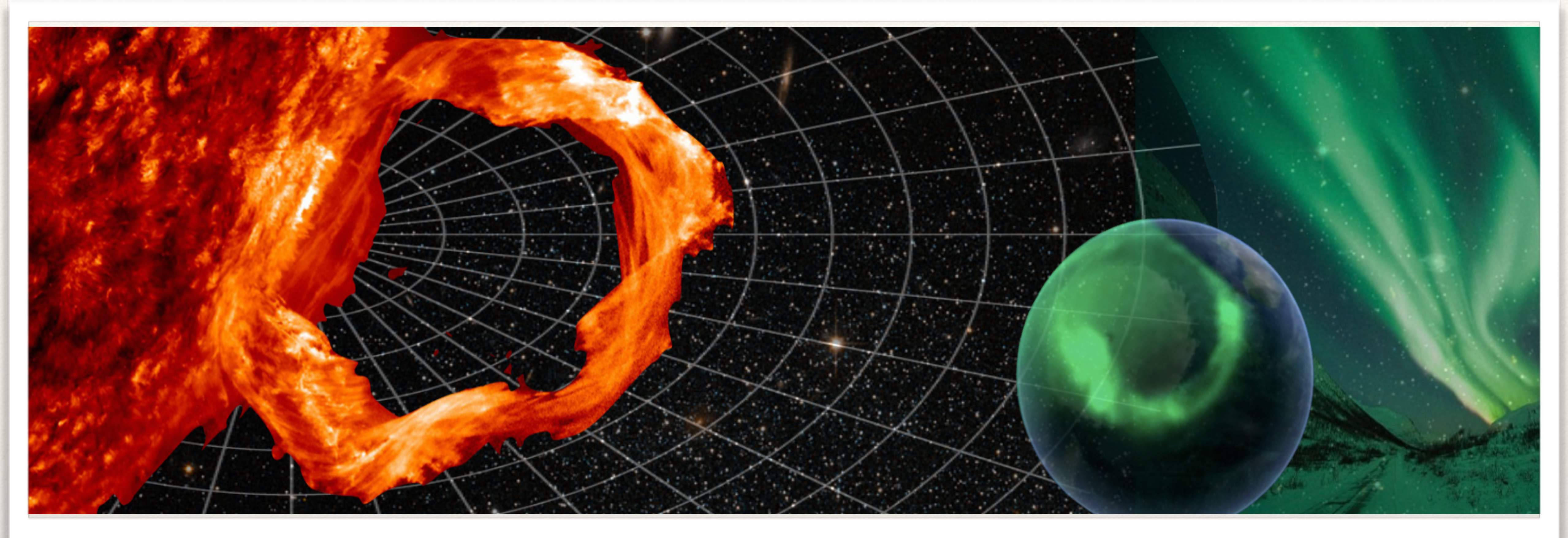
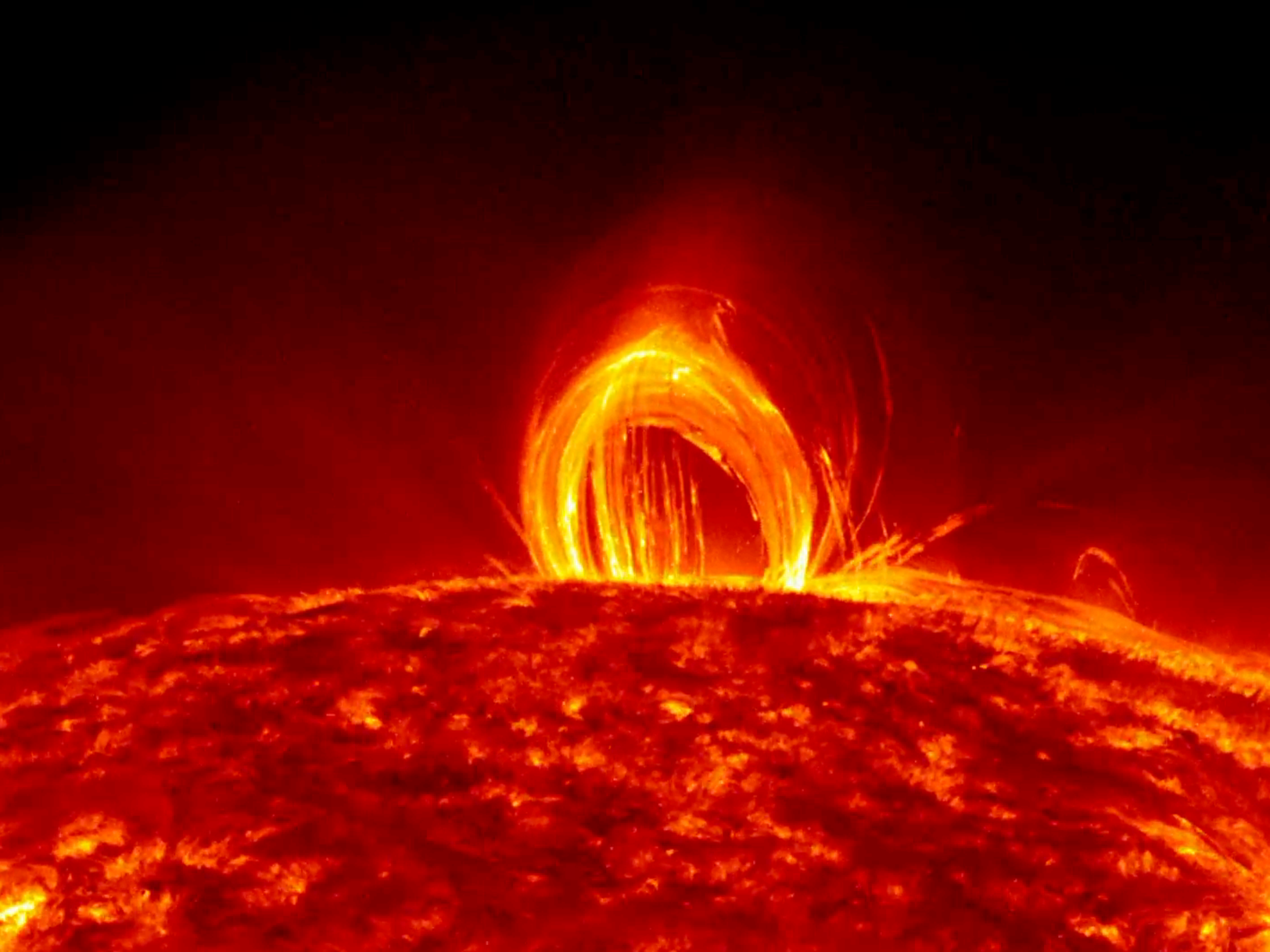


Plasmas: The Sun-Earth Connection

Jacob Trier Frederiksen

Niels Bohr International Academy



Today’s Programme

- Part I: Plasmas (“classical” electro-magnetic plasmas)
- Part II: The Sun-Earth Plasma Connection
- Part III: Solar Storms, Revisited & Modelled
- Part IV: Solving a Puzzle — The Road Ahead

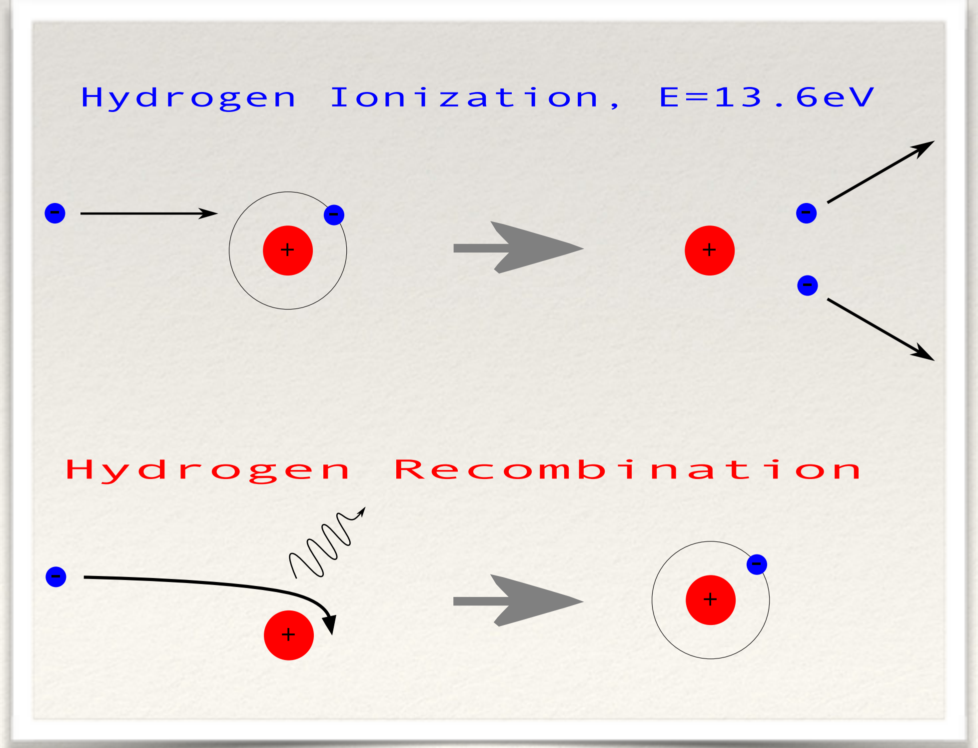
“Classical” Electromagnetic Plasmas

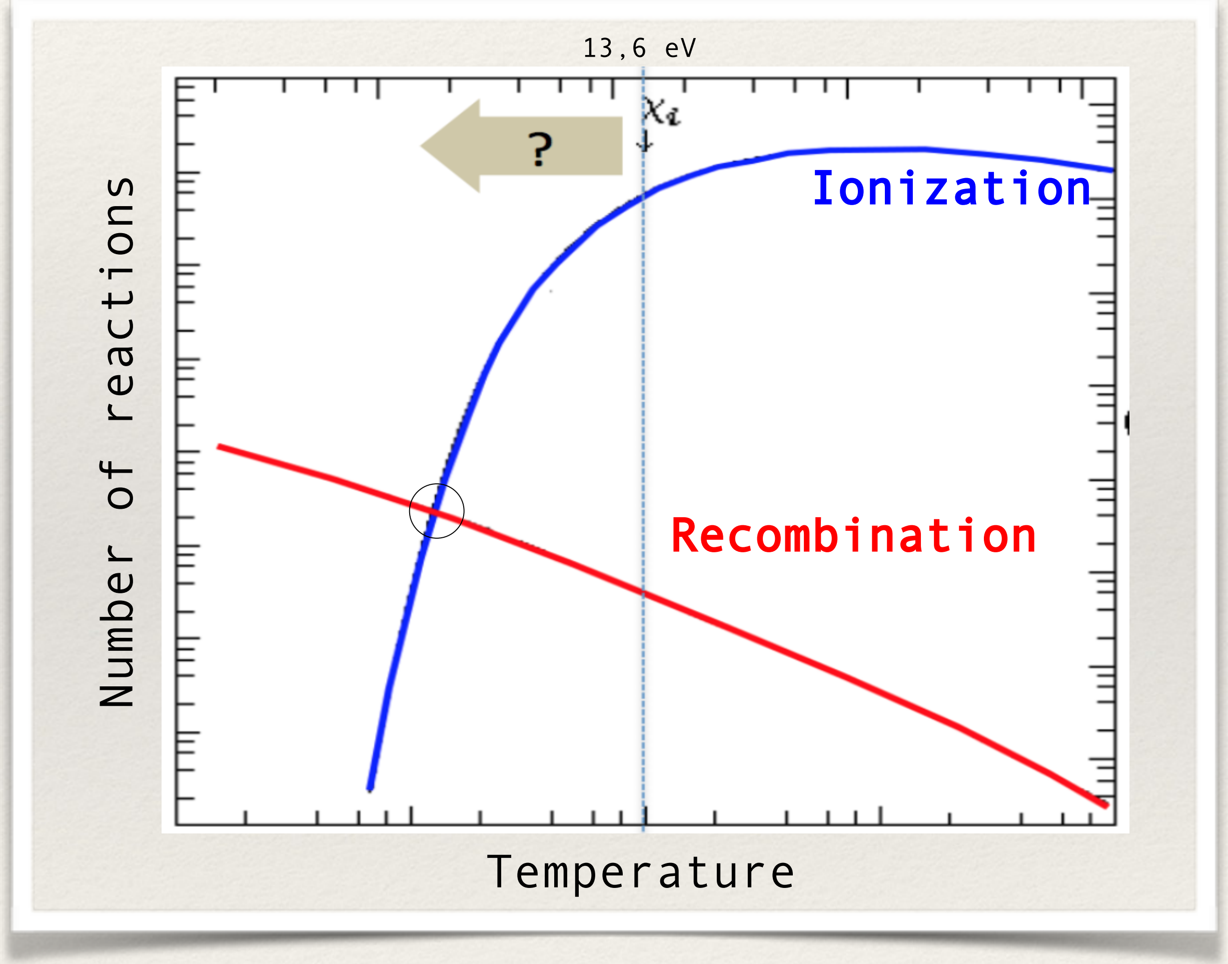
Part I

- Ionized gases
- Plasmas in the Universe
- Plasmas physical descriptions

Plasmas: Ionized Gases.

- Partially or fully ionized gases.
- Free electrons and nuclei.
- Highly electrically conducting.
- “Gas” can be magnetized.





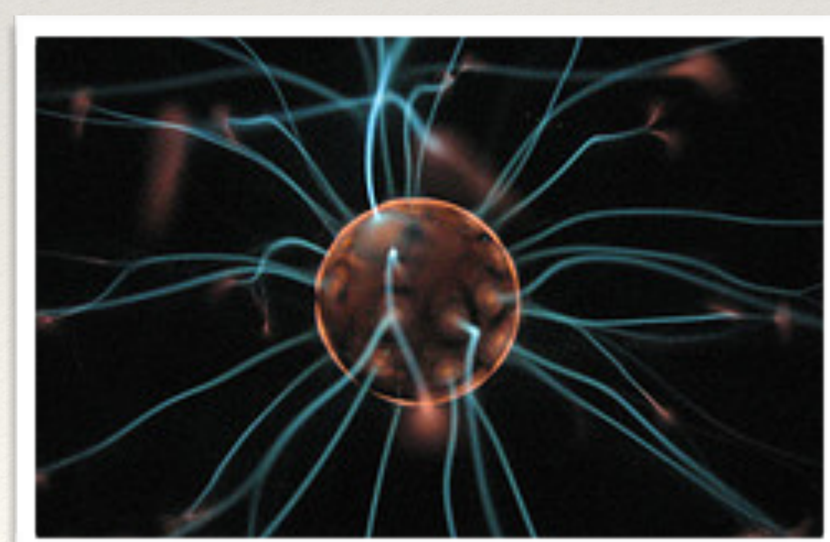
Plasmas: A Fourth State of Matter?

Solids

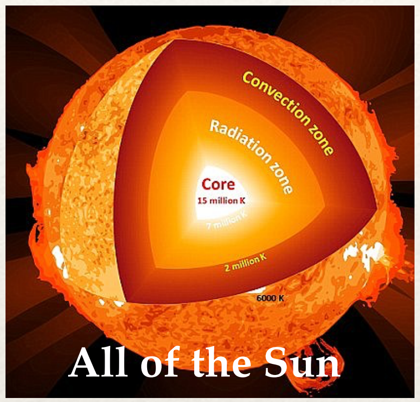
Fluids

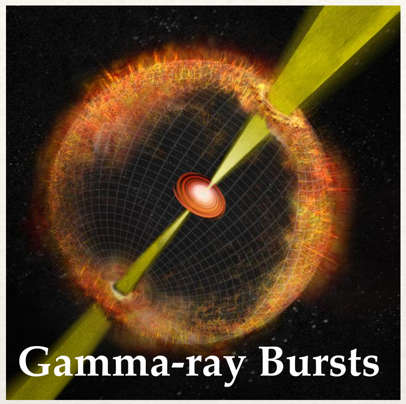
Gases

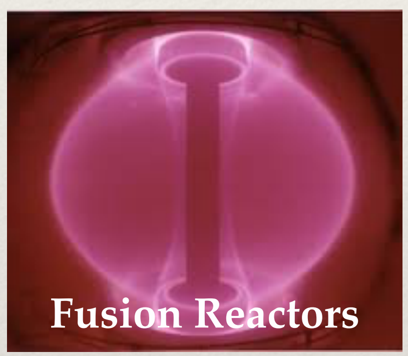
Plasmas

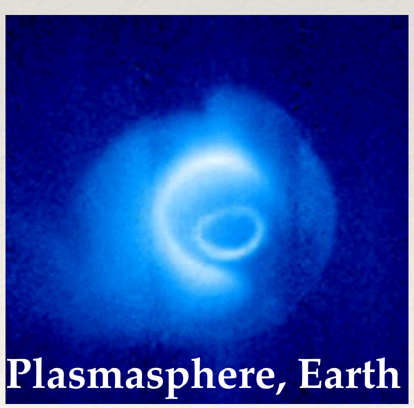


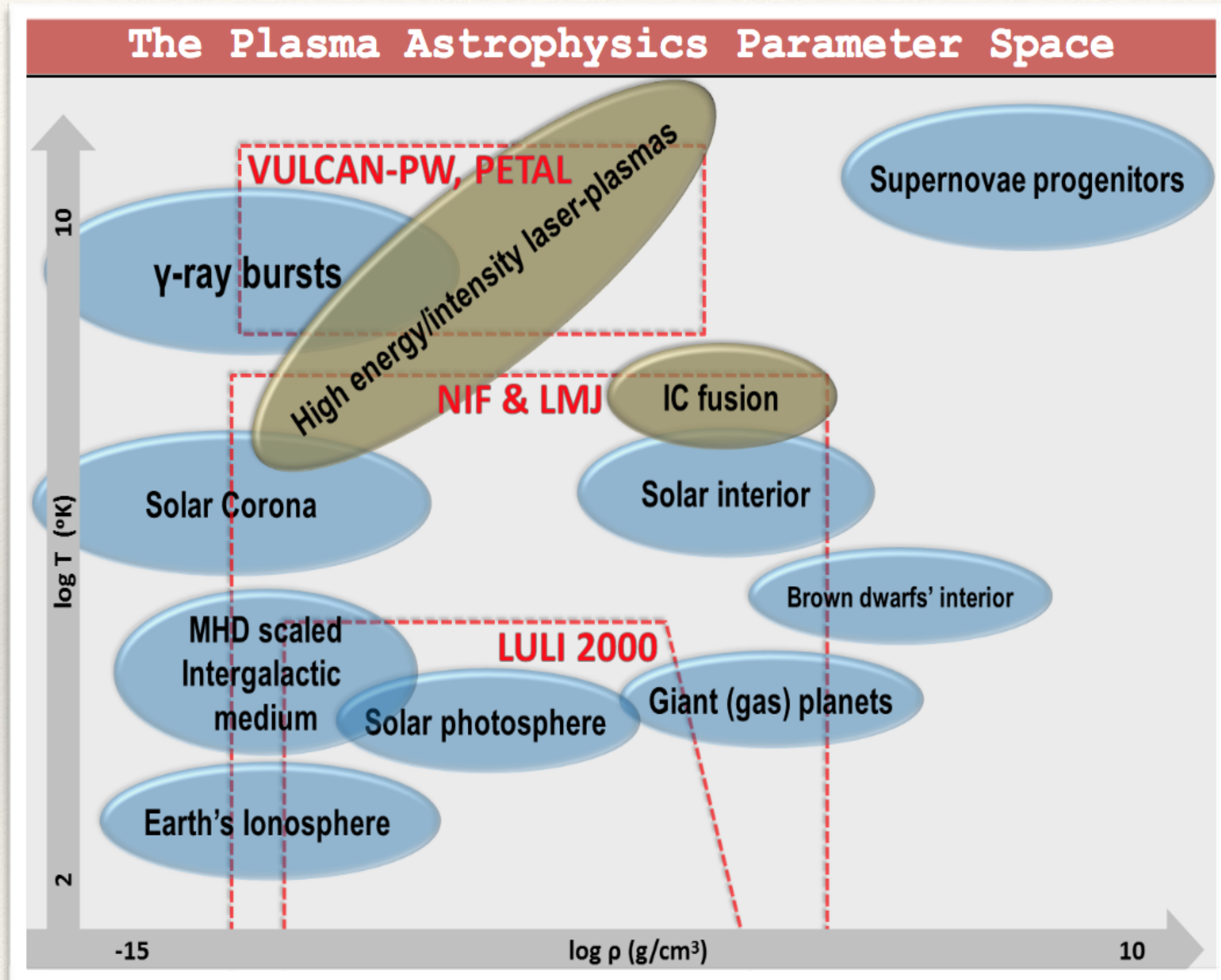
Plasmas: where do we find them?



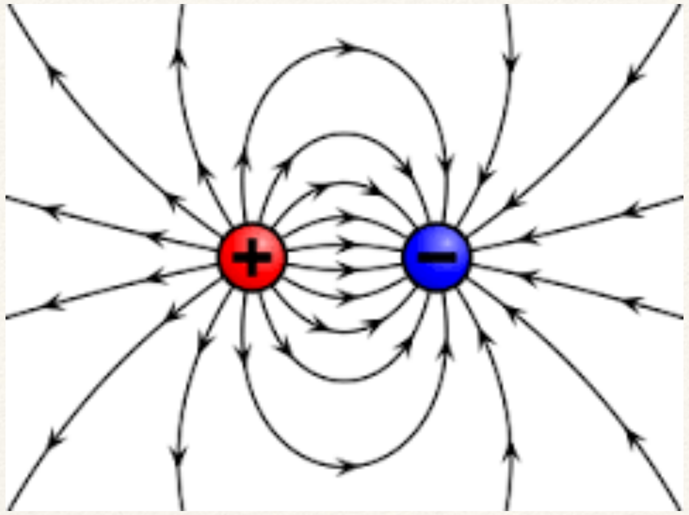




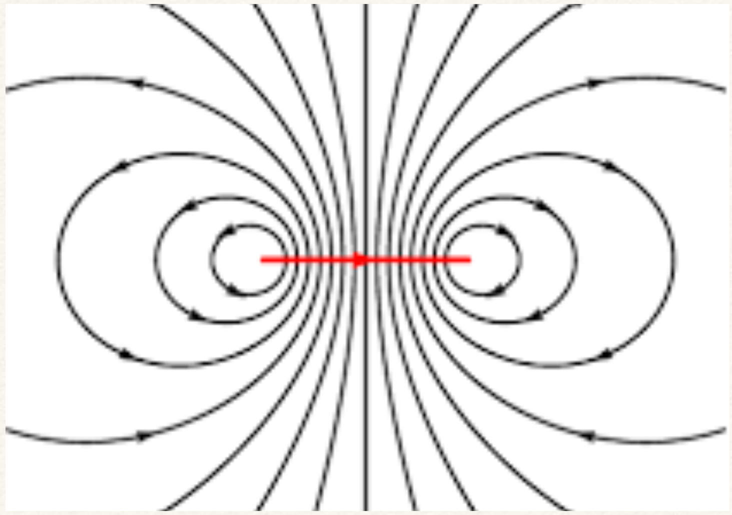




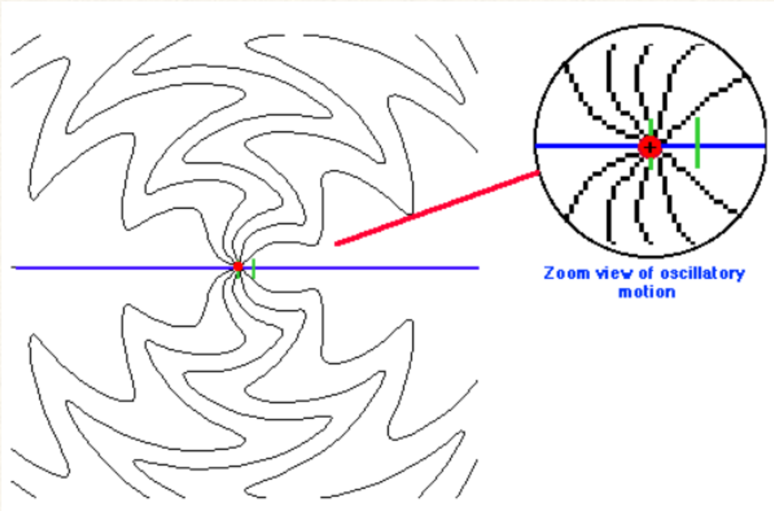
- Everywhere
- More than 90% visible baryonic matter likely in plasma state



Electricity



Magnetism



Electromagnetism

$$\nabla \cdot \mathbf{B} = \mathbf{0}$$
$$\nabla \cdot \mathbf{E} = \frac{4\pi\rho_c}{\epsilon_0}$$

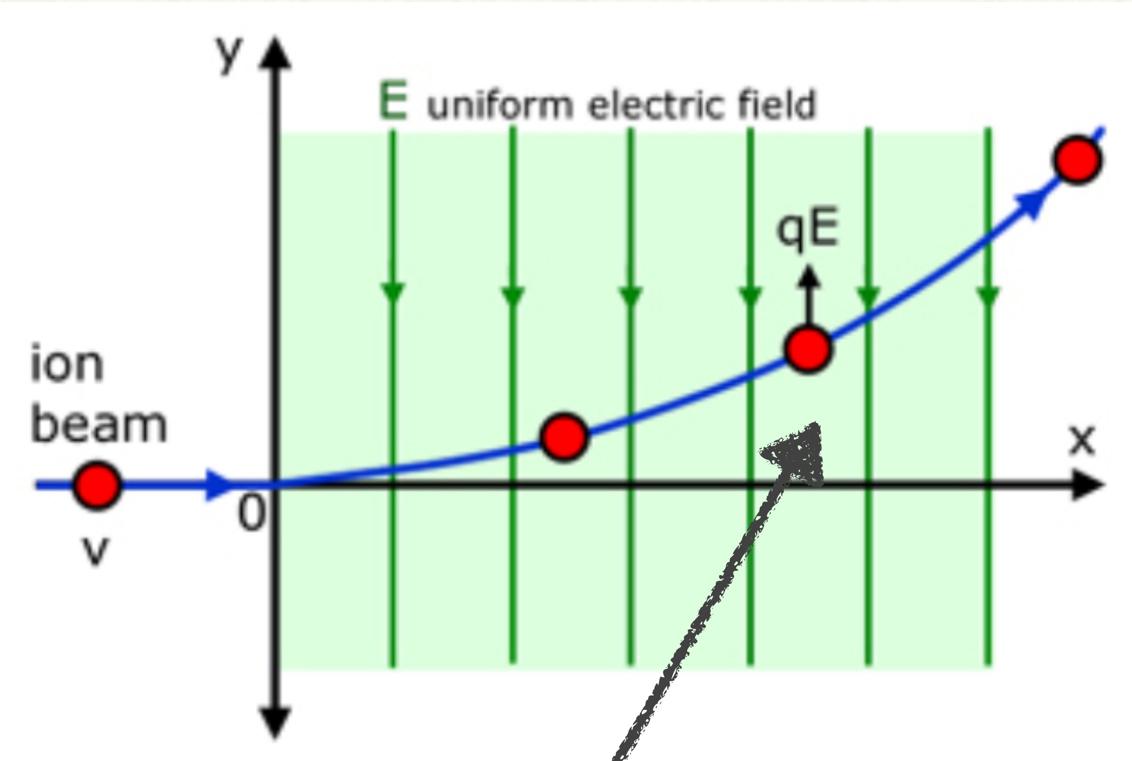
$$\frac{1}{c}\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$
$$\frac{\epsilon_0}{c}\partial_t \mathbf{E} = \frac{1}{\mu_0}\nabla \times \mathbf{B} - \frac{4\pi}{c}\mathbf{J}$$

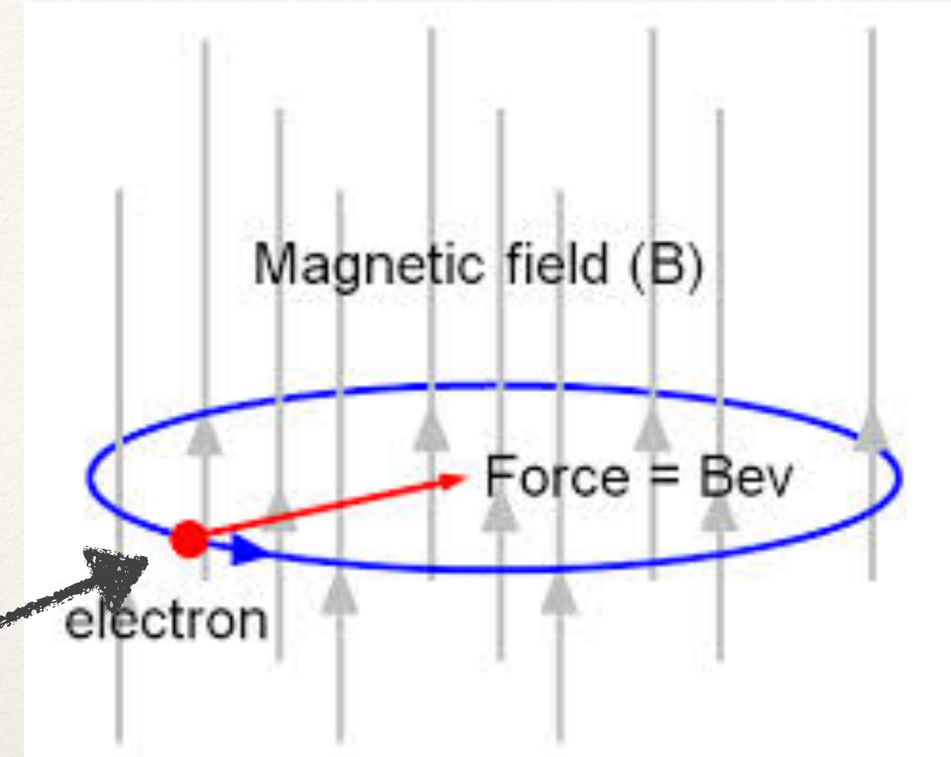
Charged Particle Fields

Plasmas: How Can We Describe Them?

Charged particles have an electric field, **E**, and a magnetic field, **B**, if they move and are accelerated.

We need Maxwell's Equations





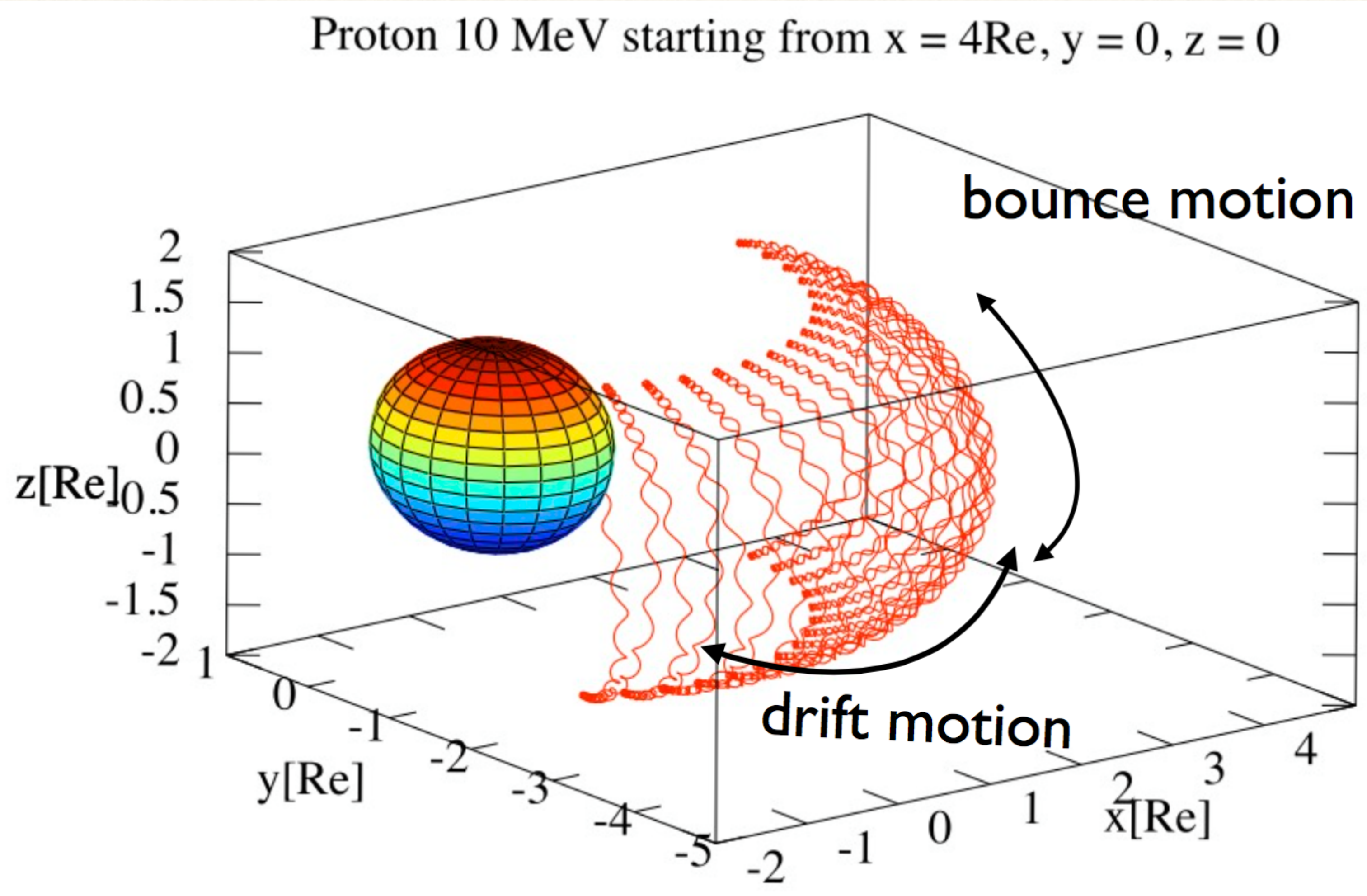
$$\mathbf{F}_{L,s} = \frac{d\mathbf{p}}{dt} = q_s(\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B}) \quad [+m_s\mathbf{g} + ...]$$

$$\mathbf{p}_s = m_s\mathbf{v}\gamma(v) = \frac{m_s\mathbf{v}_s}{\sqrt{1-\beta^2}}$$

Charged Particle Motion

Plasmas: How Can We Describe Them?

Charged Particles can be forced by electric and magnetic fields.
We need the Lorentz Force.



Earths magnetosphere modeled with magnetic dipole

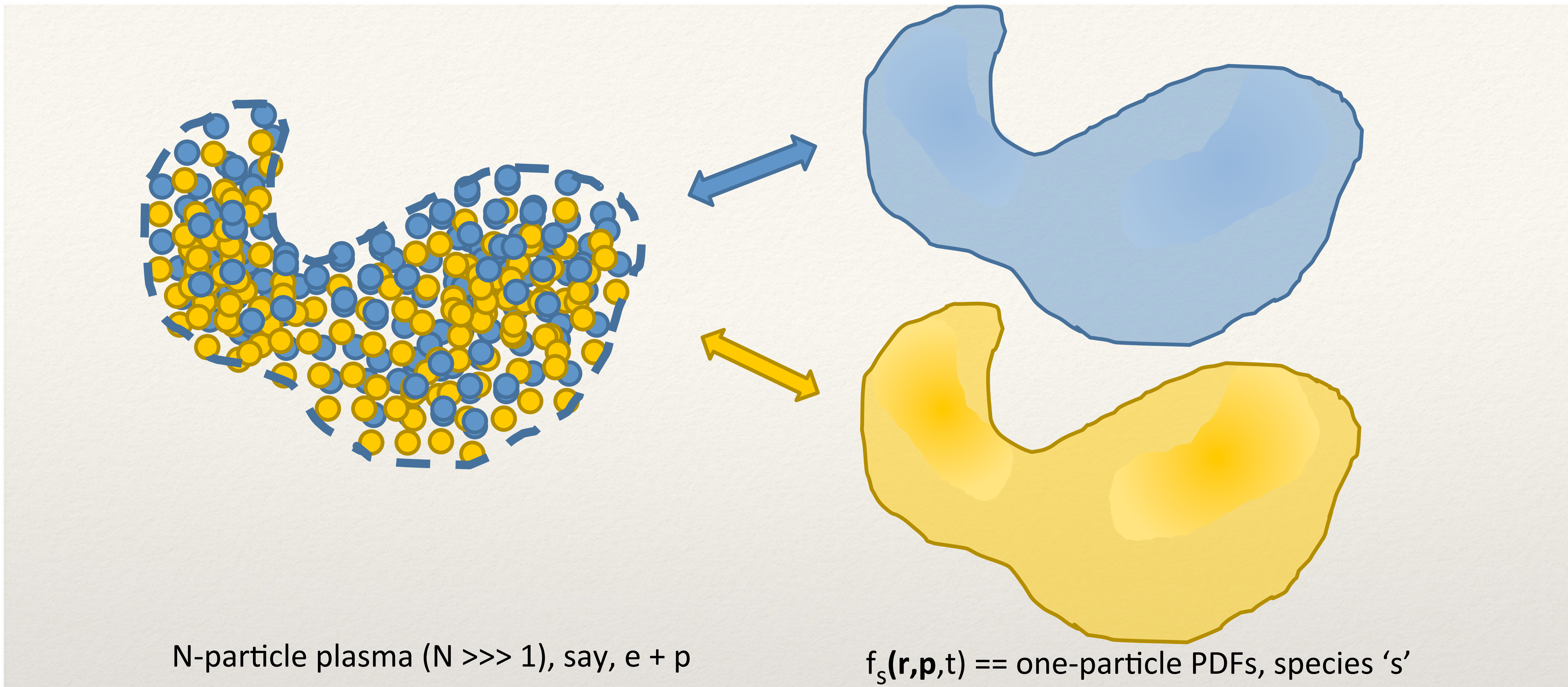
Charged Particle Motion

Plasmas: How Can We Describe Them?

Charged Particles will generally experience drift in electromagnetic fields and EM fields with gradients.

“OK, that was one particle — but a plasma is MANY particles?!?”

Yes.



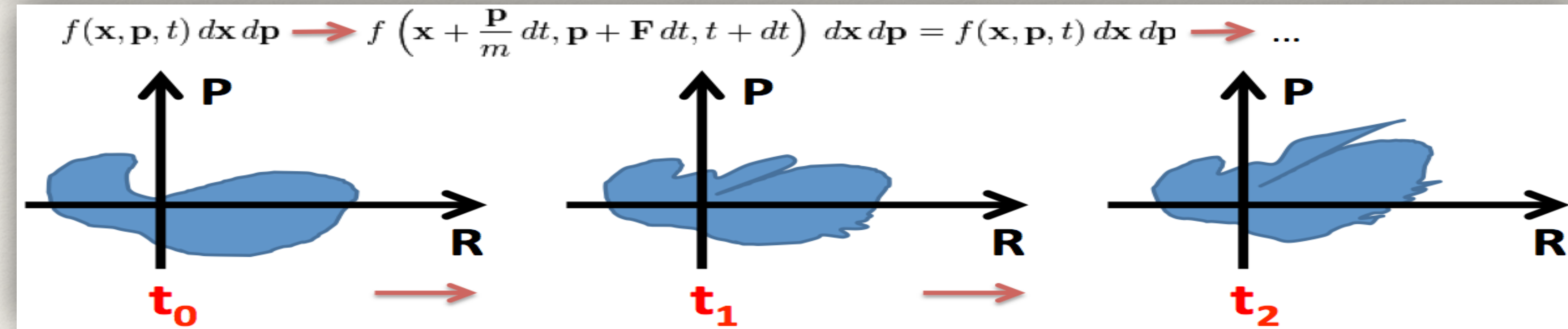
Many particles we can make into a continuum particle distribution

Plasmas: Many-particle systems

Consider many particles!

They are now *almost* a continuum.

We can define macroscopic variables, **J** and rho (charge density).

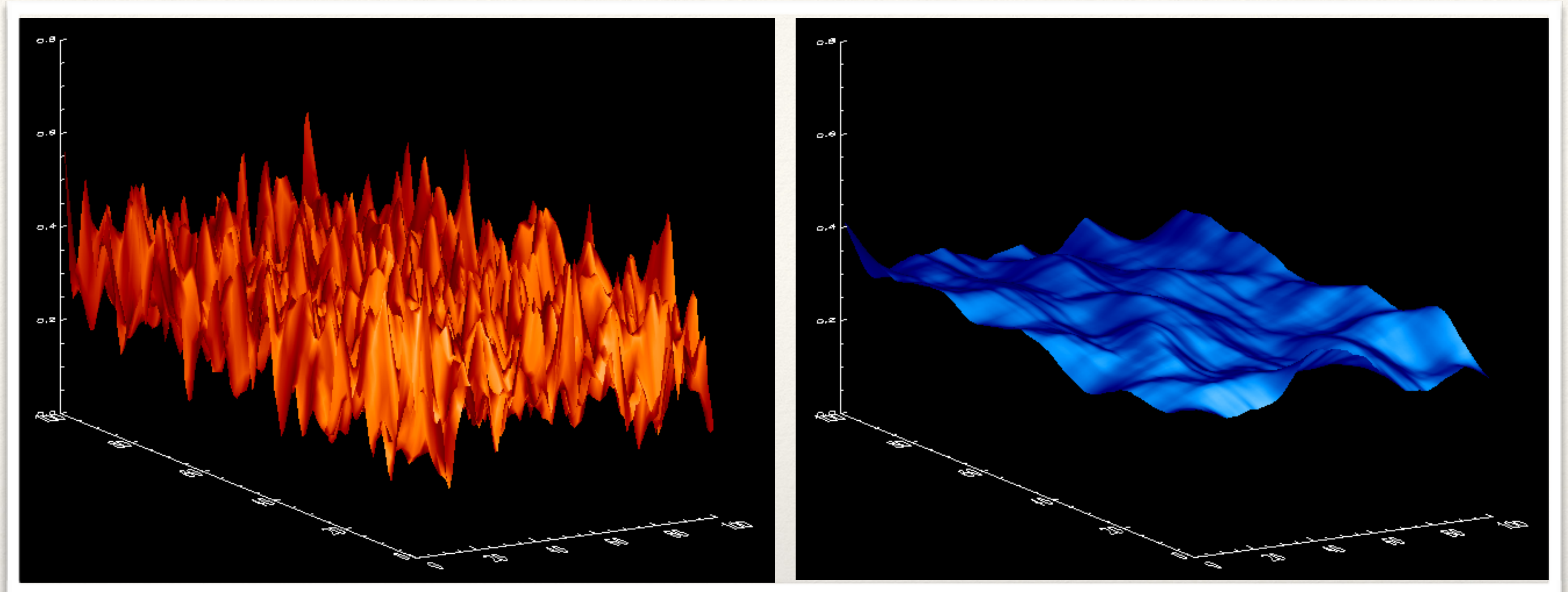


$$\frac{\partial f^i}{\partial t} + \frac{\boldsymbol{p}}{m^i}\cdot\frac{\partial f^i}{\partial \boldsymbol{x}} + \boldsymbol{F}\cdot\frac{\partial f^i}{\partial \boldsymbol{p}^i} = \left.\frac{\partial f^i}{\partial t}\right|_{coll}$$

Almost there….

Plasmas: the Boltzmann Equation

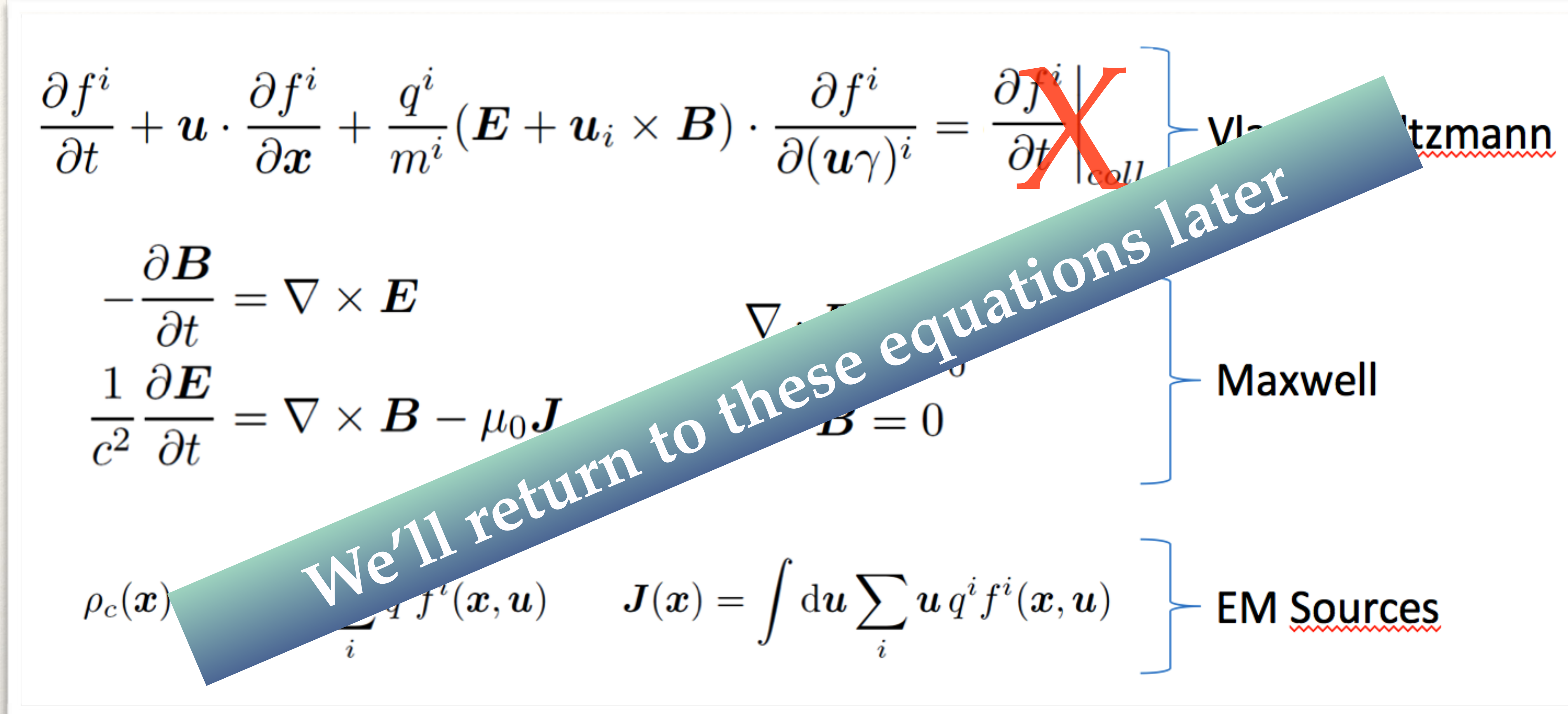
Describes how a distribution (of many, many, particles) evolves with time under forcing.



Assume collective behavior, smooth away all particle-particle (direct) interactions

Plasmas: the Vlasov Contribution

Vlasov's point of view: Electromagnetic fields are smooth mean fields produced collectively and self-consistently by all particles (+ext fields).



Plasmas: the Full-blown Set of Equations for Plasmas

Very very complicated, yet, still a gross approximation.

The 'Vlasov-Maxwell' System

“Gimme a break — Please.”

[5 minutes]

The Sun-Earth Plasma Connection & Solar Storms

Part II

- The Sun's magnetic cycle
- Solar storms
- Earth's space environment
- Space weather
- Climate questions…

Ideer

\# 39 30. september 2011 15

FOTO: NASA

Solstorm og nordlys

Måske var De en af de heldige, som natten til den 27. september kunne nyde nordlyset over Danmark. Det skyldtes, at en kraftig solstorm ramte Jordens atmosfære. Stormen, der består af magnetisk ladede partikler, havde sit udspring i et udbrud fra solplet nummer 1302 i mandags. Solpletten har allerede haft to tidligere udbrud den 22. og 24. september.

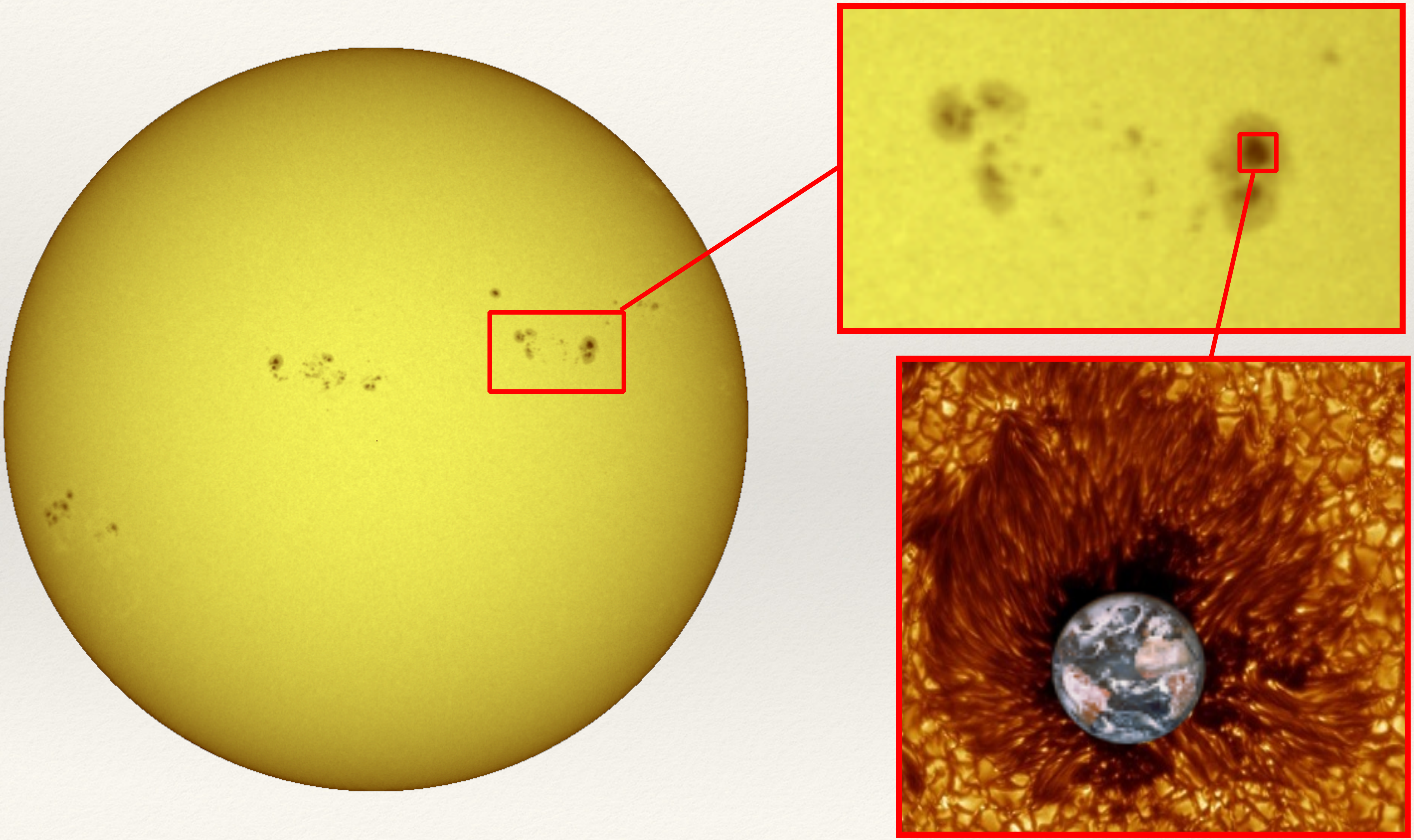
"Today's Space Weather"

Danish Media

One-half Solar Cycle Ago…

Cycle #24 approaching peak in '13-'14-ish..

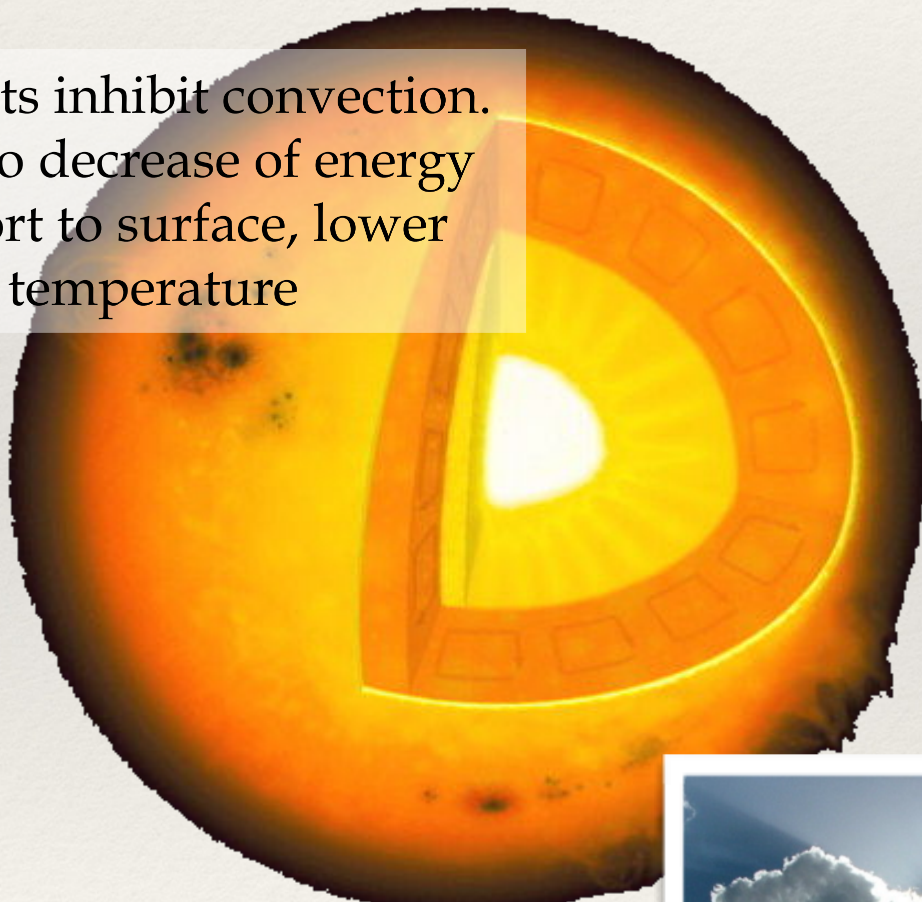
The Sun's "Surface" - The Photosphere



Our Star

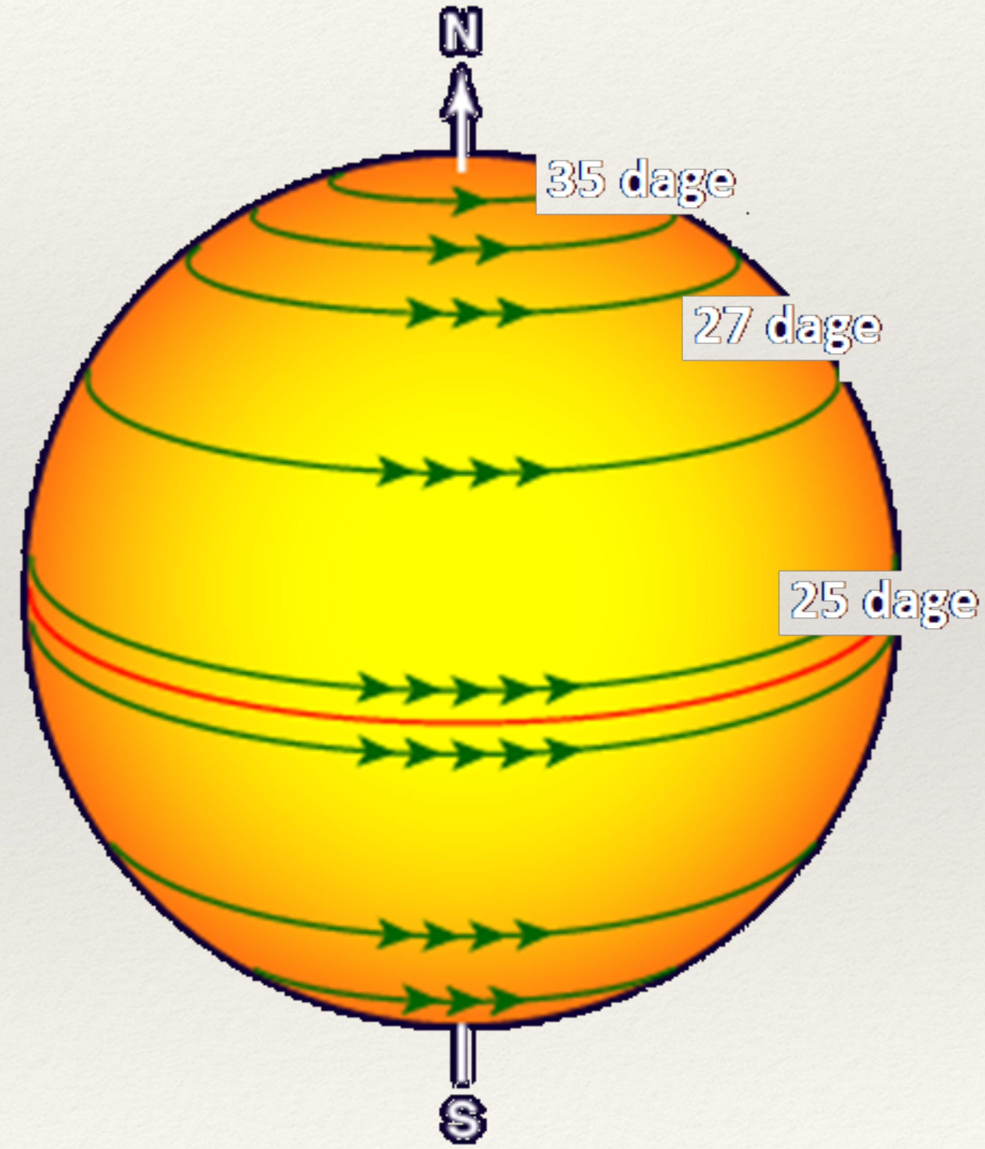
Stellar Structure of the Sun

Sunspots inhibit convection. Leads to decrease of energy transport to surface, lower surface temperature

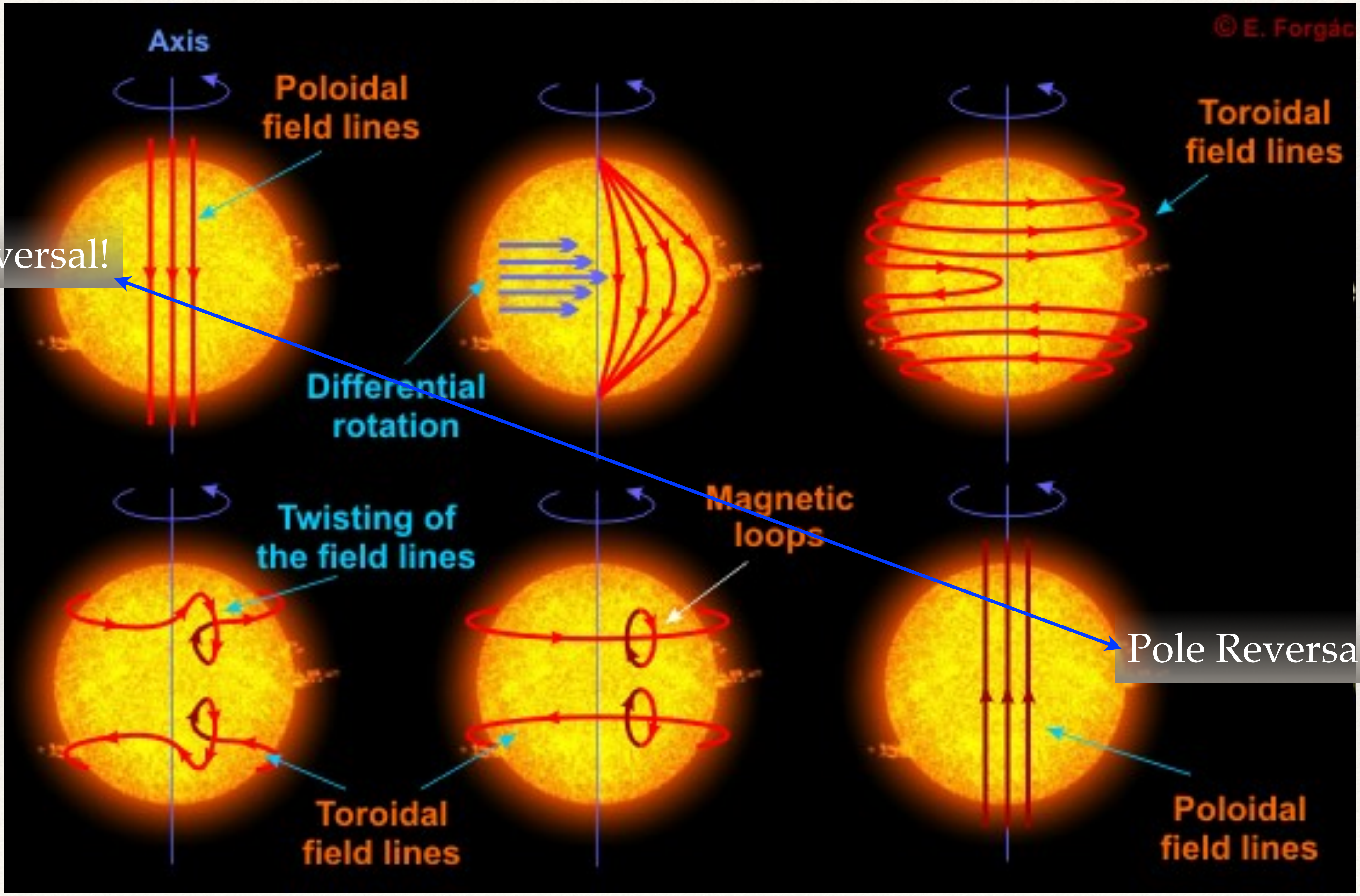


The photosphere is very thin, only about **0.04%** R_{sun}!!

The Sun's Surface Rotation



Theory of Sun Spot Generation

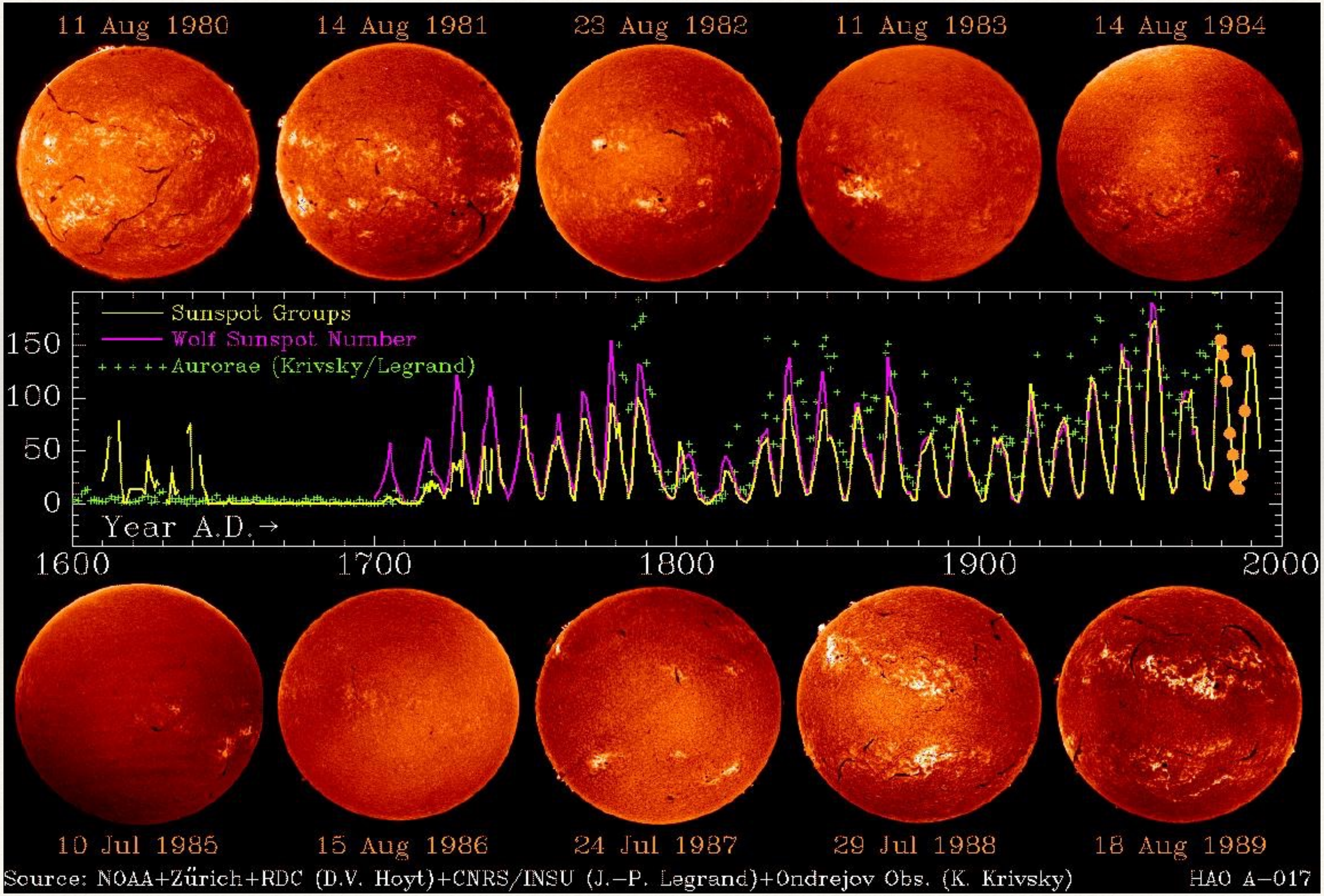


Pole reversal!

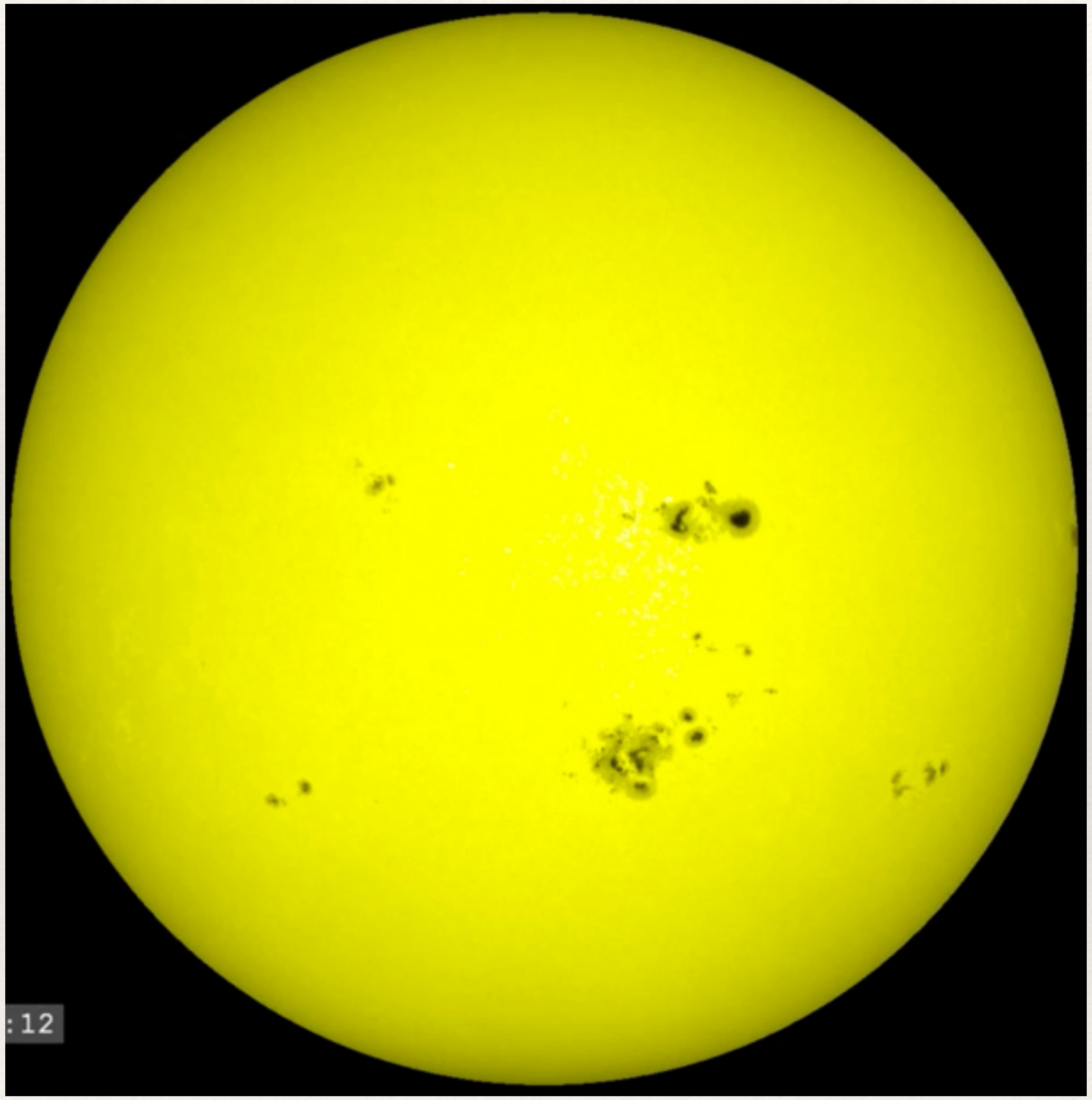
Pole Reversal!

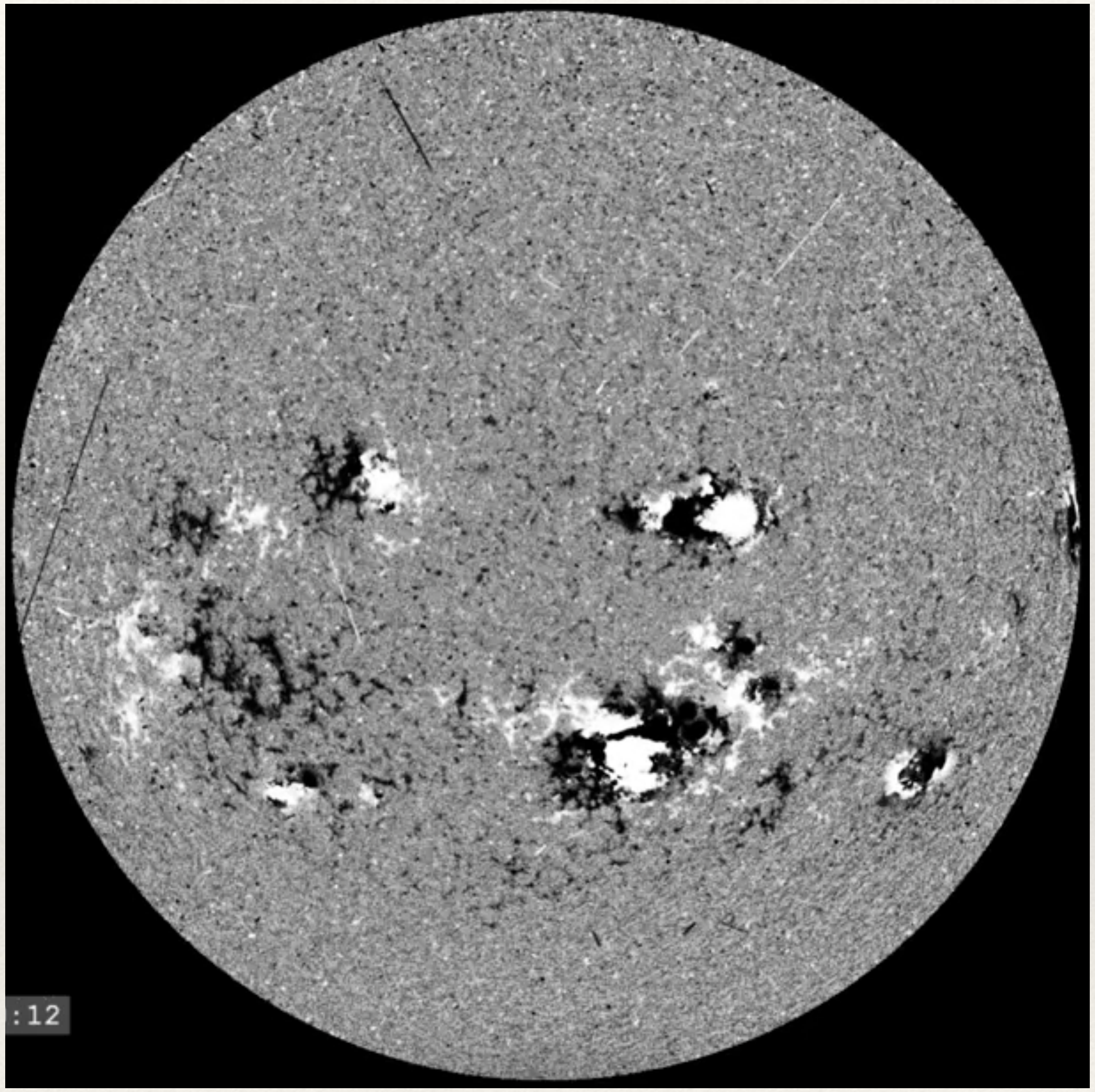
Sunspots – A (very) Brief History…

Cycles #21 & #22 (max-to-max)

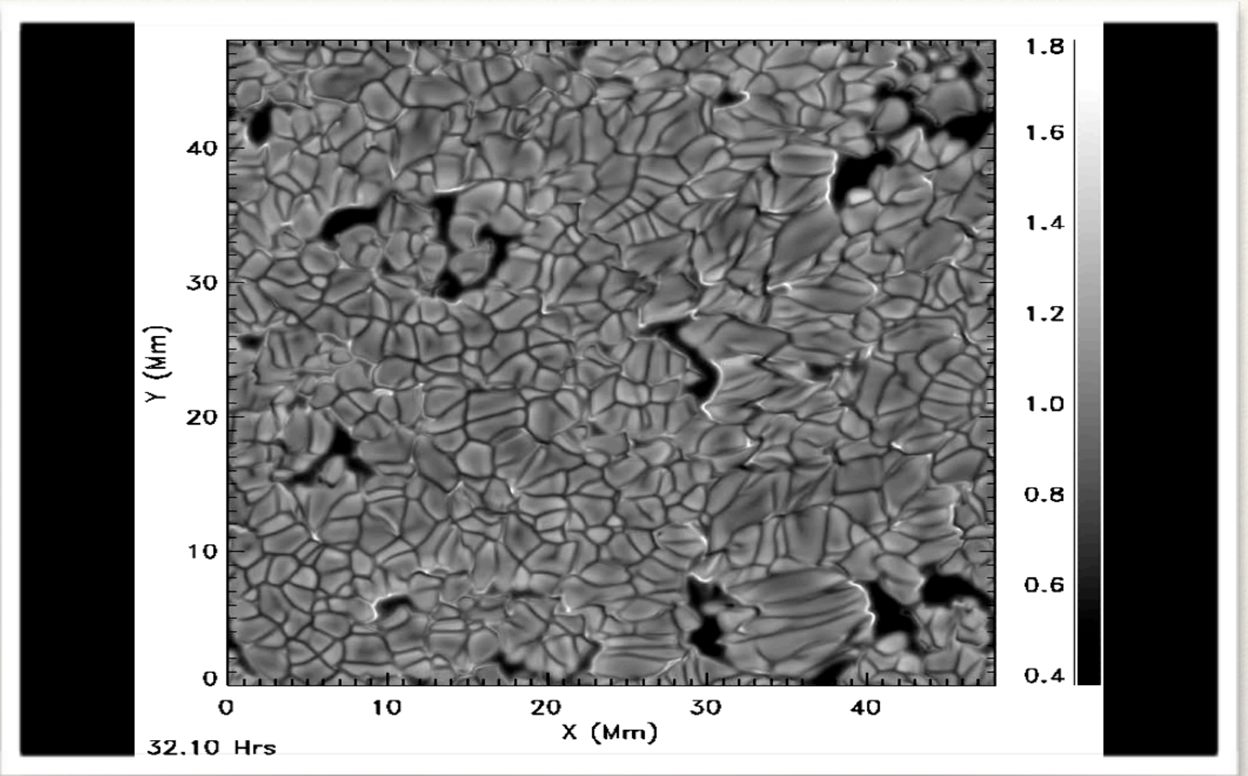


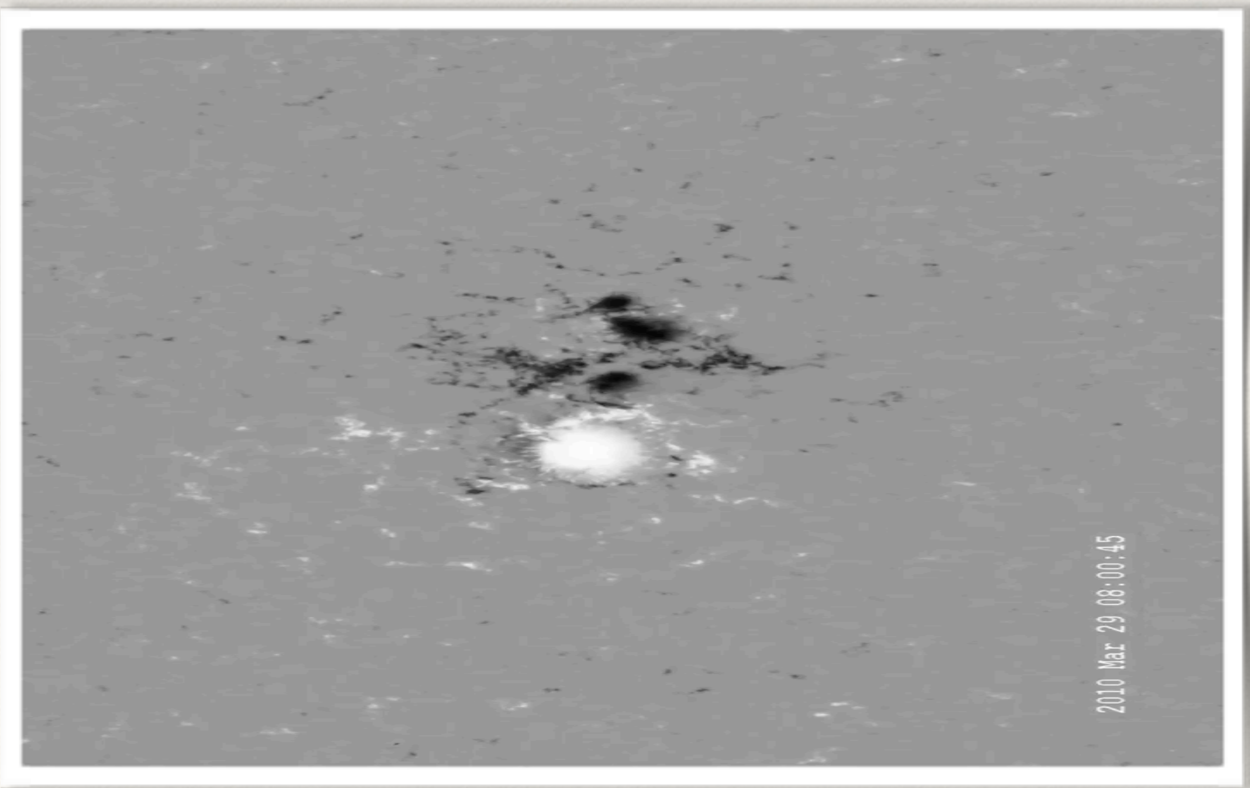
Sunspots = Magnetic Flux Emergence

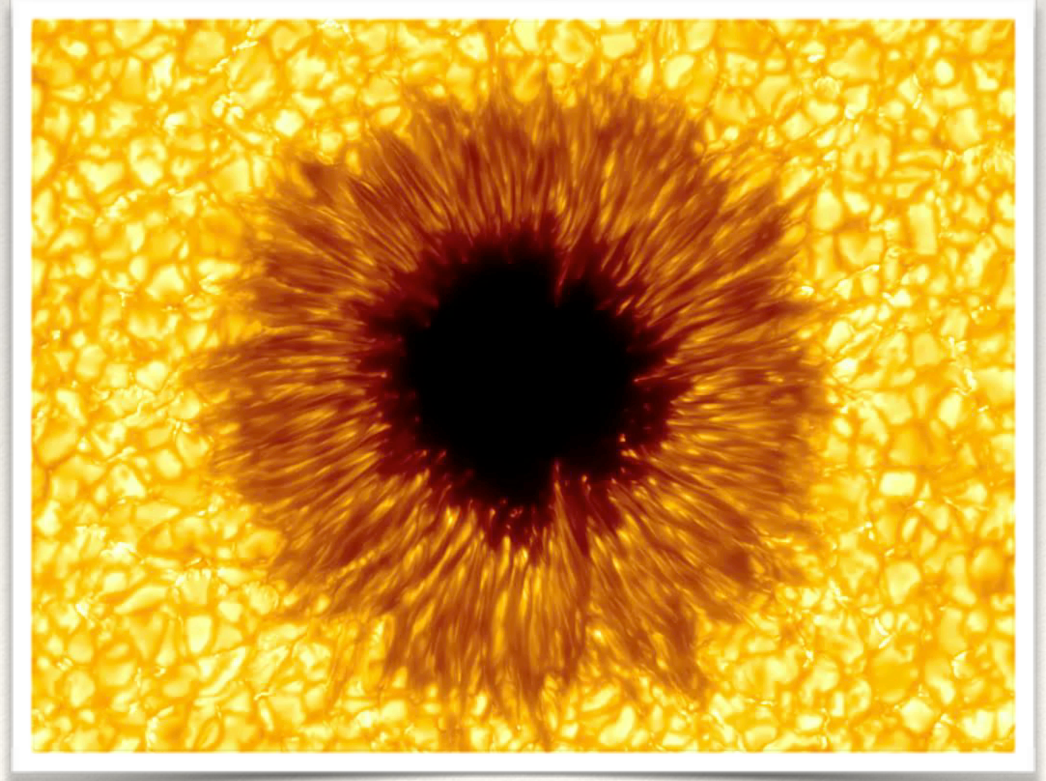




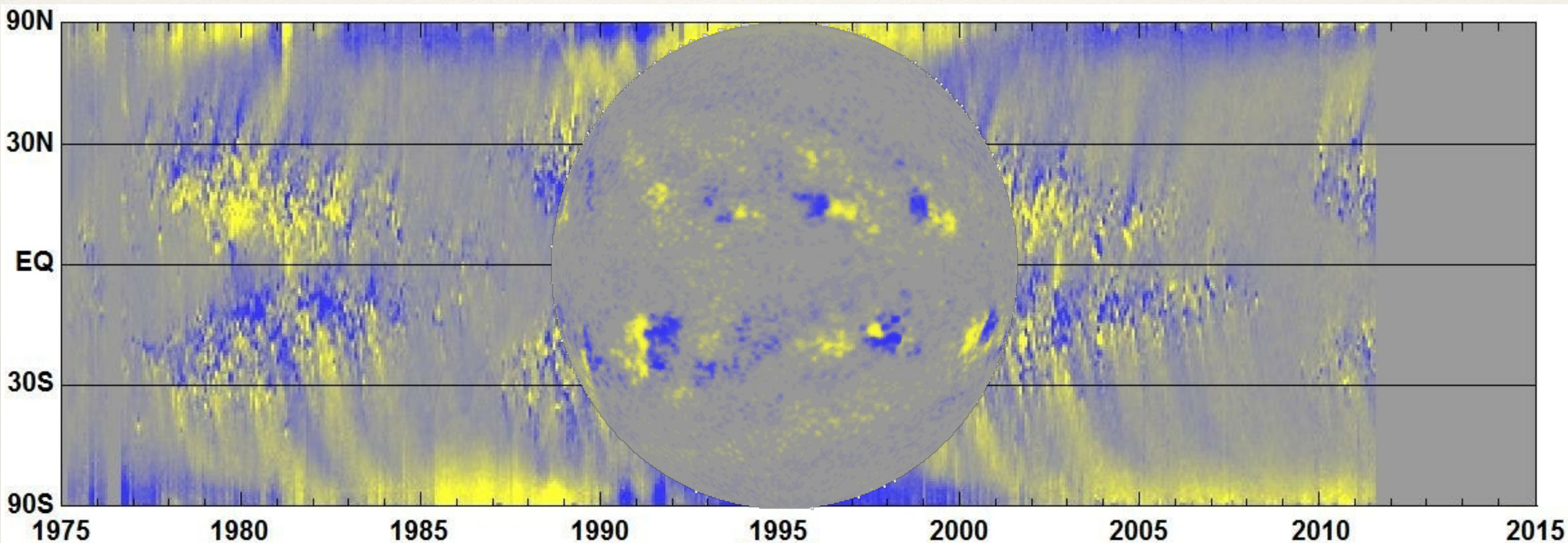
Sunspots = Magnetic Flux Emergence





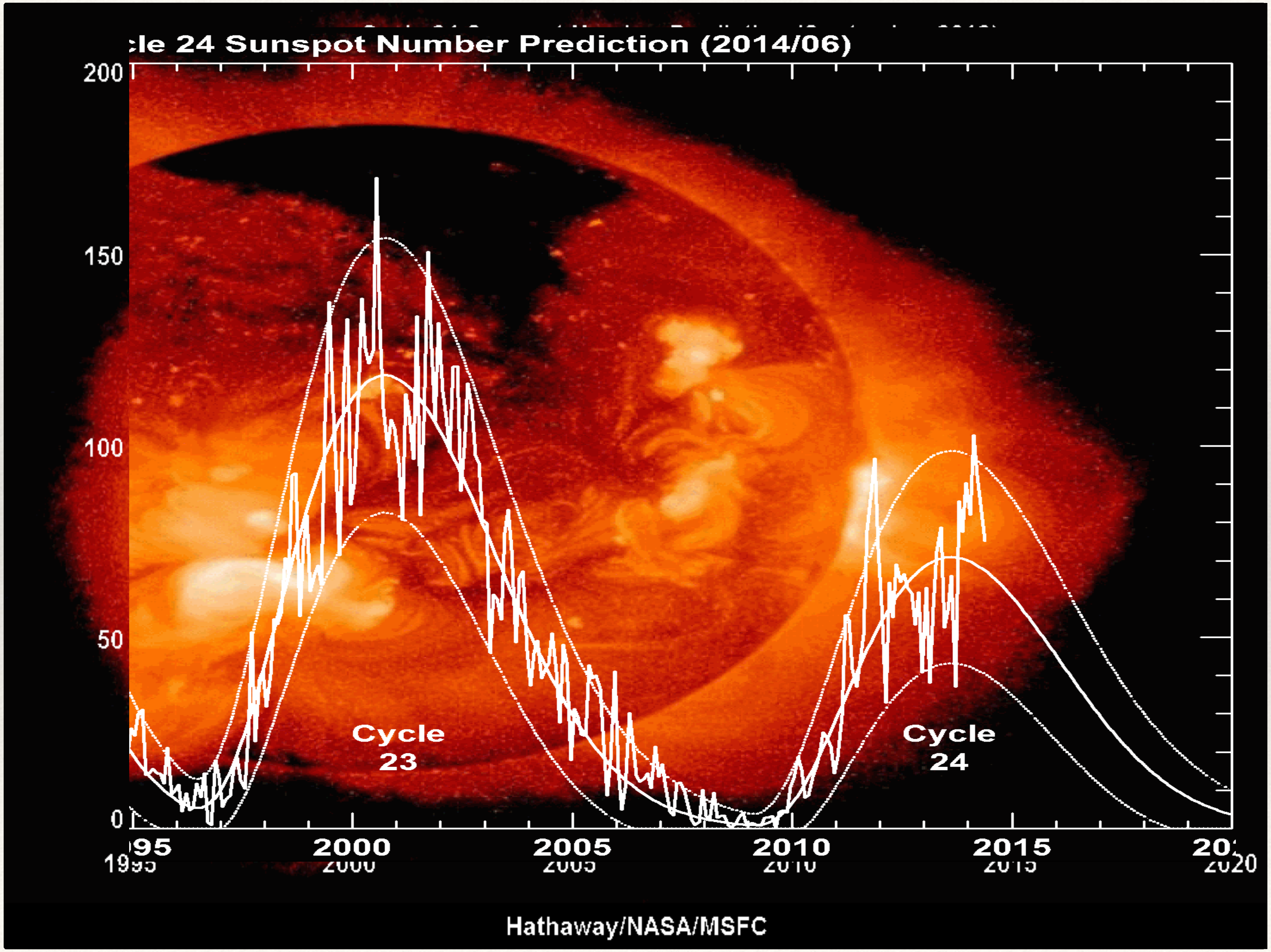


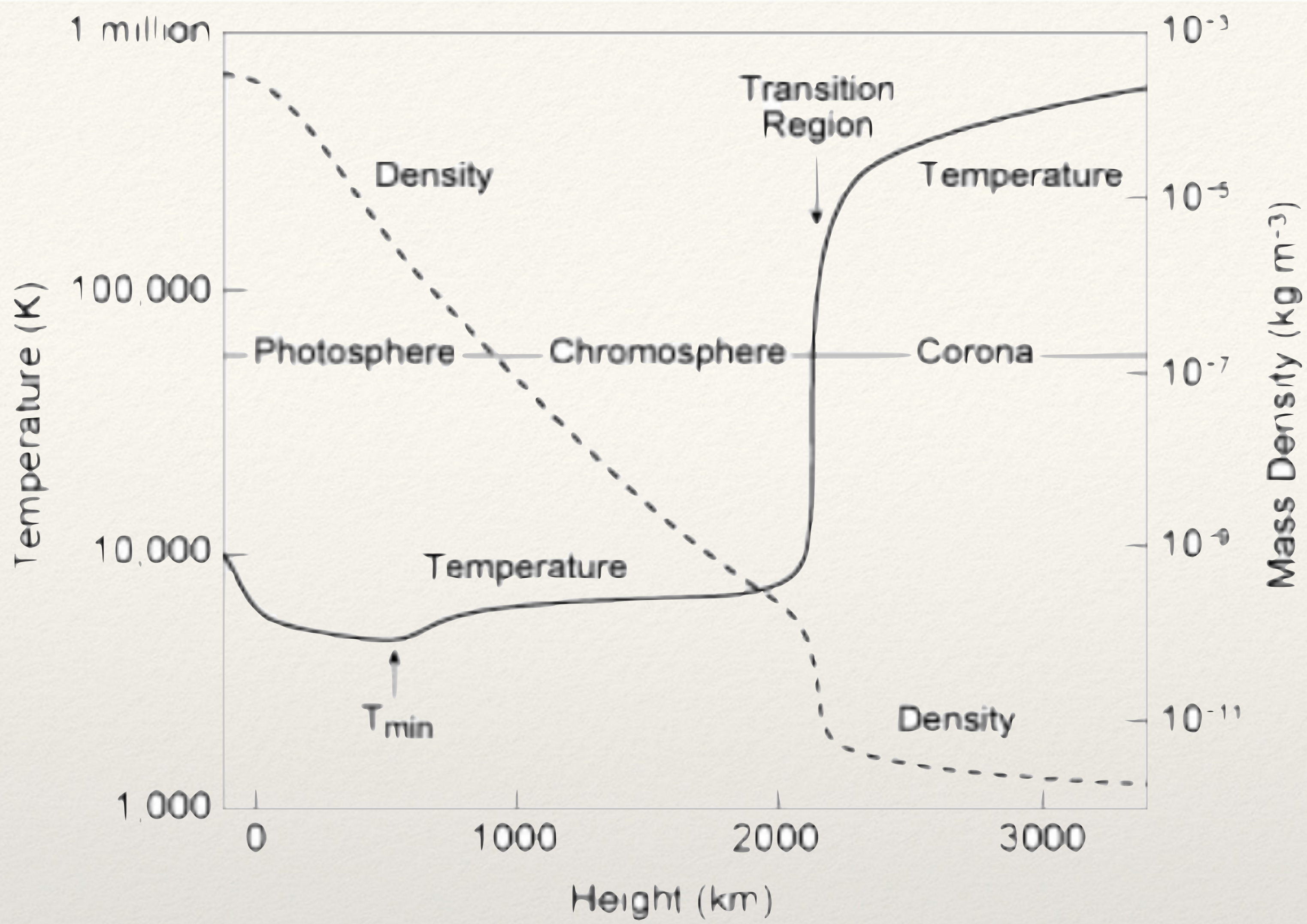
Solar Cycles – Deconvolved



Credit: D. Hathaway, NASA

Solar Cycle #24 – Maximum Prediction Revisited

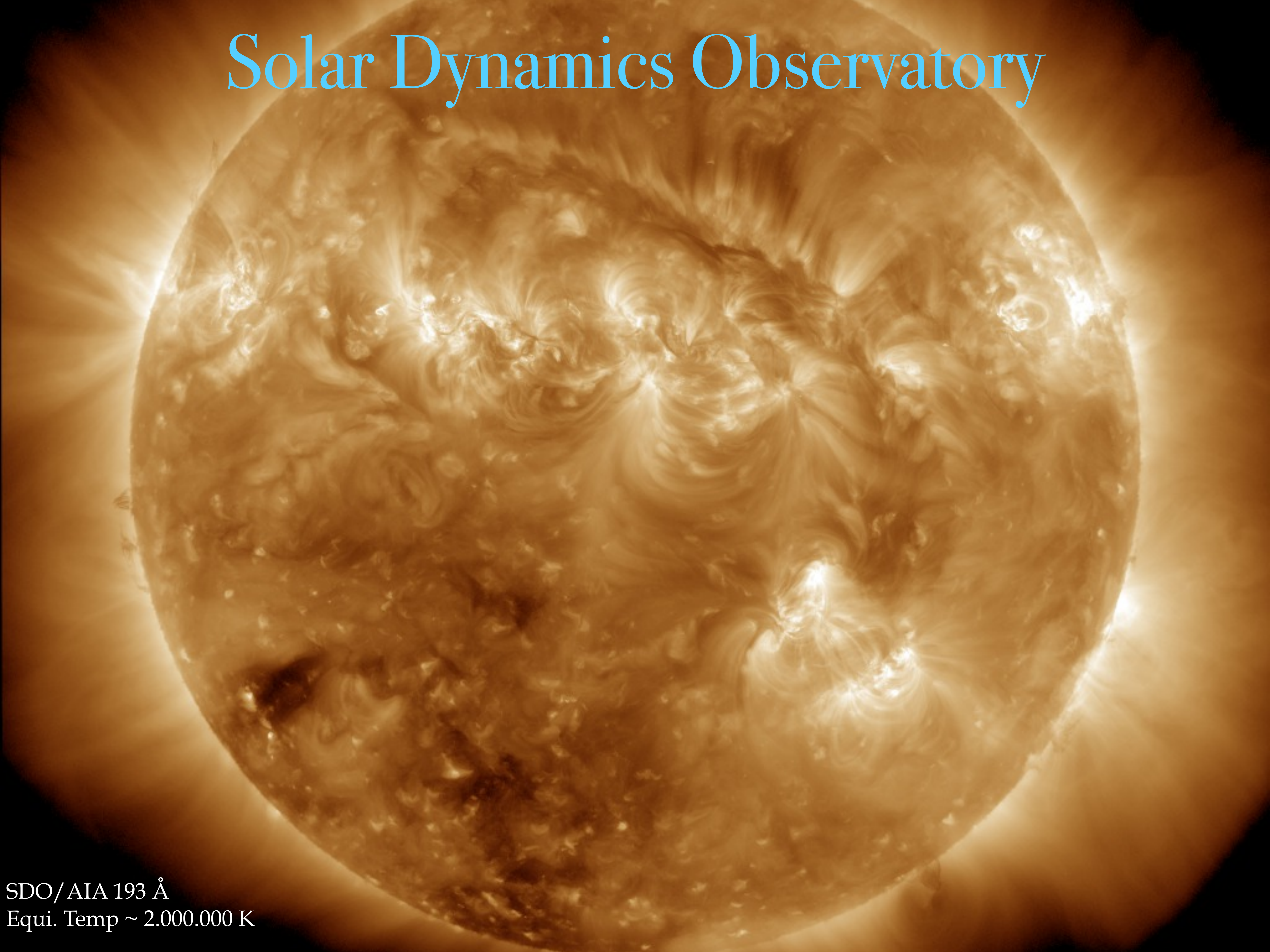




Extreme Profile

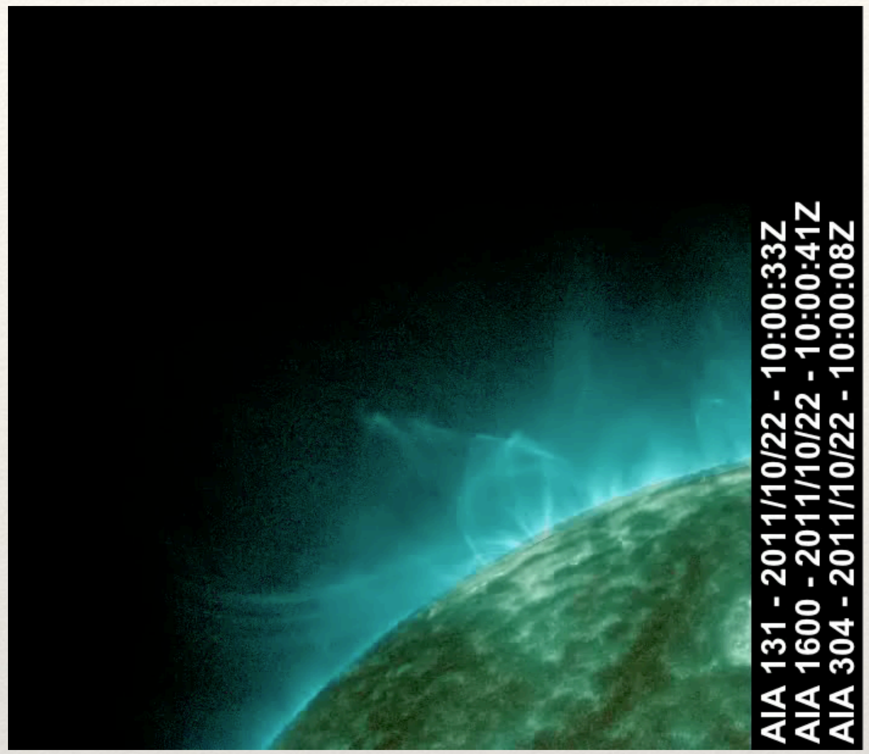
The Solar Atmosphere

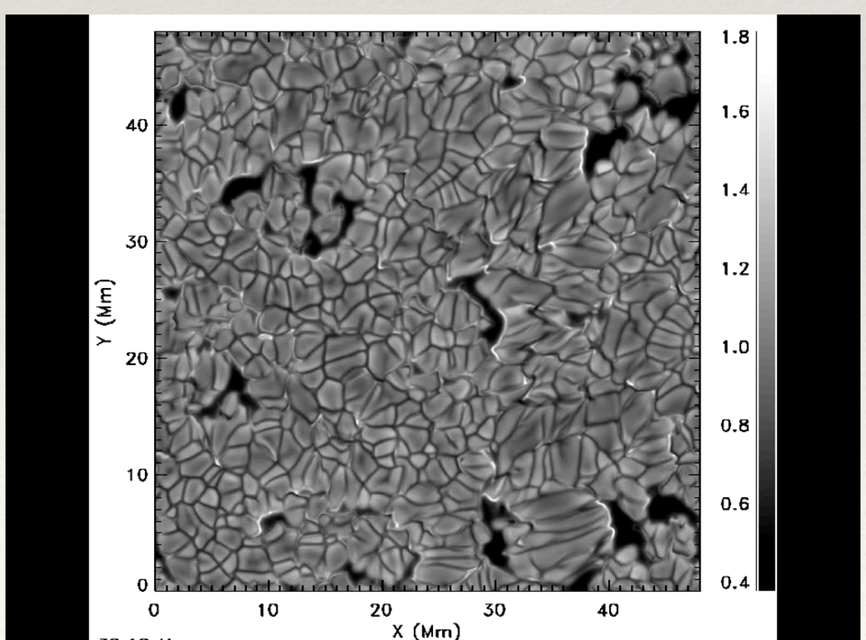
Solar Dynamics Observatory

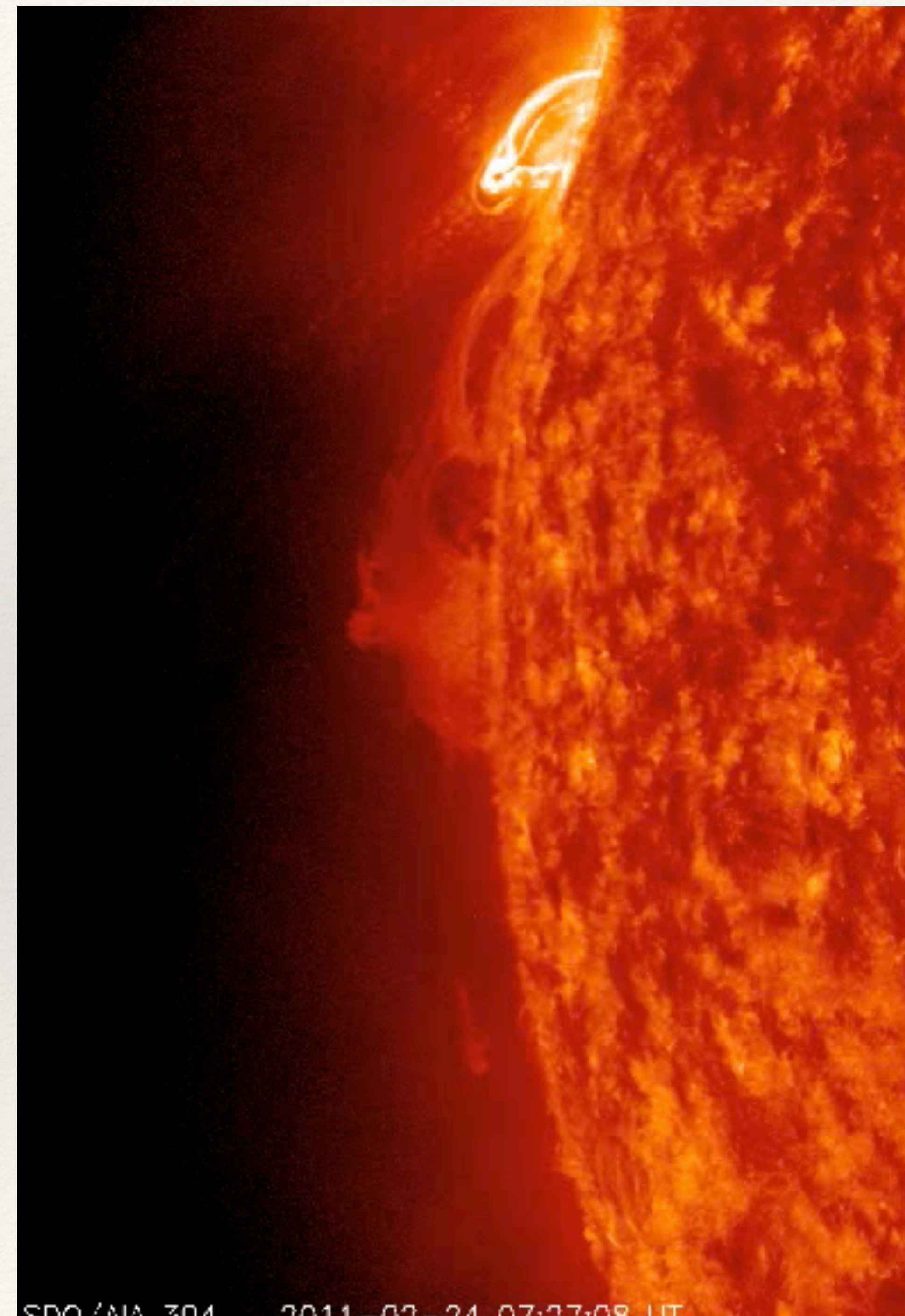


SDO/AIA 193 Å
Equi. Temp ~ 2.000.000 K

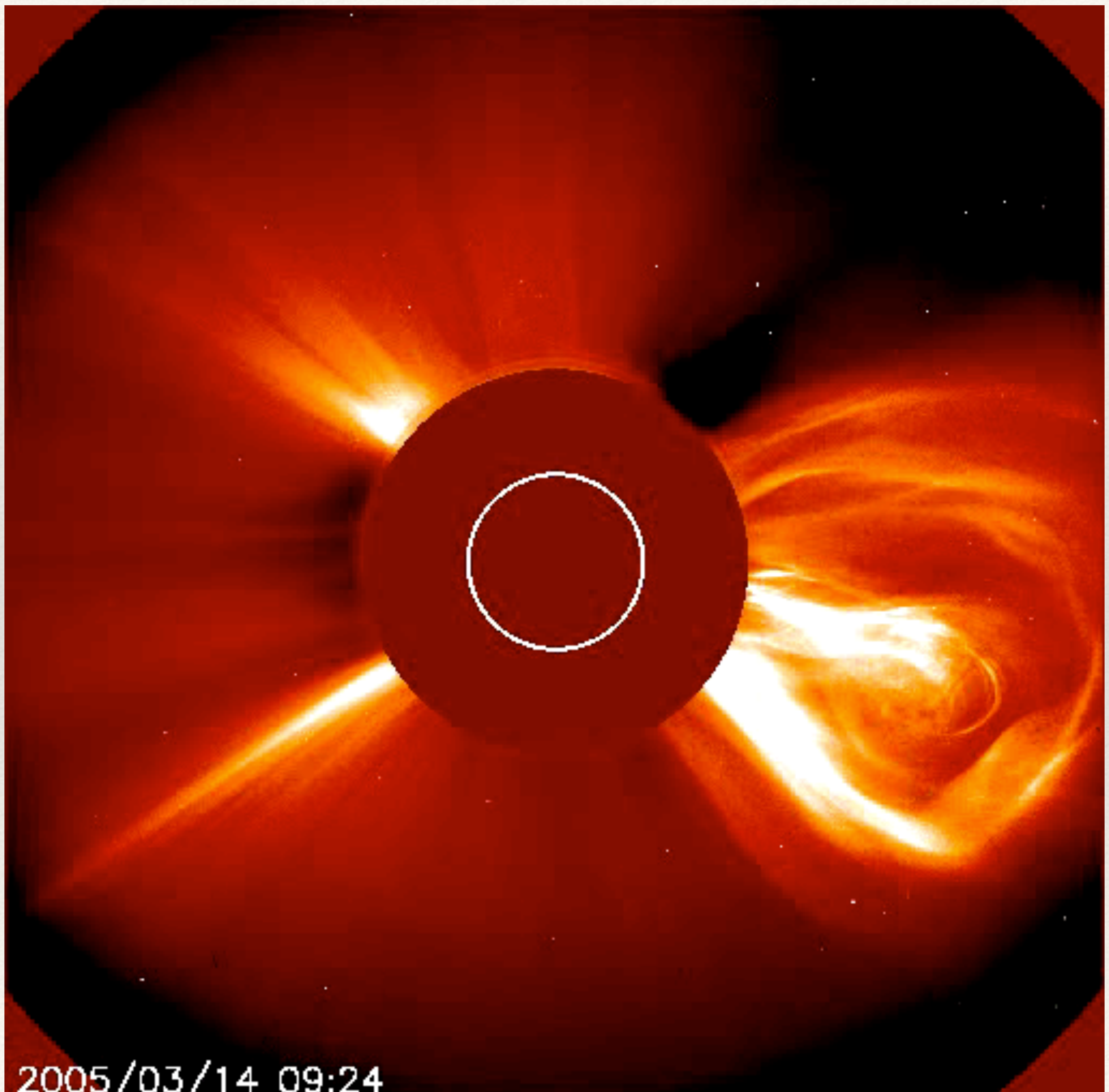
A Solar Storm Launches

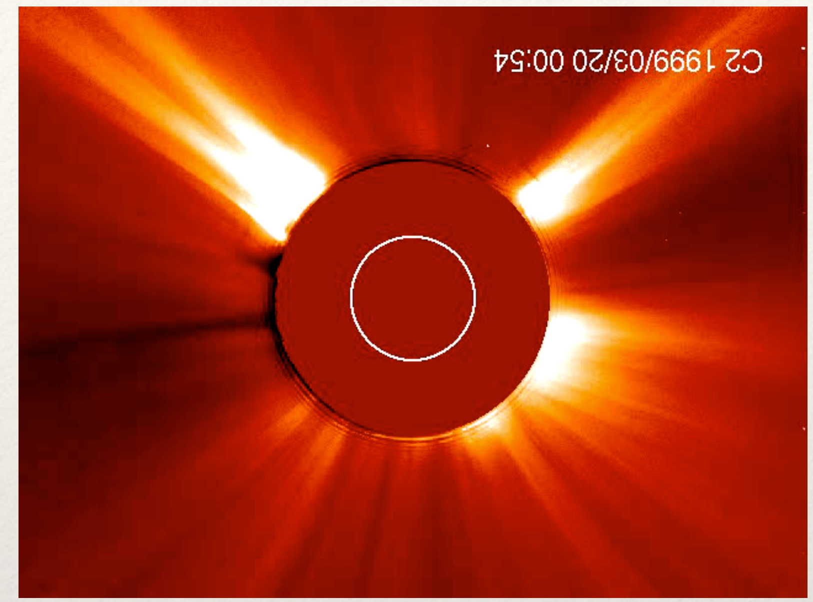


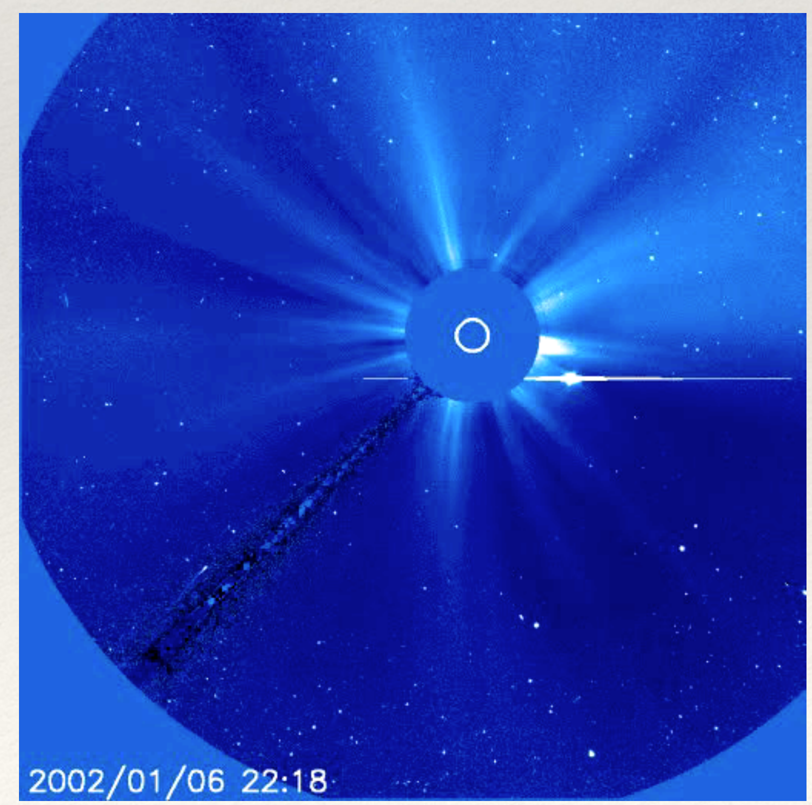




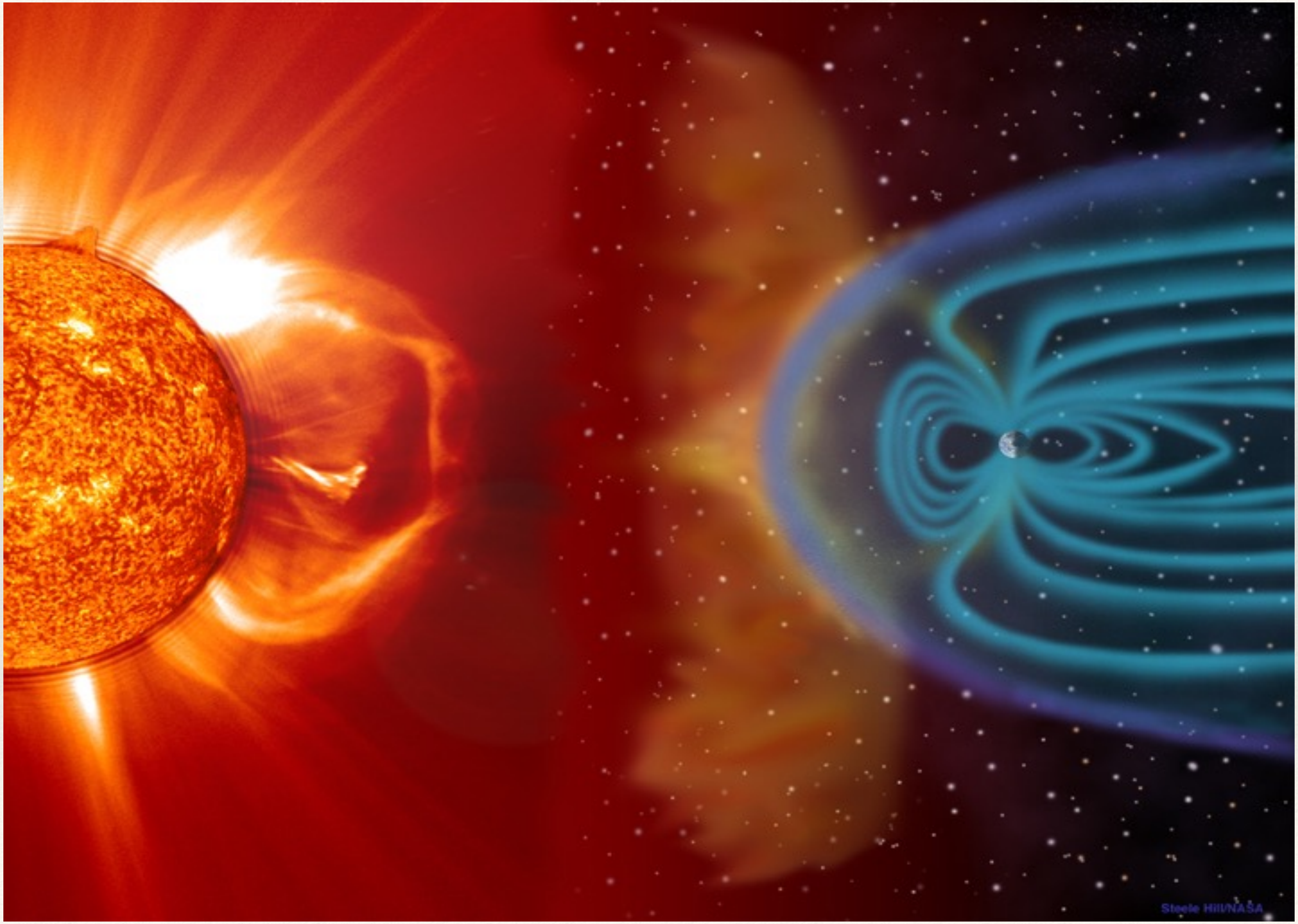
The Solar Wind and the Storm







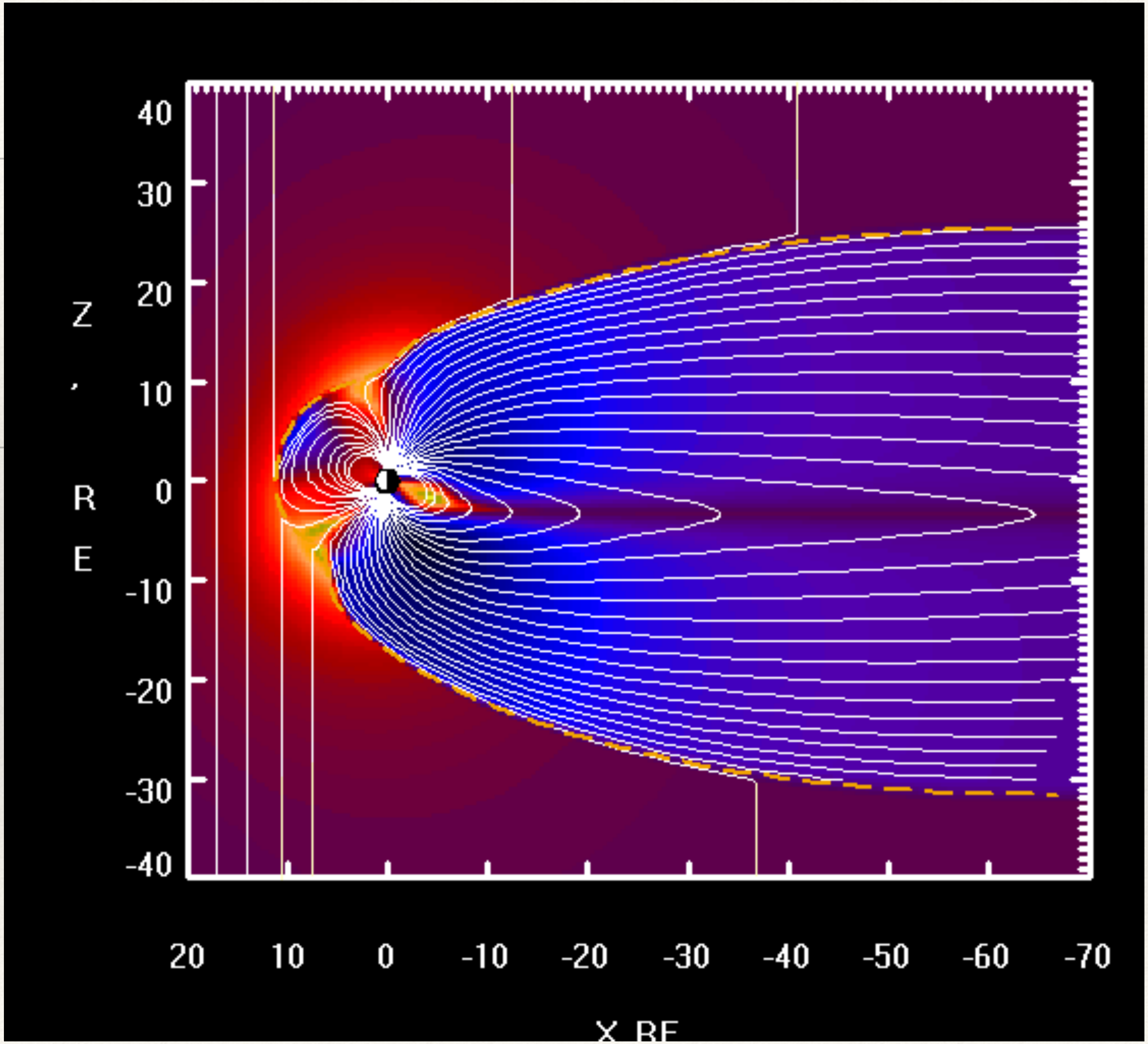
The Sun-Earth Plasma Connection



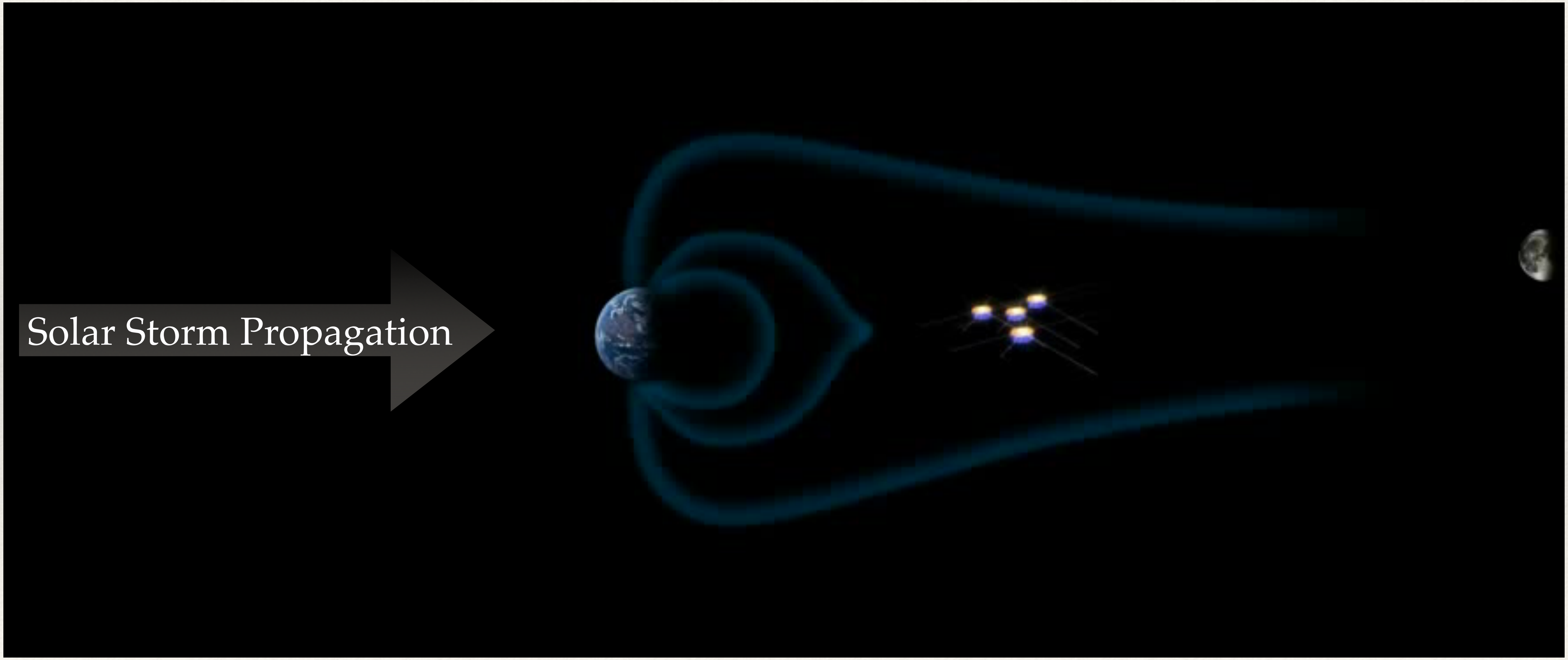
Blowin' in The Wind

Geomagnetic Storms

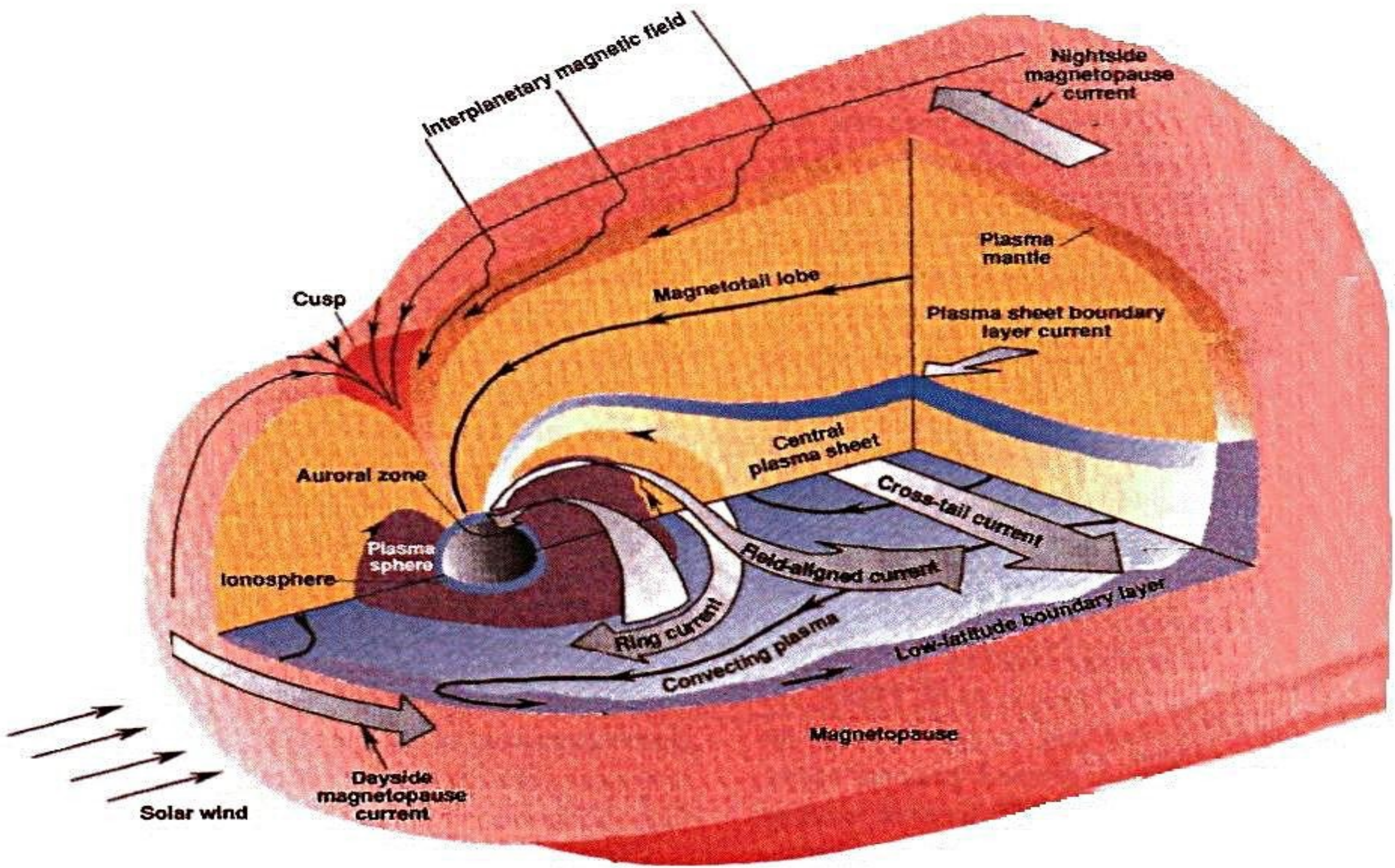
Disruptions in the magneto-tail lead to strong currents and inductive magnetic fields on Earth



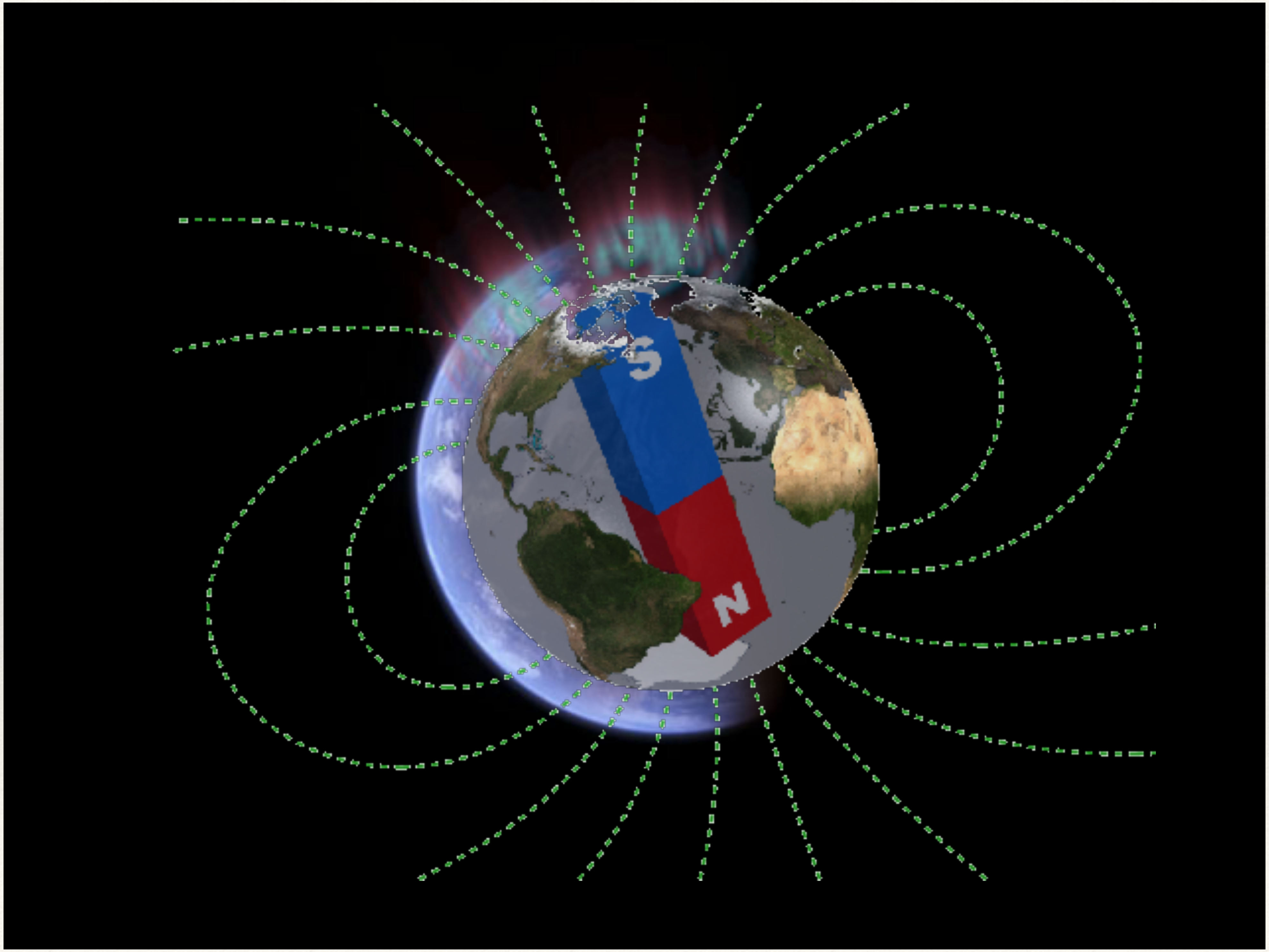
CLUSTER Satellites 'see' Electro-jet During Solar Storm



Earth's Complicated Current Systems

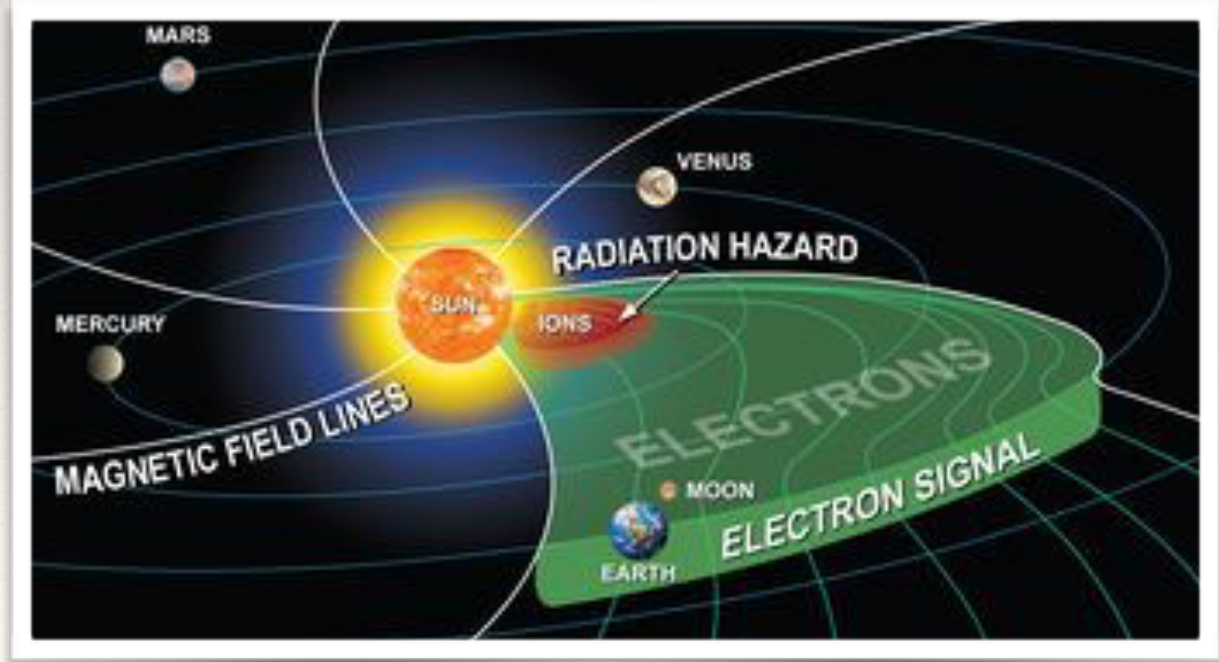


Where Will Solar Storms Go?



Some Effects of Solar Storms

- Aurora Borealis
- Satellite Damage
- Power grid fall-out
- Pipelining at risk
- Data loss - or delay
- Radiation hazard for spaceborne mission



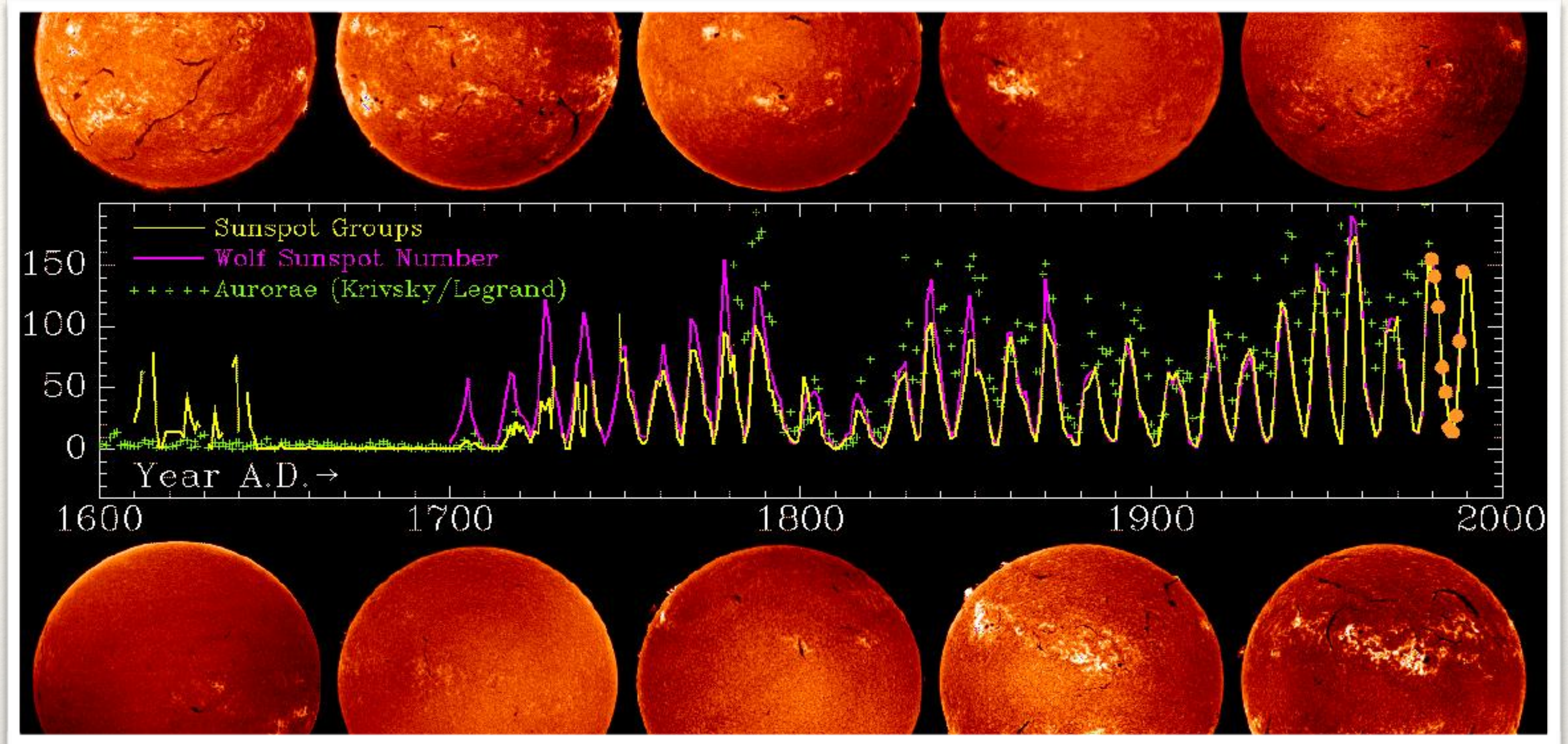
Example, Quebec 1989

- Power grid fall-out i largest part of Quebec Province
- Aurorae observed in Texas, latitude about as Morocco!

Transformer coil of Quebec powerplant, post ’89 storm,

Aurorae Seen From the ISS

Credit ISS crew / NASA, sept.17, 2011. Timelapsed movie from 12:22-12:45.

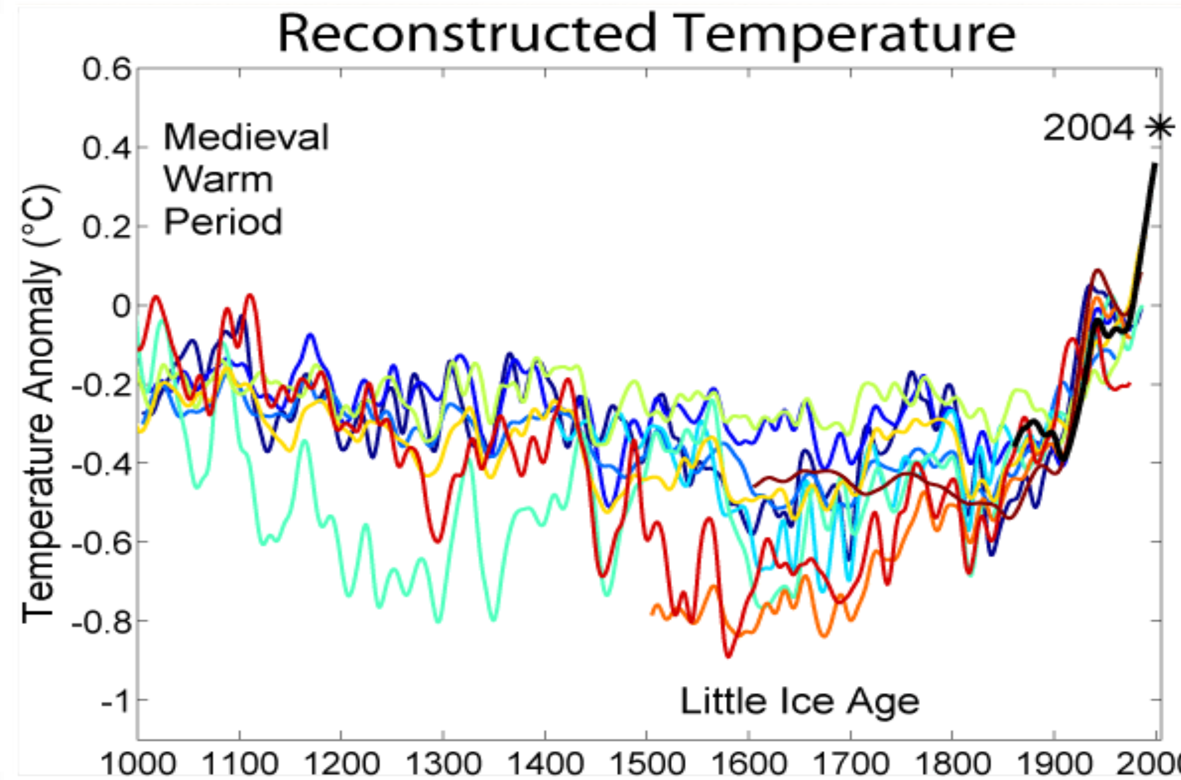


Historical Sunspot Data: almost 400 years of "useless" counting.

Climate Questions…

Interesting perspectives

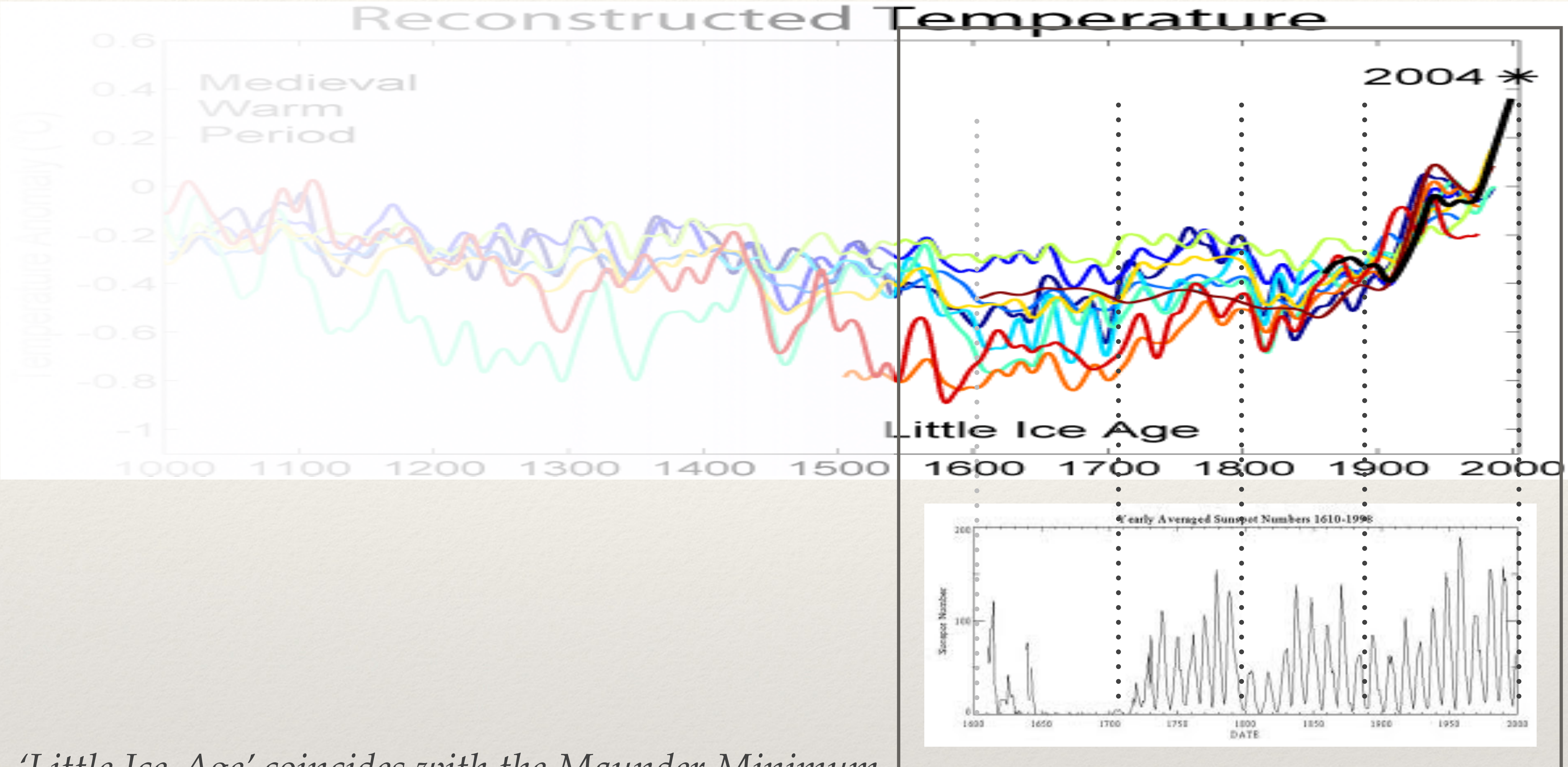
Does the solar cycle influence Earth in usual ways?



'Little Ice-Age' coincides with the Maunder Minimum

Climate Questions…

A coincidence?
Perhaps.



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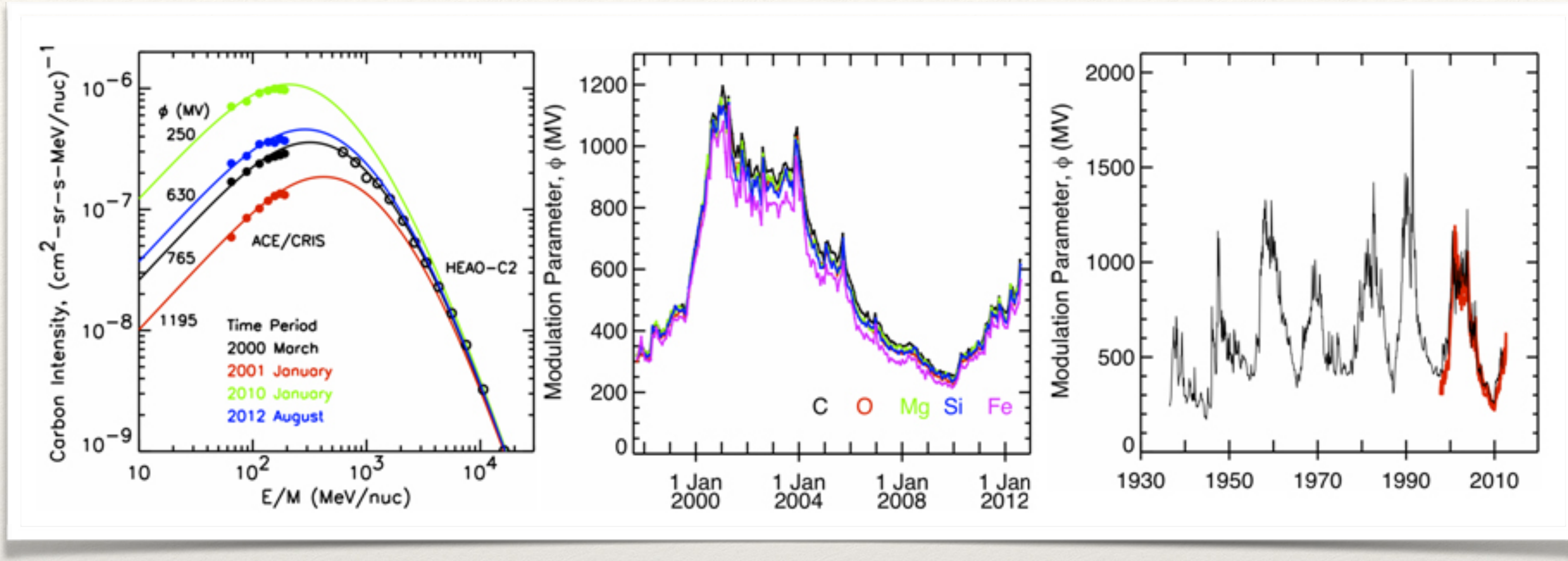


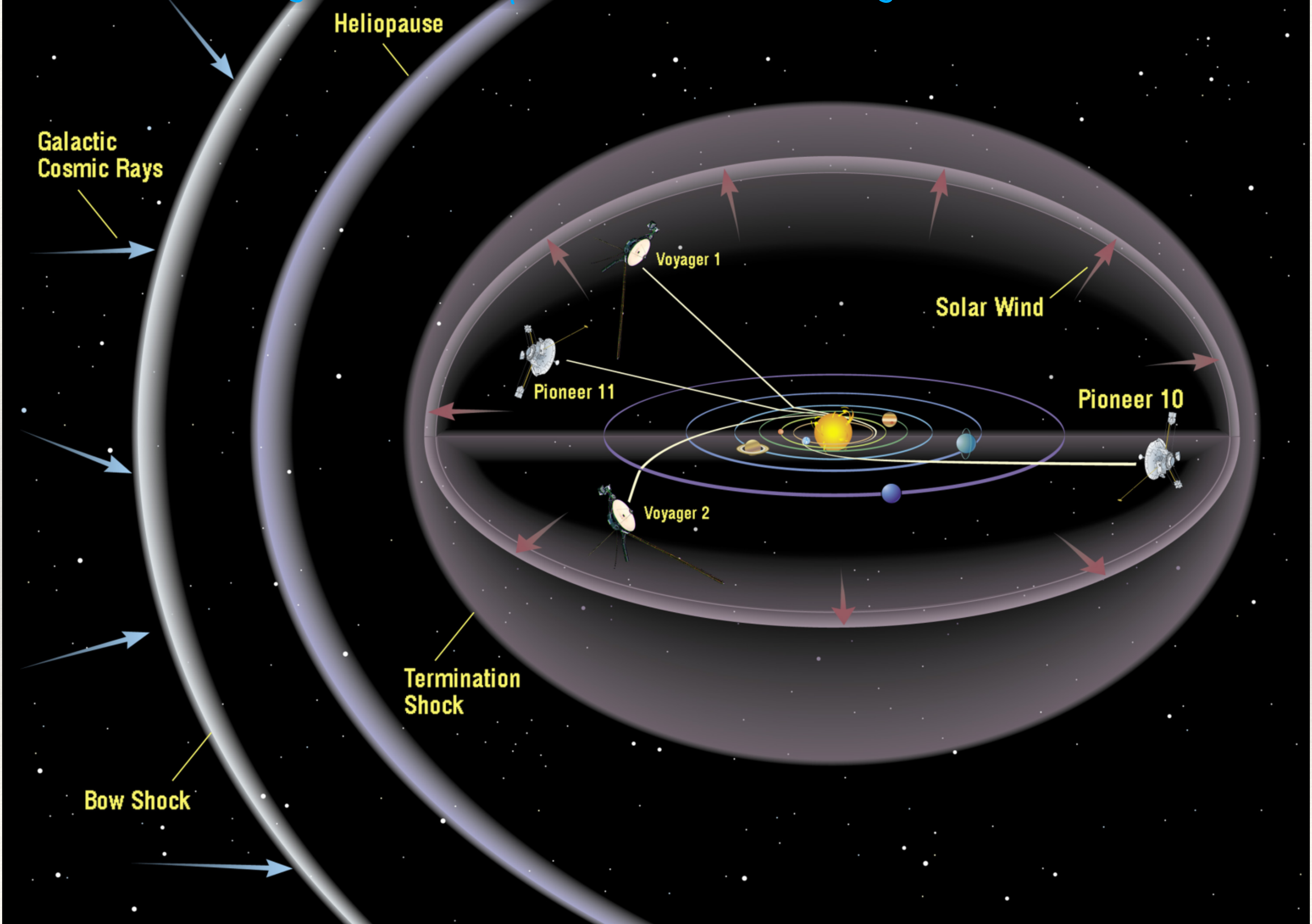
Solar Modulation of Cosmic Ray Spectrum

Climate Questions…

The Cosmic Ray Spectrum is correlated with the solar cycle.

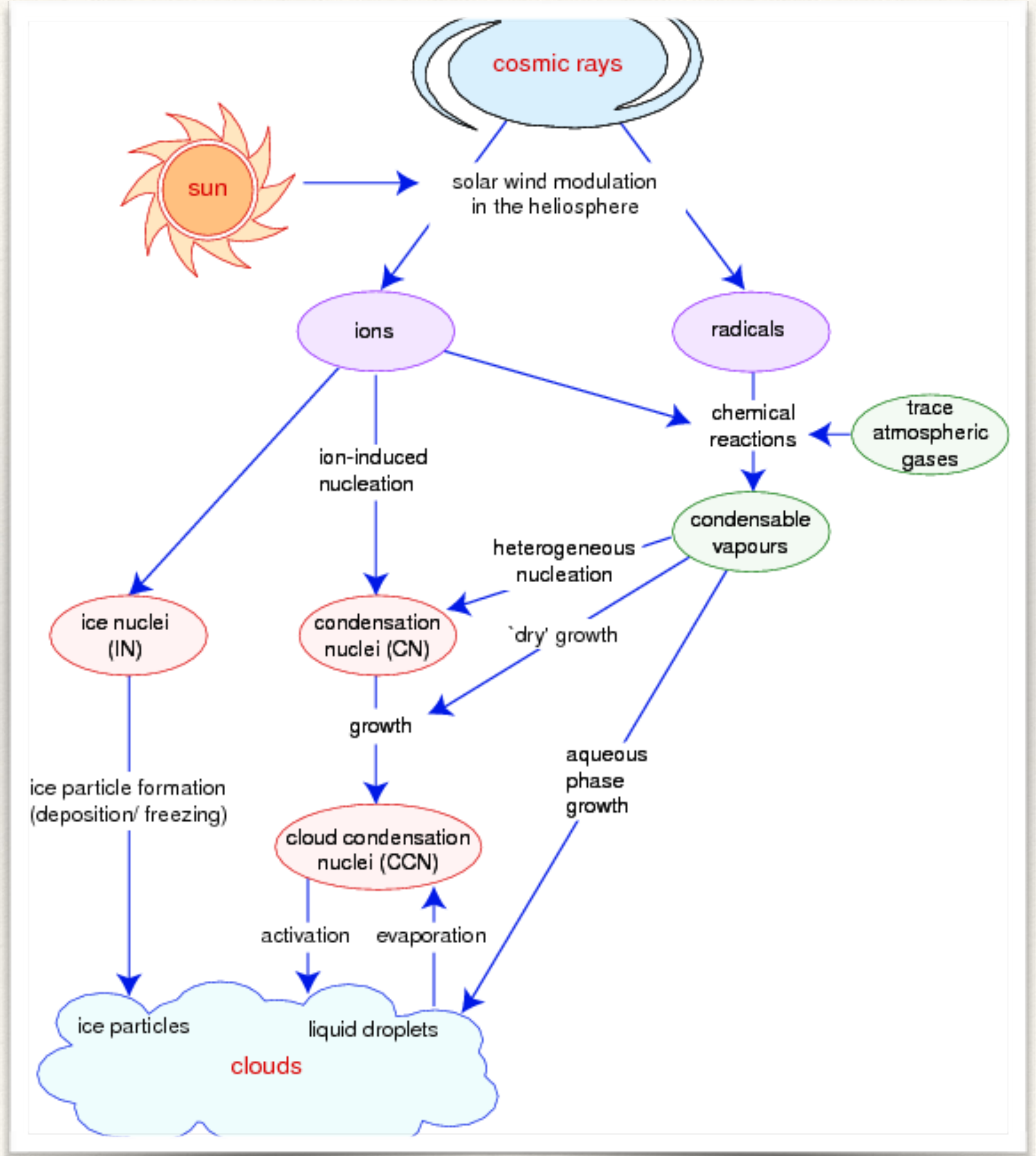
More active Sun?
Less cosmic rays.

The magnetized heliosphere shields the solar system, and Earth



Climate Questions… end?

- Cloud nucleation by cosmic rays?
- Cloud formation?
- Would influence global cloud coverage.
- Thence, global temperatures.
- Effect, if any, most likely benign.
- Not verified, in some cases even contradicted by simulations.
- However not falsified totally either.
- Yet a long way to go, as for clouds in general.



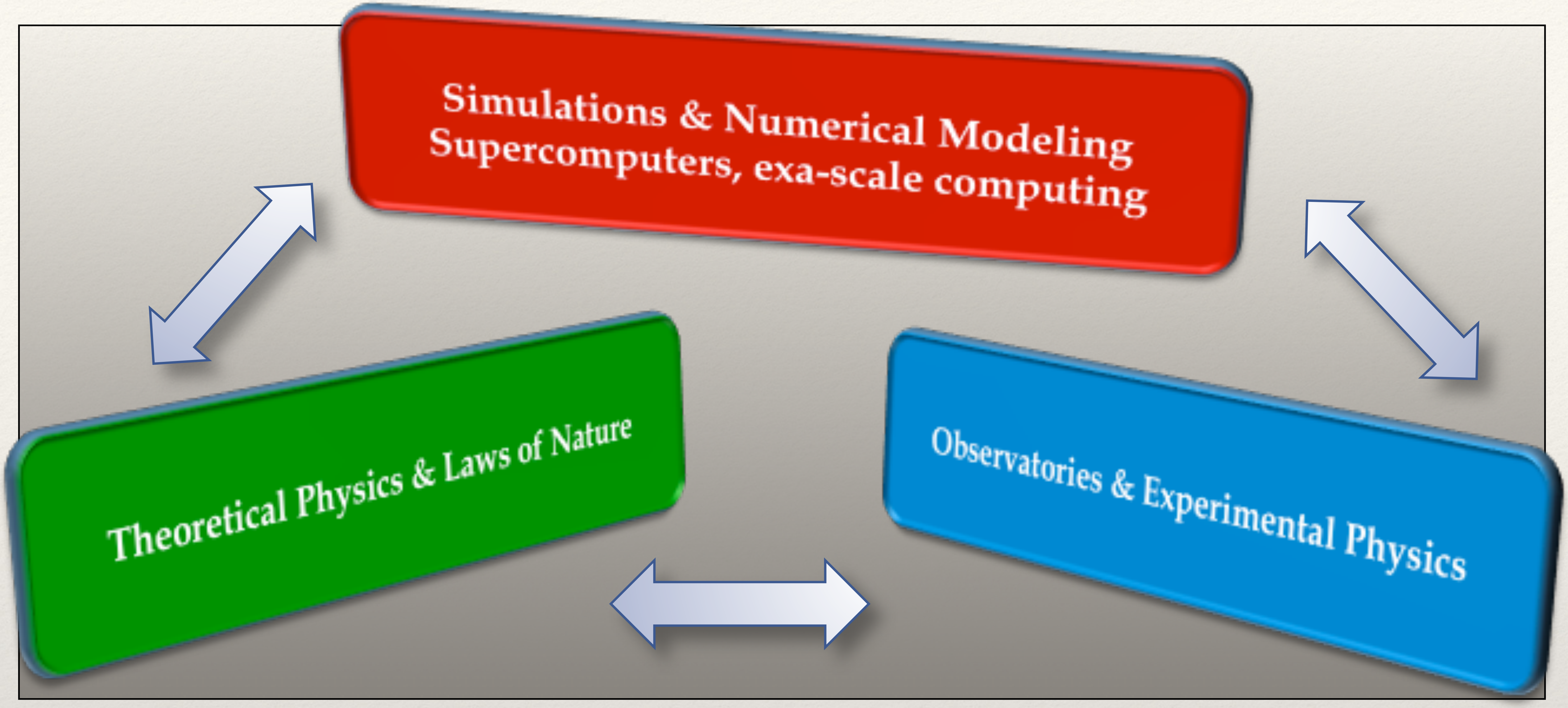
“Gimme’ a break — Please.”

[10 minutes]

Solar Storms, Revisited & Modelled

Part III

- A Third Branch in Science
- Computational Modeling
- Detailed Numerical Studies of a Flaring Active Region

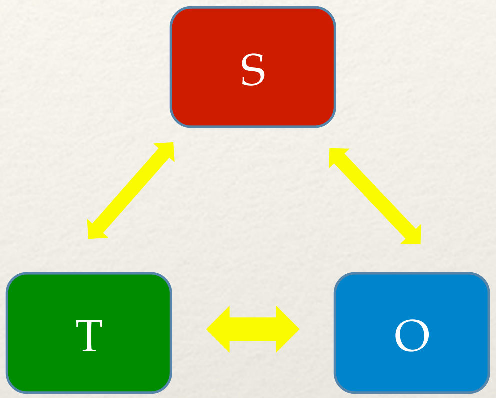


From Two to Three Players in Science

Computational (Astro)physics

- Exa-scale Computing offers:
  - 10^{18} FLOPS
  - 10^{18} Bytes
- A Realistic Player When Investigating Hypotheses
- Eventually Even Predictive

The Sun provides an Excellent "Laboratory" for this 'Triad of Science'

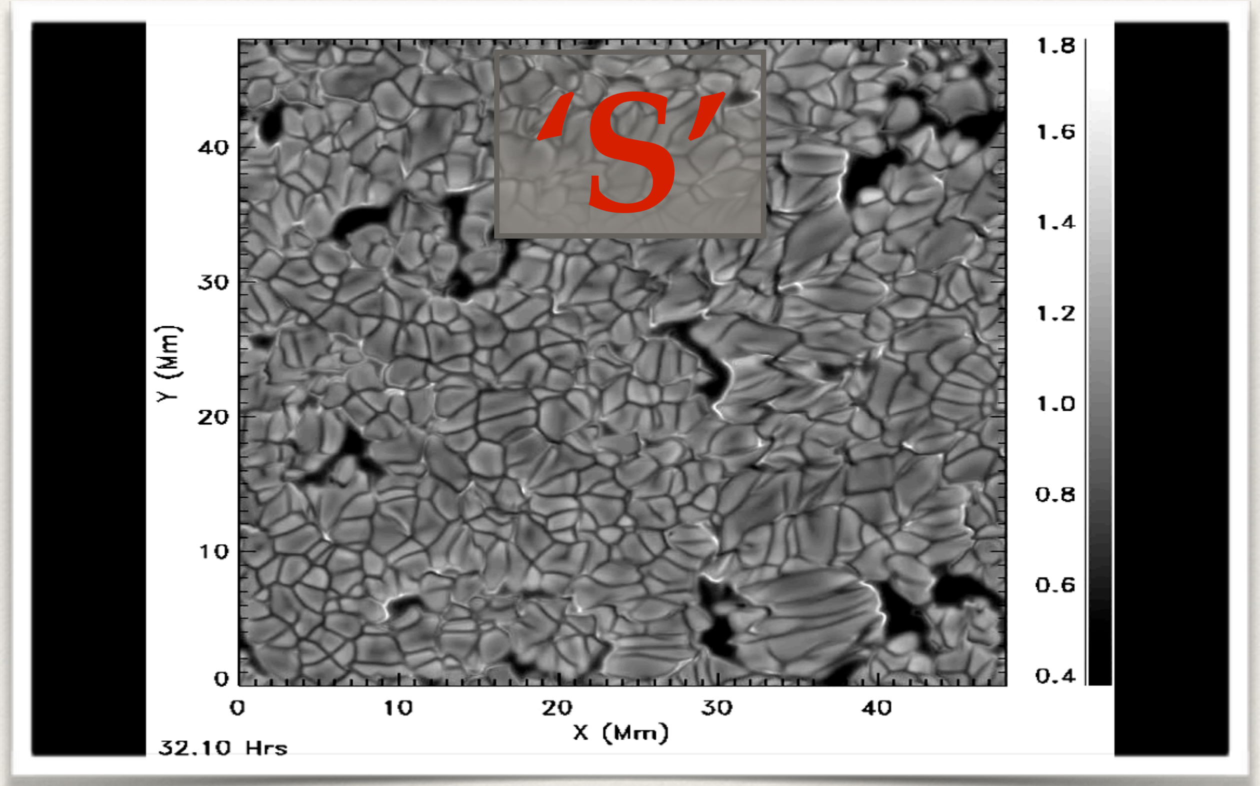


- From **theory** we get the fundamental equations and Laws of Nature to tell us what to look for.
- From **observations** we get data to feed modelers.
- From **simulations** we get results that can test hypotheses.
- Detailed **simulations** can even yield predictive results(!)

The Sun as a “Laboratory”

Example of verification & adjustment of computer simulations.

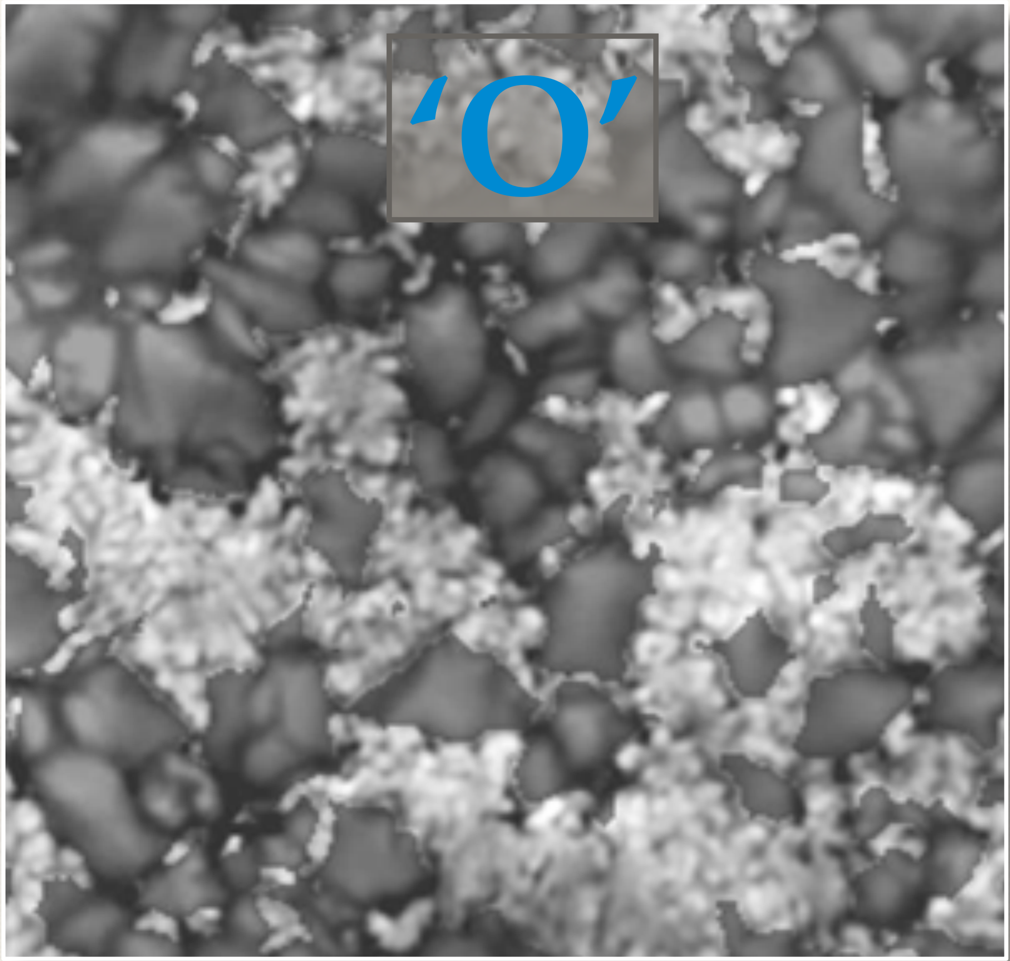
2 days of photospheric footage. The Solar Dynamics Observatory “white” light (~5200K).



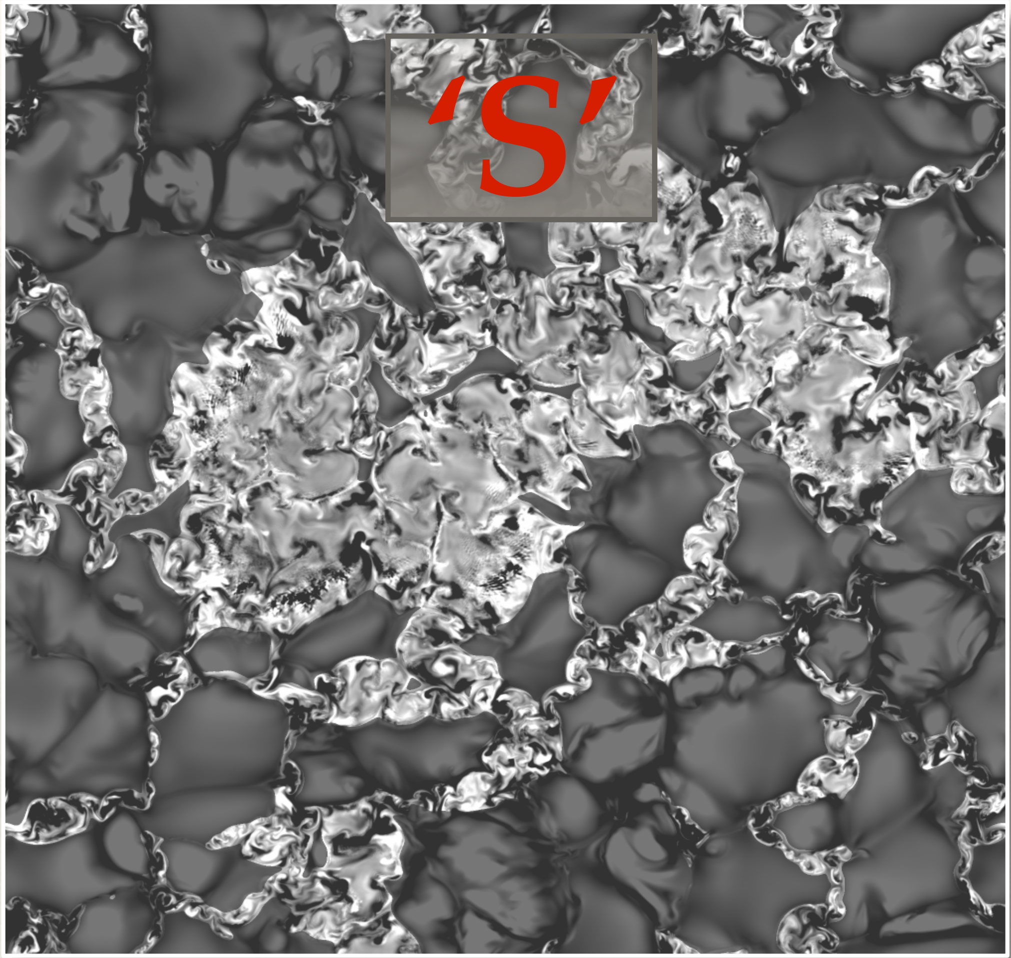
2 days of photospheric footage. The Stagger Code (NBI) in “white” light (~5200K).

The Sun as a “Laboratory”

Example of “predictive” power of computer simulations.

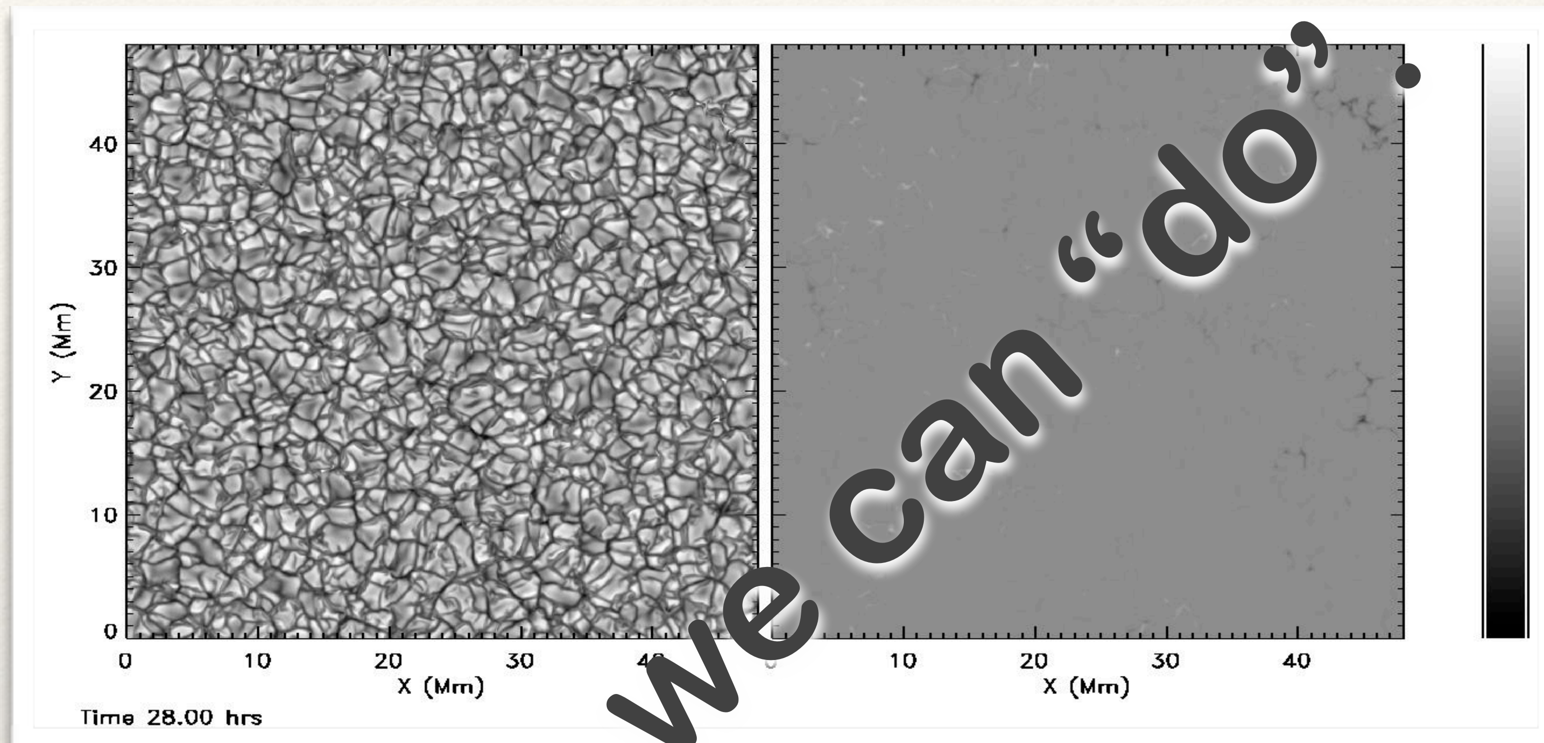


Credit: Swedish 1-m Solar Telescope
Narayan & Scharmer (2010)



Credit: ”Active region magneto-convection”
Nordlund *et al.*, NBI/Cph (~2010)

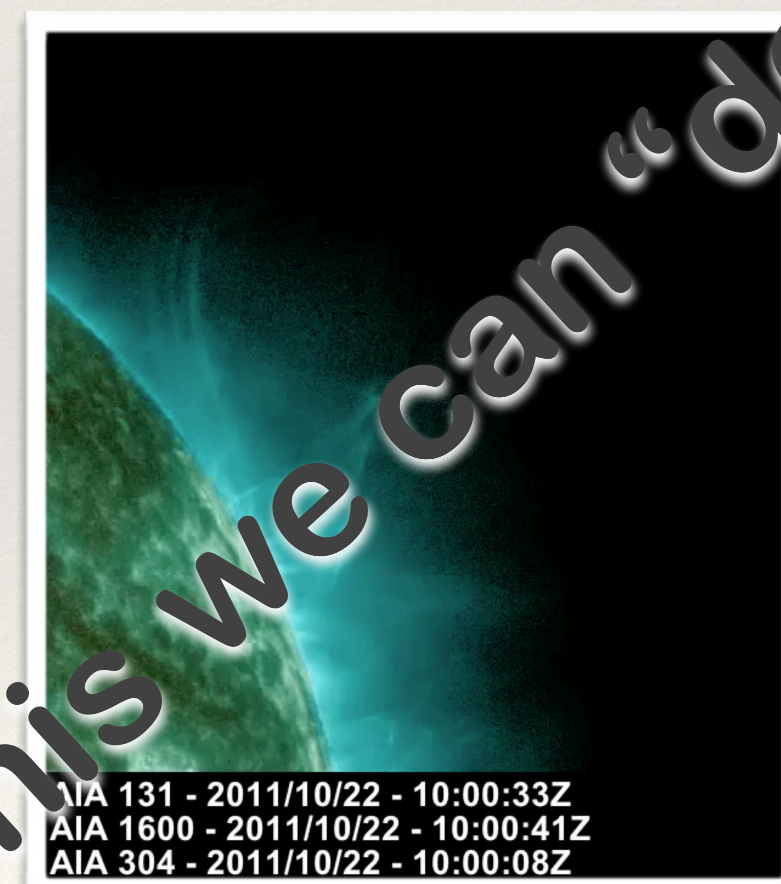
Essentials of Solar Storm Initiation



This we can "do".

- Photospheric driving stress-energy into Coronal magnetic field
- Release of magnetic stress-energy and Coronal heating.

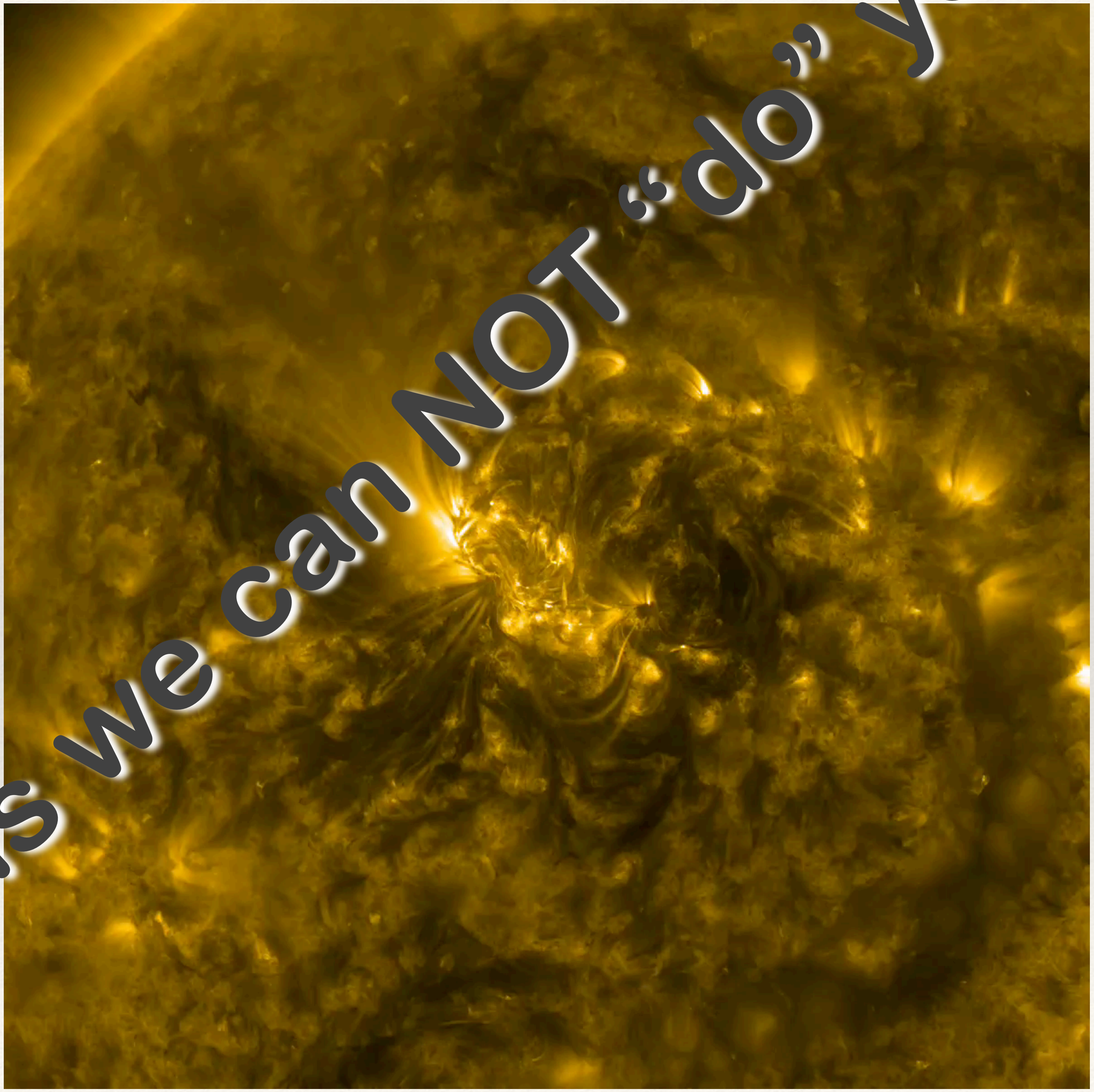
- Deep photospheric convection
- Transport of magnetic flux
- Magnetic flux emergence



This we can "do"

Essentials of Solar Storm Initiation

- Explosive relaxation of stress-energy
- Flaring
- Realistic coronal mass ejections — CMEs
- Solar energetic particle events — SEPs

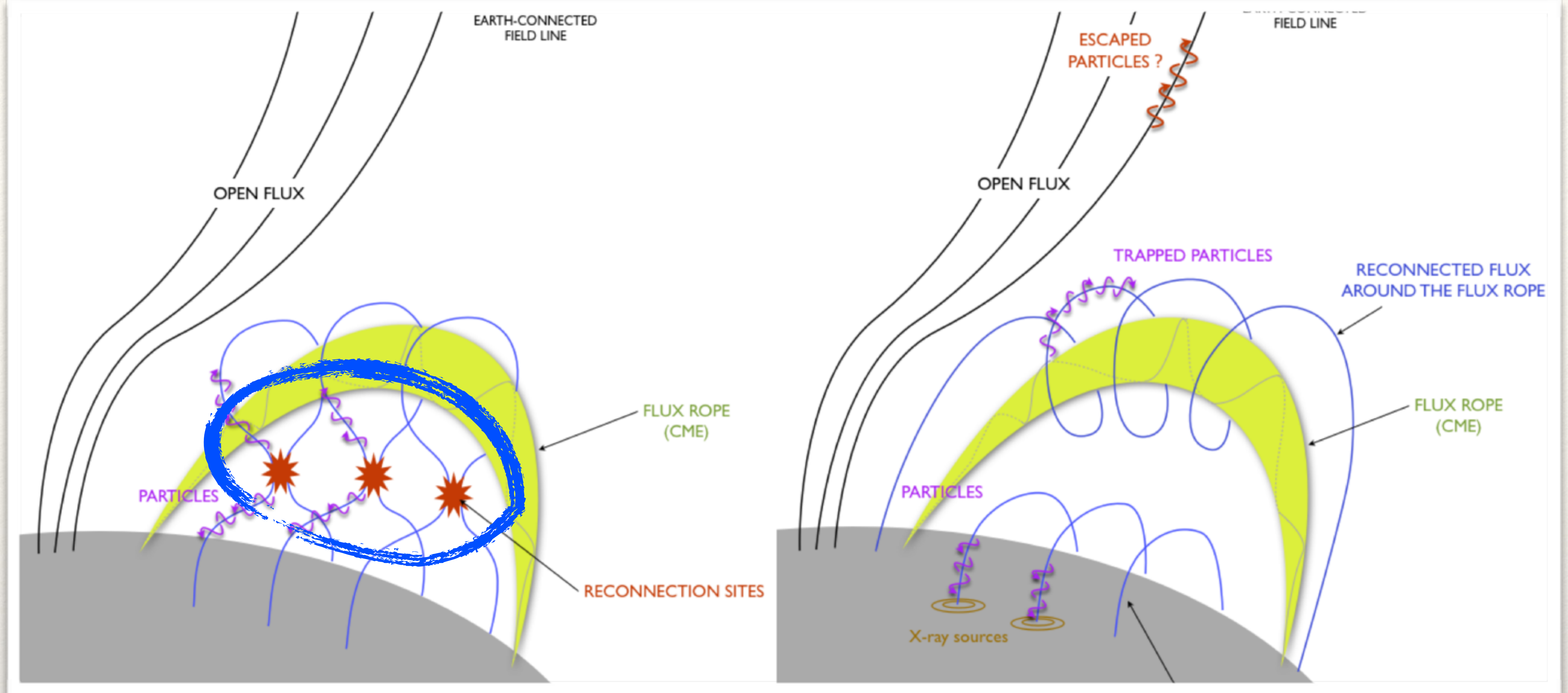


This we can NOT “do” yet.

Solving a Puzzle? — The Road Ahead

Part IV

- A 'generic' solar storm configuration
- The "puzzle" of Magnetic Reconnection
- Numerical plasma physics, today.
- Numerical plasma physics, tomorrow?



Lorem Ipsum Dolor

A ‘Generic’ Solar Storm Configuration

- Flux rope becomes buoyant and lifts into the Corona.
- Magnetic Reconnection sets in.
- Flux rope explosively lifts into interplanetary MF.

The "Puzzle" of Magnetic Reconnection (MR)

The **fully kinetic plasma** description — we already saw this, remember? :-)

$$\frac{\partial f^i}{\partial t} + \boldsymbol{u} \cdot \frac{\partial f^i}{\partial \boldsymbol{x}} + \frac{q^i}{m^i}(\boldsymbol{E} + \boldsymbol{u}_i \times \boldsymbol{B}) \cdot \frac{\partial f^i}{\partial (\boldsymbol{u}\gamma)^i} = \left.\frac{\partial f^i}{\partial t}\right|_{coll}$$

Vlasov-Boltzmann

$$-\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{E} \qquad \nabla \cdot \boldsymbol{E} = \frac{\rho_c}{\epsilon_0}$$

$$\frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} = \nabla \times \boldsymbol{B} - \mu_0 \boldsymbol{J} \qquad \nabla \cdot \boldsymbol{B} = 0$$

Maxwell

$$\rho_c(\boldsymbol{x}) = \int \mathrm{d}\boldsymbol{u} \sum_i q^i f^i(\boldsymbol{x}, \boldsymbol{u}) \qquad \boldsymbol{J}(\boldsymbol{x}) = \int \mathrm{d}\boldsymbol{u} \sum_i \boldsymbol{u}\, q^i f^i(\boldsymbol{x}, \boldsymbol{u})$$

EM Sources

The "Puzzle" of Magnetic Reconnection (MR)

The **Magneto-Hydrodynamic approximation** 'MHD' — a single magnetized fluid

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad \nabla \cdot \mathbf{B} = 0$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \mathbf{J} \times \mathbf{B} - \nabla p \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{p}{\rho^{\gamma}} \right) = 0$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

Ohm's Law — **no (low) resistivity** => no magnetic diffusion!

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

Ampere's Law — **'slow(er)' phenomena** (no $\frac{\partial E}{\partial t}$ term)

The "Puzzle" of Magnetic Reconnection (MR)

From MHD approximation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + \frac{\eta_{res}}{\mu_0} \nabla^2 \boldsymbol{B}$$

Lundquist Number

$$S = \frac{\mu_0 V L}{\eta_{res}} \simeq \frac{|\nabla \times (\boldsymbol{V} \times \boldsymbol{B})|}{|(\eta/\mu_0) \nabla^2 \boldsymbol{B}|}$$

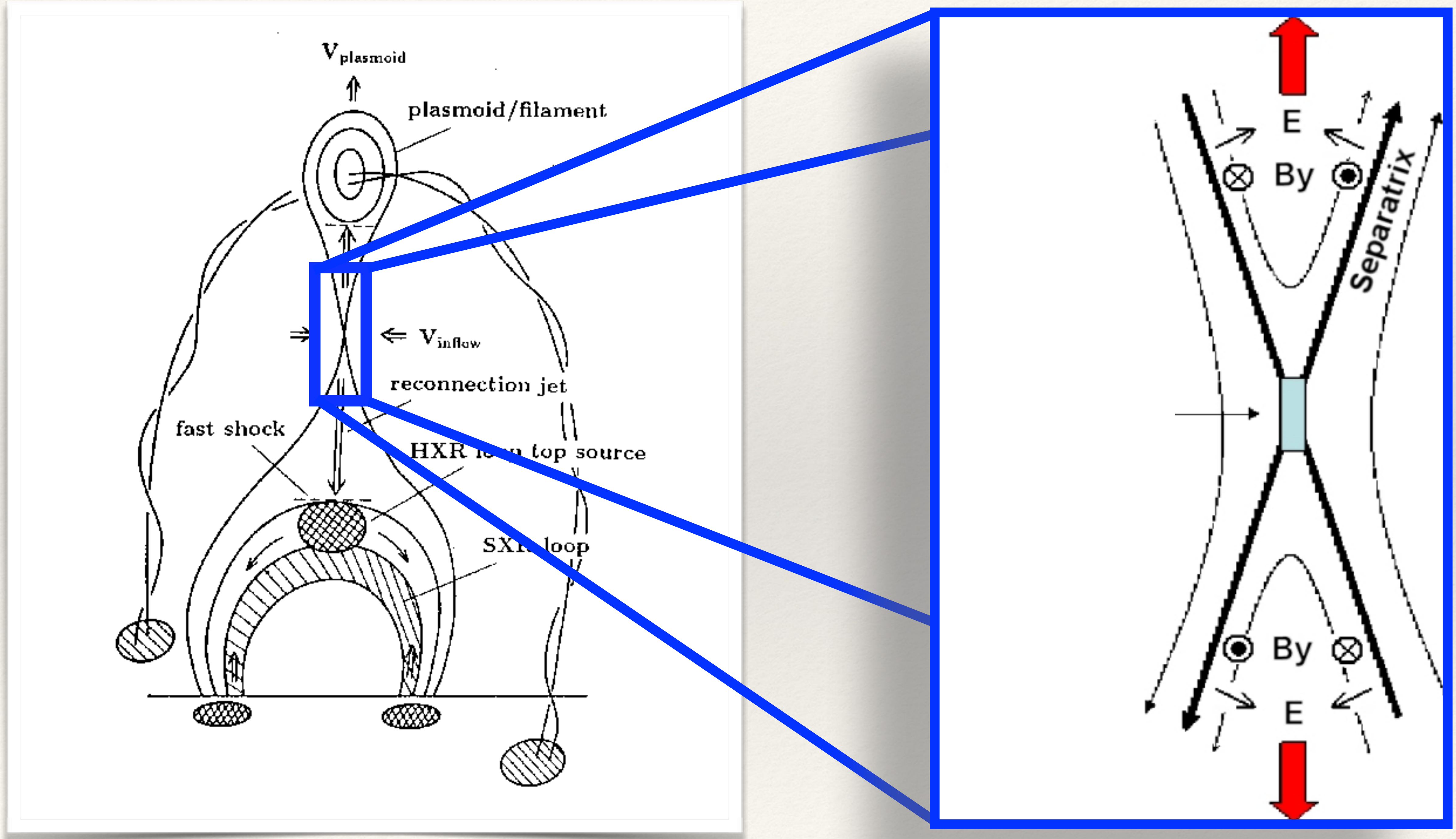
Advection

Diffusion

The Solar Corona

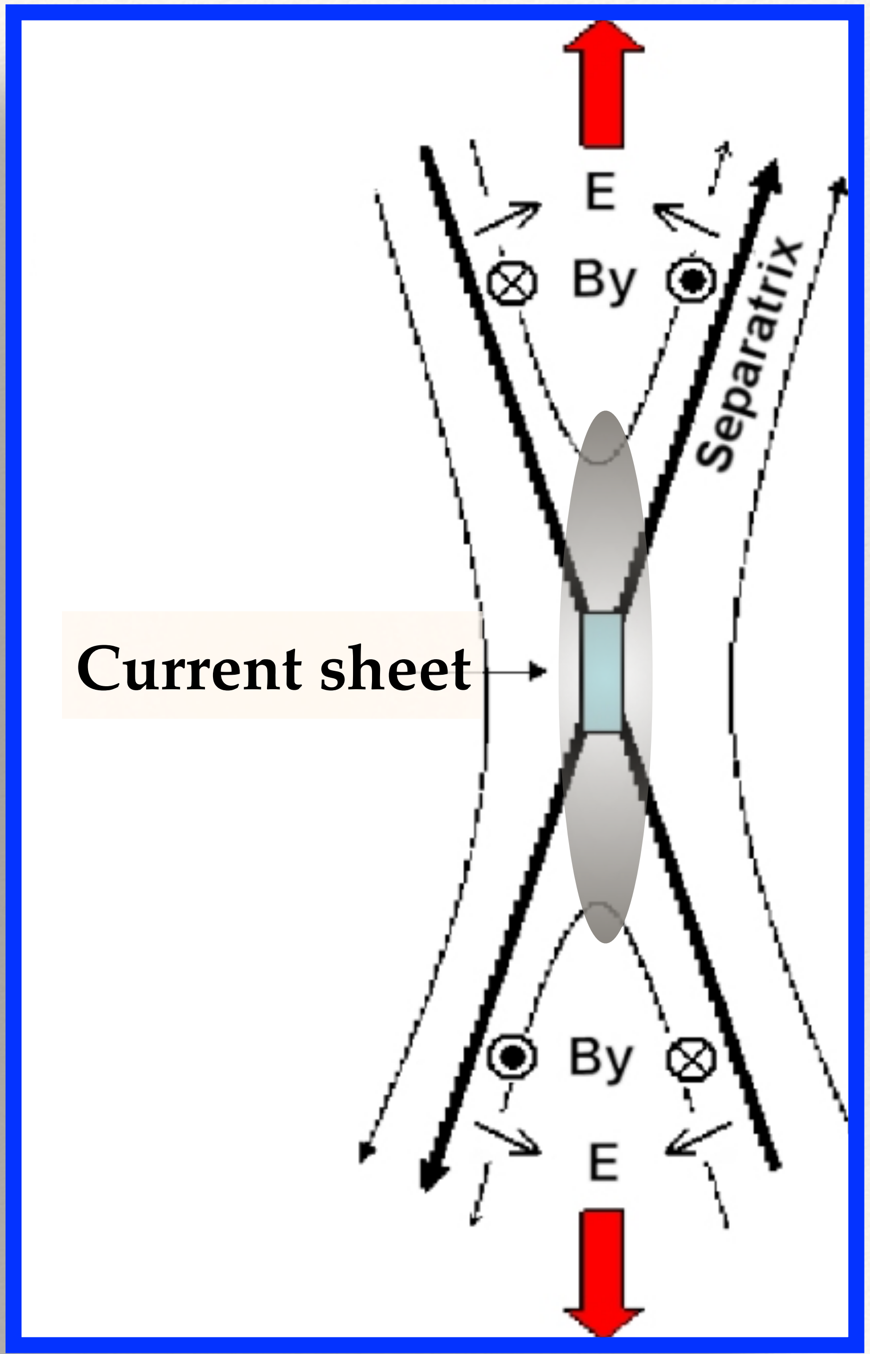
$$S \sim 10^{14}$$

The "Puzzle" of Magnetic Reconnection (MR)



The "Puzzle" of Magnetic Reconnection (MR)

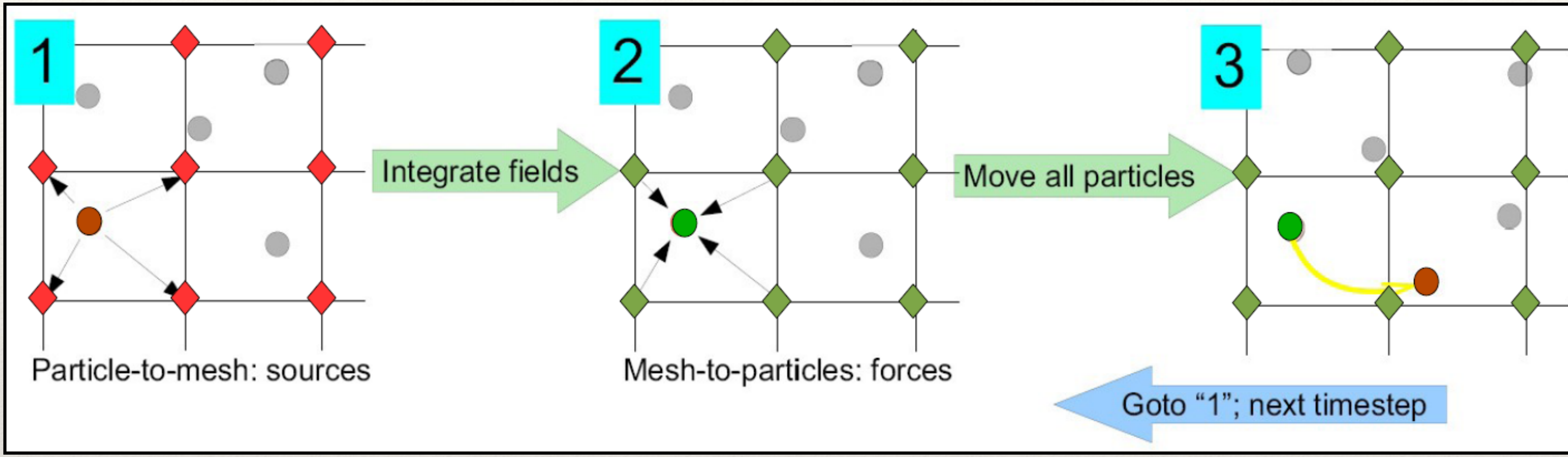
- Large scale MR region: ~10.000.000 m.
- Naiively, MR rate very low (years).
- But: we need high MR rate at flaring sites (~mins or secs)!
- Three efficient ways:
    1. **Assume non-2D (i.e. 3D) geometry! :-)**
    2. **Make current sheets thin!**
    3. **Make resistivity high!**
- Howto? Current sheets will fragment until MR rate fits the driving force.
- What does that mean? We need to describe events:
    - **i) on 1000-km spatial, and ~hour, time scales**
    - **ii) …and on ~meter, and ~microsecond scales.**



$$\begin{aligned} \nabla \times \frac{1}{\mu_0}\mathbf{B} &= \frac{4\pi}{c}\mathbf{J} + \frac{\epsilon_0}{c}\frac{\partial \mathbf{E}}{\partial t} \\ \nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \cdot \mathbf{E} &= 4\pi\rho_c/\epsilon_0 \\ \nabla \cdot \mathbf{B} &= 0\ , \end{aligned}$$

$$\mathbf{F}_L = \frac{\partial \mathbf{p}_s}{\partial t} = \frac{\partial m_{0s}\gamma(v)\mathbf{v}_s}{\partial t} = \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v_s} \times \mathbf{B})$$

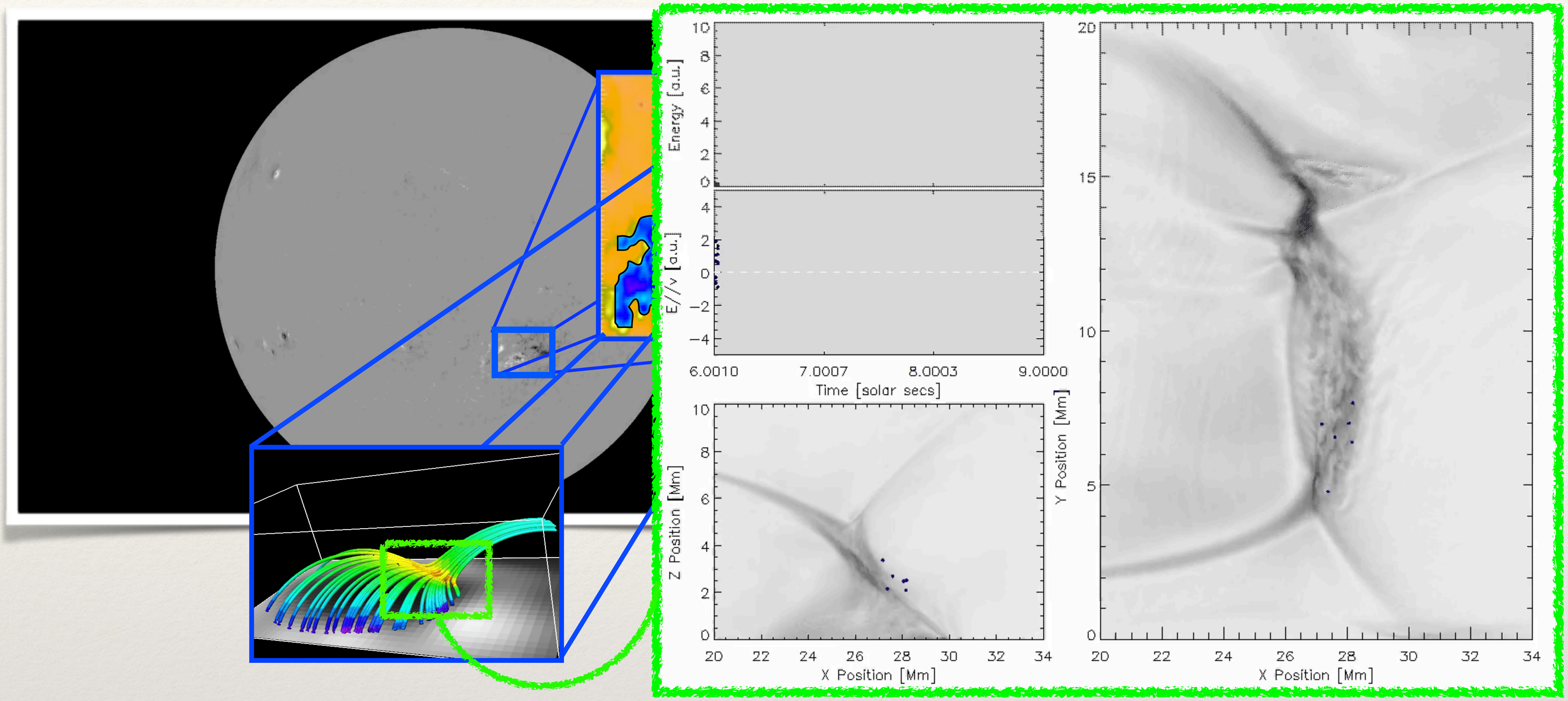
$$\frac{\partial f}{\partial t} + \mathbf{p} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t}\right)\bigg|_{coll.} = 0$$



Particle-In-Cell Codes

Kinetic Modeling of Plasmas

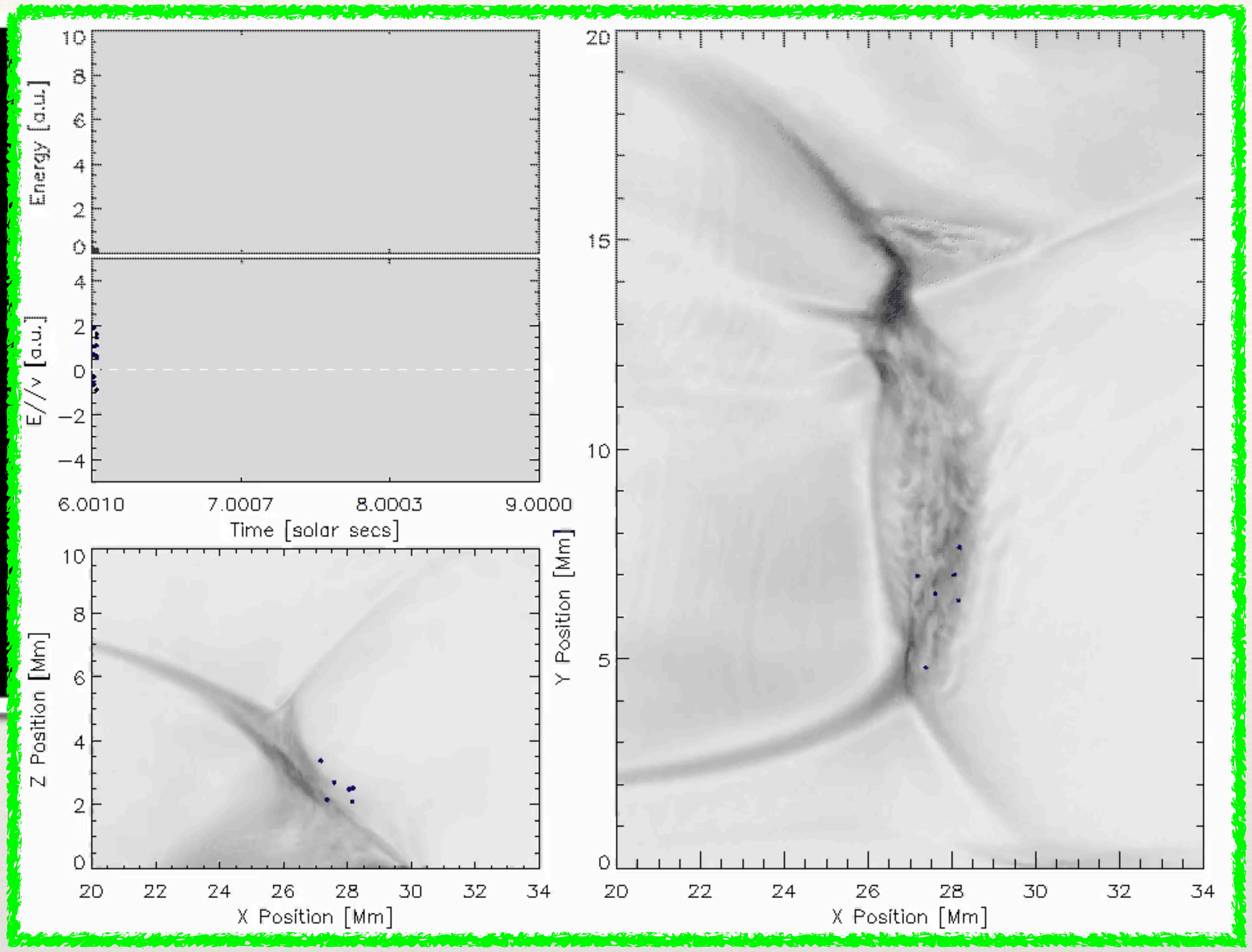
- Explicitely integrate EOM for billions of particles
- Construct Maxwell source terms
- Solve Maxwell’s equations



World's Largest Simulation — 135 billion particles — of kinetics in Solar Flaring Active Region.

Computational Modeling of Solar Storms – Today.

- Import magnetic field data from SOHO to MHD code.
- Run MHD code until 'something happens'.
- Port snapshot to fully kinetic code for full dynamics result.



World's Largest Simulation — 135 billion particles — of kinetics in Solar Flaring Active Region.

Computational Modeling of Solar Storms – Today.

- Particles are accelerated
- Mean free paths are system scale
- MHD needed on large scales, but ALSO kinetics on large scales.

World's Future MHD-KineticPIC Combo Simulation….?

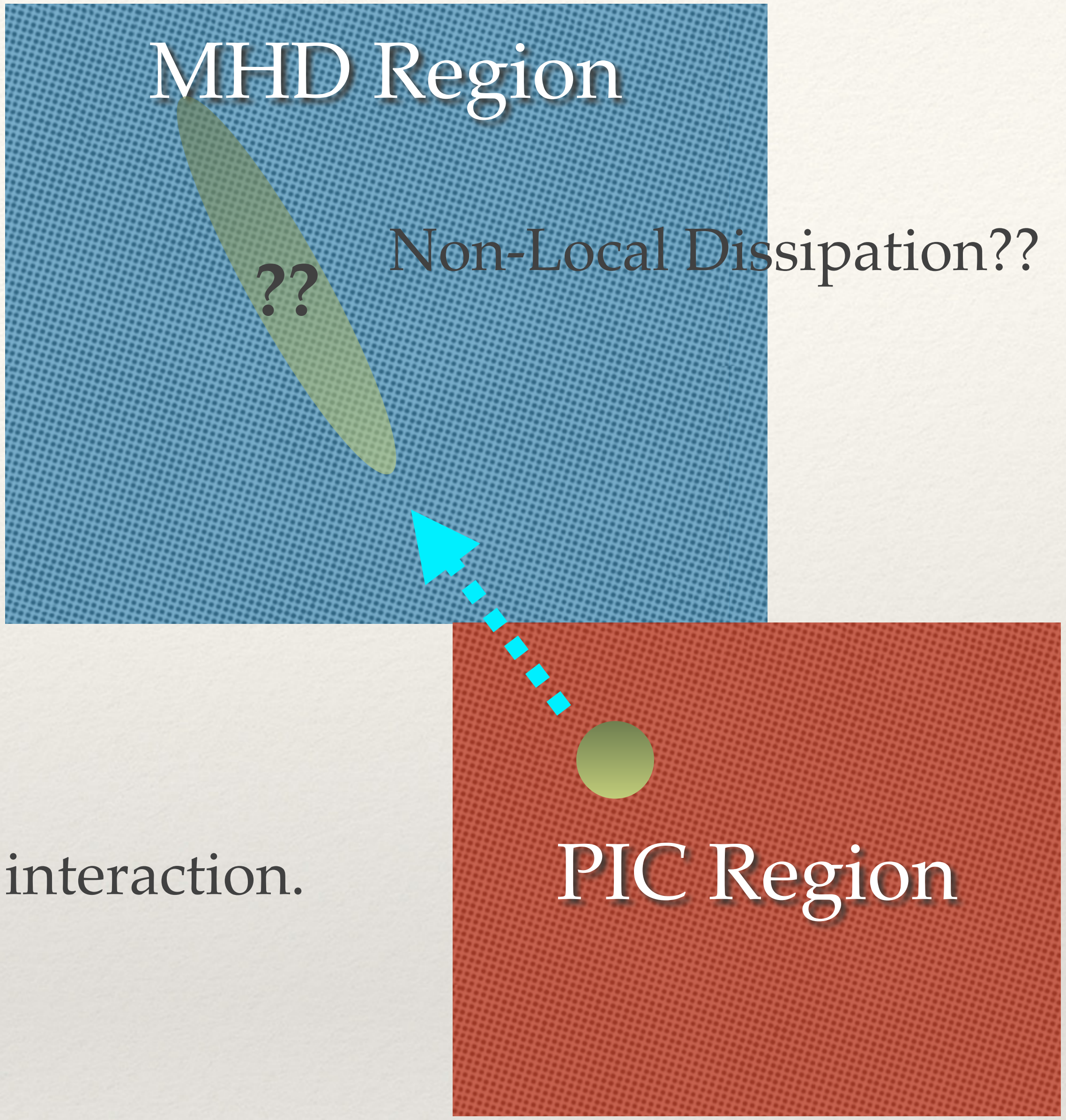
Numerical Plasma Physics, Tomorrow?

A successful numerical plasma model seems FORCED to incorporate particle — or PIC — kinetics on large scales, and COMBINE with MHD.

That is the state-of-the-art future.

The ambitious would go this way

Numerical Plasma Physics, Tomorrow?



Collision term which incorporates wave-particle interaction.

$$\frac{\partial f^i}{\partial t} + \boldsymbol{u}\cdot\frac{\partial f^i}{\partial \boldsymbol{x}} + \frac{q^i}{m^i}(\boldsymbol{E}+\boldsymbol{u}_i\times\boldsymbol{B})\cdot\frac{\partial f^i}{\partial(\boldsymbol{u}\gamma)^i} = \left.\frac{\partial f^i}{\partial t}\right|_{coll}$$

Possibly by some Fokker-Planck coupling. Very much “future work”.

$$\frac{\partial p_s}{\partial t}+\vec{v}\cdot\vec{\nabla} p_s+\frac{Z_s e}{m_s}\left(\vec{E}+\vec{v}\times\vec{B}\right)\cdot\vec{\nabla}_v p_s = -\frac{\partial}{\partial v_i}\left(p_s\langle\Delta v_i\rangle\right)+\frac{1}{2}\frac{\partial^2}{\partial v_i\partial v_j}\left(p_s\langle\Delta v_i\Delta v_j\rangle\right) + \left.\frac{\partial f^i}{\partial t}\right|_{coll}$$

All other relevant terms

Thank You for Being Here Tonight!