Studying the Temporal Variation of the Cosmic-Ray Sun Shadow Using IceCube Data

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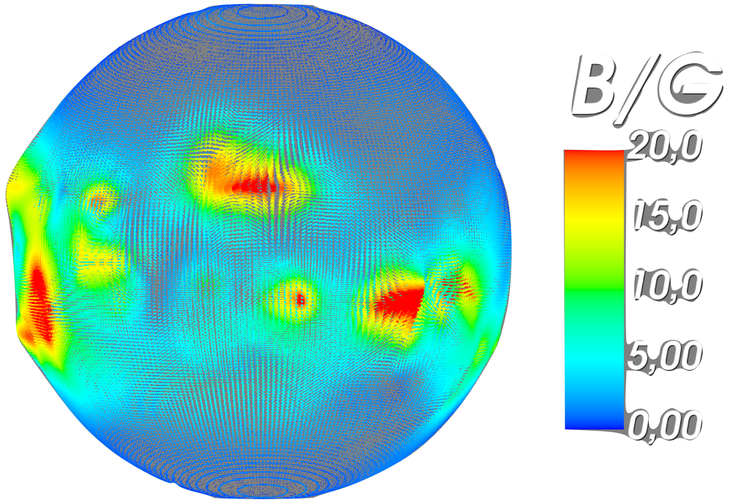

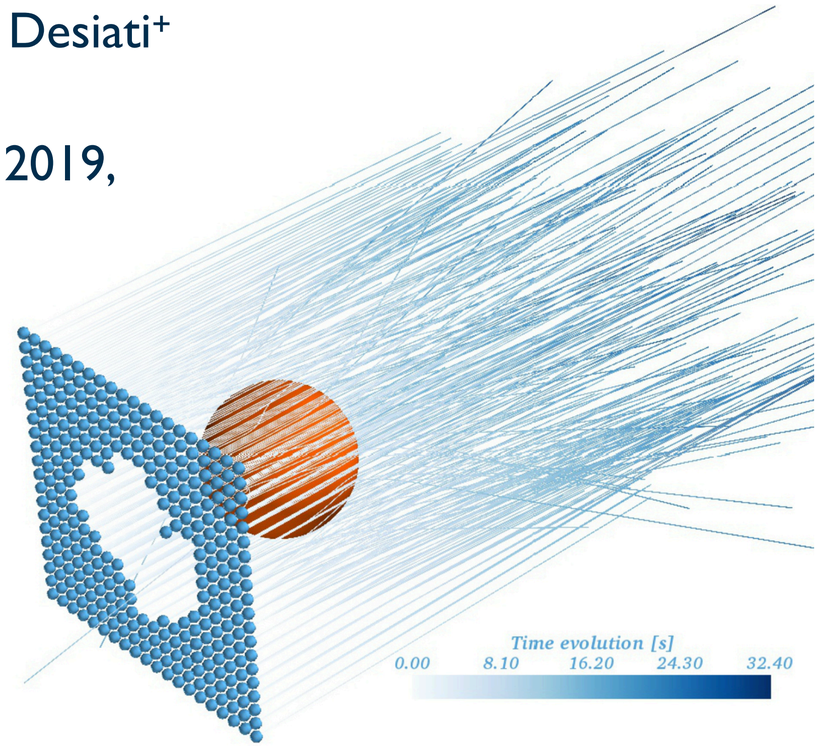

Motivation

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- Number of observed secondary muons from directions around Moon/Sun is reduced due to blocked cosmic rays (CRs)
- Shadowing effect measured with high statistical significance by several experiments (e.g. Tibet, ARGO-YBJ, HAWC)
- Moon shadow serves as a standard candle (known apparent size, no magnetic field)
- Sun shadow serves as indirect measurement of solar magnetic field ➡ Compare models
  - Tibet, PRL 111, 2013: ~10 TeV CRs, measuring air showers
  - Here: ~55 TeV CRs, measuring atmospheric muons

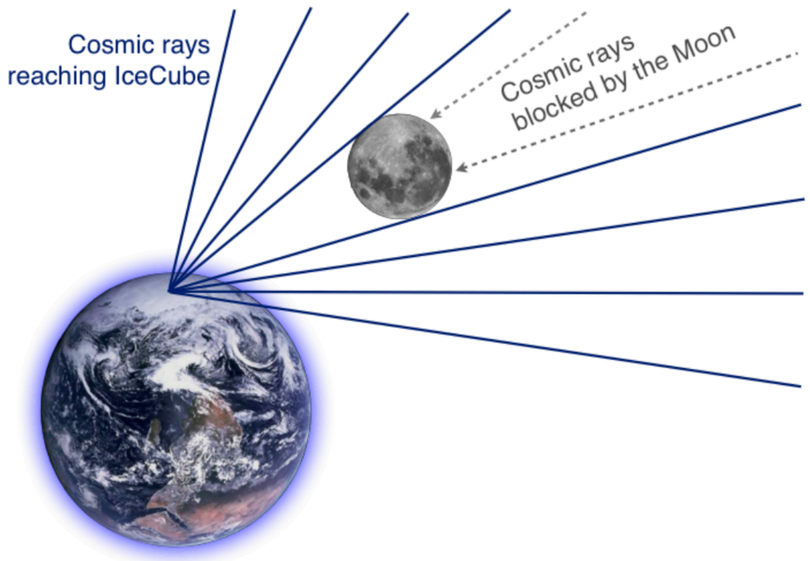


Figure credit: M. Santander

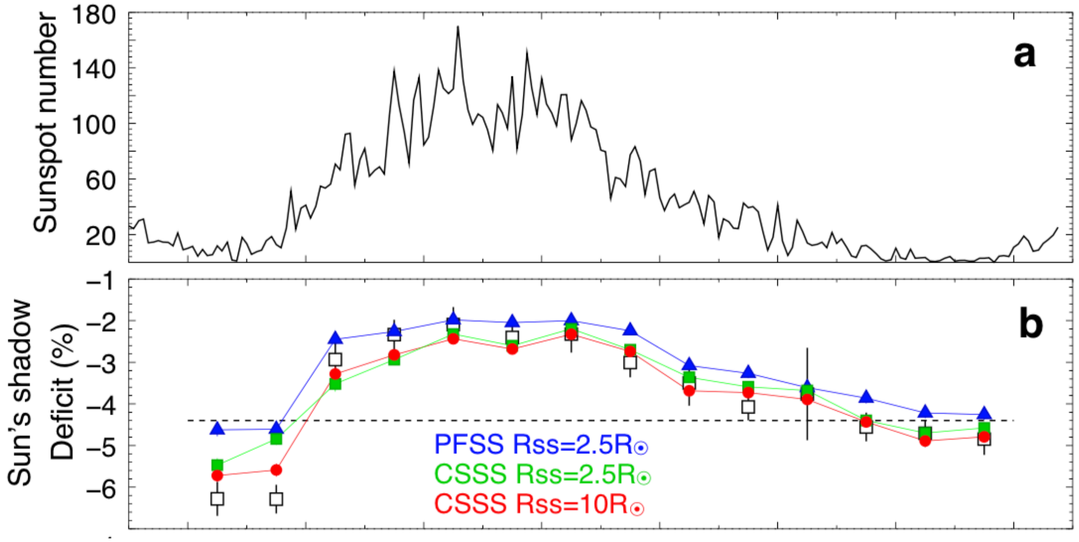


Figure from Tibet, PRL 111, 2013

Analysis Method

Analysis Method

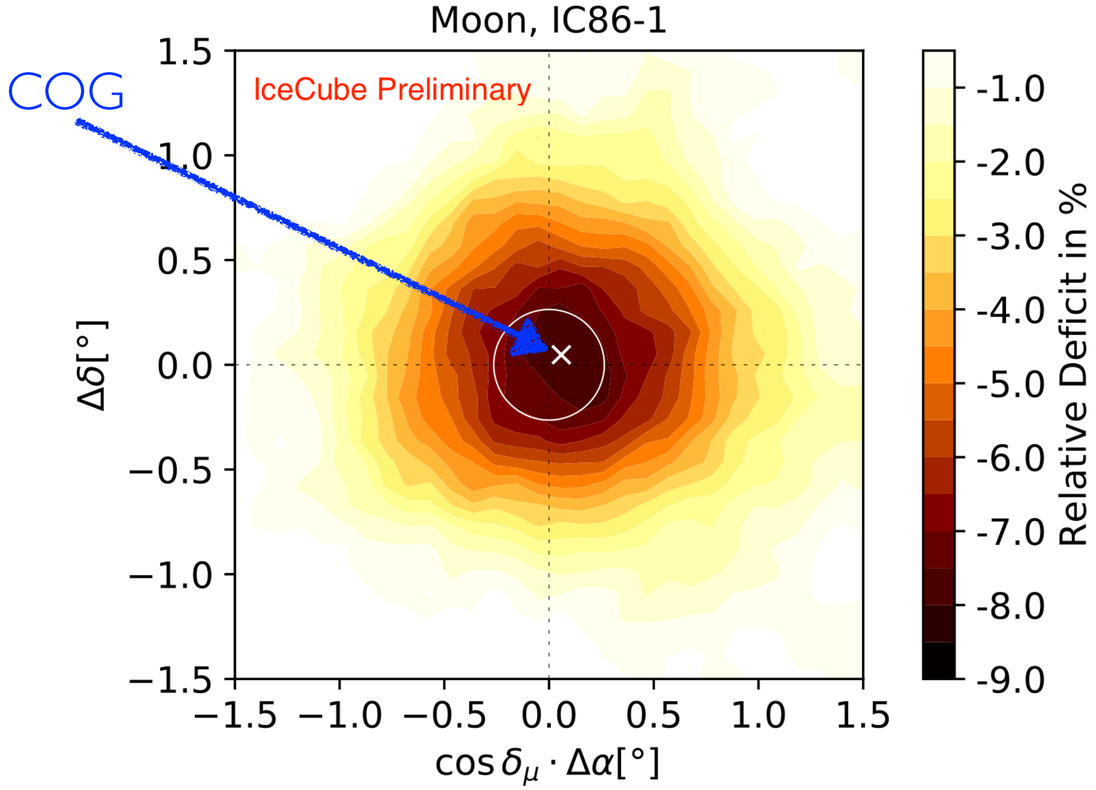
- Right ascension/decl. relative to Moon/Sun
- On- and off-source windows ($6^\circ \times 6^\circ$ each)
- Bin-wise ($0.1^\circ \times 0.1^\circ$) relative deficit in on-source region in a 2D grid
- Visualize the shadow:
  - Boxcar smoothing (0.7° smoothing radius)
  - Determine center of gravity (COG)
- Numerical analysis:
  - Relative deficit within 1.0° around COG

Relative coordinates:

$$\Delta\alpha = \alpha_\mu - \alpha_{\mathrm{S/M}}$$
$$\Delta\delta = \delta_\mu - \delta_{\mathrm{S/M}}$$

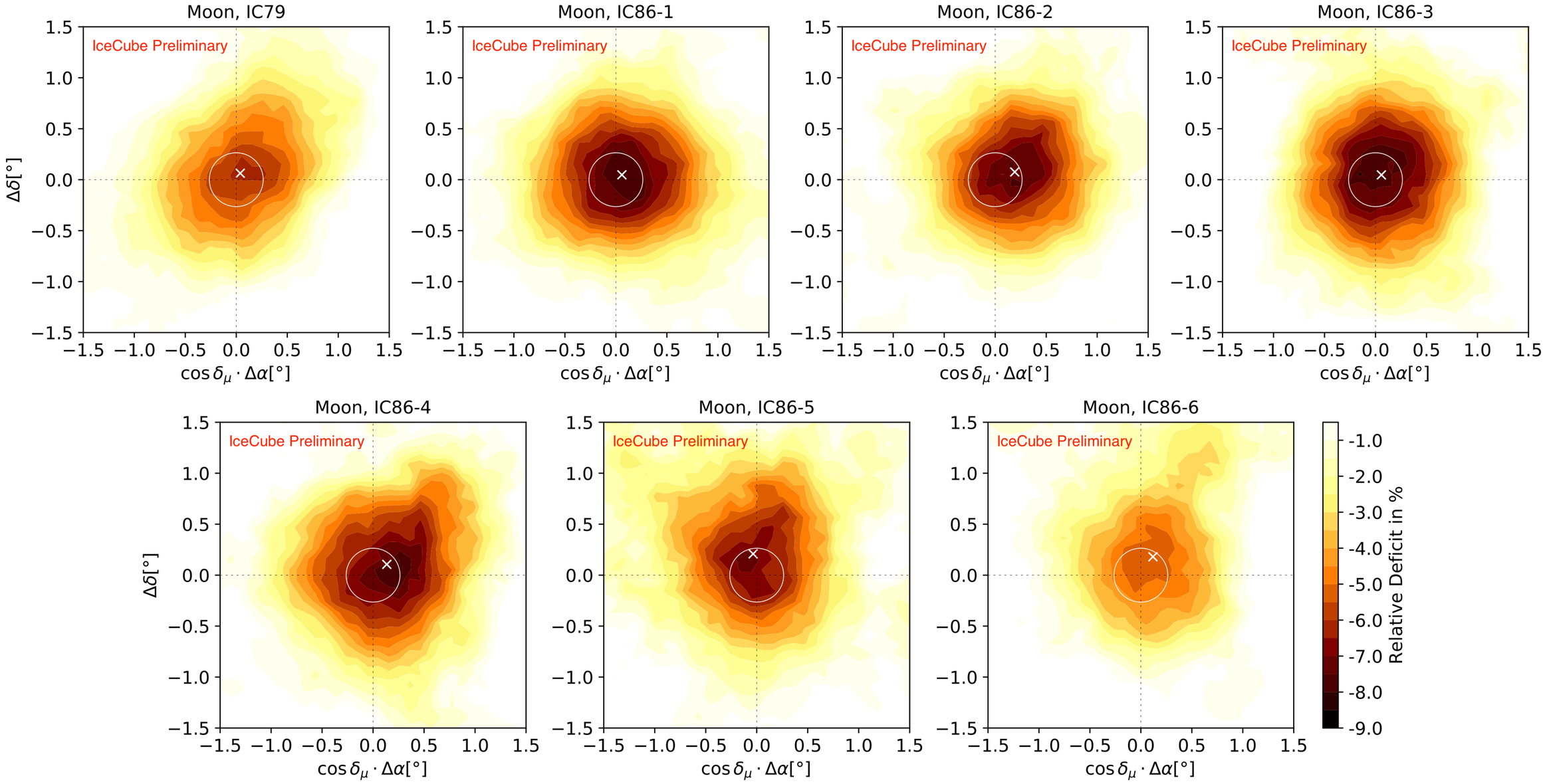
Relative deficit:

$$\frac{\Delta N}{\langle N \rangle} = \frac{N_{\mathrm{on}} - \langle N_{\mathrm{off}} \rangle}{\langle N_{\mathrm{off}} \rangle}$$



Results: Part I

Results: Moon

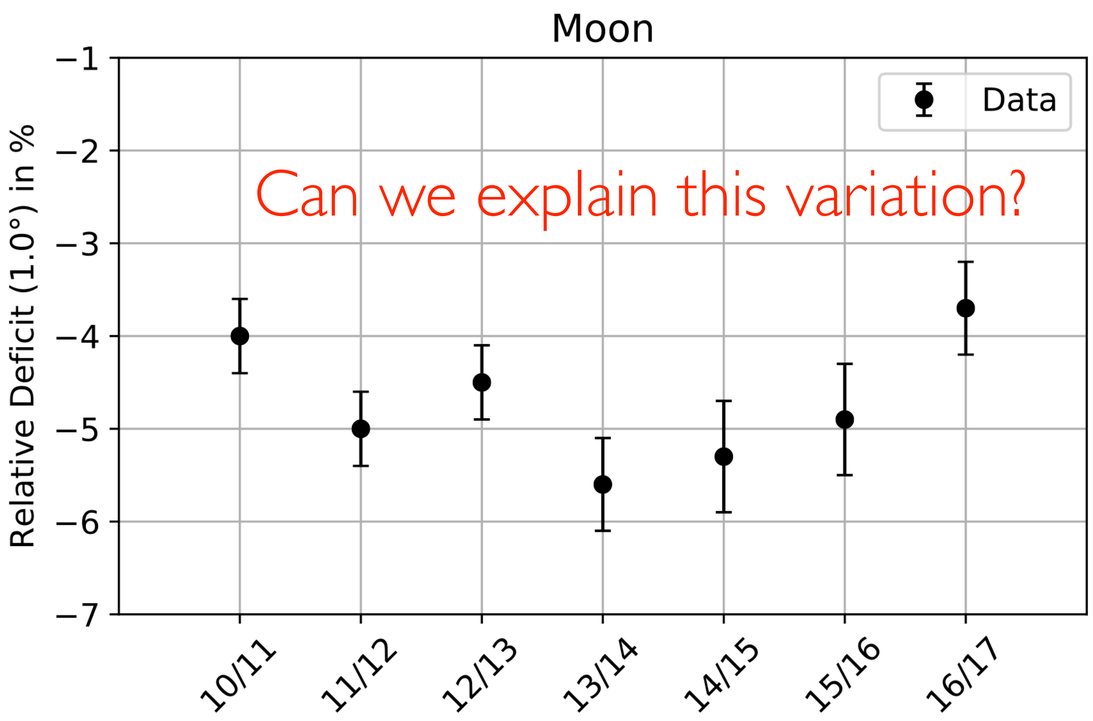


Results: Moon

- Cosmic rays „see“ Moon as unmagnetized ball
- In 2D: disk-like cosmic-ray sink
- Expect relative deficit to depend on average elevation and apparent Moon radius

Object	Year	Events / 10^6	Avg. Elev. / °	Radius / °
Moon	2010/11	7.9	22.1	0.261
Moon	2011/12	7.7	20.7	0.270
Moon	2012/13	6.4	18.9	0.274
Moon	2013/14	4.5	17.7	0.272
Moon	2014/15	3.8	16.9	0.265
Moon	2015/16	4.1	16.7	0.257
Moon	2016/17	5.1	17.2	0.251

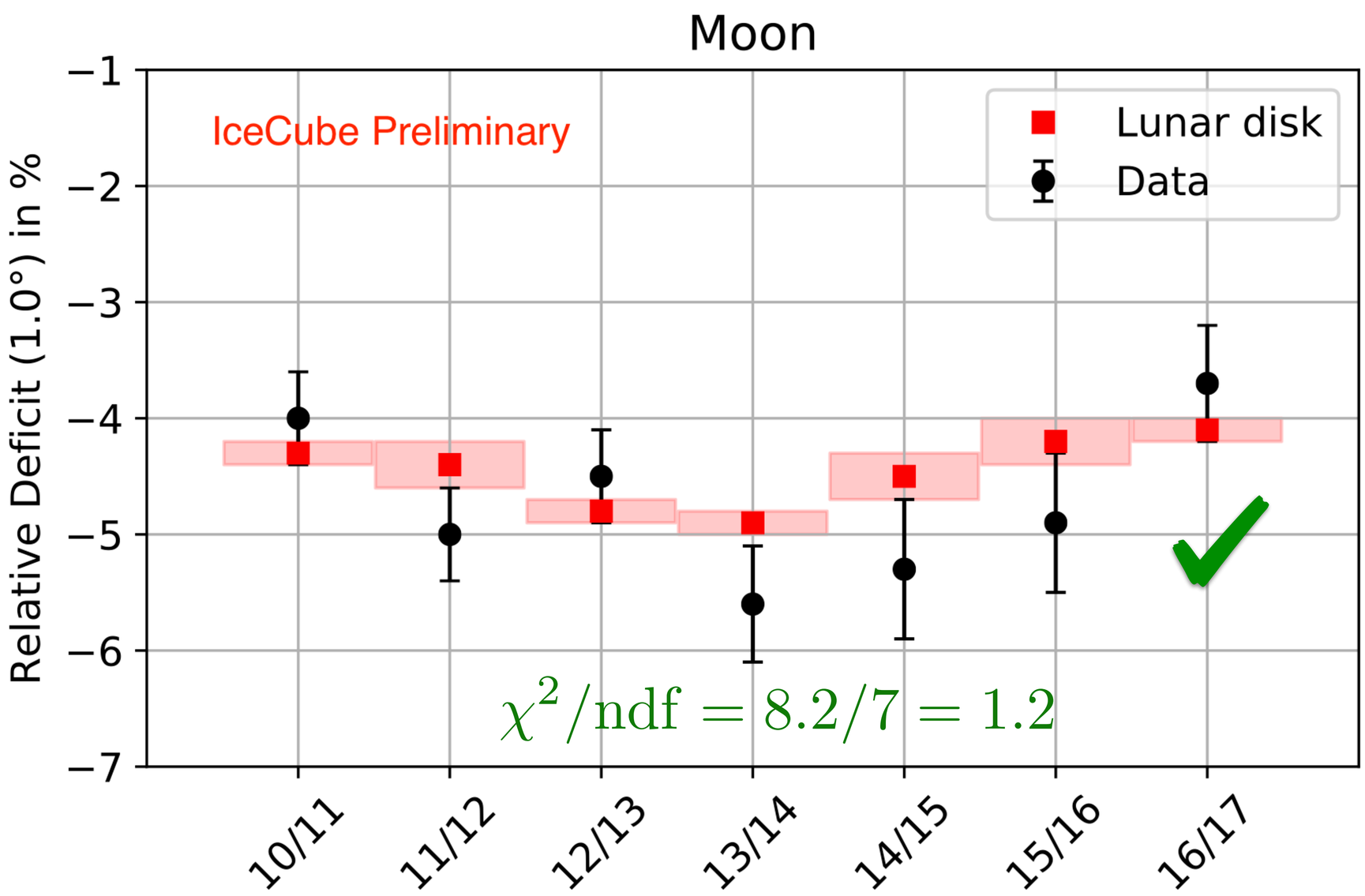
!



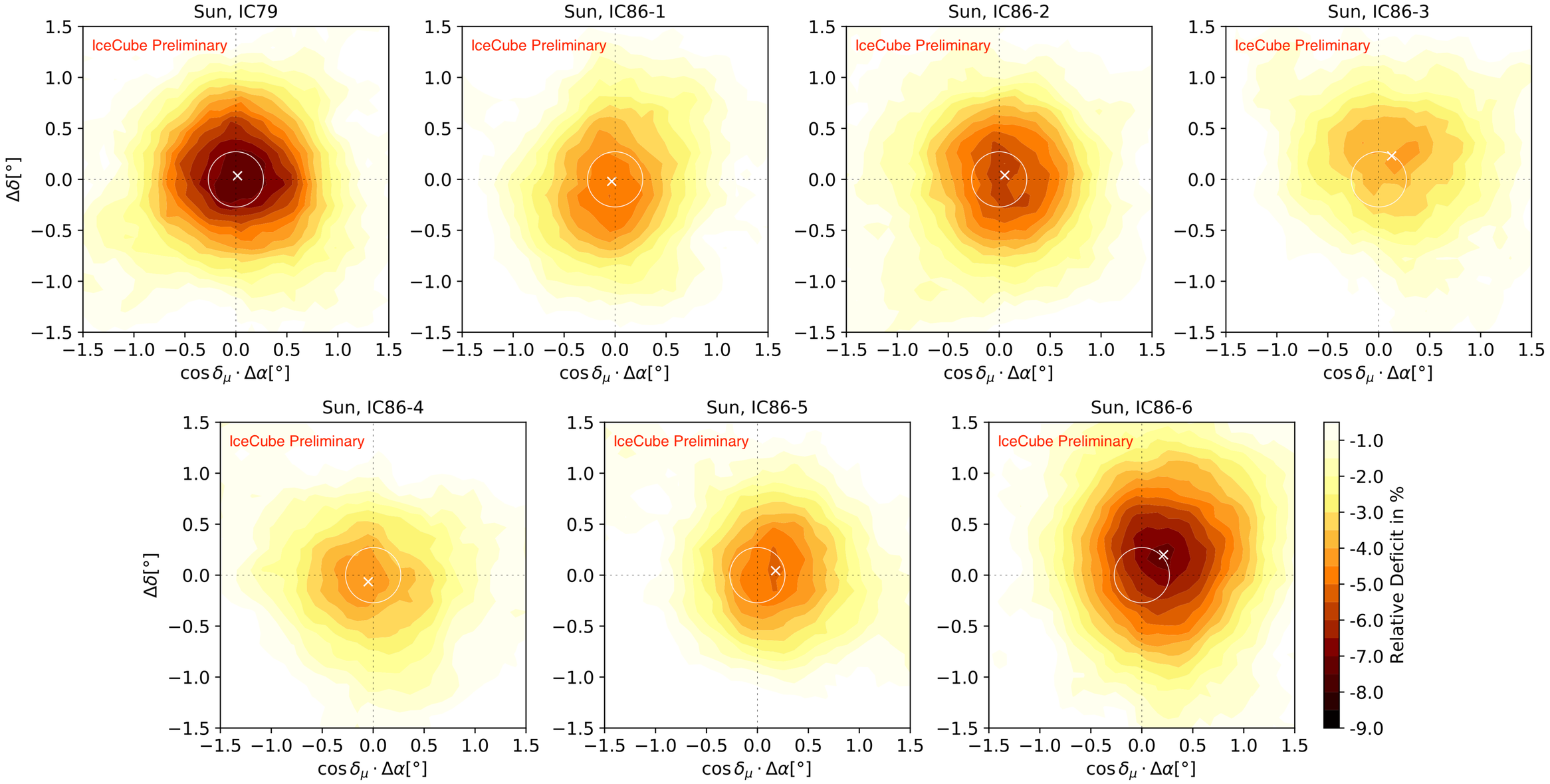
Key to (almost) all questions: simulations

- Exclude events with primary cosmic-ray direction within Moon disk

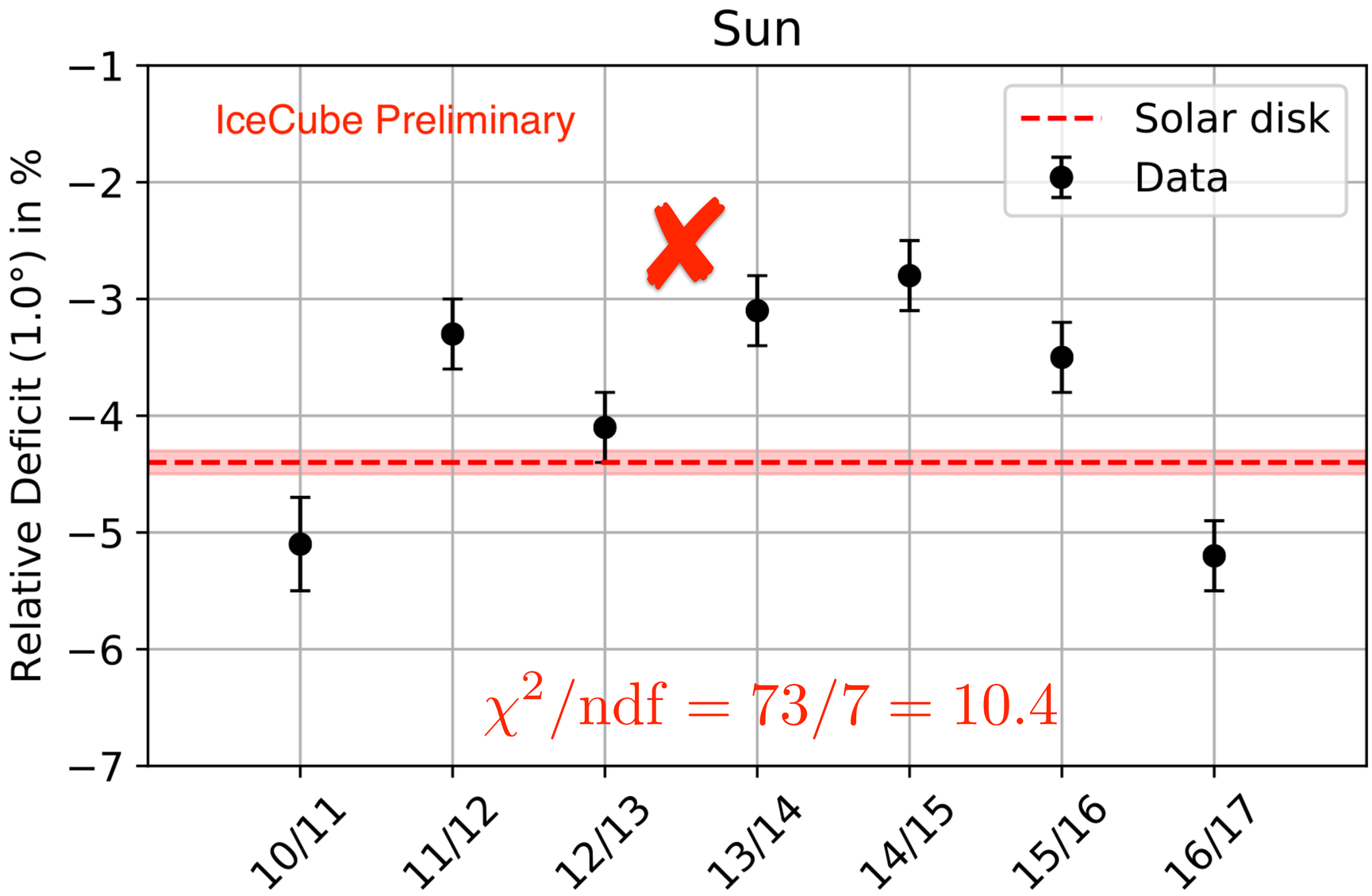
Results: Moon



Results: Sun


Sun, IC79
Sun, IC86-1
Sun, IC86-2
Sun, IC86-3
Sun, IC86-4
Sun, IC86-5
Sun, IC86-6
IceCube Preliminary
$\Delta\delta[°]$
$\cos\delta_\mu \cdot \Delta\alpha[°]$
Relative Deficit in %
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0

Results: Sun

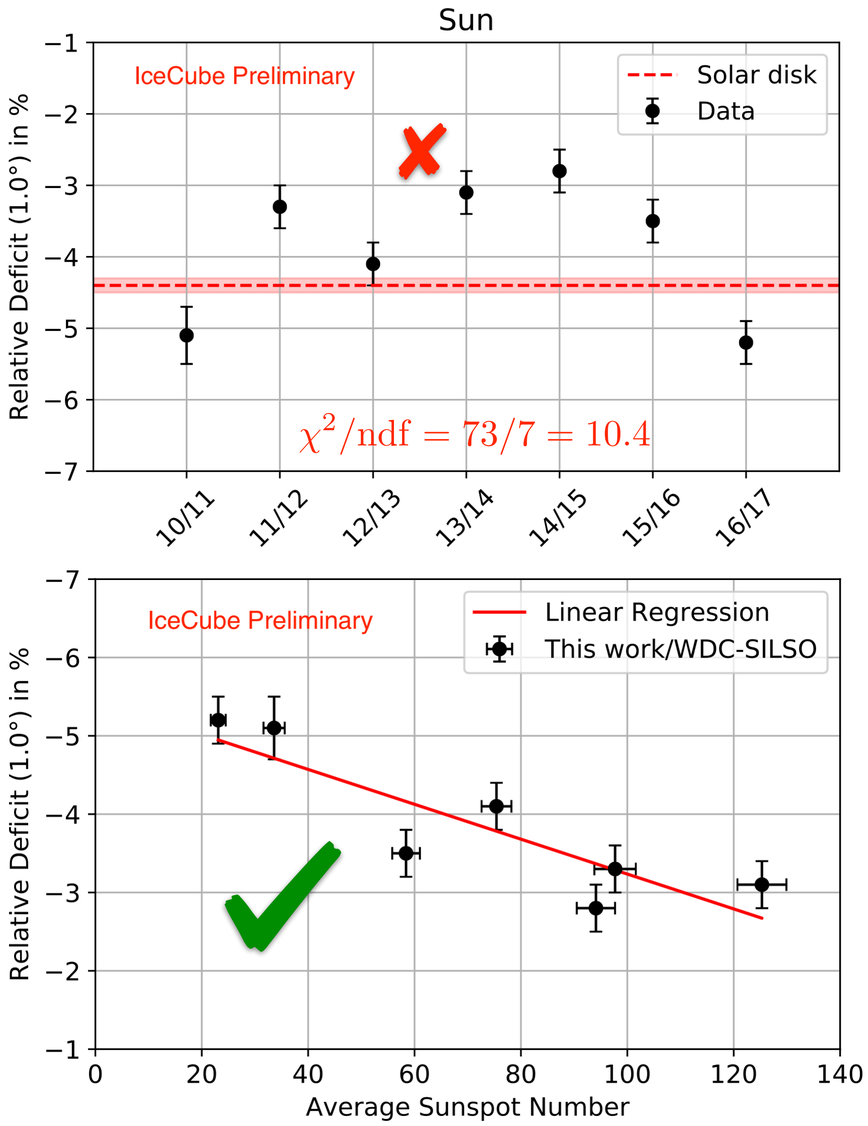

Sun
IceCube Preliminary
Solar disk
Data
Relative Deficit (1.0°) in %
−1
−2
−3
−4
−5
−6
−7
$\chi^2/\mathrm{ndf} = 73/7 = 10.4$
10/11
11/12
12/13
13/14
14/15
15/16
16/17

Results: Sun

- Relative deficit of Sun shadow varies with time despite constant parameters (**solar activity?**)

Object	Year	Events / 10^6	Avg. Elev. / °	Radius / °
Sun	2010/11	9.0	22.1	0.271
Sun	2011/12	13.1	21.8	0.271
Sun	2012/13	13.1	21.8	0.271
Sun	2013/14	13.2	21.8	0.271
Sun	2014/15	13.2	21.8	0.271
Sun	2015/16	13.3	21.8	0.271
Sun	2016/17	13.3	21.8	0.271

- Unmagnetized solar disk model excluded at $\sim 7\sigma$
- Correlation of relative deficit with solar activity is likely (p=3%)
- Linear dependence of relative deficit on SSN preferred at $\sim 6\sigma$

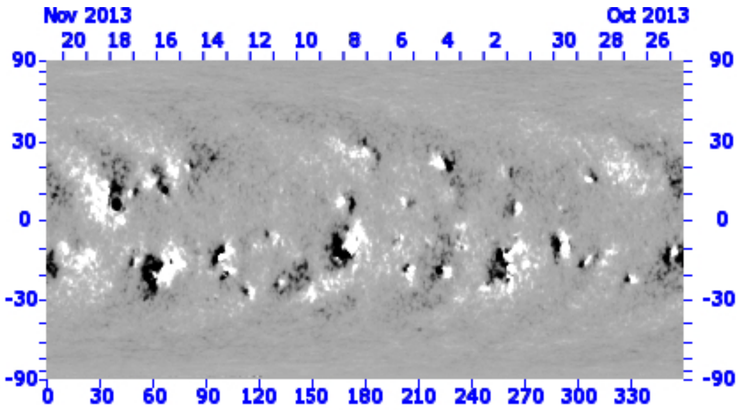


Sunspot data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels

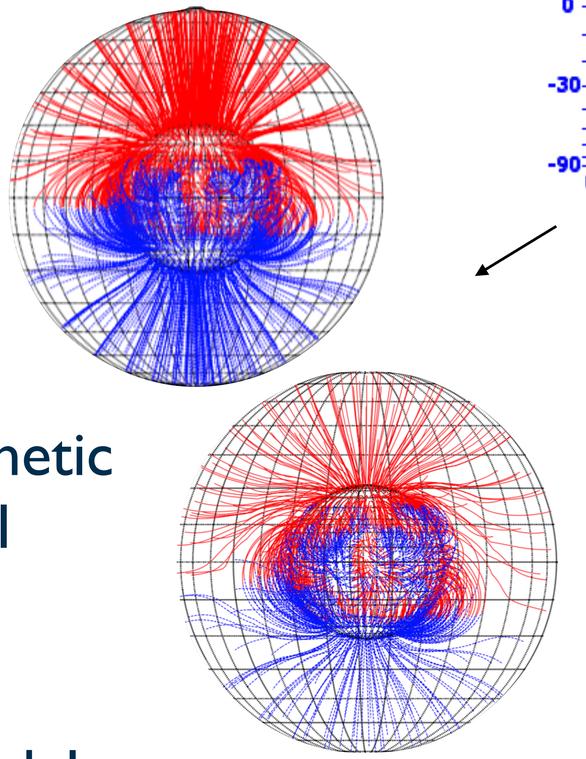
Solar Magnetic Field

Modeling the Solar Magnetic Field

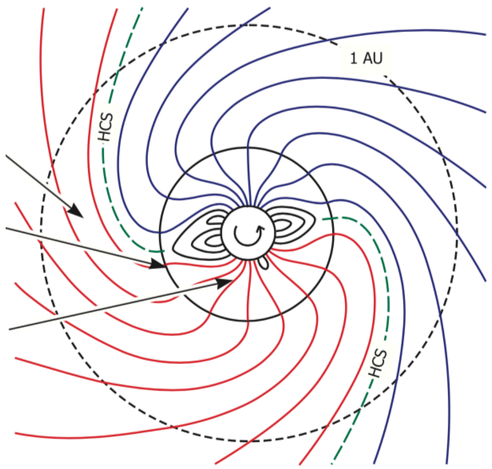
- Synoptic magnetograms measure the photospheric magnetic field strength
- Two coronal magnetic field models:
  - Potential Field Source Surface (PFSS) (Schatten+, Sol. Phys., 6, 442, 1969)
  - Current Sheet Source Surface (CSSS) (Zhao+, J. Geophys. Res., 100, A1,1995)
- Both use „source surface" where all magnetic field lines are assumed to be purely radial
- Beyond „source surface“, Parker spiral (Parker, ApJ, 128, 664–676, 1958) is implemented using a simple analytical model of the solar wind speed



NSO/SOLIS magnetogram (CR2143).



PFSS/CSSS model (CR1910). Figure from Tibet, PRL 111, 1, 2013.



Schematic view of the Parker spiral (Owens & Forsyth, Living Rev. Sol. Phys., 2013).

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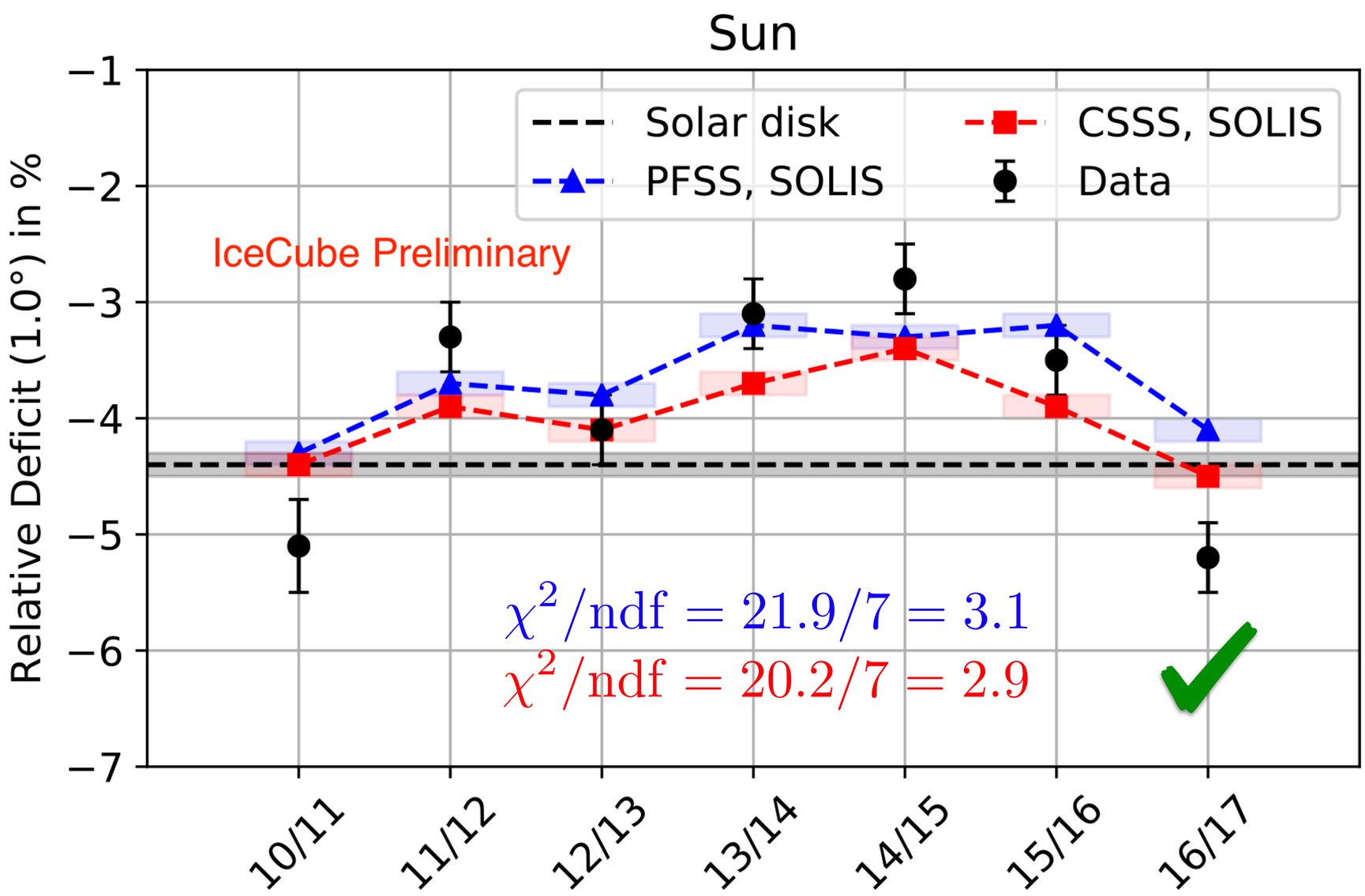
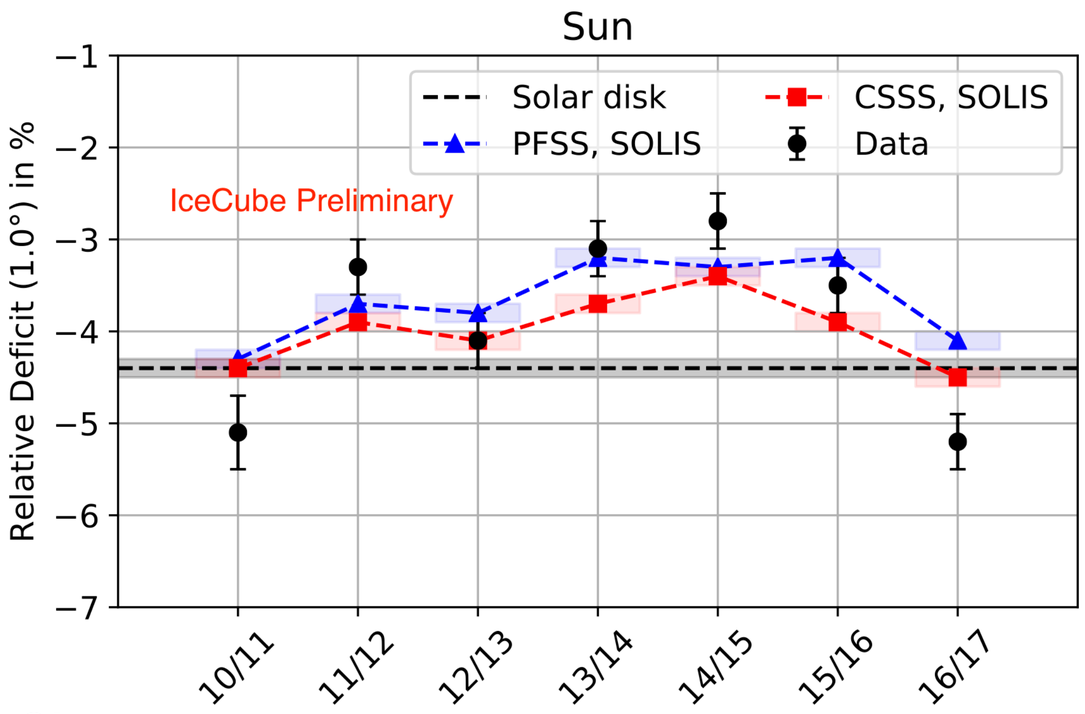
Results: Part II

Results: Sun


Sun
Solar disk
CSSS, SOLIS
PFSS, SOLIS
Data
IceCube Preliminary
Relative Deficit (1.0°) in %
−1
−2
−3
−4
−5
−6
−7
10/11
11/12
12/13
13/14
14/15
15/16
16/17
$\chi^2/\mathrm{ndf} = 21.9/7 = 3.1$
$\chi^2/\mathrm{ndf} = 20.2/7 = 2.9$

Results: Sun

- Observed variation in the data reproduced by simulations
- Years with low solar activity not well-described by models
- CSSS and PFSS models preferred over solar disk, but tensions exist



- Neglected/smaller effects:
  - (Latitude-dependent) solar wind velocity profile
  - Geomagnetic field
  - Earth-directed coronal mass ejections (ECMEs)
  - Different magnetogram normalizations

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Summary

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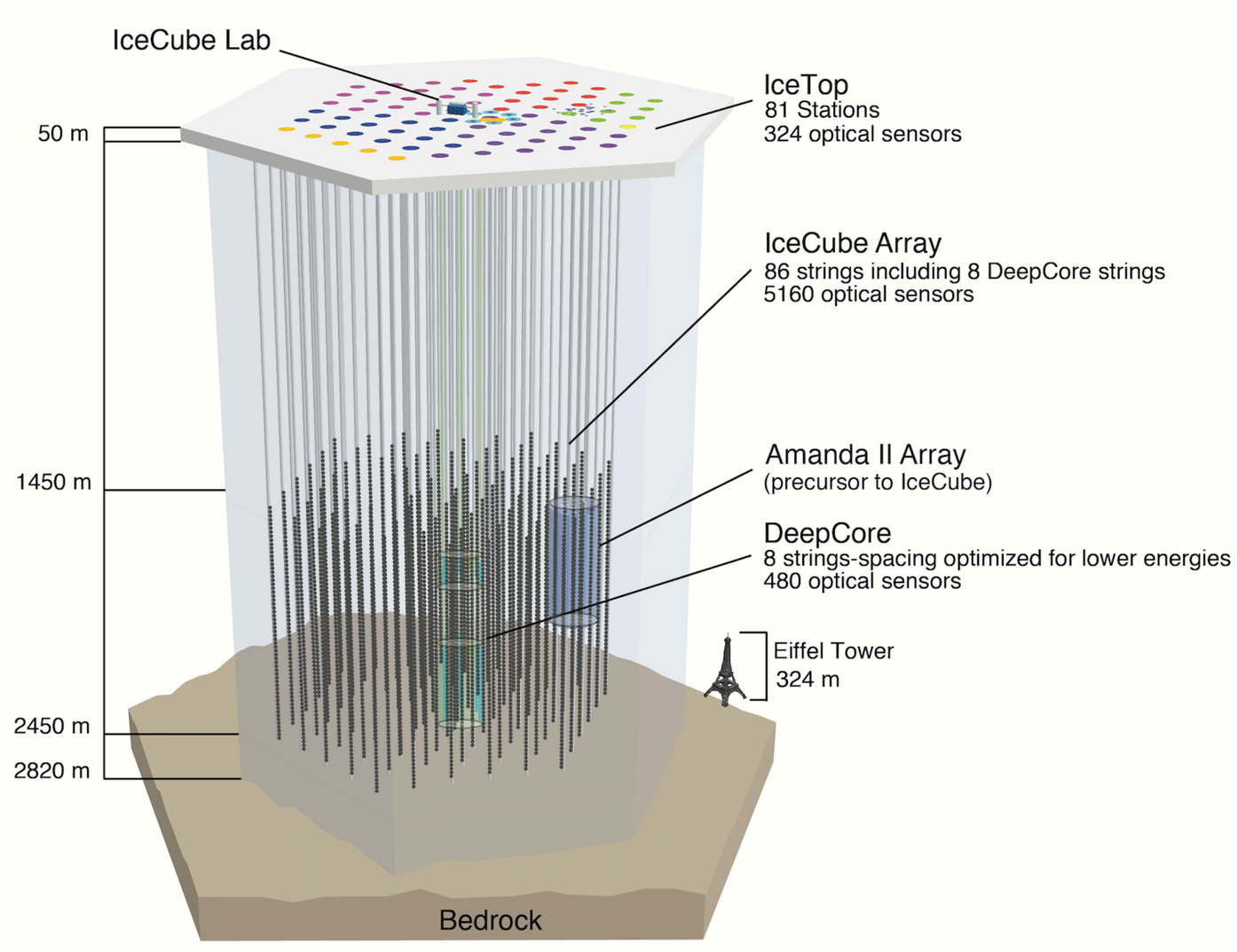
- IceCube detects Moon and Sun shadows with high statistical significance
- Moon shadow consistent with simulations based on lunar disk size and average elevation
- Sun shadow varies in correlation with sunspot number (p-value for non-correlation: ~3%)
- PFSS/CSSS models clearly preferred over solar disk model
- Evaluating solar magnetic field models using IceCube data — for the first time!

- **The cosmic-ray sun shadow in IceCube is a useful new tool for solar physics**

Backup

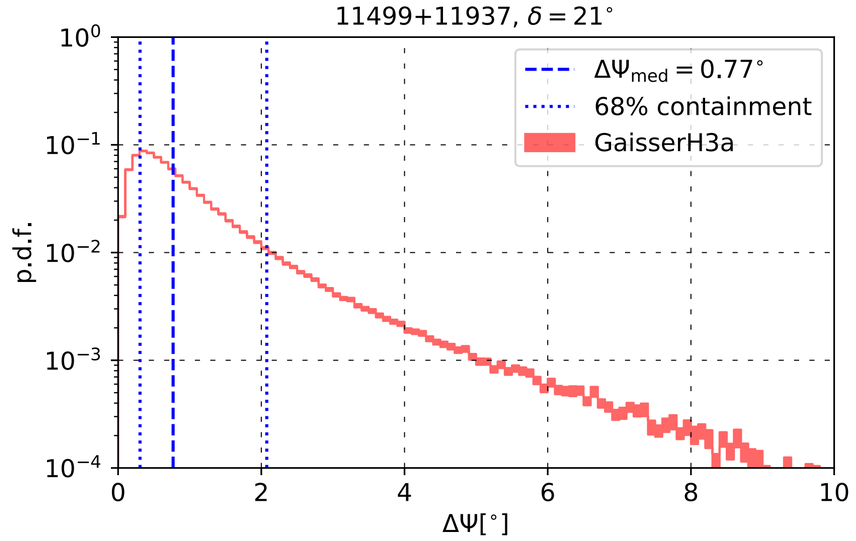
The IceCube Neutrino Observatory

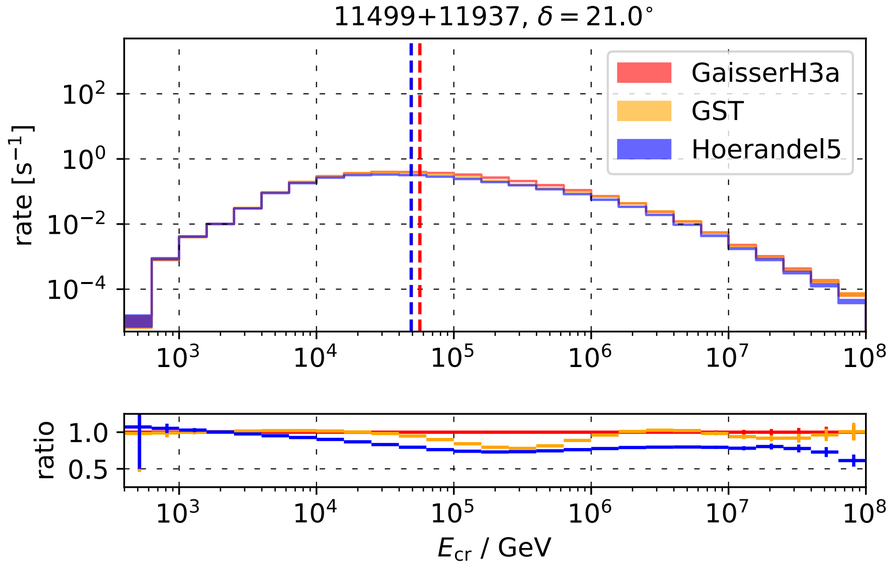
- IceCube is a neutrino detector at the geographic South Pole
- Instrumented volume: $\sim 1\mathrm{km}^3$
- 5160 digital optical modules deployed on 86 strings
- Large amount of data: muon trigger rate of about 2100 events per second
- Here: atmospheric muons constitute data sample



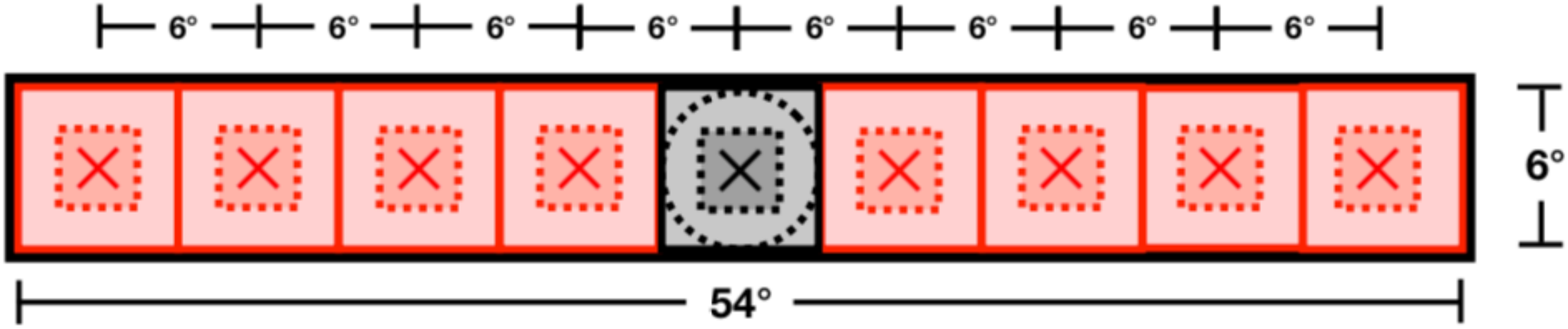
The Moon/Sun Shadow Data Sample

- IceCube uses filters, that follow the path of Moon/Sun across the sky
- Filters are active, when Moon/Sun are above the horizon
- Full azimuth band (360°) for +-10° declination band around object
- Quality cuts on track reconstruction parameters
- Median angular error: ~ 0.75°
- Median energy: ~ 55 TeV

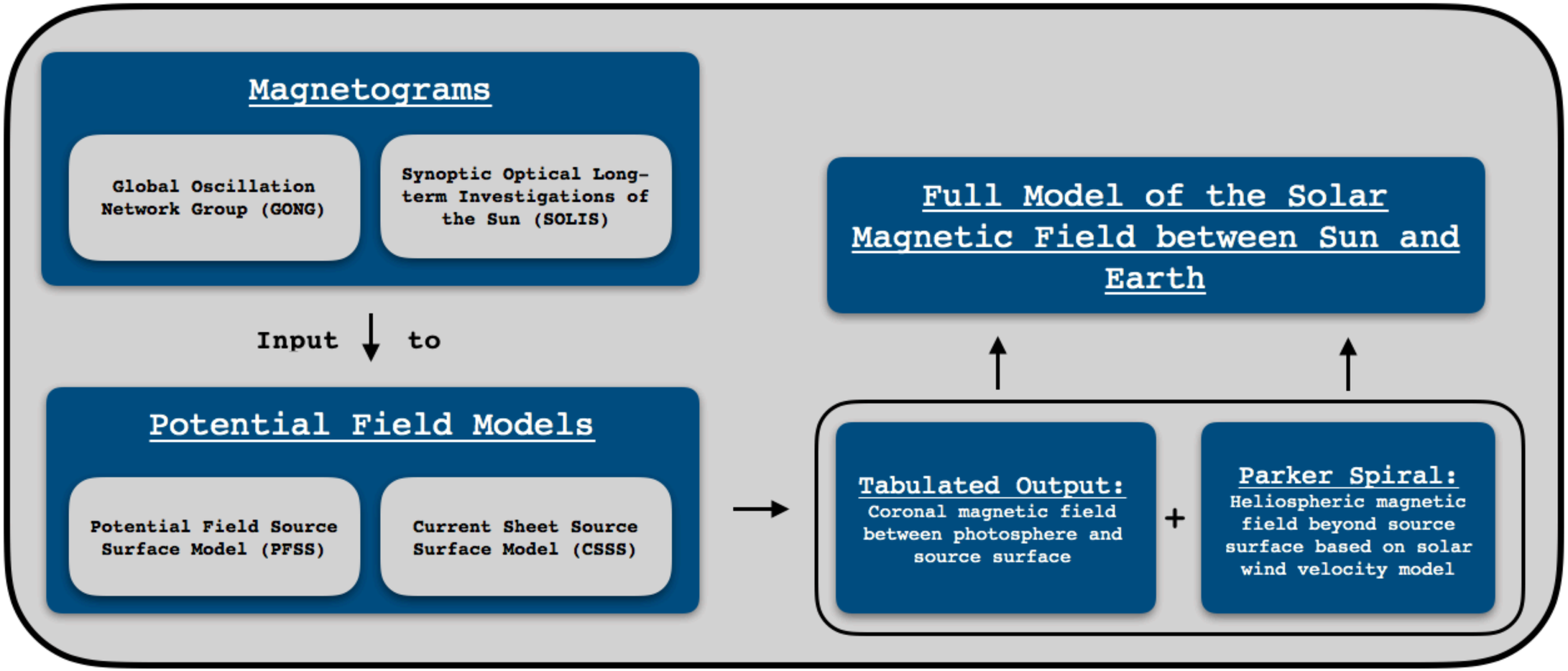




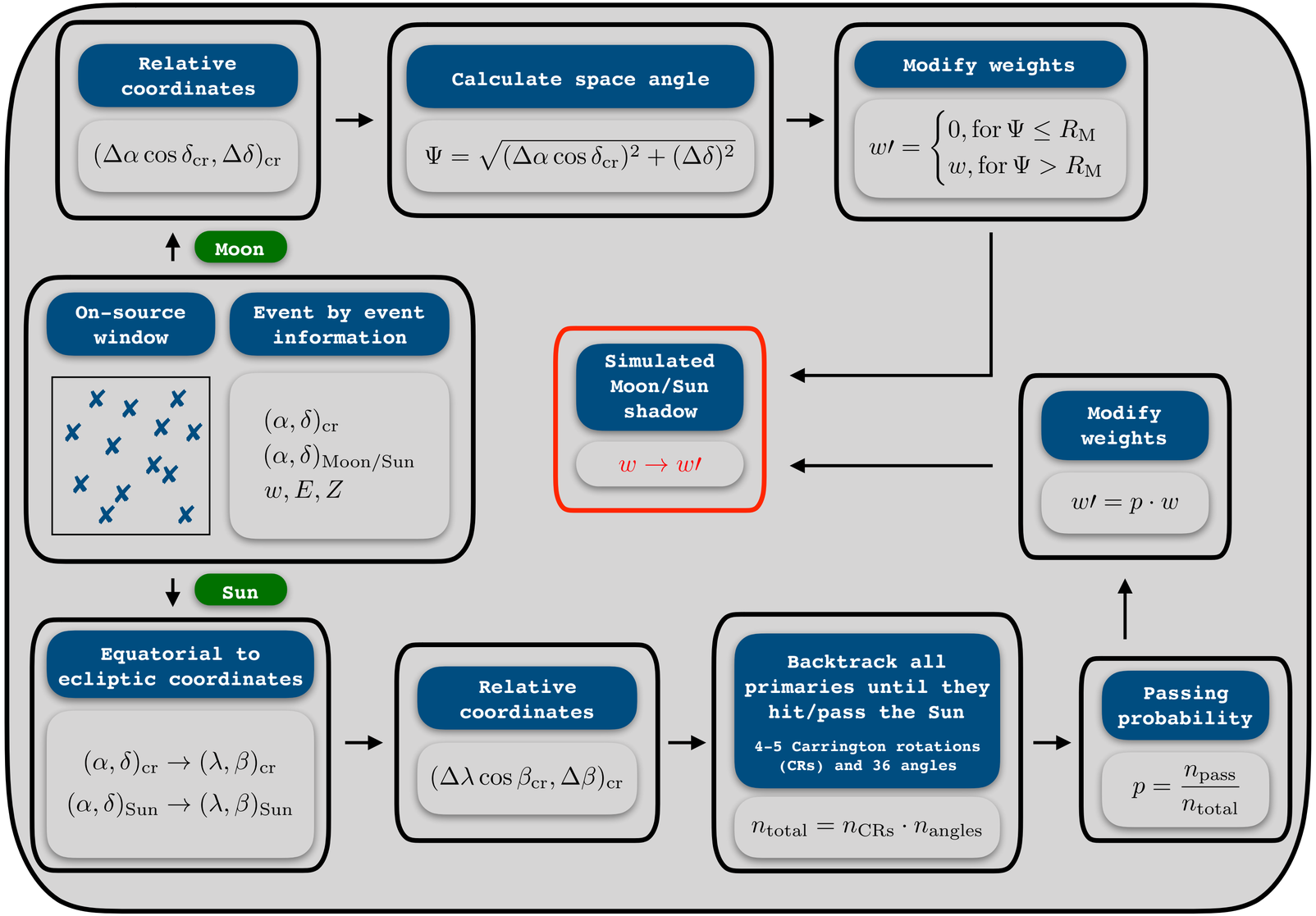
On- and off-source windows



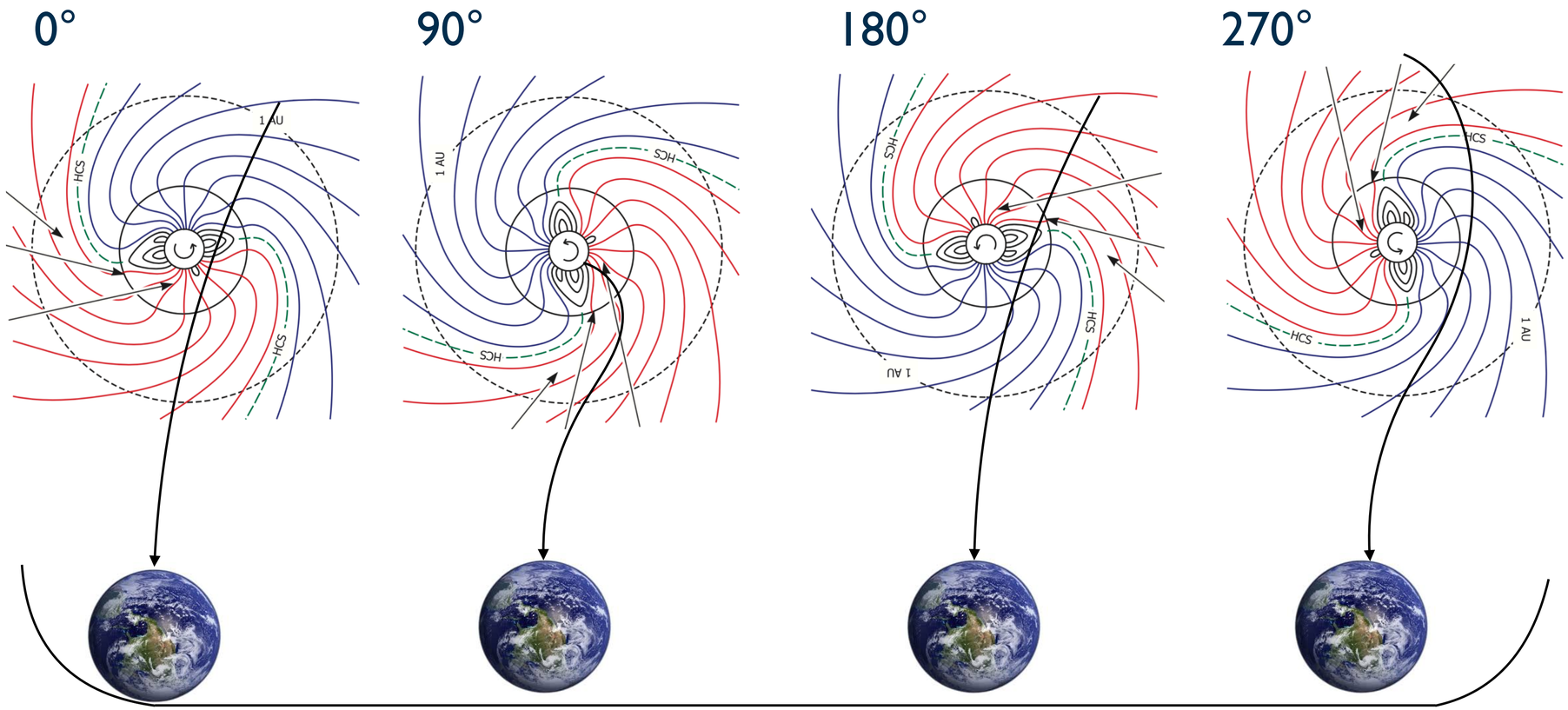
Solar Magnetic Field



Simulations: Basic Principle



Simulating the Sun shadow



1 Carrington
Rotation ~ 27.3 days

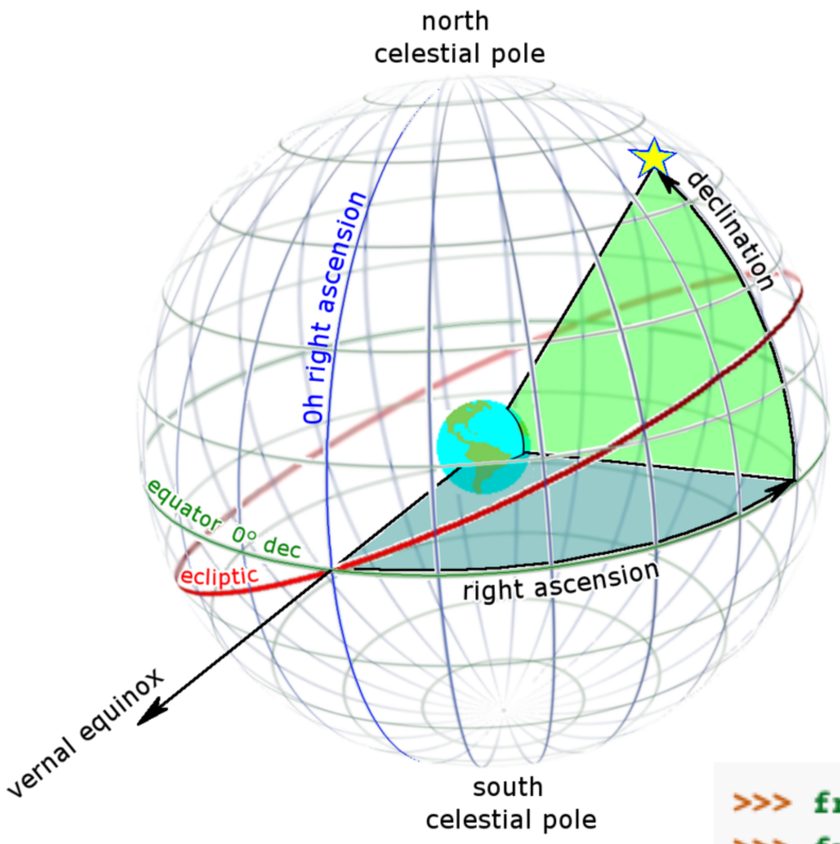
$$p = \frac{n_{\text{pass}}}{n_{\text{total}}}$$

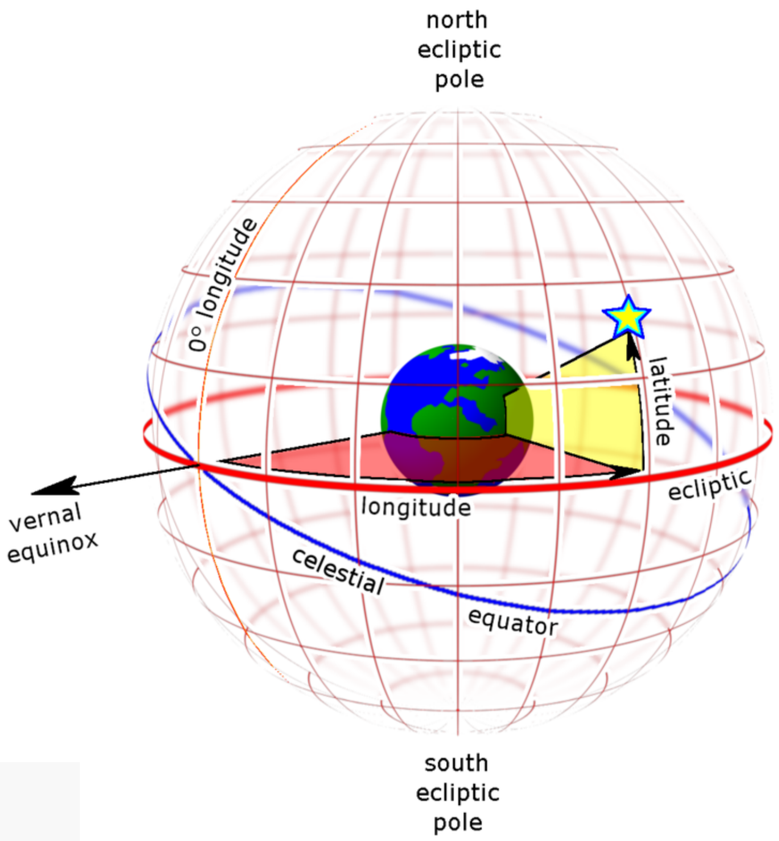
$$w\prime = p \cdot w$$

1/4 hits -> p=0.75

For the Moon, p is a step function depending on r

Coordinate transformations






```
>>> from astropy import units as u
>>> from astropy.coordinates import SkyCoord
```

```
>>> c_icrs = SkyCoord(ra=10.68458*u.degree, dec=41.26917*u.degree, frame='icrs')
>>> c_icrs.galactic
<SkyCoord (Galactic): (l, b) in deg
    (121.17424181, -21.57288557)>
```