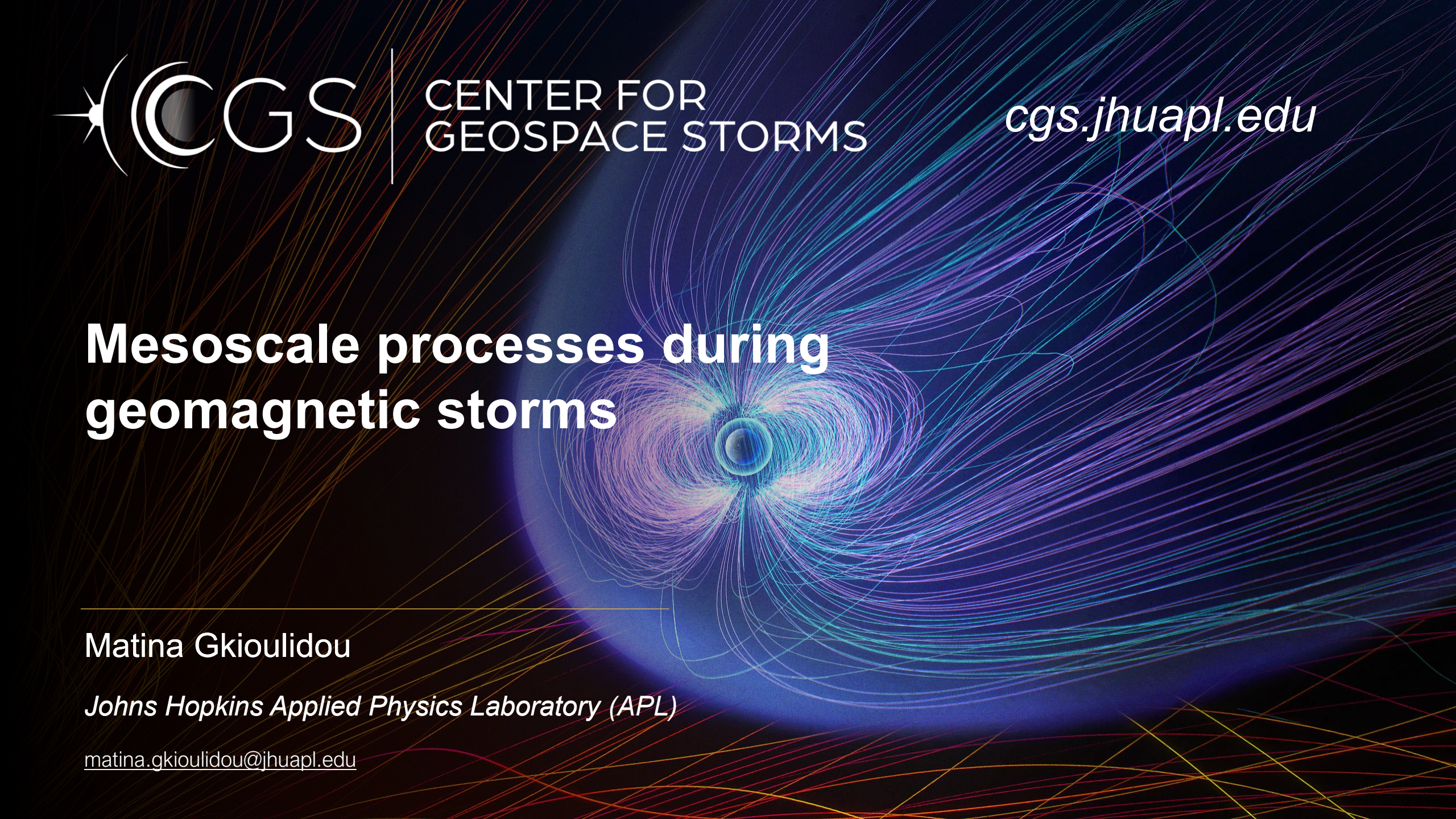
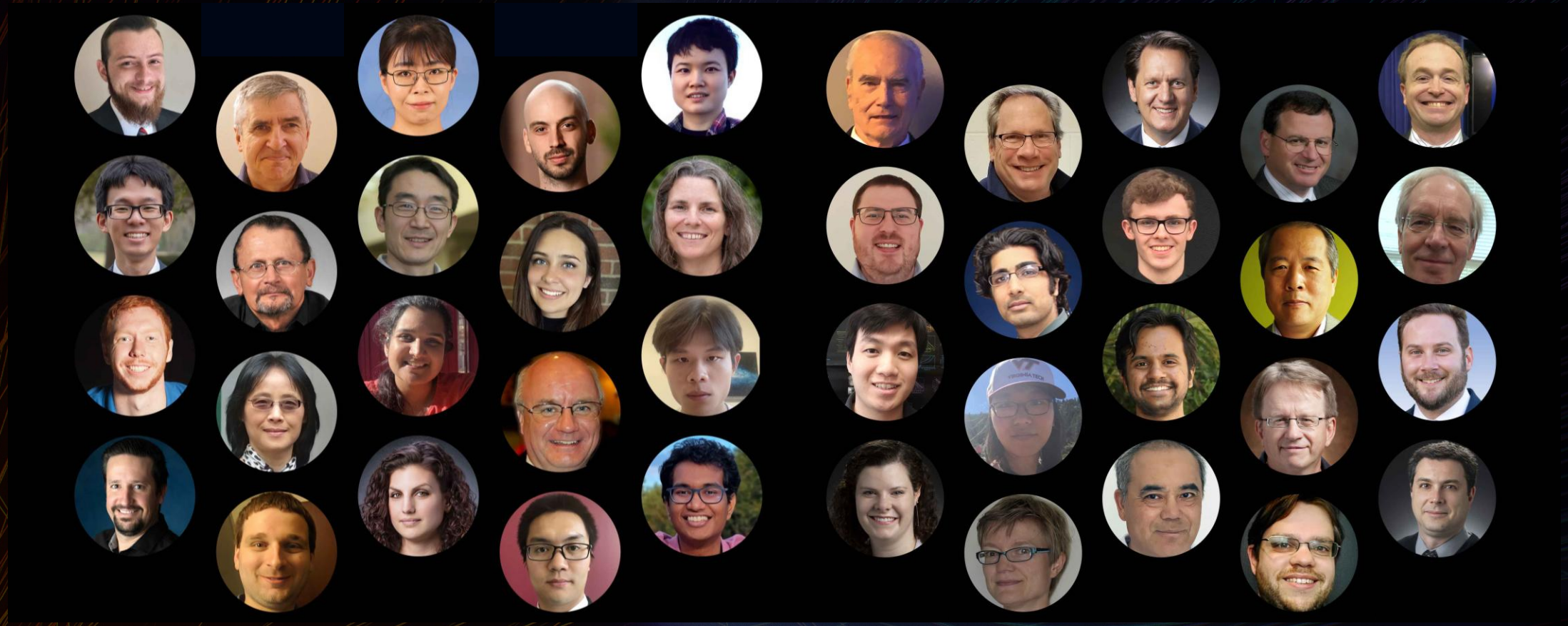


Mesoscale processes during geomagnetic storms

Matina Gkioulidou

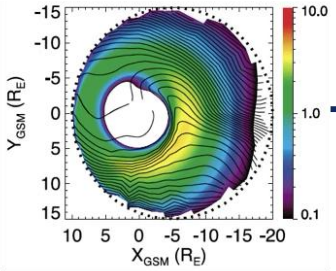
Johns Hopkins Applied Physics Laboratory (APL)

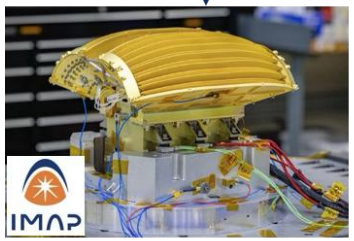
matina.gkioulidou@jhuapl.edu

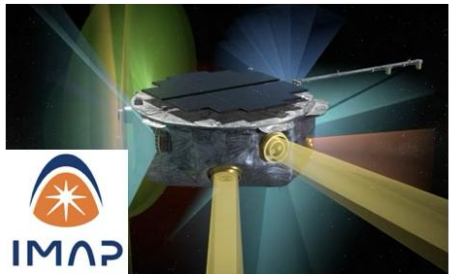


Who am I?

- Physics major - turned ring-current modeler - turned NASA's Van Allen Probes mission data analyst - turned instrument lead on NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission - turned project scientist of the IMAP mission
- Today I am wearing my Center for Geospace Storms (CGS) Data Analysis Section Head







Lessons Learned

- Trying something new can lead you to something you never imagined you'd enjoy doing.
- Just like NO model is perfect, NO Data is perfect either! If anything, it takes a LOT of work to make it as good as possible.

frontiers | Frontiers in Astronomy and Space Sciences

TYPE Review
PUBLISHED 27 April 2023
DOI 10.3389/fspas.2023.1151339

OPEN ACCESS

EDITED BY
Jay R. Johnson,
Andrews University, United States

REVIEWED BY
Victor Sergeev,
Saint Petersburg State University, Russia
Maria Alexeevna Shukhtina,
Saint-Petrsburg State University, Russia
Xu-Zhi Zhou,
Peking University, China
Gaeta Zimbardo,
University of Calabria, Italy

*CORRESPONDENCE
Christine Gabrielse,
christine.gabrielse@aero.org

RECEIVED 26 January 2023
ACCEPTED 14 April 2023
PUBLISHED 27 April 2023

CITATION
Gabrielse C, Gkioulidou M, Merkin S, Malaspina D, Turner DL, Chen MW, Ohtani S-i, Nishimura Y, Liu J, Birn J, Deng Y, Runov A, McPherron RL, Keesee A, Yin Lui AT, Sheng C, Hudson M, Gallardo-Lacourt B, Angelopoulos V, Lyons L, Wang C-P, Spanswick EL, Donovan E, Kaeppler SR, Sorathia K, Kepko L and Zou S (2023), Mesoscale phenomena and their contribution to the global response: a focus on the magnetotail transition region and magnetosphere-ionosphere coupling. *Front. Astron. Space Sci.* 10:1151339. doi: 10.3389/fspas.2023.1151339

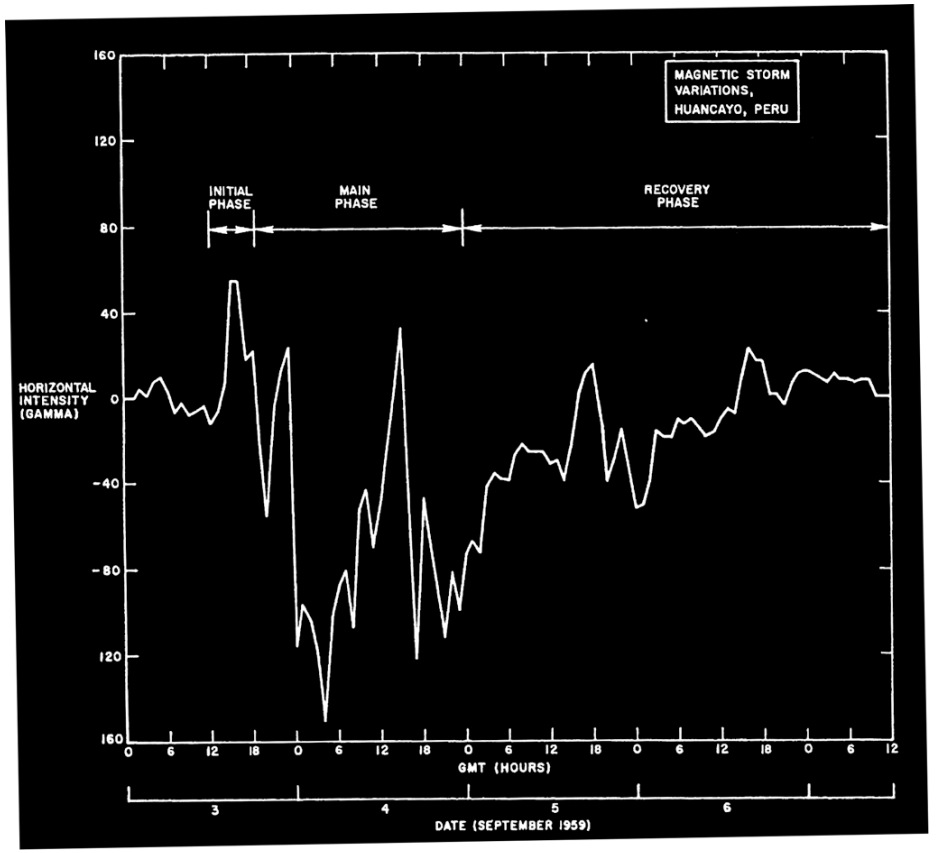
Mesoscale phenomena and their contribution to the global response: a focus on the magnetotail transition region and magnetosphere-ionosphere coupling

Christine Gabrielse[1]*, Matina Gkioulidou[2], Slava Merkin[2], David Malaspina[3], Drew L. Turner[2], Margaret W. Chen[1], Shin-ichi Ohtani[2], Yukitoshi Nishimura[4], Jiang Liu[5,6], Joachim Birn[7], Yue Deng[8], Andrei Runov[5], Robert L. McPherron[5], Amy Keesee[9], Anthony Tat Yin Lui[2], Cheng Sheng[8], Mary Hudson[10,11], Bea Gallardo-Lacourt[12,13], Vassilis Angelopoulos[5], Larry Lyons[6], Chih-Ping Wang[6], Emma L. Spanswick[14], Eric Donovan[14], Stephen Roland Kaeppler[15], Kareem Sorathia[2], Larry Kepko[12] and Shasha Zou[16]

[1]The Aerospace Corporation, El Segundo, CA, United States, [2]John Hopkins Applied Physics Laboratory, Laurel, MD, United States, [3]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, United States, [4]Electrical and Computer Engineering Department, Boston University, Boston, MA, United States, [5]Earth, Planetary, and Space Sciences Department, University of California, Los Angeles, Los Angeles, CA, United States, [6]Atmospheric and Ocean Sciences Department, UCLA, Los Angeles, CA, United States, [7]Space Science Institute, Boulder, CO, United States, [8]Department of Physics, University of Texas, Arlington, TX, United States, [9]Department of Physics and Astronomy and Space Science Center, University of New Hampshire, Durham, NH, United States, [10]Department of Physis and Astronomy, Dartmouth College, Hanover, NH, United States, [11]NCAR HAO, Boulder, CO, United States, [12]NASA Goddard Space Flight Center, Greenbelt, MD, United States, [13]The Catholic University of America, Department of Physics, Washington, DC, United States, [14]Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada, [15]Department of Physics and Astronomy, Clemson University, Clemson, SC, United States, [16]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, United States

Magnetic Field Variations During Geomagnetic Storms

Adolf Schmidt
(1860-1944)



In 1916 Adolf Schmidt attributed the “main phase decrease” of the horizontal component o
the magnetic to the existence of a ring current.

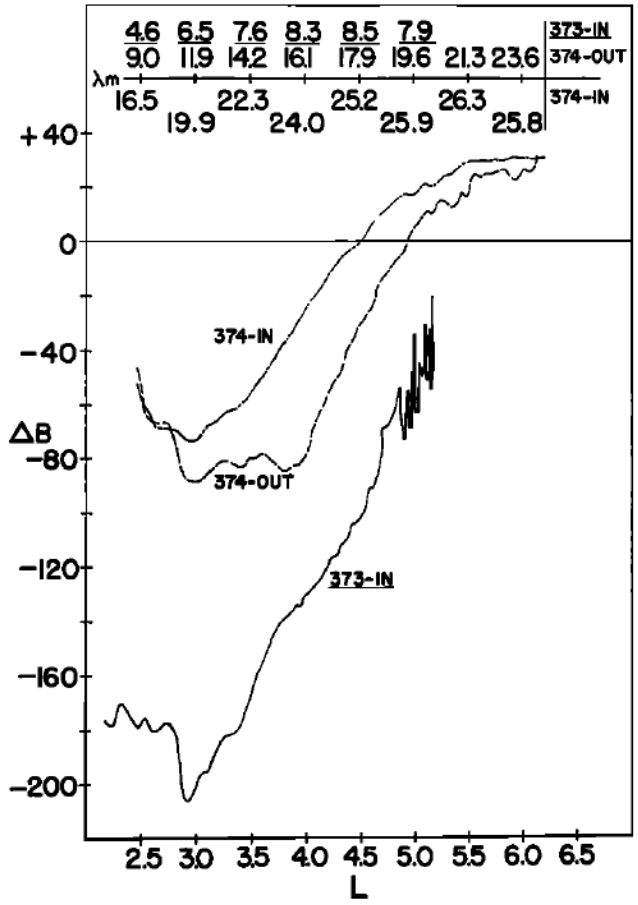
Inflation of the Inner Magnetosphere During a Geomagnetic Storm

Inflation of the Inner Magnetosphere during a Magnetic Storm

LAURENCE J. CAHILL, JR.

University of California, San Diego, at La Jolla

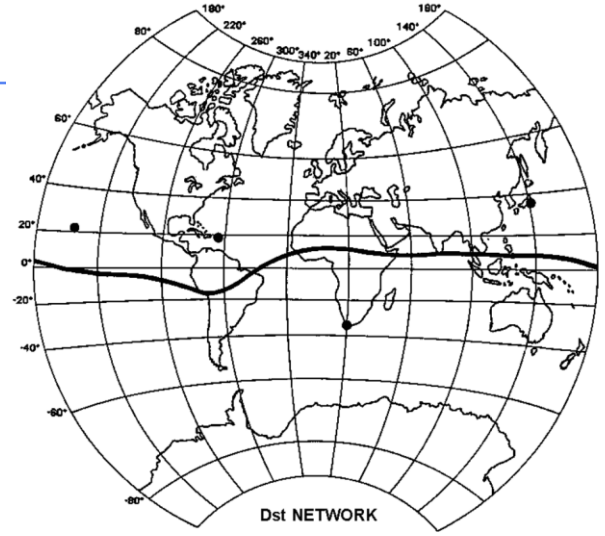
A great magnetic storm commenced on April 17, 1965. Explorer 26 carried a moving magnetic observatory through the inner magnetosphere, $L = 2$ to $L = 6$, many times during the development and recovery of the storm. The main phase was asymmetrical and was apparently caused by the rapid growth of a large body of charged particles in the evening and late afternoon quadrants. The recovery phase was more symmetrical and appears to be due to inflation of the magnetosphere by a belt, centered at $L = 3.5$ on the equator, of charged particles encircling the earth. The decay time constant of this belt was about 4 days.

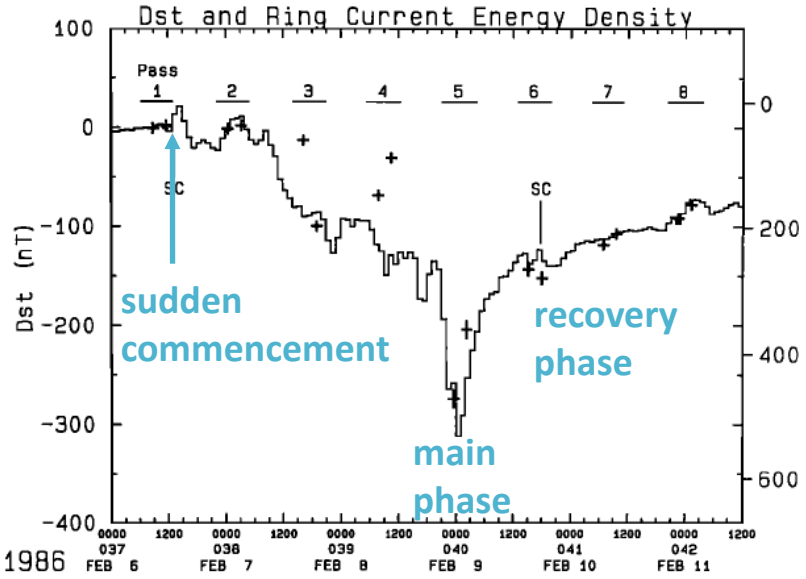


Cahill, [1966]

Disturbance storm time (Dst) Index

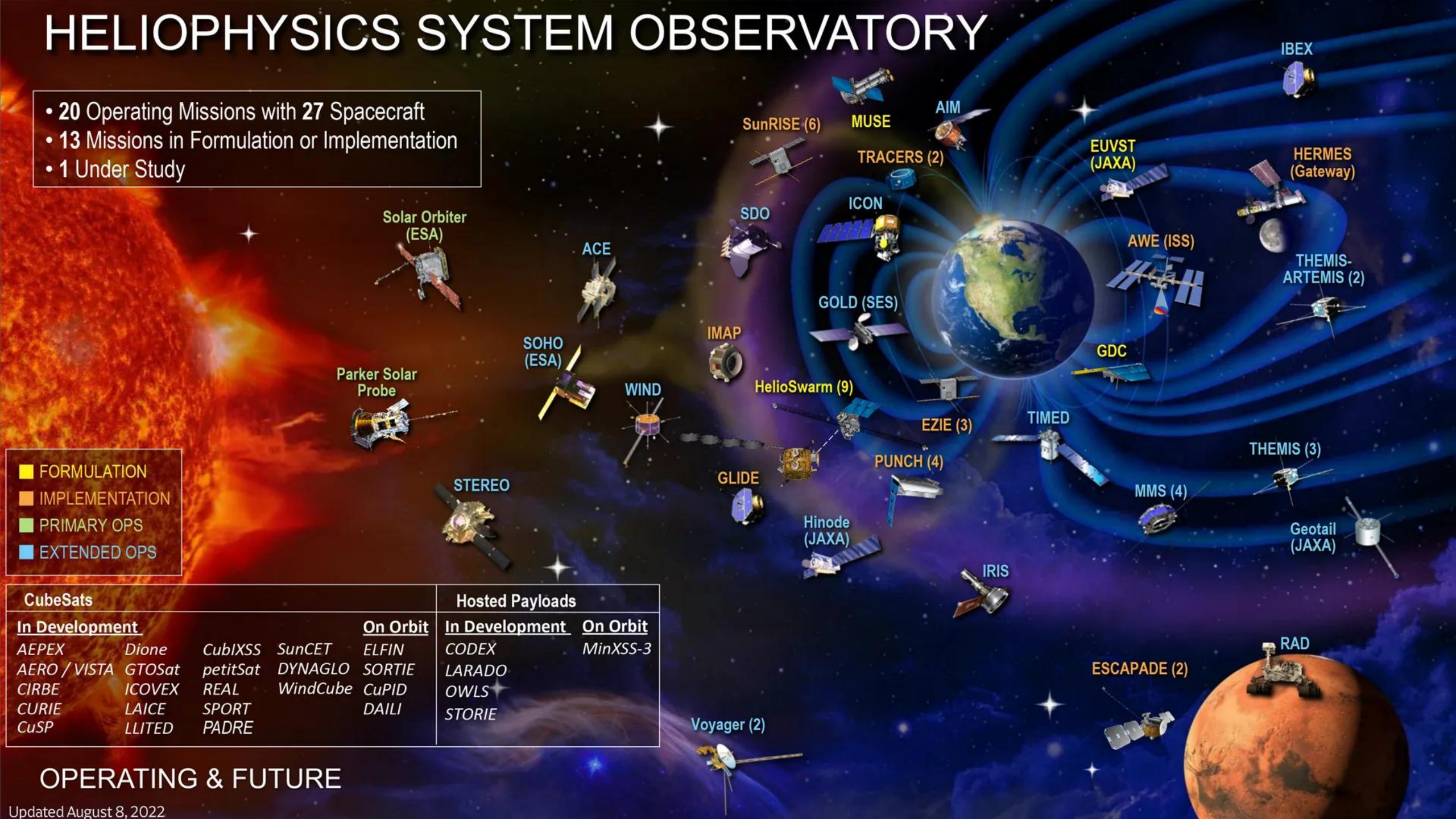
- Dst index is an index measuring the disturbance of the horizontal component of the ground magnetic field (array of equatorial magnetometers around the globe)
- Based on the Dst index variation, the evolution of a typical geomagnetic storm is divided into:
  - sudden commencement
  - main phase
  - recovery phase





HELIOPHYSICS SYSTEM OBSERVATORY

- **20** Operating Missions with **27** Spacecraft
- **13** Missions in Formulation or Implementation
- **1** Under Study



- FORMULATION
- IMPLEMENTATION
- PRIMARY OPS
- EXTENDED OPS

CubeSats					Hosted Payloads	
In Development				**On Orbit**	**In Development**	**On Orbit**
AEPEX	*Dione*	*CubIXSS*	*SunCET*	*ELFIN*	*CODEX*	*MinXSS-3*
AERO / VISTA	*GTOSat*	*petitSat*	*DYNAGLO*	*SORTIE*	*LARADO*	
CIRBE	*ICOVEX*	*REAL*	*WindCube*	*CuPID*	*OWLS*	
CURIE	*LAICE*	*SPORT*		*DAILI*	*STORIE*	
CuSP	*LLITED*	*PADRE*				

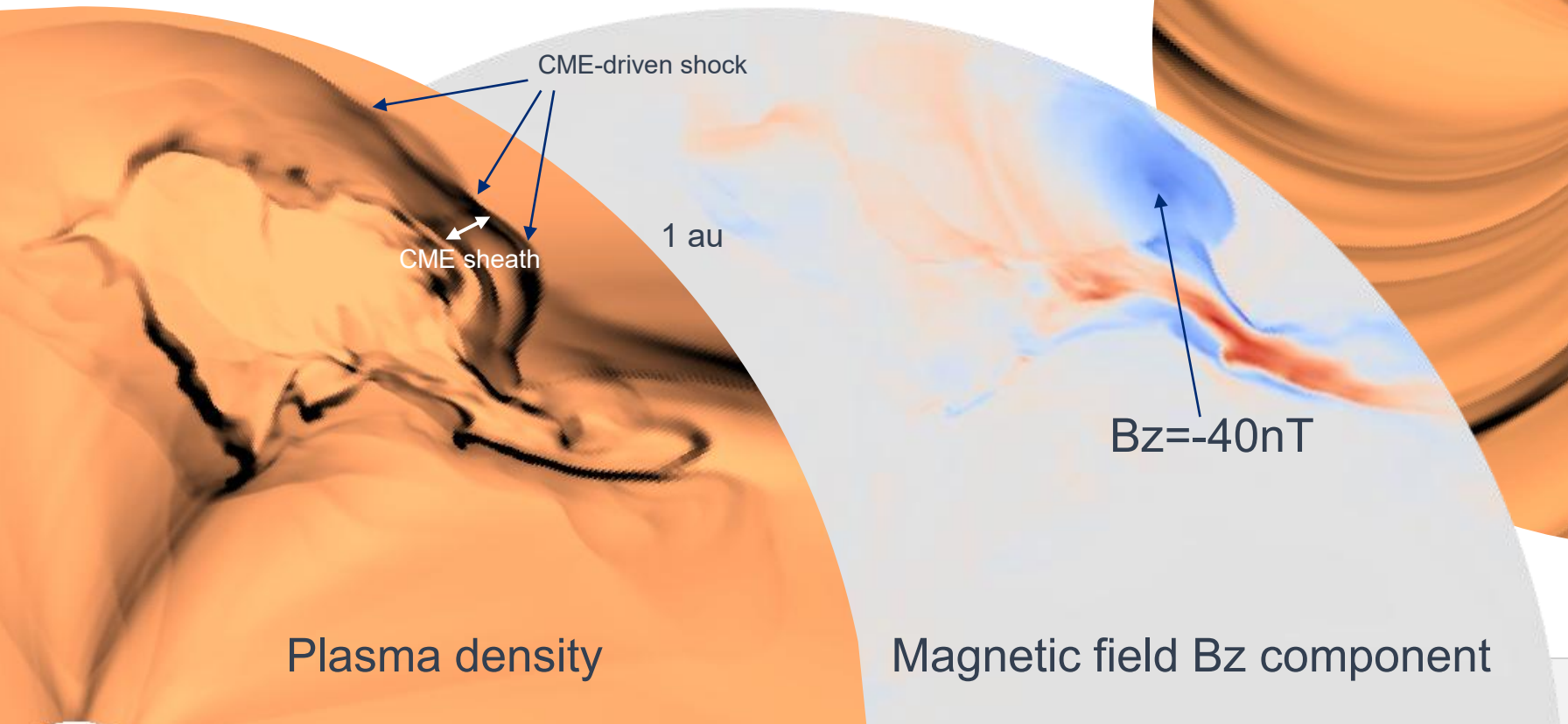
OPERATING & FUTURE

Updated August 8, 2022

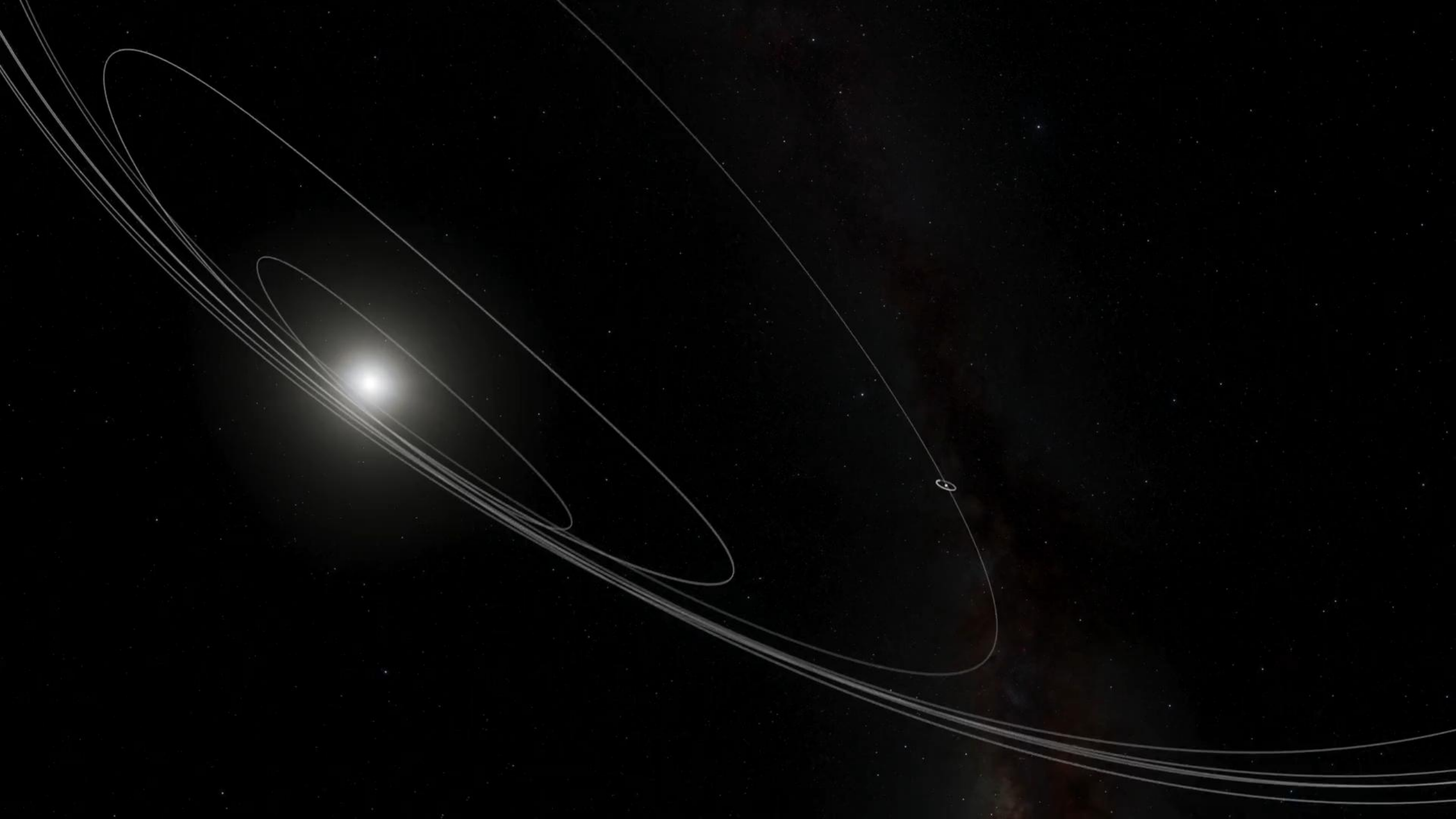
Geospace storms are unique events

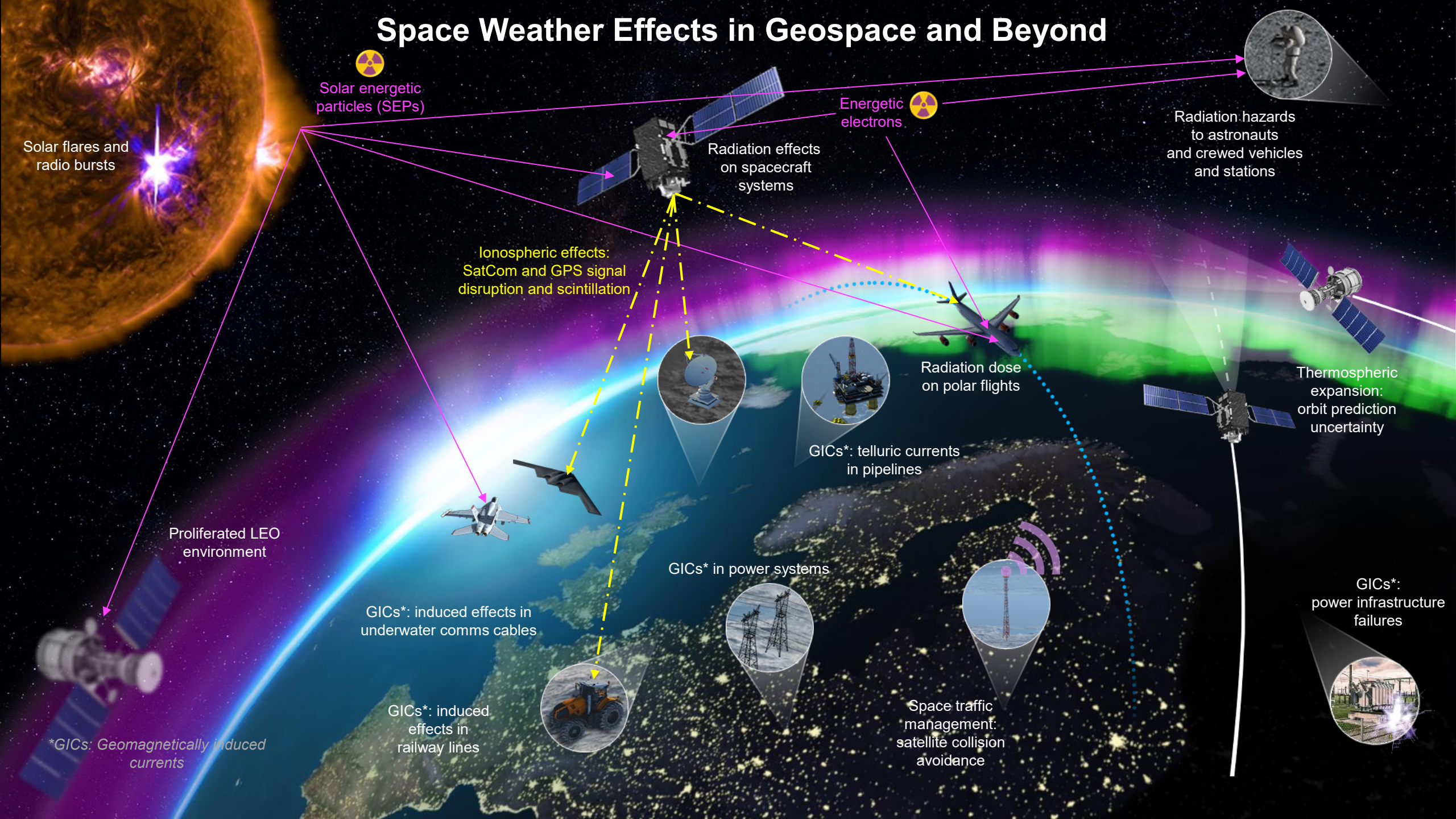
"Climbing mount improbable" (R. Dawkins)

- Geospace (geomagnetic) storms are a relatively rare occurrence and how they unravel is determined by a confluence of multiple factors across the Sun-Earth system



GAMERA-Helio simulation.
E. Provornikova
A. McCubbin (APL)

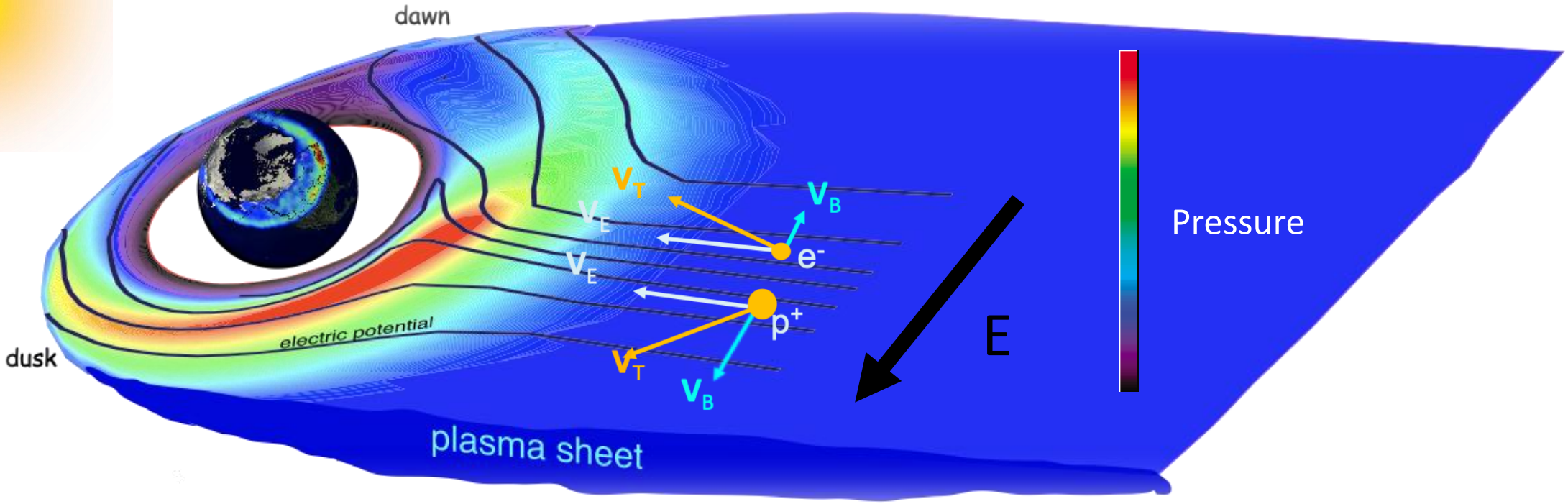



Space Weather Effects in Geospace and Beyond
Solar flares and radio bursts
Solar energetic particles (SEPs)
Energetic electrons
Radiation effects on spacecraft systems
Radiation hazards to astronauts and crewed vehicles and stations
Ionospheric effects: SatCom and GPS signal disruption and scintillation
Radiation dose on polar flights
Thermospheric expansion: orbit prediction uncertainty
GICs*: telluric currents in pipelines
Proliferated LEO environment
GICs* in power systems
GICs*: induced effects in underwater comms cables
GICs*: induced effects in railway lines
Space traffic management: satellite collision avoidance
GICs*: power infrastructure failures
*GICs: Geomagnetically induced currents

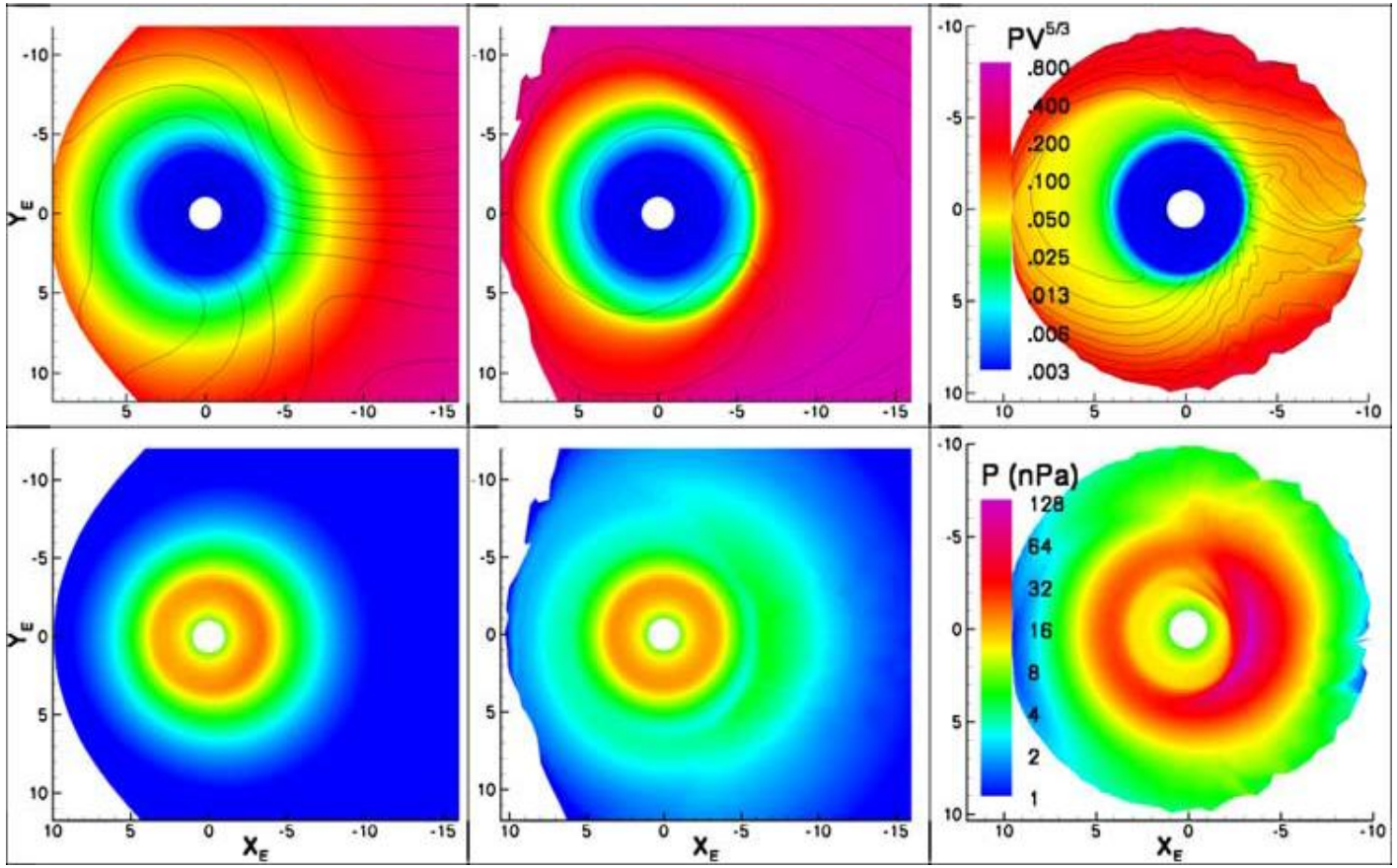
Textbook transport

Ring current

- Solar wind: protons, Helium ions
- Ionosphere: O^+
- Energies of tens to hundreds of keV

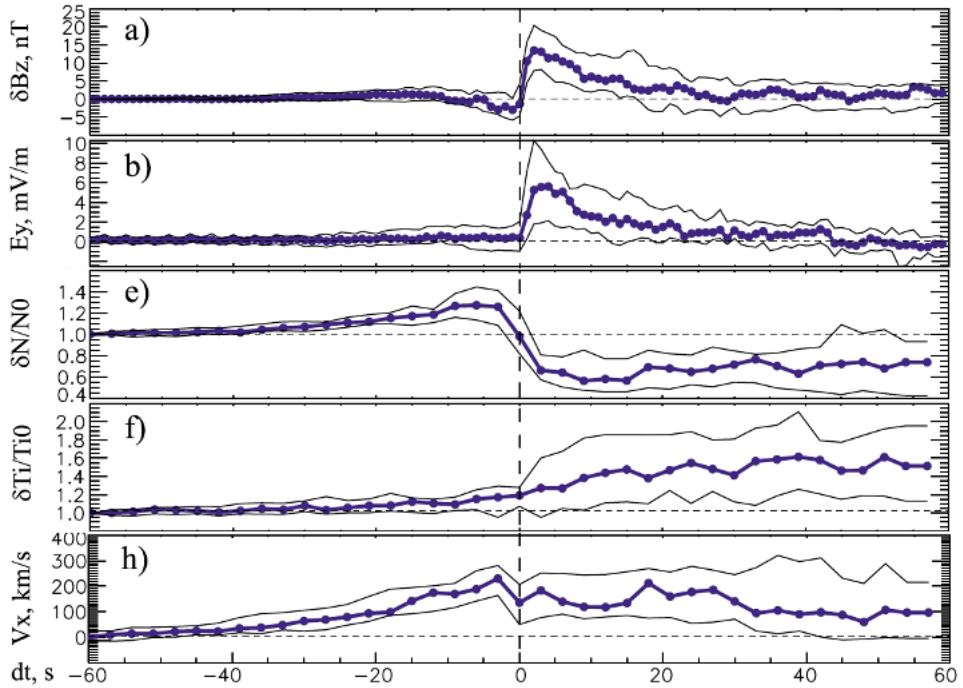


Storm time transport and acceleration with self-consistent inner magnetosphere models



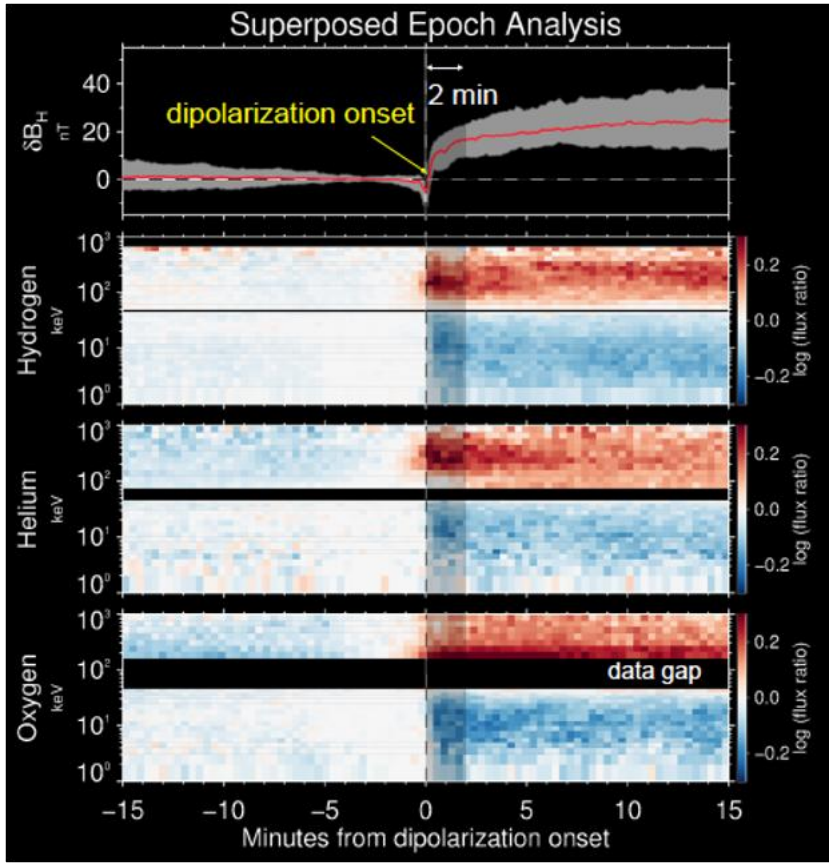
Producing storm-time ring current pressures using models with self-consistent electric (ionospheric feedback and shielding) and magnetic (force balanced) fields, under steady state convection, is a challenge.

In-Situ Observations of Mesoscale Transport In the Plasma Sheet And Inner Magnetosphere



Runov et al., 2011 [JGR]: Superposed epoch analysis of dipolarization fronts and the associated particle and BBF signatures ***in the plasma sheet***, based on THEMIS data

- *Plasma Sheet (~10-20 R_E from Earth):*
  - Bursty Bulk Flows (BBFs),
  - Dipolarization Fronts (DFs),
- *Inner Magnetosphere (inside GEO):*
  - Energetic ion injections



Motoba et al., 2018 [JGR]: Superposed epoch analysis of dipolarization fronts ***inside geosynchronous orbit*** based on Van Allen Probes data

Mesoscale Processes Are the Bridge Connecting the Local and Global Nature of Geospace

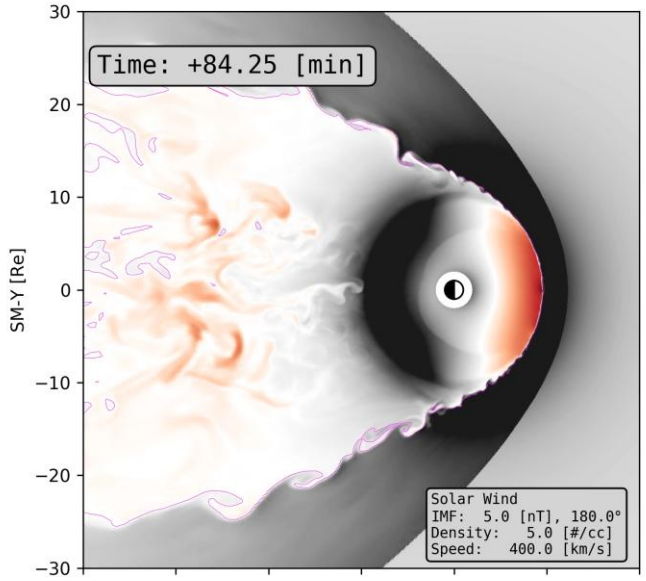
Understanding geomagnetic disturbances to the level of predictability remains elusive, because we still do not understand the mesoscale (1000 km to few R_E in the magnetotail, ~10s-100s km in the ionosphere) processes and their global implications.

Geospace is a complex system (multi-scale and multi-physics)

Tackling the “tyranny of scales”

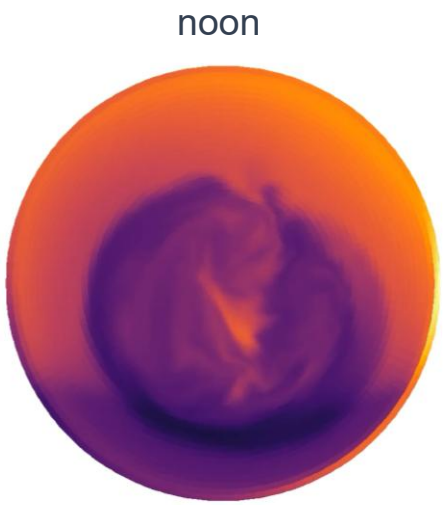
- Because of collective cross-scale interactions in stormtime geospace, understanding and predicting space weather requires models that **treat geospace as a whole**.
- **Mesoscale processes are important** because they lead to emergent global behavior.
- A “whole geospace model” must include **two-way coupling to the lower atmosphere**.

Magnetosphere



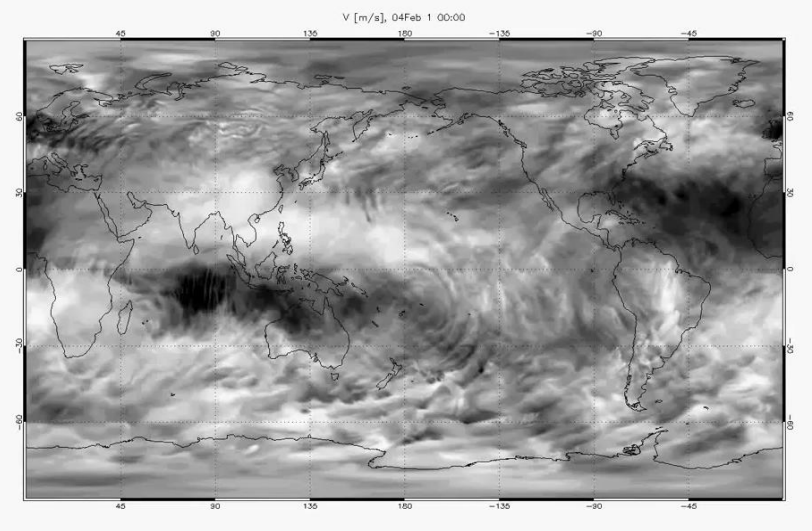
~0.1–300 Re

Ionosphere-Thermosphere



70–1,000 km

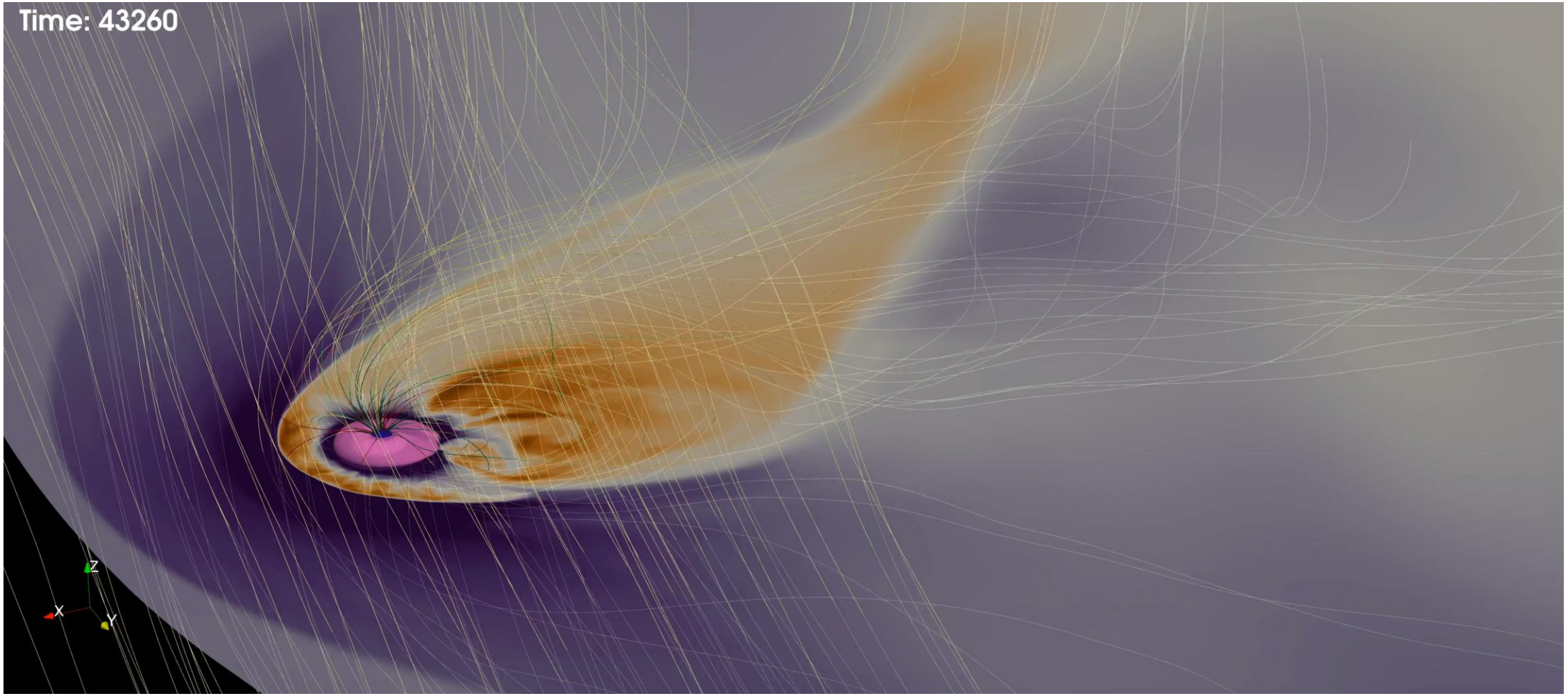
Lower & Middle atmosphere



0-70 km

A whole-of-geospace simulation of the May 2024 Superstorm

Storms are violent and dynamic disruptions of entire geospace



- Basic process of magnetospheric convection (mass and magnetic flux circulation) is still poorly understood.

Multiscale Atmosphere-Geospace Environment

from 0 to 2,000,000 km altitude

Treating and resolving
critical mesoscale processes
to discover, understand and quantify
emergent cross-scale dynamics

Magnetosphere

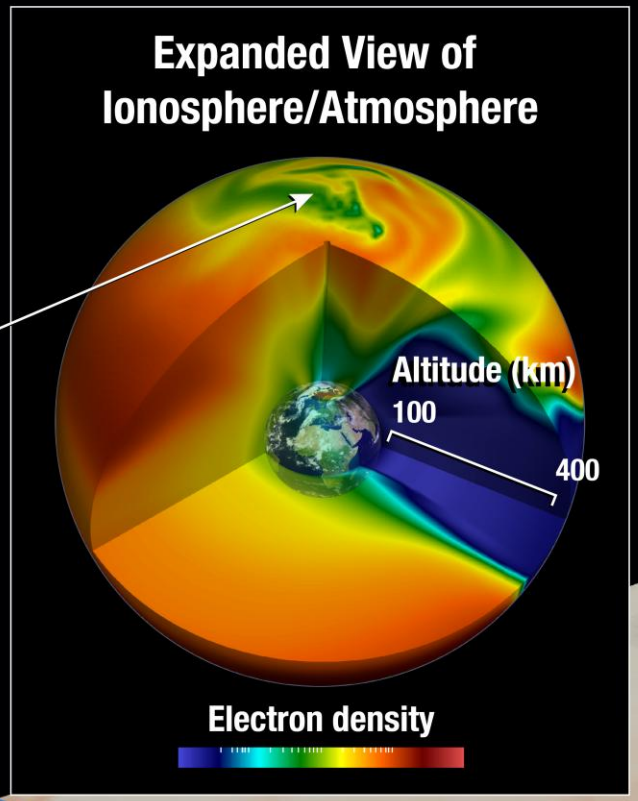
Atmosphere

Ionosphere

Solar Wind

Pressure

Magnetic Field



MAGE fulfills three key requirements:

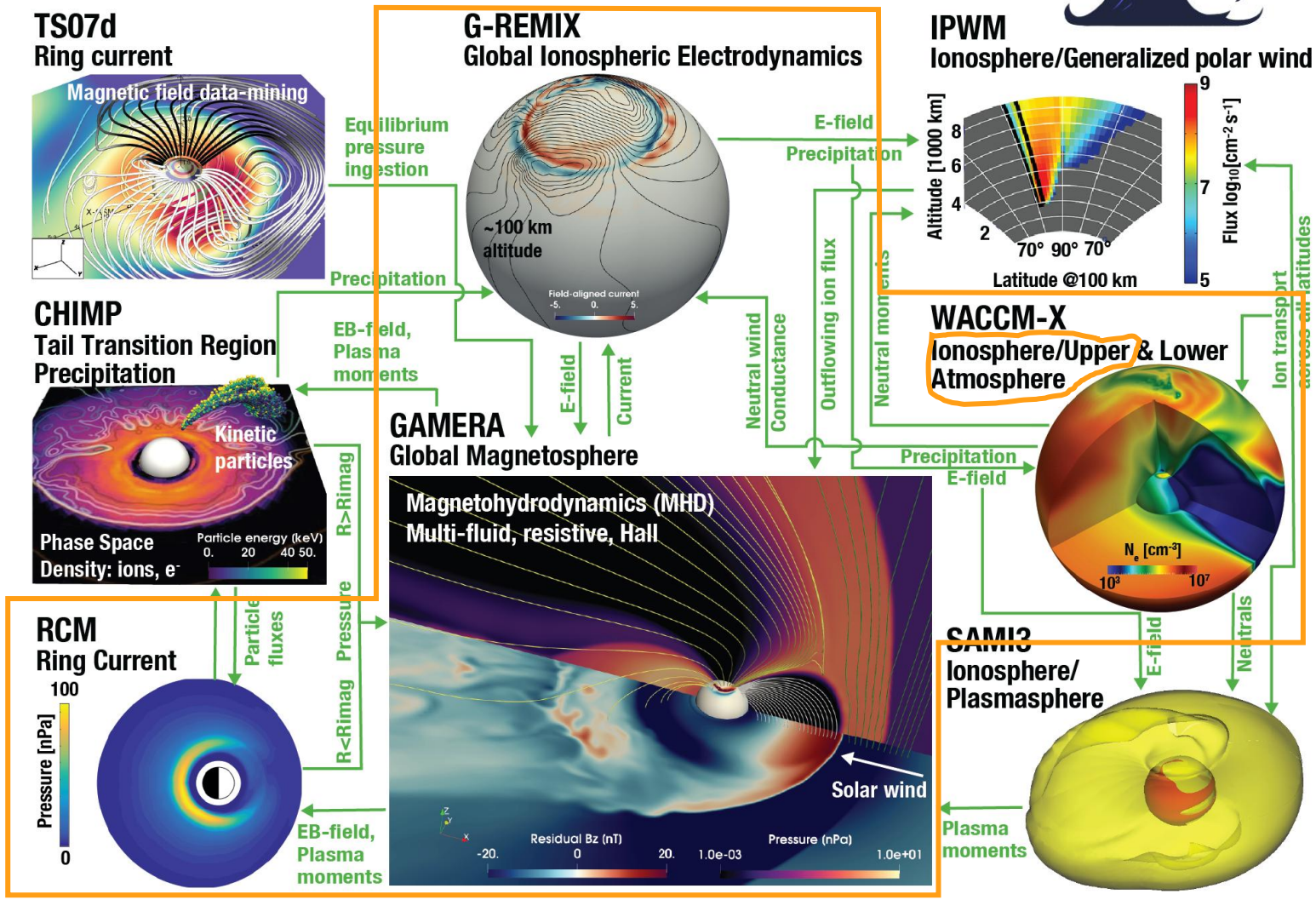
- Describes geospace as a whole
- Resolves critical mesoscale processes in all relevant domains
- Couples geospace and lower atmosphere

MAGE
Multiscale Atmosphere-Geospace Environment

cgs.jhuapl.edu/Models

The MAGE Vision

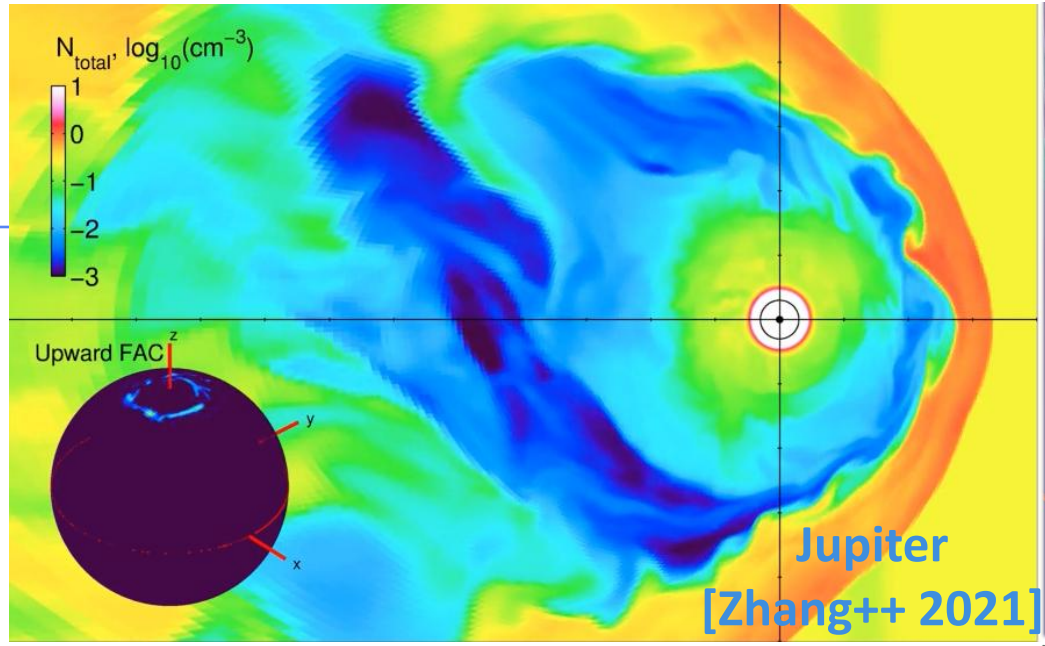
Multiscale Atmosphere-Geospace Environment

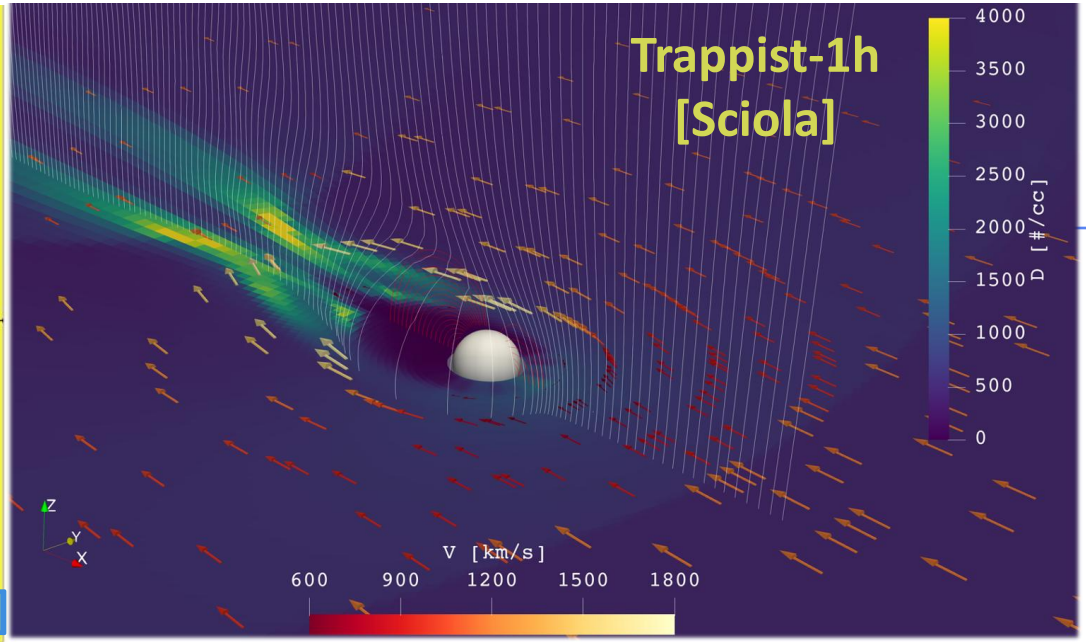


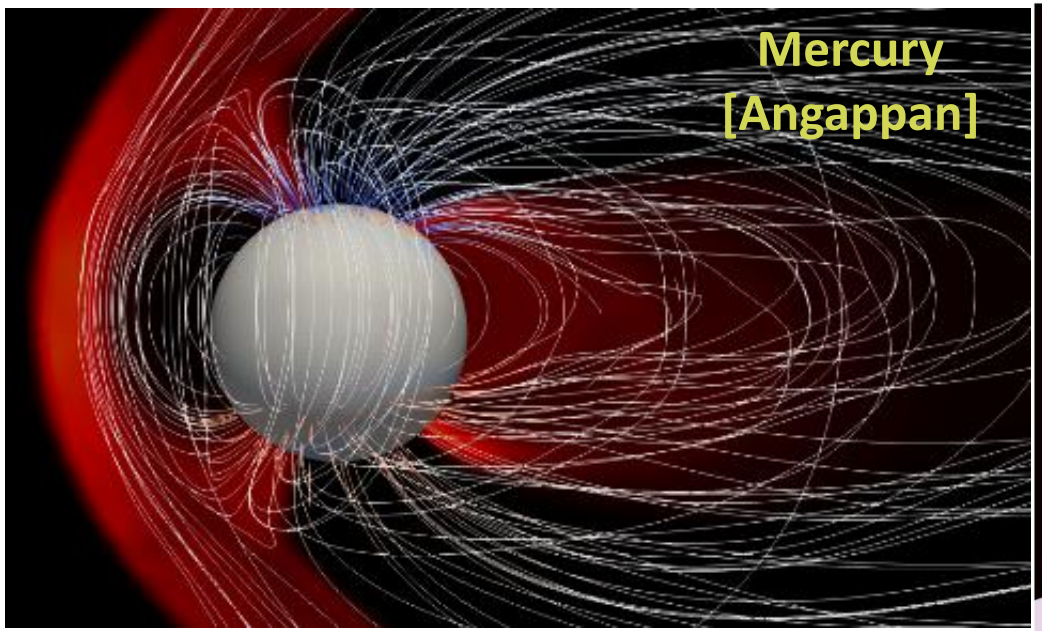
- **MAGE is a complex coupled model for studying the geospace-atmosphere system**
  - Describes geospace as a whole
  - Resolves critical mesoscale processes in all relevant domains
  - Couples geospace and lower atmosphere
- **Roadmap of CCMC and OSS releases**
  - Available for runs on request at the NASA CCMC as of April 2024

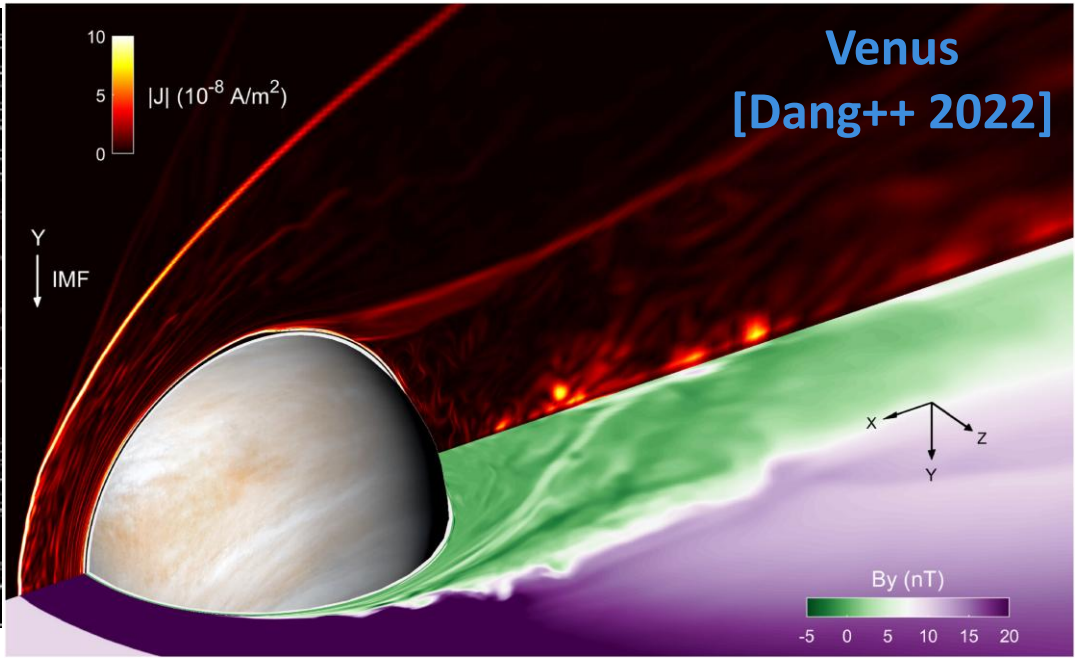
GAMERA

- Solves MHD equations on arbitrary hexahedral grids (non-orthogonal/singular coordinates)
- Modern Fortran, multiple layers of heterogeneous parallelism
- Standard (Athena) MHD tests published (Zhang et al., ApJS 2019)
- Multiple space plasma applications (Earth, Venus, Jupiter, Saturn, Mercury, heliosphere)
- Enables simulations that would be prohibitive unless high-order numerics and an adapted grid were used



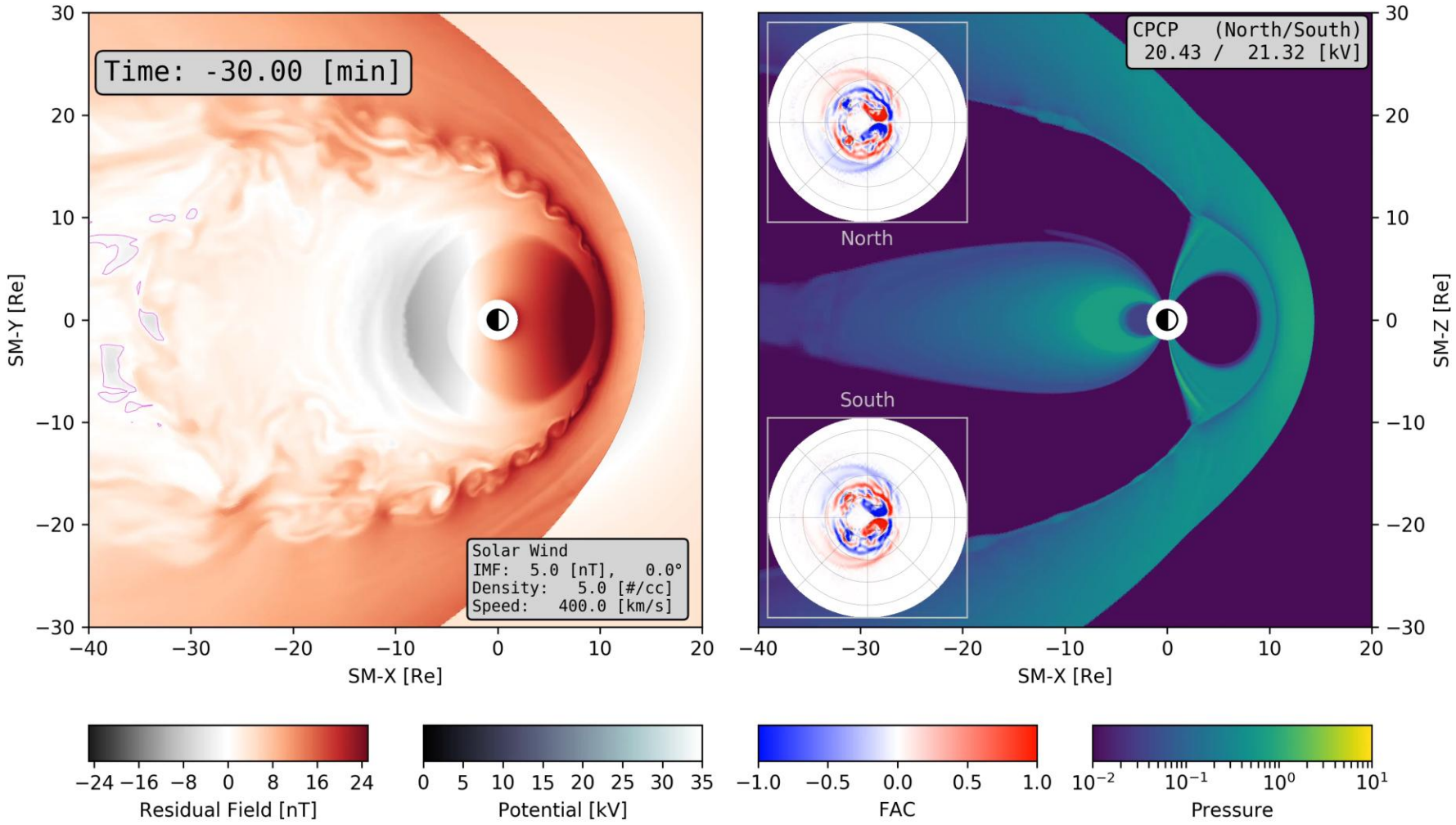




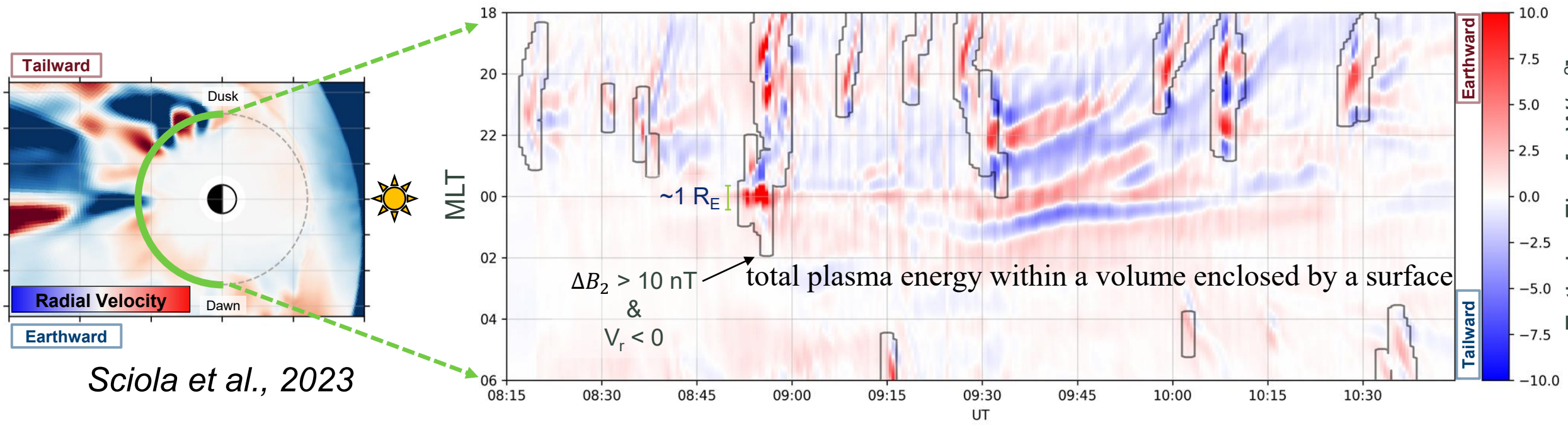


Better models mean better physics

GAMERA: The highest-resolution ever global magnetosphere simulation



Mesoscale processes with global effects:
Quantifying the contribution of BBFs/bubbles to storm-time ring current buildup



- 50% of the net Earthward transport of plasma energy through the 6 R_E arc is contained within BBFs
  - Serves as a lower bound of the total contribution of bubbles to the ring current
- Return flows (tailward flows within boxed regions) transport outward an average of 40% of thermal energy transported inwards by bubbles
  - Important to consider when quantifying the net contribution of bubbles to the ring current, just considering Earthward flows will overestimate

What is the auroral manifestation of the multi-scale, storm-time magnetospheric transport?

Mesoscale auroral forms: a manifestation of magnetospheric processes and M-I coupling

Auroral streamers

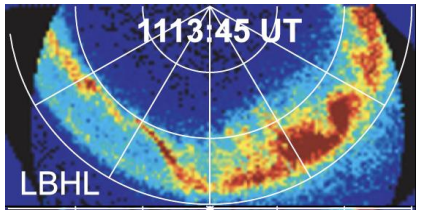
- Statistically associated with the occurrence of fast flows and injections in the nightside magnetosphere, as they have been locally observed by in-situ satellites.
- **What governs the fate of a streamer is still unknown**: sometimes they turn into omega bands and sometimes their equatorward motion is stopped leading to a larger scale west-east expanding auroral intensification, hypothesized to be associated with fast flow braking and divergence as the injections move from the more stretched outer to the more dipolarized inner magnetosphere.

Giant undulations

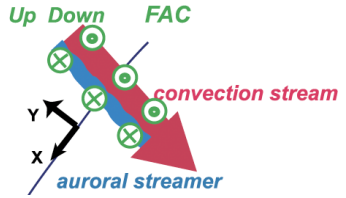
- mirror of omega bands on the equatorward edge of the duskside auroral oval observed during the early main phases of storms.
- **How to they occur?**

Omega bands

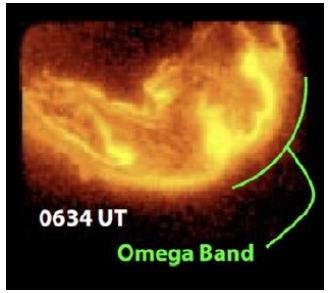
- a series of undulations on the morning auroral oval observed during the deep main phase of geomagnetic storm, co-located with potentially hazardous ground magnetic disturbances leading to geomagnetically induced currents.
- **How do they occur?**



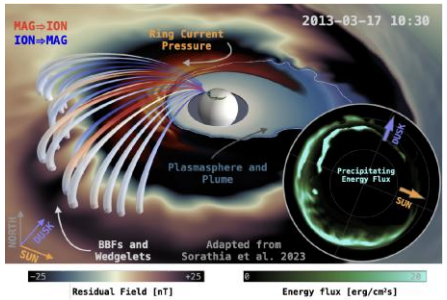
Polar UVI observations of an auroral streamer



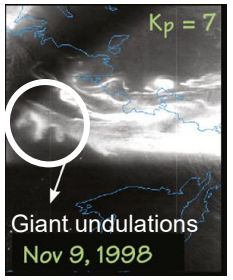
Schematic of a streamer formation



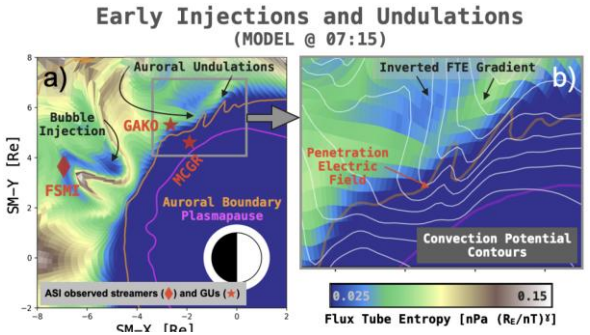
POLAR VIS images
after **Henderson et al. 2002**



Global geospace simulations of Omega bands after **Sorathia et al. 2023**



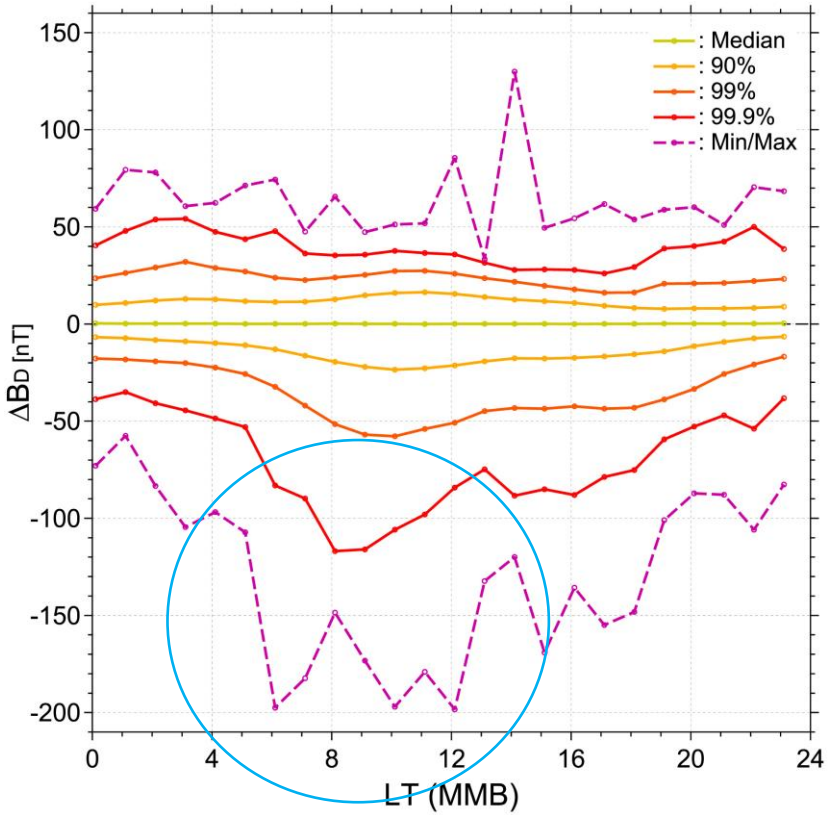
DMSP/OLS imagery
after **Henderson et al. 2010**



Global geospace simulations of Giant Undulations after **Sorathia et al. 2024**

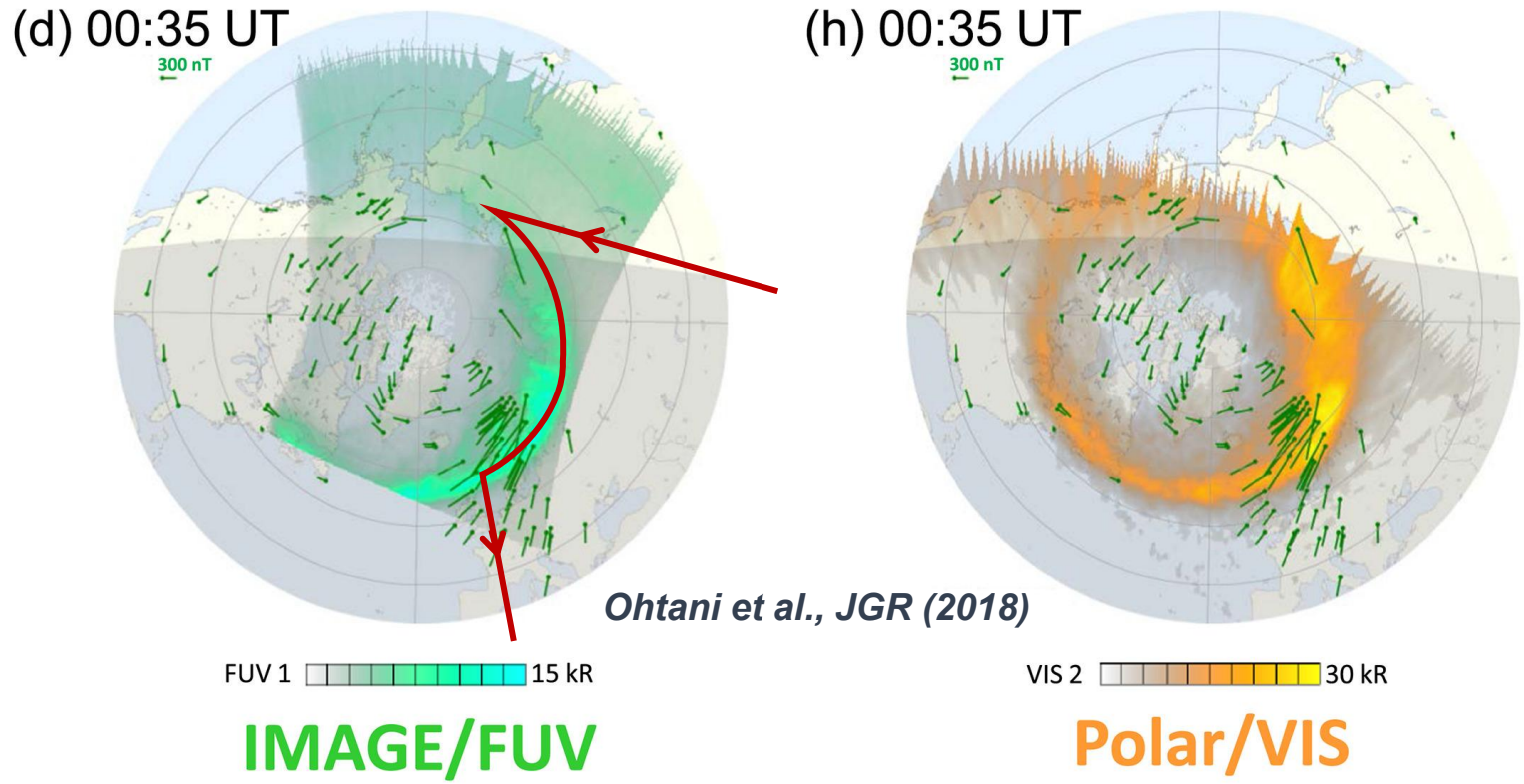
Mesoscale processes with global effects
Dawnside Current Wedge (observations)

Repetitive feature during storms



Midlatitude ground dB skewed dawnward during strong storms

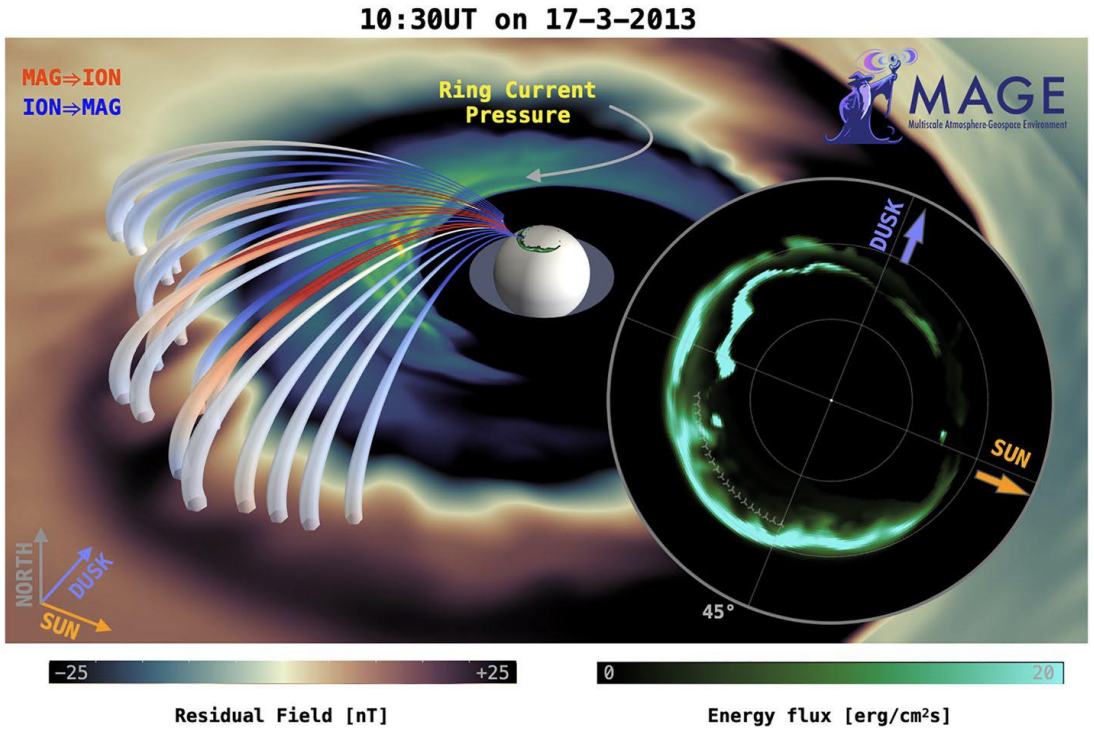
Stormtime electrojet: Dawnside wedge current system?

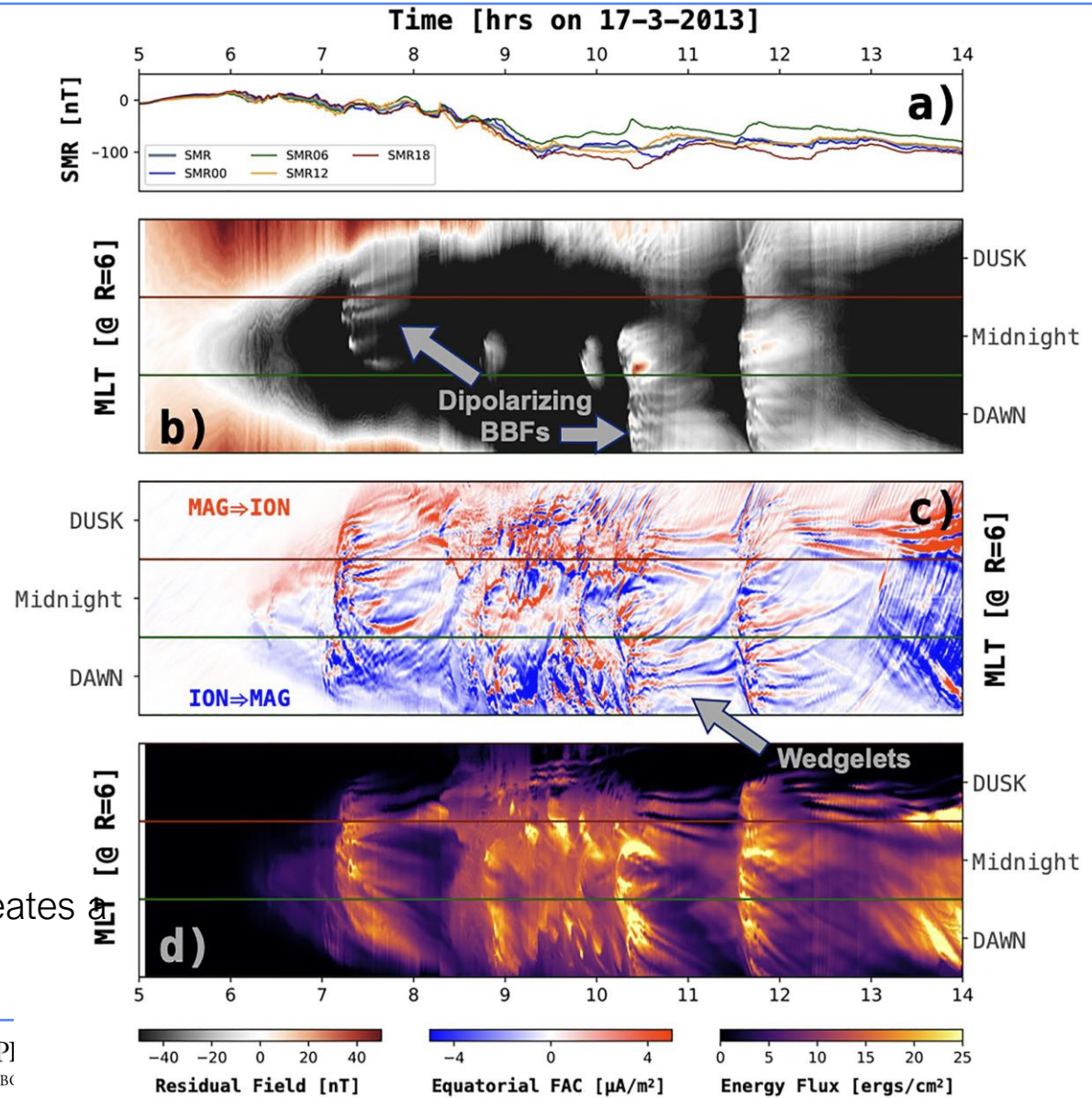


Model requirements: global magnetosphere, ring current, ionospheric outflow, plasmasphere, precipitation and thermosphere

Mesoscale processes with global effects

Dawnside Current Wedge (simulations)





- A dusk-biased ring current asymmetrically inflates the magnetotail.
- This dusk-biased inflation inhibits duskside reconnection.
- The dawnside reconnection launches mesoscale bubbles across the dawnside plasma sheet and into the inner magnetosphere, which creates a multiscale enhancement of the AEJ

Geospace is a complex system

It is coupled strongly across domains and scales

"The tyranny of scales"

Poorly constrained initial & boundary conditions

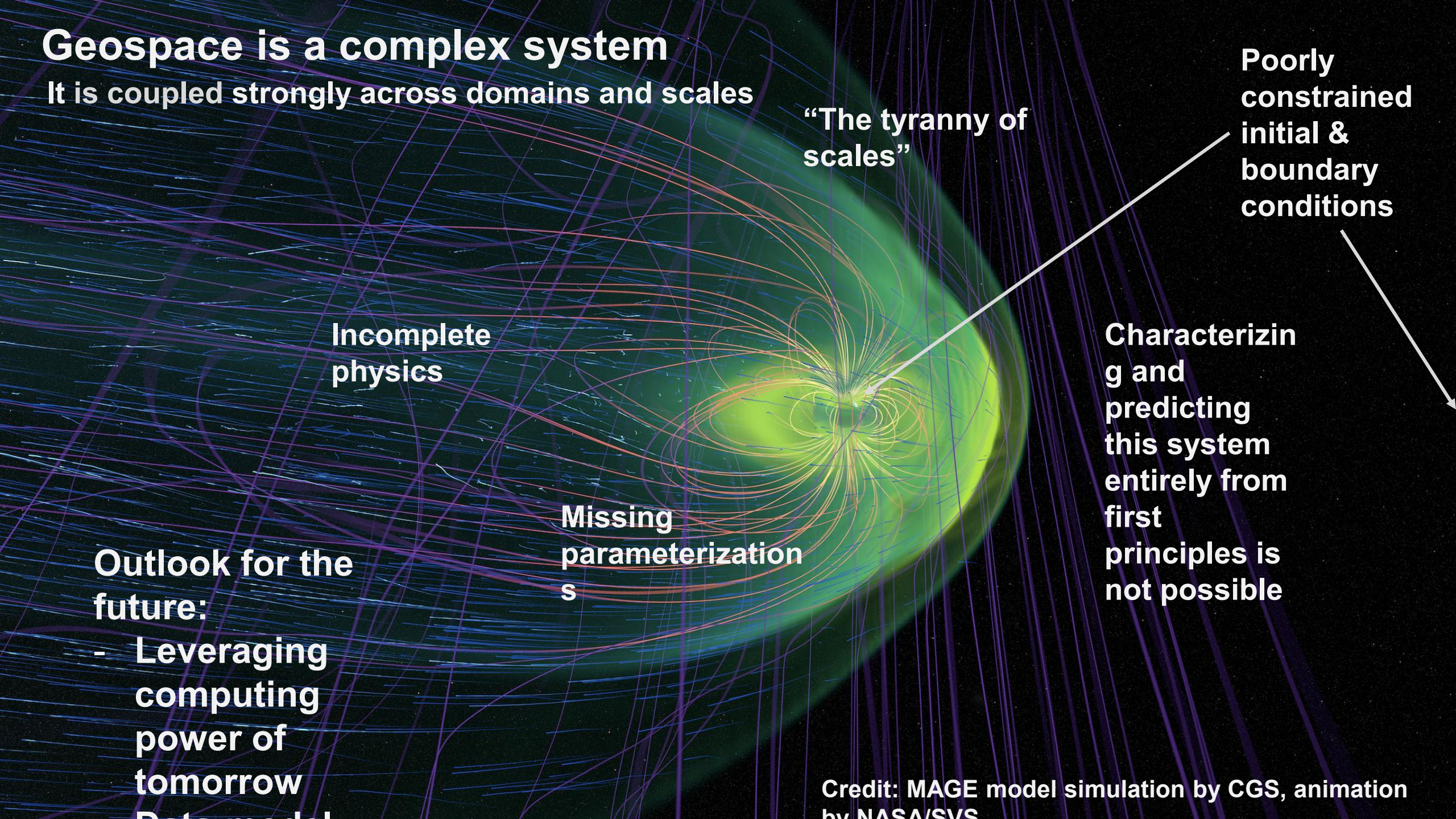
Incomplete physics

Characterizing and predicting this system entirely from first principles is not possible

Missing parameterizations

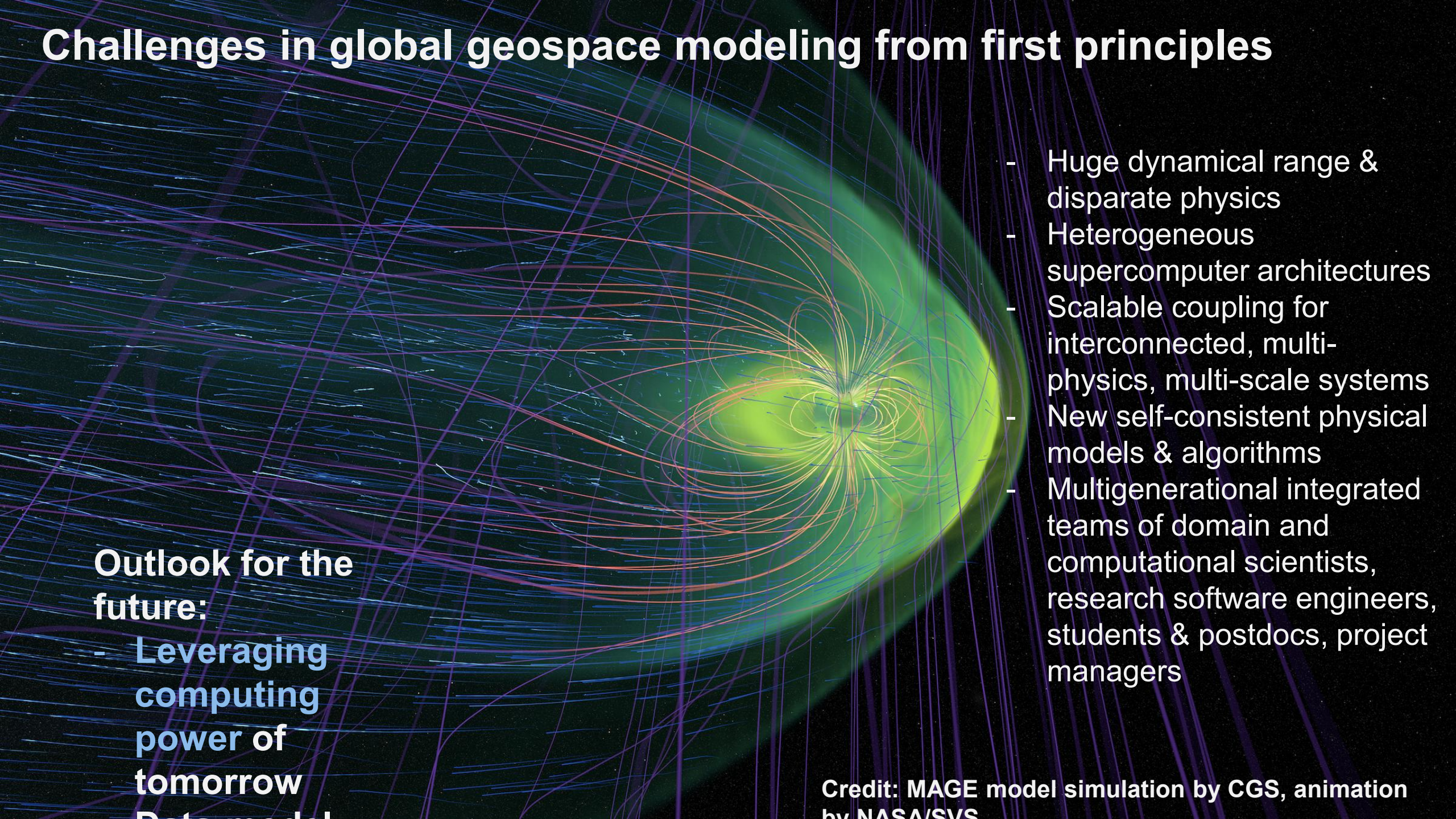
Outlook for the future:

- Leveraging computing power of tomorrow



Credit: MAGE model simulation by CGS, animation by NASA/SVS

Challenges in global geospace modeling from first principles



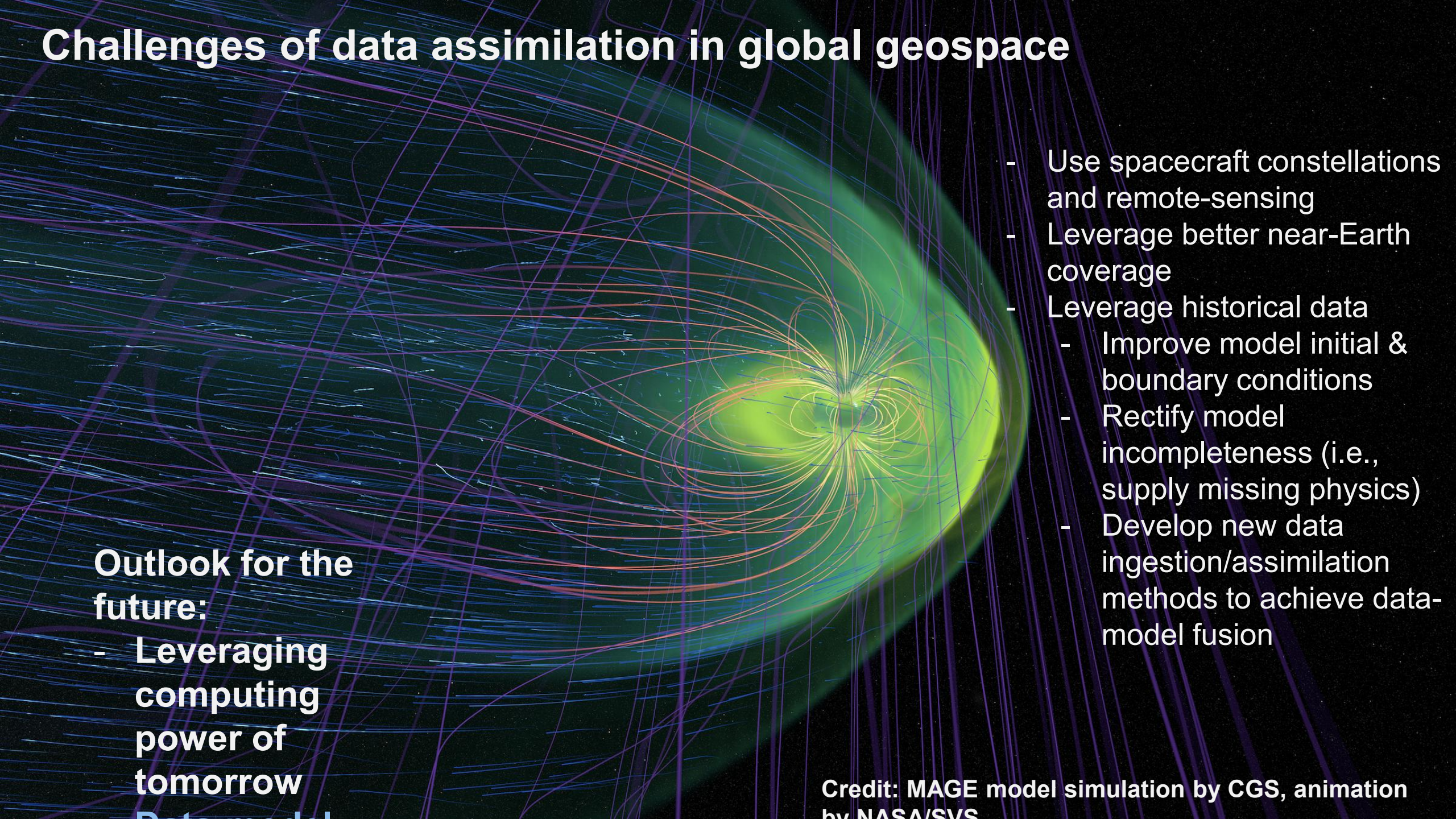
- Huge dynamical range & disparate physics
- Heterogeneous supercomputer architectures
- Scalable coupling for interconnected, multi-physics, multi-scale systems
- New self-consistent physical models & algorithms
- Multigenerational integrated teams of domain and computational scientists, research software engineers, students & postdocs, project managers

Outlook for the future:

- **Leveraging computing power of tomorrow**

Credit: MAGE model simulation by CGS, animation by NASA/SVS

Challenges of data assimilation in global geospace



- Use spacecraft constellations and remote-sensing
- Leverage better near-Earth coverage
- Leverage historical data
  - Improve model initial & boundary conditions
  - Rectify model incompleteness (i.e., supply missing physics)
  - Develop new data ingestion/assimilation methods to achieve data-model fusion

Outlook for the future:

- **Leveraging computing power of tomorrow**

Credit: MAGE model simulation by CGS, animation by NASA/SVS