Solar Space Weather

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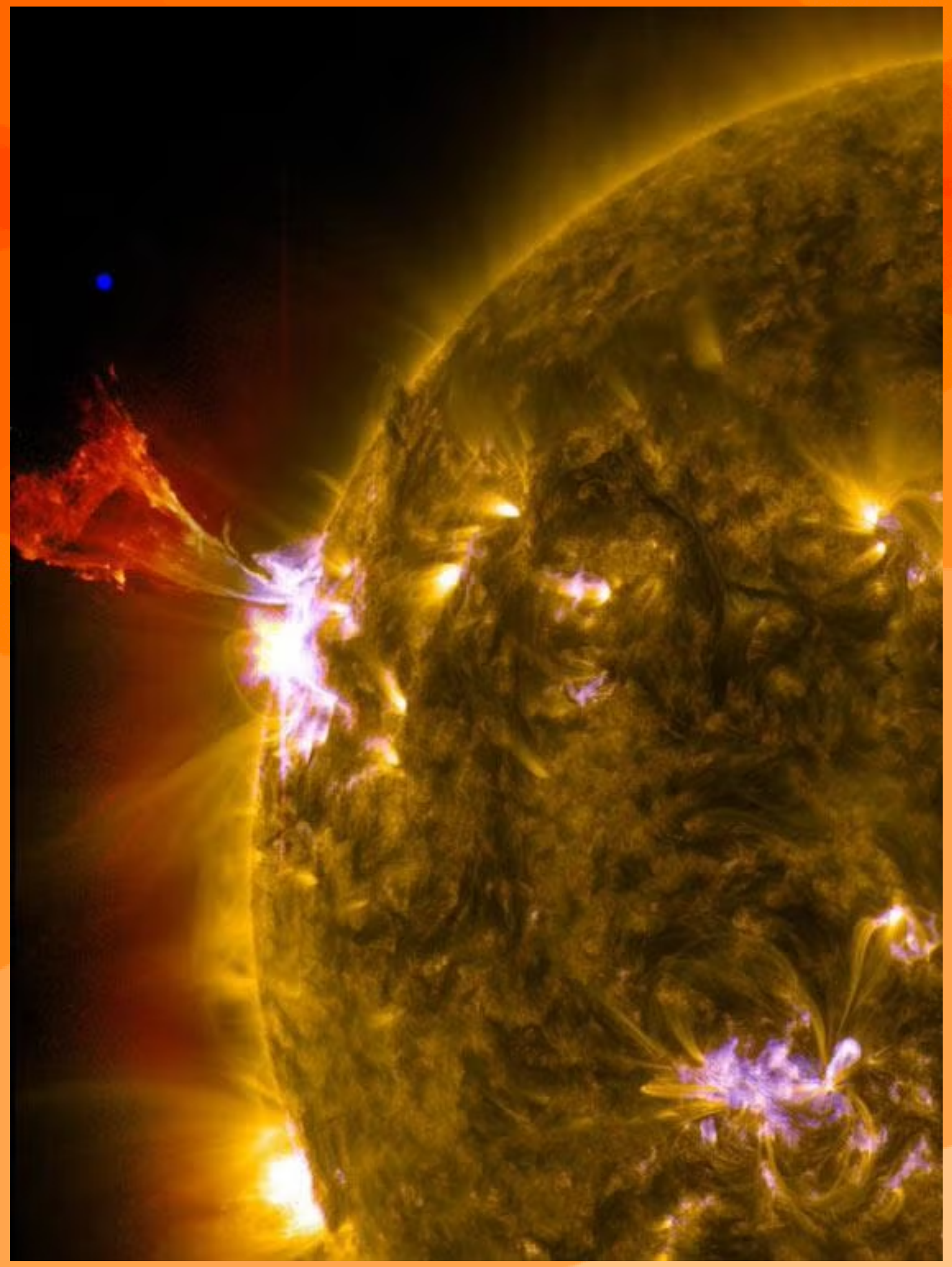
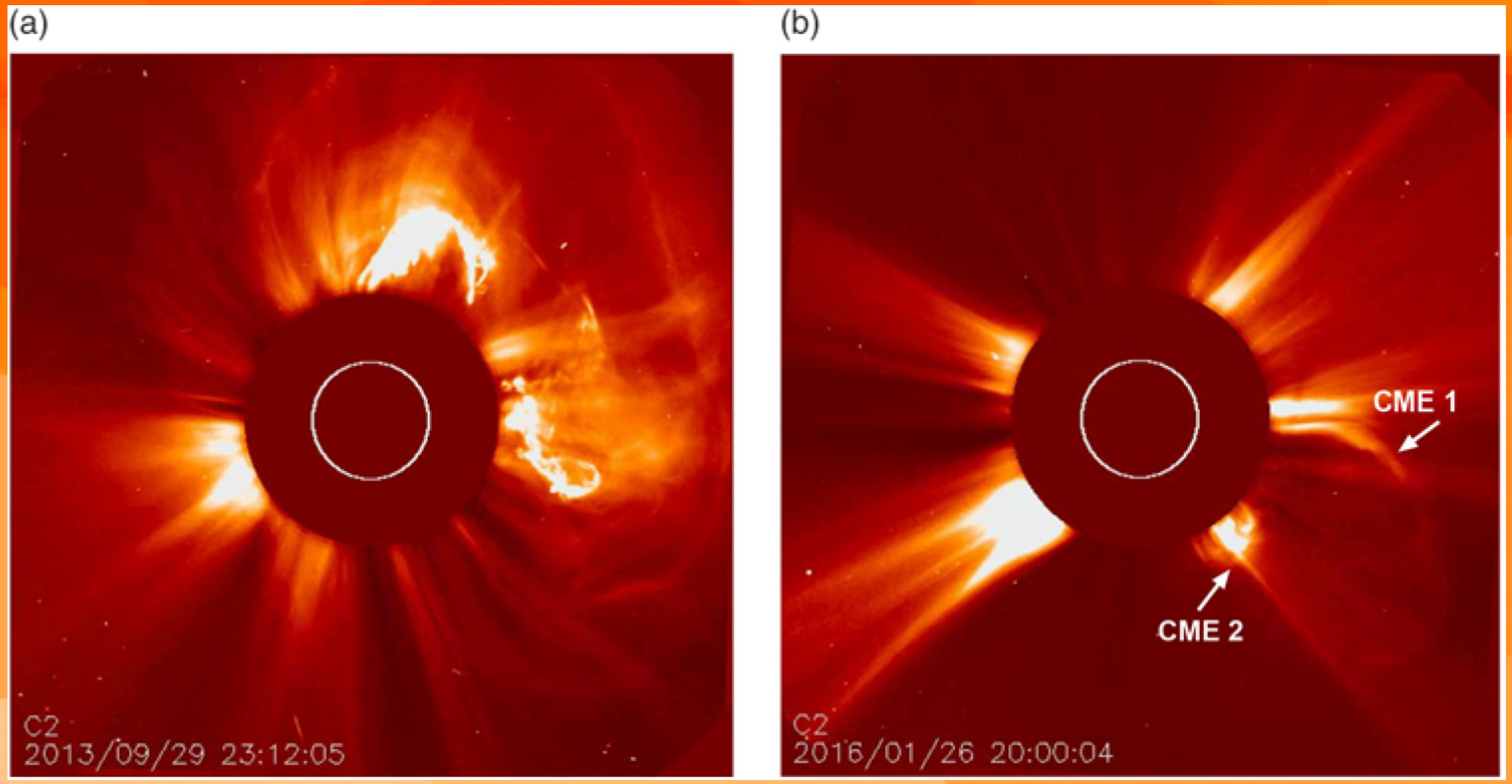
Solar activity

- **Solar Flare:** A sudden burst of energy and radiation from the Sun's surface, primarily in the form of X-rays and extreme ultraviolet light. Flares happen near sunspots and affect Earth almost instantly, impacting radio and satellite communications.
- **Coronal Mass Ejection (CME):** A massive cloud of plasma and magnetic field released from the Sun's corona. CMEs travel slower than flares, taking 1-3 days to reach Earth, and can cause geomagnetic storms that disrupt power grids and GPS.





Solar weather in a nutshell

Solar weather in a nutshell

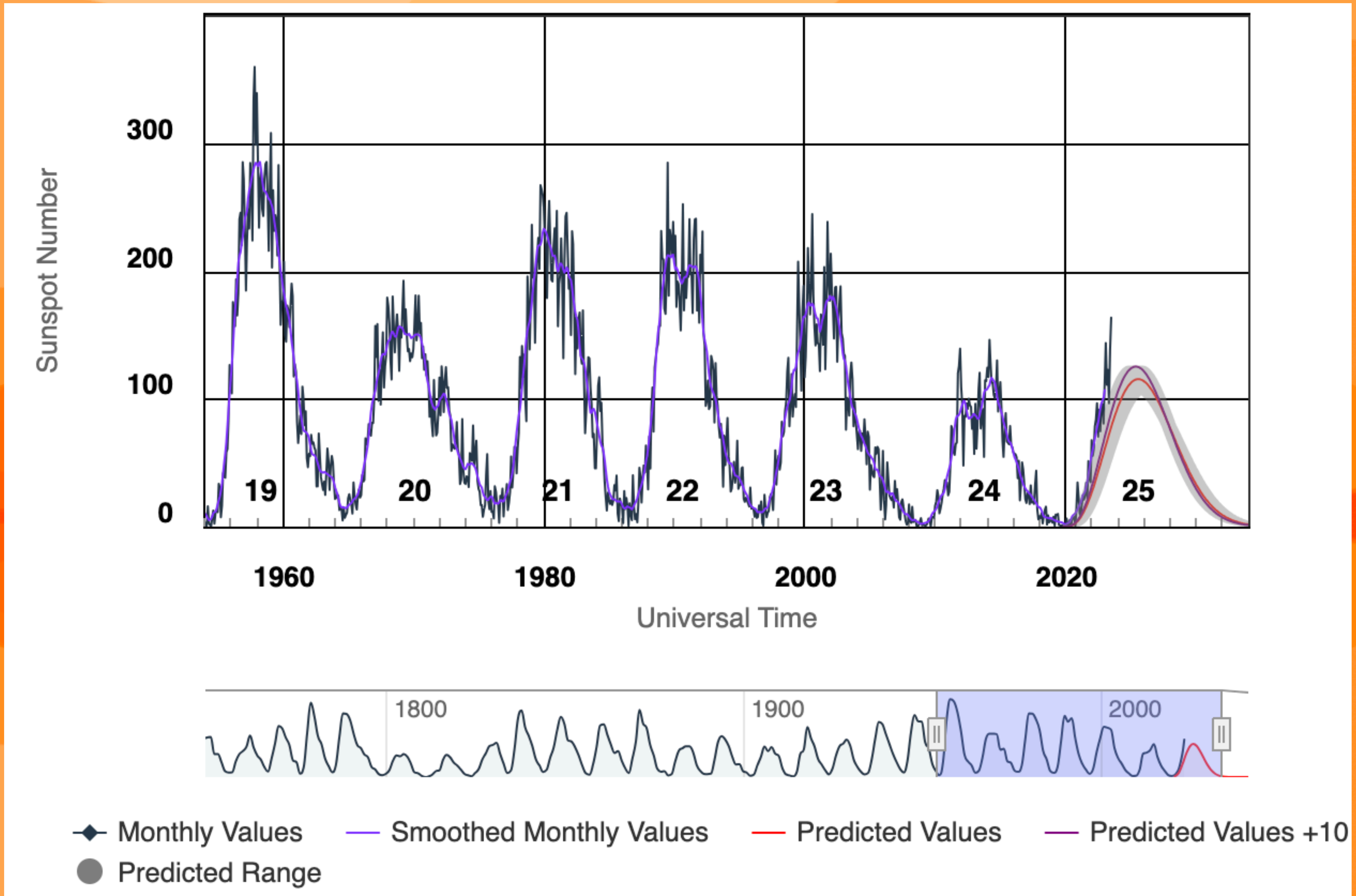
6. Impacts

- Aurora borealis 😍
- Radiation Exposure (Astronauts and airline crew members) 😕
- Satellite communication disruptions (incl. GPS nav.) 🛰😤
- **Power grid disruptions** 🤦💡
- **Pipeline corrosion** 🤦
- Health effects 🤦🫀

Solar weather in a nutshell

Solar cycles

- **What is a Solar Cycle?**
  - An approximately 11-year cycle of solar activity, marked by fluctuations in sunspot numbers, solar flares, and coronal mass ejections (CMEs)
- **Phases of the Solar Cycle:**
  1. Solar Minimum: Low sunspot activity, fewer solar storms, and minimal geomagnetic impact on Earth.
  2. Solar Maximum: High sunspot numbers, increased solar flares and CMEs, with stronger geomagnetic storms impacting Earth.
- **Current Cycle:**
  - We are currently in Solar Cycle 25, expected to peak around 2025.

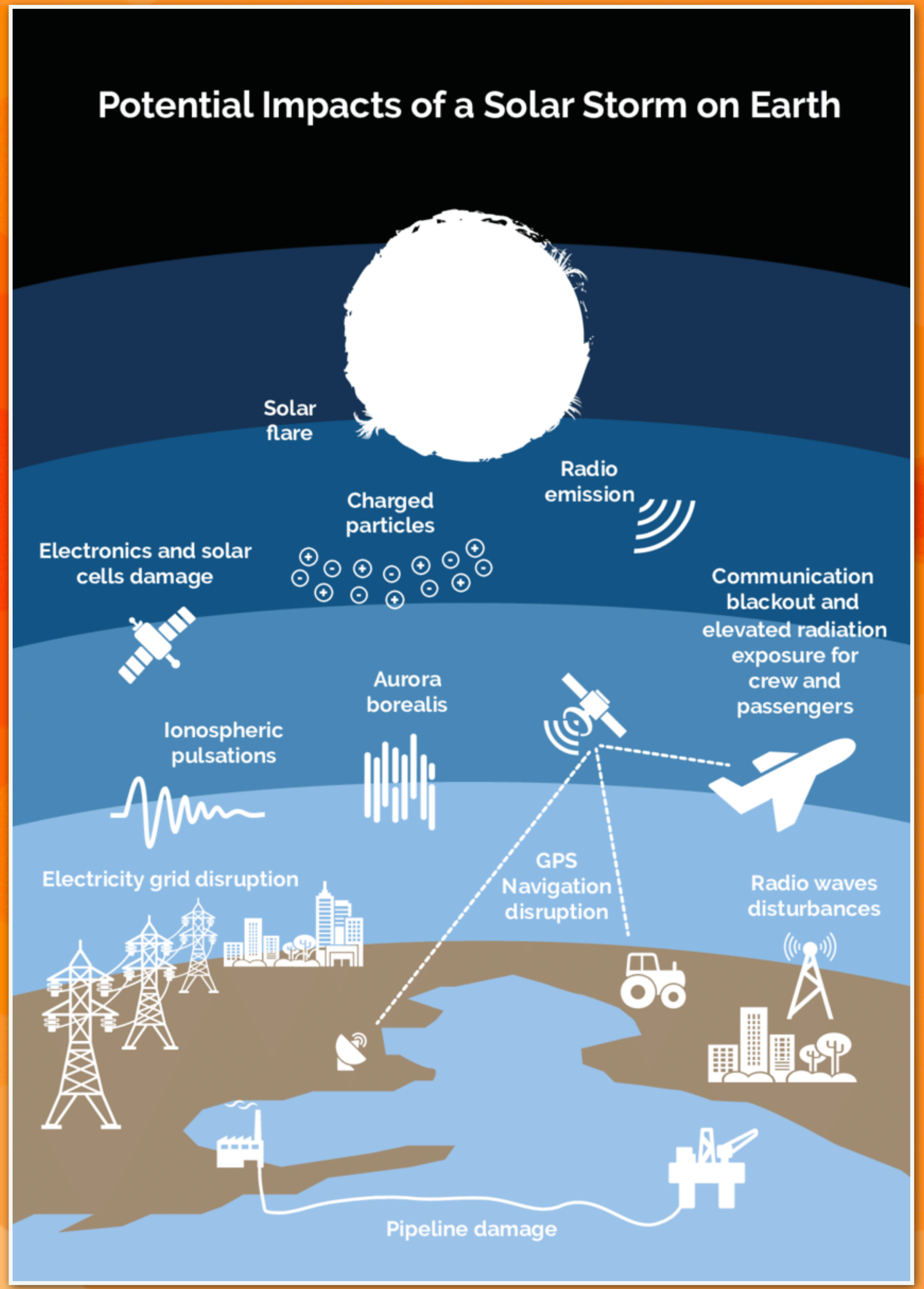


During solar maximum, increased solar storms can disrupt satellites, power grids, and communication systems.

Potential Impacts of Solar Storms

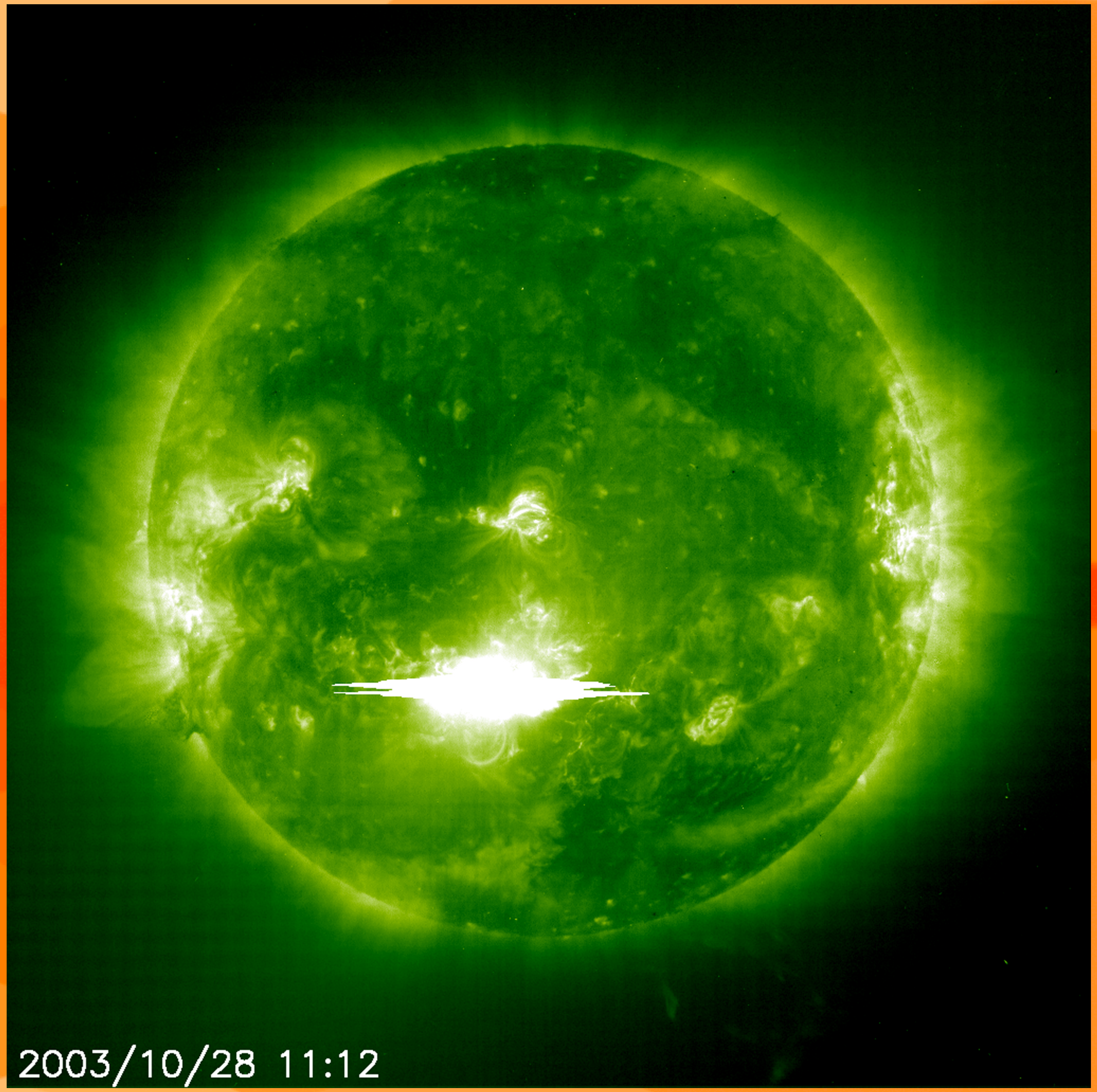
- **G-scale (G1-G5)** measures geomagnetic storm severity, from minor (G1) to extreme (G5), based on Earth's magnetic disruption

- G1 (Minor)
  - Small power grid fluctuations
  - Minor satellite communication issues
  - Auroras at high latitudes
- G2 (Moderate)
  - Limited impact on power systems
  - Satellite orientation adjustments may be needed
  - Auroras visible at slightly lower latitudes
- G3 (Strong)
  - Voltage irregularities in power grids
  - Intermittent GPS and satellite disruptions
  - Auroras visible in mid-latitudes
- G4 (Severe)
  - Widespread voltage control issues; potential power outages
  - Significant satellite, GPS, and communication disturbances
  - Auroras visible in lower latitudes
- G5 (Extreme)
  - Extensive power grid failure risks
  - Severe satellite and GPS disruptions
  - Intense auroras visible as far as tropical latitudes



Major Solar Storms and Their Impact: A Historical Overview

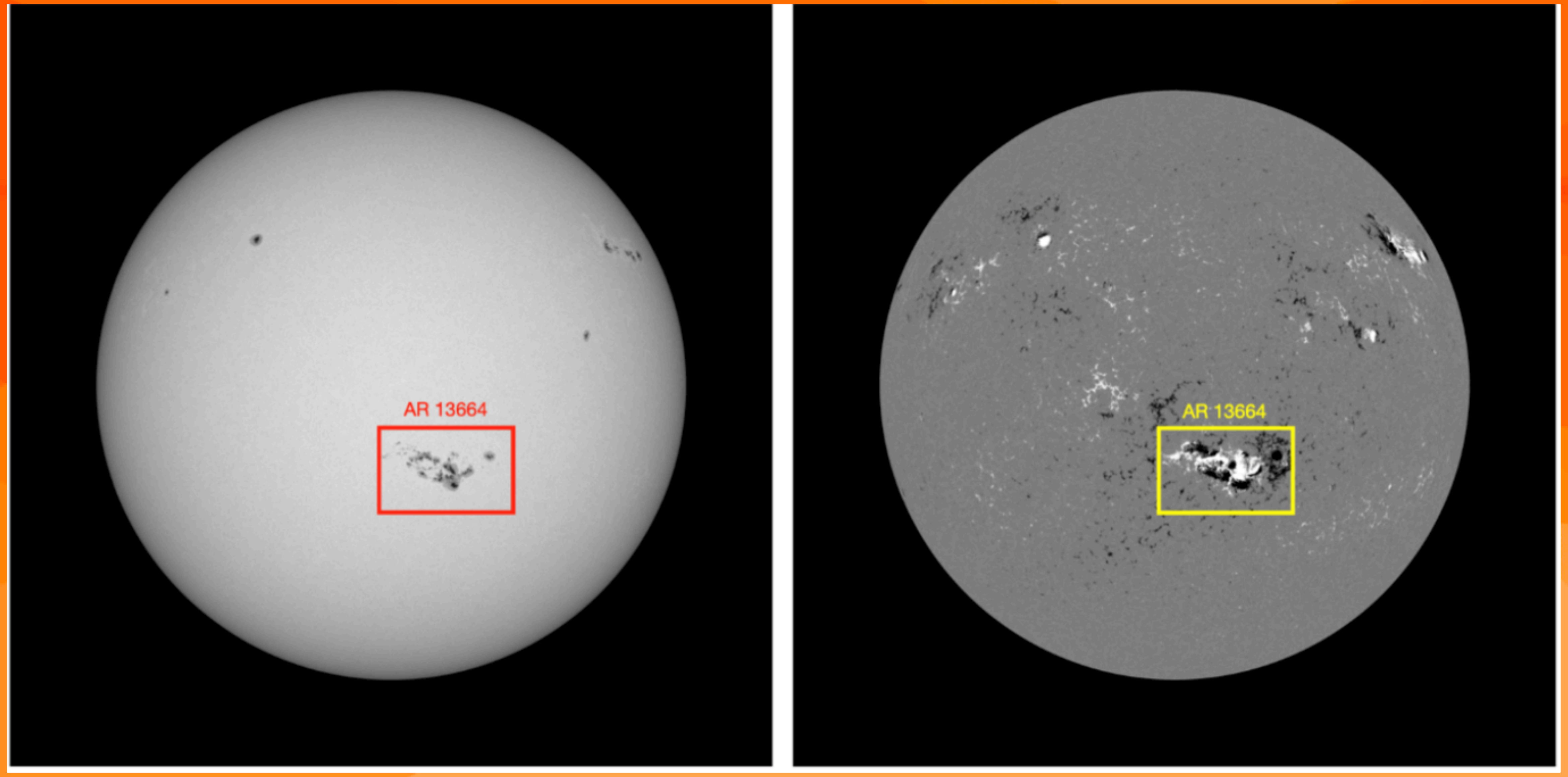
- **Carrington Event (1859):** Originated from a massive coronal mass ejection (CME). G5 storm, lasting about 8 days. Caused telegraph failures and auroras in the Caribbean.
- **Halloween Storms (2003):** Originated from multiple X-class flares. G3 to G5 range, lasting from October 28 to November 4, 2003. Disrupted satellites, GPS, and power grids.
  - Solar Flare Scale (X, M, C) measures flare intensity, from C-class (weakest) to X-class (most intense).
- **Solar Storm of 1921:** Caused by a CME. G5 storm, lasting several days. Damaged telegraphs, set fires, and affected global communications.
- **March 1989 Storm:** Originated from a CME. G4 storm, lasting 1-2 days. Caused a 9-hour power outage in Quebec and satellite disruptions.



The Solar and Heliospheric Observatory (SOHO) spacecraft captured this image of a solar flare as it erupted from the sun early on Tuesday, October 28, 2003. The flare was recorded as a massive X45-class solar storm

May 2024 Mother's Day Superstorm

- **Classification:** Driven by powerful coronal mass ejections (CMEs).
- **Cause:** In early May, two large sunspots, AR3663 and AR3664, appeared on the Sun's visible surface (AR = Active Region).



- AR3664 was 16 times the size of Earth and responsible for the geomagnetic storms on May 10-11.

- **Satellites:** Increased atmospheric drag on low Earth orbit (LEO) satellites, causing altitude drops and requiring emergency maneuvers, which raised collision risks.
- **Ground Effects:** Potential disruptions in GPS, radio, and power grids; vivid auroras observed at unusually low latitudes across Europe and North America.


Le Monde

SCIENCE · SPACE AND ASTRONOMY

Rare northern lights seen in Paris region and across the world

NASA had announced that it was expecting such events, after observing explosions on the Sun's surface.

By Jean-Baptiste Jacquin

Published on May 11, 2024, at 12:04 pm (Paris) · 1 min read · Lire en français

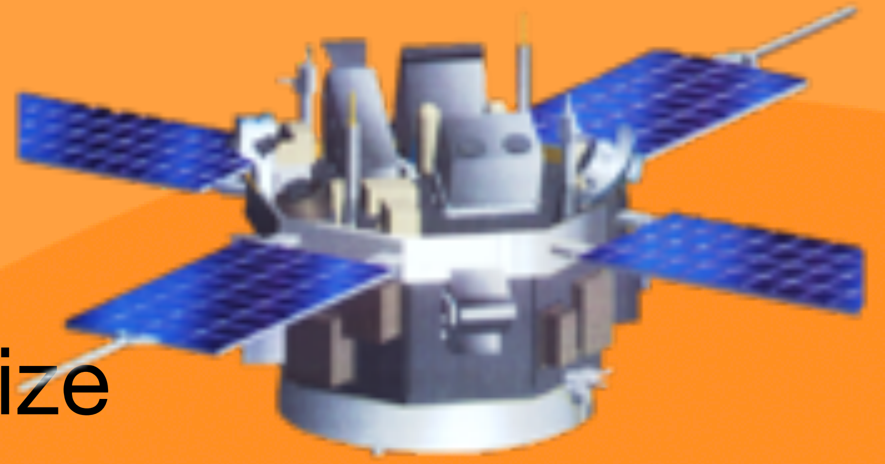
How we can predict when solar storms will occur?

Predicting Solar Storms Using Machine Learning

Overview:

- Machine Learning Forecasting leverages large datasets from solar observations (sunspots, flares, solar wind) to predict solar storm activity.

How It Works:



- Data Analysis: Machine learning models are trained on years of solar storm data to recognize early indicators of storms.

Start date	Duration (days)	SYM-H (nT)
14/02/1998	8	−119*
02/08/1998	6	−168*
19/09/1998	10	−213
16/02/1999	8	−127*
15/10/1999	10	−218
09/07/2000	10	−347
06/08/2000	10	−235*
15/09/2000	10	−196*
01/11/2000	14	−174*
14/03/2001	10	−165*
06/04/2001	10	−275
17/10/2001	10	−210
31/10/2001	10	−320
17/05/2002	10	−116*
15/11/2003	10	−490
20/07/2004	10	−208
10/05/2005	10	−302*
09/04/2006	10	−110*
09/12/2006	10	−211*
01/03/2012	10	−149

Start Date	Duration (days)	SYM-H (nT)
22/06/1998	8	−120
02/11/1998	10	−179*
09/01/1999	9	−111
13/04/1999	6	−122
16/01/2000	10	−101*
02/04/2000	10	−315
19/05/2000	9	−159*
26/03/2001	9	−437
26/05/2003	11	−162*
08/07/2003	10	−125*
18/01/2004	9	−137*
04/11/2004	10	−394*
10/09/2012	25	−138
28/05/2013	7	−134
26/06/2013	8	−110
11/03/2015	10	−234
22/08/2018	12	−205

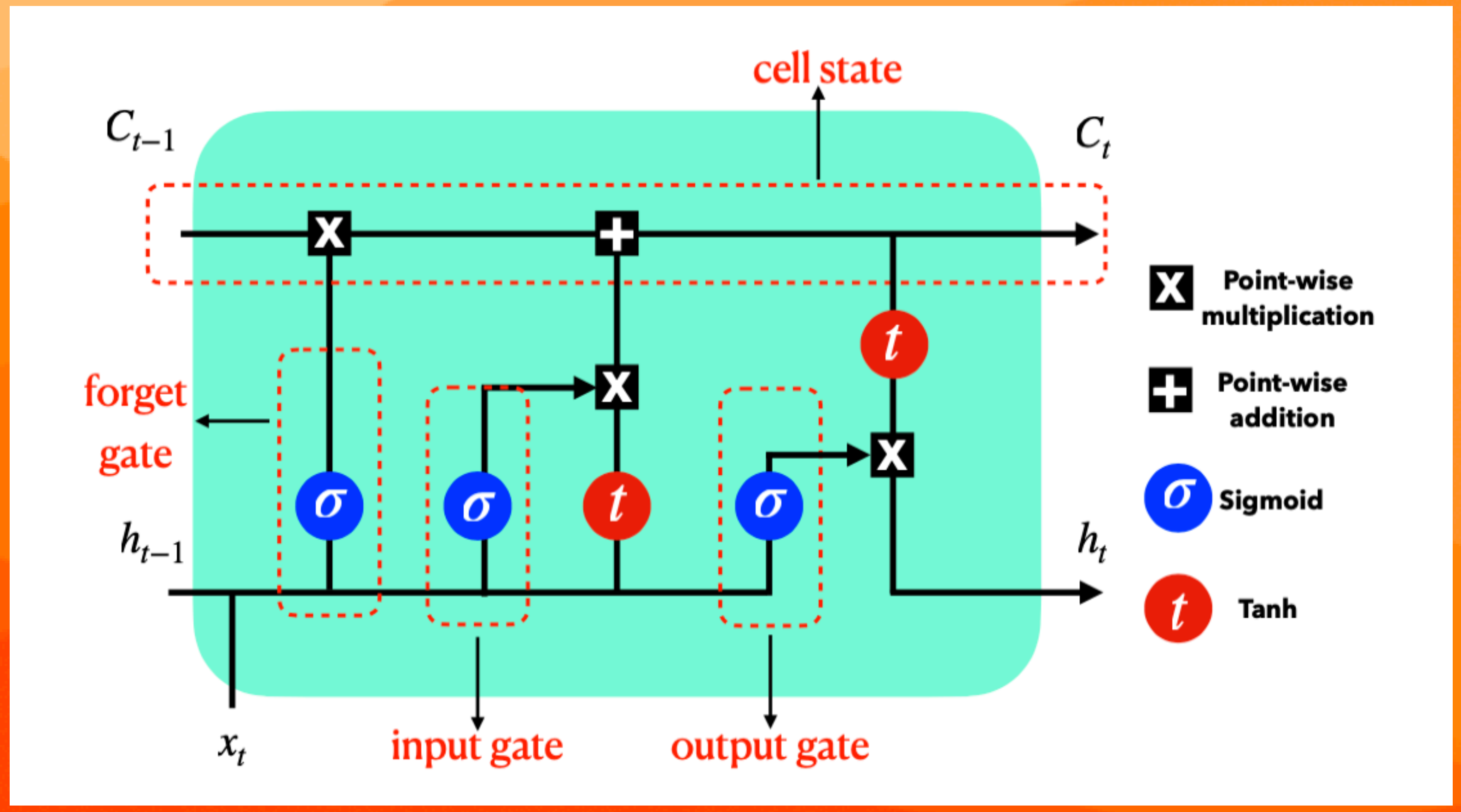
Data from NASA's ACE spacecraft at L1 contains **42 of the most intense geomagnetic storms**, distributed in two solar cycles (1998-2018)

Start Date	Duration (days)	SYM-H (nT)
28/04/1998	10	−268
19/09/1999	7	−160
25/10/2003	9	−432*
18/06/2015	10	−207*
01/09/2017	10	−146*

SYM-H index is a key measure of geomagnetic storm intensity

Deep-learning Model

- *Long Short-Term Memory (**LSTM**) Neural Network (in Keras)*

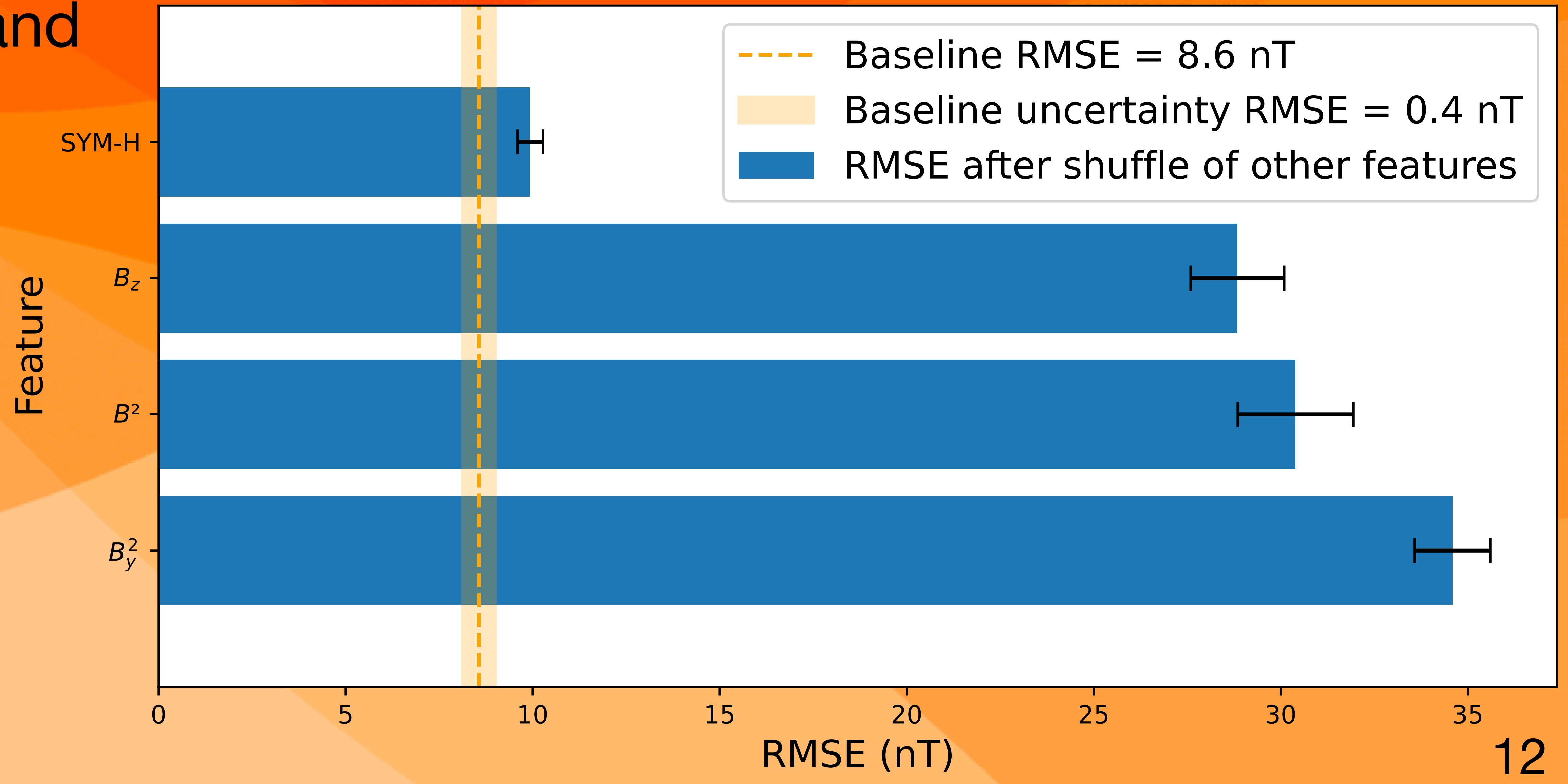


- **LSTM (Long Short-Term Memory)** is a type of recurrent neural network (RNN) designed to handle sequential data. It excels in tasks like time series prediction and natural language processing by maintaining long-term dependencies. **—> We use this one!**
- **CNN (Convolutional Neural Network**). Unlike LSTMs, CNNs excel in extracting local features but are not designed to handle temporal sequences.

- **Optimization:** Optuna, a Bayesian-based algorithm optimized hyperparameters, including the number of layers, neurons, and learning rate, ensuring optimal LSTM performance.

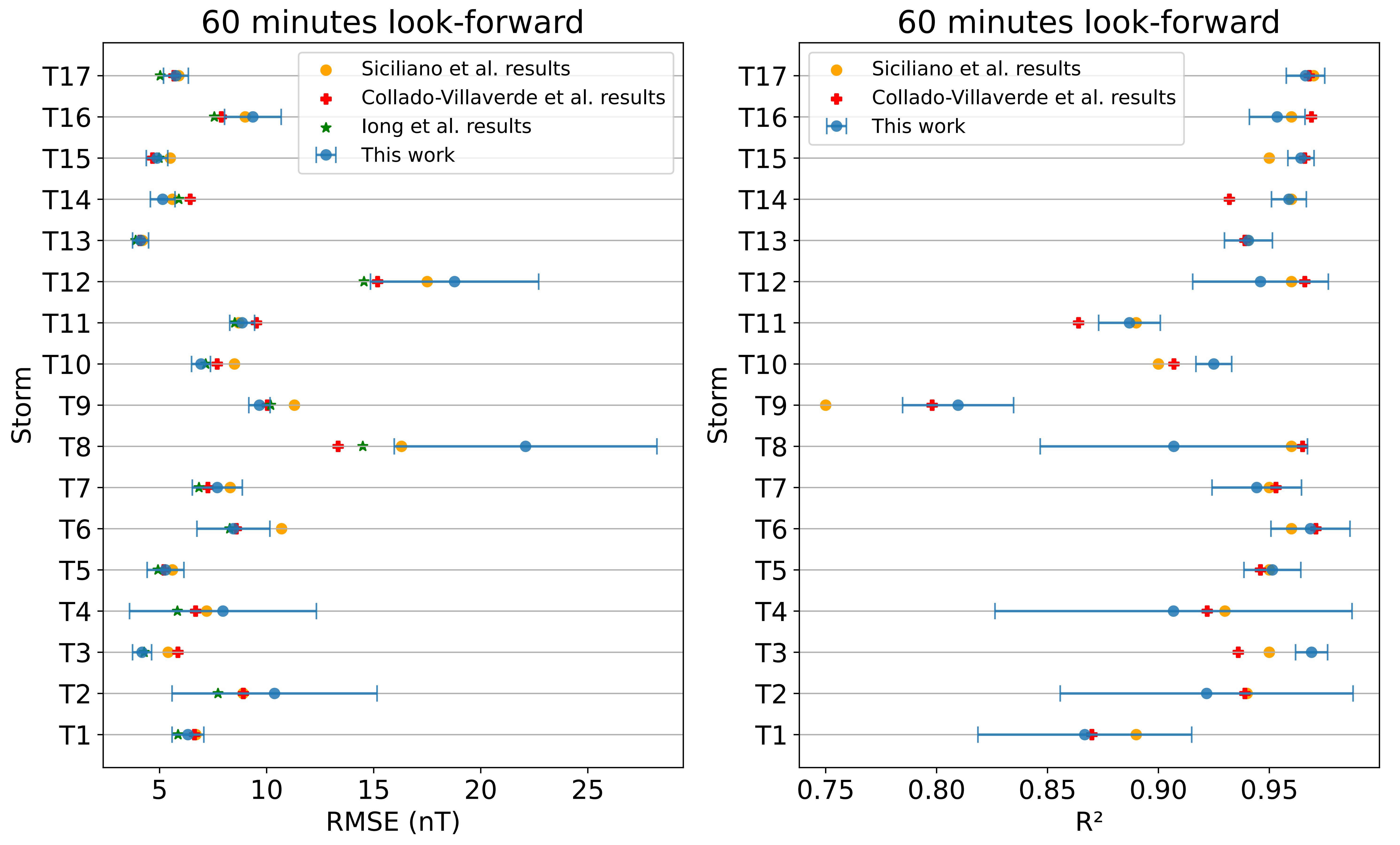
Uncertainty Quantification:

- Block Bootstrapping: Preserved the temporal structure of the data.
- Concrete Dropout: Enhanced dropout probabilities for improved regularization and uncertainty management.



LSTM Results

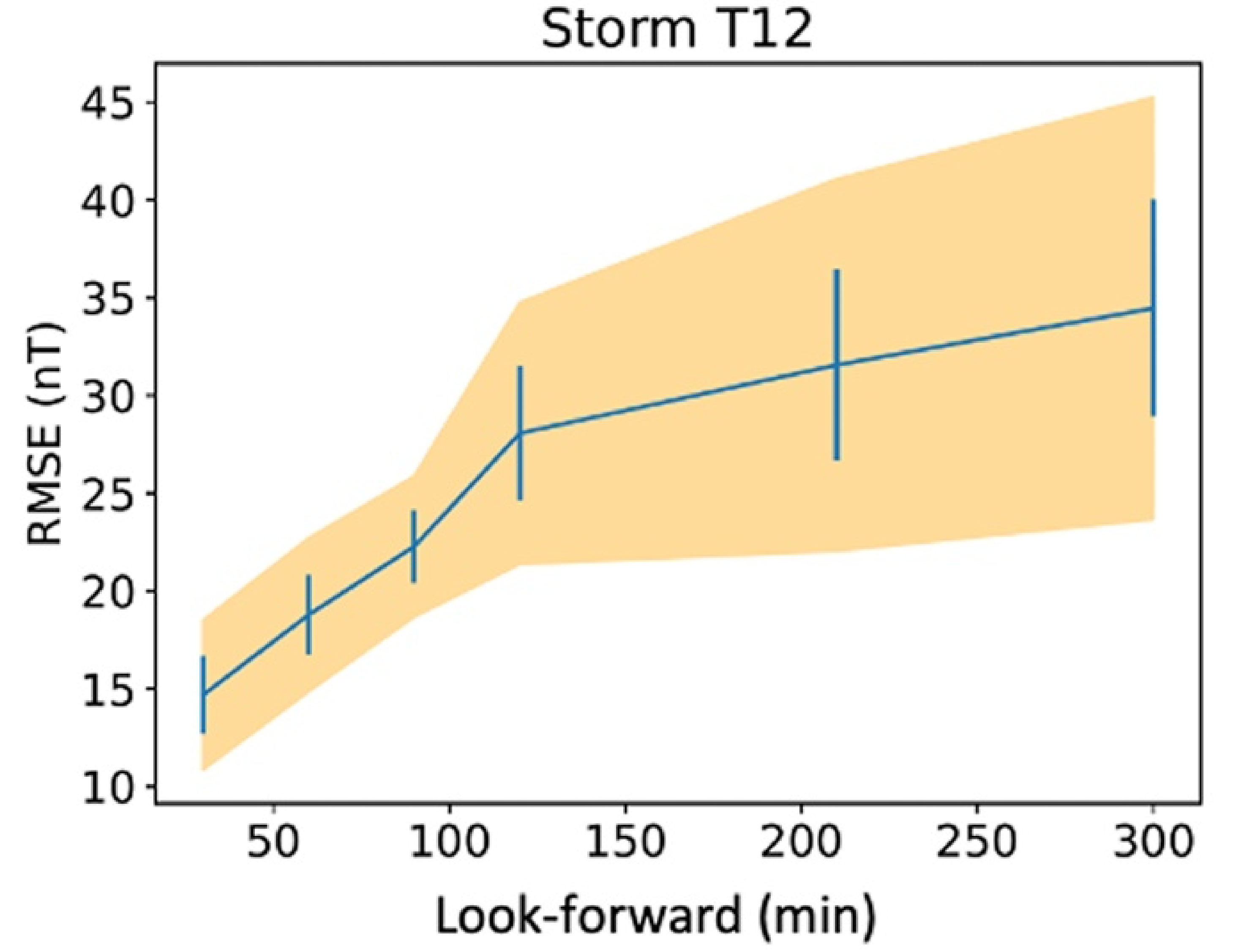
- **Forecasting SYM-H index 1-hour ahead (full storm range)**



Metrics used are RMSE and R2 for comparisons with other results:

$$R^2(y,\hat{y}) = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y}_i)^2}$$

$$RMSE(y,\hat{y}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}$$



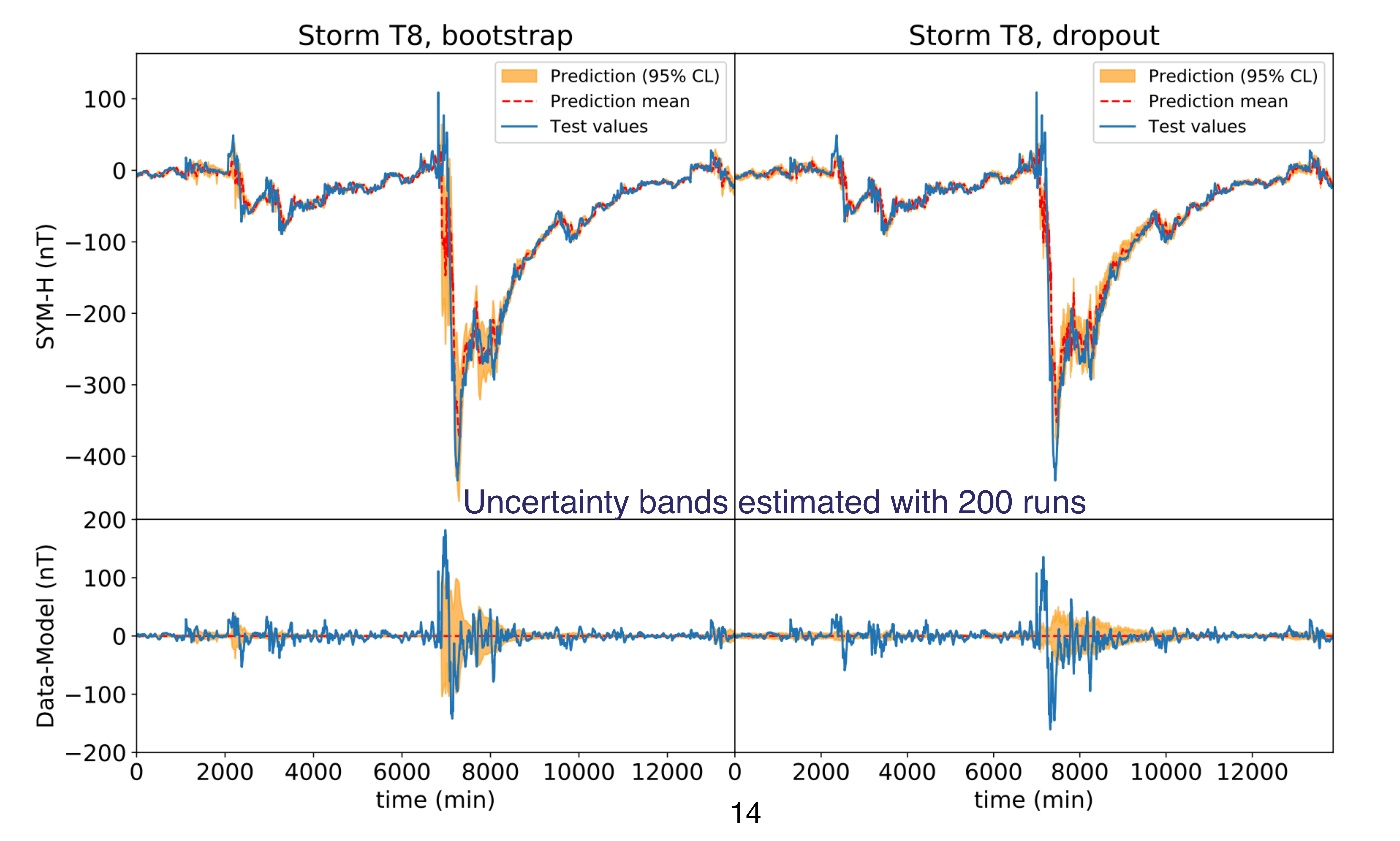
- **Comparison of SYM-H predictions with public results:**
  - RMSE lower value the better, R squared the higher the better

Uncertainty bands derived from the block-bootstrapping method using 200 runs

Forecasting Full Storm

Forecasting SYM-H index 1-hour ahead (full storm)

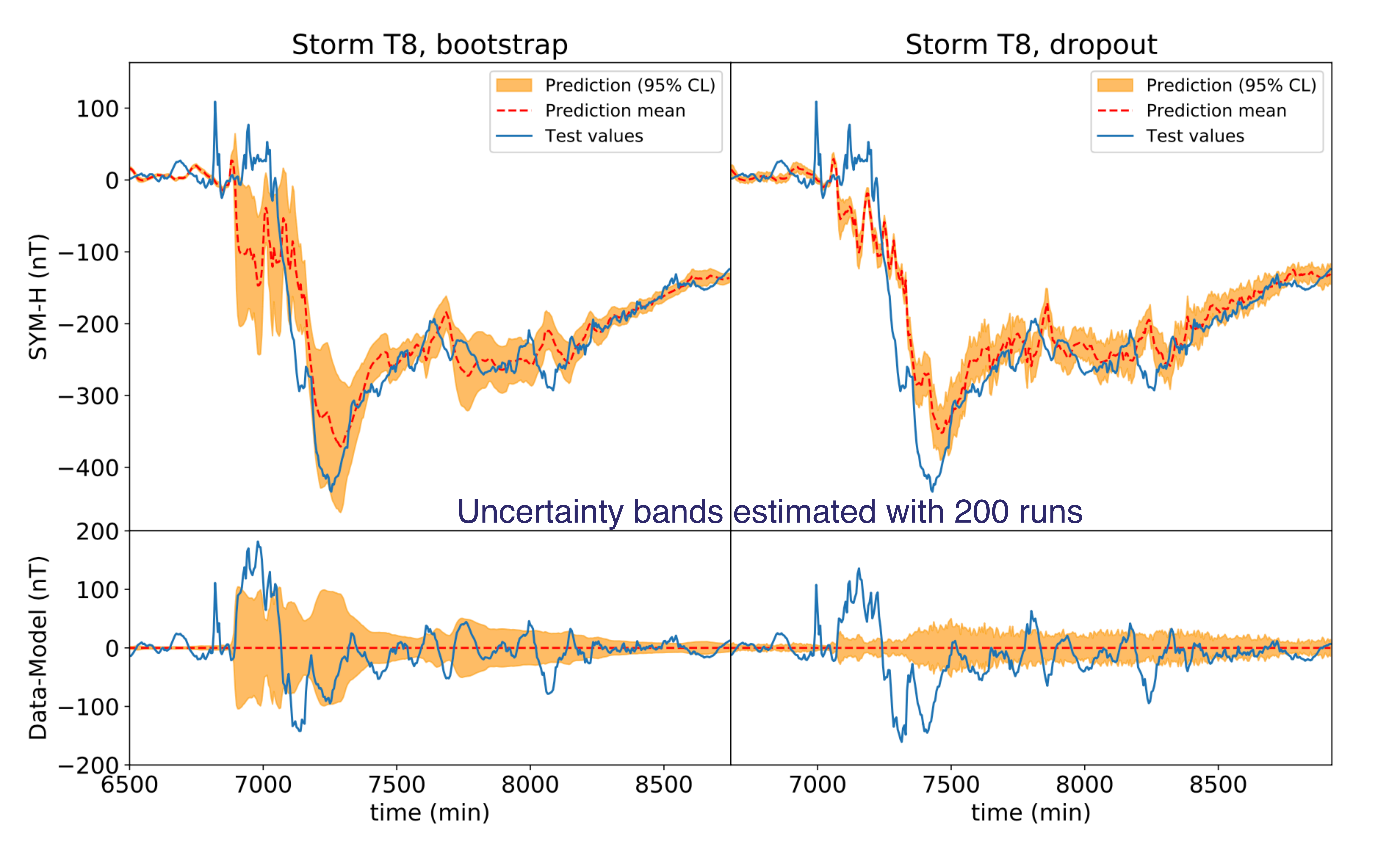
- Orange bands represent the 95% CL of the predicted value by our model



Forecasting Peak Range

Forecasting SYM-H index 1-hour ahead (storm-peak range only)

- Orange bands represent the 95% CL of the predicted value by our model



Conclusion and Goals

- Predicting solar storms is vital to safeguard critical infrastructure, such as satellites, power grids, and communication systems, from potential disruptions caused by solar flares and coronal mass ejections

- **Ultimate goal**
  - Develop a predictive model to have a **real-time early warning system** to warn about the impact of future violent solar storms on **Spanish critical infrastructures**
  - Real-time **vulnerability map** of the Spanish power network to the **GIC hazards** from our resistivity models

- Starting to build a **simple prediction model**
  - Using past values of **IMF data** (B^2, B_y^2, B_z) at **L1** point by the ACE spacecraft
  - Predict future values of SYM-H multiple-hour ahead
  - Robust model based on the state-of-the-art **LSTM** architecture
  - Establish the **necessity of estimating model uncertainties** to have a reliable model