ガンマ線・宇宙線物理

副題:Tibet ASγ 実験により
宇宙線の起源・加速機構・伝播
の解明に挑む

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11/Mar/2016

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0. Introduction

宇宙線観測の歴史

1912年　オーストリア人のヘスによって発見される

上空に行くほど放射線の強度が強くなることを見出した

1936年 ノーベル物理学賞を受賞

1950年　乗鞍岳に朝日の小屋が建つ (東京大学宇宙線観測所の前身)

日本での宇宙線研究の幕開け

1950年代 から1970年代

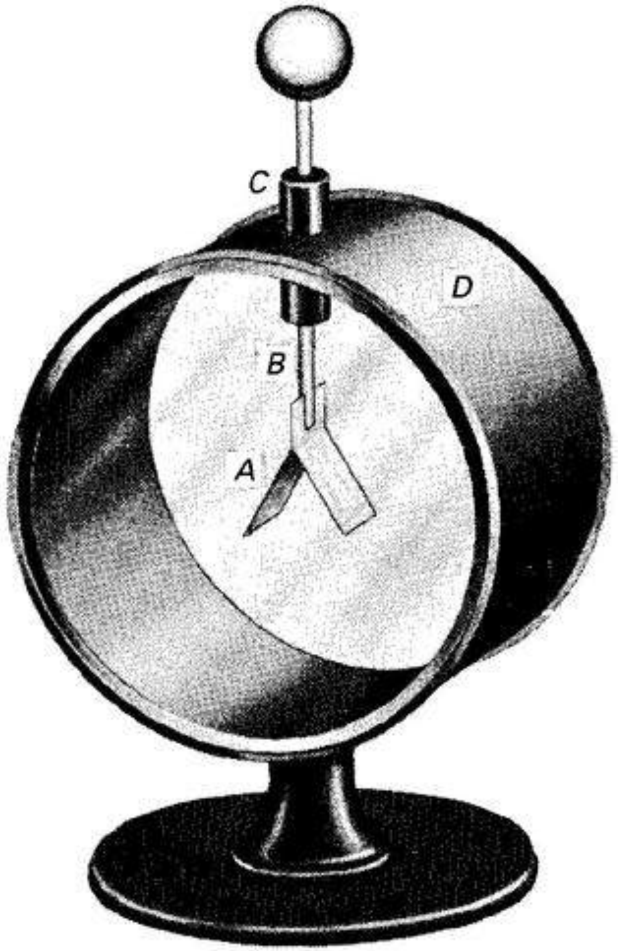
原子核物理学としての側面が強い

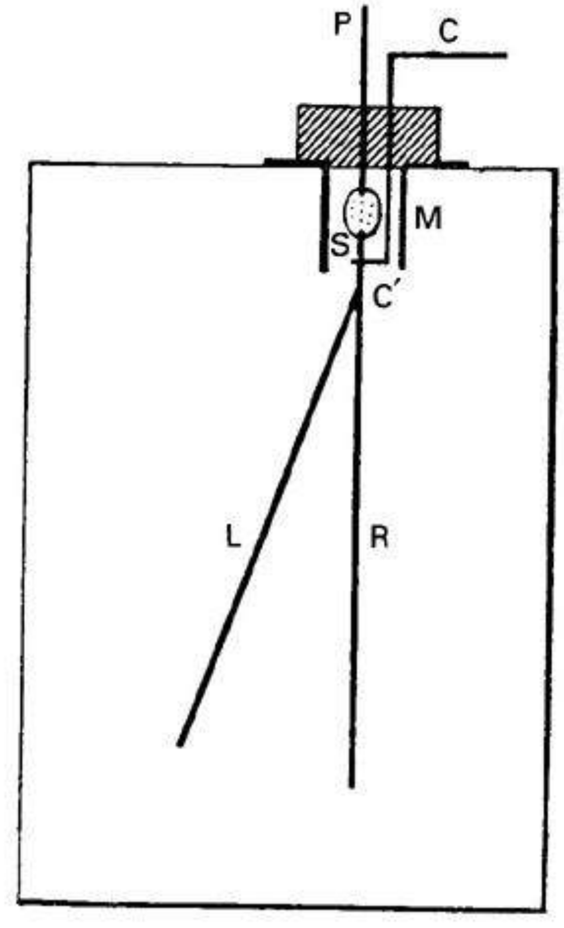
1989年　かに星雲からTeVガンマ線が観測される

1990年代 以降

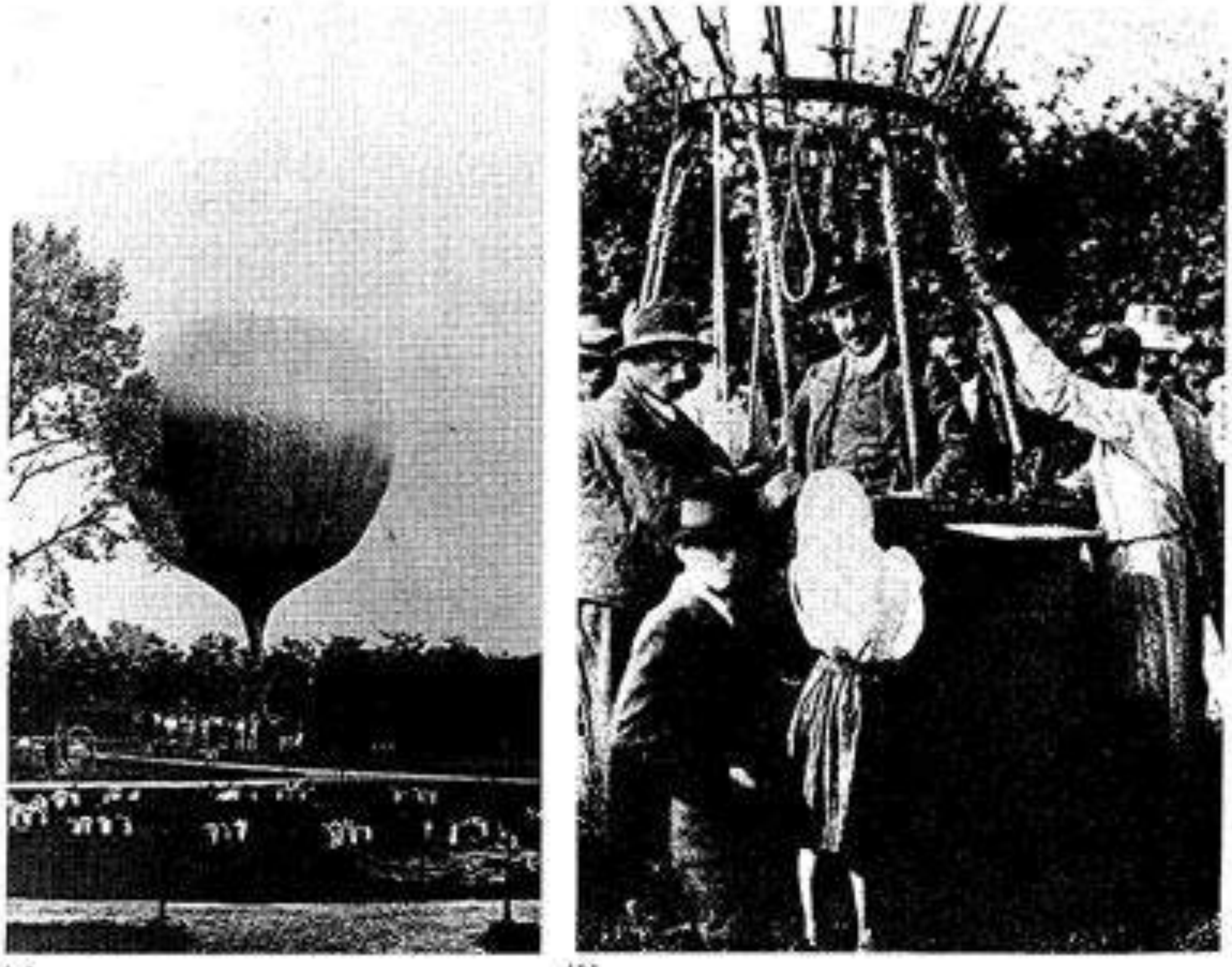
天文学としての側面が強くなる

宇宙線発見のきっかけとなった箔検電器





熱気球に乗り込むヘス

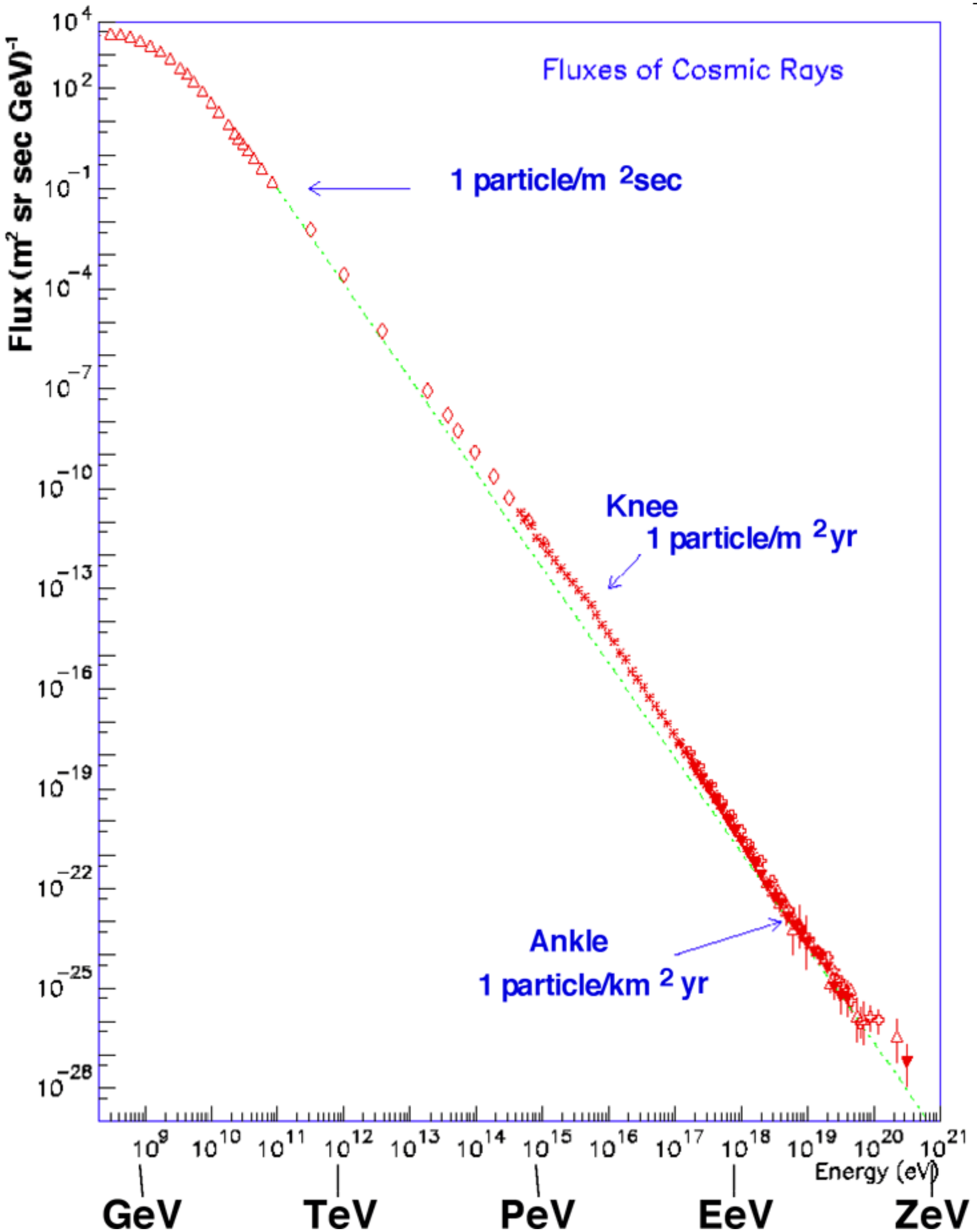


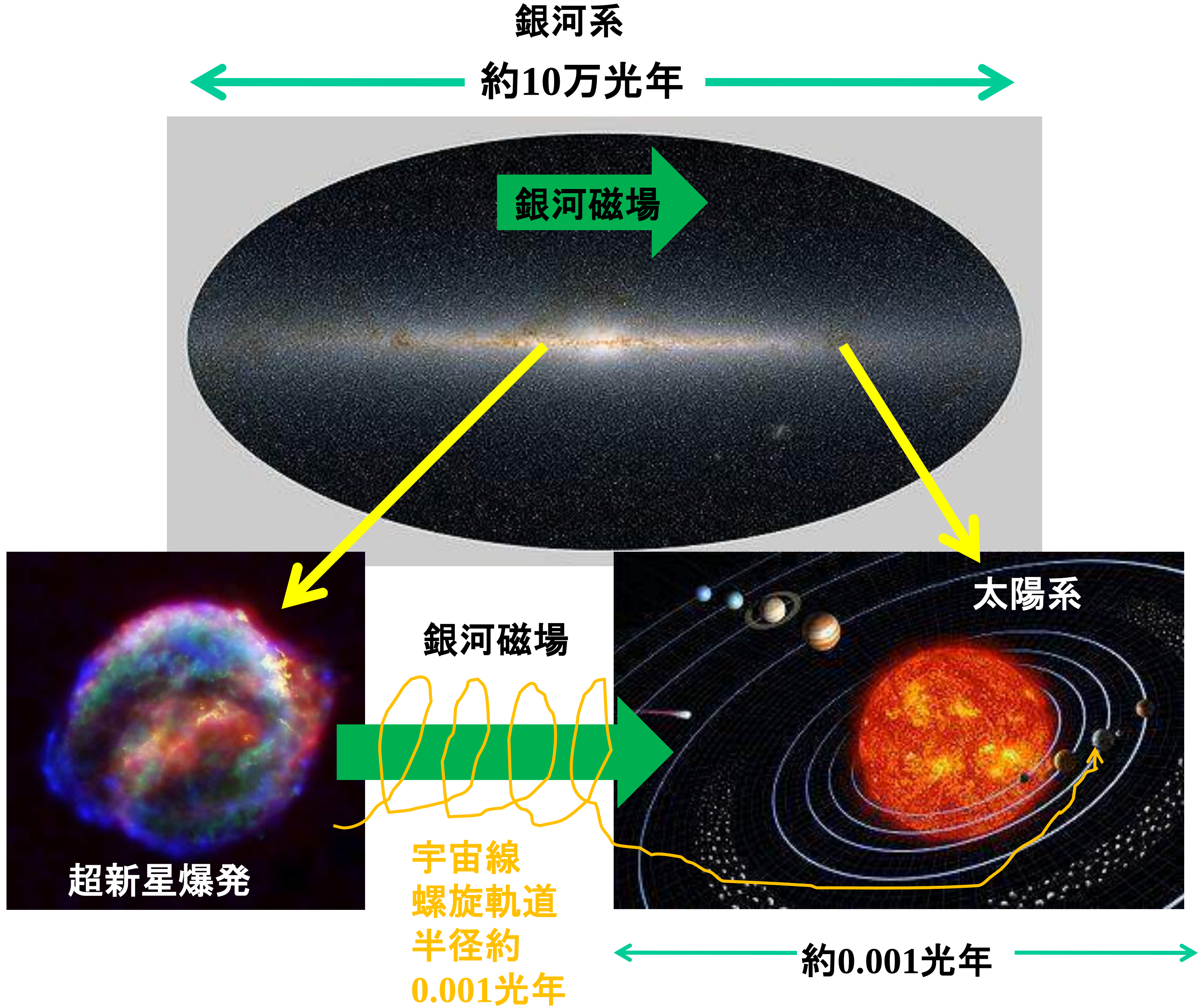
(a) (b)

原子核宇宙線のエネルギースペクトル

ニー (Knee, およそ 10^{15} eV)以下のエネルギーの宇宙線は銀河系内で、それ以上のエネルギーの宇宙線は銀河系外からやってきていると考えられている。

エネルギーの高い宇宙線は極端に頻度が低くなるので、巨大な有効面積を持つ観測装置が必要になる。




銀河系
約10万光年
銀河磁場
超新星爆発
銀河磁場
宇宙線
螺旋軌道
半径約
0.001光年
太陽系
約0.001光年

宇宙線の源を捜すには･･･

原子核宇宙線は宇宙空間の磁場に曲げられて、
地球に到達したときには元の方向の情報を失って、
全天ほぼ一様にやってくる。

原子核宇宙線の到来方向を観測しても、源はわからない。

原子核宇宙線は源の近くでガンマ線を生成することがある。

非常にエネルギーの高いガンマ線が特定の方向から来ていると、
その方向に原子核宇宙線の起源がある可能性が高い。

宇宙線の観測

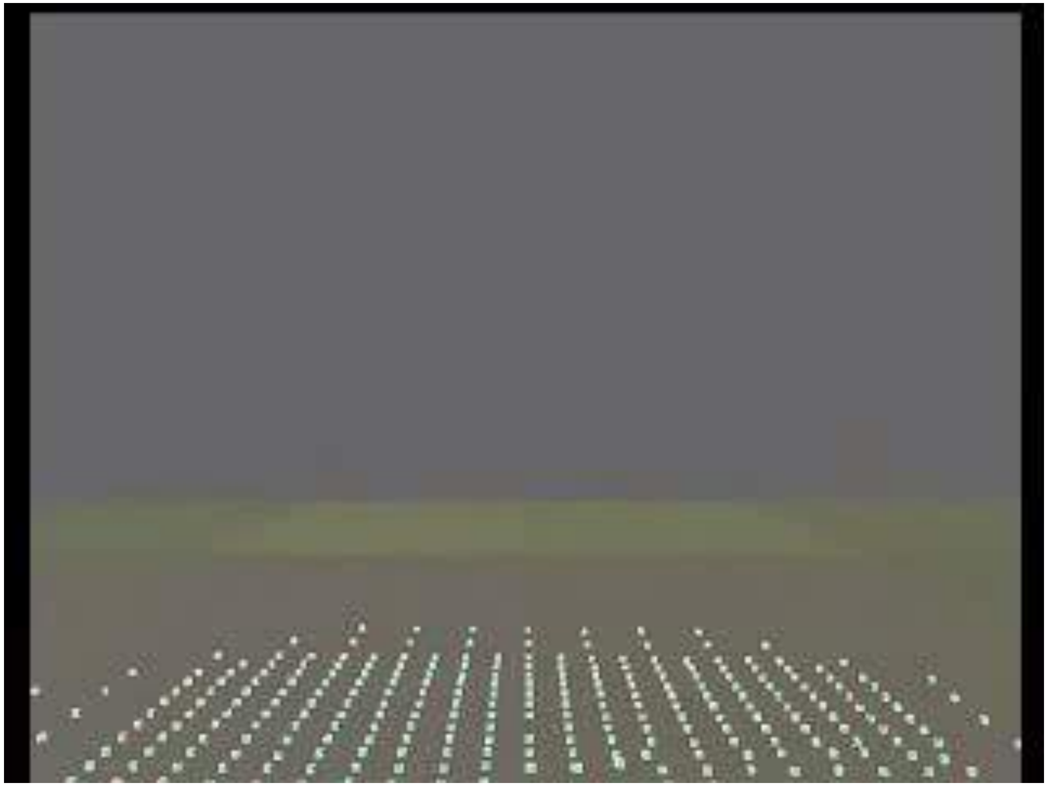
衛星・気球	原子核宇宙線・電子線 10^9 eV ～ 10^{14} eV
チェレンコフ望遠鏡	ガンマ線 10^{11} eV ～ 10^{14} eV
空気シャワーアレイ	原子核宇宙線・ガンマ線 10^{12} eV ～ 10^{20} eV
大気蛍光法	原子核宇宙線 10^{18} eV ～ 10^{20} eV

空気シャワー

空気シャワーを起こす前の宇宙線を一次宇宙線、
空気シャワーの粒子を二次粒子と呼ぶ

地表に到達するのは
ほとんどが二次粒子で
ミューオンが多い

手のひら程度の面積で
1秒間に1個

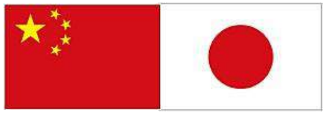


宇宙線の大気圏突入 (空気シャワー)

1.　Tibet ASγ Experiment

= Tibet A(ir)S(hower) gamma Experiment の略称

The Tibet ASγ Collaboration



M. Amenomori[1], X. J. Bi[2], D. Chen[3], T. L. Chen[4], W. Y. Chen[2], S. W. Cui[5], Danzengluobu[4], L. K. Ding[2], C. F. Feng[6], Zhaoyang Feng[2], Z. Y. Feng[7], Q. B. Gou[2], Y. Q. Guo[2], H. H. He[2], Z. T. He[5], K. Hibino[8], N. Hotta[9], Haibing Hu[4], H. B. Hu[2], J. Huang[2], H. Y. Jia[7], L. Jiang[2], F. Kajino[10], K. Kasahara[11], Y. Katayose[12], C. Kato[13], K. Kawata[14], M. Kozai[13], Labaciren[4], G. M. Le[2], A. F. Li[15,6,2], H. J. Li[4], W. J. Li[2,7], C. Liu[2], J. S. Liu[2], M. Y. Liu[4], H. Lu[2], X. R. Meng[4], T. Miyazaki[13], K. Mizutani[11,16], K. Munakata[13], T. Nakajima[13], Y. Nakamura[13], H. Nanjo[1], M. Nishizawa[17], T. Niwa[13], M. Ohnishi[14], I. Ohta[18], S. Ozawa[11], X. L. Qian[6,2], X. B. Qu[19,2], T. Saito[20], T. Y. Saito[21], M. Sakata[10], T. K. Sako[14], J. Shao[2,6], M. Shibata[12], A. Shiomi[22], T. Shirai[8], H. Sugimoto[23], M. Takita[14], Y. H. Tan[2], N. Tateyama[8], S. Torii[11], H. Tsuchiya[24], S. Udo[8], H. Wang[2], H. R. Wu[2], L. Xue[6], Y. Yamamoto[10], K. Yamauchi[12], Z. Yang[2], S. Yasue[25], A. F. Yuan[4], T. Yuda[14], L. M. Zhai[2], H. M. Zhang[2], J. L. Zhang[2], X. Y. Zhang[6], Y. Zhang[2], Yi Zhang[2], Ying Zhang[2], Zhaxisangzhu[4], X. X. Zhou[7]

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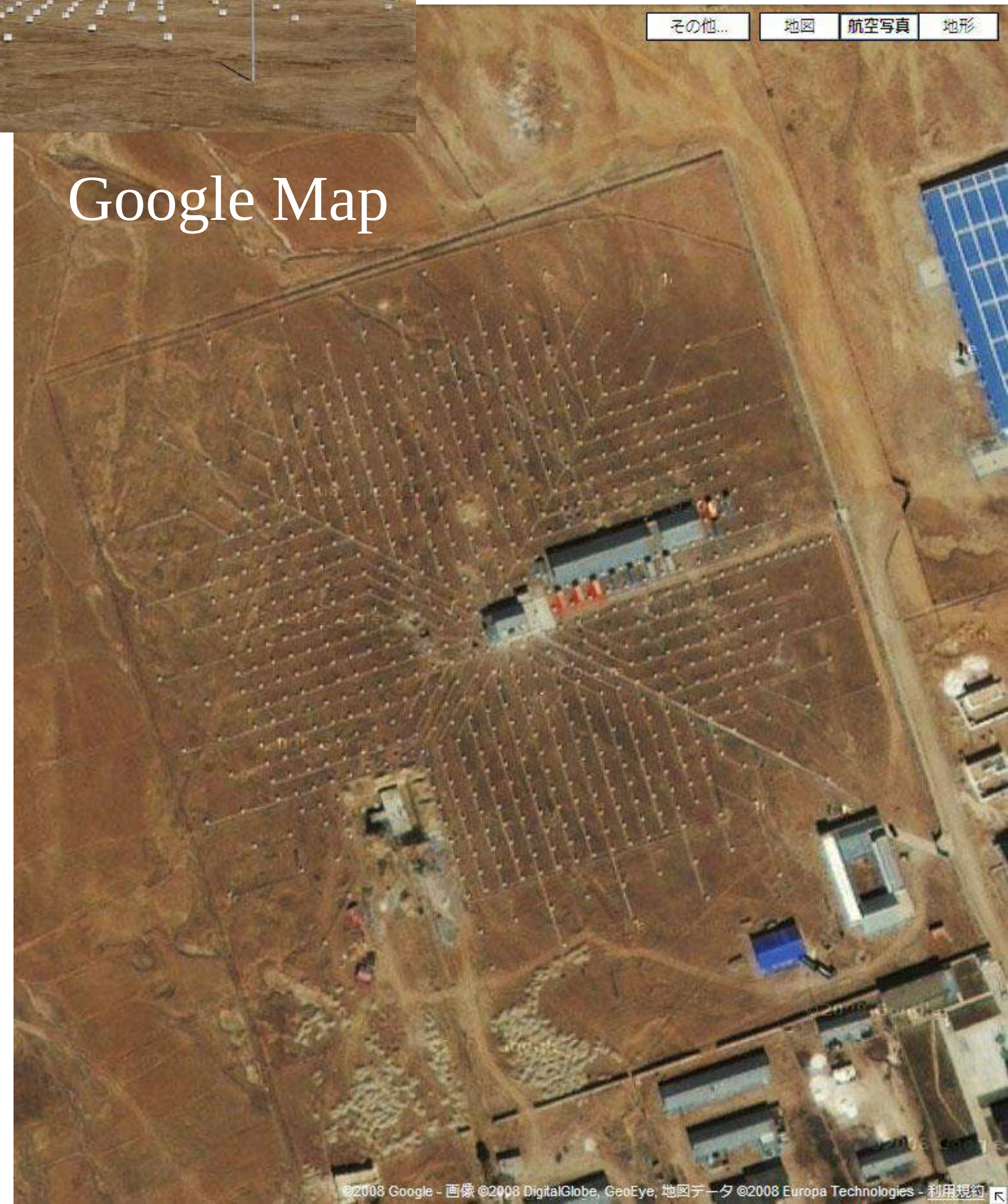
Yangbajing Cosmic Ray Observatory

$90^{\circ}522$**E**, $30^{\circ}102$**N**, 4,300 m a.s.l. (606g/cm^2)

Yangbajing,
Tibet, China
4300 m a.s.l. = 606 g/cm^2



Tibet Air Shower Array

Tibet III (37000 m^2)

Total 789 detectors
Mode Energy
~3 TeV
Angular Resolution
~0.9 deg @ 3 TeV
Trigger Rate
~1700 Hz

Research Purpose

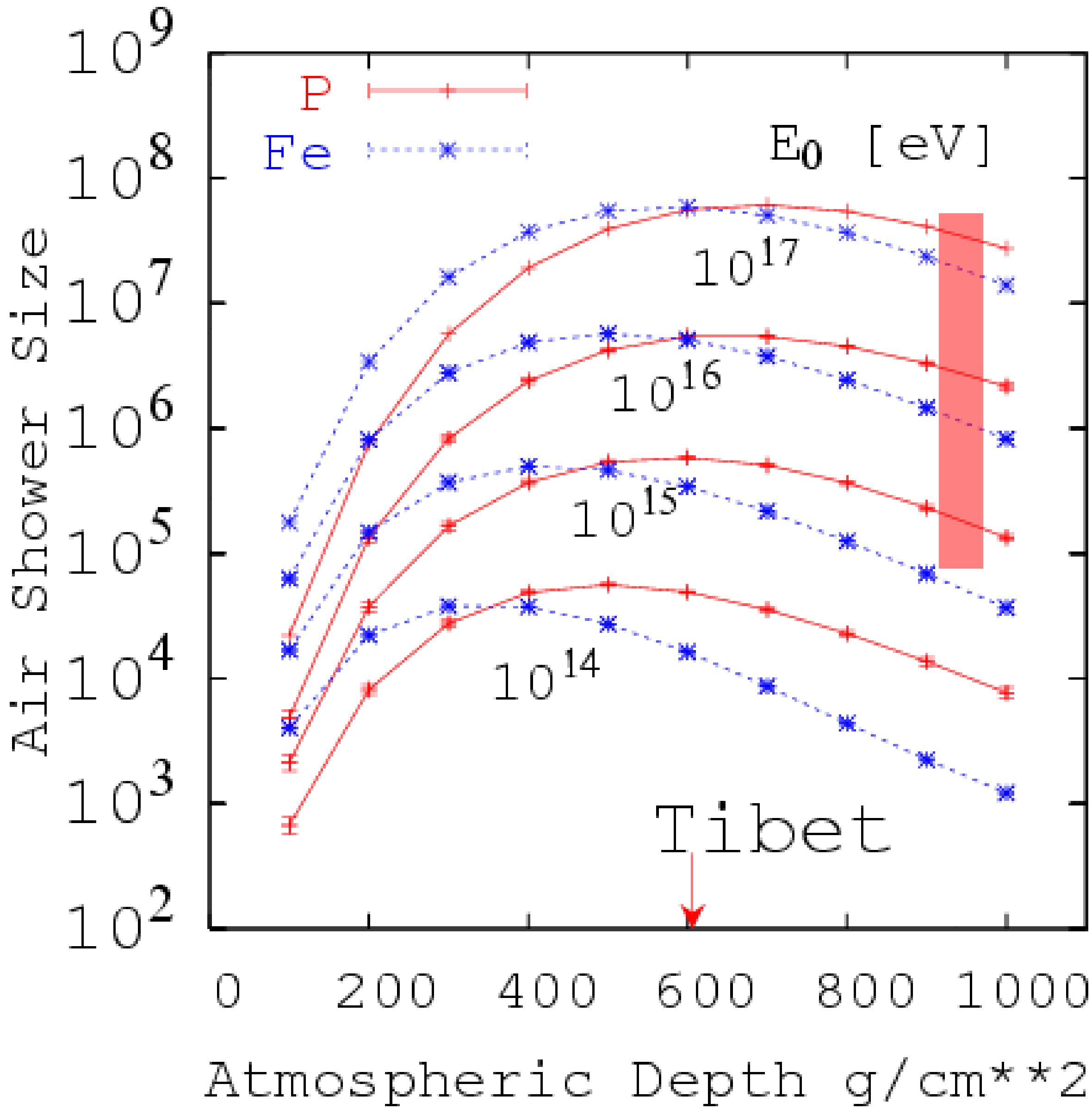
Complementary to Air Cherenkov Telescopes
Wide-field-of-view（~2sr） high-duty cycle CR telescope

1. **3TeV~100TeV cosmic γ rays**
2. **3TeV ～100 PeV primary cosmic rays**

-> Origin, acceleration, propagation mechanism of cosmic rays

3. **The Sun's shadow in cosmic rays**
（Shielding effect on cosmic rays by the Sun)
-> Global structure of solar and interplanetary magnetic fields

Longitudinal development of AS



Why Tibet?

1. TeV CR/γ

   Attenuation

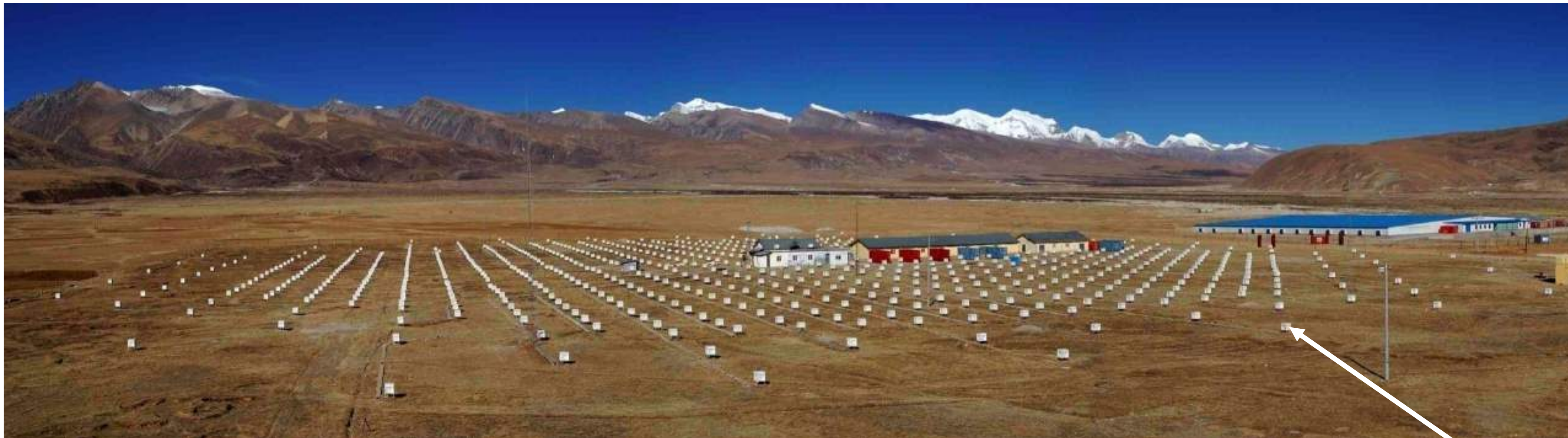
   @sea level

2. Good Energy determination in Knee

   (10^{15}-10^{16}eV)

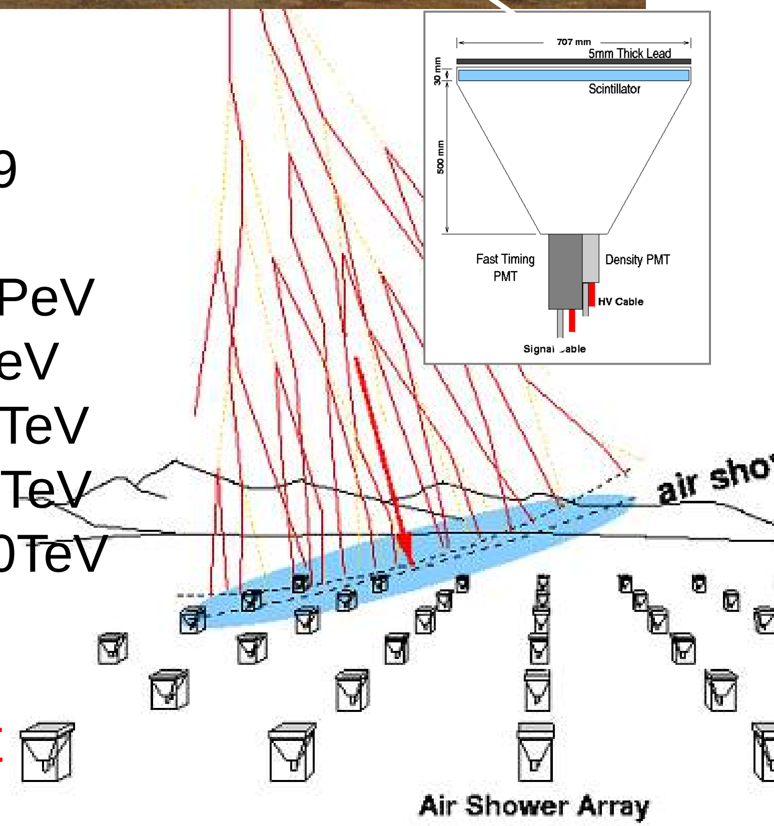
   (p or Fe)

Tibet-III Air Shower (AS) Array

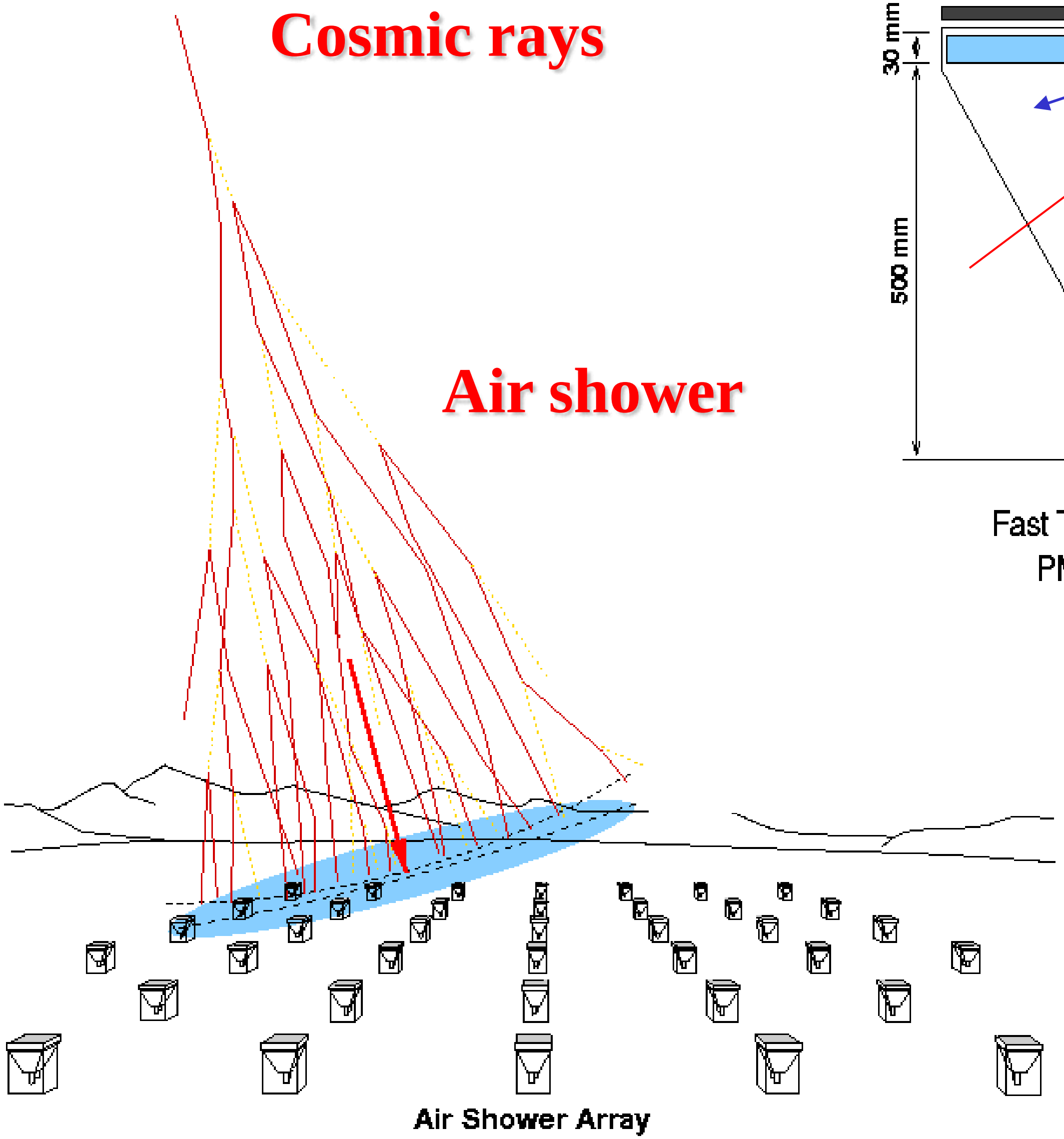


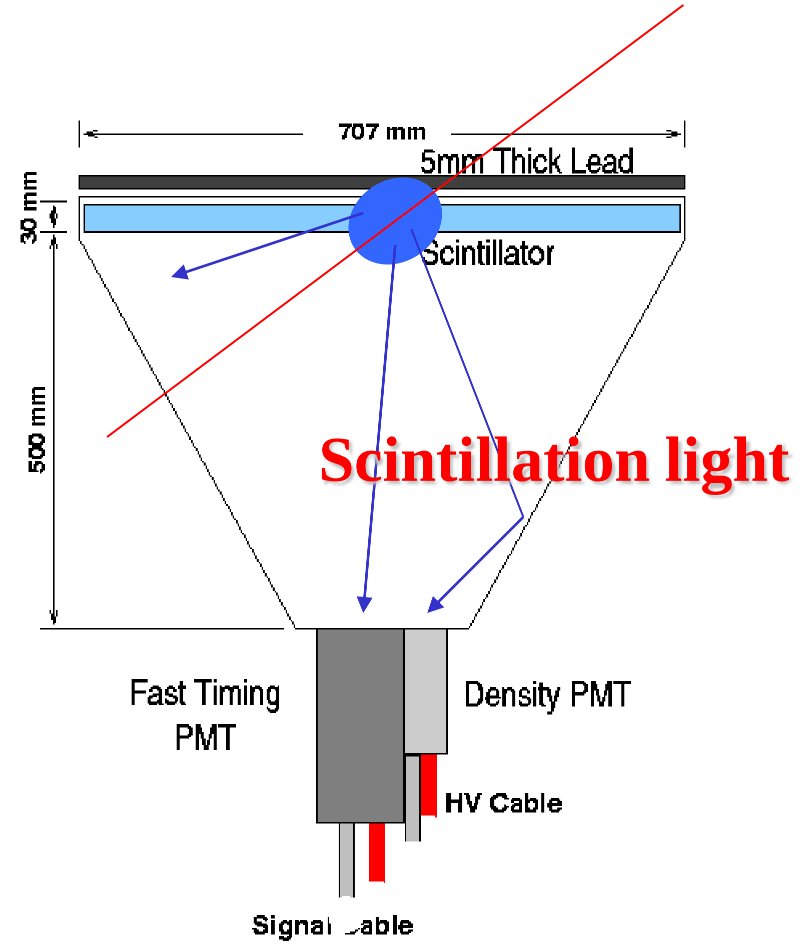
- Number of Scinti. Det. — 0.5 m^2 x 789
- Effective Area for AS — ~37,000 m^2
- Energy region — ~TeV - 100 PeV
- Angular Resolution (Gamma rays) — ~0.4 @10 TeV, ~0.2 @100 TeV
- Energy Resolution (Gamma rays) — ~70% @10 TeV, ~40% @100TeV
- F.O.V. — ~2 sr

2nd particles Timing & Energy deposit



Detection Principle

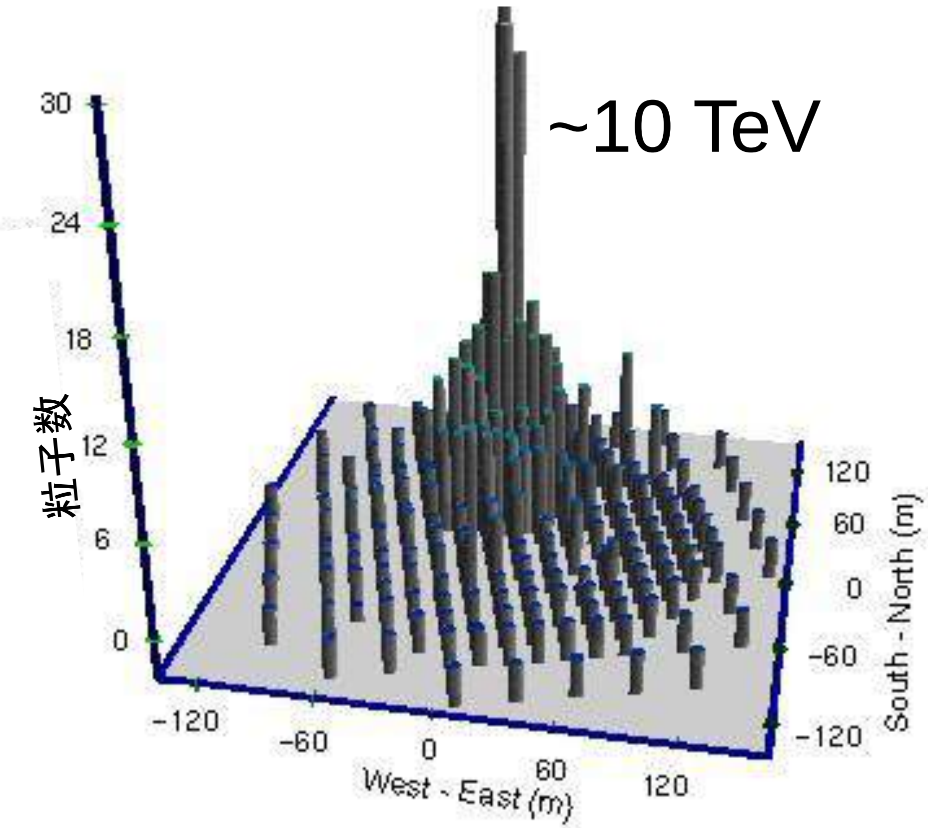


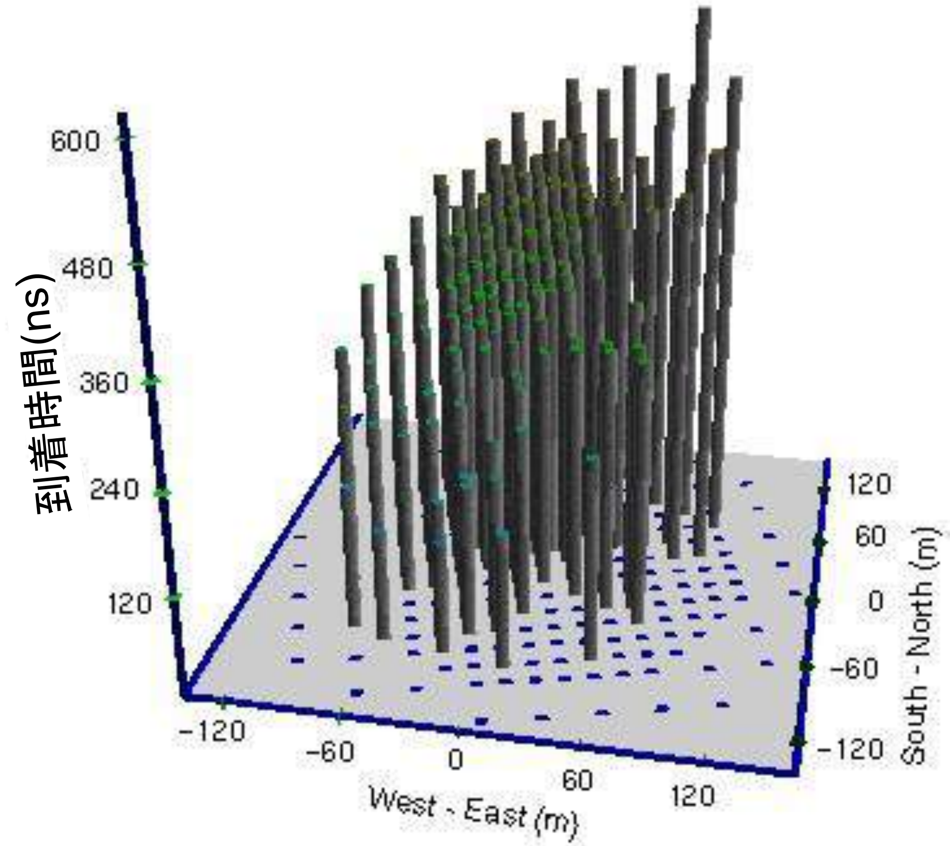


Air Shower Detection

2nd particle density → Cosmic ray energy

2nd particle timing → Cosmic ray direction



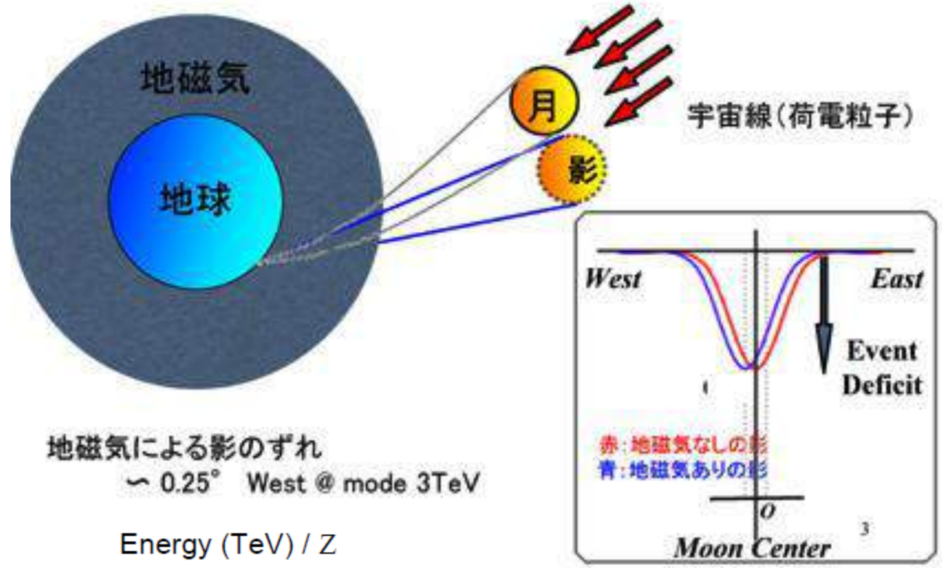


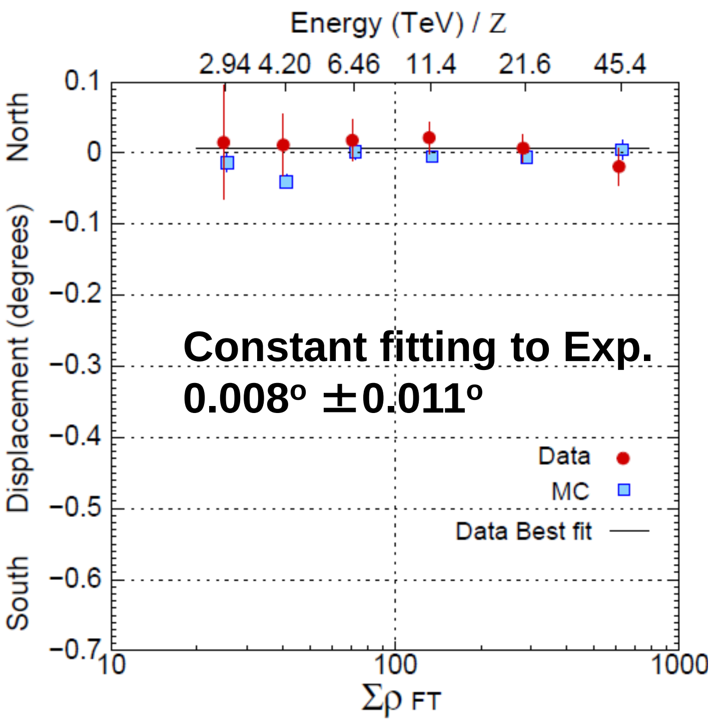
Air shower rate triggered by Tibet III ~1700Hz

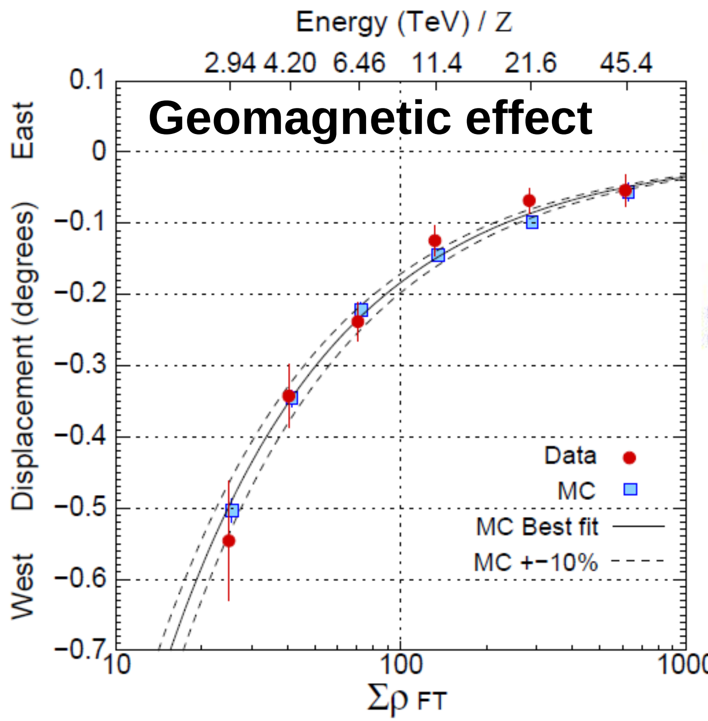
Performance by Moon's Shadow

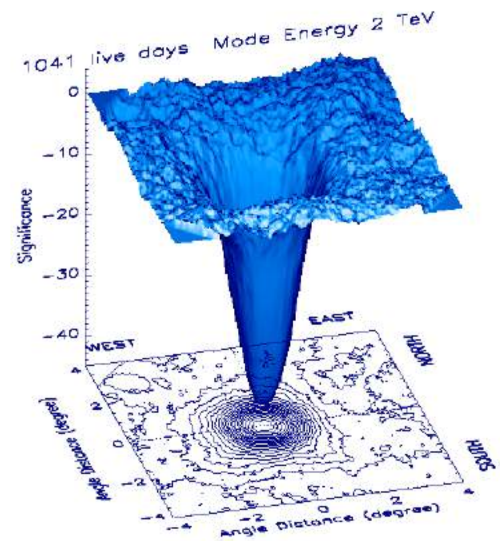
The Astrophysical Journal, 692, 61–72(2009)

- Absolute Energy Scale
- Angular Resolution
- Pointing Accuracy









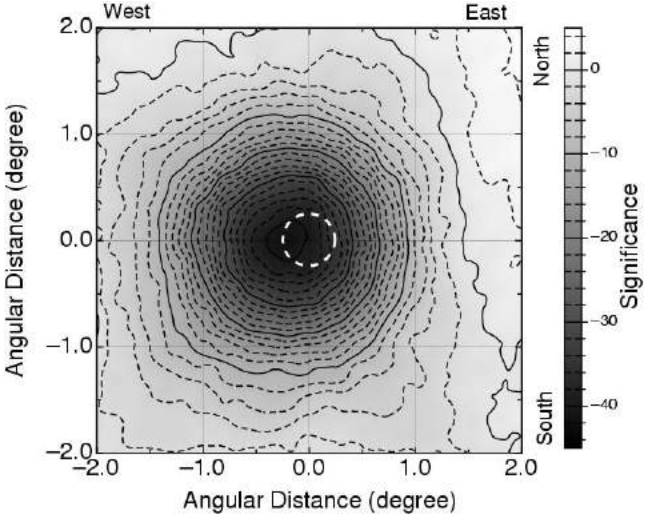
Pointing Error < 0.011°

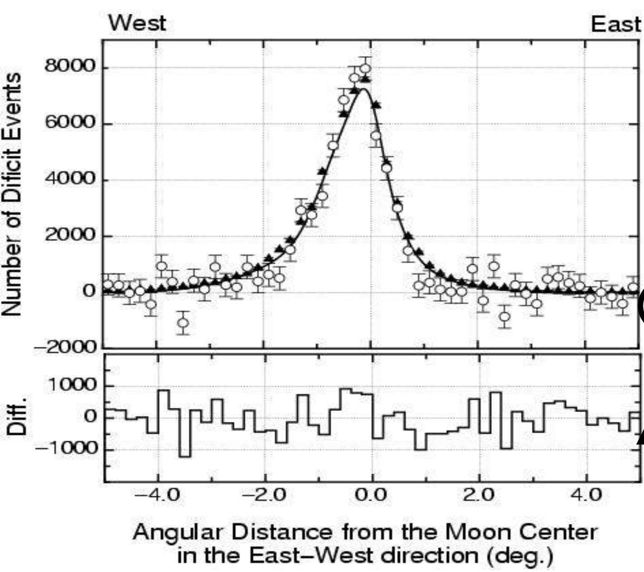
Absotute Energy Scale Error < 12%
+4.5%(±8.6stat.±6.7syst.)%

Search for TeV anti-protons by the Moon's shadow

Amenomori et al.
Astroparticle Physics, 28, (2007) 137-142

3TeV 40σ



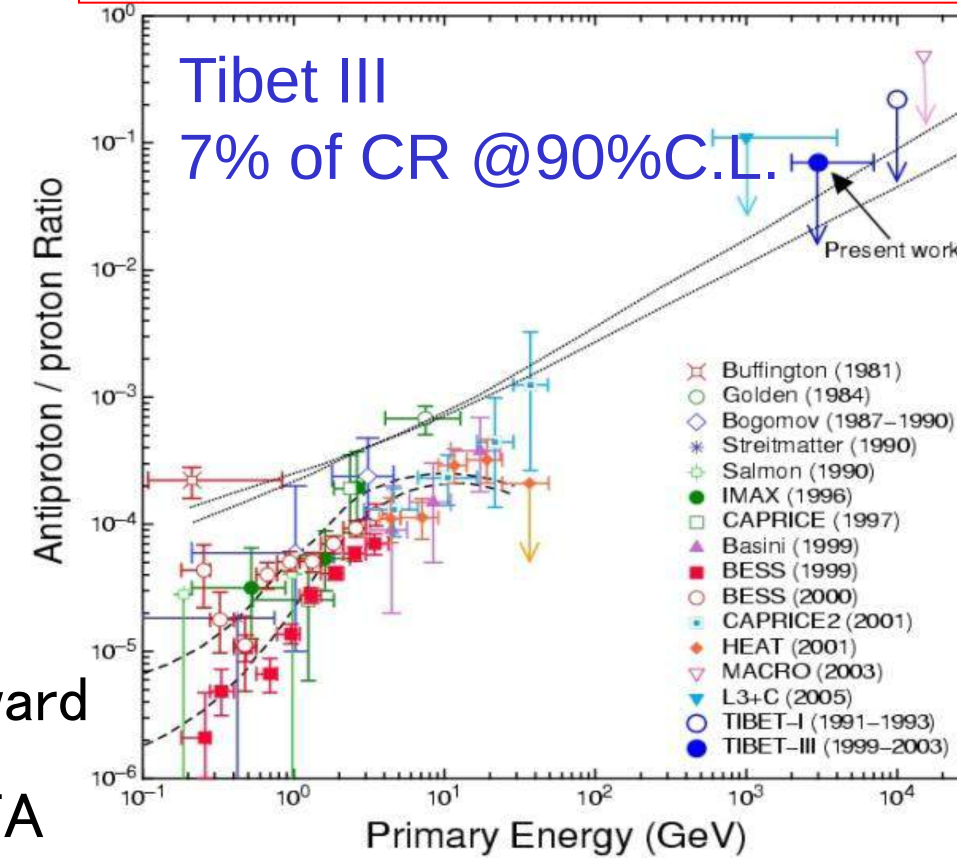


0.23°

Westward

○ :DATA

△ :MC



Dashed line: leaky box

M.Simon et al. ApJ 499 (1998)250.

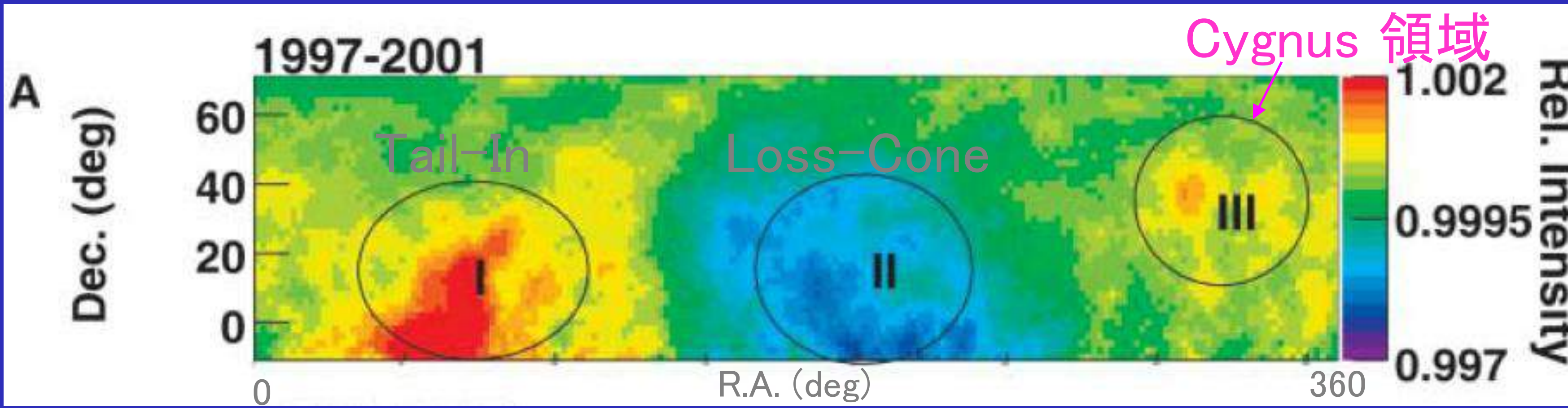
Dotted line: extragalactic anti-matter model

S.A. Stephan et al. Space Sci. Rev. 46 (1987) 31.

2. γ-ray physics

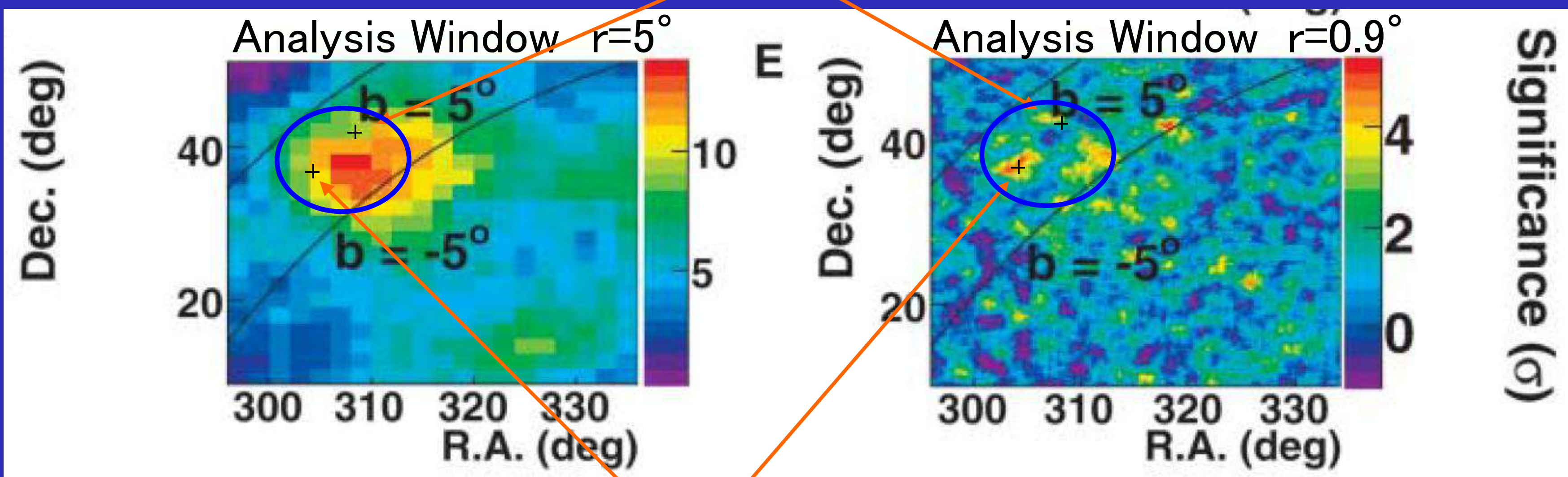
Cosmic Ray Anisotropy at sidereal time frame (Tibet ASγ)

Anisotropy Map *Amenomori et al, Science, 314, 439 (2006)*



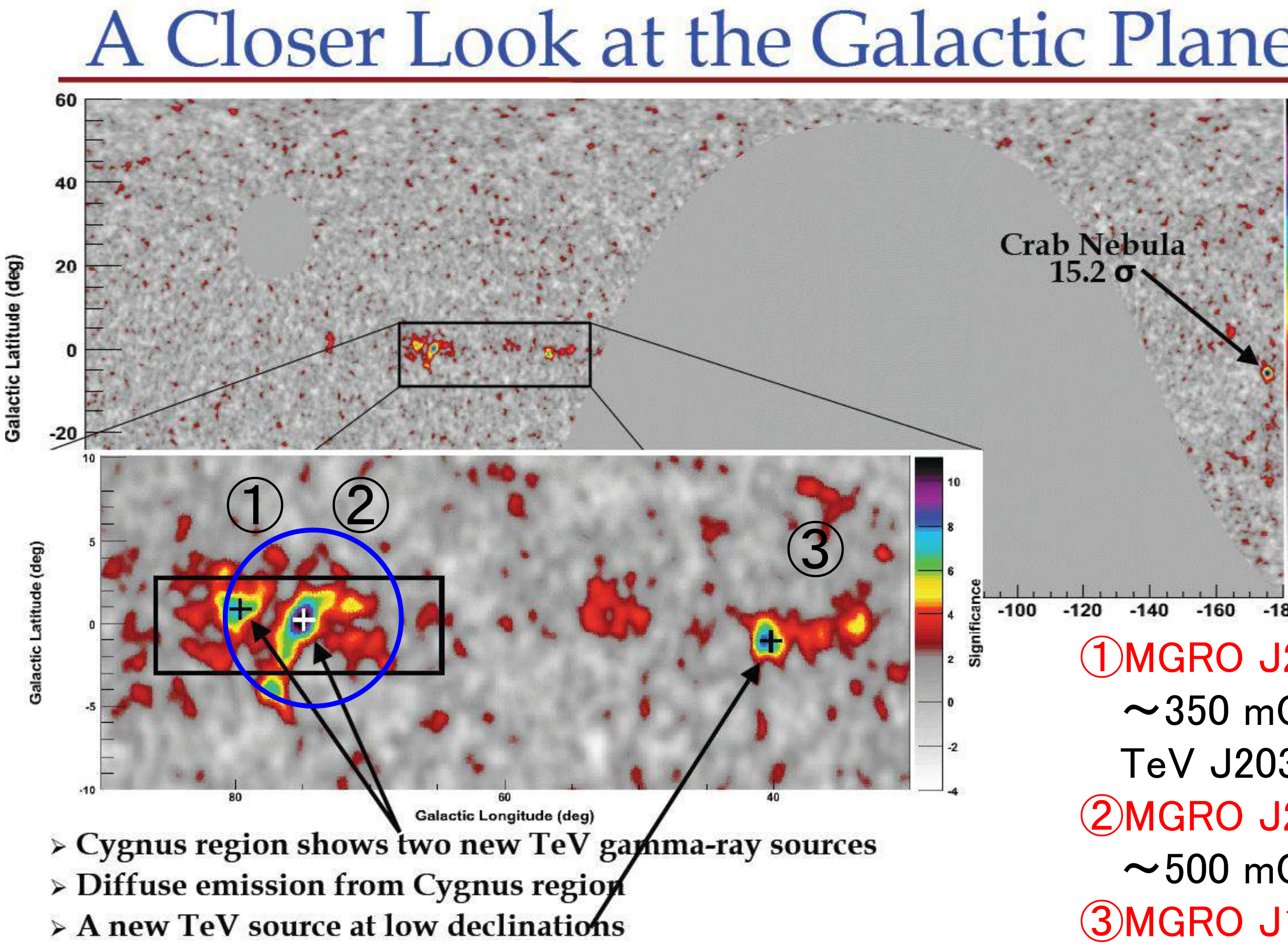
Cygnus Region

①MGRO J2033+42



②MGRO J2019+37

Cygnus領域 Milagro 全天サーベイ(2007年)



12TeV

①MGRO J2033+42
～350 mCrabs Diffuse
TeV J2032+4130?

②MGRO J2019+37
～500 mCrabs Diffuse

③MGRO J1909+06
～850 mCrabs Point-like?

First GLAST Symposium,
A. Abdo, "Discovery of TeV Gamma Ray Emission from the Cygnus Region with Milagro Using a New Background Rejection Technique"
http://glast.gsfc.nasa.gov/science/symposium/2007/thursday/7.3_Abdo.pdf

Observation of TeV Gamma Rays from the Fermi Bright Galactic Sources with the Tibet Air Shower Array (Amenomori et. al.)

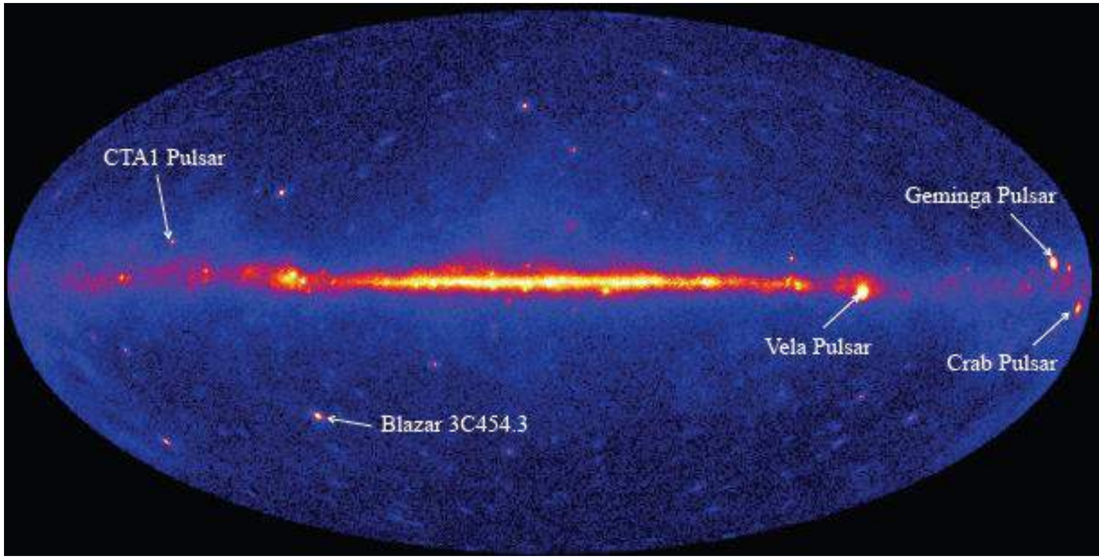
ApJ 709(2010)L6-L10

(**arXiv:0912.0386**)

Introduction

Large Area Telescope(LAT)
on the Fermi Gamma-Ray
Space Telescope

Lanched in June 2008



FERMI/LARGE AREA TELESCOPE BRIGHT GAMMA-RAY SOURCE LIST
Abdo, A. A. et al. 2009, ApJS, 183, 46 (July 2009, astrp-ph submitted in Feb. 2009)

Fermi LAT 3 month observation
>100MeV,
>10σ

205 most significant sources (120 extragalactic sourcs)
A typical 95% uncertainty radius of source position: 10′ ～ 20′

Milagro Observation of TeV Emission from Galactic Sources
In the Fermi Bright Source List *(Abdo, A. A. et al 2009, ApJ, 700, L127)*

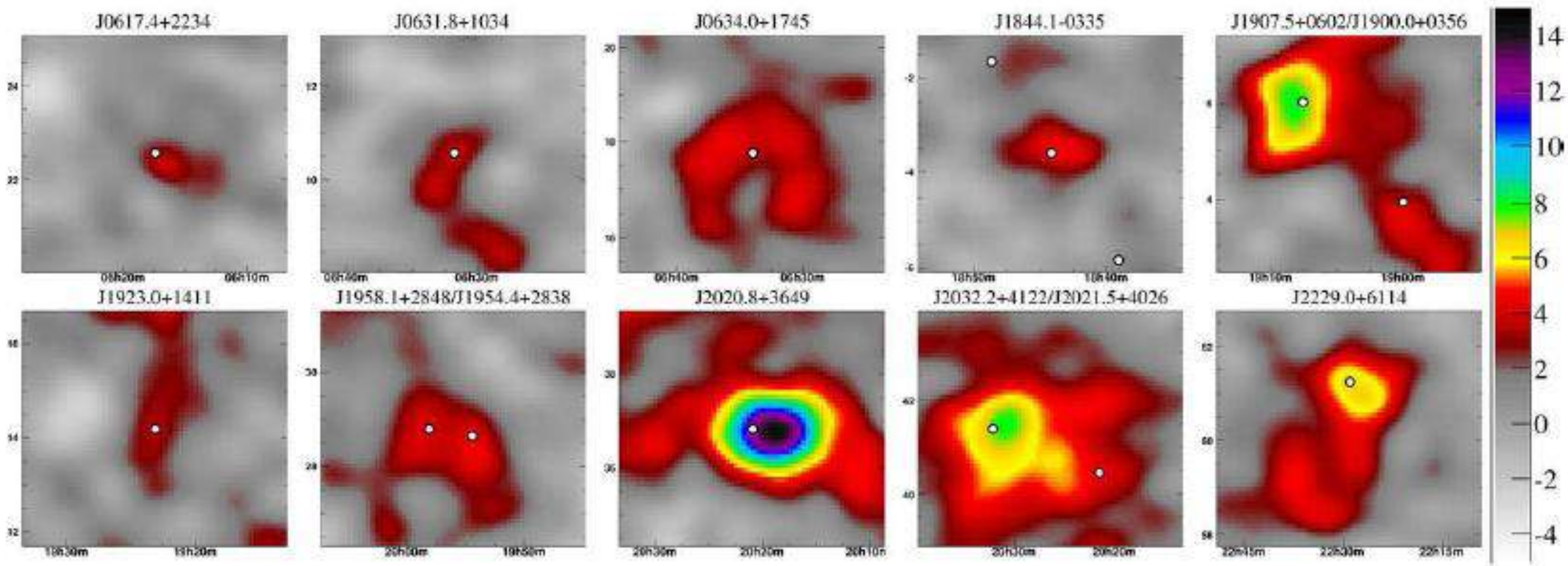


Fig. 1.— The 3σ sources from Table 1, omitting the Crab. Each frame shows a 5°x5° region with the LAT sources indicated by white dots. The data has been smoothed by a Gaussian of width varying between 0.4° and 1.0°, depending on the expected angular resolution of events. Horizontal axes show Right-Ascension and vertical axes show Declination. The colors indicate the statistical significance in standard deviations.

34 sources selected from 205 Fermi sources
(Not extragalactic & Dec.>-5.0°)

Eγ ~ 35 TeV

PSR	16
HXB	1
SRN	5
UNID	12

Milagro Results

Name (0FGL)	type	RA (deg)	DEC (deg)	l (deg)	b (deg)	Flux ($\times 10^{-17}$ TeV^{-1} sec^{-1} cm^{-2})	Signif. (σ's)	TeV assoc.
J0007.4+7303	PSR	1.85	73.06	119.69	10.47	< 90.4	2.6	
J0030.3+0450	PSR	7.60	4.85	113.11	-57.62	< 20.9	-1.7	
J0240.3+6113	HXB	40.09	61.23	135.66	1.07	< 26.2	0.7	LSI +61 303
J0357.5+3205	PSR	59.39	32.08	162.71	-16.06	< 16.5	-0.1	
J0534.6+2201	PSR	83.65	22.02	184.56	-5.76	162.6 ± 9.4	17.2	Crab
J0613.9-0202	PSR	93.48	-2.05	210.47	-9.27	< 60.0	-0.0	
J0617.4+2234	SNR[a]	94.36	22.57	189.08	3.07	28.8 ± 9.5	3.0	IC443
J0631.8+1034	PSR	97.95	10.57	201.30	0.51	47.2 ± 12.9	3.7	
J0633.5+0634	PSR	98.39	6.58	205.04	-0.96	< 50.2	1.4	
J0634.0+1745	PSR	98.50	17.76	195.16	4.29	37.7 ± 10.7	3.5	MGRO C3 Geminga
J0643.2+0858		100.82	8.98	204.01	2.29	< 30.5	0.3	
J1653.4-0200		253.35	-2.01	16.55	24.96	< 51.0	-0.5	
J1830.3+0617		277.58	6.29	36.16	7.54	< 32.8	0.2	
J1836.2+5924	PSR	279.06	59.41	88.86	25.00	< 14.6	-0.9	
J1844.1-0335		281.04	-3.59	28.91	-0.02	148.4 ± 34.2	4.3	
J1848.6-0138		282.16	-1.64	31.15	-0.12	< 91.7	1.7	
J1855.9+0126	SNR[a]	283.99	1.44	34.72	-0.35	< 89.5	2.2	
J1900.0+0356		285.01	3.95	37.42	-0.11	70.7 ± 19.5	3.6	
J1907.5+0602	PSR	286.89	6.03	40.14	-0.82	116.7 ± 15.8	7.4	MGRO J1908+06 HESS J1908+063

14 sources were detected with >3σ

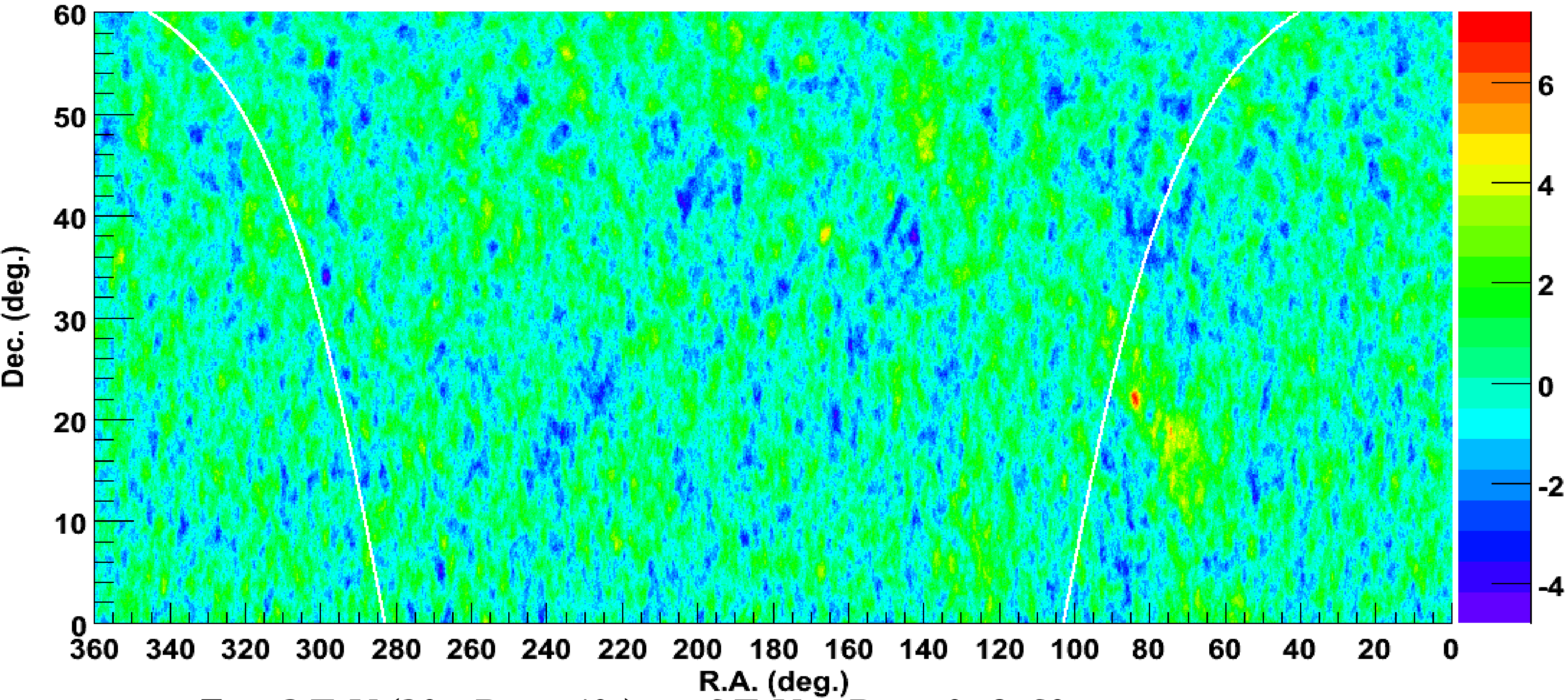
J1911.0+0905	SNR[a]	287.76	9.09	43.25	-0.18	< 41.7	1.5	
J1923.0+1411	SNR[a]	290.77	14.19	49.13	-0.40	39.4 ± 11.5	3.4	HESS J1923+141
J1953.2+3249	PSR	298.32	32.82	68.75	2.73	< 17.0	0.0	
J1954.4+2838	SNR[a]	298.61	28.65	65.30	0.38	37.1 ± 8.6	4.3	
J1958.1+2848	PSR	299.53	28.80	65.85	-0.23	34.7 ± 8.6	4.0	
J2001.0+4352		300.27	43.87	79.05	7.12	< 12.1	-0.9	
J2020.8+3649	PSR	305.22	36.83	75.18	0.13	108.3 ± 8.7	12.4	MGRO J2019+37
J2021.5+4026	PSR	305.40	40.44	78.23	2.07	35.8 ± 8.5	4.2	
J2027.5+3334		306.88	33.57	73.30	-2.85	< 16.0	-0.2	
J2032.2+4122	PSR	308.06	41.38	80.16	0.98	63.3 ± 8.3	7.6	TEV 2032+41 MGRO J2031+41
J2055.5+2540		313.89	25.67	70.66	-12.47	< 17.6	-0.0	
J2110.8+4608		317.70	46.14	88.26	-1.35	< 24.1	1.1	
J2214.8+3002		333.70	30.05	86.91	-21.66	< 20.7	0.6	
J2229.0+6114	PSR	337.26	61.24	106.64	2.96	70.9 ± 10.8	6.6	MGRO C4
J2302.9+4443		345.75	44.72	103.44	-14.00	< 13.2	-0.6	

Tibet-III Data Analysis

All-sky Data by the Tibet-III Array (Phase 1-9 Ver.B4)

$\Sigma\rho_{FT} > 10^{1.25}$ && zenith <40^o
Inout && 1.25p Any4 && Residual Error <1.0m
Search Window Size: $R_s(\Sigma\rho_{FT}) = 6.9 / \sqrt{\Sigma\rho_{FT}}$ (Variable)

1999 Nov – 2008 Dec
1915.5 live days



$E\gamma \sim 3$ TeV (20^o<Dec.<40^o), ~ 6 TeV at Dec.=0^o & 60^o

Target sources in the Fermi Bright Source List

The Fermi Bright Source List: 205 sources

Not identified as extragalactic: 85 sources

0^{o} < Declination < 60^{o} 27 sources

Pulsar (PSR)	13
Supernova remnant (SNR)	5
Unidentified	9

Table 1

Summary of the Tibet-III Array Observations of the *Fermi* Sources

Fermi LAT Source (0FGL)	Class	R.A. (deg)	Decl. (deg)	Tibet-III Signi. (σ)	Milagro[a] Signi. (σ)	Source Associations
J0030.3+0450	PSR	7.600	4.848	1.7	−1.7	
J0357.5+3205	PSR[b]	59.388	32.084	−1.7	−0.1	
J0534.6+2201	PSR	83.653	22.022	6.9	17.2	Crab
J0617.4+2234	SNR	94.356	22.568	0.2	3.0	IC 443
J0631.8+1034	PSR	97.955	10.570	0.3	3.7	
J0633.5+0634	PSR[b]	98.387	6.578	2.4	1.4	
J0634.0+1745	PSR	98.503	17.760	2.2	3.5	Geminga
J0643.2+0858		100.823	8.983	−1.2	0.3	
J1830.3+0617		277.583	6.287	−0.2	0.2	
J1836.2+5924	PSR[b]	279.056	59.406	−0.3	−0.9	
J1855.9+0126	SNR	283.985	1.435	0.7	2.2	W44
J1900.0+0356		285.009	3.946	1.0	3.6	
J1907.5+0602	PSR[b]	286.894	6.034	2.4	7.4	MGRO J1908+06 HESS J1908+063
J1911.0+0905	SNR	287.761	9.087	1.7	1.5	G43.3 − 0.2
J1923.0+1411	SNR	290.768	14.191	−0.3	3.4	W51 HESS J1923+141

Geminga

Tibet-III 2σ

∼0.3 Crabs

Table 1
Summary of the Tibet-III Array Observations of the *Fermi* Sources

Tibet-III 2σ〜0.3 Crabs

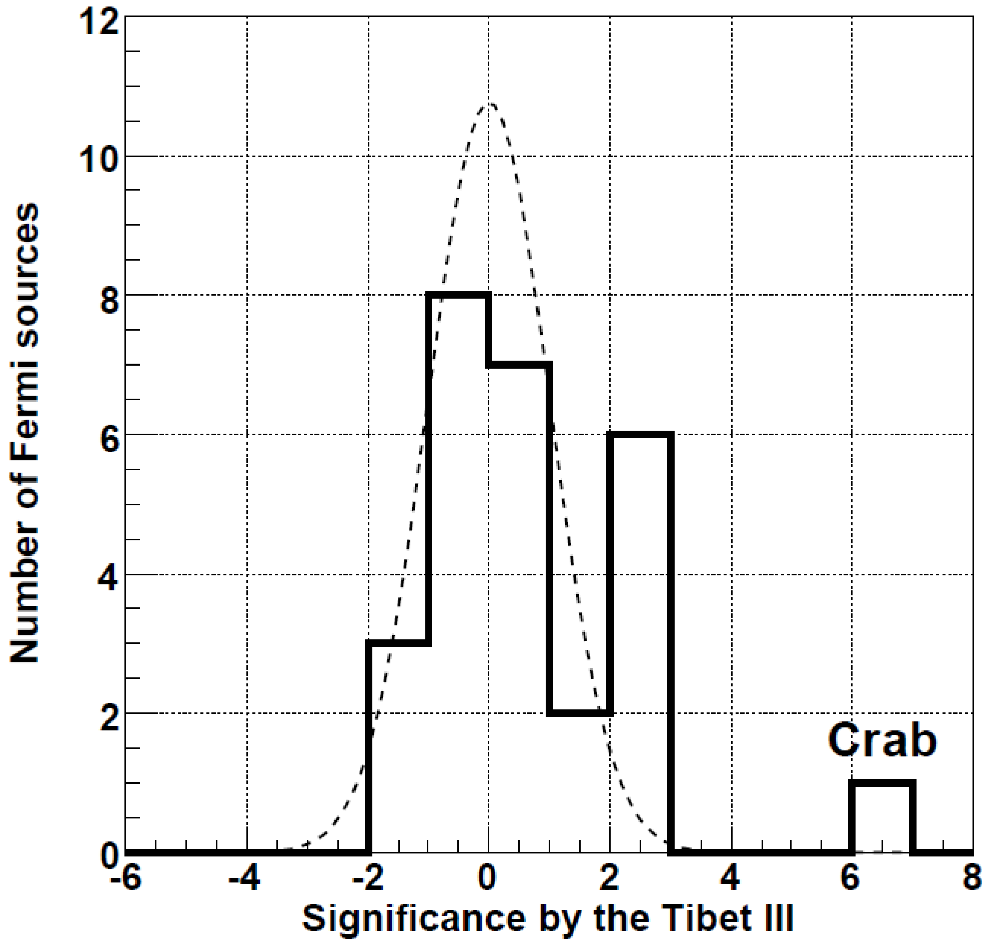
Fermi LAT Source (0FGL)	Class	R.A. (deg)	Decl. (deg)	Tibet-III Signi. (σ)	Milagro[a] Signi. (σ)	Source Associations
J1953.2+3249	PSR	298.325	32.818	−0.0	0.0	
J1954.4+2838	SNR	298.614	28.649	0.6	4.3	G65.1+0.6
J1958.1+2848	PSR[b]	299.531	28.803	0.1	4.0	
J2001.0+4352		300.272	43.871	−0.5	−0.9	
J2020.8+3649	PSR	305.223	36.830	2.2	12.4	MGRO J2019+37
J2021.5+4026	PSR[b]	305.398	40.439	2.2	4.2	
J2027.5+3334		306.882	33.574	−0.3	−0.2	
J2032.2+4122	PSR[b]	308.058	41.376	2.4	7.6	TeV J2032+4130 MGRO J2031+41
J2055.5+2540		313.895	25.673	−0.0	−0.0	
J2110.8+4608		317.702	46.137	0.3	1.1	
J2214.8+3002		333.705	30.049	−1.0	0.6	
J2302.9+4443		345.746	44.723	−0.0	−0.6	
LAT PSR J2238+59[c]	PSR[b]	339.561	59.080	2.5	4.7	

Cygnus region

New Fermi-LAT Pulsar, Not included in analysis

All 7 sources >2σ are associated with pulsars. →PWNs?
Six of them are coincident with Milagro sources.
Remaing one have still positive significance 1.4σ by Milagro.

Statistics



Total: 27 sources

>2σ: 7 sources

Fig. 1.— Histograms show significance distribution of the *Fermi* bright sources observed by the Tibet-III array. The dashed curve indicates the expected normal Gaussian distribution.

Chance Probability

Expected number of sources >2σ
27 × 0.02275 (2σ Upper prob.) = 0.61

Upper probabiriy for 7 events against λ=0.61
assuming Poisson statistics

$$p(A=7) = 1 - \sum_{k=0}^{A-1} \frac{e^{-\lambda}\lambda^k}{k!}$$

$$= 3.8 \times 10^{-6} \sim 4.5\sigma$$

Without Crab
$\lambda = 26 \times 0.02275$ (2σ Upper prob.) = 0.59
$P(A=6) = 3.6 \times 10^{-5} \sim 4\sigma$

Flux consistency between the Tibet-III and the Milagro

	Tibet σ	Milagro σ	Expected σ from Milagro
J0534.6+2201	6.9	17.2	-
J0633.5+0634	2.4	1.4	0.56
J0634.0+1745	2.2	3.5	1.40
J1907.5+0602	2.4	7.4	2.97
J2020.8+3649	2.2	12.4	4.97
J2021.5+4026	2.2	4.2	1.68
J2032.2+4122	2.4	7.6	3.05

Underestimated?

J2020.8+3649 flux:

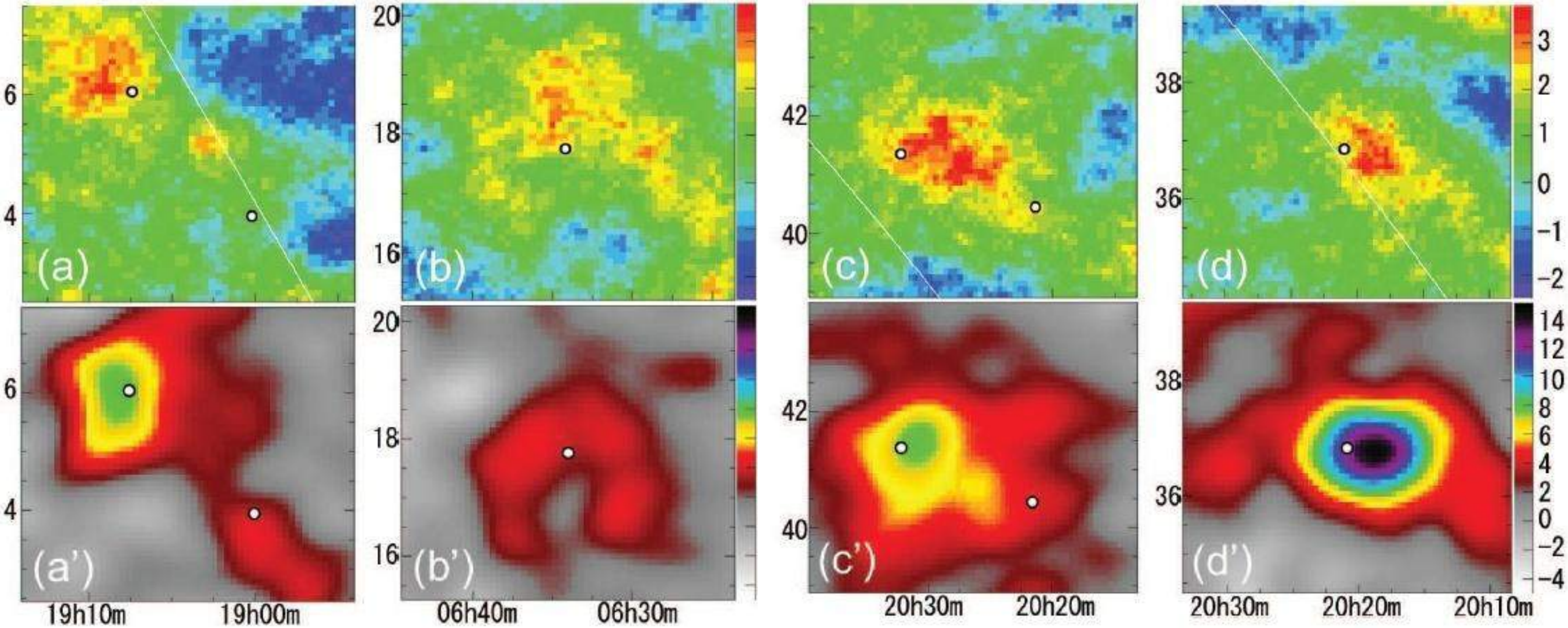
Tibet-III (30±14)% of the Crab flux above 3 TeV

Milagro (67±7)% of the Crab flux above 35 TeV

$\Delta = 2.3\sigma$

difference between them is calculated to be 2.3σ. It can be interpreted by either statistical fluctuation, harder energy spectrum than the Crab, or an extended source instead of the assumed point-like source in this analysis.

Tibet-III

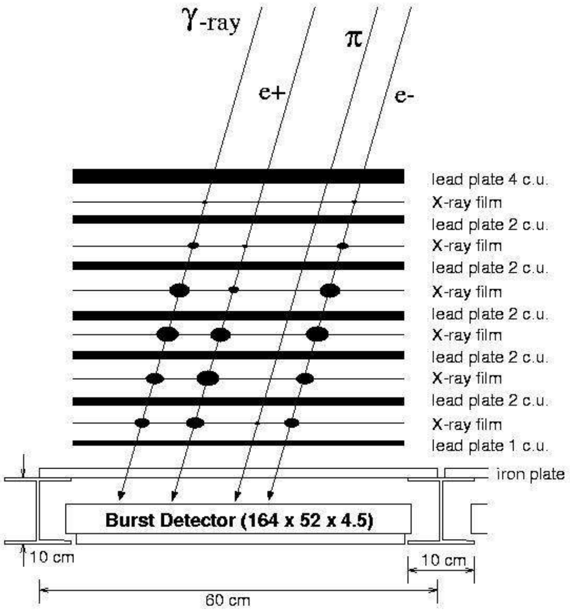


Milagro

Fig. 2.— Comparisons of significance maps around the *Fermi* sources between the Tibet-III array (a)–(d) and the Milagro experiment (a')–(d') taken from Abdo et al. (2009c). Selected are *Fermi* sources with $\geq 2\sigma$ significance by the Tibet-III array and $\geq 3\sigma$ by the Milagro experiment except for the Crab. White points in each image show the *Fermi* source positions: (a)(a') J1907.5+0602/J1900.0+0356; (b)(b') J0634.0+1745 (Geminga); (c)(c') J2021.5+4026/J2032.2+4122; (d)(d') J2020.8+3649. The horizontal axis, vertical axis, and color contours indicate the right ascension, declination, and significance, respectively.

3. Knee Physics

TIBET Hybrid Experiment



How to obtain proton spectrum?

Hybrid system

BD(burst) : (x,y) time Burst Size (below EC)

1st trigger

TAG

EC(γfamily) : (x,y) (ϑ, ϕ) ΣE_γ

AS array: time (ϑ, ϕ) N_e

(Simulation)

E_0

EC-Xray film image → Scanner → (GUI Software) family detection

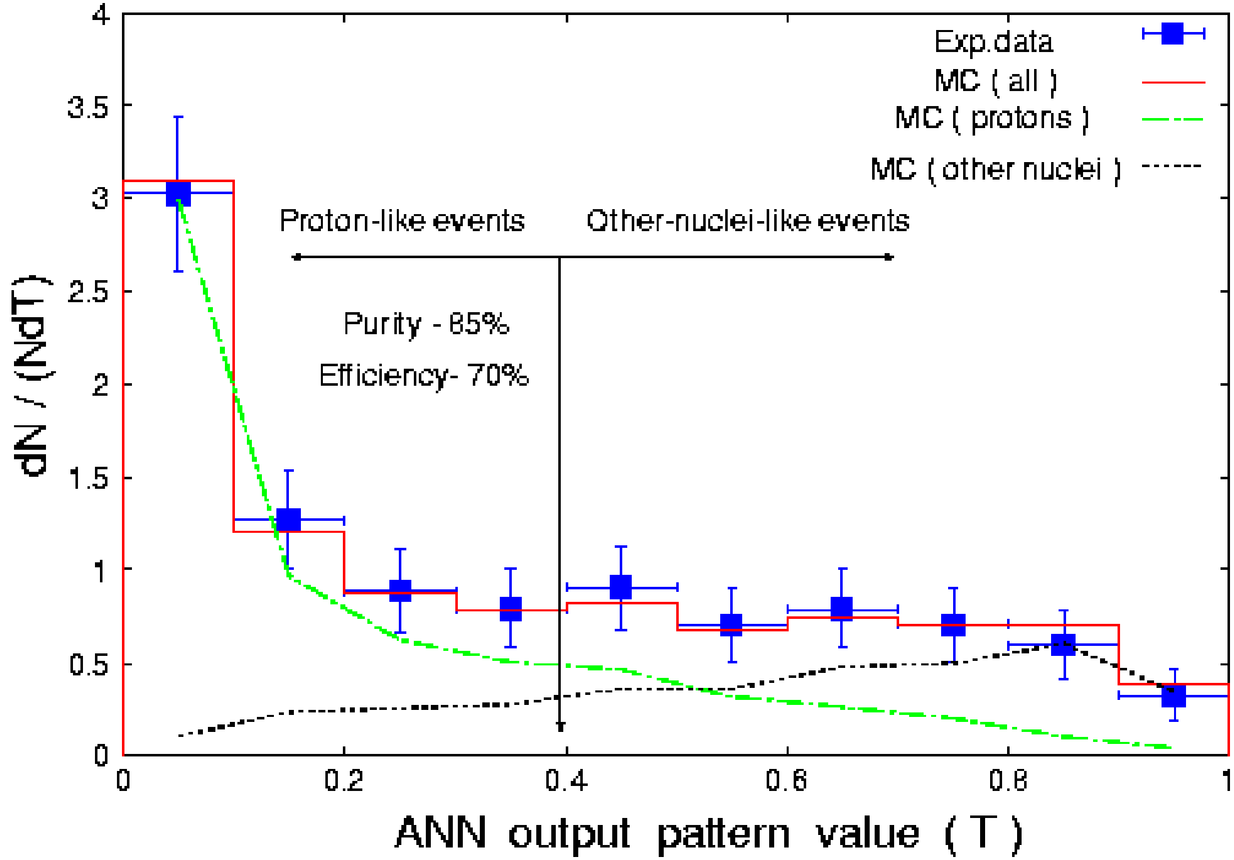
AS+family matching event → ANN → Proton Identification ~100 eV/699 days

(Correlations)

Artificial Neural Network

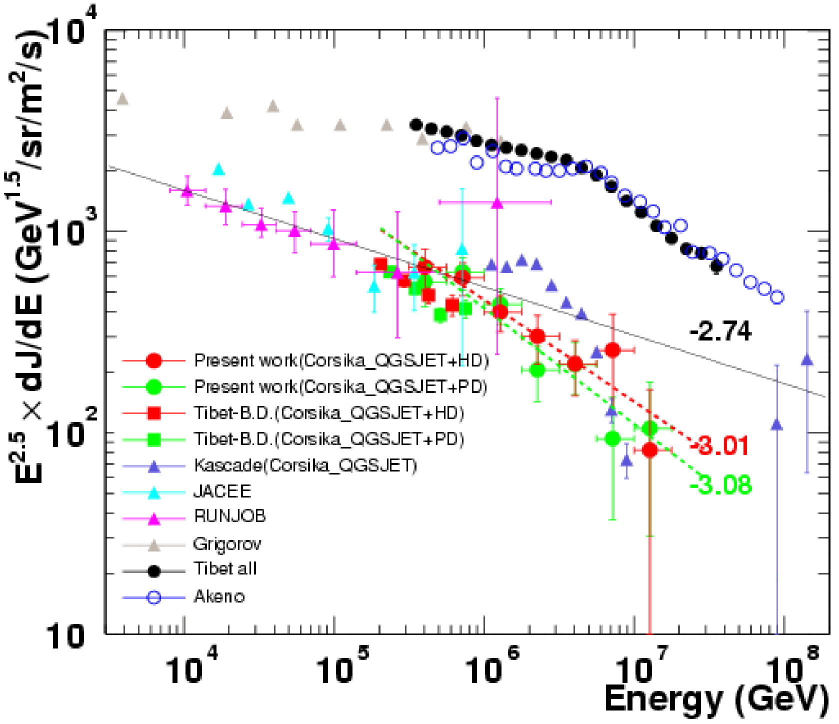
JETNET 3.5

Parameters for training: N_γ, ΣE_γ, $\langle R_\gamma \rangle$, $\langle ER_\gamma \rangle$, N_e, θ

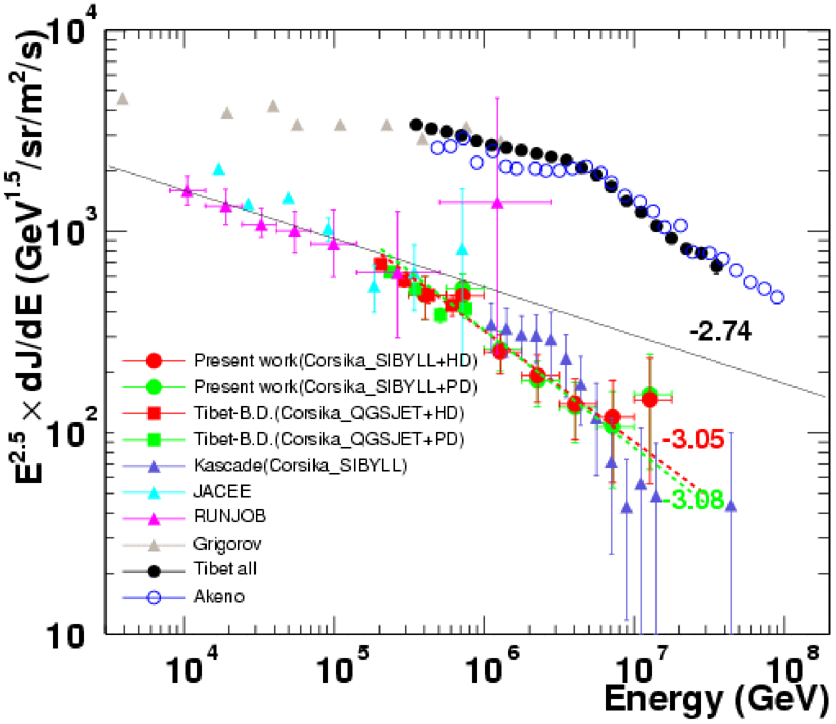


Primary proton spectrum

(a) (by QGSJET model)



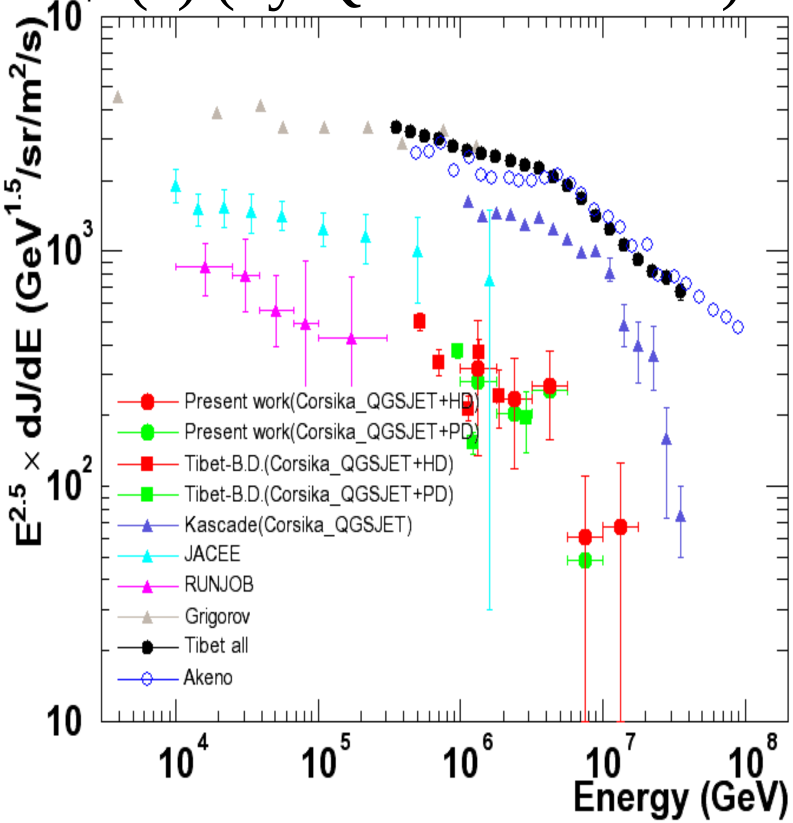
(b) (by SIBYLL model)



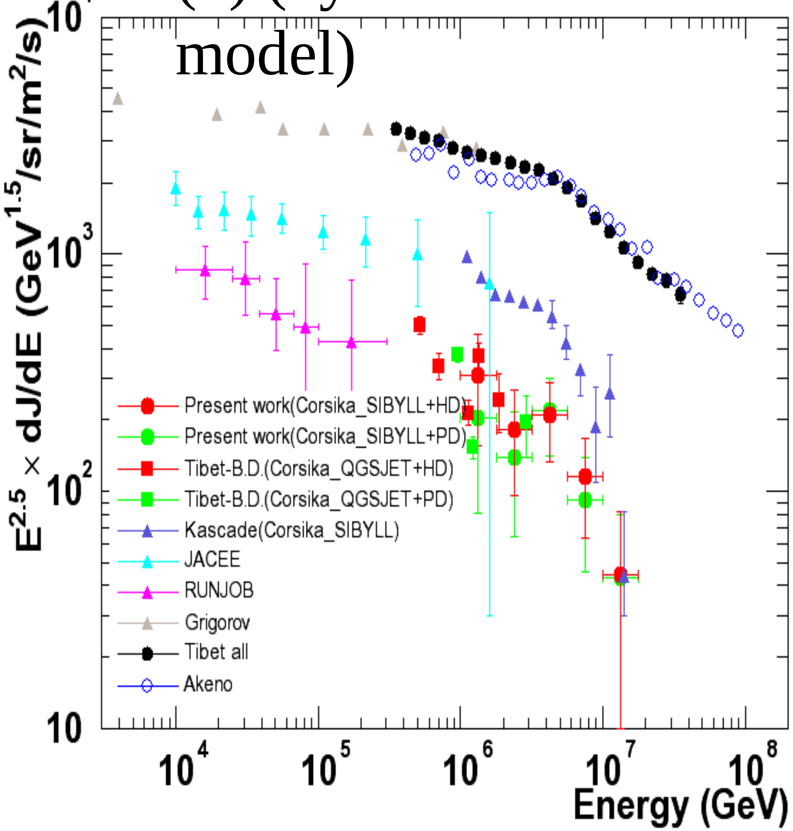
(KASCADE data: astro-ph/0312295)

Primary helium spectrum

(a) (by QGSJET model)



(b) (by SIBYLL model)

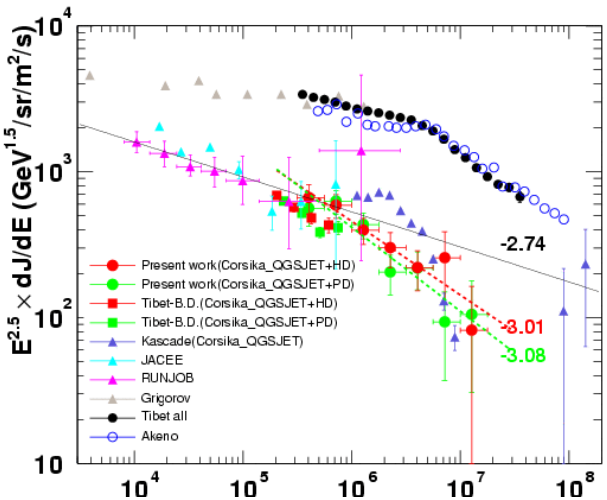


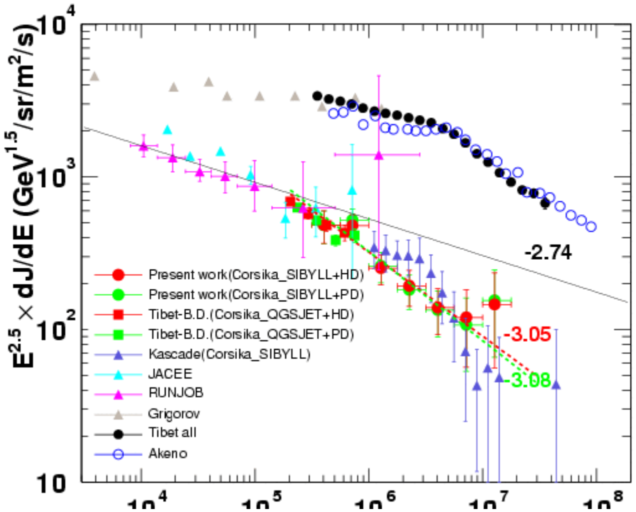
p+helium selection: purity=93%, efficiency=70%

Primary Cosmic Ray Energy Spectrum

CORSIKA_QGSJET

CORSIKA_SIBYLL

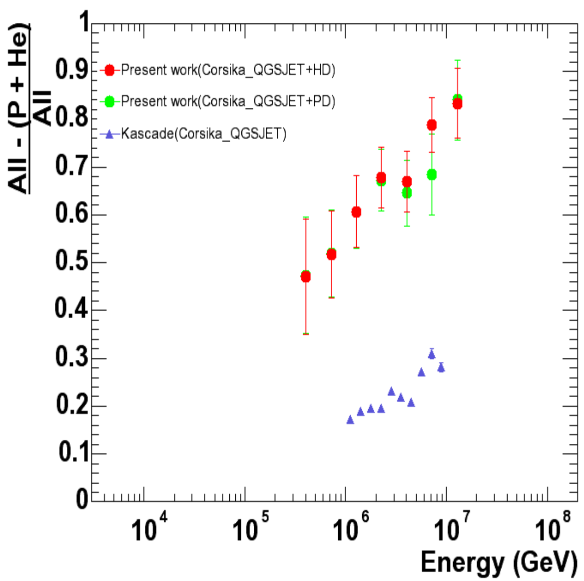


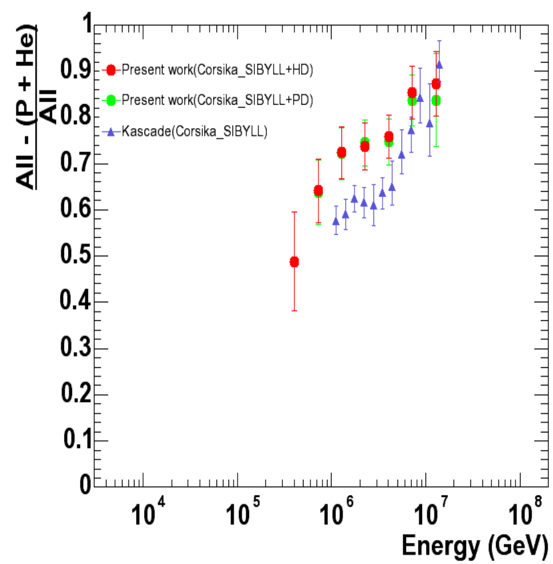


Proton

Small model dependence

(30 %)





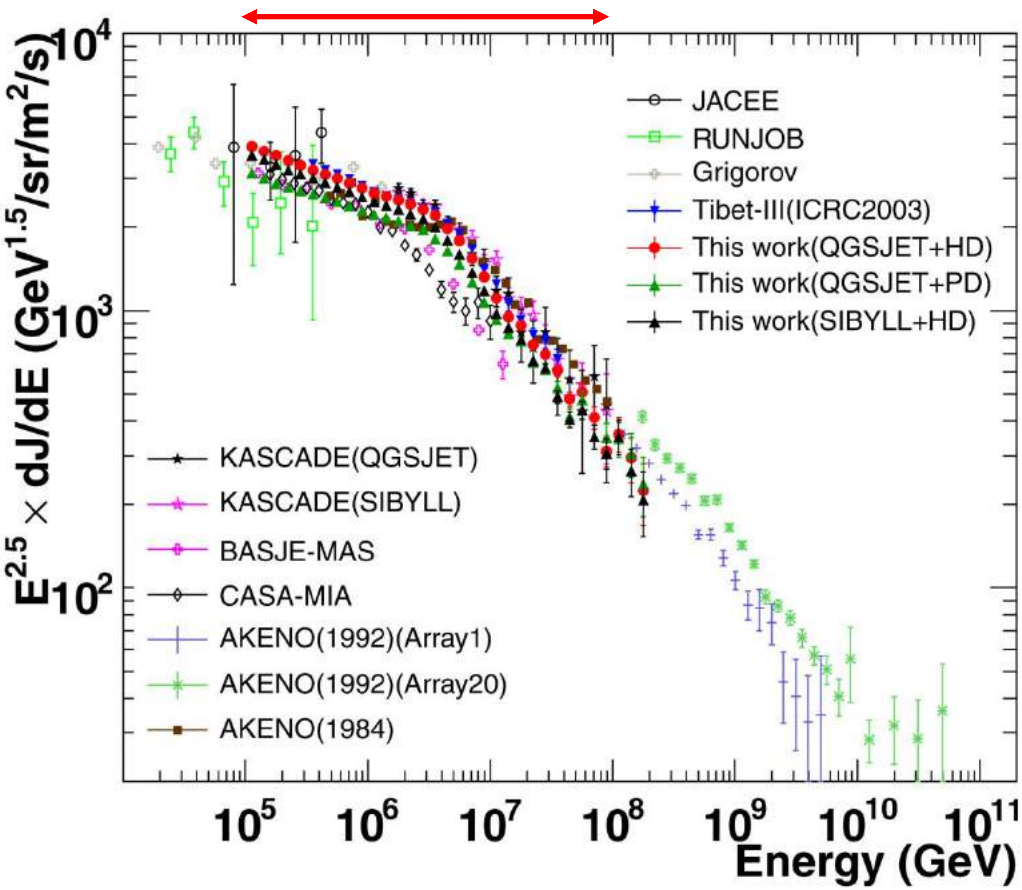
$$\frac{\text{All} - (\text{p+He})}{\text{All}}$$

PL B632 (2006) 58-64

All Particle Energy Spectrum in the Knee region

Amenomori *et al.*,
ApJ, **678**, 1165 (2008)

10^{14}eV ～ 10^{17}eV (3 orders)



Model	Index of spectrum	Energy range (eV)
QGSJET +HD	−2.67±0.01	< 10^{15} eV
	−3.10±0.01	> 4×10^{15} eV
QGSJET +PD	−2.65±0.01	< 10^{15} eV
	−3.08±0.01	> 4×10^{15} eV
SIBYLL +HD	−2.67±0.01	< 10^{15} eV
	−3.12±0.01	> 4×10^{15} eV

Multiple source model

(Slide from M.Shibata,Y.N.U.)

Cutoff spectrum is written as

$$\frac{dj(E,\varepsilon)}{dE} = j_0 E^{-\gamma} \exp(-\frac{E}{\varepsilon}).$$

Distribution of sources with acceleration limit ε is assumed as,

$$S(x) = \frac{1}{\Gamma(\Delta\gamma)} \frac{1}{x^{1+\Delta\gamma}} \exp(-\frac{1}{x})$$

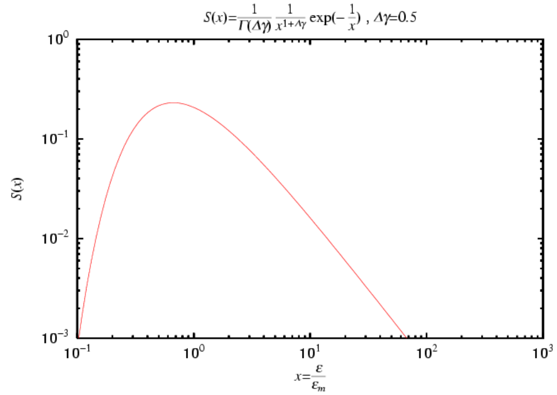
where $x = \varepsilon/\varepsilon_m$, ε_m is the minimum value of the acceleration limit. $S(x)$ is normalized as

$$\int_0^\infty S(x)dx = 1.$$

Then, superposition of the multiple sources gives following formula for cosmic-ray energy spectrum.

$$\frac{dJ}{dE} = \int_0^\infty \frac{dj(E,\varepsilon)}{dE} S(\frac{\varepsilon}{\varepsilon_m}) \frac{d\varepsilon}{\varepsilon_m} = \frac{j_0 E^{-\gamma}}{(1+E/\varepsilon_m)^{\Delta\gamma}}$$

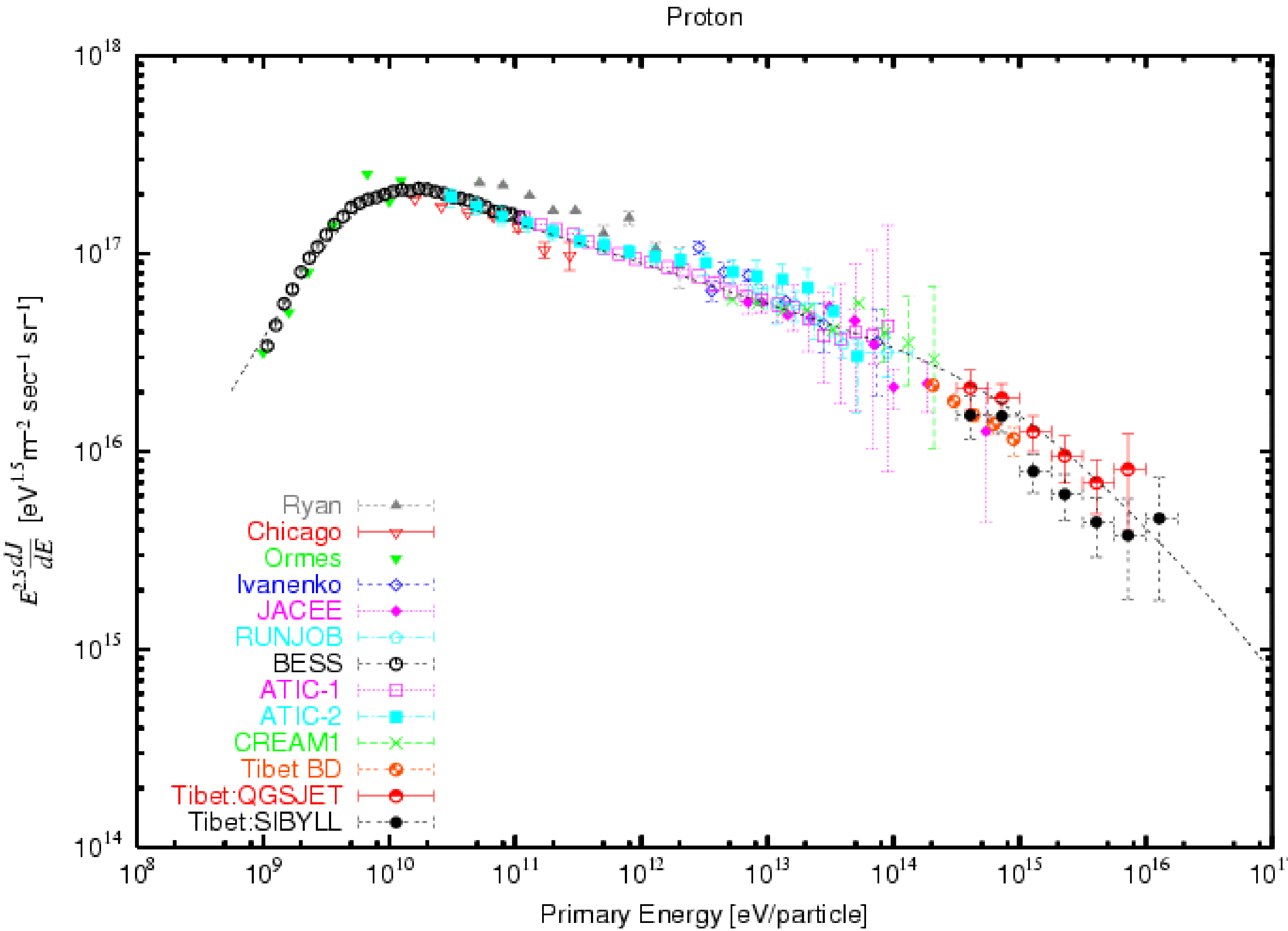
$\boldsymbol{\varepsilon_m \equiv \varepsilon_b}$



Distribution of acceleration power of cosmic rays

Proton Spectrum

Direct measurement and Tibet combined



(Slide from M.Shibata,Y.N.U.)

Broken power law formula to describe proton spectrum

$$\frac{dj}{dE} = j_0 E^{-\gamma}[1 + \frac{E}{\varepsilon_b}]^{-\Delta\gamma}$$

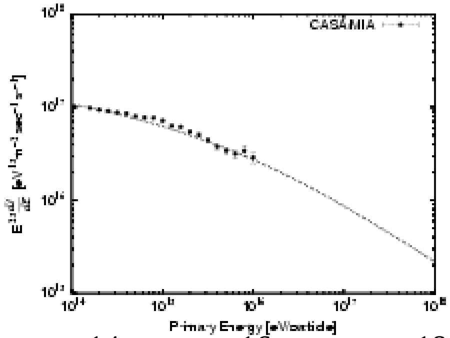
ε_b : break point (7x10^{14} eV for proton)
$\Delta\gamma$: difference of power index before and after the break point
（$\Delta\gamma$ ＝0.4）

(Slide from M.Shibata, Y.N.U.)

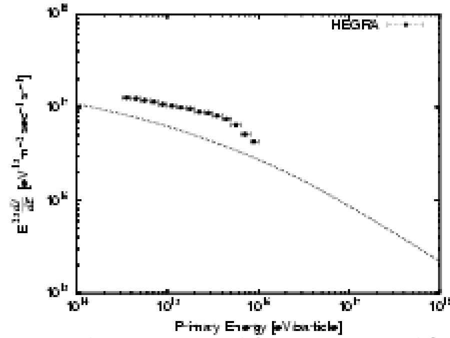
All particle spectrum around the knee

(Slide from M.Shibata, Y.N.U.)

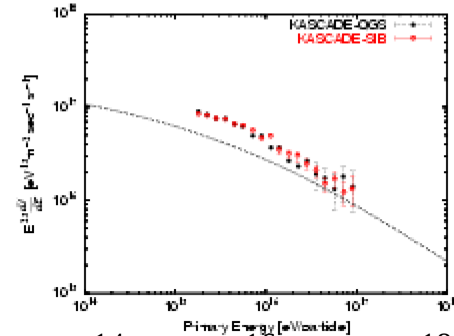
CASA/MIA HEGRA KASCADE



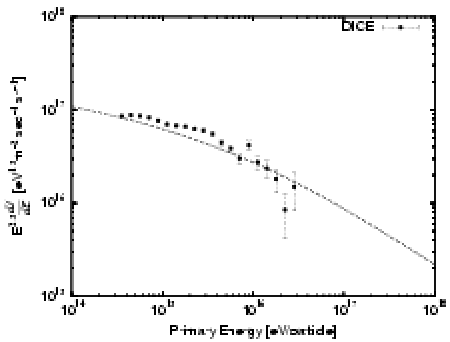
10^{14} 10^{16} 10^{18}



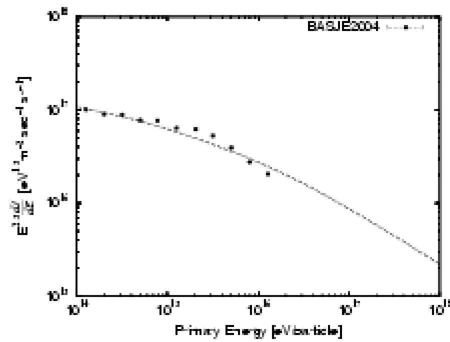
10^{14} 10^{16} 10^{18}



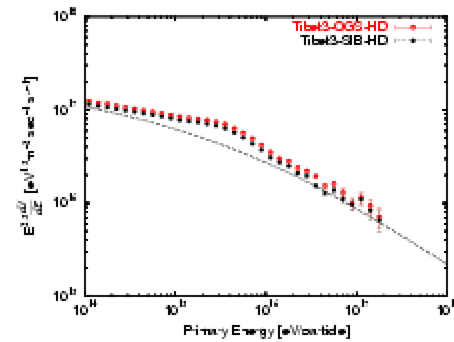
10^{14} 10^{16} 10^{18}



10^{14} 10^{16} 10^{18}



10^{14} 10^{16} 10^{18}

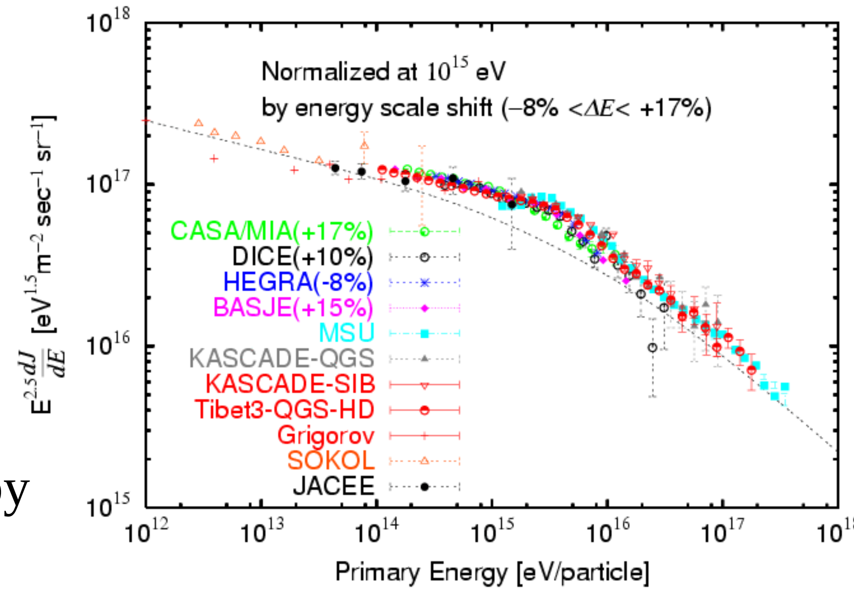


10^{14} 10^{16} 10^{18}

DICE BASJE TIBET

Extra component

All data agree if we apply energy scale correction within 20% by normalizing to direct observations.

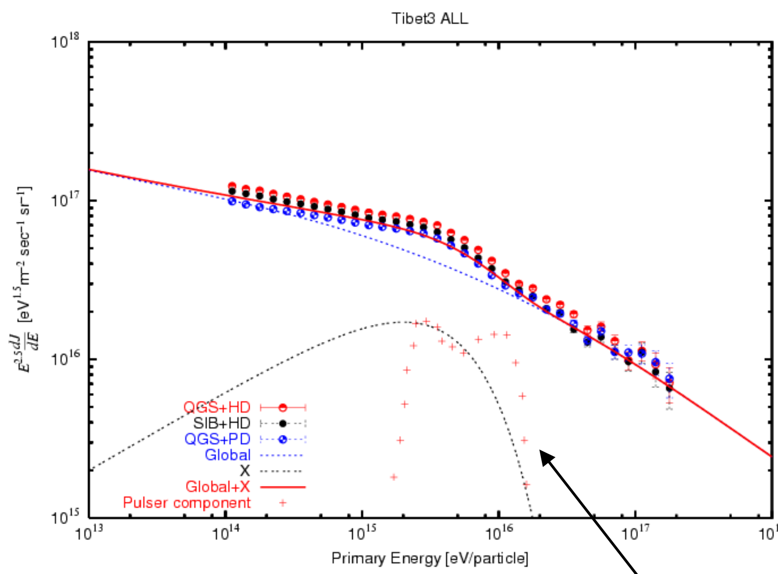


Extra component can be approximated by

$$E^{-2}\exp[-\frac{E}{4\mathrm{PeV}}],$$

suggesting **nearby source(s).**

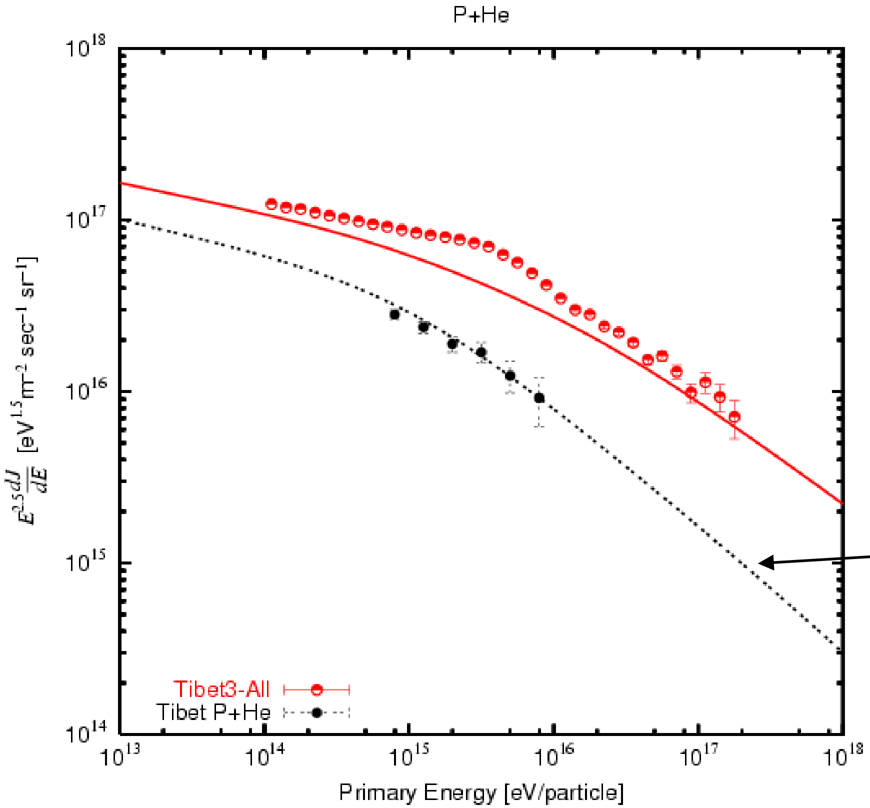
Since P and He component do not show the excess at the knee, the extra component should be attributed to heavy element such as Fe.



(W.Bednarek and R.J.Protheroe ,2002,APh)

(Slide from M.Shibata, Y.N.U.)

Tibet P +He spectrum does not show excess at the knee



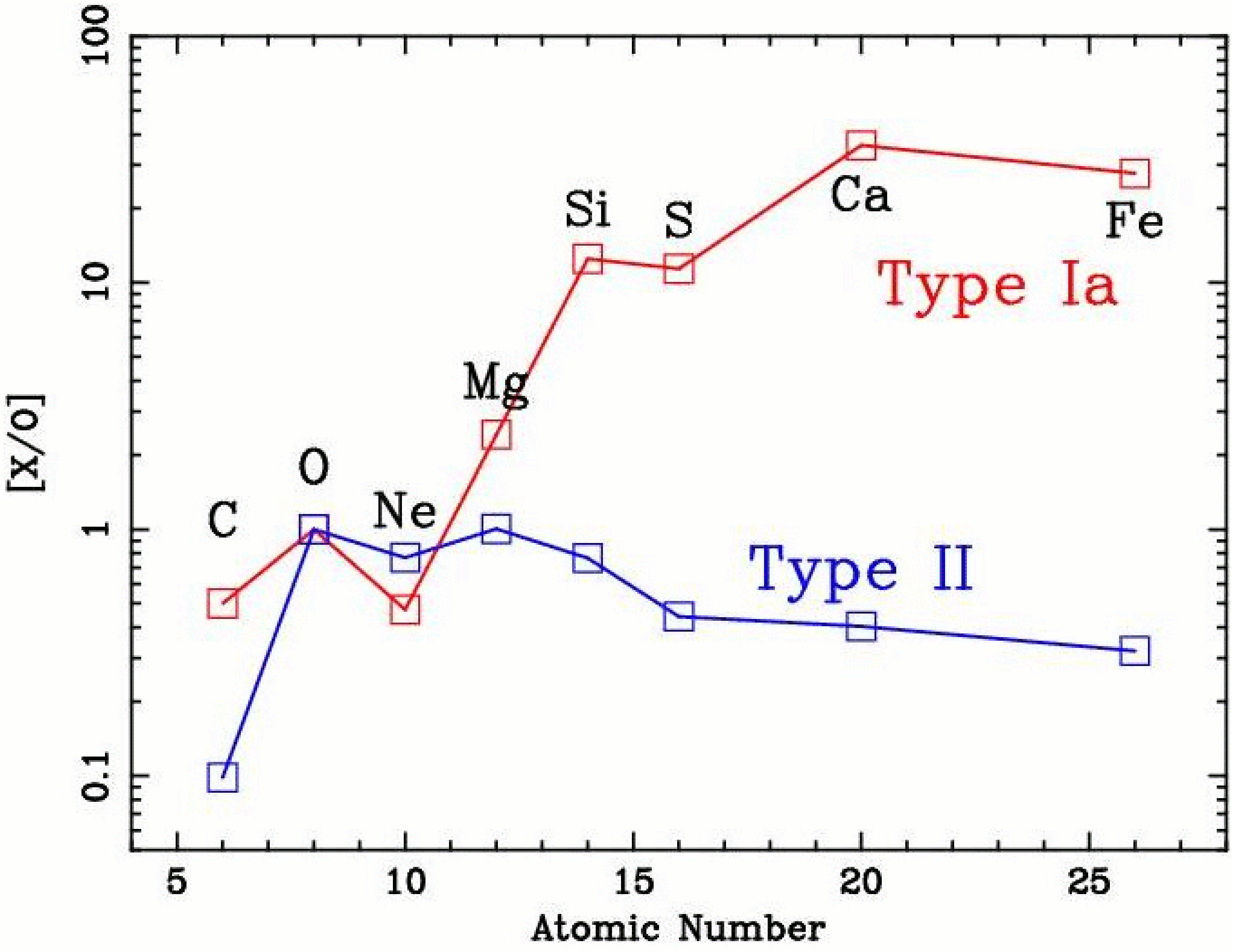
Tibet All particle
Data vs. Expected by multiple source model

P+He
Data vs. Expected by multiple source model

(Slide from M.Shibata, Y.N.U.)

(Slide from M.Shibata Y.N.U.)

Chemical composition of SN ejecta

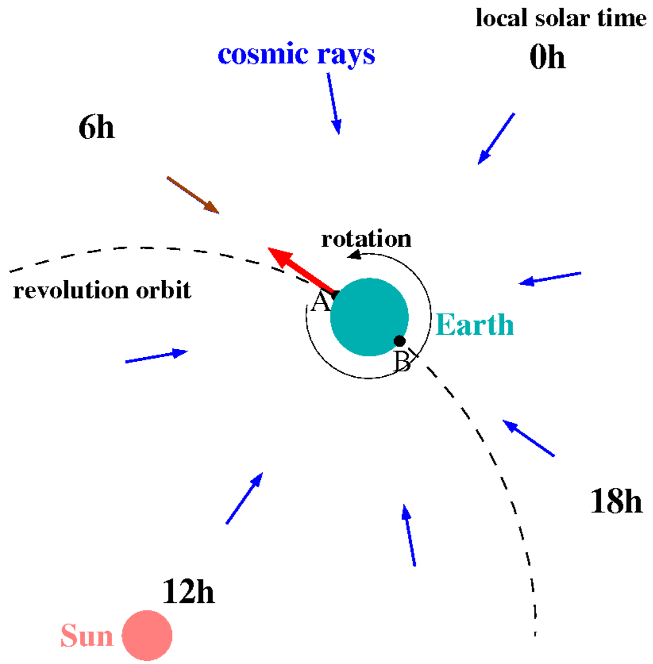


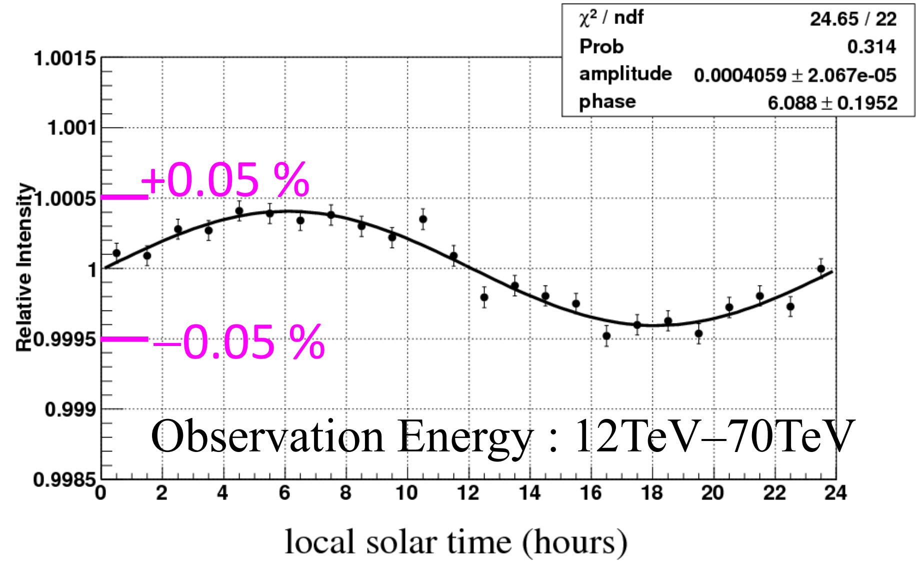
(Nomoto,K et al. Nucl. Phys. A, 621, 467, 1997)

4. Anisotropy

Compton-Getting Anisotropy at Solar Time Frame

Amenomori et al., ApJL, 672 (2008) L53



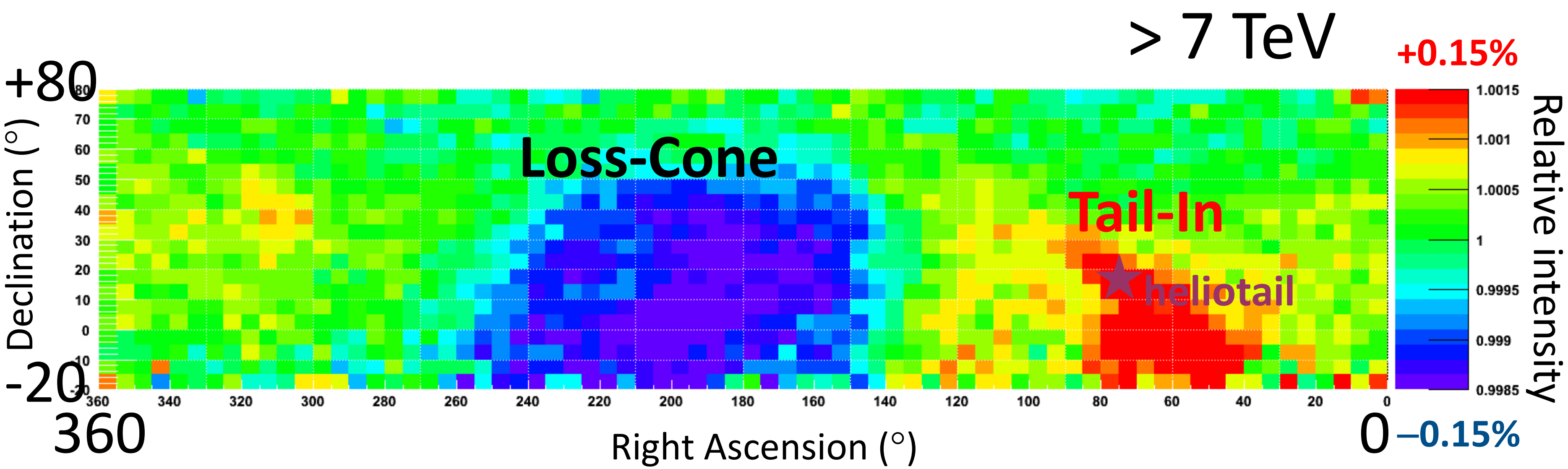


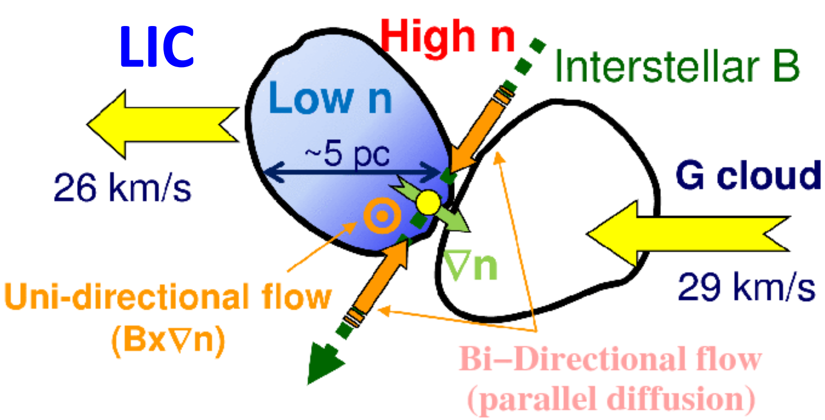
Expected	Amplitude 3.86 x 10^{-2} %	Phase 6 [hr]
Data	Amplitude (4.06 ±0.21) x 10^{-2} %	Phase 6.1±0.2 [hr]

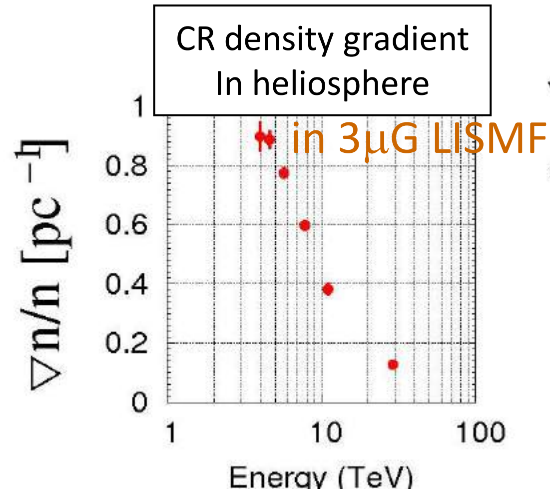
➡ **CG detected at 19.6σ consistent with expected**

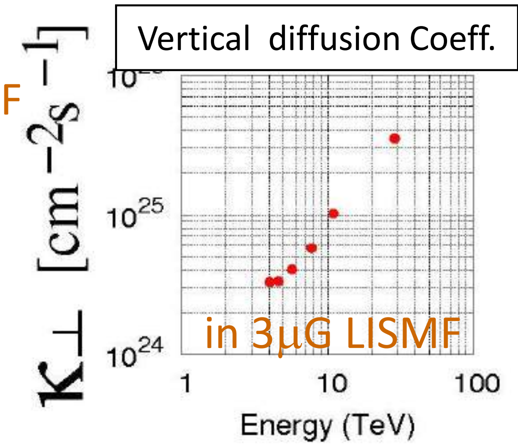
- Reliability and calibration for sidereal anisotropy (~ 0.01%)
- Only Tibet ASγ experiment showing a clear sinusoidal curve

Modeling Sidereal Anisotropy : Origin of anisotropy





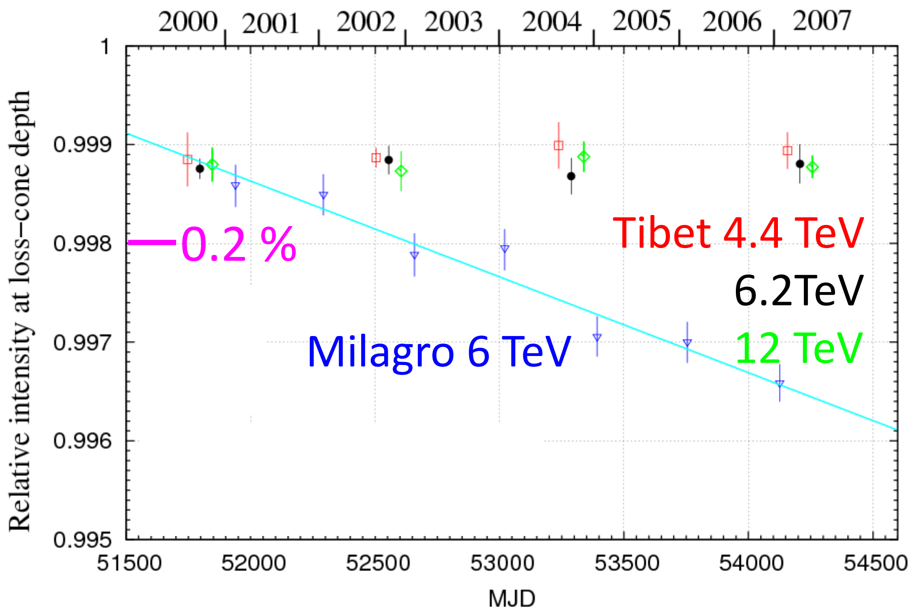


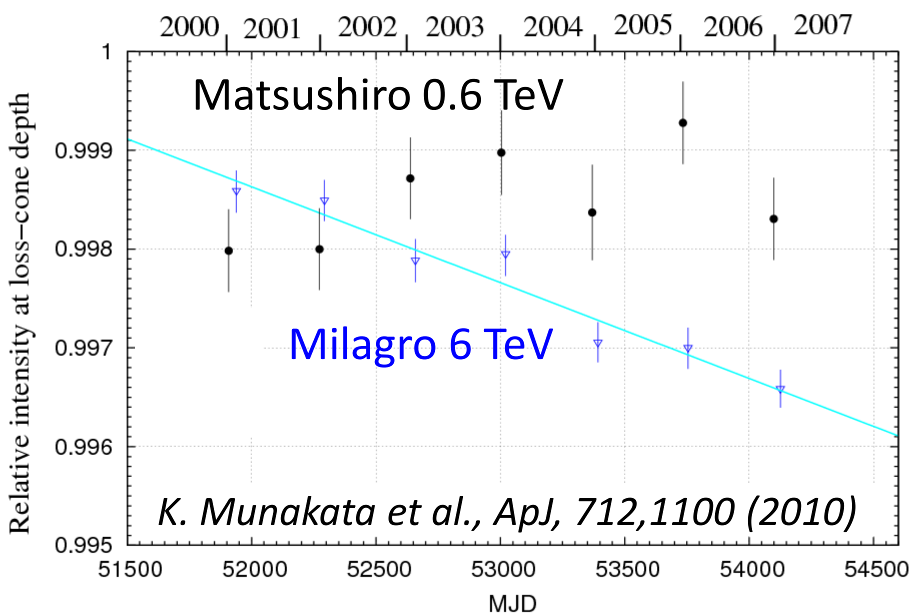


➡ Stimulus to CR transport theory and future space-ship experiment like Voyagers

Sidereal Anisotropy : Yearly Variation of Loss-Cone Amplitude?

Amenomori et al., App, 36 (2012) 237





K. Munakata et al., ApJ, 712,1100 (2010)

Fitting by α (MJD–53000) + β

Milagro 6 TeV

$\alpha = (0.97 \pm 0.11) \times 10^{-4}$ % [/day]

Tibet 4.4 TeV

$\alpha = (0.05 \pm 0.13) \times 10^{-4}$ % [/day]

inconsistent with Milagro (6.1σ)

6.2 TeV

$\alpha = (0.004 \pm 0.099) \times 10^{-4}$ % [/day]

inconsistent with Milagro (6.6σ)

11 TeV

$\alpha = (-0.002 \pm 0.095) \times 10^{-4}$ % [/day]

inconsistent with Milagro (6.7σ)

Matsushiro 0.6 TeV

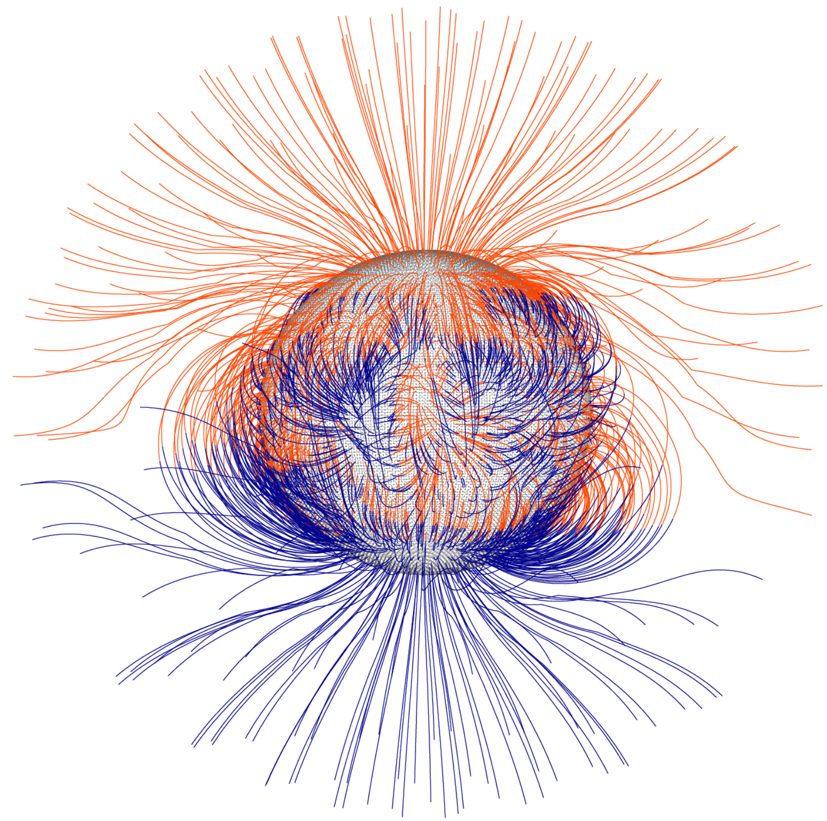
p0 = $(0.32 \pm 0.22) \times 10^{-4}$ % [/day]

inconsistent with Milagro (5.3σ)

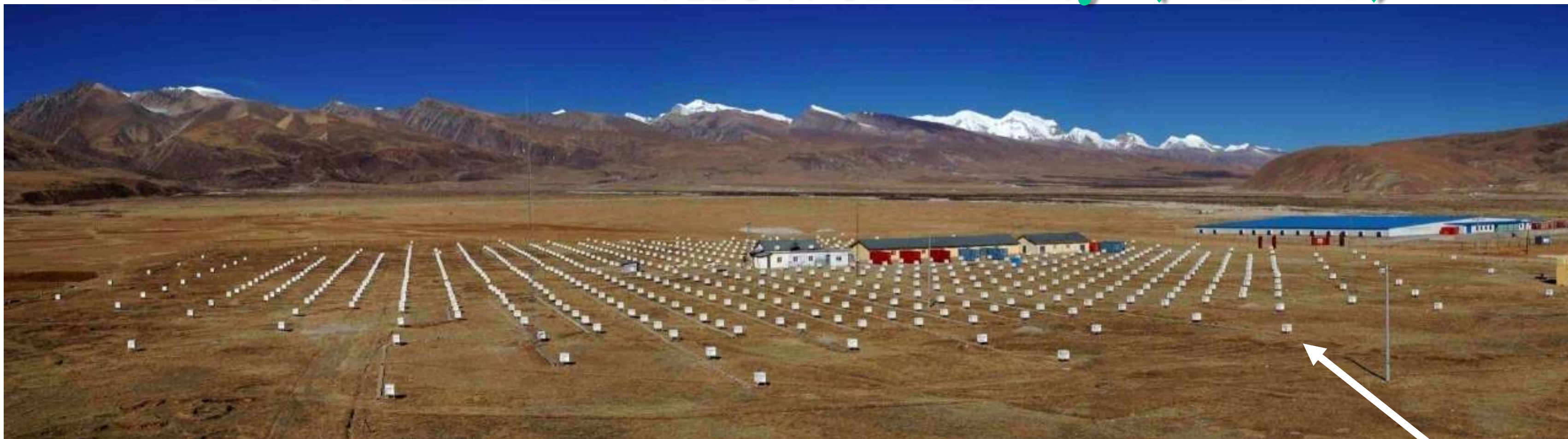
Milagro's yearly variation of Loss-Cone amplitude ruled out at multi-TeV & sub-TeV

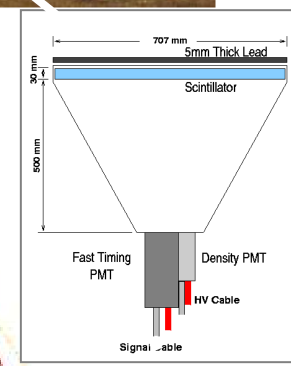
5. The Sun's Shadow

Probe of the Solar Magnetic Field with the “Cosmic-Ray Shadow” of the Sun



Tibet-III Air Shower Array (>1999)



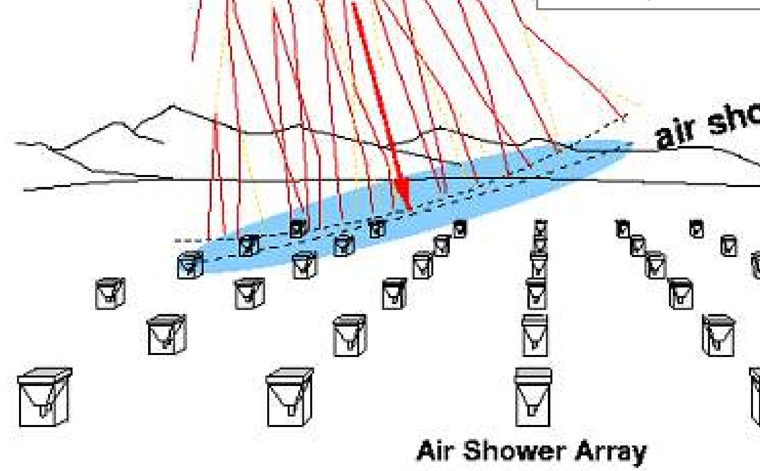


- Tibet (90.522°E, 30.102°N) 4300m a.s.l.

- No. of detectors 0.5 m^2 x 789 (7.5m spacing)

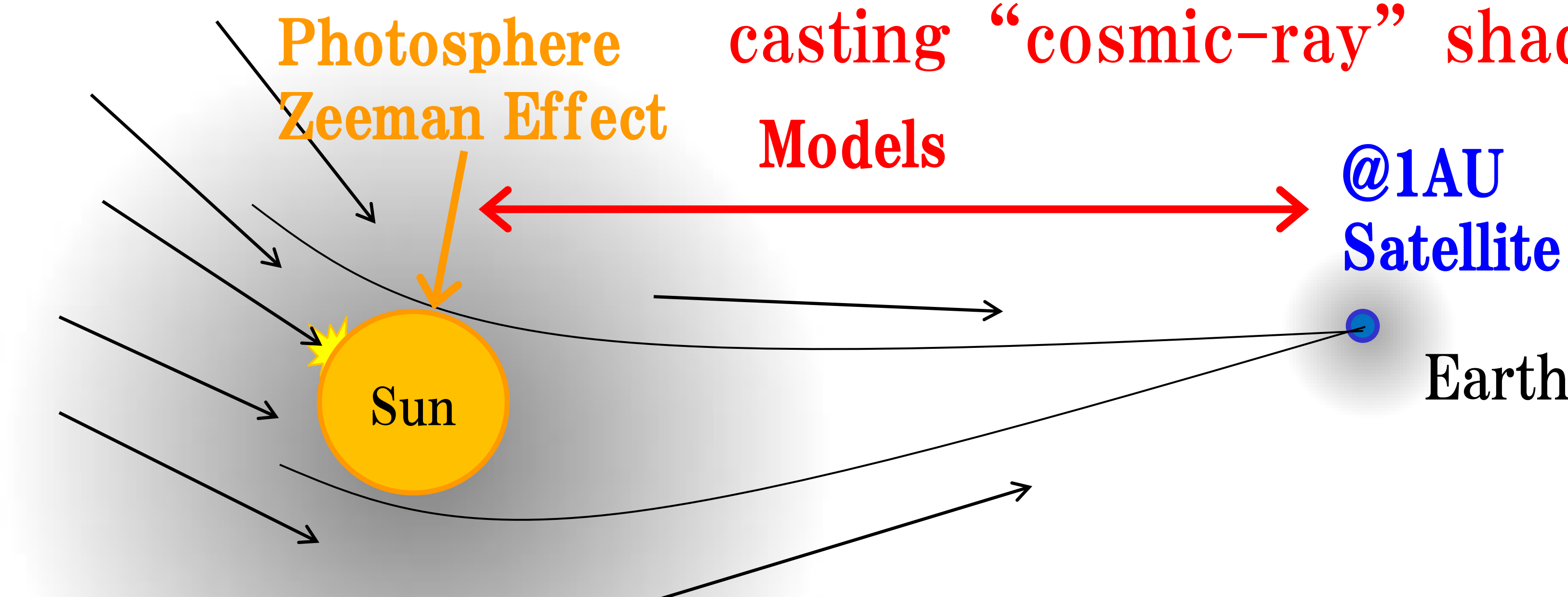
→To keep the AS data consistency from 1996, we use the Tibet-II array configuration (221 detectors, 15m spacing)

- Modal Energy 10 TeV
- Angular Resolution 0.9°



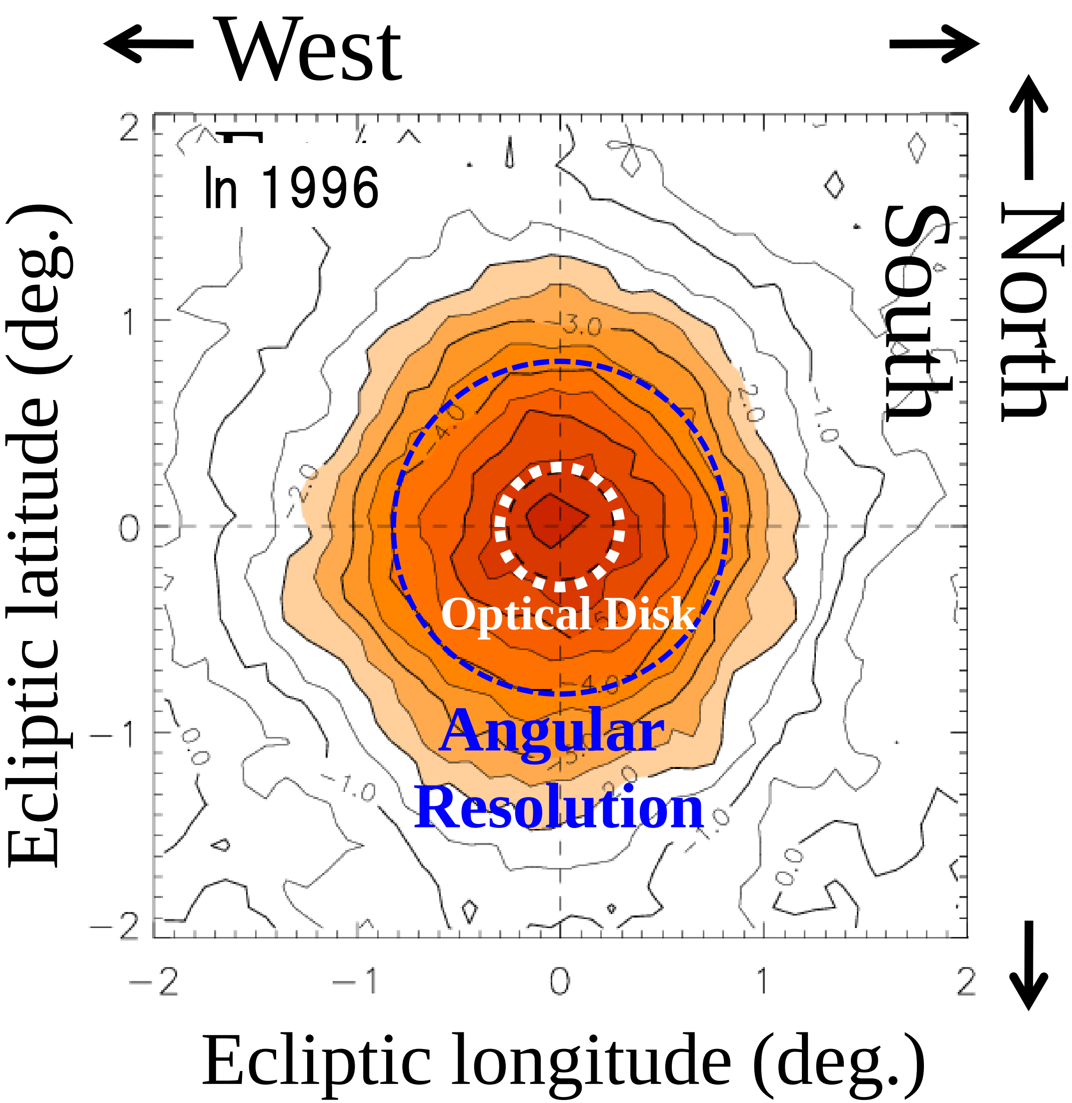
Sun's Shadow

Sun blocks HE cosmic rays,
casting "cosmic-ray" shadow



TeV Charged Paritcles
Larmor Radius
$\sim$7.4AU (B=30μG near Earth)
$\sim 0.16R_\odot$(B=300mG near Sun)
Probe of solar magnetic fields!

Analysis of the Sun's Shadow

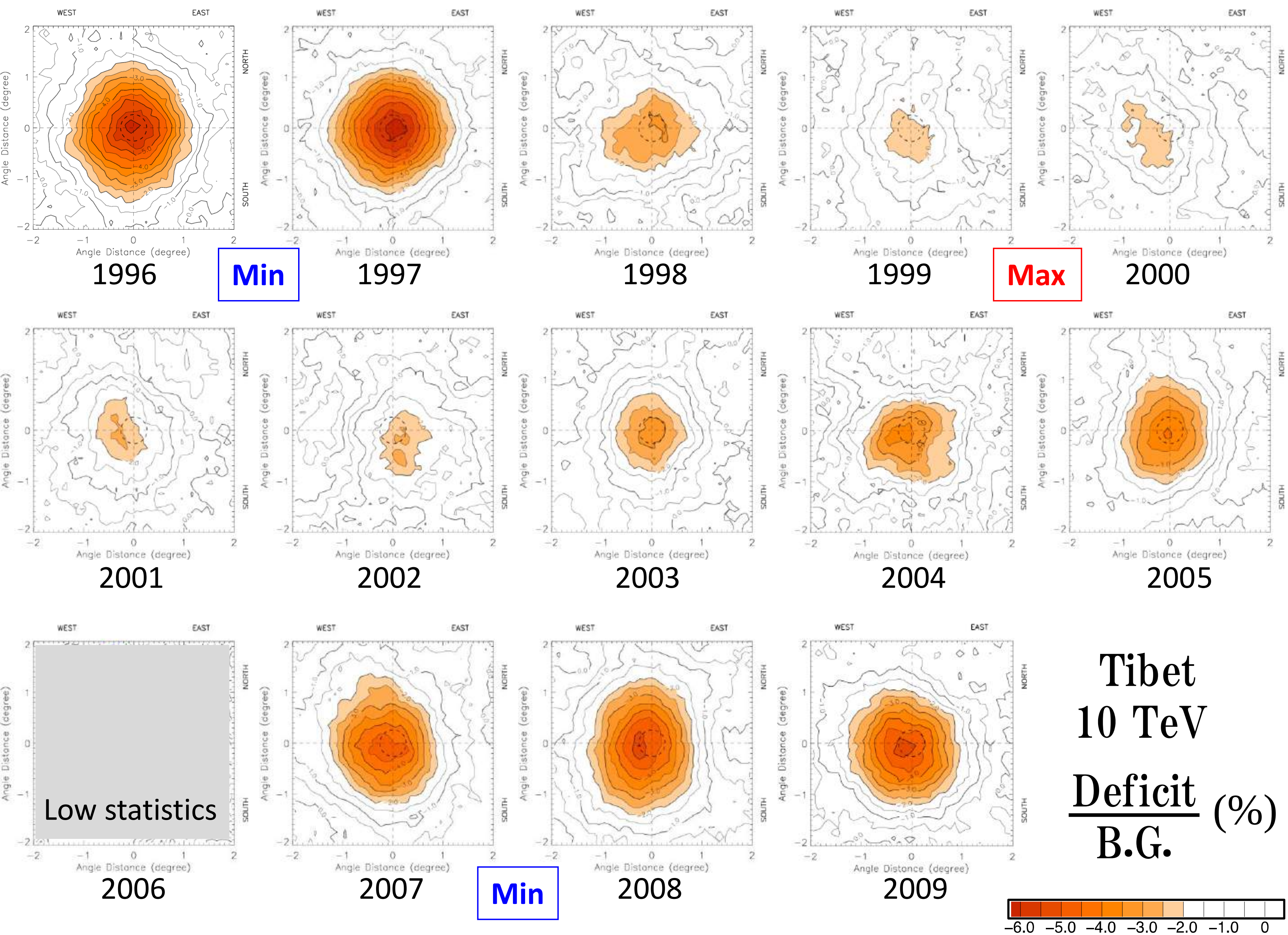


4^ox4^o Cosmic ray density Map centered at the Sun (Ecliptic coordinate)

Deficit ratio to CR flux
Maximum −6% to CR flux

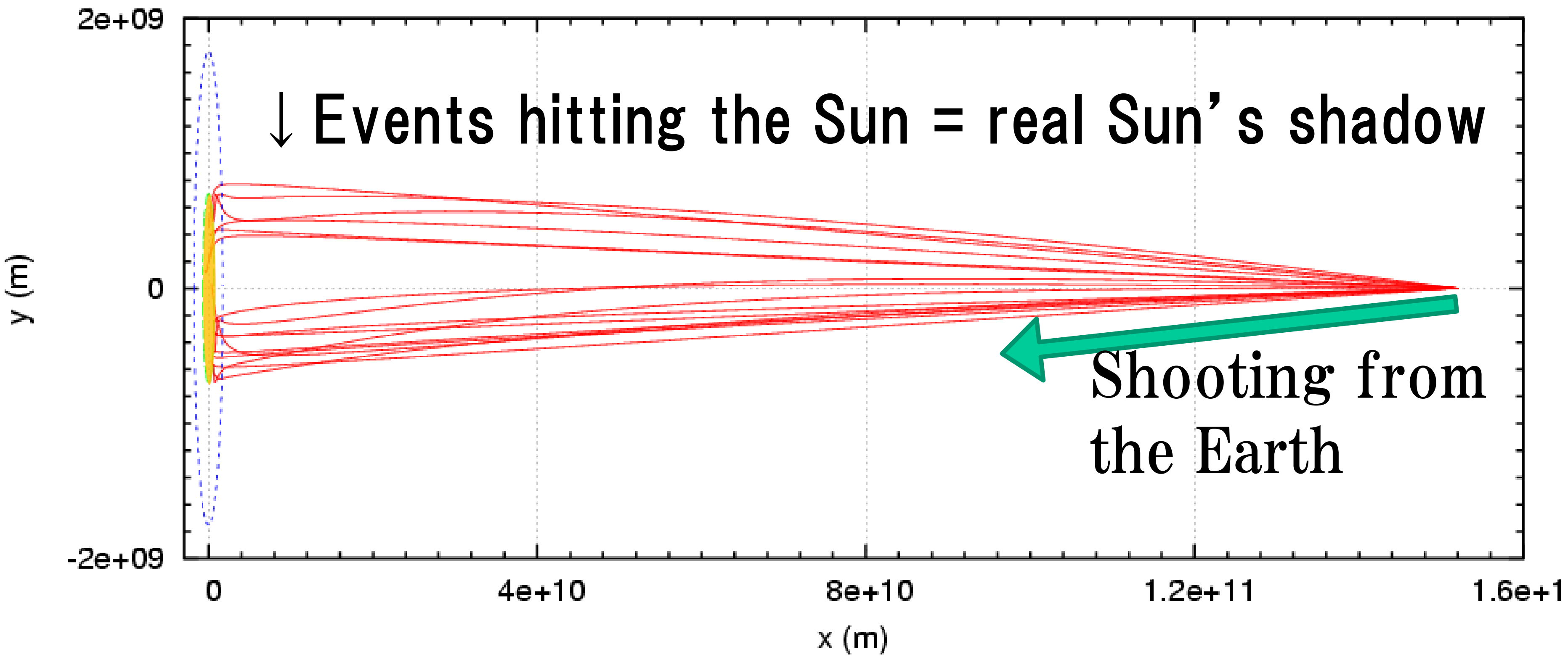
Angular resolution(0.9^o)
Optical disk size(0.26^o)

In this map, we analyze deficits and positions depending on properties of the solar magnetic field


1996
Min
1997
1998
1999
Max
2000
2001
2002
2003
2004
2005
2006
Low statistics
2007
Min
2008
2009
Tibet
10 TeV
Deficit / B.G. (%)
−6.0 −5.0 −4.0 −3.0 −2.0 −1.0 0
WEST
EAST
NORTH
SOUTH
Angle Distance (degree)

MC Simulation

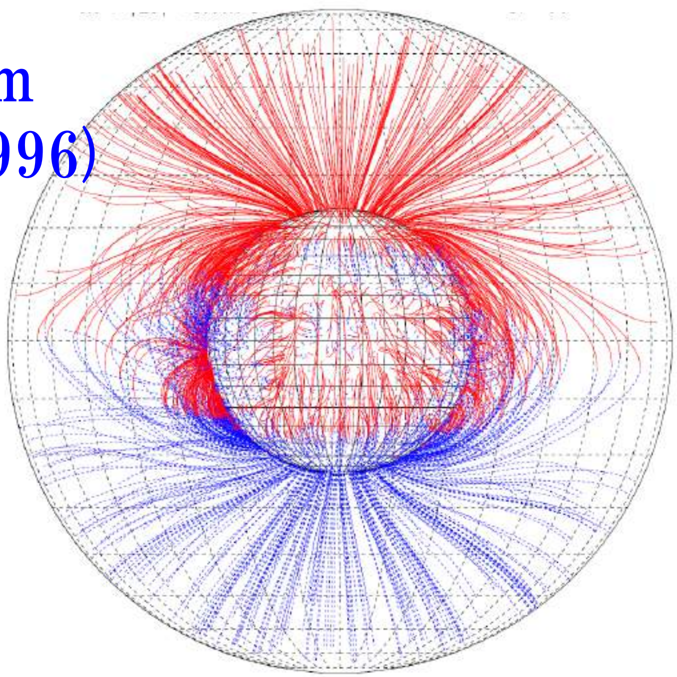
Antiparticles are traced back to the Sun from the Earth assuming the detailed magnetic fields

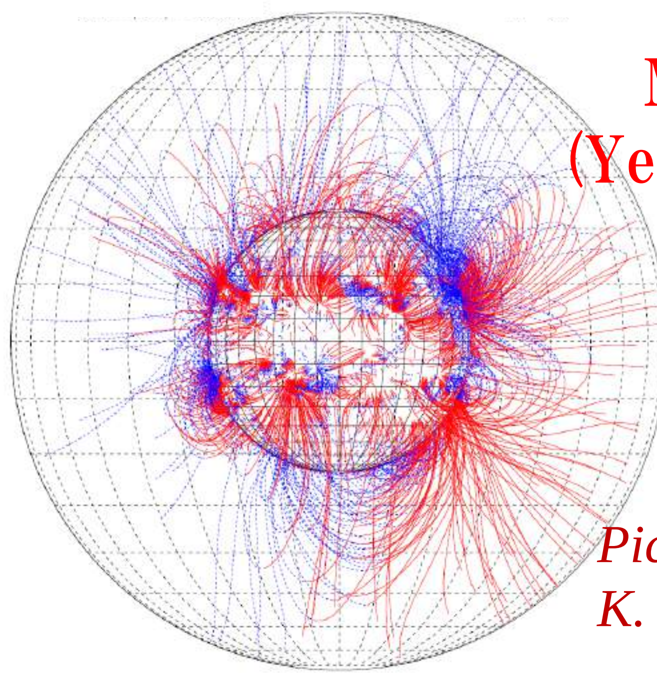


Magnetic fields

Coronal -> Source Surface models (PFSS / CSSS)
derived from photospheric MF observation
for each Sun rotation (~27 days)
IMF -> Parker Spiral Model
including latitudinal dependence of solar wind
Geomag. -> Dipole model

Minimum
(year 1996)
PFSS





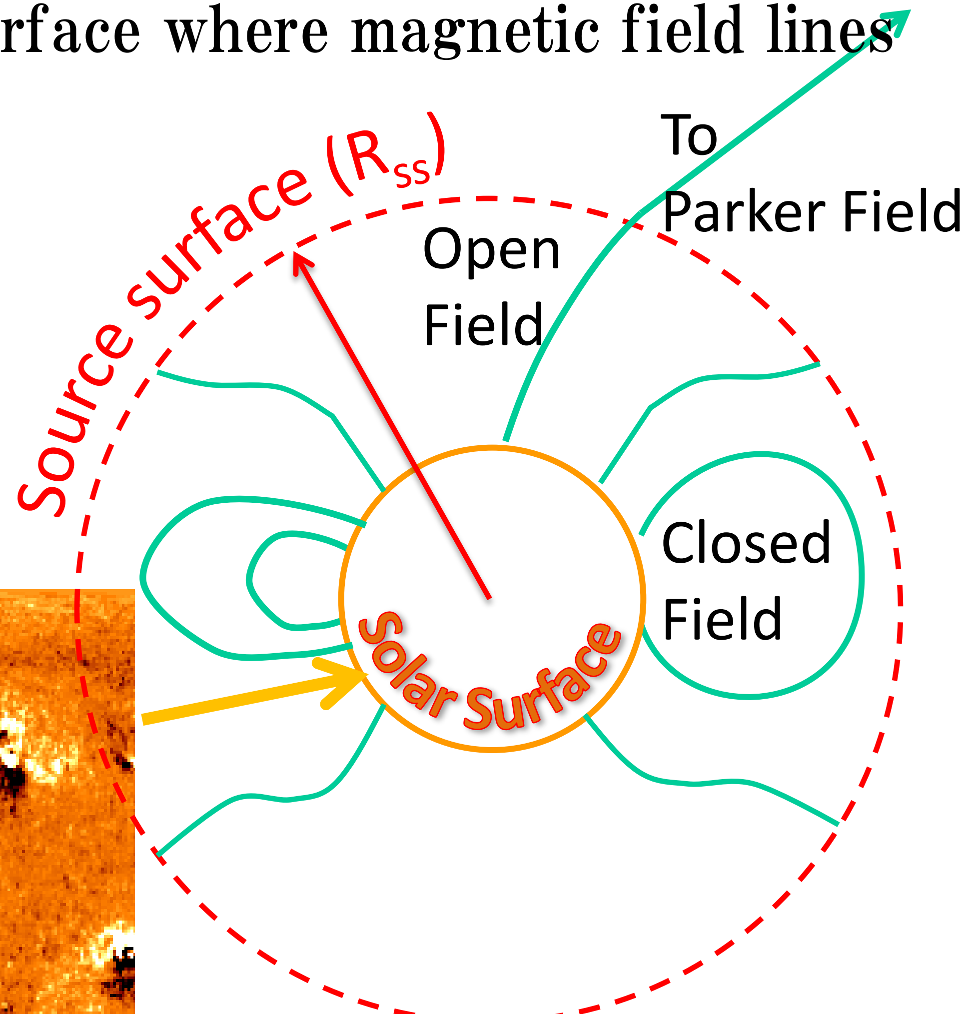
Maxmum
(Year 2000)
PFSS

Pictures from
K. Hakamada

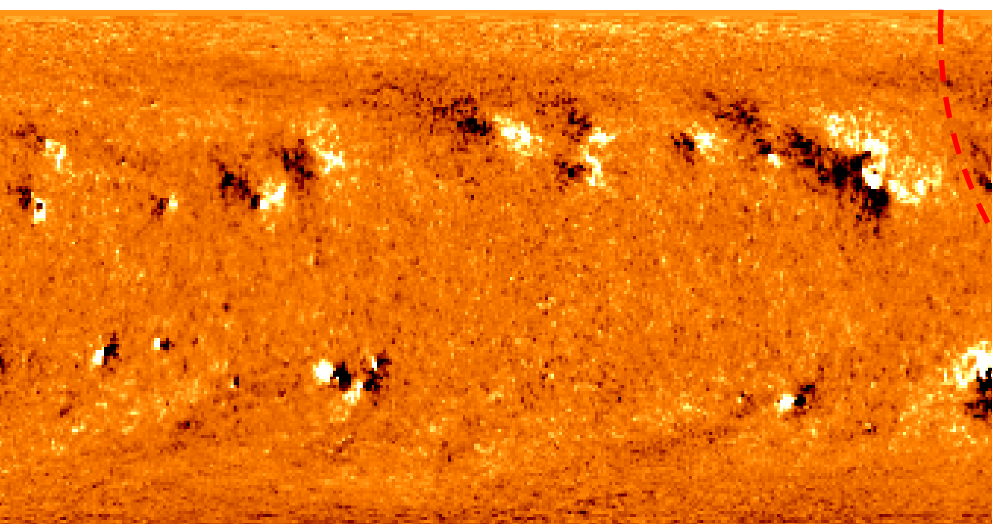
Source Surface Model

B is calculated from observed photospheric magnetic fields based on the Maxwell equation. The source surface is defined as a boundary spherical surface where magnetic field lines become purely radial.

Standard R_{ss}=～$2.5R_{\odot}$



Magnetograph (Zeeman Effect)
The Kitt Peak Vacuum Telescope
(FeI 868.8, 630.1 and 630.2nm)



Source Surface Models

1. PFSS (Potential Field Source Surface) [widely used]

assumes electric currents are negligible in the corona

$$\nabla \times \mathbf{B} = 0 \rightarrow \mathbf{B} = -\nabla\Psi$$

$$\nabla \cdot \mathbf{B} = 0$$

Laplace Equation

$$\nabla^2 Y = 0$$

Hakamada, Solar Physics (1995)

2. CSSS (Current Sheet Source Surface)

includes large-scale horizontal currents

$$\frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla \mathbf{p} - \rho \frac{GM}{r^2}\hat{\mathbf{r}} = 0$$

Magnetostatic force balance equation

$$\mathbf{J} = \frac{1}{\mu_0 r}[1-\eta(r)]\left[\frac{1}{\sin\theta}\frac{\partial^2\Psi}{\partial\phi\partial r}\hat{\theta} - \frac{\partial^2\Psi}{\partial\phi\partial r}\hat{\phi}\right]$$

$$\mathbf{B} = -\eta(r)\frac{\partial\Psi}{\partial r}\hat{r} - \frac{1}{r}\frac{\partial\Psi}{\partial\theta}\hat{\theta} - \frac{1}{r\sin\theta}\frac{\partial\Psi}{\partial\phi}\hat{\phi}$$

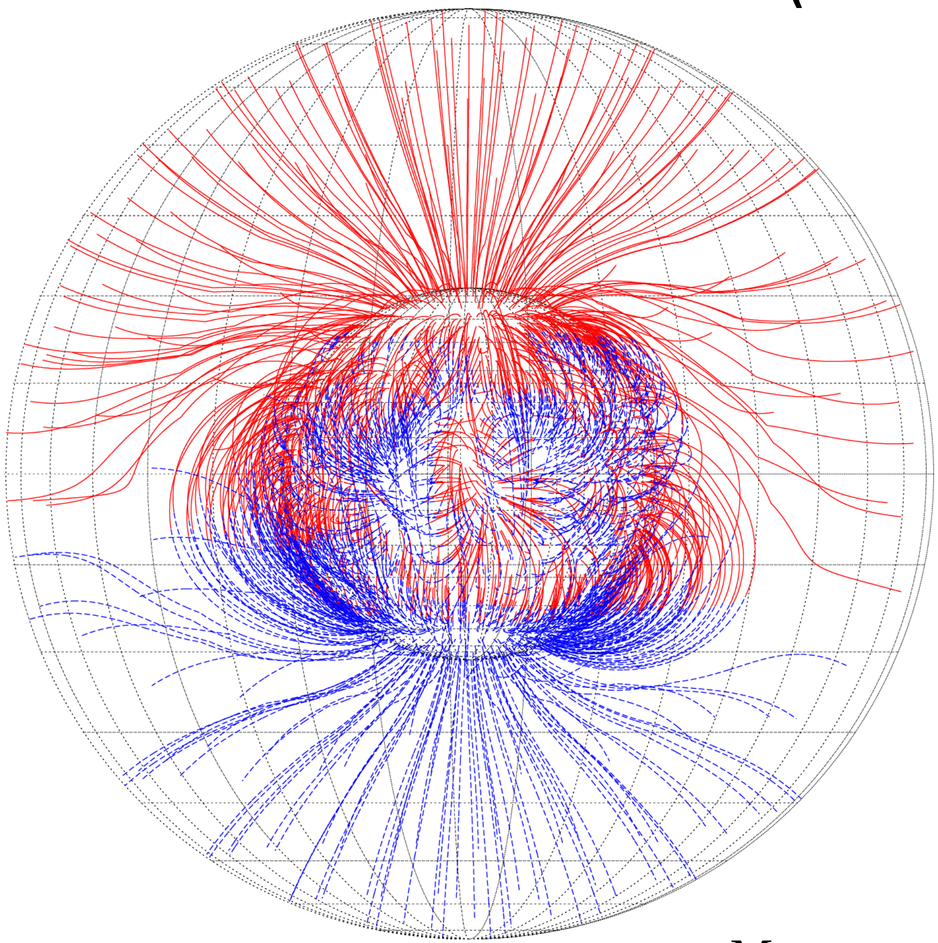
Zhao & Hoeksema, JGR (1995)

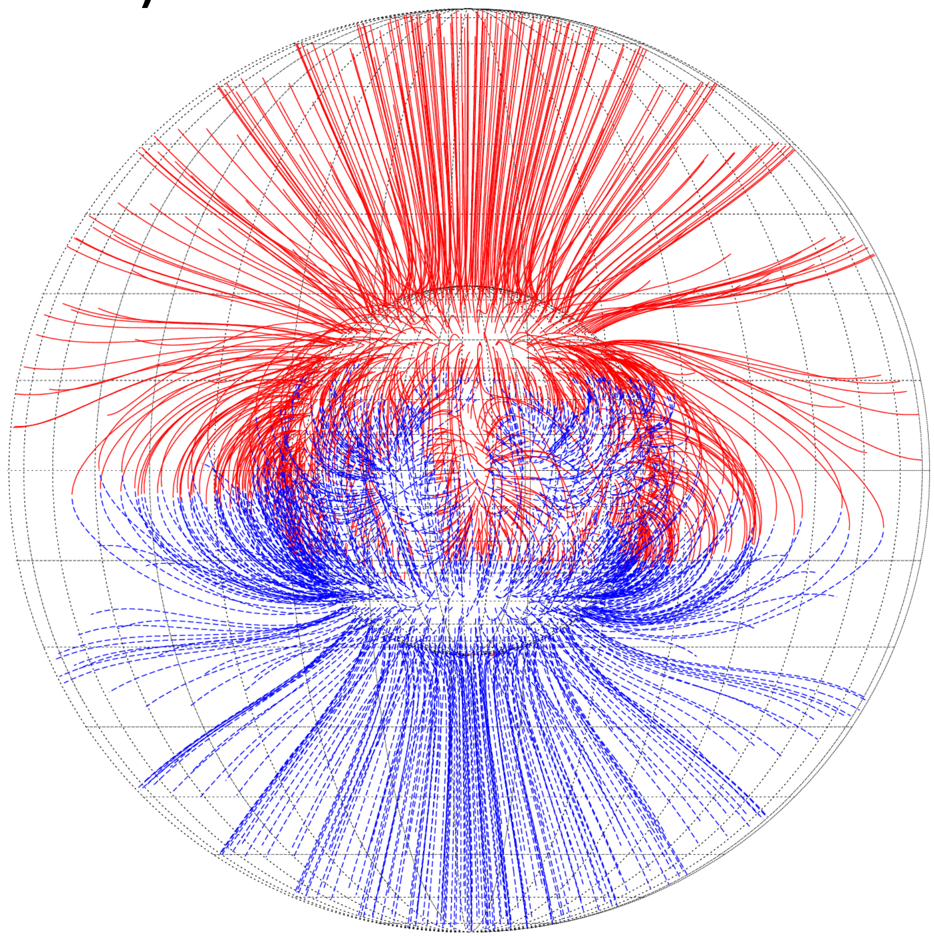
Coronal Field Models

CSSS

CR1910
(Year1996)

PFSS

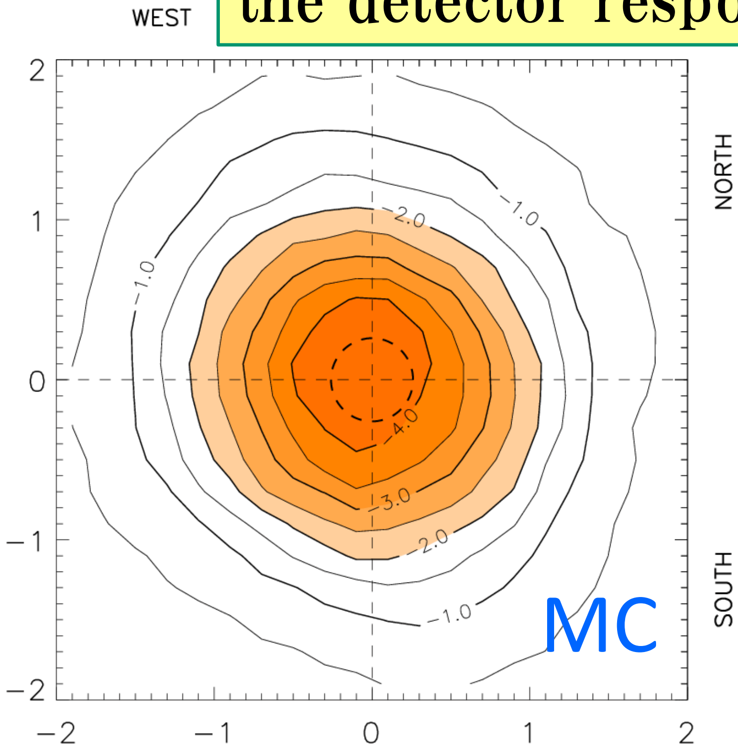




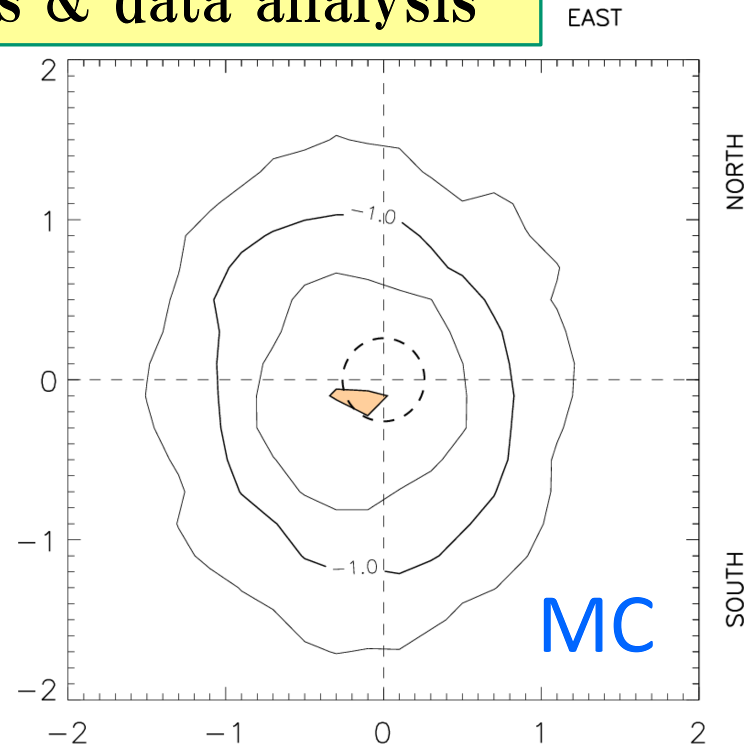
Magnetgraph: Kitt Peak
Harmonic order   N=10

Examples of MC Result (PFSS)

Density map of events hitting the Sun
MC takes into account of
Cosmic-ray compositions & spectra
the detector responses & data analysis

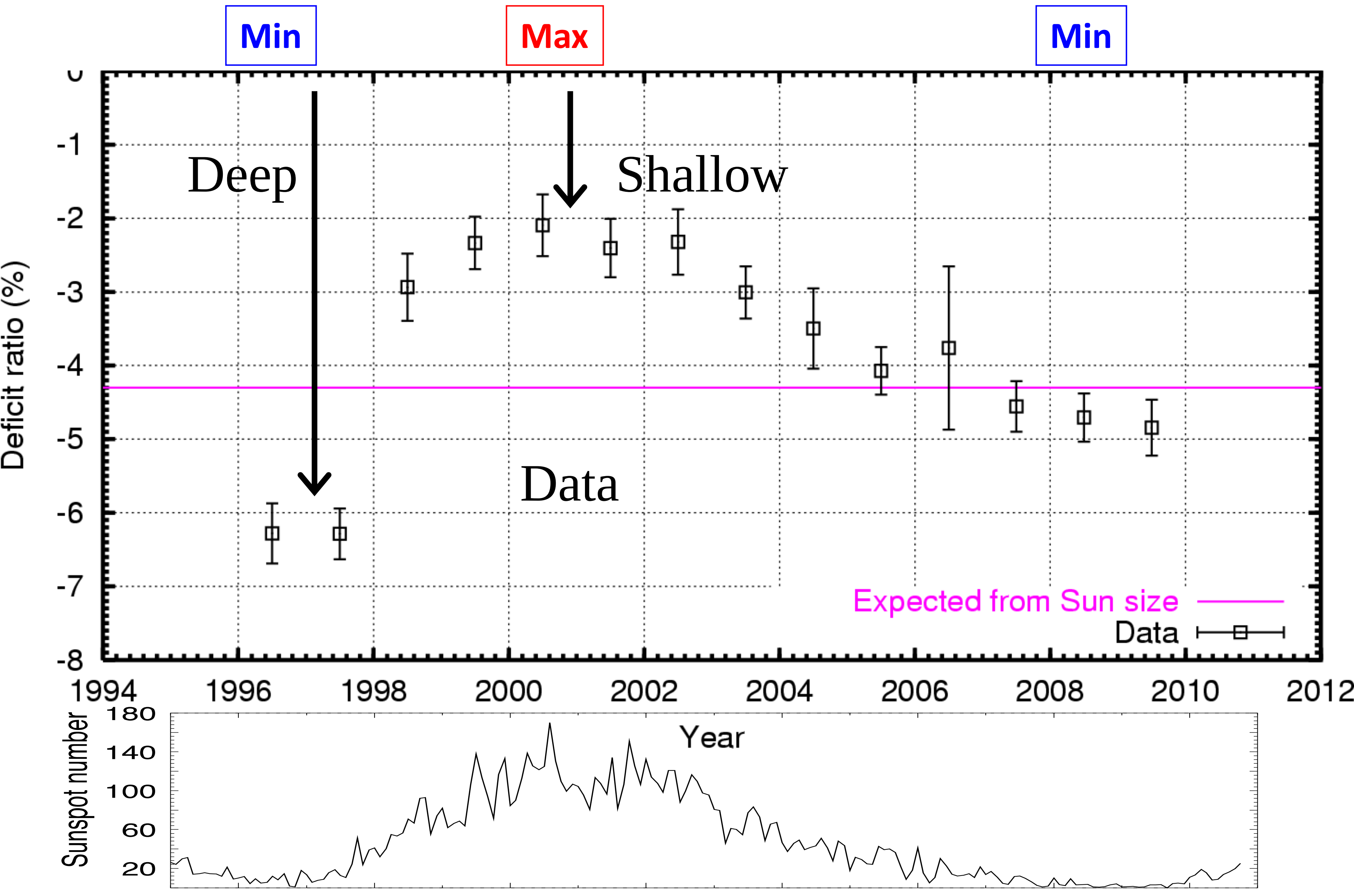


Minimum
in 1996 (CR1910)

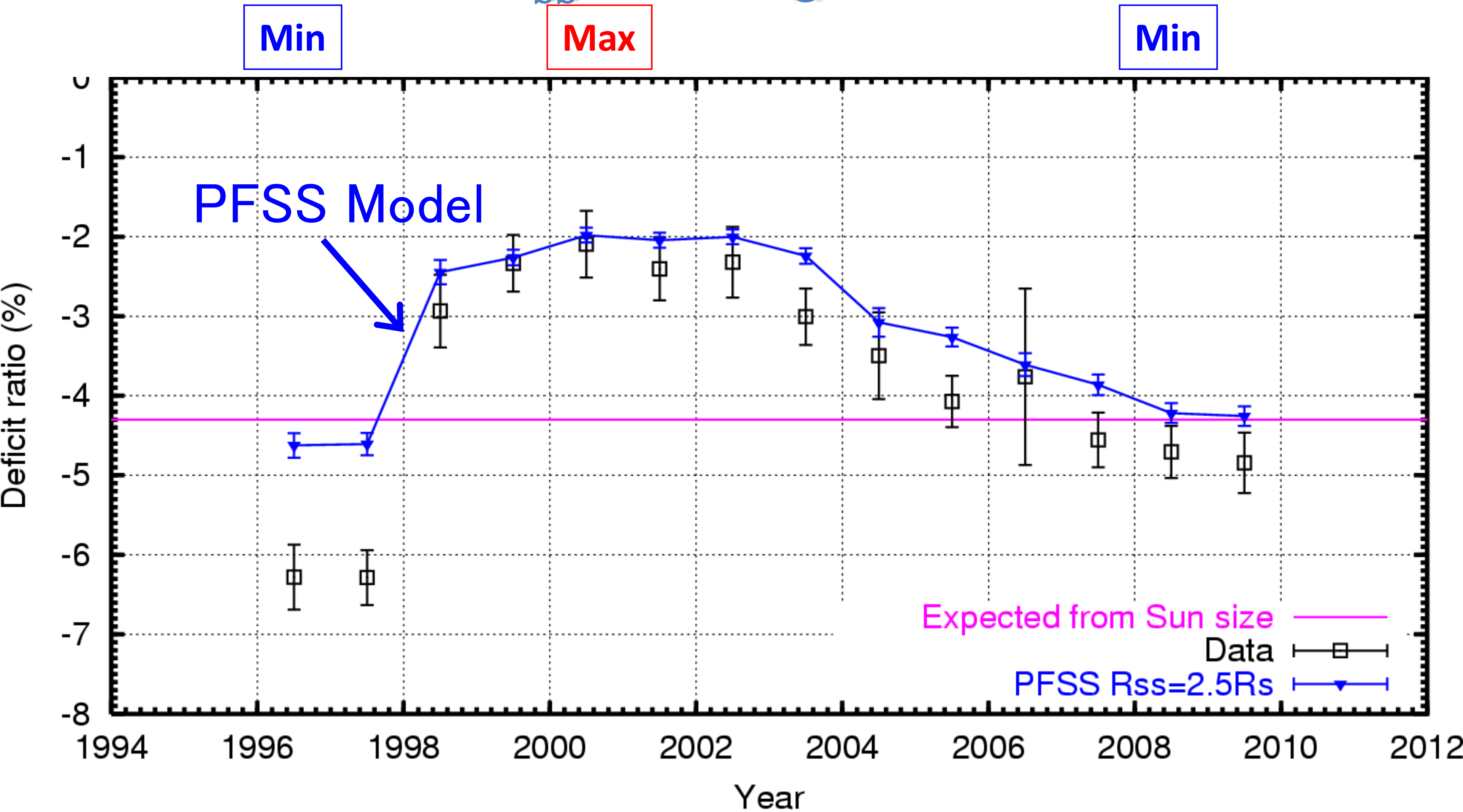


Maximum
In 2001 (CR1978)

Observational Data (10TeV)



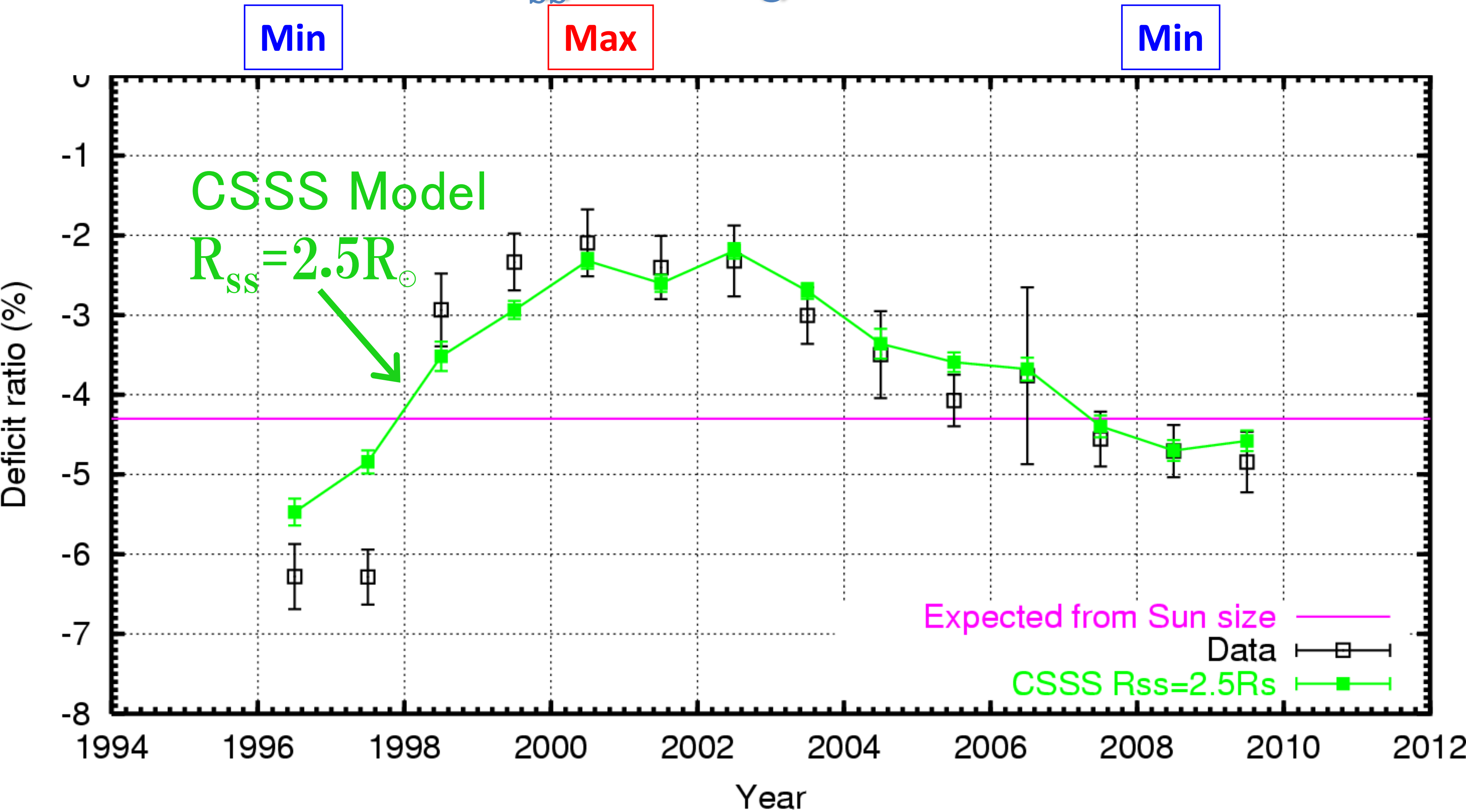
PFSS Model $R_{ss}= 2.5R_{\odot}$ (10TeV)



Data - MC $\chi^2/\mathrm{dof} = 55.2/14$ (7.9×10^{-7})

Tendency Ok

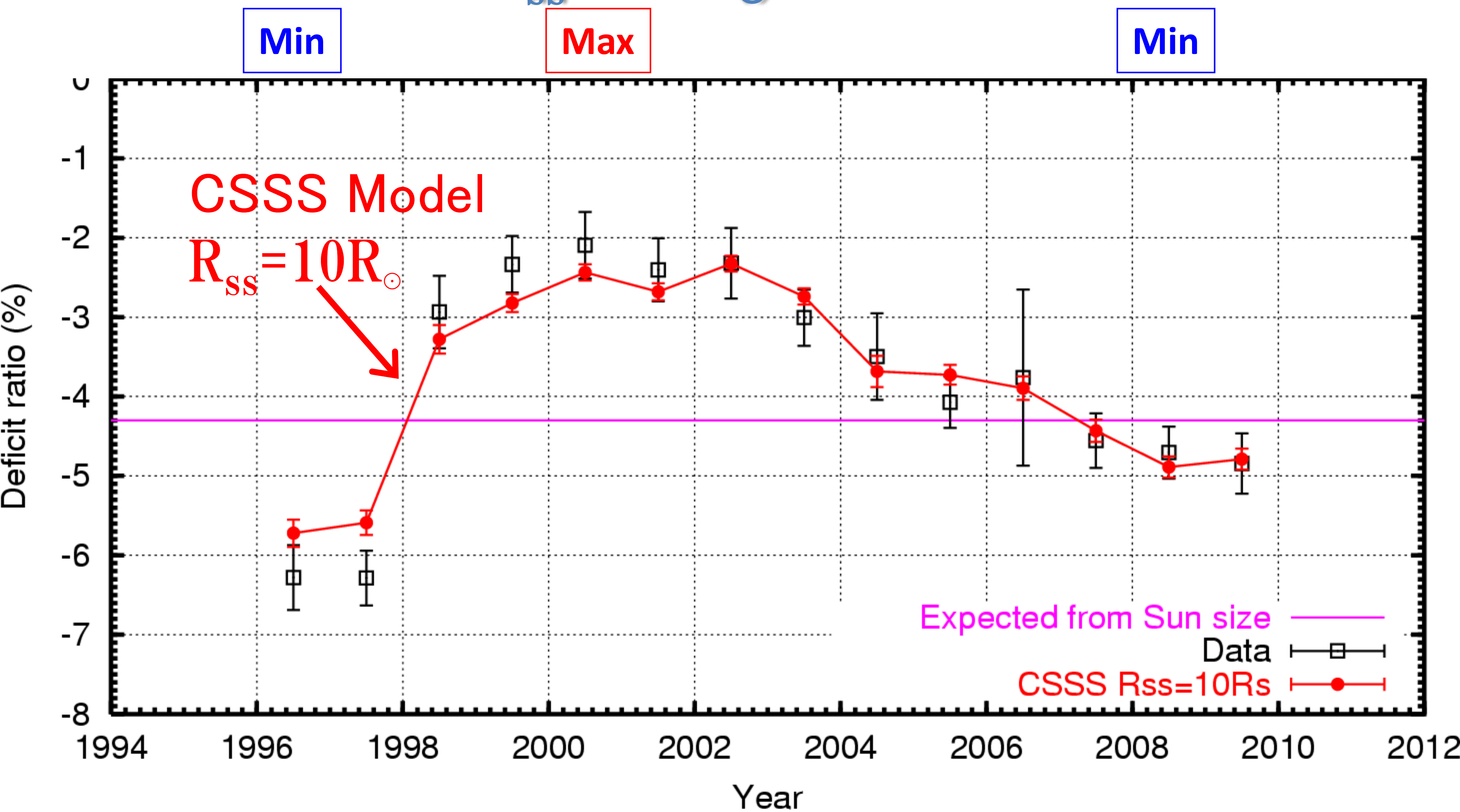
CSSS Model R_{ss}= 2.5$R_\odot$ Result (10TeV)



Data - MC χ^2/dof = 26.2/14 (0.024)

Consistent

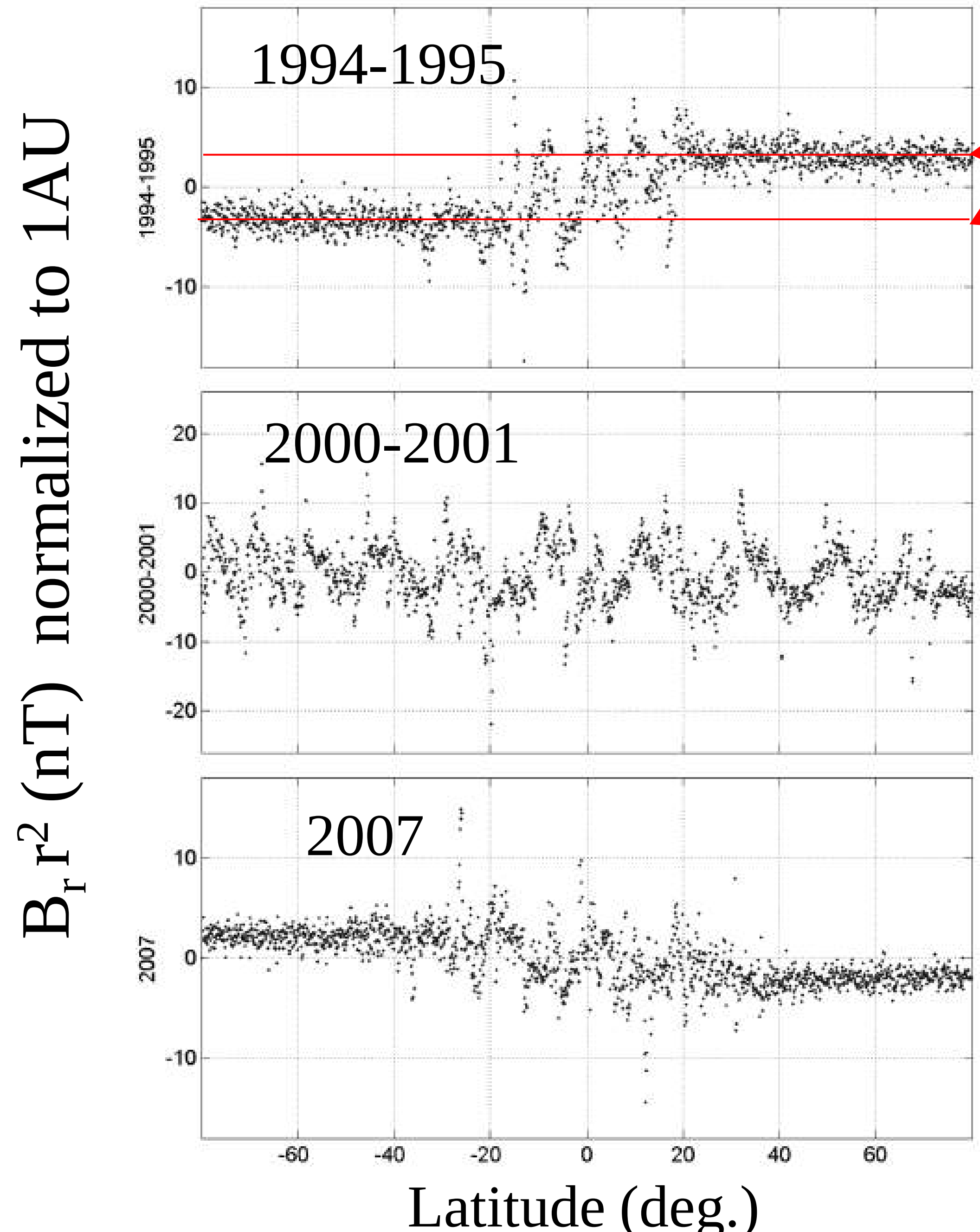
CSSS Model R_{ss}= 10$R_\odot$ Result (10TeV)



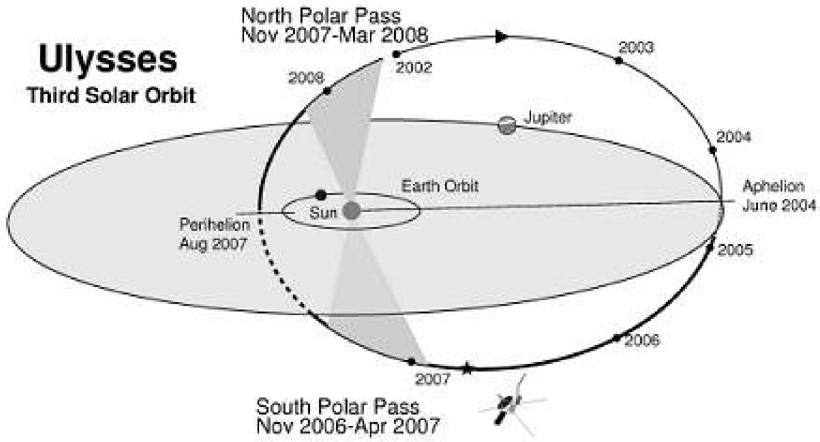
Data - MC χ^2/dof = 10.3/14 (0.74)

MC well reproduces data

Ulysses Observation



"Split monopole" Structure



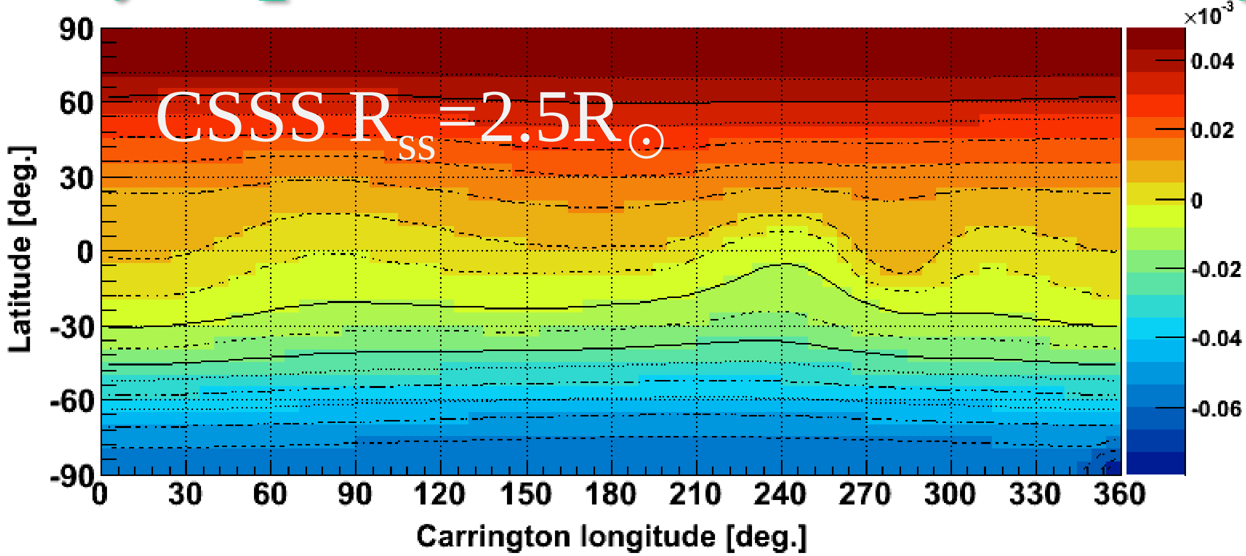
Ulysses data

Perihelion 1.3AU

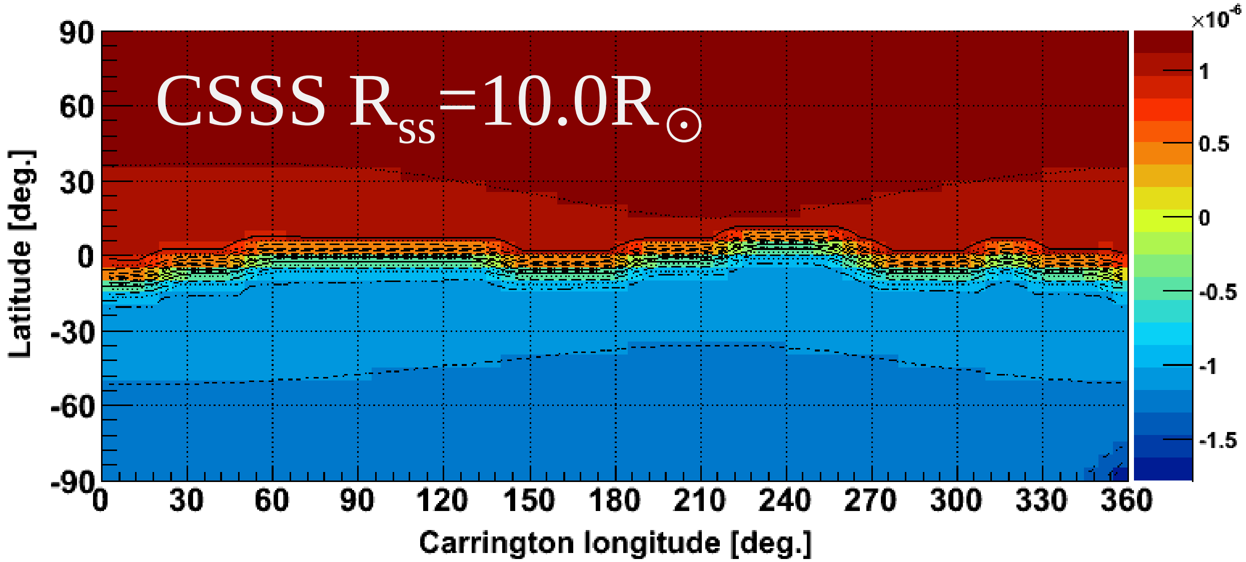
Aphelion 5.4AU

Virtanen and Mursula, JGR, 115, A09110 (2010)

Synoptic Chart in CR1910 by the CSSS



Changing gradually



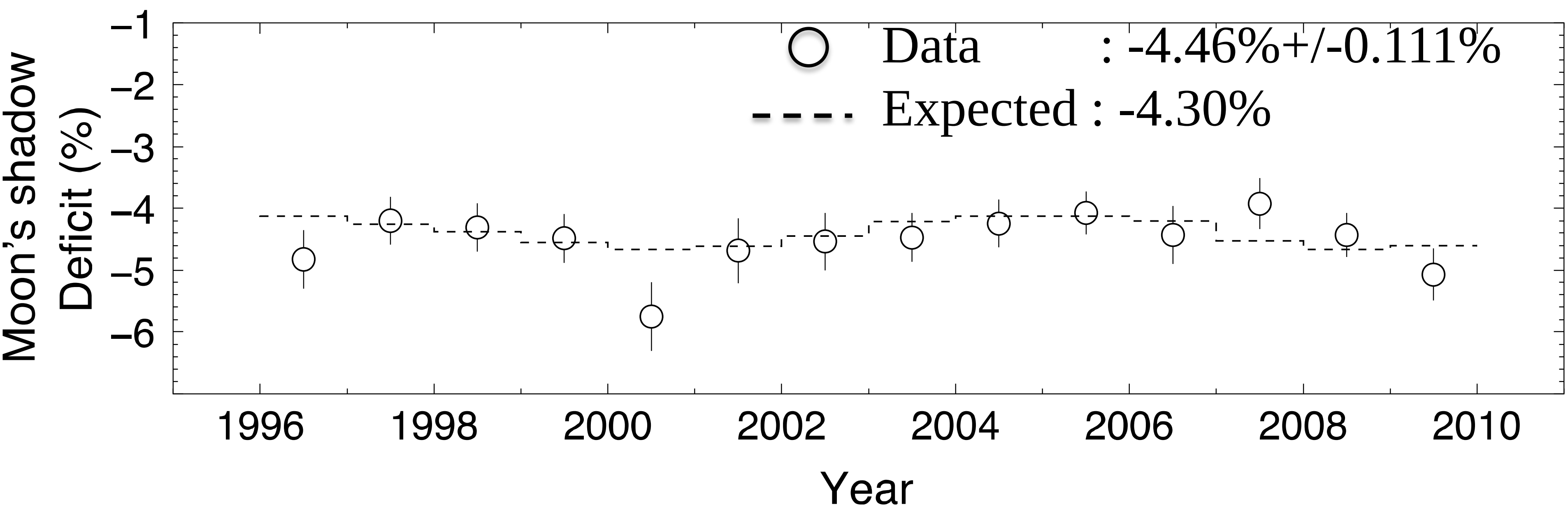
Step at the equator

Reproduce Ulysses obs.

Systematic Error

From Deficit Intensity Variation of the Moon's Shadow

Variation is consistent with flat.
Average deficits is consistent with the expected −4.3%.



Quadratic sum:

$$s_{sys} = \sqrt{(D_{data} - D_{expected})^2 + s_{data}^2} = \sqrt{(4.46 - 4.30)^2 + (0.111)^2} = \boxed{0.19\%}$$

Summary of χ^2 Test (Data-MC)

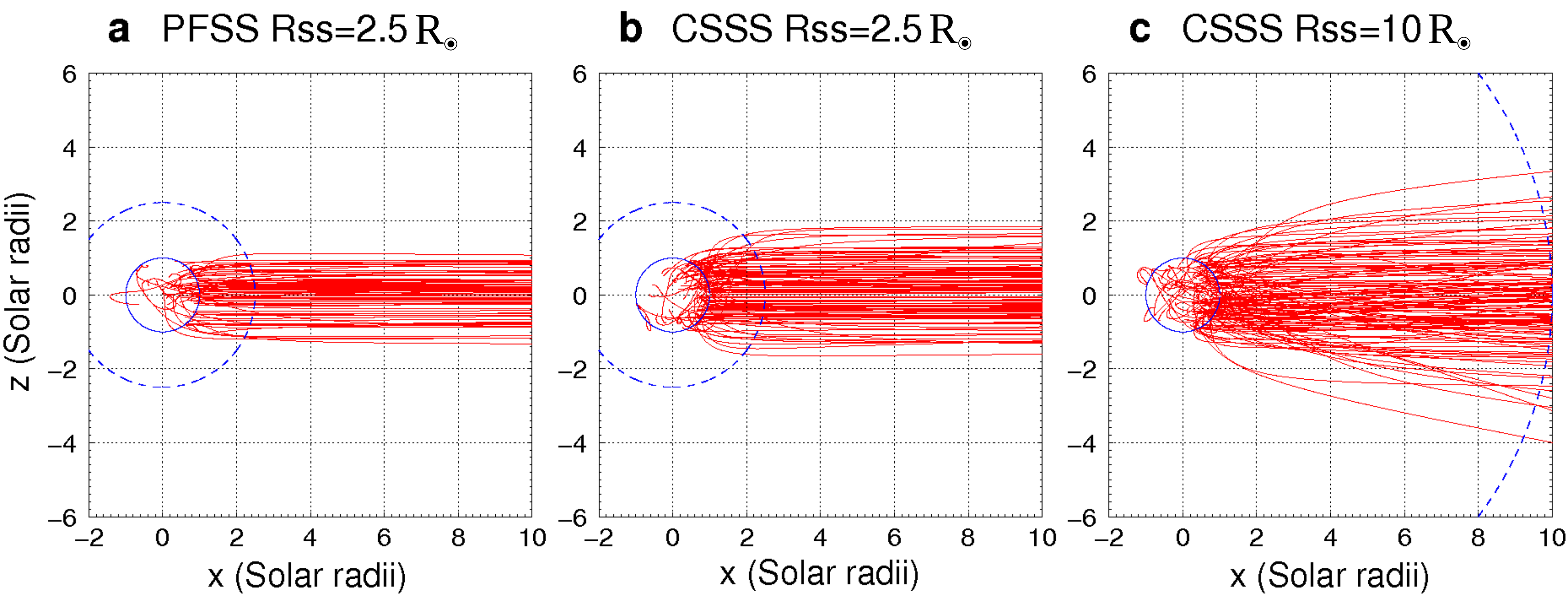
$$\chi^2 = \sum_{i=1}^{14} \frac{(D^i_{\rm obs} - D^i_{\rm MC})^2}{(\sigma^i_{\rm obs})^2 + (\sigma^i_{\rm MC})^2 + \langle\sigma_{\rm sys}\rangle^2}$$

Models	Data - MC $\chi 2$/d.o.f.	Probability
PFSS R_{ss}= $2.5R_\odot$	44.5(55.2)/14	4.9×10^{-5} (7.9×10^{-7})
CSSS R_{ss}= $2.5R_\odot$	21.1(26.2)/14	0.099(0.024)
CSSS R_{ss}= $10R_\odot$	8.3(10.3)/14	0.87(0.74)

* PFSS R_{ss}>>2.5 omitted -> unrealistic structure
* ( ) only statistical error

Cosmic Ray Trajectory ~10TeV in 1996 (CR1910)

Focusing effect



In the CSSS model case,
antiparticles can easily move along the open field lines of the ordered coronal magnetic field through the source surface at high latitude.

Sun's shadow summary

- Observation of the Sun's shadow (1996～2009) covering Solar Cycle 23

  → anti-correlation to 11-yr period solar activities

- Sensitivity to Sun-Earth magnetic field

  → Sun's shadow sensitive to coronal magnetic field
  → CSSS magnetic field model adopting currents in the coronal atmosphere reproducing DATA better than PFSS model

Reference: M. Amenomori et al., Phys. Rev. Lett., **111**, 011101 (5pp) (2013)

6. Future Prospects

What we have found out:

Crab, Mrk501 , Mrk421, Fermi-source Correlation observed,

Possible diffuse γ-ray signal from Cygnus region?

P, He, all-particle E-spectrum (Galactic cosmic rays accelerated to the knee region ~10^{15} eV)

Sharp Knee!?

What we should do next:

1. 100 TeV (10 – 1000 TeV) region γ-ray astronomy

   Where do galactic cosmic rays under knee come from?

2. E-spectrum of heavy component around ‘ knee’

   All-particle knee = CNO? Fe knee?

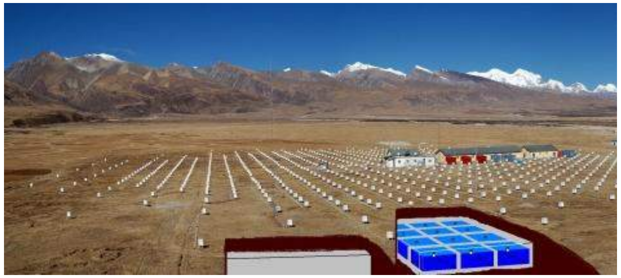
☐ Next Plans

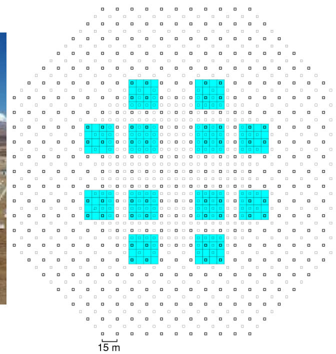
Gamma ray: Tibet Muon Detector (MD) Project

&

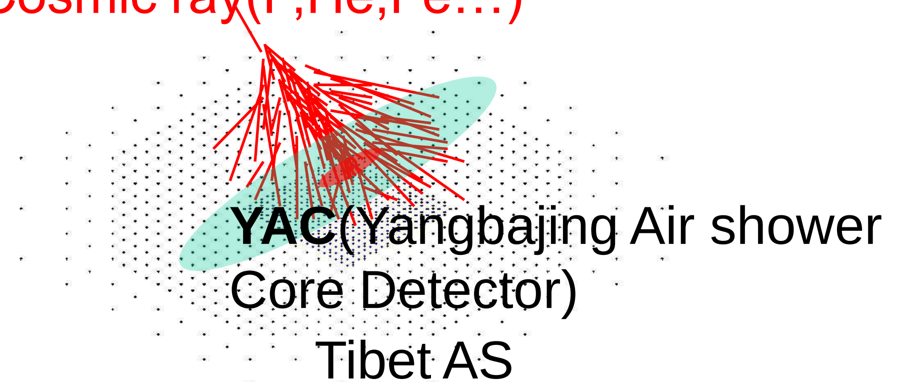
Cosmic Rays: Tibet Yangbajing Airshower Core (YAC) Detector Project

Tibet Muon Detector (MD) Project

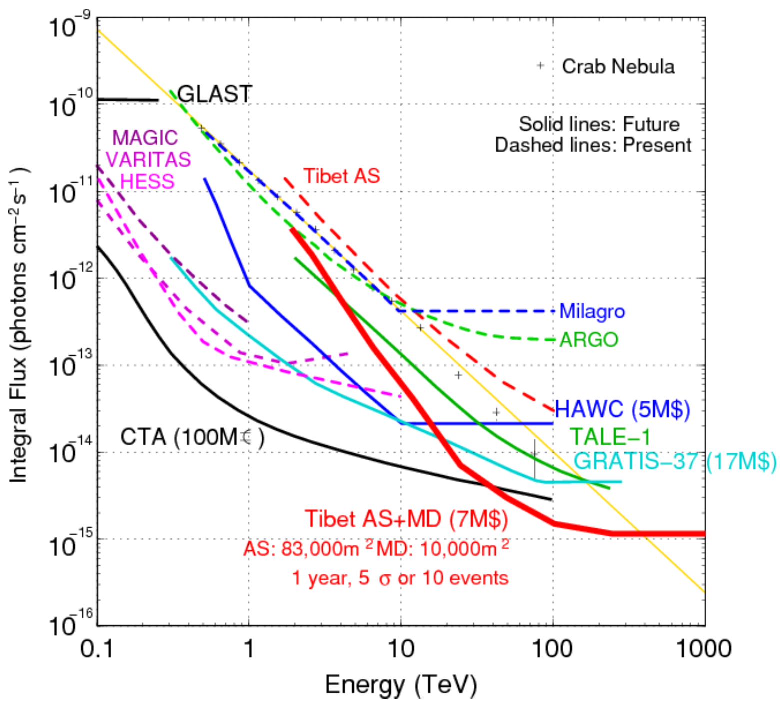




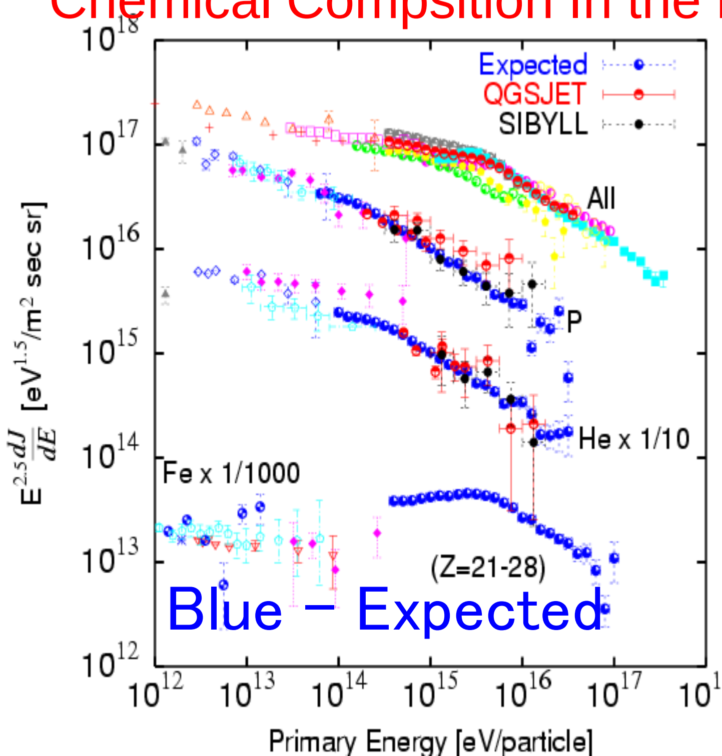
Tibet Air Shower Core Detector (YAC) Project



10-1000TeV Gamma



Chemical Compsition In the Knee



1. 100 TeV γ-ray astronomy

Let's see 100 TeV-region (10-1000TeV) gamma rays by

Tibet-III (AS) + a large underground

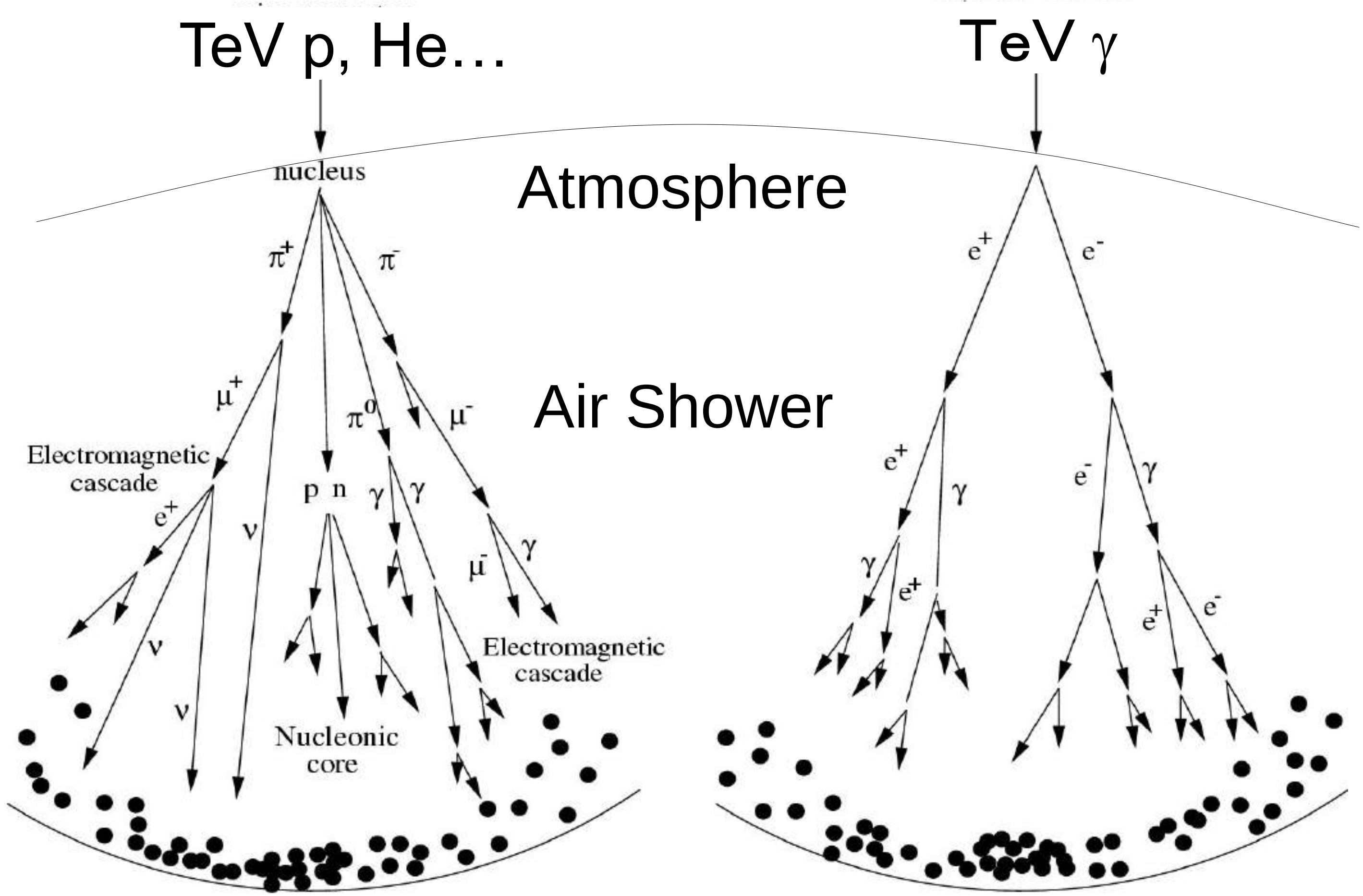
muon detector array (MD)

(~10000m^2 in total)!

>Origin of cosmic rays and acceleration mechanism and limit at SNRs.

>Diffuse gamma rays

p/γ discrimination by muons



Number of muons（<100 m from core, 4300m a.s.l.）

100TeV Proton	100TeV Gamma
~50	~1

Tibet Muon Detector (MD) Array

7.2m x 7.2m x 1.5m depth   Water pool

20"ΦPMT x 2   (HAMAMATSU R3600)

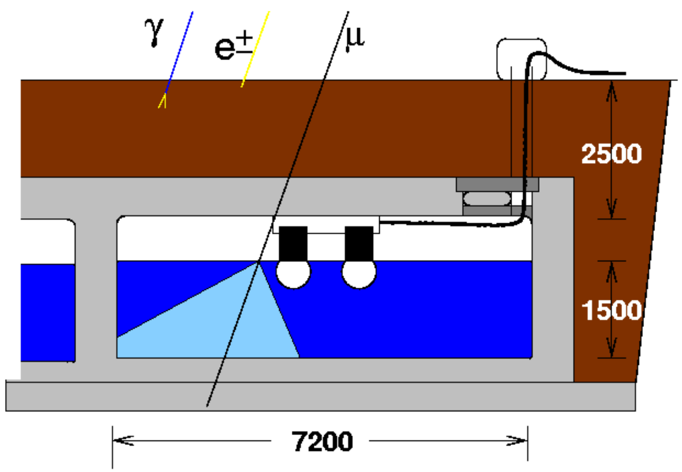
Underground 2.5m (~515g/cm^2~19X_0)

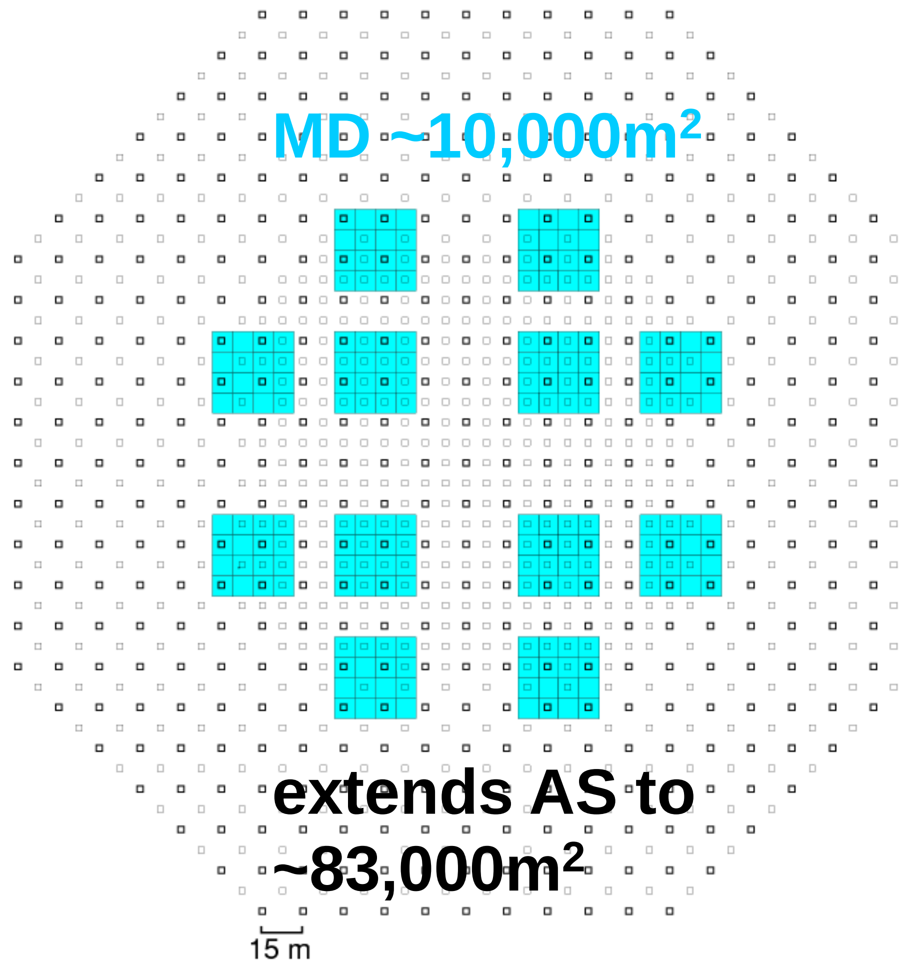
Material:

- ☐ Concrete pool
- ☐ White paint

192 detctors

Total ~10,000 m^2





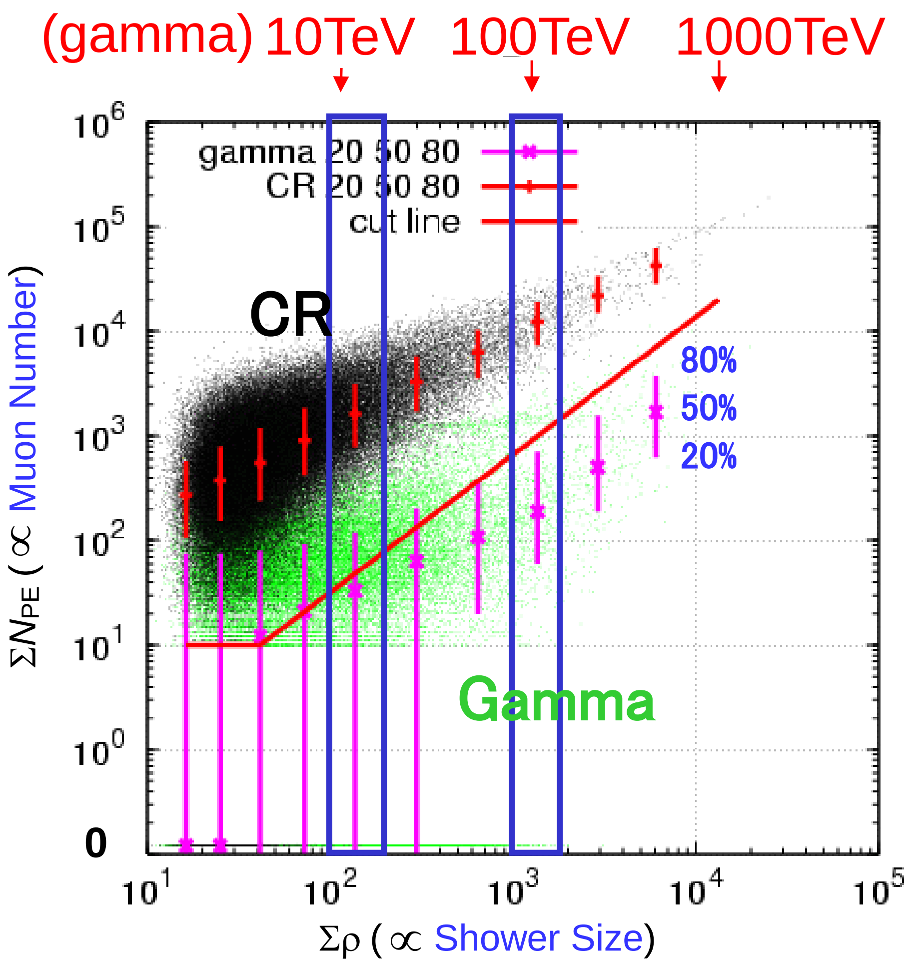
Counting the number of muons accompanying an air shower

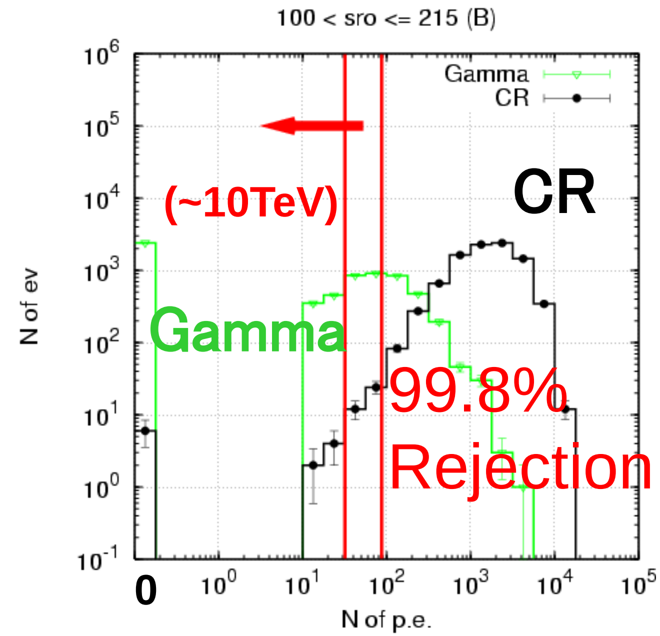
➡ p/γ discrimination

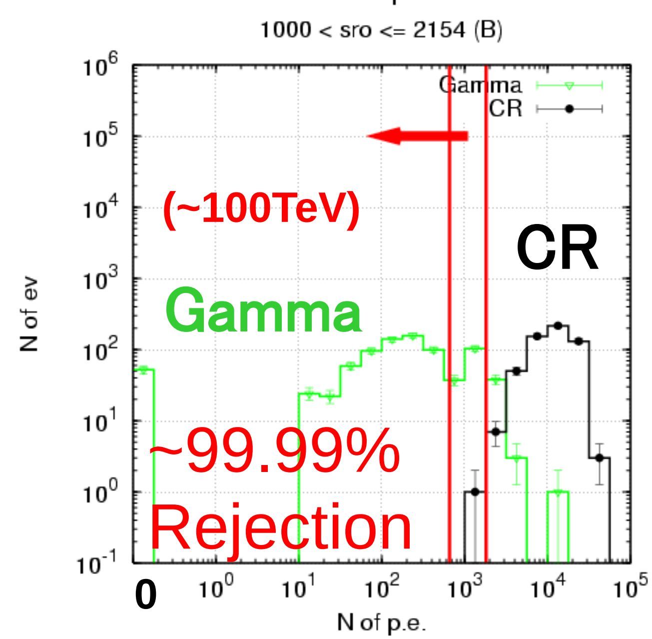
Muon Number vs. Shower Size (Simulation)

$\Sigma\rho$: Sum of particle density by all scintillation det.
>> Shower Size

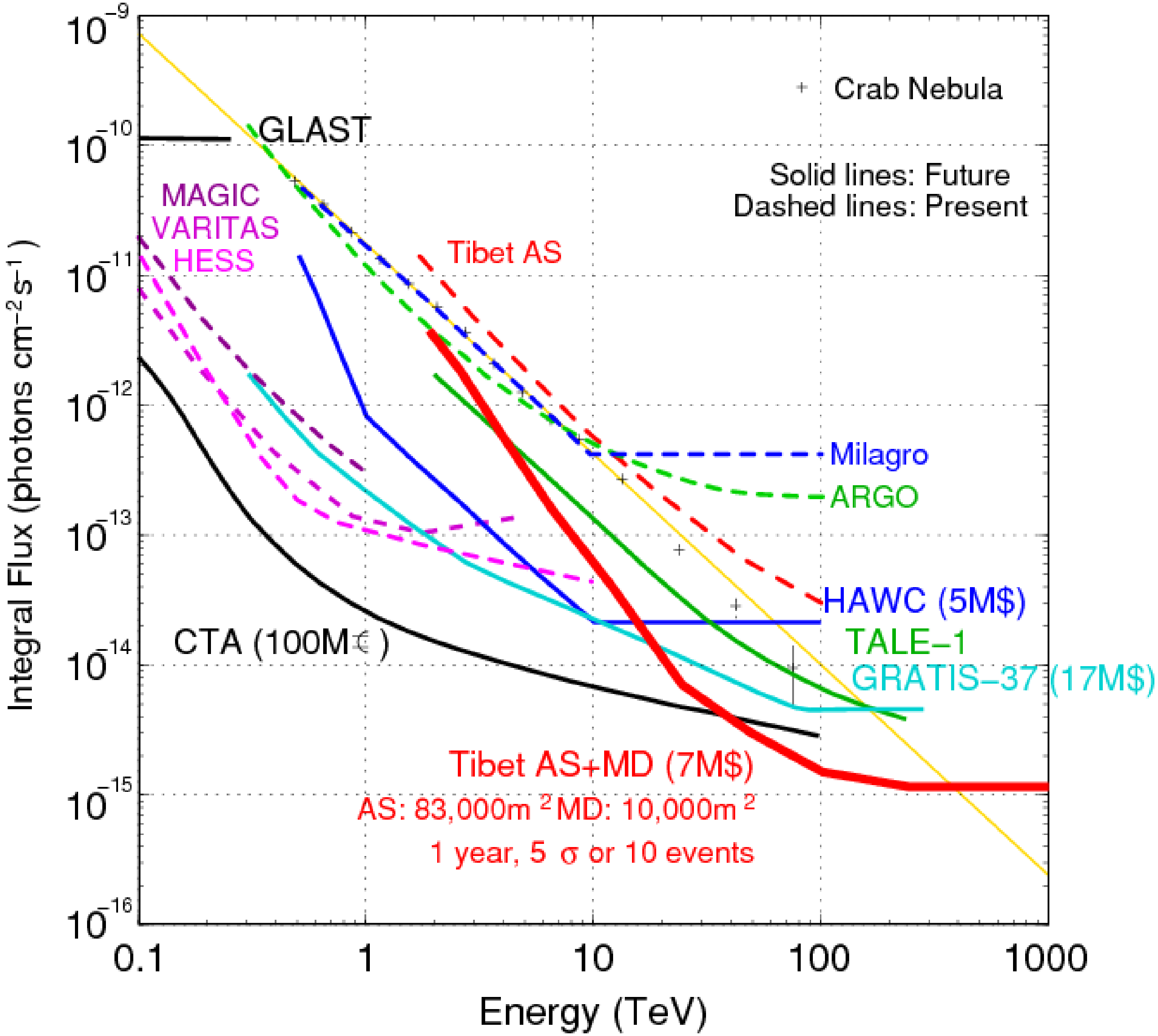
ΣN_{PE}: Sum of photoelectrons by all muon det.
>> Muon number
(Threshold of MD N_{PE} >10 p.e.)







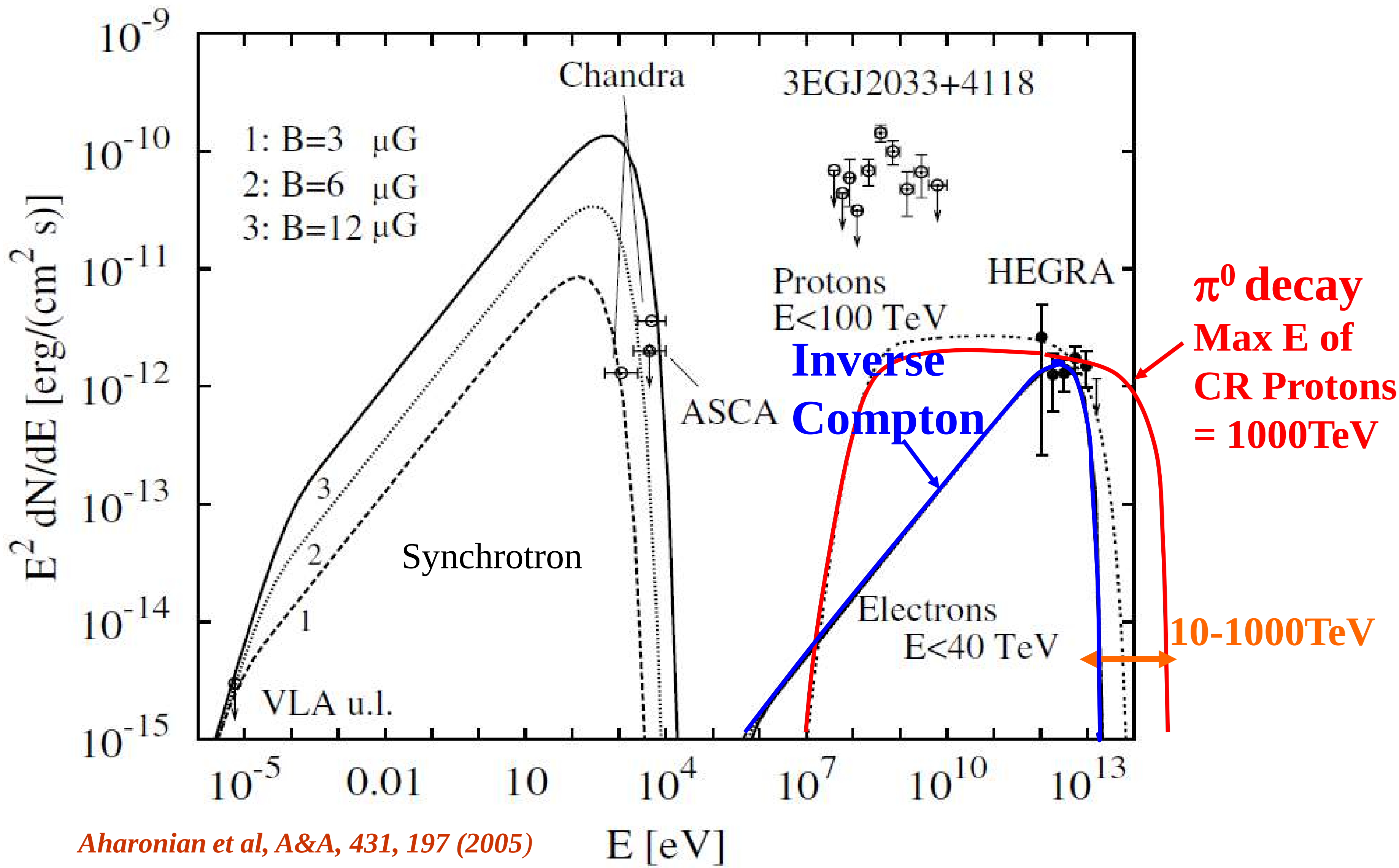
Other Future Plans（5σ or 10 events）



Gamma Ray Observation in the 100 TeV region

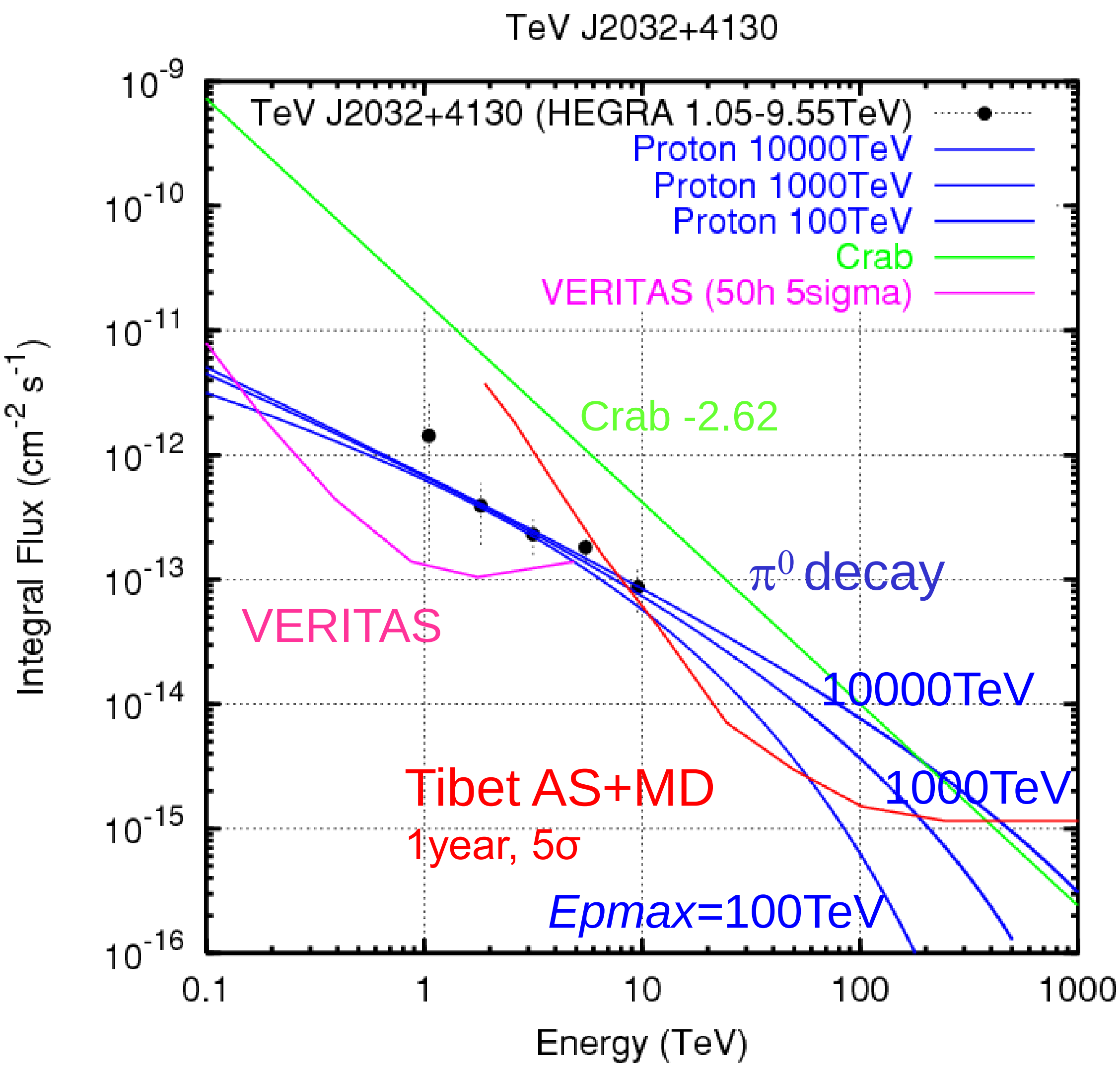
TeV J2032+4130 (~5% Crab)

1. Hard spectral index at TeV energies
2. Faint in other wavelengths



Aharonian et al, A&A, 431, 197 (2005)

TeV J2032+4130 and π^0 decay model



TeV J2032+4130
Unidentified source
Cyg X-3 in Cyg OB2
HEGRA obs.~158 hours
Extended ~6.2′

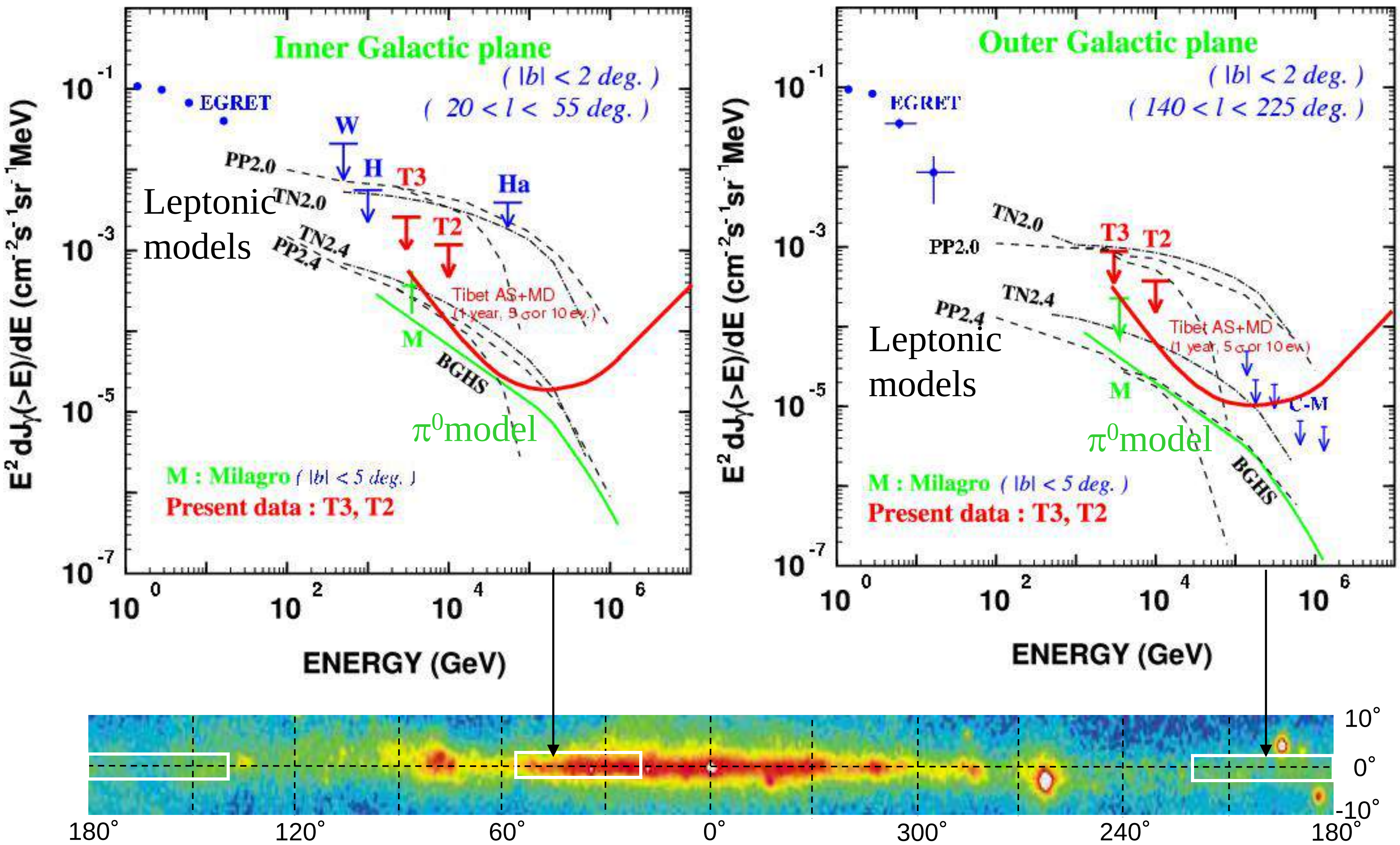
π^0 decay model

Aharonian et al. A&A, 464, 235(2007)

Kelner et al., PRD 74, 034018 (2006)

Aharonian et al, A&A, 431, 197 (2005)

Diffuse gamma rays from Galactic Plane



EGRET data

MD summary

Tibet MD

$\sim$83000 m^2 Airshower Array (AS) +

$\sim$10000 m^2 Water Cherenkov Muon Detectors (MD)

→100 TeV(10–1000TeV) γ–ray observation (CR acceleration limit & Diffuse γ)

Expected Sensitivity

F(>100(20)TeV) $\sim 10^{-15}$ cm^{-2} s^{-1} $\sim$10 (5) % Crabs

→More than 10 times better sensitivity

  >HESS (>10–20TeV),   >CTA (>30–40TeV)

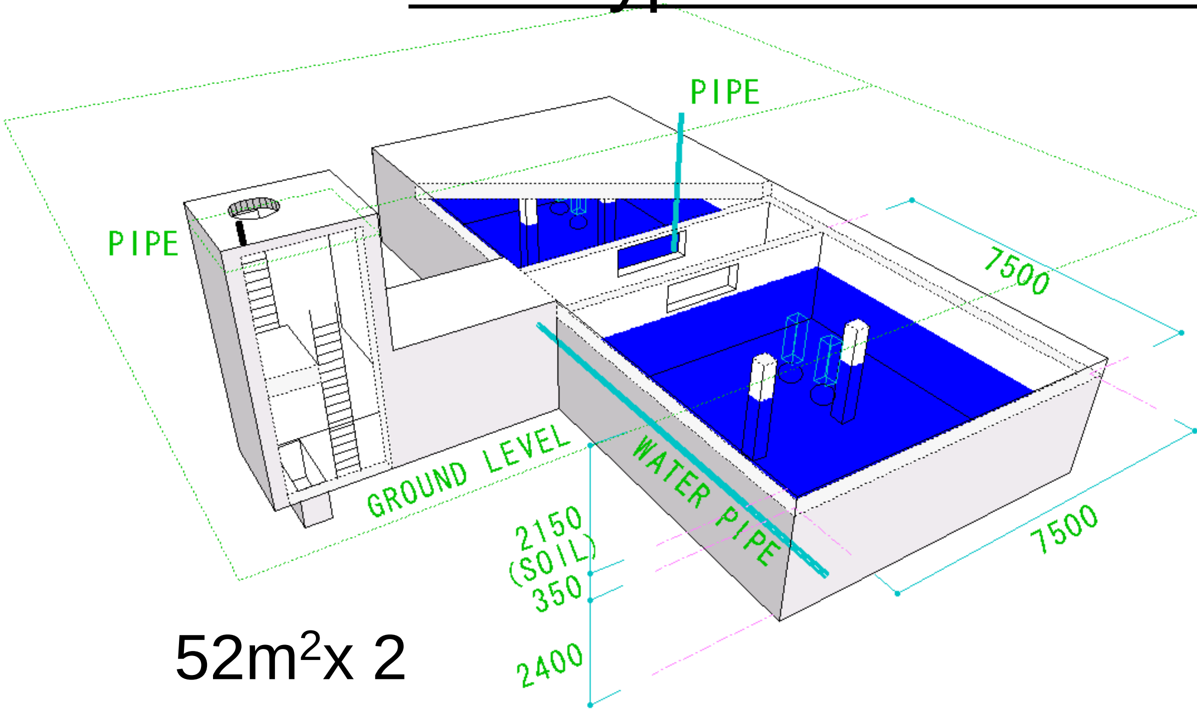
Source Candidates for 100 TeV g–ray emission in our field of view.:

Possible (1 year) : Diffuse γ from Milky way,
Crab, TeV J2032+4130,
MGRO J2019+37, MGRO J1908+06, MGRO J2031+41
HESS J1837–069, Mrk 421

Interesting (Several years) : Cas A, M87, HESS J1834–089, HESS J0632+058
Mrk 501, LS I +61 303, IC443, Extragalactic Diffuse γ???

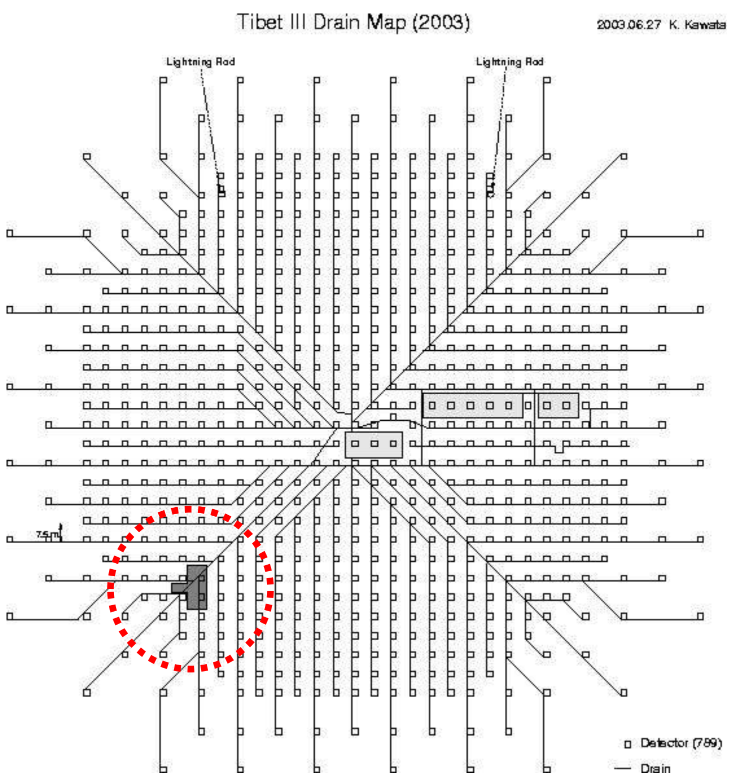
Unknown : several –10 !?

Prototype Muon Detector in Tibet

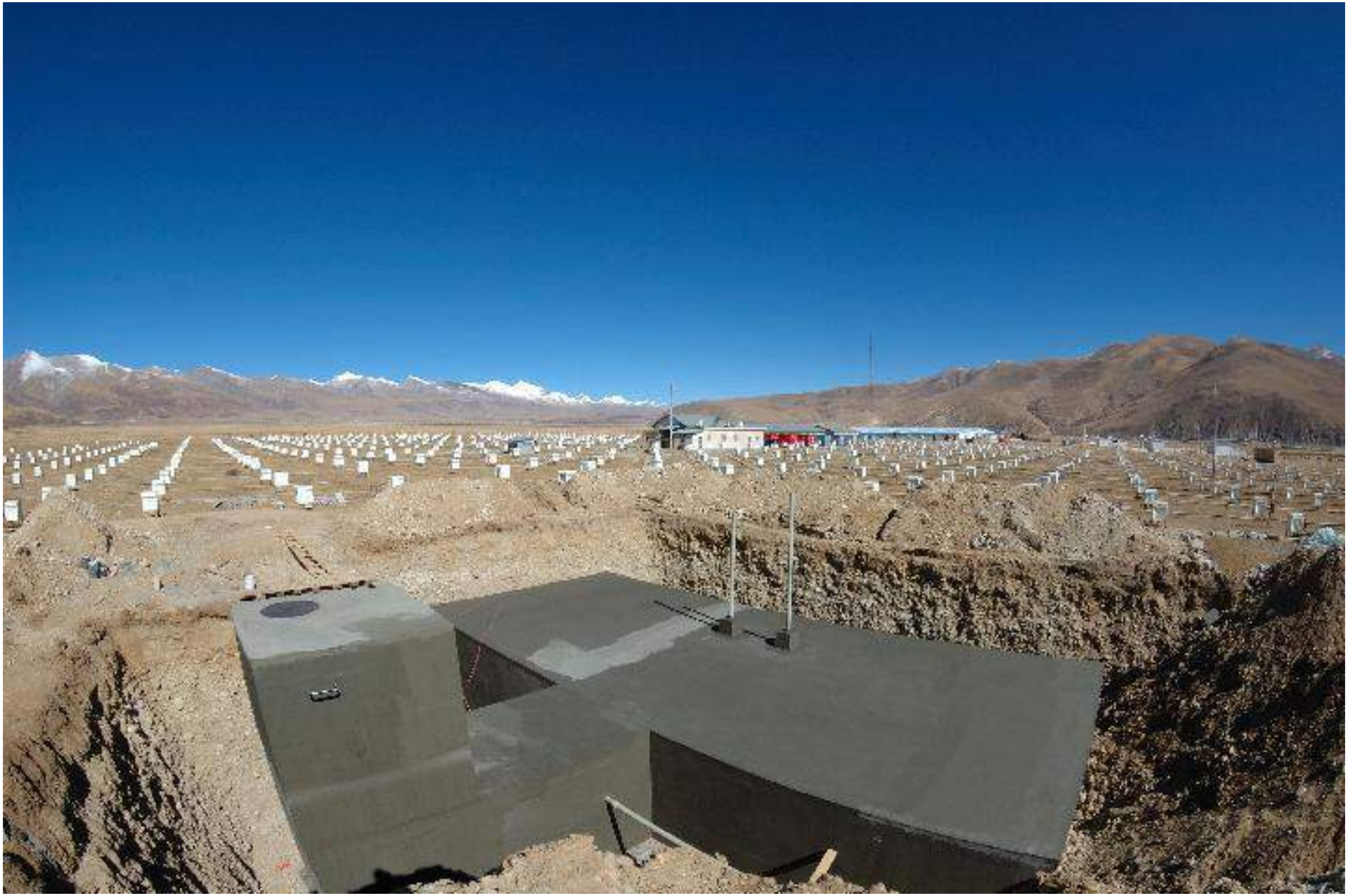


Construction from Sep. 2007
Data taking from Dec. 2007

$52m^2$x 2



- Construction feasibility in Tibet ?
- MC simulation OK?
- γ observation above multi 100 TeV



16 November, 2007 Prototype Muon Detector

Prototype Muon Detector after backfilling

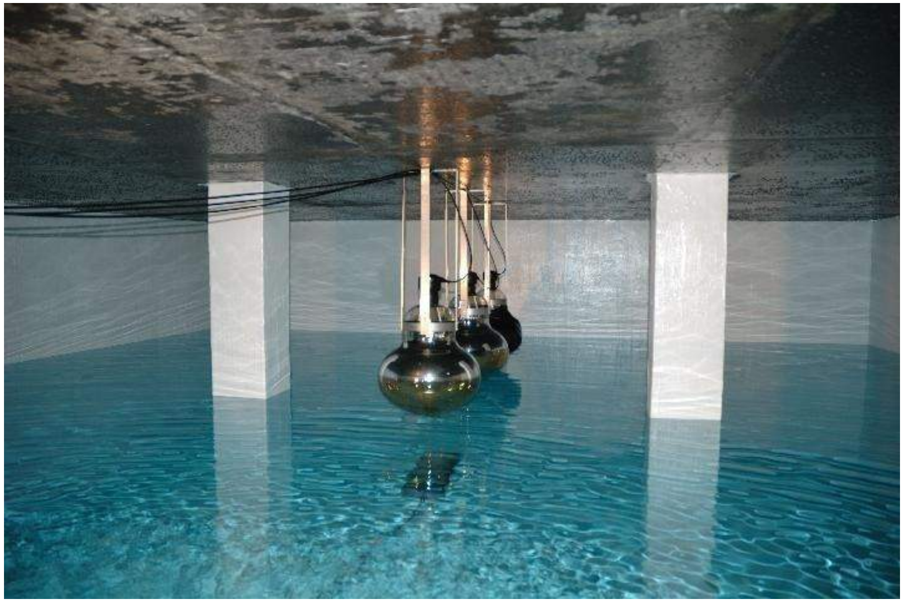
Inside of the Prototype MD

Clear underground water
from a nearby well

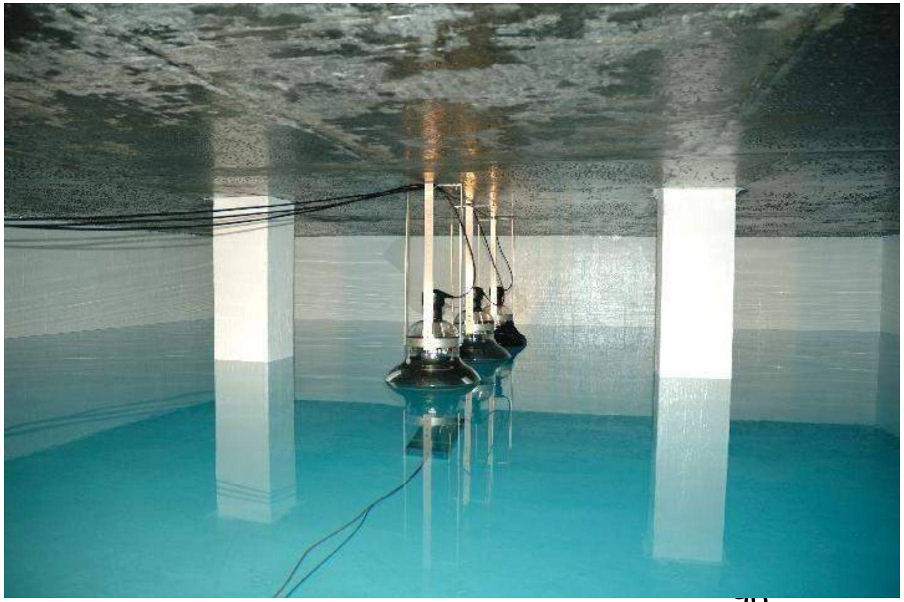
20”ϕ PMT x 3:
(Normal gain x 2, 1/100 gain x 1 for test)

Water depth : 1.5 m

White paint

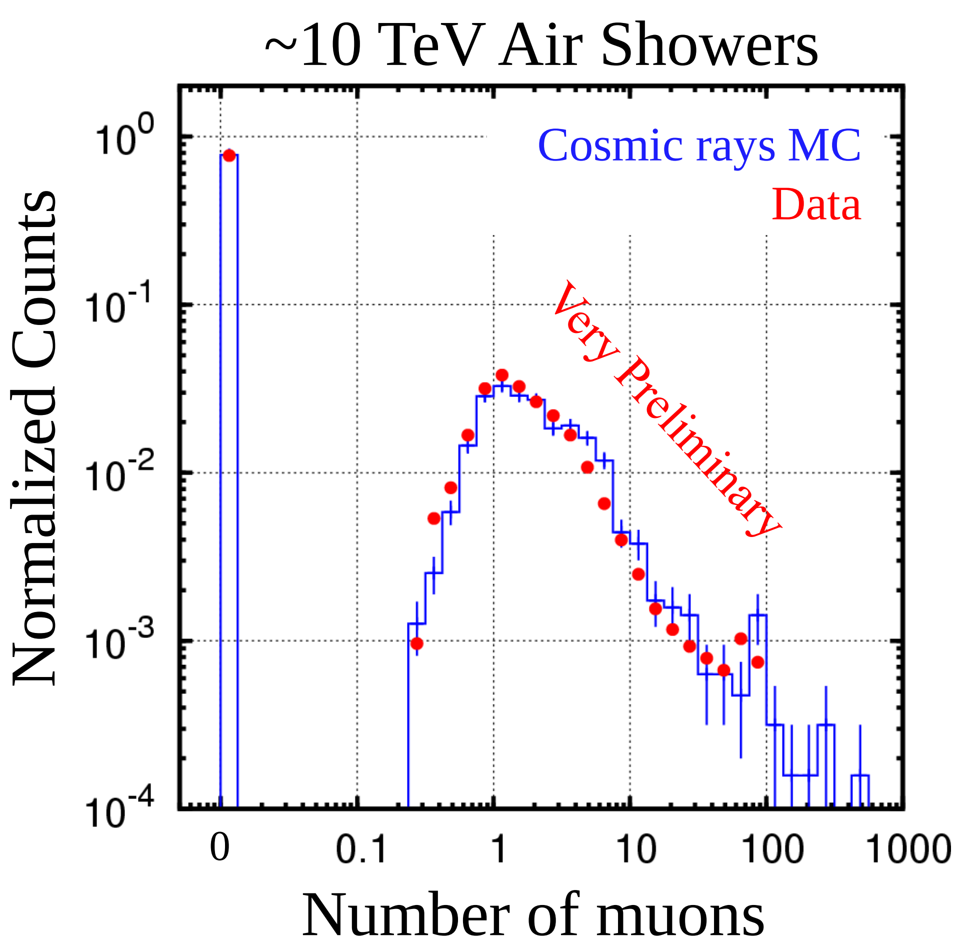


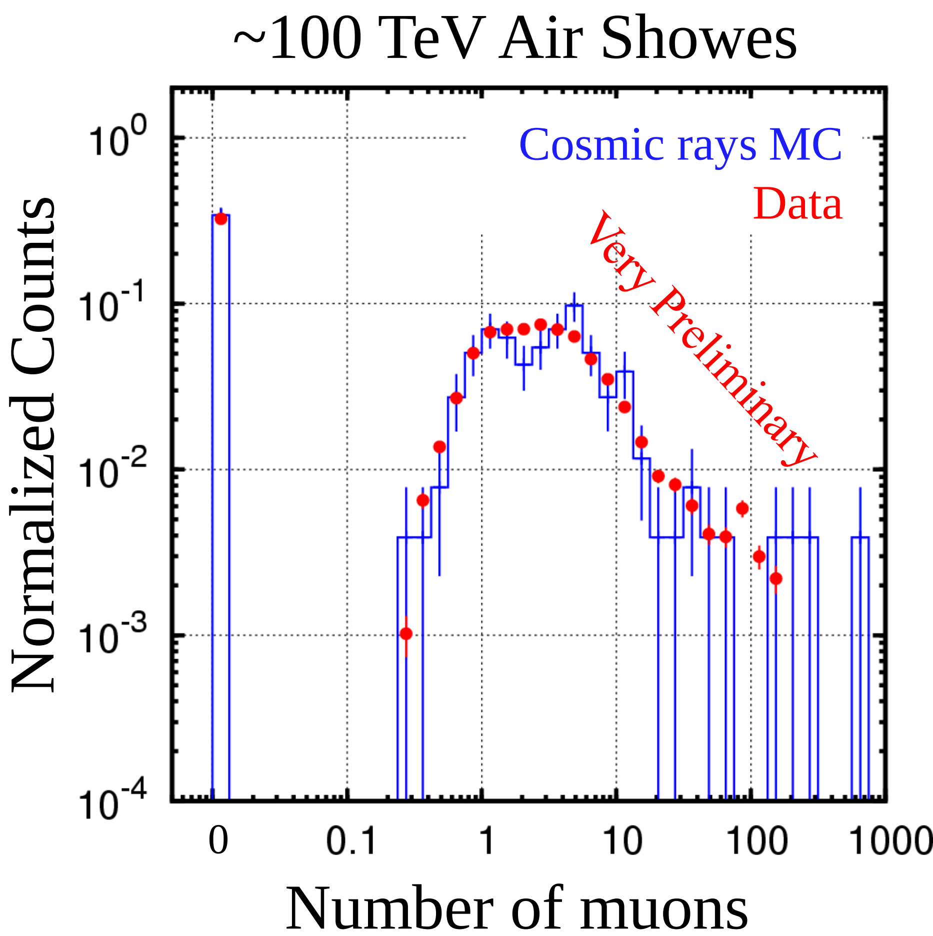
Pouring very clear well-water



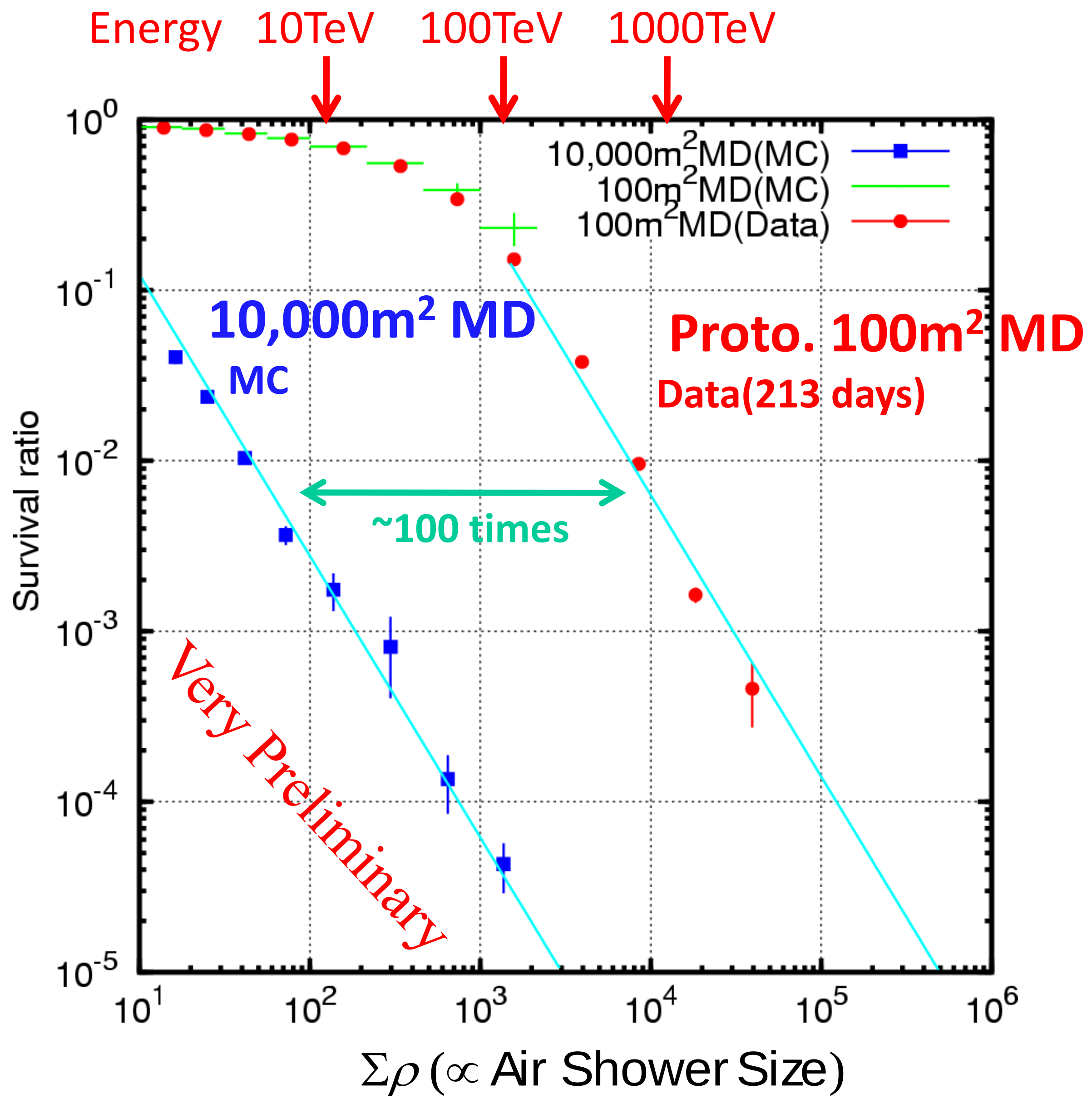
Filled up water 1.5 m in depth

Number of muons





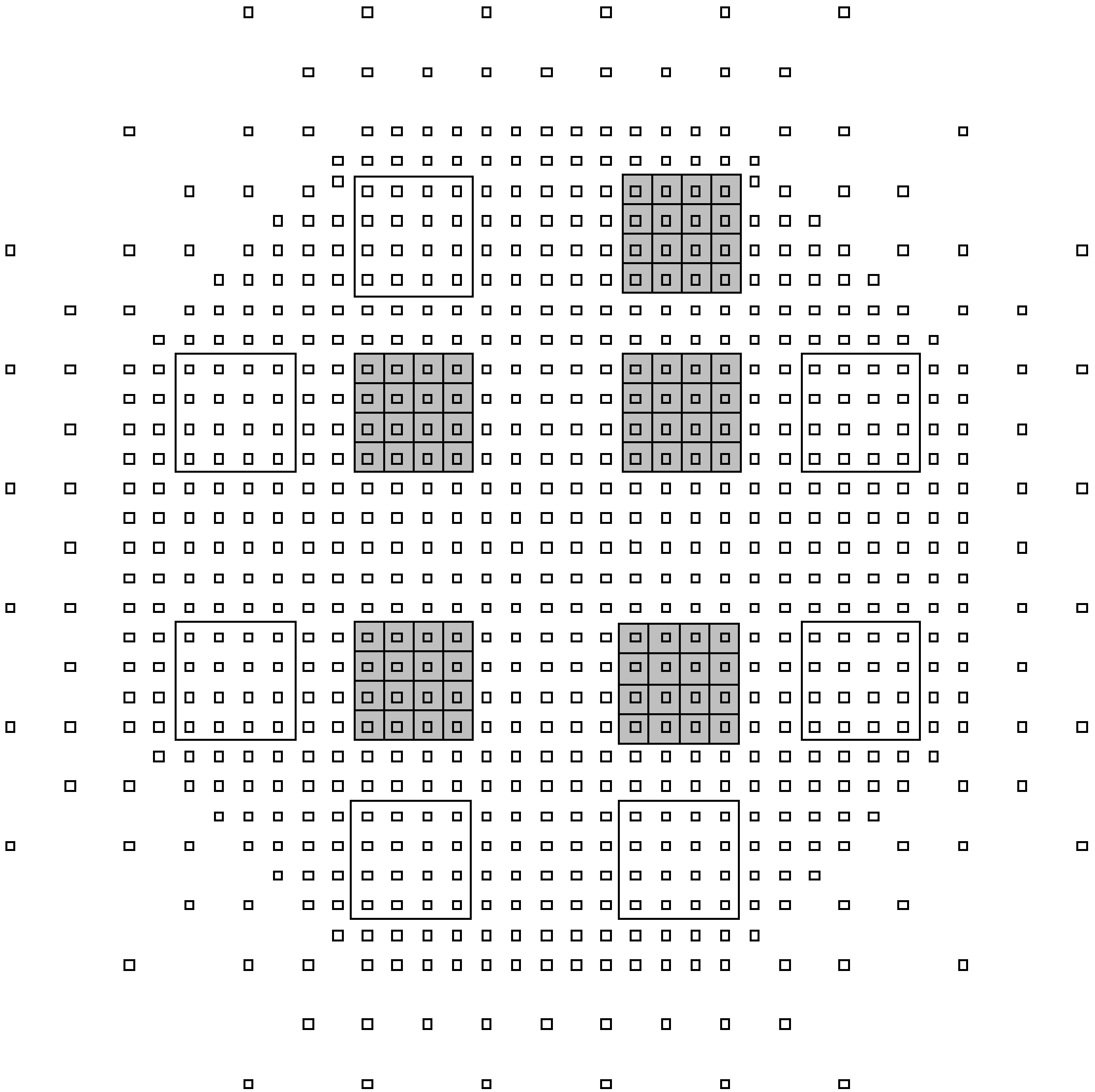
Cosmic Ray (Nucleus) Survival Ratio



Status of MD Construction

5/12 Full MD

Construction Completed and Started Data-taking In 2014



MD construction scene

Installing a 20 inch PMT in a MD cell.

Tyvek sheet walls and two 20 inch PMTs

MD Summary

Prototype MD (52 m^2 x 2 cells)

– **Successfully completed** (2007)

Data vs MC in reasonable agreement

CR survival ratio: ~0.2 %@~1 PeV

-> Full ($10^4 m^2$) MD @~10 TeV

-> Full ($10^4 m^2$) MD MC: OK up to ~10TeV

5/12 Full MD Data-taking Started in 2014

YAC II
(Dense version)
（under construction）

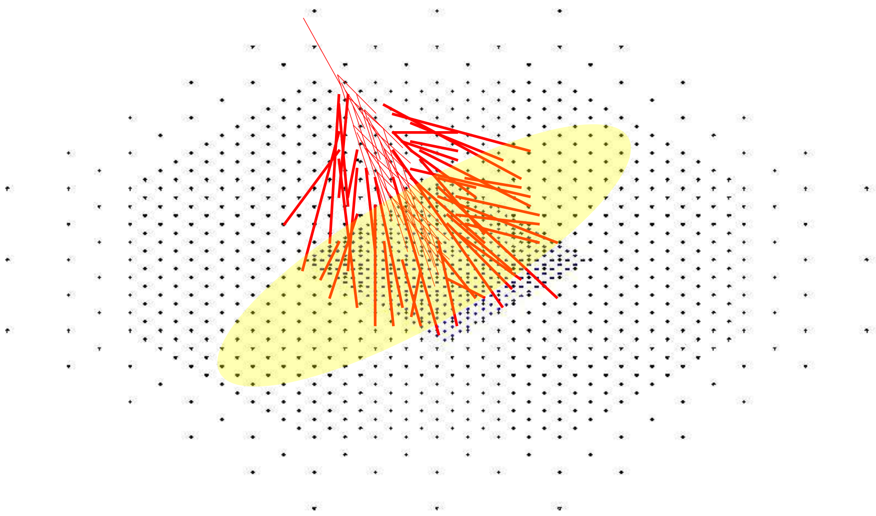
YAC II detector consists of 100 burst detectors with 1.5m spacing between detectors.

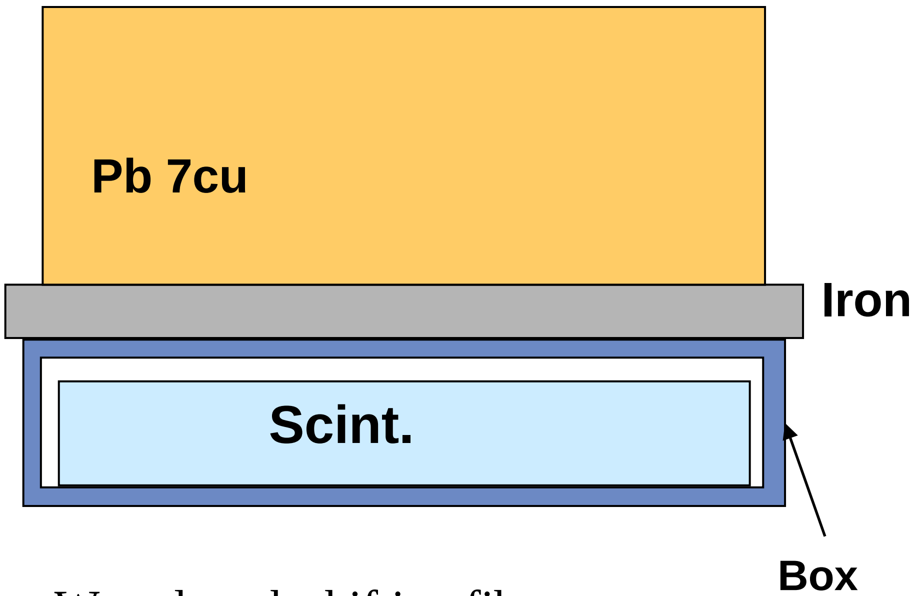
Total area of the array is 160 m^2 located near the center of Tibet III AS array.

It is designed to measure proton and helium spectra in the knee region. **<u>Expected number of protons (>100TeV) and helium (>200TeV) using HD model are 2300 and 800 per one year, respectively.</u>**

Design of YAC-II

40cm x 50cm, 100 channels S=160m^2

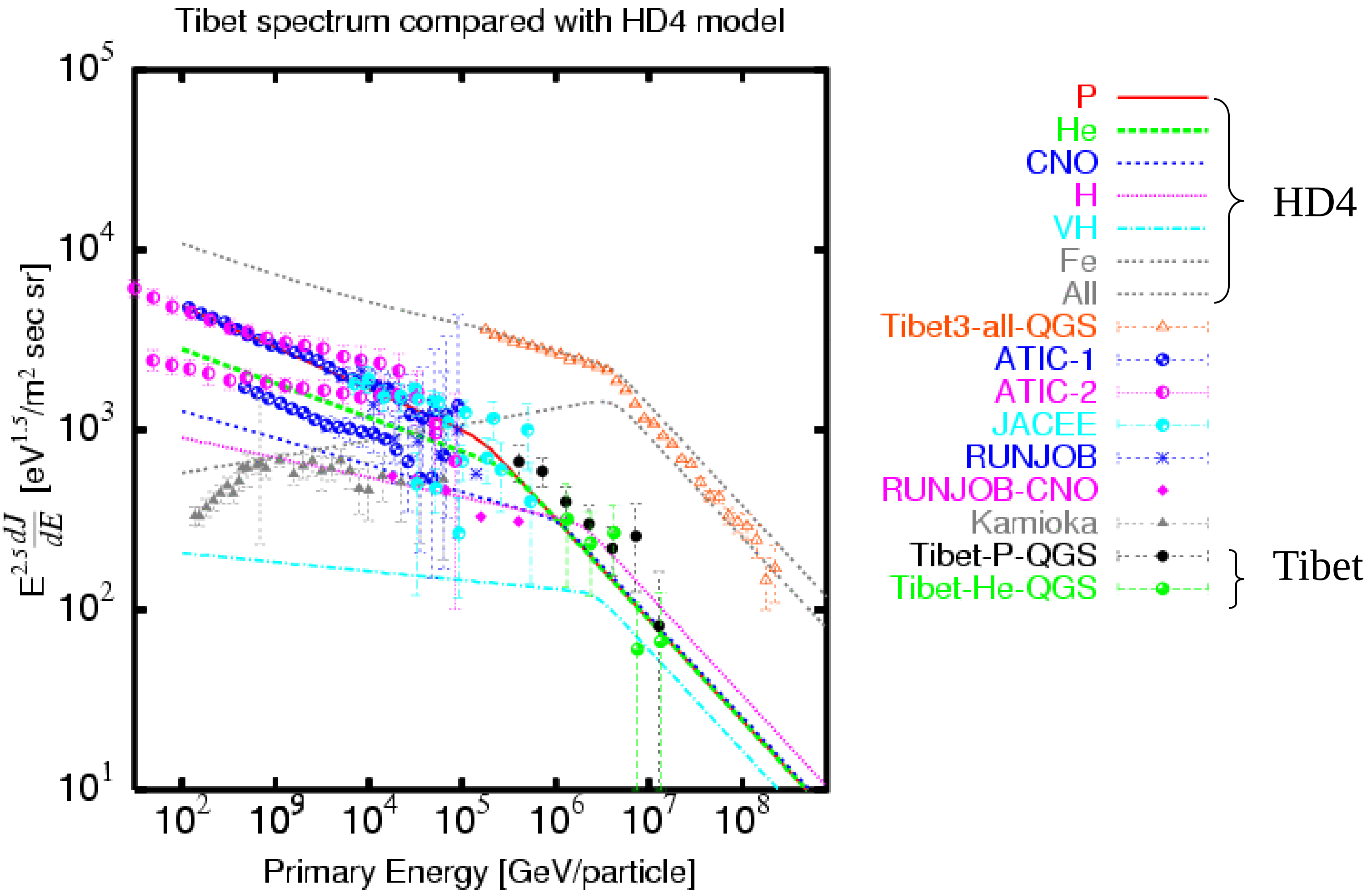




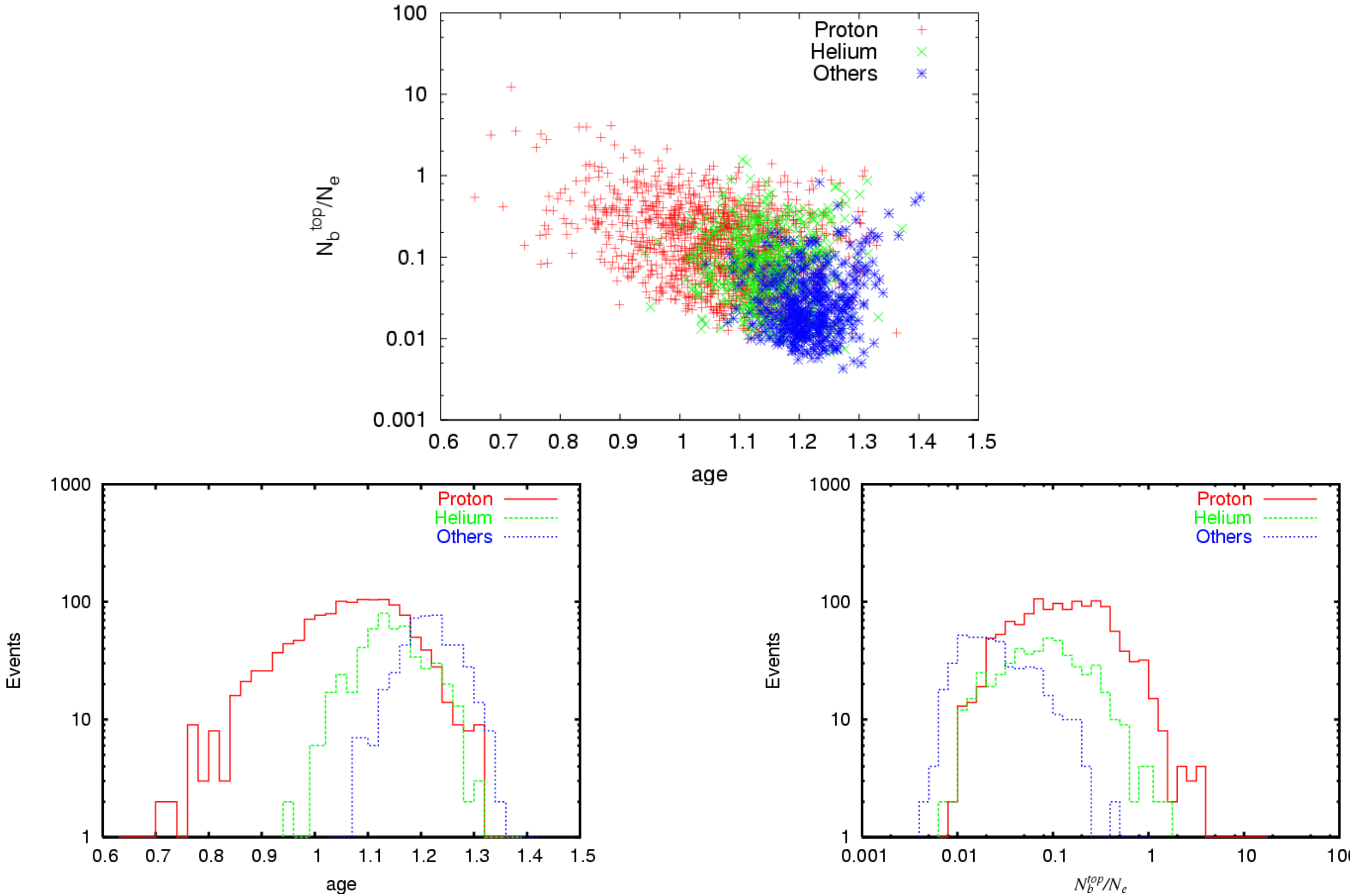
1.5m spacing 100ch
N_b>100electrons,
any 1 (>30GeV)

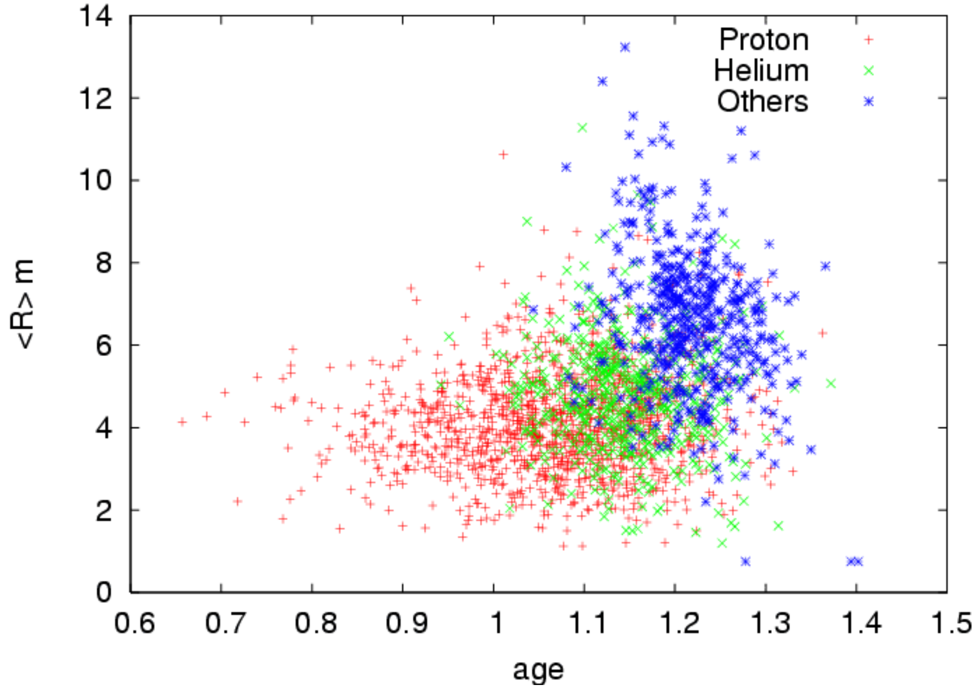
Wave length shifting fiber
+ 2 PMTs
(Low gain & High gain)
$10^2 < N_b < 10^6$

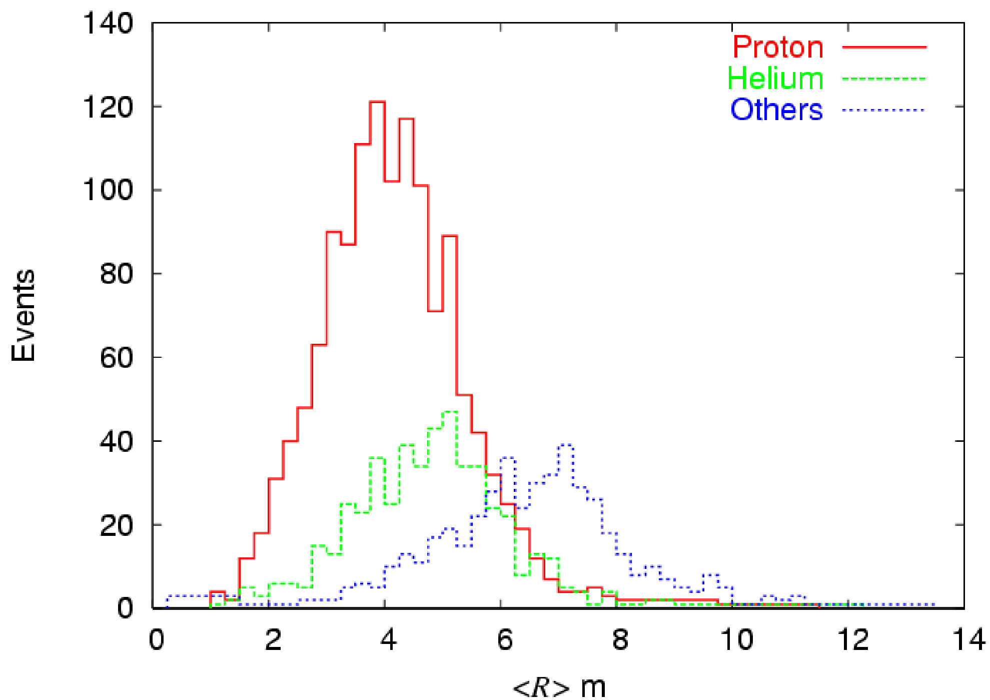
Tibet All, P, He spectrum



Features of YAC-II observables

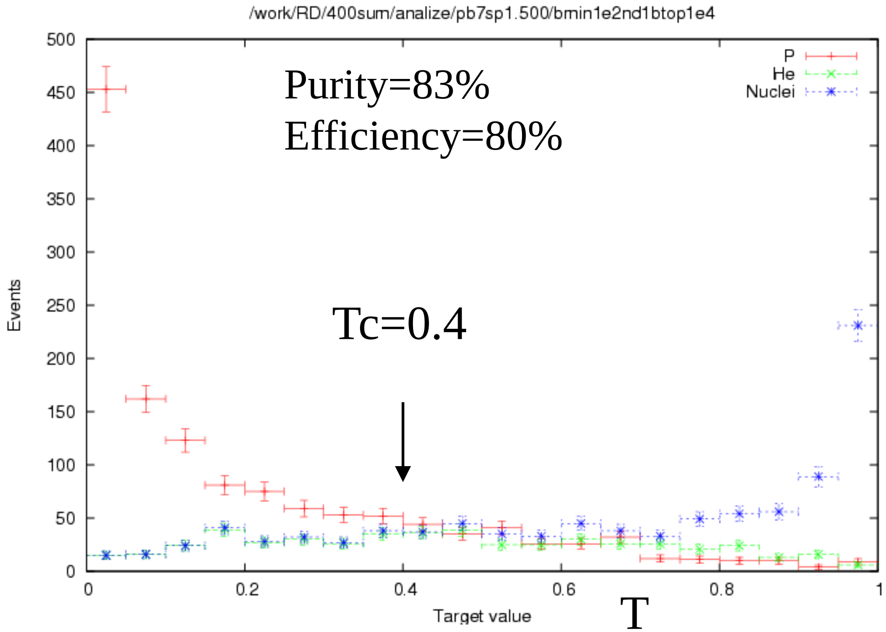



Proton
Helium
Others
<R> m
age

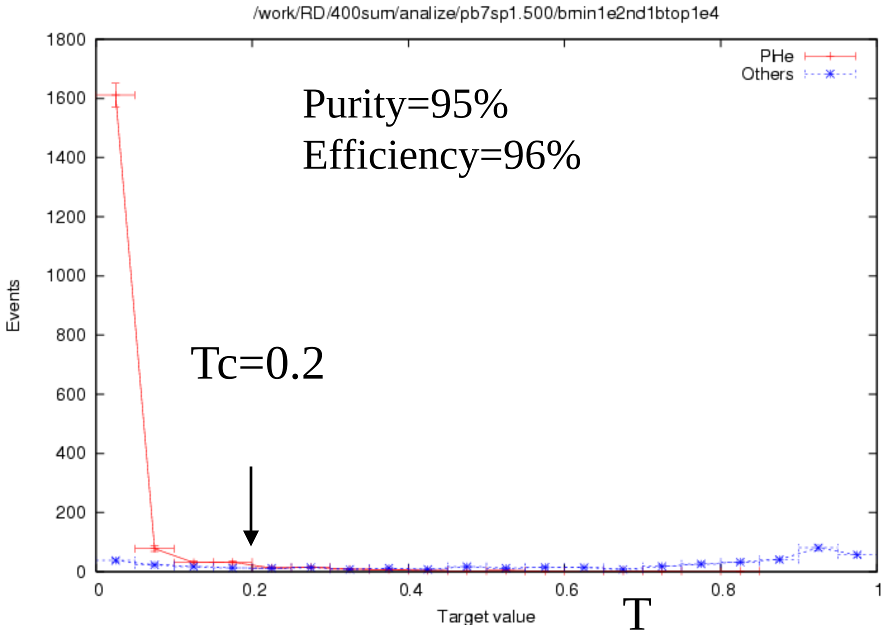

Proton
Helium
Others
Events
<R> m

ANN output

Proton separation



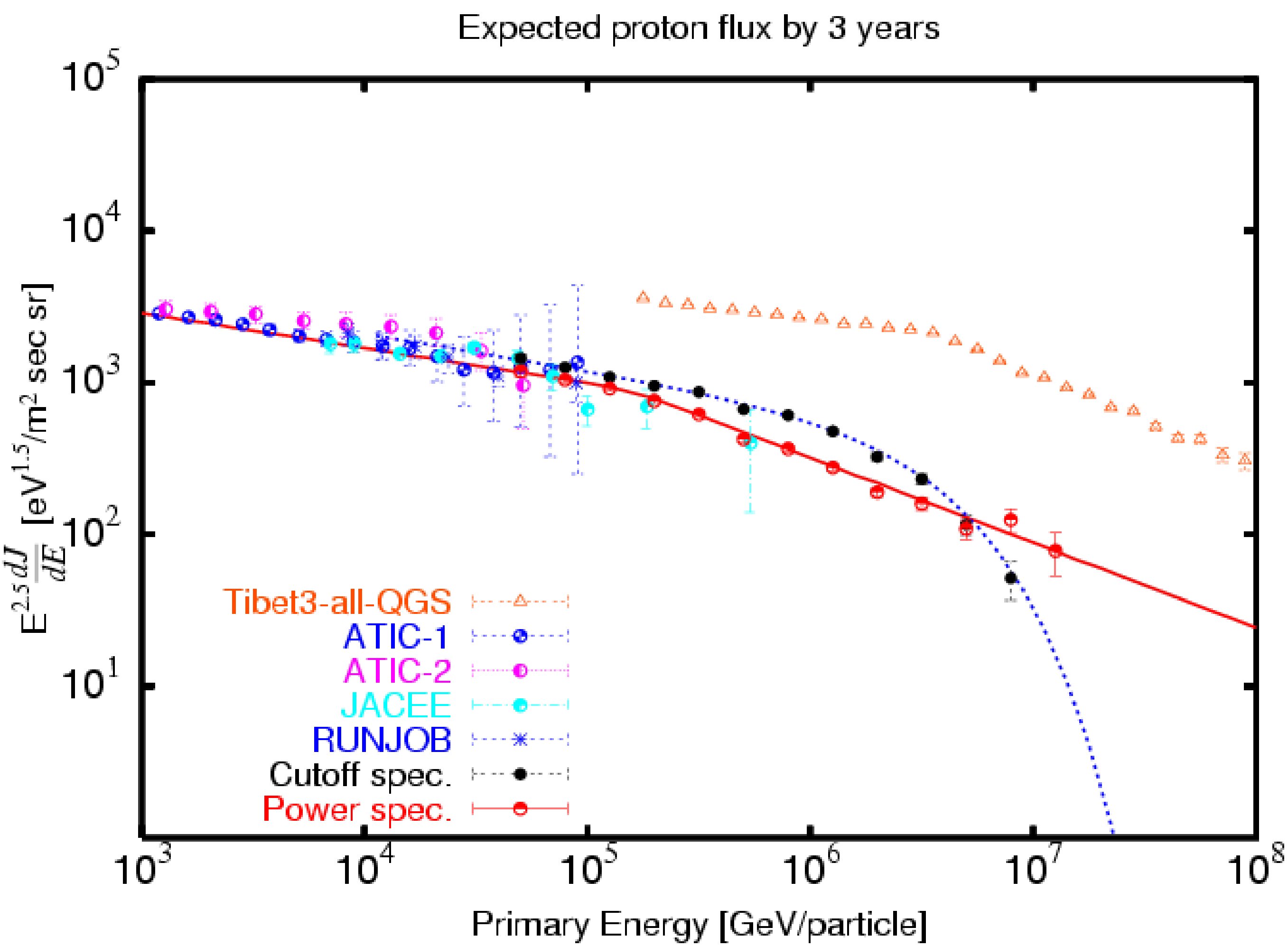
P+He separation



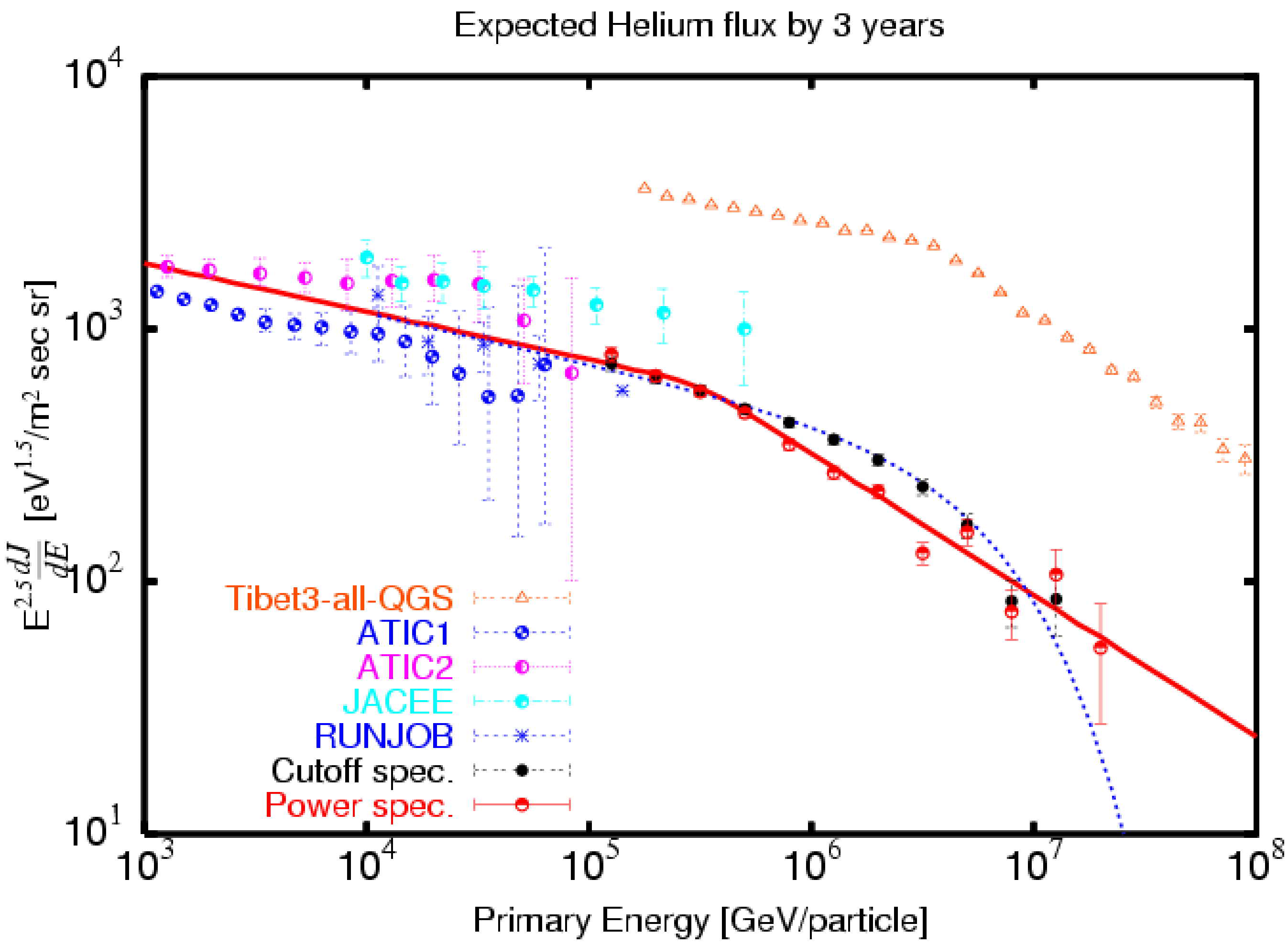
Contamination is exclusively by helium nuclei.
The fraction of helium events missidentified as protons is about 40% of helium events by Tc=0.4.

20% of heavier nuclei than helium contaminates to P+He region.

Expected proton spectrum (YAC-II)



Expected He Spectrum (YAC-II)



YAC III
(Wide version) 2.5 M USD

YAC III detector consists of 400 burst detectors with 3.75m spacing between detectors.

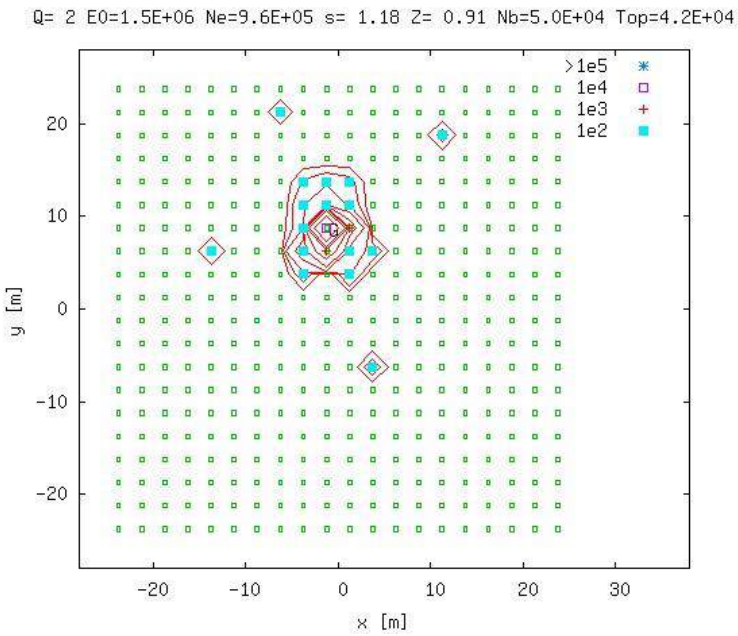
Total area of the array is 5000 m^2 located near the center of Tibet III AS array.

It is designed to measure iron group spectra in the knee region. **Expected number of irons (>1000TeV) using HD model is 4400 per one year.**

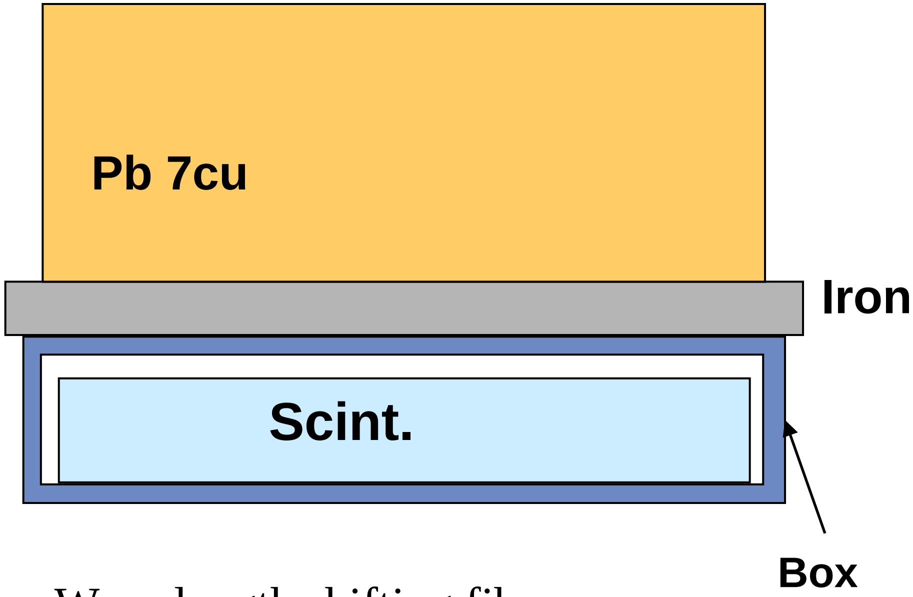
Design of YAC-III

40cm x 50cm, 20x20 channels

$S=5000m^2$

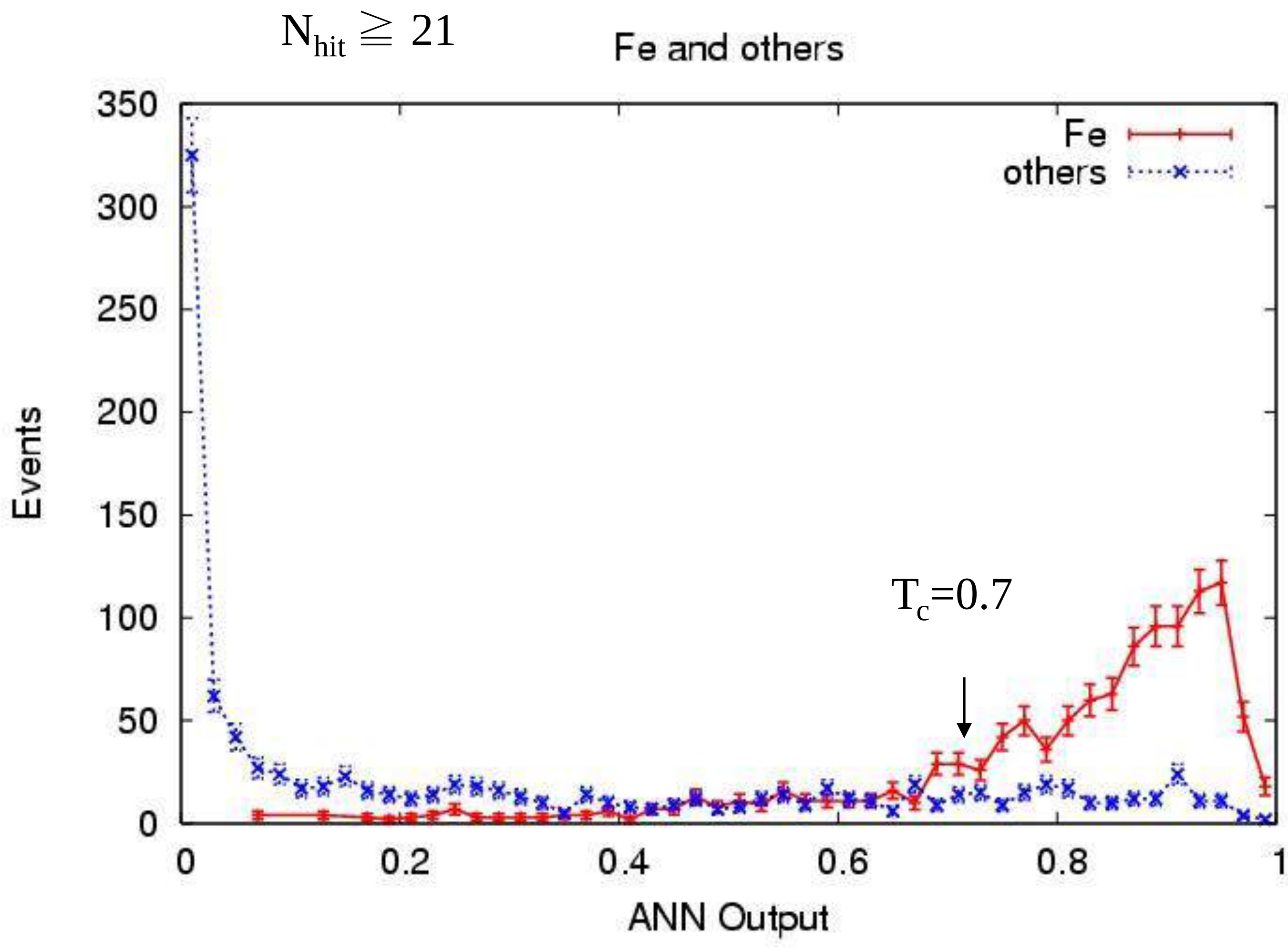


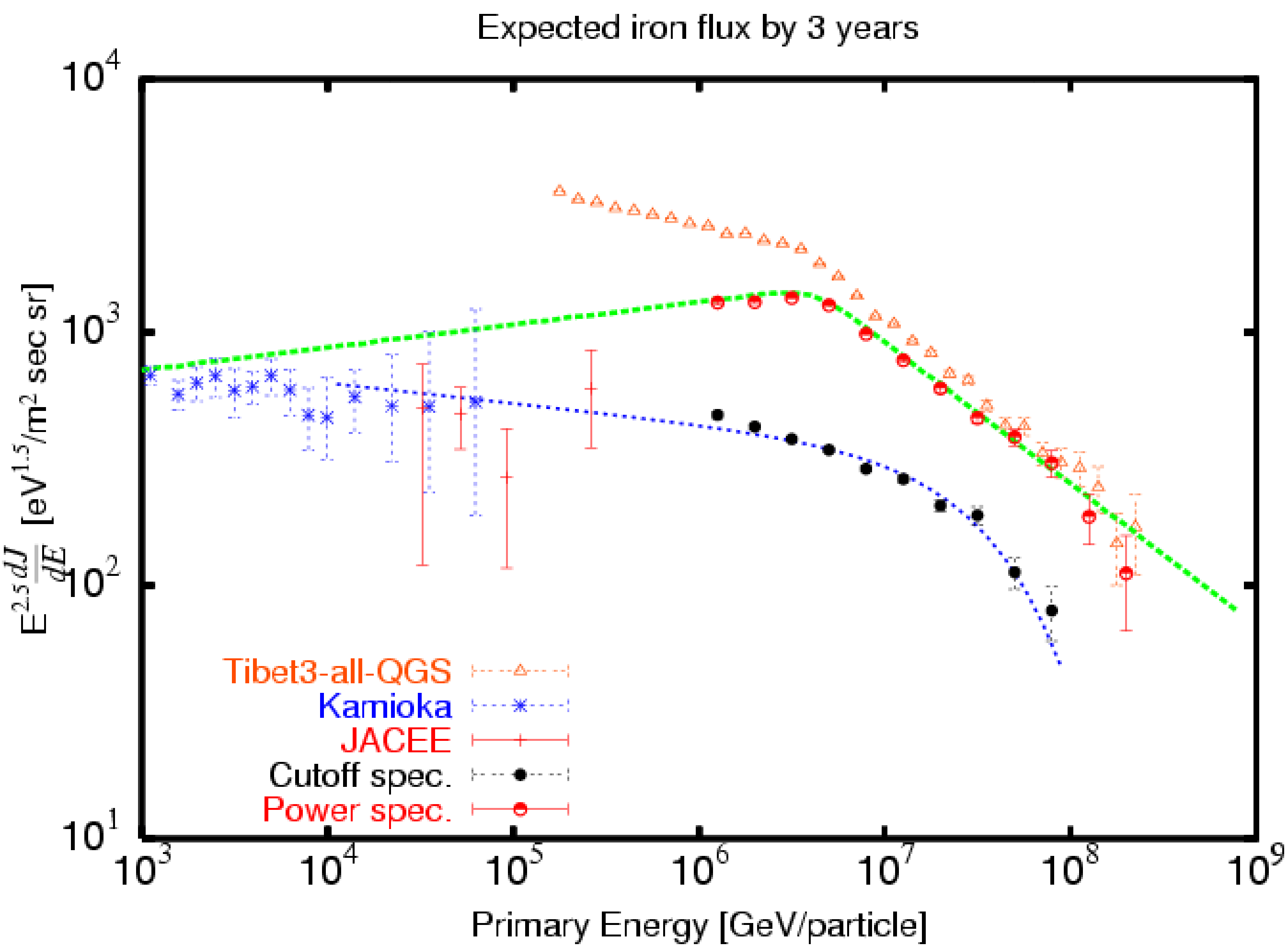
3.75m spacing 400ch
N_b>100, any 5
(>30GeV)



Wave length shifting fiber
+ 2 PMTs
(Low gain & High gain)
$10^2 < N_b < 10^6$

Separation of Fe by YAC III

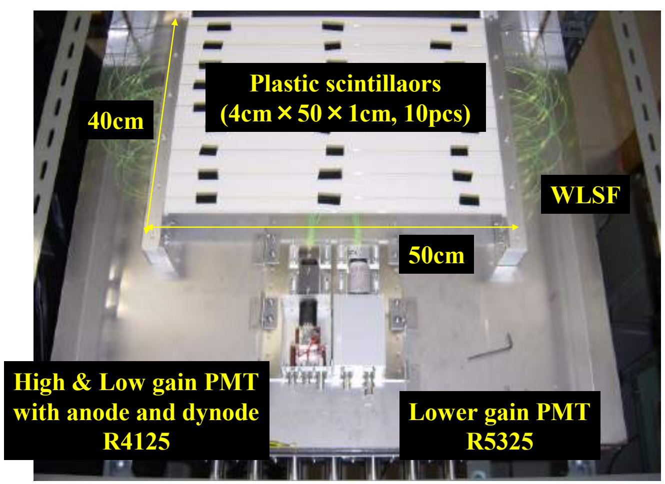




Expected iron flux by 3 years
$E^{2.5}\frac{dJ}{dE}$ [eV$^{1.5}$/m^2 sec sr]
Primary Energy [GeV/particle]
10^1
10^2
10^3
10^4
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Tibet3-all-QGS
Kamioka
JACEE
Cutoff spec.
Power spec.

Proto-type YAC Detector

Prototype of YAC
(Yangbajing Air shower Core detector)



YAC-II Data-taking Started in 2014

Sumary of MD & YAC status

- R&D DONE for MD&YAC
- 5/12 MD Data-taking started in 2014

  YAC-II Data-taking started in 2014
- Good timing for you:

  100 TeV γ astronomy

  CR chemical composition

End