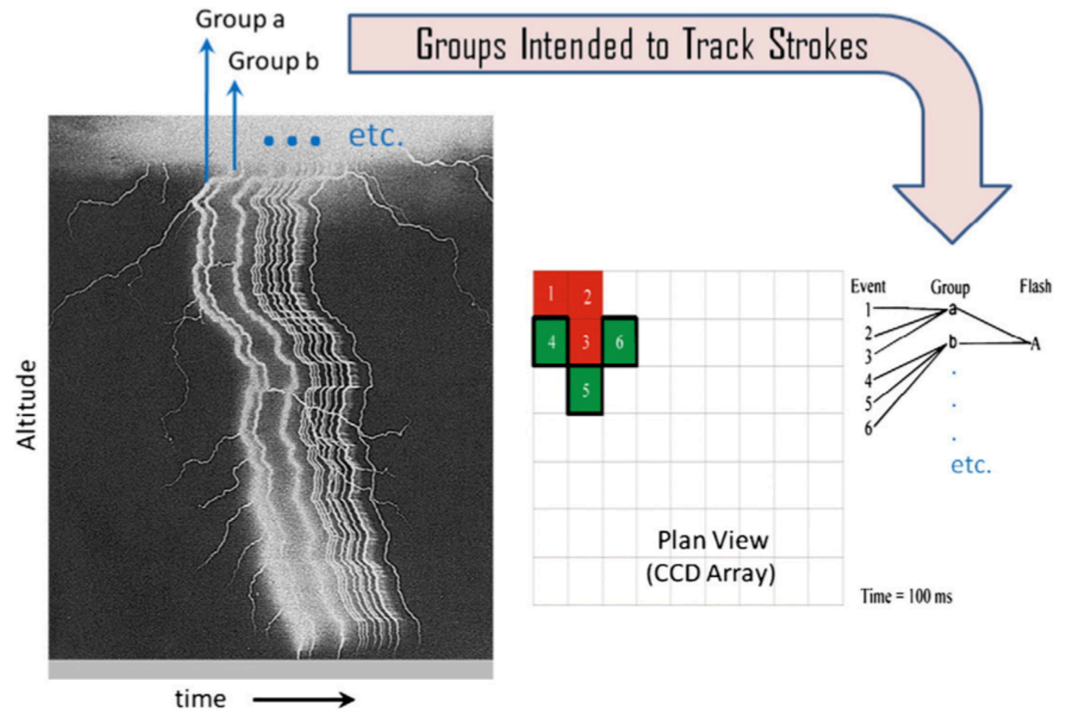
Pipeline Development and Statistical Analysis of Bolides Detected by the GOES Geostationary Lightning Mappers

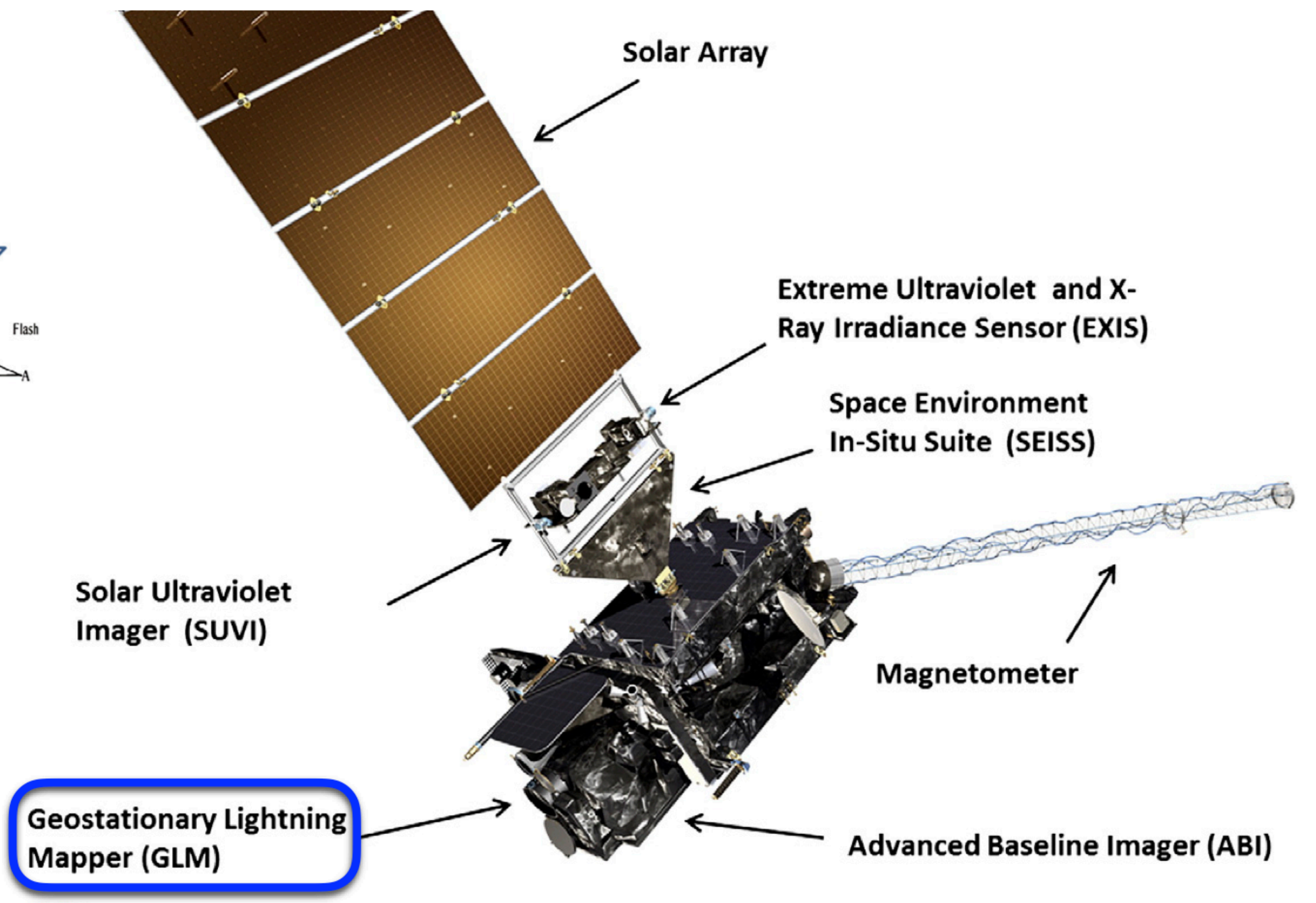
Jeffrey Smith
SETI Institute
with Robert Morris (SETI), Randy Longenbaugh (Sandia Labs), Anthony Ozerov (Columbia), Tasan Smith-Gandy (Williams College), Nina McCurdy (NASA Ames), Jessie Dotson (NASA Ames)

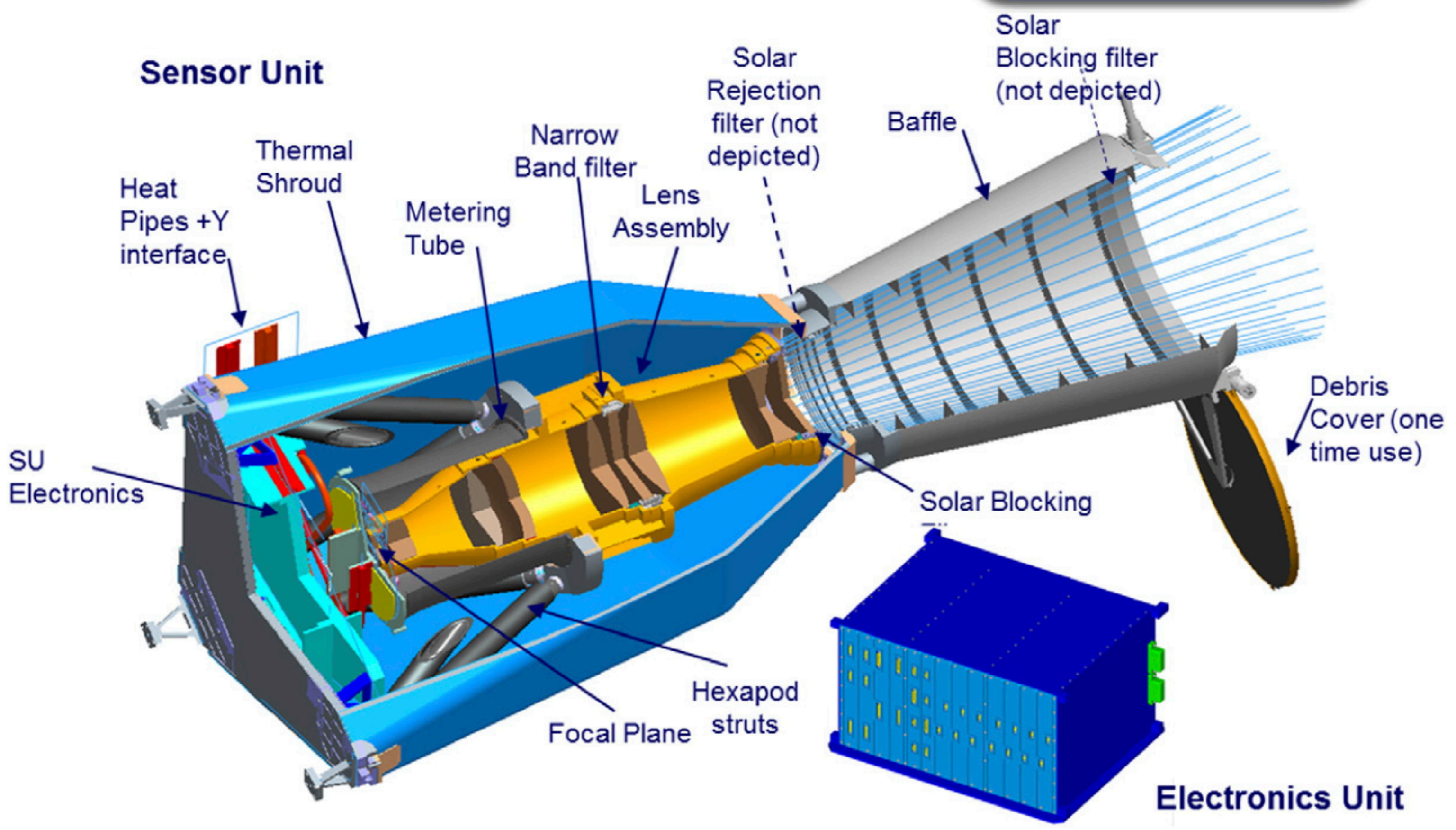
EU-ESA Workshop on NEO Imminent Impactors Warning Coordination
13 December, 2022

What is GOES GLM?

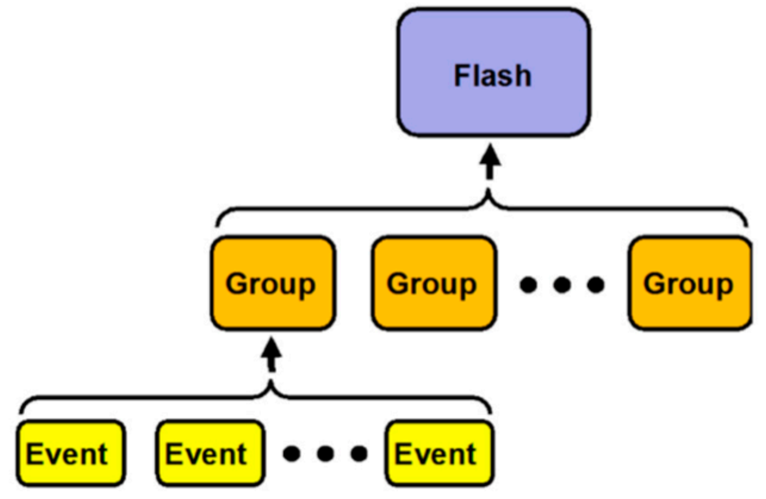
- Geostationary Lightning Mappers (GLM) onboard the Geostationary Operational Environmental Satellite (GOES) 16 and 17 weather satellites, operated by the National Oceanic and Atmospheric Administration (NOAA).
- Designed to detect lightning, but has other uses…
  - In Jenninskens et al., Meteorit. Planet. Sci. 53 (2018) 2445-2469 was shown to be capable of detecting bolides.
- Together, GLM on GOES 16 and 17 covers most of the Western Hemisphere with overlapping viewing fields over the Americas, providing near-hemispherical, continuous coverage with public data releases.
- This semi-global viewing area and public data access represents an unprecedented opportunity to observe meteors continually and on large scale.

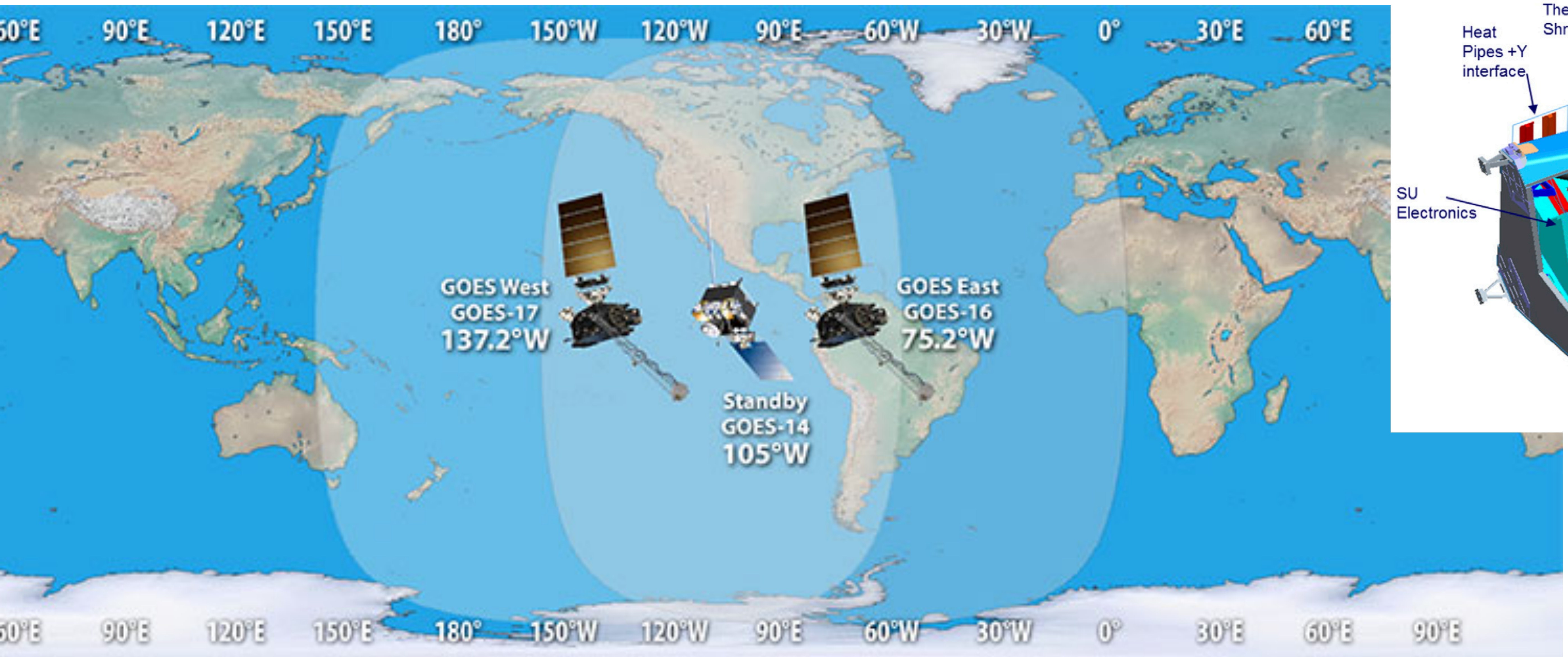






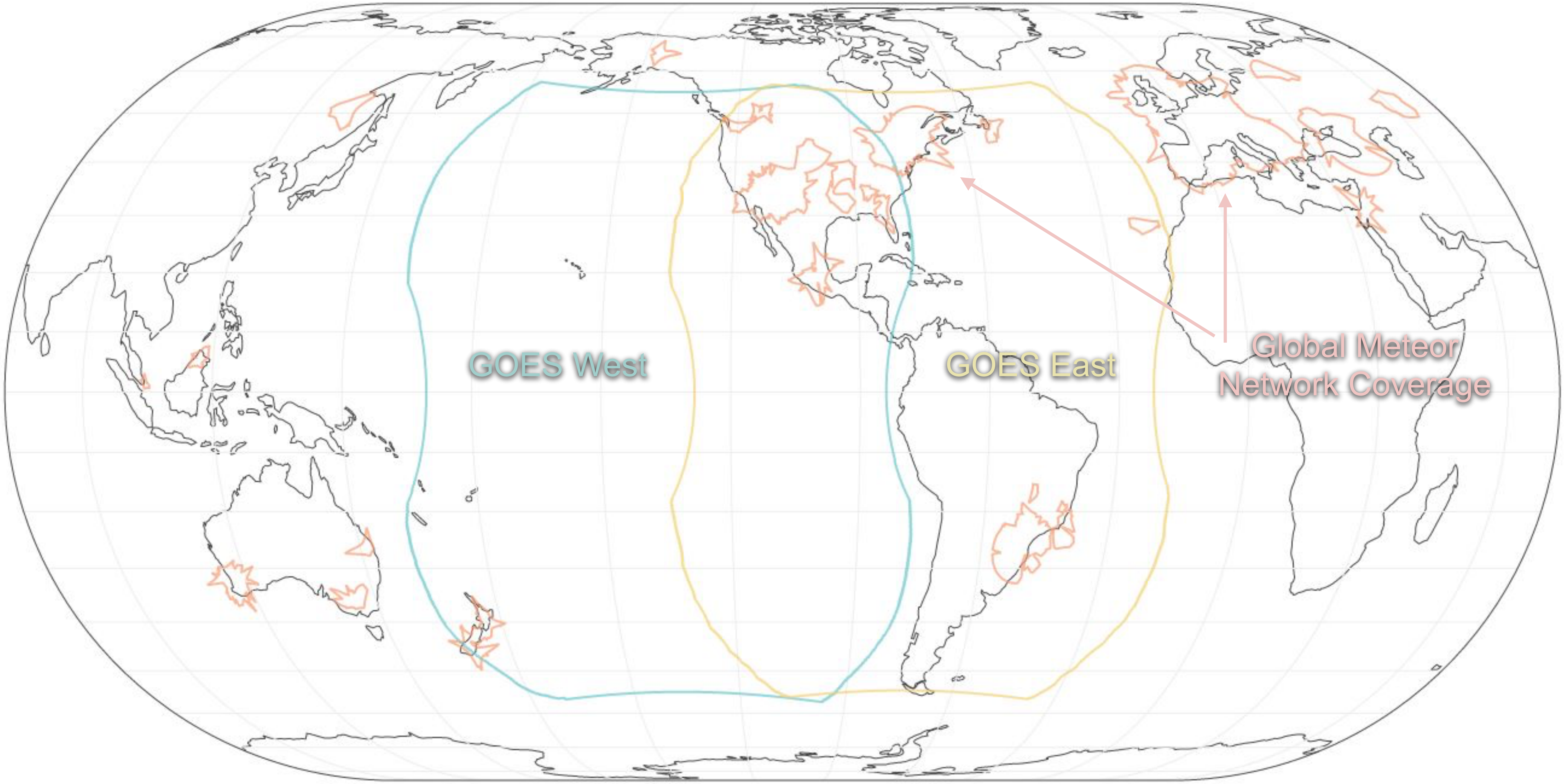
- Data hierarchical structure designed for lightning but bolide events and light curves can be extracted with custom data processing.





Why GOES Lightning Mapper Data?

- Ground-based and LEO meteor detectors have limited sight.
  - Fine for small meteors; there are plenty to find!
  - Fireballs and bolides are too rare, only a ~handful hit the Earth per day.
  - Want hemispherical coverage => Geostationary orbit ideal



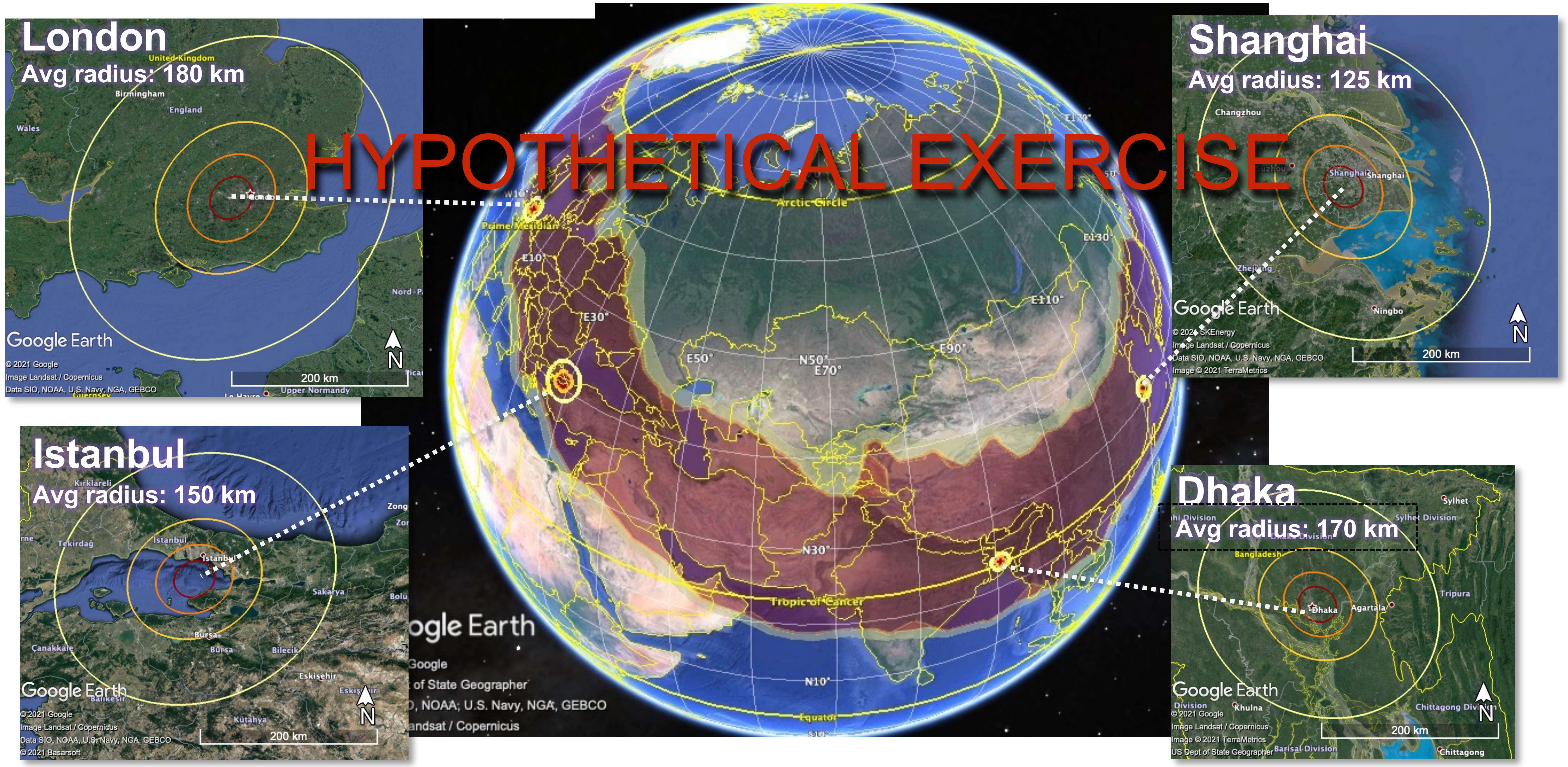
Why Do We Want More Bolide Light Curves?

NASA's Asteroid Threat Assessment Project's (ATAP) primary goal is to develop tools and models to assess the threat due to large Earth impacting bodies in order to inform responders on how best to prepare and respond.

- We need a uniformly processed set of calibrated bolide light curves in order to properly tune our entry models (originally developed for re-entering spacecraft) to ascertain what type and size of ground impact will occur.
- Most ground based camera systems have limited sky view, are not always well calibrated and easily saturate, and thus do not produce accurate disintegration light curves. GOES GLM solves these issues.

But there are also other direct applications:

- NEO meteoroid population studies.
- Statistical analysis of bolide impact populations.
- With the stereo detection nature of the GOES 16 and 17 it is possible to reconstruct the trajectory of the bolides

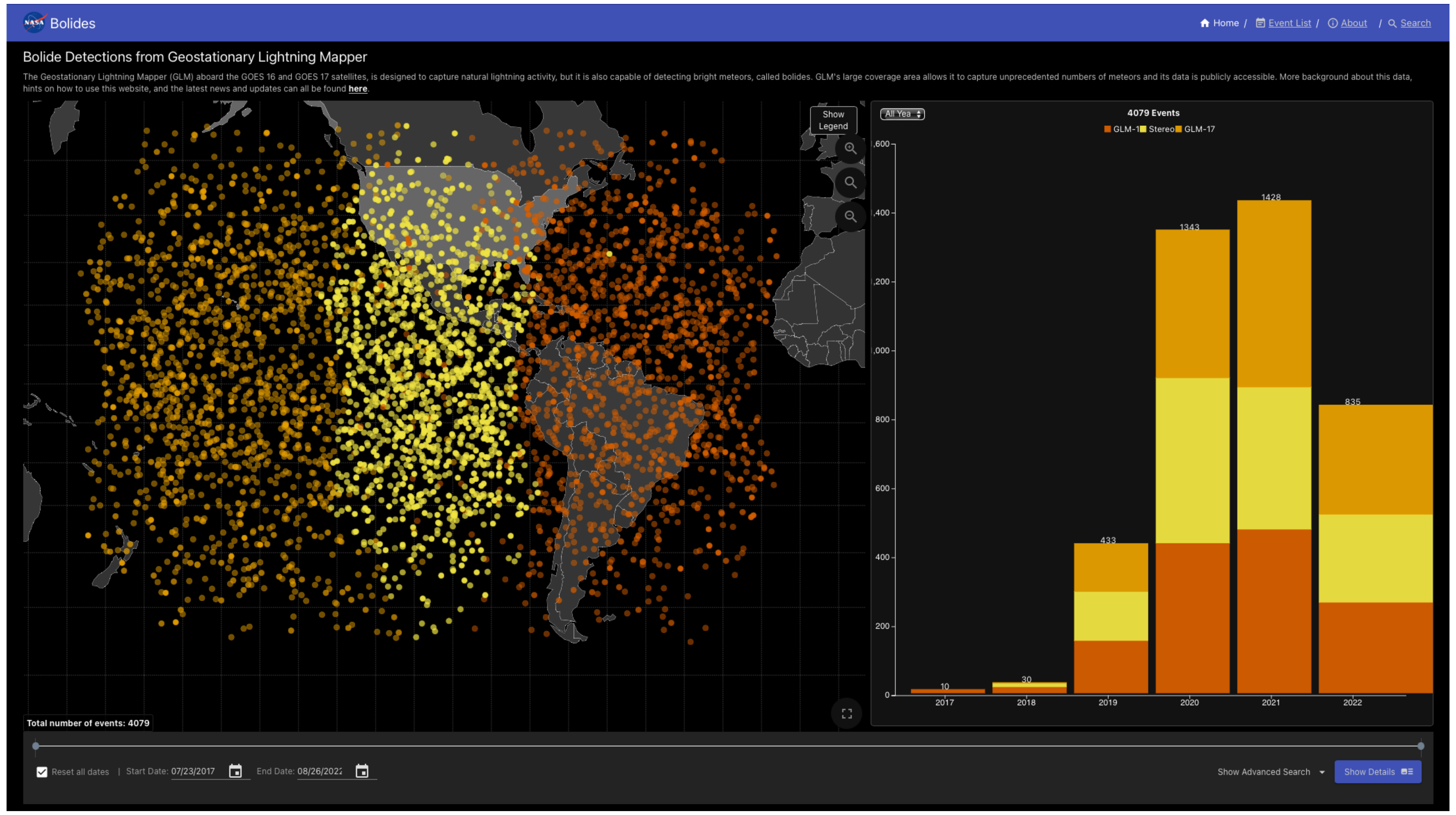


- Serious
- Severe
- Critical
- Unsurvivable

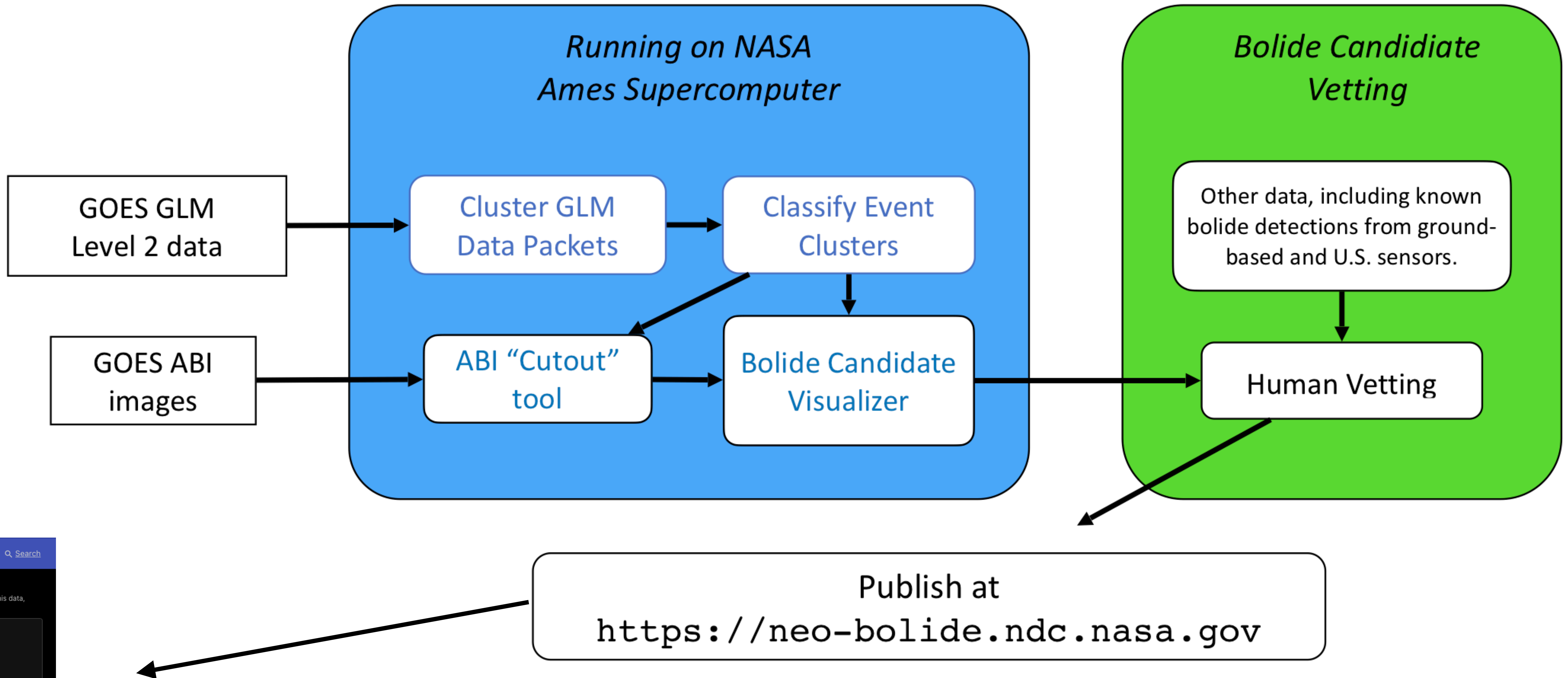
Damage swath: Full range of regions potentially at risk to local ground damage, from all modeled cases (including unlikely worst-case objects and all sampled impact locations). **Sample average damage areas:** Average blast damage areas from several worst-case high-population locations across the swath.

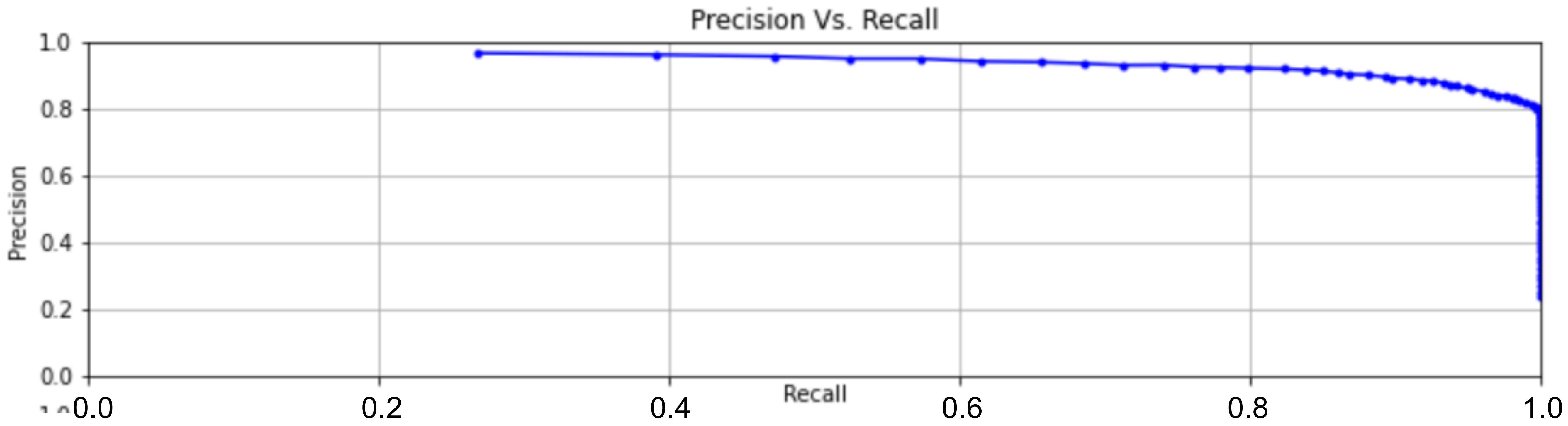
How We Detect Bolides

- Uses GLM Level 2 data products for detection
- Does not use GLM flashes. We cluster our own bolides using the group data.
- Uses supervised learning to train Random Forest classifier to detect.
  - Iterative improvements over time as we grow our training data set
- Human manual vetting before publishing at https://neo-bolide.ndc.nasa.gov

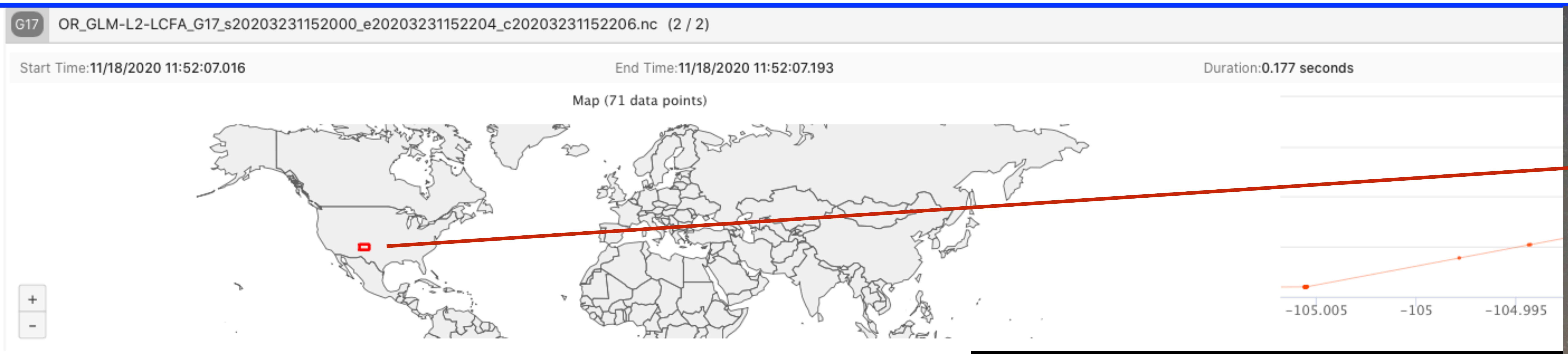


Current GOES GLM Bolide Detection Pipeline



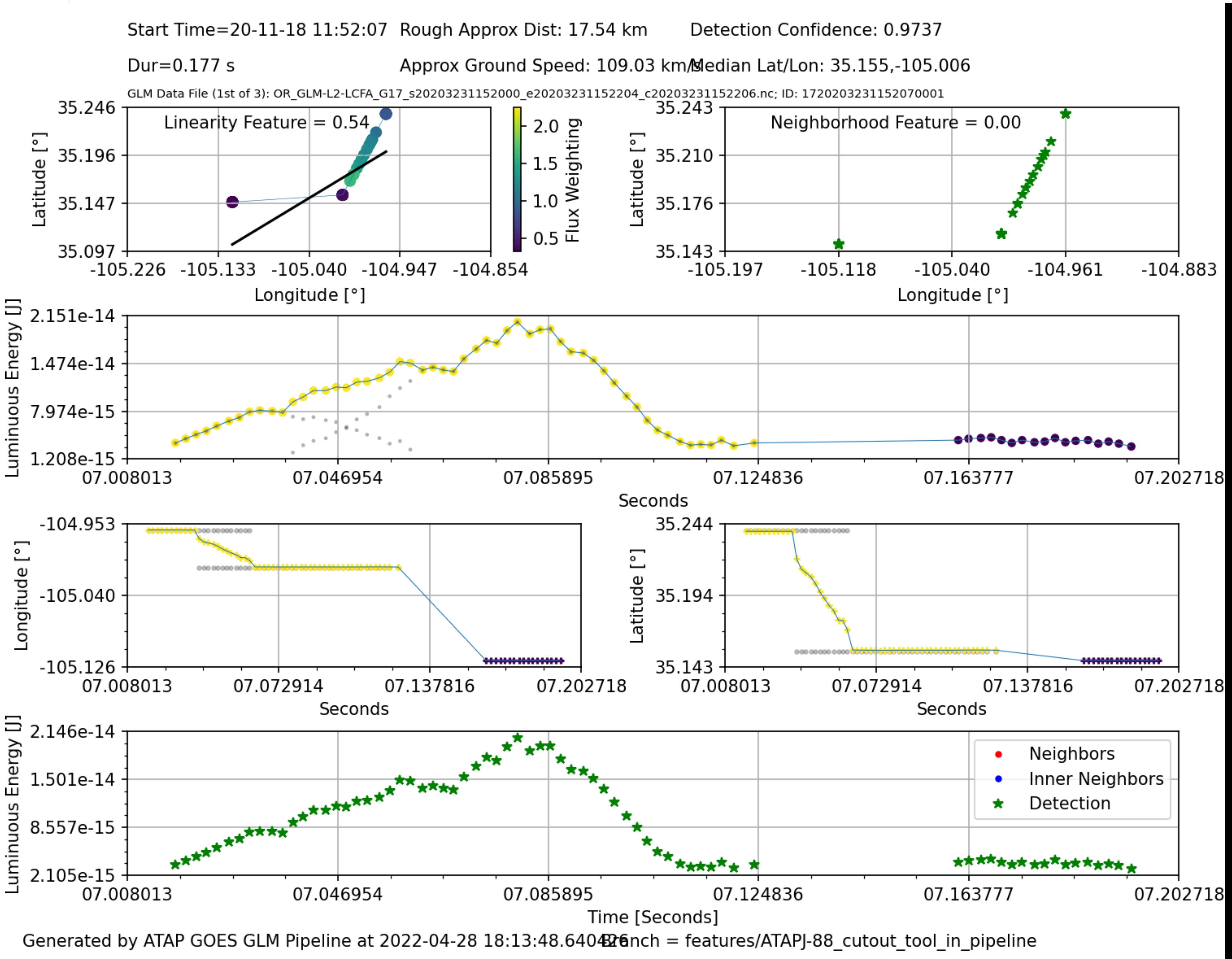


A Bolide!

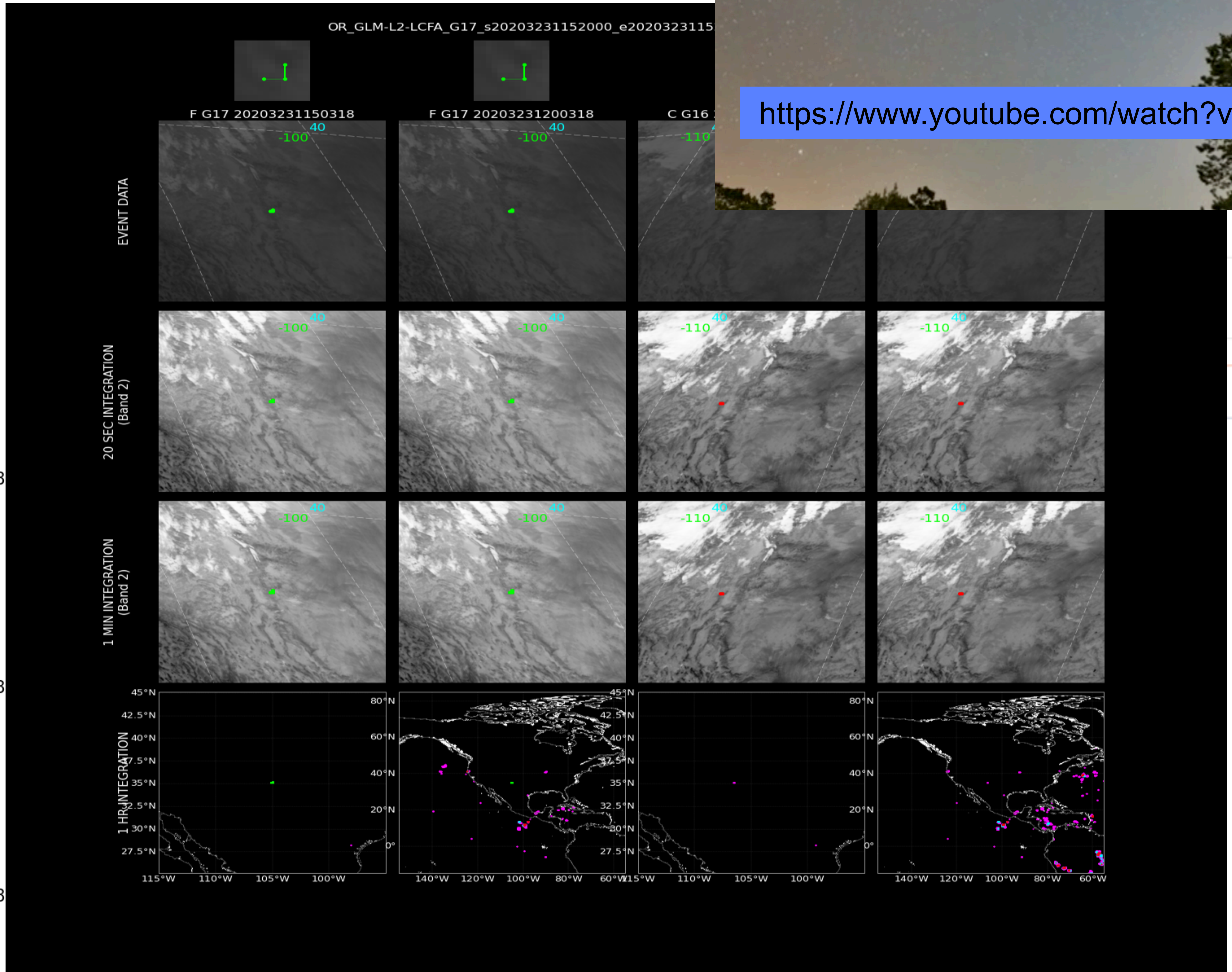


G17
OR_GLM-L2-LCFA_G17_s20203231152000_e20203231152204_c20203231152206.nc (2 / 2)
Start Time:11/18/2020 11:52:07.016
End Time:11/18/2020 11:52:07.193
Duration:0.177 seconds
Map (71 data points)
-105.005
-105
-104.995

https://www.youtube.com/watch?v=eFmFQ7d-Me4



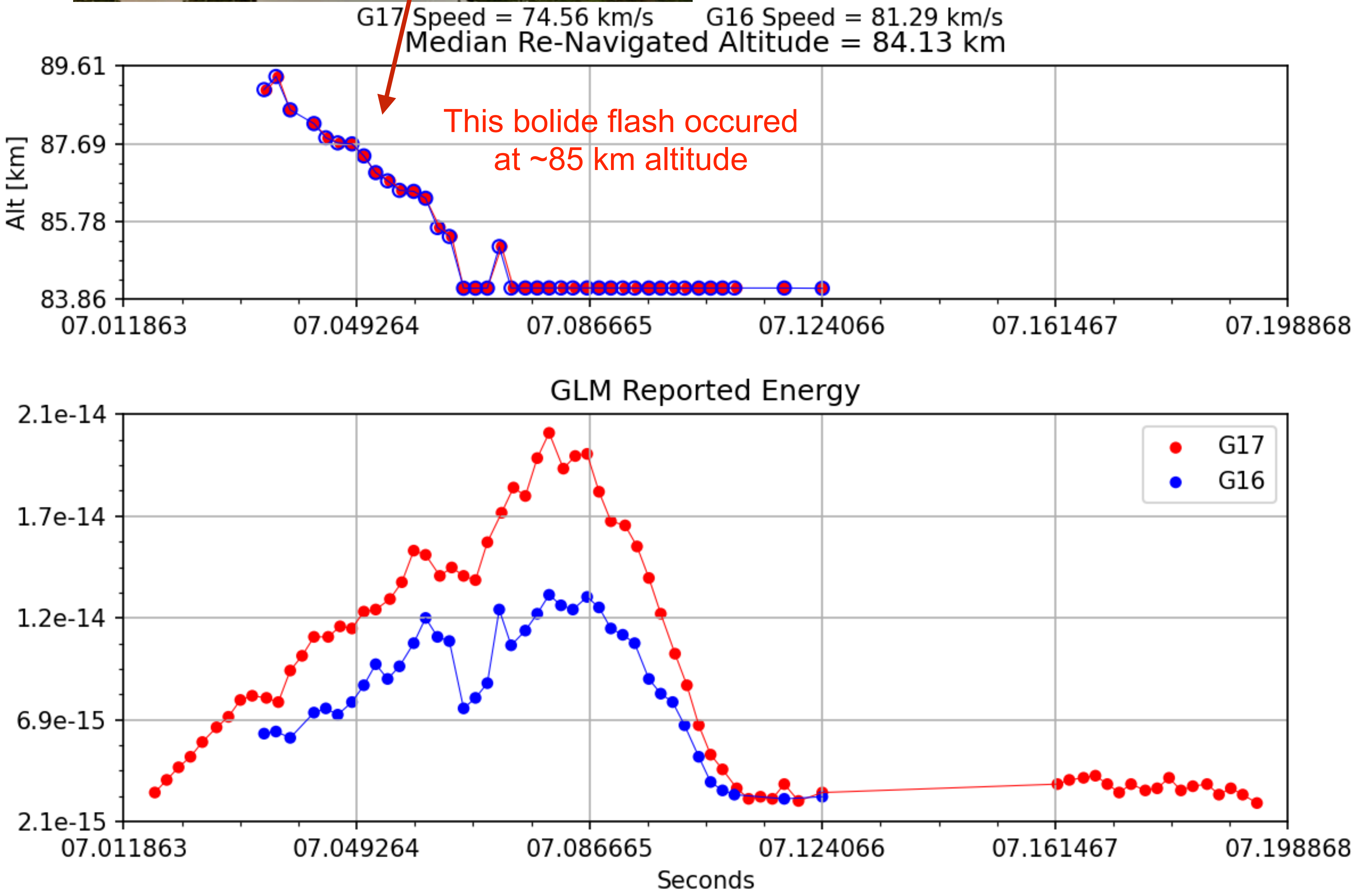
Start Time=20-11-18 11:52:07 Rough Approx Dist: 17.54 km Detection Confidence: 0.9737
Dur=0.177 s Approx Ground Speed: 109.03 km/s Median Lat/Lon: 35.155,-105.006
GLM Data File (1st of 3): OR_GLM-L2-LCFA_G17_s20203231152000_e20203231152204_c20203231152206.nc; ID: 17202032311520700001
Linearity Feature = 0.54
Neighborhood Feature = 0.00
Flux Weighting
Latitude [°]
Longitude [°]
Luminuous Energy [J]
Seconds
Neighbors
Inner Neighbors
Detection
Time [Seconds]
Generated by ATAP GOES GLM Pipeline at 2022-04-28 18:13:48.640426 branch = features/ATAPJ-88_cutout_tool_in_pipeline

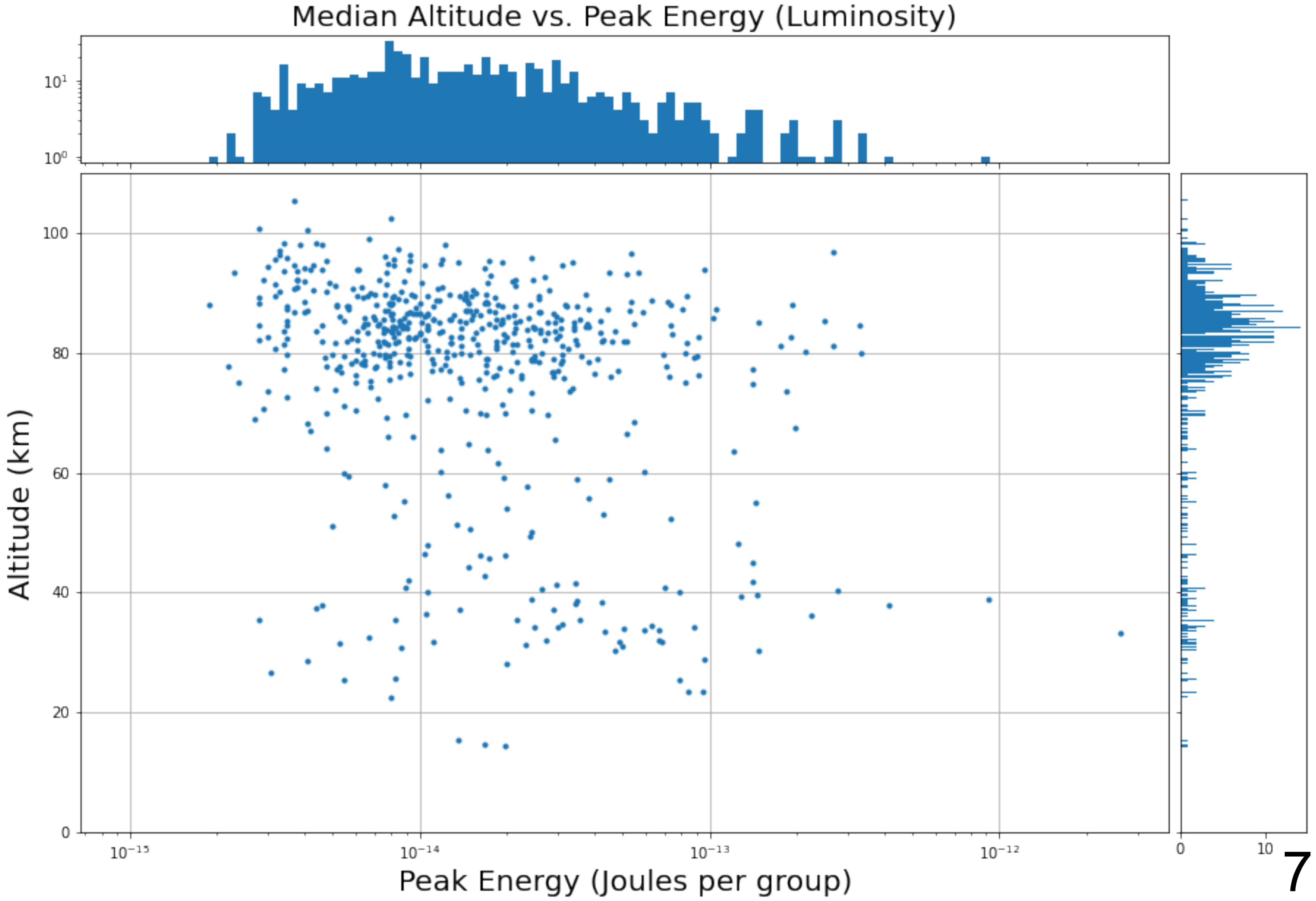


OR_GLM-L2-LCFA_G17_s20203231152000_e2020323115
F G17 20203231150318
F G17 20203231200318
C G16
EVENT DATA
20 SEC INTEGRATION (Band 2)
1 MIN INTEGRATION (Band 2)
1 HR INTEGRATION

Stereo Detection Is Important

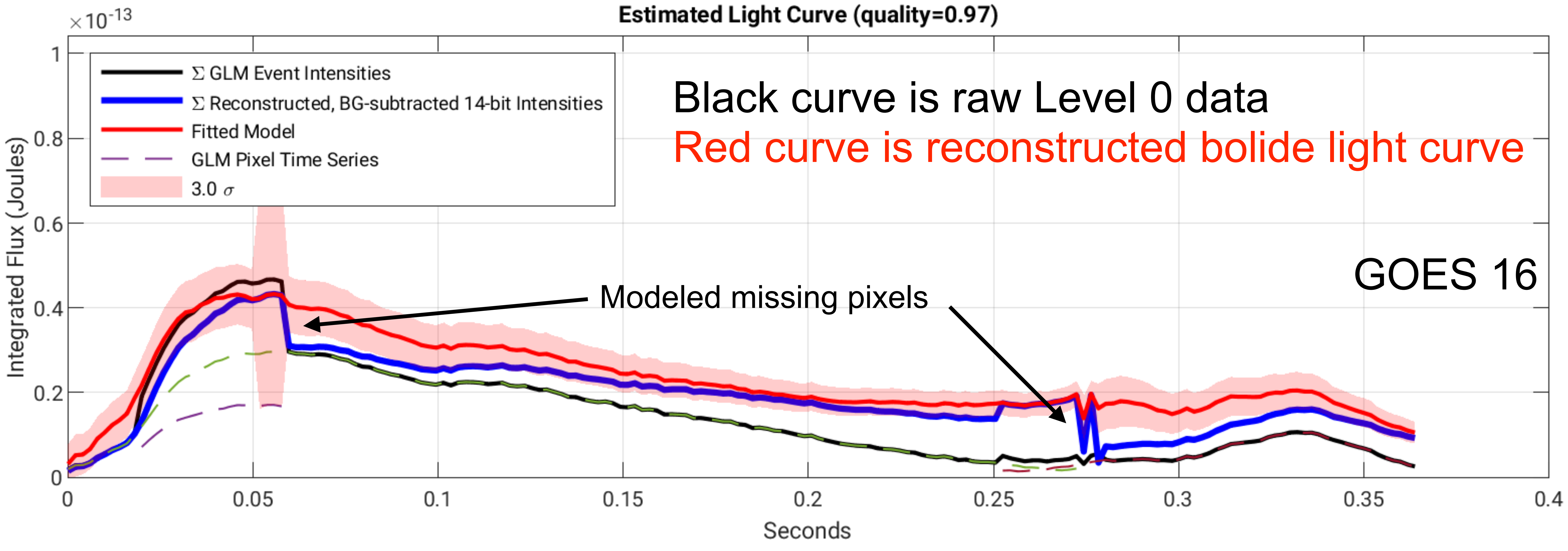
- Collecting data from multiple remote sensors is critical to inferring the energy deposition and pre-entry characteristics of asteroids/meteoroids.
- Allows for velocity reconstruction
  - Where in atmosphere is energy deposited?
  - Trajectory reconstruction and solar system origins of meteoroid

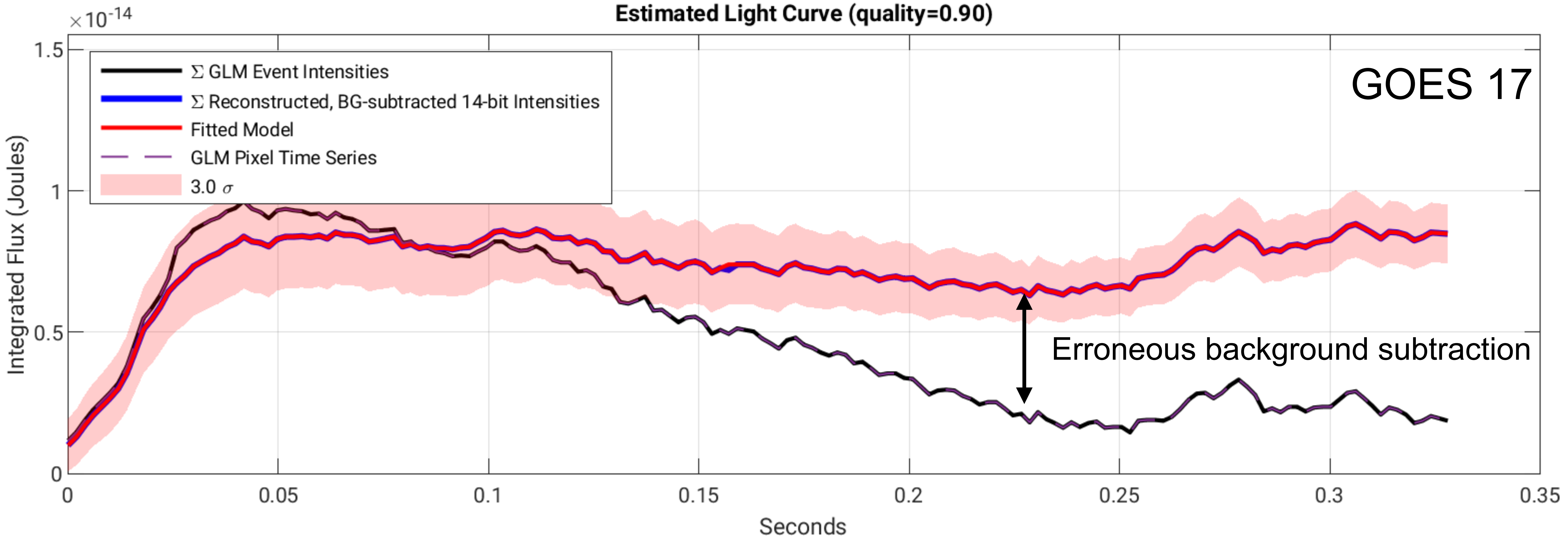




Generating Bolide Light Curves From Lightning Data

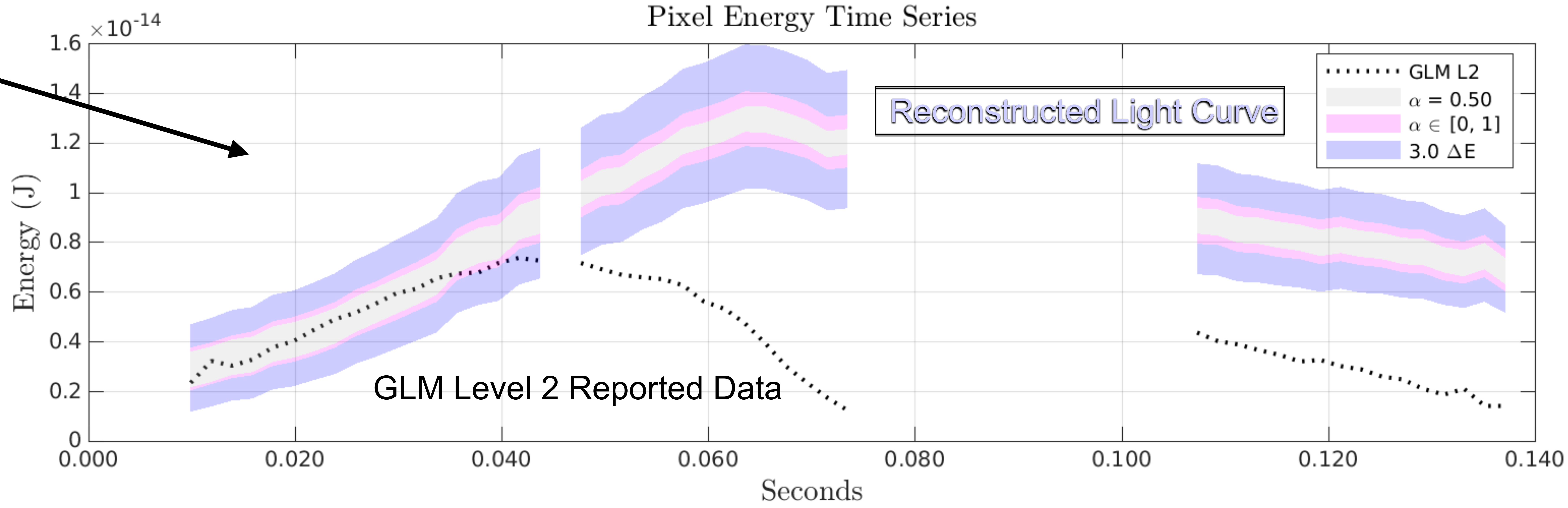
- GLM ground segment processing and L2 data products are designed for lightning studies
  1. Assumes non-traveling objects
     - Flashes and groups not ideal event grouping methodology
  2. Assumes brief flashes
     - Background subtraction increases for static sources
  3. Does not record full extent of bolide flash (I.e. missing pixels)
     - Only downlinks brightest pixels
- We have developed our own light curve reconstruction pipeline for bolides
  1. Re-cluster events for bolides
  2. Correct background
  3. Use PRF modeling to fill missing pixels
- See paper:
  Morris, R.L., Smith, J.C., Dotson, J.L., Stern, E.C. and Longenbaugh, R.S., *Correction and calibration of atmospheric impact observations in GOES GLM data.* Meteorit. Planet Sci. (2022)



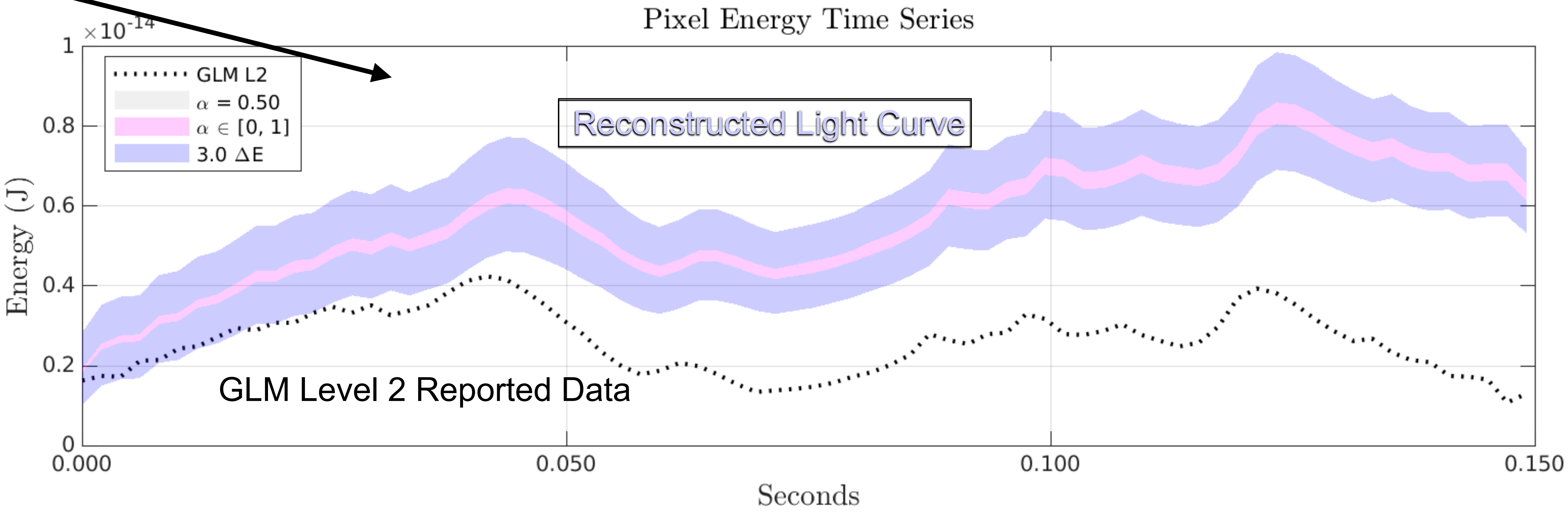


Light Curve Correction Aids Proper Interpretation

- Original GLM Level 2 data implies two peaks
  - Reconstructed shows just a single peak



- Original GLM Level 2 data implies first peak brighter than second
  - Reconstructed shows second peak is brighter



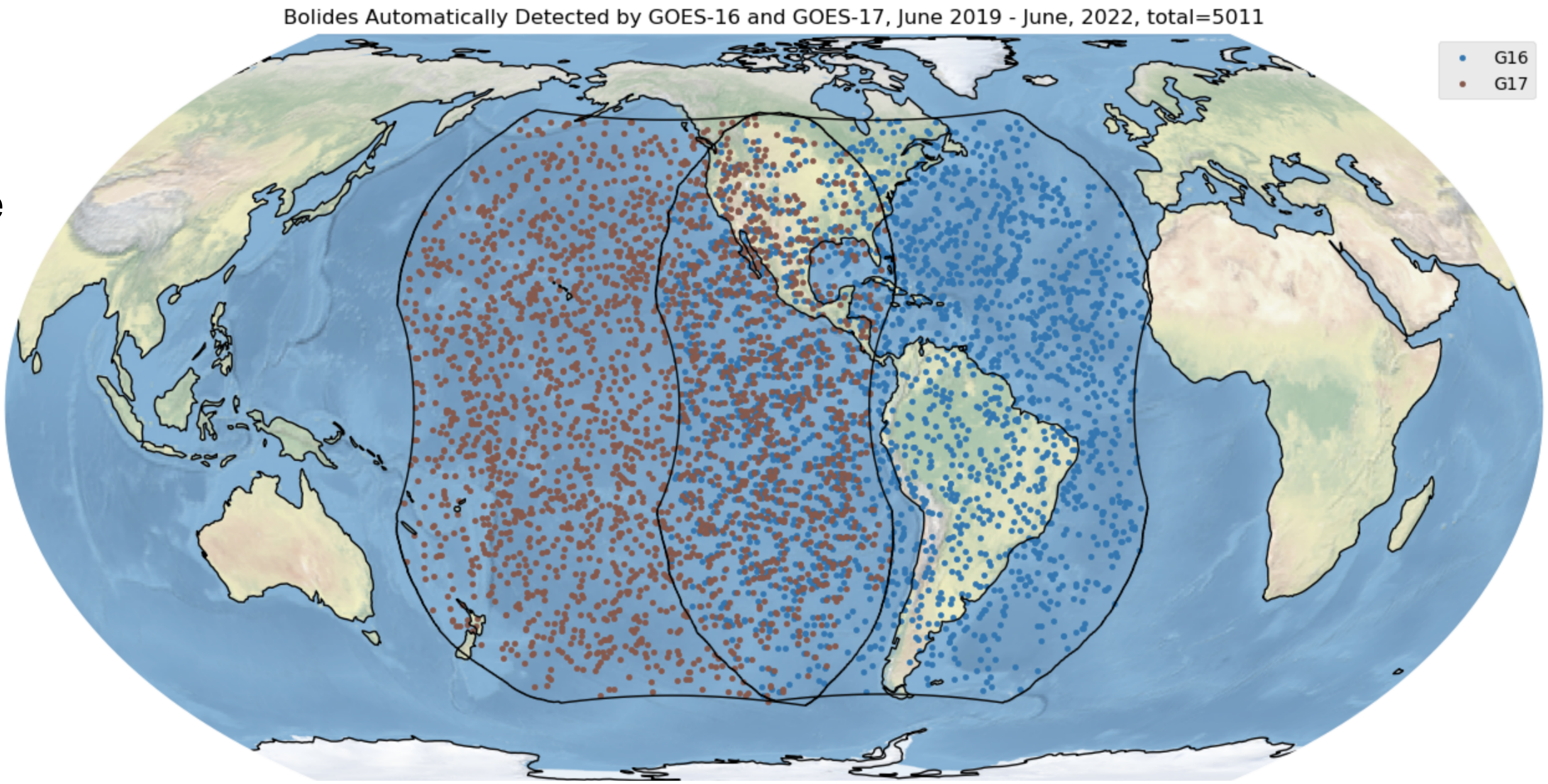
- ***Reconstructed Light Curves not yet posted on our website, but we are working on publishing them…***

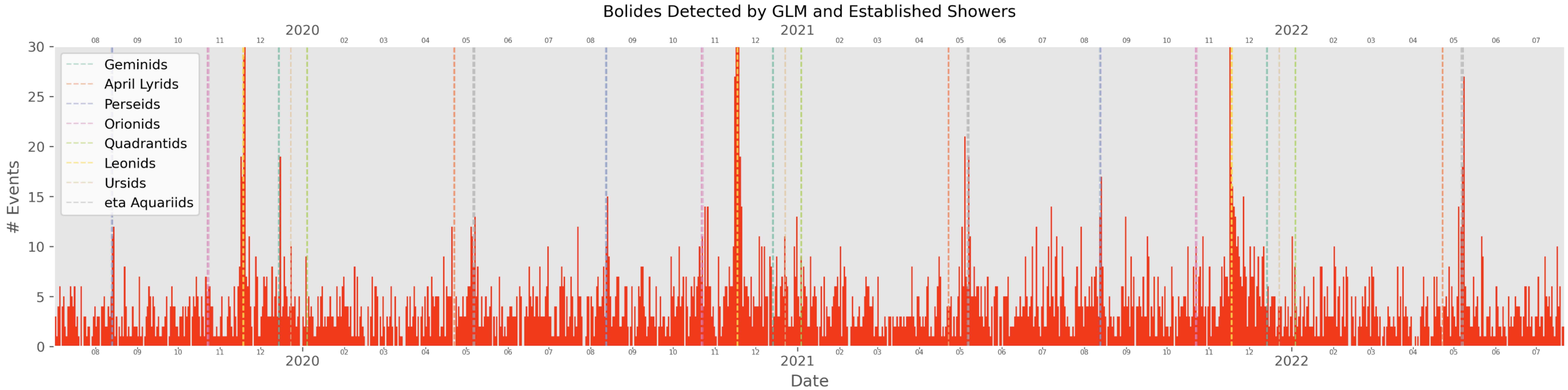
Detection Biases

- In order to study the distribution of bolides impacting the Earth, we need to remove all detection biases in the instrument and detection algorithms.

Performance

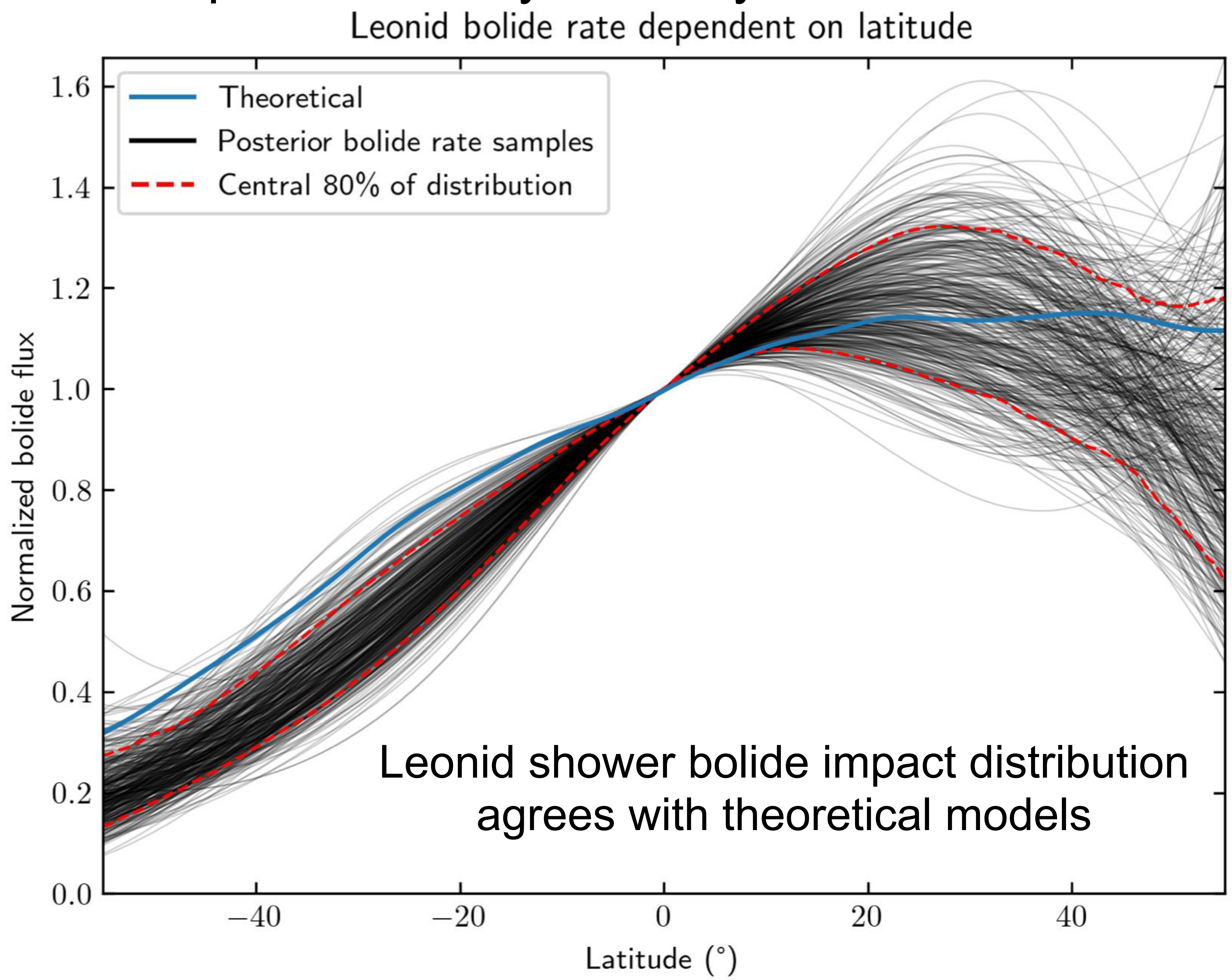
- Current detection precision before manual vetting is 88% and increasing.
- Goal is to be fully automated; no human vetting necessary. Also to report bolides within a minute of the impact.
- Can rapidly reprocess all data for statistically consistent data analysis
- **4514 Bolides** currently published on website (https://neo-bolide.ndc.nasa.gov)
  - Each bolide detection confidence rated (low, median, high).
  - Number detected is huge compared to all previously published bolides.

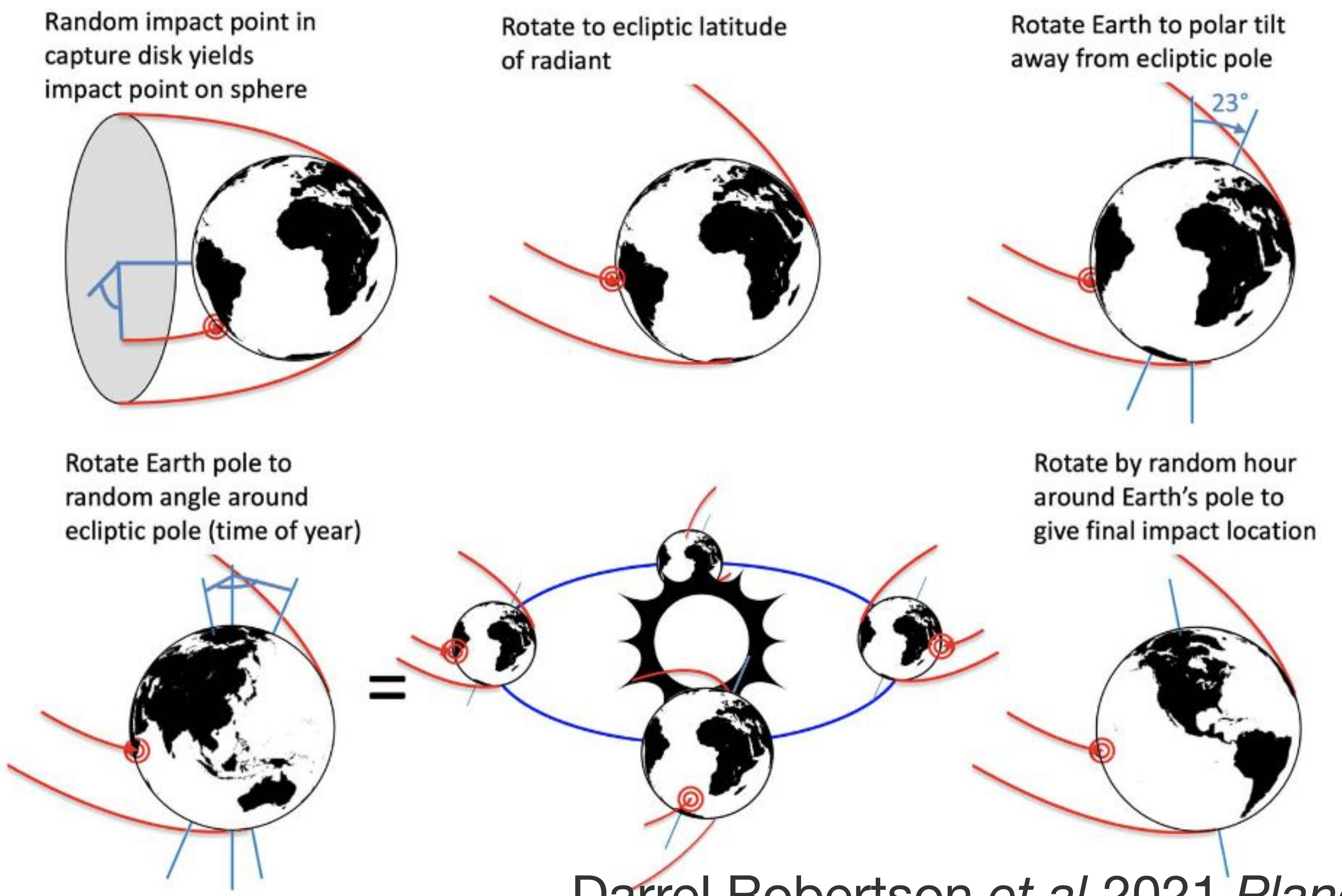




Distribution of Bolides Over Globe

- Want to assess accuracy of theoretical models of bolide impact distribution.
- Developed Markov Chain Monte Carlo Poisson model of bolide impacts.
- Paper in draft by Anthony Ozerov



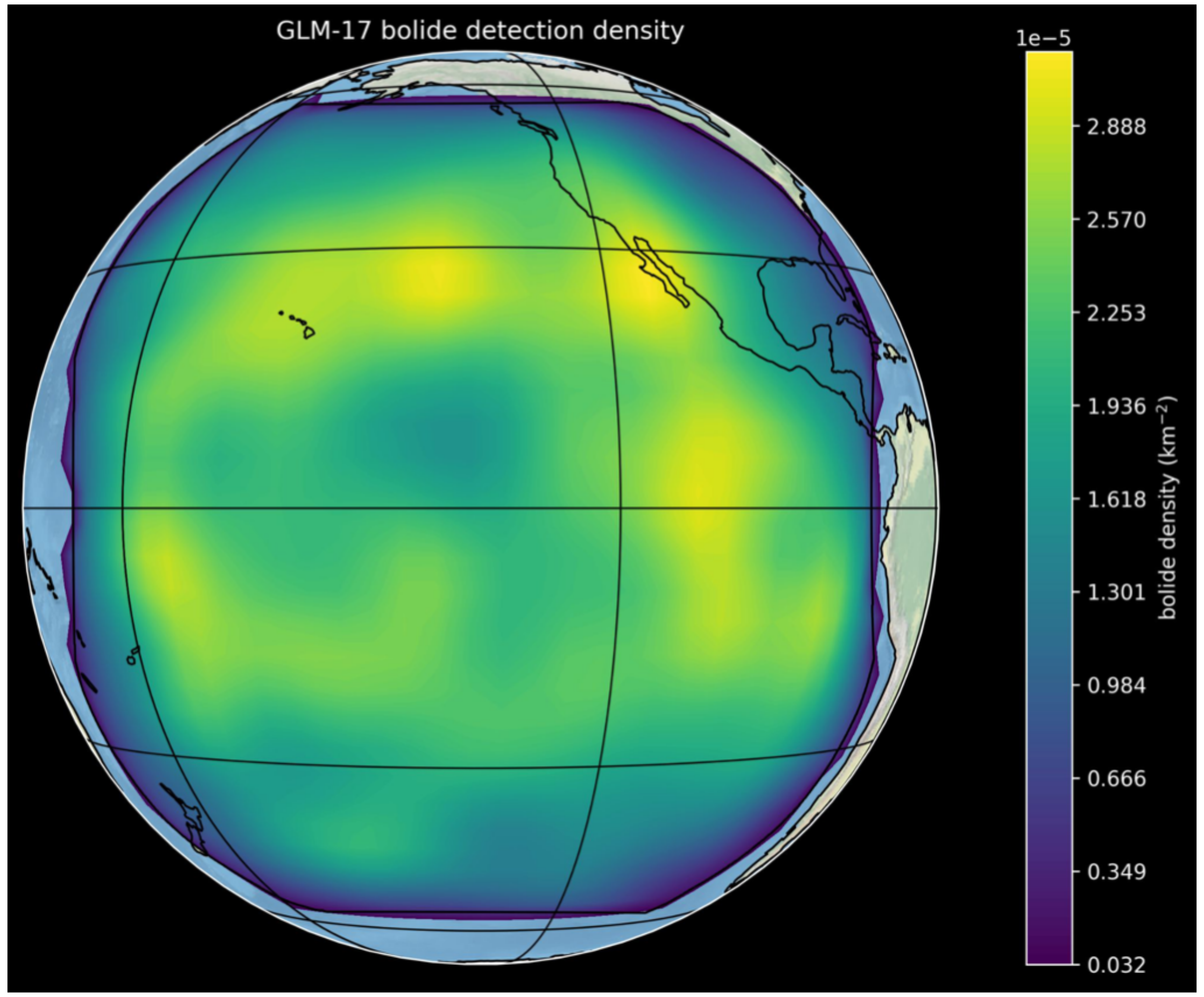


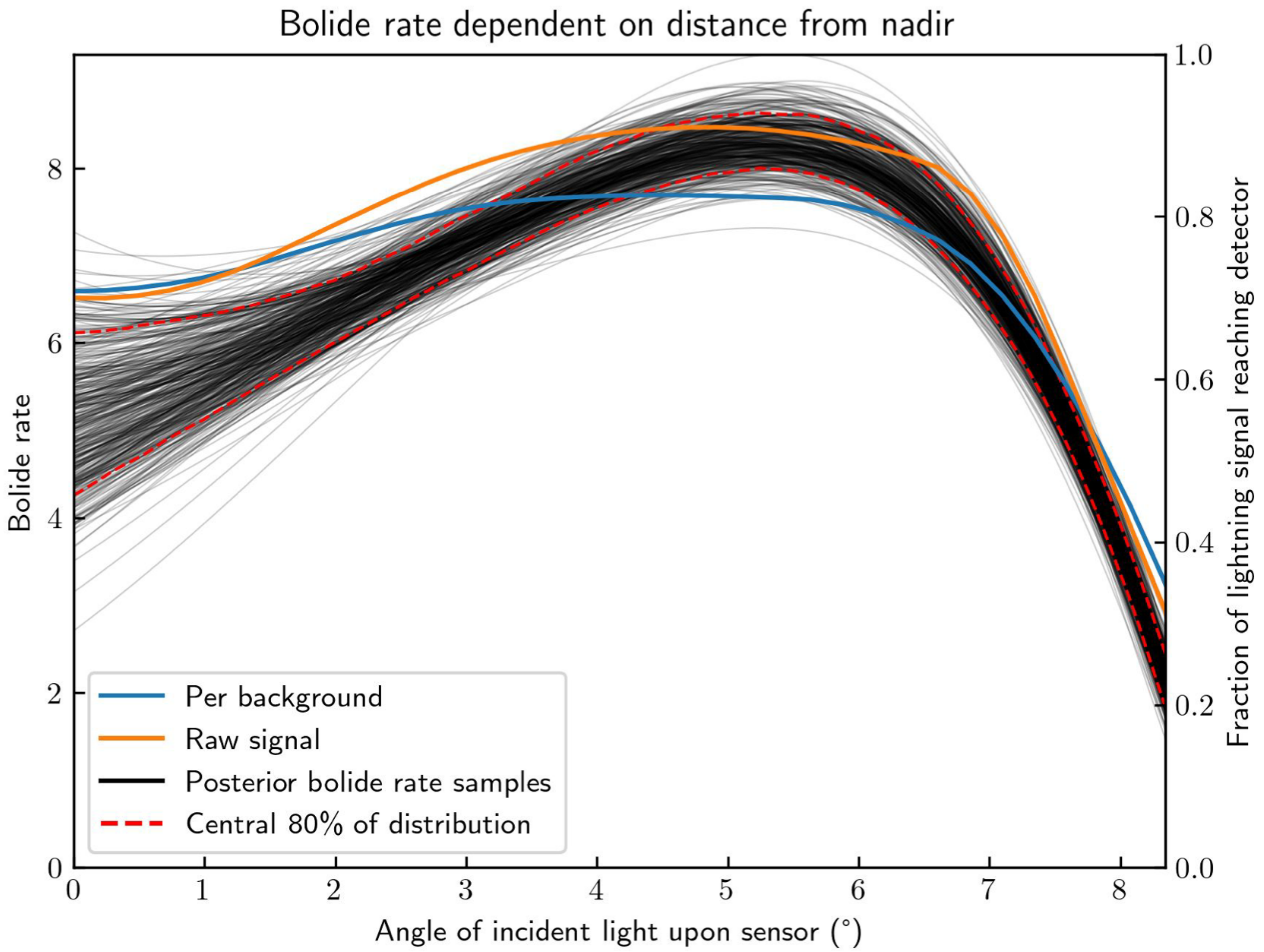
Darrel Robertson *et al* 2021 *Planet. Sci. J.* **2** 88

- Account for instrumental biases:
  - Non-global FOV
  - More massive and faster bolides expected to be easier to detect (spectra varies by velocity)
  - Angle of incidence onto CCD will impact detection bandpass
    - A systematic bias in measured energy when using Level 2 data
- Good agreement with theoretical models

Bolide Detection Efficiency Over GLM FOV

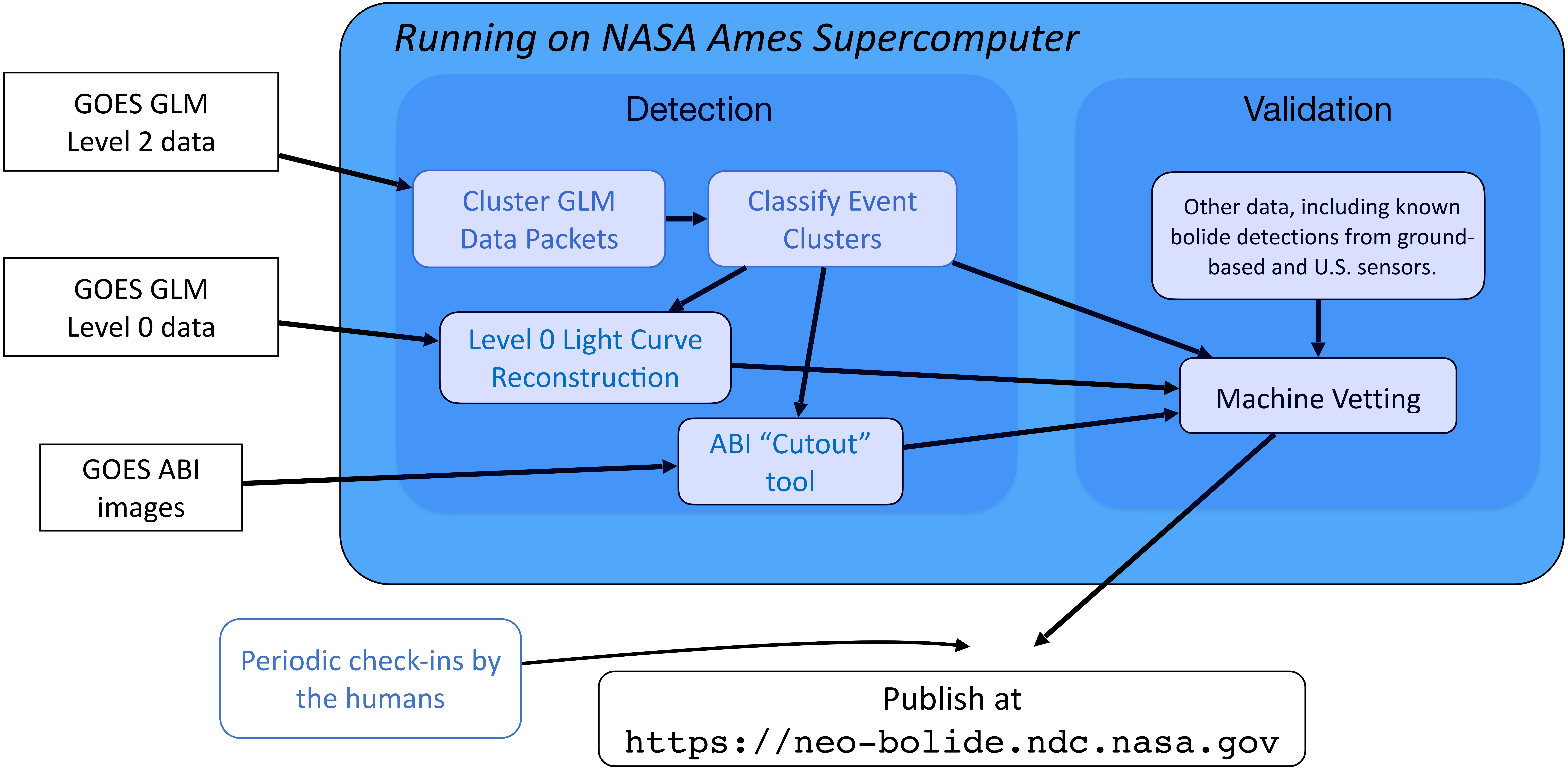
- Bolide detection efficiency varies over field of view.
  - Alignment of bolide flash spectra and GLM bandpass varies with angle of incidence, hence location on globe.
  - GLM ground segment applies a gain correction to account for angle of incidence, we can measure this dependence.





- Bolide models indicate that the ratio of continuum to line emission flux is dependent on the brightness of the bolide, hence, the GLM gain factor is not entirely correct for bolides and we can measure a change in detection efficiency with distance to nadir.
- Our measured dependence with distance from nadir agrees with the gain ratio curve.

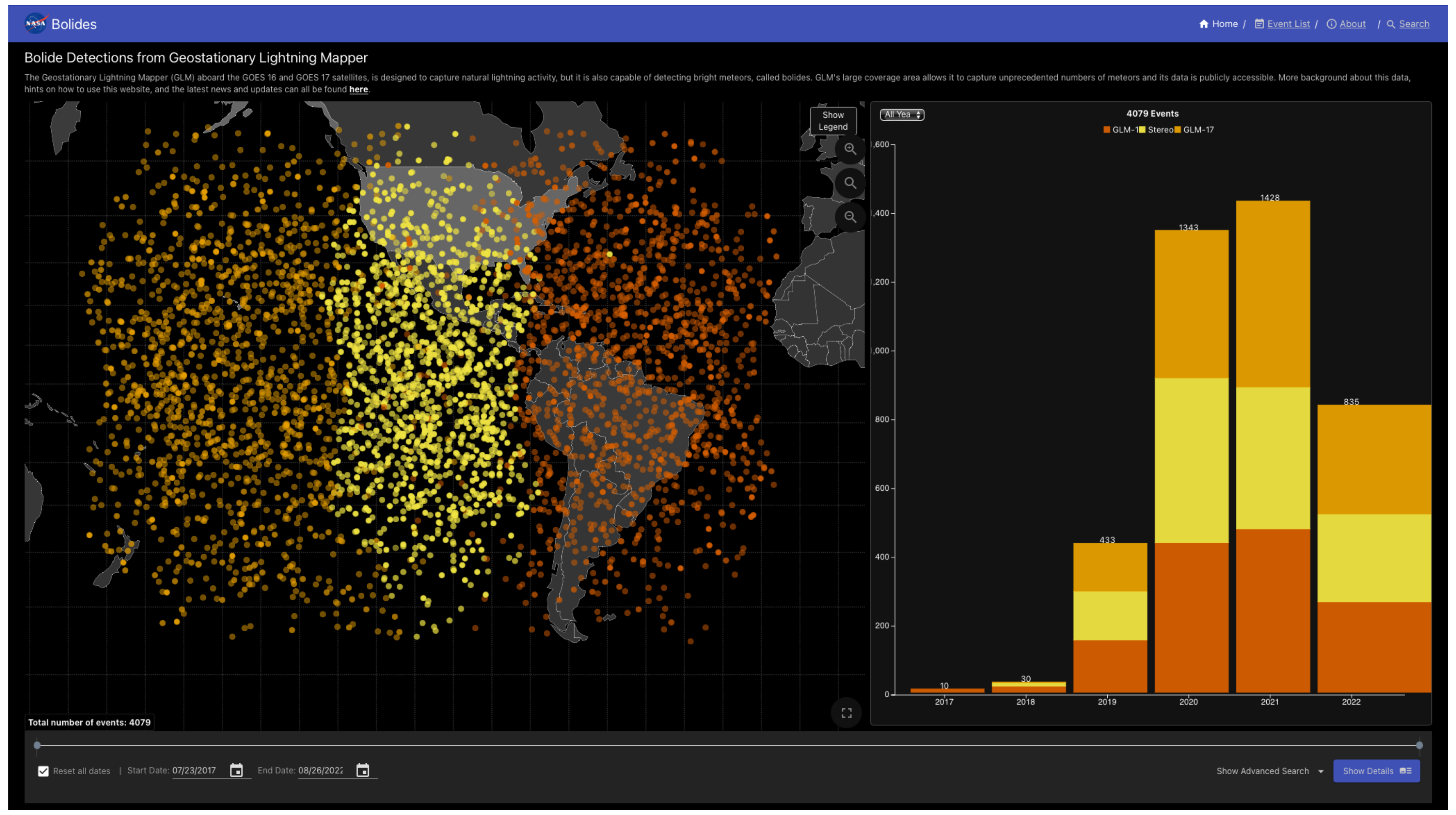
Desired GOES GLM Bolide Detection Pipeline



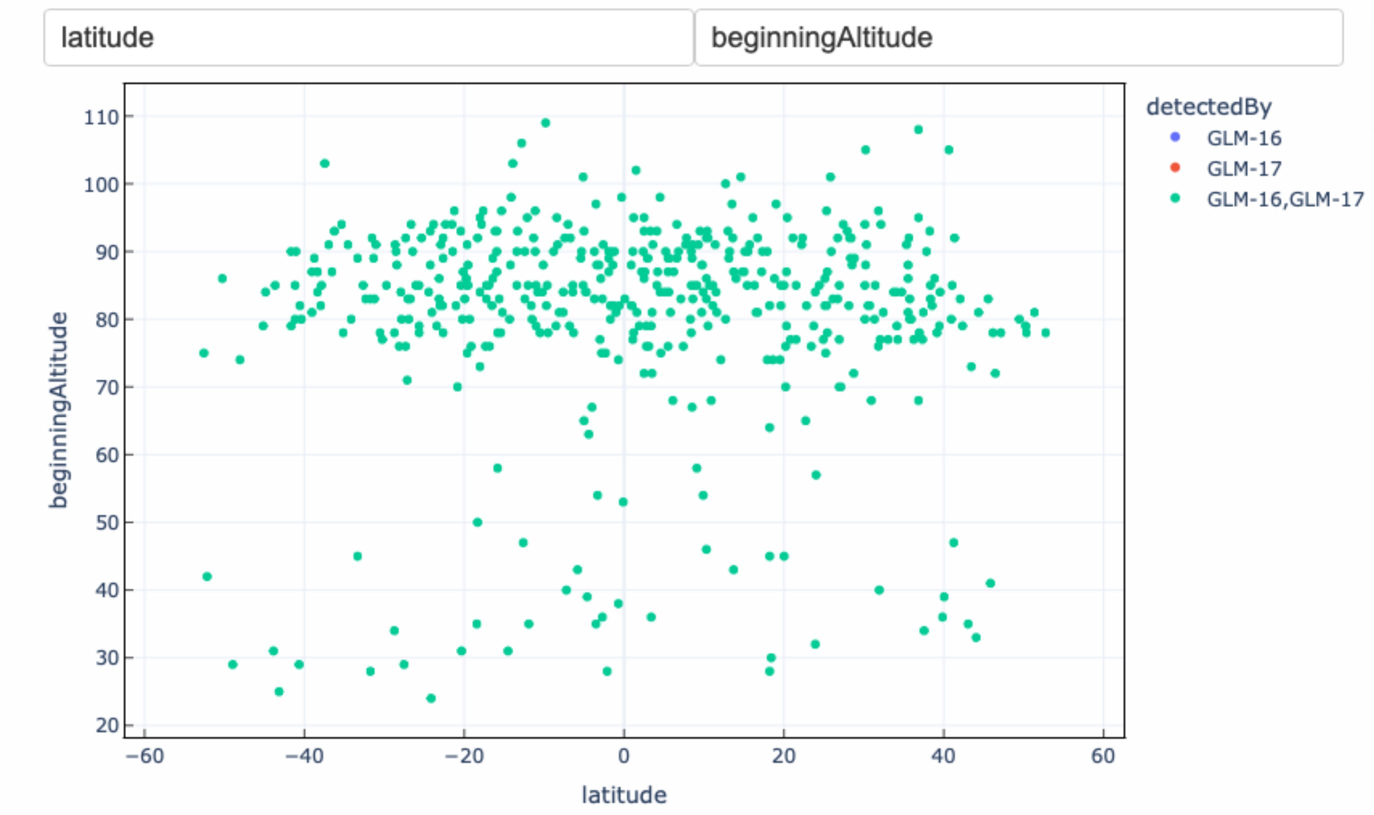
Global Bolide Monitoring

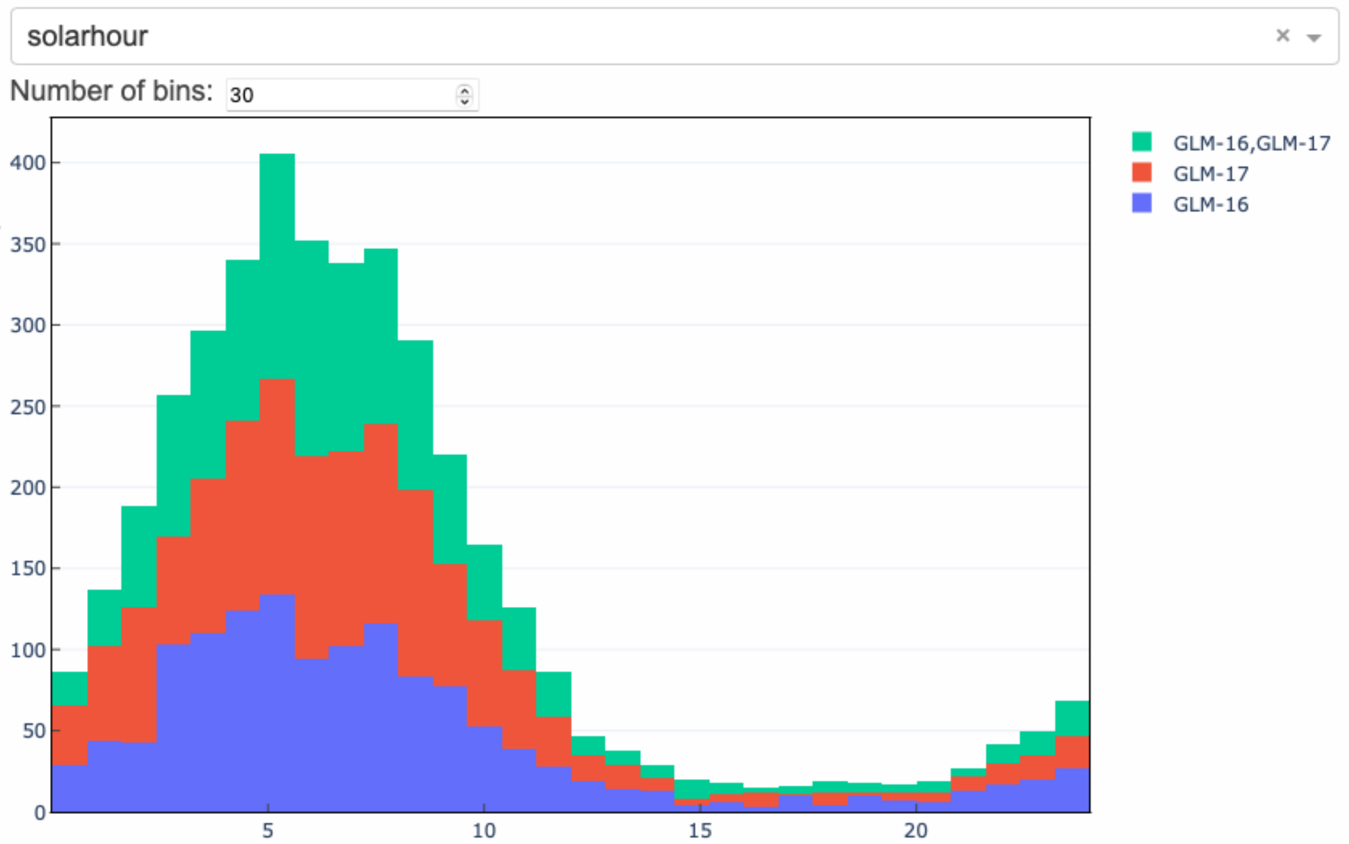
Available Resources

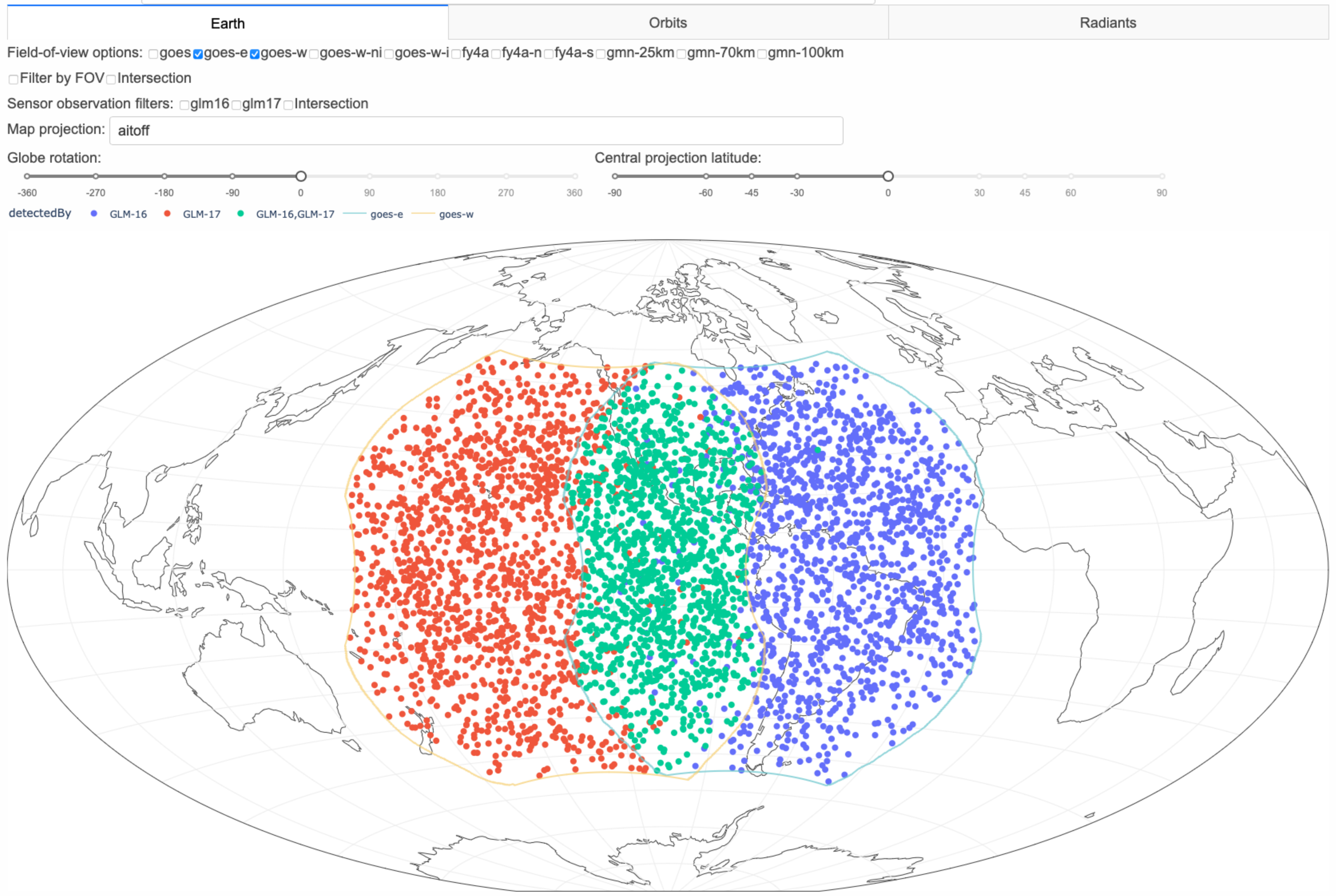
- A now slightly outdated paper:
  - J.C. Smith et al. “An Automated Bolide Detection Pipeline for GOES GLM,” Icarus, Vol 368, 2021
- Official NASA website for fully vetted bolides:
  - **https://neo-bolide.ndc.nasa.gov**



- Experimental Interactive Bolide Data Visualizer:
  - **https://bolides.seti.org**
  - Can view data from:
    1. GLM,
    2. U.S. Government sensors,
    3. Global Meteor Network
    4. IAU Meteor Data Center







- We also have fully automatic data sets which are statistically consistent (versus manually vetted data, but statistically inconsistent, on NASA website)

Thank You

Smith, J. C., et al., *An automated bolide detection pipeline for GOES GLM*, Icarus, p. 114576. (2021)

Morris, R.L., et al., *Correction and calibration of atmospheric impact observations in GOES GLM data*. Meteorit. Planet Sci. (2022)

https://neo-bolide.ndc.nasa.gov

https://bolides.seti.org