

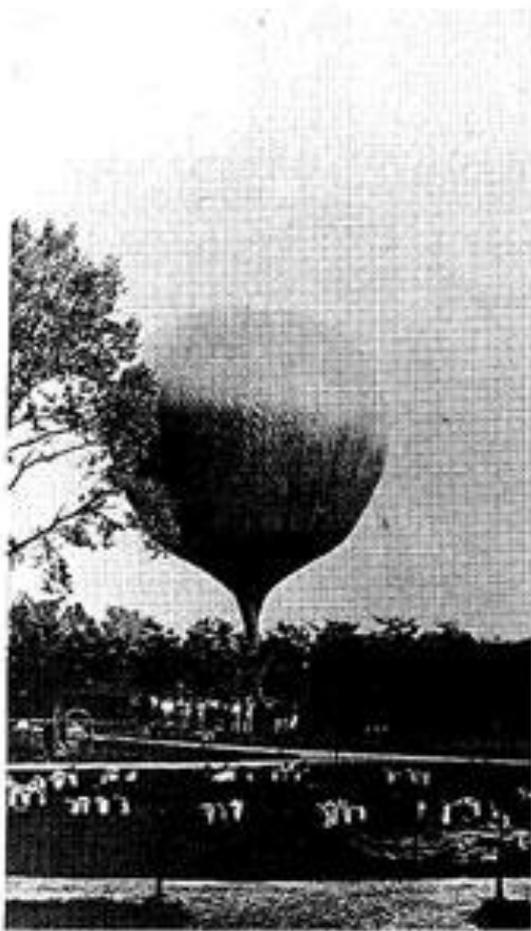
ガンマ線・宇宙線物理

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

瀧田正人, ICRR, U. of Tokyo

Spring School, @ICRR U. of Tokyo,
4/Mar/2021

Discovery of cosmic rays by Victor HESS (in 1912) getting on a balloon



(a)

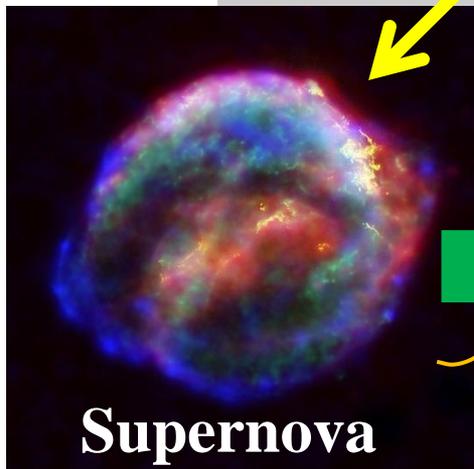
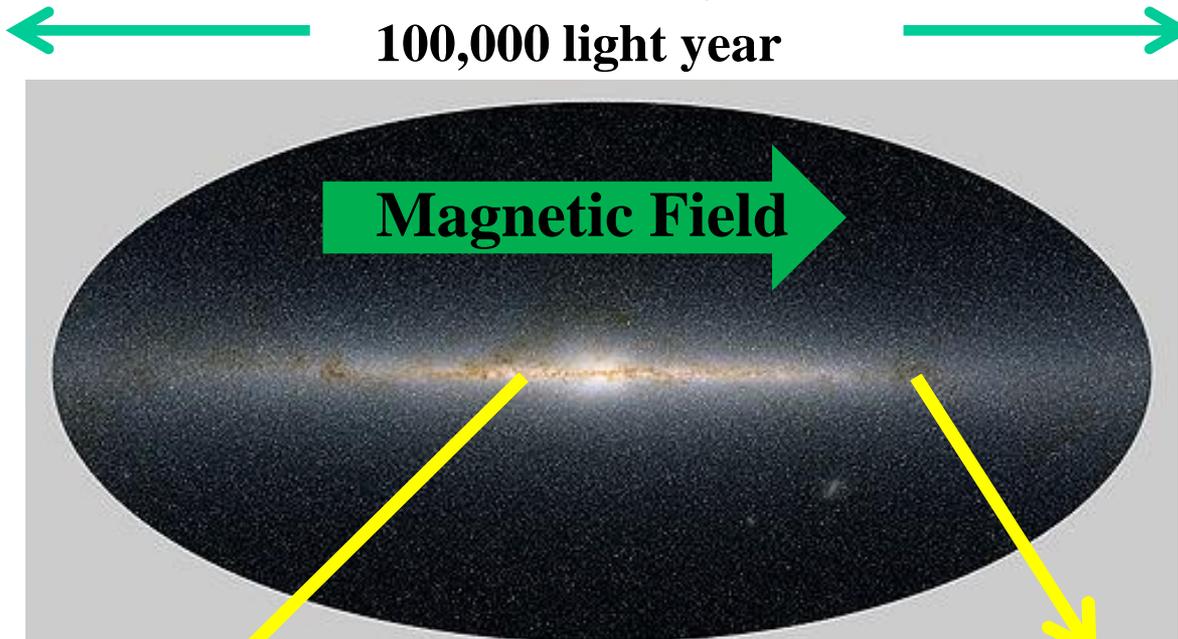


(b)

Cosmic rays: Particles from outer space (H, He, C, N, O,...Fe nuclei)

Our Galaxy

100,000 light year



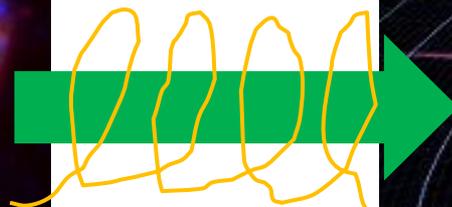
Supernova

**Origin of
Comic Rays !?**



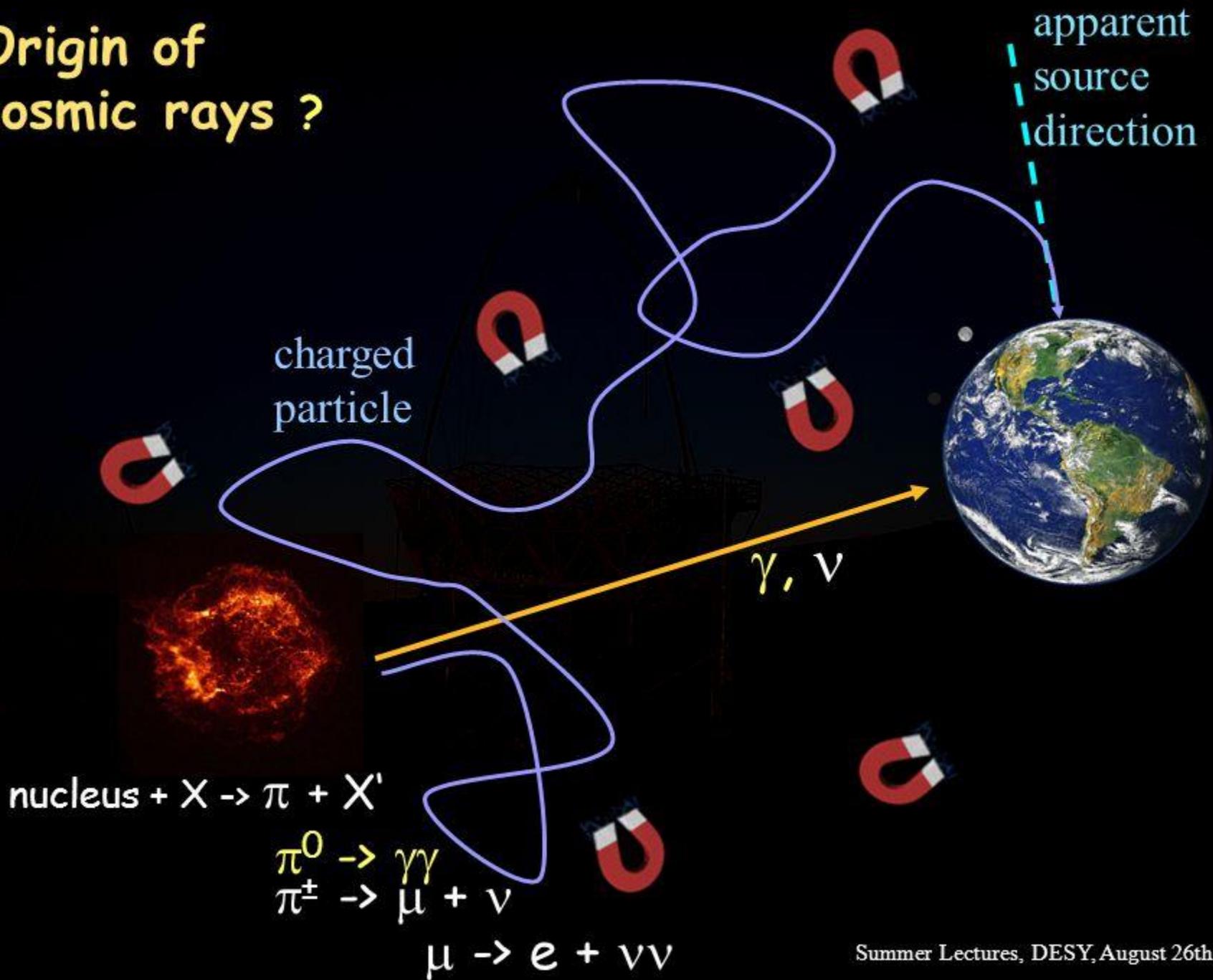
Solar System

**0.001
light year**



**Cosmic
Ray
Trajectory**

Origin of cosmic rays ?



チベット空気シャワー観測装置の研究目的

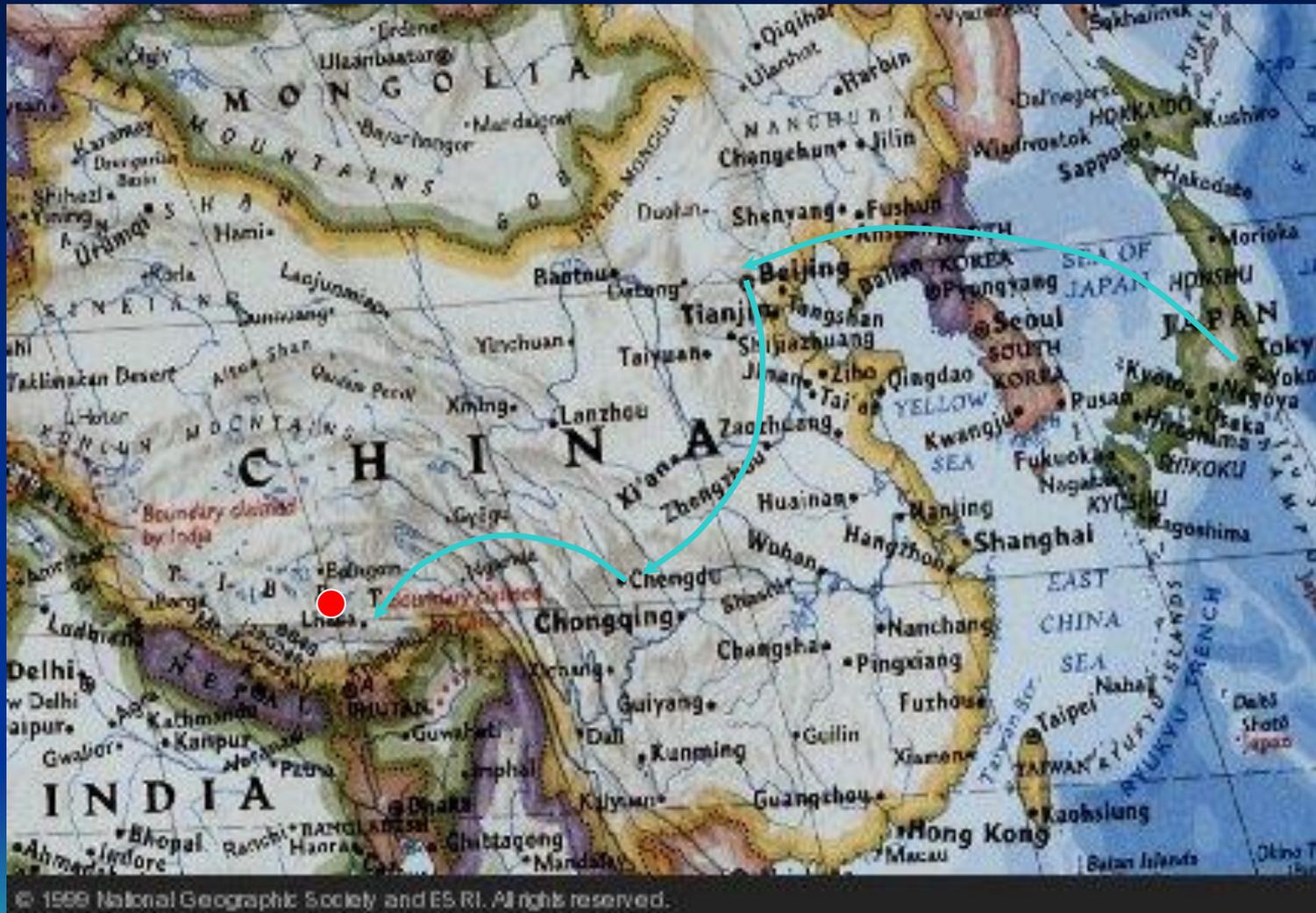
大気チェレンコフ望遠鏡と相補的な
広視野(約2sr)連続観測高エネルギー宇宙線望遠鏡

3~100TeVの高エネルギーガンマ線放射天体の
探索、 $10^{14} \sim 10^{17}$ の一次宇宙線の観測から、
宇宙線の起源、加速機構、伝播の研究を行う。

太陽活動期における“太陽の影”
(太陽による宇宙線の遮蔽効果)を観測し、
太陽近傍および惑星間磁場の大局的構造を知る。



Our site : Tibet



Yangbajing , Tibet, China

$90^{\circ} 53E$, $30^{\circ} 11N$, 4,300 m a.s.l. ($606g/cm^2$)

Why in Tibet?

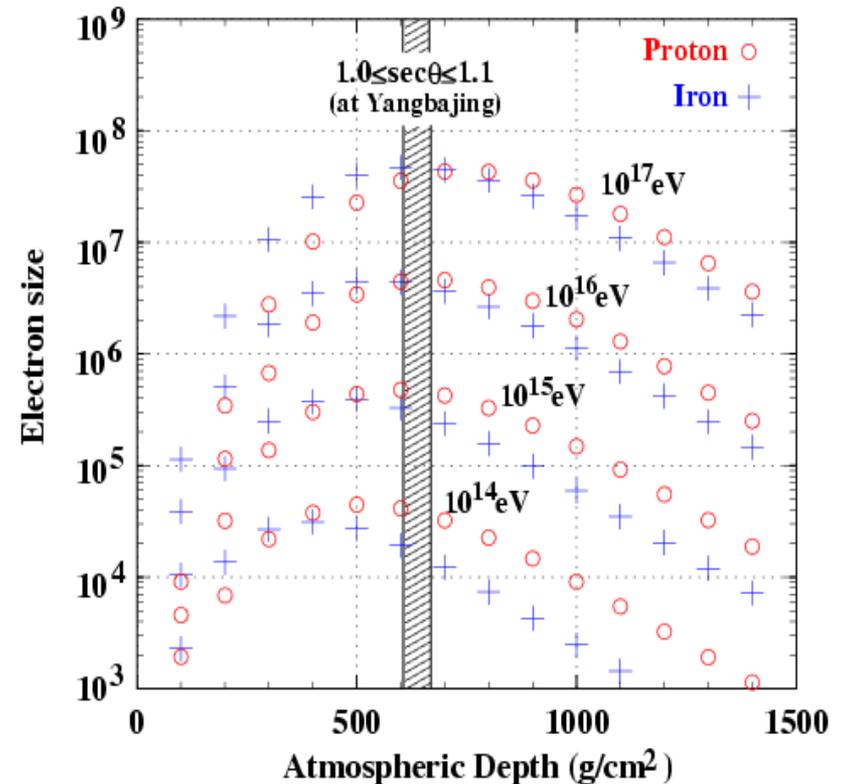
1. 1-100TeV領域宇宙 γ 線

->大気中で減衰

->Sea Level に到達しない。

2. Knee領域宇宙線

->エネルギー決定精度の
原子核依存性が少ない。





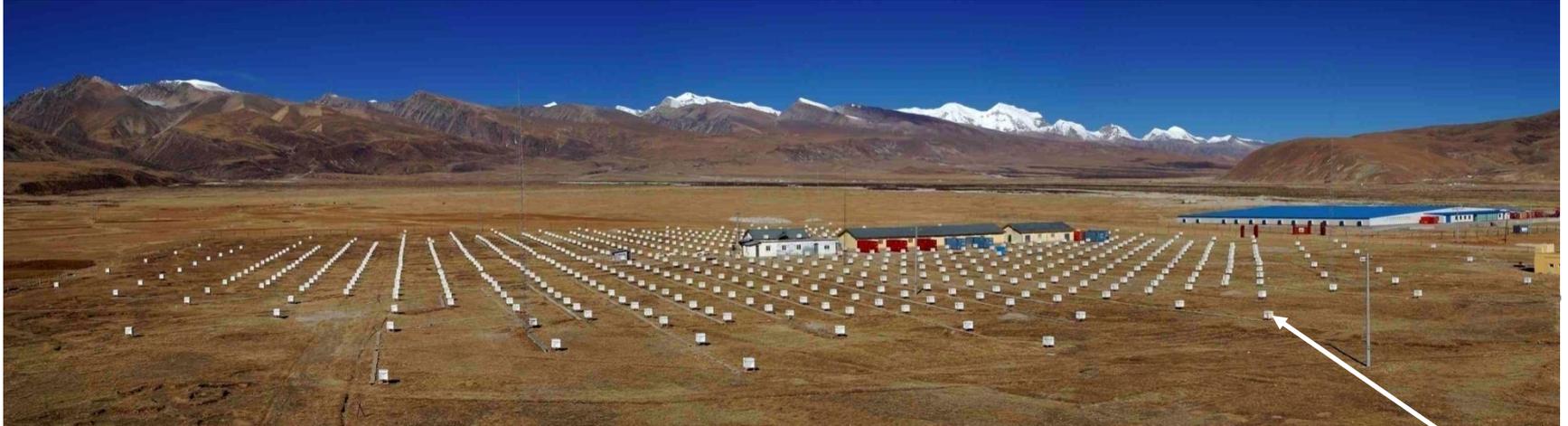
The Tibet AS γ Collaboration



M. Amenomori(1), Y. W. Bao(2), X. J. Bi(3), D. Chen(4), T. L. Chen(5), W. Y. Chen(3), Xu Chen(3), Y. Chen(2), Cirennima(5), S. W. Cui(6), Danzengluobu(5), L. K. Ding(3), J. H. Fang(3,7), K. Fang(3), C. F. Feng(8), Zhaoyang Feng(3), Z. Y. Feng(9), Qi Gao(5), A. Gomi(10), Q. B. Gou(3), Y. Q. Guo(3), Y. Y. Guo(3), H. H. He(3), Z. T. He(6), K. Hibino(11), N. Hotta(12), Haibing Hu(5), H. B. Hu(3), J. Huang(3), H. Y. Jia(9), L. Jiang(3), P. Jiang(4), H. B. Jin(4), K. Kasahara(13), Y. Katayose(10), C. Kato(14), S. Kato(15), K. Kawata(15), M. Kozai(16), D. Kurashige(10), Labaciren(5), G. M. Le(17), A. F. Li(18,8,3), H. J. Li(5), W. J. Li(3,9), Y. Li(4), Y. H. Lin(3,7), B. Liu(19), C. Liu(3), J. S. Liu(3), L. Y. Liu(4), M. Y. Liu(5), W. Liu(3), X. L. Liu(4), Y.-Q. Lou(20, 21, 22), H. Lu(3), X. R. Meng(5), K. Munakata(14), H. Nakada(10), Y. Nakamura(3, 15), Y. Nakazawa(23), H. Nanjo(1), C. C. Ning(5), M. Nishizawa(24), M. Ohnishi(15), T. Ohura(10), S. Okukawa(10), S. Ozawa(25), L. Qian(4), X. Qian(4), X. L. Qian(26), X. B. Qu(27), T. Saito(28), M. Sakata(29), T. Sako(15), T. K. Sako(15), J. Shao(3,8), M. Shibata(10), A. Shiomi(23), H. Sugimoto(30), W. Takano(11), M. Takita(15), Y. H. Tan(3), N. Tateyama(11), S. Torii(31), H. Tsuchiya(32), S. Udo(11), H. Wang(3), Y. P. Wang(5), Wangdui(5), H. R. Wu(3), Q. Wu(5), J. L. Xu(4), L. Xue(8), Y. Yamamoto(29), Z. Yang(3), Y. Q. Yao(4), J. Yin(4), Y. Yokoe(15), N. P. Yu(4), A. F. Yuan(5), L. M. Zhai(4), C. P. Zhang(4), H. M. Zhang(3), J. L. Zhang(3), X. Zhang(2), X. Y. Zhang(8), Y. Zhang(3), Yi Zhang(33), Ying Zhang(3), S. P. Zhao(3), Zhaxisangzhu(5) and X. X. Zhou(9)

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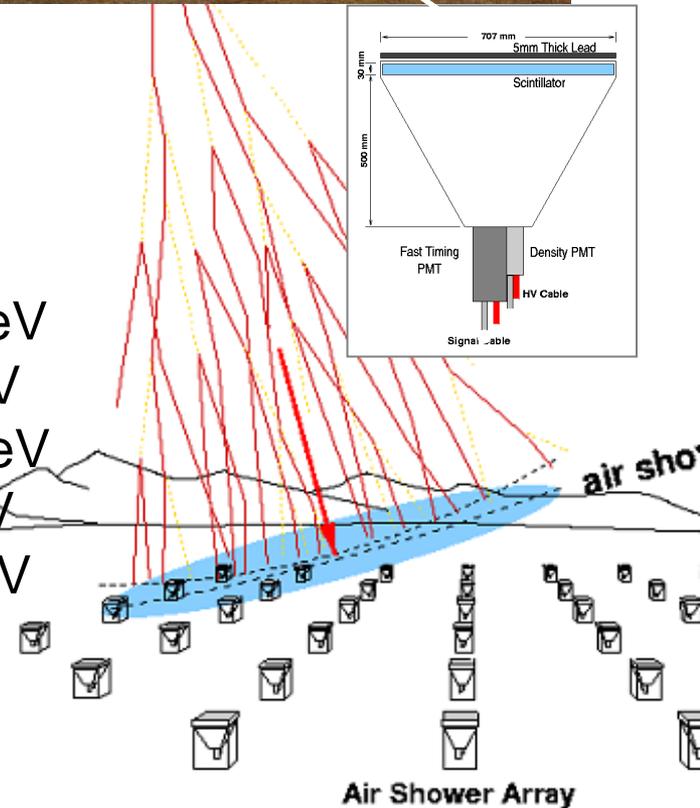
Tibet-III Air Shower (AS) Array



4,300 m a.s.l. (606 g/cm²)

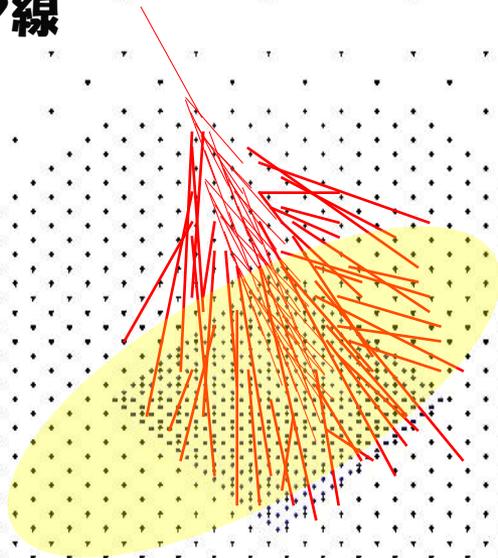
- ❑ Number of Scinti. Det.
- ❑ Effective Area for AS
- ❑ Energy region
- ❑ Angular Resolution
(Gamma rays)
- ❑ Energy Resolution
(Gamma rays)
- ❑ F.O.V.
- ❑ Trigger Rate

0.5 m² x 789
~37,000 m²
~3TeV - 100 PeV
~0.4° @10 TeV
~0.2° @100 TeV
~50% @10 TeV
~20% @100TeV
~2 sr
1.7 KHz

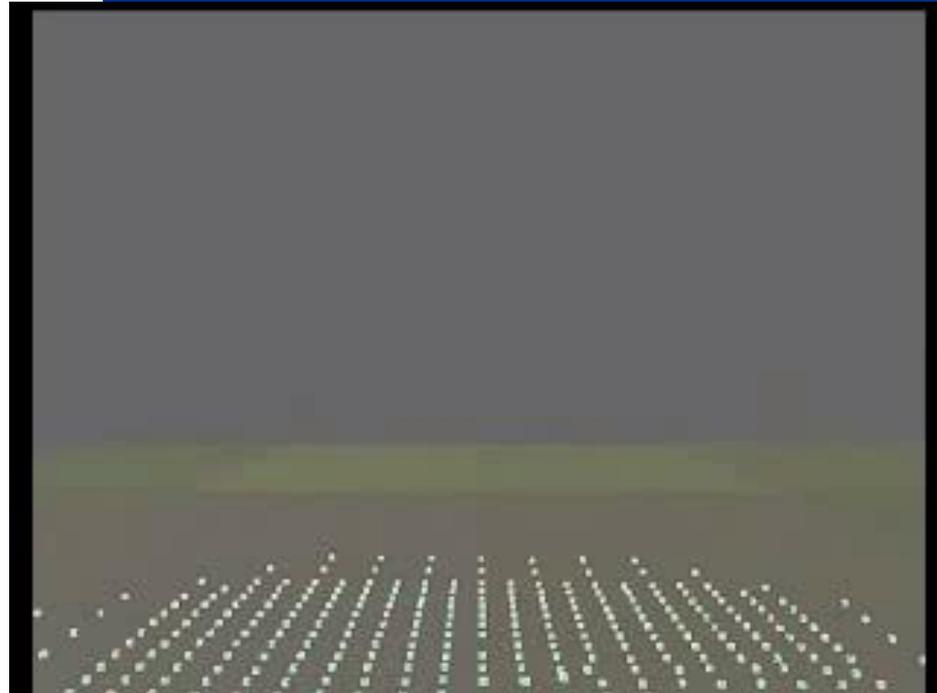


空気シャワー

高エネルギー原子核宇宙線（陽子等）や
宇宙ガンマ線



空気シャワー（電子・
陽電子・ガンマ線
ミューオン）



Air Shower Detection

2nd particle density

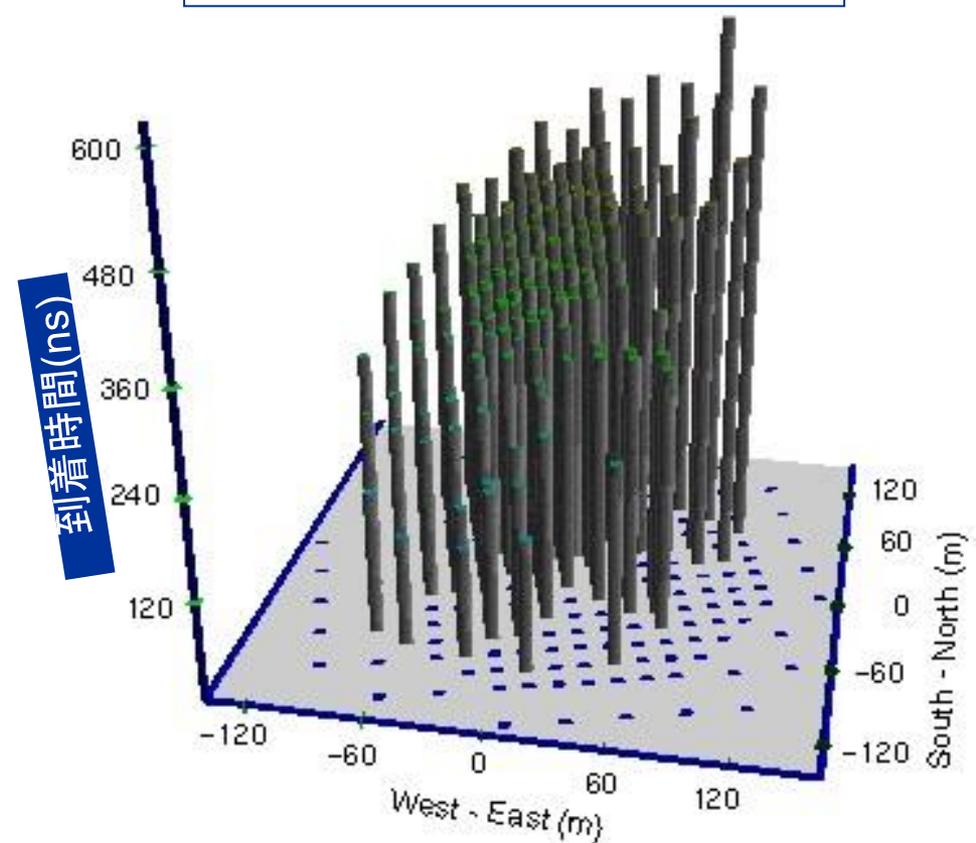
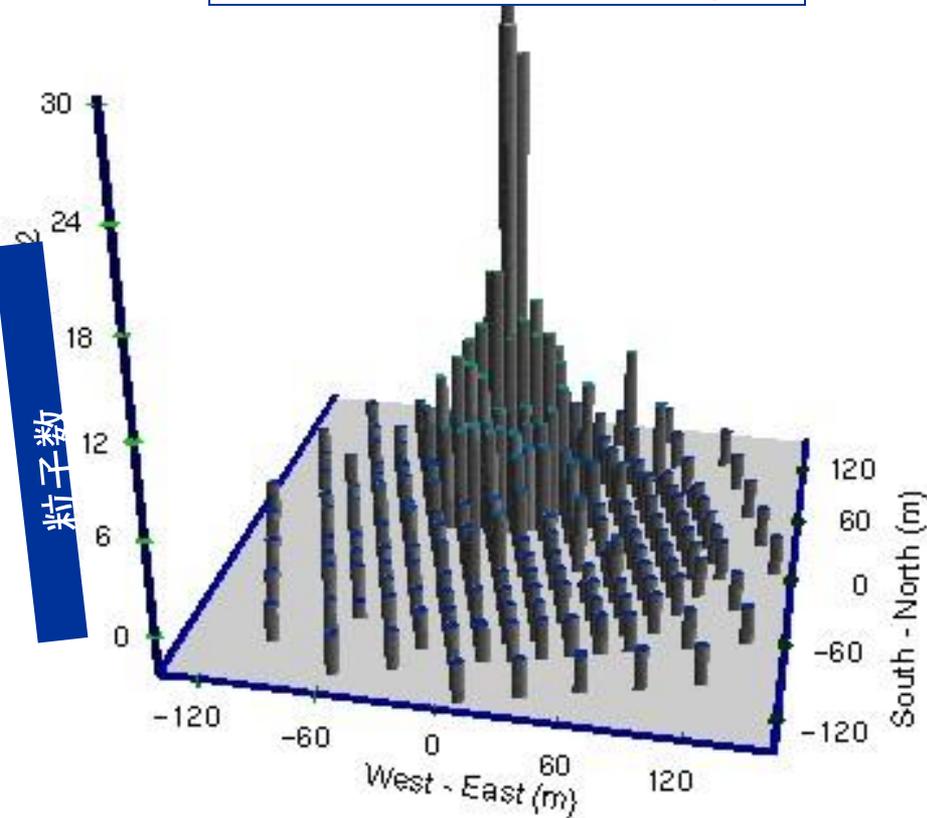


Cosmic ray energy

2nd particle timing



Cosmic ray direction

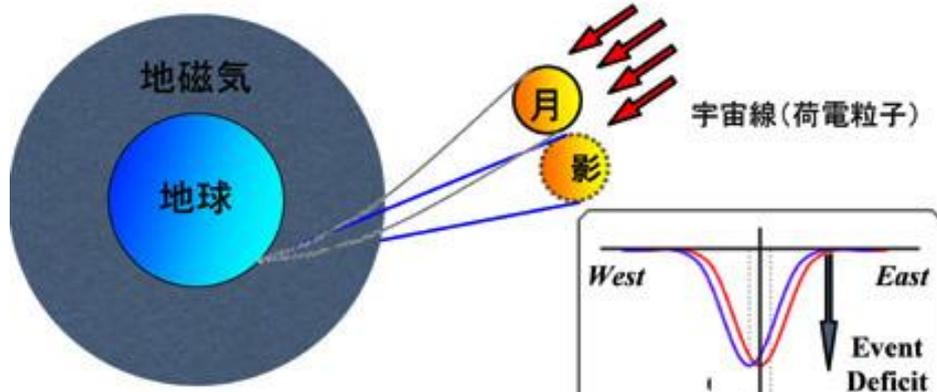


Air shower rate triggered by Tibet III ~1700Hz

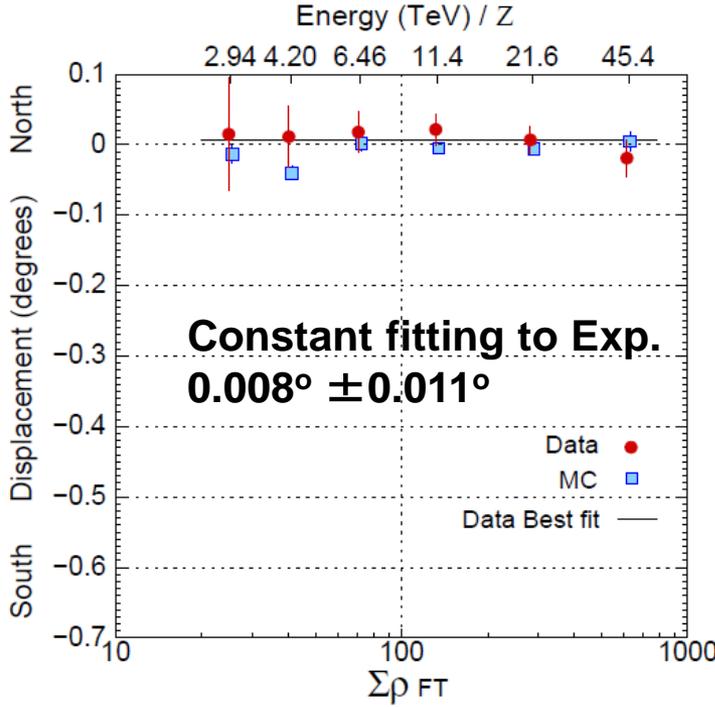
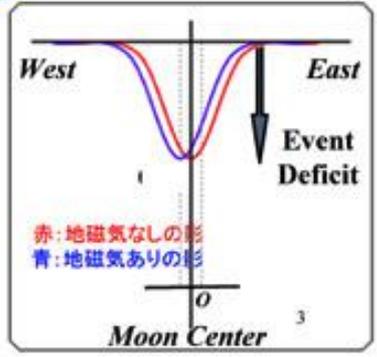
Performance by Moon's Shadow

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

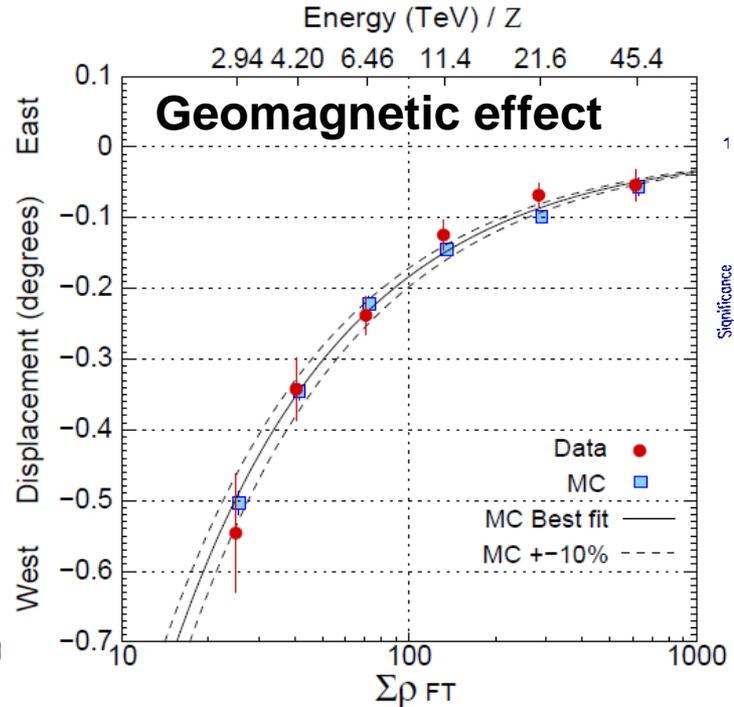
- ❑ Absolute Energy Scale
- ❑ Angular Resolution
- ❑ Pointing Accuracy



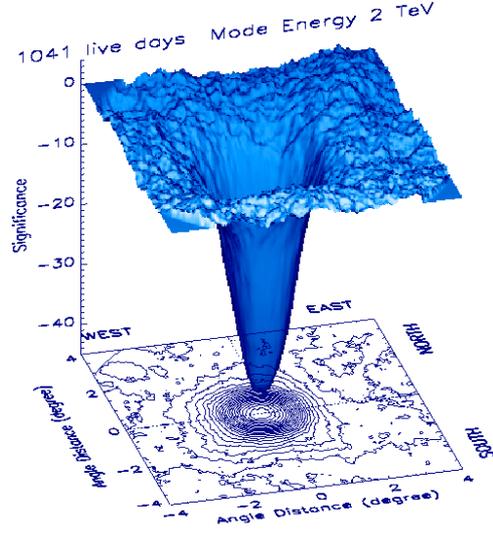
地磁気による影のずれ
 ~ 0.25° West @ mode 3TeV



Pointing Error
 < 0.011°

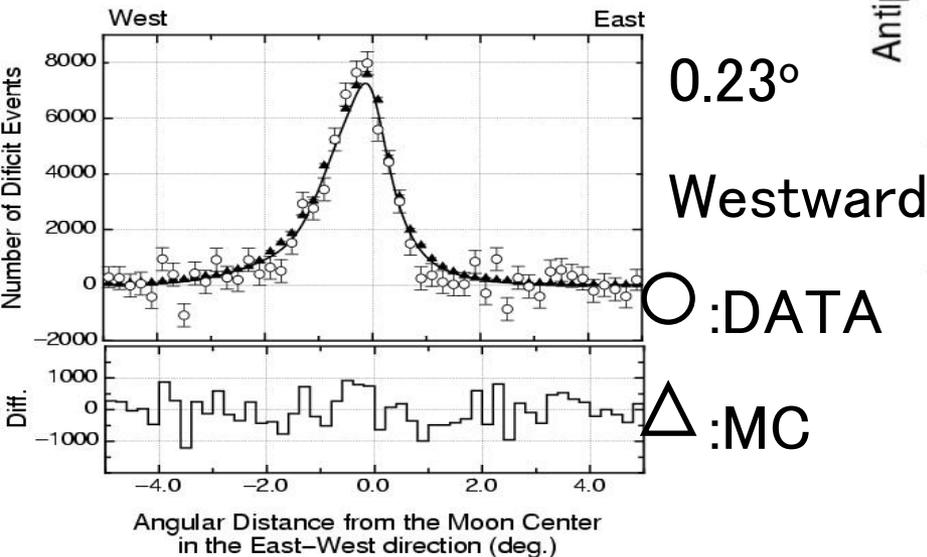
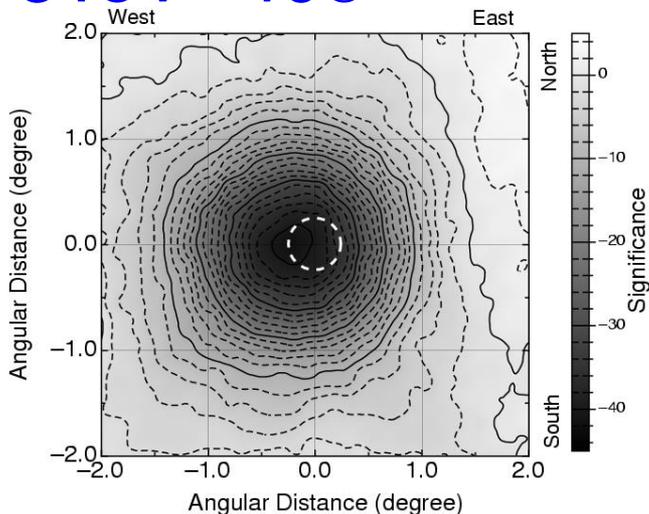


Absotute Energy Scale Error < 12%
 +4.5%(±8.6stat.±6.7syst.)%

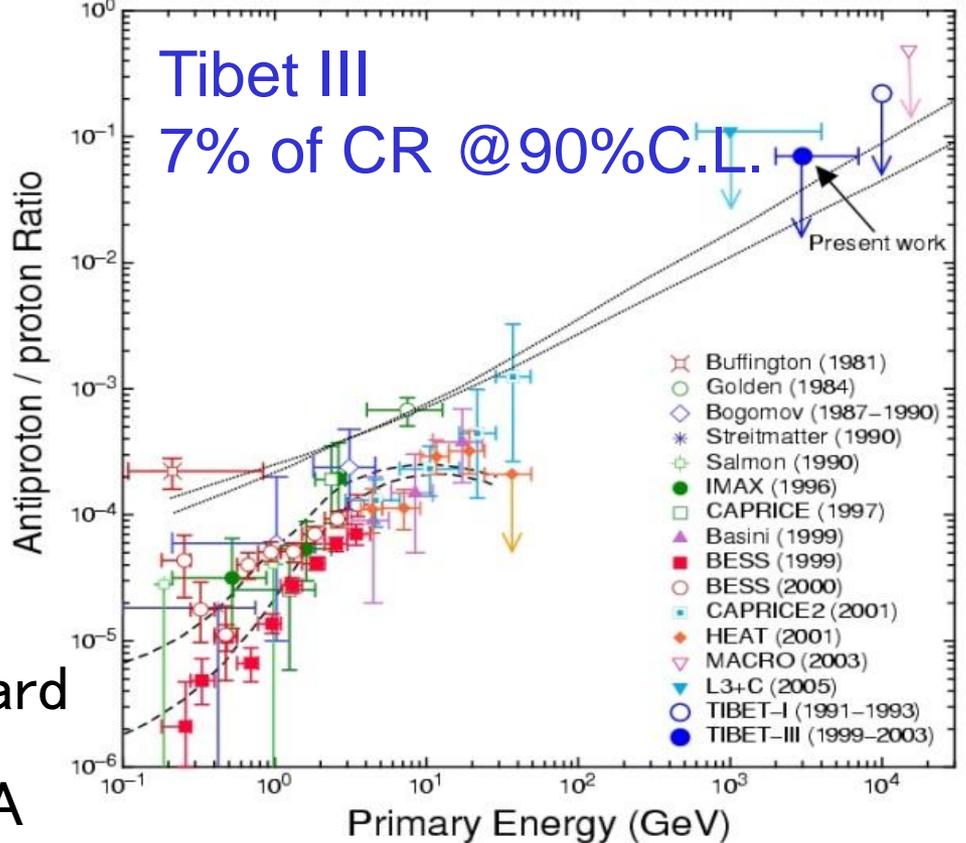


Search for TeV anti-protons by the Moon's shadow

3TeV 40 σ



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



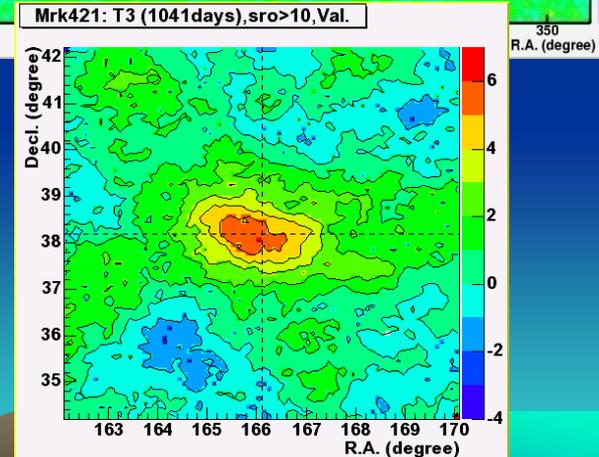
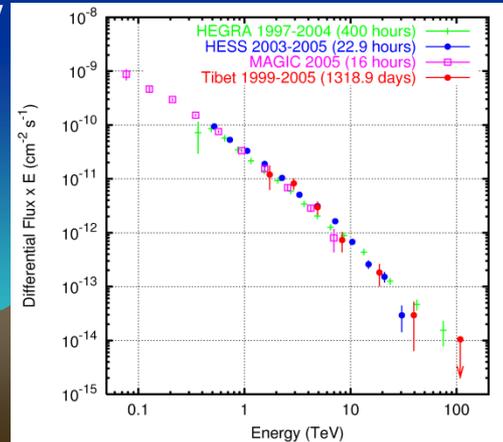
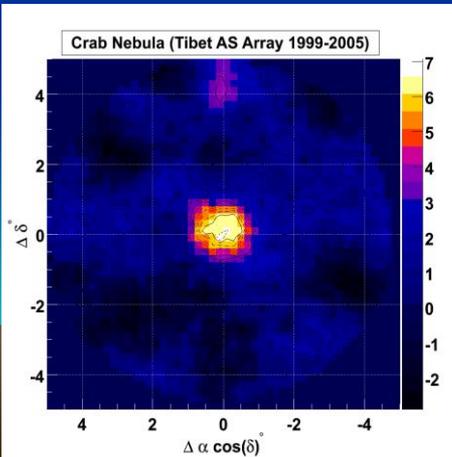
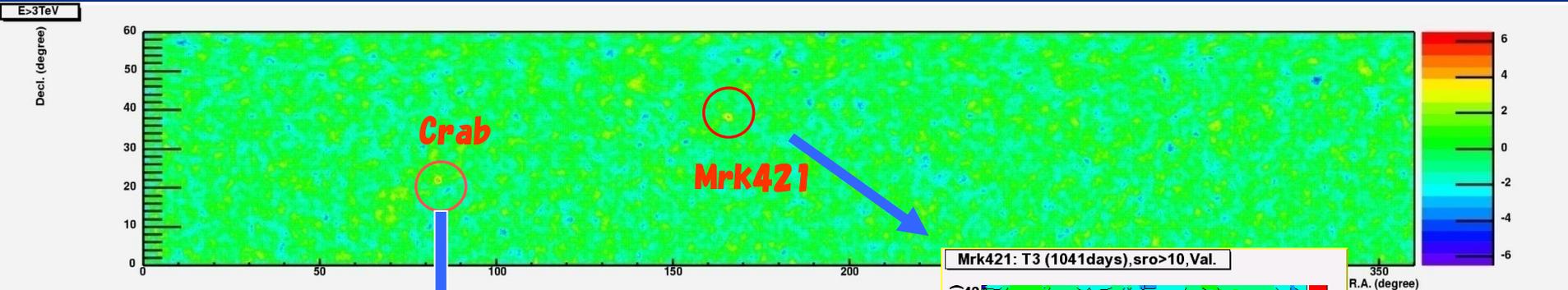
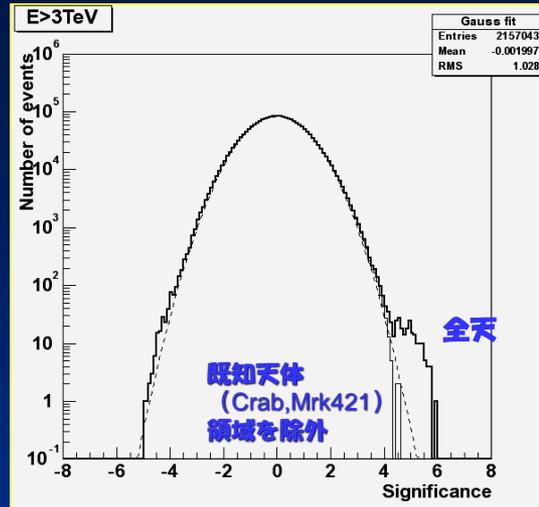
Dashed line: leaky box
M.Simon et al. ApJ 499 (1998)250.
Dotted line: extragalactic anti-matter model
S.A. Stephan et al. Space Sci. Rev. 46 (1987) 31.

ガンマ線放射天体の探索

千ベットで観測された点源

- ★ 超新星残骸 かに星雲からの定常ガンマ線
- ★ 活動的銀河核 Mrk421, Mrk501からのフレアガンマ線

1999—2003年 全北天探索

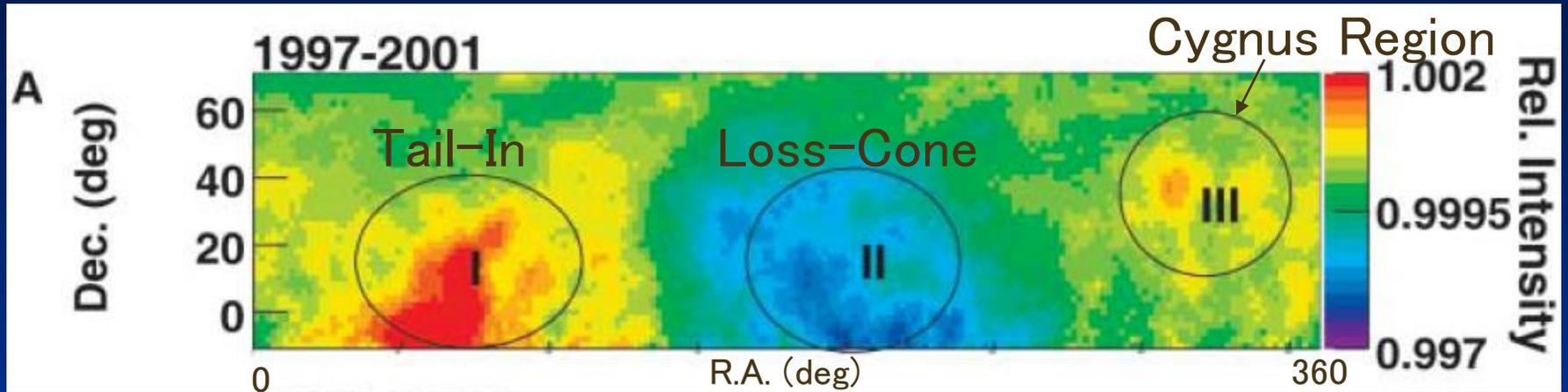


2000—2001年フレア

Cosmic Ray Anisotropy at multi-TeV energies (宇宙線)の伝播

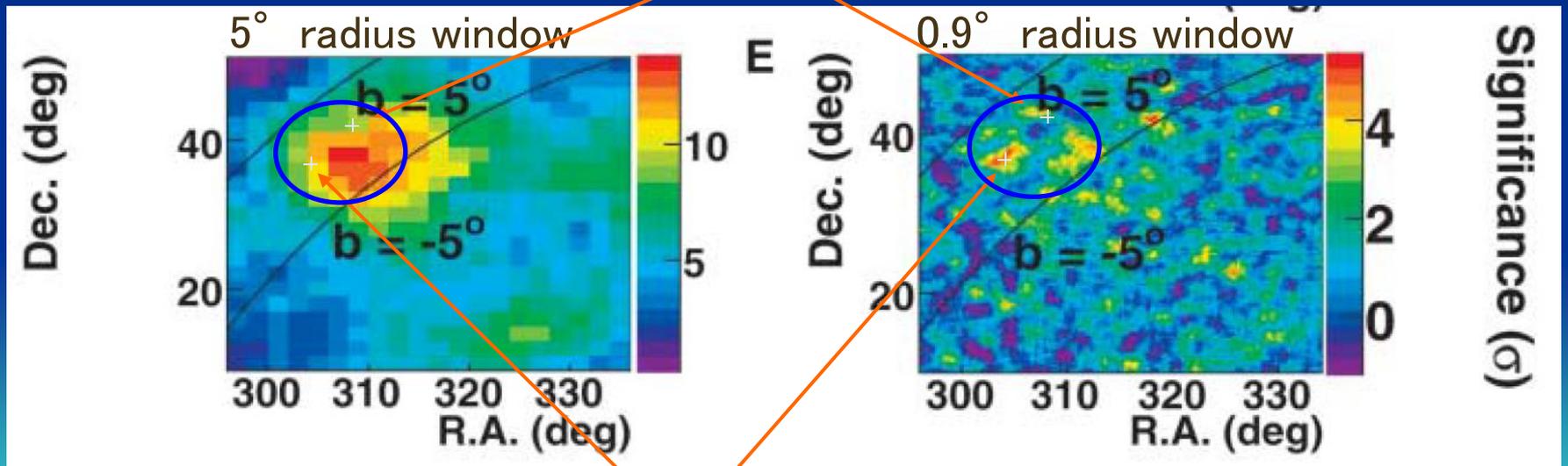
2D Large-scale Anisotropy Map

Amenomori et al, Science, 314, 439 (2006)



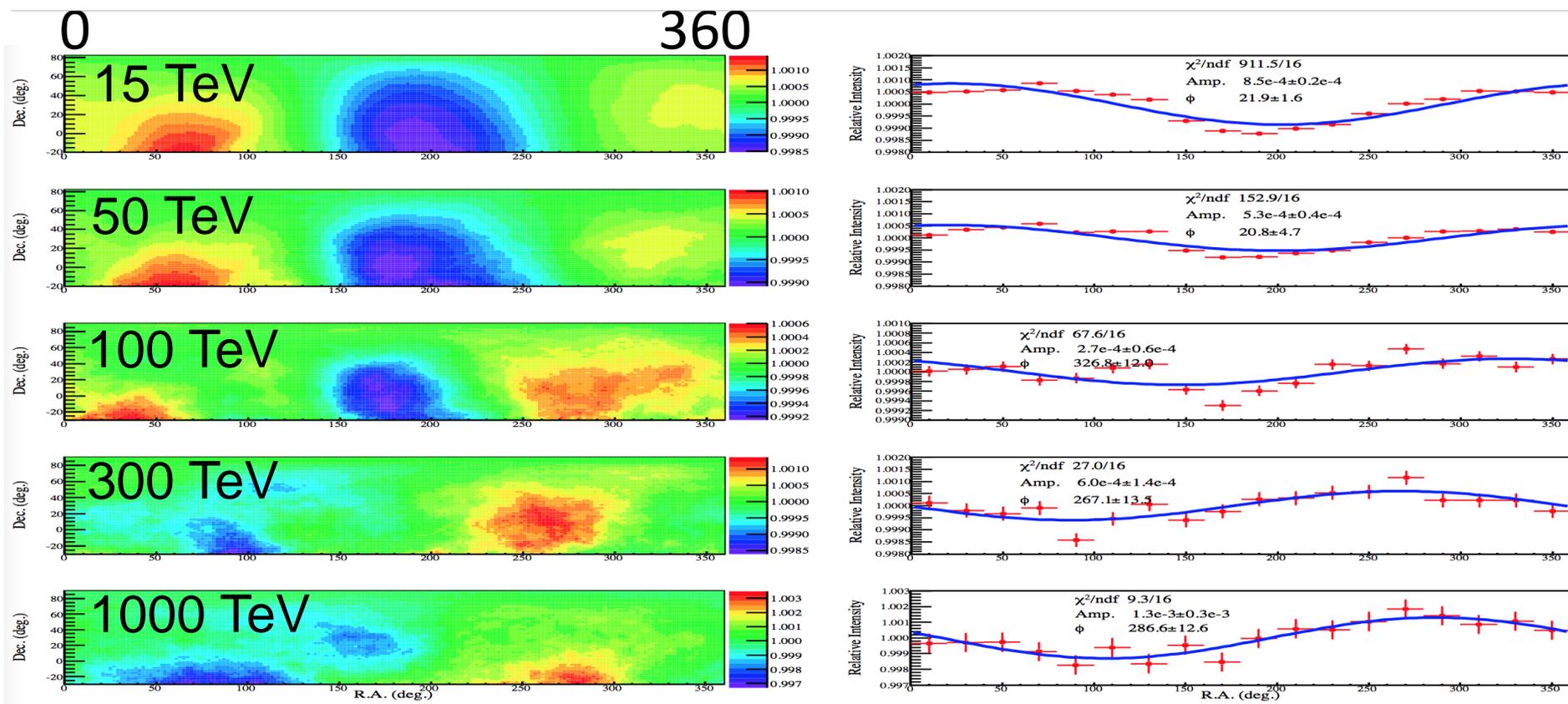
Cygnus Region

① MGRO J2033+42



② MGRO J2019+37

10-1000TeV CR Sidereal Anisotropy (Tibet)

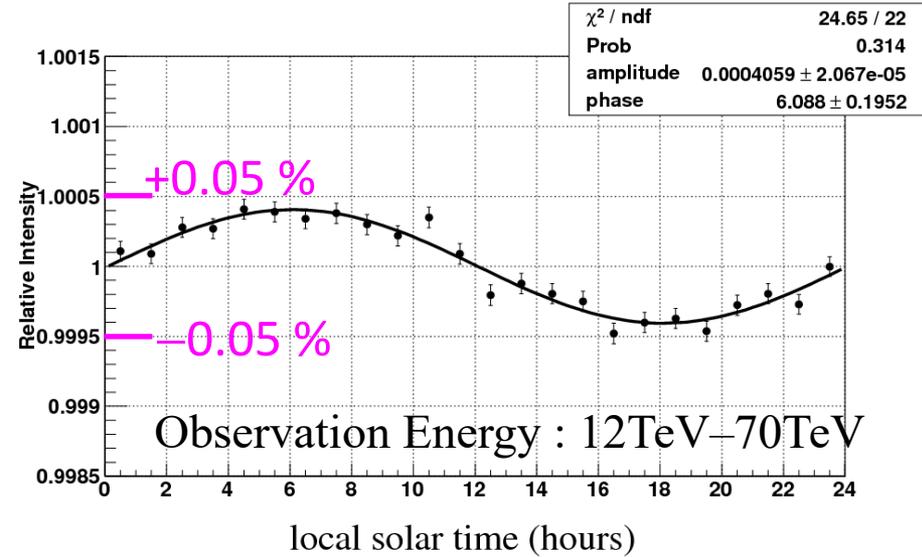
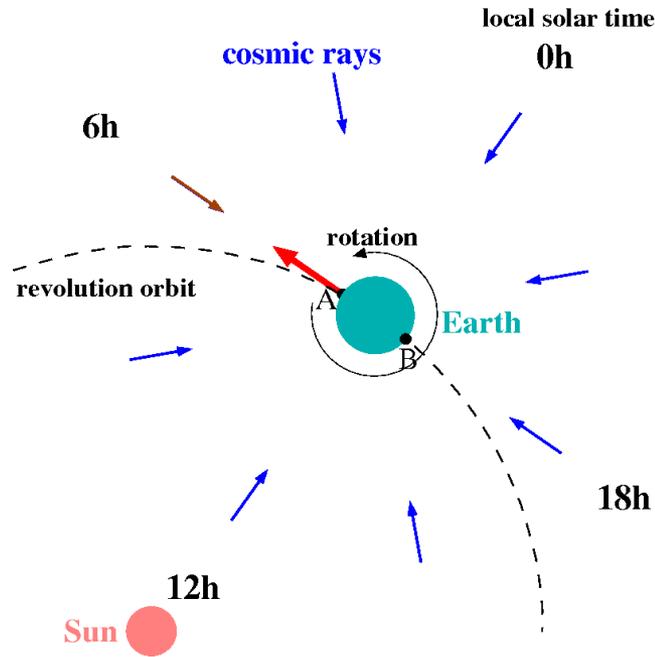


M. Amenomori et al, ApJ, **836**, 153-1-7, (2016)

>300 TeV new component!, consistent with IceCube >400 TeV

Compton-Getting Anisotropy at Solar Time Frame

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



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

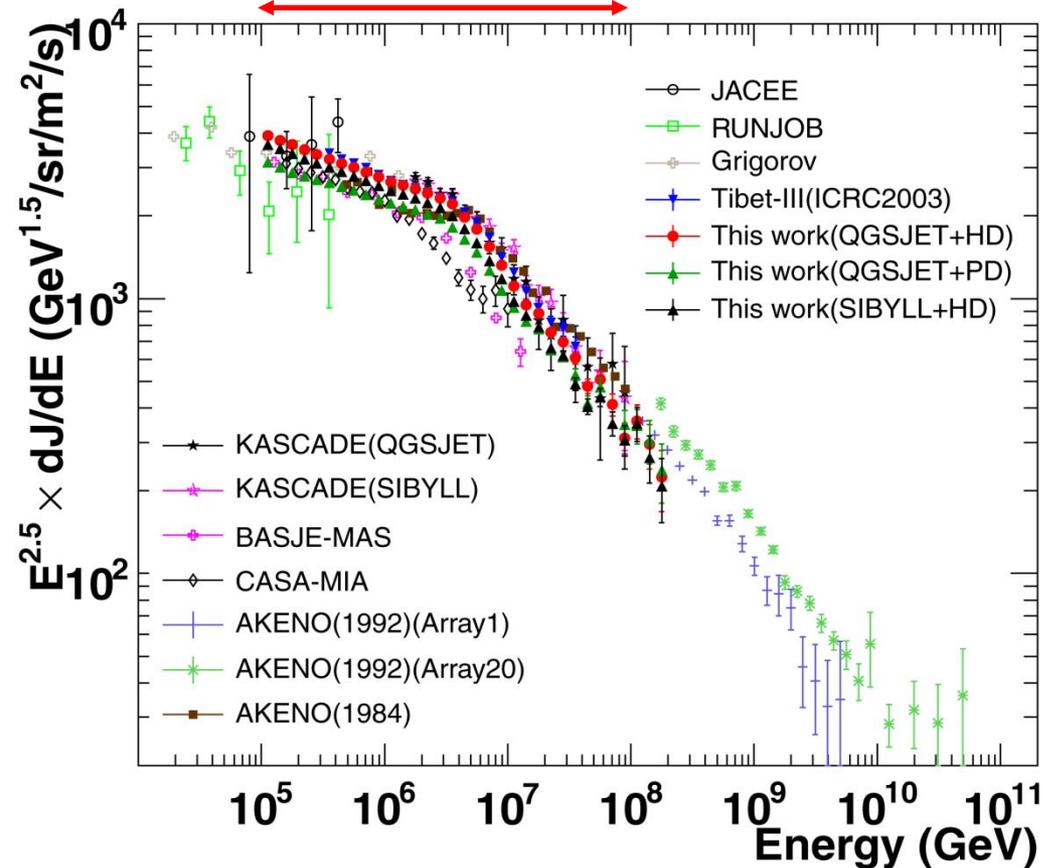
➔ CG detected at 19.6σ consistent with expected

- Reliability and calibration for sidereal anisotropy ($\sim 0.01\%$)
- Only Tibet AS γ experiment showing a clear sinusoidal curve

All Particle Energy Spectrum in the Knee region

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

$10^{14} \text{ eV} \sim 10^{17} \text{ eV}$ (3 orders)

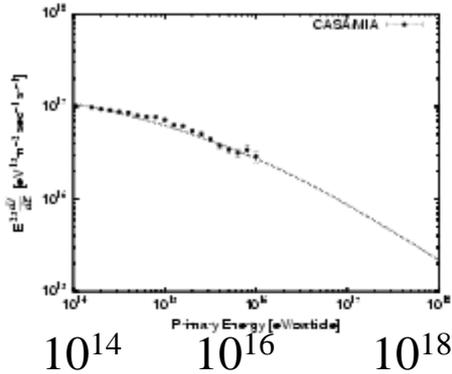


Model	Index of spectrum	Energy range (eV)
QGSJET +HD	-2.67 ± 0.01	$< 10^{15} \text{ eV}$
	-3.10 ± 0.01	$> 4 \times 10^{15} \text{ eV}$
QGSJET +PD	-2.65 ± 0.01	$< 10^{15} \text{ eV}$
	-3.08 ± 0.01	$> 4 \times 10^{15} \text{ eV}$
SIBYLL +HD	-2.67 ± 0.01	$< 10^{15} \text{ eV}$
	-3.12 ± 0.01	$> 4 \times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

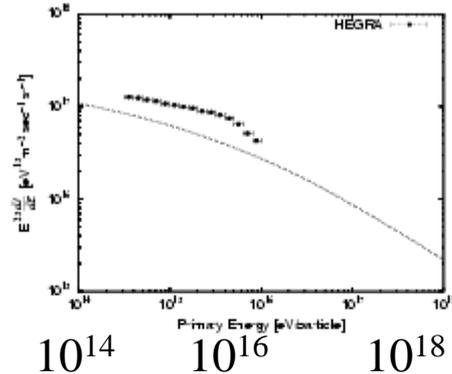
All particle spectrum around the knee

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

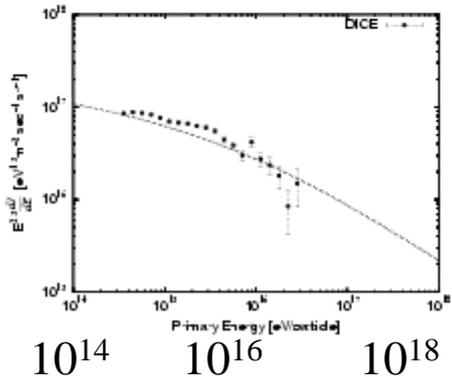
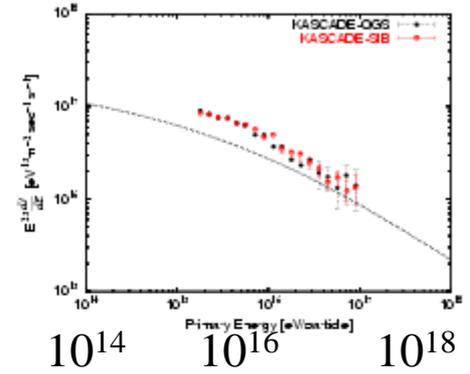
CASA/MIA



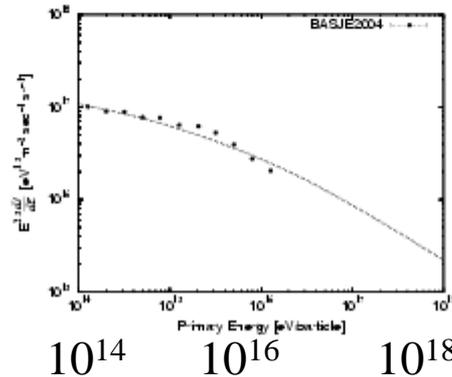
HEGRA



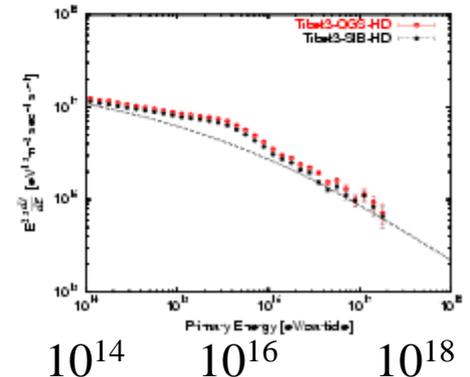
KASCADE



DICE



BASJE



TIBET

Extra component

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

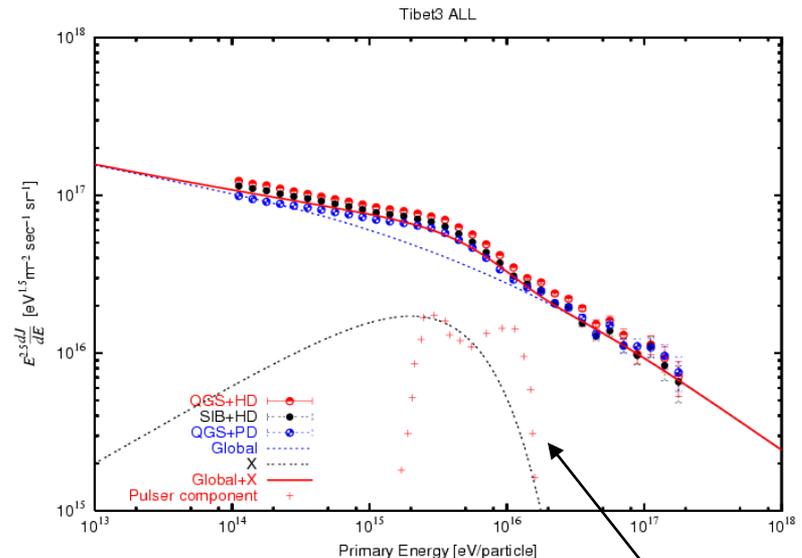
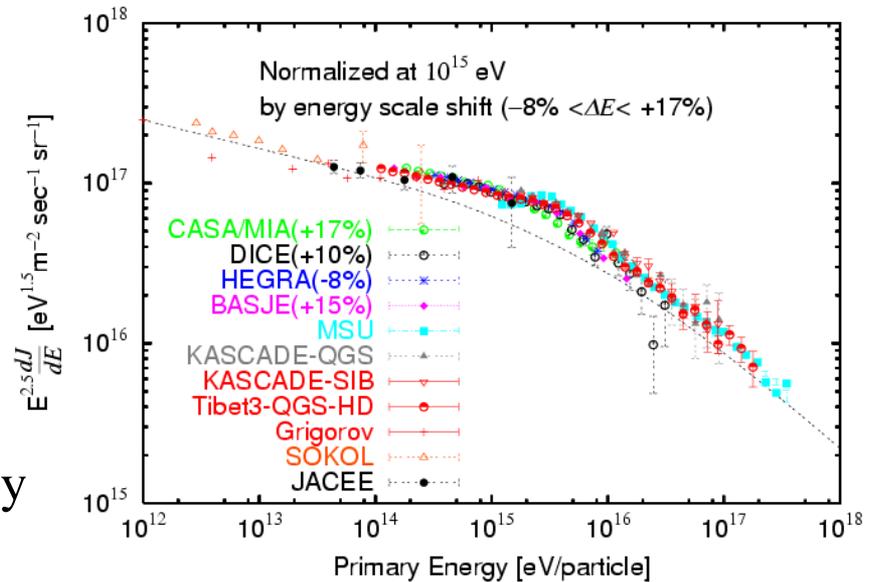
Extra component can be approximated by

$$E^{-2} \exp\left[-\frac{E}{4\text{PeV}}\right],$$

suggesting **nearby source(s)**.

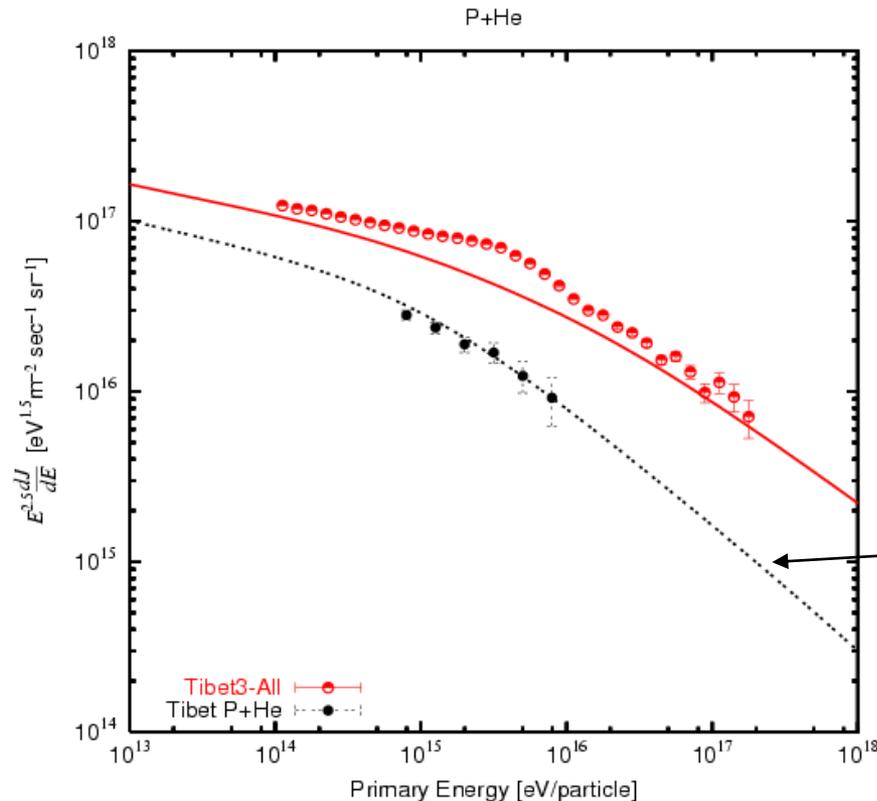
Since P and He component do not show the excess at the knee, the extra component should be attributed to heavy element such as Fe.

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



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

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



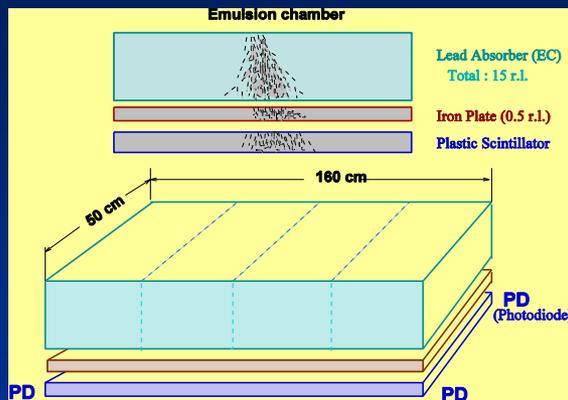
Tibet All particle
Data vs. Expected by
multiple source
model

P+He
Data vs. Expected by
multiple source
model

一次宇宙線陽子・He成分の観測

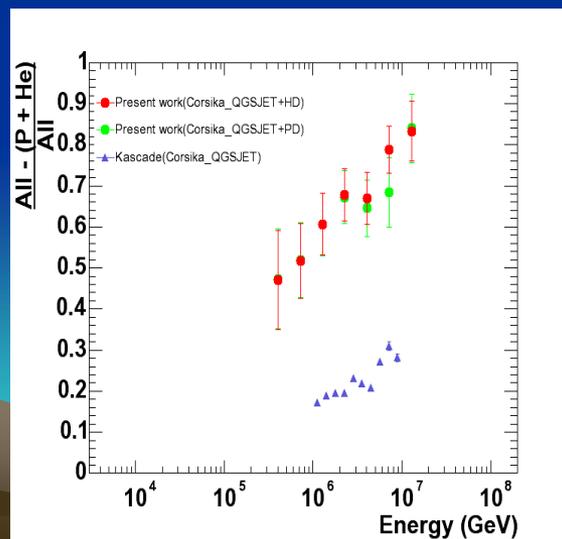
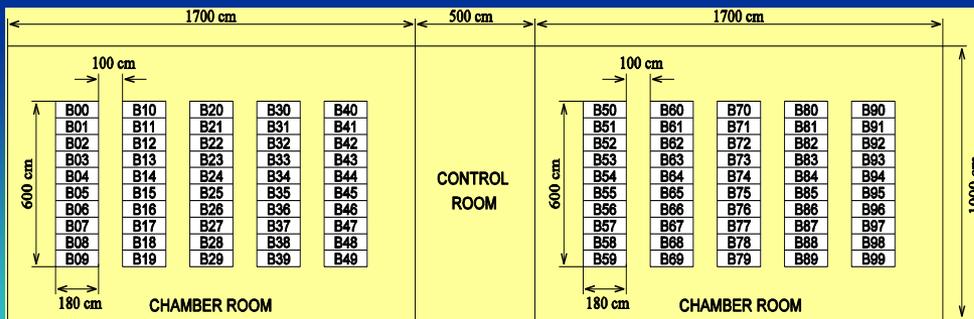
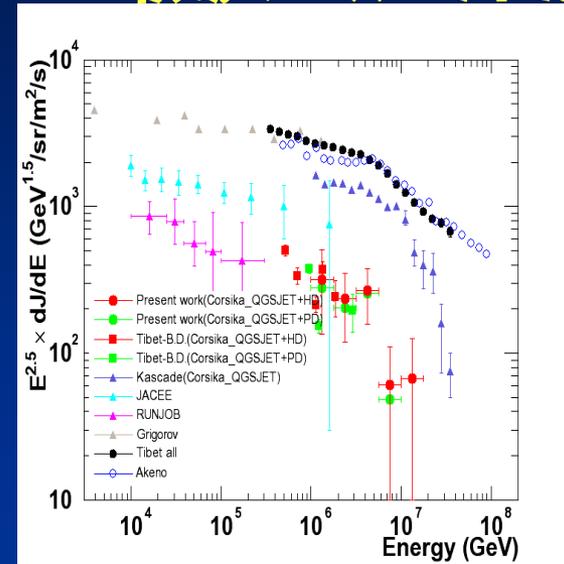
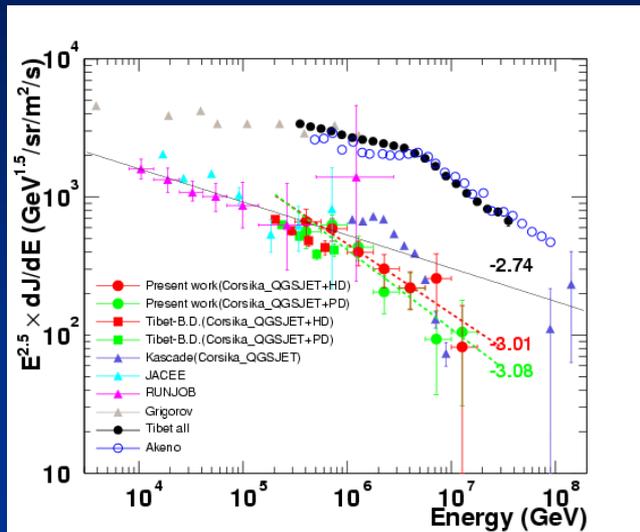
Knee領域の陽子スペクトル

Knee領域のHeスペクトル



Burst検出器 : 100台

検出器総面積 : 80 m²

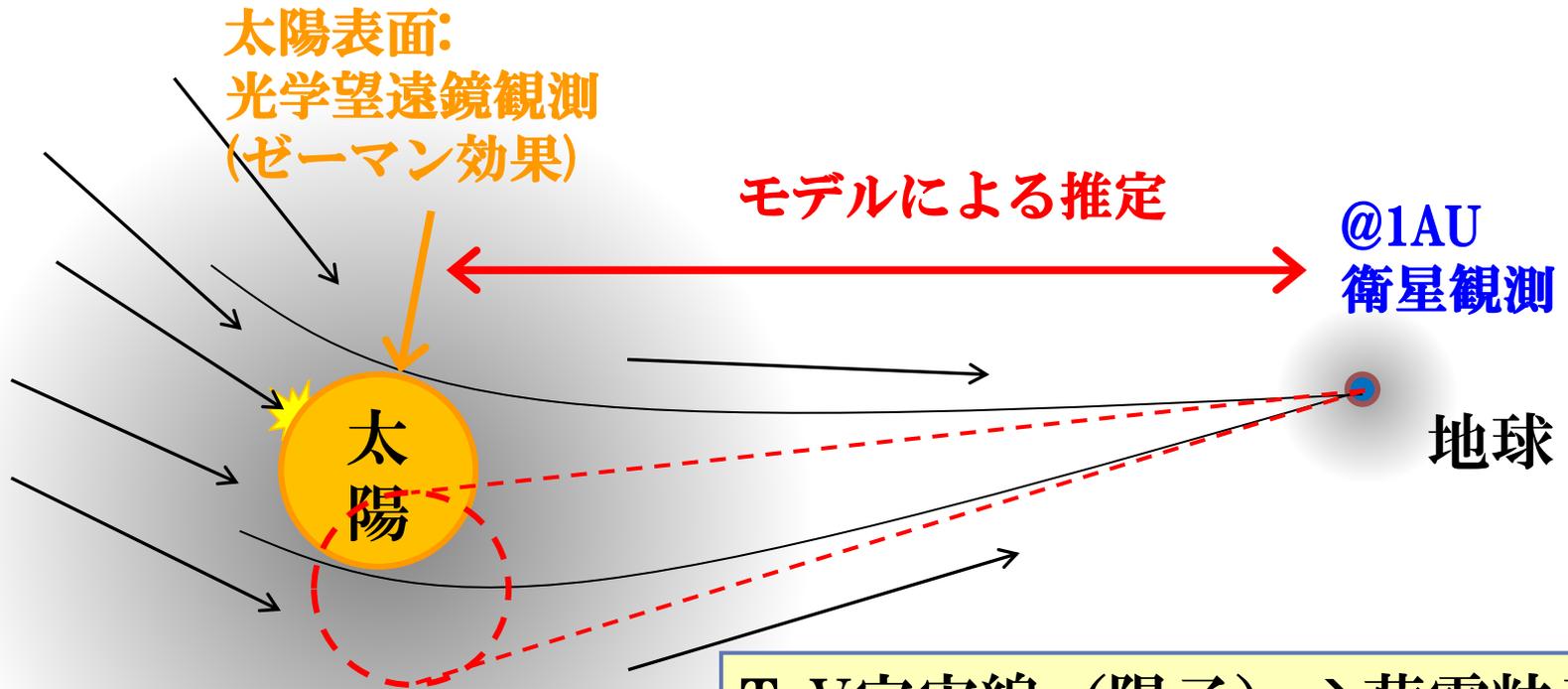


エネルギーが
高いと

重粒子の割合
が増加

「太陽の影」影

太陽による宇宙線の遮蔽



「太陽の影」の
深さ、方向、形に影響

TeV宇宙線 (陽子) → 荷電粒子
ラーモア半径
~7.4AU (B=30 μ G 地球近辺)
~0.16 R_{\odot} (B=300mG 太陽近辺)
→ 太陽磁場構造のプローブ!

仮定する太陽圏の磁場

コロナ磁場 → 2つのSource Surface モデル (PFSS / CSSS)

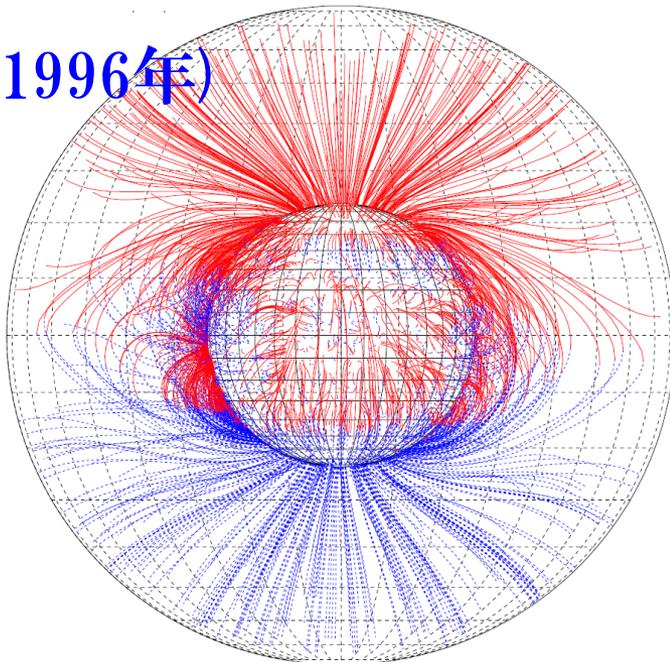
Kitt Peak の太陽表面磁場の観測から推測する
太陽の1自転周期(~27日)ごとの平均モデル

惑星間磁場 → パーカー・スパイラルモデル

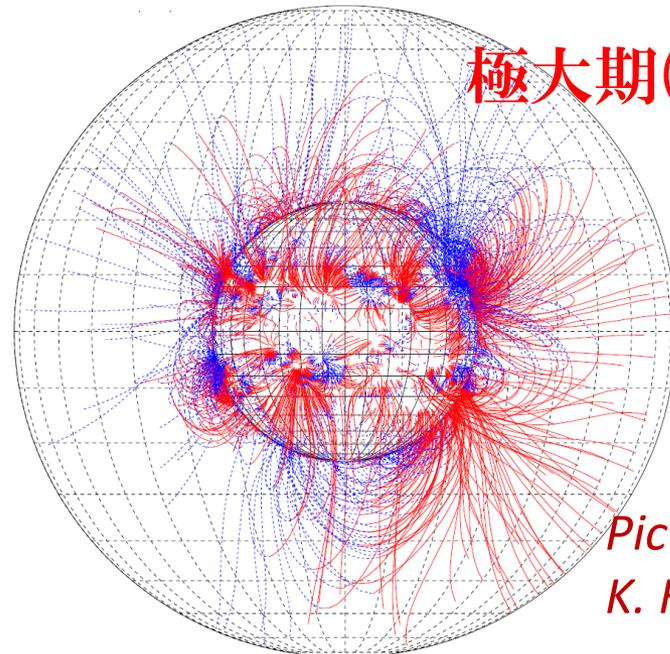
太陽風速度は名大IPS観測の緯度依存を考慮

地磁気 → 双極子磁場モデル

極小期(1996年)
PFSS



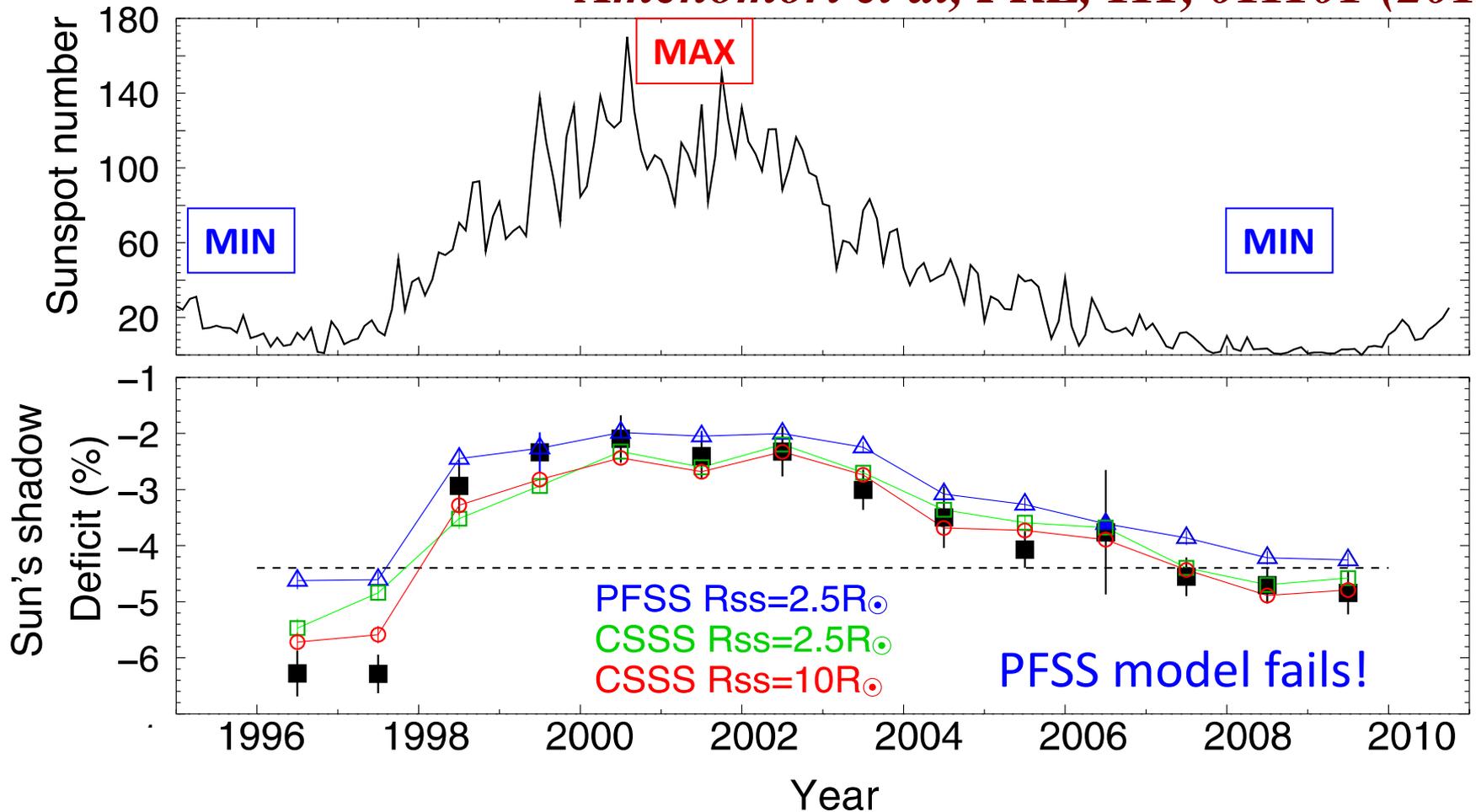
極大期(2000年)
PFSS



*Pictures from
K. Hakamada*

Past Results (Tibet-II >10TeV)

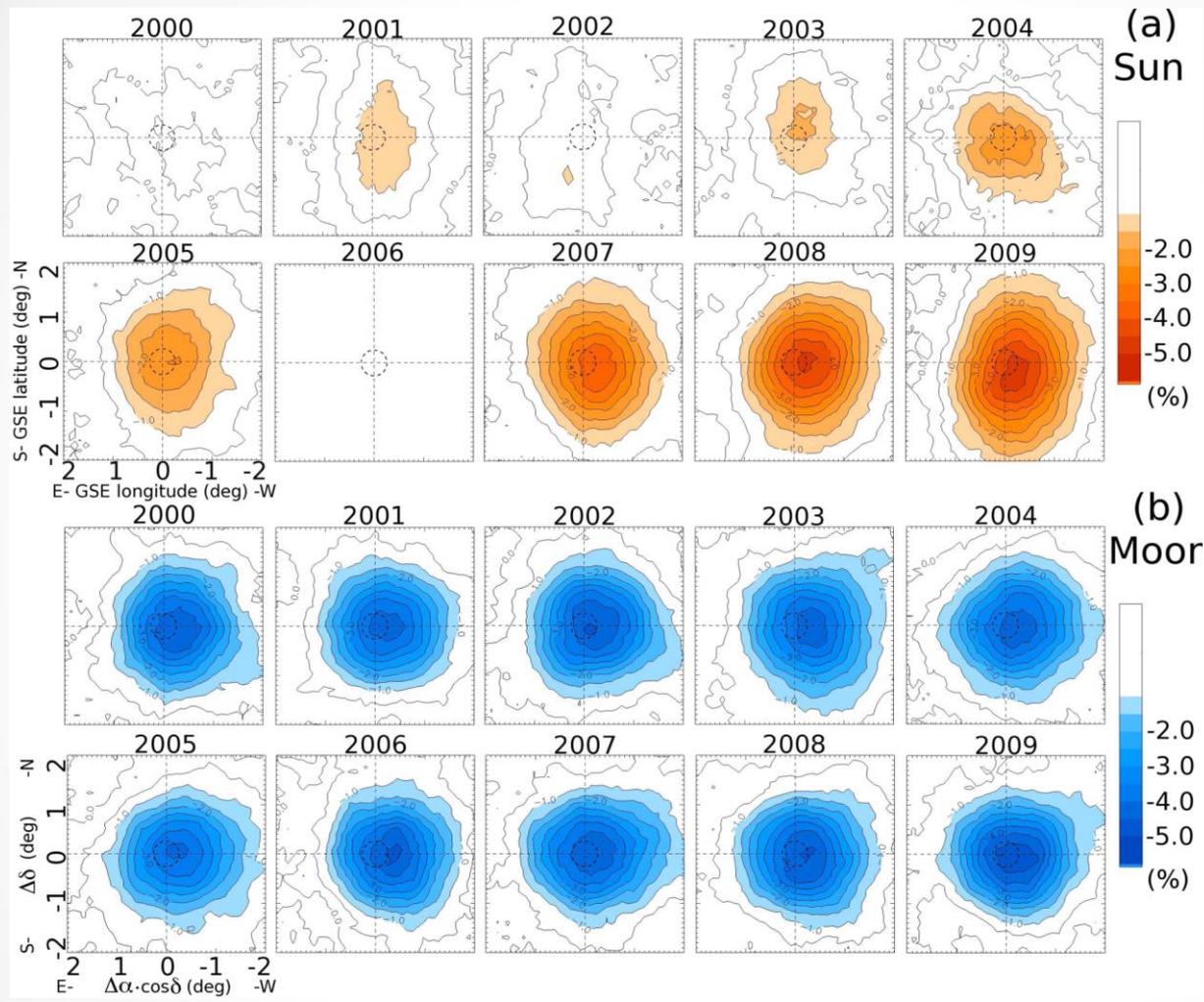
Amenomori et al, PRL, 111, 011101 (2013)



- ✓ Discovery of a clear anti-correlation of the deficits with SN
- ✓ Comparison b/w coronal MF models (PFSS/CSSS)

太陽の影の観測 TeV領域

Amenomori et al., ApJ, 860,13 (2018)

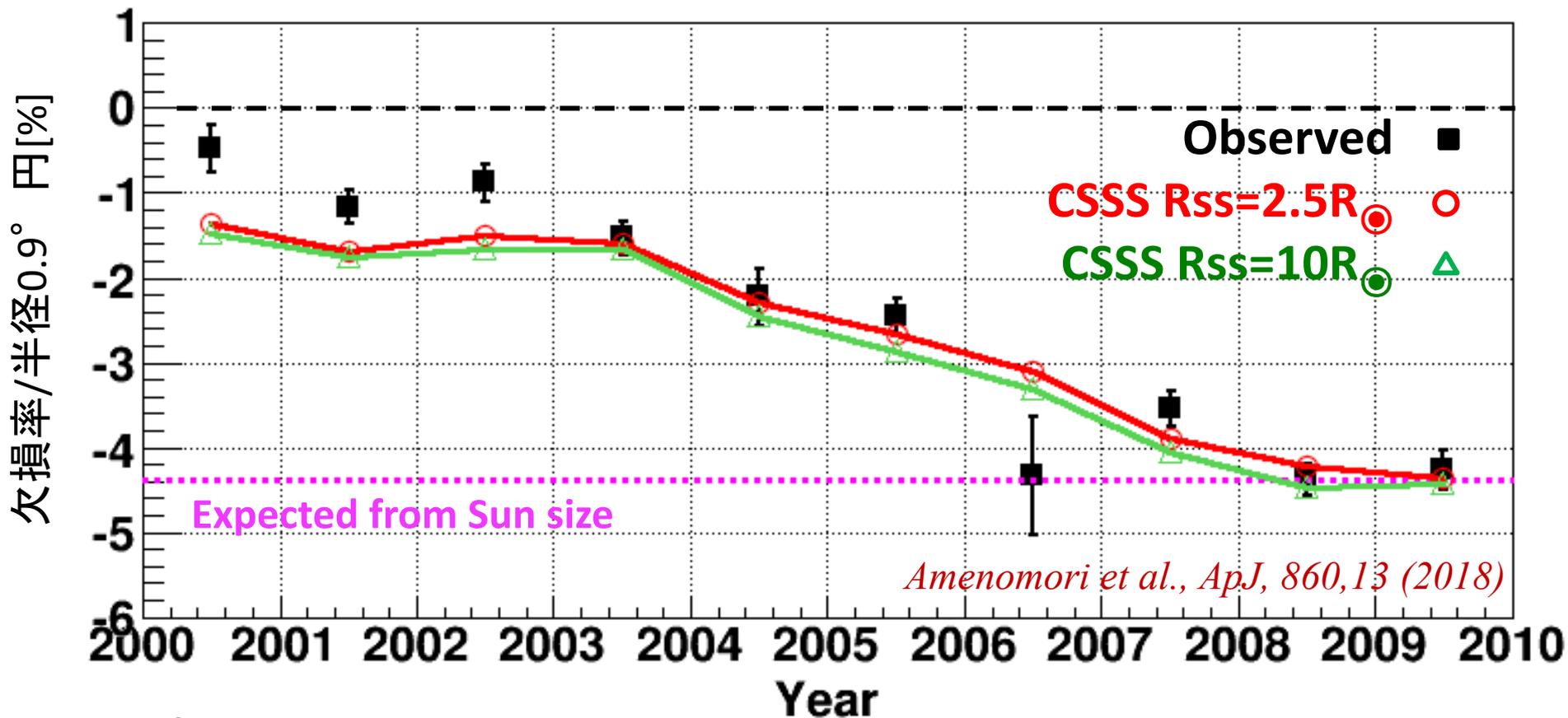


太陽の影
→太陽コロナ磁場の影響で変動

月の影

- ✓ Tibet-III (>3TeV) 2000年-2009年(10年間)
- ✓ 太陽方向を中心にした4°×4°の欠損率マップ

影の深さの変化 全期間 - 3 TeV



χ^2 test :

$$\chi^2 / \text{dof} = 32.1 / 10 \quad (3.4\sigma)$$

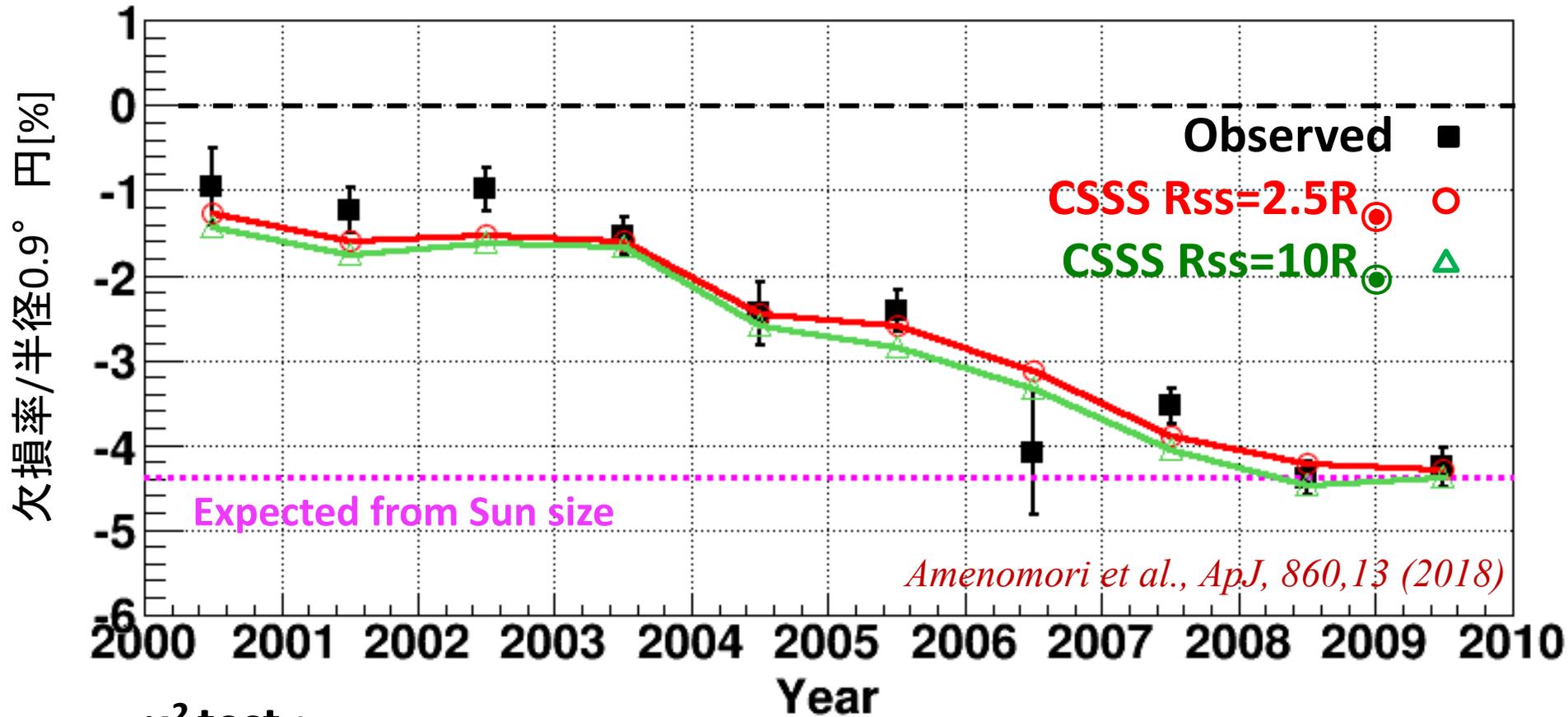
$$\chi^2 / \text{dof} = 46.9 / 10 \quad (4.8\sigma)$$

3 TeV : CSSSは極大期を再現しない?
(10TeVはCSSSで良く再現されている)



Coronal Mass Ejection
の影響?

影の深さの変化 CME発生期間を除く



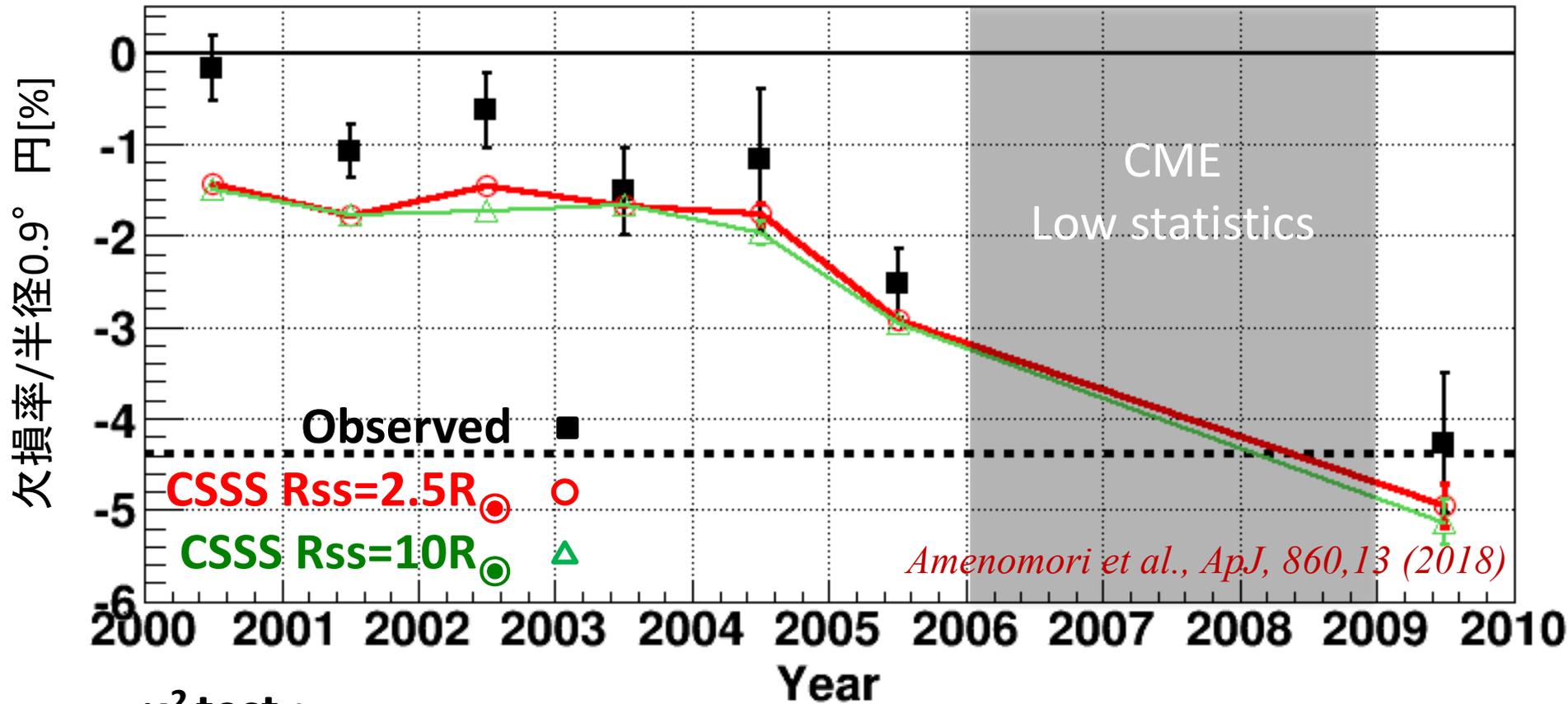
χ^2 test :

$\chi^2 / \text{dof} = 12.2 / 10 (0.6\sigma)$

$\chi^2 / \text{dof} = 21.0 / 10 (2.0\sigma)$

活動期ではCMEが多く影が深くなり
実験データを再現
→ 磁場モデルにはCME等の
短期変動は考慮されない

影の深さの変化 CME発生期間のみ



χ^2 test :

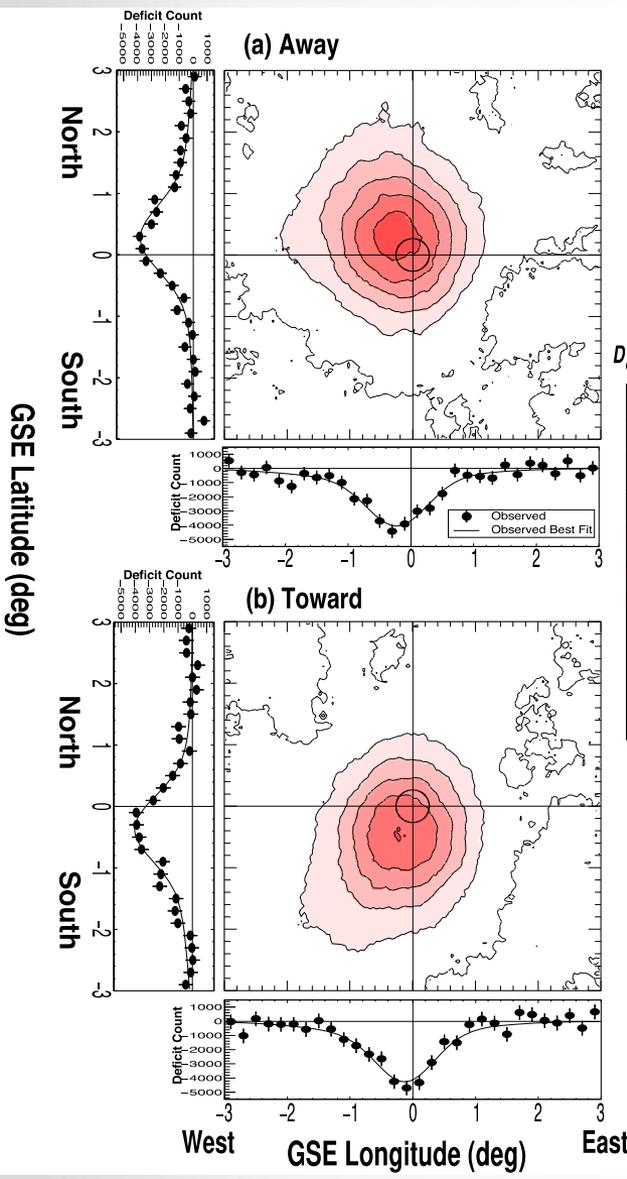
$\chi^2 / \text{dof} = 23.9 / 7 (3.0\sigma)$

$\chi^2 / \text{dof} = 29.4 / 7 (3.7\sigma)$

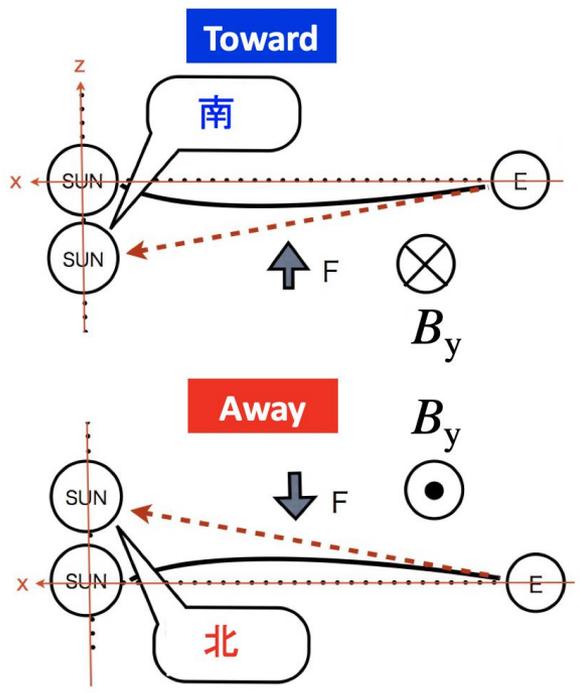
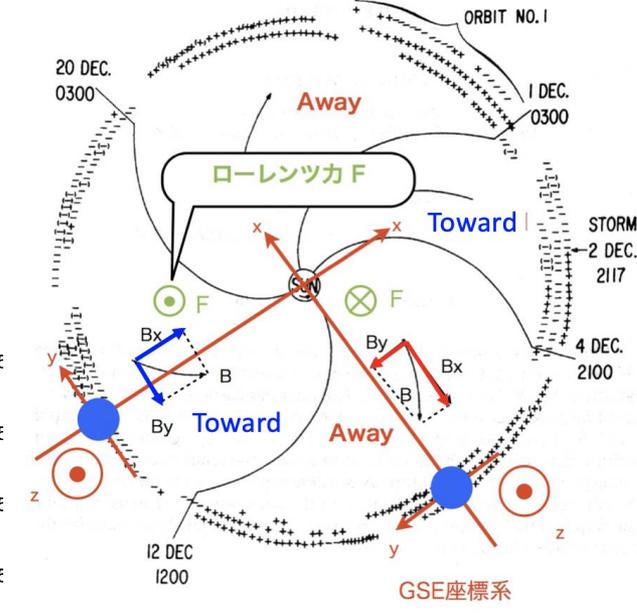
CMEは太陽の影を薄める効果
→ 将来的に宇宙天気予測が可能?

影の方向の観測 Toward/Away

Amenomori et al., PRL, 120, 031101(2018)



惑星空間磁場の間接測定



南北 惑星間空間磁場(IMF)には、極性が逆の Away セクターと Toward セクターが存在し、磁場の B_y (B_y) の符号によって宇宙線の曲がる方向が逆になる

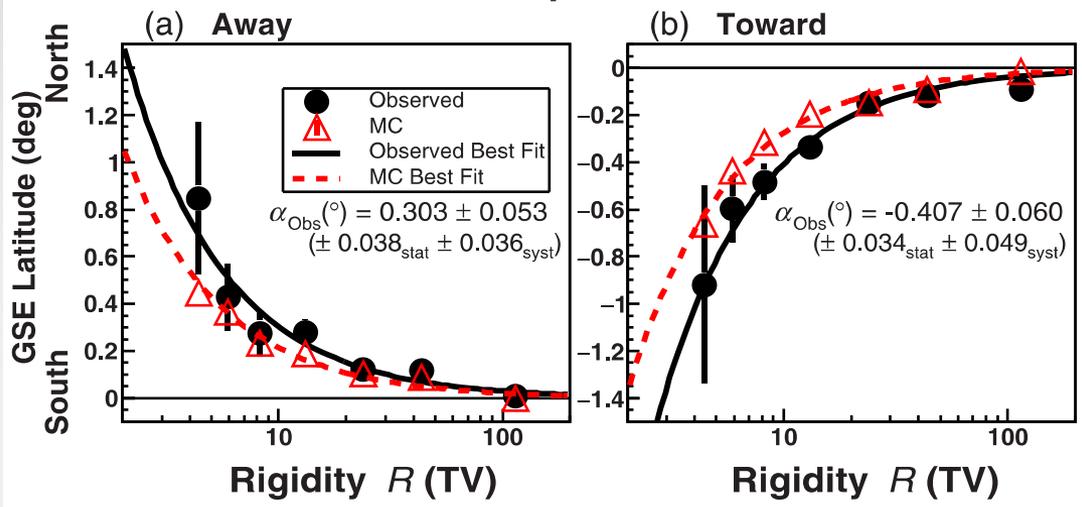
Toward'sector: $B_y < 0 \Rightarrow$ 南向きのずれ

Away'sector: $B_y > 0 \Rightarrow$ 北向きのずれ

影の方向の観測 Toward/Away

Amenomori et al., PRL, 120, 031101(2018)

N-S Displacement



南北方向のズレ

Data/MC比 →

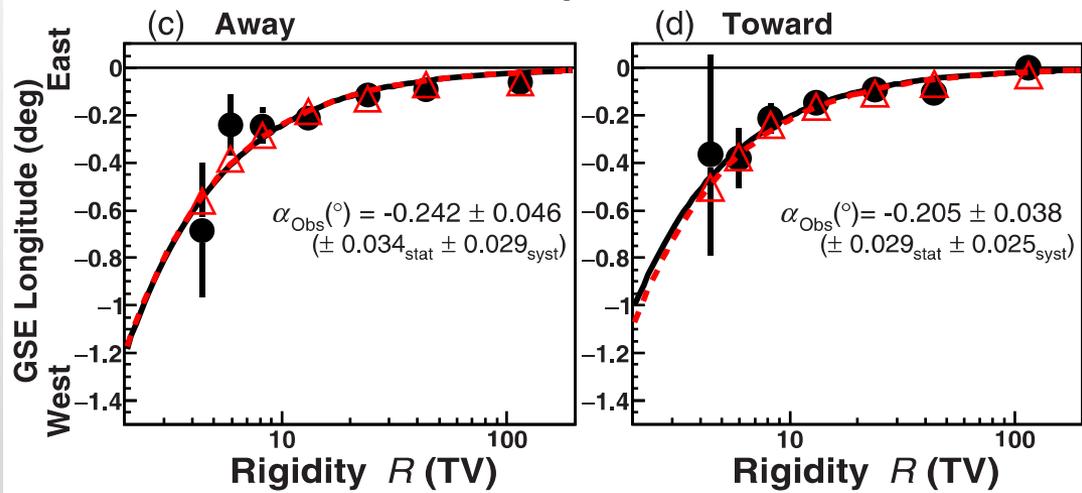
Away : $1.54 \pm 0.21_{\text{stat}} \pm 0.20_{\text{syst}}$

Toward : $1.62 \pm 0.15_{\text{stat}} \pm 0.22_{\text{syst}}$

磁場モデルの問題か？

- ポテンシャルフィールドモデル
- 太陽表面磁場計測の系統誤差 (モデルへのインプット)

E-W Displacement



東西方向のズレ

→ ほとんど地磁気で説明できる

これまでわかった事:

1. Several bright TeV γ point sources !

Possible diffuse γ signal from Cygnus region?!

2. P, He, all-particle E-spectrum (Galactic cosmic rays accelerated to the knee region)

エネルギーと共に重粒子の割合が増加

これからするべき事:観測装置の感度向上

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

Where do galactic cosmic rays under knee come from? (Tibet-III + MD) -> PeVatron(宇宙線の起源)

2. Chemical composition (p ?, Fe?) (Tibet-III + YAC)

p & Fe knee \rightarrow if Z (原子番号)倍 \rightarrow SNR加速

□ Next Plans (南北両天での広視野連続観測)

1. 北半球 (チベットでon-going)

Tibet AS + MD + YAC EXPERIMENT

Gamma ray: Tibet Muon Detector (**MD**)

Cosmic Rays: Tibet Yangbajing Air shower Core
detector (**YAC-II**)

2. 南半球 (ボリビアで計画中)

ALPACA PROJECT

Tibet AS + MD: 100 TeV γ -ray astronomy

100 TeV領域 (10-1000TeV)ガンマ線天文学

By

**Tibet-III (AS) + a large underground
muon detector array (MD)**

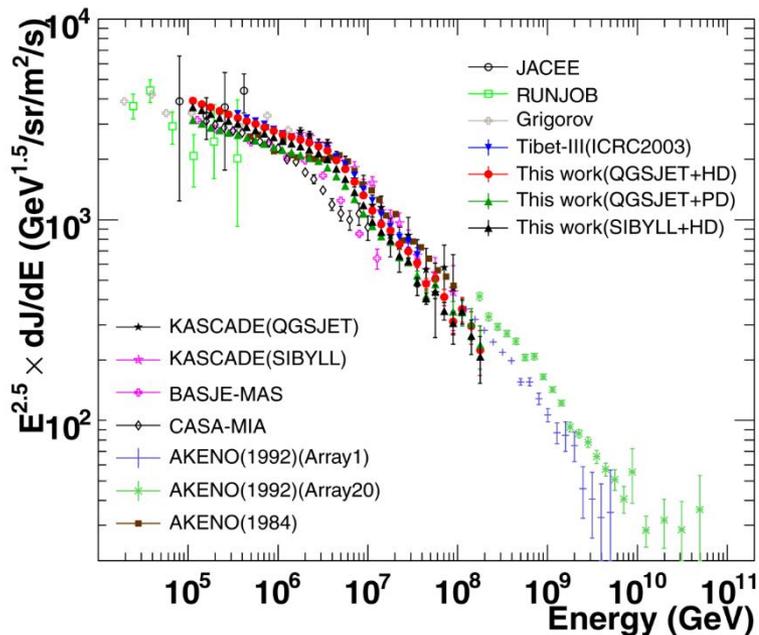
100 TeV以上のガンマ線を観測できれば世界初

>Origin of cosmic rays and acceleration

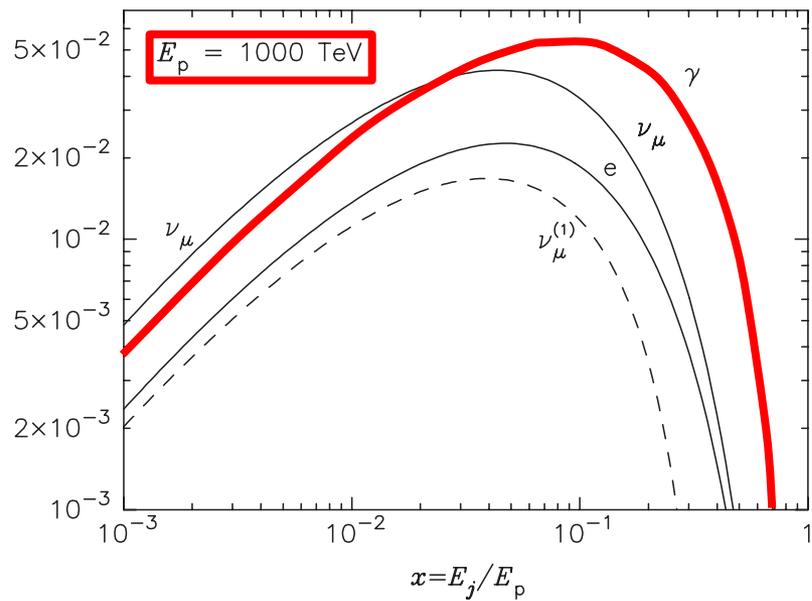
mechanism (PeVatron) and limit at SNRs.

>Diffuse gamma rays

Origin of Cosmic Rays at the Knee



$x^2 F_j(x, E_p)$ Kelner et al., PRD 74, 034018 (2006)



宇宙線スペクトル

- ✓ SNRなどでの(斜め)衝撃波加速により宇宙線を100~数1000TeV程度まで加速可能
- ✓ Knee~ 4 PeVまでは銀河系内起源?

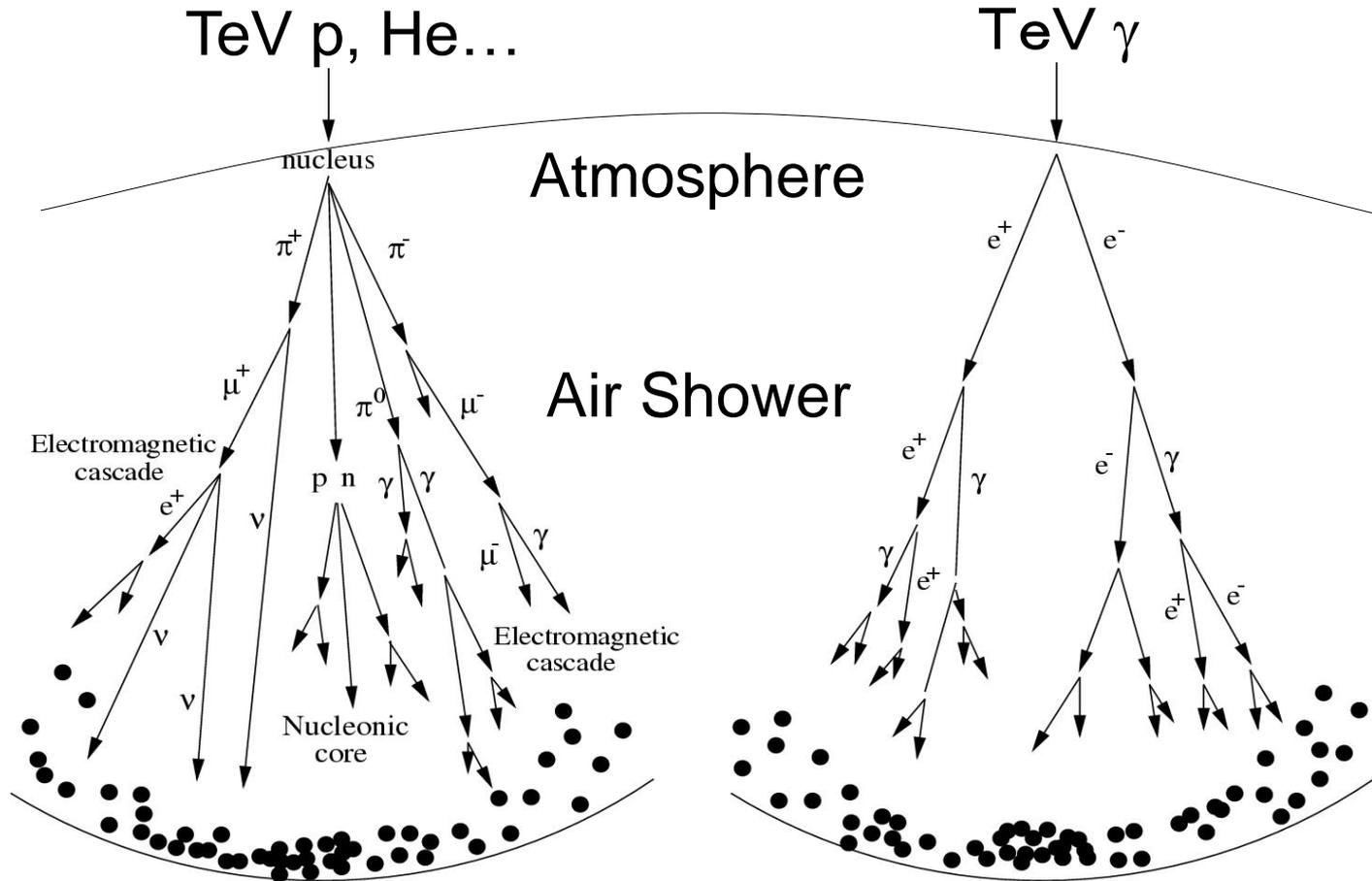
ガンマ線スペクトル

- ✓ 宇宙線+星間物質 $\rightarrow \pi^0 + \dots \rightarrow 2\gamma$
- ✓ 陽子の最大エネルギーの一桁下のガンマ線・ニュートリノが生成

PeV宇宙線を加速している天体 = **PeVatron**

CMBによる吸収で銀河系内または超近傍天体

p/γ discrimination by muons



100TeV Proton
~50

100TeV Gamma
~1

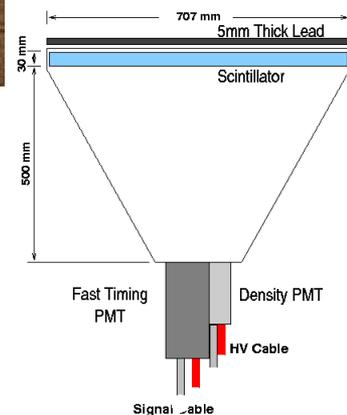
チベット空気シャワー観測装置



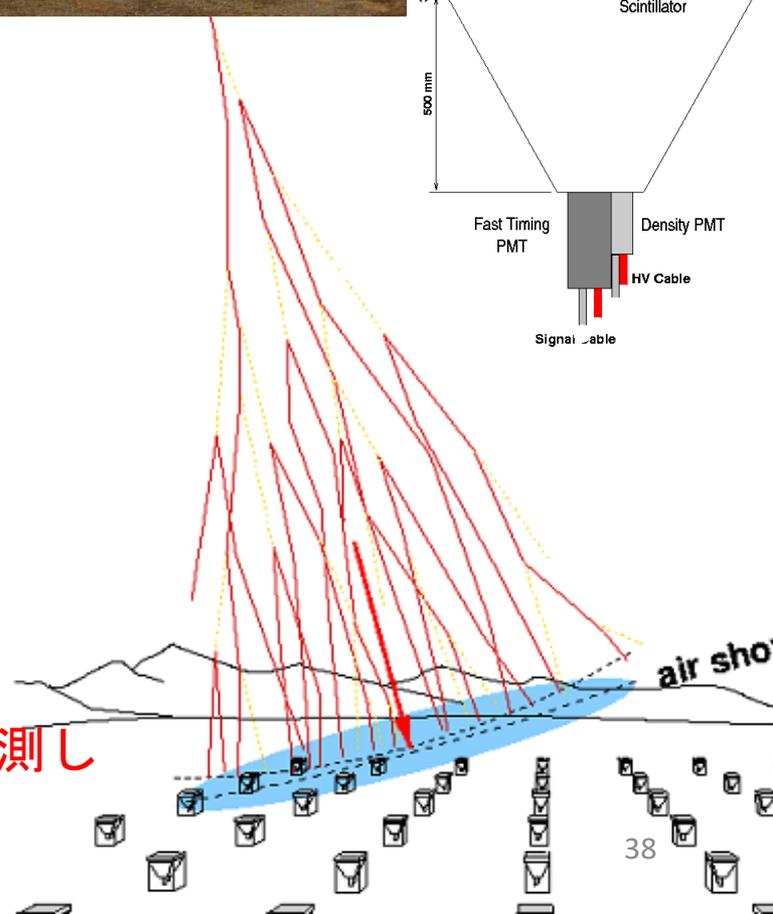
□ チベット (90.522°E, 30.102°N) 標高4300 m

現行スペック

- シンチレーション検出器数 0.5 m² x 597
- 空気シャワー有効面積 ~65,700 m²
- 観測エネルギー >TeV
- 角度分解能 ~0.5°@10TeV γ
~0.2°@100TeV γ
- エネルギー分解能 ~40%@10TeV γ
~20%@100TeV γ
- 視野 ~2 sr



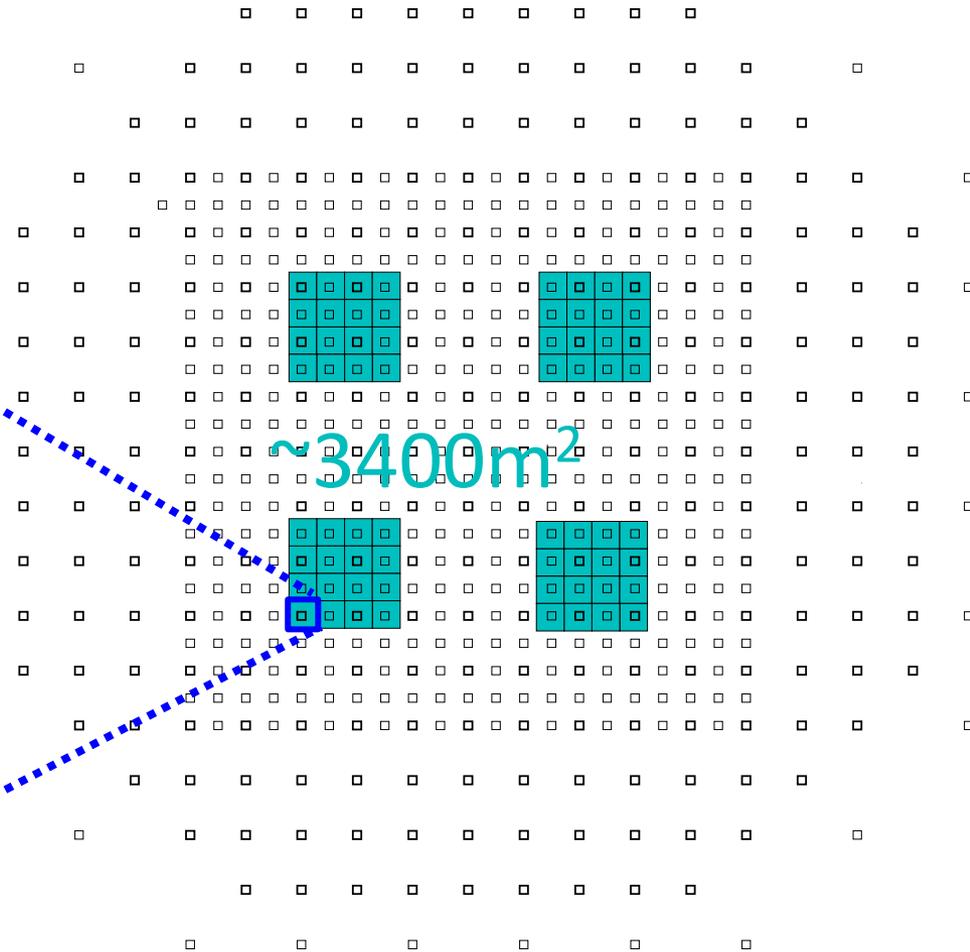
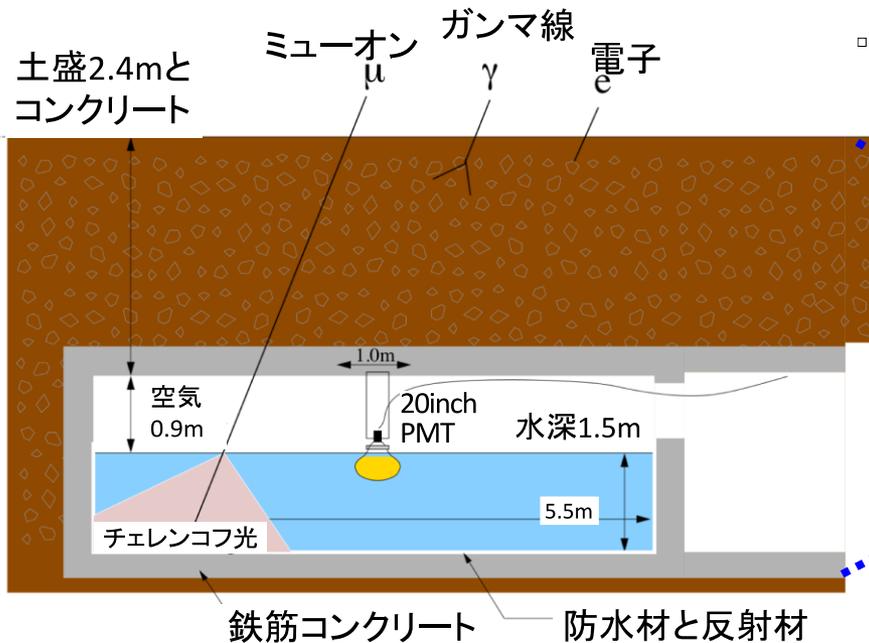
→ 空気シャワー中の二次粒子(主に e^{\pm}, γ)を観測し
一次宇宙線エネルギー、方向を決定



水チェレンコフ型ミュオン観測装置

◦ *Kawata et al., JPS meeting (2018)*

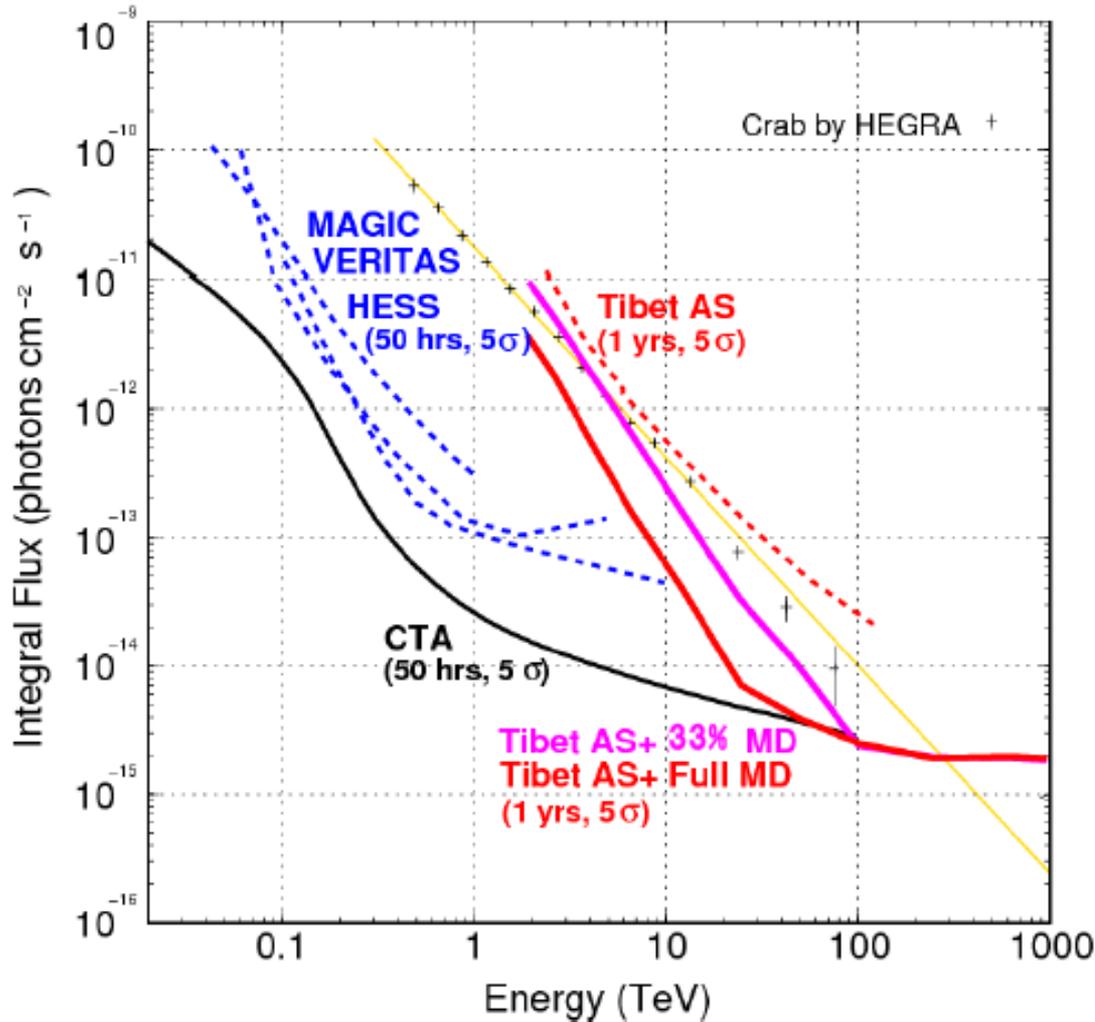
- ✓ 地下 2.4m (物質厚 $\sim 515\text{g}/\text{cm}^2 \sim 19X_0$)
- ✓ 7.35m \times 7.35m \times 水深1.5m 水槽
- ✓ 20" Φ PMT (HAMAMATSU R3600)
- ✓ 水槽材質：コンクリート+タイベック



→ 空気シャワー中のミュオン数を測定し、ガンマ線／核子選別

2014年2月 - 2017年5月 有効観測時間：720日

Sensitivity to γ -ray point sources (AS 1yr/ IACT 50hrs, 5σ or 10 ev)



+Full:10000m² MD

X ~10 @10TeV

X ~10 @100TeV

+33%: 3400m² MD

X 3~4 @10TeV

X ~10 @100TeV



MD construction scene



Installing a 20 inch PMT in a MD cell.



Tyvek sheet walls and two 20 inch PMTs

2013/10/10



Image © 2014 CNES / Astrium



2013/10/10

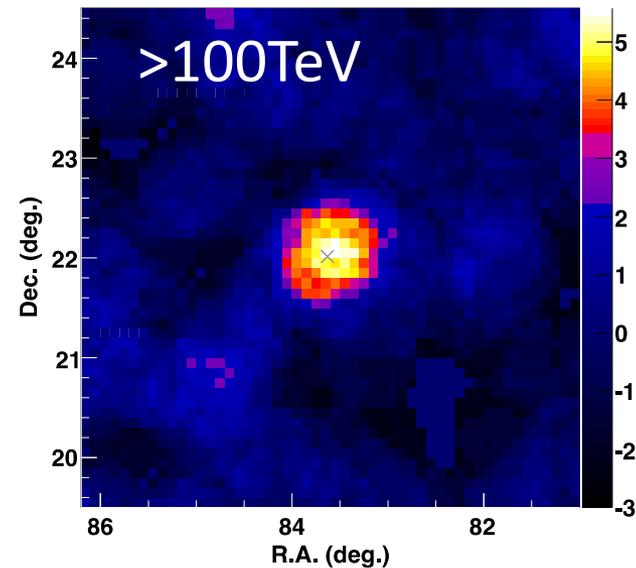
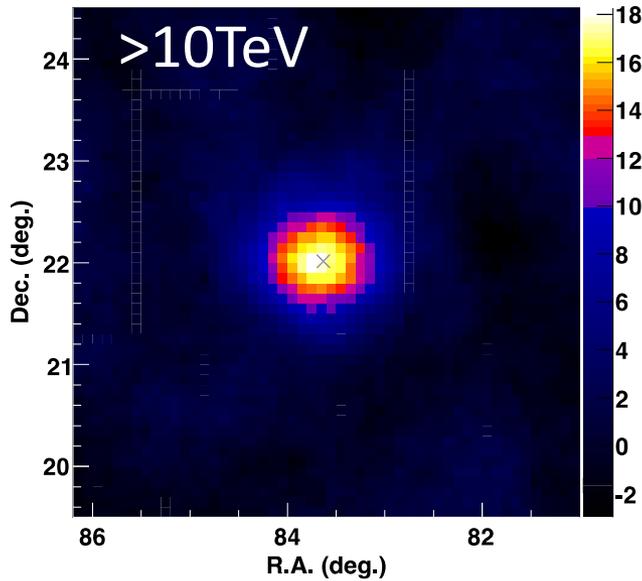


3,400m²
地下施設

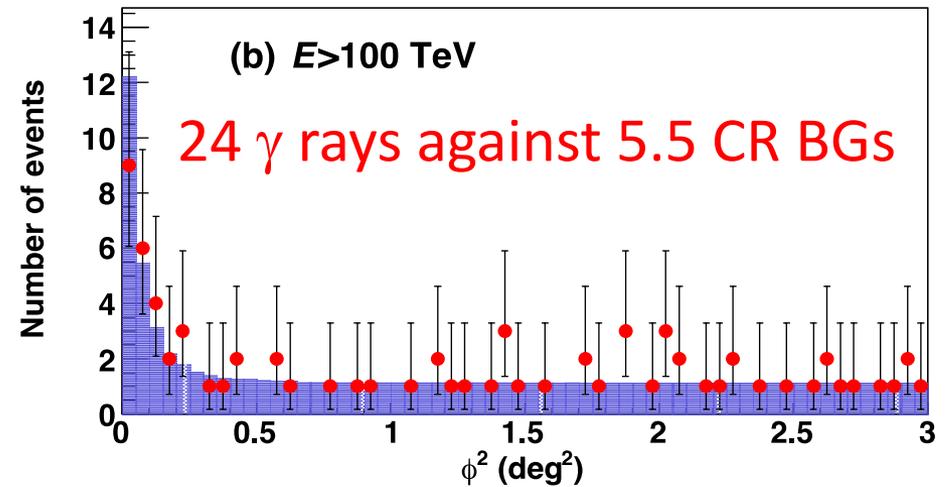
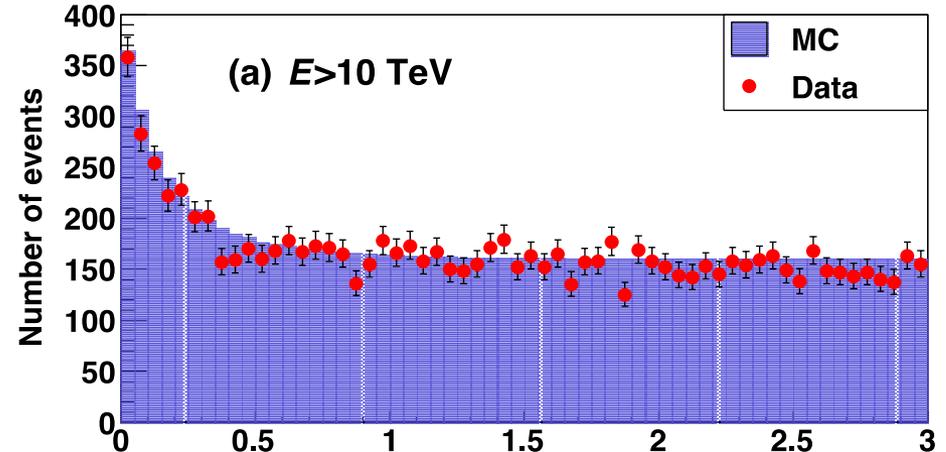


Image © 2014 CNES / Astrium

かに星雲の観測(チベット実験)



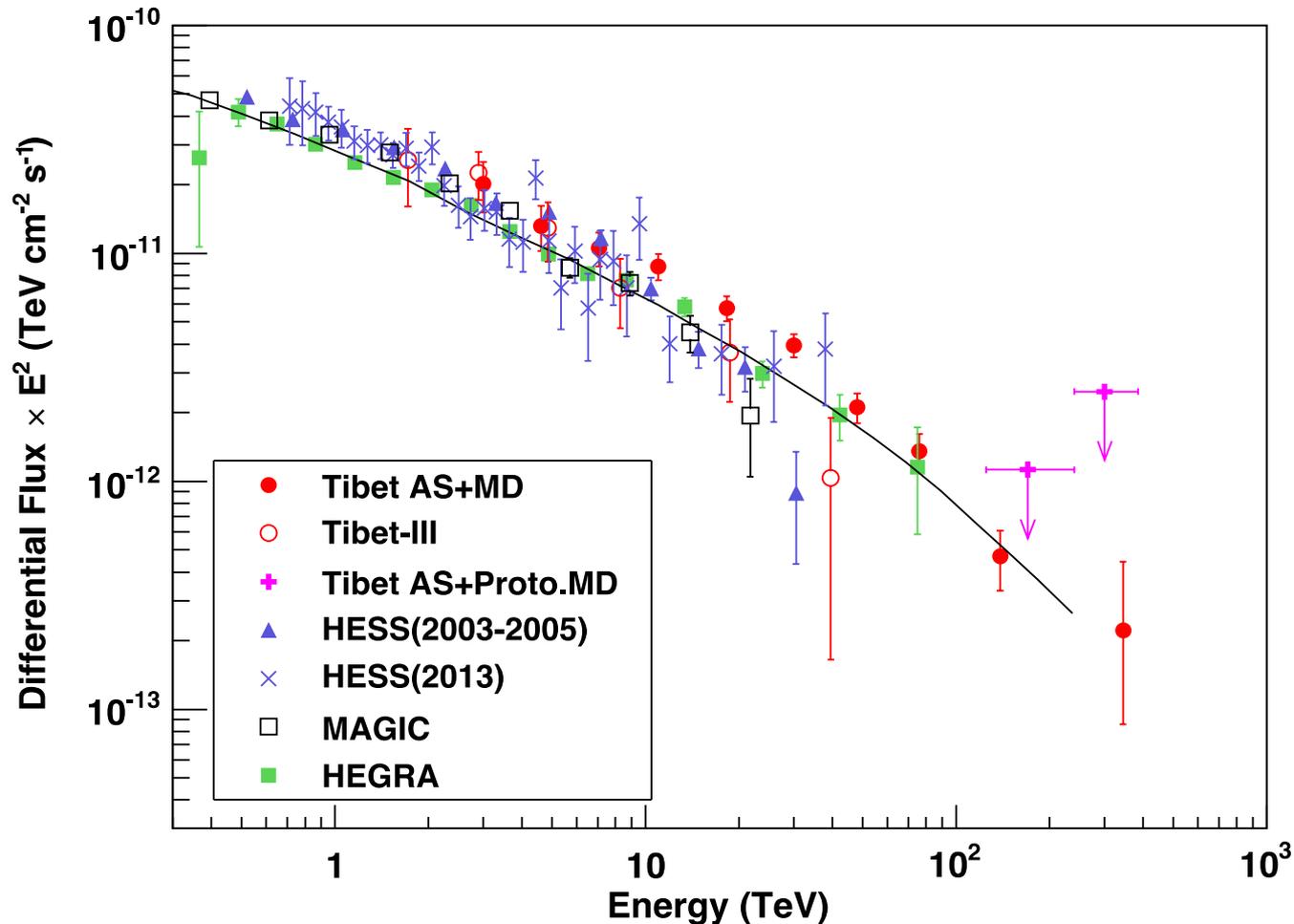
Data vs MC



First Detection of Sub-PeV γ (5.6σ)

Amenomori et al., PRL, 123, 051101 (2019)

「かに星雲」のエネルギースペクトル



The highest energy $\gamma \sim 450 \text{ TeV} \rightarrow$ sub-PeV **ガンマ線天文学の始まり**

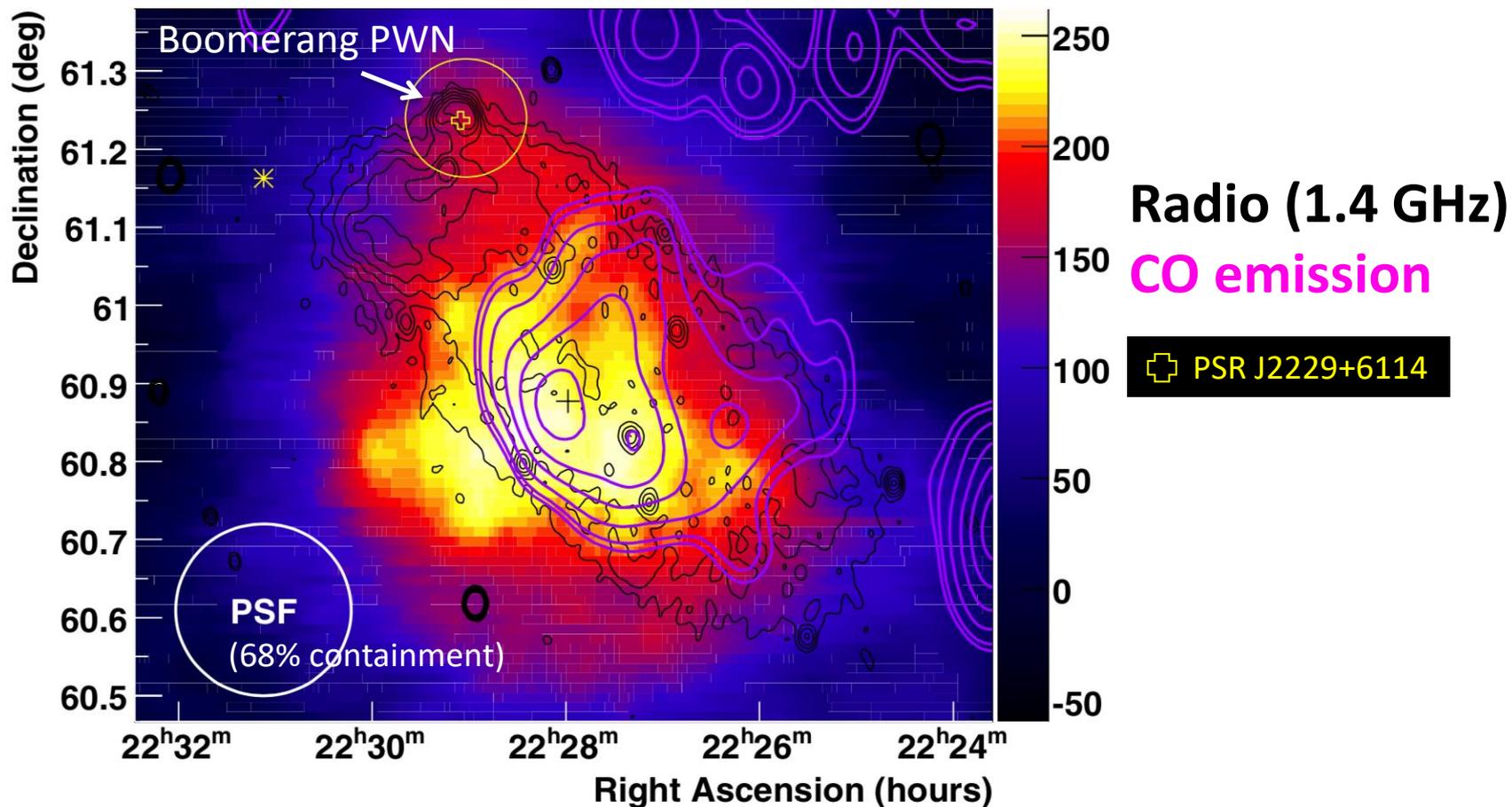
Amenomori et al., PRL 123, 051101, (2019)

曲線：HEGRA のデータ (*Aharonian+, ApJ, 614, 897 (2004)*) を基とした場合の逆コンプトンモデルで期待されるガンマ線頻度

SNR G106.3+2.7 (VERITAS による観測)

Excess count map > 0.63 TeV

V. A. Acciari et al., *ApJL*, 703, L6 (2009)



➤ 年齢 10 kyr 距離 0.8 kpc (if SNR is associated with Boomerang PWN)

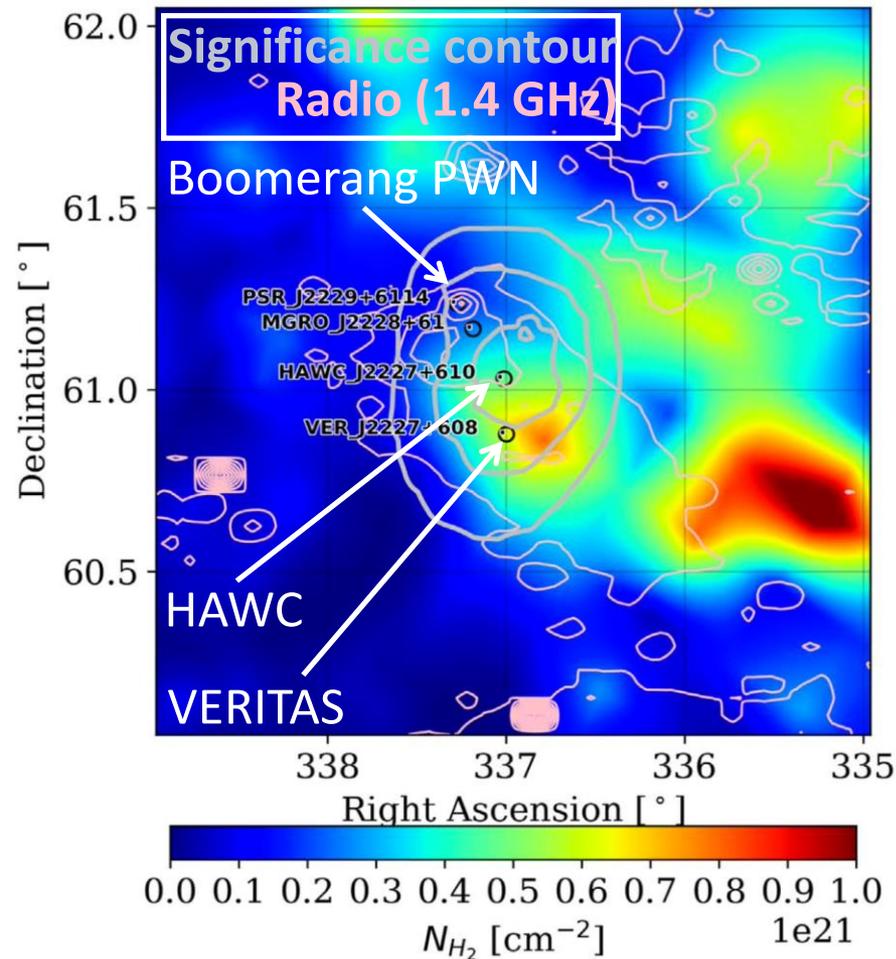
大きさ 14pc x 6pc

Kothes et al, ApJ, 560, 236 (2001)

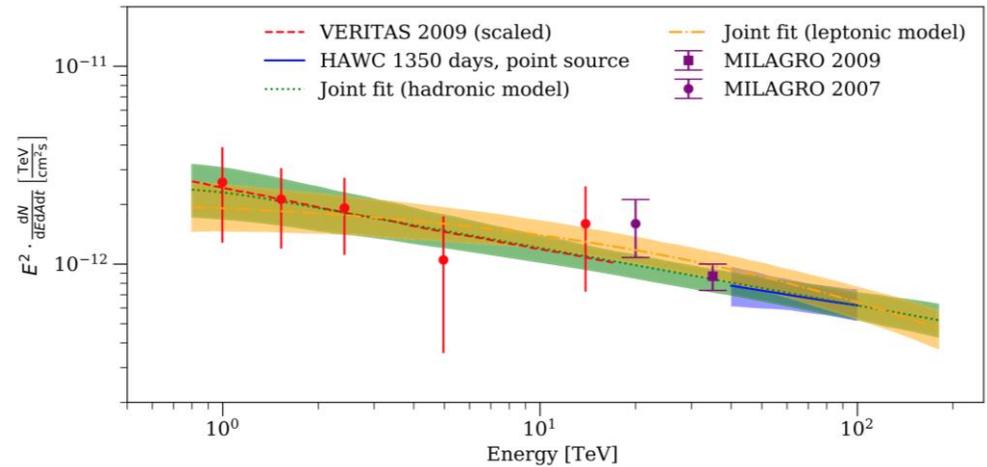
➤ ガンマ線(>0.63 TeV)放射領域の中心は分子雲の場所に一致

SNR G106.3+2.7 (HAWC による観測)

Albert et al., *ApJL*, 896, L29 (2020)

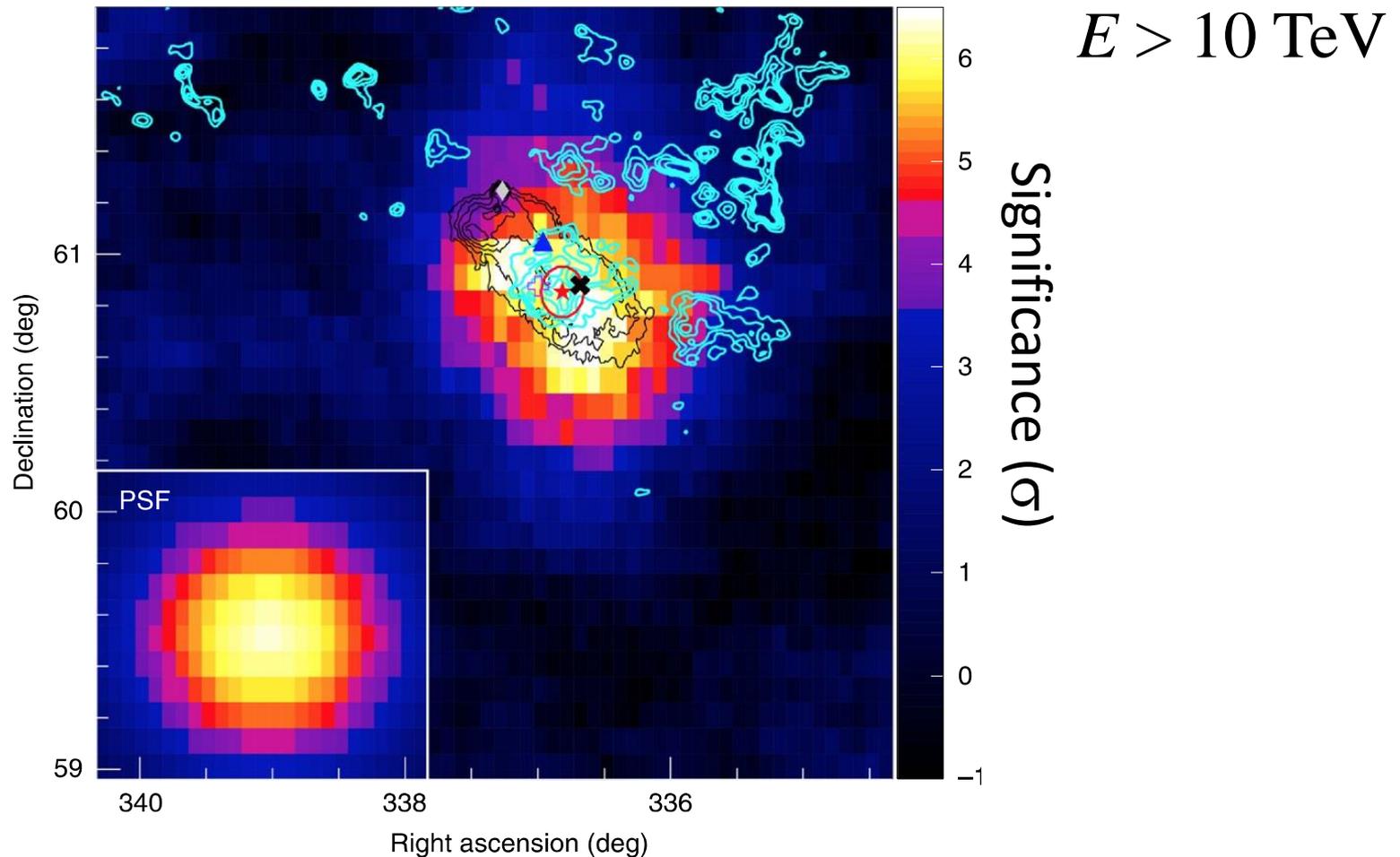


Energy spectrum



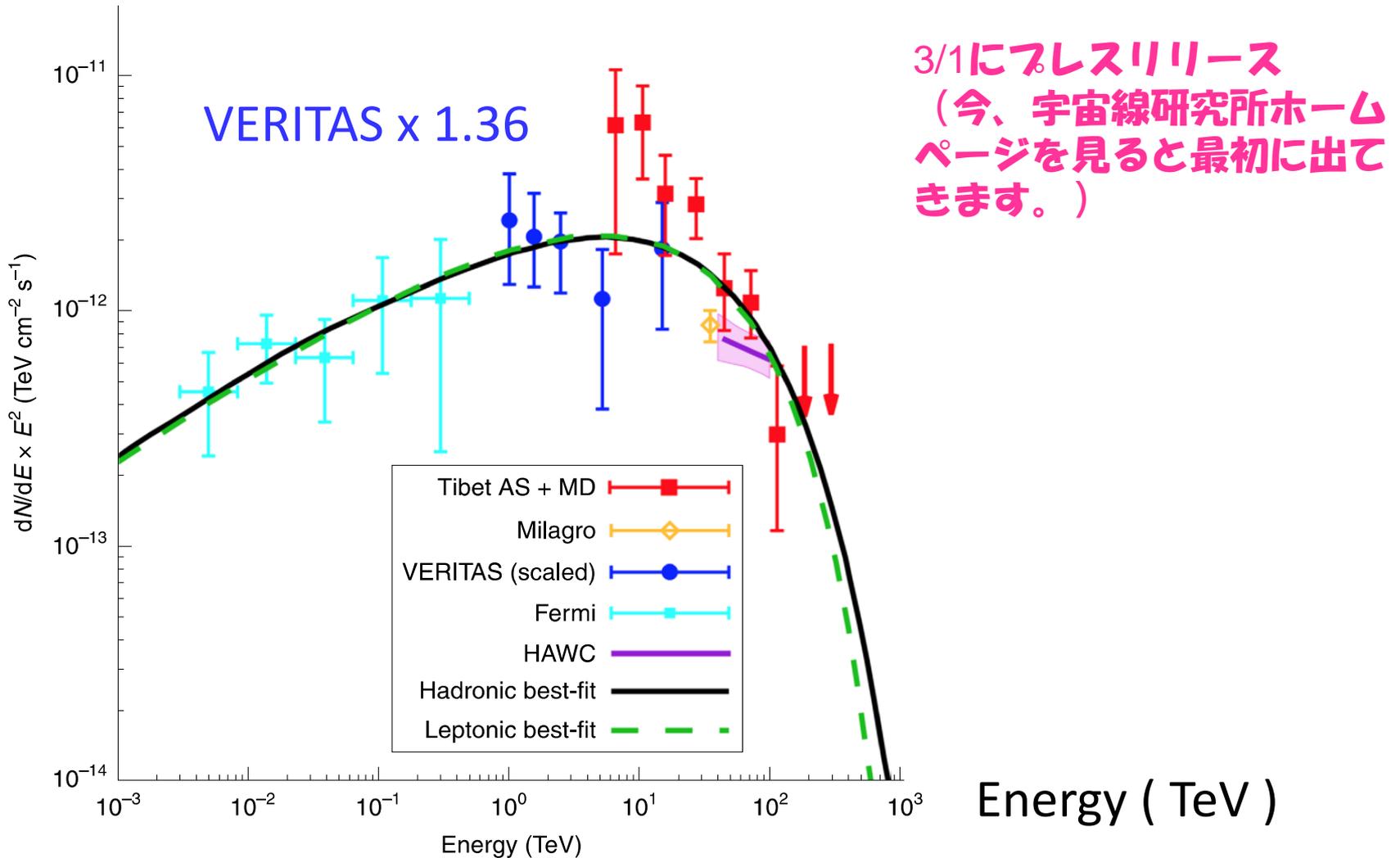
- Source position はパルサー位置、分子雲位置ともに無矛盾
- スペクトルは 100 TeV 近くまで伸びている

チベット実験の観測結果：SNR G106.3+2.7



- ✓ 観測領域は CO放射領域から示唆される分子雲&超新星残骸の領域と一致
※VERITASの結果と一致

チベット実験の観測結果：SNR G106.3+2.7



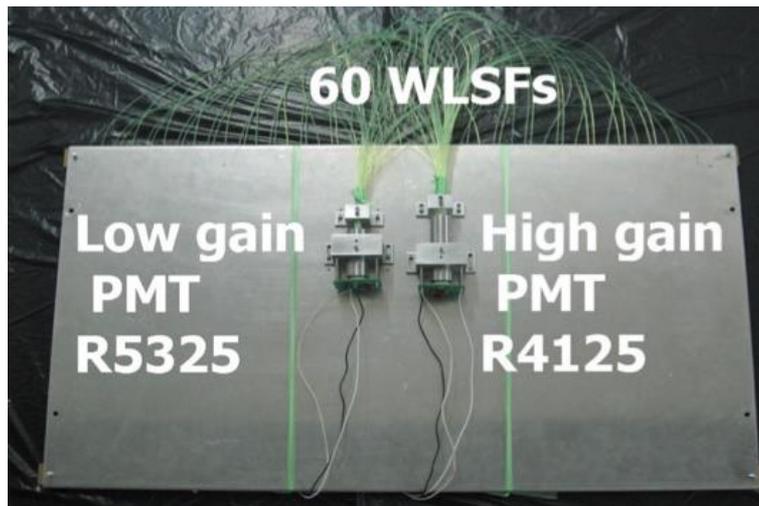
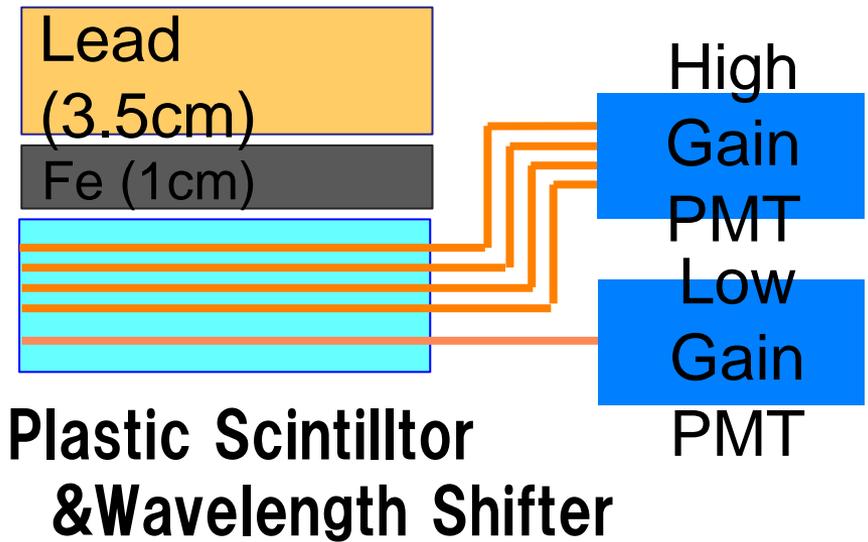
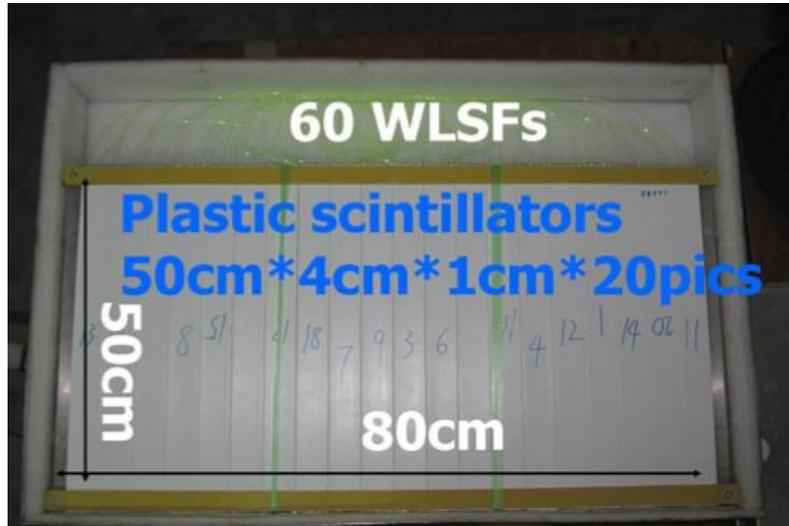
超新星残骸 & 分子雲の方向からsub-PeVガンマ線を世界初検出
-> 初めてのPeVatronの候補！

YAC計画 (Yangbajing Airshower Core detectors)
Towards Chemical composition and energy spectrum
measurement in the Knee Energy Region



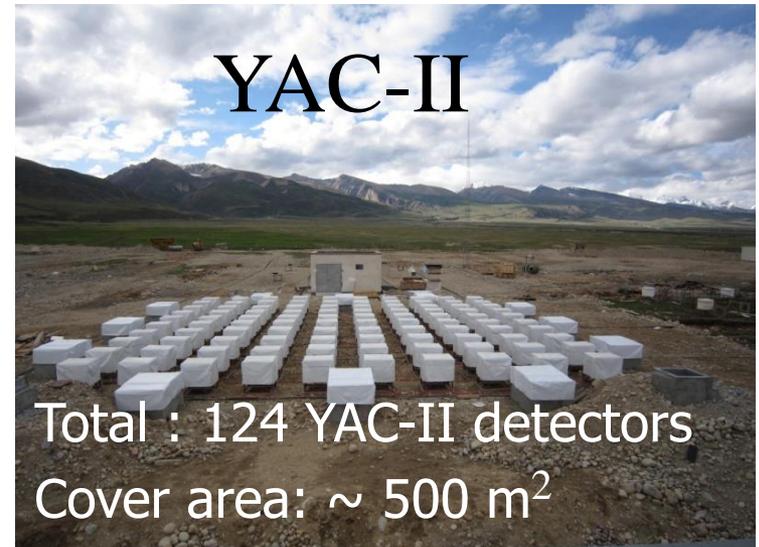
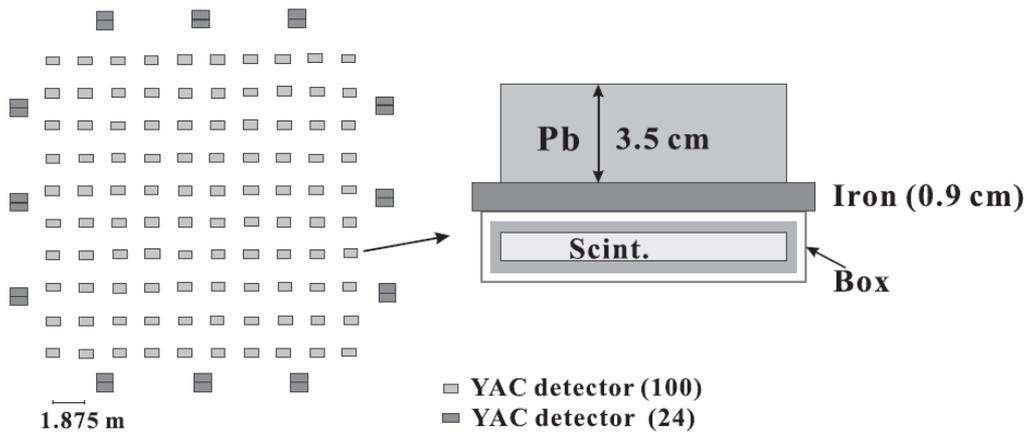
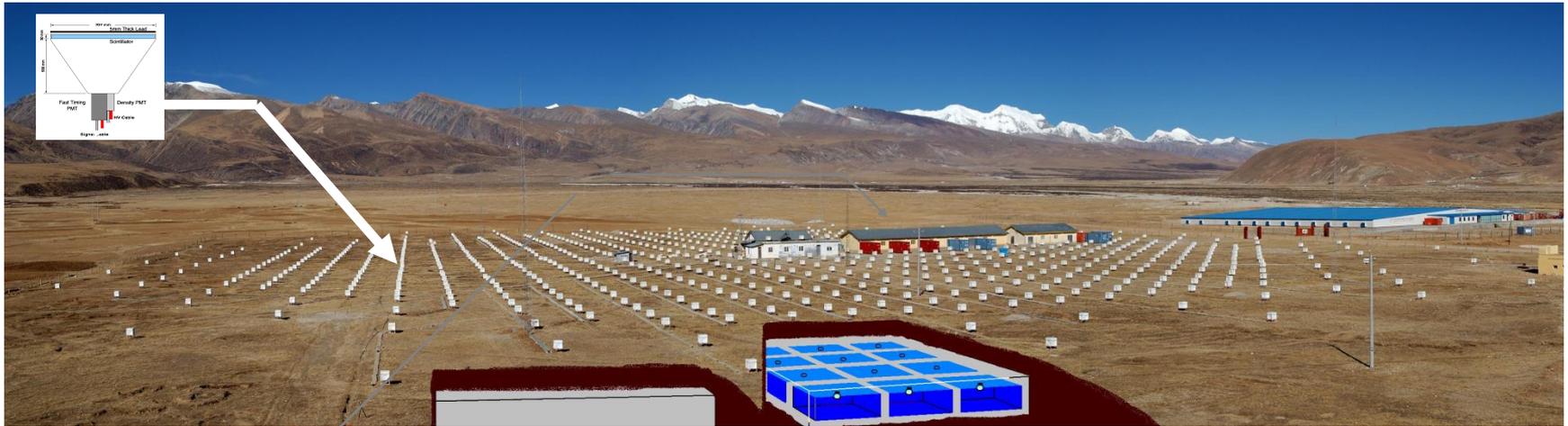
Yak

YAC-II (Yangbajing Air-shower Core) detectors for chemical composition study in Knee region

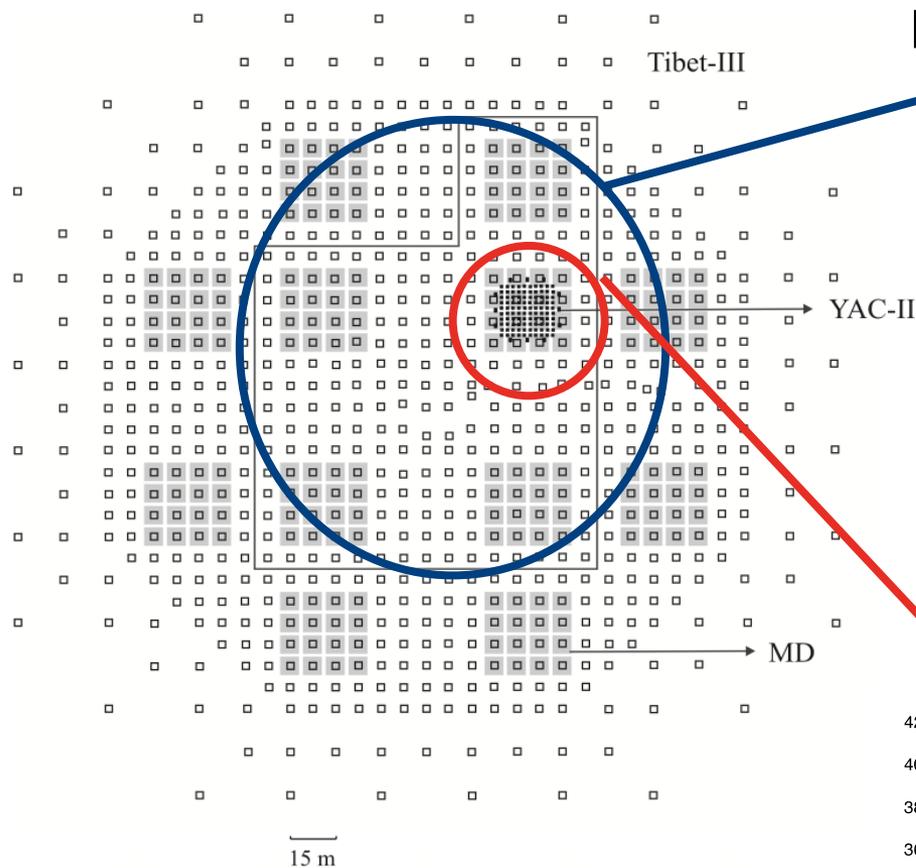


2PMTs cover $1 \sim 10^6$ particles

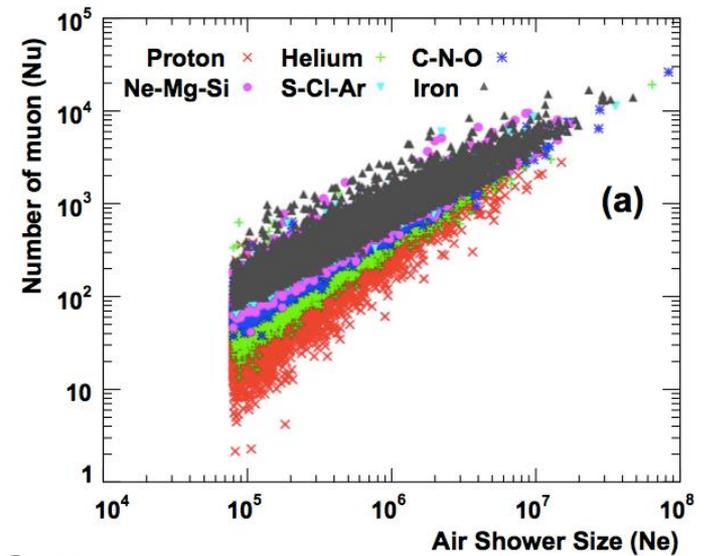
YAC-II started in 2014, accumulating data



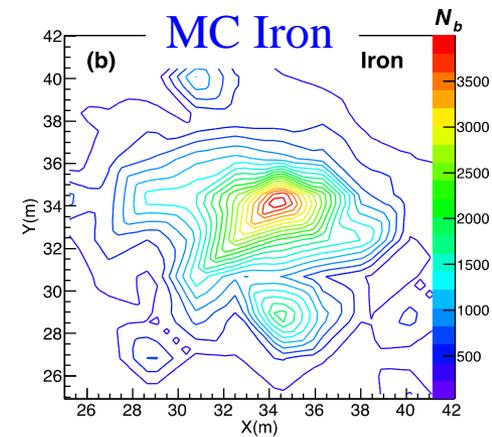
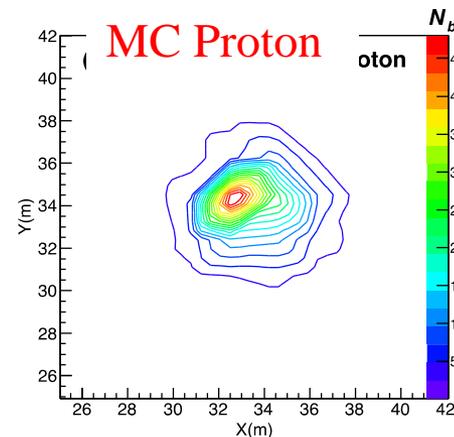
Tibet-III + YAC-II + MD (MC) for Knee Study



Muon Detector MC Ne- N_μ Plot

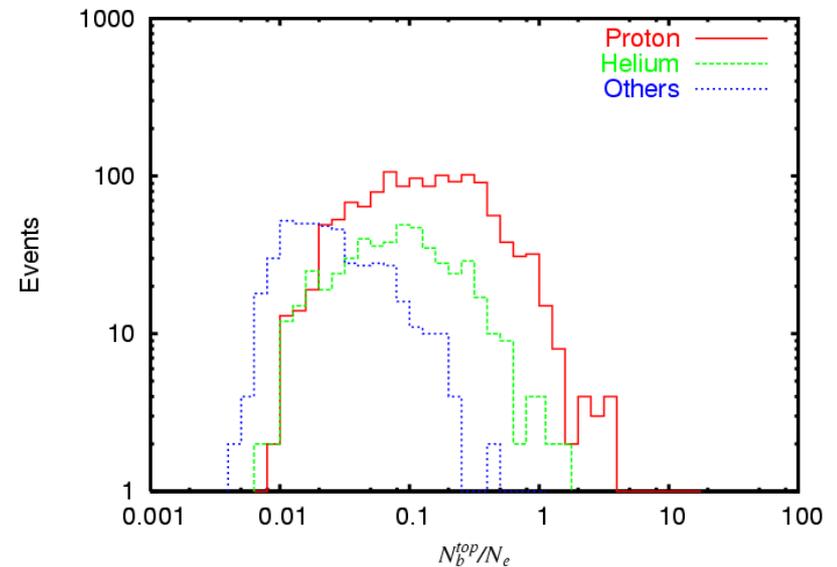
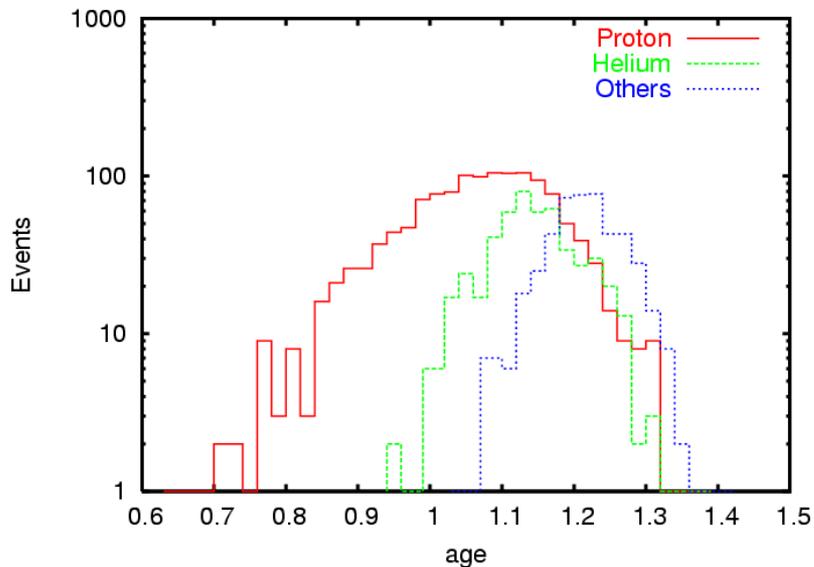
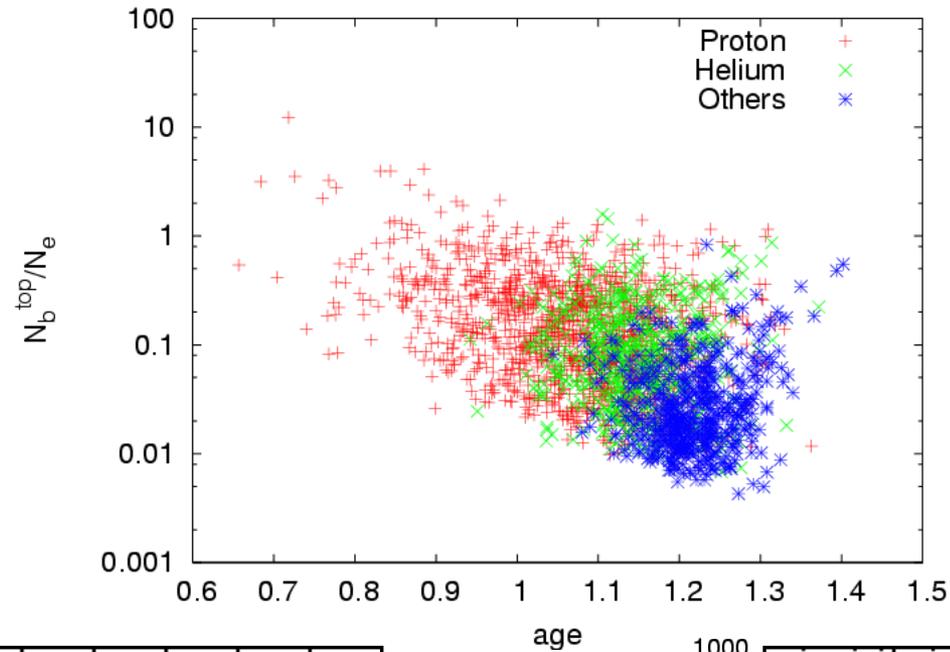


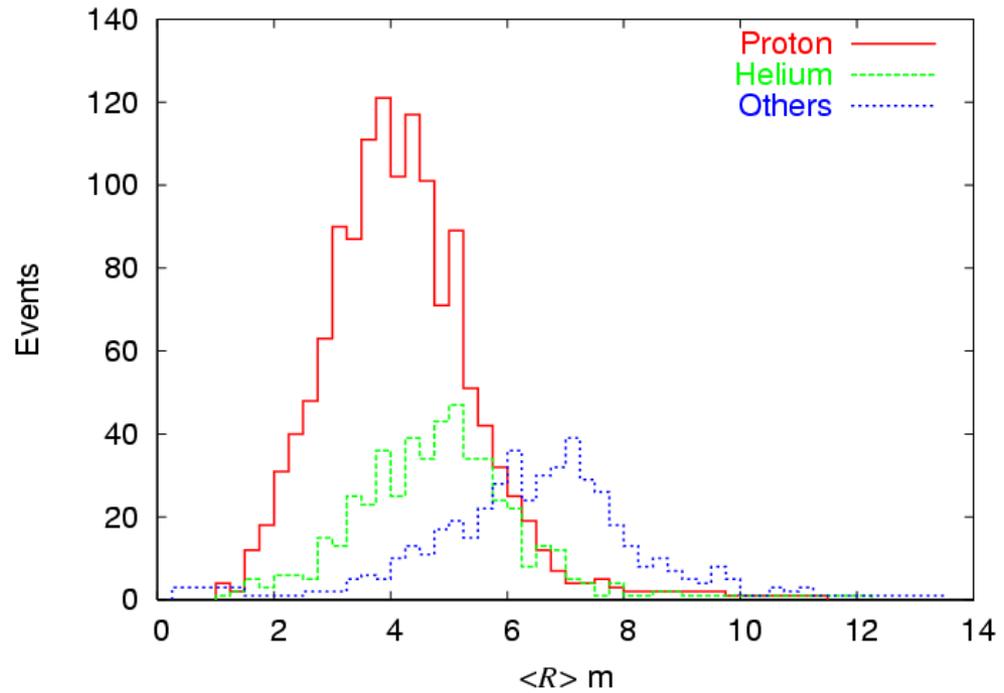
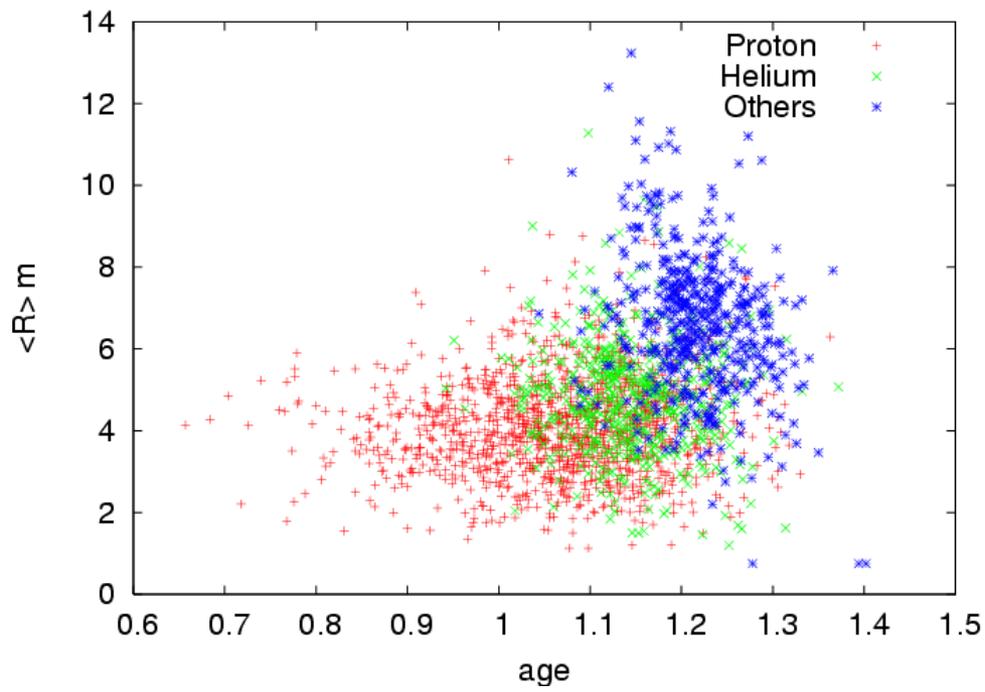
YAC-II



J.Huang et al, *Astropart.Phys.* 66
(2015) 18–30

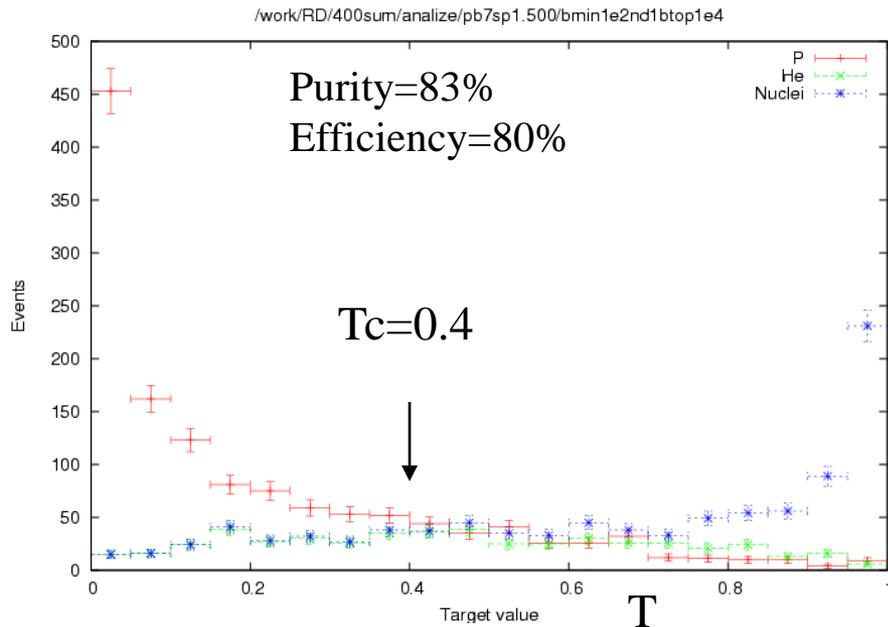
Features of YAC-II observables





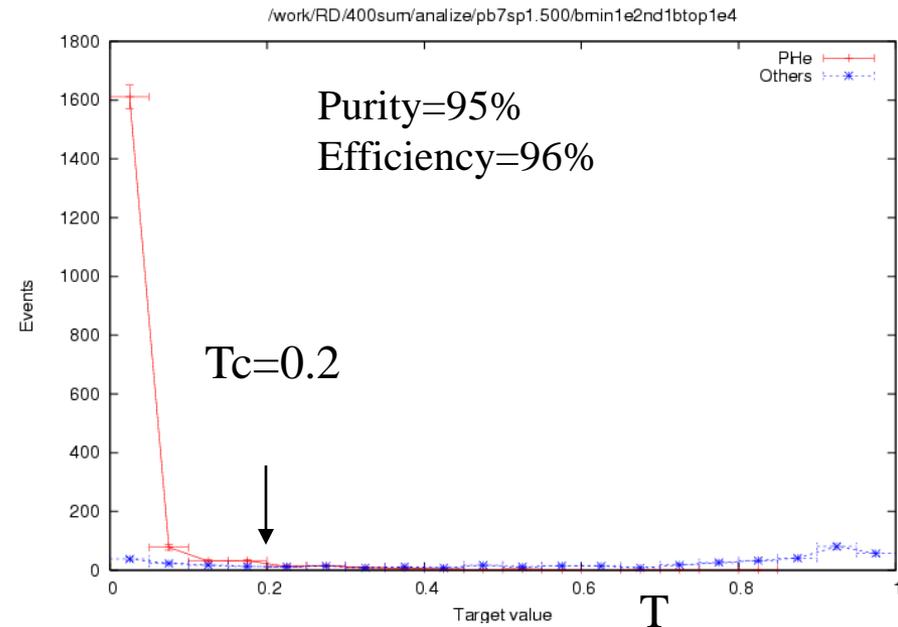
ANN output

Proton separation



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

P+He separation



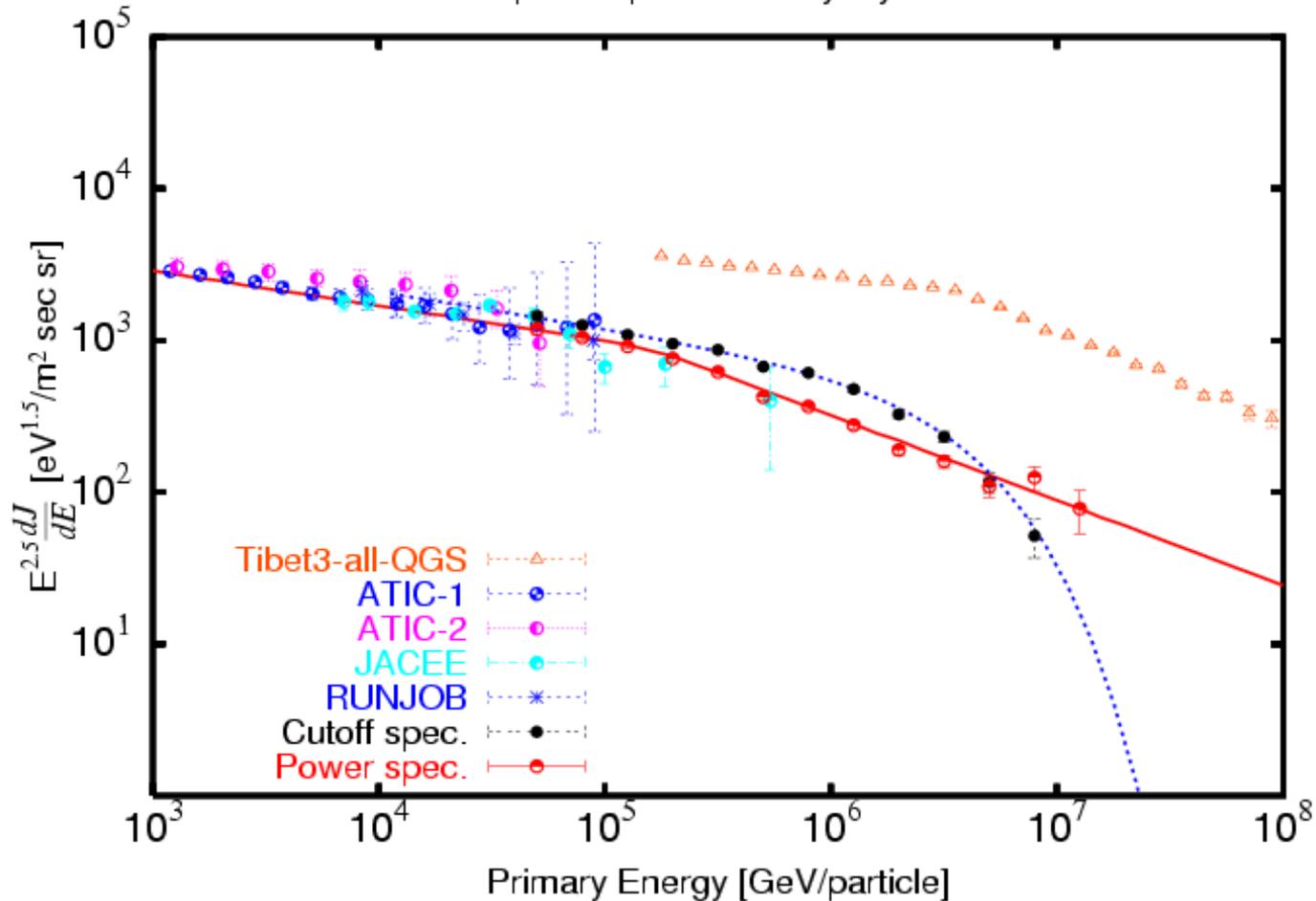
20% of heavier nuclei than helium contaminates to P+He region.

Expected proton spectrum

(YAC-II)

Proton kneeを探せ

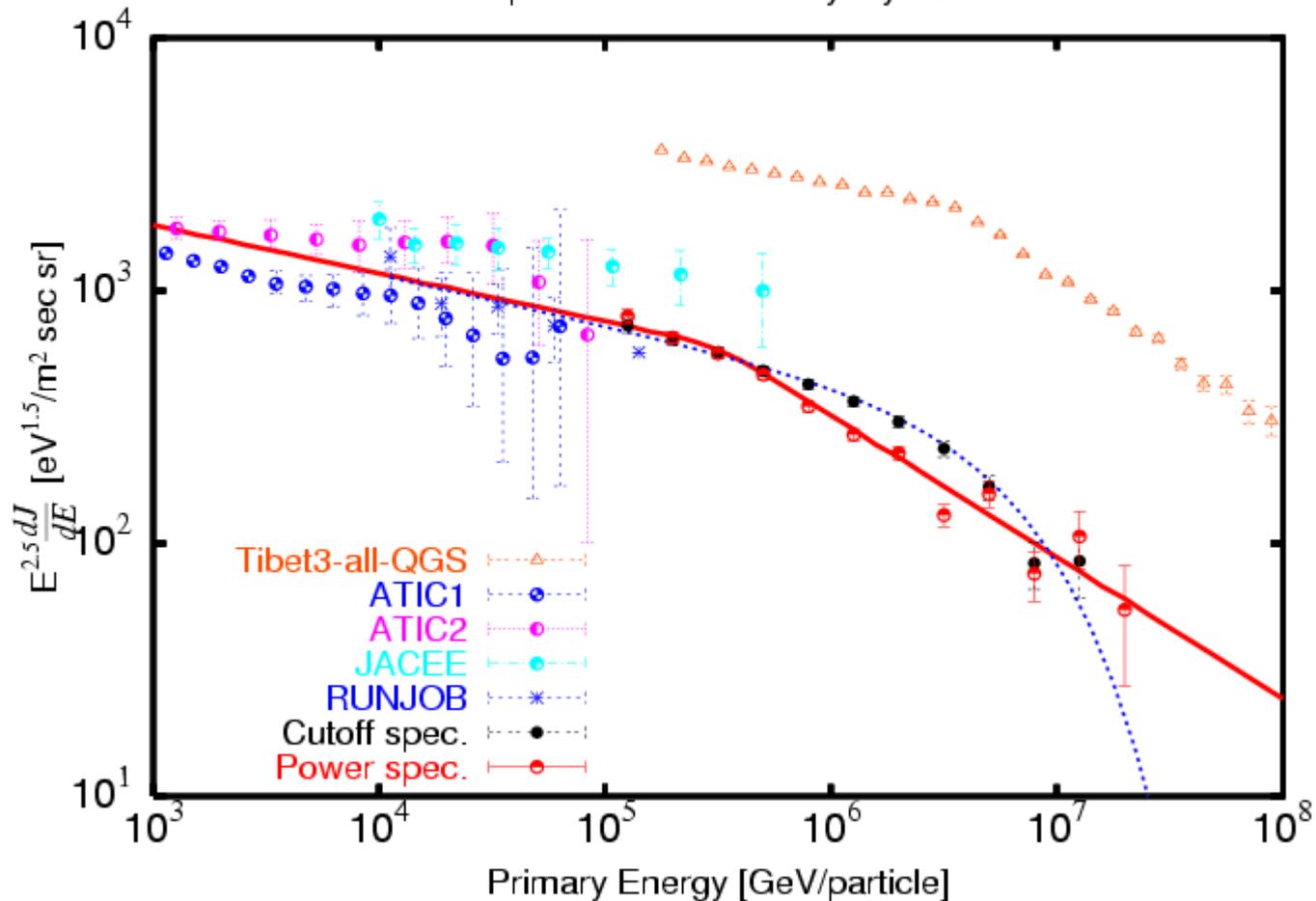
Expected proton flux by 3 years



Expected He Spectrum (YAC-II)

Helium kneeを探せ

Expected Helium flux by 3 years



The **ALPACA** Experiment

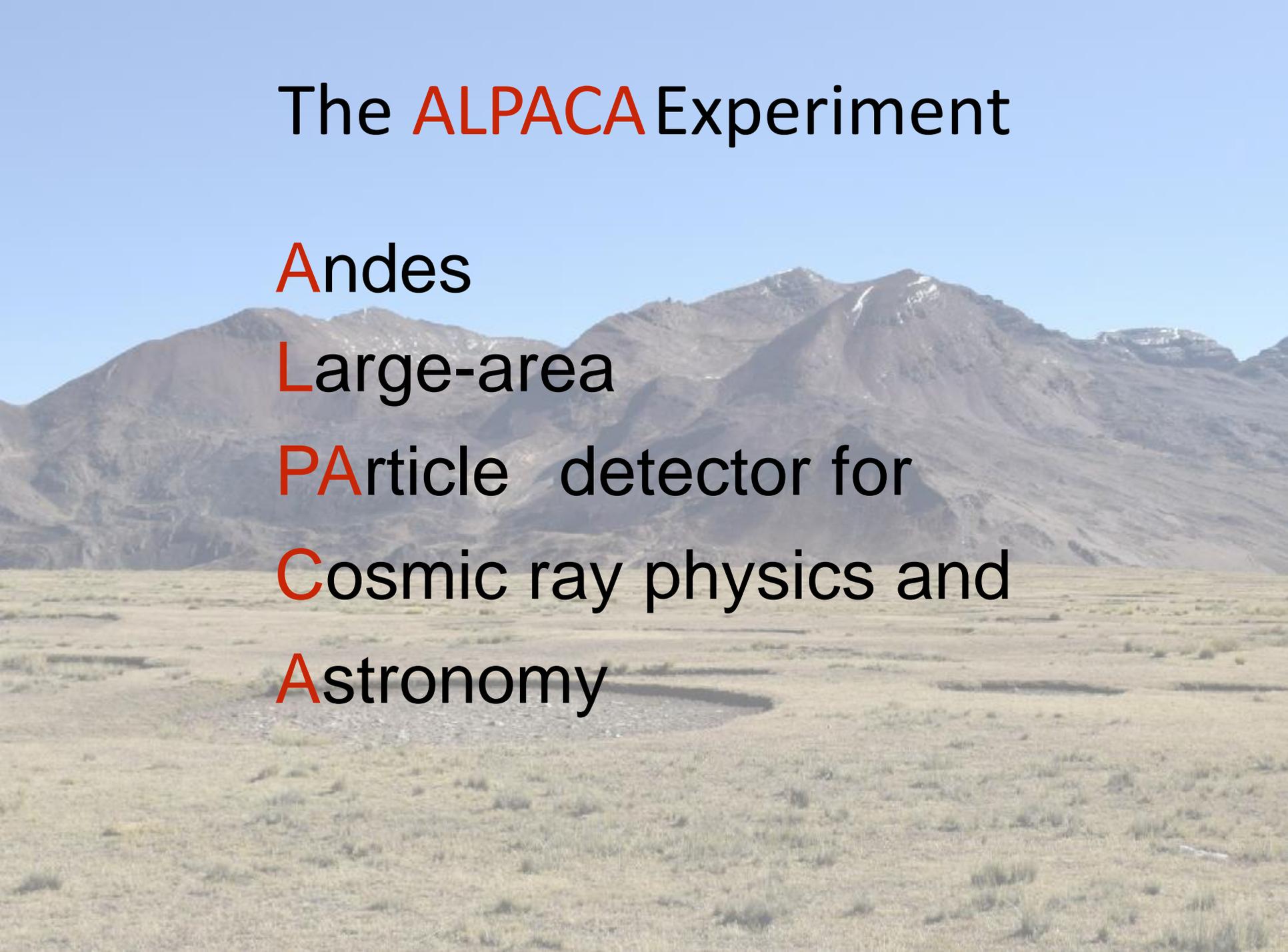
Andes

Large-area

Particle detector for

Cosmic ray physics and

Astronomy





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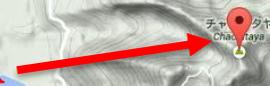
ALPACA Site

Mt. Chacaltaya, Bolivia



Site Survey

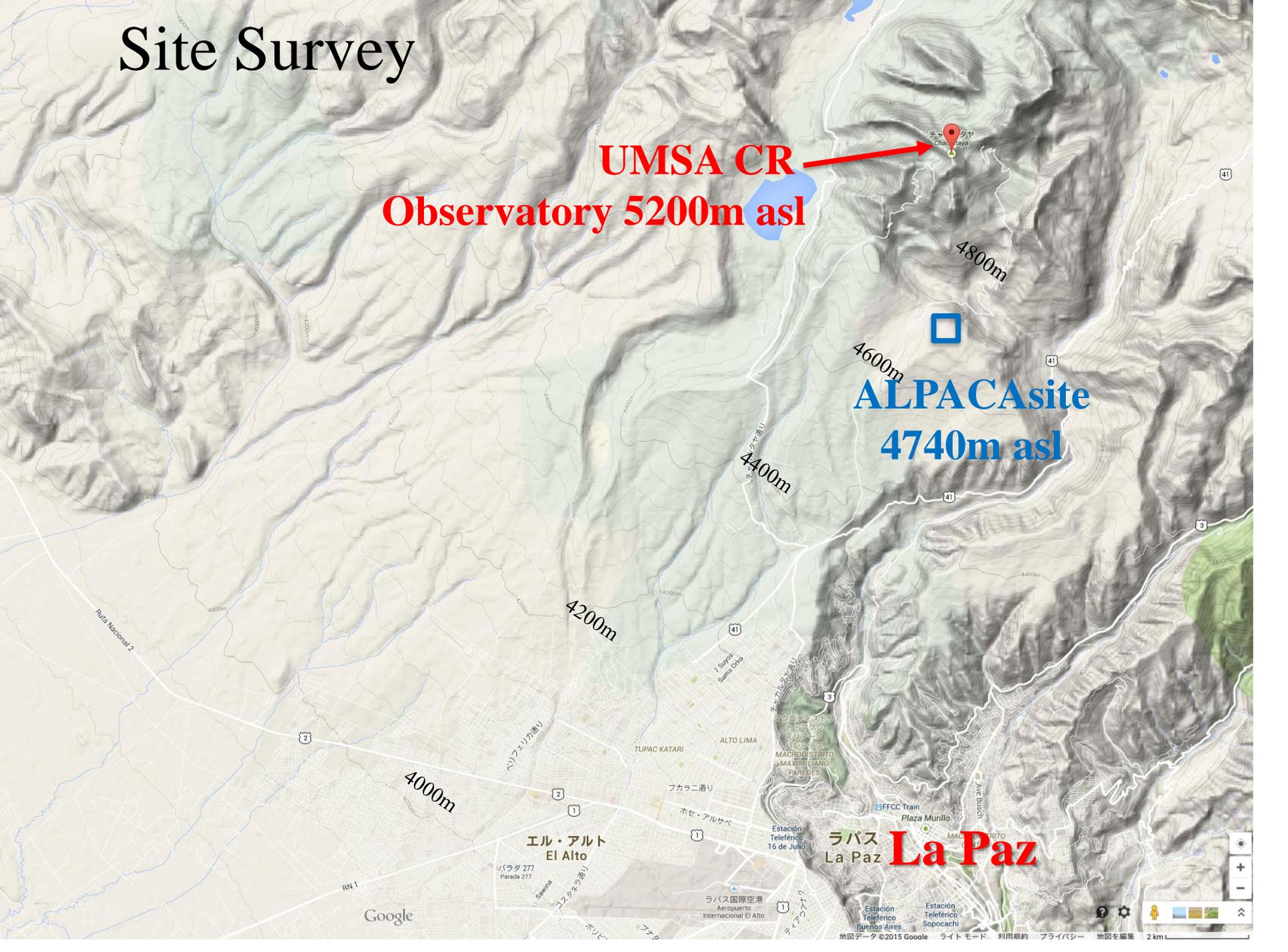
UMSA CR
Observatory 5200m asl



ALPACA site
4740m asl



ラパス La Paz



UMSACosmic Ray Laboratory

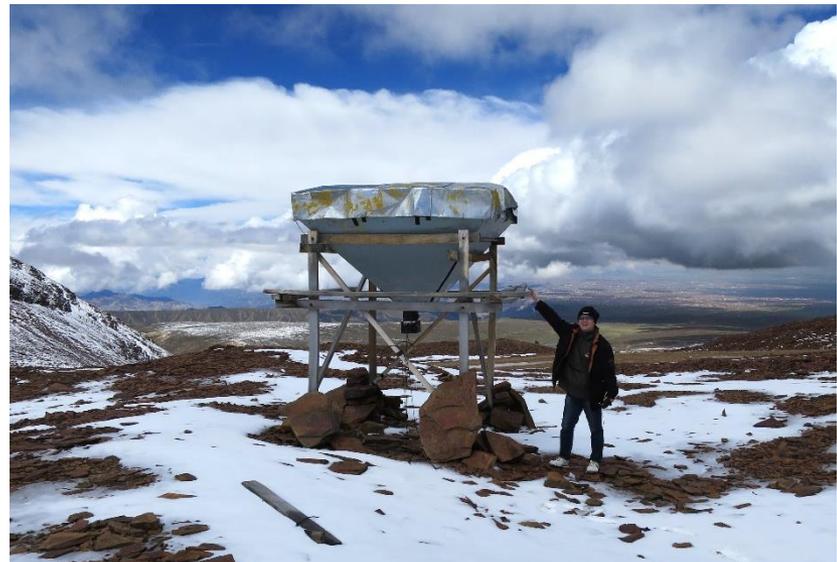


✓ Mt Chacaltaya(5,200m asl)

✓ CR Lab at the highest altitude

✓ Discovery of pion

C. F. Powell in1947 (1950 Nobel Prize)



Main purpose of ALPACA

- 100 TeV γ -ray astronomy in South
- Locating origin of cosmic rays

by detecting cosmic 100 TeV gamma rays
from cosmic ray accelerator in our galaxy:

PeVatrons!

Why in Bolivia

- Flat land at high altitude: (> 4000m)
Cosmic rays absorbed in atmosphere before reaching sea level
- Galactic Center: Observable in the southern hemisphere (not in the northern hemisphere)
Most promising candidate of the origin of cosmic rays
- Long-term collaboration between Bolivia and Japan
(Good infrastructure: Electricity, water, road,...)
Since 1962 in the field of cosmic rays, for example, BASJE

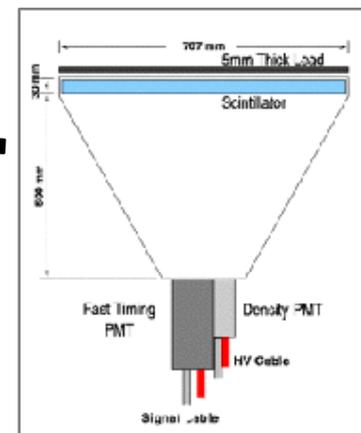
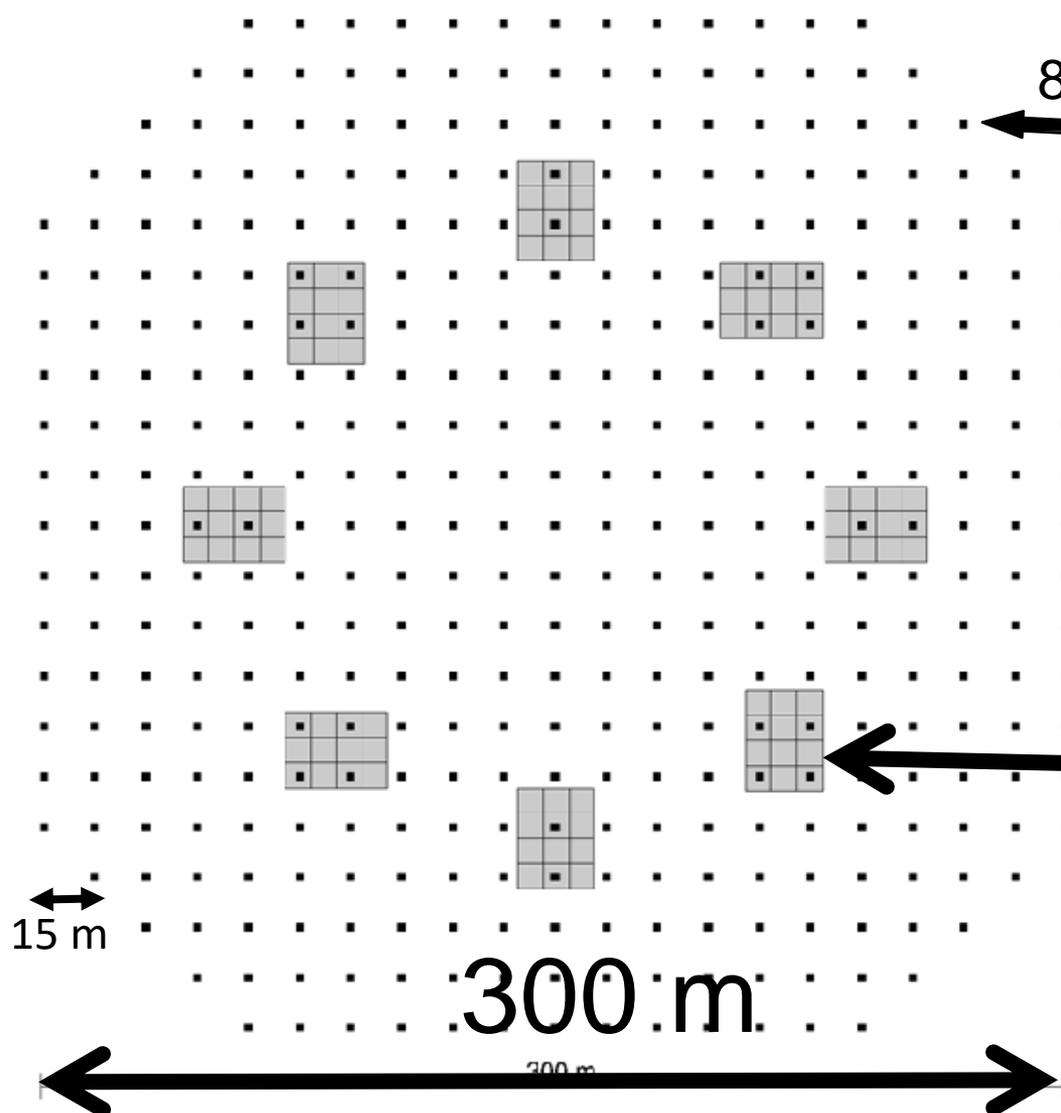
Observation Cite: **Chacaltaya Plateau**

500 m × 500 m flat within $\pm 1^\circ$

4,740 m above sea level (16° 23' S, 68° 08' W)



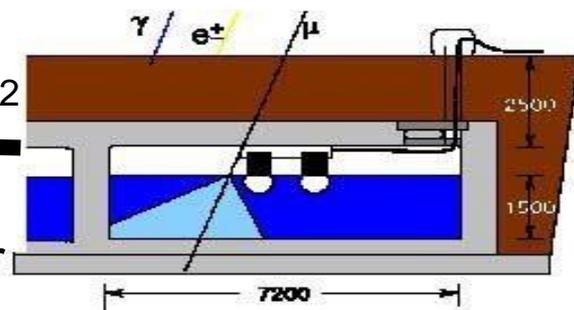
Schematic view of ALPACA



1m² plastic scintillation detector

5,400 m²

Muon Detector Array



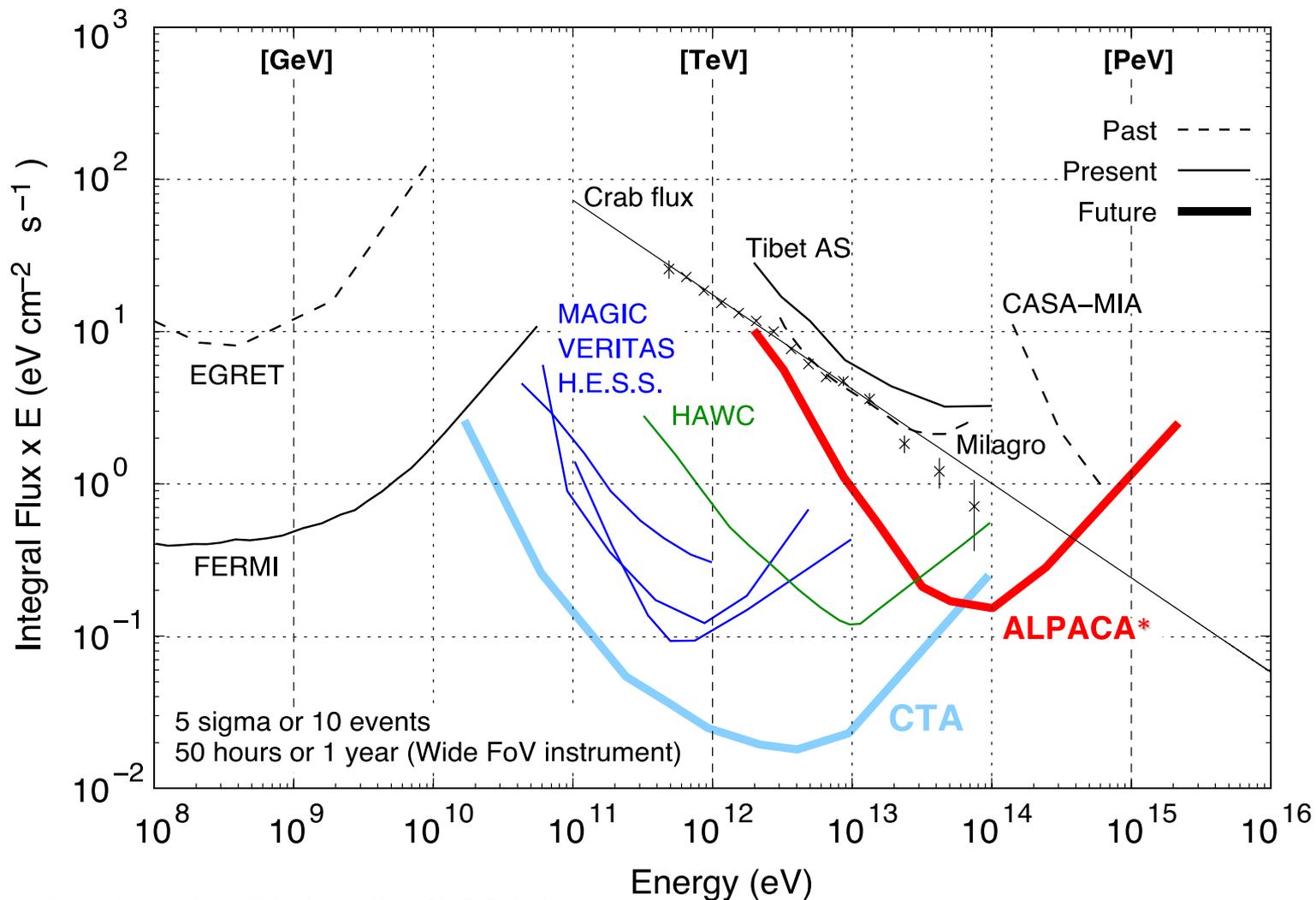
Underground water Cherenkov muon detector (56 m² / unit)

- 1 m² AS Detector x 401 (82,800 m²)
- 56 m² Muon Detector x 96 (5,400 m²)

Performance of ALPACA air shower array

Location:	4,740 m above sea level (16° 23' S, 68° 08' W)
# of scintillation detectors	1 m ² x 401 detectors
Effective area	~83,000 m ²
Modal energy	~5TeV
Angular resolution	~0.2° @ 100 TeV
Energy resolution	~20-25% @ 100TeV
Field of view	~2 sr

ガンマ線点源に対する感度



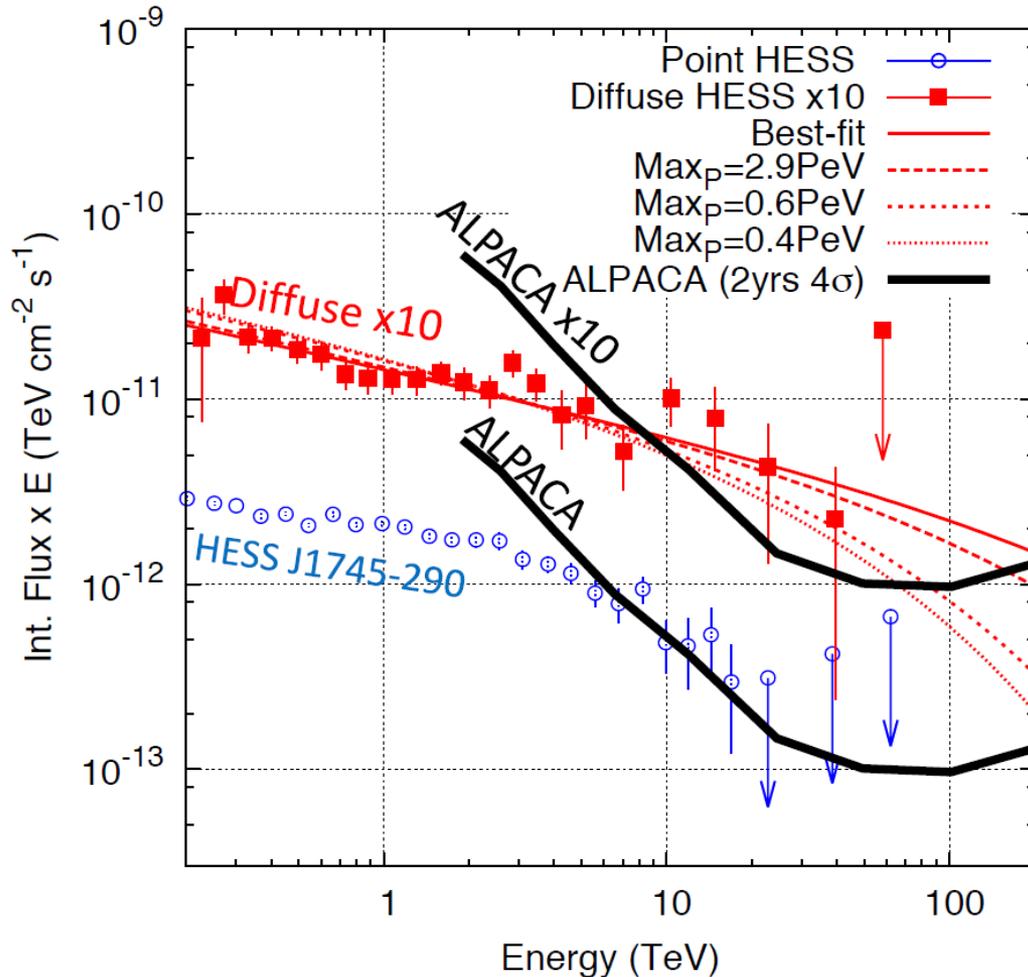
CTA Review by Kubo (JPS 2015)
M.Daniel, Proc. of 28th Texas Sympto. (2015)

*Based on MC Simulation
For the Tibet AS+MD

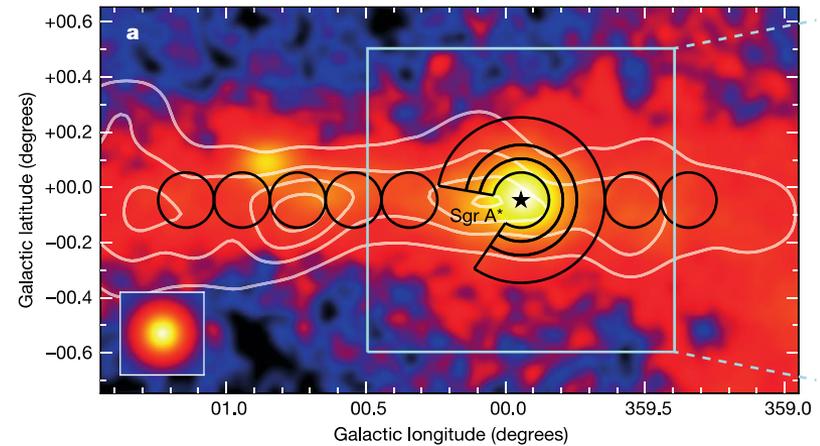
Target γ Sources

- Galactic Center
- Fermi Bubbles
- Young SNR
- Other Galactic Point-like Sources
- Nearby Extragalactic Sources

Galactic Center as PeVatron?



- ✓ Detection of diffuse component
- ✓ $>100\text{TeV}$ γ -ray expected
- ✓ PeVatron candidate

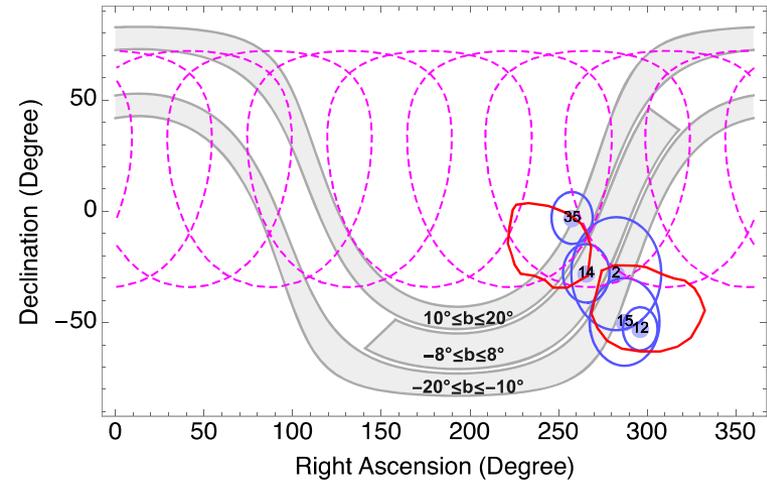


Abramowski, et al, Nature (2016)

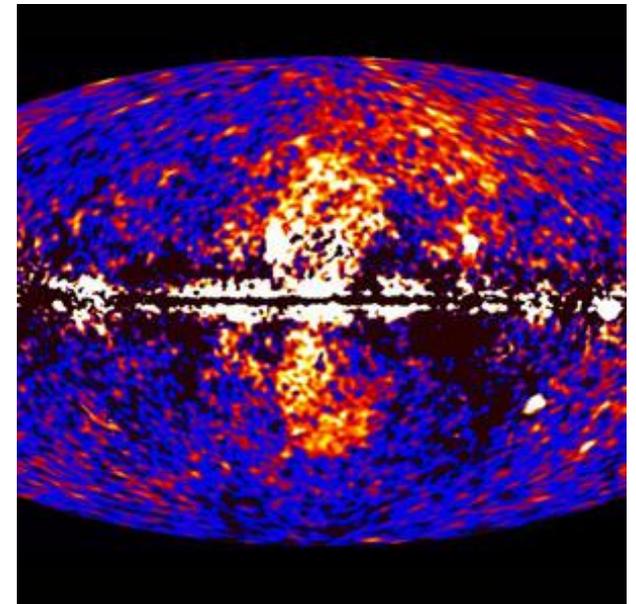
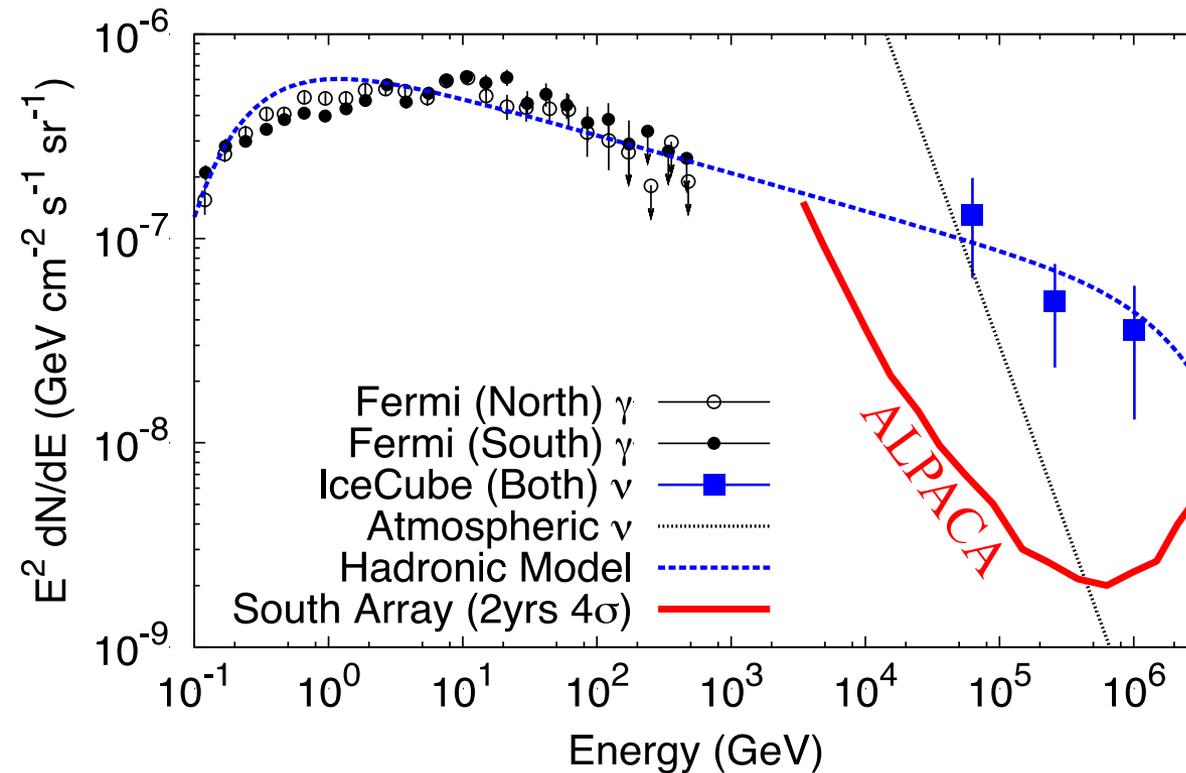
$$\delta \sim -29^\circ$$

Fermi Bubbles

- ✓ sub-PeV γ rays expected, if sub-PeV ν 's detected by IceCube are of hadronic origin.
- ✓ Fermi Bubbles: Very extended ($\sim 0.8\text{sr}$) γ -ray sources difficult for IACTs to cover them all.

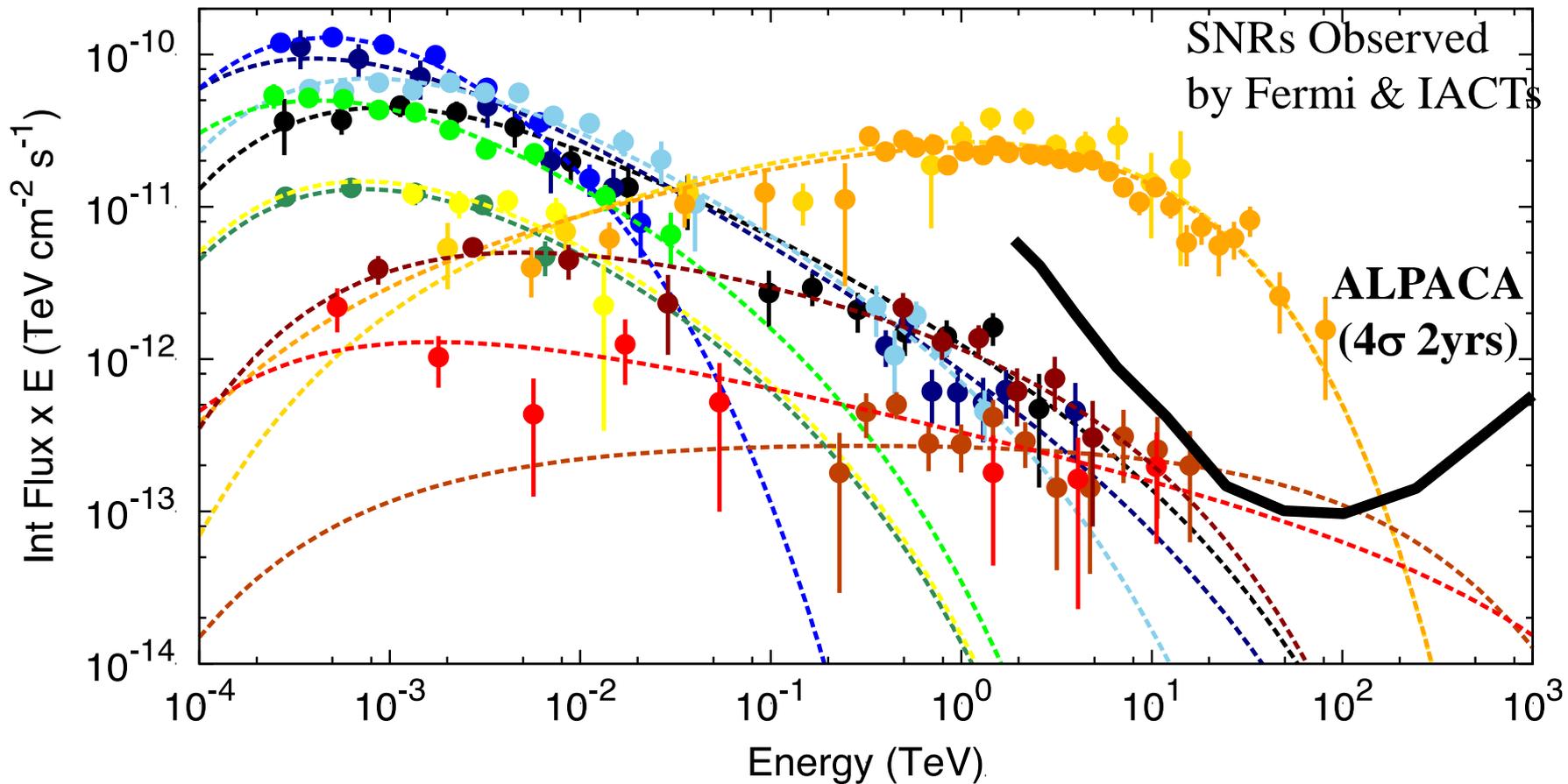


C. Lunardini, et al, PRD (2015)



Bubbles observed by Fermi-LAT

Young SNRs

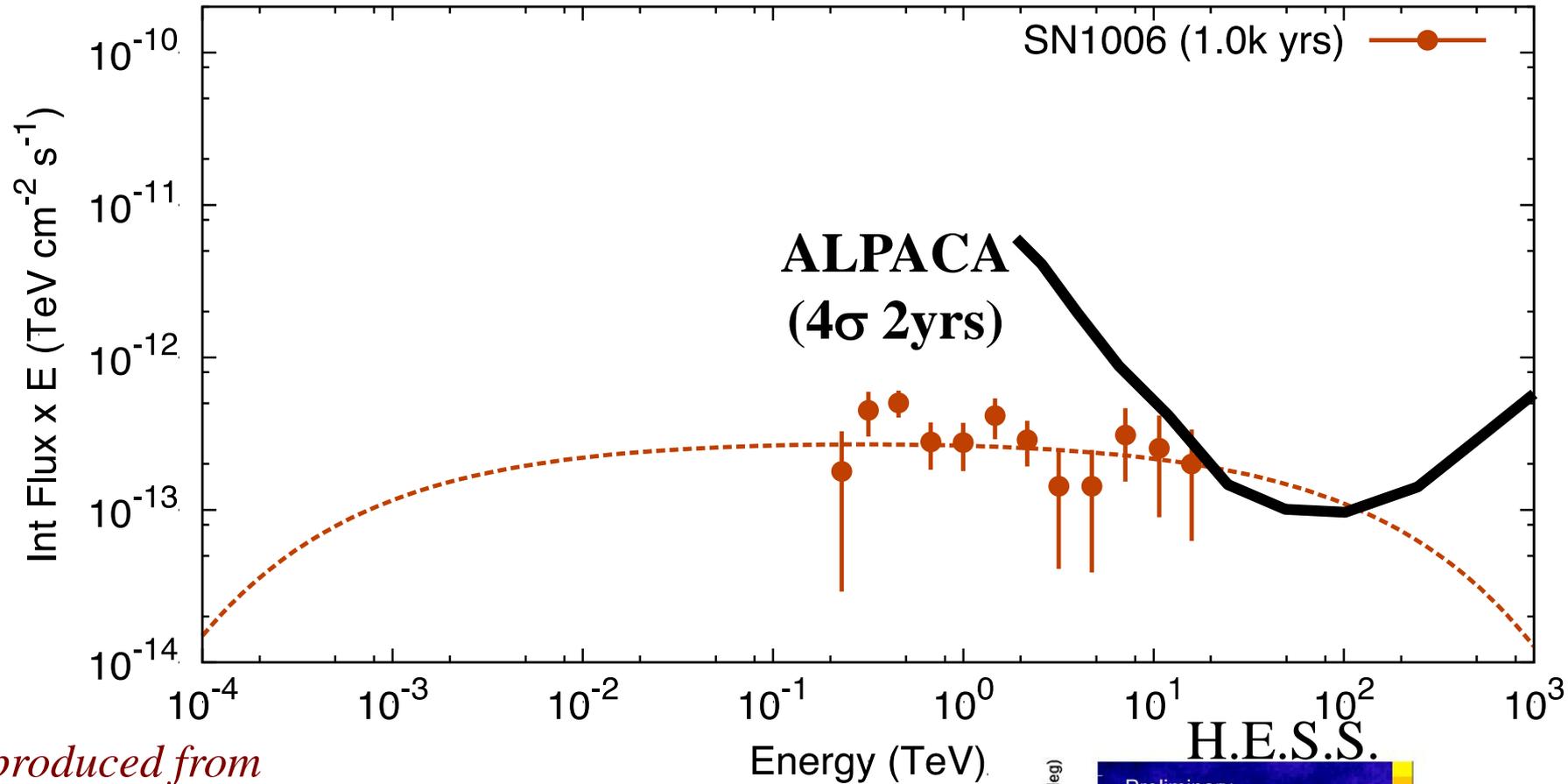


*Reproduced from
slides presented by
S. Funk (TeVPA
2011)*

W51C (35k yrs)	—●—
W28 (30k yrs)	—●—
W44 (20k yrs)	—●—
IC443 (10k yrs)	—●—
Cyg Loop (5.0k yrs)	—●—
W49B (4.0k yrs)	—●—

PuppisA (3.7k yrs)	—●—
RXJ0852 (2.5k yrs)	—●—
RXJ1713 (2.0k yrs)	—●—
SN1006 (1.0k yrs)	—●—
Tycho (0.4k yrs)	—●—
CasA (0.3k yrs)	—●—

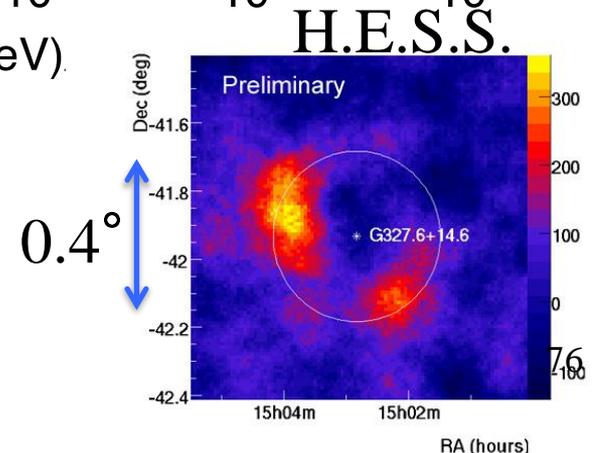
Young SNRs



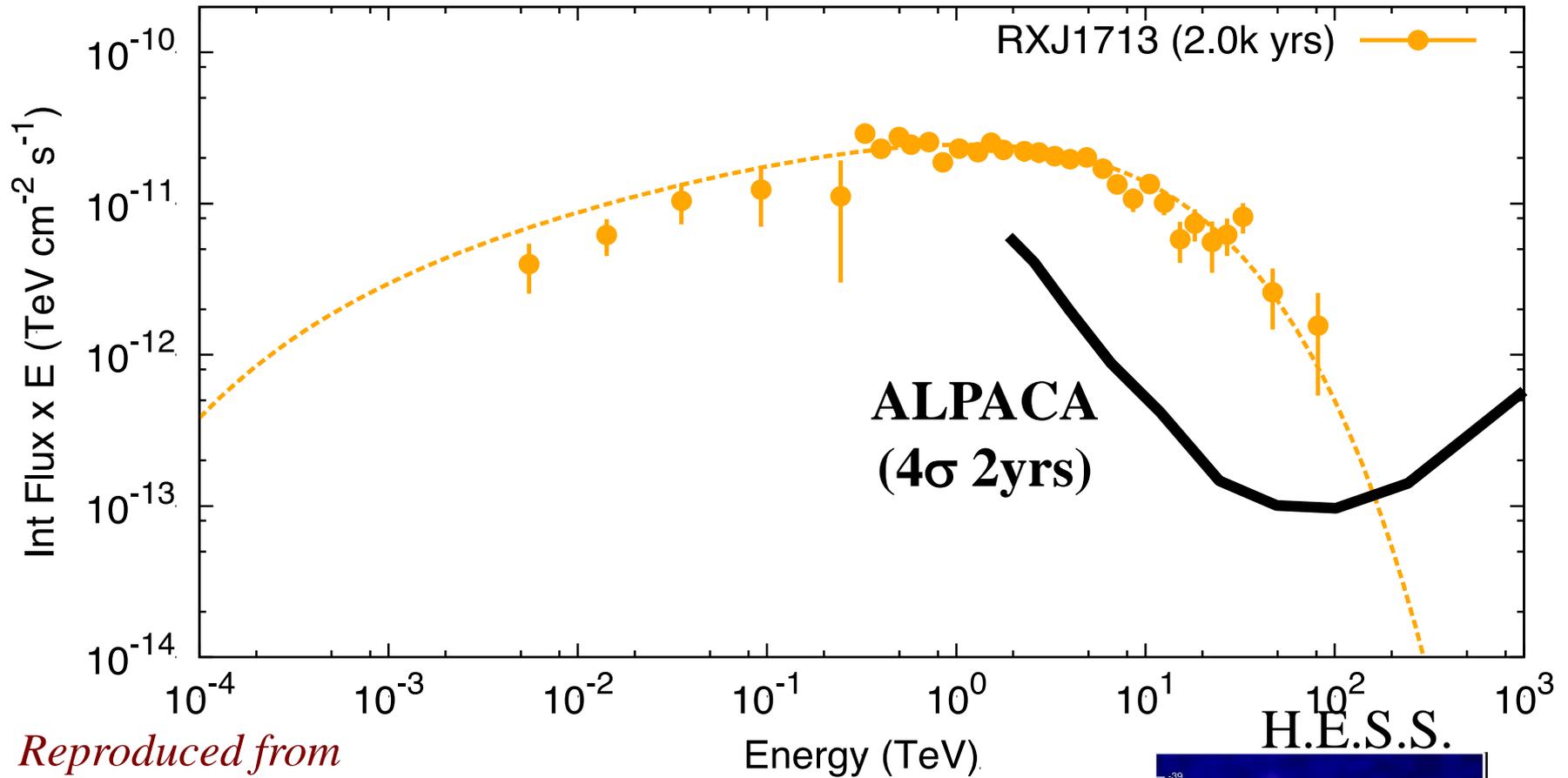
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SNRs Observed
by Fermi & IACTs

$\delta \sim -42^\circ$



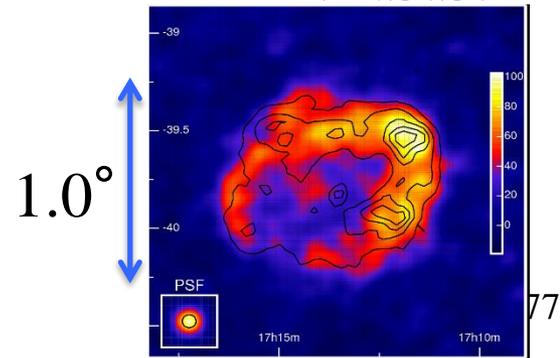
Young SNRs



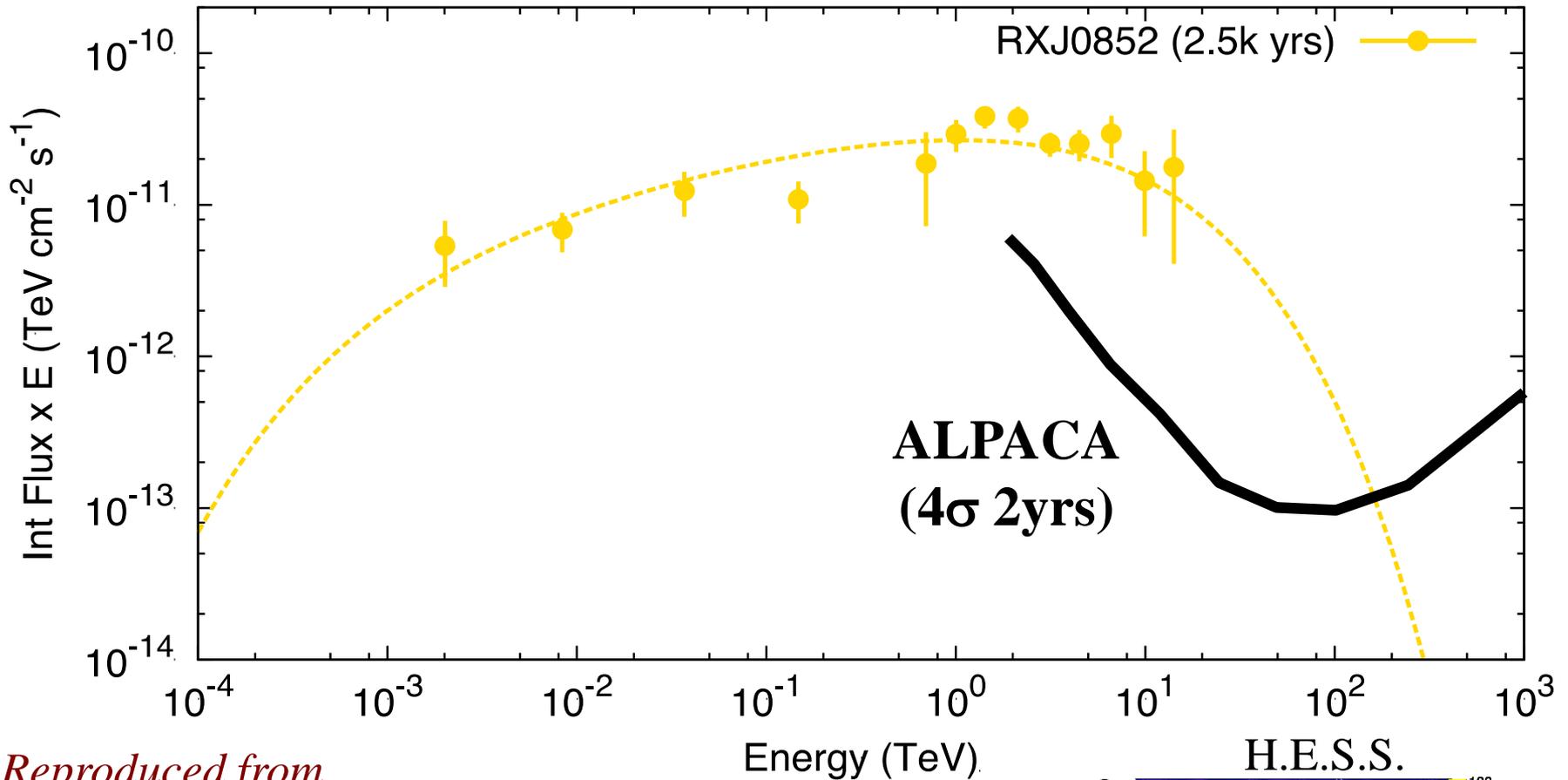
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SNRs Observed
by Fermi & IACTs

$\delta \sim -40^\circ$



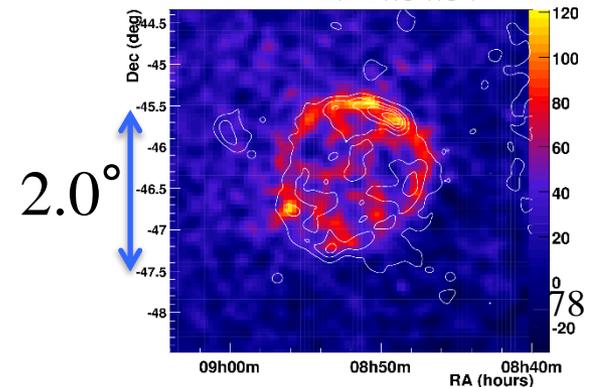
Young SNRs



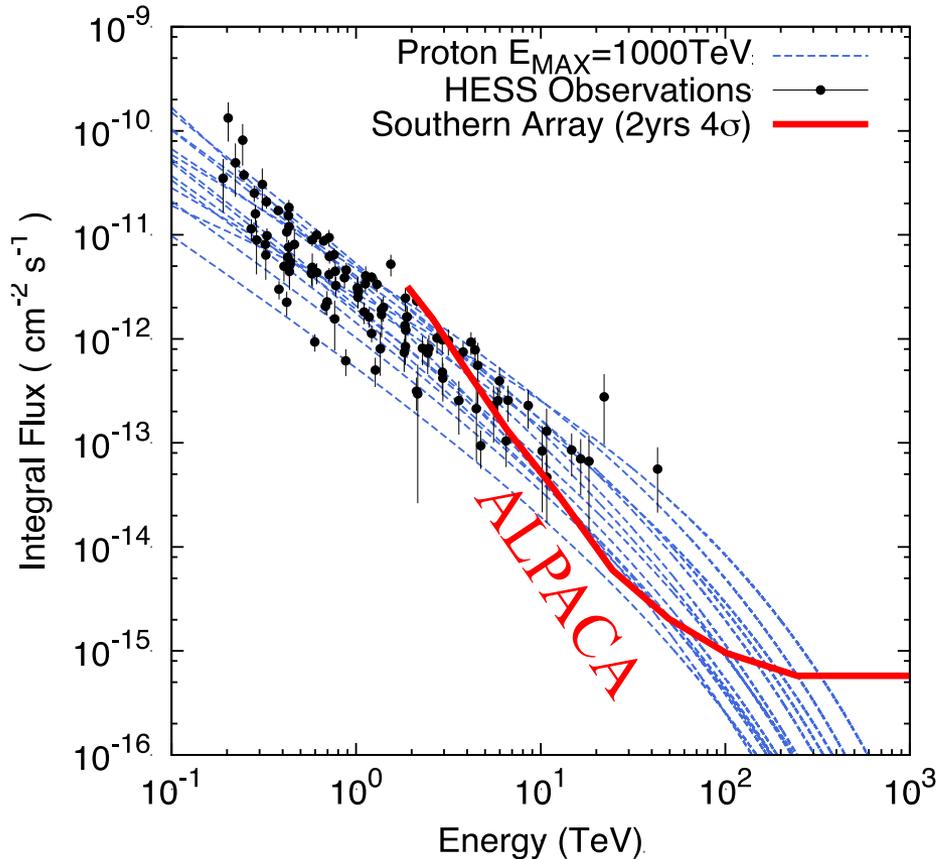
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slides presented by
S. Funk (TeVPA
2011)*

SNRs Observed
by Fermi & IACTs

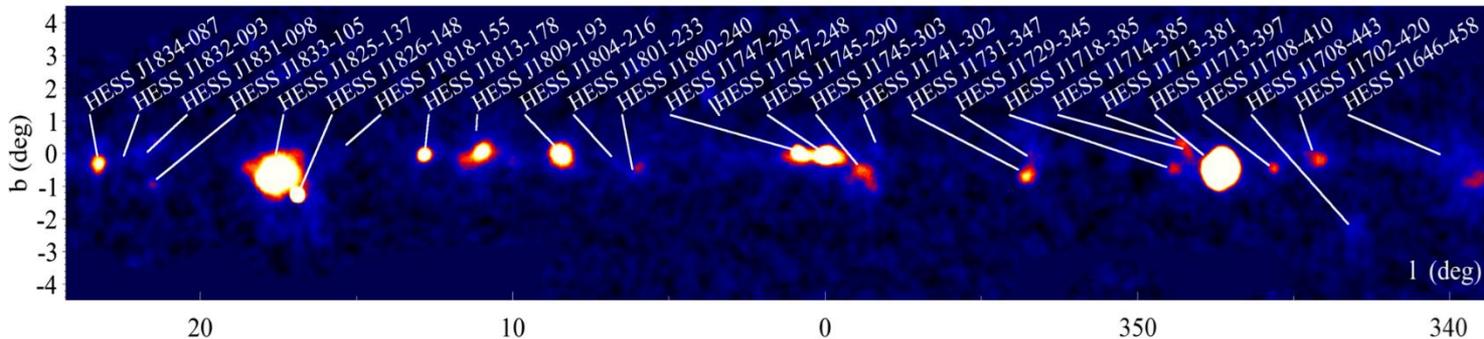
$\delta \sim -46^\circ$



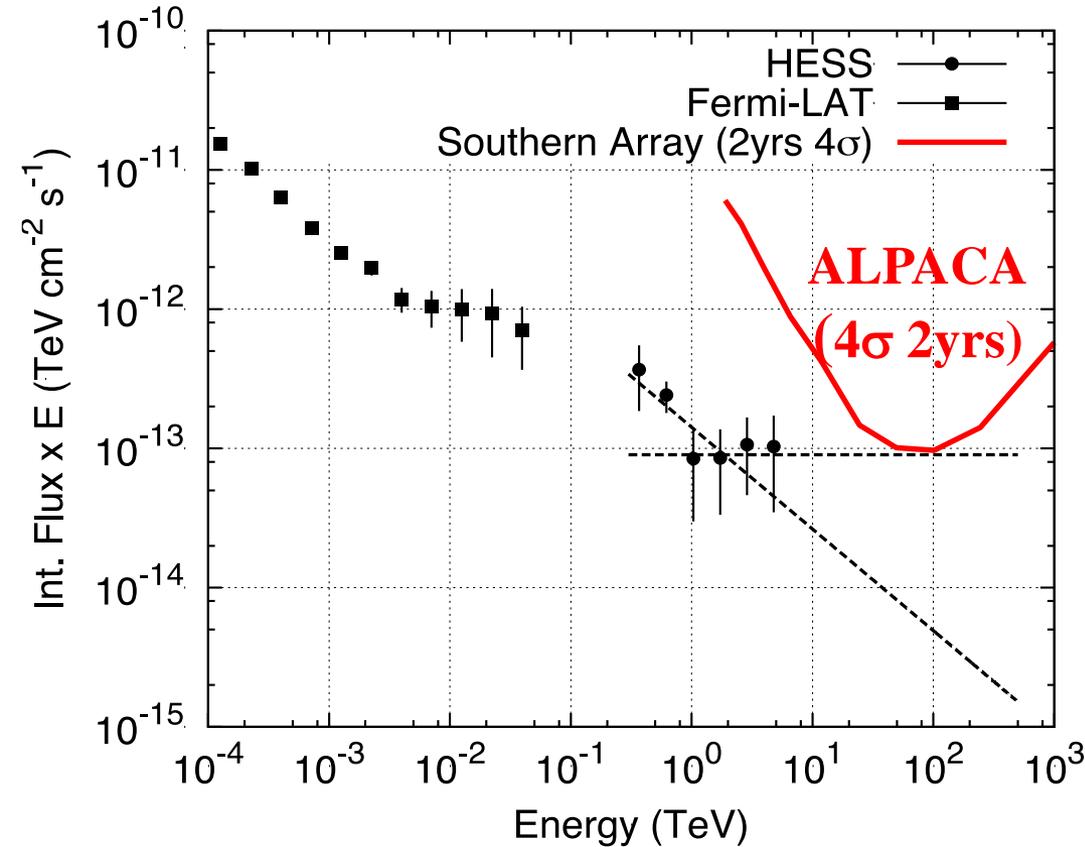
Other Galactic Sources



- ✓ More than dozen sources
 - ✓ Many sources are dark in other wave length
→ Dark particle accelerator
 - ✓ Many candidate of PWN (excess is located near pulsar)
- Aharonian et al, ApJ, 636, 777 (2006)*
- ✓ Diffuse γ from Galactic plane

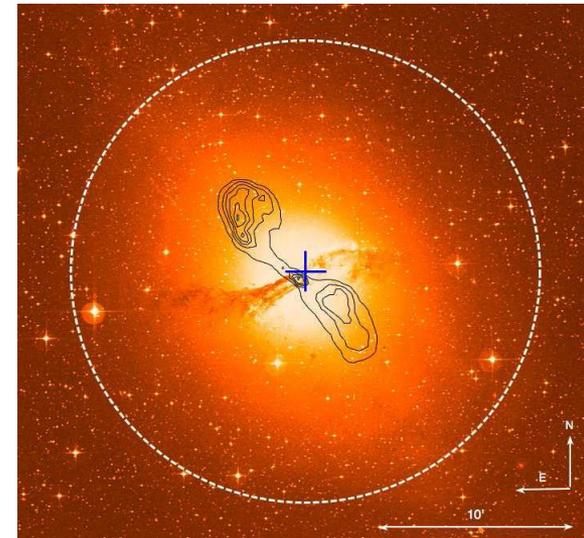


Nearby Extragalactic Source CenA



- ✓ Distance: 3.8Mpc very nearby!
- ✓ Relativistic jet
- ✓ Flat spectrum above TeV region?
- ✓ No significant time variation?

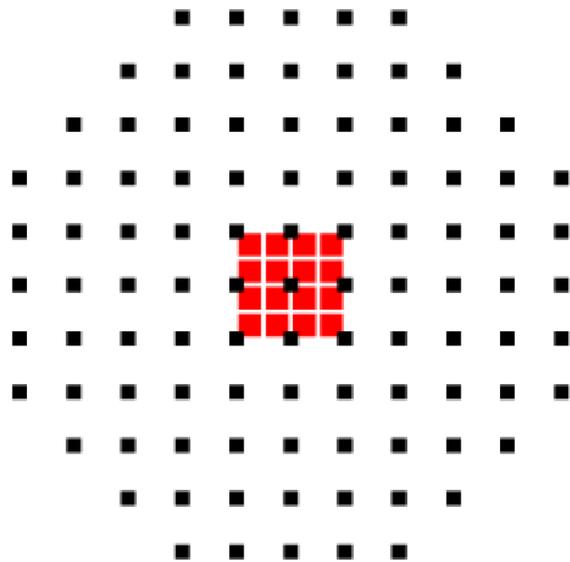
Aharonian et al, ApJ, 695, L40 (2009)
Sahakyan, et al, ApJ, 770, L6(2013)



$\delta \sim -43^\circ$

The ALPAQUITA Experiment

The prototype experiment of ALPACA



↔ 15 m

■ Scintillation detectors (1 m²)

■ Muon detectors

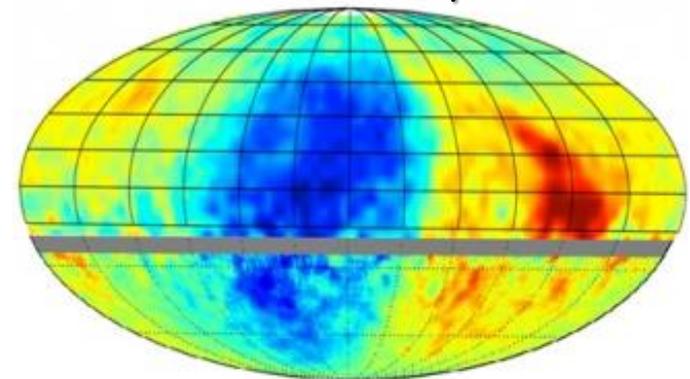


- Surface air-shower array: 18,450 m² (~1/4 of the ALPACA surface array)
- MD: 900 m² (56 m² × 16 cells)
- Motivation: Moon & Sun shadow, CR anisotropy, Thunder cloud & CR, VHE γ -ray sources @ 100TeV
- The surface array is now under construction
- MD will be constructed in 2021
Also aim the start of DAQ

ALPAQUITA実験：物理目標

- 南天における宇宙線異方性の観測
 - IceCube $E_{th} \sim 10 \text{ TeV}$ ($-90^\circ < \text{Dec.} < -20^\circ$)
 - ALPAQUITA $E_{th} \sim 5 \text{ TeV}$ ($-70^\circ < \text{Dec.} < +30^\circ$)
 - 銀河中心も含む赤緯での異方性解析
- 太陽(月)の影の観測
 - 赤道に近いので一年を通して観測可能
 - 月の影 $\sim 15\text{-}20\sigma / \text{year}$
- 雷と宇宙線の研究
 - 電場計と気象モニター
- 明るいガンマ線源の探索

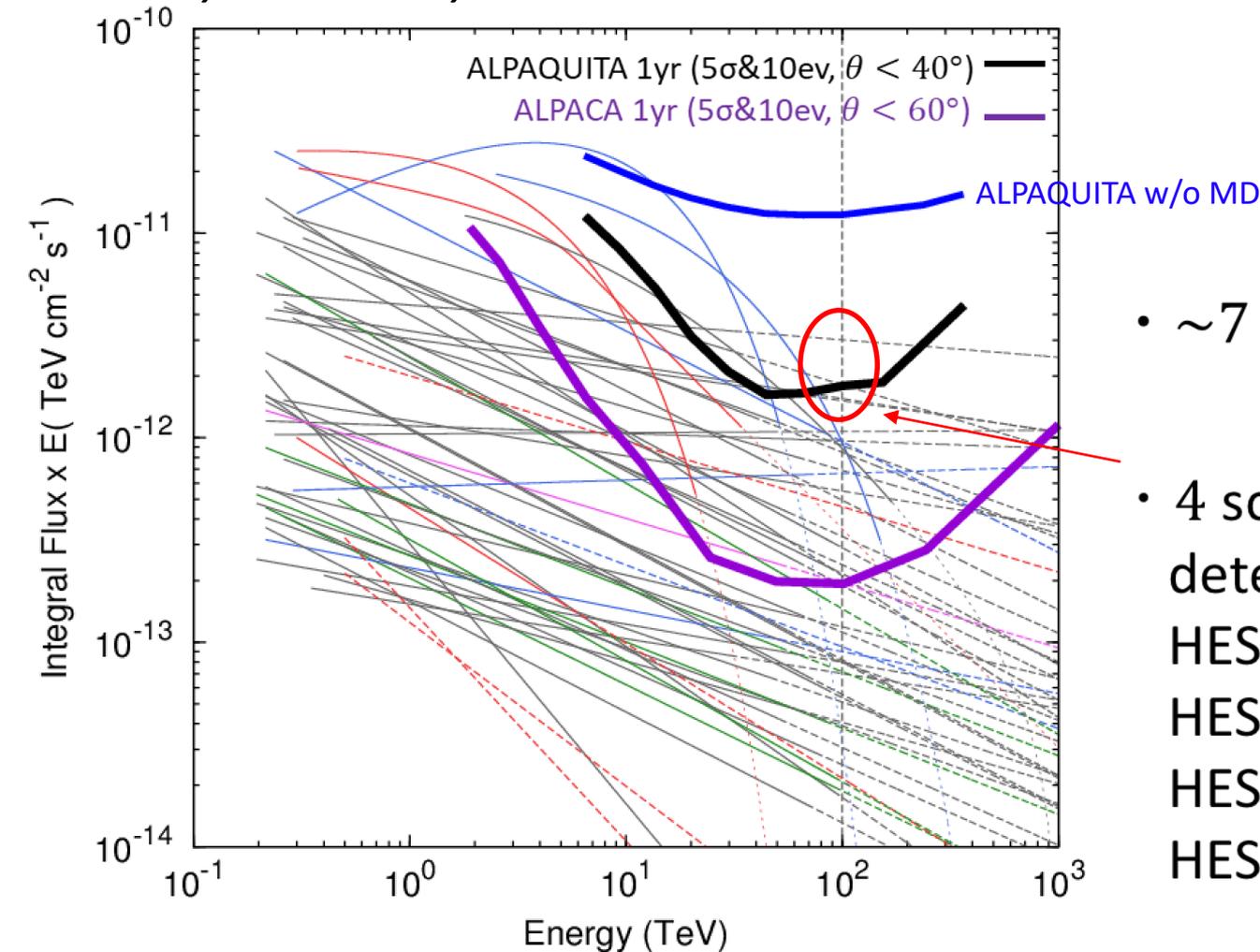
北天：Tibet AS γ 5TeV



南天：IceCube 20TeV

Sensitivity to VHE Gamma-ray Sources

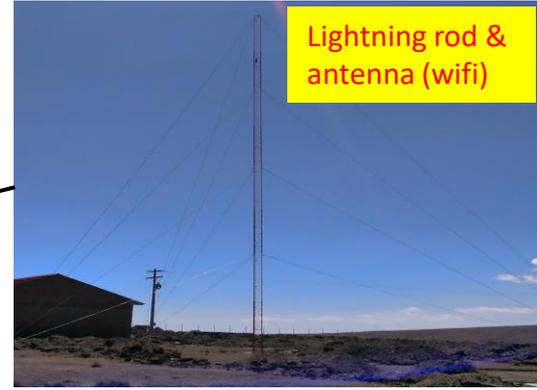
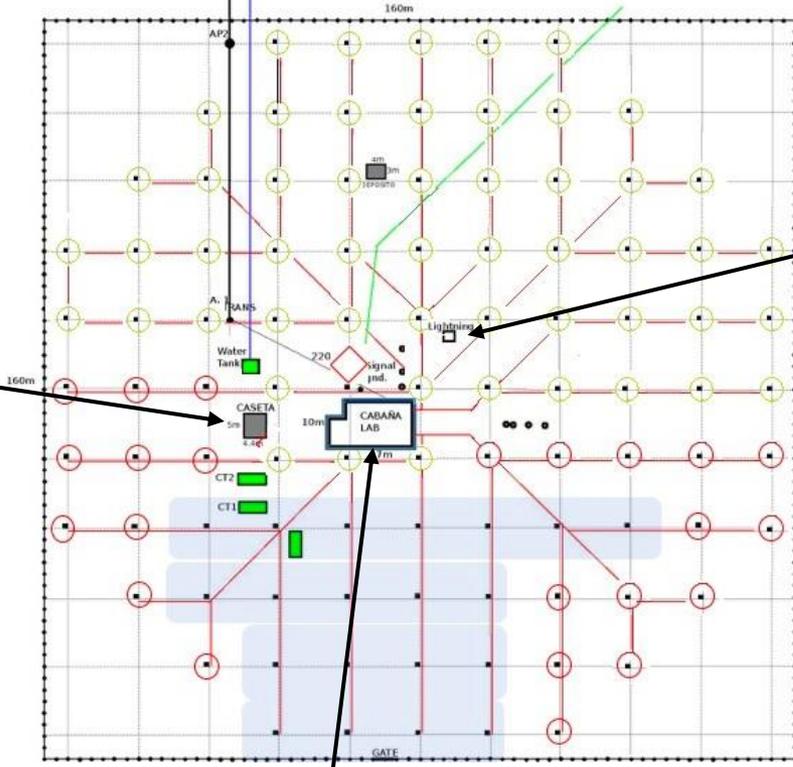
Sensitivity curves in $1\text{yr}5\sigma$



- ~ 7 sources in 1-yr obs. above 10 TeV
- 4 sources will be detected above 100 TeV !
HESS J1616-508
HESS J1702-420
HESS J1708-443
HESS J1843-033

For the energy spectra of the sources:
H.E.S.S. A&A 612, A1 (2018) & HAWC Phys. Rev. Lett 124, 021102 (2020)

ALPAQUITA Construction (the Current Status)



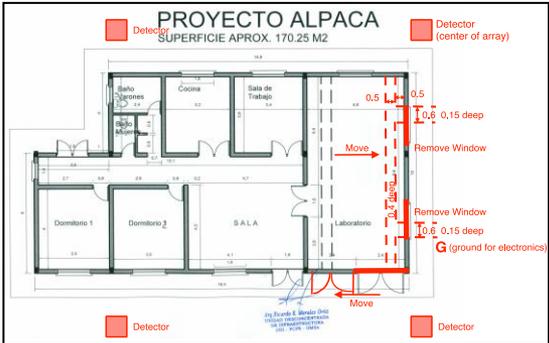
Electronics hut & detectors



Dwells for cables



Inside the electronics hut

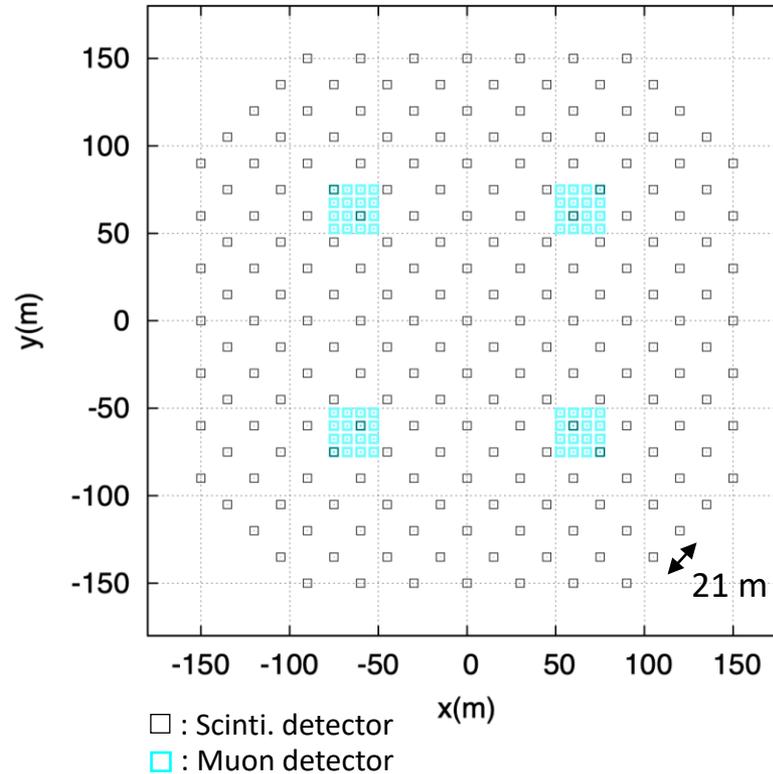


ALPAQUITA Construction (the Current Status 2)



The Half ALPACA Experiment

1st phase of the ALPACA experiment



- Surface AS array : Consists of 200 scinti. Detectors
Geometrical area : $83,000 \text{ m}^2$
- MD array : Consists of 64 MD cells
Geometrical area : $3,600 \text{ m}^2$

まとめ

- Tibet AS γ 実験: チベット高原 標高4,300m **on-going**
65,000m² AS + 3,400m² 水チェレンコフ型MD
 - ★ Targets
10 - 1000 TeV gamma-ray astronomy (**Northern sky**)
CR anisotropy, Chemical composition $\sim 10^{15}$ eV, Sun shadow
- ALPACA計画: チャカルタヤ山 中腹 標高4,740m
83,000m² AS (~400台)+ 5,400m² 水チェレンコフ型MD
 - ★ Targets
10 - 1000 TeV gamma-ray astronomy (**Southern sky**)
CR anisotropy, Chemical composition 10^{15} eV , Sun shadow
- ALPAQUITA: プロトタイプ空気シャワーアレイ
1.0 m² \times 97台、 $\sim 18,000$ m² AS + 900 m² MD **2021年**
- Half ALPACA: 83,000m² AS (~200台)+ 3,900m² MD **2022年**

Thank you for your attention!



ALPAQUITA (~1/4 AS) will be constructed in 2021₈₉

End