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Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS

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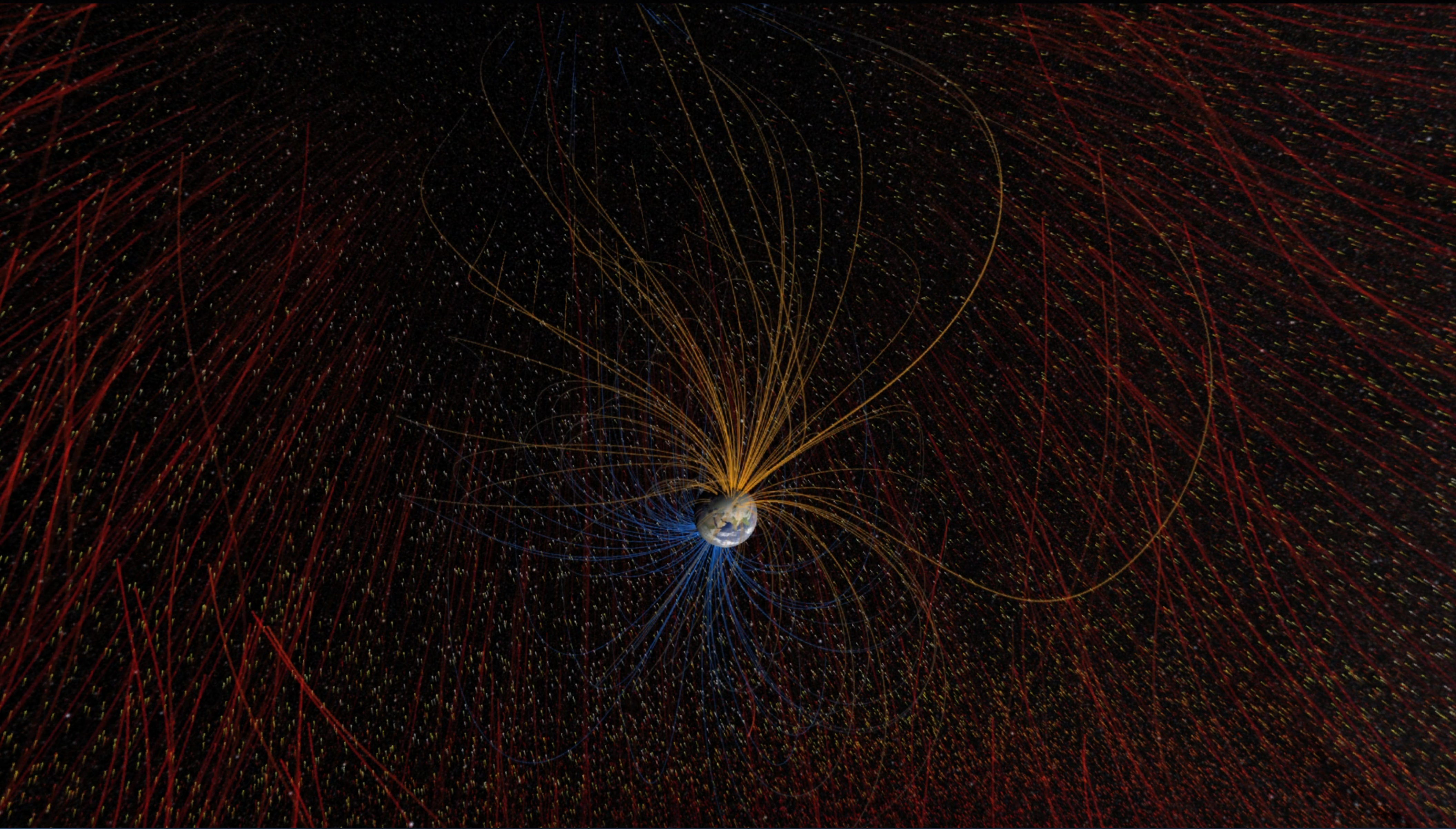
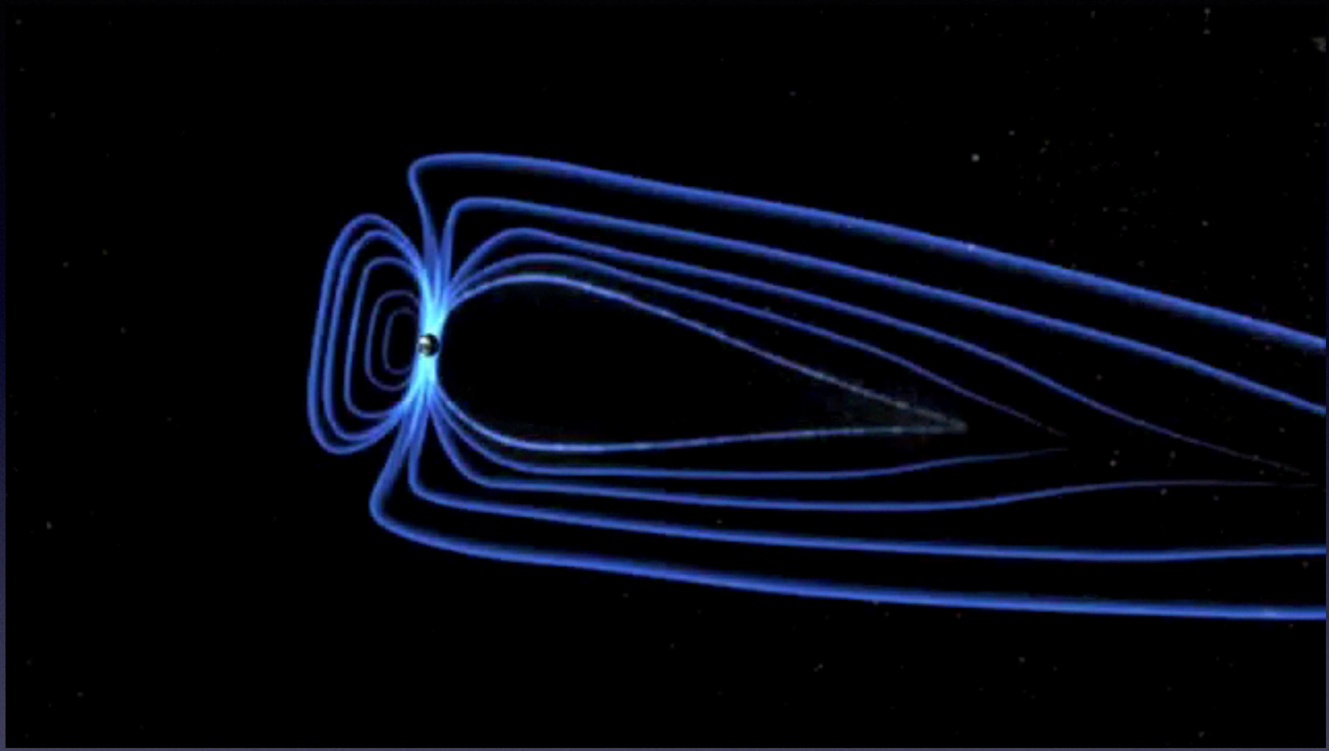
"Review current space weather capabilities and identify research and development priorities in the near, mid and long term which will provide demonstrable improvements to current information provision to space weather service users"



svs.gsfc.nasa.gov

Earth's magnetic field acts as a shield

artist's impression



https://archive.org/details/CIL-10059

artist's impression

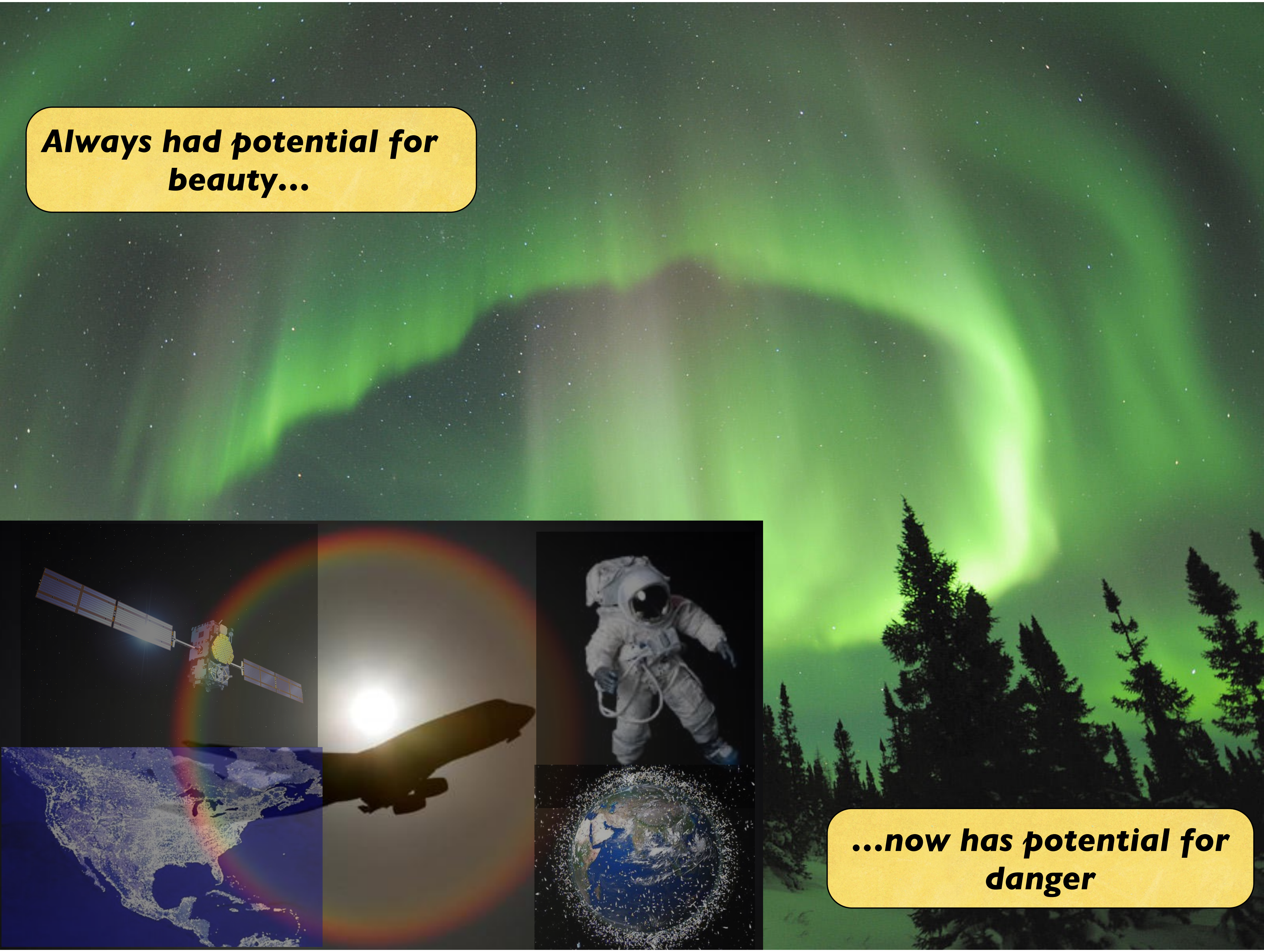
Unfortunately, that shield can break

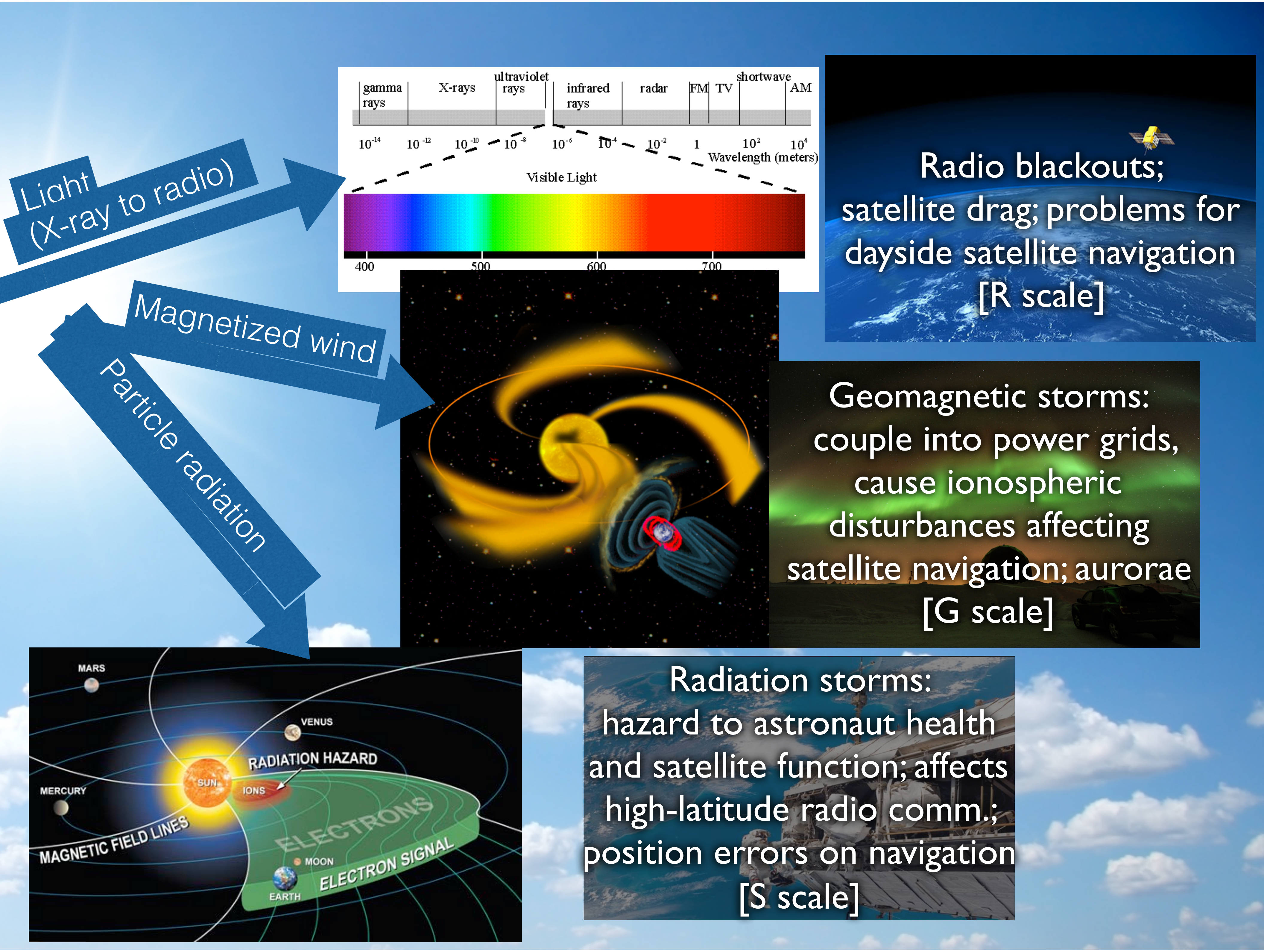
Ordinary....

Earth Science and Remote Sensing Unit, NASA-Johnson Space Center. "The Gateway to Astronaut Photography of Earth." <http://eol.jsc.nasa.gov/videos/crewearthobservationsvideos/videos_aurora.htm>

...and Extraordinary

Frederic Edwin Church (American), “Aurora Borealis”, 1865, Smithsonian American Art Museum


Always had potential for beauty...
...now has potential for danger


Light
(X-ray to radio)
Magnetized wind
Particle radiation
gamma rays
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
10^4
Wavelength (meters)
Visible Light
400
500
600
700
Radio blackouts; satellite drag; problems for dayside satellite navigation [R scale]
Geomagnetic storms: couple into power grids, cause ionospheric disturbances affecting satellite navigation; aurorae [G scale]
Radiation storms: hazard to astronaut health and satellite function; affects high-latitude radio comm.; position errors on navigation [S scale]
MARS
VENUS
RADIATION HAZARD
SUN
IONS
MERCURY
ELECTRONS
MAGNETIC FIELD LINES
MOON
ELECTRON SIGNAL
EARTH

Potential

Impacts of a major geomagnetic storm

- For a “Quebec- and Carrington-like” event: Assuming 10% of electricity supply is lost for one year, with Leontief’s input-output (IO) theory and associated tables:
  - American storm: US$ 2.4 trillion
  - European storm: US$ 3.4 trillion
  - Asia-centered storm: US$ 3.1 trillion

2754 **H. Schulte in den Bäumen et al.: How severe space weather can disrupt global supply chains**

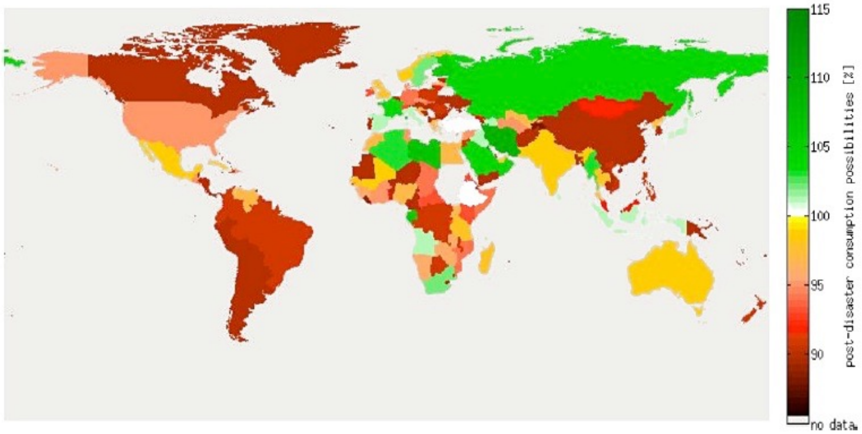


Figure 3. Effects of scenario 1, a Quebec 1989-like event centered over the Americas. Globally, the storm would reduce total consumption possibilities by 3.9 % though the effect is uneven: it is most severe in countries directly affected and their economic partners, while other countries (e.g., Russia, Saudi Arabia, France, and Egypt) may gain consumption possibilities in the post-disaster economy.

From H. Schulte in den Bäumen, D. Moran , M. Lenzen, I. Cairns, and A. Steenge; Nat. Hazards Earth Syst. Sci., 14, 2749–2759, 2014 Nat. Hazards Earth Syst. Sci., 14, 2749–2759, 2014

Potential Impacts of a major geomagnetic storm

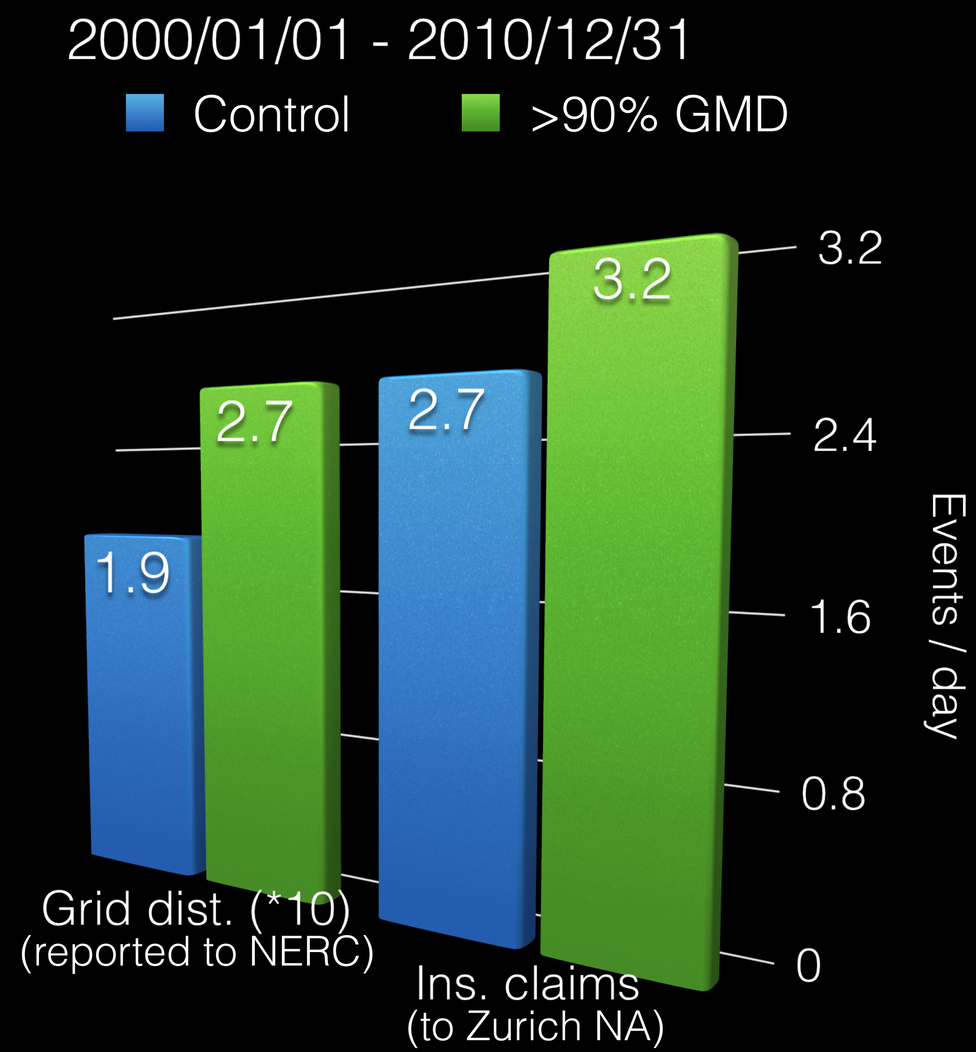
"The total population at risk of extended power outage from a Carrington-level storm … is between 20-40 million, with durations of 16 days to 1-2 years"

even for weaker storms "the potential damage to densely populated regions along the Atlantic coast is significant."

Lloyd's, 2013, Solar storm risk to the North American electric grid. Lloyd's, London, U.K.

Actual Effects of GMD on US power grid

- The ‘moderate’ geomagnetic storms of the past decade have impacts on the power grid and on the economy through ‘grid disturbances’ and insurance claims: it does not take a major storm for measurable effects.



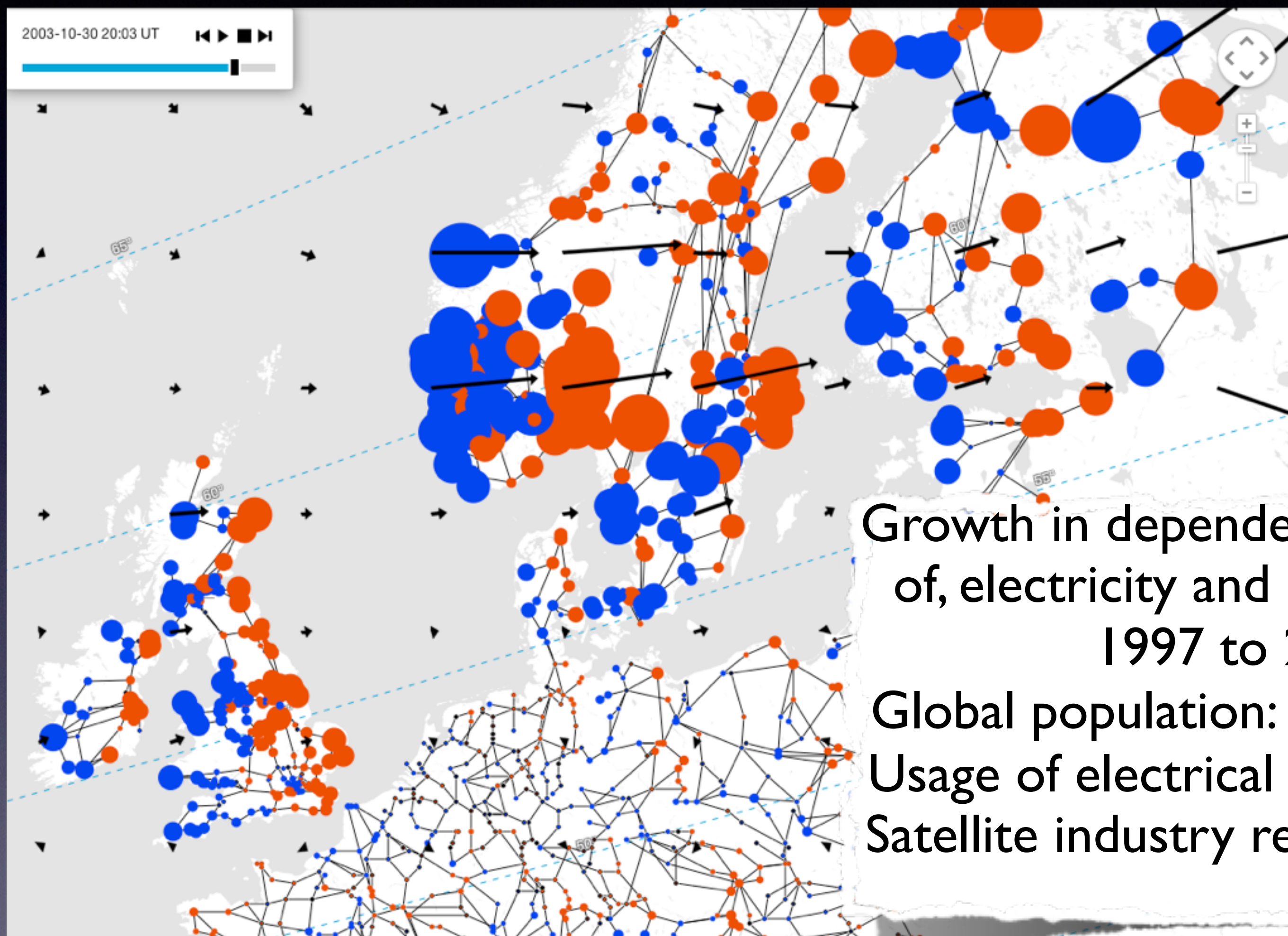
From C. J. Schrijver, R. Dobbins, W. Murtagh, and S. M. Petrinec; Space Weather, 2014 DOI 10.1002/2014SW001066

Example of impacts: power grids

The hypothetical financial impact of a “century-level event” (“Carrington-Hodgson storms”) and the estimated costs of a century of moderate space weather (“the gales between breezes and hurricanes”) through electric power systems: comparable at O(US $ 2 10^{12})

Schrijver (LMATC), Dobbins (Zurich NA), Murtagh (NOAA/SWPC), Petrinec (LM STAR Labs); 2014, Space Weather Journal

Geomagnetic variability and grid disturbances



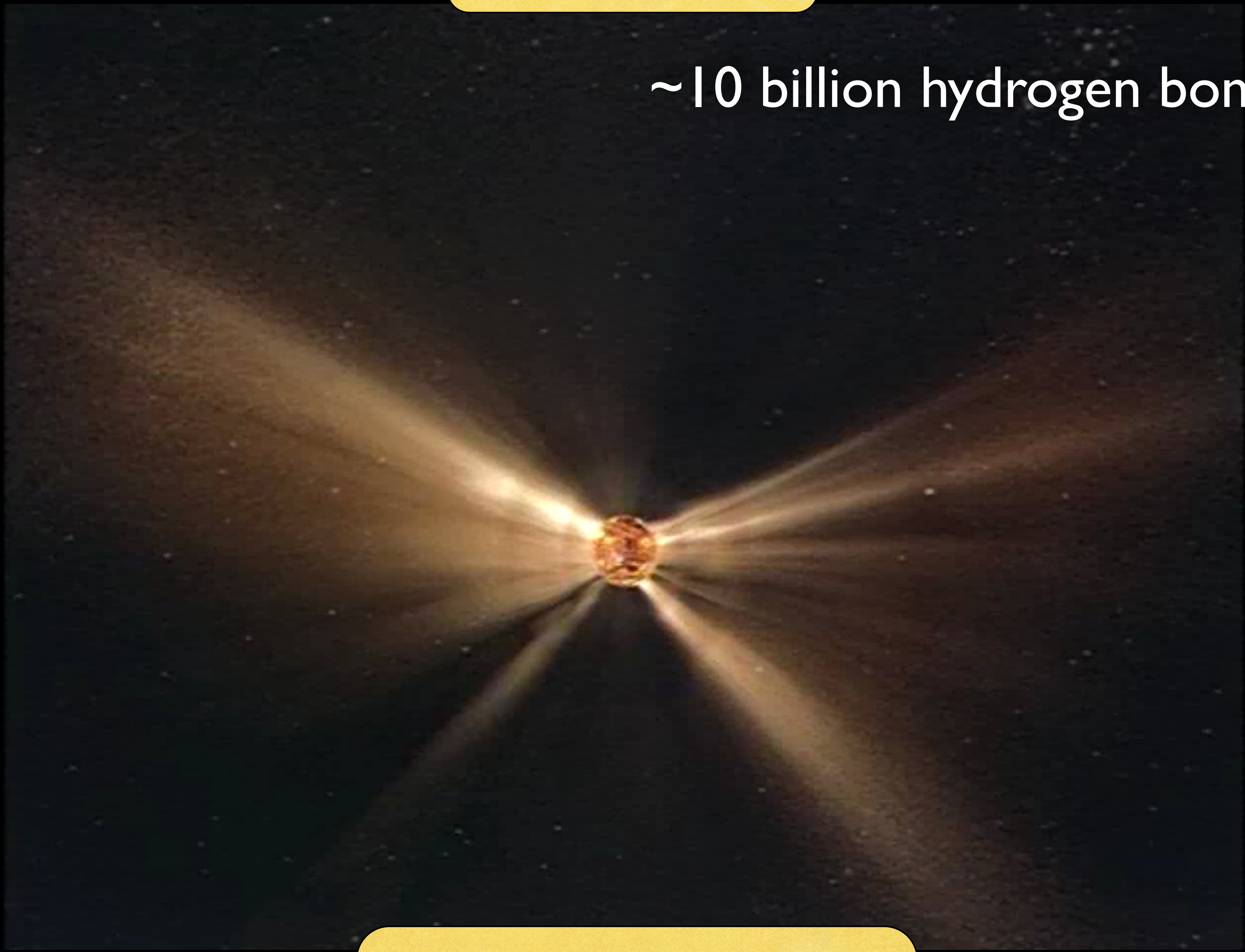
Growth in dependence on, and use of, electricity and satellites from 1997 to 2012:

Global population:	+20%
Usage of electrical power:	+60%
Satellite industry revenue:	+420%

Electric field (arrows) and GIC connecting ground and grid (circles; blue and red for opposite directions), computed from dB/dt and a model grid configuration, for the 2003/10/30 Halloween storm a few minutes before the failure in power delivery in Southern Sweden (Malmö). Courtesy Ari Viljanen.

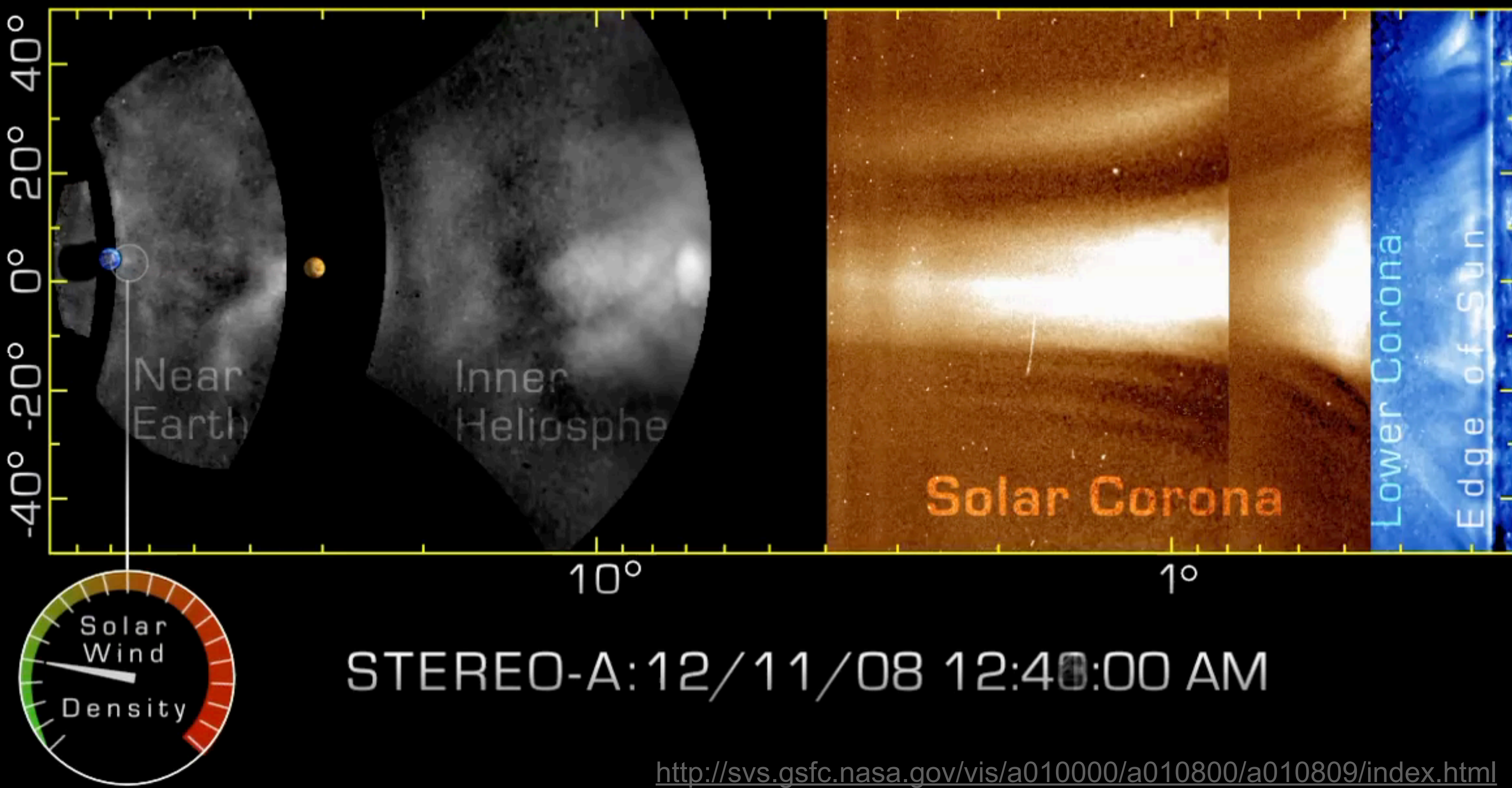
data visualization

Solar Storms



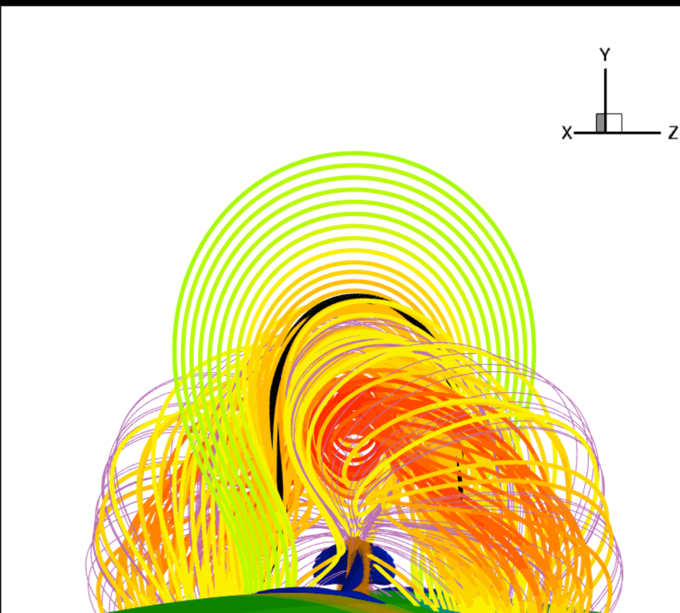
Release of energy stored in twisted magnetic fields

The good news: we usually know when something is coming!

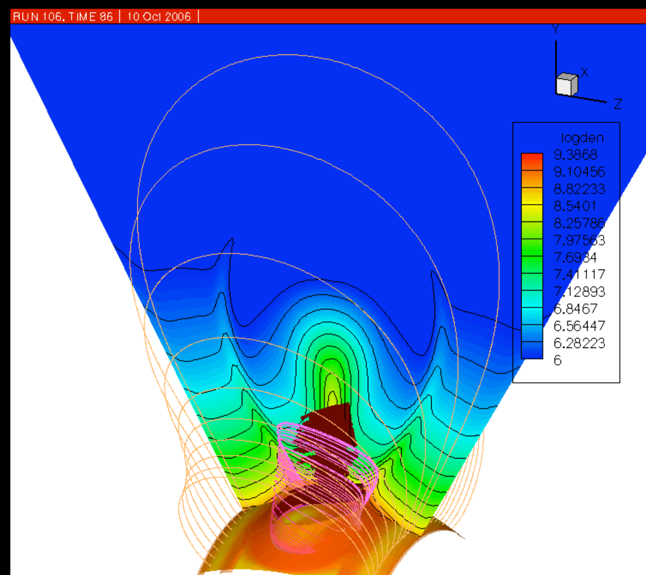


http://svs.gsfc.nasa.gov/vis/a010000/a010800/a010809/index.html

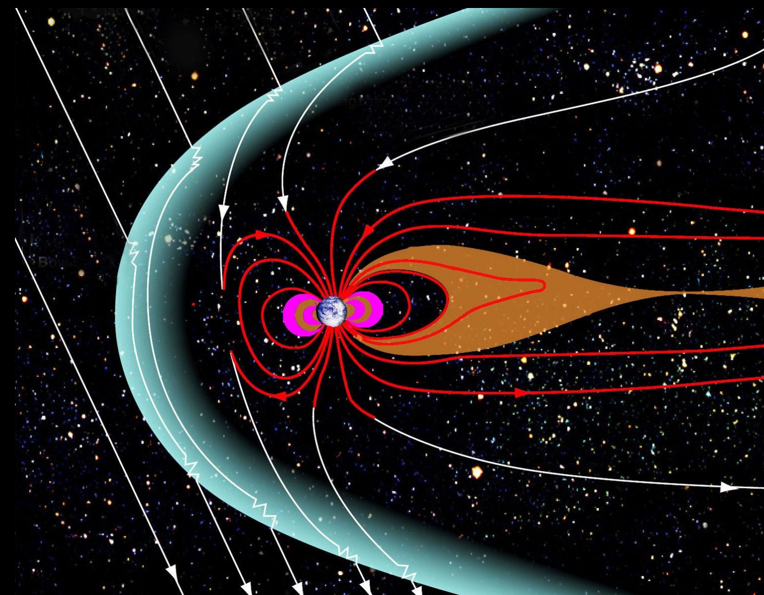
The bad news: we usually don't know its magnetic orientation



From pre-eruption magnetic source…



Through eruption…

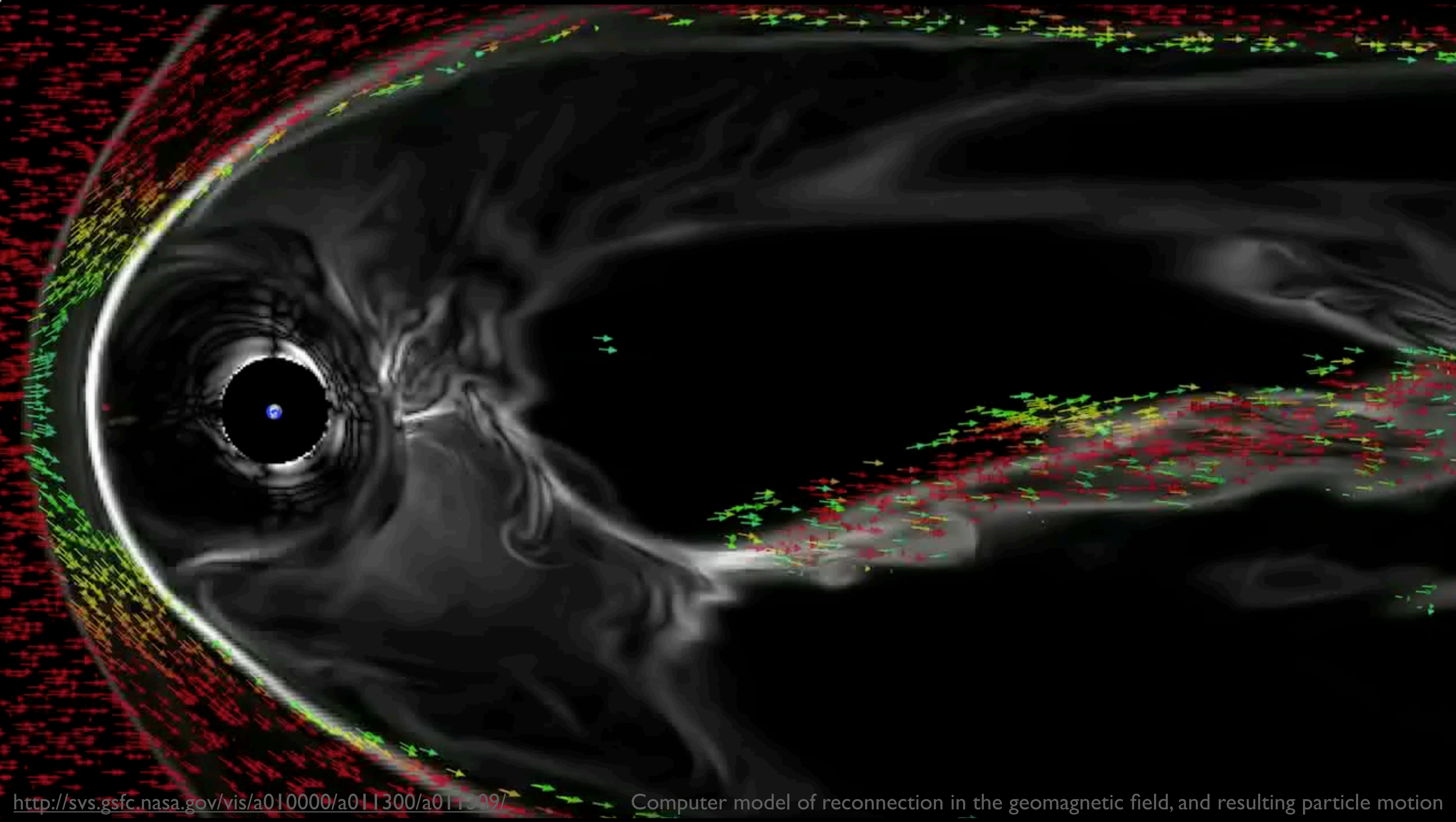


To impact at Earth?

Complication: the context surrounding a particular source matters, in both time and space.

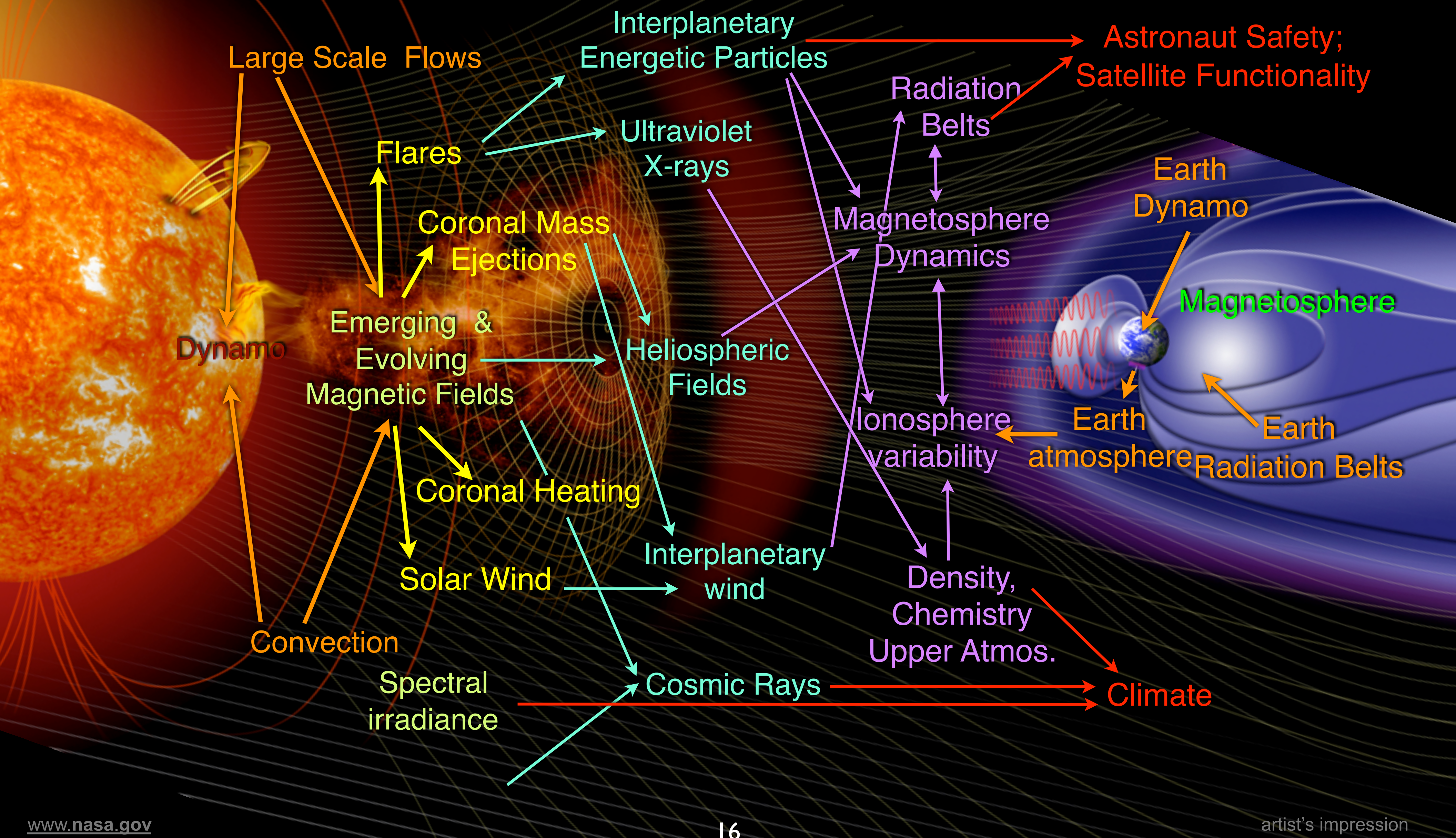
HYSTERESIS

Magnetospheric modeling: reconnection, heating, particles



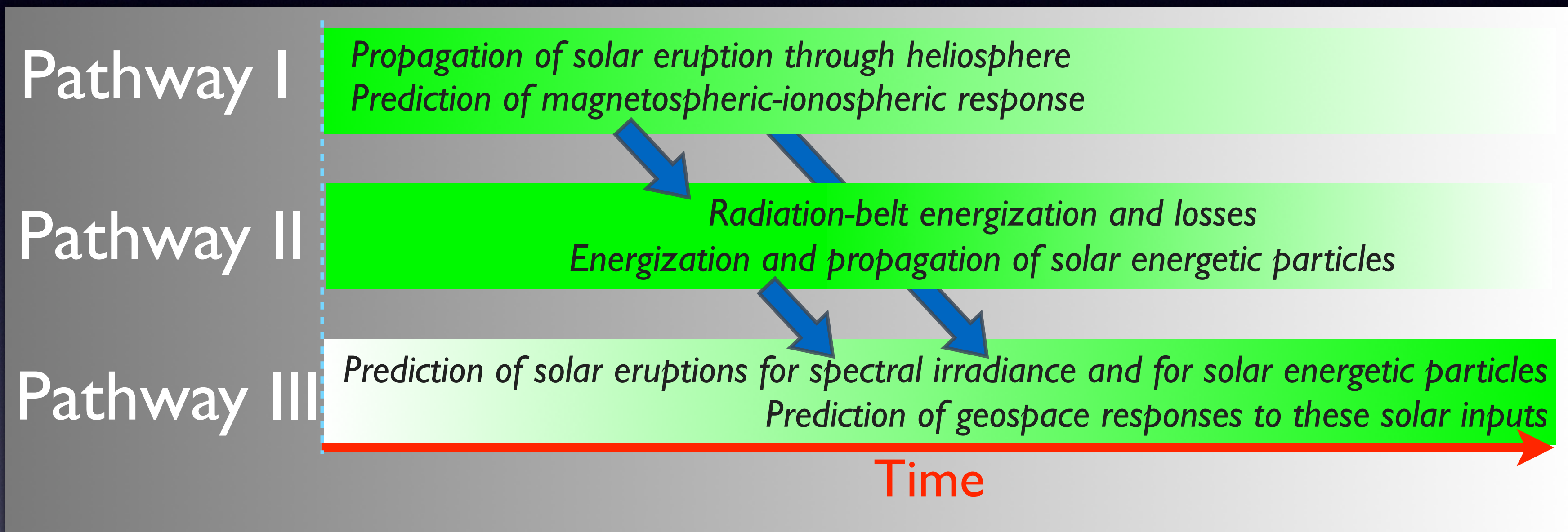
http://svs.gsfc.nasa.gov/vis/a010000/a011300/a011309/ Computer model of reconnection in the geomagnetic field, and resulting particle motion

Sun-Earth connections: a complex system of coupled processes and phenomena



Recommendations by pathway

on observational, computational, and theoretical needs



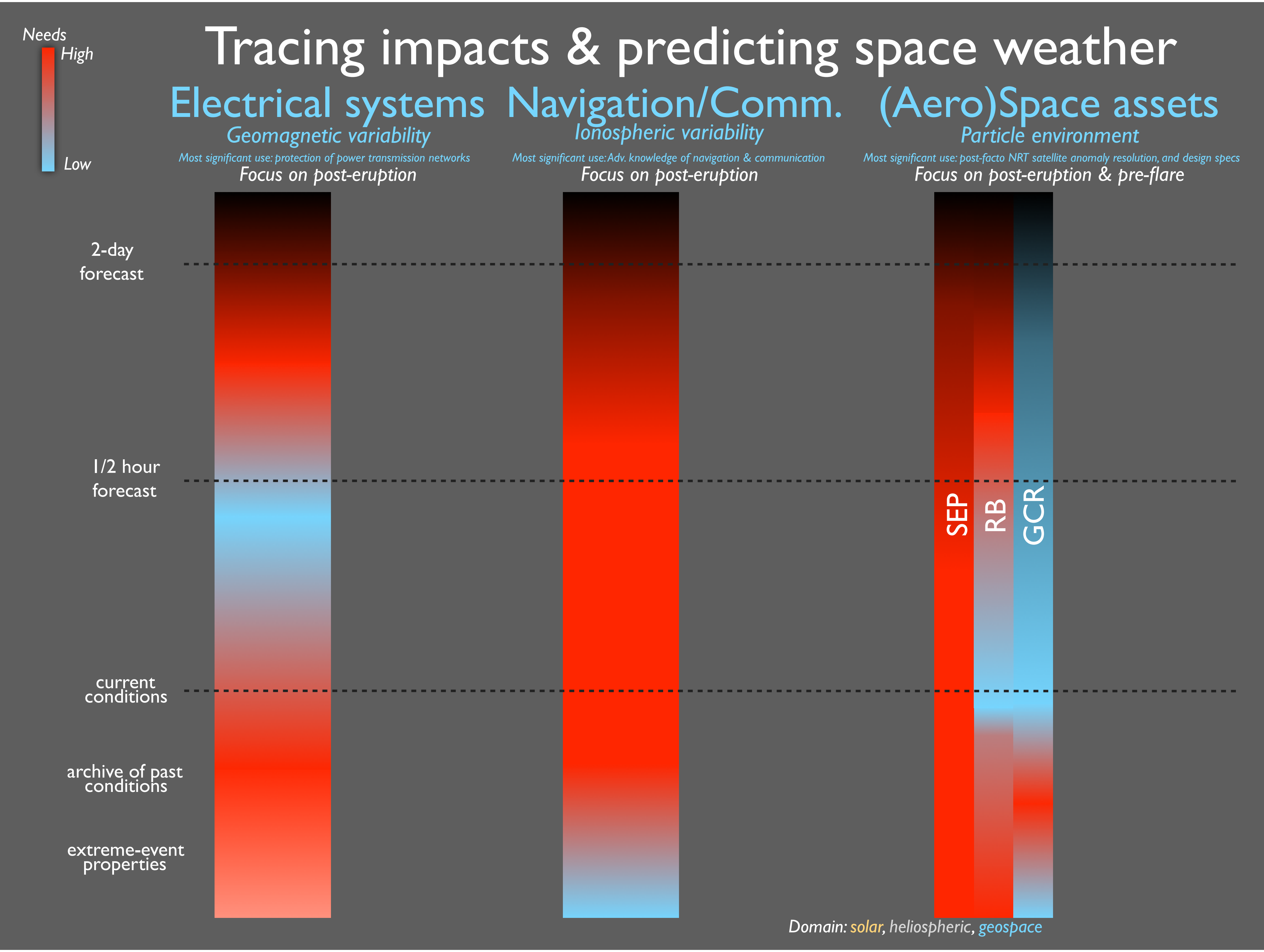
N.B. Pathways reflect a merged weighting based on assessed societal impact, scientific need, estimated feasibility, likelihood of near-term success, and sequencing in a logical order of progression.

Differential needs and feasibilities

Recommendation for next steps towards meeting user needs, grouped to enable advances on phased paths.

Character of requirements

Most significant use: / *Needed product:*	Electrical systems *Geomagnetic variability* *protection of electrical & electronic systems*	Navigation/Comm. *Ionospheric variability* *reliability of navigation and communication*	(Aero)Space assets *Space particle environment* *anomaly resolution, and design specification*
Knowledge of environment for system design	***Pathway I***	***Pathway I***	***Pathway II***
Near-real time info and short-term forecasts	***Pathway I***	***Pathway II***	***Pathways II & III***
1-2 day forecasts	***Pathway I***	***Pathway II***	***Pathway III***


Tracing impacts & predicting space weather
Needs
High
Low
Electrical systems
Geomagnetic variability
Most significant use: protection of power transmission networks
Focus on post-eruption
Navigation/Comm.
Ionospheric variability
Most significant use: Adv. knowledge of navigation & communication
Focus on post-eruption
(Aero)Space assets
Particle environment
Most significant use: post-facto NRT satellite anomaly resolution, and design specs
Focus on post-eruption & pre-flare
2-day forecast
1/2 hour forecast
current conditions
archive of past conditions
extreme-event properties
SEP
RB
GCR
Domain: solar, heliospheric, geospace

Recommendations

Research: observational, computational, and theoretical needs

- Advance the international Sun-Earth system observatory along with models to improve forecasts based on understanding real-world events through the development of innovative approaches to data incorporation;

- Understand space weather origins at the Sun, initially prioritizing post-event solar eruption modeling to develop multi-day forecasts of geomagnetic disturbance times and strengths, after propagation through the heliosphere;

- Understand the factors which control the generation of geomagnetically-induced currents (GICs) and of harsh radiation in geospace, involving the coupling of the solar wind disturbances to internal magnetospheric processes in the magnetosphere and the ionosphere below;

- Develop a comprehensive space environment specification

Recommendations

Teaming: coordinated collaborative research environment

- Quantify vulnerability of society's infrastructure for space weather by partnering with user groups;
- Build test beds in which coordinated observing supports model development;
- Standardize (meta-)data and product metrics, and harmonize access to data and model archives;
- Optimize observational coverage of the Sun-society system.

Recommendations

Collaboration between agencies and communities

- Implement open space-weather data and information policy;
- Provide access to quality education & information materials;
- Execute an international, inter-agency assessment of the state of the field on a 5-year basis to adjust priorities and to guide international coordination;
- Develop settings to transition research models to operations;
- Partner with the weather and solid-Earth communities to share lessons-learned.

National Space Weather Action Plan

Benchmarks (DOC, DOD, NASA, NSF, DOI, FCC, DHS, DOE)

Response and recovery (mostly DHS – also DOC, DOD, DOE, DOT, NASA)

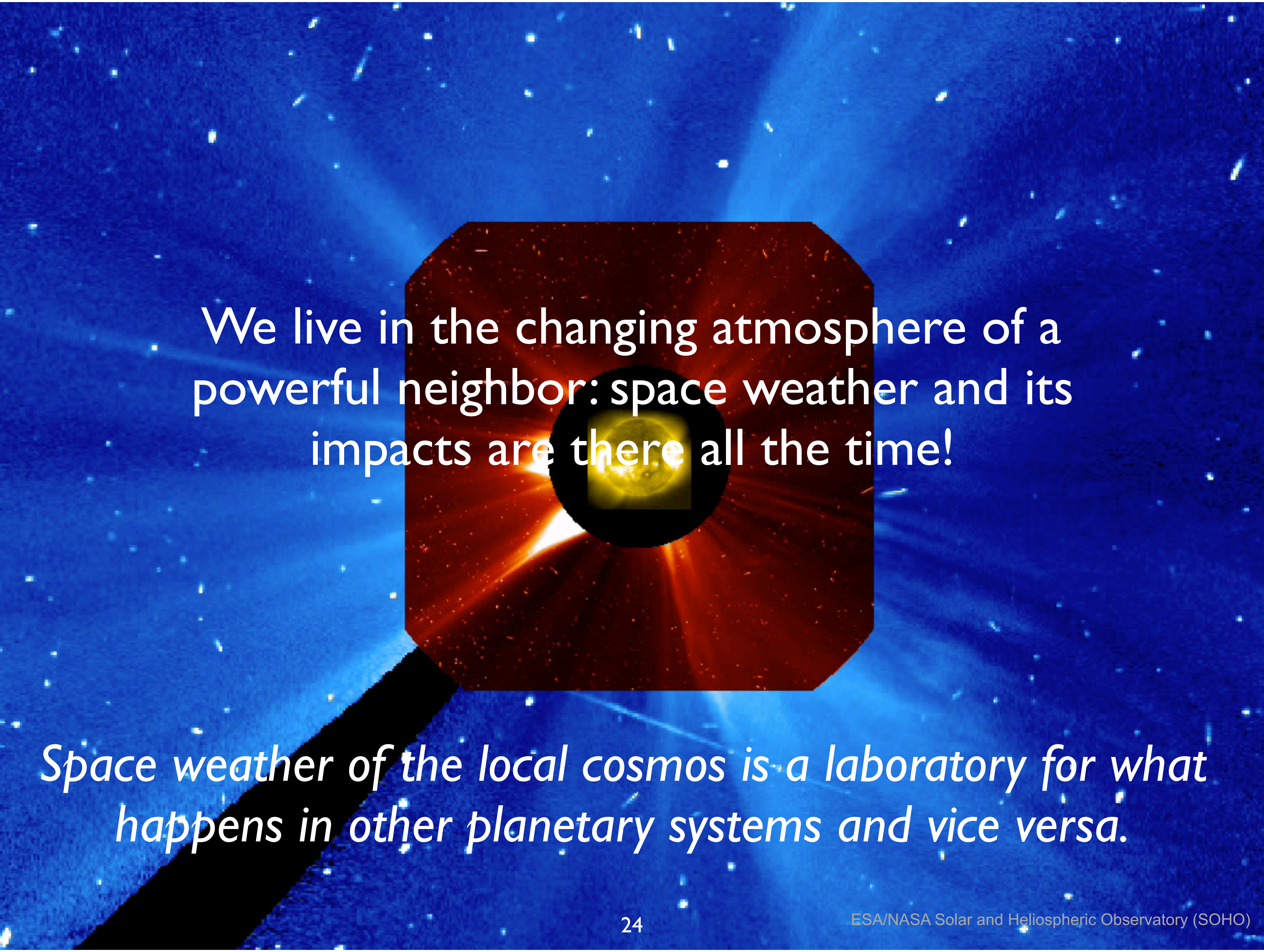
Protection and mitigation (DHS)

Assess/model/predict impact on infrastructure (DHS, DOE, DOC also NASA, DOD, DOT, NSF, DOI)

Improve SWx services through advancing understanding and forecasting (DOC, DOD, DHS, NASA, NSF, DOI)

Increase international cooperation: DOS, DOI, DOC, NASA, NSF, DOD, DHS, DOT, USPS (WMO, COSPAR, ILWS)

"NASA will promote and support the continuation of space weather as a regular topic in the international efforts of COSPAR and within the ILWS program



We live in the changing atmosphere of a powerful neighbor: space weather and its impacts are there all the time!

Space weather of the local cosmos is a laboratory for what happens in other planetary systems and vice versa.

ESA/NASA Solar and Heliospheric Observatory (SOHO)