Very high energy γ and ν

Implications for UHECR

Neutral messengers of UHECR

- Photons and neutrinos
  - Photons: plentiful but complicated
    - Interactions in sources & in transit modify spectrum
    - Can be electromagnetic in origin or hadronic
  - Neutrinos: clean but rare
    - Hadronic origin
    - No interactions in sources
    - (few in detector)

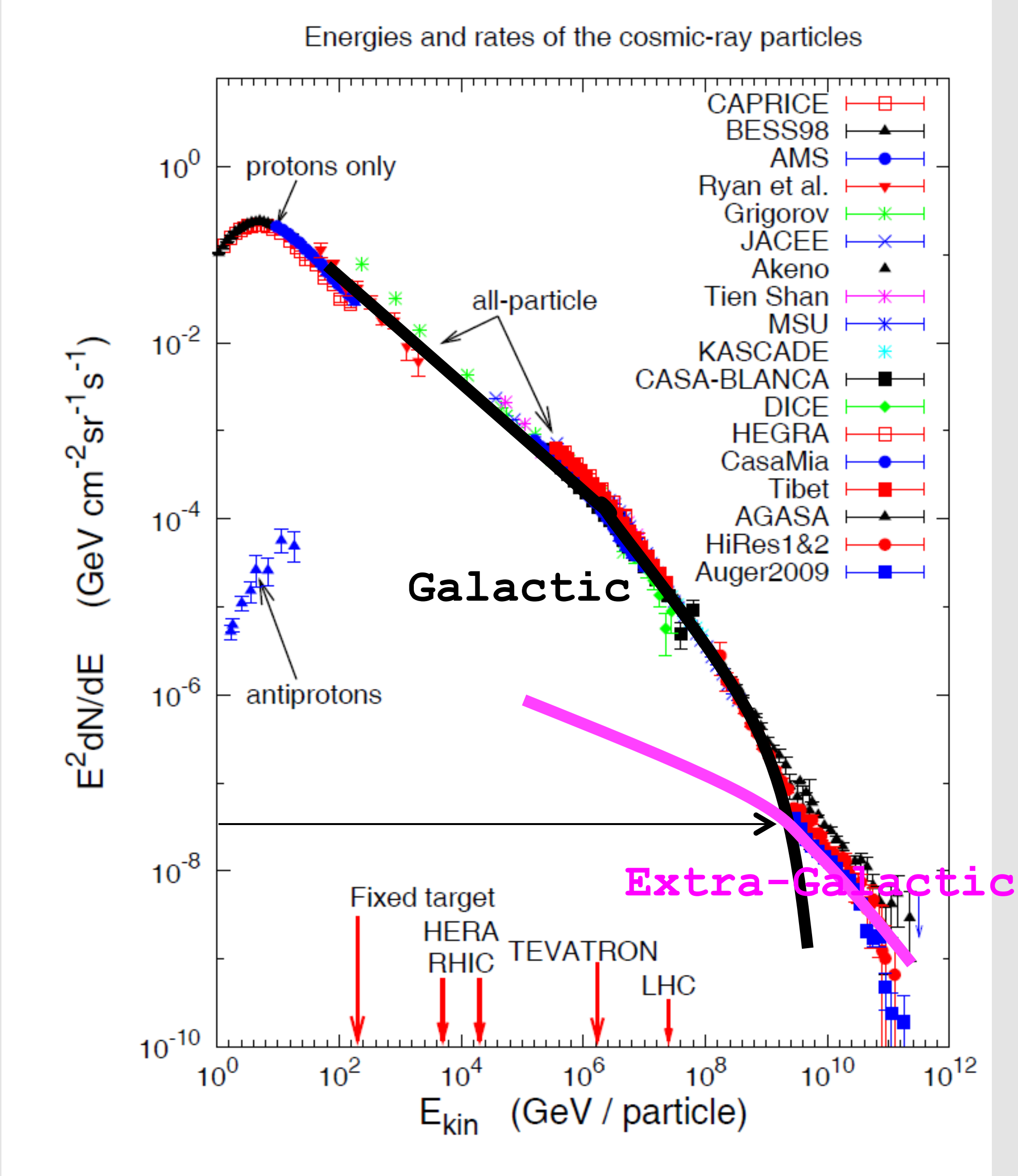
Two ways of producing γ & ν

1. At the sources of UHECR
   - Depends on details of accelerated spectrum
   - Depends on cosmic evolution of sources
   - Depends on conditions in/near the sources
2. During propagation
   - Depends on injected spectrum
     - As function of red shift and energy
   - But not on conditions at the sources

UHECR

- Energy content of UHECR determines possible sources
- Assume extra-galactic origin
- Location of transition from galactic to extra-galactic affects energy estimate
- Illustration:

$$E\frac{dN}{d\ln E} \approx 30\ eV\ cm^{-2}sr^{-1}s^{-1}$$



Power needed for extragalactic cosmic rays (assuming transition at the ankle)

- Energy in extra-galactic cosmic rays per *ln*(E):

$$\frac{4\pi}{c}\frac{EdN}{d\ln E} \approx 2 \times 10^{-20}\ erg\ cm^{-3}$$

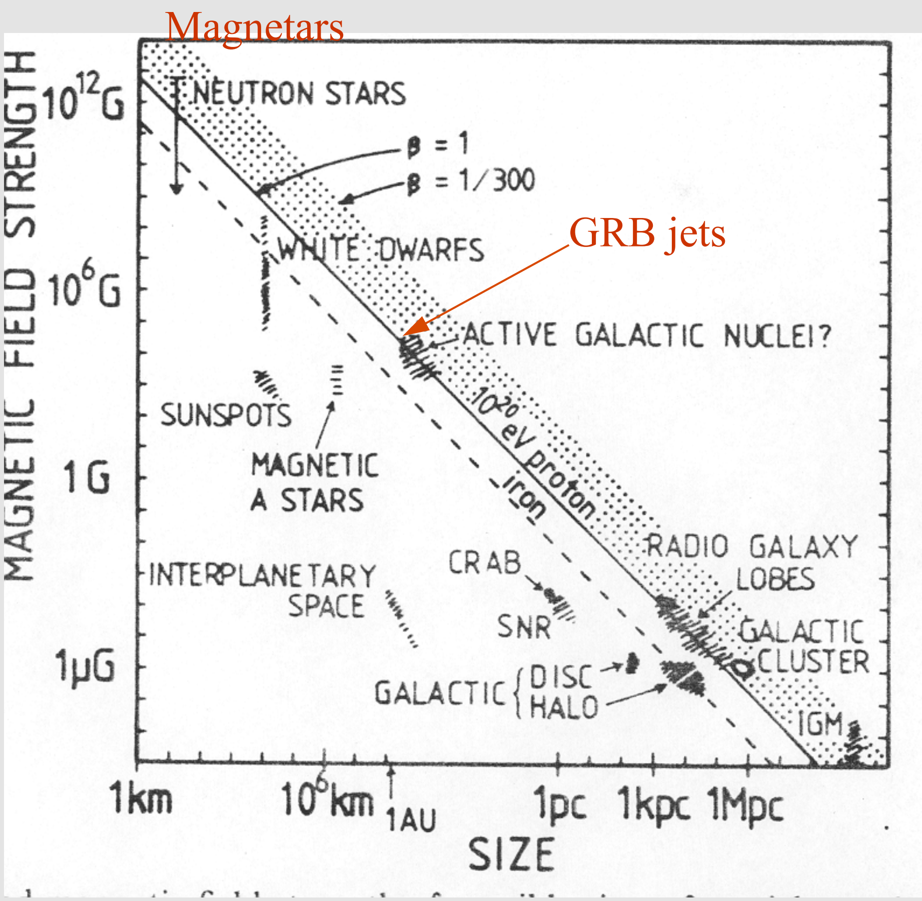
- Divide by Hubble time to estimate power required:

$$\frac{dL}{d\ln E} \approx 2 \times 10^{36}\ erg\ Mpc^{-3}s^{-1}$$

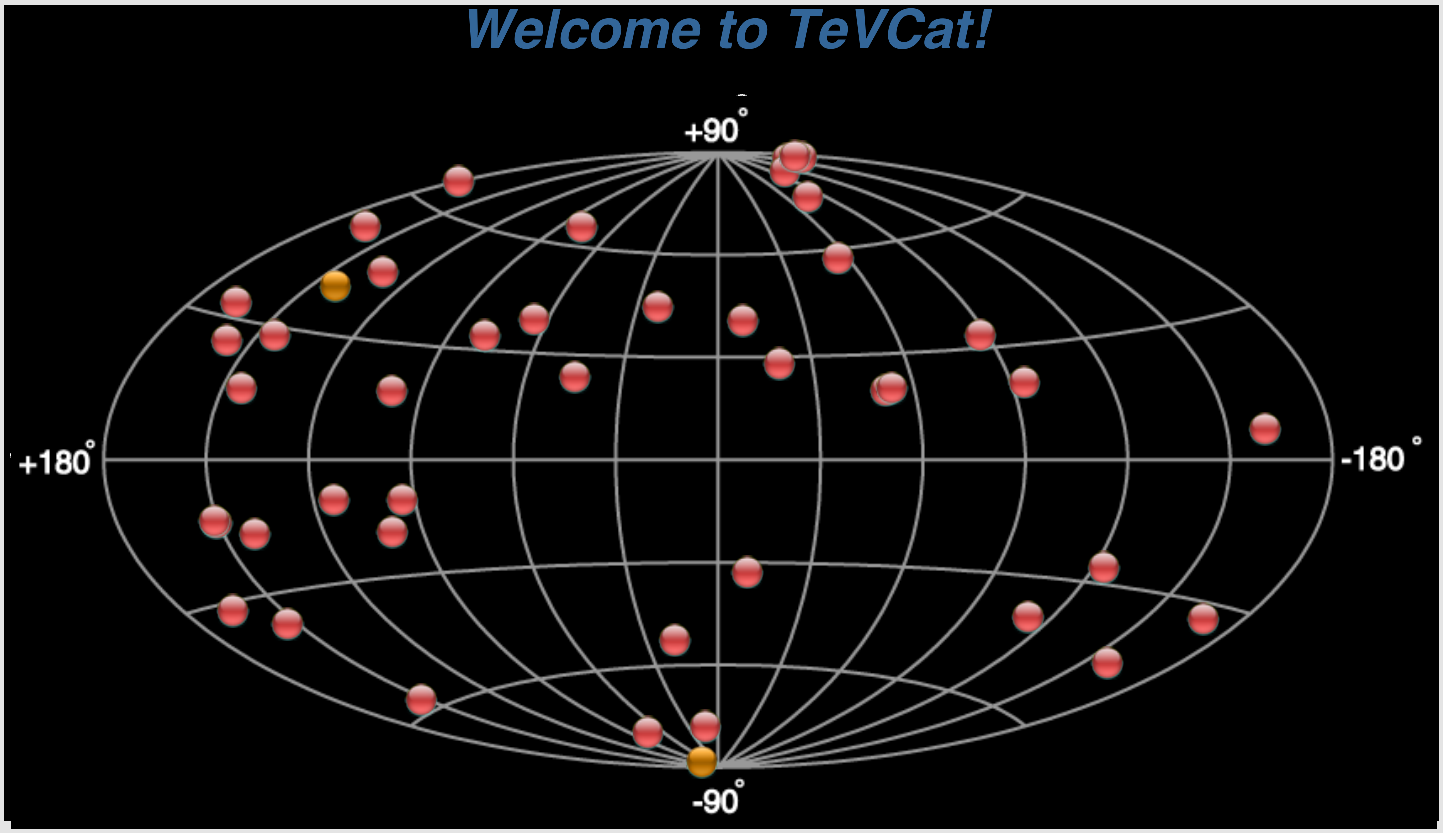
- Power required $\geq 10^{37}$ erg/Mpc^3/s
  - Estimates depend on cosmology + extragalactic magnetic fields:
  - 3×10^{-3} galaxies/Mpc^3 — 5×10^{39} erg/s/Galaxy
  - 3×10^{-6} clusters/Mpc^3 — 4×10^{42} erg/s/Galaxy Cluster
  - 10^{-7} AGN/Mpc^3 — 10^{44} erg/s/AGN
  - ~1000 GRB/yr — 3×10^{52} erg/GRB

E_{max}: the "Hillas Plot" (1984)

- $E_{max} \sim \beta_{shock}$ (ZeB) R
- Plot shows B, R to reach 10^{20} eV
- Since 1984, two more candidates
  - GRB and magnetars
- AGN and GRB favored



External galaxies observed in TeV γ



Galactic coordinates;
red dots=active galaxies; orange=starburst galaxies (M82, NGC253)

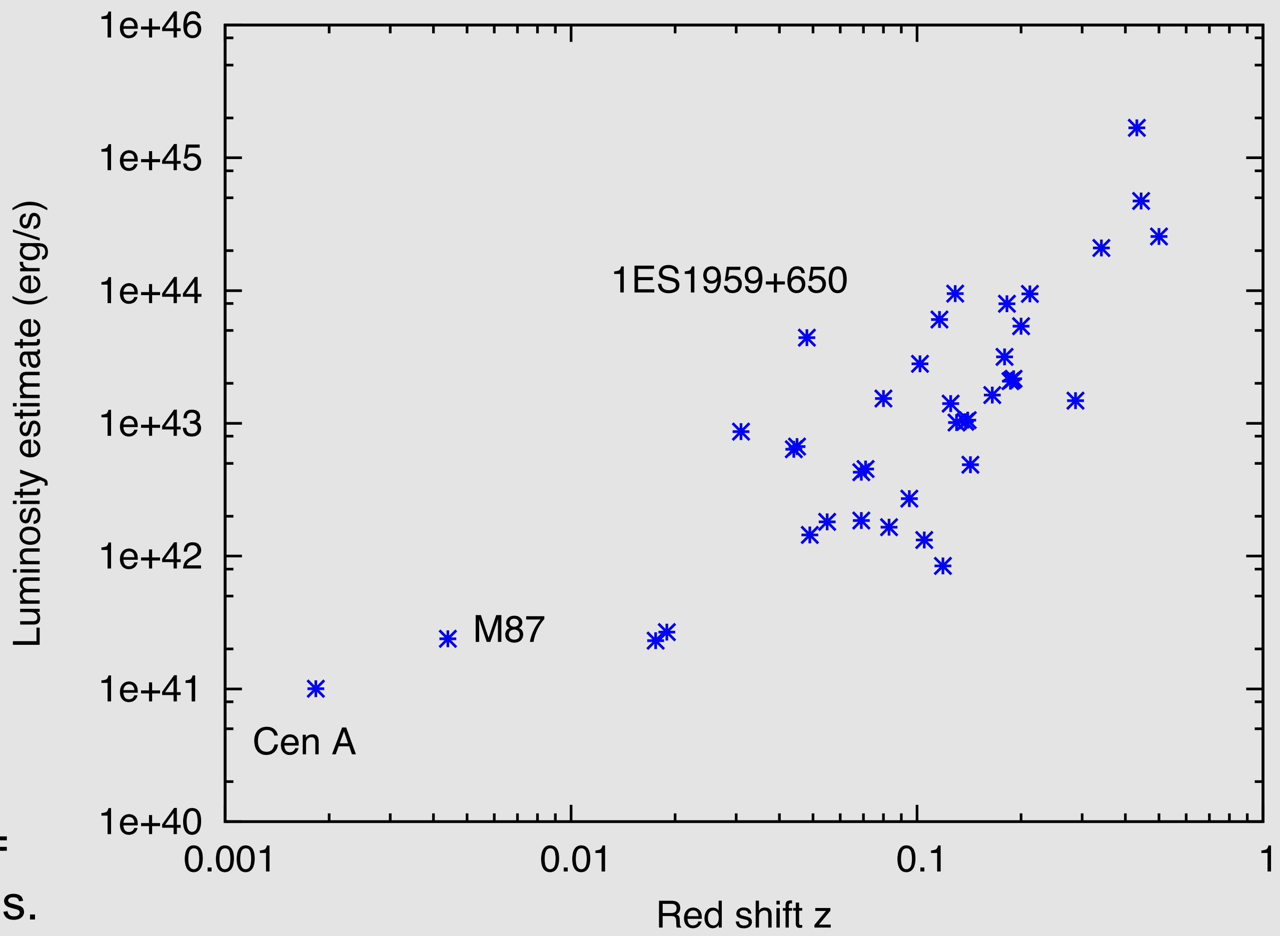
Active galaxies with > 0.1 TeV γ

39 sources from TeVCat with luminosity & z.

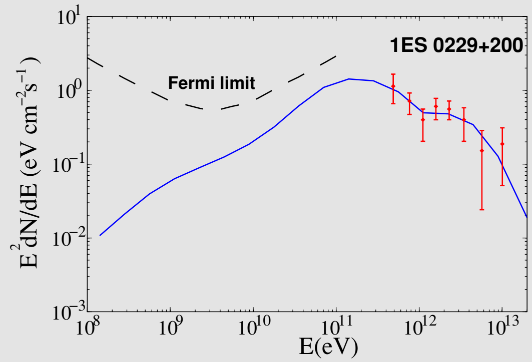
Estimate L by assuming equal γ energy per decade 1 – 1000 GeV

For blazars, $L \sim d^2$
For Cen A, M87, $L \sim 4\pi d^2$

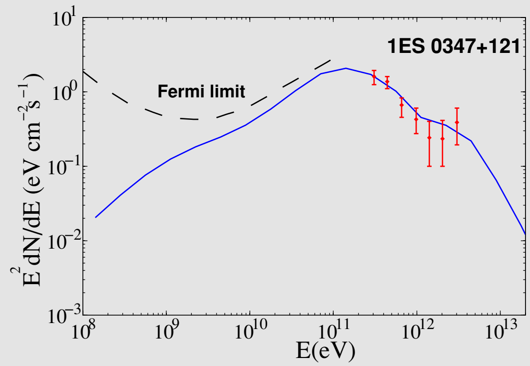
Note: 1ES1959+650 estimated for high state = 3.5 x recent VERITAS obs.



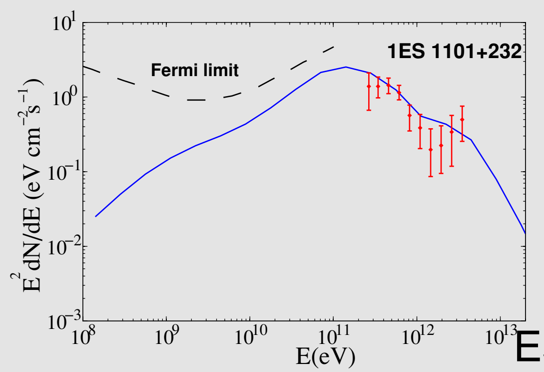
Locally produced TeV γ from 3 blazars at z = 0.14 to 0.19



(a)

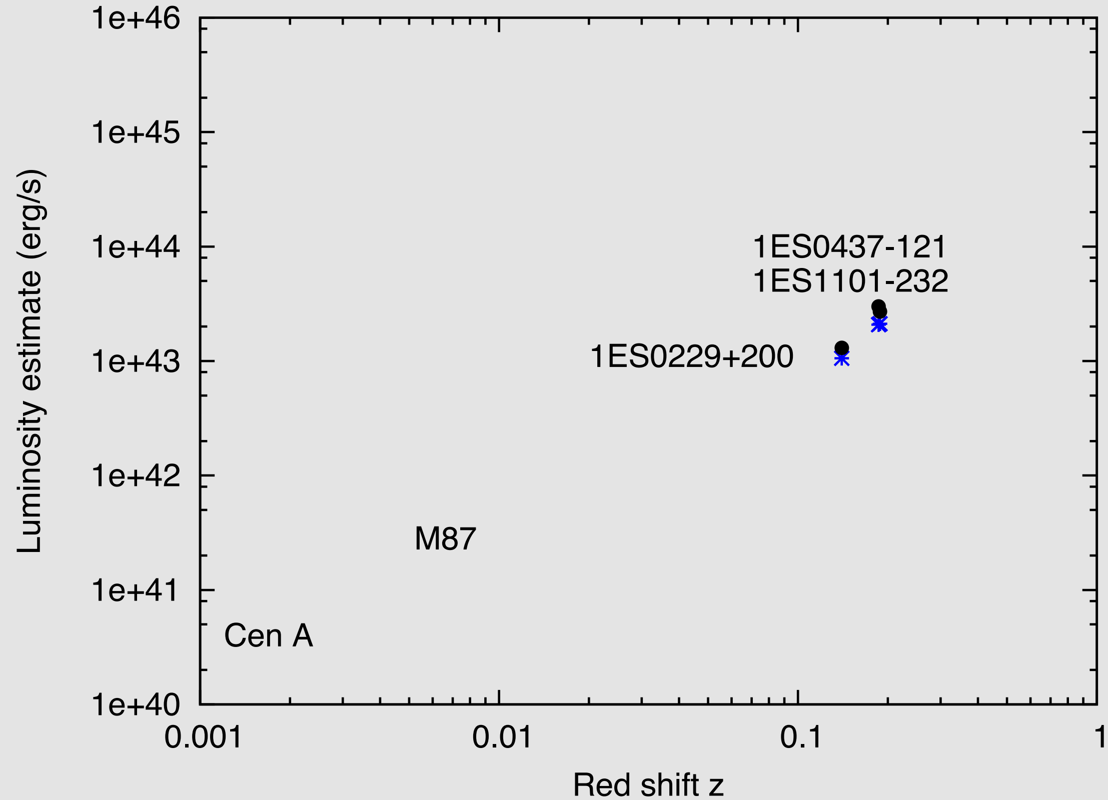


(c)



(e)

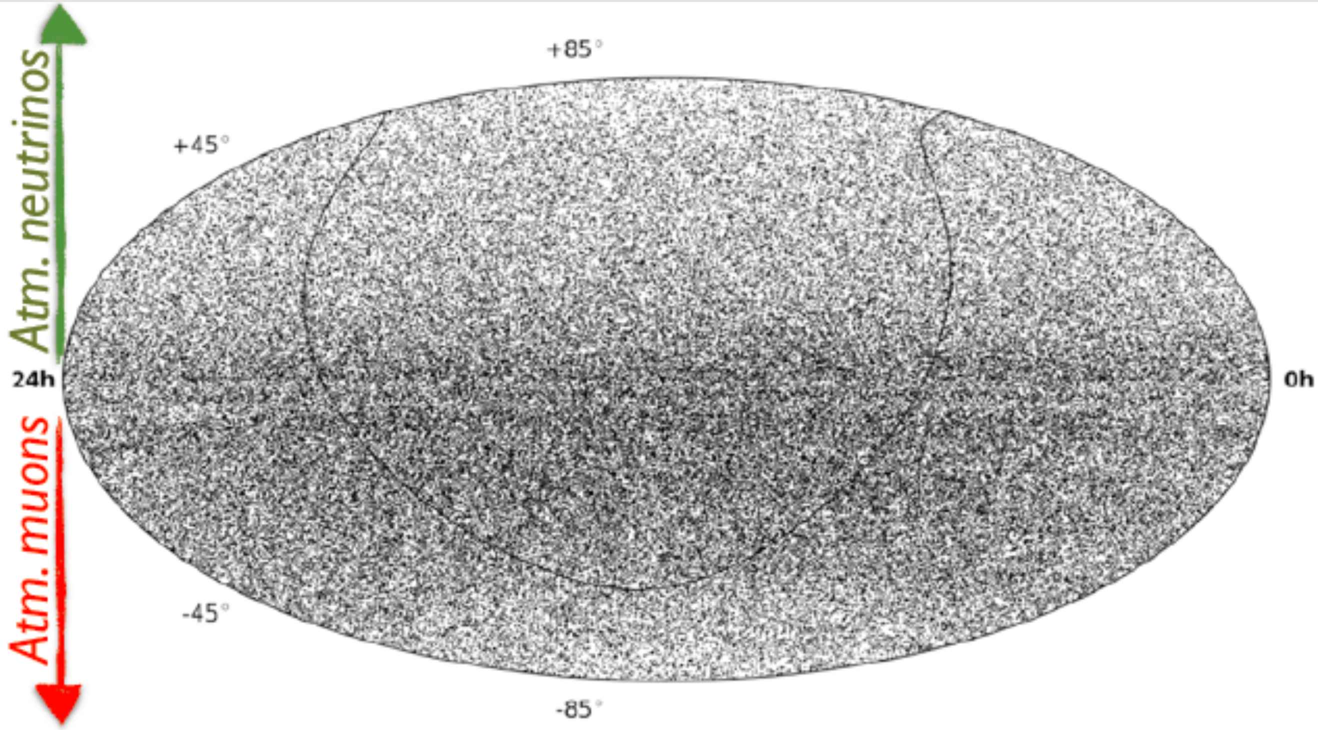
> TeV γ from source cascade on EBL; protons produce γ en-route from source. Requires low B.

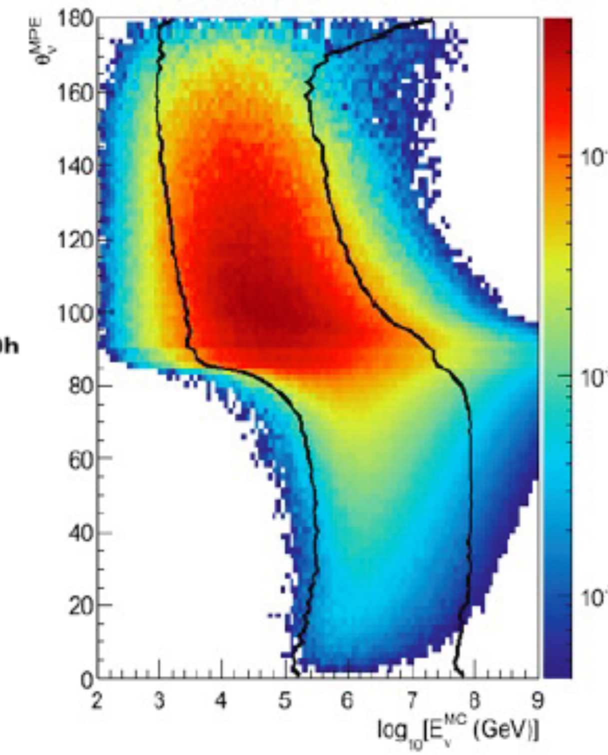


Essey, Kalashev, Kusenko & Beacom Ap. J. 731:51 (2011)

See also Razzaque, Dermer, Fiske, arXiv:1110.0853

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

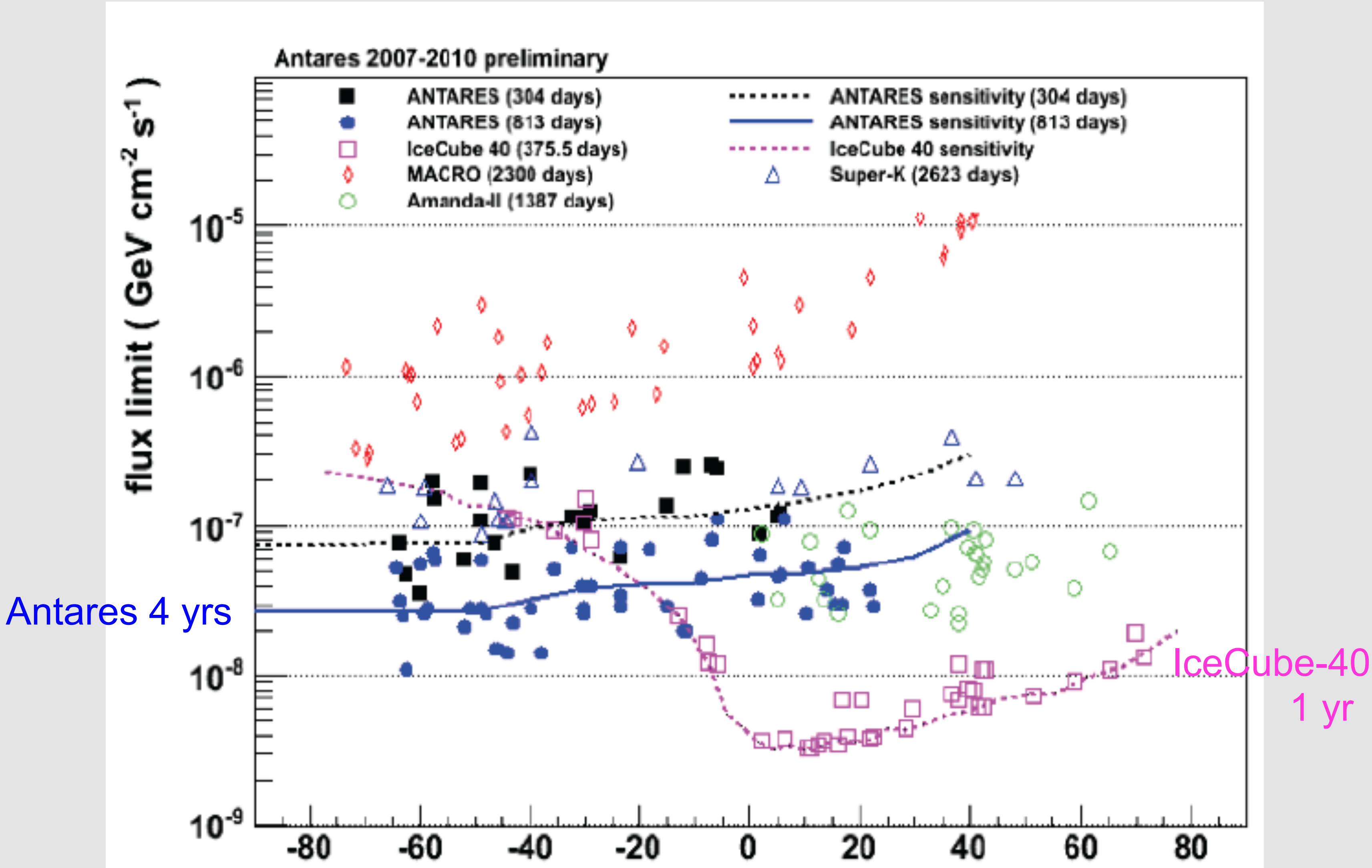
IceCube selected sources

(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	Starbust	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

Searches for selected sources



Compare IC-40 limits

Neutrino luminosity estimate for blazars:

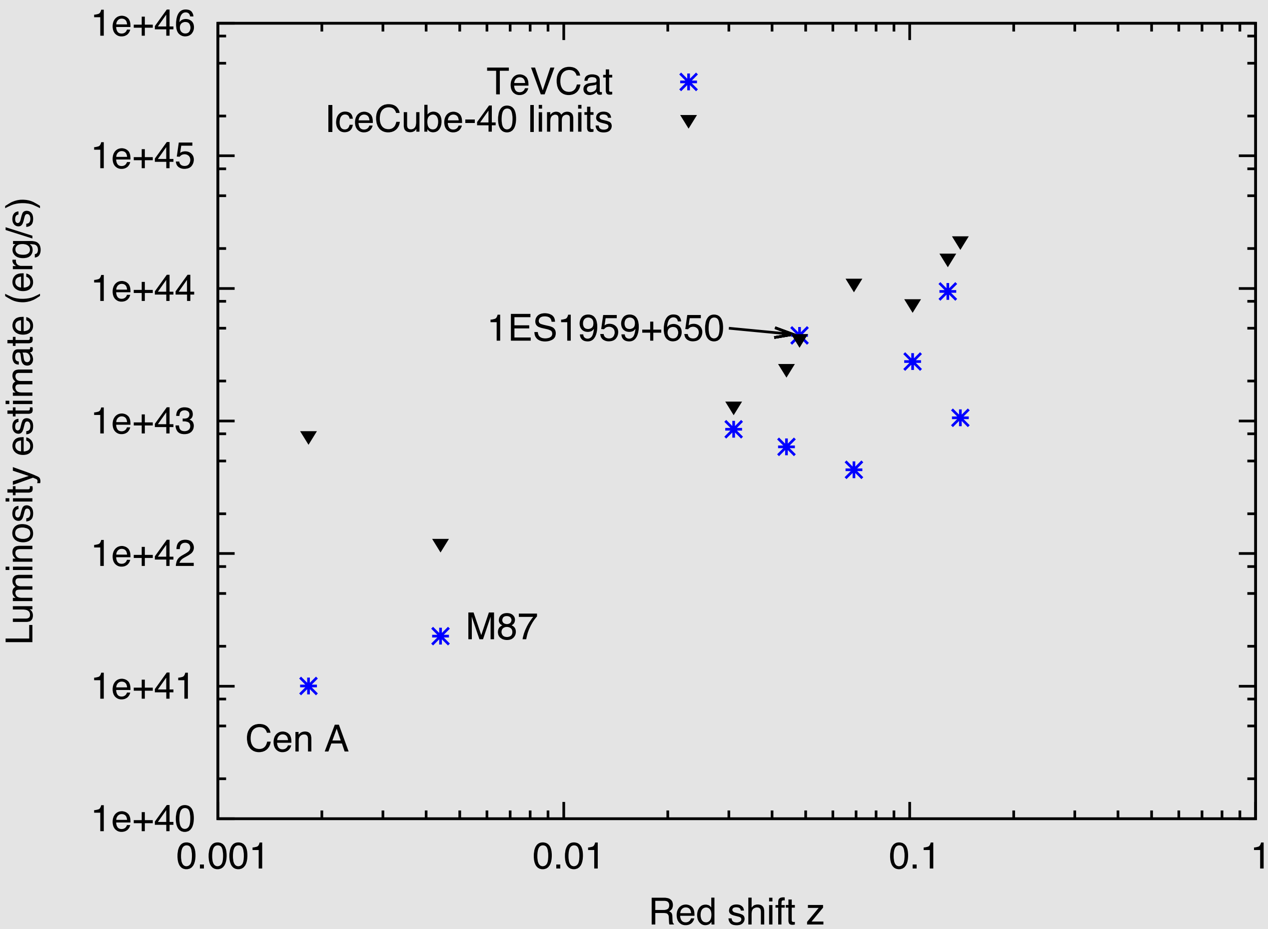
assume E^{-2} spectrum integrated over 3 decades

$$L_\nu \approx d^2 \int \frac{dE_\nu}{d\ln(E_\nu)} dE$$

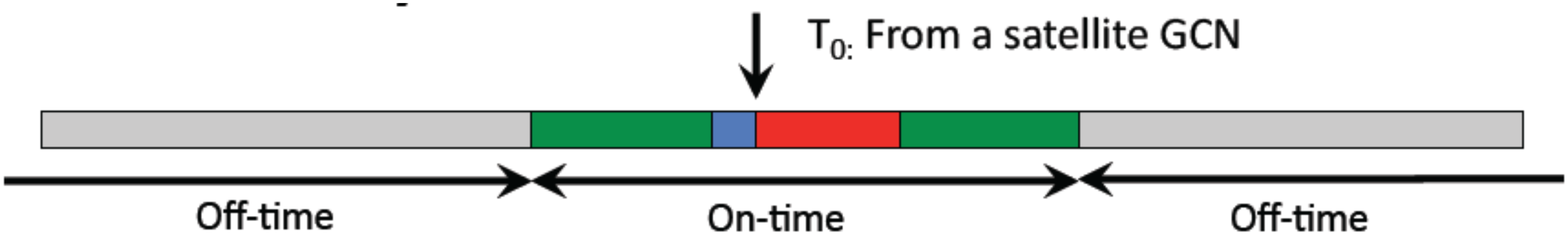
(x 4π for M87, Cen A)

Note: Cen A is overhead for IceCube

Starburst galaxy M82:
VERITAS: $L_\gamma \sim 3 \times 10^{39}$ erg/s
IceCube neutrino limit:
$L_\nu < 2 \times 10^{41}$ erg/s



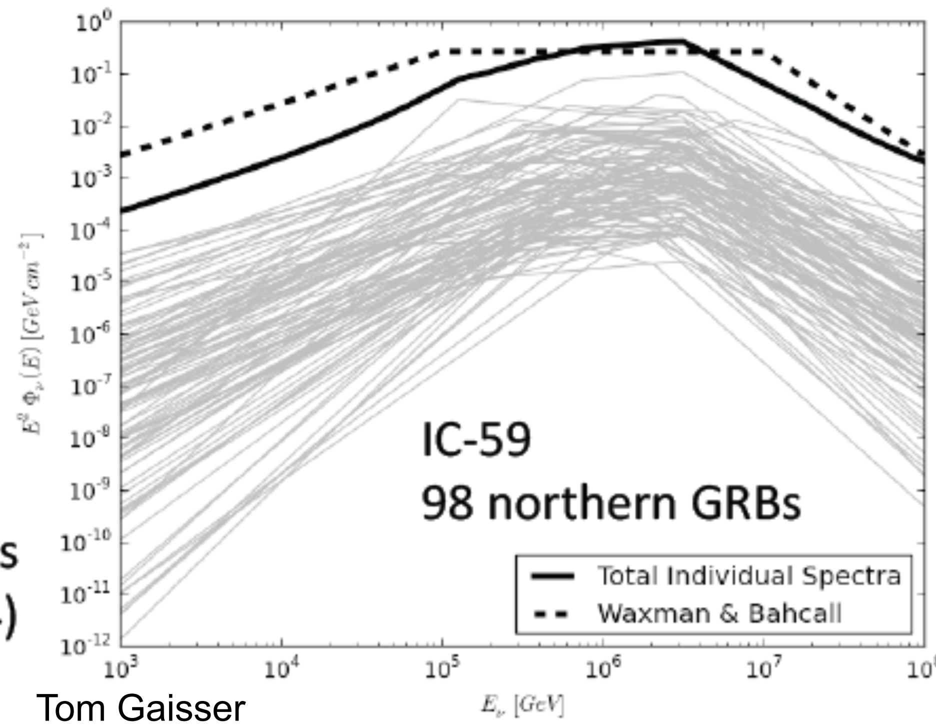
Search for neutrinos from GRB



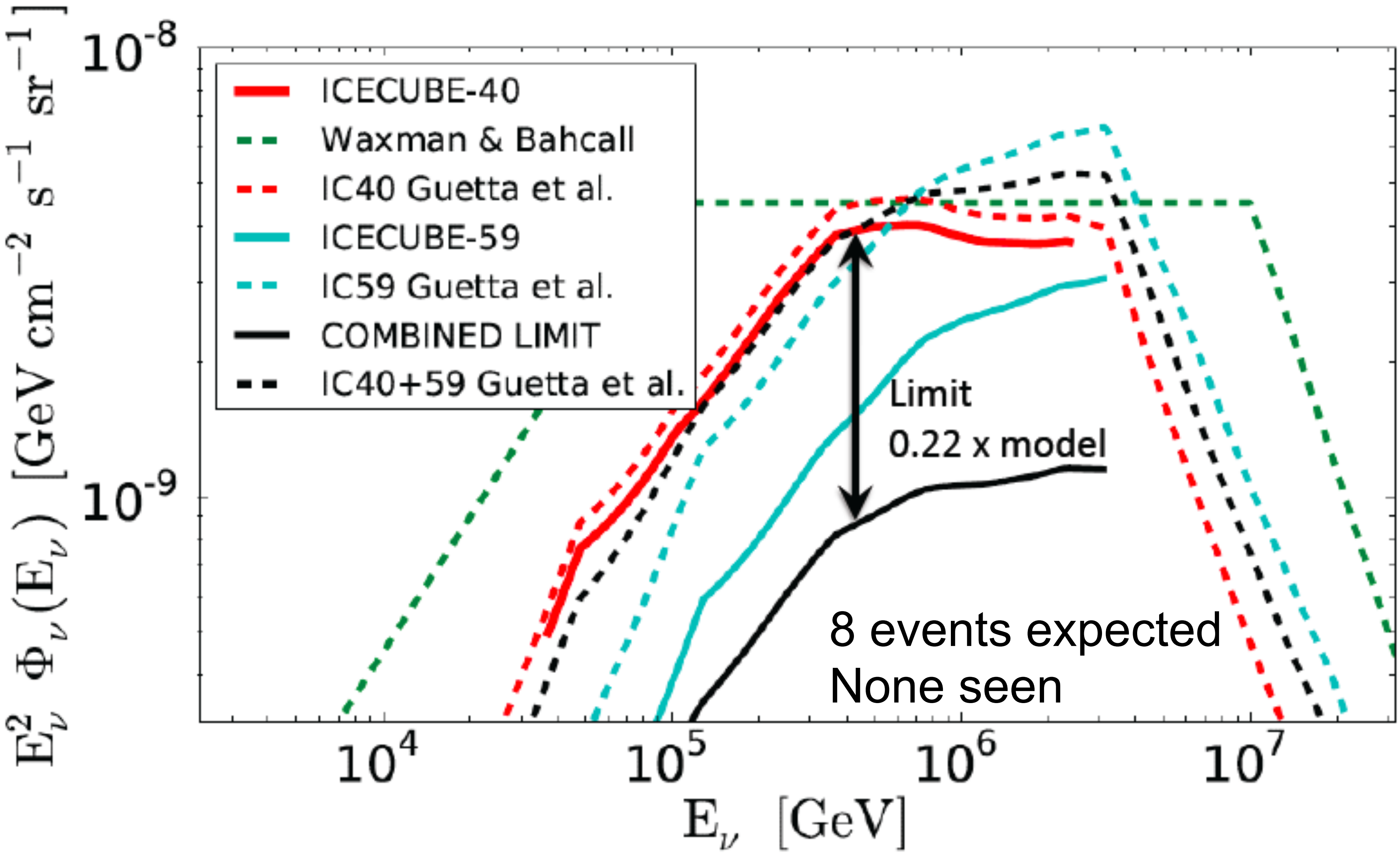
- Precursor (~100 s)
- Prompt
- Model Independent (24 h)
- Background (full year)

Very low background
One event can be significant

Individual modeling of GRBs
(Guetta et al. 2004)



Model Dependent IC-40 / IC-59 result



Search for diffuse flux of ν

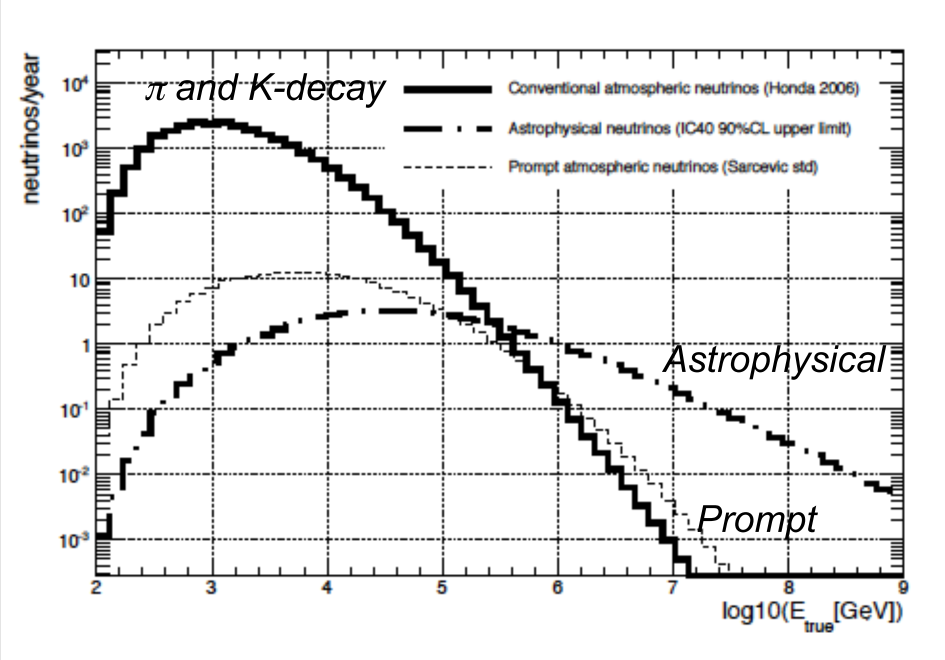
- Neutrinos are not absorbed. Therefore

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
    - ~ $\cos^{-1}(\theta)$
  - Prompt ν (10 – 600 TeV)
    - Harder spectrum to > 10^7 GeV (~$E^{-2.7}$), isotropic
  - Astrophysical ν
    - Isotropic, with E^{-2} spectrum assumed (35 – 7000 TeV)
  - Note different response for astro. ν *vs* atmos. ν



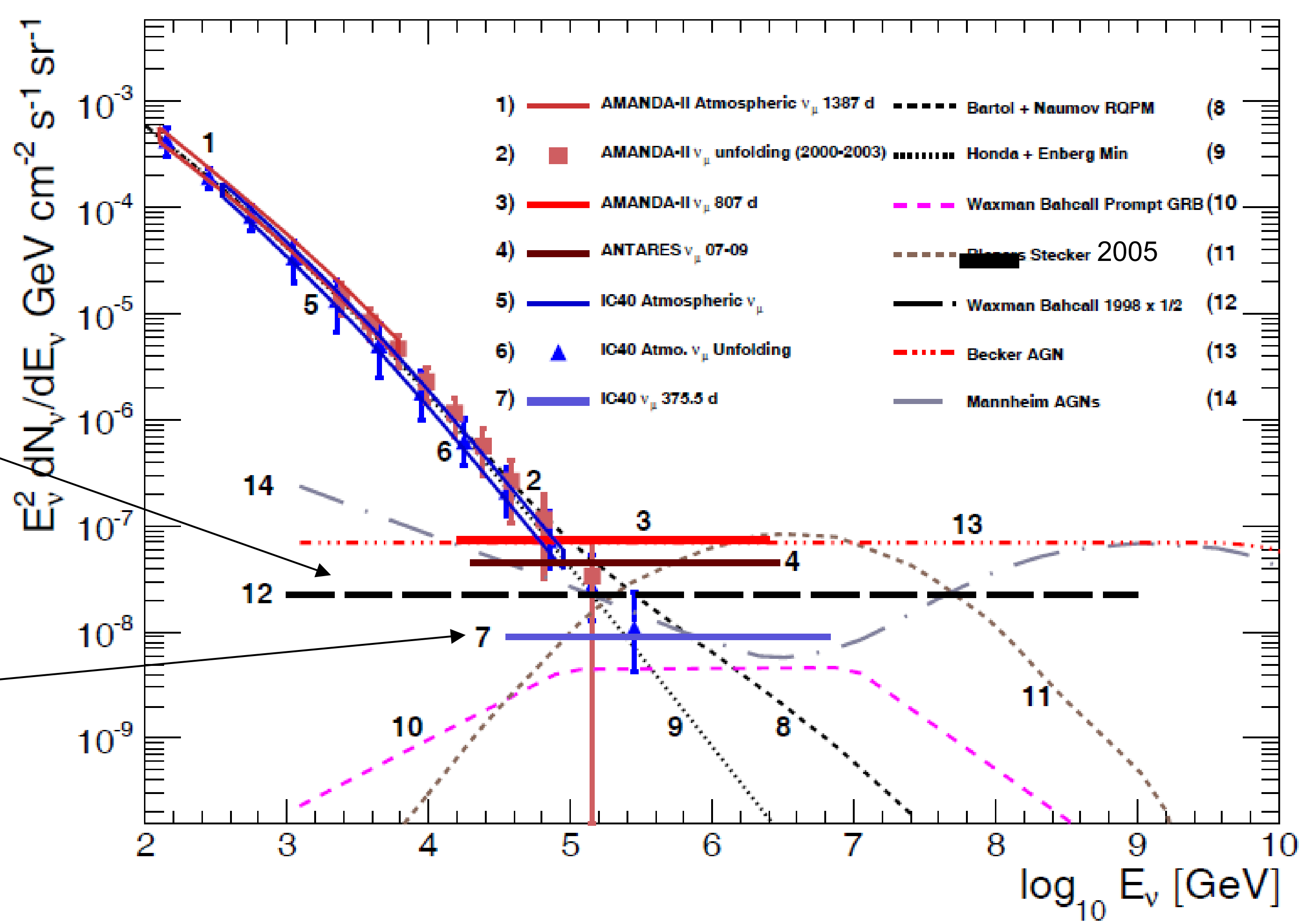
Result of fit:

- *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

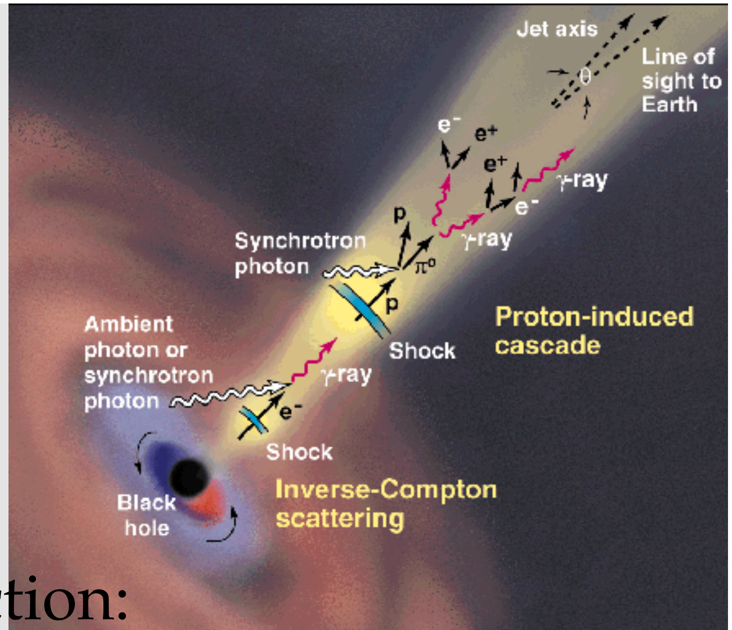
IceCube 40
arXiv:1104.5187



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

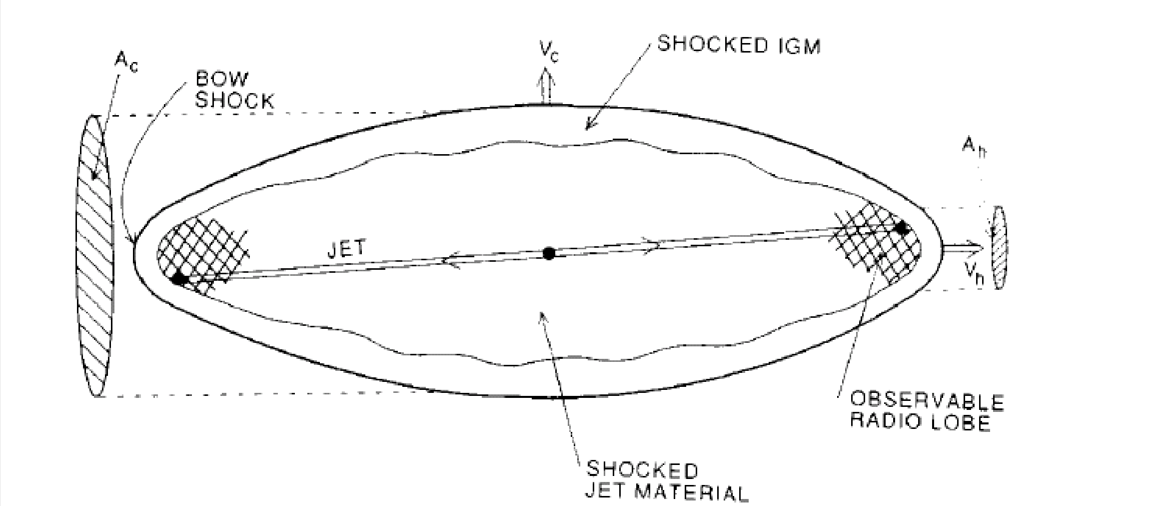
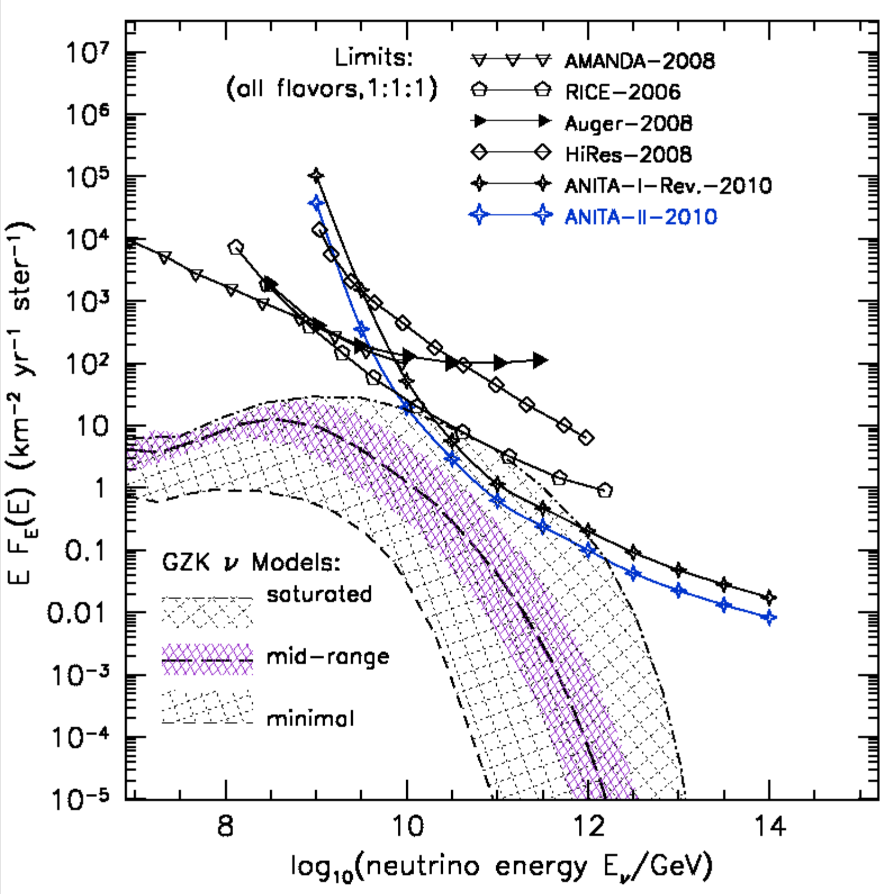


Diagram from Begelman & Cioffi, Ap.J. (1989) L21

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

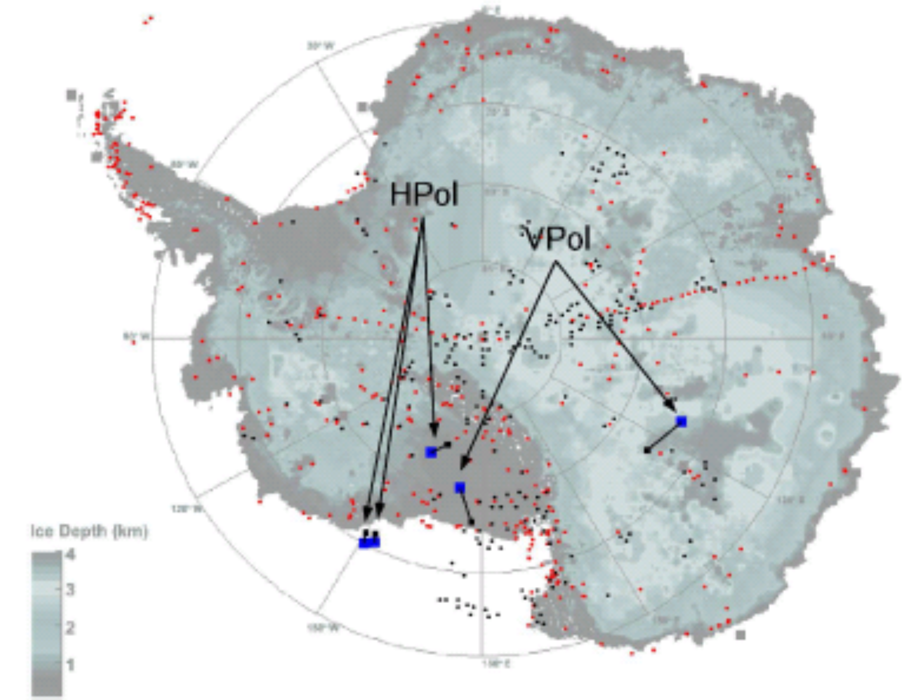
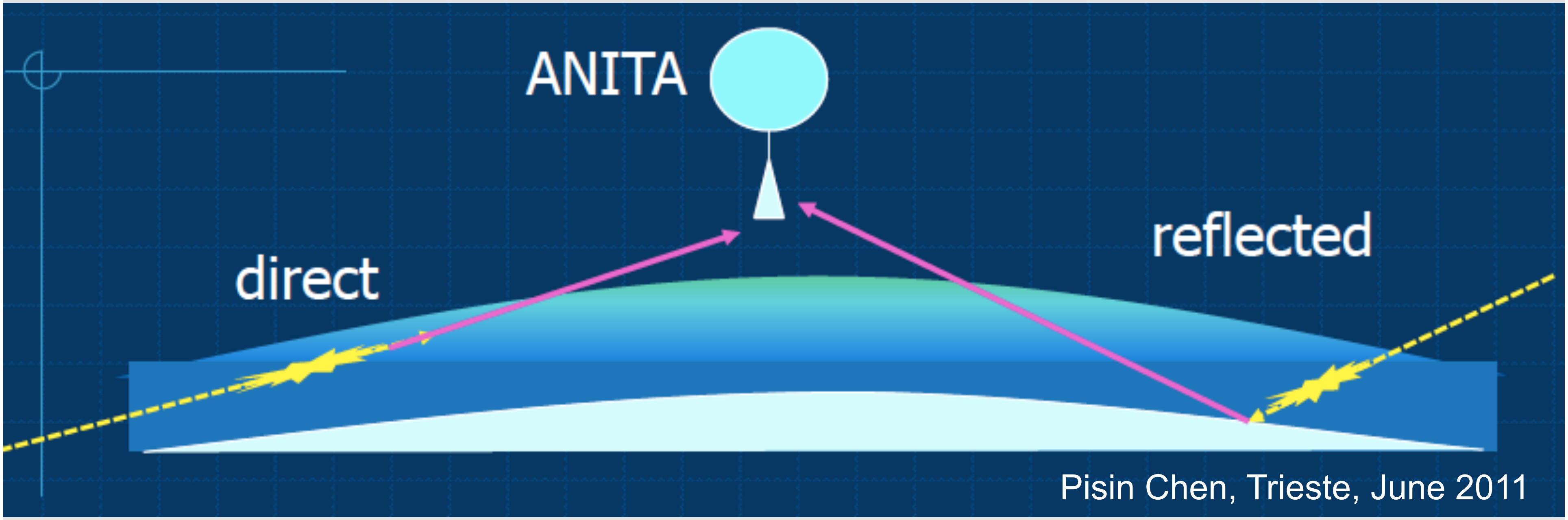


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

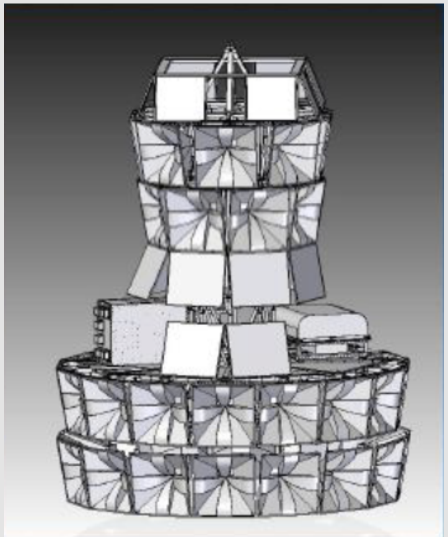
http://arxiv.org/abs/1003.2961

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

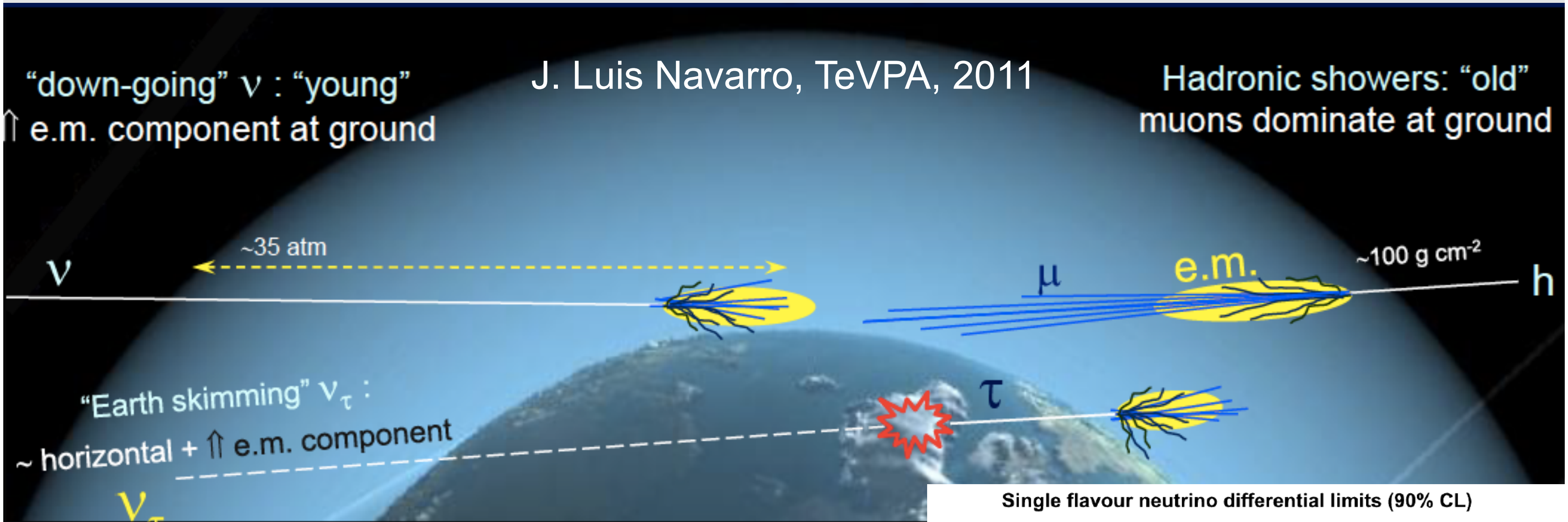
ANITA also detects ~10^{19} eV CR

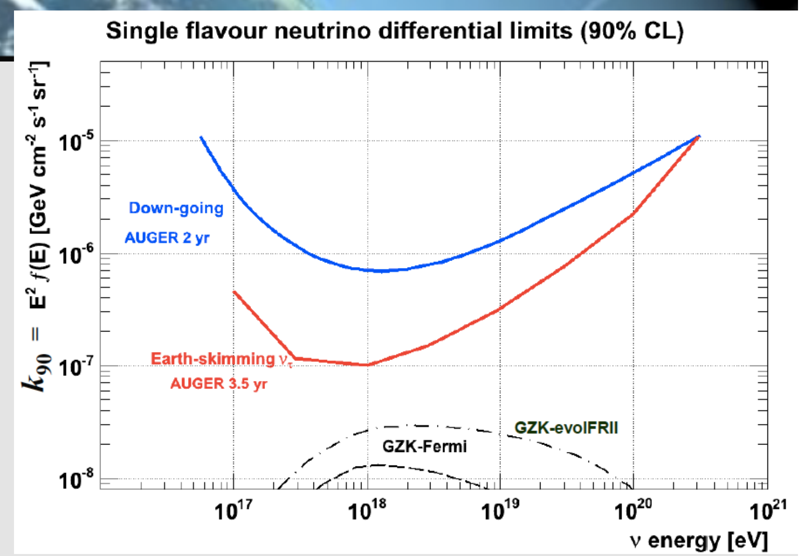


ANITA-III optimized for UHECR as well as ν will fly over Antarctica in 2013-14



Auger as a neutrino detector



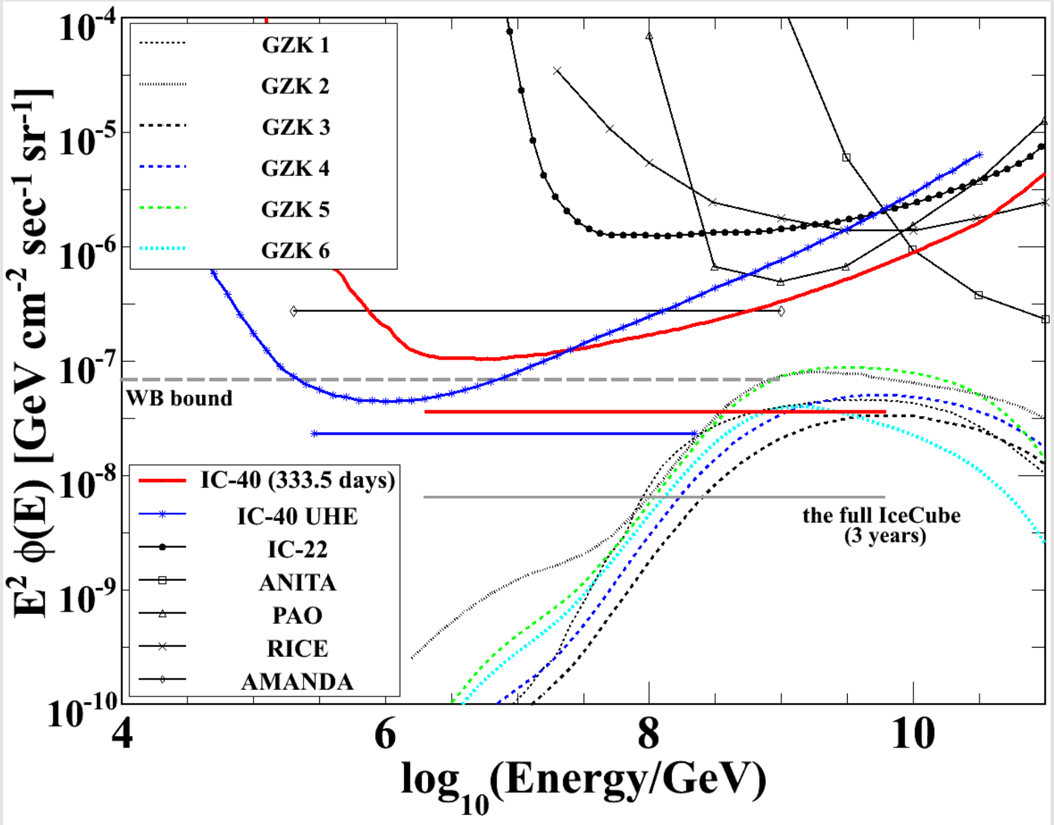


Late developing, horizontal air showers and Earth skimming $\nu_\tau \rightarrow \tau \rightarrow$ shower are signals for cosmogenic neutrinos in large air shower detectors
Expect 0.71 events in 3.5 yrs (ICRC 2011)

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

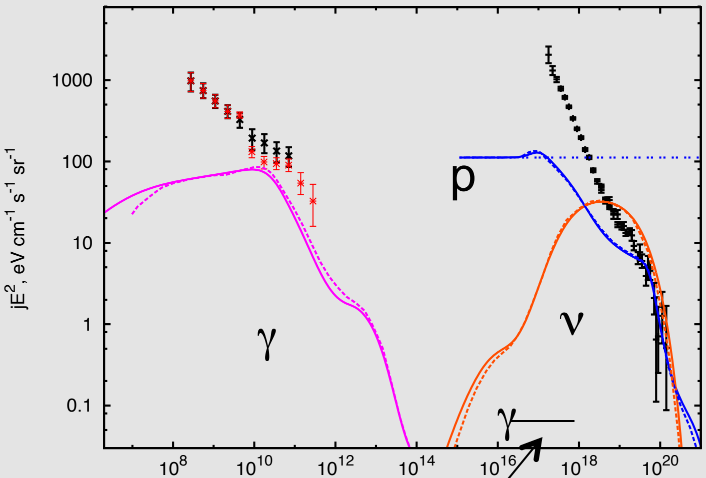
IceCube-40 arXiv:1103.4250

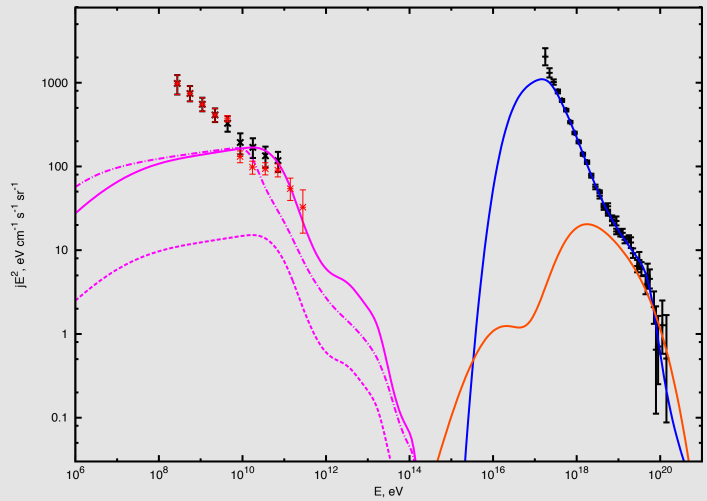


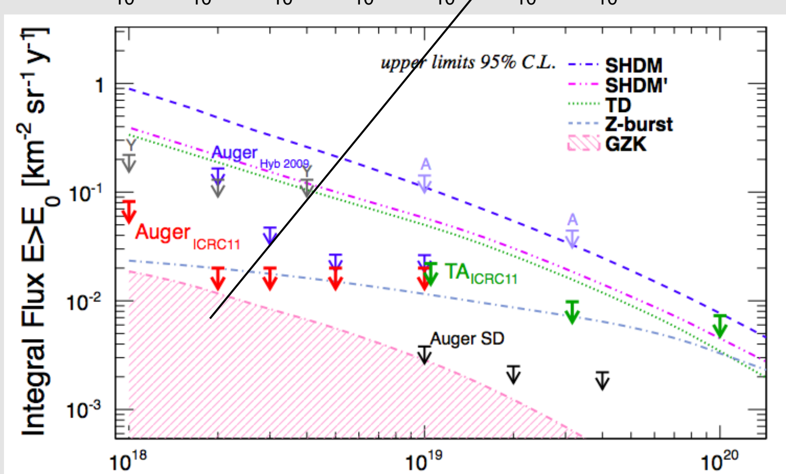
All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Cosmogenic photons

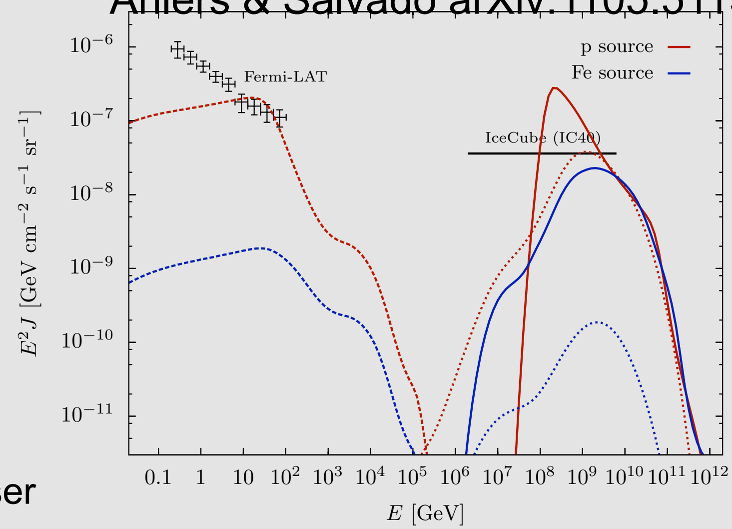
Two model calculations from Gelmini, Kalashev, Semikoz arXiv:1107.1672







Ahlers & Salvado arXiv:1105.5113



Gelmini et al., 2007

What if E_{max}/nucleon < 100 EeV?

"Disappointing model"

Aloisio, Berezinsky, Gazizov
Astropart. Phys. 34 (2011) 620.

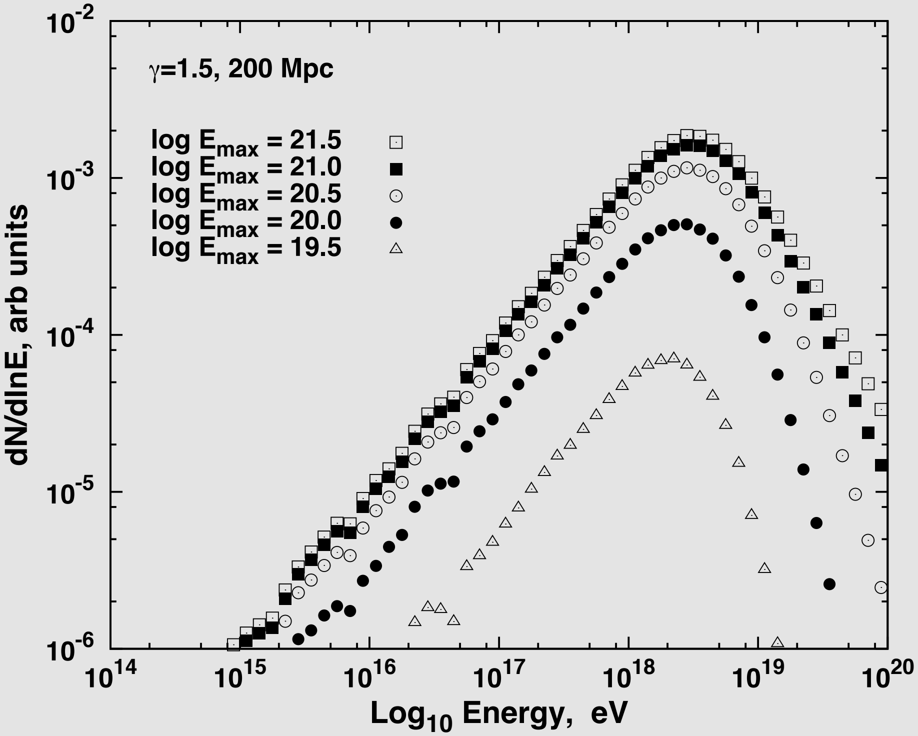


Figure 5: Muon neutrinos and antineutrinos generated in propagation of protons on 200 Mpc for different values of the maximum proton energy at acceleration.

Plot by Todor Stanev (T. Gaisser & T. Stanev, arXiv:1202.0310)

Summary

- Current neutrino limits begin to disfavor UHECR origin inside relativistic jets
  - Discovery or improved limits coming
  - IC59 + IC79 data currently in analysis
  - Full IceCube-86 operating since May 2011
- Is the cutoff the GZK effect?
  - Need to measure cosmogenic neutrinos
  - Or decrease current limit by factor of ten
  - ARA, ARIANNA, Auger next