How to predict space weather

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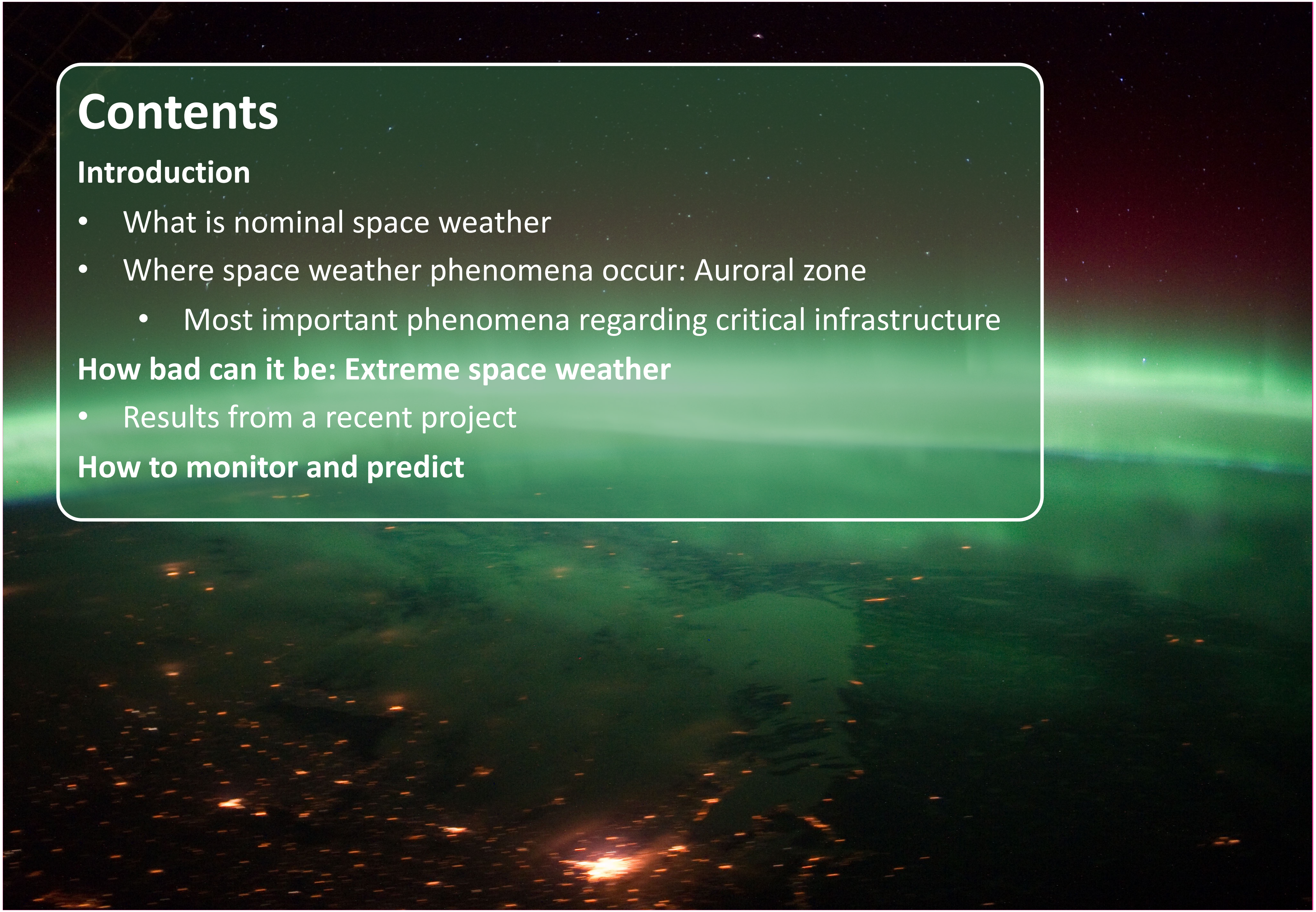

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Introduction

- What is nominal space weather
- Where space weather phenomena occur: Auroral zone
  - Most important phenomena regarding critical infrastructure

How bad can it be: Extreme space weather

- Results from a recent project

How to monitor and predict

Space weather

Definition: Conditions in the near-Earth space that can affect technological reliability or human health.

Causes: Solar eruptions and dynamics in the Earth's own magnetic domain.

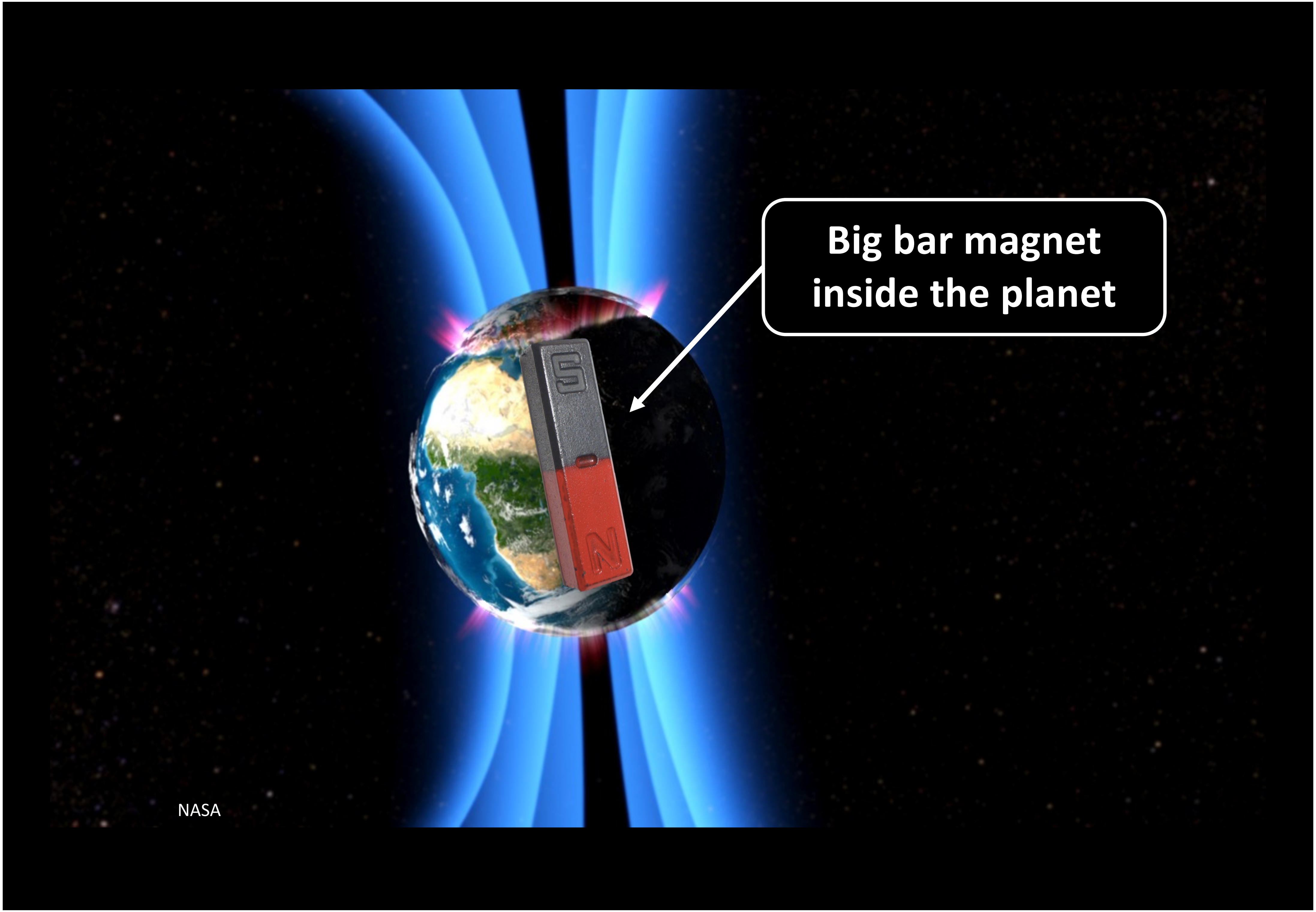
Two Solar eruption types

1. Coronal mass ejections
2. Flares

Strength: Varies. Small storms statistically 1/month, medium size storms a few per 11 years, megastorms 1/100 years.

Most important technological impacts:

1. Power grid
2. Satellite health
3. Signals (satellite, radar, radio, aviation, etc)


Big bar magnet inside the planet
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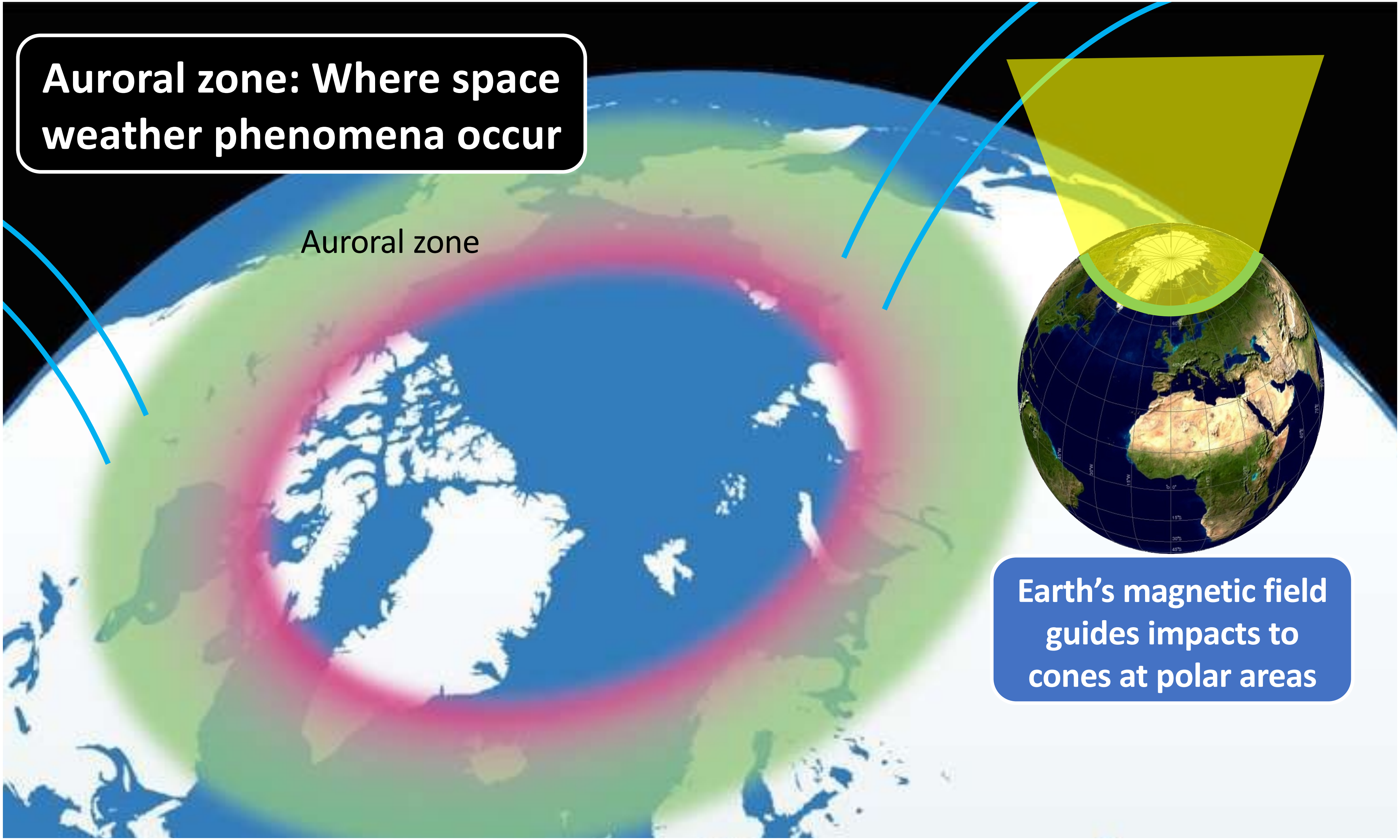
NASA

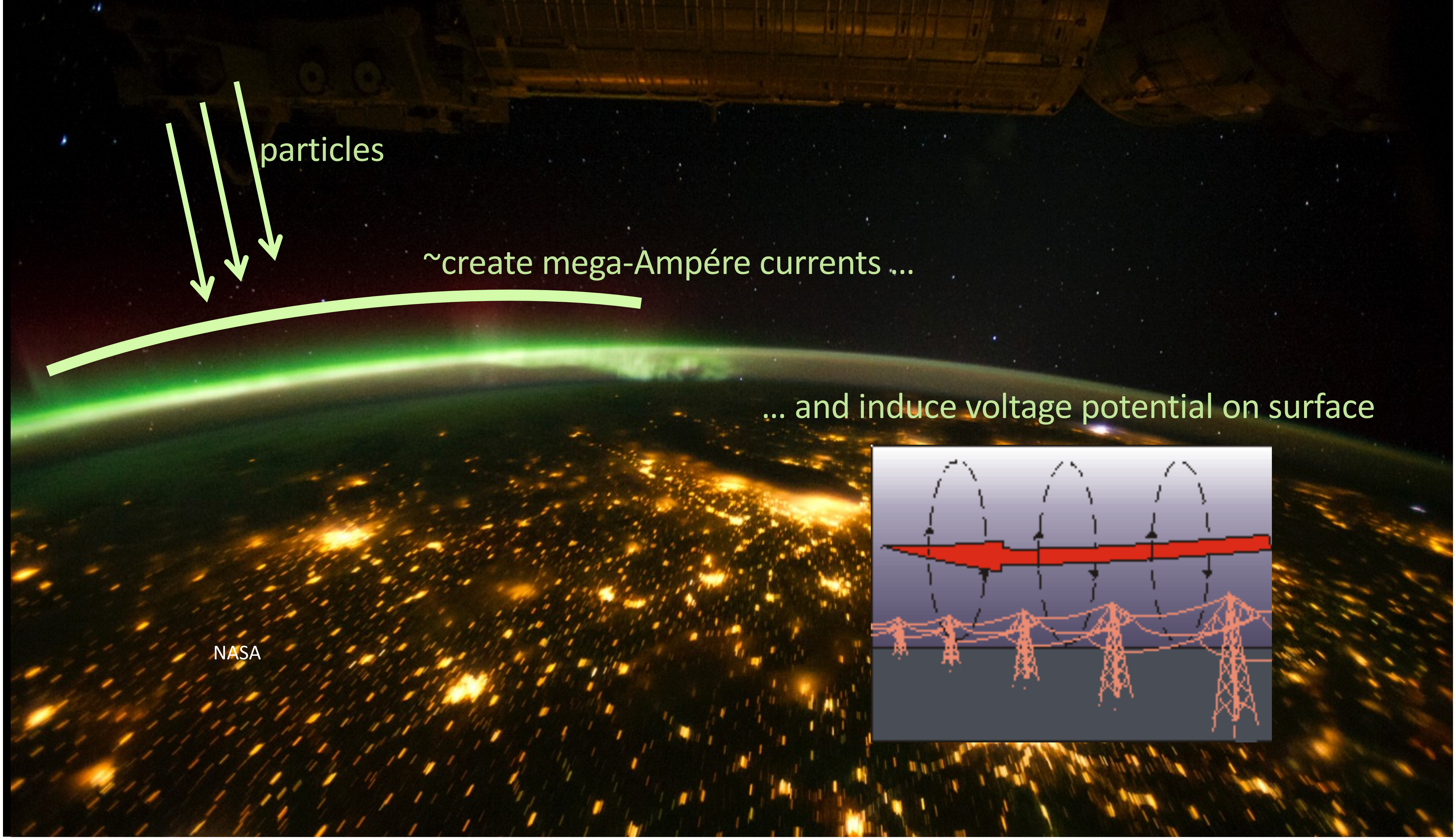

Auroral zone: Where space weather phenomena occur
Auroral zone
Earth's magnetic field guides impacts to cones at polar areas

Phenomena related to most important technological impacts:

1. Power grid – Geomagnetically induced currents
2. Satellite health – Earth's radiation environment
3. Signals – Energetic particles in the polar cap

Picture: NASA

Geomagnetically induced currents: Power grids



Phenomena related to most important technological impacts:

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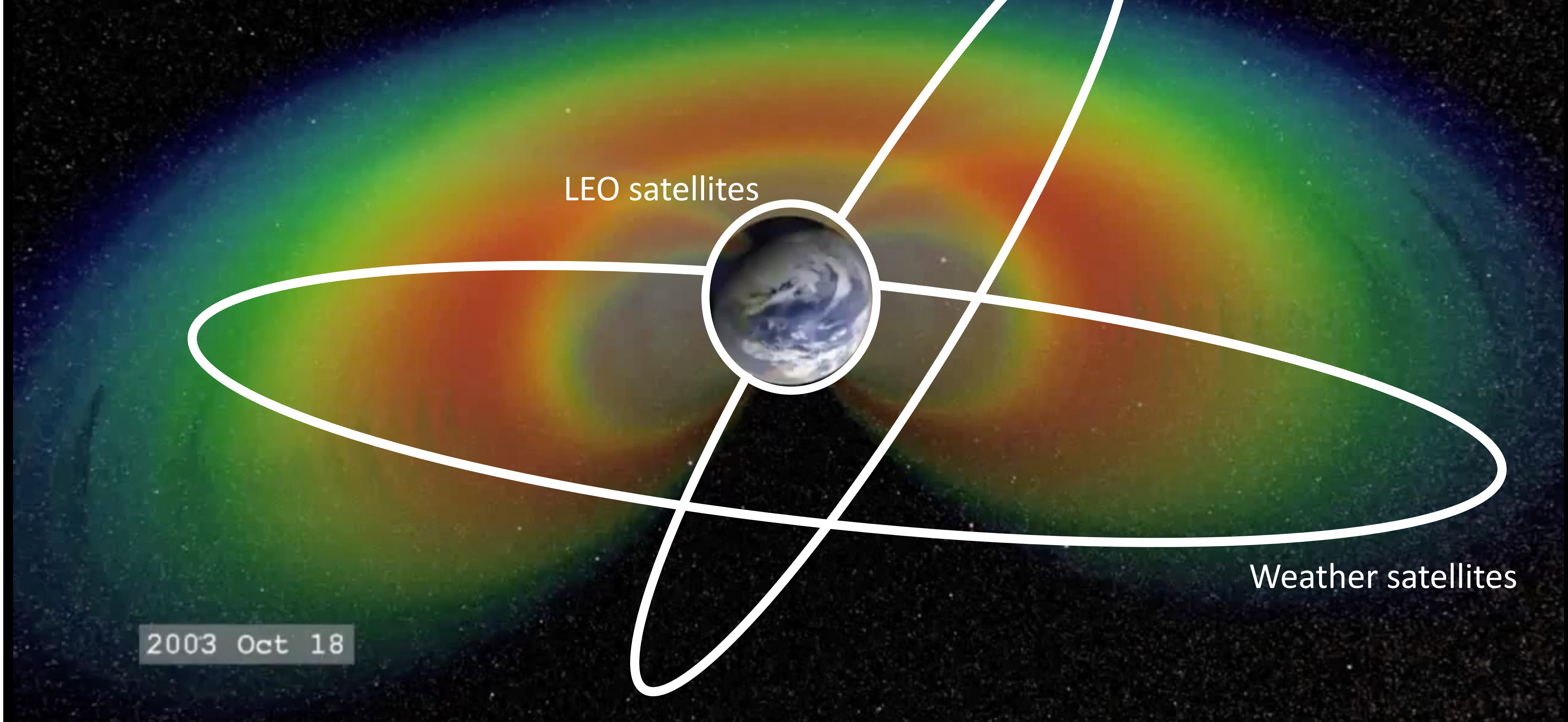
Two radiation components: Satellite health



1. **Earth's own radiation belt electrons**
   - Aging, continuous radiation dose
   - Spacecraft charging, arcading
2. **Energetic protons accelerated by the Sun**
   - Damage in hardware and software: Single event upsets

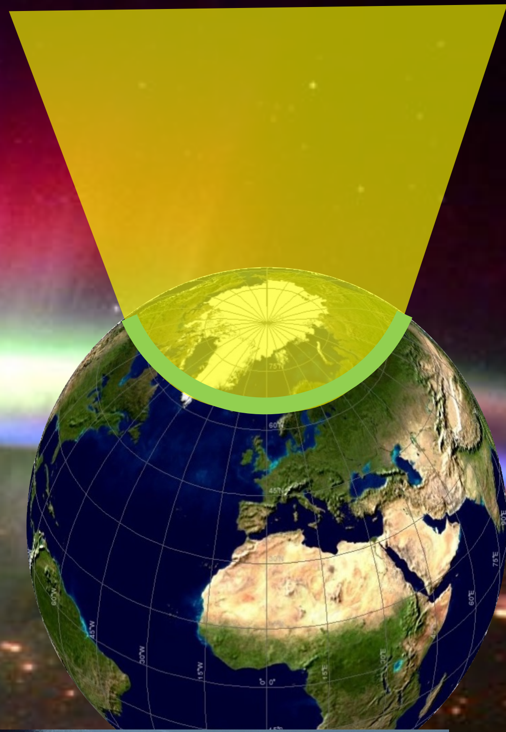
Source: NASA Sampex

Phenomena related to most important technological impacts:

1. Power grid – Geomagnetically induced currents
2. Satellite health – Earth’s radiation environment
3. Signals – Energetic particles in the polar cap

Picture: NASA

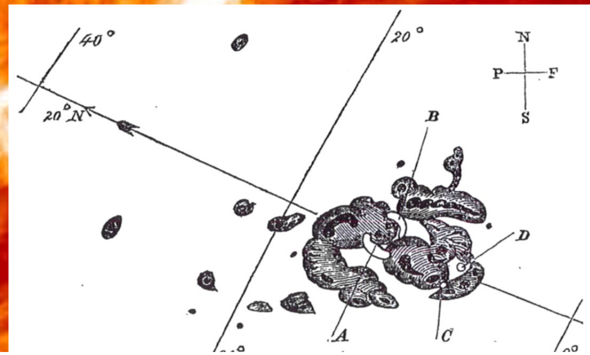
Energetic particles in polar cap: Signals



Extra particles change signal propagation conditions

1. Absorption, refraction, scintillation of signals
    - Changes signal amplitude, frequency and phase
2. Deteriorate satellite navigation accuracy
3. Deteriorate satellite-based time stamps
4. Can close polar cap aviation routes due to radio signal degradation (E.g.: January 2012)
5. Radar signal degradation and loss

Picture: NASA, Minna Palmroth



Carrington, R., Description of the singular appearance seen in the Sun on September 1, 1859, Monthly Notices of the Royal Astronomical Society, 20, 13-15, 1859.

Extreme space weather: Carrington-level storm

- Most extreme space weather event in the measured history.
- Solar eruption reached Earth in 17 hours (normally ~3 days).
- Magnetic disturbances lasted ~3 days (normally 1-7 days).
- Included a flare (Carrington’s flash), and a coronal mass ejection (interpreted).

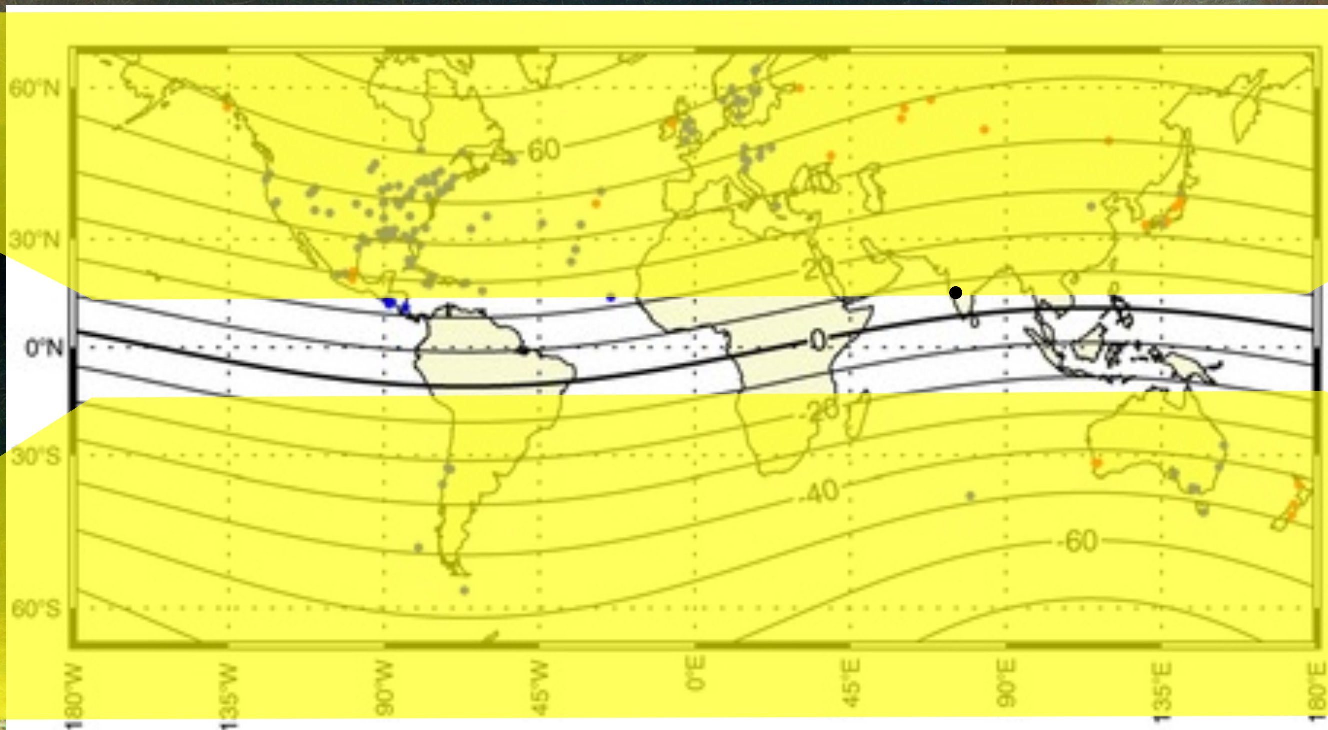
Picture: NASA

Frederic Edwin Church, Aurora Borealis, oil on canvas (1865)

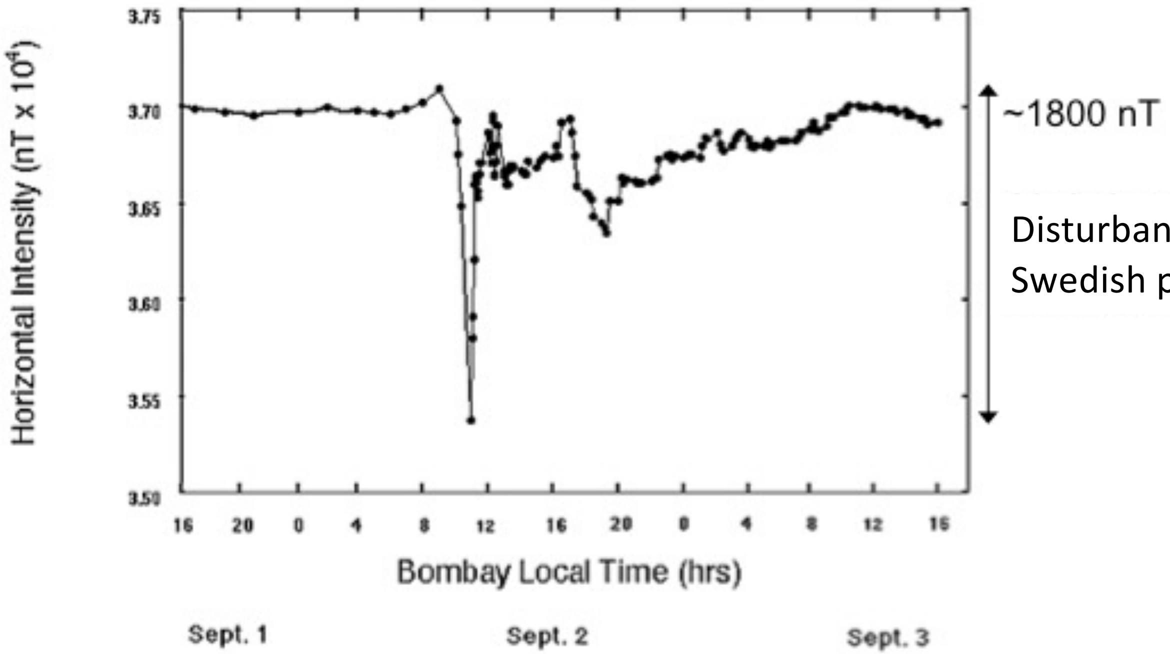
Carrington storm Sep 1859

- Rocky mountain gold diggers woke up in the middle of the night.
    - Aurorae brighter than the full moon, and one could read in their light.

Auroral sightings (Hayakawa et al., 2019, https://doi.org/10.1029/2019SW002269)

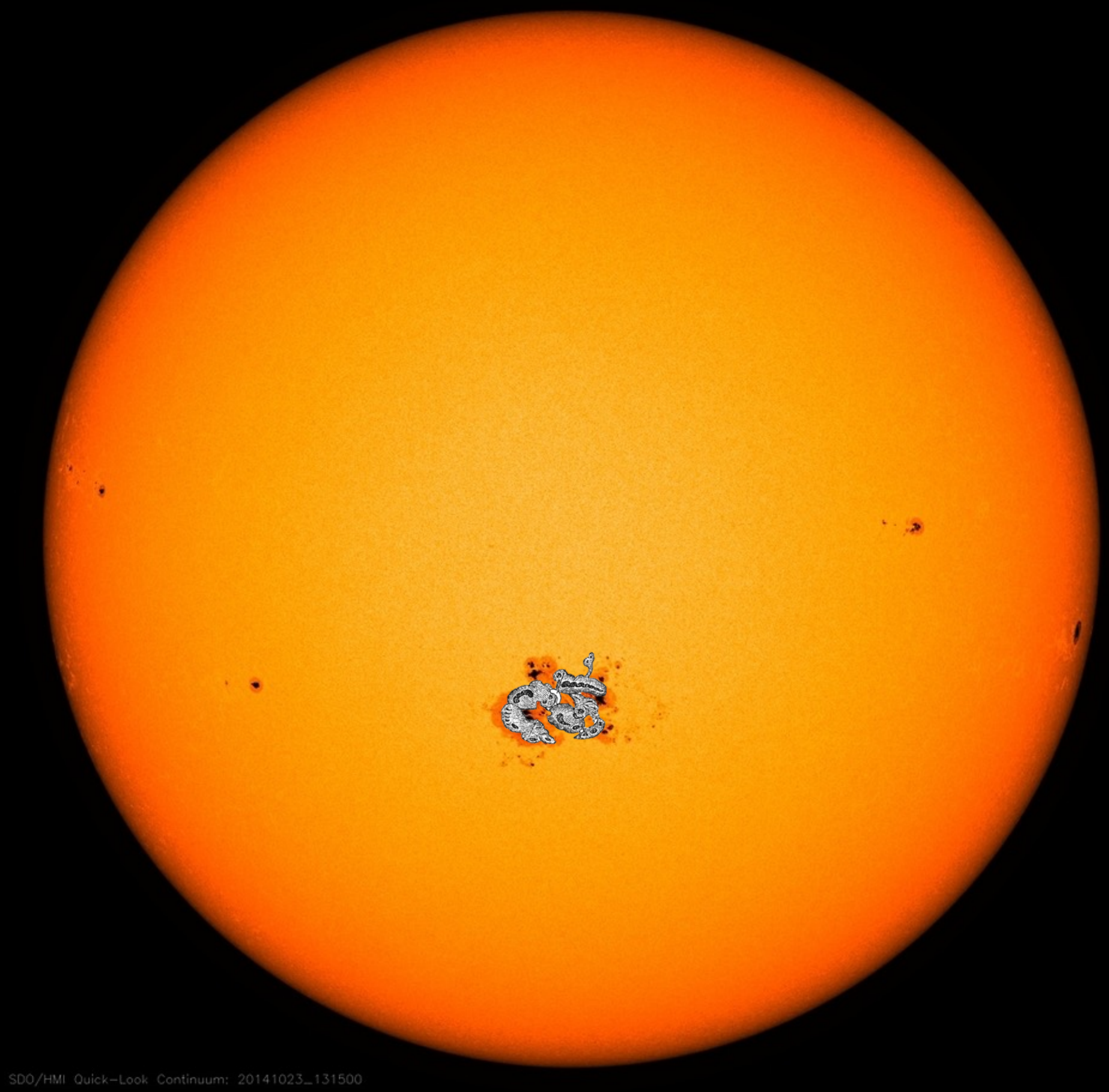


Mumbai magnetometer recordings 1.-3.9.1859



Disturbance of the same magnitude tripped the Swedish power grid in Malmö, 30.10.2003.

Tsurutani et al., Journal of Geophysical Research: Space Physics, Vol 108, 1268, doi:10.1029/2002JA009504, 2003

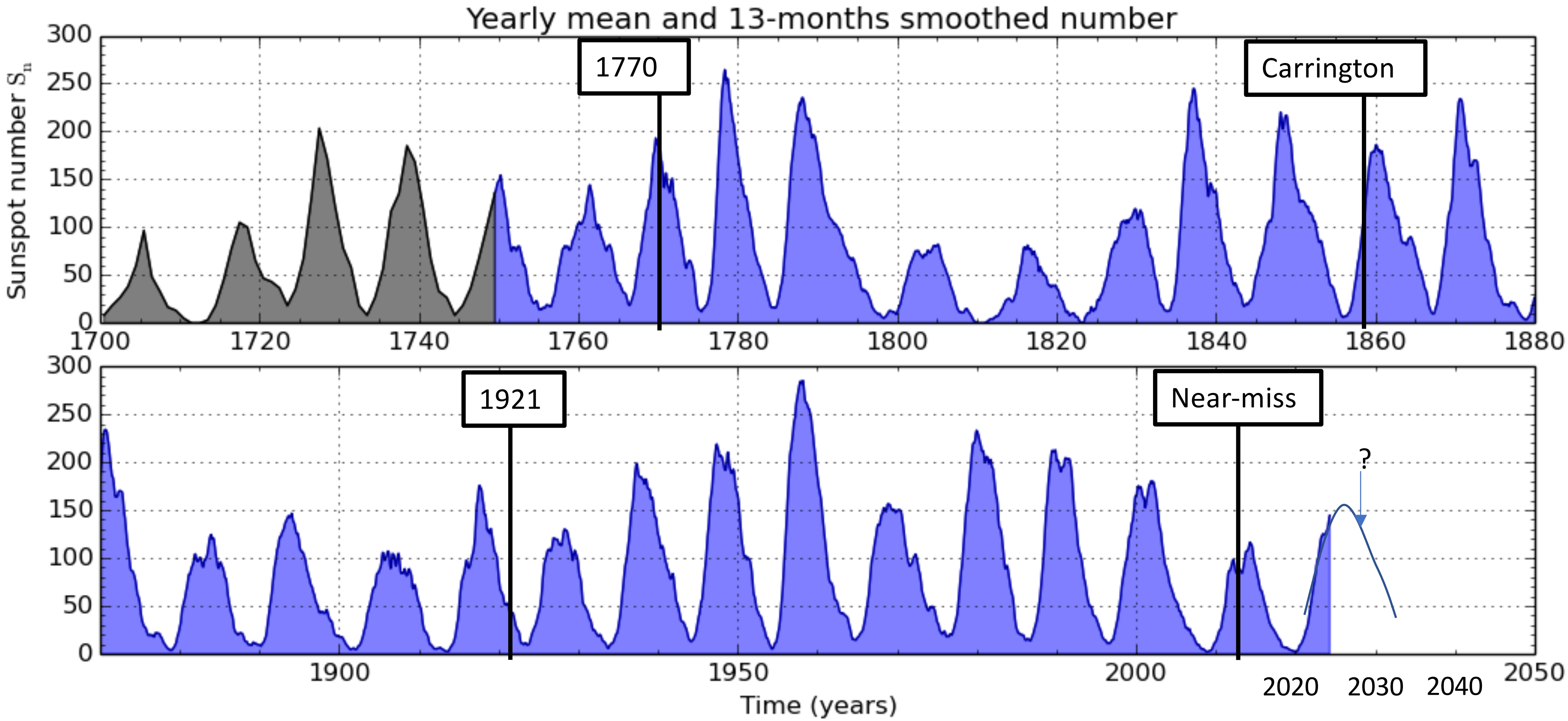


Recurrence likelihood

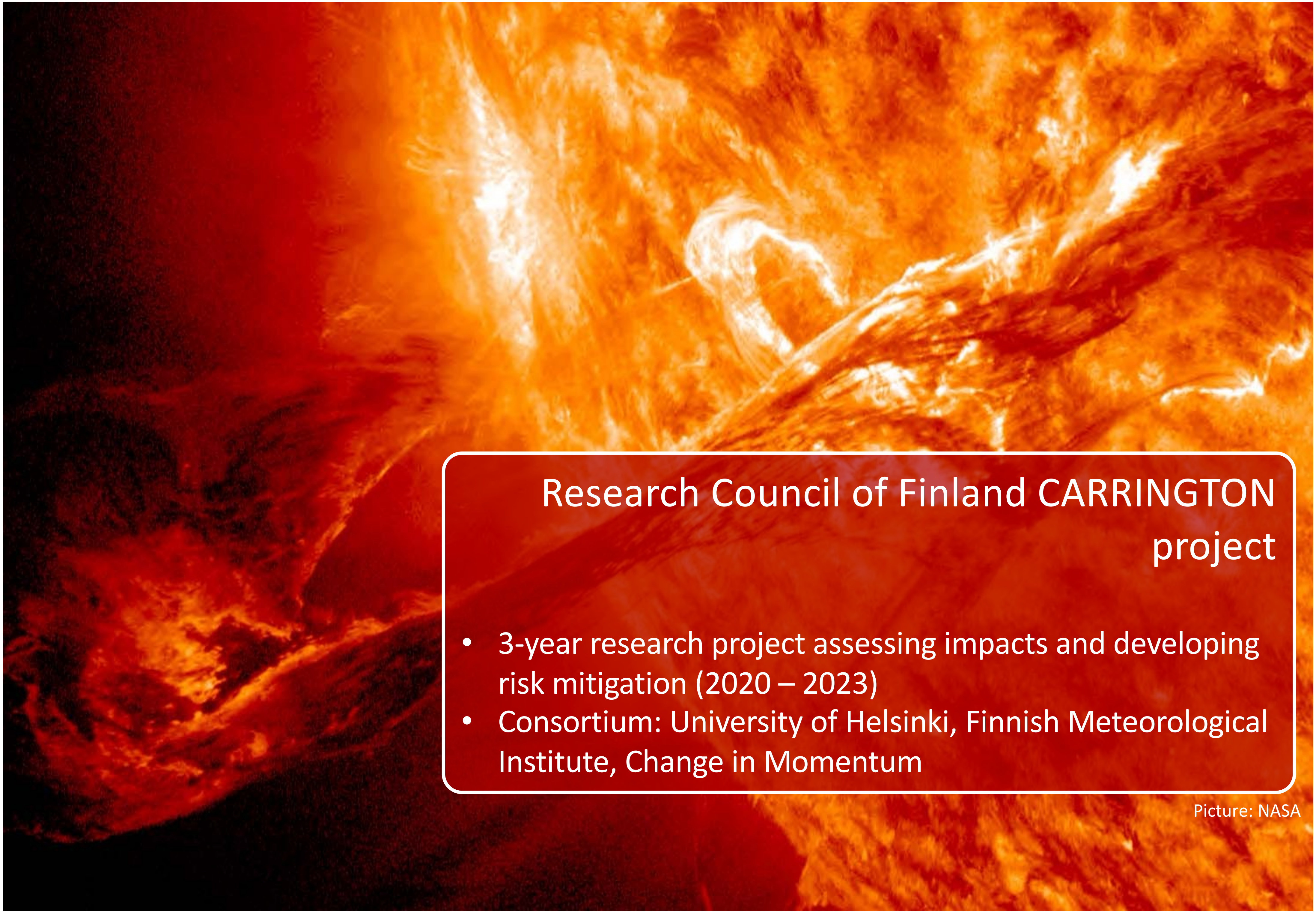
1. Thumb “rule”: Once in 100-150 years.
   - Or twice in a year – Sun does not obey thumb rules
2. Riley et al (2012): Recurrence likelihood 12% in the next decade.
3. Chapman et al (2020): 0.7% annual recurrence risk.
4. Background picture from Sun in Oct 2014. Spot in the centre is similar size with the Carrington spot.
5. 2012 NASAs Stereo satellite observed a Carrington-scale eruption, which bypassed Earth by a couple of days (Liu et al., 2014).

Picture: NASA

Measuring solar activity: Number of sunspots



Sunspot archive: http://sidc.be



Research Council of Finland CARRINGTON project

- 3-year research project assessing impacts and developing risk mitigation (2020 – 2023)
- Consortium: University of Helsinki, Finnish Meteorological Institute, Change in Momentum

Picture: NASA

Research questions:

- **Strength and geographic extent of geomagnetically induced currents**
  ➔ Power grid risks
- **Flux and energy of particles on satellite orbits:**
  - Satellite risks
  - Impact on navigation

Methods:

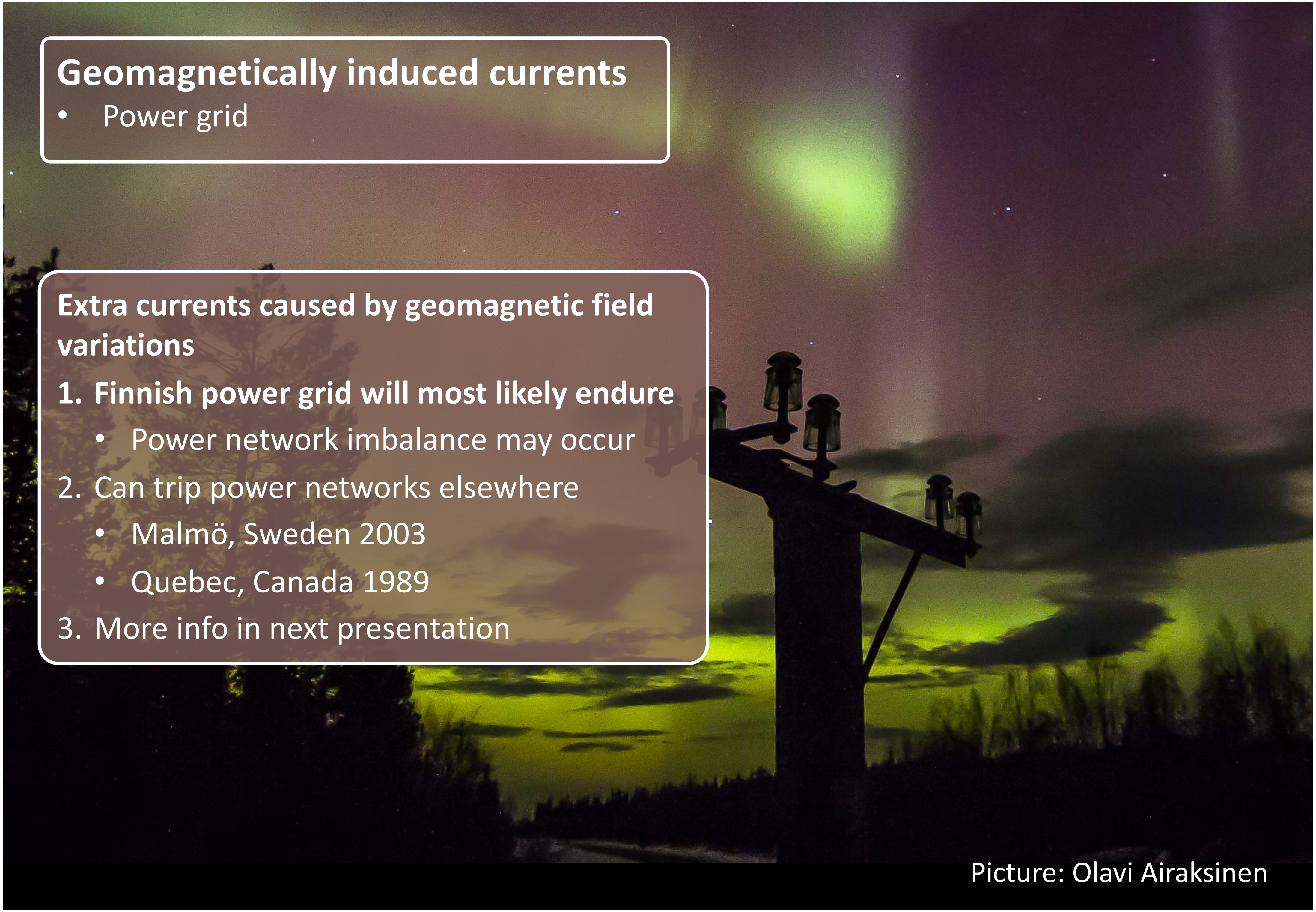
- Modelling and extreme value theory
- Interviews with experts

Goals

- Disseminate knowledge of this risk to stakeholders
- In cooperation with stakeholders, develop plans for risk mitigation

Results per technology

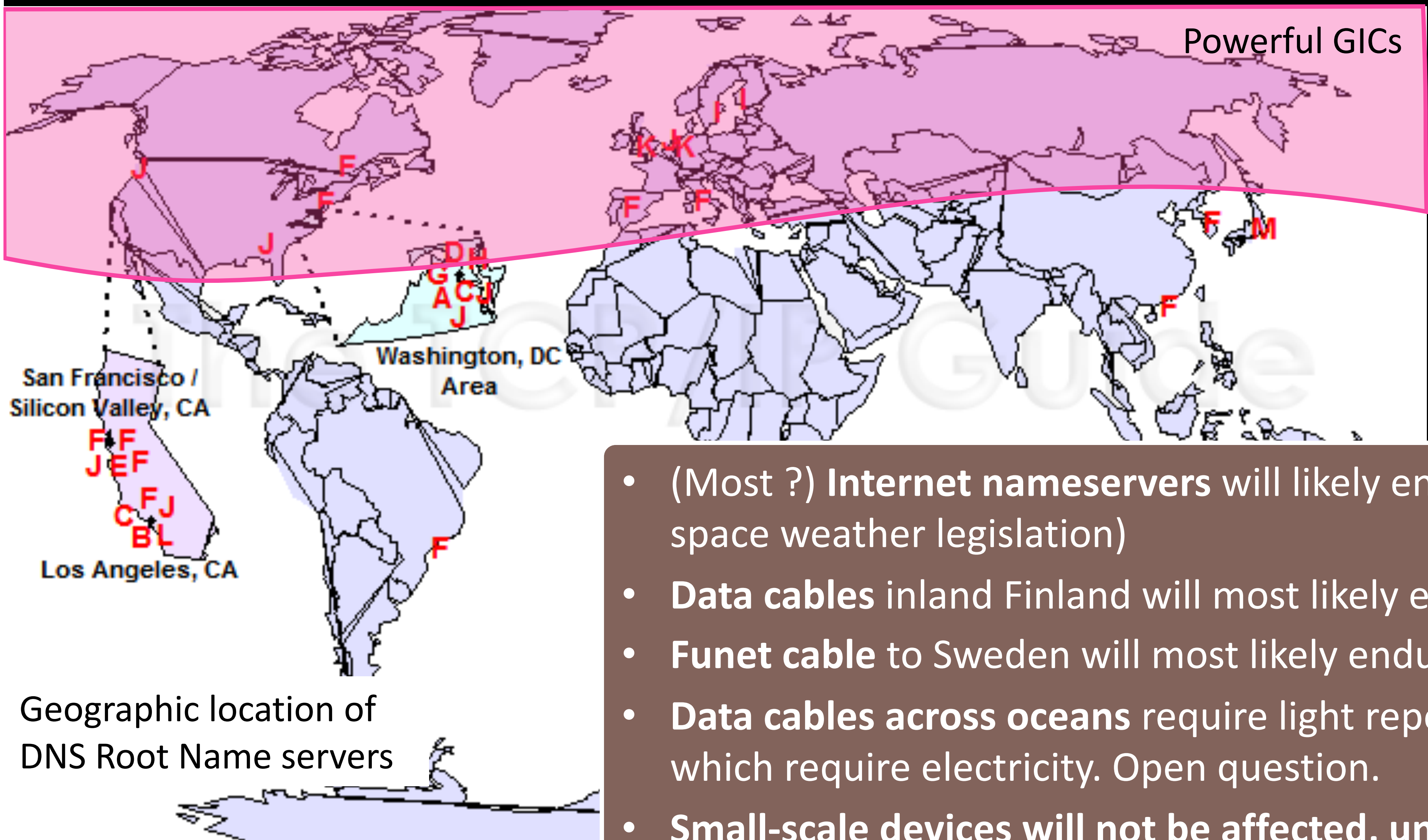
- Fusing together several models
- Interviews with technology experts
- In the following, we assume the duration of the storm is 3-4 days



Picture: Olavi Airaksinen

Geomagnetically induced currents

- Effects in other foreseen systems

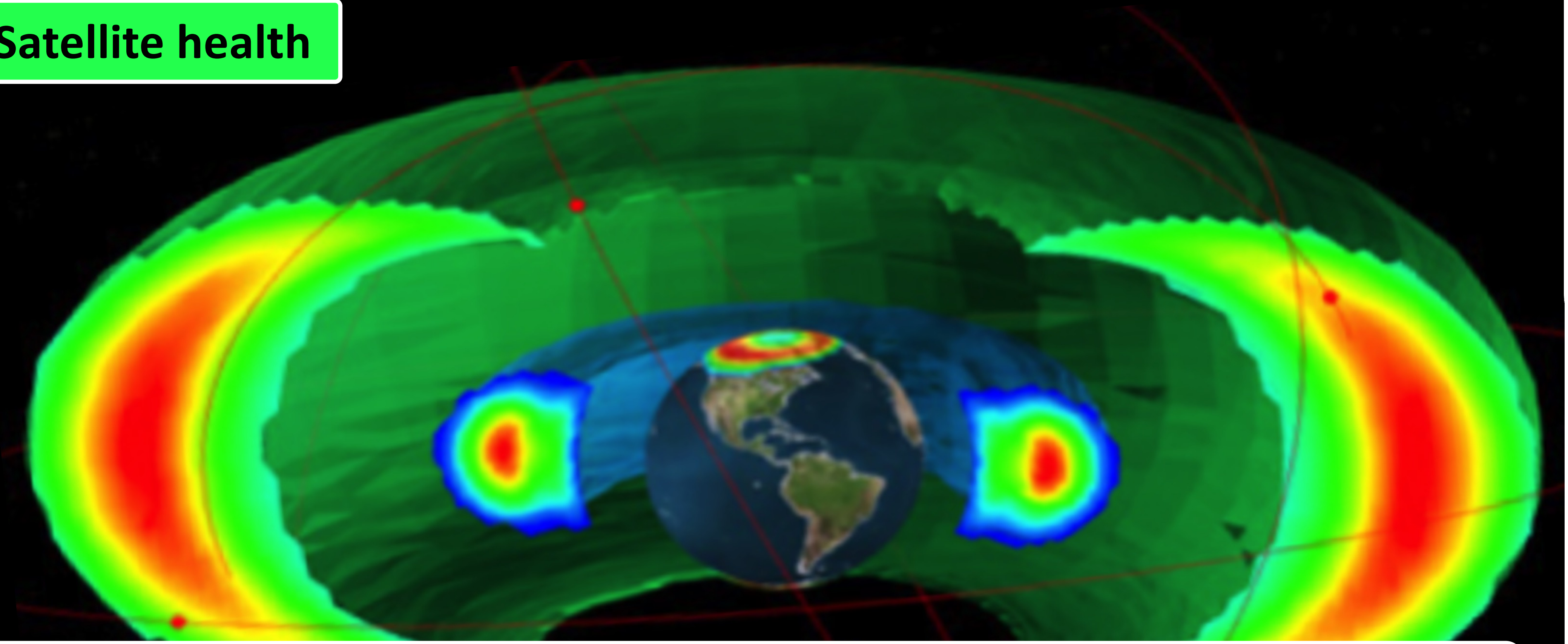


Geographic location of DNS Root Name servers

- (Most ?) **Internet nameservers** will likely endure (US space weather legislation)
- **Data cables** inland Finland will most likely endure (fiber)
- **Funet cable** to Sweden will most likely endure
- **Data cables across oceans** require light repeaters, which require electricity. Open question.
- **Small-scale devices will not be affected, unless they cannot withstand 10 mV/m**

Pic: http://www.tcpipguide.com

Satellite health



1. **The expected total dose due to relativistic electrons causes significant aging of solar panels**
2. **Solar energetic protons causes memory system corruptions**
   - “Old-space”: Satellites go automatically to safemode [ESA experts]
   - ”New space”: Satellites likely start rebooting. Continuing mission after storm?

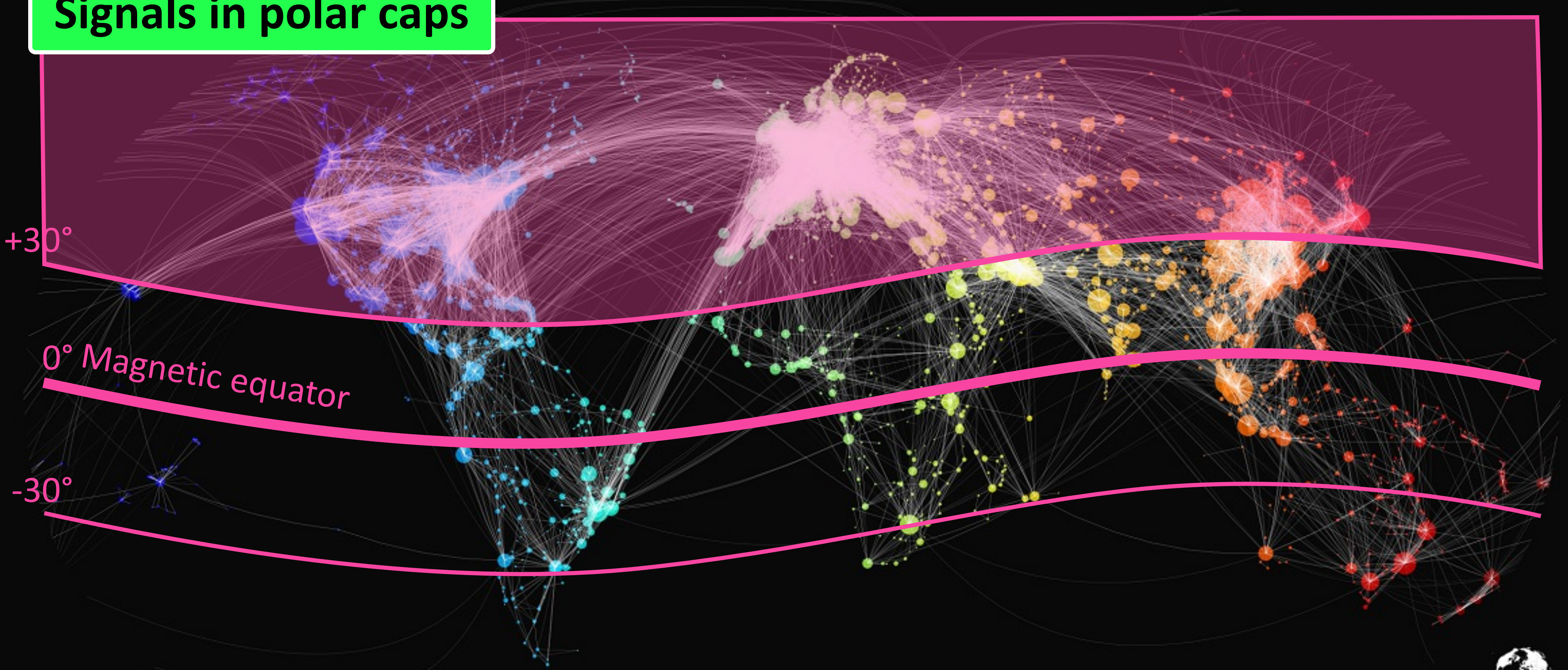
➔ “New-space” business satellites will be under a major threat

Satellite health
- **Safemode**

1. **”Halloween storm” in 2003, 3-5x smaller than Carrington (Gopalswamy et al., 2005)**
    - Reported satellite problems: electronic upsets, housekeeping and science noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating
    - Most Earth-orbiting spacecraft went to safemode: all non-essential systems are shut down and only essential functions such as thermal management, radio reception and attitude control are active

    ➔ **Signals are not provided during safemode.**
2. **If GPS, GALILEO, GEO satellites go to safemode, they will not provide**
    - Timestamps
    - Navigation and positioning signals
    - Weather and Earth observation data
    - Safemode can be intermittent depending on conditions.

Signals in polar caps



Airways. @PythonMaps
This map shows the world's flight paths and airports. It maps 10,000 airports and 67,663 routes linking those airports.
Data source - https://openflights.org/data.html

Energetic particles poleward of the auroral zone

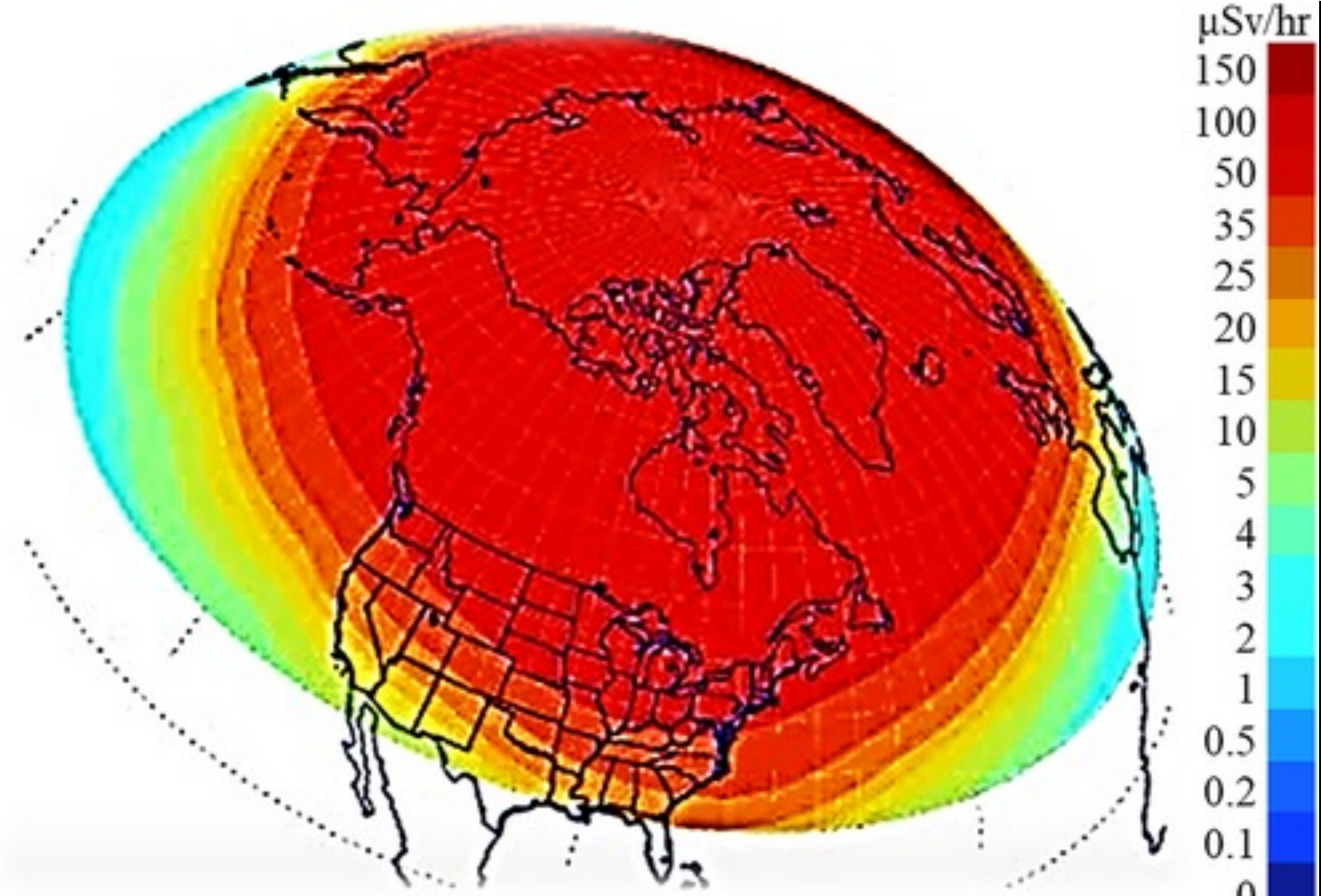
- Signal conditions deteriorate in the cones

➔ **Flight routes within low signal connectivity will likely be rerouted (e.g., in Jan 2012)**

Aviation problems

Halloween storm (2003) Xue et al., 2023:

- 3-5x smaller than Carrington
- HF communication blackouts: rerouting and cancellations (~2 M€/day)
- Satellite navigation failures (2 M€/day)
- Preventing radiation exposure: cancellations ~50 M€/day)



Effective dose at the altitude of 11 km during Halloween storm 2003

European Union recommends radiation dose limits:

- 20 mSv per year averaged over 5 years (a total of 100 mSv within 5 years) for aircrews
- 1 mSv/year for the general public during flight
- 1 mSv throughout the the whole pregnant radiation workers during flight

Mobile networks

Functioning network needs precise time (GNSS or ePRTC atomic clock, synced to GNSS)

GNSS time stamp signal may

- Deteriorate due to bad signal conditions or
- Not be available due to GNSS satellite safe-mode

It is operator-specific, how time synchronisation has been arranged

- Easier and more cost-efficient to get the clock from GNSS
- 90% of GNSS receiver shipments is to telecommunication sector [1]

With atomic clocks, network should survive

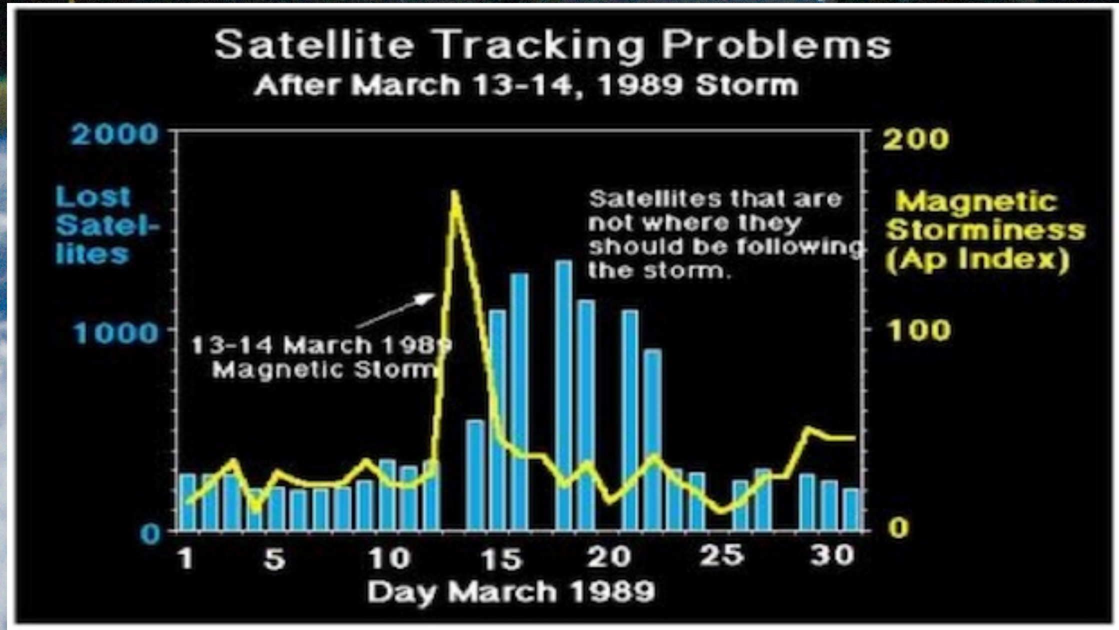
- Without atomic clocks, network should last for a few hours

“[GNSS synchronisation] has become pervasive […] thousands of GNSS receivers are relied upon for network synchronization.” [2]

➔ **Globally, there likely are networks which stop functioning due to Carrington-scale storm**

[1] https://www.euspa.europa.eu/system/files/reports/gnss_market_report_2017_-_timing.pdf
[2] https://sync.empowerednetworks.com/wp-content/uploads/2017/05/Microchip_Enhanced_Primary_Reference_Time_Clock_Solution_White_Paper.pdf

Additionally: Ohmic heating increases friction at LEO altitudes



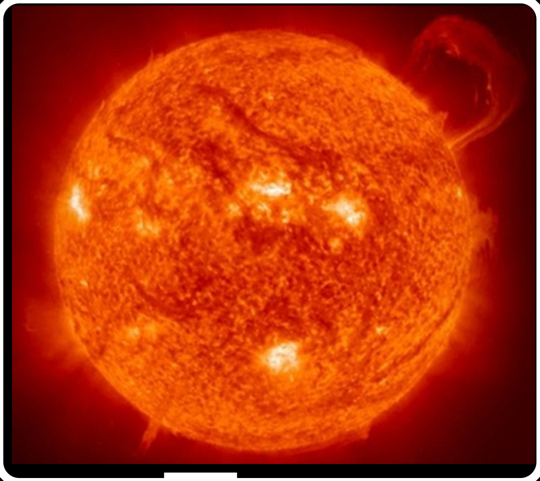
North American Aerospace Defense Command (NORAD) data

GOCE 2013
- Insignificant geomagnetic storm hastened de-orbiting for about 6 hours (4 orbits)

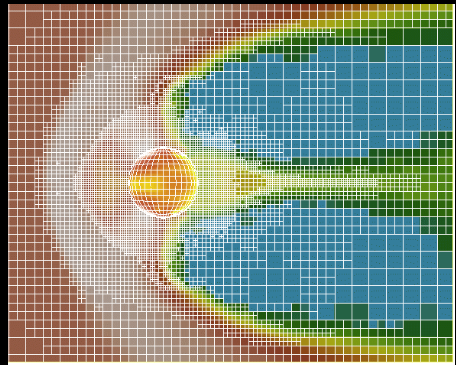
Starlink 2022:
- Loss of 40 satellites due to a small geomagnetic storm

Re-entry wake of shuttle Atlantis. Picture credit: ESA/NASA

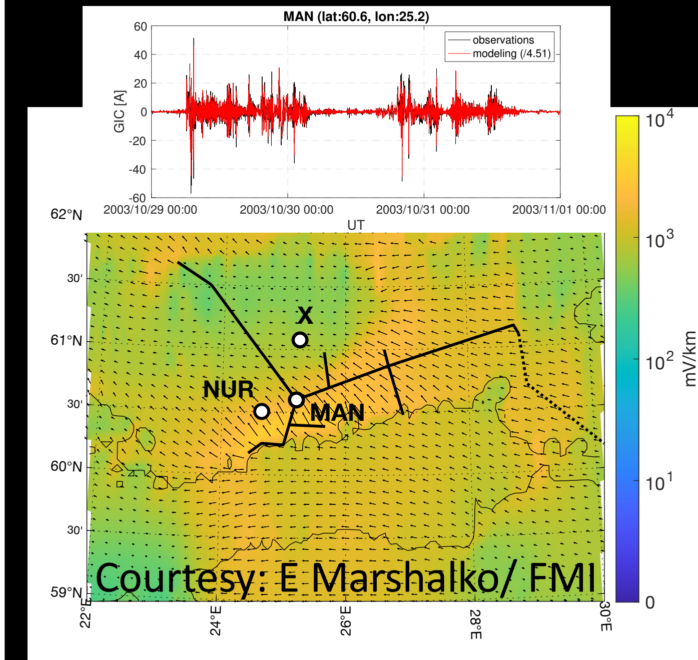
Prediction: Principle for nominal space weather



Use real-time model



Forecast

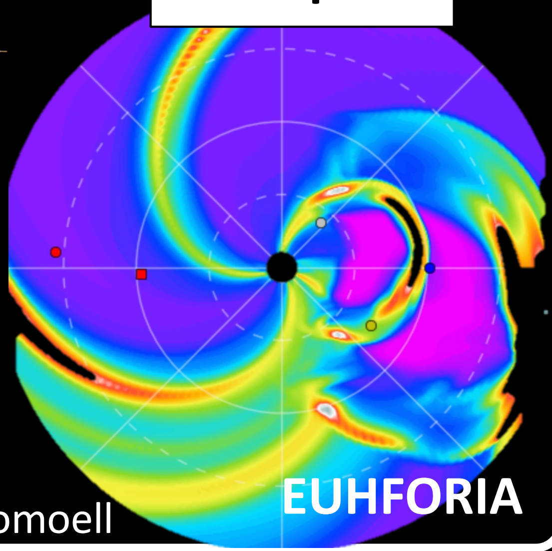


Solar wind

1) Lagrange point: Measured properties

2) Or model based on remote measurements

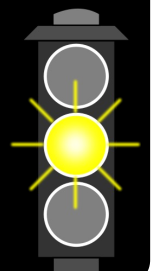
Physical description



Courtesy: J. Pomoell

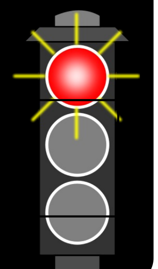
1) Lead time: ~1 hr

Accuracy

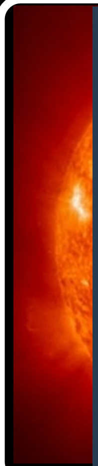


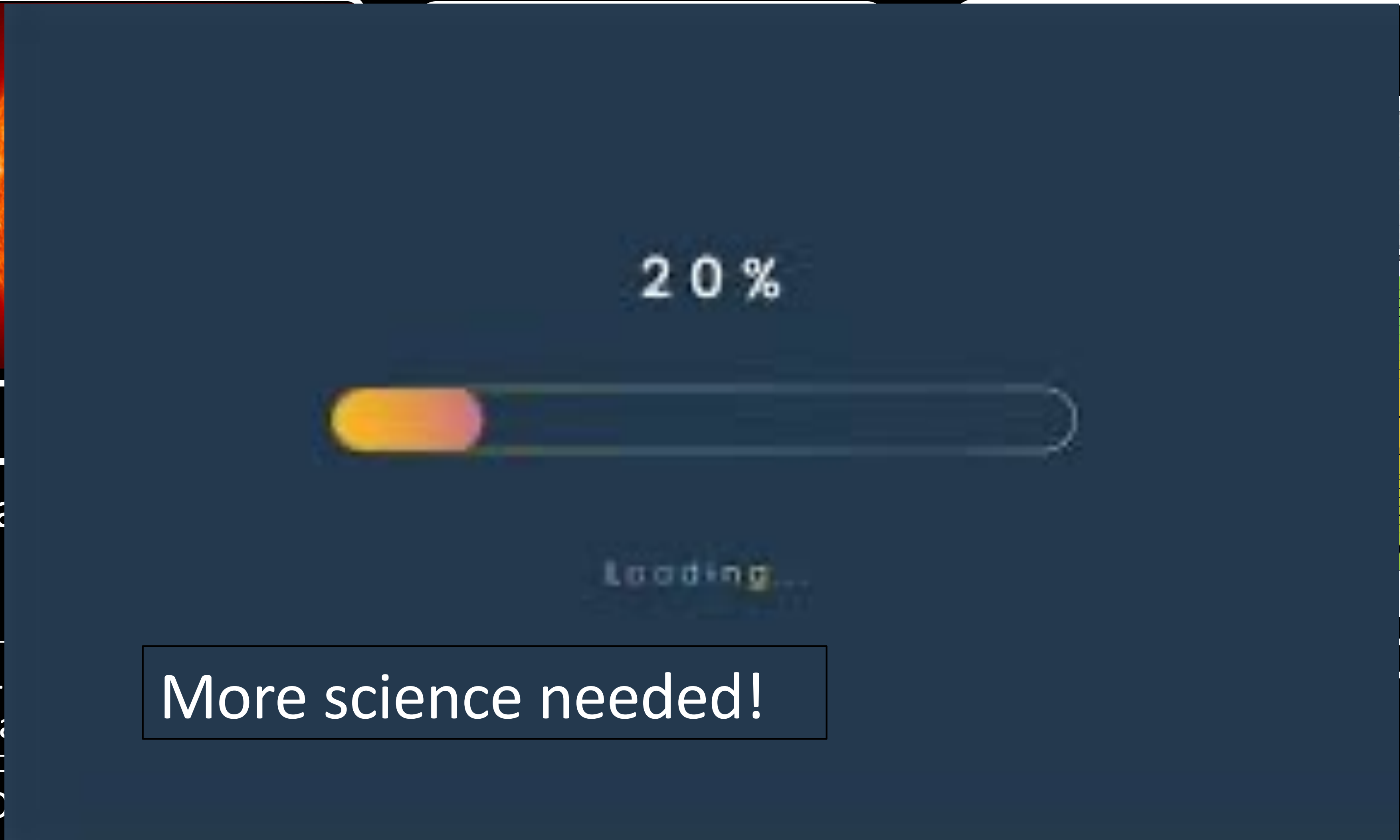
2) Lead time: ~3 days

Accuracy

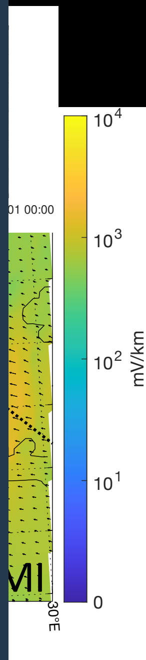


Prediction: Principle for extreme space weather





More science needed!



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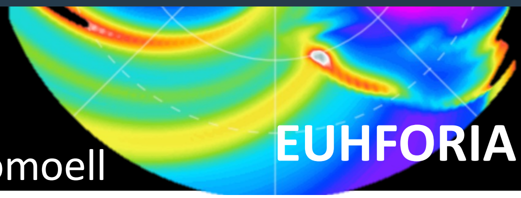
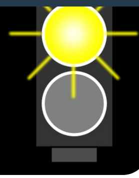
remote measurements



Courtesy: J. Pomoell

time:

Accuracy



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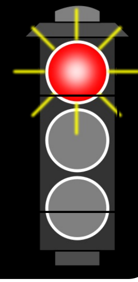
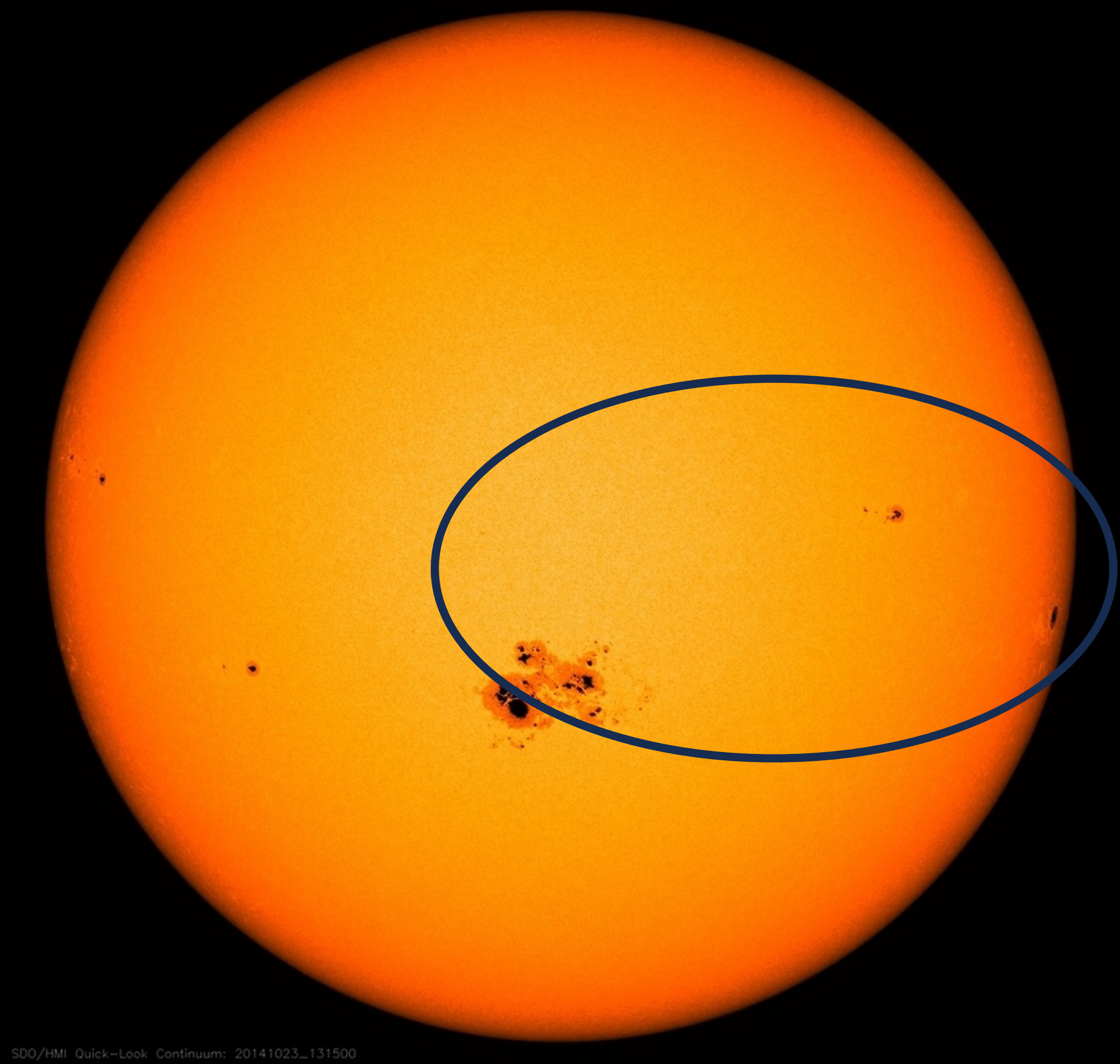


Extreme space weather scenario

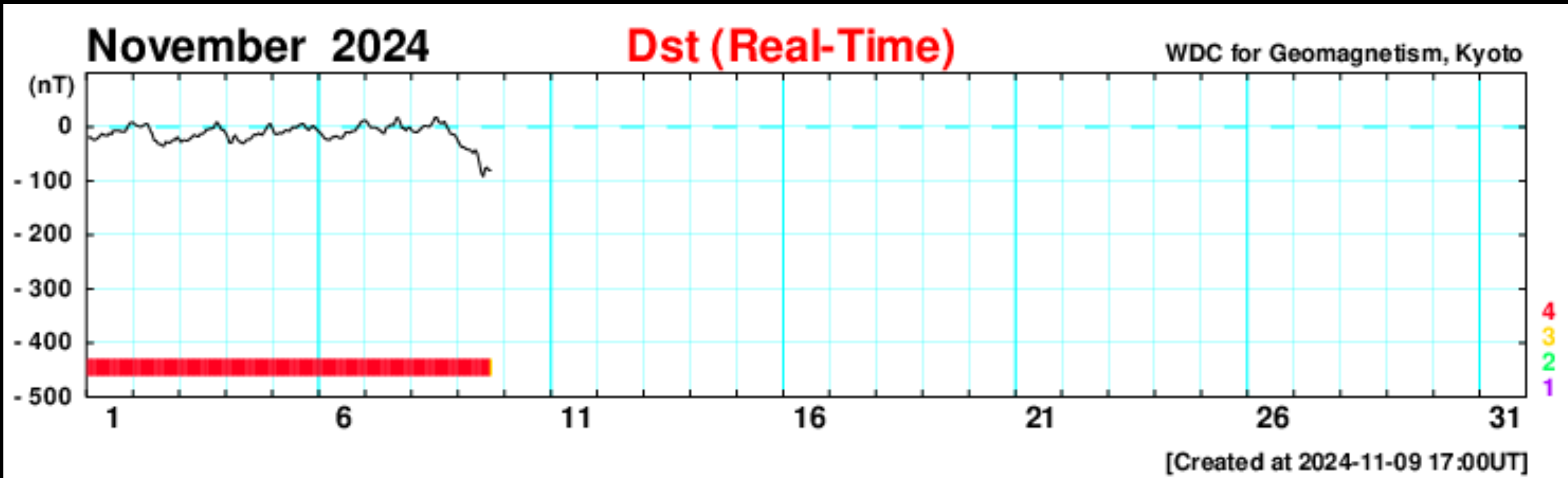


1. **Sunspots and active regions are monitored 24/7**
    - E.g., at FMI 24/7 space weather centre
2. If a spot erupts in the marked region, it can be “geoeffective”
    - Then, observations and models are used to estimate travel time to Earth
3. But physical impacts cannot be yet be determined with very high accuracy
    - More science, measurements and models are needed

How to monitor the current situation

FMI 24/7 Space weather service

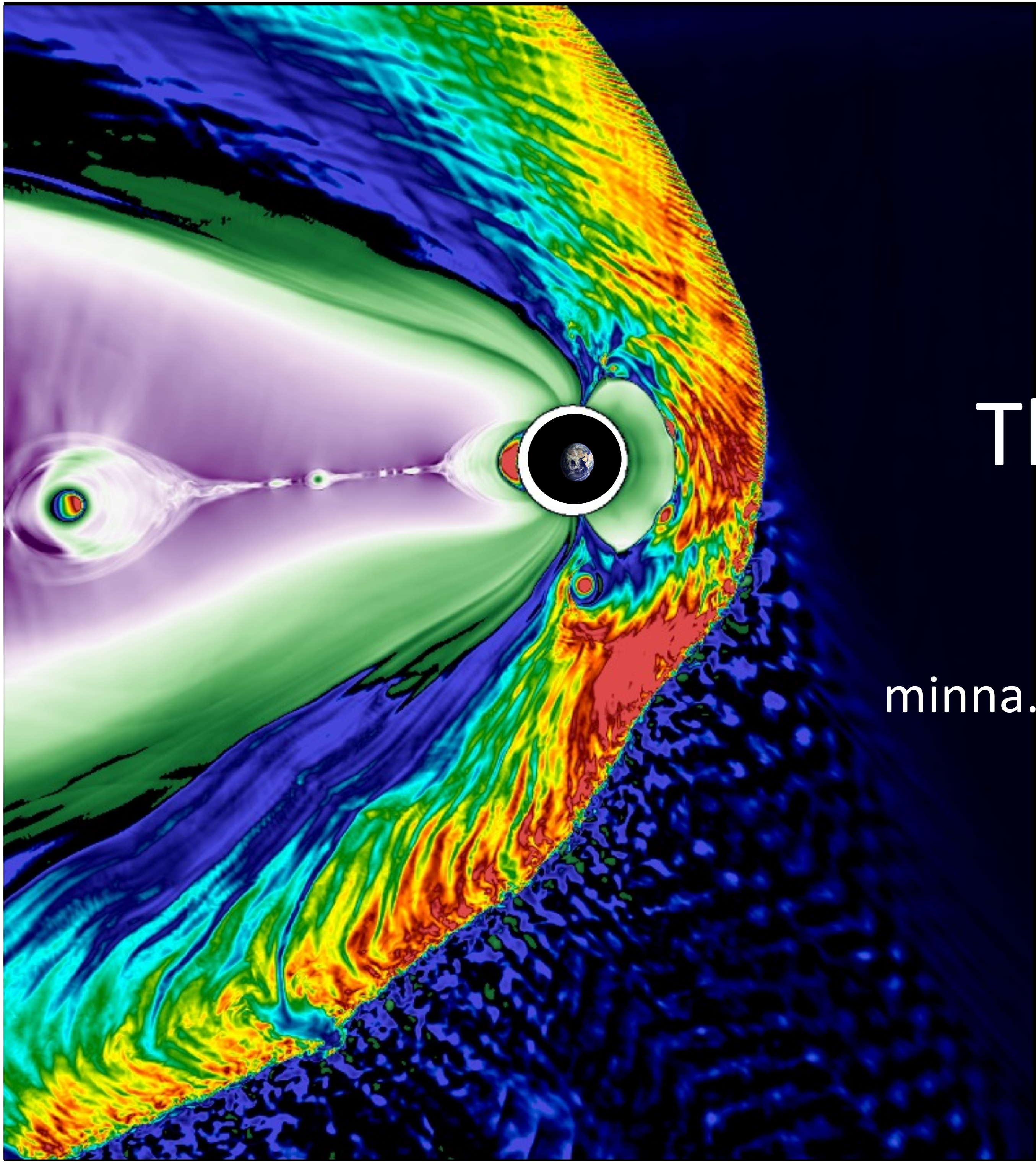
Storm index “Dst”:
–100 nT: aurora in Stockholm
–300 nT: in Rome
–1500 nT: in Caribbean



Summary

Carrington storm is 3-5 times larger than anything observed during space age

- Impacts expected in
  - Global power supply
  - Systems using GNSS signals (e.g., mobile networks)
  - Aviation
  - Satellites
- Effects may be surprising for technologies that prepare for “more of the same”
- ➔ Check whether your system has a dependency on
  - GNSS signals
  - Power supply that has vulnerabilities
  - Satellites
- If your system depends on a Carrington-sensitive technology, carry out further tests and monitor continuously
- We are already on loaned time
  - Next Carrington can come tomorrow, or thrice in the next 100 years.



Thank you!

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