Tibet ASγ Experiment

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May 16, 2019

The Tibet ASγ Collaboration

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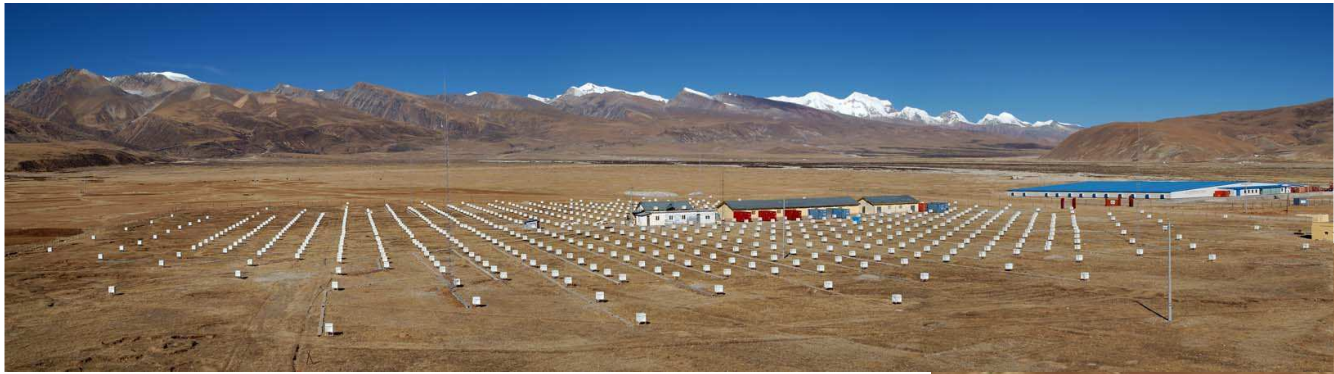
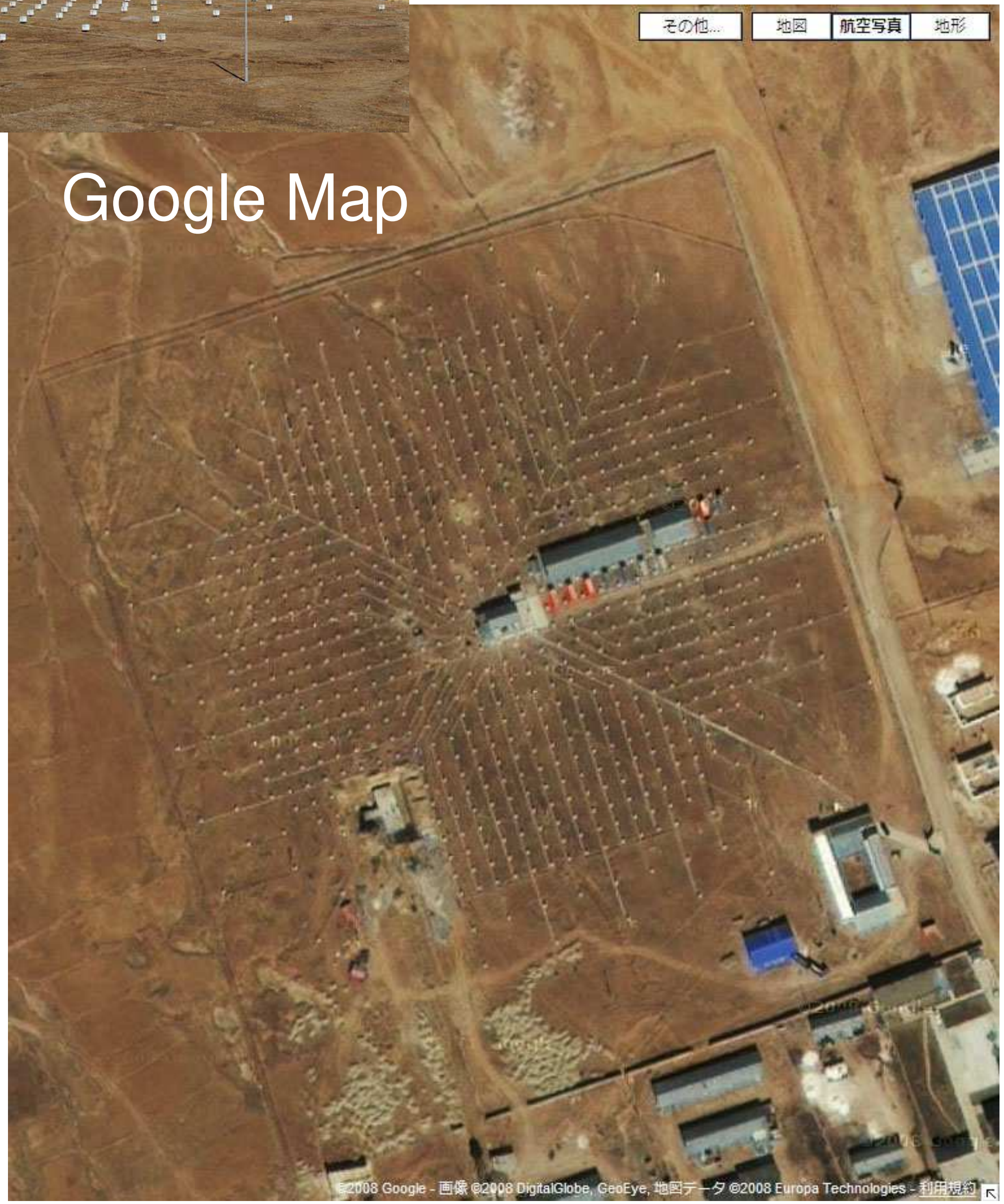
Yangbajing Cosmic Ray Observatory

90˚522**E**,   30˚102**N**, 4,300 m a.s.l. (606g/cm^2)



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



Tibet Air Shower Array

Tibet III (37000 m^2)

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

Research Purpose

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

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

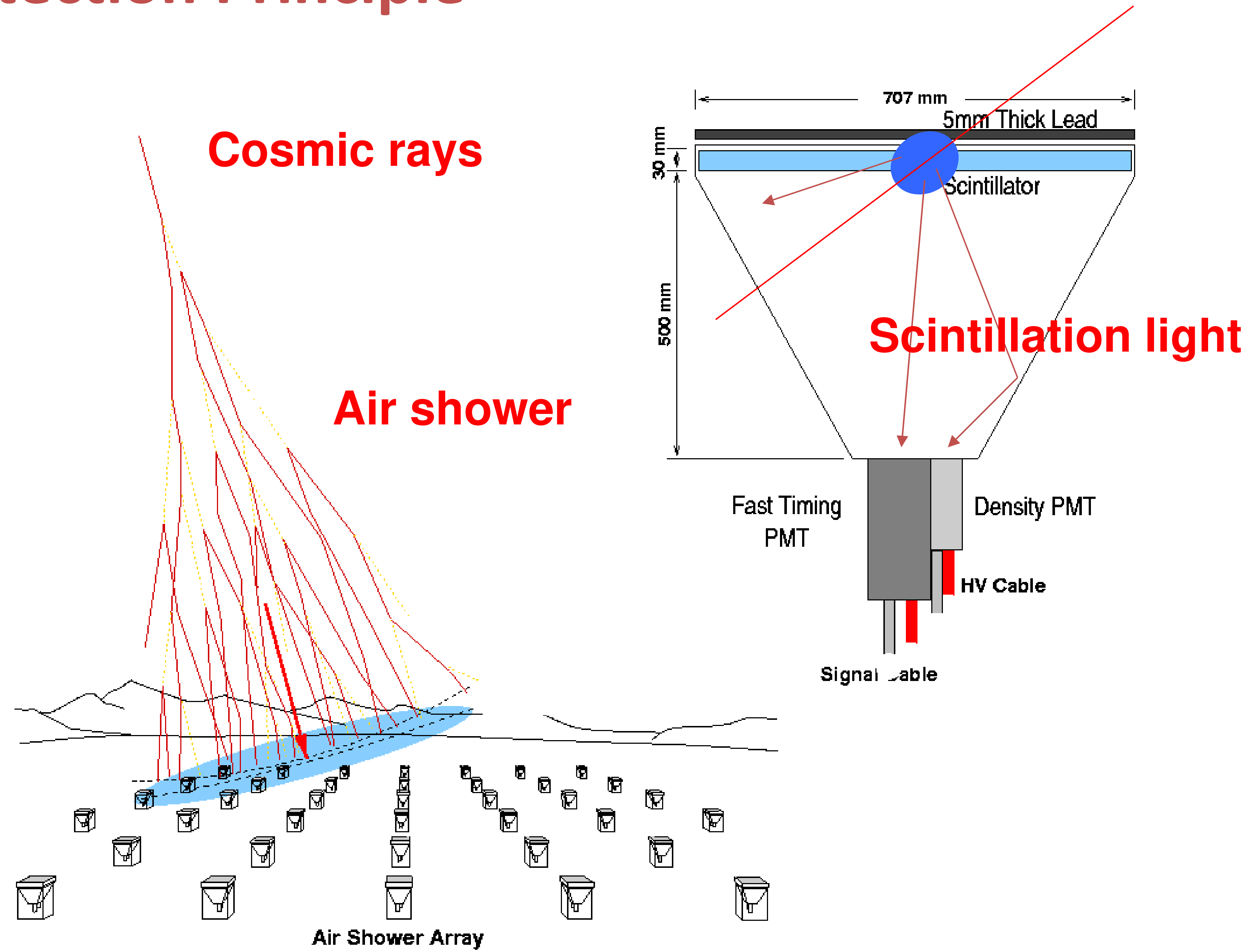
-> Origin, acceleration, propagation mechanism of cosmic rays

3. **The Sun shadow in cosmic rays**

（Shielding effect on cosmic rays by the Sun)

-> Global structure of solar and interplanetary magnetic fields

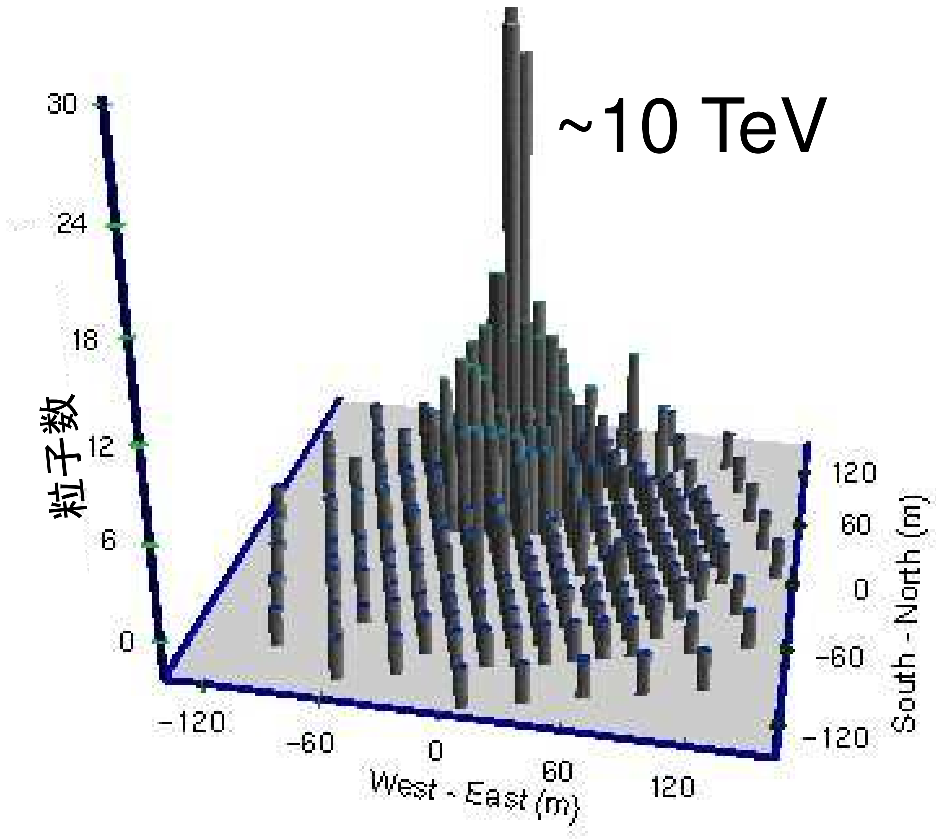
Detection Principle

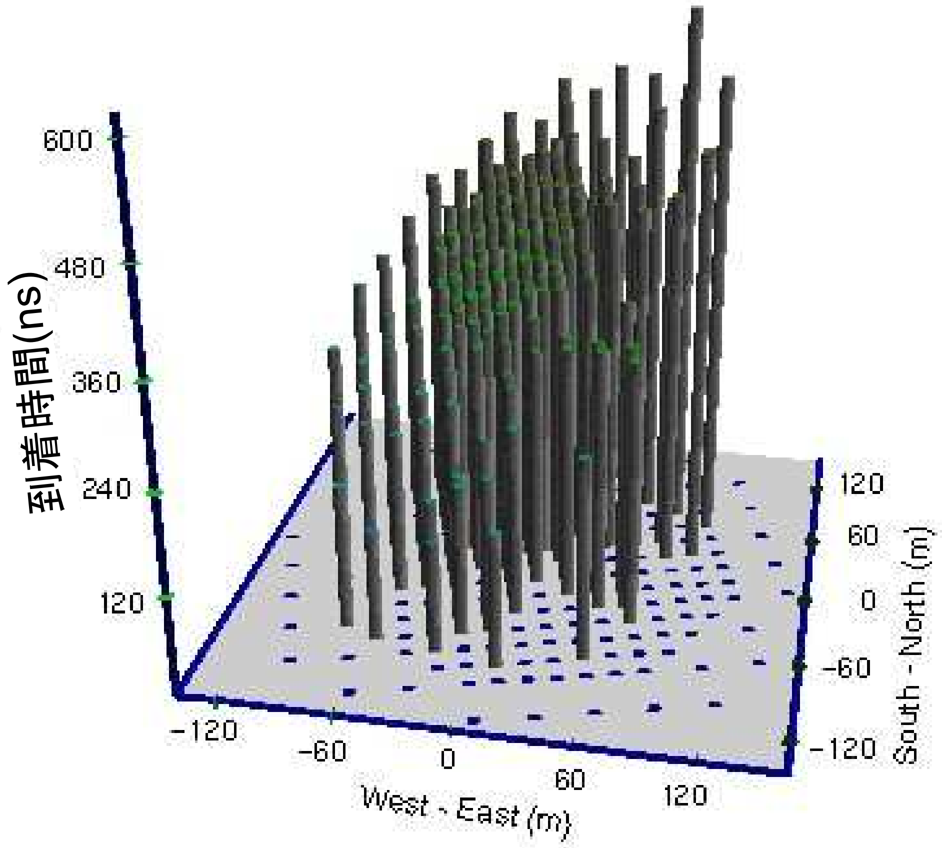


Air Shower Detection

2nd particle density → Cosmic ray energy

2nd particle timing → Cosmic ray direction



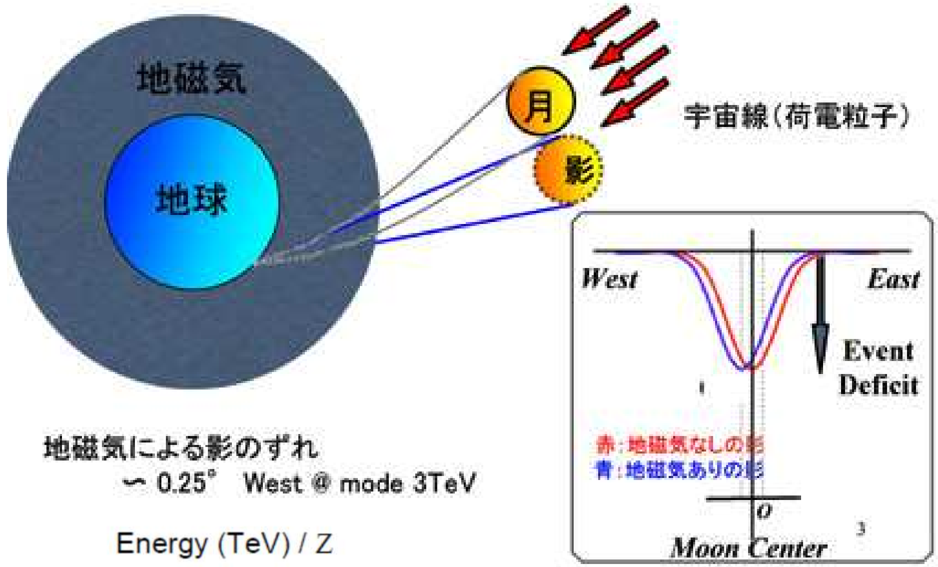


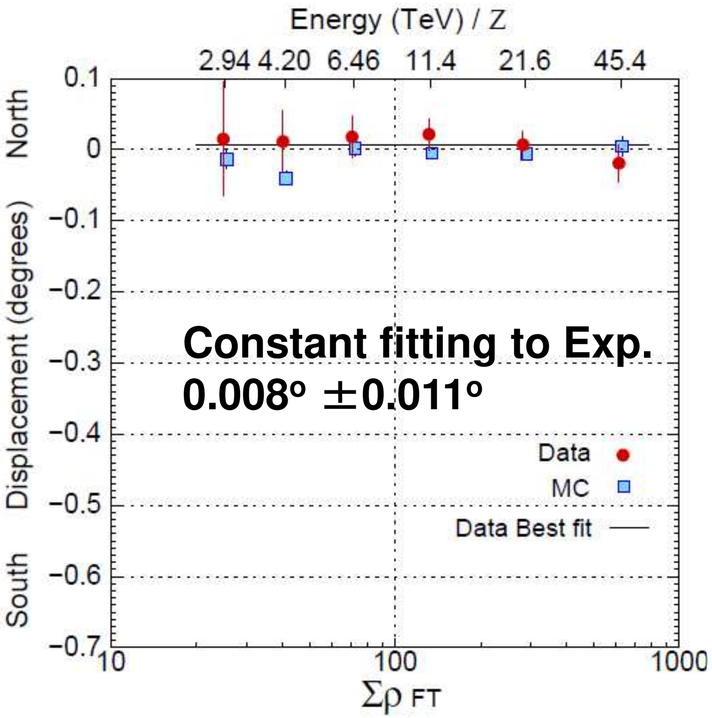
Air shower rate triggered by Tibet III ~1700Hz

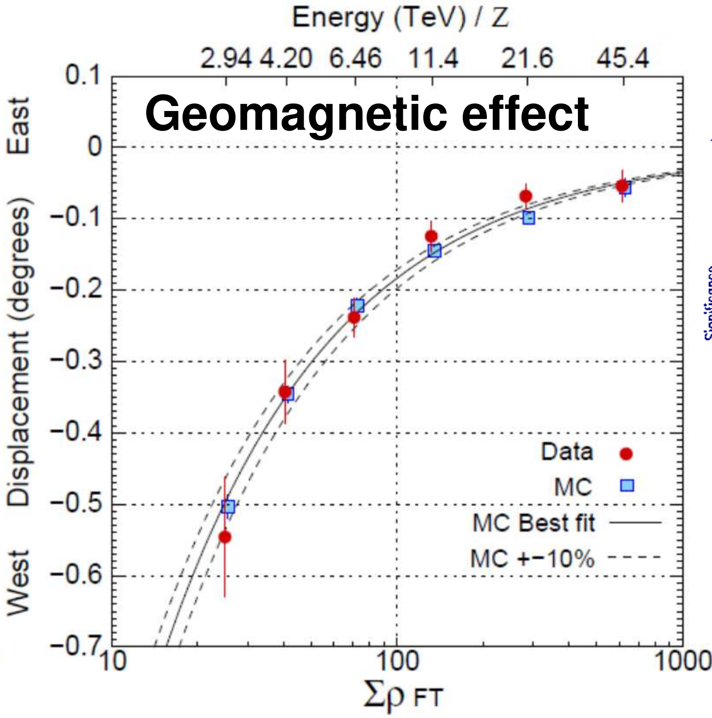
Performance by Moon’s Shadow

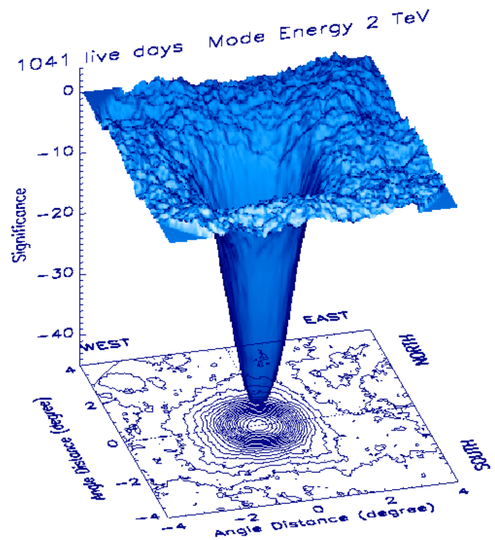
The Astrophysical Journal, 692, 61-72(2009)

- Absolute Energy Scale
- Angular Resolution
- Pointing Accuracy





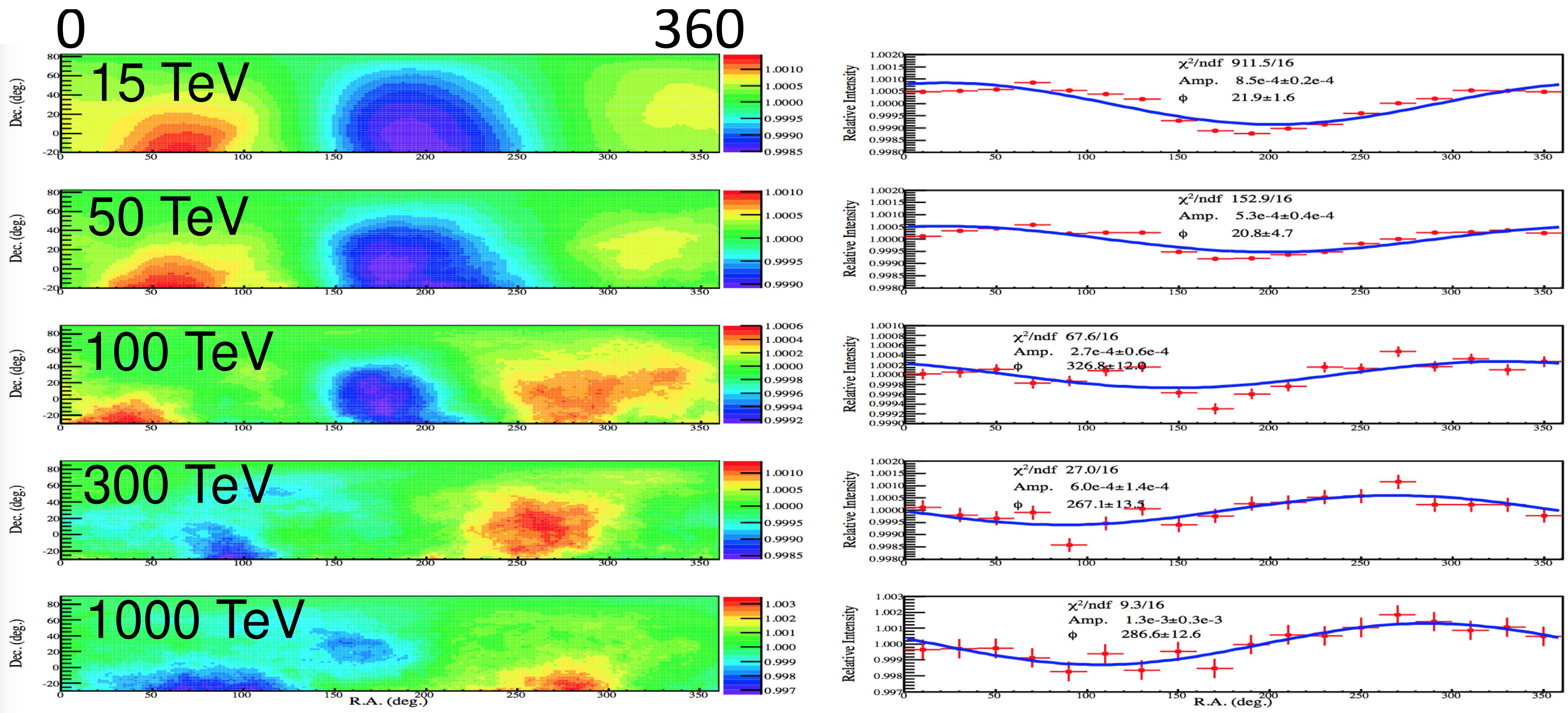




Pointing Error < 0.011°

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

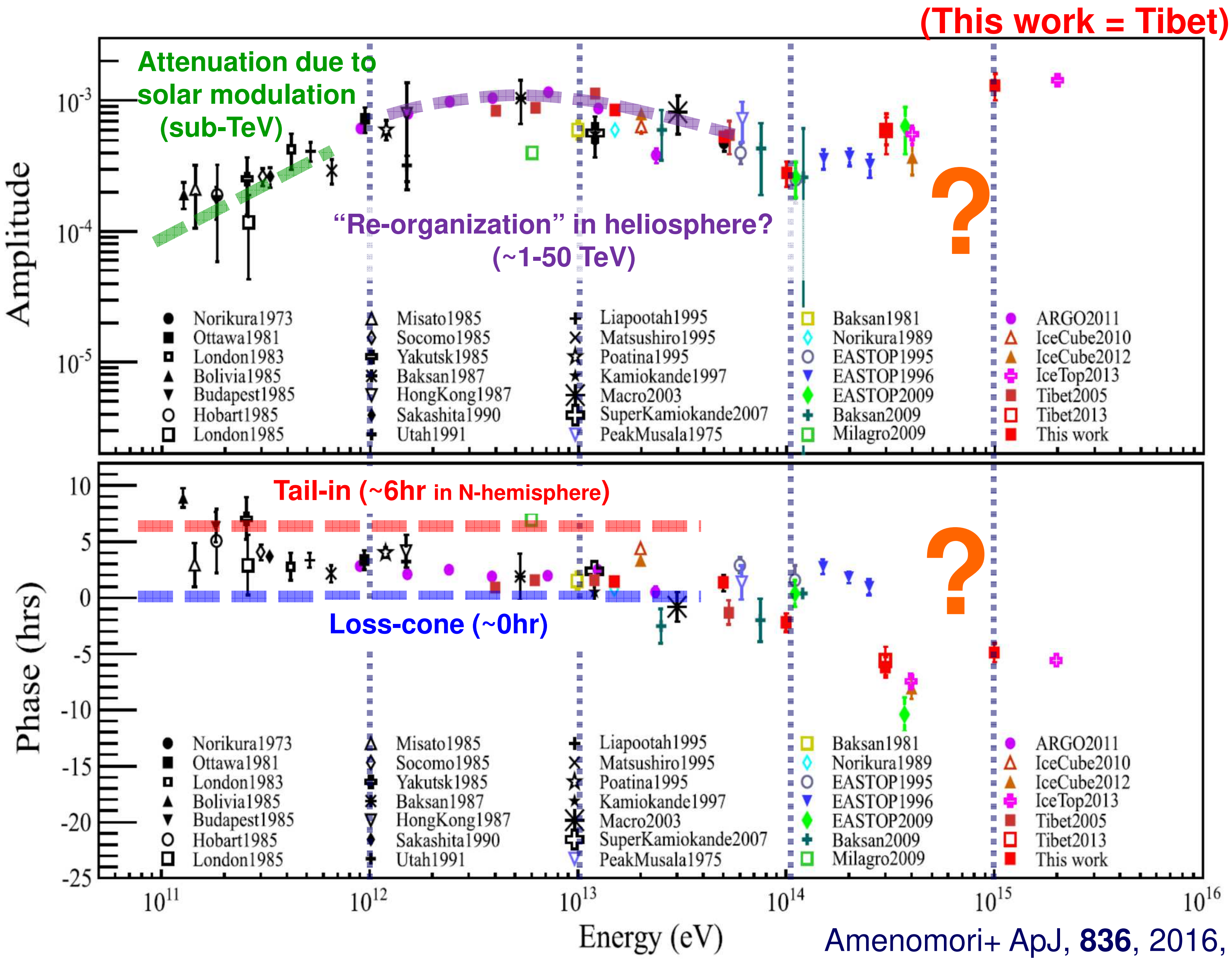
10-1000TeV CR Sidereal Anisotropy (Tibet)



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

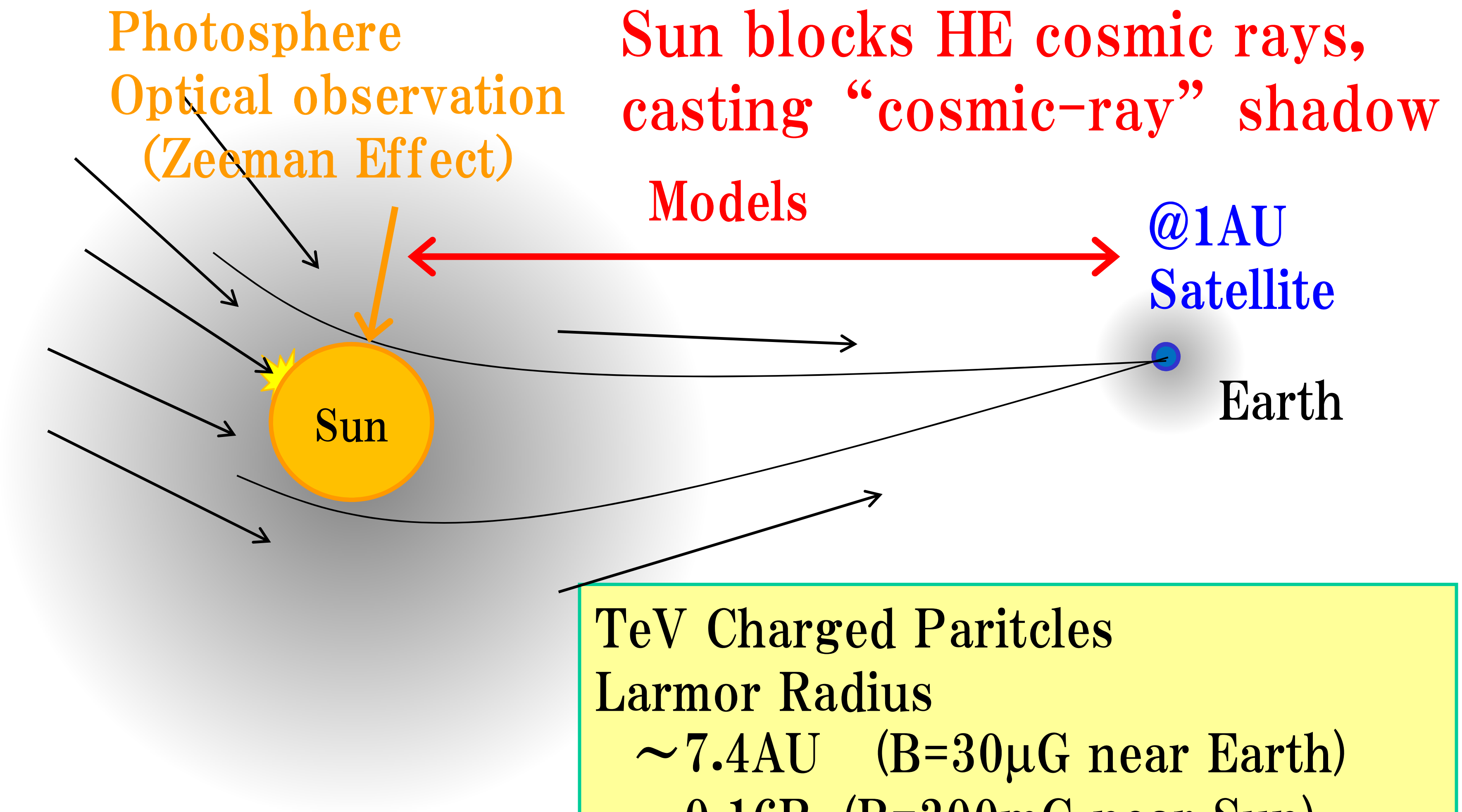
>300 TeV new component!, consistent with IceCube >400 TeV

Sidereal diurnal anisotropy of CRs

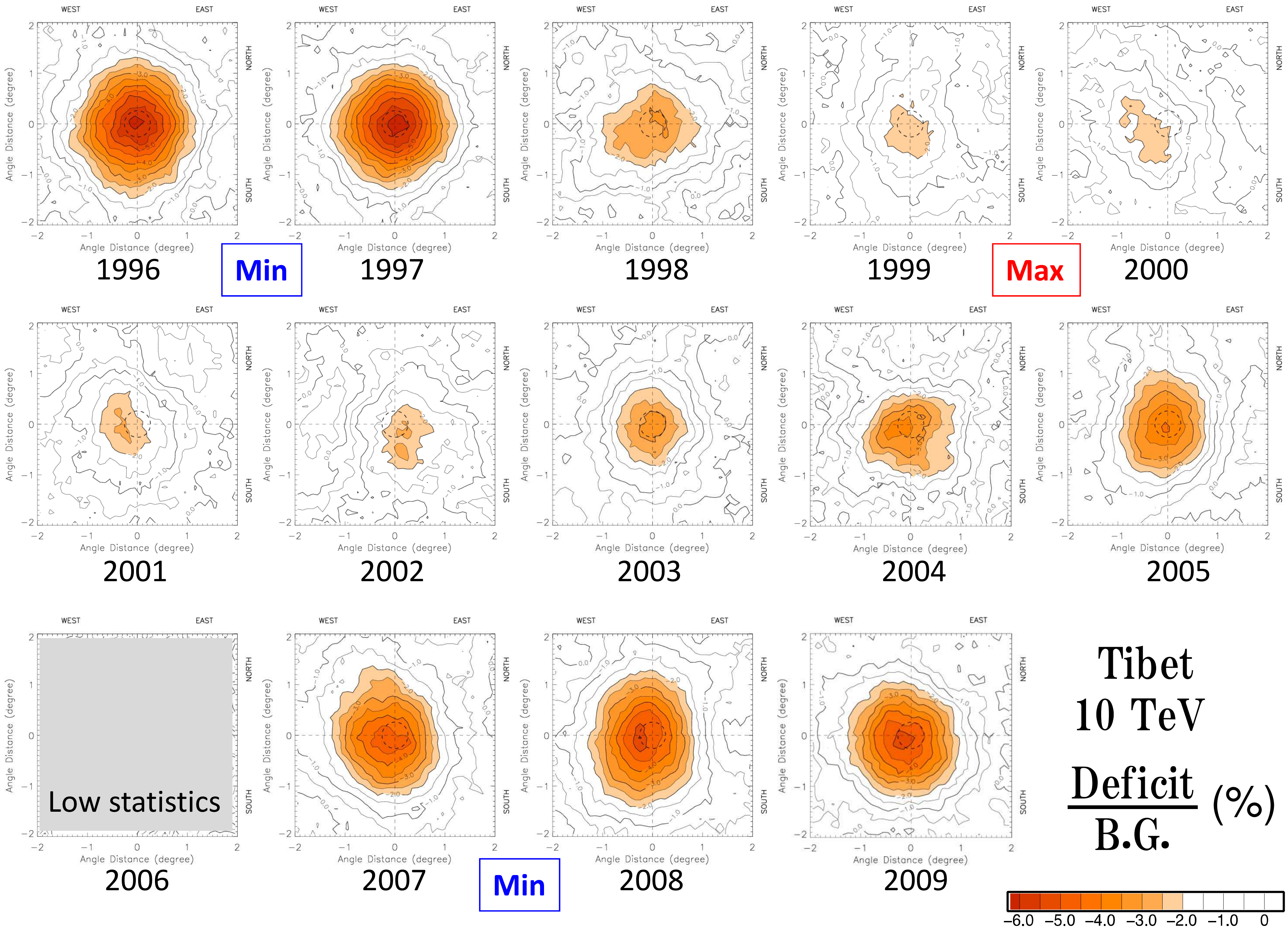


Amenomori+ ApJ, **836**, 2016, 153

Sun's Shadow



TeV Charged Paritcles
Larmor Radius
$\sim$7.4AU (B=30μG near Earth)
$\sim 0.16R_\odot$(B=300mG near Sun)
-> Probe of large-scale MFs!
-> Useful for space weather forcast



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

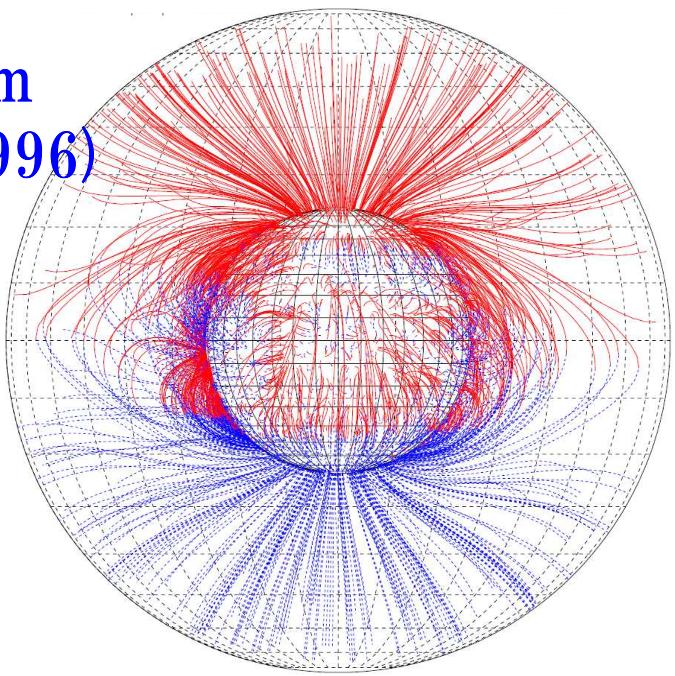
Magnetic fields

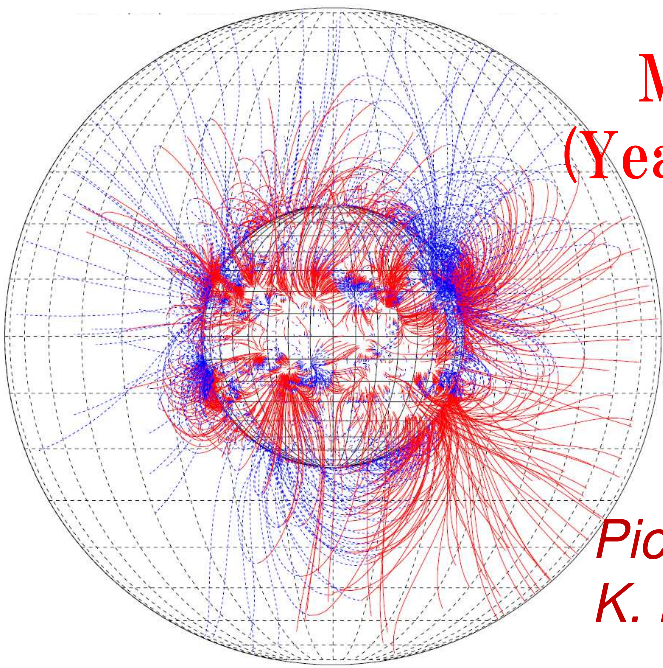
Coronal -> Source Surface models (PFSS / CSSS)
derived from photospheric MF observation
for each Sun rotation (~27 days)

IMF -> Parker Spiral Model
including latitudinal dependence of solar wind

Geomag. -> Dipole model

Minimum
(year 1996)
PFSS





Maxmum
(Year 2000)
PFSS

Pictures from K. Hakamada

Source Surface Models

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

assumes electric currents are negligible in the corona

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

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

Laplace Equation

$$\nabla^2 \Psi = 0$$

Hakamada, Solar Physics (1995)

2. CSSS (Current Sheet Source Surface)

includes large-scale horizontal currents

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

Magnetostatic force balance equation

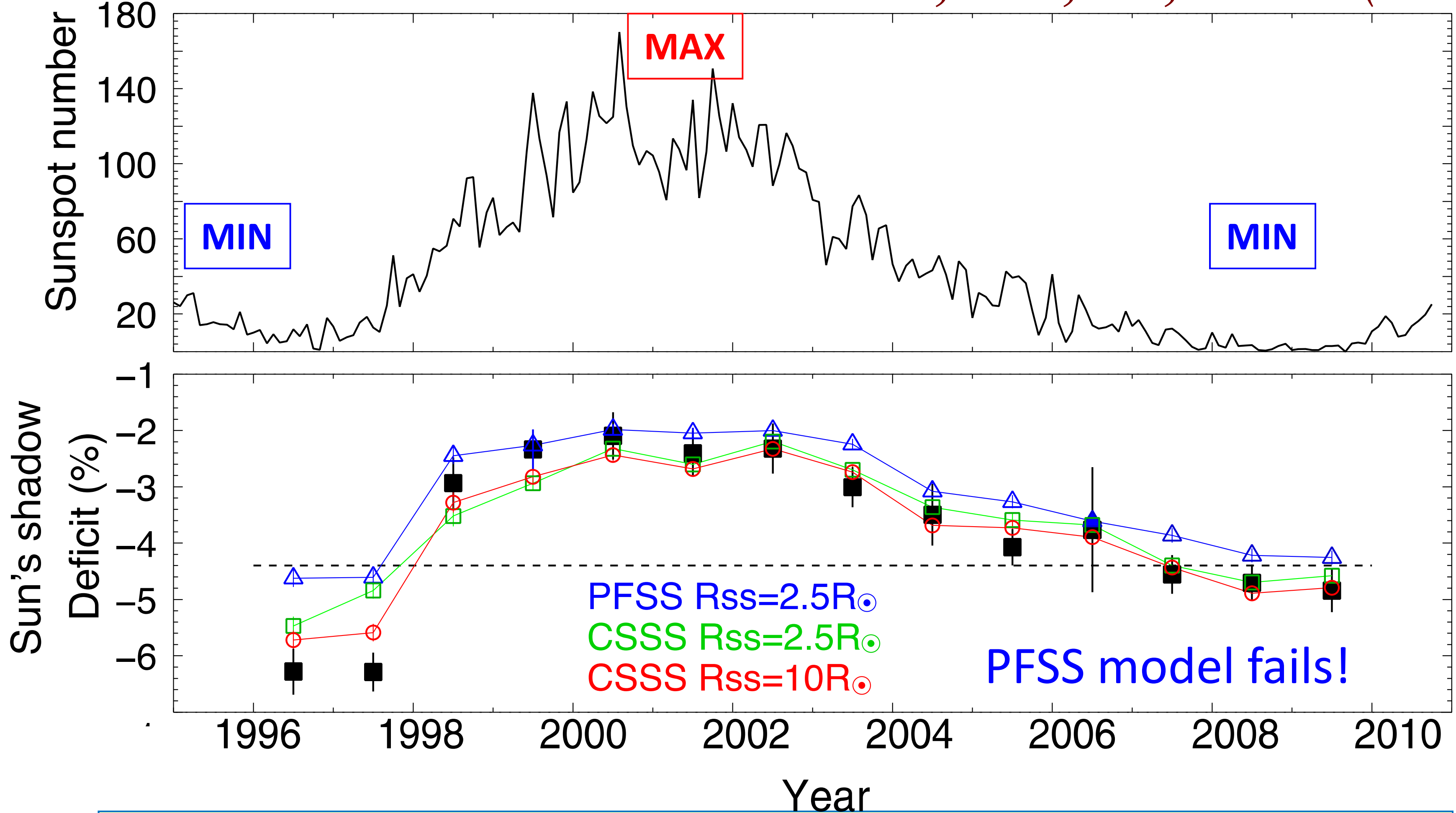
$$\mathbf{J} = \frac{1}{\mu_0 r}[1-\eta(r)]\left[\frac{1}{\sin\theta}\frac{\partial^2 \Psi}{\partial\phi\partial r}\hat{\theta} - \frac{\partial^2\Psi}{\partial\phi\partial r}\hat{\phi}\right]$$

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

Zhao & Hoeksema, JGR (1995)

Depth change (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)

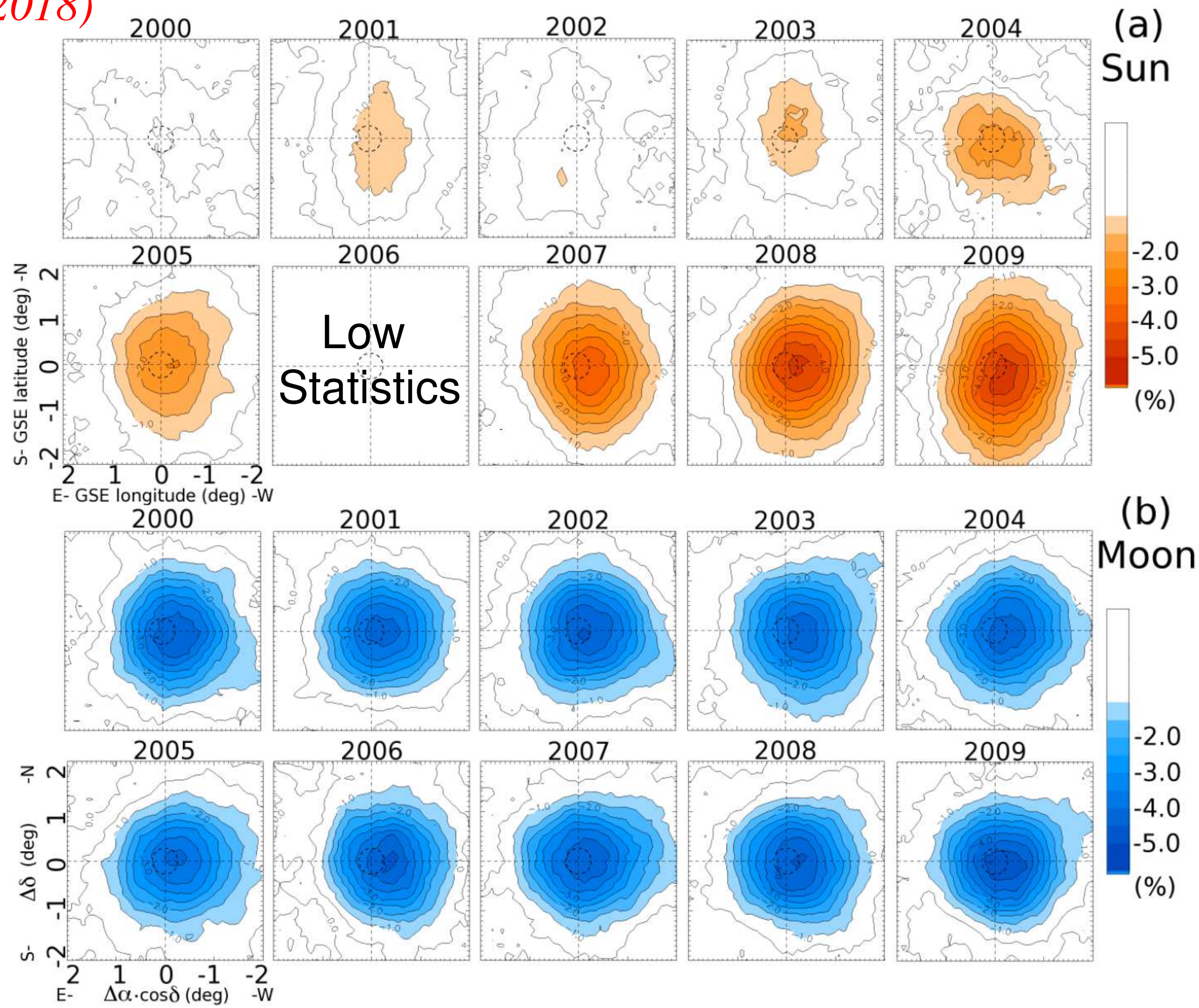
→ A clear solar-cycle variation of the deficits
CRs are scattered by solar magnetic field.

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

Sun

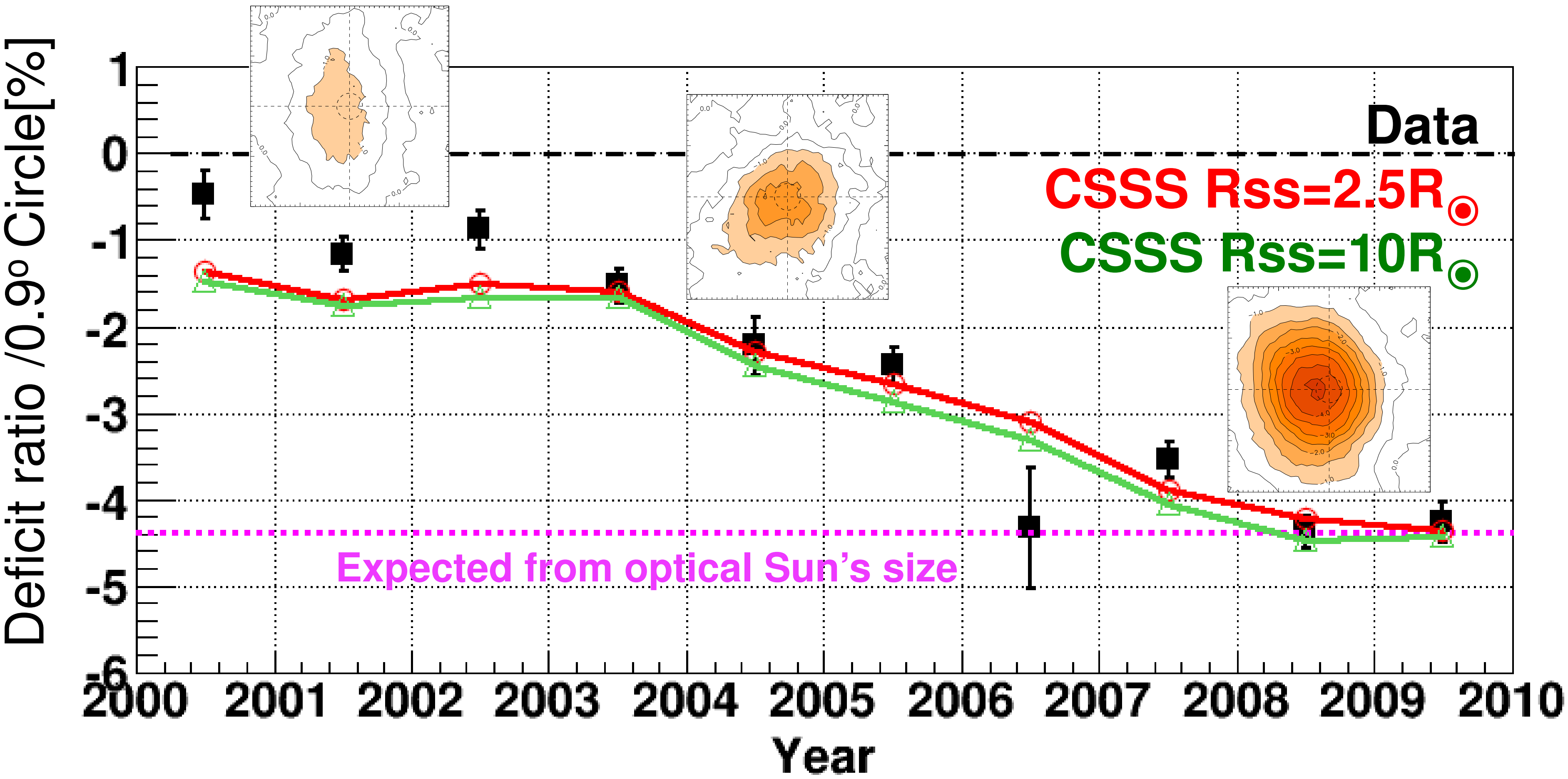
2000–2009
Tibet-III
(>3TeV)

Moon



→ Shift westward by geomagnetic field
Detector stability calibration

Deficit – Obs/MC **All Data** - 3 TeV



χ^2 **test :**

χ^2 / dof = 32.1 / 10 (3.4σ)

χ^2 / dof = 46.9 / 10 (4.8σ)

*only stat. error

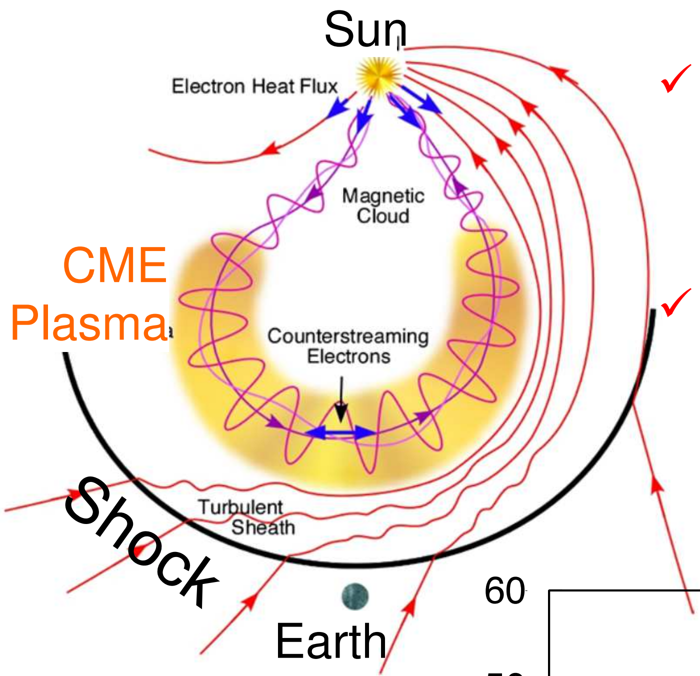
CSSS does not reproduce well at the solar maximum

Influence of CMEs?

http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm

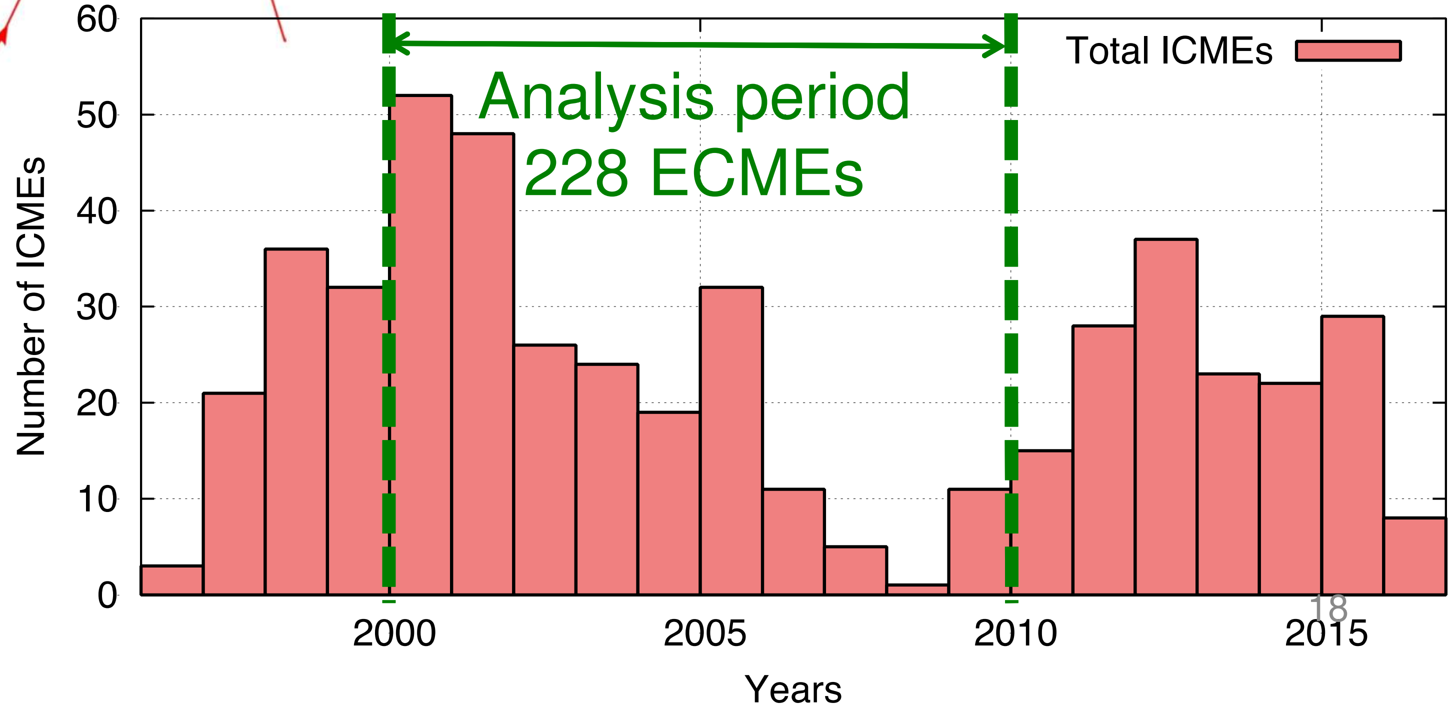
CME Catalog

Richardson & Cane, Solar Phys (2010)

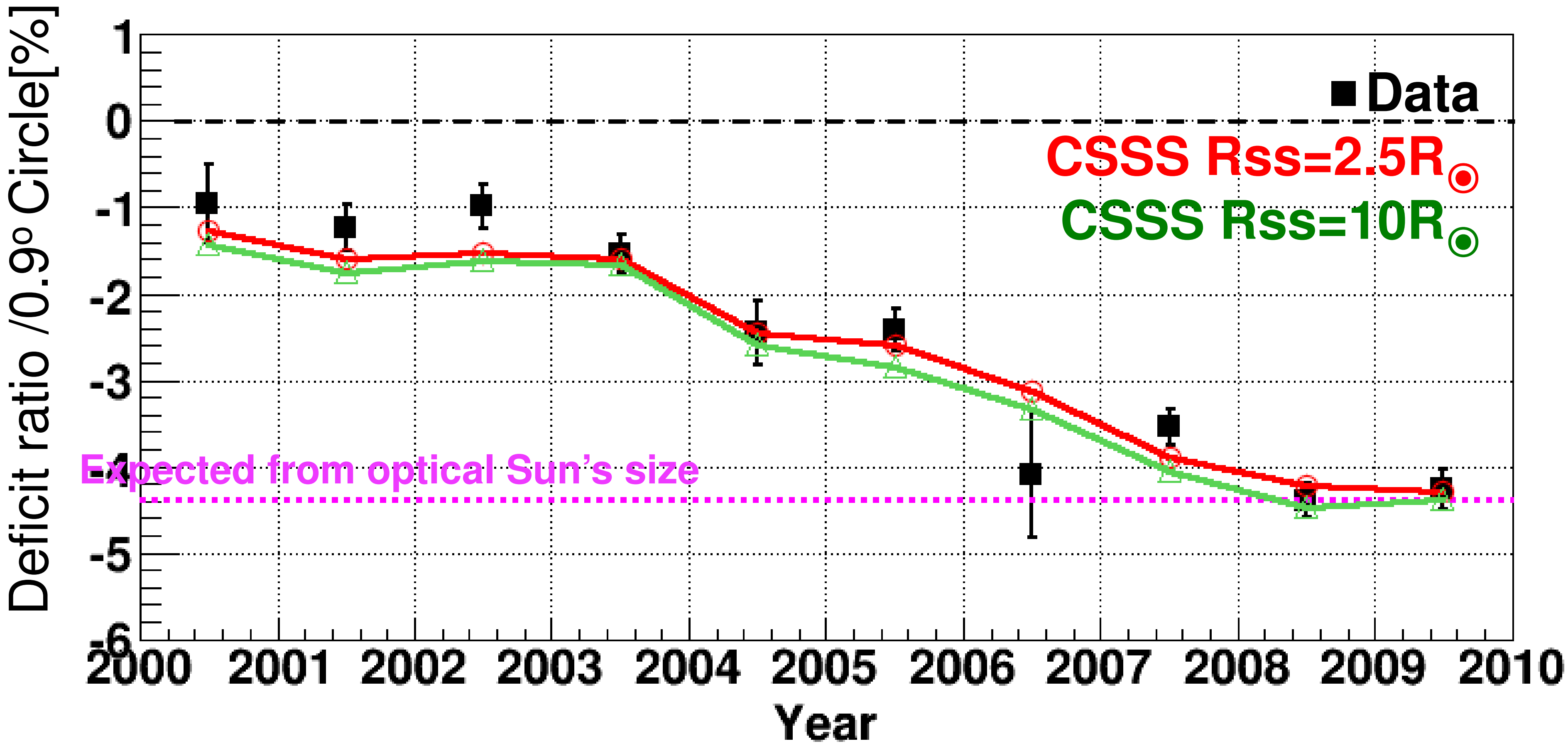


✓ Richardson & Cane Catalog
- CME plasma information observed at the earth
- Only Earth-directed CMEs (ECMEs) are listed

✓ Exclude transit periods of ECMEs from the analysis
- ECME start is the eruption time at the Sun
- ECME end is plasma end at the earth.
- ECME transit period is ~4 ±1 days



Deficit – Obs/MC **Exclude ECMEs** - 3 TeV



χ^2 test :

χ^2 / dof = 12.2 / 10 (0.6σ

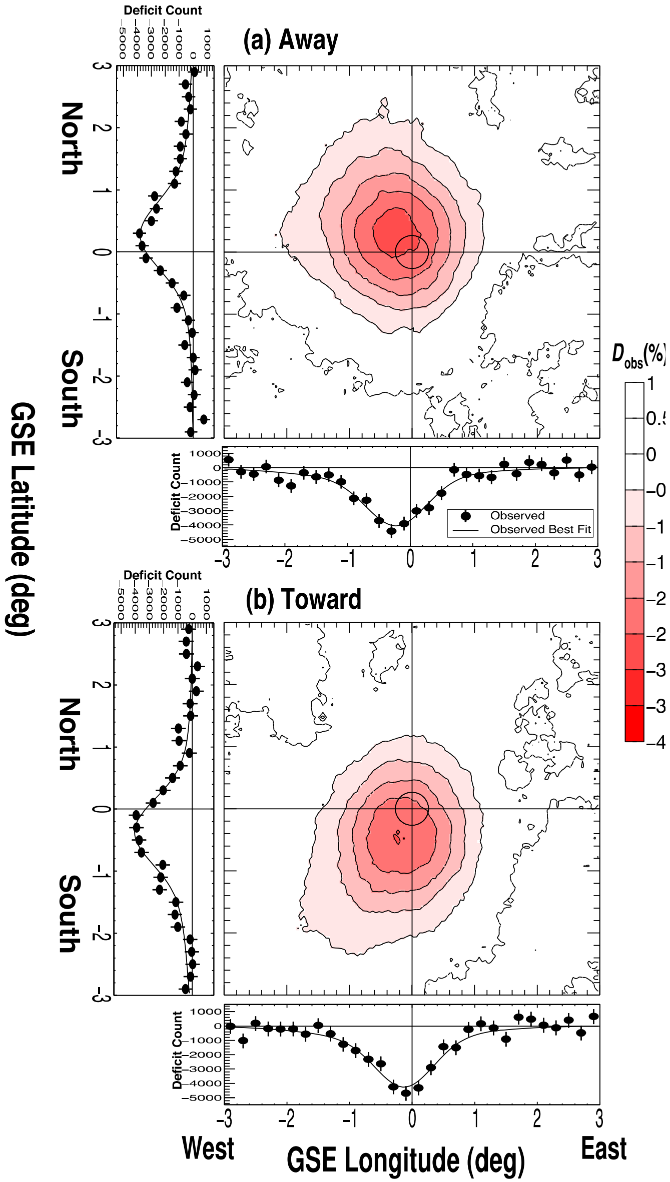
χ^2 / dof = 21.0 / 10 (2.0σ

*only stat. error

Exclude ECMEs → CSSS works

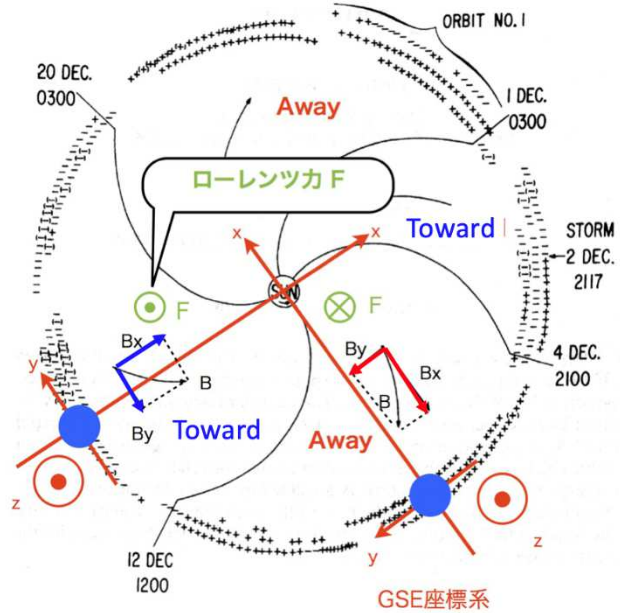
First evidence for influence of ECMEs on the Sun shadow at 3 TeV

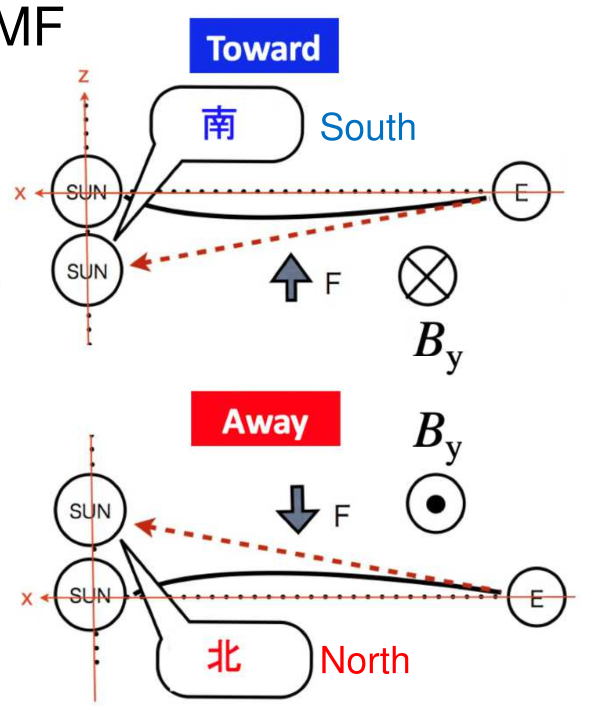
North-South Displacement (Toward/Away)



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

Indirect measurement of IMF

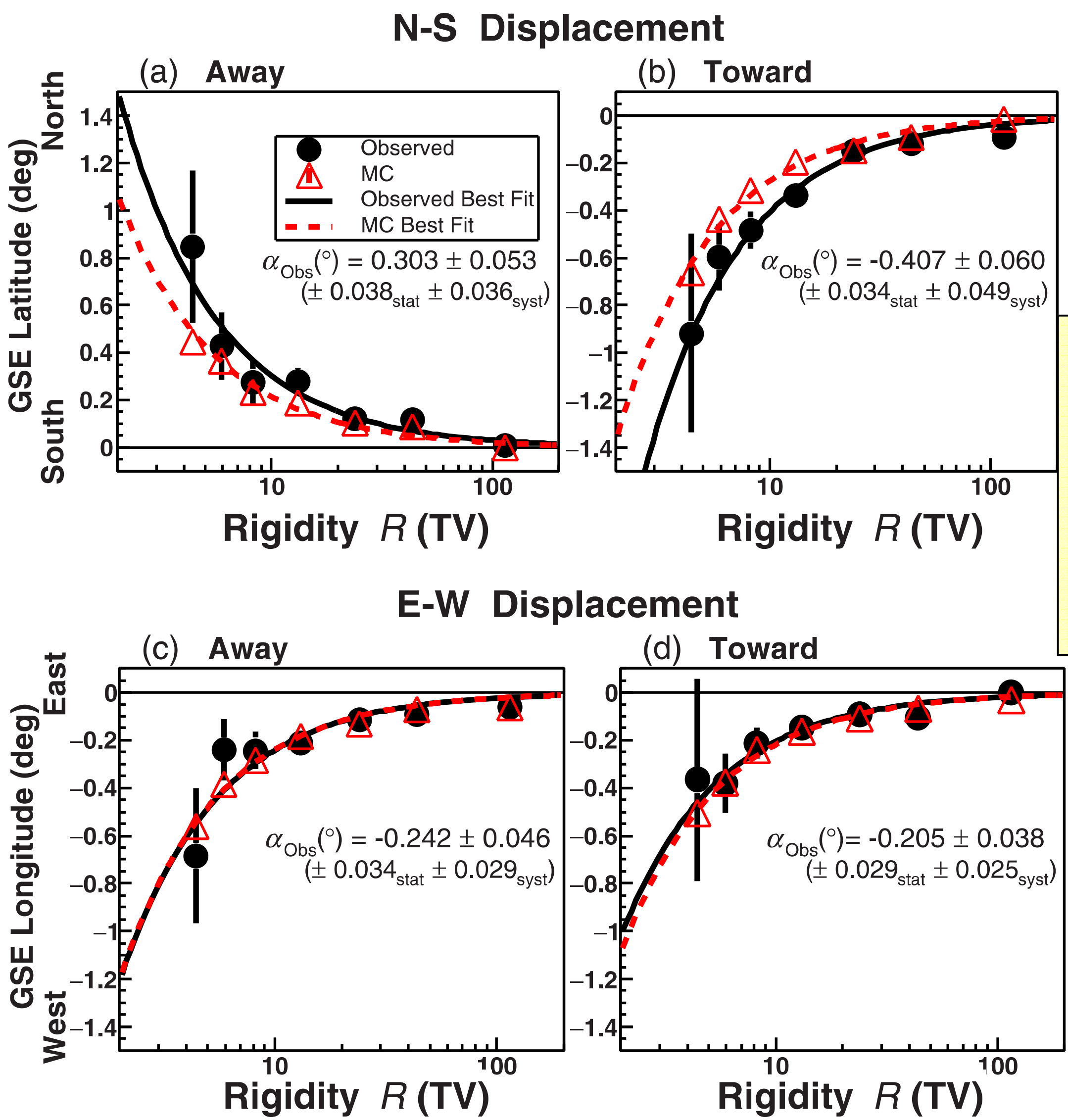




IMF: purely radial => $B_z = 0$
Assignment of the sector polarity with B_x & B_y observed two days later
$B_x < 0$ & $B_y > 0$ => Away sector
$B_x > 0$ & $B_y < 0$ => Toward sector

North–South Displacement (Toward/Away)

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



North-South displacement

Data/MC ratio →

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

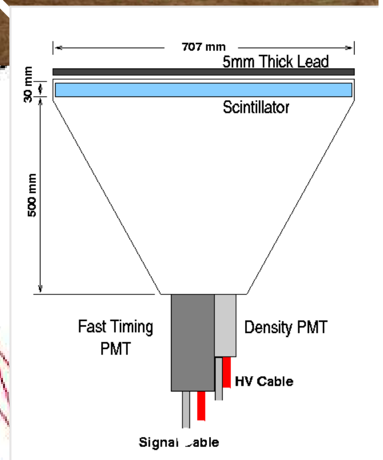
Toward : 1.62 $\pm 0.15_{stat} \pm 0.22_{syst}$

Problem of magnetic field model?
- Potential field model?
- Systematic uncertainties in solar $B_{surface}$ measurements? (Input parameter to model)

East-West displacement

→ Explained by geomagnetic field

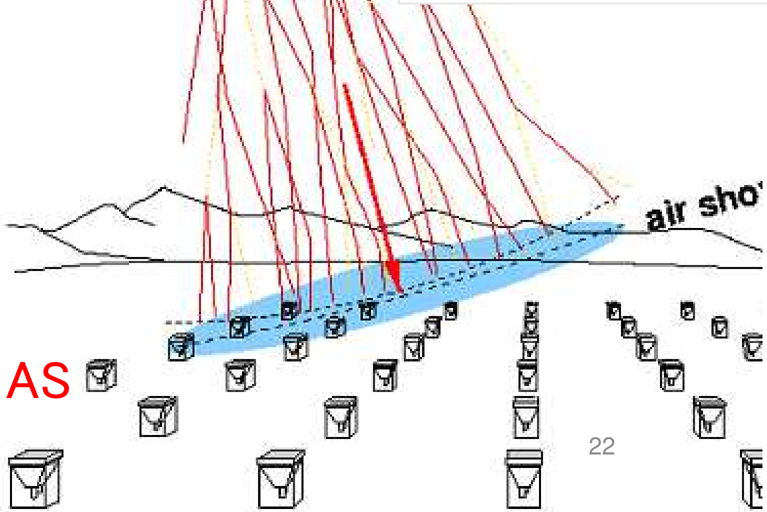
Tibet Air Shwer Array Now



- Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

<u>Performance</u>

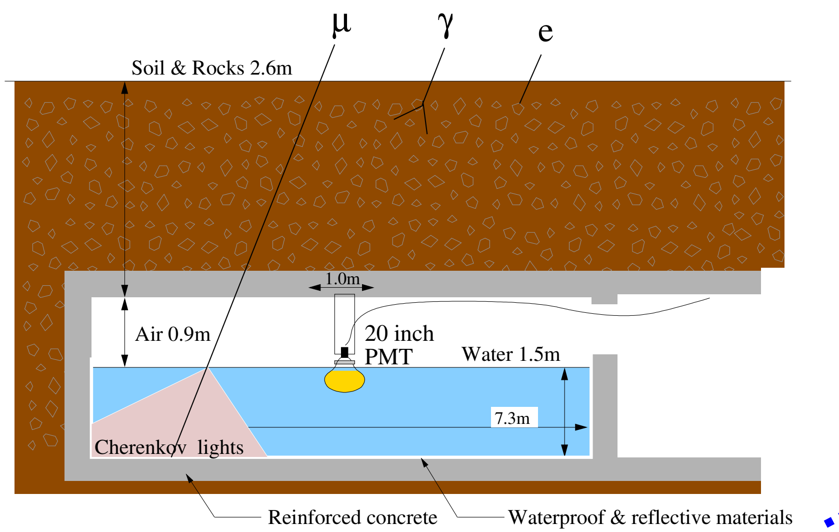
- # of detectors — 0.5 m^2 x 597
- Effective area — ~50,000 m^2
- Angular resolution — ~0.5° @10TeV, ~0.2° @100TeV
- Energy resolution — ~40%@10TeV γ, ~20%@100TeV γ

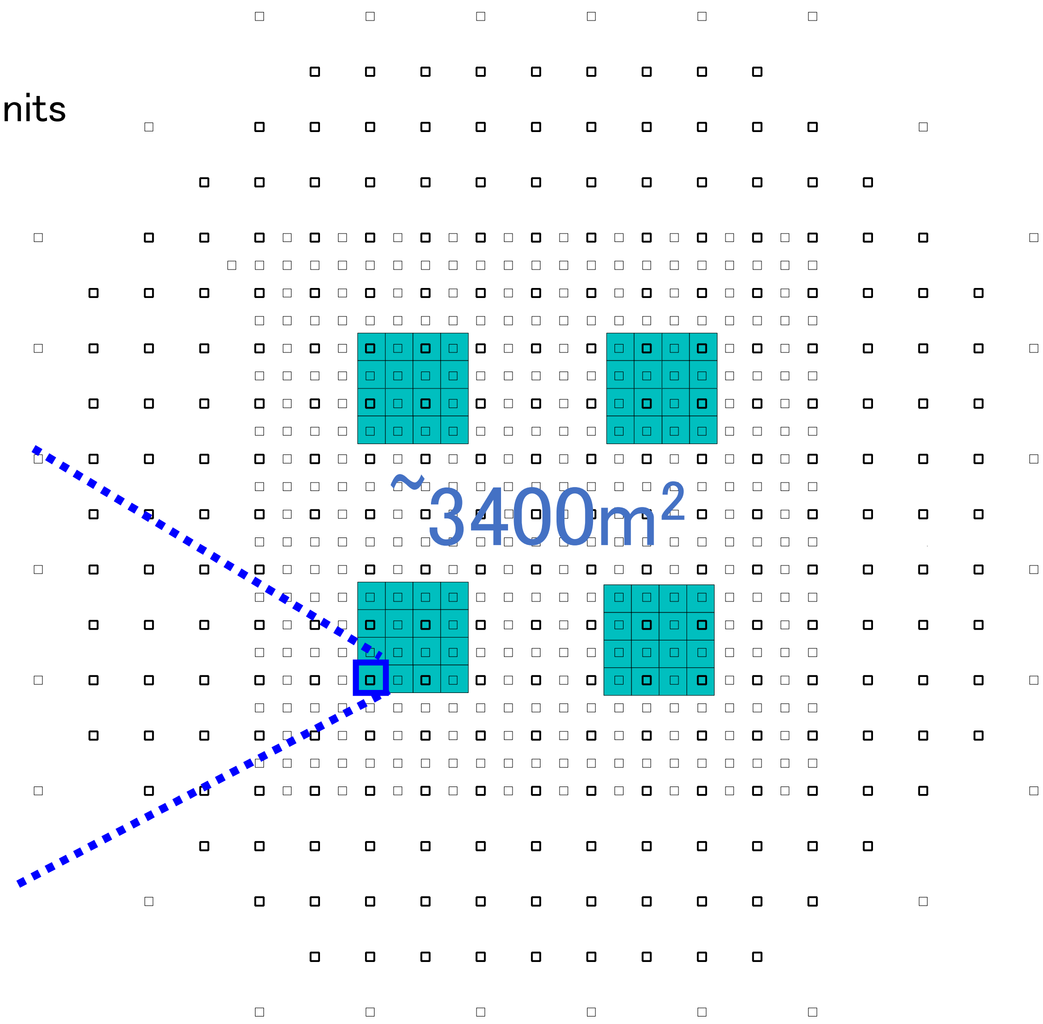


→Observation of secondary (mainly e$^{+/-}$, γ) in AS
Determination of E and direction of primary

Water Cherenkov underground μ detectors

- ✓ 2.4m underground (~ 515g/cm2 ~19 X_0)
- ✓ 7.35m × 7.35m × 1.5m deep (water) x 64 units
- ✓ 20" Φ PMT (HAMAMATSU R3600)
- ✓ Concrete pools + Tyvec sheets





→Measurement of # of μ in AS -> γ/CR discrimination

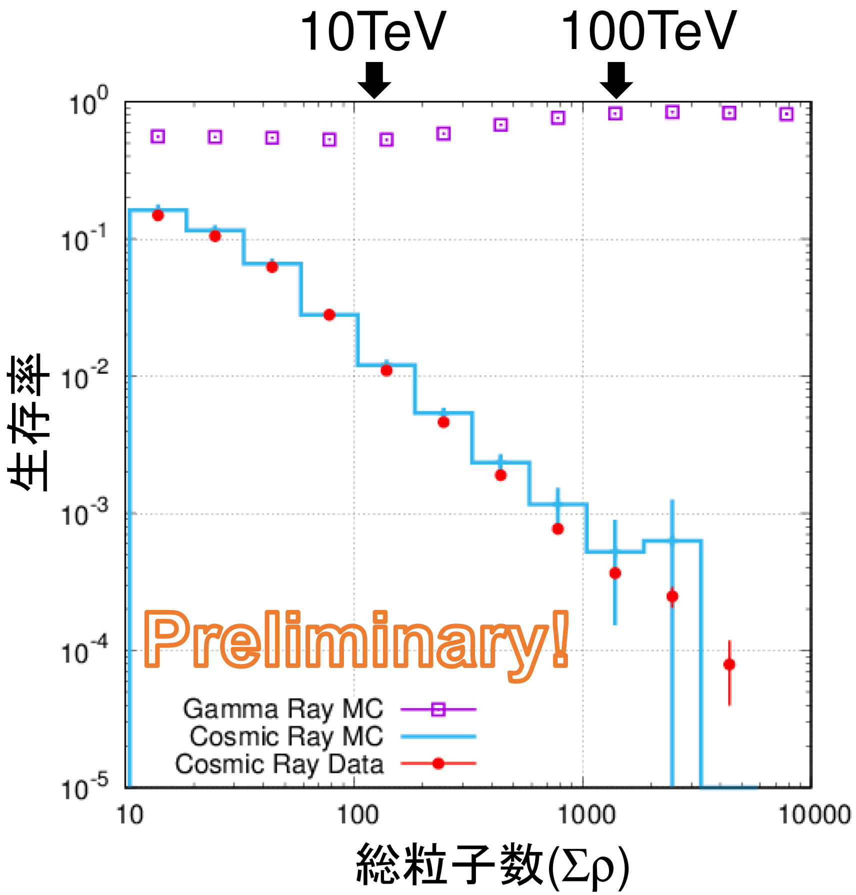
DATA: February, 2014 - May, 2017 Live time: 720 days

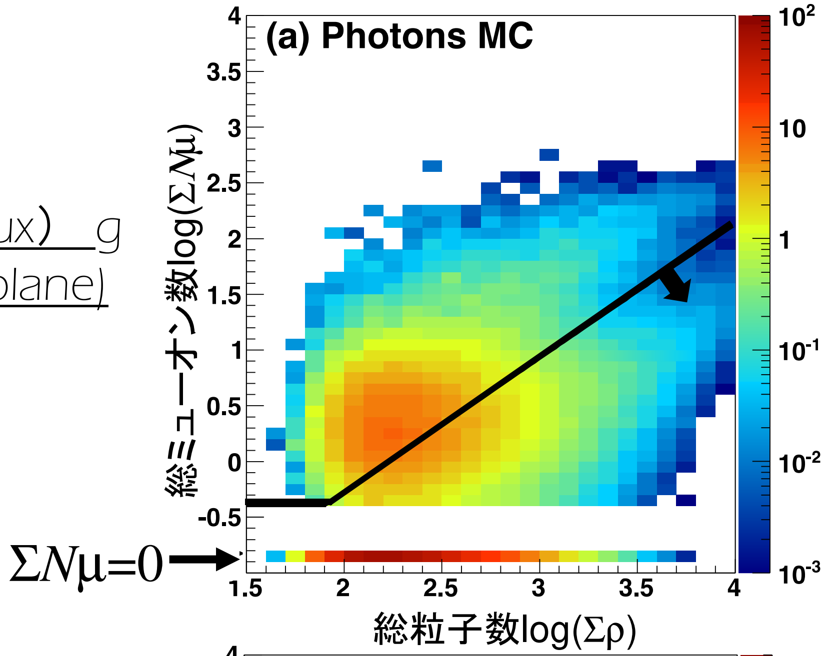
E(Σρ) vs. Nμ Plot

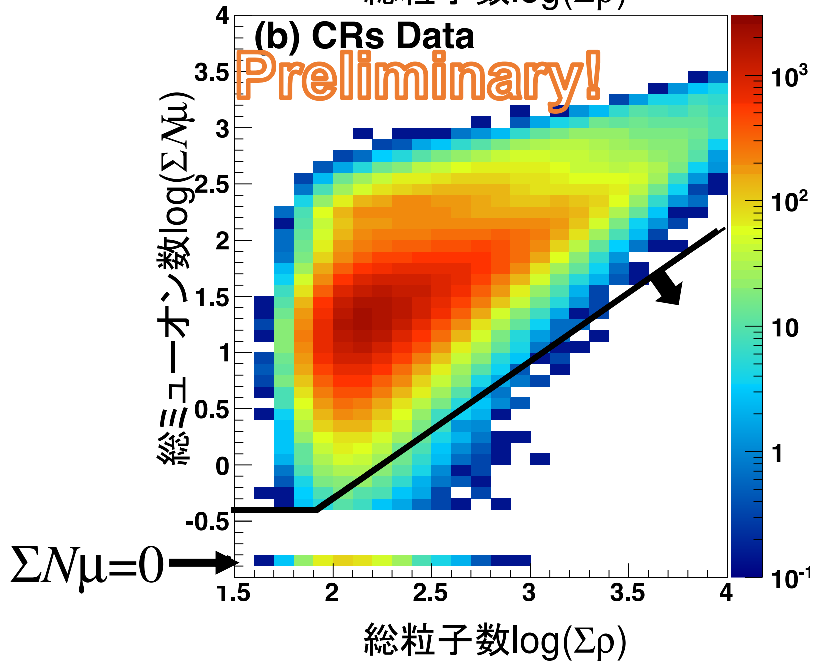
→Optimization of cut

γ:　　MC sample（Crab orbit & Crab Flux）g

CR：DATA(excluding Crab and Galctic plane)





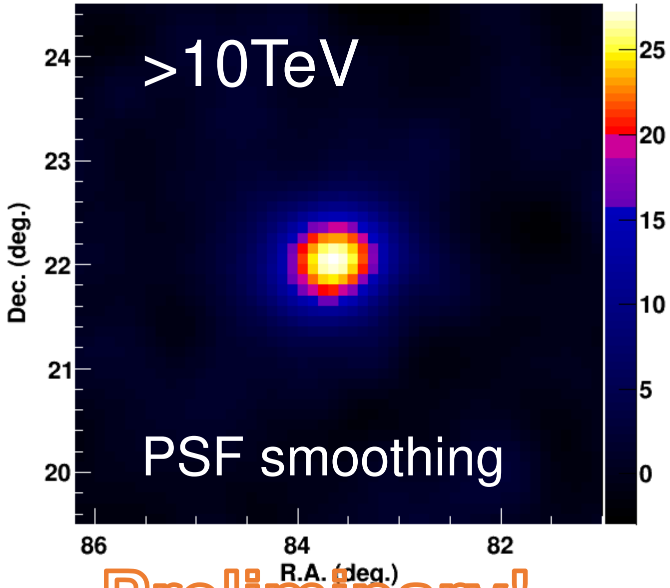


After Nμ cut,˜ 99.9 % CR rejection & ˜90 % γ efficiency @ 100 TeV

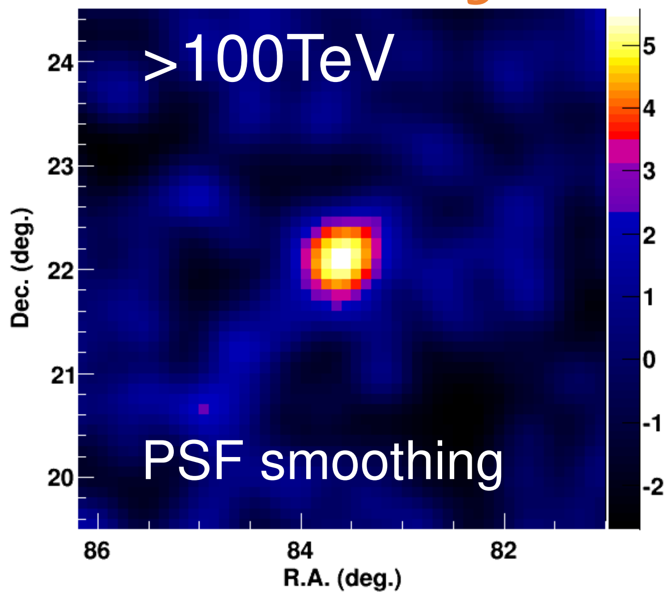
>10TeV g-ray emission from Crab

Preliminary!

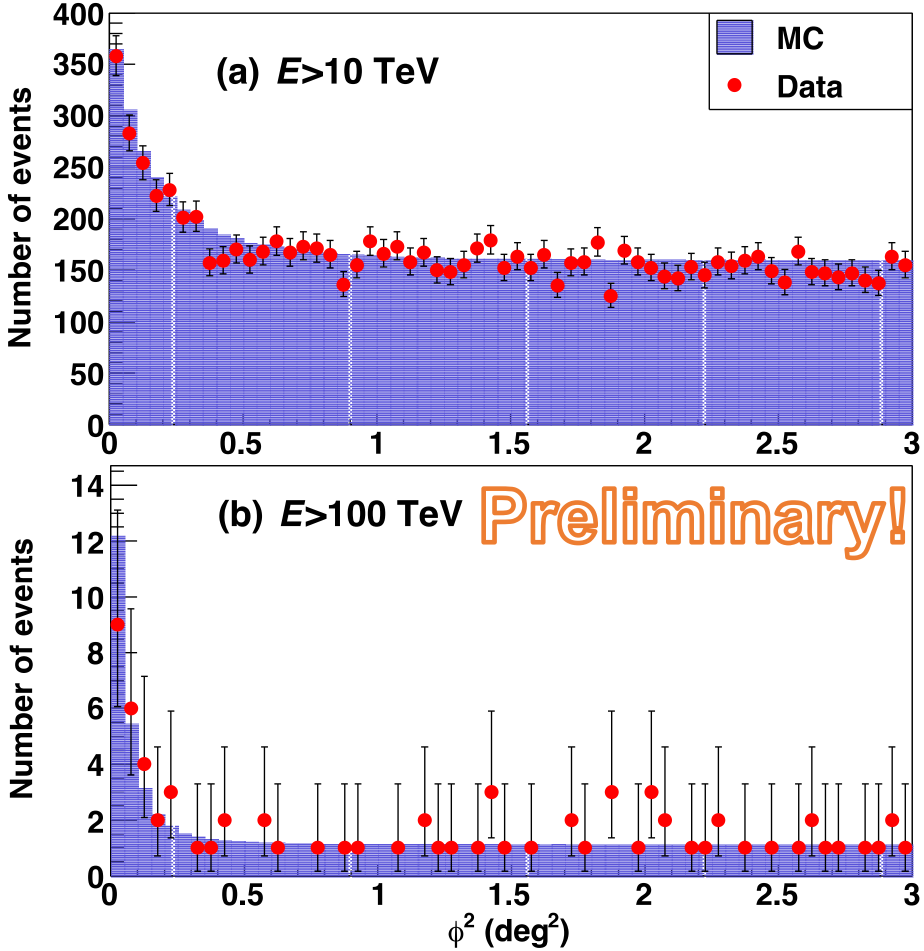
Submitted to PRL



Preliminary!



Data vs MC



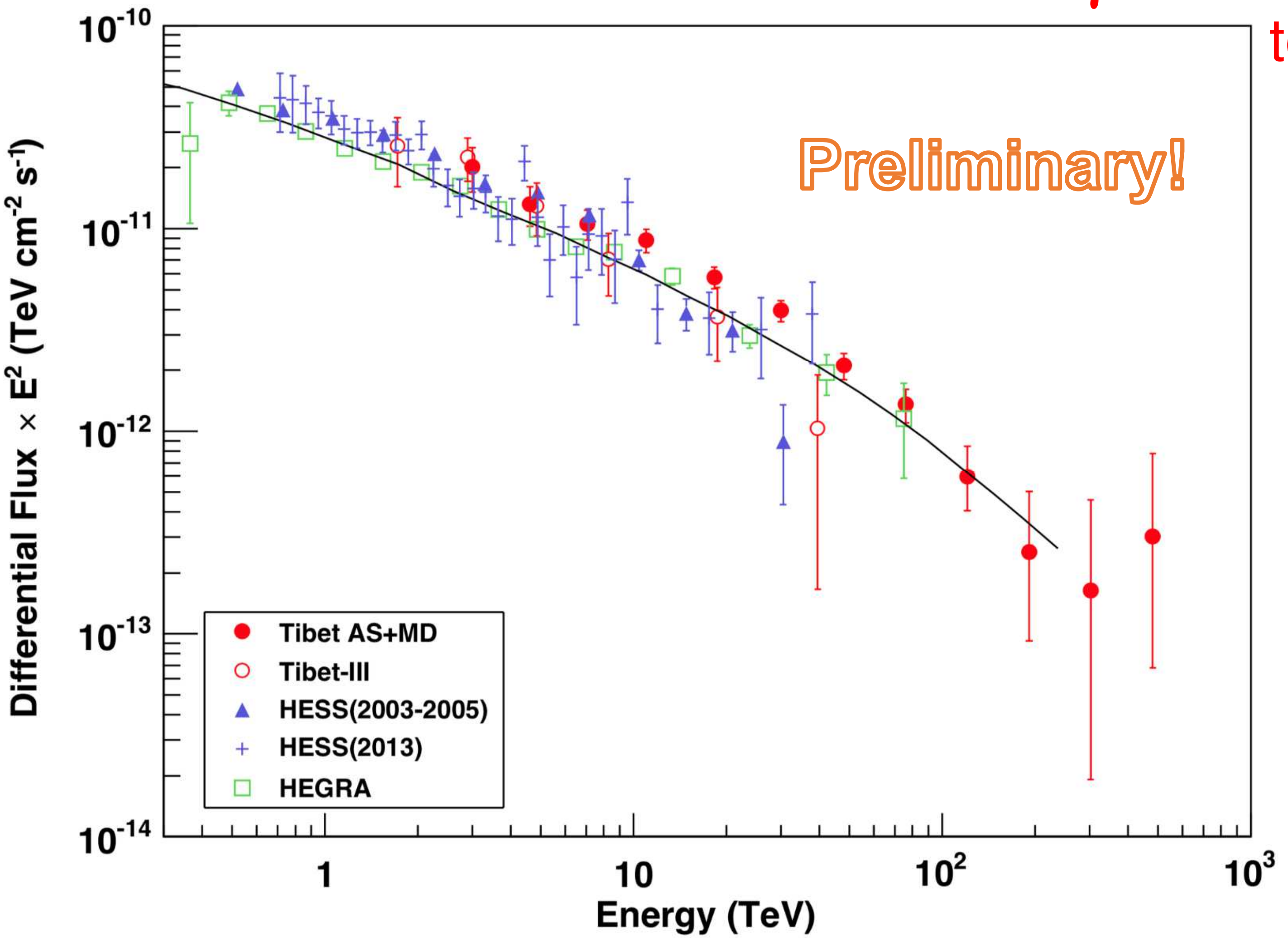
ϕ^2 distributions: consistent with point source

First Detection of Sub-PeV γ

γ-ray energy spectrum from Crab

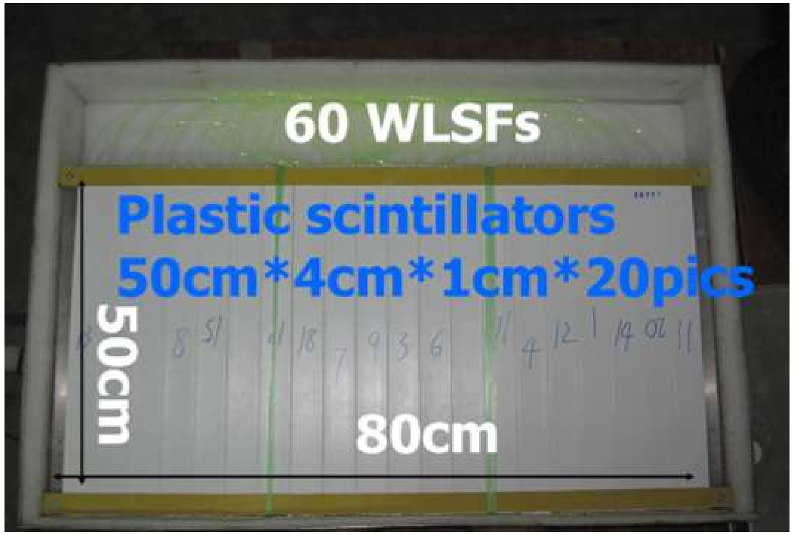
First Detection of sub-PeV γ

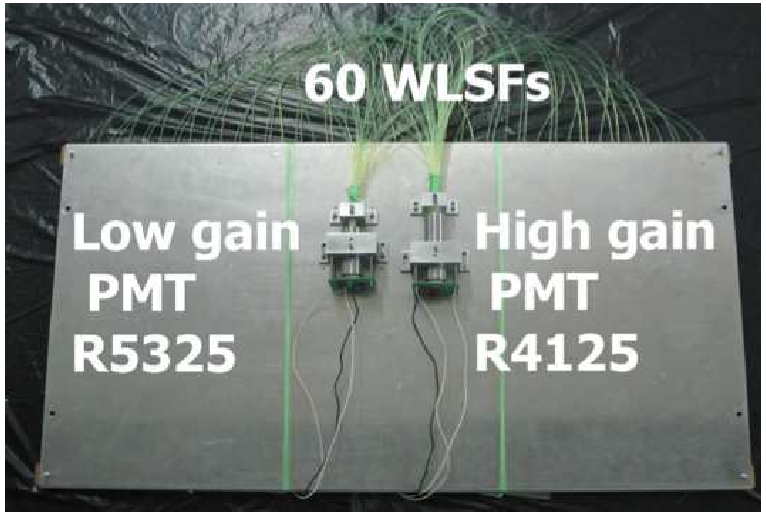
Submitted to PRL

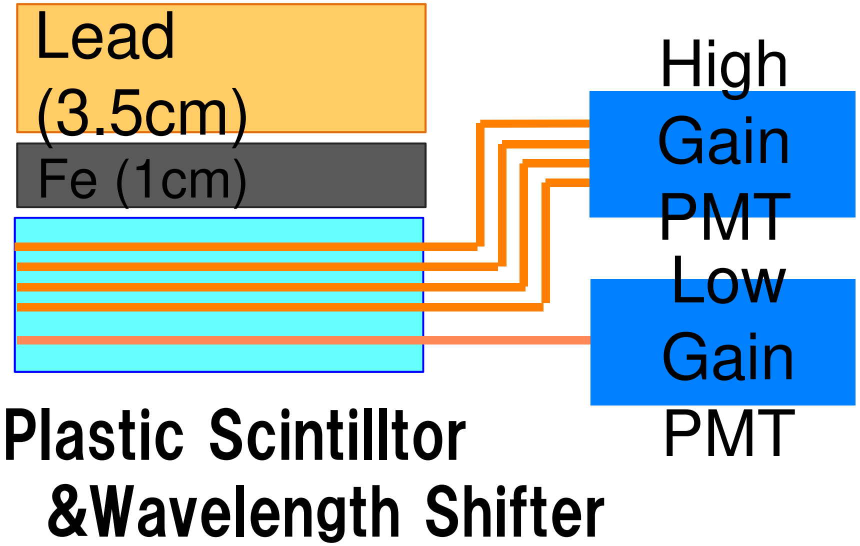


Thick curve: the calculated flux by (IC model by HEGRA) normalized to HEGRA data *Aharonian+, ApJ, 614, 897 (2004)*

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

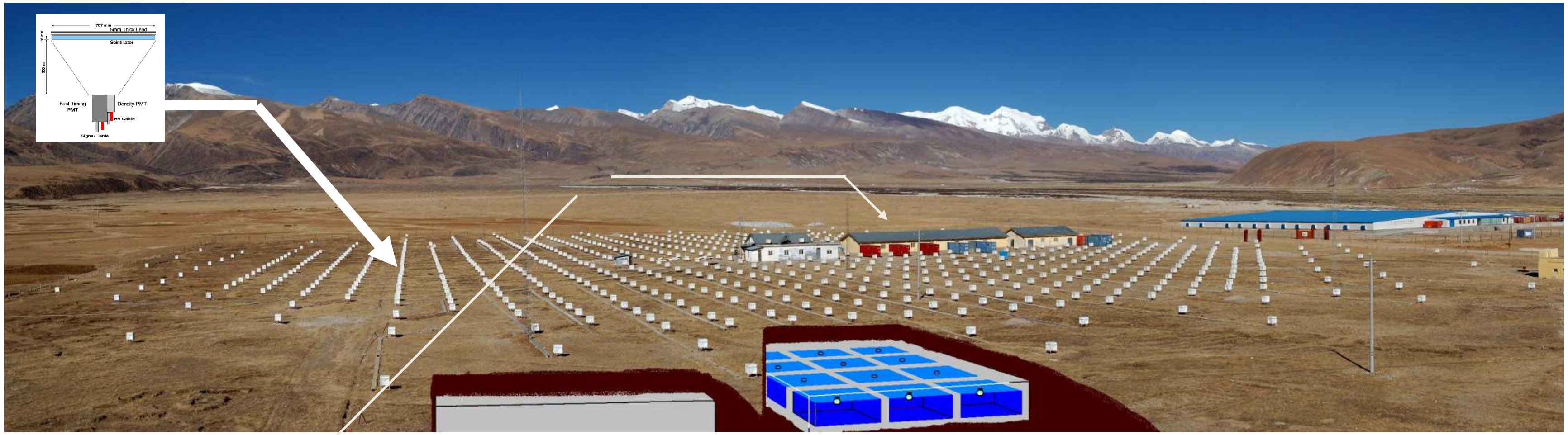


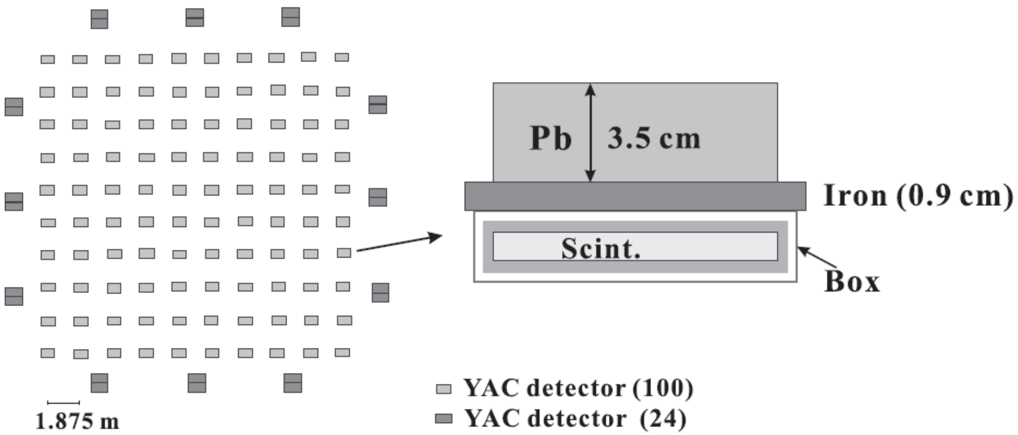




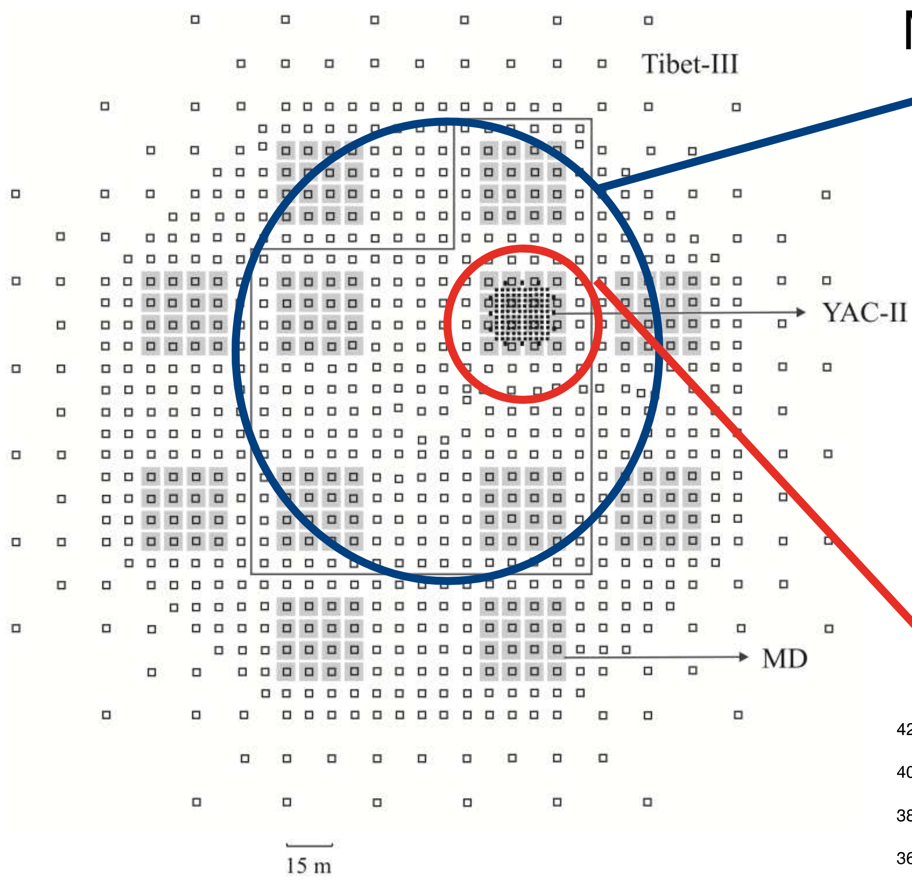
2PMTs cover 1~10^6 particles

YAC-II started in 2014, accumulating data



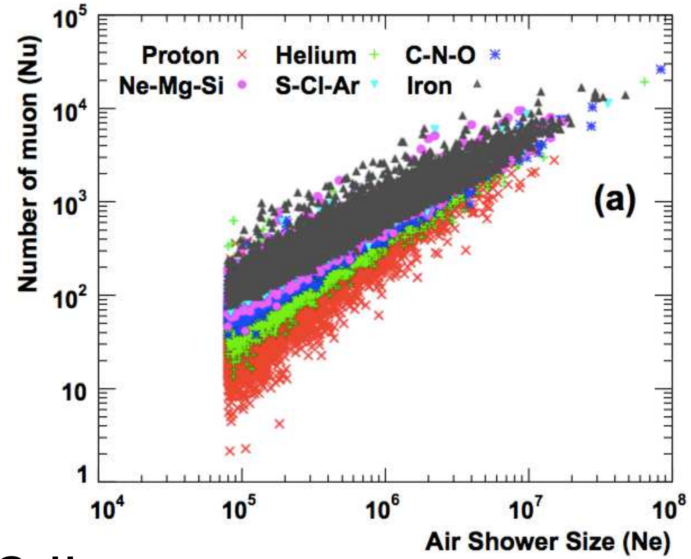


Tibet-III + YAC-II + MD (MC) for Knee Study

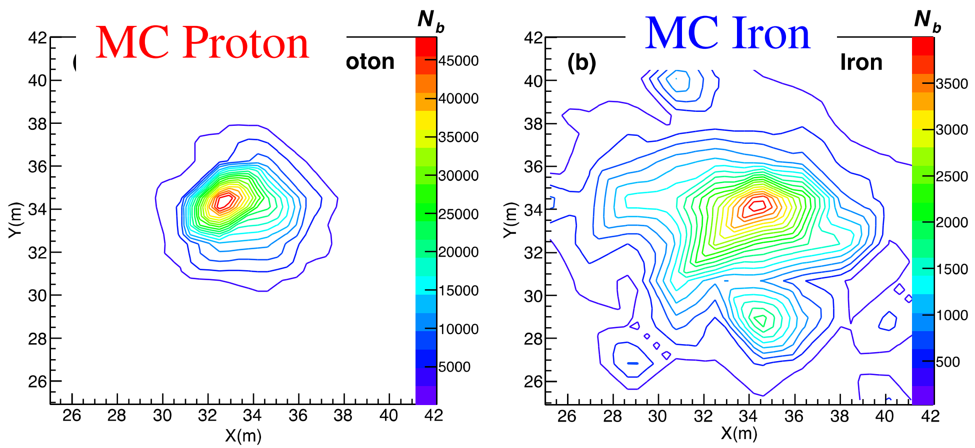


Muon Detector

MC Ne-Nμ Plot



YAC-II



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

Conclusions

- 10 - 1000 TeV CR sidereal anisotropy
  - ✓ New component > a few hundred TeV
    Origin?
- Sun Shadow in CR
  - ✓ Depth: Sensitive to coronal magnetic field @ 10 TeV, Sensitive to ECME @ 3 TeV, useful for solar MF modeling
  - ✓ North-South displacement: Suggesting underestimation of IMF in solar MF model
- First detection of sub-PeV γ -> Sub-PeV γ astronomy
  PeVatron search
- Tibet AS + MD + YAC will continue:
  sub-PeV γ & Knee physics & Sun shadow
- ALPACA – Next talk

END

Thank you!