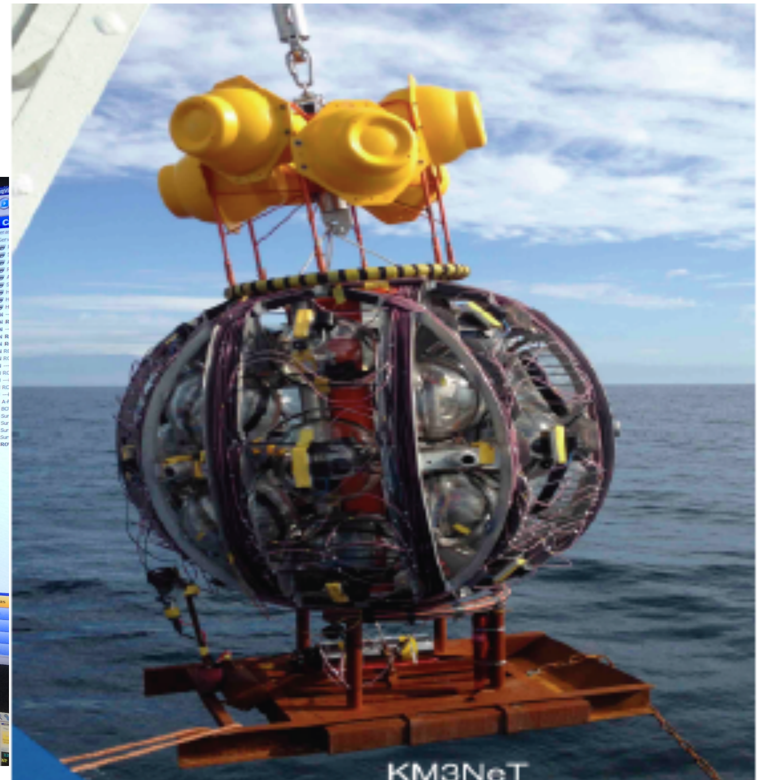




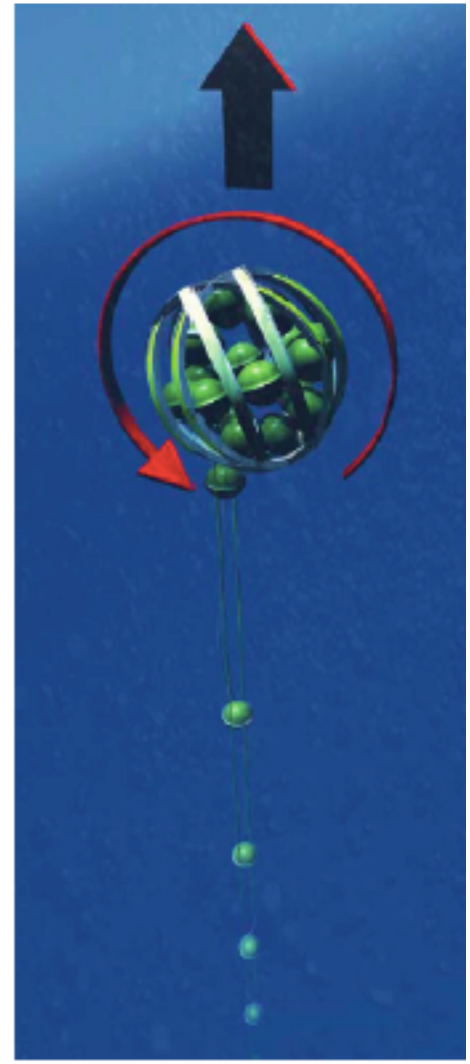
New ideas: Abalone,…

What technologies for the coming future?





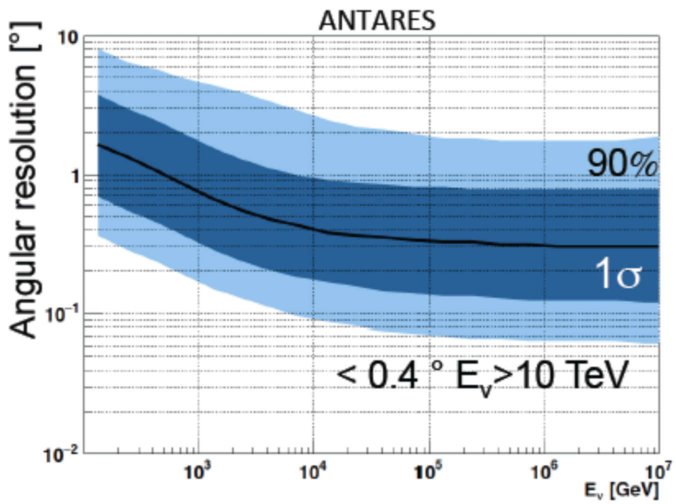
rapid deployment
autonomous unfurling
recoverable

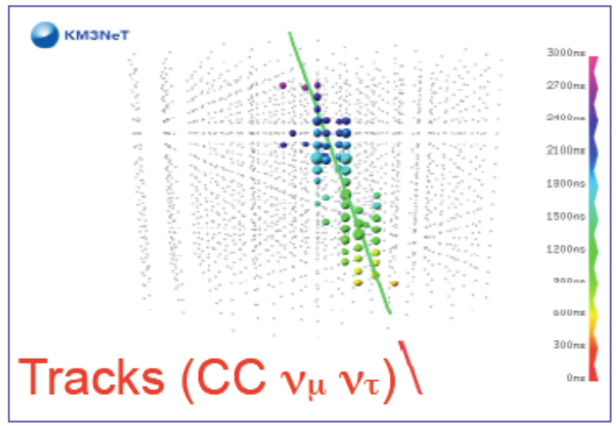


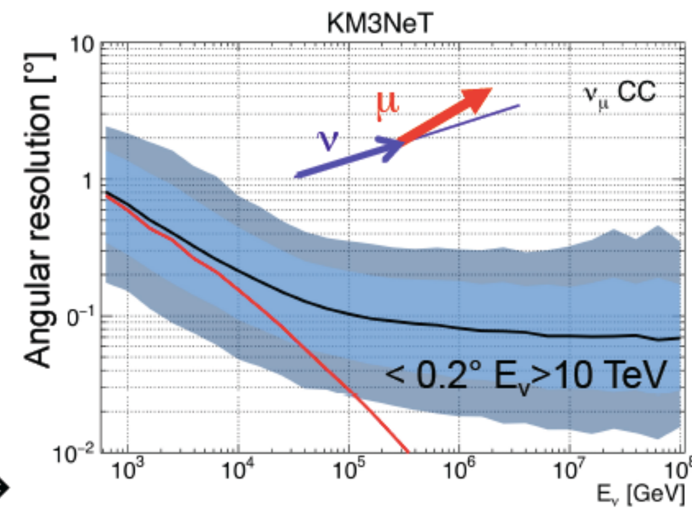
KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

ARCA

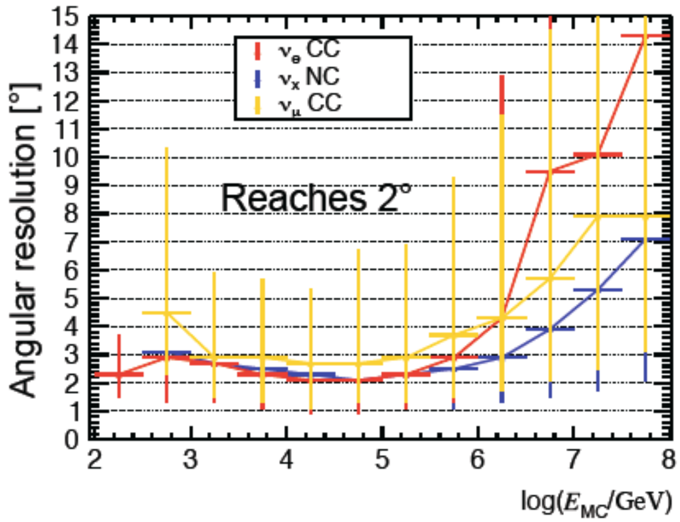
Reconstruction Performances

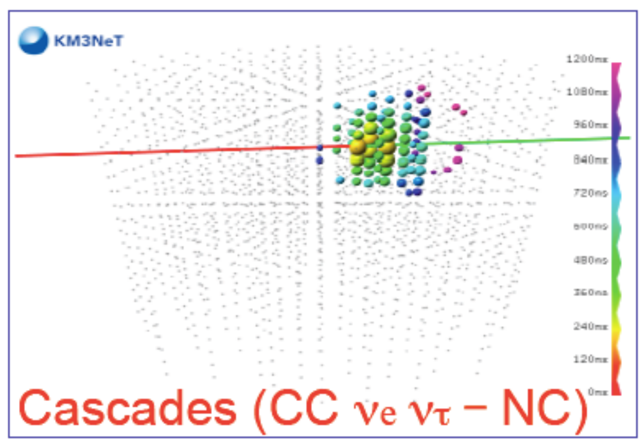


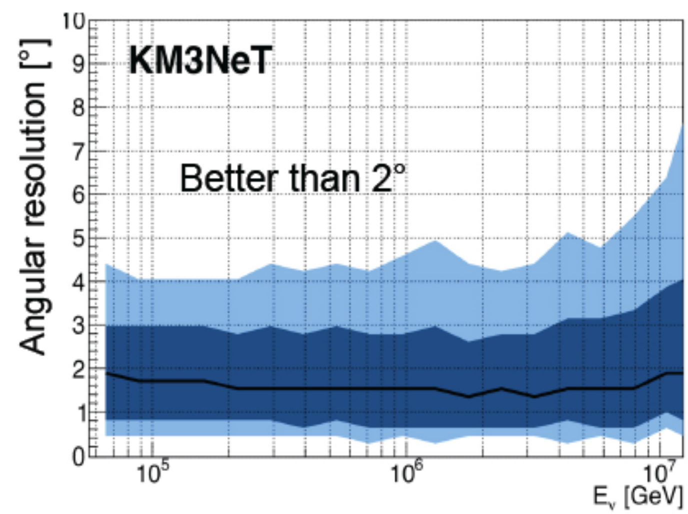




←0.35 Log(Eμ) Resolution 0.27→







←10% Energy Resolution 5%→

Getting to know the medium...

Light propagating in a medium is absorbed and scattered.

$$I = I_0 \frac{A}{4\pi R^2} e^{-R/\lambda_{att}^{eff}}$$

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scatt}}$$

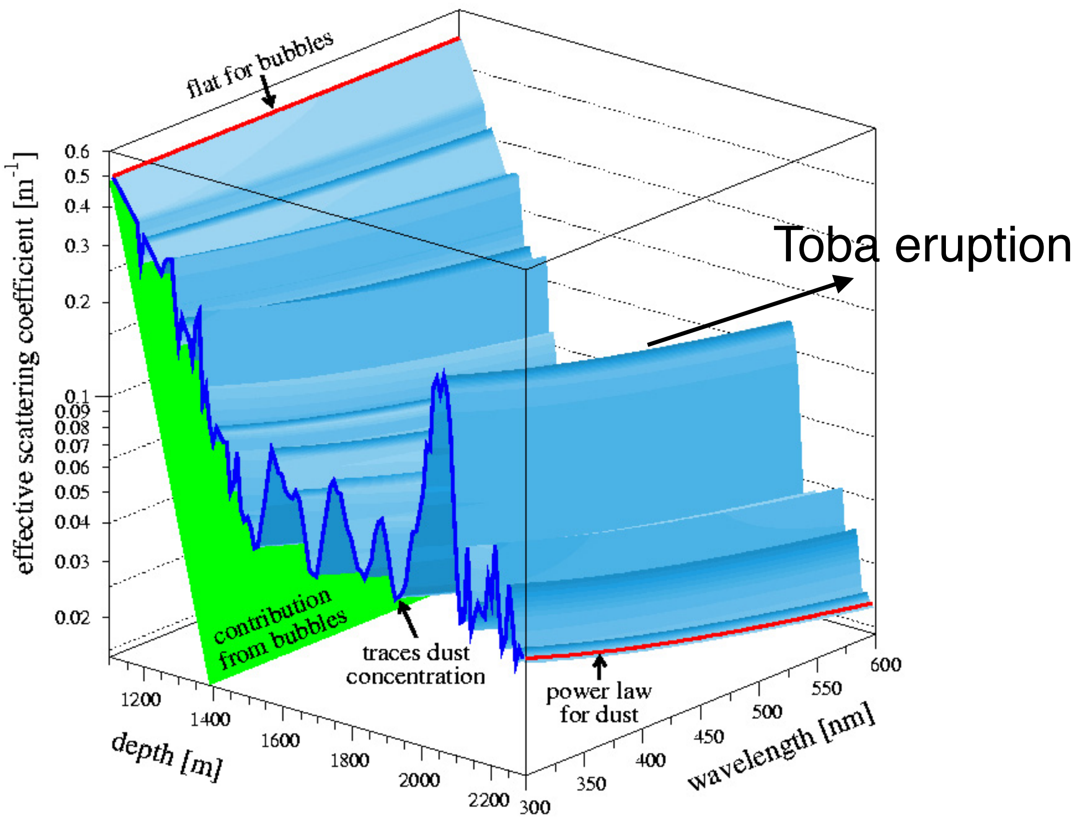
$$\lambda_{sct}^{eff} \simeq \frac{\lambda_{sct}}{1 - \langle \cos\theta \rangle}$$

Scattering is the main factor limiting the angular resolution together with PMT TTS and electronics resolution.

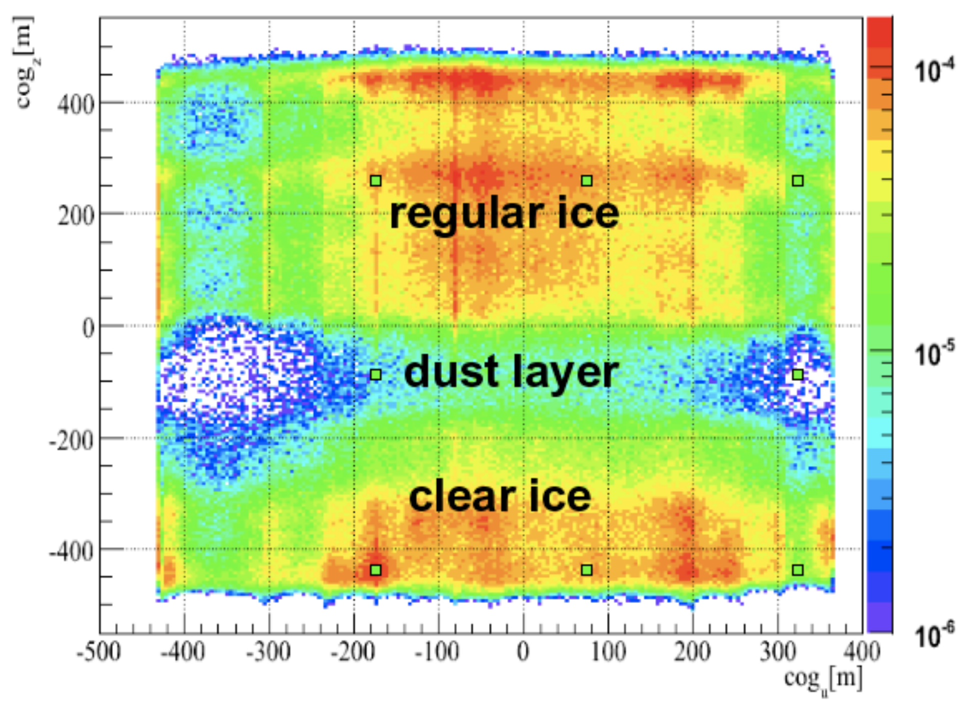
Sea water: λ_{att} ~ 50 m λ_{abs} ~ 50-60 m λ^{eff}_{scatt} > 200 m @ 450 nm

Polar ice: λ_{abs} ~ 110 m λ^{eff}_{scat} ~ 20 m @ 400 nm

Ice scattering and absorption is depth dependent

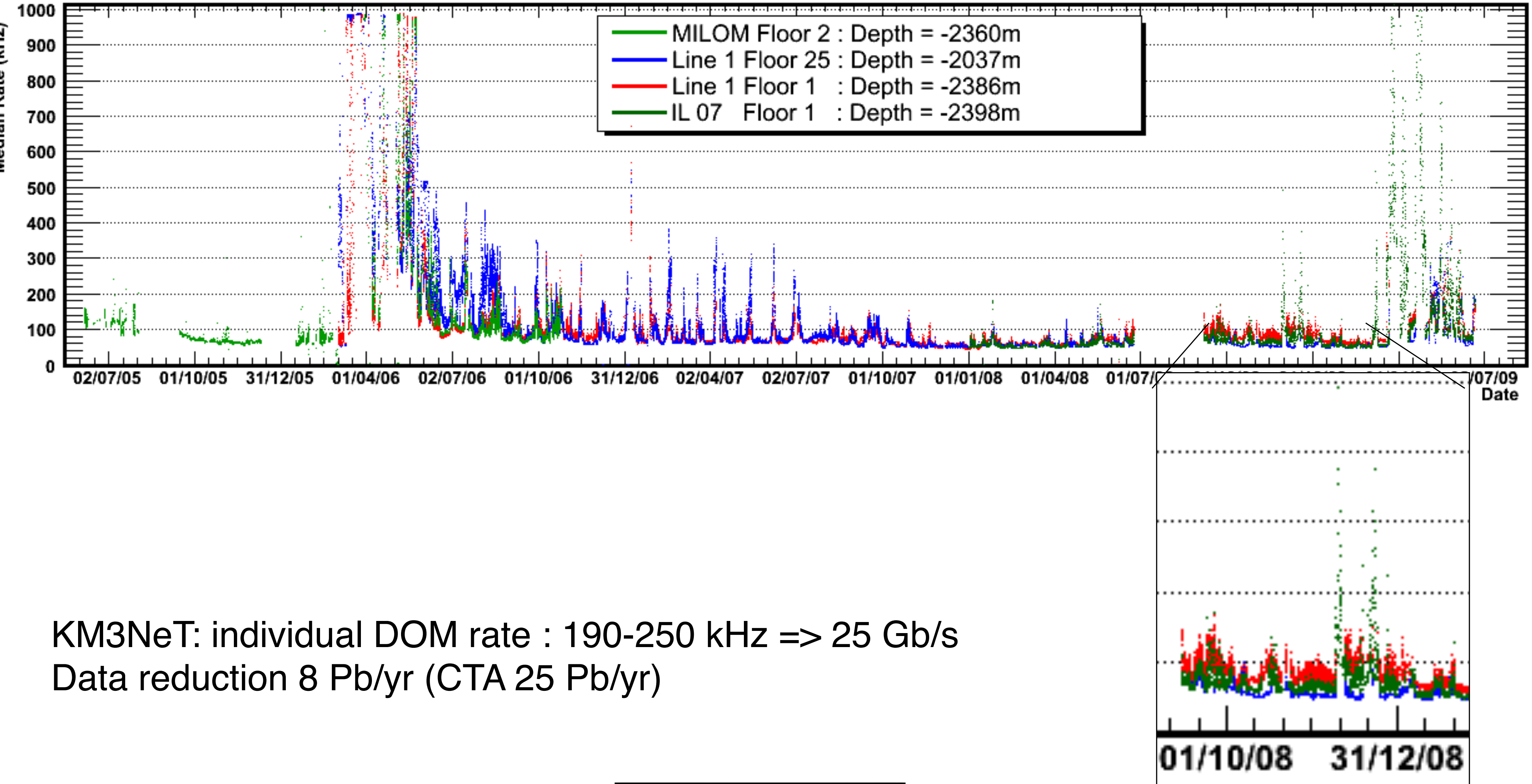


Muon 'radiography' of ice



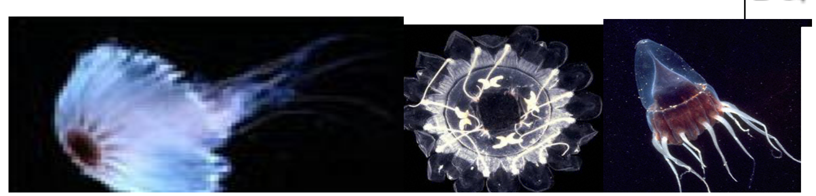
ANTARES environmental noise

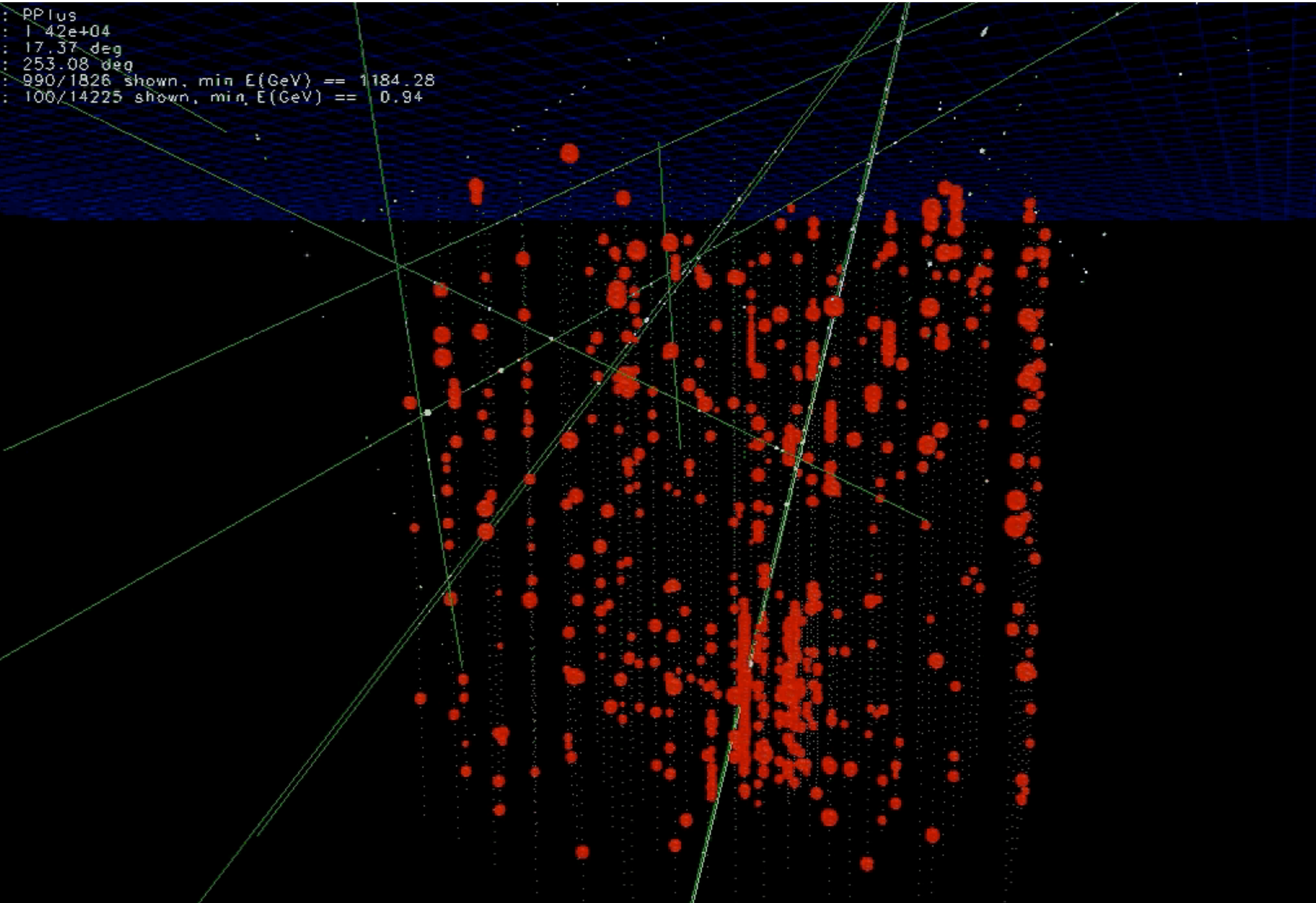
the measurement of ^{40}K coincidences between adjacent PMTs of the same DOM allows the photon detection efficiency to be monitored in real time with high precision. The variable nature of optical noise due to bioluminescence is controlled by sampling it for each individual PMT with a frequency of 10 Hz.



KM3NeT: individual DOM rate : 190-250 kHz => 25 Gb/s

Data reduction 8 Pb/yr (CTA 25 Pb/yr)

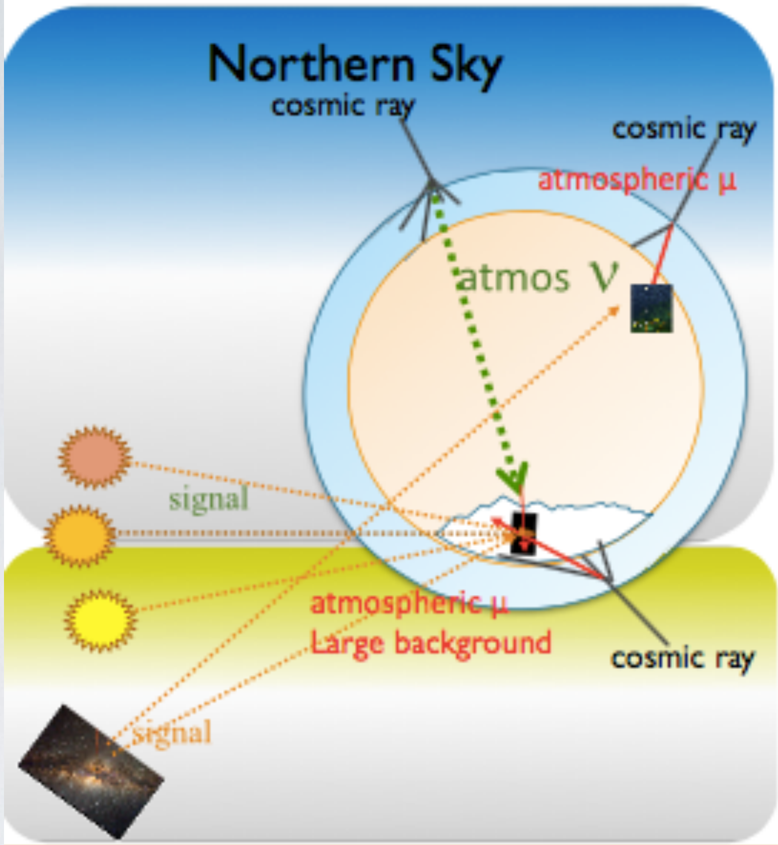




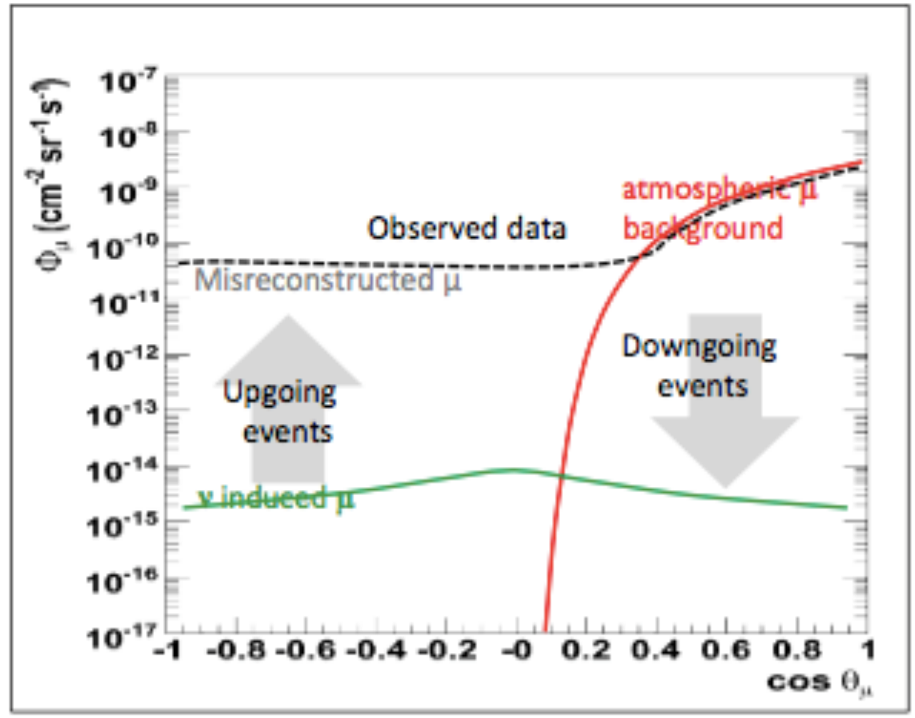
You have seen only 10 nms of data taking

The backgrounds

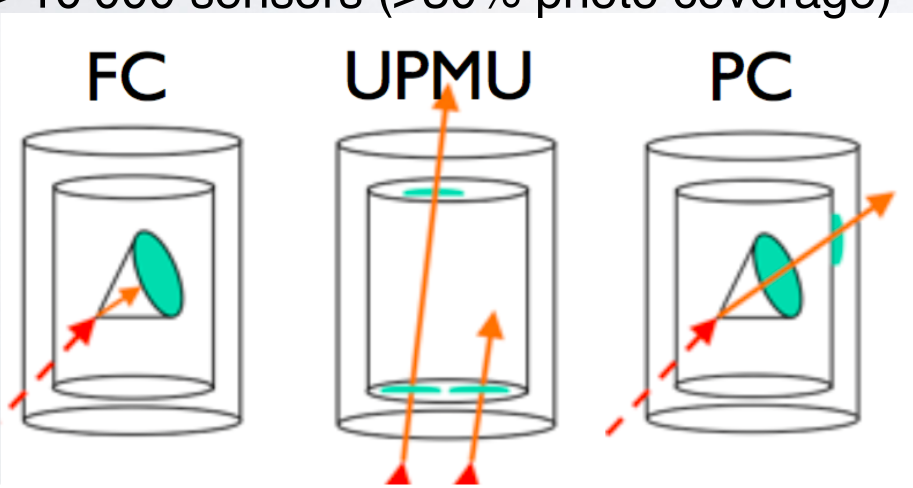
Rameez's lecture



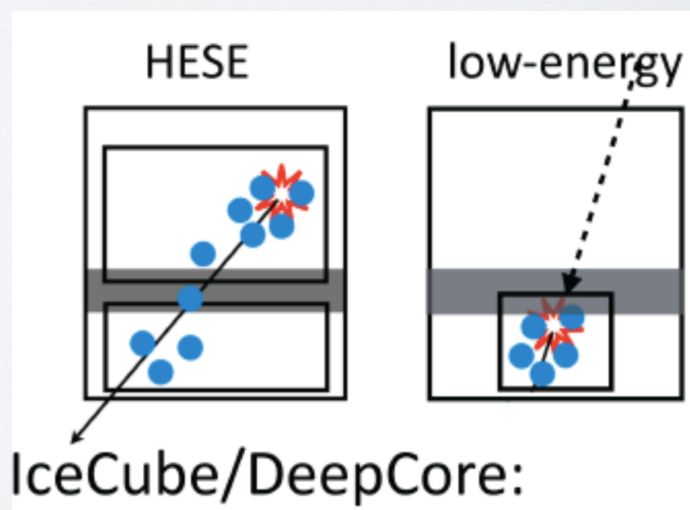
Example : IceCube



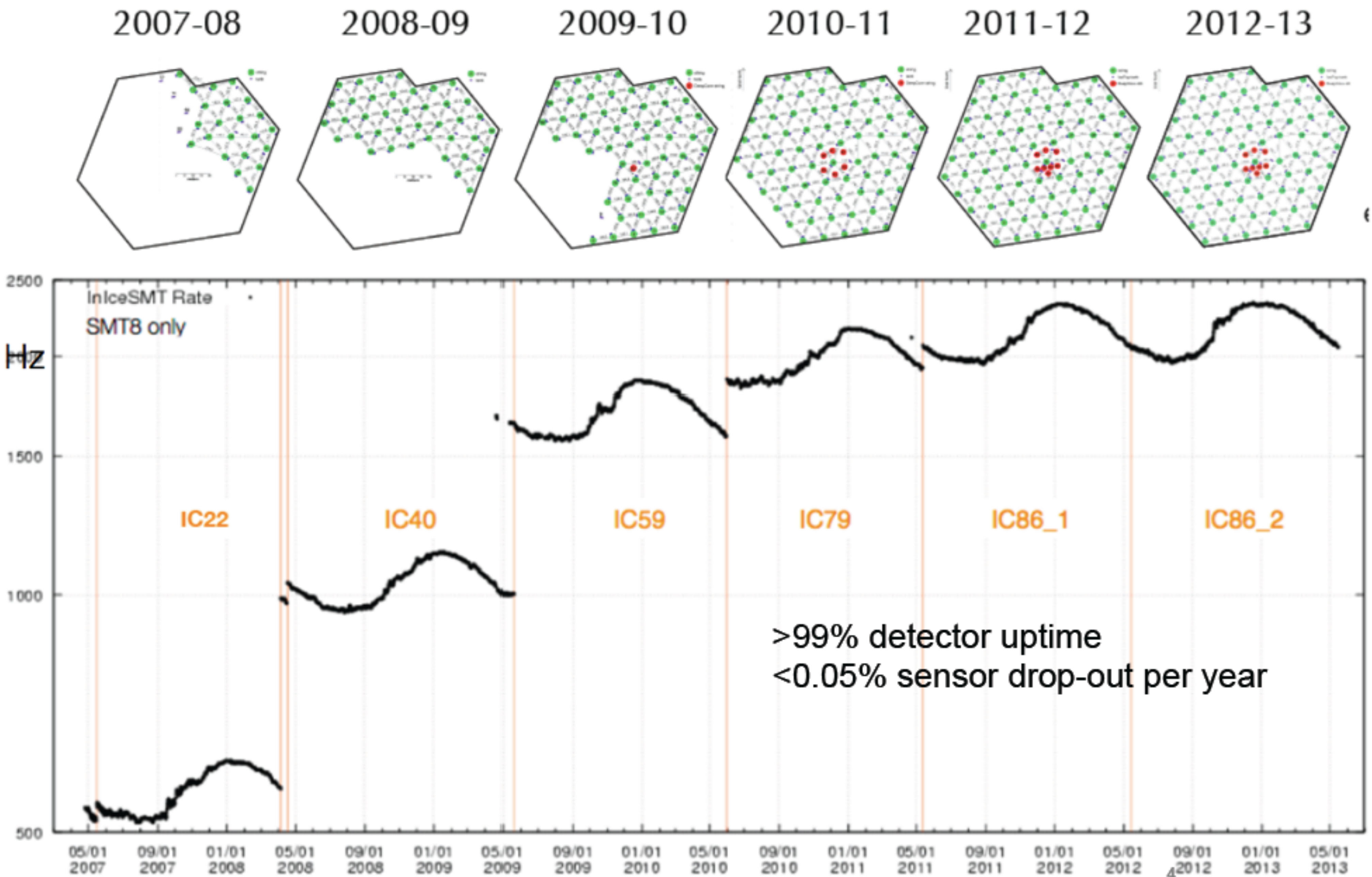
Eg Super-Kamiokande Cherenkov imaging
> 10'000 sensors (>30% photo coverage)



Sparse detectors with instrumented cores



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

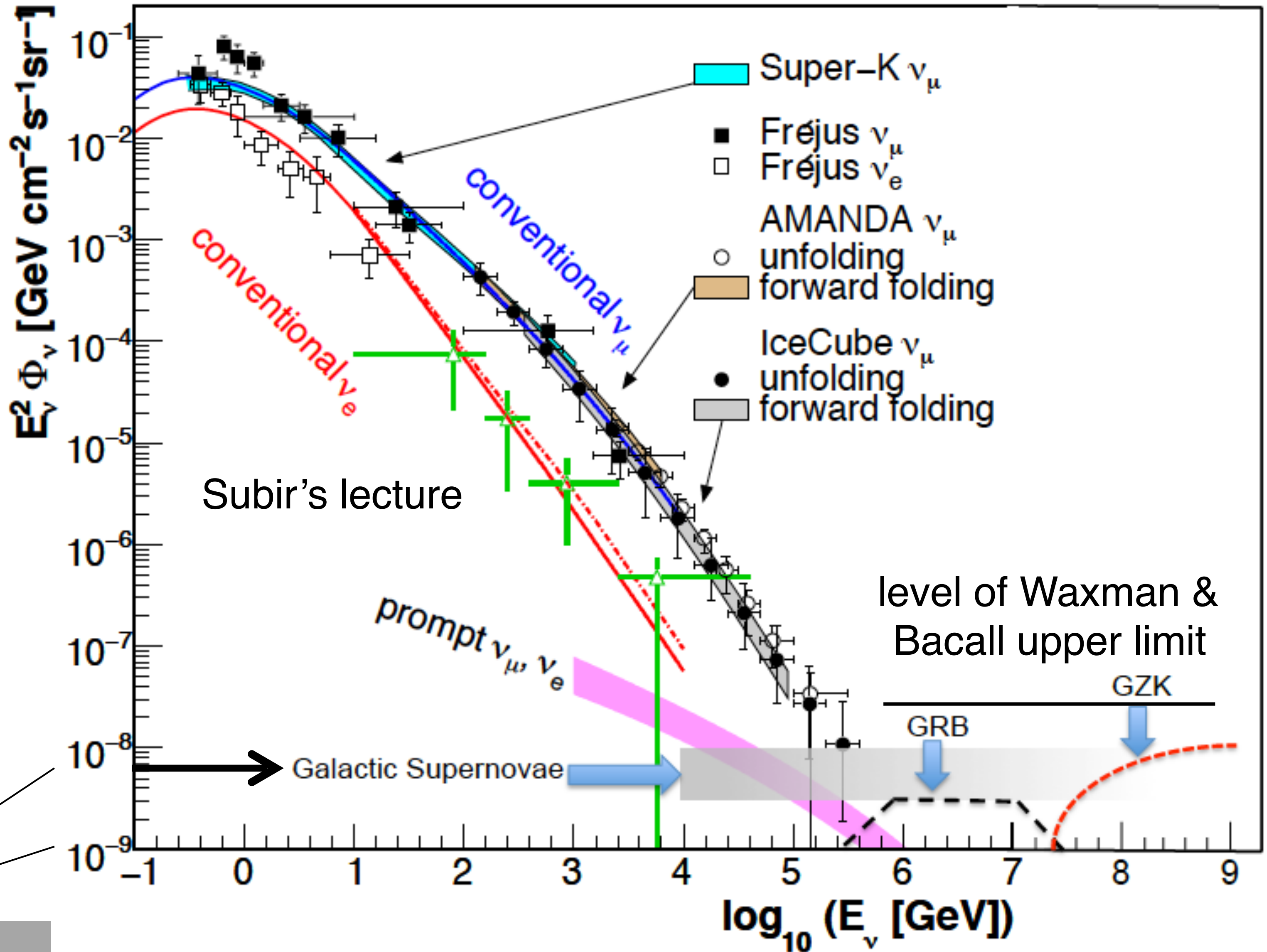


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$dN/dE \sim E^{-2}$

1-10 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

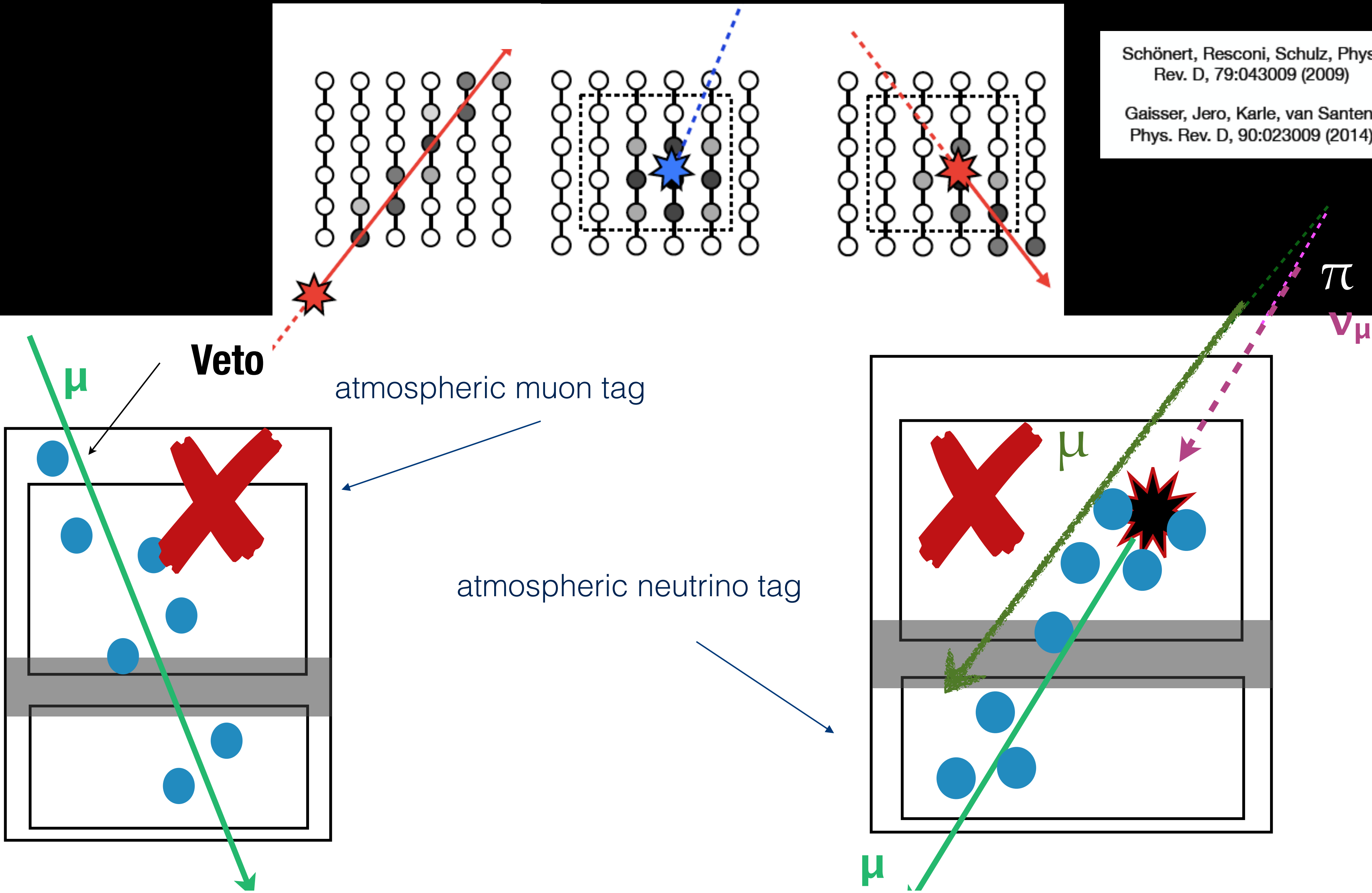
100 TeV

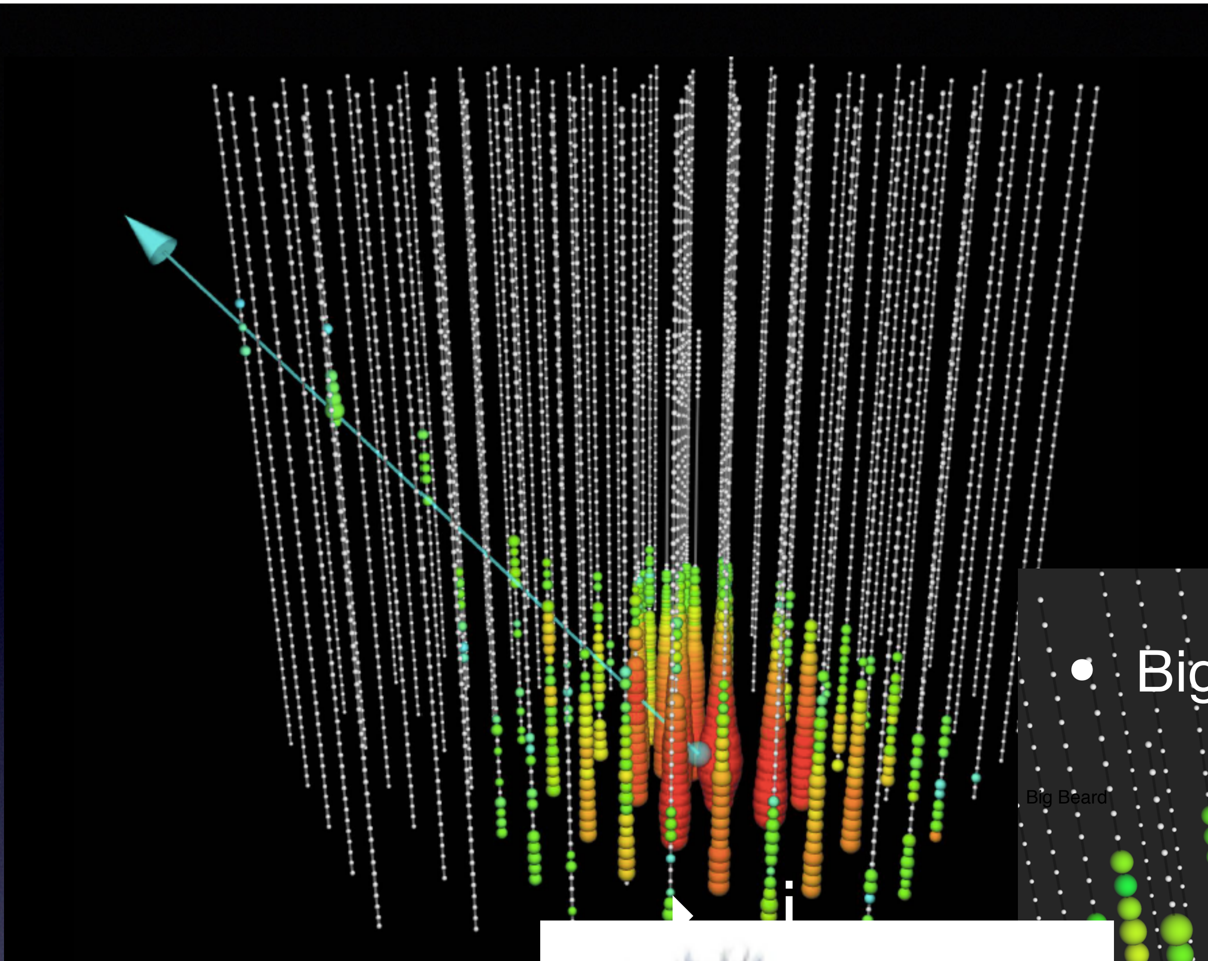
Neutrino selection & background rejection

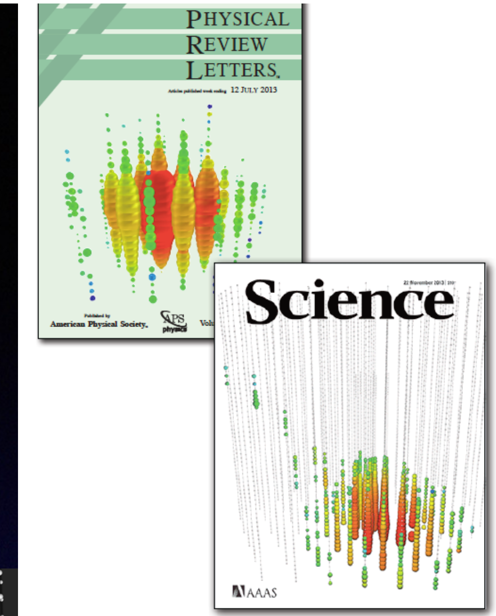
Upgoing thoroughgoing neutrino induced muons - Earth is a filter - or vertex identification of 'starting events' (tracks and cascades)

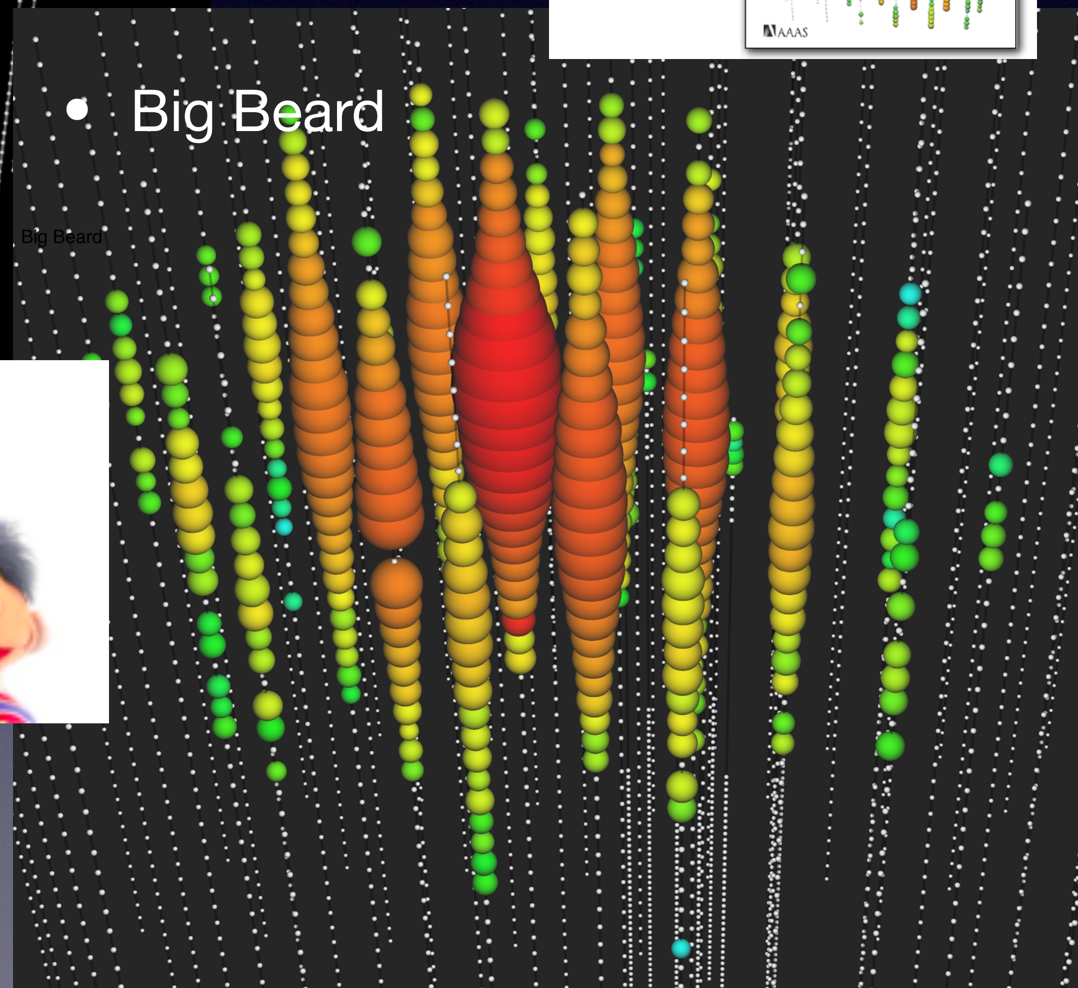
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)







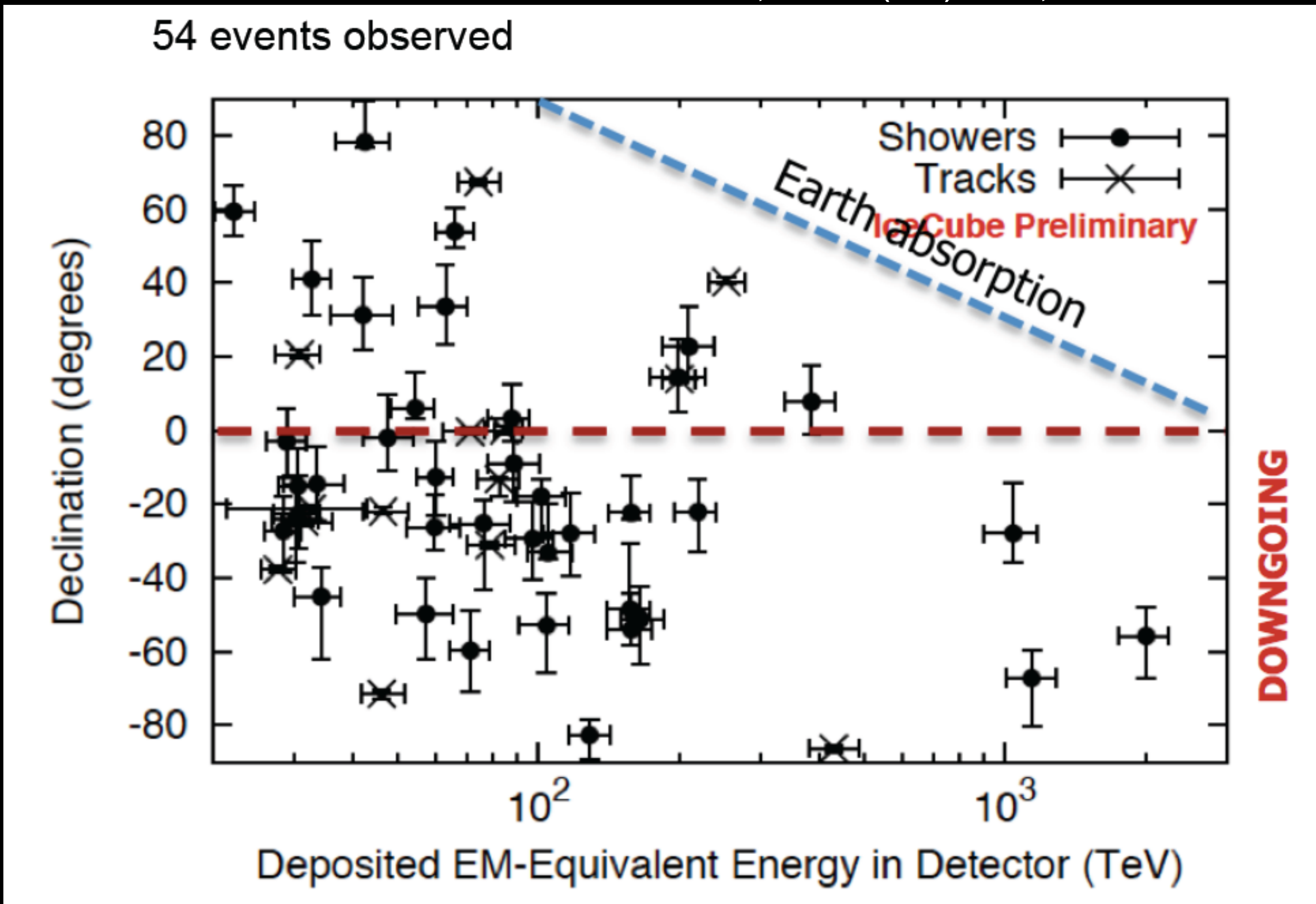


- Big Beard

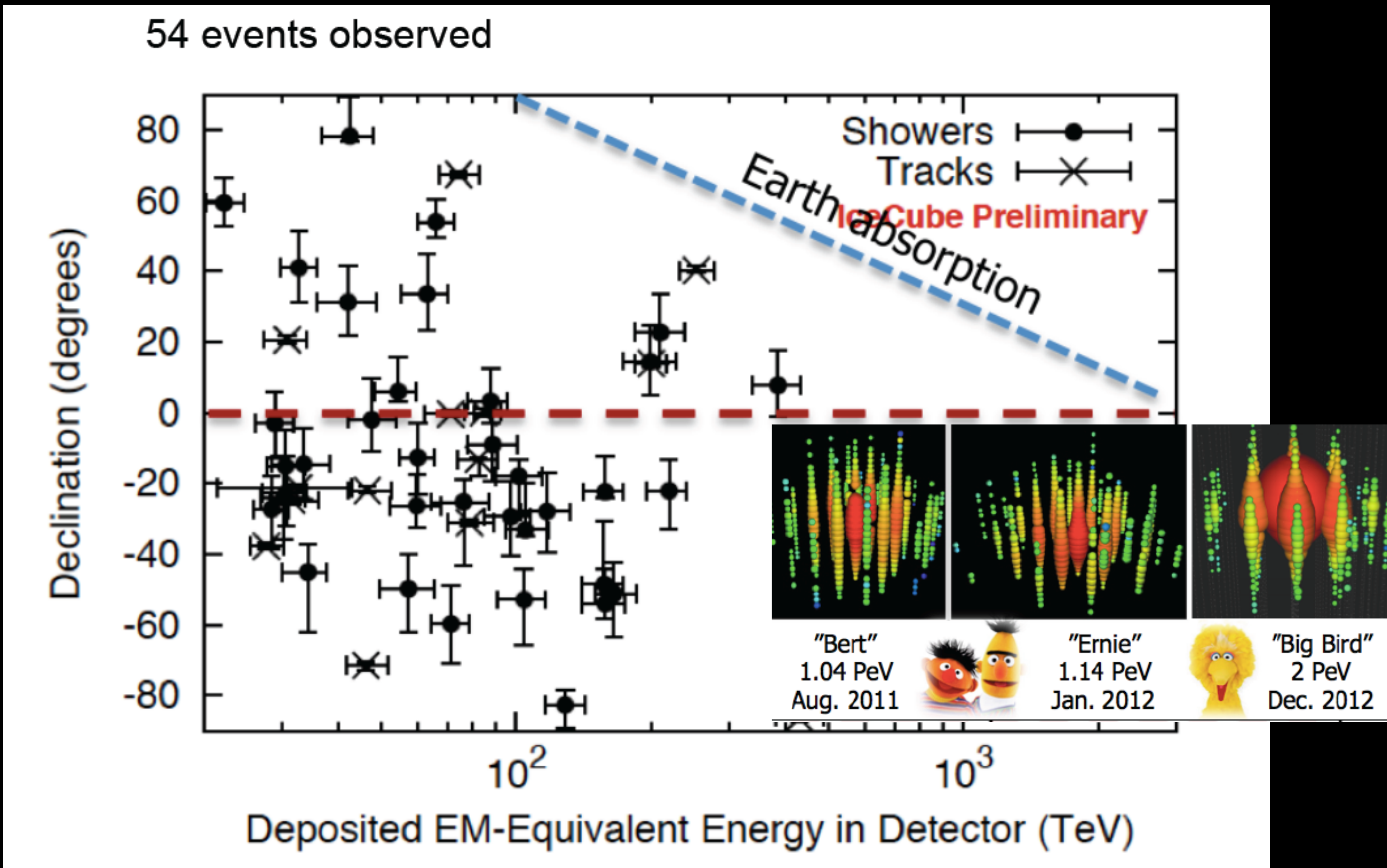
After 3 yrs 37 event
with background:
$6.6^{+5.9}_{-1.6}$ atm. neutrinos
8.4±4.2 atm. muons

High Energy Starting Events (4 yr)

Kopper, Giang, Kurahashi, ICRC 2015, POS 1081, PRL 113 (2014) 101101, Science 2013



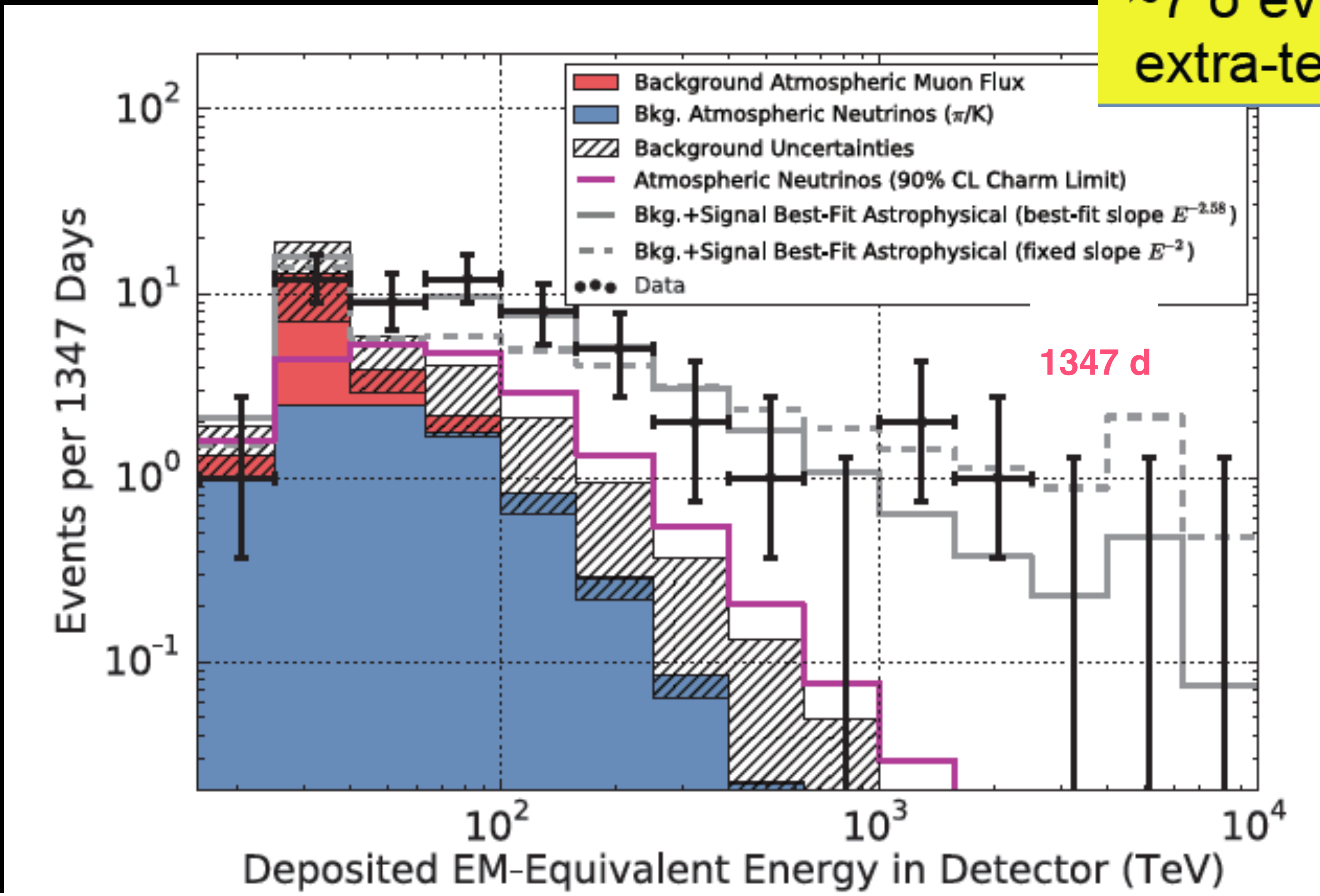
High Energy Starting Events (4 yr)



4 yr (2010-14) of HESE

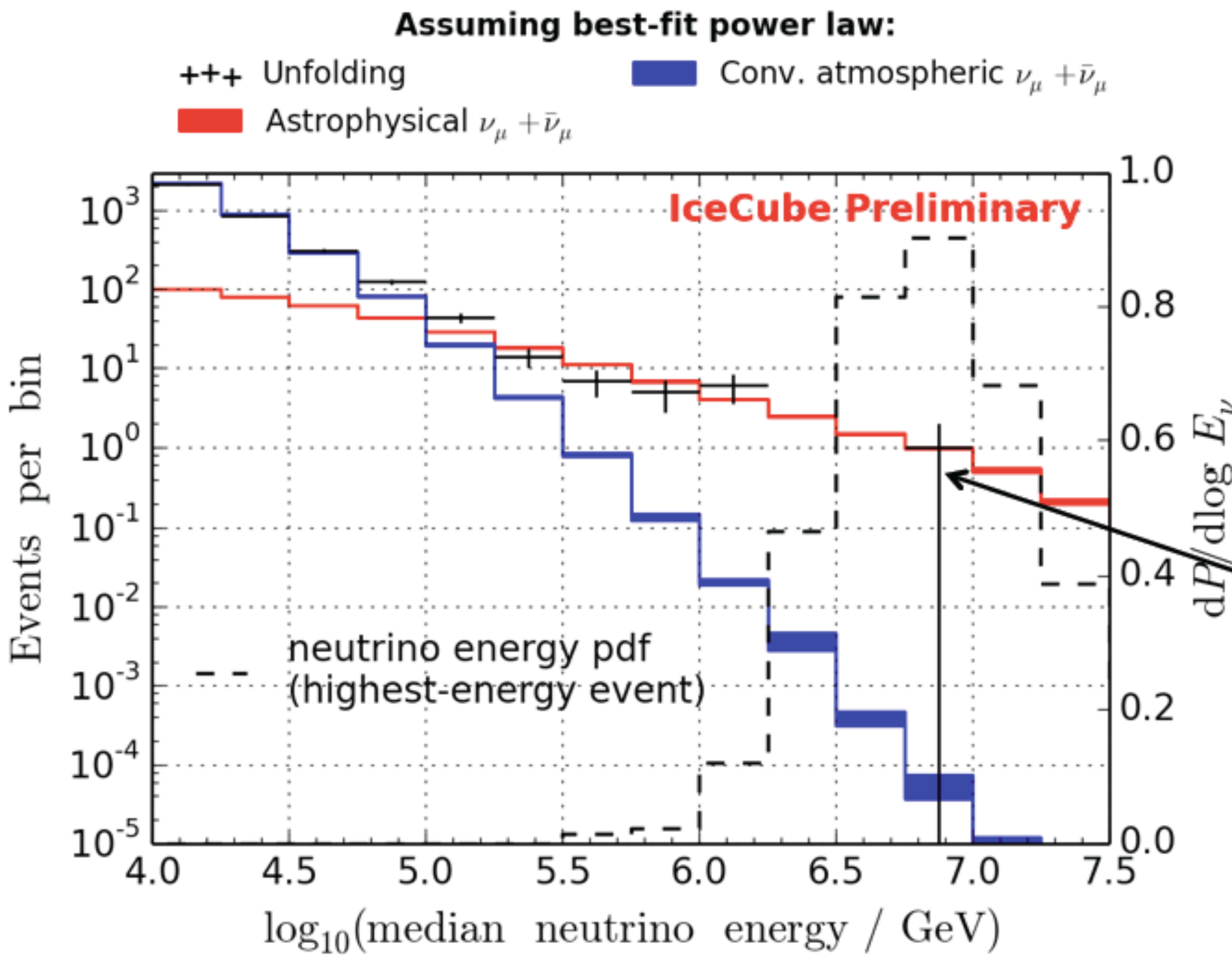
Anti-coincidence veto + >6000 p.e. (>30 TeV)
54 events (17+events in PRL 113 (2014) 101101) of which 2 are evident background events.
Background: Measured: 12.6 ± 5.1 atmospheric muon events
Atmospheric prompt component estimated using a previously set limit on atmospheric neutrinos with 59 strings: $9.0_{-2.2}^{+8.0}$

~7 σ evidence for extra-terrestrial ν

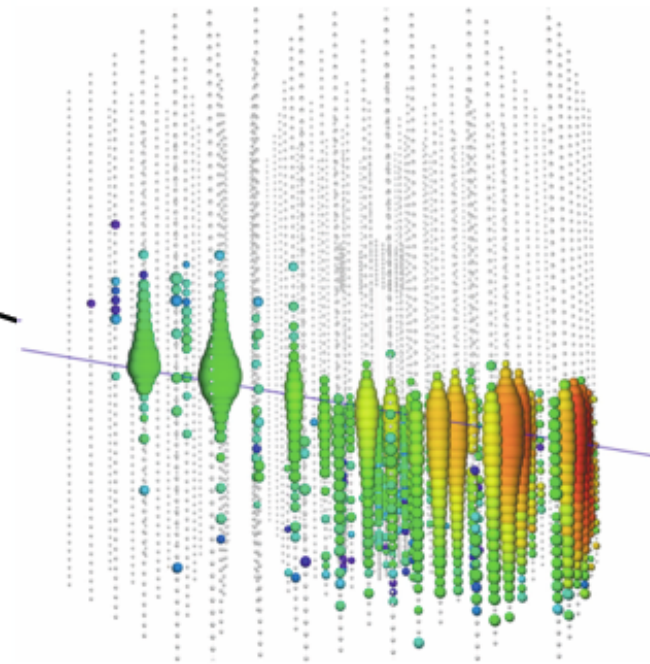


Through going muon tracks

Best fit astrophysical spectral index of γ = 2.13 ± 0.13

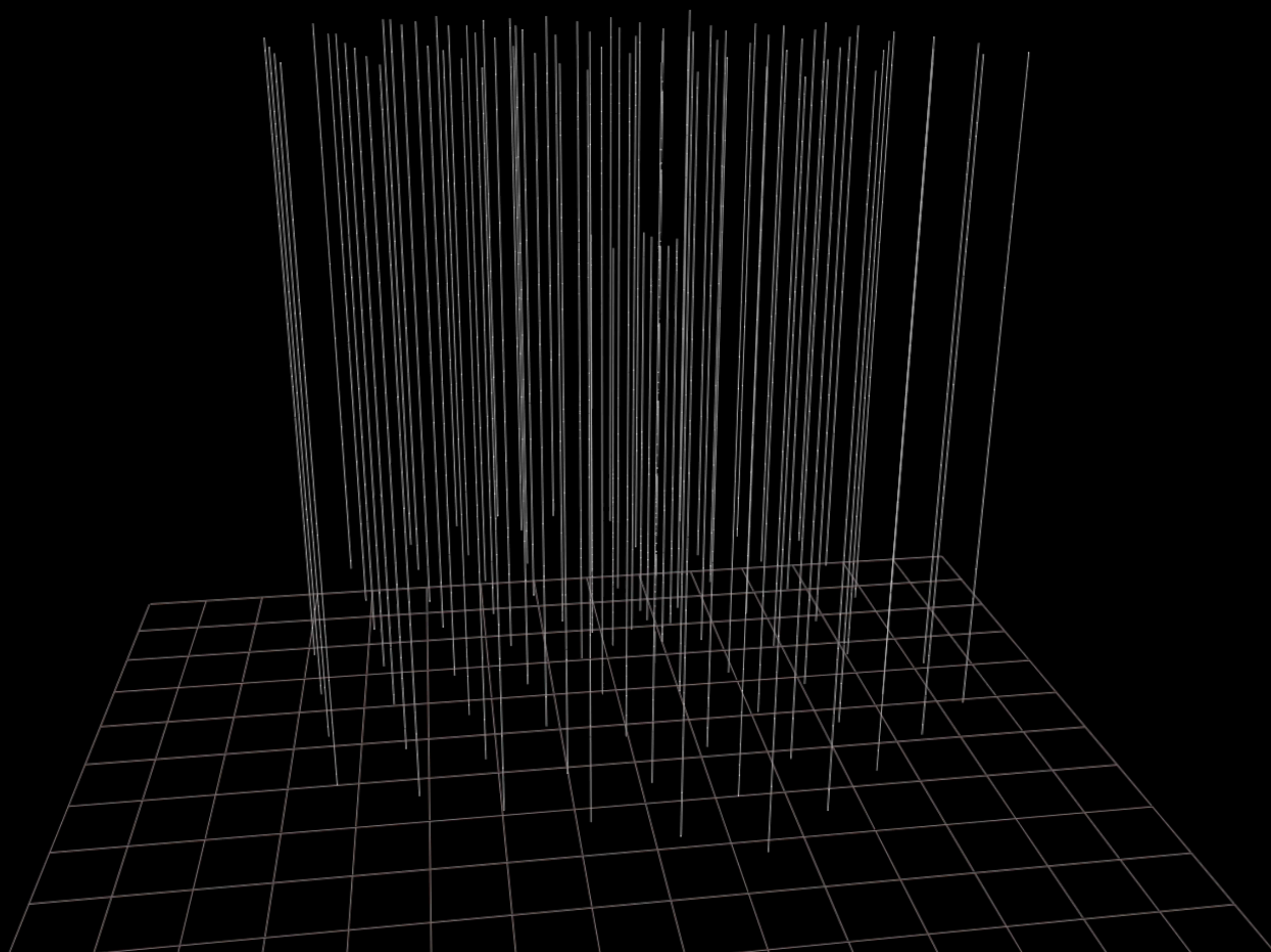


5.6 sigma detection of astrophysical neutrinos with through-going muons analysis



Deposited energy: 2.6±0.3 PeV

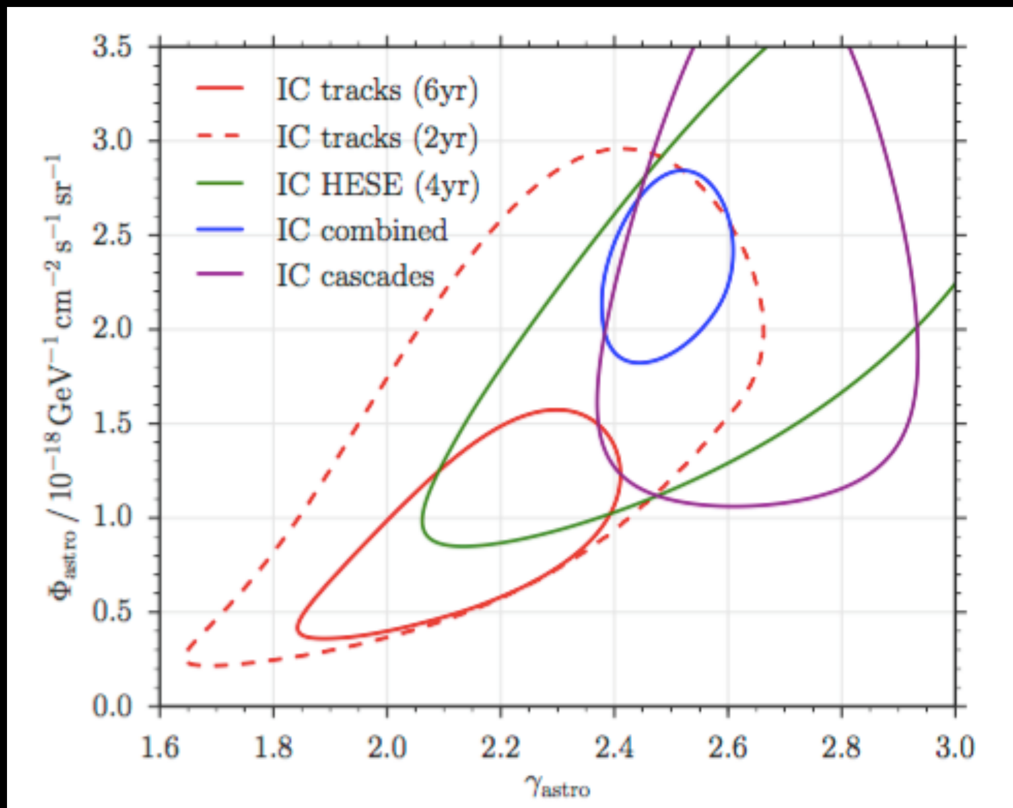
subm. to ApJ



ICECUBE

Combined fit

http://arxiv.org/pdf/1607.08006v1.pdf



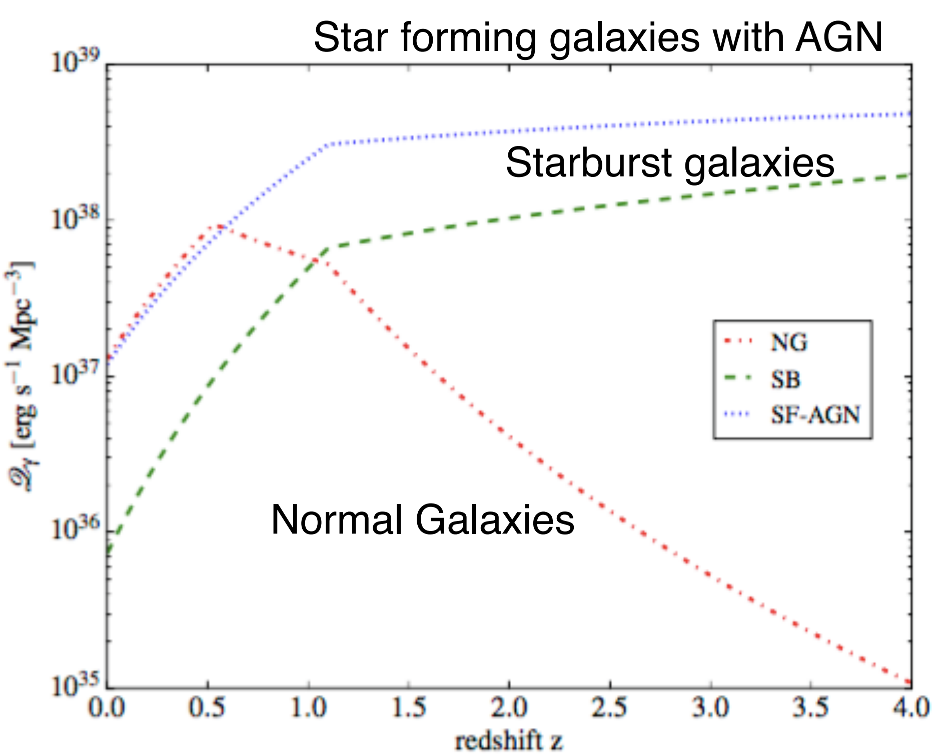
The p-value for obtaining the combined fit result and the result reported here from an unbroken powerlaw flux is 3.3σ, and is therefore in significant tension.

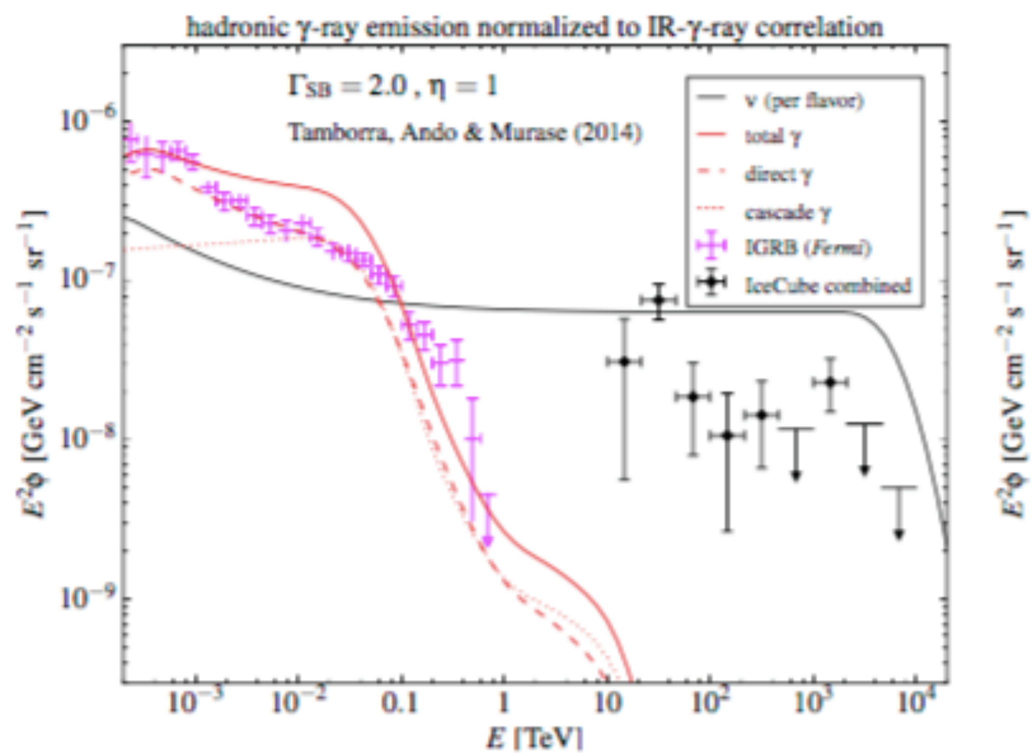
Possible diffuse sources: star forming galaxies

The hadronic emission of SFGs is thought to originate from CR interactions in interstellar space, analogous to the diffuse emission observed from the Galaxy. If escape time is dominated by diffusive escapes the hadronic emission follows a $dN/dE \propto E^{-\Gamma-\delta}$ spectrum.

Model by Tamborra et al, 2014 where the contribution of single components of star forming regions to hadronic gammas and neutrinos is treated with separate luminosity functions normalized to observed IR and assuming the gamma-IR derived by Fermi.

In Bechtol et al 2016, they assume that SB galaxies have harder spectral index than $\Gamma = \delta + ½$





Bechtol et al. arXiv:1511.00688

Possible diffuse sources: starburst galaxies (pp)

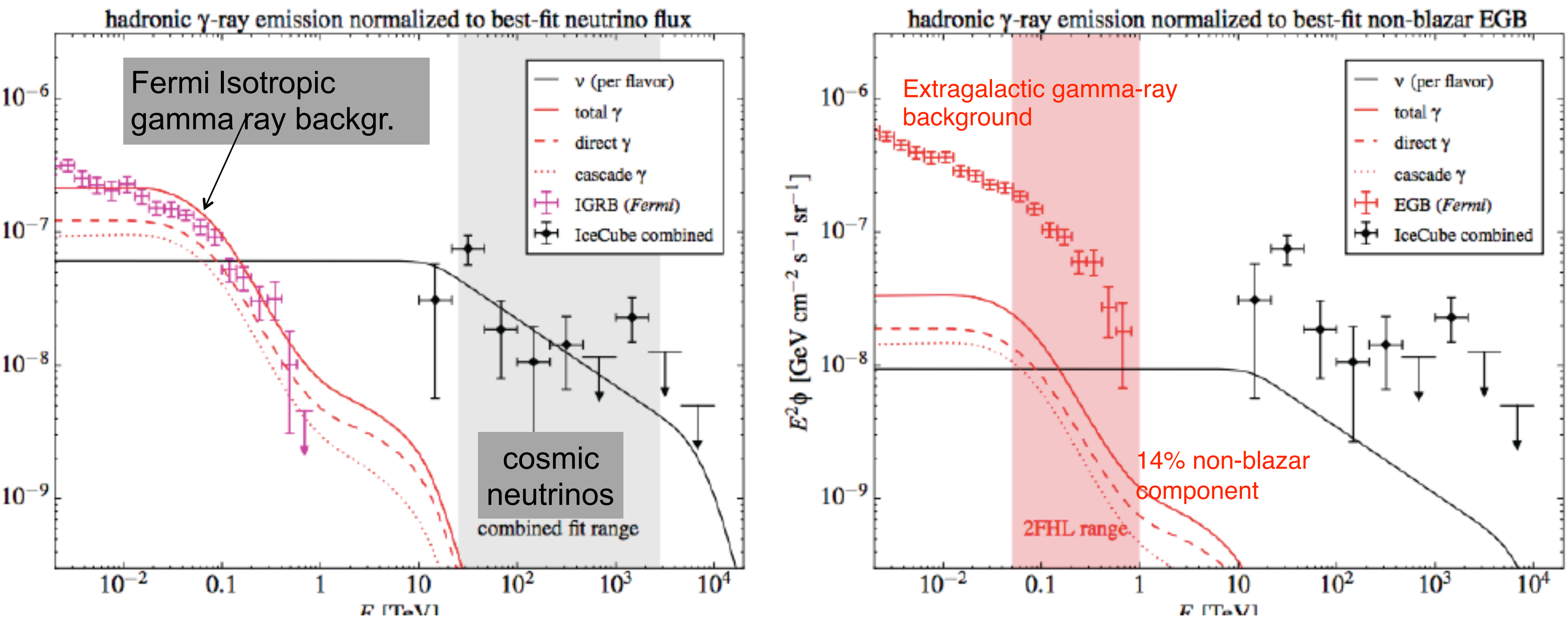
Plot on the left: if gammas are normalized to the IceCube > 100 TeV neutrinos, they are compatible with the Fermi isotropic gamma-ray background.

Plot on the right: The predicted neutrino flux from pp in SFG is constrained by the non-blazar (at 14% level with 28% uncertainty) Fermi diffuse extragalactic gamma-ray flux (0.1-820 GeV).

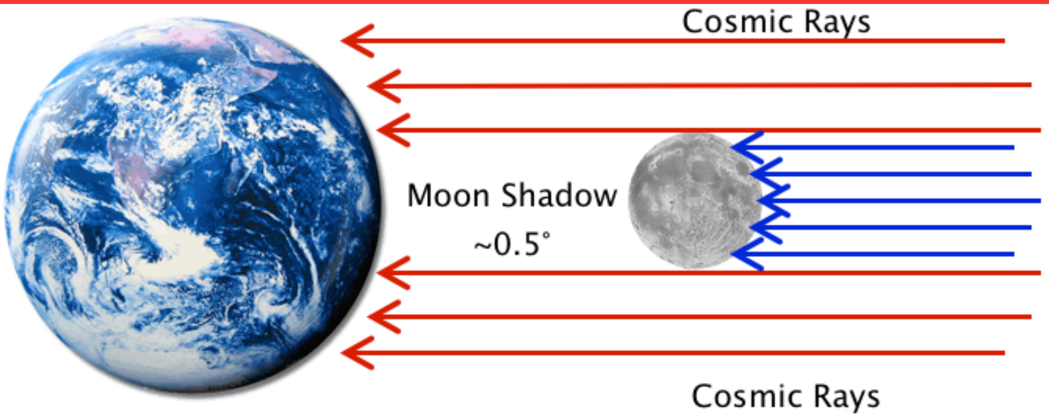
Comparing the plots we can realize that starburst galaxies can contribute less than 30% to the diffuse neutrino (25 TeV-2.8 PeV). Similar arguments lead to a limit of about 20% for blazar contribution.

Fit in E range 25 TeV to 2.8 PeV of IceCube data:
$E^2\phi(E) = 6.7+1.1 \times 10^{-8}(E/100\ \mathrm{TeV})^{-0.5\pm0.09}$ GeV cm^{-2} s^{-1} sr^{-1}

Bechtol et al. arXiv:1511.00688



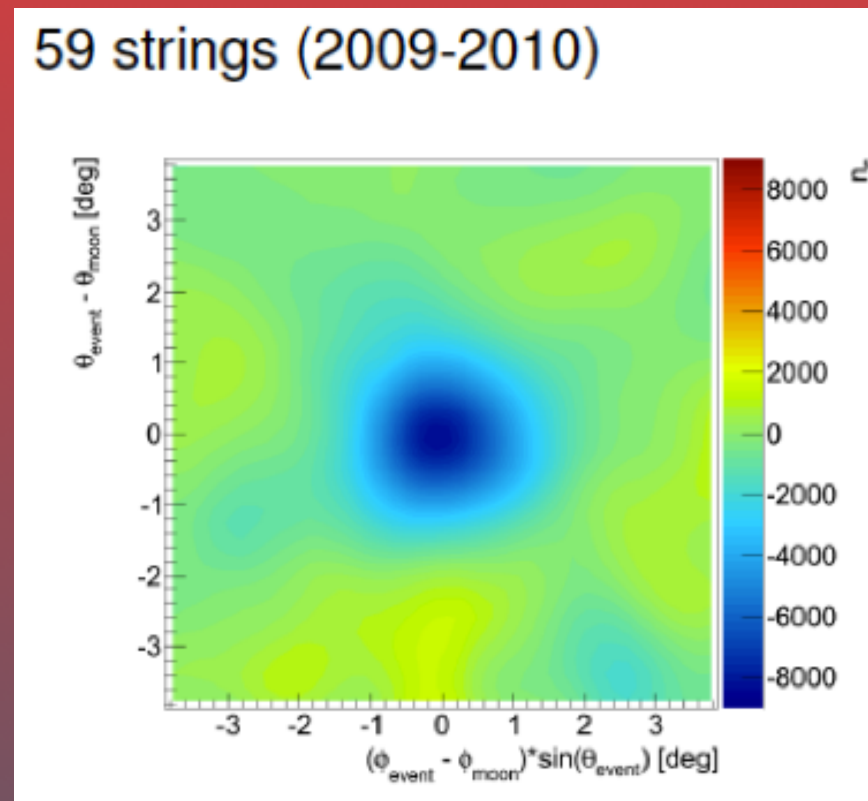
Use the Moon to verify pointing



Moon shadow LH analysis :

> 6 σ

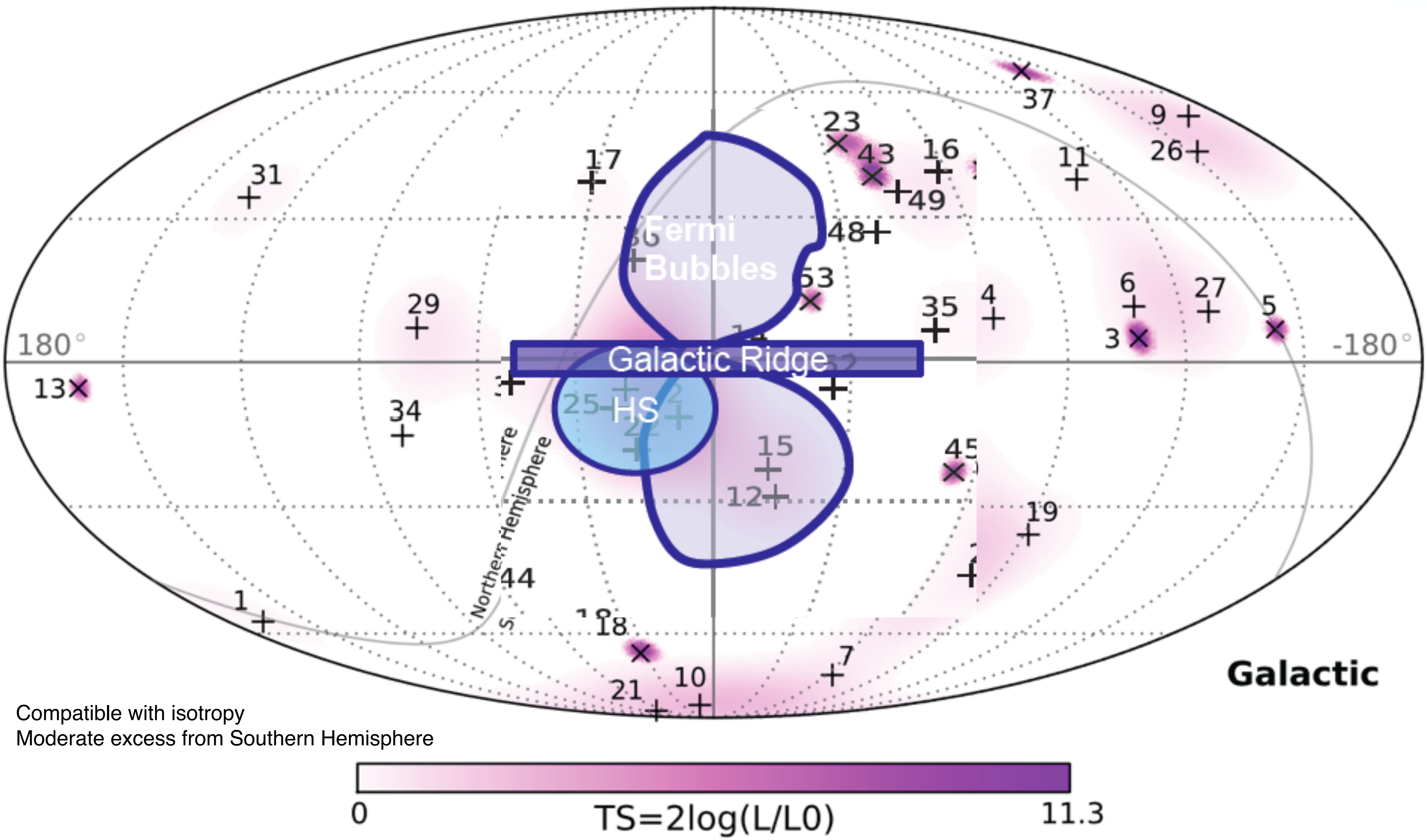
0.2° shift from expected position



- $n_s^{obs} = -8660 \pm 565 \pm 681$
- $n_s^{exp} = -8192 \pm 91$
- $\vec{x}_s^{obs} = (-0.1° \pm 0.1°, 0.0° \pm 0.1°)$

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.89.102004

Sky map of 54 High Energy Starting Events



Compatible with isotropy
Moderate excess from Southern Hemisphere

Clustering of events test and did not yield significant evidence.
A galactic plane clustering test using a fixed width of 2.5° around the plane (post trial p-value 7%) and using a variable-width scan (post trial p-value 2.5%).

UHECR-neutrinos

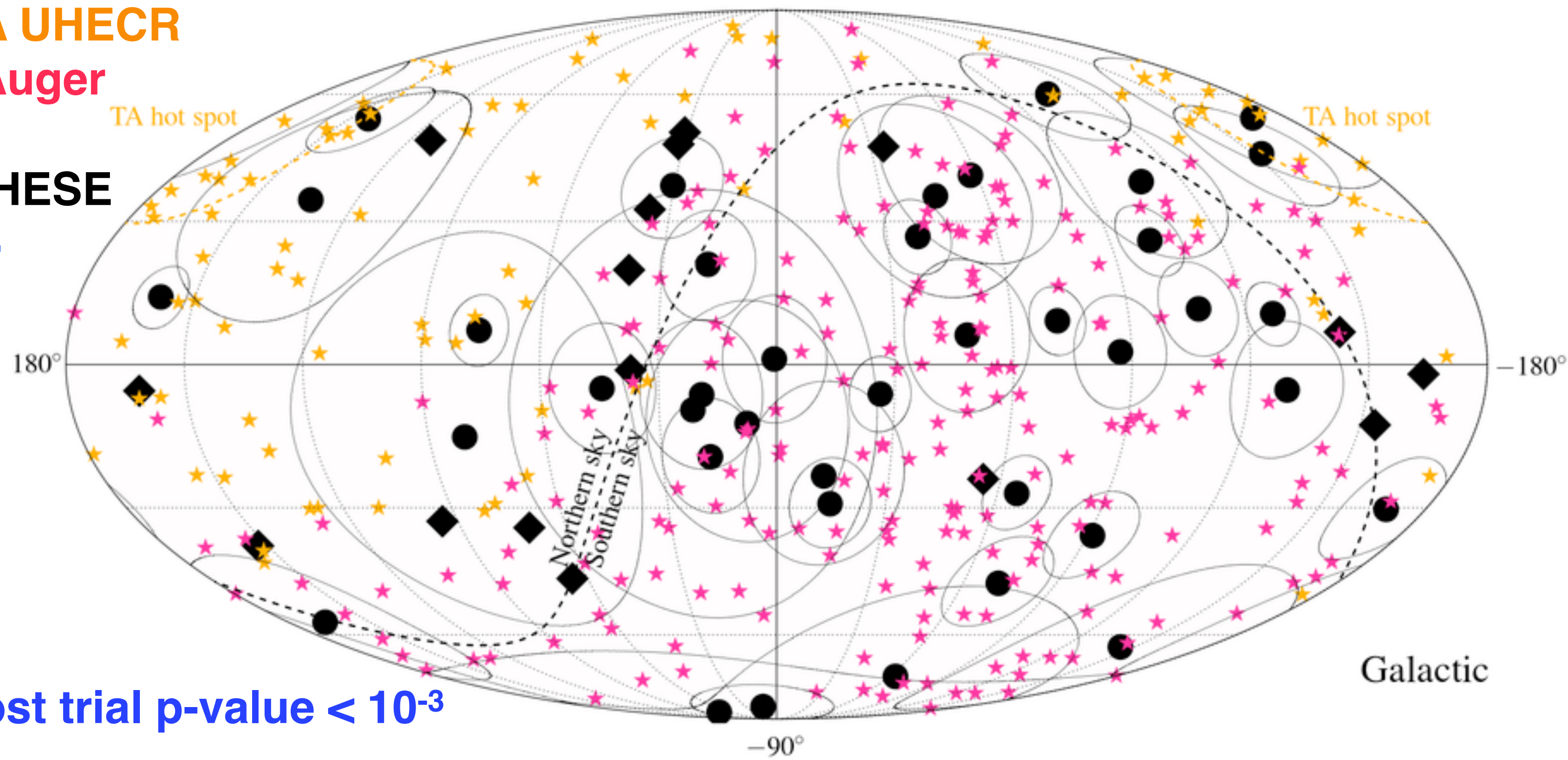
231 events (E>52 EeV, zenith angle <80°, ang. res. ≤0.9°) between 01/01/2004 to 31/03/2014°

87 events (E>57 EeV, zenith angle <55°, ang. res. ≤1.5°) between 11/05/2008 to 01/05/2014°

The Pierre Auger Collaboration, Astrophys. J. 804 (2015) 1 and PoS(ICRC2015)310.
The Telescope Array Collaboration, Astrophys. J. Lett. 790 (2014) L21.

Orange stars: TA UHECR
Magenta stars: Auger

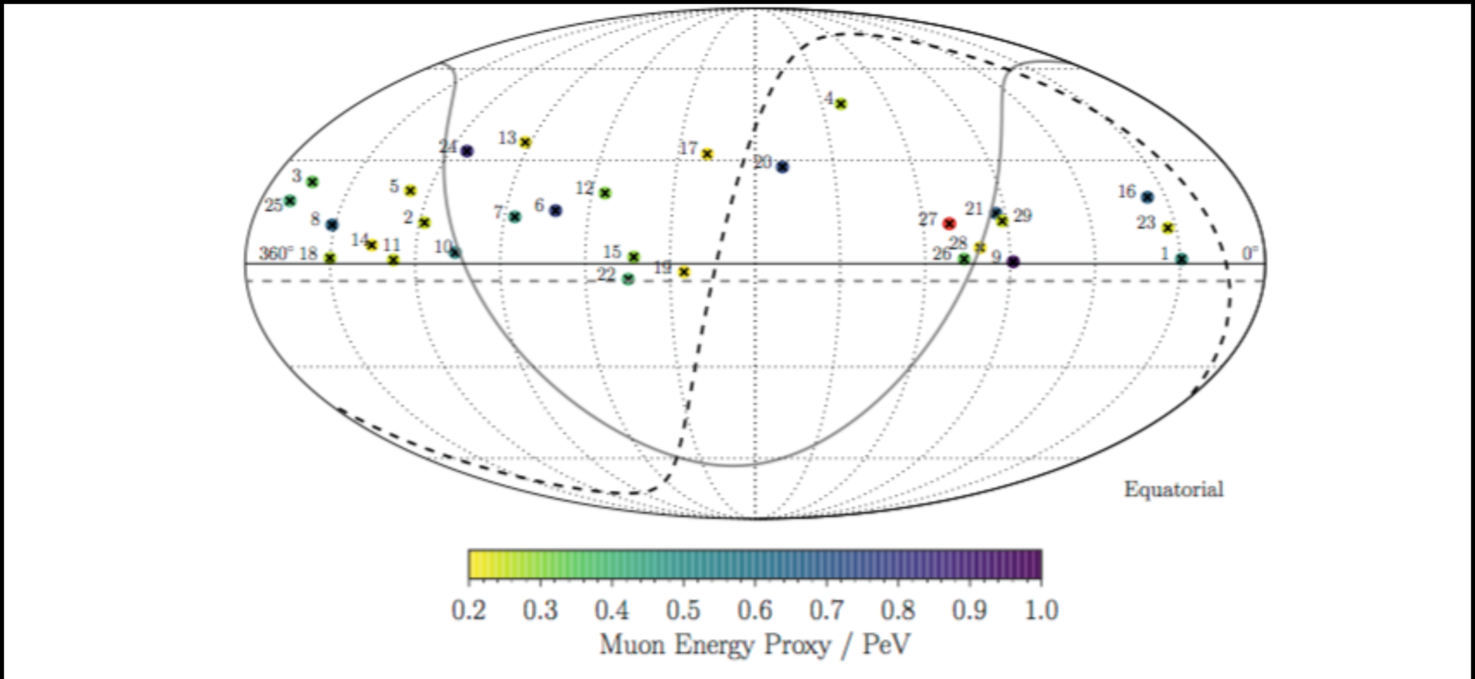
Black symbols: HESE
Blue: diffuse ν_μ - induced tracks

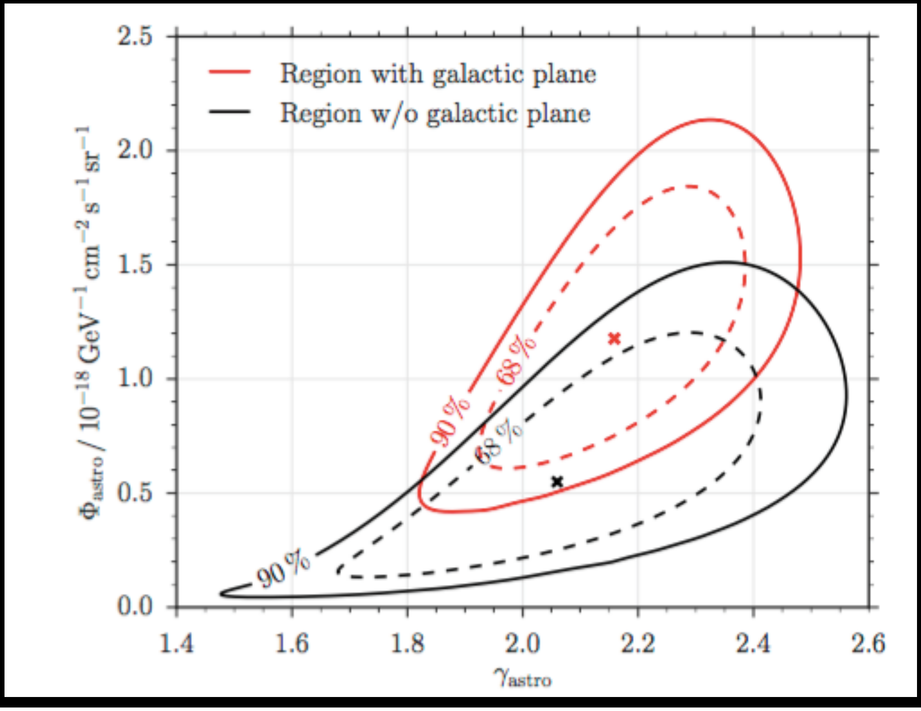


For cascades post trial p-value < 10^{-3}

HESE 4 yr (> 30 TeV): 39 cascades (ang. res. ~20°) + 7 tracks (ang. res. ~1°)
9 ν_μ induced upgoing muons with E> 100 TeV (PRL 115 (2015) 081102)

> 200 TeV tracks





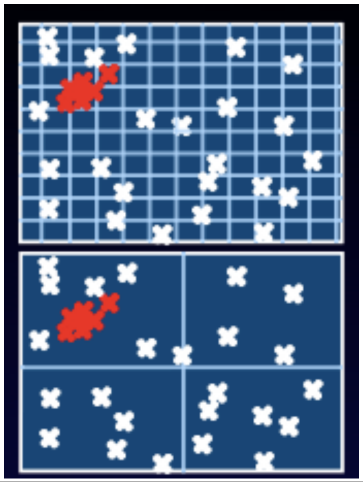
A slightly larger and softer flux if including the galactic plane but no excess is significant.
A subdominant contribution from the galactic plane cannot be excluded

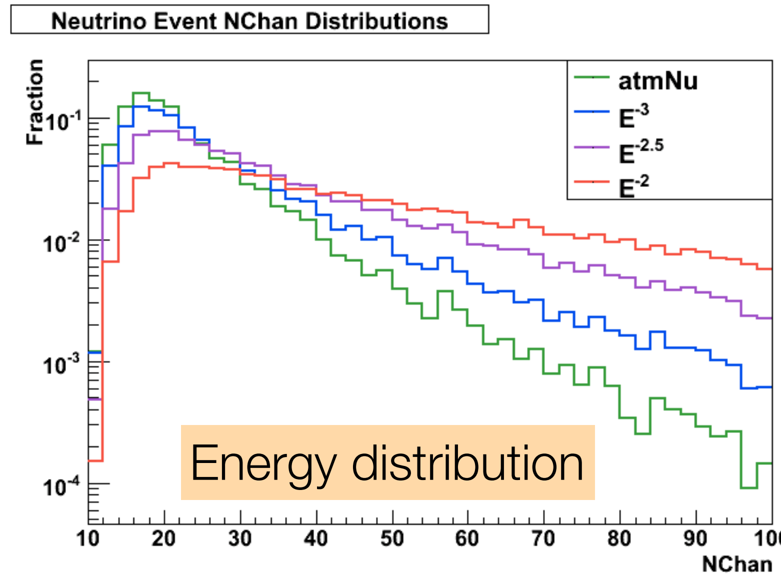
Test of hypothesis: small signals amongst a large background

Braun et al Astropart. Phys. 29 (2008) 299

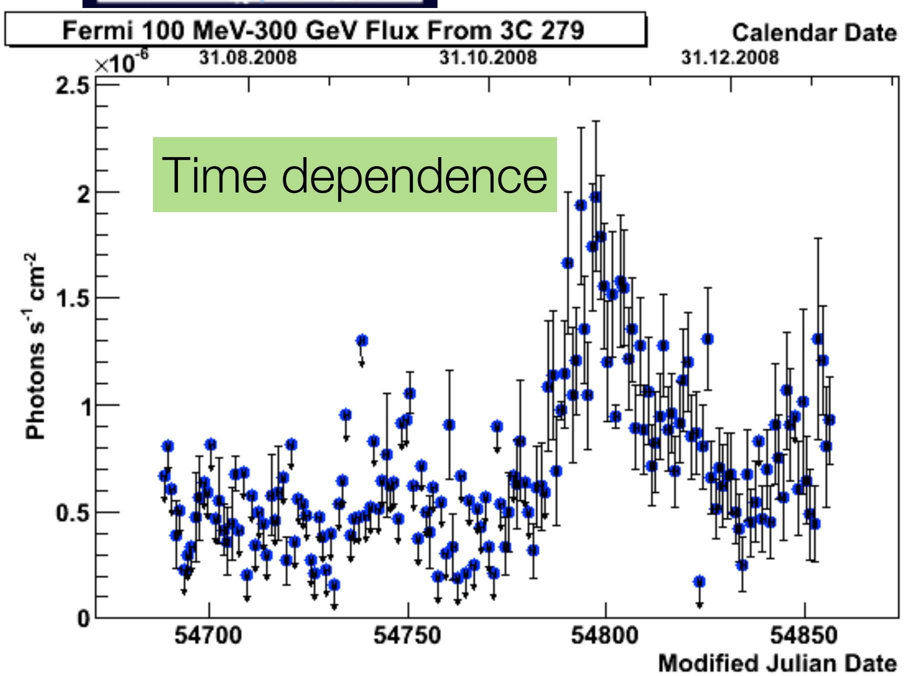
binned methods not optimal

LH ratio methods exploit the power of all variables characterizing signal against background



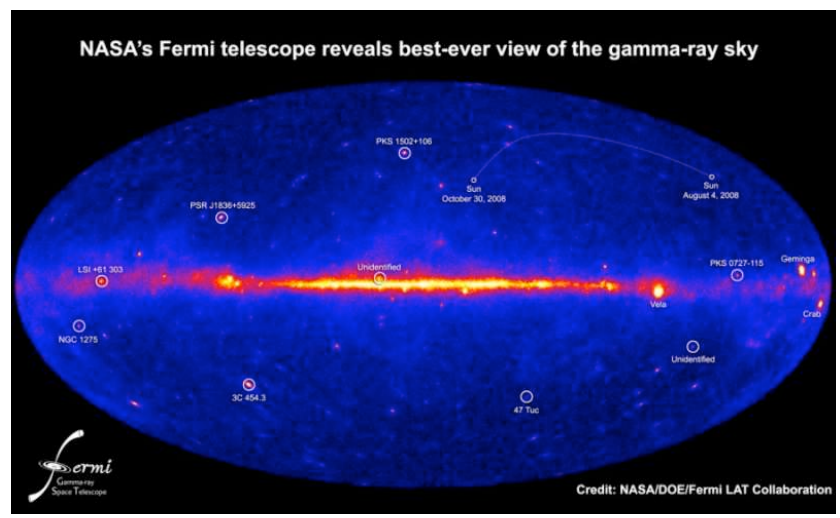


Energy distribution



Time dependence

or shape of sources



Hypothesis Testing

- H_0 = only atmospheric neutrinos are present
- H_1 = In addition to the atmospheric neutrinos there exists a point source of neutrinos
- Testing the compatibility of the data with these 2 hypotheses is accomplished by computing the test statistics. One then can define a rejection region ω = if λ is in ω, hypothesis H_0 is rejected in favor of H_1. But it is always possible that H_0 is wrongly rejected. The probability that this happens is related to the Confidence Level of the test:
- So the CL defines the rejection region.

$$1 - CL \equiv P(\lambda \in \omega | H_0)$$

- The probability to reject H_0 in favor of H_1 if H_1 is indeed the correct hypothesis is called the power of the test

$$power \equiv P(\lambda \in \omega | H_1)$$

- At a fixed level of significance, the power of the test corresponds to the sensitivity for discovering the signal and it depends on the level of separation between the test statistic distributions for H_0 and H_1.

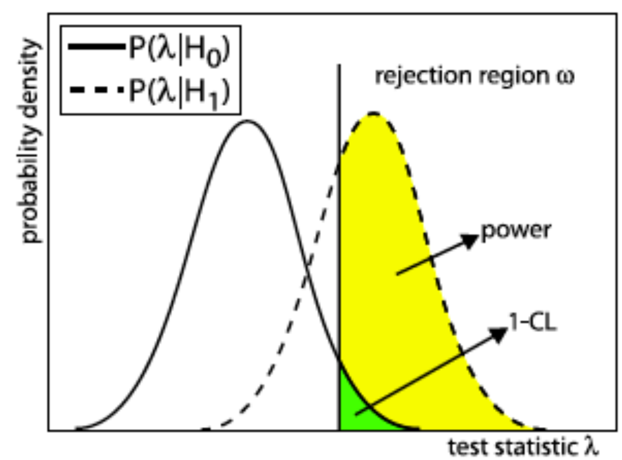
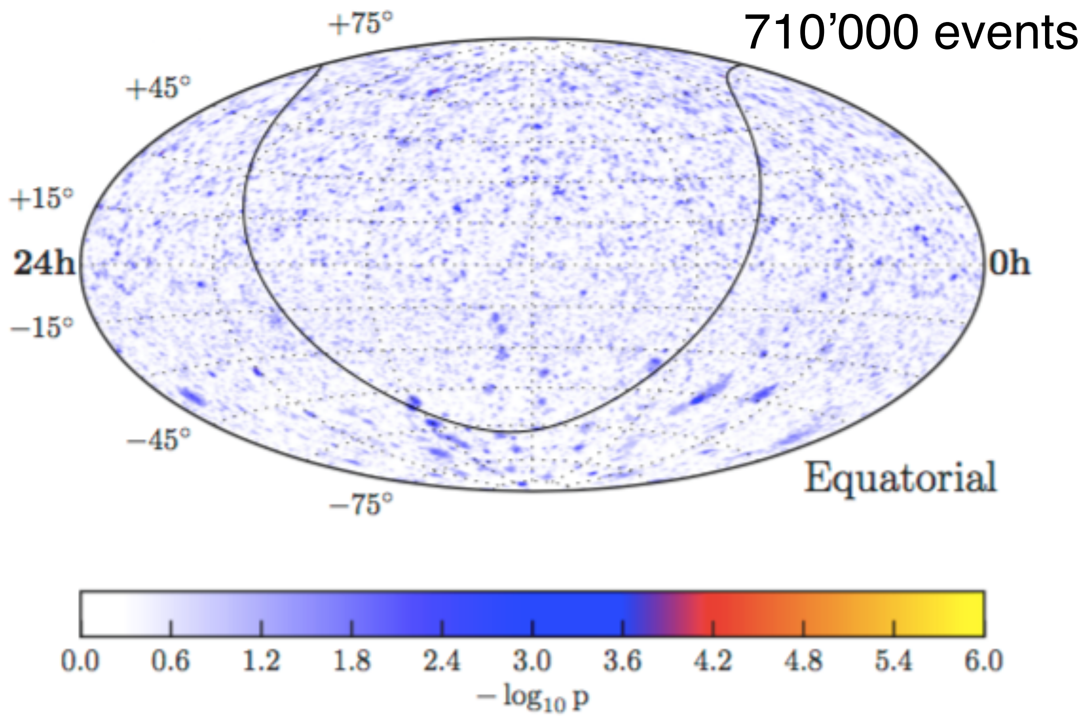
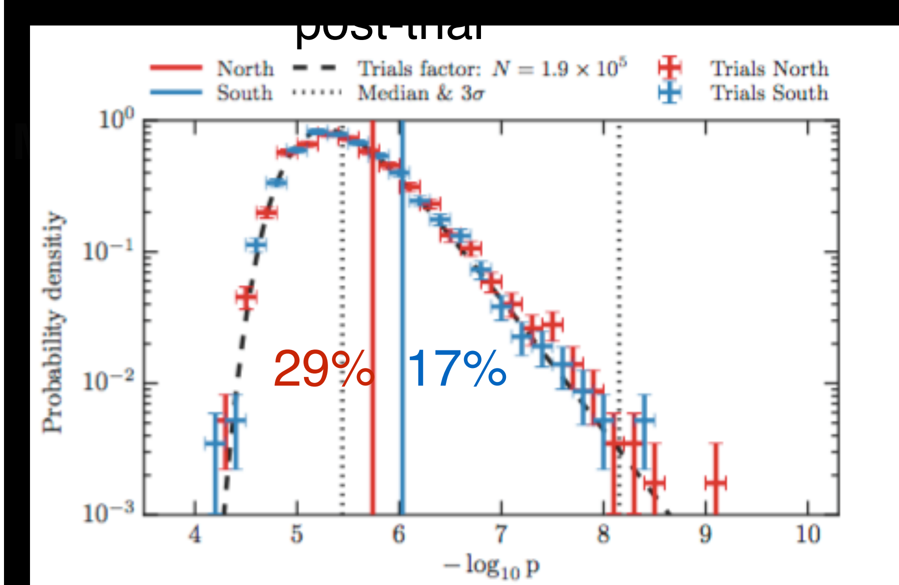
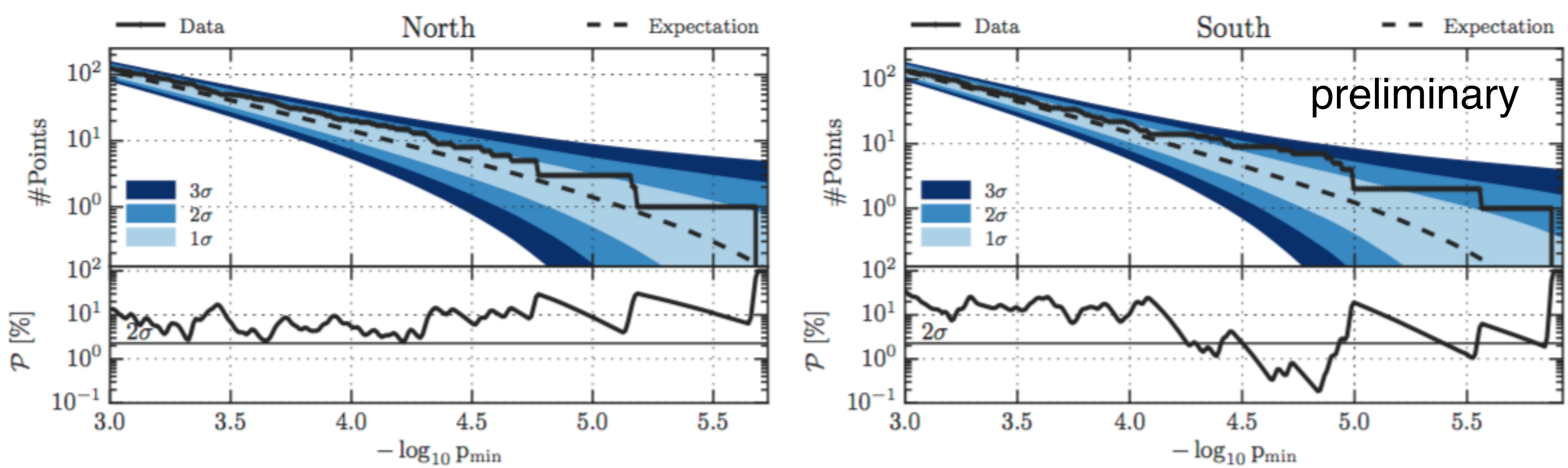


Figure 6.5: *Illustration of hypothesis testing. The probability density functions of the test statistic for H_0 and H_1 are shown. The rejection region ω is the region to right of the vertical line. The filled regions are related to the confidence level and the power of the test.*

7 yrs of point source searches



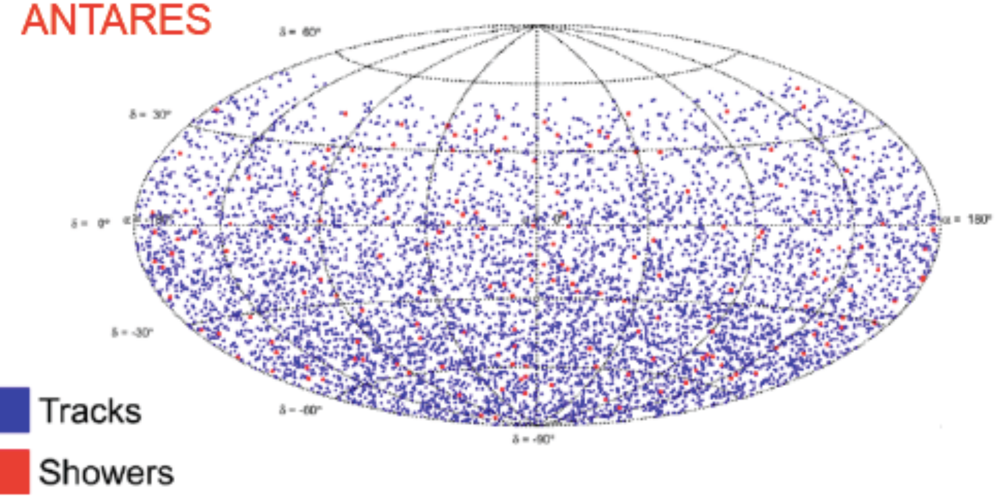




In the North the min pre-trial p-value in 2.8% for 1 point corresponding after trials to 25%.
In the South 7 points (2.1 expected) are more significant than 0.6% pre-trial and 8.2% after-trial.

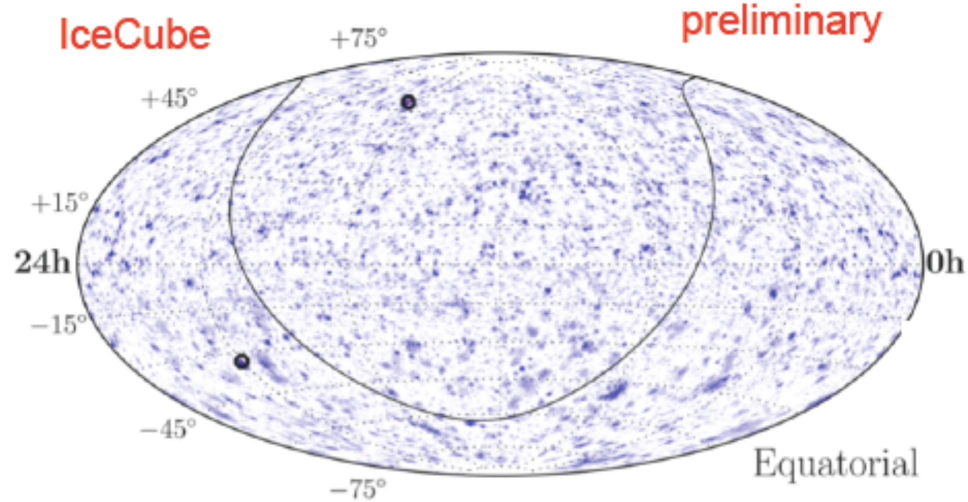
No significant cluster of neutrinos found: Neutrinos alone do not (yet) reveal a source

ANTARES



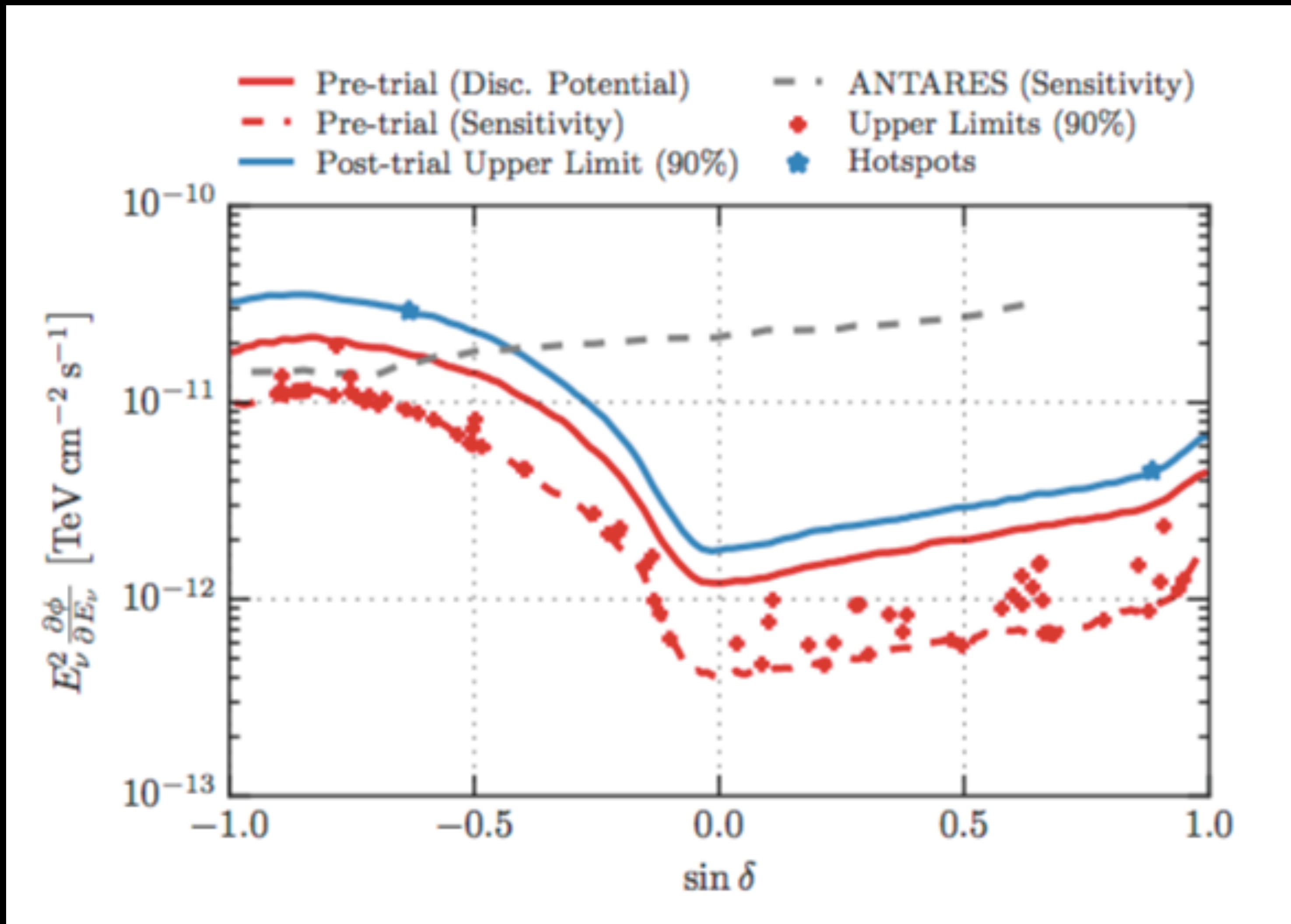
ANTARES ApJ 786 2014

IceCube



IceCube presented at ICRC 2015

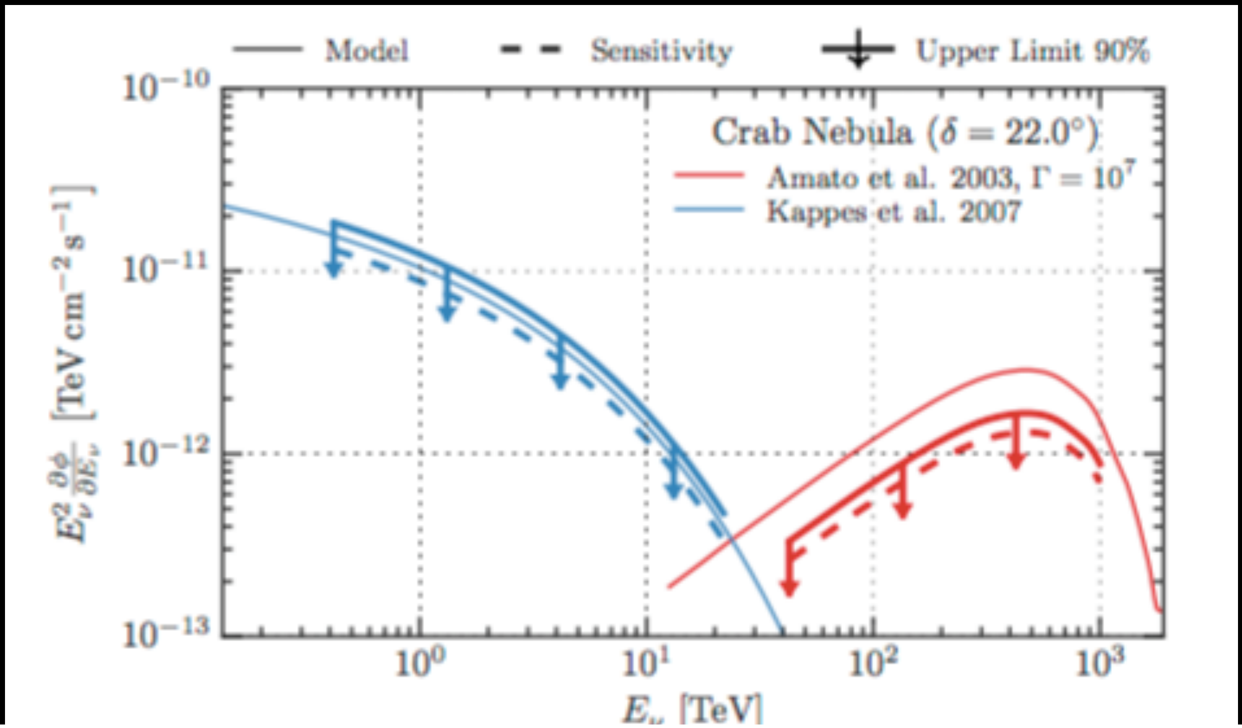
Upper limits 90%cl



Constraining models

Crab Nebula (Amato et al 2003)not standard DSA but resonant cyclotron absorption model accelerating protons in PWN wind. Prediction in the figure assumes a Lorentz factor of electrons of 10^7 and target material parameter μ = 20.
We can constrain at 90% CL to 14.
μ = 5 total mass isotropically distributed(Festen et al 1997)
Atoyan and Aharonian, 1996: 1 <μ < 20
(based on compatibility between the bremsstrahlung gamma-rays and observed flux > 1 GeV)

$$n_t = \mu\,\bar{n}_t = \mu\,\frac{M_N}{m_p}\,\frac{3}{4\pi R_N^3} = 10\,\mu\,\frac{M_{N\odot}}{R_{pc}^3}\ \mathrm{cm}^{-3}$$

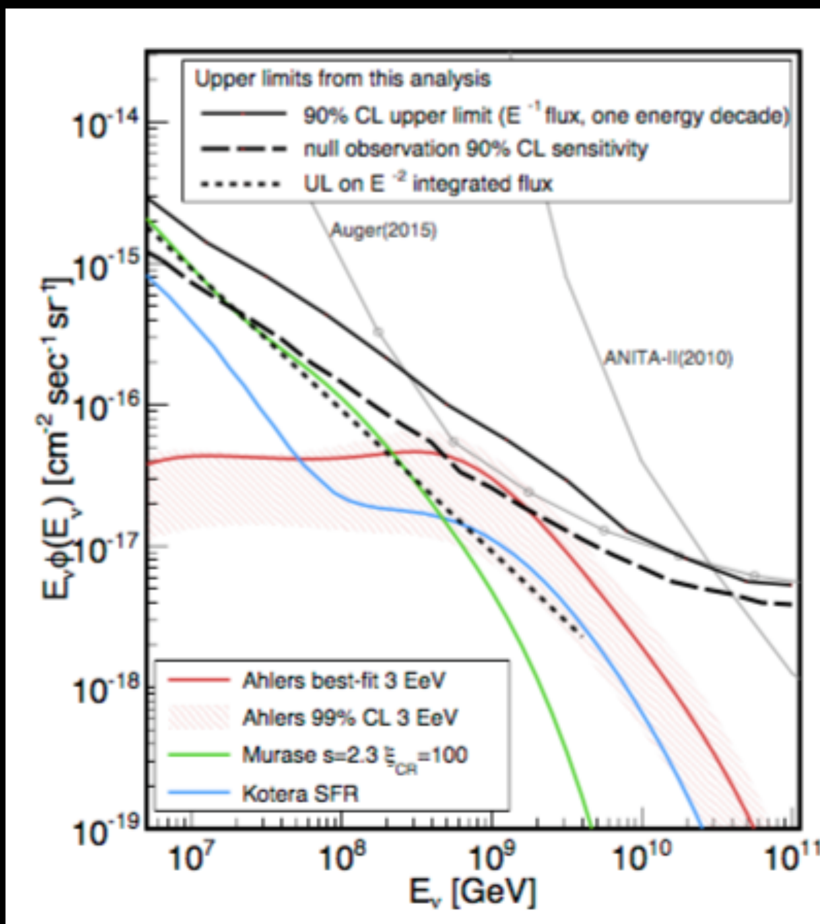


Cosmogenic neutrinos?

$$1)\ p+\gamma \rightarrow \Delta^{+} \rightarrow p\pi^{0}$$
$$2)\ p+\gamma \rightarrow \Delta^{+} \rightarrow n\pi^{+}$$

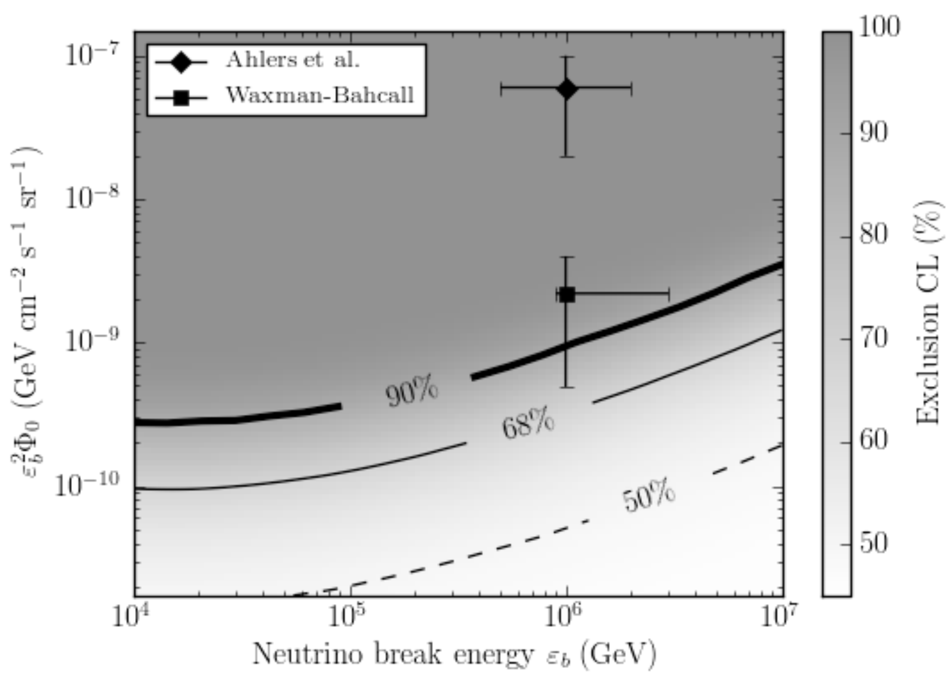
on cosmic CMB

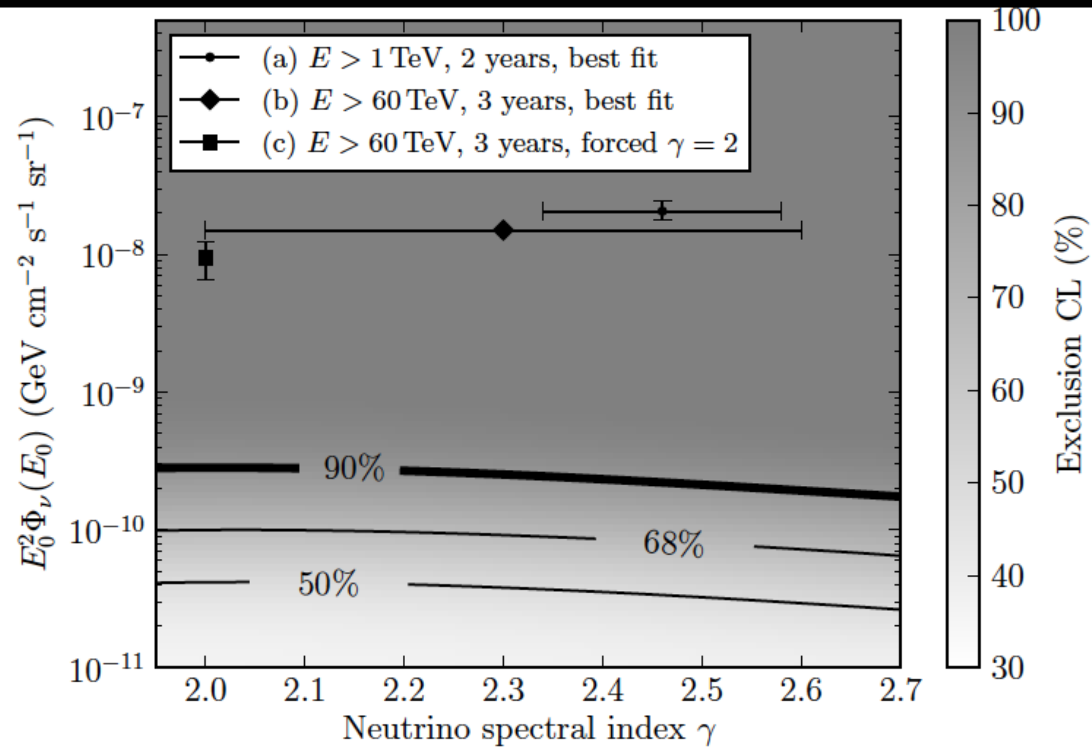
Two events were observed in the present 2426-day IceCube sample.
The best estimates of the deposited energy
are $(7.7 \pm 2.0) \times 10^{5}$ GeV and $(2.6 \pm 0.3) \times 10^{6}$ GeV,



Gamma-ray bursts

Stringent limits on both CR-normalized and burst-physics-normalized models (Ahlers et al, 2011 - n escape; WB 1997, Katz et al 2009 - p escape).4 years of IceCube : Northern sky datcorrelated with 506 GRBs



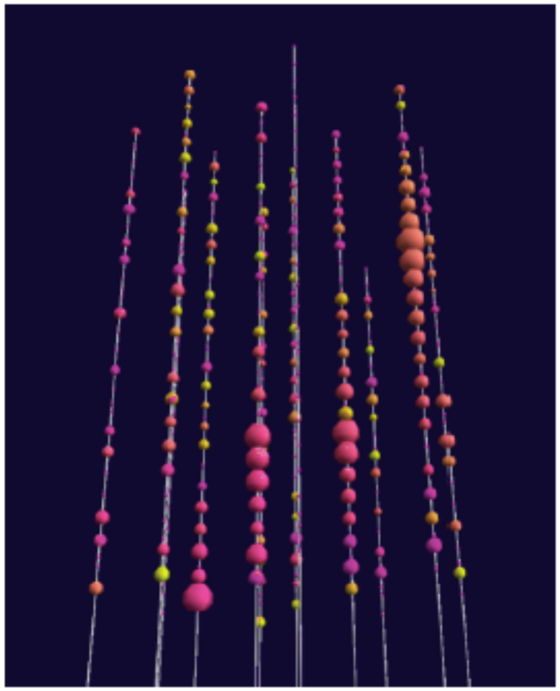


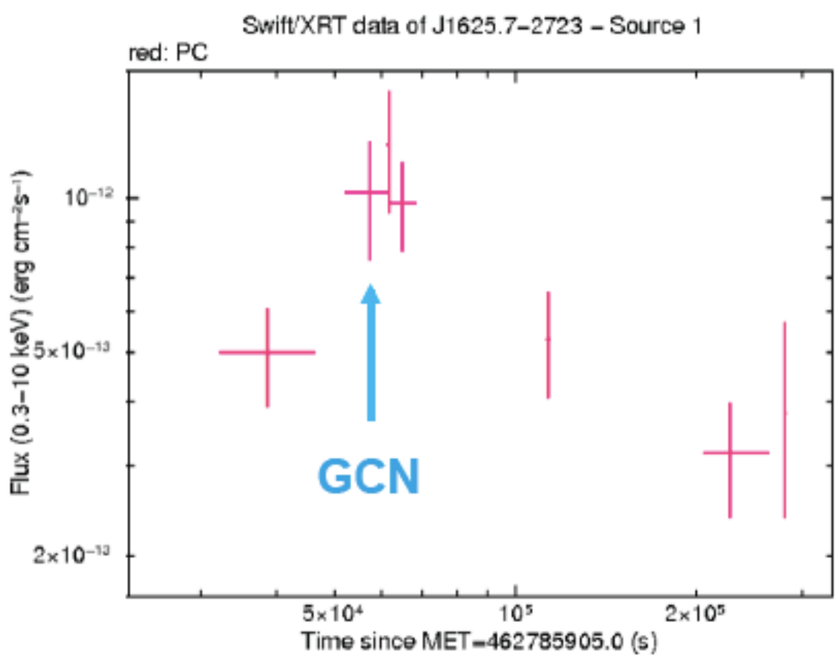
If the observed astrophysical signal in HESE and TeV all flavor starting events analysis is parametrized as a power law, the possible contribution to the observed quasi-diffuse nu flux would be only ~1%.

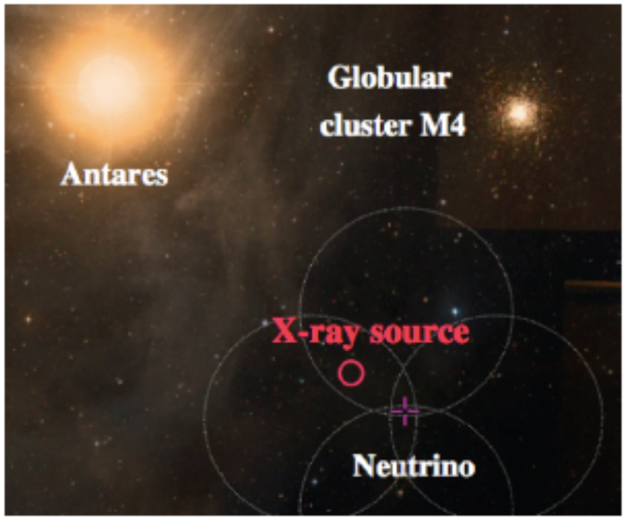
M. Richman et al.
M. G. Aartsen et al., ApJ 805 (2015) L5

ANTARES Optical / X-ray Follow-up: ANT150109A

- Single Neutrino at 60 TeV
- Triggered optical (MASTER, Tarot, Zadko) and X-ray observations (Swift)
- Variable X-ray source found → ATel 7987
- Follow-up observations identified source as a variable star





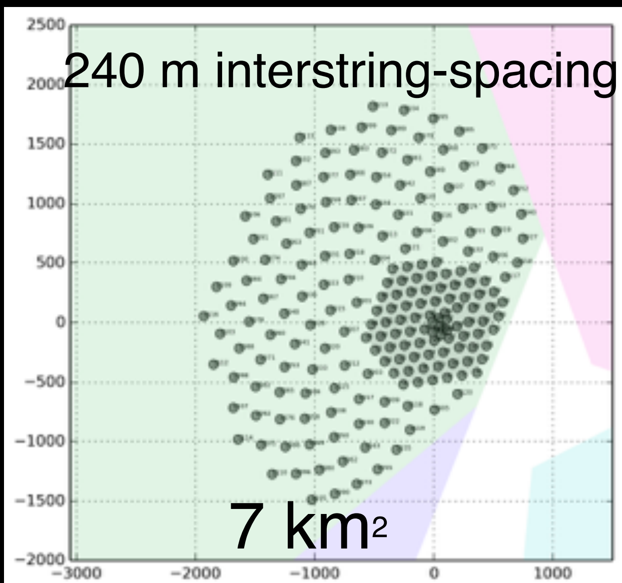


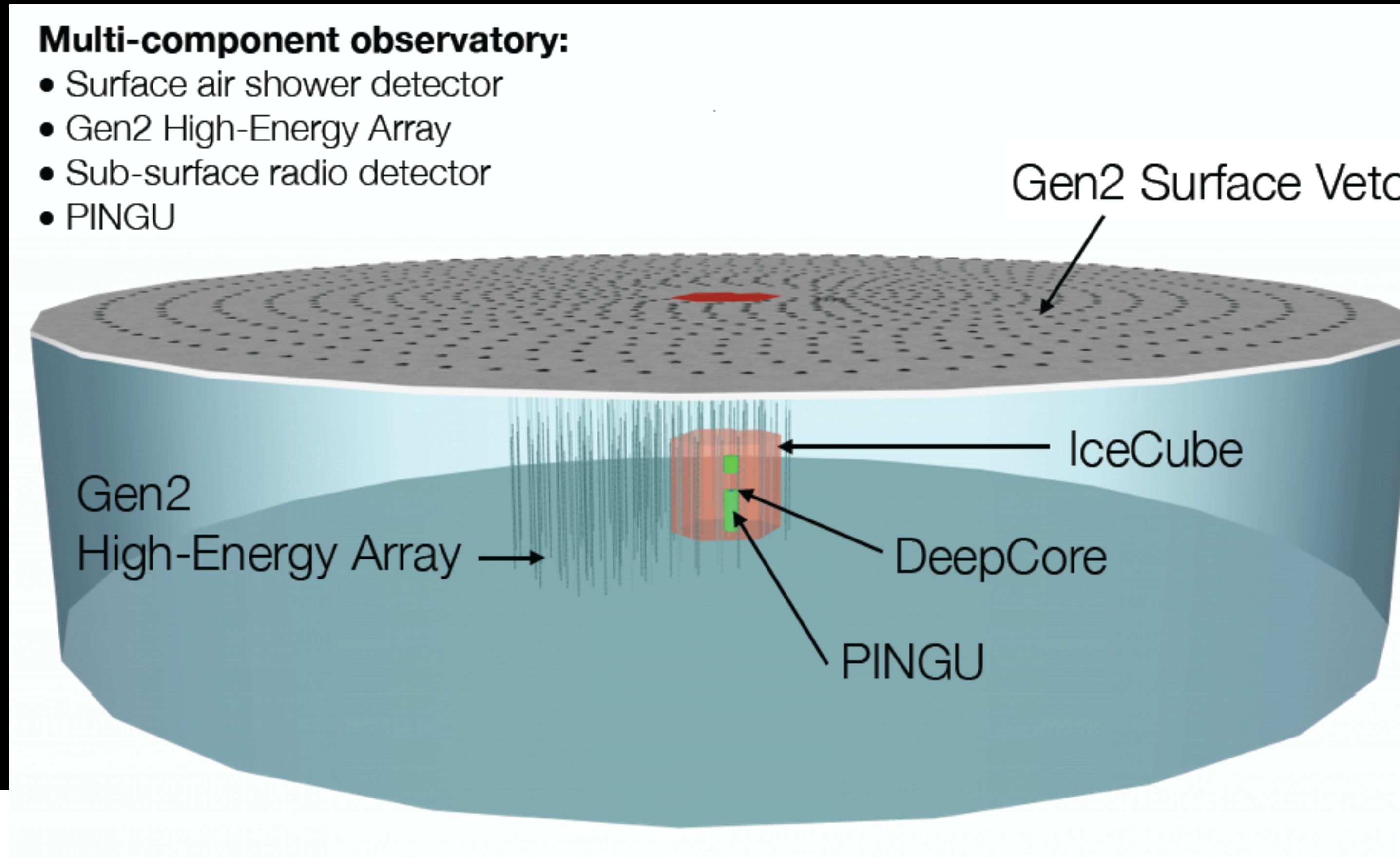
ANTARES Coll., presented at AMON workshop 2015

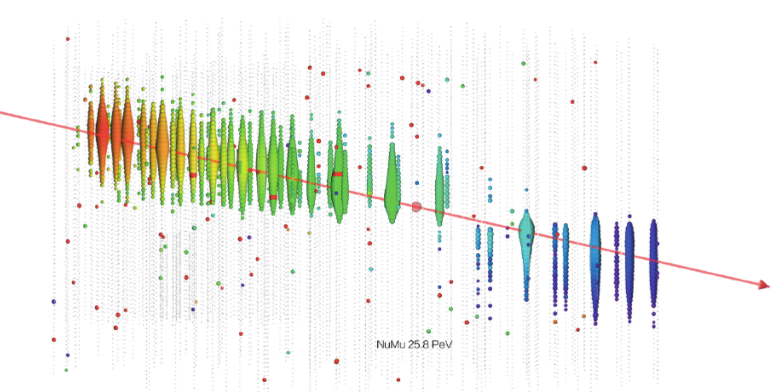
DESY

IceCube Gen2

- ~120 new strings, 80 DOMs per string, instrumented over 1.25 km
- ~10 x IC volume for contained event analysis above 200 TeV







ApP-conclusions: a lot of open questions

- Multi-messenger astro-physics is possible!
- Where are the CR point sources?
- What are the spectra? Cutoffs?
- What is the flavor composition?
- Are neutrino transient sources accessible?
- GZK neutrinos start to be at reach?
- Is there a WIMP miracle ? (Rameez’s lecture)

PP-conclusions: a lot of open questions

- Where are the prompt? muons and neutrinos (Subir)
- eV sterile neutrino can excluded (Jason)
- Hierarchy determination depends on ability to calibrate the GeV ice

Most probable answer: we need a larger detector with a dense inner core