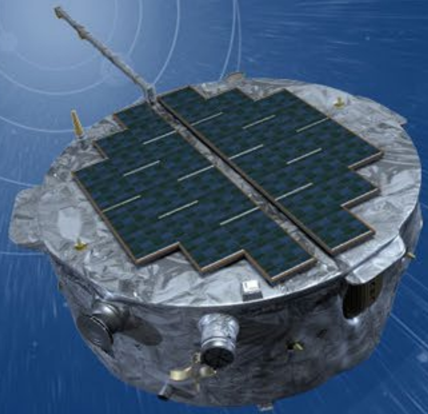
ENA Imager Modeling with a Reusable Software Framework



Summary of ENA Imager Algorithms

and Flux Estimation Modeling

Oct 16, 2024

Nick Dutton*, Scott Turner, Kevin Liu, IMAP Lo/ Hi / and Ultra teams

*Presenter

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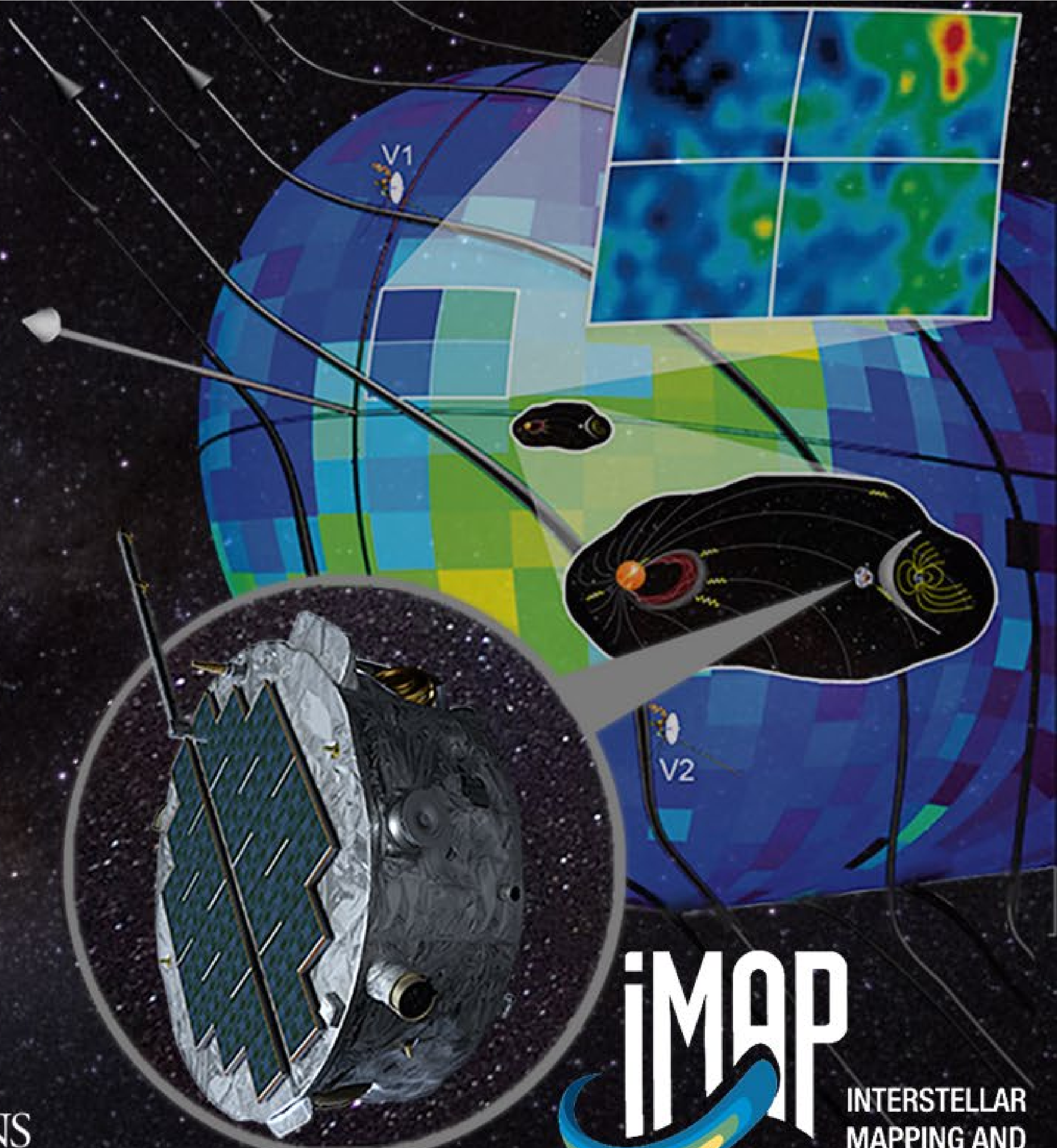
Overview

- Background
  - Quick Overview of IMAP's Mission
  - Overview of Energetic Neutral Atom (ENA) Imagers
- Modeling Approach
  - Overview of Software Framework used for Modeling
  - Forward Modeling Approach
  - Flux Reconstruction
- Selected Results
  - IBEX vs IMAP Predicted Performance
  - Flux Reconstruction Videos
- Summary



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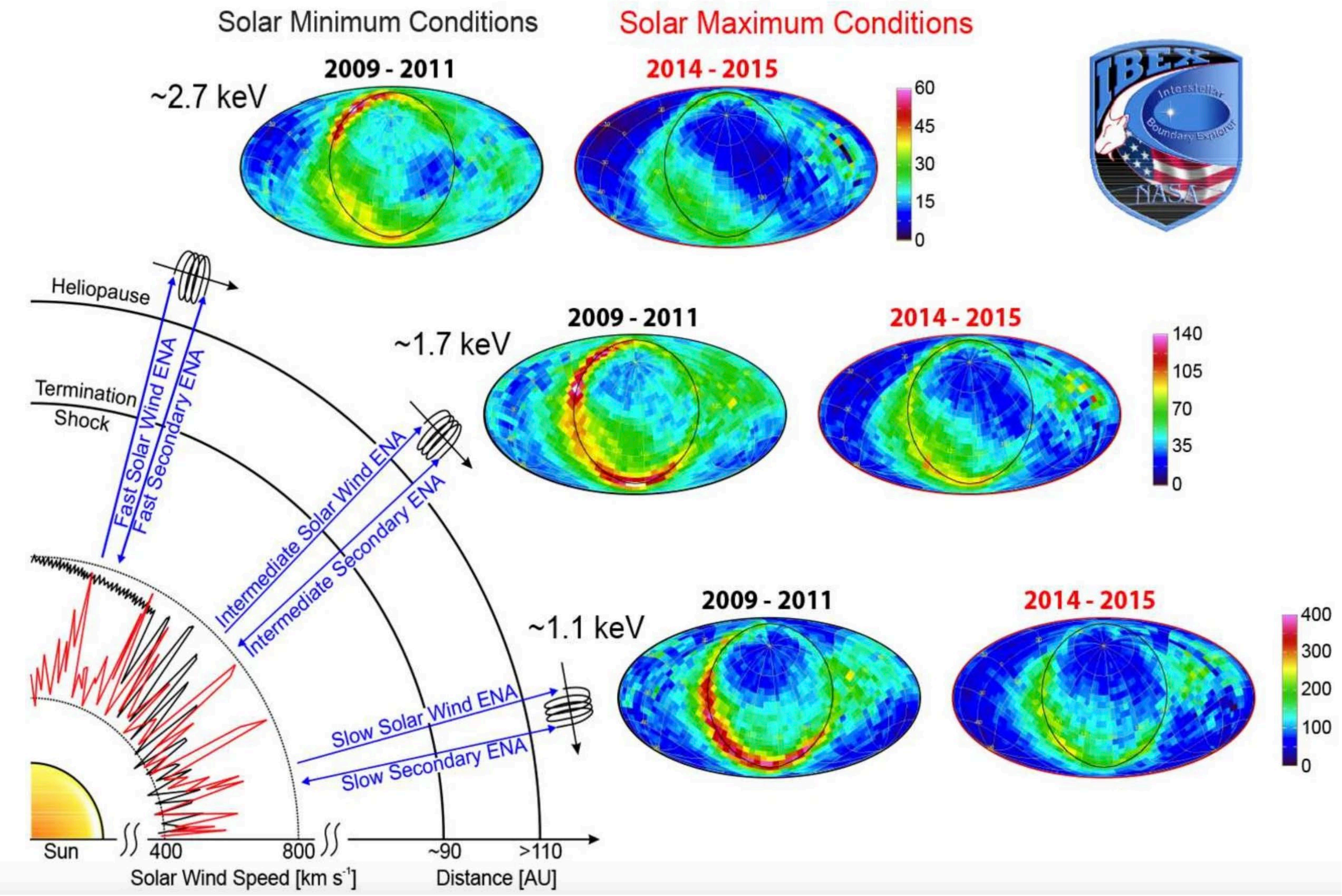
iMAP INTERSTELLAR MAPPING AND ACCELERATION PROBE

IMAP Mission Overview

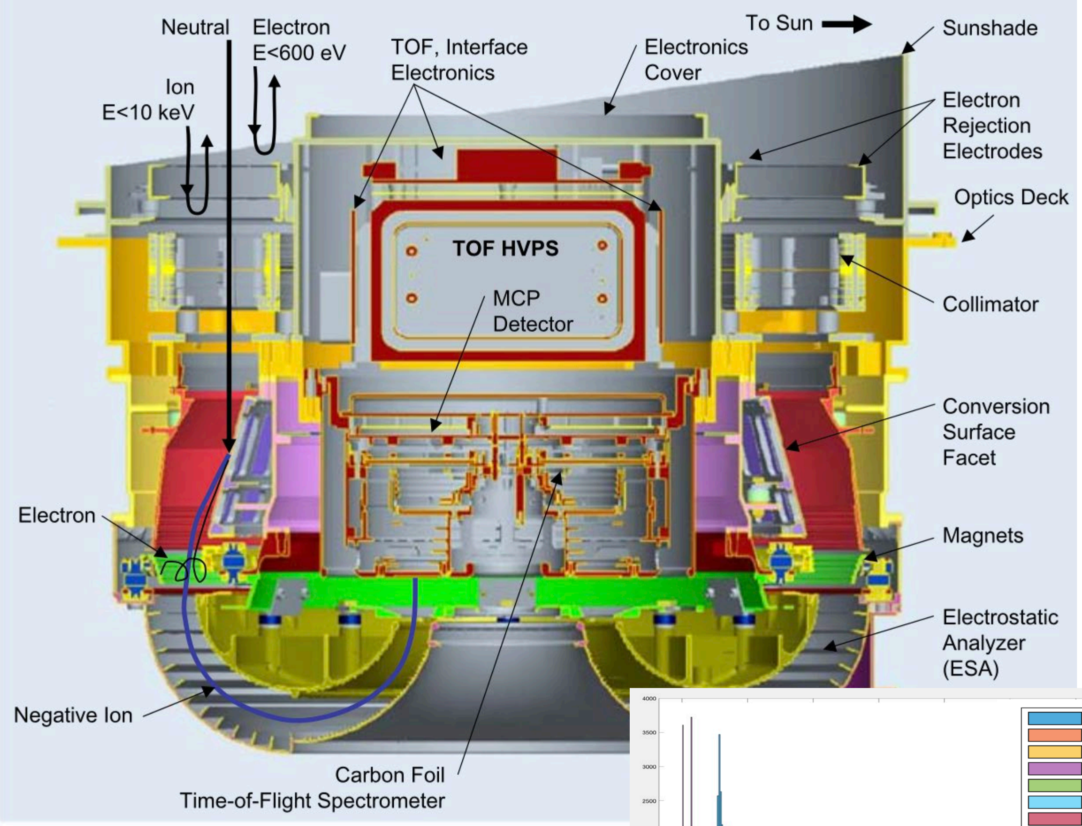


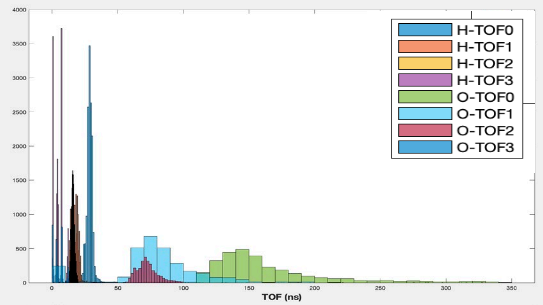
Galli et al. *The Heliosphere and Local Interstellar Medium from Neutral Atom Observations at Energies Below 10 keV*

SCIENCE OBJECTIVES

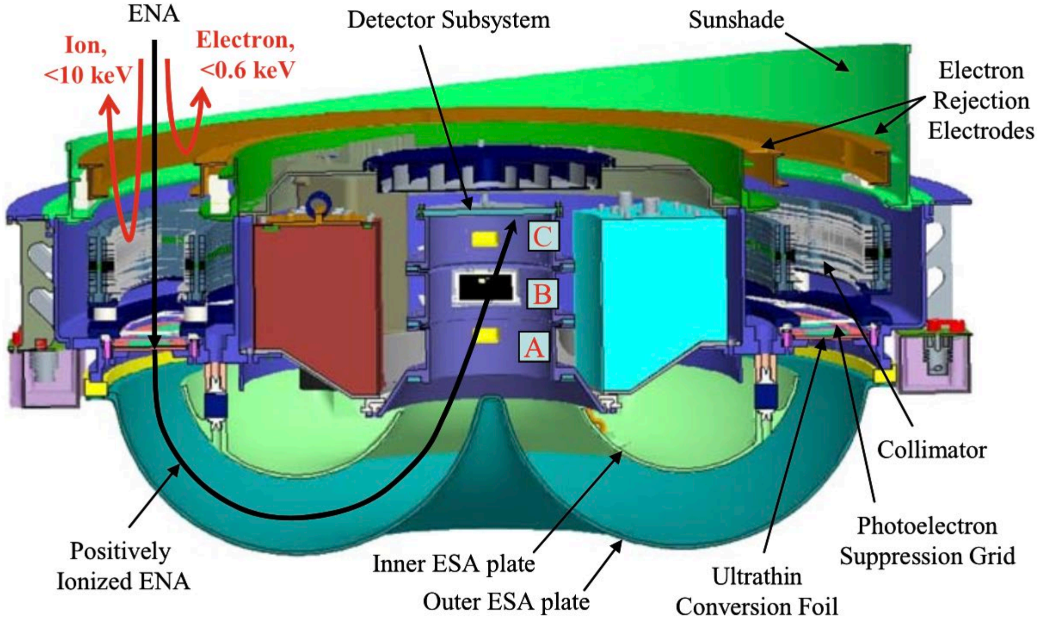
- Improve understanding of the composition and properties of the local interstellar medium (LISM)
- Advance understanding of the temporal and spatial evolution of the boundary region in which the solar wind and the interstellar medium interact
- Identify and advance the understanding of processes related to the interactions of the magnetic field of the Sun and the LISM
- Identify and advance understanding of particle injection and acceleration processes near the Sun, in the heliosphere and heliosheath

Single Pixel ENA Camera Overview





IBEX-Lo



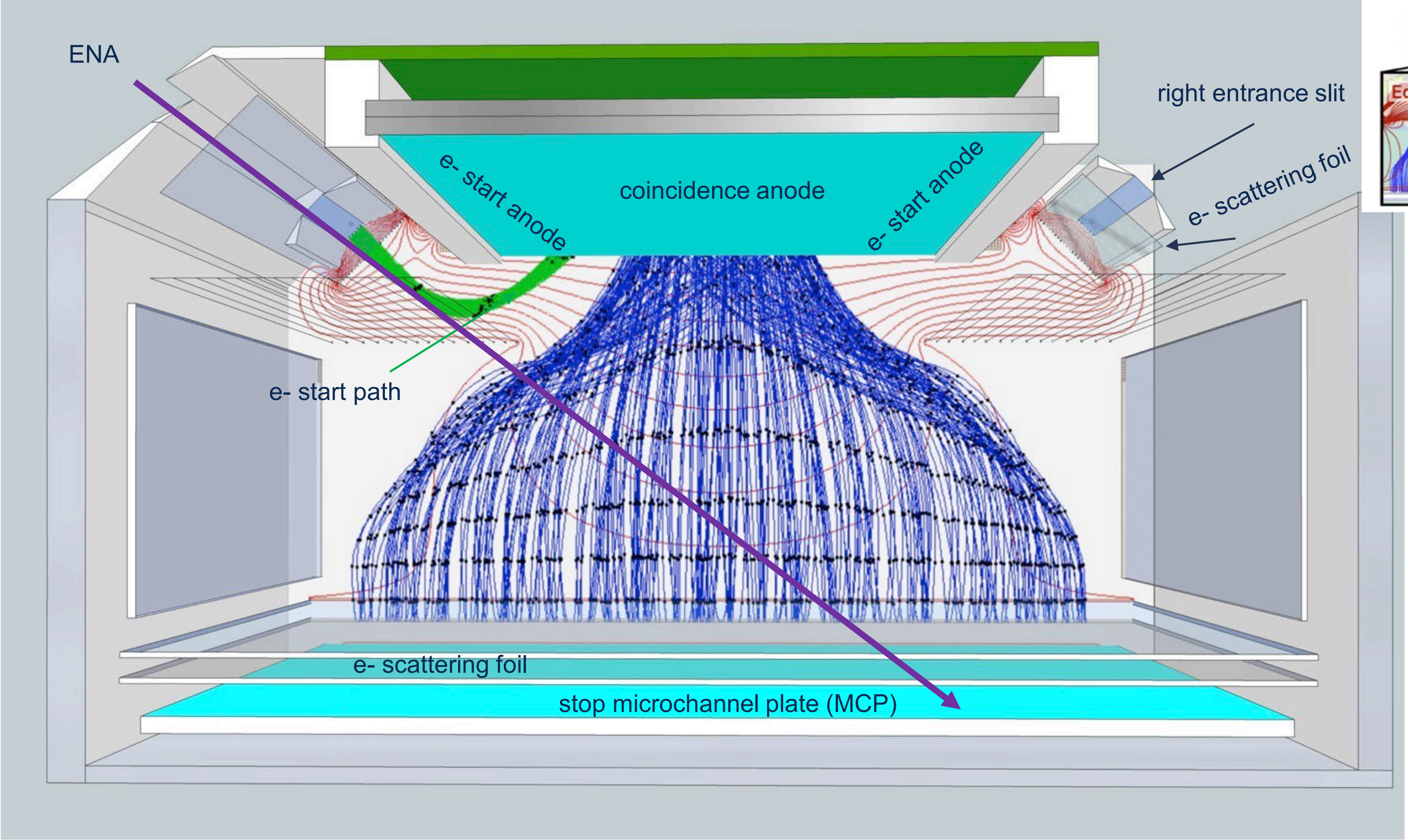
IBEX-Hi

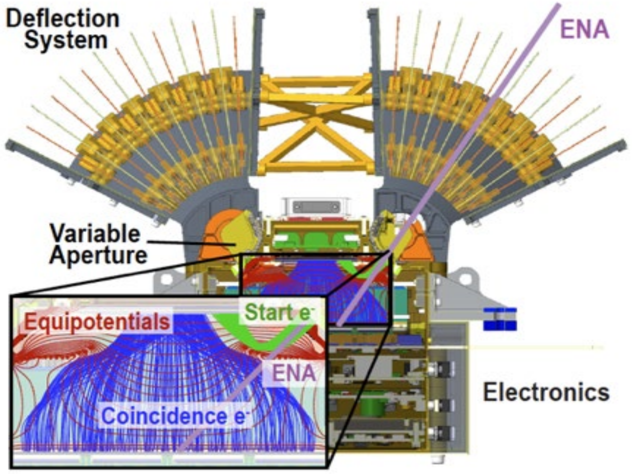
- IMAP-Hi employs a quad TOF system
- IMAP-Lo, on Gimbal + improved DLC Surface

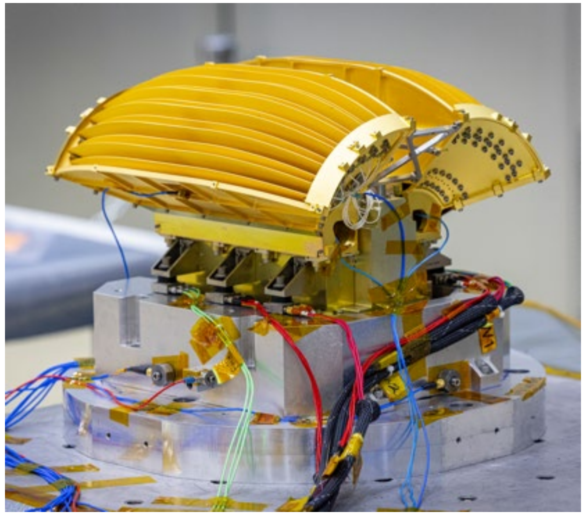
Left Figure) Fuselier, et al: The IBEX-Lo Sensor

Right Figure) Funsten, et al: The IBEX-Hi Neutral Atom Imager

IMAP-Ultra Overview



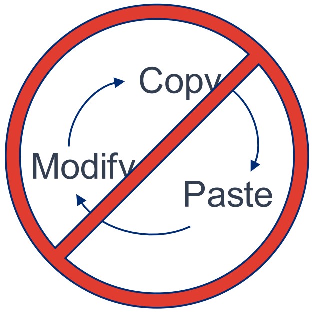




Modeling Objectives & Benefits

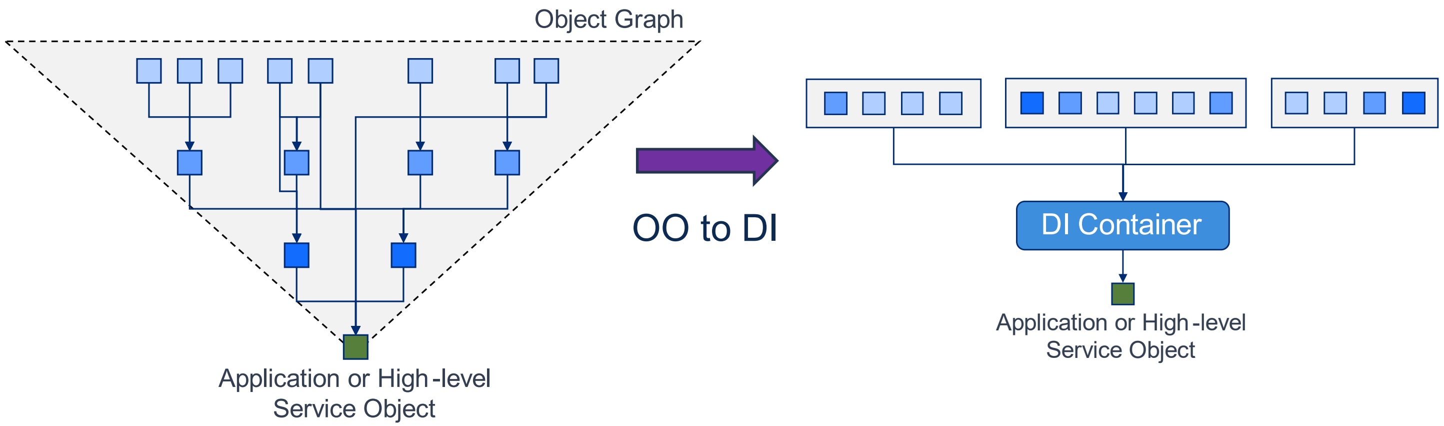
- Modeling Objectives
  - Build a flexible tool that can simulate particle detections for ENA Instruments
  - Implement algorithms for reconstruction of input flux from the Heliosphere
  - Estimate counts, instrument exposure time in the sky, sky projected sensitivities
- Benefits
  - Confirm and compare geometric mapping algorithms
  - Measure of “goodness” for Flux reconstruction
  - Provide Simulated Event Data Sets to Instrument Teams and Science Operations Center IMAP pipeline for Algorithm V&V
  - Instrument models are reusable for other missions, with swappable calibration inputs

An "Experimental" Framework written in Java (DSIIM)



- Software Framework Goals
  - Flexibility in order to reduce software duplication between similar tasks
  - Remove Copy-Paste-Modify mantra for software development and analysis
  - Rapid Deployment (Faster, Better, Cheaper)

- Approach
  - Dependency Injection
    - Flatten complex object graphs
    - Enhances Modularity
    - Abstract data and inputs to functions outside of the software itself
  - Framework facilitates:
    - Unix Design Philosophy
      - Write small, focused modules that does 1 thing well (reusable)
      - Anticipate outputs of one program to be input of another
    - Command-line driven API for optionally overriding default inputs
    - External Variable Properties Expansion
    - Configuration Runtime Capture



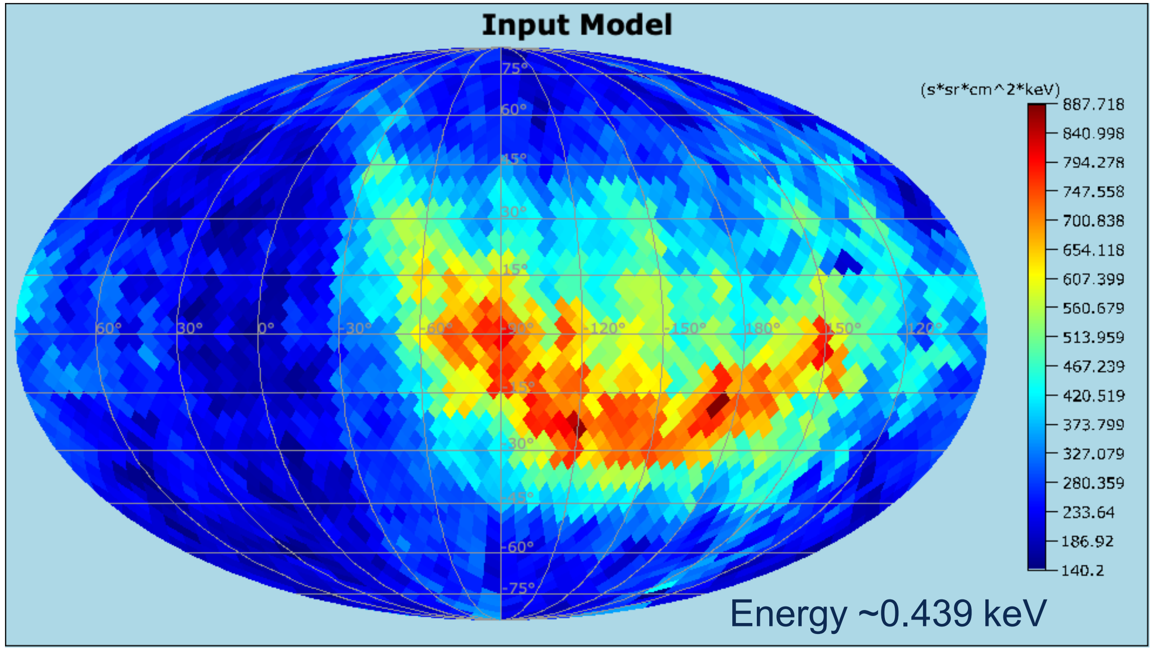
Git-like command-line interface with subcommands

```
Commands:
  fluxgrid    Build an N-Dimensional Flux Grid
  exposure    Compute Exposure Time for an Imager with a FOV
  boresight   Compute the Boresight or Exposure Time for a Single Pixel Camera
  counts      Determine Counts as Detected by an ENA Imager
  events      Simulate Direct Event Data
  map         Build, Plot, or Alter Map Data of Various Types
  help        Displays help information about the specified command
```

*DSIIM – Data Simulator for Imagining Instruments and Missions

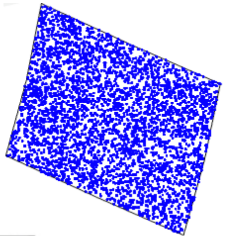
Forward Simulation Approach – Environment

- Environmental Model Input are Differential Flux [#/(cm2 s sr keV)] Maps of ENAs (Hydrogen)
  - **Flat Flux of 500** [#/(cm^2 s sr keV)] for every energy channel – Simple Flux Reconstruction Validation
  - **IBEX Lo/Hi & INCA Interpolated Spectra** – Qualitative and Spatial Assessment
  - **IMAP Logo Flux Map** – Quantitative and Spatial Assessment

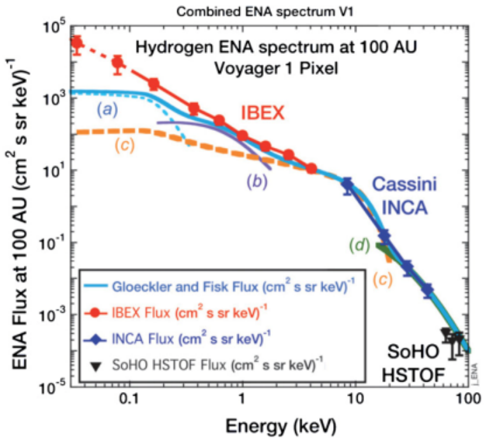


IBEX Lo/Hi & Cassini INCA Interpolated Spectra

- Input maps and calculations can be done on various Tessellations (HEALPix, Abrate, Square Pixels)
- ENAs within a Pixel (Instrument Agnostic)
  - Particles come from anywhere within a pixel and are randomly distributed

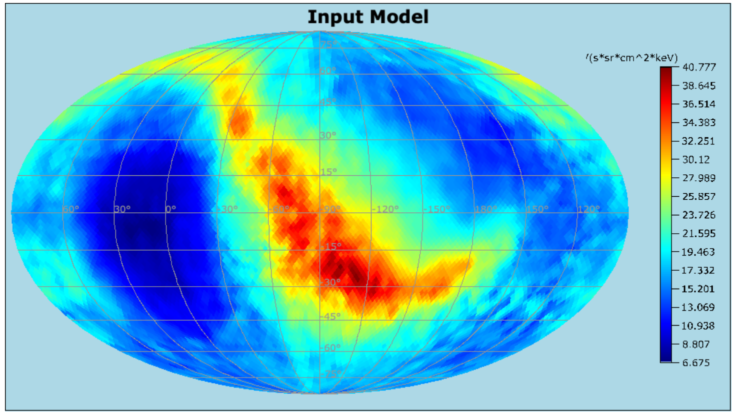


- Flux Follows Power Law
  - J = A*E^γ



Forward Simulation Approach – Instrument (Lo/Hi)

- Instrument FOVs currently modeled as cone with half-angle θ_{FOV} (9° for Lo, 4.0° for Hi)
- At a given instant, for each ESA Setting: For each pixel in the IFOV, the Flux J_s is computed from power law ($J_s = A_{pix} E_s^{\gamma}$)
- $JT_k = \int J(E)T(E)dE = \sum_s [(E_{s+1} - E_s)(J_s T_s + J_{s+1} T_{s+1})/2]$
- $< \#_{triples} > = \frac{t_{exp} * \Omega_{pix} * E * PSF * \sum(GF_{triples} * JT)}{N_{ESA}}$
  - E_s and T_s are energy and transmission samples along the transmission function for the given ESA setting
  - Ω_{pix} is the solid angle of the HEALPix pixel
  - E is the energy midpoint for the given ESA channel
  - $GF_{triples}$ is the calibrated GF factors (H) provided in the excel files
  - $PSF = \frac{3}{\pi \theta_{FOV}^2}\left(1 - \frac{\alpha}{\theta_{FOV}}\right)$ where α is the angle of the incoming particle off IMAP-Lo / IMAP-Hi boresight
  - N_{ESA} ESA steps to account for non-simultaneous energy observations over the course of a day (2 spins per ESA step)
- Poisson distribution is then fit with the mean number of triples, then randomly sampled to provide the integer $\#_{triples}$
- The total number of counts for the given pixel in the sky is then incremented by $\#_{triples}$
- The time in which the event occurs is then given as a random (full spin) offset from the spin phase to account for the full day (we only actually spin the spacecraft 1 rotation per day in the model – but this is changing)
- Direct Event for doubles, triples, quads (combinations of AB / BC for doubles, etc) is then added to the list of events

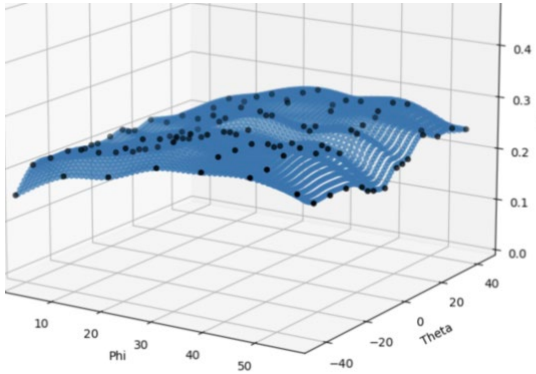


Input Flux @ 2.52 keV

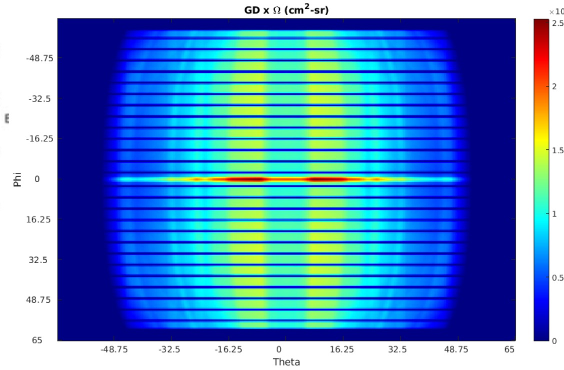
Flux Reconstruction – Lo and Hi

- For a given energy channel and pixel, the flux is calculated as the sum of the counts divided by a time and sensitivity factor (Let's call it TS)
- For a given ESA Setting: For each pixel in the sky, the time and sensitivity factor is computed as:
- $\mathrm{TS_k} = t_{exp} \sum_s \left[(E_{s+1} - E_s)\left(E_s^{\gamma} T_s + E_{s+1}^{\gamma} T_{s+1}\right) E_{trans}^{-\gamma}/2 \right] \left(\frac{E_{trans}}{E_{chan}}\right)^{\gamma} E_{chan} \left(\frac{GF_{triples}\, te_{xp}}{N_{ESA}}\right)$
- K index here is for a given pixel
- E_{trans} is a transition energy relevant if fitting between IBEX and INCA data;
- Then $\mathrm{Flux_k} = C_k/TS_k$

- Ultra Forward Simulation and Flux Reconstruction is done very differently



Ultra Calibrated Efficiencies



Ultra Geometric Factor

Lo - Exposure Time with Pivot Pointing Plan

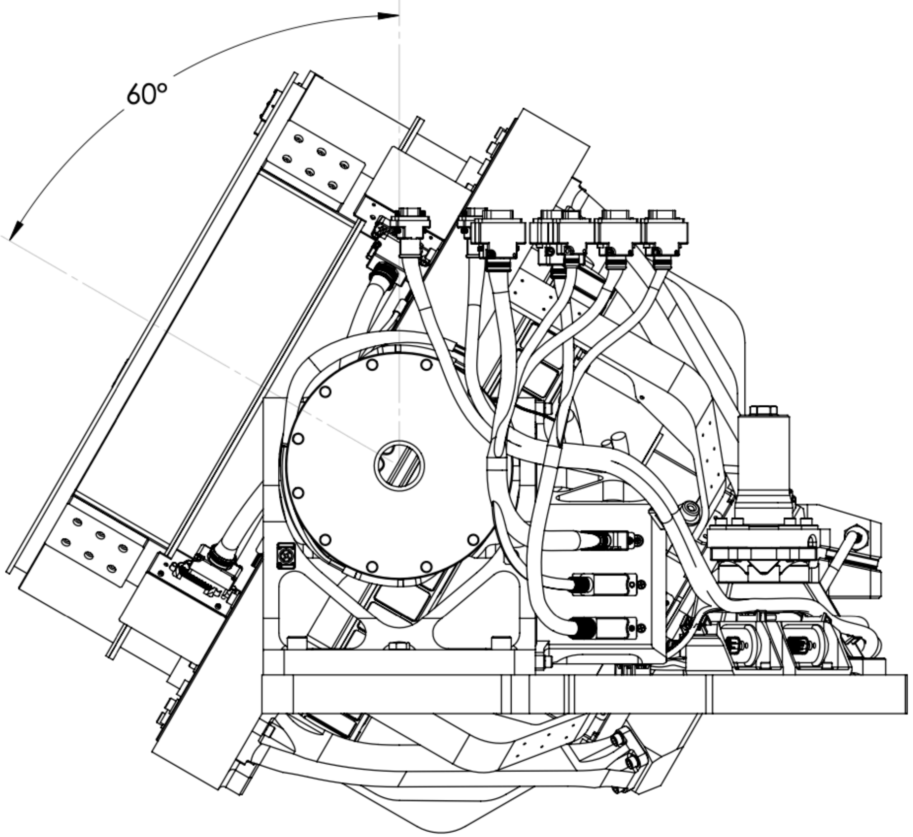


Table 3. Draft Operation Plan for the First Year of IMAP-Lo Observations

Day of Year	Viewing angle range	Focus of observation
Every other odd days (4n+1)	105°	H, D, He (direct), O, Ne
Every other odd days (4n-1)	75°	H, D, He (direct and indirect), O, Ne
Even days (2n)	90°	ENAs

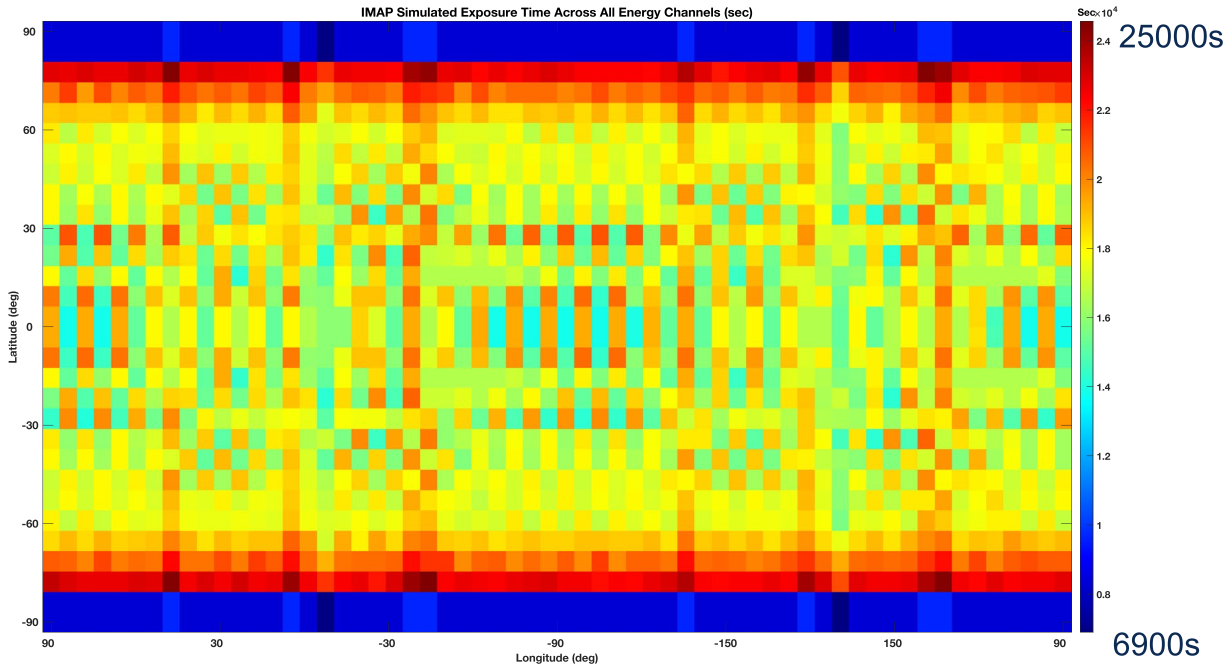
Table 3. Draft Operation Plan for the Second Year of IMAP-Lo Observations

Day of Year	Pivot angle range	Focus of observation
Every other odd days 1-33 (4n+1; n = 0, 1, ..., 8)	75°	O, Ne
Every other odd days 37-189 (4n+1; n = 9, 10, ..., 47)	120°	H, D, He (direct), O, Ne
Every other odd days 193-277 (4n+1; n = 48, 49, ..., 69)	160°	He (direct), O, Ne
Every other odd days 281-365 (4n+1; n = 70, 71, ..., 91)	75°	He (indirect)
Every other odd days 3-151 (4n-1; n = 1, 2, ..., 38)	105°	H, D, He (direct), O, Ne
Every other odd days 155-203 (4n-1; n = 39, 40, ..., 51)	148°	He (direct), O, Ne
Every other odd days 207-363 (4n-1; n = 52, 53, ..., 91)	60°	He (direct and indirect)
Every other even days 2-362 (4n-2; n = 1, 2, ..., 91)	90°	ENAs
Every other even days 4-364 (4n; n = 1, 2, ..., 91)	135°	ENAs

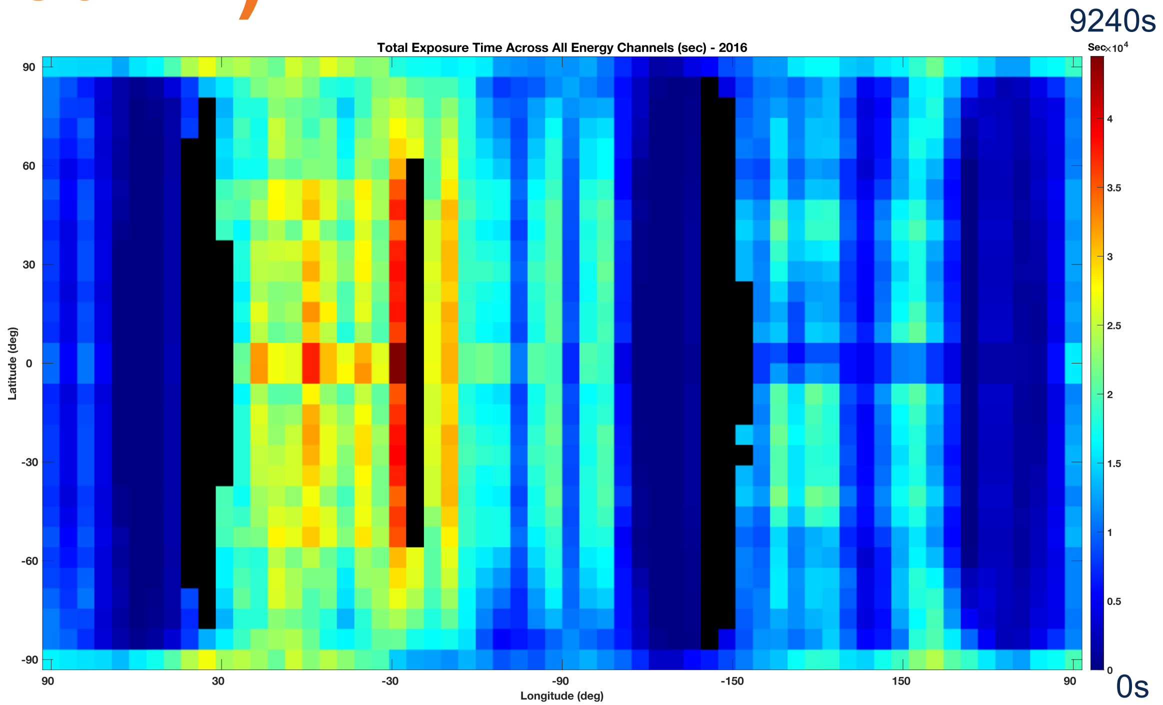
Note: Year 2 Pivot Pointing Plan may need to be adjusted if launch slip

* Maps not on same color scale

IMAP-Lo Exposure Time (Year 1)



IMAP-Lo Year 1 Sim

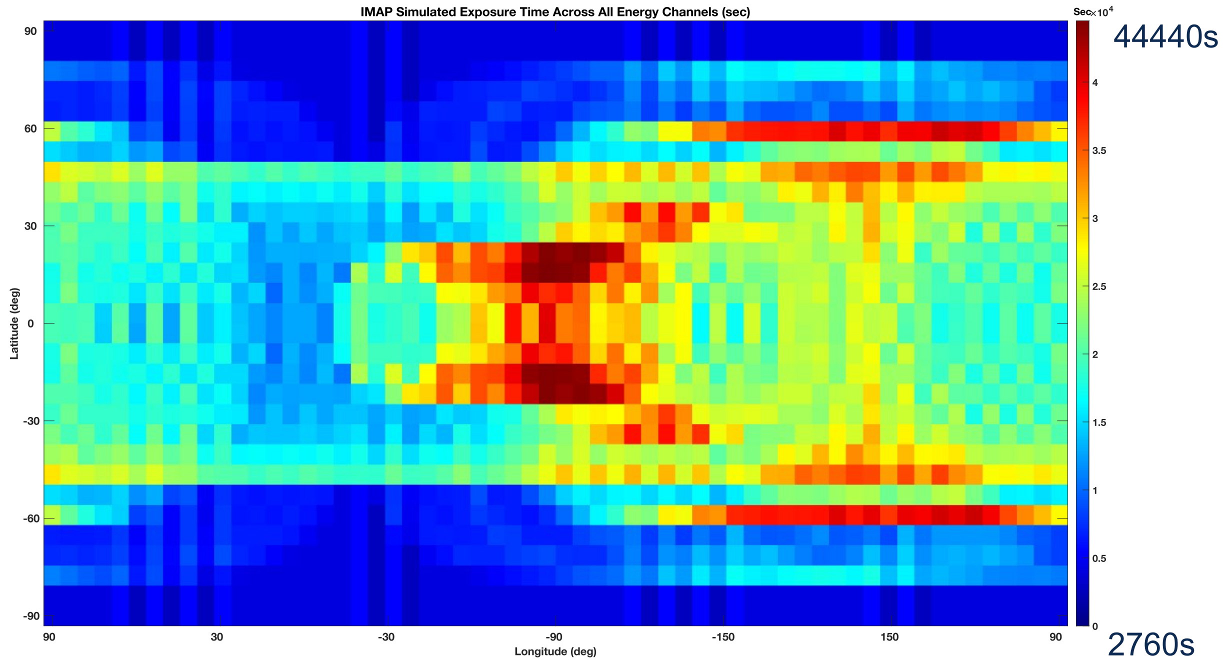


IBEX-Lo 2016 Total Exposure

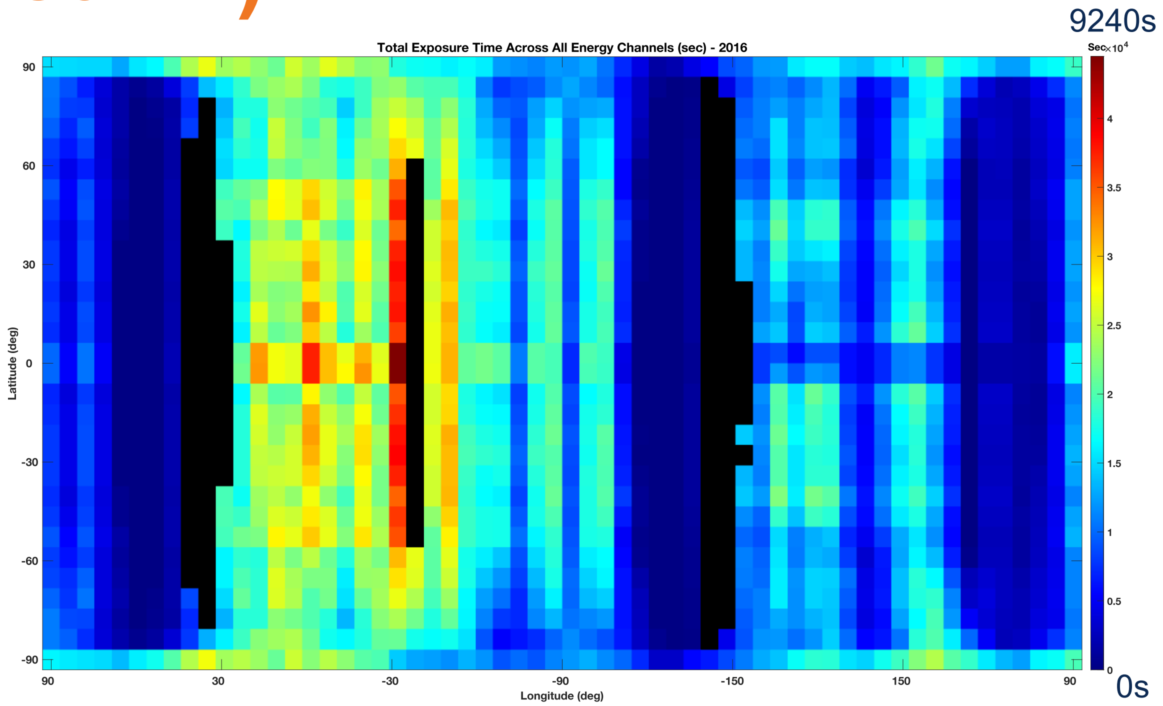
- IMAP-Lo Total Exposure Time: ~96.2% of the year or ~12.0% of the year per energy channel
- High Latitudes (±60°-90°): ~30.1% of year
- Mid Latitudes (±30°-60°): ~33.3% of year
- Equatorial Latitudes (-30°- +30°): ~32.8% of year

- IBEX-Lo Total Exposure Time: ~14.6% of the year or ~1.8% of the year per energy channel
- High Latitudes (±60°-90°): ~4.7% of year
- Mid Latitudes (±30°-60°): ~4.9% of year
- Equatorial Latitudes (-30°- +30°): ~5.0% of year

IMAP-Lo Exposure Time (Year 2)



IMAP-Lo Year 2 Sim

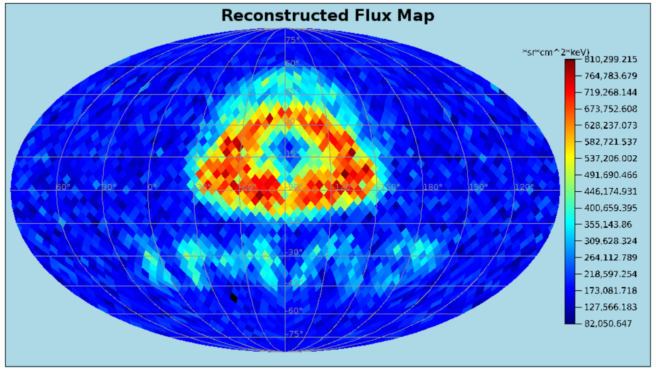


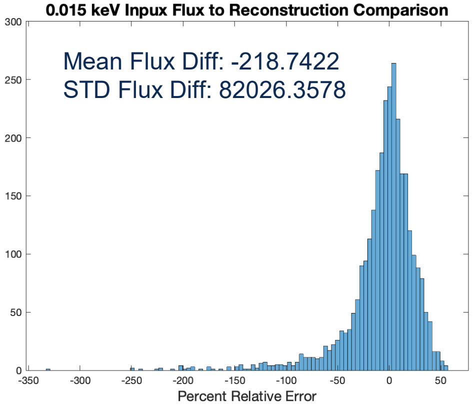
IBEX-Lo 2016 Total Exposure

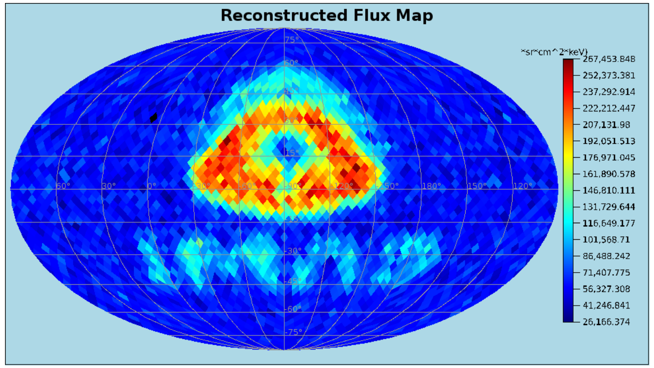
- IMAP-Lo Total Exposure Time: ~96.2% of the year or ~12.0% of the year per energy channel
- High Latitudes (±60°-90°): ~13.3% of year
- Mid Latitudes (±30°-60°): ~39.8% of year
- Equatorial Latitudes (-30°- +30°): ~43.0% of year

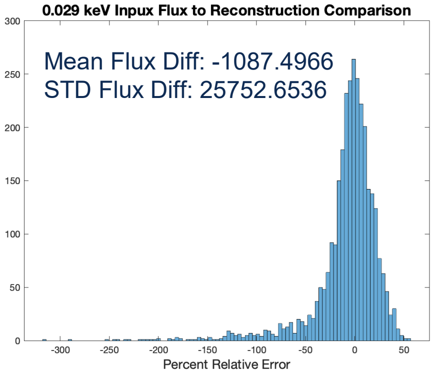
- IBEX-Lo Total Exposure Time: ~14.6% of the year or ~1.8% of the year per energy channel
- High Latitudes (±60°-90°): ~4.7% of year
- Mid Latitudes (±30°-60°): ~4.9% of year
- Equatorial Latitudes (-30°- +30°): ~5.0% of year

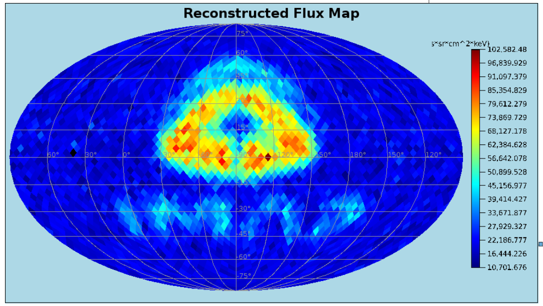
IMAP-Lo Flux Reconstruction Examples (1 Year)

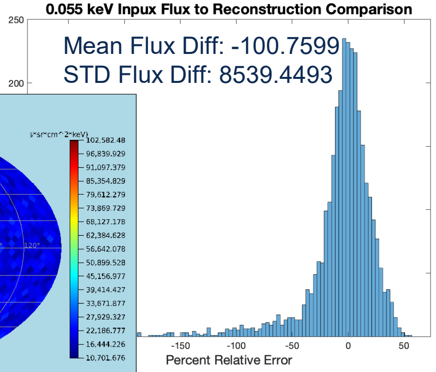


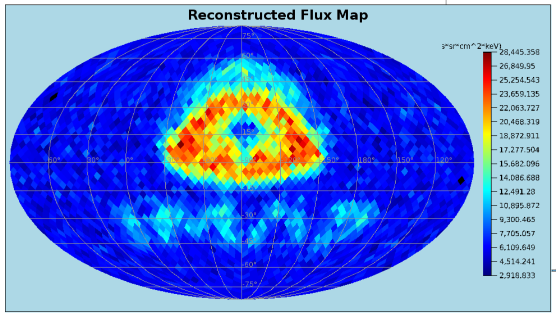


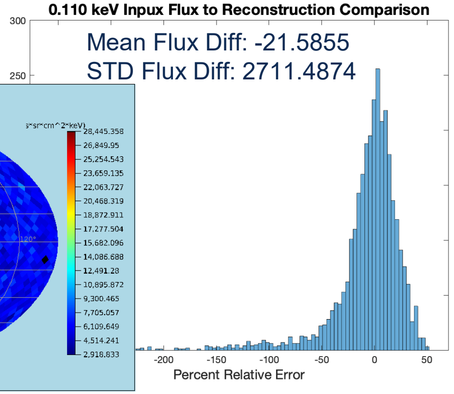


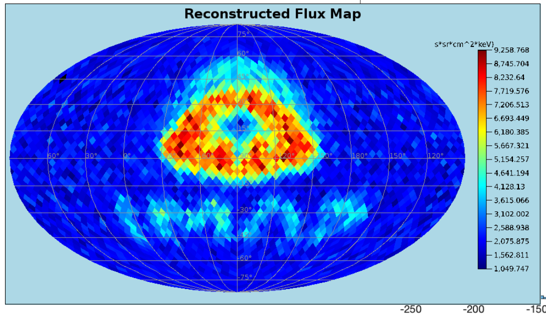


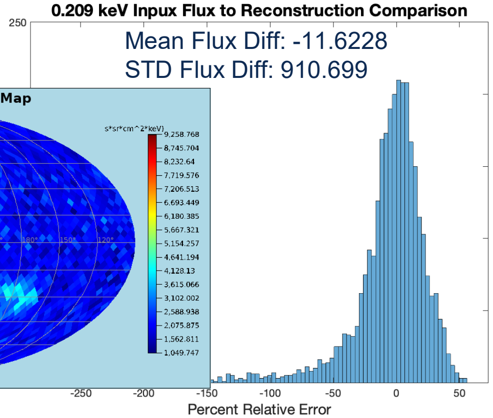


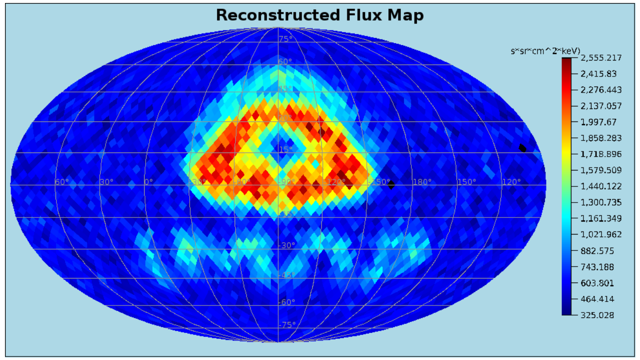


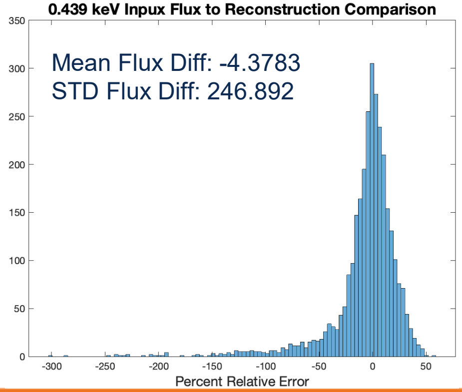


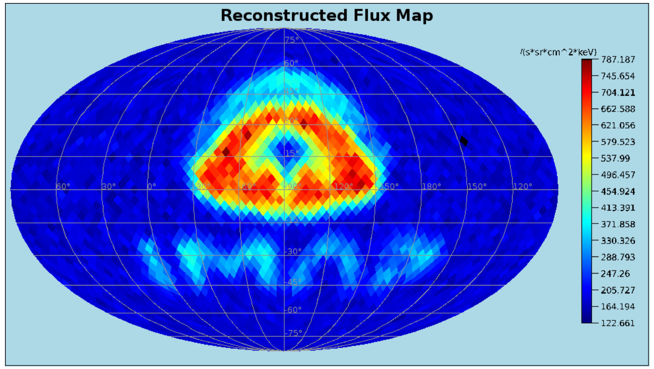


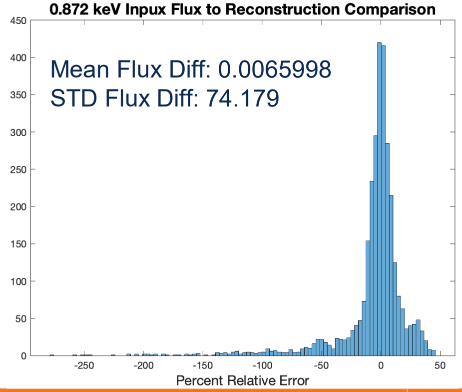






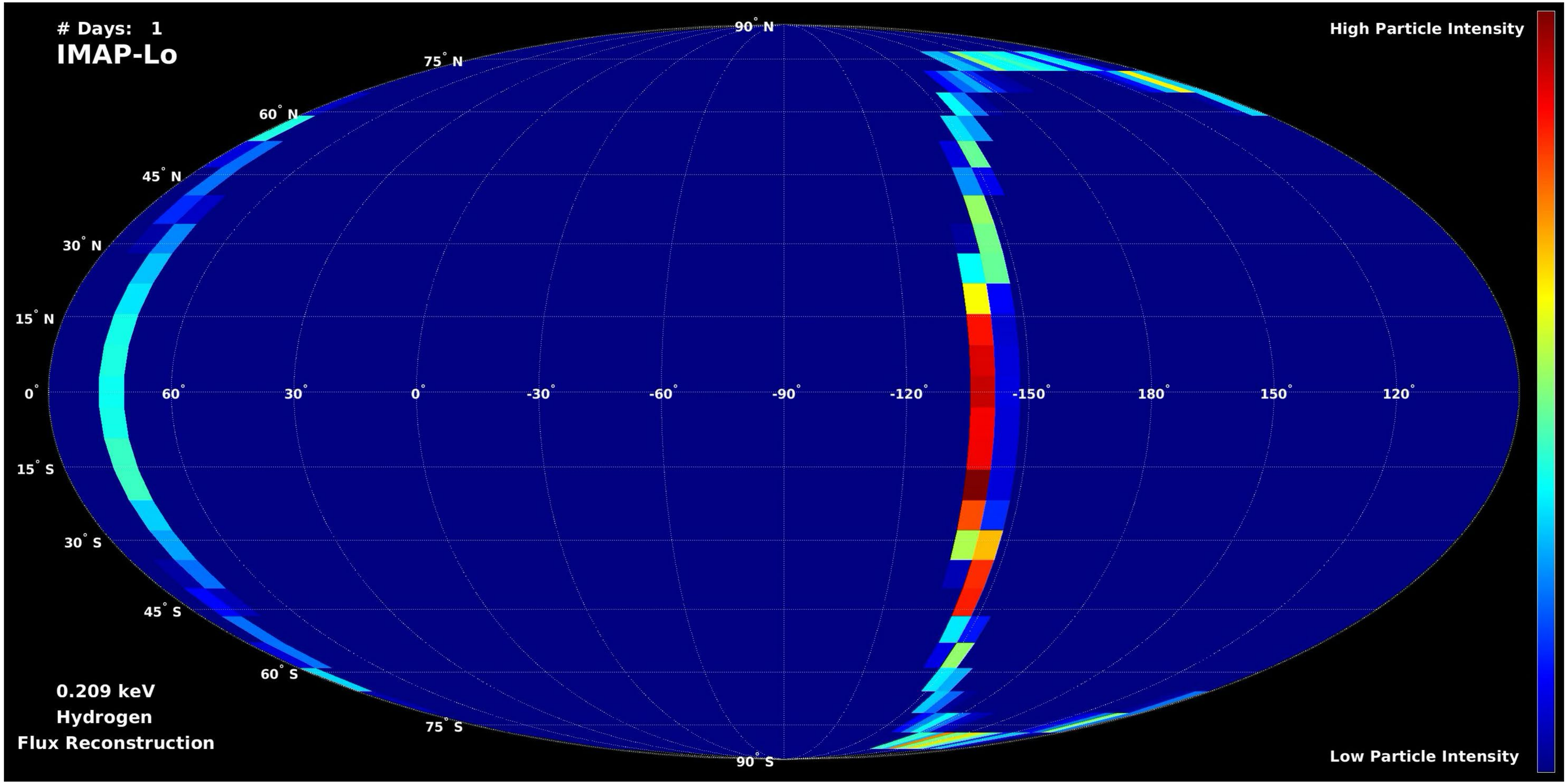






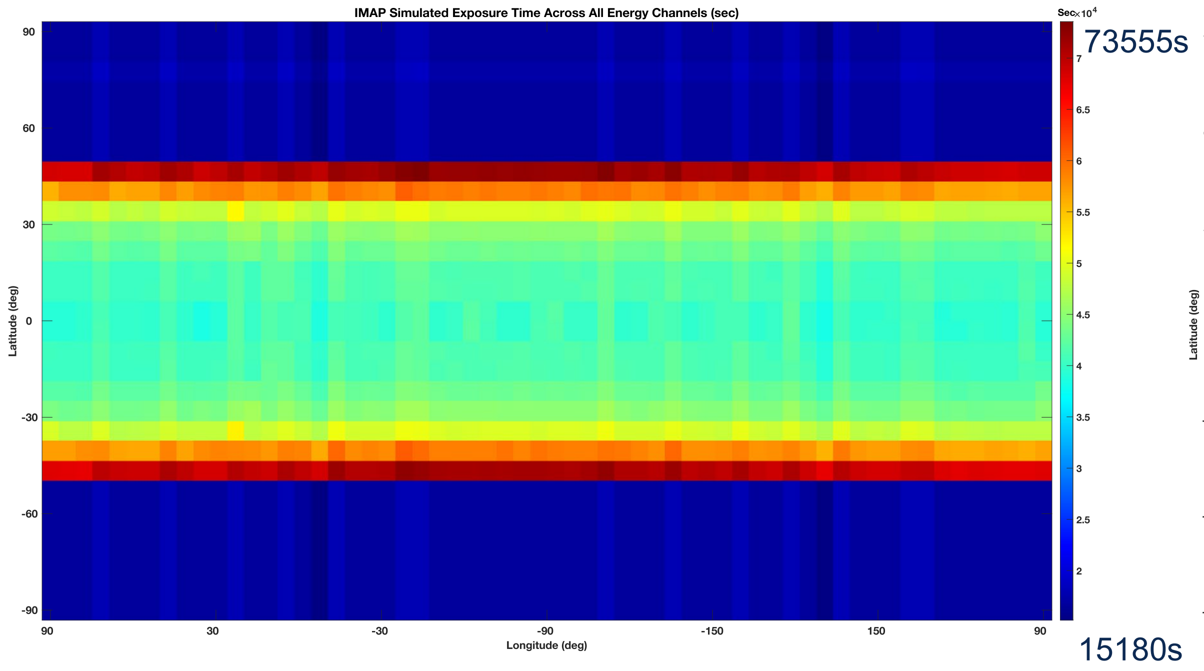
IMAP-Lo Flux Reconstruction (Year 2) 6x6 deg

- Earlier in the year, focus is on higher latitudes
- As time moves forward, Lo pivots towards the ecliptic to focus more on ISN
- Will be some gaps in polar coverage on 2x2 pixel maps

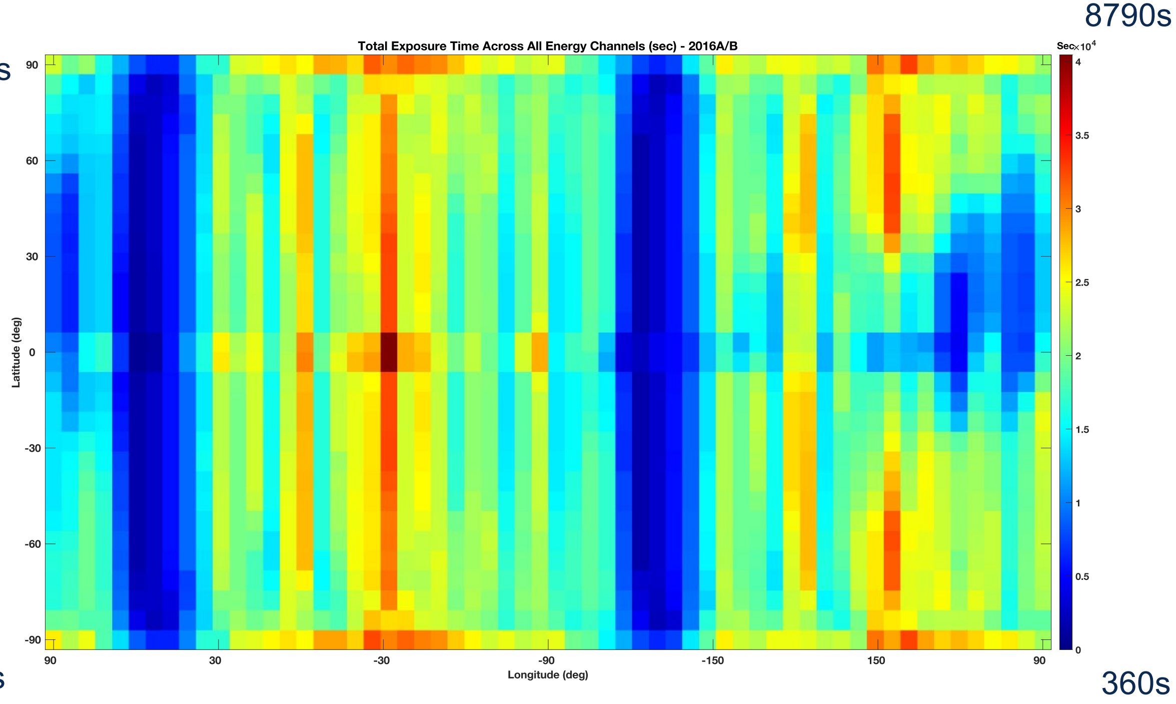


* Maps not on same color scale

IMAP-Hi (90&45) Exposure Time



IMAP-Hi Sim



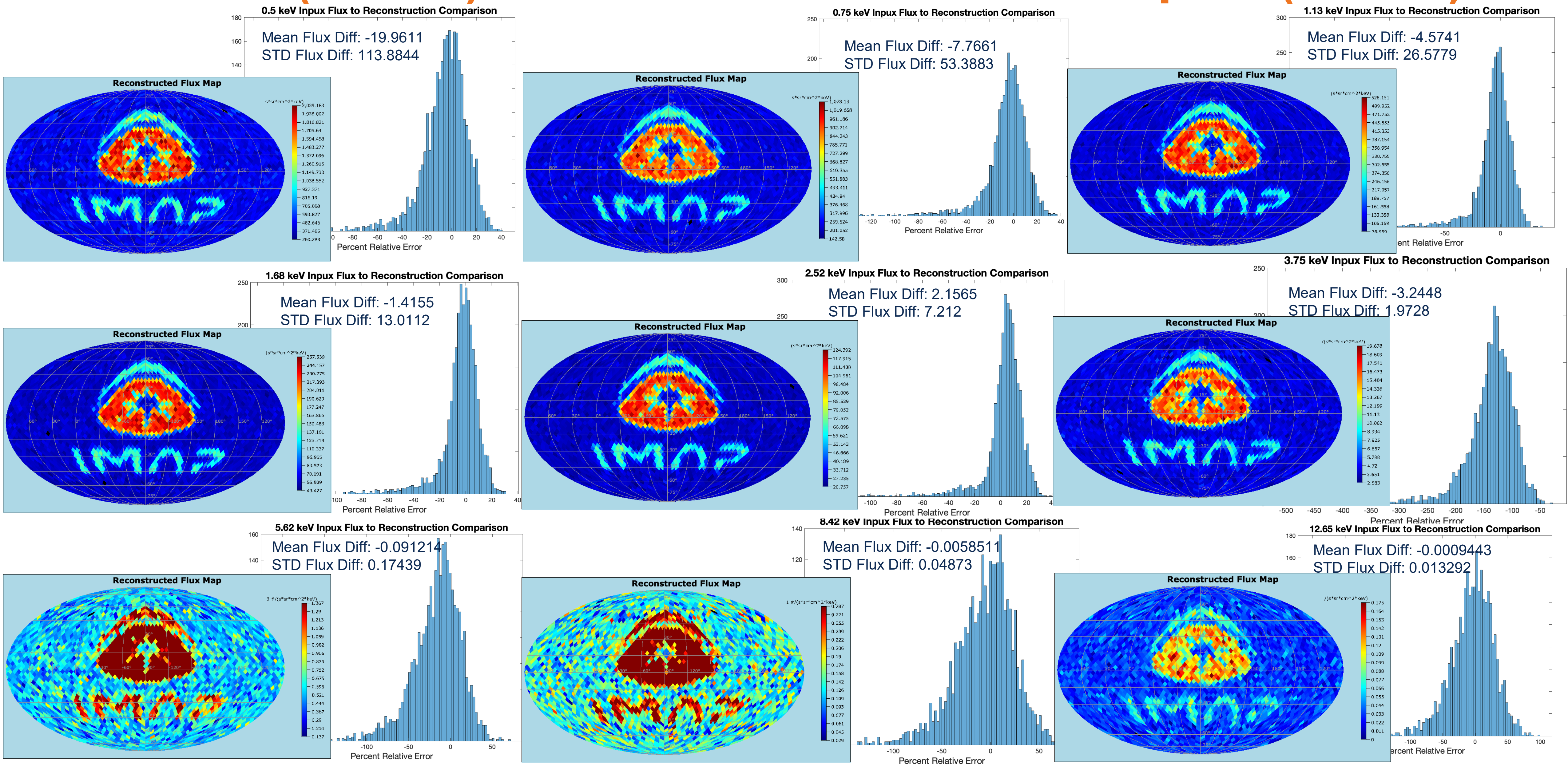
IBEX-Hi 2016 Total Exposure

- IMAP-Lo Total Exposure Time: ~96.2% of year/head or ~10.7% of the year/energy channel/head
- High Latitudes (±60°-90°): ~32.2% of year
- † Mid Latitudes (±30°-60°): ~80.2% of year
- † Equatorial Latitudes (-30°- +30°): ~80.0% of year

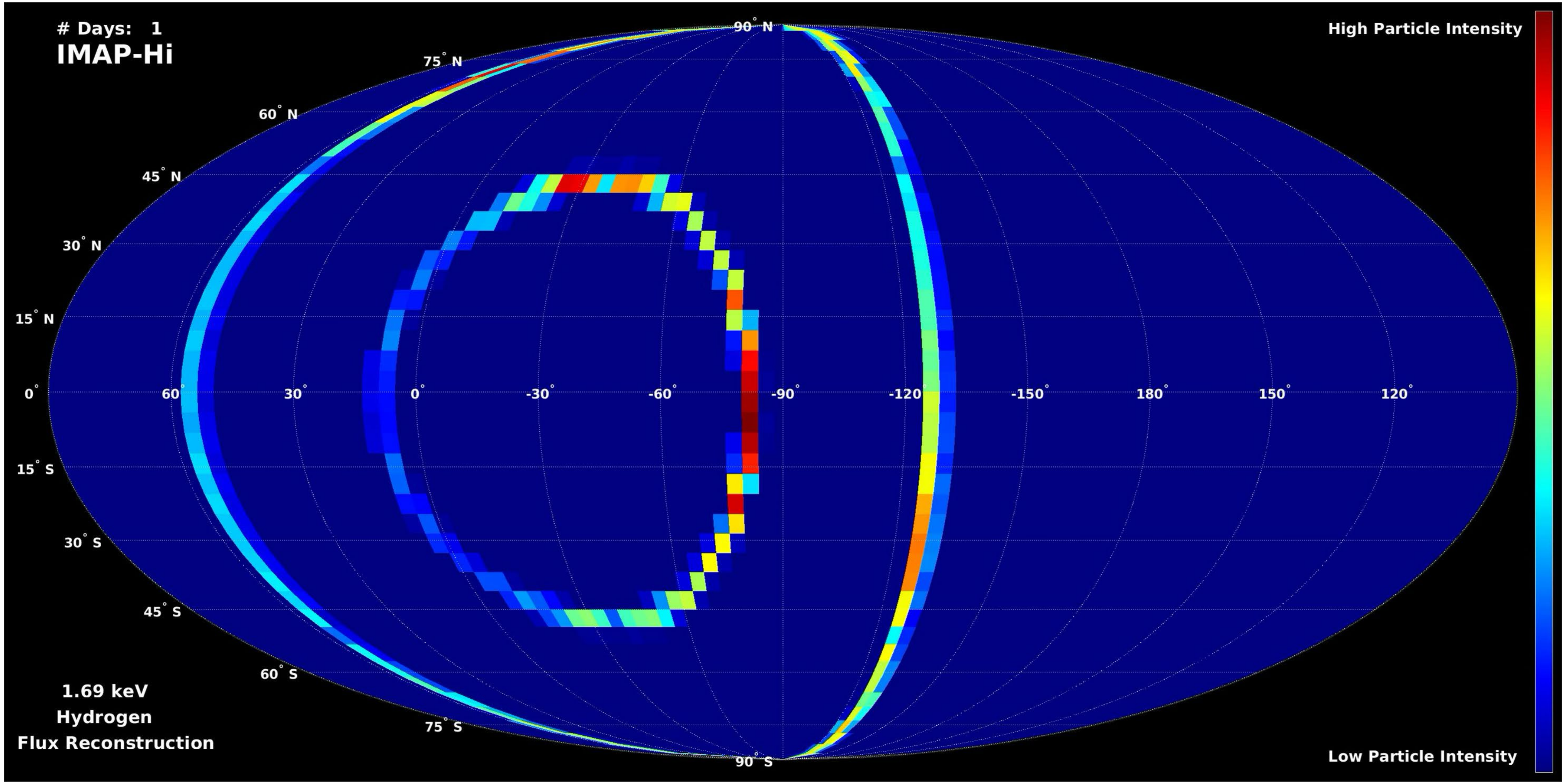
† Not Simultaneous overlapping coverage

- IBEX-Hi Total Exposure Time: ~24.5% of the year or ~4.1% of the year per energy channel
- High Latitudes (±60°-90°): ~7.1% of year
- Mid Latitudes (±30°-60°): ~7.8% of year
- Equatorial Latitudes (-30°- +30°): ~7.4% of year

IMAP-Hi (90&45) Flux Reconstruction Examples (1 Year)



IMAP-Hi90 and Hi45 Flux Reconstruction 4x4 deg

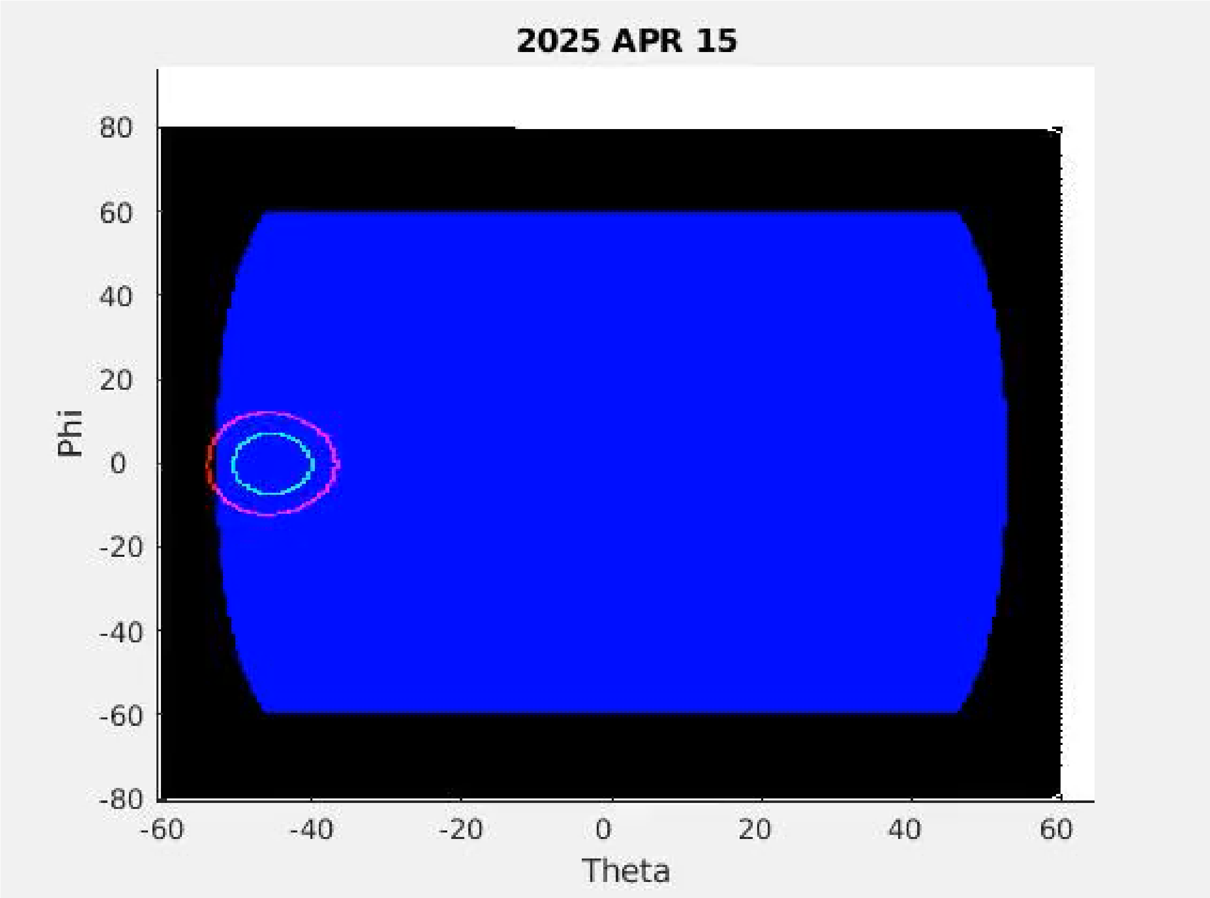


- Will be ~45 days before any sensor overlap in exposure times

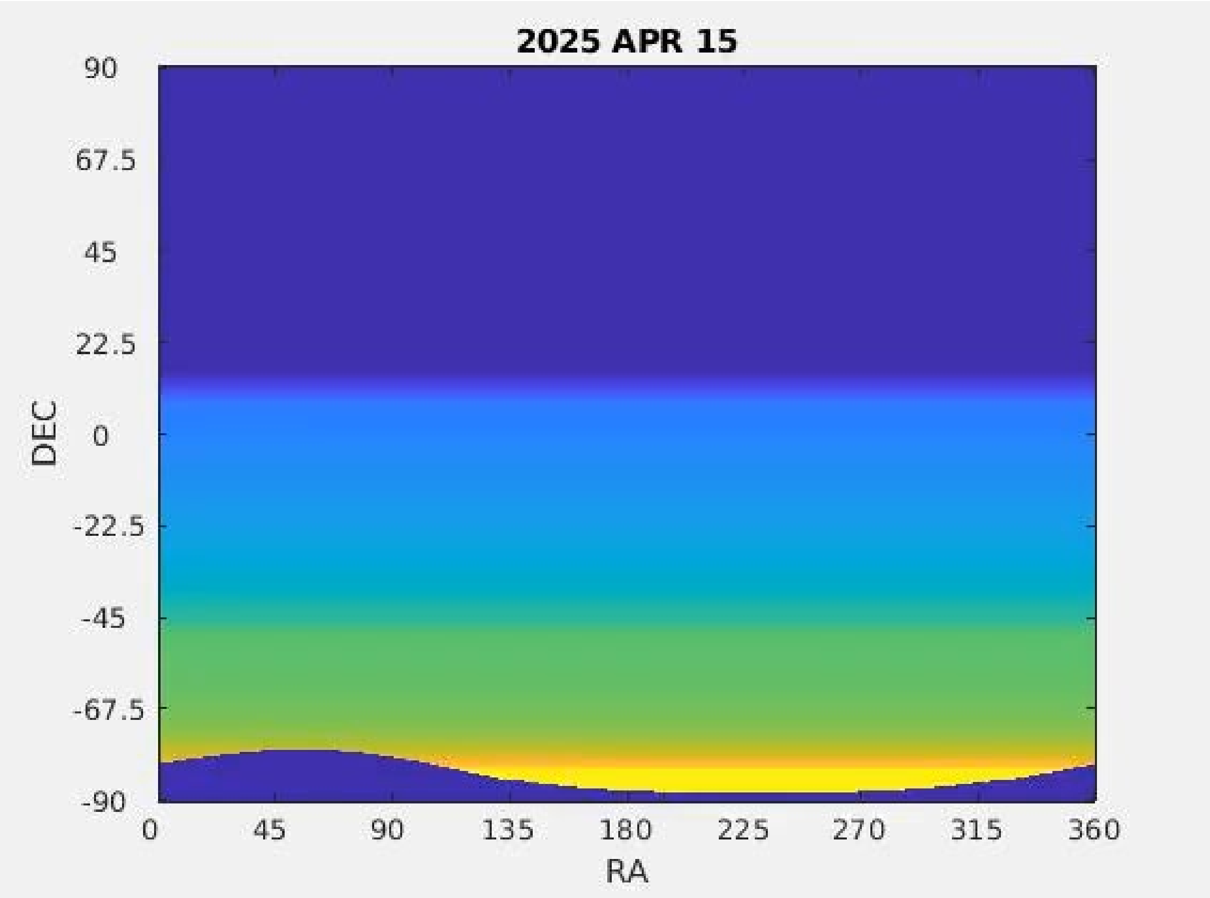
- IMAP-Hi has 9 ESA steps as opposed to IBEX's 5/6

Ultra-45 Spatiotemporal Culling Examples

Earth, Moon, Jupiter in Ultra-45 Inst Frame

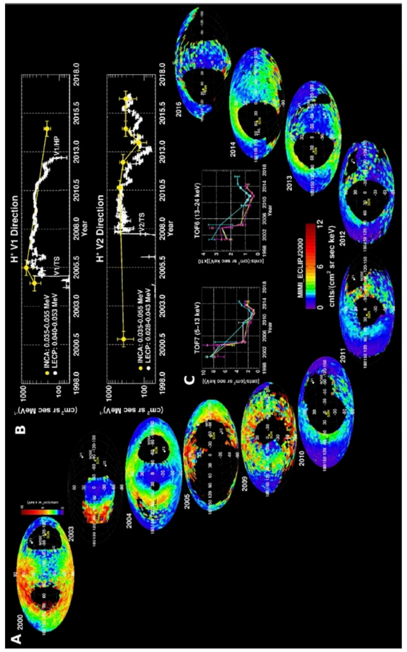


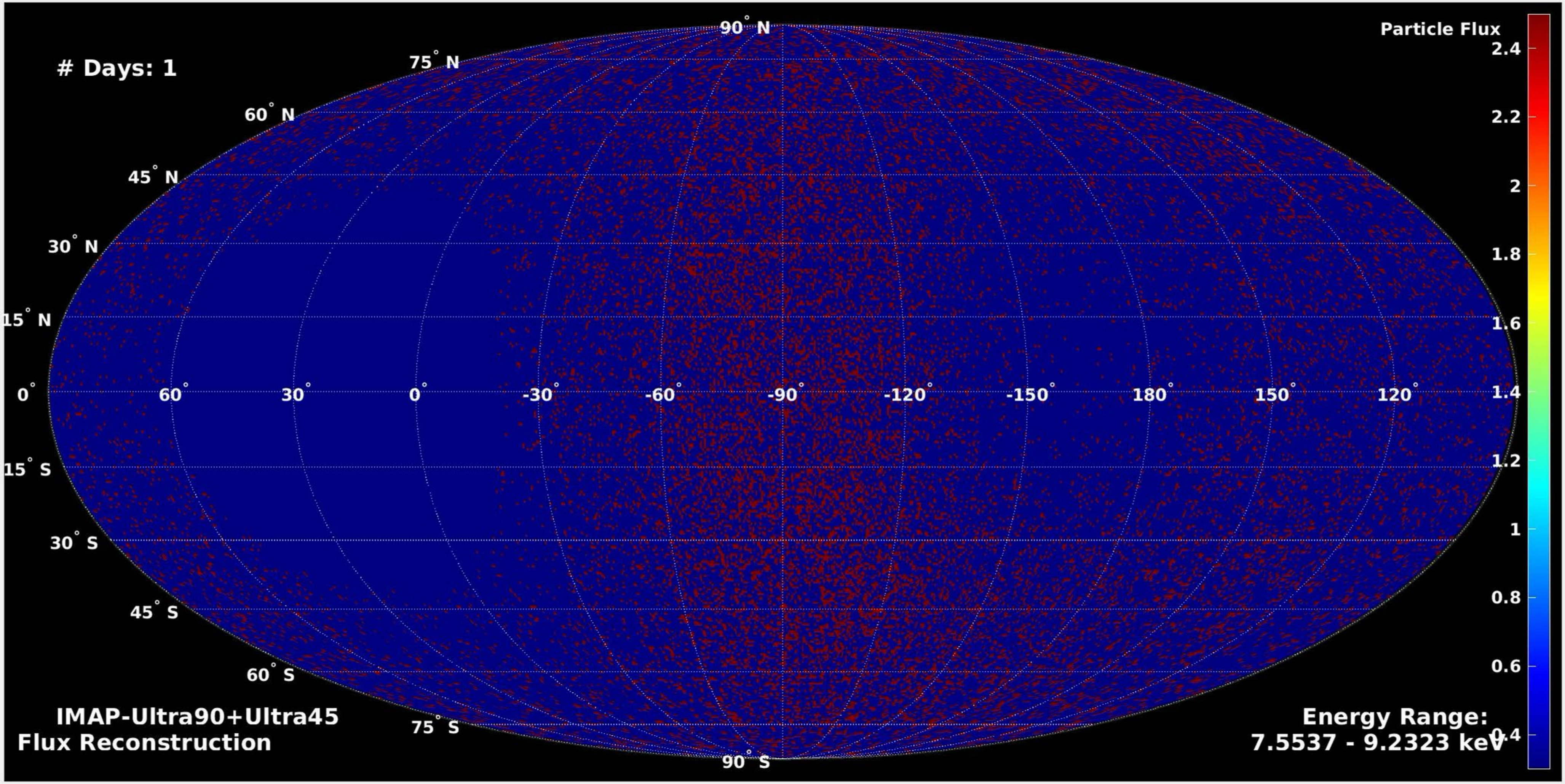
30Re, 4Rm, 100Rj culling in DPS Frame



Ultra Combined Flux Reconstruction

- 0.5 deg pixels
- No Scattering
- Uses multi-year INCA flux as input model



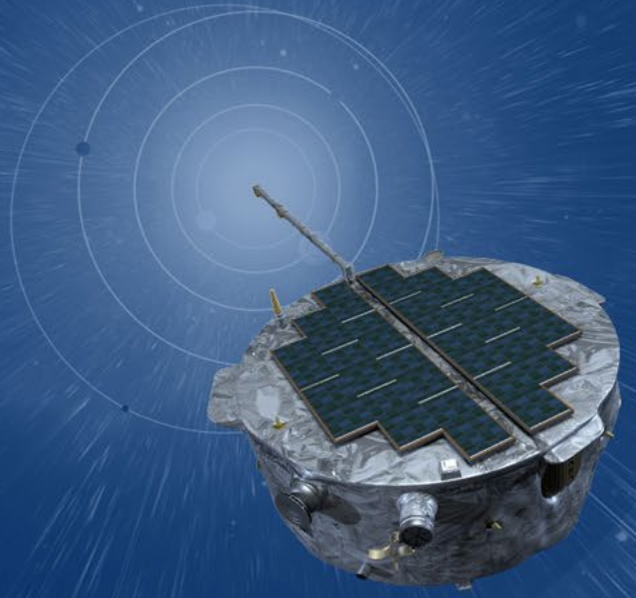


Summary

- Using this model, we've been able to validate new algorithms
- Create new calibration data products (Spun Exposure Times, Efficiencies, Sensitivities, etc.) necessary for processing at the SOC
- Provide simulated individual particle detection events for a full year for all ENA instruments to the SOC for validating the pipeline

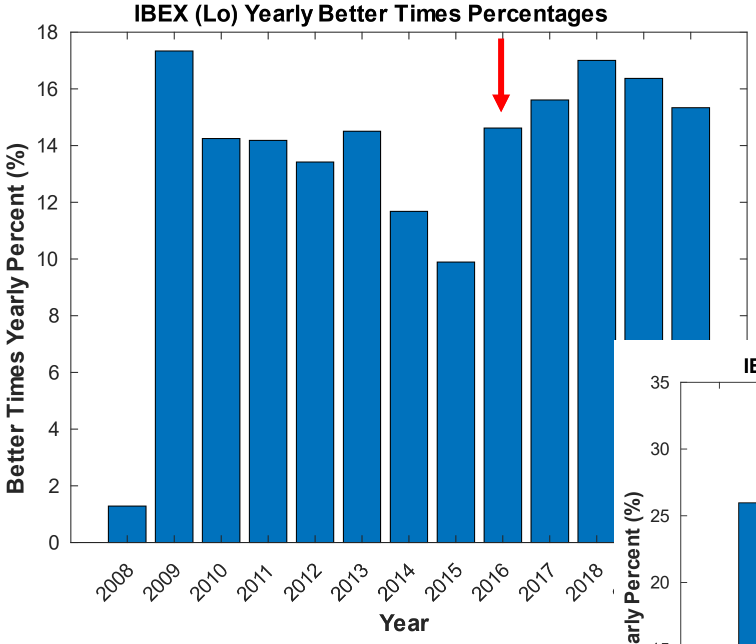
- Improvements of IMAP over IBEX (pessimistically):
- Ultra will have full sky flux estimates in ~90 days as opposed to ~11 years of data compiled from Cassini/INCA
- Even with more energy channels on IMAP-Hi, with the increase in total exposure time, we still get more viewing opportunity per ESA setting (per head) than IBEX by 2.5x
- IMAP-Lo estimated to have over 6x the exposure time compared to IBEX for the year 1 plan
- IMAP-Lo estimated to have over 8x the exposure time for mid latitudes, and ~9x for equatorial latitudes

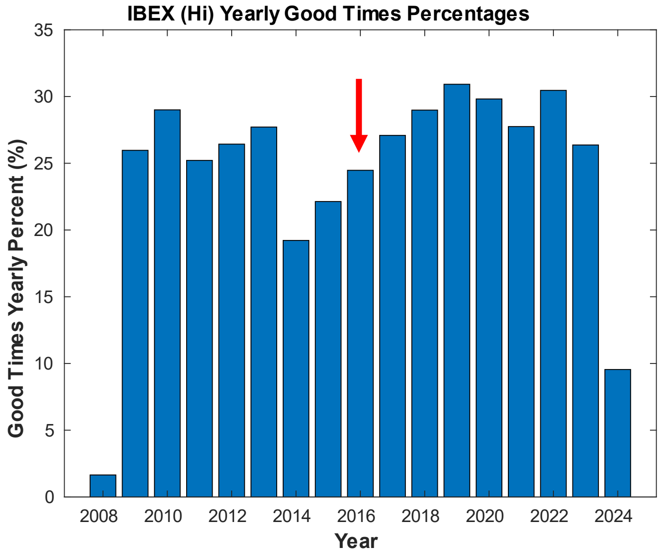
IMAP



Good Times Expectations

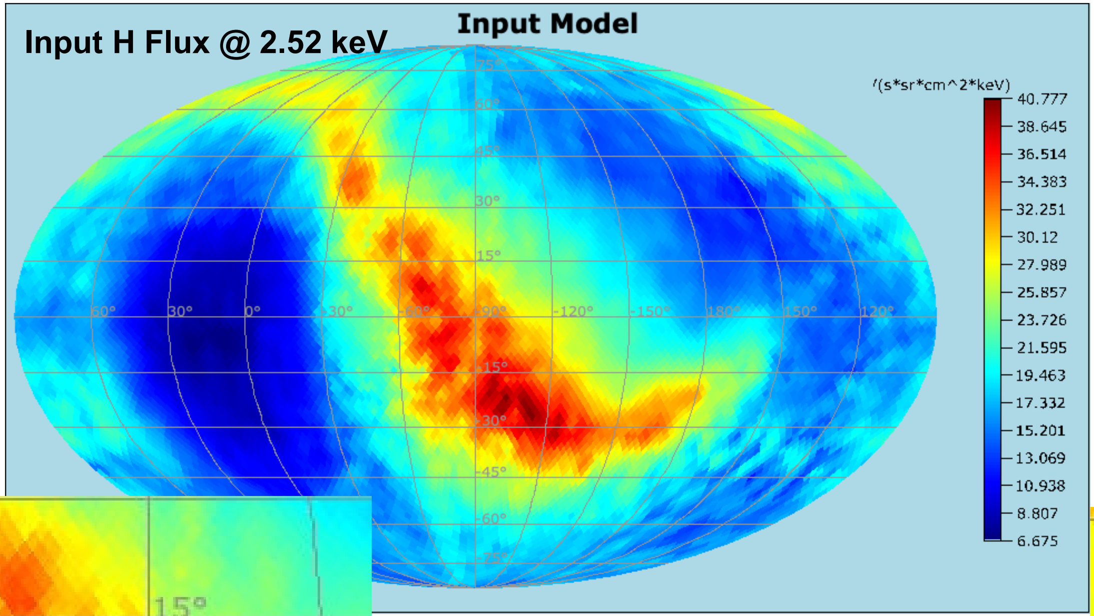
- Benefits of IMAP Orbit and Location over IBEX
  - Minimal magnetosphere restrictions on collection time (Ultra-45 Spatial Cull of Earth's Magnetosphere)
  - Minimal Earth/Moon exclusion (Ultra-45 exception)
  - Dual use of pivot platform and 2x instrument heads for Hi and Ultra
  - ~34 minute assumption (4.5 deg slew) for repoint:
    - 97.64 % good times per year
  - ~7.5 minute assumption (1 deg slew) for repoint:
    - 99.49 % good times per year
  - Both estimates are optimistic and only account for repoint times.
  - A significant improvement over the:
    - < 10%-18% from IBEX-Lo Better Times
    - < 20%-30% from IBEX-Hi Good Times
  - For the analysis in this presentation I assume ~23 hours per 24 hour Pointing of good times and compare against a 2016 IBEX year
    - ~96 % good times per year

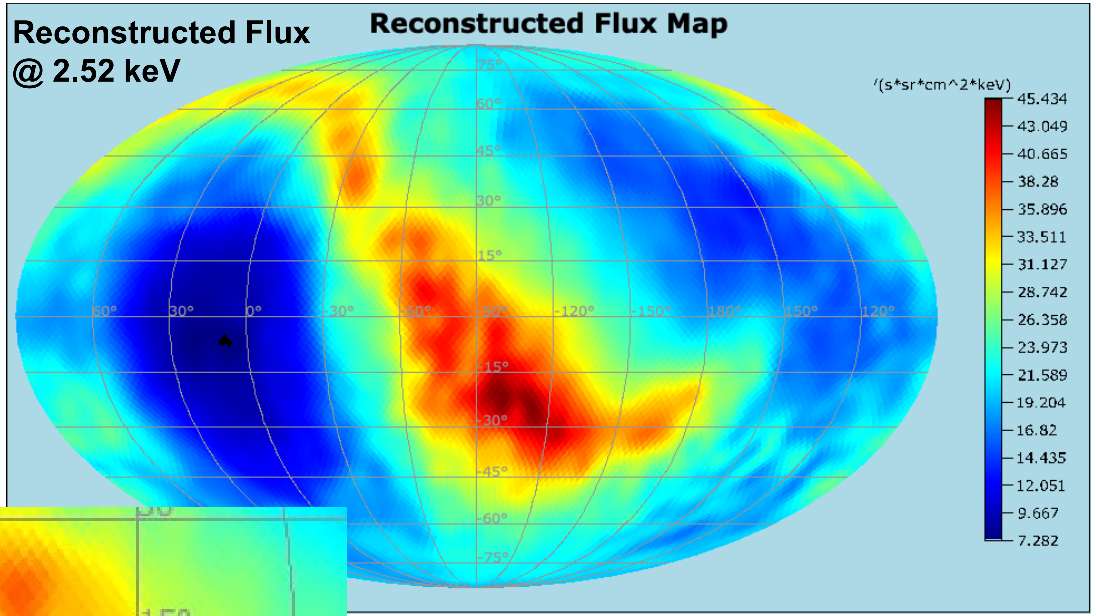


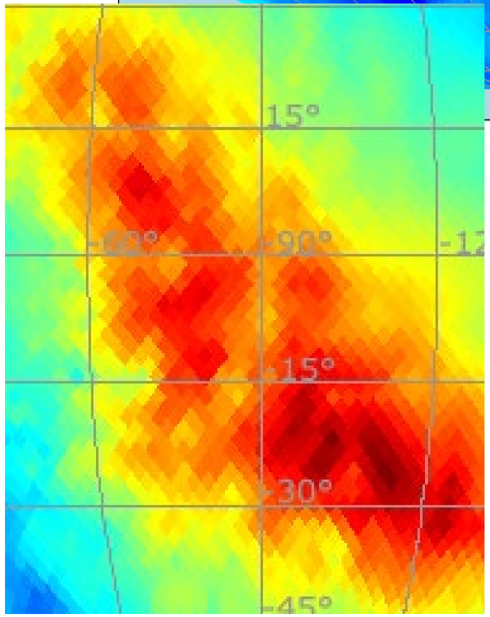


* Figures on right count time if any energy channel had a good time (Overly Optimistic)

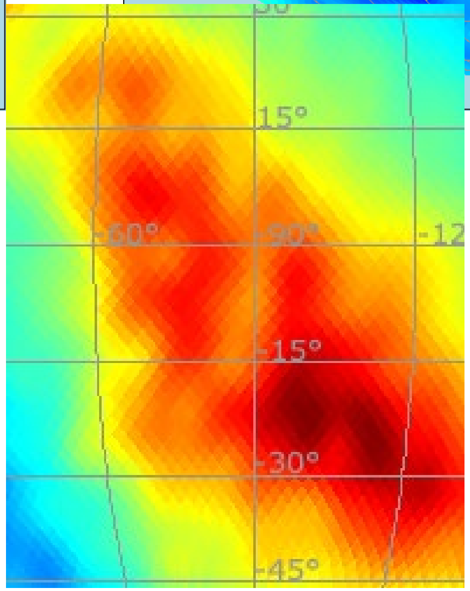
Flux Reconstruction – Hi90; 6 Month Map

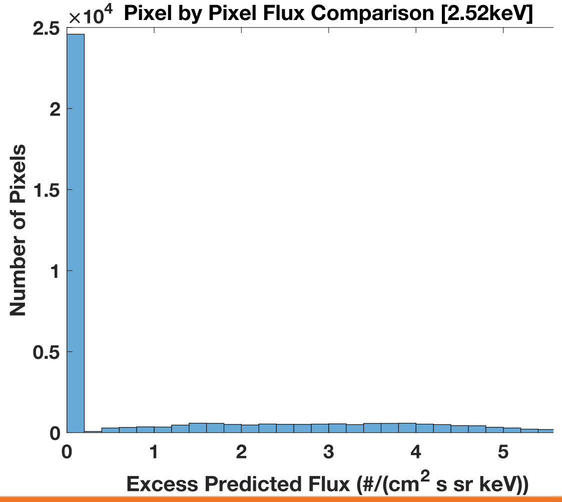




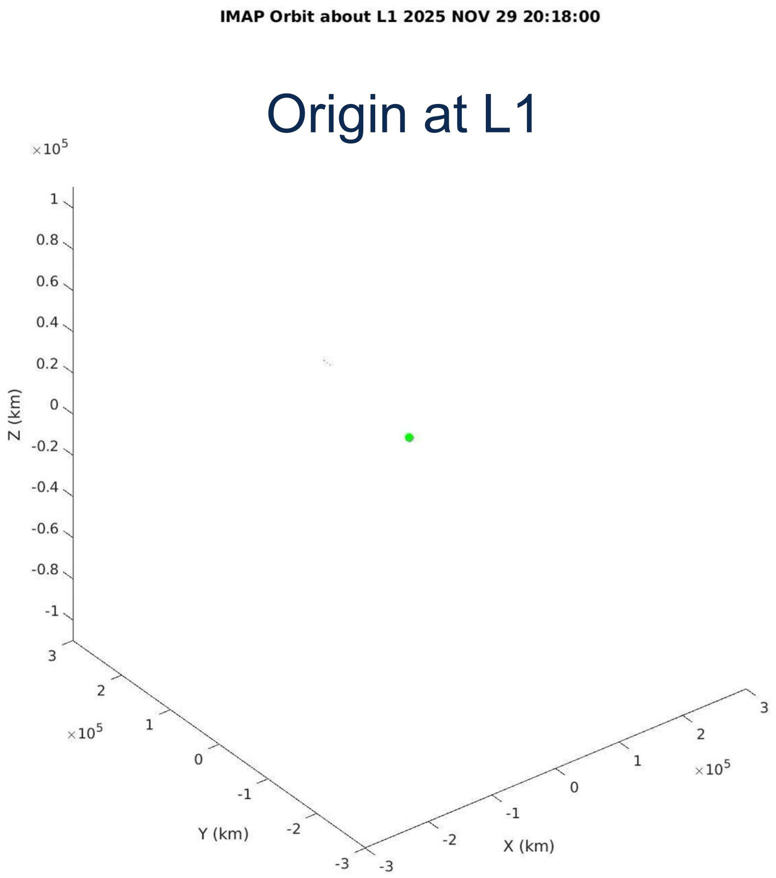


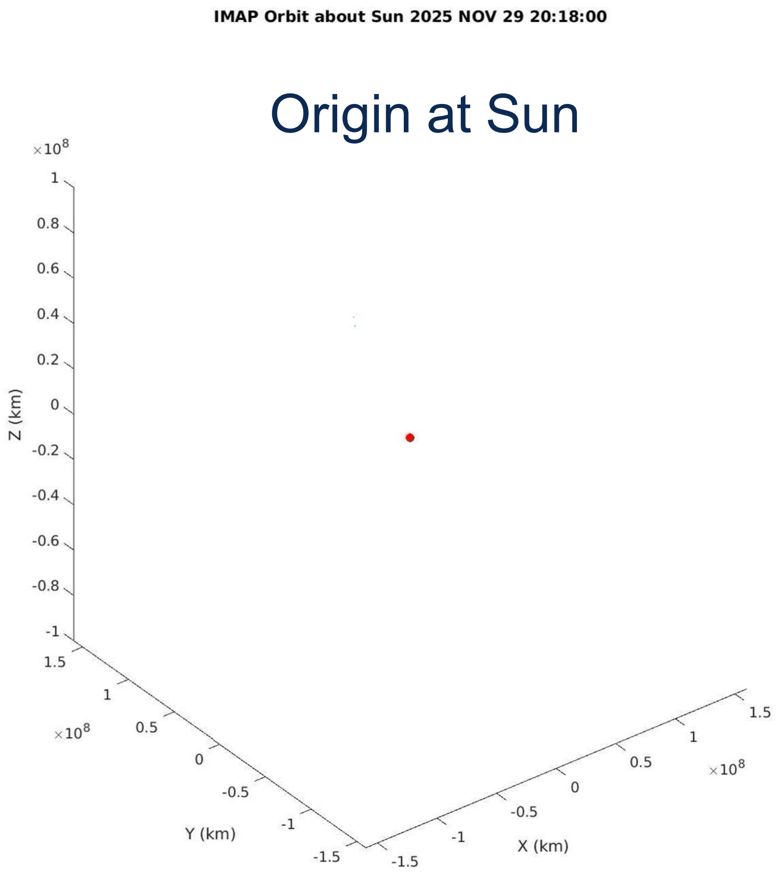
* Tessellation is HEALPix and not a standard product that will come from the SOC
* Map resolution is ~1.8 x 1.8 deg
* No Poisson stats used





IMAP Orbit with Repoint (bad) Times

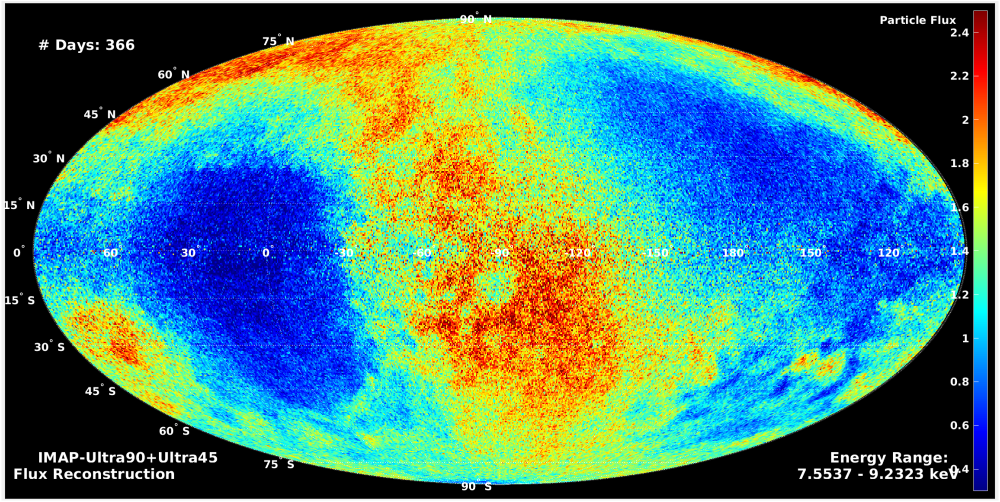




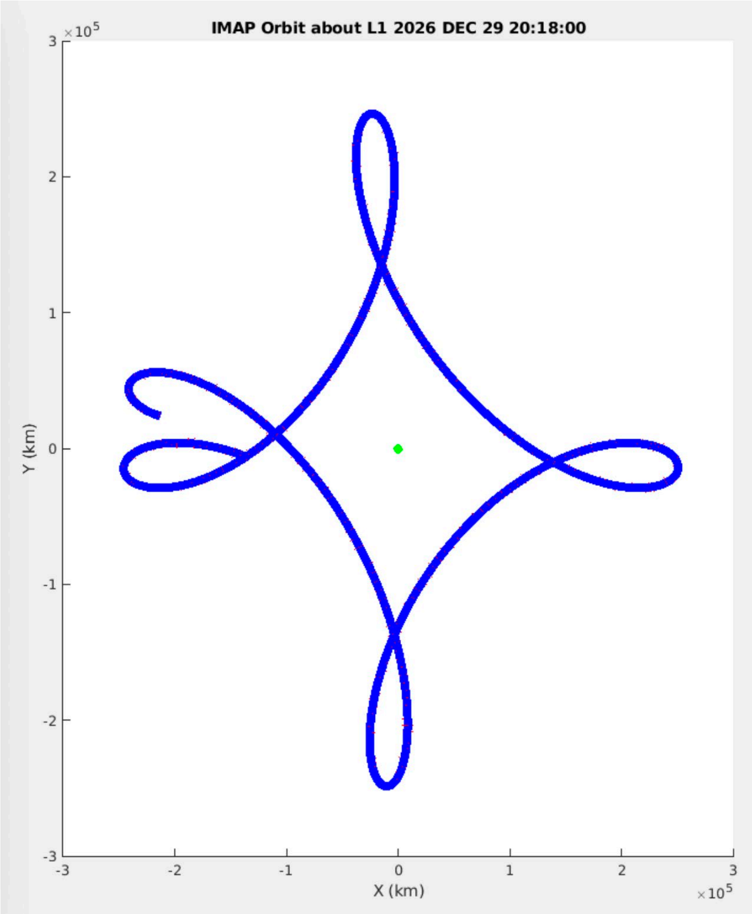
- Time to “science start” is about 3.5 months for L1OI from launch + checkout time
- Videos on left show orbit about L1 (left) and the Sun (right) in Ecliptic coordinates at approximate “science start” time based on recent launch pushback (July 2025)
  - Orbit is based on previous trajectory assuming April 2025 launch
- Small red spikes assume repointing of ~34 minutes per repoint

Overview

- Quick Overview of IMAP's Mission
- Overview of Energetic Neutral Atom (ENA) Imagers
- Overview of Software Framework used for Modeling
- Forward Modeling Approach
- IBEX vs IMAP Predicted Performance
- Summary



Ultra 90+45 Combined Flux Reconstruction Map



1 Year IMAP Orbit with origin at Sun-Earth L1

Instrument Sensitivities

Lo

IBEX

Table 3 $G\Delta E/E$ for the IBEX-Lo sensor, determined from calibration

Energy Step	Center Energy (eV)	$G\Delta E/E$ for any double coincidence hydrogen (cm^2 sr eV/eV)	$G\Delta E/E$ for triple coincidence hydrogen (cm^2 sr eV/eV)
1	14	7.5×10^{-5}	2.7×10^{-5}
2	27	1.5×10^{-4}	5.3×10^{-5}
3	52	2.2×10^{-4}	8.1×10^{-5}
4	102	2.5×10^{-4}	9.1×10^{-5}
5	197	2.5×10^{-4}	9.0×10^{-5}
6	451	2.9×10^{-4}	1.0×10^{-4}
7	908	5.4×10^{-4}	1.9×10^{-4}
8	1903	7.6×10^{-4}	2.7×10^{-4}

IMAP

i	E Center [keV]	GF Triple [cm^2sr keV/keV]
1	0.015	7.29E-06
2	0.029	1.41E-05
3	0.055	2.17E-05
4	0.11	2.43E-05
5	0.209	2.41E-05
6	0.439	2.82E-05
7	0.872	5.23E-05
8	1.821	7.41E-05

Hi

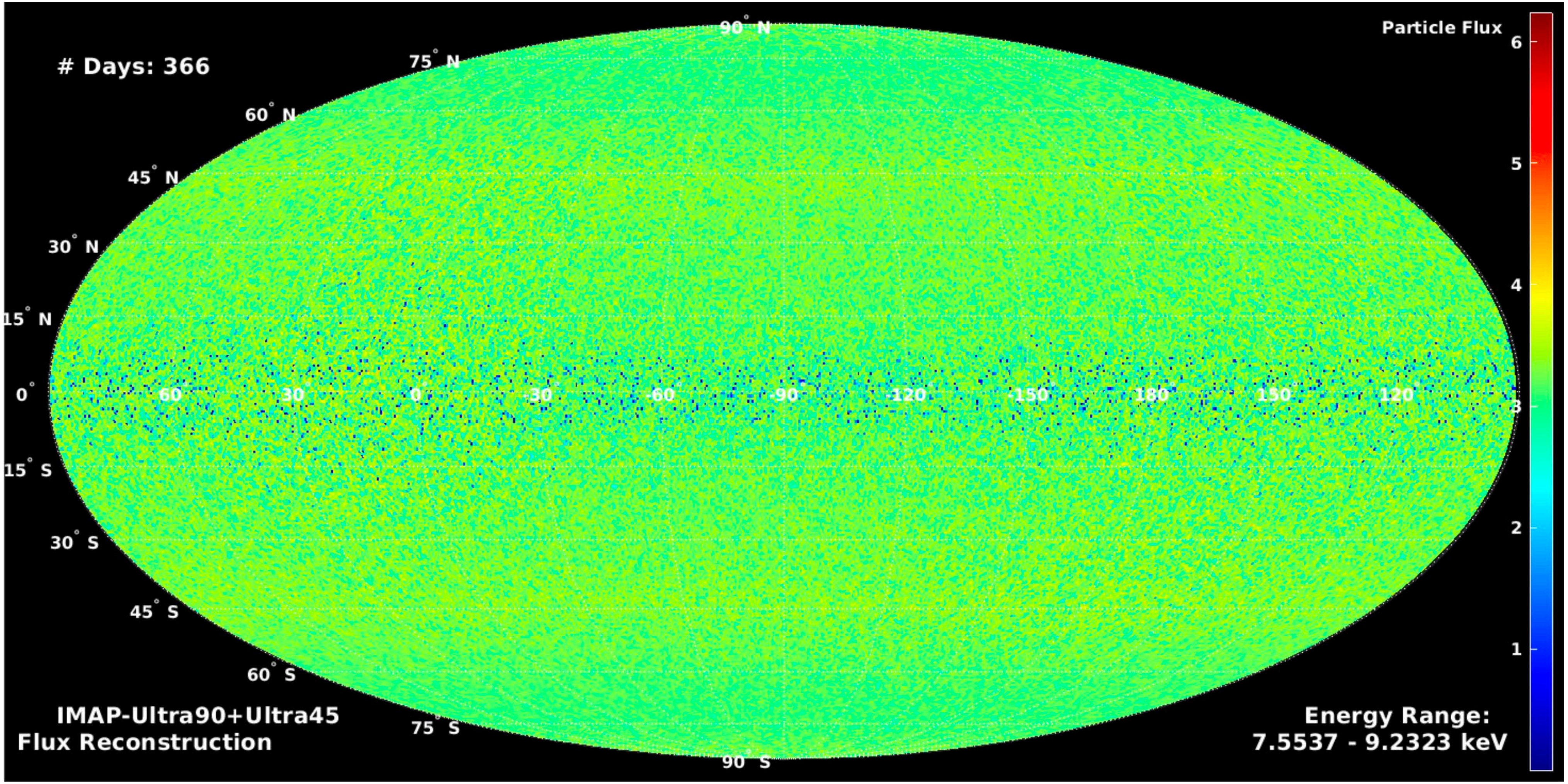
IBEX

ESA step	G^E, double coincidence: Long AB + Long BC + Qual(Not_C) AC	G^E, triple coincidence: Qual(Not_C) ABC
1	0.00060	0.00013
2	0.0016	0.00041
3	0.0028	0.00075
4	0.0053	0.0013
5	0.0086	0.0024
6	0.015	0.0045

IMAP

Predicted ESA Passbands				IMAP G_E [cm^2 sr eV/eV] (predicted)				IMAP G_E [cm^2 sr eV/eV] (measured)			
Energy Step	E_{-HW} [keV]	E_0 [keV]	E_{+HW} [keV]	Doubles	Triples	Quad	Total	Doubles	Triples	Quad	Total
1	0.41	0.51	0.62	0.00020	0.00011	0.00003	0.00034				
2	0.61	0.76	0.91	0.00042	0.00023	0.00006	0.00071				
3	0.91	1.14	1.37	0.00080	0.00042	0.00010	0.00132	0.00069	0.00045	0.00022	0.00135
4	1.34	1.69	2.05	0.00130	0.00075	0.00011	0.00216				
5	2.00	2.51	3.02	0.00202	0.00108	0.00026	0.00337				
6	2.90	3.74	4.57	0.00300	0.00163	0.00041	0.00504	0.0026	0.0020	0.0010	0.0057
7	4.37	5.58	6.79	0.00457	0.00266	0.00071	0.0078				
8	6.48	8.35	10.22	0.0075	0.0052	0.0017	0.014	0.0069	0.0059	0.0037	0.017
9	9.94	12.76	15.58	0.0122	0.0094	0.0034	0.025	0.0085	0.0080	0.0057	0.022

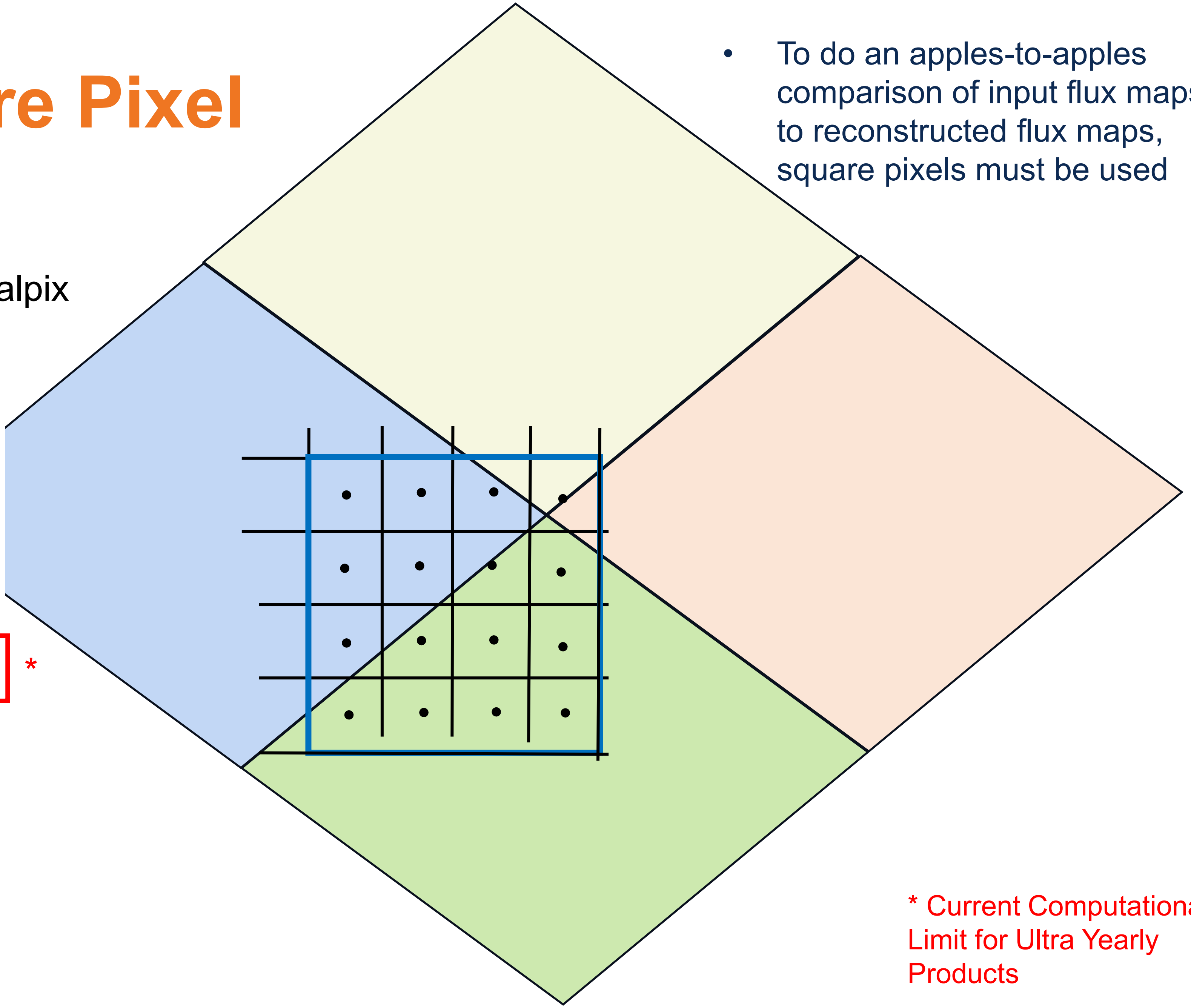
Positional Uncertainty due to Foil Scattering



HEALPix to Square Pixel Binning Example

Ex: square pixel on intersections of healpix

HEALPix Pixel Information				
Res	NSide	NPixels	Mean Spacing (deg)	Area (sterad)
0	1	12	58.6323	$1.0471976 \times 10^{+00}$
1	2	48	29.3162	$2.6179939 \times 10^{-01}$
2	4	192	14.6581	$6.5449847 \times 10^{-02}$
3	8	768	7.3290	$1.6362462 \times 10^{-02}$
4	16	3072	3.6645	$4.0906154 \times 10^{-03}$ *
5	32	12288	1.8323	$1.0226539 \times 10^{-03}$
6	64	49152	0.9161	$2.5566346 \times 10^{-04}$
7	128	196608	0.4581	$6.3915866 \times 10^{-05}$
8	256	786432	0.2290	$1.5978967 \times 10^{-05}$
9	512	3145728	0.1145	$3.9947416 \times 10^{-06}$
10	1024	12582912	0.0573	$9.9868541 \times 10^{-07}$

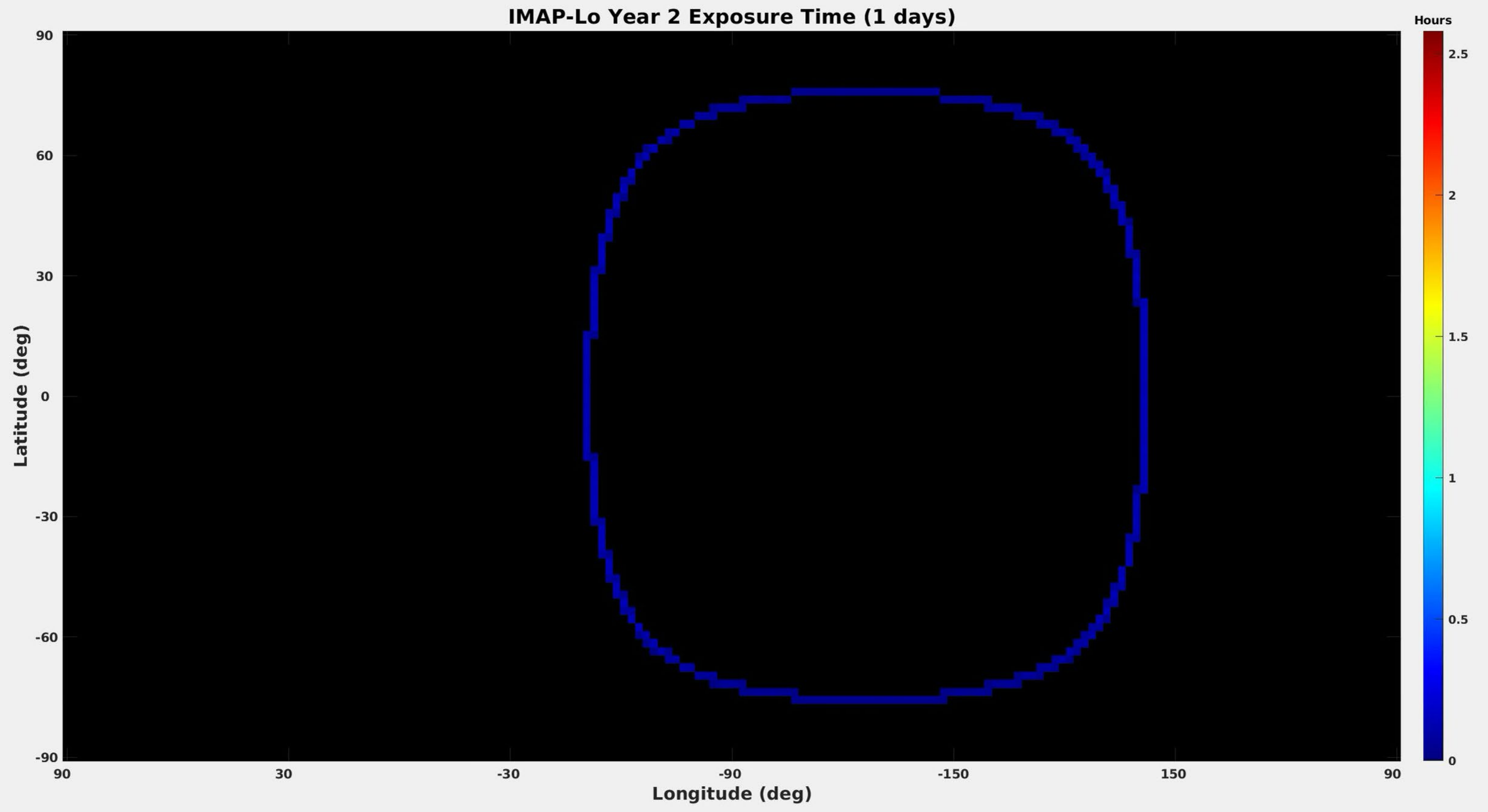


- To do an apples-to-apples comparison of input flux maps to reconstructed flux maps, square pixels must be used

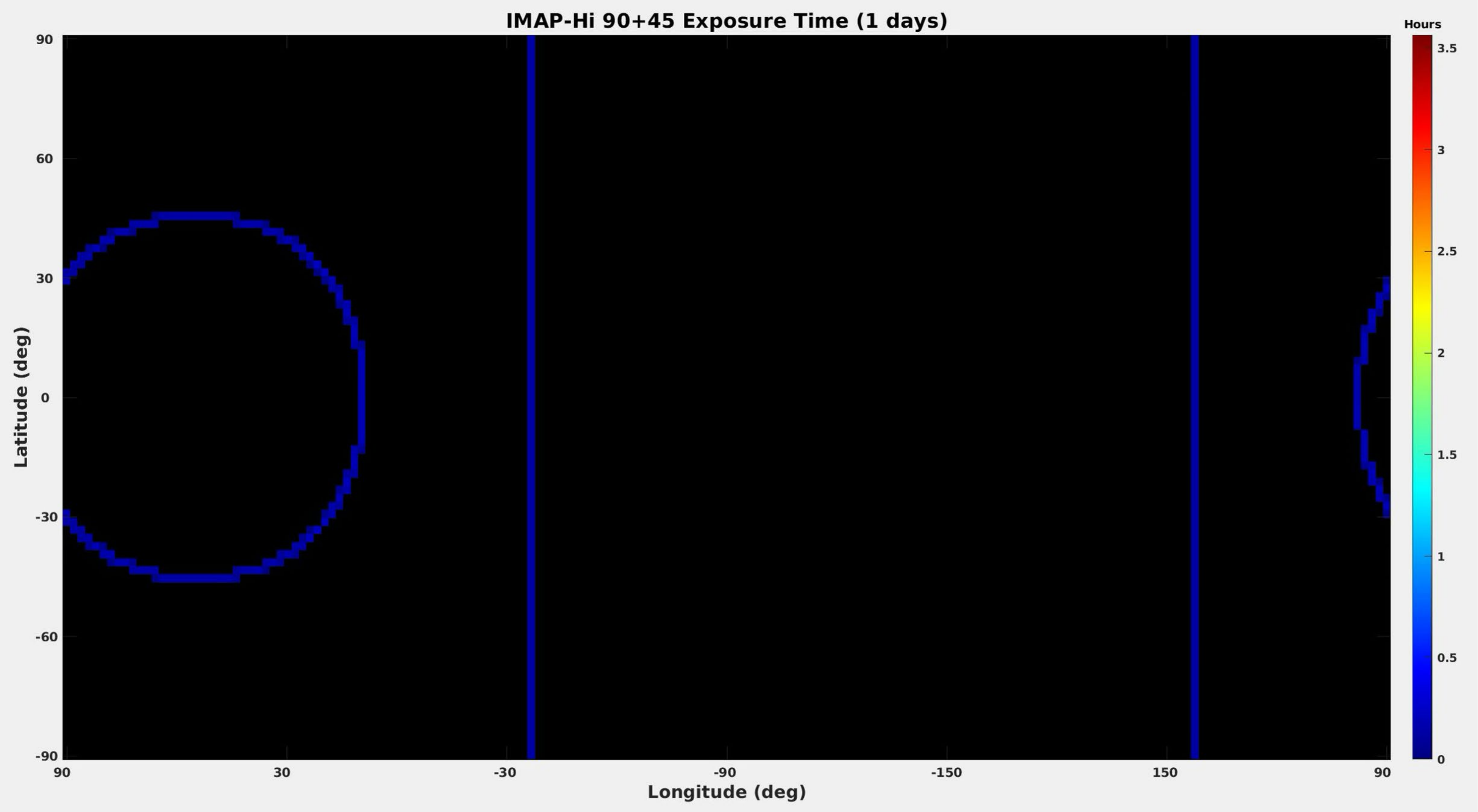
* Current Computational Limit for Ultra Yearly Products

IMAP-Lo Exposure Time (Year 2) 2x2 deg

- Earlier in the year, focus is on higher latitudes
- As time moves forward, Lo pivots towards the ecliptic to focus more on ISN
- Will be some gaps in polar coverage on 2x2 pixel maps



IMAP-Hi90 and Hi45 Exposure Time 2x2 deg



- Will be ~45 days before any sensor overlap in exposure times
- ~160 days before Hi-45 touches the nose
- Times here are again summed over all energy ranges
- IMAP-Hi has 9 ESA steps as opposed to IBEX's 5/6