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EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

HST as a particle detector or Geophysics with HST

Susana Deustua

A collaboration to understand Earth's geomagnetic field at ~500 km above the surface.

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Geoffrey Cromwell (USGS)

With many thanks to Chris Long (STSCI).

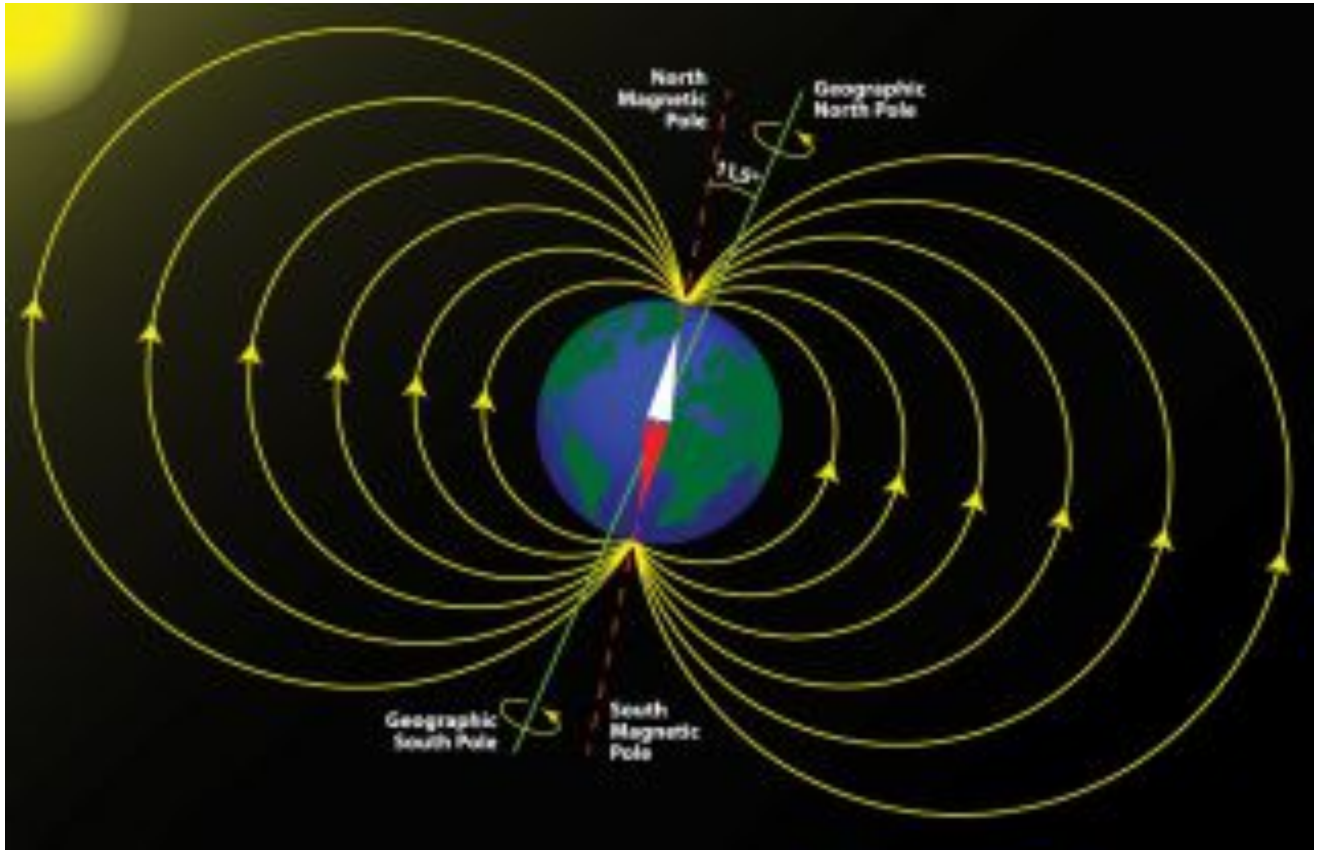
The question:

Does the external geomagnetic field vary in low earth orbit?

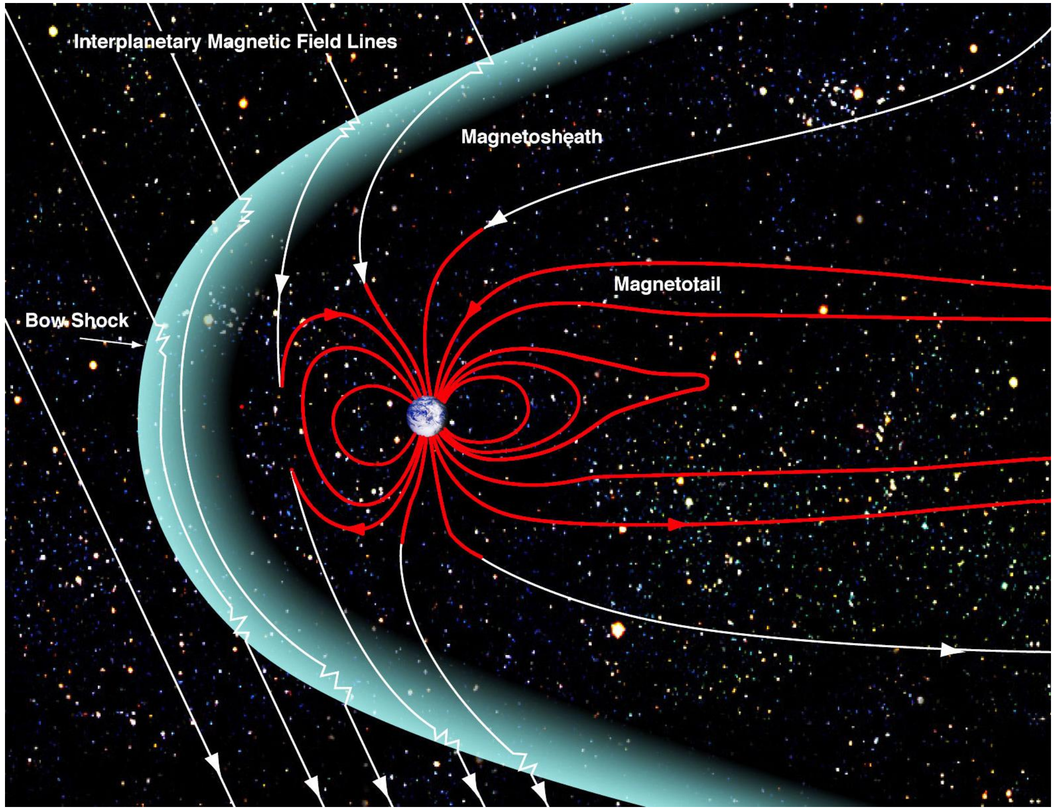
The Terrestrial Magnetic Field

A. Internal magnetic field (at and below the surface)

- Geodynamo, magnetic dipole M
- Geographic pole ≠ magnetic pole
- Secular variations in magnetic field properties
    - Geophysical observatories



The Terrestrial Magnetic Field



B. External magnetic field (above the surface)
   - continually changing due to the solar wind.
   - space weather –
     - size, shape, shielding of atmosphere
     - communication disruptions
     - satellite drag

The Project

The question:

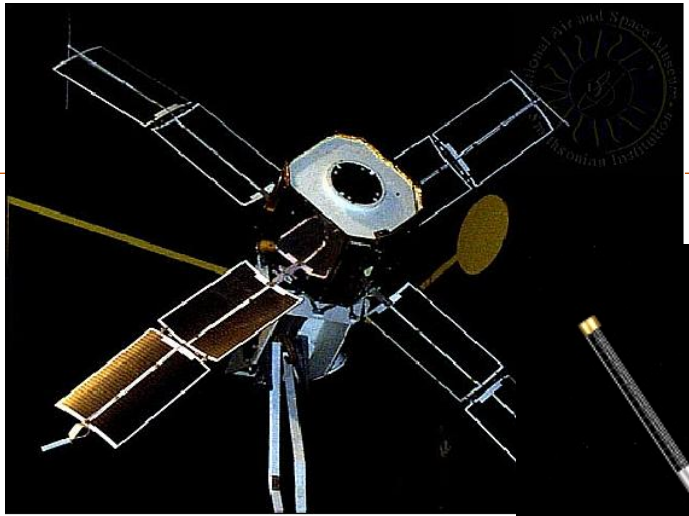
Does the external geomagnetic field vary in low earth orbit?

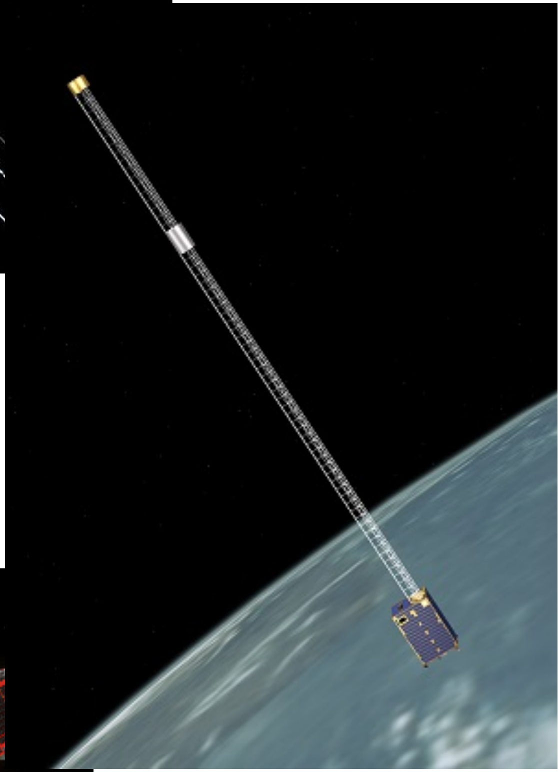
Why use Hubble Space Telescope?

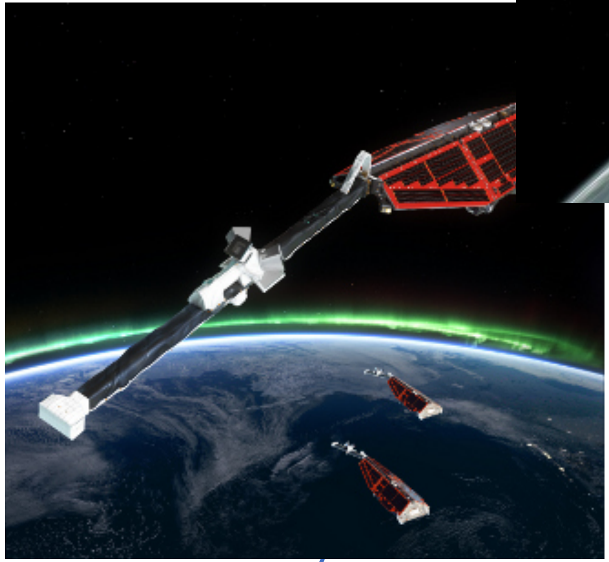
1. Long baseline
   - HST has been in operation ~30 years, covering almost 3 solar cycles

Geophysics Satellites

Satelilte	Goal	Operation	Perigee/Apogee (km)
MagSat (APL)	H	1979 – 1980	Polar, 350/578
Orsted (Danish)	Scalar & vector, particles	1999 – 2014	Polar 632/833
CHAMP (	Scalar & vector, gravity	2000 - 2010	Polar, 454
SAC-C (argentina)	Scalar & vector	2000-2013	Polar, 680/700
PAMELA	CRs	2006 - 2016	Polar, 350/610
AMS-02 (US)	Antimatter, particles	2011- present	ISS, 350
SWARM (A,B,C) (ESA)	Scalar & vector,	2013- present	Polar, 460/530







The Project

The question:

Does the external geomagnetic field vary in low earth orbit?

Why use Hubble Space Telescope?

1. Long baseline
   - HST has been in operation ~30 years, covering almost 3 solar cycles

How to do this:

Easy! Find, characterize and count each cosmic ray in every image

- cosmic rays are charged particles
- charged particles are bound to magnetic fields
- therefore cosmic ray observables are affected by changes in magnetic field

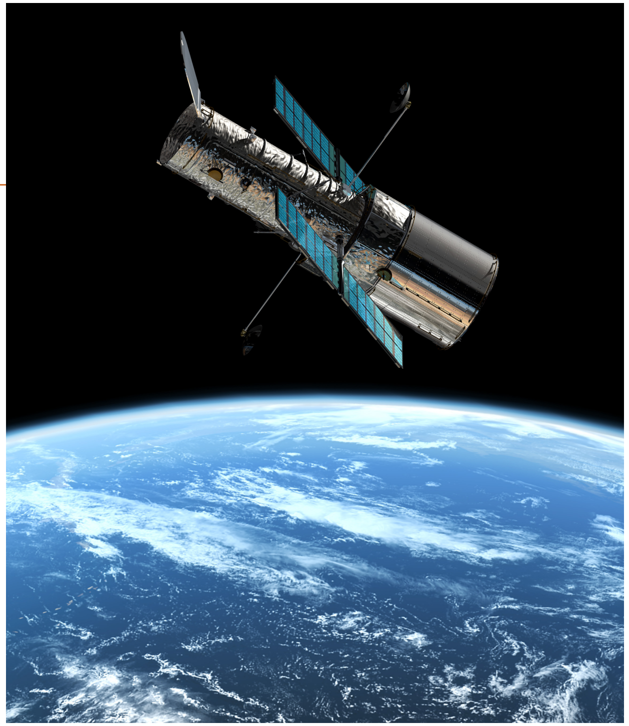
The Project

HST Archival Proposal #14587 (Co-PI: S. Deustua and G. Tancredi)

Geophysics with Hubble Space Telescope to probe the geomagnetic field in the orbital environment of HST using cosmic ray detections in active and legacy instruments

160,000 orbit program!

Hubble Space Telescope



- 2.4 m diameter primary mirror
- Wavelength range: 1000 Å to 2.5 micrometers
- Launched in 1990
- Altitude ~ 550 km above the sur
- Inclination = 28.5 degrees
- Orbital period = 95 minutes
- Servicing missions: 4 (5 visits)

Hubble Space Telescope Instruments

Active Instruments

- FGS
- STIS(1997): 1 CCD, NUV-MAMA, FUV-MAMA
- ACS (2002): WFC(2 CCDs), HRC(1 CCD), SBC (MCP)
- COS (2009): MCP, MAMA
- WFC3 (2009): UVIS (2 CCDs), IR (1 HgCdTe)

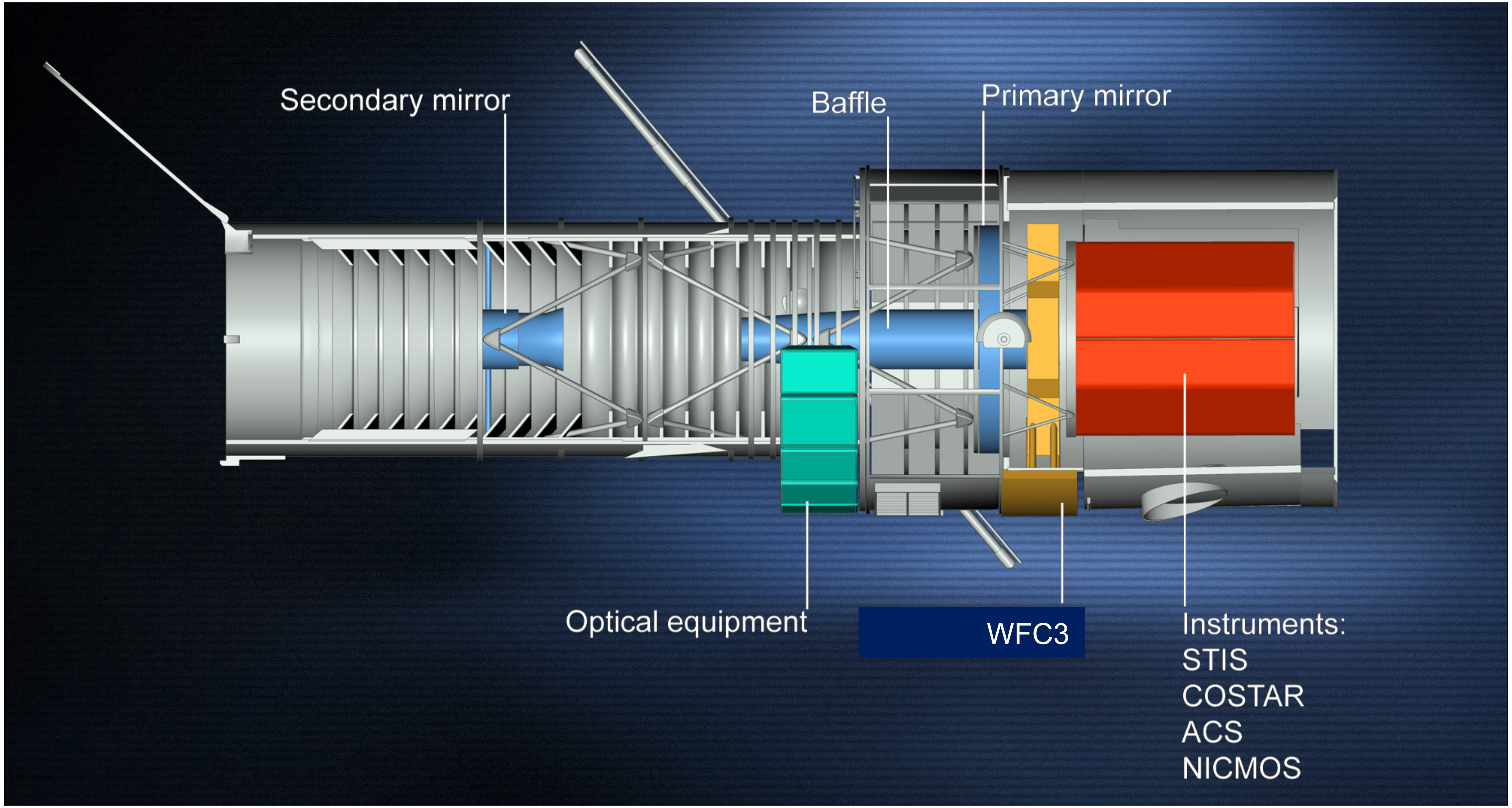
Inactive Instruments

- NICMOS (1997-2008) 3 HgCdTe

Legacy Instruments

- WFPC2 (1993-2009)– 4 CCDs
- WF/PC (1990-1993) – 8 CCDs
- GHRS (1990-1997)
- FOC 1990-2002
- FOS (1990-1997)
- HSP (1990-1993)

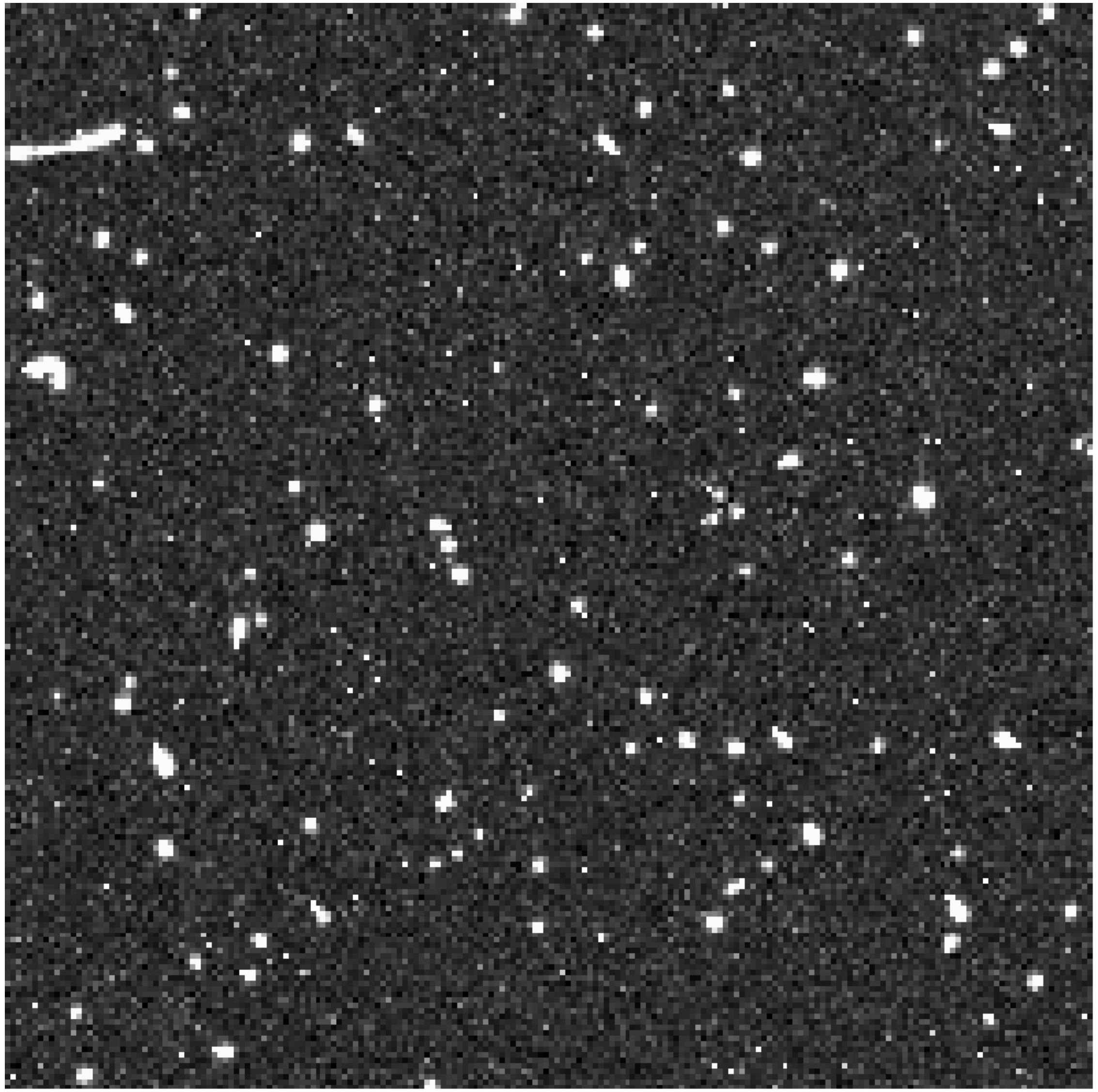
Hubble Telescope Layout



In the beginning…

Start with dark images (shutter closed)

- Easy to find and identify cosmic rays
- Remove hot, unstable, dead pixels



Example of a dark image from WFC3 /UVIS camera subarray

In the beginning…

1. Pilot study using PyRAF, LACOSMIC
   - 4 years of WFC3/UVIS darks
   - easier to find CRs when not polluted by light from actual astrophysical sources.

showed numbers, shape, energy deposited can be recovered, stored in database

Then …

2. Moving to python (and the basis for Sergio’s Masters Thesis in Computing)

- MAST copied 100,000 images onto 5 hard disks for us
- Painfully uploaded onto the Azure Platform
- Python code adapted from PyRAF scripts
- Image based, bad/hot pixels confuse CRs
- All WFC3/UVIS, ACS/WFC images

… and now

3. Improvements

- Exploit DQ array information – bad, hot, warm, unstable pixels
- Active instrument data available on AWS (Amazon Web Services)
  - no painful I/O
- Python 3.5
- Completely parallelized
- Fully documented using Read the Docs
- Data stored in HDF5 files (extracted data can be very large, room for improvement)
- Speed
  - 2.1 TB -> 14 hrs AWS vs. 3 days local runtime

Challenges:

- WFPC2 ≠ ACS/WFC, WFC3/UVIS
- HgCdTe ≠ CCD

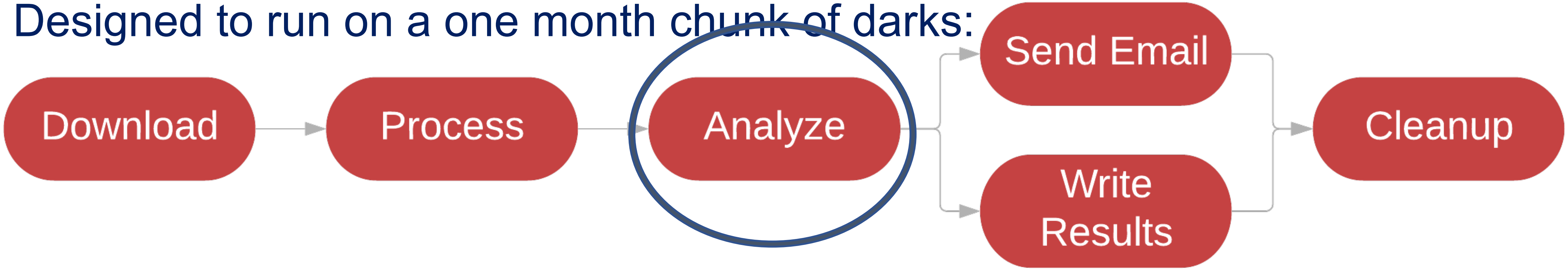
… and now

HSTcosmicrays

- Written entirely in python (requires v3.5 or higher) ☺
- Completely parallelized! ☺ ☺
- AWS friendly! ☺ ☺ ☺
- Fully documented using Read the Docs! ☺^{4}
- Data stored in HDF5 files (extracted data can be very large, room for improvement)

<u>Analyzing ACS/WFC (2.1TB)</u>
AWS Runtime: 14hrs
Local Runtime: 3 days

Designed to run on a one month chunk of darks:



… and now

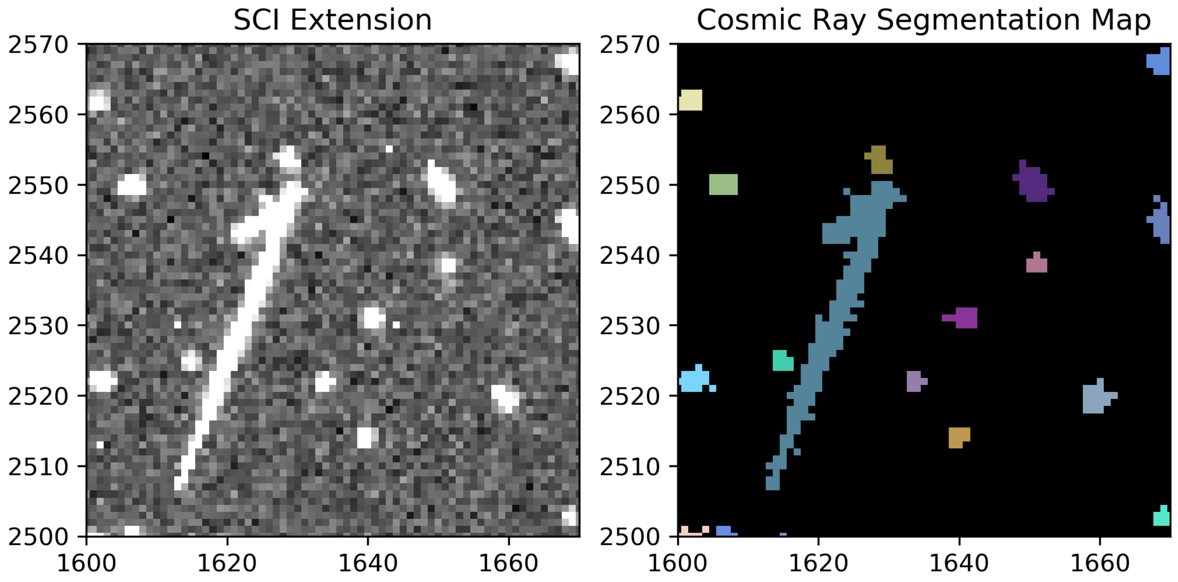
- Run connected-component labeling algorithm using the 8 connectivity matrix
  - Results in unique labels for each individual cosmic ray and the pixel it affects

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & p & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

- Cosmic rays are identified using either the SCI or DQ extensions

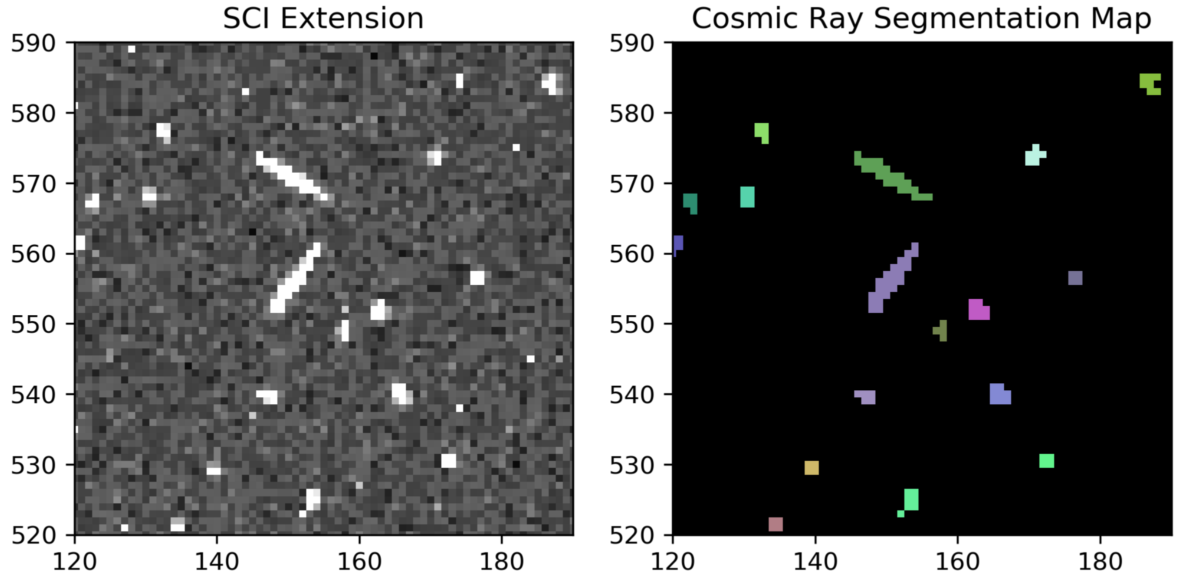
DQ (ACS, STIS, WFC3)

Run labeling on all pixels marked with the DQ bit flag used by the instrument to identify cosmic rays



SCI (WFPC2)

Run labeling on binary image of all pixels that are 5σ above the background



The Imagers

Continuous coverage from 1994 to present!

→ Complete coverage of Solar Cycle 23 (1996 – 2008)

→ Complete coverage (so far) of Solar Cycle 24 (2008 –)

Instrument	Detector Size (cm^2)	Detector Thickness (μm)	Operational Period
WFPC2	5.76	~ 10	1994 to 2009
STIS/CCD	4.624	13.24 – 14.83	1997 to 2004, 2009 to Present
ACS/HRC	4.624	12.49 – 16.03	2002 to 2007
ACS/WFC	37.748	12.60 – 17.10	2002 to 2007, 2009 to Present
WFC3/UVIS	37.804	13.50 – 18.00	2009 to Present

The Dataset

Instrument	Image Count	Data Volume (MB)	Total EXPTIME (hr)	Cosmic Ray Count
WFPC2	13,317	130,506.6	5,098	118,057,406
STIS/CCD	31,430	311,430	3,765	61,717,583
ACS/HRC	5,477	54,770	1,462	27,685,921
ACS/WFC	13,311	2,129,760	3,498	553,055,881
WFC3/UVIS	12,373	1,979,680	3,040	526,545,187
Totals	75,908	4,609,016	16,863	1,287,061,978

The Pipeline: Extracted Information

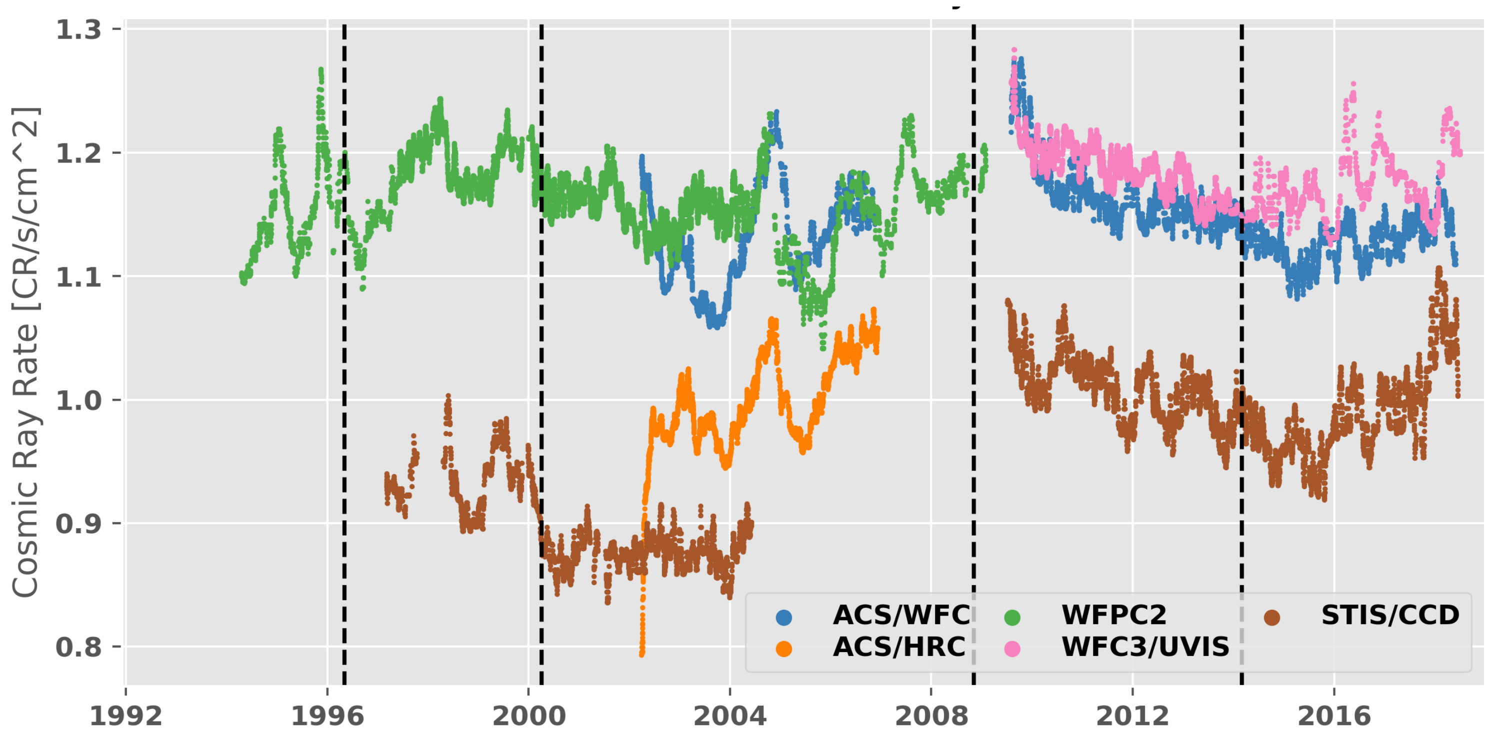
Image metadata

- Altitude
- Latitude
- Longitude
- Observation date
- Start of observation
- End of observation
- Total integration time
- WCS Information

Cosmic ray properties

- Total energy deposited [e^-]
- Cosmic ray rate [$CR/s/cm^2$]
- (x, y) positions of pixels affected by the cosmic ray
- Cosmic ray size in pixels
- Width of cosmic ray energy distribution
  - ”sigma size” ($FWHM/2\sqrt{2\ln 2}$)
- Shape of cosmic ray energy distribution
  - Symmetric or not

Results: Cosmic Ray Flux



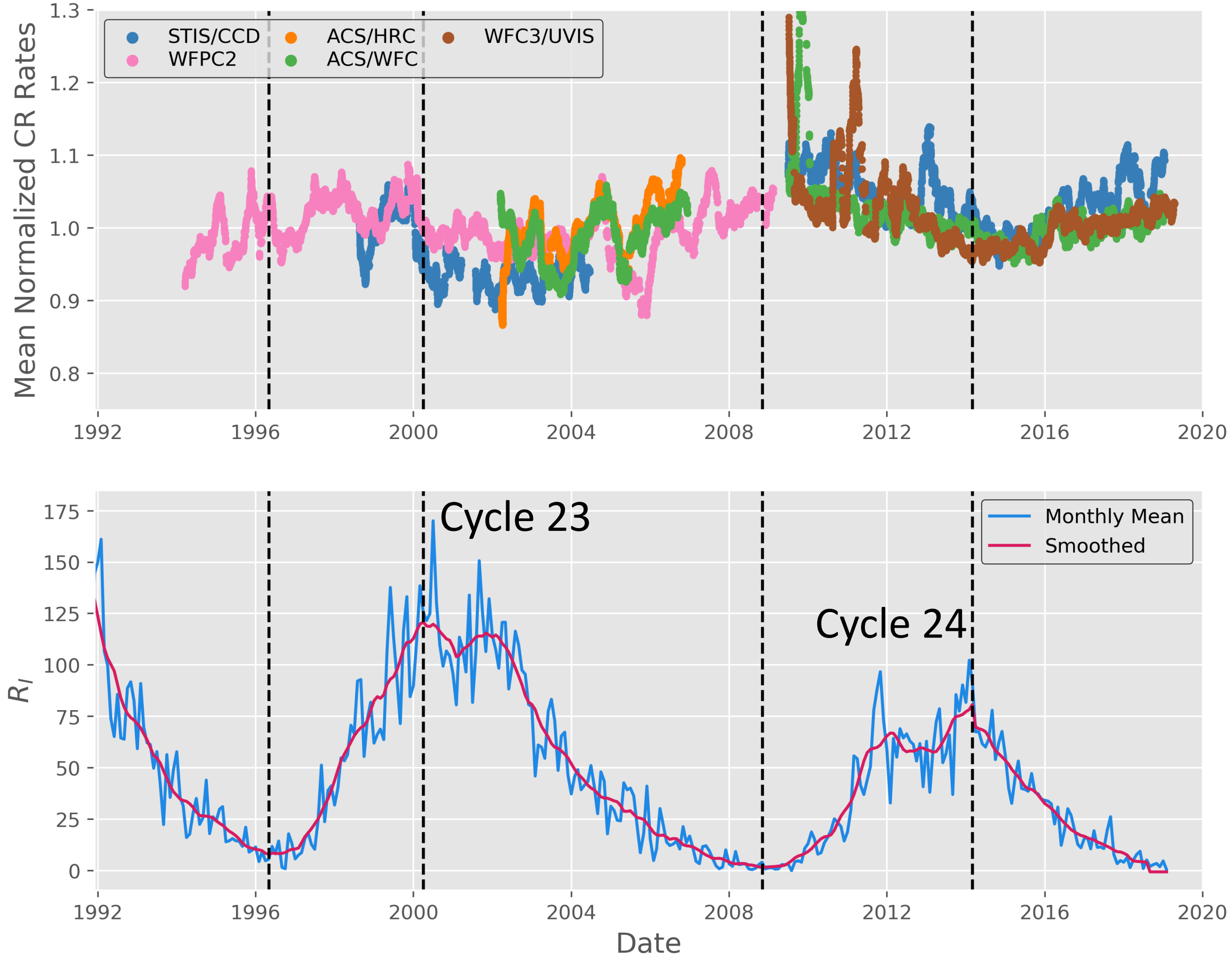
"Raw" CCD Cosmic ray rate (Number/sec/cm^2)

a) rates per instrument track

b) Good agreement between
- pre SM4 ACS/WFC & WFPC2
- post SM4 ACS/WFC & WFC3/UVIS

c) STIS/CCD and ACS/HRC rate levels are different
- Volume?
- CR threshold difference in DQ array?
- CCD thickness variation?

Results: Cosmic Ray Flux



- Normalized CR rates for the 5 CCD instruments, between ~1994 and the present, and solar activity (international sunspot number) during the same period.
- CR rate anti-correlated with solar activity

Solar Cycle No.	Peak	Min	Length years
24	2013	2019?	11?
23	2002	2009	11.6
22	1989	1996	10

Results: Cosmic Ray Incidence vs Time

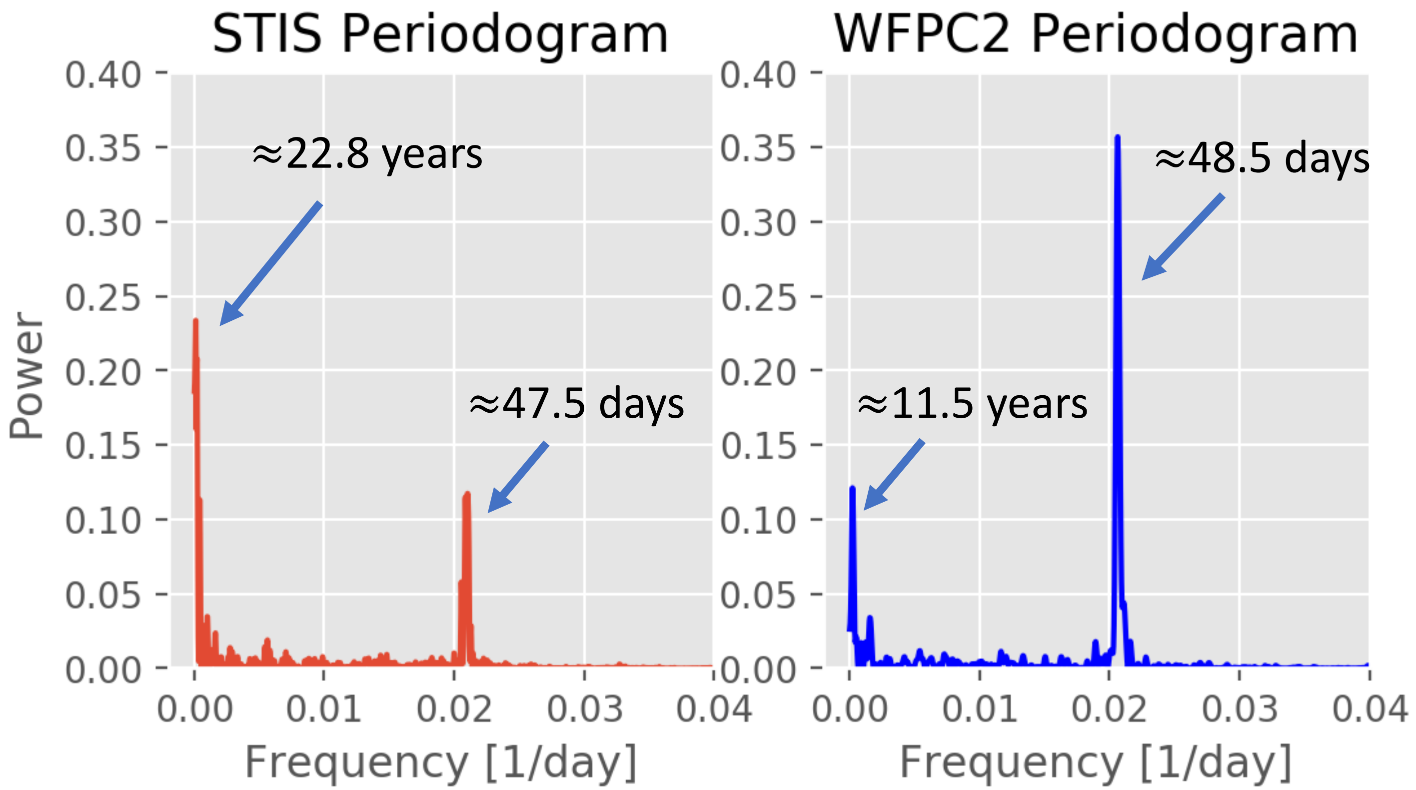
Spectral analysis reveals two peaks

Peak 1:

- Roughly corresponds to the 11 year cycle of solar activity

Peak 2:

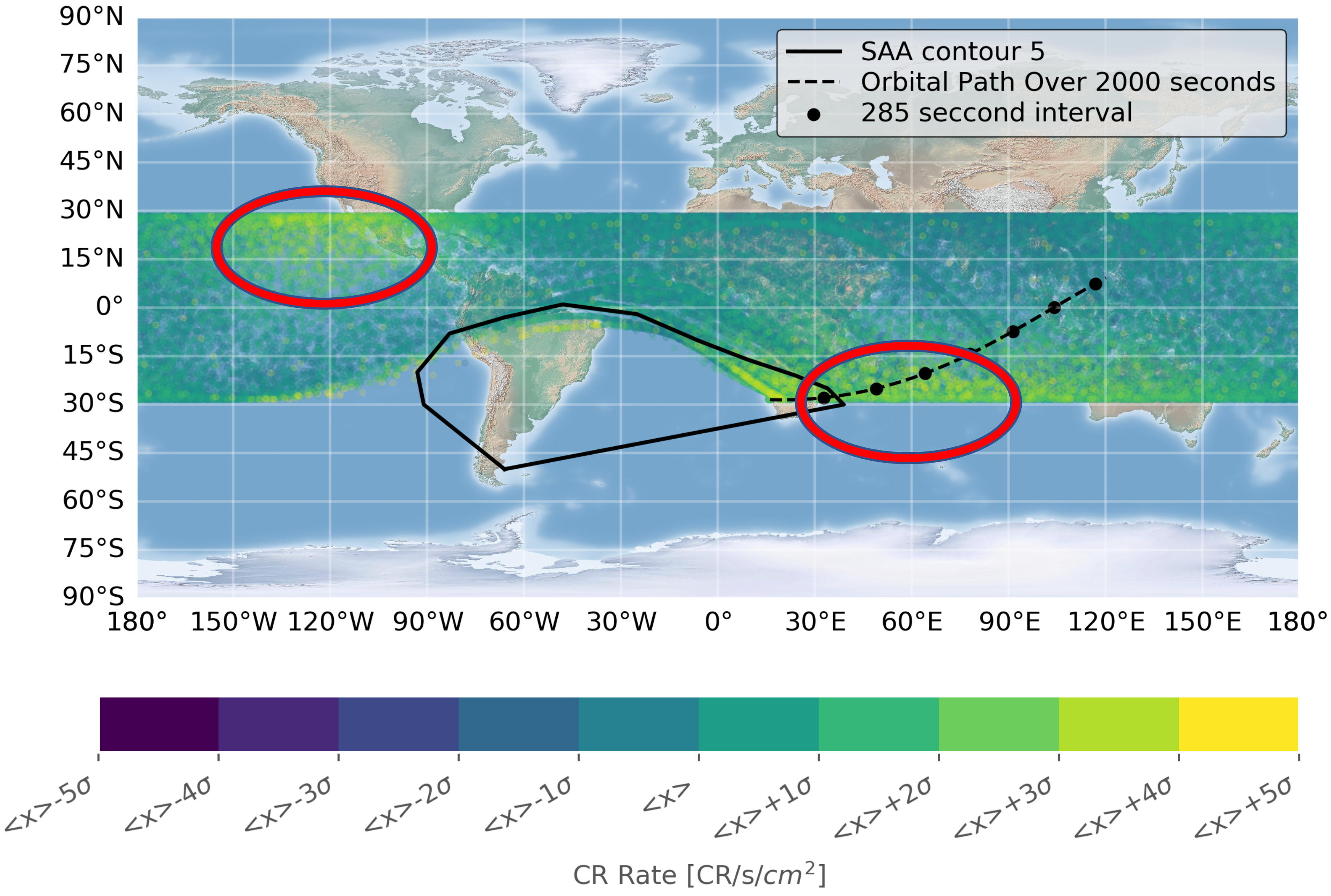
- Higher frequency signal that has a period of about 48 days
- progression of HST's orbital elements?
- Some other reason?



Results: Cosmic Ray Incidence vs Location

Deviation from the mean rate of all identified cosmic rays.

Two “hotspots” outside the SAA



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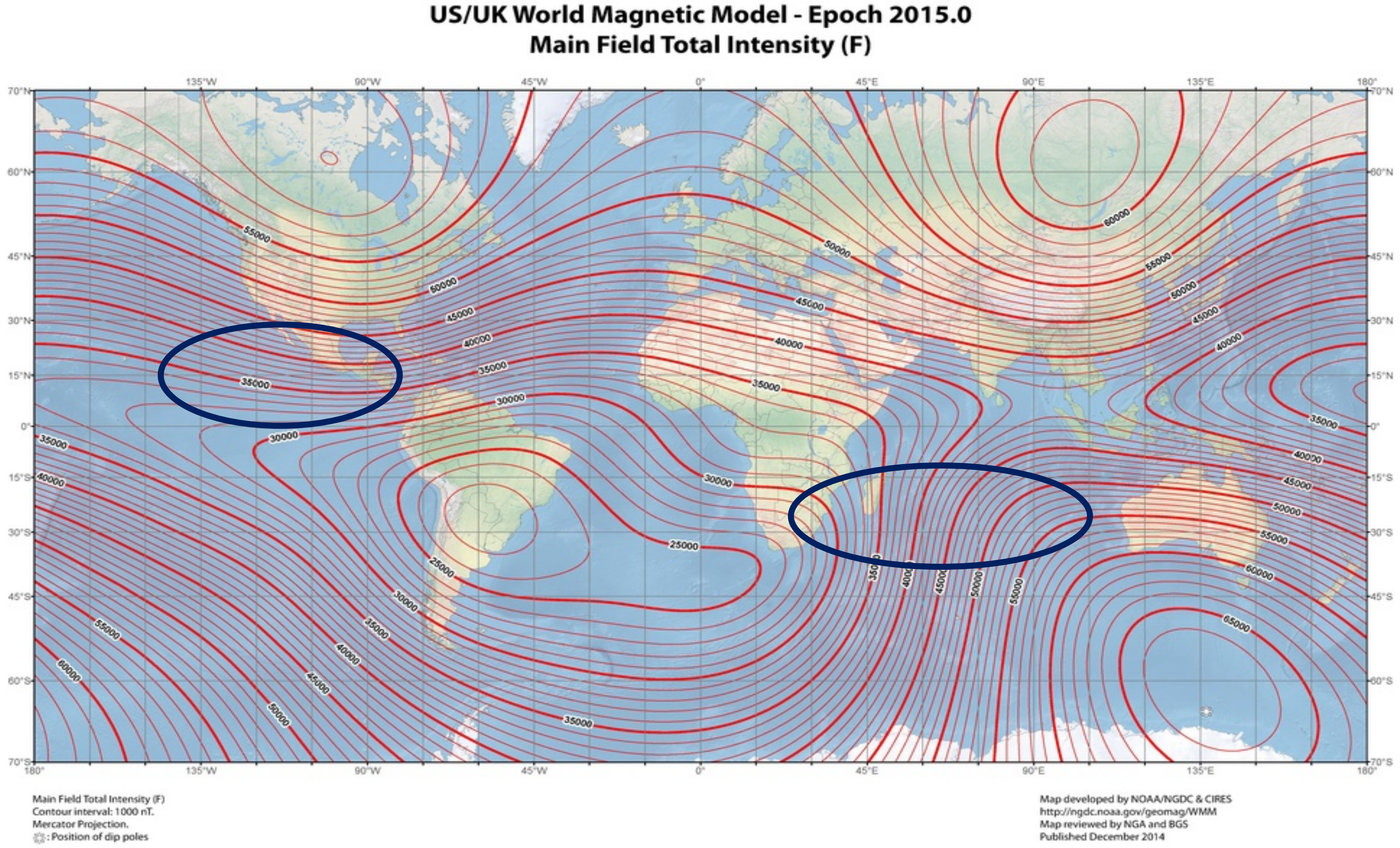
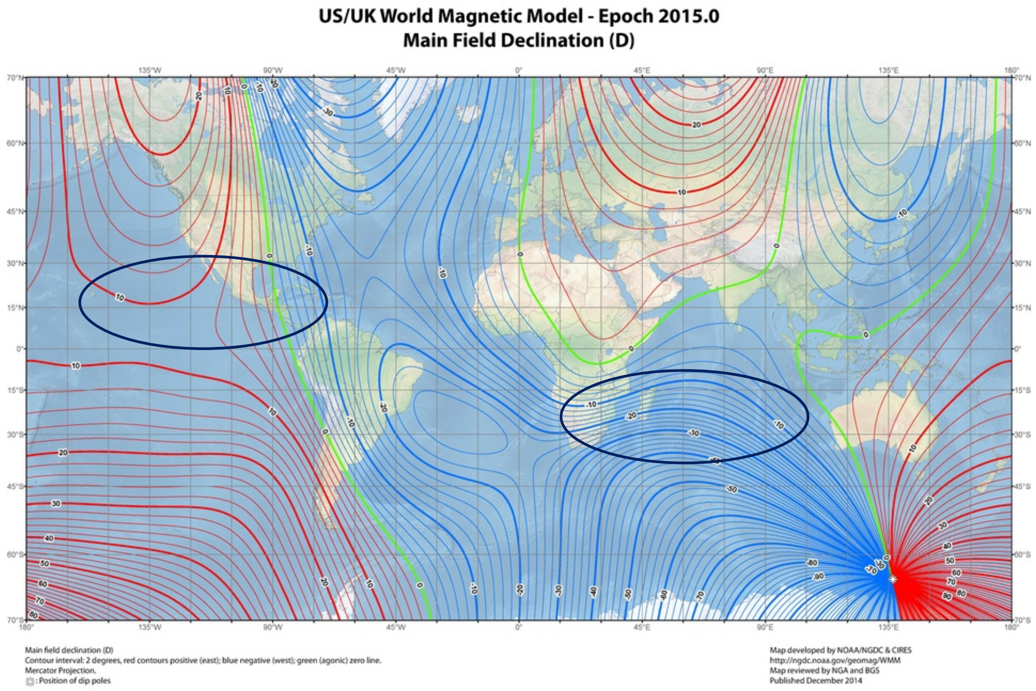
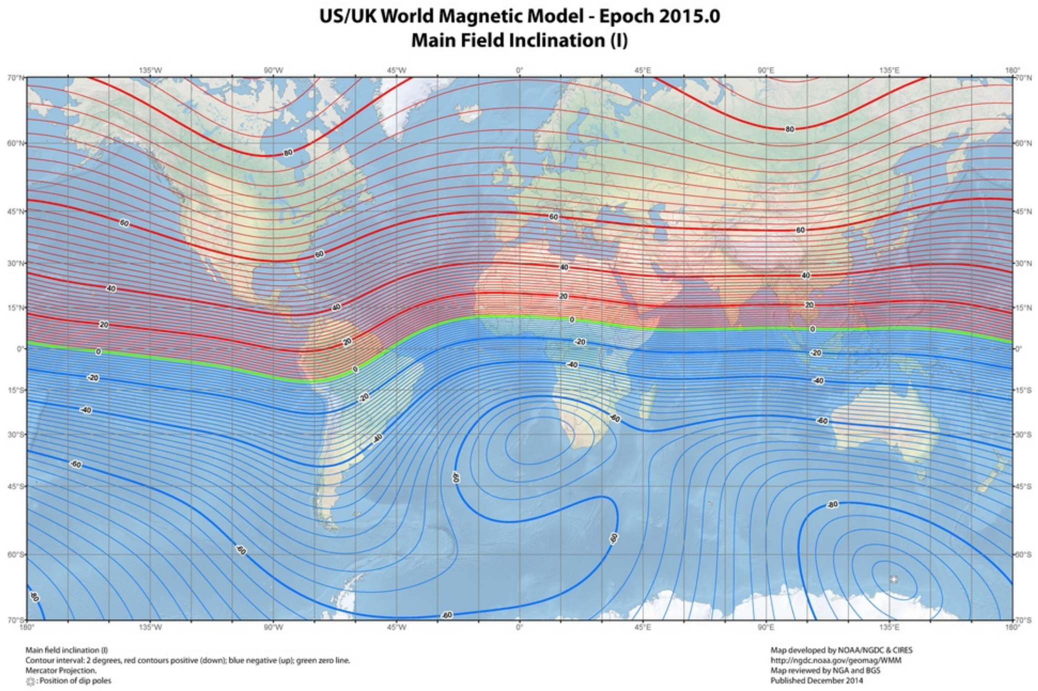
US/UK World Magnetic Model: Field Total Intensity



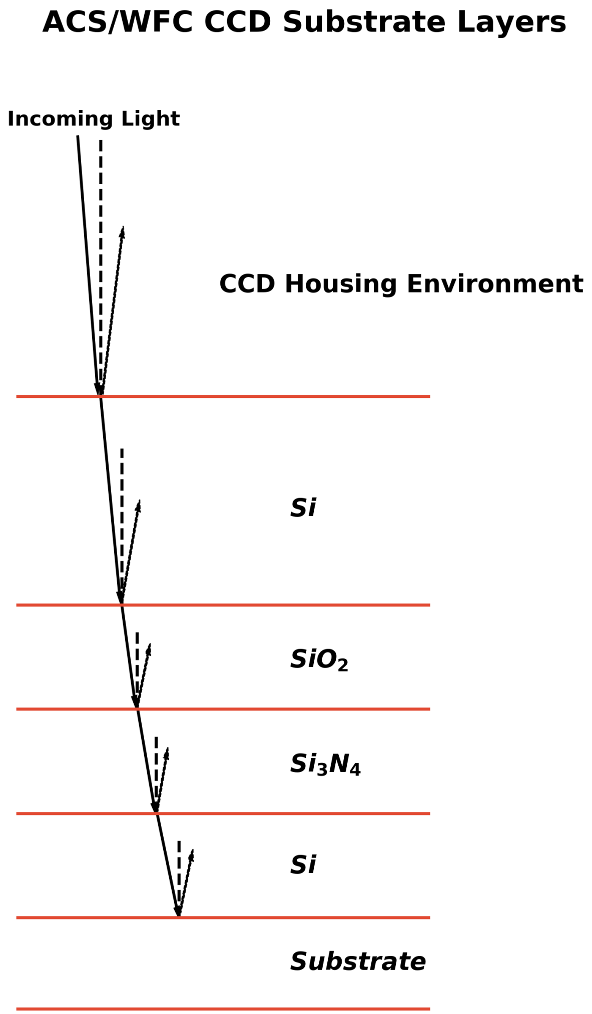
Magnetic Declination and Inclination

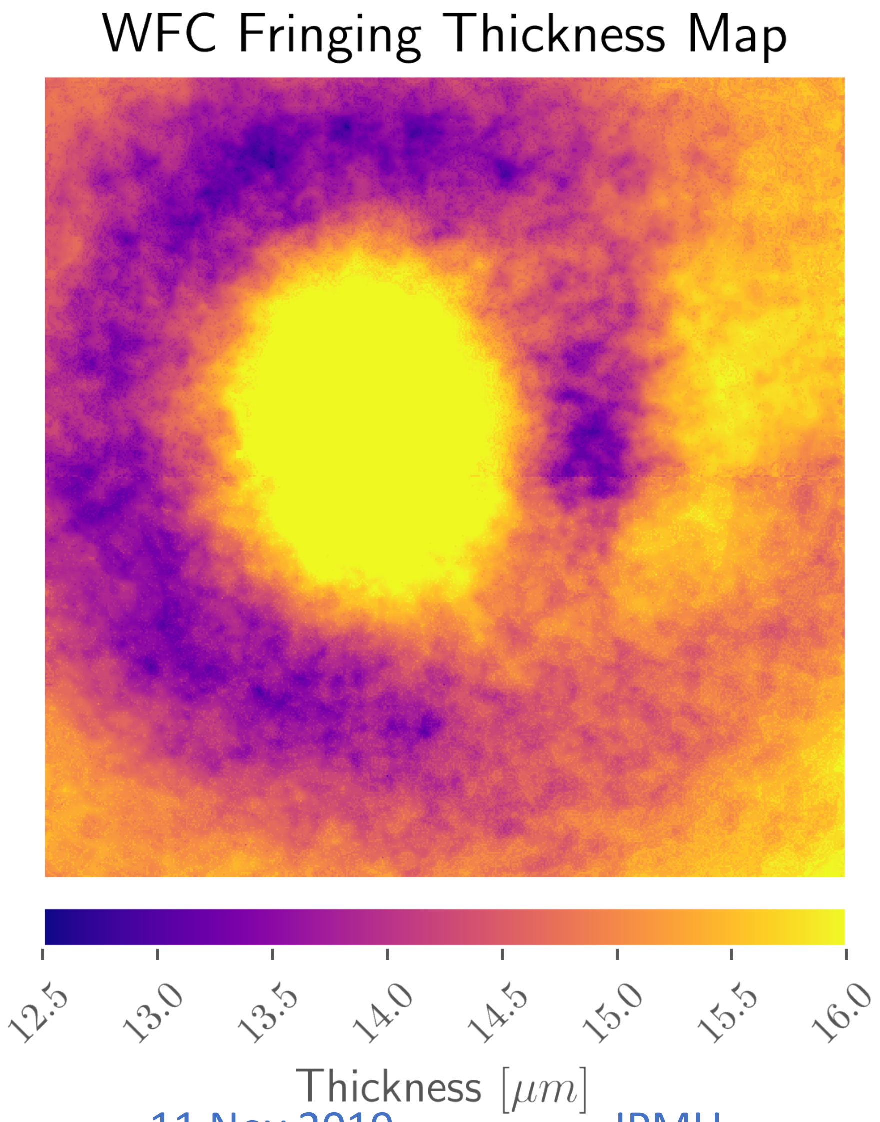


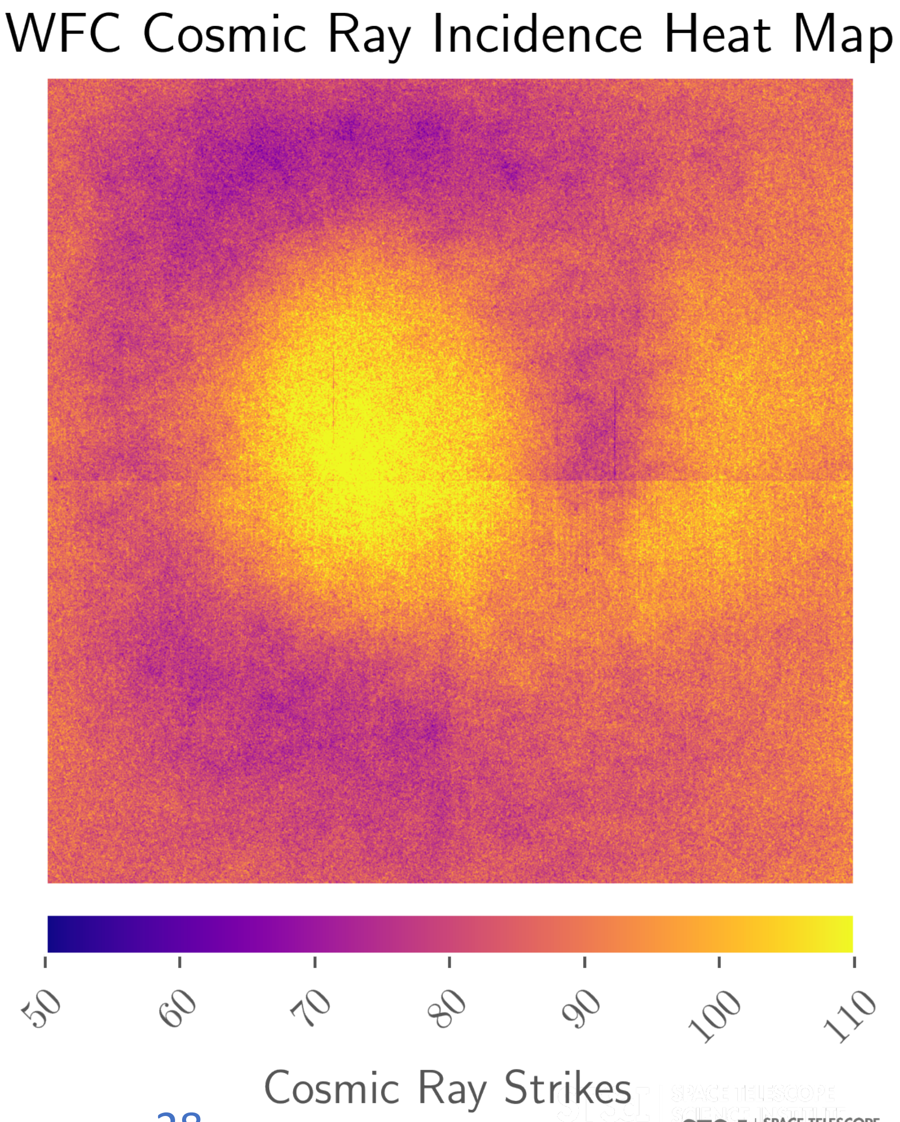


Declination: angle between true and magnetic north
Inclination: angle between the horizontal plane and the total field vector

Results: Mapping CCD Thickness with Cosmic Rays







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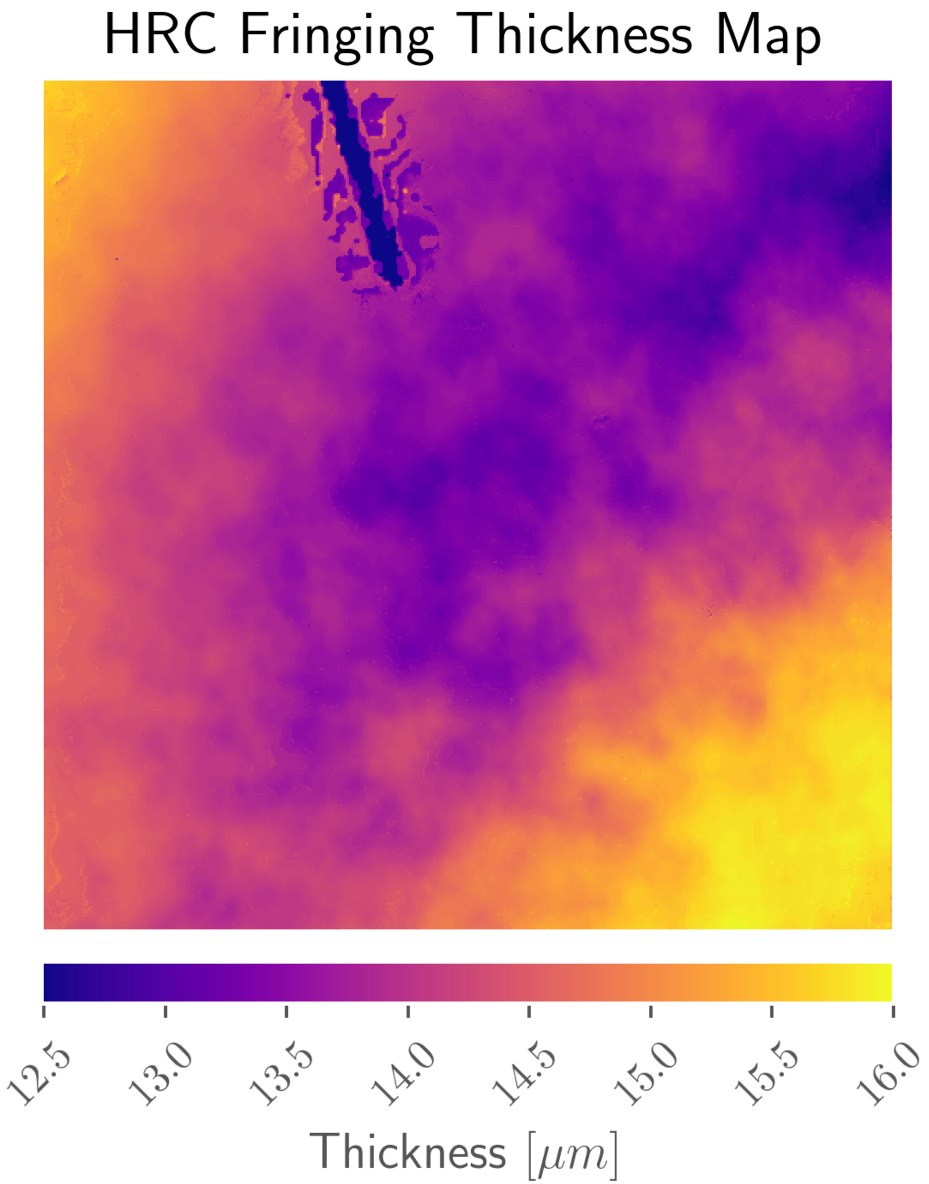

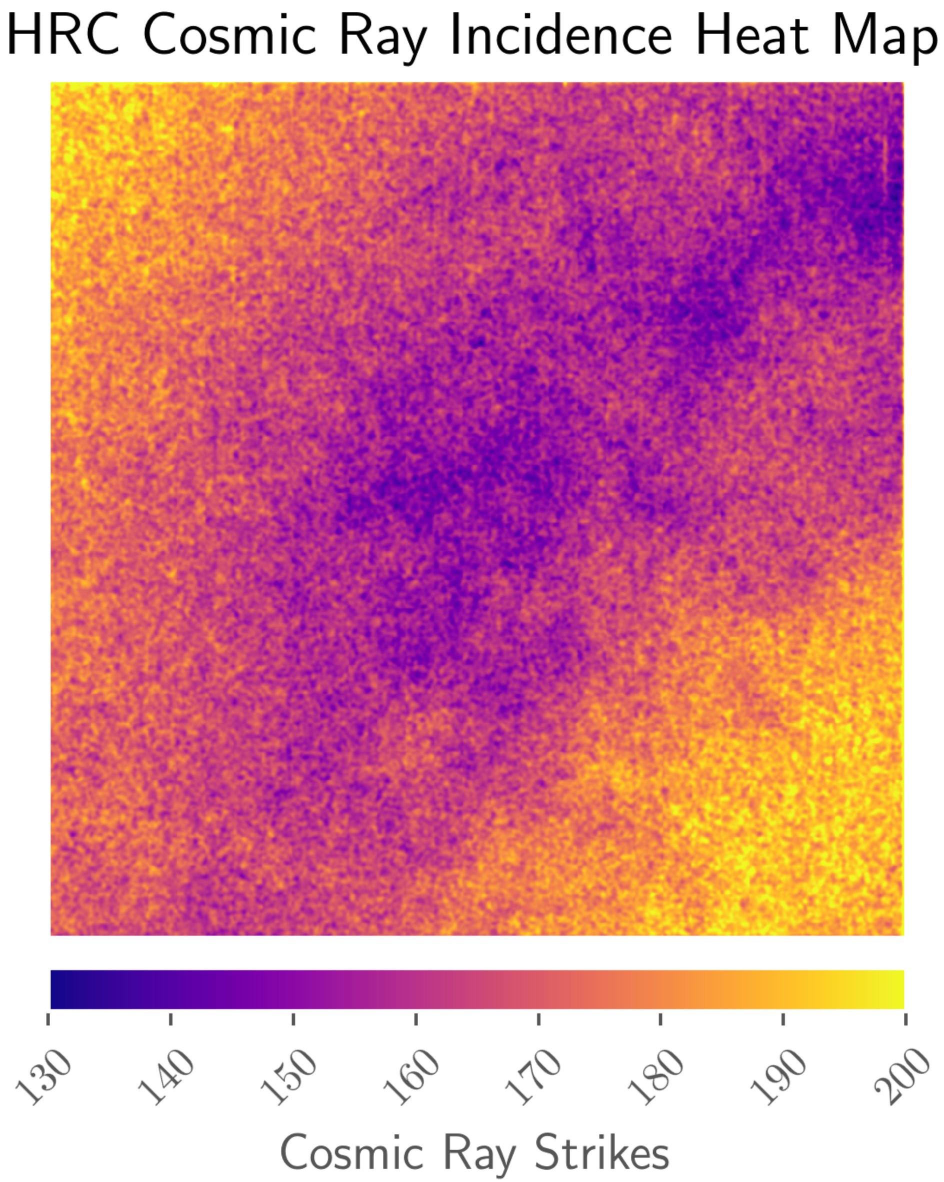

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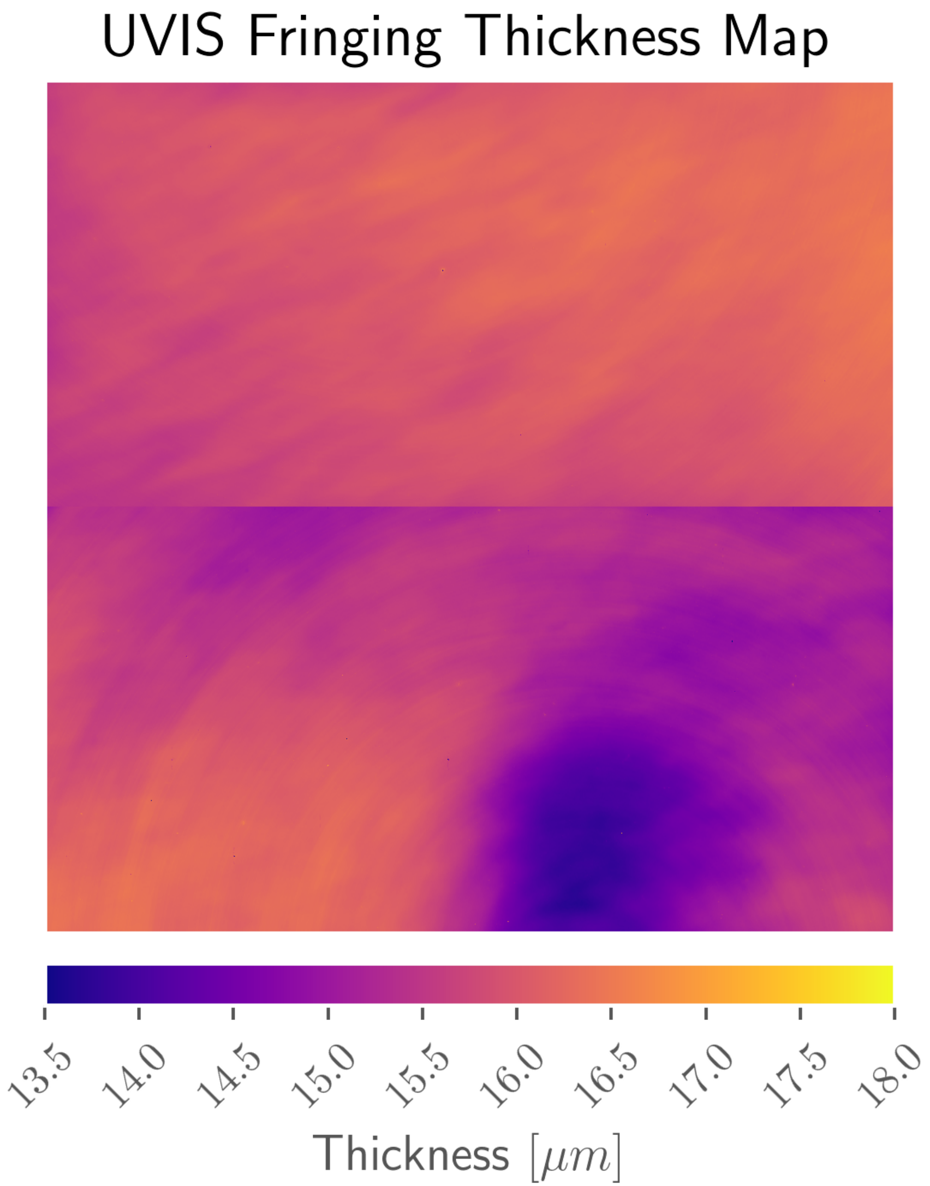
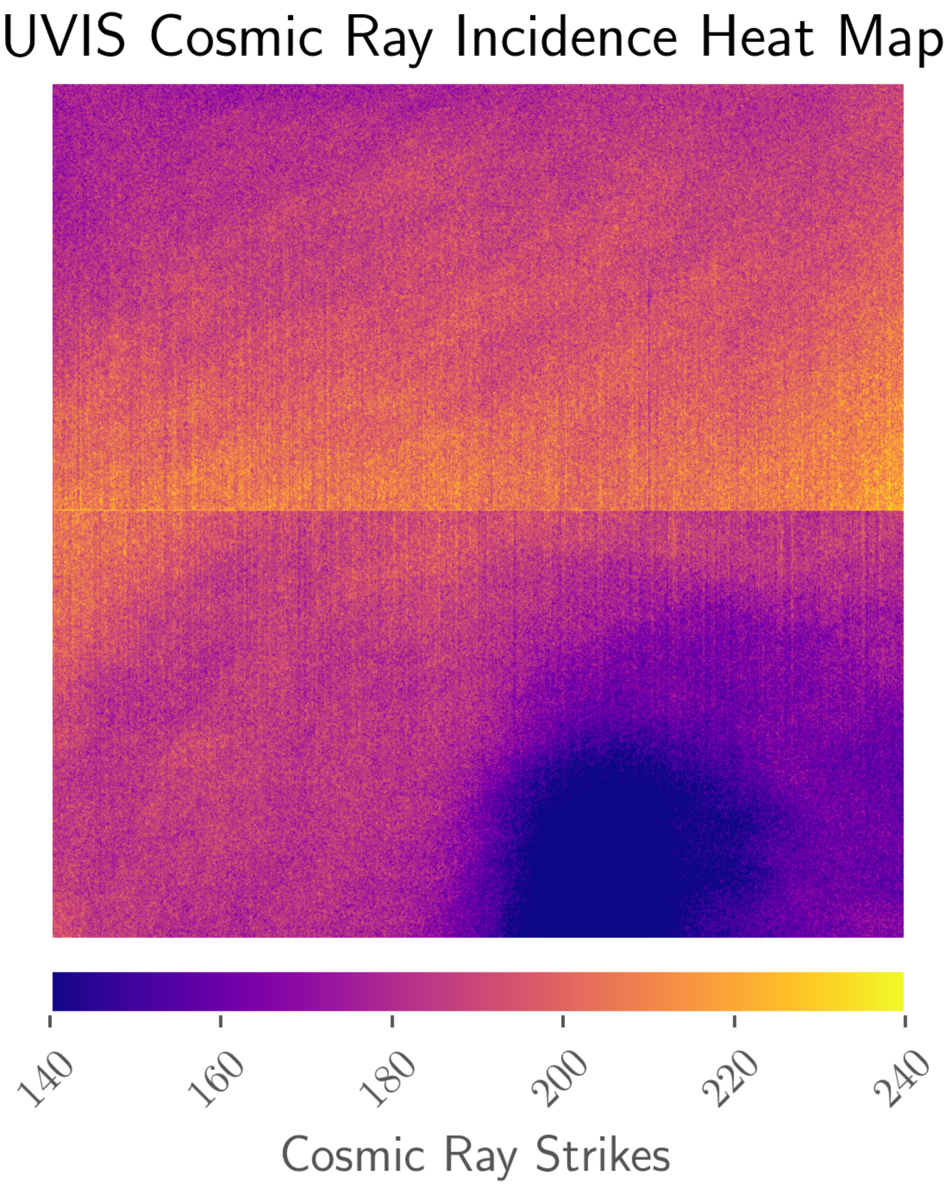




Results: Particle Physics with HST

- Each particle deposits energy by ionizing Si atoms and creating electron-hole pairs.
  - Explained very well by Bethe-Bloch theory
- The most probable value, Δ_p, of deposited energy is described by the Landau distribution and calculated as follows:

Max energy transferred by incoming particle

Ratio of energy lost and mean excitation energy, I

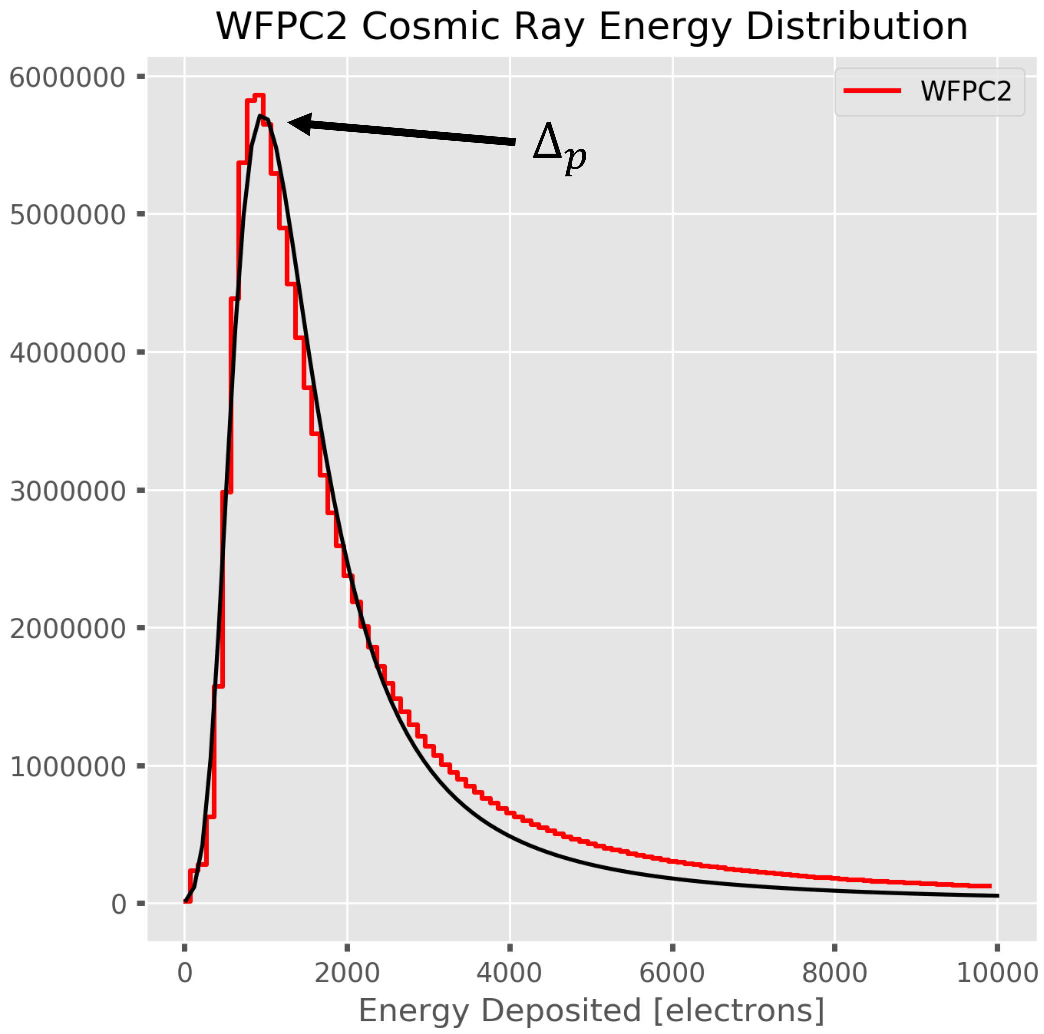
Constants

$$\Delta_p = \xi_{Si}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \ln\frac{\xi_{Si}}{I} + 0.2 - \beta^2 + \delta\right]$$

Stopping Power of Si: $\xi_{Si} = \frac{17.8*x}{\beta^2}\ eV/\mu m$

Mean excitation energy: I

Detector thickness: x , and $\beta = {}^{v}/_{c}$; $\gamma = \frac{1}{\sqrt{1-\beta^2}}$



Where to next

Machine learning – get all the CRs in all external exposures

Compare to SWARM, ORSTED et al

Model/calculate mag fields

Estimate mix of charged particles

Identify HgCdTe cosmic rays

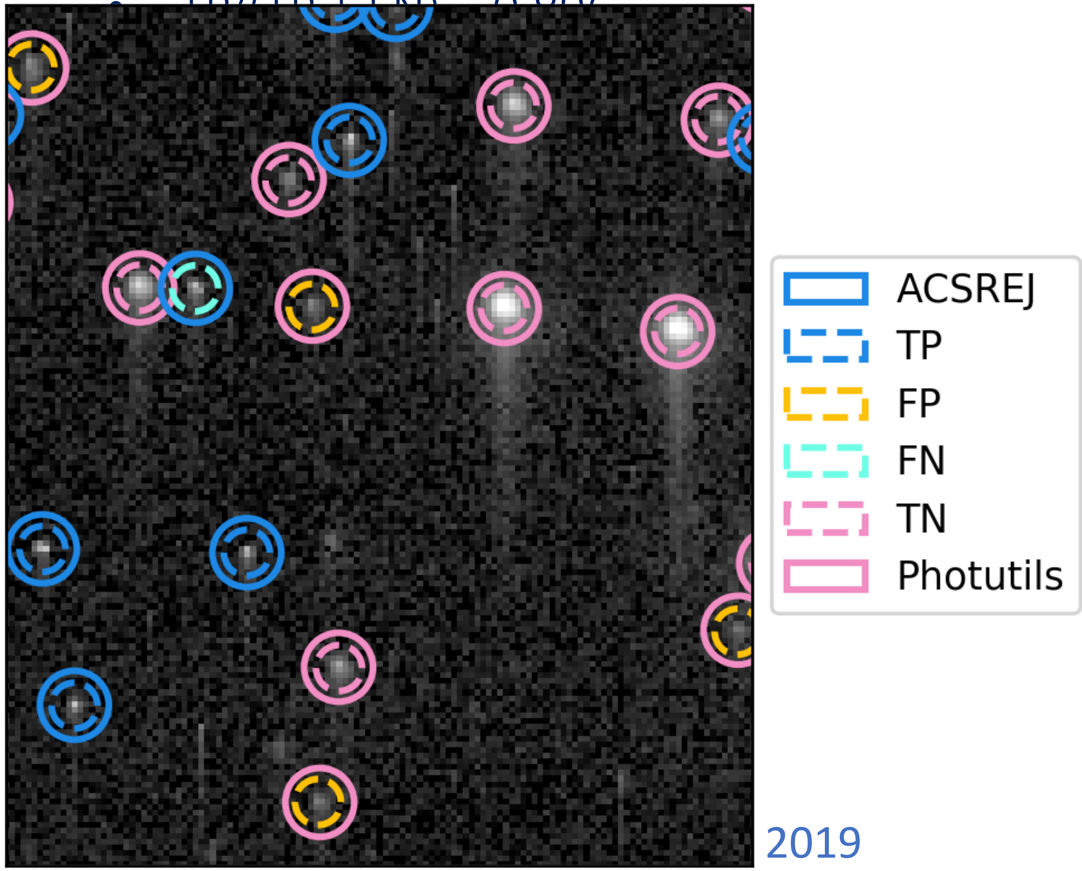
Determine volume

Sort CRs by HST altitude, parameters

Calculate detector thickness from fringe maps and landau dist’n

Results: Machine Learning

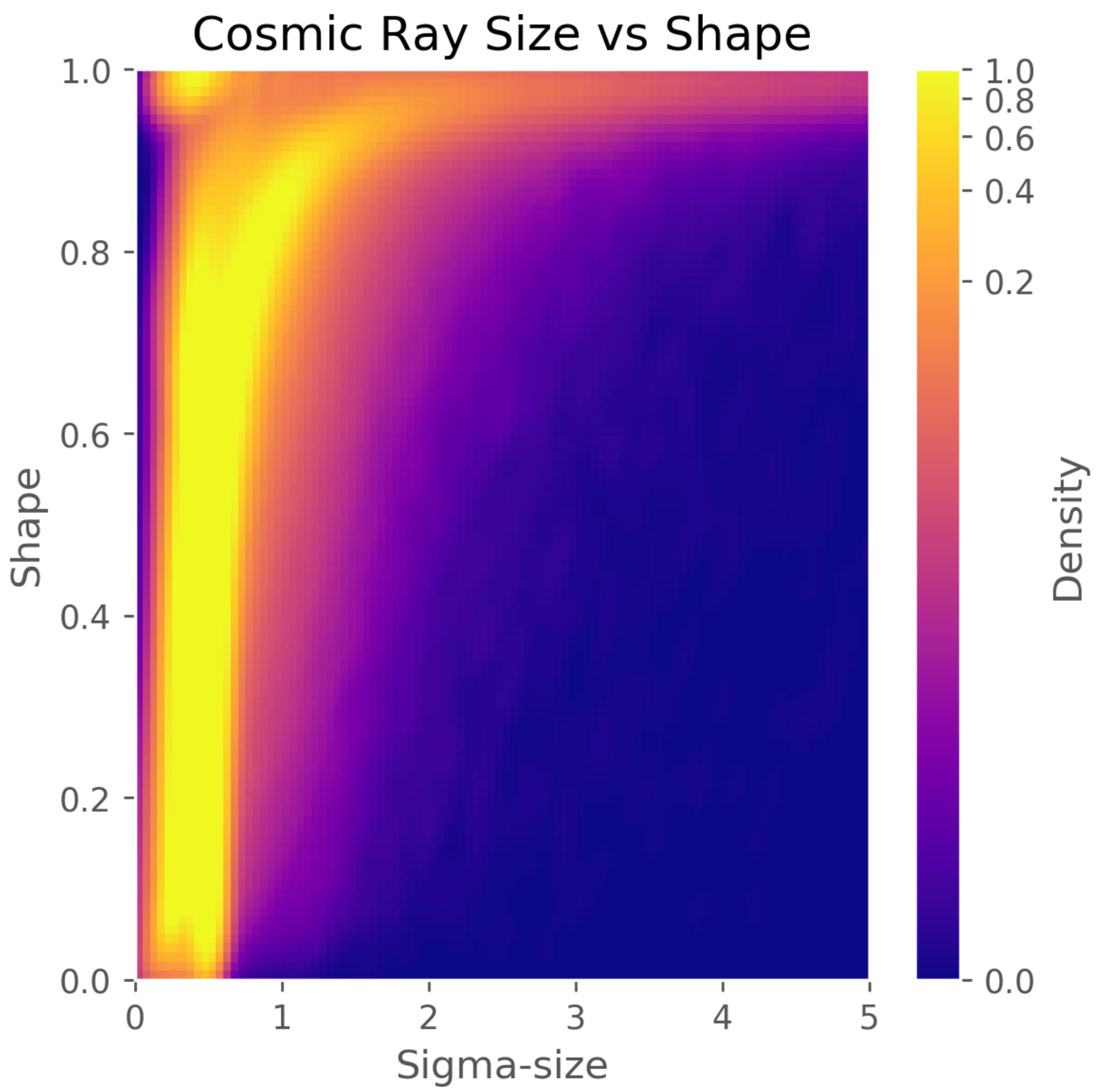
- How well did we predict a cosmic ray? (Precision)
  - TP/(TP + FP) = 0.751
- How well did we do with identifying actual cosmic rays? (Recall)



		Actual	
		Cosmic Ray	Star
Predicted	Cosmic Ray	0.330 True Pos.	0.109 False Pos.
	Star	0.038 False Neg.	0.500 True Neg.

Results: Machine Learning

- Leverage what we already know!
  - Cosmic rays are narrow and not very round
  - Stars can only be as narrow as the PSF and are they're round
- Train a KNearestNeighbors classifier to identify what type of object a source is based on where it falls in the 2D parameter space defined by sigma-size and shape.
- Training set 832,000 sources
  - 416,000 stars from 47 Tuc
  - 416,000 cosmic rays from this work



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Future Work

- Investigate ways to handle IR data more efficiently.
  - Up-the-ramp sampling seems to be pretty inconsistent
- Model particle tracks through HST
  - Distribution of thicknesses a particle must traverse at arbitrary incidence
  - How much energy is lost before reaching the detector?
- Determining particle types
  - mostly protons other particles.
- Analyze external data observations
- Compare CR flux measurements to geomagnetic field.

References

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EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

Results: Cosmic Ray Incidence vs Time

Galactic Cosmic Rays

- observed rate at earth is known to be anti-correlated with solar activity
- We see the expected bulk trends ☺

Unexpected signal!