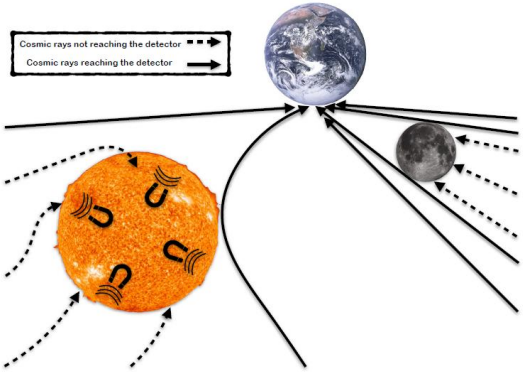

Measuring the Cosmic Ray Sun and Moon Shadow with IceCube

Niclas Krieger, Jonas Hellrung, Paolo Desiati, and Julia Becker Tjus for the IceCube Collaboration

RUHR-UNIVERSITÄT BOCHUM
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Bundesministerium für Forschung, Technologie und Raumfahrt

Deutsche Forschungsgemeinschaft
German Research Foundation

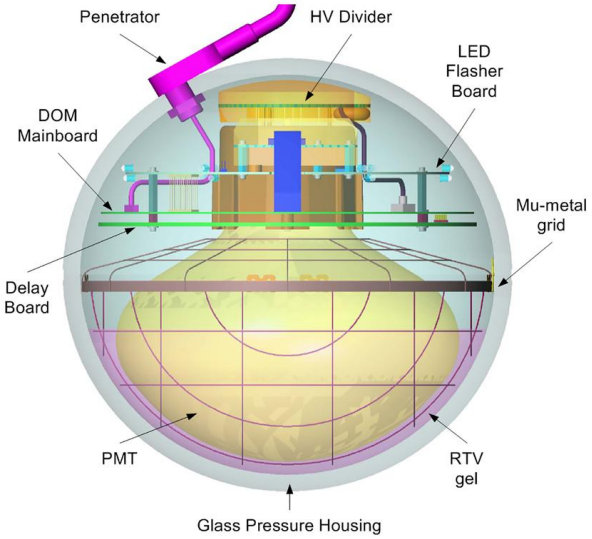
SFB1491

RAPP

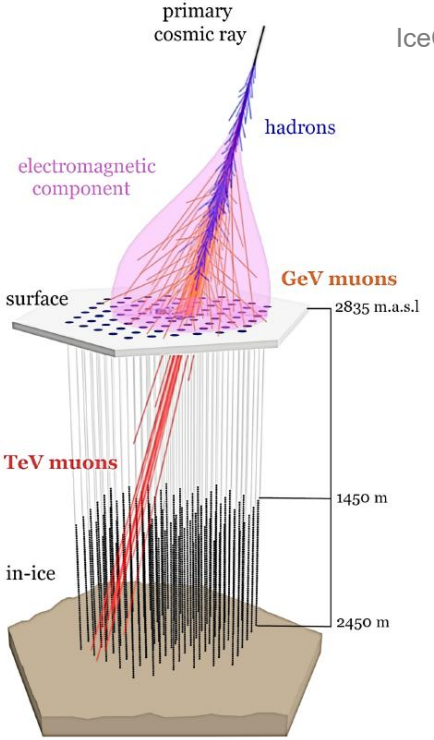
NSF

IceCube Neutrino Observatory

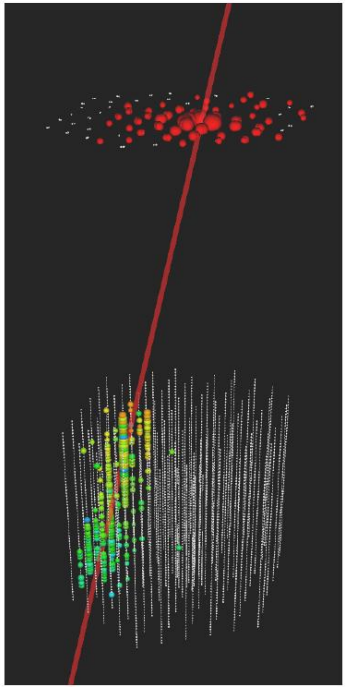
IceCube Neutrino Observatory



IceCube Collab.



IceCube Coll, *arXiv preprint arXiv:2107.09387* (2021).



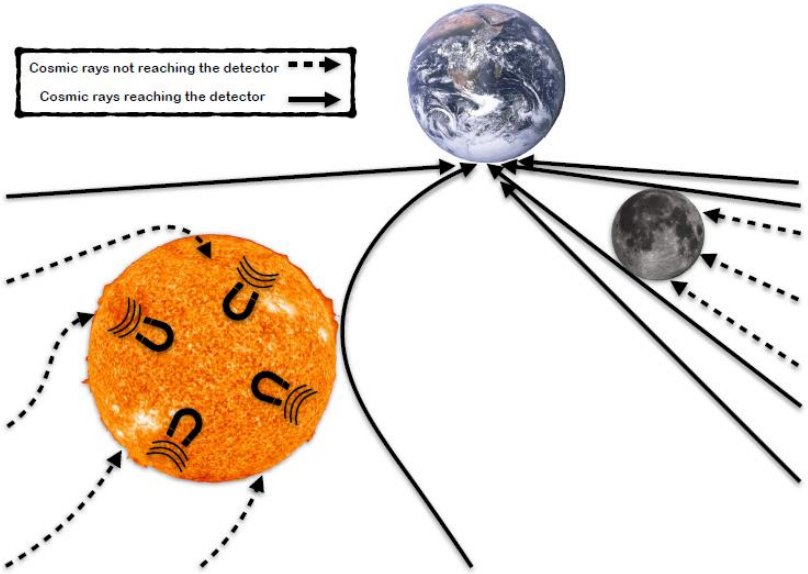
Cosmic Ray Shadows

CRs interact in atmosphere leading to a cascade of secondary particles

Using in ice muons as tracers for CRs

Less detectable CRs by blocking and/or deflecting → Relative deficit / CR shadow:

- Moon: angular resolution, reconstruction test
- Sun: study the Solar Magnetic Field
  → Focus of my work

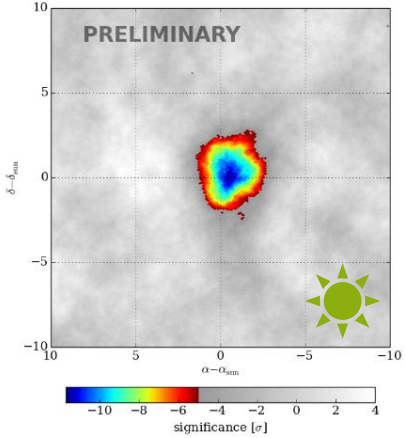


F. Tenholt, 2019, PhD Thesis

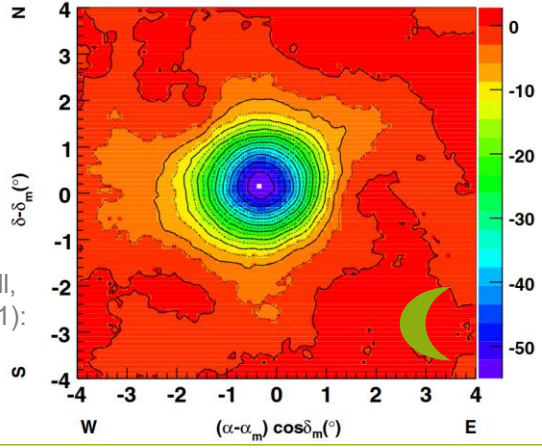
Existing Analysis

IceCube Collaboration, PRD 103, 042005 (2021)

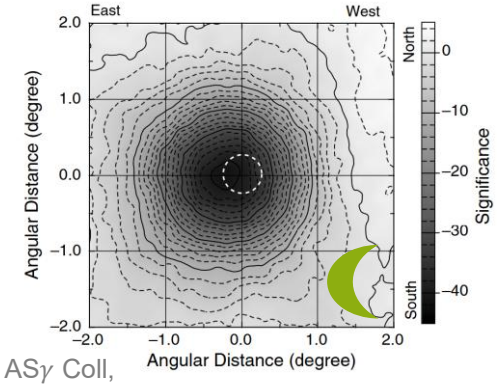
- Analysis performed on IceCube data from 2010 to 2017
- Since then many changes in data processing
- Not only IceCube, but also others like HAWC, ARGO-YBJ and Tibet ASγ



HAWC Coll, No. arXiv: 1508.07351. 2016.



ARGO-YBJ Coll, *PRD* 84.2 (2011): 022003.

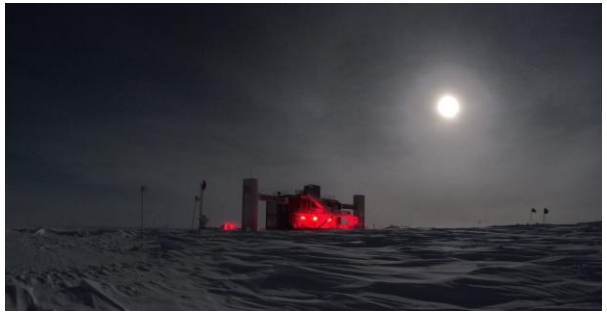


Tibet ASγ Coll, *AP* 28.1 (2007): 137-142.

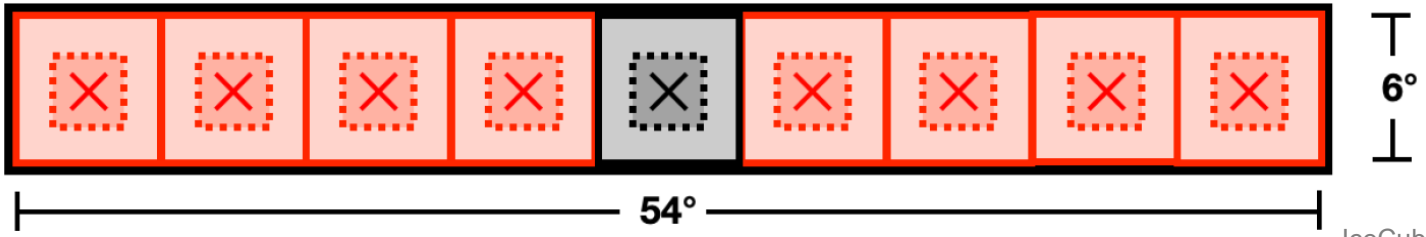
Analysis Procedure: Filtering

Filter does the following checks:

- Is the Moon/Sun above the horizon?
- Does the detector see enough light?
- Is the event in a 60° x 12° window around the Moon/Sun?

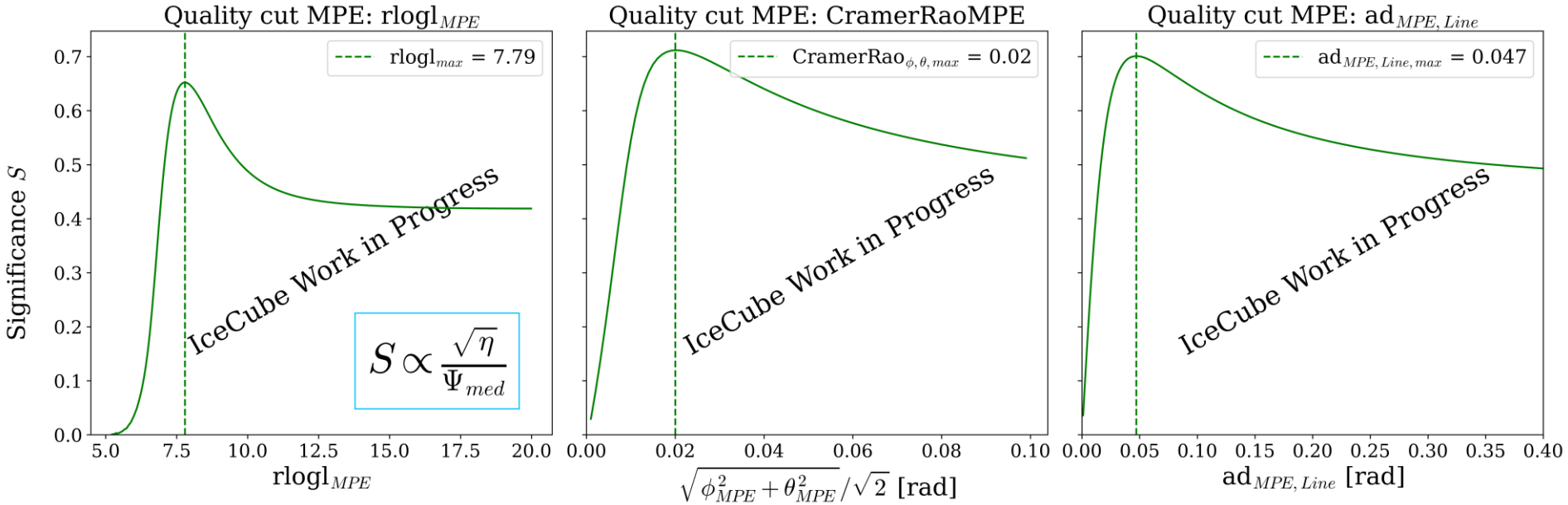


Camille Parisel, IceCube/NSF



IceCube Coll., PRD, 103, 042005 (2021)

Analysis Procedure: Quality Cuts

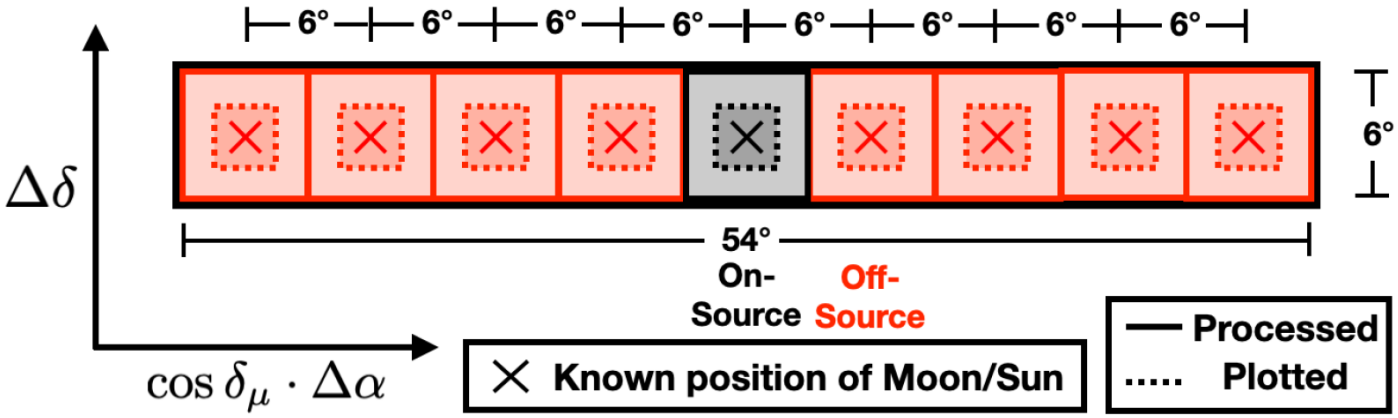


S: Statistical significance η: Events passing the cuts

Ψ_{med} : Median space angle between CR and reconstructed direction

→ 5-component CORSIKA simulation used for estimating the quality cuts

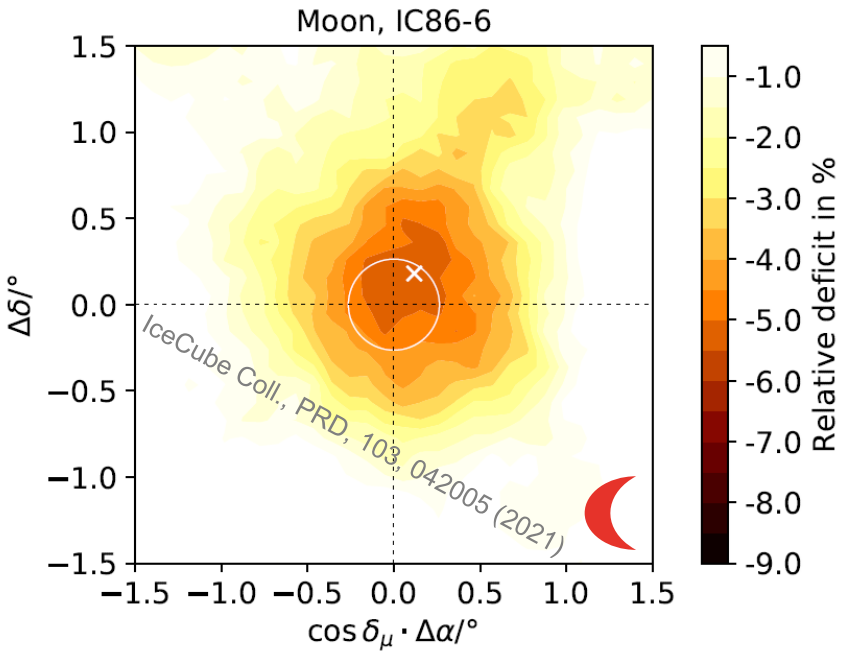
Analysis Procedure: Relative Deficit



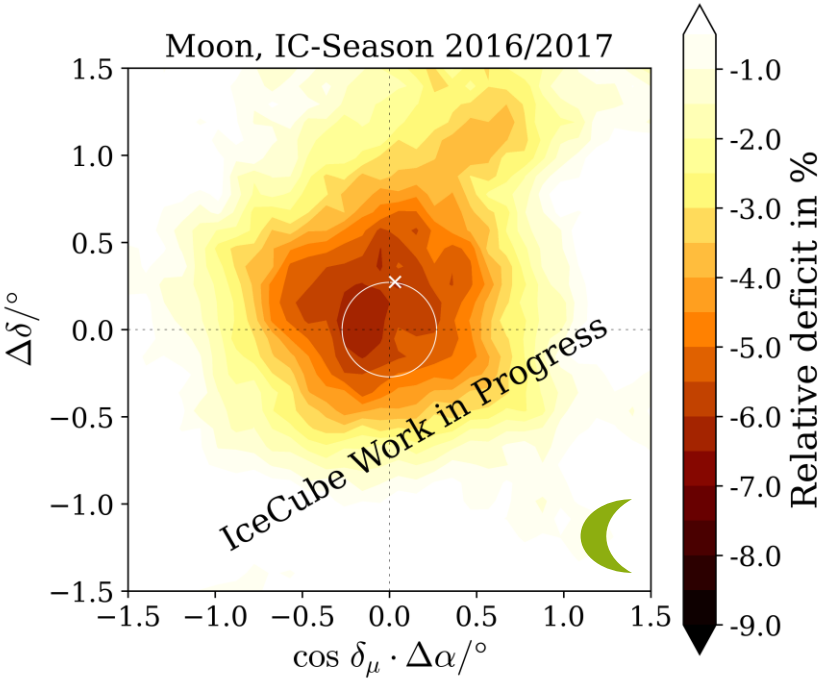
IceCube Coll., PRD, 103, 042005 (2021)

$$\left(\frac{\Delta N}{\langle N_{\text{off}}\rangle}\right)^{i,j} = \frac{N_{\text{on}}^{i,j} - \langle N_{\text{off}}\rangle^{i,j}}{\langle N_{\text{off}}\rangle^{i,j}} \qquad \langle N_{\text{off}}\rangle^{i,j} = \frac{1}{8}\sum_{n=1}^{8}\left(N_{\text{off}}^{i,j}\right)_n$$

Comparing Previous vs. New Processed Data

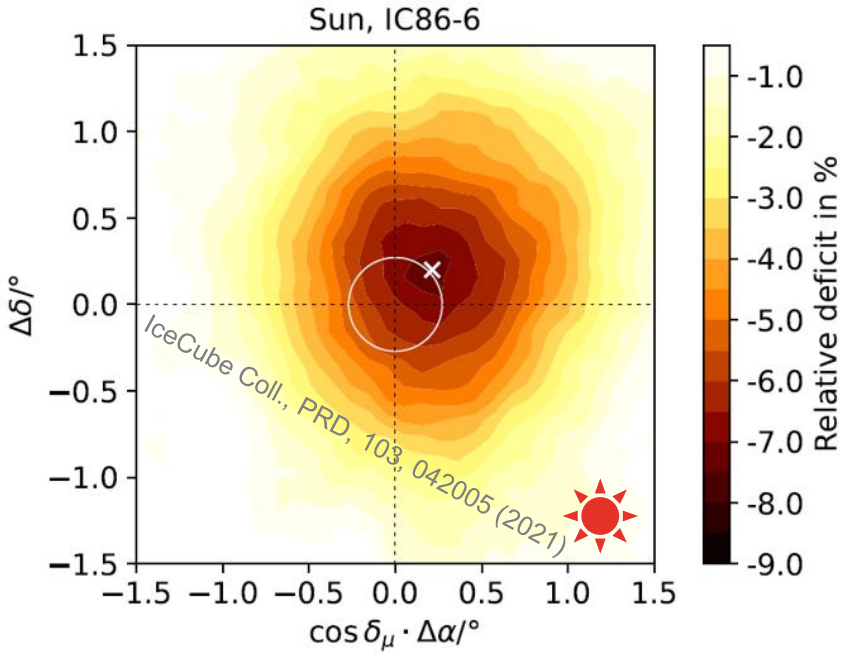


5.1 Mio Events

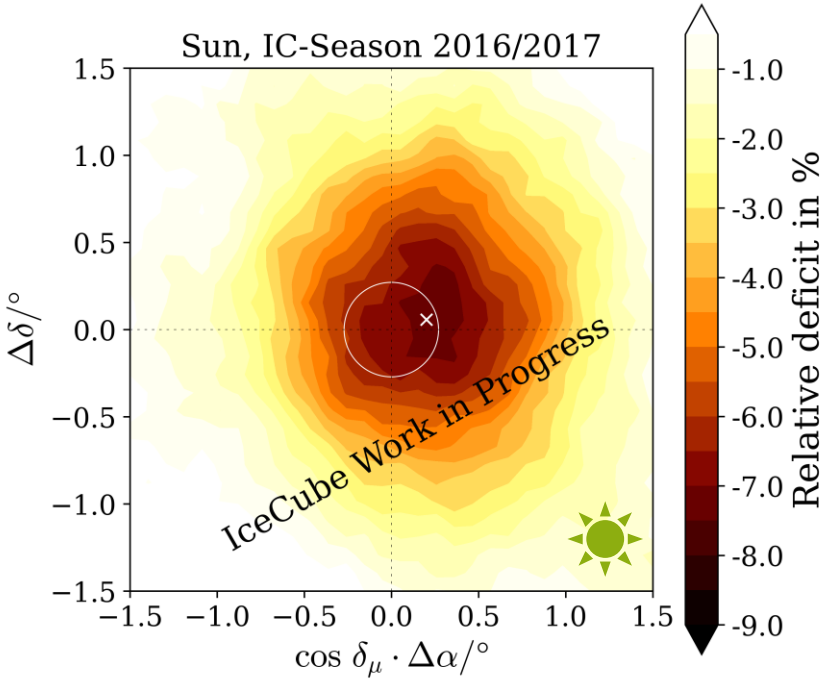


3.75 Mio Events

Comparing Previous vs. New Processed Data

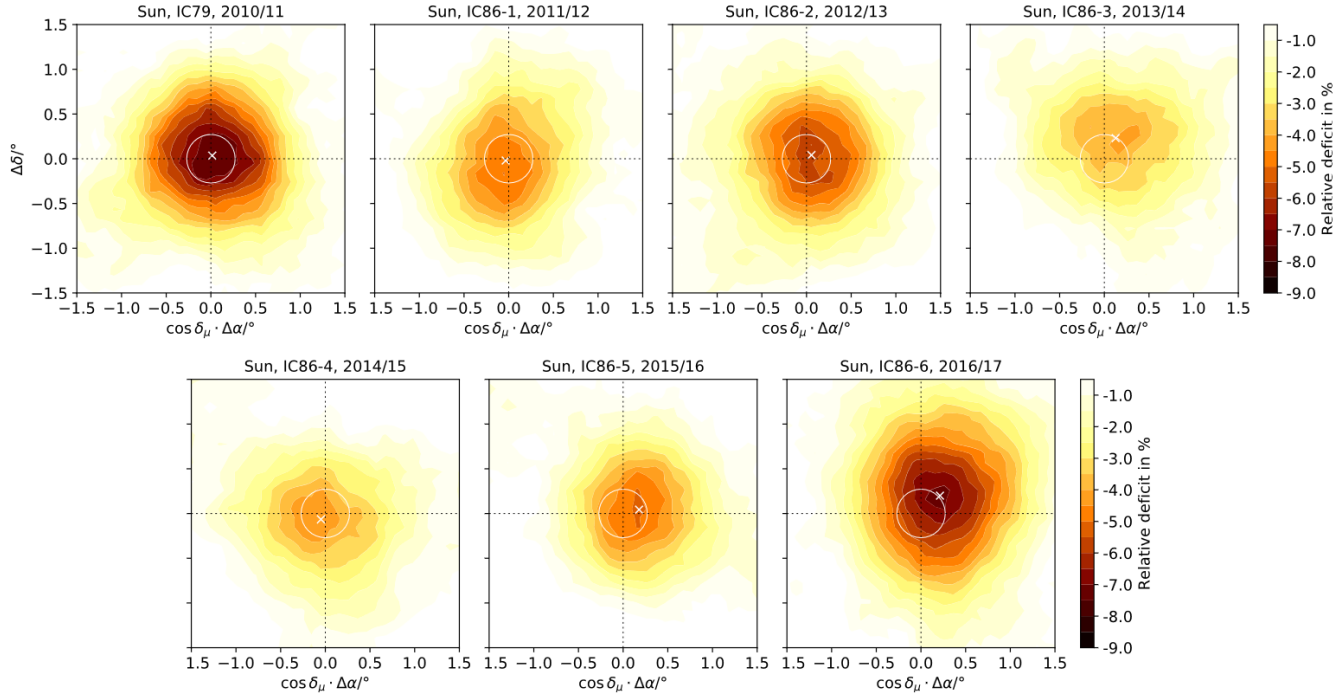


13.3 Mio Events



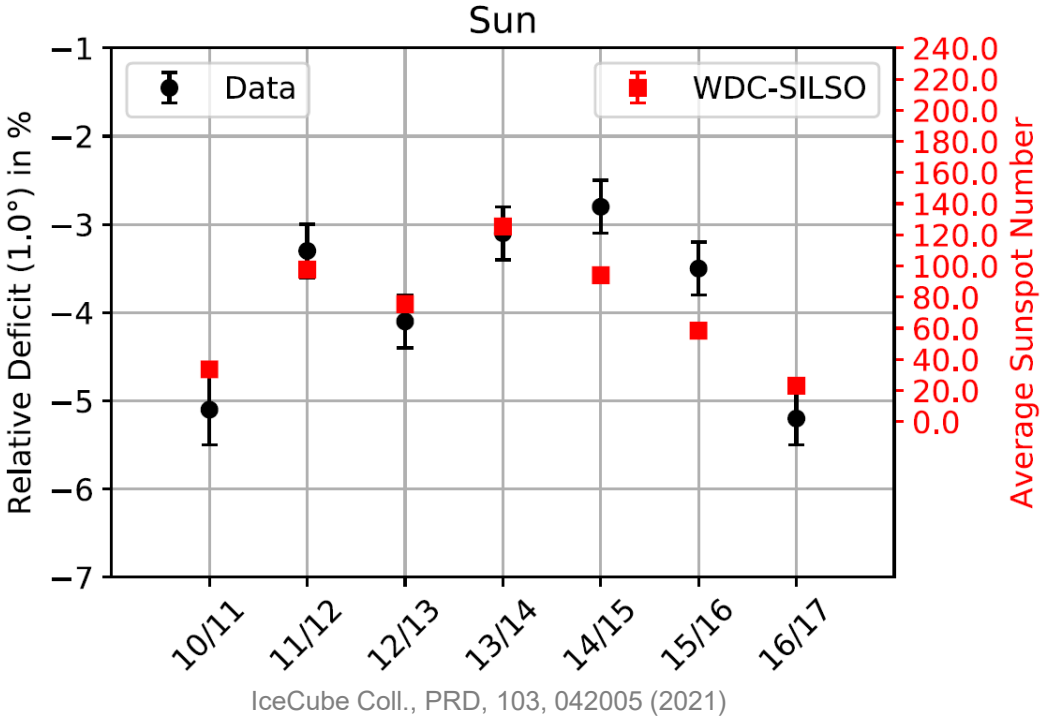
9.89 Mio Events

Cosmic Ray Sun Shadows



IceCube Coll., PRD, 103, 042005 (2021)

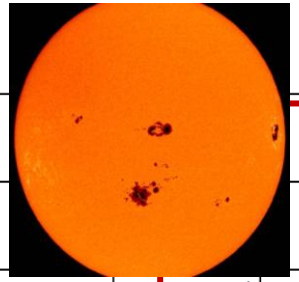
Solar Cycle Sunspot Number aka Activity



IceCube Coll., PRD, 103, 042005 (2021)

- Sunspot number as an indicator for Solar activity
- Relation between the Solar activity and the Sun shadow
- Correlation is recognisable

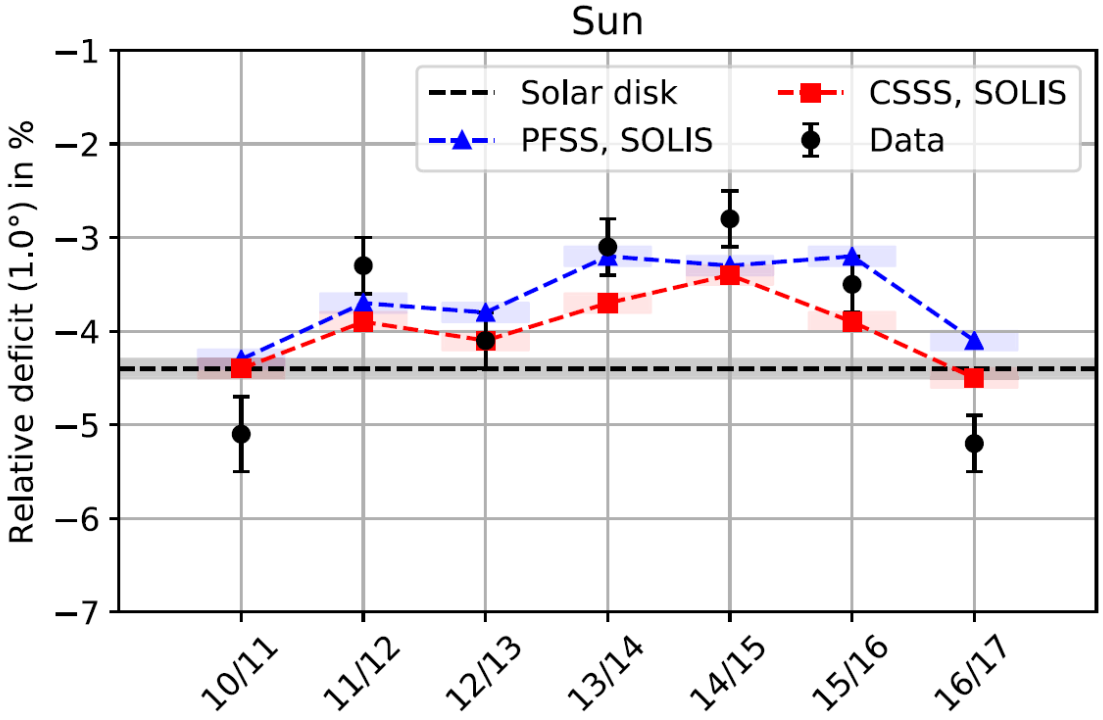
Solar Cycle Sunspot Number aka Activity



https://www.weather.gov/fsd/sunspots, access on July 20th 2026

https://www.swpc.noaa.gov/products/solar-cycle-progression, access on July 20th 2026

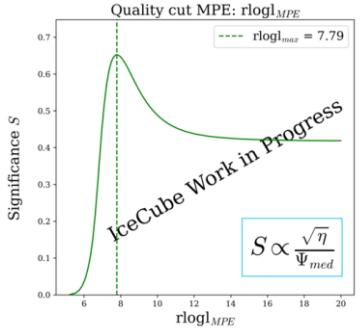
Using CR Sun Shadow: SMF Models

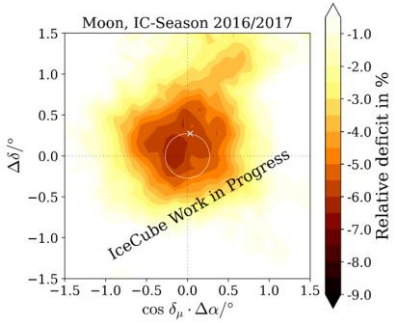


IceCube Coll., PRD, 103, 042005 (2021)

Summary

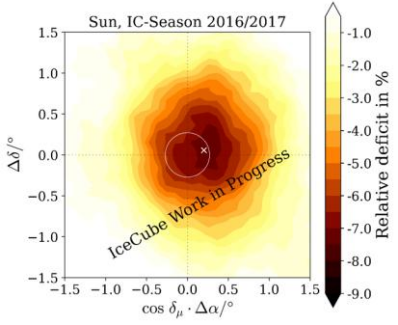
- Analysis:
  - Sun & Moon produce CR shadow
  - Sun shadow: study the SMF





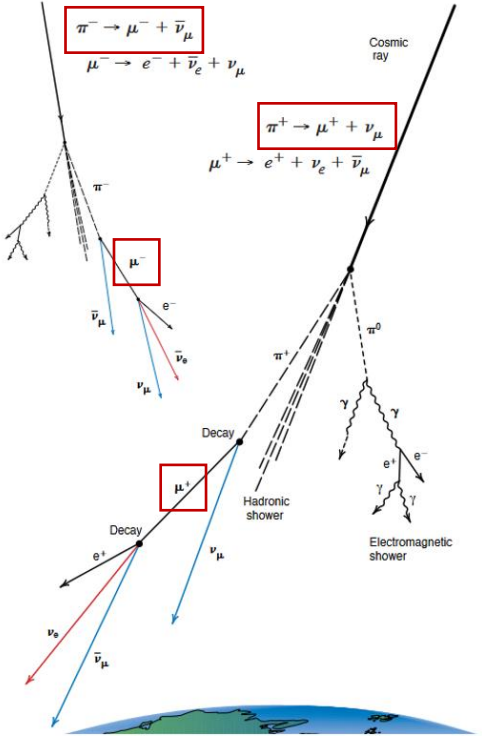
- Done:
  - Moved to modern software
  - New quality cuts

  - Tested with 2016/2017-IceCube season:
    - Overall structure of Moon and Sun shadow reproduced
    - Slight deviation in COG and the shape
      → Expected due to new cuts; more events filtered



Backup

Cosmic Ray Air Shower



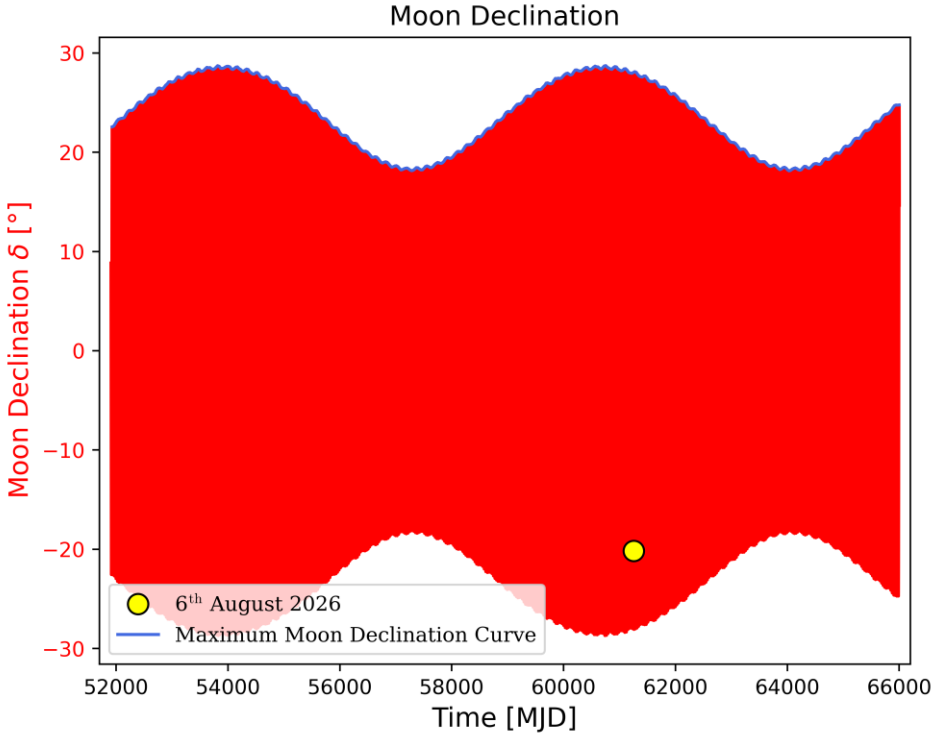
M. Santander, 2013, PhD Thesis

- Earth‘s atmosphere: cosmic rays interact with air molecules
- Decay processes lead to muons, e.g. pion decay:

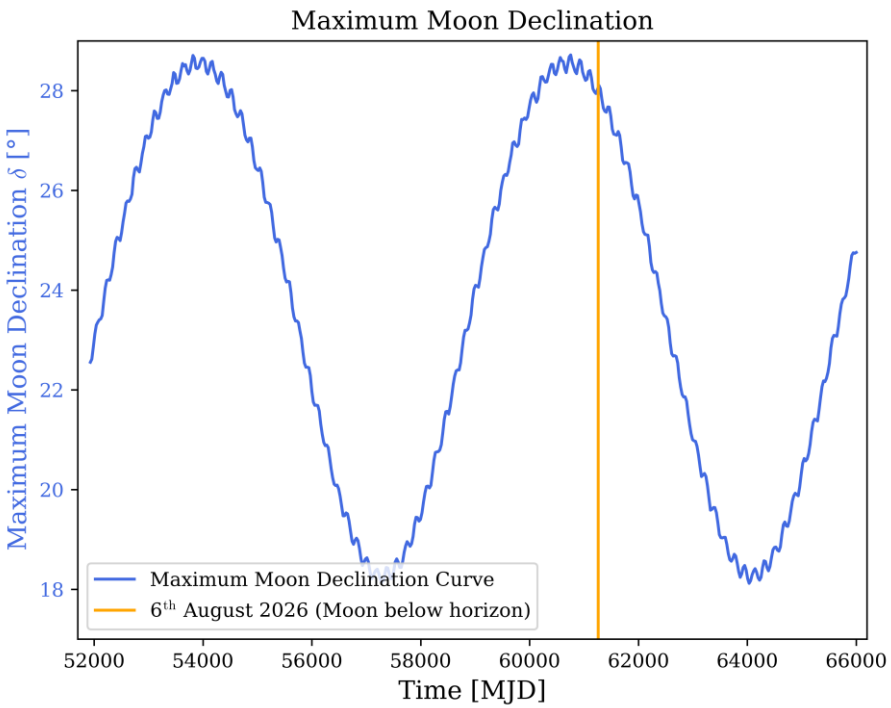
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

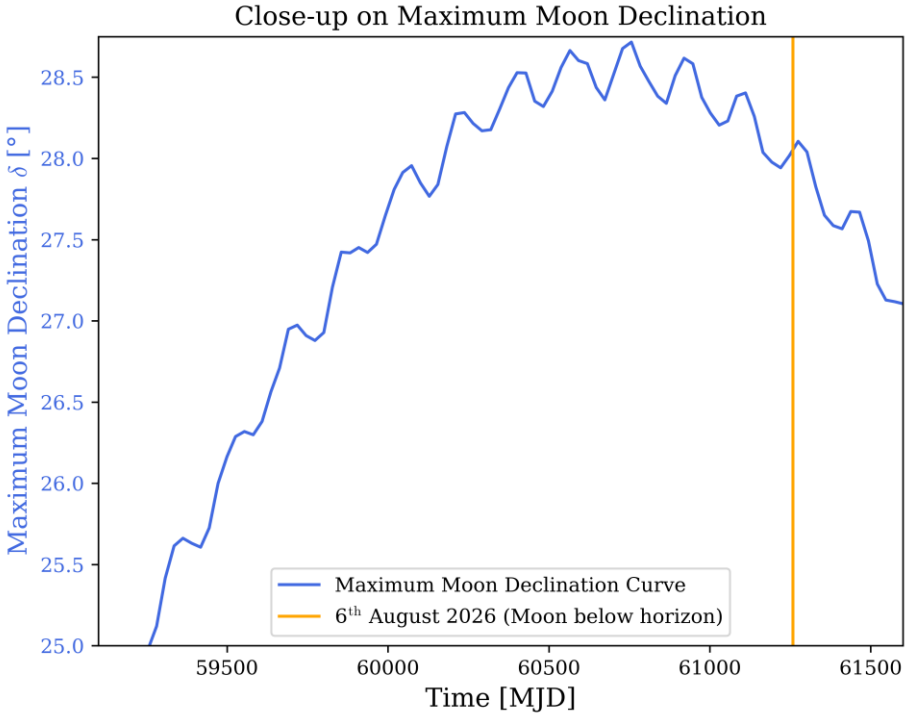
- Muons (in ice) are used as tracers for cosmic rays
- Investigate:
  - Particle interaction in forward direction
  - Cosmic rays themselves
  - Relative deficit in the cosmic-ray flux

Moon Declination

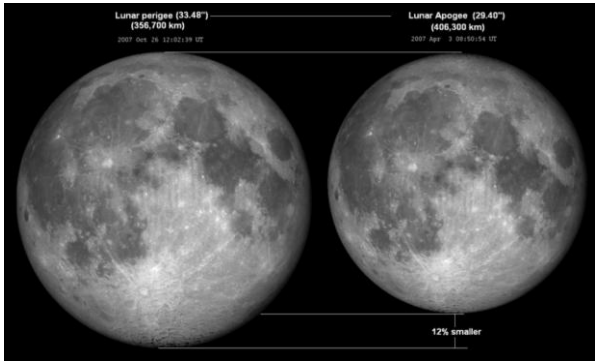


Moon Declination

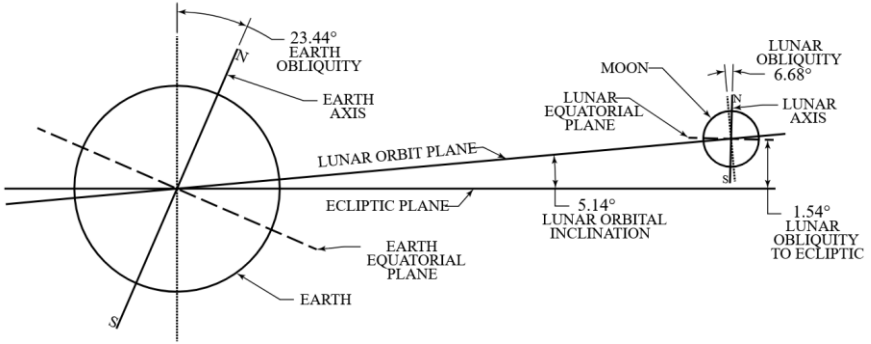




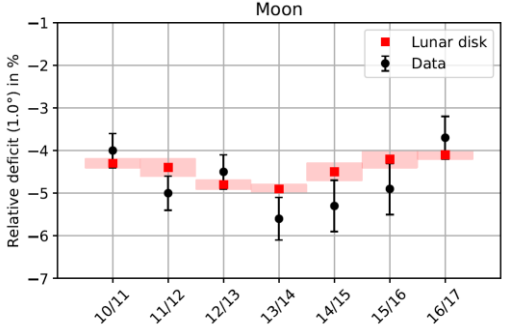
Seasonal Moon



https://upload.wikimedia.org/wikipedia/commons/c/c8/Lunar_perigee_apogee.png, access on July 20th 2026



https://upload.wikimedia.org/wikipedia/commons/4/46/Lunar_Orbit_and_Orientation_with_respect_to_the_Ecliptic.svg, access on July 20th 2026



IceCube Coll., PRD, 103, 042005 (2021)

- Moon takes on varying sizes angularly on the sky due to an eccentricity of $e \approx 0.0549$ D'Eliseo, M.M., 2012. The quasi-elliptic motion of the Moon. *Chinese Journal of Physics*, *50*(5), pp.720-731.
- The greater the Moon, the more events will get blocked
  → Relative deficit increases

Processing and Quality Cuts

- Re-estimating the cuts:
  - Estimated 2011 or so
  - New Ice Models
  - New Software/Naming
  - …
- Processing:
  - Clean-up
  - New Software/Naming
    - Especially important with the new filters

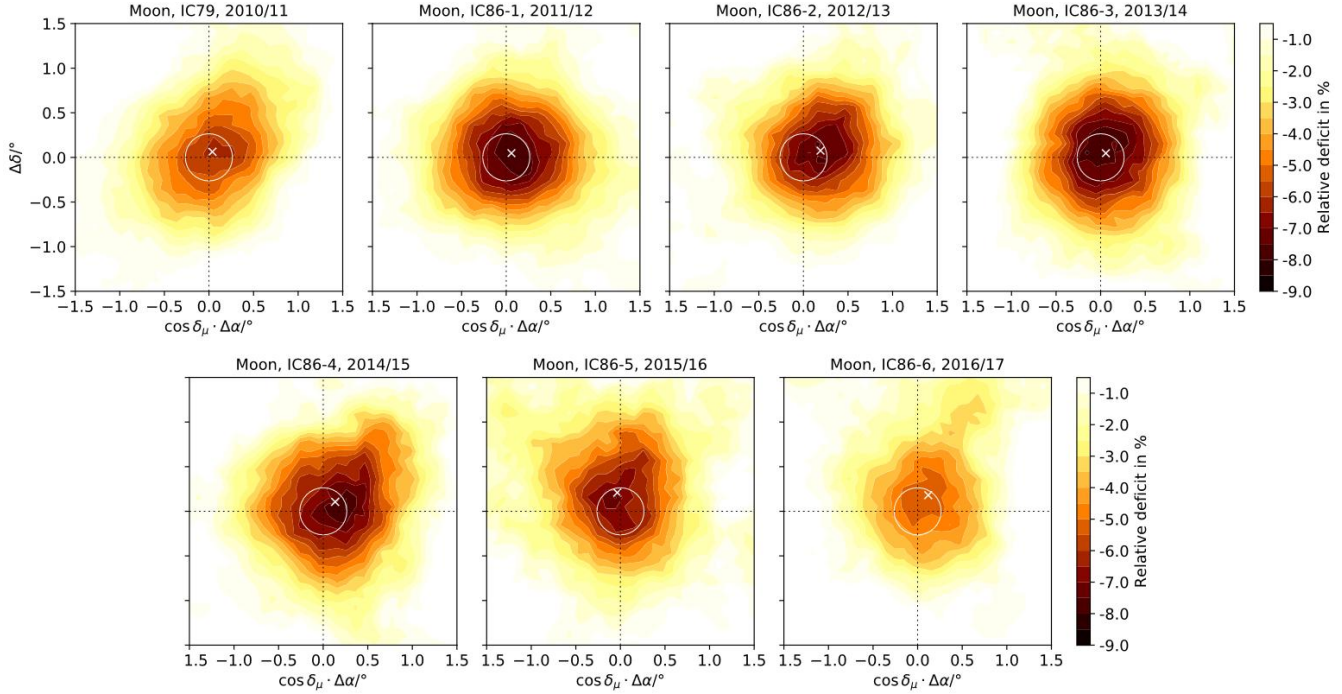
„Old“ cuts:

- Reduced log-likelihood: $rlogl < 8.1$

  → With MPEFit
- Angular uncertainty: $\sigma_{pb} < 7.1°$

  → With Paraboloid fit
- Have been estimated with a CORSIKA set
- Should have cut down to ~30% of the initial data

Moon Shadow of the years 2010-2017



IceCube Coll., PRD, 103, 042005 (2021)

Quality Cuts - Details

$$rlogl = \frac{\log \mathcal{L}}{n_{\mathrm{dof}}}$$

Likelihood for the best track solution

Number of degrees of freedom:
in the track it is equal to the number of DOMs triggered by the event minus the number of free parameters in the fit
→ 5 for MPEFit (2 for direction and 3 for position)

$$cov(\theta_m, \theta_k) \geq I(\vec{\theta})^{-1}$$

Module to calculate an estimator for the angular resolution of a reconstructed track

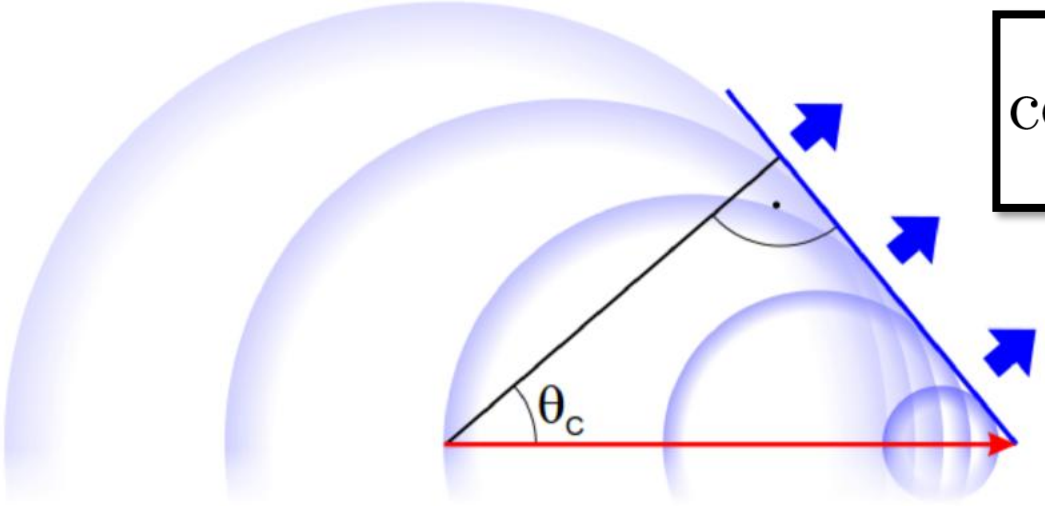
Fisher-matrix

$$I_{mk}(\vec{\theta}) = -\left\langle \left[\sum_{i=1}^{modules} \frac{\partial^2}{\partial\theta_k \partial\theta_m} \ln p(t_i; \vec{\theta}) \right] \right\rangle$$

Probability density function

Track parameters: direction and vertex of the track

Cherenkov Radiation



$$\cos\theta_c = \frac{1}{\beta n}$$

For ultra-relativistic particle $\beta \approx 1$ and typical refraction index of ice $n_{\mathrm{ice}} \approx 1.3$ leads to a Cherenkov angle of $\theta_c \approx 40°$

→ Charged particle (e.g. a muon) propagating through a medium and its velocity exceeds the speed of light in the medium, this leads to emitting Cherenkov radiation

M. Wallraff. “Design, Implementation and Test of a New Feature Extractor for the IceCube Neutrino Observatory”. Diploma thesis. RWTH Aachen, 2010

Force-Free Models

Dominance of the magnetic field → Gravitational and plasma pressure force are negligible → **Force-free Equation**:

$$\vec{0} = \vec{j} \times \vec{B} - \vec{\nabla} p + \rho \vec{g} \longrightarrow \vec{j} \times \vec{B} = \vec{0} \longrightarrow \vec{\nabla} \times \vec{B} = \alpha(\vec{x}) \vec{B}$$

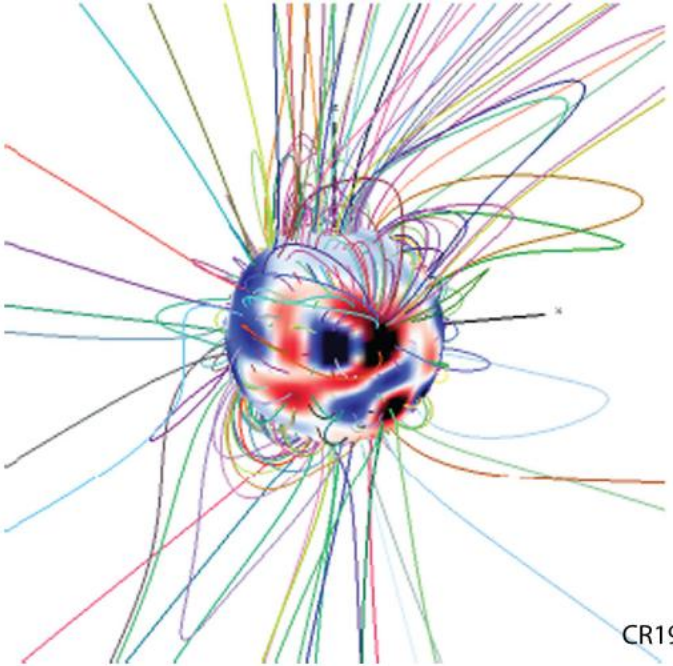
No electric currents ($\vec{j} = \vec{0}$) in the solar corona results in a curl-free magnetic field

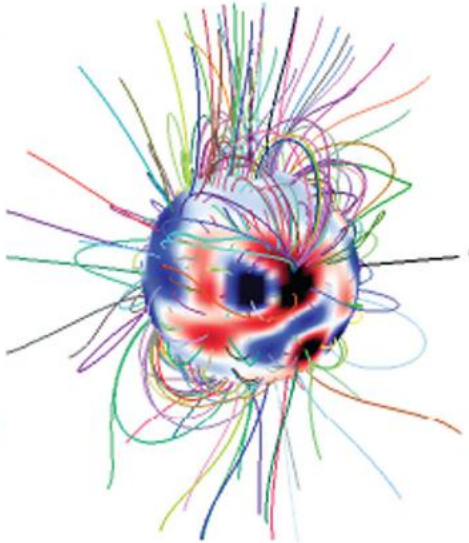
$$\vec{j} = \frac{1}{\mu_0}(\vec{\nabla} \times \vec{B}) \longrightarrow \vec{\nabla} \times \vec{B} = \vec{0} \longrightarrow \vec{B} = -\vec{\nabla}\Phi \longrightarrow \vec{\nabla}^2 \Phi = \Delta \Phi = 0$$

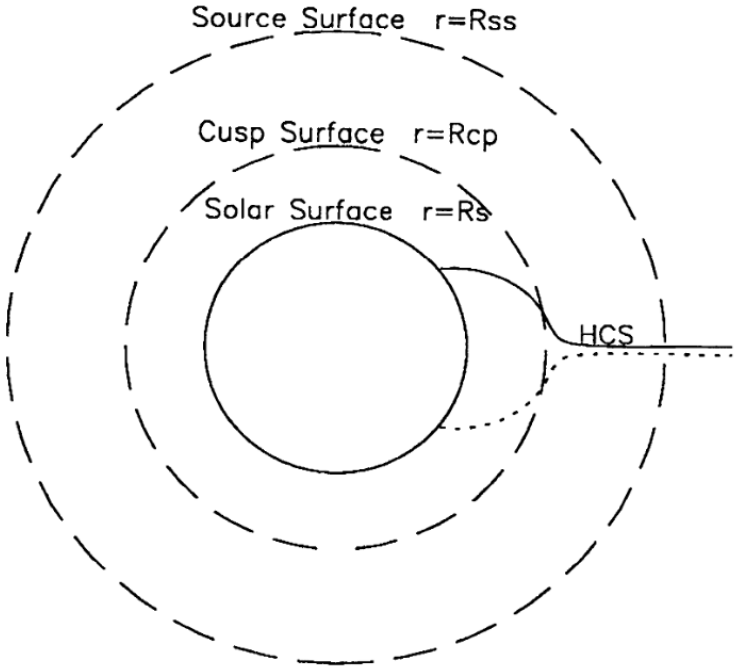
→ **Potential-field source-surface (PFSS):**
Spherical source surface: all magnetic field lines are assumed to be purely radial, reflecting the coronal plasma streaming radially outwards and forming the solar wind

→ **Current sheet-source surface (CSSS):**
Divides the solar atmosphere into the three parts
Different parts are separated by two spheres with the inner sphere at the *cusp radius* R_{cp} and the outer sphere at the source-surface radius R_{ss}.

Force-Free Models



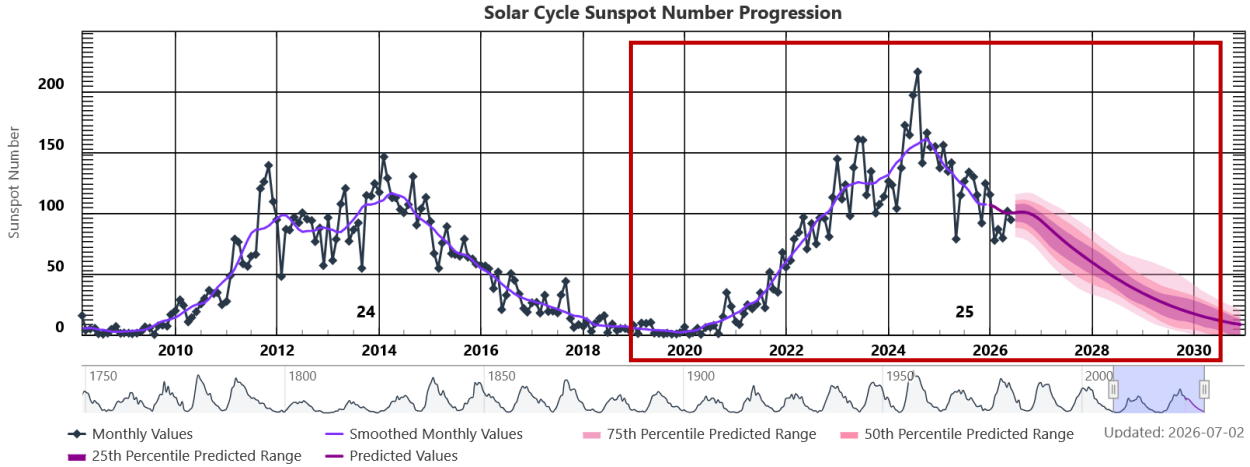




Wiegelmann, Thomas, Gordon JD Petrie, and Pete Riley. *Space Science Reviews* 210.1 (2017): 249-274.

Zhao, Xuepu, and J. Todd Hoeksema. *Journal of Geophysical Research: Space Physics* 100.A1 (1995): 19-33.

Solar Cycle Sunspot Number aka Activity



https://www.swpc.noaa.gov/products/solar-cycle-progression, access on July 20th 2026

Relative Sunspot Number: $R = k(10g + n)$

Number of individual spots: n

Number of sunspot groups: g

Oberserver factor: k