Publication Plan: Gamma Rays from the Quiescent Sun

Nicholas Cannady

Reminder – what's this all about?

- Seckel, Stanev, and Gaisser (SSG) predicted in 1991 a signal from the solar atmosphere due to cosmic-ray proton interactions
  - Comprises neutrinos, hadrons (including antiparticles), and photons
  - Photons predicted to be the most easily detectable signal, expected to be seen by EGRET but initially was not (Thompson et al. 1997)

Solar gamma rays

- **Background**
  - SSG model
  - IC halo
  - Fermi 2011
  - Tang et al.
- Paper plan
- Analysis targets
- Status
- Ongoing work

Seckel, Stanev, and Gaisser 1991

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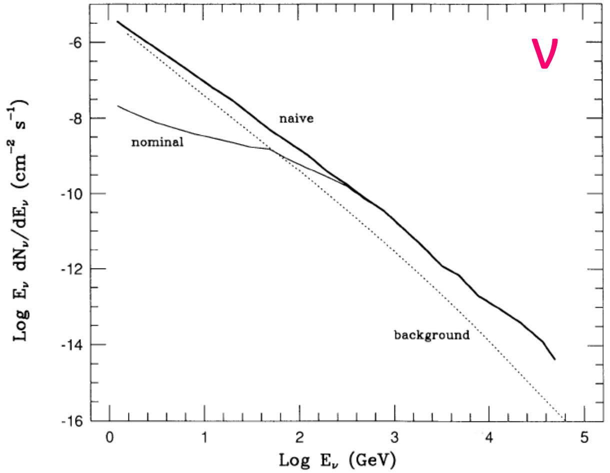

FIG. 4.—Neutrino flux at Earth for different assumptions about cosmic-ray transport. The bold curve shows an upper limit using the naive absorption rate shown as the bold curve in Fig. 3. The solid curve gives our nominal result. The background from terrestrial cosmic-ray cascades is shown for a solid angle equal to the size of the Sun's disk.

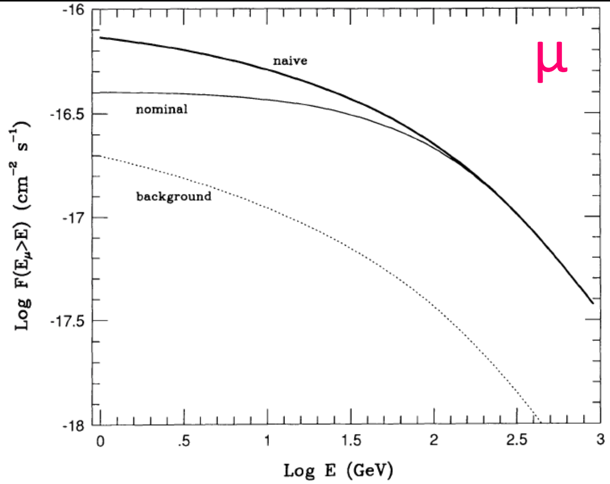

FIG. 5.—Underground muon flux from solar albedo neutrinos, integrated above a threshold energy, *E*. The curves are for the same models as in Fig. 4.

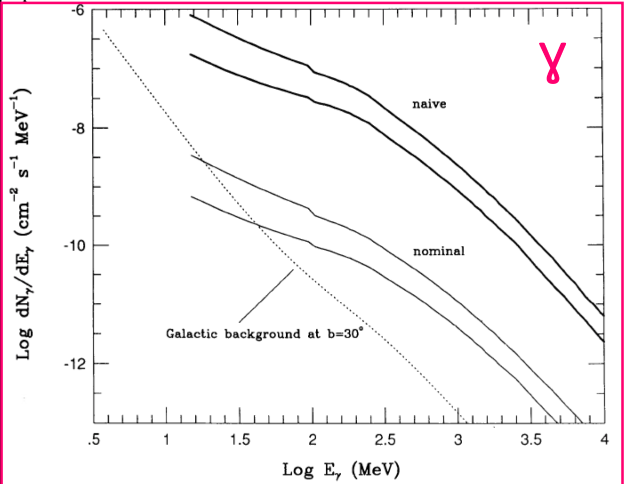

FIG. 7.—Differential photon flux at Earth for different assumptions about cosmic-ray propagation. Weighting of the curves is the same as in Fig. 4: bold for naive, light for nominal. In each pair of curves the upper curve shows the γ-ray albedo assuming charged particle trajectories for the cascade development, and the lower curve shows the result for neutral particle trajectories. The dotted curve shows the Galactic background for a disk the size of the Sun.

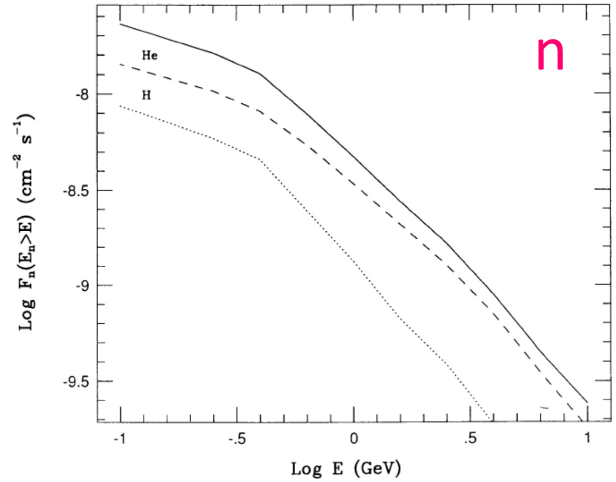

FIG. 9.—Neutron flux at Earth due to cosmic-ray interactions in the Sun. The dotted (*dashed*) curve shows the production due to incident protons (^{4}He). The contribution from ^{4}He is due mostly to spallation of incident nuclei, whereas incident protons contribute through inelastic process at higher energies and target spallation at lower energies.

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- Due to the intense photon field near the Sun, it is also expected that cosmic-ray electrons will create an inverse Compton (IC) halo
  - Extended emission reaching far beyond the solar disk
  - New analysis of full EGRET dataset found the IC halo and disk components to be significantly detected (Orlando and Strong, 2008)

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Orlando and Strong, 2008

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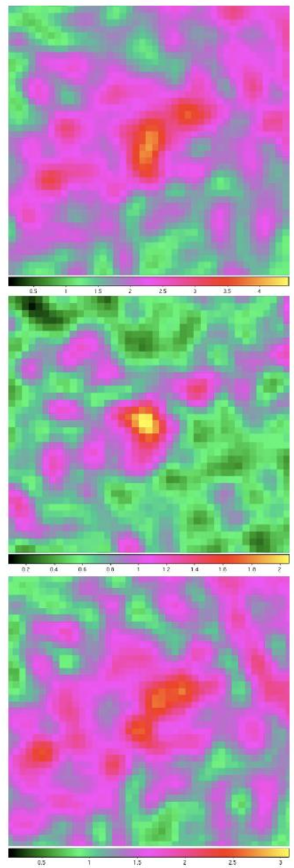

Fig. 11. EGRET Sun-centred counts maps (*top to bottom*) >100 MeV, >300 MeV and 100–300 MeV. The colorbar shows the counts per pixel. The area is 20° on a side and the maps are Gaussian smoothed to 3°.

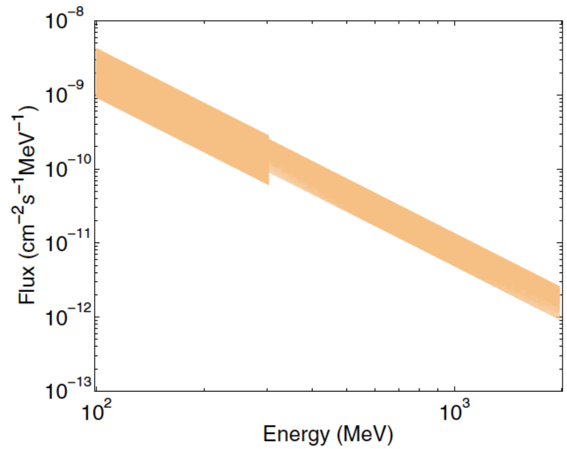

Fig. 15. Solar disk spectrum. The orange regions defines the possible values obtained by varying the mean flux within 1σ errors and for $\gamma = 2.4$, the mean value of the spectral index.

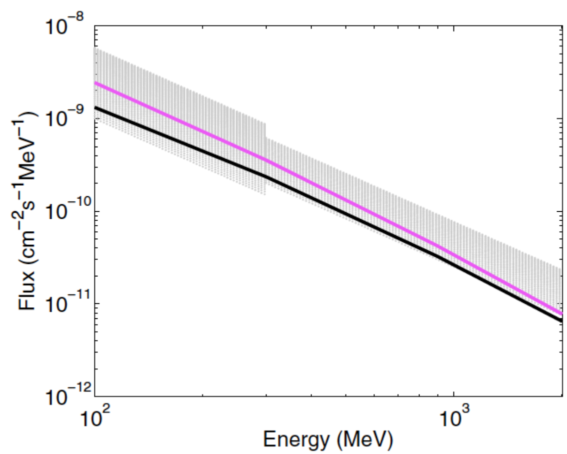

Fig. 16. Solar extended spectrum. Gray regions define the possible values obtained by varying the mean flux within 1σ errors and for $\gamma = 1.7$, the mean value of the spectral index. Black line is the model for the naive case of 1000 MV modulation. For comparison, the pink line shows the model for the naive case of 500 MV modulation.

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  - Extended emission reaching far beyond the solar disk
  - New analysis of full EGRET dataset found the IC halo and disk components to be significantly detected (Orlando and Strong, 2008)
- Both the disk and halo components are significantly detected in the first two years of Fermi LAT observations (Abdo et al. 2011)
  - Disk component higher than SSG "nominal" but below "naive" model, consistent with E^{-2} spectrum up to 10 GeV
  - Halo component roughly falls as θ^{-1} and E^{-2}

Tang et al. 2018 and Linden et al. 2018

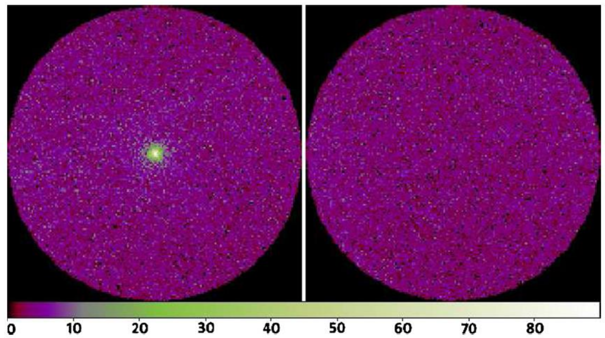
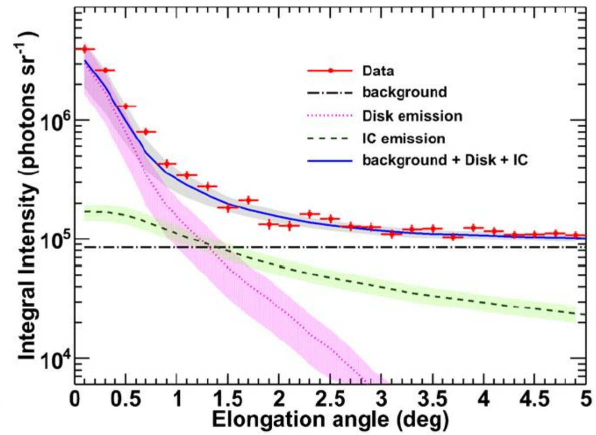


Figure 1. Count maps for events ⩾100 MeV taken between 2008 August and 2010 February and centered on the Sun (left) and on the trailing source (so-called fake-Sun, right) representing the background. The ROI has $\theta = 20°$ radius and pixel size 0.°25 × 0.°25. The color bar shows the number of counts per pixel.



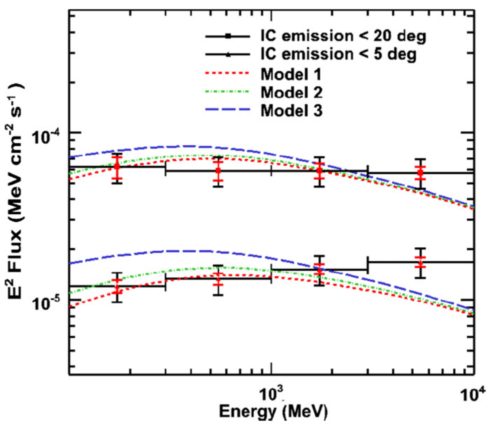


Figure 7. Energy spectra of the IC emission for elongation angles ⩽5° and ⩽20° as observed by *Fermi*-LAT and compared with model predictions. Statistical error bars (larger) are shown in black; systematic errors (smaller) are red.

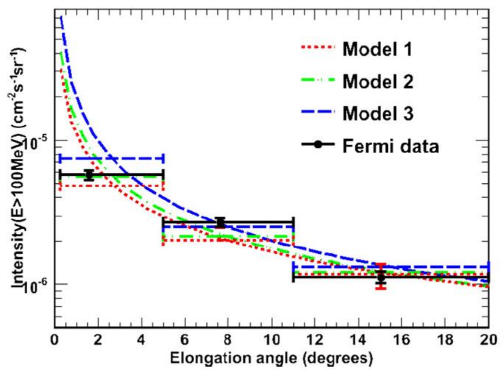


Figure 8. Intensity profile for the IC component vs. elongation angle compared with the model predictions. Statistical error bars (smaller) are shown in black; systematic errors (larger) are shown in red. To allow a direct comparison with the models, the model predictions are also shown binned with the same bin size as used for data.

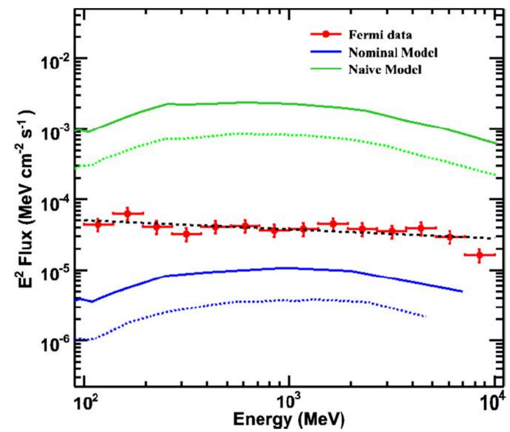


Figure 9. Energy spectrum for the disk emission as observed by the *Fermi*-LAT. The curves show the range for the "nominal" (lower set, blue) and "naive" (upper set, green) model predictions by Seckel et al. (1991) for different assumptions about CR cascade development in the solar atmosphere (see the text for details). The black dashed line is the power-law fit to the data with index 2.11 ± 0.73.

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  - Disk component higher than SSG "nominal" but below "naive" model, consistent with E^{-2} spectrum up to 10 GeV
  - Halo component roughly falls as θ^{-1} and E^{-2}
- Analysis of 11 years of LAT data at OSU extended this to >100 GeV
  - Hard spectrum continues to high energies with a dip from 30 – 50 GeV
  - Anti-correlation of flux with solar cycle; >100 GeV only seen at solar min.
  - Resolved disk shows changing emission region with solar cycle

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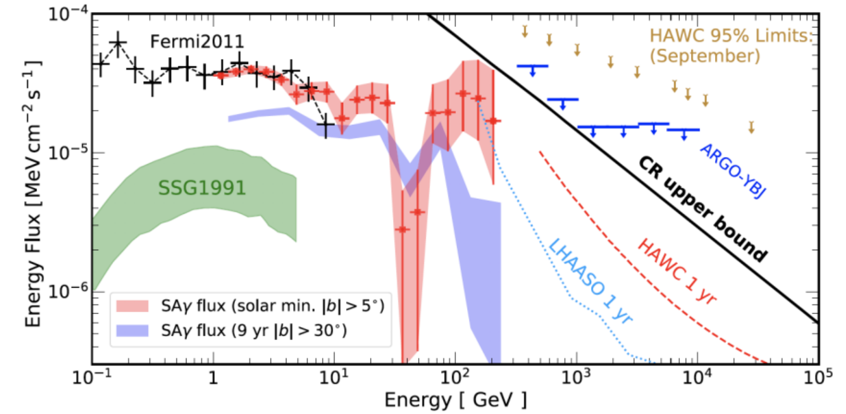

FIG. 5. The 9 year averaged SAγ flux and the solar minimum SAγ flux (76 weeks of data from 2008-8-7 to 2010-1-21), which is significantly harder above 100 GeV. We also show the point source sensitivities of HAWC [23] and LHAASO [24,25], as well as the preliminary limits from HAWC ([47], one month of data) and ARGO-YBJ [48]. The theoretical maximum gamma-ray flux that the Sun can produce with cosmic rays (CR upper bound; see text for detail) is shown by the black solid line.

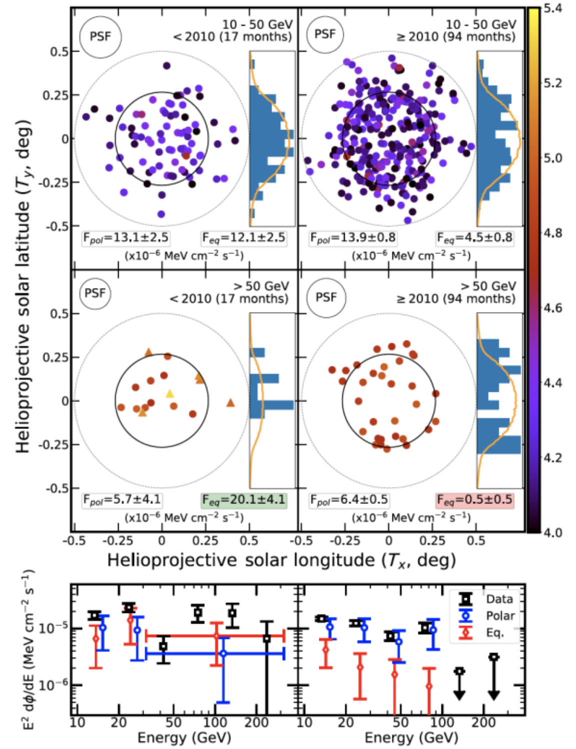

FIG. 2. (Top panel) The location and energy of solar γ rays in helioprojective coordinates. Data are cut into two temporal and two energy bins. The solid disk indicates the solar circle, and the dashed circle indicates the 0.5° ROI. The average 68% containment region of γ rays in each bin is depicted at the top left. The histogram depicts the T_y positions of photons compared to the expectation from isotropic solar emission smeared by the PSF (orange line). Events > 100 GeV are marked with triangles rather than circles. We stress that the exposure after solar minimum significantly exceeds the exposure during solar minimum. Thus, the observed number of counts does not indicate the relative flux. In each bin, we report the flux from the modeled polar and equatorial components, as described in the text. (Bottom panel) The energy spectrum of polar and equatorial emission, divided into regions during (left) and after (right) solar minimum. The polar emission is approximately constant, while the equatorial emission decreases drastically after solar minimum.

What can we contribute?

- Clear across multiple analyses and multiple instruments:
  - There is emission from the disk of the quiescent Sun in excess of SSG
  - There is an extended IC halo around the Sun
- (Opinion): What's probably true:
  - The intensity of the disk emission is somehow affected by the solar cycle
  - The disk emission extends beyond tens of GeV
- What's left:
  - The morphology of the disk emission changes with solar cycle
  - There is a dip in the disk emission spectrum for E ~ 30 – 50 GeV

Solar gamma rays
- Background
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What can we contribute?

- Clear across multiple analyses and multiple instruments:
  - There is emission from the disk of the quiescent Sun in excess of SSG
    - Easy to confirm - we definitely see this already!
  - There is an extended IC halo around the Sun
    - Will take as fact in likelihood analysis
- (Opinion): What's probably true:
  - The intensity of the disk emission is somehow affected by the solar cycle
    - Time dependence of CALET measurement
  - The disk emission extends beyond tens of GeV
    - Our exposure is not high enough beyond a few tens of GeV
- What's left:
  - The morphology of the disk emission changes with solar cycle
    - High-energy statistics not high enough to probe this
  - There is a dip in the disk emission spectrum for E ~ 30 – 50 GeV
    - We reach these energies (barely)

Intensity and hardness of spectrum

- A more specific itemization of what we would like to publish:
  - A spectral fit along with our spectrum
  - Power-law index consistency with Fermi2011 result
  - Normalization in excess of SSG prediction

Solar gamma rays

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  - Hard spectrum
  - Flux variability
  - No dip
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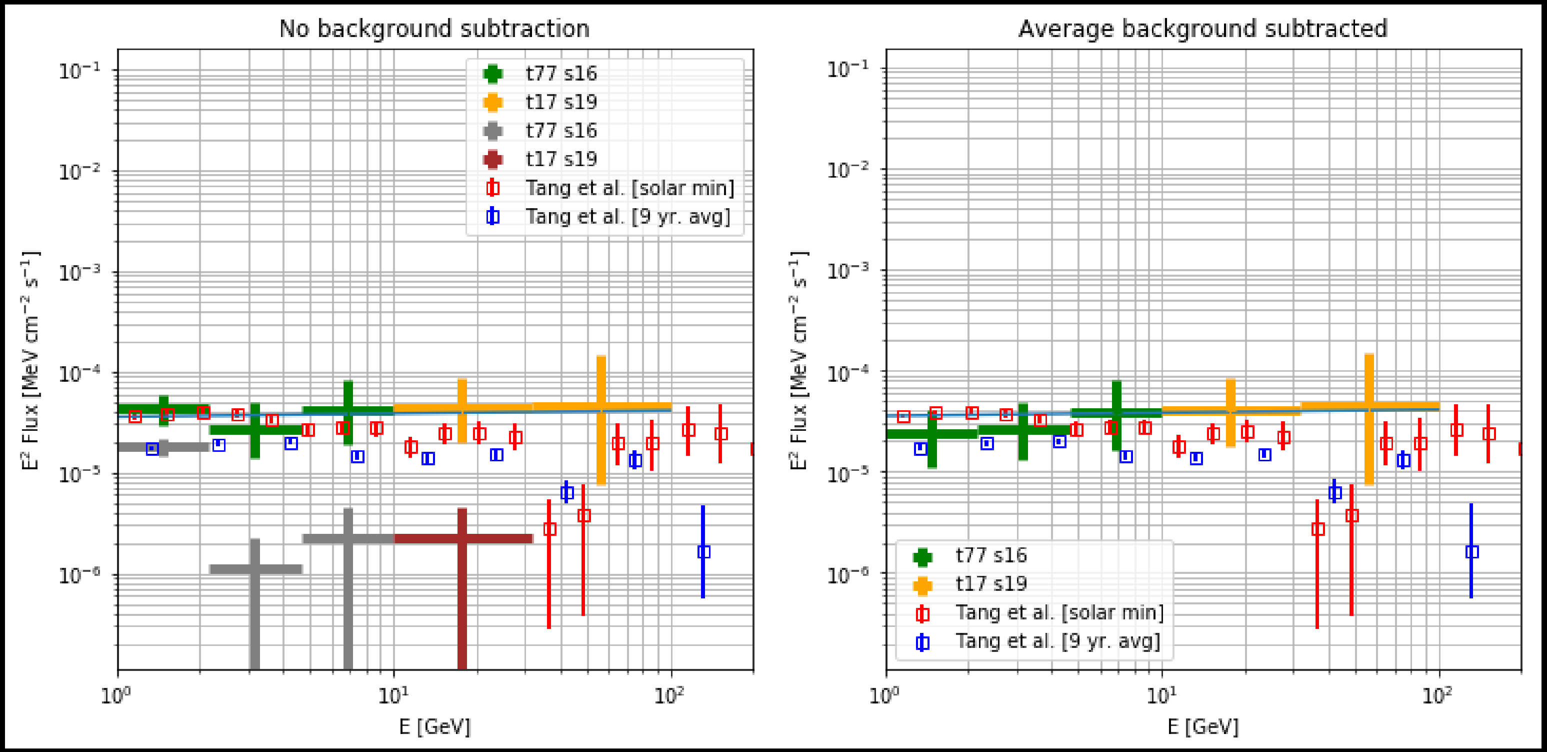

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Variability of the CALET measurement

- A more specific itemization of what we would like to publish:
  - A spectral fit along with our spectrum
  - Power-law index consistency with Fermi2011 result
  - Normalization in excess of SSG prediction
- A measure of the variability present in the CALET data
  - Do we detect a significant increase in the solar minimum period?
  - If so, a quantitative statement about the significance

Solar gamma rays
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No dip present in the CALET measurement

Solar gamma rays

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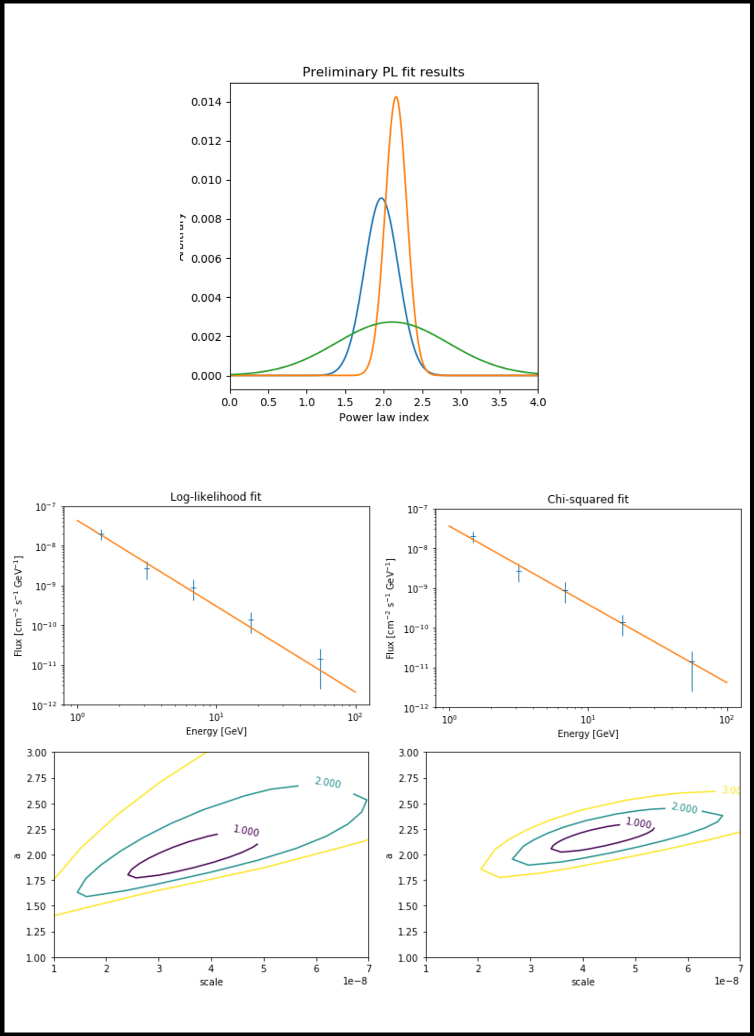
- A measure of the variability present in the CALET data
  - Do we detect a significant increase in the solar minimum period?
  - If so, a quantitative statement about the significance
- A measure of the (in)consistency of the CALET measurement with the spectral dip present in the Tang et al. result
  - In addition to trying the power-law fitting above, model a power law with a spectral dip
  - Can we significantly reject a dip at any "severity?"

Fitting the measured spectrum

- Preliminary calculation of the flux was done and a power law was fit
  - CAVEAT: currently no treatment of the IC flux is taken into account

- Chi-squared fitting (with Poisson errors)
  - Scale: (3.6 ± 1.2) e-8
  - Index: (1.97 ± 0.22)
- Likelihood fitting
  - Scale: (4.3 ± 1.1) e-8
  - Index: (2.16 ± 0.14)
- Fermi2011 results
  - Index: (2.11 ± 0.73) (why is the error so large?)



Solar gamma rays
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- **Status**
  - Spectral fit
  - Background modeling
  - Variability
- Ongoing work

Properly including ROI and background

- Current treatment of disk emission:
  - Select window based on average angular resolution at energy for >95% containment of photons from the disk
- Current treatment of backgrounds:
  - Galactic plane: remove 10° window around plane region
  - Point sources: remove 5° window around source list (Crab, Geminga, Vela, CTA 102, a few other AGN)
  - Moon: remove 5° window around Moon position at each time
  - IC halo: neglect

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  - Moon: remove 5° window around Moon position at each time
  - IC halo: neglect
- Planned treatment of disk emission:
  - Select events in region of interest of constant angular size
  - Remove contribution from bright sources as above
  - Include IC halo and disk component morphologically in likelihood
    - Per Tang et al., IC angular extent as θ^{-1}, except 0 in disk region
    - Normalization of IC halo left as nuisance parameter
    - Assuming spectral shape according to $\theta < 5$ result for Fermi2011?

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Testing the variability in the CALET dataset

Solar gamma rays
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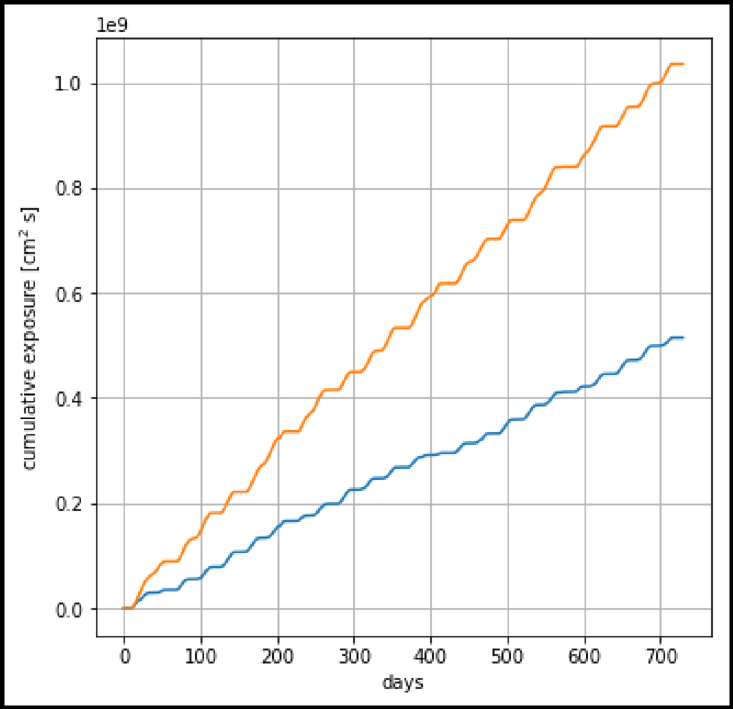
Some dependence on solar cycle is suggested in CALET data

- Exposure accumulation is roughly linear (somewhat low for 2019)
- ISS structures in FOV can impact this result through exposure loss



2015	2 months	2	0
2016	12 months	6	0
2017	12 months	11	2
2018	12 months	13	2
2019	10 months	7	0

Testing the variability in the CALET dataset

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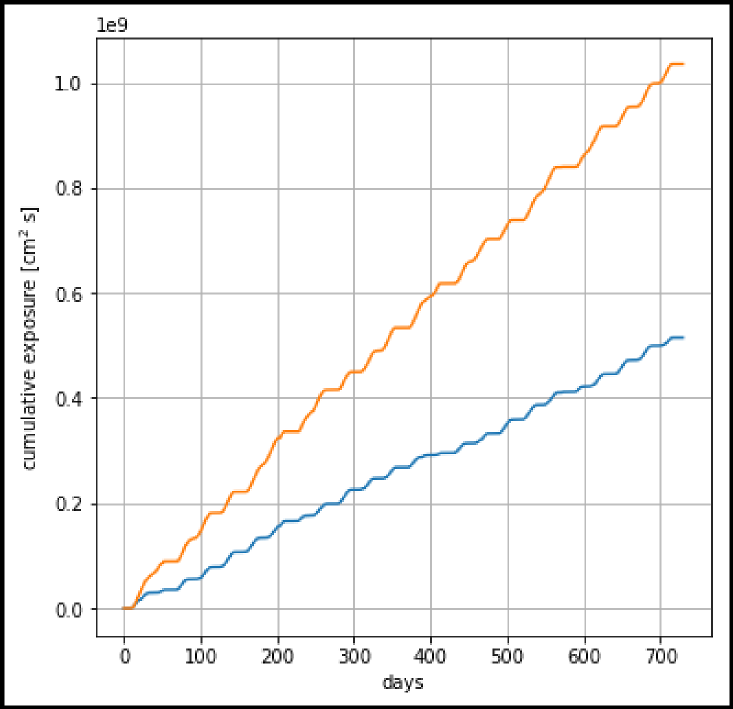
Some dependence on solar cycle is suggested in CALET data

- Exposure accumulation is roughly linear (somewhat low for 2019)
- ISS structures in FOV can impact this result through exposure loss
- Finer time binning makes this seem not as clear...

2015/11 – 2016/02	4	0
2016/03 – 2016/06	0	0
2016/07 – 2016/10	4	0
2016/11 – 2017/02	3	0
2017/03 – 2017/06	3	2
2017/07 – 2017/10	3	0
2017/11 – 2018/02	3	0
2018/03 – 2018/06	4	1
2018/07 – 2018/10	4	1
2018/11 – 2019/02	3	0
2019/03 – 2019/06	1	0
2019/07 – 2019/10	6	0



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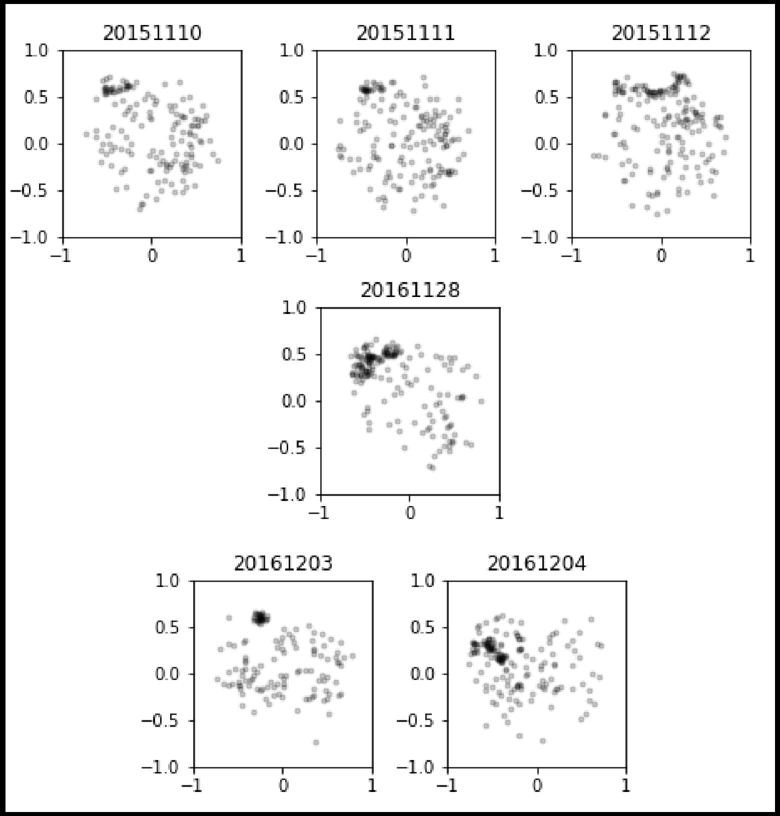
2018	12 months	13	2
2019	10 months	7	0

Revisiting the problem of ISS structures in FOV

- Thanks to Asaoka-san, most ISS structure contamination is removed
- Since the number of photons is so low for the solar analysis, must be very careful about removing as much as possible, especially if it affects the high-energy photons
  - When checking daily maps, it is clear that there is some residual contamination in the photon dataset
  - During Waseda visit, learned to make daily cuts to add to the database
  - Recently completed removal of "urgent concern" regions
  - Event and exposure files being generated now
  - Next, the days that are flagged but maybe not "urgent"



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- **Ongoing work**
  - ISS structure treatment
  - Increasing acceptance

Expanding beyond CHD charge identification?

- Increasing the exposure (esp. at high energies) is always nice, but for this analysis it requires expanding the acceptance

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Why not just improve charge selection?

Solar gamma rays
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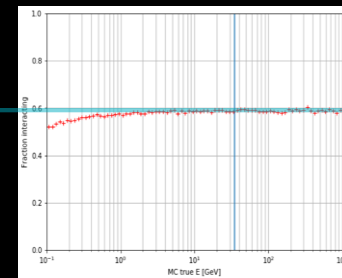
➢ **Ongoing work**
- ISS structure treatment

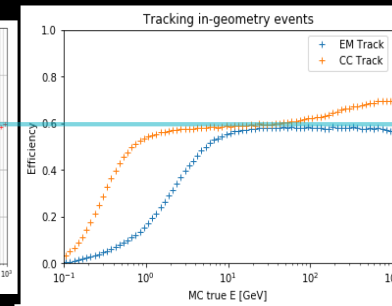
➢ Increasing acceptance

current selection

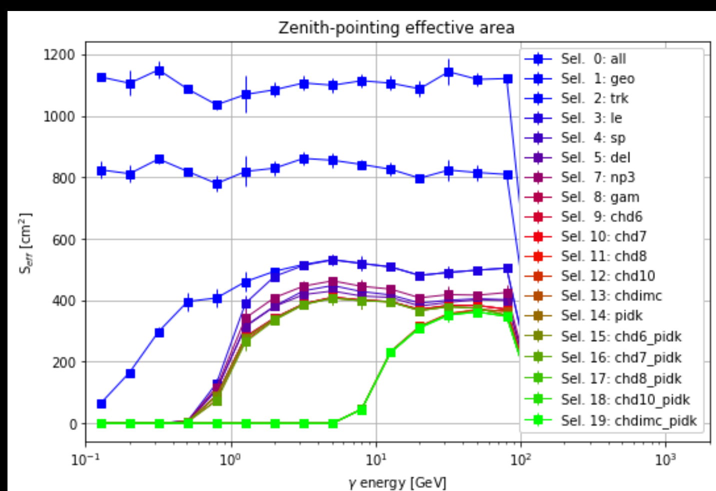
track passes:
- CHD top
- TASC top

first interaction:
- below IMC 1 (Np < 8)
- above IMC 6 (Np > 2)





- Tracking efficiency converges to pair production efficiency
  - we track photons with E > 1 GeV with ~100% efficiency
  - no noticeable improvements possible in tracking



Charge cut only loses <~ 10% of gamma events at intermediate energies

More statistics requires more open geometry

Expanding beyond CHD charge identification?

- Increasing the exposure (esp. at high energies) is always nice, but for this analysis it requires expanding the acceptance
- Can be investigated using the new photon and electron datasets generated at LSU HPC facilities (and the old proton dataset)
- Started working with graduate student at Ritsumeikan University (Zenita-san) in regards to this selection

Summary

- We plan to publish the solar analysis in the coming months
- Improved modeling of the source environment in the likelihood is being implemented and tested
- ISS structure removal is being performed at a daily basis to remove remaining clear obstructions
- Preliminary power-law fitting of the disk emission gives a result consistent with the Fermi 2011 result
- The dip at 30 – 50 GeV remains undetected by CALET even with improved statistics
- There is evidence of an increase of the flux during solar minimum, but 2019 is an outlier
- Testing feasibility of opening acceptance to IMC-only charge selection

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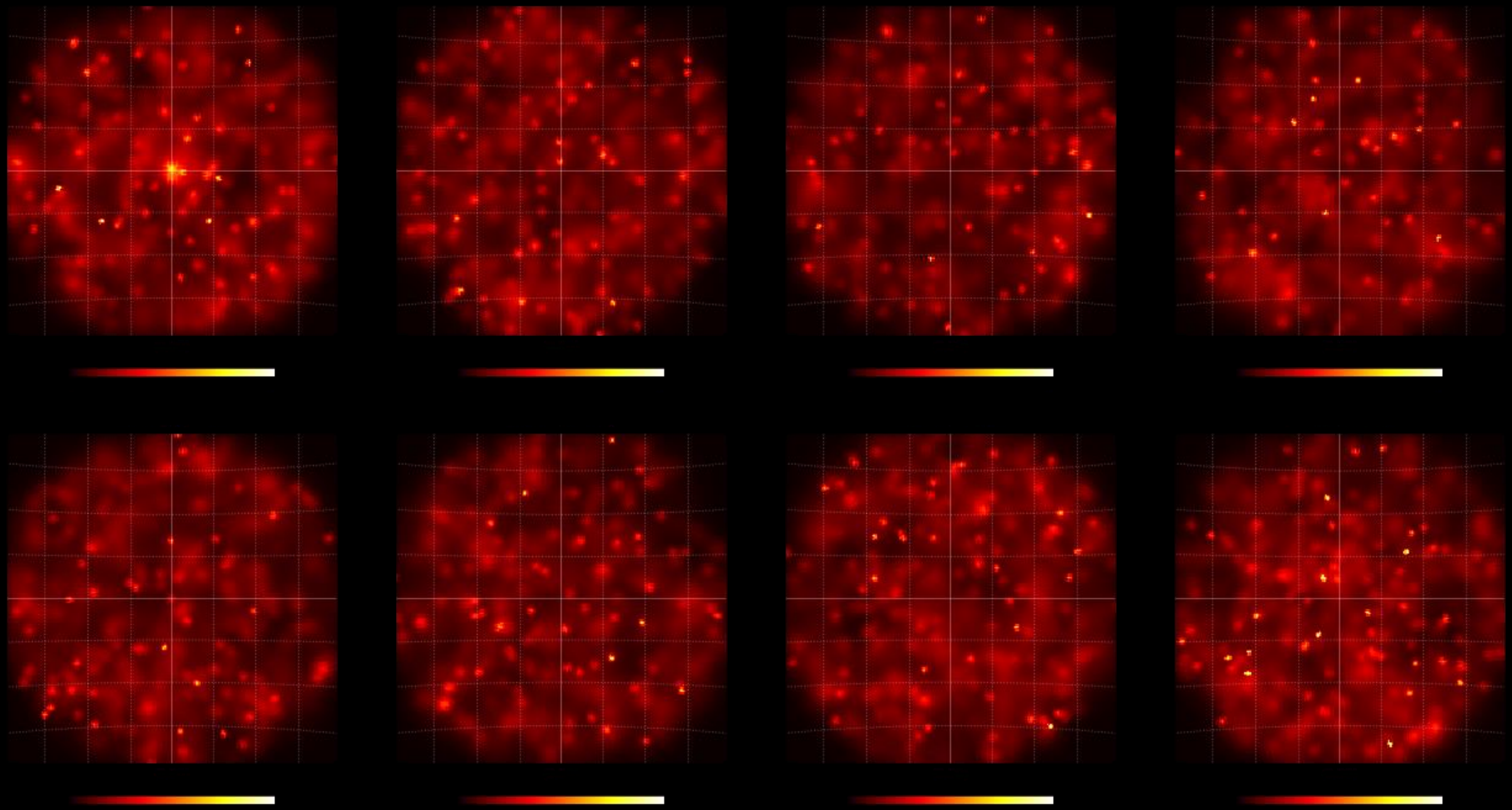
Real and fake Sun frames

Backup slides

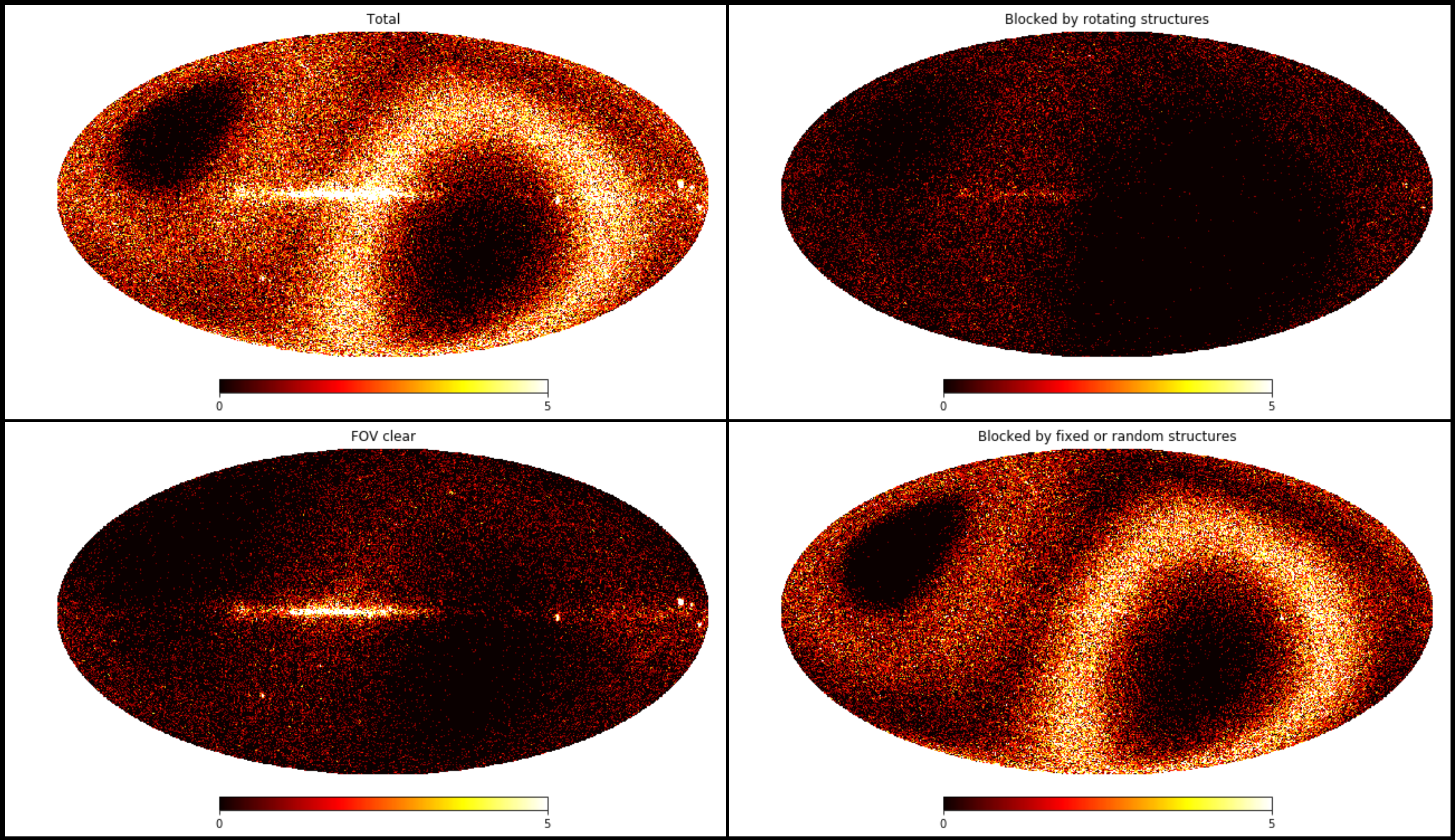
- Frame maps



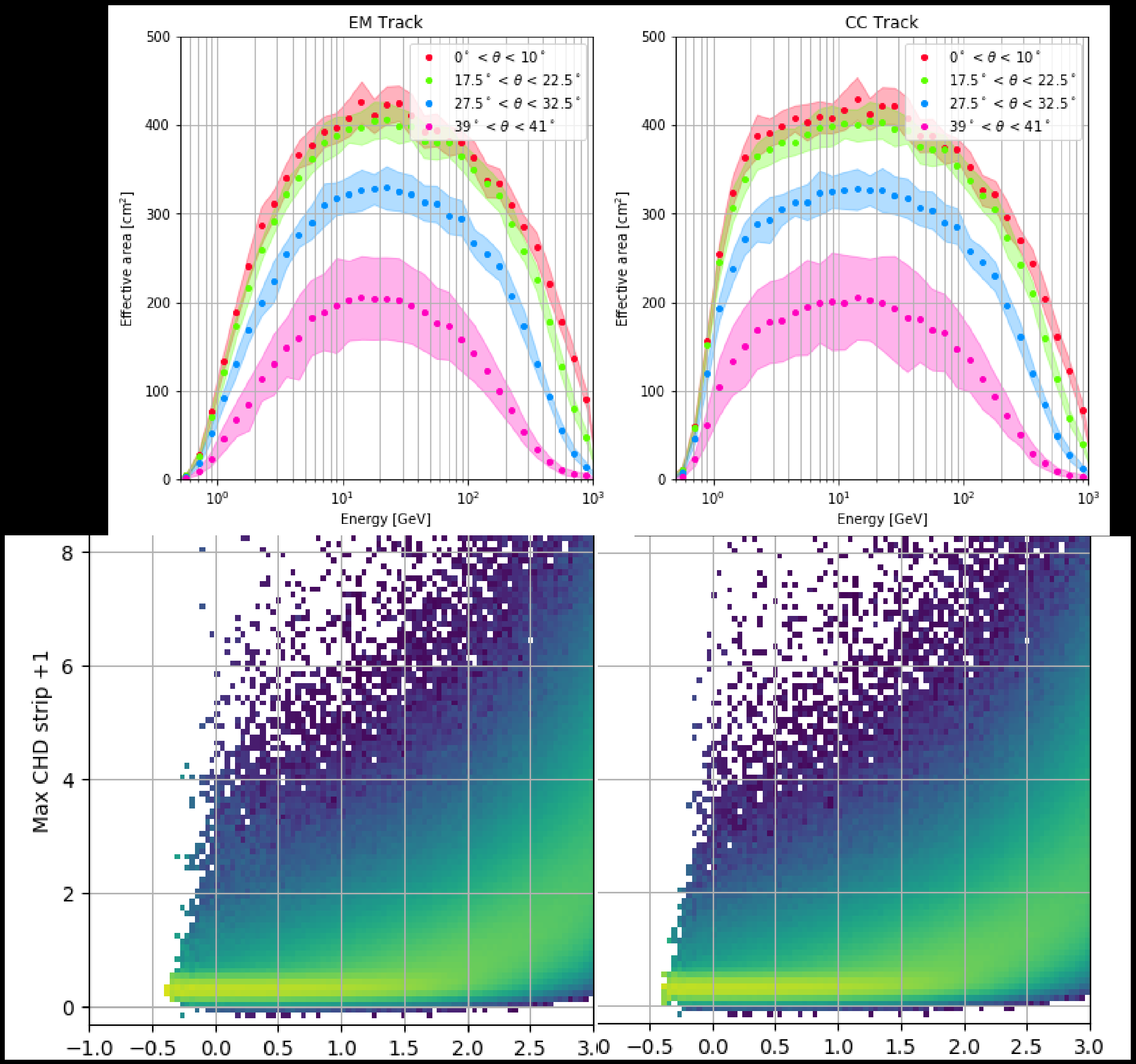
LE events removed by FOV cuts

Backup slides

- Cut events



Backscatter effect on efficiency



Backup slides

- Backscatter