

Observations of the Sun in GeV Gamma Rays by CALET on the ISS

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for the CALET Collaboration

Observations from Fermi-LAT

- Seckel, Stanev, Gaisser 1991 (*ApJ* 382:652)
 - CR electrons and protons interacting with Solar photosphere and corona

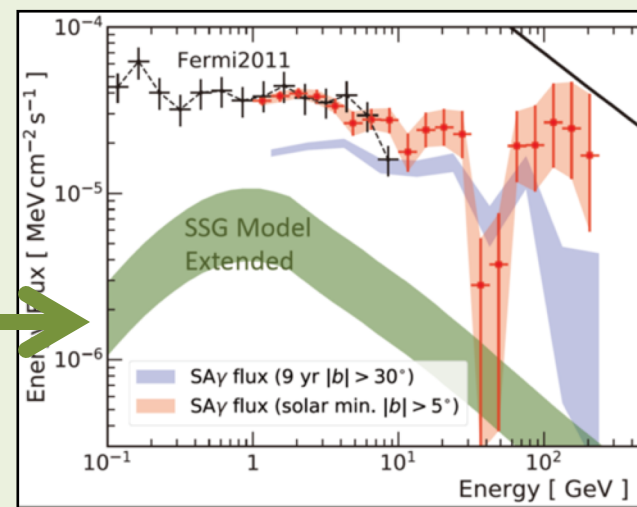


Image: Tang et al. 2018, PRD 98, 6, 063019

Black points: LAT at previous solar min.

Blue region: LAT between solar mins.

Red region: Solar min. cumulative flux

Black line: Limit of all protons being reversed and converted to photons

Green region: Expectation from SSG model, extended to higher energies

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- Abdo et al. 2011 (*ApJ* 734:116)
 - Hard spectrum ($\alpha \approx 2$)
 - Actual flux in excess of expectation ($\sim 7\times$)

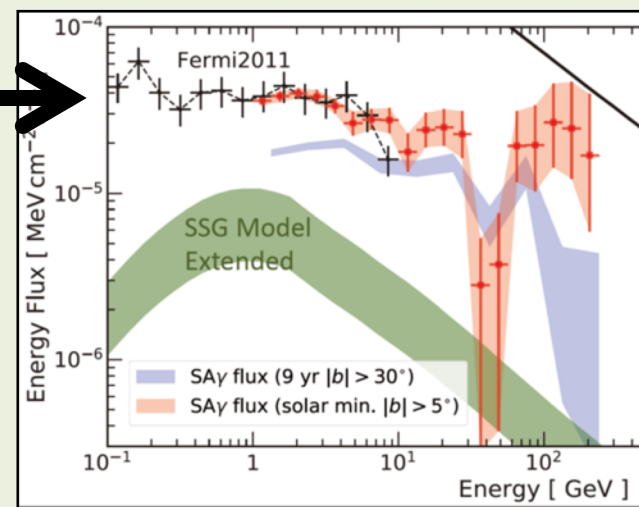


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- Tang et al. 2018 (*PRD* 98 063019)
Linden et al. 2018 (*PRL* 121 131103)
 - Events at $E > 100$ GeV, only at solar min.
 - Dip at 30–50 GeV?

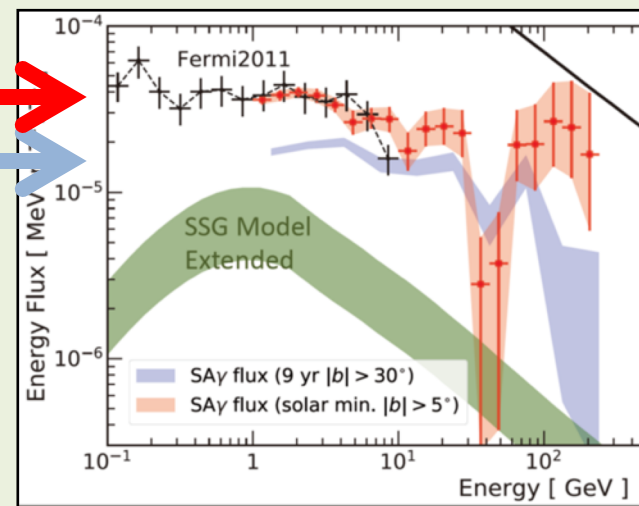


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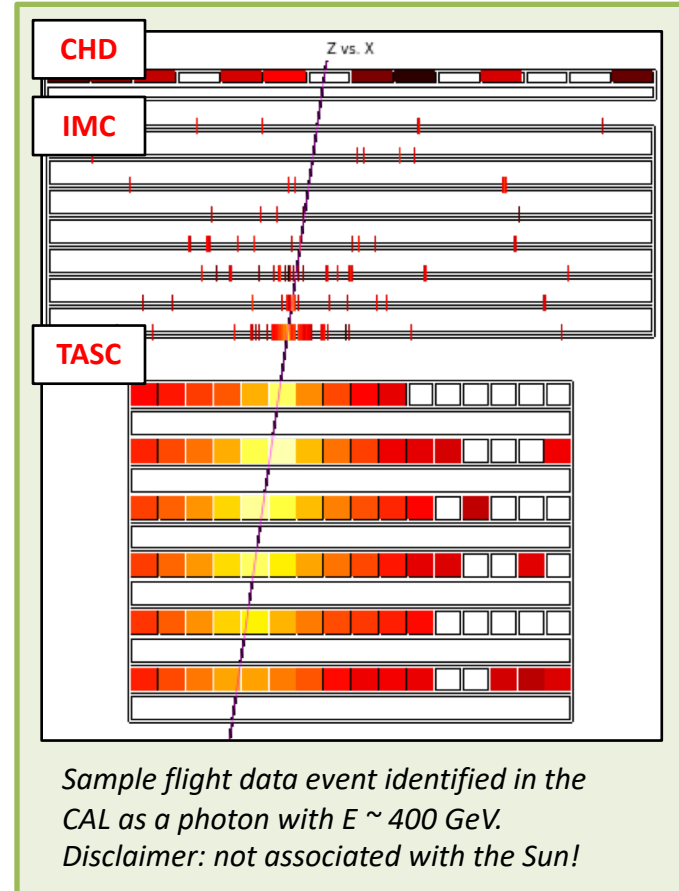
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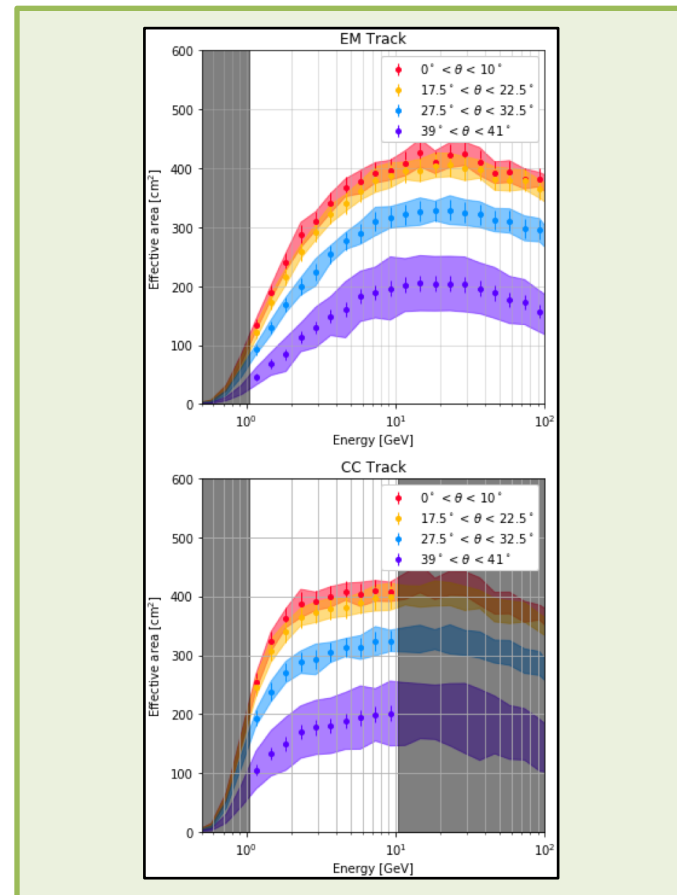
Potential for follow-up with CALET

- Asaoka et al. 2018 (*AP 100:29*)
 - CALET calorimeter
 - LE- γ trigger at low latitudes



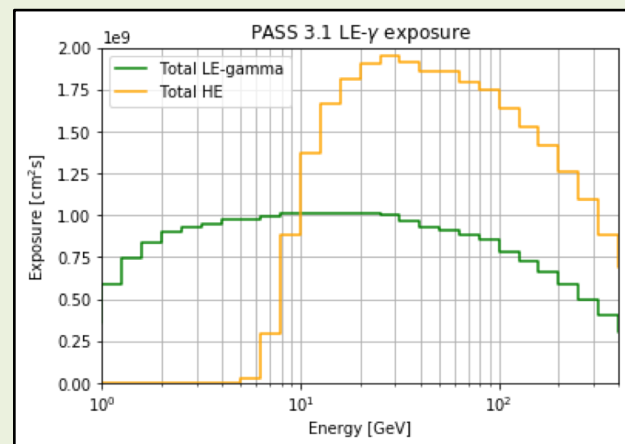
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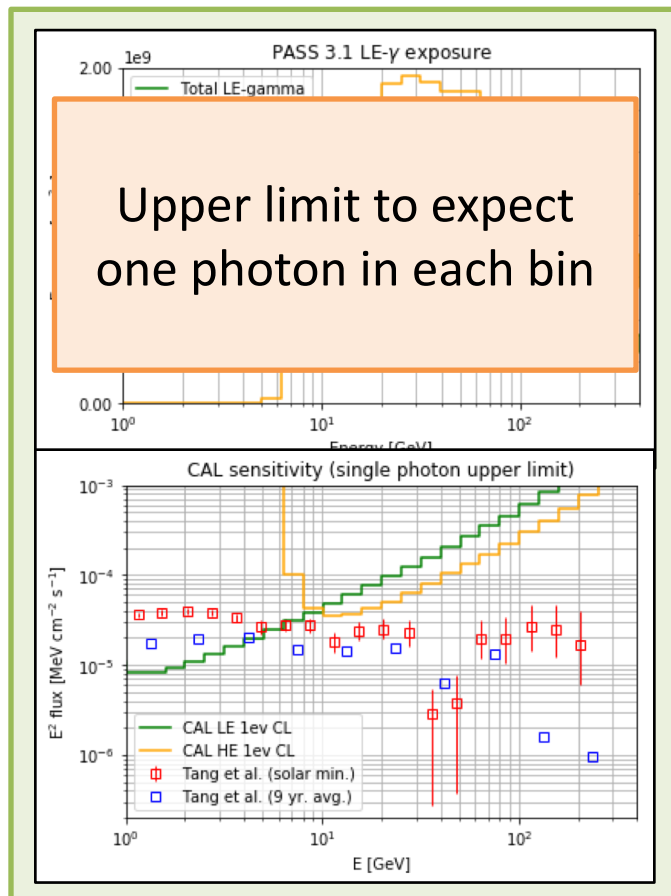
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 - CALET calorimeter sensitive to photons of GeV energies
- Pass 3.1 dataset contains first three years of CALET operations
 - Solar exposure calculated at Sun position each day at 12:00



Total cumulative exposure for PASS 3.1 dataset (35 months)

Potential for follow-up with CALET

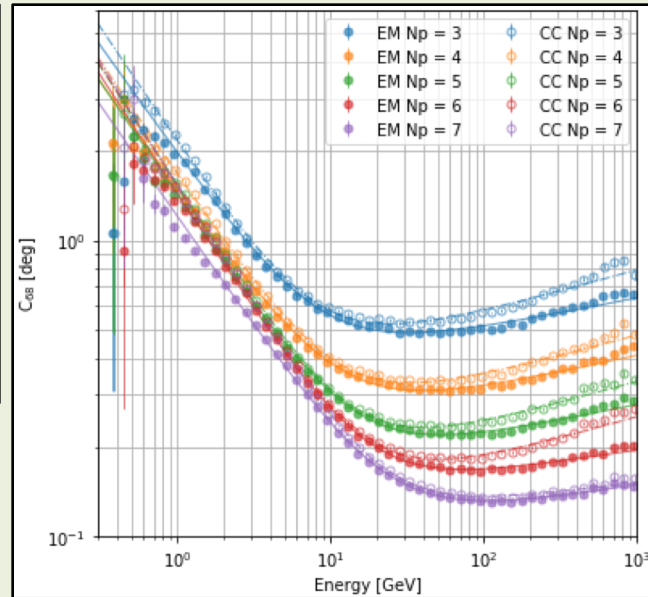
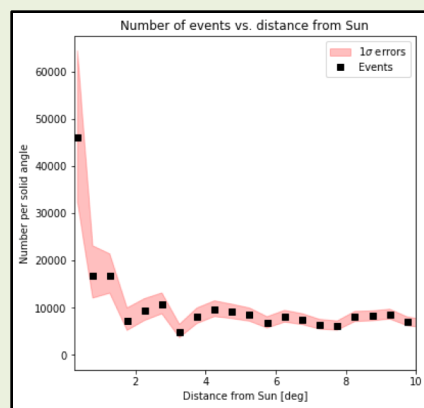
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 - CALET calorimeter sensitive to photons of GeV energies
- Pass 3.1 dataset contains first three years of CALET operations
 - Solar exposure calculated at Sun position each day at 12:00
 - Expected single photon detection in each bin approaches Tang et al. 2018 flux



Event selection

Galactic plane veto: $|b| > 10$ deg

- LE- γ trigger used for $E < 10$ GeV
 - CC Track trajectory
 - Moderate background
 - Moderate statistics
 - Ang. res. ~ 1 deg
 - Window: $R_{\odot} + 68\%$ cont.

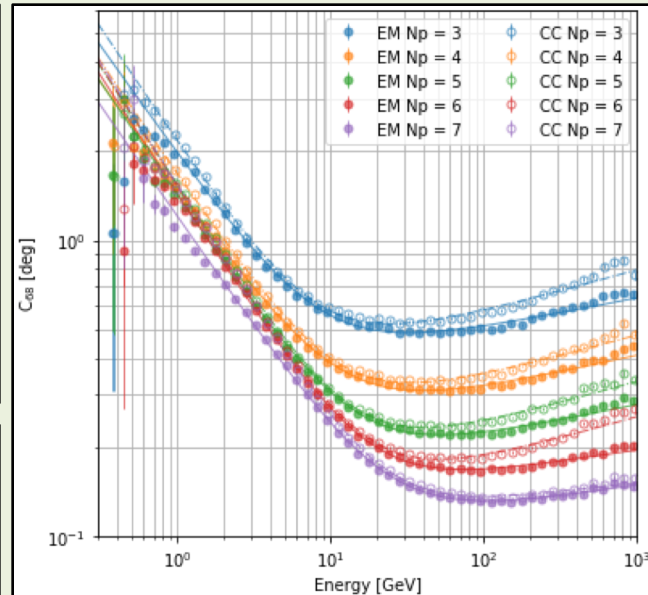
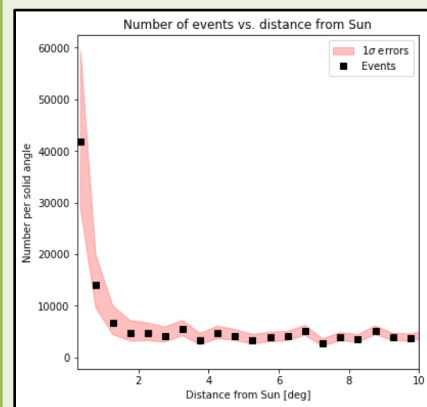
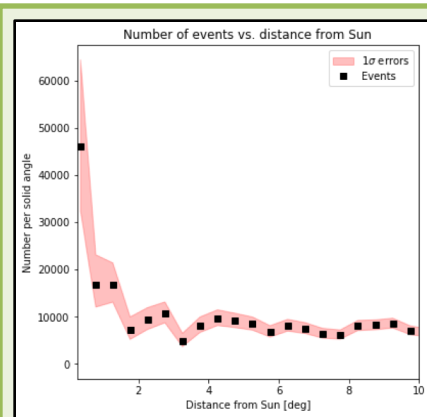


Angular resolution of LE-selected events for CAL gamma-ray candidates.

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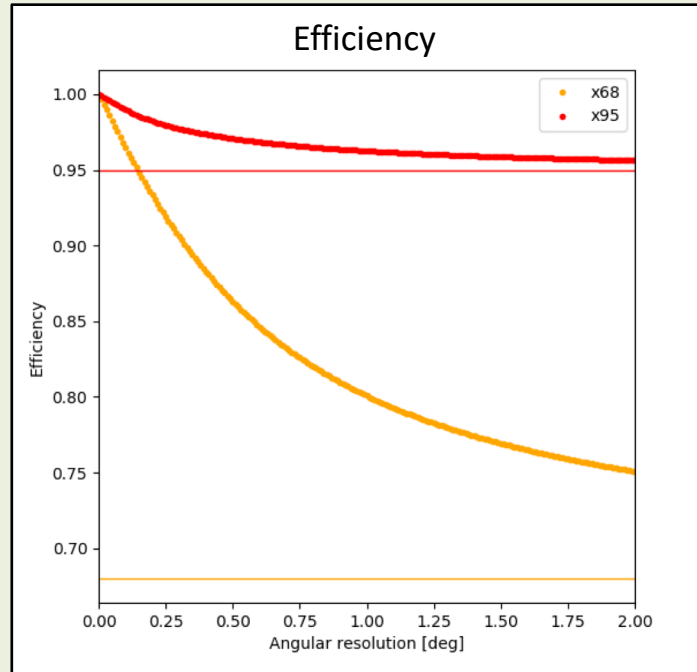
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 - Ang. res. ~ 1 deg
 - Window: $R_{\odot} + 68\%$ cont.
- HE trigger used for $E > 10$ GeV
 - EM Track trajectory
 - Low background
 - Low statistics
 - Ang. res. ~ 0.2 deg
 - Window: $R_{\odot} + 95\%$ cont.

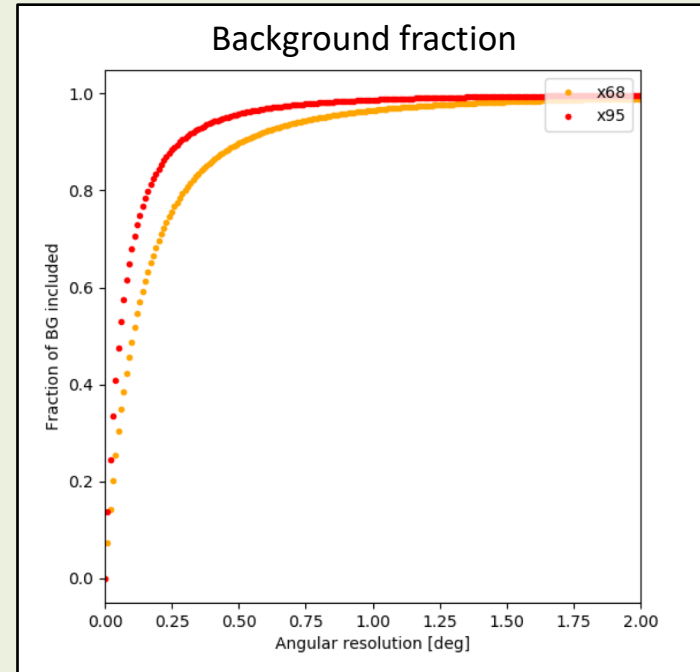


Angular resolution of LE-selected events for CAL gamma-ray candidates.

Detection efficiency and BG fraction



Probability to associate photons from Solar disk given a window size and losses from PSF smearing



Fraction of background seen in window given blockage from Solar limb and PSF smearing outside events into window

Putting it all together

- Consider event consistent with solar gamma-ray if angular separation from the sun position is less than $(R_{\text{Sun}} + \theta_{68})$ or $(R_{\text{Sun}} + \theta_{95})$
 - Scale number of events seen by previously derived efficiencies as a function of energy

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- Accumulate total exposure using sun position at noon on each day
 - Sun moves only $\sim 1^\circ$ per day – comparable to effective area pixel

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- Accumulate expected background from Fermi-LAT observations and daily exposure
 - Scale expected background numbers by previously derived fraction

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- Calculate flux

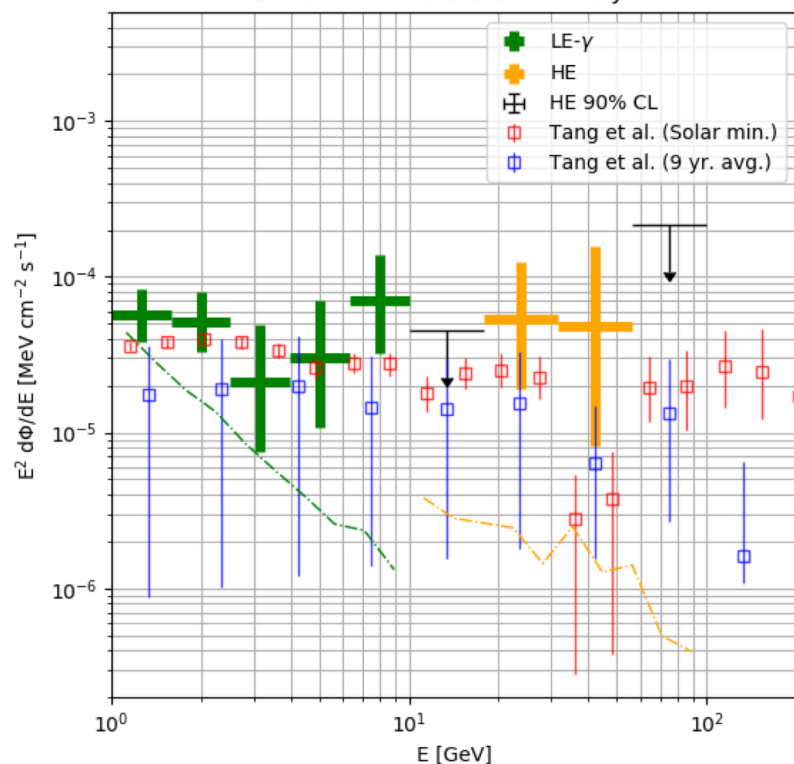
Preliminary fluxes

Galactic plane veto: $|b| > 10$ deg

- Results with LE- γ trigger consistent with Fermi-LAT measurements
- Three photons candidates associated with Sun position with energies $E > 10$ GeV
 - All three in 2017 & 2018
 - Consistent with Tang et. al continuum
 - Dip not detected but not confidently ruled out

PRELIMINARY

E^2 flux for PASS 3.1 Solar analysis

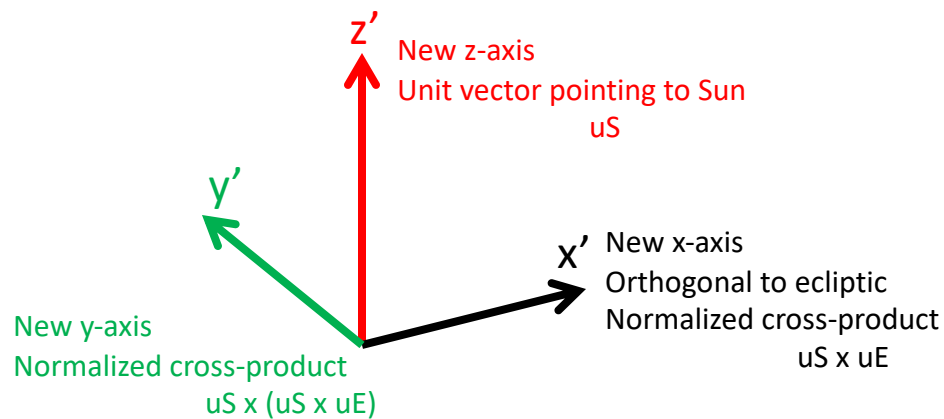


Summary

- CALET detects the Sun in GeV gamma rays significantly over the background signal
- Pass 3.1 dataset contains three photon candidates associated with Sun position with $E > 10$ GeV
 - Flux measurement consistent with Tang et al. continuum
 - Dip at 30-50 GeV not detected in CAL analysis, but not confidently ruled out
- Analysis refinement in progress
 - Expanding HE photon geometry to increase exposure at $E > 10$ GeV
 - Robust background trials including false Sun studies
 - Increase angular window to include IC halo contribution
 - Observations throughout solar minimum & solar cycle 25

Backup

Sun-centered frame transformation



Event direction unit vector uQ (equatorial)

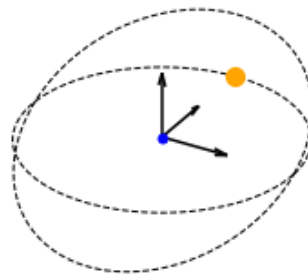
$$qX = uQ \cdot x'$$

$$qY = uQ \cdot y'$$

$$qZ = uQ \cdot z'$$

$$\theta = \arccos(qZ)$$

$$\phi = \arctan(qY / qX)$$



Sun-centered frame maps

