# Daring to think of the impossible: The story of Vlasiator

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Chair of Board, Technology Academy Finland

Read also: https://doi.org/10.3389/fspas.2022.952248

European Research Council erc

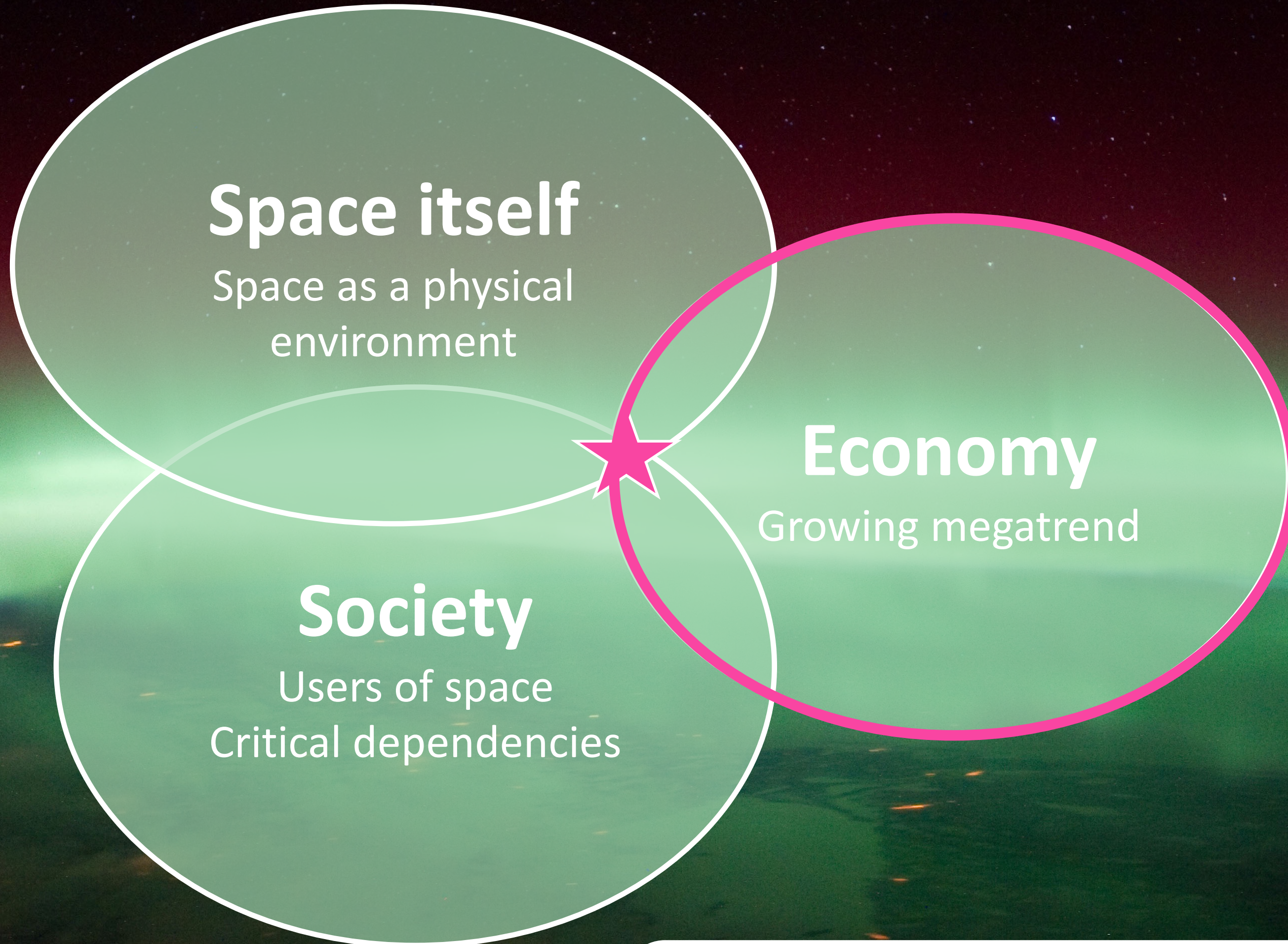
SUOMEN AKATEMIA
FINLANDS AKADEMI
ACADEMY OF FINLAND

CSC

PRACE

EuroHPC Joint Undertaking

# Context

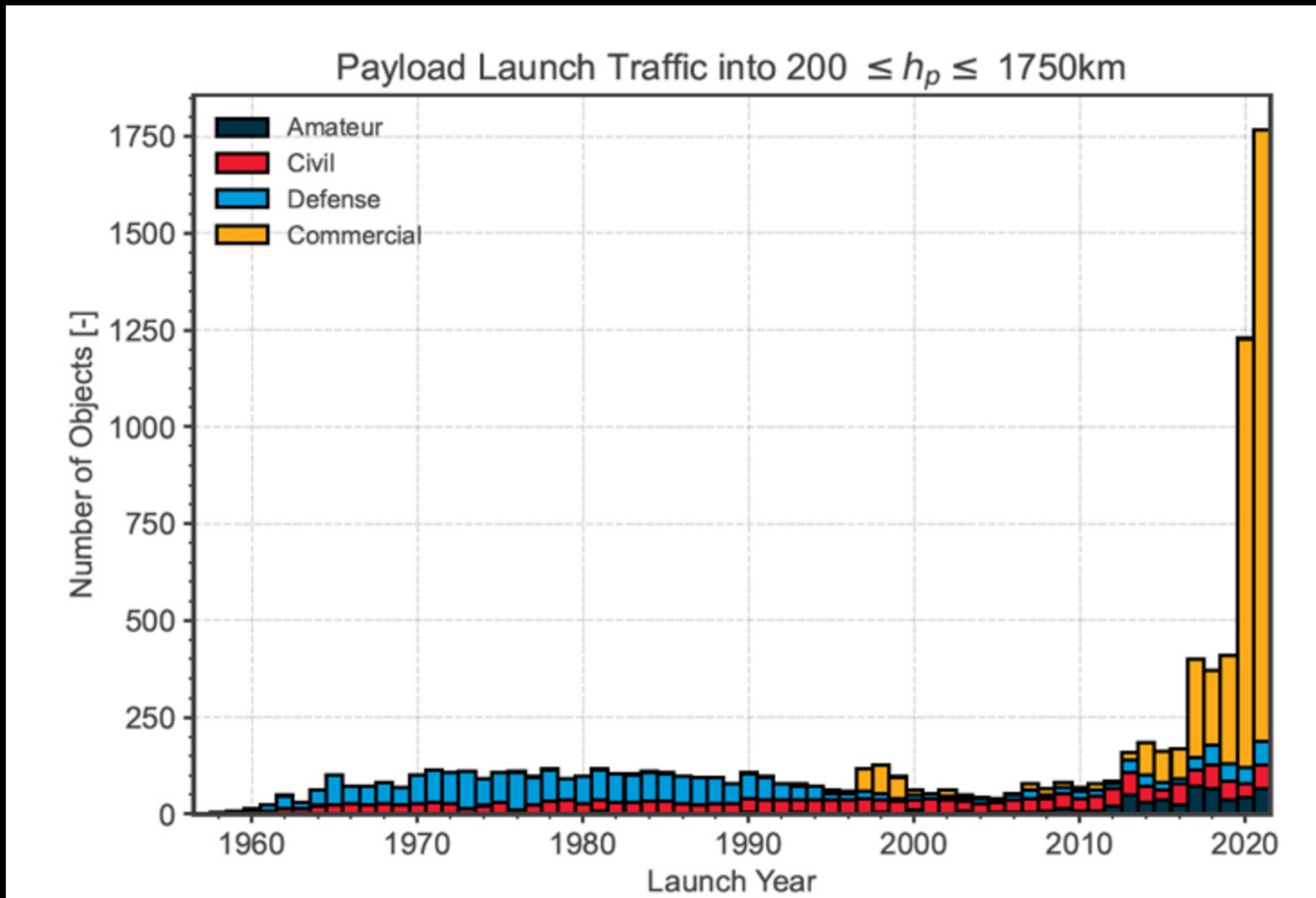



**Sustainability theory for the near-Earth space**

- Palmroth+ *Space Policy*, 2021
- Palmroth and Hukkinen, *in prep*

# Space is a megatrend

Number of all spacecraft *https://www.esa.int/Space_Safety/Space_Debris/ESA_s_Space_Environment_Report_2022*

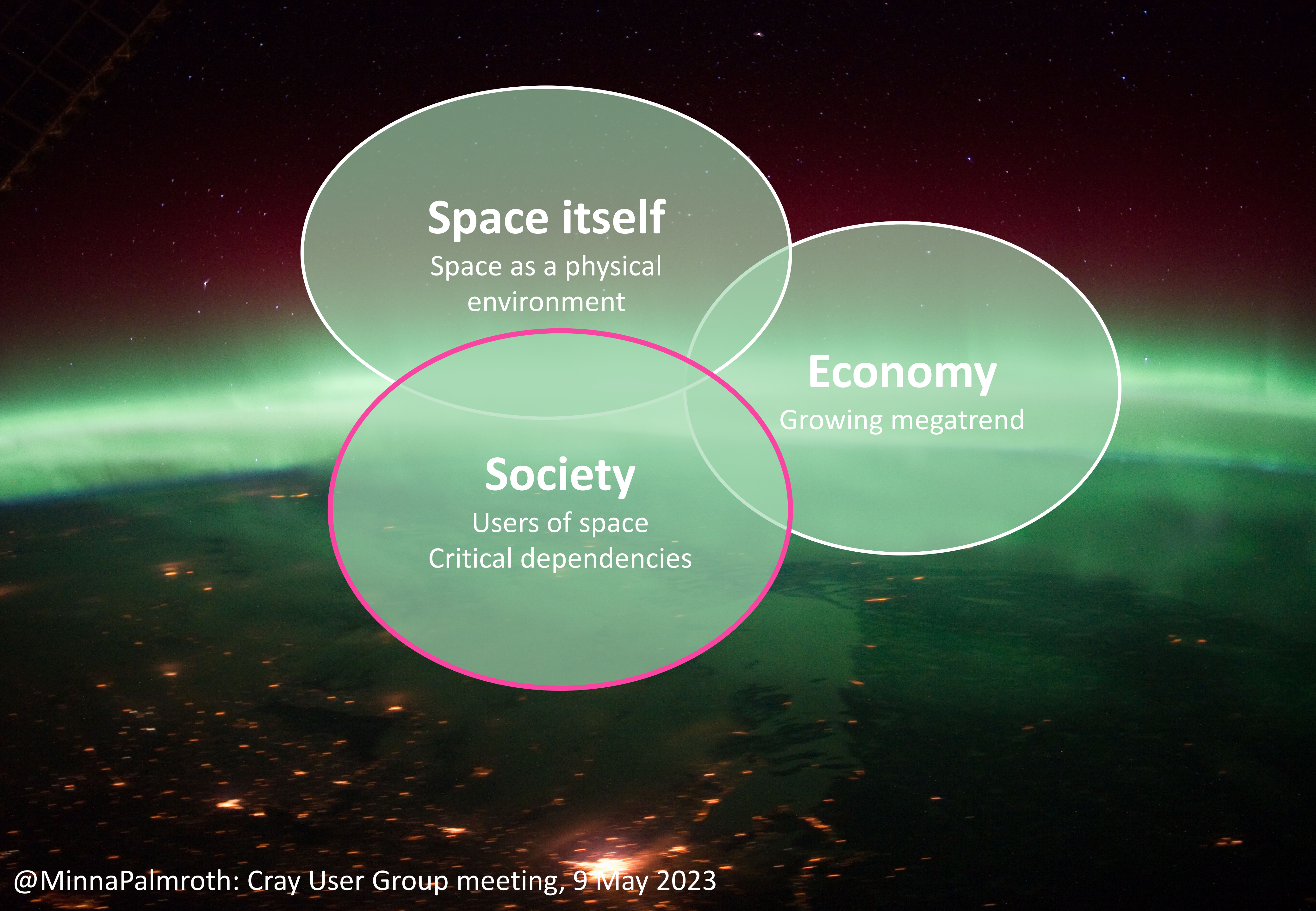



@MinnaPalmroth: Cray User Group meeting, 9 May 2023

# Space economy is growing

Investment banks predict that the global space economy, valued at about $469 billion in 2023, could grow to $1 trillion or more in the 2040s.

*Source: Space News, 5.7.2018: https://spacenews.com/a-trillion-dollar-space-industry-will-require-new-markets/*

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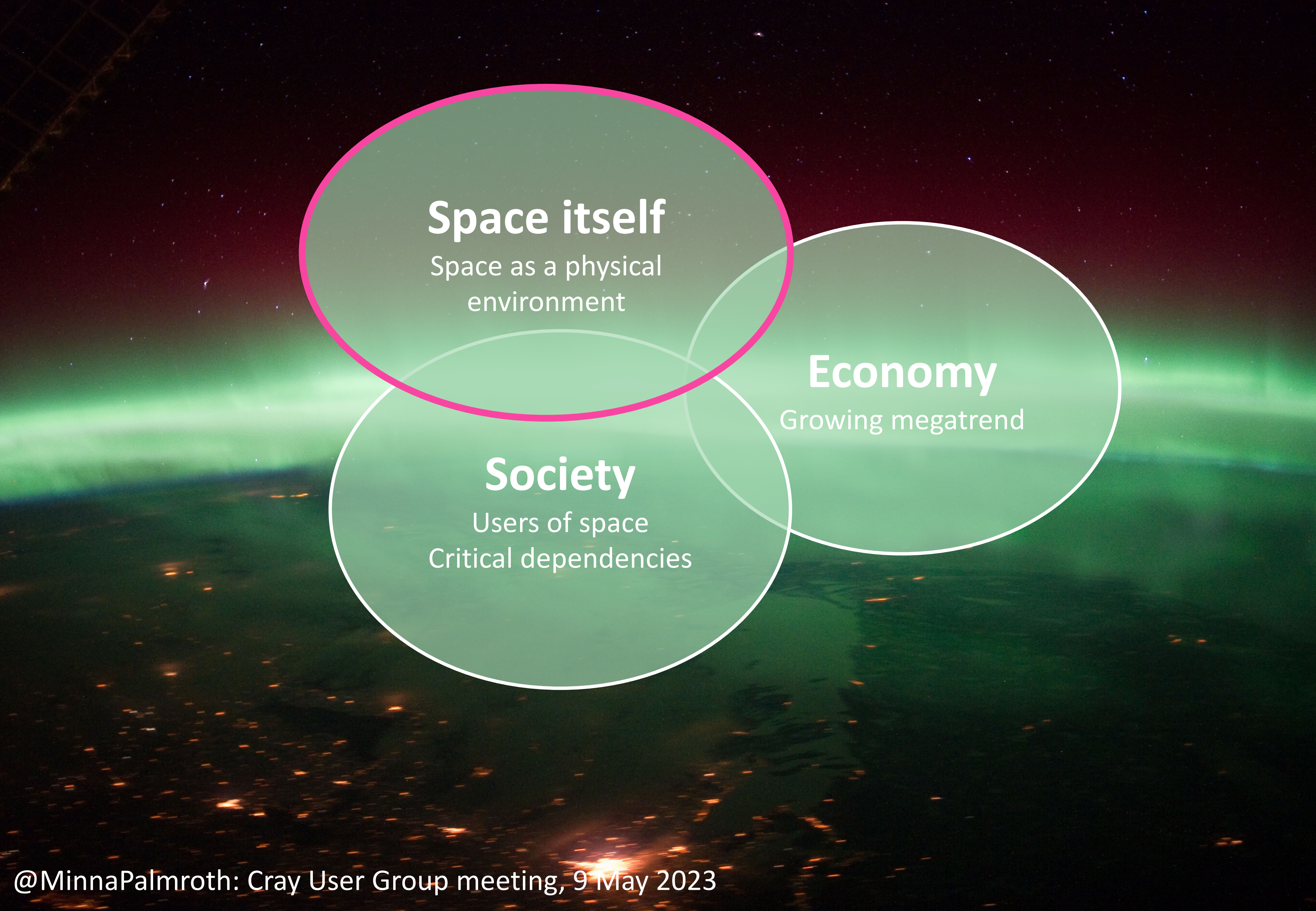
# Space is part of our life


**Applications depending on space**

- Positioning
- Navigation
- Timestamps
    - E.g., in banking and mobile networks
- Earth observation
- Weather forecasts
- Climate change monitoring
- Satellite TV and phone
- Military
- ETC!


Space itself
Space as a physical environment
Economy
Growing megatrend
Society
Users of space
Critical dependencies

# Conditions in space



Picture: NASA

# Space weather

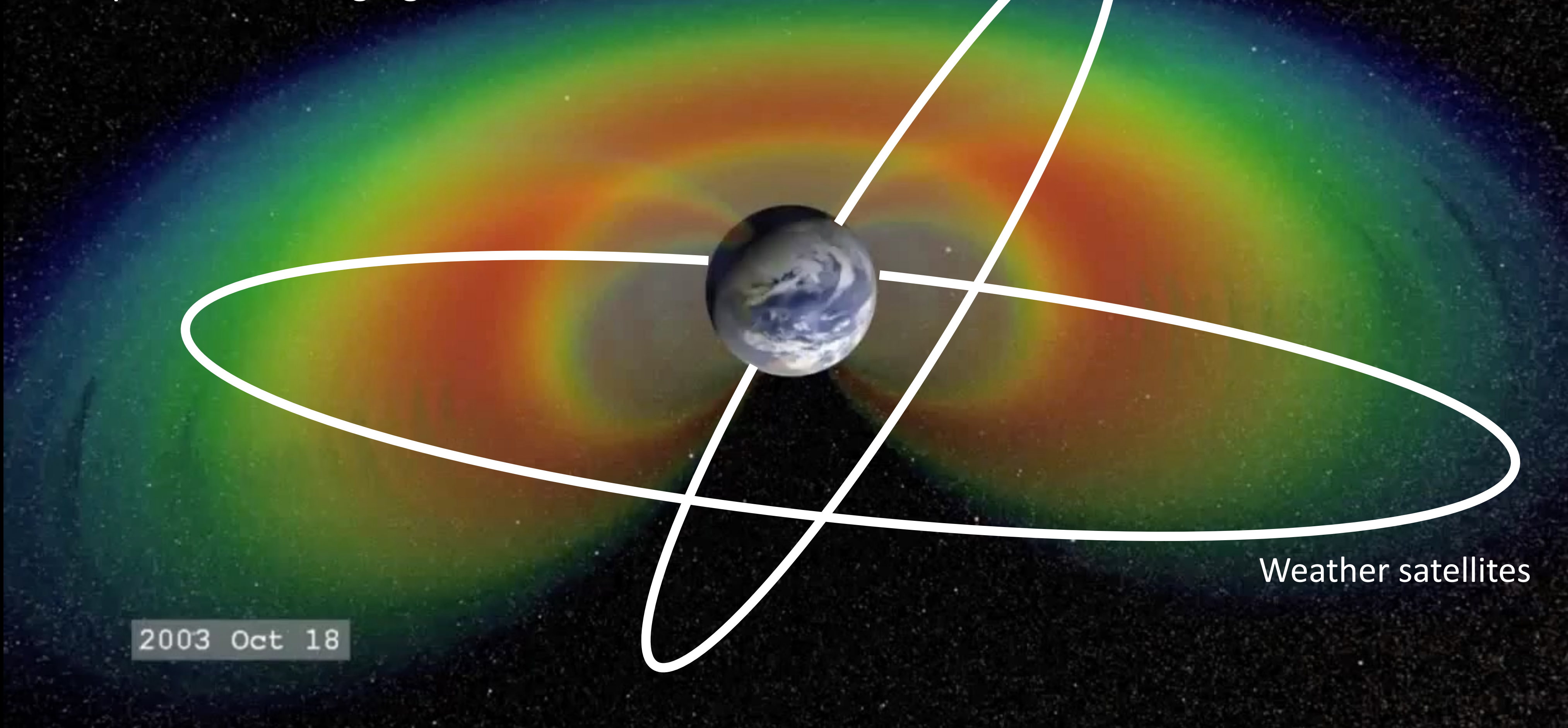
Conditions in near-Earth space which affect technological reliability or human health.

Very long list of phenomena. Highlighting just two from the perspective of the economic use of space.

Picture: NASA

Satellites sail in plasma

1. Single event upsets due to high-energy electrons
2. Aging due to continuous radiation dose
3. Spacecraft charging




Source: NASA Sampex

## Signal weather

**Extra particles change signal propagation conditions**

1. Absorption, refraction, scintillation of signals
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

# Many people think we understand space…

We don't.

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Movie: NASA/ THEMIS animation

To understand and eventually predict, we need

# Global modelling

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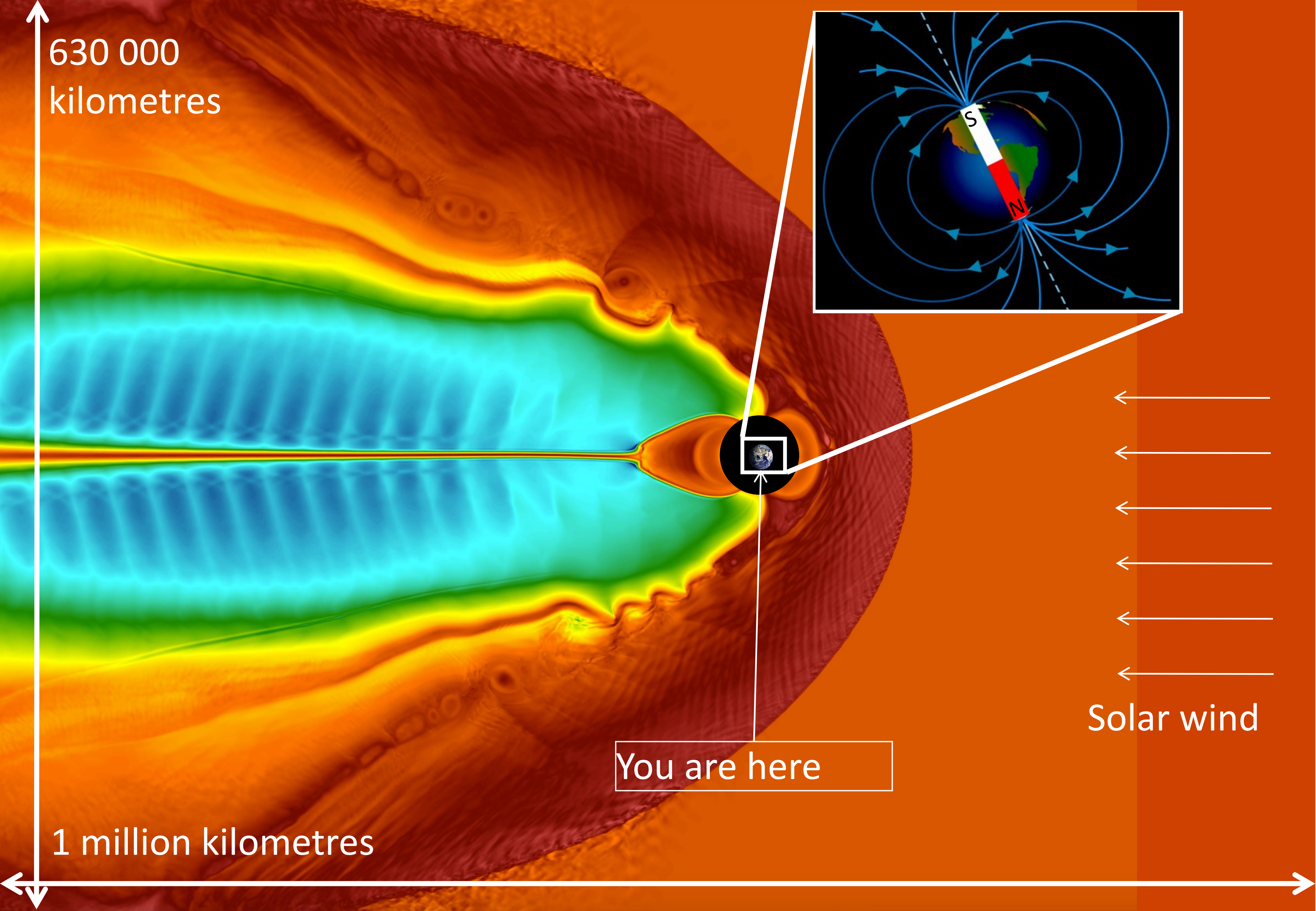
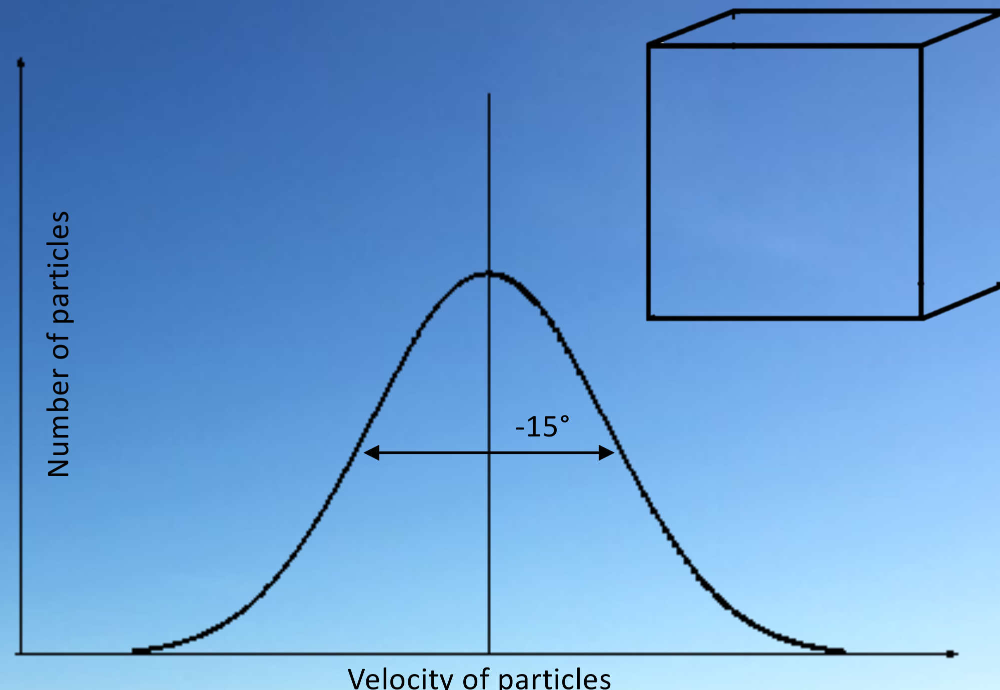
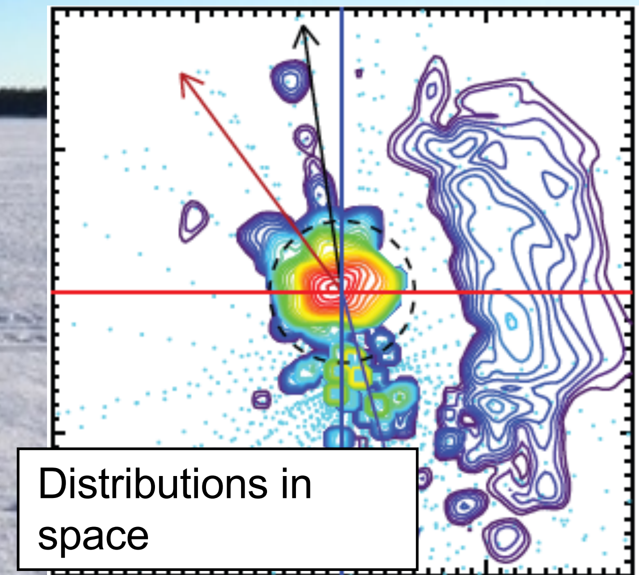
Picture: NASA

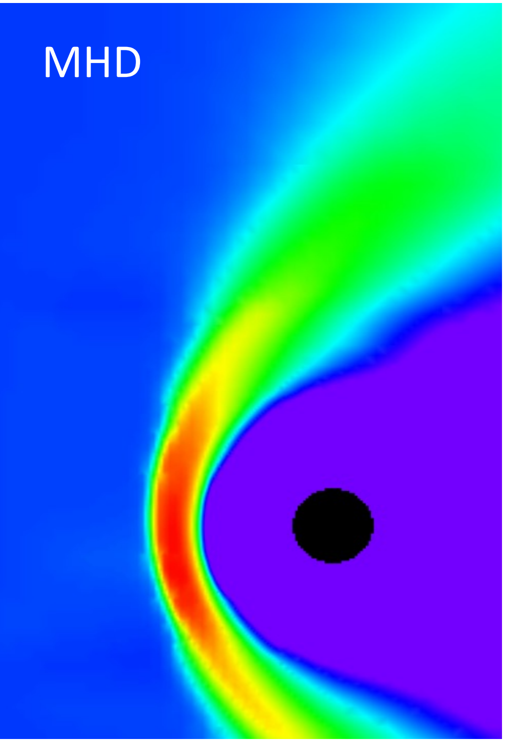

630 000 kilometres
S
N
Solar wind
You are here
1 million kilometres

# First approximations: Fluid simulations

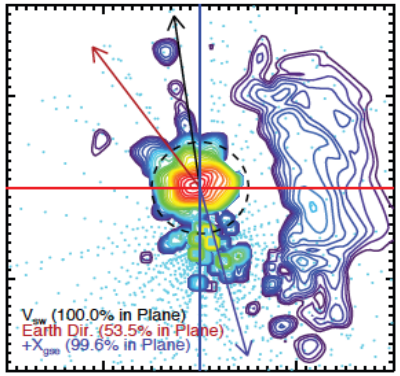


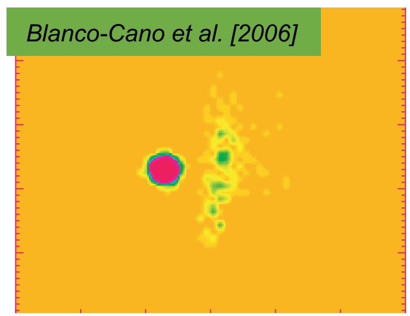

# Everything depends on how to model the plasma distribution function



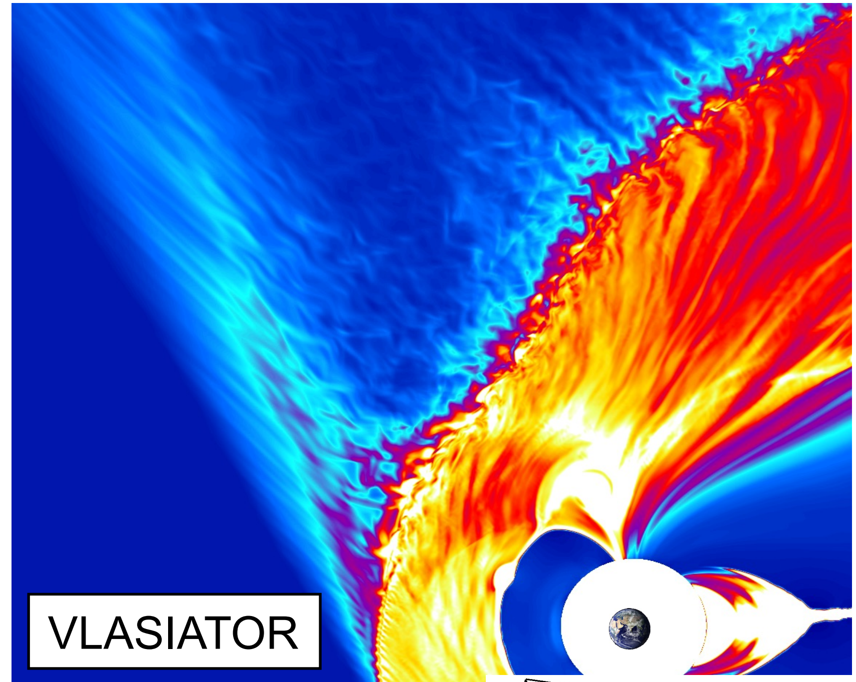

MHD: Distribution function is not modelled. Single value is used for temperature.

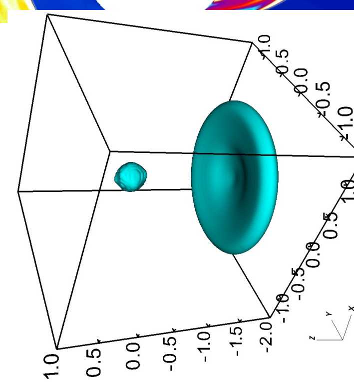



Observations (THEMIS spacecraft)



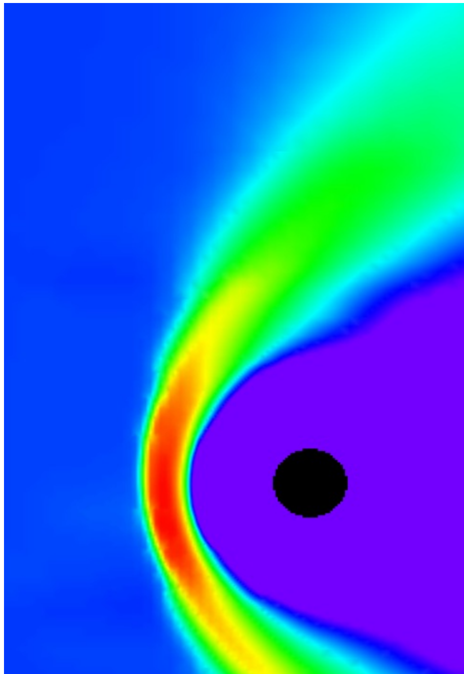

Particle-in-cell (PIC). Distribution is constructed from particle statistics.



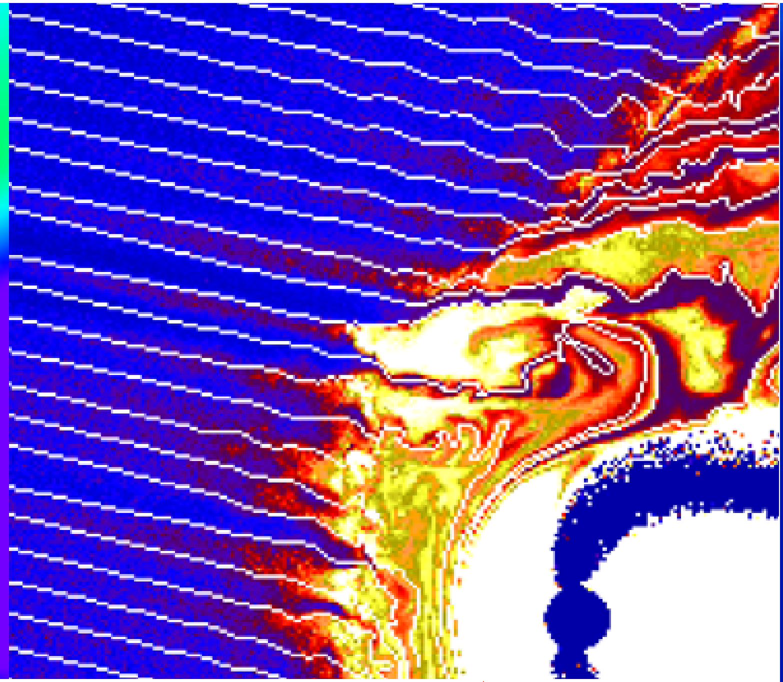



Vlasiator: Distribution function is modelled perfectly. No assumptions.

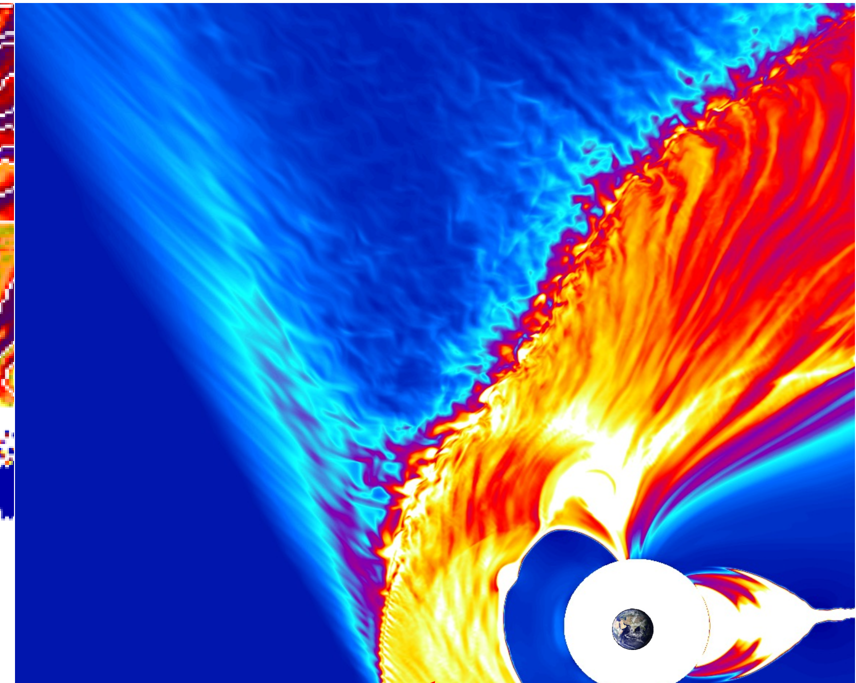
# Global modelling techniques



*GUMICS-4, FMI*



*Karimabadi et al., 2014*



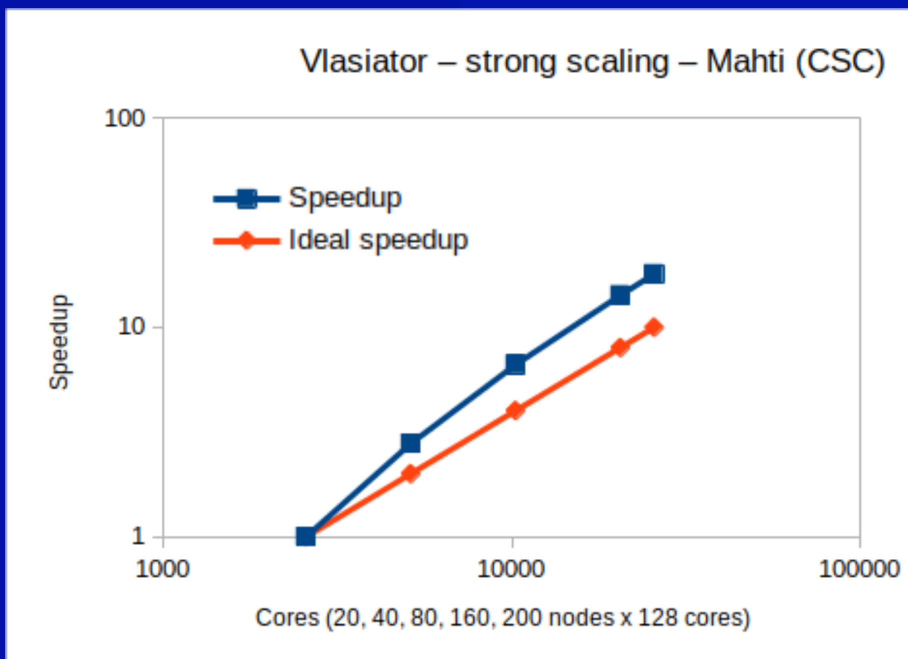
helsinki.fi/vlasiator

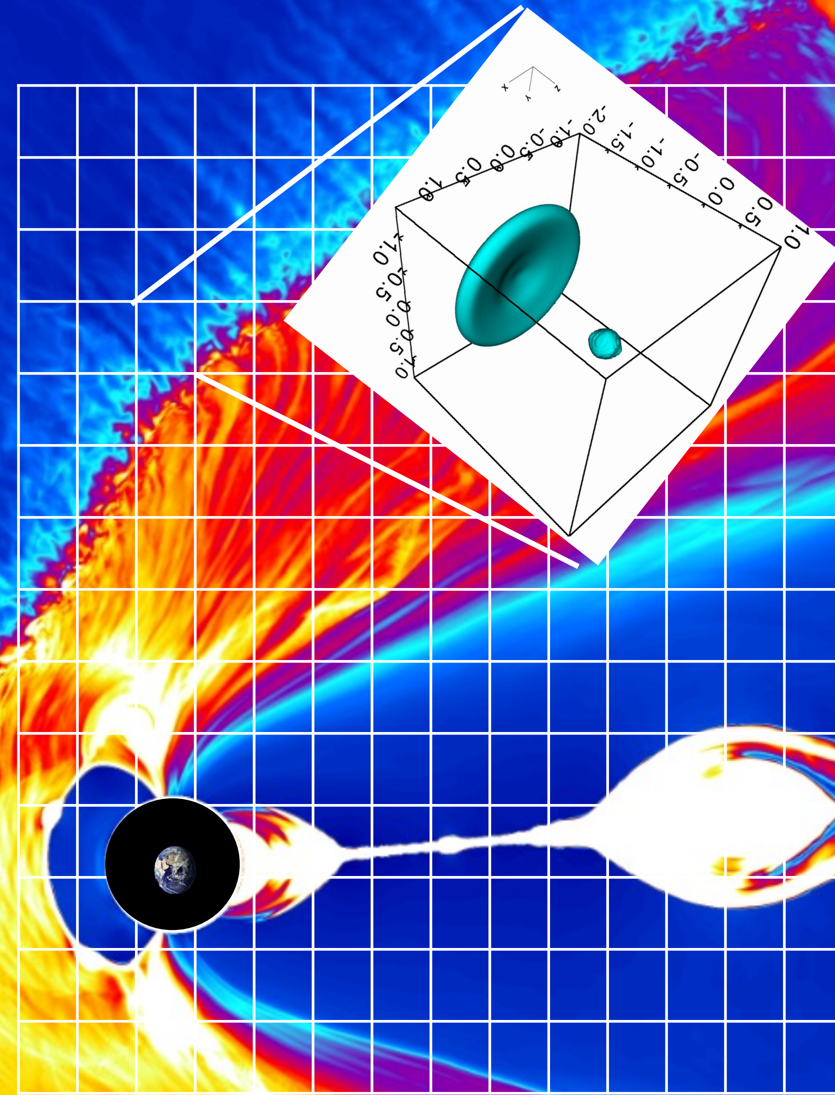
| | **Global fluid (MHD)** | **Hybrid particle-in-cell** | **Hybrid-Vlasov (Vlasiator)** |
|---|---|---|---|
| **Ions** | Fluid | Particles | Distribution functions |
| **Electrons** | Fluid | Fluid | Fluid |
| **Run time** | Real-time to weeks | Weeks | Weeks – months |
| **Scale of applications** | Fluid scale (1000 km)<br>Now: Solar system | Ion kinetic effects (10 – 1000 km)<br>Global = Solar wind, magnetosphere (+ ionosphere) | |

VLASIATOR

**Unique 6D model beyond magnetohydrodynamics**

- **At 3D location, solve also the 3D particle distribution**
- **Self consistent: EM-fields & velocity space moments**
- **Total number of cells: $10^{12}$**
- **Over $10^5$ timesteps**
- **Compute at scale using CPUs and GPUs, without idling**



**More information:** http://helsinki.fi/vlasiator

***Contact PI***: *Minna.Palmroth@helsinki.fi*

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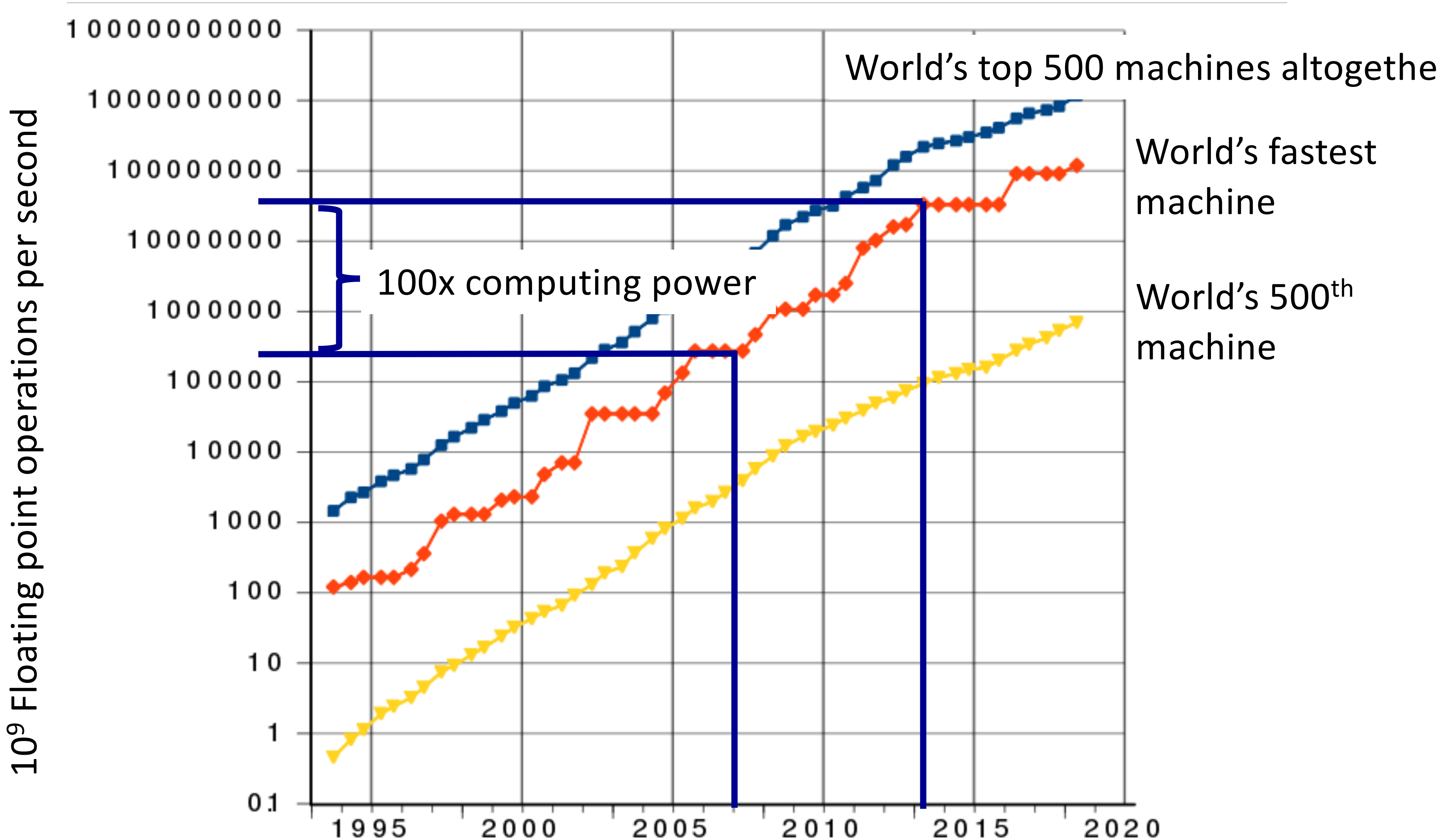
Picture: Rob Travis
@MinnaPalmroth: Cray User Group meeting, 9 May 2023

# One does not simply…

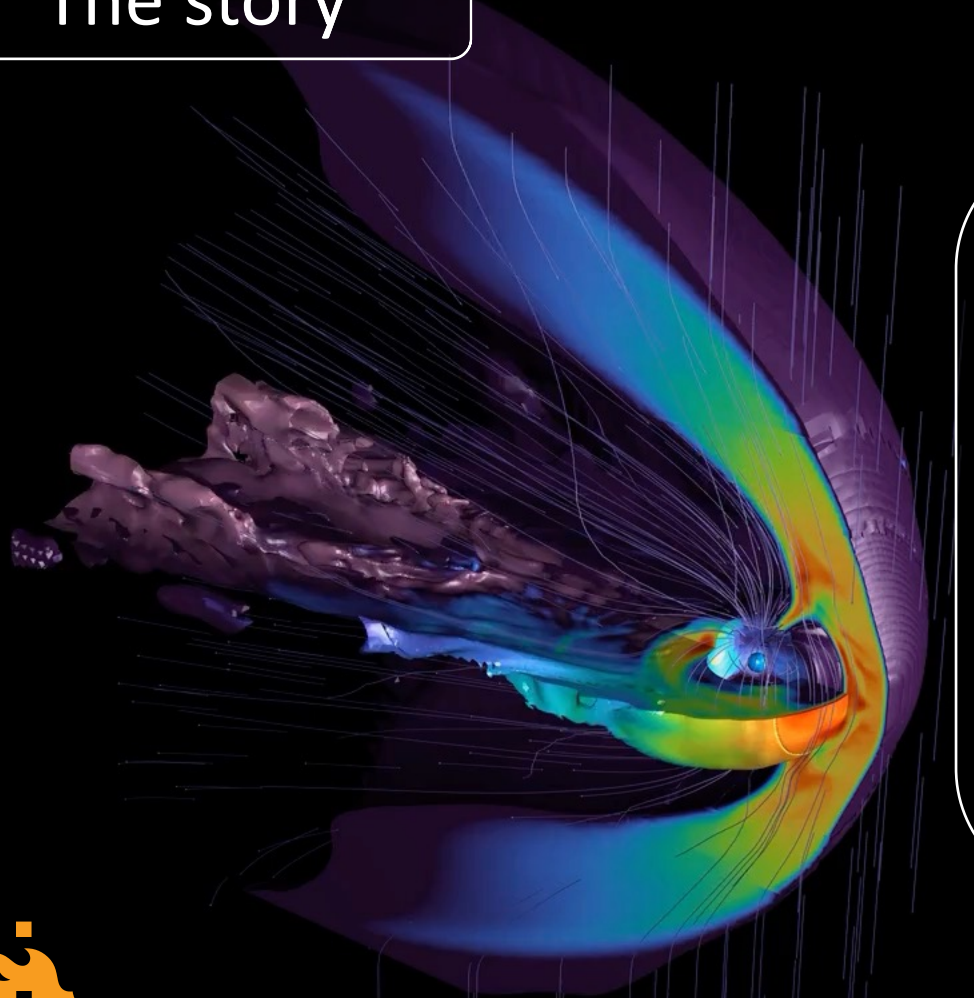
…build an army for 100 000 compute cores

Sean Bean in Lord of the Rings: Fellowship of the Ring




Picture: Wikipedia

# The story



2007: First ERC grant (Starting)
2011: 6D Test-Vlasov in MHD fields
2012: Access to Europe’s supercomputers
- First 5D runs (2D3V)

2015: Second ERC grant (Consolidator)
2019: Towards 6D (AMR)
- First preliminary run @CSC

2021: (Jan 13)
- First 6D production run @HLRS
- Around 15 MCPUh
- Data per run: ~30 T

2022: Dynamic ionosphere added

erc erc PRACE PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE CSC

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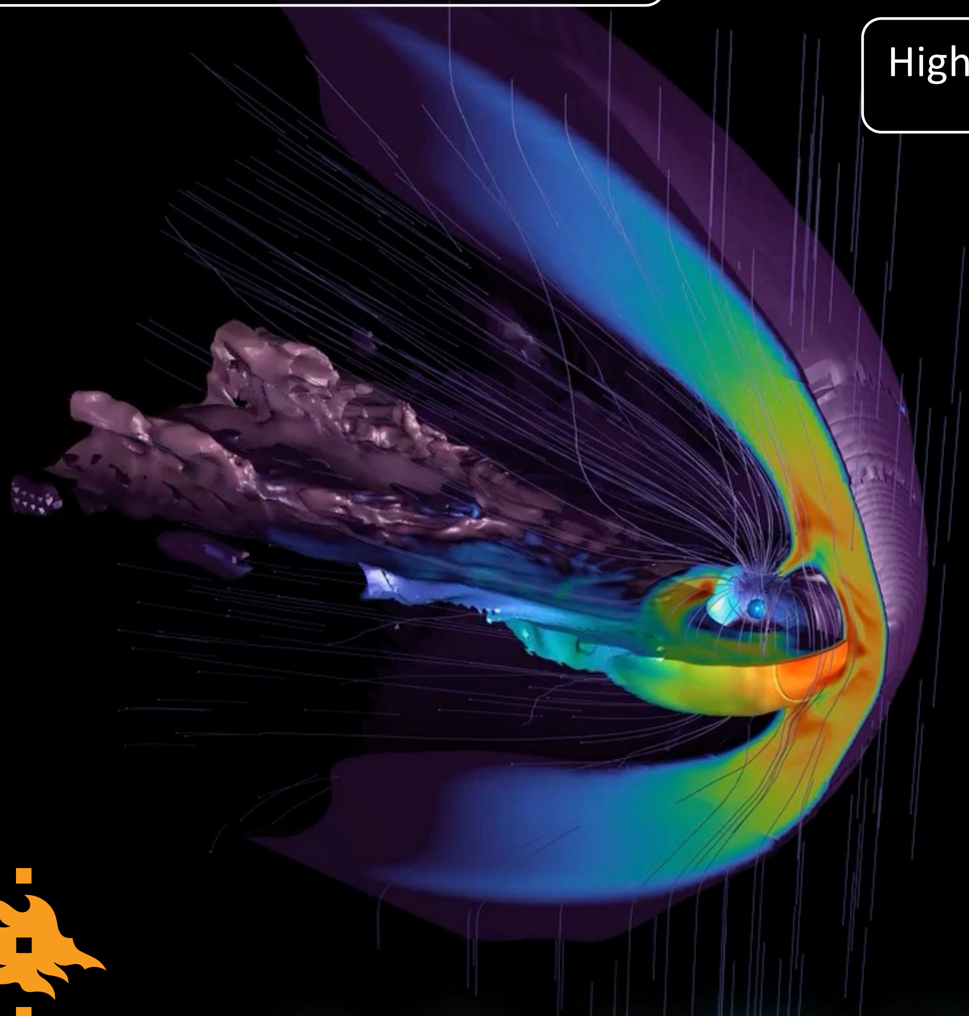
VLASIATOR

# Vlasiator ecosystem



High-performance computing

New methods & capabilities

New science

Applications

New Space Economy

Societal preparedness

Policy advising

Outreach

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# High-performance computing

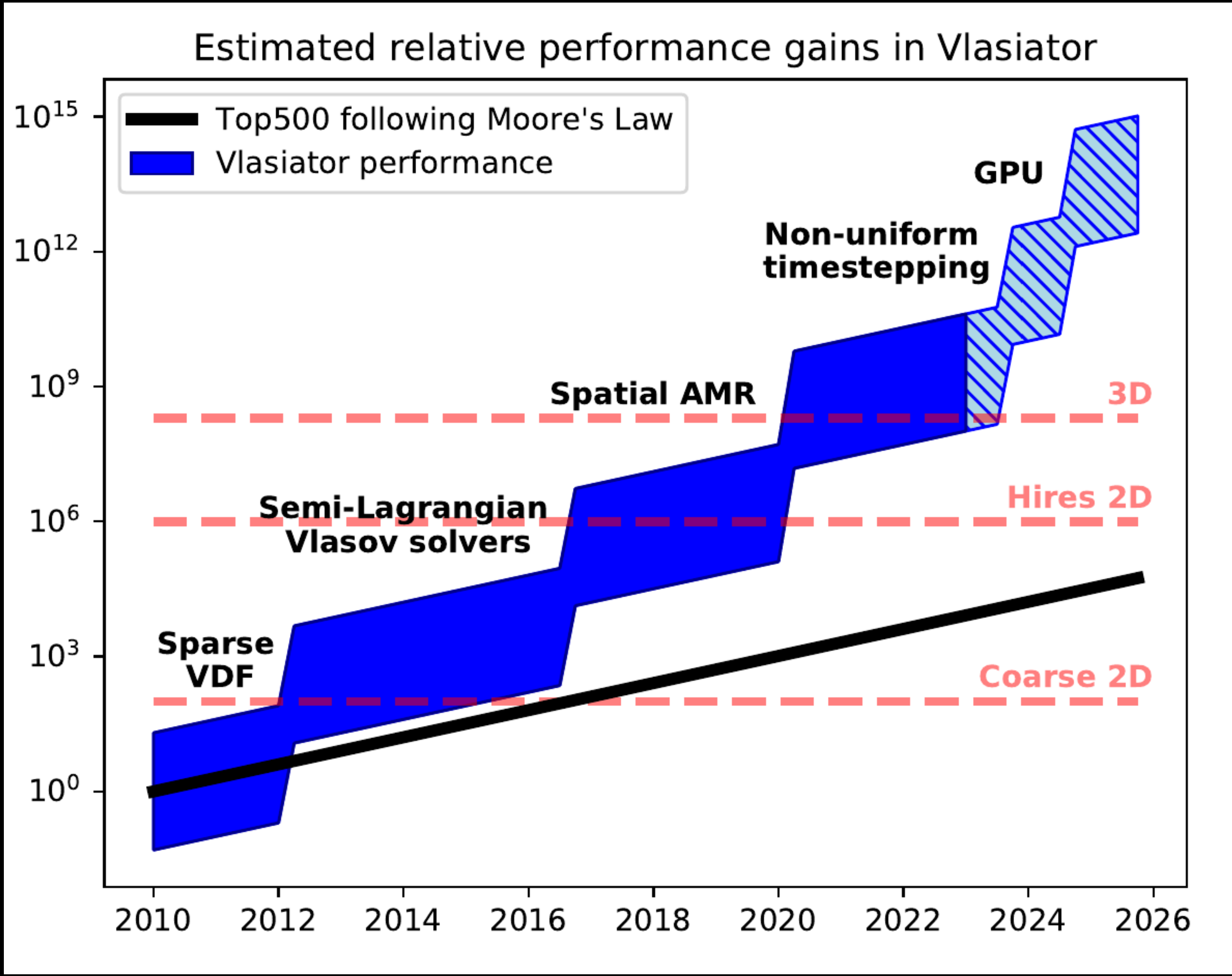


Image by Y. Pfau-Kempf

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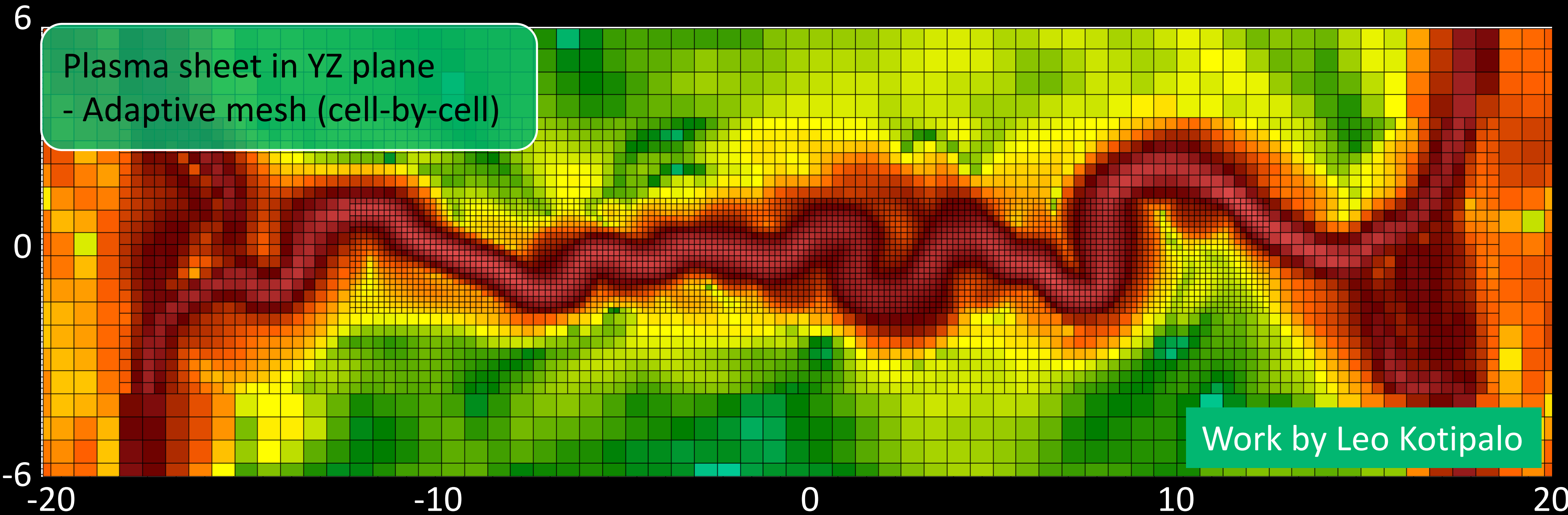
# Enabling 6D: In a nutshell





- Subgrid functions for VDFs on coarse grid
- LUMI: Top 3 (world), Top 1 (Europe)
- Velocity space → GPU
  - By M. Battarbee
  - Initial results: 10-20x faster
- Part of European Centre of Excellence in Code development (EuroHPC).

Read also: https://doi.org/10.1063/5.0134387

# Highlights of the HPC technology

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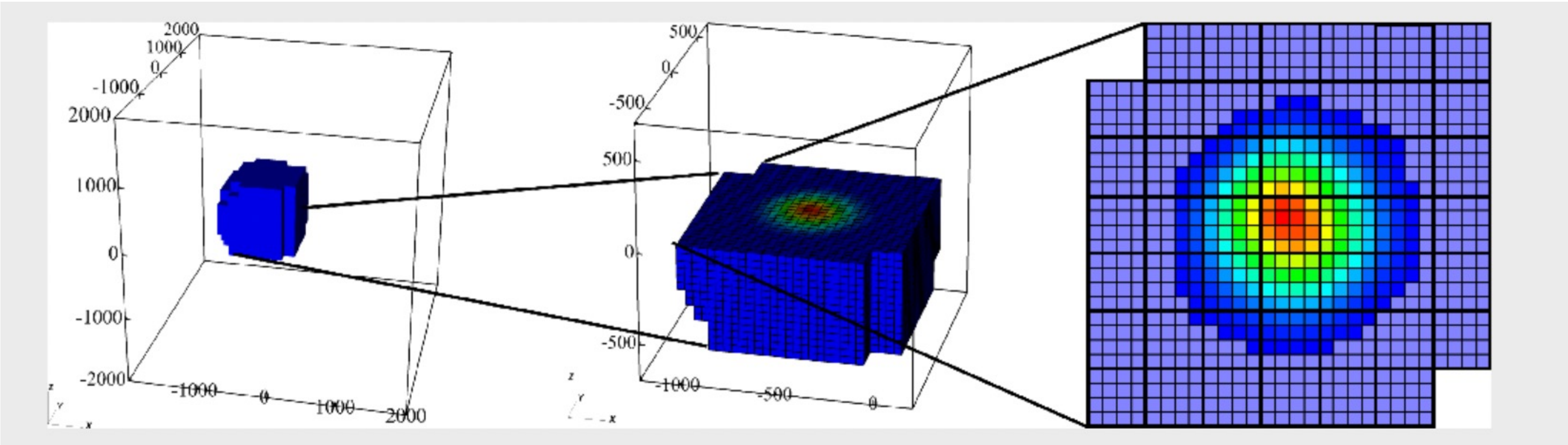
Picture: NASA

# Memory requirement - the curse of 6D

- Spatial resolution of ~200 km
  - → 3822 cells in every spatial direction
- –2000 ... 2000 km/s velocity space
- 30 km/s velocity resolution
  - → 134 cells in every velocity direction
- $3822^3 \times 134^3 = 1.343 \times 10^{17}$ cells
  - 4 bytes per cell (assuming zero overhead)
  - → 477 petabytes of RAM with the simplest 32 bit floating point number per cell
  - Compare to 6.9 petabytes lustre on LUMI
  - → Obviously, we need to do something smarter.

From Ganse et al., 2023 (Phys. Plasmas)

# Memory requirement - the curse of 6D

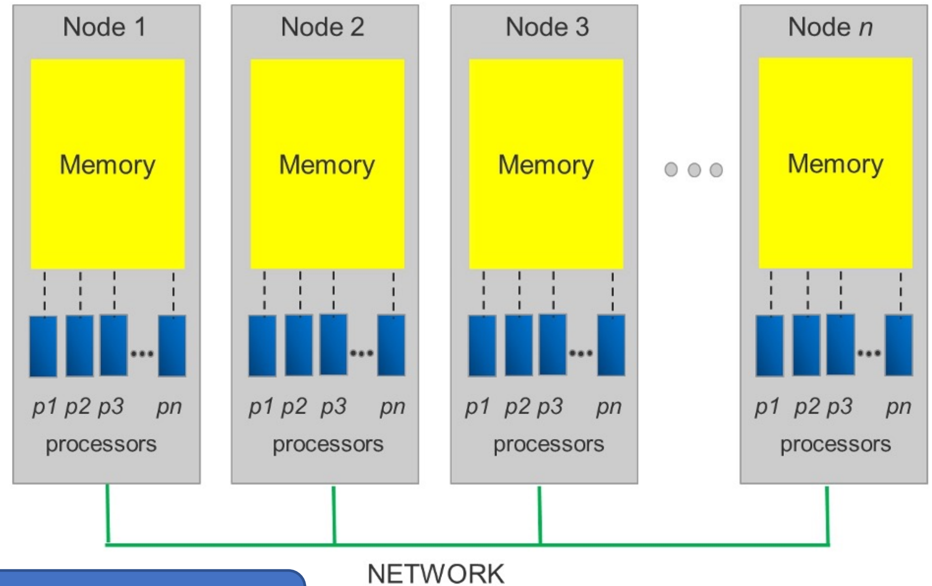



- Vlasiator uses a sparse phase space to reduce memory requirements
- Only non-empty blocks and their neighbours are stored and processed.
- Effective phase space volume can be reduced by 98%
- Results are comparable to spacecraft electrostatic detector cutoff.
- 3D3V simulations possible with ~30 TB memory use (with AMR and sparse V-space)

Credits: U. Ganse

# Parallelization on three levels

1. Across nodes on clusters & supercomputers - MPI
   - Domain decomposition of real space
   - Implemented by DCCRG library (*https://github.com/fmihpc/dccrg*)
   - Frequent load balancing
2. Across cores on nodes – OpenMP
3. Across core – Vectorization




- Efficient parallel I/O using VLSV file format
- Scaling (almost) linearly to >180,000 CPUs on LUMI-C
  - Strategic partnership with CSC – IT Center for Science
  - Numerous PRACE and EuroHPC Tier-0 grants

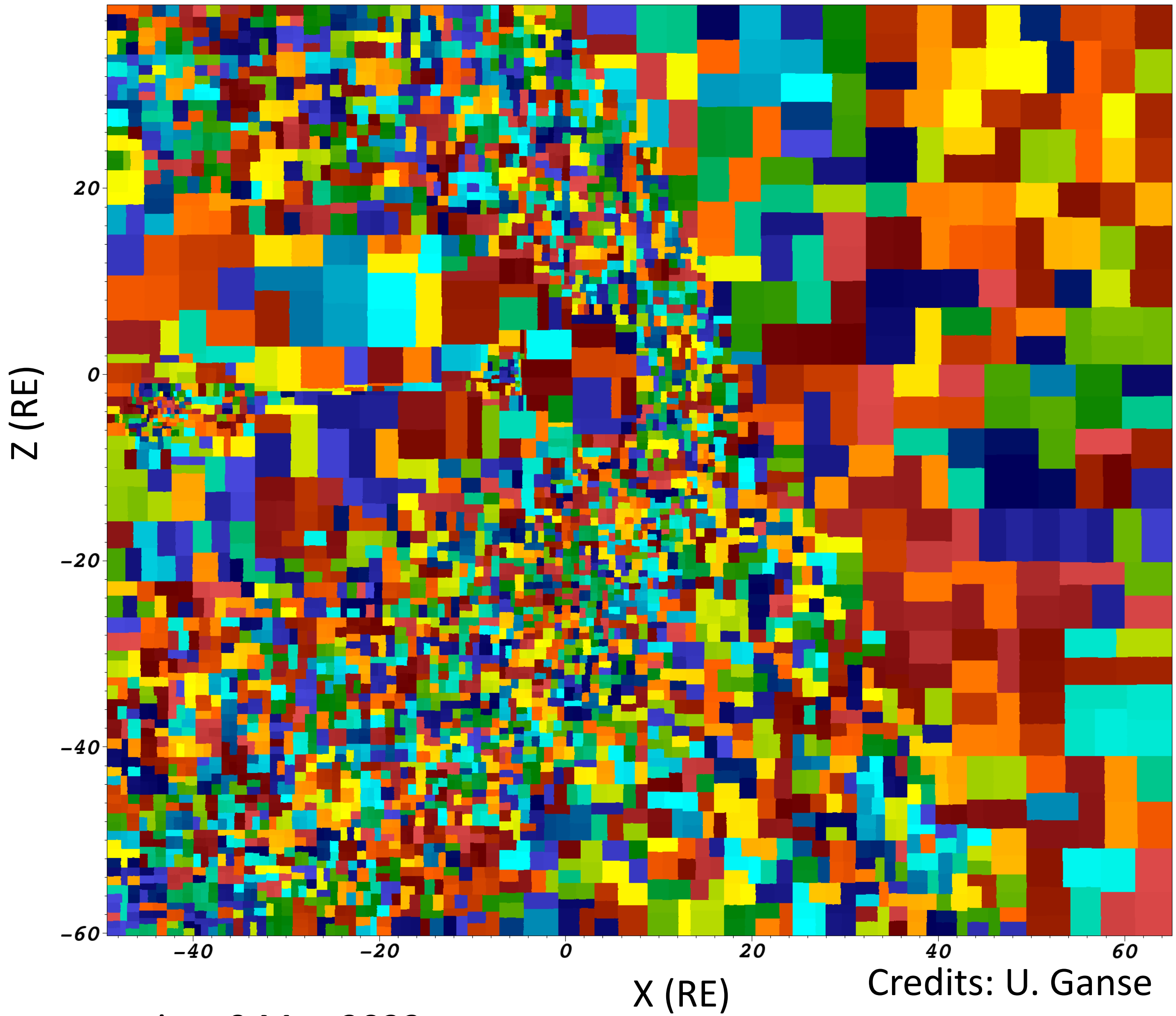
CSC

Credits: U. Ganse

# Computational domain decomposition over processor space

**Load-balancing real space over all participating CPUs with Zoltan :**

- Spatial neighbours might be local or remote
  - Data needs to be gathered from the right place
- After updates, data may be leaked to other CPUs.

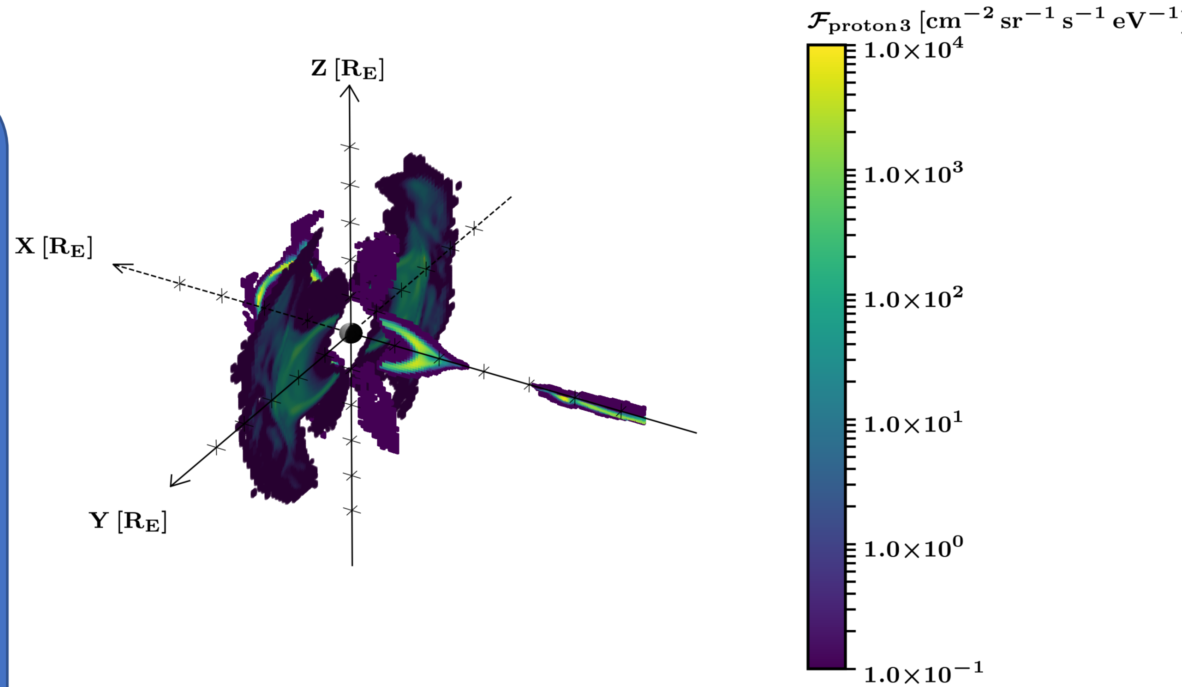



Credits: U. Ganse

# Runtime data reduction and analysis

**Storing the whole simulation is impractical for all timesteps**

- All data in restart files
- Otherwise we choose relevant data for I/O
- Data reducers (in-house)
- Complex analysis carried out *in situ* (at runtime)
    - Automatic decisions for e.g., cell refinement




Method to get the precipitating flux and spectrum from magnetospheric distribution functions: Grandin et al., 2019 (Annales). Results from Grandin (SWSC 2023).

# Velocity space → GPUs

| Process | CPU only [s] | CPU + GPU [s] |
|---|---|---|
| Propagate | 10,249 | 1,329 |
| Velocity space | 9,975 | 1,317 |
| Semi-lagr. acceleration | 9,699 | 1,305 |

- Ported acceleration solver (part of the velocity space process) with one GPU stream is nearly 8x as fast as the CPU-only version.
- Porting of other solvers and optimization for multi-stream access is underway.

Credits: M. Battarbee

# Portability and future technologies

- Vlasiator currently runs on AMD-64, ARM, RISCV, and PowerPC
- CPU + GPU architectures (with NVIDIA and AMD)
- Ongoing development for scalable vector architectures and European accelerator project (EPAC)
- Sufficient portability for future architectures
  - This was always our strategy!
- Quantum computing? Forward propagation of a physical system isn't exactly fitting to Quantum.


Vlasiator running on Aarch64 (64bit ARM) on our Lead Developer's mobile!
Credits: Urs Ganse & Eleanna Asvestari

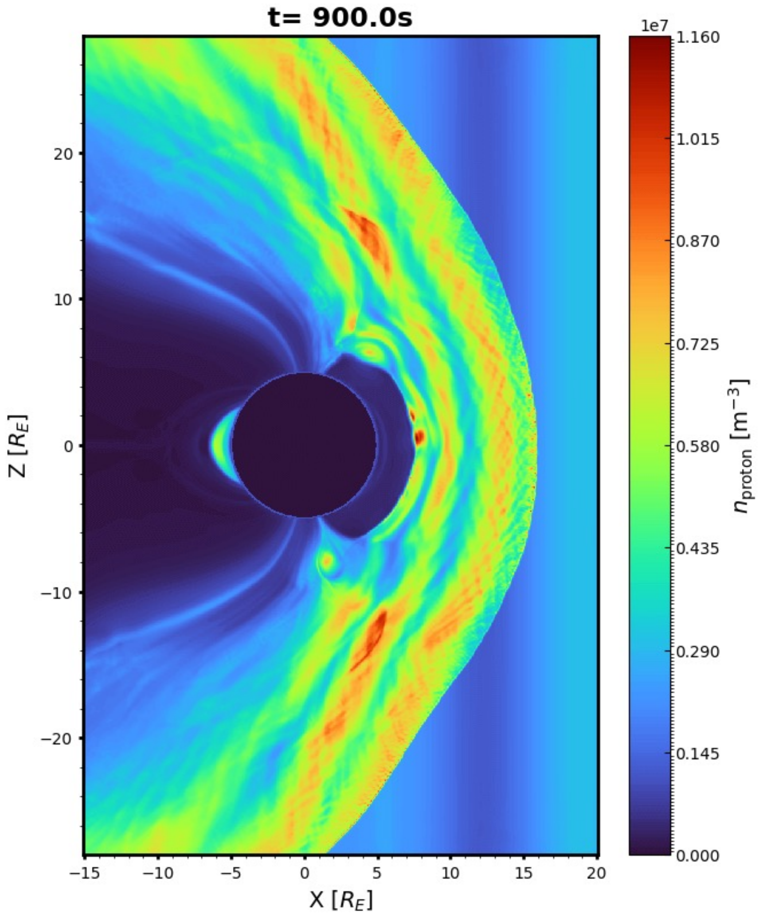
Examples of

# New methods and capabilities



Picture: NASA

Time-varying solar wind conditions
(work by H. Zhou)




[Zhou+ 2022 Frontiers]

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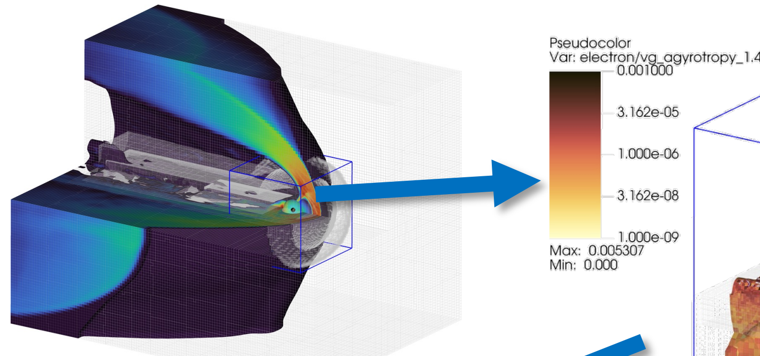
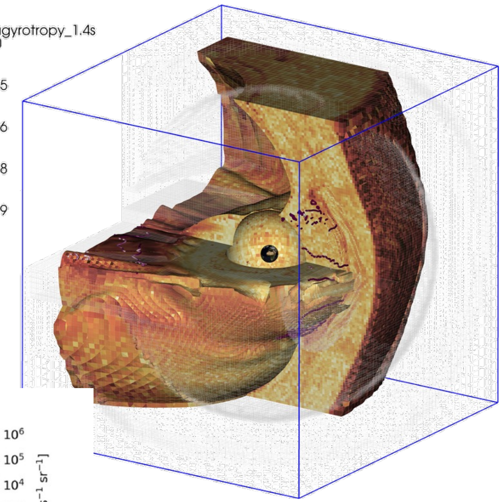
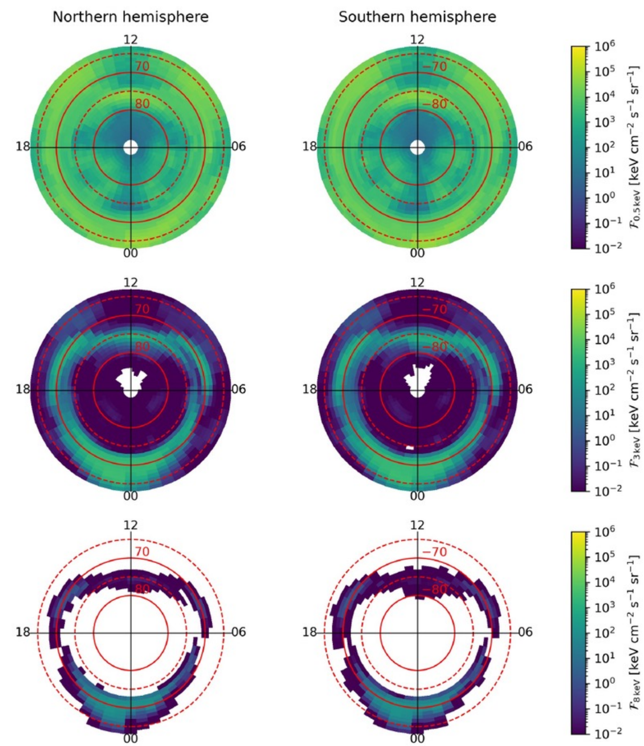
eVlasiator: 3D global Vlasov electrons



Electron precipitation

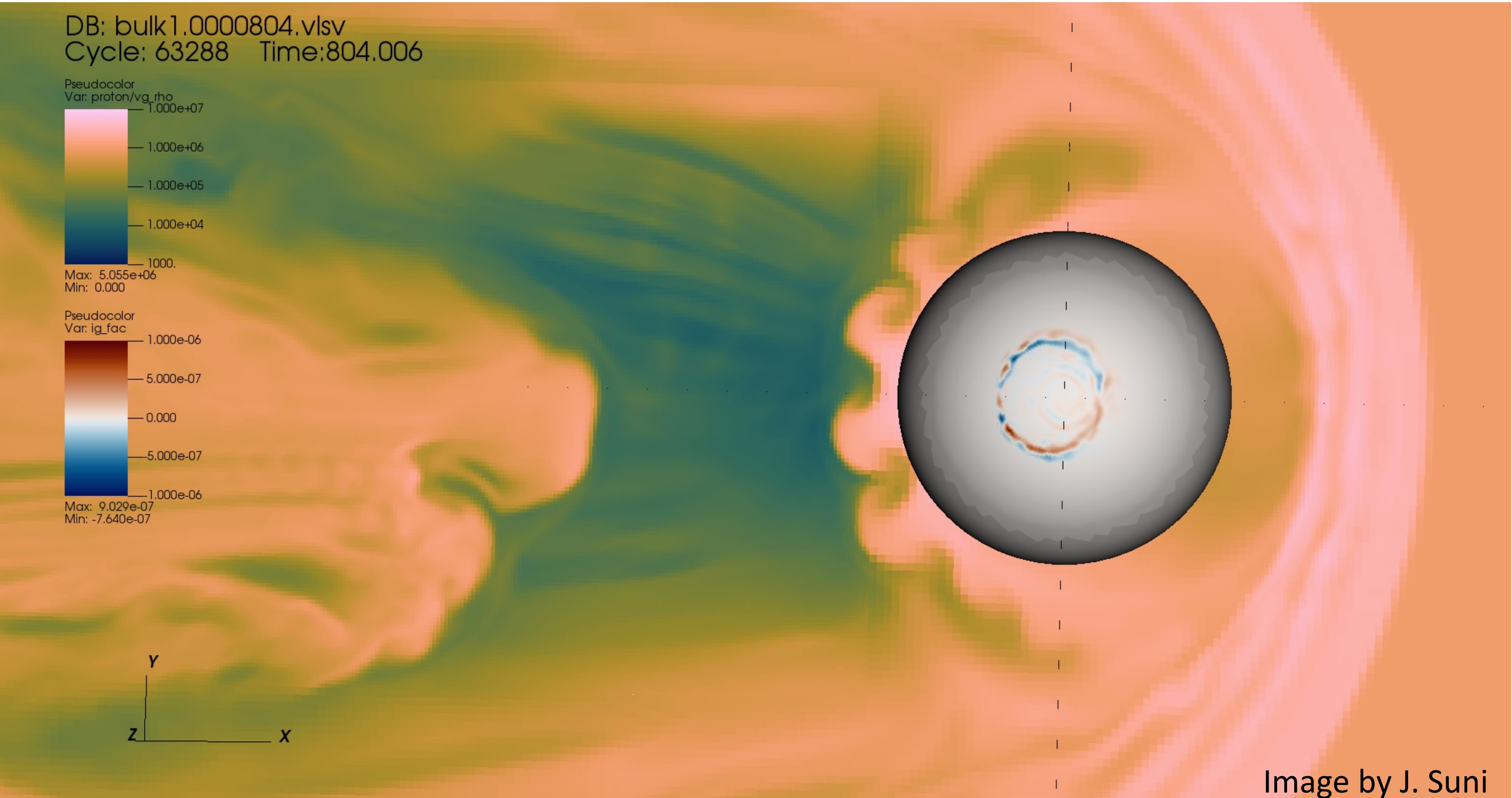



See also:

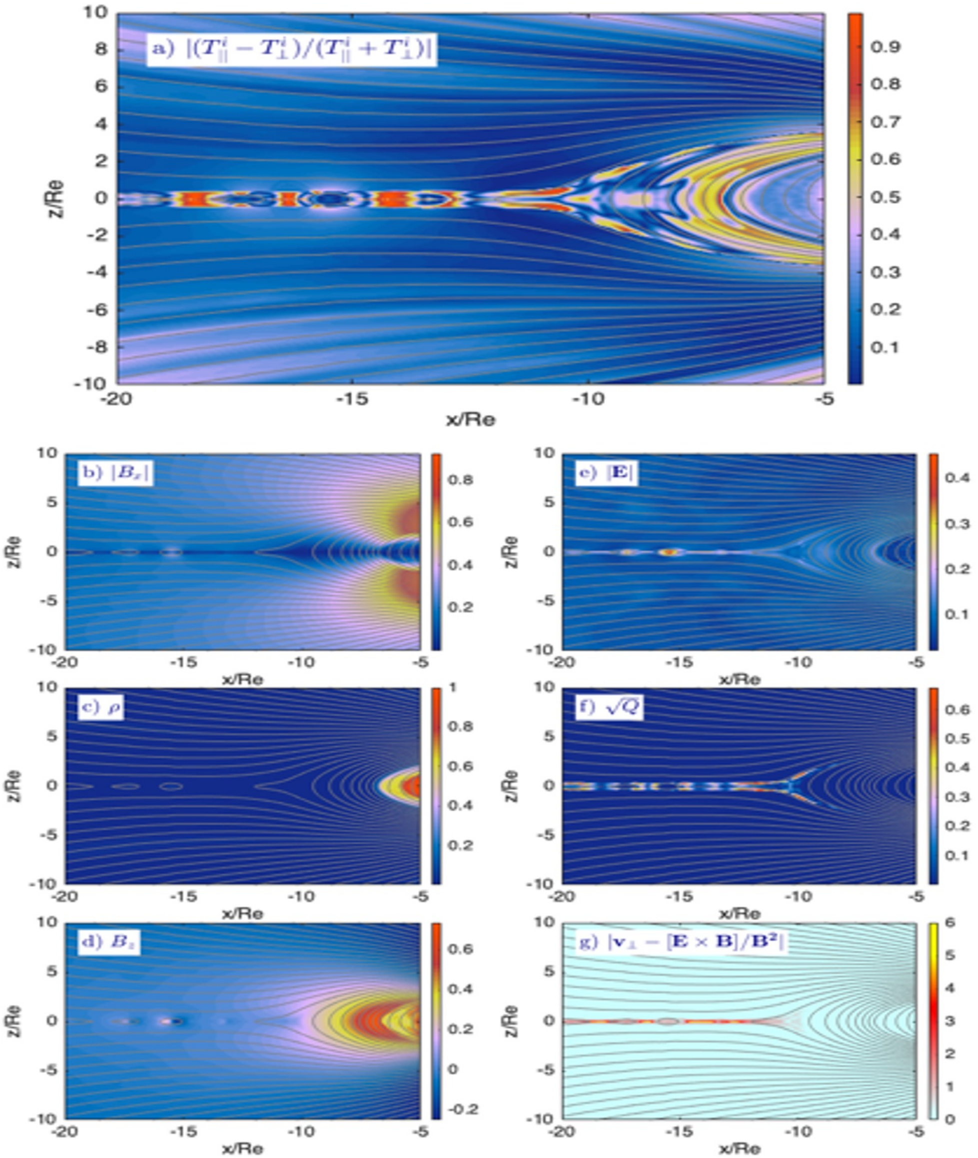
- Battarbee+ AnnGeo 2021
- Alho+ GRL 2022

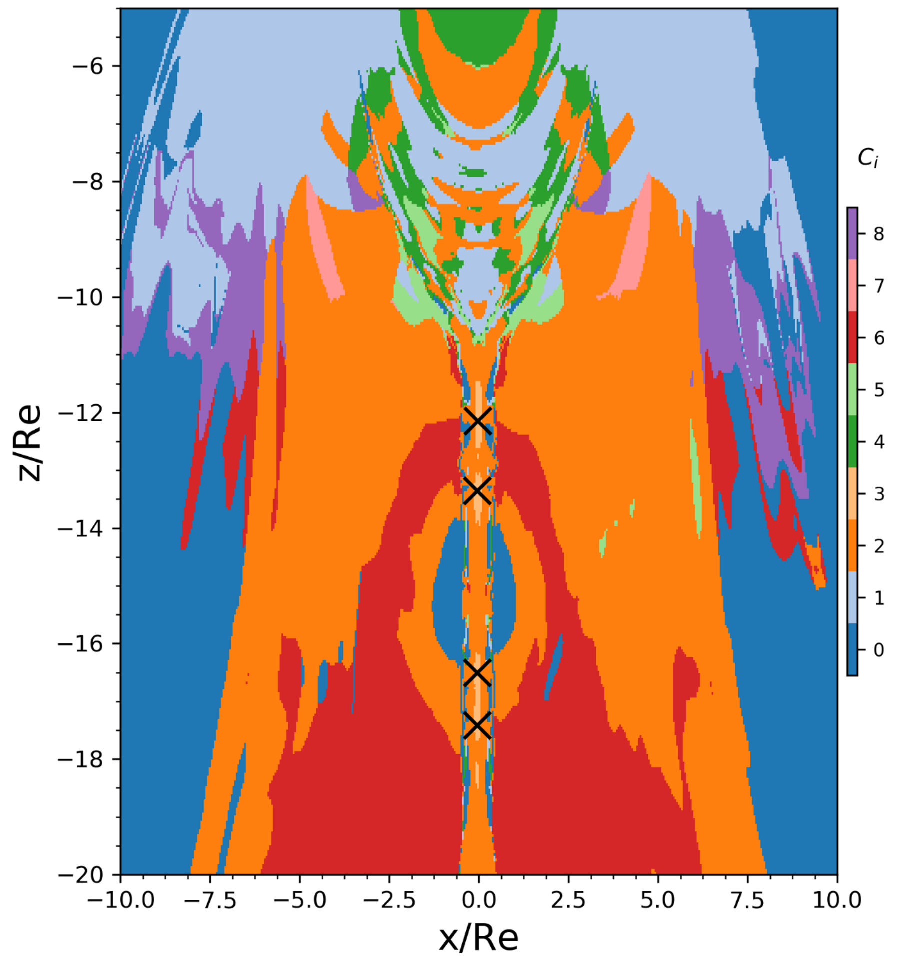
# Electrostatic ionosphere

## Similar philosophy for coupling as in MHD simulations (production run ongoing)



# Finding reconnection with unsupervised machine learning




Work by M. Bussov (in prep)

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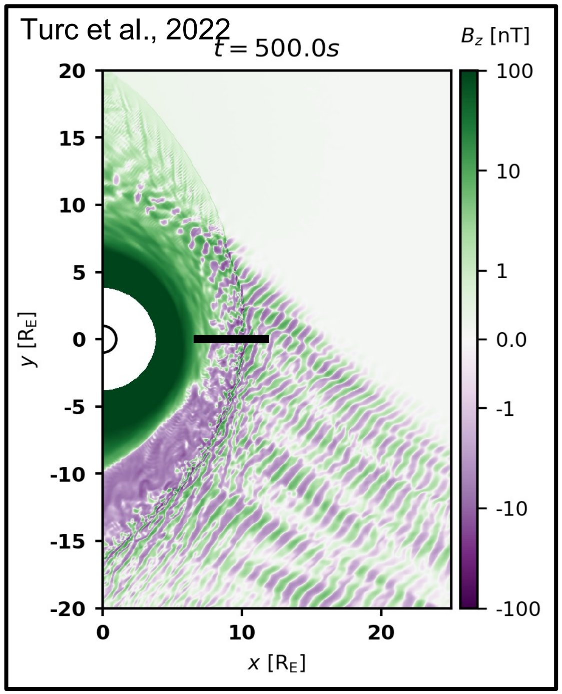
Highlights of

# New science



Picture: NASA

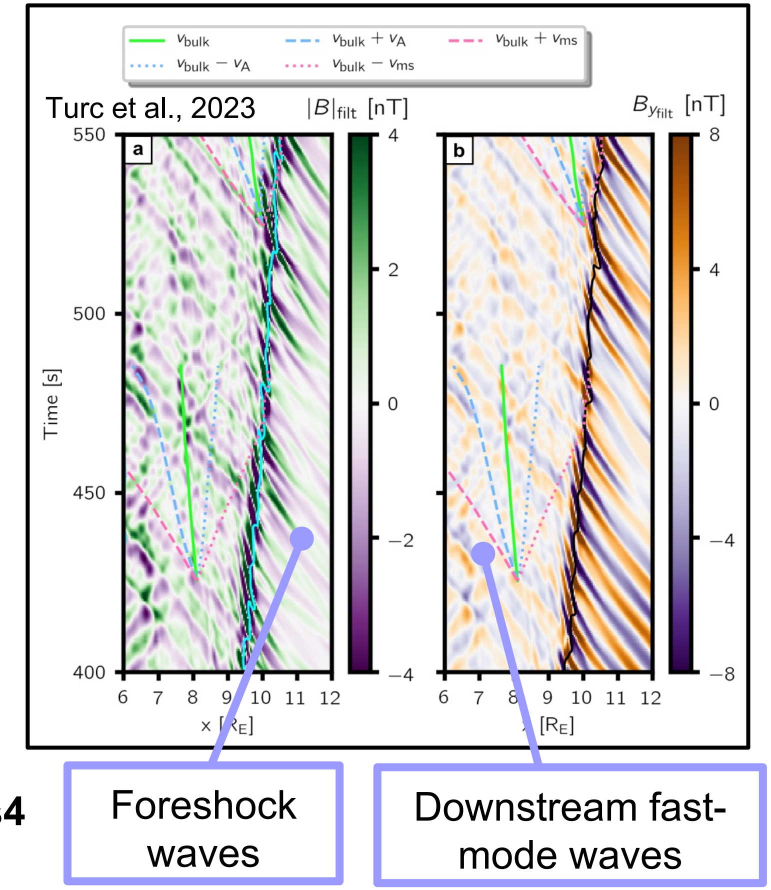
# Foreshock wave transmission problem solved




Using 2D Vlasiator simulations, we showed that foreshock waves propagate through the magnetosheath as fast-mode waves.

These waves are however not just "directly transmitted" through the shock, but are created by the foreshock waves modulating the plasma parameters just upstream of the shock

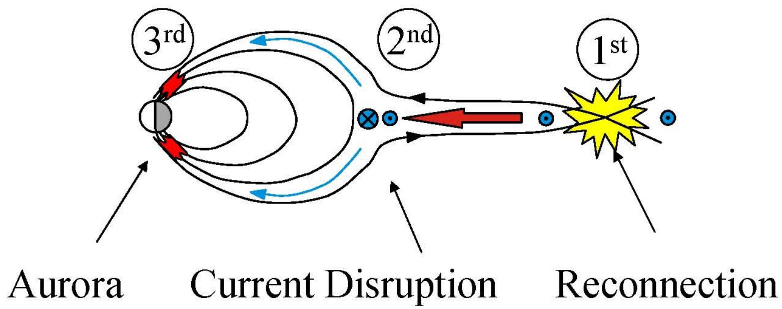
**Turc et al., 2023, Nature Physics https://www.nature.com/articles/s41567-022-01837-z**



# Earth's magnetosphere erupts, too

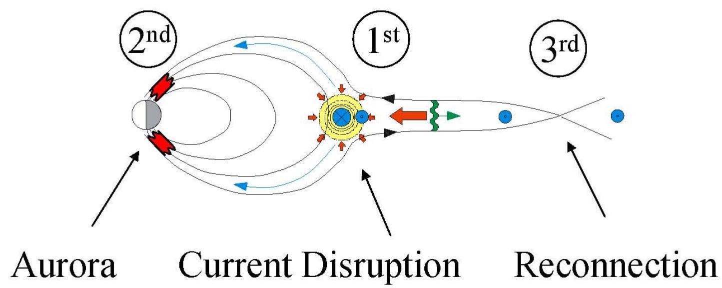
- like the Sun and at least Mercury, Venus and Jupiter, but we don't know how

**Near-Earth Neutral line**
e.g., Baker+, *JGR*, 1996

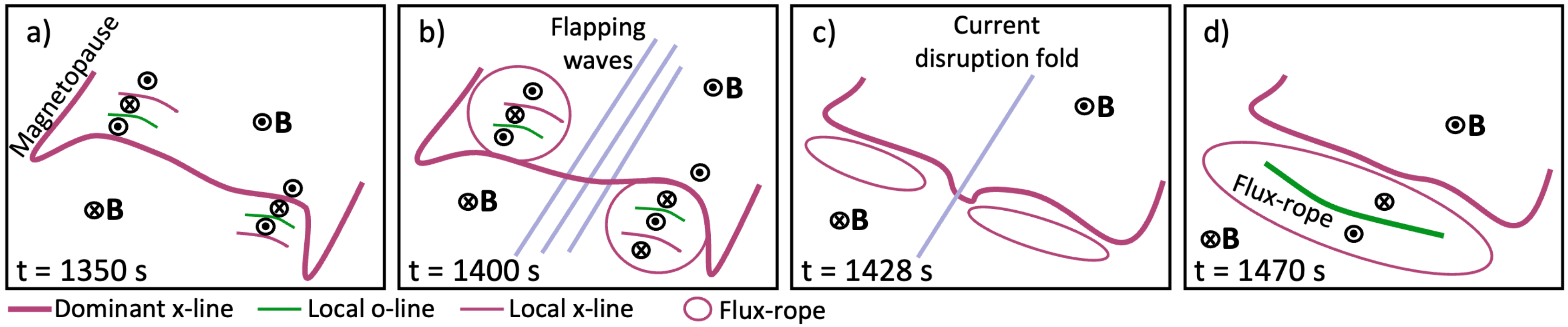



- Reconnection launches a plasmoid tailward
- … and fast flows earthward
- Dipolarisation disrupts the magnetotail current

**Current disruption**
e.g., Lui, *JGR*, 1996




- A 3D plasma instability grows in transition region
- … disrupts the magnetotail current
- … launches waves that trigger reconnection
- plasmoid release, fast flows, and dipolarization




**Vlasiator suggests reconciliation:**

**Palmroth et al., 2023, Nature Geosciences, accepted in principle**

✓ **NENL**: Reconnection – current disruption – plasmoid

✗ **BUT**: Current disruption not in the same local time as reconnection **AND NOT** due to fast flows

✓ **CD**: Current disruption @ transition region – spreads outwards – large-scale reconnection – plasmoid

✗ **BUT**: CD caused by flapping, which is caused by reconnection

VLASIATOR **scenario:**

- Two reconnection sites @flanks move to centre: **plasmoid**
- Centre disrupts the current due to current sheet flapping

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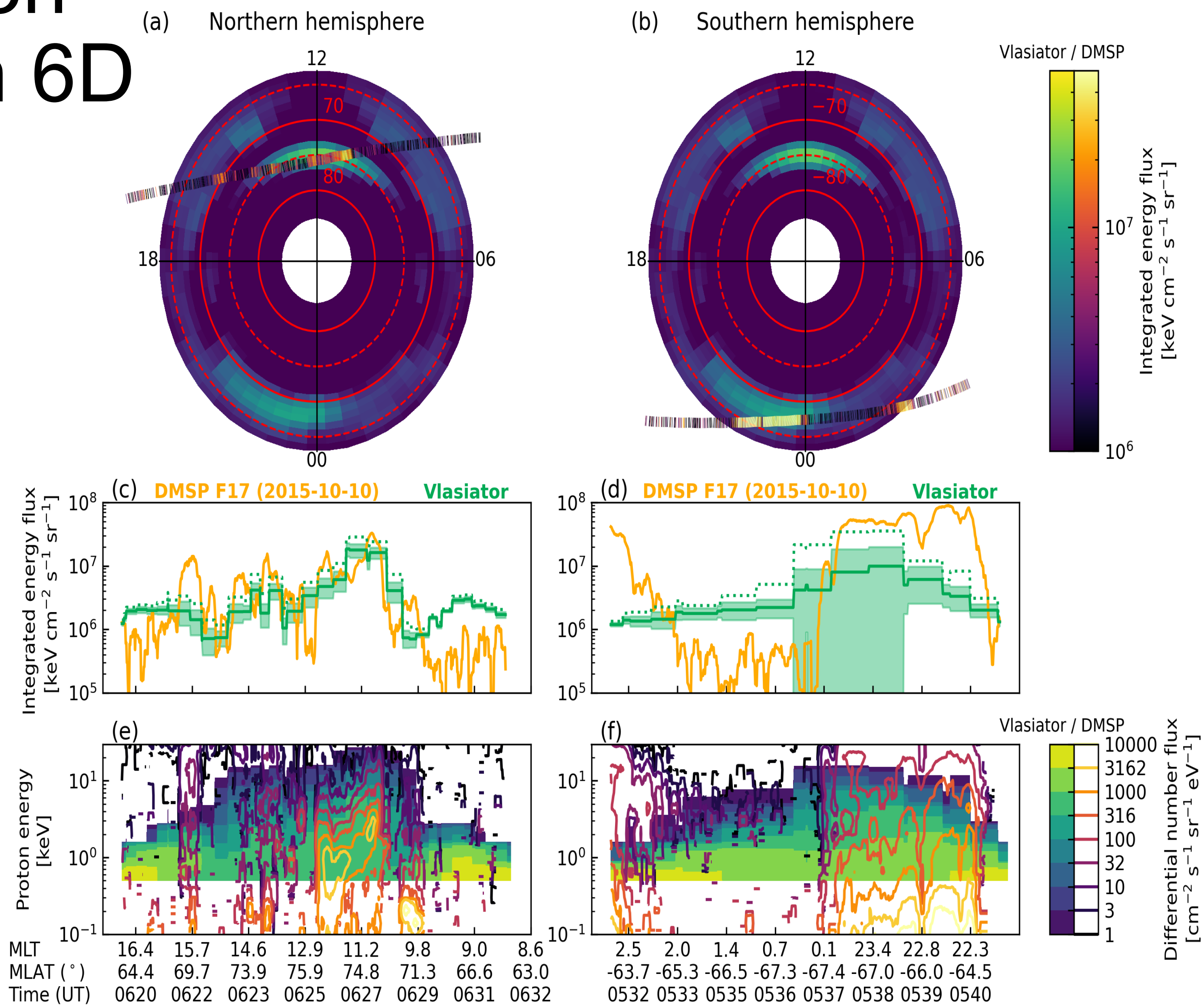
# Auroral proton precipitation in 6D

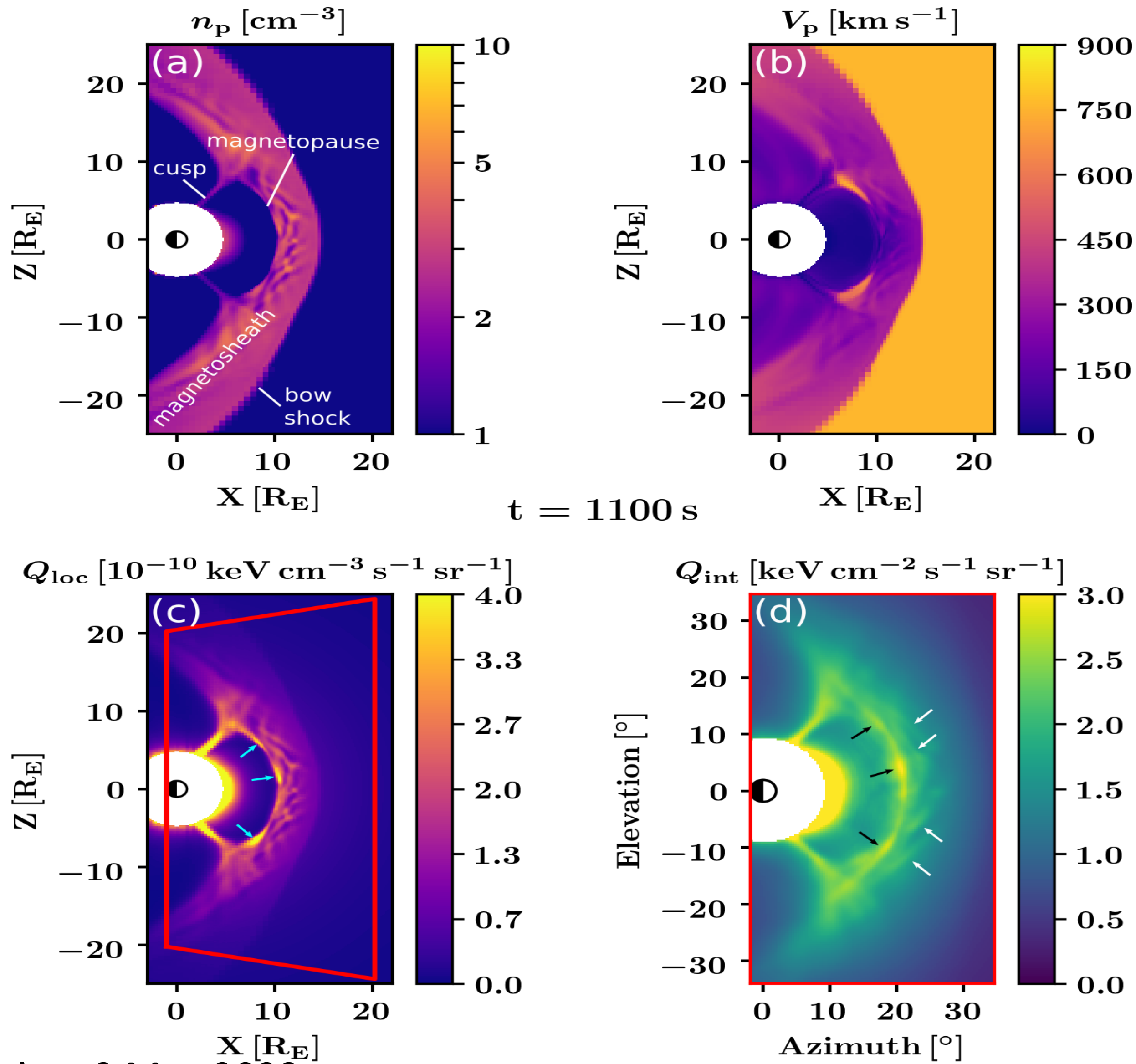
- We evaluate the differential flux of precipitating protons (0.5–50 keV) in a 6D run with southward IMF
- Good qualitative and quantitative agreement with DMSP/SSJ measurements during similar driving conditions




Grandin et al. (submitted), preprint on arXiv: https://arxiv.org/abs/2301.06578

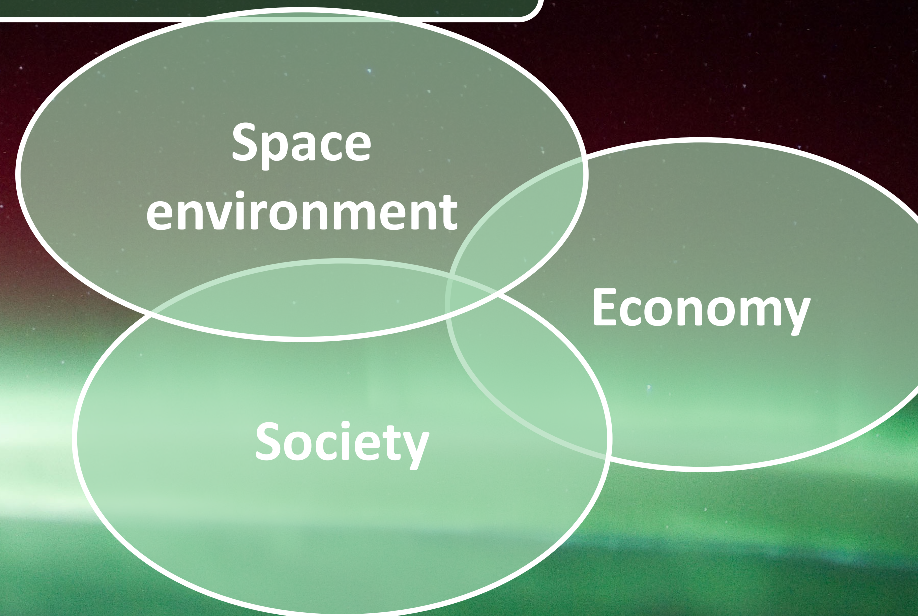
# Helping to build satellite instruments

- Solar wind charge exchange reactions generate soft X-ray emissions which will be studied by the SMILE (ESA & China) and LEXI missions
- We simulate soft X-ray images with a 6D run with southward IMF




Grandin et al. (submitted), preprint on arXiv: https://arxiv.org/abs/2301.13325

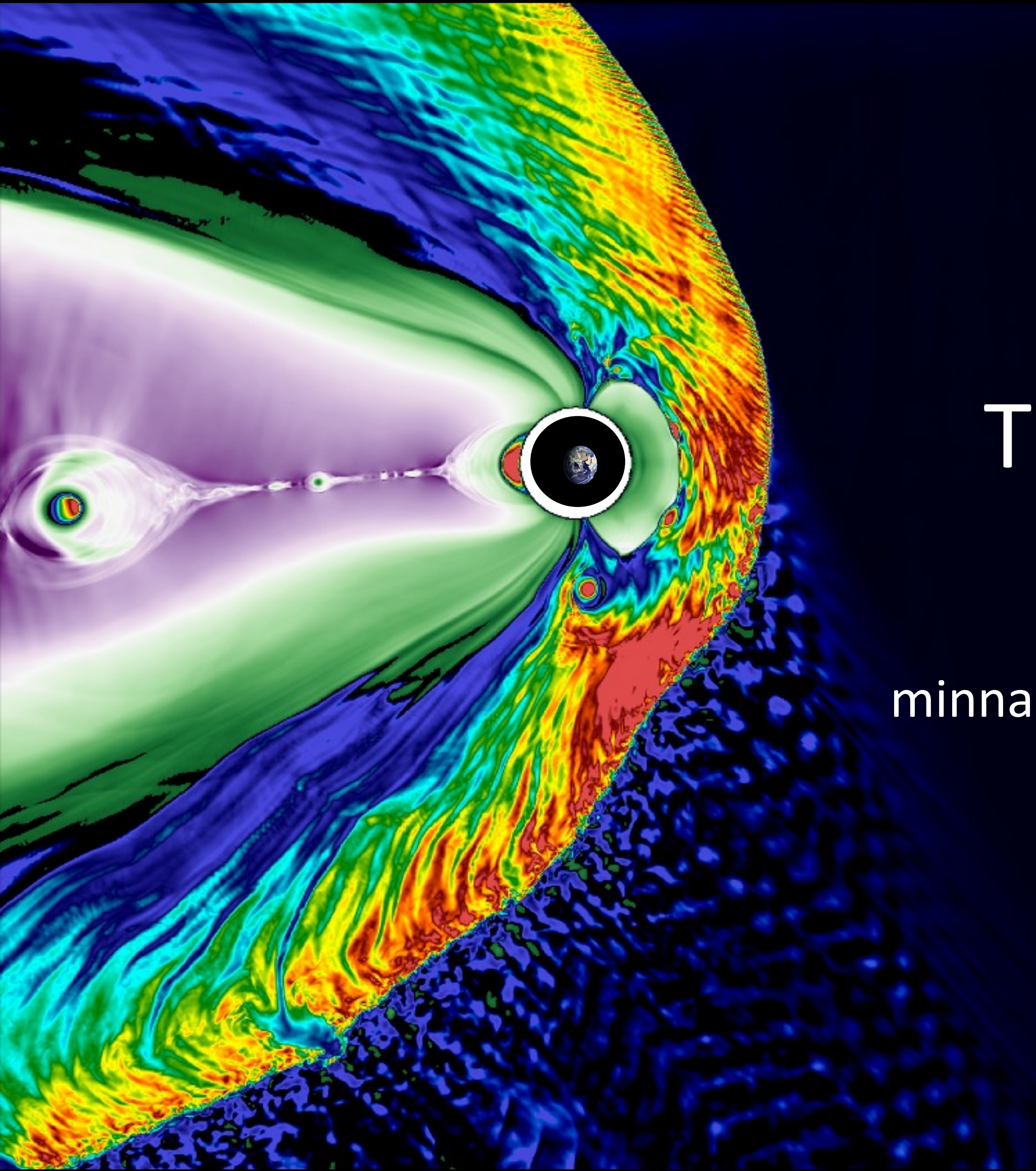
# In summary: Why study near-Earth space?




**Because we live here.**

- Economic use of space is skyrocketing.
- Our modern way of life is critically dependent on space.

**We need to understand the near-Earth space to be able to protect ourselves, our society, and our way of life.**



# Thank you!

Contact:
minna.palmroth@helsinki.fi