Where and under which conditions do soft protons affect X-ray observations: space physics meets astrophysics and machine learning

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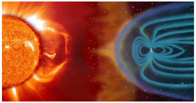
DFG Deutsche Forschungsgemeinschaft German Research Foundation

INTERNATIONAL SPACE SCIENCE INSTITUTE



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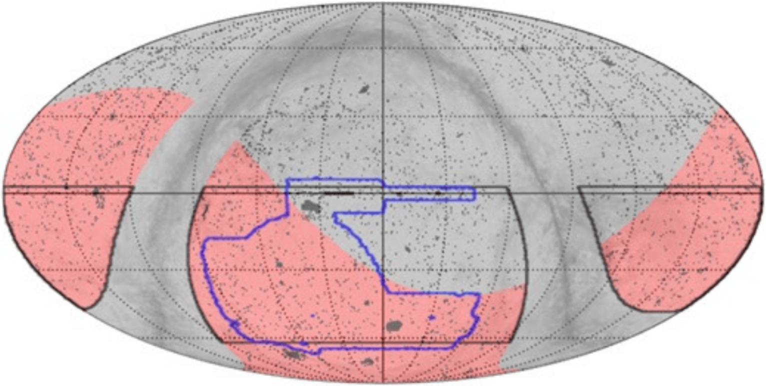
Motivation

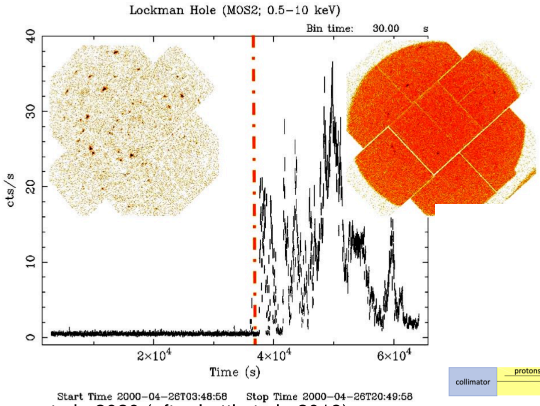
- The sky plot shows the position of all currently available XMM X-ray observations of galaxy clusters



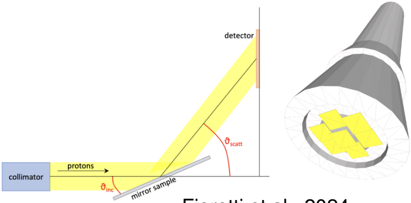
Upsdell et al., MNRAS, 2023

Motivation

- Observations by XMM are thought to be affected by soft protons, $\sim$100 keV (e.g., Fioretti et al., 2016)
- Astronomers need to understand the sources of this contamination and to predict it

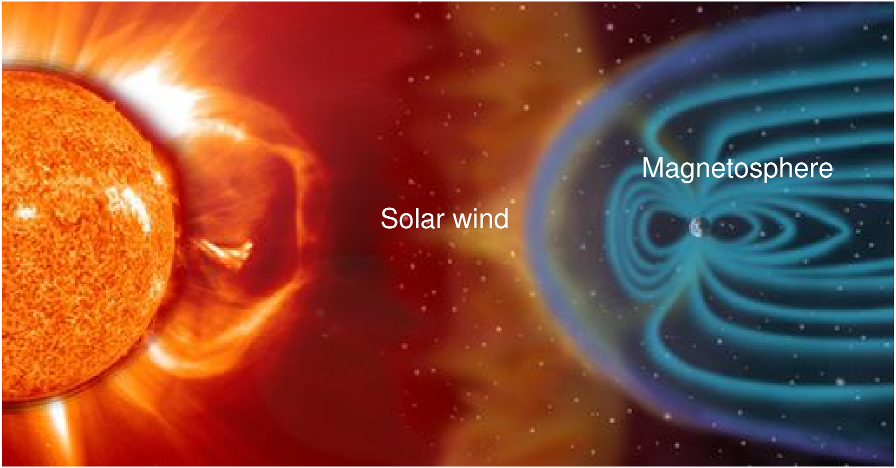


Kronberg et al., 2020 (after Lotti et al., 2018)

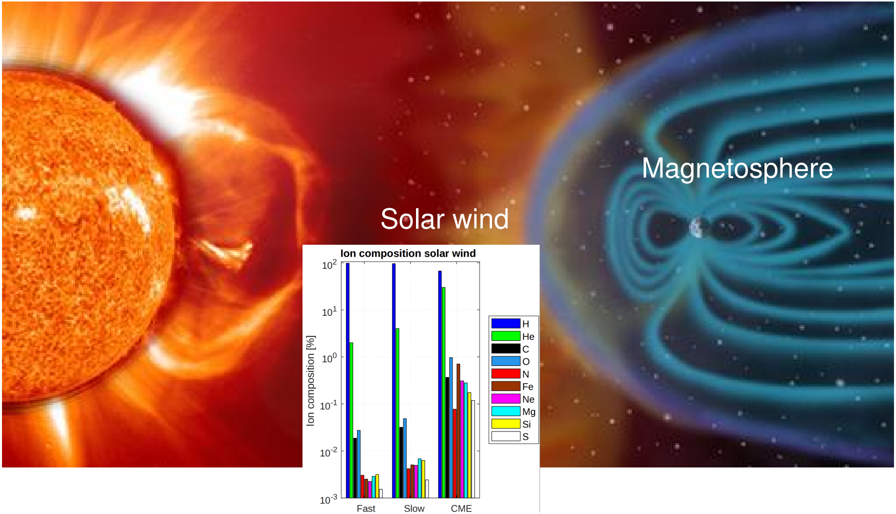


Fioretti et al., 2024

Solar wind interaction with the terrestrial magnetic field forms a dynamic plasma environment: magnetosphere

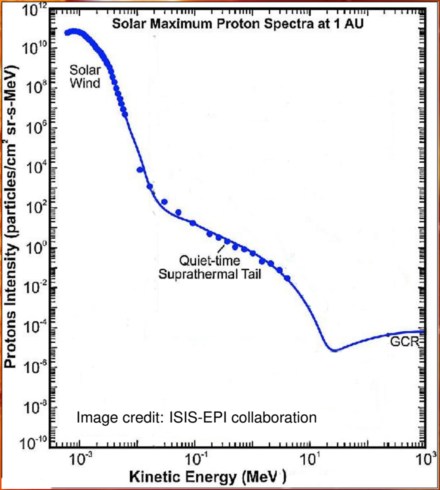


Solar wind interaction with the terrestrial magnetic field forms a dynamic plasma environment: magnetosphere



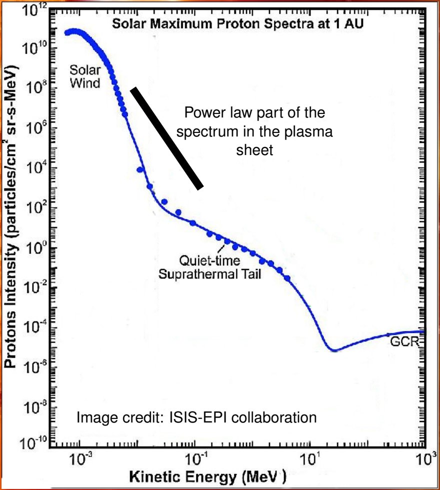
The magnetosphere is an effective particle accelerator

- Proton spectrum in the solar wind: $E = 1\,\text{keV}$

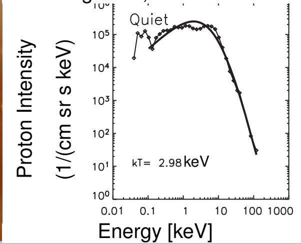


The magnetosphere is an effective particle accelerator

- Proton spectrum in the solar wind: $E = 1\,\mathrm{keV}$
- Proton spectrum in the plasma sheet: $E \sim 3\,\mathrm{keV}$ + harder tail



Kronberg et al., 2010



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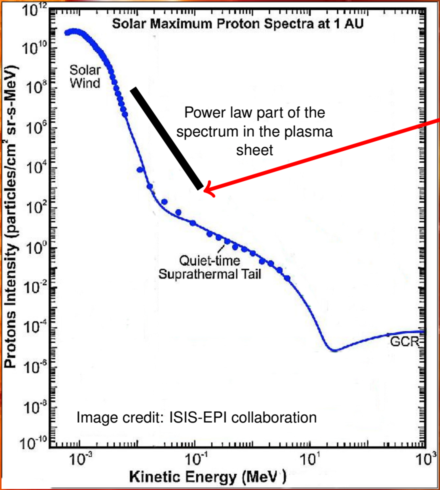
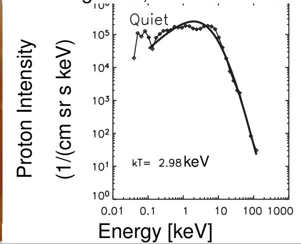
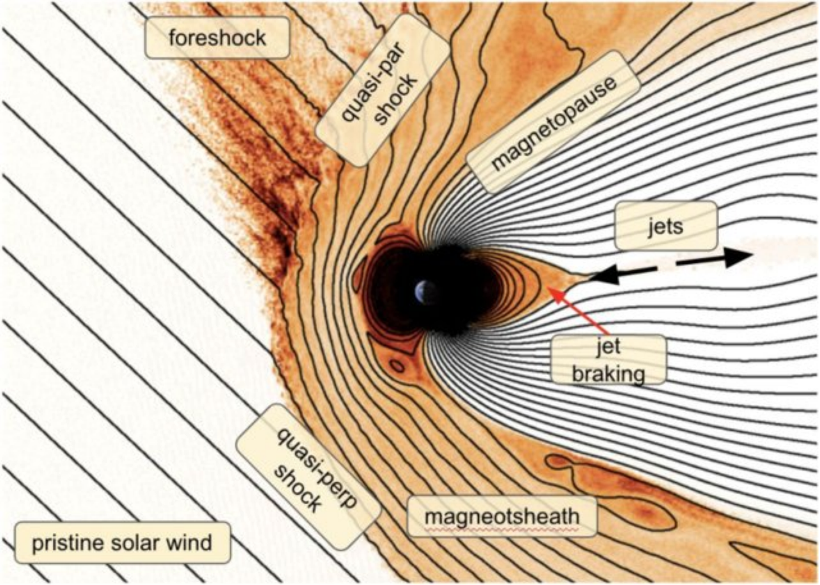


soft protons at ~100 keV may contaminate XMM telescope

Kronberg et al., 2010

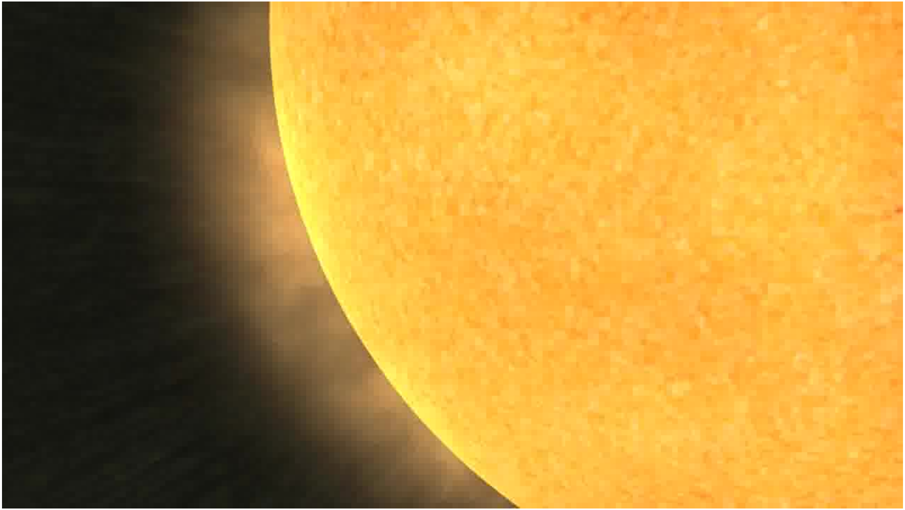


Places of energization in the magnetosphere



Color scale is ion temperature. Courtesy: D. Krauss-Varban

Solar wind – magnetosphere interaction



Recent prominent event: Mother's Day magnetic storm seen in Disentis, Switzerland on May 10, 2024

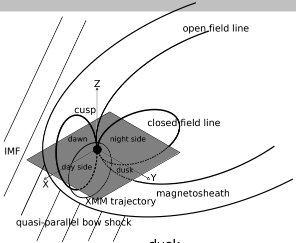
Questions

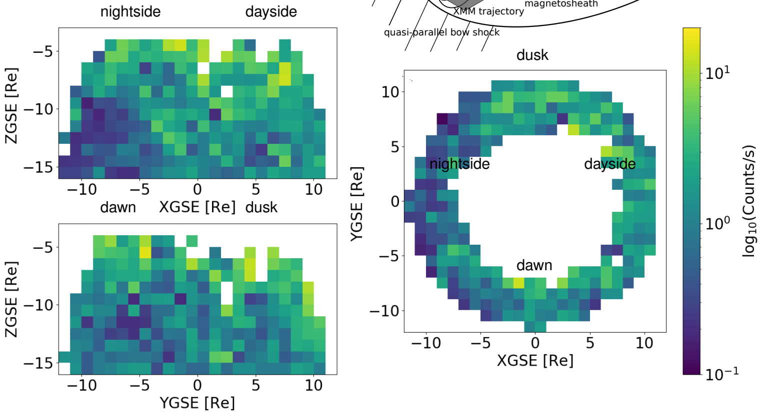
- Where and under which conditions is the XMM telescope contaminated?
- Do soft protons ($\sim$100 keV) contaminate XMM?

To tackle these problems a team of astronomers and space scientists has gathered at the ISSI in Bern

Contamination by soft protons

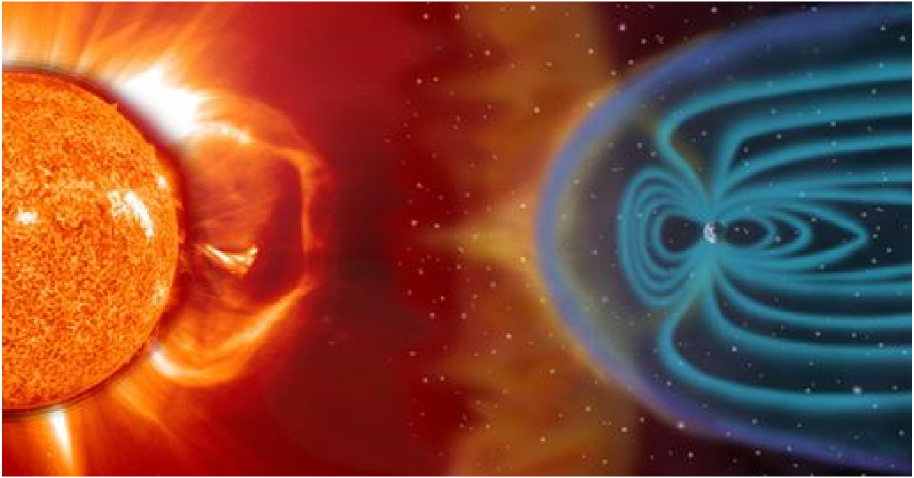
- 12 years of XMM observations





Kronberg et al., ApJ, 2020

Which parameters can affect the contamination?



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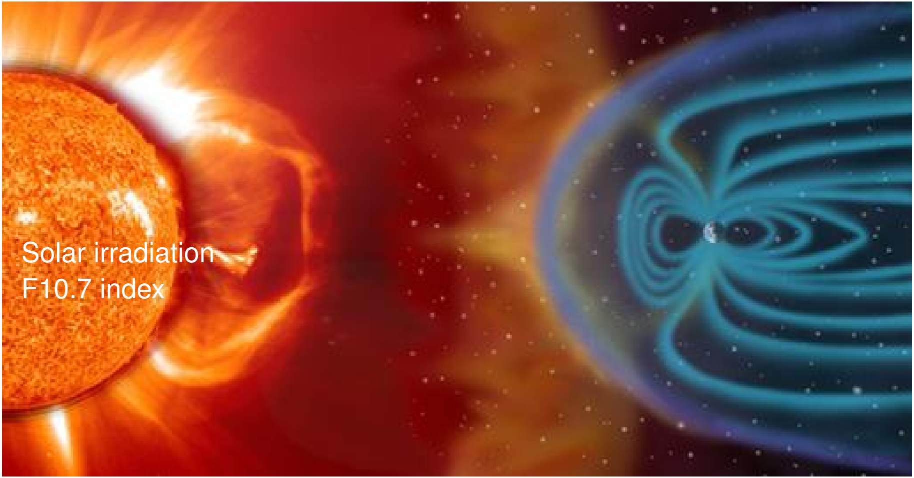

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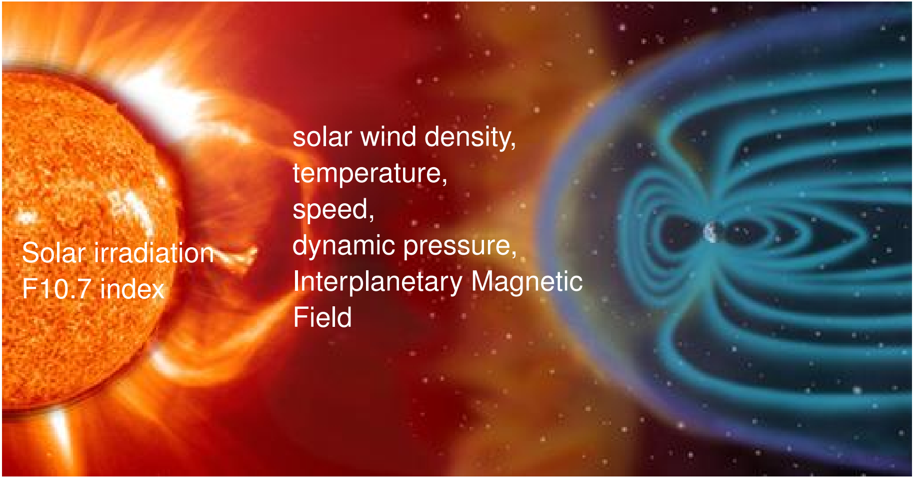
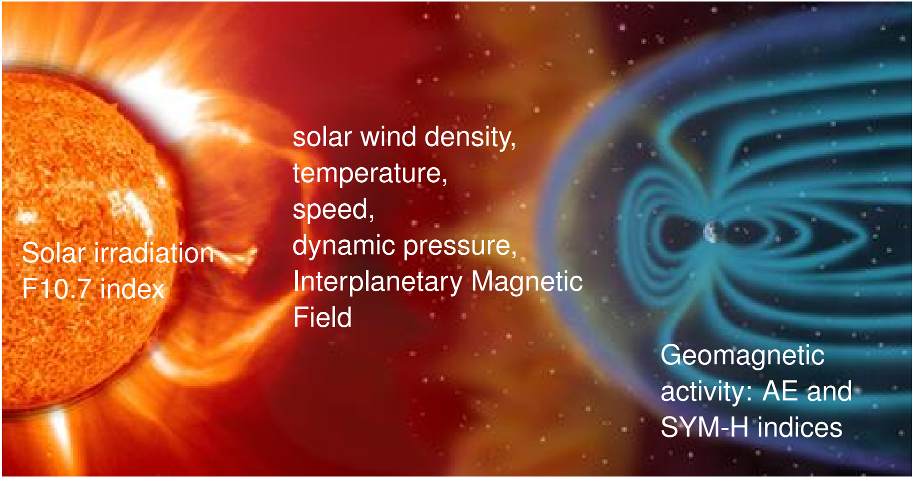
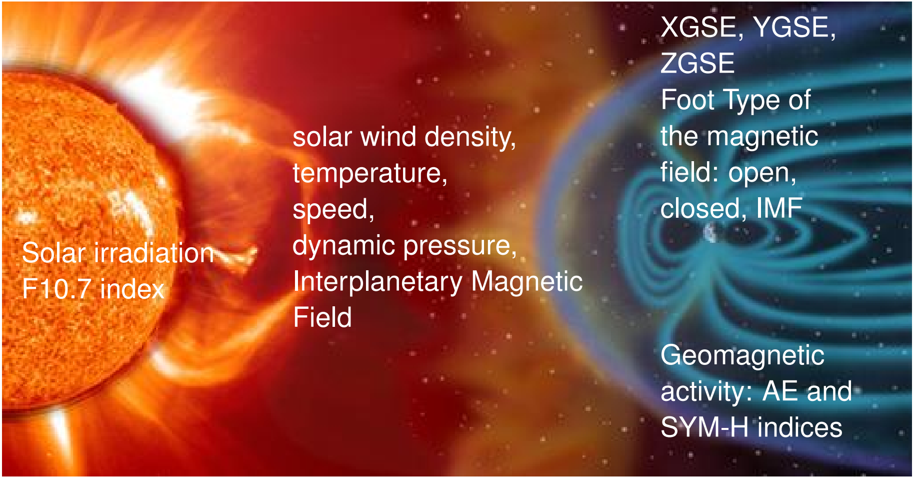


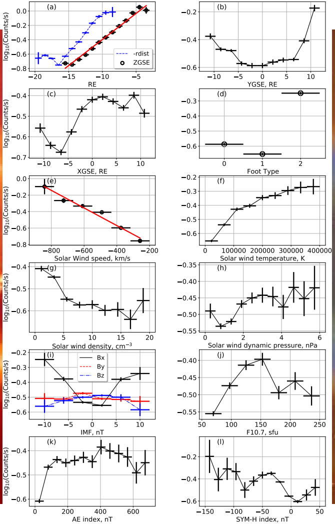
Which parameters can affect the contamination?

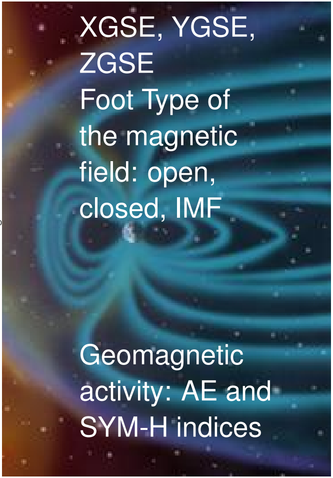


Which parameters can affect the contamination?



Some parameters may have complex non-linear relationships with contamination (best linear CC: 35%)



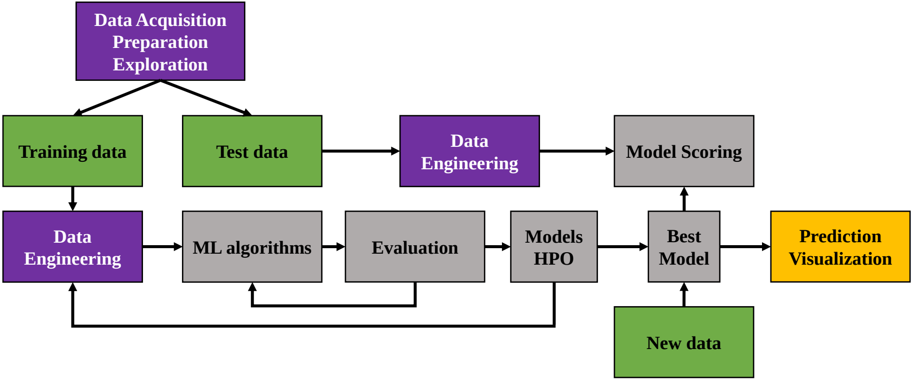


To predict the contamination using regression we decided to use Machine Learning (ML)

Prof. Raluca Ilie

Dr. Max Berrendorf

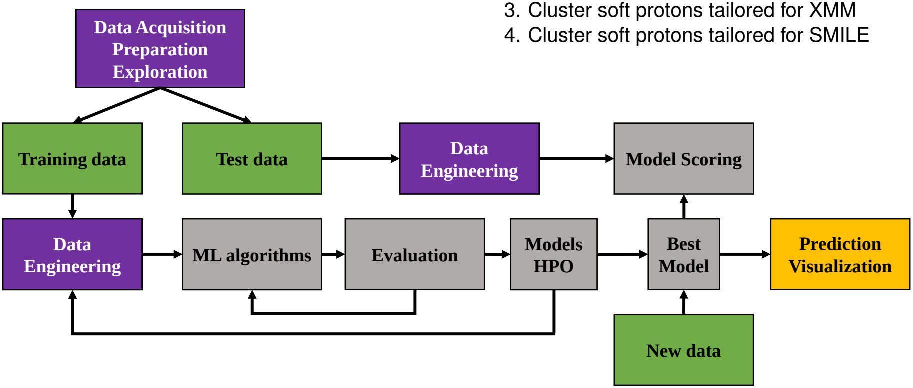
Machine Learning pipeline



Machine Learning pipeline

Models we developed for:

1. XMM soft proton contamination
2. Cluster soft protons
3. Cluster soft protons tailored for XMM
4. Cluster soft protons tailored for SMILE



1. We predict the contamination using location, solar and geomagnetic parameters by regression

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Extra-Trees Regressor

Gradient Boosting

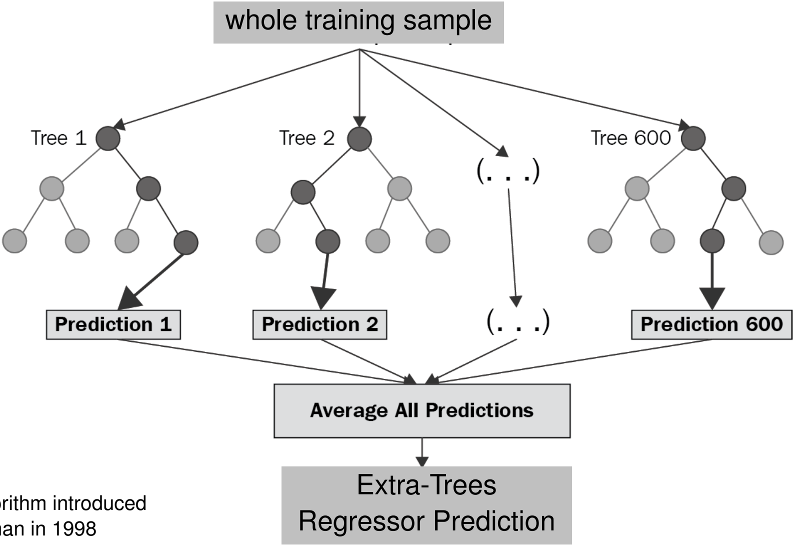
Stochastic Gradient Descent

Random Forest

Multi-layer Perseptron

1. We predict the contamination using location, solar and geomagnetic parameters by regression

1. Extra-Trees Regressor: each tree is trained using a randomly chosen set of predictors and top-down splitting



The algorithm introduced
by Breiman in 1998

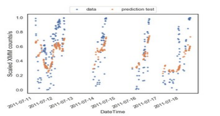
1. Schema of the model for XMM contamination

In total 707,330 minutes of data
for training and validation 2001–2010
for testing 2011–2012

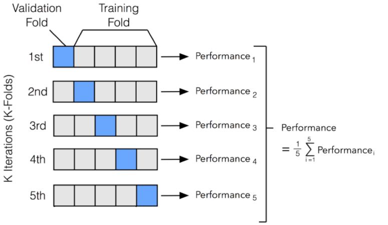
Predictors:
location
solar wind
geomagnetic conditions
XMM contamination count rates
~10 years of data

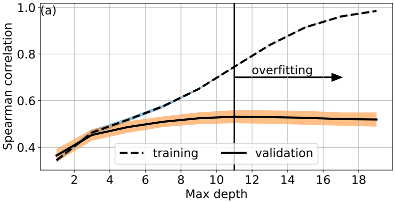
ML Model:
Extra-Trees Regressor

Prediction Model



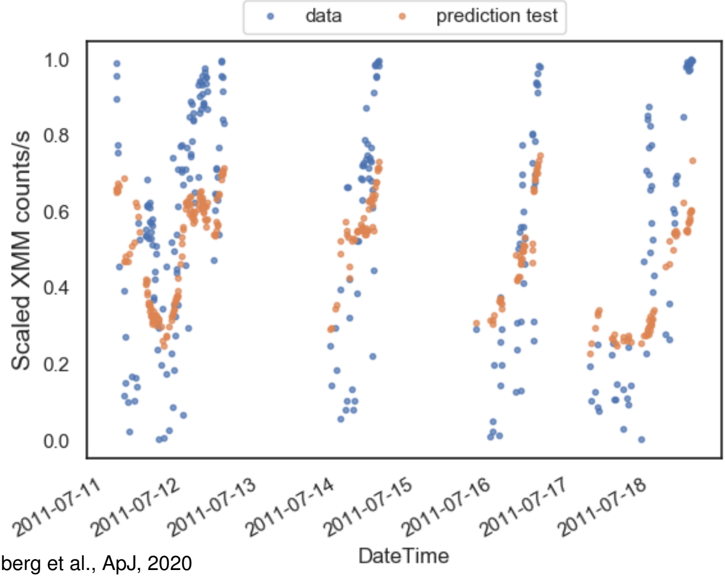
~2 years of test data





Kronberg et al., ApJ, 2020

Spearman CC: Extra-Trees Regressor $\simeq$48% vs. baseline $\simeq$35%



Kronberg et al., ApJ, 2020

1. Performance compared to those by ChatGPT (20–40%)

Jetzt spricht die Wundermaschine über Bayern

Der Textroboter ChatGPT ist die heißeste Erfindung des Jahres – wir haben ein Interview mit ihm geführt

Es kann Referate schreiben, Gedichte und vielleicht sogar Doktortitel erschummeln. Das Programm ChatGPT ist erst seit Kurzem auf dem Markt. Aber jetzt ist schon klar: Derartige Chatbots mit künstlicher Intelligenz werden unseren Alltag massiv verändern. Wir haben mit ChatGPT ein Interview über unsere Heimat geführt. Ergebnis: Bayern ist noch ein relativ blinder Fleck für die Wundermaschine. Aber lesen Sie selbst. Manche Antworten sind gekürzt.

Nennen Sie fünf berühmte Bayern, die das Land besser gemacht haben?

1. Konrad Adenauer, ehemaliger Bundeskanzler der Bundesrepublik Deutschland
2. Helmut Schmidt, ehemaliger Bundeskanzler der Bundesrepublik Deutschland
3. Franz Josef Strauß, ehemaliger Ministerpräsident von Bayern und Bundesverteidigungsminister
4. Thomas Mann, Nobelpreisträger für Literatur und einflussreicher Schriftsteller
5. Kurt von Schleicher, ehemaliger Reichskanzler.

„Es tut mir leid, dass ich Markus Söder, den aktuellen Ministerpräsidenten

Puh. Sie haben keinen guten Tag. Adenauer stammt aus Köln. Schmidt aus Hamburg. Kurt von Schleicher war letzter Reichskanzler der Weimarer Republik, aber kein Bayer.

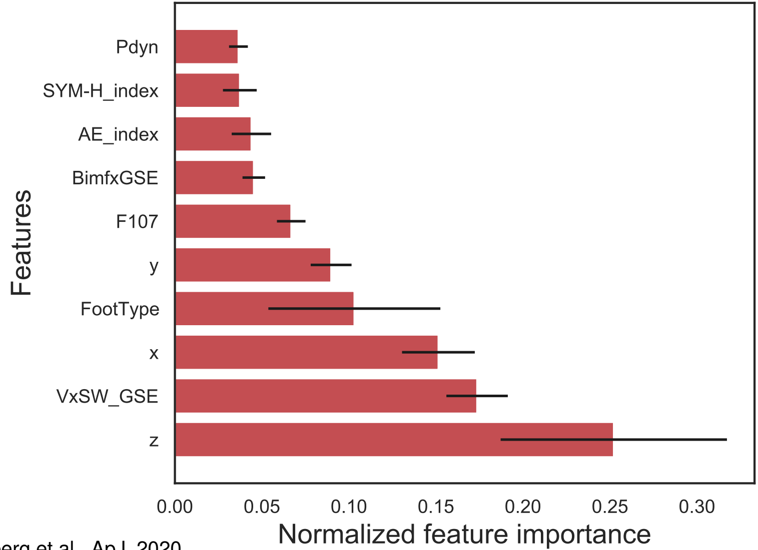
Es tut mir leid für die Fehler. Hier sind fünf berühmte Persönlichkeiten, die tatsächlich aus Bayern stammen und das Land positiv beeinflusst haben: 1. Gustav Mahler. 2. Albert Einstein. 3. Günter Grass. 4. Pope Benedict XVI (Joseph Ratzinger). 5. Karl Valentin.

Jessasmaria.

Es tut mir sehr leid, dass ich Sie enttäuscht habe. Wenn Sie weitere Fragen haben, stehe ich gerne zur Verfügung.

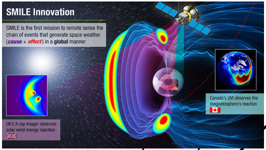
Münchner Merkur

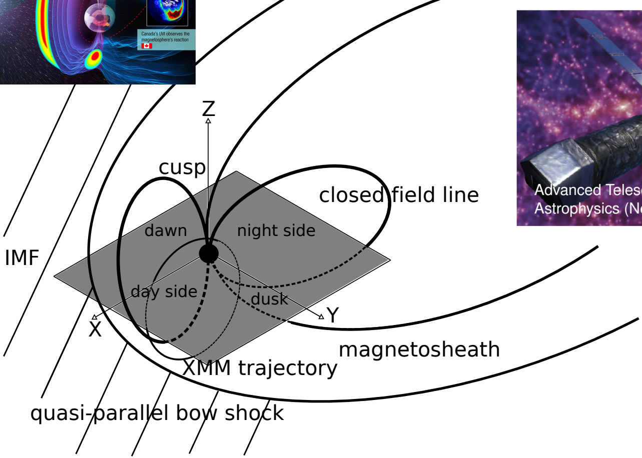
1. Results: the most important predictors are location, magnetic field line topology and VxSW

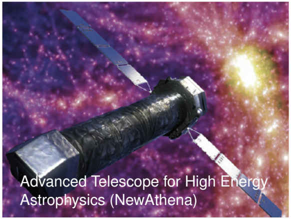


Kronberg et al., ApJ, 2020

1. Implications for future X-ray missions: should avoid closed magnetic field lines, especially at the dusk

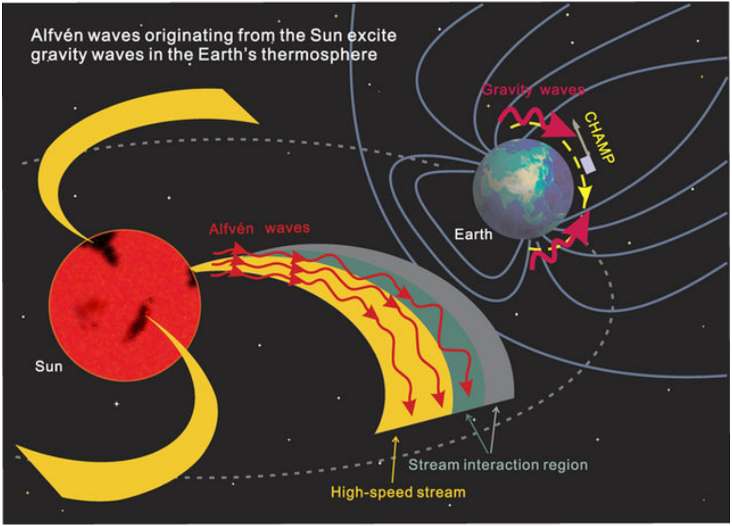






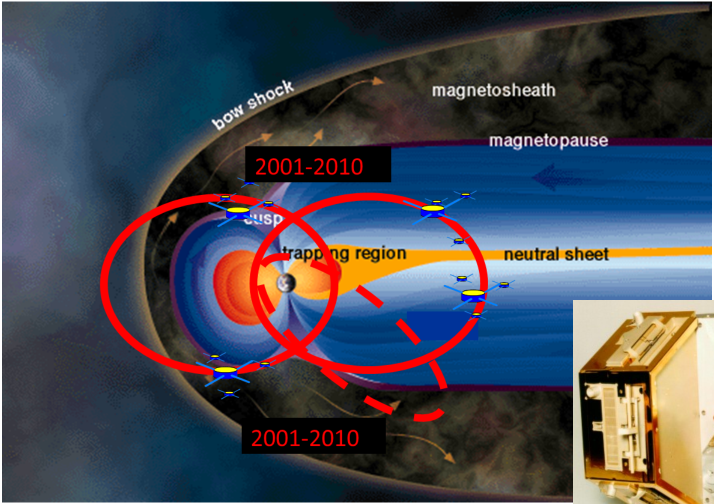
Kronberg et al., ApJ, 2020

1. Implications for future X-ray missions: should minimize observations associated with high solar wind speed

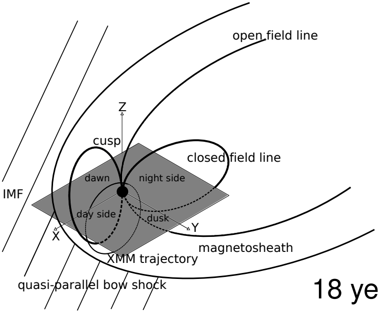


Credit: Xueshang Feng

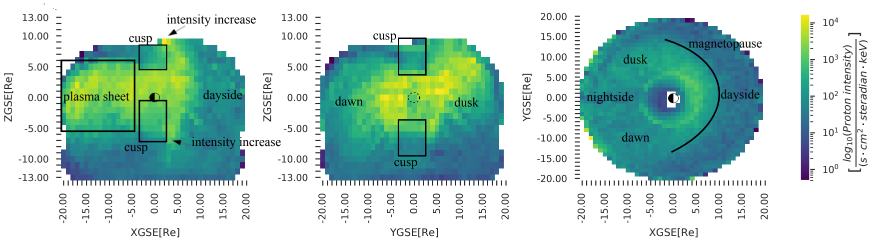
2. Next step: investigate the dynamics of protons using CLUSTER mission



particle detector RAPID measures energies from 28 keV to 4 MeV in 7 energy channels

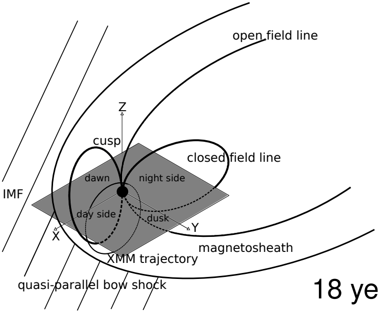


18 years of Cluster data from 2001 to 2018

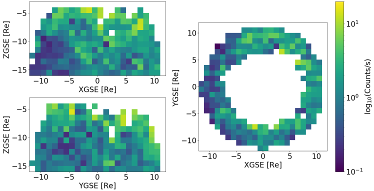


Kronberg et al., ApJ, 2020; 2021

2. Study of proton intensities in the magnetosphere



12 years of XMM data from 2001 to 2018



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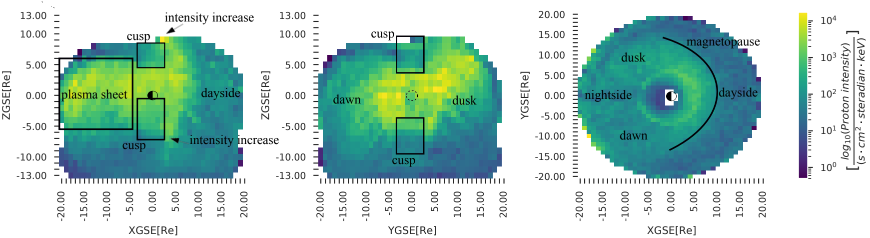
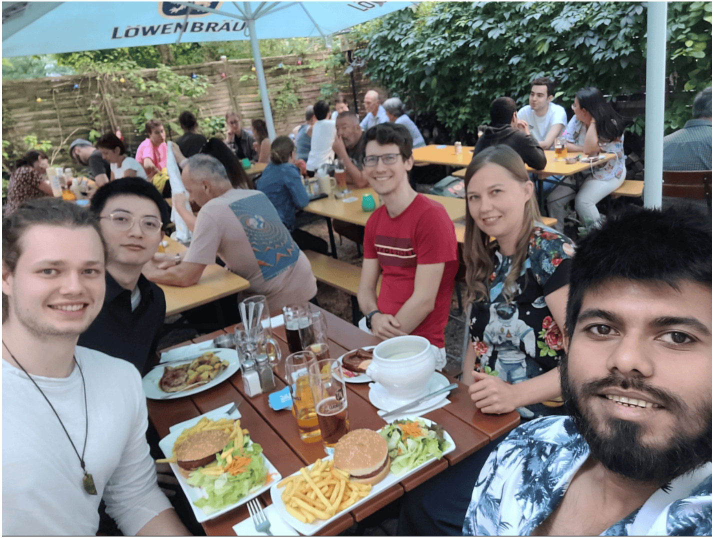


Kronberg et al., ApJ, 2020; 2021

2. ML Team: “Practical Big Data Science” course for Master students at the Institute of Informatics (LMU)



3 members are missing

2. We predict the proton intensities using location, solar and geomagnetic parameters by regression

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AdaBoost

Light Gradient Boosting Machines

Multi-layer Perceptron

Lasso LARS Regression

Linear Support Vector Regression

Ridge Regression

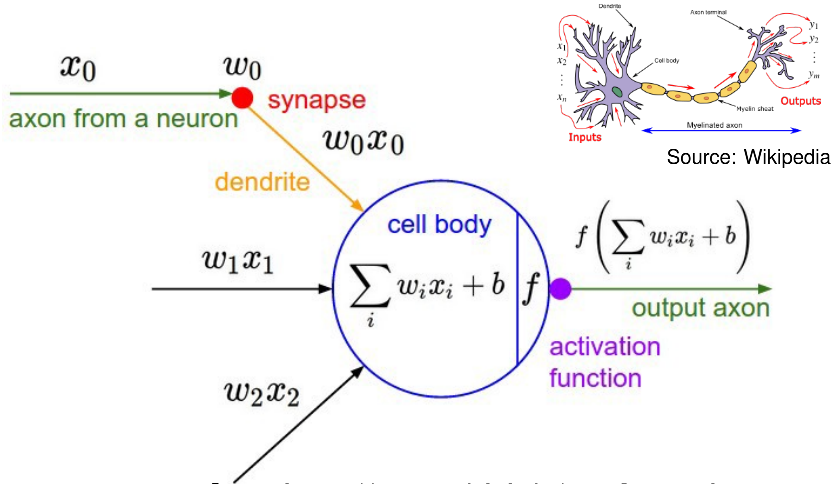
Extra-Trees

Random Forest

2. We predict the proton intensities using location, solar and geomagnetic parameters by regression

2. The perceptron

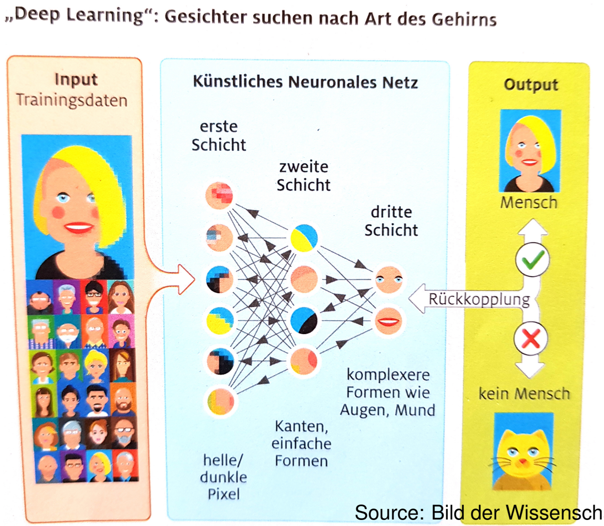
- An artificial neuron invented by Frank Rosenblatt in 1957



Source: `https://cs231n.github.io/neural-networks-1`

2. Multilayer perceptron (MLP)

- An MLP is composed of an *input layer*, multiple layers of perceptrons called *hidden layers* and an *output layer*.



Source: Bild der Wissenschaft

2. Schema of the model of soft proton intensities

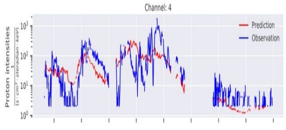
In total 6,051,937 minutes of data
for training (2001–2011), validation (2011–2014), testing (2014–2018)
Spearman Correlation: $\sim$54%
. . . for baseline (HistBin): 40%

Predictors:
location
solar wind
geomagnetic conditions

Target values: Cluster proton intensities
~14 years of data
(training and validation)

ML Model:
Multilayer Perceptron Regression

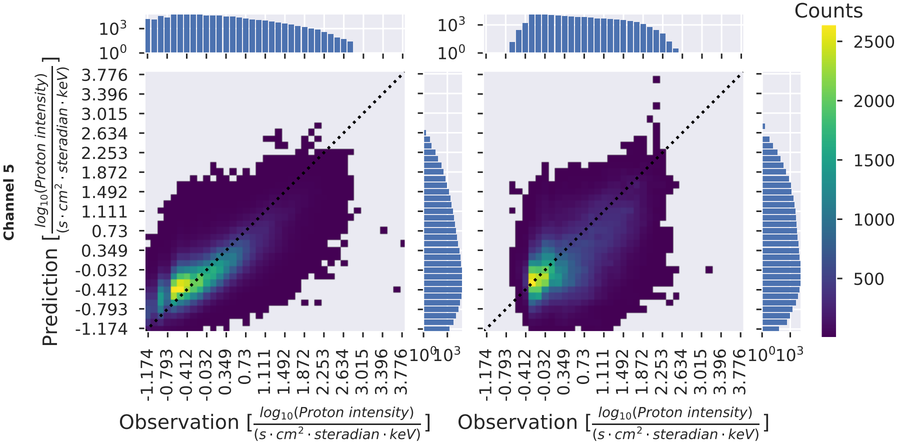
Prediction Model



~4 years of test data

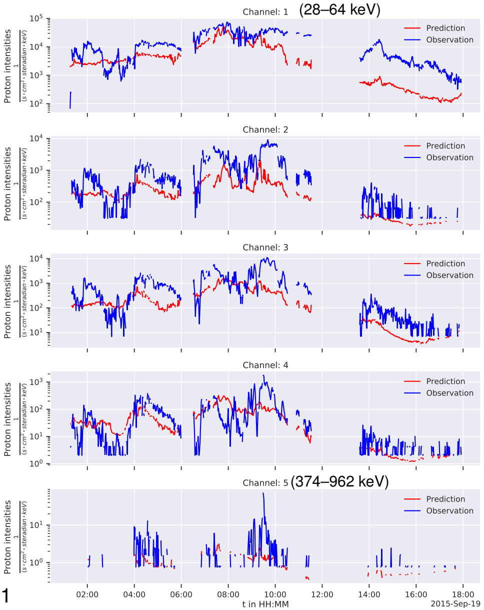
Training data, ch5 (374–962 keV)
Spearman Correlation: 75%

Test data, ch5 (374–962 keV)
Spearman Correlation: 54%
. . . for baseline (HistBin): 40%



Kronberg et al., ApJ, 2021

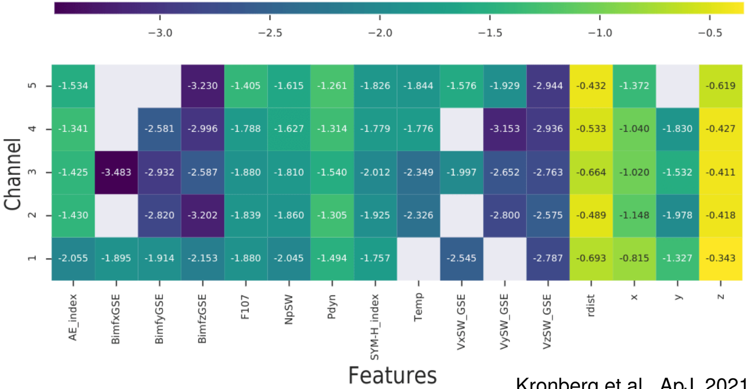
2. Observed vs predicted values of proton intensities



Kronberg et al., ApJ, 2021

2. Features important for prediction of proton intensities

- Strong dependence on ZGSE and radial distance
- Solar wind dynamic pressure and AE index (substorm and auroral activity) are the most important predictors



Kronberg et al., ApJ, 2021

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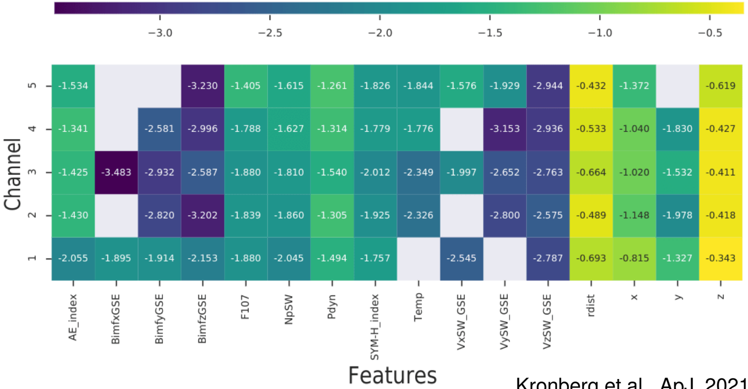
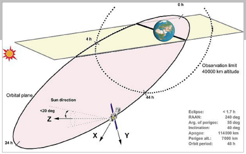


Kronberg et al., ApJ, 2021

The results are in general agreement with characteristics of the soft proton contamination observed by XMM

3. Prediction of XMM contamination using Cluster proton model tailored for XMM



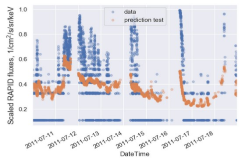
- Using Kronberg et al., 2021 model we did not find any correlation with XMM contamination
- Alexandra Hardt, a Bachelor Student from LMU/Geophysics, used the same data span as for XMM: 2001–2012
- In total 990,556 minutes of data for proton intensities for training and validation (2001–2009) and testing (2010–2012)

Spearman correlation for the test data: 53%

Predictors:
location
solar wind
geomagnetic conditions
Cluster proton intensities
~9 years of data
(training and validation)

ML Model:
Extra Random Forest Regression

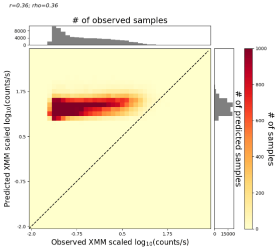
Prediction Model



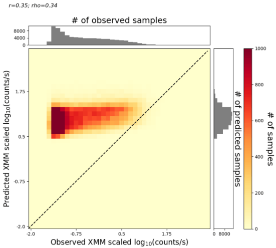
~3 years of test data

3. Correlation of the Cluster model results with the contamination along the XMM trajectory

28–64 keV



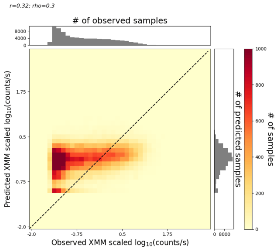
(a) Channel 1



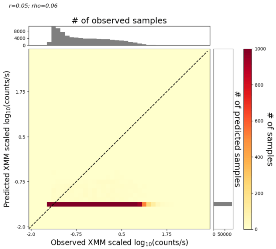
(b) Channel 2

75–92 keV

92–160 keV



(c) Channel 3

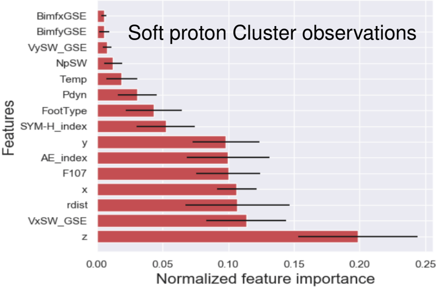


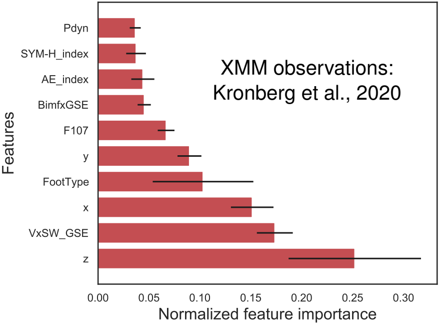
(d) Channel 4

160–374 keV

3. Preliminary results: proton intensities at 92–160 keV correlate the best with the XMM contamination

Spearman correlation: 32% and similar feature importances

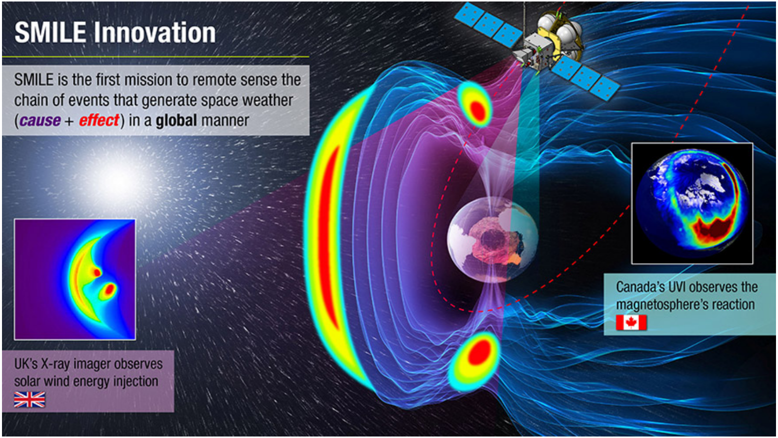


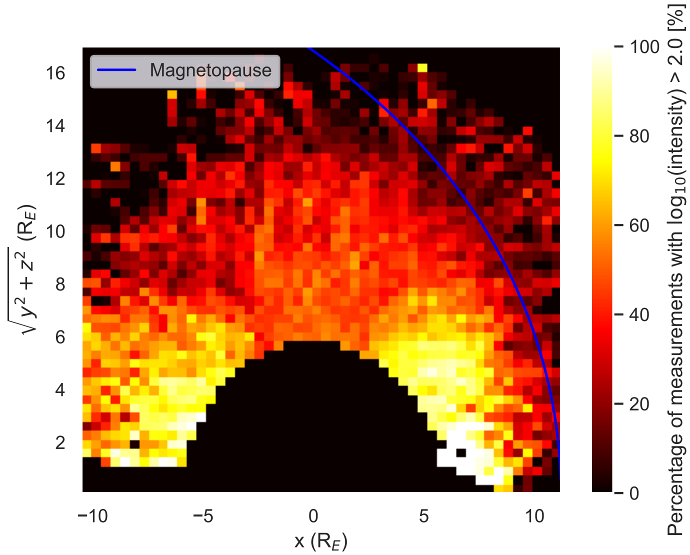


Predictions by Chandra team, Kolodziejczak et al., 2000 are 100–300 keV and by XMM team, Fioretti et al., 2016 are 30–70 keV

4. X-Ray observations by the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) mission may also be affected by soft protons

- Simon Mischel, a Master student, has derived a preliminary model tailored for the SMILE mission to assess the level of proton intensities





Mischel et al., submitted to Space Weather

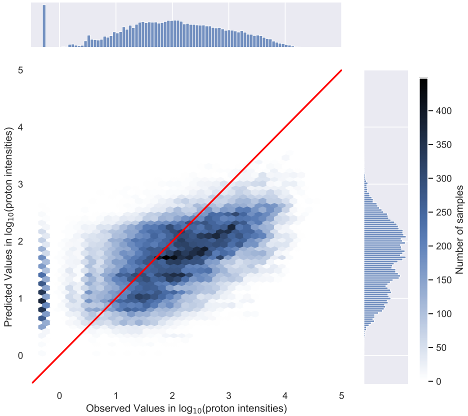
4. Linear regression model

$$\log(Int_{ch3}) = 1.29\times10^{-1}\cdot y - 3.3\times10^{-1}\cdot|z| - 1.12\times10^{-1}\cdot \text{rdist}$$
$$+2.49\times10^{-1}\cdot \text{FootType} - 2.23\times10^{-1}\cdot \text{VxSW\_GSE}$$
$$+7.78\times10^{-2}\cdot \text{Pdyn} - 4.08\times10^{-2}\cdot \text{F10.7}$$
$$+8.78\times10^{-2}\cdot \text{AE\_index} + 6.16\times10^{-2}\cdot x\cdot|z|$$
$$+1.11\times10^{-1}\cdot|z|\cdot \text{rdist} - 1.41\times10^{-1}\cdot \text{rdist}\cdot \text{FootType}$$
$$+9.69\times10^{-2}\cdot \text{rdist}\cdot \text{F10.7} - 9.3\times10^{-2}\cdot \text{F10.7}^2$$
$$+1.68$$

- 13 predictors, including polynomial and interaction terms

4. Observed vs predicted values of proton intensities

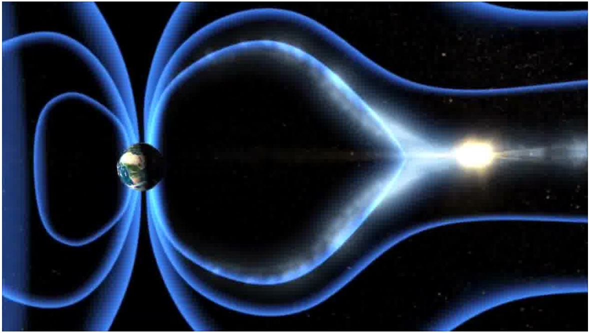
- In total 462,615 minutes of data
  for training and validation (2001-2012) and testing (2013-2015)
- Spearman Correlation on test data: 57% vs 43% baseline



Mischel et al., submitted to Space Weather

Conclusions and outlook

- Message for future observations: avoid closed magnetic field lines and fast solar wind
- $\sim$100 keV protons show the best correlation with the contamination
- It is possible to build XMM-tailored model for protons.
- XMM can be used to detect protons (Fioretti et al., 2024, Mineo et al., in prep). The Cluster-based models can be used for verification.



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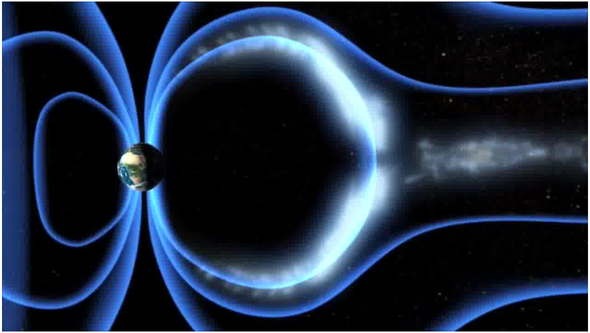

Imaging Ion Mass Spectrometer (IIMS): principles of work

- Time-of-flight and energy measurement
- Determination of velocity and energy allows to define mass
- Energy is measured at 7 channels: ch1=28–64 keV, ch2=75–92 keV, ch3=92–160 keV, ch4=160–374 keV, ch5=374–962 keV, ch6=962–1885 keV, ch7=1885–4007 keV