Cosmic rays (large scale) anisotropies from 10^{13} eV up to EHE

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OUTLINE

- CR anisotropies: definition and reason for the measurement (propagation)
- The experimental problem
- Existing data on large-scale anisotropies

Prologue

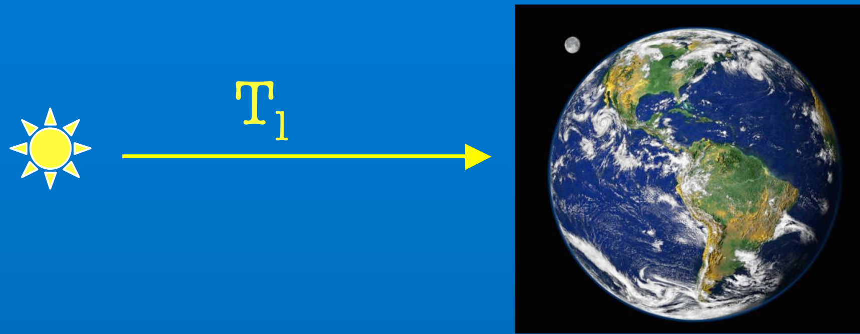
- ✓ Main question about CRs: origin
- ✓ Answer:
  - ✓ identification of the sources (... ECR astronomy)
  - ✓ energy ...
  - ✓ ... opies)
    ... arge
    ... pagation
    ... (absence of large scale
    ... tronomy? Small scale anisotropy

Need to study all these observables simultaneously to build a unified picture of CRs in our Galaxy.
Anisotropy study essential and complementary tool
My point of view: experimental one

Difficult t... unified picture for CR propagation in the Galaxy

- ✓ Due to many complicated processes inherent in the CR transport
- ✓ Mathematical complexity in the diffusion processes of CRs
- ✓ **Difficulties in the experimental measurement of CR anisotropies**

Anisotropy: a simple description



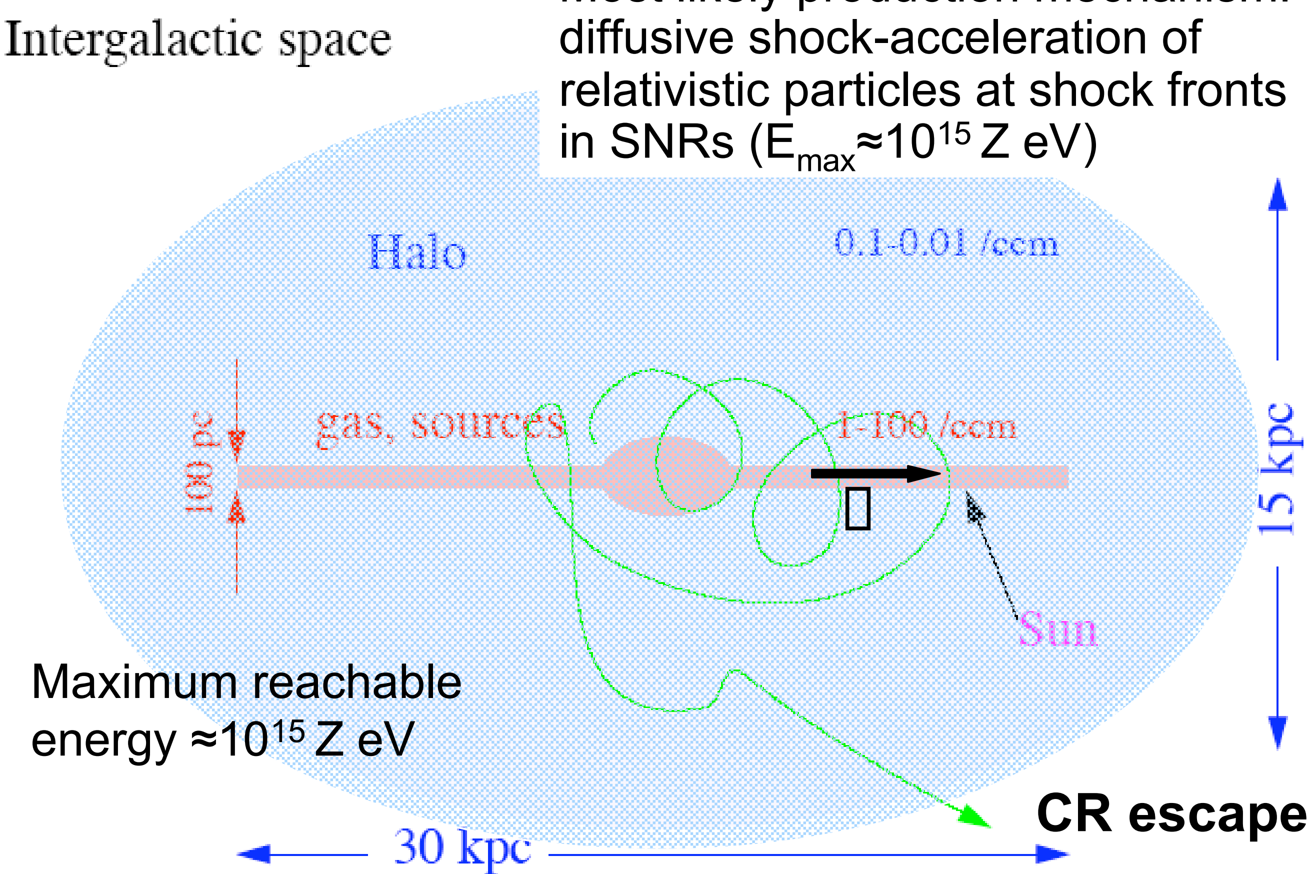
- T_l=(light) time to reach the Earth from a source on a straight line
- □=time for a CR to reach the Earth
- □=T/□
- If □==T, □=100%, CRs arrive directly to Earth. Maximum anisotropy
- If □== , □=0%, CRs completely isotropized by the magnetic field

Any deviation from isotropy reflects a "motion":

✓Either the motion of CR from the source to the sink in the intergalactic space...

✓... or the motion of the Earth/Solar System with respect to an isotropic gas in the rest frame (e.g., CRs "gas)

The motion of CR from the source to the sink in the intergalactic space...



Most likely production mechanism: diffusive shock-acceleration of relativistic particles at shock fronts in SNRs ($E_{max} \approx 10^{15}$ Z eV)

Maximum reachable energy $\approx 10^{15}$ Z eV

CR escape

"Naïve" sketch of CR propagation in the Galaxy

Accelerated galactic CRs trapped by the Galactic magnetic field B (few μG)

Transport of CRs determined by the Larmor Radius

$$r_g[pc] = \frac{E_{15}[10^{15}\,eV]}{B[\mu G]Z}$$

Probability that CRs escape when they encounter the boundary, after τ_{esc} (leakage from the Galaxy)

CRs diffusion and anisotropy

Diffusive regime in the Galactic magnetic field

Average motion of CRs highly random (near-isotropic flux)

Diffusion coefficient depends on diffusion mean free path

$$D = \frac{1}{3}\lambda_D v$$

When there is diffusion, there are density gradients (CRs flow away from Galactic plane) -> anisotropy δ

$$\delta = \lambda_D \frac{\partial N}{\partial x}\frac{1}{N} = \frac{3D}{v}\left|\frac{\nabla N}{N}\right|$$

CRs diffusion and anisotropy

v=particle velocity

□=gaseous disk density (1proton/cm^3)

h=scale height of the gaseous disk ≈ 100 pc

H=scale height of the halo ≈ 700 pc

$□_{esc}$=thickness of traversed matter

==> D≈10^{29} cm^2/sec

$$□_{esc} = □v \frac{hH}{D}$$

Expected anisotropy □≈v_D/v=D/H≈10^{-4}

D increases with E (hence □ increases with E)

$$D \quad R^m$$

Alternative versions of diffusion

$$D \quad R^{0.6}\ \mathrm{cm}^2\mathrm{s}^{-1}$$

pure diffusion (“leaky-box”)
Regular magnetic field

$$D \quad R^{0.3}\ \mathrm{cm}^2\mathrm{s}^{-1}$$

diffusion + distributed reacceleration in ISM (regular magnetic field + random turbulent field)

$$D \quad R^{0.15 \div 0.2}\ \mathrm{cm}^2\mathrm{s}^{-1}$$

diffusion + Hall diffusion (drift)

Anisotropy amplitude should correspondingly rise with energy

...or the motion of the Earth/Solar System wrt an isotropic gas in the rest frame i.e., the **Compton-Getting** effect

- ✓ Expected galactic CR anisotropy due to Earth's orbital motion around the sun (in solar time):

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos\theta$$

I=CR intensity, γ=power-law index of CR spectrum (2.7), v=detector velocity ≈ 30 km/s, θ=angle between detector motion and CR arrival direction

$$\frac{\Delta I}{\langle I \rangle}(\mathrm{exp}) \approx 0.047\%$$

A detector on the Earth moving around the Sun scans various directions in space while the Earth spins. Maximum at 6 hr (when the detector is sensitive to a direction parallel to the Earth's orbit)

- ✓ Possible galactic CR anisotropy due to Solar system motion through the CR "gas" (in sidereal time) ?

- ✓ Possible extra-galactic CR anisotropy due to Solar system motion (v≈350 km/s) through the universal rest frame (CMB "gas") ?

$$\frac{\Delta I}{\langle I \rangle}(\mathrm{exp}) \approx 0.6\%$$

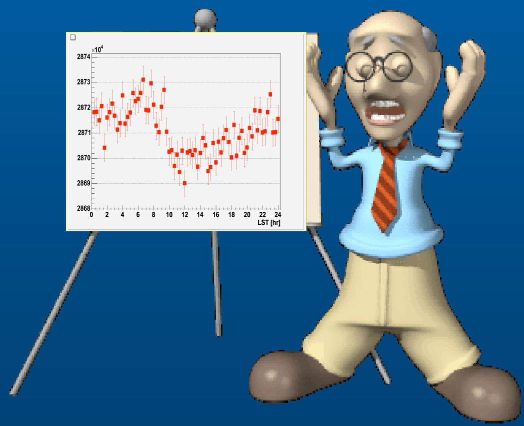
Why measuring the CR anisotropy?

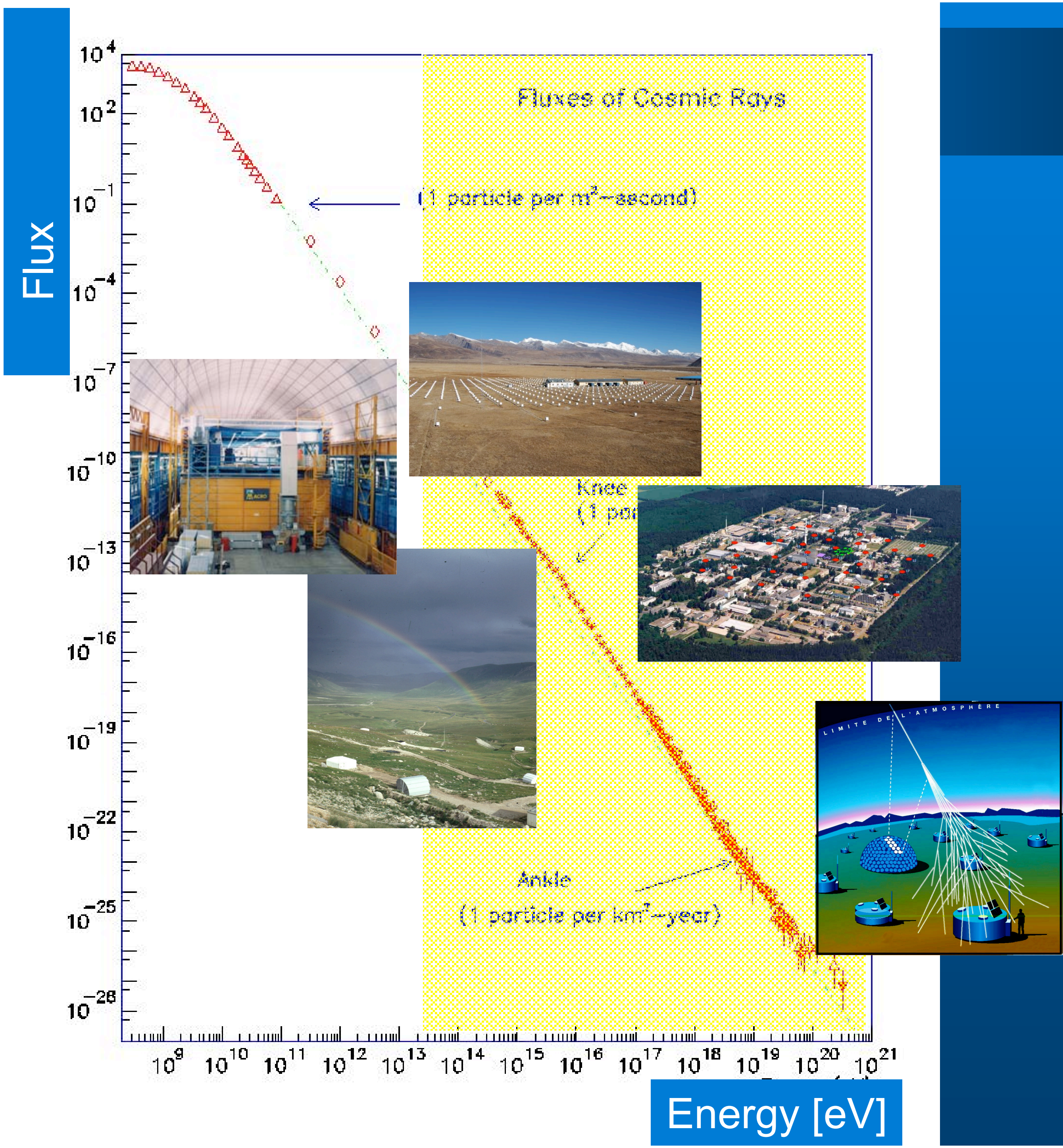
- ✓ With respect to the knee:
  - ✓ Origin of the knee from a diffusion process as a rigidity dependent leakage effect from the Galaxy -> anisotropy should increase as $E^{0.6}$ (or $E^{0.3}$ if there is re-acceleration in the ISM)
  - ✓ Origin of the knee from a Hall effect (drift of CRs in a direction perpendicular to the regular field direction) -> weak increase of anisotropy as $E^{0.2}$
  - ✓ Origin of the knee from change in the acceleration efficiency at the source -> no change in the anisotropy towards the knee
  - ✓ Change in particle interactions in atmosphere at the knee region (but the knee is observed in all EAS components, e.m., muon, and hadron, hence astrophysical solution favored) -> no change in the anisotropy towards the knee

Why measuring the CR anisotropy?

- ✓ With respect to the highest energies:
  - ✓ Increase of anisotropy amplitude expected (Larmor radius comparable to galactic disk thickness) before the transition?
  - ✓ After the transition galactic->extra-galactic cosmic rays: large-scale isotropy. Cosmological Compton-Getting effect? Possible signature between:
    - ✓ Transition @ ankle (≈5 10^{18} eV): cross-over from the steep end of the galactic to the flatter X-galactic flux
    - ✓ Or dip @ ankle (produced by e+e- production of X-galactic protons with CMB photons -> transition @ lower energies (≈ 5 10^{17} eV)
  - ✓ At EHE -> point source astronomy

The experimental challenge





At E>few tens of TeV, measurements are indirect (fluxes too low) and are performed through Extensive Air Shower Arrays (or through underground muon detectors)

The problems (from an experimental point of view)

- ✓ Small amplitude, statistical problem: need for
  - ✓ long-term observations
  - ✓ large collecting areas
- ✓ Spurious effects to be kept as small as possible: need for
  - ✓ detector uniformity (over area),
  - ✓ detector stability (over time),
  - ✓ continuity of operation.
- ✓ EAS arrays mostly located in “unfriendly” ambient, (e.g., at mountain level): large variations of T, meteorological effects
- ✓ EAS rate depends on atmospheric pressure (showers more or less absorbed depending on traversed atmosphere/pressure)
- ✓ Consistency checks necessary

Principles of anisotropy measurement

- EAS arrays have **uniform exposure in □** (thanks to Earth's rotation) but not in □ (field of view limited by geographical position, zenith angle dependence of shower detection and reconstruction)
- Classical (and most used) technique: analysis in r.a., through **harmonic analysis** of the counting rate within a defined declination band (Raileigh formalism)
- Rayleigh formalism gives amplitude A, phase □ (hour angle of the maximum intensity) and probability P for detecting a spurious amplitude due to fluctuations of a uniform distribution

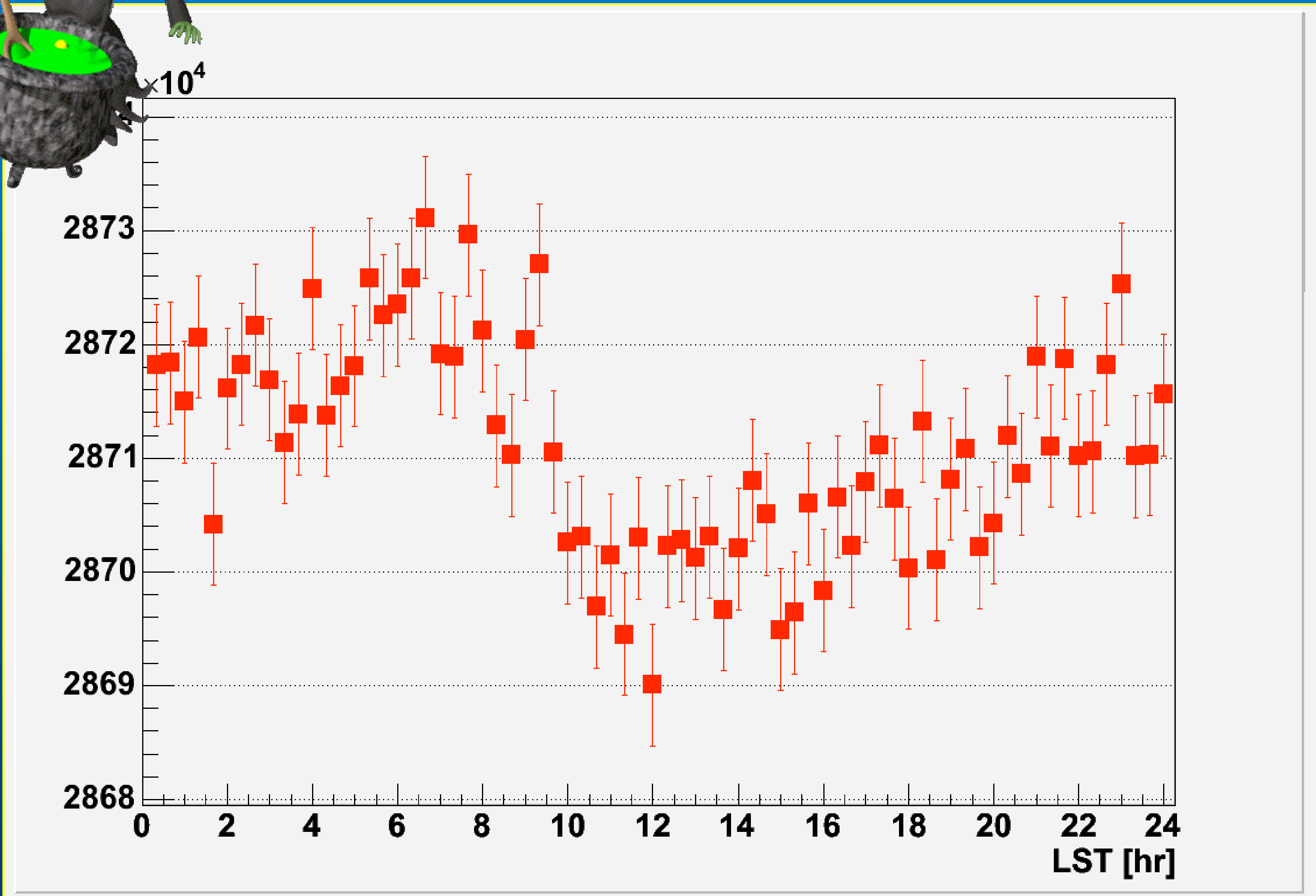
$$A = \square \cos d$$

d= observation declination

Anisotropy measurement in practice

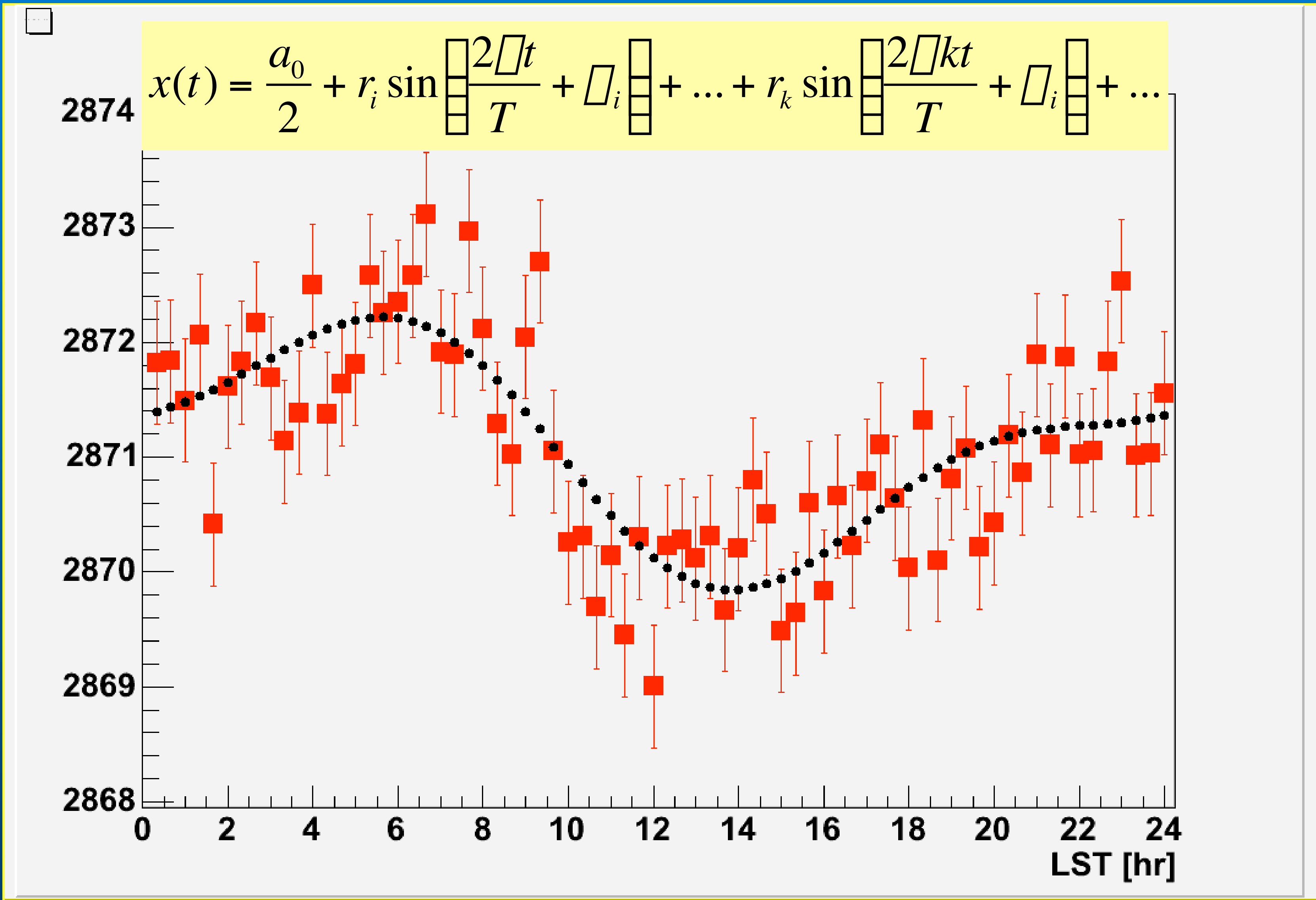
- ✓ For each detected EAS we determine
  - ✓ Arrival time
  - ✓ Arrival direction
  - ✓ Right ascension (sidereal time) & declination
  - ✓ “Energy”
- ✓ We correct counting rates for pressure and temperature
- ✓ After correction for P,T, we apply “safety” cuts:
  - ✓ Quality cuts on data
  - ✓ Full years of data taking
  - ✓ Full sidereal days only

After all the "cooking": the sidereal time distribution

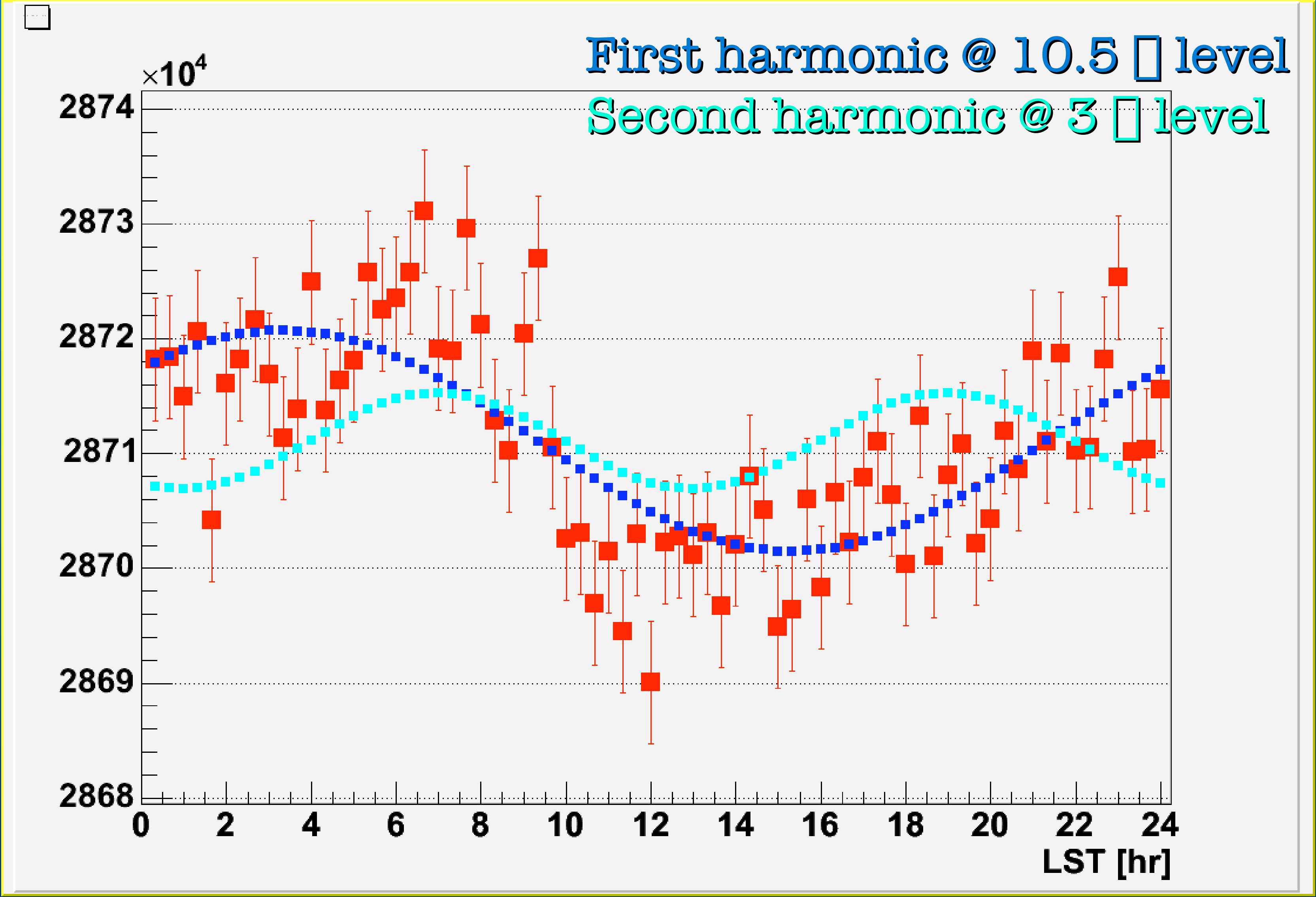


After all the cooking: the sidereal time distribution

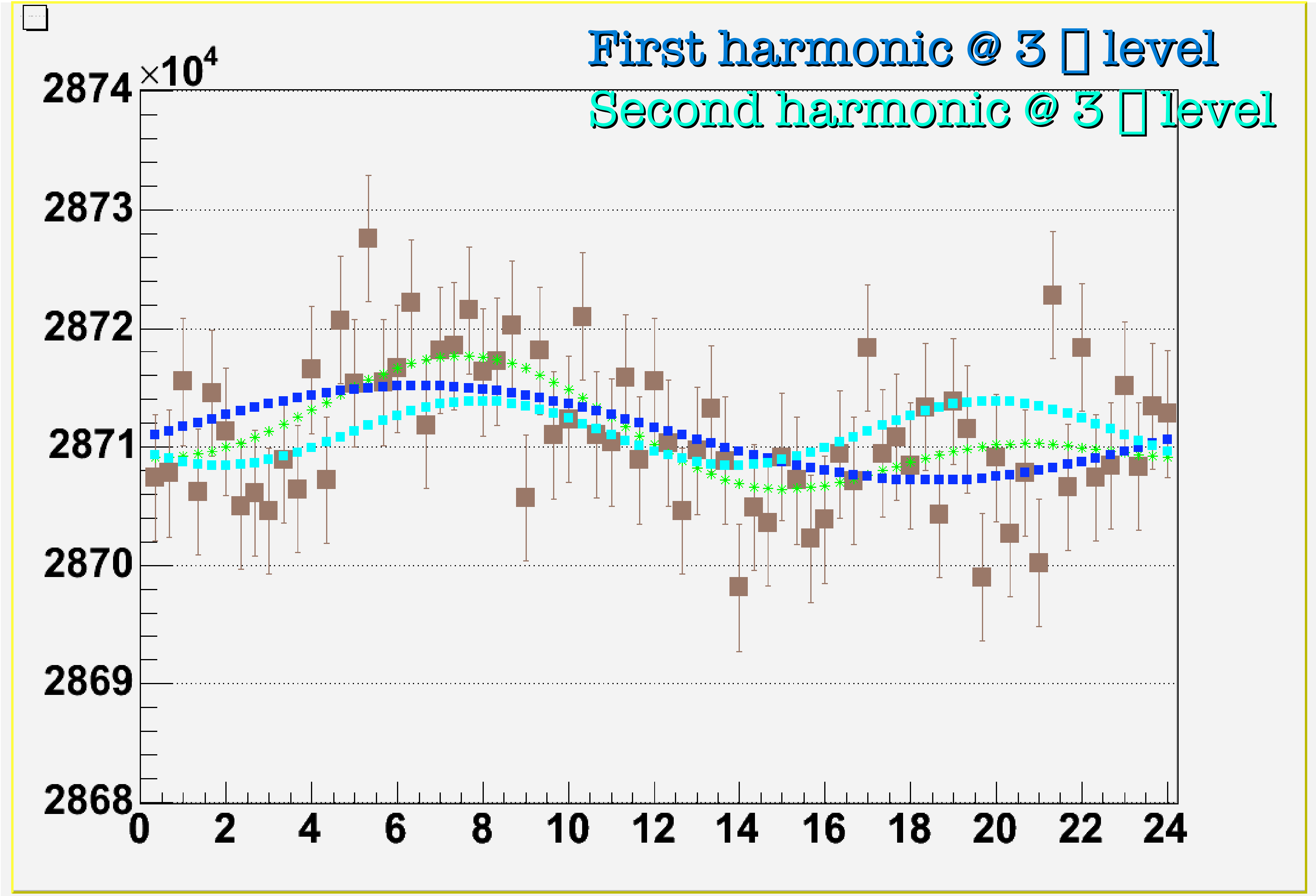
$$x(t) = \frac{a_0}{2} + r_i \sin\left(\frac{2\pi t}{T} + \varphi_i\right) + \ldots + r_k \sin\left(\frac{2\pi k t}{T} + \varphi_i\right) + \ldots$$



After all the cooking: the sidereal time distribution



X-check: the anti-sidereal time distribution



The observational “status of the art”

Existing data (up to 100 TeV)

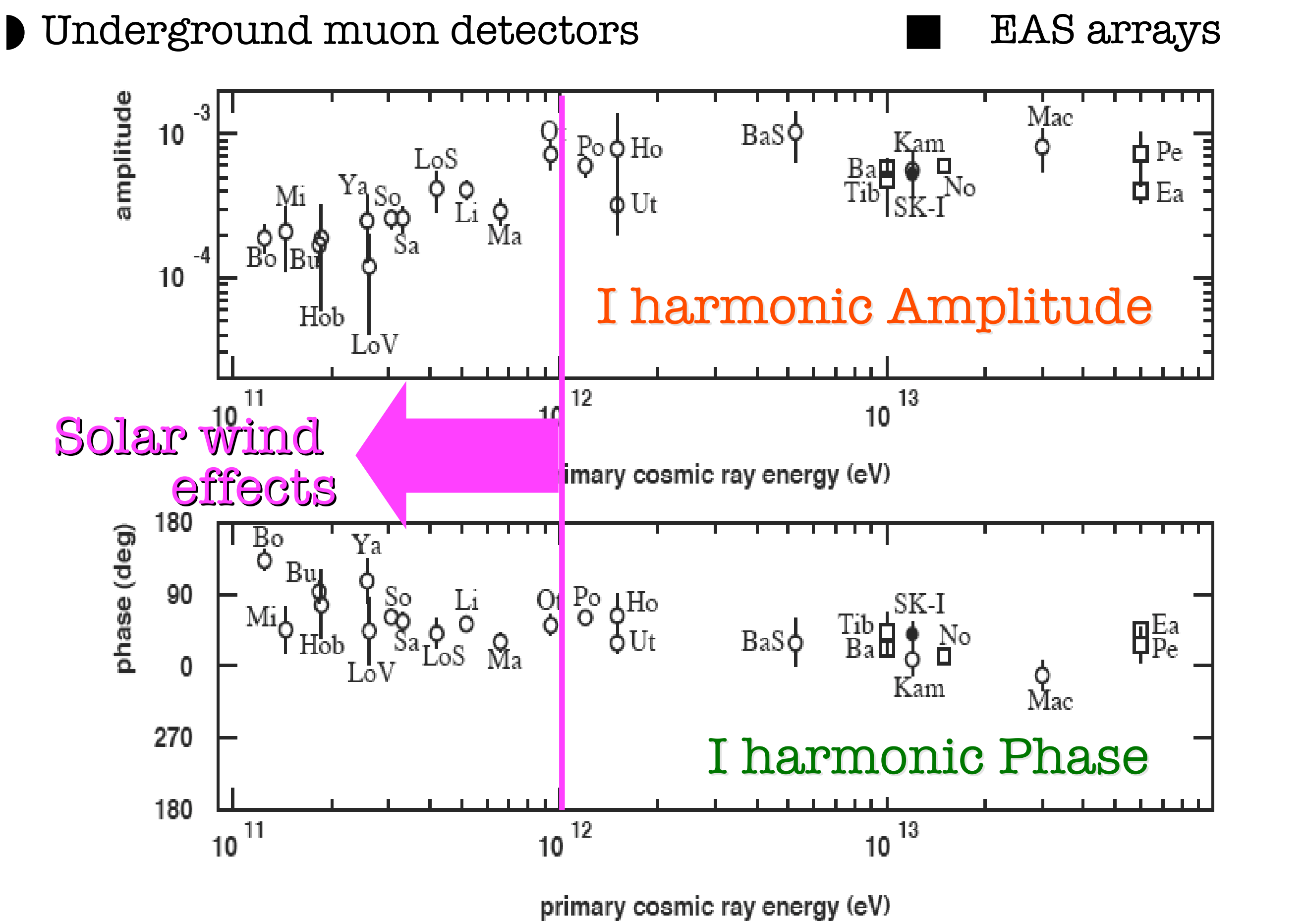


FIG. 3: Amplitude and phase of the first harmonic fit to zenith-type plots from various cosmic ray experiments. The energy in the horizontal axis is either the median or the log-mean energy. Circles: muon detectors. Squares: extensive air shower array. Filled circle: SK-I. Data references: Bo = Bolivia (vertical) [12], Mi = Misato (vertical) [13], Bu = Budapest [13], Hob = Hobart (vertical) [13], Ya = Yakutsk [13], LoV = London (vertical) [13], So = Socomo (vertical) [12], Sa = Sakashita (vertical) [14], LoS = London (south) [15], Li = Liapootah (vertical) [16], Ma = Matsushiro (vertical) [17], Ot = Ottawa (south): [18], Po = Poatina (vertical) [19], Ho = Hong Kong [20], Ut = Utah [21], BaS = Baksan (south) [22], SK-I (this report), Kam = Kamiokande [10], Mac = MACRO [11], Tib = Tibet (vertical) [23], Ba = Baksan air shower [24], No = Mt. Norikura [3], Ea = EAS-TOP [25], Pe = Peak Musala [26].

- ✓ Data on sidereal anisotropies: good consistency up to 100 TeV (above 10 TeV, measurements by EAS arrays, below by underground muon detectors or high altitude EAS arrays)
- ✓ Amplitude and phase of the I harmonic rather constant

A ≈ 5-10 10^{-4},

□ = 23-2.6 hr

Kamiokande & MACRO @ ≈10^{13} eV
(underground muon detectors)

KAMIOKA: 3 kt water Cherenkov detector

PRD 56 (1997) 23

$E_{th}(p) \approx 1.2\ 10^{13}$ eV

MACRO: 5 kt streamer tubes/scintillator detector

PRD 67 (2003) 042002

$E_{th}(p) \approx 20\ 10^{13}$ eV

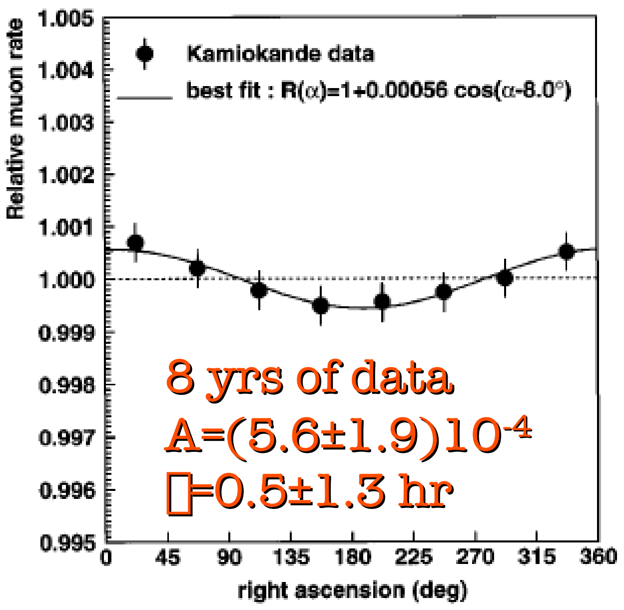


FIG. 1. Cosmic-ray muon rate as a function of the right-ascension of the arrival direction in Kamiokande. The average muon rate was normalized to be 1. The solid line shows the best-fit curve, assuming the first Fourier harmonics: $R(\alpha)=1+r_0\cos(\alpha-\alpha_0)$, where $r_0=5.6\times10^{-4}$ and $\alpha_0=8.0°$.

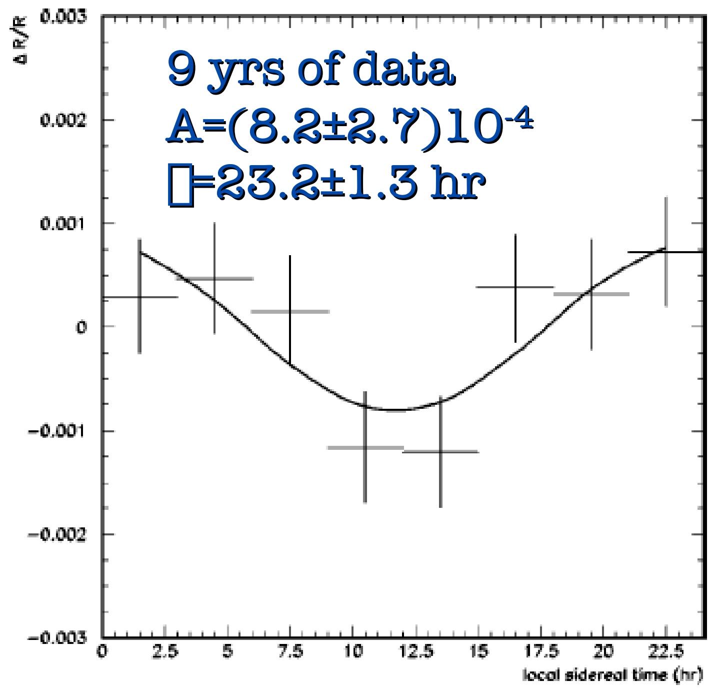
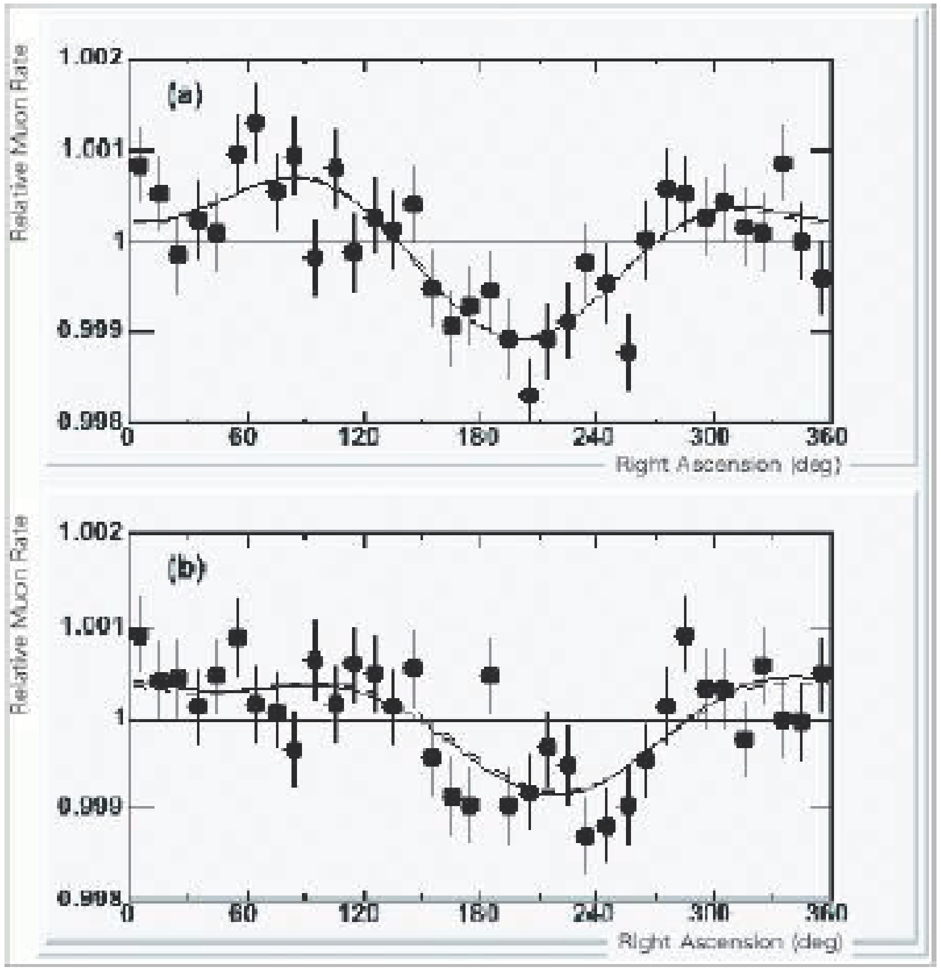


FIG. 4. Deviations of the muon rate from the mean muon rate binned according to the local sidereal time at the Gran Sasso. Superposed is the best-fit curve of the form Eq. (13) representing the modulation.

More recently: Super-Kamiokande @ ≈10^{13} eV

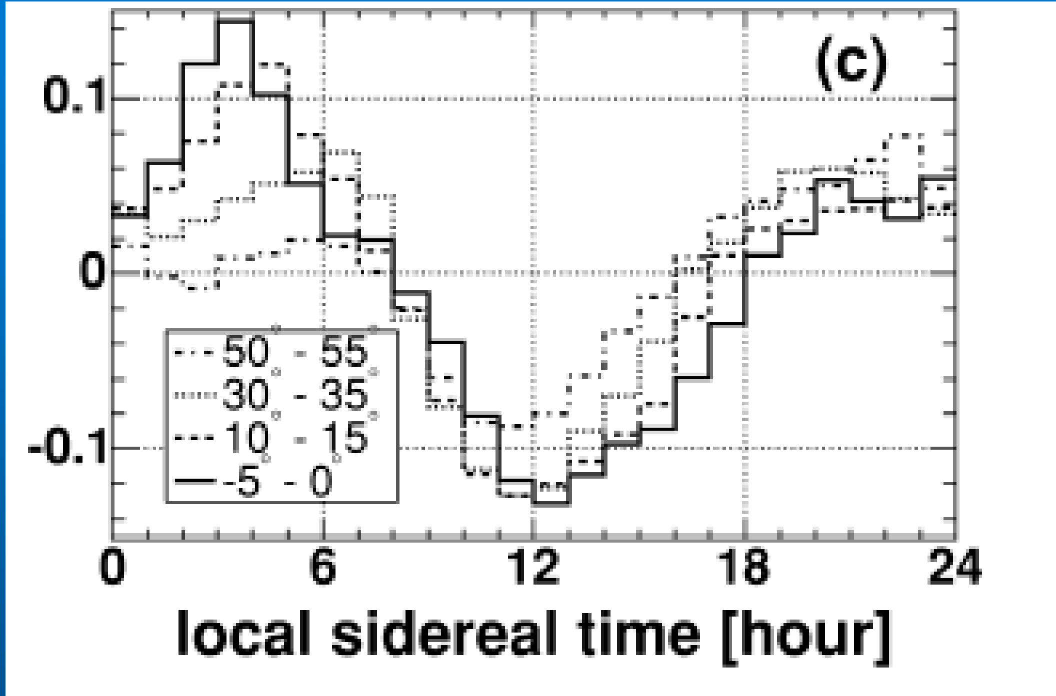
50 kt water
Cherenkov
detector (Japan)



SK (5 yrs)
Astro-ph/0508468
A=(6.6±1.1)10^{-4}
=1.6±0.5 hr

High altitude EAS array @ ≈10^{13} eV (Tibet)

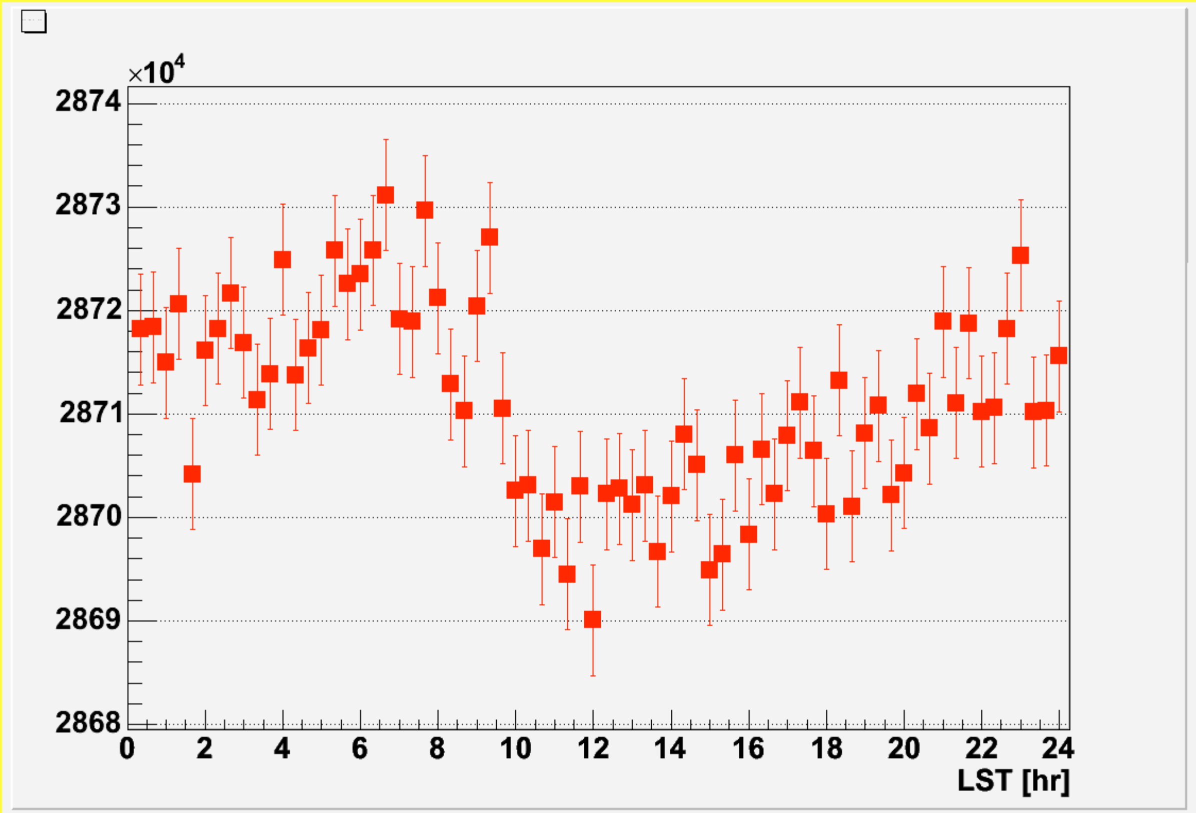
4300 m a.s.l.
Area 2 10^4 m^2
522 scint., 7.5 m apart
E>4 TeV (up to 50 TeV)
5 yrs of data
4 different energies



Tibet As-[illegible] (Ap. J, 626 (2005) L29)
A(@4 TeV)=(8.3±0.5)10^{-4}
[illegible]=(0.9±0.2) hr

EAS arrays at 100 TeV (EAS-TOP)

2000 m a.s.l.
Area 1 10^5 m^2
35 scint., 80 m apart
E>100 TeV
10 yrs of data



10 yrs of data
$A=(3.4\pm0.3)10^{-4}$
=(3.3±0.4) hr
S=10.3

+

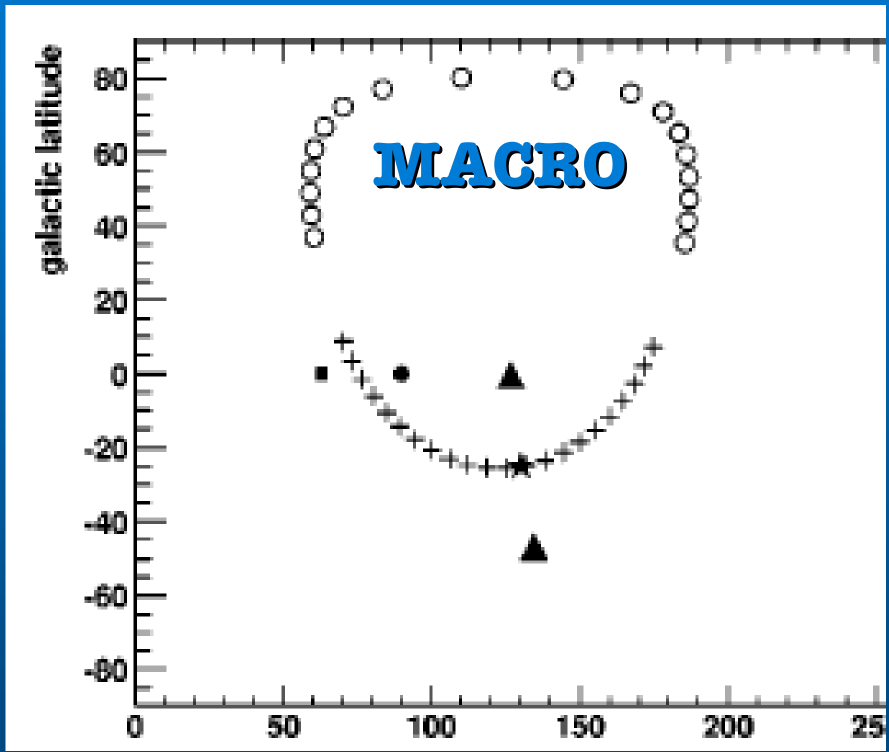
I harmonic in anti-sidereal time @ 3, much lower level than sidereal

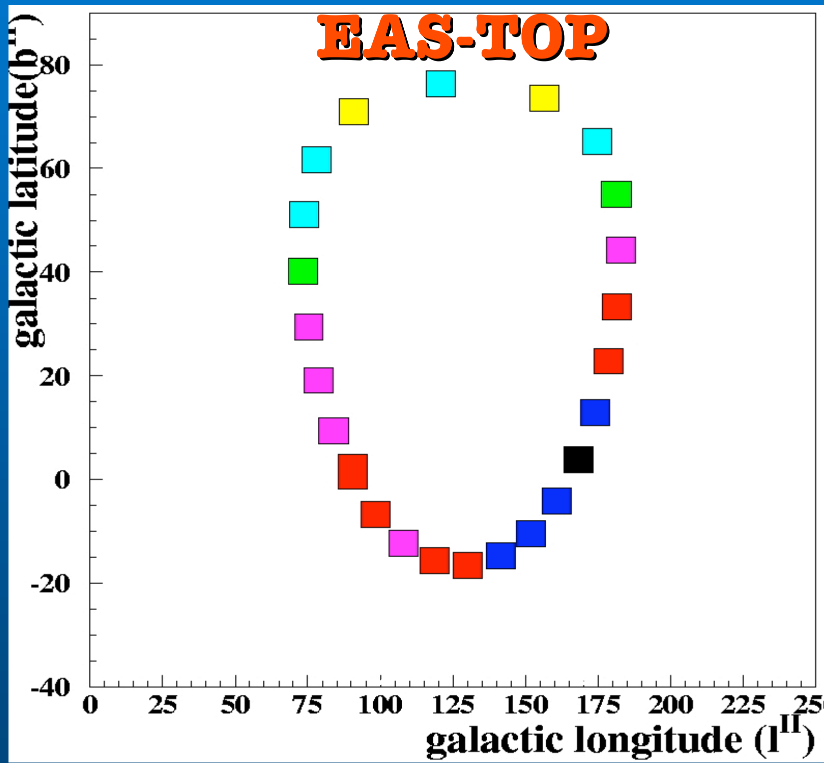
+

Observed solar anisotropy due to CG effect

Astronomical interpretation?

Mapping of the observed sidereal wave in galactic coordinates

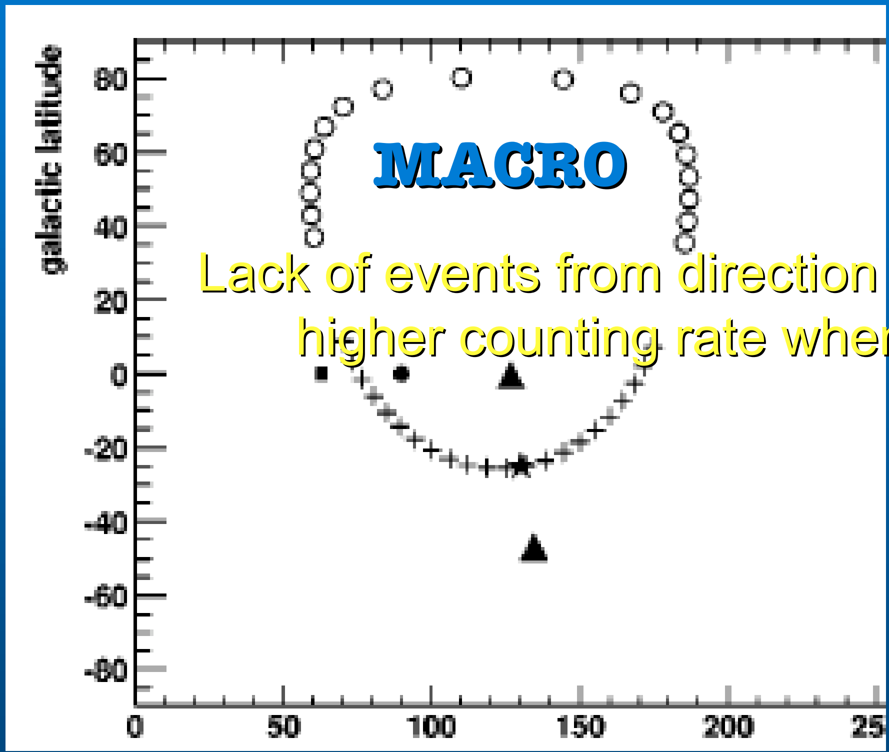


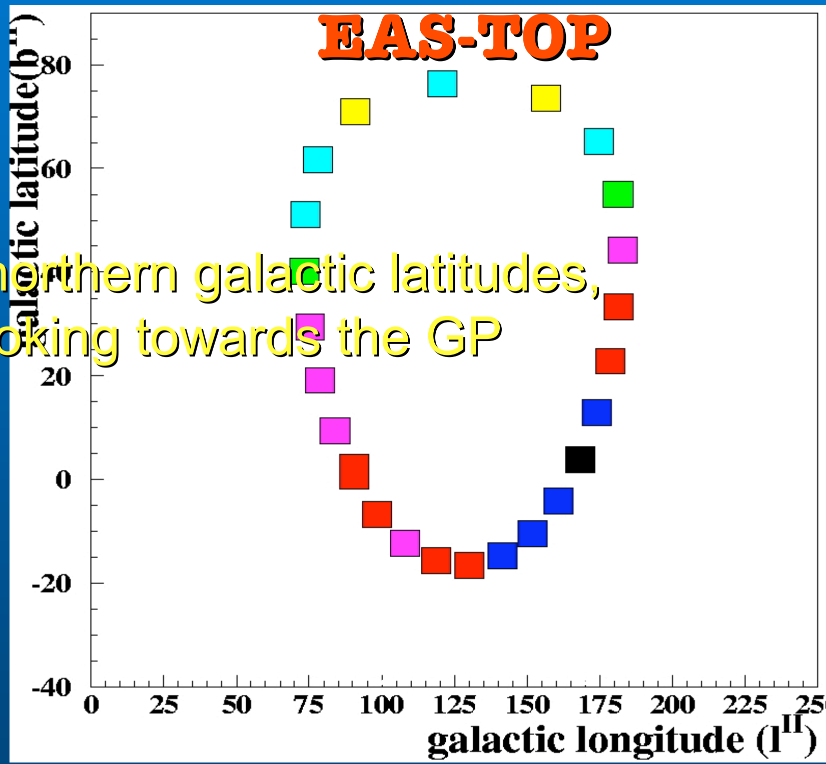


Lack of events from direction of northern galactic latitudes, higher counting rate when looking towards the GP

Astronomical interpretation?

Mapping of the observed sidereal wave in galactic coordinates





Lack of events from direction of northern galactic latitudes, higher counting rate when looking towards the GP

SK: harmonic analysis in 10 bands -> sky map: excess region in the Taurus region (toward the center of the Orion Arm)

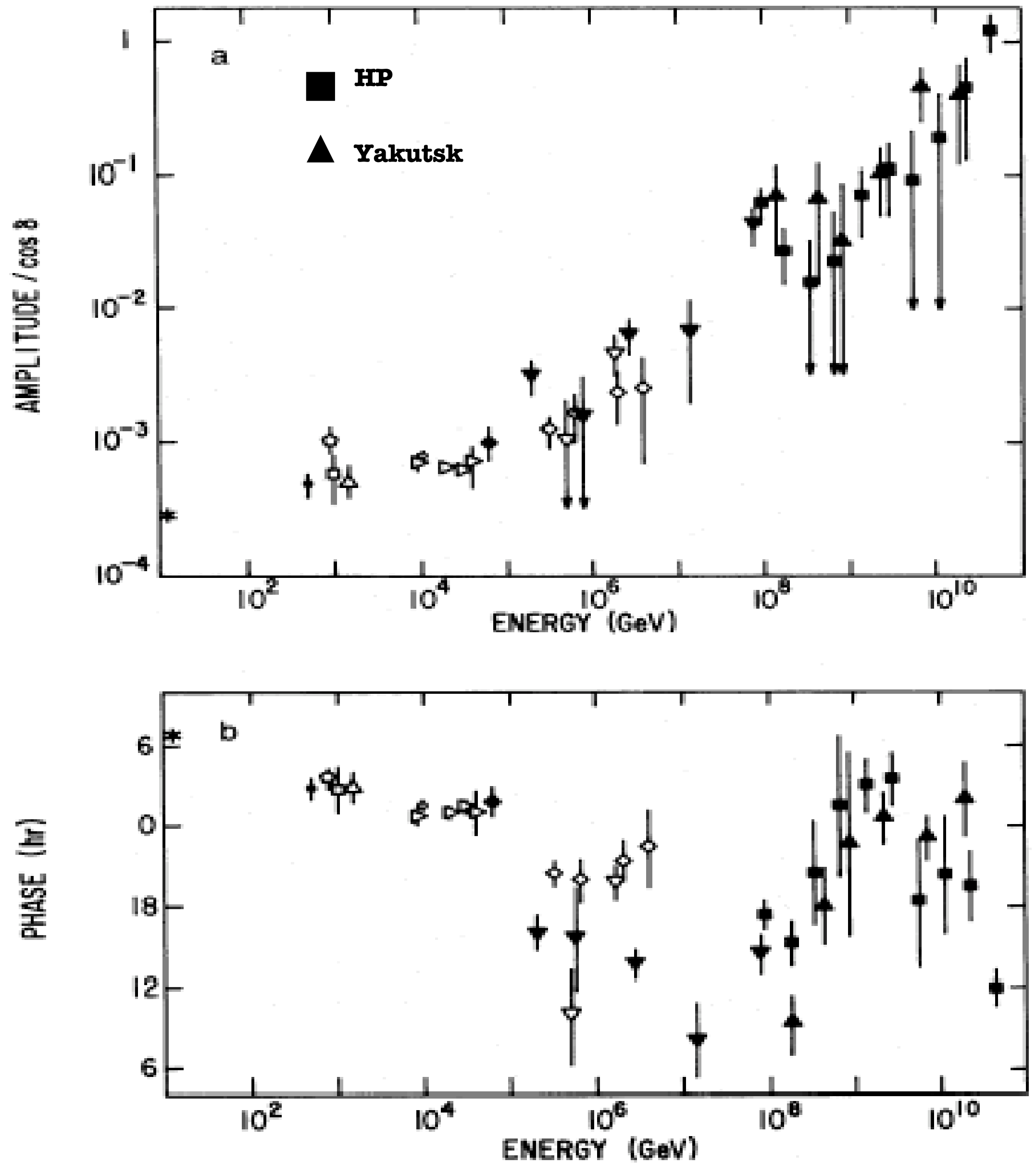
Conclusions on existing data (up to 100 TeV)

- ✓ Existing data on sidereal anisotropies show good consistency up to 100 TeV (above 10 TeV, measurements by EAS arrays, below by underground muon detectors or high altitude EAS arrays)
- ✓ **Amplitude and phase of the I harmonic rather constant ($A \approx 5\text{-}10\ 10^{-4}$, □=23-2.6 hr)**
- ✓ Consistent with large-scale diffusive propagation of CRs in the Galaxy, phase consistent with “excess” when looking towards the galactic disc (Orion Arm?)
- ✓ Amplitude not changing with energy:
  - ✓ Compton-Getting effect not excluded: due to the motion of the solar system wrt to the CR rest system ? (v>25 km/s)
  - ✓ Convective mechanism in the propagation?

Existing data up to 100 EeV

- ✓ "Old" experiments: Apparently larger amplitudes at higher energies, but statistical uncertainties large ("noise" effect)
- ✓ Above 10^{17} eV, containement of CR in the galactic magnetic field should start to fail. Escape of CR should induce detectable large scale anisotropies. Galactic plane enhancement?
- ✓ *At even higher energies, charged particle "astronomy"?*

Existing data up to 100 EeV



Haverah Park and Yakutsk claimed significant anisotropies at 10^{17}-10^{19} eV (P≈0.3%, A≈1%)
Interpreted as excess from the GP

Anisotropy “amplitude” increases as number of events decreases

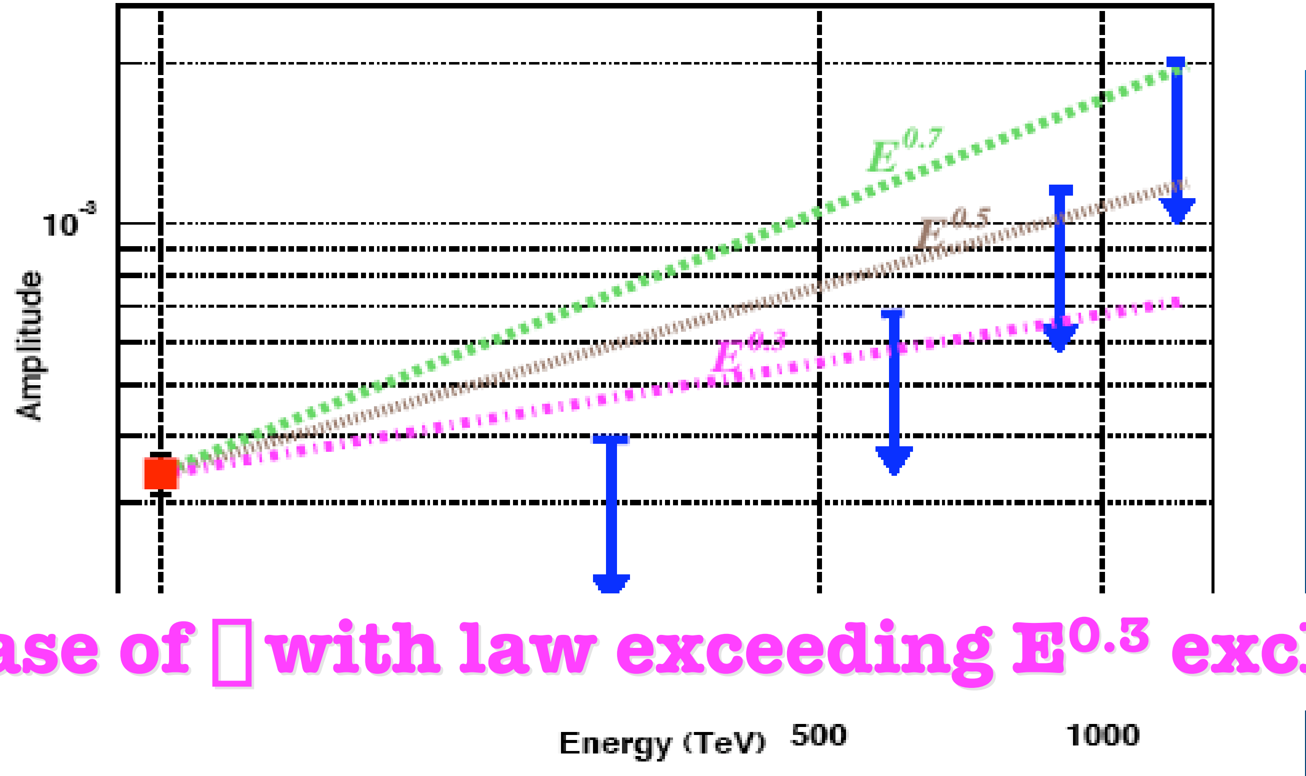
$$\Box = \frac{I_{max} \Box I_{min}}{I_{max} + I_{min}}$$

$$\Box \quad \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

EAS -TOP up to 1 PeV

E_0 [TeV]	A_{sol} (10^4)	ϕ_{sol} [hr]	A/σ	A_{sid} (10^4)	ϕ_{sid} [hr]	A/σ
100	2.7 ± 0.3	4.3 ± 0.5	8.2	3.4 ± 0.3	3.3 ± 0.4	10.3
300	4.4 ± 1.0	4.4 ± 0.8	4.6	2.0 ± 1.0	12.2 ± 1.9	2.0
600	2.4 ± 1.7	5.2 ± 2.7	1.4	2.8 ± 1.7	13.5 ± 2.3	1.7
900	5.2 ± 2.8	4.6 ± 2.1	1.8	4.6 ± 2.8	12.8 ± 2.3	1.6
1200	3.6 ± 5.0	0.5 ± 5.4	0.7	8.9 ± 5.0	13.0 ± 2.1	1.8

T



Increase of with law exceeding $E^{0.3}$ excluded

Kascade @ 1-10 PeV

Sea level
Area 4 10^4 m^2
252 scint., 13 m apart
E>0.6 PeV
4 yrs of data
Ap.J, 604 (2004) 687

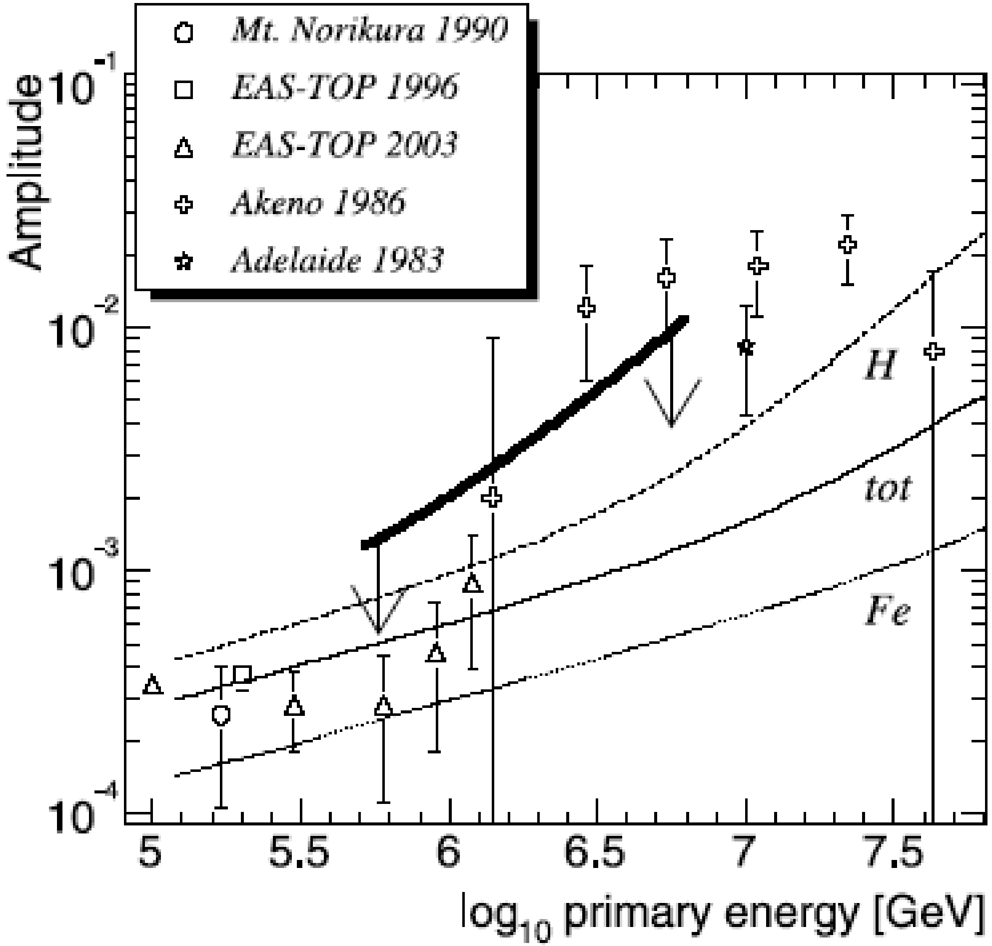
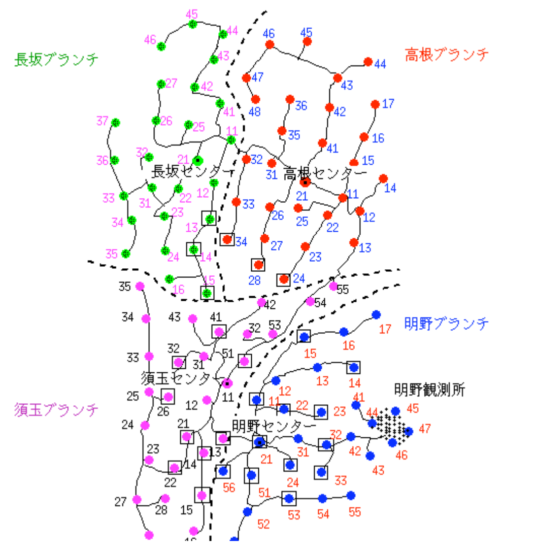


FIG. 6.—KASCADE upper limits (95%) of Rayleigh amplitudes *A* vs. primary energy (*thick line*) compared to reported results from the literature (Nagashima et al. 1990; Aglietta et al. 1996, 2003; Kifune et al. 1986; Gerhardy & Clay 1983). Model predictions from Candia et al. (2003) for the total anisotropy and for the anisotropies of the proton and iron components are also shown (*thin lines*).

AGASA, Fly's Eye, Sugar at 1 EeV

- AGASA: 4% dipole-like enhancement oriented towards the Galactic Center at $E>10^{18}$ eV. Neutron emission from GC?
- Corroborated by Fly's Eye (galactic plane enhancement) and SUGAR (offset from the GC of 7.5°)
- AGASA and Fly's Eye too far north in latitude to directly observe the Galactic Center
- Yakutsk and HiRes give a limit (still not excluding AGASA findings)
- No large scale anisotropies at higher energies (but data sample are still limited)
- Still waiting for Auger data



AGASA harmonic analysis

900 m above sea level
Area 100 km^2
111 scint., 1 km apart
11 yrs of data
E> 1.2 10^{17} eV

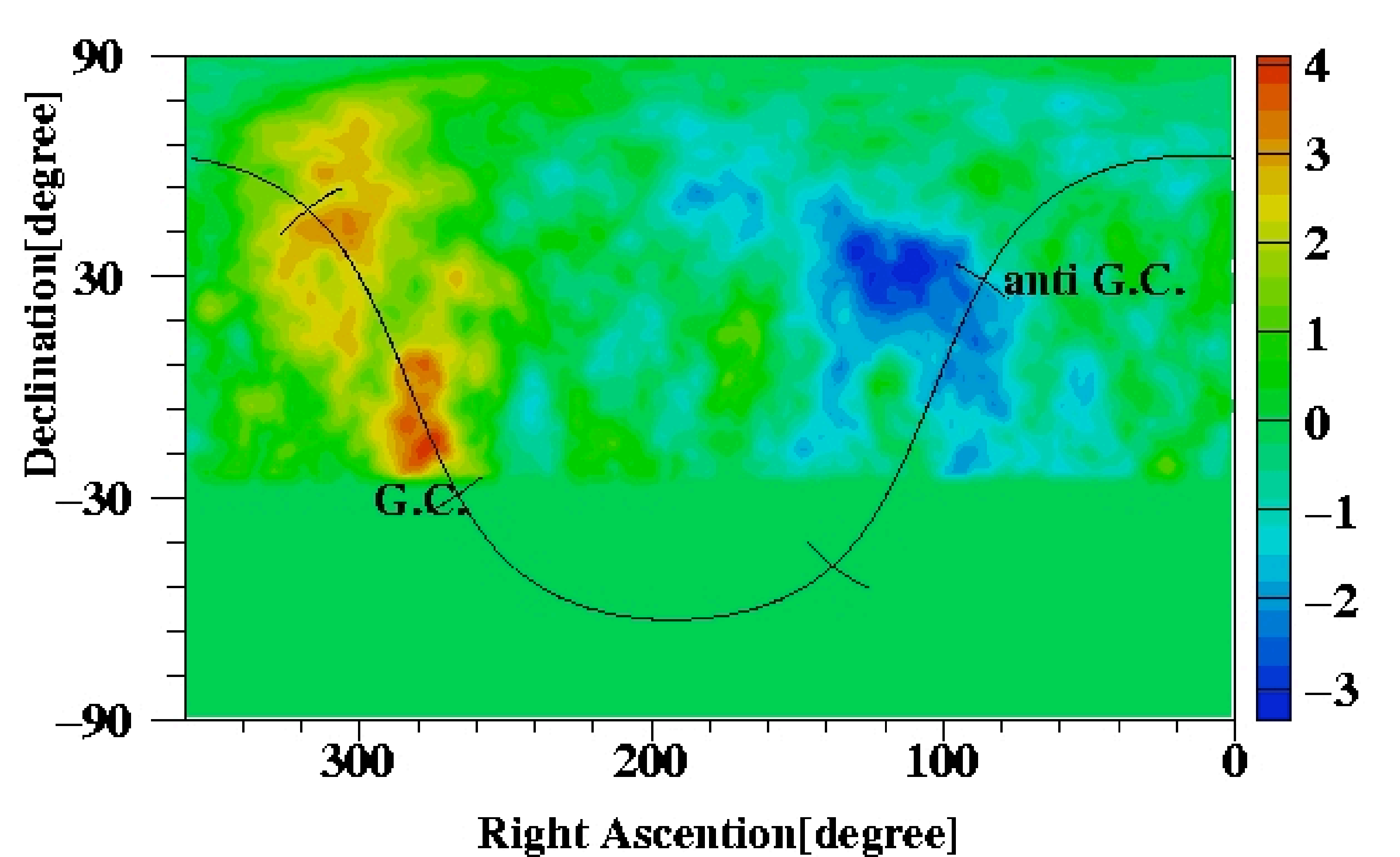
Energy range/ EeV	#	Amplitude [%]	Phase	k	P_{prob}
1/8–1/4	19146	1.6	211	1.37	0.25
1/4–1/2	32921	1.2	35	1.32	0.26
1/2–1.0	31657	1.0	298	0.87	0.41
1.0–2.0	18274	4.1	300	7.95	0.00035
2.0–4.0	6691	3.1	269	1.62	0.19
4.0–8.0	1913	2.9	278	0.41	0.66

Anisotropy of amplitude 4% around 10^{18} eV found in first harmonic analysis.
No significant large scale anisotropy at higher energies (up to ≈10^{20} eV)

AGASA Sky Map

With a two-dimensional map (pixel size 20˚) a 4 excess is found near the GC region

Significance []



AGASA GC excess interpretation

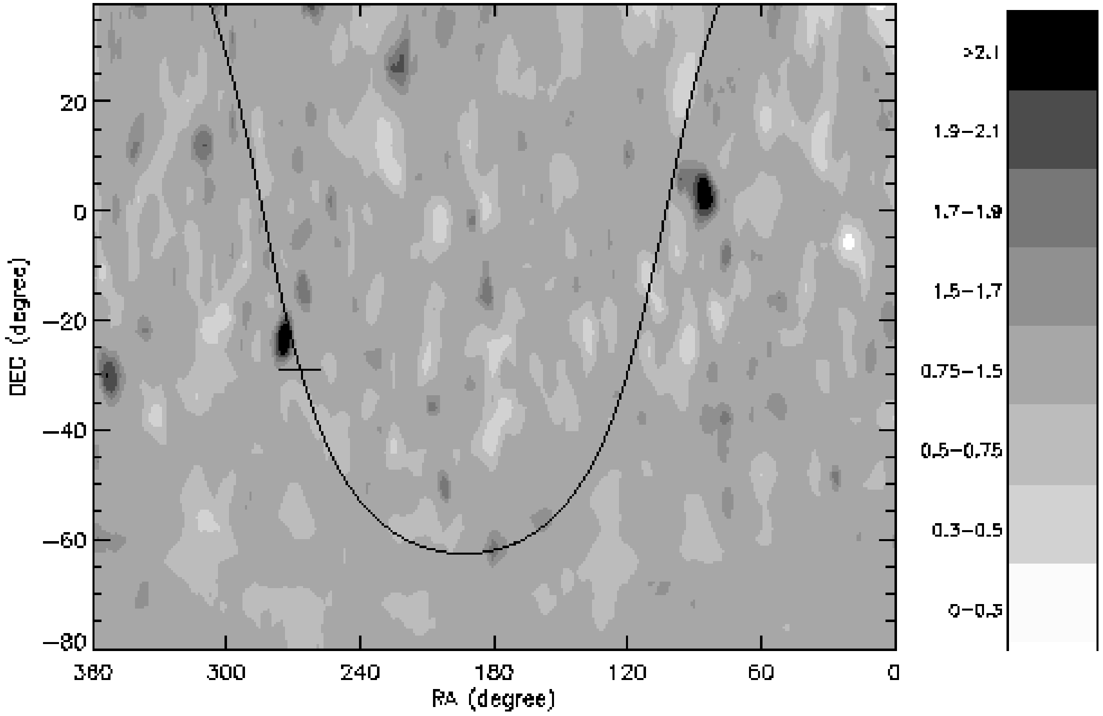
- Cosmic ray protons. Excess directed towards the GP, apparently correlated with the nearby spiral arms (hence CR are still galactic at these energies)
- Neutrons primaries. Decay length for n at 10^{18} eV is ≈ 10 kpc: can propagate from GC without decaying or bending in magnetic field. Neutrons from interactions of heavy nuclei with ambient photons or matter in the GC.

SUGAR Sky Map

Area 70 km^2
47 scint., 1.6 km apart
E> 2 10^{17} eV

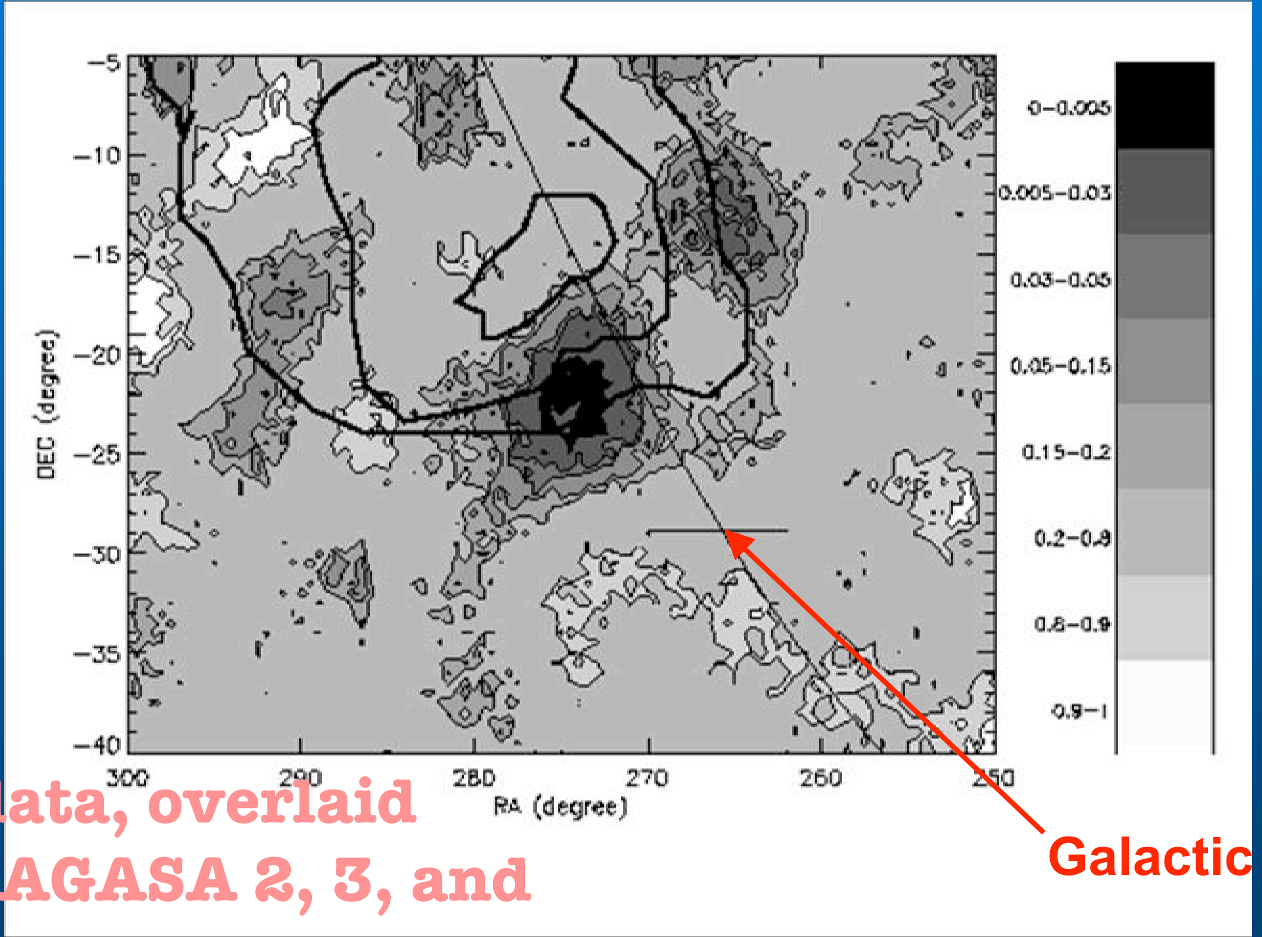
- Excess is centered at (□,□) = (274^0, - 22^0)
- Statistical significance 2.6 □
- No hint of a signal from the true Galactic Center (peak is 7.5^0 away)
- Signal is no larger than would be expected from a point source
- 4 deg. ang. resolution

Fractional excess



Galactic center, (□,□) = (266.4, -28.9)

Combined Anisotropy Data



SUGAR data, overlaid with the AGASA 2, 3, and 4 sigma contours

Pierre Auger Observatory

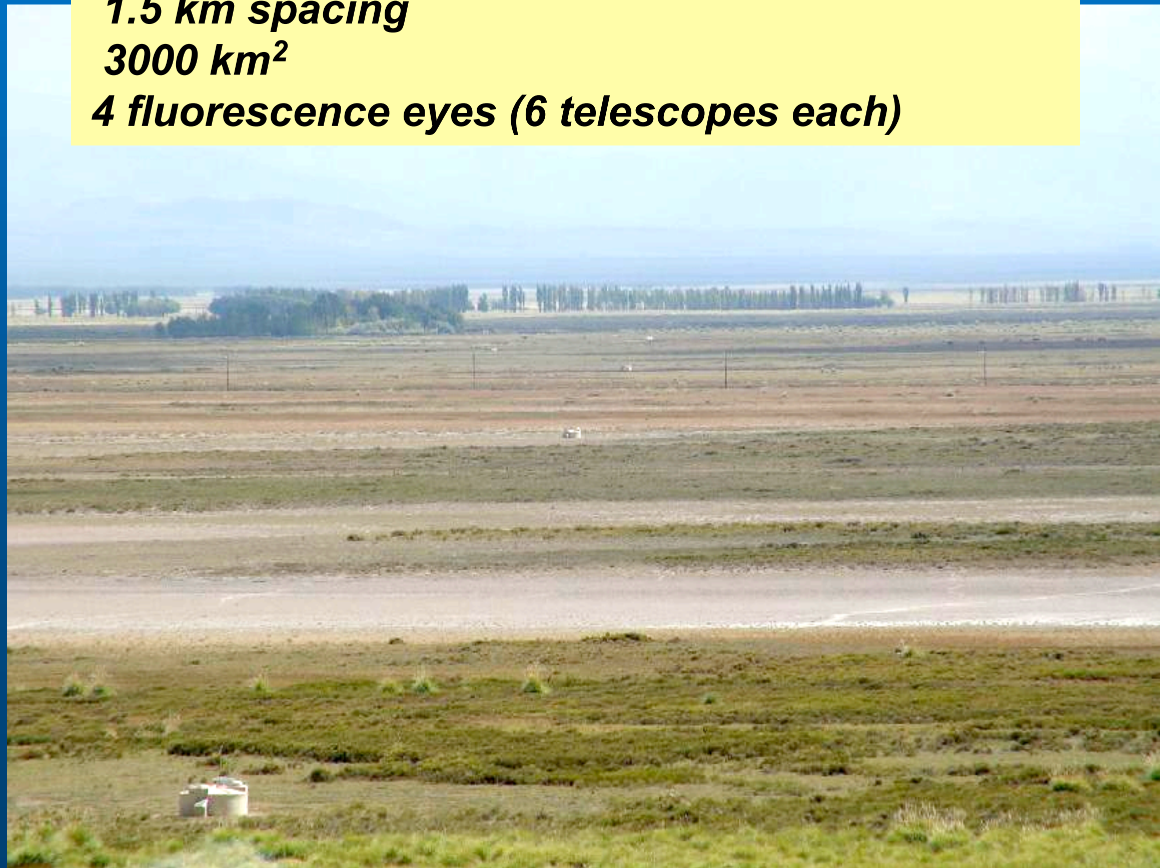
Hybrid EAS array under construction in Argentina

1600 detector stations

1.5 km spacing

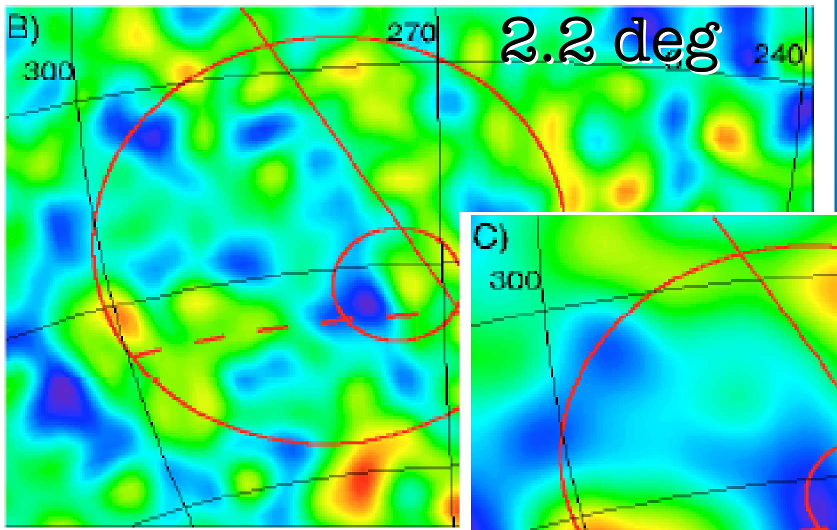
3000 km^2

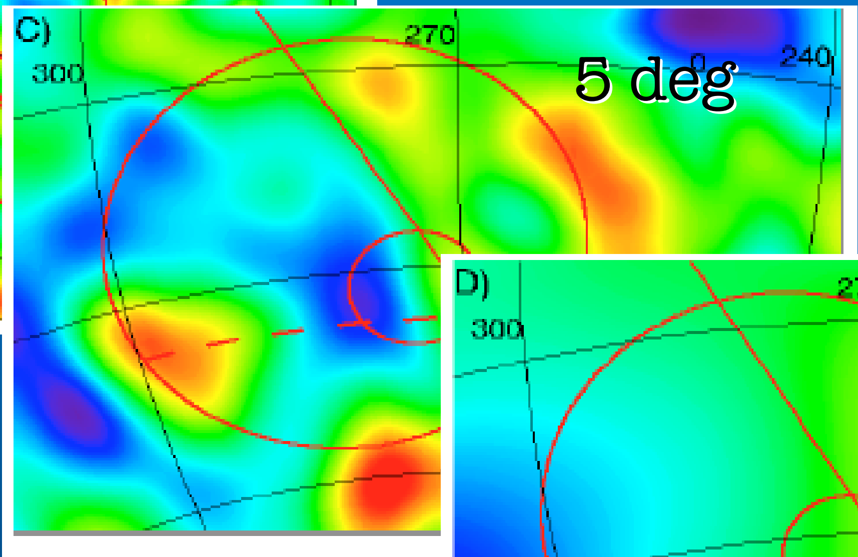
4 fluorescence eyes (6 telescopes each)

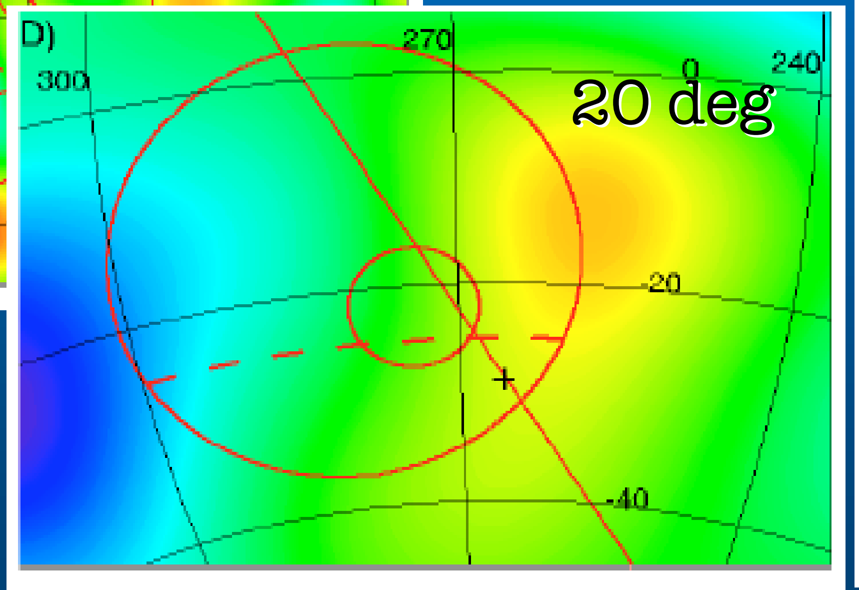


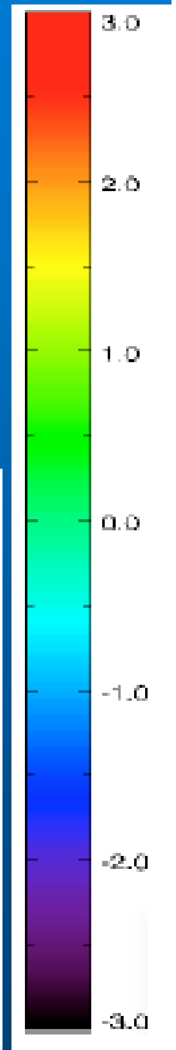
Pierre Auger Observatory

Point-like source search, with different bin sizes









+: GC
Solid line: GP
Dashed line: field of view limit for Agasa
Small circle: SUGAR excess
Large circle: AGASA excess

And to conclude…

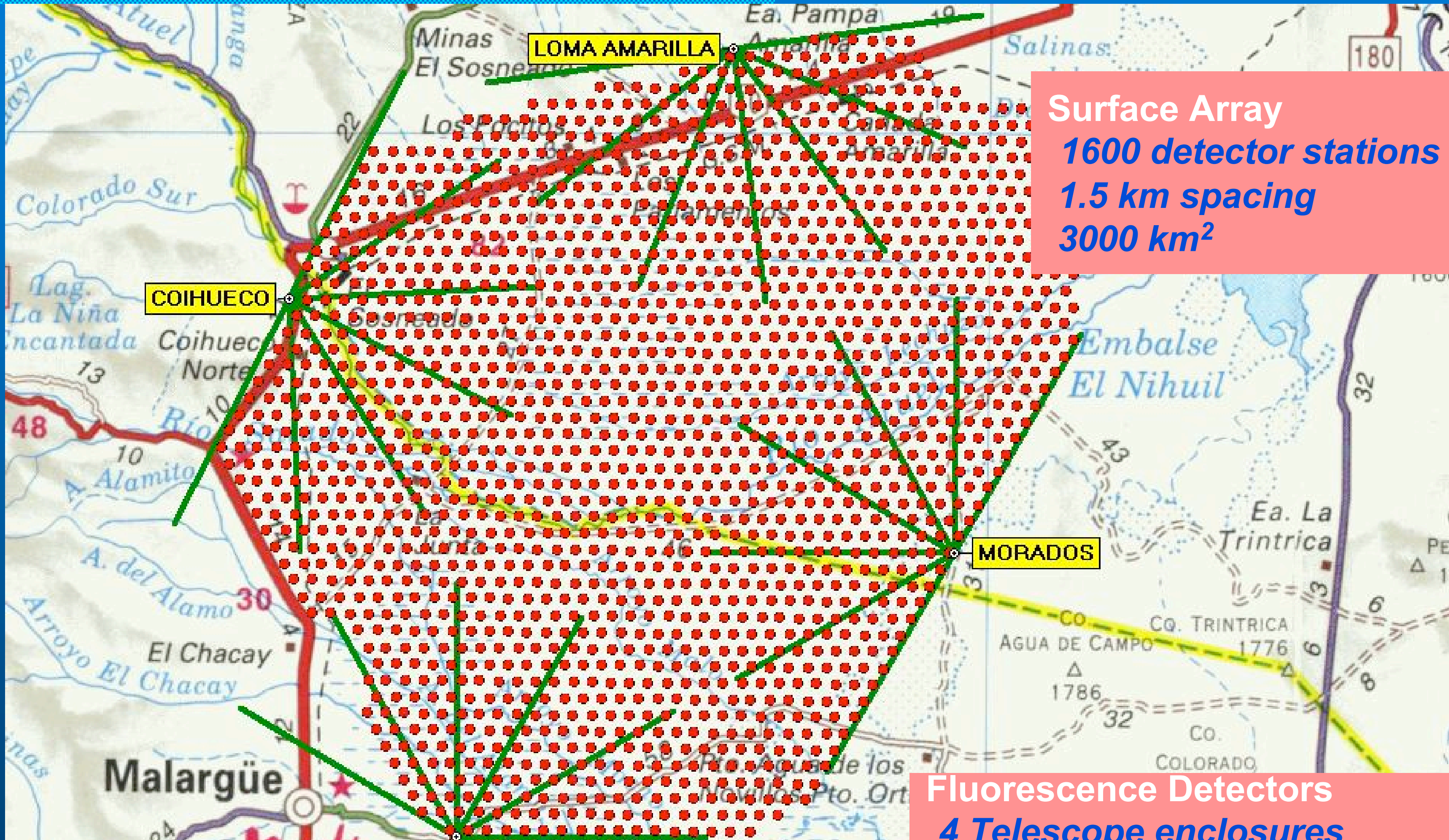
Advertisement

Experimental challenge for the present/future

Kascade-Grande (FZK):
252+37 detectors
≈150 m spacing
≈ 0.5 km^2
E>10^{16} eV

Anisotropy measurement @ 10^{17} eV (where CRs should not be diffusing anymore in the Galaxy)

Experimental challenge for the present/future



Surface Array

1600 detector stations

1.5 km spacing

3000 km^2

Fluorescence Detectors

4 Telescope enclosures

Anisotropy measurement @ $10^{18\text{-}20}$ eV (galactic/X-galactic transition, charged-particles astronomy)

The end