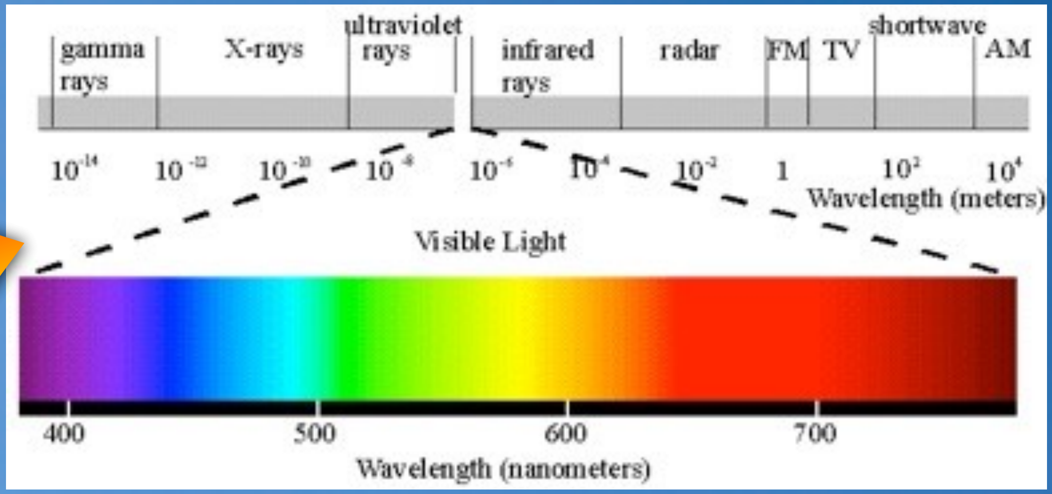
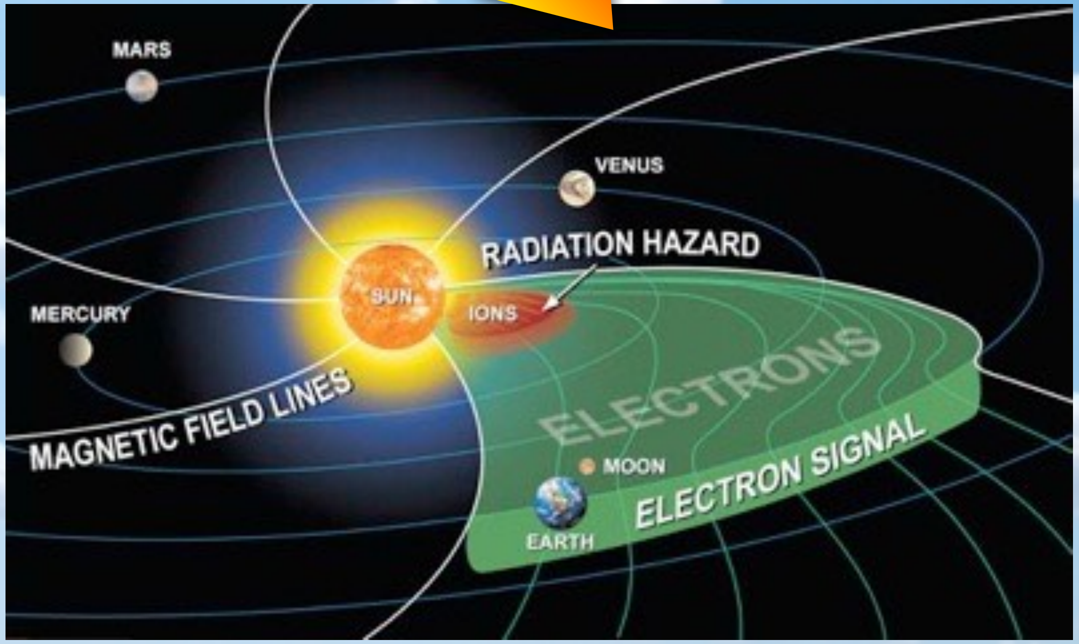
# What the Sun sends our way

Light (X-ray to radio)



Magnetized wind

Particle radiation



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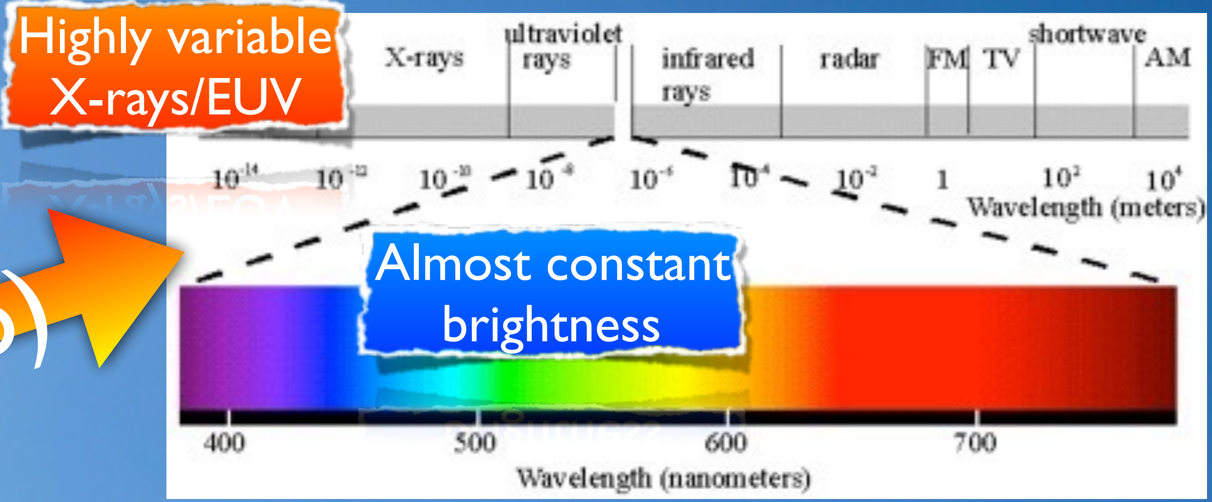
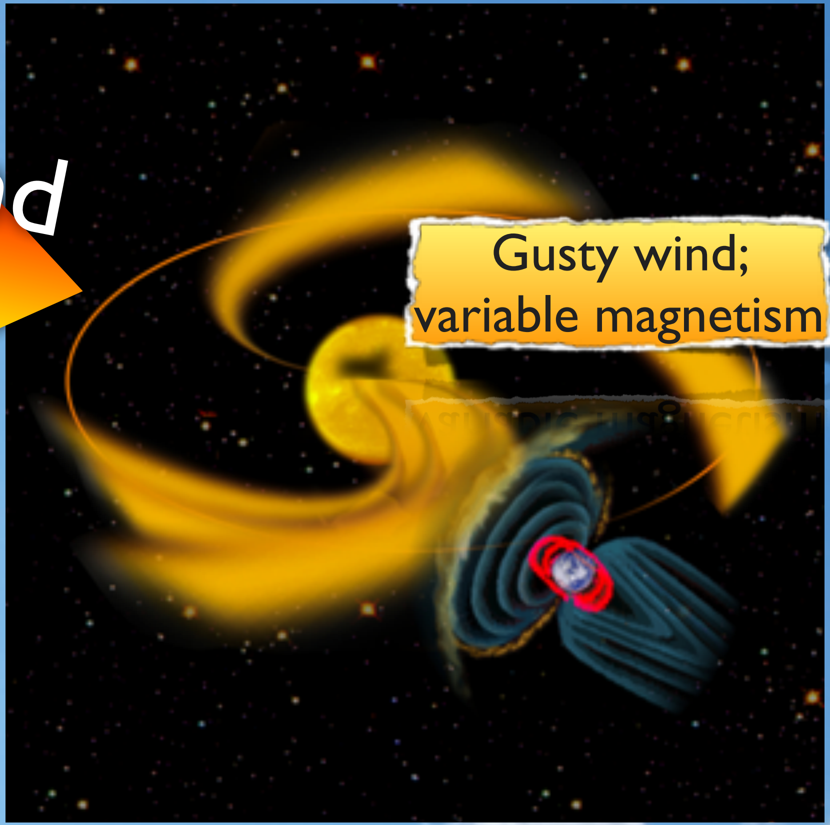


Highly variable X-rays/EUV

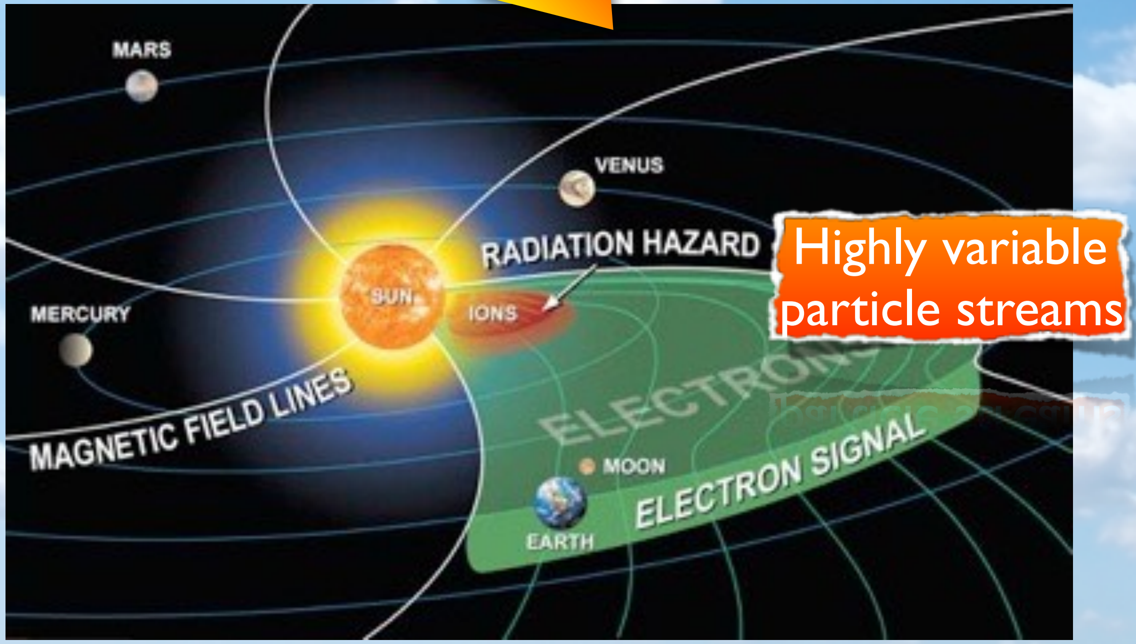
Almost constant brightness

Magnetized wind



Gusty wind; variable magnetism

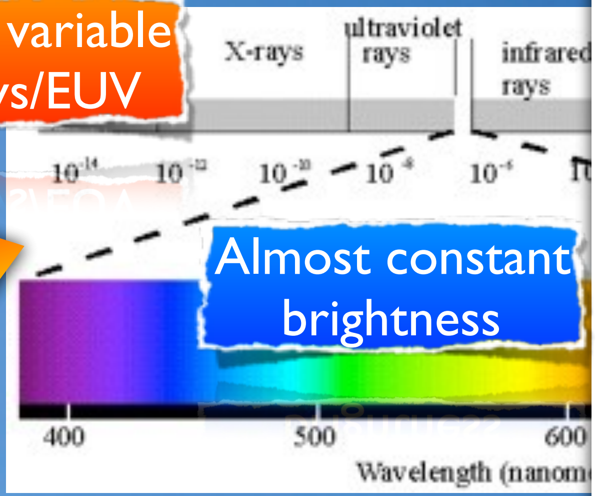
Particle radiation



Highly variable particle streams

# What the Sun sends our way

Light (X-ray to radio)



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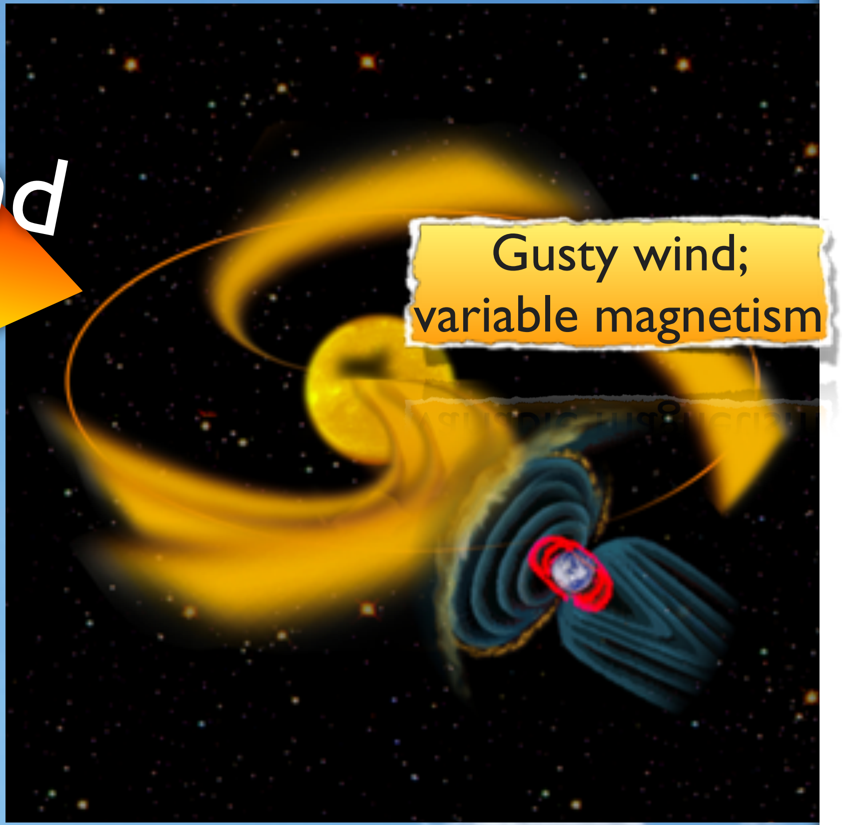
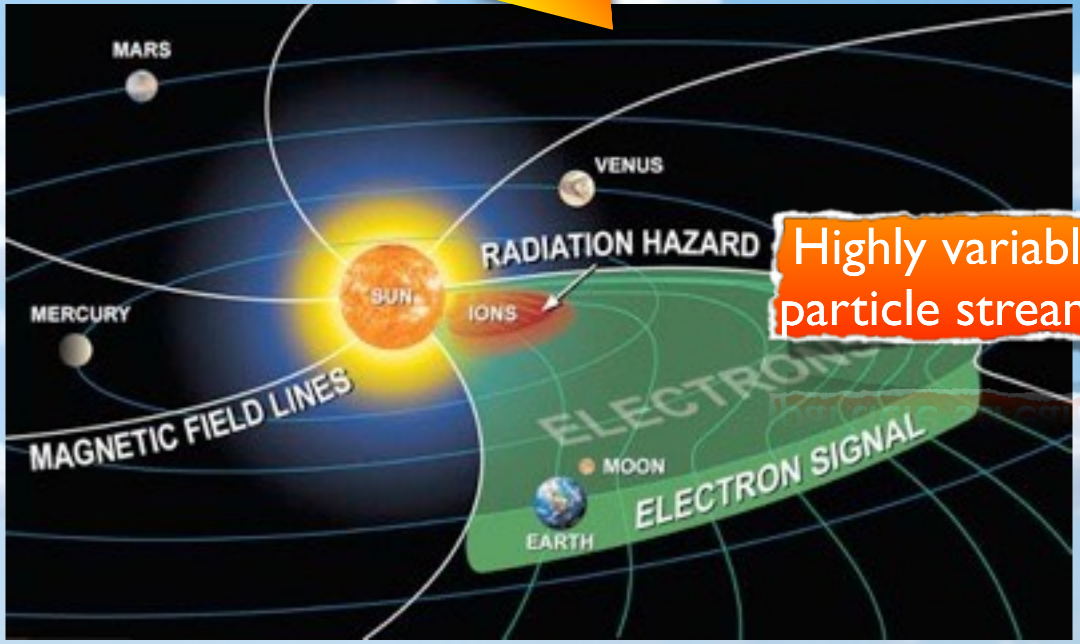
Magnetized wind



Gusty wind; variable magnetism

Particle radiation



Highly variable particle streams

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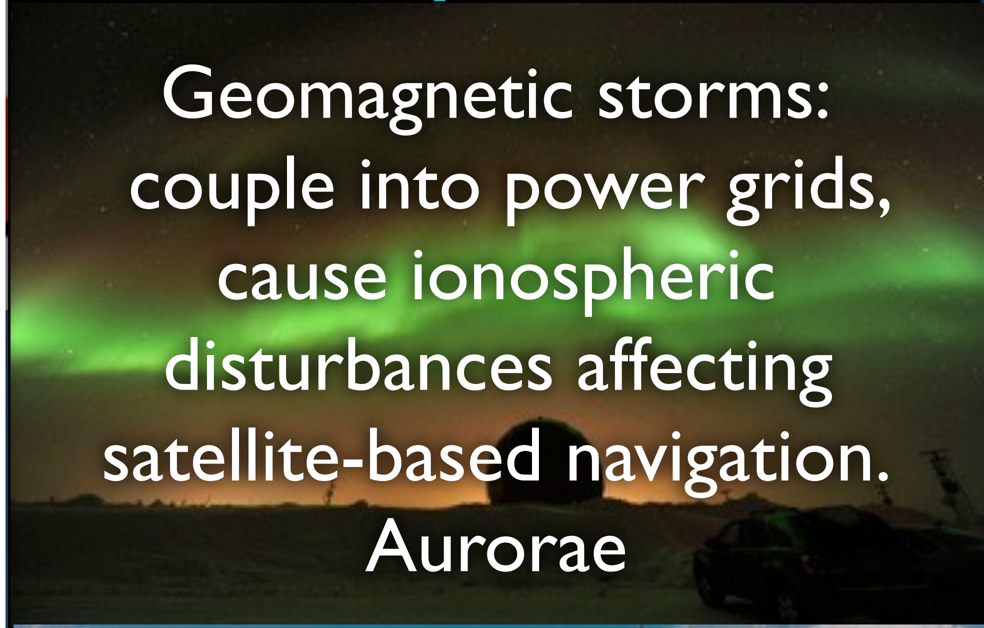
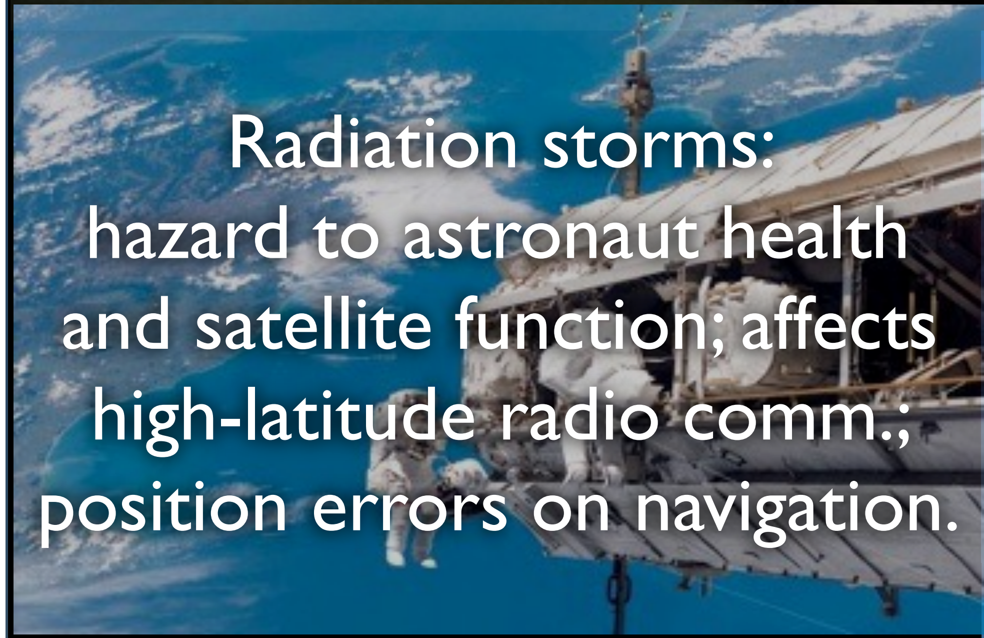
# *Examples of space weather phenomena:*



Geomagnetic storms: couple into power grids, cause ionospheric disturbances affecting satellite-based navigation. Aurorae



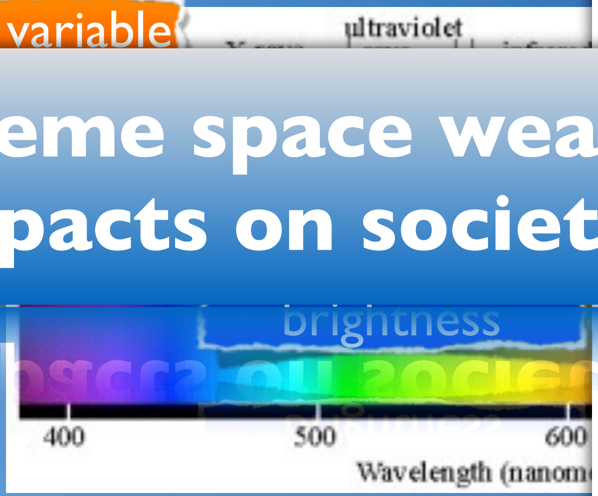
Radiation storms: hazard to astronaut health and satellite function; affects high-latitude radio comm.; position errors on navigation.

Radio blackouts. Satellite drag affecting orbits and re-entry.

What the Sun

# 1) Moderate-to-extreme space weather has substantial impacts on society.

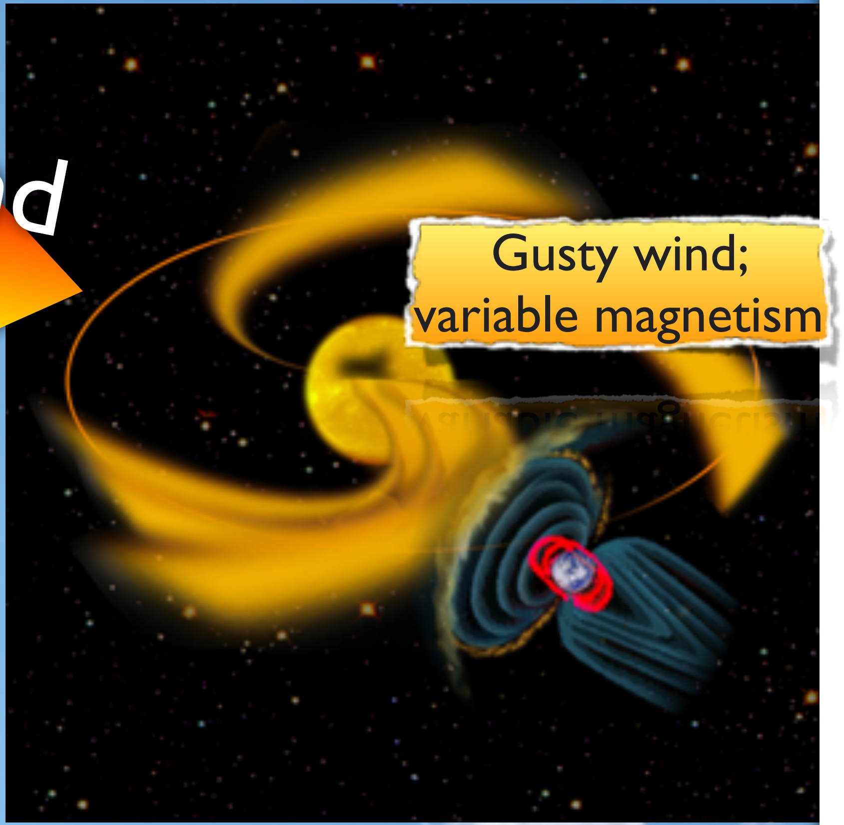
Highly variable



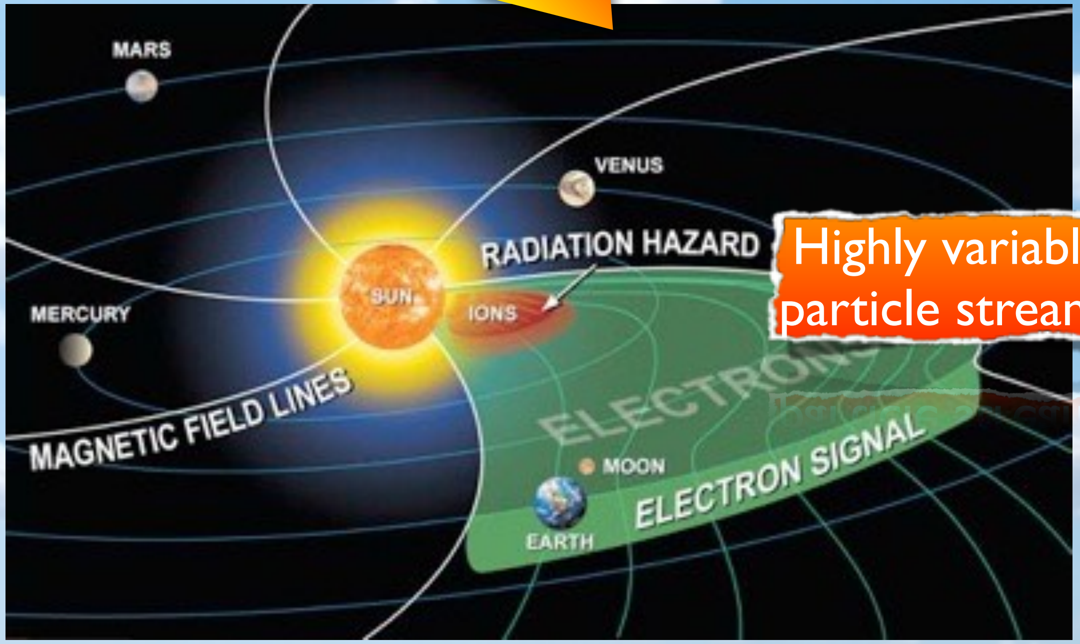
Light (X-ray to radio)

Magnetized wind

Particle radiation

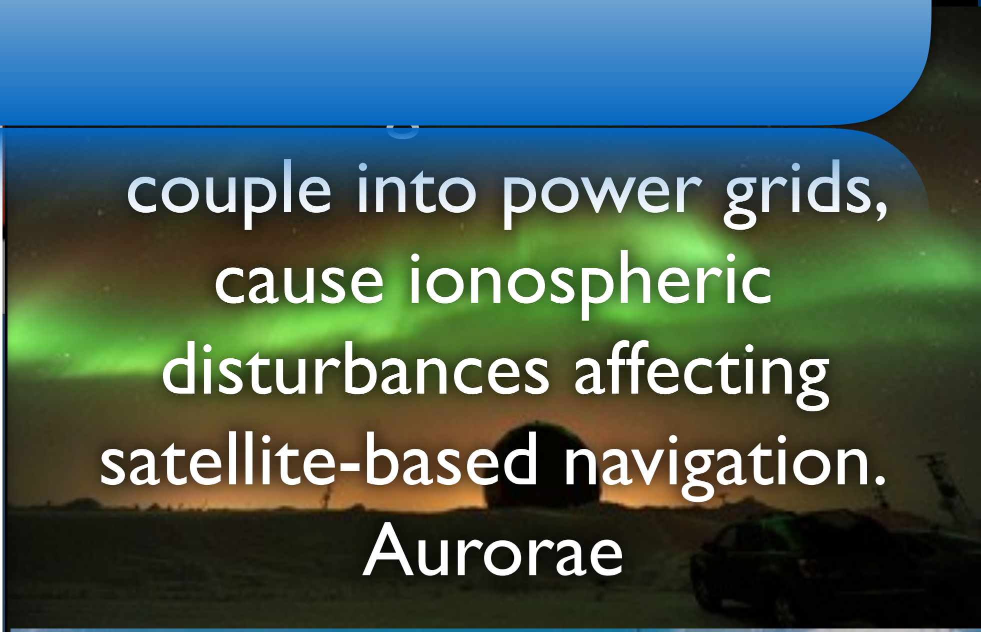


Gusty wind; variable magnetism

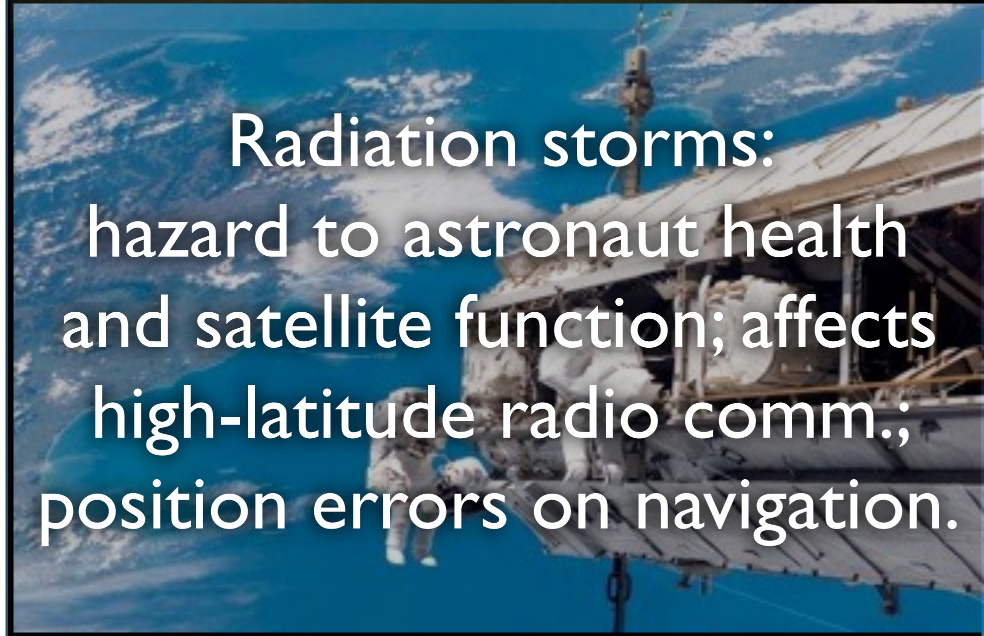


Highly variable particle streams

## Examples of space



couple into power grids, cause ionospheric disturbances affecting satellite-based navigation. Aurorae



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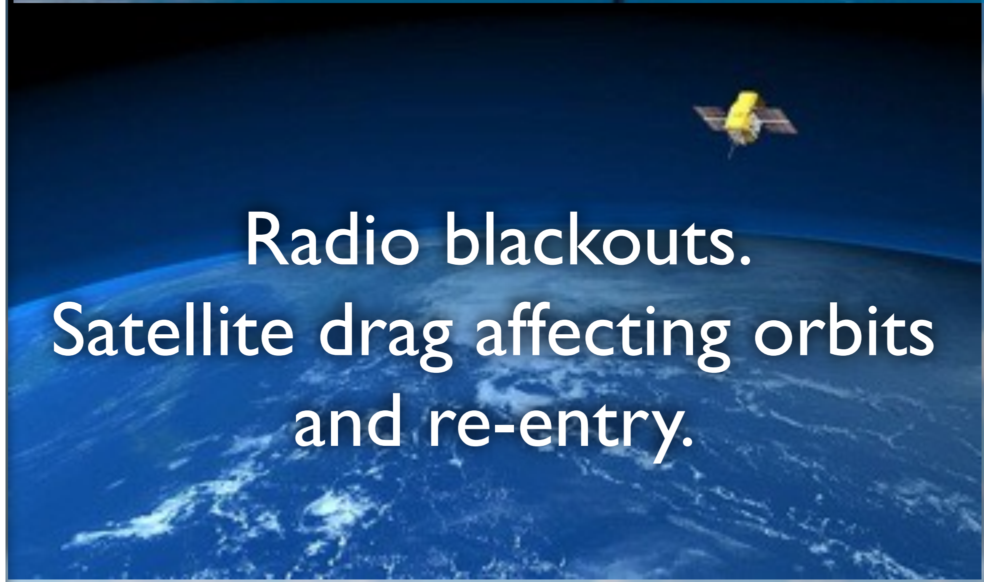

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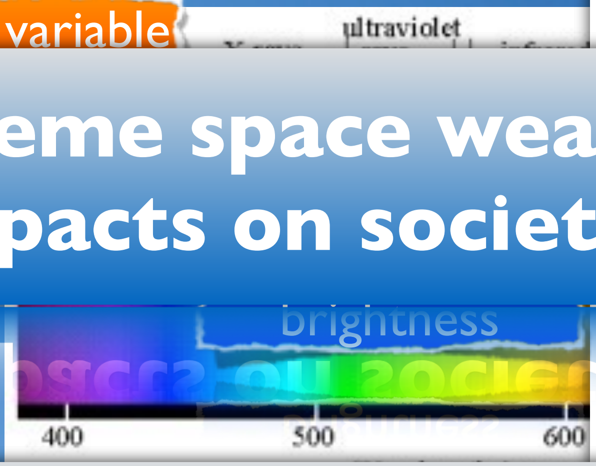
# What the Sun

## Examples of space

# 1) Moderate-to-extreme space weather has substantial impacts on society.

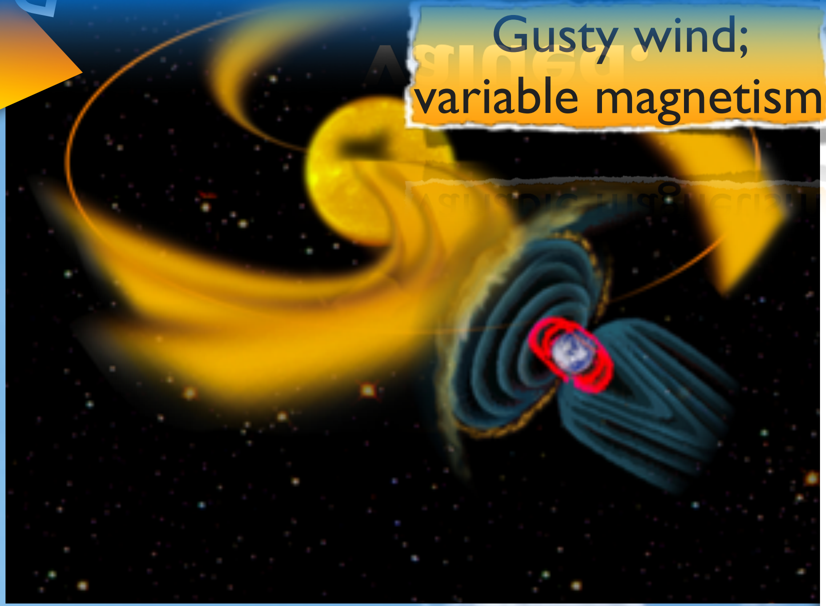
# 2) SWx situational awareness is operationally mature, and valued.

Highly variable

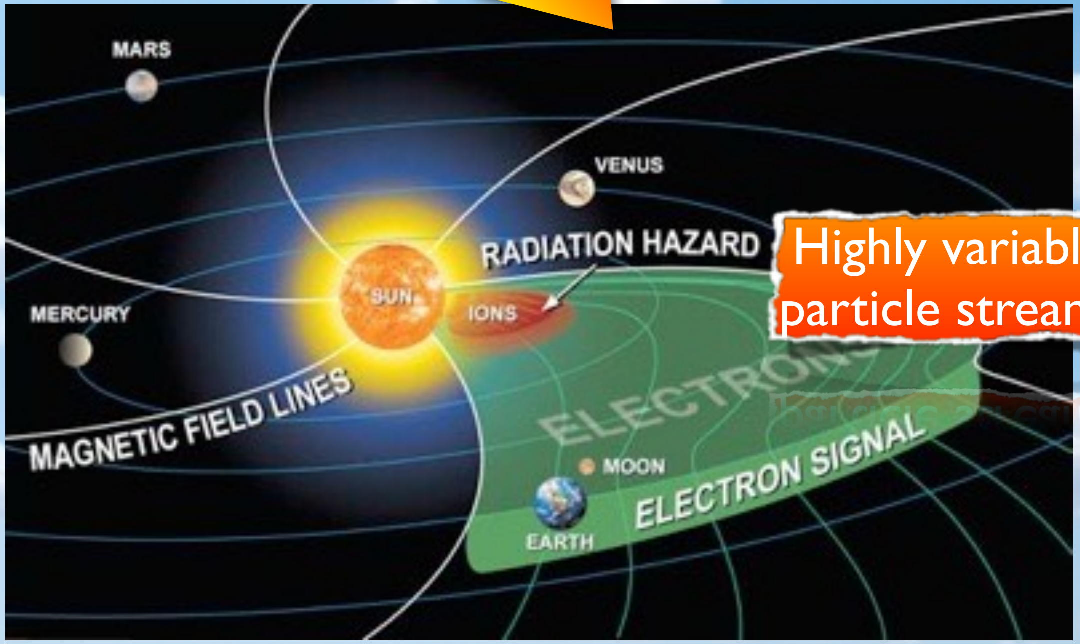


Light
ray to radio)

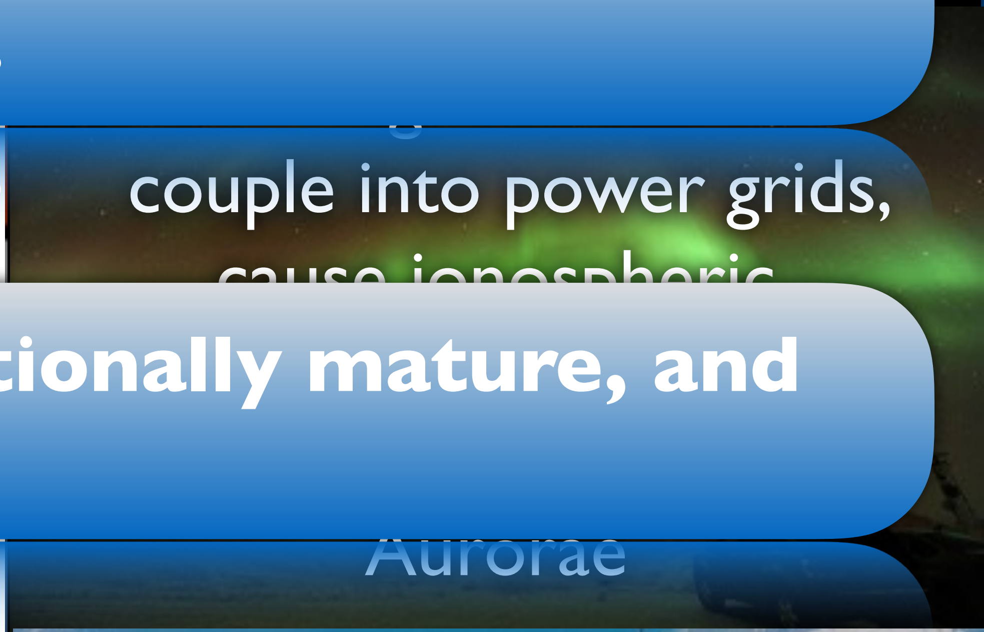
article radiation



Gusty wind;
variable magnetism

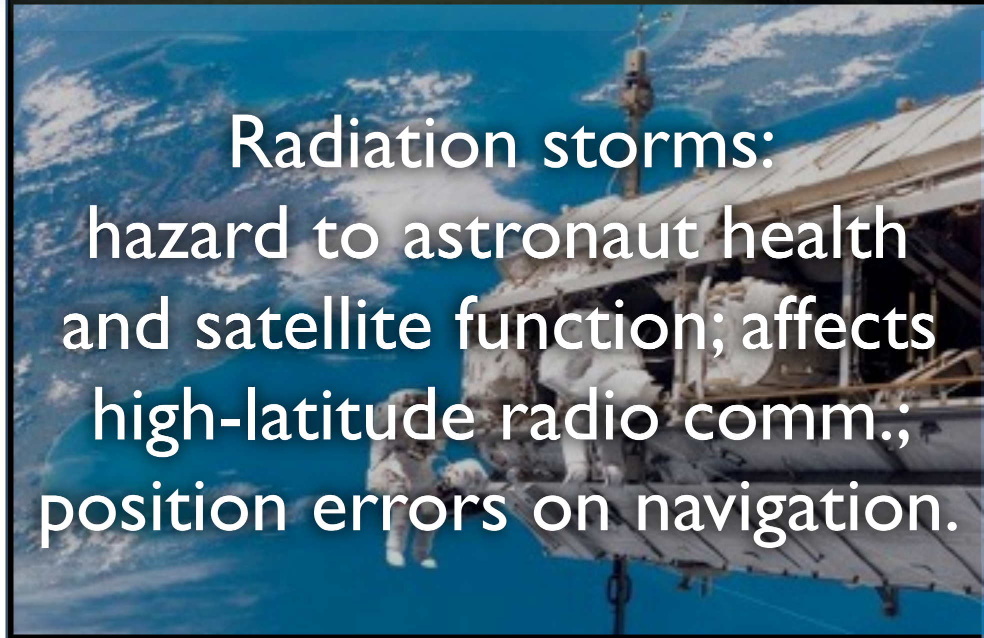


Highly variable
particle streams



couple into power grids,
cause ionospheric

Aurorae



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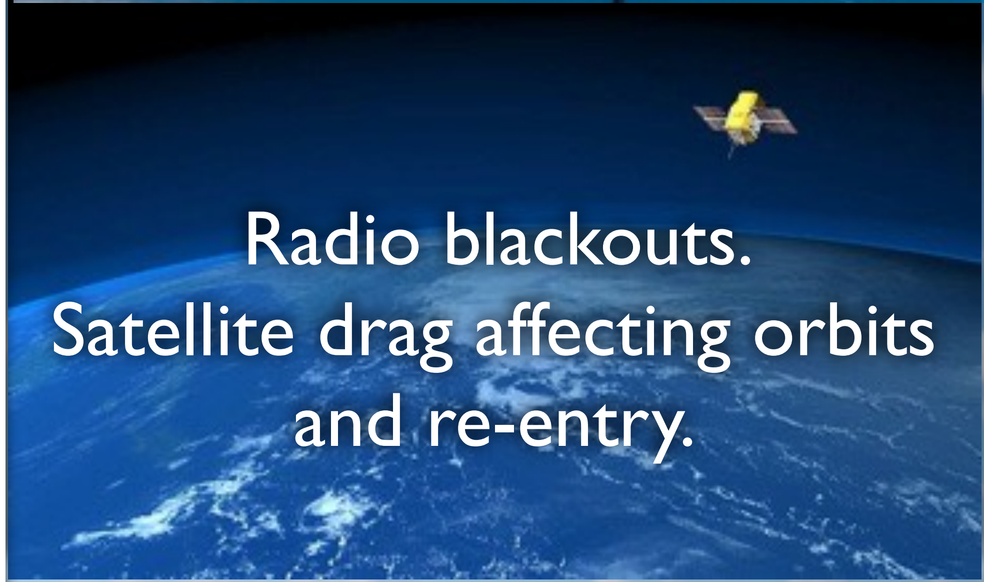

Radio blackouts.
Satellite drag affecting orbits and re-entry.

## 1) Moderate-to-extreme space weather has substantial impacts on society.

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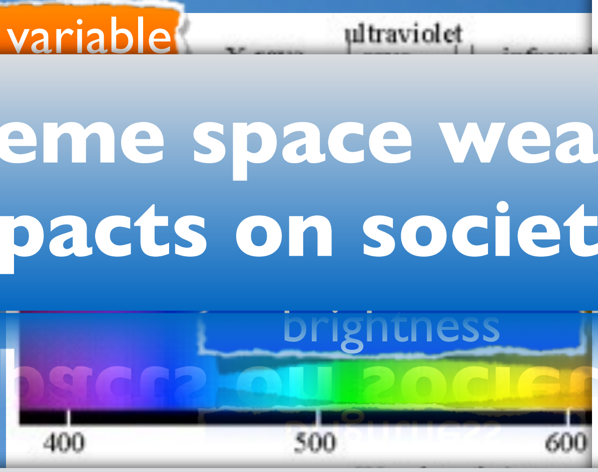
## 3) Reliable, actionable forecasts require significant advances in science and in value assessment.*, **, ***

What the Sun S

Examples of space



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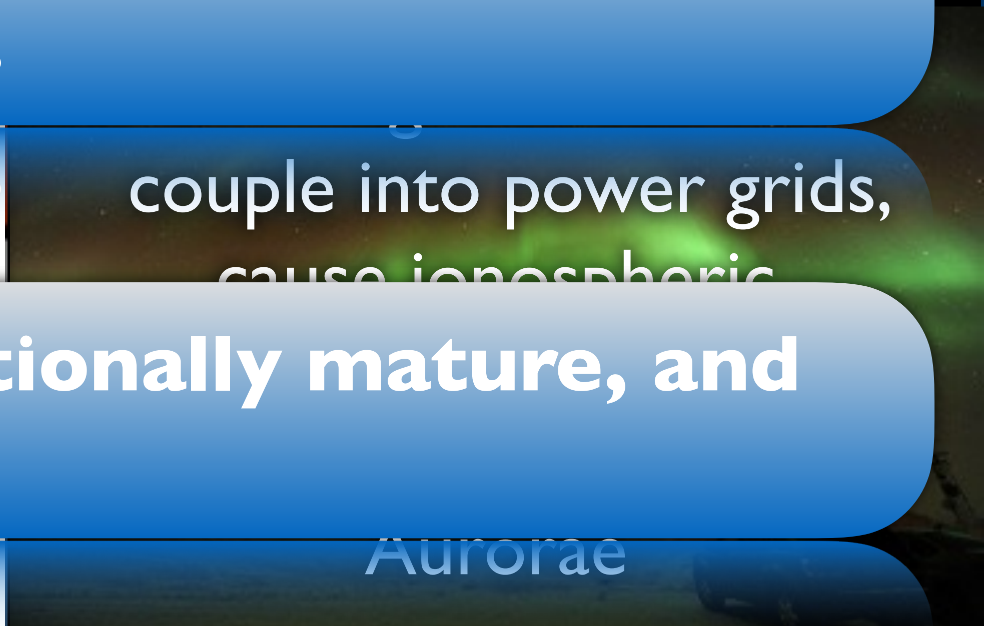
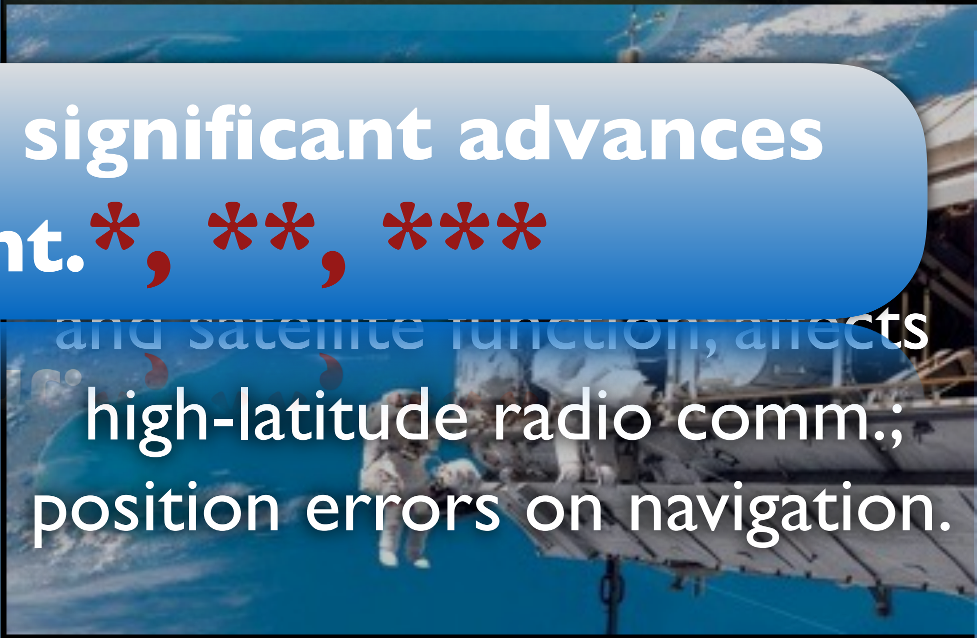


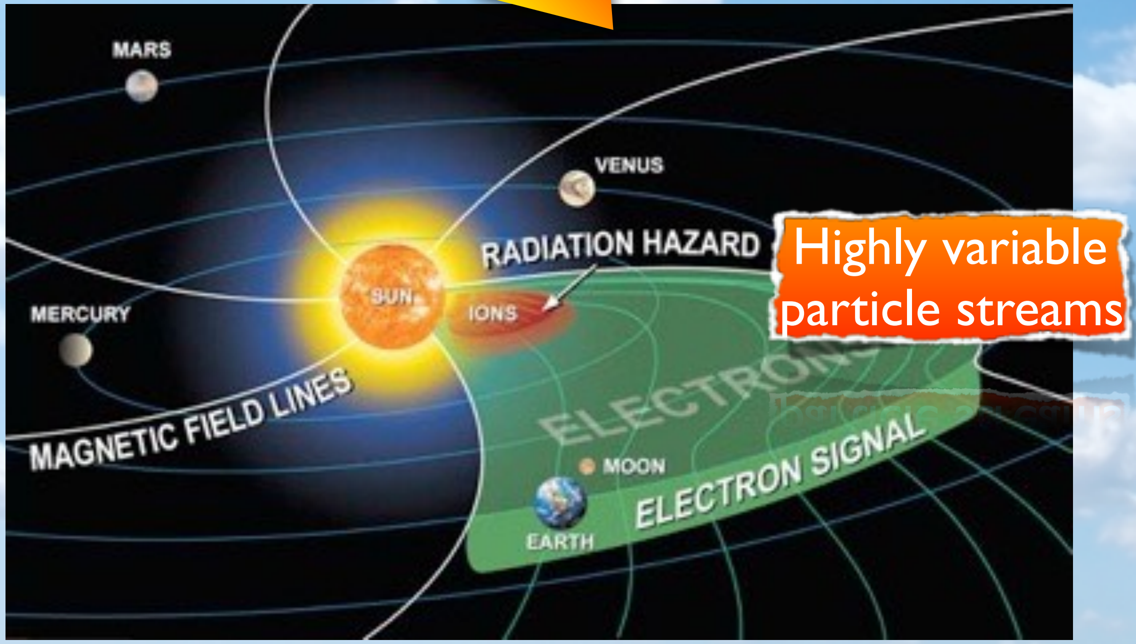
couple into power grids, cause ionospheric

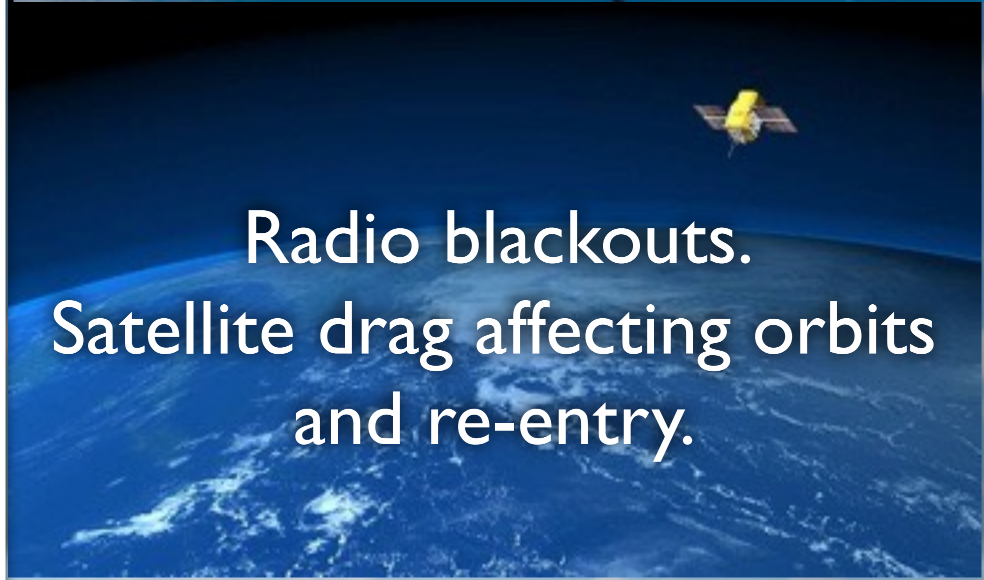
Aurorae

Particle radiation



and satellite function; affects high-latitude radio comm.; position errors on navigation.





Radio blackouts. Satellite drag affecting orbits and re-entry.

What the Sun

Highly variable

ultraviolet

Examples of space

## 1) Moderate-to-extreme space weather has substantial impacts on society.

Light (X-ray to radio)

brightness

400 500 600

couple into power grids,

cause ionospheric

## 2) SWx situational awareness is operationally mature, and valued.

Aurorae

Gusty wind; variable magnetism

## 3) Reliable, actionable forecasts require significant advances in science and in value assessment.*, **, ***

and satellite function; affects

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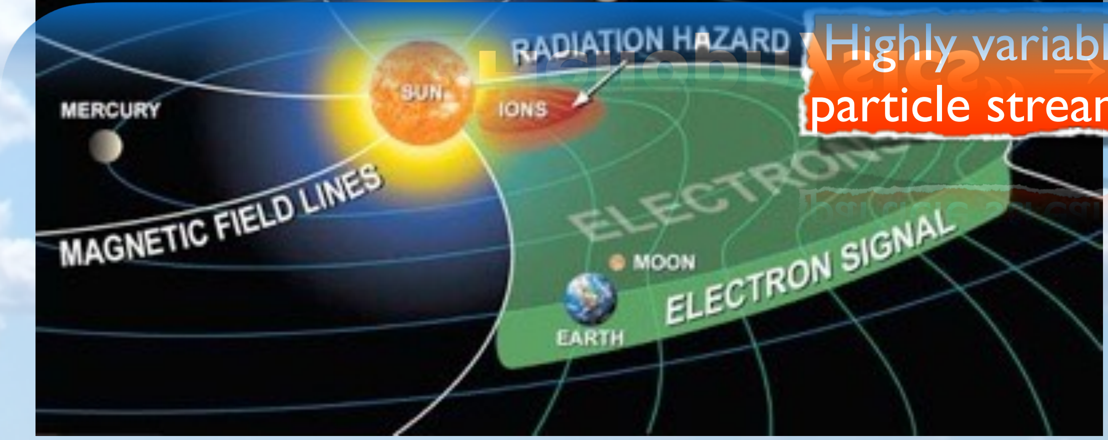
## 4) “Sun-Earth Connections” = “Space weather science” = “Heliophysics” → “Interdisciplinary science”



Highly variable particle streams

Radio blackouts.
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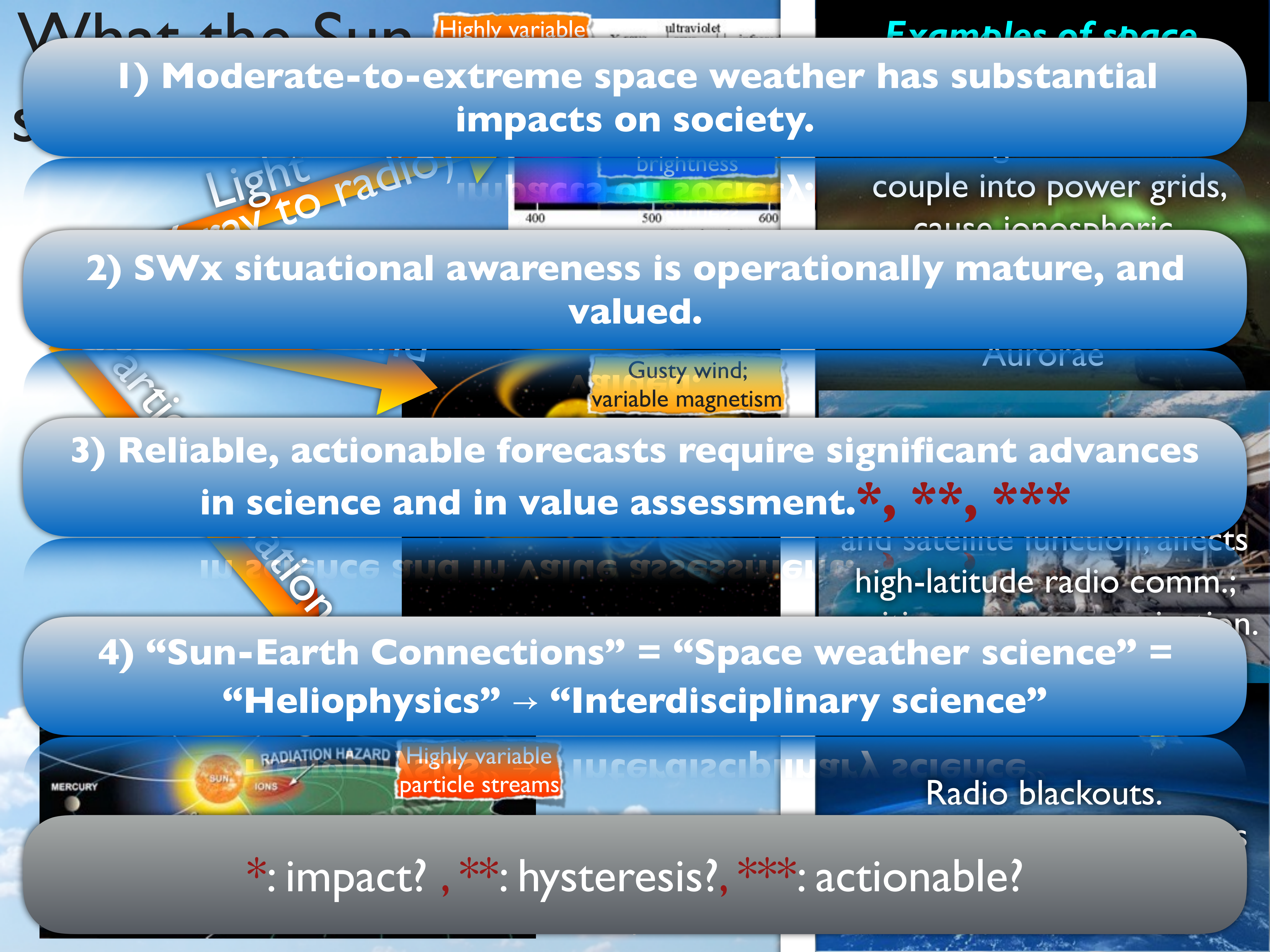

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**4) “Sun-Earth Connections” = “Space weather science” = “Heliophysics” → “Interdisciplinary science”**

*: impact? , **: hysteresis?, ***: actionable?

# *Weather: all around us, all the time*

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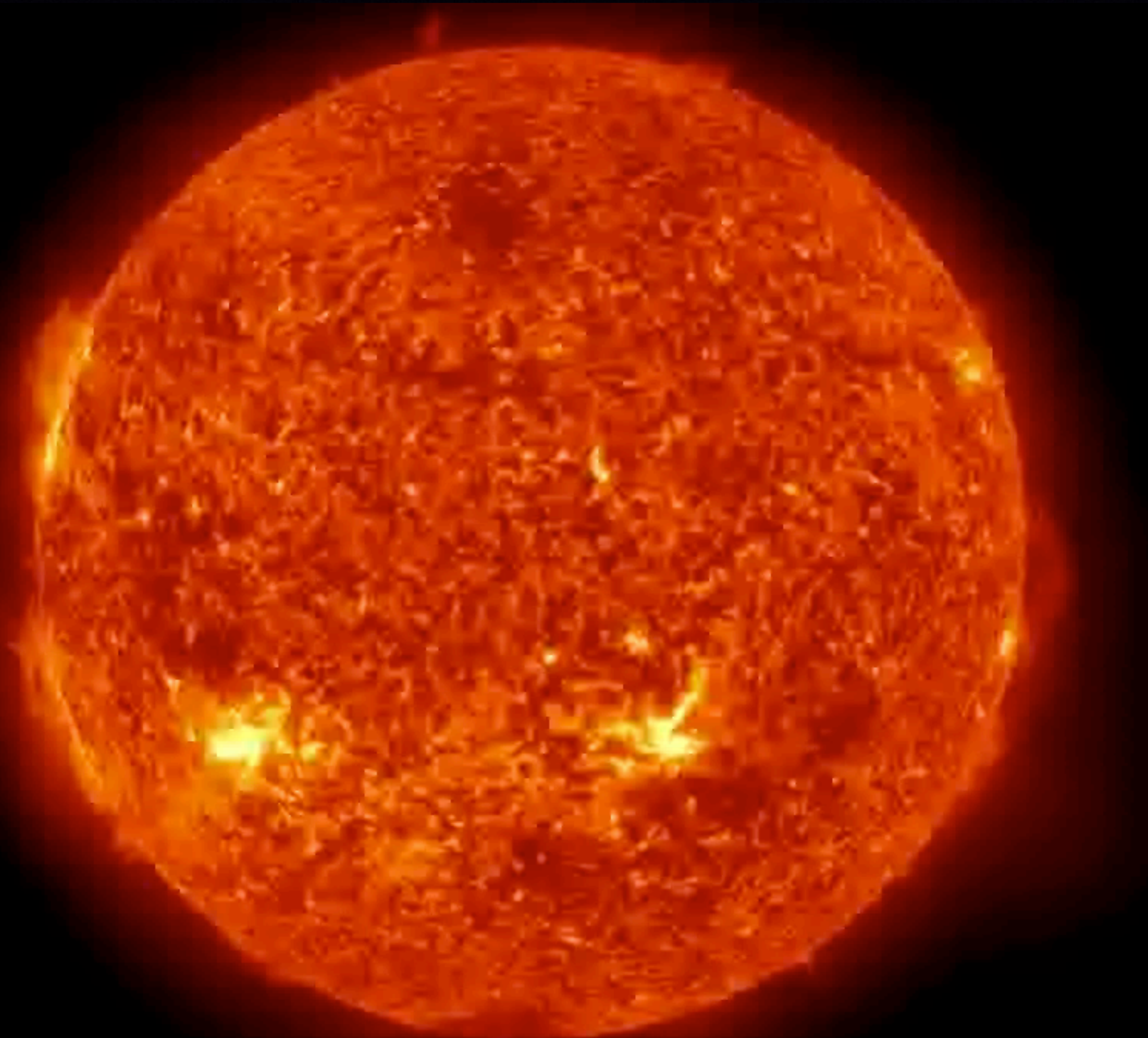
# Space weather: all around us, all the time



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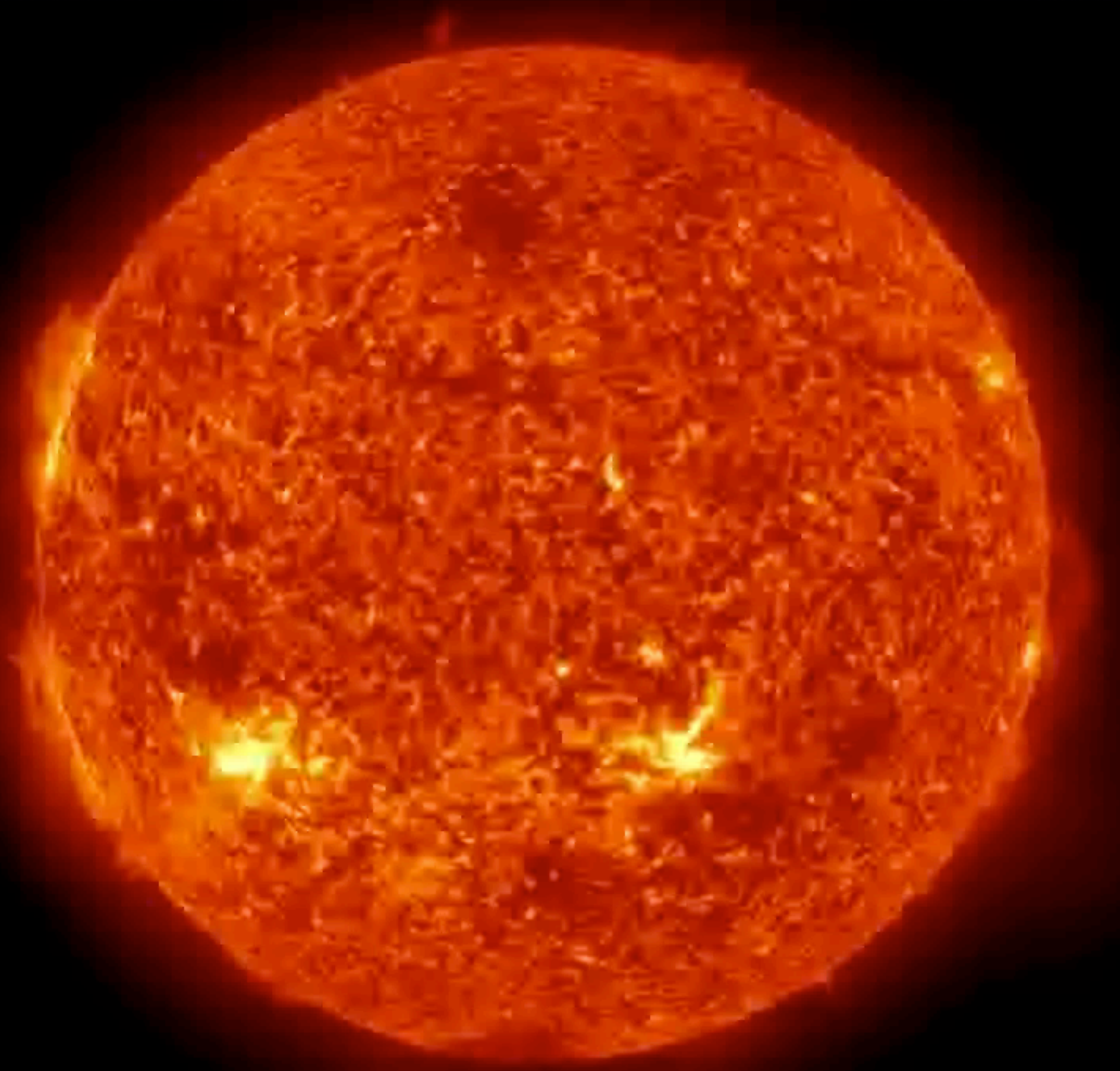

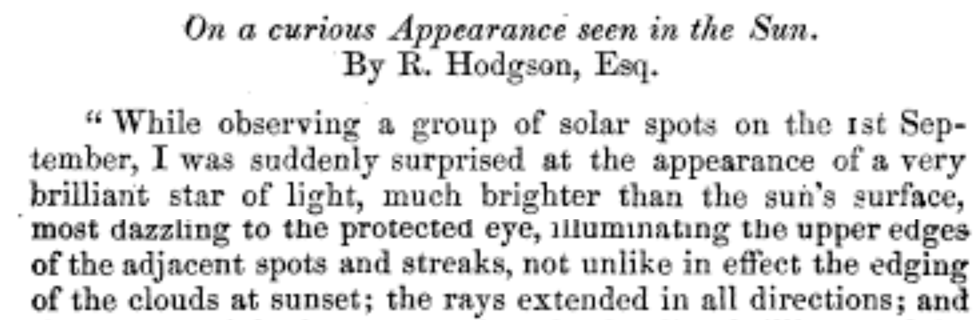

### *On a curious Appearance seen in the Sun.*
By R. Hodgson, Esq.

"While observing a group of solar spots on the 1st September, I was suddenly surprised at the appearance of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset; the rays extended in all directions; and

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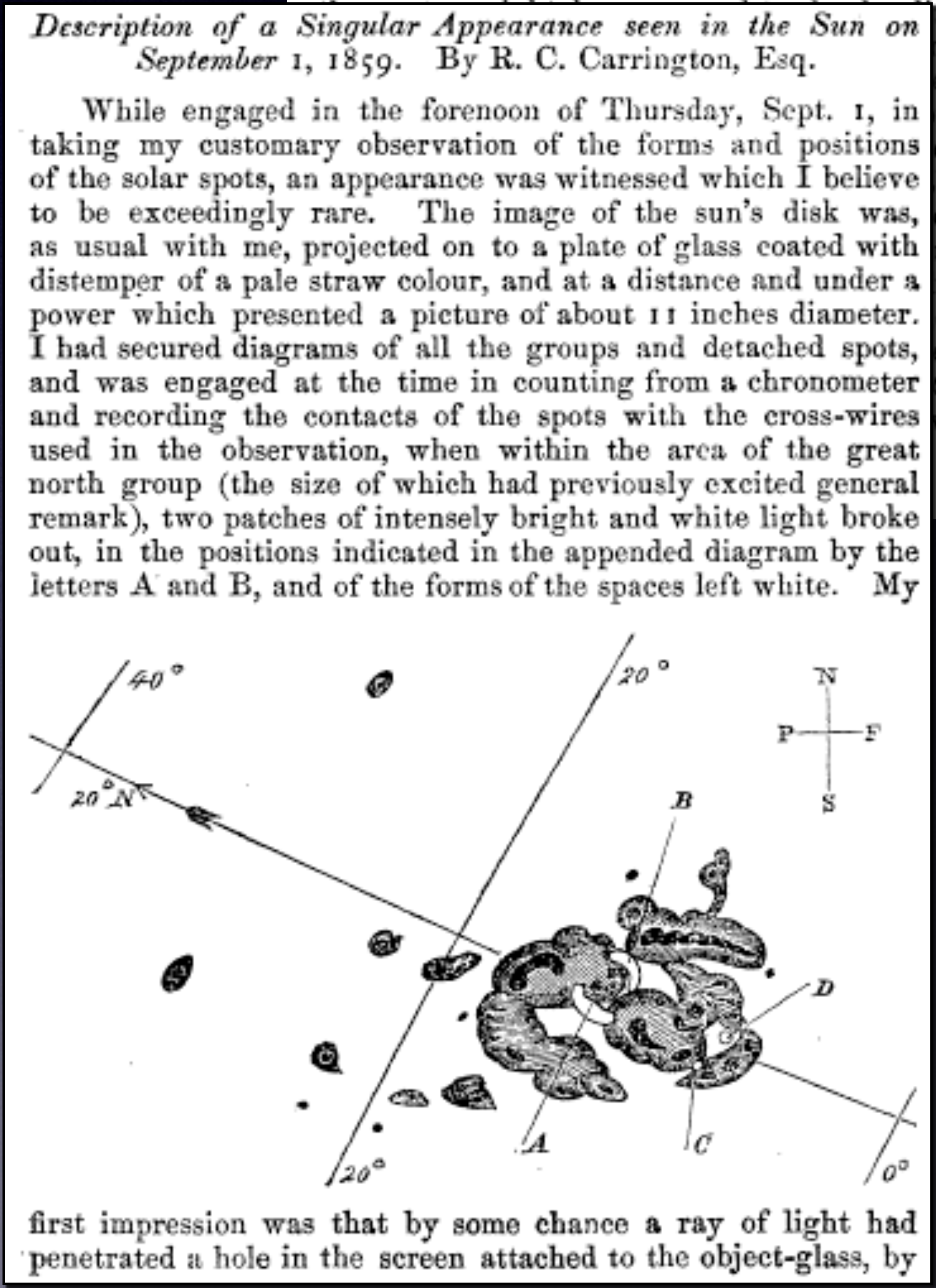
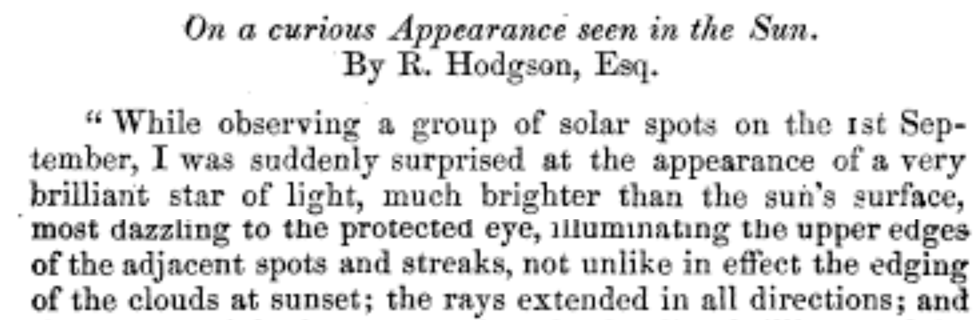


### *Description of a Singular Appearance seen in the Sun on September 1, 1859.* By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

eol.jsc.nasa.gov

# Solar flaring and the connection to geospace: discovered in 1859



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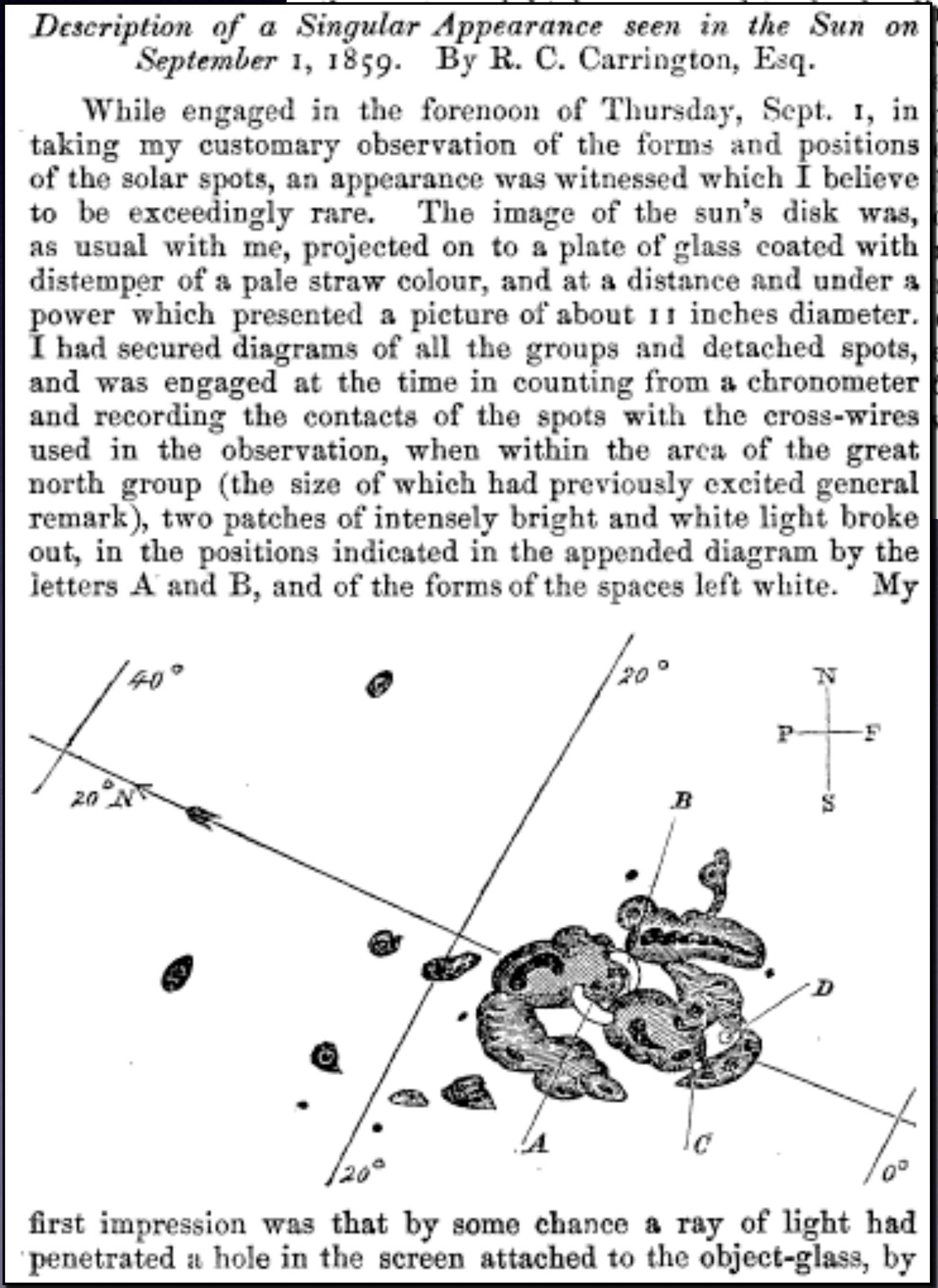

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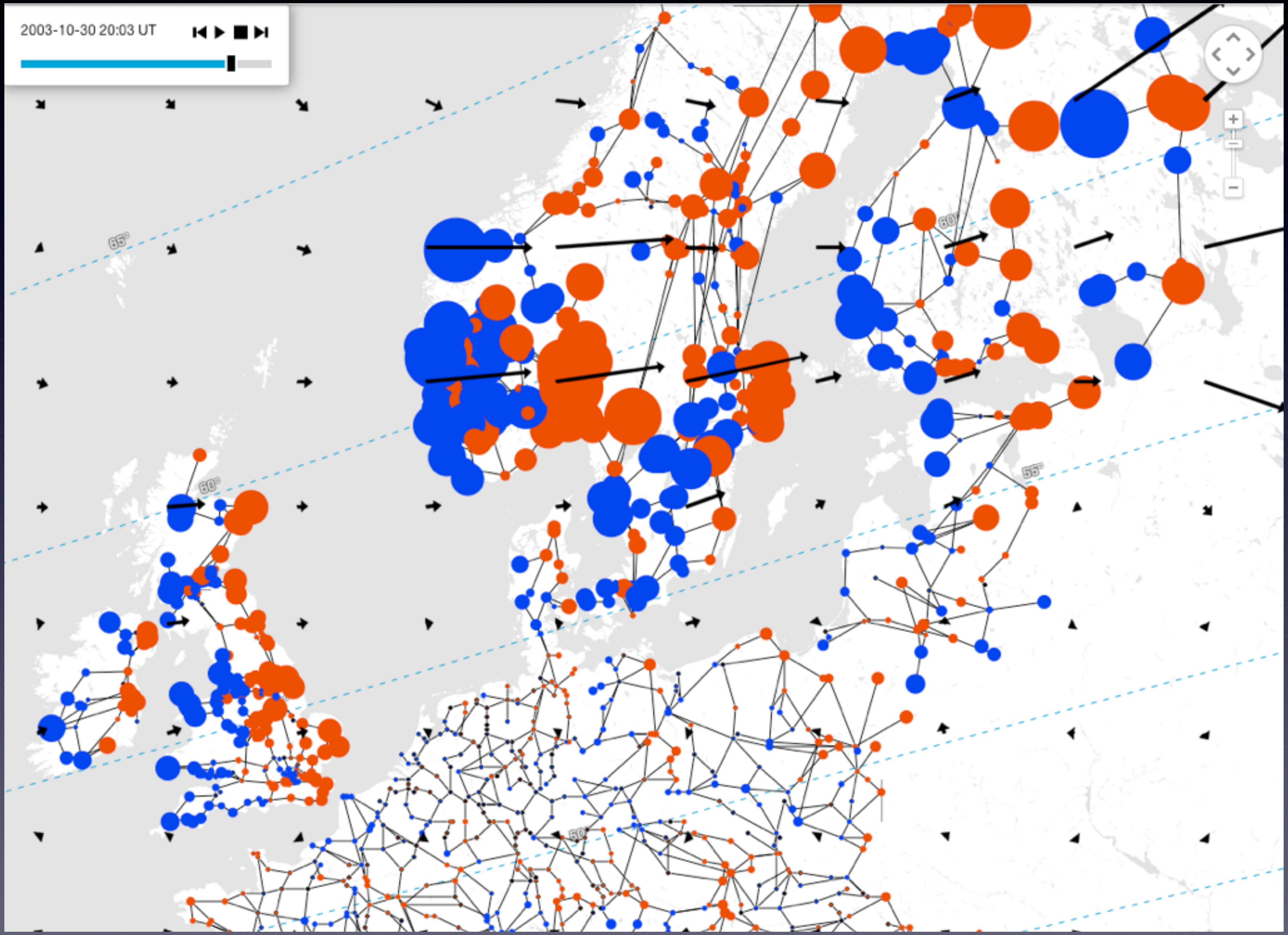
# Geomagnetic variability and grid disturbances



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.

# Risk analysis (2016)

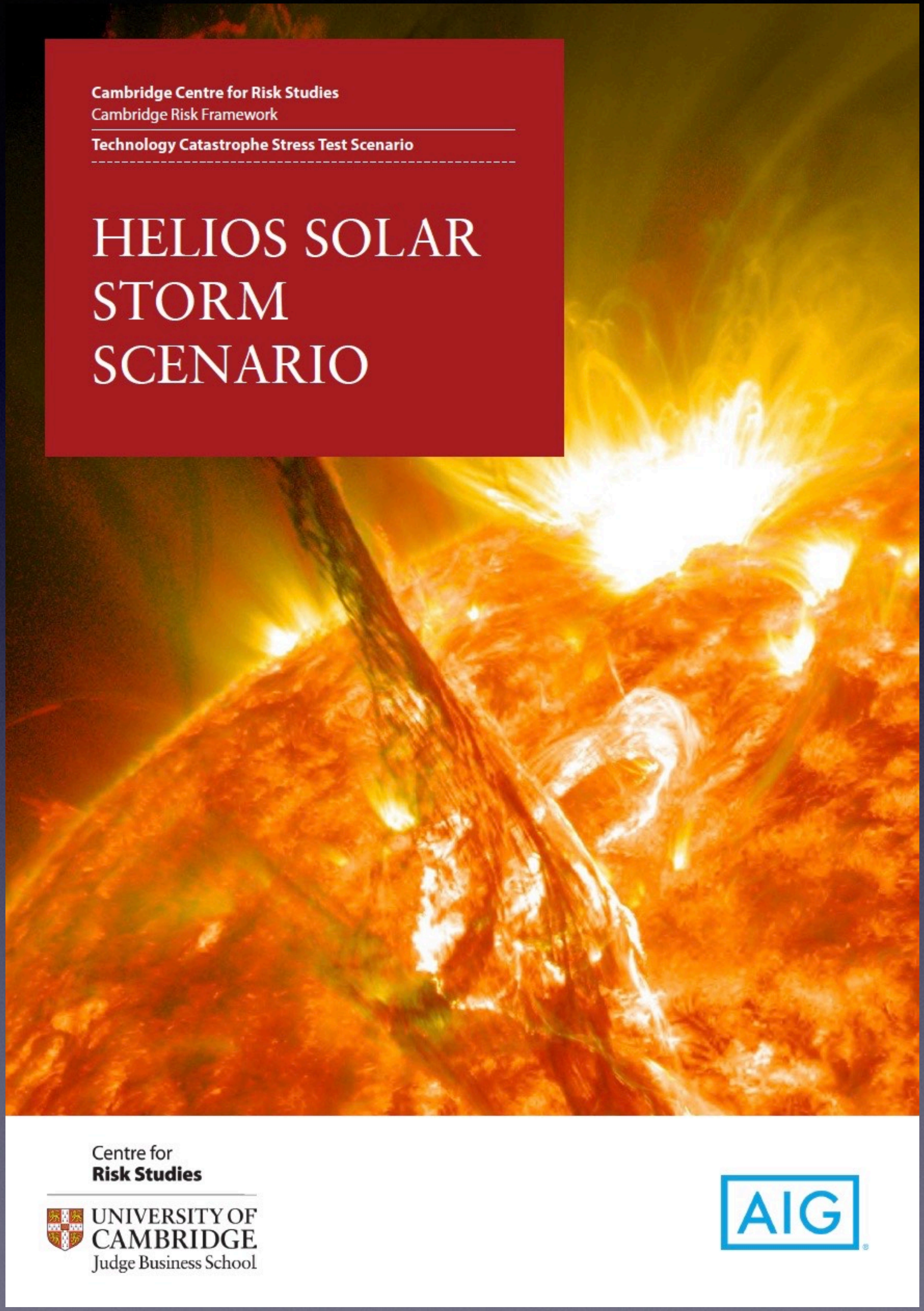
“ … we provide a catastrophe scenario for a US-wide power system collapse that is caused by an extreme space weather event affecting Earth: the Helios Solar Storm Scenario.

… high voltage transmission grids in the USA, resulting in power blackouts along with consequential insurance claims and economic losses

Global supply chain disruptions are conservatively estimated to range from $0.5 to $2.7 trillion across the three scenario variants.

The Helios Solar Storm has a global GDP@Risk ranging from $140 to $613 billion across the three scenario variants (representing between 0.15% and 0.7% of global GDP over the projected five year period).”

*N.B. COMPARABLE TO LOSSES DUE TO MODERATE STORMS MEASURED OVER A CENTURY!*



**Cambridge Centre for Risk Studies**
Cambridge Risk Framework
**Technology Catastrophe Stress Test Scenario**

HELIOS SOLAR STORM SCENARIO

Centre for
**Risk Studies**
UNIVERSITY OF CAMBRIDGE
Judge Business School

AIG

# How severe can space weather storms be?

Reviewed by Schrijver & Beer, 2014; EOS, v. 95, no. 24, pp. 201-208

* Baker et al., 2013, Space Weather Journal, **DOI:** 10.1002/swe.20097: "extreme space weather conditions such as those during March of 1989 or September of 1859 can happen even during a modest solar activity cycle"

# How severe can space weather storms be?

- Observations of Sun-like stars suggest that solar flares may reach energies up to 100-300 times above those observed in the past four decades.
- Ice and rocks from Earth and Moon tell us that energetic particle storm intensities appear to saturate at a few times the space-age maximum.
- Theory of geomagnetic storms suggests they may not be able to exceed twice the strength of the powerful 1859 Carrington event *(which may not be as rare as once thought: consider the 2012/07/23 heliospheric storm that missed Earth*)*, at least not when using Dst as a metric.

All these potential extremes exceed the levels to which modern technologies, connected in a network of growing complexity, have been exposed.

Reviewed by Schrijver & Beer, 2014; EOS, v. 95, no. 24, pp. 201-208

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# Advancing space weather science to protect society's technological infrastructure: a COSPAR/ILWS roadmap

chaired by

**Karel Schrijver** and **Kirsti Kauristie**

Lockheed Martin Adv. Techn. Lab, Palo Alto, CA

Finnish Meteorological Institute, Helsinki Finland

*COSPAR site:* *http://tinyurl.com/swxrm*

*Advances in Space Research 55, 2745 (2015)*

- Alan Aylward; University College London, UK
- Sarah Gibson; UCAR High Altitude Observatory, Boulder, CO, USA
- Alexi Glover; ESA-Rhea System, Germany
- Nat Gopalswamy; NASA/GSFC, Greenbelt, MD, USA
- Manuel Grande; Univ. Aberystwyth, UK
- Mike Hapgood; RAL Space, and STFC Rutherford, Appleton Lab., UK
- Daniel Heynderickx; DHConsultancy, Belgium
- Norbert Jakowski; Deutsches Zentrum für Luft und Raumfahrt, Germany
- Vladimir Kalegaev; Skobeltsyn Inst. of Nucl. Phys., Moscow, Russia
- Kirsti Kauristie, co-chair; Finnish Meteorological Institute, Finland
- Giovanni Lapenta; KU Leuven, Belgium
- Jon Linker; Predictive Science Inc., San Diego, CA, USA
- Liu Siqing; Nat'l Space Science Center, Chinese Acad. of Sciences, China
- Cristina Mandrini; Inst. de Astr. y Fis. del Espacio, Buenos Aires, Argentina
- Ian Mann; Univ. Alberta, Canada
- Tsutomu Nagatsuma; Space Weather and Env. Inf. Lab., NICT, Japan
- Dibyendu Nandi; Indian Inst. of Science, Ed. and Res., Kolkata, India
- Clezio De Nardin; INPE, Brazil
- Takahiro Obara; Tohoku University, Japan
- Paul O'Brien; Aerospace Corporation, USA
- Terry Onsager; NOAA Space Weather Prediction Centre, USA
- Hermann Opgenoorth; Swedish Institute of Space Physics, Sweden
- Karel Schrijver, chair; Lockheed Martin ATC, USA
- Michael Terkildsen; IPS Radio and Space Services, Australia
- Cesar Valladares; Boston College, USA
- Nicole Vilmer; LESIA Observatoire de Paris, France

science.nasa.gov

# COSPAR/ILWS Charge

The RoadMap

I. focuses on high-priority challenges in key areas of research
II. leading to a better understanding of the space environment and
III. a demonstrable improvement in the provision of timely, reliable information
IV. pertinent to effects on civilian space- and ground-based systems,
V. for all stakeholders around the world.

The RoadMap prioritizes those advances that can be made on short, intermediate and decadal time scales, identifying gaps and opportunities from a predominantly, but not exclusively, geocentric perspective.

"Space weather refers to the variable state of the coupled space environment related to changing conditions on the Sun and in the terrestrial atmosphere."

e-Home: https://cosparhq.cnes.fr/scientific-structure/cospar-scientific-roadmaps

# Fundamental questions

What will leave the Sun?
How will things evolve en-route to geospace?
What will it cause to happen in geospace?
How will that affect technology?
How can that affect society?
How can society respond to the threat?
How does any of these steps depend on what came before?
*[Hysteresis, pre-conditioning, ... "event studies" should become "interval studies of the system"]*

*Needs*

*High*

*Low*

# Tracing impacts & predicting space weather

## 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

*Domain: solar, heliospheric, geospace*

*Needs*
*High*
*Low*

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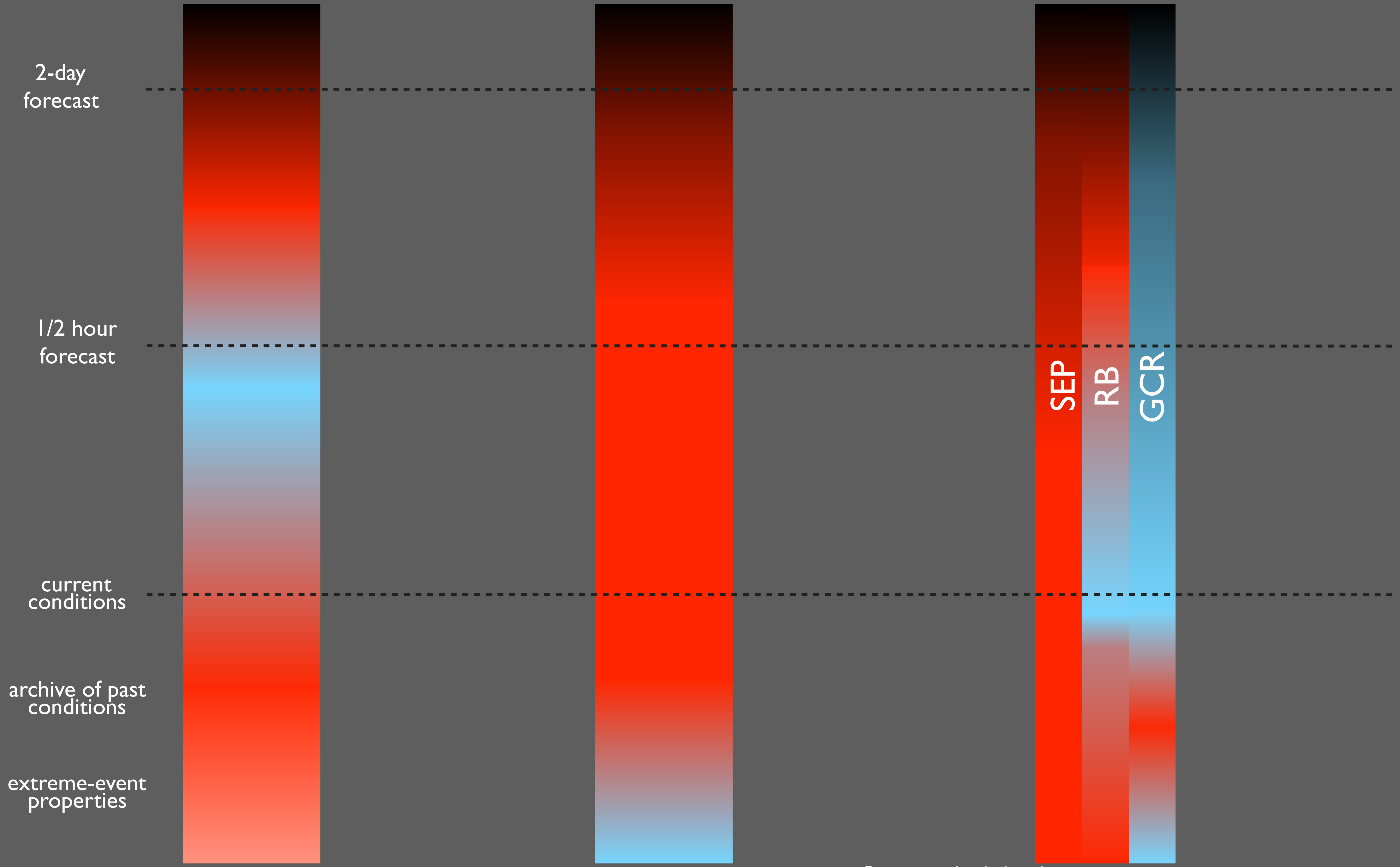

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# Tracing impacts & predicting space weather

*Needs*
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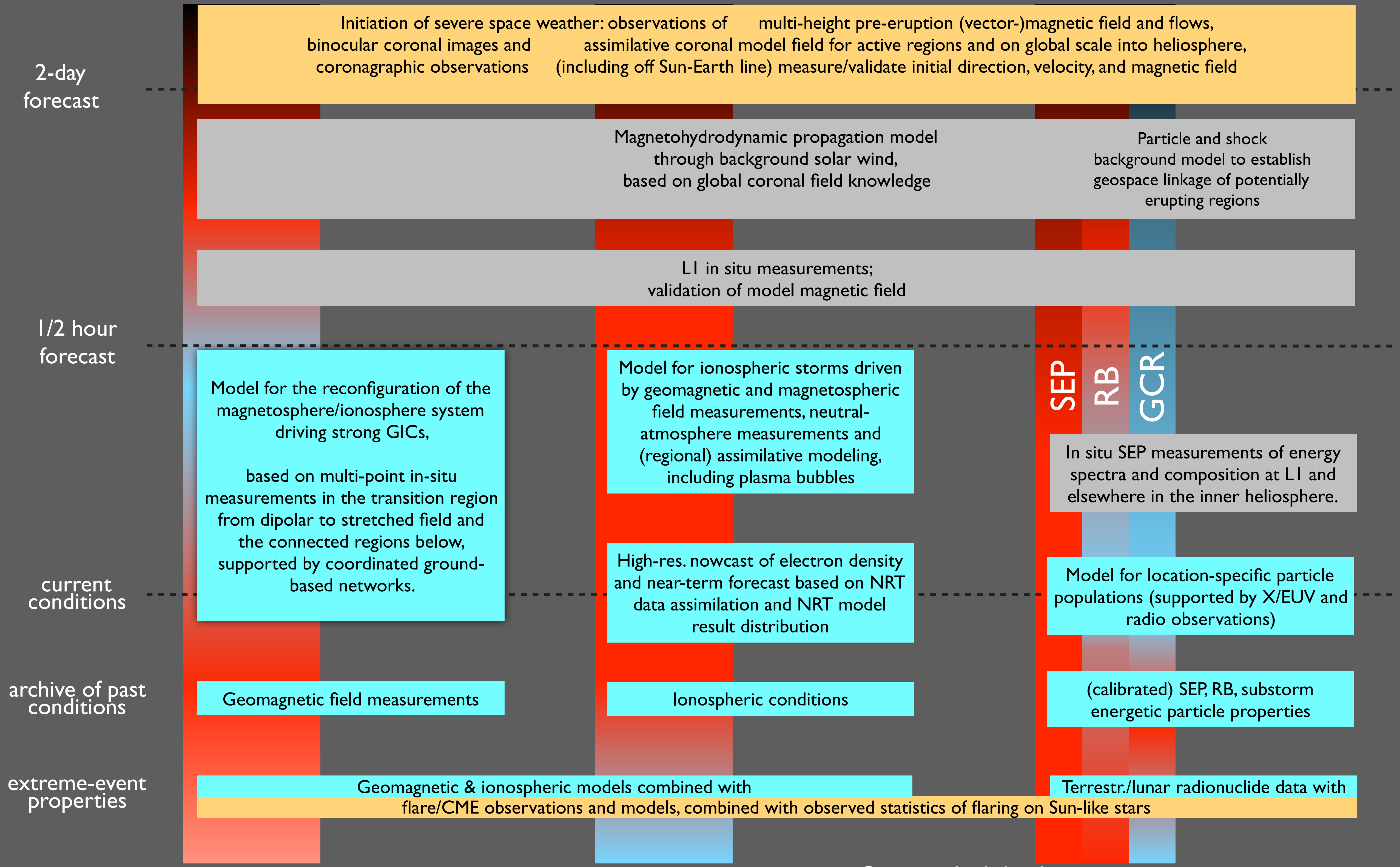

Initiation of severe space weather: observations of multi-height pre-eruption (vector-)magnetic field and flows, binocular coronal images and assimilative coronal model field for active regions and on global scale into heliosphere, coronagraphic observations (including off Sun-Earth line) measure/validate initial direction, velocity, and magnetic field

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Geomagnetic field measurements

Ionospheric conditions

(calibrated) SEP, RB, substorm energetic particle properties

Geomagnetic & ionospheric models combined with

Terrestr./lunar radionuclide data with

flare/CME observations and models, combined with observed statistics of flaring on Sun-like stars

*Domain: solar, heliospheric, geospace*

Needs
High
Low

# Tracing impacts & predicting space weather

## 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*

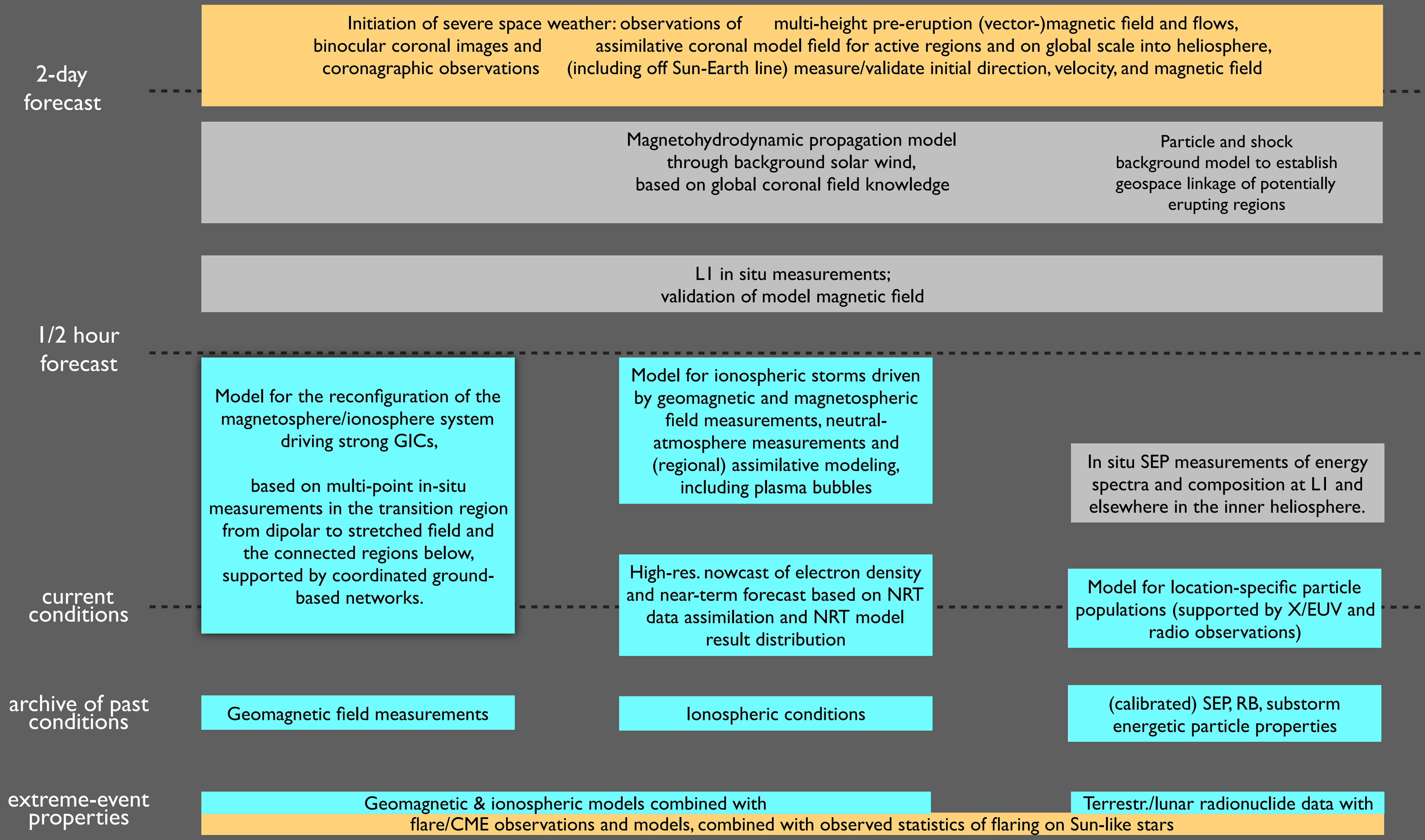
*Focus on post-eruption*

## (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

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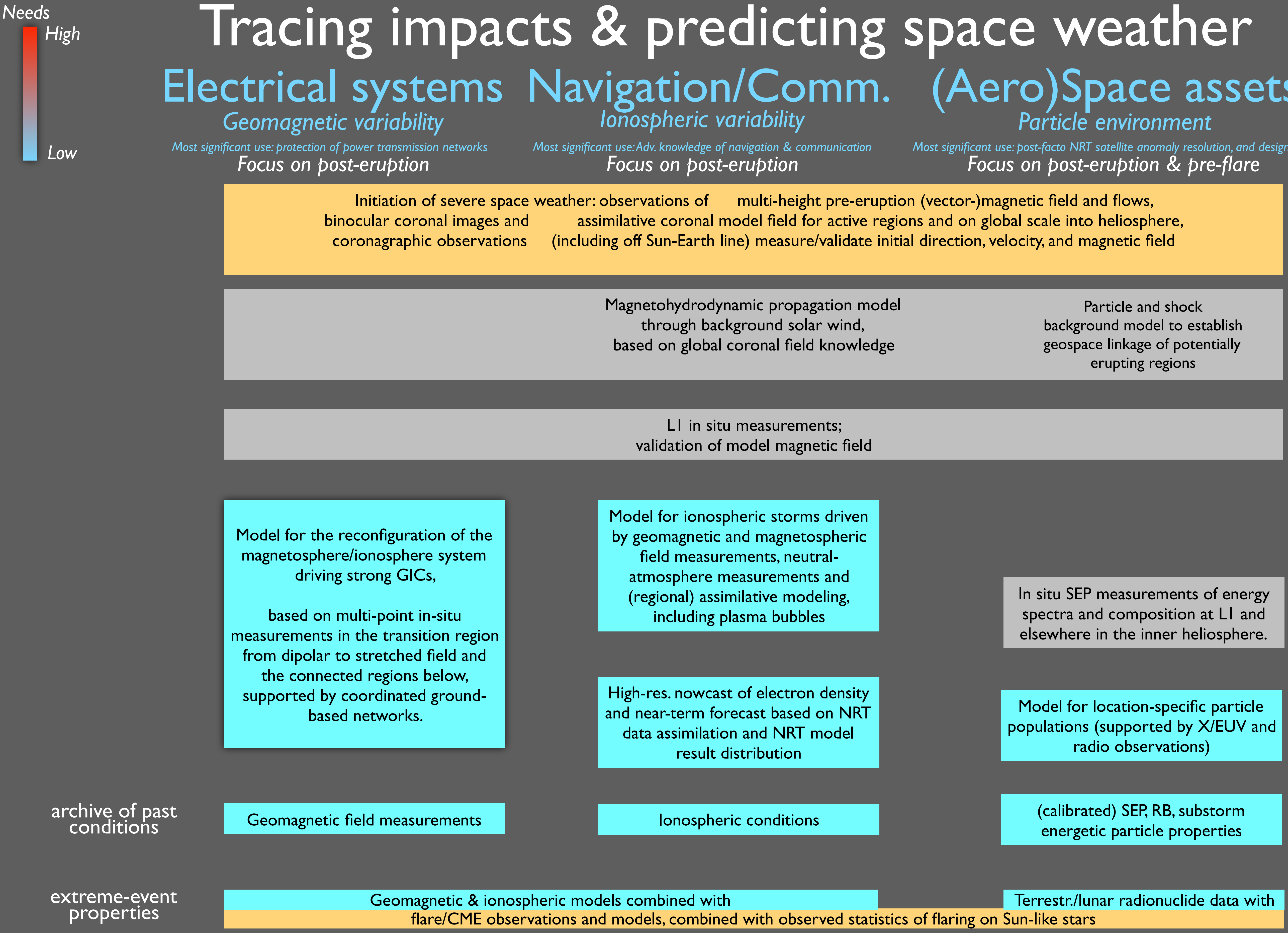

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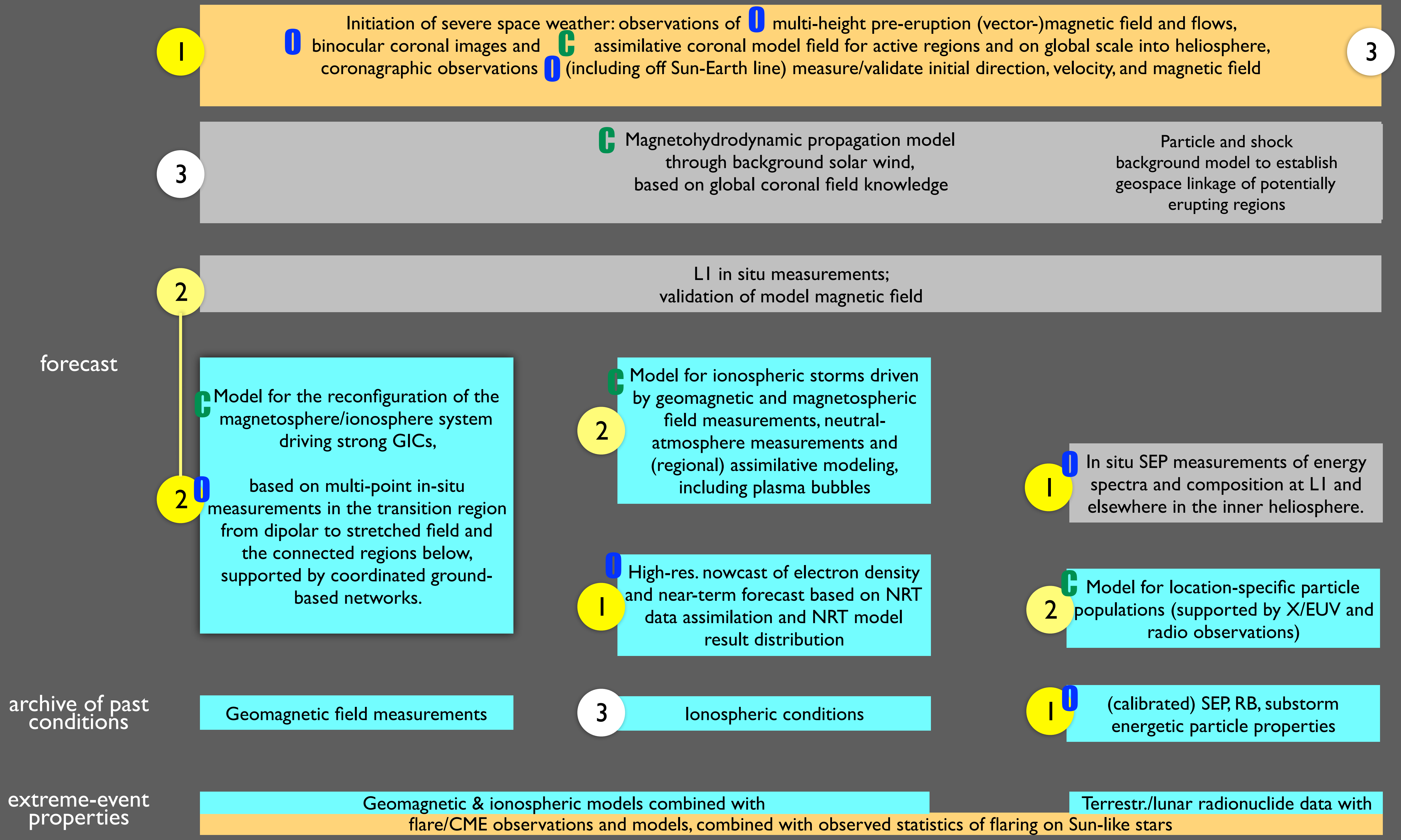

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# Tracing impacts & predicting space weather

1 Urgency/feasibility

O Opportunity for improved under-standing & services.

C Scientific or technical challenge

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# Highest-priority recommendations in brief

In a collaborative international effort:

## Research: observational, computational, and theoretical needs

1. **“Augment the system observatory”**
2. **“Initial focus: Know what $\vec{B}$ is coming”**
3. **“Initial focus: Establish the GMD-GIC response”**
4. **“Quantify conditions to expect”**

## Teaming: coordinated collaborative research environment

I. **“Uncover susceptibility”**
II. **“Focus resources”**
III. **“Ease access to data”**
IV. **“Grow coverage affordably”**

## Bridging communities: collaboration between agencies and communities

A. **“Trust partners”**
B. **“Learn about SWx and its impacts”**
C. **“Evolve priorities and coordinate”**
D. **“Make use of advancing knowledge”**
E. **“Avoid duplication and mistakes”**

# Highest-priority recommendations

## Research: observational, computational, and theoretical needs

In a collaborative international effort:

1. **"Augment the system observatory":** Advance the international Sun-Earth system observatory along with data-driven models to improve forecasts based on understanding of real-world events through the development of innovative approaches to data incorporation, including data-driving, data assimilation, and ensemble modeling

2. **"Initial focus: Know what $\vec{B}$ is coming":** Understand space weather origins at the Sun and their propagation in the heliosphere, initially prioritizing post-event solar eruption modeling to develop multi-day forecasts of geomagnetic disturbance times and strengths, after propagation through the heliosphere

3. **"Initial focus: Establish the GMD-GIC response":** 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.

4. **"Quantify conditions to expect":** Develop a comprehensive space environment specification, first to aid scientific research and engineering designs, later to support forecasts

# Highest-priority recommendations

## Teaming: coordinated collaborative research environment

In a collaborative international effort:

I) **"Uncover susceptibility": Quantify vulnerability** of humans and of society's infrastructure to space weather jointly with stakeholder groups.

II) **"Focus resources": Build test beds in which coordinated observing supports model development:** (a) state-of-the-art environments for numerical experimentation and (b) focus areas of comprehensive observational coverage, as tools to advance understanding of the Sun-Earth system, to validate forecast tools, and to guide requirements for operational forecasting.

III) **"Ease access to data": Standardize (meta-)data and product metrics, and harmonize access to data and model archives:** for observational and model data products, for data dissemination, for archive access, for intercalibration, for tests of models and forecasts.

IV) **"Grow coverage affordably": Optimize observational coverage of the Sun-society system:** Increase coverage of the Sun-Earth system by combining observations with data-driven models, by optimizing use of existing ground-based and space-based resources, by developing affordable new instrumentation and exploring alternative techniques, and through partnerships between scientific and industry sectors.

# Highest-priority recommendations

## Bridging communities: collaboration between agencies and communities

In a collaborative international effort:

A. **"Trust partners": Implement an open space-weather data and information policy:** Promote data sharing through (1) open data policies, (2) trusted brokers for access to space-weather impact data, and (3) partnerships with the private sector.

B. **"Learn about SWx and its impacts": Provide access to quality education and information materials for all stakeholder groups:** Identify and collect or develop educational materials on space weather and its societal impacts, and support resource hubs for these, and for space-weather related data and data products.

C. **"Evolve priorities and coordinate": Execute an international, inter-agency assessment of the state of the field on a 5-year basis to adjust priorities subject to scientific, technological, and user-base developments to guide international coordination:** perform comprehensive assessments of the state of the science of space weather on a 5-year basis to update prioritization data, models, and research infrastructure, and to provide that as guide to agencies around the world.

D. **"Make use of advancing knowlege": Develop settings to transition research tools to operations.** Collaborative activities to evaluate skills of models at forecasting/specifying parameters of high operational value. Determine the suitability of research models for use in a space weather service center. Identify performance gaps in research and (operational) models and encourage developments in high-priority areas.

E. **"Avoid duplication and mistakes": Partner with the weather and solid-Earth communities to share lessons learned** to improve understanding of the couplings between weather and space-

# Recommendations by pathway

on observational, computational, and theoretical needs

## Pathway I: ... for impacts of GMD/GIC on electrical systems

to obtain >1d forecasts of incoming CME field, and anticipated geomagnetic response, and ionospheric disturbances.

## Pathway II: ... for the particle environment of (aero)space assets

to improve environmental specification and near-real-time conditions

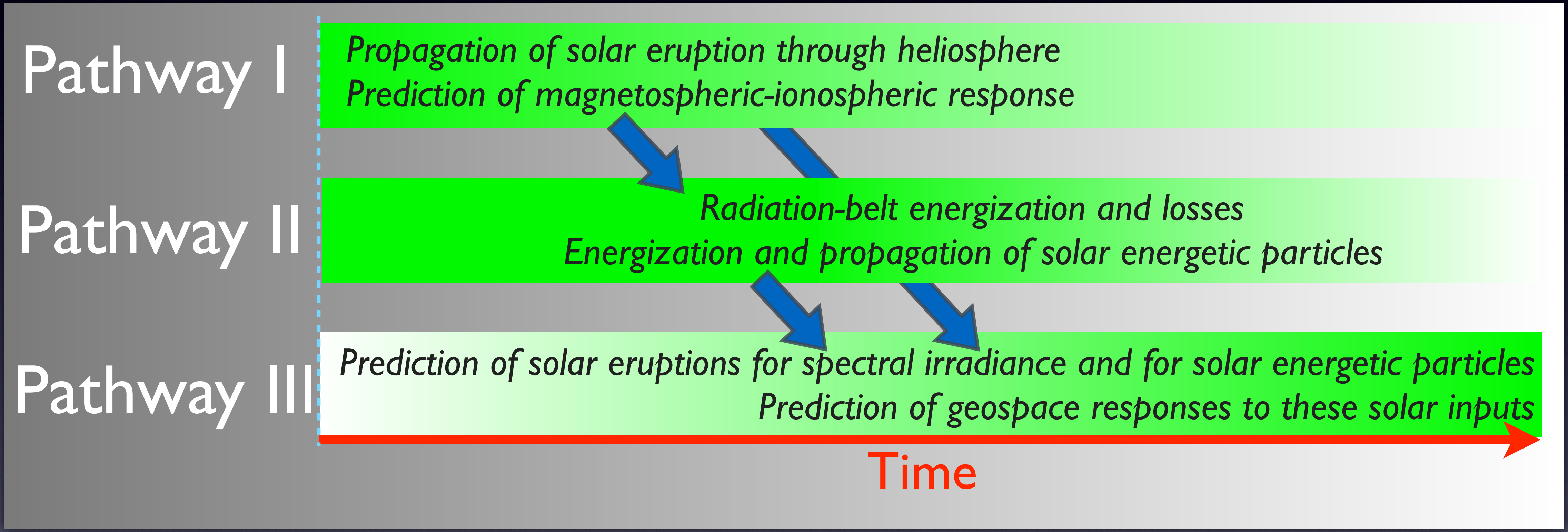
## Pathway III: ... to enable pre-event forecasts of flares and SEPs

to enable short-term forecasts, including all-clear conditions, for particles and ionospheric conditions

*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.*

# Recommendations by pathway

## on observational, computational, and theoretical needs



Pathway I

*Propagation of solar eruption through heliosphere*
*Prediction of magnetospheric-ionospheric response*

Pathway II

*Radiation-belt energization and losses*
*Energization and propagation of solar energetic particles*

Pathway III

*Prediction of solar eruptions for spectral irradiance and for solar energetic particles*
*Prediction of geospace responses to these solar inputs*

Time

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# Differential needs and feasibilities

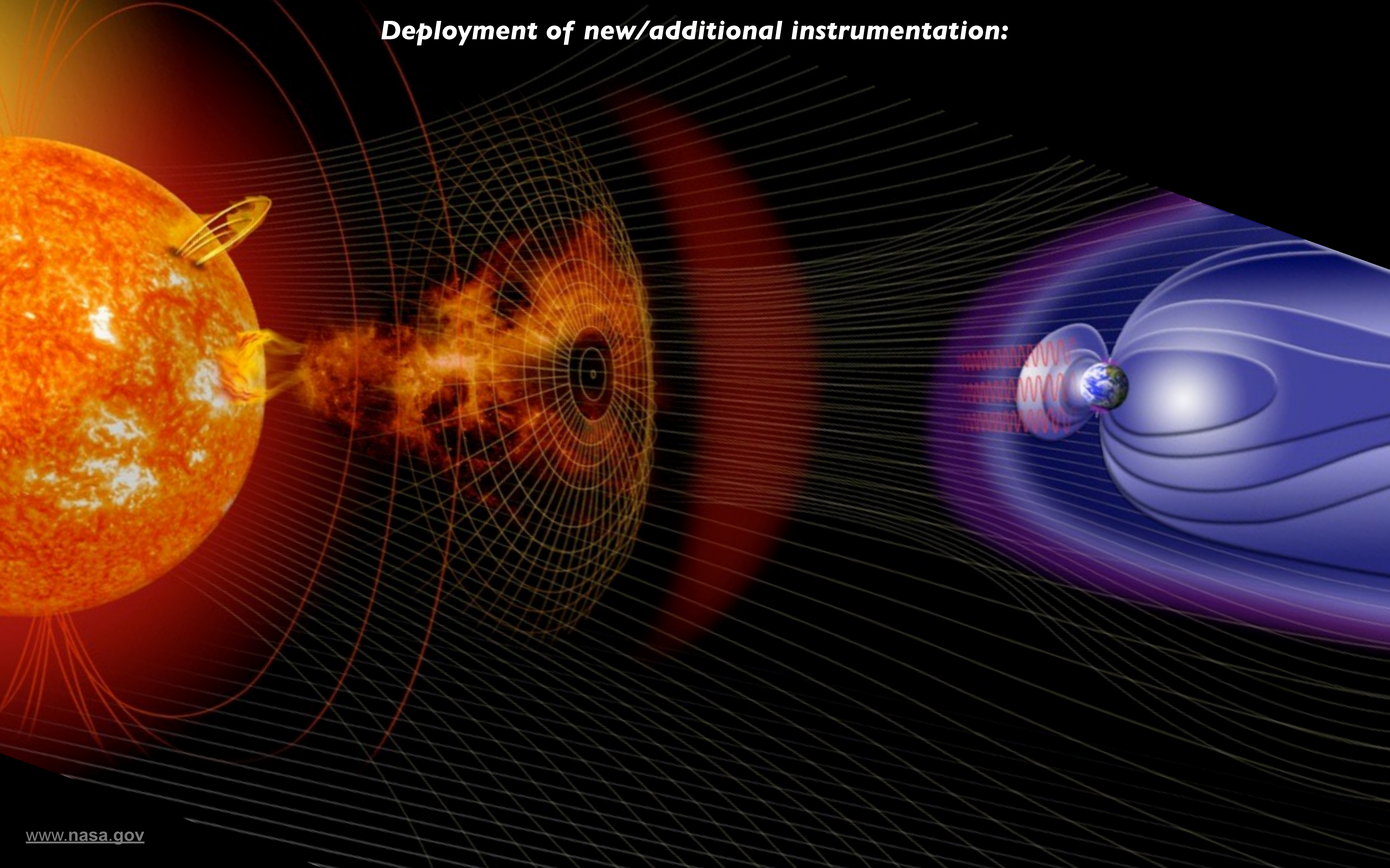
Recommendation for next steps towards meeting user needs, grouped to enable advances on phased paths.

Character of requirements

| *Most significant use:*<br>*Needed product:* | Electrical systems<br>*Geomagnetic variability*<br>*protection of electrical & electronic systems* | Navigation/Comm.<br>*Ionospheric variability*<br>*reliability of navigation and communication* | (Aero)Space assets<br>*Space particle environment*<br>*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 III*** | ***Pathways II & III*** |
| 1-2 day forecasts | ***Pathway I*** | ***Pathway III*** | ***Pathway II*** |

# Pathway I: observational, computational, and theoretical needs to forecast GIC effects more than 12hrs ahead

***Deployment of new/additional instrumentation:***



www.nasa.gov

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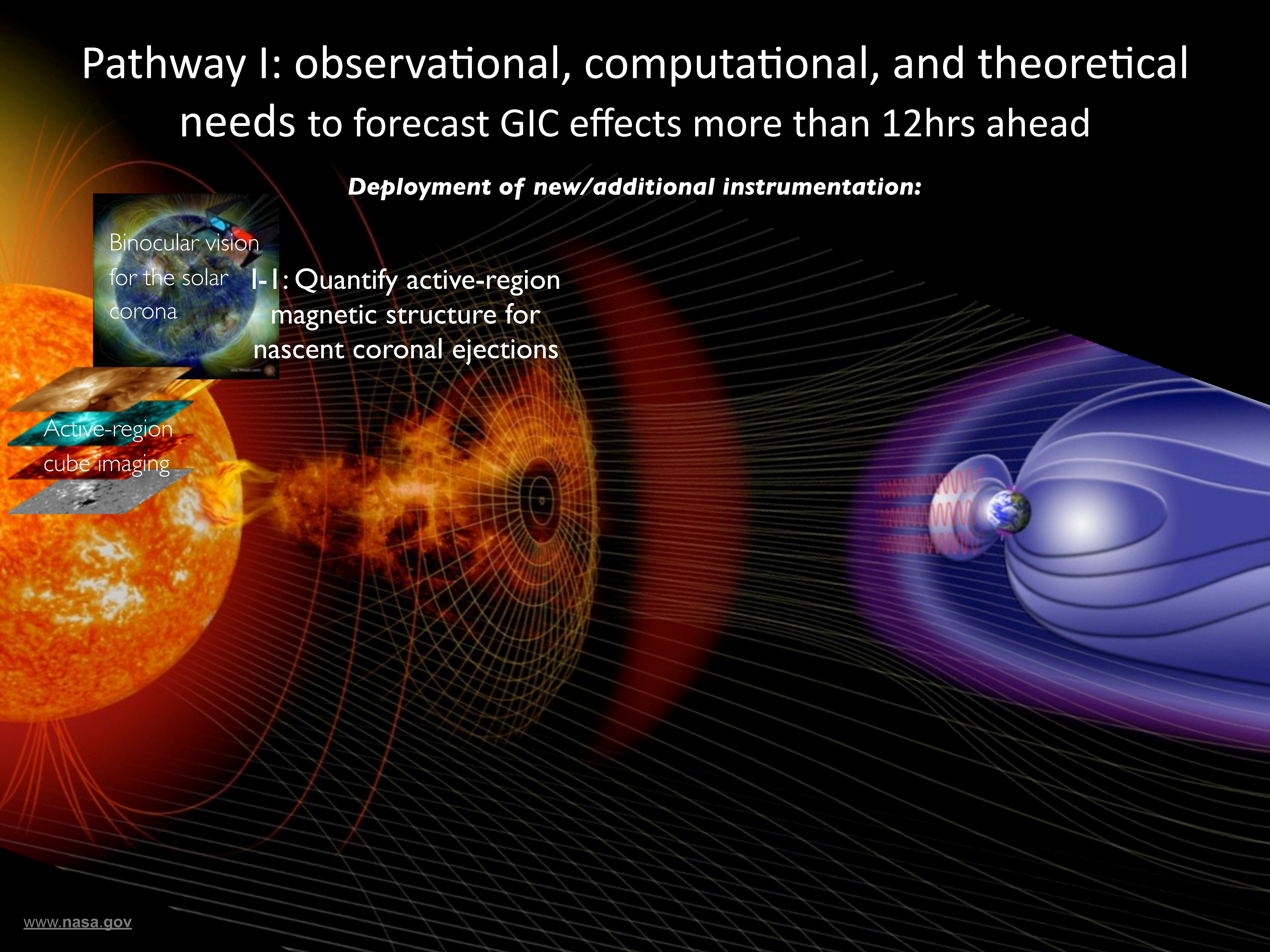

Binocular vision for the solar corona

I-1: Quantify active-region magnetic structure for nascent coronal ejections

Active-region cube imaging

www.nasa.gov

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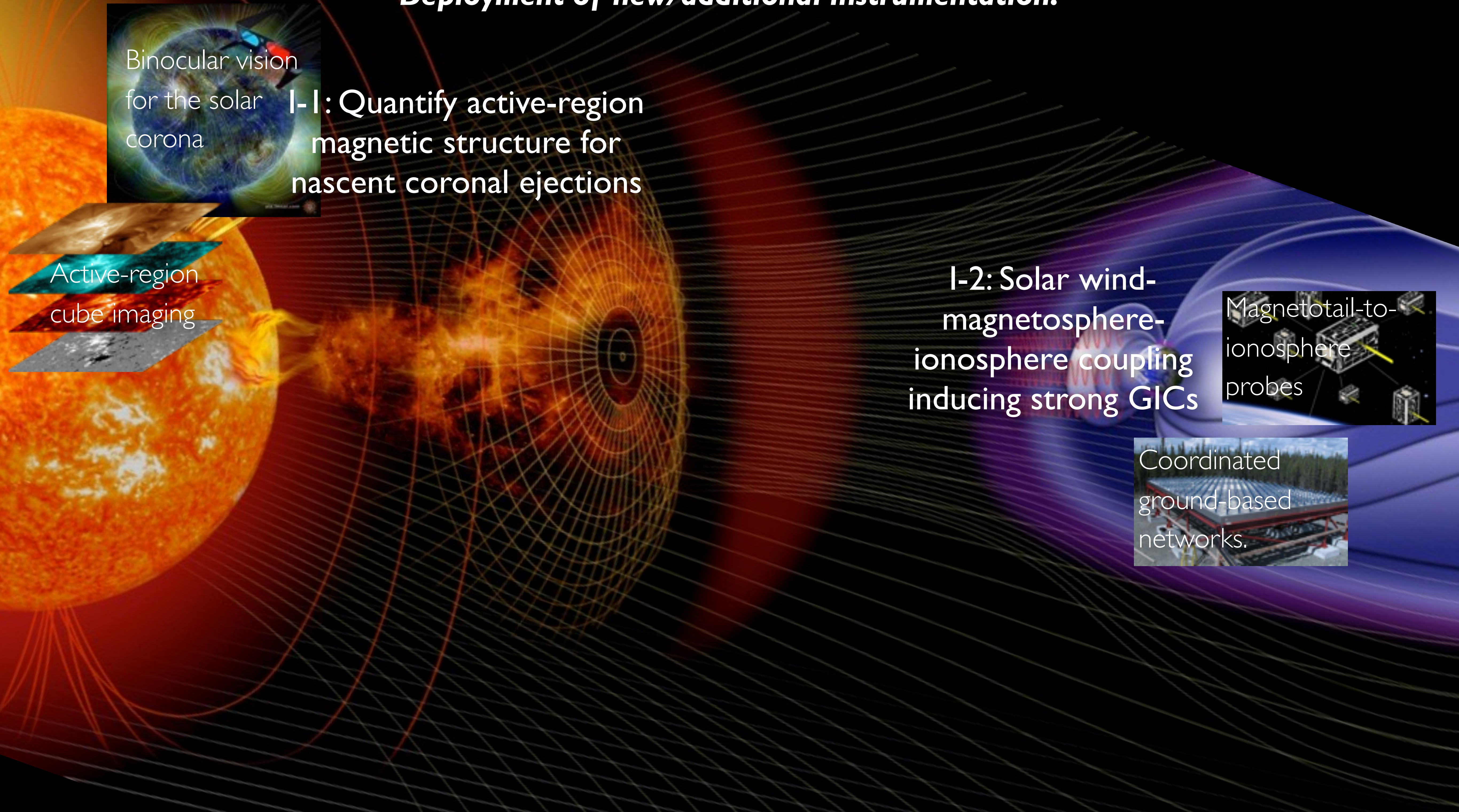

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Magnetotail-to-ionosphere probes

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www.nasa.gov

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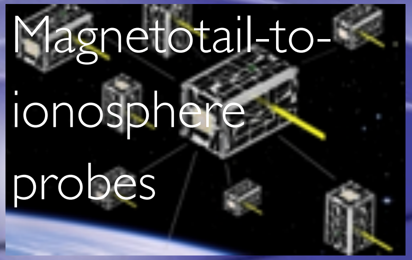

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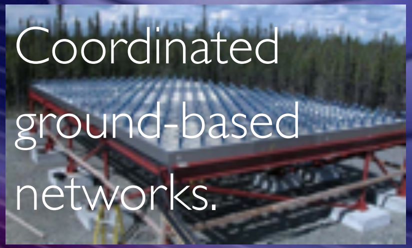

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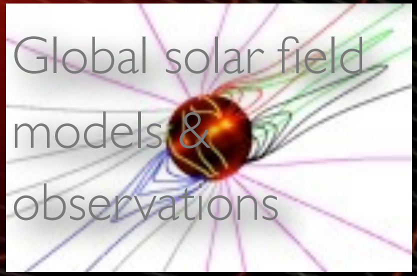
I-3: Global corona to drive models for the solar-wind plasma and field



Global solar field models & observations

www.nasa.gov

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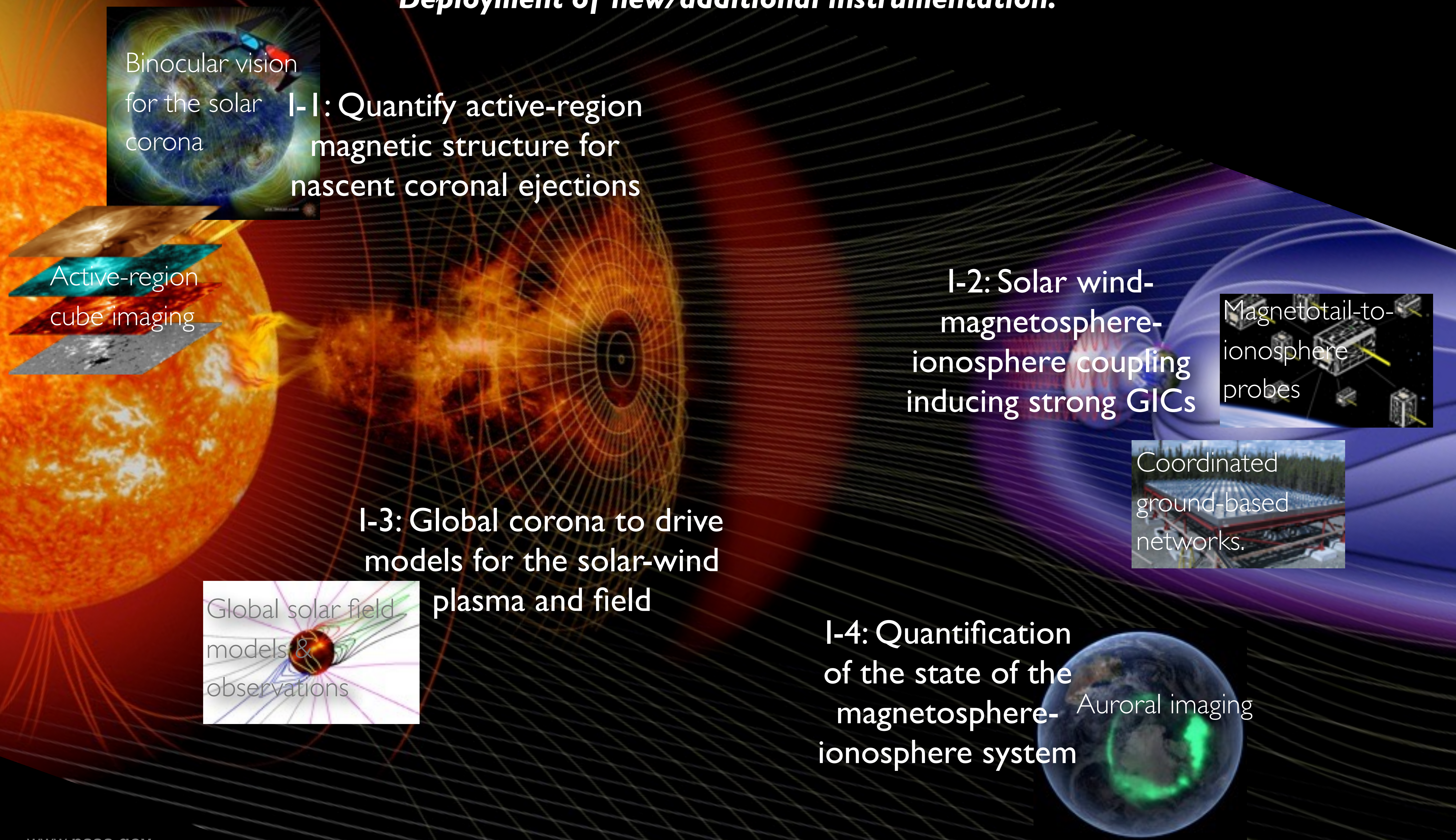

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I-4: Quantification of the state of the magnetosphere-ionosphere system

Auroral imaging

www.nasa.gov

# Pathway II: observational, computational, and theoretical needs for the radiation-belt environment

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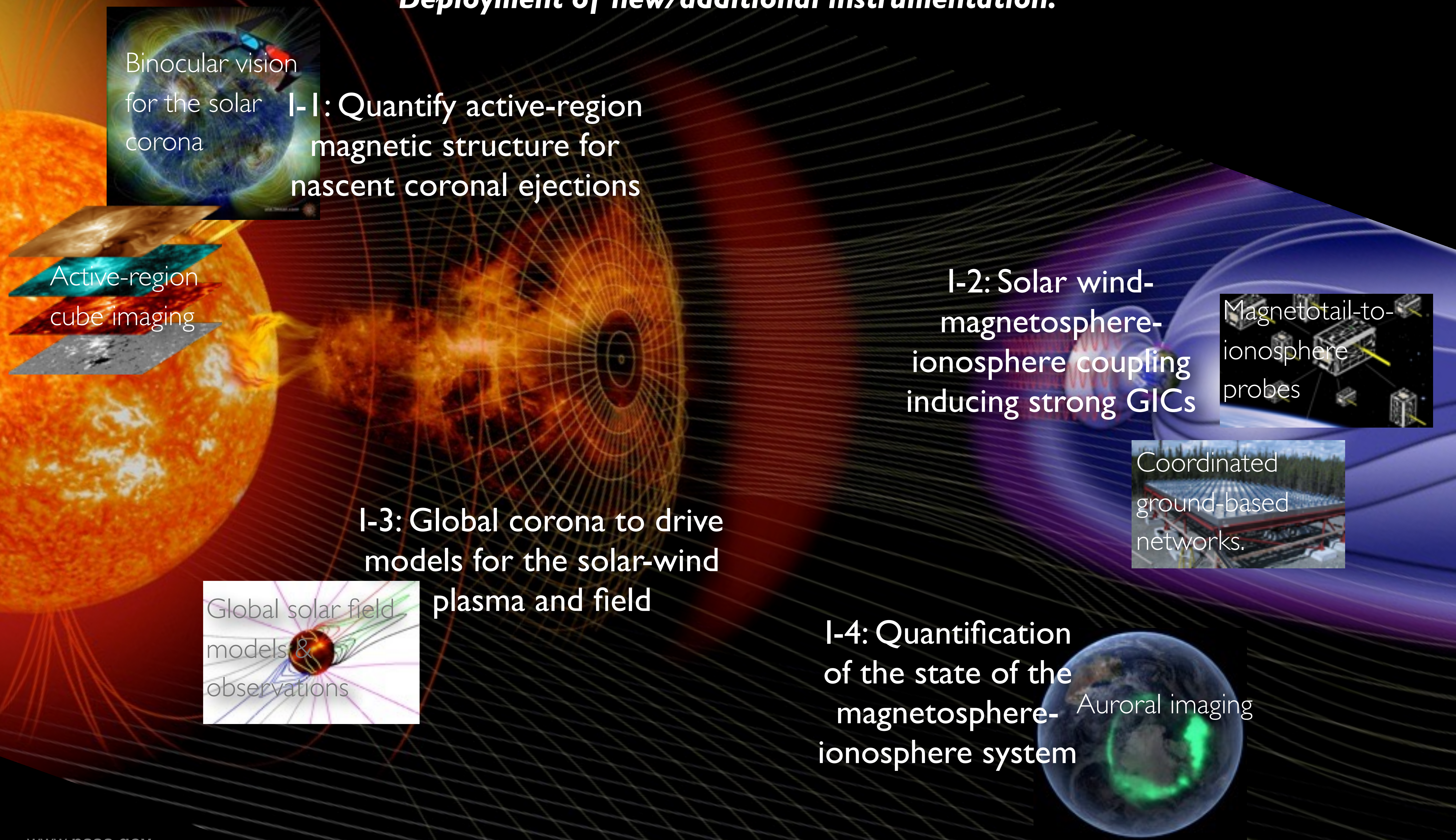

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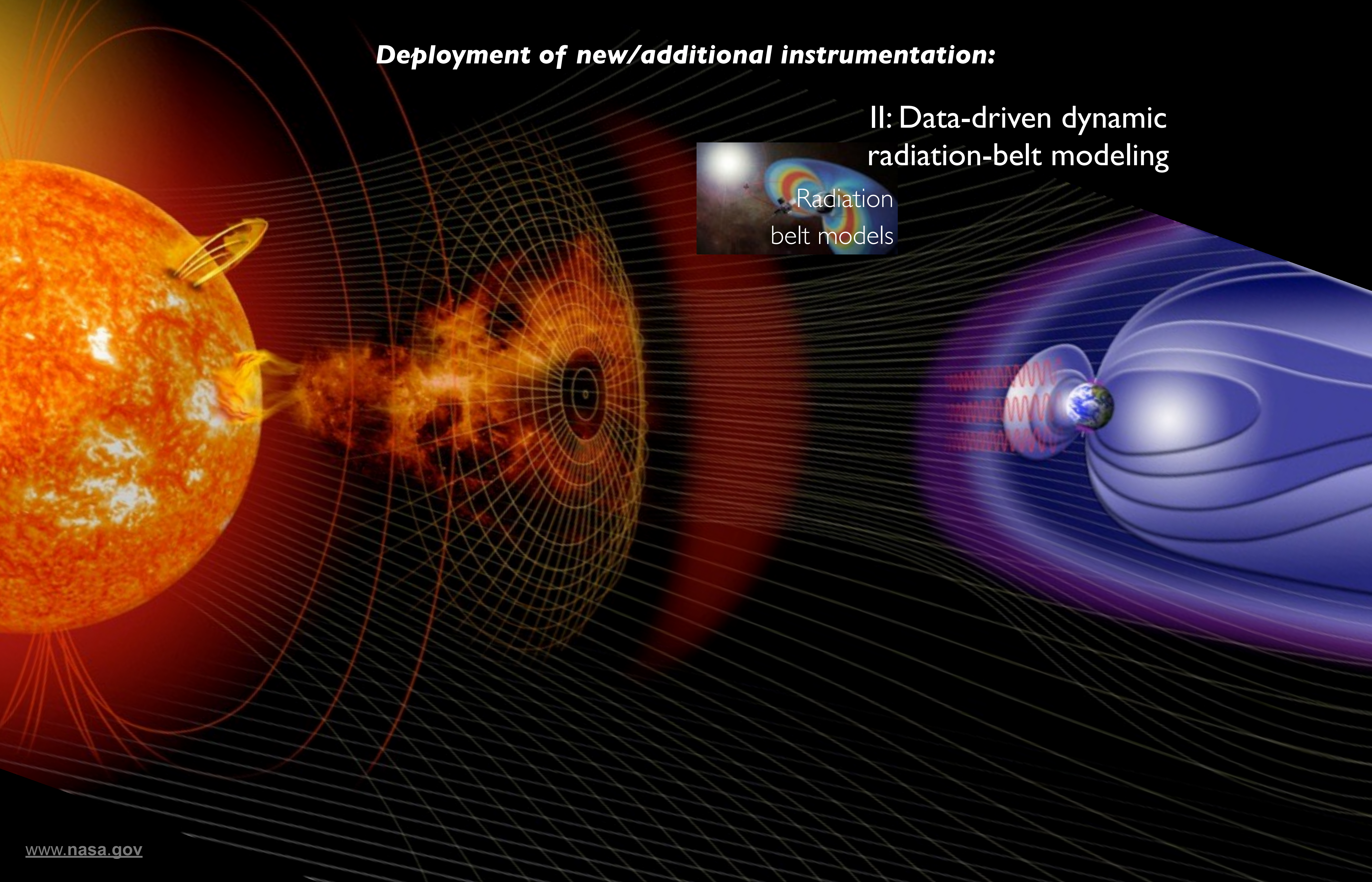
# Pathway II: observational, computational, and theoretical needs for the radiation-belt environment

***Deployment of new/additional instrumentation:***

II: Data-driven dynamic radiation-belt modeling



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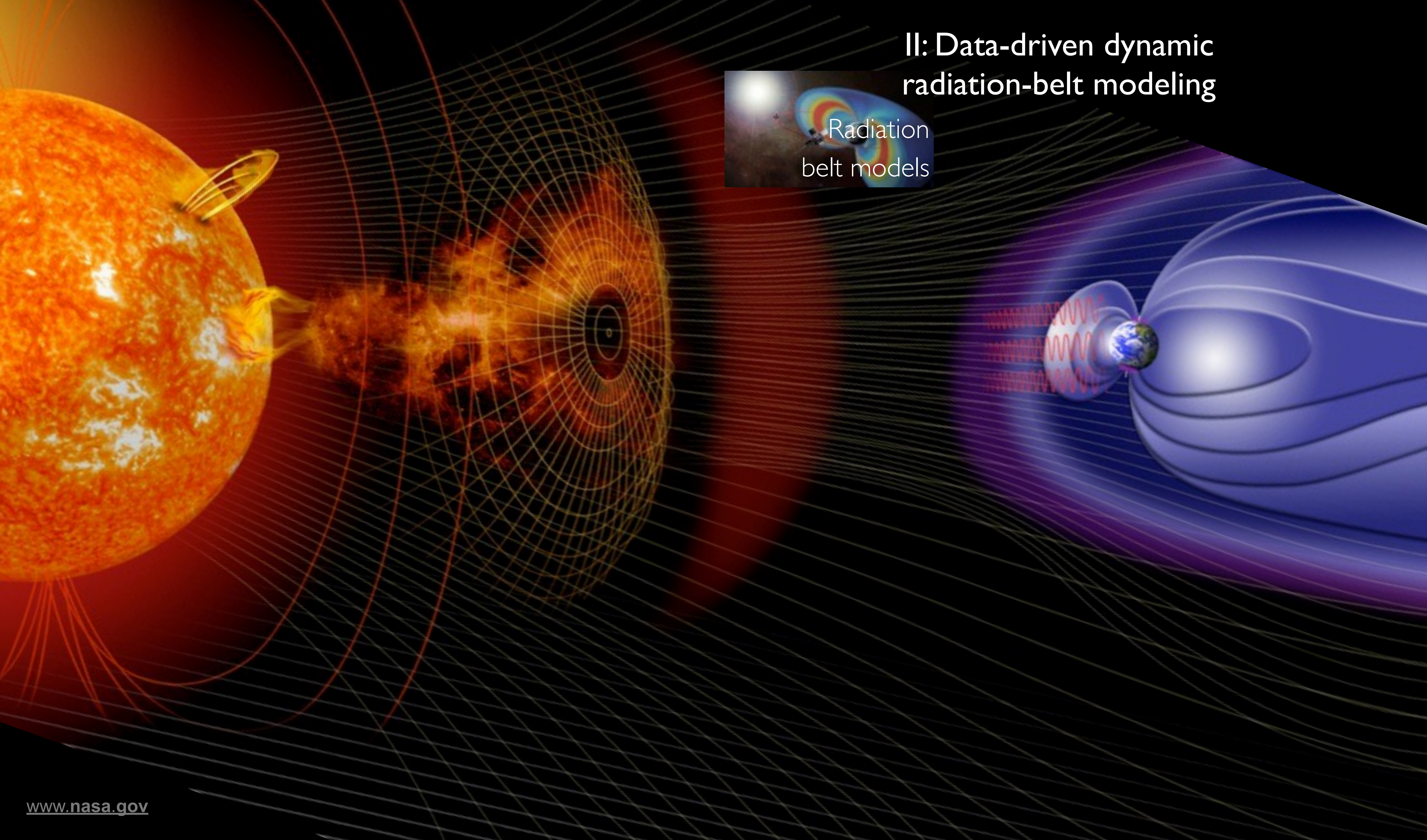
# Pathway III: observational, computational, and theoretical needs to enable pre-event forecasts of flares and SEPs

***Deployment of new/additional instrumentation:***

II: Data-driven dynamic radiation-belt modeling



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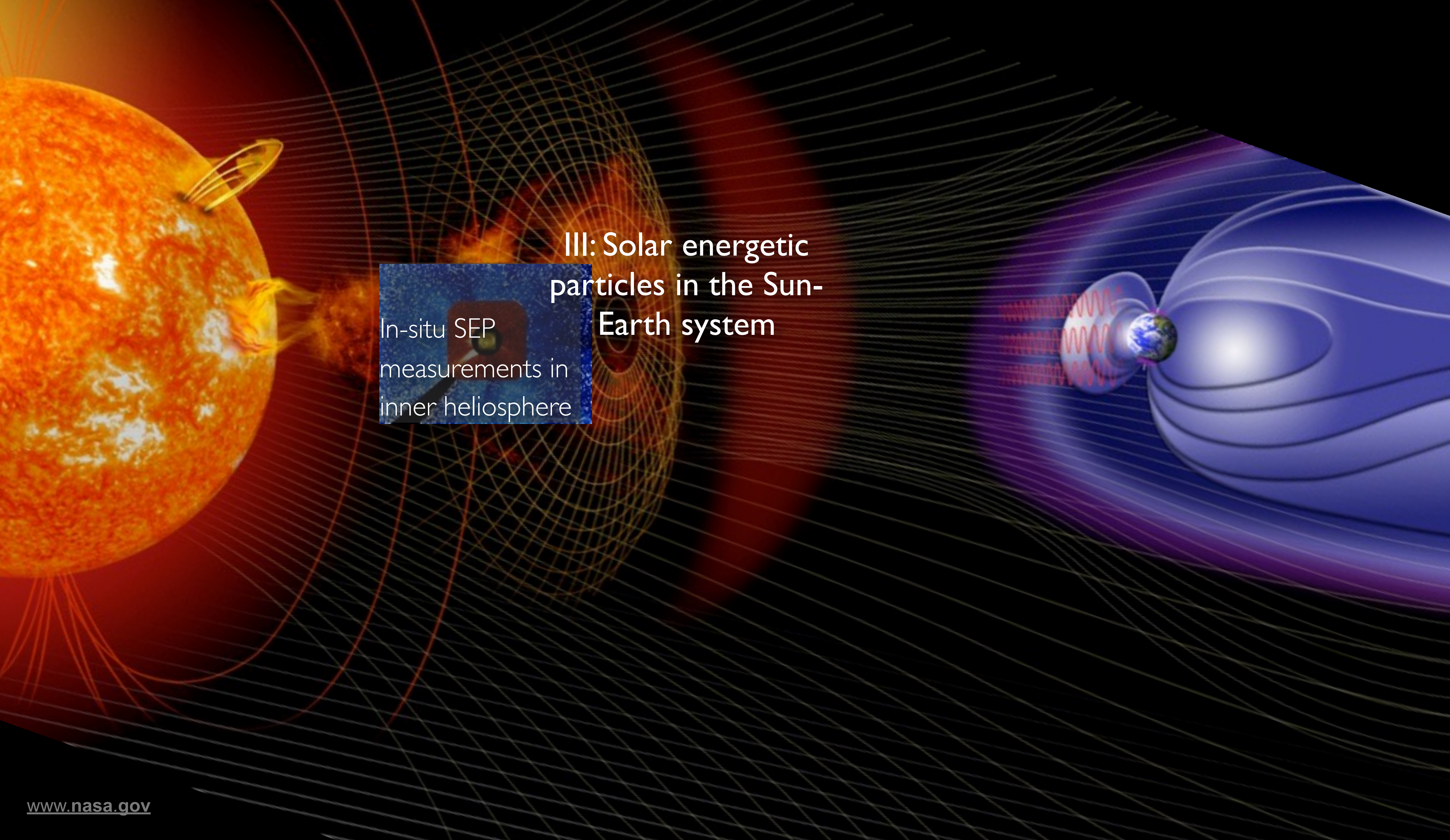

III: Solar energetic particles in the Sun-Earth system

In-situ SEP measurements in inner heliosphere

www.nasa.gov

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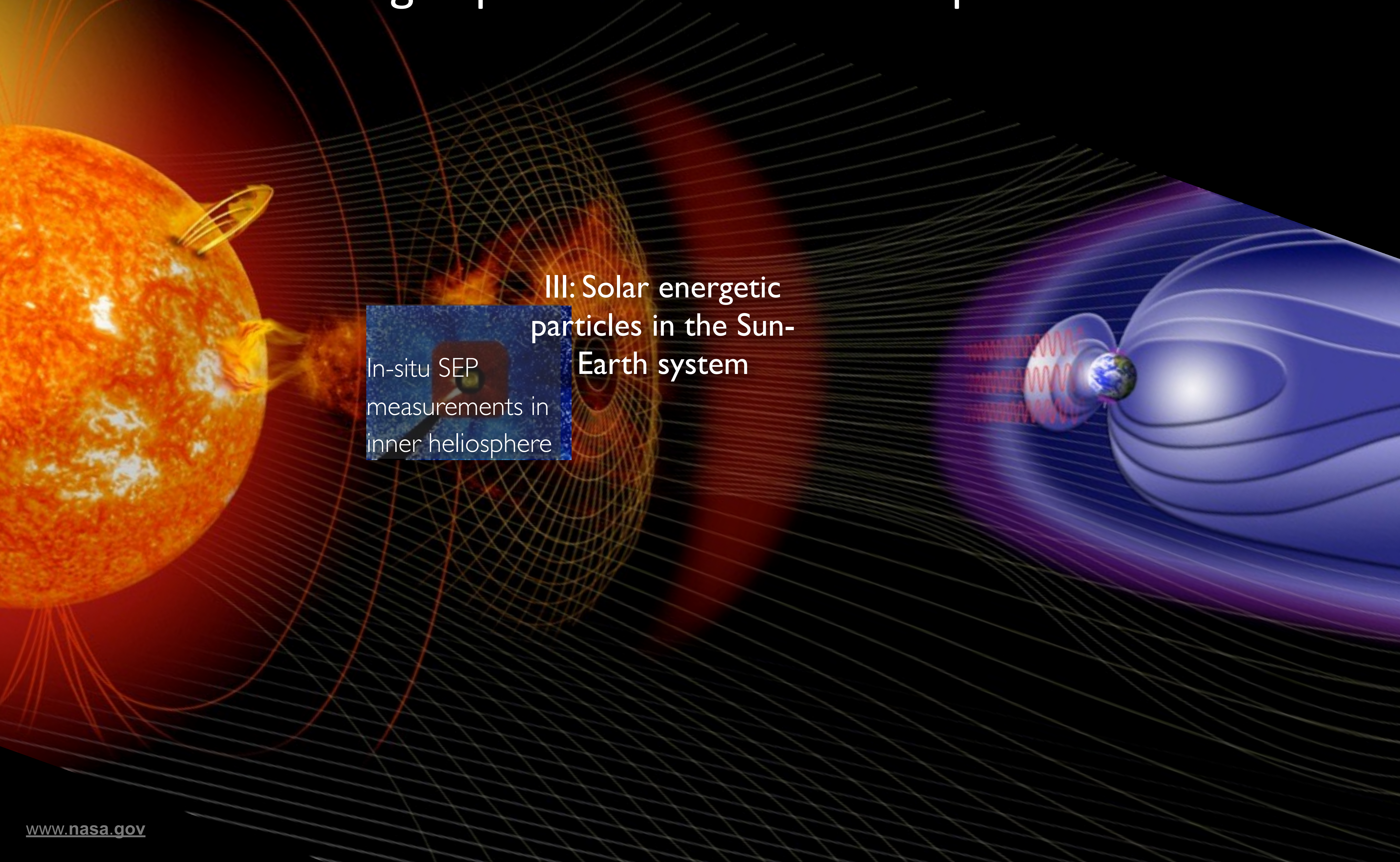

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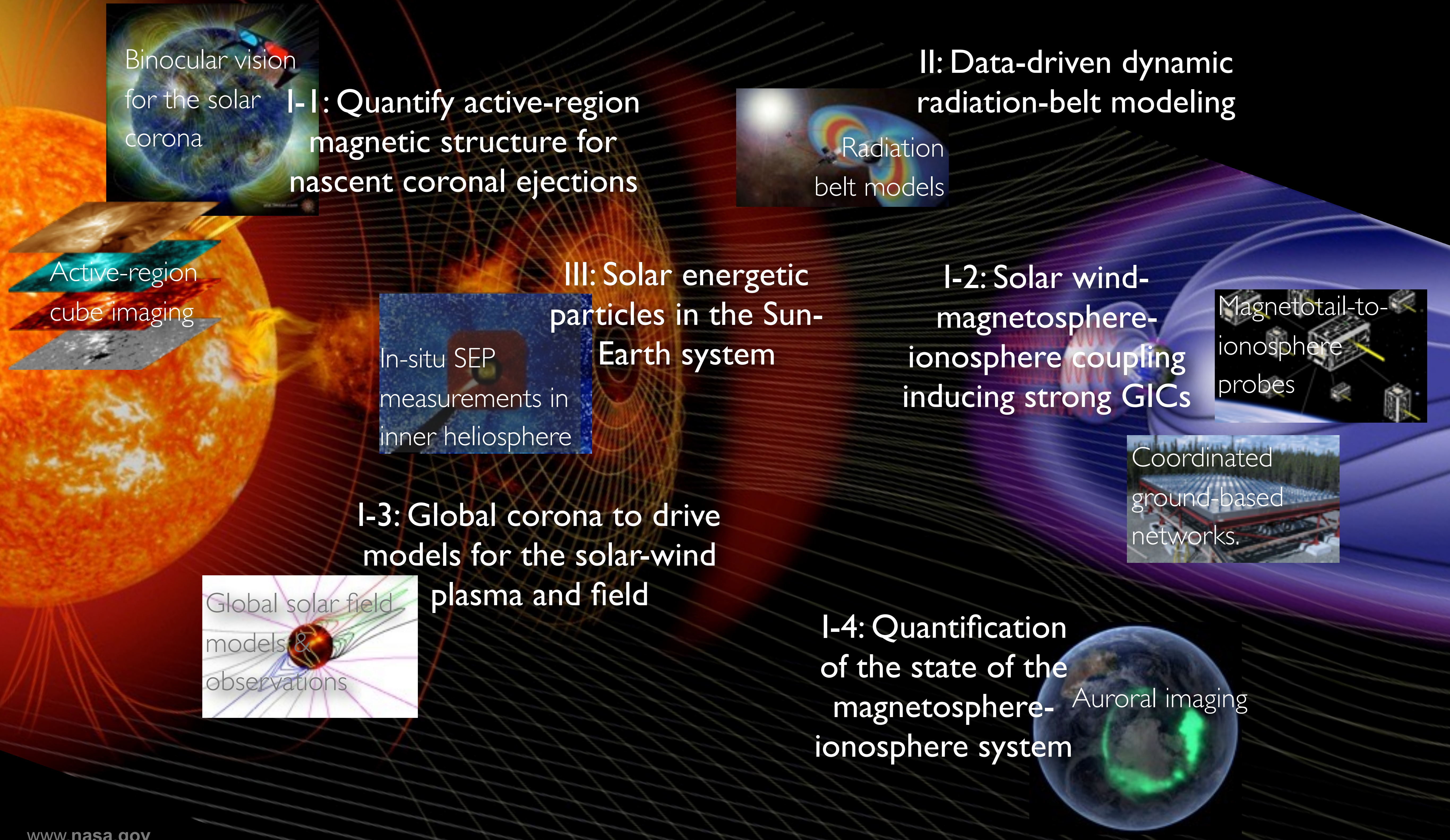

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ESA/NASA Solar and Heliospheric Observatory (SOHO)

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

*Domain volume, non-linearities, multi-process and cross-scale couplings, and hystereses require focused study before we can claim understanding and before we can expect to reliably forecast.*

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