Neutrino Astronomy and IceCube

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for the IceCube Collaboration

Cen A
radio/optical

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Contents

- *The UHECR-Gamma-Neutrino connection*
- *IceCube and ANTARES results for diffuse fluxes and point sources*
- *Cosmic ray anysotropies*

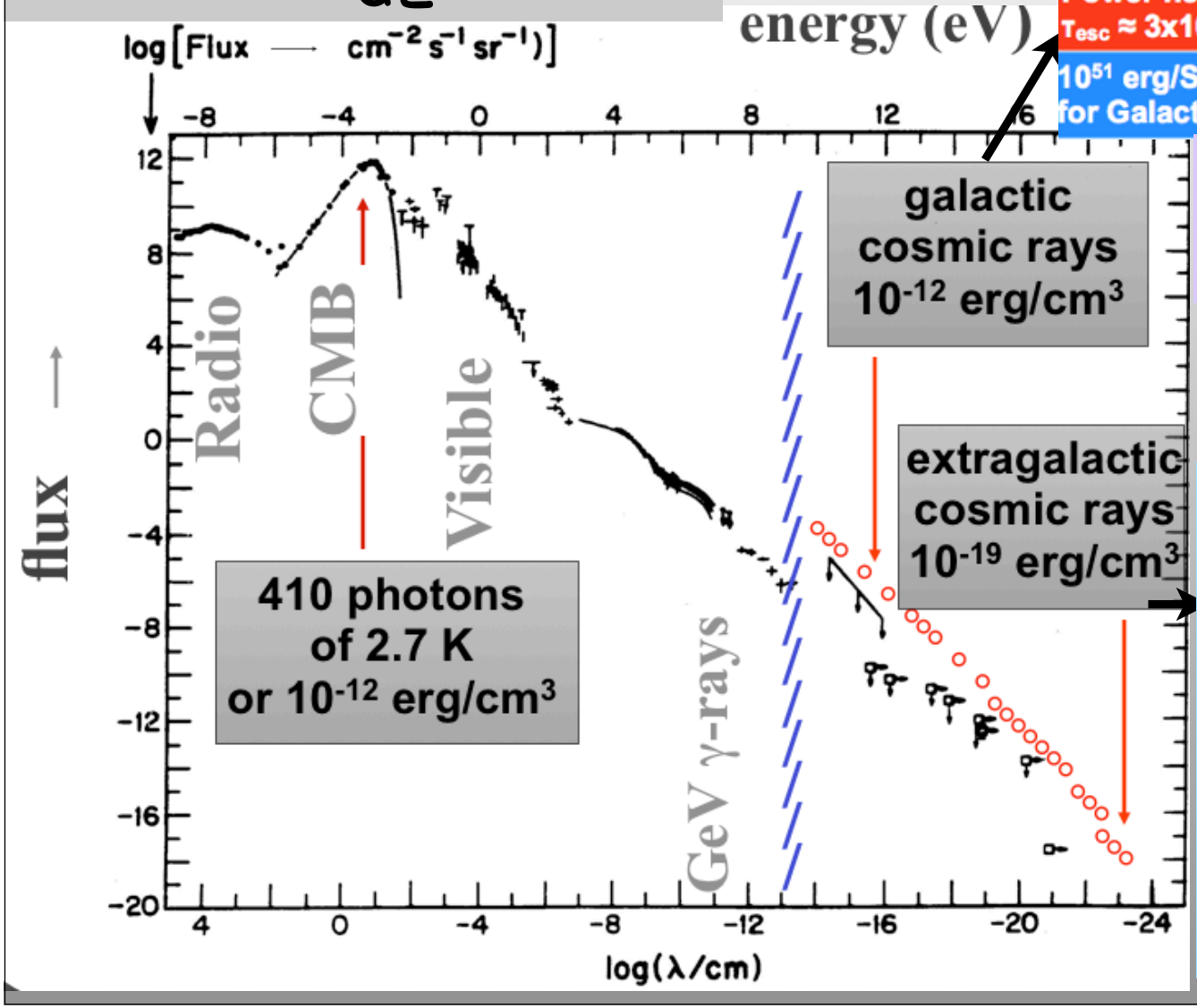
UHECRs $\lesssim$50 Mpc for E $\gtrsim 10^{20}$ eV

neutrinos

gammas $\gtrsim$10 Mpc for E$\lesssim$100 TeV

energy density flux = velocity x density

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



Power needed: $\rho_E / \tau_{esc} \approx 10^{-26}$ erg/cm^{3}s
$\tau_{esc} \approx 3 \times 10^6$ yrs escape time from Galaxy

10^{51} erg/SN every 30 years ~10^{-25} erg/cm^3 s for Galactic disk volume ~10^{67} cm^3

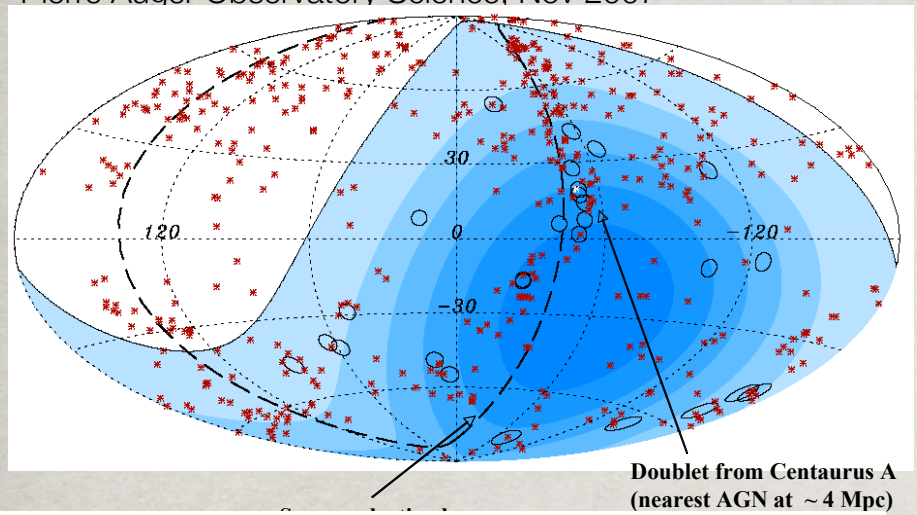
10% of 10^{51} erg SN (3/century in the Galaxy)

Power needed by a population of sources with E^{-2} to generate this energy density over the Hubble time is $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}

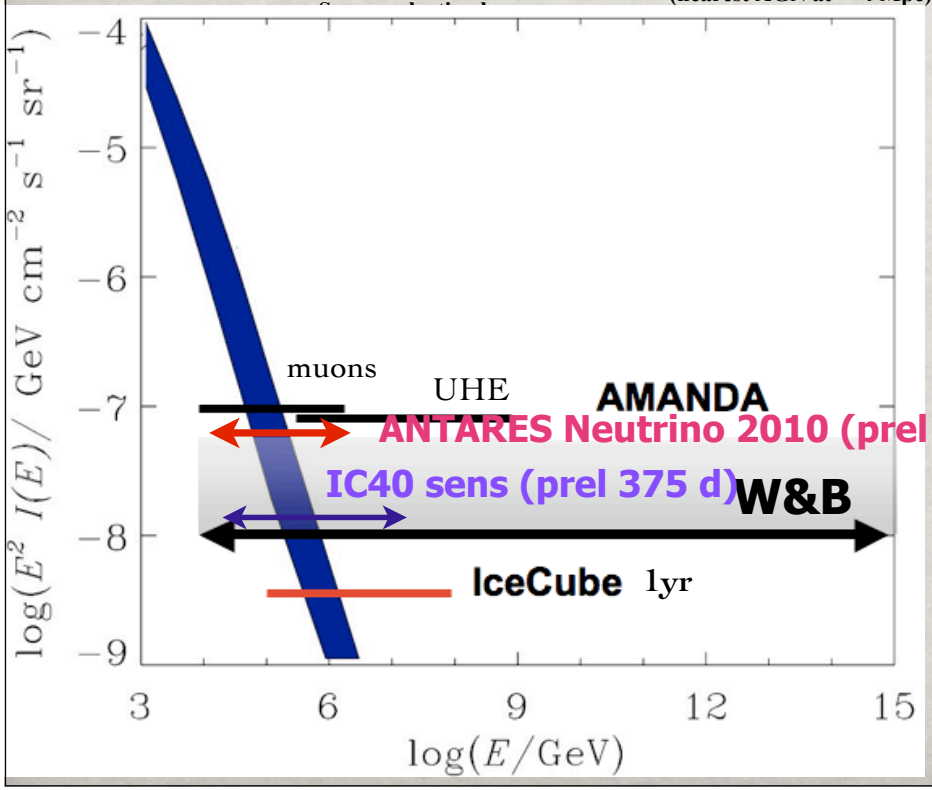
3×19^{39} erg/s per galaxy
3×10^{42} erg/s per cluster of galaxies
2×10^{44} erg/s per AGN
2×10^{52} erg per cosmological GRB.

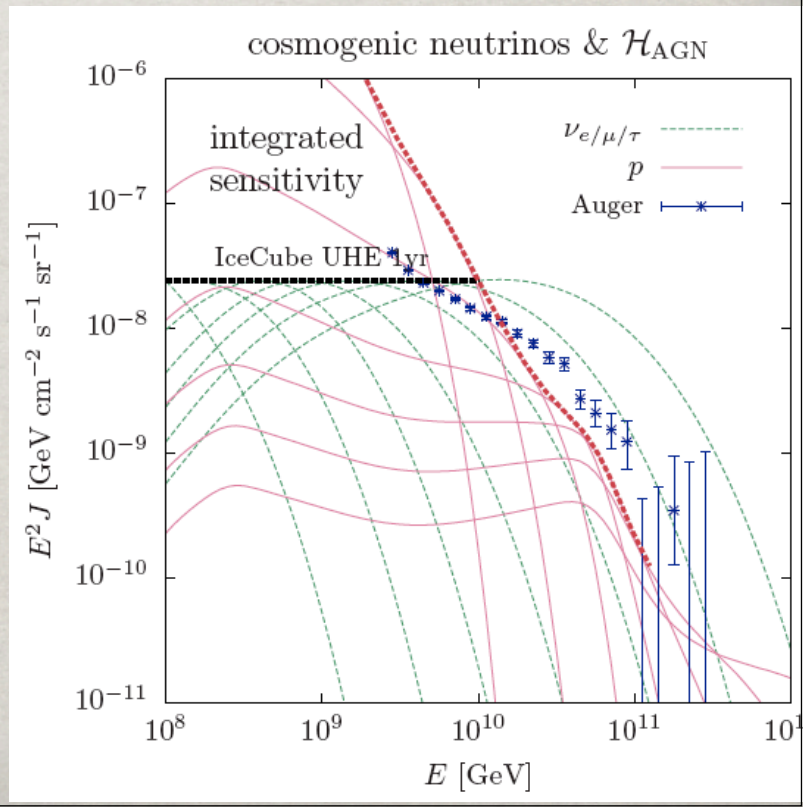
Neutrino - Pierre-Auger UHECR

Pierre Auger Observatory Science, Nov 2007



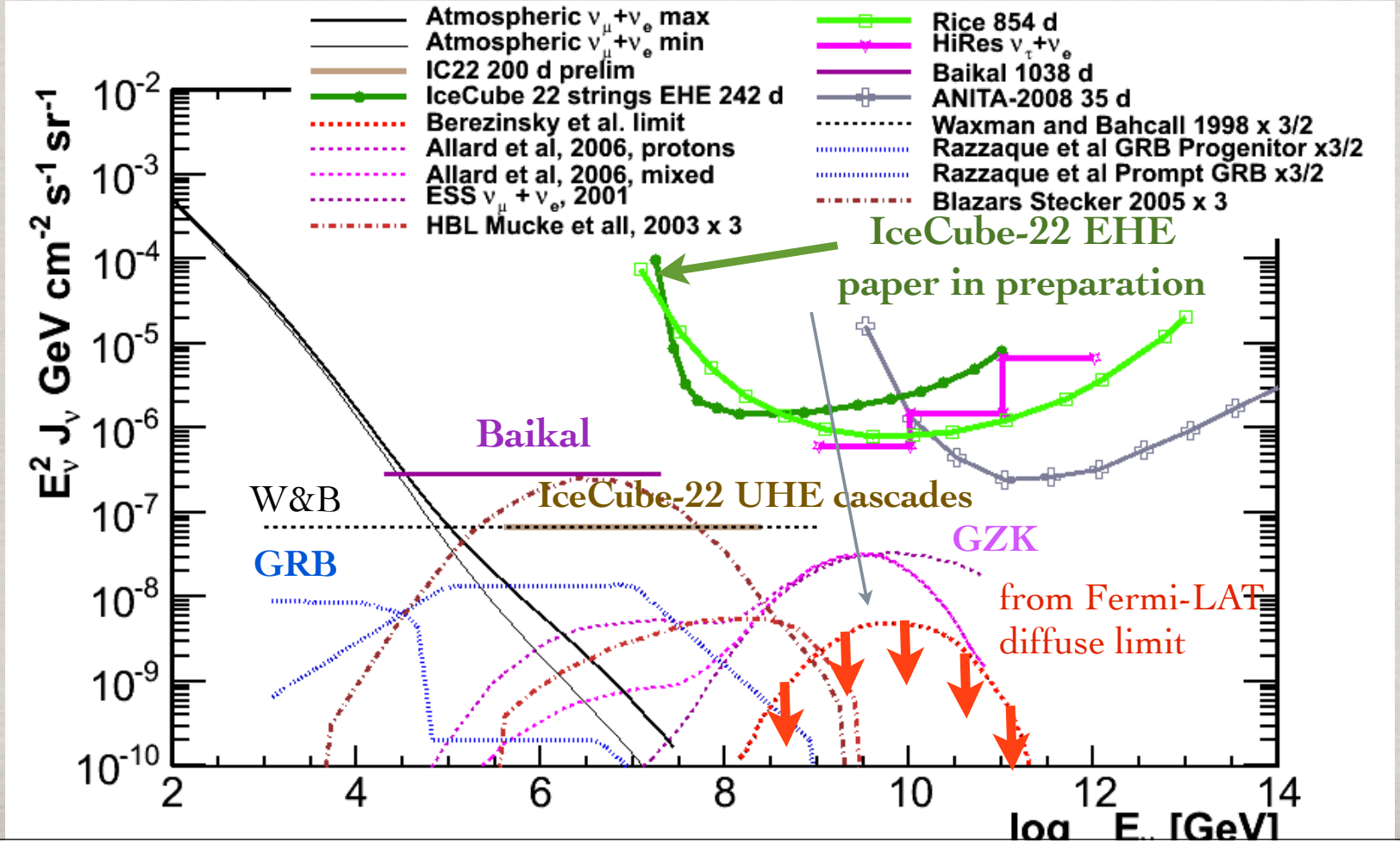
UHE neutrino constraints from IceCube have impact on the cosmogenic neutrino fluxes from a population of AGNs with strong source evolution $\propto(1+z)^5$ and consequently on the proton fraction in UHECRs (Ahlers et al, 2009). Green curves: cosmogenic neutrinos with Emax between 10^8-10^{12} GeV. Solid red curves: protons producing the neutrinos. Red dashed curve = proton envelope





UHE-Neutrino-gamma connection

UHECR interactions on CMB produce neutrinos and gammas. Gammas produce cascades unlike neutrinos. Fermi-LAT extra-galactic diffuse bound(arXiv:1002:3603) limits the energy density in cascades which in turn limits the expected UHE neutrino flux (Berezinski et al., arXiv:1003.4959).



Are there neutrinos in UHECR directions?

- 1) 22 P.Auger + 13 HiReS events in IceCube-22 string FoV; similar search in ANTARES

- 2) UHECR deflections with respect to neutrino sources unknown: assume gaussian smear with sigma= 3 deg

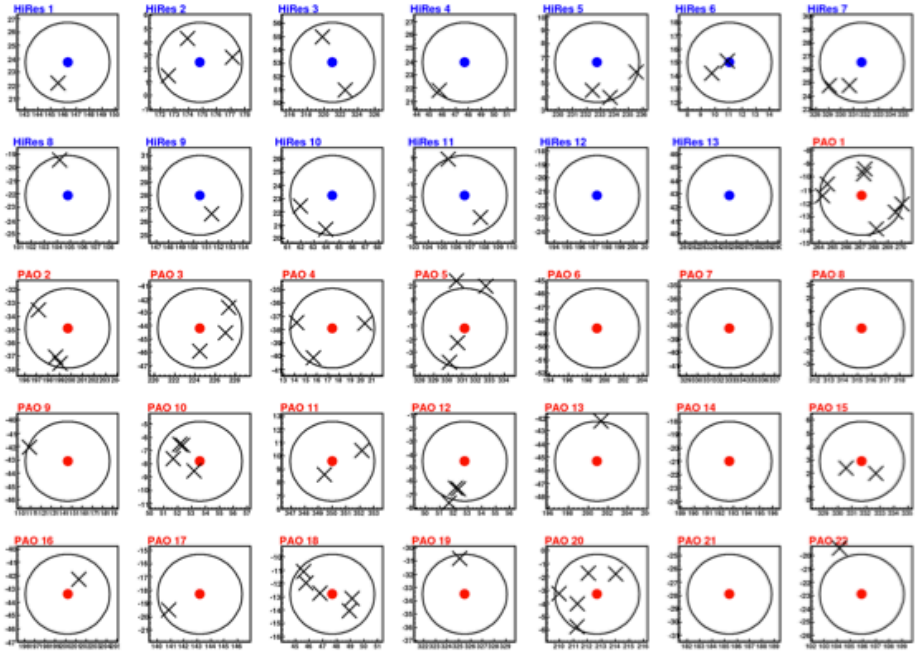
R. Lauer PhD Thesis
Vulcano 2010

IceCube-22 events:

Expected: 43.7

Excess prob.: 0.98% (2.33 σ)

Compatible with background



CR-Gamma-neutrino connection

Alvarez-Muniz and Halzen ApJ 576 (2002)

$$p + A \rightarrow \pi^0 + \pi^+ + \pi^-$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^+ \rightarrow \mu\nu_\mu$$

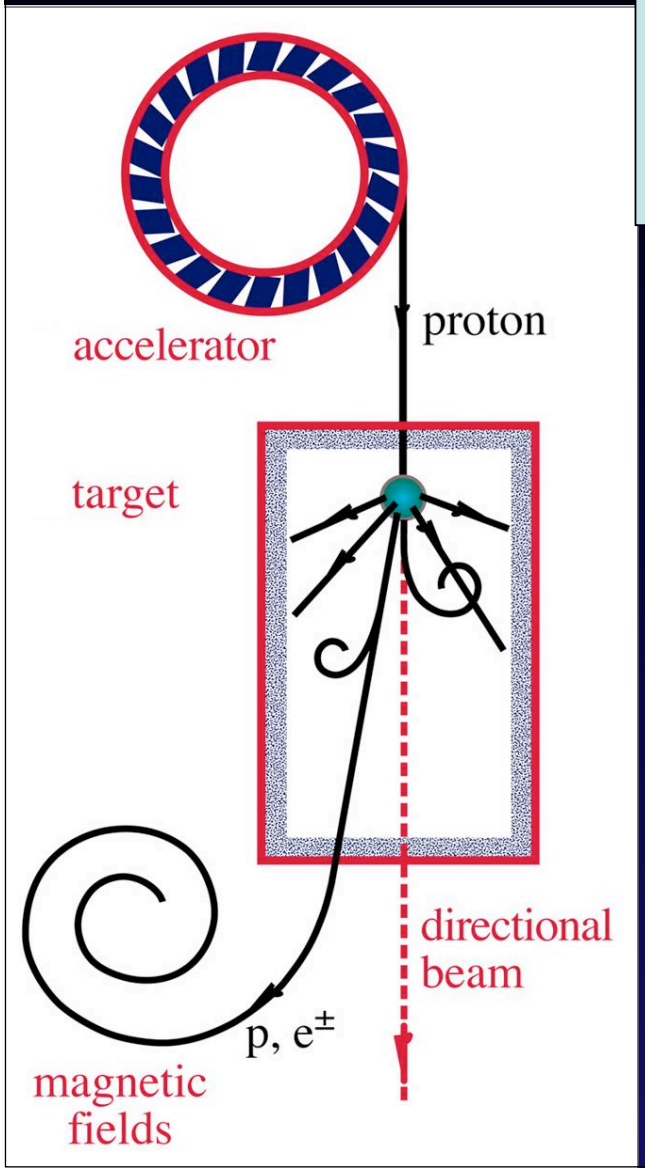
$$\mu \rightarrow e + 2\nu_\mu + \nu_e$$

At higher energies:

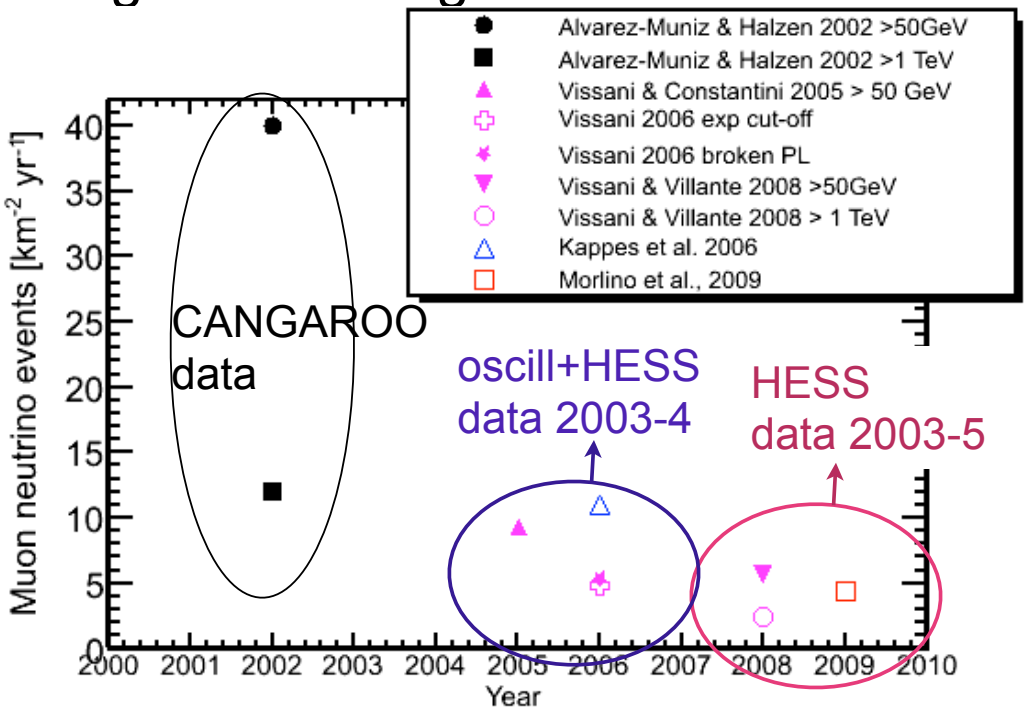
$$1)\ p + \gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$

$$2)\ p + \gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$

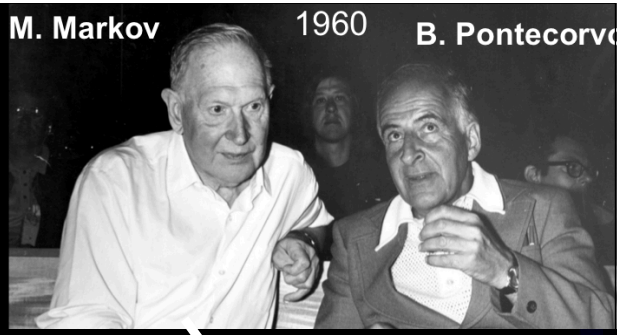
ν/γ after oscillations ~ 0.5 for E^{-2}



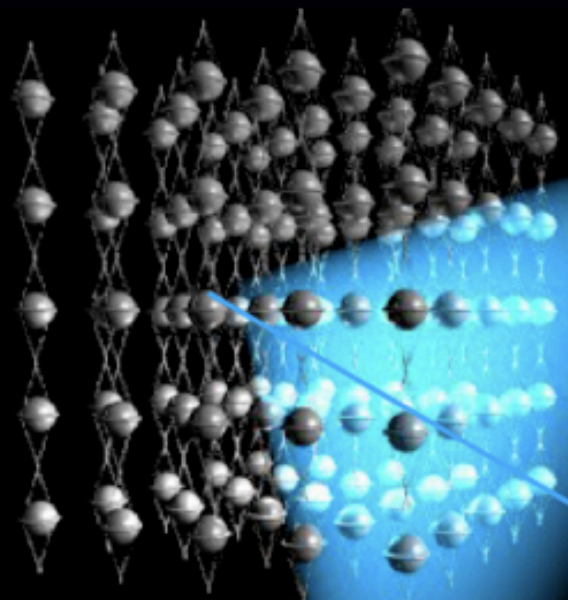
Neutrino-gamma fluxes can be estimated using measured gamma fluxes.



Concept of Neutrino Telescope



we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.



$\beta \sim 1$ and $\theta_c \sim 41^o$

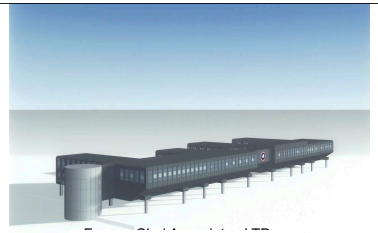
muon

nuclear reaction

3D lattice of PMTs

$$\theta \approx \frac{1.5\,\mathrm{deg}}{\sqrt{E_\nu(TeV)}}$$

Between 300-600 nm about 3.5 x 10^4 Cherenkov photons/m of a muon track

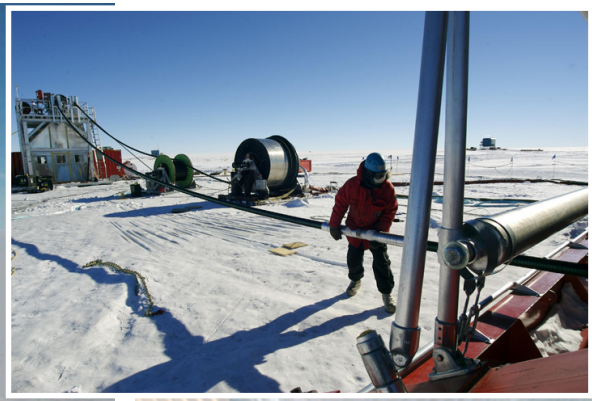


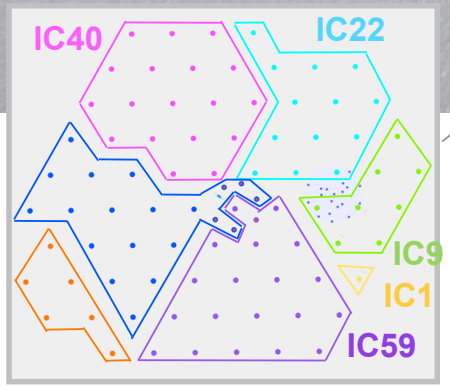
IceCube Neutrino Observatory
South Pole Drilling Seasons

1996/2000 Seasons - AMANDA
2005/2006 Season - First String
2006/2007 Season - 8 Strings
2007/2008 Season - 13 Strings
2008/2009 Season - 18 Strings
2009/2010 Season - 16 to 19 Strings
2010/2011 Season - 18 to 20 Strings
2011/2012 Season - 20 strings!!

since about a month →

79 out of 86 strings are taking data

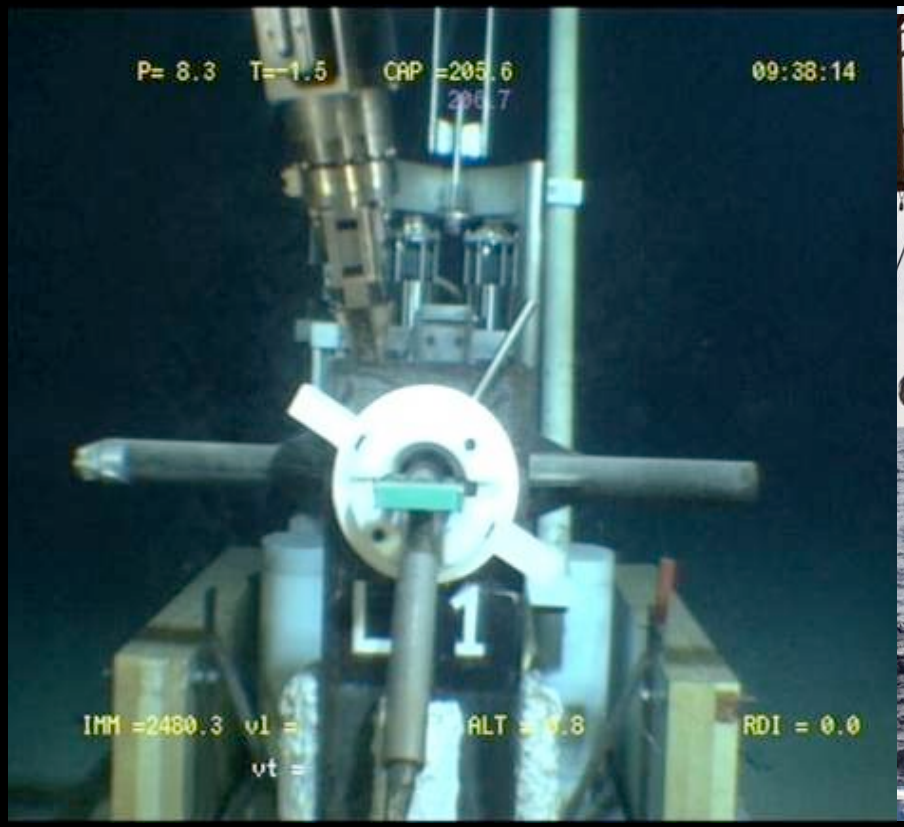




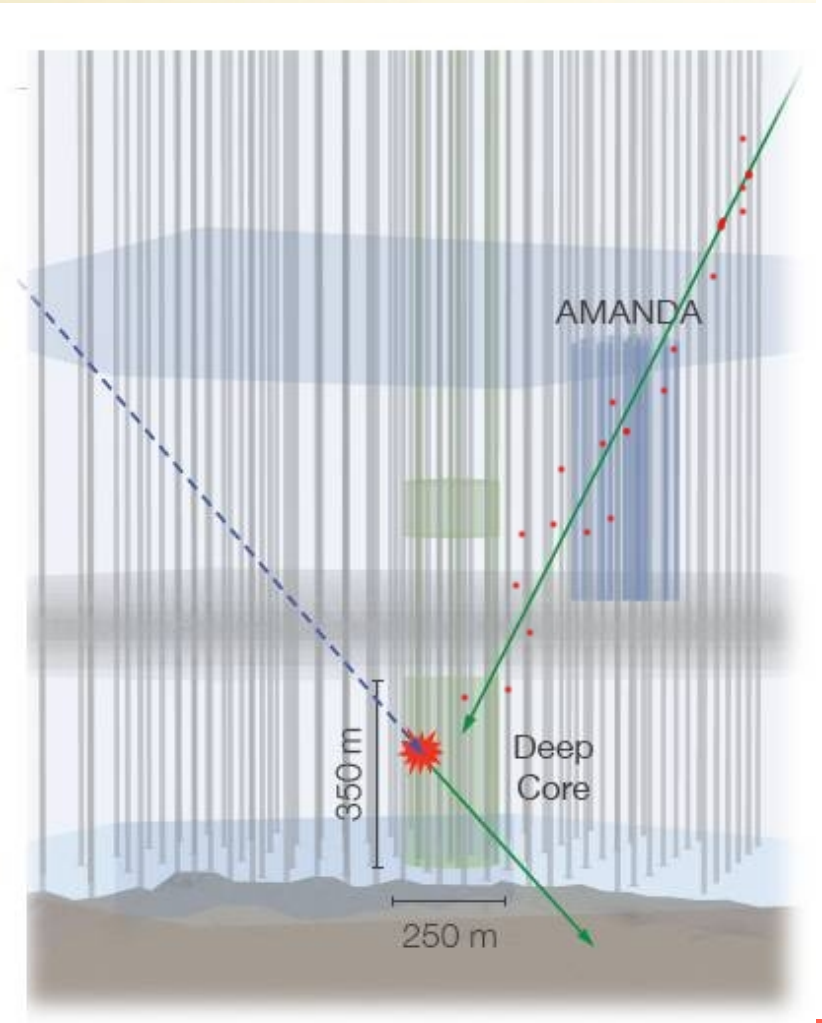
- Avg. time to deep drill hole 41hrs
- Avg. hole depth 2452 m
- Avg. drilling rate 1.7 m/min
- Avg. fuel per hole 5,520 gal
- Drill thermal power output 4.7 MW
- Avg. string deployment time 8 hrs

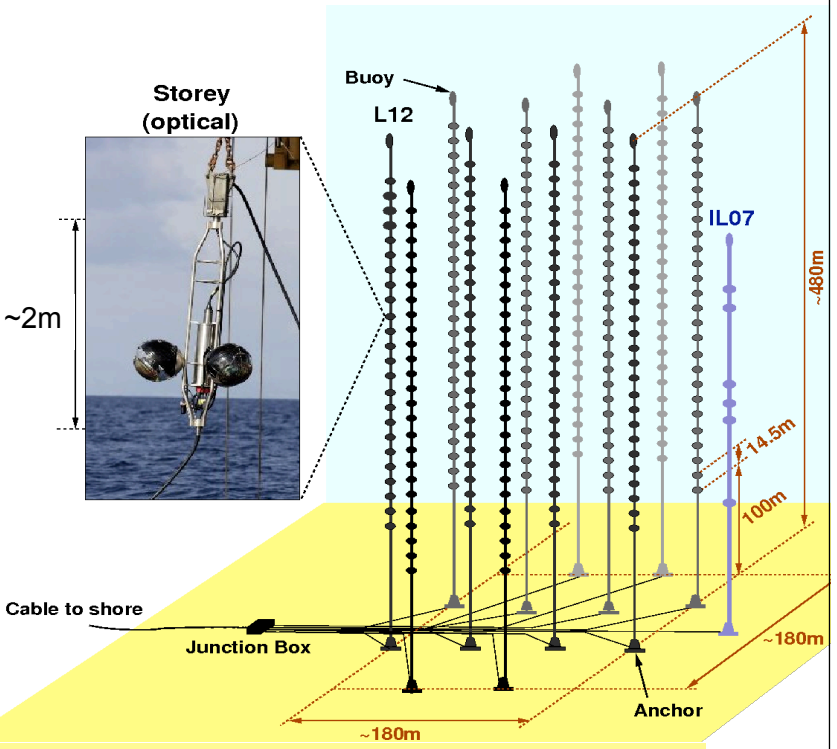
Technological challenges

ANTARES

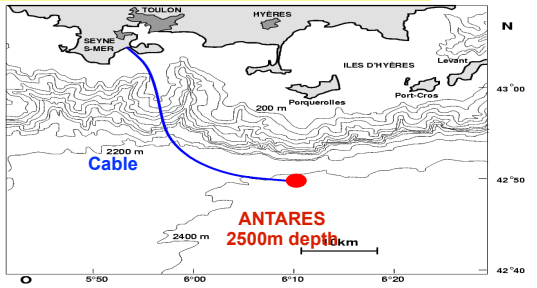


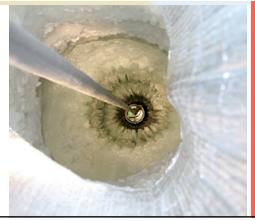
IceCube and ANTARES





12 lines with 25 storeys each; total of 885 PMTs
2.5 km deep, 40 km offshore
First lines in 2006, Completed 30 May, 2008





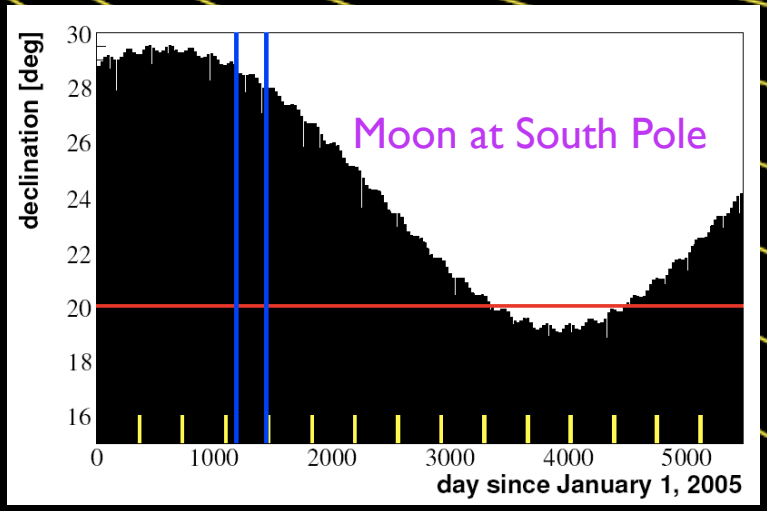
IceCube: 80 strings, 60 OMs/string, 17 m between OMs,125 m between strings
DeepCore of IceCube: comprise 6 additional strings of high QE PMTs)

Telescope standard candle: the moon shadow

0.5°

Primary CR average energy around 10^5 GeV

G.W. Clark, 1957

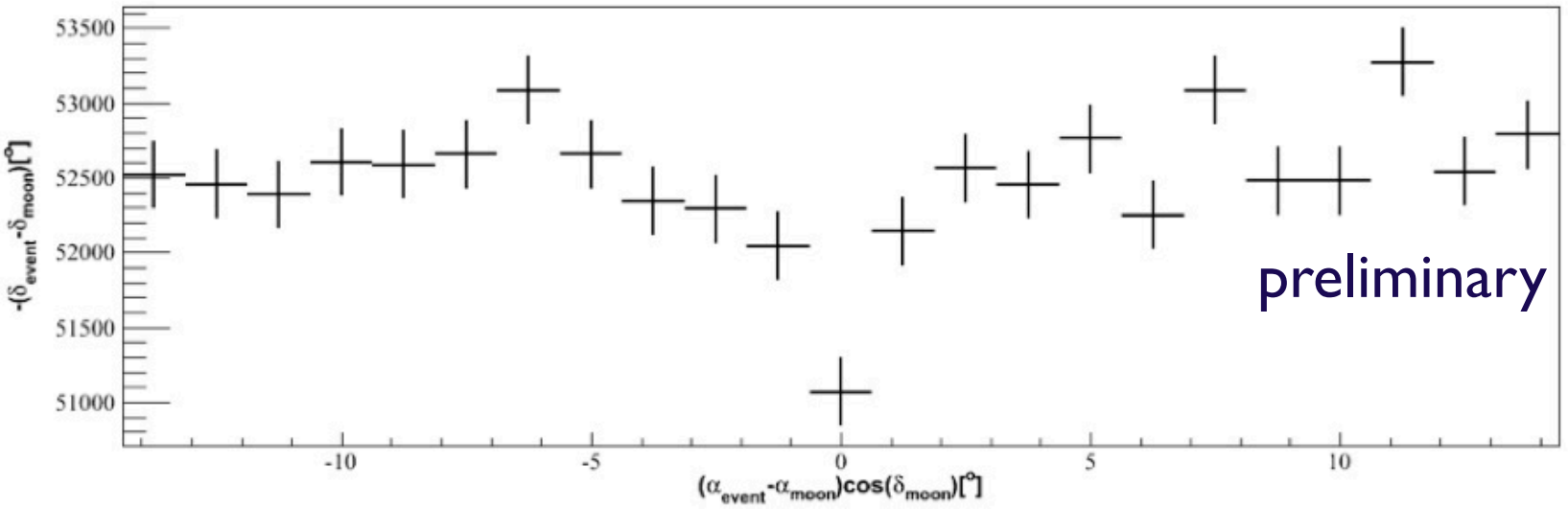


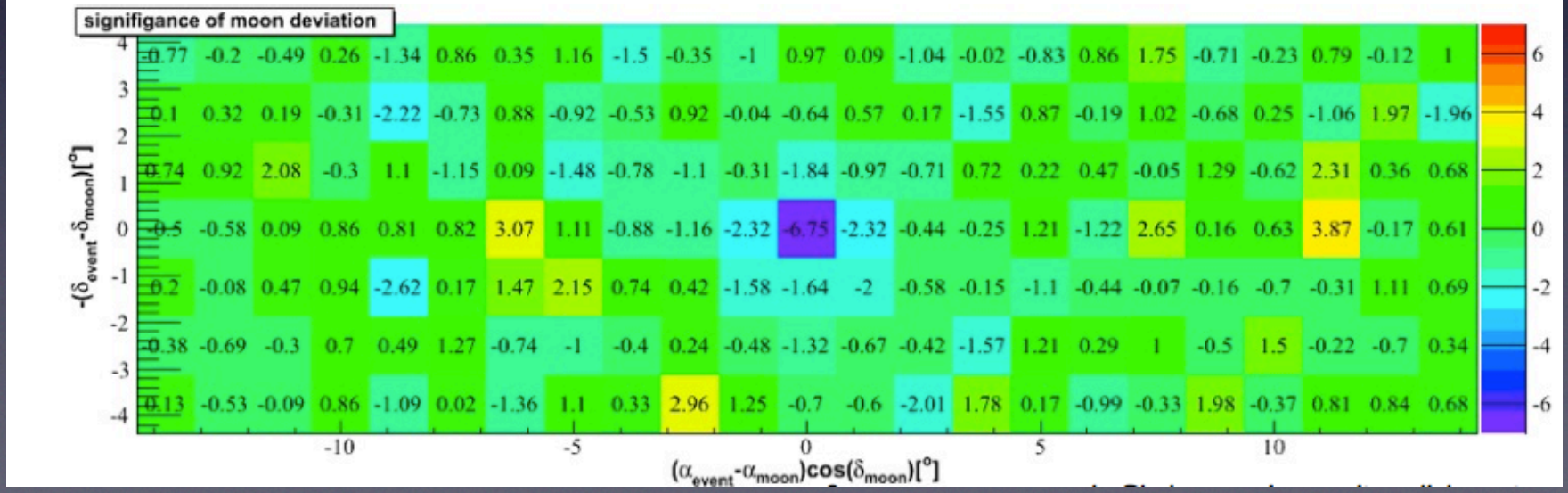
Moon shadow in the muons

- 14 lunar months in IceCube 40 strings
  n. of standard deviations from Li&Ma:

$$S = \frac{N_S}{\hat{\sigma}(N_S)} = \frac{N_{on} - \alpha N_{off}}{\sqrt{\alpha(N_{on} + N_{off})}}$$

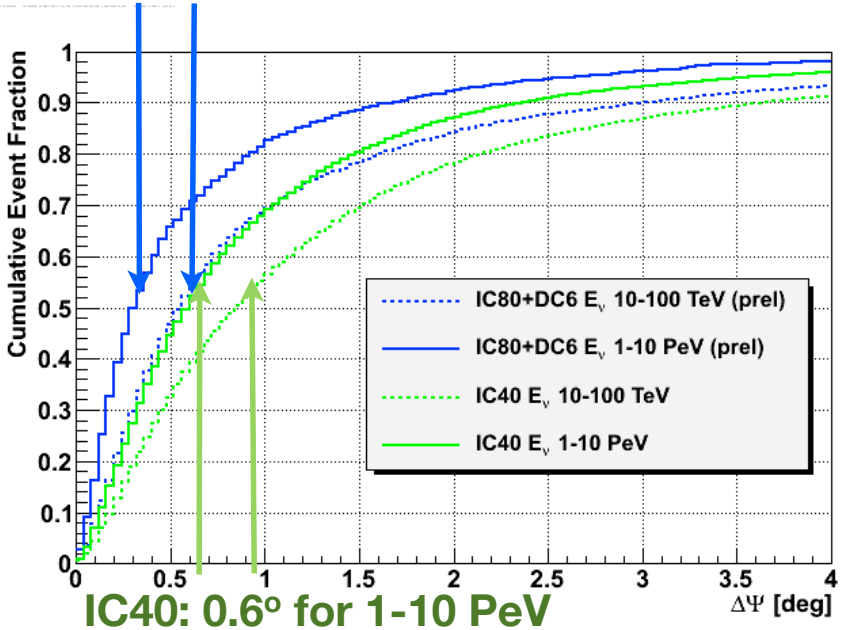
arXiv:1002.4900
only 8 lunar months





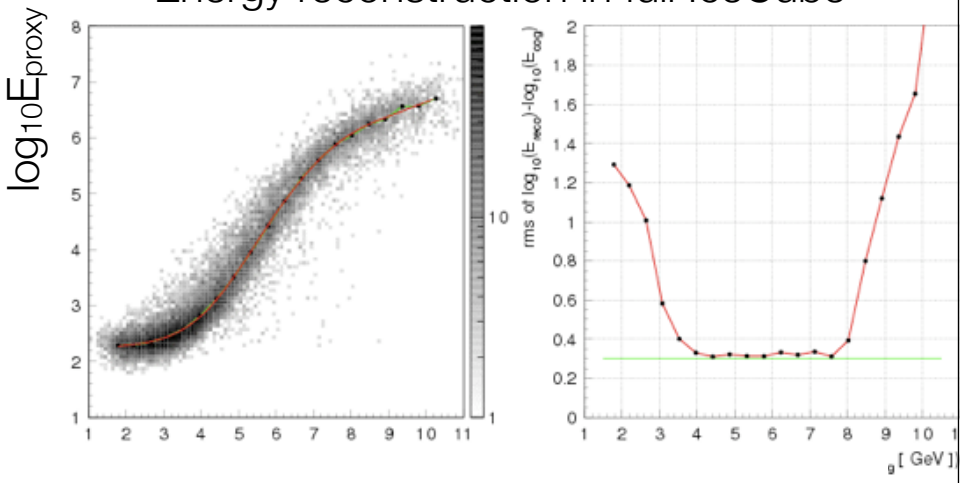
Point spread function and Energy proxy

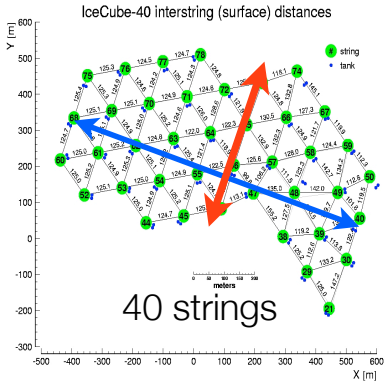
IC86: 0.3° for 1-10 PeV and 0.5° for 10-100 TeV.



IC40: 0.6° for 1-10 PeV
0.9° for 10-100 TeV.

Energy reconstruction in full IceCube





IceCube-40 is affected by not being symmetric.

Resolution ~ a factor of 2

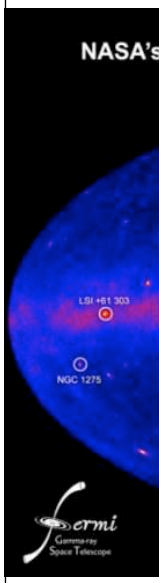
ICRC 2009

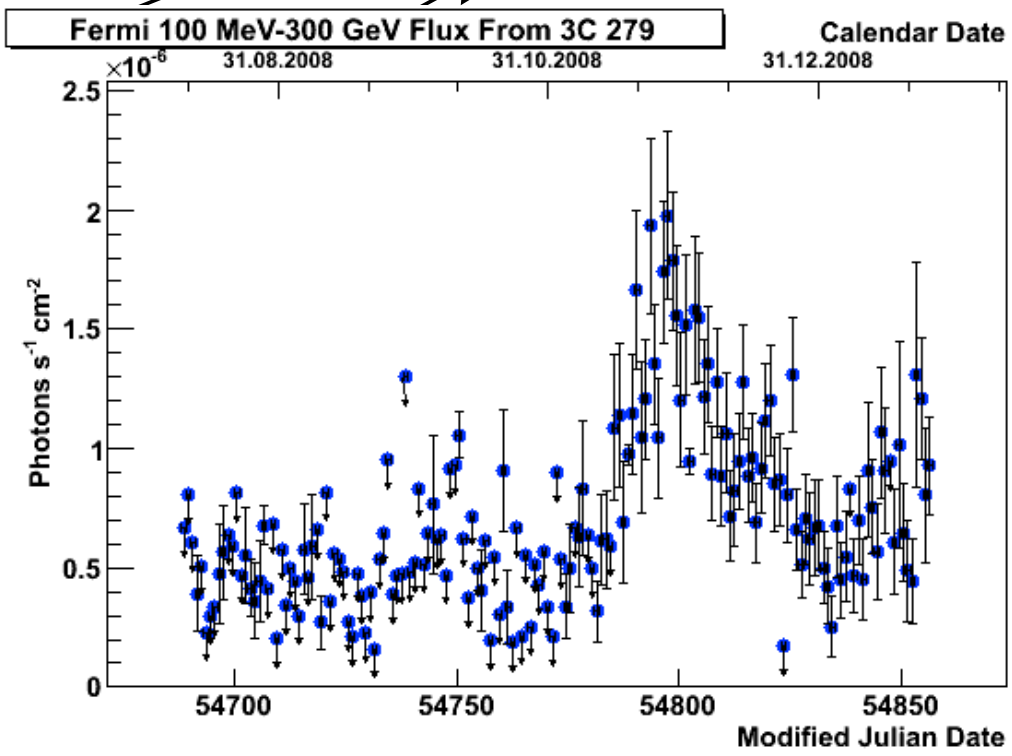
Point-source methods using Maximum Likelihood ratio test

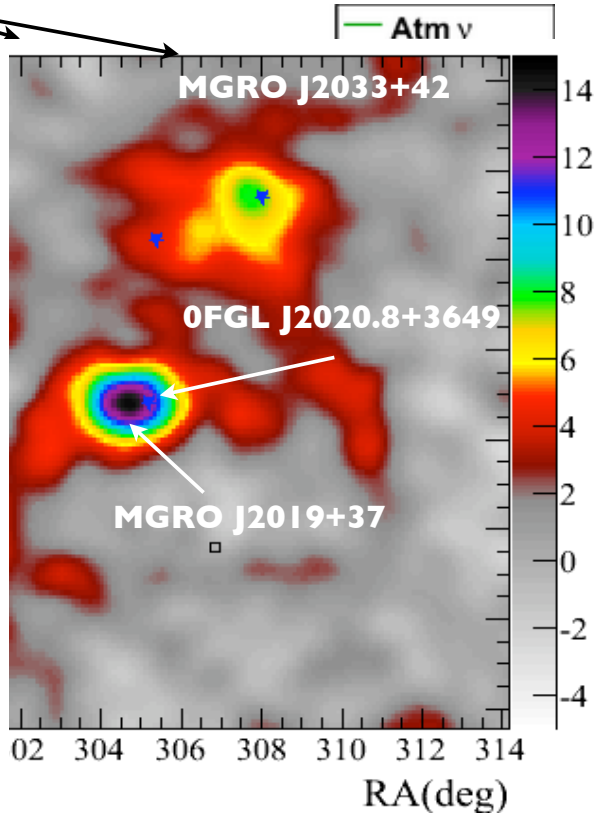
LH ratio methods exploit the power of several variables characterizing signal against background.

Neutrino telescope data are background dominated (atmospheric muons/neutrinos)
Background pdf from time-scrambled data samples ⇒ the significance is solid

Signal pdf: direction x time x energy for flares (GRBs, AGNs) es







J. Braun et al. Astrop. Phys. 33 (2010) 175.; J. Braun et al. Astropart. Phys. 29 (2008) 299 and arXiv:0801.1604.

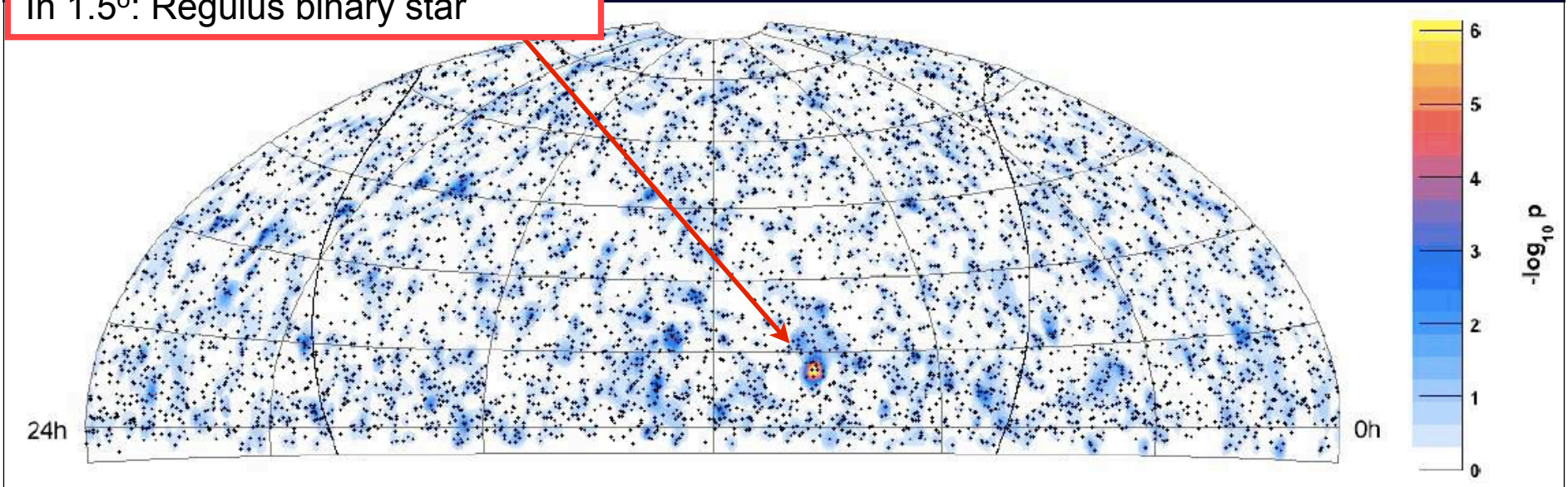
IceCube Sky Maps (22 strings)

RA= 153.4°, dec = 11.4°
nsrc = 7.7 gamma = -1.65
post-trial = 1.34% (2.2 sigma)
most of the significance comes from ≈ 300 TeV events
Not time dependent
In 1.5°: Regulus binary star

Neutrino Flux needed for this significance ($TeV^{-1}\ cm^{-2}\ s^{-1}$)

E^{-2} 2.2×10^{-11}
$E^{-1.65}$ 3.6×10^{-12}

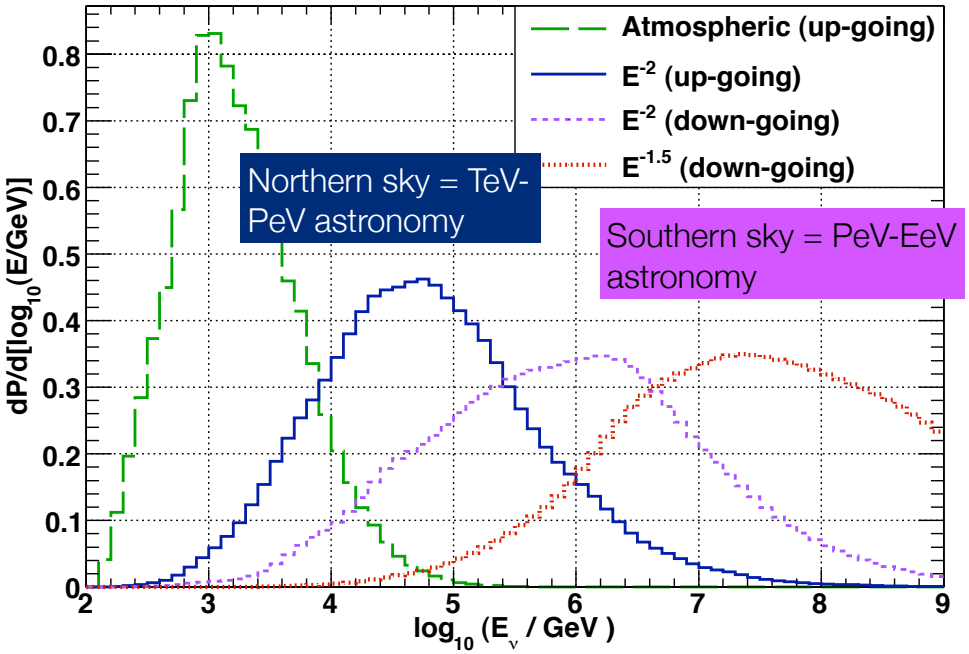
5114 events/276 days



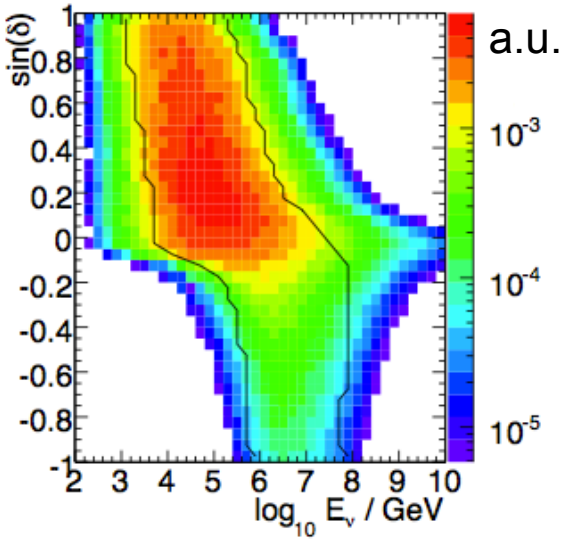
Astrop. J. L 701 (2009) L47-L51

Phys. Rev. Lett. 103, 221102 (2009)

Northern and Southern astronomy…

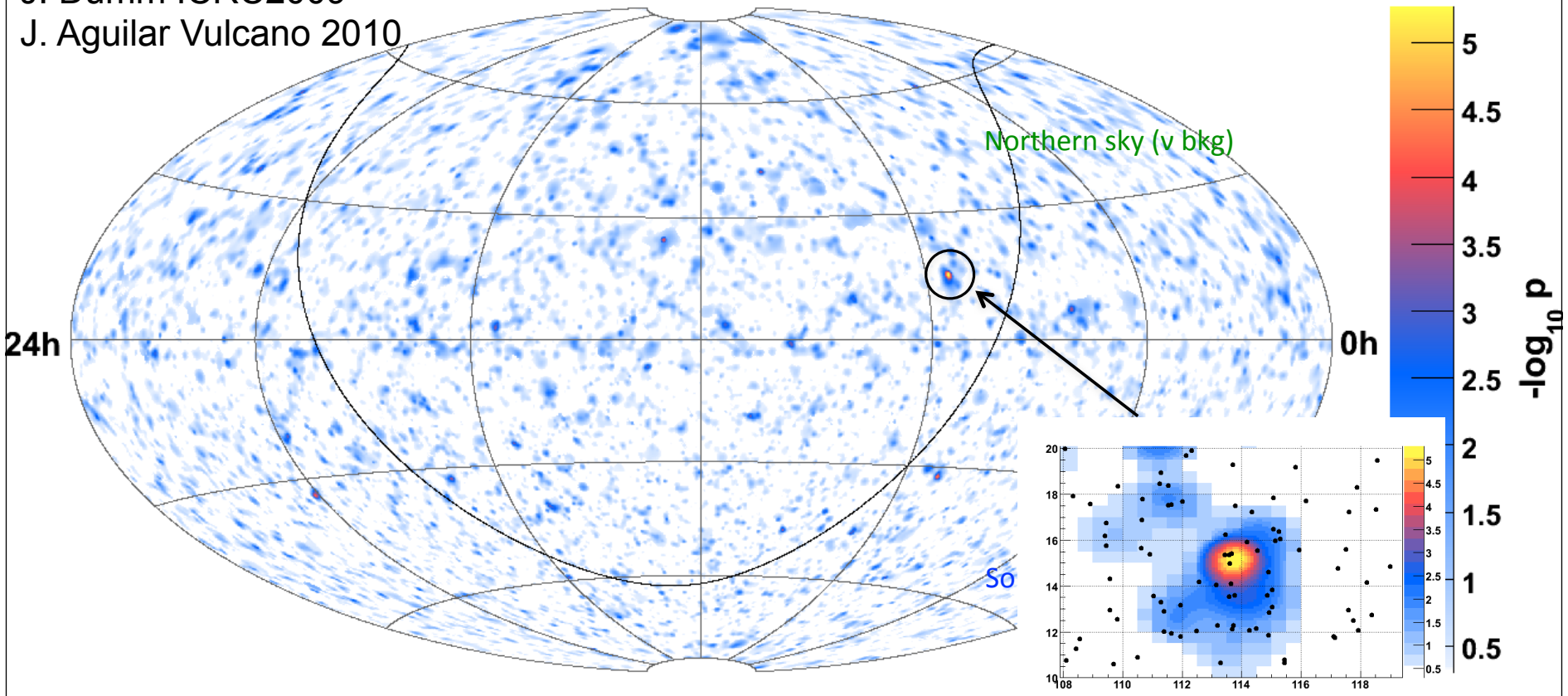


Fraction of simulated E^{-2} neutrinos at analysis level



40-string all skymap

J. Dumm ICRC2009
J. Aguilar Vulcano 2010

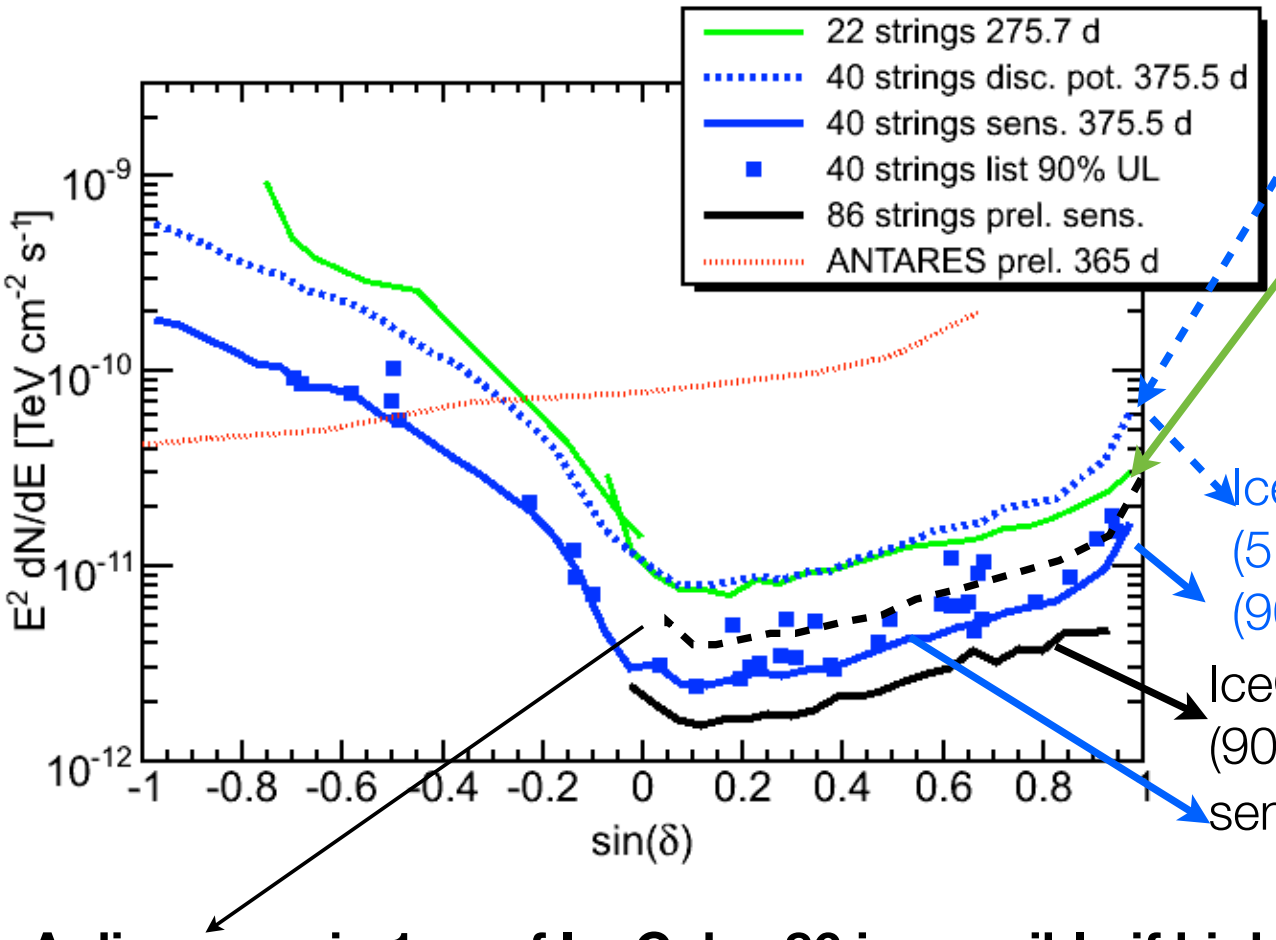


Livetime = 375.5 days
Apr 5, 2008- May 20,2009
 # Events = 36900
(14121 up-going,
22779 down-going)

Ra=113.75, Dec=15.15
Pre-trial $-\log_{10}$(p-value) = 5.28
Best-fit # of source events = 11.0
Best-fit spectral index = 2.05

All-sky search: post-trial p-value = **18.1%**
Source list: post-trial p-value = **62%**

Sensitivity (90% cl) and Discovery Potential (5sigma) to E^{-2} fluxes



IceCube-40 discovery flux (5 σ) is almost ruled out by IceCube-22 sensitivity flux (90%cl.)

IceCube-40 discovery flux (5 σ)/IceCube-40 sensitivity (90%cl) ~3

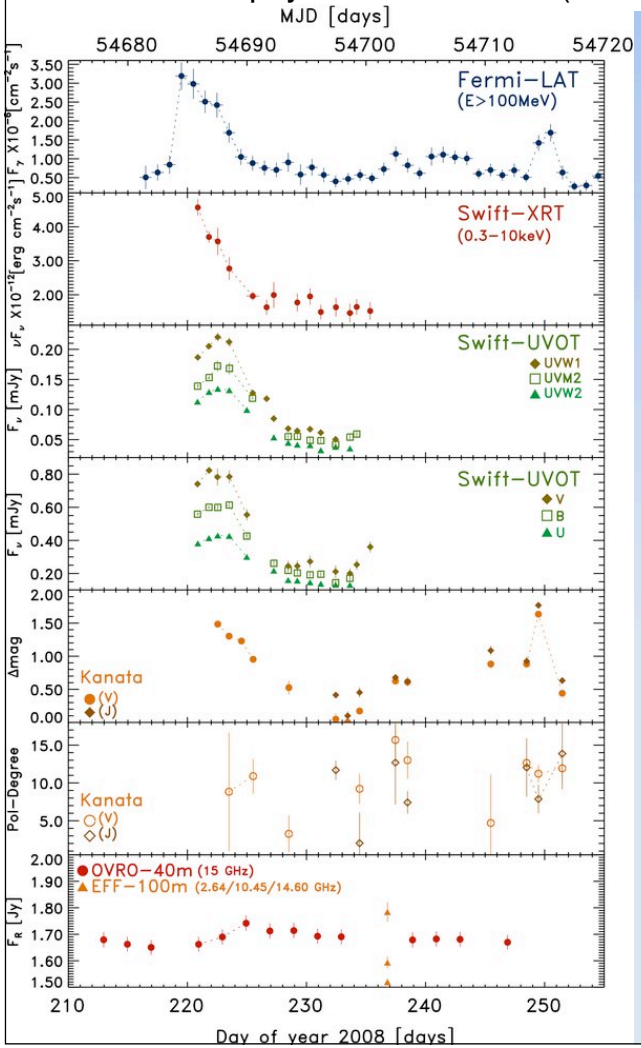
IceCube-86 sensitivity (90%cl) ~2 IceCube-40 sensitivity

A discovery in 1-yr of IceCube-86 is possible if highest significances in IceCube-40 continue to grow.

Search for flares using MWL information

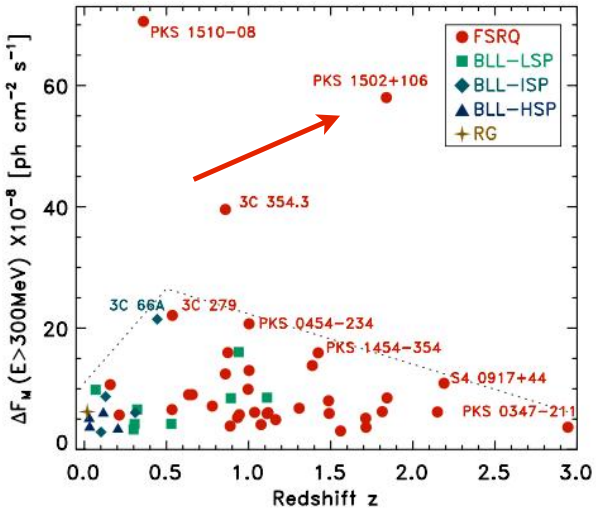
15 in coincidence with 40 string: best p-value for PKS 1502+106, with a time window of ~8 days, p-value after trials 29% so compatible with backgr.

Fermi-LAT Astrophysical Journal **710** (2010) 810

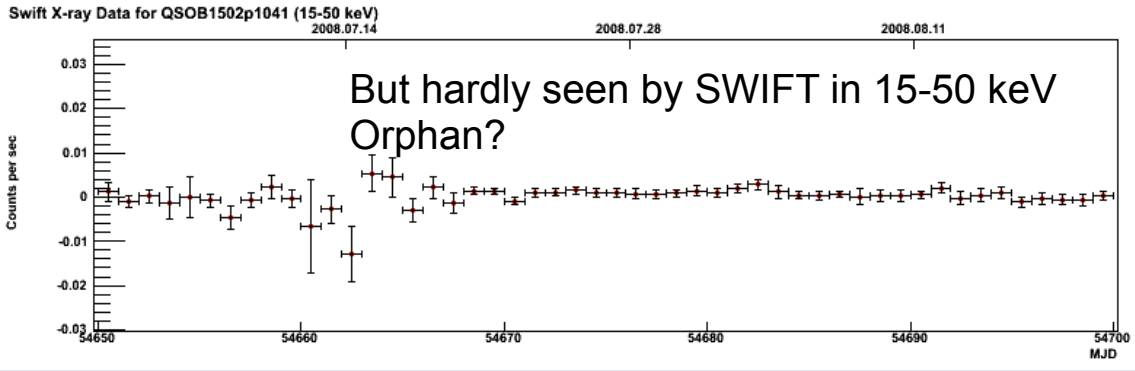


We scanned all time scales from ms to yr => the hottest spot is for 2 events in 22 sec (prob. 58% after trials).

Preliminary



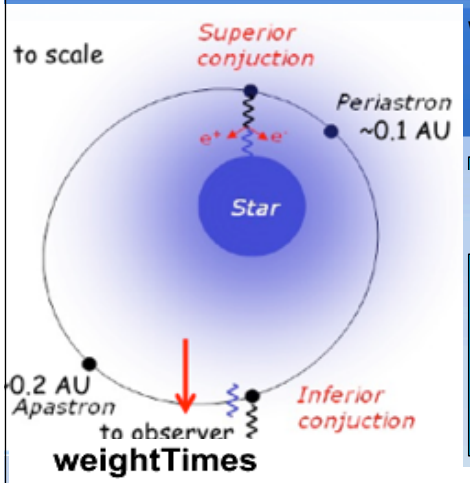
Observed maximum of subsequent weekly flux variations vs redshift for the 53 brightest variable sources (arXiv: 1004.0348)



But hardly seen by SWIFT in 15-50 keV
Orphan?

Binary systems and Micro-quasars

Period assumed by optical experiments, phase and mean of the emission is fit.

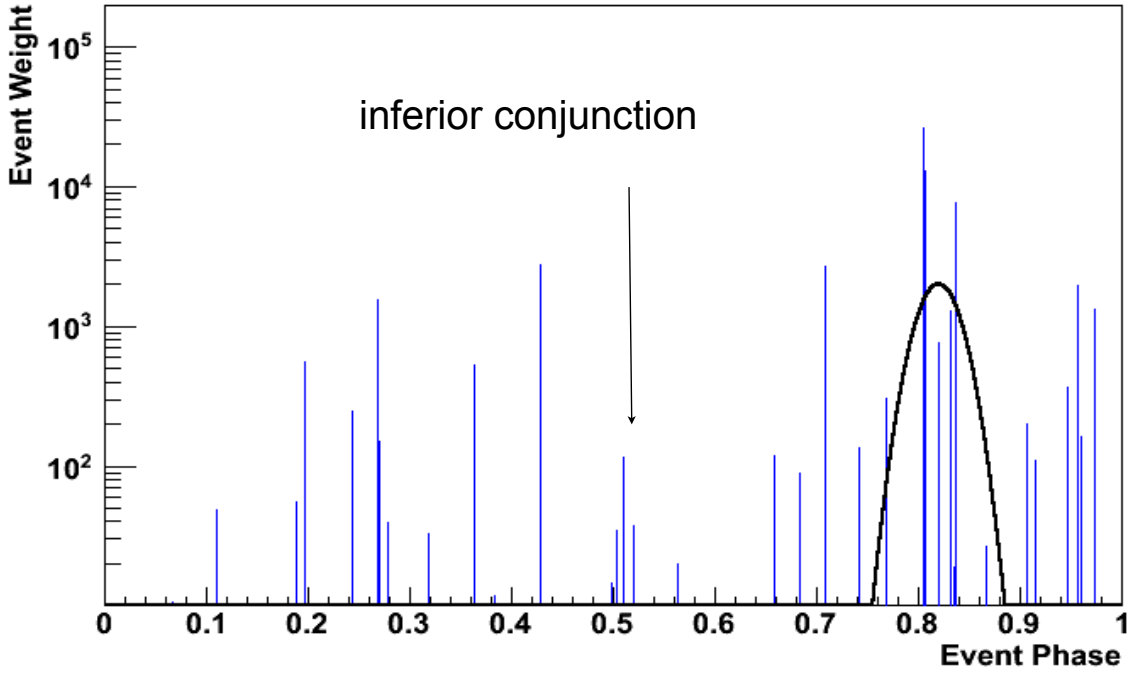


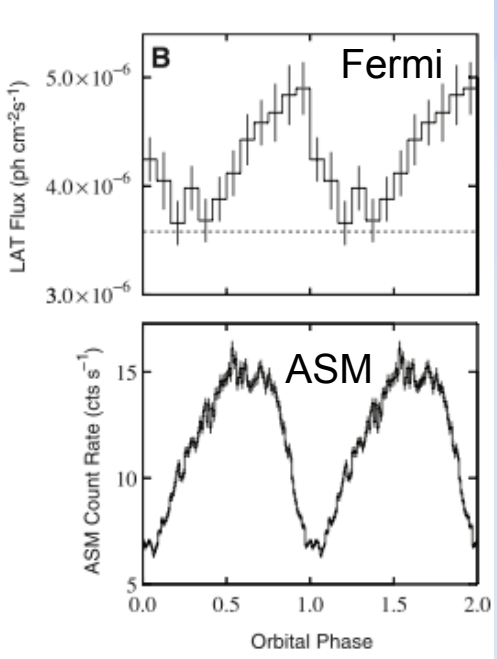
We need 7 events at dec = 40° to discover at 5σ (50% prob) a source with sigma of the emission = T/20.

Source	(Ra, Dec)	Period	pretrialP	NSrc	Gamma	mean	sigma_w
Cygnus X3	**(308.107,40.958)**	**0.199679**	**0.00186**	**4.27**	**3.75**	**0.820**	**0.02**

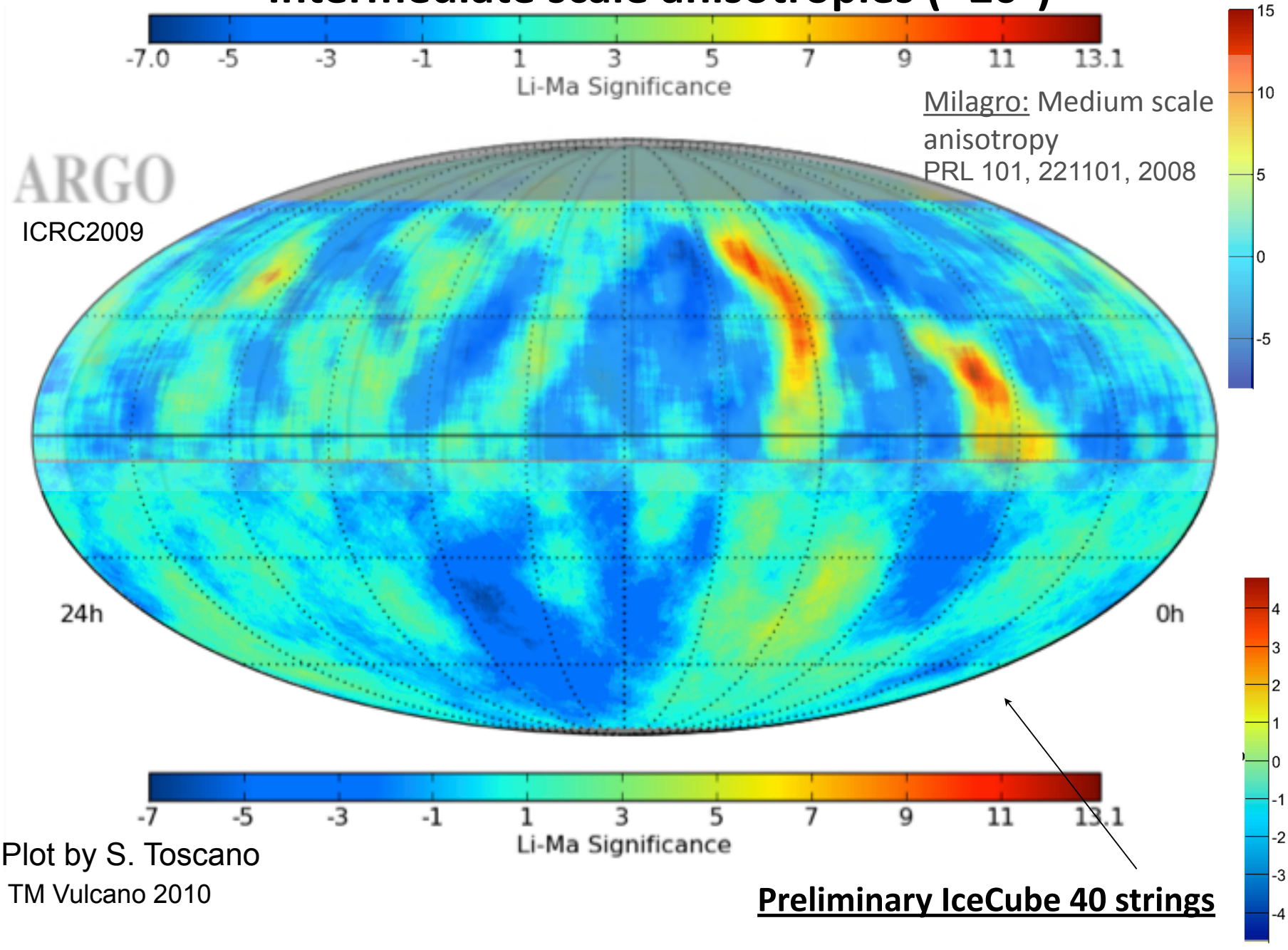
Post trial p-value = 1.8% for a catalogue of 7 objects, hence compatible with background

Preliminary





Intermediate scale anisotropies (~20°)



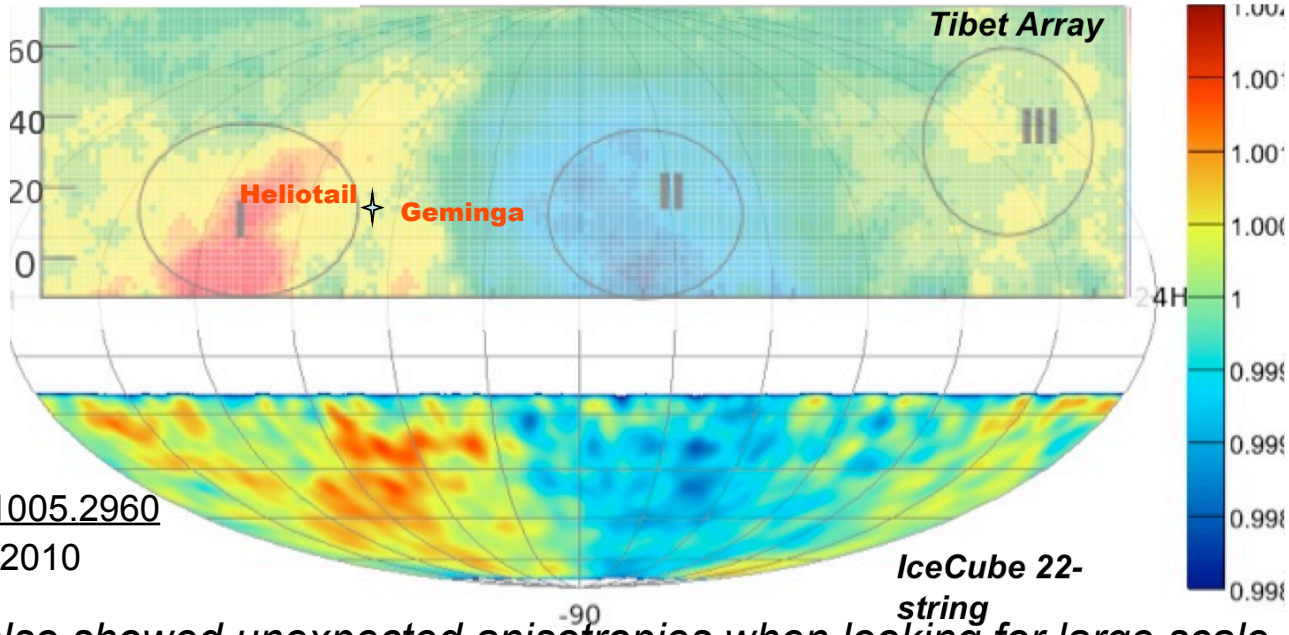
Plot by S. Toscano

TM Vulcano 2010

Preliminary IceCube 40 strings

Large Scale Anisotropies: IceCube-22 strings versus Milagro

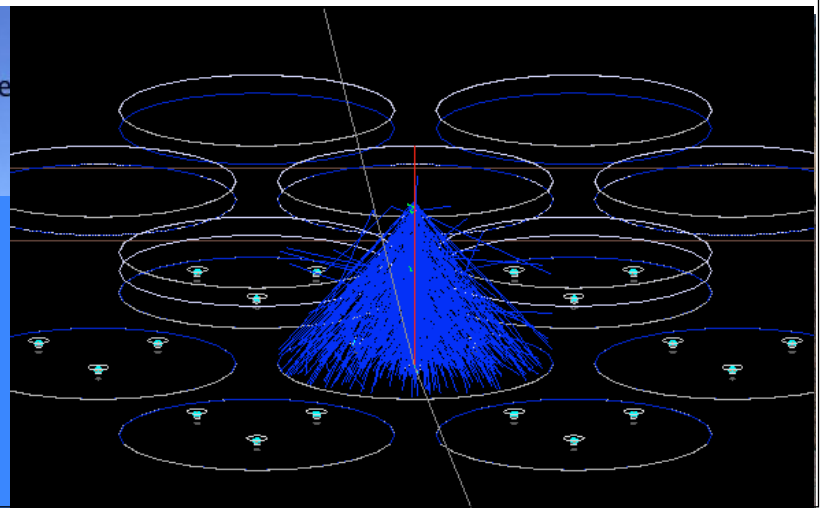
Science 314, 2006



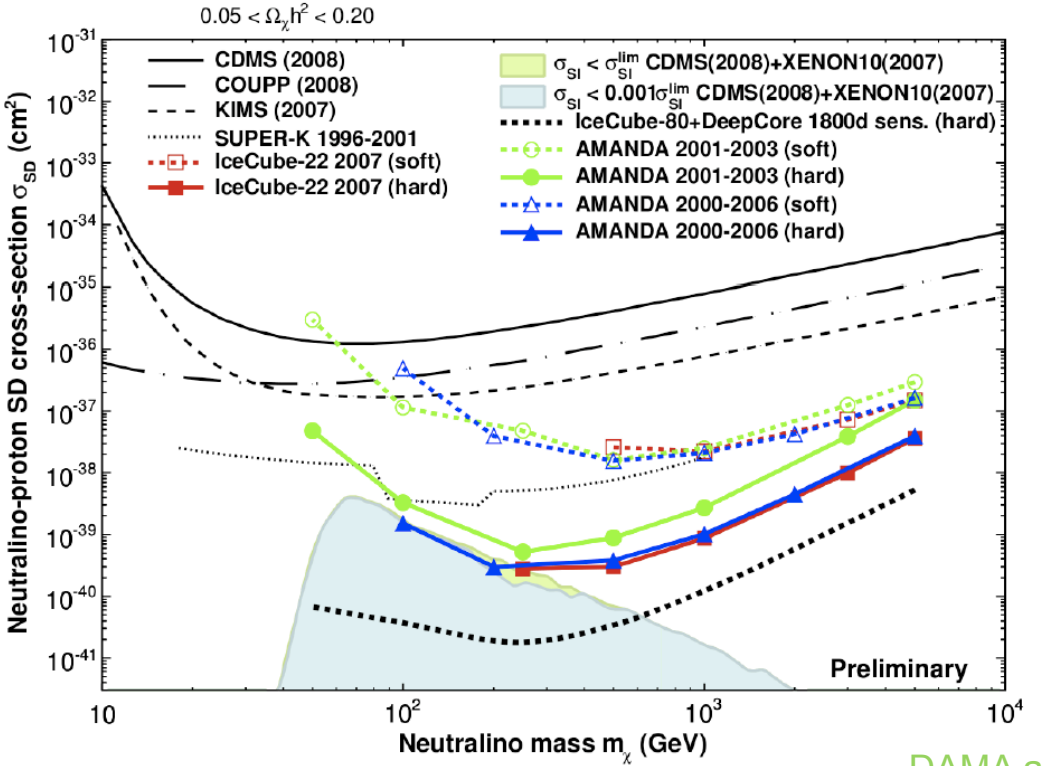
http://arxiv.org/abs/1005.2960
P. Desiati, Beyond 2010

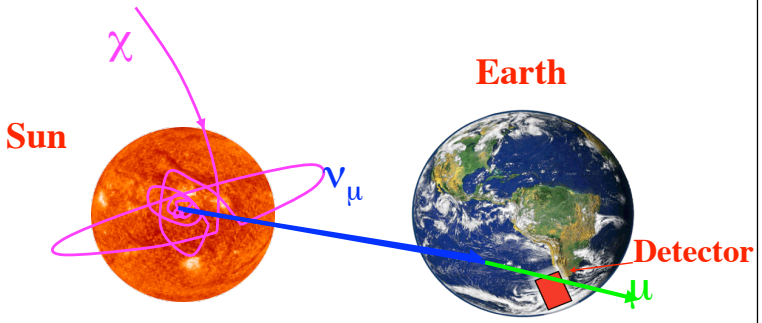
Tibet, Milagro also showed unexpected anisotropies when looking for large scale anisotropies. Map dominated by charged cosmic rays.

HAWC construction is starting!
x15 better sensitivity than Milagro.
~20,000 m² 300 water tanks with 3 PMTs
at 4100m a.s.l. in Mexico



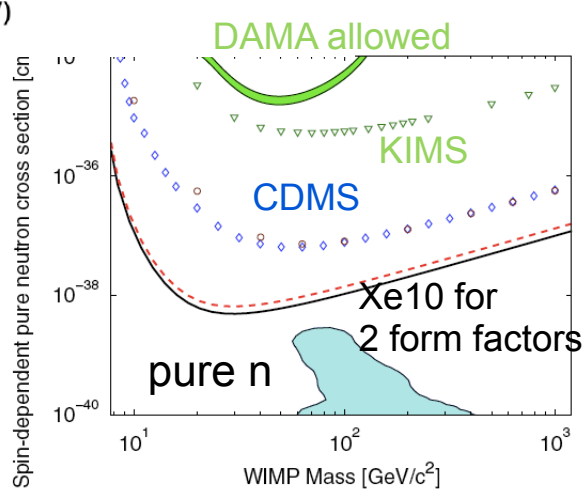
WIMP searches

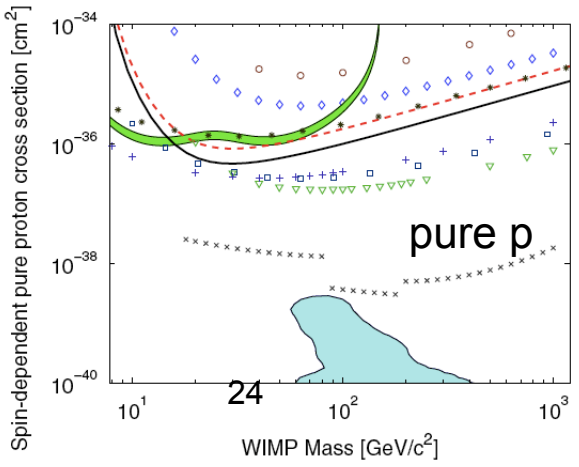




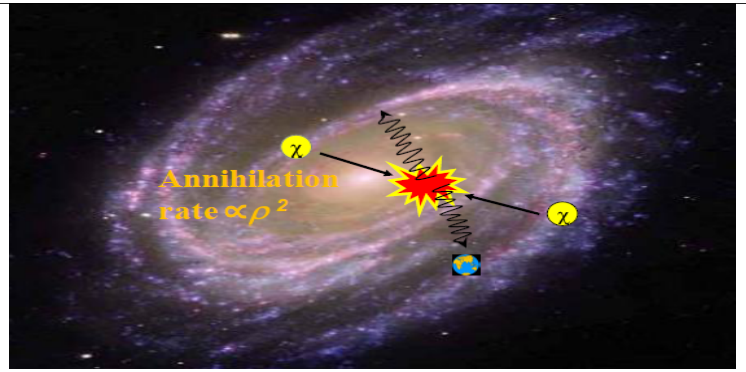
IceCube 22 strings, effective livetime 104 d
PRL 102 (2009) 201302
AMANDA, J. Braun at ICRC2009

Xenon 10 spin dependent
PRL 101 (2008)



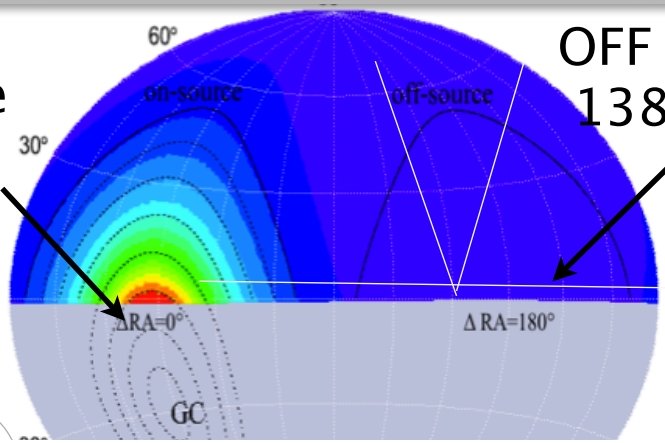


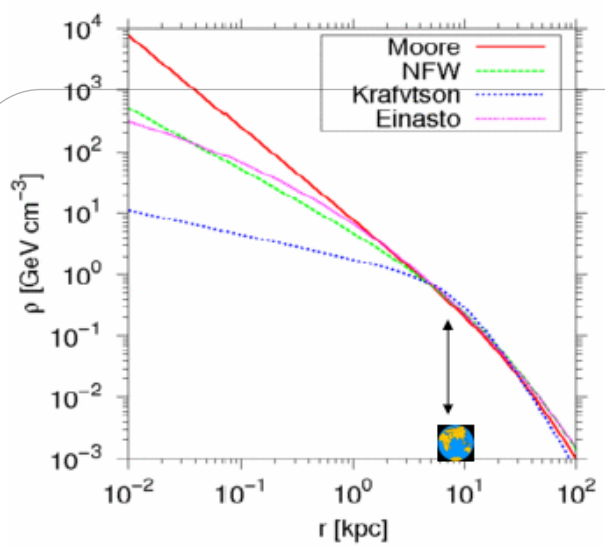
DM from the Galactic halo



ON source
1367 evts

OFF source
1389 evts

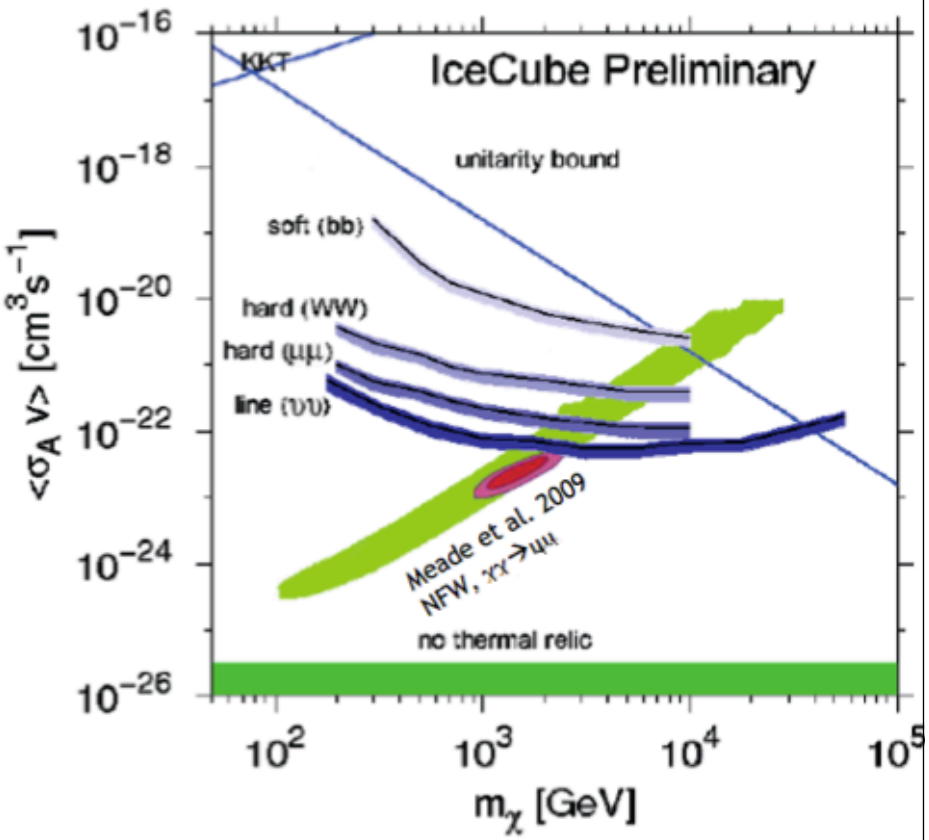




Signal scales with $\langle\sigma_A v\rangle$
=> limit

$$\frac{d\Phi}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

limit — Constrain — Halo



Conclusions

IceCube *and* ***ANTARES*** *are beginning to explore the* ***region < WB limit***

Some outcomes of analyses are at the level of ***1%*** *but in astronomy such significance is to be considered a* ***fluctuation of background.***

Cosmic ray anisotropies *are an* ***intriguing puzzle*** *possibly hinting to* ***local CR sources.***

IceCube *and* ***HAWC*** *will* ***substantially contribute to solve it.***

DeepCore will improve IceCube performance for < 100 GeV physics (DM, oscillations, galactic sources)