Anisotropy of primary cosmic ray flux in Super-Kamiokande

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for the Super-Kamiokande collaboration

Mar-6-2006 @ La Thuile 2006

New astronomy using underground cosmic-ray muons

(G.Guillian et al., submitted to PRD, astro-ph/0508468)

1. Super-Kamiokande detector and cosmic-ray muon data
2. Data analysis and results
3. Consistency with other experiments
4. Interpretation of the SK results
5. Conclusion

Super-Kamiokande

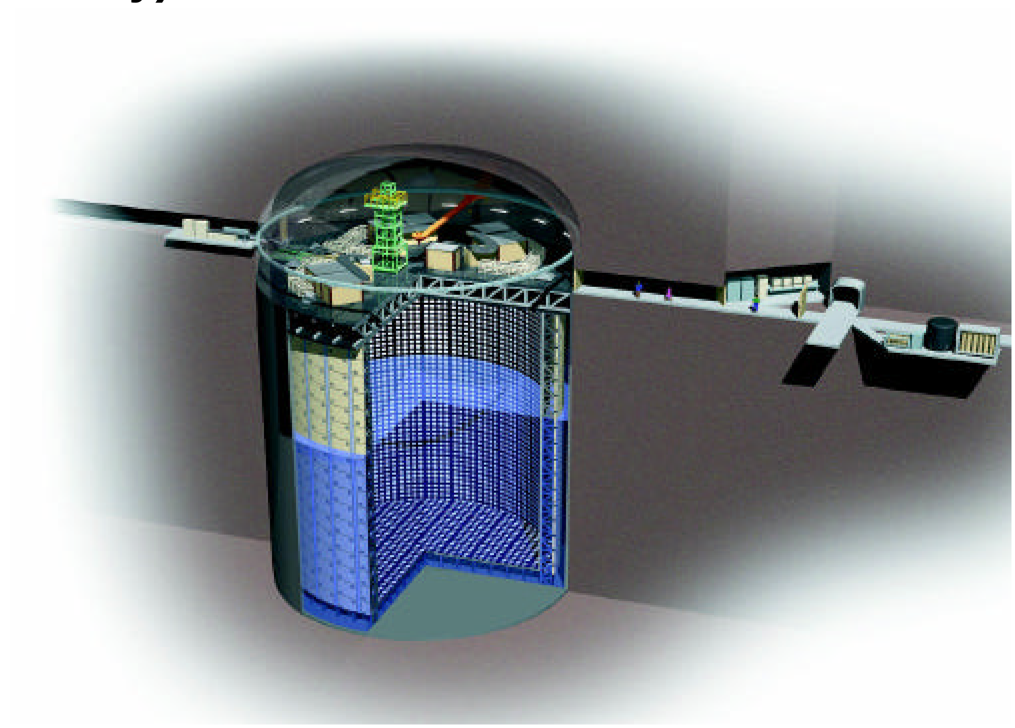
- **50kt water Cherenkov detector with 11146 20-inch F PMTs.**
- **Located at ~2400m.w.e. underground in Kamioka mine, in Japan, geographical coordinates are 36.43^{o}N latitude and 137.31^{o}E longitude.**
- **SK-1: April 1996 – July 2001**

  Accident in November 2001 during dead-PMT exchange

  SK-2: January 2003 – October 2005 (half PMT density)

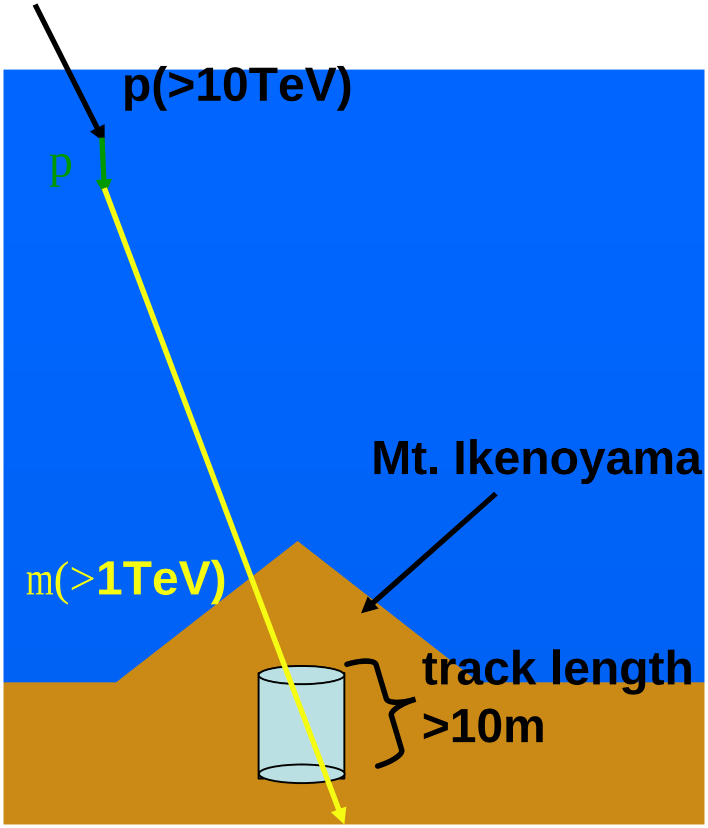
  SK-3: July 2006 – (full recovery)
- **Many successful results on neutrino physics, specially on atmospheric neutrinos and solar neutrinos.**

  → Koshio's talk
- **In neutrino physics, cosmic-ray muons are always background.**

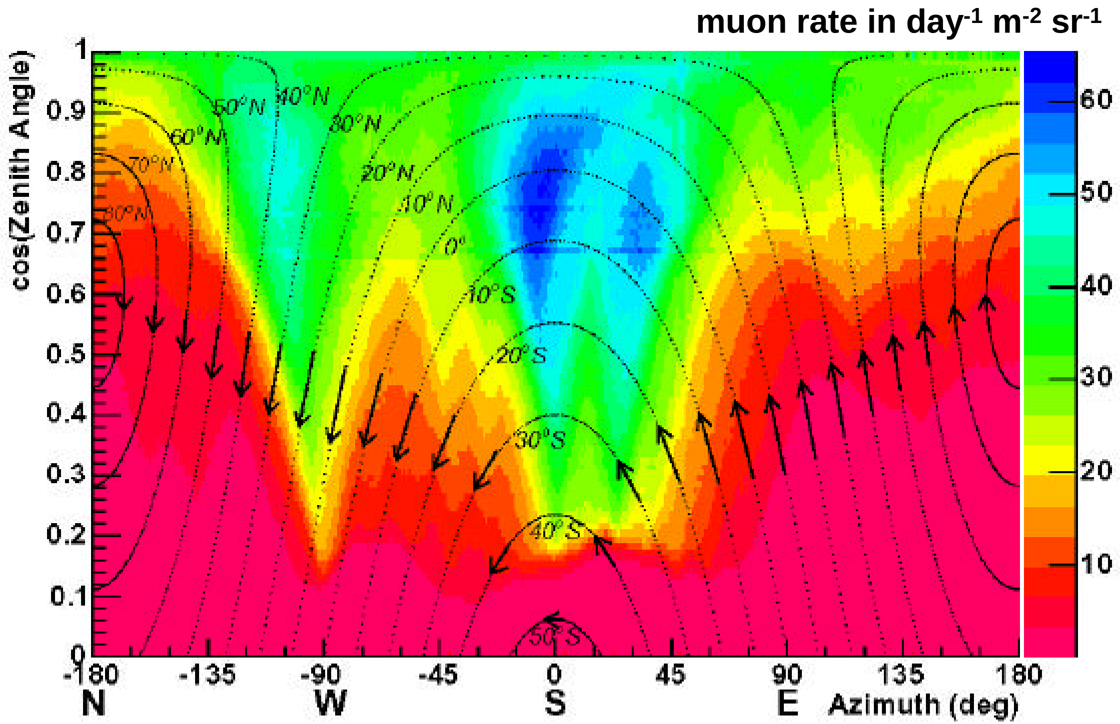


Cosmic-ray muon data

- **Cosmic-ray muons play the leading role in this subject!**
- **June 1, 1996 ~May 31, 2001 (5 calendar years in SK-1 period)**
- **Number of cosmic-ray muons is 2.54×10^{8} events from 1000~1200m^2 of detection area in 1662.0 days live time. Average muon rate is ~1.77Hz.**
- **After track reconstruction, muons with track length in the detector longer than 10m are selected. The muon number is 2.10×10^{8}, corresponding to 82.6% efficiency. Angular resolution of track reconstruction is less than 2^{o}.**
- **Because of more than 2400m.w.e. rock overburden, muons with energy larger than ~1TeV at ground level can reach the detector. Energy of parent cosmic-ray primary protons (or heavier nuclei) is larger than ~10TeV.**



Cosmic-ray muon rate in the horizontal coordinate



The muon rate is almost constant.

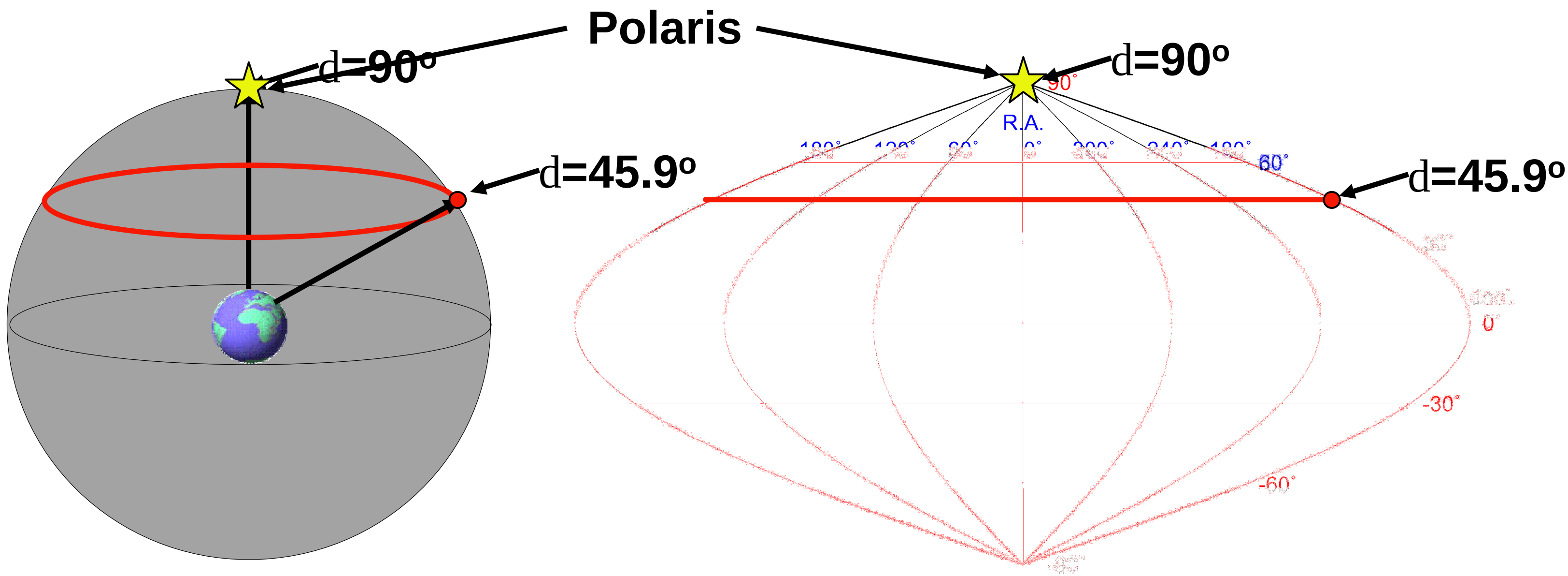
Time variation is much smaller than 1%.

- This distribution merely reflects the shape of the mountain.
  (Muon flux from south is larger because rock overburden is small.)
- The Earth rotates. Fixed direction in the horizontal coordinate moves on the celestial sphere.

  The time variation of muon flux from fixed direction in the horizontal coordinate can be interpreted as anisotropy of primary cosmic ray flux intensity in the celestial coordinate.

Definition of the celestial coordinate

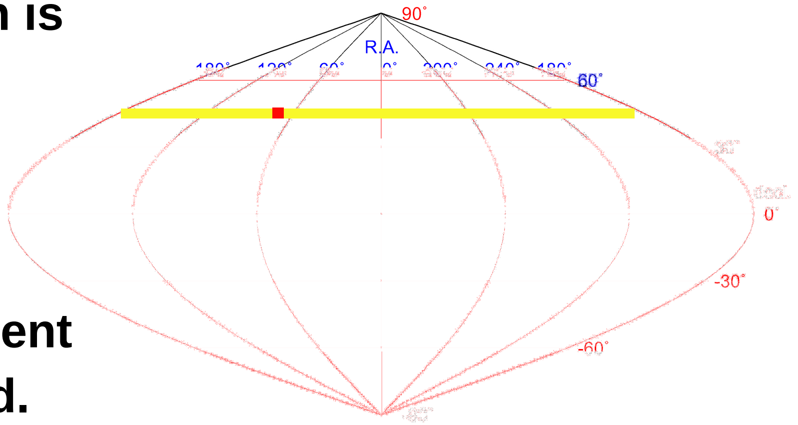
- **Position on the Earth's surface is expressed by latitude and longitude. In the same way, position of the celestial sphere is expressed by declination (d) and right ascension (R.A. or a).**



- **The direction of the zenith at the north pole corresponds to d=90º.**
- **The latitude of La Thuile is 45.9ºN.**
  The zenith direction corresponds to d=45.9º.
  With the rotation of the Earth, the zenith direction travels the d=45.9º line.
- **Fixed direction in the horizontal coordinate travels d=constant line.**
  It returns to the same right ascension after 1 sidereal day (360º rotation).

The analysis method

? Muon flux from each celestial position is compared with average of the same declinations.



? Since 360º of right ascension is scanned in one sidereal day,
right ascension distribution is equivalent to time variation of sidereal-day period.

? Cosmic-ray muon flux may vary by other reasons. They are:

- Change of upper atmospheric temperature
- Orbital motion of the Earth around the Sun
- An interference of one day variation and one year variation may produce fake one sidereal-day variation.

These background time variations are carefully evaluated and removed to extract ~0.1% of real primary cosmic-ray anisotropy.

? For more details, see G.Guillian et al., astro-ph/0508468

Anisotropy maps

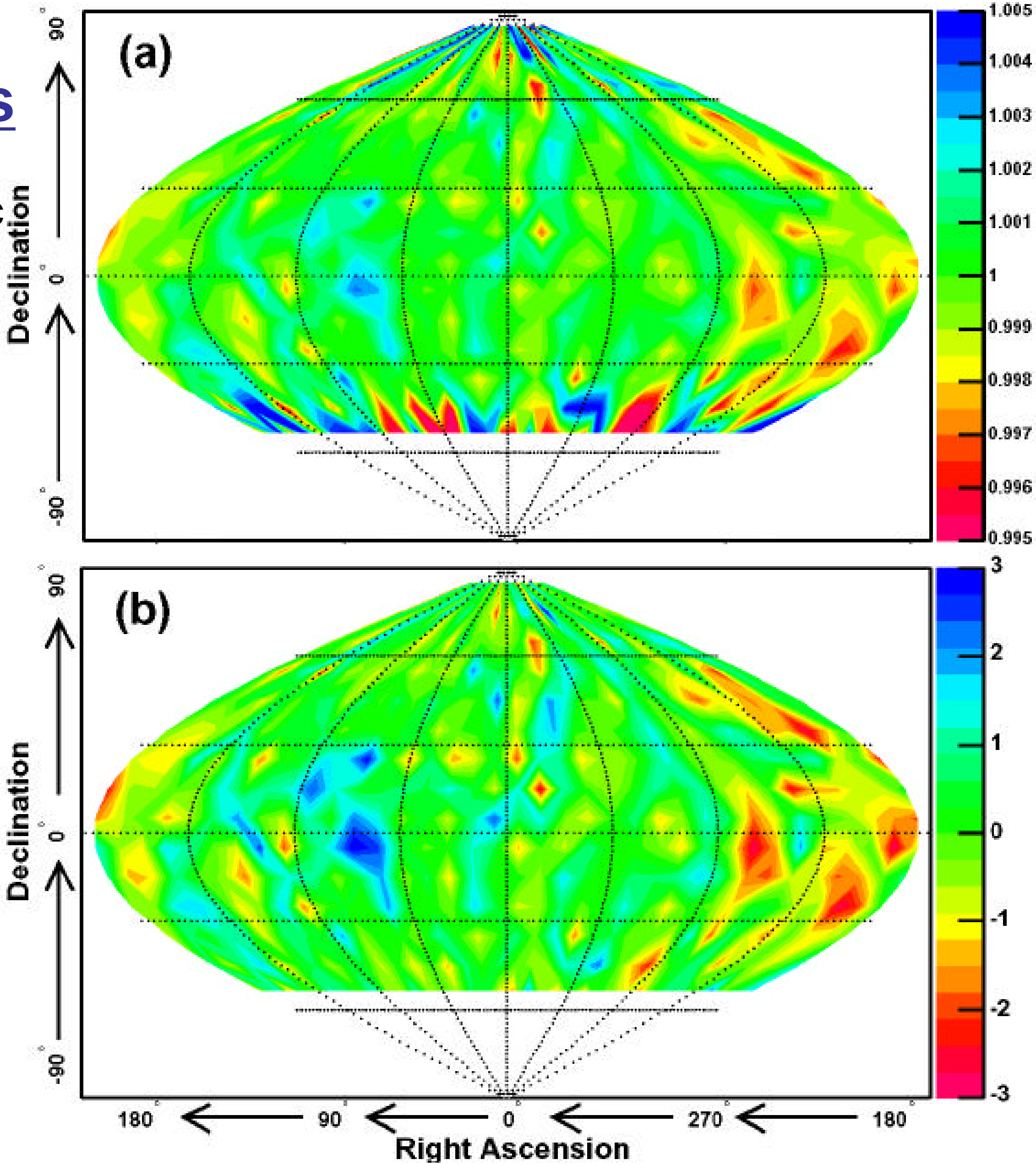
- First sky map of cosmic ray primaries obtained from underground muon data

  (a) amplitude

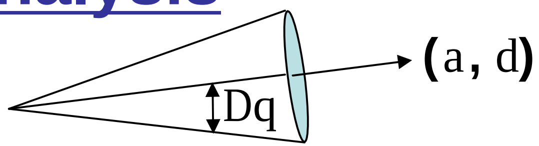
  -0.5% to +0.5%

  (b) significance

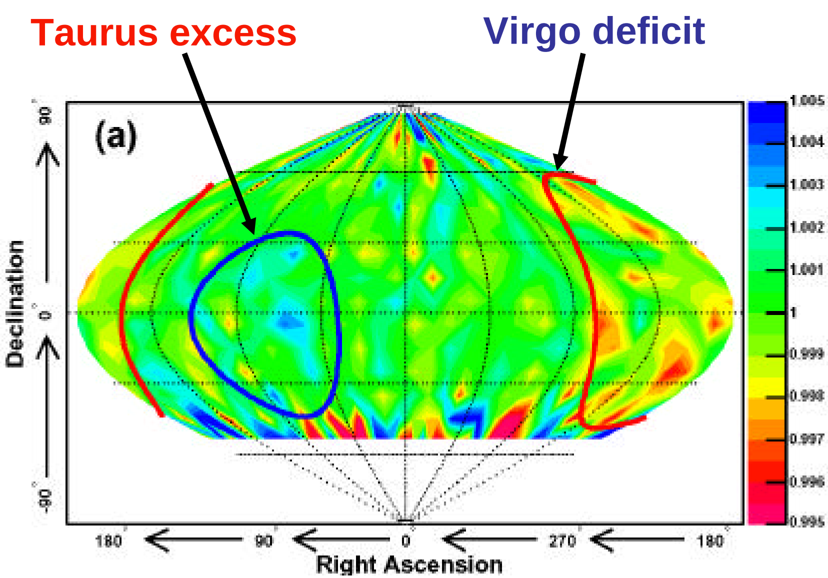
  -3s to +3s



Excess and Deficit analysis



- An angular window is defined by direction (a,d) and size (Dq).
- If number of muon events in the angular window is larger/smaller than the average by 4 standard deviations (chance probability : 6.3×10^{-5}), the angular window is defined as excess/deficit.
- (a,d) and Dq are adjusted to maximize the statistical significance.
- One excess and one deficit are found.



Taurus excess

Amplitude : $(1.04 \pm 0.20) \times 10^{-3}$

Center : (a, d) = ($75^o \pm 7^o$, $-5^o \pm 9^o$)

Size : Dq = $39^o \pm 7^o$

Chance probability : 2.0×10^{-7}

(5.1×10^{-6} if trial factor is considered)

Virgo deficit

Amplitude : $-(0.94 \pm 0.14) \times 10^{-3}$

Center : (a, d) = ($205^o \pm 7^o$, $5^o \pm 10^o$)

Size : Dq = $54^o \pm 7^o$

Chance probability : 2.1×10^{-11}

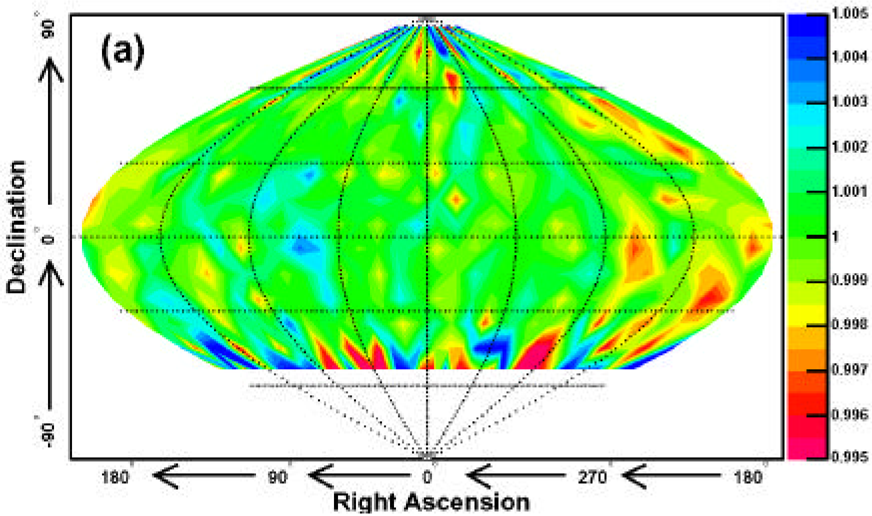
(7.0×10^{-11} if trial factor is considered)

Comparison with other sky maps

- Preliminary sky maps from 2 g-ray telescopes and one underground proton decay experiment.

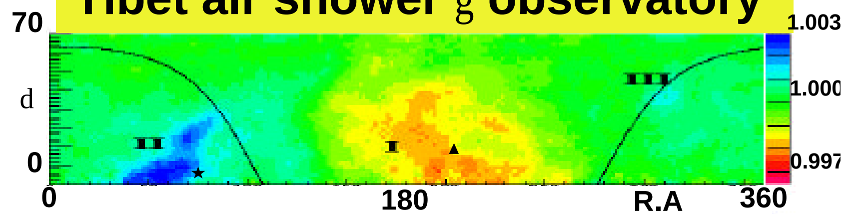
  (although they are not published in any refereed papers…….)
- g-ray telescopes observe not only muon but also g-rays.

Super-Kamiokande

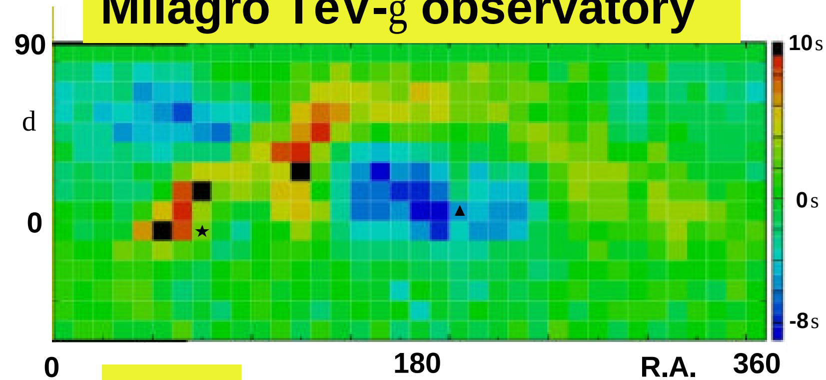


- The SK sky map agree with three observations.

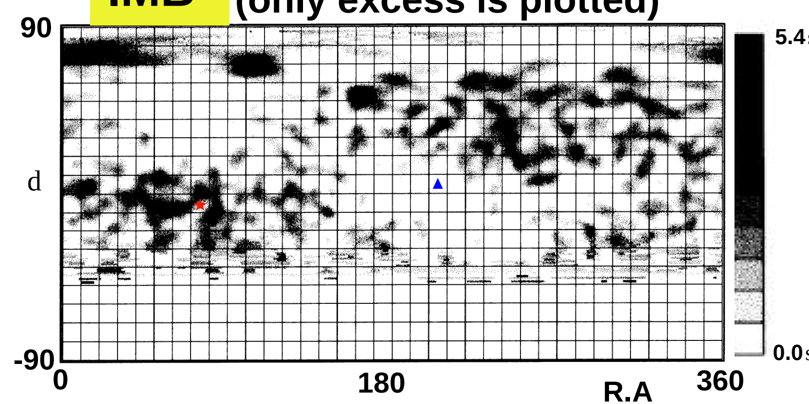
Tibet air shower g observatory



Milagro TeV-g observatory



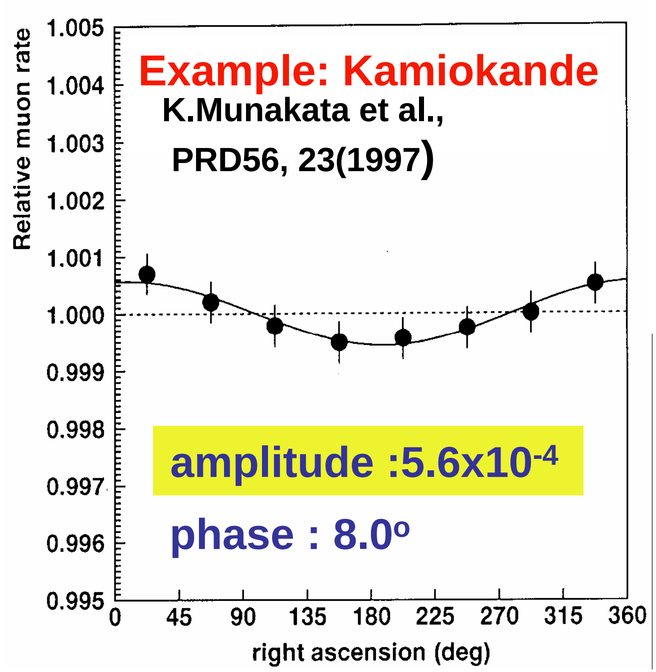
IMB (only excess is plotted)

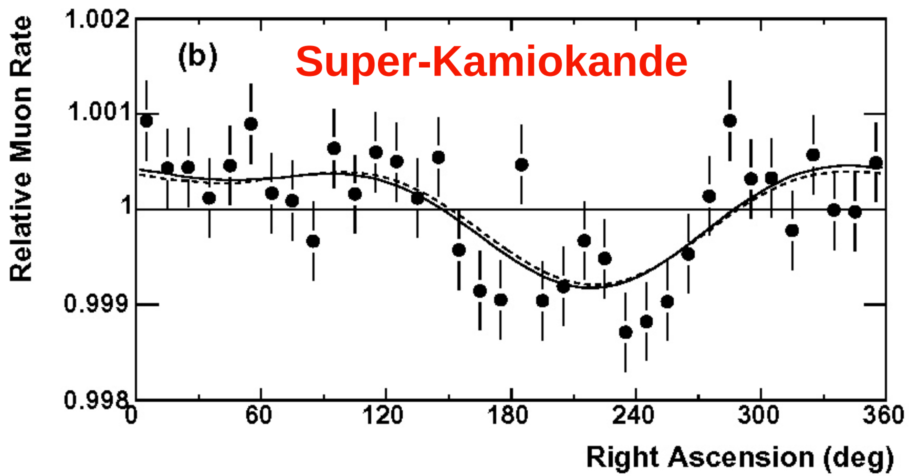


Consistency with past experiments

- Many muon observatories (including Kamiokande) have reported 1-dimensional right ascension anisotropy.

- Their analysis procedure is very primitive.
  - No track reconstruction and assume that all muons come from zenith.
  - Declination dependence cannot be analyzed.
  - The right ascension distribution is fitted with first harmonics, and calculate the amplitude and phase.



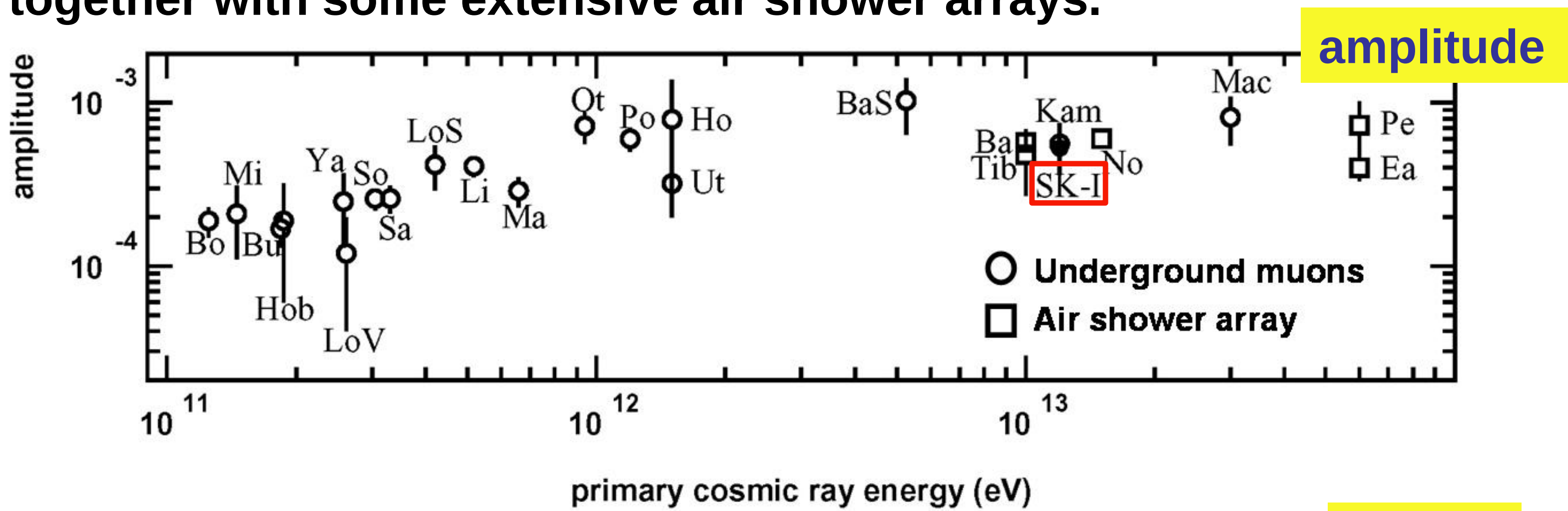


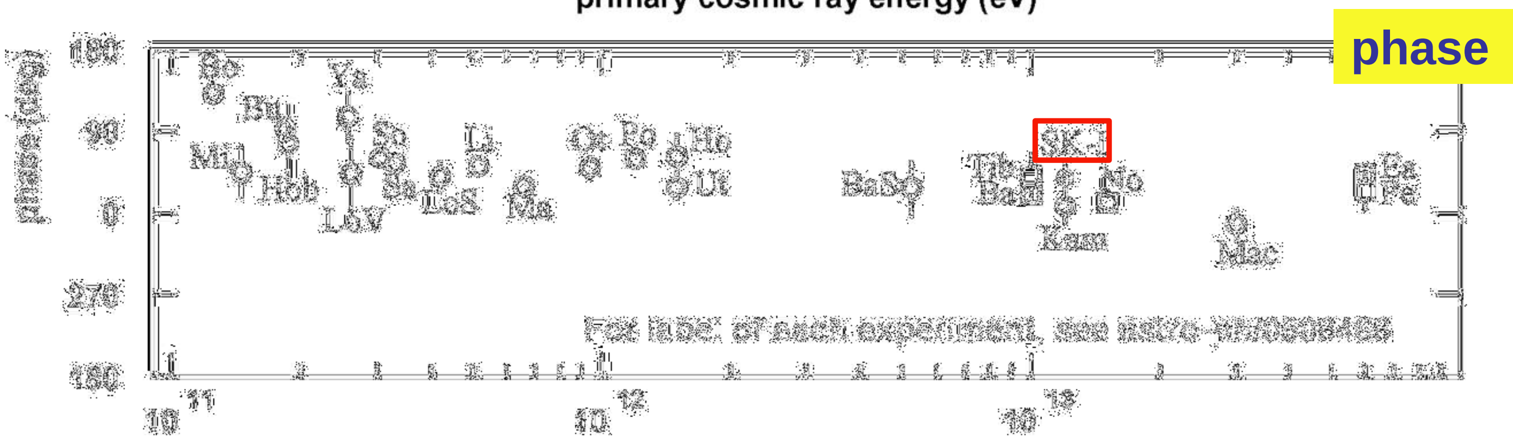
amplitude : $(5.3 \pm 1.2)\times10^{-4}$

phase (first harmonics) : $40^{o} \pm 14^{o}$

Anisotropies by various experiments

- **Results of the first harmonics analysis by various muon experiments together with some extensive air shower arrays.**





- **The SK results agree with other experiments.**

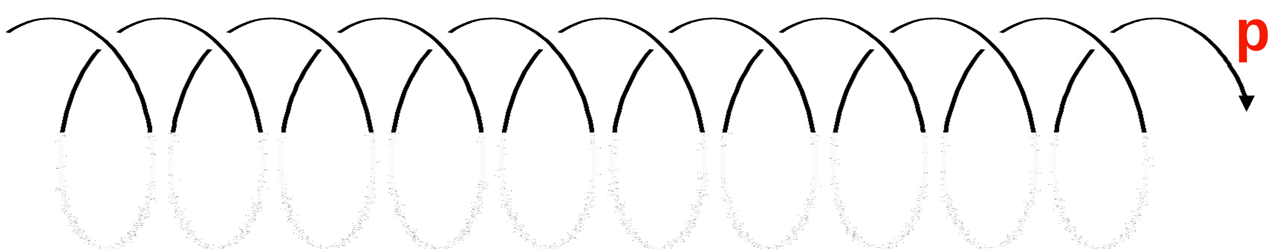
Can protons be used in astronomy?

- Travel directions of protons are bent by galactic magnetic field in Milky Way, which is estimated to be **~3x10^{-10} Tesla**.

  If the direction of the magnetic field is vertical to the proton direction, radius of curvature for **10TeV** protons is **~3x10^{-3}pc** (parsec).

- Radius of the solar system is **~2x10^{-4}pc** and radius of Milky Way galaxy is **~20000pc**. Therefore, 10TeV protons keep their directions from outside of the solar system, but they may loose their directions in the scale of galaxy.

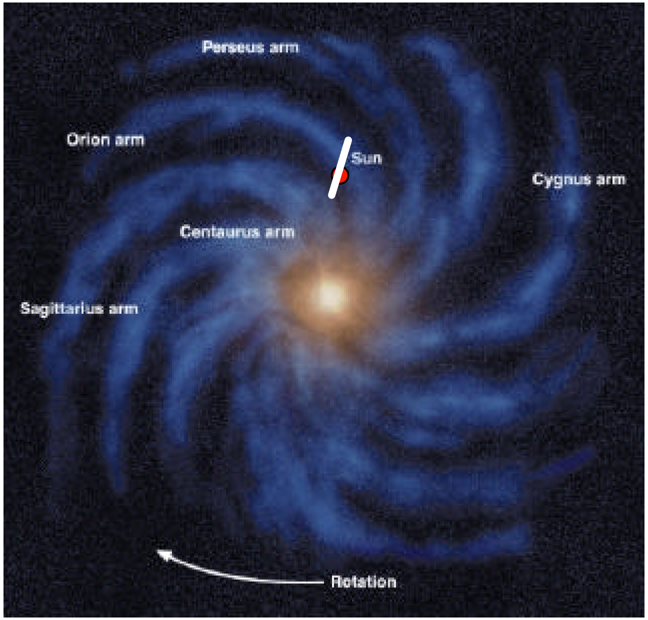
- However, momentum component parallel to the magnetic field remain after long travel distance if the magnetic field is uniform.

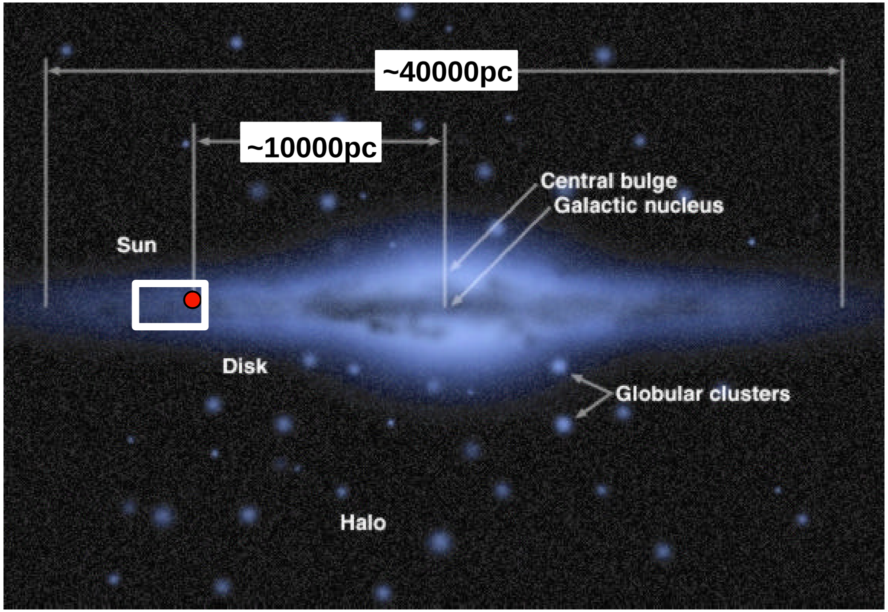


Note that the galactic magnetic field is thought to be uniform within the order of $\gtrsim$ 300pc.

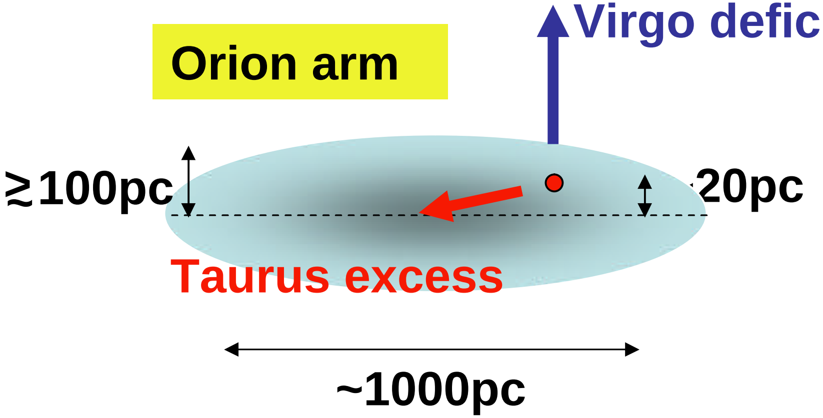
The actual reach of the directional astronomy by protons is unknown.

Excess/deficit direction and Milky Way galaxy





● Our position

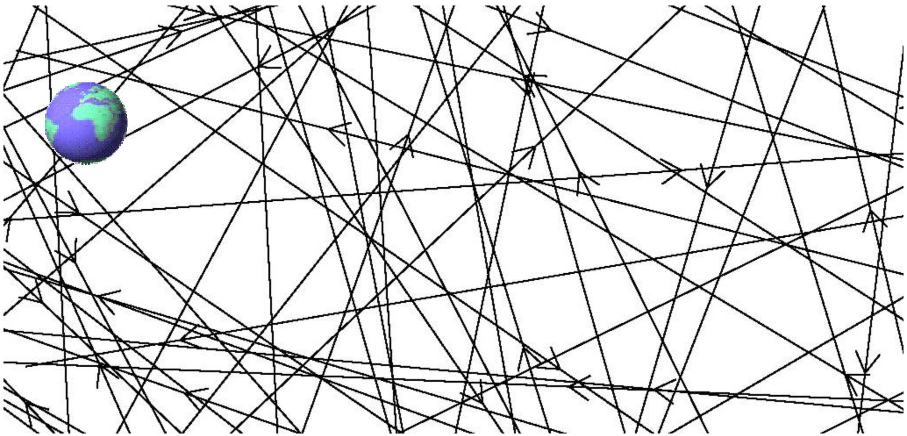


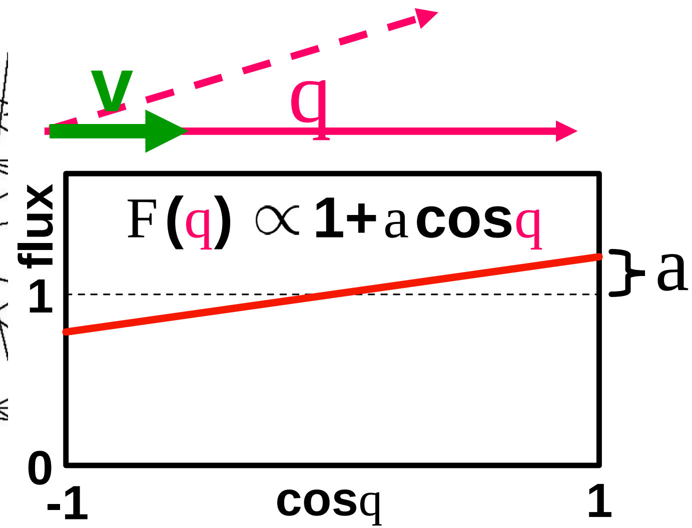
The excess/deficit direction agree with density of nearby stars.

(Note again that the uniformity of the galactic magnetic field is ≳ 300pc.)

Compton-Getting effect

- Assume that "cosmic ray rest system" exists, in which cosmic ray flux is isotropic. If observer is moving in the rest system, cosmic ray flux from the forward direction become larger.





- The flux distribution shows dipole structure, which is written as $F(\theta) \propto 1+\alpha\cos\theta$.
- α is proportional to the velocity of the observer.

  If v=100km/s, $\alpha=1.6\times10^{-3}$ for 10TeV cosmic-rays.
- If Taurus excess (1.04×10^{-3}) and Virgo deficit (-0.94×10^{-3}) were in opposite direction, it might be explained by Compton-Getting effect of v~60km/s ……

Compton-Getting effect

- **Angular difference between Taurus excess and Virgo deficit is ~130^{o}. The Taurus-Virgo pair is difficult to be explained by Compton-Getting effect.**
- **Other excess/deficit in SK data are much smaller than Taurus/Virgo.**
- **Clear Compton-Getting effect is absent.**
  The relative velocity is less than several ten km/s.
  The cosmic ray rest system is together with our motion.
- **This relative velocity is smaller than other relative velocities.**
  - **Solar system – Galactic center: ~ 200km/s**
  - **Solar system – micro wave background radiation: ~ 400km/s**
  - **Milky Way – Great Attracter: ~ 600km/s**
  - **(the Sun – the Earth: ~ 20km/s)**
- **Two possibilities cannot be denied.**
  - **Compton-Getting effect is cancelled with some other excess/deficit.**
  - **Direction of motion is North pole or South pole (d~90^{o} or d~-90^{o}).**

Does the Crab Pulsar explain the Taurus excess?

Crab Pulsar

- **A neutron star in the supernova remnant, Crab Nebula**
- **The supernova explosion in 1054.**
- **The distance from the earth is ~2000pc (about 1/5 of G.C.).**
- **The celestial position is in the Taurus ; (a,d)=(83.63°, 22.02°)**
- **Angular difference with the center of the Taurus excess is ~28°.**

- **Clue to examine whether high energy cosmic rays are accelerated by supernovae or not.**

Proton flux from Crab Pulsar

Expected proton flux from Crab Pulsar

Total energy release from the Crab Pulsar is calculated from the spin-down of the pulsar and is 4.5×10^{-38} erg s^{-1} .

Assume that all energy release goes to the acceleration of protons up to 10TeV and the emission of particles is isotropic.

The proton flux at the Earth is ~$0.6 \times 10^{-7} cm^{-2} s^{-1}$. ------(A)

Observed proton flux from SK data

The Taurus excess observed in SK is converted to the primary proton flux at the surface of the Earth.
The proton flux is ~$1.8 \times 10^{-7} cm^{-2} s^{-1}$. ------(B)

If (A) and (B) are compared, SK observation cannot explain the expectation from the Crab Pulsar by a factor of about 3.

In this calculation, two extremely optimistic assumptions are employed.

- **all energy release goes to 10TeV protons**
- **protons traveled straight to the Earth**

Conclusion

- First anisotropy map of primary cosmic-rays (> 10TeV) is obtained from 2.10×10^{8} cosmic-ray muons in 5 years of Super-Kamiokande data.

- One excess and one deficit are found.

Taurus excess

Amplitude : $(1.04 \pm 0.20) \times 10^{-3}$

Center : (a, d) = $(75^{o} \pm 7^{o}, -5^{o} \pm 9^{o})$

Size : Dq = $39^{o} \pm 7^{o}$

Chance probability : 2.0×10^{-7}

(5.1×10^{-6} with trial factor)

Virgo deficit

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Size : Dq = $54^{o} \pm 7^{o}$

Chance probability : 2.1×10^{-11}

(7.0×10^{-11} with trial factor)

- The excess/deficit direction agree with density of nearby stars.

- No Compton-Getting effect.
  The cosmic ray rest system is together with our motion.

- The Taurus excess is difficult to be explained by the Crab Pulsar.

- In 1987, Kamiokande started new astronomy beyond “lights”.
  In 2005, Super-Kamiokande started new astronomy beyond “neutral particles”.

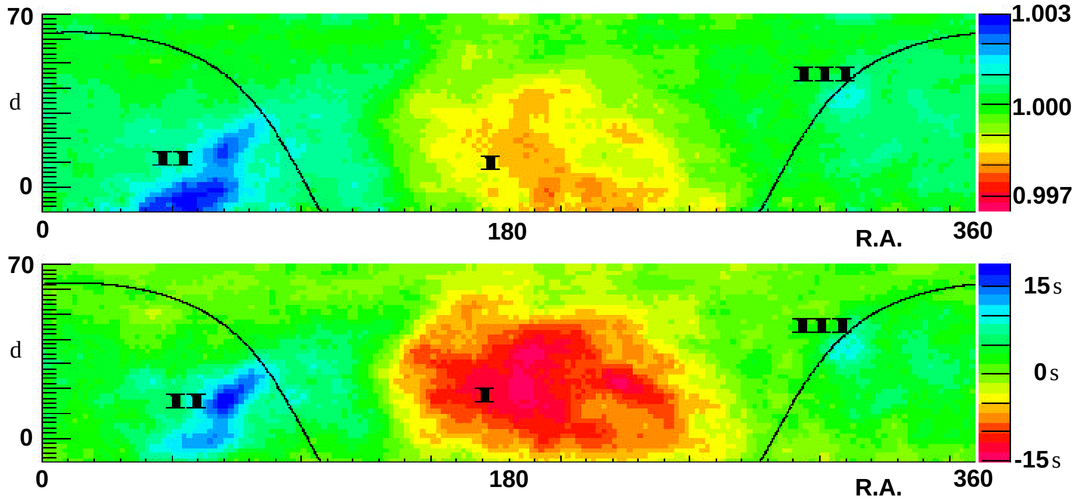
Hey Yuichi, are you bragging?

Supplements

Tibet Air-Shower g observatory

- Air shower array located at Yangbajing, Tibet (30.11^{o}N,90.53^{o}E, 4300m above sea level).
- Area of **22050m^2** is covered with **553** scintillation counter array.

- Each counter has a plastic scintillator plate of **0.5m^2** in area and **3cm** in thickness.
- Read by fast-timing 2-inch f PMT.
- A 0.5cm thick lead plate is put on each counter.
- Thres. energy is **3TeV**.
- g-ray and proton cannot be distinguished.
- From Nov. 1999 to Nov. 2003, **1.36x10^{10}events** are accumulated from **918 live days**.

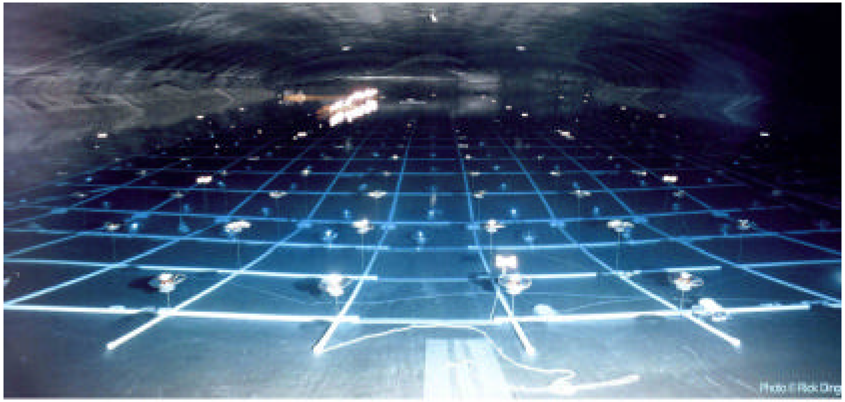


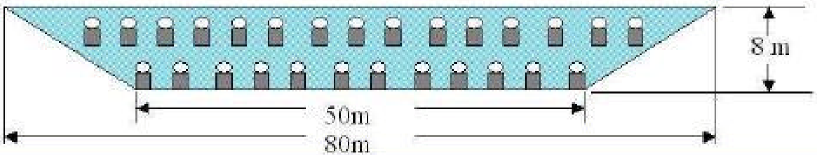
29th International Cosmic Ray Conference Pure (2005)00, 101
See also M.Amenomori et al., ApJ, 633, 1005(2005)

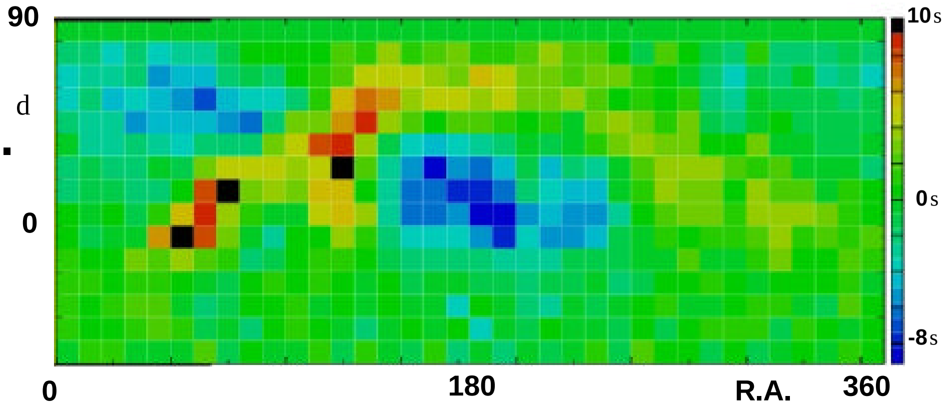
Milagro TeV-g observatory

- Water Cherenkov TeV-g observatory at Jemez Mountains, New Mexico (35.9ºN, 106.9ºW, 2630m above sea level).
- In a 60m x 80m x 8m(depth) pond, 723 8-inchf PMTs are placed with 2.8m x 2.8m spacing. 450 PMTs are in 1.5m deep, and 273 PMTs are in 6.5m deep.
- The top layer is sensitive to g-ray showers and hadronic showers, but the bottom layer is sensitive only to hadronic shower.

  Useful for g/p separation.
- Sensitive to 0.1 ~ 100TeV g-rays. (Median ~ 2.5TeV)
- Operational since 2000.

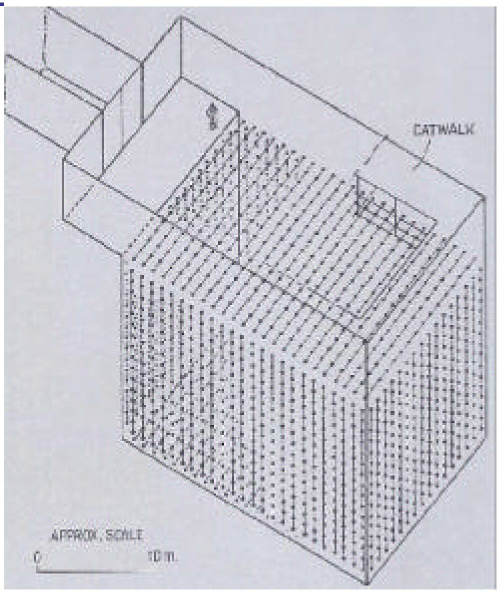


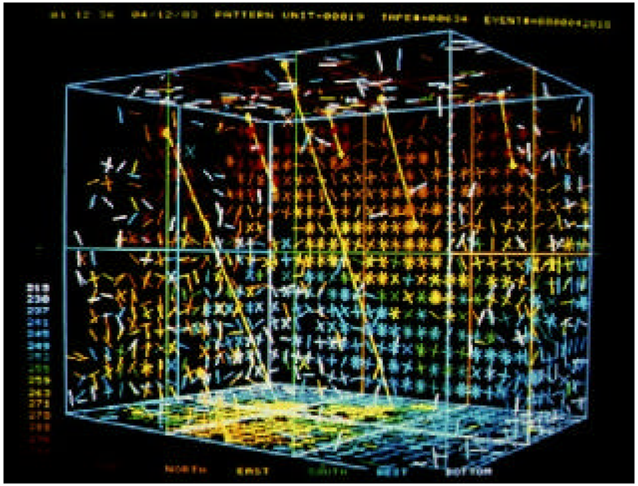


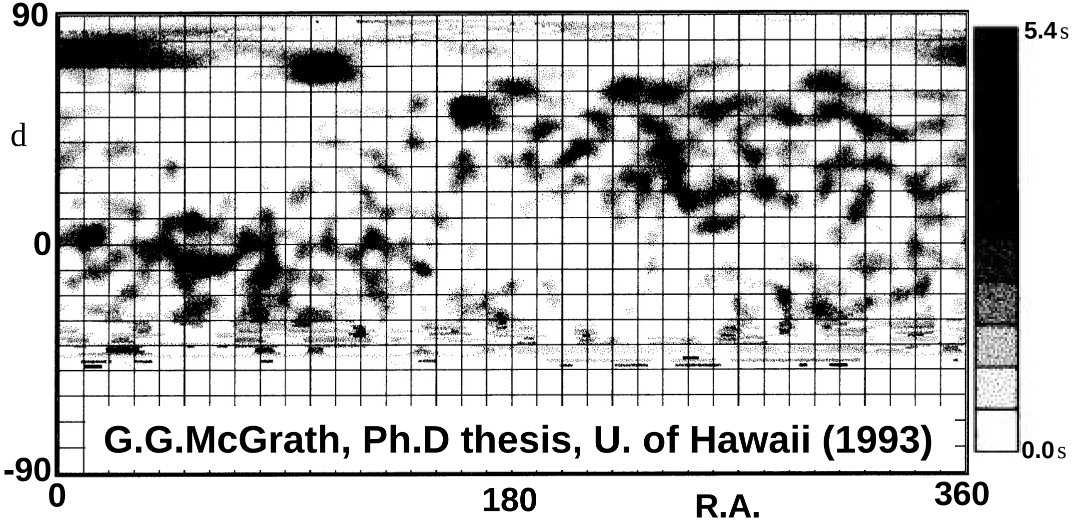


IMB (Irvine-Michigan-Brookhaven) proton decay experiment

- Water Cherenkov detector at Morton-Thiokol salt mine in Fairport, Ohio (41.72^{o}N, 81.27^{o}W, 1570m.w.e underground).
- Water in 18mx17mx22.5m hexahedron tank are viewed by 2048 8-inch f PMTs.
- In 1514.7 days live time (Sep. 1982 – Mar. 1991), 3.5×10^{8} cosmic-ray muons are triggered. Because of data size problem, only unbiased 5.0×10^{7} muons are recorded and used in the analysis.







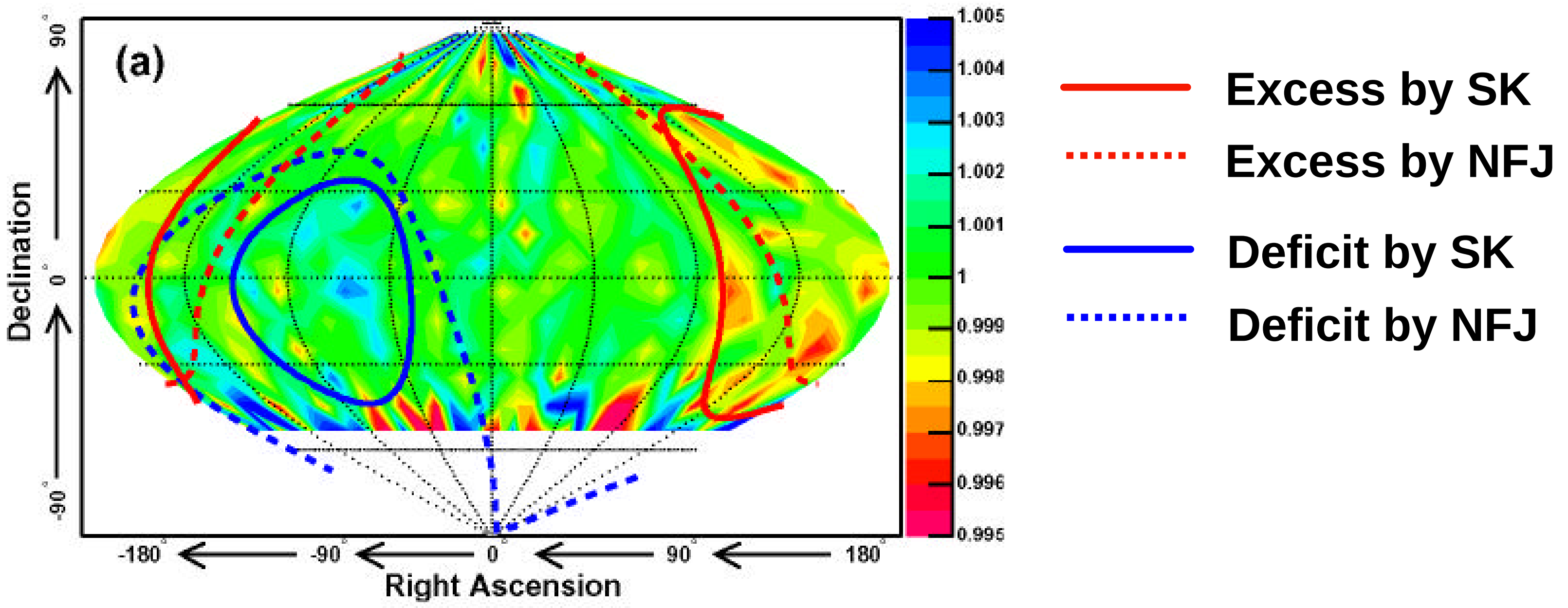
G.G.McGrath, Ph.D thesis, U. of Hawaii (1993)

NFJ model

- **Nagashima, Fujimoto and Jacklyn reconstructed 2-dimensional sky map from amplitudes, phases, threshold energies and latitudes of all experiments.**

  They drew an excess cone and a deficit cone on the sky map.

  NFJ model : J. Geophys. Res. No.A8 103, 17429 (1998)



- **Agreement with SK is reasonable.**

One solar day and one sidereal day

- The difference between one solar day and one sidereal day comes from the orbital motion of the Earth around the Sun.

For simplicity, 1 year is taken as exactly 365 days. The true number is 365.2422….days.

One solar day

One sidereal day

- In one solar day, the earth rotate about 360 x (366/365) degrees and face the solar direction again.
  The time period is exactly 24 hours.

- In one sidereal day, the earth rotate exactly 360 degrees and face the same celestial position again.
  The time period is about 24 x (365/366) = 23.9344… hours.

A fake one sidereal day periodicity produced by interference of daily and seasonal periodicities

- Muon flux may change in daily and in seasonally. Products of the one-day period and one-year period make a fake one sidereal day period term.

t_1 = 1 day = 24 hours

t_2 = 365 days

$$\cos a \cos b = \frac{1}{2}\left(\cos(a+b)+\cos(a-b)\right)$$

If you do not remember this formula, go back to high school!

$$F_{\text{day-year}} = A\underbrace{\cos\left(\frac{t}{t_1}\right)}_{\text{daily}}\underbrace{\cos\left(\frac{t}{t_2}\right)}_{\text{seasonal}} = \frac{A}{2}\left(\cos\left(\frac{t}{t_1}+\frac{t}{t_2}\right)+\cos\left(\frac{t}{t_1}-\frac{t}{t_2}\right)\right)$$

$$= \frac{A}{2}\left(\cos\left(\frac{t}{t_1 t_2/(t_1+t_2)}\right)+\cos\left(\frac{t}{t_1 t_2/(t_2-t_1)}\right)\right)$$

$$= \frac{A}{2}\left(\cos\left(\frac{t}{(365/366)\text{x}24\text{hrs}}\right)+\cos\left(\frac{t}{(365/364)\text{x}24\text{hrs}}\right)\right)$$

- A periodicity of one sidereal-day (23.9344…. hours) appears.
- Another interference term of the same amplitude appears simultaneously. The period is 24.6658….. hours.
- The effect of interference is calculated from Fourier analysis of 24.6658… hours period.

Why atmospheric muon flux correlates with temperature of upper atmosphere

? Cosmic ray muons are produced by the decay of pions.

p + N $\longrightarrow$ X's + p's

cosmic ray primary

upper atmosphere

→ m + n

or

→ absorbed in the atmosphere

? Temperature of upper atmosphere

Density of atmosphere

Pion decay rate and absorption rate

Cosmic ray muon flux

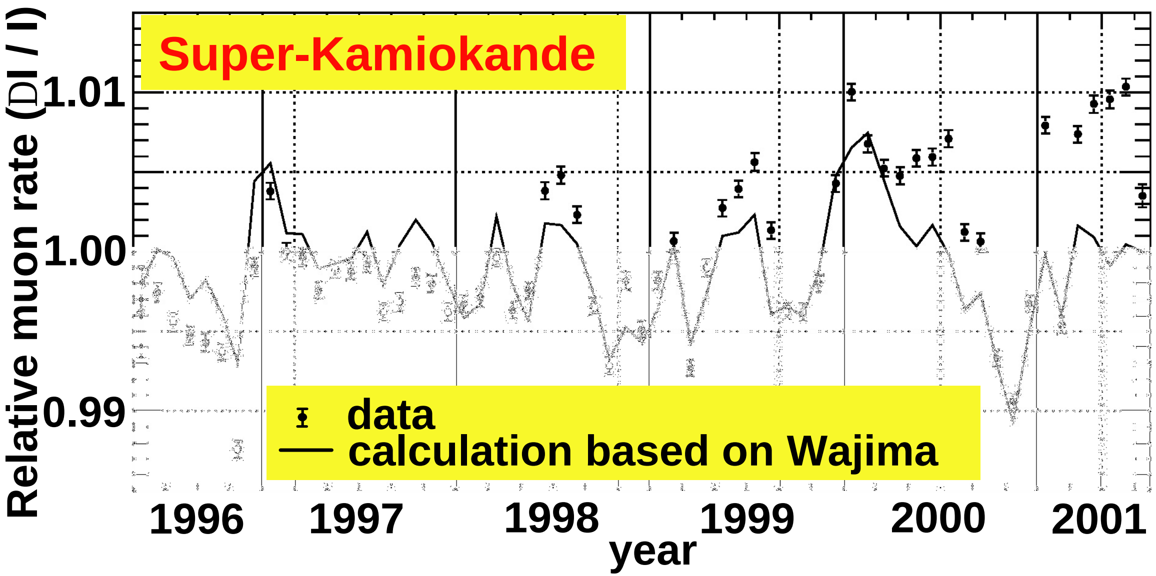
? This effect is cancelled in the sidereal variation analysis, because the change has longer (~week or ~month) time scale.

Monthly muon flux and calculation from upper atmospheric temperature

- Monthly SK data are compared with calculations based on atmospheric temperature.

Atmospheric temperature data

- Measurement at the nearest meteorological observatory located at Wajima, 116km from Kamioka
- Atmospheric temperature are recorded at 21 different altitude twice a day by radio sonde technique.



Wajima Observatory and Matsushiro Observatory

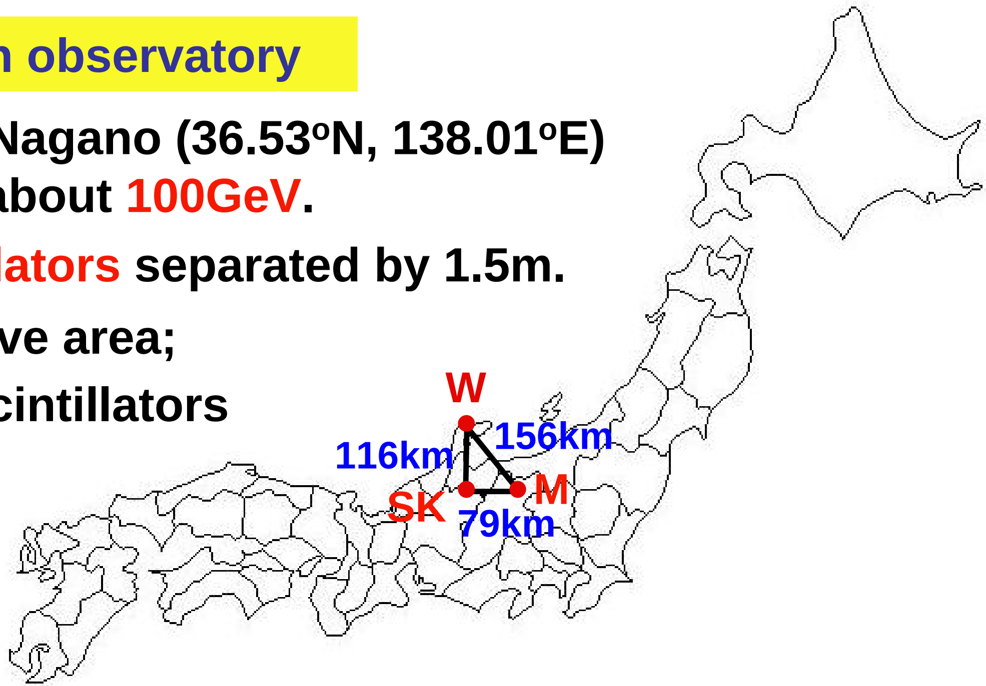
Wajima Observatory of the Japan Meteorological Agency

- The nearest meteorological observatory to both Kamioka and Matsushiro (37.38ºN, 136.90ºE)
- Measure the temperature of the upper atmosphere twice a day by radio sonde technique.
- The measurement is at 21 different altitude. The highest observation altitude is 20mb.

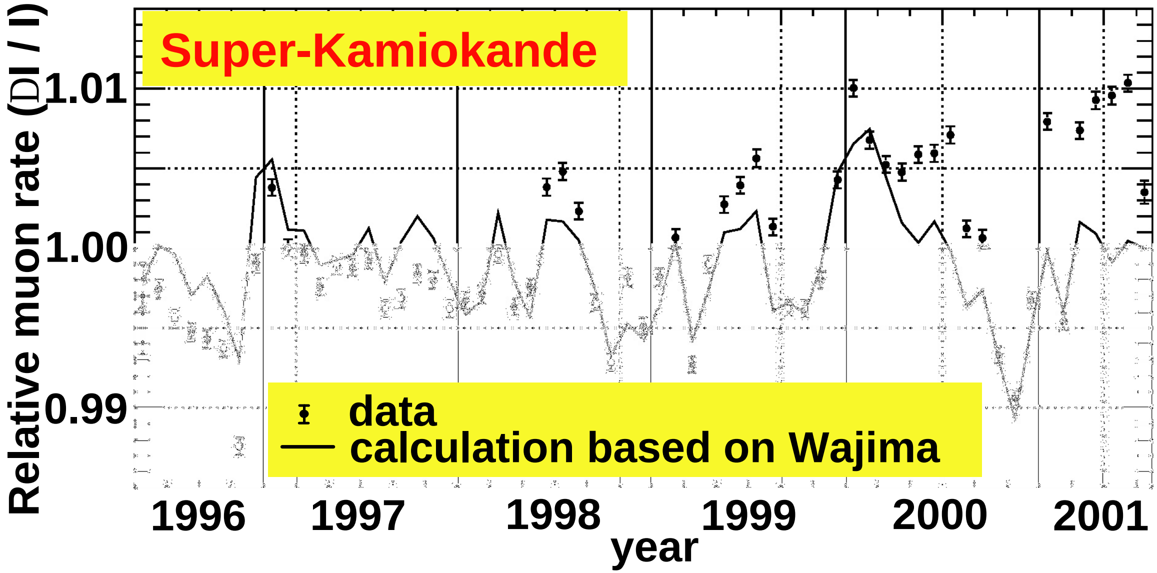
Matsushiro underground muon observatory

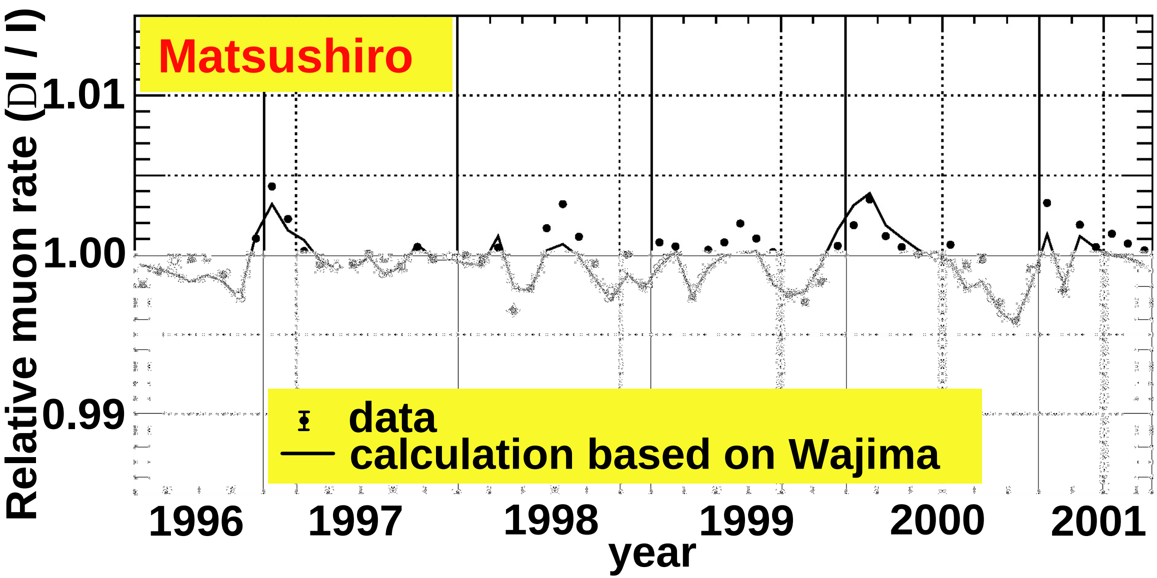
- 220 m.w.e. underground in Nagano (36.53ºN, 138.01ºE) Threshold muon energy is about 100GeV.
- Two layers of plastic scintillators separated by 1.5m.
- Each layer has 25m^2 sensitive area;

  25 1m x 1m x 0.1m plastic scintillators viewed by 5-inch PMTs.
- Muon events are triggered by the coincidence of the two layers.



Monthly muon flux in SK and Matsushiro

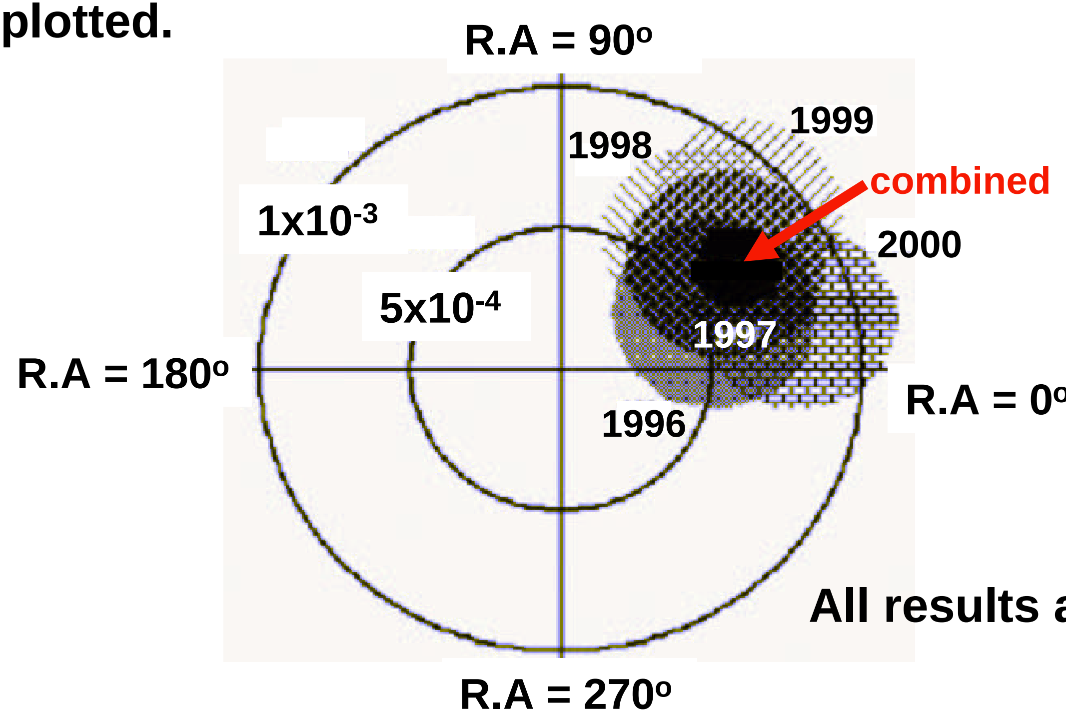




- Both experiments agree with the calculations based on the atmospheric temperature data by Wajima.
- SK data is more sensitive to the atmospheric temperature by a factor of ~2.

Robustness of the analysis

- **The 5-years muon data is divided into 5 one-year data sets. Amplitudes and phases of the right ascension distribution are plotted.**



All results are in good agreement.

- **Analysis with different path-length criteria (instead of 10m cut) was also executed. The result is essentially unchanged.**