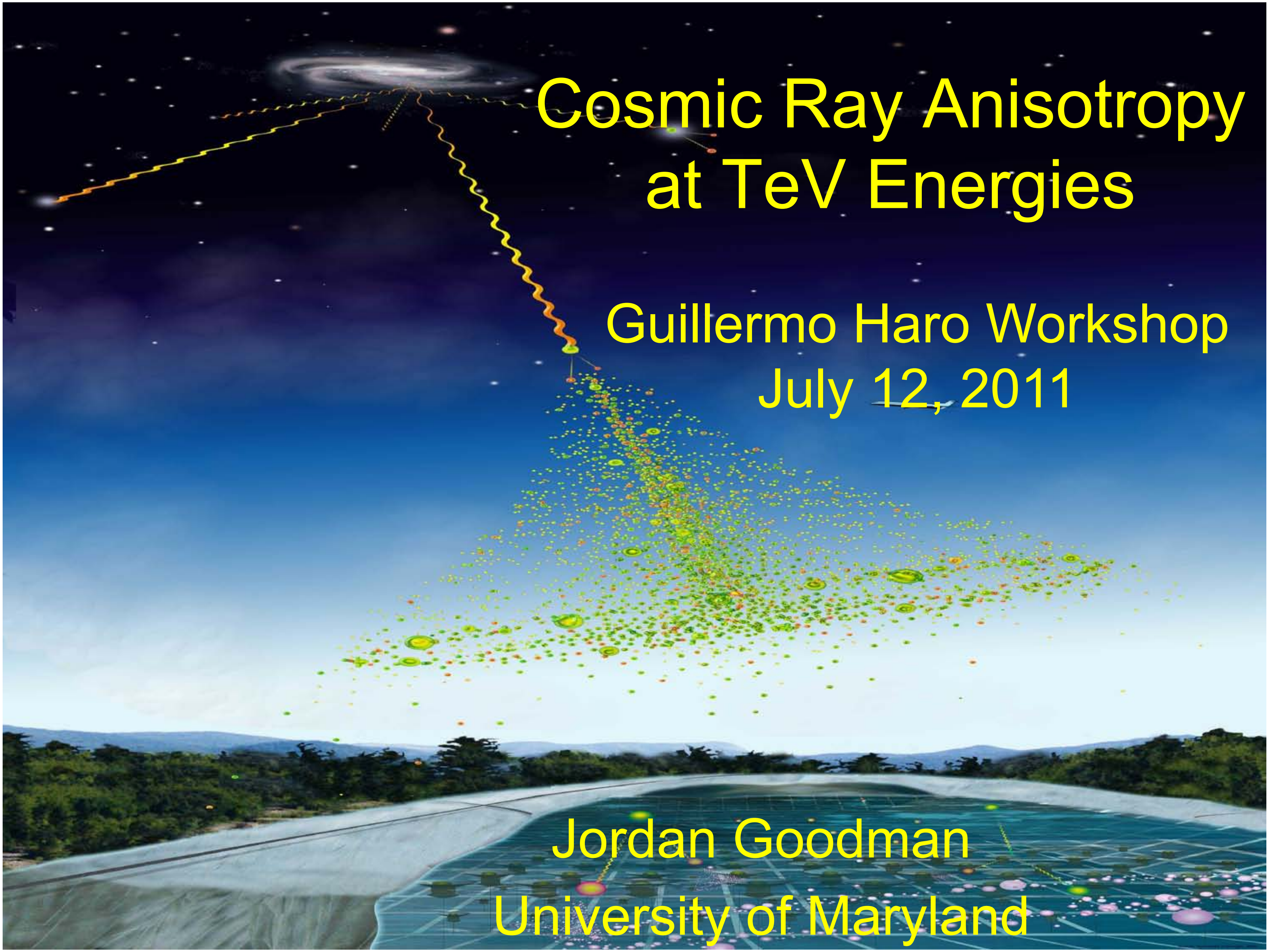


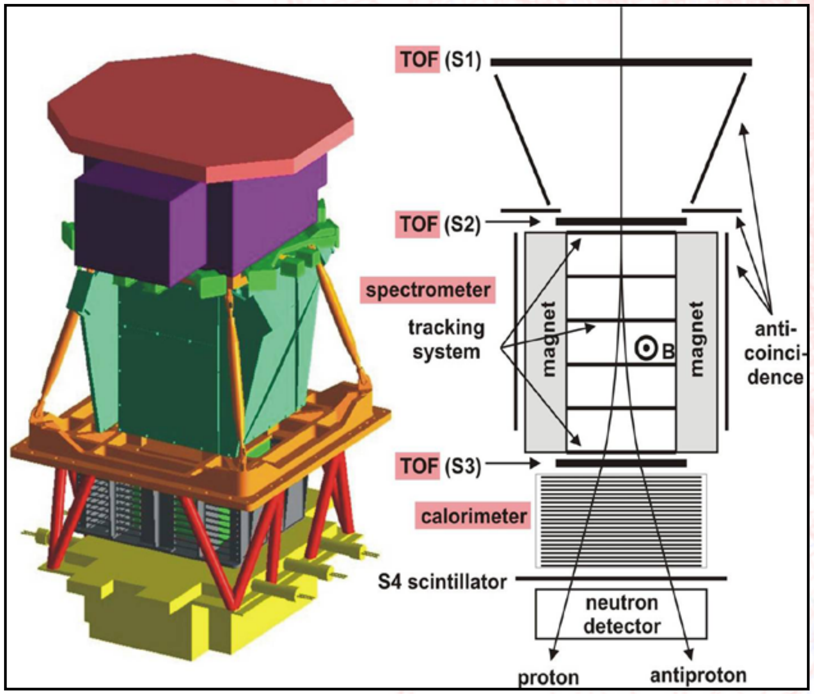
Cosmic Ray Anisotropy at TeV Energies

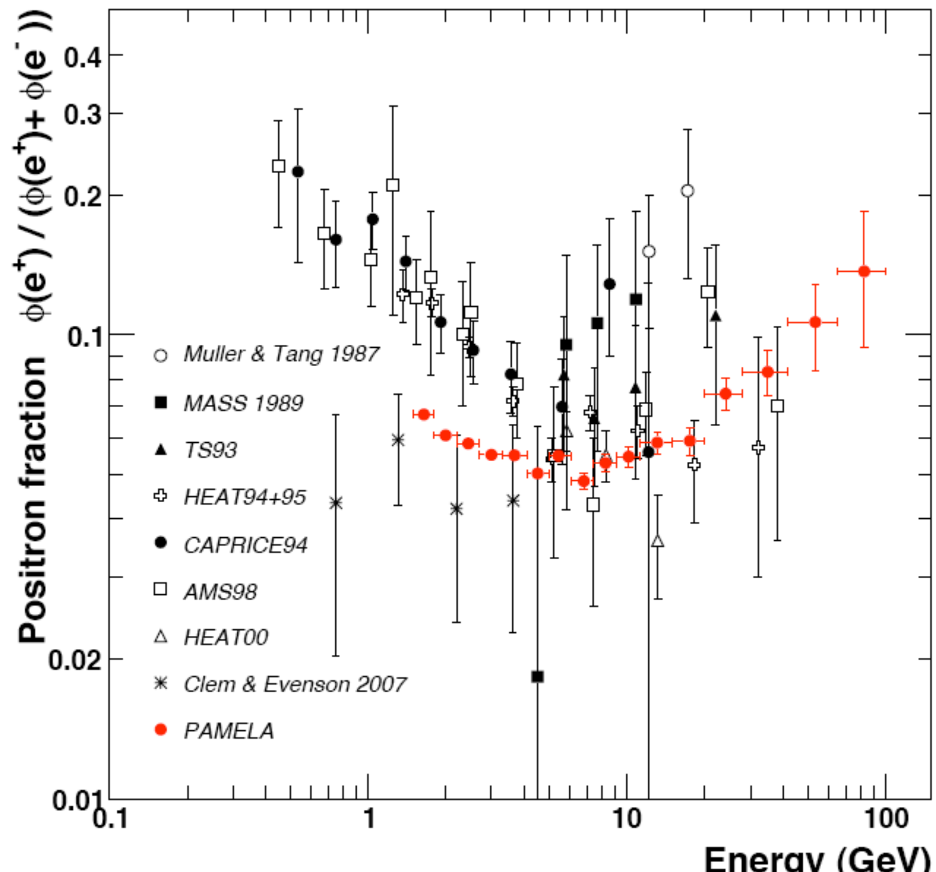
Guillermo Haro Workshop
July 12, 2011

Jordan Goodman
University of Maryland

PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics





Adriani, O. et al. preprint available at http://www.arxiv.org/abs/0810.4995 (2008)

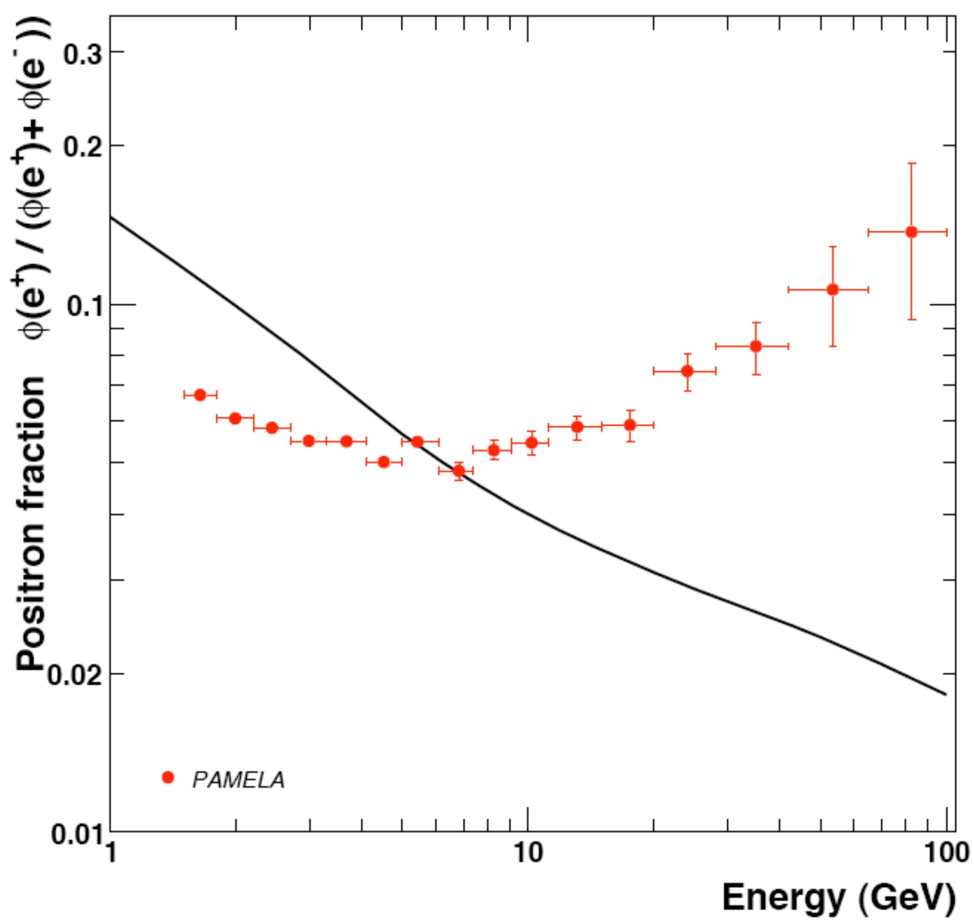
Pamela Results

"Either a significant modification in the acceleration and propagation models for cosmic-rays is needed, or a primary component is present"

Candidates for a primary component...

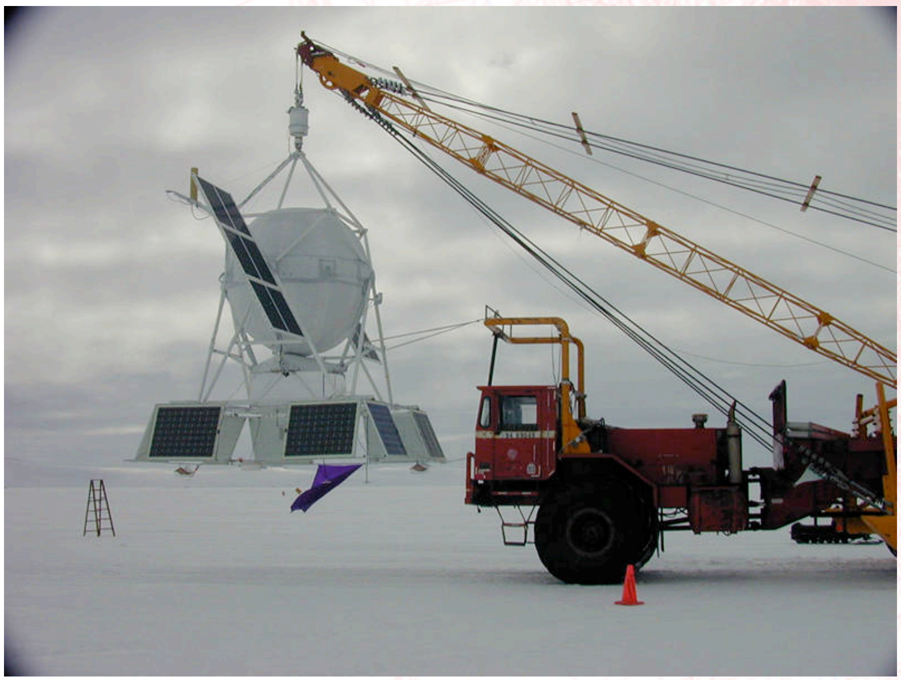
(1) annihilation of dark matter particles in the vicinity of our galaxy.

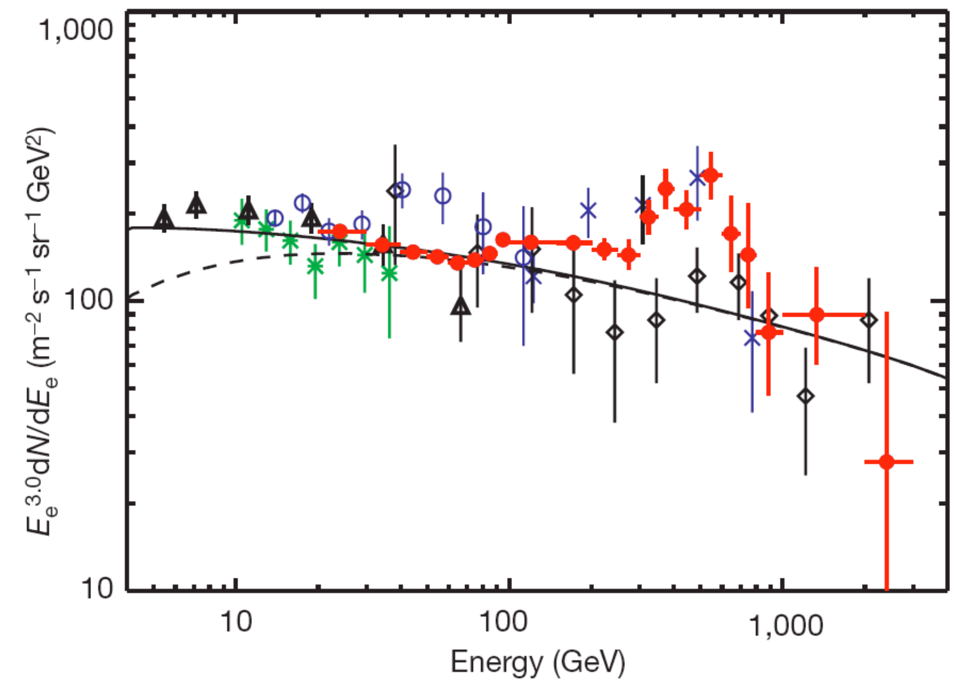
(2) a contribution from near-by astrophysical sources, such as pulsars.



ATIC

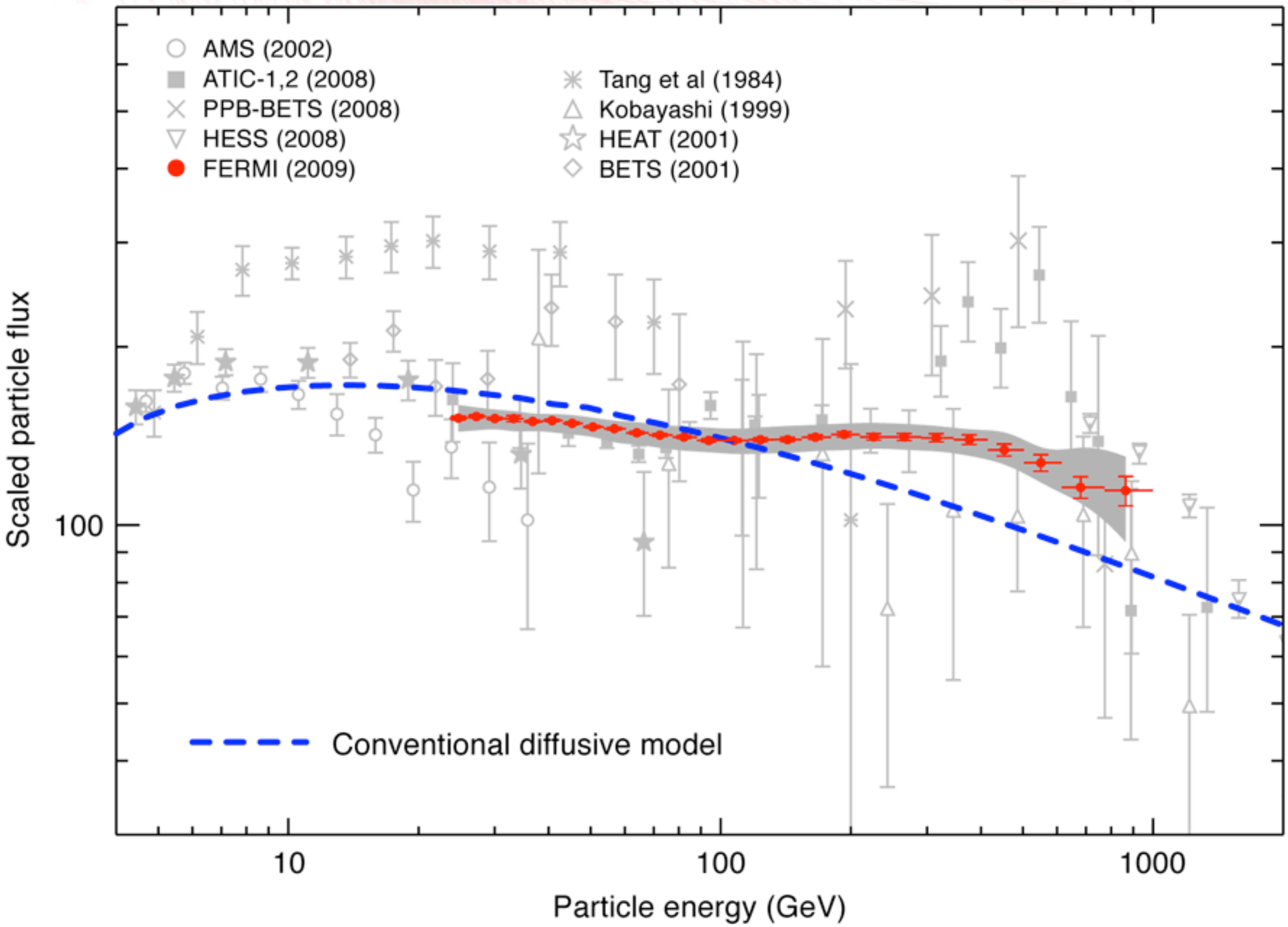
Advanced Thin Ionization Calorimeter (ATIC) observed an anomalous electron excess.





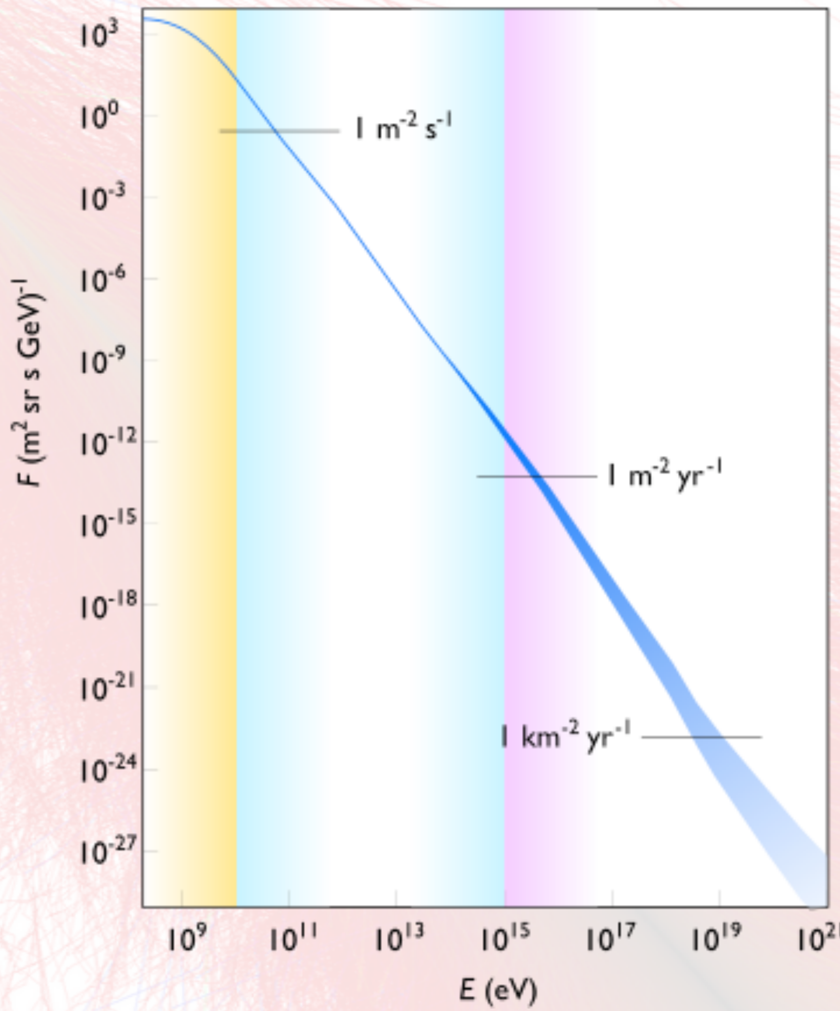
Lett to Nature Vol 456I20 November 2008

Fermi and ATIC



Galactic CR

- The total energy density of CR particles is about 1 eV/ cm^{-3}.
- About 1% of energy from SN required to sustain CR abundance.
- At 1 TeV, B~1uG, Gyro-Radius ~ 200AU (5x size of Solar System), 0.001pc → Highly isotropic

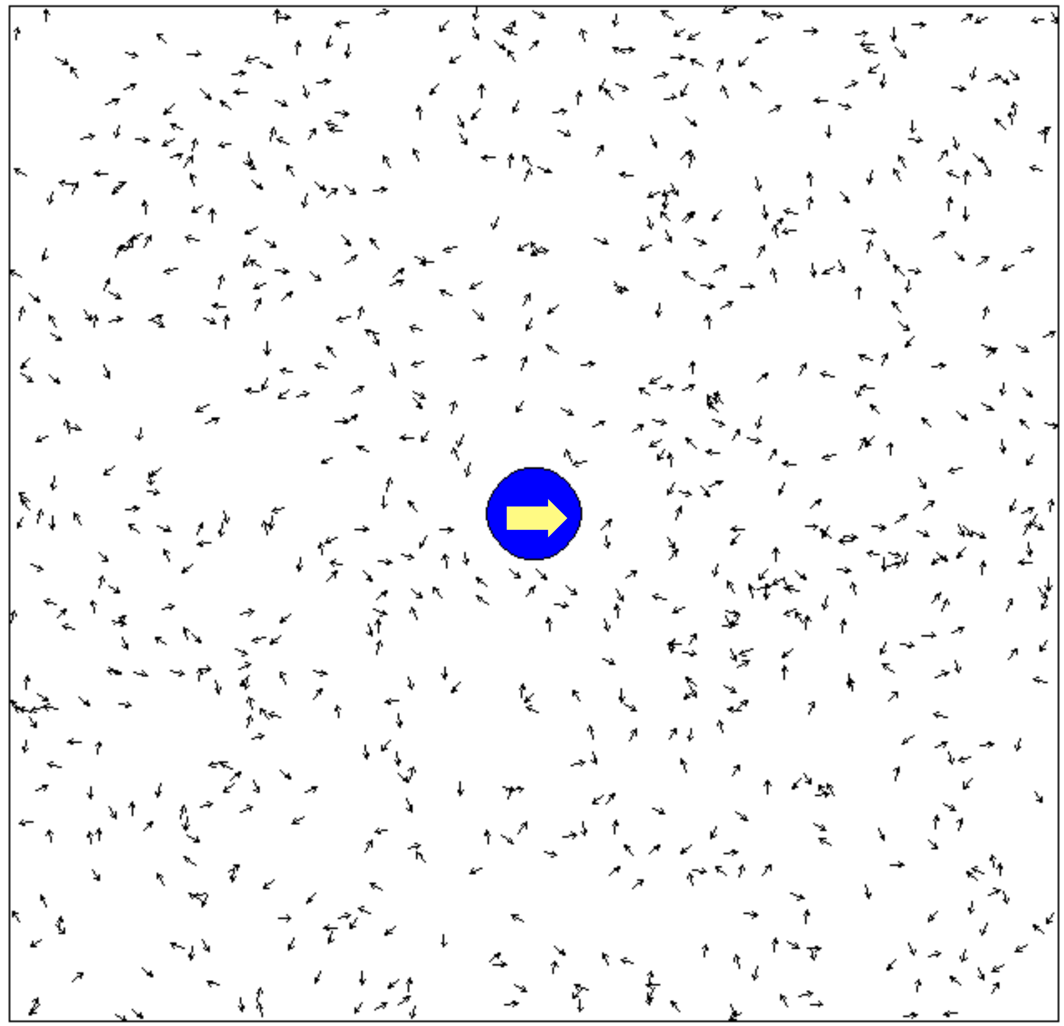


Compton-Getting Effect

The motion of the earth through a cosmic-ray 'aether' creates a forward-backward anisotropy in the direction of motion

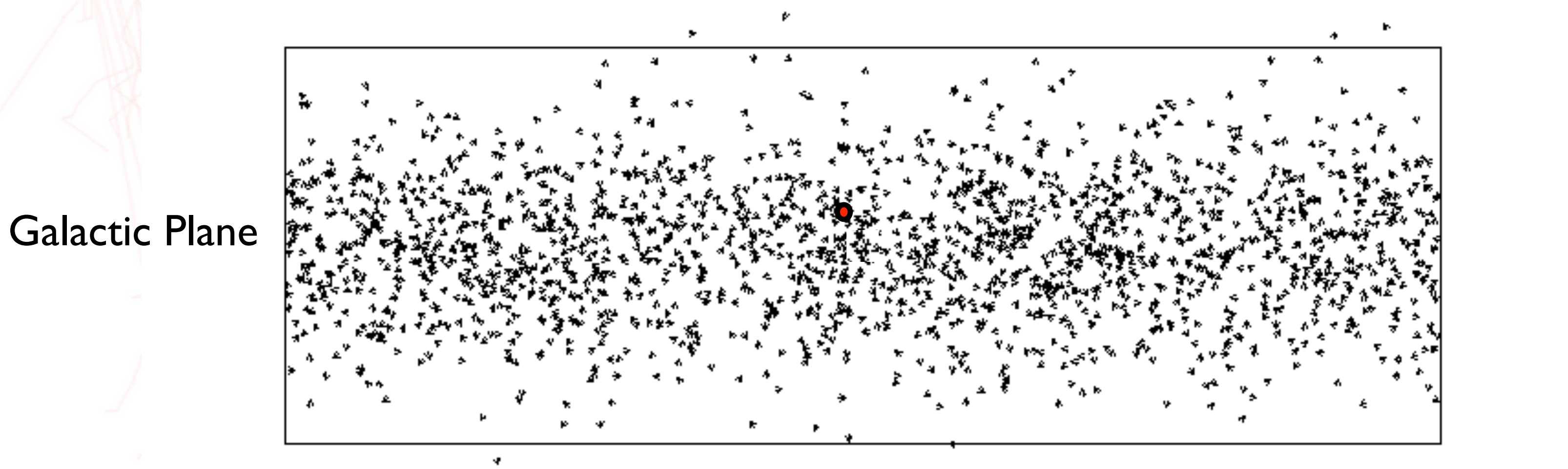
If CR's stationary w.r.t galactic rotation, a large anisotropy should be visible (~0.5%).

Phys Rev Vol 47, No11 (1935)

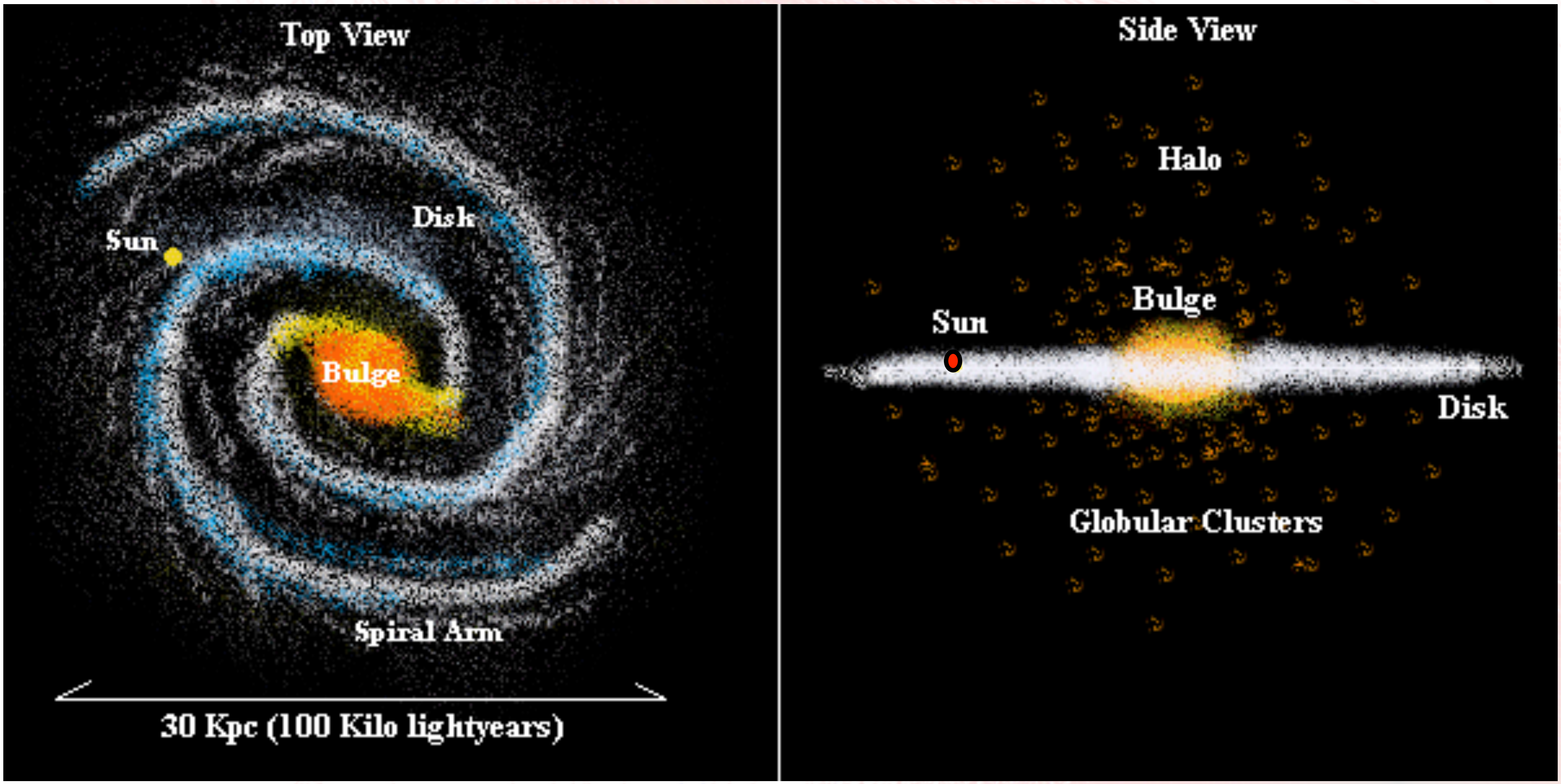


Other sources of anisotropy

- Diffusion from the galactic plane (higher matter density) into the galactic halo (lower matter density).



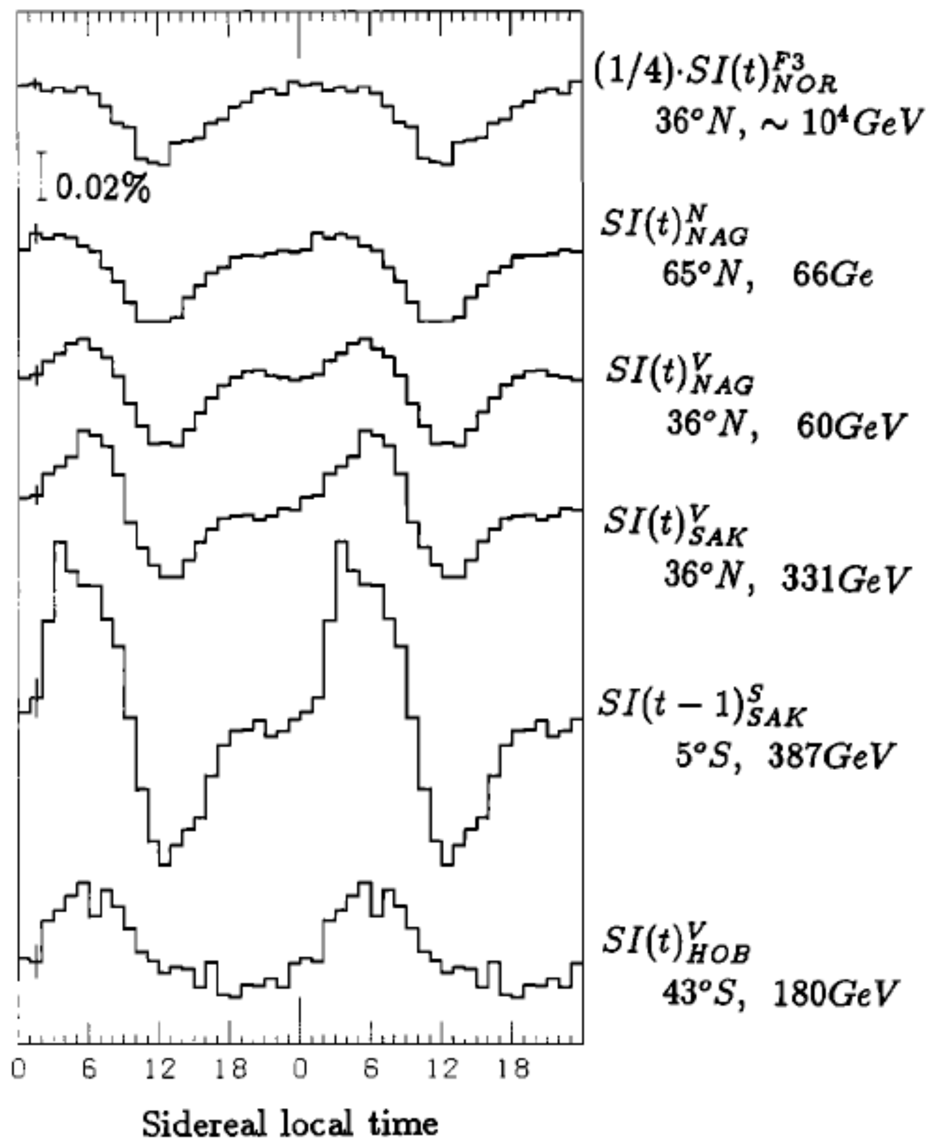
- Local CR sources.


Top View
Disk
Sun
Bulge
Spiral Arm
30 Kpc (100 Kilo lightyears)
Side View
Halo
Bulge
Sun
Disk
Globular Clusters

Early detection of Anisotropy

Sidereal counting rates for various experiments

Anisotropy ~few parts in 10,000 observed.

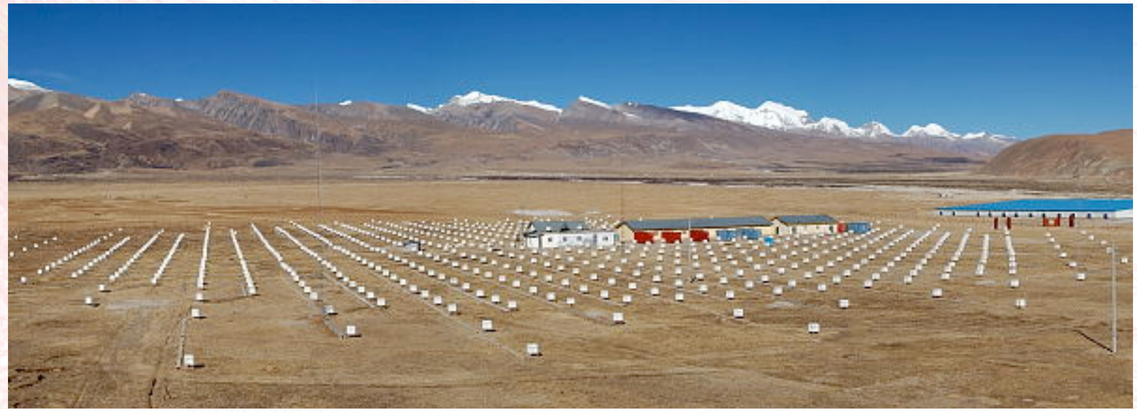


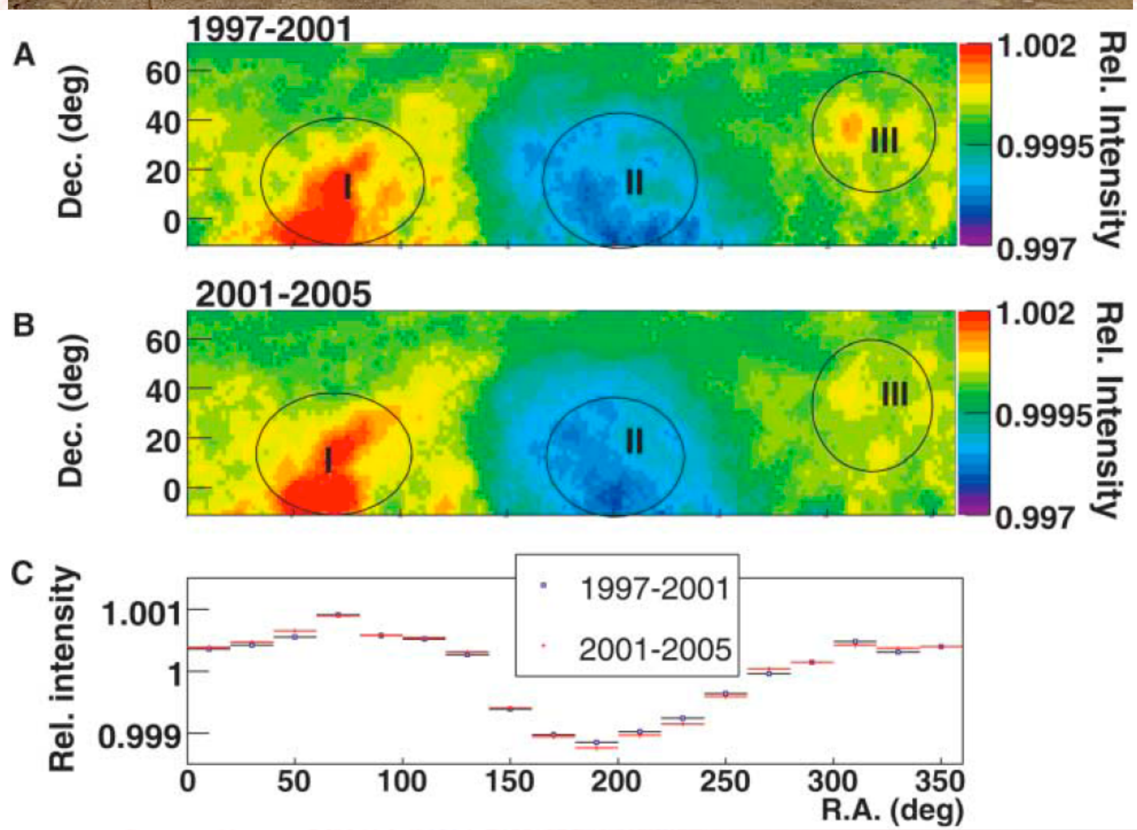
Nagashima, K., K. Fujimoto, and R. M. Jacklyn (1998) J.Geophys. Res., 103(A8), 17,429–17,440.

Tibet Air Shower Array

2006-
High statistics examination of anisotropy with a surface detector

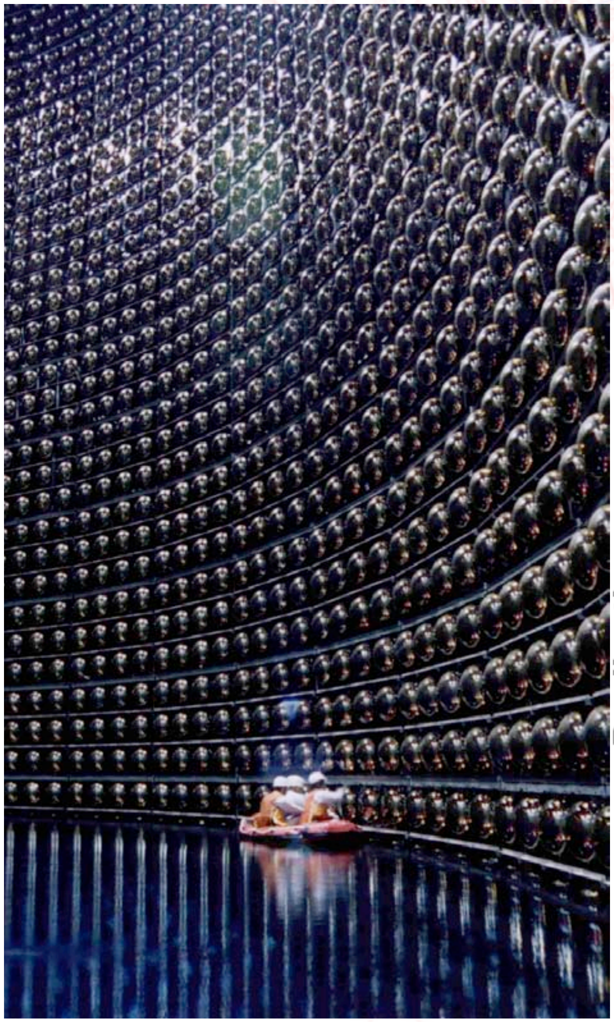
Dipole amplitude ~4/1,000ths



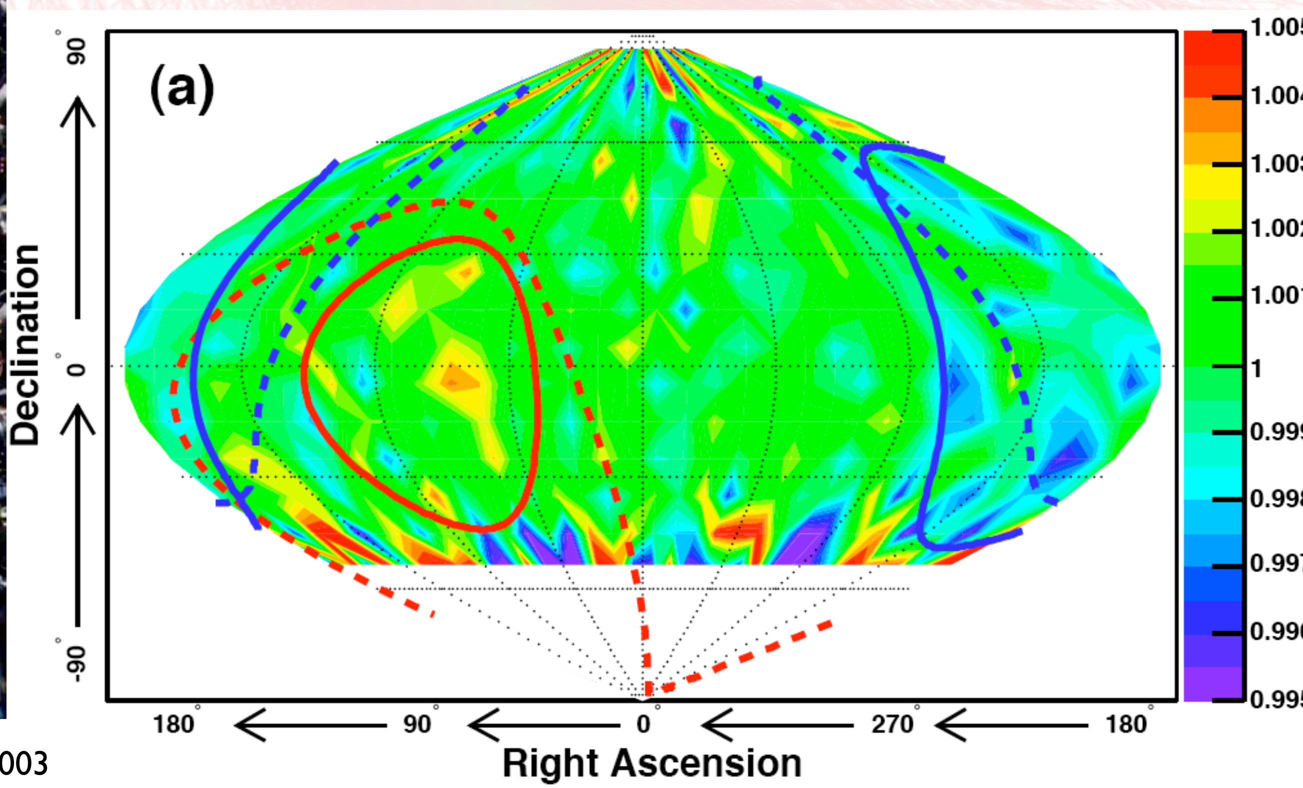


M. Amenomori, *et al. Science* ***314****, 439 (2006)*

Super-K neutrino detector

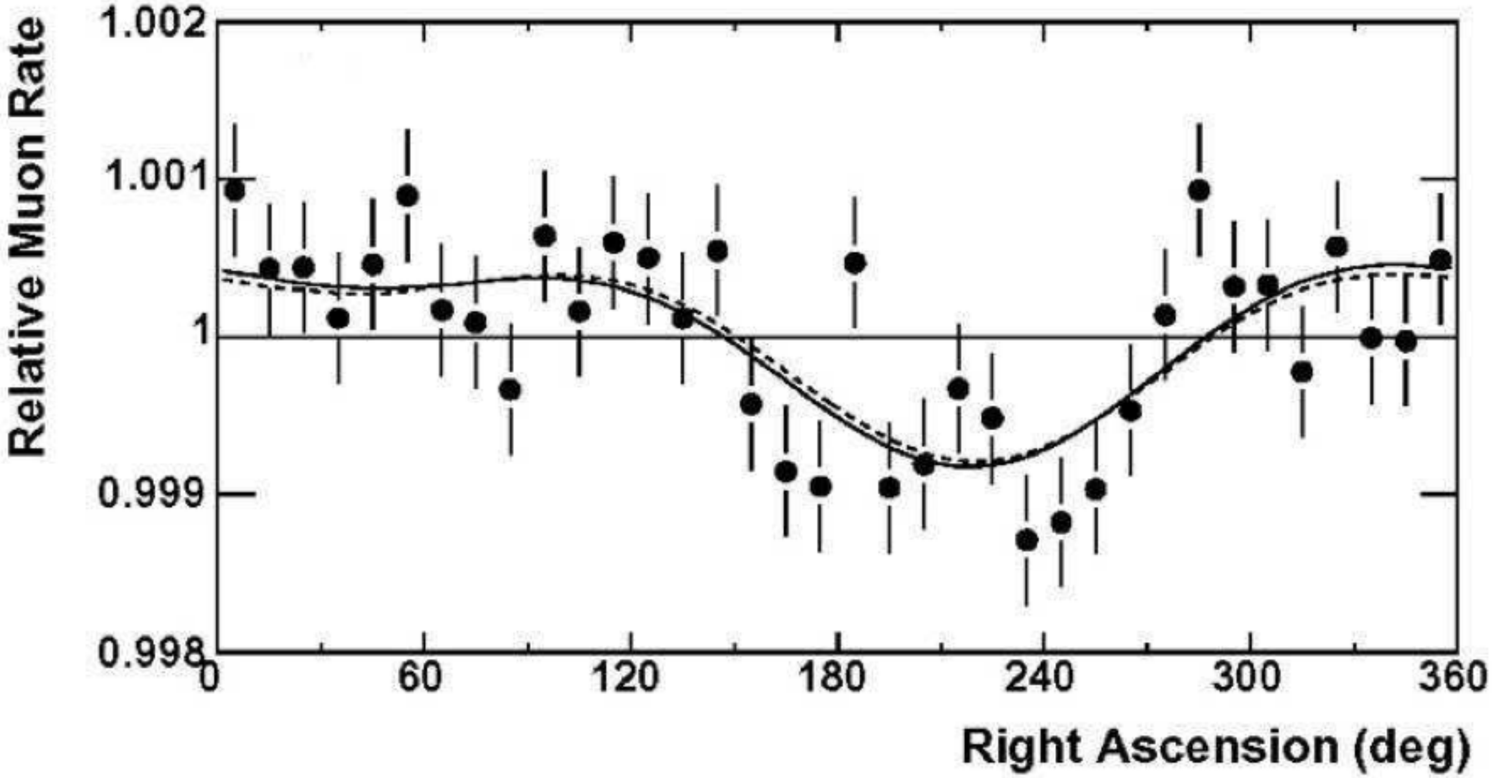


Observe muon secondaries from CR air showers



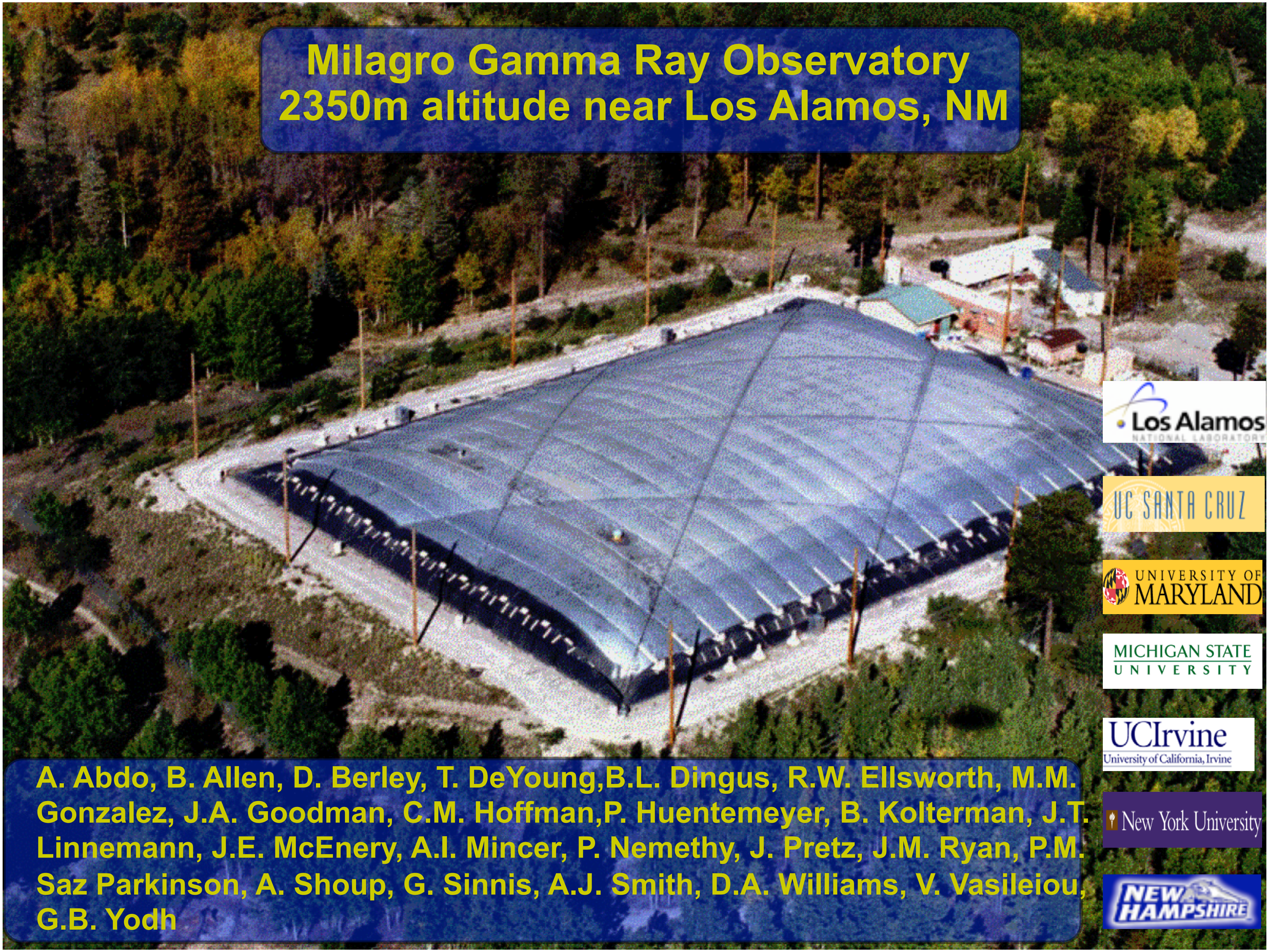
Guillian et al,Phys.Rev. D75 (2007) 062003

Super-K



Relative Muon Rate
1.002
1.001
1
0.999
0.998
0
60
120
180
240
300
360
Right Ascension (deg)

Milagro Gamma Ray Observatory
2350m altitude near Los Alamos, NM



A. Abdo, B. Allen, D. Berley, T. DeYoung,B.L. Dingus, R.W. Ellsworth, M.M. Gonzalez, J.A. Goodman, C.M. Hoffman,P. Huentemeyer, B. Kolterman, J.T. Linnemann, J.E. McEnery, A.I. Mincer, P. Nemethy, J. Pretz, J.M. Ryan, P.M. Saz Parkinson, A. Shoup, G. Sinnis, A.J. Smith, D.A. Williams, V. Vasileiou, G.B. Yodh

Los Alamos NATIONAL LABORATORY

UC SANTA CRUZ

UNIVERSITY OF MARYLAND

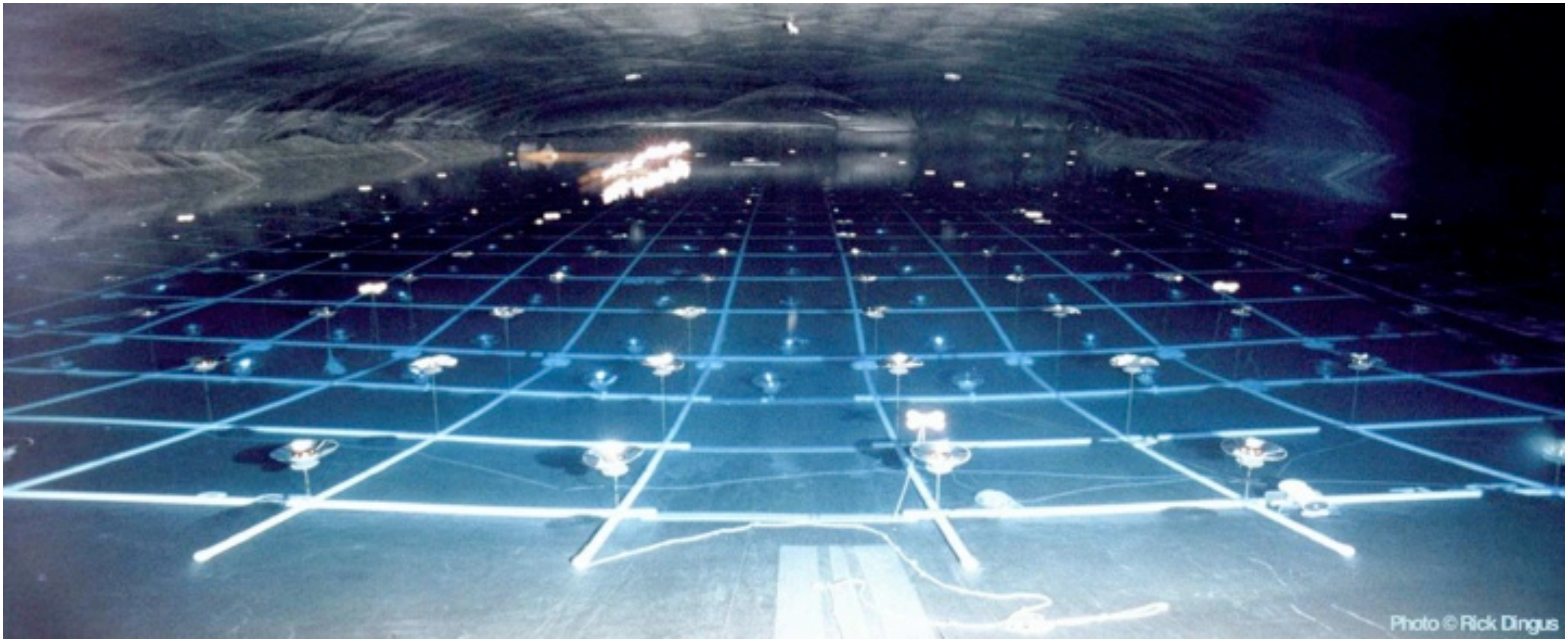
MICHIGAN STATE UNIVERSITY

UCIrvine University of California, Irvine

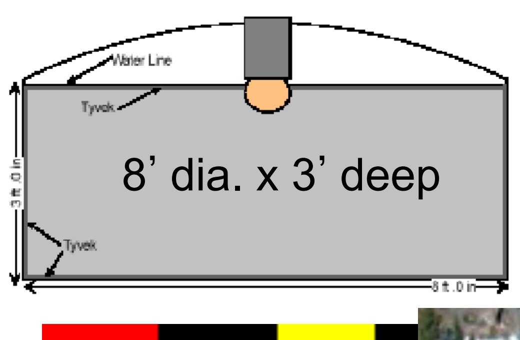
New York University

NEW HAMPSHIRE

Inside the Milagro Detector



Array of 175 Outriggers



Milagro Operations

2001-2004
Pond Only

2004-2008
Full Detector

Operations Ended in May 2008

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 48 NUMBER 5 JUNE 2008

Milagro maps out gamma-ray sky

MUON COOLING
MICE beam takes its first steps p5

LHC FOCUS
Big wheels to detect muons in ATLAS p30

OPEN DAYS
When the world came to see CERN p35

Trigger: ~60 PMTs hit within 180ns window

Event Rate ~1700 Hz with 8% dead time. Due almost entirely to CR p(70%) He(25%) C,O, Ne, Mg,Si,Fe(5%)

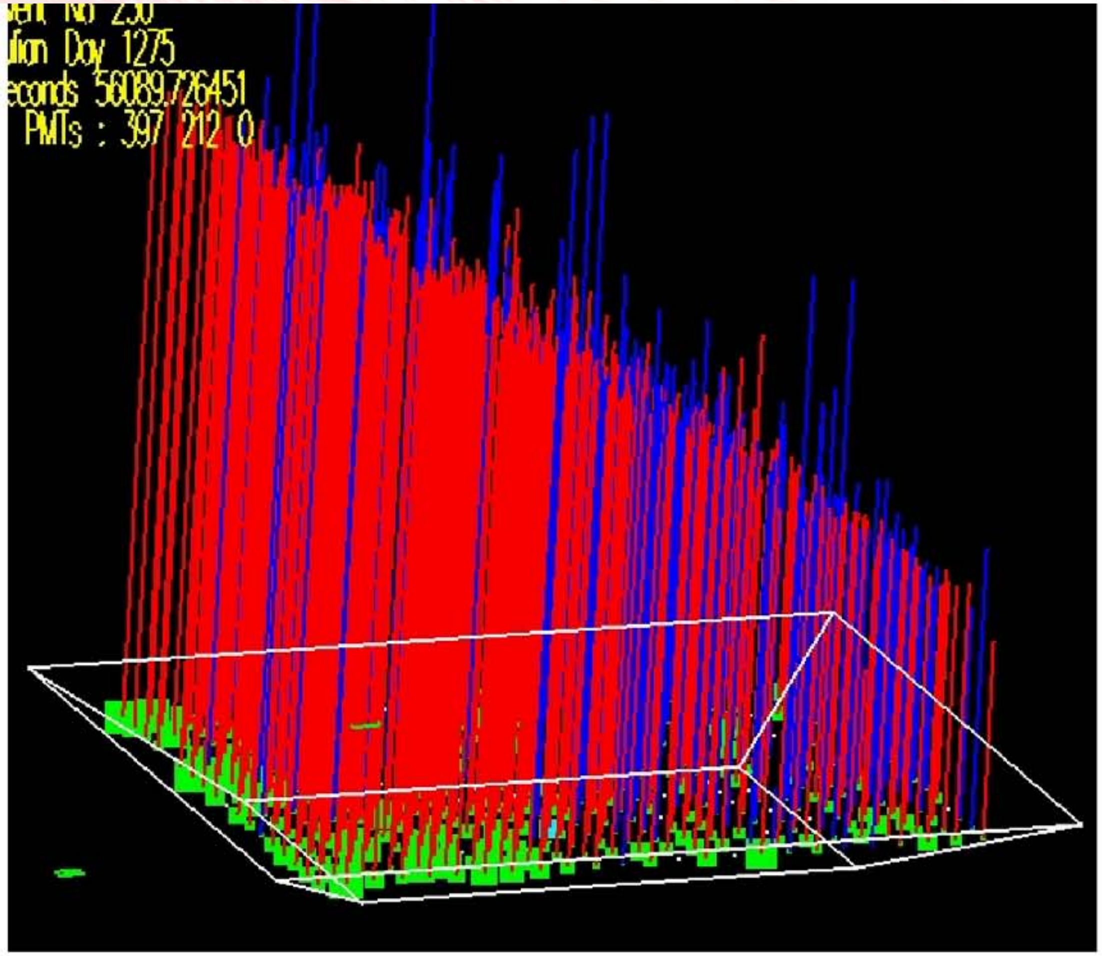
Operational for 7 years, 4 years with outrigger array.

>90% on-time

Online reconstruction only, "raw" data not recorded.

Angular resolution <1°

>300 x 10^9 events logged.



2 Approaches to CR anisotropy

1) Forward backward asymmetry method to study "large scale anisotropy".

Derive shape of large scale features.

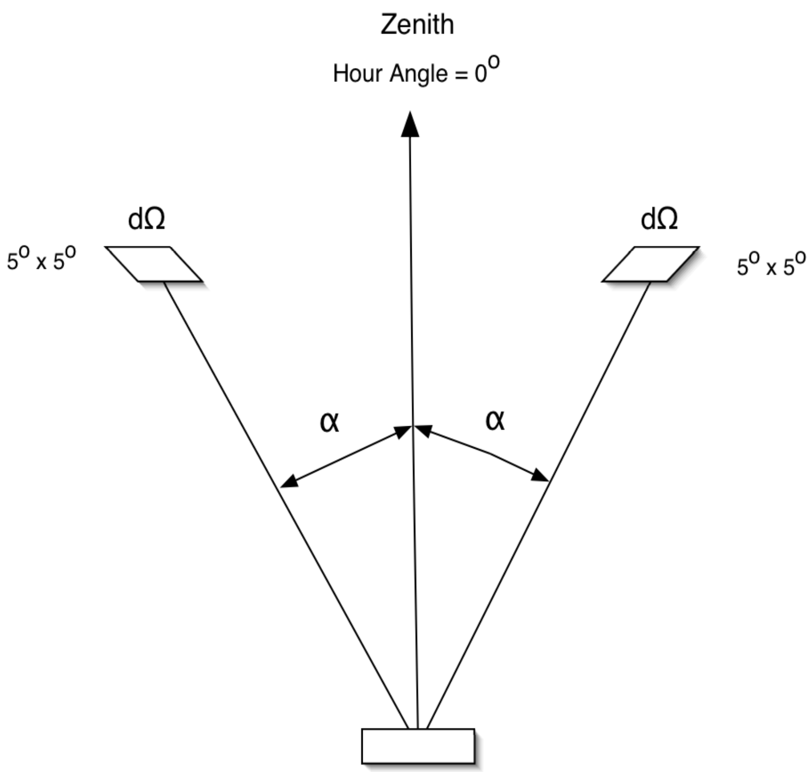
2) "Direct Integration" background subtraction to study "intermediate scale anisotropy".

Background derived from vicinity of source.
High pass filter.

Systematics in Anisotropy Measurements

- Systematic effects can be large:
  - Day/night variations
  - Seasonal variations
    - Milagro rate depends on atm pressure
    - Afternoon thunderstorms happen in the summer afternoons when a particular region of the sky is overhead
    - The top of the pond freezes at night in the winter...

Search for Large scale anisotropy



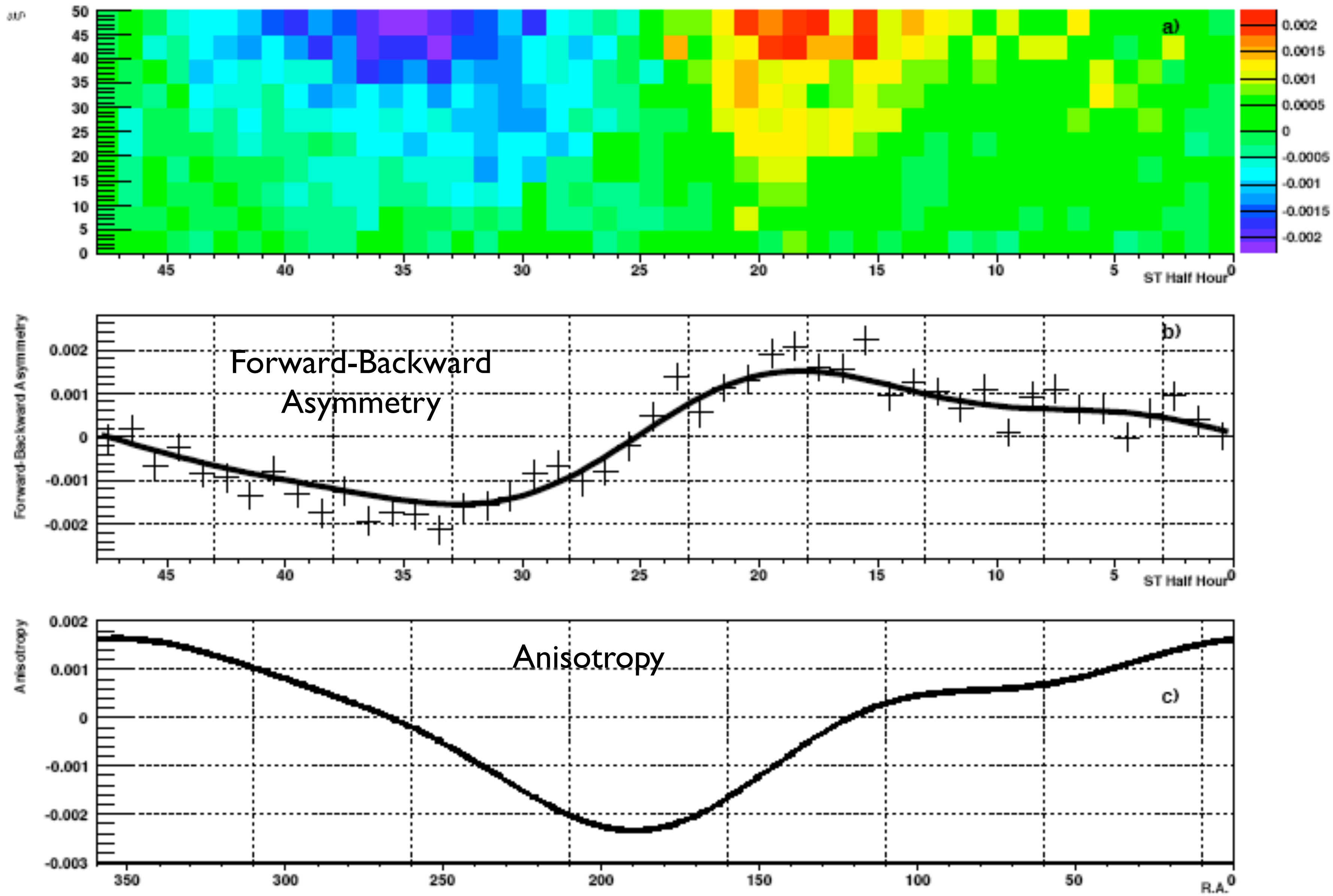
Forward-backward asymmetry technique

This technique basically takes a derivative of the rate wrt position in the sky and is independent of overall rate

Declination strips (5 degrees)

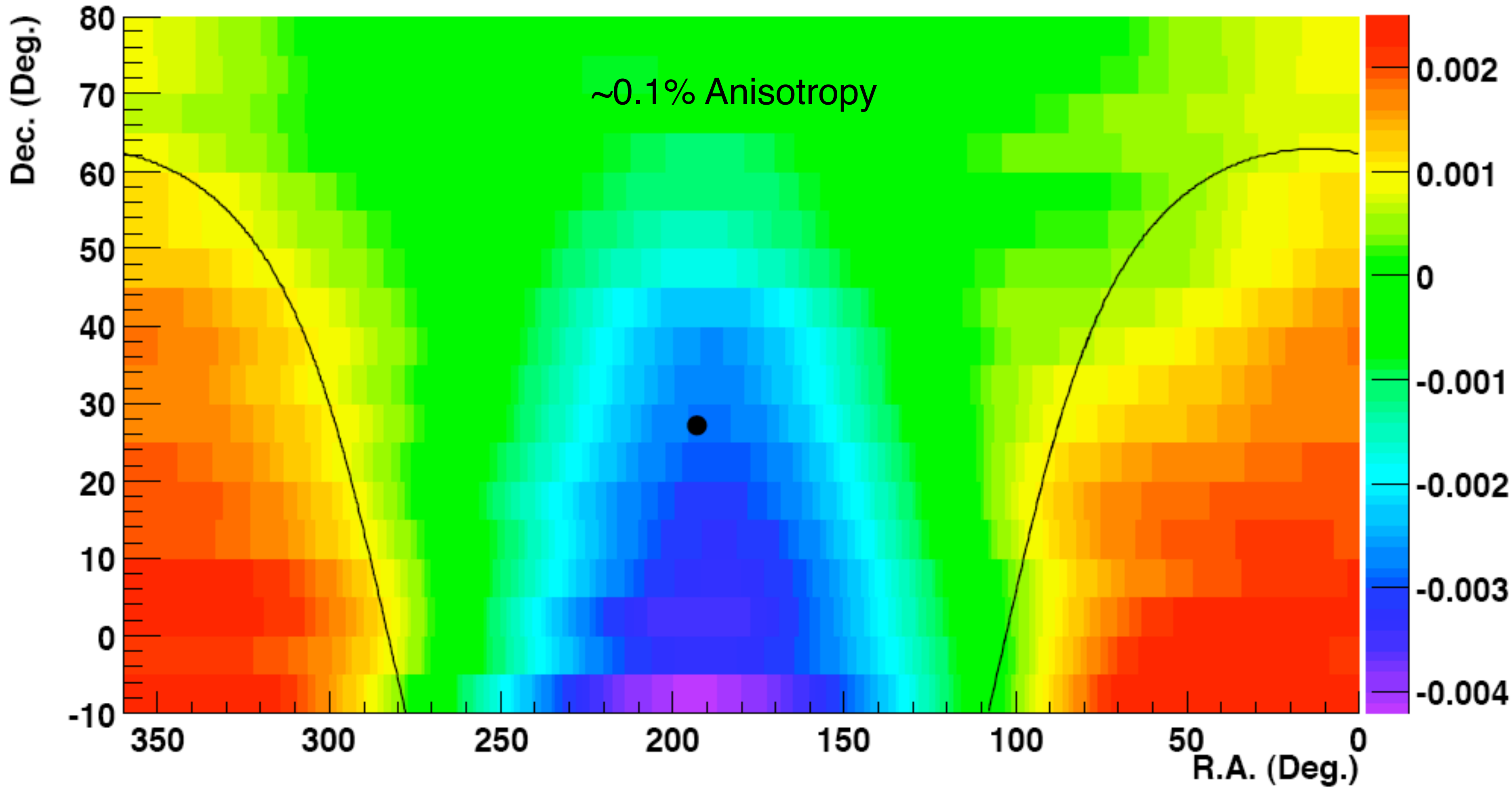
$$FBAsymmetry(\theta,\alpha) = \frac{R(\theta+\alpha) - R(\theta-\alpha)}{R(\theta+\alpha) + R(\theta-\alpha)}$$

7 years of data
95 billion events in sample
6 TeV median proton energy

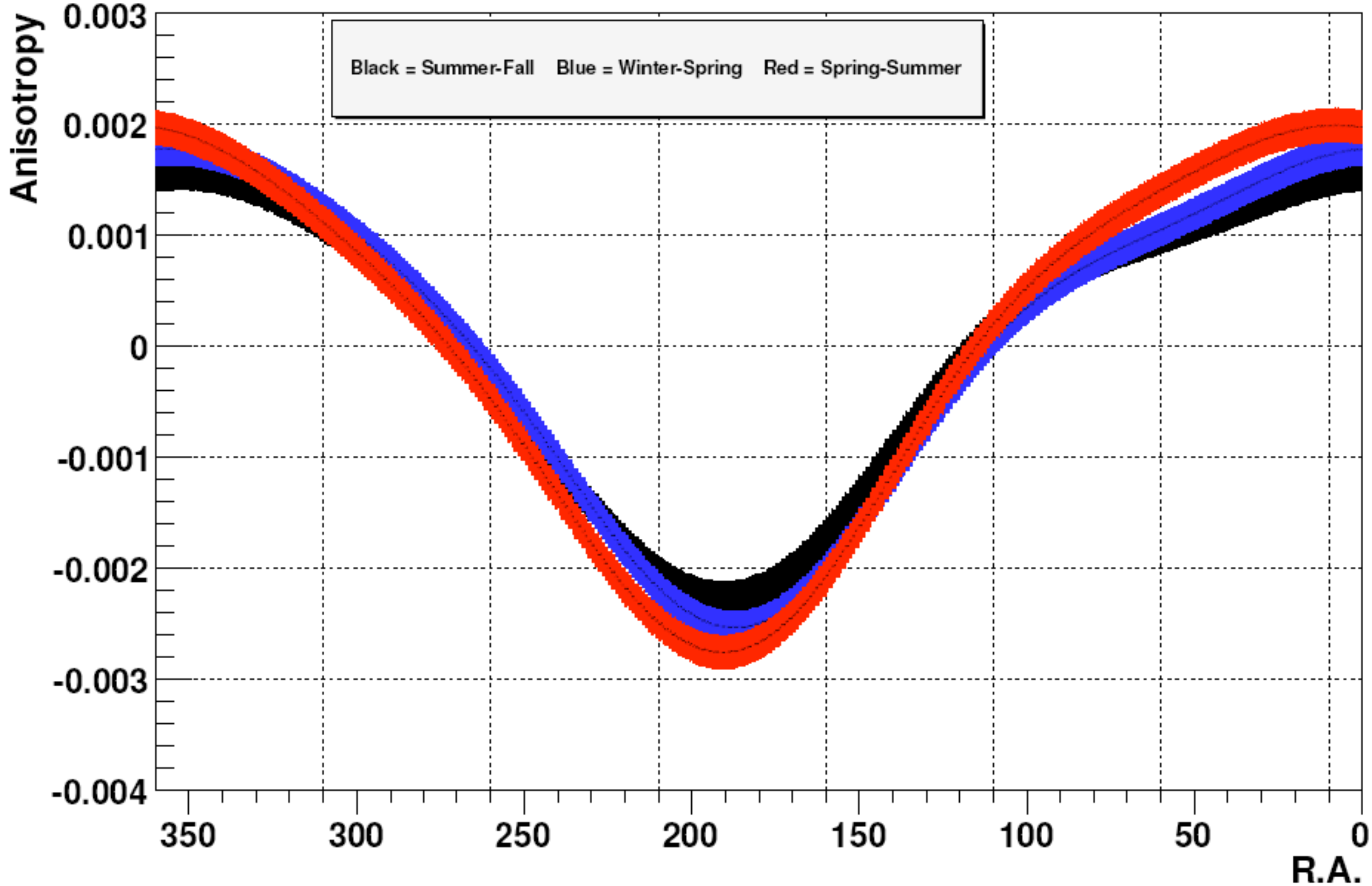


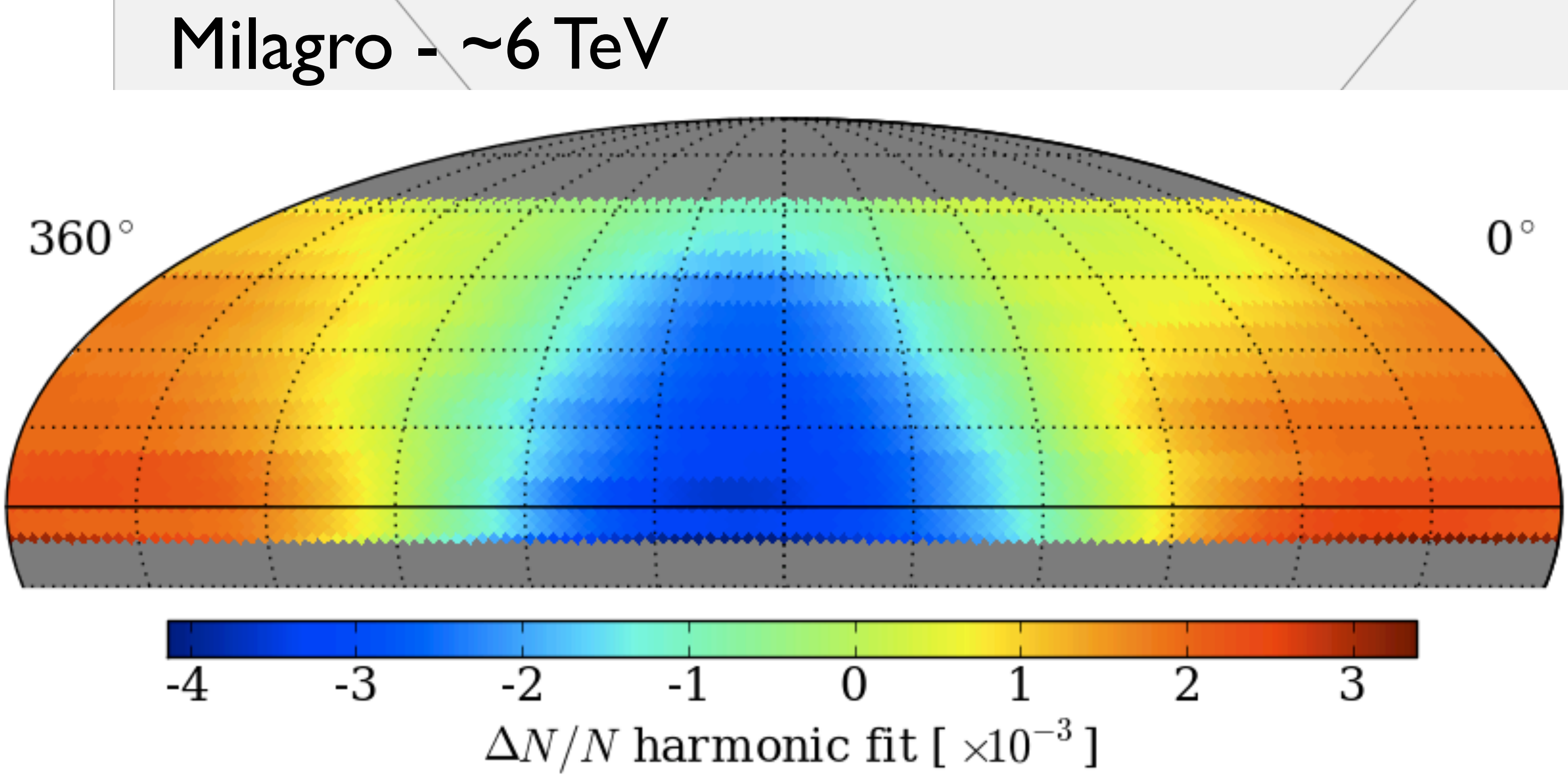
a)
b)
Forward-Backward Asymmetry
c)
Anisotropy
ST Half Hour
R.A.
Forward-Backward Asymmetry
Anisotropy

Sky Map of CR large scale anisotropy (Declination strips are not correlated)

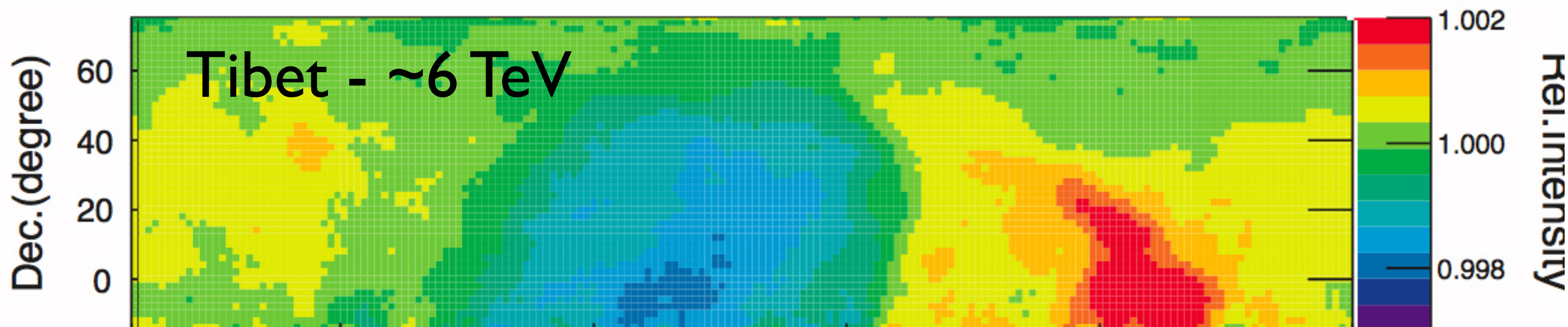


Seasonal Variation



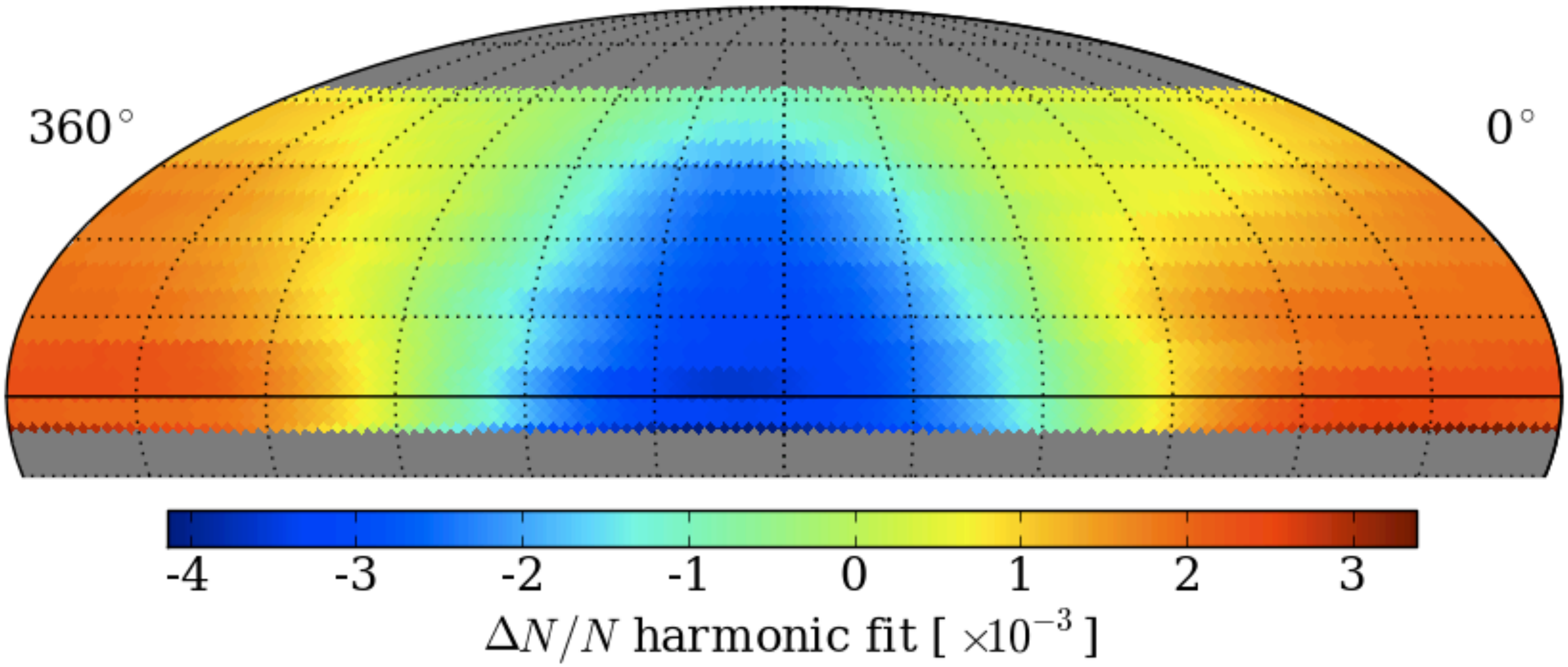


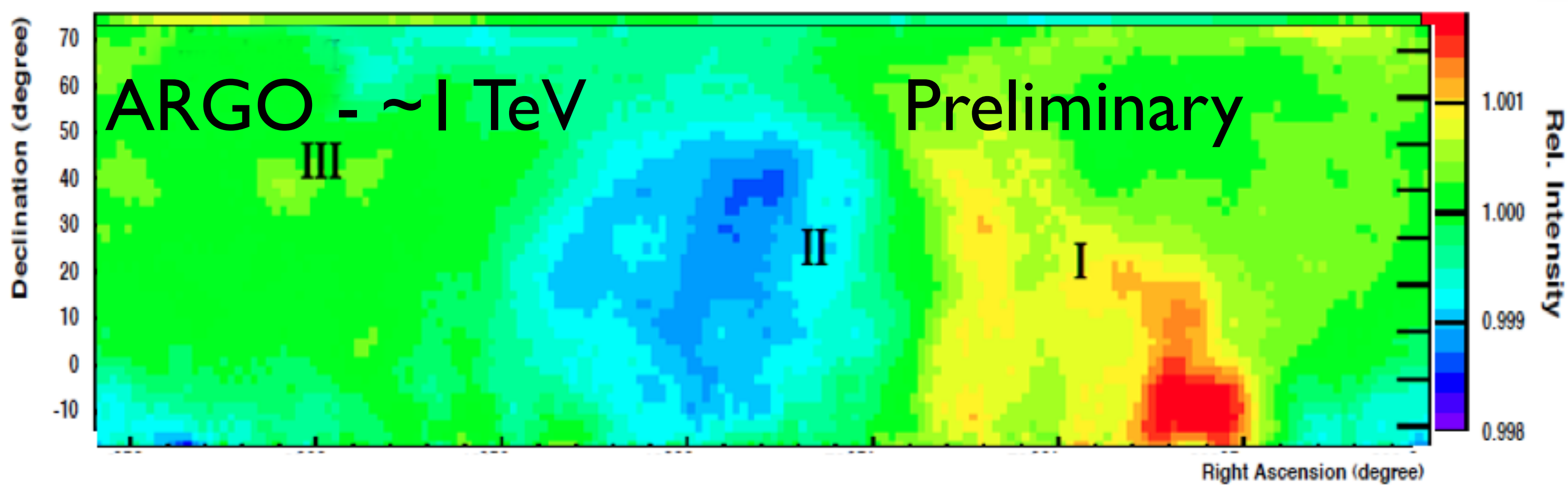
Milagro - ~6 TeV
360°
0°
-4
-3
-2
-1
0
1
2
3
$\Delta N/N$ harmonic fit [$\times 10^{-3}$]



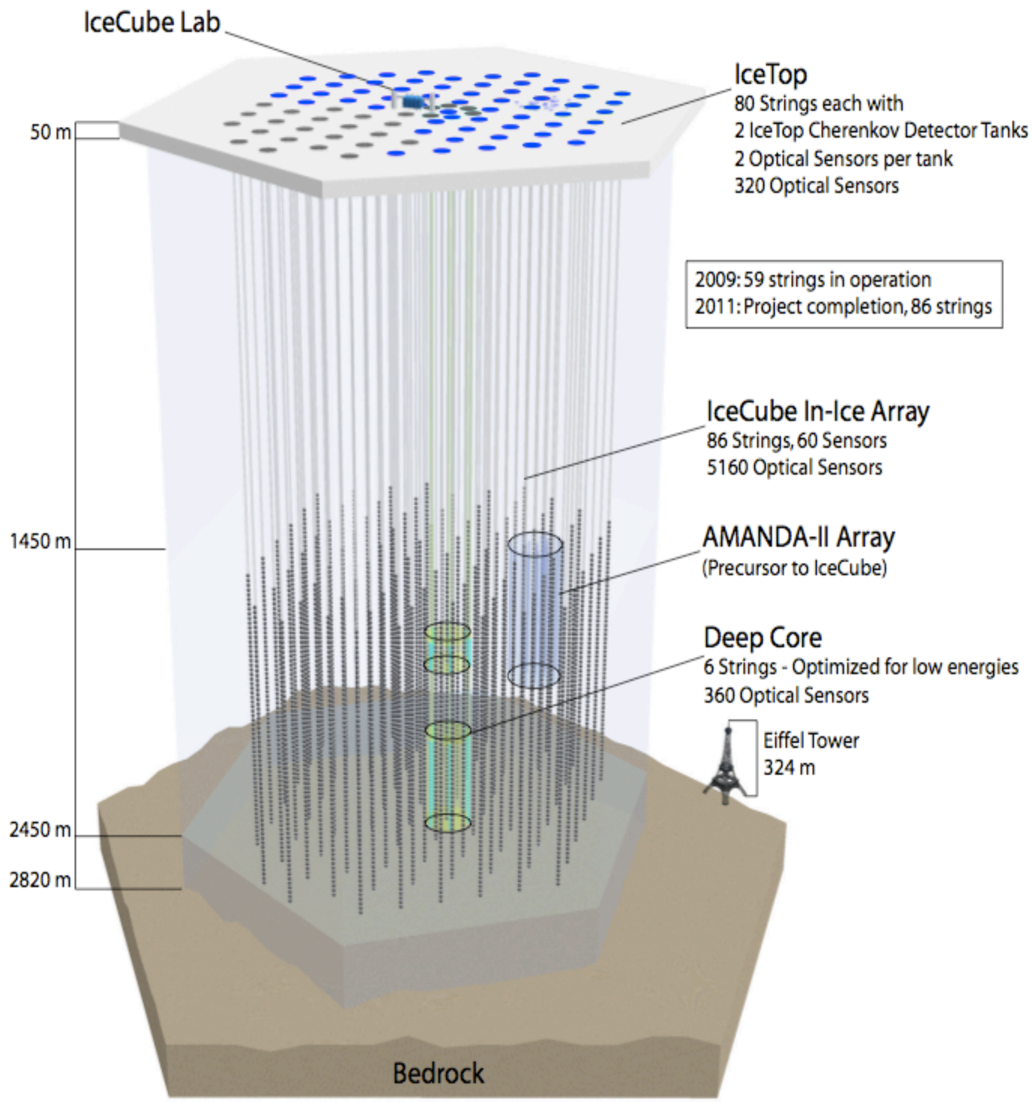
Tibet - ~6 TeV
Dec.(degree)
60
40
20
0
1.002
1.000
0.998
Rel. intensity

Milagro - ~6 TeV

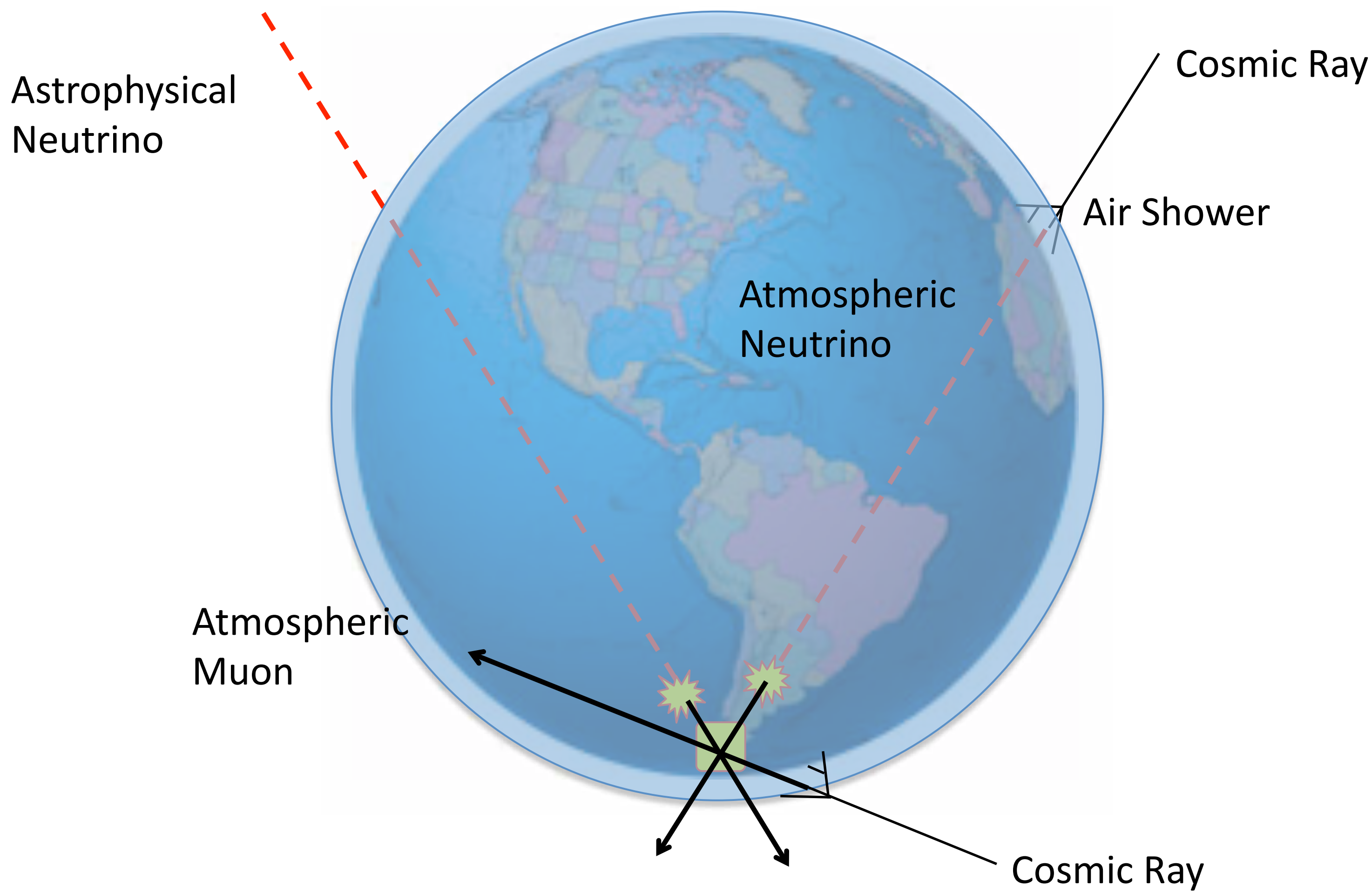




IceCube

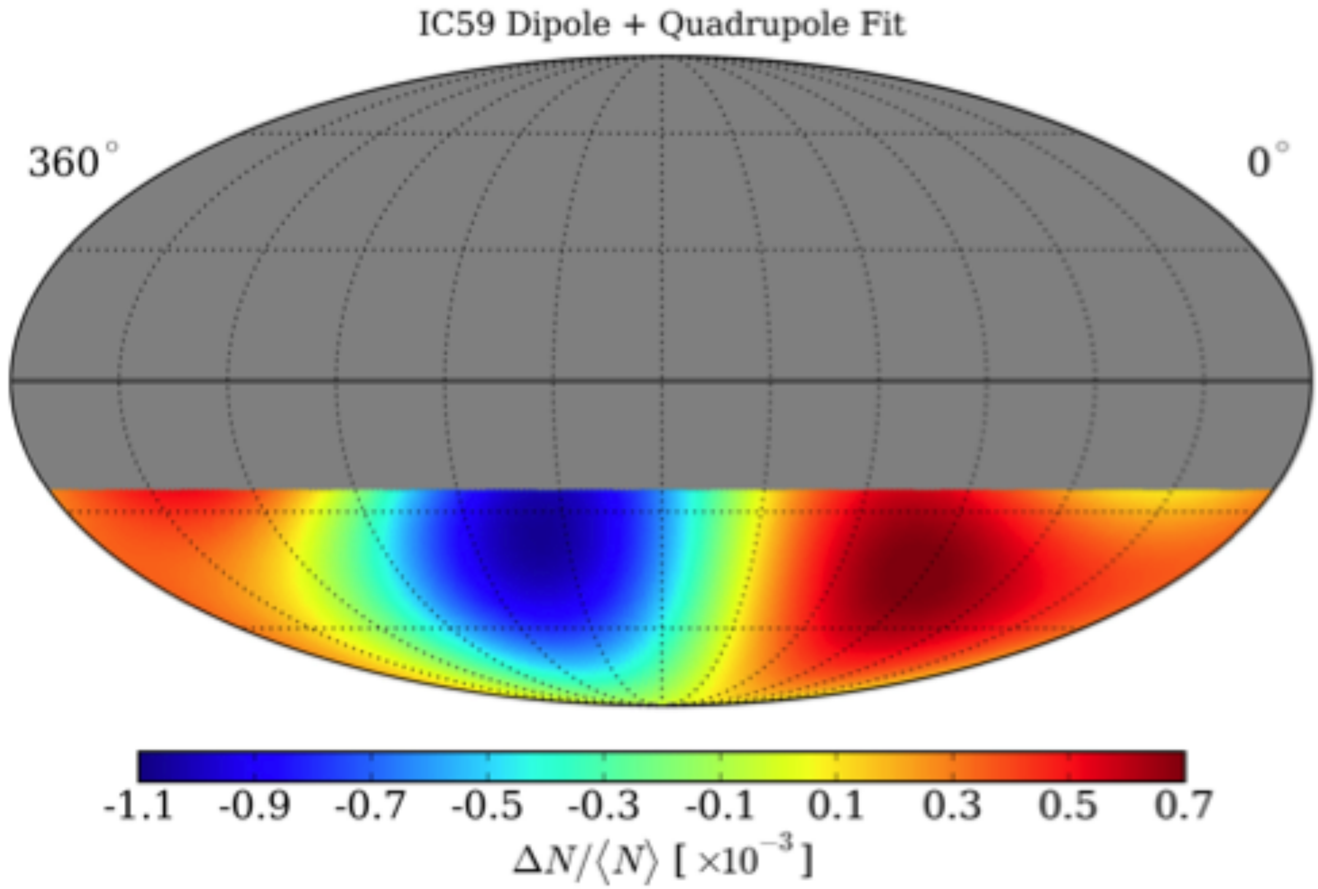

IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
2009: 59 strings in operation
2011: Project completion, 86 strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

IceCube

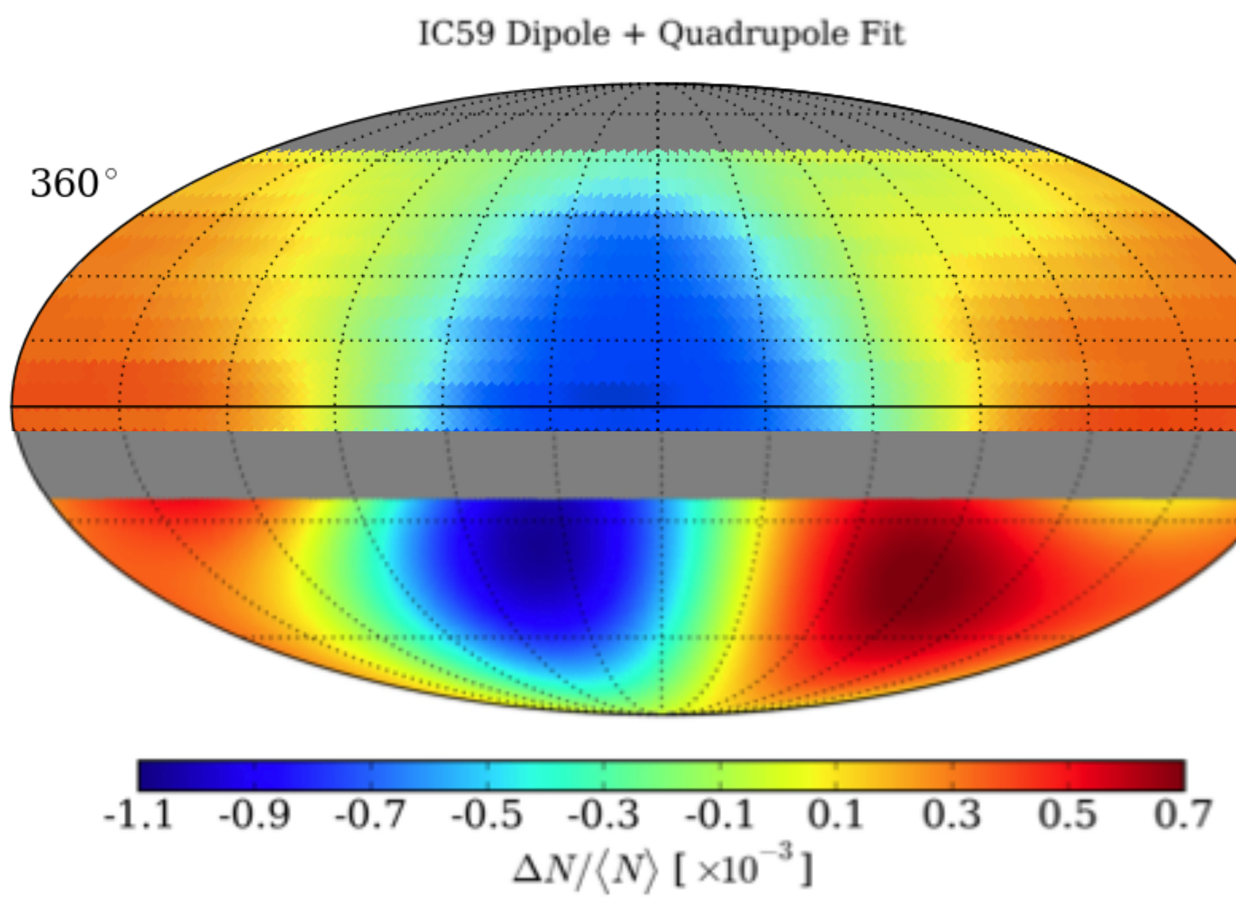


IcCube uses Atmospheric muons from the Southern Hemisphere

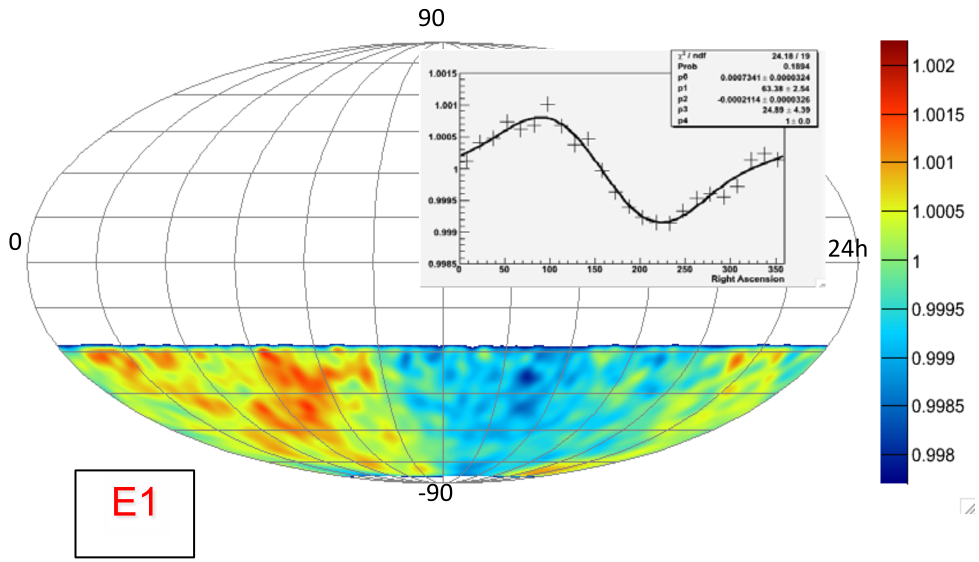
IceCube 59 string data- 2009-10

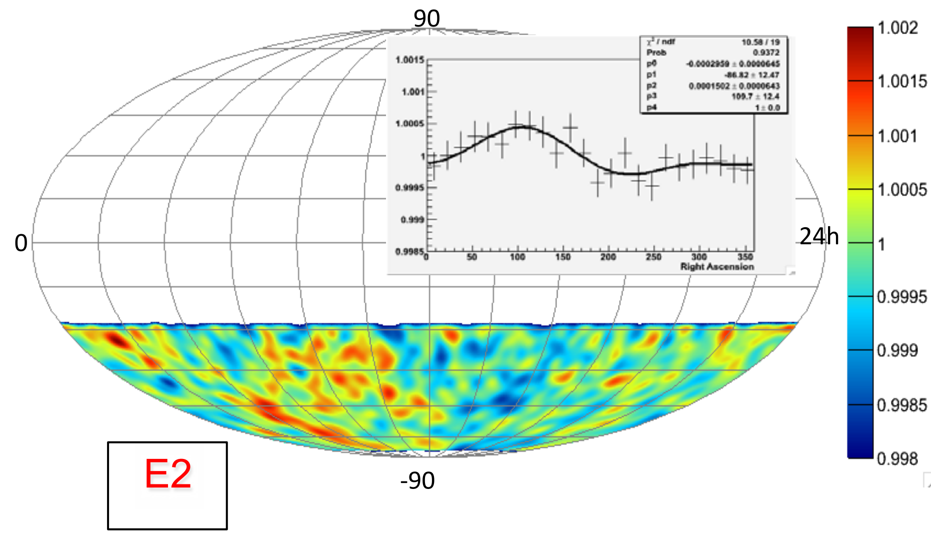


Milagro & IceCube

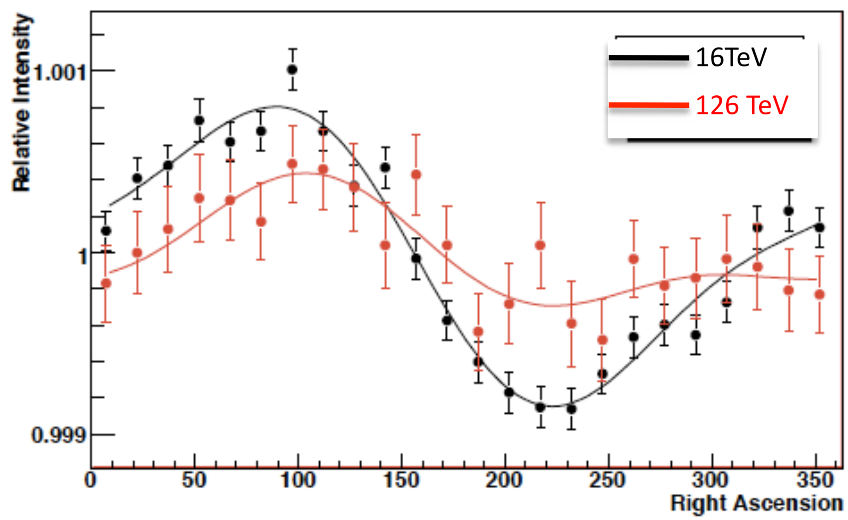


IceCube Anisotropy Persists at higher energies



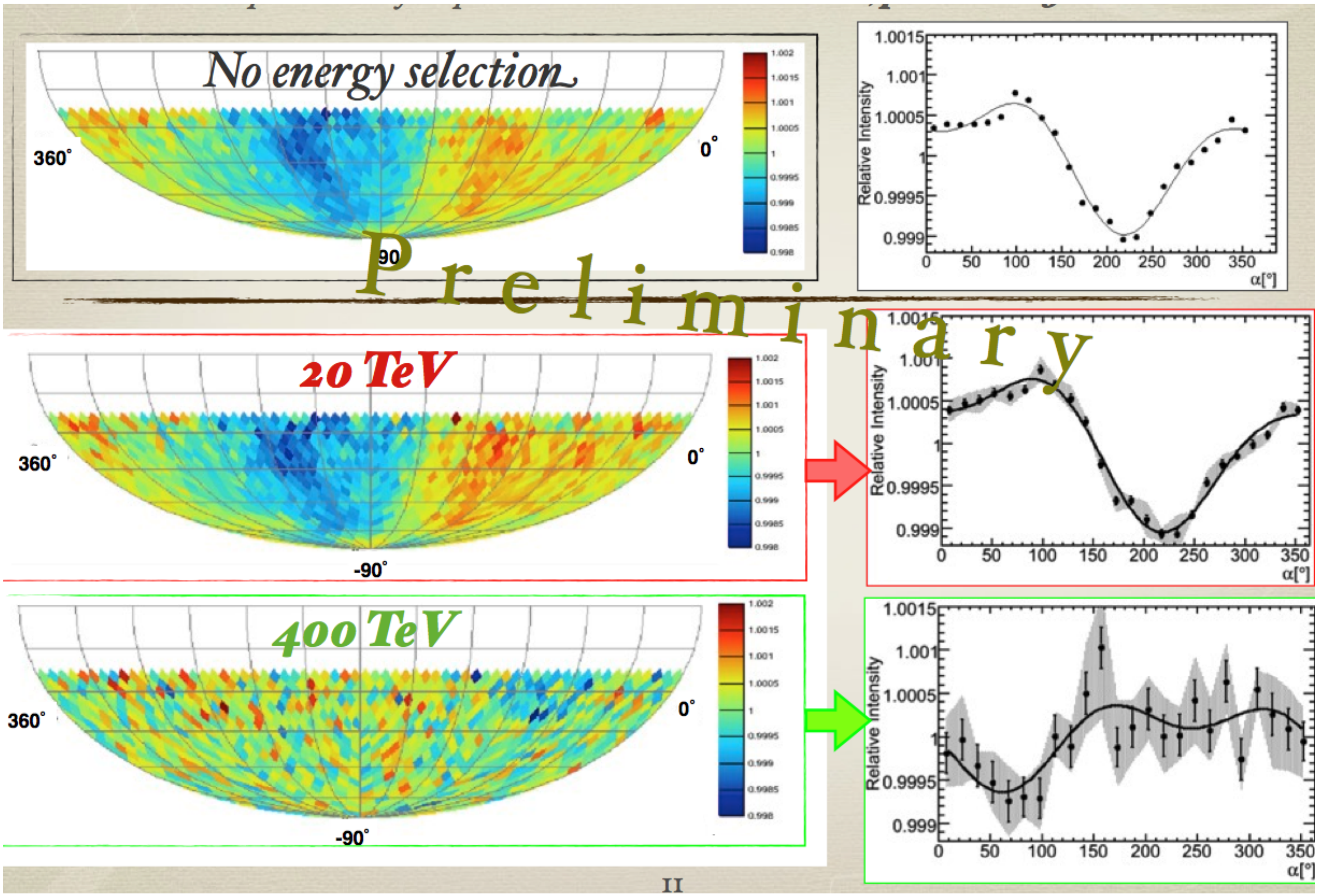


Median Energy	Number events	Amplitude x10^{-4}	Phase
16 TeV (E1)	3.3×10^{9}	7.3±0.3	63.4±2.6
126 TeV (E2)	9.6×10^{8}	2.9±0.6	93.2±12

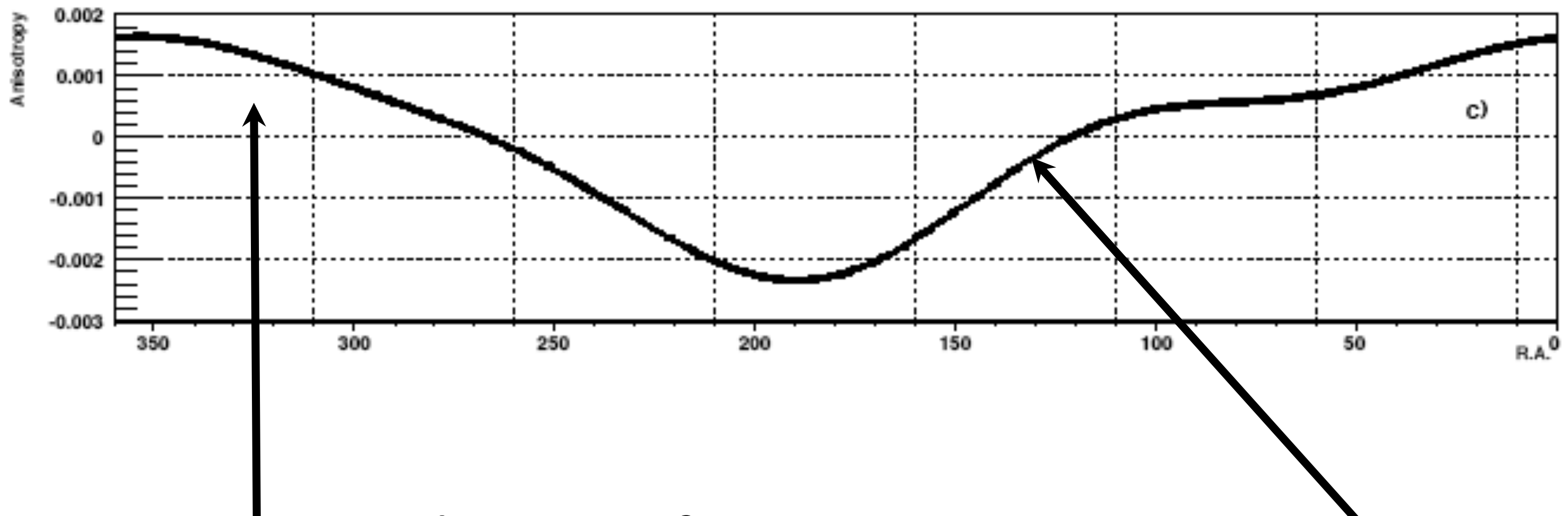


From Abbasi - Snowpac 10

IceCube Anisotropy vs Energy

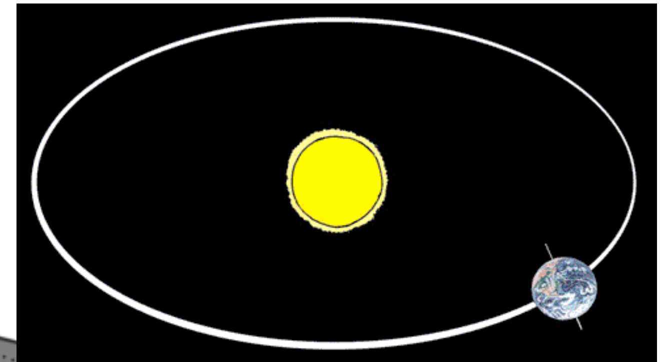


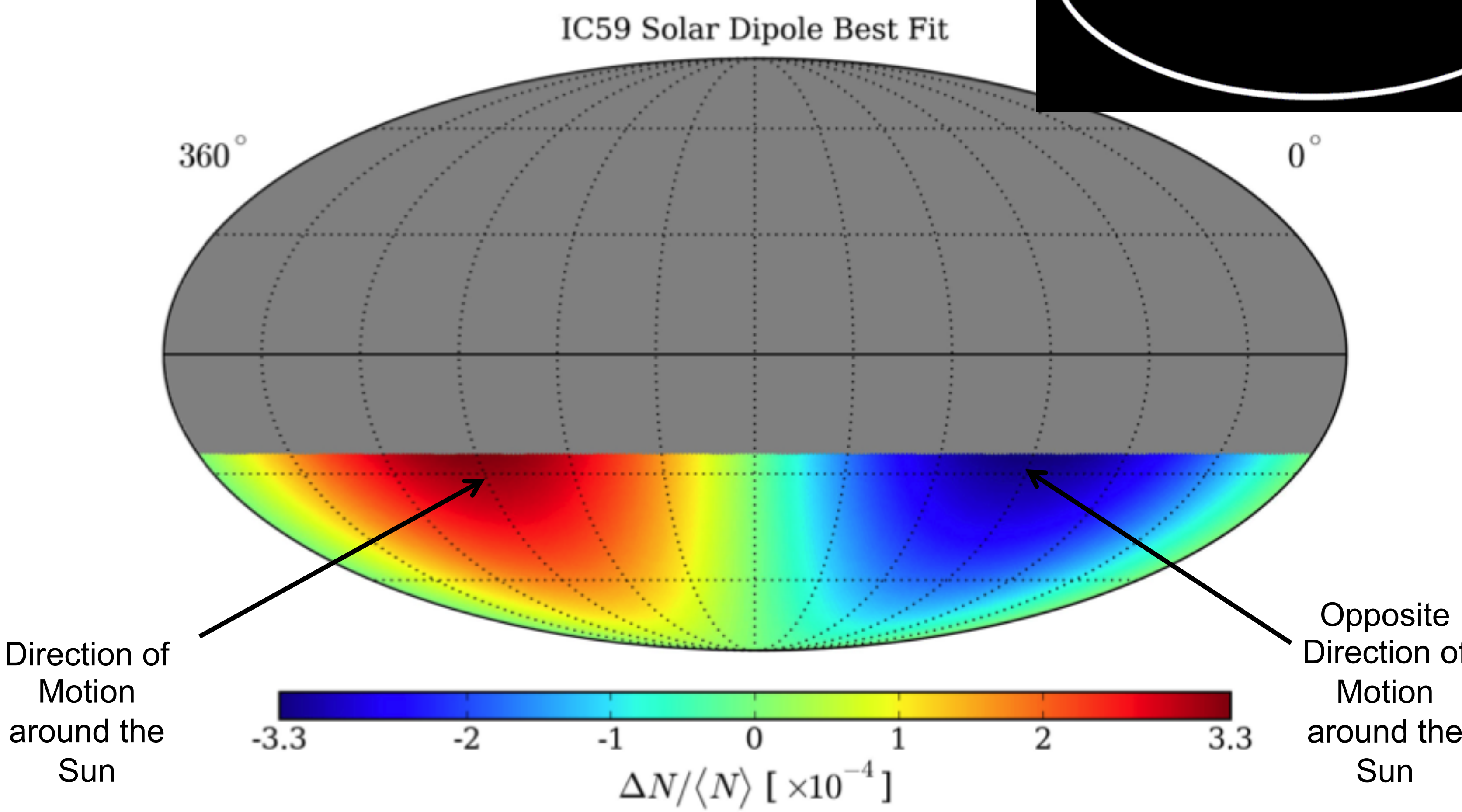
Galactic Compton Getting



- Expected excess from CG in R.A. 300-350
  - » Expected deficit from CG in R.A. 100-150
- Expected a ~0.5% anisotropy
- Unlikely a major part of the effect as Milagro sees 0.1% and in a different place

Solar "CG" Effect can be seen



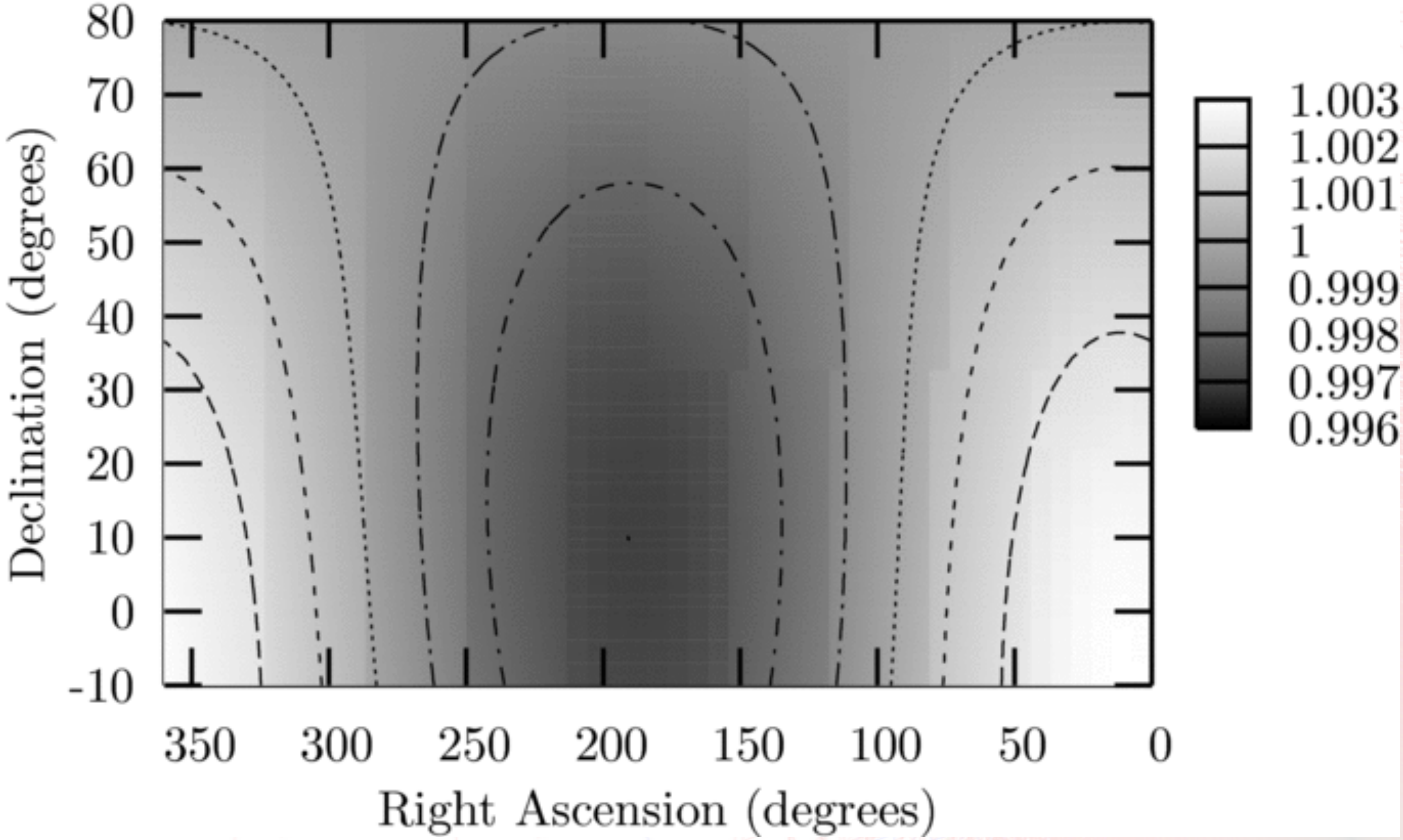


Galactic Magnetic Fields

- Eduardo Battaner, Joaqúın Castellano, and Manuel Masip '09
  - They combine effects of the regular and the turbulent (fluctuating) magnetic fields in our vicinity.
  - They use a galactic $B_{galactic}$ ~3-5 μG and a fluctuating field of B_{random} ~3-5 μG
  - They show that they can match the Milagro results in both in shape and strength
  - The preferred anisotropy direction is orthogonal to the local regular magnetic field

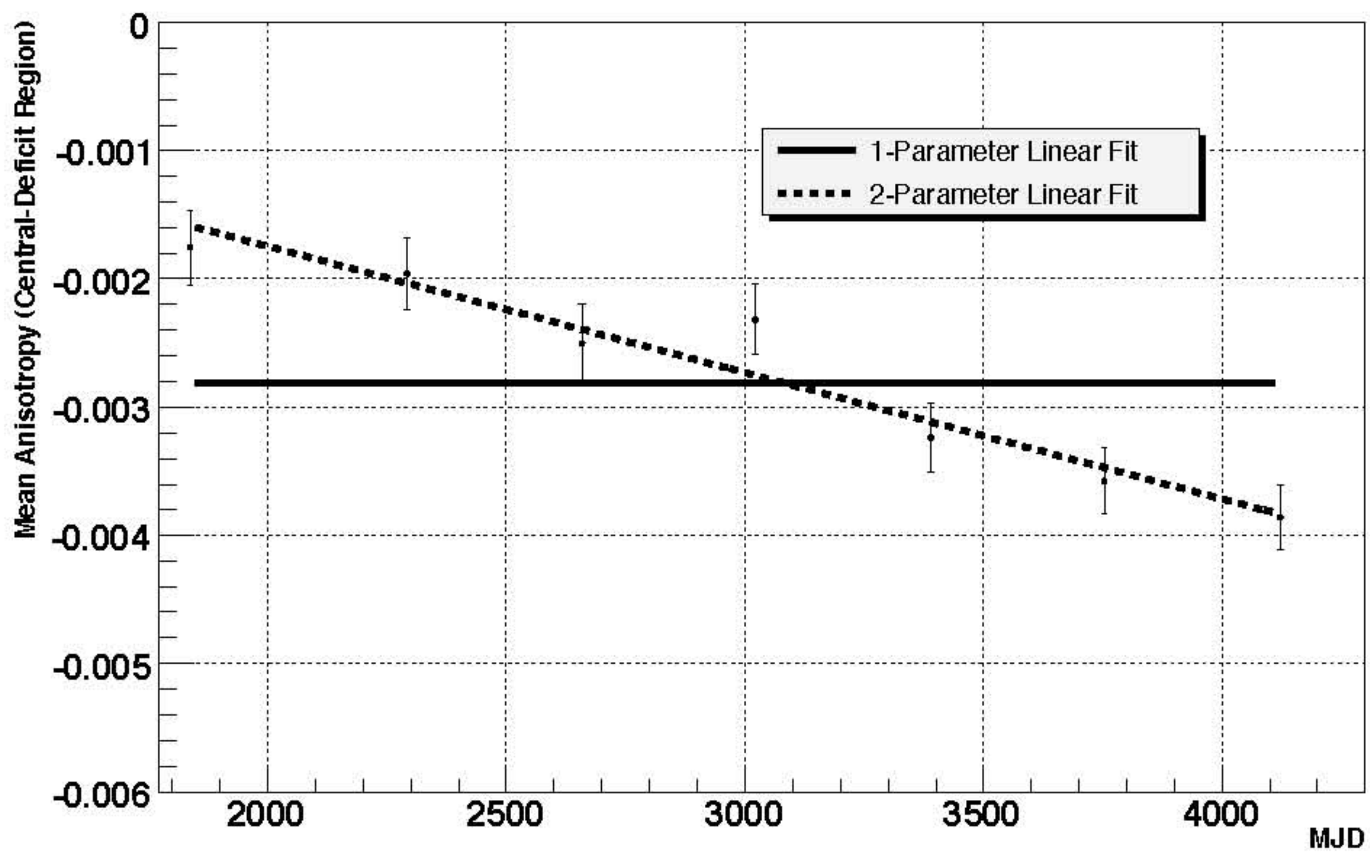
Galactic Magnetic Fields?

Eduardo Battaner, Joaqúın Castellano, and Manuel Masip ‘09



Deficit Growing with Time?

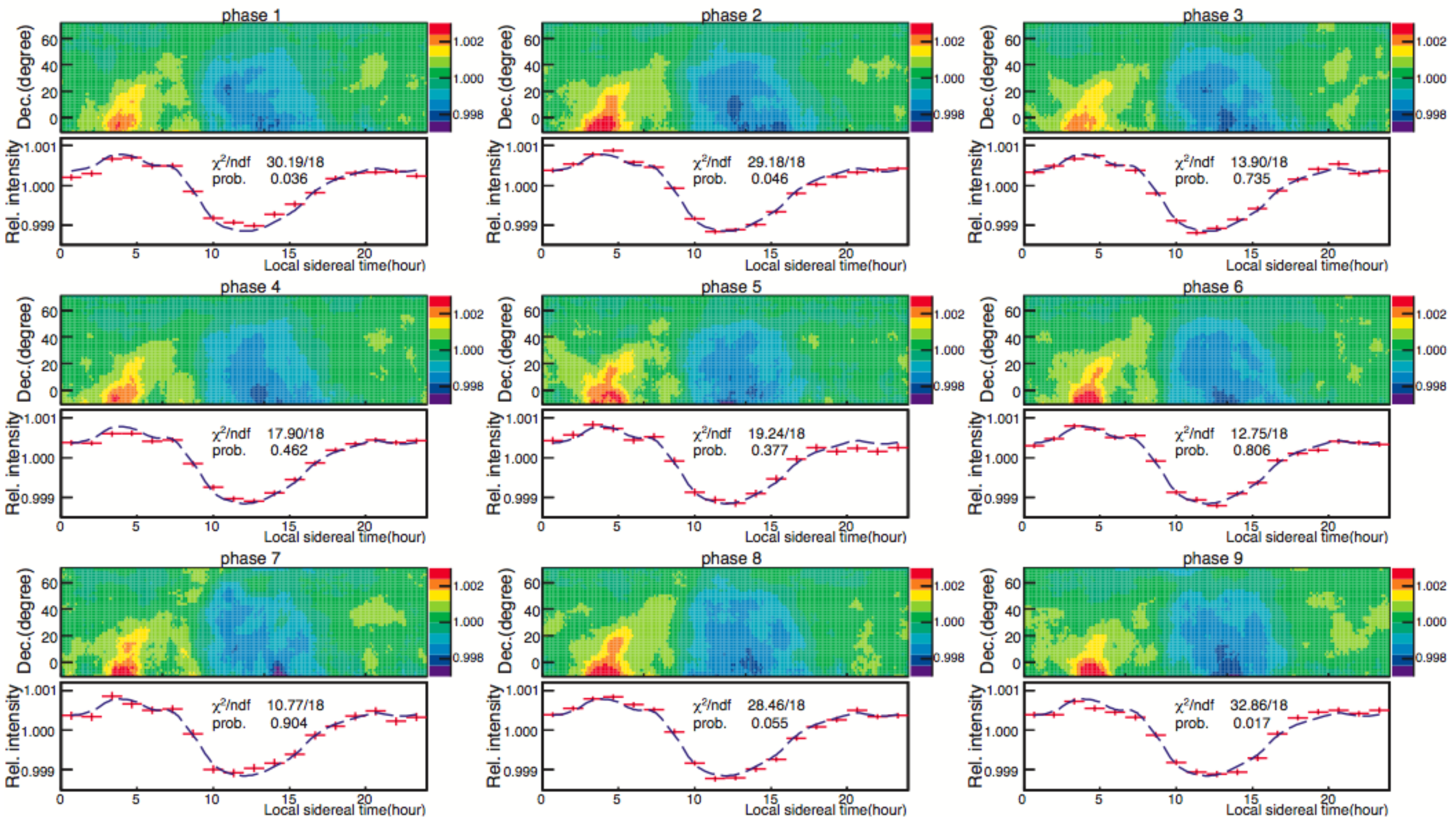
Milagro data



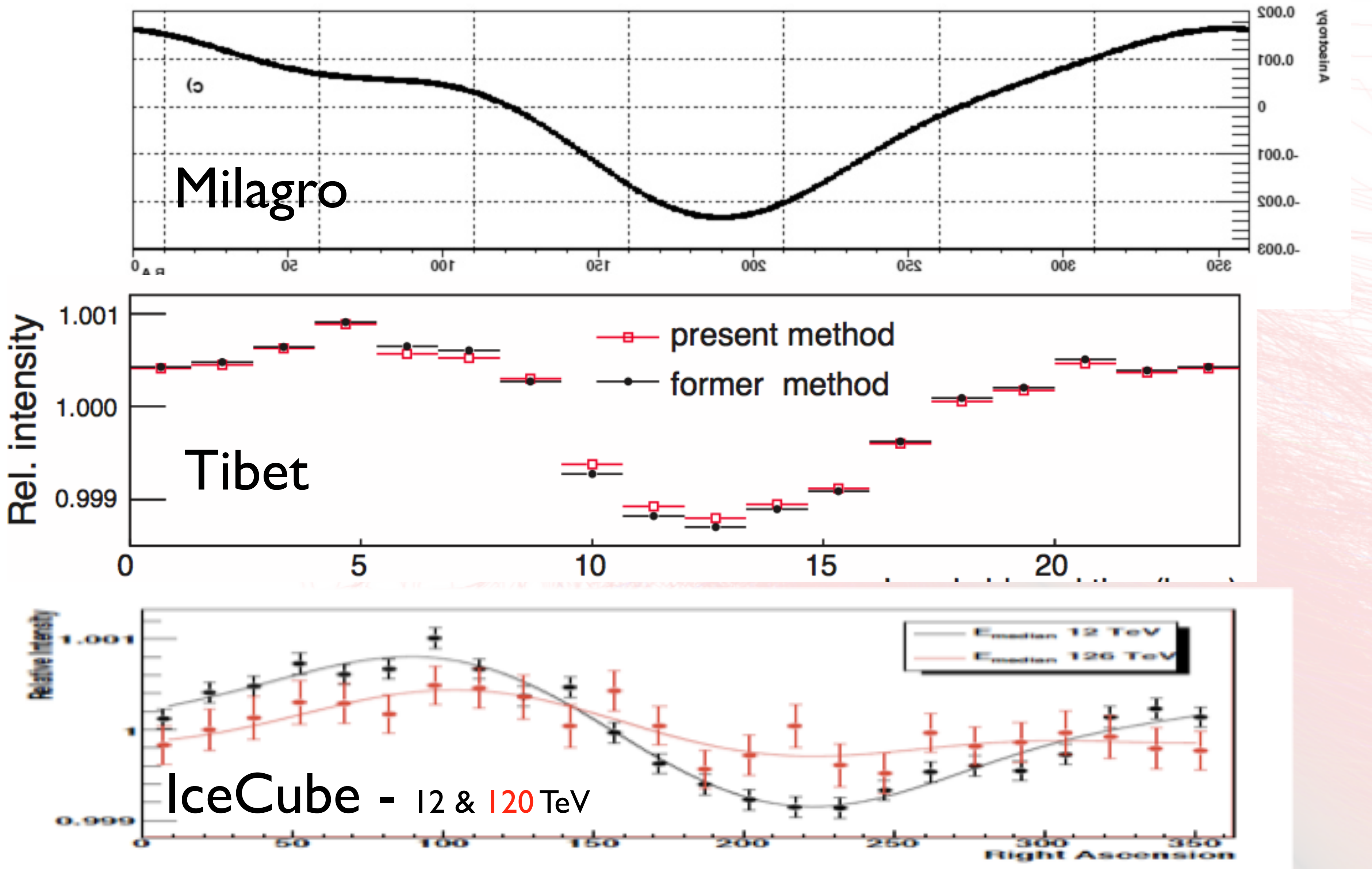
Tibet Data - same interval

Phase	Start time	End time	Live days	Number of used CR events
1	Nov. 18, 1999	Jun. 29, 2000	173.1	5.16×10^9
2	Oct. 28, 2000	Oct. 11, 2001	283.7	8.14×10^9
3	Dec. 05, 2001	Sep. 19, 2002	201.8	5.59×10^9
4	Nov. 18, 2002	Nov. 18, 2003	259.1	6.34×10^9
5	Dec. 14, 2003	Oct. 10, 2004	123.6	3.07×10^9
6	Oct. 19, 2004	Nov. 15, 2005	277.6	6.79×10^9
7	Dec. 07, 2005	Nov. 03, 2006	114.5	2.71×10^9
8	Nov. 06, 2006	Feb. 25, 2008	269.2	6.36×10^9
9	Mar. 02, 2008	Dec. 03, 2008	212.9	4.91×10^9

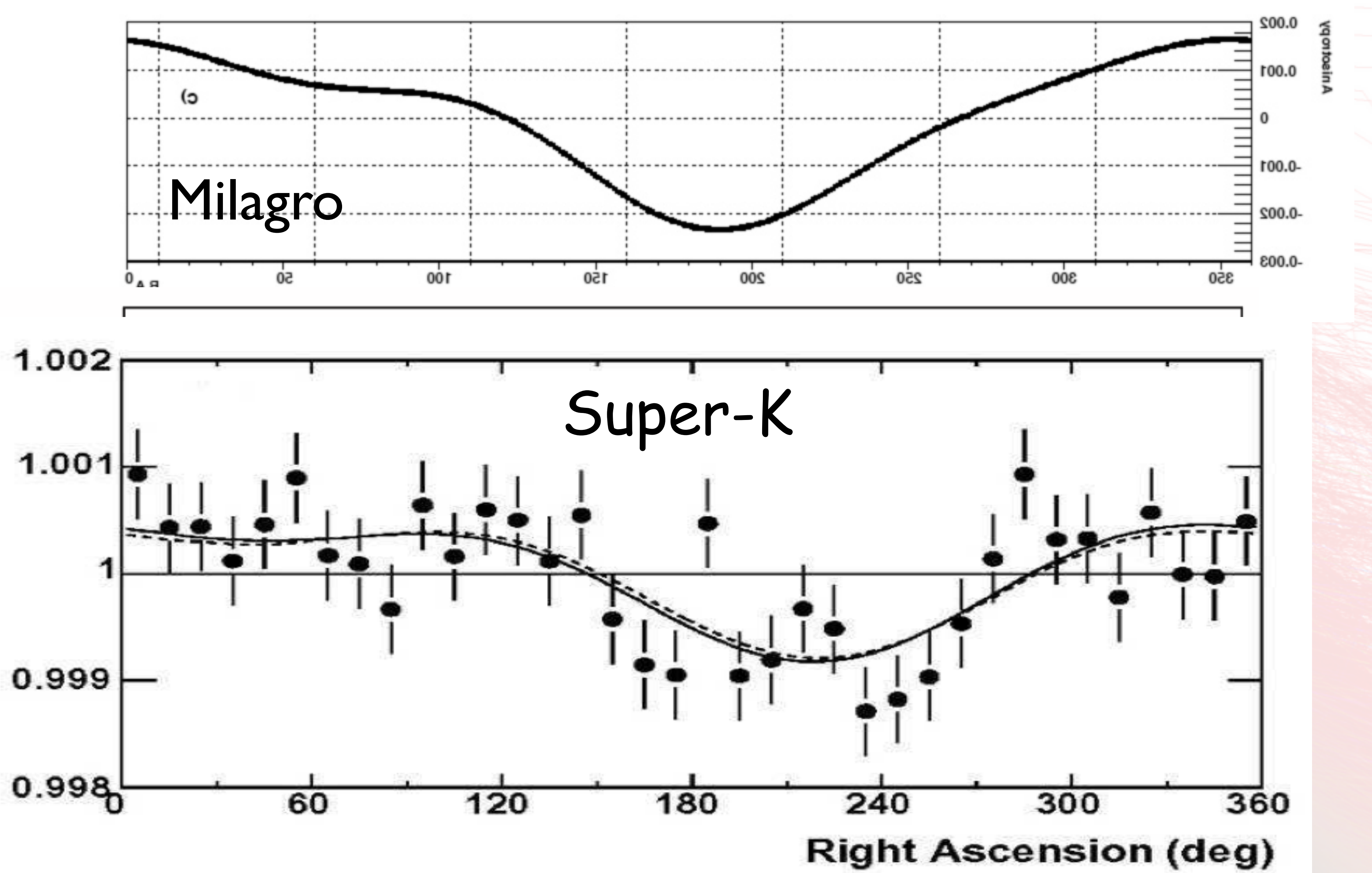
Tibet doesn't see it



Milagro, Tibet, & IceCube



Milagro, Super-K



Large Scale Anisotropy

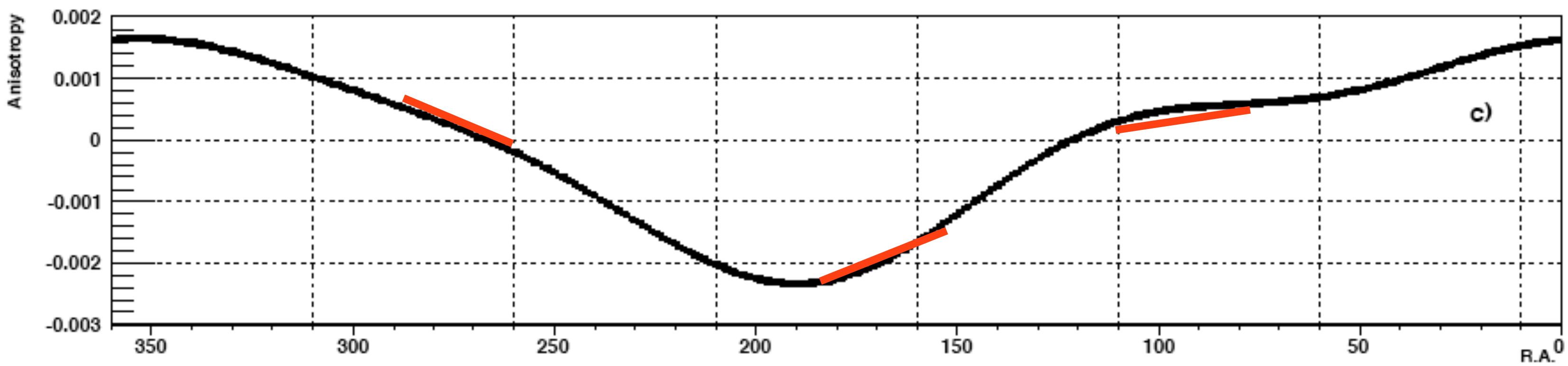
- All experiments see the large scale anisotropy
- All see the same phase
- The amplitude appears to vary slightly perhaps decreasing with energy
- Amplitude and Phase are inconsistent with Compton-Getting
- May be due to local galactic mag. fields

Milagro intermediate scale study

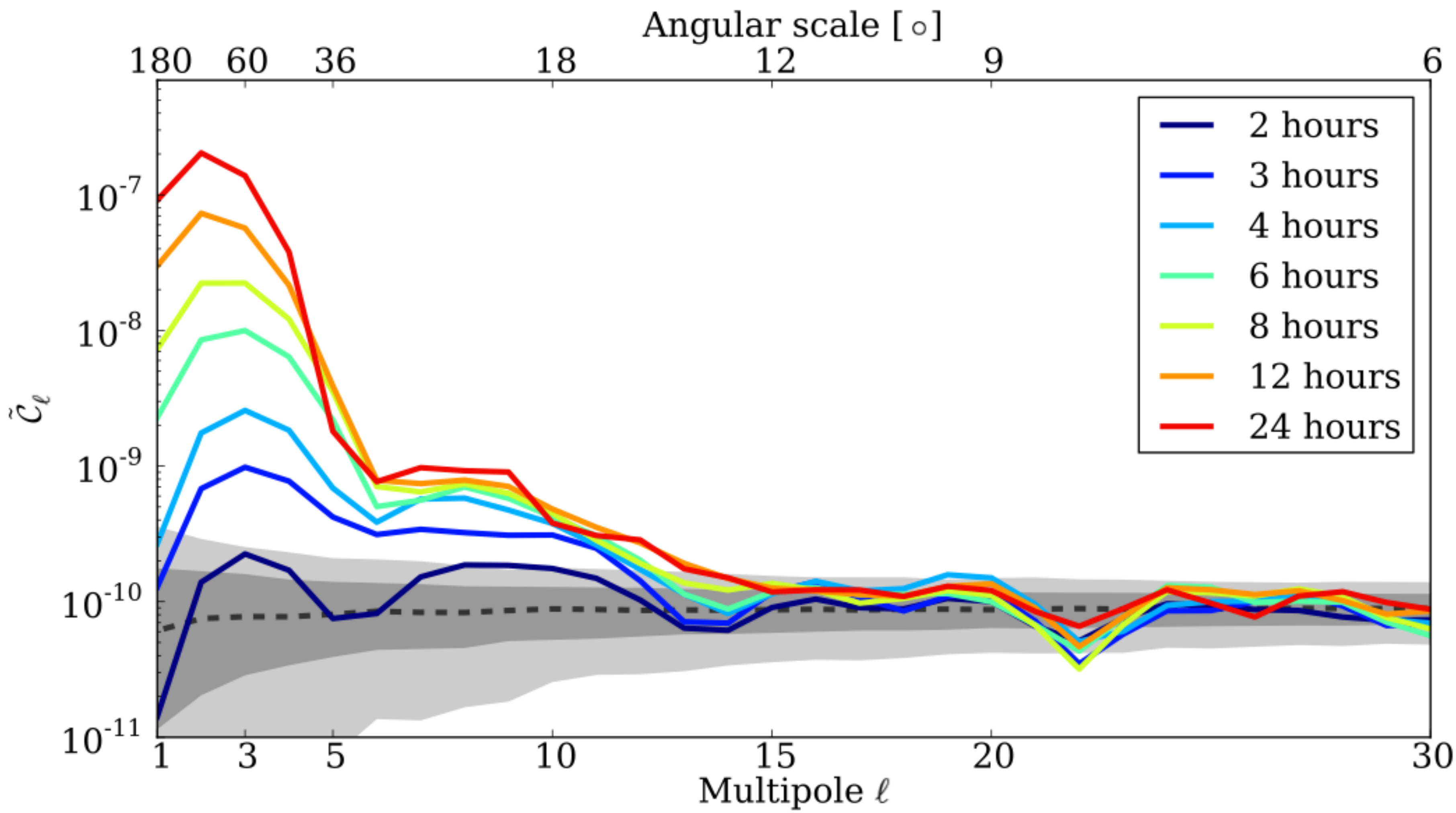
Suppression of large scale features

2hr background interval

as in our point source search



Our expectation was a uniform sky

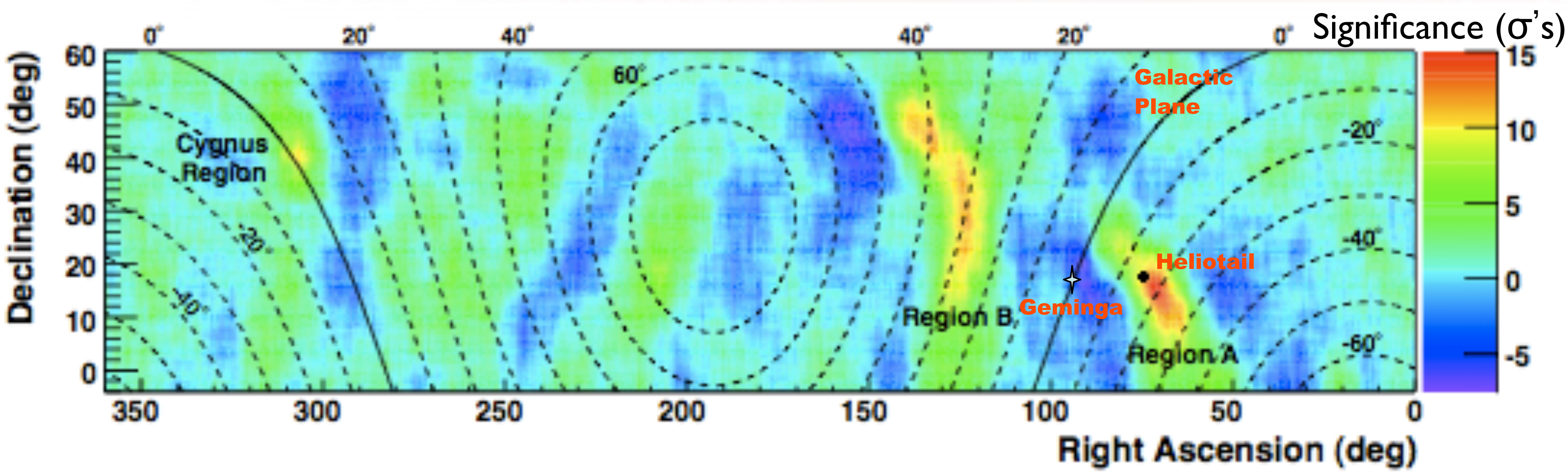


Angular scale [∘]
180
60
36
18
12
9
6
2 hours
3 hours
4 hours
6 hours
8 hours
12 hours
24 hours
$\tilde{C}_\ell$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1
3
5
10
15
20
30
Multipole ℓ

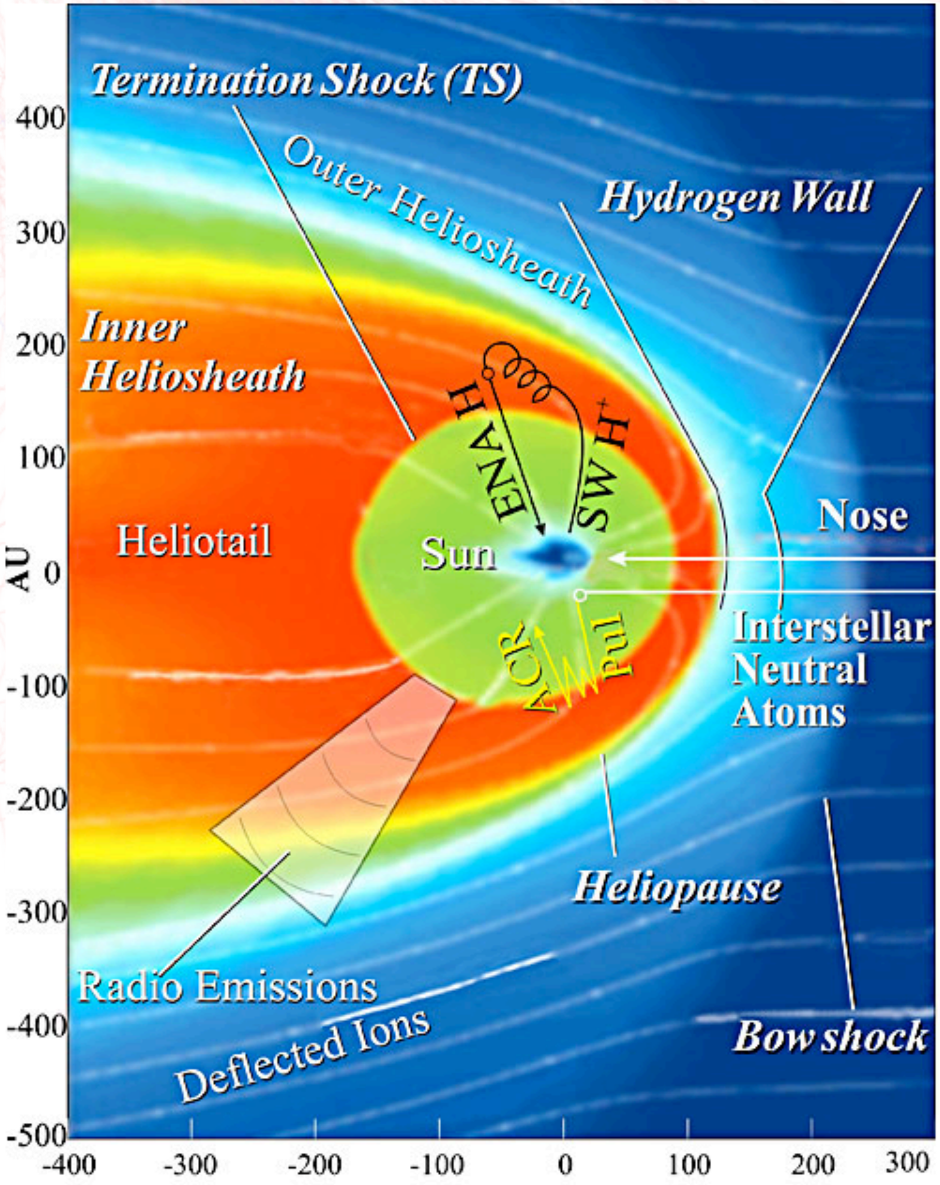
Milagro intermediate scale

- Anisotropy on the 5-10 degree scale.
- Peak excess ~7 x 10^{-4} (much smaller than the LSA)

- Explanations are difficult because the gyro-radius of a 10 TeV proton in a 1 μG field is 0.01 parsecs=2,000 AU (Solar System is 40AU – nearest Star is 271,000 AU.)



Helio-Tail

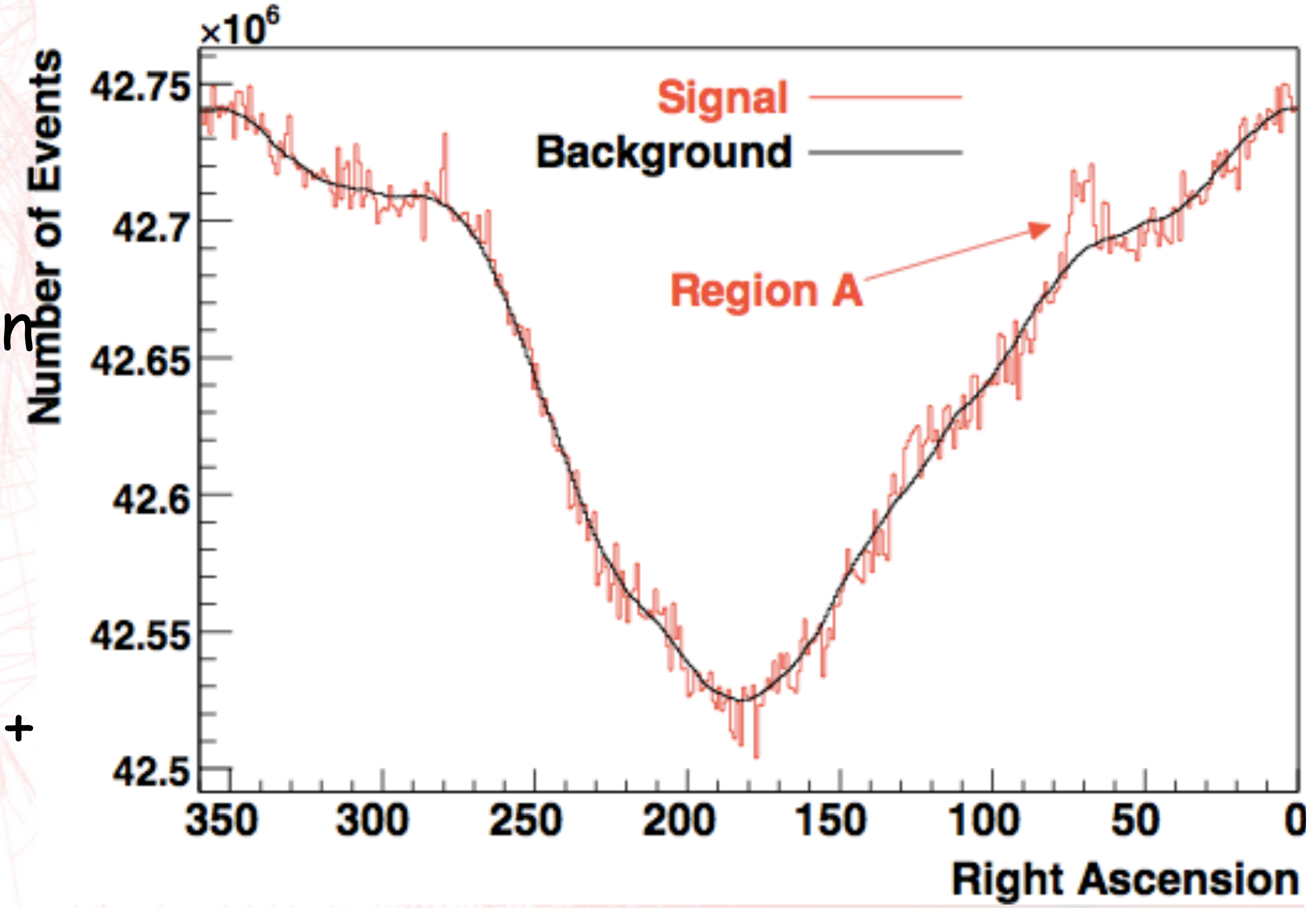


Termination Shock (TS)
Outer Heliosheath
Hydrogen Wall
Inner Heliosheath
ENA H
SW H+
Heliotail
Sun
Nose
ACR
PuI
Interstellar Neutral Atoms
Heliopause
Radio Emissions
Deflected Ions
Bow shock
AU
400
300
200
100
0
-100
-200
-300
-400
-500
-400
-300
-200
-100
0
100
200
300

No Background Subtraction

RA strip for Dec range 10°-20 background estimate is shown in black.

Large scale structure due to exposure variation + LSA



- Milagro can separate gamma-ray and hadron induced events through the presence of large depositions in the bottom layer.

- Region A:

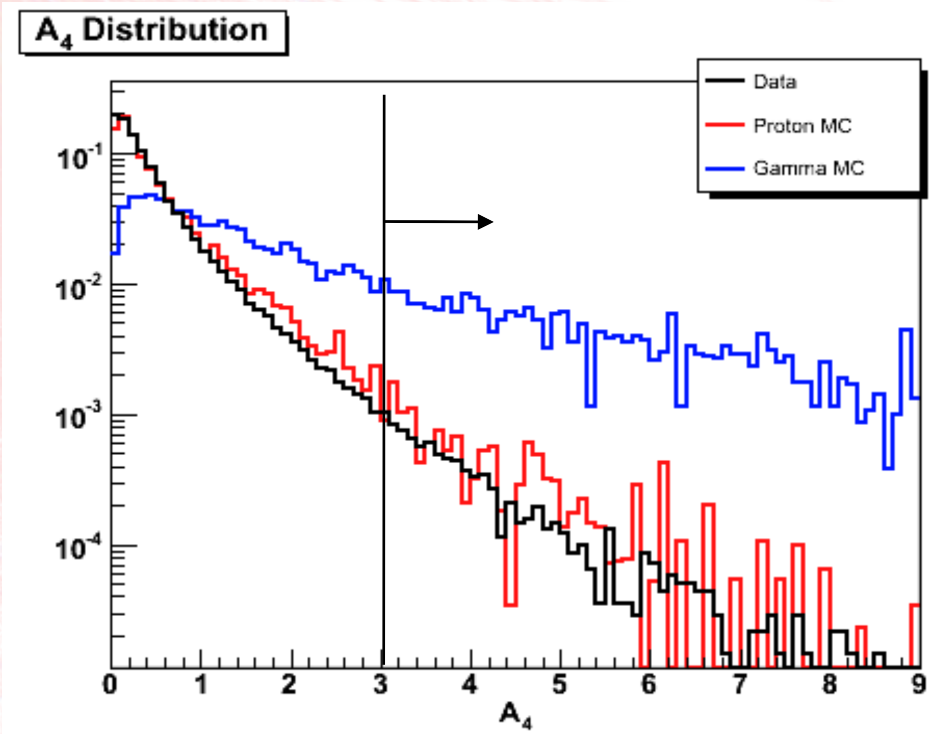
χ^2(hadron) = 10.3/16 dof

χ^2(gamma) = 124.0/16 dof

- Region B:

χ^2(hadron) = 19.0/16 dof

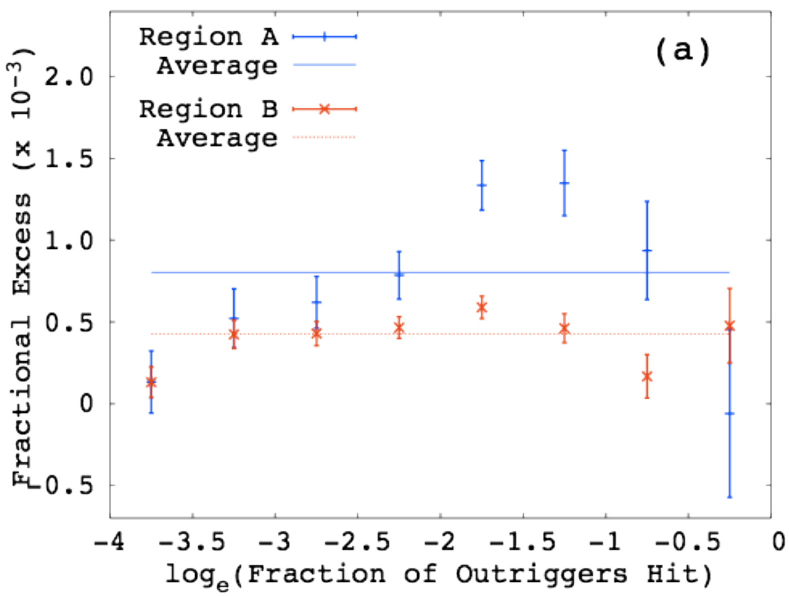
χ^2(gamma) = 84.8/16 dof

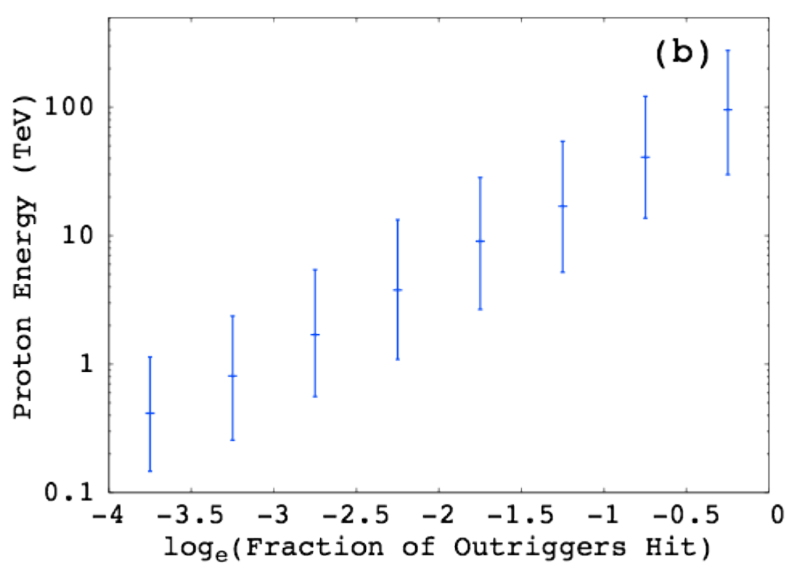


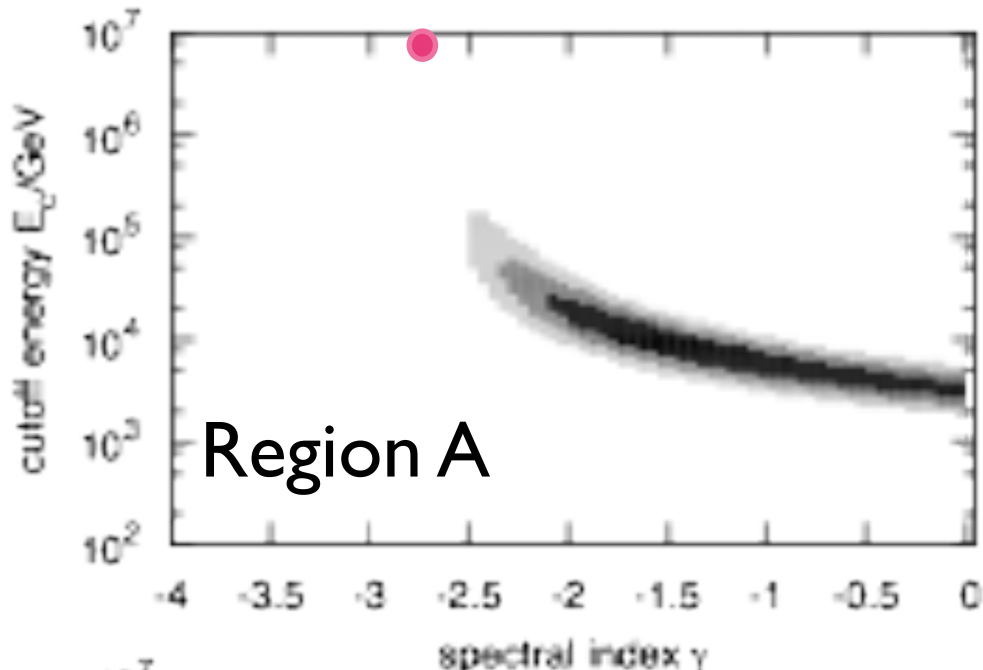
$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$

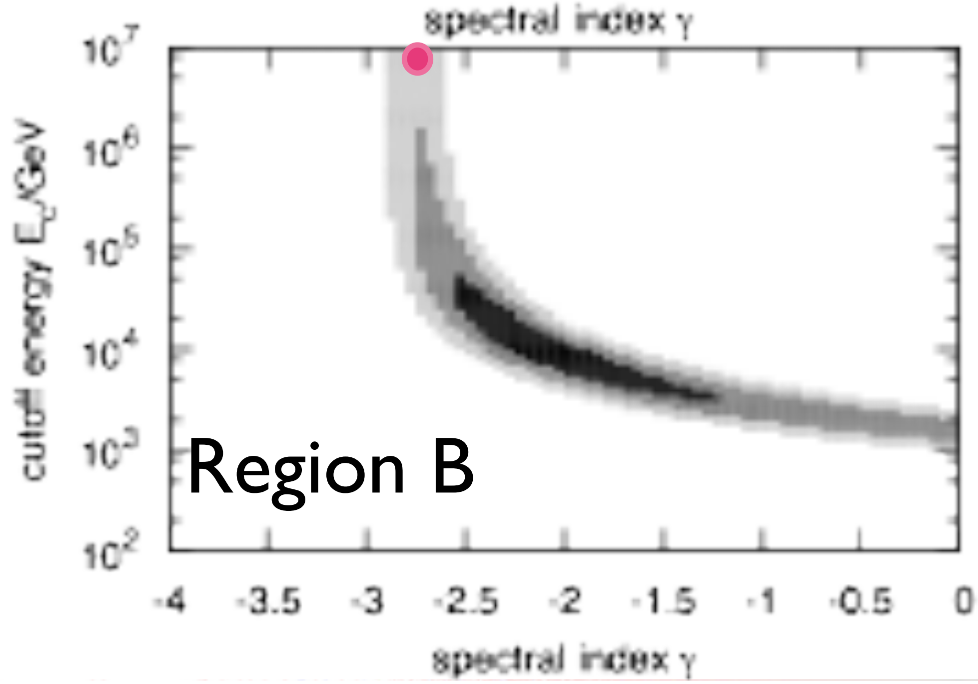
mxPE:	maximum # PEs in bottom layer PMT
fTop:	fraction of hit PMTs in Top layer
fOut:	fraction of hit PMTs in Outriggers
nFit:	# PMTs used in the angle reconstruction

Spectral fit to excess

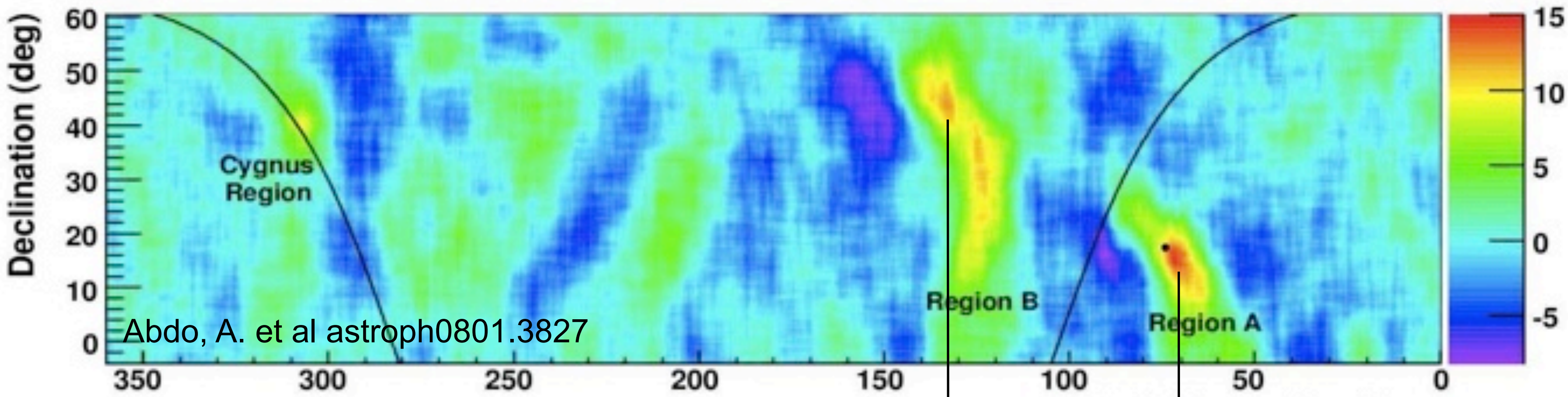




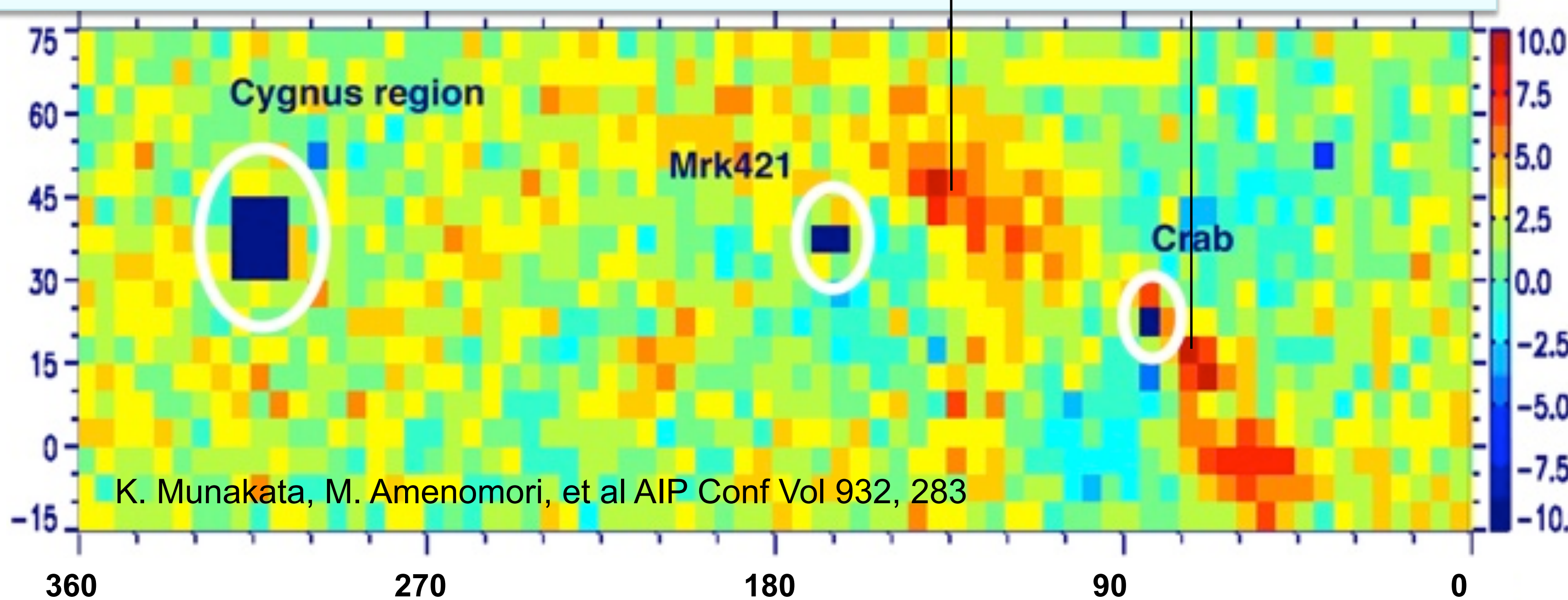




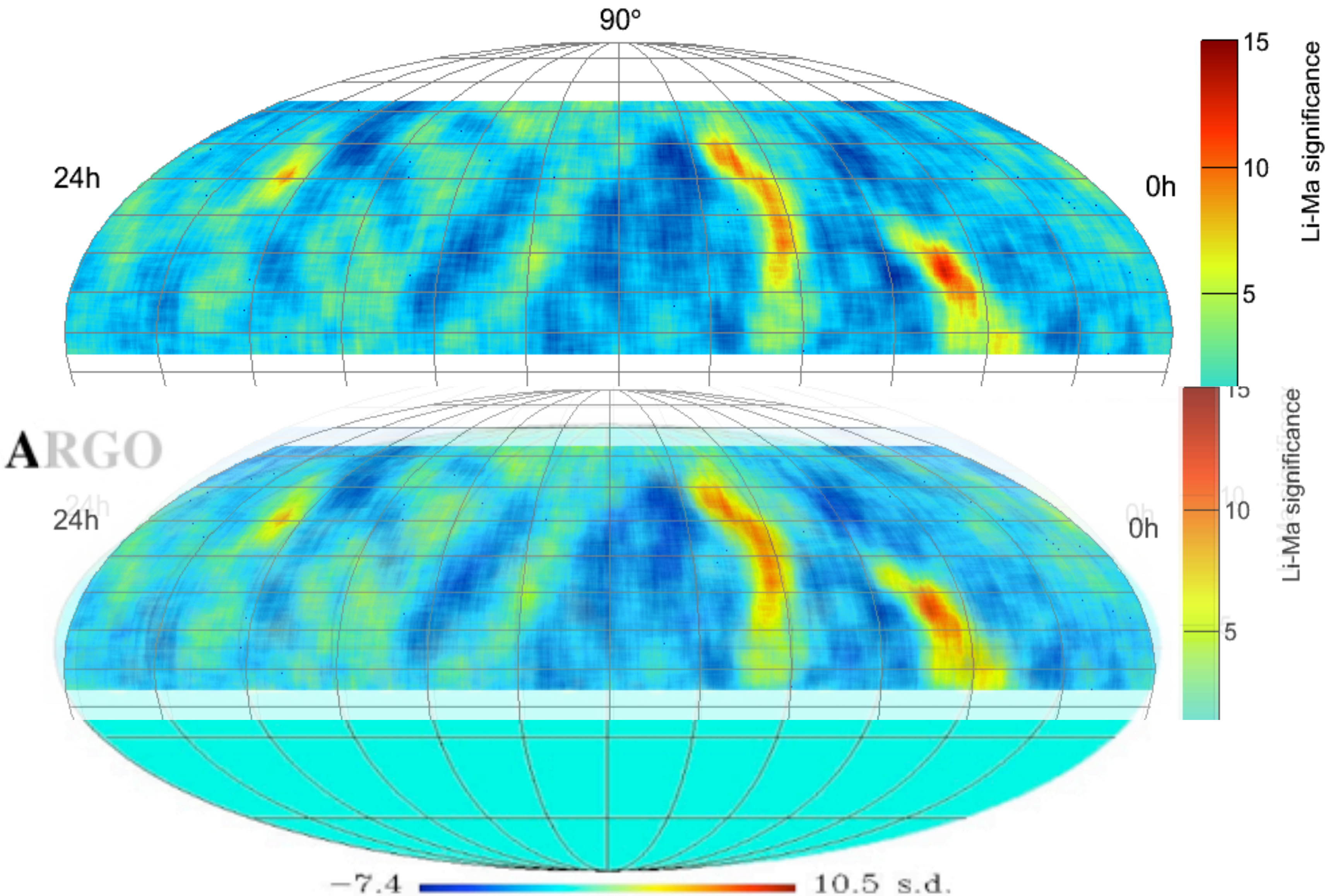
Milagro Observation using Background Calculation over 2 hour (30^o in RA) intervals



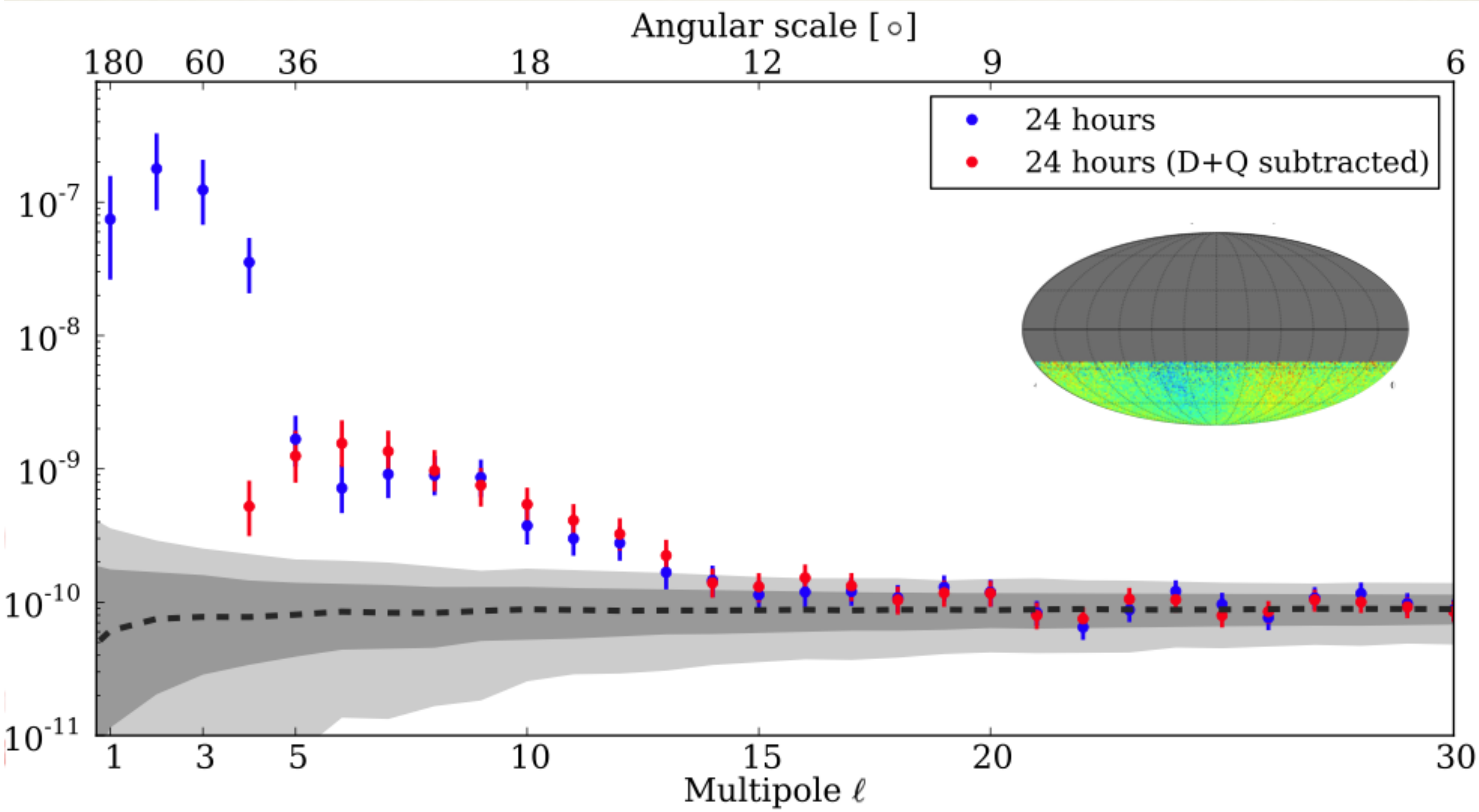
Tibet AS Observation after subtracting model of large scale anisotropy



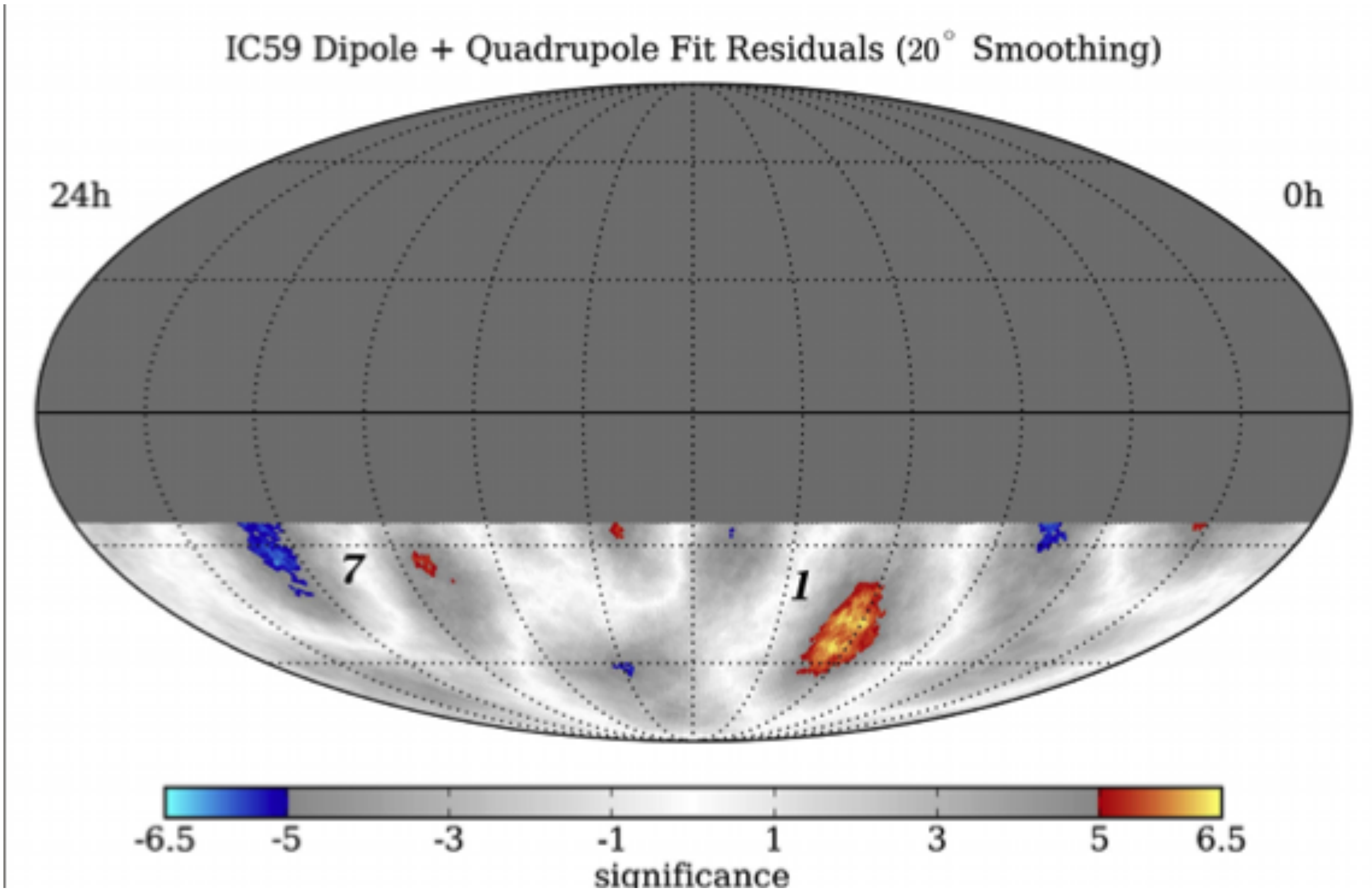
Milagro Results



http://people.roma2.infn.it/~aldo/RICAP09_trasp_Web/Vernetto_ARGO_RICAP09ar.pdf

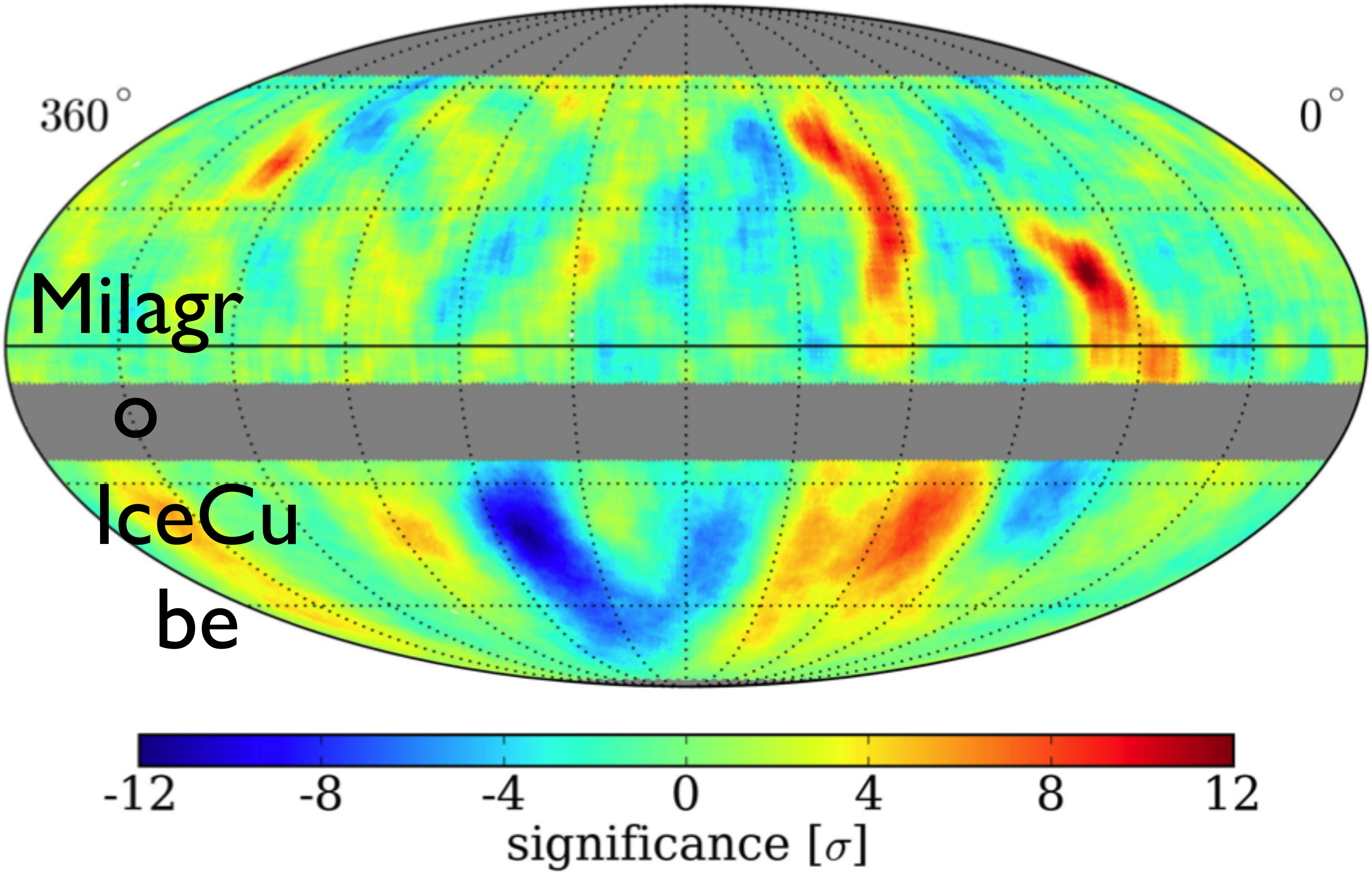


Angular scale [∘]
180
60
36
18
12
9
6
24 hours
24 hours (D+Q subtracted)
10-7
10-8
10-9
10-10
10-11
1
3
5
10
15
20
30
Multipole ℓ



IC59 Dipole + Quadrupole Fit Residuals (20° Smoothing)
24h
0h
7
1
-6.5
-5
-3
-1
1
3
5
6.5
significance

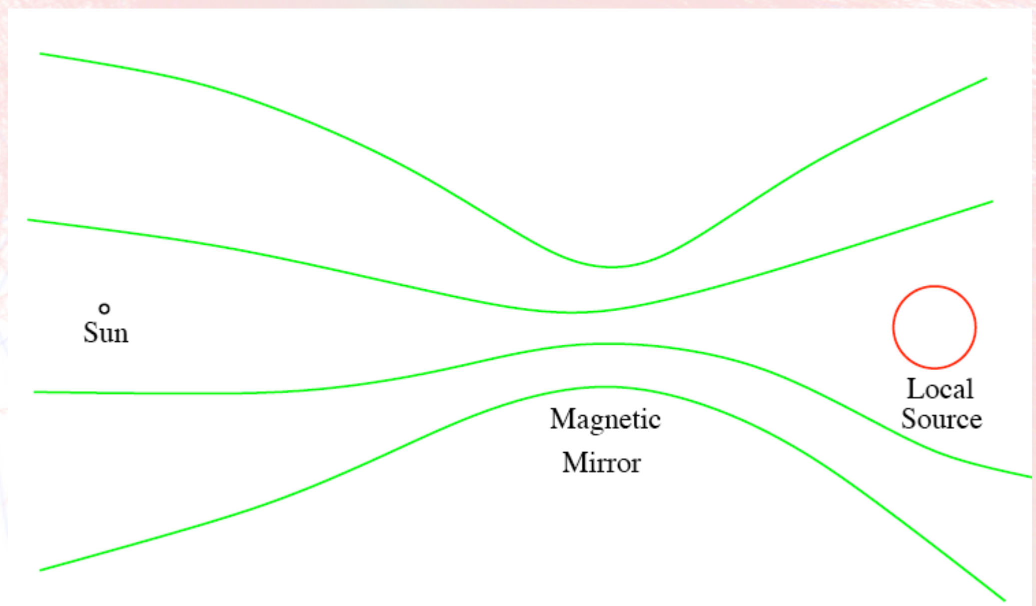
Milagro (1-10TeV) & IceCube (20TeV)



Aharonian/Drury

- Secondary neutron production in the heliotail rejected.
- Suggest nearby accelerator combined with local interstellar magnetic field configuration.

- Suggest a local accelerator would also be detectable in the VHE electron spectrum



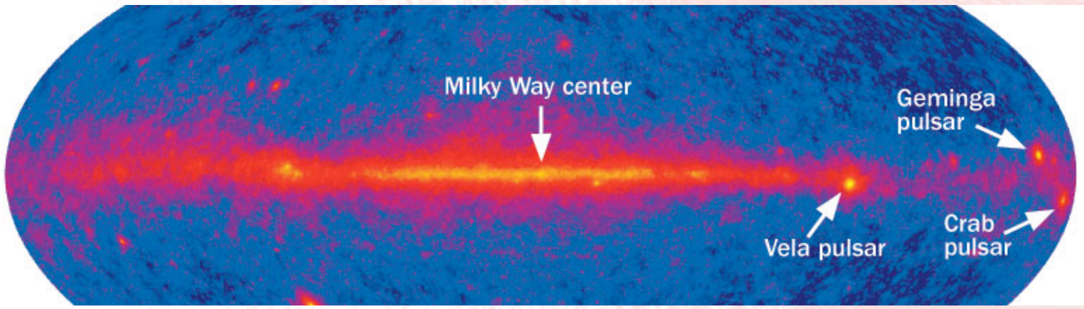
Salvati & Sacco

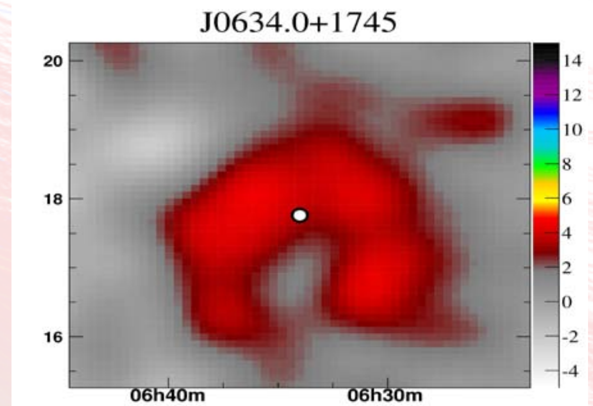
- Flux too large to be explained by acceleration at the heliopause by ~100x
- Position of A,B in the general direction of Geminga.
  - Age=3.4×10^5y, d=150pc, moved ~20^o-30^o in lifetime.
  - Diffusion length (1uG, 1 TeV) ~65pc
- Diffusion could explain hard spectrum since low energy particles have shorter diffusion length.
- "If the observed cosmic ray excess does indeed arise from the Geminga SN explosion, the long–sought "smoking gun" connecting cosmic rays with supernovae would finally be at hand. It could be said that, while looking for the 'smoking gun', we were hit by the bullets themselves."

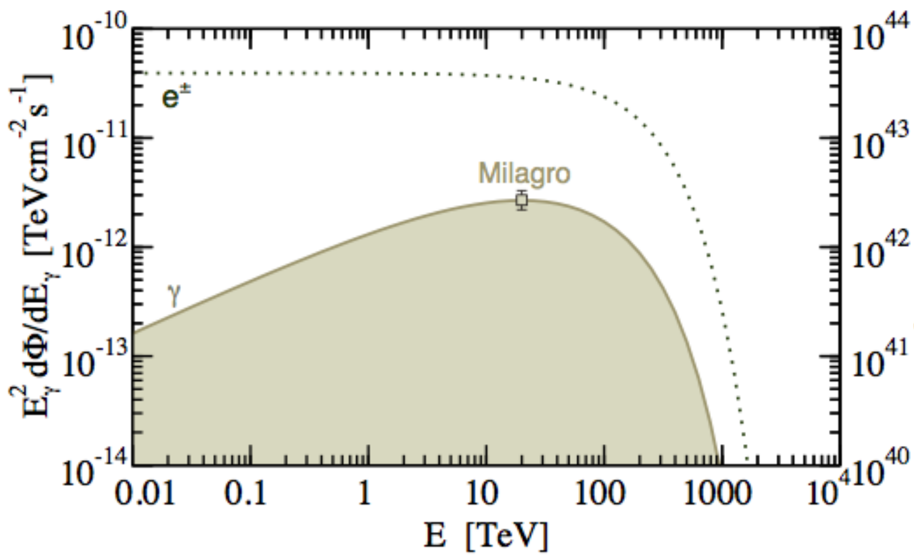
Astronomy & Astrophysics

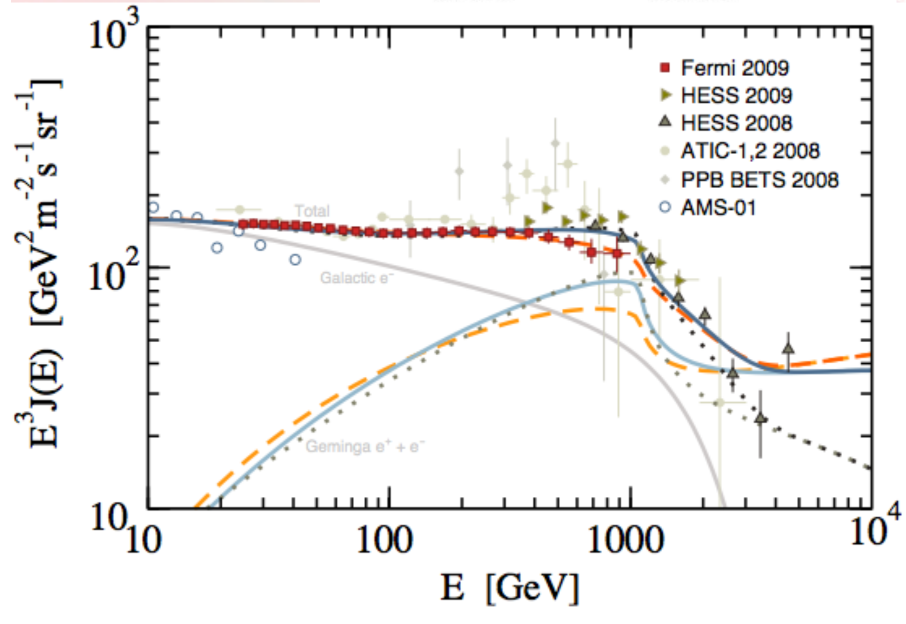
Yuksel, Kistler and Stanev (09)

- They explain the Pamela excess and Milagro data with Geminga as the source (~150pc)



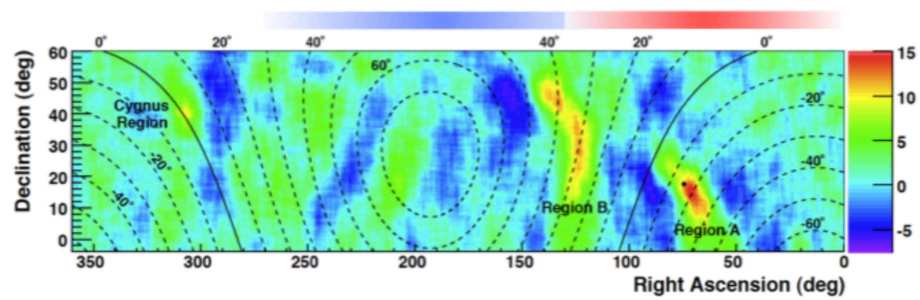






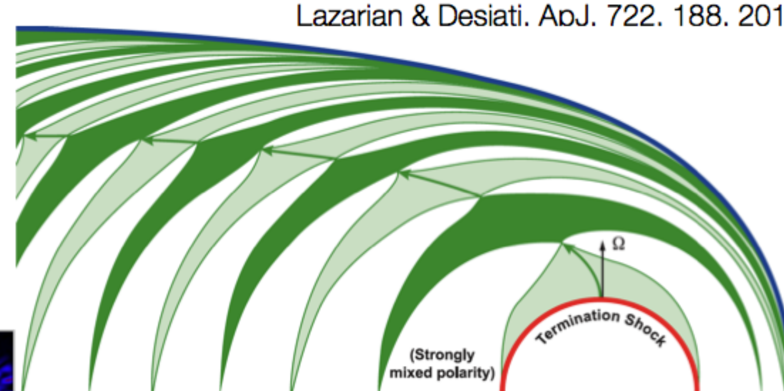
origin of "tail-in anisotropy"

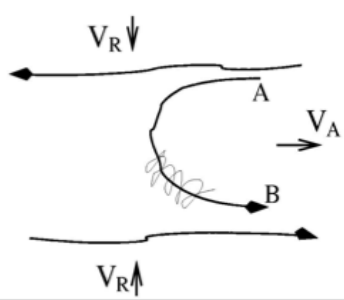
- first-order Fermi acceleration in magnetic reconnection regions in the heliotail
- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail
- weakly stochastic magnetic reconnection
- harder spectrum up to ~10 TeV (Milagro, ARGO)

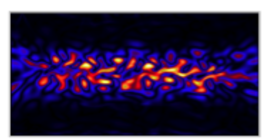


Abdo et al., Phys. Rev. Lett., 101, 221101, 2008

Lazarian & Desiati, ApJ, 722, 188, 2010







Conclusion

- Milagro results provide evidence of “local” acceleration. Geminga?
- CR vicinity is complex
- PAMELA/ATIC results depend on the understanding of the local astrophysics.
- Connecting DM to the cosmos will be difficult in the absence of a detailed understanding of the more conventional backgrounds.

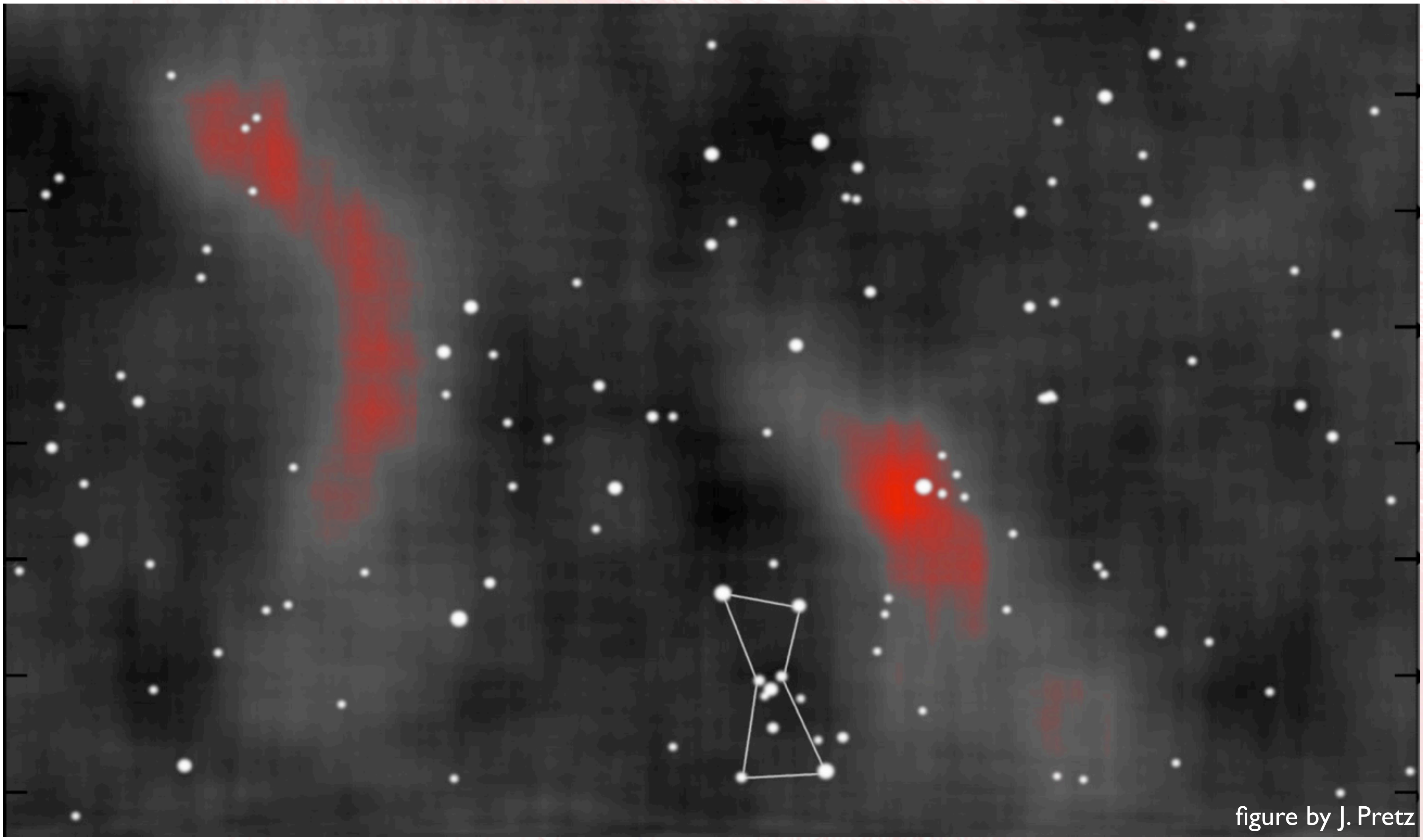
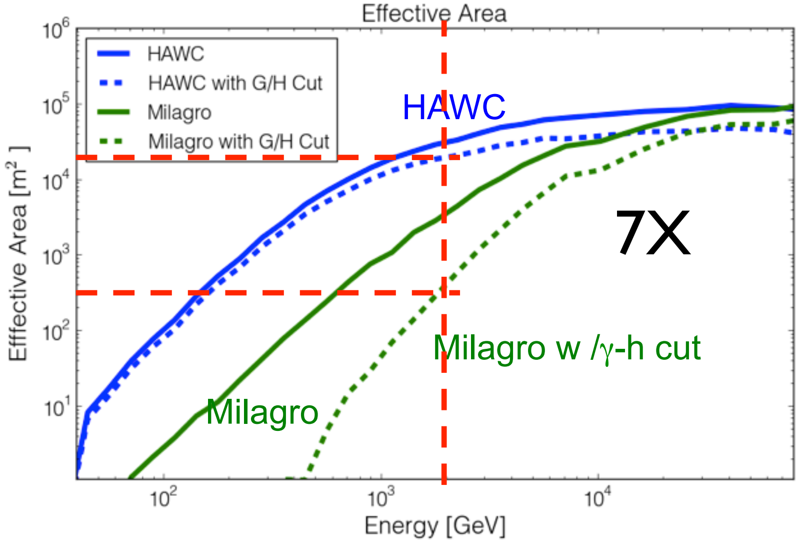
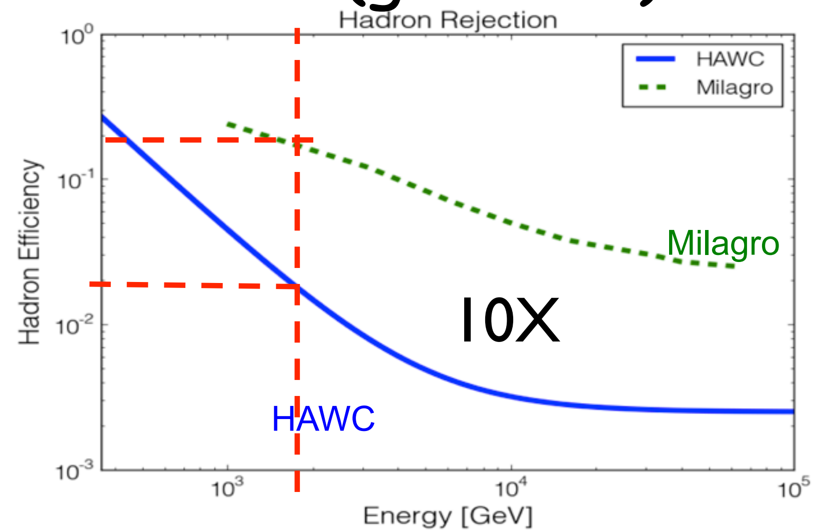


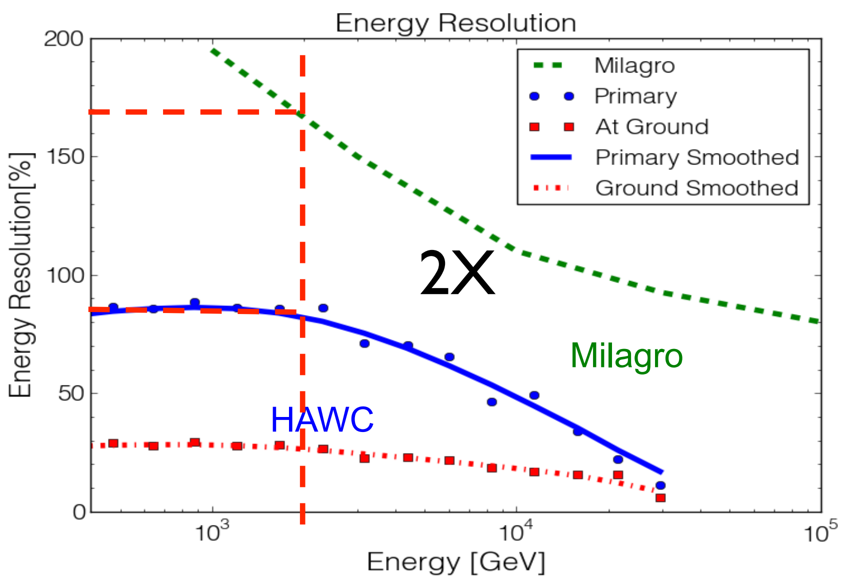
figure by J. Pretz

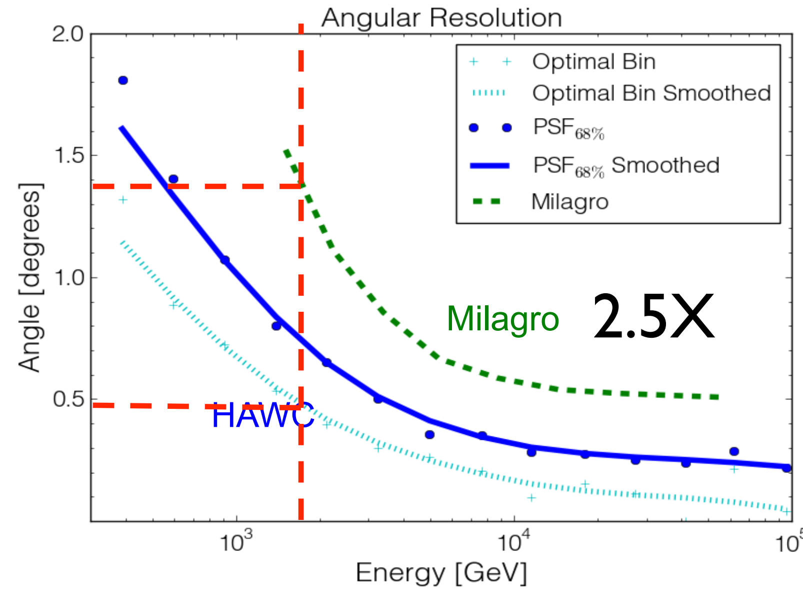

The HAWC
(High Altitude Water Cherenkov)
Observatory

HAWC Performance at 2 TeV (gammas)









HAWC & Cosmic Ray Anisotropy

- HAWC with better energy resolution and gamma-hadron rejection can:
  - –Measure the spectrum with much higher precision
    - We will be able to tell if the spectrum is flatter and if and where it cuts off
  - –Measure the gamma-ray fraction