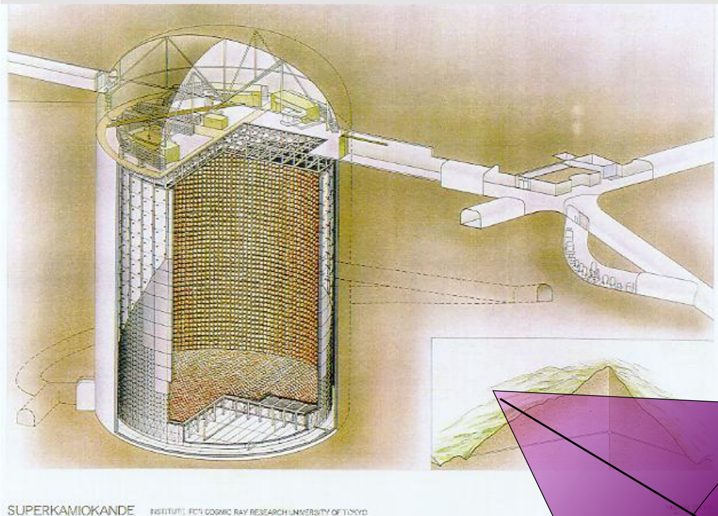
High energy neutrinos

Review of results from
IceCube (including IceTop),
Antares, Baikal
& ANITA

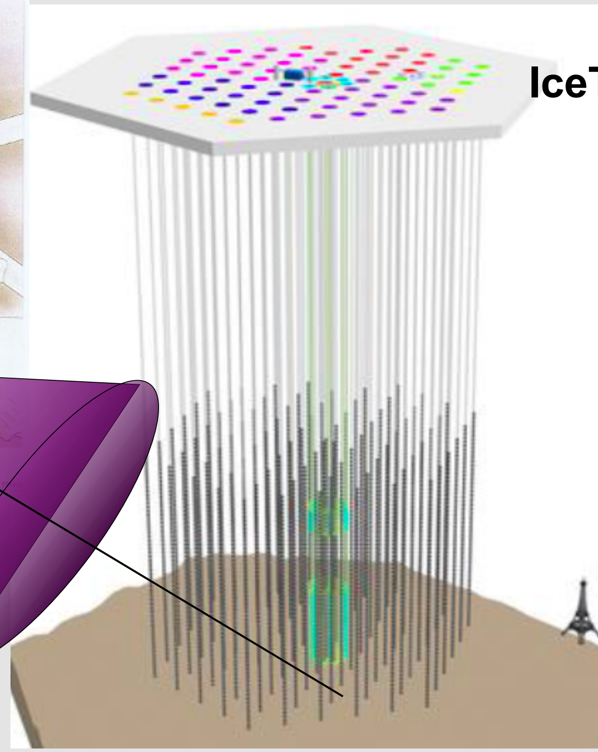
Detecting neutrinos in $H_2 0$

Proposed by Greisen, Reines, Markov in 1960

Heritage:
- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA



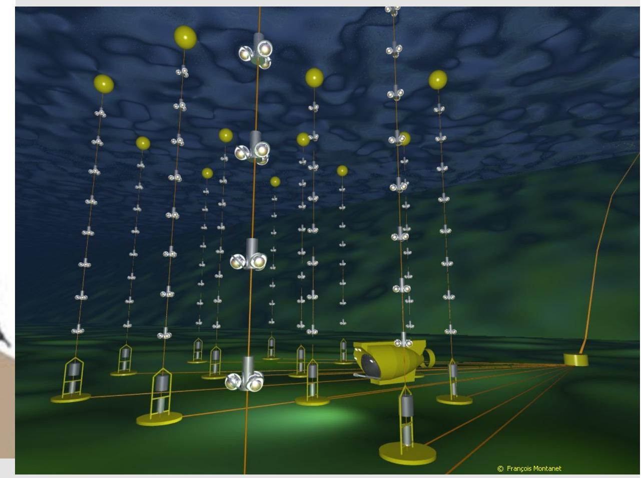
Super-K



IceTop

SNO

IceCube: 86 strings
& 81 IceTop stations



ANTARES

All use Cherenkov light from charged products of ν interactions

High-energy Neutrino telescopes

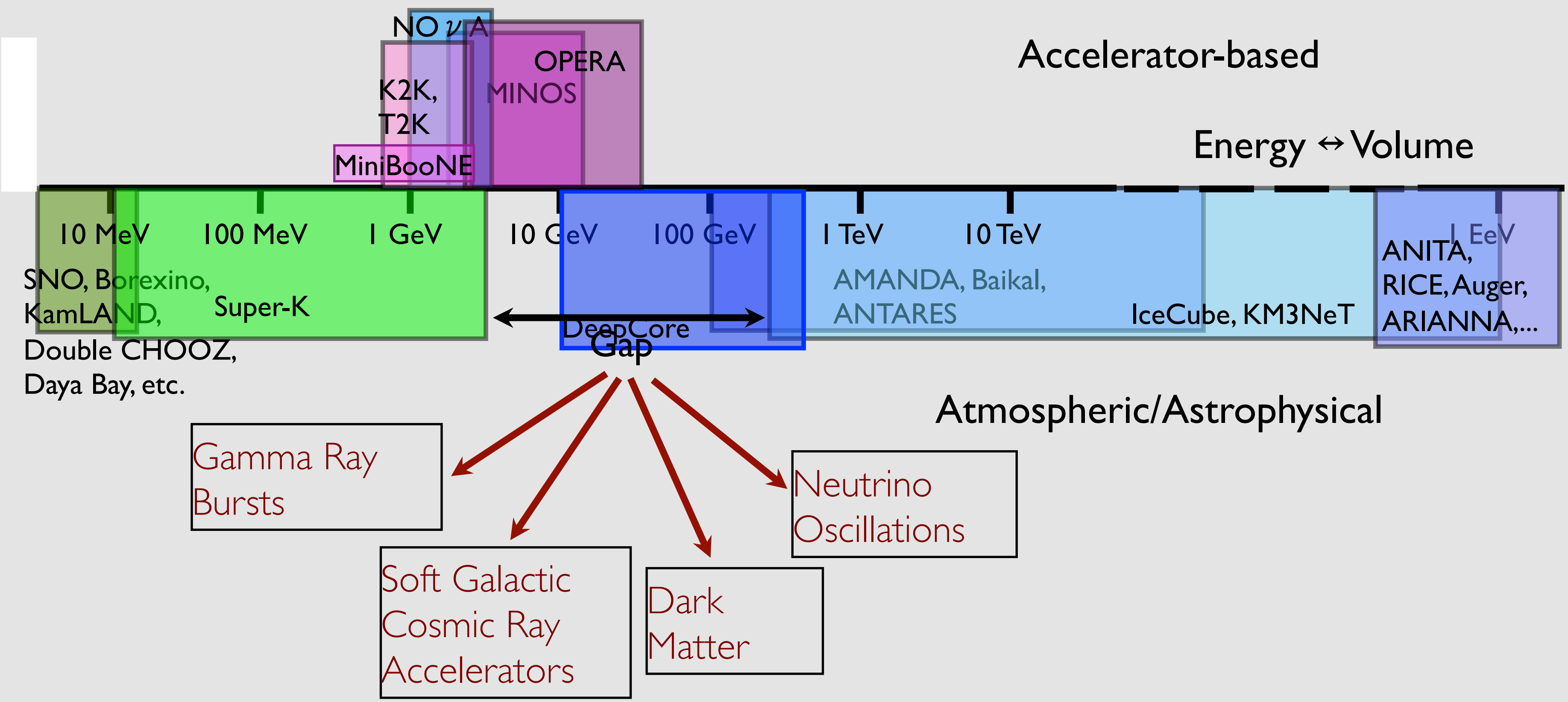
Detector	Number of OMs	Enclosed volume (Megatons)	Depth (m.w.e.)	Status
Baikal (NT200+)	230	10	1100-1310	Operating
AMANDA	677	15	1350-1850	2000 - 2009
ANTARES	900	10	2050-2400	Operating
IceCube	5160 + 324	900	1350-2280	Operating
(IceCube DeepCore subarray)	(480)	(15)	(1950 - 2280)	Operating
KM3NeT	$\sim$10,000	km^3	2300-3300 (NEMO)	Design study
		km^3	3000-4000 (NESTOR)	
		km^3	1400-2400 (ANTARES site)	
GVD (future Baikal)	$\sim$2500	km^3	800-1300	Design study

Large volume--coarse instrumentation--high energy (> TeV)

as compared to Super-K with 40% photo-cathode over 0.05 Mton

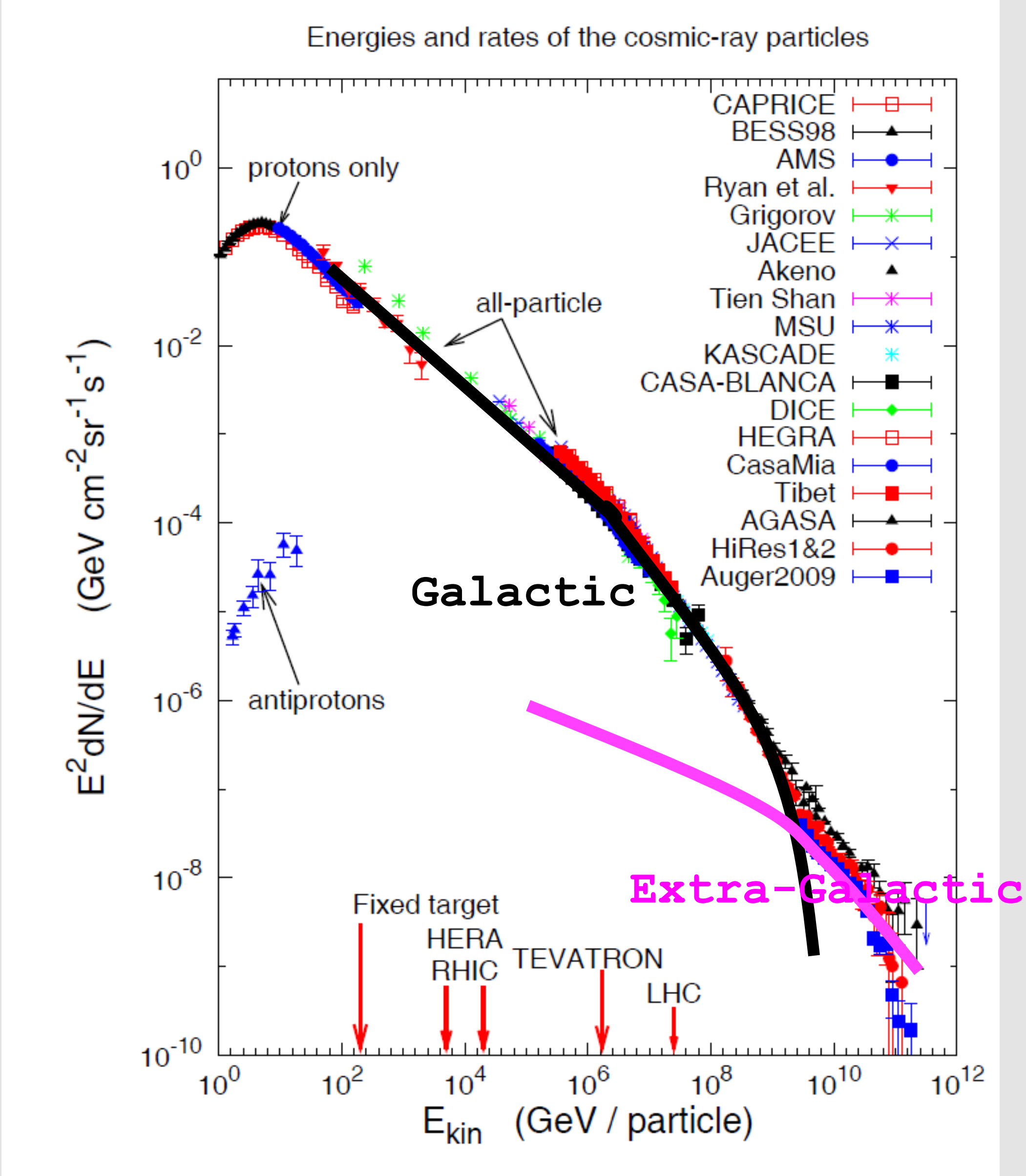
= 4 x 10^5 cm^2 / kT compared to 50 for Antares & 2 for IceCube

The Neutrino Detector Spectrum



Cosmic-ray connection - I

- Galactic SNR can accelerate particles into nearby molecular clouds
- Extra-galactic jets (in AGN or GRB) may share power between c.r. & ν
- Expect a few TeV ν/yr in a gigaton detector in hadronic scenarios
- Sets km^3 scale for HE neutrino astronomy

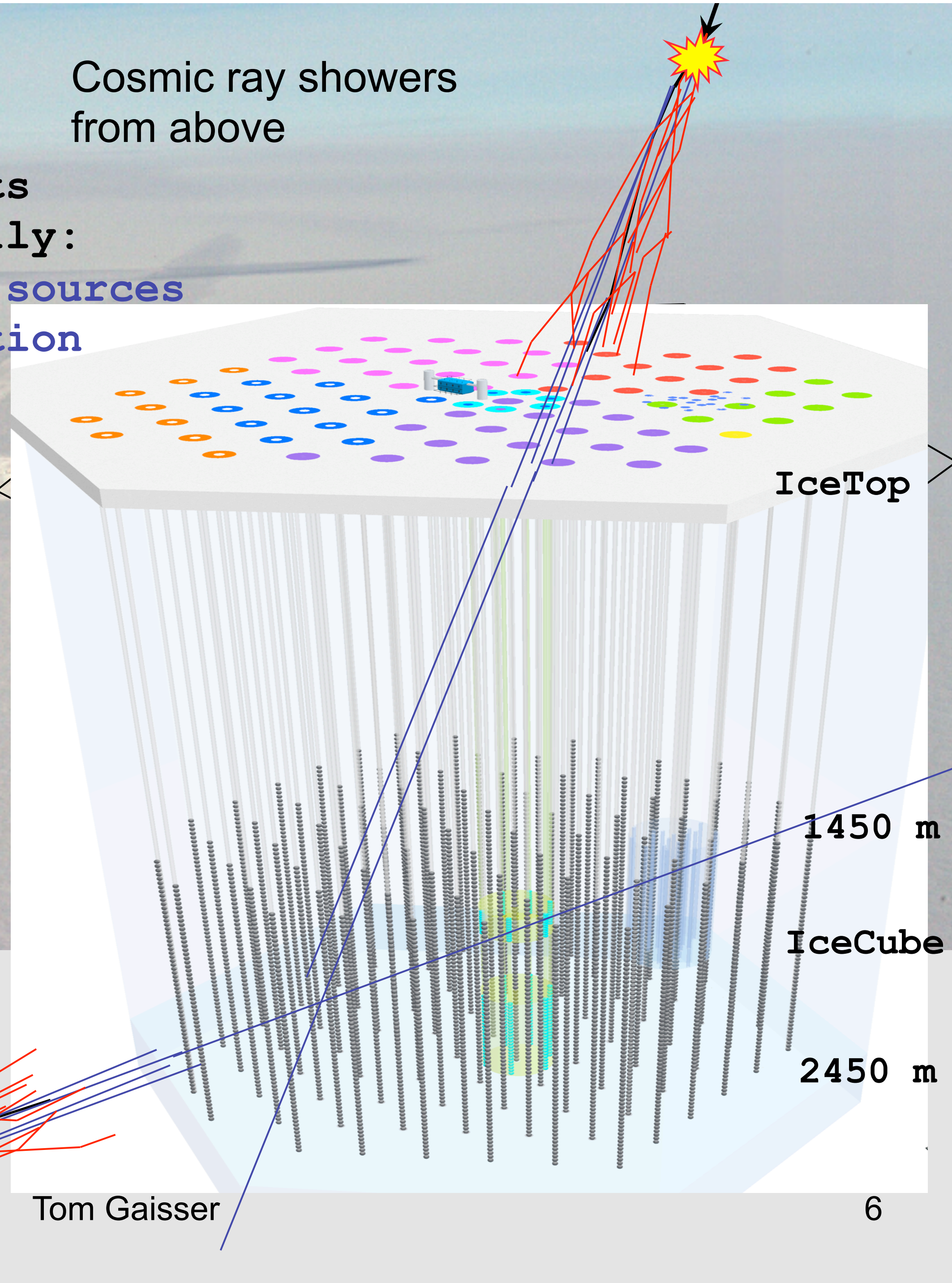


Cosmic ray showers
from above

Two different kinds of events
Closely related scientifically:

- Neutrinos from cosmic ray sources
- Cosmic rays after propagation

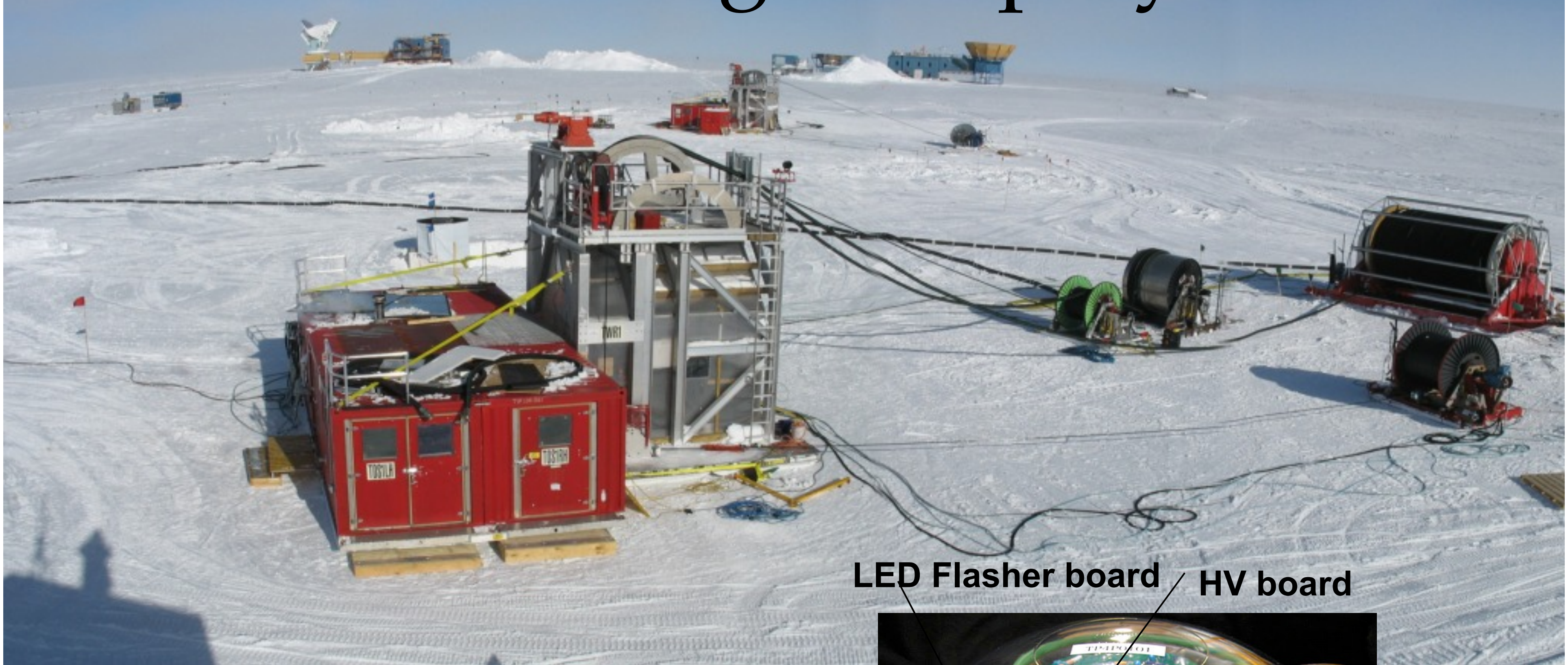
South Pole
2835 m.a.s.l.



Neutrinos from all directions

Primarily ν_μ-induced μ
from below

IceCube drilling & deployment

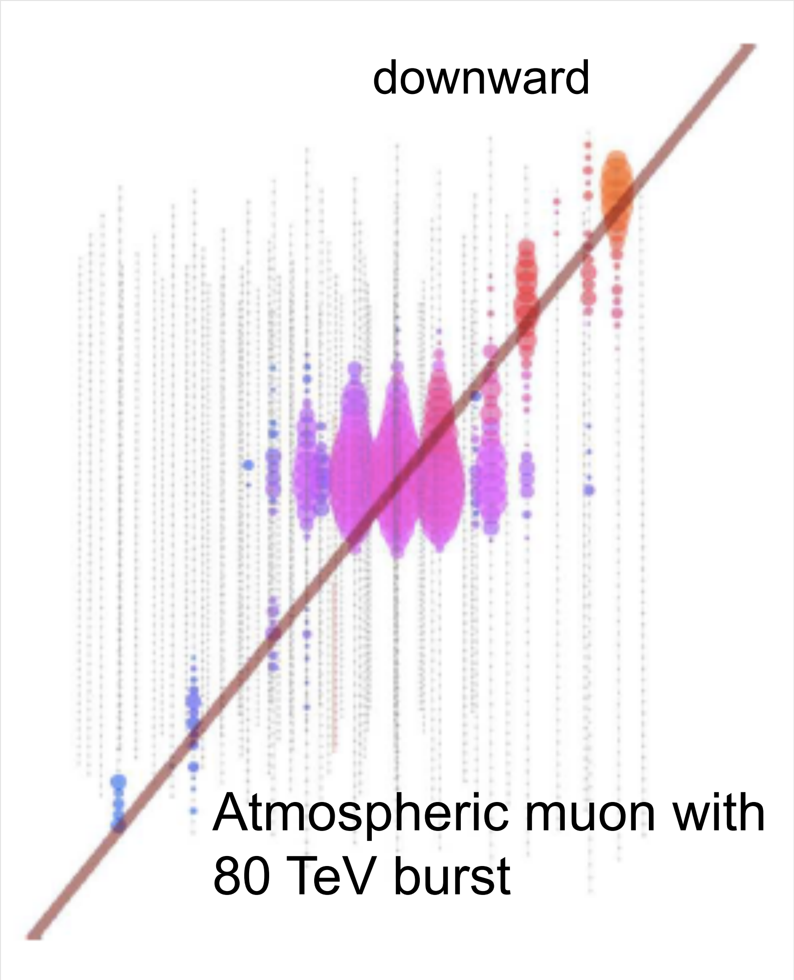


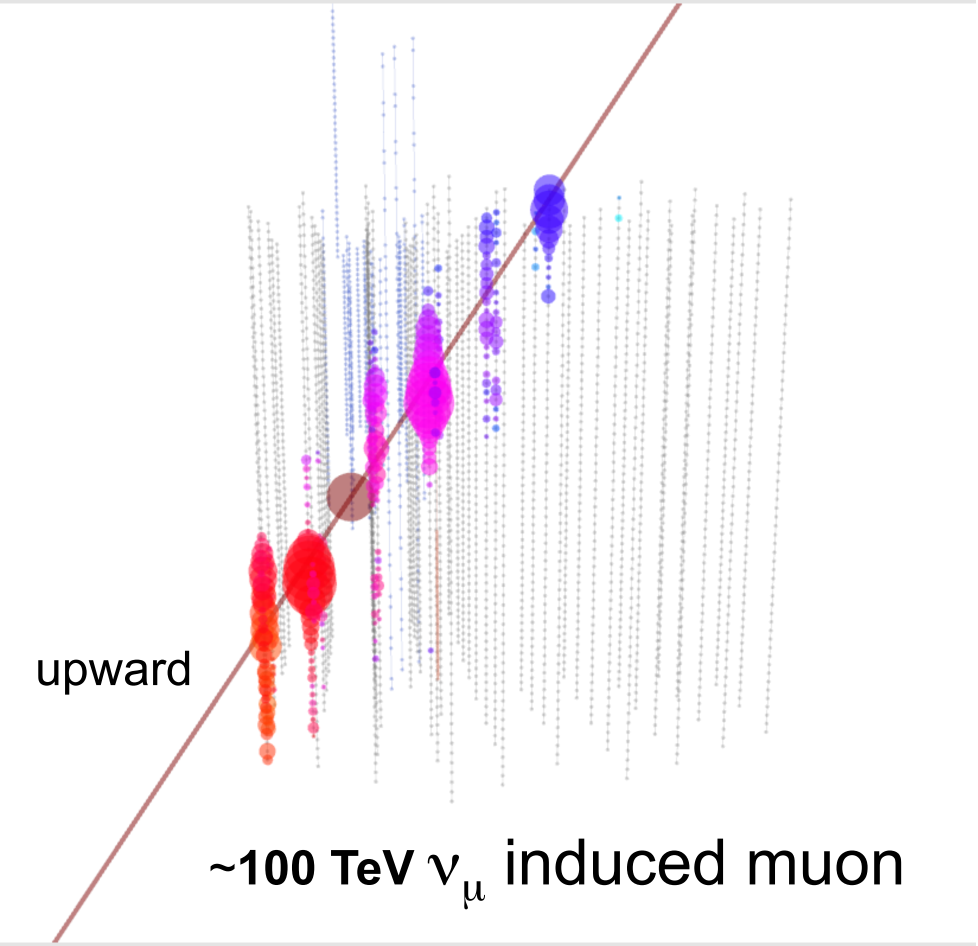
Digital Optical Module

Timing accurate to <3 ns over full array including IceTop

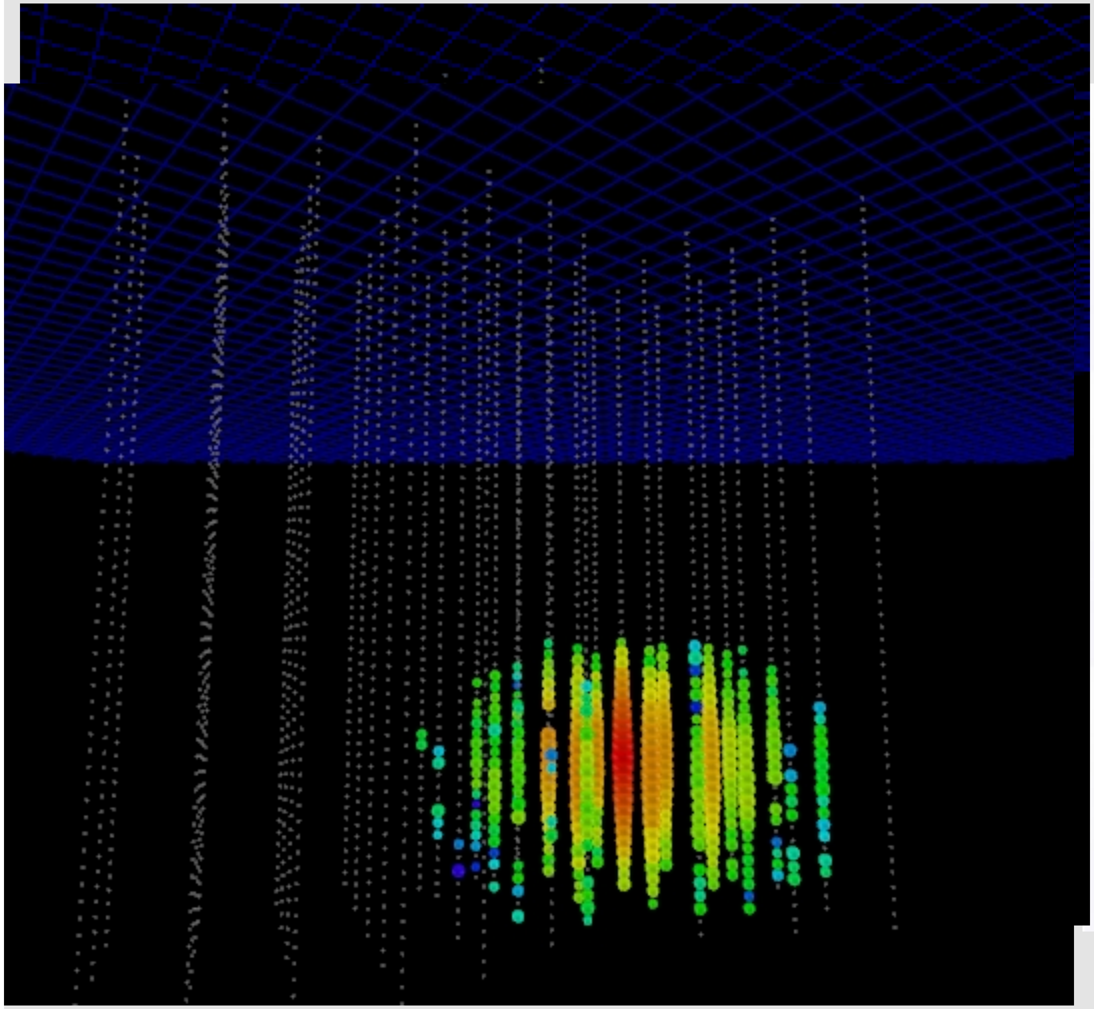
High-energy events in IceCube

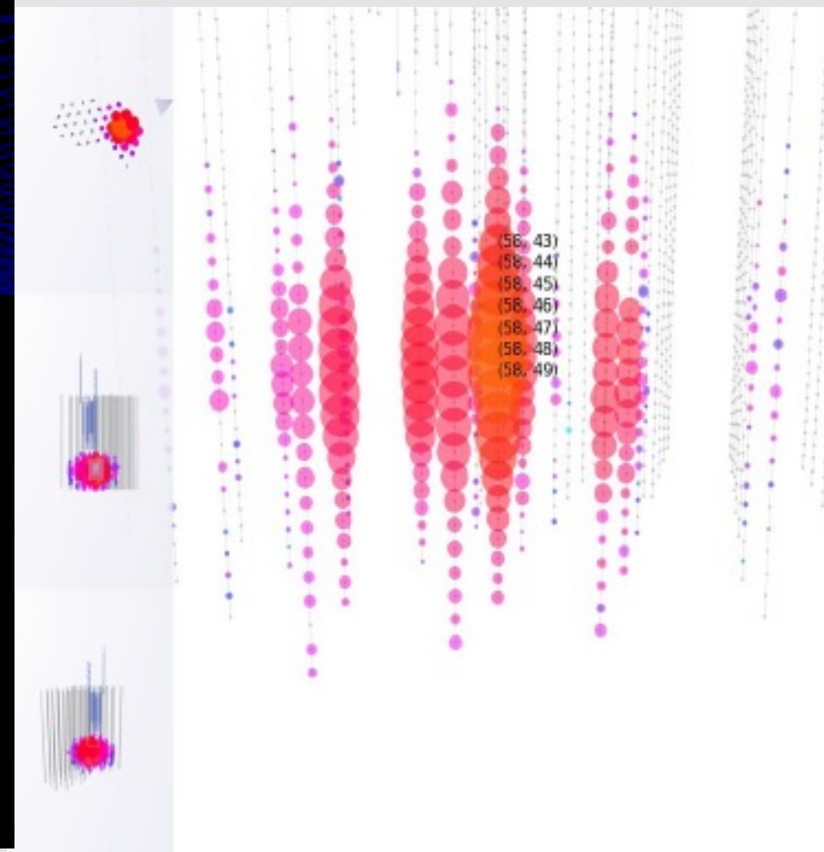
Color code: red/orange = earlier; magenta/blue = later





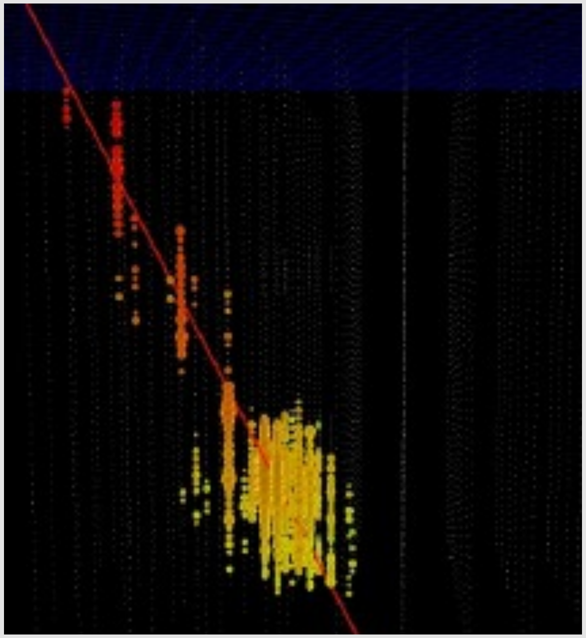
High energy cascade candidate



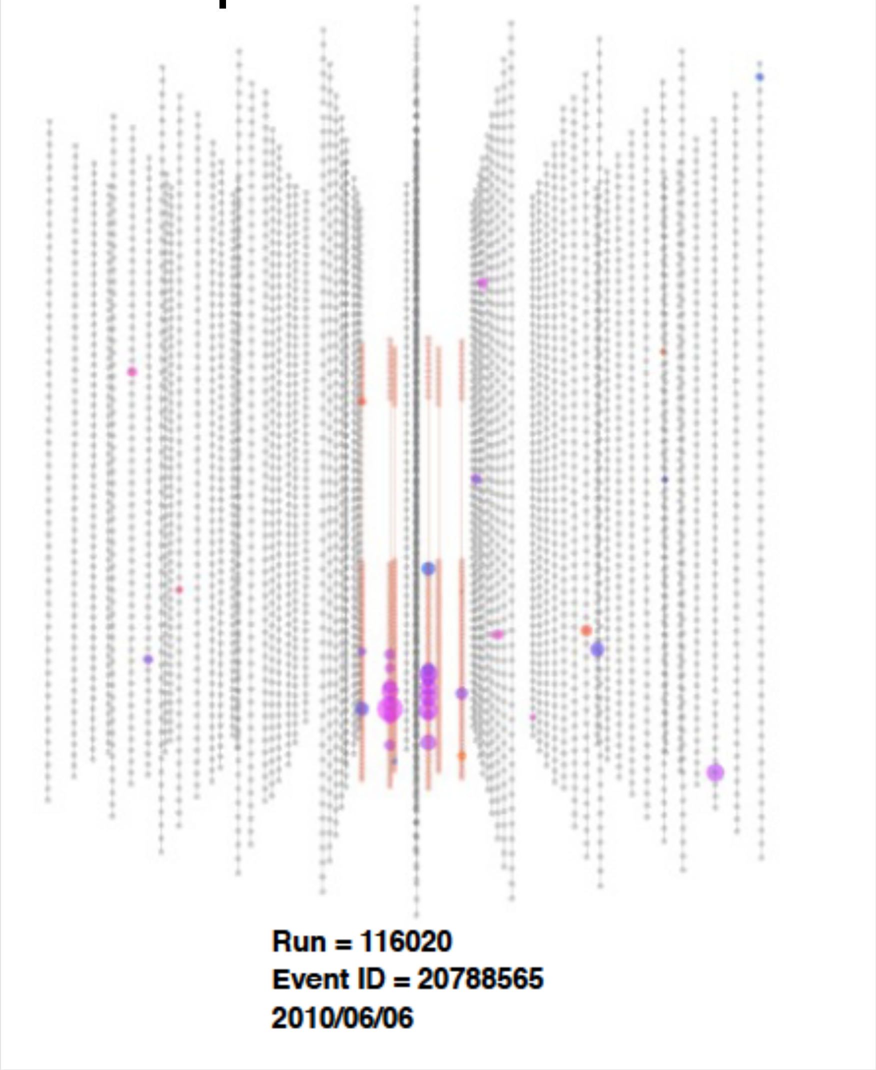


A cascade event, candidate for a high energy ν_e ~50 TeV

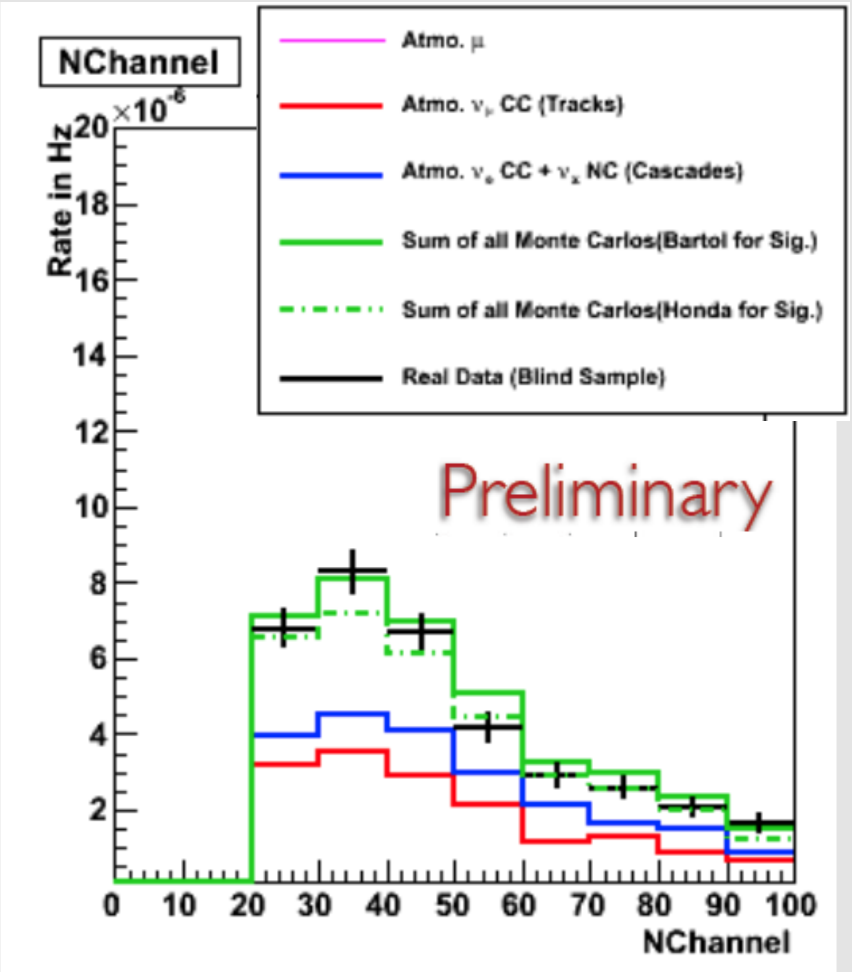
Downward muon bundle illuminates Deep Core subarray

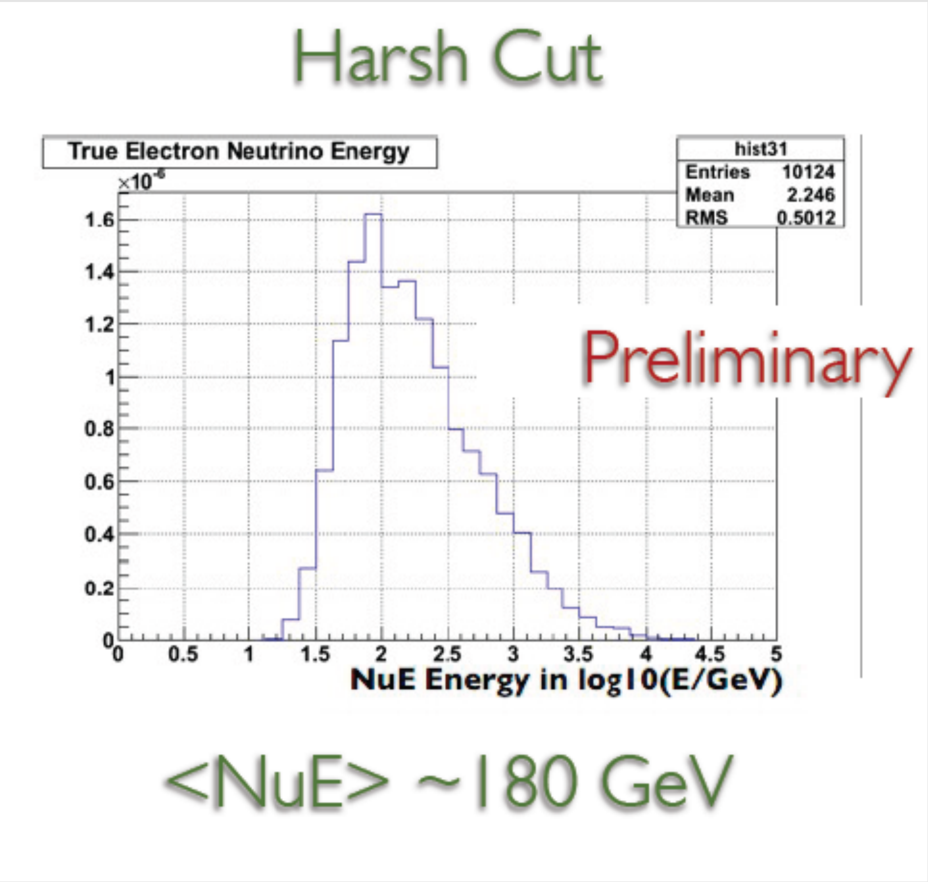


Cascade event candidate in Deep Core

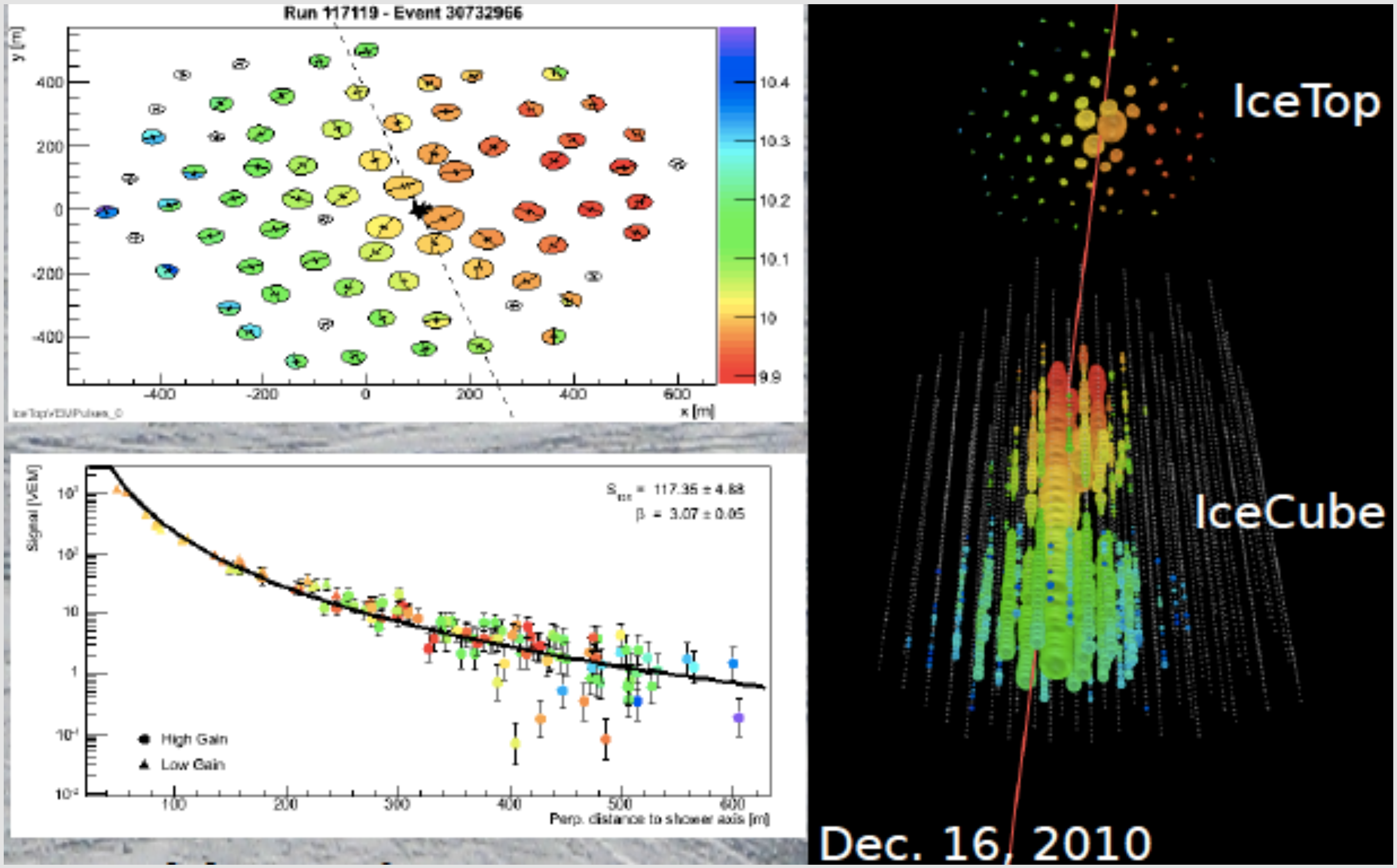


Cascade events with Deep Core





Air shower in IceCube/IceTop

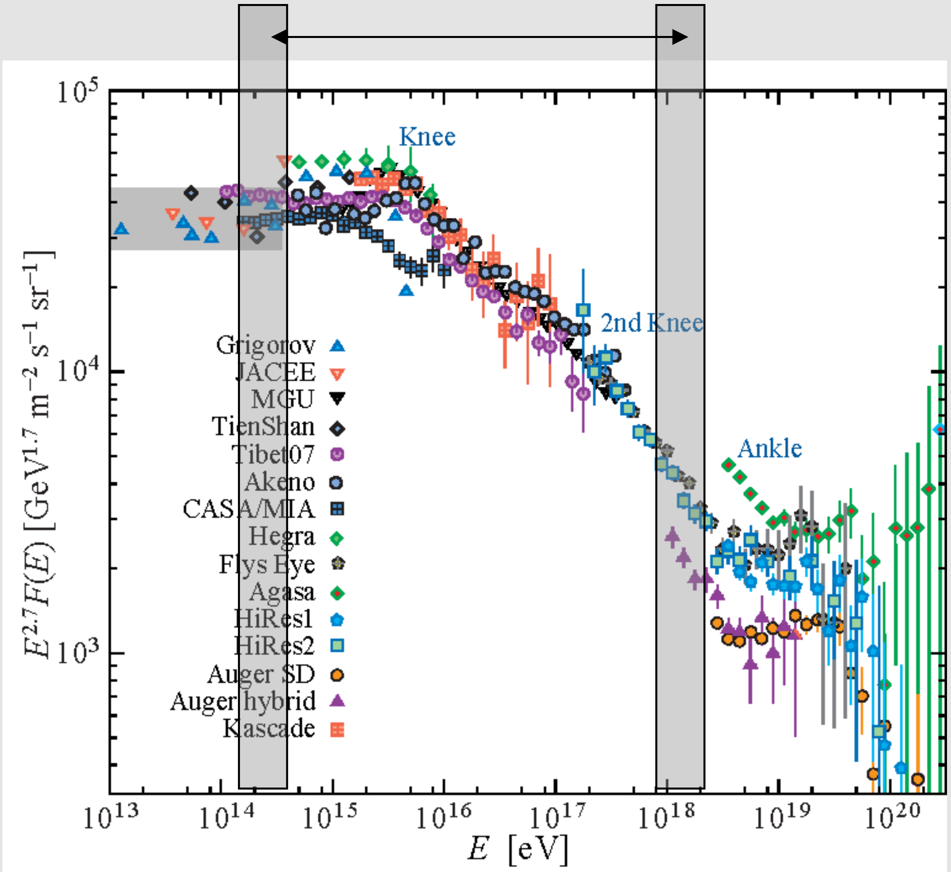


Zenith angle = 5.6 deg, E ~ 170 PeV

Energy range of IceCube / IceTop

- **Threshold energy**
  - ≤ 300 TeV
- **Maximum energy**
  - Limited by km^2 size
  - Coincident events
    - $A \cdot \Omega$ = 0.3 km^2 sr
    - E_{max} = EeV
  - IceTop only ($\theta < 60^o$)
    - $A \cdot \Omega$ = 3 km^2 sr
    - E_{max} = 3 EeV

< PeV **≥ EeV**

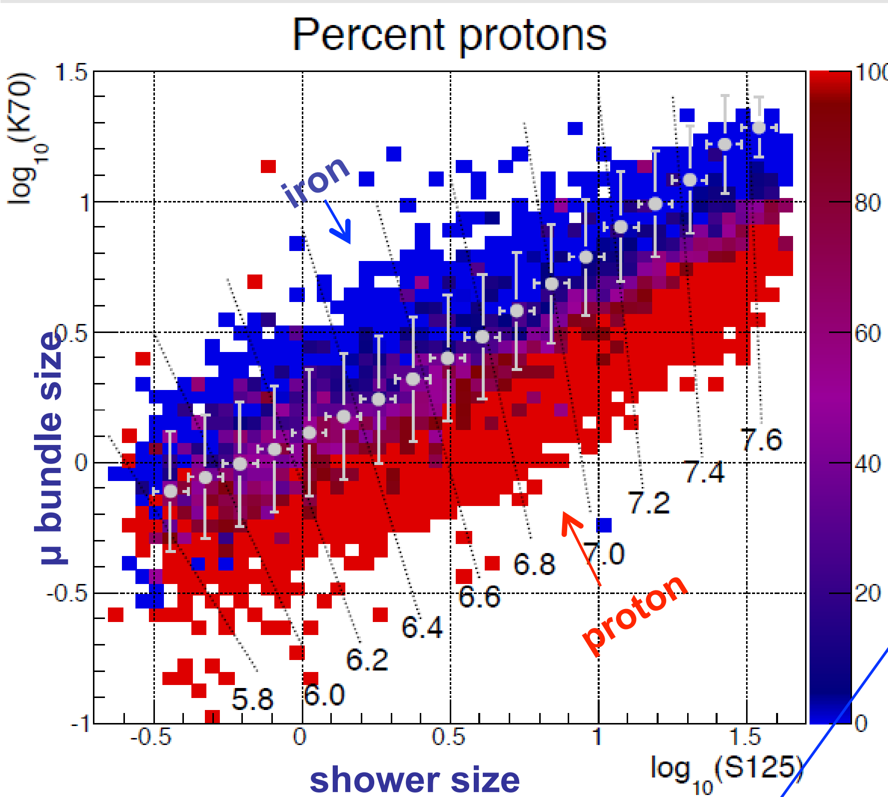


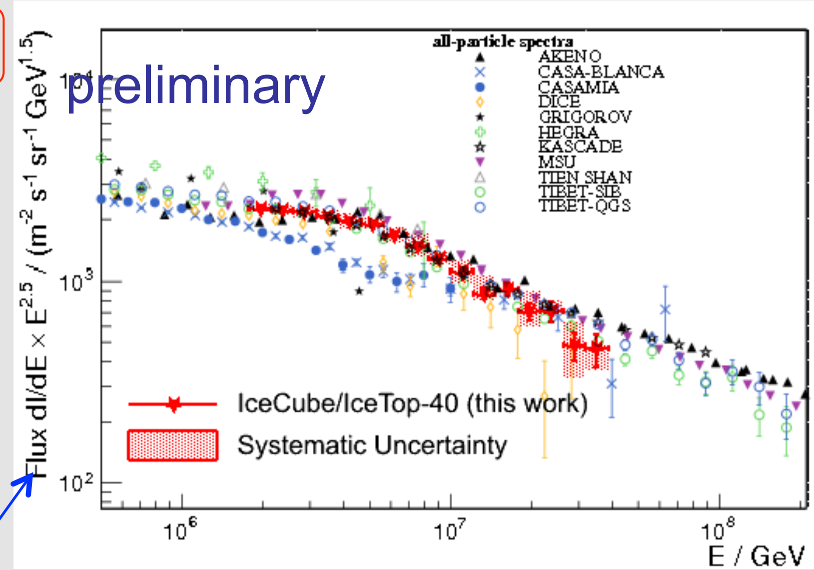
Anchor to direct measurement of composition ~300 TeV

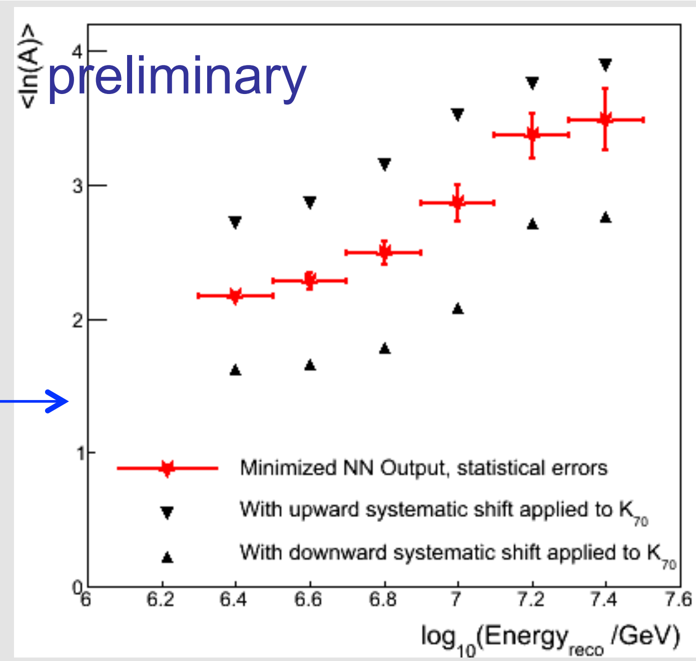
Look for transition to extra-galactic < EeV

IceTop – InIce Coincidences IC 40

ICRC paper #923



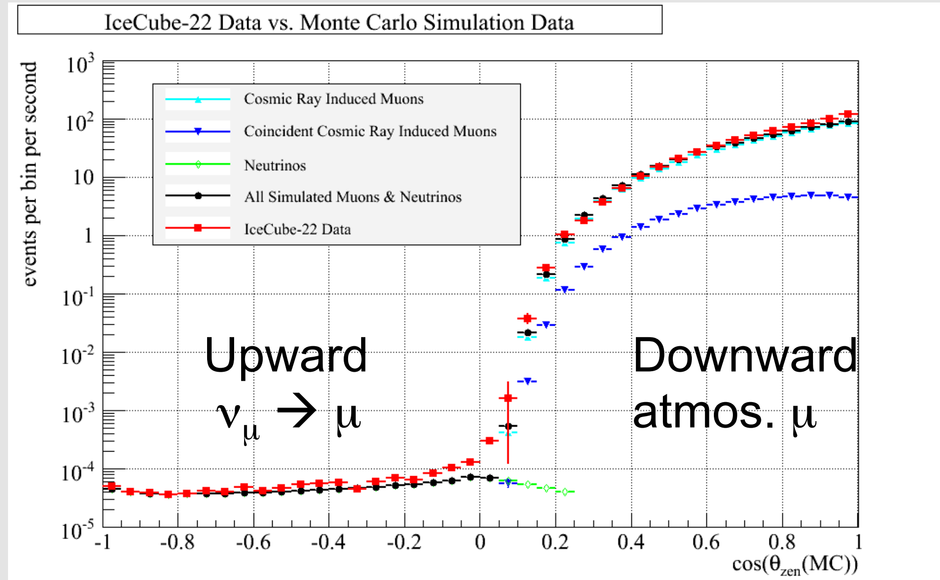




unfolding: energy & mass

Muons underground

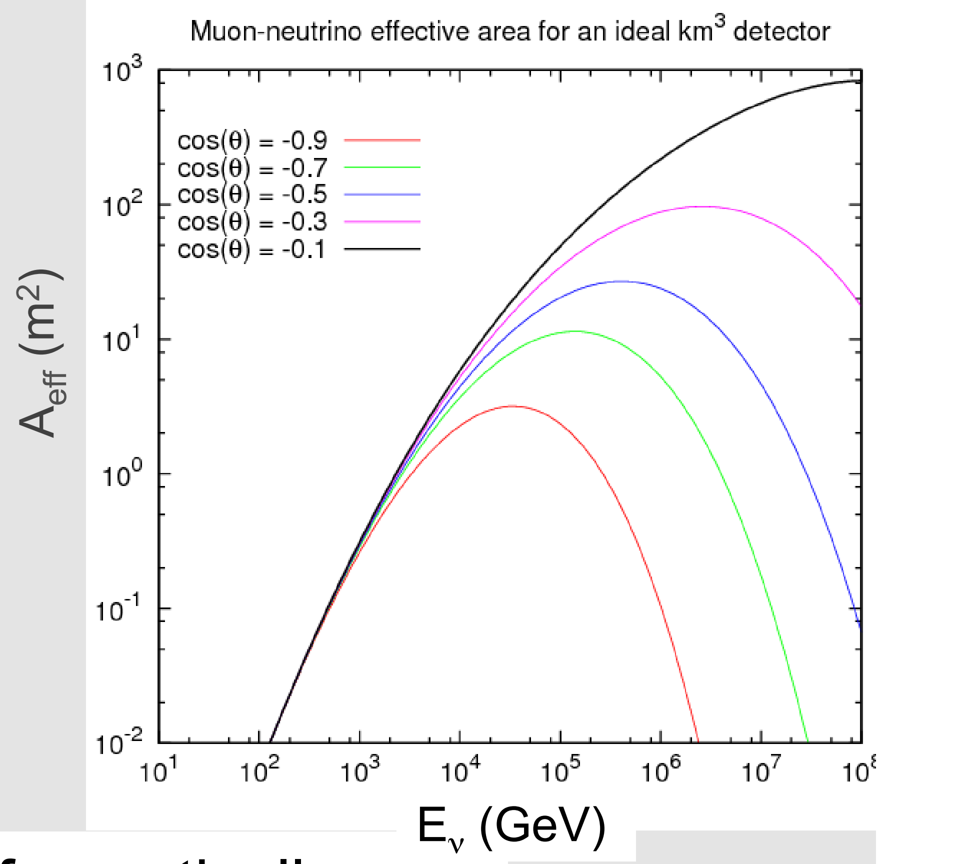
- Muons enter detector from all directions
- At 2 km in water downward muons are 10^6 x upward rate
- Analysis must distinguish true upward events from misreconstructed atmospheric muons



All-sky plot of muons in IceCube-22 from 2007 (P. Berghaus, IceCube, ISVHECRI-2008 arxiv.org/abs/0902.0021)

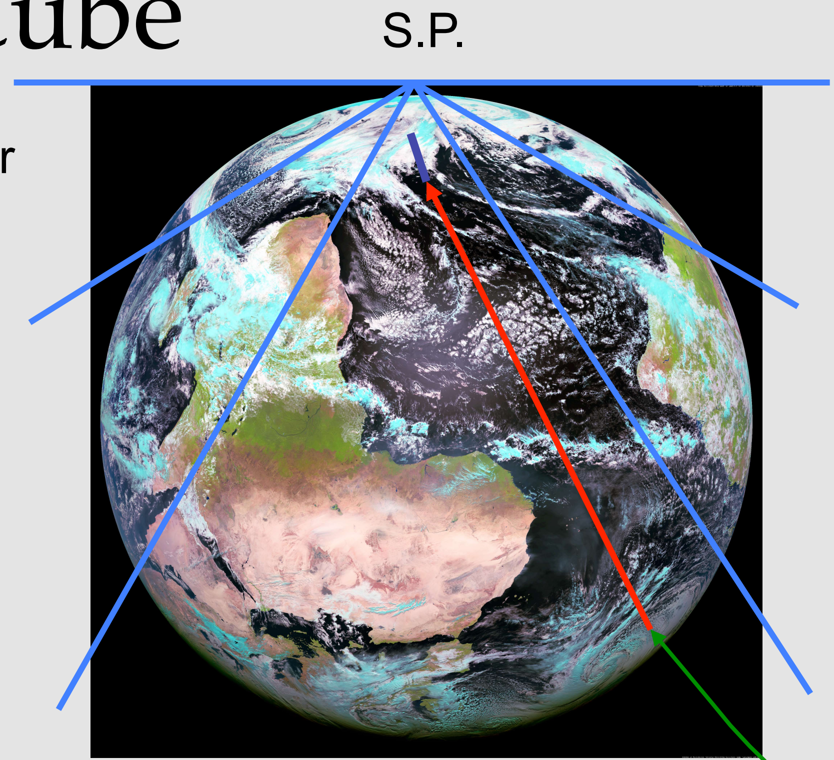
Detecting muon neutrinos

- Rate = Neutrino flux
  x Absorption in Earth
  x Neutrino cross section
  x Size of detector
  x Range of muon (for ν_μ)
- Range favors ν_μ
  – ~4 to 15 km.w.e. for E_ν ~ 10 to 1000 TeV



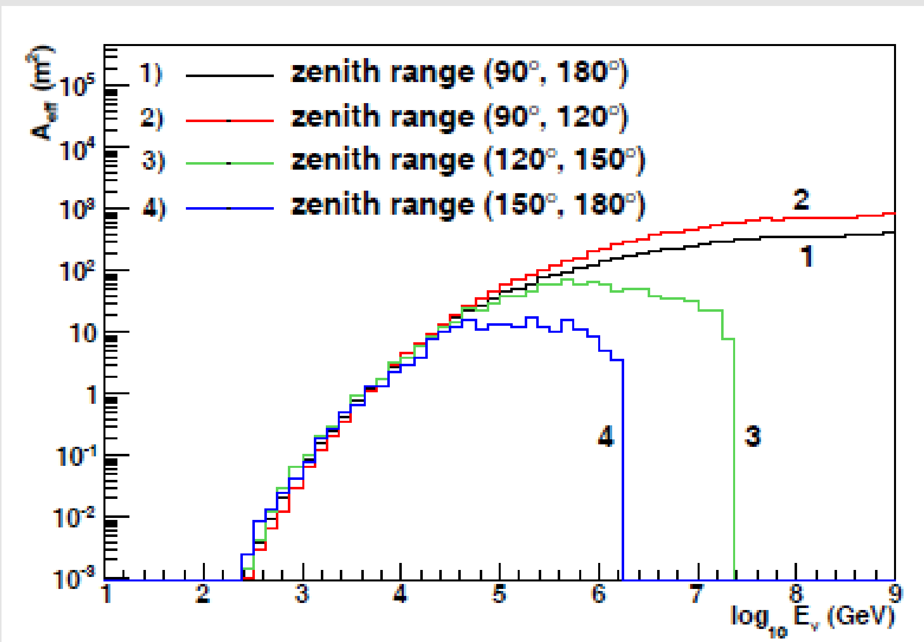
Earth becomes opaque to ν, first for vertically upward (~30 TeV) then for more horizontal (~PeV)

Upward ν_μ in IceCube



Zone 1, l: -30 to -90 ; 3.14 sr
Zenith: $90 < \theta < 120^o$
(40% of Zone 1 is over the Antarctic continent)

Zone 2, l: -30 to +30; 2.30 sr
Zenith $120 < \theta < 150^o$

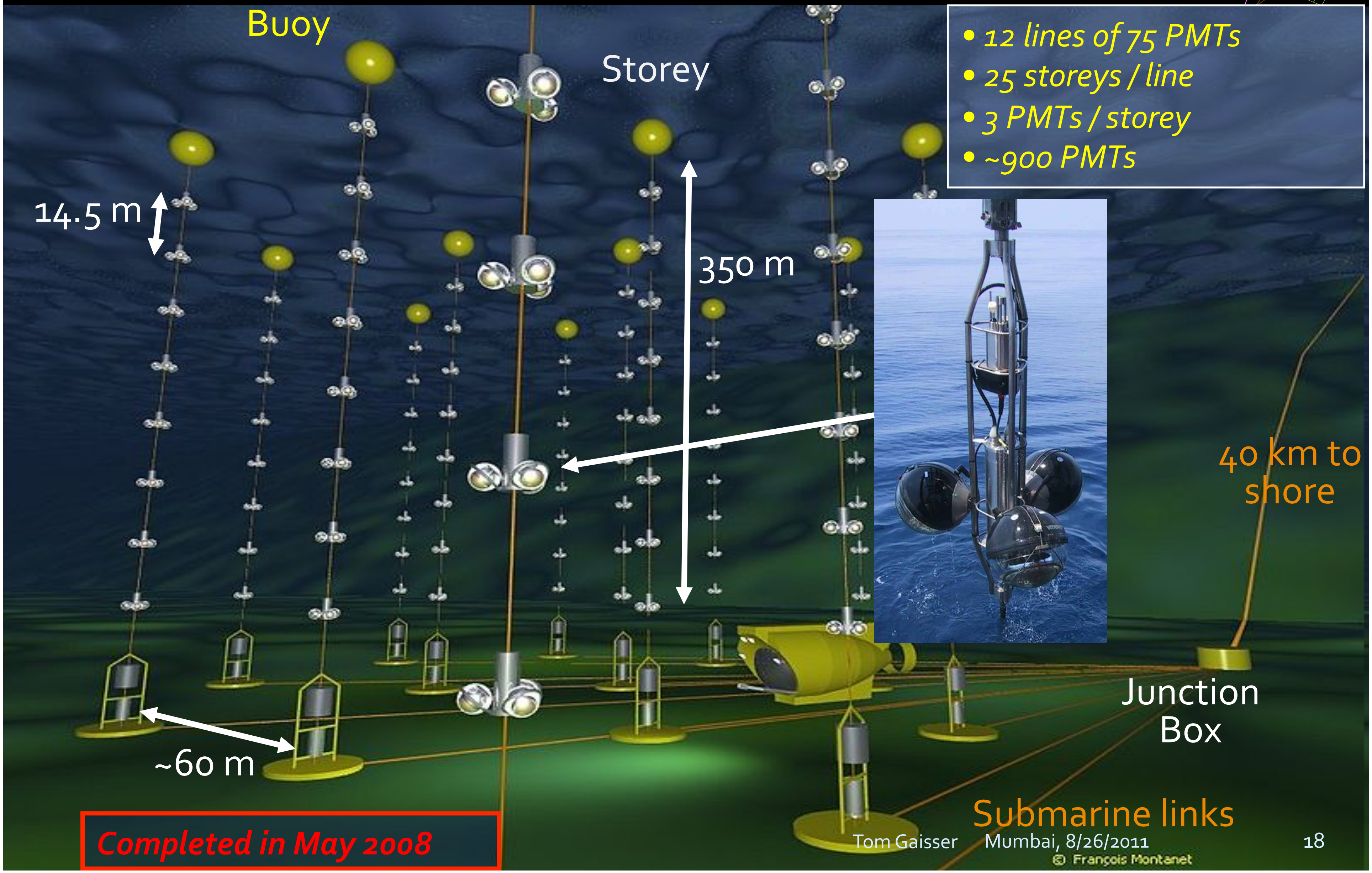


Zone 3, l: +30 to +90, 0.84 sr
Zenith: $150 < \theta < 180^o$

Cosmic ray produces ν in atmosphere that puts a **muon** into the detector

The ANTARES detector

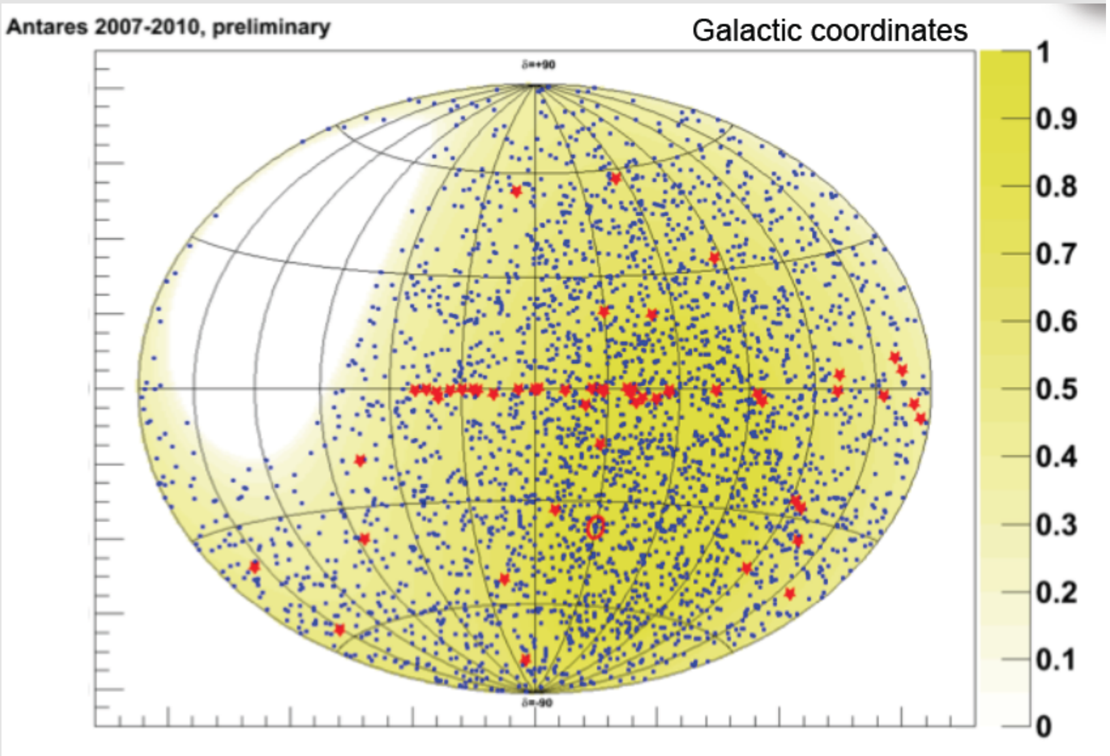
- *12 lines of 75 PMTs*
- *25 storeys / line*
- *3 PMTs / storey*
- *~900 PMTs*



Completed in May 2008

Searching for point sources --three stategies

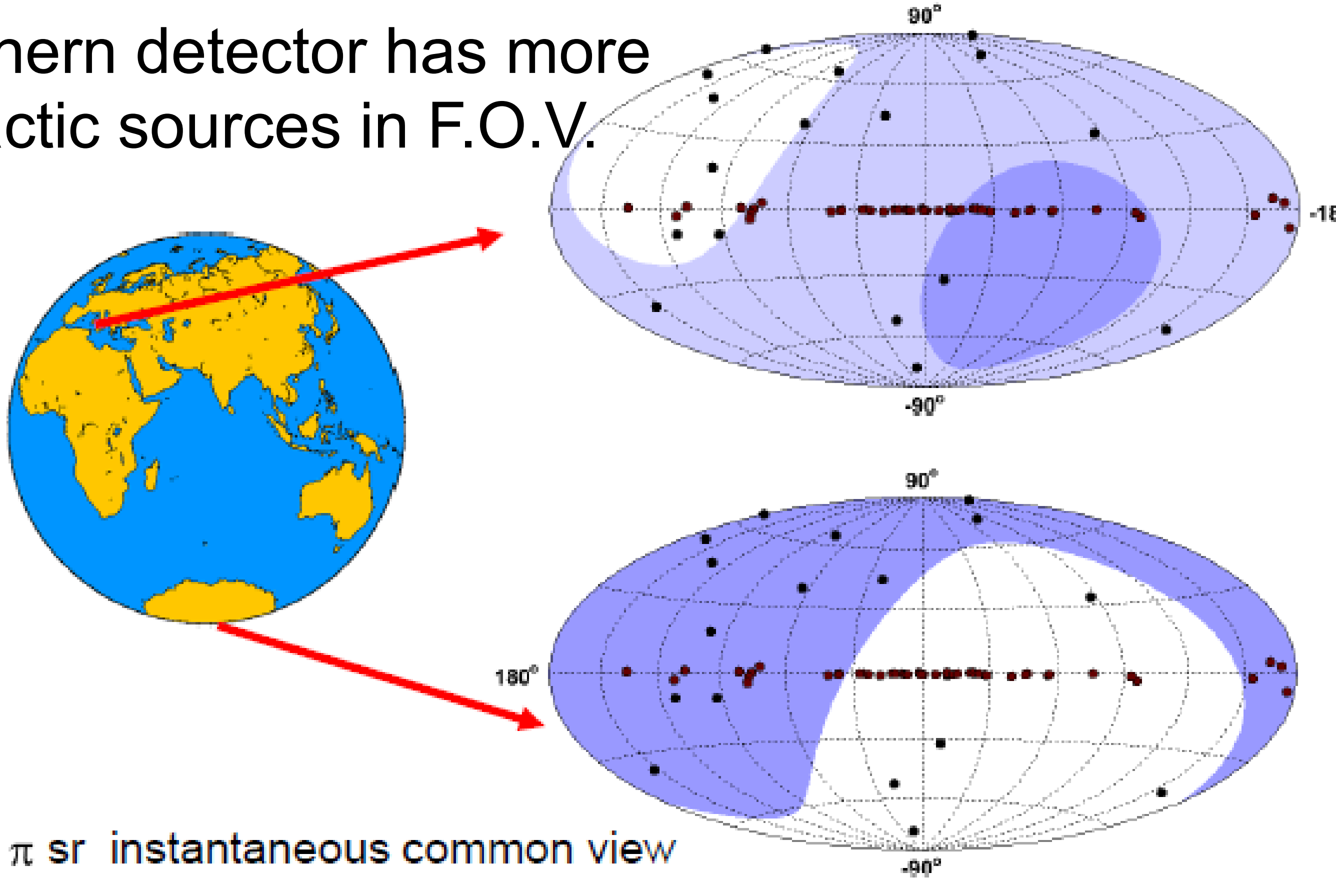
1. All sky
2. Selected sources
3. Flaring sources
   - Triggered
   - untriggered



Antares search 2007 – 2010.
Red boxes are selected sources
(Claudio Bogazzi, ICRC 2011)

Sky coverage in Galactic coordinates **(Gisela Anton, ν-2010)**

Northern detector has more Galactic sources in F.O.V.



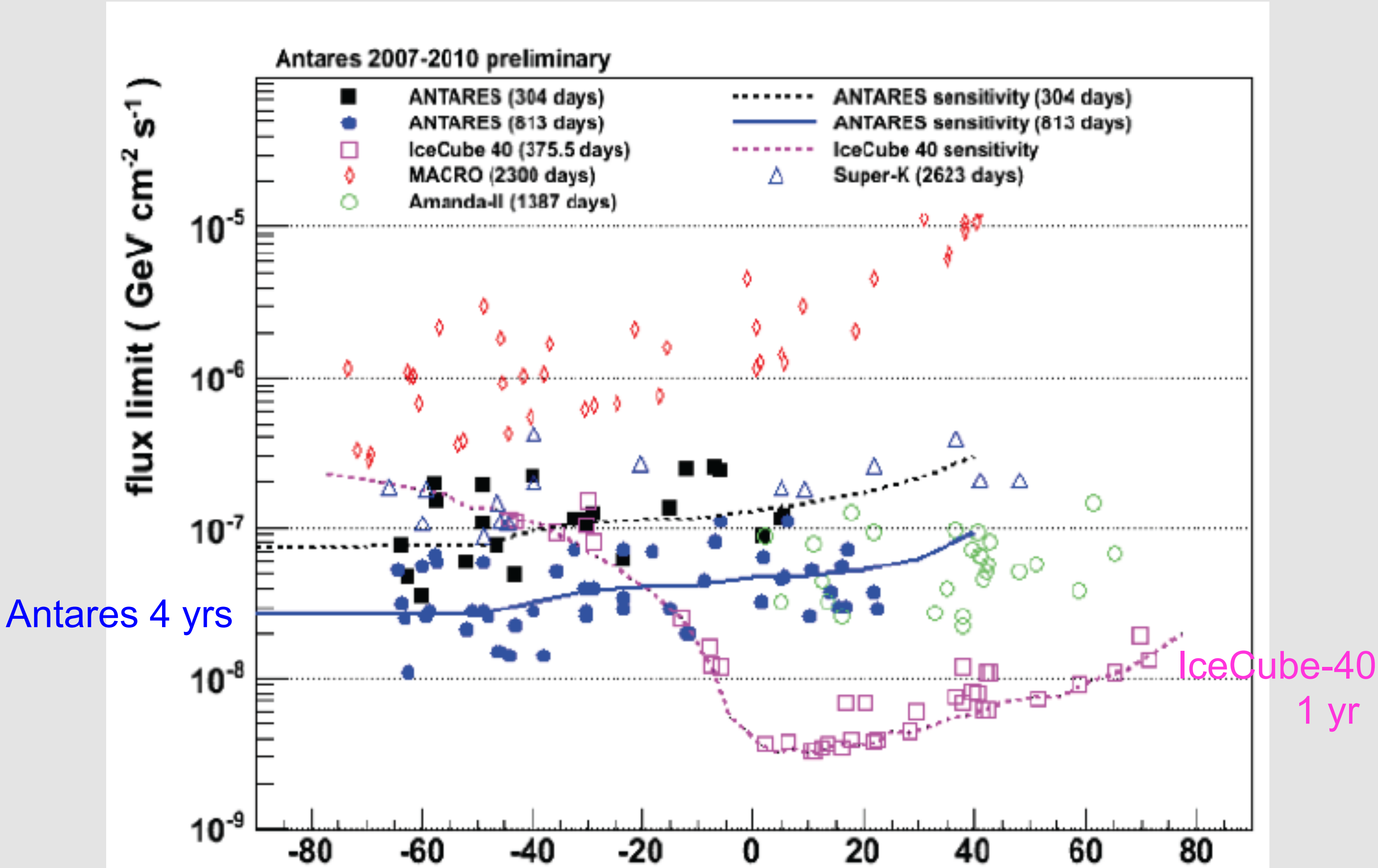
ANTARES
- 75%
- 25% – 75%
- 25%

TeV γ-Sources
- galactic
- extragalactic

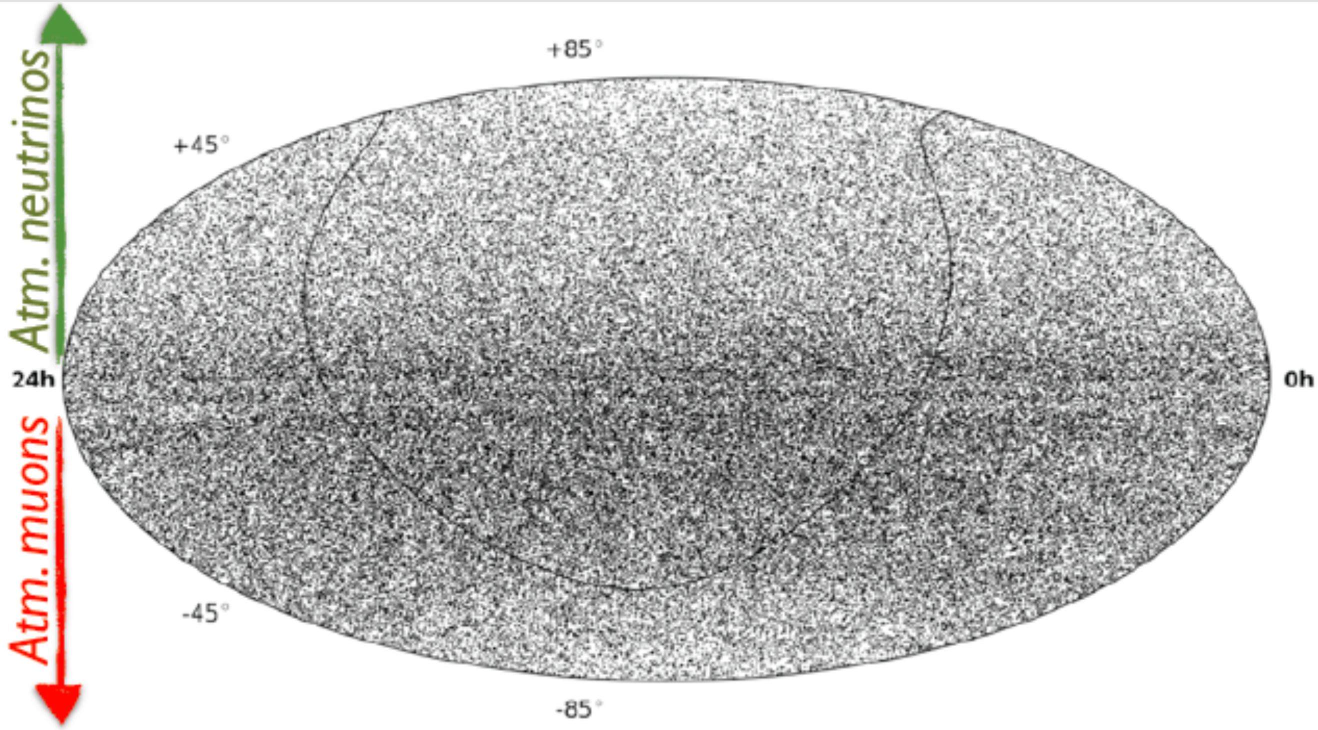
IceCube)
- 100%
- 0%

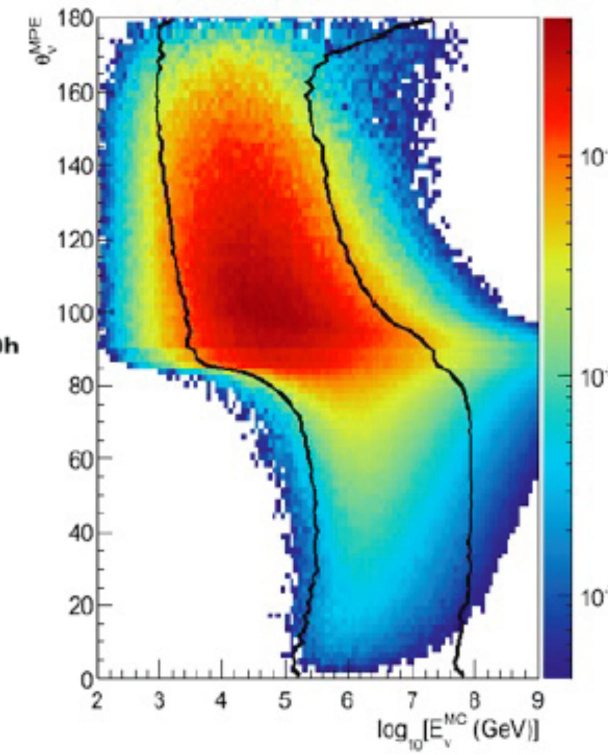
0.5 π sr instantaneous common view
1.5 π sr common view per day

Searches for selected sources



Search for point sources in IceCube





- *Total events: 43339 (upgoing) + 64230 (downgoing)*
- *Livetime: 348 days (IC59) + 375 days (IC40)*

Note high energy threshold for downward events

IceCube selected sources

(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	--
MGRO J2019+37	305.22	36.83	PWN	-	--
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	--
IC443	94.18	22.53	SNR	1.5 kpc	--
Geminga	98.48	17.77	Pulsar	100 pc	--
Crab Nebula	83.63	22.01	SNR	2 kpc	--
1ES 1959+650	300.00	65.15	HBL	z = 0.048	--
1ES 2344+514	356.77	51.70	HBL	z = 0.044	--
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	--
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	--
W Comae	185.38	28.23	HBL	z = 0.1020	--
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	--
3C 123.0	69.27	29.67	FRII	1038 Mpc	--
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3
PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	--
3C 273	187.28	2.05	FSRQ	z = 0.158	--
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	***201.37***	***-43.02***	***FRI***	***3.8 Mpc***	***0.14***
PKS 1454-354	***224.36***	***-35.65***	***FSRQ***	***z = 1.42***	***0.14***
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	--
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	--
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	--
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	--
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	--
Cyg X-3	308.11	40.96	MQSO	9 kpc	--
LSI 303	40.13	61.23	MQSO	2 kpc	--
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

Search for diffuse flux of ν

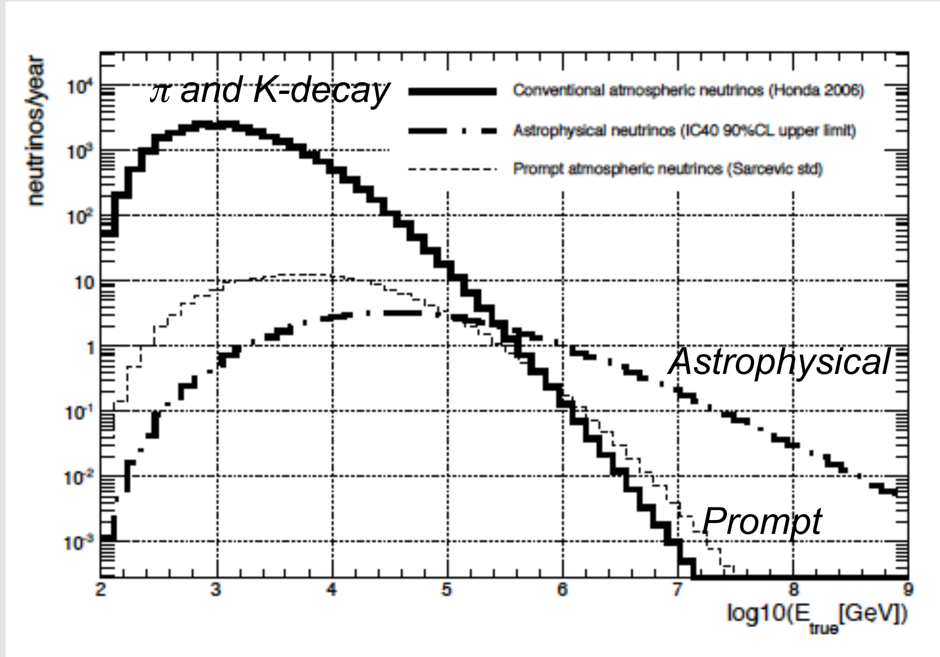
- Neutrinos are not absorbed. Therefore

All sources out to Hubble radius contribute

- Hard spectrum
  - Expect -2.0 to -2.4 differential spectral index
  - Compared to -3.0 to -3.7 for atmospheric ν
- Look for excess of high-energy events above background of atmospheric neutrinos

Measurement of ν_μ-induced μ

- Fit 3 components:
  - Atmospheric ν from $K^\pm$ and $\pi^\pm$ (0.3 – 85 TeV)
    - Use Honda 2007 to 10 TeV
    - + power-law extrapolation
    - $\sim \cos^{-1}(\theta)$
  - Prompt ν (10 – 600 TeV)
    - Harder spectrum to > 10^7 GeV ($\sim E^{-2.7}$), isotropic
  - Astrophysical ν
    - Isotropic, with E^{-2} spectrum assumed (35 – 7000 TeV)
  - Note different response for astro. ν *vs* atmos. ν



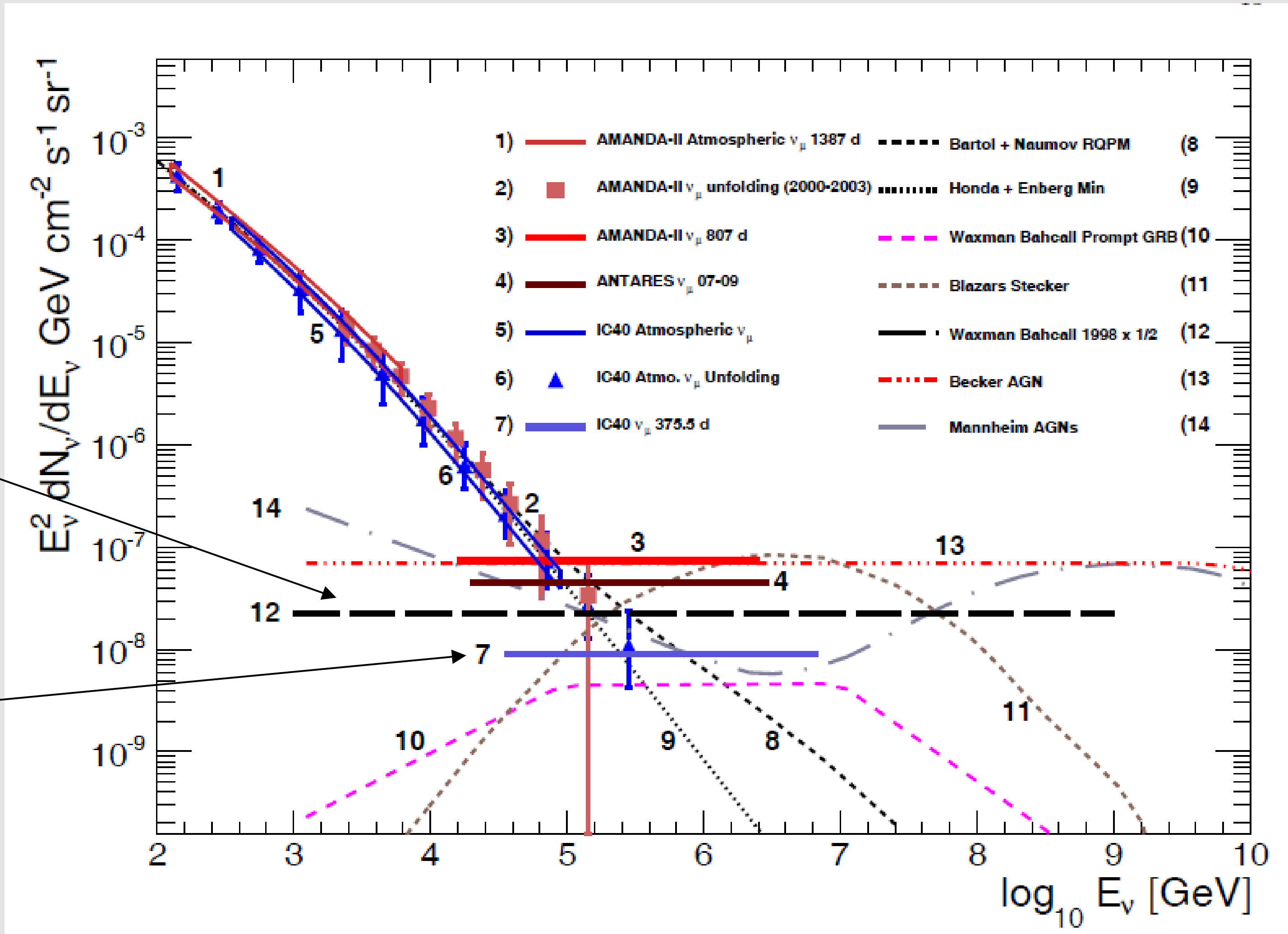
Result of fit:

- *Consistent with only K, π atmospheric ν to 100 TeV*
- *Charm component not yet seen “intrinsic” charm in doubt?*
- *No astrophysical neutrinos seen yet*

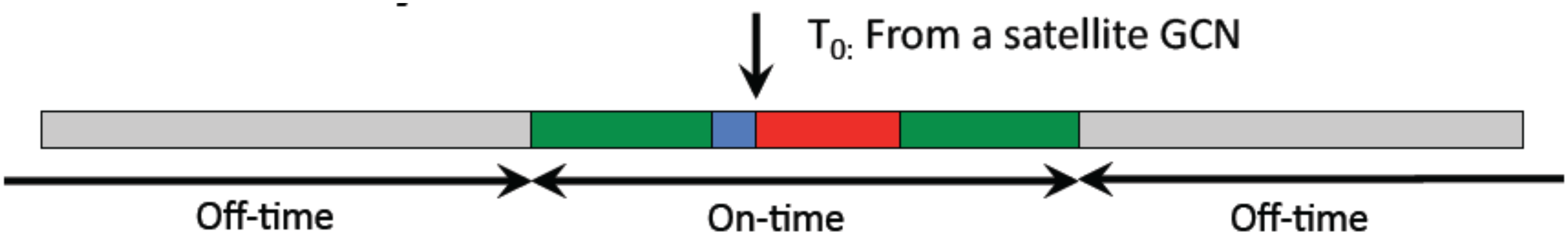
IceCube ν_μ: measurements & limits

Waxman -Bahcall Limit

IceCube 40
arXiv:1104.5187

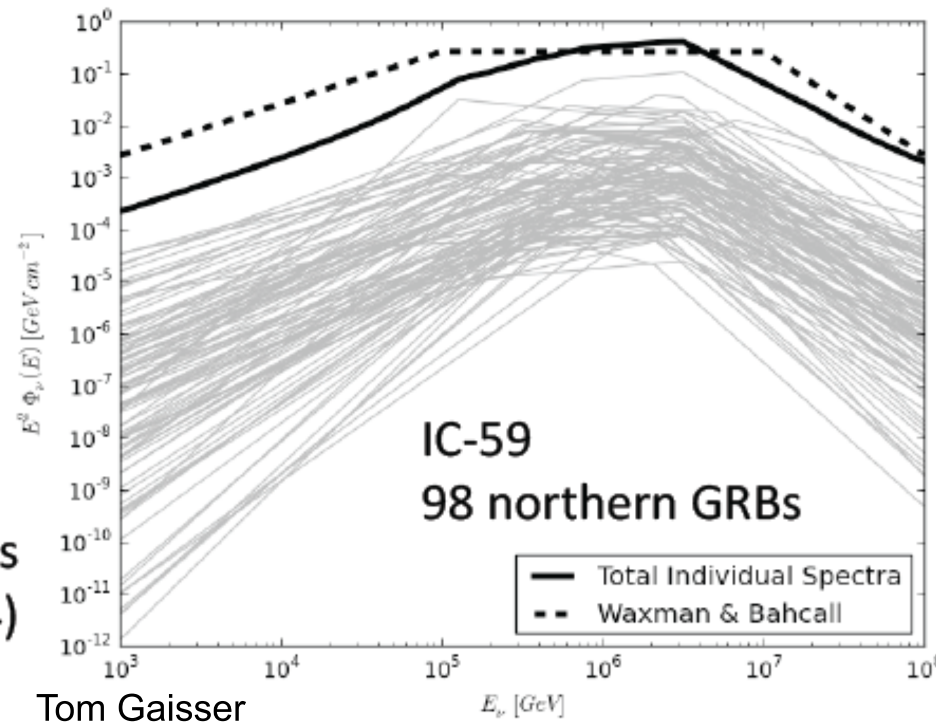


Search for neutrinos from GRB



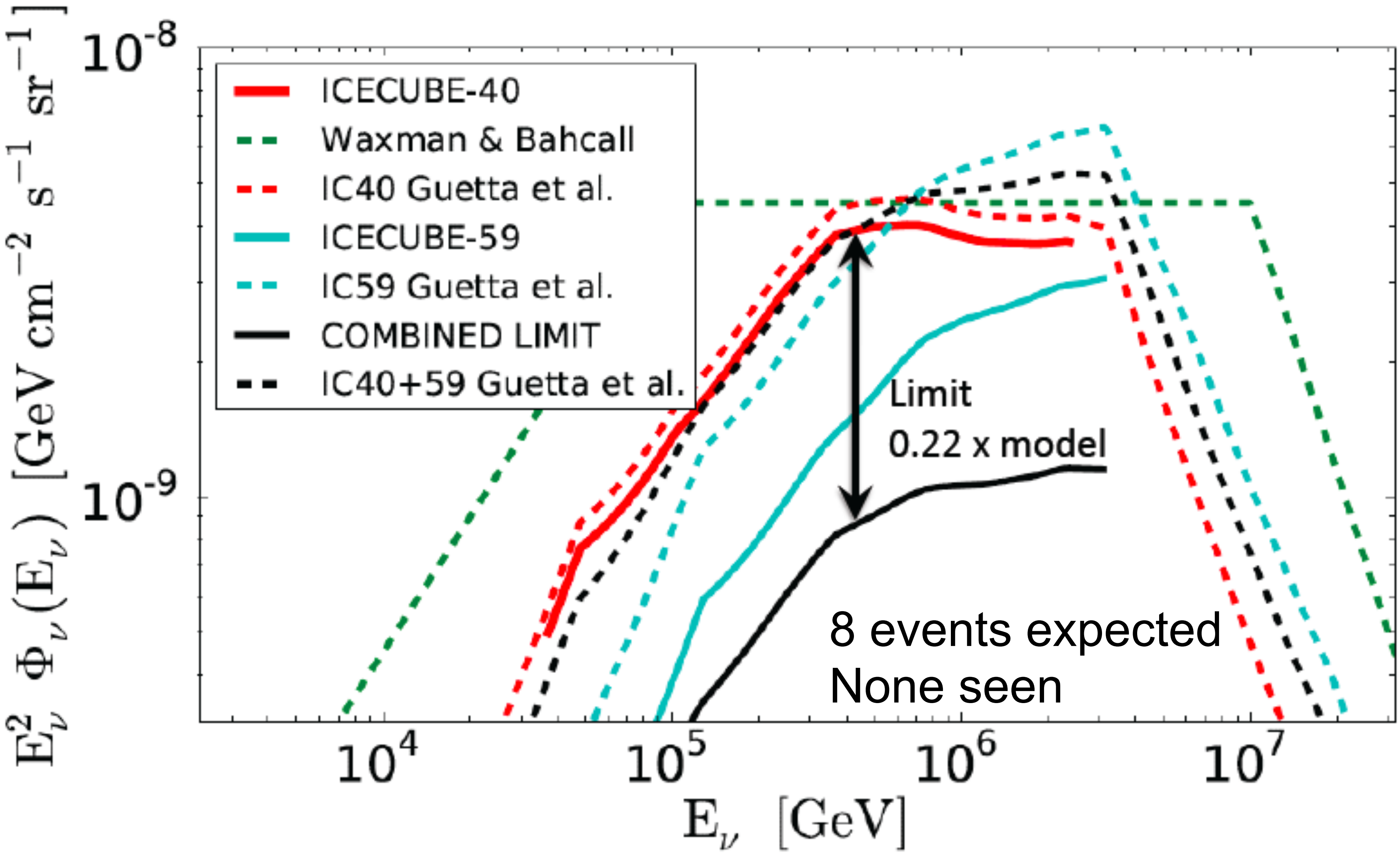
- Precursor (~100 s)
- Prompt
- Model Independent (24 h)
- Background (full year)

Very low background
One event can be significant



Individual modeling of GRBs
(Guetta et al. 2004)

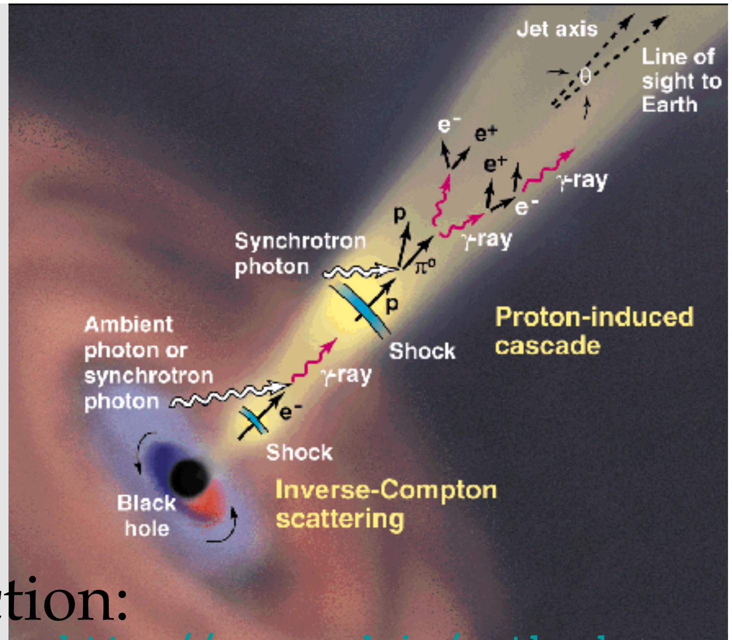
Model Dependent IC-40 / IC-59 result



Where are the neutrinos?

What do the limits mean?

Generic model I



http://www.ucd.ie/math-phy/rieger/science.gif

- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\,\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR
- This picture disfavored as limits go below W-B

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Generic model II

- UHECR are accelerated in external shocks analogous to SNR
  - See E.G. Berezhko, 0809.0734 & 0905.4785
  - mixed composition (accelerate whatever is there)
  - Low density of target material
  - → lower level of TeV-PeV neutrino production

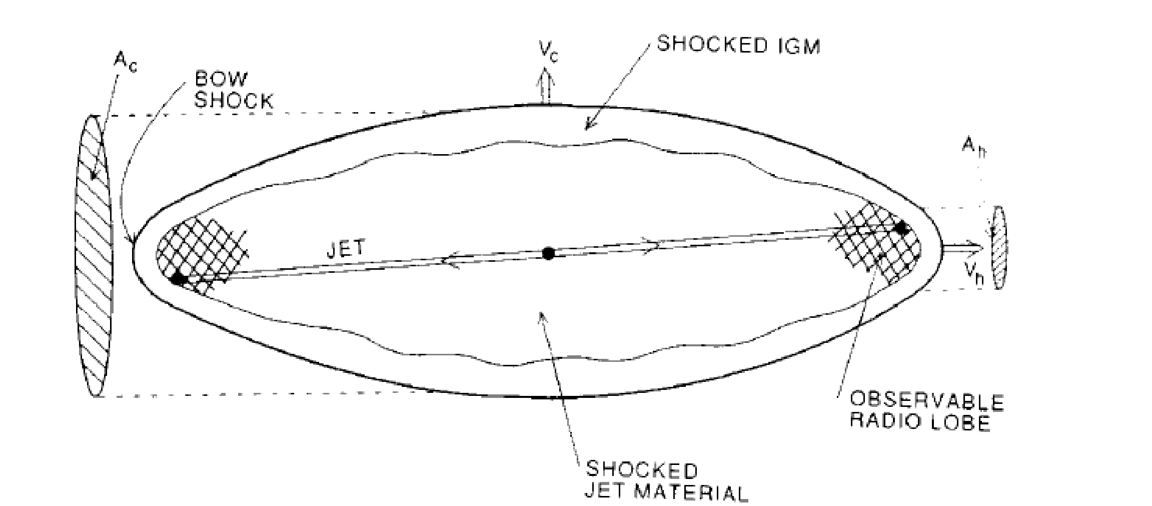
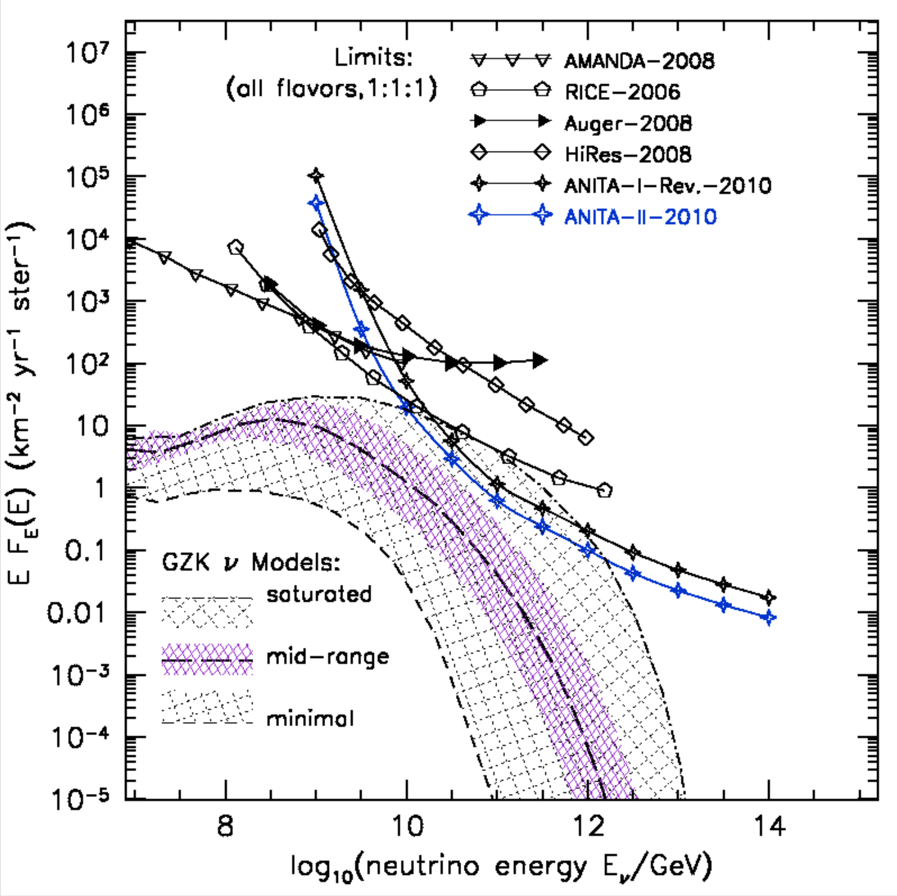


Diagram from A.Ferrari, Ann Revs A&A 36 (1998) 539

Cosmogenic (GZK) neutrinos

- Cosmic ray connection - II
- UHECR exist, therefore
  - Neutrino production occurs during propagation via
  - $p + \gamma_{CMB} \rightarrow \pi^+ \rightarrow \nu$
  - $E_{th} \sim 5 \times 10^{19}$ eV
  - Even if no ν from CR sources
- Intensity depends on
  - Spectrum at sources
  - Evolution of sources
  - Composition of UHECR (Heavy nuclei give less ν)



ANITA arXiv:1011.5004

Radio Detection of neutrinos

ANITA-II over Antarctica

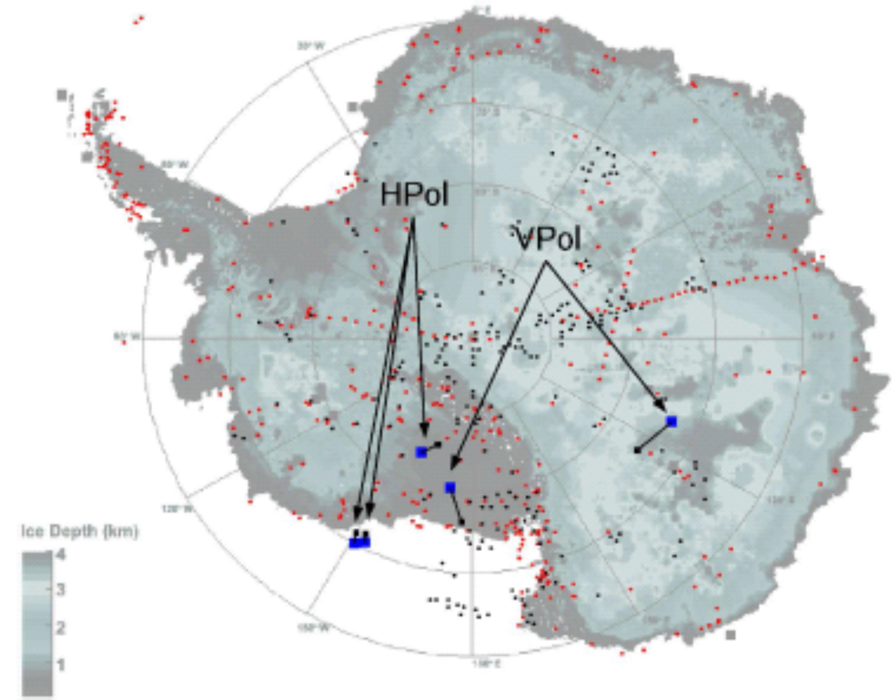
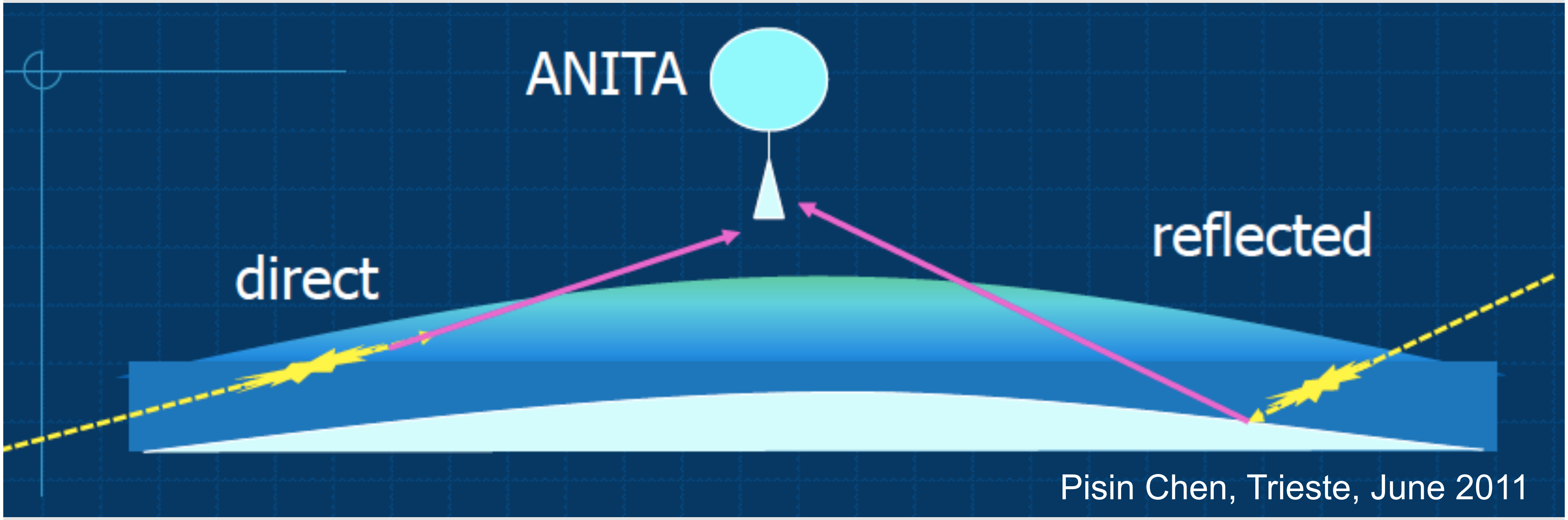


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

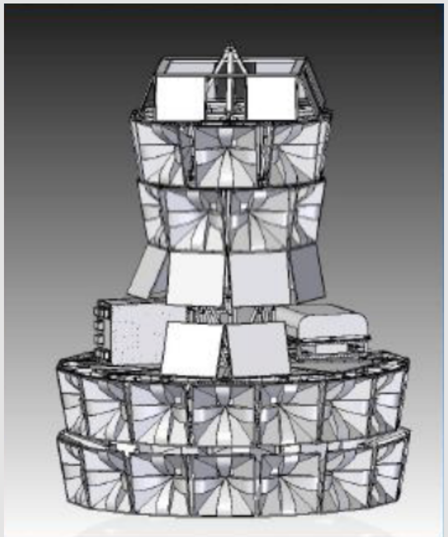
http://arxiv.org/abs/1003.2961

Vpol:1 neutrino candidate;
HPol:3 > 10^{19} eV cosmics

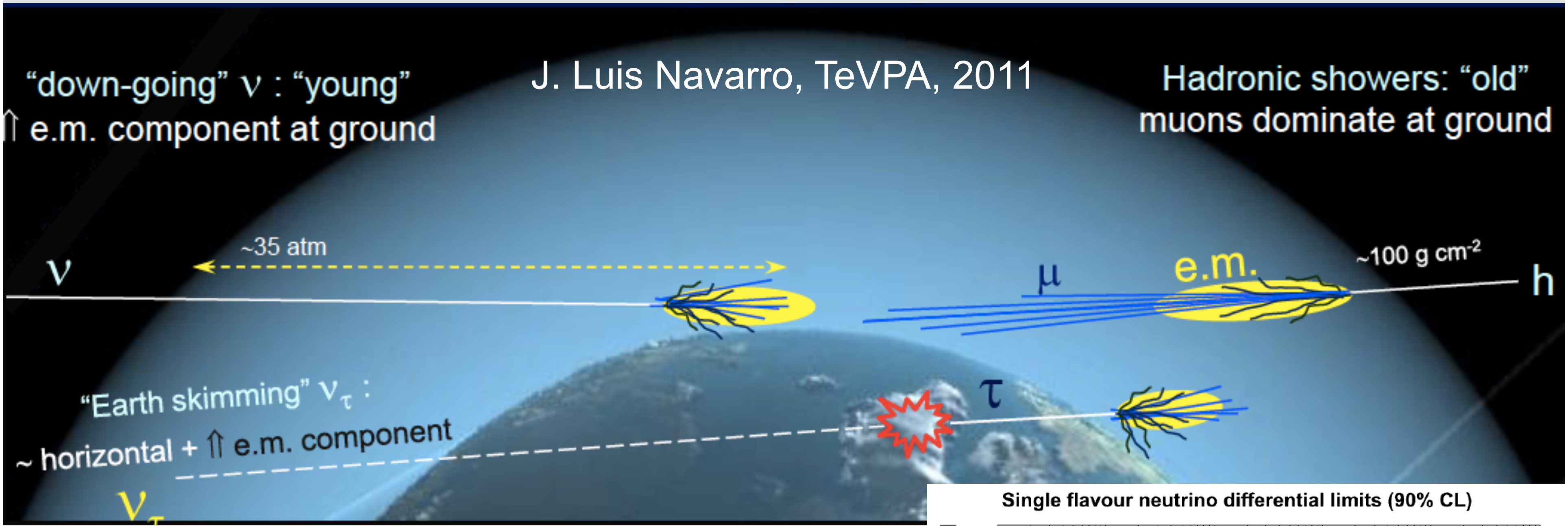
ANITA also detects ~10^{19} eV CR

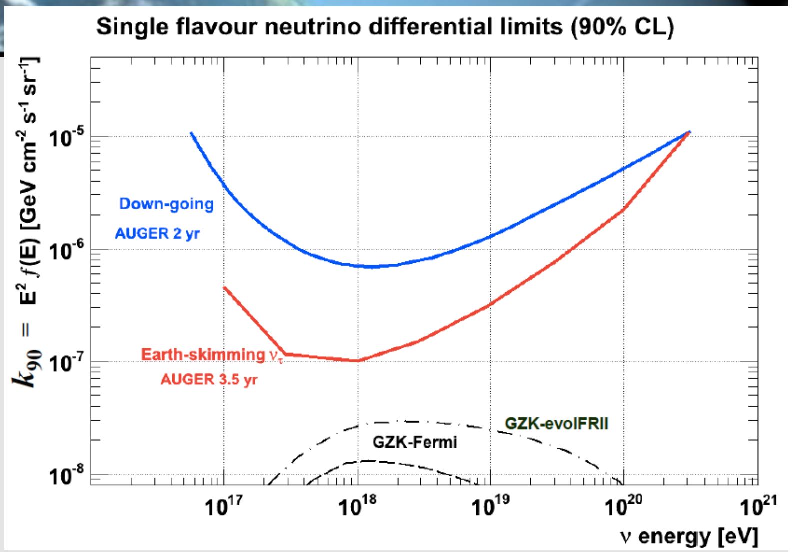


ANITA-III optimized for UHECR as well as ν will fly over Antarctica in 2013-14



Auger as a neutrino detector



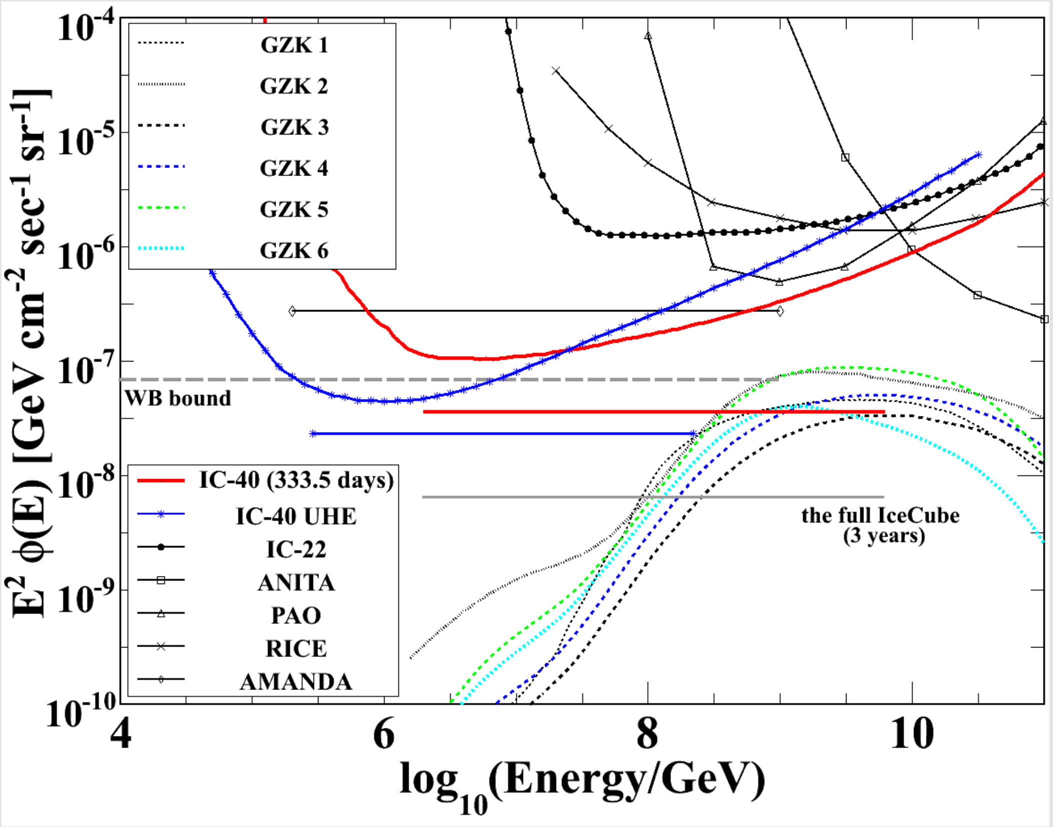


Late developing, horizontal air showers and Earth skimming $\nu_\tau \rightarrow \tau \rightarrow$ shower are signals for cosmogenic neutrinos in large air shower detectors

IceCube limits on cosmogenic ν

- GZK search looks for
  - very bright events
  - near the horizon
  - with compact initial burst of light
  - Complementary to diffuse ν_μ search that starts by measuring atmospheric ν_μ
  - Blue lines show results that include cascades
  - Model 6 (Fermi max): expect 0.4 events

IceCube-40 arXiv:1103.4250



All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Summary

- Pushing below Waxman-Bahcall "limit" in 100 TeV – 10 PeV range disfavors proton dominance of CR in 1 – 100 PeV range
- Expect rapid improvements in IceCube sensitivity to astrophysical ν:
  - IC59 + IC79 data currently in analysis
  - Include both cascade and track-like events
  - Full IceCube-86 operating since May 2011
- Need larger acceptance to measure cosmogenic neutrinos

Future projects

- Km3NeT: plan for multi-gigaton detector in Mediterranean
- Measure cosmogenic (GZK) neutrinos in EeV range
  - ARA (Askaryan Radio Array)
    - First test deployment next to IceCube in January, 2011
    - Further deployments planned for next season at South Pole
  - ARIANNA radio antennas on Ross Ice Shelf
- Beyond Deep Core for lower energy. Two stages:
  1. Lower threshold below 10 GeV for WIMP searches & oscillations
  2. Very dense instrumentation for proton decay
- Dark Matter Ice – two pilot scintillators deployed at 2500 m in IceCube holes in December, 2010
  - Seasonal variation of background opposite to DAMA,
  - Seasonal variation of DM signal universal