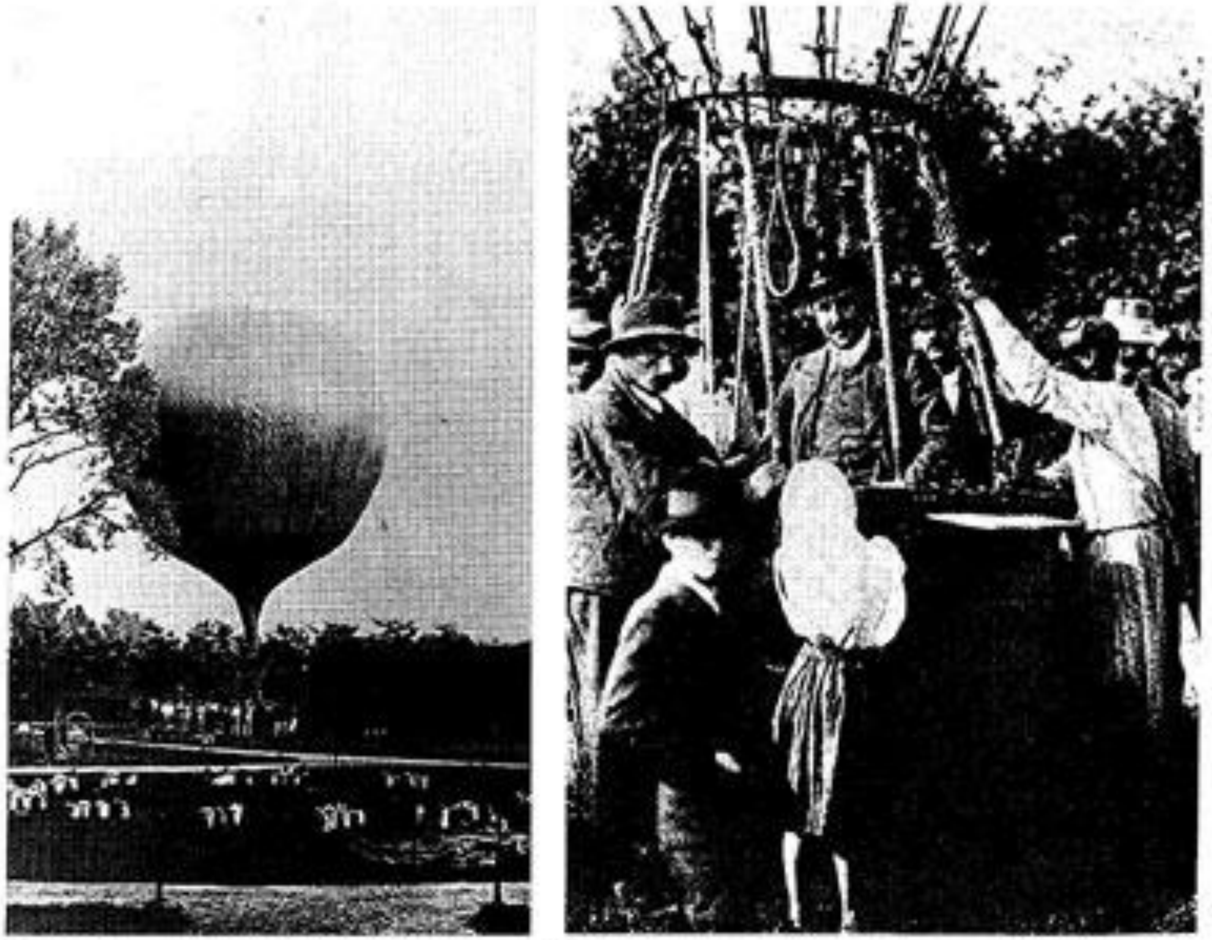
ガンマ線･宇宙線物理

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

瀧田正人, ICRR, U. of Tokyo

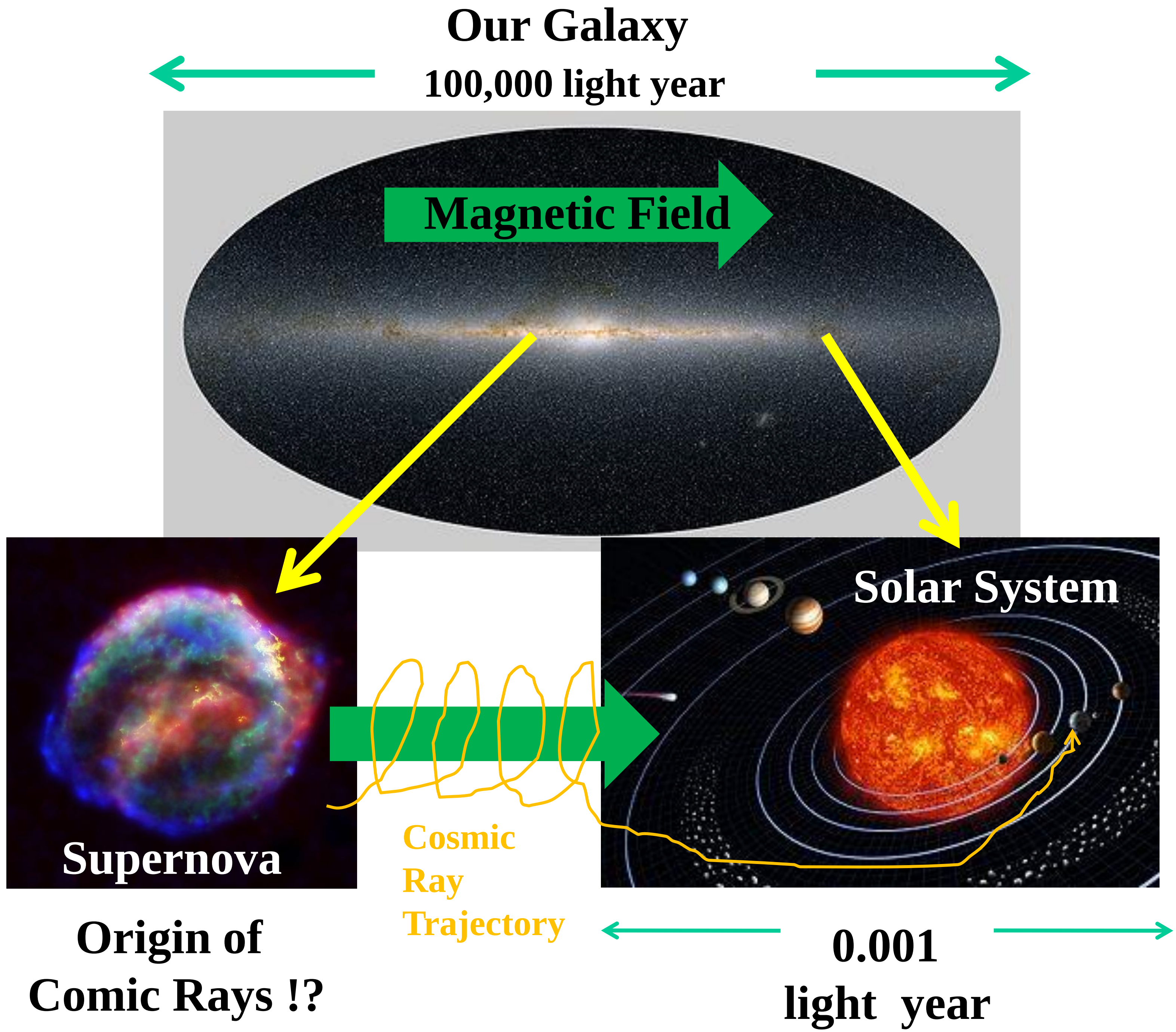
Spring School, @ICRR U. of Tokyo,
March 8, 2023

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



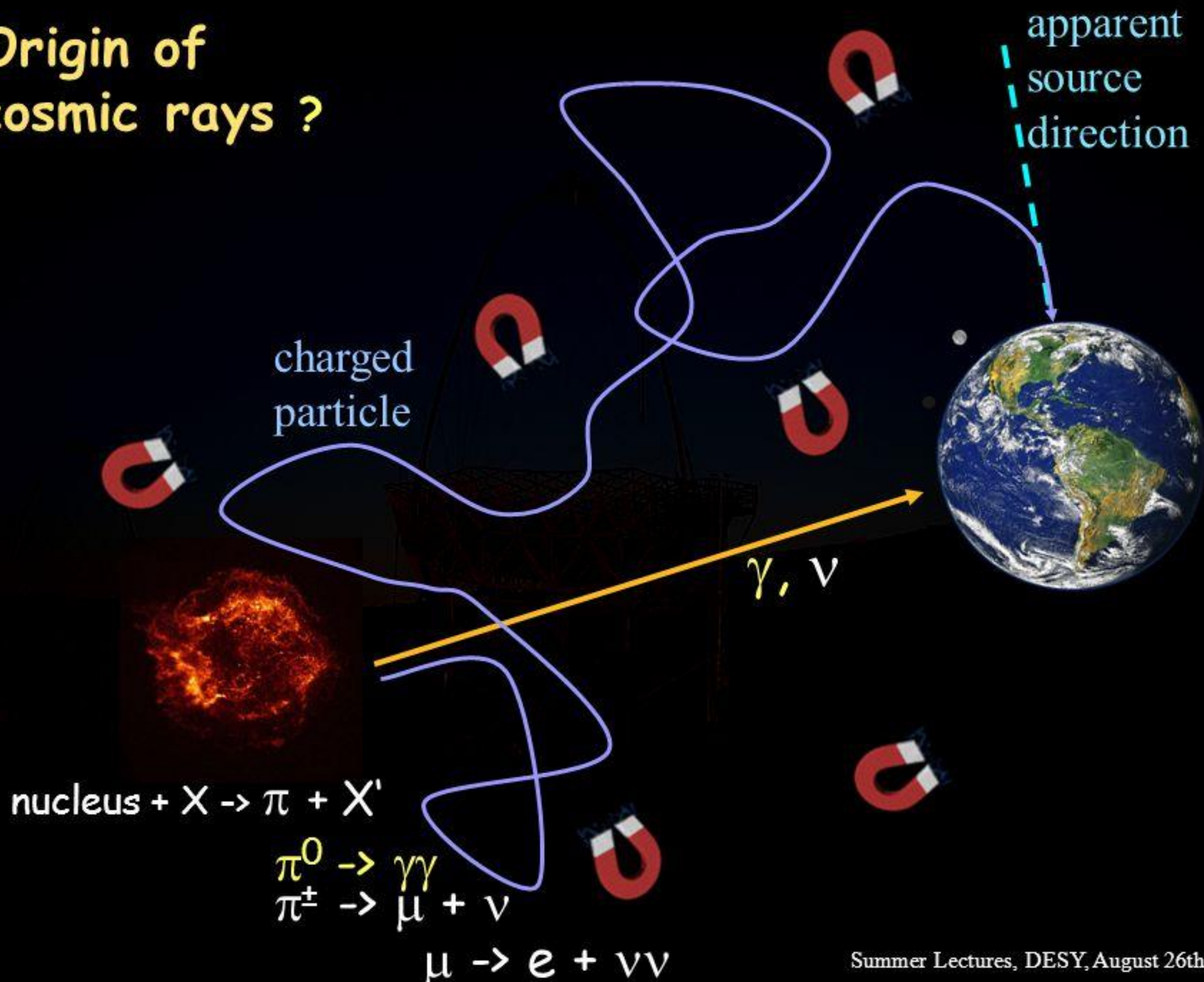
(a) (b)

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



Our Galaxy
100,000 light year
Magnetic Field
Supernova
Solar System
Cosmic
Ray
Trajectory
Origin of
Comic Rays !?
0.001
light year

Origin of cosmic rays ?



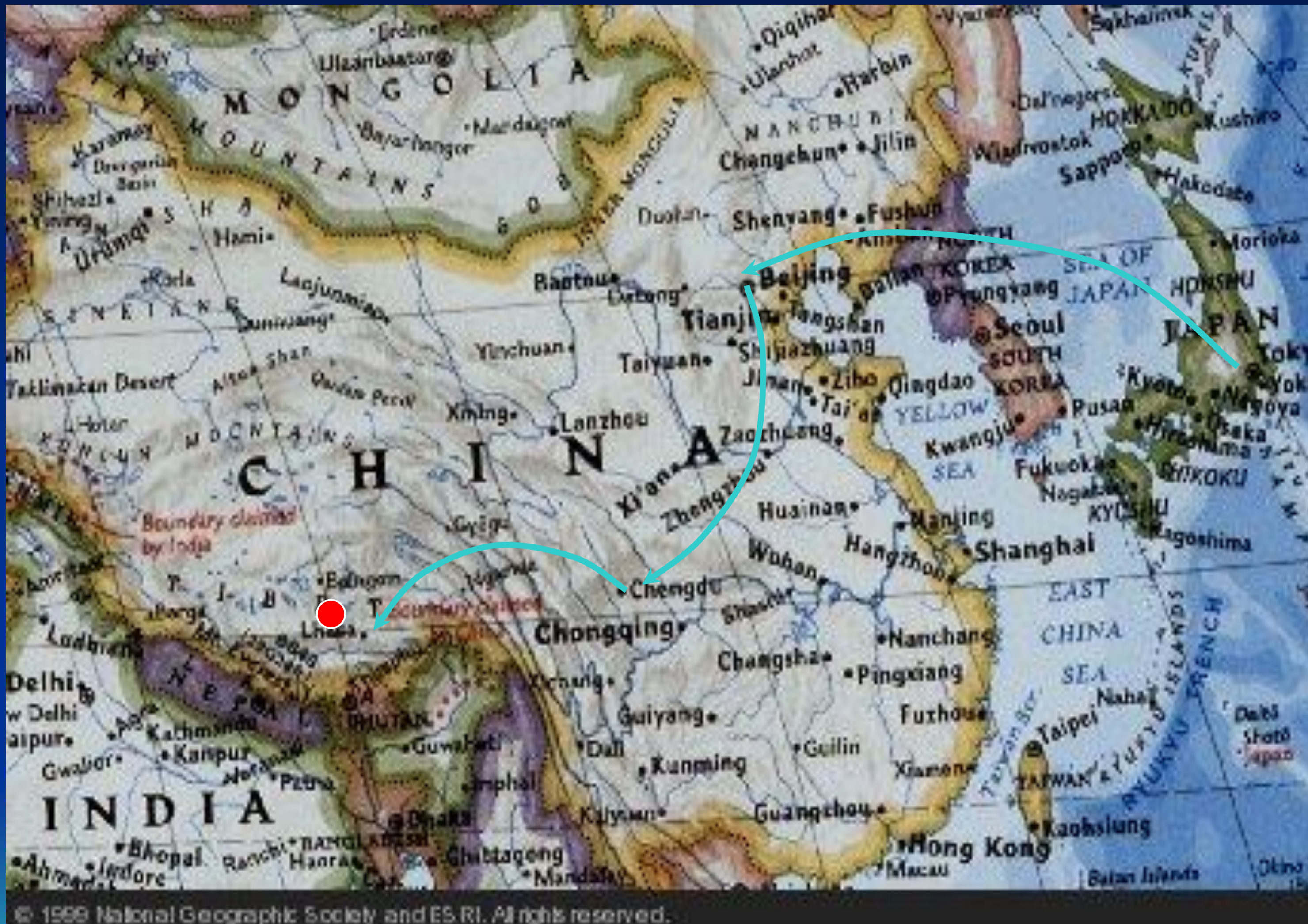
チベット空気シャワー観測装置の研究目的

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}～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



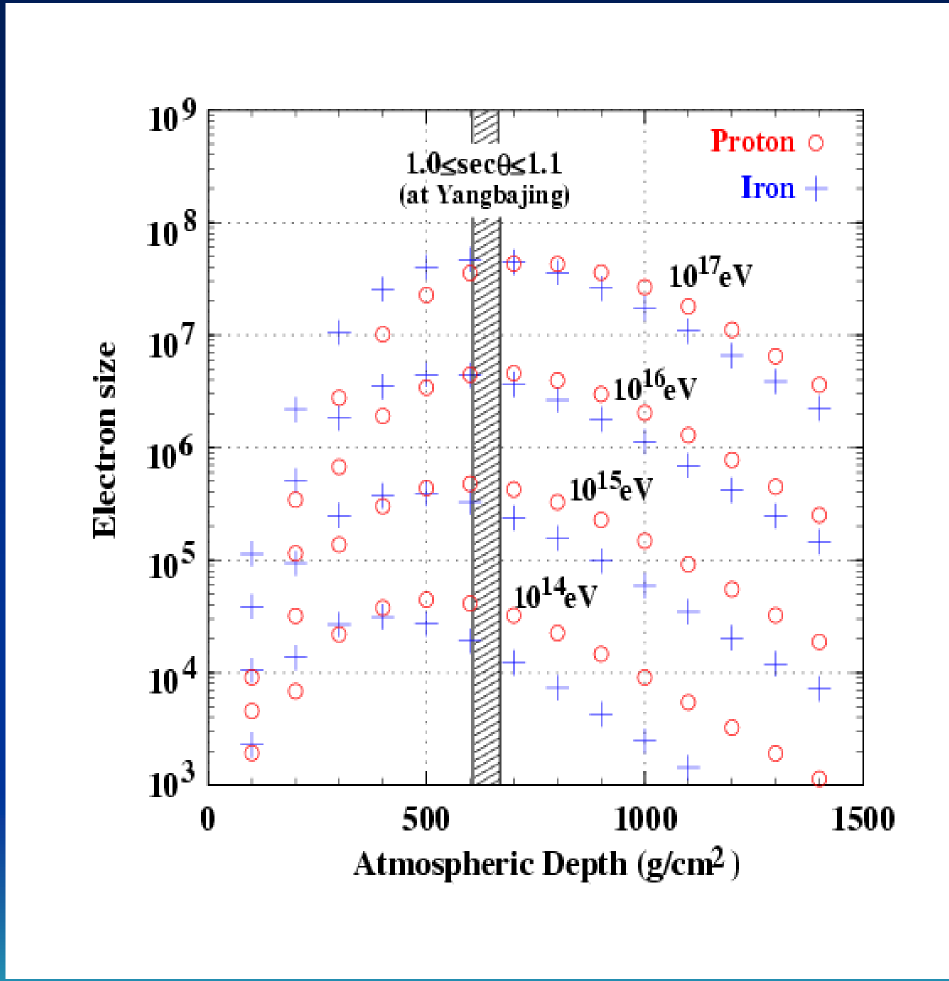
Yangbajing , Tibet, China

90°53**E**, 30°11**N**, 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。



Tibet ASγ Collaboration

1990年発足

現在 33機関・121名

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

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31 Research Institute for Science and Engineering, Waseda Univ., Japan.
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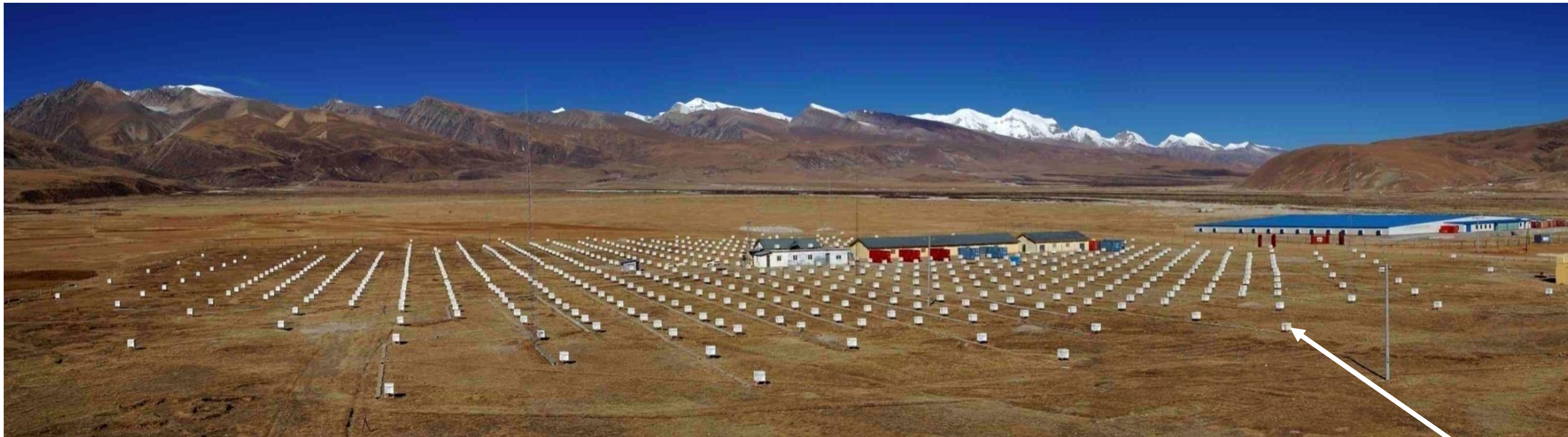
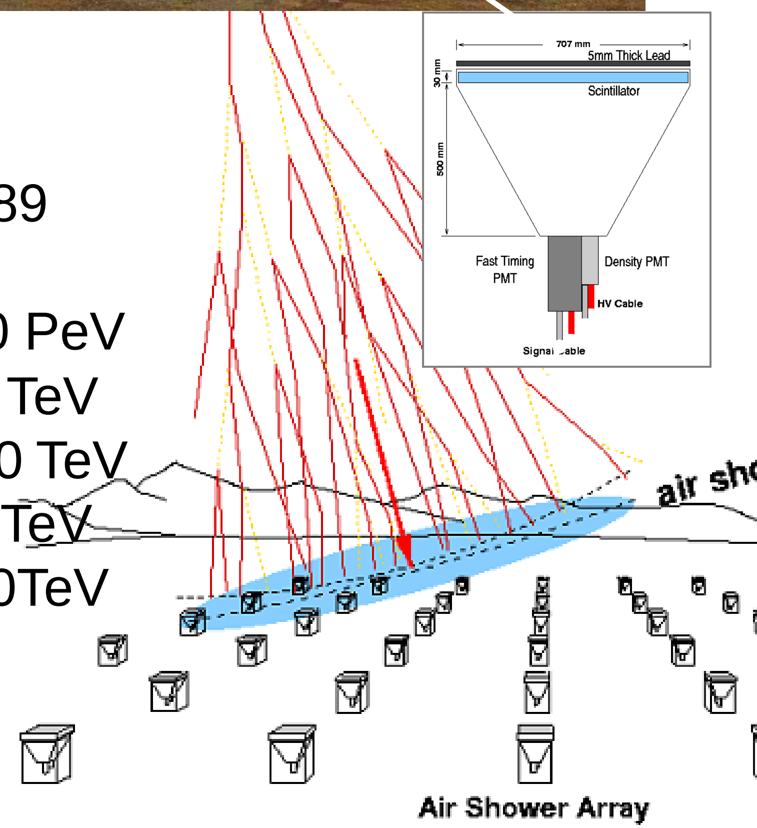
33 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, China.

Tibet-III Air Shower (AS) Array

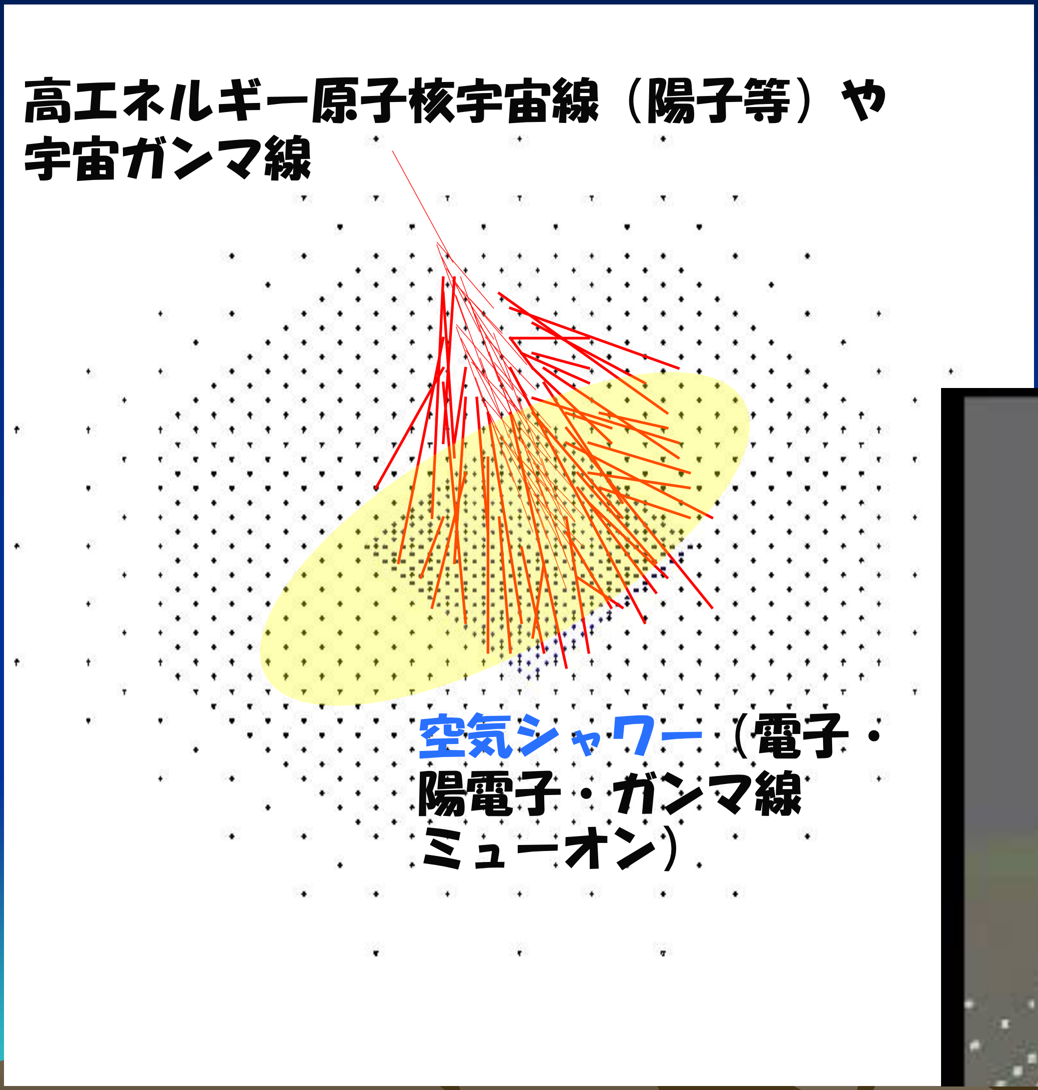


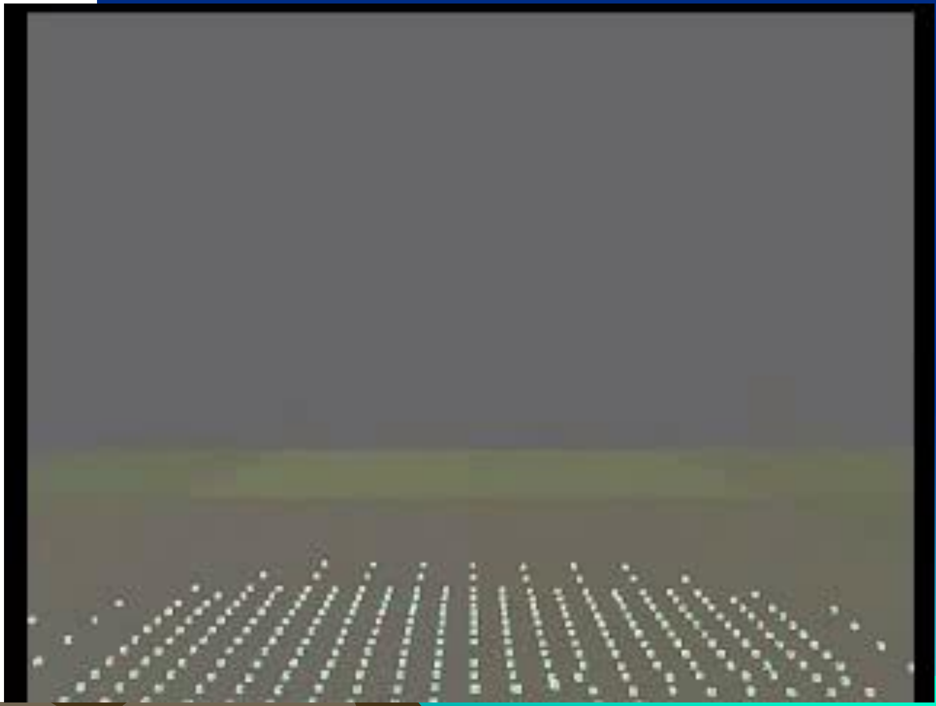
4,300 m a.s.l. (606 g/cm^2)

☐ Number of Scinti. Det.	0.5 m^2 x 789
☐ Effective Area for AS	~37,000 m^2
☐ Energy region	~3TeV - 100 PeV
☐ Angular Resolution (Gamma rays)	~0.4° @10 TeV ~0.2° @100 TeV
☐ Energy Resolution (Gamma rays)	~50% @10 TeV ~20% @100TeV
☐ F.O.V.	~2 sr
☐ Trigger Rate	1.7 KHz



空気シャワー





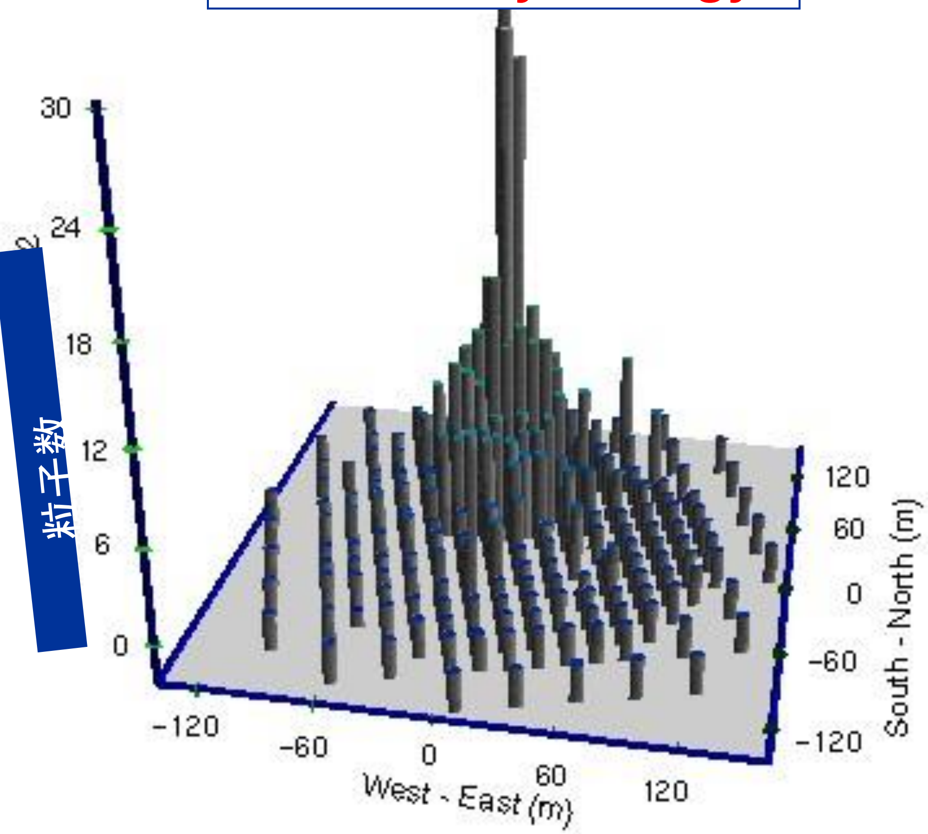
Air Shower Detection

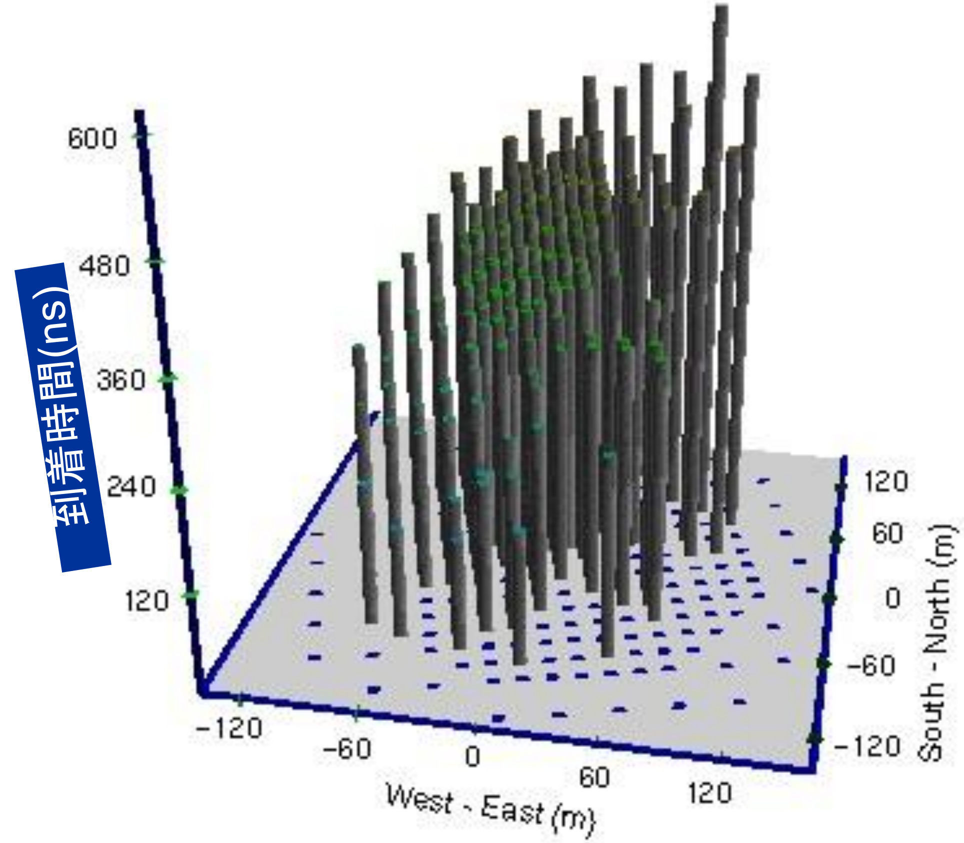
2nd particle density

Cosmic ray energy

2nd particle timing

Cosmic ray direction



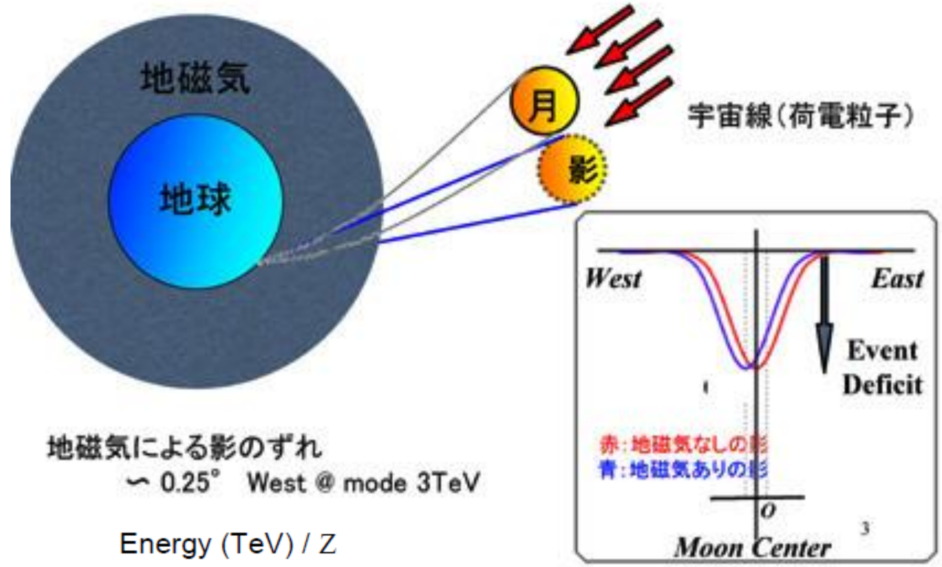


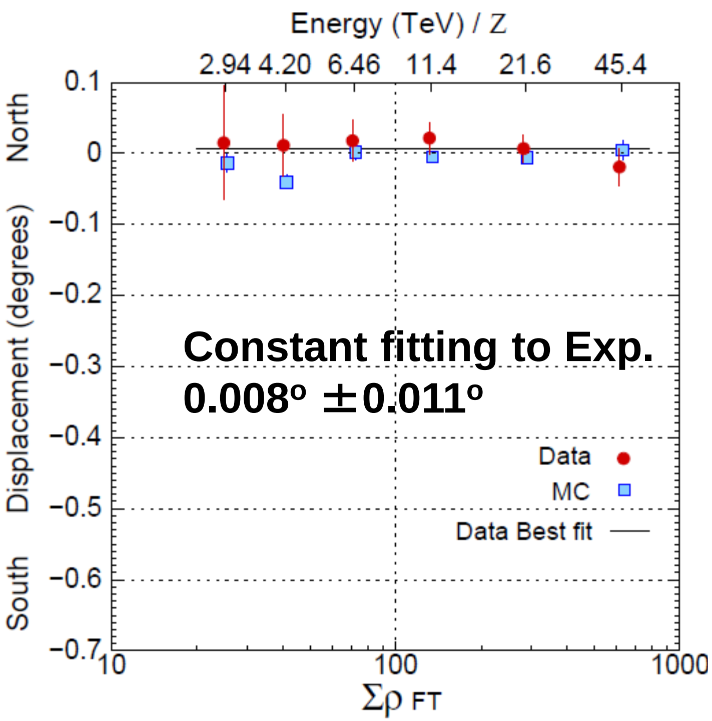
Air shower rate triggered by Tibet III ~1700Hz

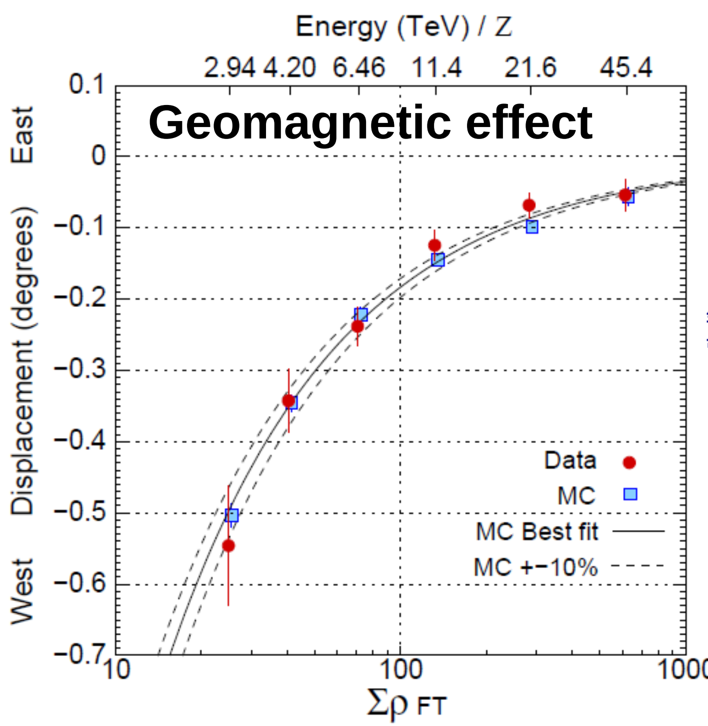
Performance by Moon's Shadow

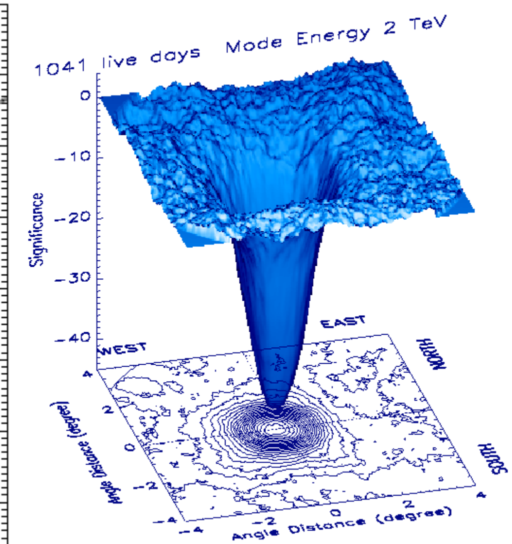
The Astrophysical Journal, 692, 61–72(2009)

- Absolute Energy Scale
- Angular Resolution
- Pointing Accuracy









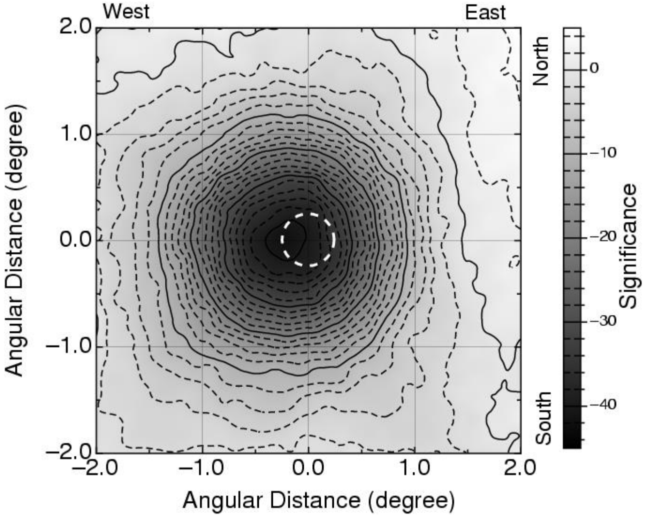
Pointing Error
< 0.011°

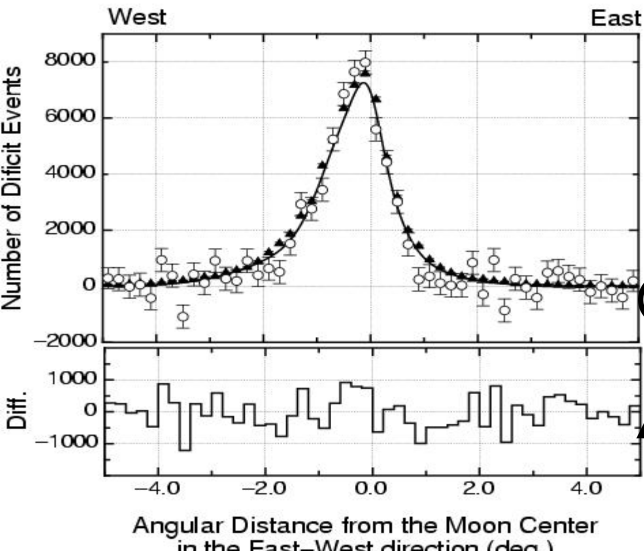
Absotute Energy Scale Error < 12%
+4.5%(±8.6stat.±6.7syst.)%

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

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

3TeV   40σ



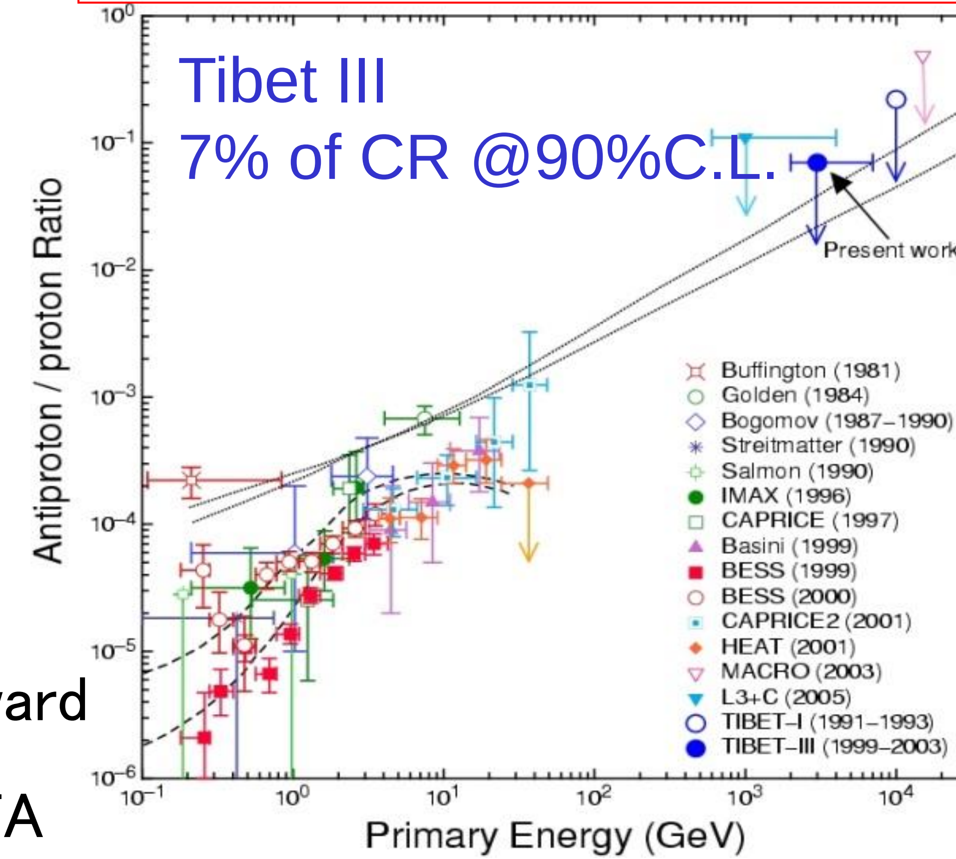


0.23°

Westward

○ :DATA

△ :MC



Tibet III
7% of CR @90%C.L.

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.

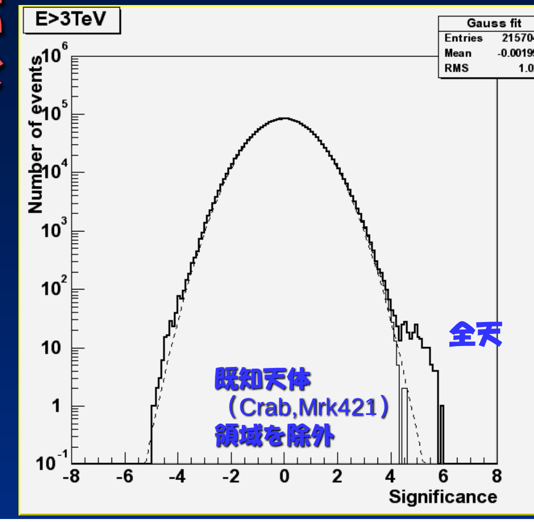
ガンマ線放射天体の探索

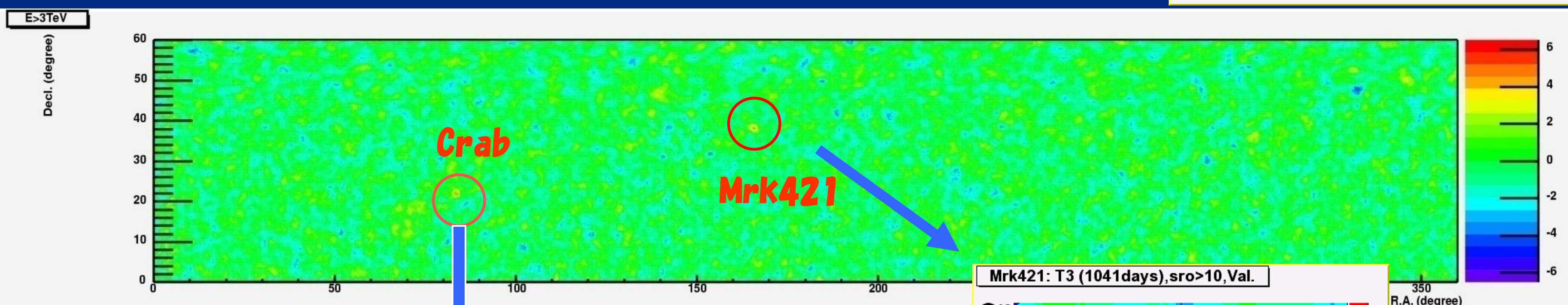
チベットで観測された点源

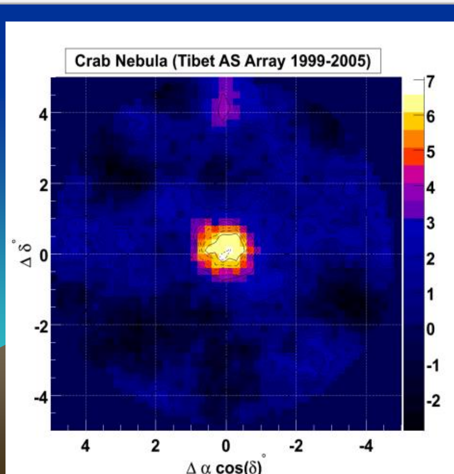
★　超新星残骸　かに星雲からの定常ガンマ線

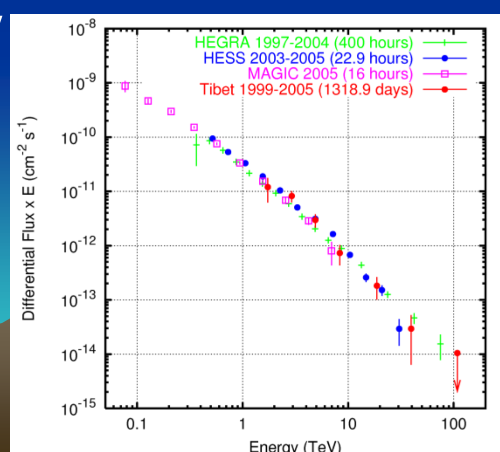
★　活動的銀河核　Mrk421, Mrk501からのフレアガンマ線

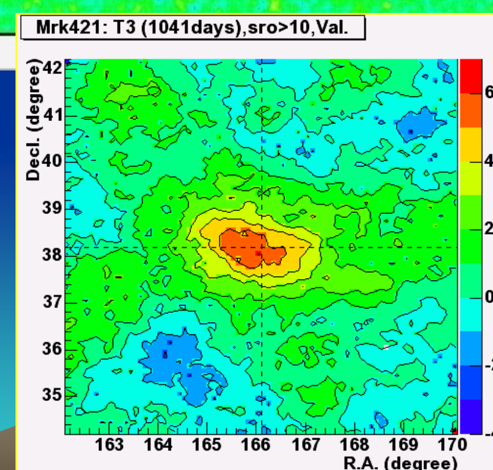
1999－2003年　全北天探索









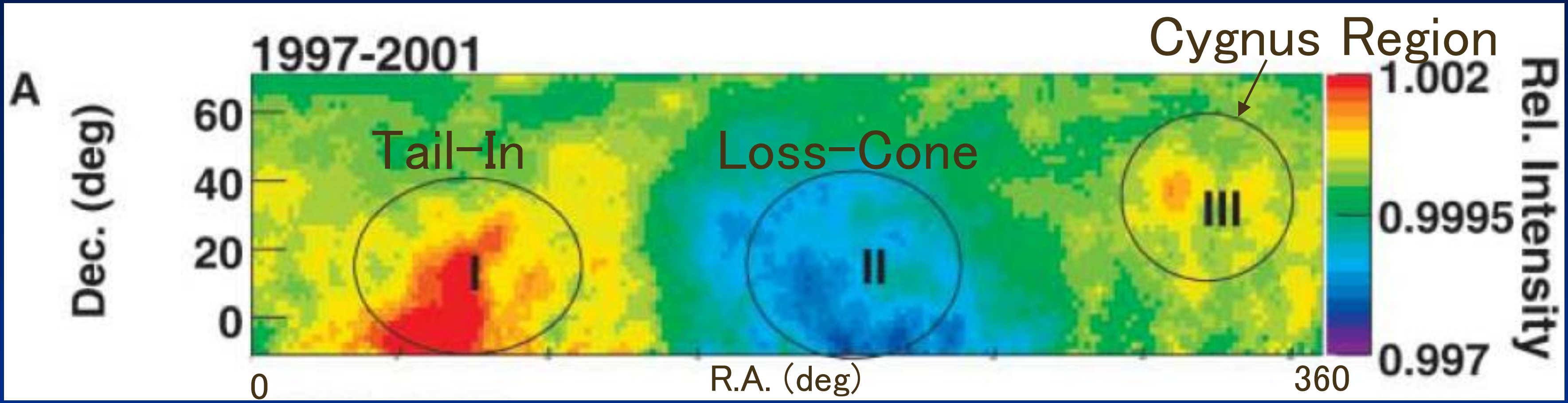


2000－2001年フレア

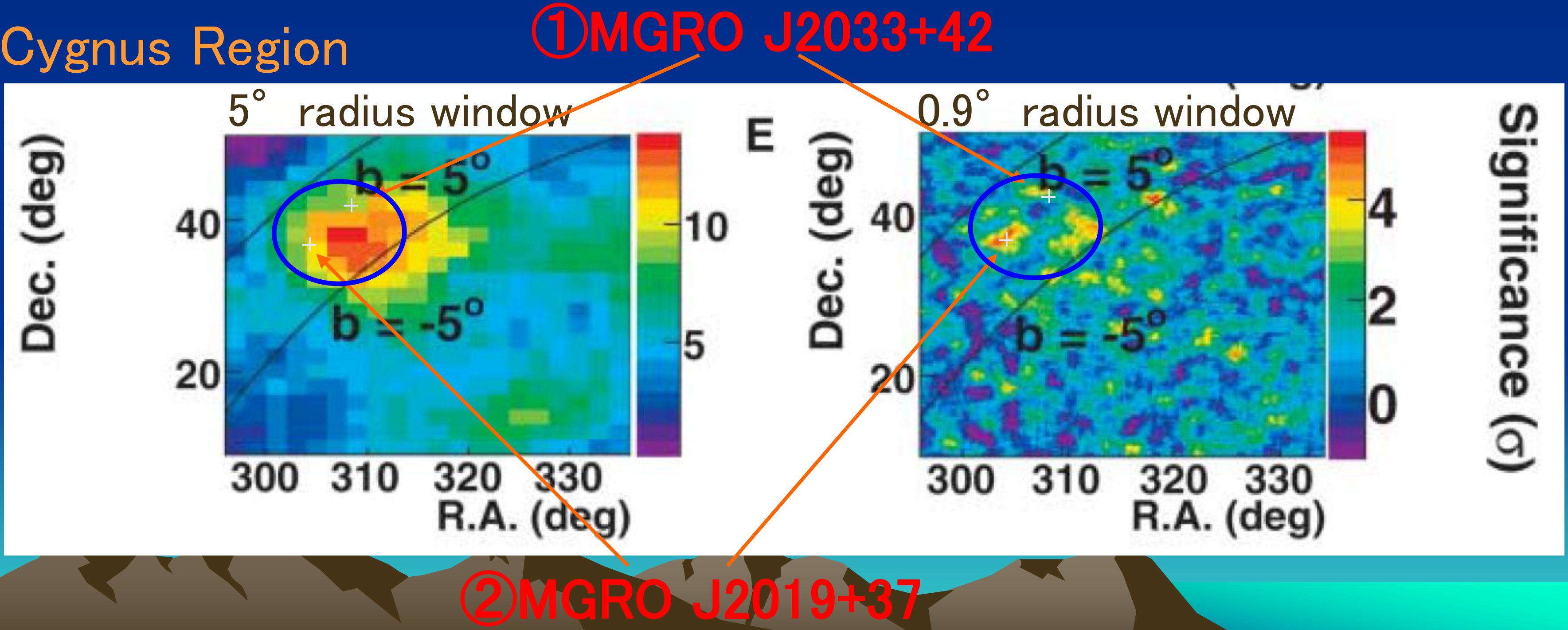
Cosmic Ray Anisotropy at multi-TeV energies（宇宙線）の伝播

2D Large-scale Anisotropy Map

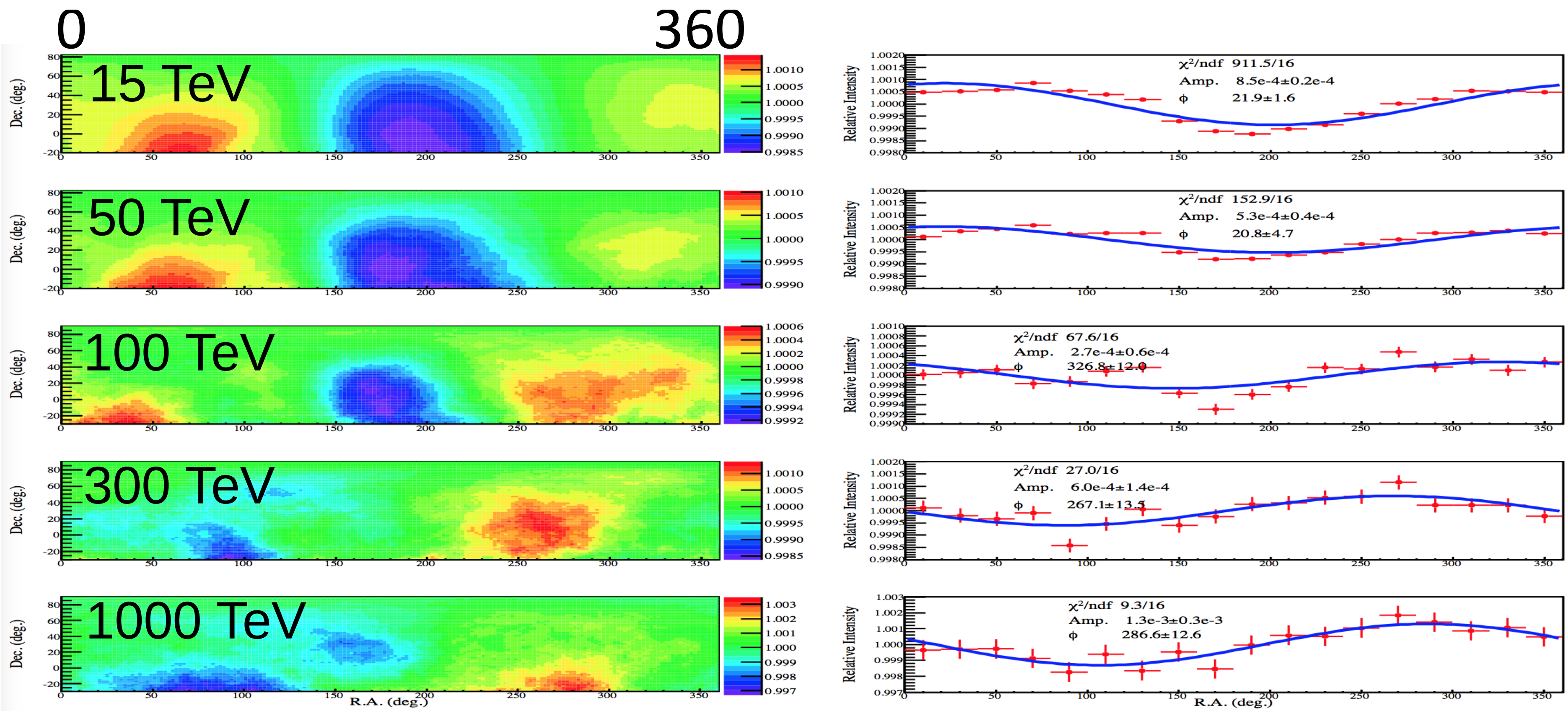
Amenomori et al, Science, 314, 439 (2006)



Cygnus Region



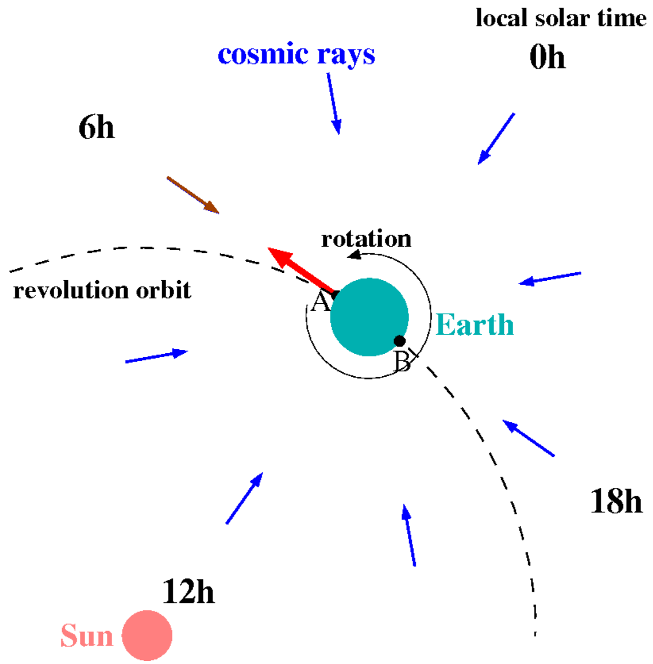
10-1000TeV CR Sidereal Anisotropy (Tibet)



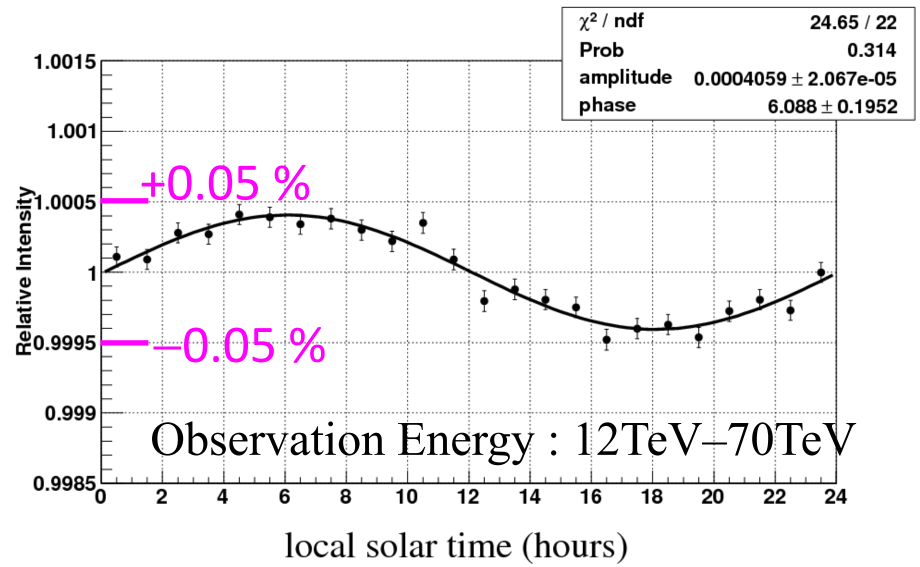
M. Amenomori et al, ApJ, **836**, 153-1-7, (2016)

>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 3.86×10^{-2} % Phase 6 [hr]

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

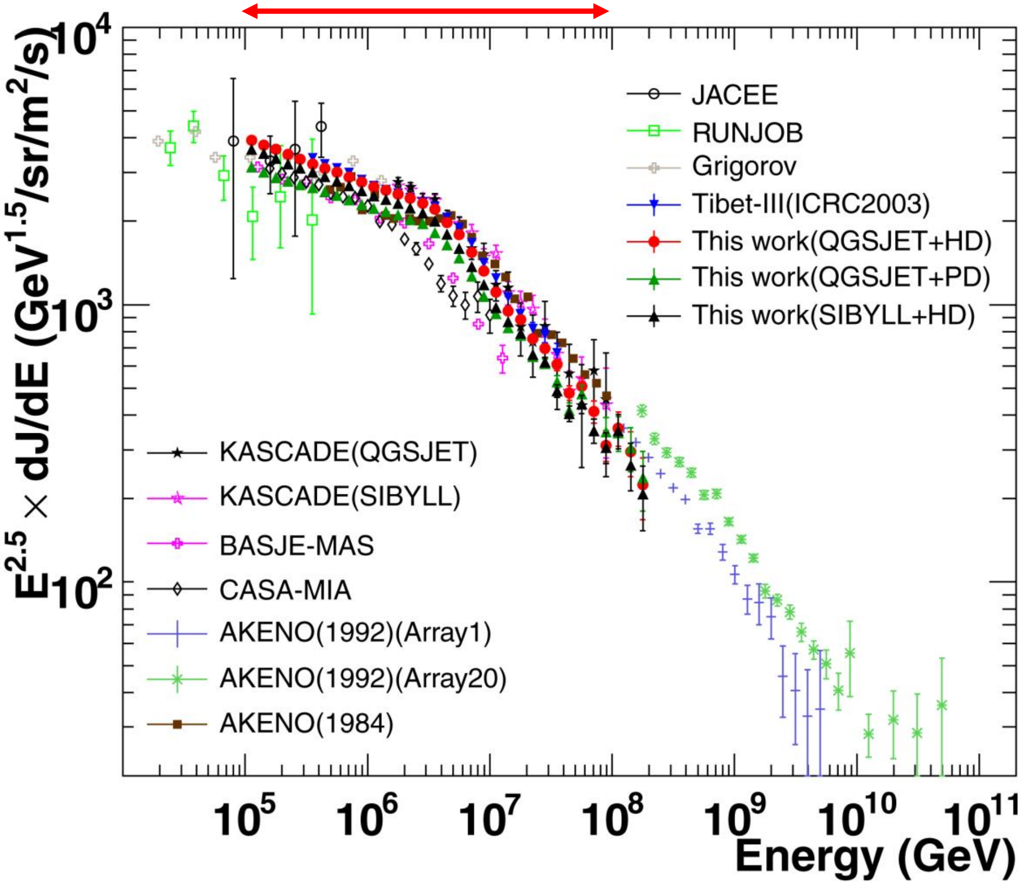
➡ **CG detected at 19.6σ consistent with expected**

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

All Particle Energy Spectrum in the Knee region

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

10^{14}eV ～ 10^{17}eV (3 orders)

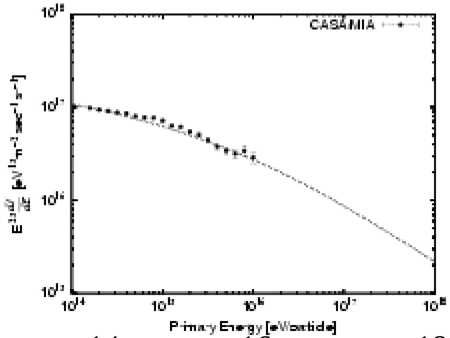


Model	Index of spectrum	Energy range (eV)
QGSJET +HD	−2.67±0.01	< 10^{15} eV
	−3.10±0.01	> 4×10^{15} eV
QGSJET +PD	−2.65±0.01	< 10^{15} eV
	−3.08±0.01	> 4×10^{15} eV
SIBYLL +HD	−2.67±0.01	< 10^{15} eV
	−3.12±0.01	> 4×10^{15} eV

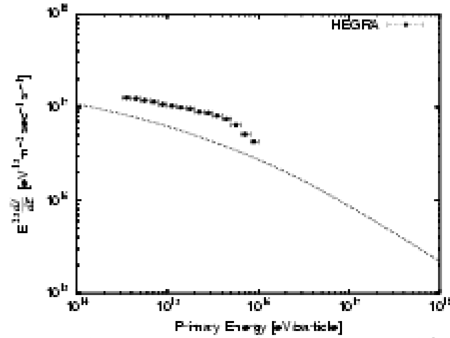
All particle spectrum around the knee

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

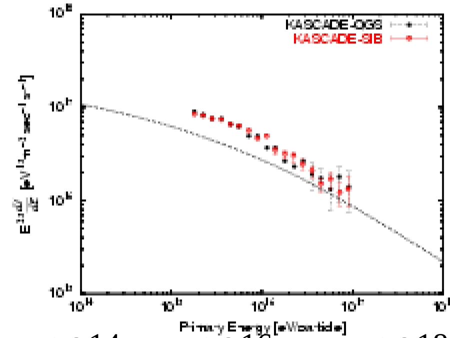
CASA/MIA HEGRA KASCADE



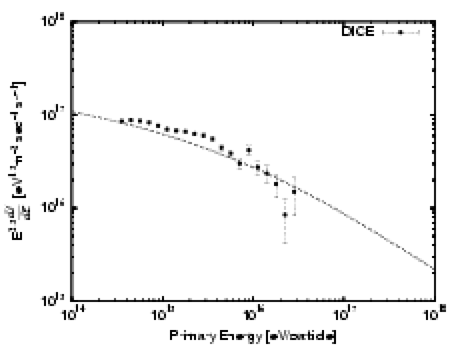
10^{14} 10^{16} 10^{18}



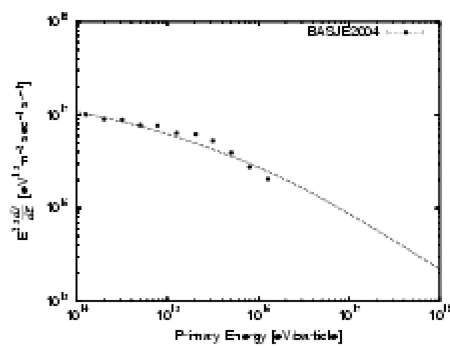
10^{14} 10^{16} 10^{18}



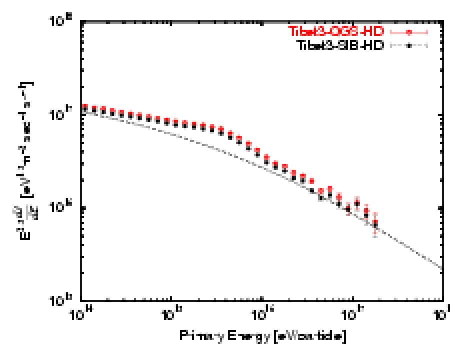
10^{14} 10^{16} 10^{18}



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



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

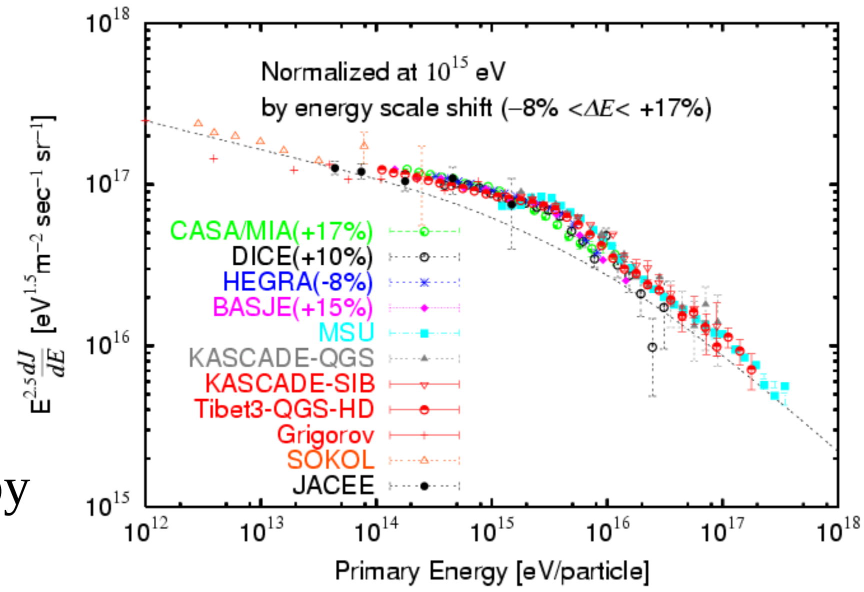


10^{14} 10^{16} 10^{18}

DICE BASJE TIBET

Extra component

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

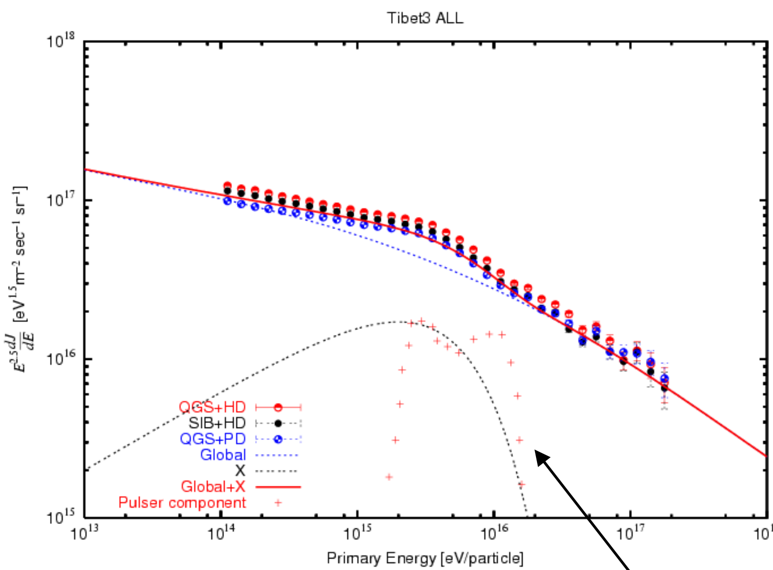


Extra component can be approximated by

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

suggesting **nearby source(s).**

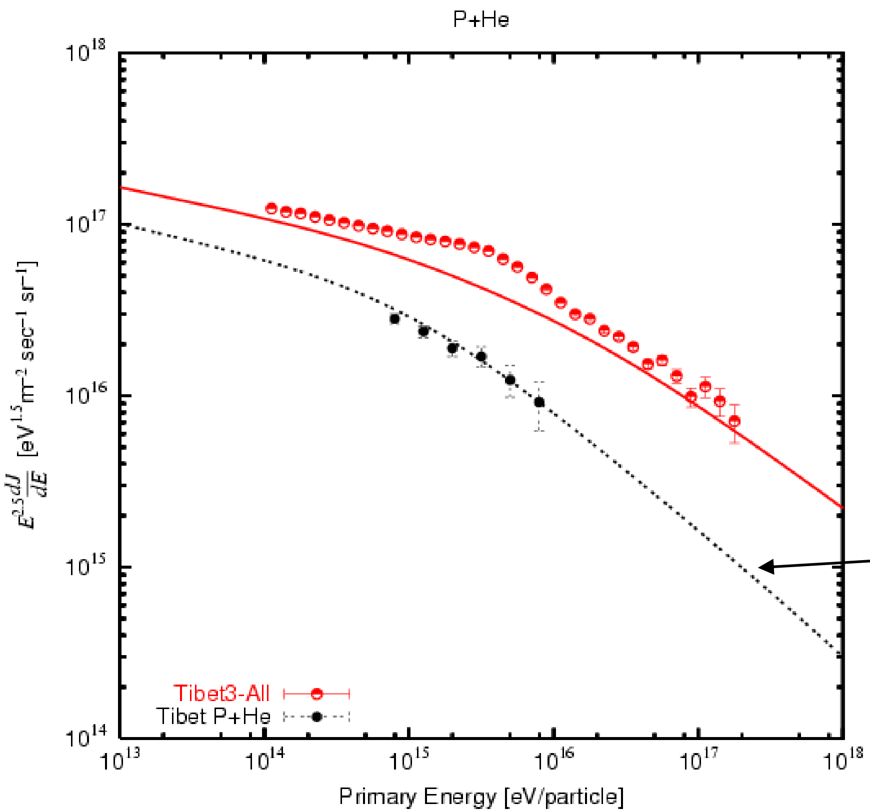
Since P and He component do not show the excess at the knee, the extra component should be attributed to heavy element such as Fe.



(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

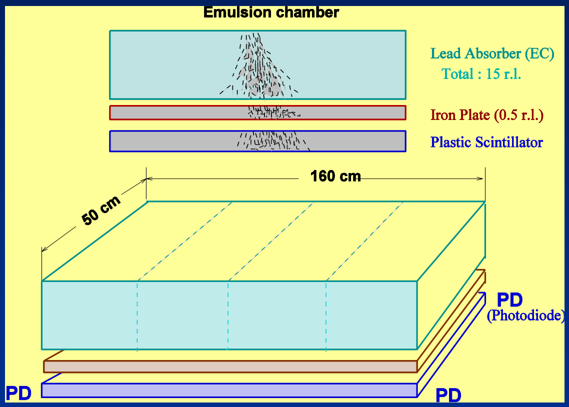


Tibet All particle
Data vs. Expected by multiple source model

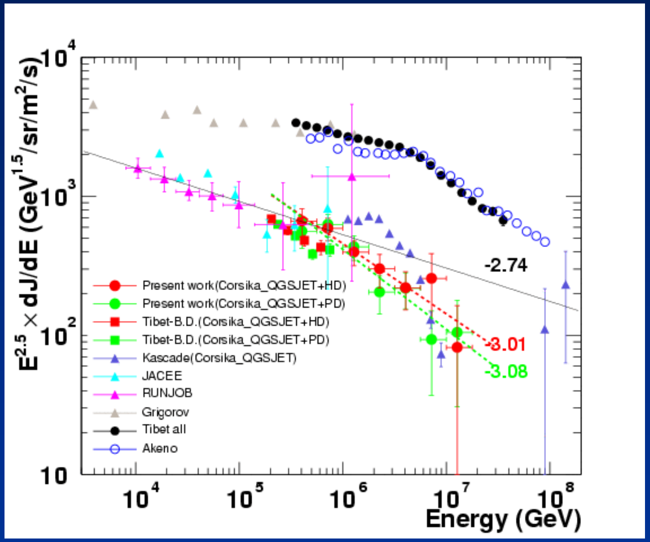
P+He
Data vs. Expected by multiple source model

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

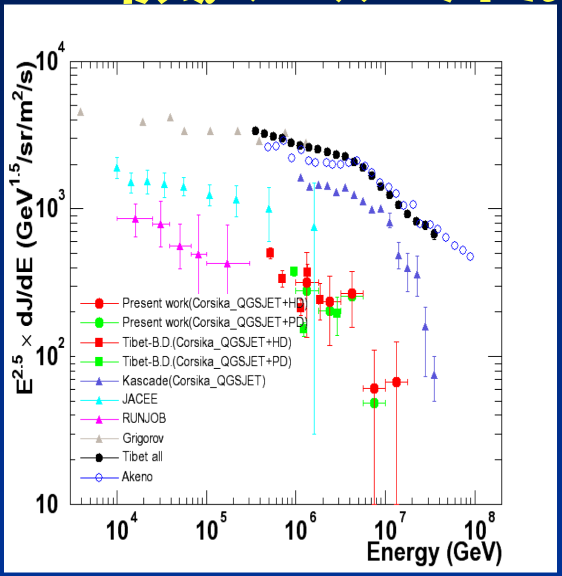
一次宇宙線陽子・Ｈｅ成分の観測



Knee領域の陽子スペクトル

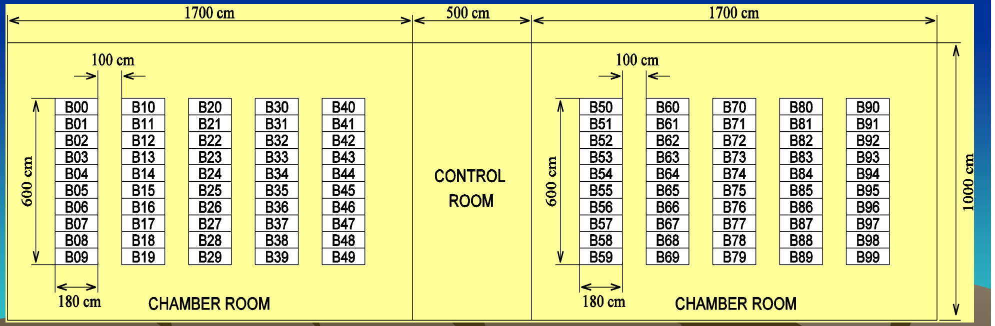


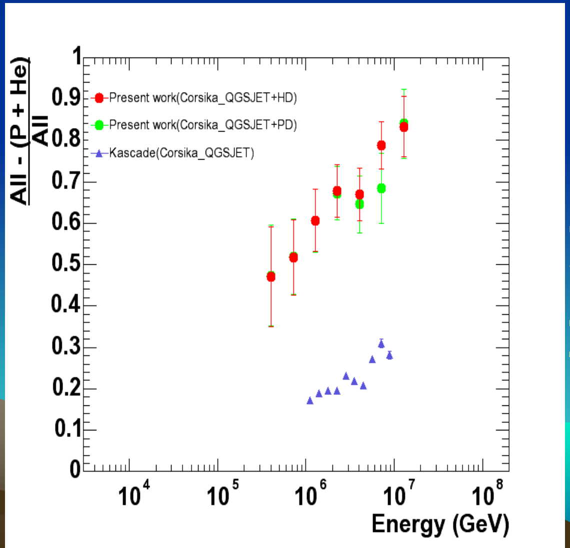
Knee領域のHeスペクトル



Burst検出器：100台

検出器総面積：80㎡

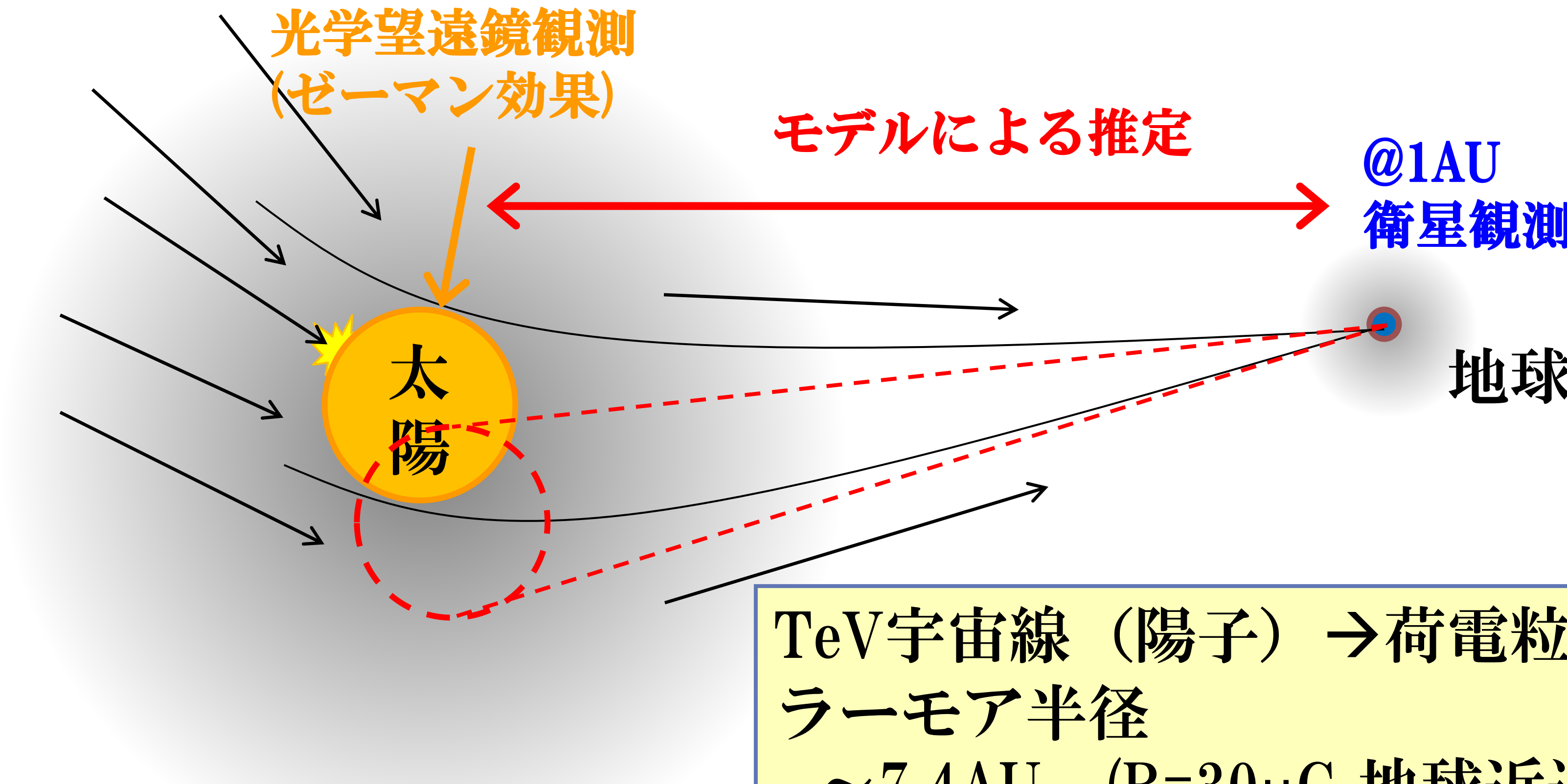




エネルギーが高いと

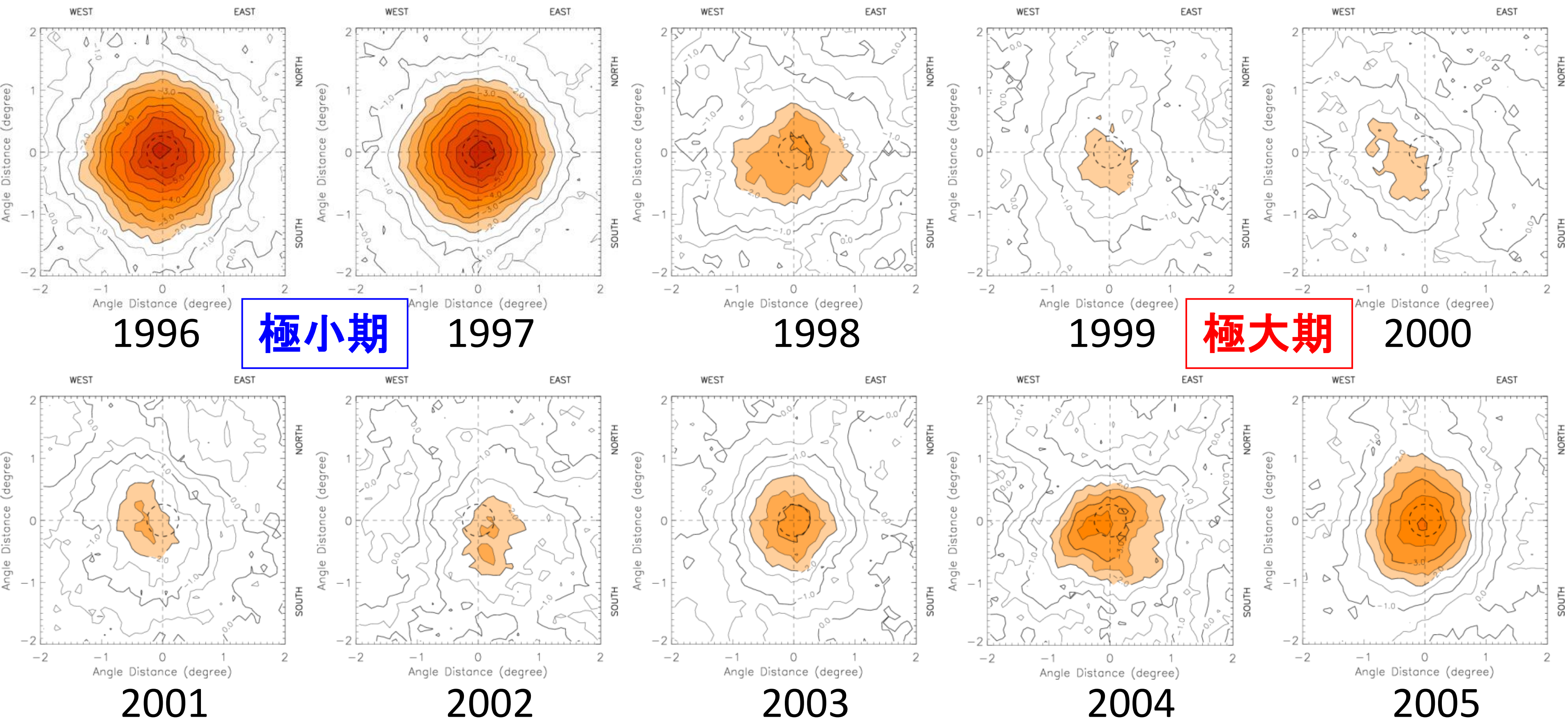
重粒子の割合が増加

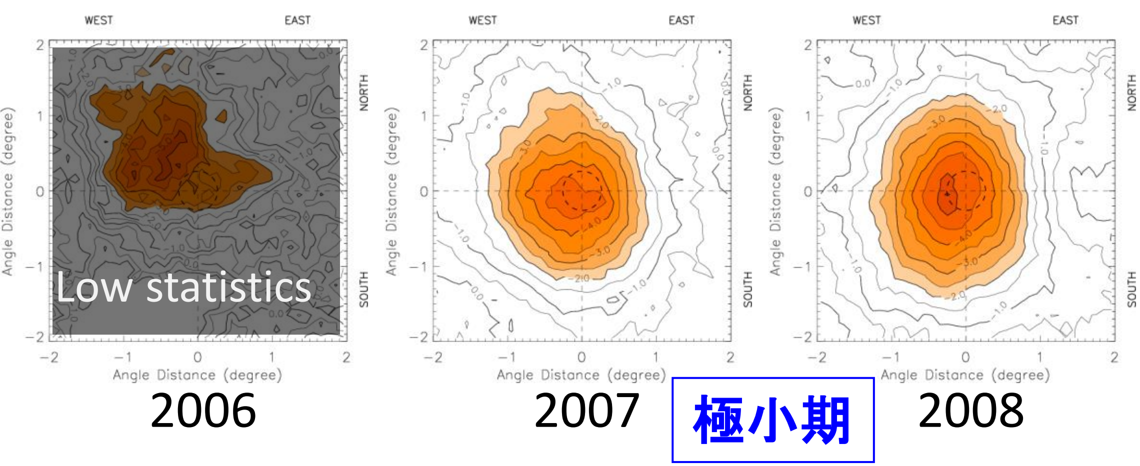
「太陽の影」 太陽による宇宙線の遮蔽



「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=30μG 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！





太陽の影 10 TeV 年変化 Tibet-II Excess/B.G.(%)

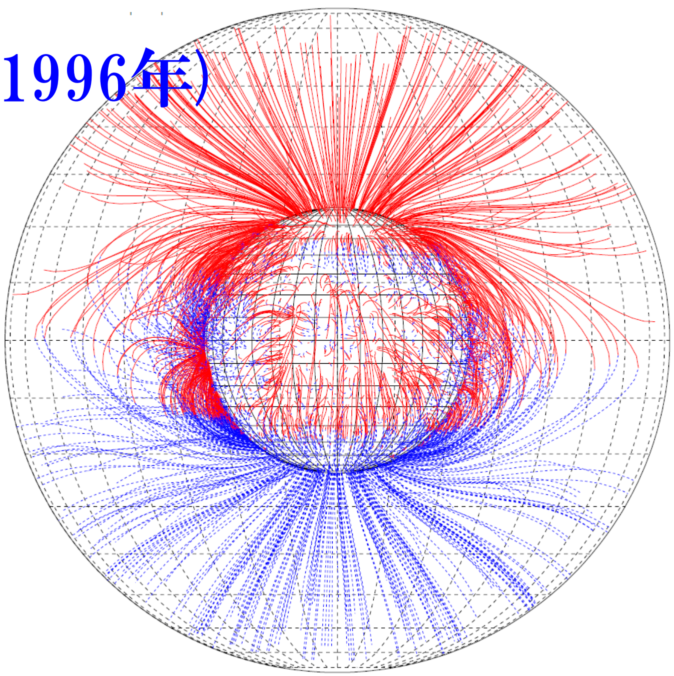
仮定する太陽圏の磁場

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

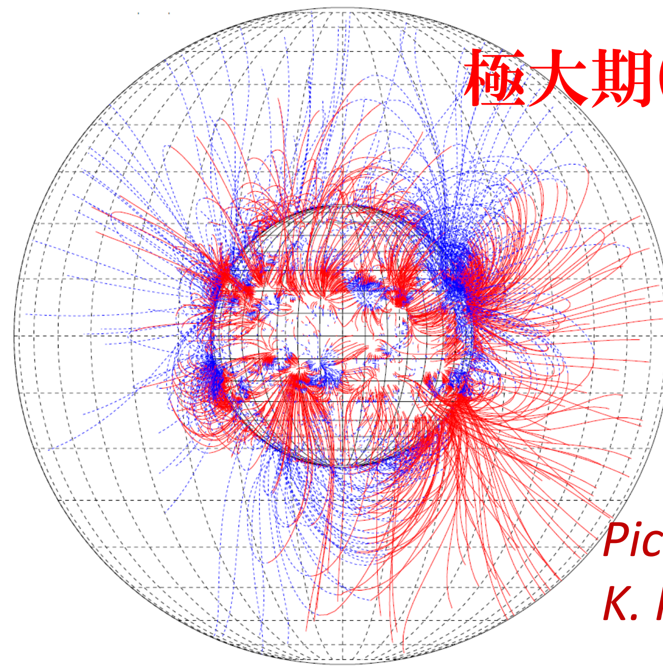
惑星間磁場 → パーカー・スパイラルモデル
太陽風速度は名大IPS観測の緯度依存を考慮

地磁気 → 双極子磁場モデル

極小期(1996年)
PFSS



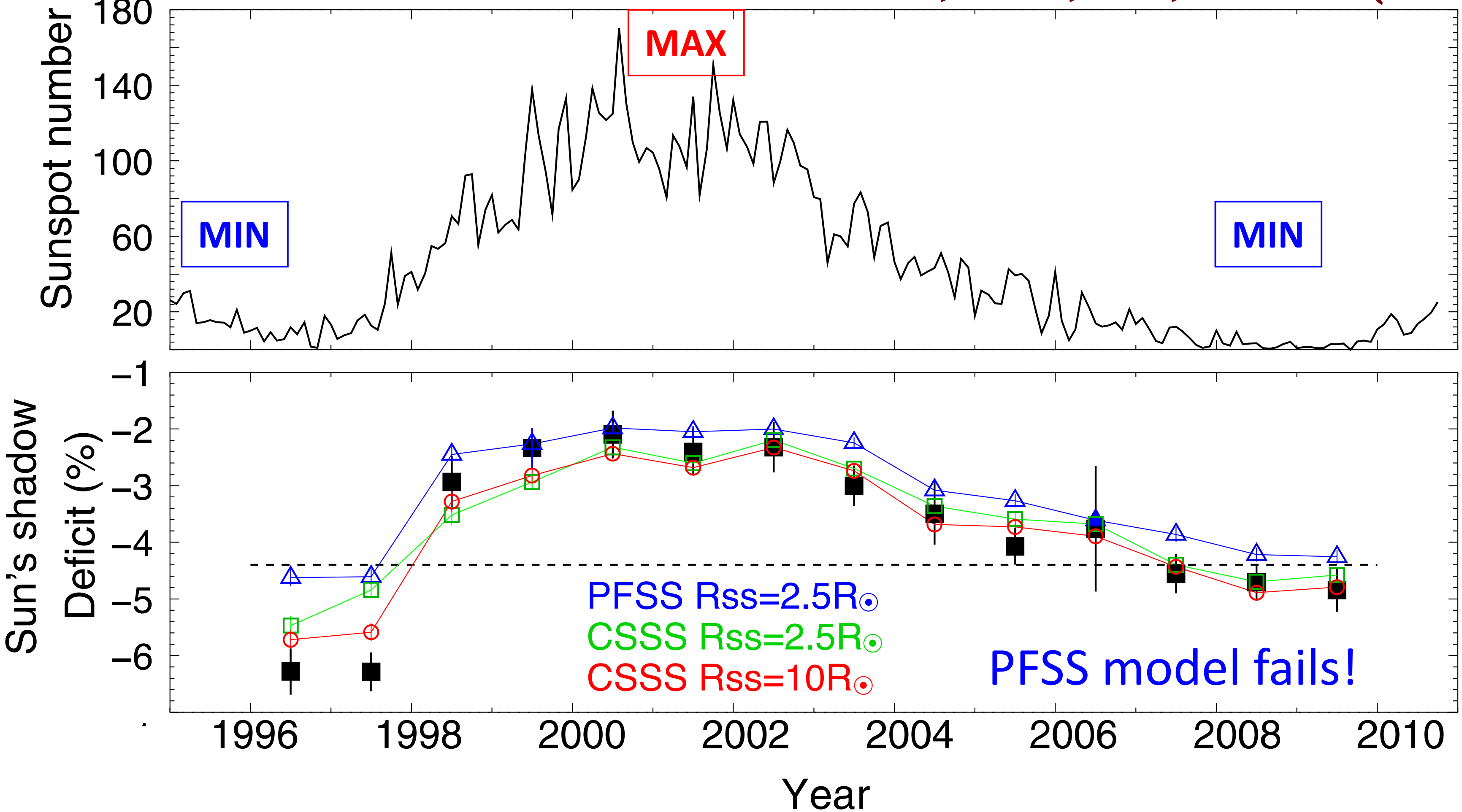
極大期(2000年)
PFSS



Pictures from K. Hakamada

Past Results (Tibet-II >10TeV)

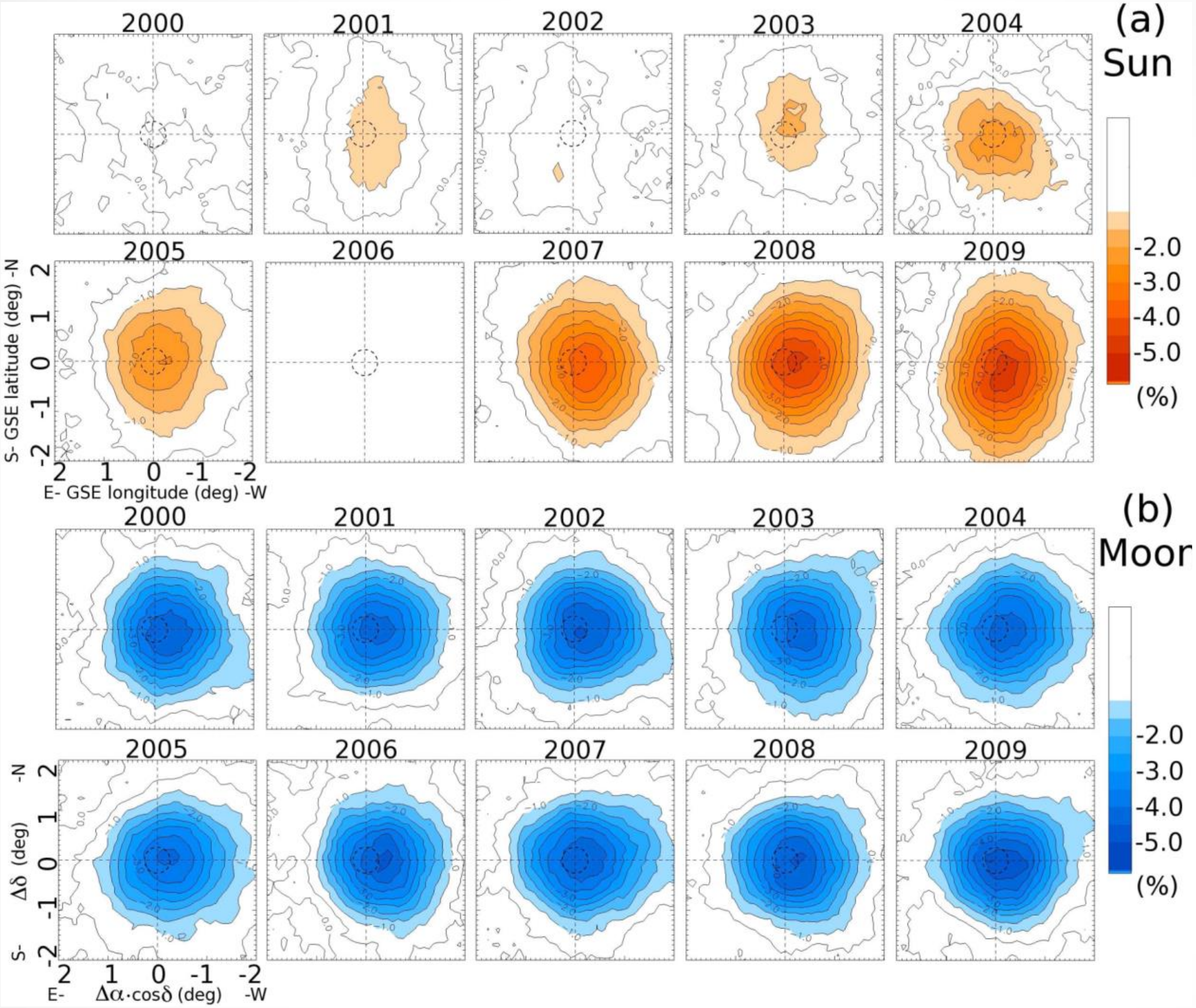
Amenomori et al, PRL, 111, 011101 (2013)



- ✓ 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)

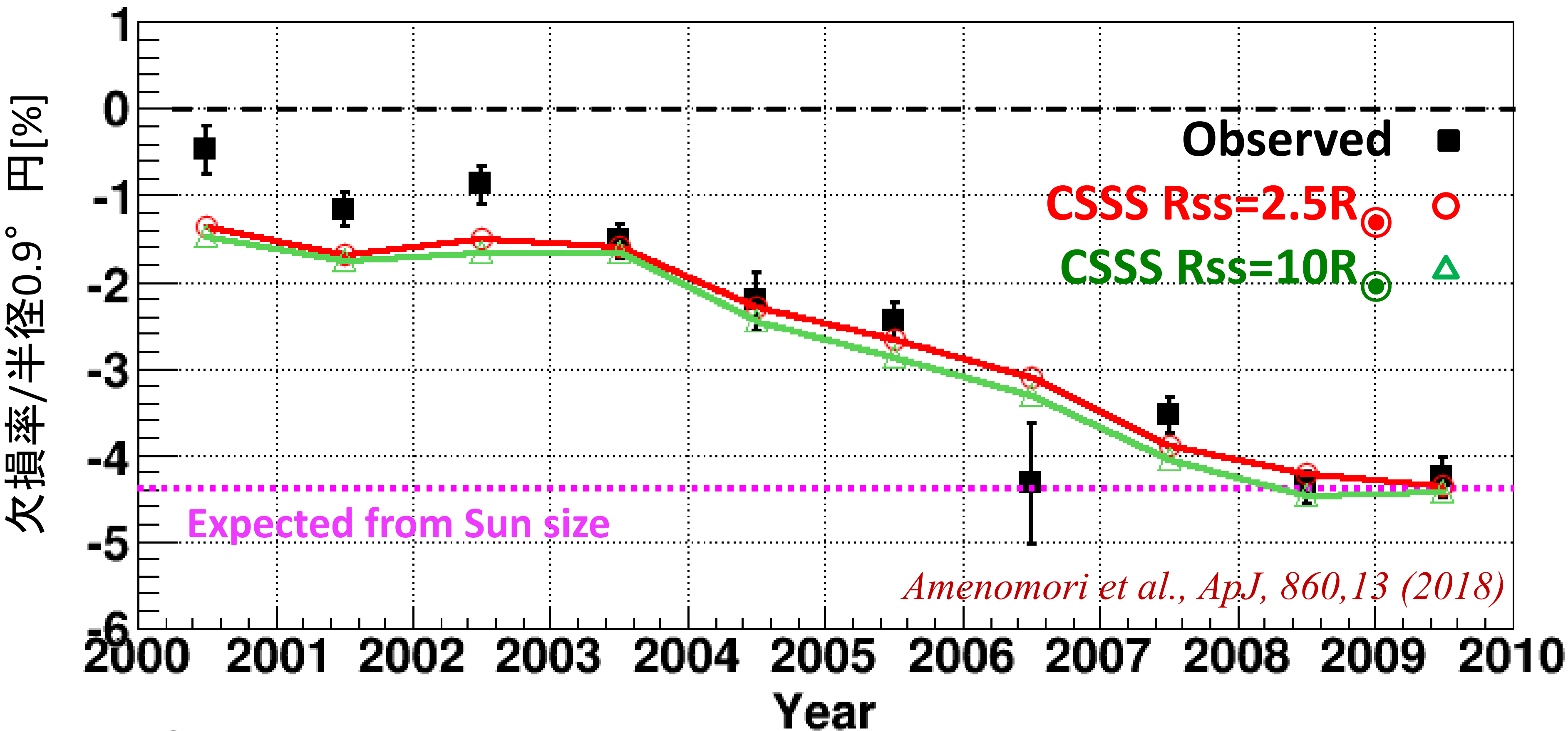


太陽の影
→太陽コロナ磁場
の影響で変動

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 :

χ^2 / dof = 32.1 / 10 (3.4σ)

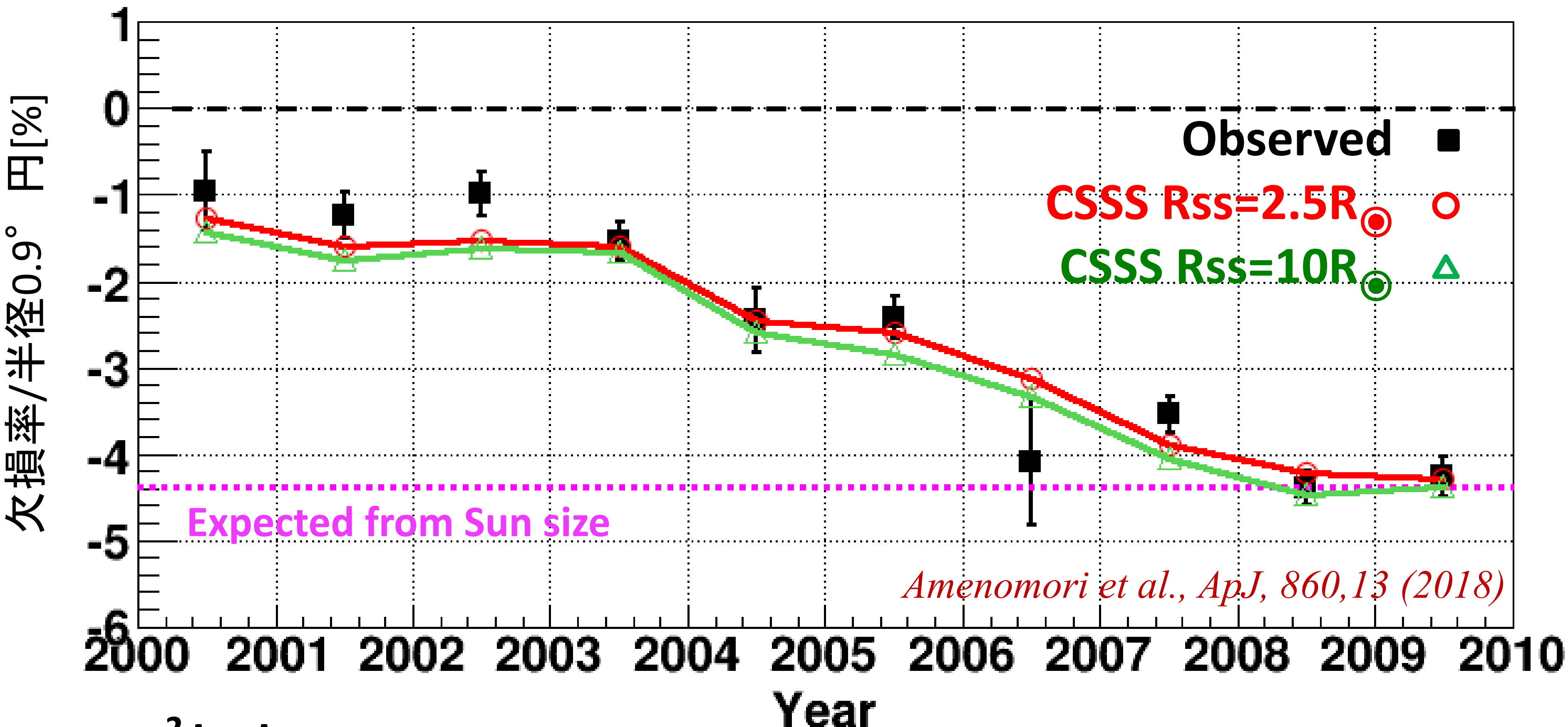
χ^2 / dof = 46.9 / 10 (4.8σ)

３TeV：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？

Earth-directed CME catalog (Richardson & Cane 2010)

影の深さの変化 CME発生期間を除く



χ^2 test :

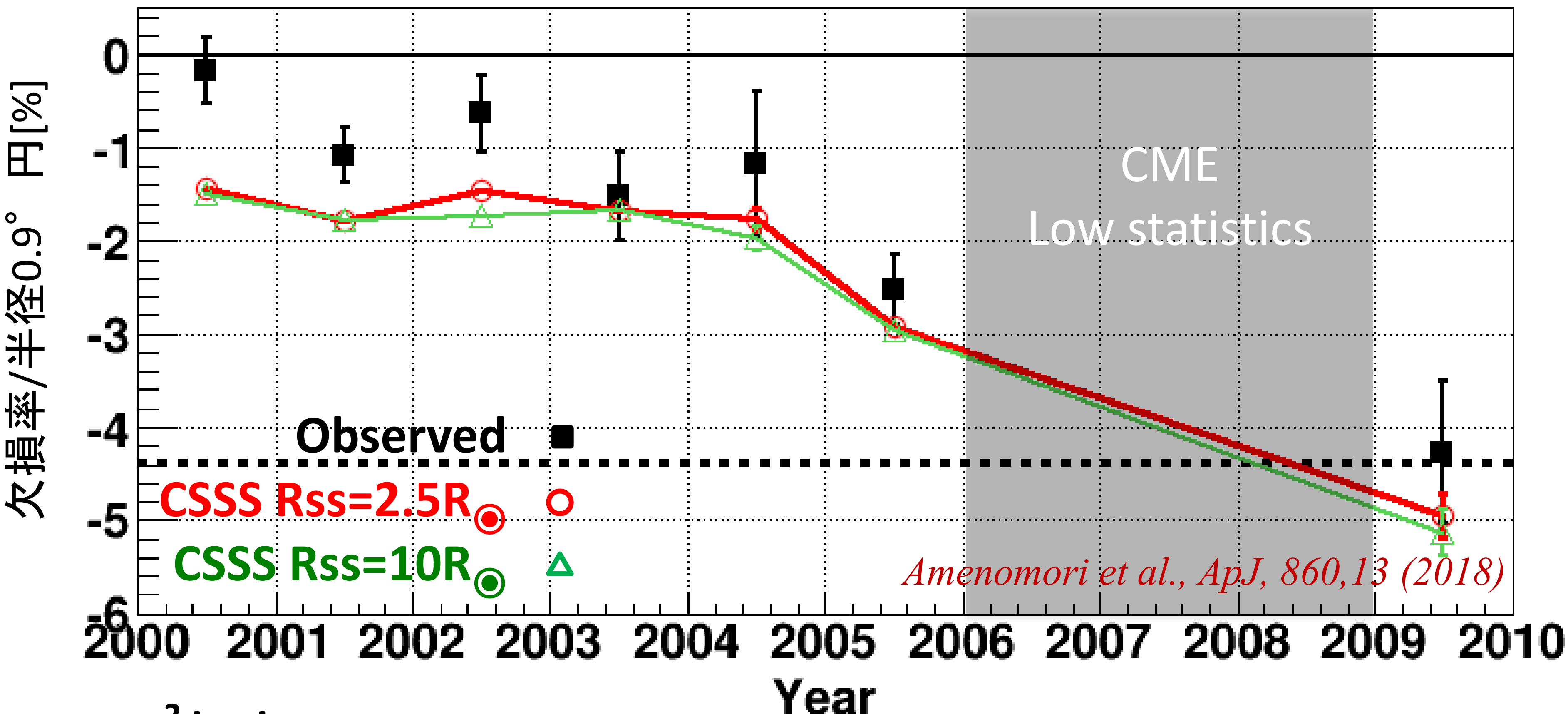
χ^2 / dof = 12.2 / 10 (0.6σ)

χ^2 / dof = 21.0 / 10 (2.0σ)

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

Earth-directed CME catalog (Richardson & Cane 2010)

影の深さの変化 <u>CME発生期間のみ</u>



<u>χ^2 test :</u>

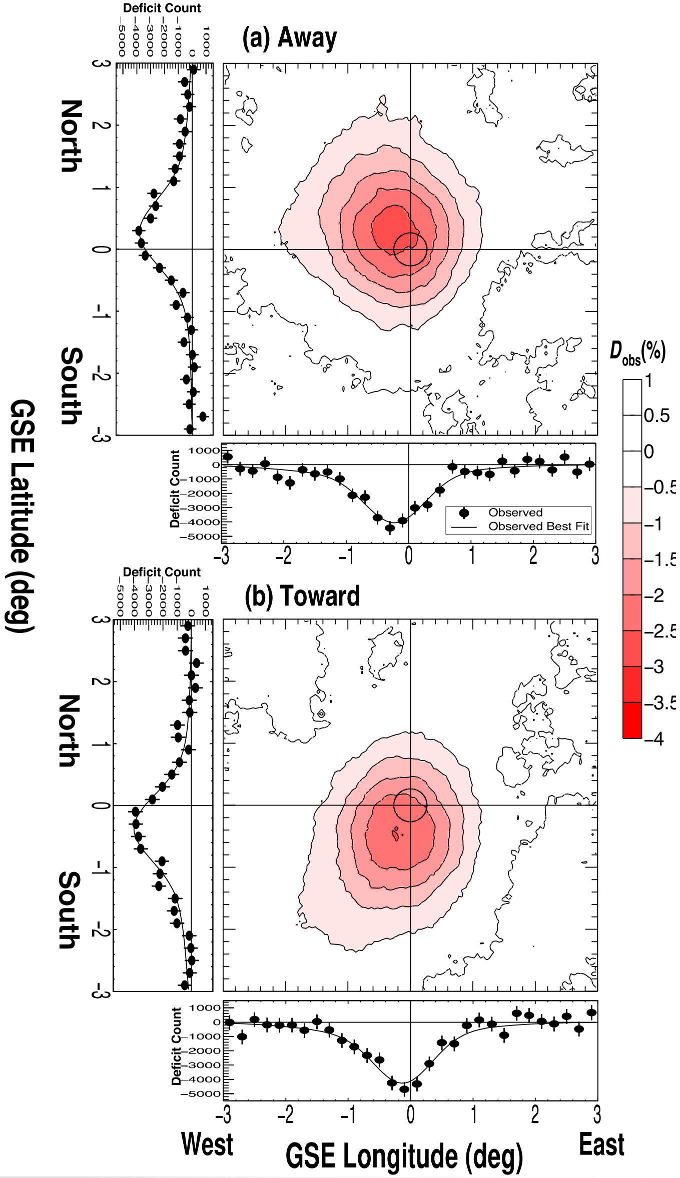
χ^2 / dof = 23.9 / 7 (3.0σ)

χ^2 / dof = 29.4 / 7 (3.7σ)

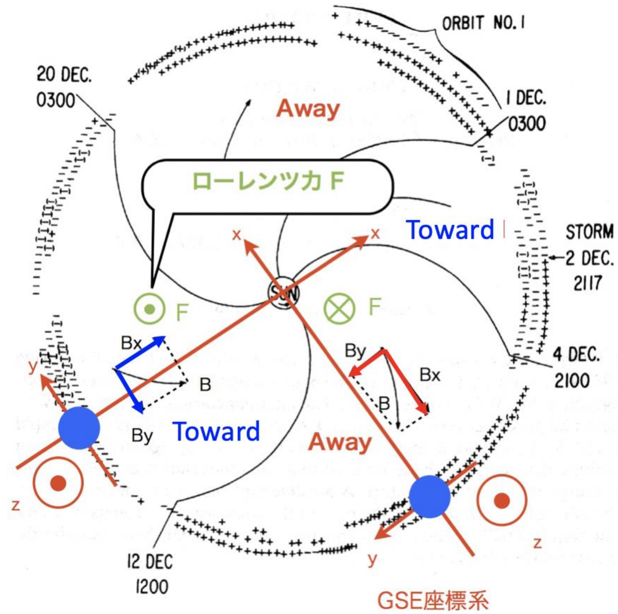
CMEは太陽の影を薄める効果
→ 将来的に宇宙天気予測が可能?

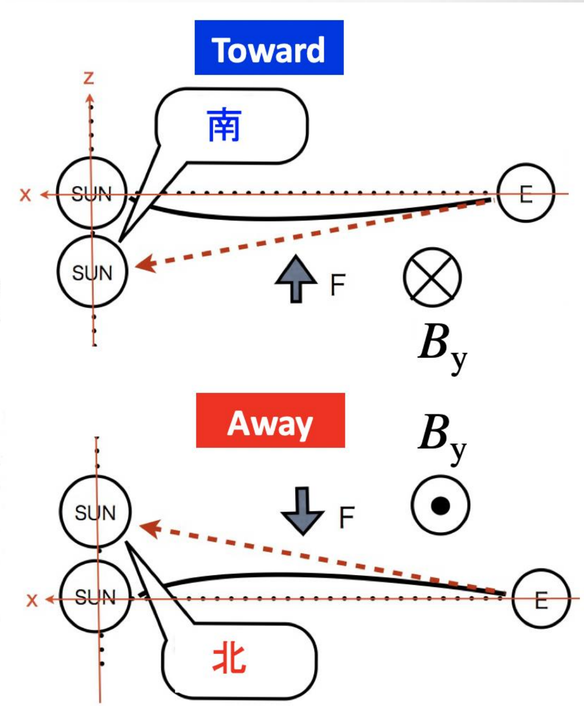
影の方向の観測 Toward/Away

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



惑星空間磁場の間接測定

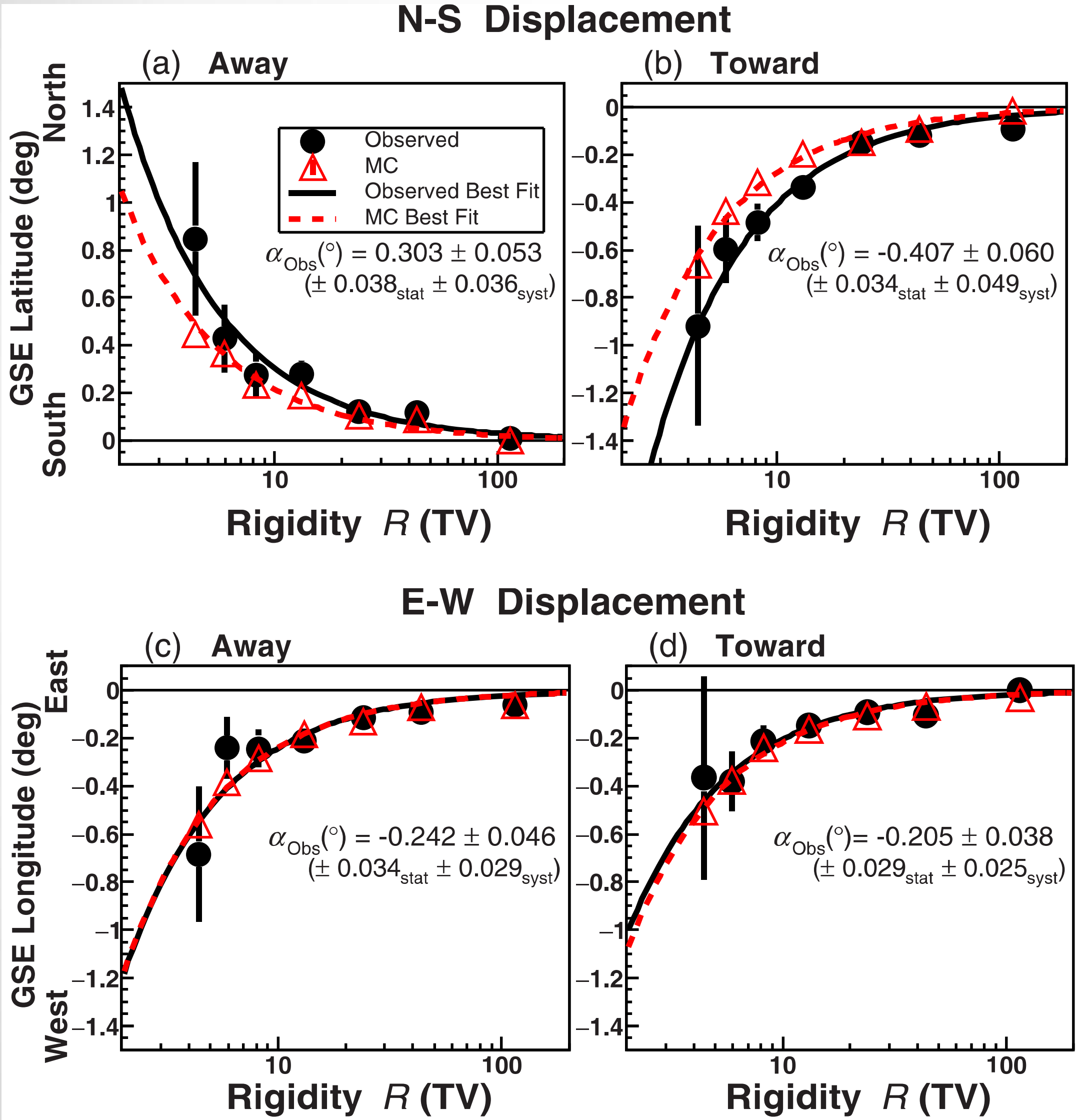




IMFのSector 構造 (Toward/Away)
→ Spiral structure が B_x and B_y をつくる。
→ B_y が Sun 太陽の影を Toward / Away Sector のときに、南 / 北 へずらす。

影の方向の観測 Toward/Away

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



南北方向のズレ

Data/MC比 →

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

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

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)

東西方向のズレ

→ ほとんど地磁気で説明できる

γ線とKnee一次宇宙線でこれまでにわかった事:

1. Several bright TeV γ point sources !
   Possible diffuse γ signal from Cygnus region?!
2. P, He, all-particle E-spectrum (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―＞if Z（原子番号）倍―＞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（ボリビアで建設中）

    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

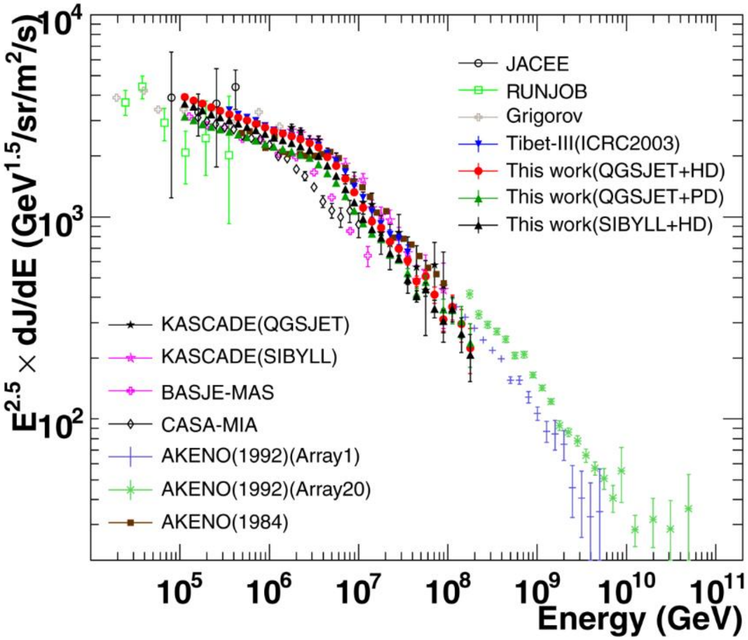
muon detector array (MD)

100 TeV以上の ガンマ線を観測できれば世界初

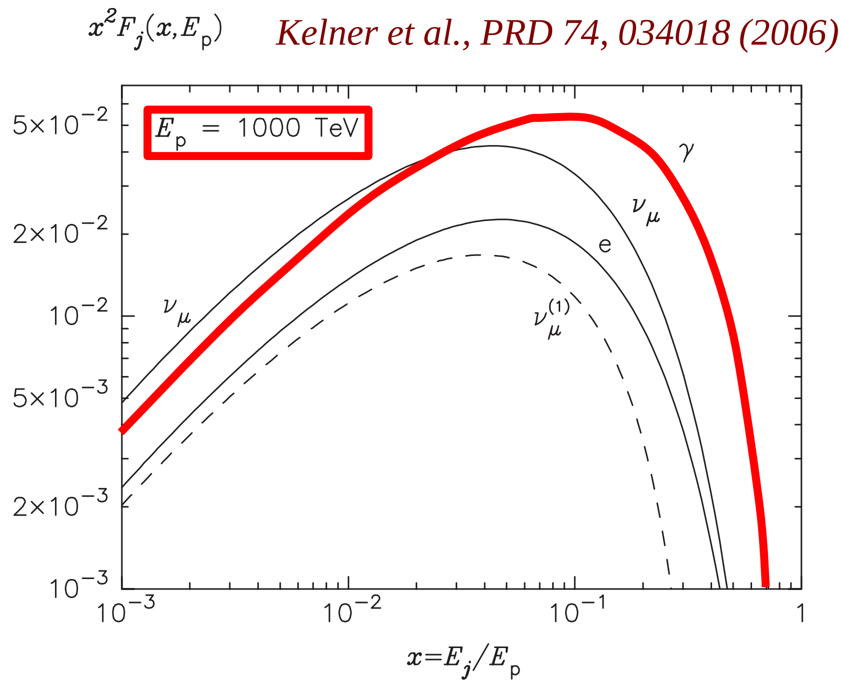
>Origin of cosmic rays and acceleration mechanism (PeVatron) and limit at SNRs.

>Diffuse gamma rays

Origin of Cosmic Rays at the Knee



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



<u>宇宙線スペクトル</u>

✓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~４PeVまでは銀河系内起源？

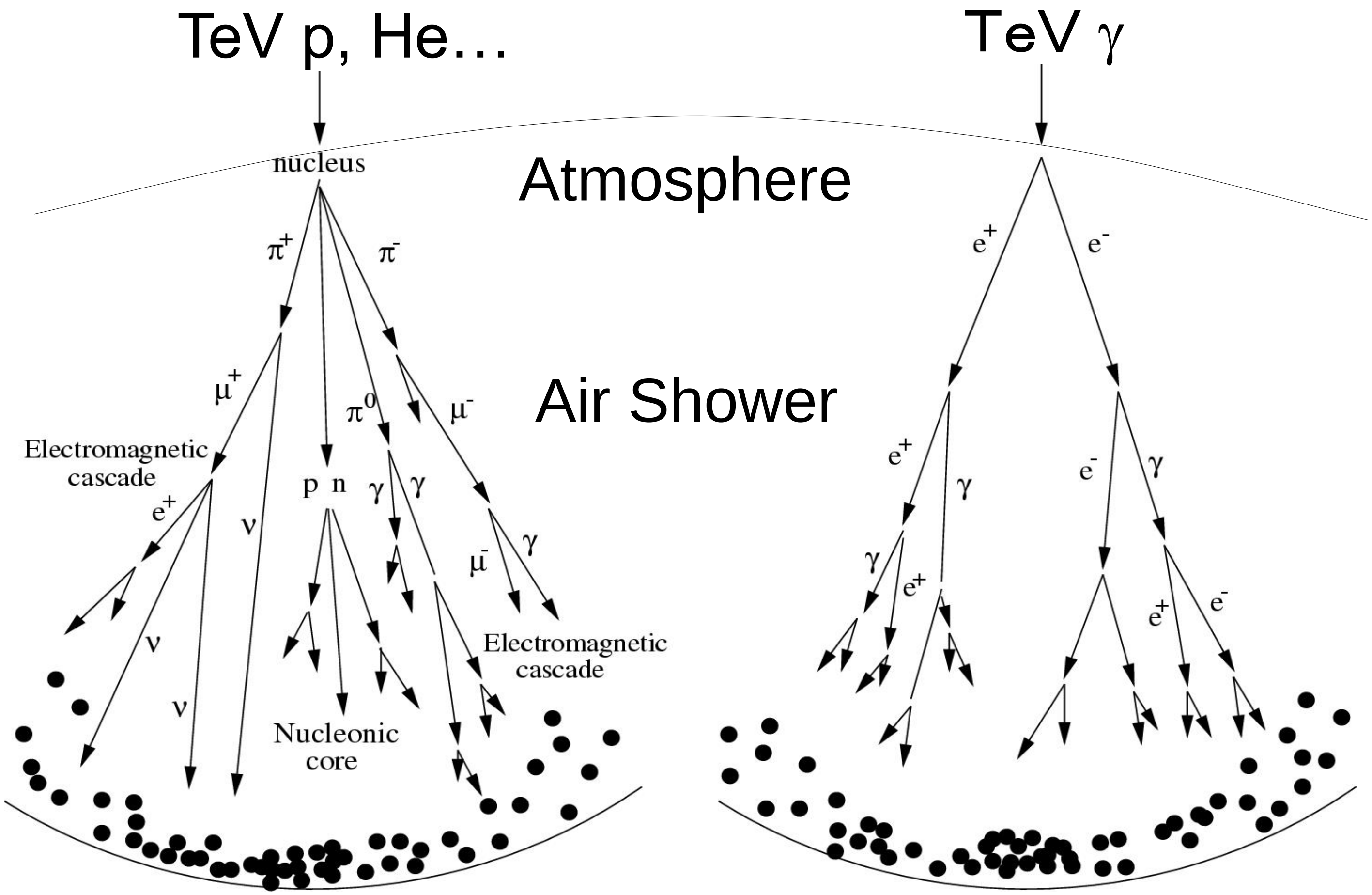
<u>ガンマ線スペクトル</u>

✓ 宇宙線＋星間物質→π^0＋…→2γ

✓ 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

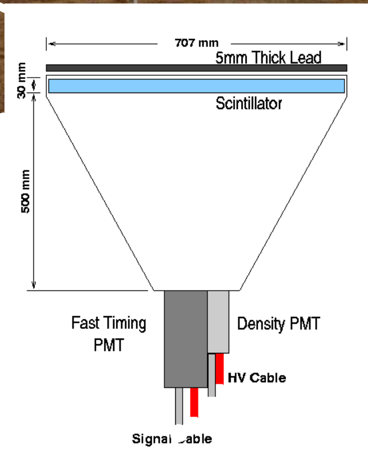


Number of muons（<100 m from core, 4300m a.s.l.）

100TeV Proton ~50

100TeV Gamma ~1

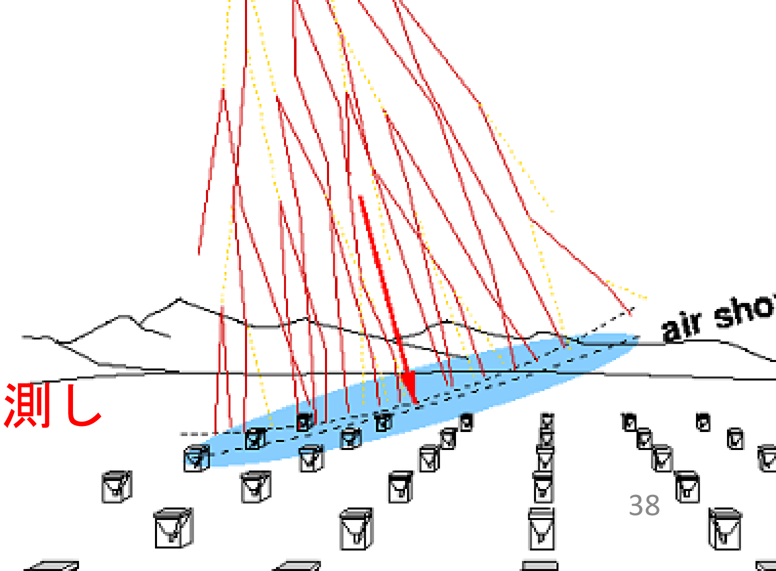
チベット空気シャワー観測装置



- □ チベット (90.522°E, 30.102°N) 標高4300 m

<u>現行スペック</u>

- □ シンチレーション検出器数　0.5 m^2 x 597
- □ 空気シャワー有効面積　~65,700 m^2
- □ 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

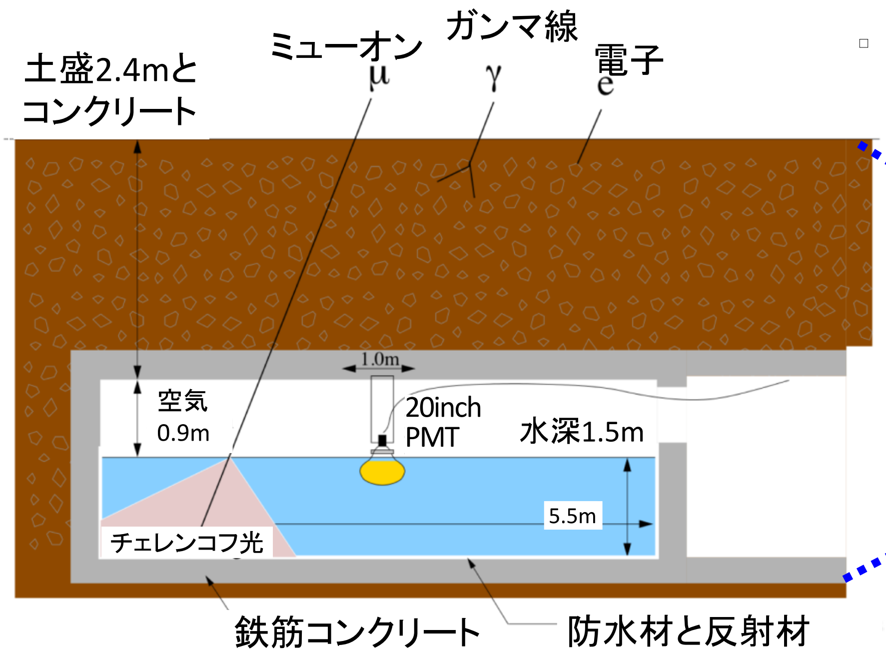


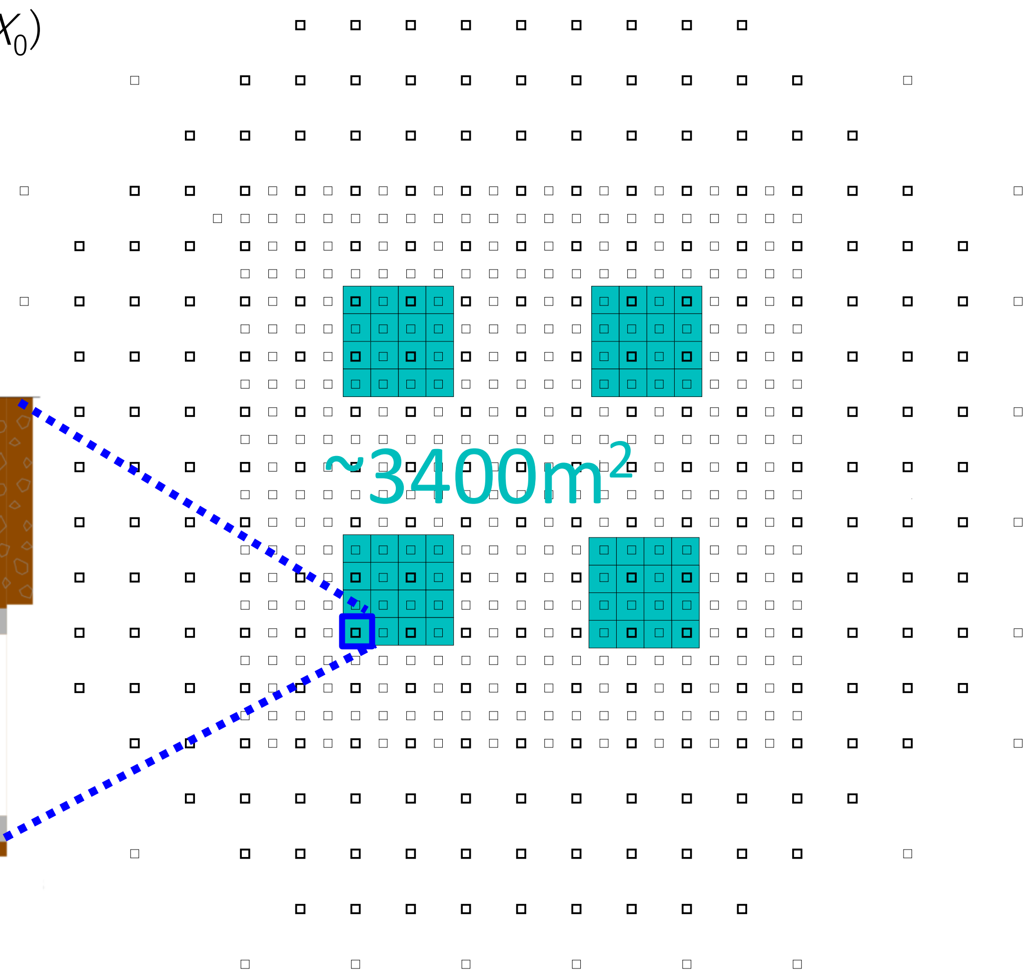
→空気シャワー中の二次粒子(主にe$^{+/-}$,γ)を観測し
一次宇宙線エネルギー、方向を決定

水チェレンコフ型ミューオン観測装置

Kawata et al., JPS meeting (2018)

- ✓ 地下 2.4m (物質厚 ~ 515g/cm2 ~19X_0)
- ✓ 7.35m×7.35m×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

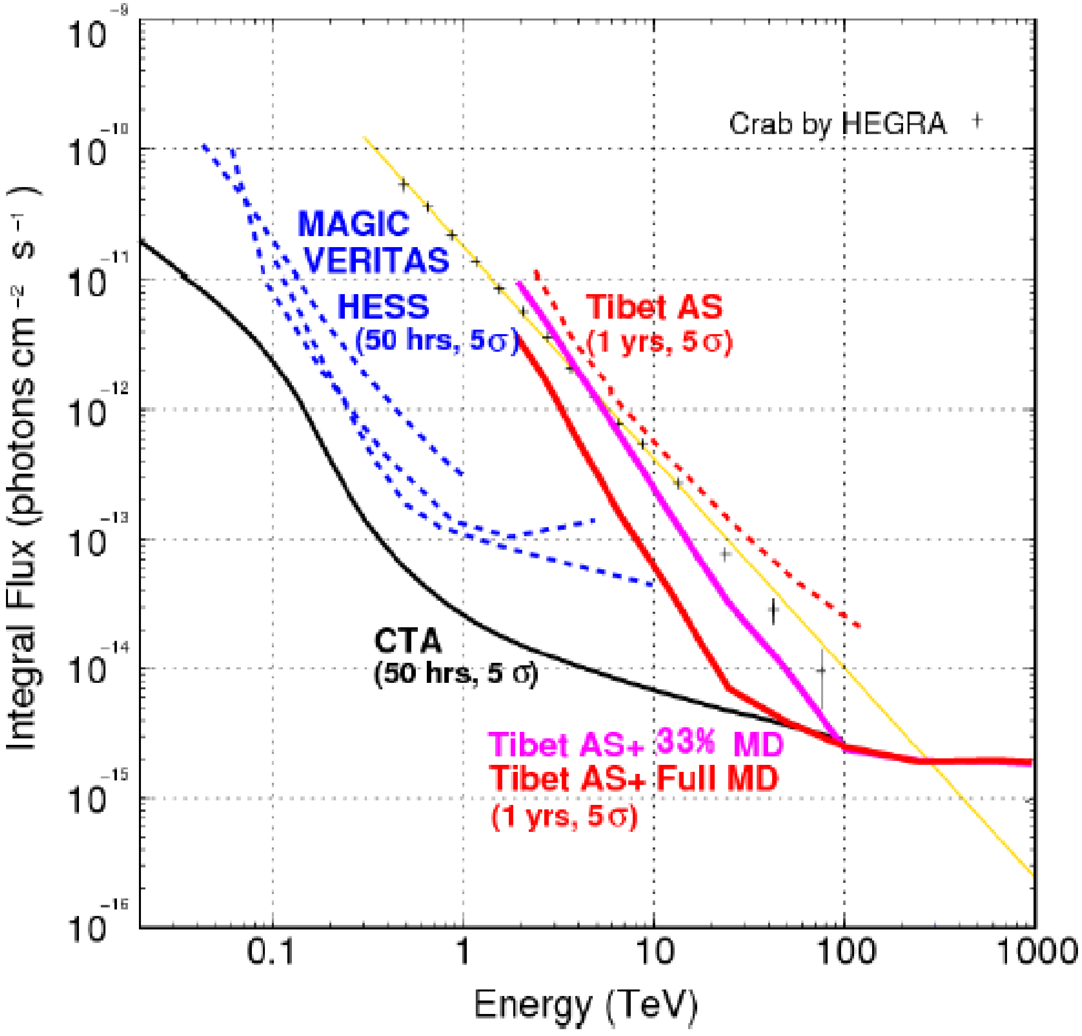




→空気シャワー中のミューオン数を測定し、ガンマ線／核子選別

2014年2月 ー 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:10000m^2 MD

X ~10 @10TeV
X ~10 @100TeV

+33%: 3400m^2 MD

X 3~4 @10TeV
X ~10 @100TeV

MD construction scene

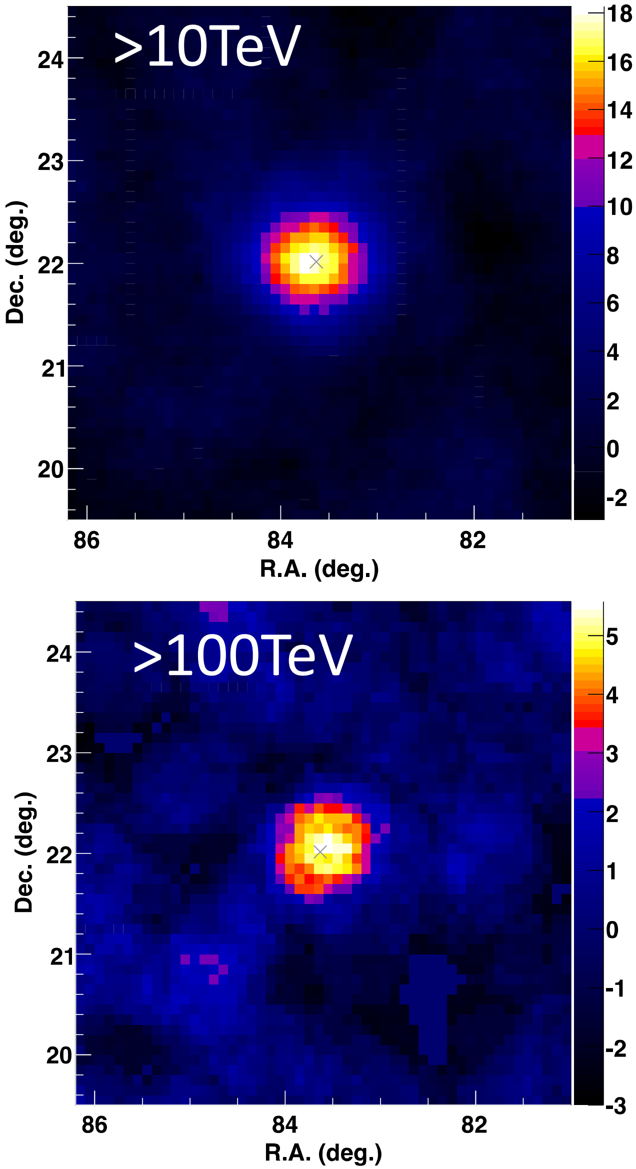
Installing a 20 inch PMT in a MD cell.

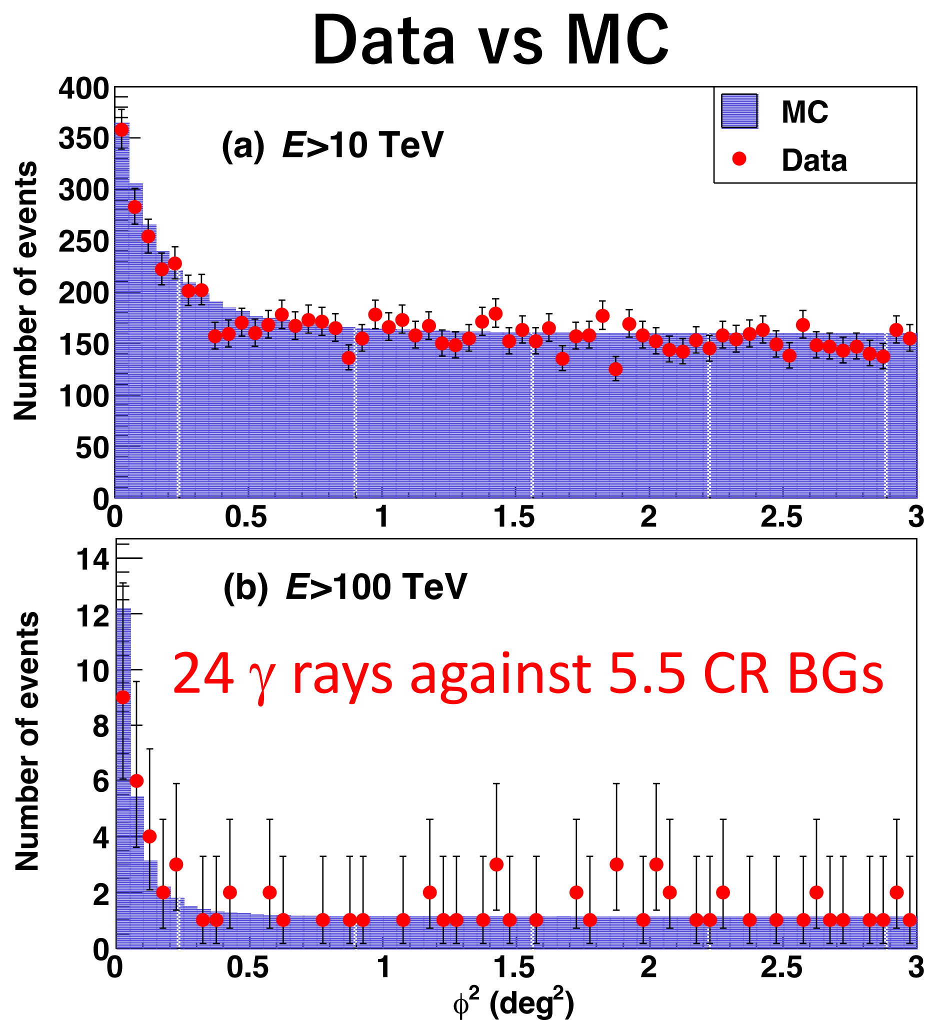
Tyvek sheet walls and two 20 inch PMTs


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)

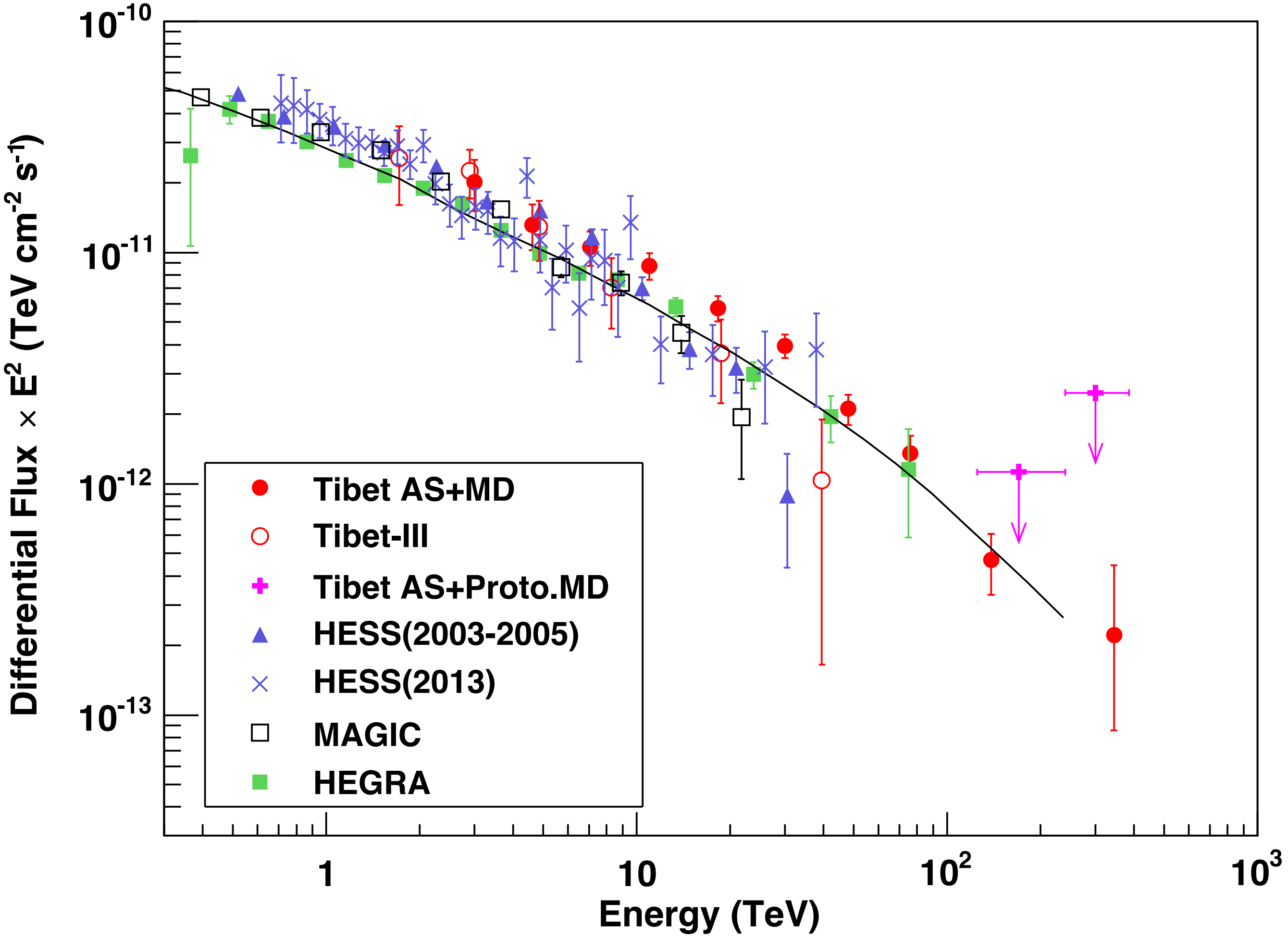




First Detection of Sub-PeV γ (5.6σ)

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 γ ~450 TeV → sub-PeV **ガンマ線天文学の始まり**

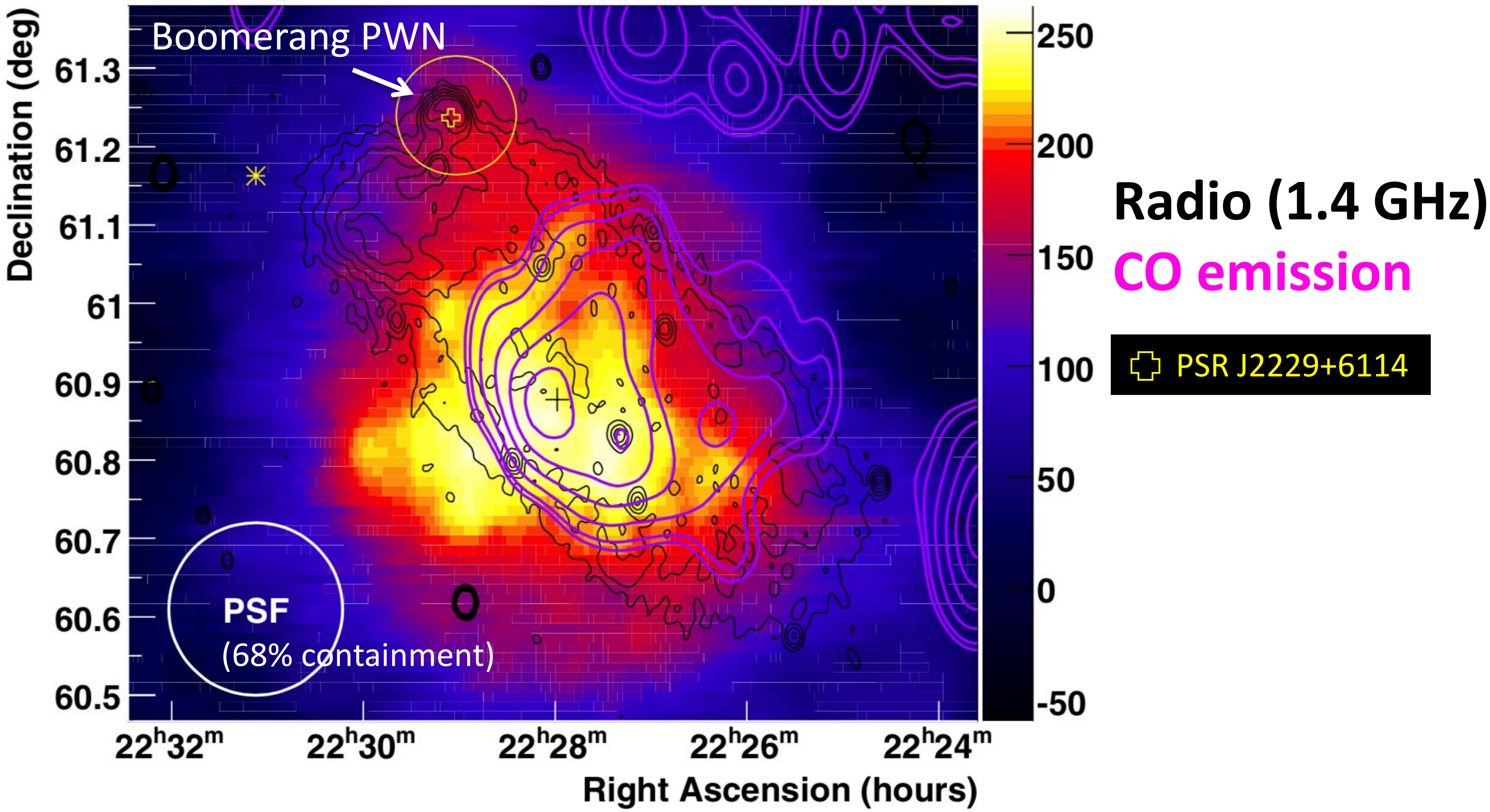
Amenomori et al., PRL 123, 051101, (2019)

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)

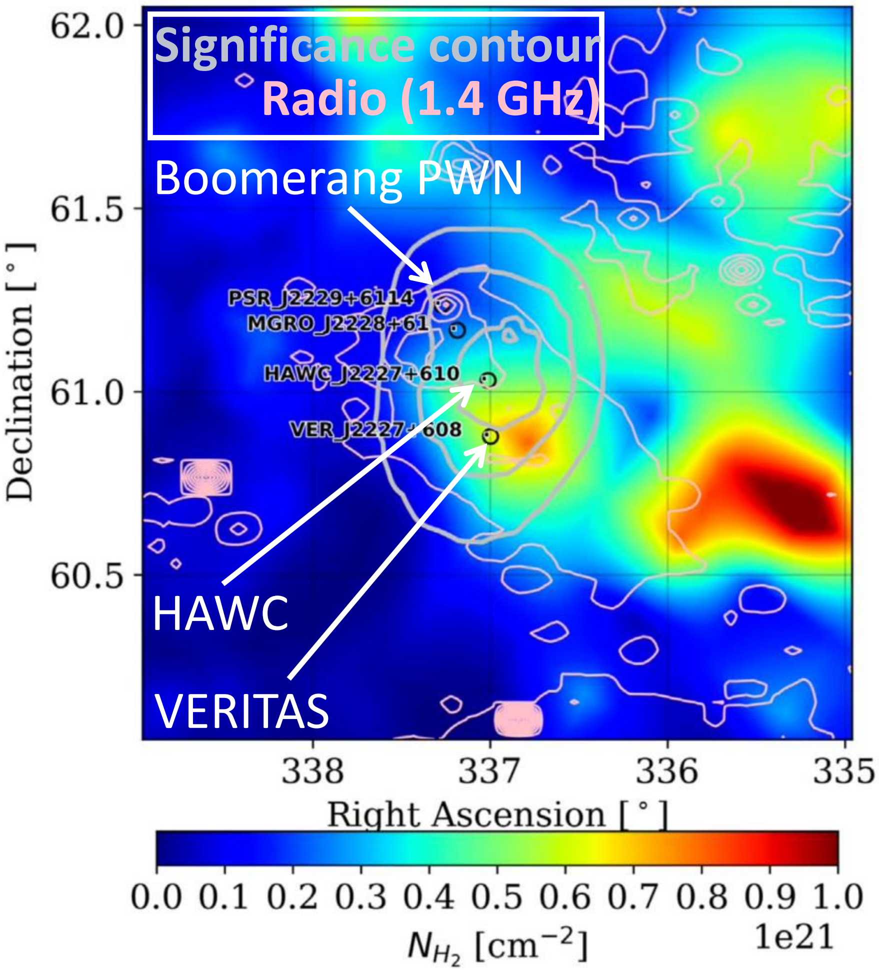


- 年齢 10 kyr　距離　0.8 kpc (if SNR is associated with Boomerang PWN)
  大きさ 14pc x 6pc

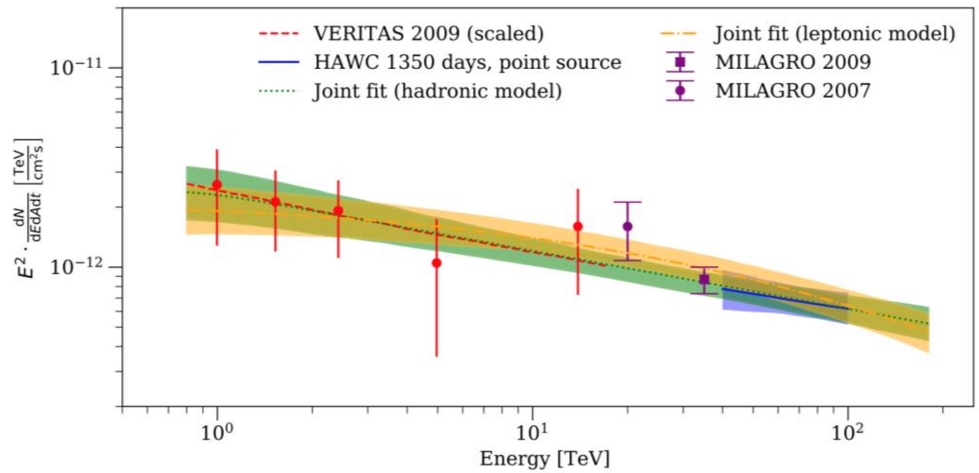
  Kothes et al, ApJ, 560, 236 (2001)
- ガンマ線(>0.63 TeV)放射領域の中心は分子雲の場所に一致

SNR G106.3+2.7 (HAWC による観測)

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

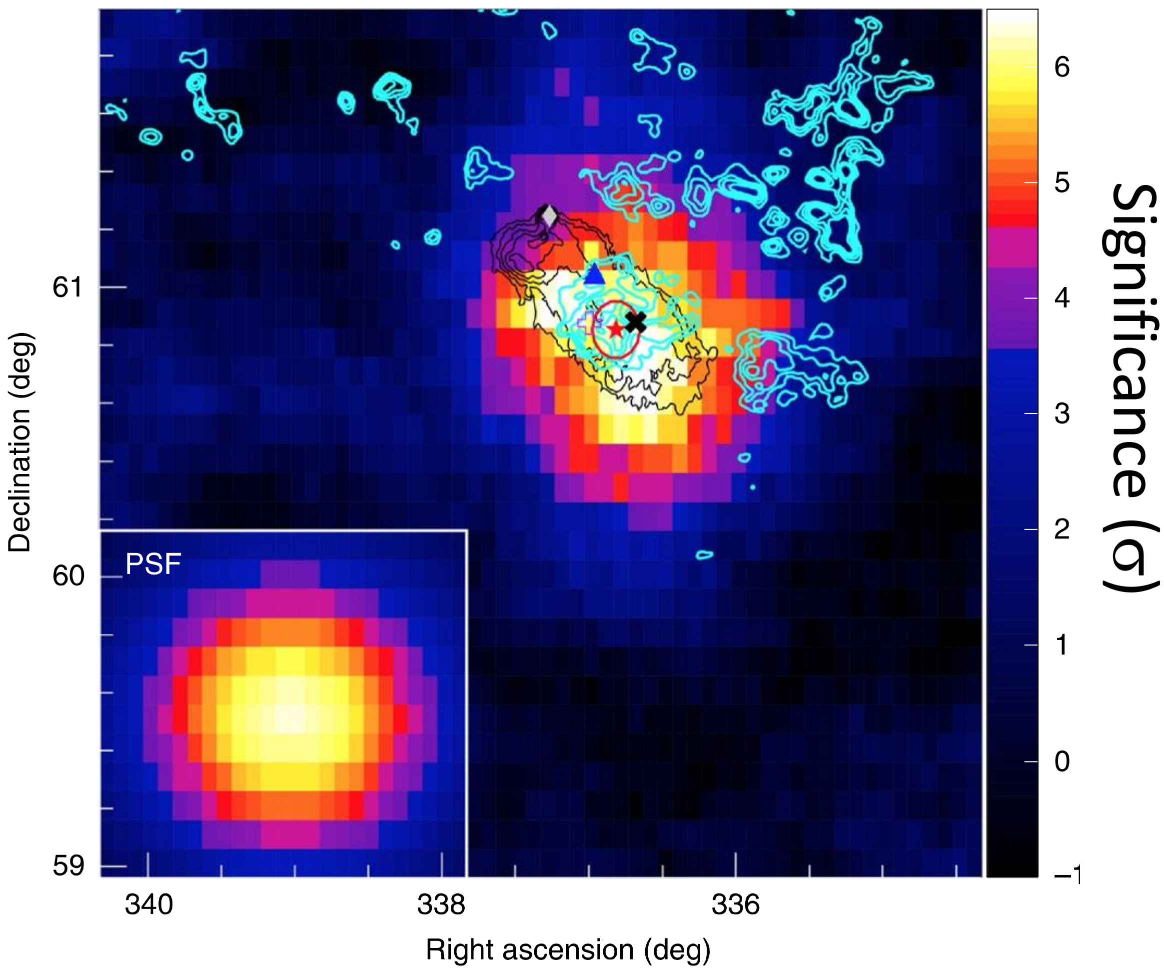


Energy spectrum



- 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

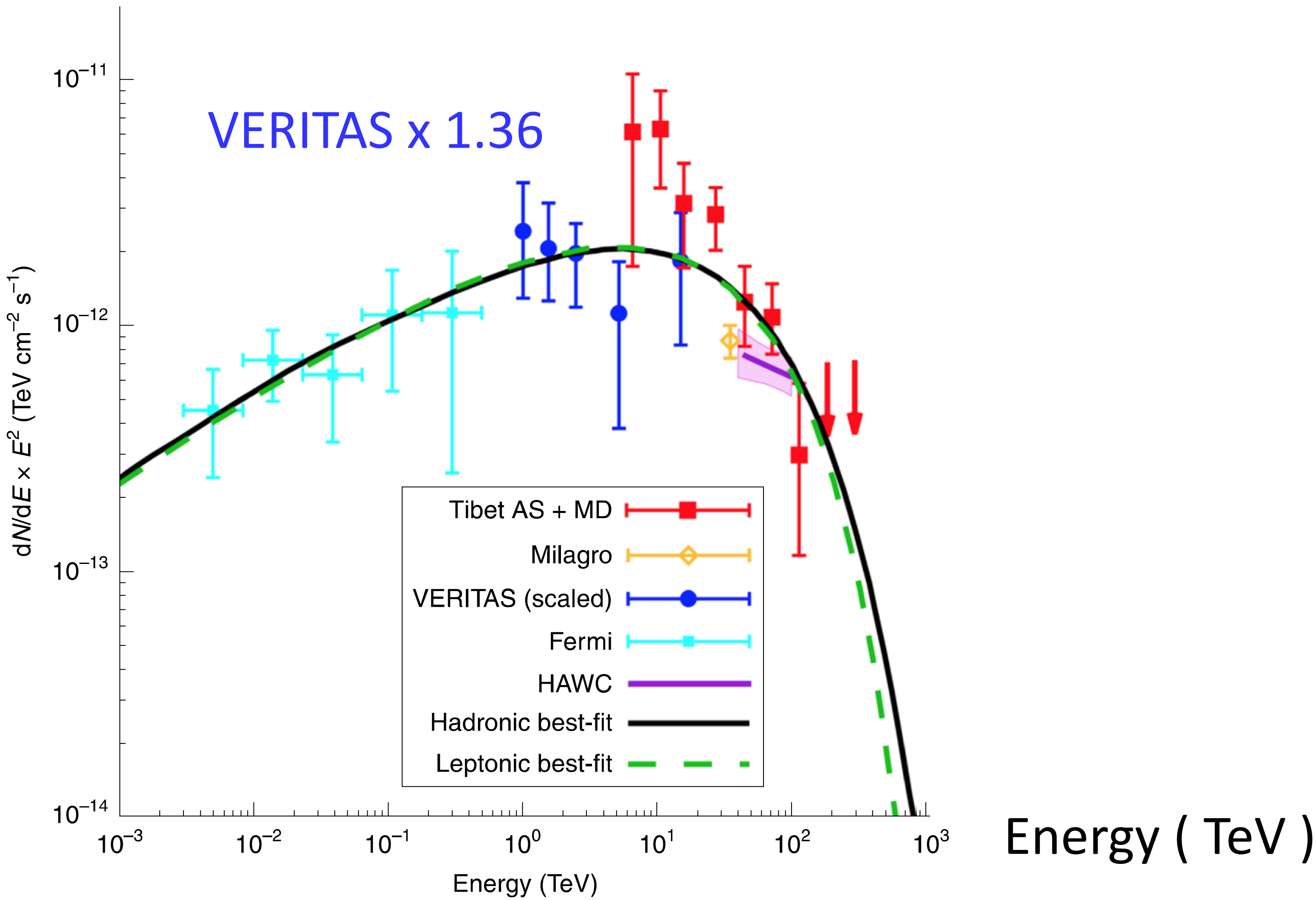
チベット実験の観測結果：SNR G106.3+2.7



- ✓ 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

M. Amenomori et al., Nature Astronomy, 2021, https://doi.org/10.1038/s41550-020-01294-9

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！

M. Amenomori et al., *Nature Astronomy*, 2021, https://doi.org/10.1038/s41550-020-01294-9

sub-PeV銀河面拡散ガンマ線

銀河系PeV宇宙線プール

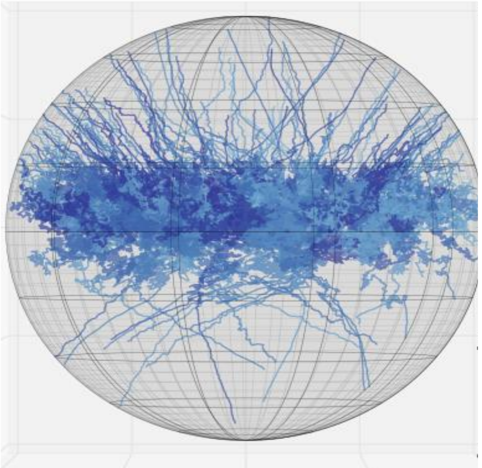
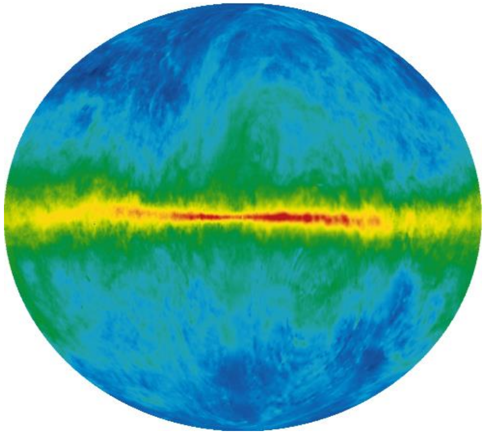


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop

×

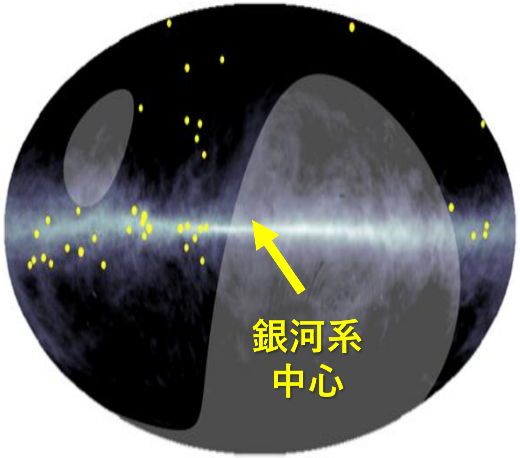
銀河系星間物質（陽子）



Radio (21cm) HI Map
Hartmann et al. (1997)
Dickey & Lockman (1990)

＝

sub-PeVガンマ線
（0.4 – 1 PeV）



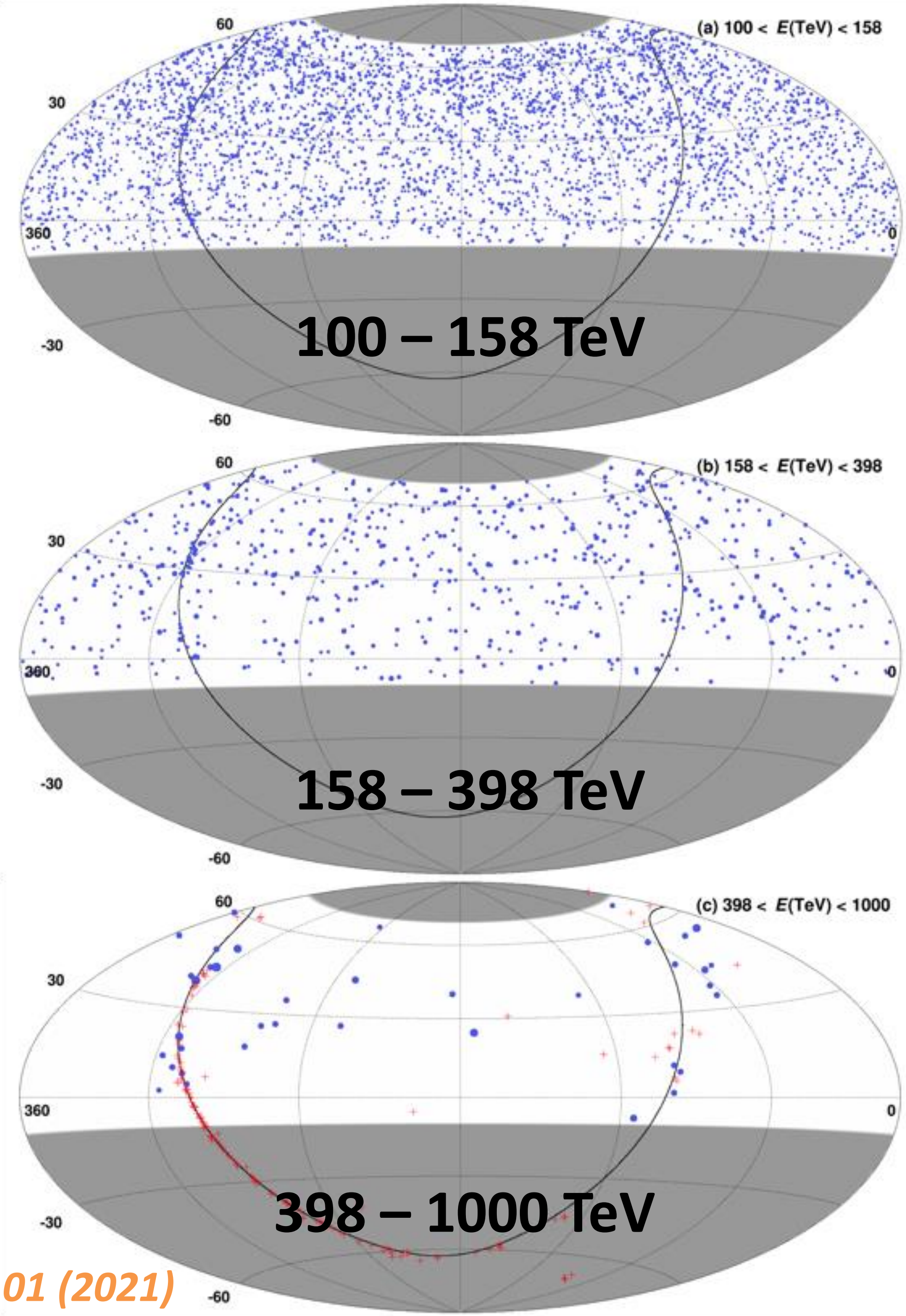
Tibet ASγ 実験

Amenomori+, PRL **126**, 141101 (2021)

- ✓ 銀河面からのPeV宇宙線起源のsub-PeV拡散ガンマ線を世界初観測
- ✓ 銀河系内にPeVatronが存在することを実験的に証明
- ✓ 最高ガンマ線エネルギー　～ 1 PeV

Event Distribution

Equatorial coordinates



Blue points:
Tibet AS +MD
(Circle size ∝ Energy)

Red plus marks:
TeV sources
(TeVCat catalog)

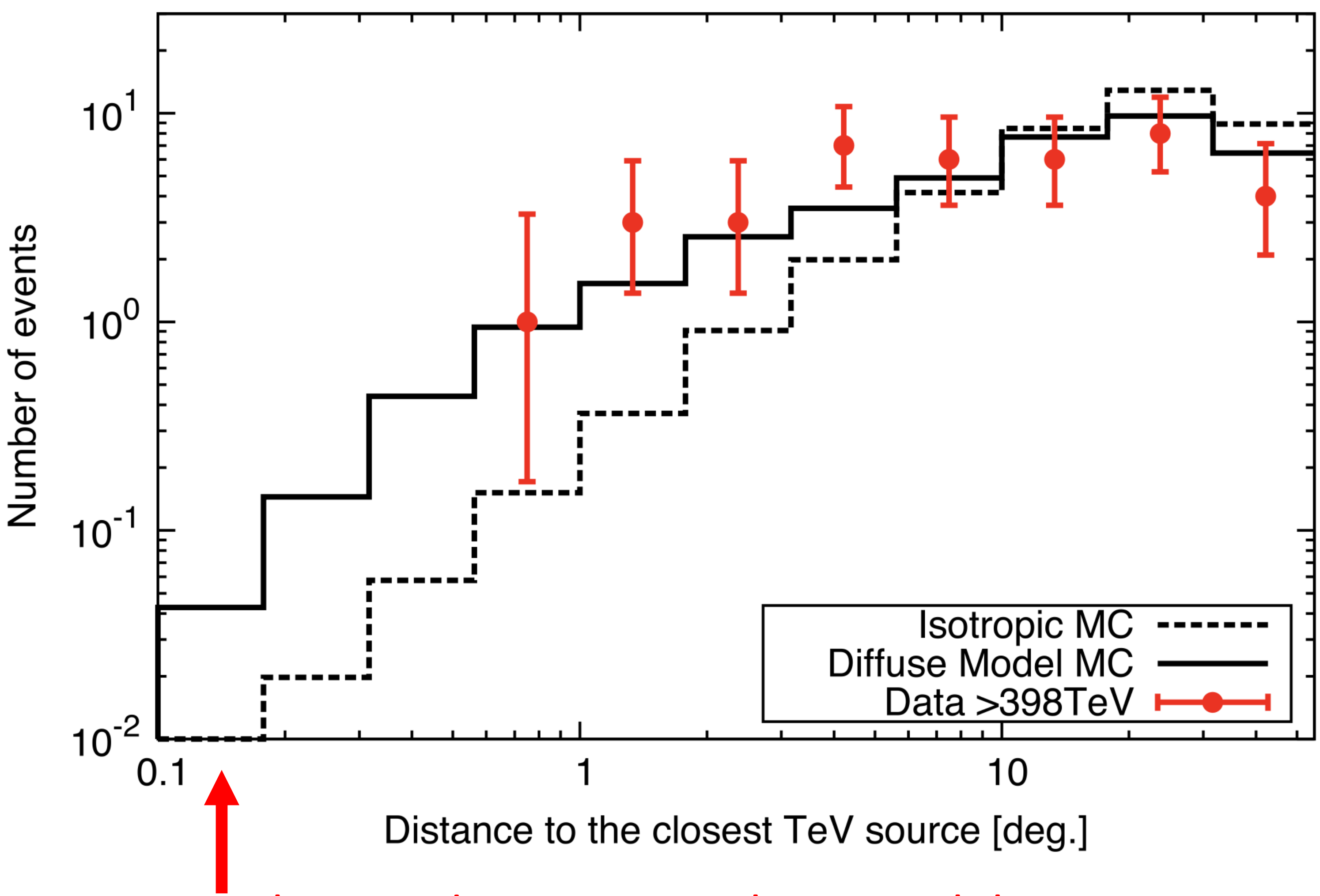
>0.398 PeV ($10^{2.6}$ TeV)
38 events in our FoV

→Not from known TeV sources!
& No signal > 10 TeV around them

M. Amenomori et al., PRL, 126, 141101 (2021)

Distribution of distance to the closest TeV source for events > 0.398 PeV

M. Amenomori et al., PRL, 126, 141101 (2021)



no peak around 0 -> no correlation with known TeV sources

Diffuse Model: Lipari & Vernetto, PRD 98, 143003, (2018)

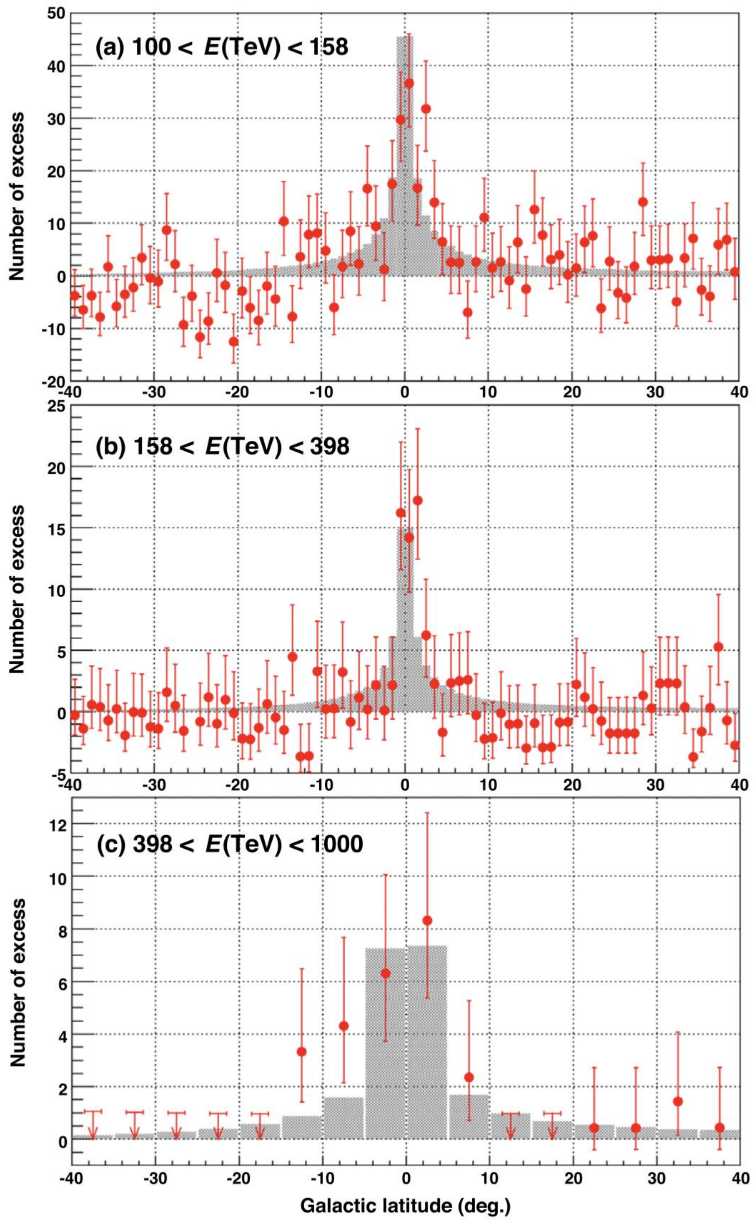
Galactic latitude distributions

M. Amenomori et al., PRL, 126, 141101 (2021)

100 – 158 TeV

158 – 398 TeV

398 – 1000 TeV



Shaded Histograms: Model shape normalized to DATA (|b|<5º)

Model: Lipari & Vernetto, PRD 98, 143003, (2018)

Number of sub-PeV events in the direction of galactic plane observed by Tibet AS+MD array

M. Amenomori et al., PRL, 126, 141101 (2021)

Highest gamma-ray energy = 0.957 (+ 0.166 - 0.141) PeV
(Eres ~10 % around 400 TeV & energy scale uncertainty ~13% in quadrature)

TABLE S1. Number of events observed by the Tibet AS+MD array in the direction of the galactic plane. The galactic longitude of the arrival direction is integrated across our field of view (approximately $22^\circ < l < 225^\circ$). The ratios (α) of exposures between the ON and OFF regions are 0.135 for $|b| < 5^\circ$ and 0.27 for $|b| < 10^\circ$, respectively.

		$\lvert b\rvert < 5^\circ$			$\lvert b\rvert < 10^\circ$	
Energy bin (TeV)	$N_{\rm ON}$	$N_{\rm BG}$ $(= \alpha N_{\rm OFF})$	Significance (σ)	$N_{\rm ON}$	$N_{\rm BG}$ $(= \alpha N_{\rm OFF})$	Significance (σ)
100 – 158	513	333	8.5	858	655	6.6
158 – 398	117	58.1	6.3	182	114	5.1
398 – 1000	16	1.35	6.0	23	2.73	5.9

TABLE S2. Galactic diffuse gamma-ray fluxes measured by the Tibet AS+MD array.

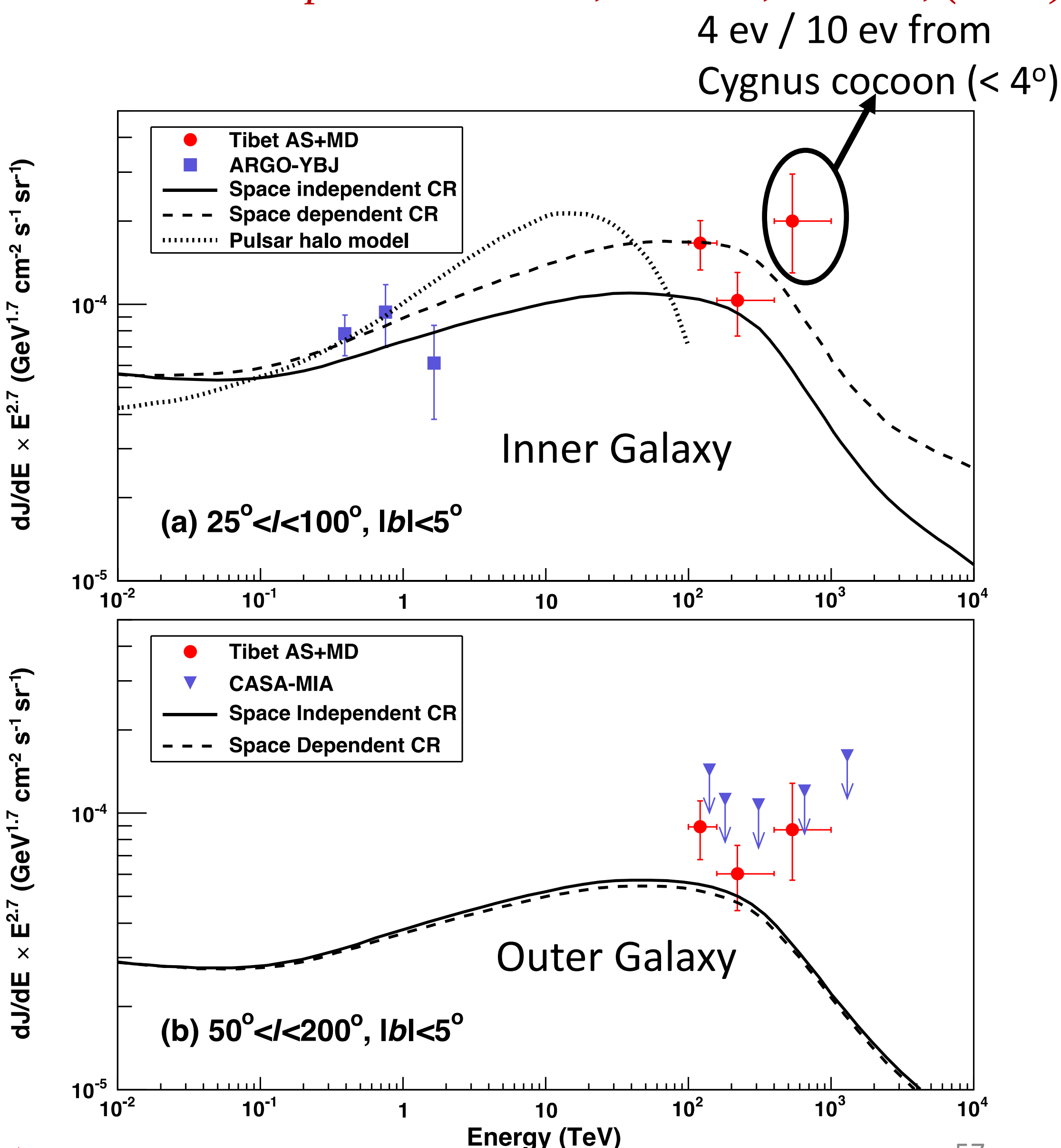
Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ, \lvert b\rvert < 5^\circ$) ($\rm TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$)	Flux ($50^\circ < l < 200^\circ, \lvert b\rvert < 5^\circ$) ($\rm TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$)
100 – 158	121	$(3.16 \pm 0.64) \times 10^{-15}$	$(1.69 \pm 0.41) \times 10^{-15}$
158 – 398	220	$(3.88 \pm 1.00) \times 10^{-16}$	$(2.27 \pm 0.60) \times 10^{-16}$
398 – 1000	534	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

Energy Spectrum

Models: Lipari & Vernetto, PRD 98, 143003, (2018)

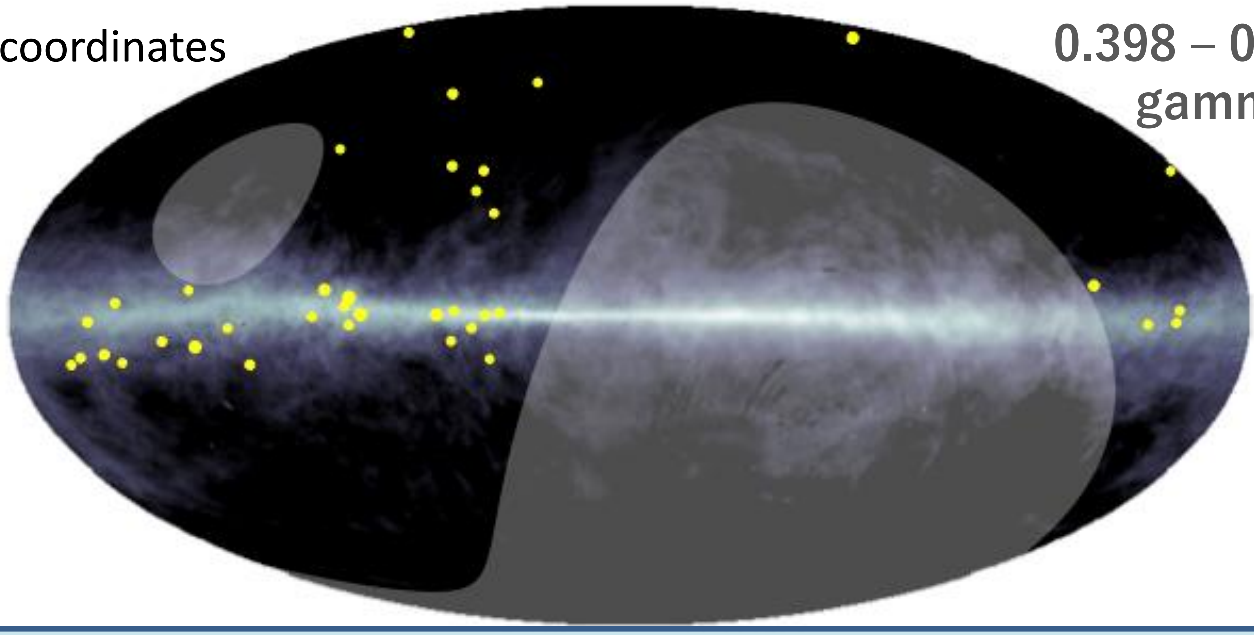
After excluding the contribution from the known TeV sources (within 0.5° in radius) listed in the TeVCat catalog
(~13% to the diffuse flux, but no contamination to events > 0.398 PeV)

The measured fluxes are reasonably consistent with Lipari's galactic diffuse gamma-ray model assuming the hadronic cosmic-ray origin.



Amenomori+., PRL 126, 141101,(2021)

Electron origin? vs Proton origin?



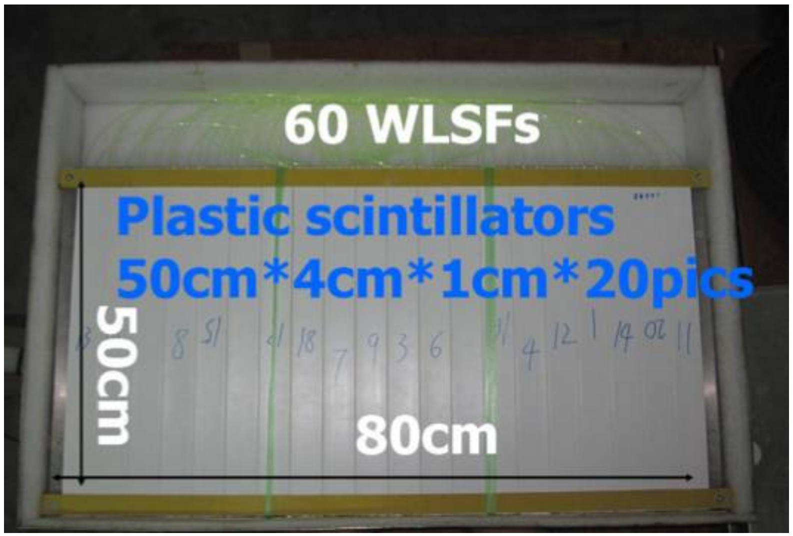
- ✓ Observed gamma rays are isolated, not coming from known gamma-ray sources.
  → **Electrons** lose their energy quickly, so they **should stay near the source**.
  → **Protons** don't lose energy and **can escape farther from the source**.

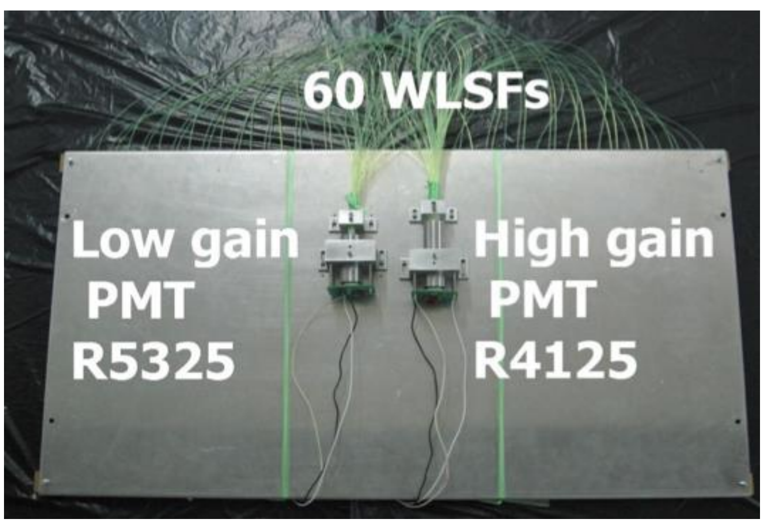
Strong evidence for sub-PeV γ rays induced by cosmic rays

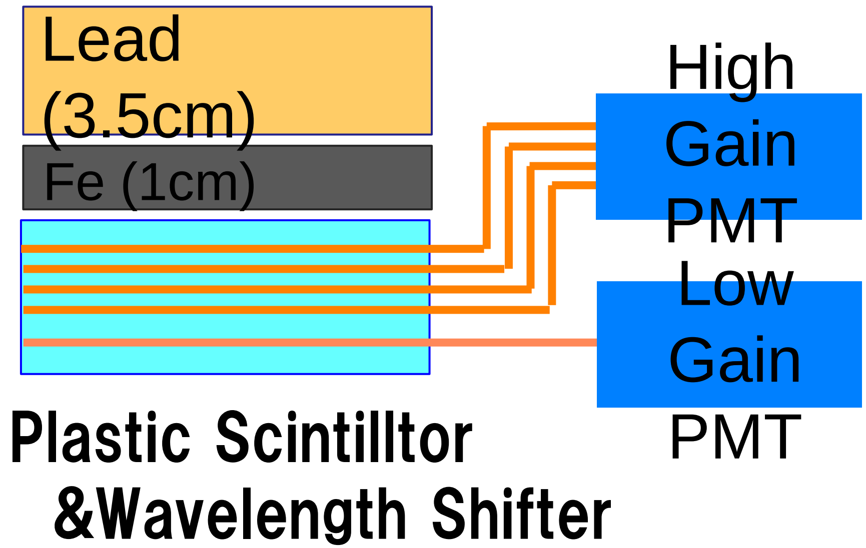
- ✓ This is the first evidence for existence of PeVatrons, in the past and/or present Galaxy, which accelerate protons up to the Peta electron volt (PeV) region.

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

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

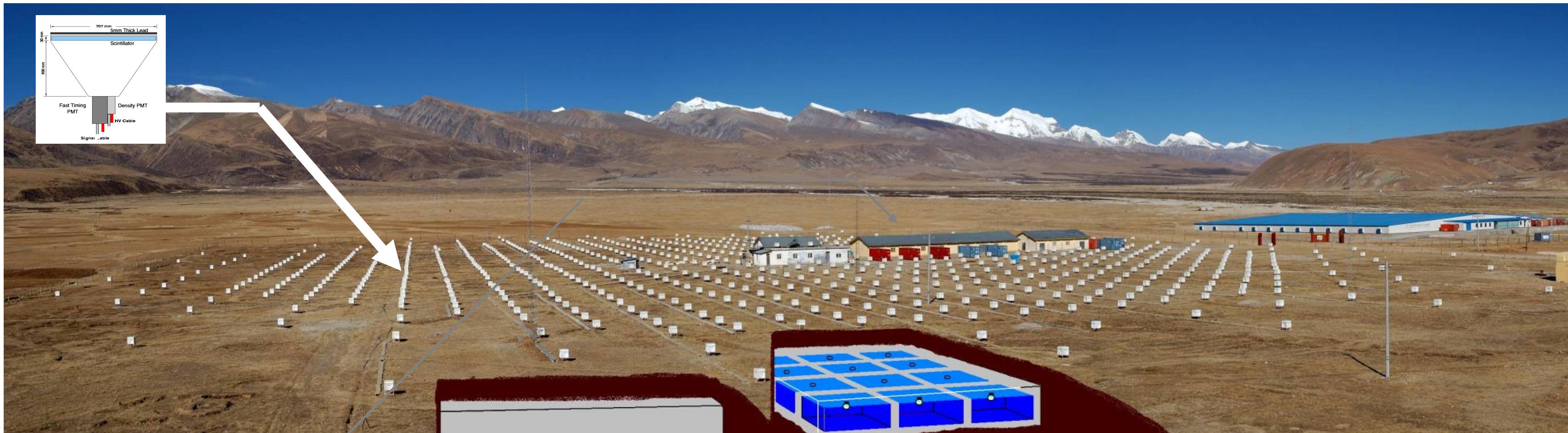


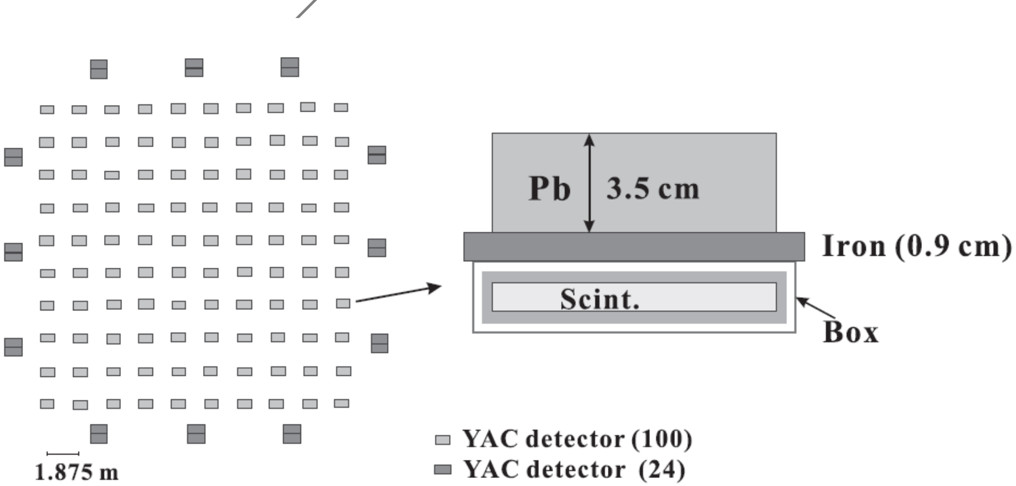


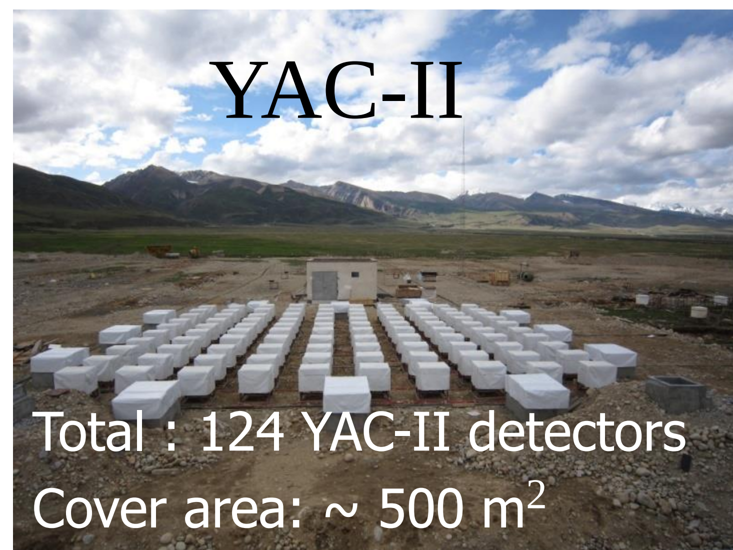


2PMTs cover 1~10^6 particles

YAC-II started in 2014, accumulating data

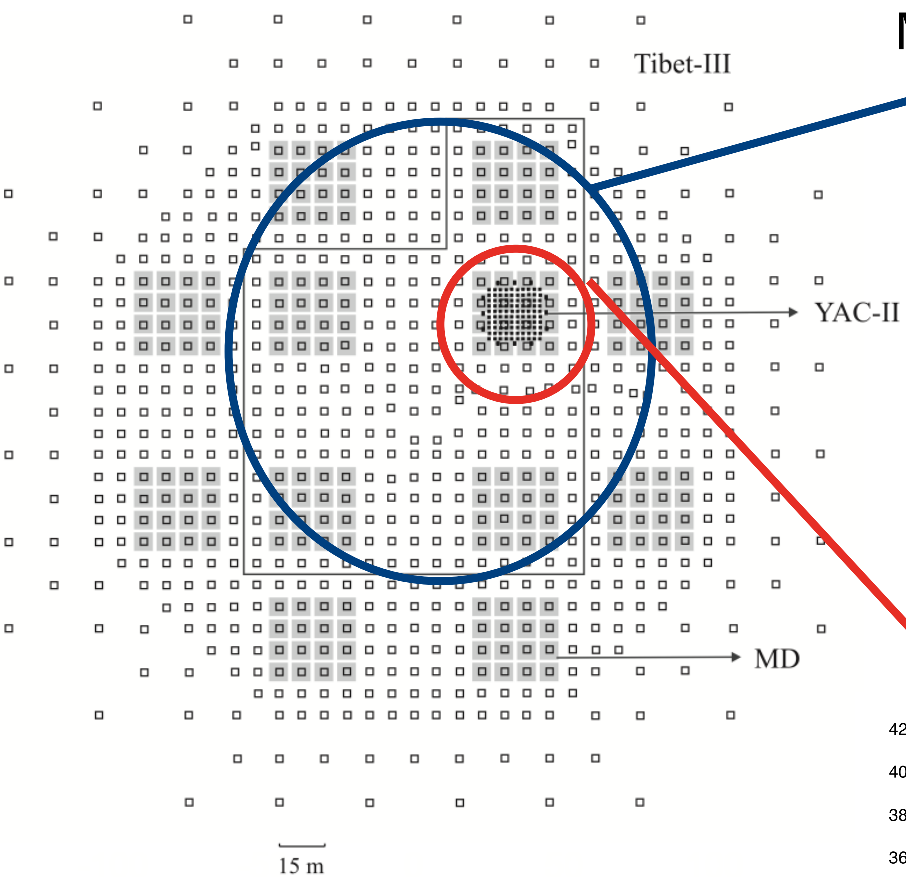




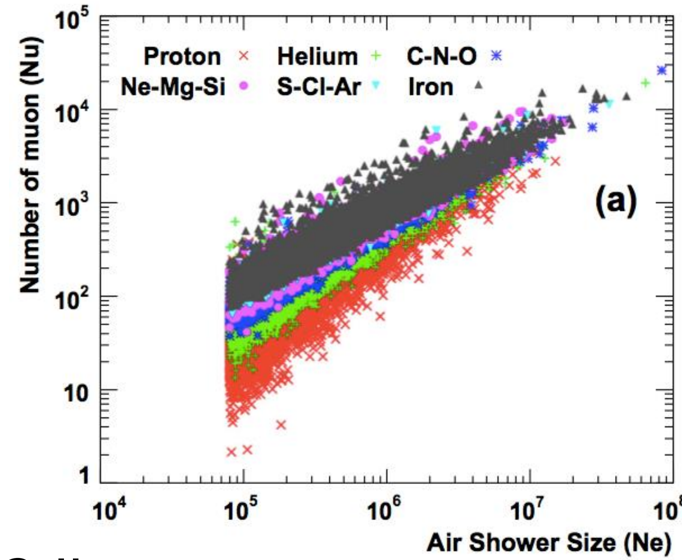


Tibet-III + YAC-II + MD (MC) for Knee Study

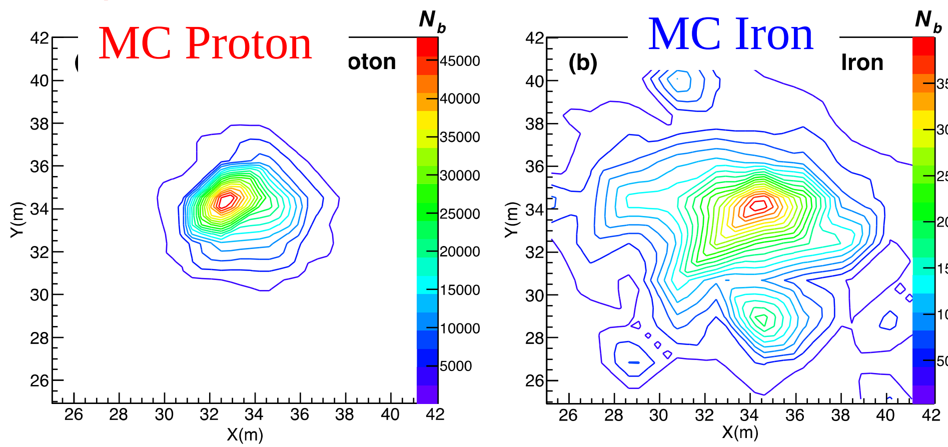
Muon Detector



MC Ne-Nμ Plot

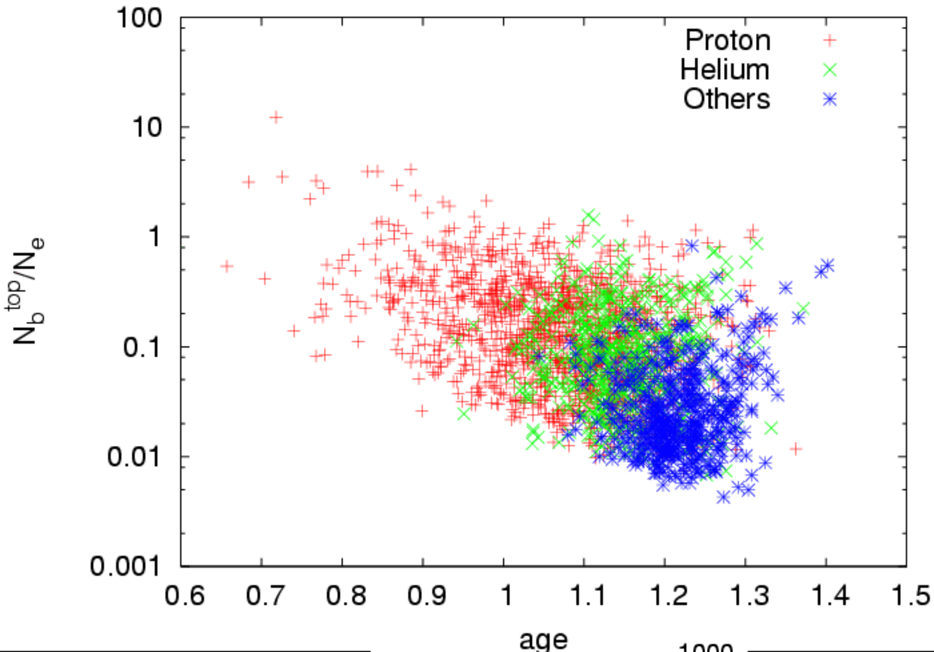


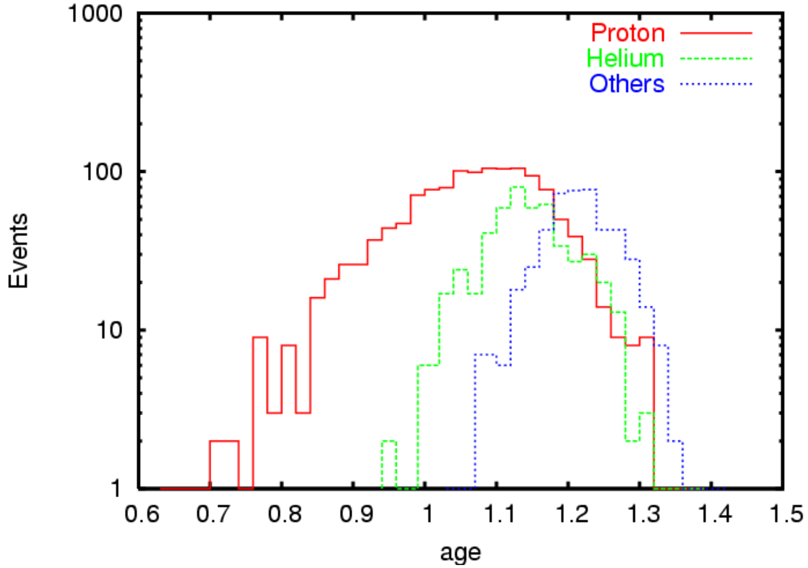
YAC-II

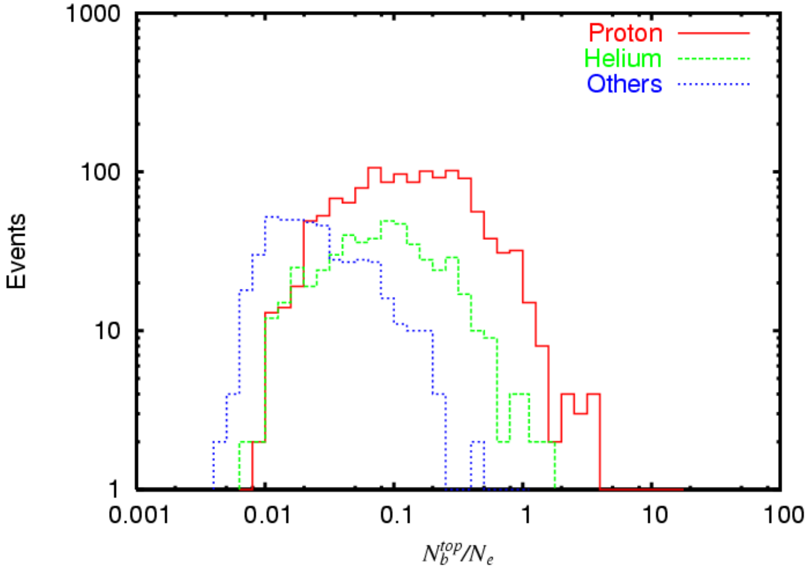


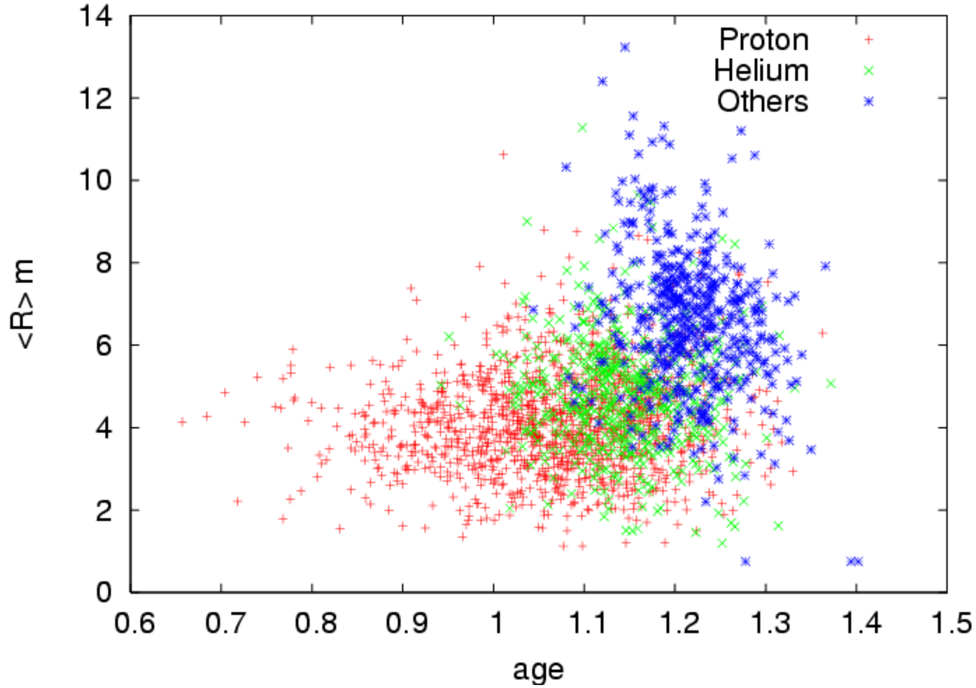
J.Huang et al,Astropart.Phys. 66 (2015) 18-30

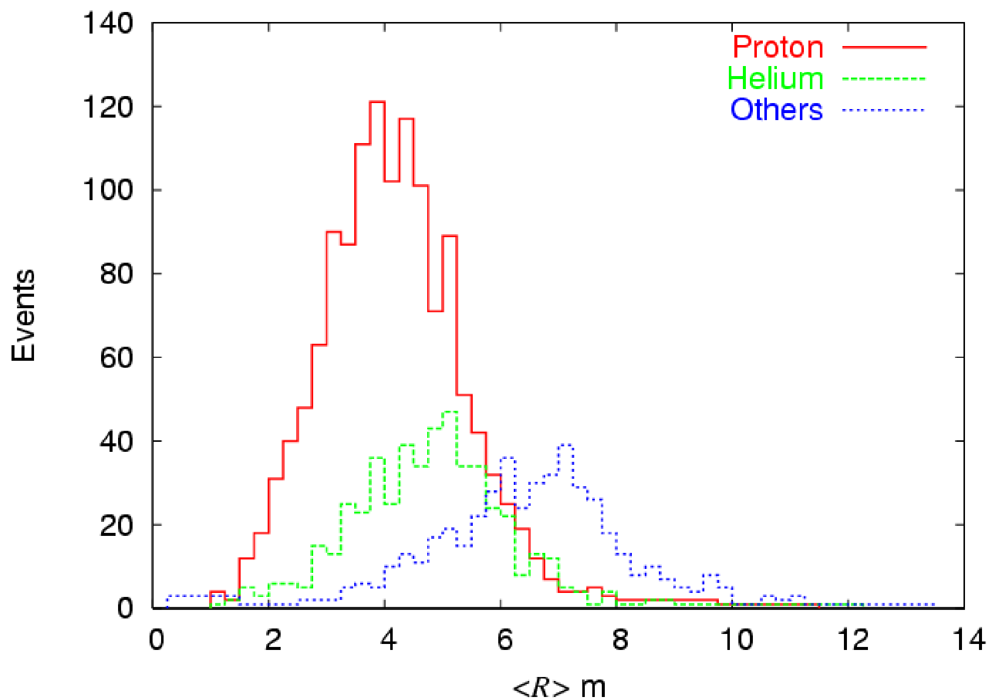
Features of YAC-II observables





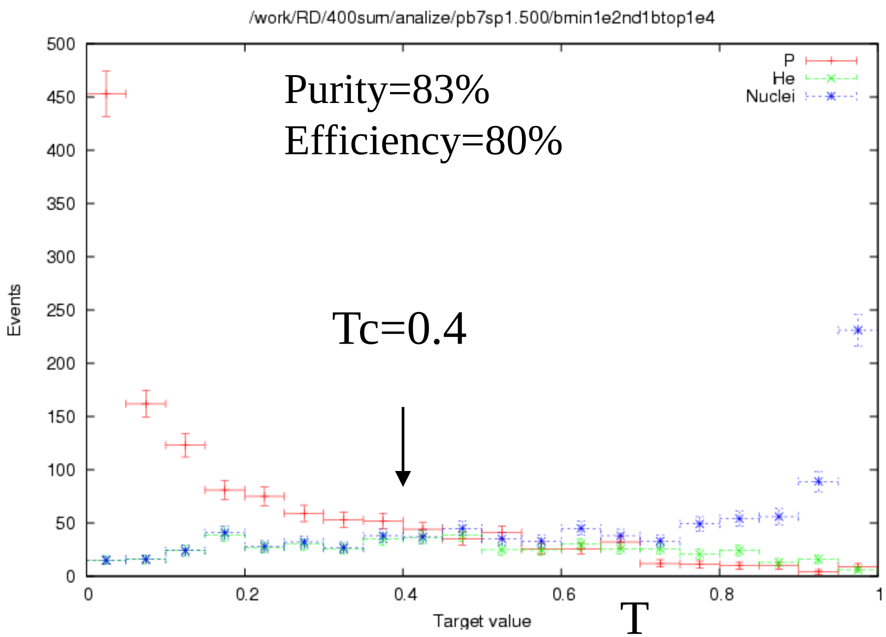



Proton
Helium
Others
<R> m
age

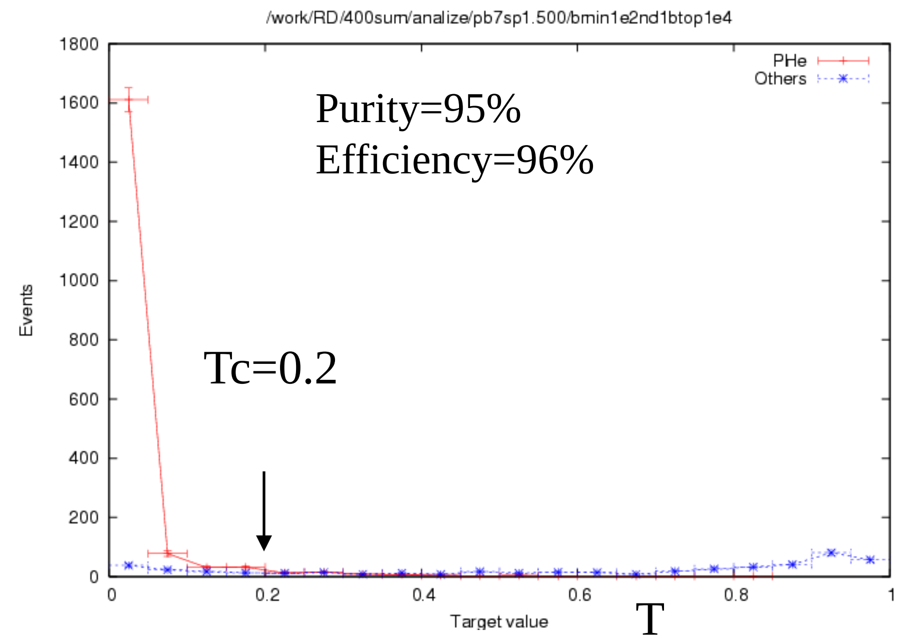

Proton
Helium
Others
Events
<R> m

ANN output

Proton separation



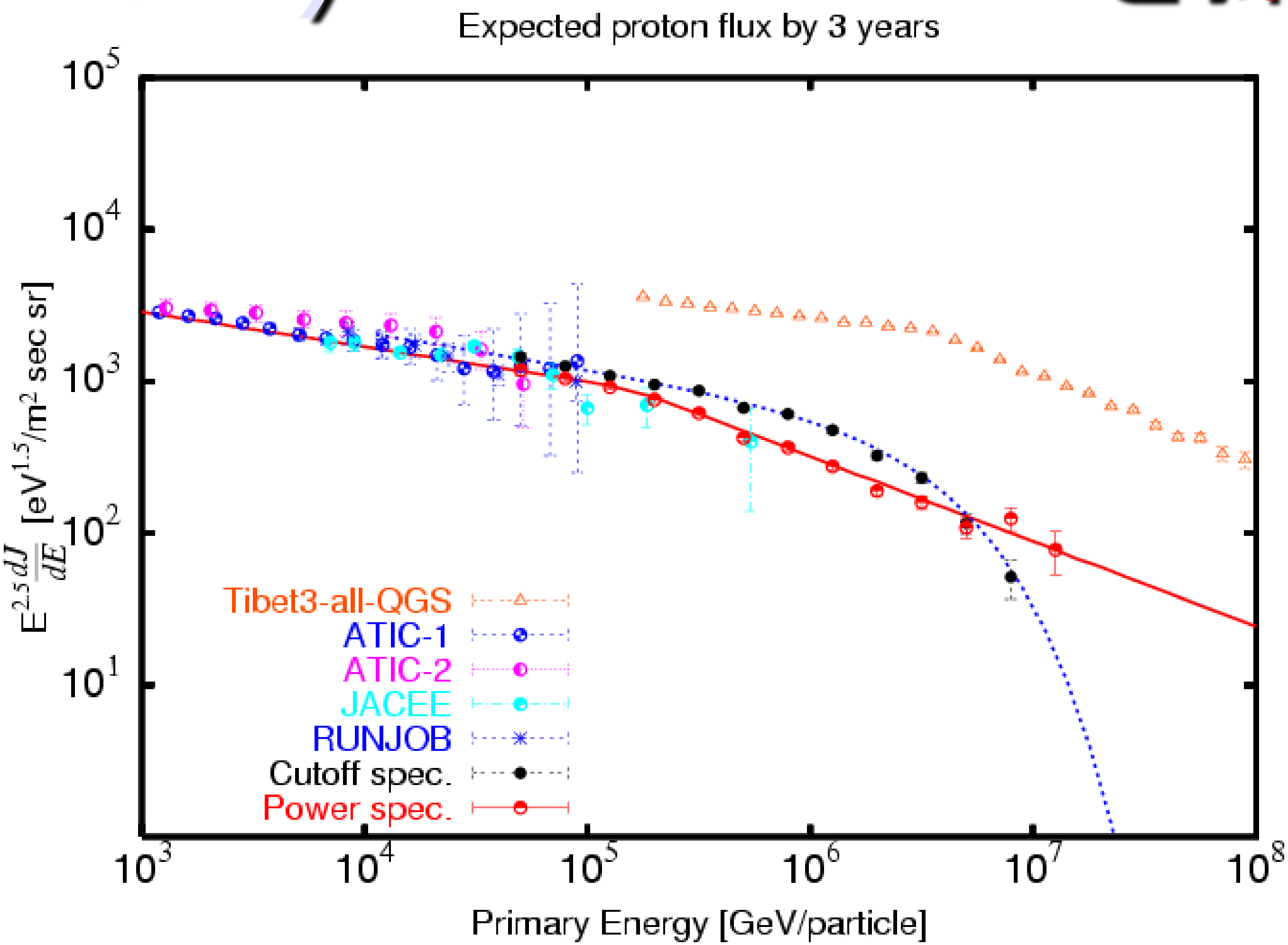
P+He separation



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

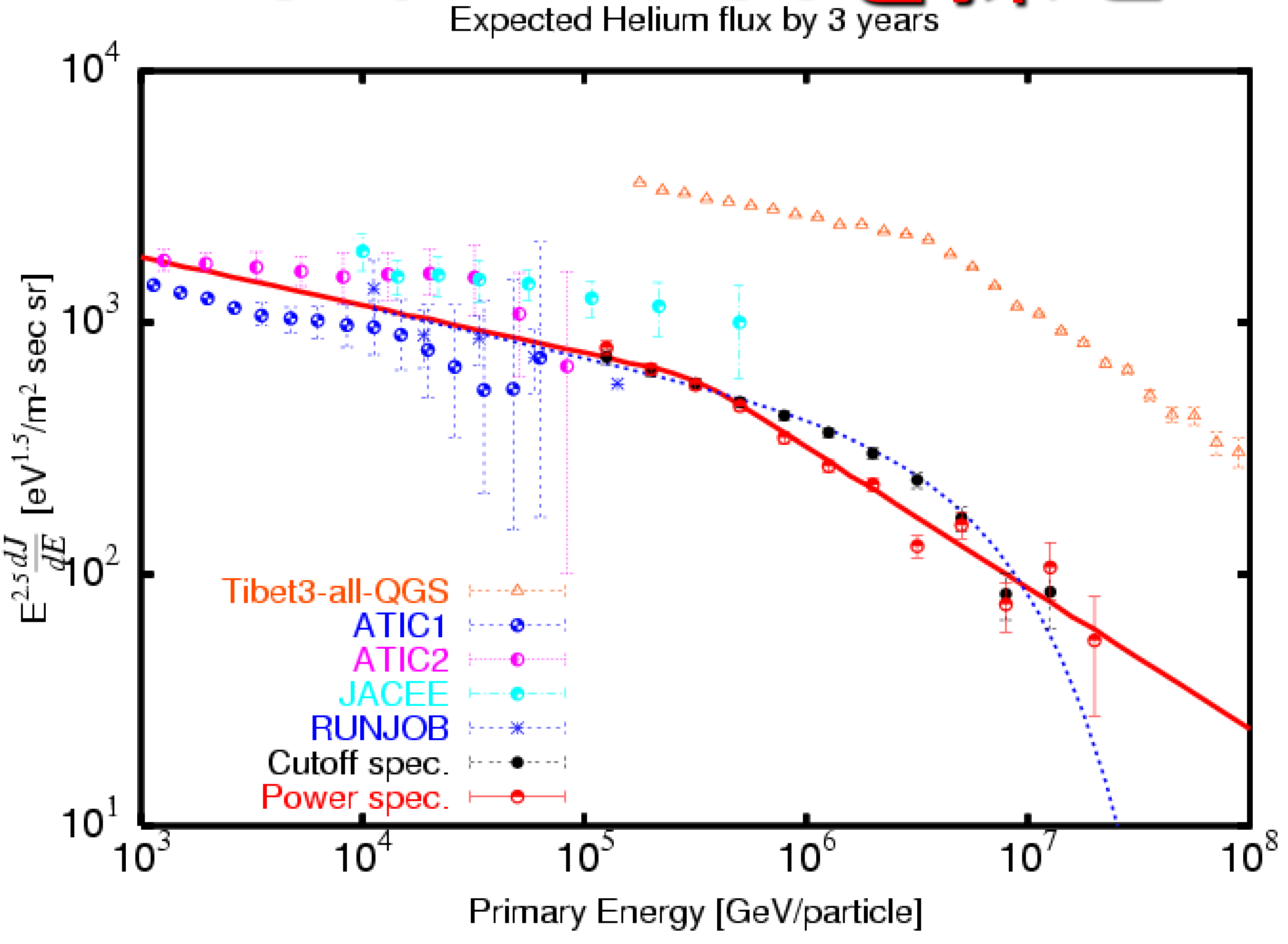
20% of heavier nuclei than helium contaminates to P+He region.

Expected proton spectrum (YAC-II) Proton kneeを探せ



Expected He Spectrum (YAC-II)

Helium kneeを探せ



The ALPACA Experiment

Andes

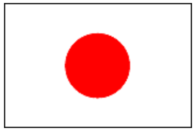
Large-area

PArticle detector for

Cosmic ray physics and

Astronomy

The ALPACA Collaboration

M. Anzorena [A], C. A. H. Condori [C], E. de la Fuente [D], A. Gomi [E], Y. Hayashi [B], K. Hibino [F], N. Hotta [G], A. Jimenez-Meza [D], Y. Katayose [E], C. Kato [B], S. Kato [A], I. Kawahara [E], T. Kawashima [A], K. Kawata [A], T. Koi [H], H. Kojima [I], D. Kurashige [E], R. Mayta [J,K], P. Miranda [C], K. Munakata [B], K. Nagaya [E], Y. Nakamura [A], C. Nina [C], M. Nishizawa [M], R. Noguchi [E], S. Ogio [A], M. Ohnishi [A], S. Okukawa [E], A. Oshima [H], M. Raljevich [C], H. Rivera [C], T. Saito [N], Y. Sakakibara [E], T. Sako [A], T. K. Sako [A], T. Sasaki [F], S. Shibata [I], A. Shiomi [L], M. Subieta [C], N. Tajima [O], W. Takano [F], M. Takita [A], Y. Tameda [P], K. Tanaka [Q], R. Ticona [C], I. Toledano-Juarez [D], H. Tsuchiya [R], Y. Tsunesada [J,K], S. Udo [F], K. Yamazaki [H], Y. Yokoe [A] et al. (The ALPACA Collaboration)

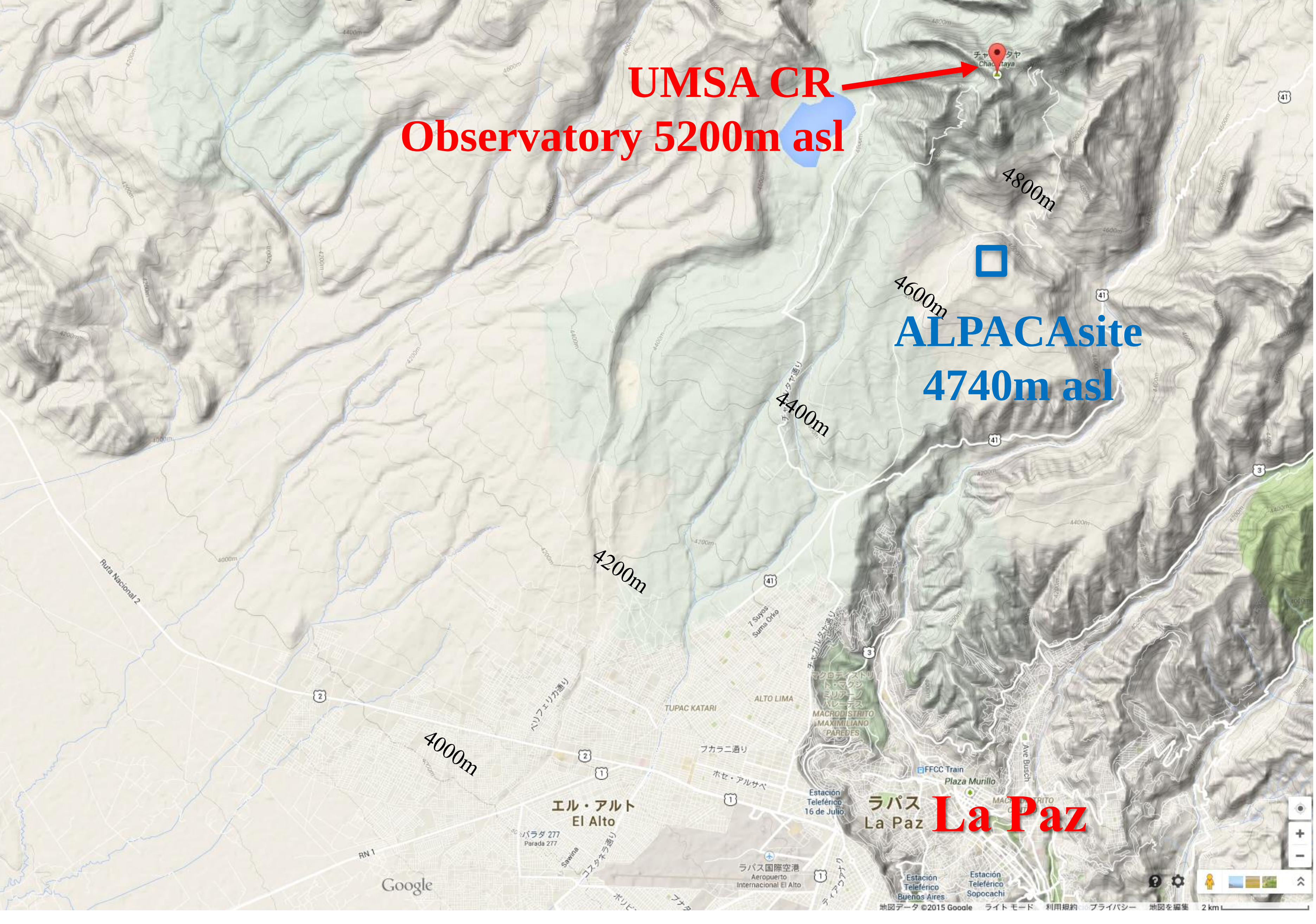
ICRR, Univ. of Tokyo [A], Dept. of Phys., Shinshu Univ.[B], IIF, UMSA [C], Univ. de Guadalajara [D], Fac. of Engn., Yokohama Natl. Univ.[E], Fac. of Engn., Kanagawa Univ.[F], Utsunomiya Univ.[G], Coll. of Engn., Chubu Univ.[H], Astro. Obs., Chubu Univ.[I], Grad. Sch. of Sci., Osaka Metro. Univ.[J], NITEP, Osaka Metro. Univ.[K], Coll. of Ind. Tech., Nihon Univ.[L], NII [M], Tokyo Metro. Coll. of Ind. Tech.[N], RIKEN [O], Fac. of Engn., Osaka Electro-Comm. Univ.[P], Fac. of Info. Sci., Hiroshima City Univ.[Q], JAEA [R]

共同研究者51名

ALPACA Site

Mt. Chacaltaya, Bolivia

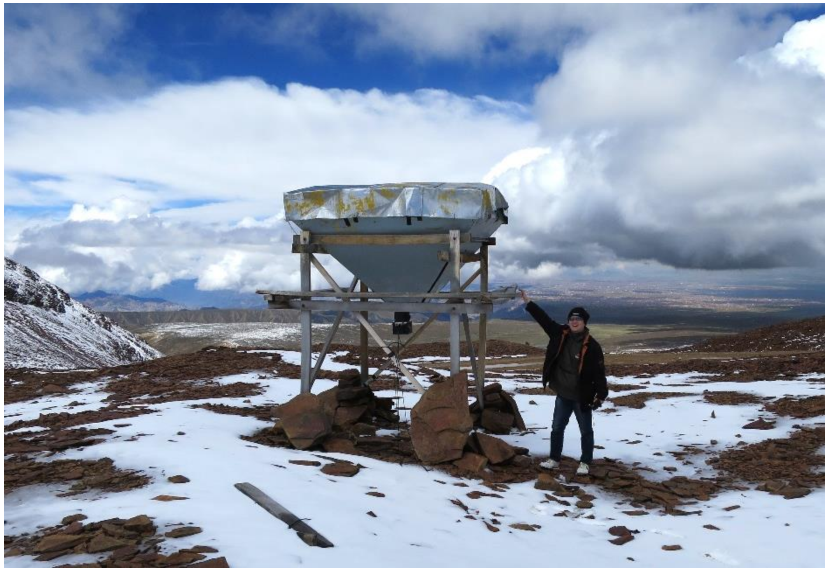
Site Survey



UMSA CR
Observatory 5200m asl
ALPACAsite
4740m asl
4800m
4600m
4400m
4200m
4000m
La Paz
El Alto
Ruta Nacional 2
TUPAC KATARI
ALTO LIMA
Plaza Murillo
FFCC Train
Ave Busch
Estación Teleférico 16 de Julio
Estación Teleférico Sopocachi
Estación Teleférico Buenos Aires
Aeropuerto Internacional El Alto
Parada 277
RN 1
ラパス
エル・アルト
ラパス国際空港
Google
地図データ ©2015 Google
2 km

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 comic 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

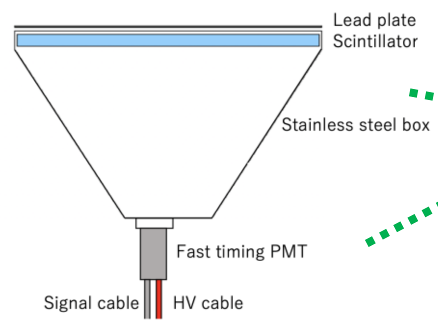
Observation Cite: **Chacaltaya Plateau**

500 m × 500 m flat within ± 1°

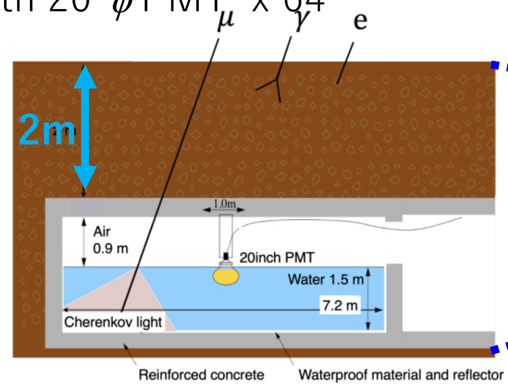
4,740 m above sea level (16° 23’S, 68° 08’W)

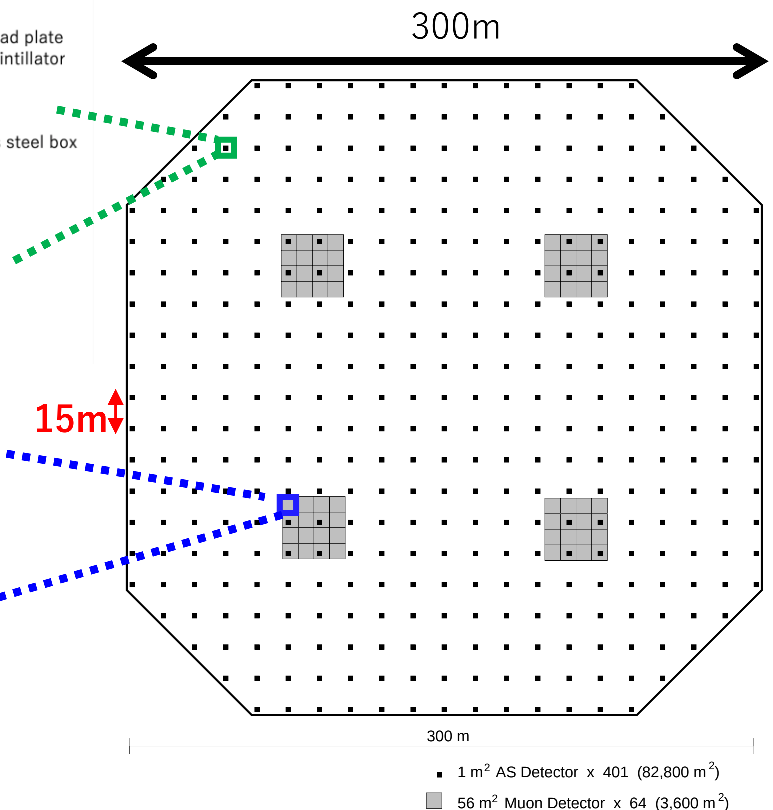
Original ALPACA design

1. **Array coverage 82,800m^2**
   = 401 x 1m^2 plastic scintillators



2. **Underground water Cherenkov muon detector (MD) 3600m^2**
   Soil over 2m ($\sim 16 X_0$)
   = 56m^2 with 20"ϕ PMT x 64 cells



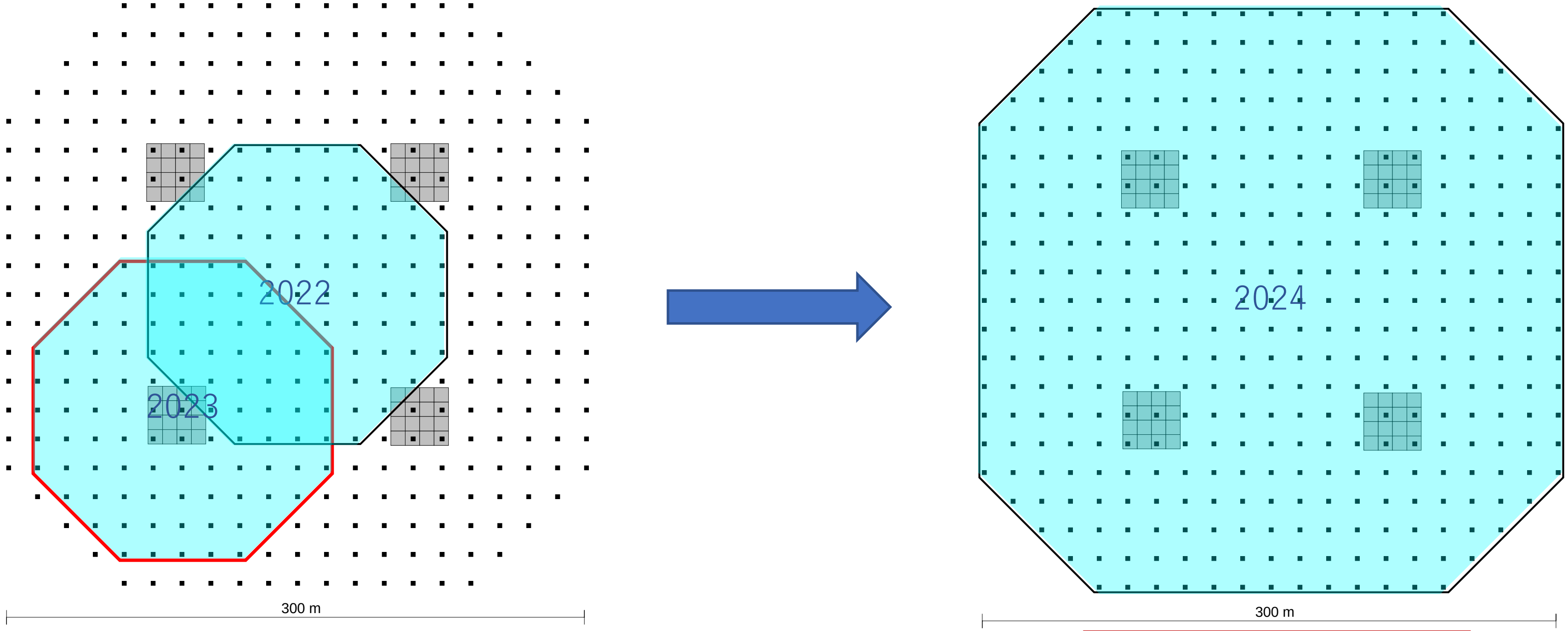


- ✓ Cosmic-ray BG rejection power >99.9% @100TeV.
- ✓ Angular resolution ~0.2° @100TeV, Energy resolution ~20%@100TeV
- ✓ 100% duty cycle, FOV θ_{zen}<40° (well studied), θ_{zen}<60° (in study)

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

ALPACA staging plan



ALPAQUITA in 2023

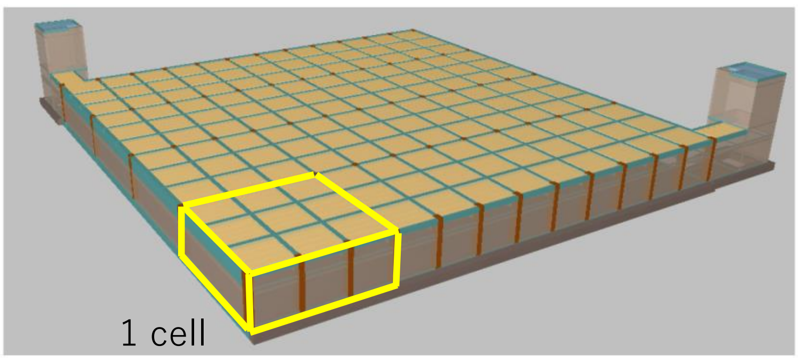
(97 + 60) SDs + 1 MD

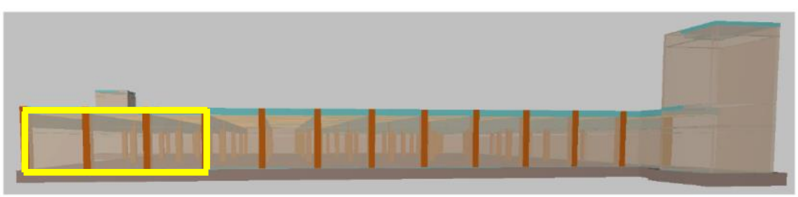
ALPACA in 2024

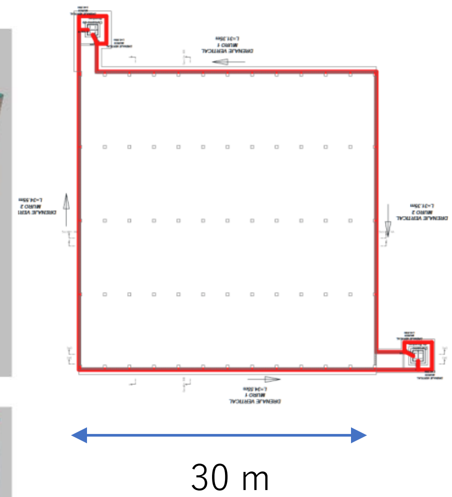
401 SDs + 4 MD

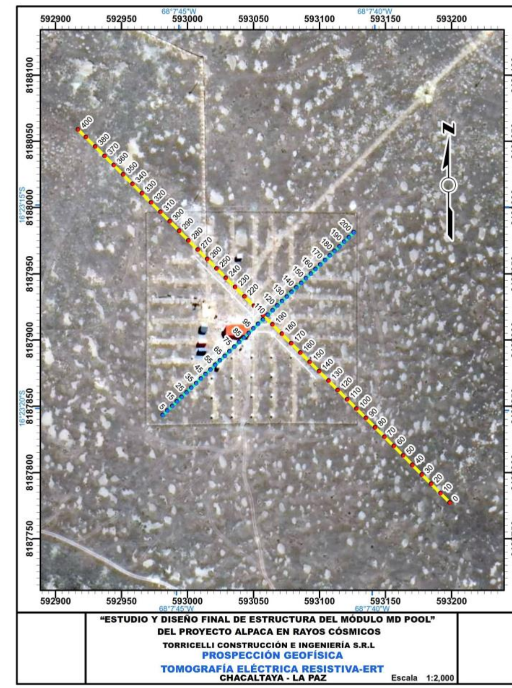
MD design (1 MD = 4 x 4 cells)

地質調査　⇒　問題無し





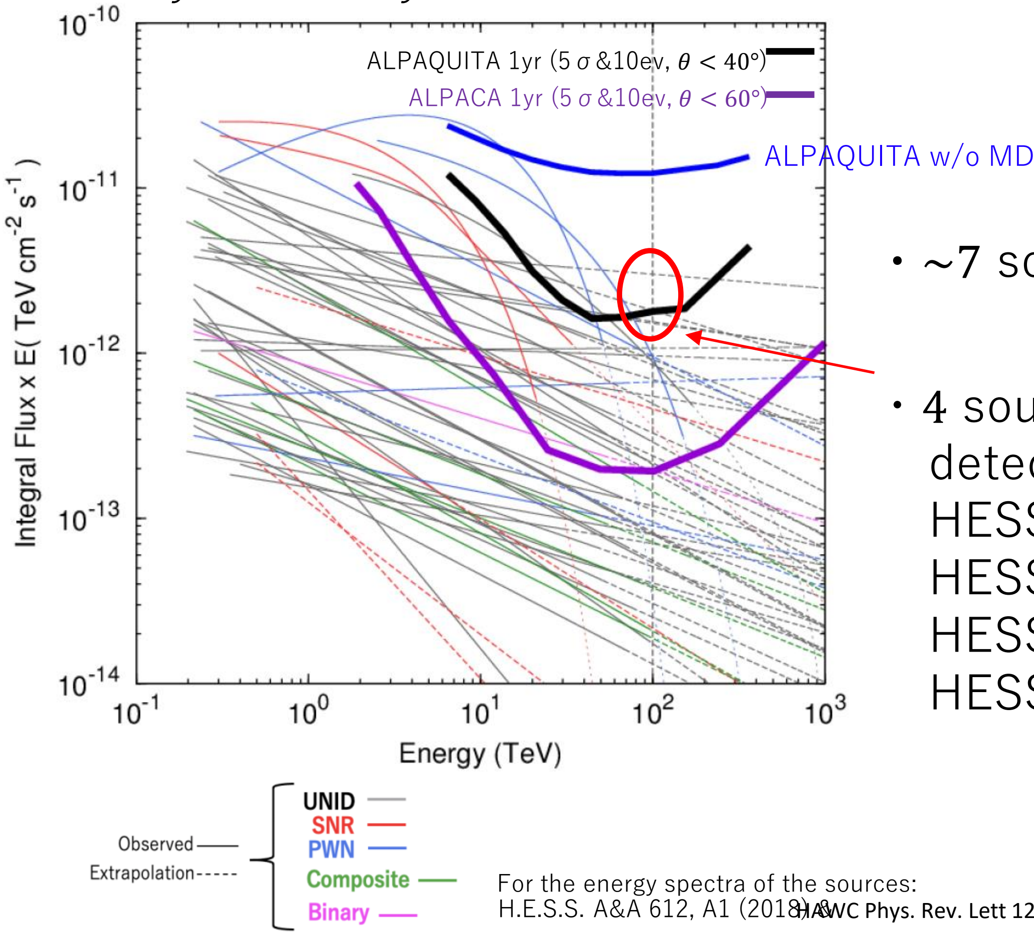




2023: 1 MD
2024: 3 MDs

Sensitivity to VHE Gamma-Ray Sources

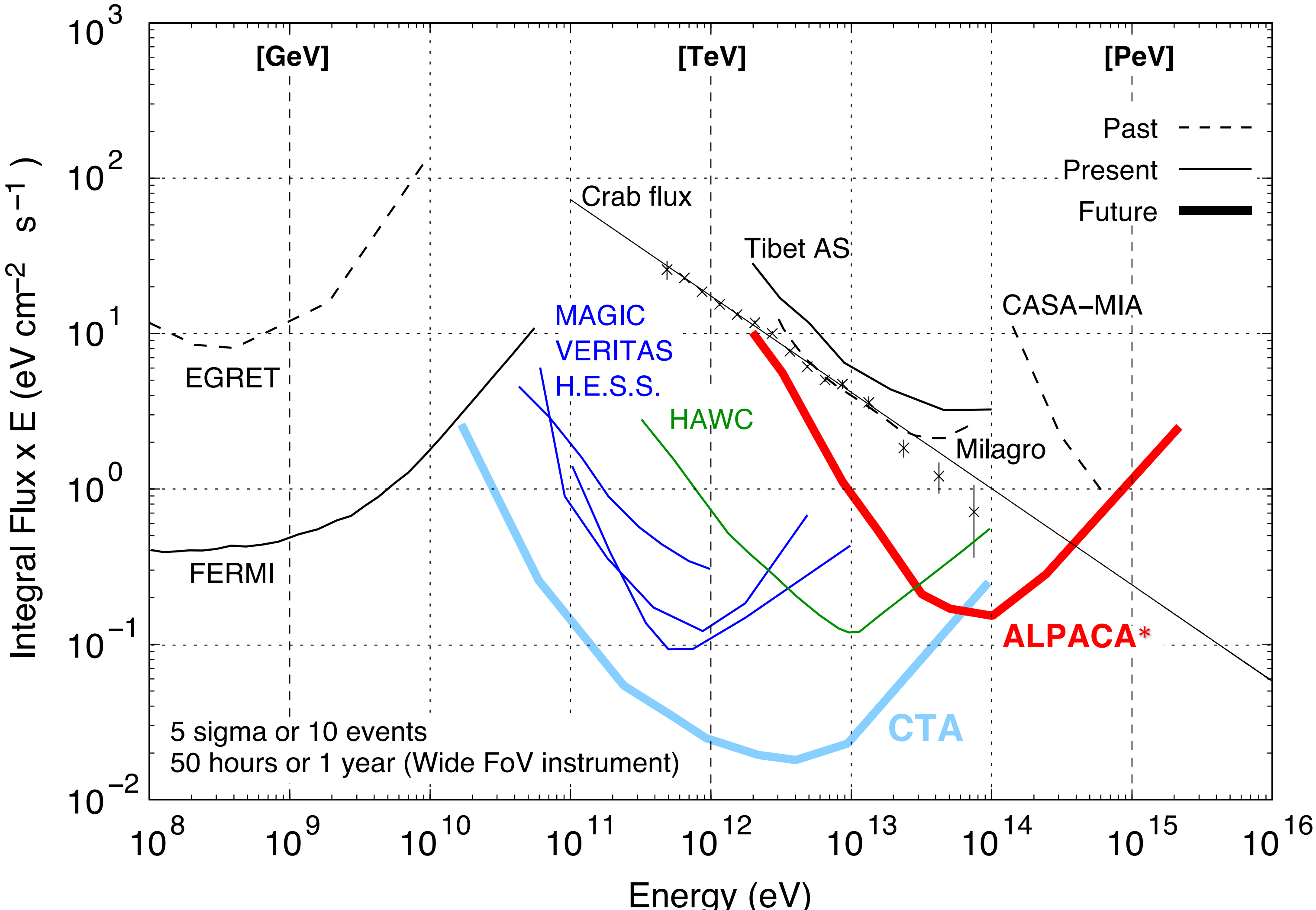
Sensitivity curves in 1yr5 σ



- ~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)

ガンマ線点源に対する感度



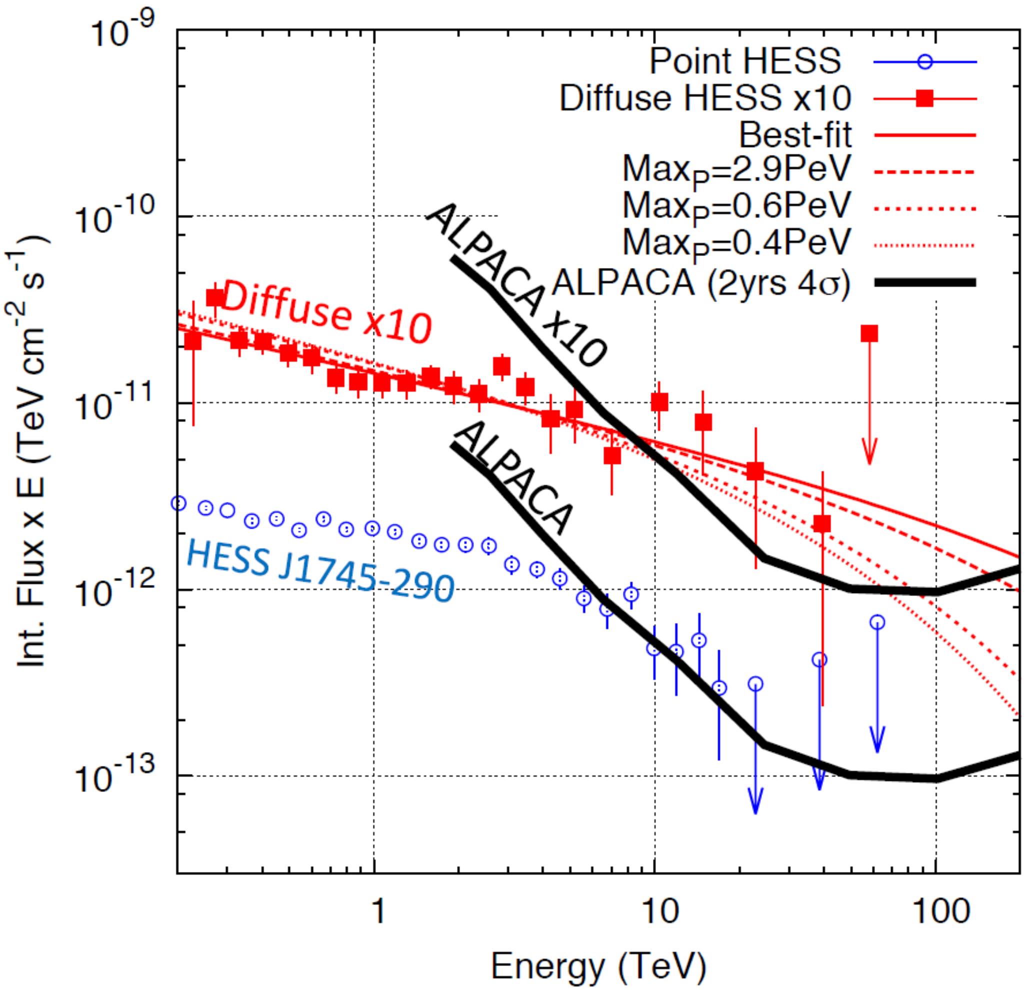
CTA Review by Kubo (JPS 2015)
M.Daniel, Proc. of 28th Texas Sympo. (2015)

*Based on MC Simulation
For the Tibet AS+MD

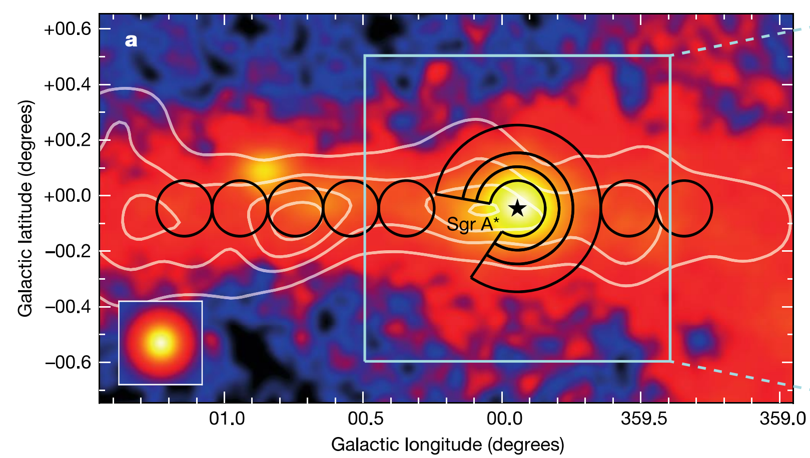
Target γ Sources

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

Galactic Center as PeVatron?



- ✓ Detection of diffuse component
- ✓ >100TeV γ−ray expected
- ✓ PeVatron candidate

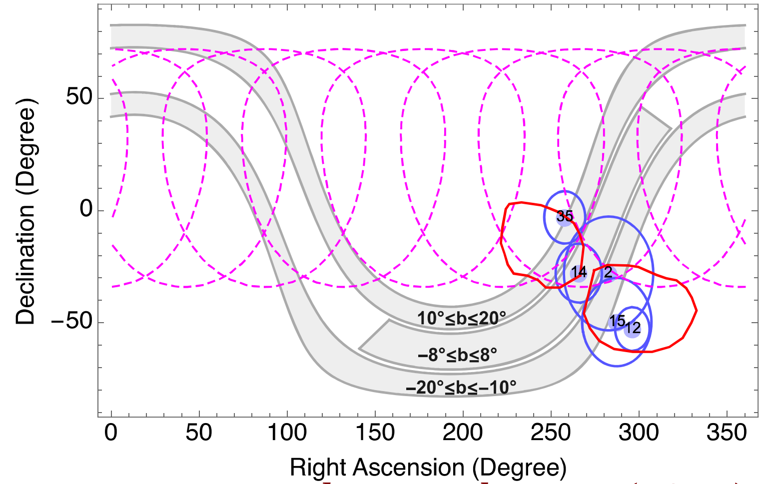


Abramowski, et al, Nature (2016)

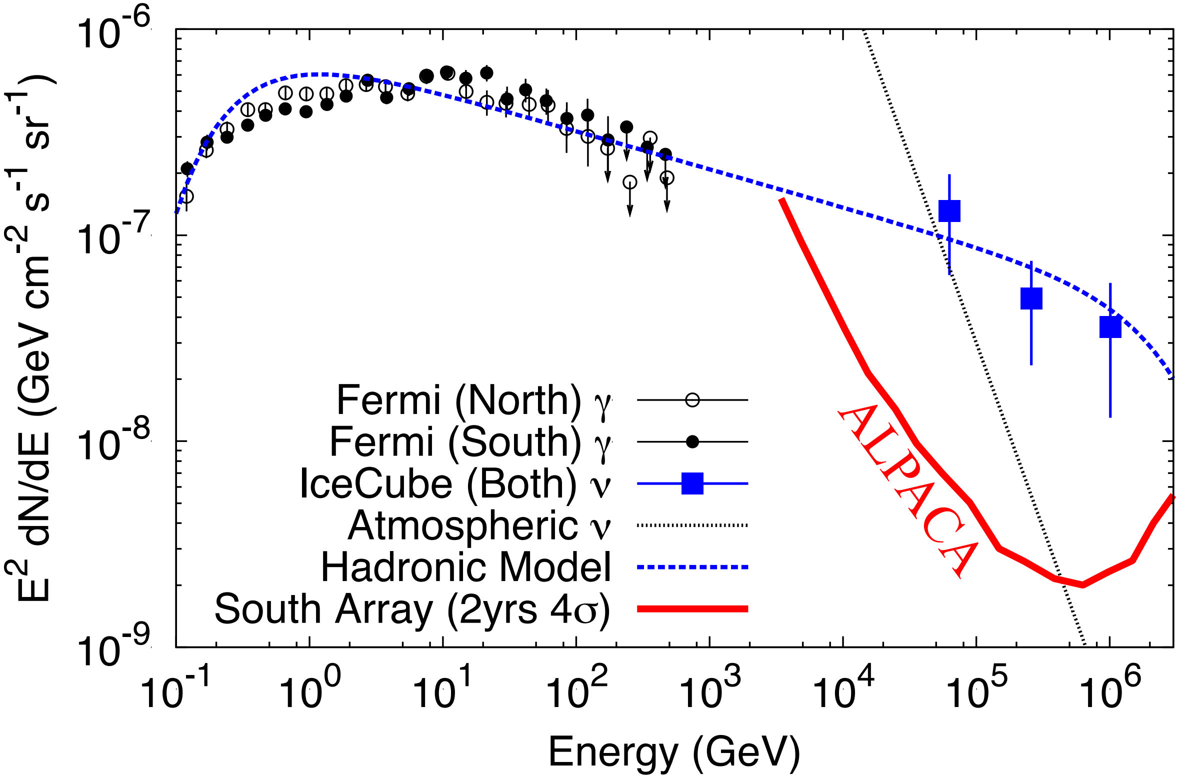
$\delta \sim -29°$

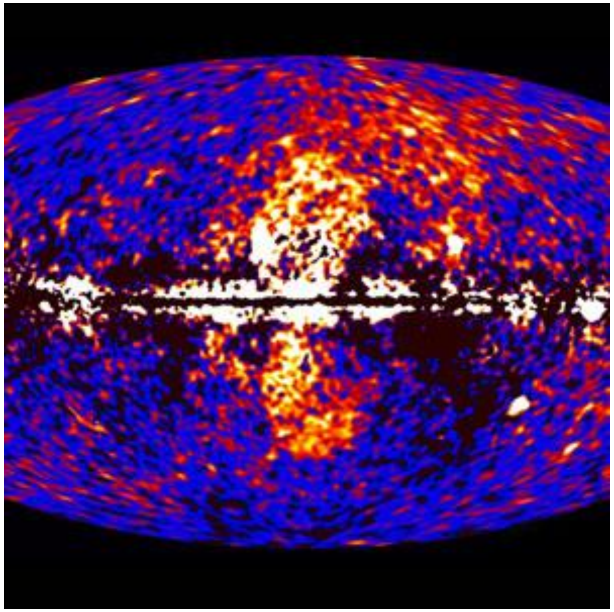
Fermi Bubbles

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



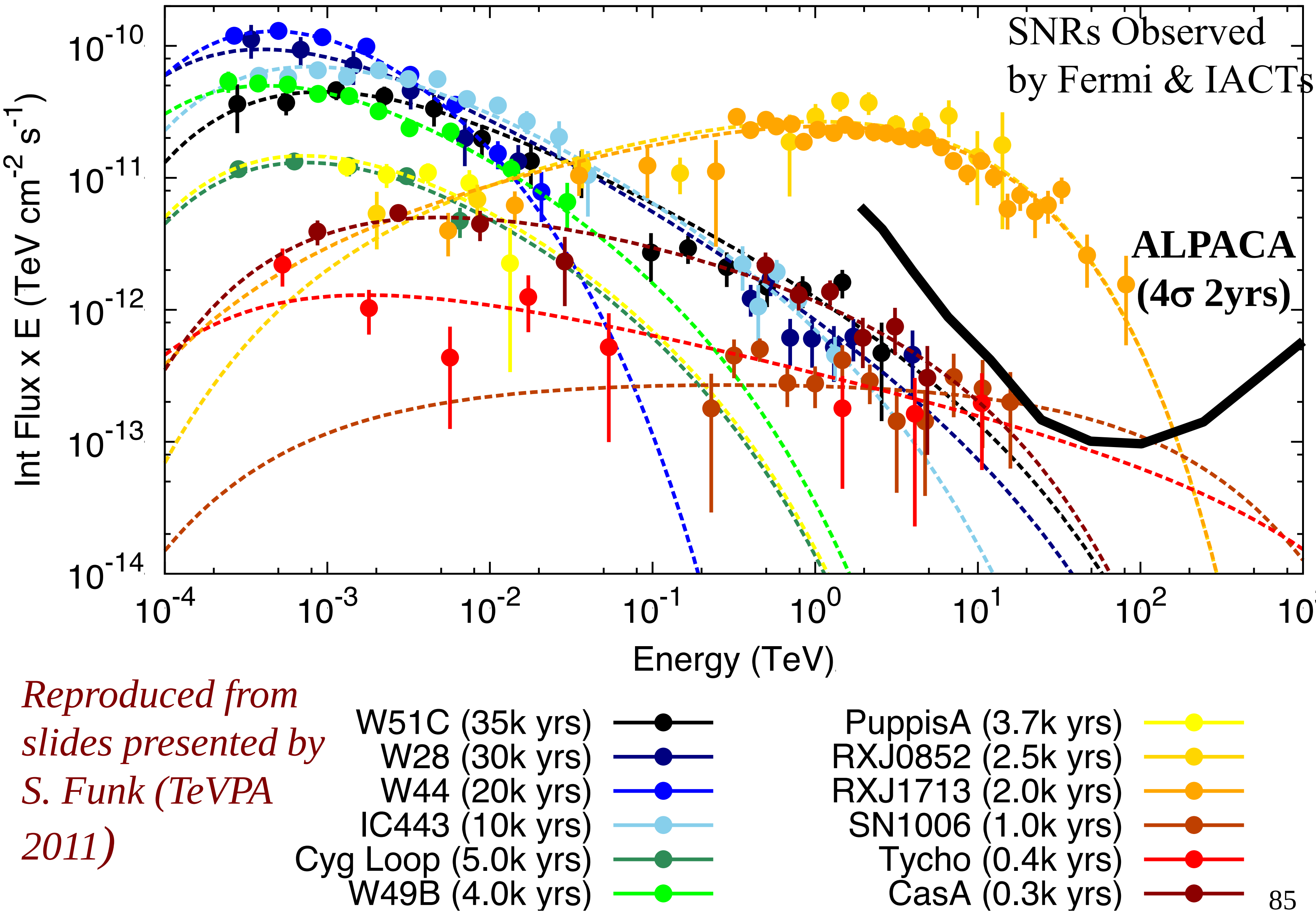
C. Lunardini, et al, PRD (2015)





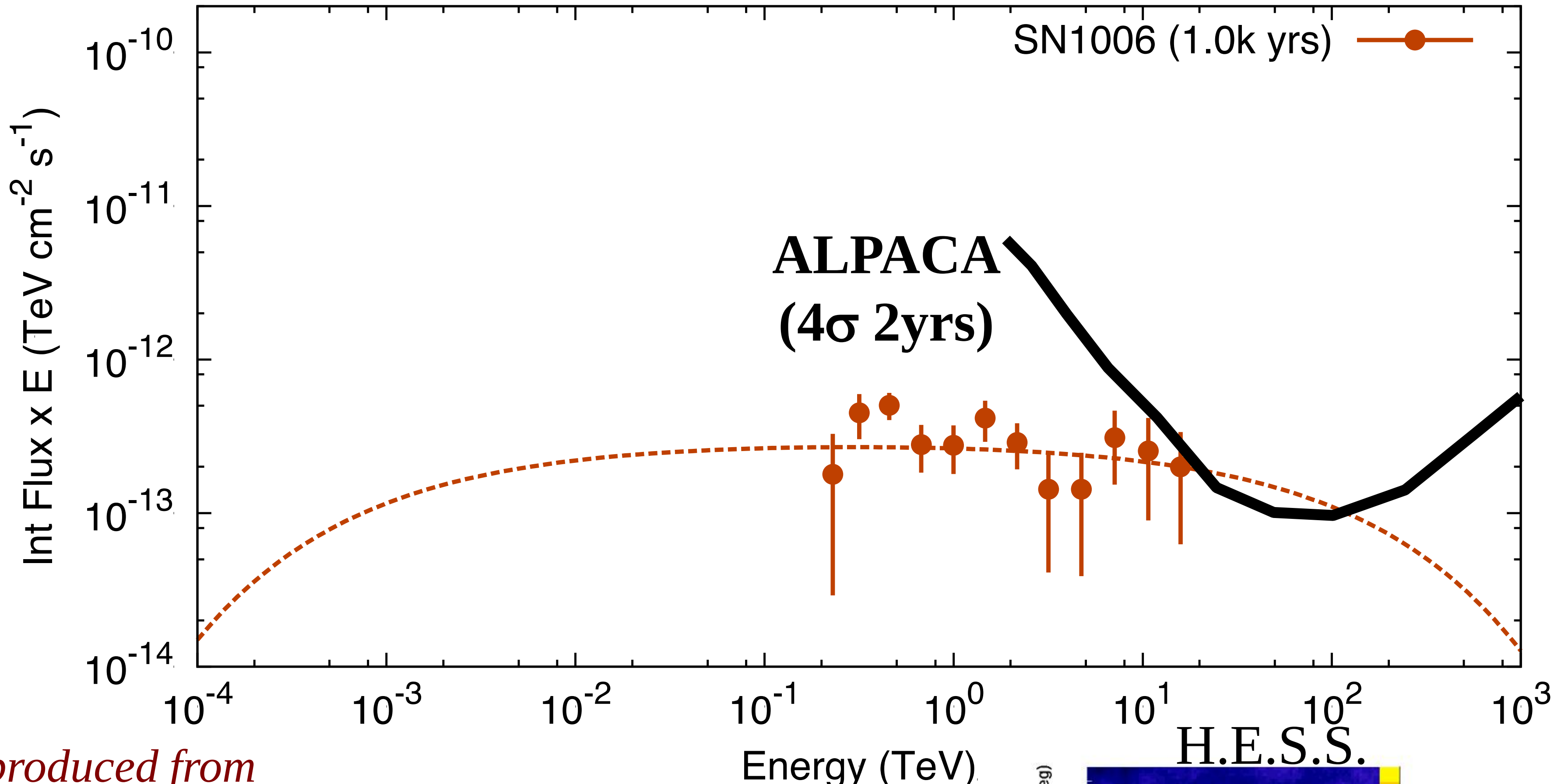
Bubbles observed by Fermi-LAT

Young SNRs



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

Young SNRs

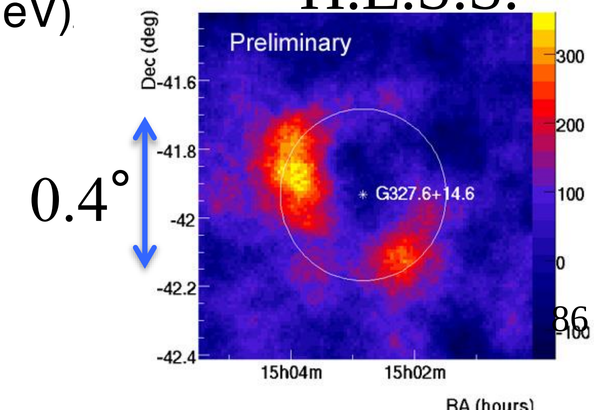


Reproduced from slides presented by S. Funk (TeVPA 2011)

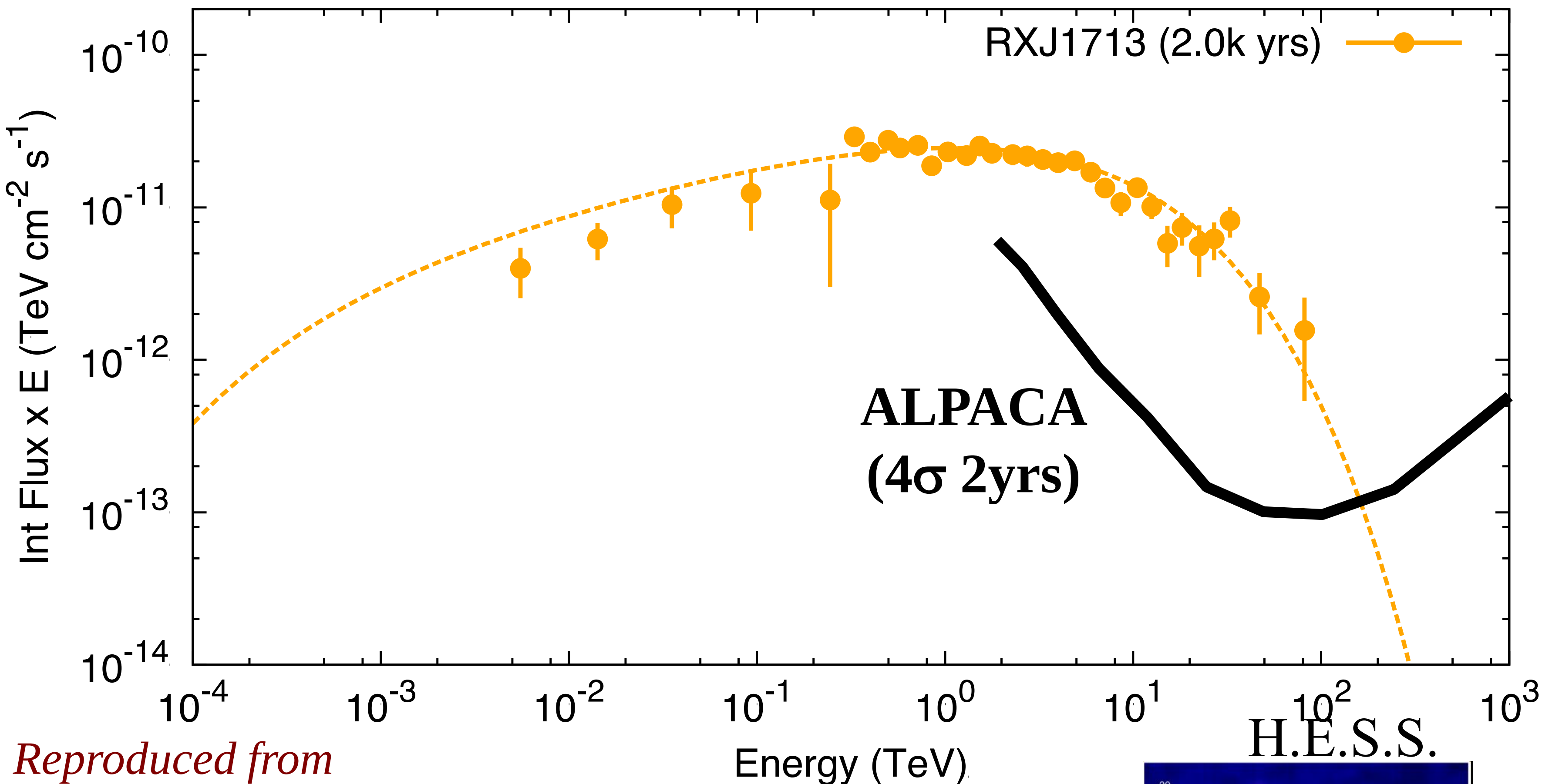
SNRs Observed by Fermi & IACTs

$\delta \sim -42^\circ$

H.E.S.S.



Young SNRs

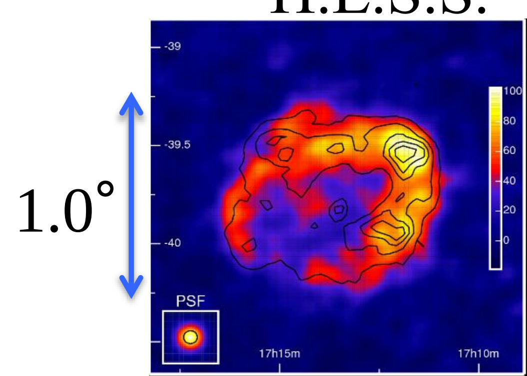


Reproduced from slides presented by S. Funk (TeVPA 2011)

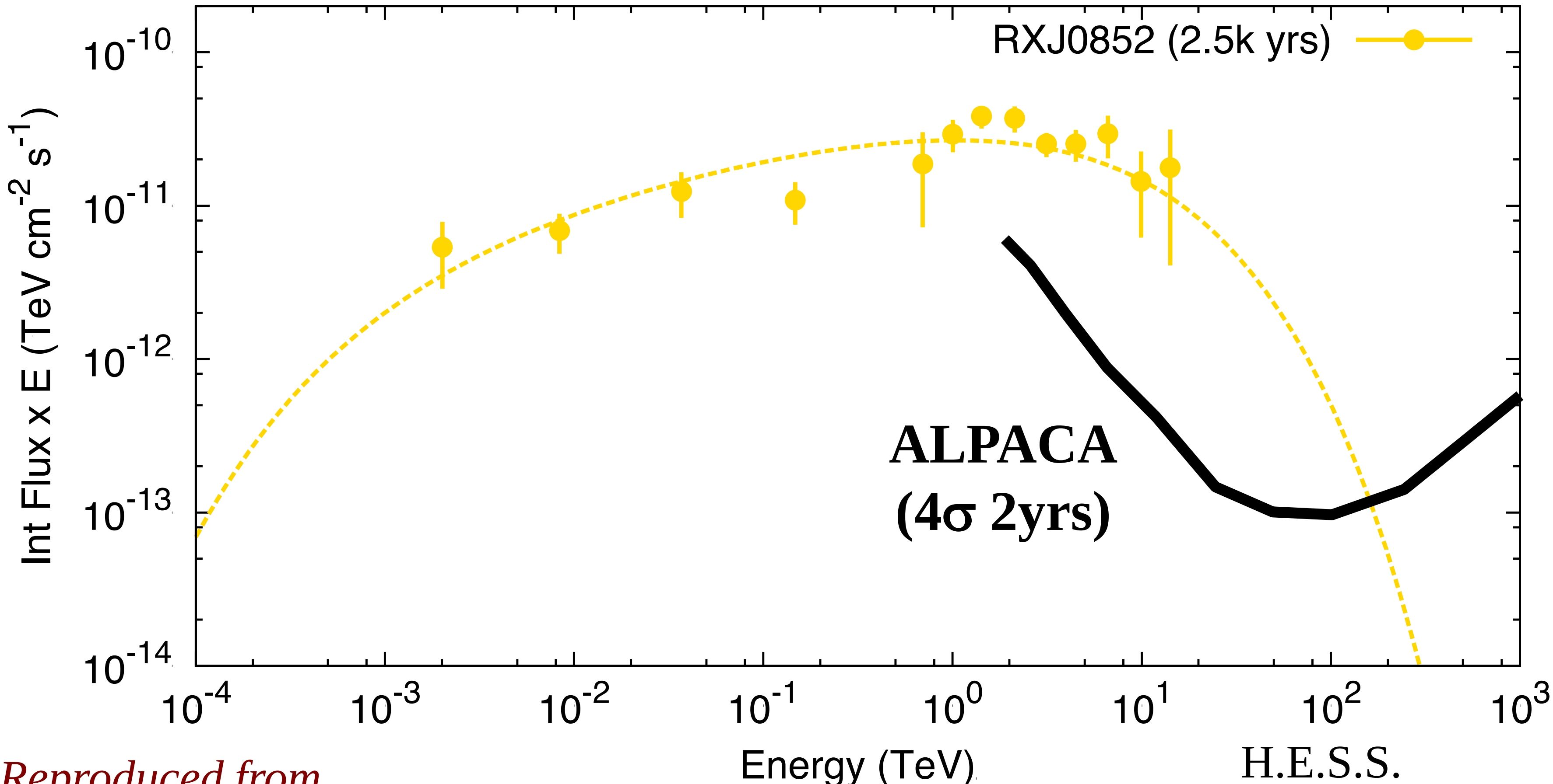
SNRs Observed by Fermi & IACTs

$\delta \sim -40^\circ$

H.E.S.S.



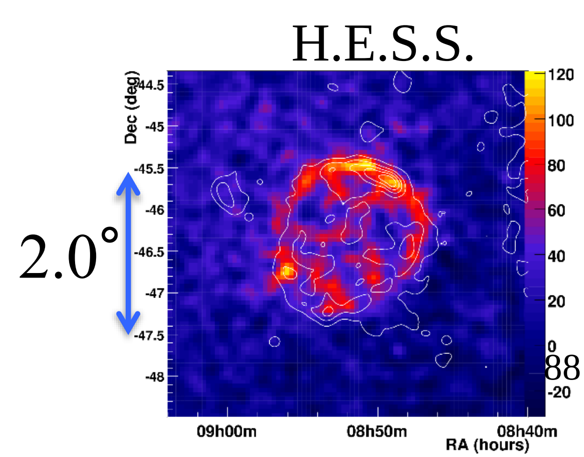
Young SNRs



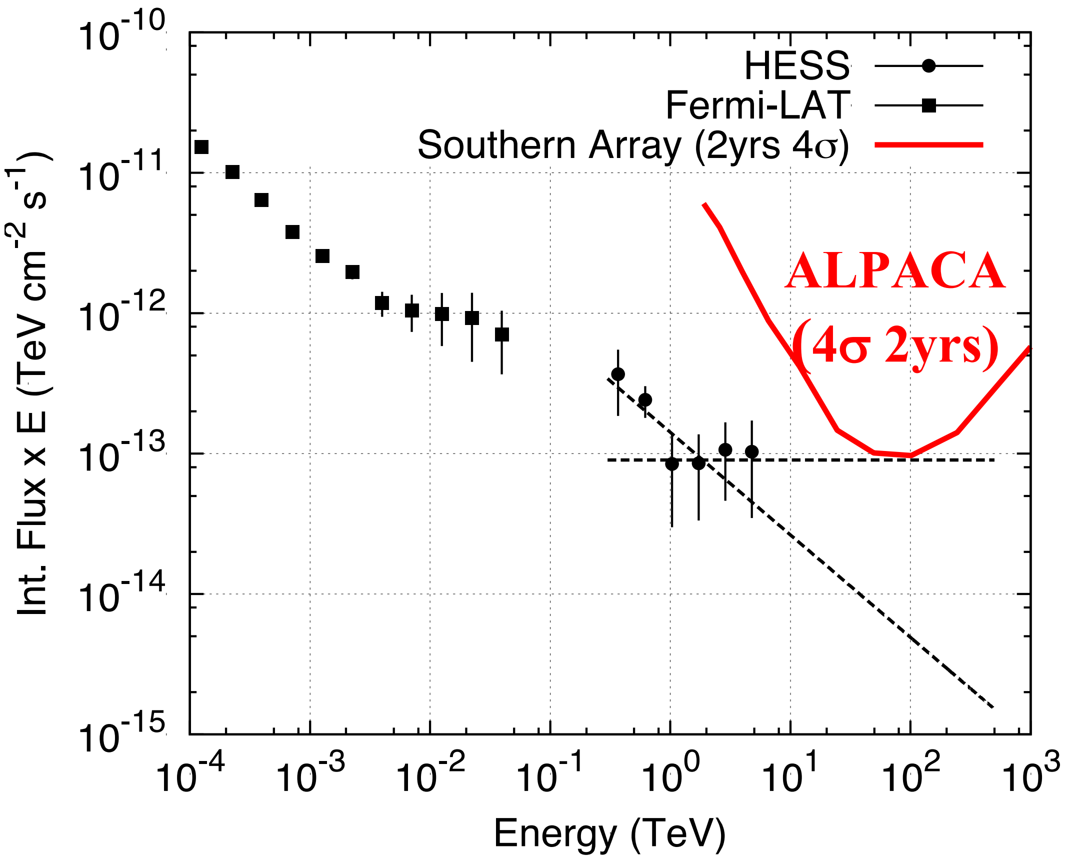
Reproduced from slides presented by S. Funk (TeVPA 2011)

SNRs Observed by Fermi & IACTs

$\delta \sim -46°$

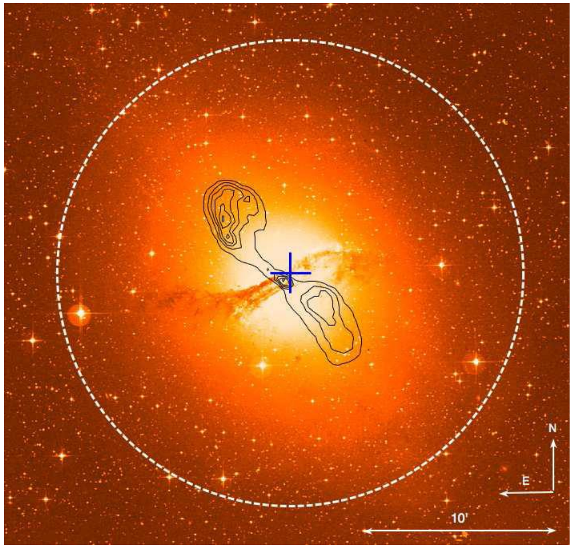


Nearby Extragalactic Source CenA



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

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



$\delta \sim -43^\circ$

ALPAQUITA実験：物理目標

- 南天における宇宙線異方性の観測
  - IceCube　Eth=~10TeV (-90^o<Dec.<-20^o)
  - ALPAQUITA Eth= ~5TeV (-70^o<Dec.<$+30^o$)

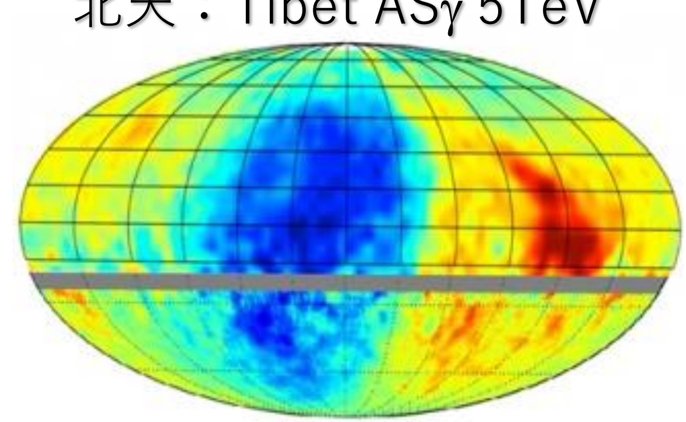
  → 銀河中心も含む赤緯での異方性解析

- 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 ~15-20σ / 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 ASγ 5TeV



南天：IceCube 20TeV

ALPAQUITA AS Array Performance for Gamma Rays

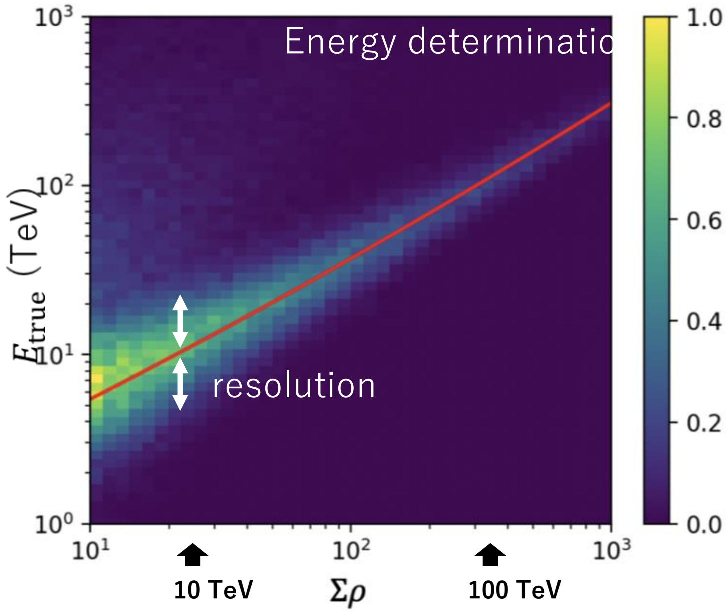
Target events: Gamma rays w/ $\Gamma = -2.5$ & $\theta_{\mathrm{true}} < 40°$

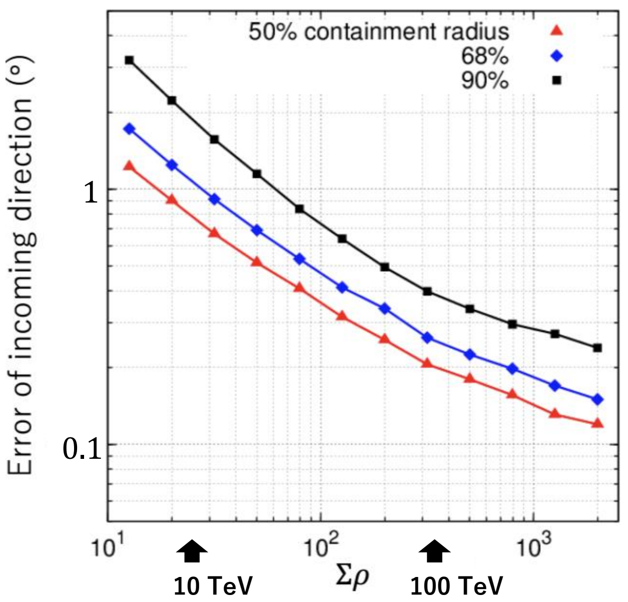
Trigger efficiency* 100% ≥20 TeV

Energy resolution $+27\%\ -21\%$ @ 100 TeV

Angular resolution $\simeq 0.2°$ @ 100 TeV (50% containment)

*Efficiency for events w/ true core positions inside the AS array



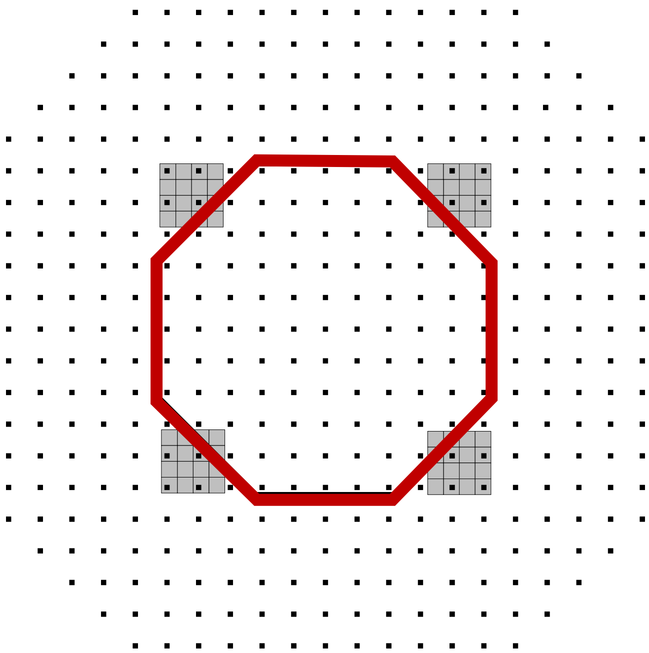


$\Sigma\rho$: Total density of particles recorded the AS array

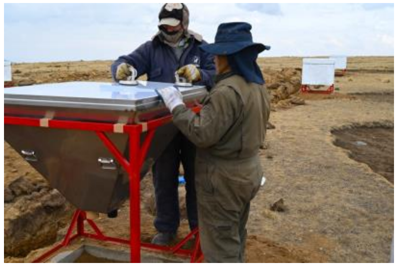
ALPAQUITA
(little ALPACA)

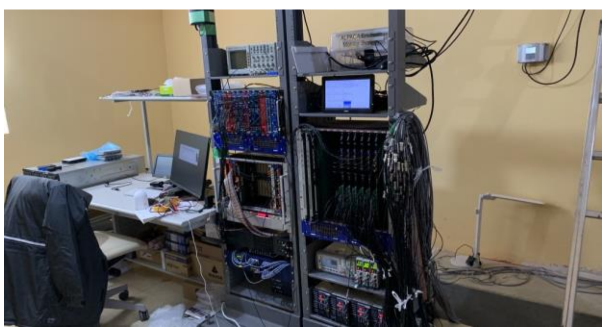
- Prototype array of 25% ALPACA area coverage
  - 97 surface detectors
  - 1 MD

- Targets
  - Infrastructure establishment
  - A few bright >100TeV sources
  - CR anisotropy



MD 設計済、まもなく工事開始

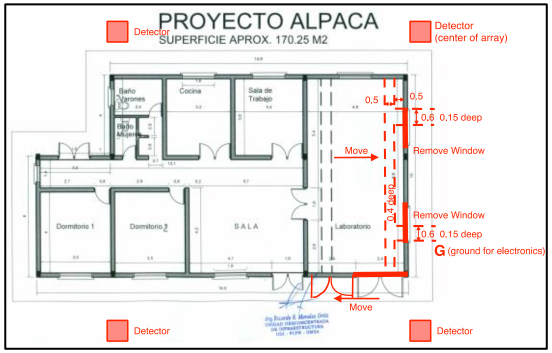




2022年5月末～（3年ぶり！）

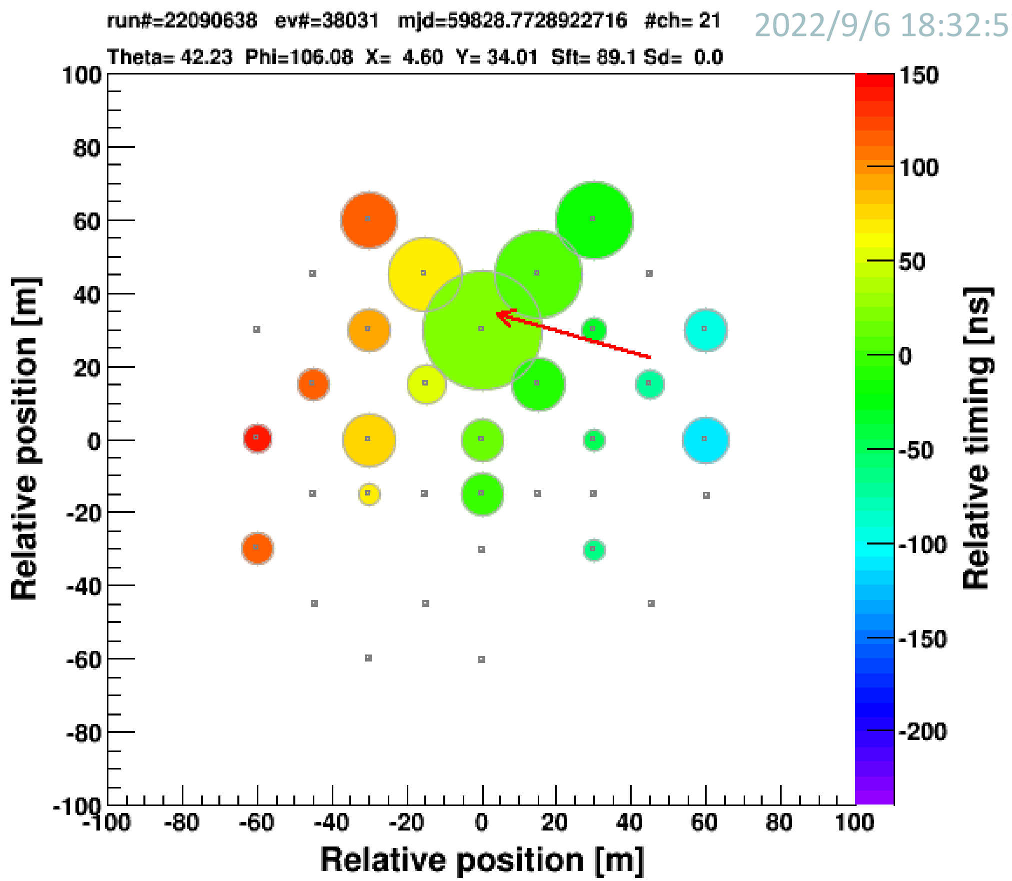
ALPAQUITA & infrastructure

- Central electronics hut
- Perimeters
- Powerline（branch from the substation-Chacaltaya observatory line）
- Cable drains
- Lightning rods
- Long distance Wifi
- Water system

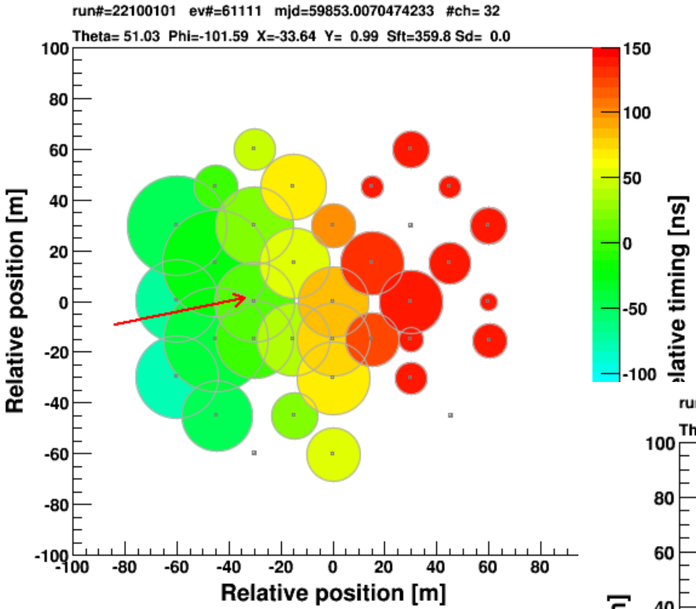


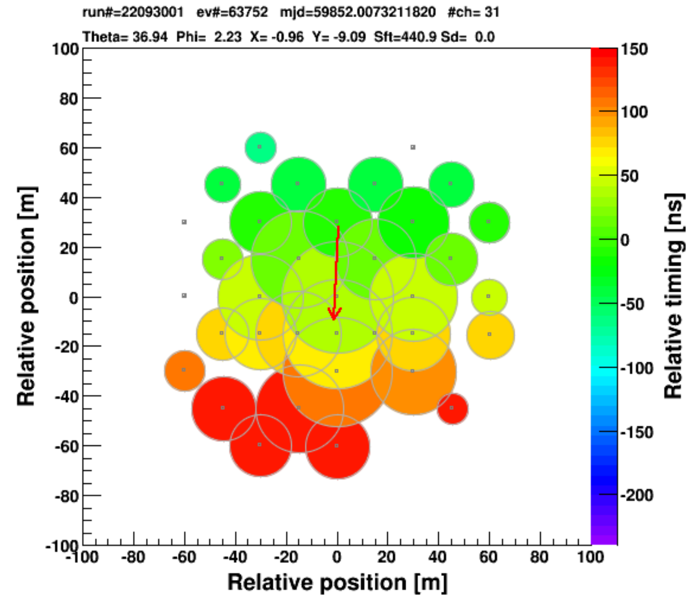
First Good Event

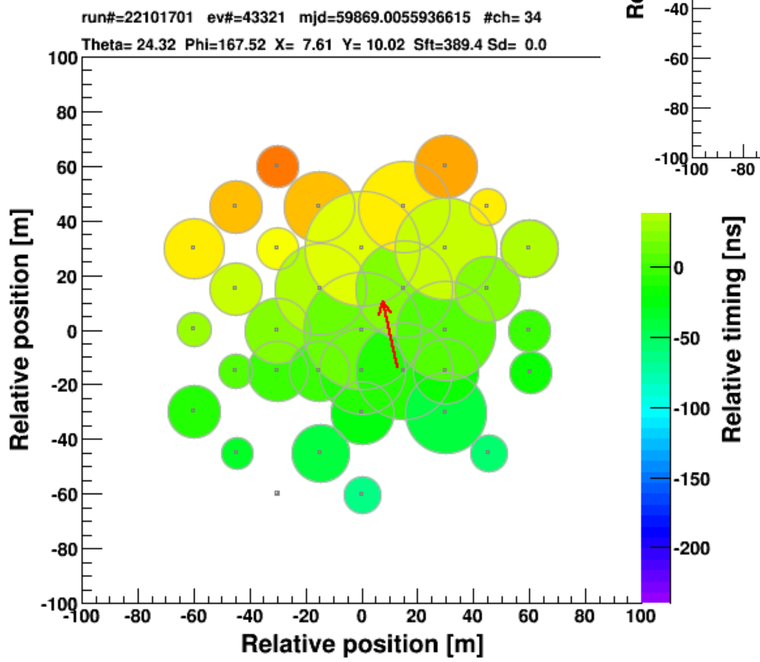
2022/9/6 18:32:57.892266 (UT)



Big Events!

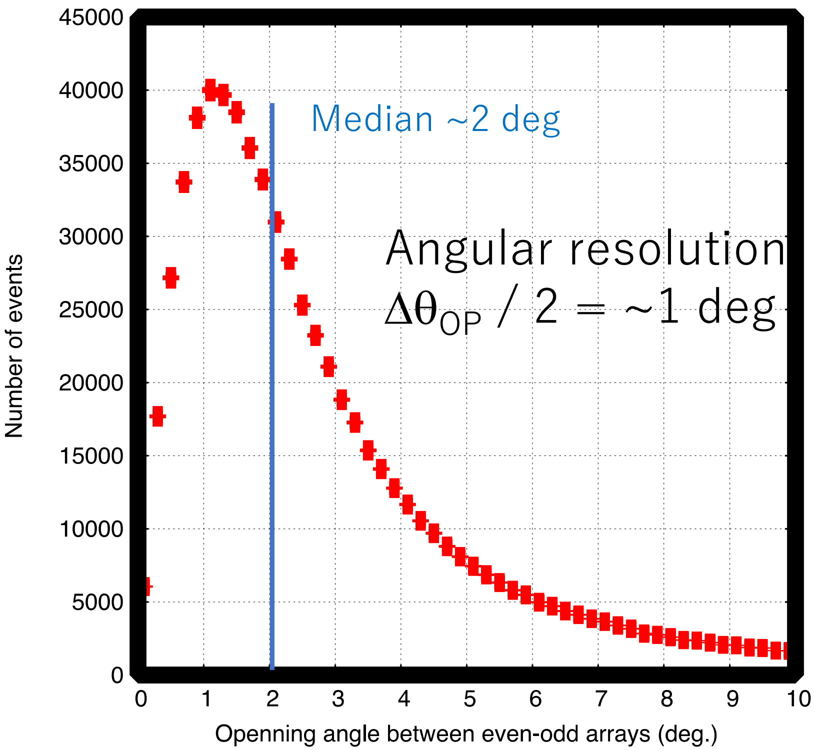

run#=22100101 ev#=61111 mjd=59853.0070474233 #ch= 32
Theta= 51.03 Phi=-101.59 X=-33.64 Y= 0.99 Sft=359.8 Sd= 0.0
Relative position [m]
Relative position [m]
Relative timing [ns]

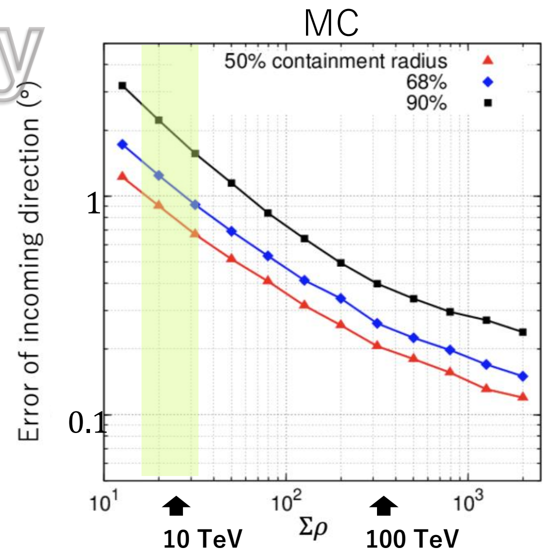

run#=22093001 ev#=63752 mjd=59852.0073211820 #ch= 31
Theta= 36.94 Phi= 2.23 X= -0.96 Y= -9.09 Sft=440.9 Sd= 0.0
Relative position [m]
Relative position [m]
Relative timing [ns]


run#=22101701 ev#=43321 mjd=59869.0055936615 #ch= 34
Theta= 24.32 Phi=167.52 X= 7.61 Y= 10.02 Sft=389.4 Sd= 0.0
Relative position [m]
Relative position [m]
Relative timing [ns]

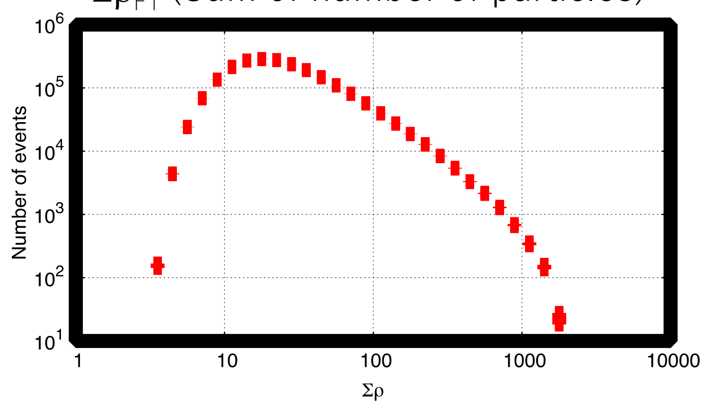
Even-Odd Array

Preliminary



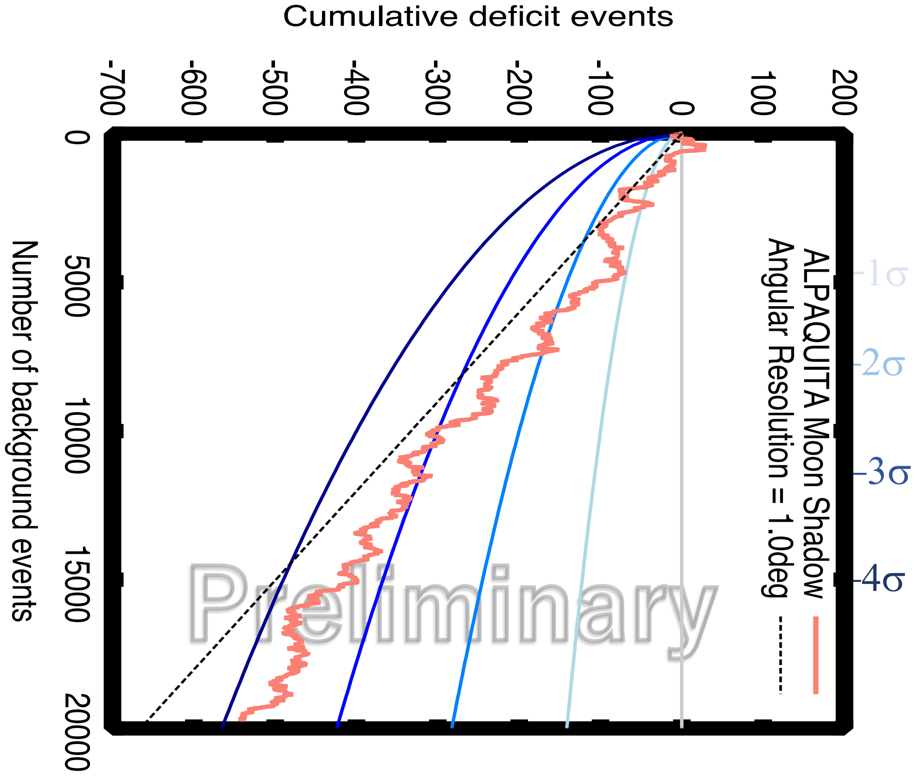


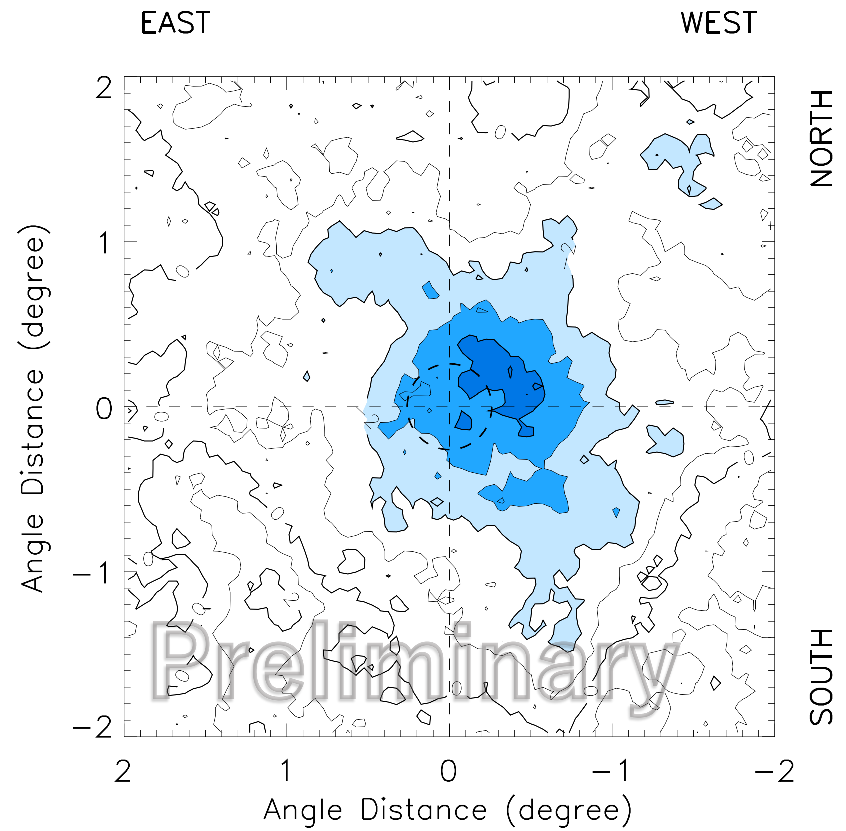
$\Sigma\rho_{FT}$ (Sum of number of particles)



Moon Shadow

before calibration of the PMT transit time





Observation time ~118 days

まとめ

- Tibet ASγ 実験: チベット高原 標高4,300m on-going
  65,700m² 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 ~ 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)+ 3,600m² 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 ×157台、0.4×ALPACA AS＋ 900 m² MD
  2022-23年 (2022年にASの一部が稼働開始)

- ALPACA: 83,000m² AS + 3,600m² MD 2024年

Thank you for your attention!

ALPAQUITA AS started partial operation in 2022

End