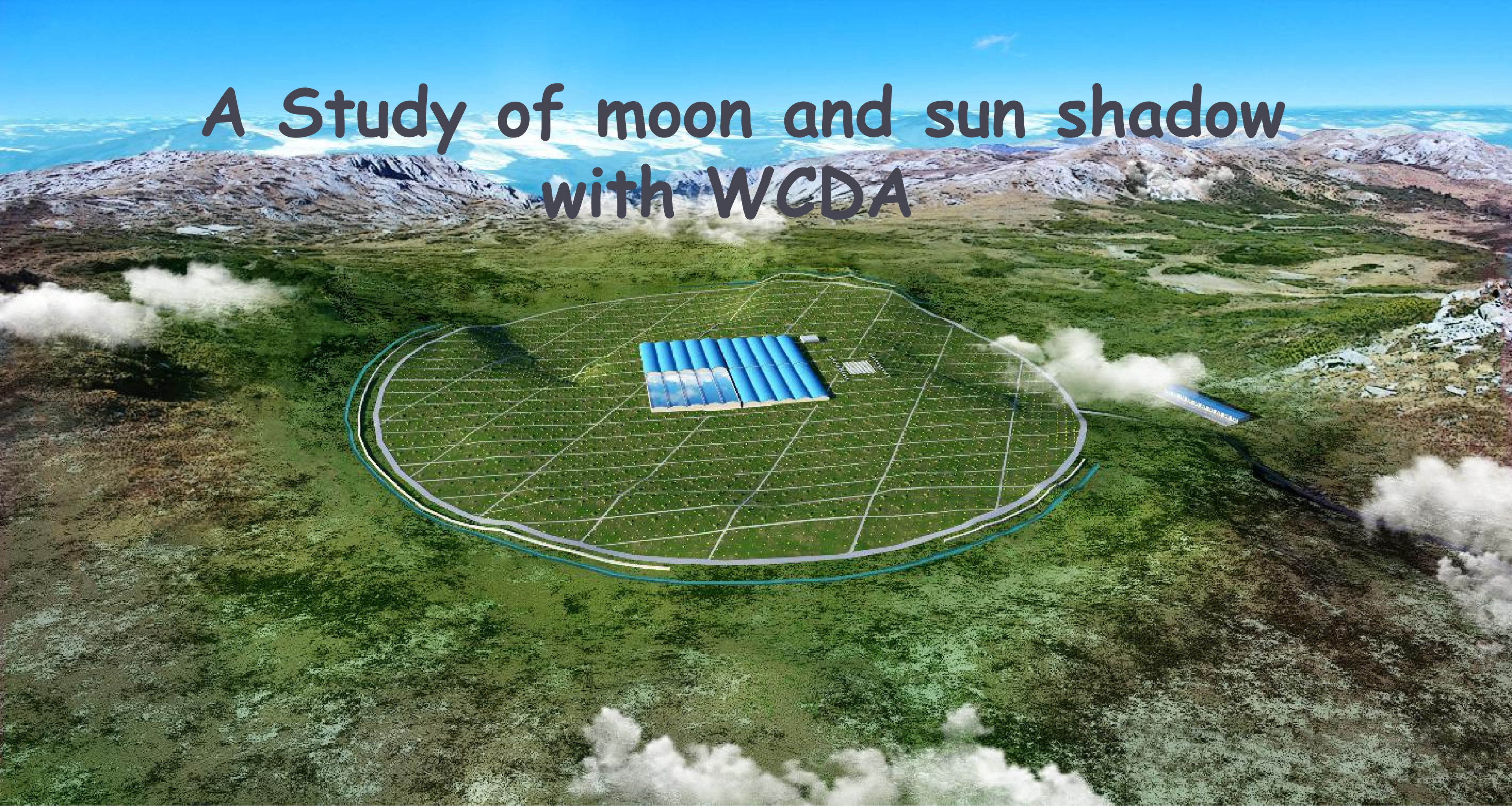
A Study of moon and sun shadow with WCDA



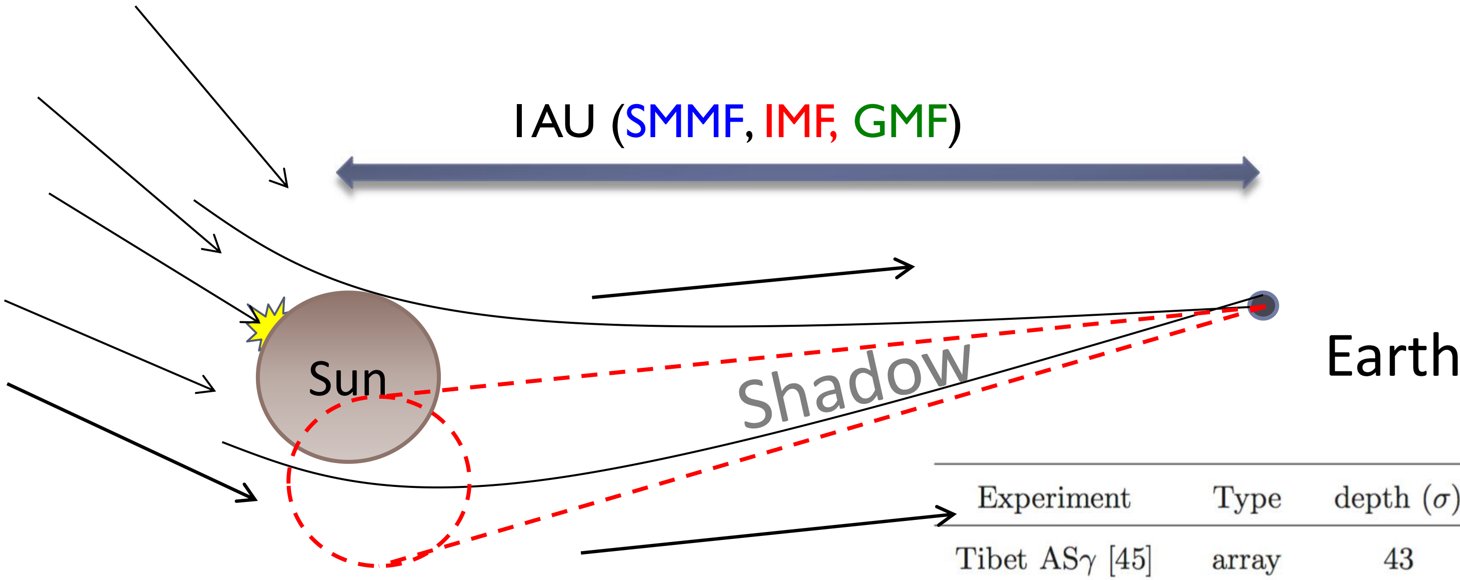
查敏、王岩谨、廖文英、Mohsin Saeed

17/01/2017 – 20/01/2017
2017 LHAASO General meeting @ Yunnan university

outline

- Physics from sun/moon shadow study
- A simulation code construction
- Some simulation results
- Future working steps

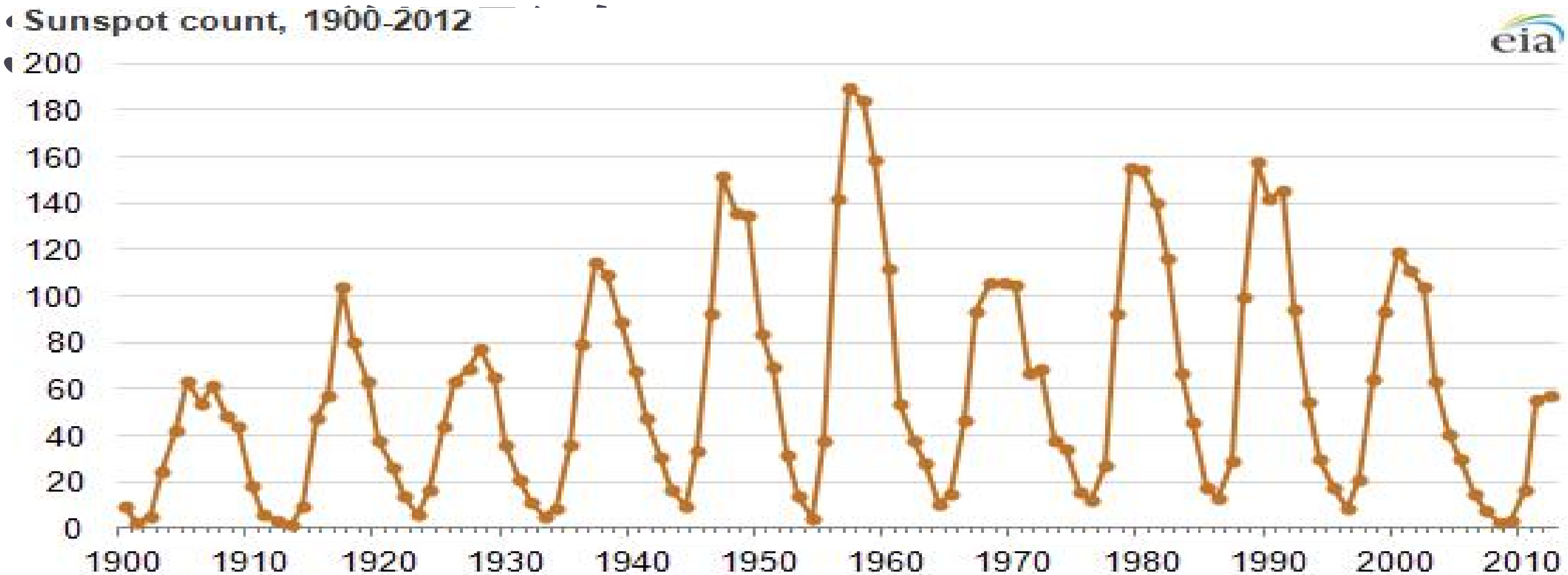
The Sun blocks Cosmic Rays

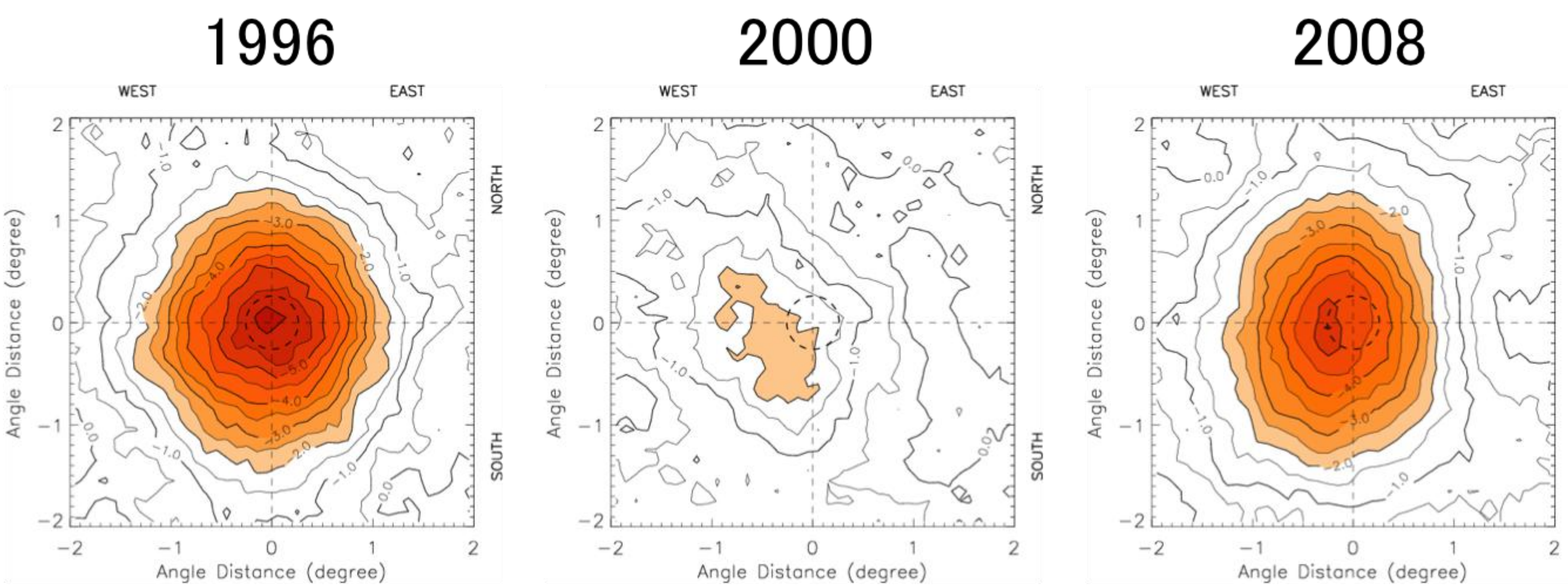


- 1957, Concept by Clark
- 1991, first Sun+Moon shadow 4.9sigma by CYGNUS
- Only several σ sun shadows with CASA, Milagro, SOUDAN2, MACRO, L3+C
- Further physics with ASγ, ARGO-YBJ

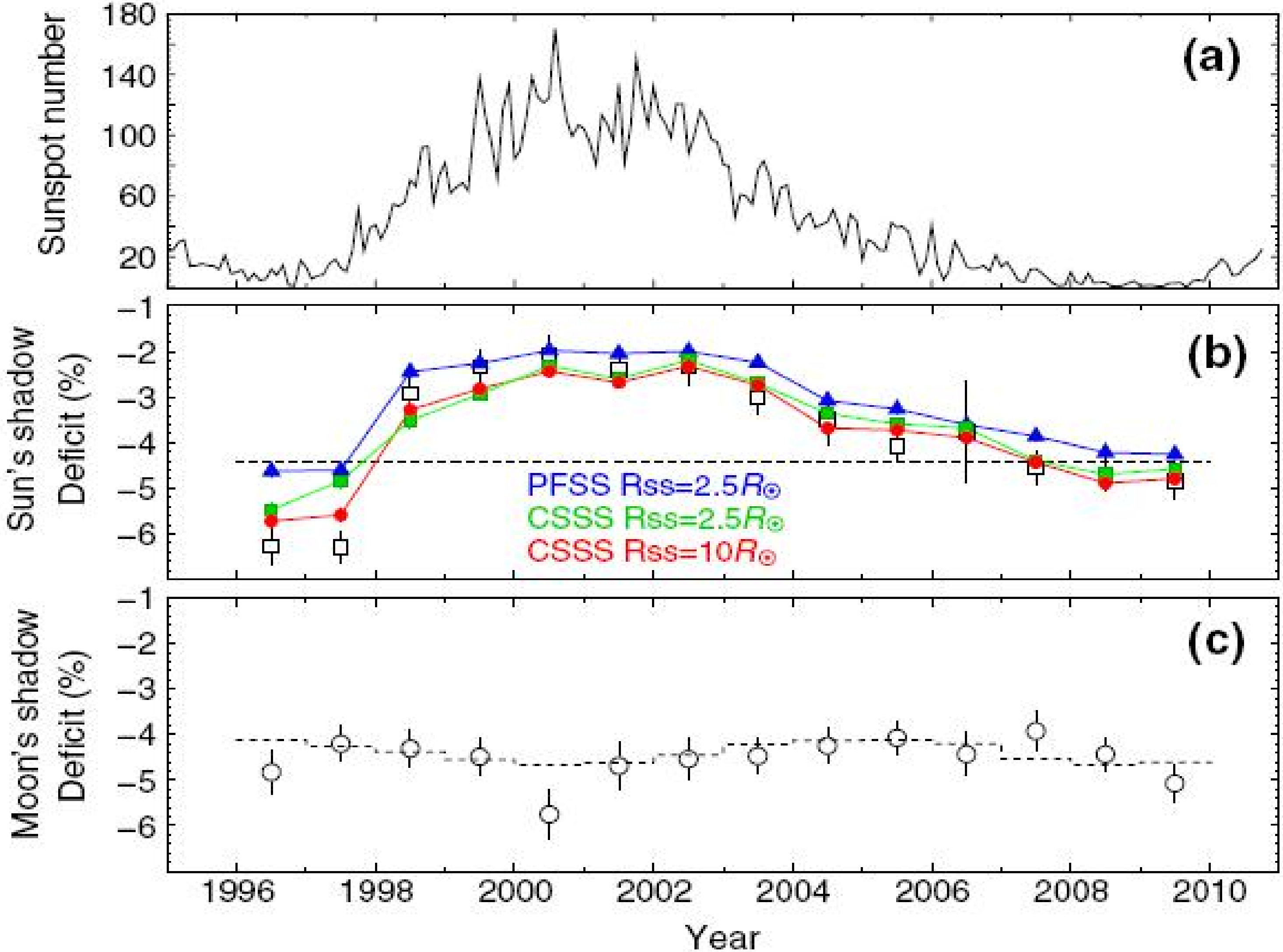
Experiment	Type	depth (σ)	energy	$\bar{p}$/p limit
Tibet ASγ [45]	array	43	3 TeV	0.07 90% CL
IceCube [47]	neutrino	5	TeV	
L3+C [48]	muon	9.4		0.11 90% CL
MACRO [49]	muon	6.5	TeV	0.52 68% CL
Soudan 2 [50]	muon	5	TeV	
Cygnus [28]	proton	4.9	20 TeV	
CASA [46]	proton	4.7	100 TeV	
Bust [51]	muon	3		
ARGO-YBJ[56]	array	55	1.4 TeV	0.05 90% CL
			5 TeV	0.06 90% CL
HEGRA[57]	array		50 TeV	
GRAPES-3[58]	array	5		
MINOS[52]	muon			

A probe to explore magnetic fields and space weather



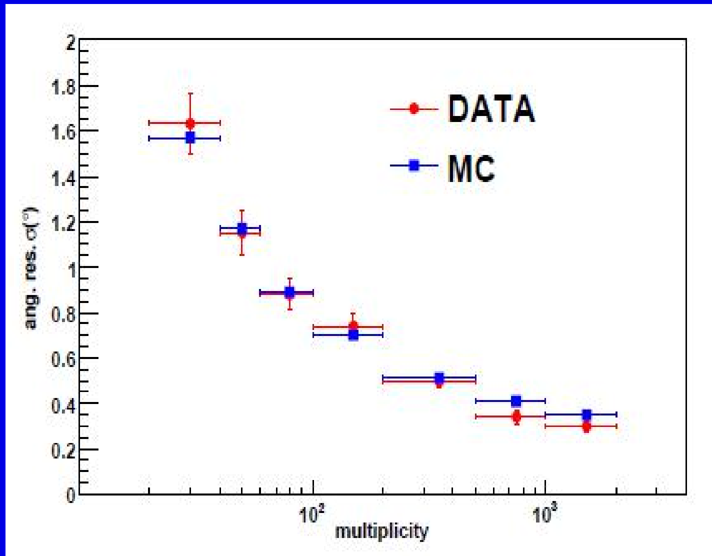


Tibet ASr 合作组研究结果

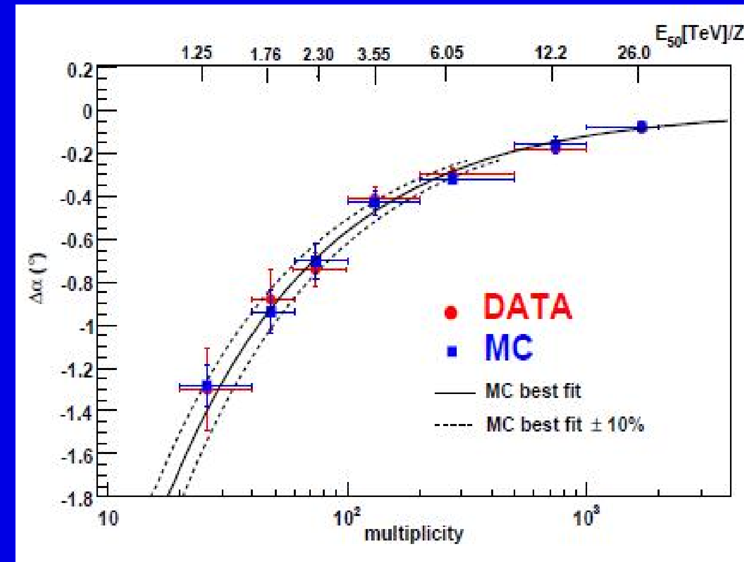


PRL 111, 011101 (2013)

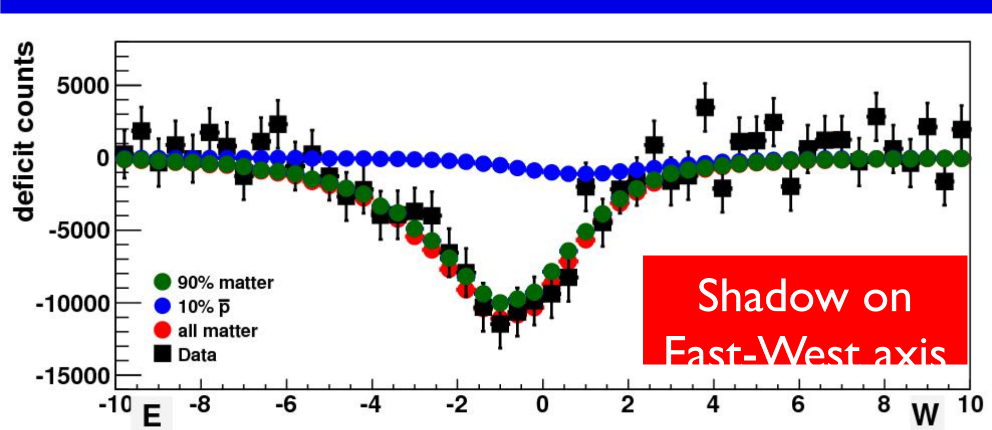
Angular resolution vs hit multiplicity



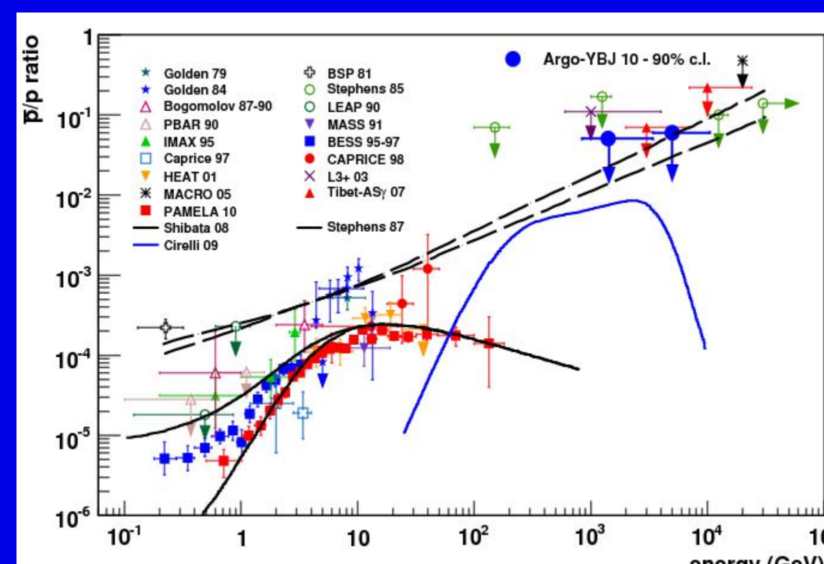
Shadow displacement on the East-West axis



Looking for an East deficit as antiproton signal

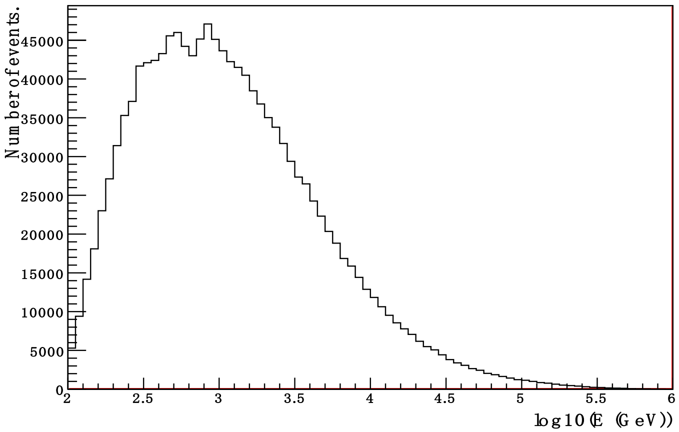


Upper limits of the antiproton flux



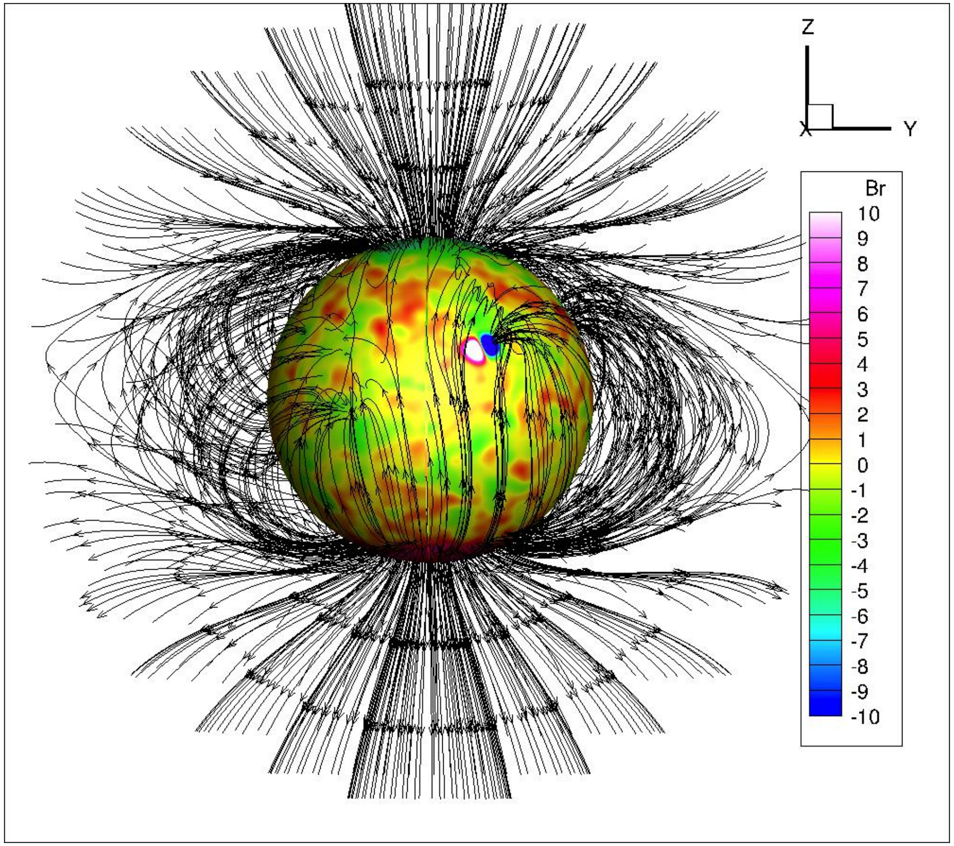
Sun/Moon shadow simulation

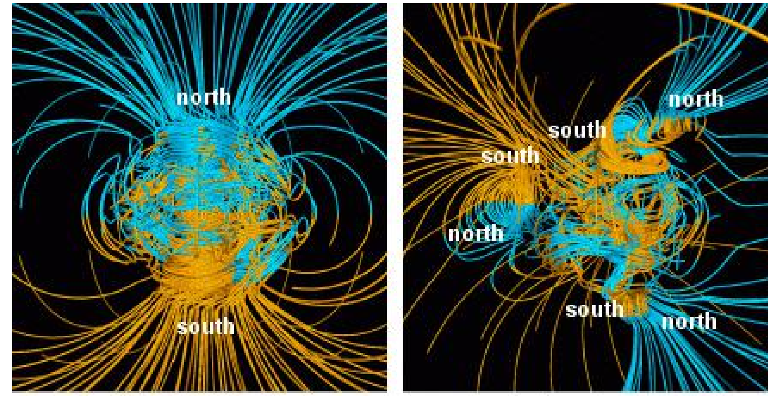
- Magnetic field models
  - Solar Magnetic field: Solar surface is measured everyday by ground based detector. But, from surface to 2.6 Rsun, the chromospheres magnetic field measurement is difficult, usually the surface measurement is extrapolated under some hypothesis (Like the PFSS model).
  - Interplanetary magnetic field: From 2.5/5.0/10.0 Rsun to 1 AU. The IMF usually is assumed a simple Archimedean spiral configuration as the Sun rotates. geomagnetic field
  - Geomagnetic field
    - Dipole / IGRF (external component)
- backtracing particles to Sun/Moon
  - May be trapped in field;
  - Hit the sun/moon disk passing through sun/moon distance.
- Add PFS to produce experimental angular resolution
- LHAASO-WCDA have a higher event rate and wider sensitive energy range , so we could check ASr result, measure sun shadow short term variations and its energy dependence. Our final aim is to give some independent quantitative measurement of the solar magnetic.



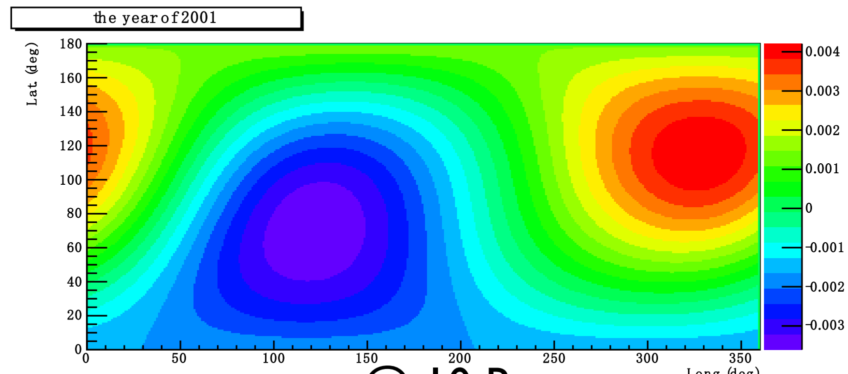
- Simulation details
  - CORSIKA-QGSJETII-GHEISHA
  - Cosmic Ray composition and flux followed Hoerandel paper
  - Direction: Crab orbit
- GEANT4 detector simulation
- Nfit>100, <E> ~3.5 TeV

PFSS-like model (Potential Field Source Surface)

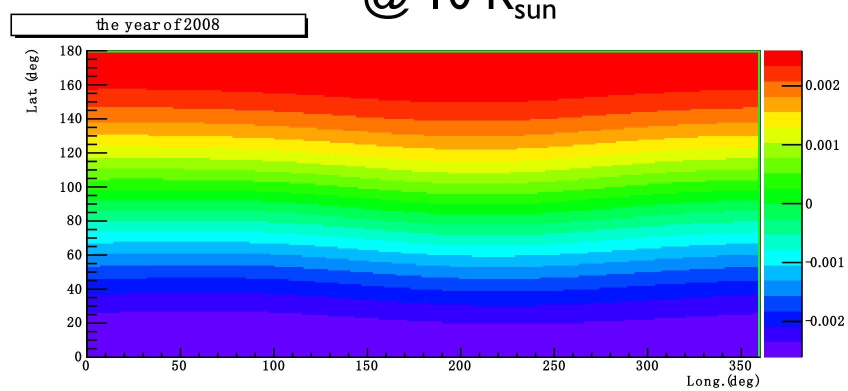




between reversals during a reversal

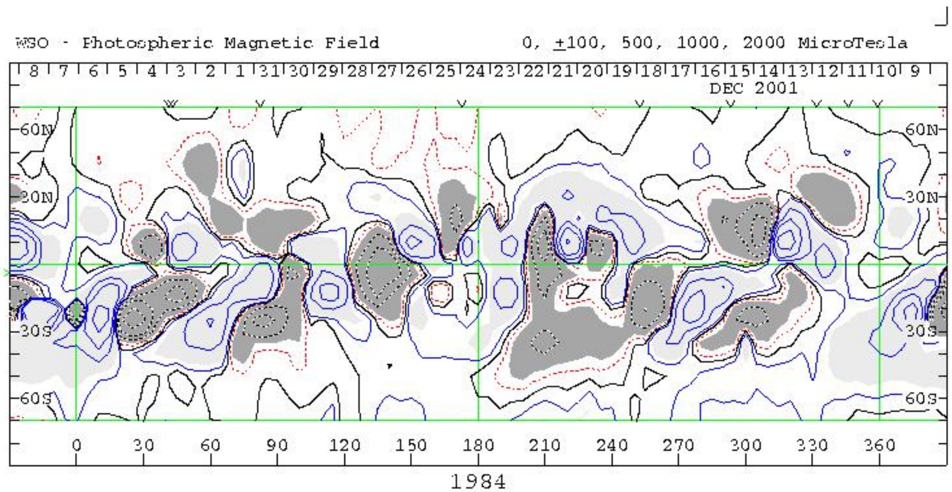


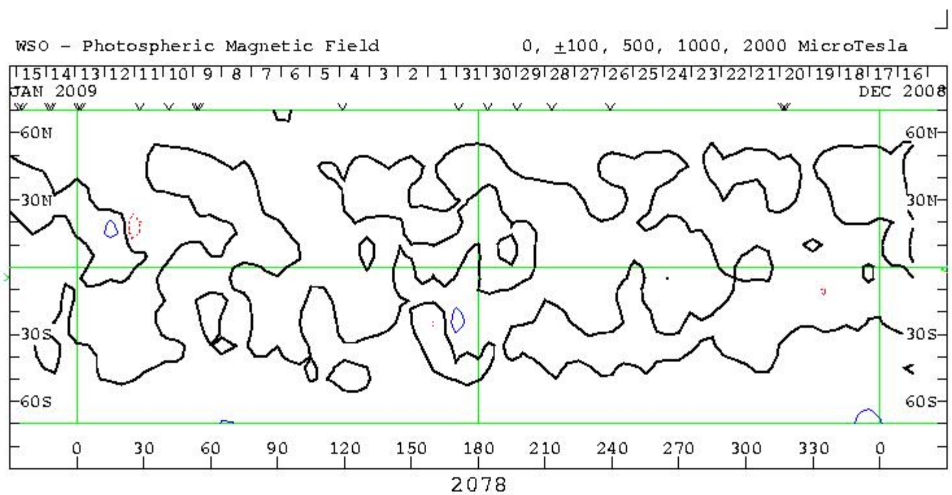
@ 10 R_{sun}

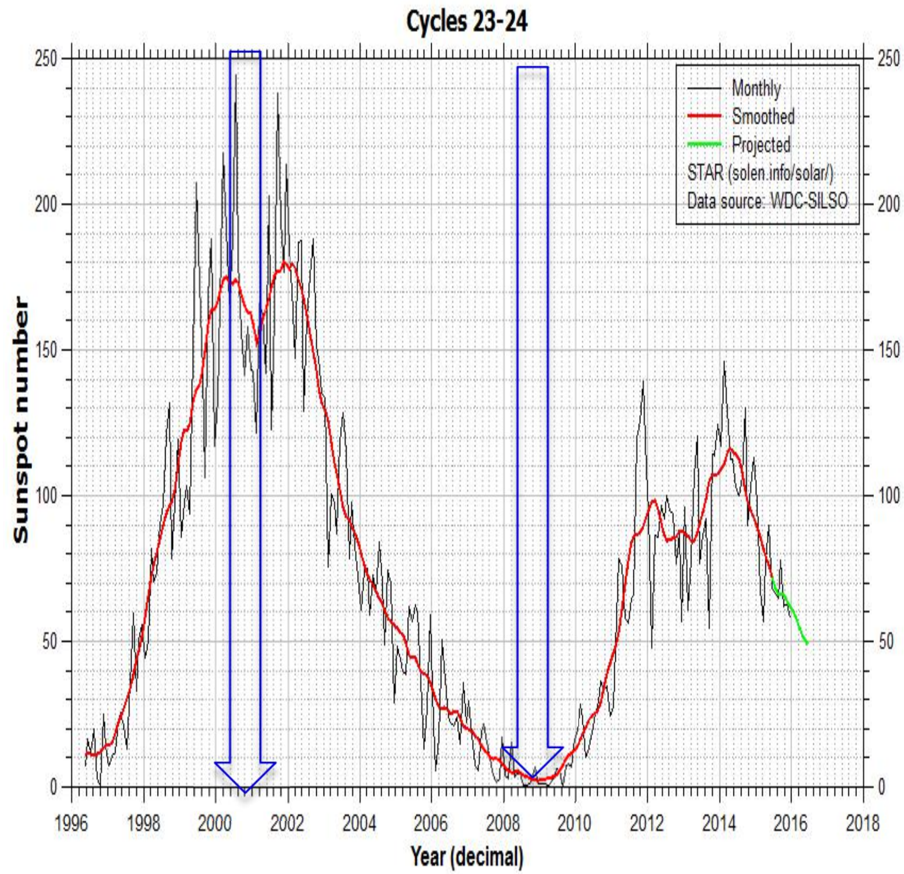


Chaowei Jiang, Xueshang Feng, Solar physics DOI 10.1007/s11207-0120074-x

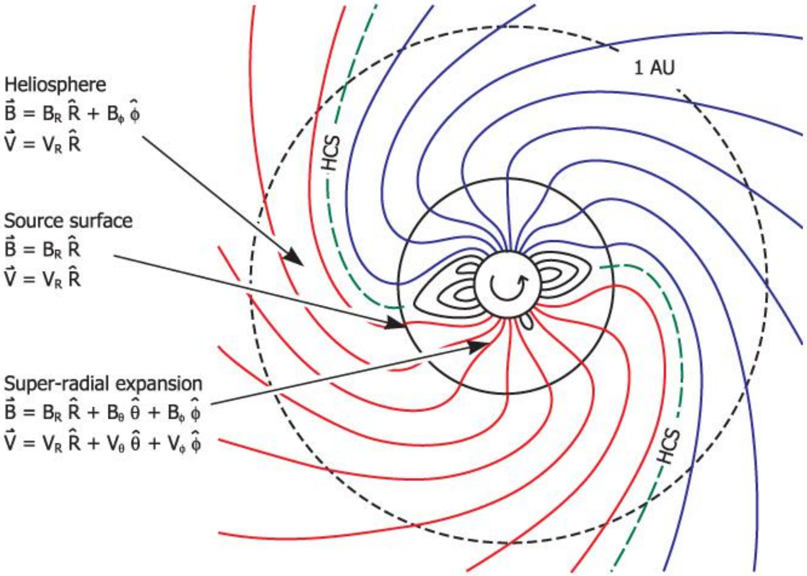
PFSS-like model





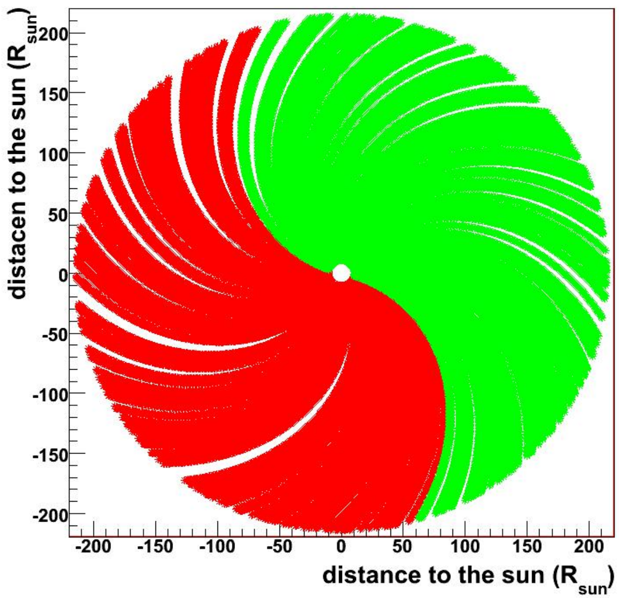


IMF: parker spiral

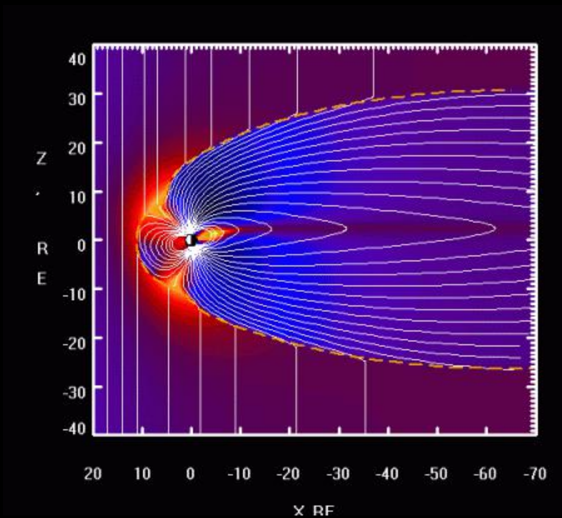


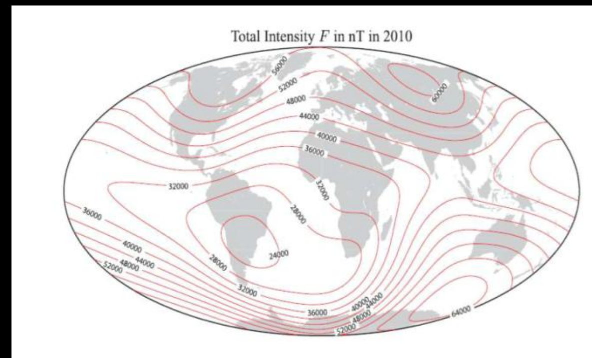
- $B_r = B_0(R_{sun}/r)^2$
- $B_\phi = B_0(R_{sun}/r)^2(r\omega_0/v_r)$
- $B_\theta = 0.$

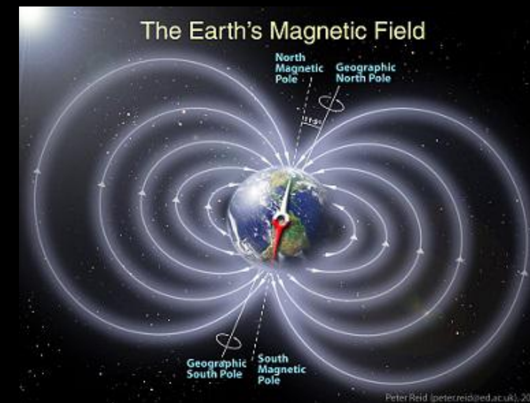
A steady sloar wind with a constant velocity of 450 km/s



geomagnetic field modeling



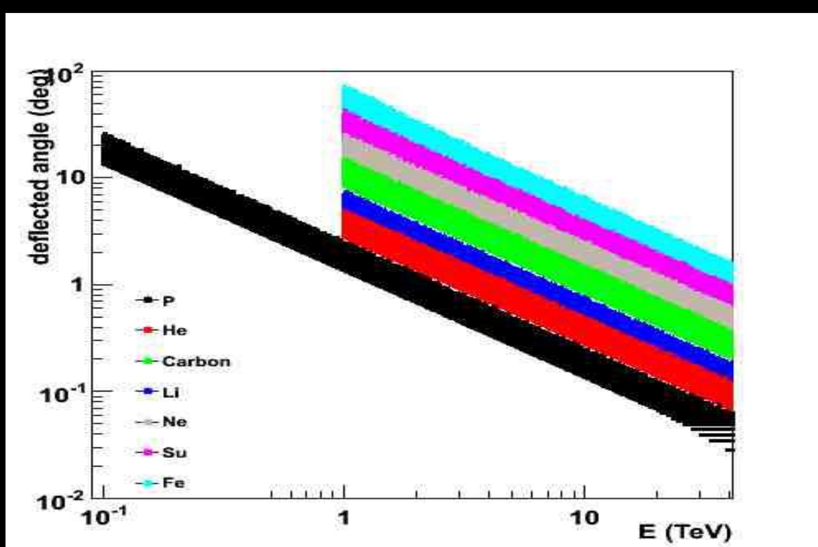


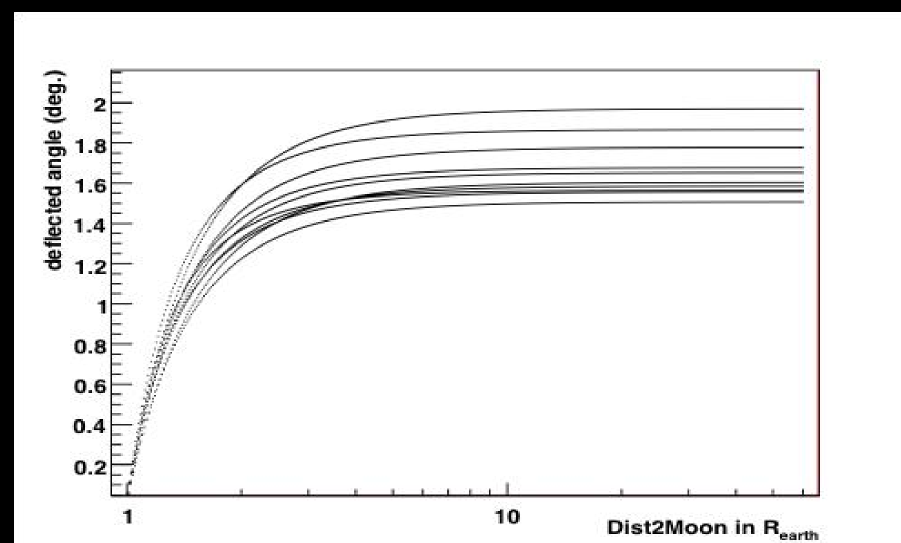


@ 20 R_{earth} B~nT gyroR 20 AU

1 TeV Proton

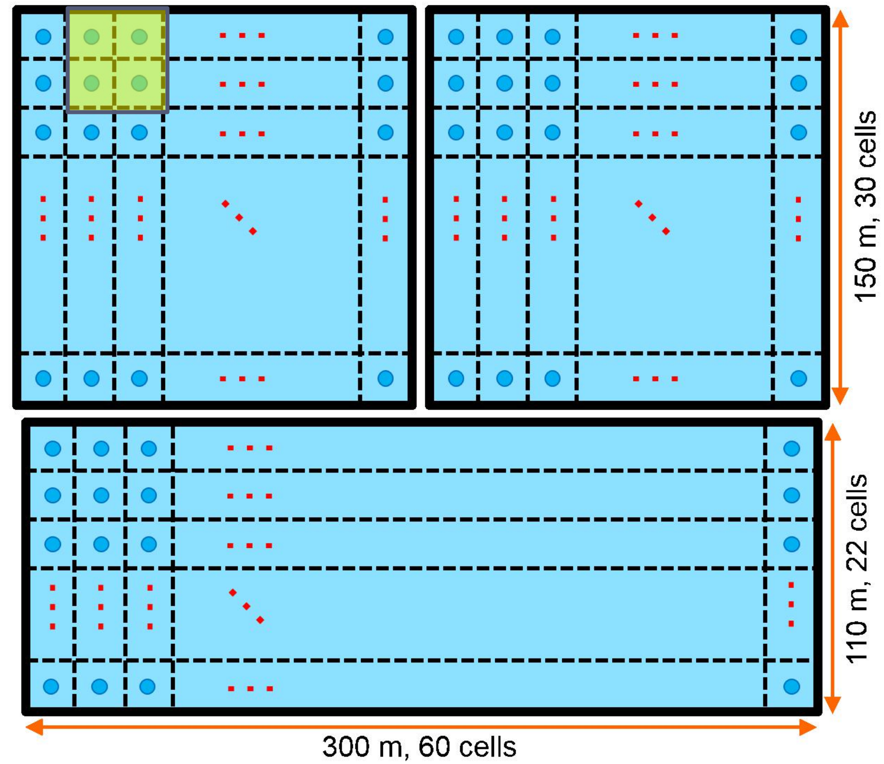
@ 1 R_{earth} B~0.5G gyroR 10 R_{earth}

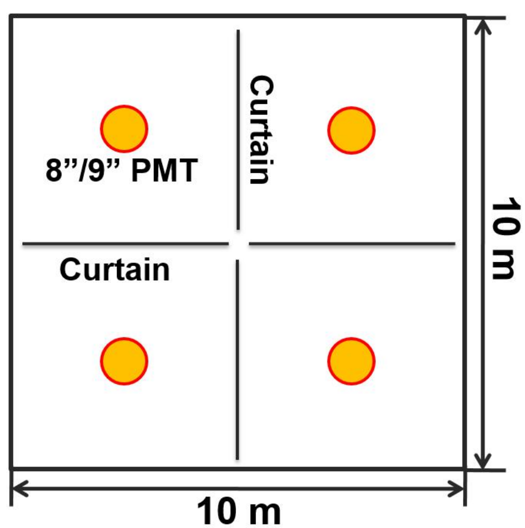


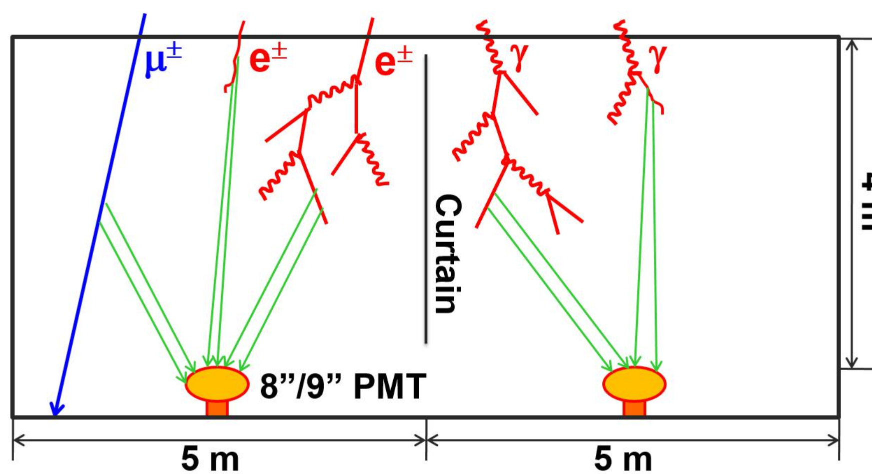


Cells of WCDA

- 3 water ponds:
  - 78,000 m^2 in total;
  - 4 m effective depth;
  - 3120 cells, with an 8"/9" PMT in each cell;
  - Cells are partitioned with black curtains.



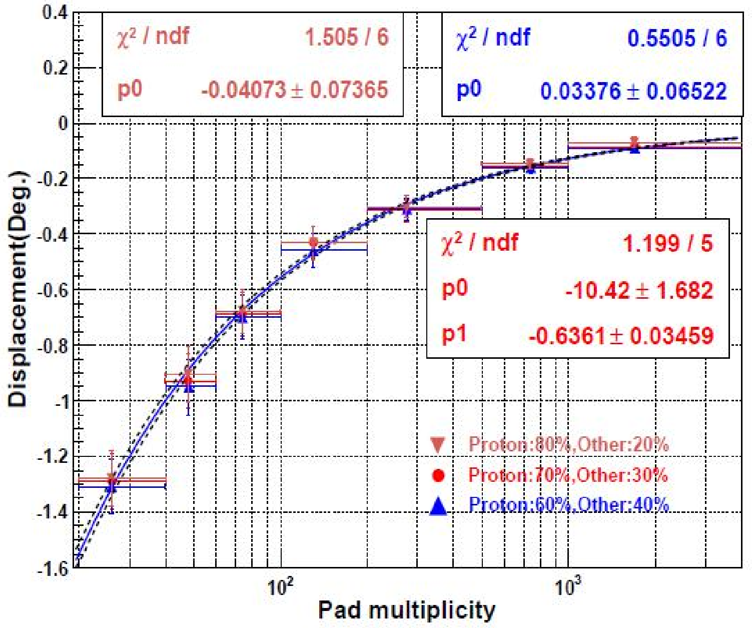


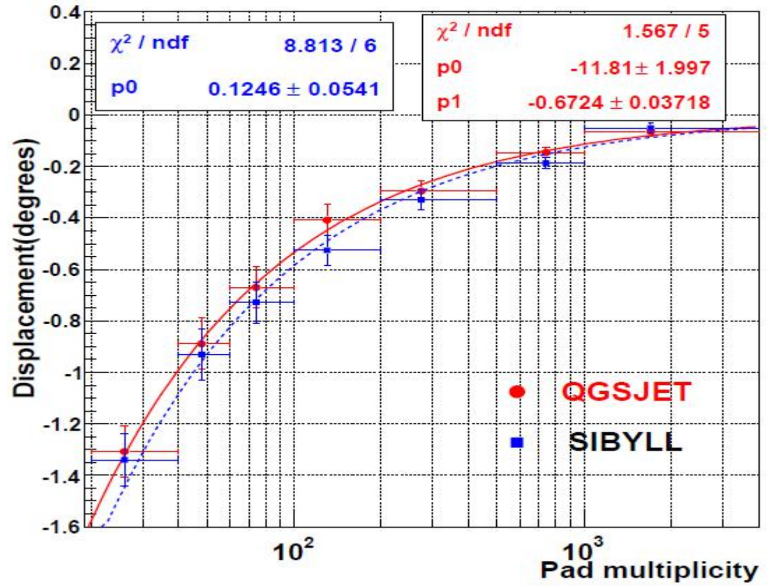


Energy scale: Moon Shadow displacement

Two systematic uncertainties may affect the Multiplicity-Energy relation:

- the assumed primary CR chemical composition (7%)
- the uncertainties of different hadronic models (6%)

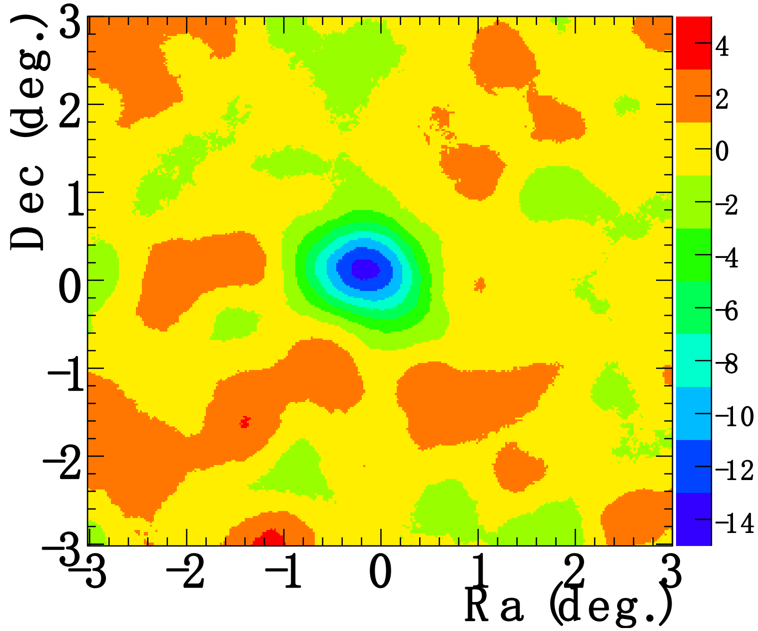


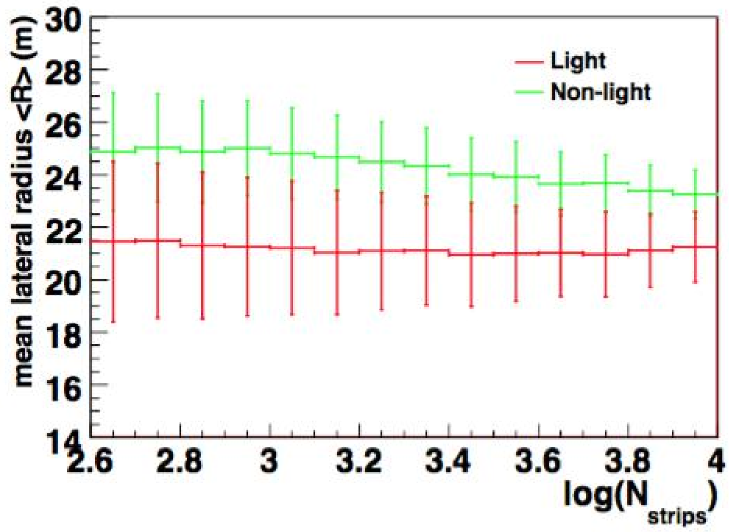


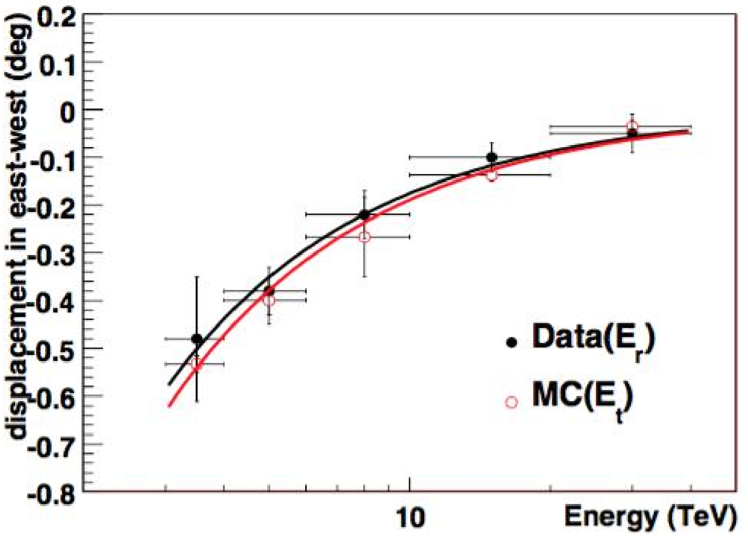
The energy scale error is estimated to be smaller than 13%
in the energy range 1 – 30 (TeV/Z).

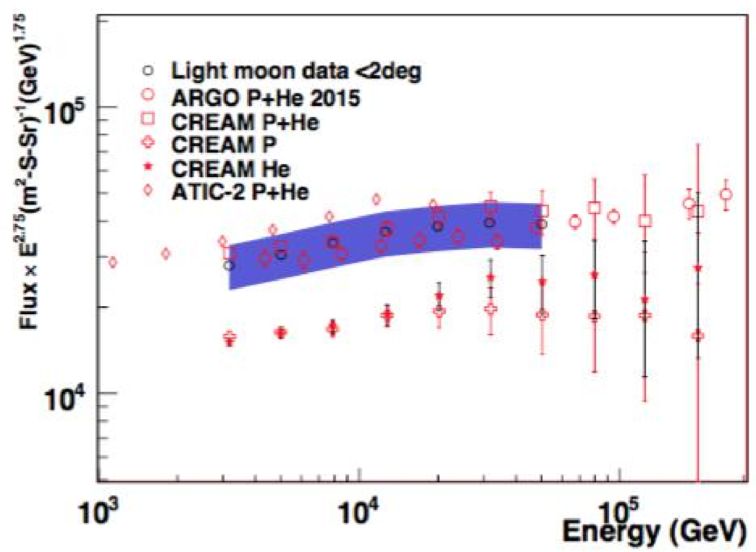
ARGO coll., Phys.Rev. D 84 (2011) 022003 / ARGO coll., Phys.Rev. D 85 (2012) 022002

Energy scale 2: light moon displacement





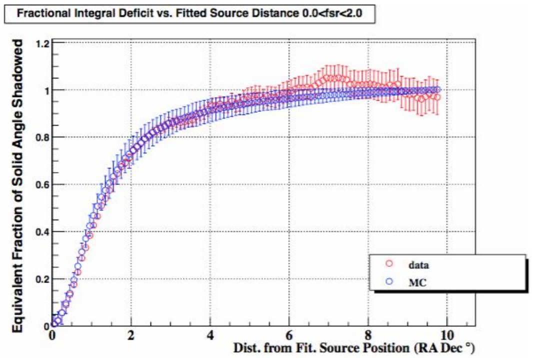


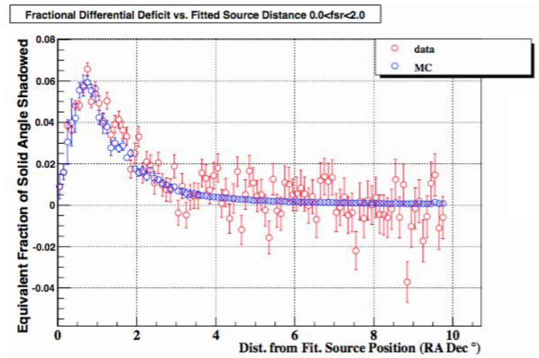


The energy scale error is estimated to be smaller than 17% in the energy range 1 – 50 (TeV).

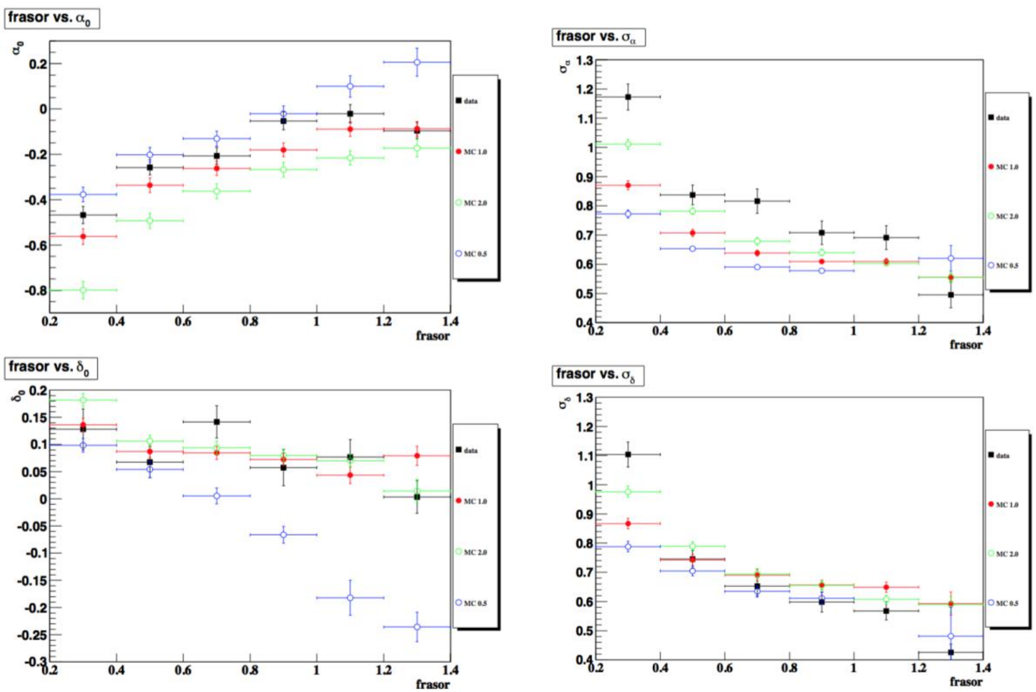
Accept by APP

Energy scale 3: from Milagro



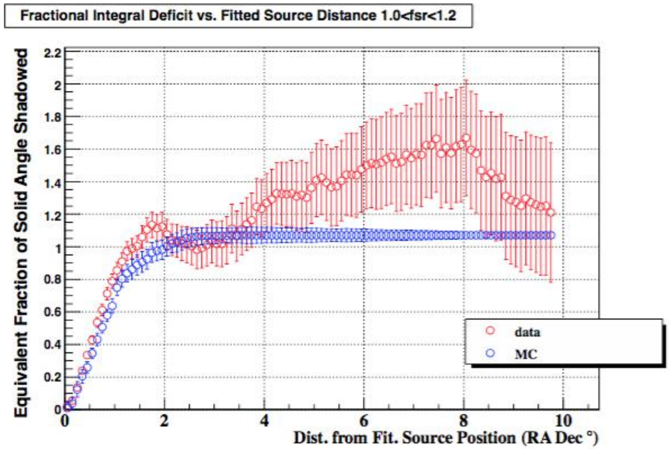


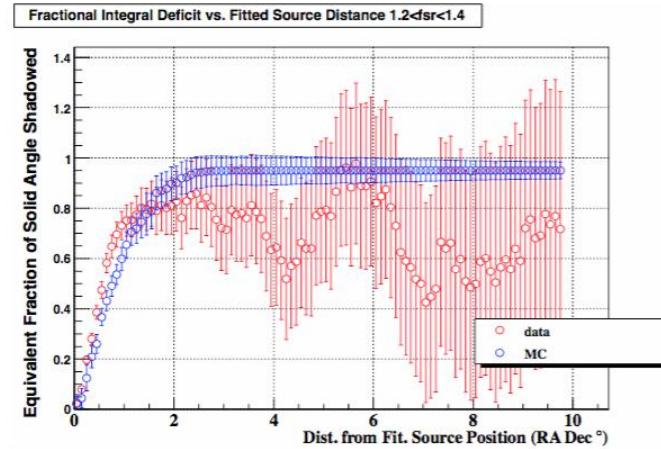
$$f(\alpha,\delta;A,\alpha_0,\delta_0,\sigma_\alpha,\sigma_\delta)=\frac{A}{2\pi\left(\sigma_\alpha^2+\sigma_\delta^2\right)}\exp\left[-\frac{1}{2}\left(\frac{(\alpha-\alpha_0)^2}{\sigma_\alpha^2}+\frac{(\delta-\delta_0)^2}{\sigma_\delta^2}\right)\right] \quad (6.1)$$

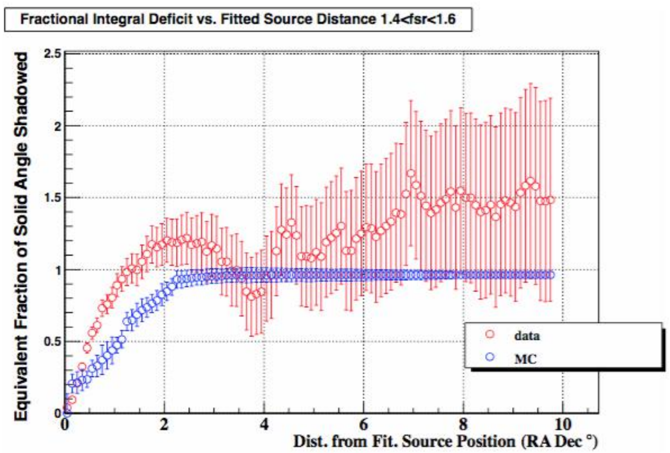


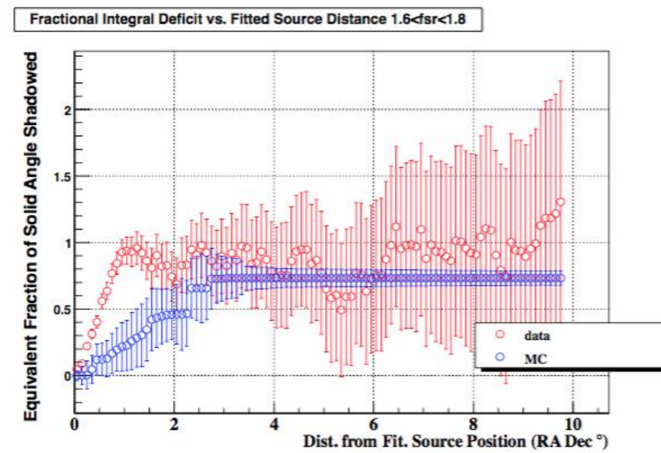
x	$\alpha_0(^\circ)$	$\delta_0\ (^\circ)$	$\sigma_\alpha\ (^\circ)$	$\sigma_\delta\ (^\circ)$
data	-0.265+/-0.019	0.106+/-0.016	0.919+/-0.021	0.779+/-0.018
2.0	-0.488+/-0.033	0.113+/-0.010	0.819+/-0.010	0.787+/-0.016
1.5	-0.442+/-0.032	0.114+/-0.010	0.798+/-0.009	0.772+/-0.015
1.3	-0.423+/-0.032	0.106+/-0.010	0.780+/-0.009	0.778+/-0.015
1.1	-0.387+/-0.032	0.111+/-0.010	0.765+/-0.008	0.775+/-0.014
1.0	-0.408+/-0.034	0.114+/-0.012	0.773+/-0.010	0.764+/-0.015
0.9	-0.367+/-0.032	0.083+/-0.011	0.752+/-0.007	0.776+/-0.014
0.8	-0.348+/-0.032	0.077+/-0.011	0.729+/-0.008	0.758+/-0.015
0.5	-0.247+/-0.031	0.054+/-0.011	0.703+/-0.006	0.730+/-0.014

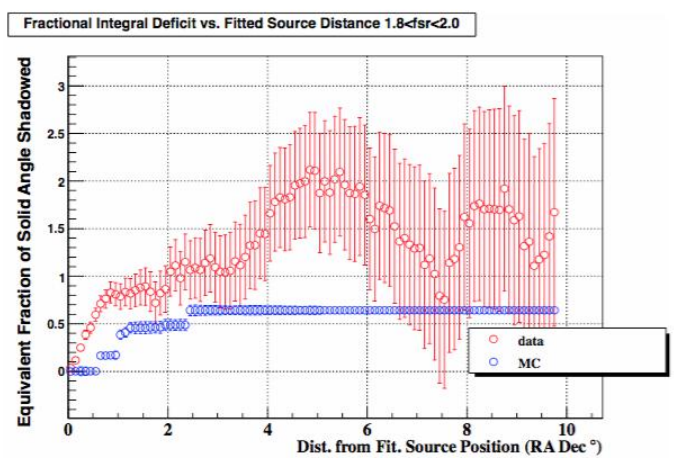
Grant E. Christopher Ph.D thesis


Fractional Integral Deficit vs. Fitted Source Distance 1.0<fsr<1.2
Equivalent Fraction of Solid Angle Shadowed
Dist. from Fit. Source Position (RA Dec °)
data
MC

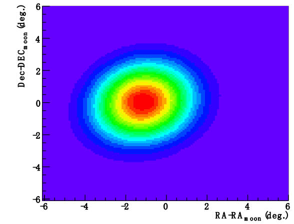

Fractional Integral Deficit vs. Fitted Source Distance 1.2<fsr<1.4
Equivalent Fraction of Solid Angle Shadowed
Dist. from Fit. Source Position (RA Dec °)
data
MC

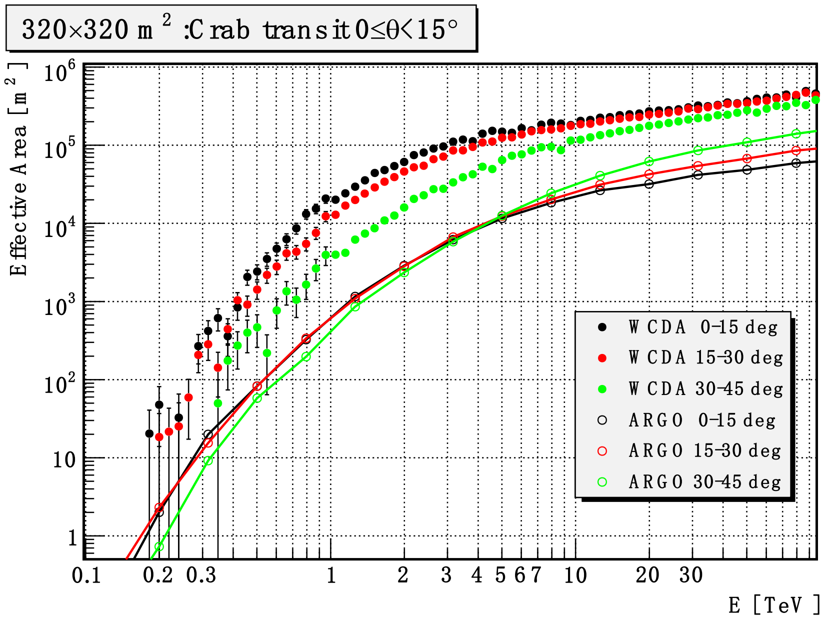

Fractional Integral Deficit vs. Fitted Source Distance 1.4<fsr<1.6
Equivalent Fraction of Solid Angle Shadowed
Dist. from Fit. Source Position (RA Dec °)
data
MC

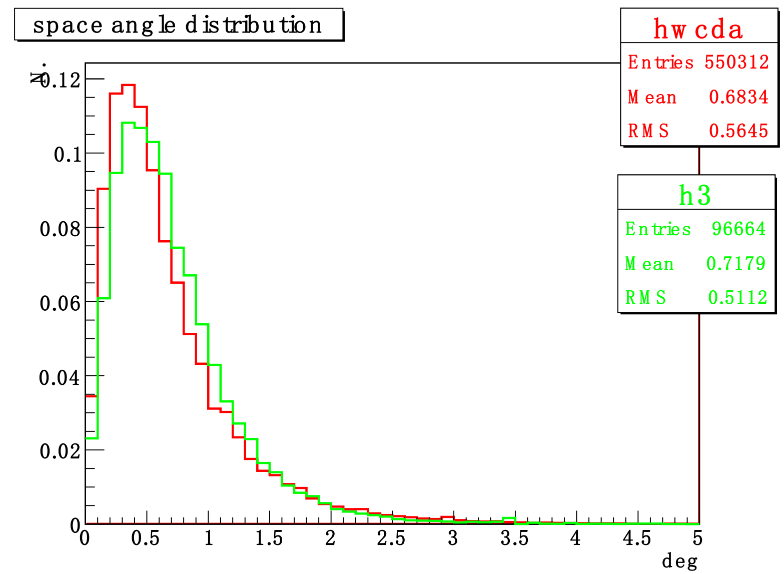

Fractional Integral Deficit vs. Fitted Source Distance 1.6<fsr<1.8
Equivalent Fraction of Solid Angle Shadowed
Dist. from Fit. Source Position (RA Dec °)
data
MC


Fractional Integral Deficit vs. Fitted Source Distance 1.8<fsr<2.0
Equivalent Fraction of Solid Angle Shadowed
Dist. from Fit. Source Position (RA Dec °)
data
MC

WCDA moon expectation

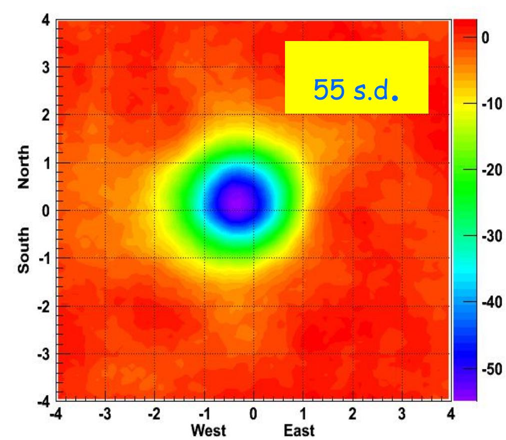


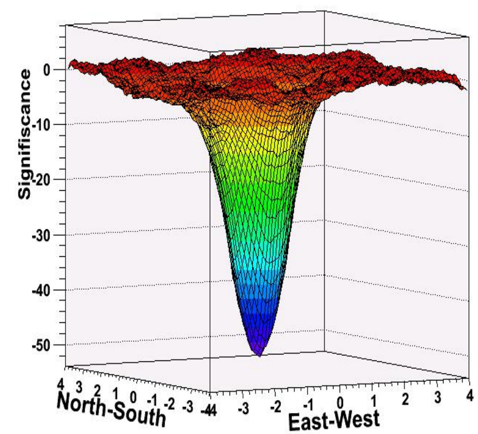




- Argo month moon data as reference;
  - 9 sigma/month
- Large effective area at 3TeV: 16X
- A little better Angular Resolution:
- WCDA moon map with nFit > 100:
  - 36 sigma/month
  - 6. sigma/transit

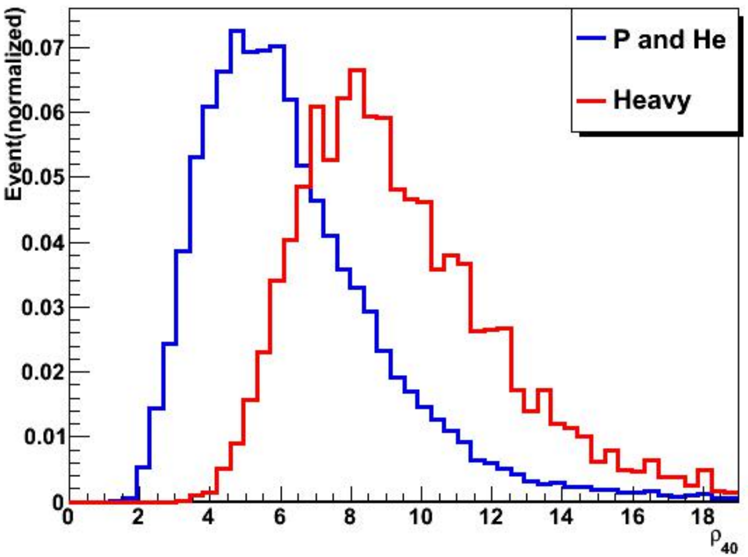
Analysis cuts : N_{HIT} > 100 and θ < 50°

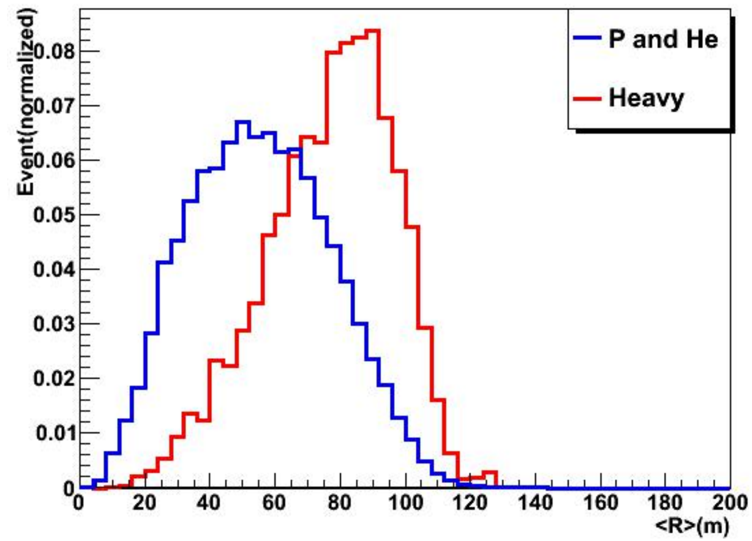




≈ 9 standard deviations / month

Light moon data or pure proton moon data



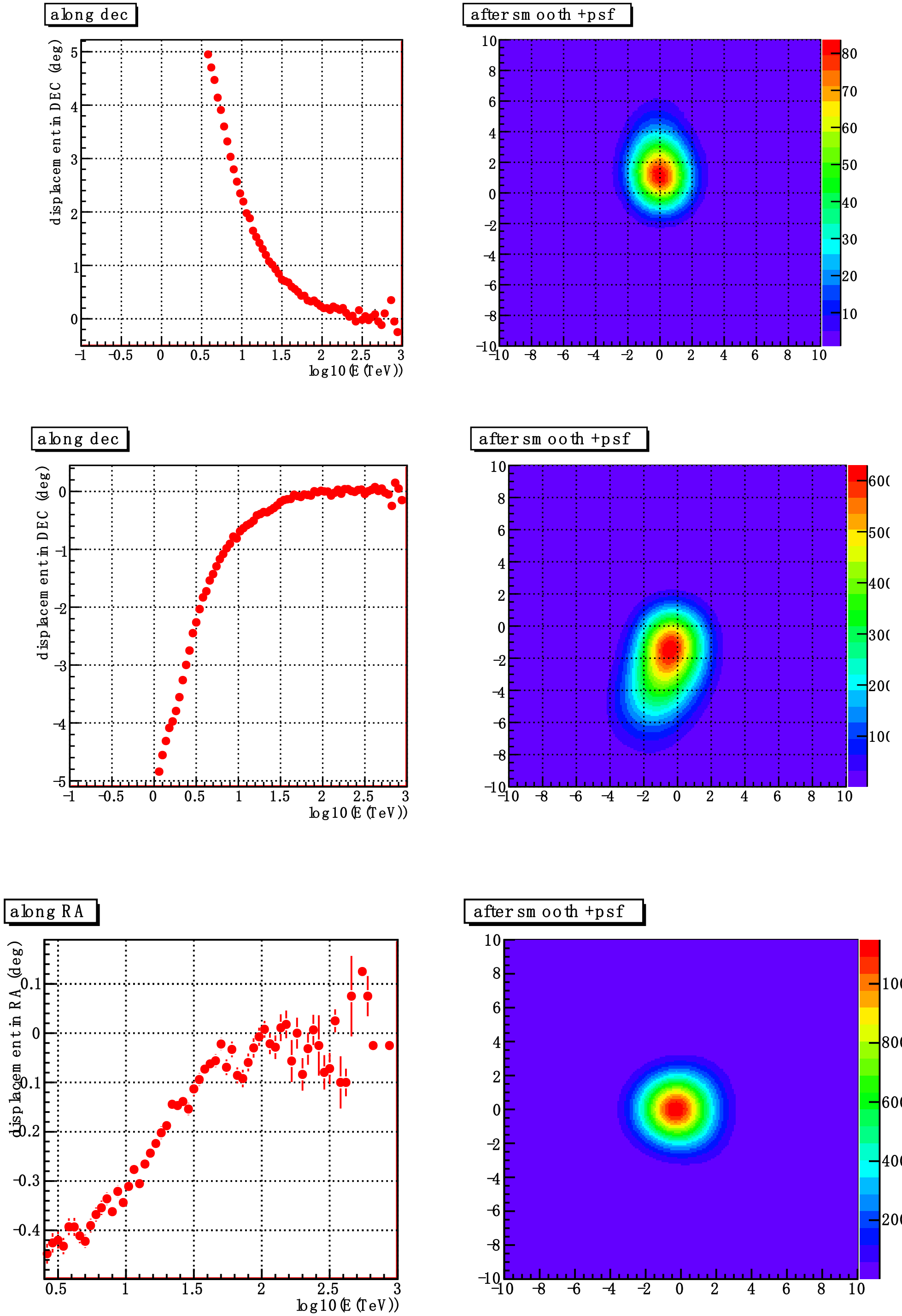


nFit	E(TeV)	P40 (light ratio)		
		4%	2%	1%
10-50	0.58	58.73%	28.50%	4%
50-200	1.49	69.41%	53.11%	41%
200-500	4.98	70.93%	55.14%	41.44%
500-800	12.47	71.71%	59.39%	48.89%
>800	27.61	51.18%	38.95%	26.61%

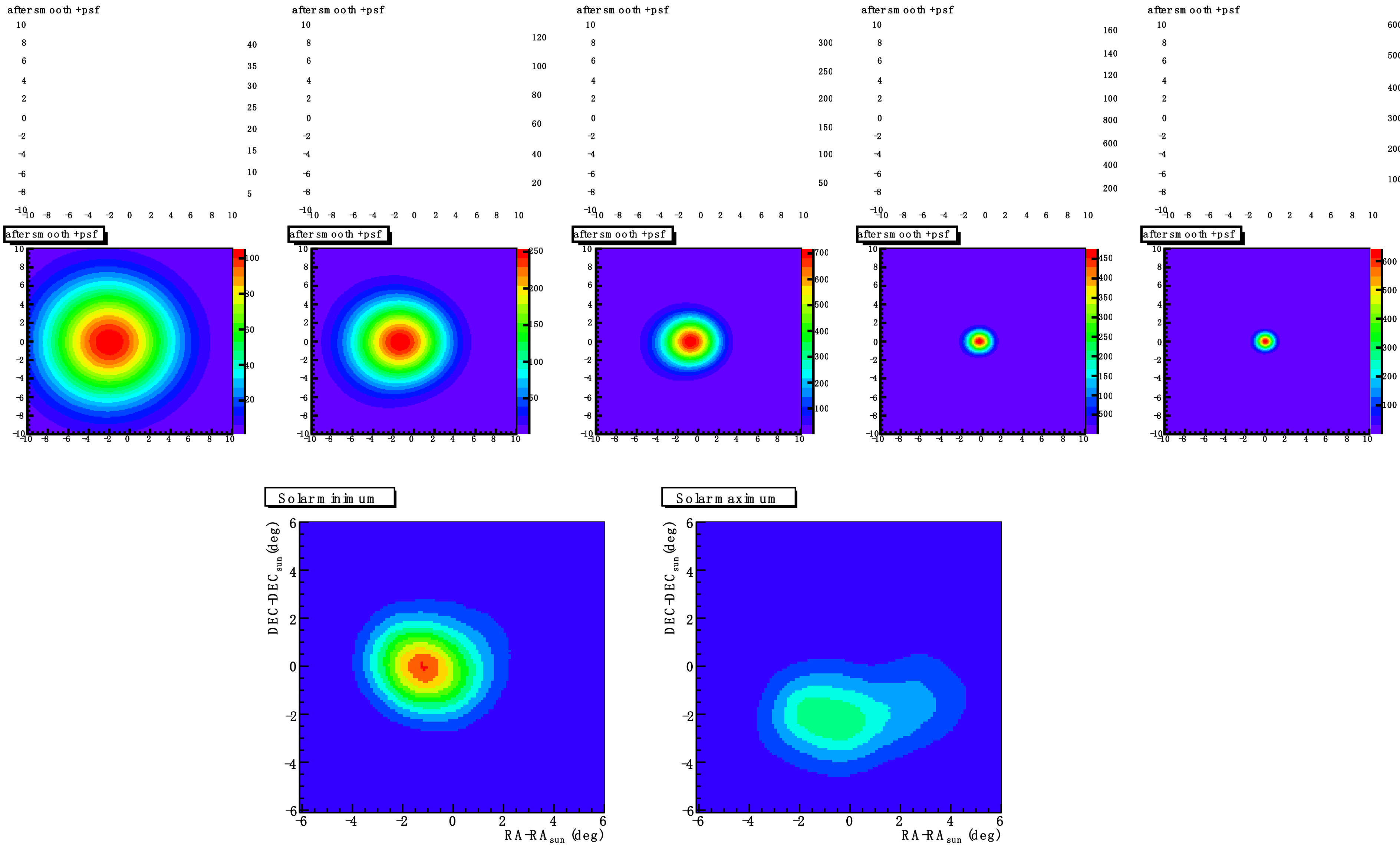
		P40 (p ratio)		
nFit	E(TeV)	10%	4%	2%
10-50	0.58	0.69%	0.69%	0.69%
50-200	1.49	31.98%	4.75%	2.75%
200-500	4.98	38.32%	22.35%	9.08%
500-800	12.47	35.55%	14.41%	2.31%
>800	27.61	21.19%	9.40%	6.76%

Light moon map: 25 sigma/month
6 months data can reproduce argo-1 work

Proton moon map: 16 sigma/month
6 months data can reproduce argo-2 work



In away sector → north
In towards sector → south

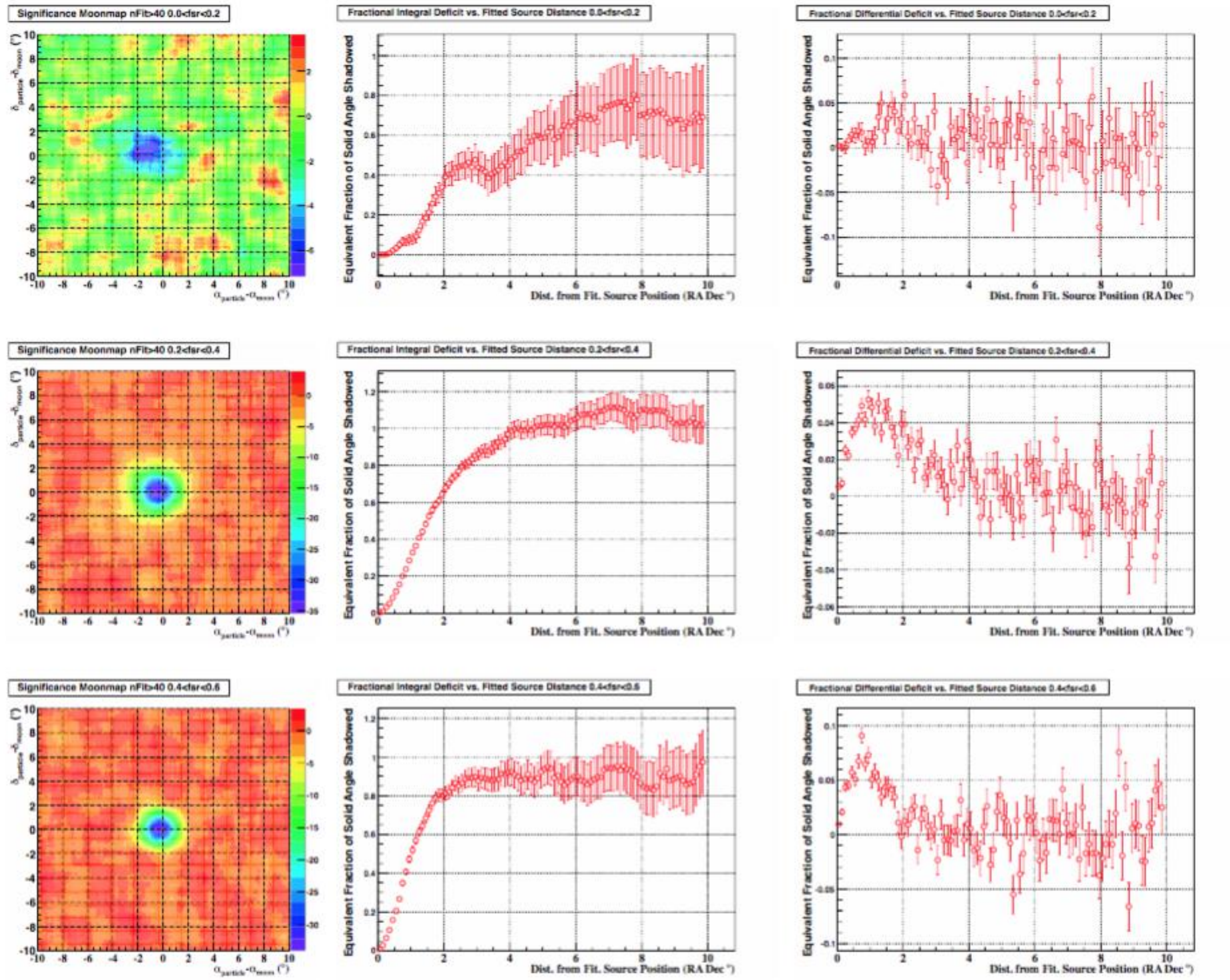


after smooth +psf
after smooth +psf
after smooth +psf
after smooth +psf
after smooth +psf
Solar minimum
Solar maximum
DEC−DEC sun (deg)
RA−RA sun (deg)

Summary and outlook

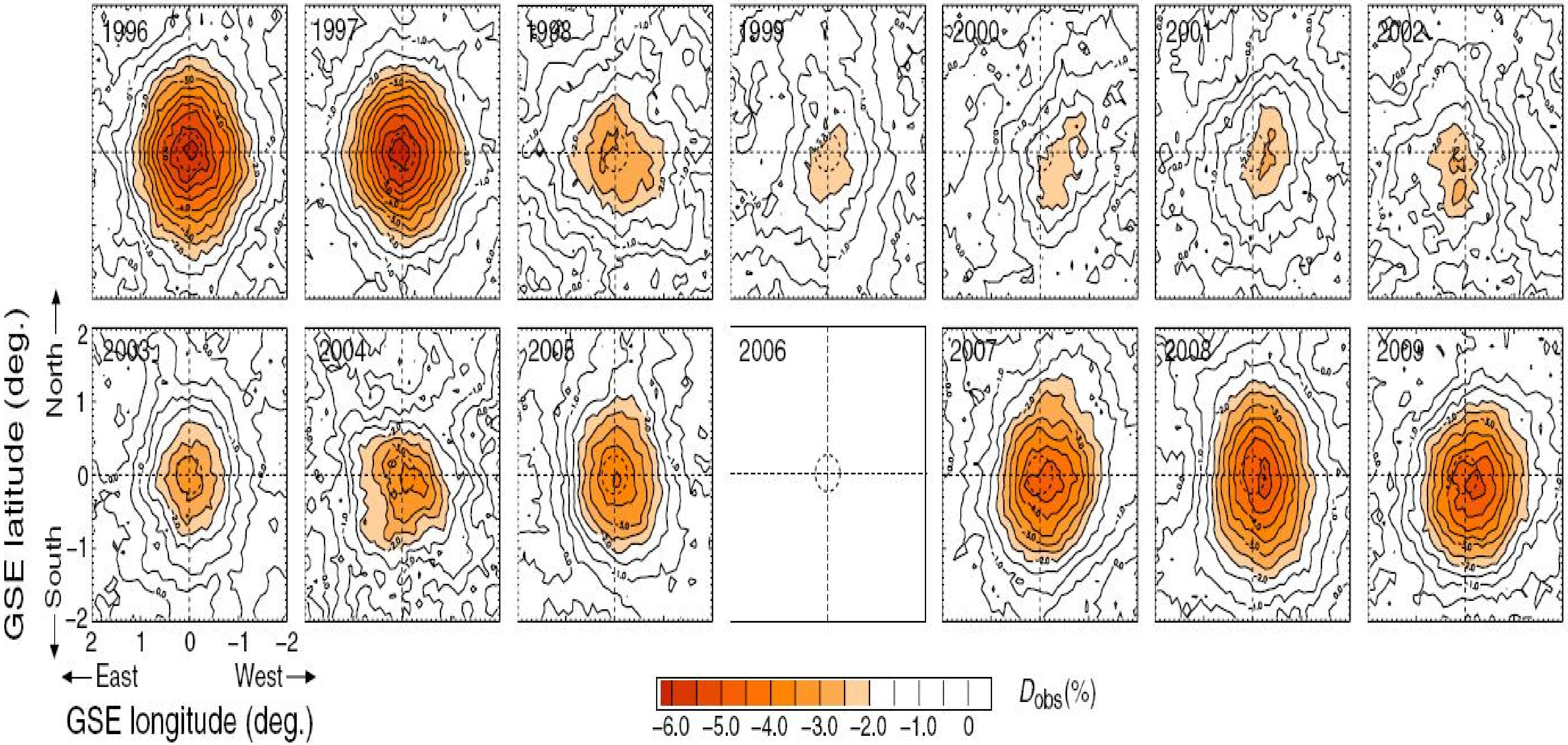
- A code to study sun/moon shadow is ready, the simulation result looks consistent with experimental observation;
- WCDA looks good at energy scale work;
- Sun/Moon shadow need air shower and detector realistic response implementation;
- Sun shadow displacement, deficit ratio as function of solar activity;
- Sun shadow results comparison @ different source surface;
- A real CME event implementation.

backup



$$f(\alpha, \delta; A, \alpha_0, \delta_0, \sigma_\alpha, \sigma_\delta) = \frac{A}{2\pi\left(\sigma_\alpha^2 + \sigma_\delta^2\right)} \exp\left[-\frac{1}{2}\left(\frac{(\alpha - \alpha_0)^2}{\sigma_\alpha^2} + \frac{(\delta - \delta_0)^2}{\sigma_\delta^2}\right)\right] \tag{6.1}$$

Tibet ASr在10TeV探测到日影随太阳活动（1996-2009）变化



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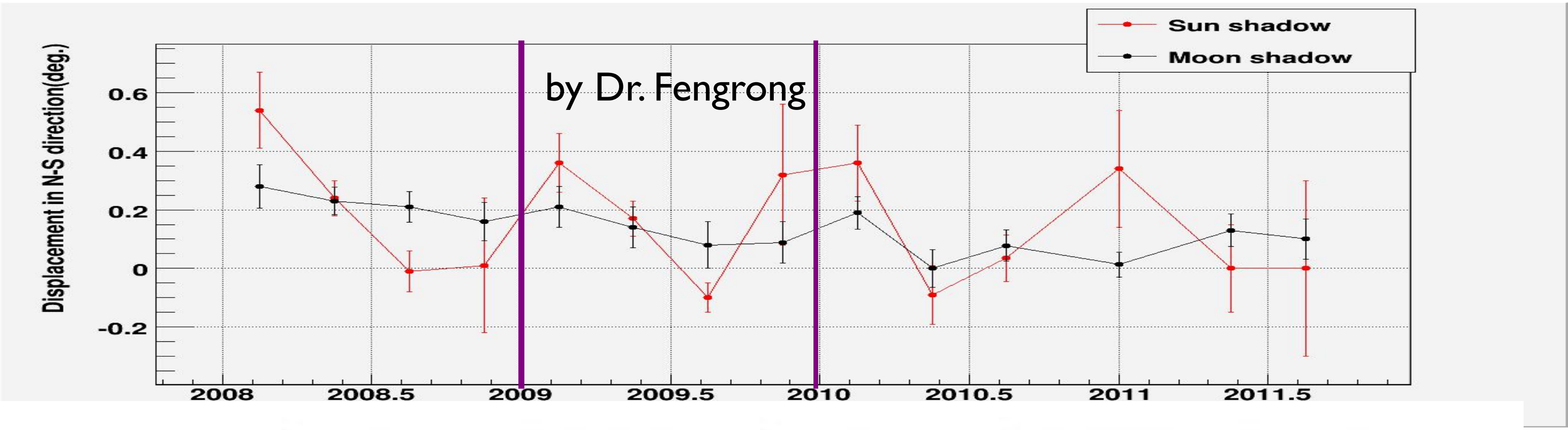
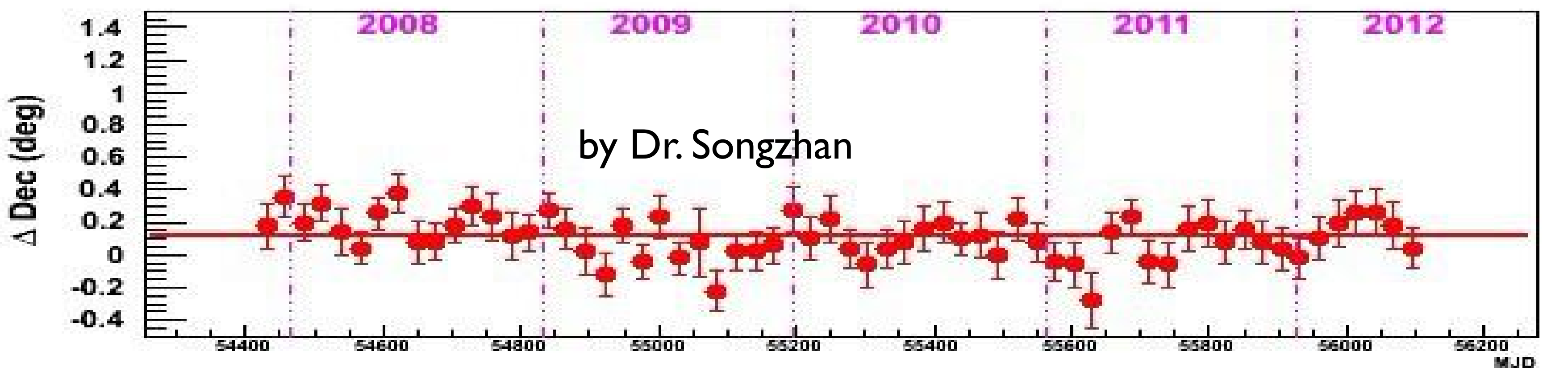
Displacement in N-S of the sun shadow VS time

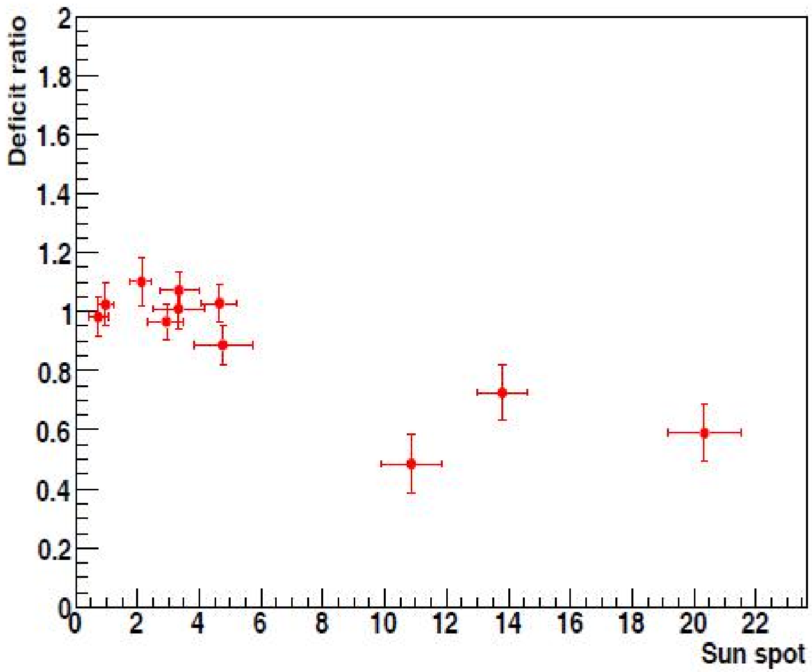




-Systemetic error are stable

-displacement in N-S direction modulated from 2008 to 2011.12

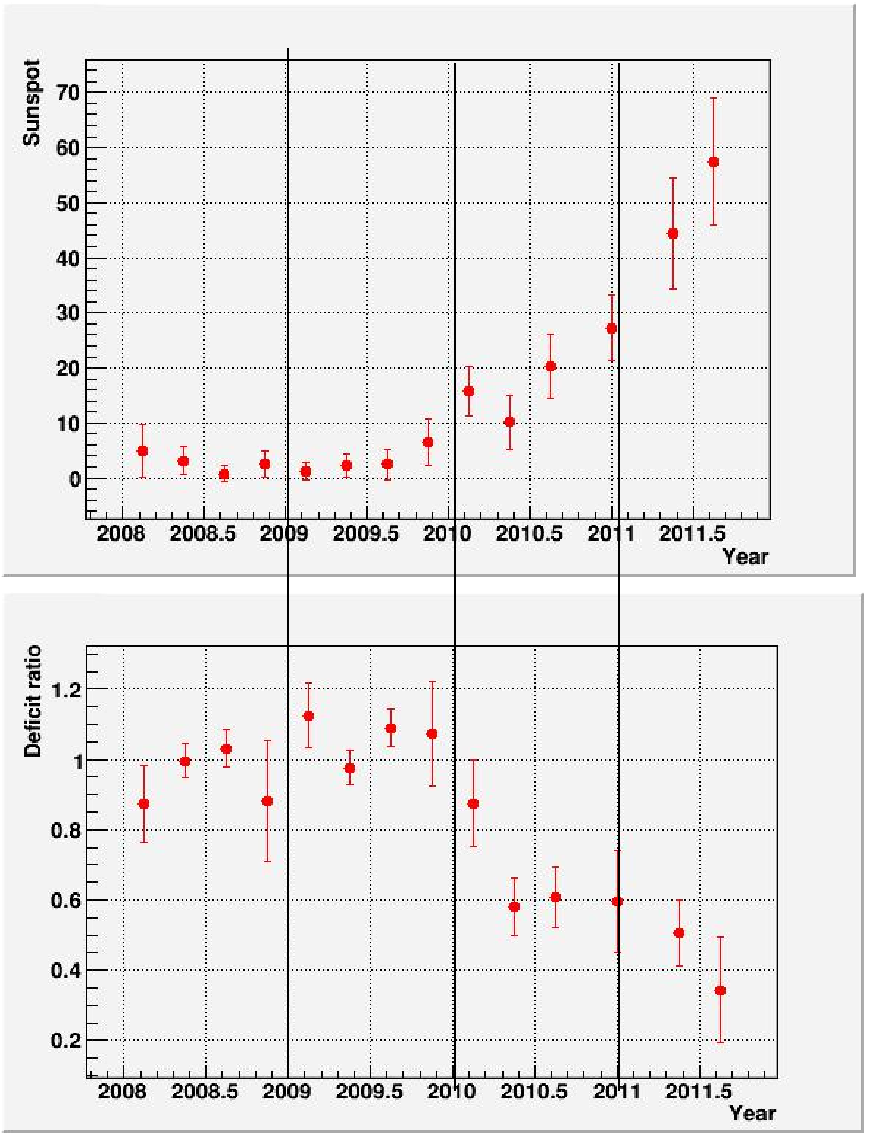
Deficit ratio Vs. Sunspot



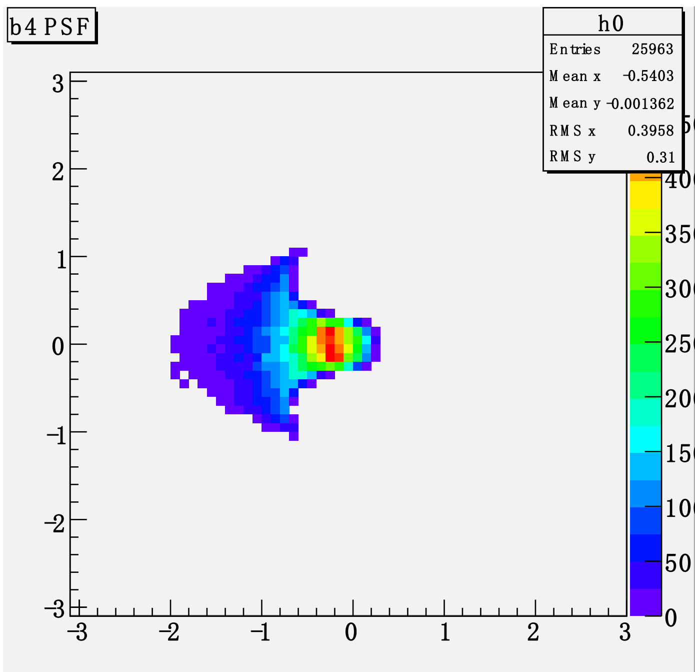
-correlation probability : 99.99%,

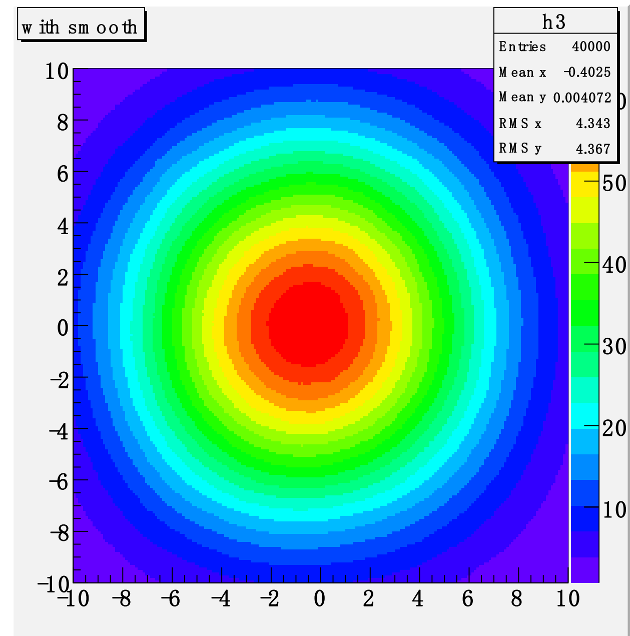
-correlation coefficient:-84%

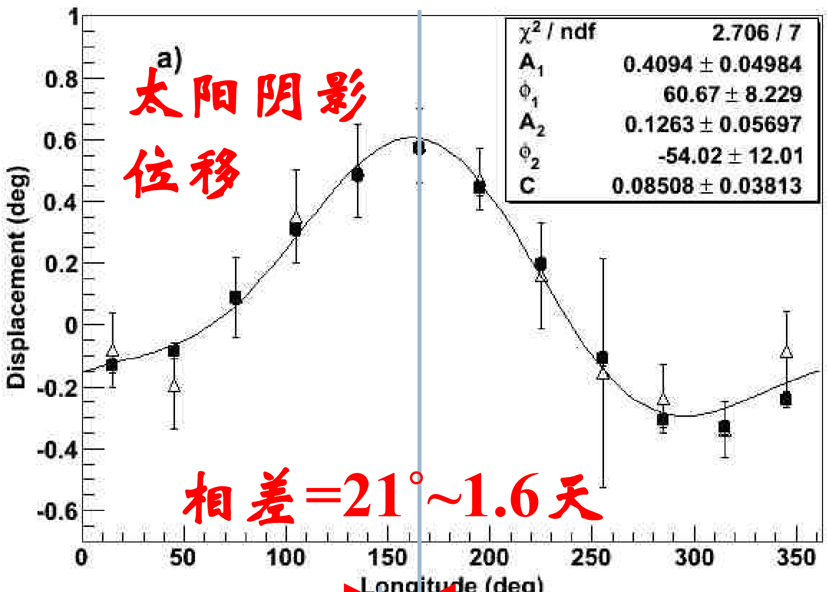
-Reported in ICRC2011

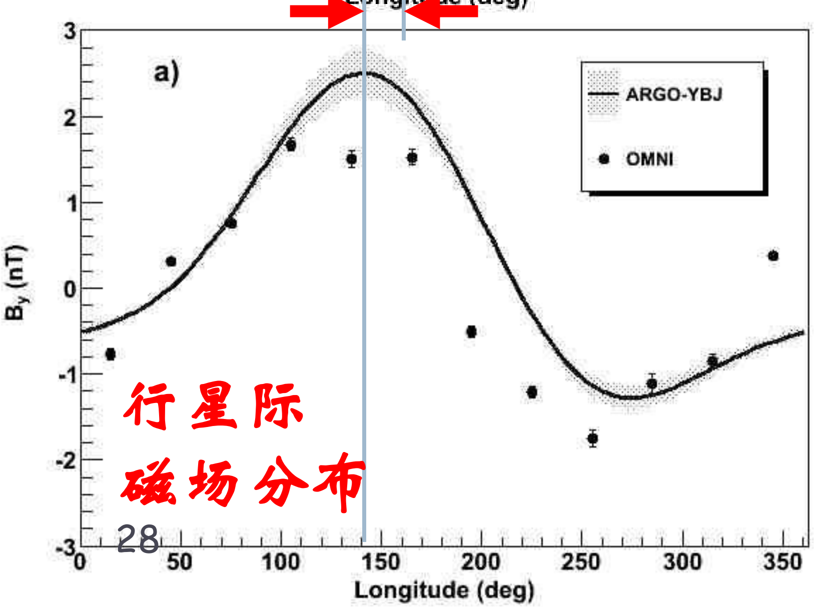


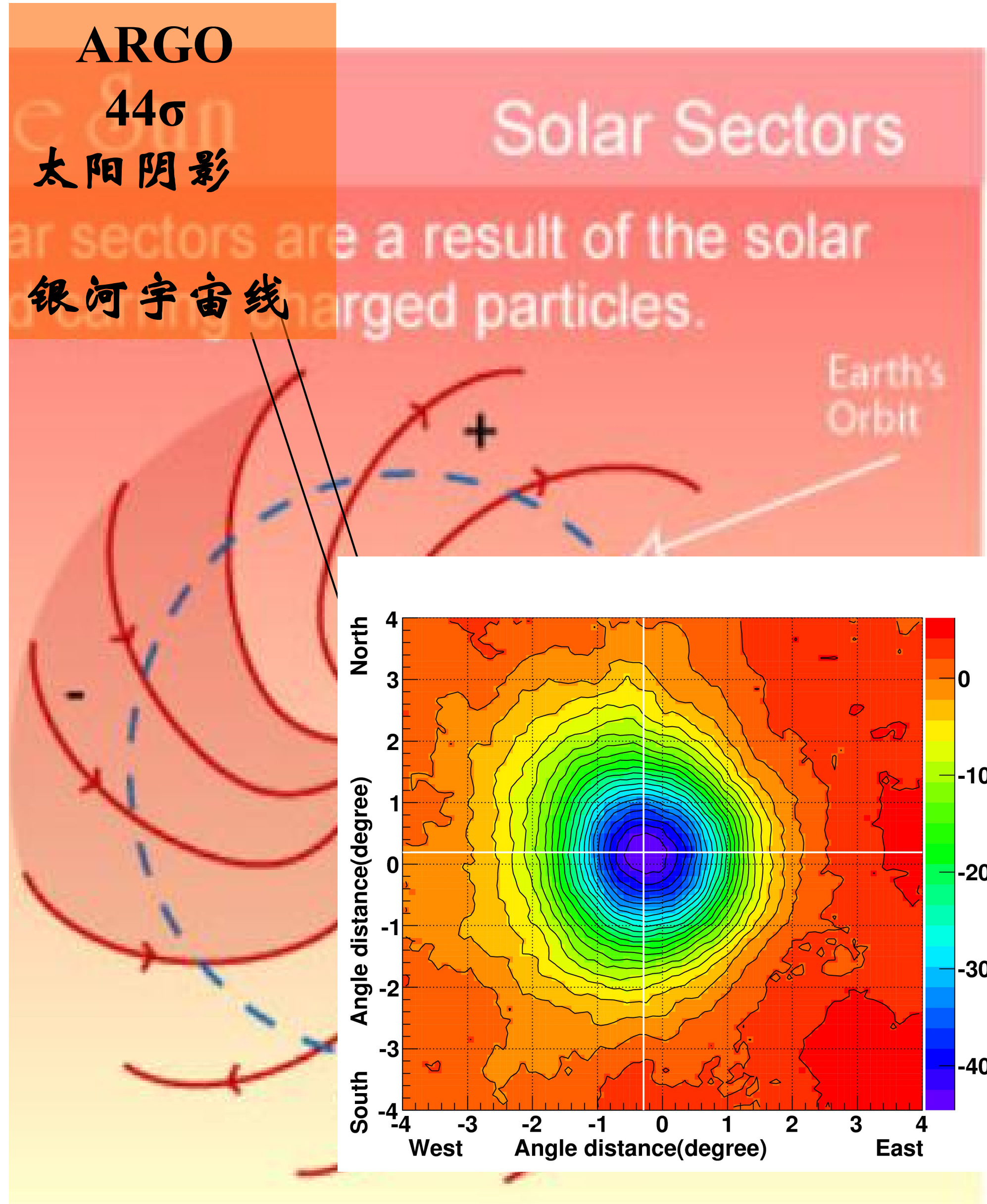
Some simulation result






a)
太阳阴影
位移
χ² / ndf 2.706 / 7
A1 0.4094 ± 0.04984
φ1 60.67 ± 8.229
A2 0.1263 ± 0.05697
φ2 -54.02 ± 12.01
C 0.08508 ± 0.03813
相差=21°~1.6天
Displacement (deg)
Longitude (deg)


a)
ARGO-YBJ
OMNI
行星际
磁场分布
By (nT)
Longitude (deg)


ARGO
44σ
太阳阴影
银河宇宙线
Solar Sectors
Earth's Orbit
North
South
West
East
Angle distance(degree)