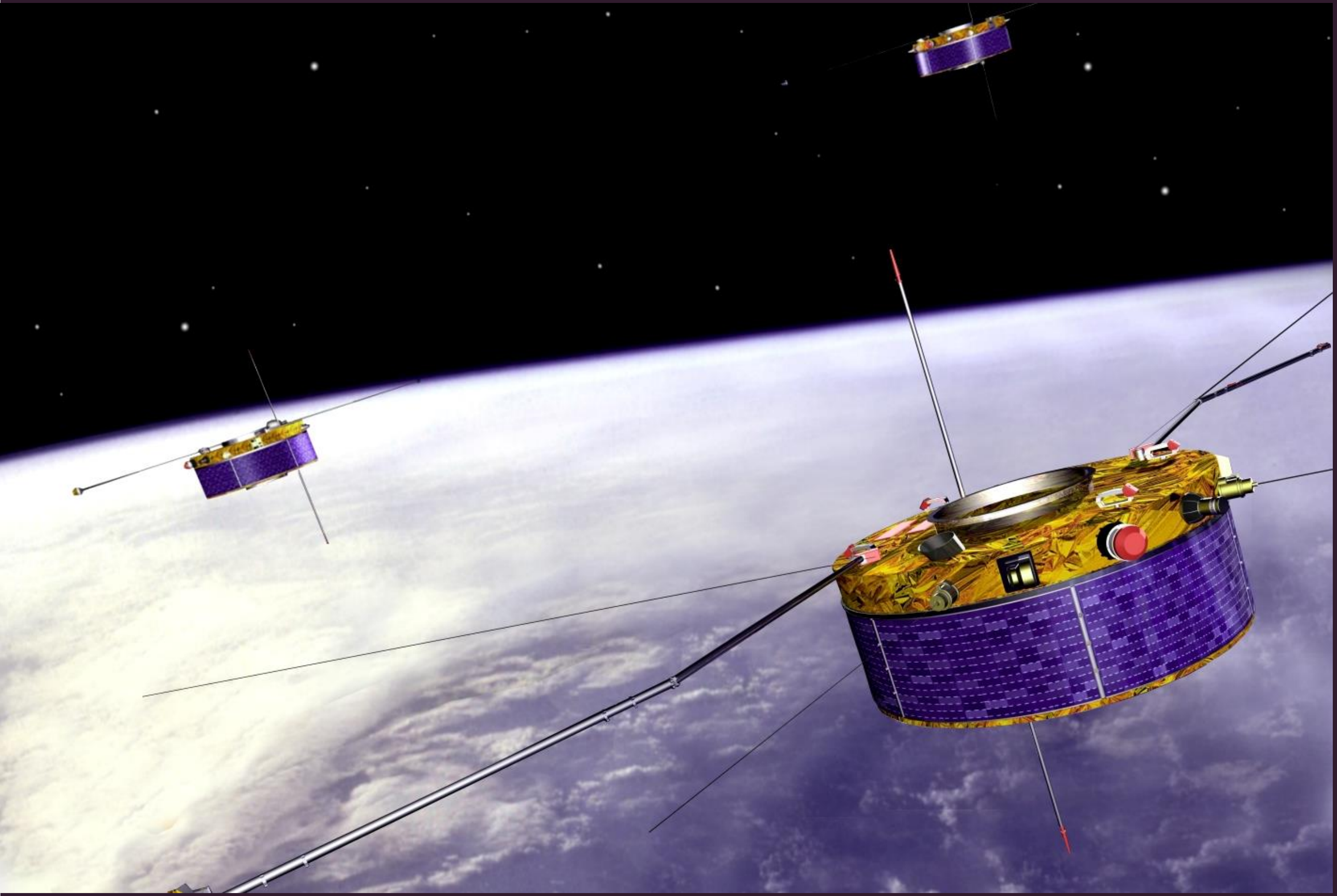


Image source: ESA 2015

Simulating solar cell degradation from proton flux during major solar storms

Vili-Arttu Ketola
vili-arttu.ketola@helsinki.fi

30 January 2024

Magnetosphere Interactions

4 slides

Outline

Solar wind fills radiation belt with more particles

- Protons dominate (inner) radiation belt particle energy
- Solar wind continuously supplies low-energy protons (100-200 keV)
- Solar storms produce MeV scale solar energetic particles
- High energy protons decay more slowly via Coulomb collisions
- Storms also change magnetosphere structure...

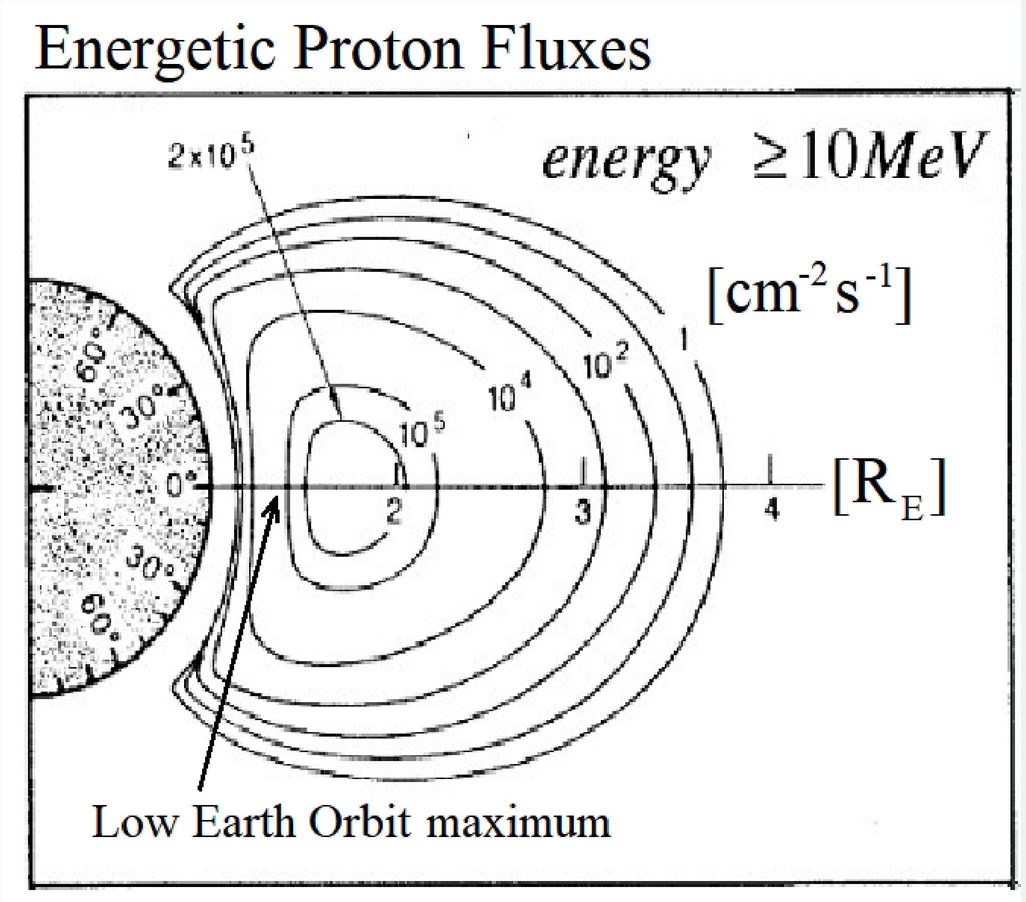


Image source: Koskinen 2011 (modified)

Largest solar storms in history are of interest

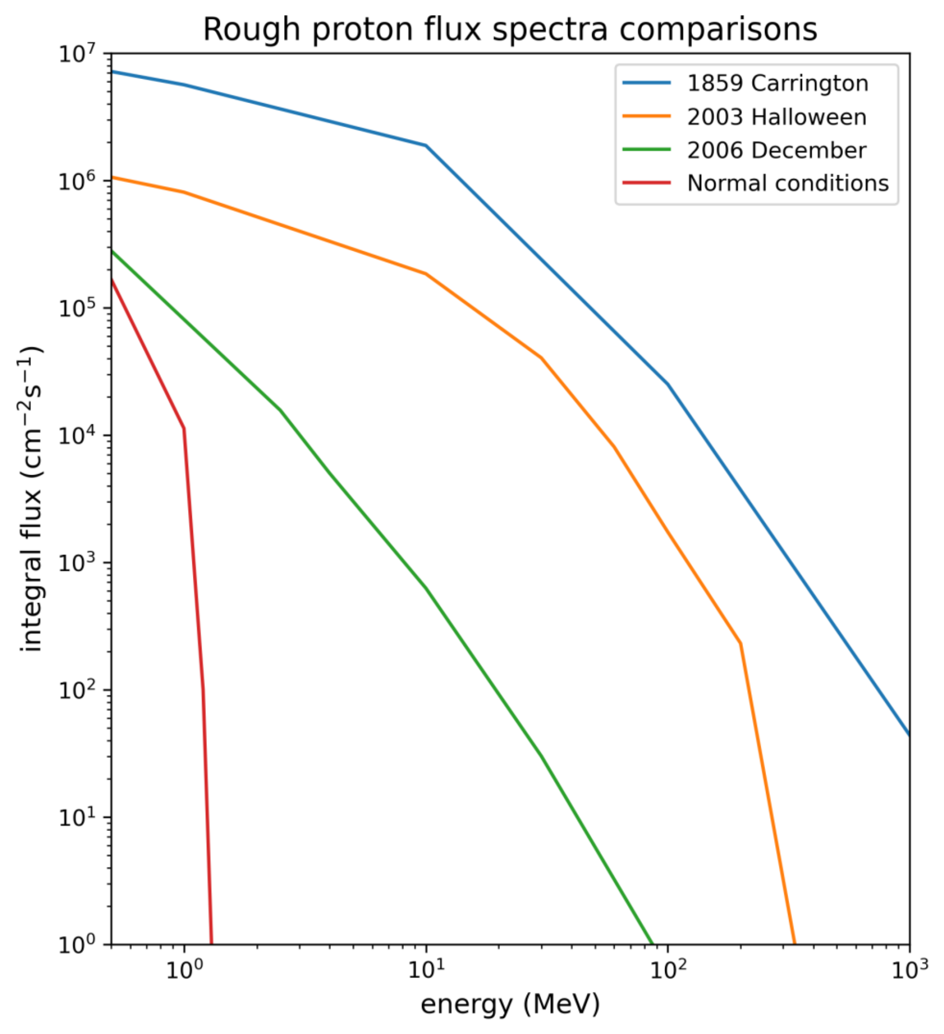
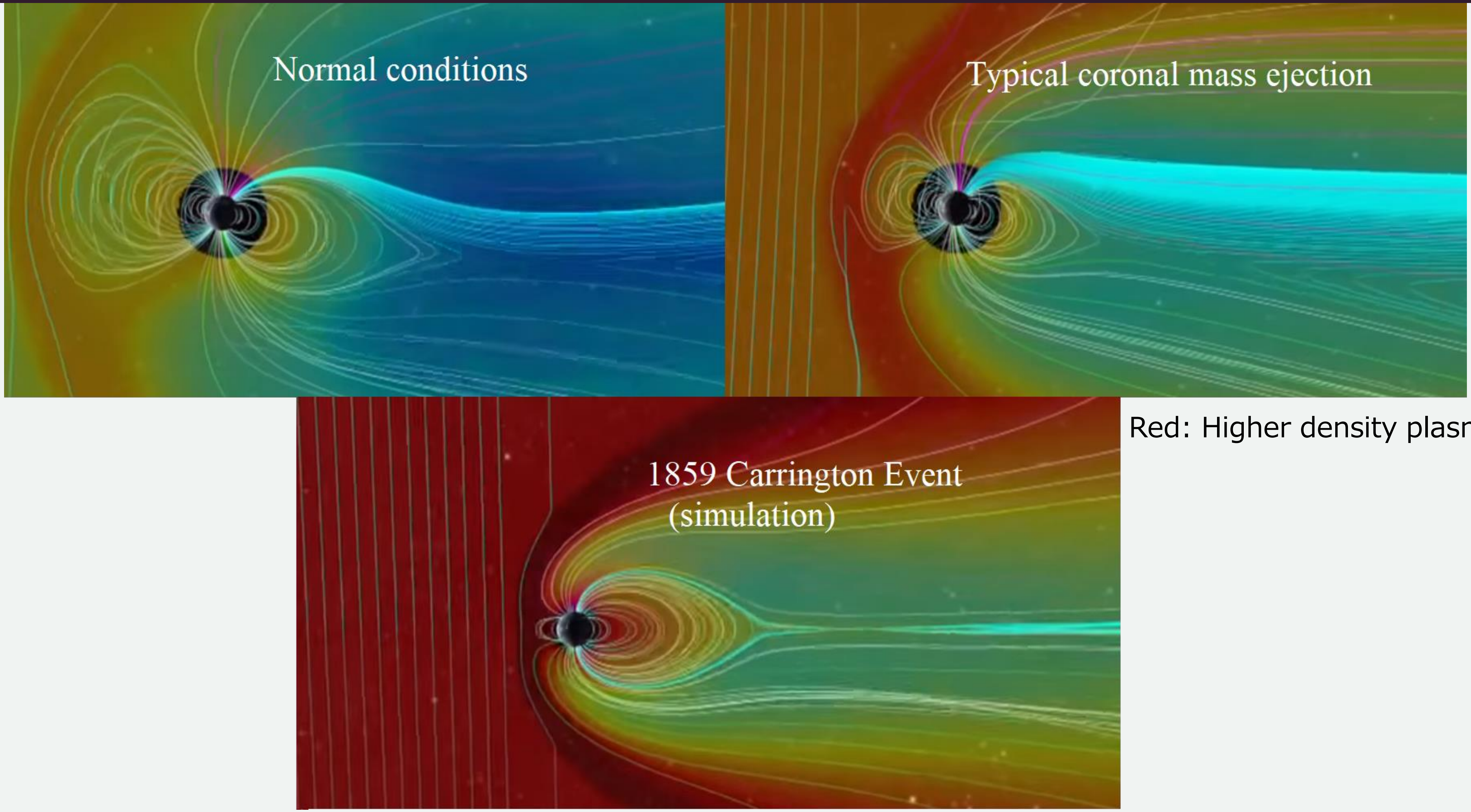


Image source: Ketola 2024

- **Solar flare discovery: 1859 Carrington Event seen in visible light**
- **2003 Halloween solar storms renewed interest in extreme events**
- **Solar storms cause magnetospheric storms and substorms**
- **Regular storms change the structure of the magnetic field**
- **Extreme storms “compress” field to inner magnetosphere and saturate with particles**

Carrington-like effect on magnetosphere structure



Red: Higher density plasma

Image source: VideoFromSpace 2014 (modified)

Radiation causes satellite anomalies

- Energetic particles cause damage via ionization, displacement, or activation
- Proton-induced displacement damage dose most significant for solar cells
- Forms gaps and interstitial particles in semiconductors, lowering efficiency
- Equivalent units only—measured in terms of non-ionizing energy loss
- Proton can also produce recoil atoms (1 MeV proton → 50 keV atoms)

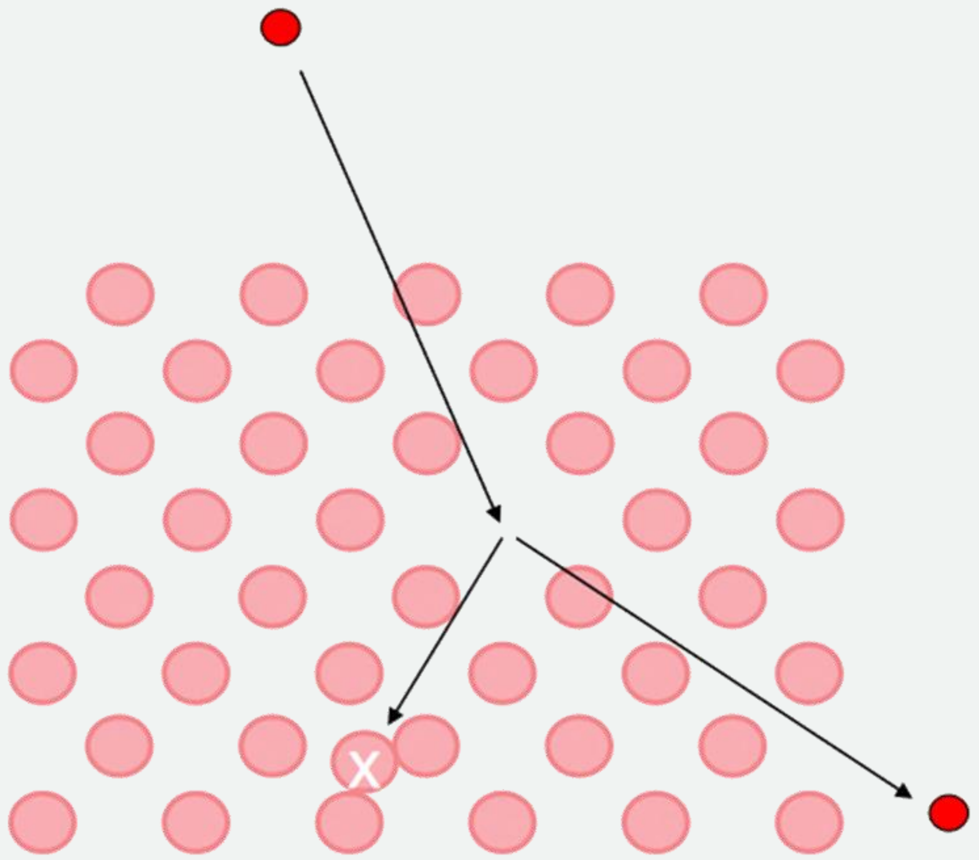


Image source: Fetzer 2023

Estimating and Simulating Extremes

3 slides

Extreme Value Theory gives fluxes

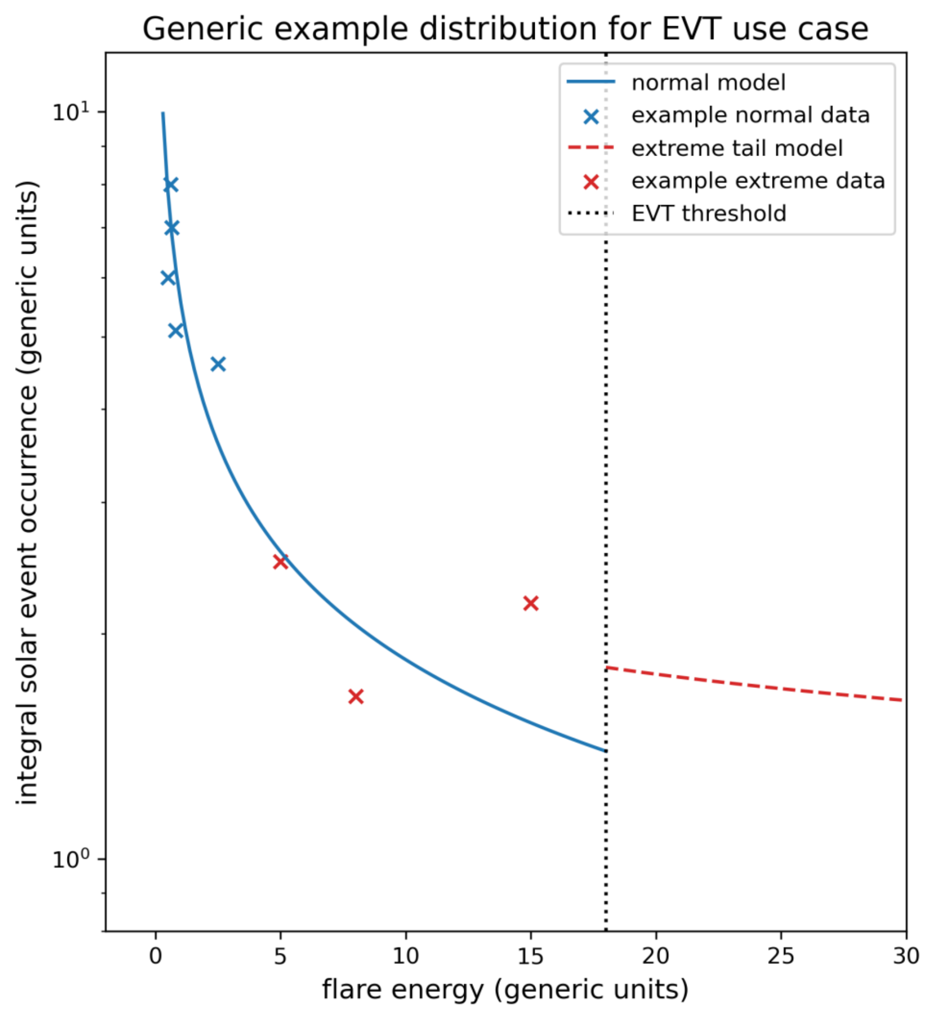


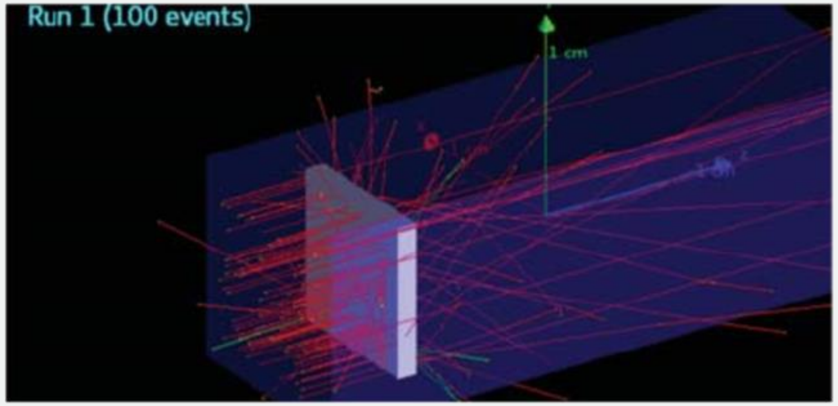
Image source: Ketola 2024

- Very few real measurements available, no data of extreme event energies
- Energy distributions fail at extreme tails. Usually modeled as power laws
- Distributions are not really Maxwellian → Hard to derive other moments
- 1. Central Limit Theorem → Independent samples look Gaussian eventually
- 2. Further theorems allow for sampling tails only above a threshold

Geant4-based simulations estimate damage

- **Geant4 particle passage simulation toolkit for large variety of applications**
- **MULASSIS interface Monte Carlo methods for solar cell damage simulation**
- **The code finds:**
  1. **Incident radiation spectra**
  2. **Attenuated spectra after shielding**
  3. **Displacement damage dose via non-ionizing energy loss**
  4. **Expected solar cell degradation**
- **Takes spectra and geometry/material info, returns particle damage and degradation**

Silicon wafer irradiation in Geant4



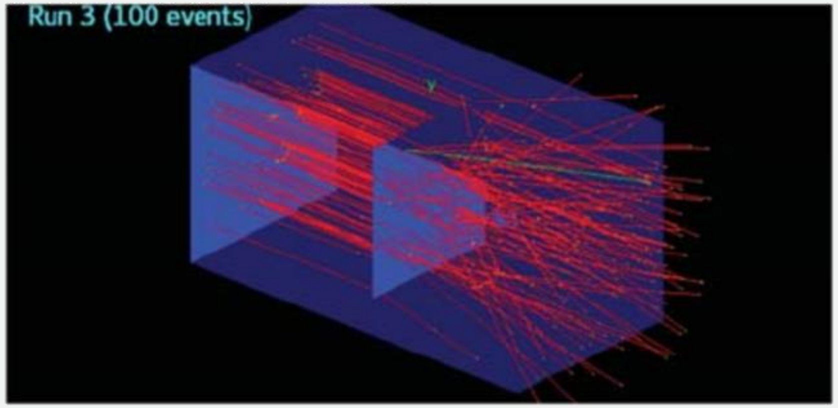


Image source: Fedoseyev 2020

Validation with a known modern storm

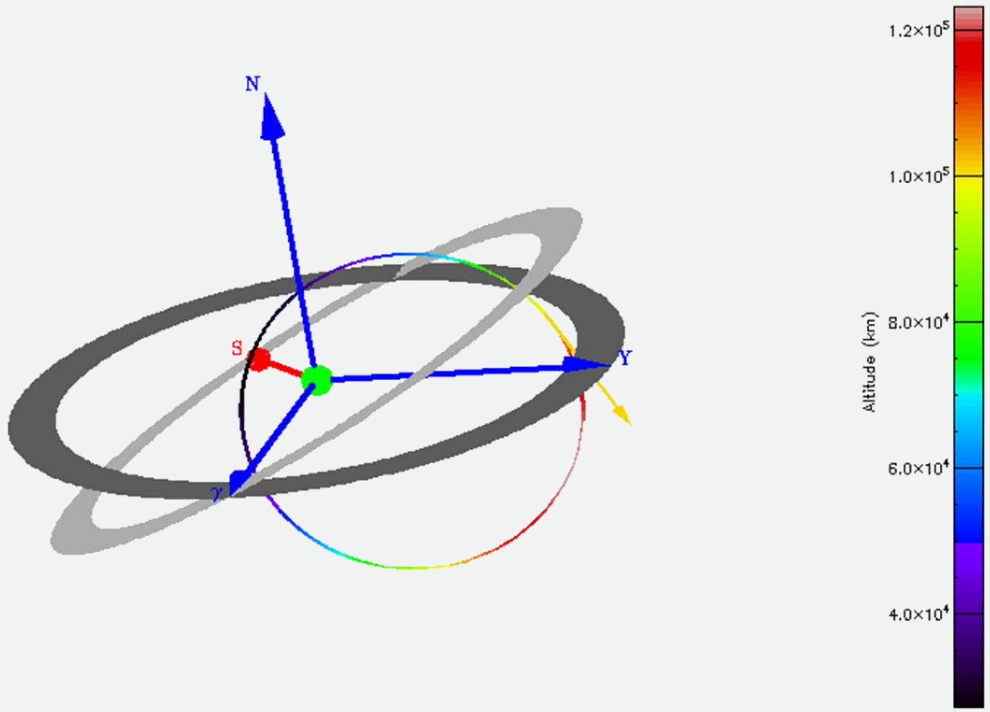


Image source: SPENVIS

- No proper Carrington data, validation would be helpful
- 2003 Halloween event: largest modern solar storm. Cluster-I-IV details known
- Radiation belt exposure time during storm calculated from orbit details
- Flux measurements from Cluster used and simulated against modeled solar cells
- Results compared to known power degradation value of 1.4%

Challenges: Assumptions Cause Problems

3 slides

Extreme Value Theory assumptions

- Independent events assumption questionable with slow flux decays
- Decay times can be calculated numerically with diffusion equations, or statistical methods like declustering
- Confidence intervals end up very large →
- Magnetosphere "condensed" means fluxes are not significantly spatially dependent
- Exposure time instead of specific orbits

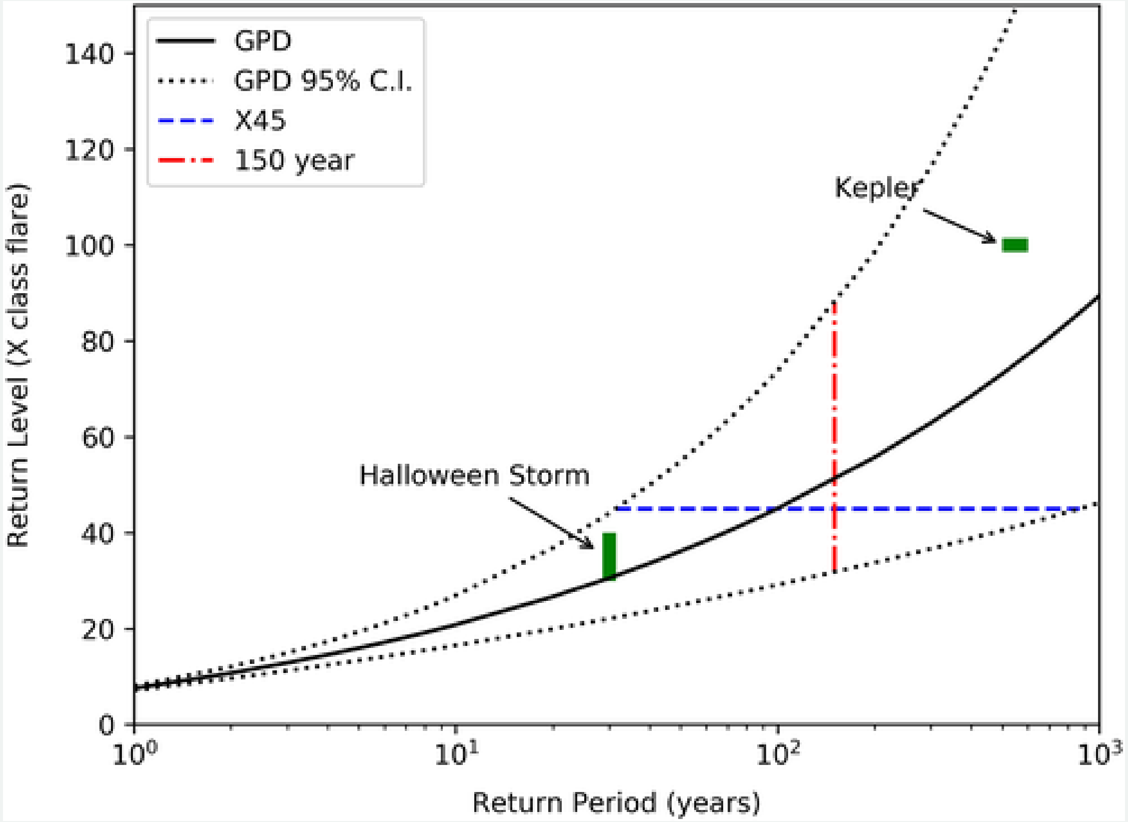


Image source: Elvidge and Angling 2018

How to model a solar cell?

- Way to model in geometry/material is really an open question
- Many solar cell types and shielding parameters etc.
- Important to make a model both simple and involved enough to cover most cases. Simple silicon/gallium-arsenide layer + shielding layer
- Another reason why validation is important
- Basic simulations only output damage. Calculating wattage loss is difficult...

The current-voltage-power problem

- Solar cell performance parameters:
  short-circuit current,
  open-circuit voltage,
  maximum voltage, current, and power
- Power has many factors: light, temp., voltage/current codependence, losses
- Maximum current → short circuit, no voltage, no power
- Maximum voltage → open circuit, no current, no power
- Calculating maximum power point and hence also power degradation is tricky

Silicon solar cell maximum power point tracking curves

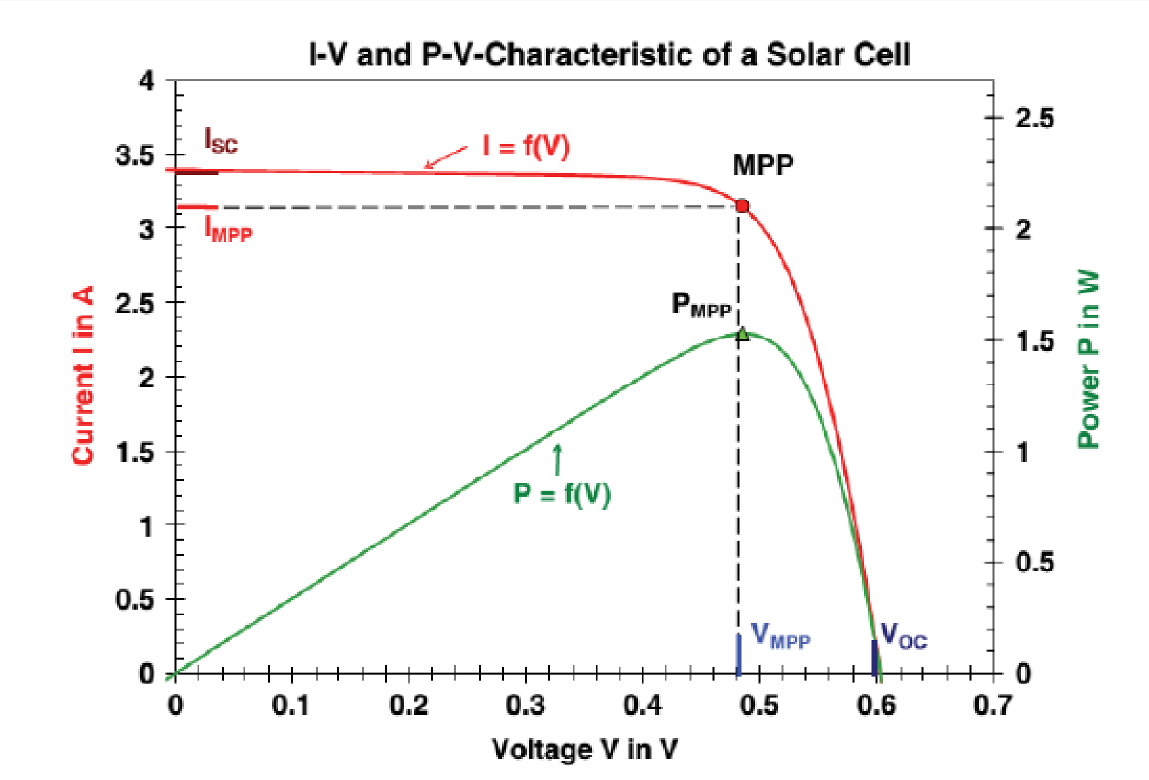


Image source: Hashim and Al-Khazzar 2015

Applications and Future Studies

2 slides

More practical applications

- Satellite manufacturers can take extreme events into consideration
- Mission expected end-of-life calculations
- Future studies on specific satellite data to estimate Carrington-like storm effects on their own orbit and solar cell properties
- Black swans and dragon king theory: Predicting extreme events is important

More theoretical applications

- Little known about Carrington-like events
- Practical applications help demystify them
- Future studies on modeling the Carrington event magnetosphere and effects
- Future studies on comparing multiple storms of different magnitudes

Thank You!