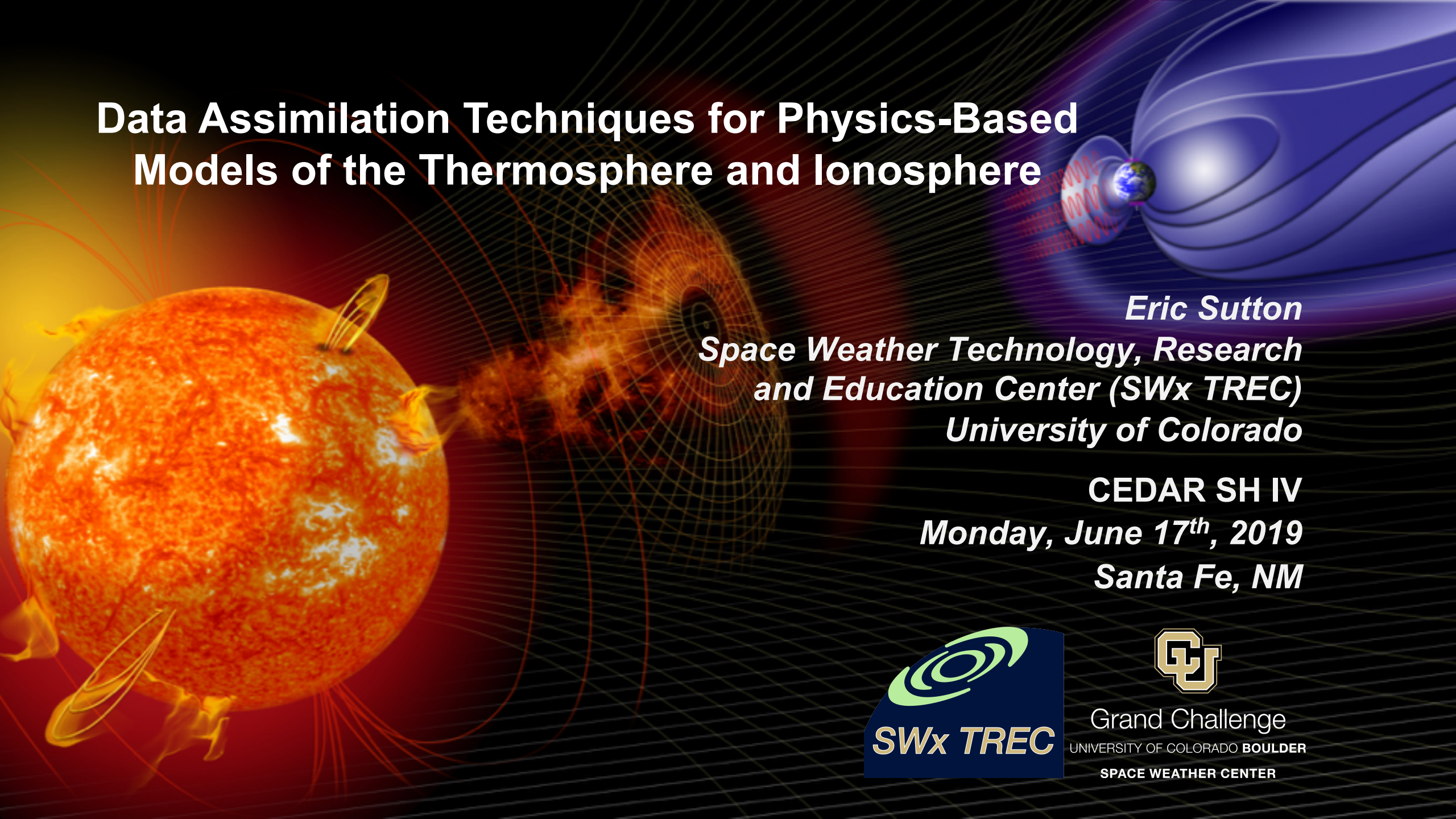
# Data Assimilation Techniques for Physics-Based Models of the Thermosphere and Ionosphere

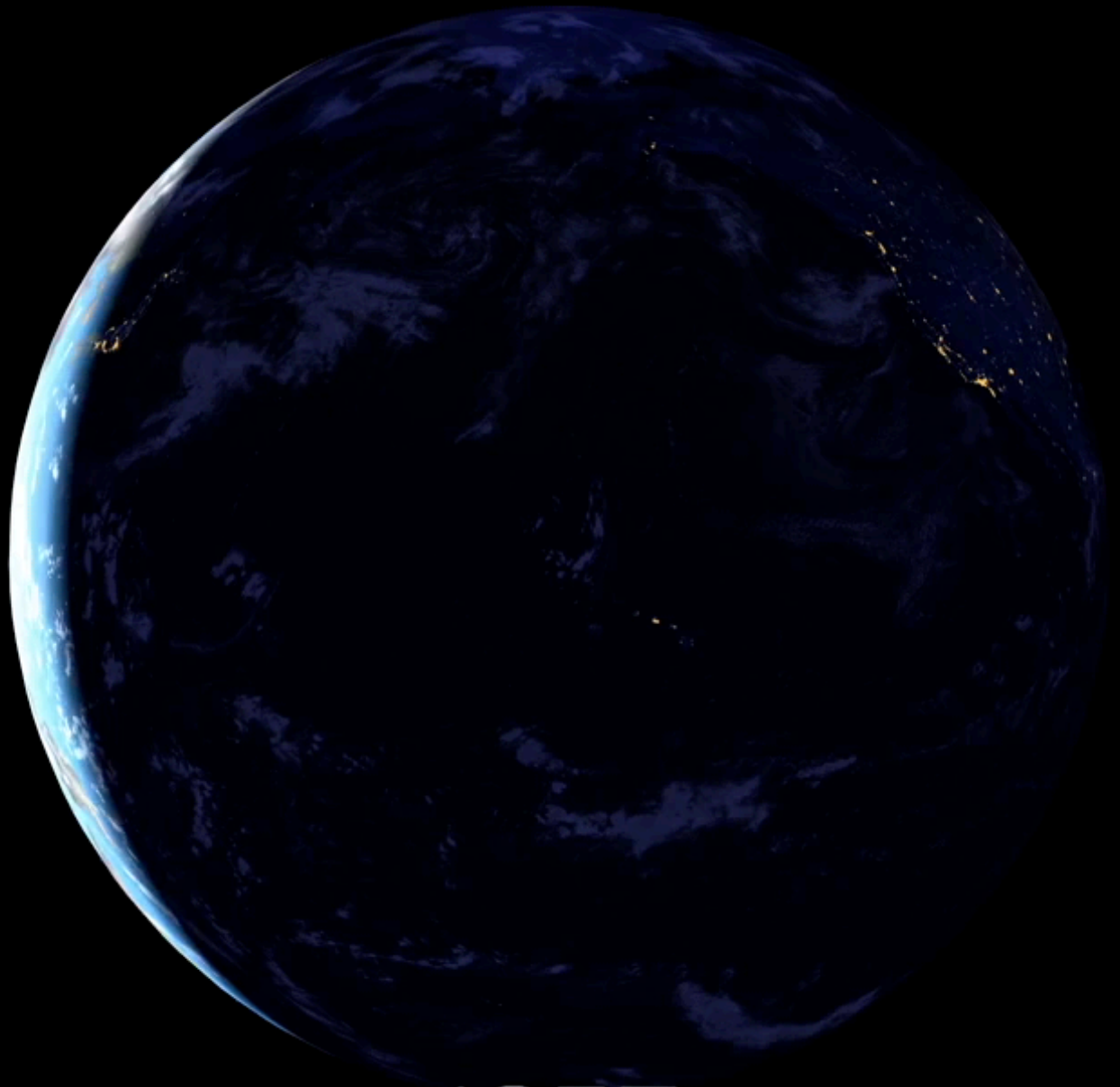


*Eric Sutton*
*Space Weather Technology, Research and Education Center (SWx TREC)*
*University of Colorado*

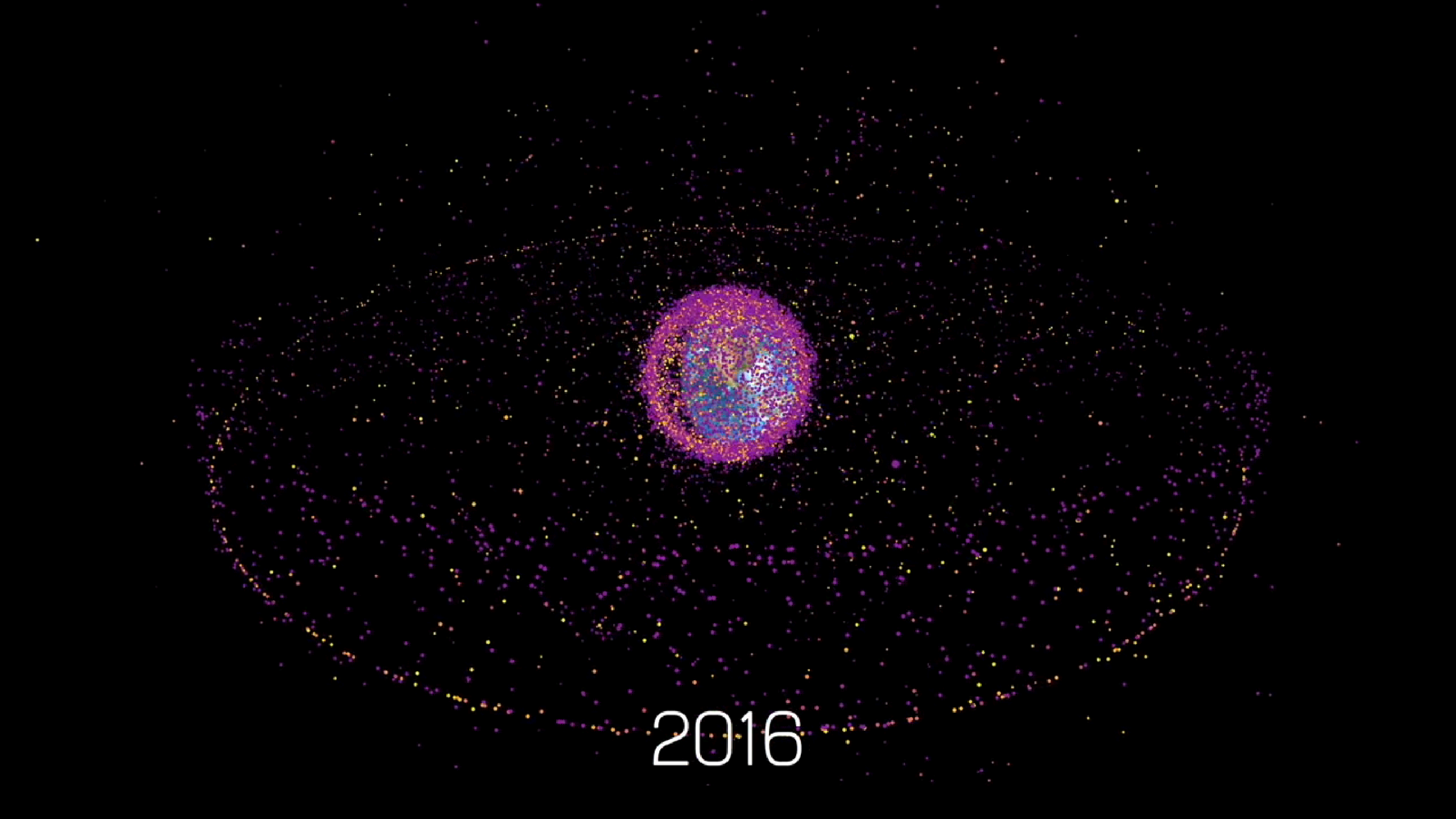
**CEDAR SH IV**
***Monday, June 17th, 2019***
***Santa Fe, NM***

SWx TREC

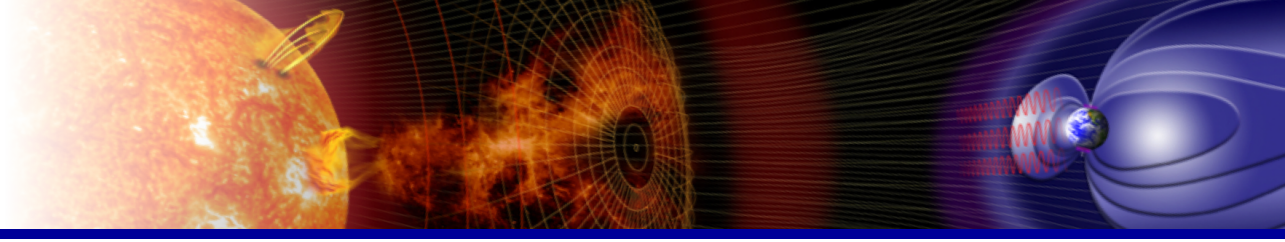
Grand Challenge
UNIVERSITY OF COLORADO **BOULDER**
**SPACE WEATHER CENTER**



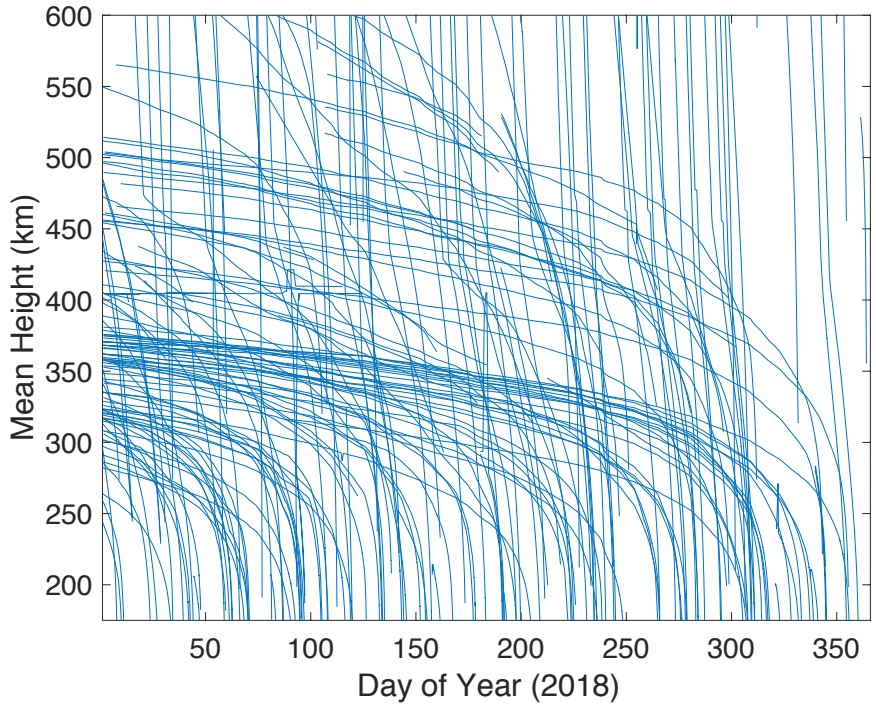
1957


2016

# Operating in LEO

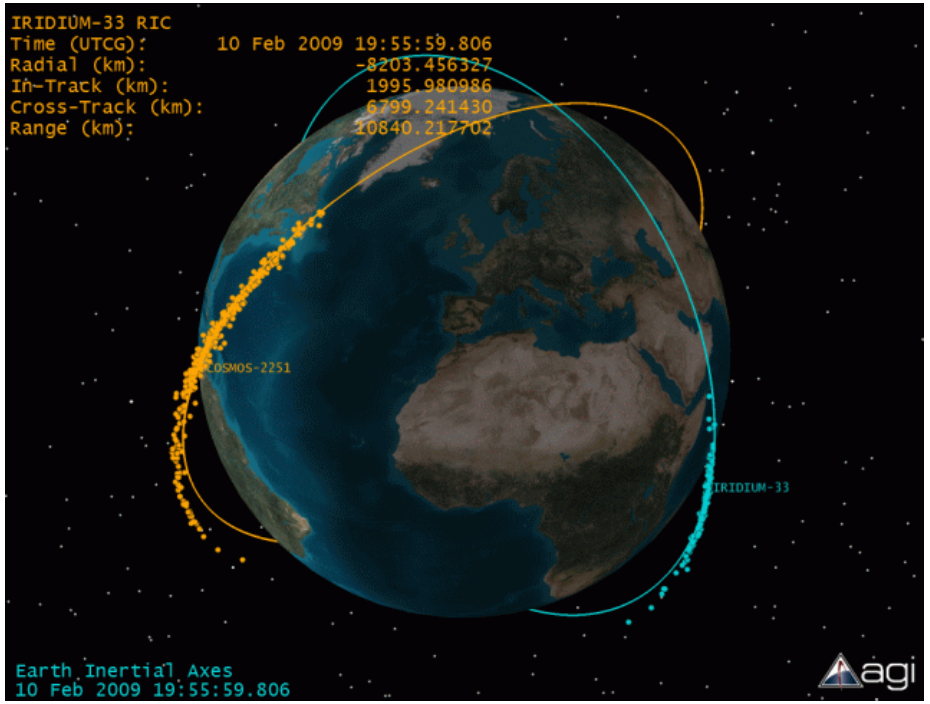


**Leveraging the Benefits:**
LEO is the only truly sustainable environment for mega constellations



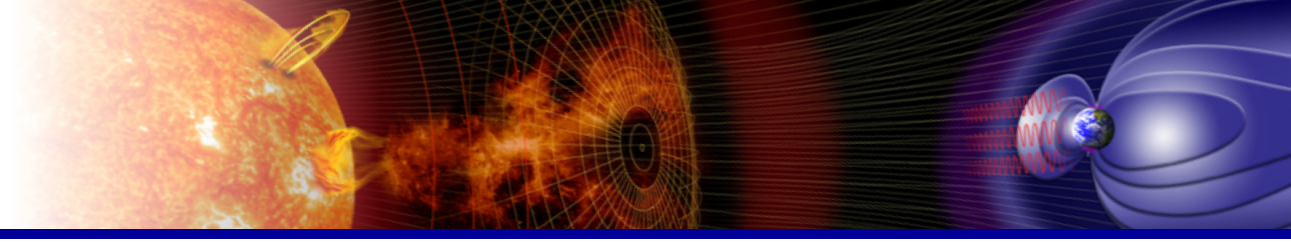

Objects that reentered in 2018

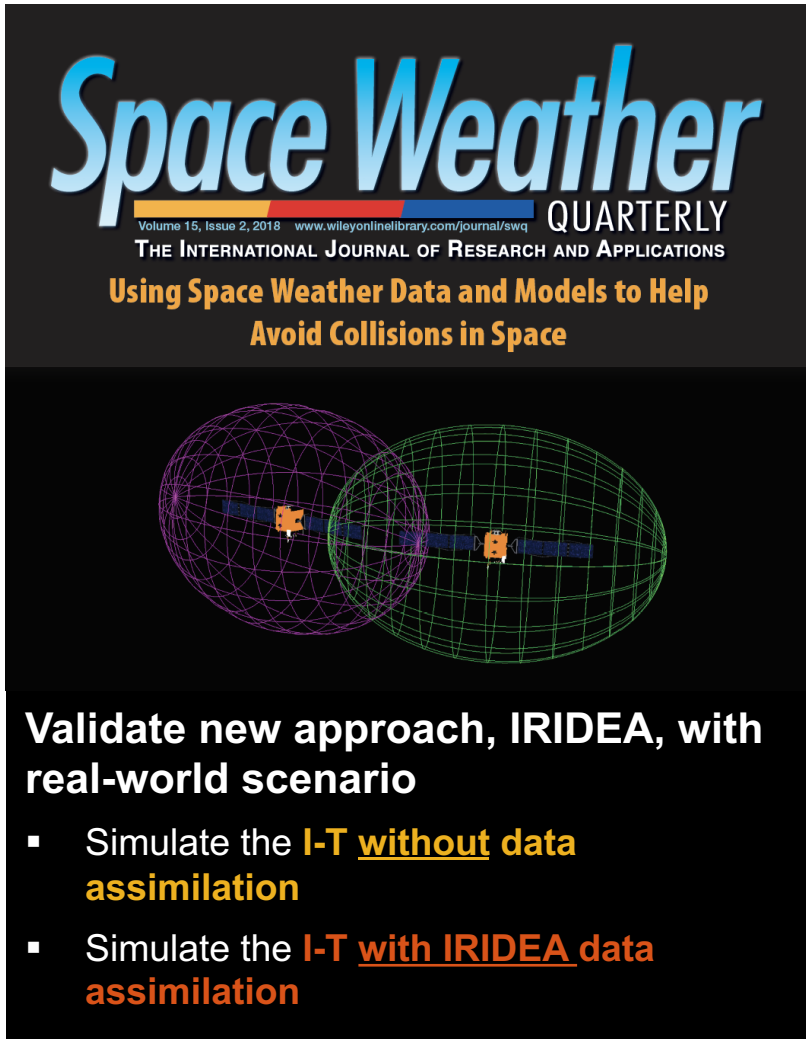
**Avoiding the Risks:**
The interaction with the atmosphere makes it difficult to predict conjunctions




IRIDIUM/Cosmos Collision + 3 hr

# Toward Better Nowcasting and Forecasting of the LEO Environment

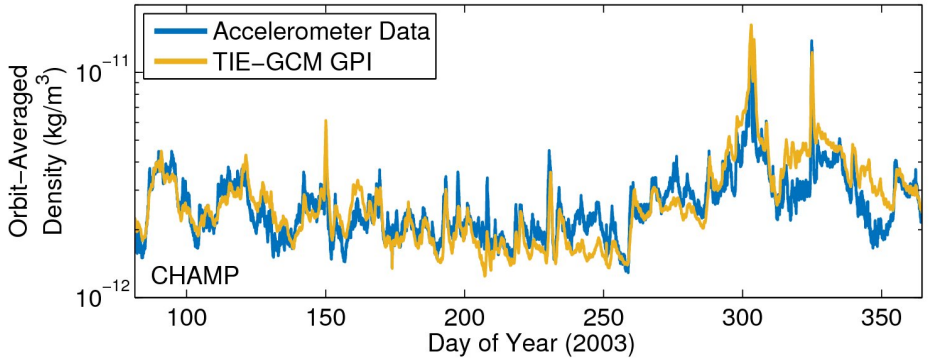




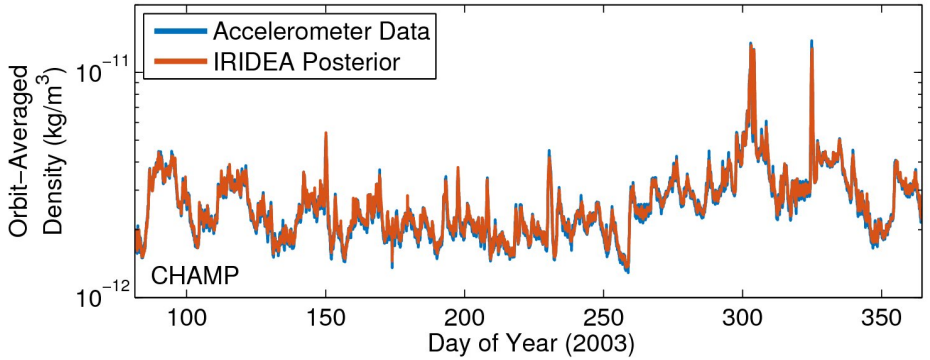

**Validate new approach, IRIDEA, with real-world scenario**

- Simulate the I-T without data assimilation
- Simulate the I-T with IRIDEA data assimilation

Without Data Assimilation




With Data Assimilation



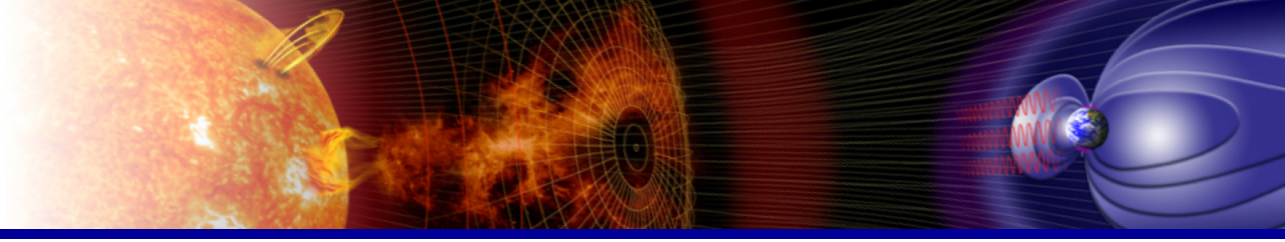

IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation



Sutton, E. K. (2018). A new method of physics-based data assimilation for the quiet and disturbed thermosphere. Space Weather, 16. https://doi.org/10.1002/2017SW001785.

# Variability of the I-T System

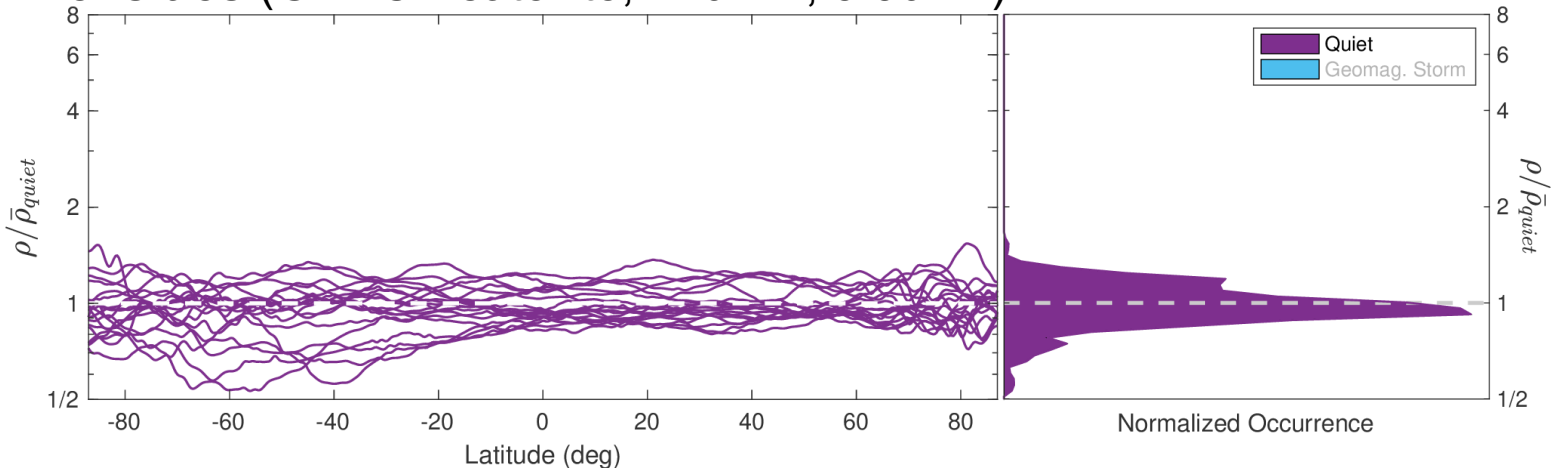
## Quiet Time



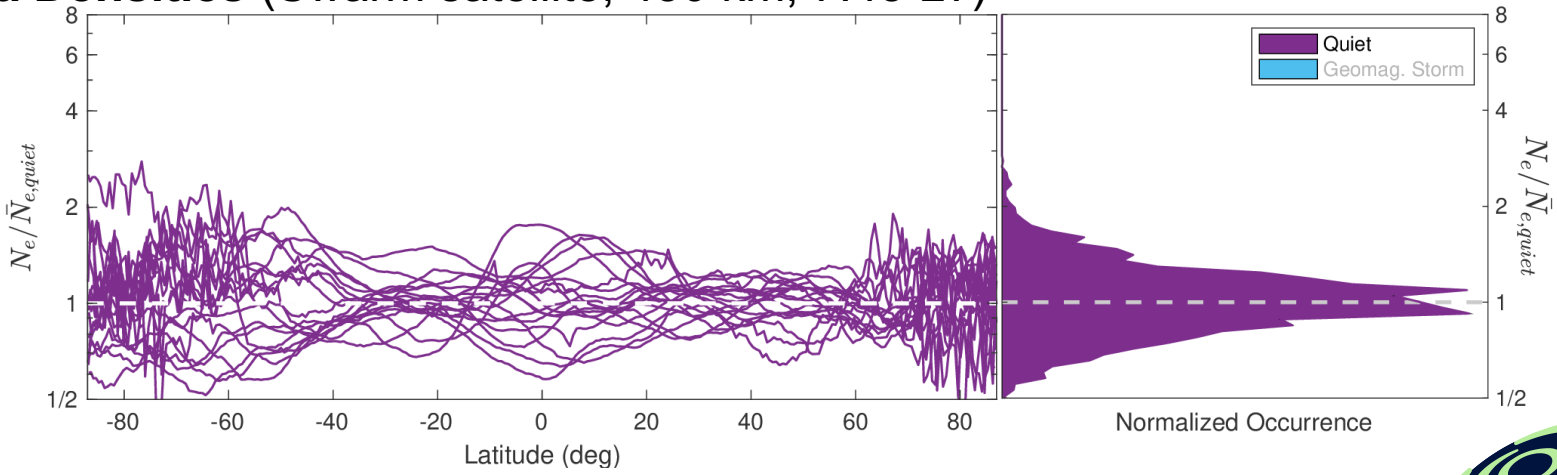
**Quiet-time orbits preceding the 2015 St. Patrick's Day Geomagnetic Storm:**

- Neutral and Plasma Densities, normalized by their average quiet-time values
- ±50–100% observed even during quiet-time
- Densities can be enhanced by a factor of ~8 during disturbed periods

**Neutral Densities** (GRACE satellite, 410 km, 5:30 LT)

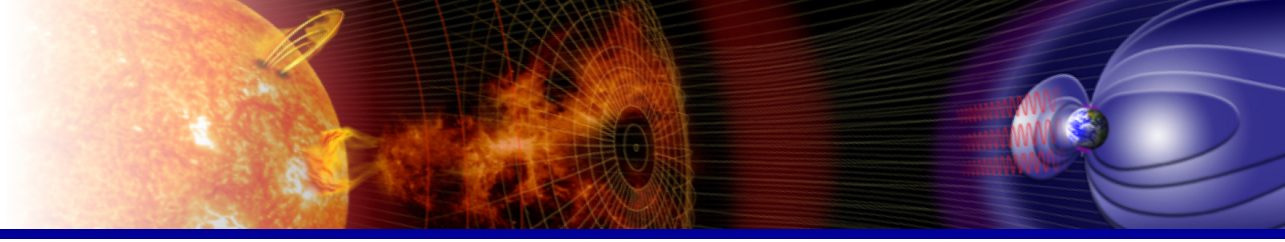



**Plasma Densities** (Swarm satellite, 450 km, 7:45 LT)



# Variability of the I-T System

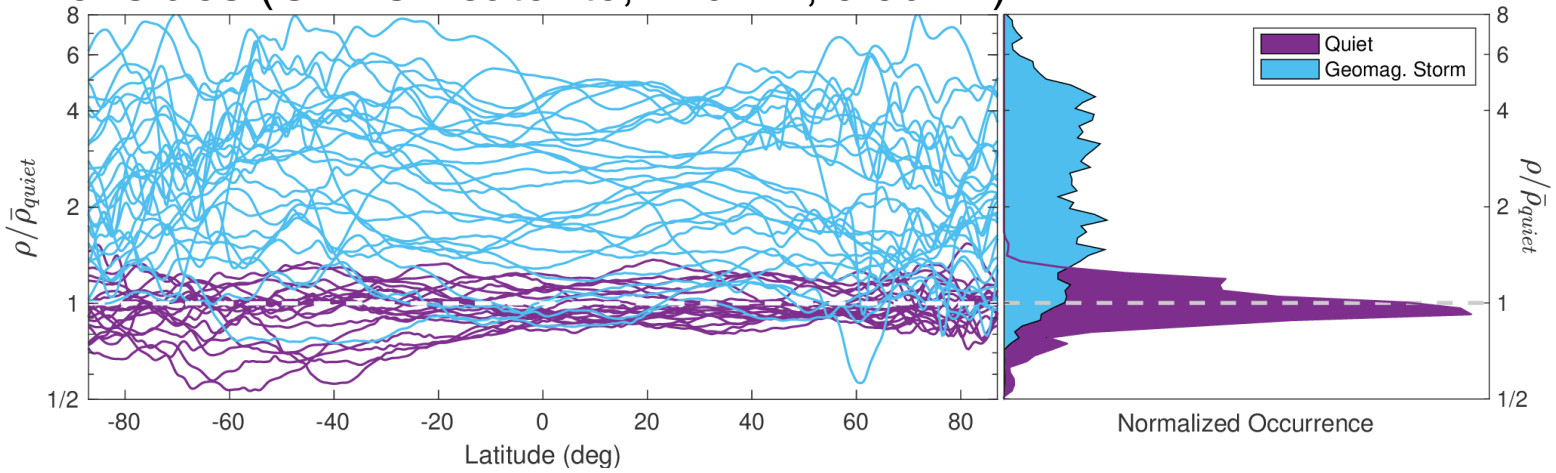
## Geomagnetic Storm



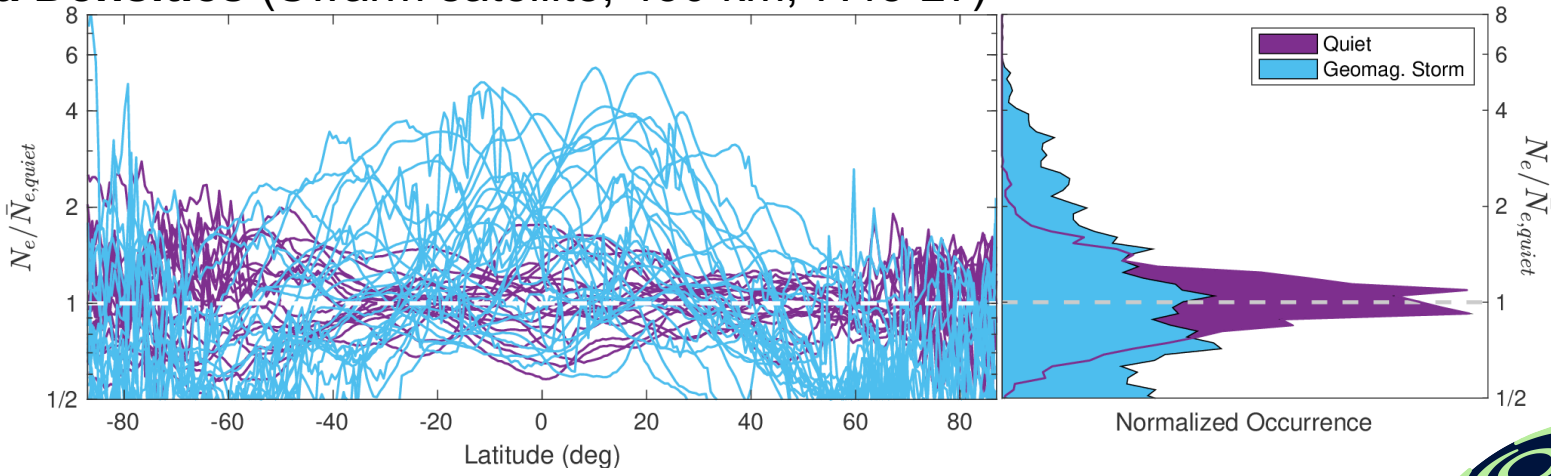
**Quiet-time and Geomagnetically Disturbed orbits during the 2015 St. Patrick's Day Geomagnetic Storm:**

- Neutral and Plasma Densities, normalized by their average quiet-time values
- **Densities can be enhanced by a factor of ~8 during disturbed periods**
- ±50–100% observed even during quiet times

**Neutral Densities** (GRACE satellite, 410 km, 5:30 LT)

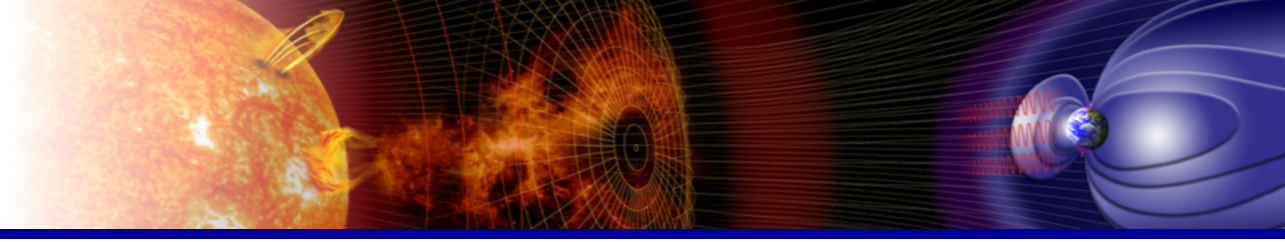



**Plasma Densities** (Swarm satellite, 450 km, 7:45 LT)



# Data Assimilation

## Different Approaches for Different Systems

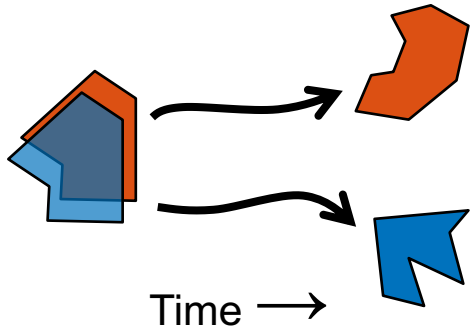


**Q: Why do we need a Different data assimilation scheme?**

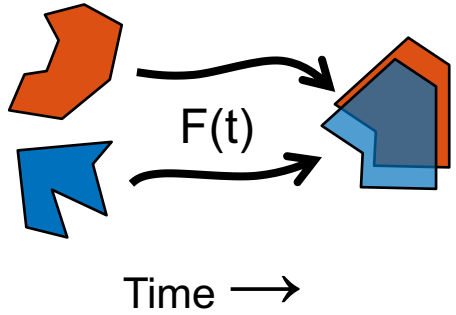
**A: Because the Ionosphere-Thermosphere (I-T) system is:**

- Highly driven
- Sparsely observed

**Chaotic System**
(e.g. tropospheric weather)

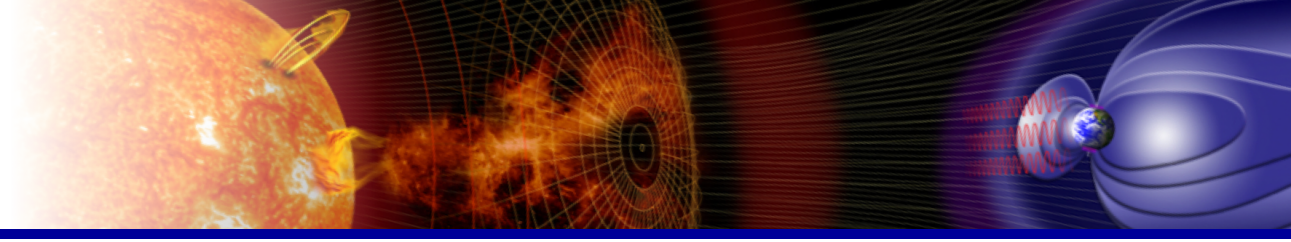


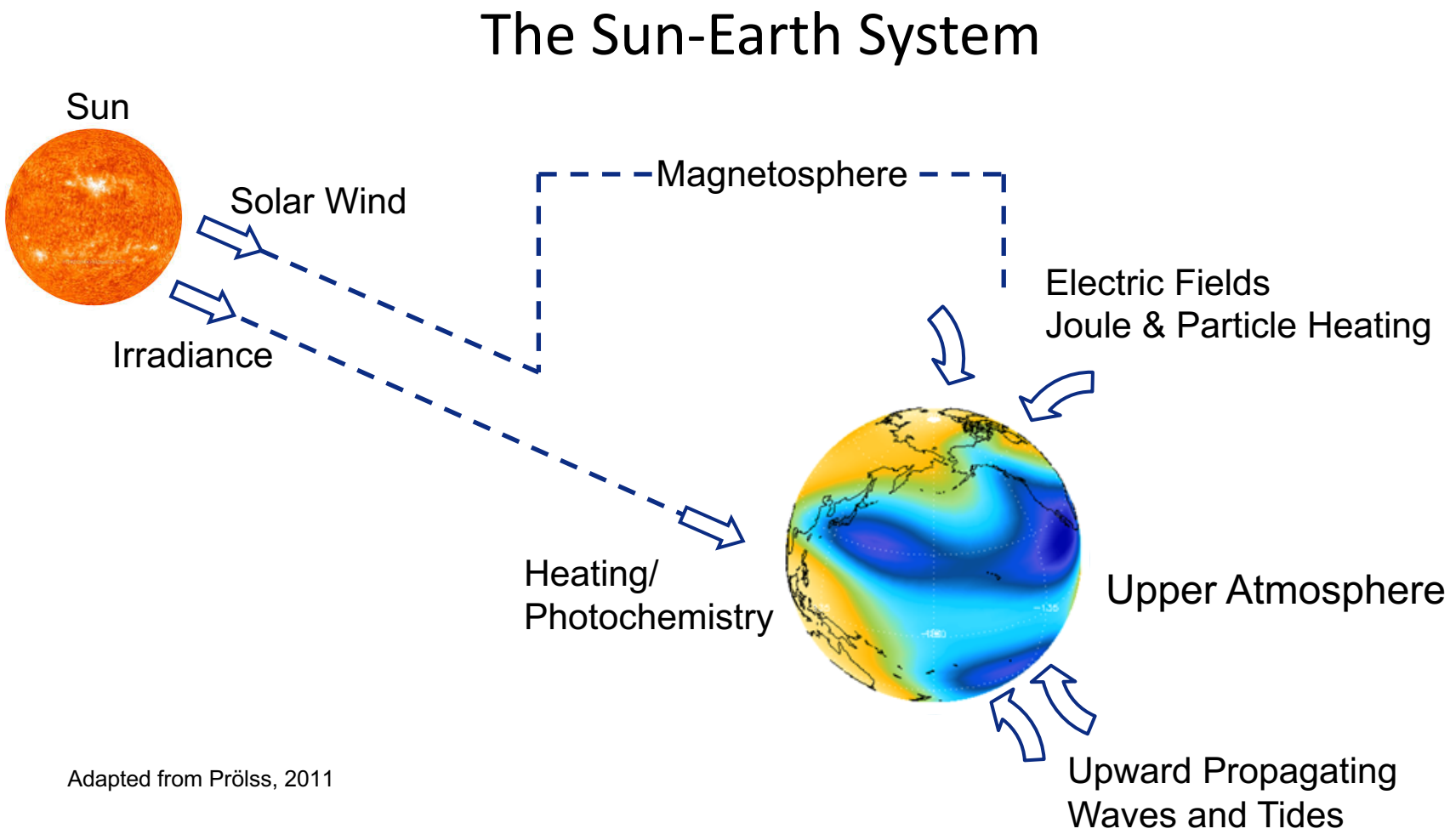

**Strongly Driven System**
(e.g. Ionosphere-Thermosphere)




[Image adopted from Codrescu et al., 2018]

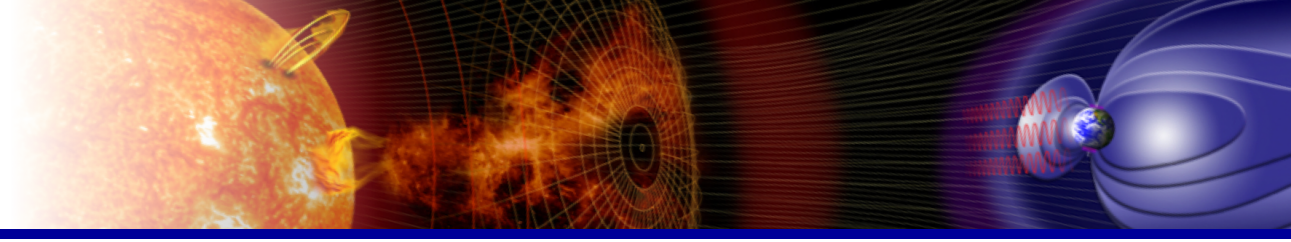
# Drivers of the I-T System



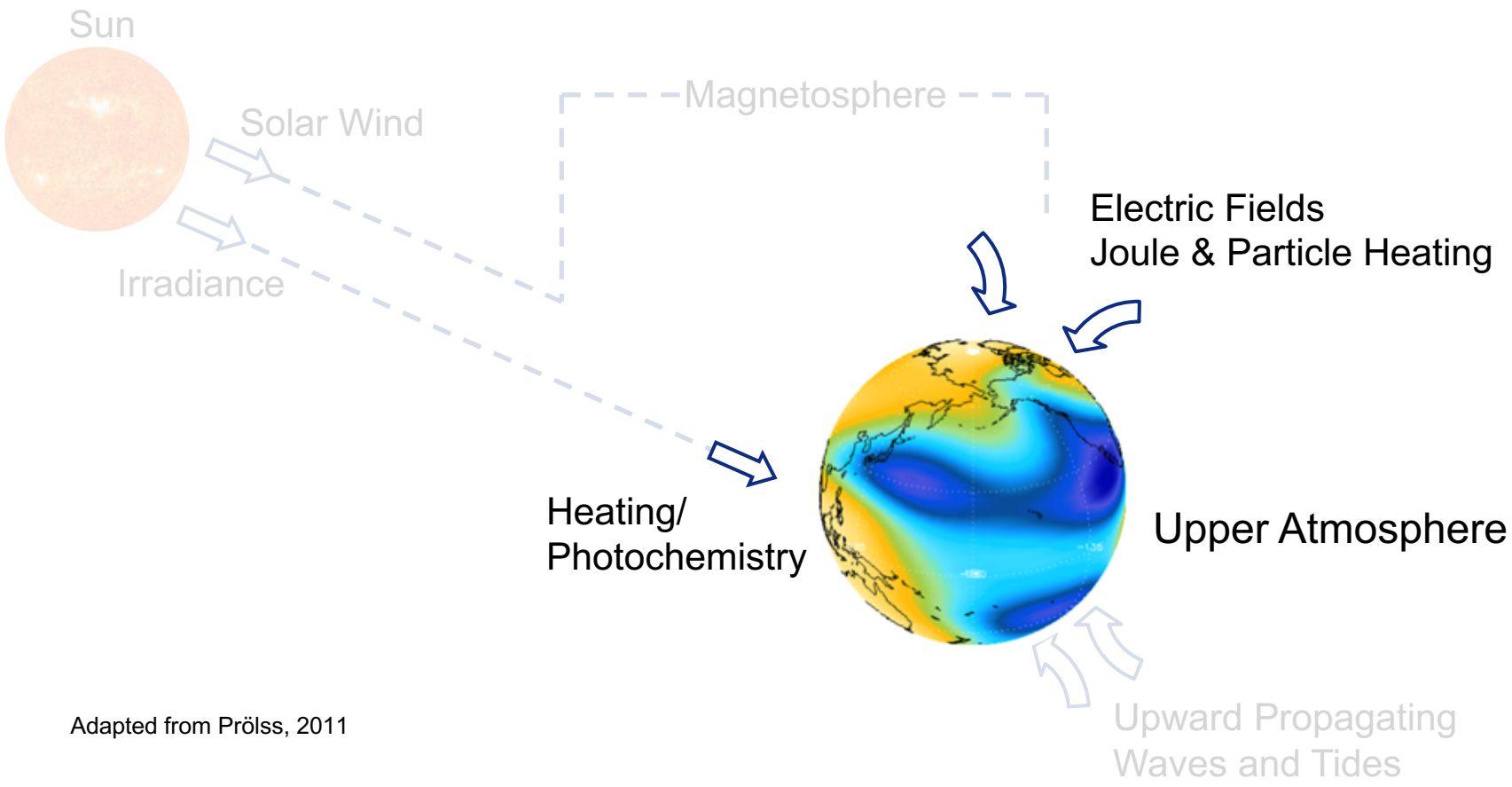



Adapted from Prölss, 2011

# Drivers of the I-T System



## The Sun-Earth System

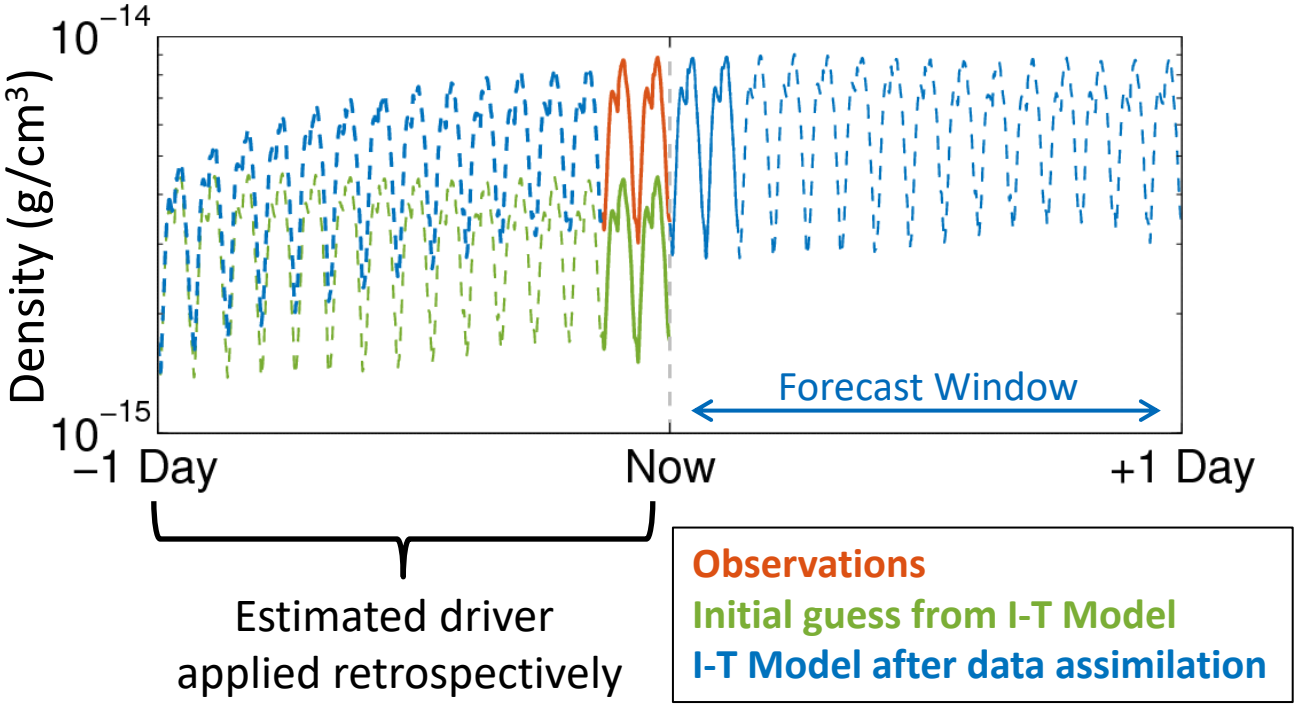



Adapted from Prölss, 2011

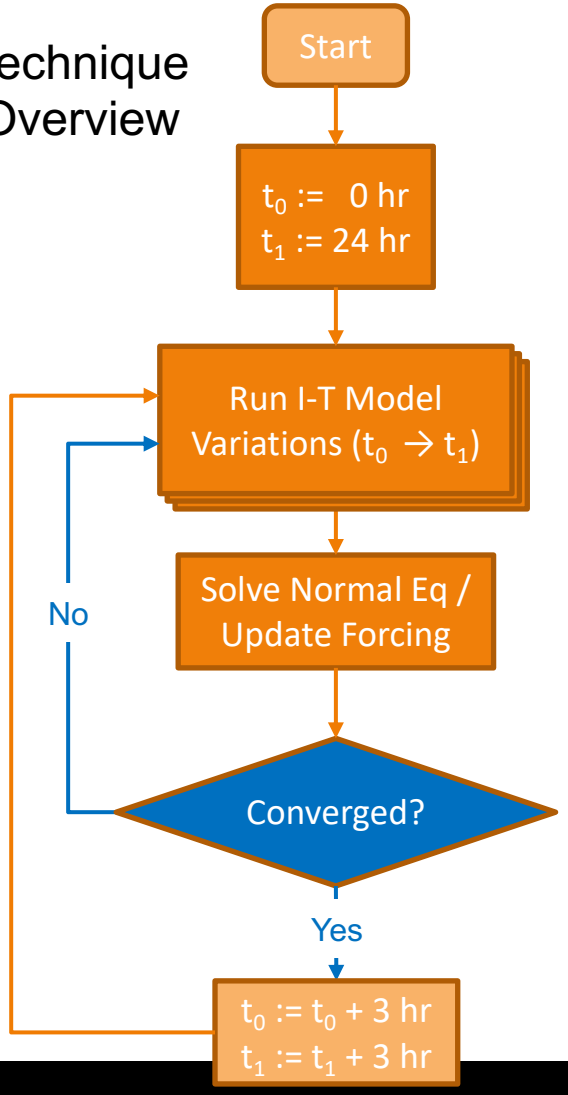
# ~~Data~~Driver Assimilation

## New Approach

- Calculate what the driver *should* be for I-T model output to match observations
- Apply new estimated driver retrospectively to allow model to equilibrate




Technique Overview

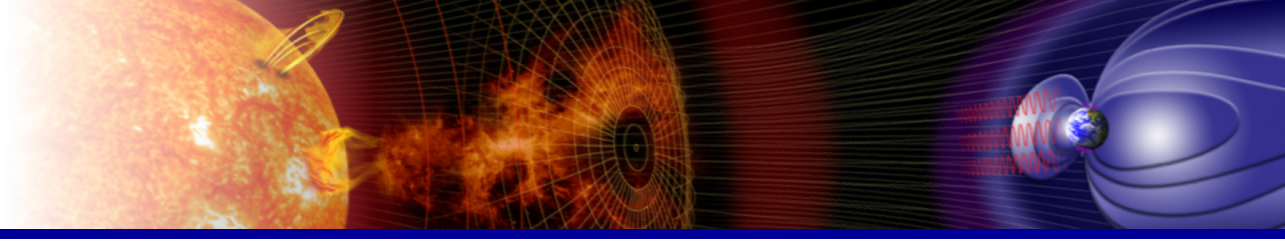





More details here: Sutton [2018, doi:10.1002/2017SW001785]

# Free Run vs. IRIDEA

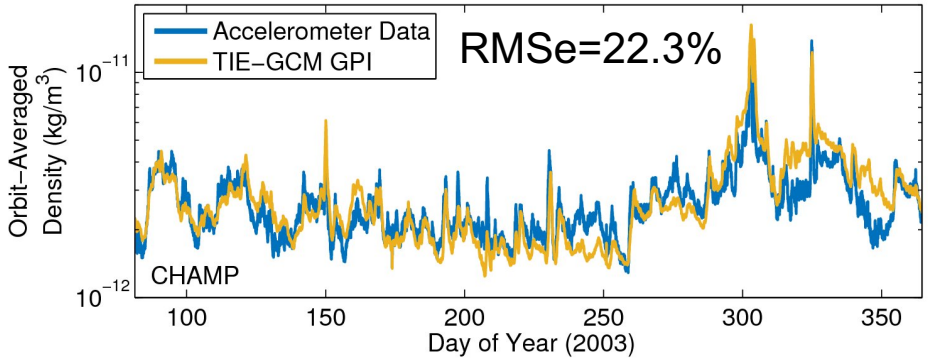
## Day 80-365, 2003

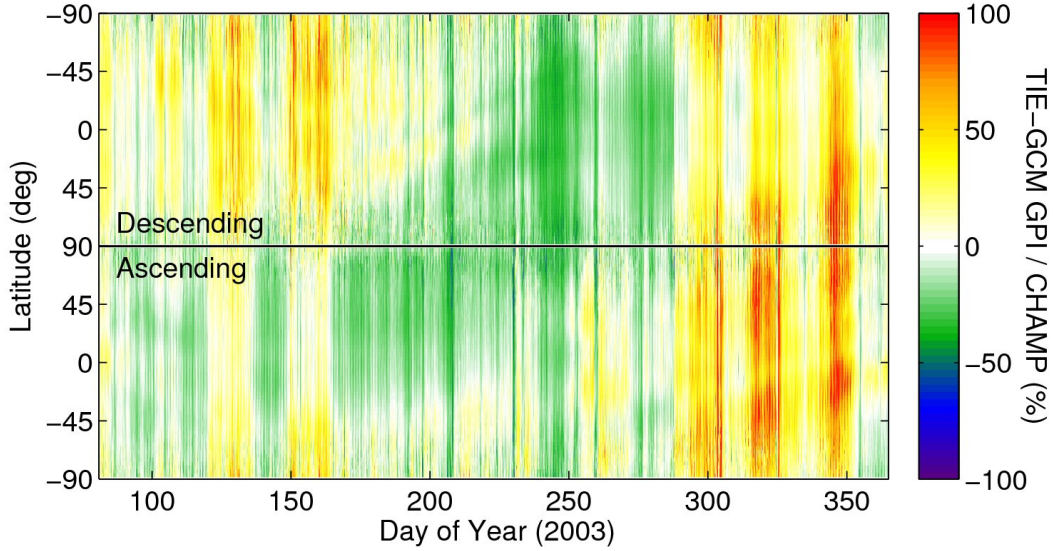


**Validate new approach, IRIDEA, with real-world scenario**

- Simulate the I-T without data assimilation
- Compare output of I-T model with observations of neutral density from CHAMP

**Without Data Assimilation**




IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation

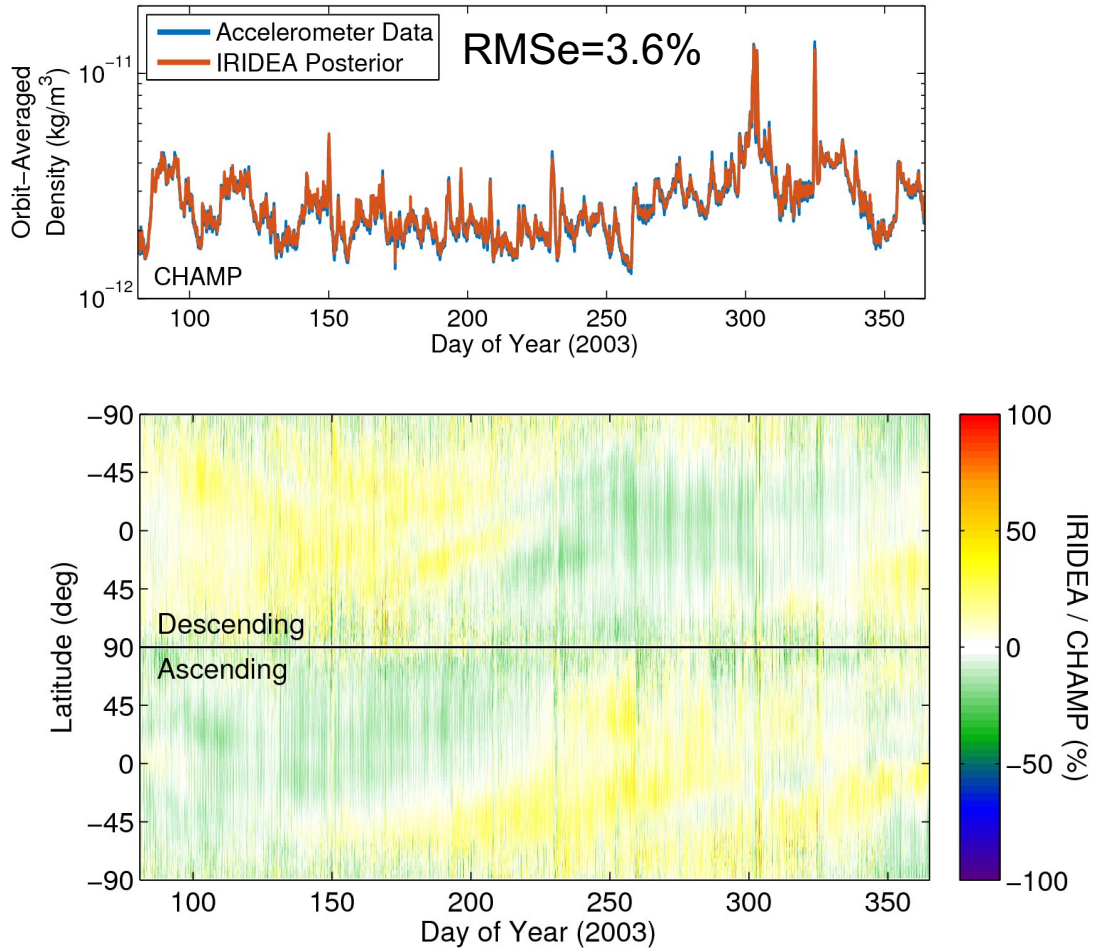
# Free Run vs. IRIDEA

**Day 80-365, 2003**

## Validate new approach, IRIDEA, with real-world scenario

- Simulate the **I-T with IRIDEA data assimilation**
  - Ingest CHAMP/STAR accelerometer observations at ~400 km
  - Estimate corrections to both solar flux and geomagnetic activity drivers
- Compare output of I-T model with observations of **neutral density from CHAMP**

**With IRIDEA Data Assimilation**




**Comparing to Ingested Data**

IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation

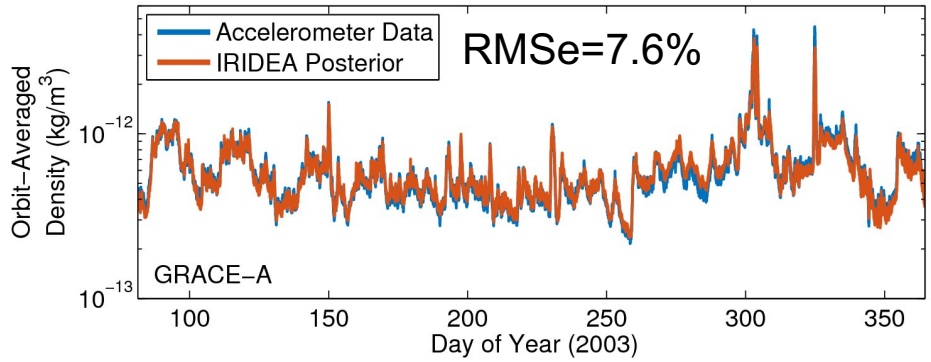
# Free Run vs. IRIDEA

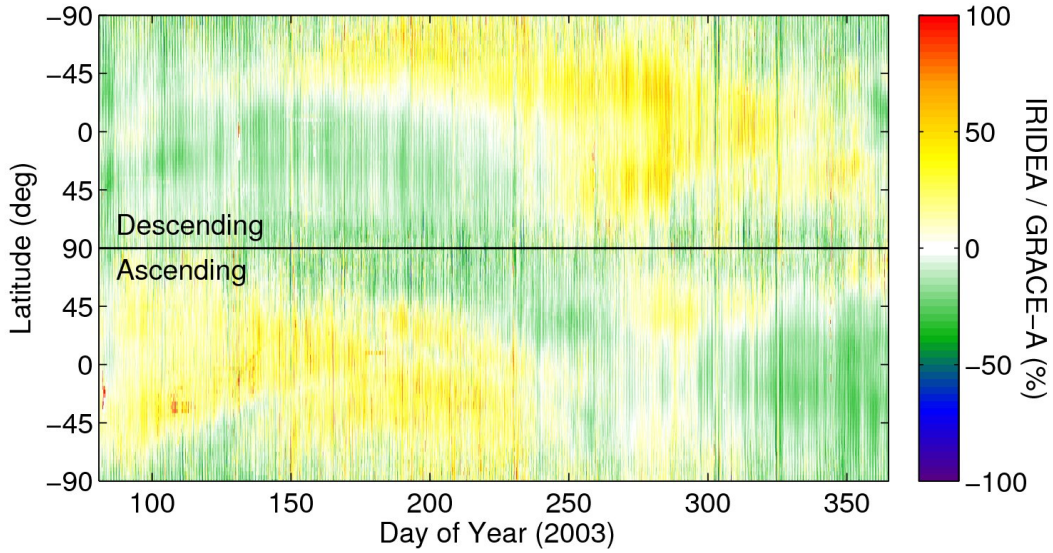
**Day 80-365, 2003**

## Validate new approach, IRIDEA, with real-world scenario

- Simulate the **I-T with IRIDEA data assimilation**
  - Ingest CHAMP/STAR accelerometer observations at ~400 km
  - Estimate corrections to both solar flux and geomagnetic activity drivers
- Compare output of I-T model with observations of **neutral density from GRACE** at ~500 km and separated in local time from CHAMP

**With IRIDEA Data Assimilation**




**Comparing to Independent Data**

IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation

# Persistent Model Features

## Day 80-365, 2003

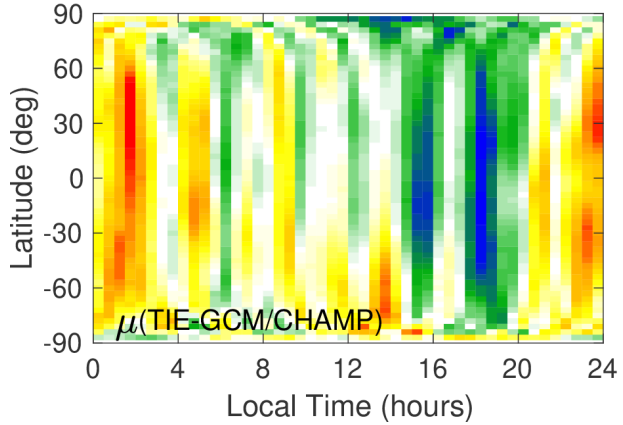
**Method allows us to:**

- Isolate internal model features from external drivers
- …while still comparing to observations

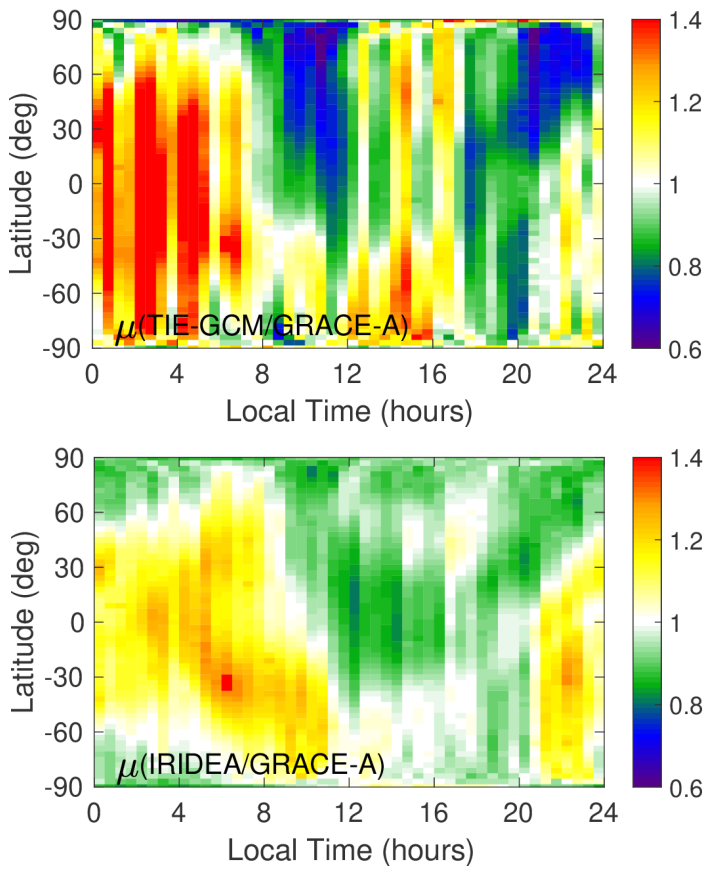
**Investigate model's internal biases:**

- Viscous and ion drag forces (e.g., Hsu et al., 2016)
- Tidal and GW influences (e.g., Jones et al., 2014)
- Cooling discrepancies
- Imposed lower boundary vs Whole Atmosphere model

CHAMP mean residuals

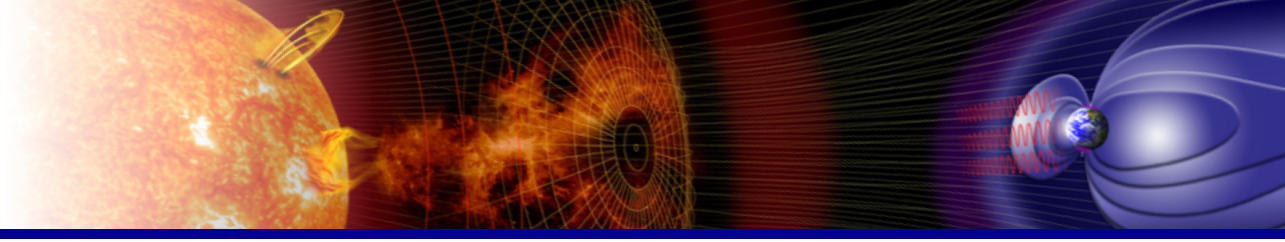



GRACE mean residuals

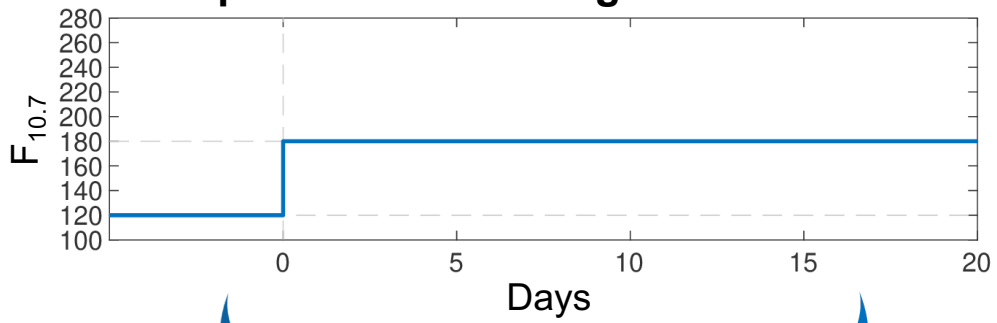


# Observational Response

## Sensitivity to Heating Sources

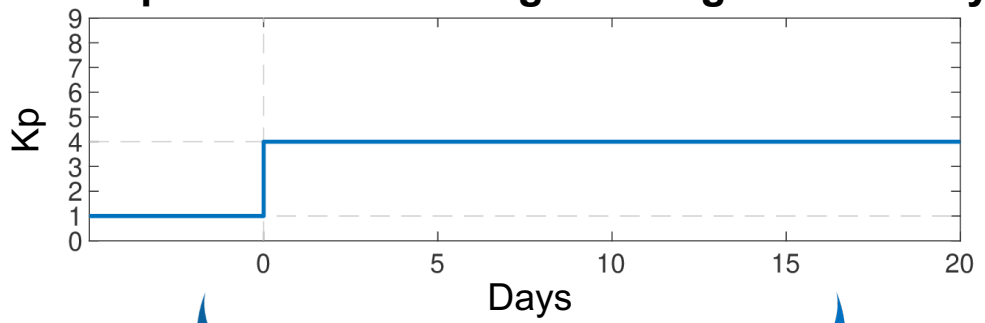


### Response to Increasing Solar Irradiance

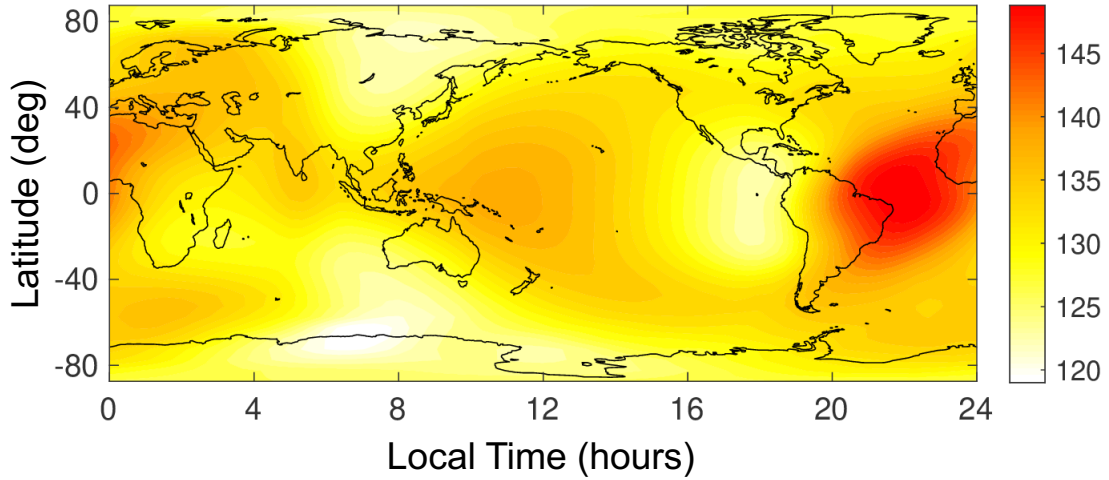



Vs.

### Response to Increasing Geomagnetic Activity




### Density Increase (%)

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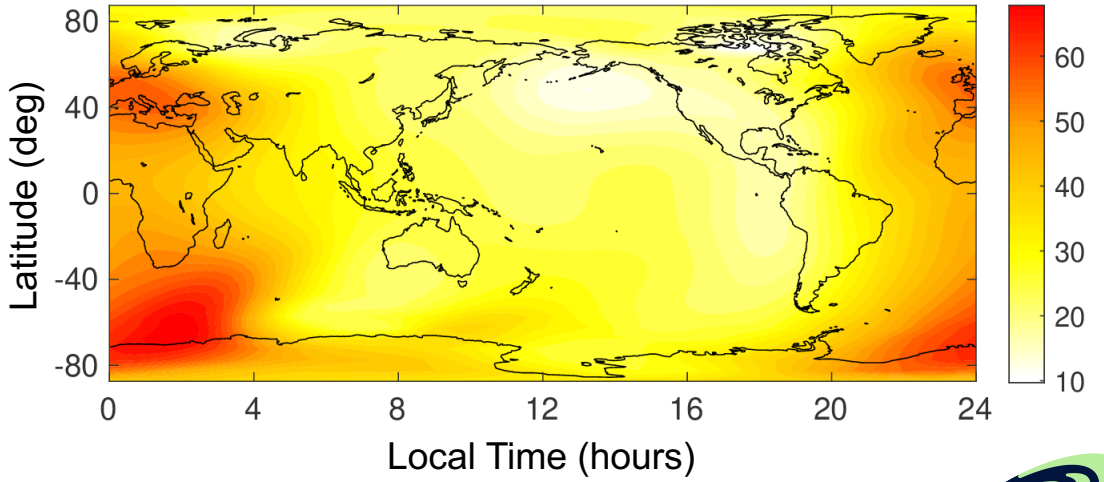

# Observational Response

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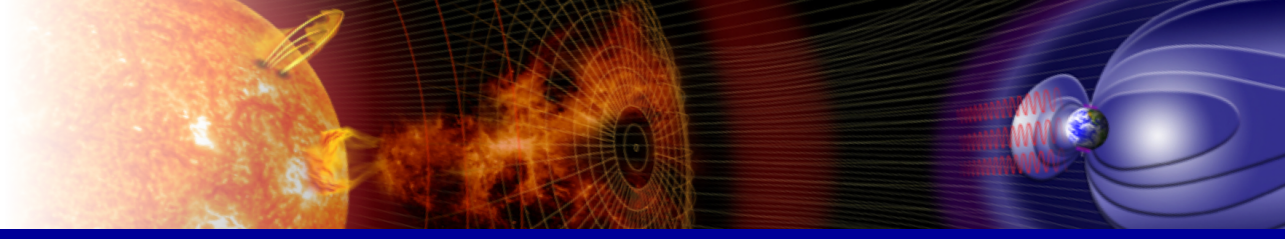
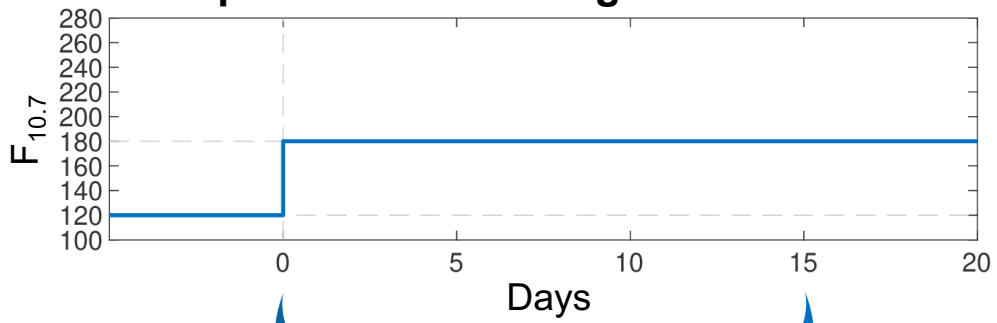


### Response to Increasing Solar Irradiance

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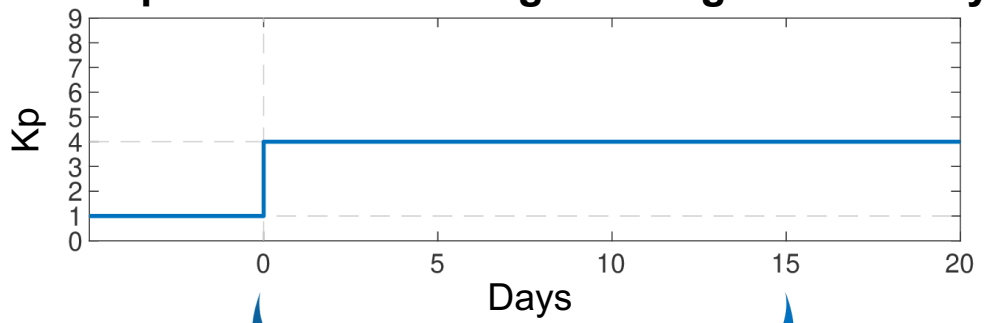
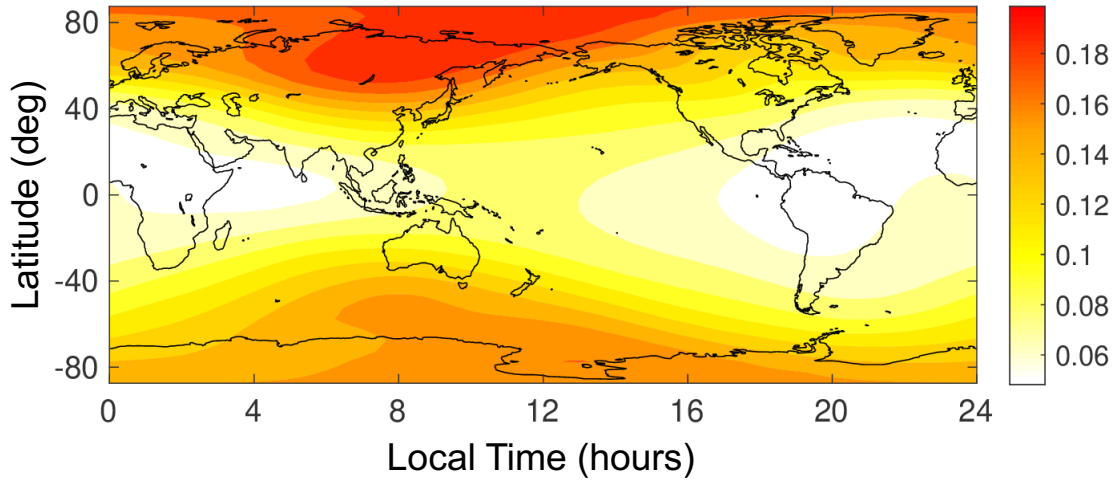



### $O/N_2$ Difference

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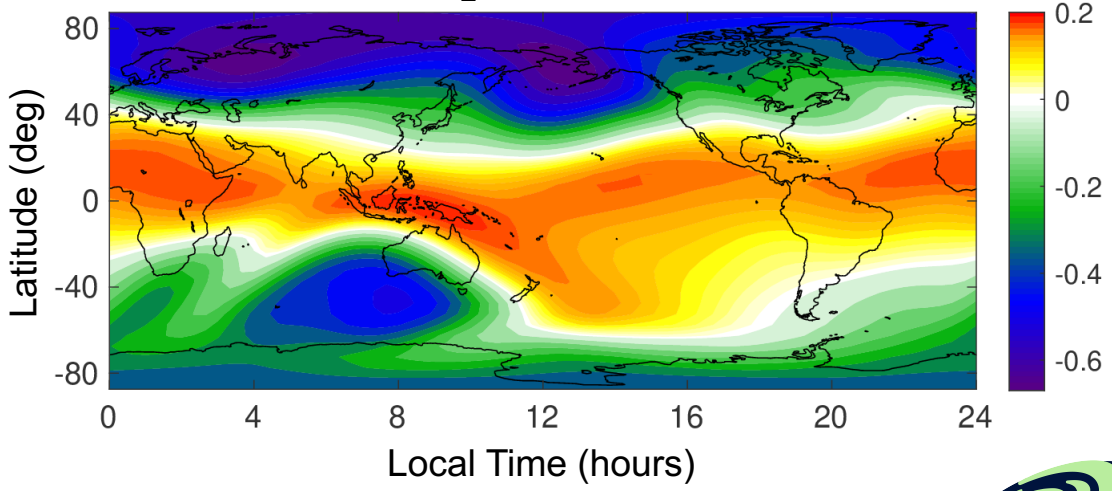


This work was made possible with support from AFOSR and the University of Colorado Grand Challenge Space Weather Center

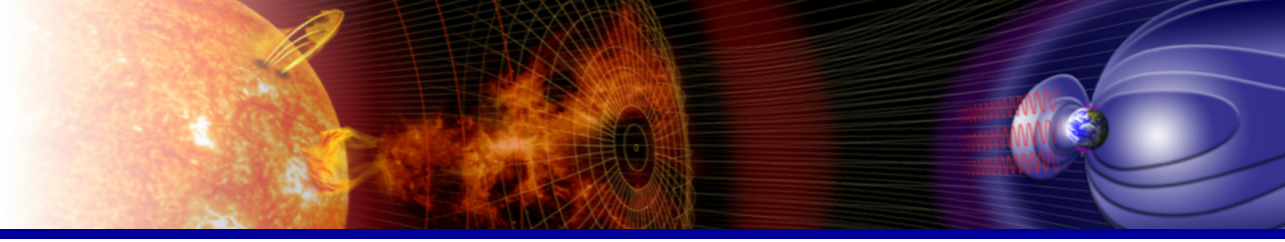
# Summary:

- LEO can be a sustainable destination for mega constellations
- Driven I-T requires a different type of data assimilation:
  Data Assimilation -> **Driver** Assimilation
- Simulation residuals are powerful tools for diagnosing internal model physics, in (approximate) isolation of external drivers
- Observations of composition complement mass densities

Thank you!

# External Drivers

## Observed vs. Estimated



**The estimated $F_{10.7}$ time series resembles the actual**

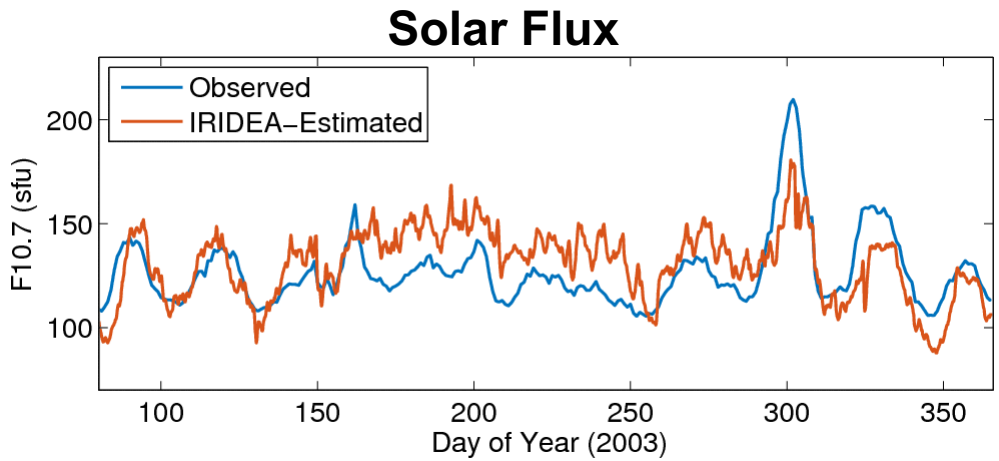
- Solar rotational modulation is evident
- But, the spikes are probably not representative of EUV variations

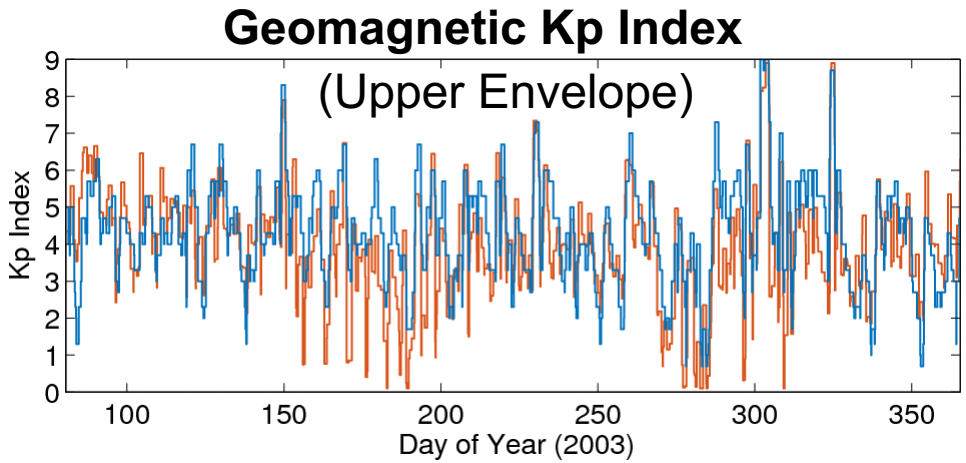
**The estimated Kp time series *somewhat* resembles the actual**

- Better correlation when a daily running-maximum filter is applied
- Does TIE-GCM have a problem cooling down **or** is correlation of the estimated drivers causing this?

**How do we better disentangle solar vs. geomagnetic influences?**

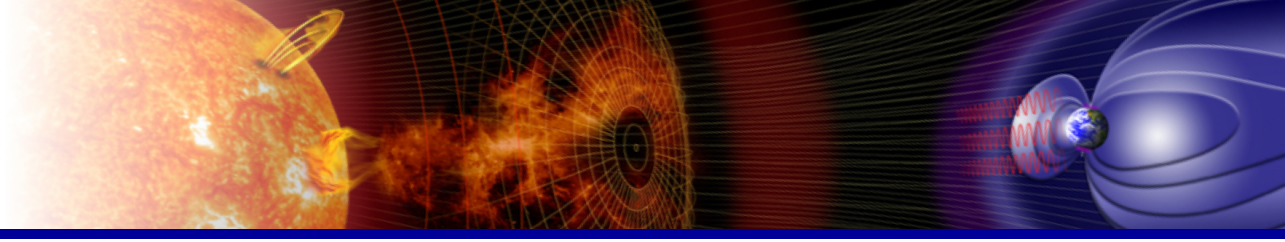
- Improve data coverage?
- Incorporate data types with better information content?
- Incorporate actual drivers into the mix?



# Model Performance Metrics

## Day 80-365, 2003



| | TIE-GCM GPI | IRIDEA | | JB-08 | MSIS | HASDM |
|---|---|---|---|---|---|---|
| | | Prior | Posterior | | | |
| CHAMP | | | | | | |
| $\mu(m/o)$ | 1.02 | 1.01 | 1.01 | 0.99 | 1.09 | 1.01 |
| $\sigma(m/o)$ | 22.2% | 6.1% | 3.3% | 13.1% | 17.4% | 5.1% |
| RMSe | 22.3% | 6.2% | 3.6% | 13.1% | 20.2% | 5.1% |
| GRACE-A | | | | | | |
| $\mu(m/o)$ | 1.03 | 1.00 | 1.01 | 0.99 | 1.13 | 0.98 |
| $\sigma(m/o)$ | 27.0% | 10.3% | 7.6% | 17.2% | 22.4% | 6.8% |
| RMSe | 27.3% | 10.4% | 7.6% | 17.2% | 26.6% | 7.2% |

Ingested Data

Independent Validation Data

Metrics

$$\mathrm{RMSe} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)^2}$$

$$\mu(m/o) = \exp\left(\frac{1}{N}\sum_{n=1}^{N}\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)$$

$$\sigma(m/o) = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}} - \ln\mu(m/o)\right)^2}$$

RMSe can be partitioned between model bias/offset (μ) and variance (σ):

$$\mathrm{RMSe}^2 = \ln(\mu(m/o))^2 + \sigma(m/o)^2$$