# Adding Complexity-Magnetohydrodynamics

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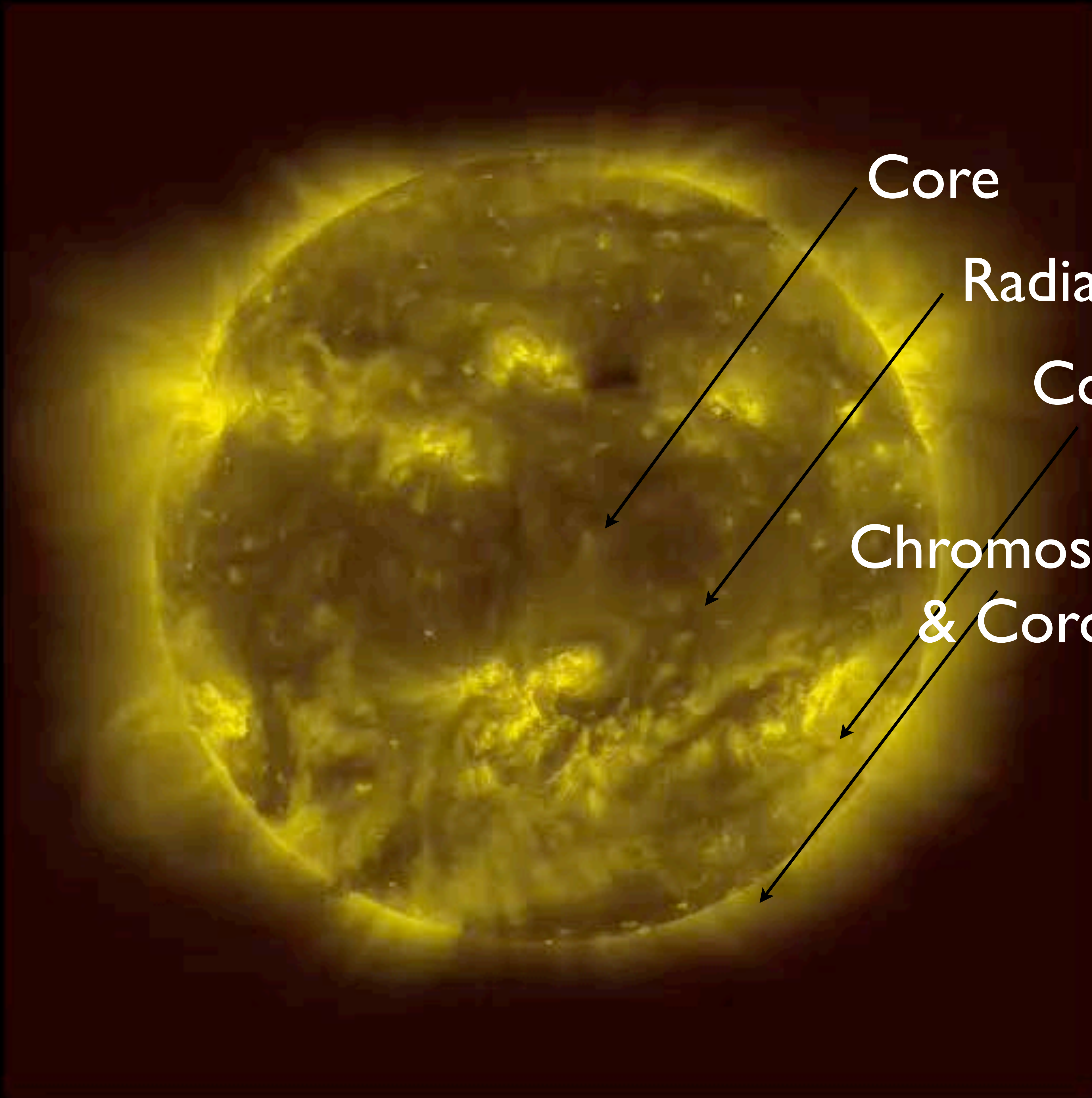
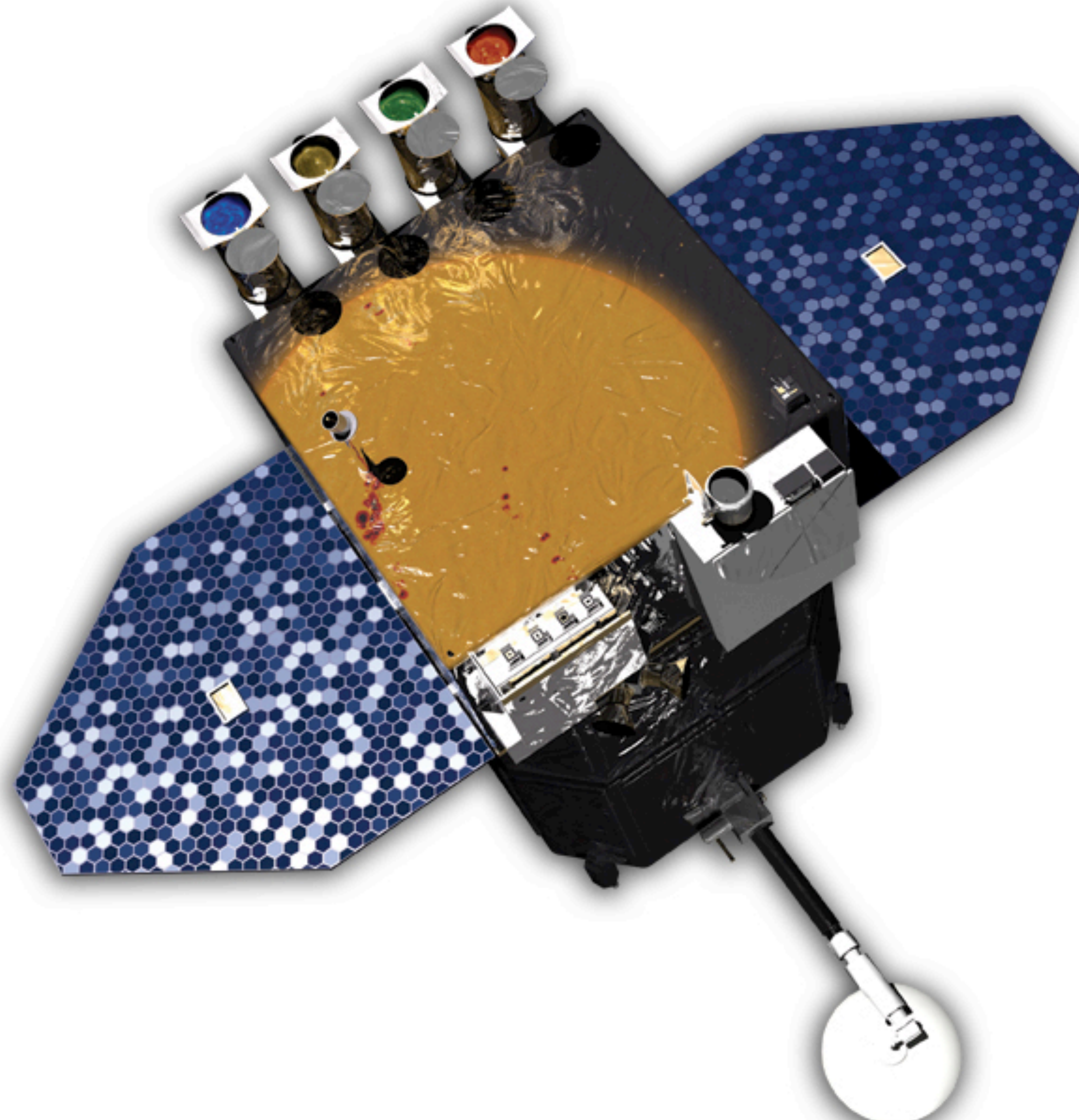

Core
Radiative zone
Convection zone
Chromosphere & Corona

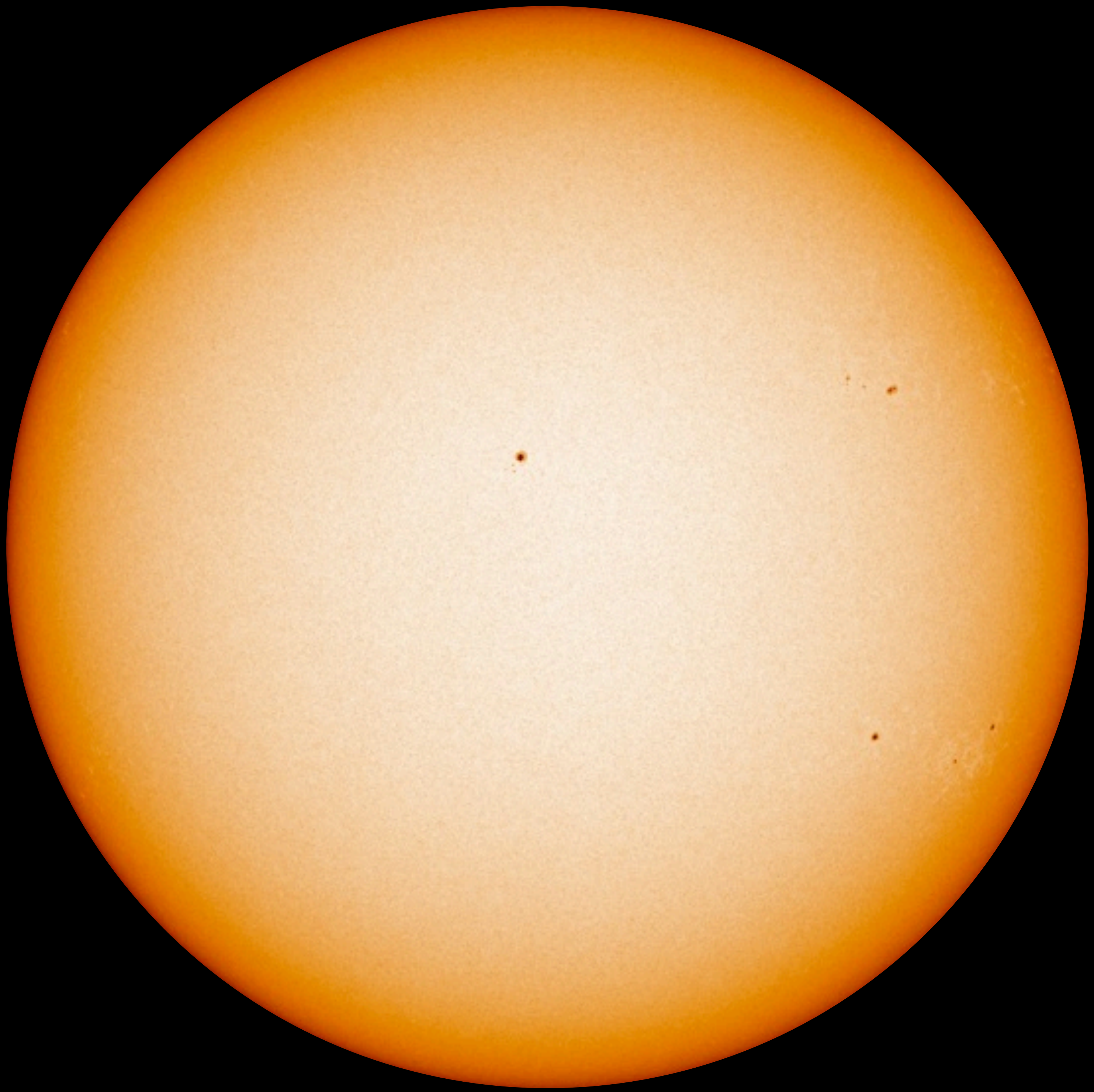
# Solar Dynamics Observatory



3200 kg
  270 kg payload
3 instruments
24/7 observations
2 TB data/day
Launch February 2010

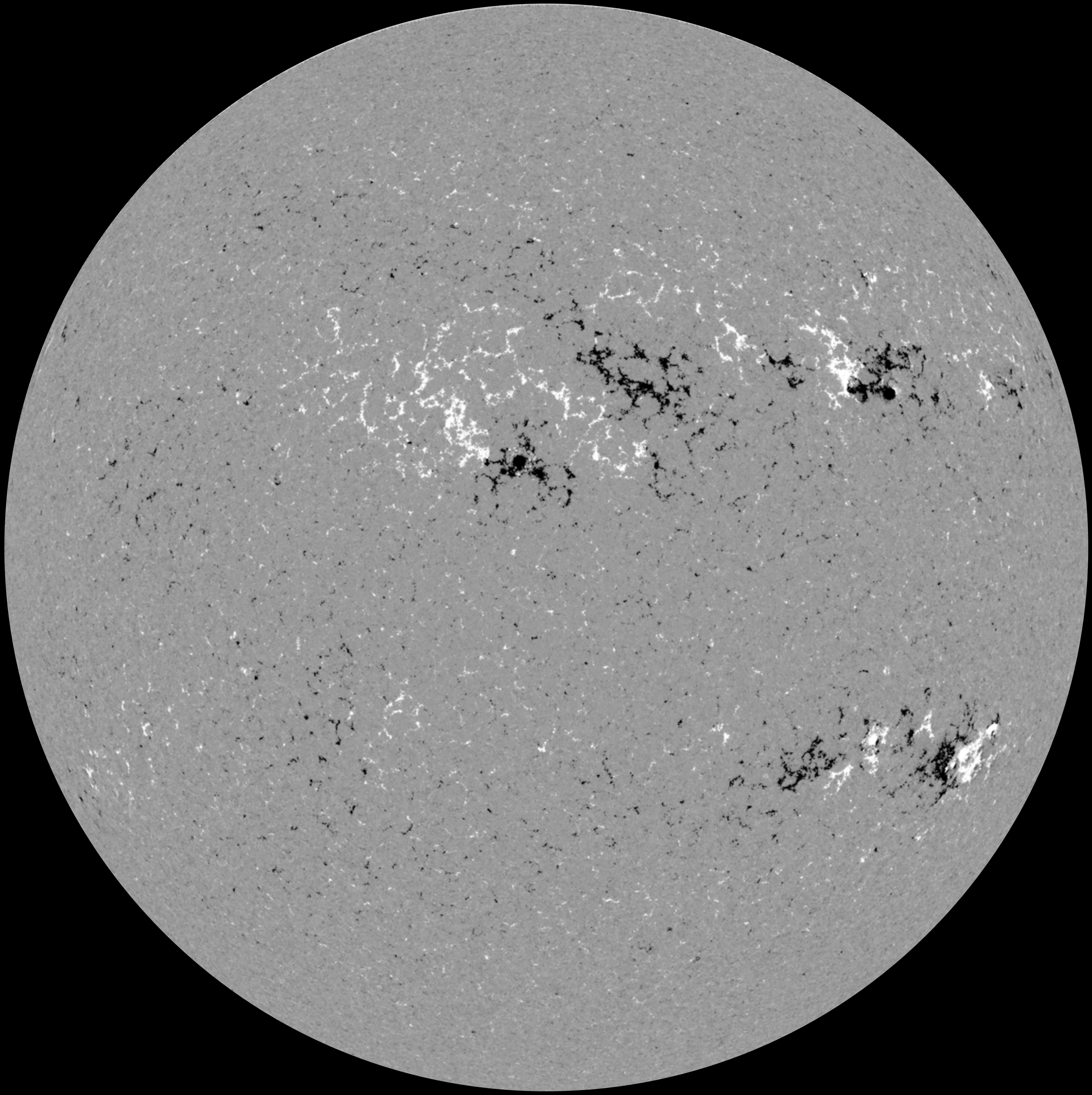
Norwegian contribution:
  science

Solar Surface 6000 K



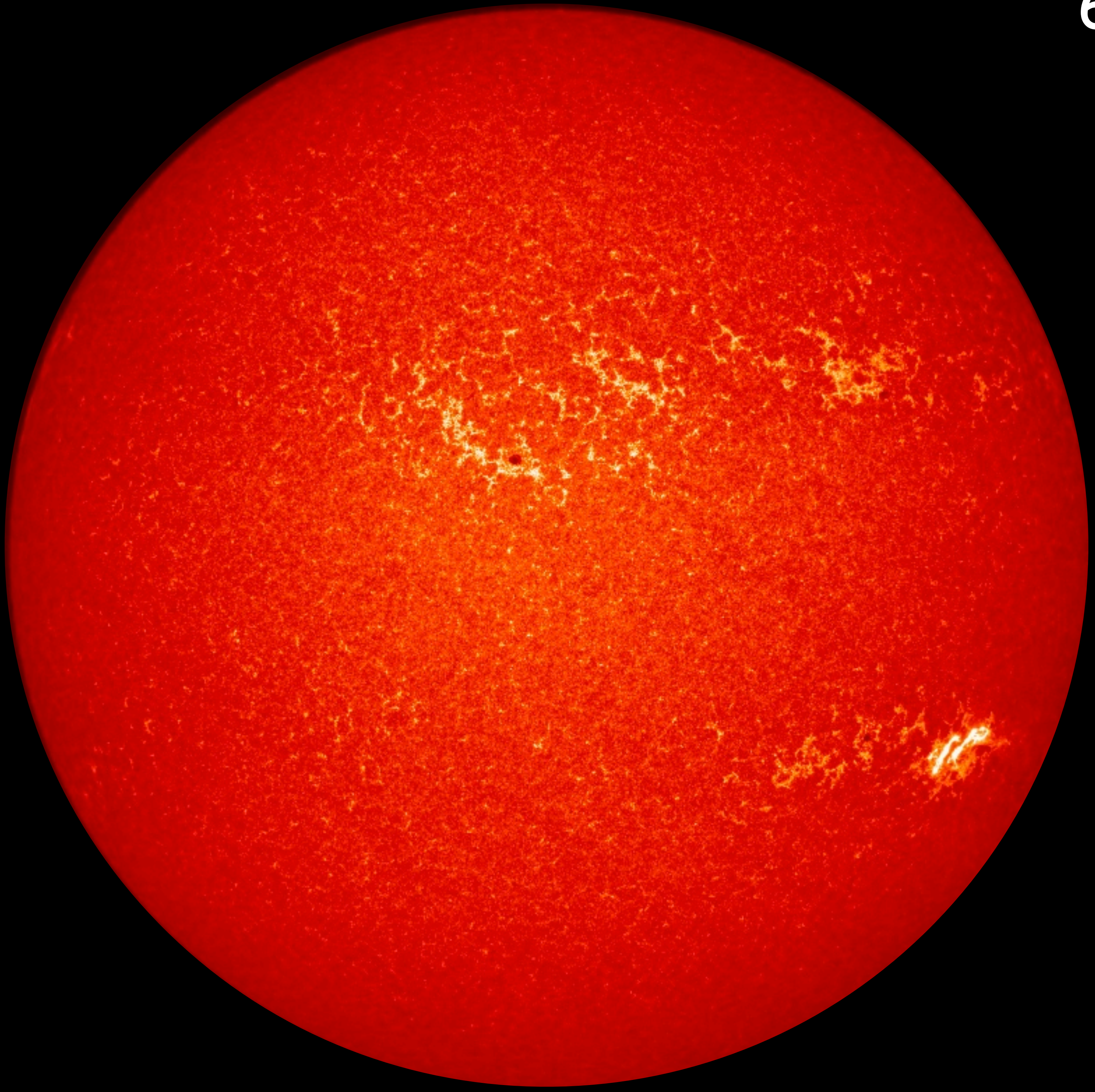
HMI/LSJU

# Surface LOS Magnetic Field

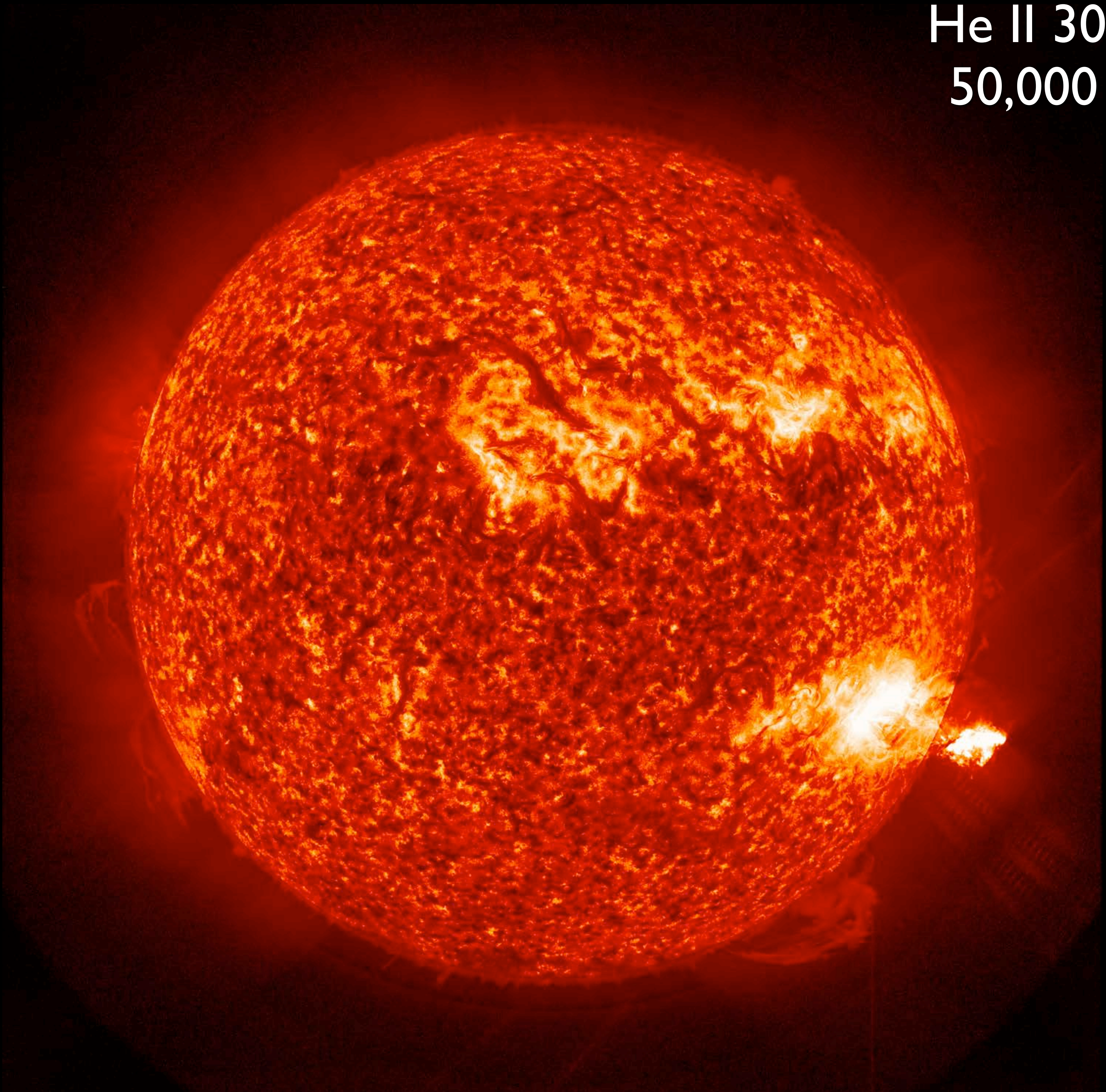


HMI/LSJU

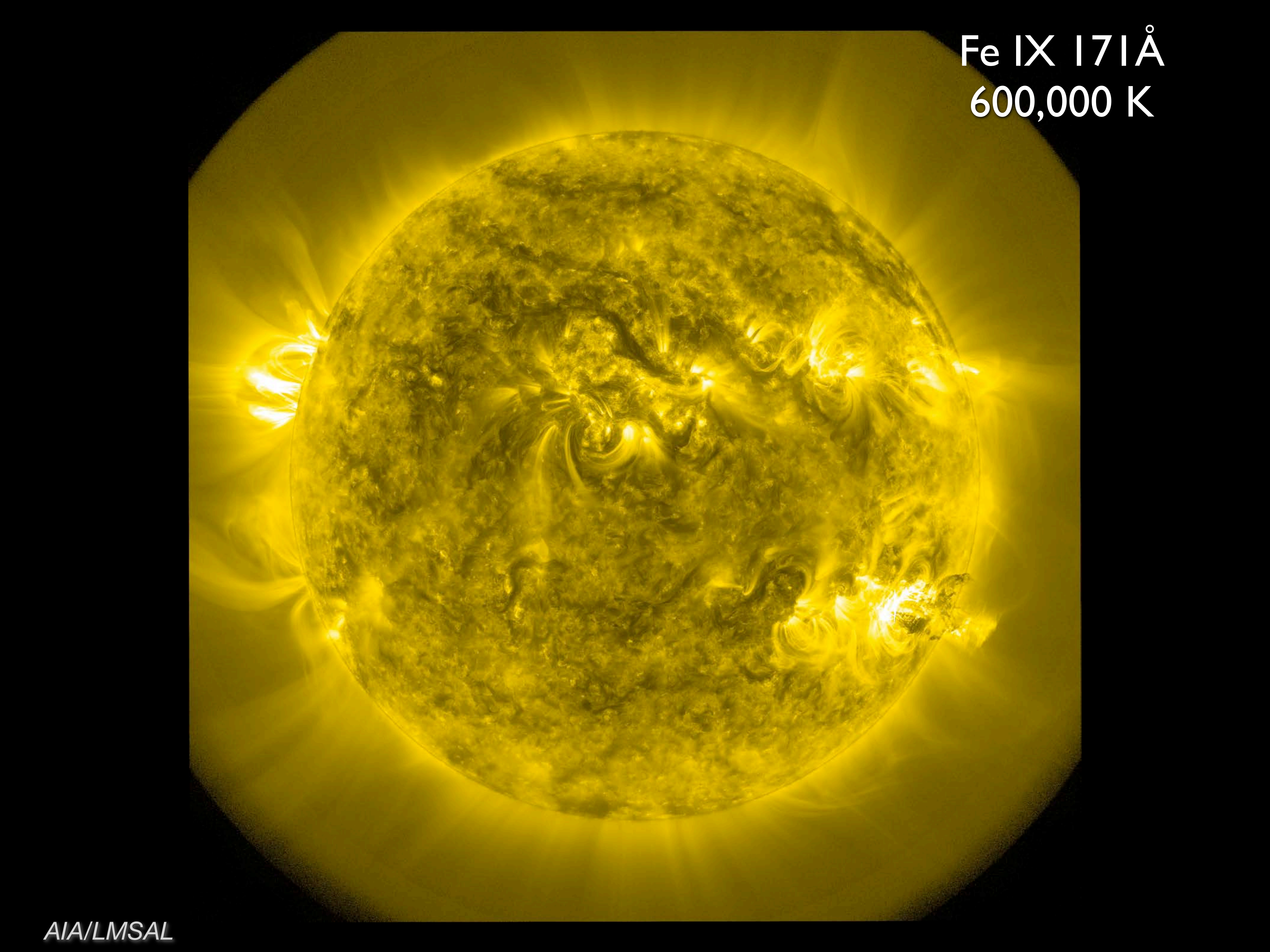
UV Continuum
1700Å
6000 K

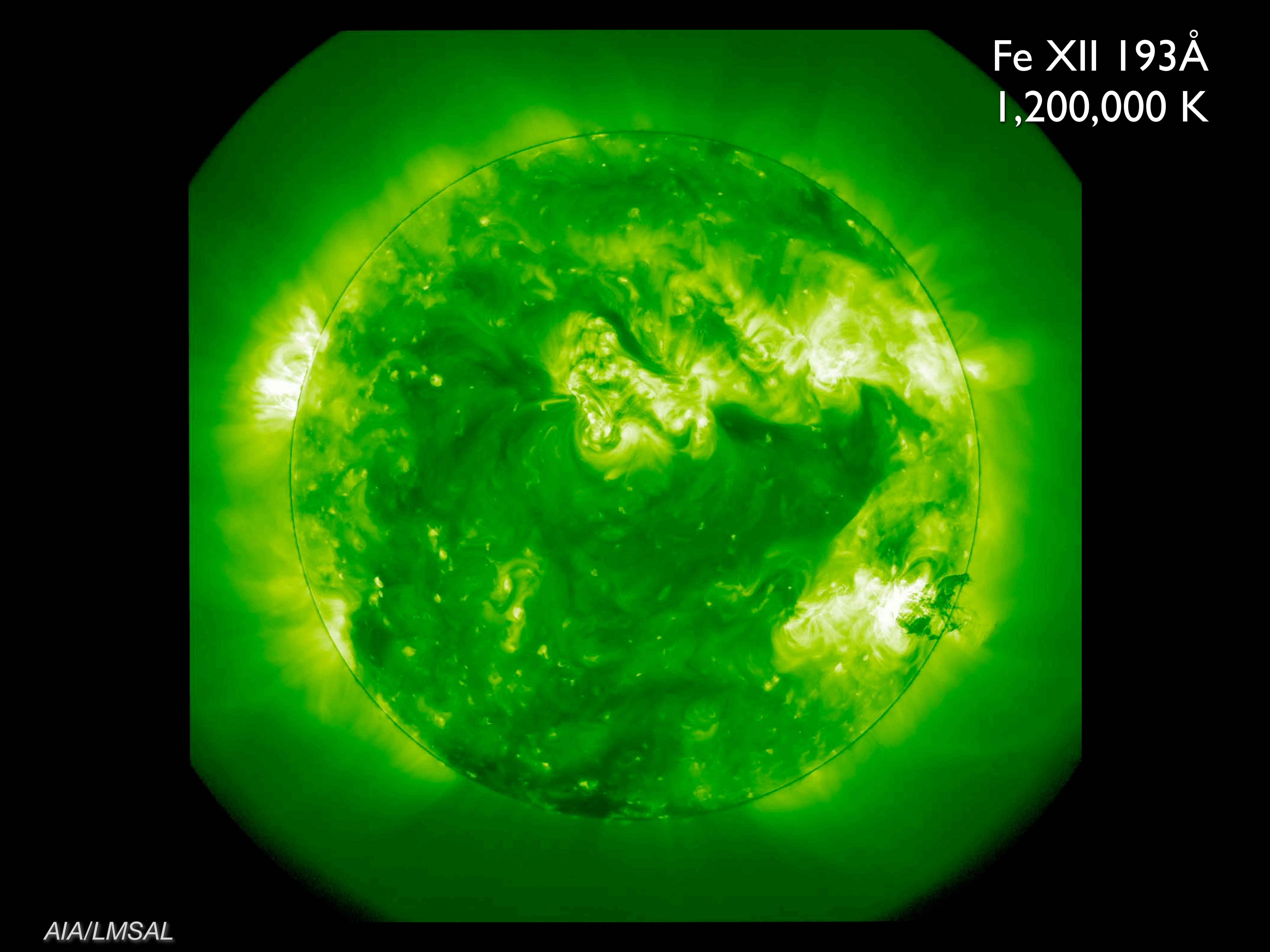


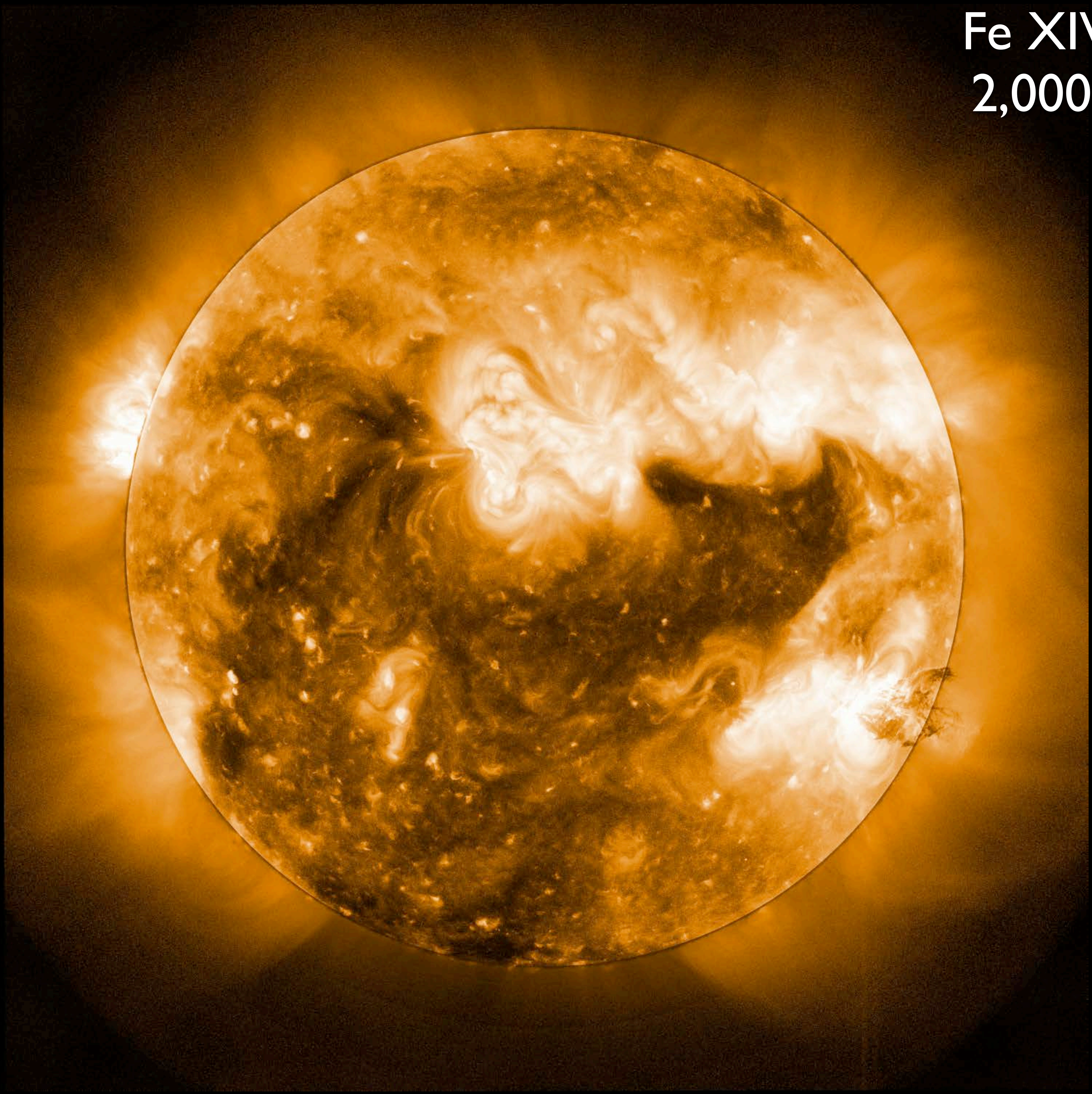
AIA/LMSAL



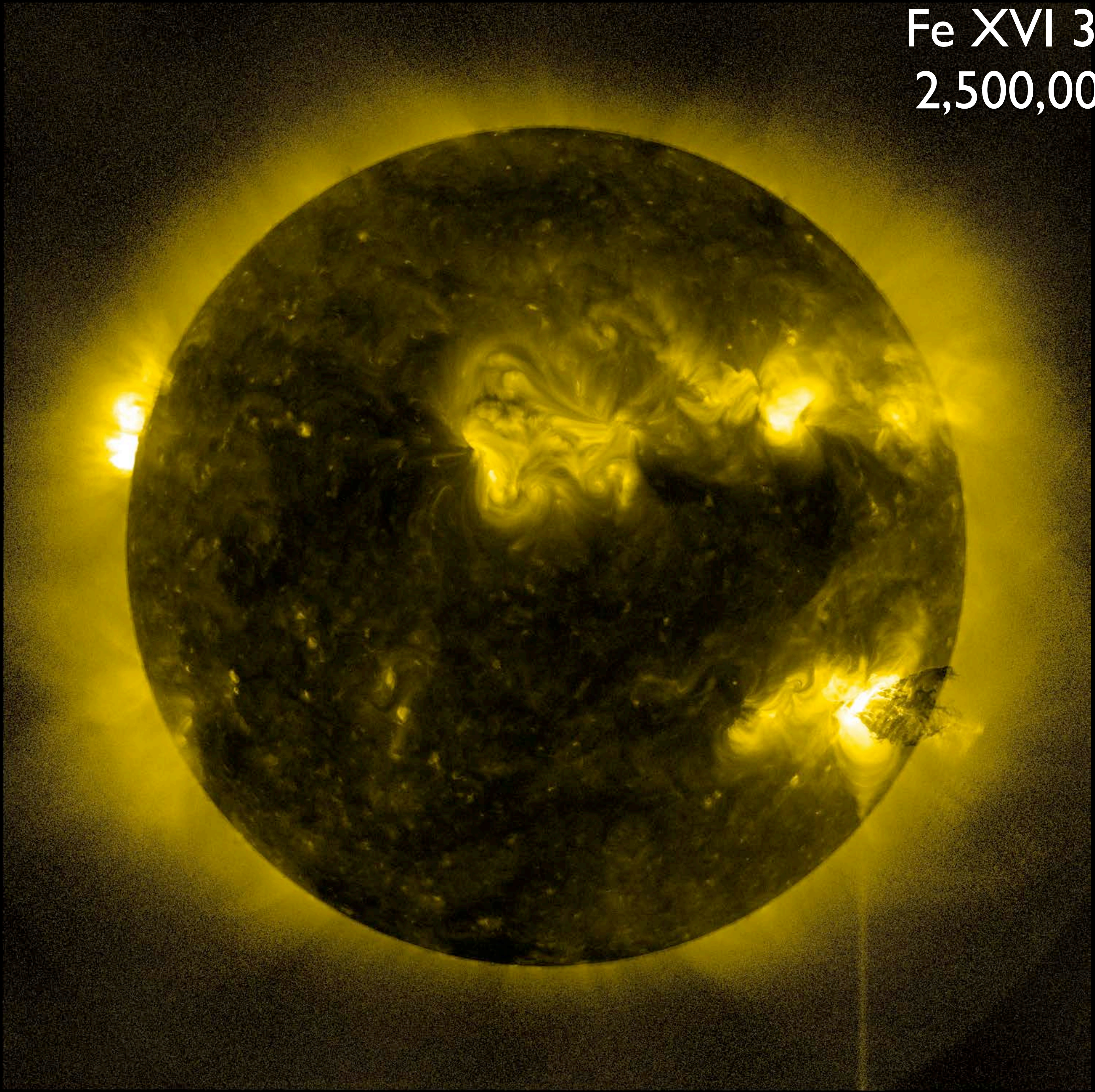

AIA/LMSAL


Fe IX 171Å
600,000 K
AIA/LMSAL

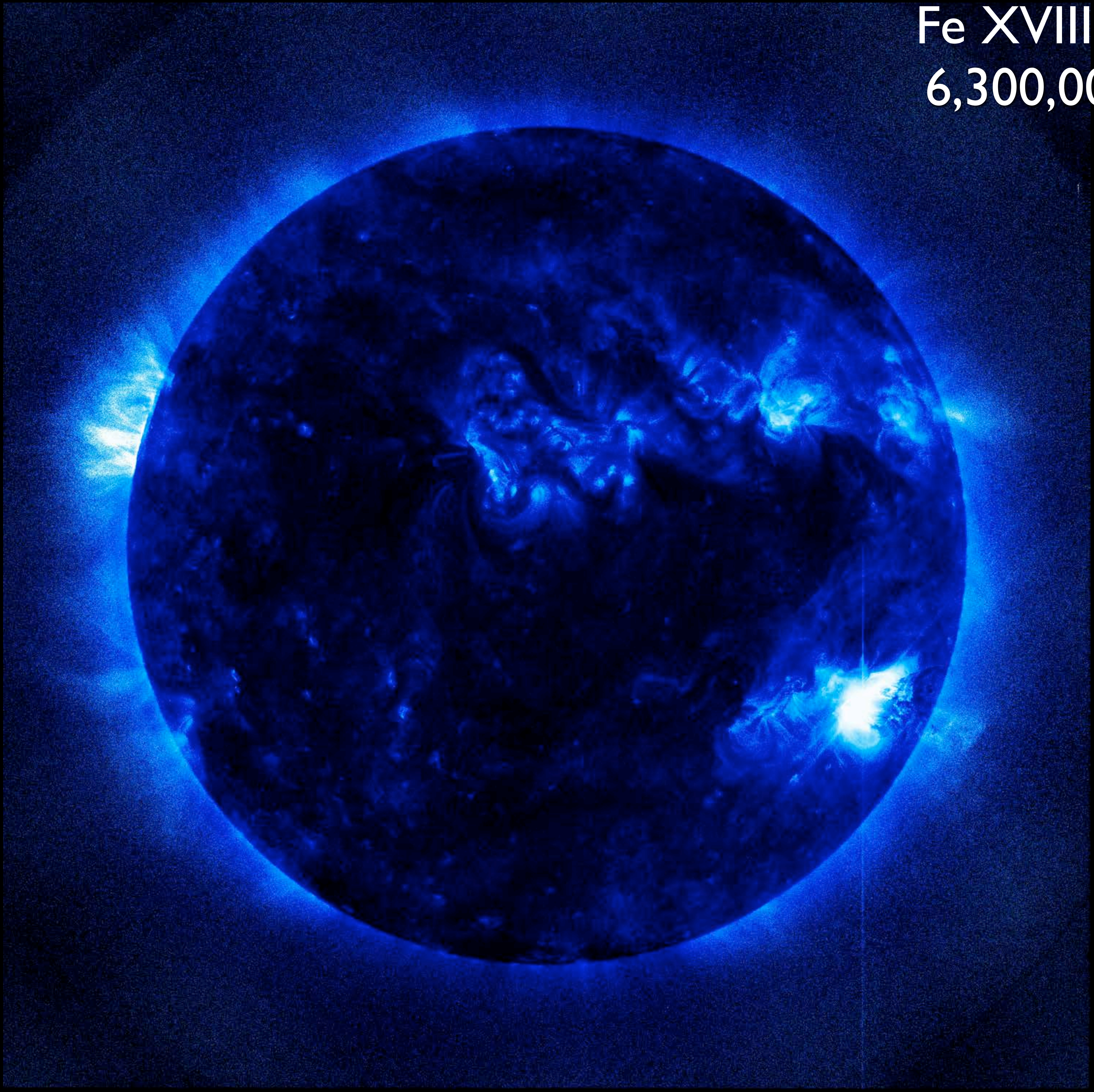

Fe XII 193Å
1,200,000 K
AIA/LMSAL



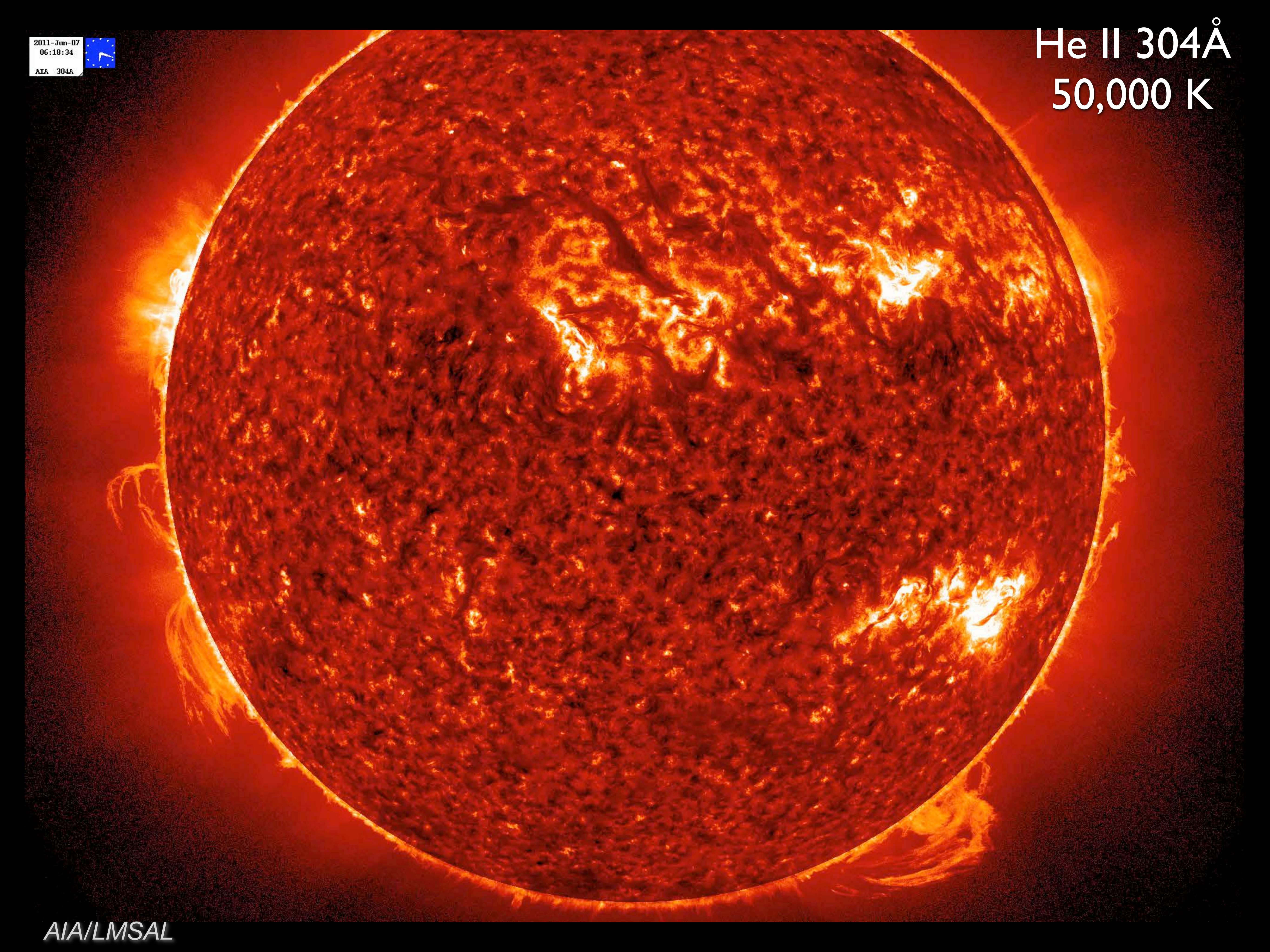

AIA/LMSAL



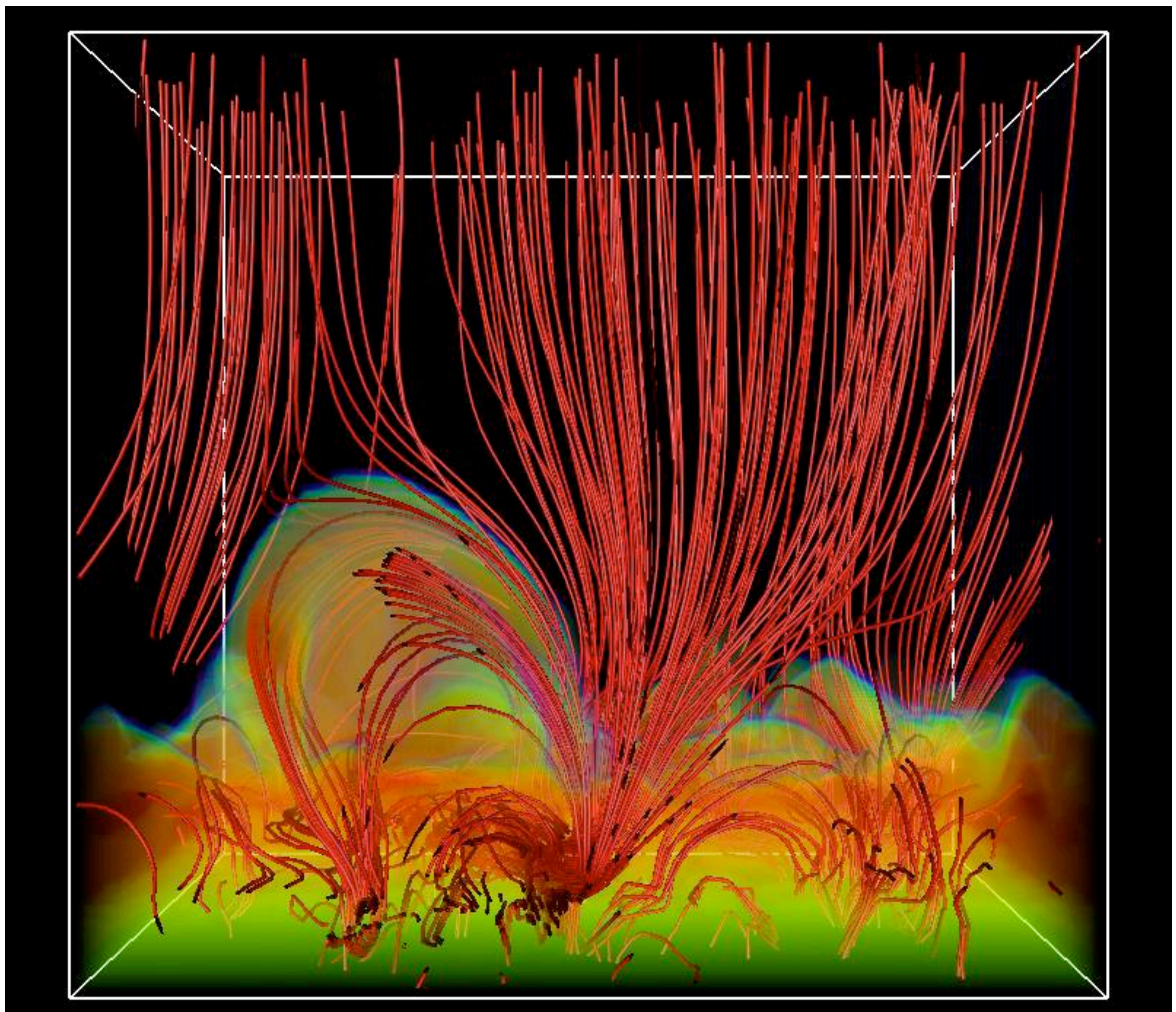

AIA/LMSAL




AIA/LMSAL


2011-Jun-07
06:18:34
AIA 304A
He II 304Å
50,000 K
AIA/LMSAL

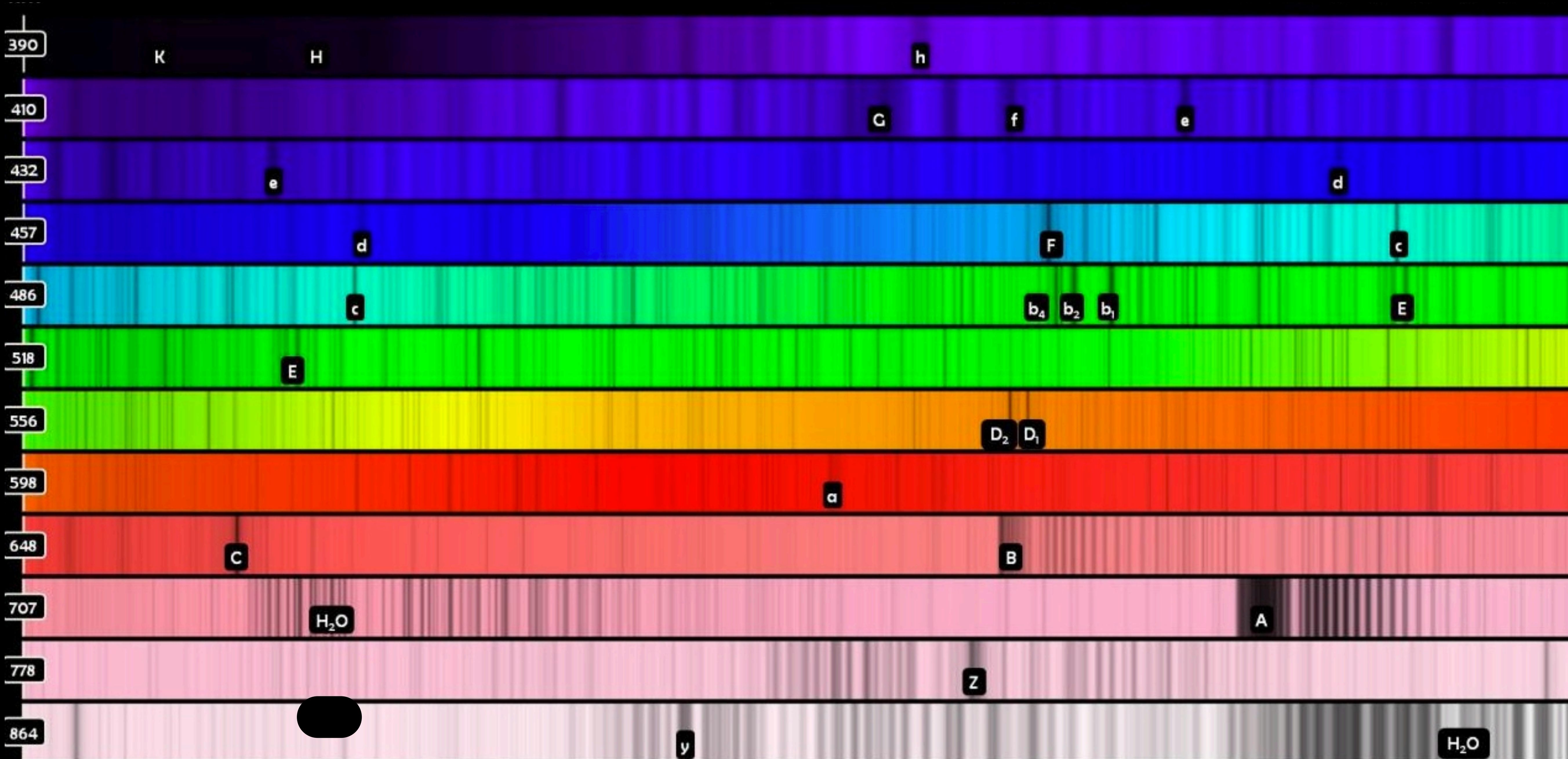
# What physics need to be included when modeling the solar chromosphere?



# Boundaries

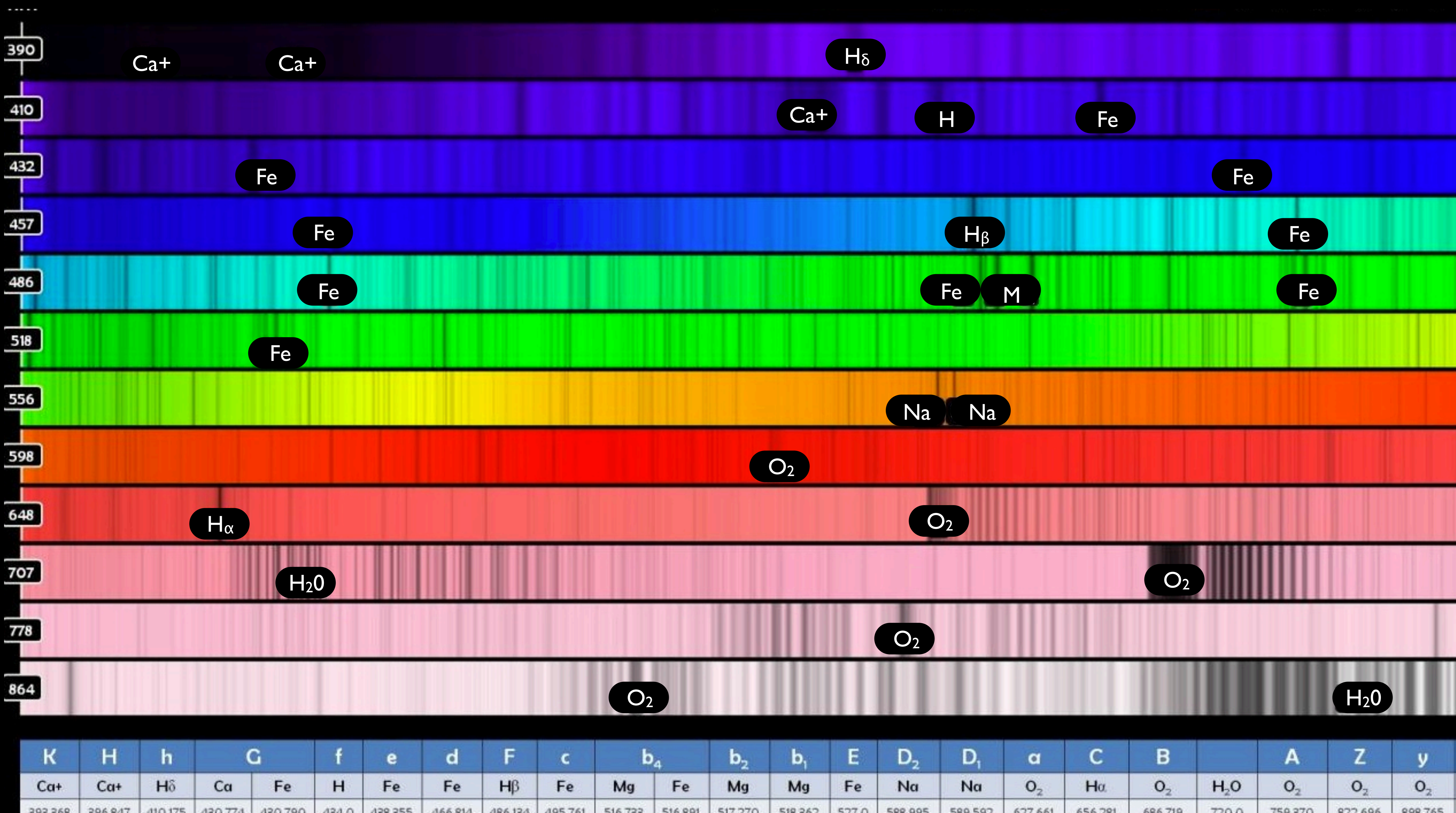
- Dynamics and energy supply from the convection zone
  - lower boundary should be in the convection zone
- Magnetic field topology should be contained in the box
  - upper boundary in the corona
  - large enough box to contain return flux
- Open system
  - open top and bottom boundaries

# Fraunhofer Spectrum 1811

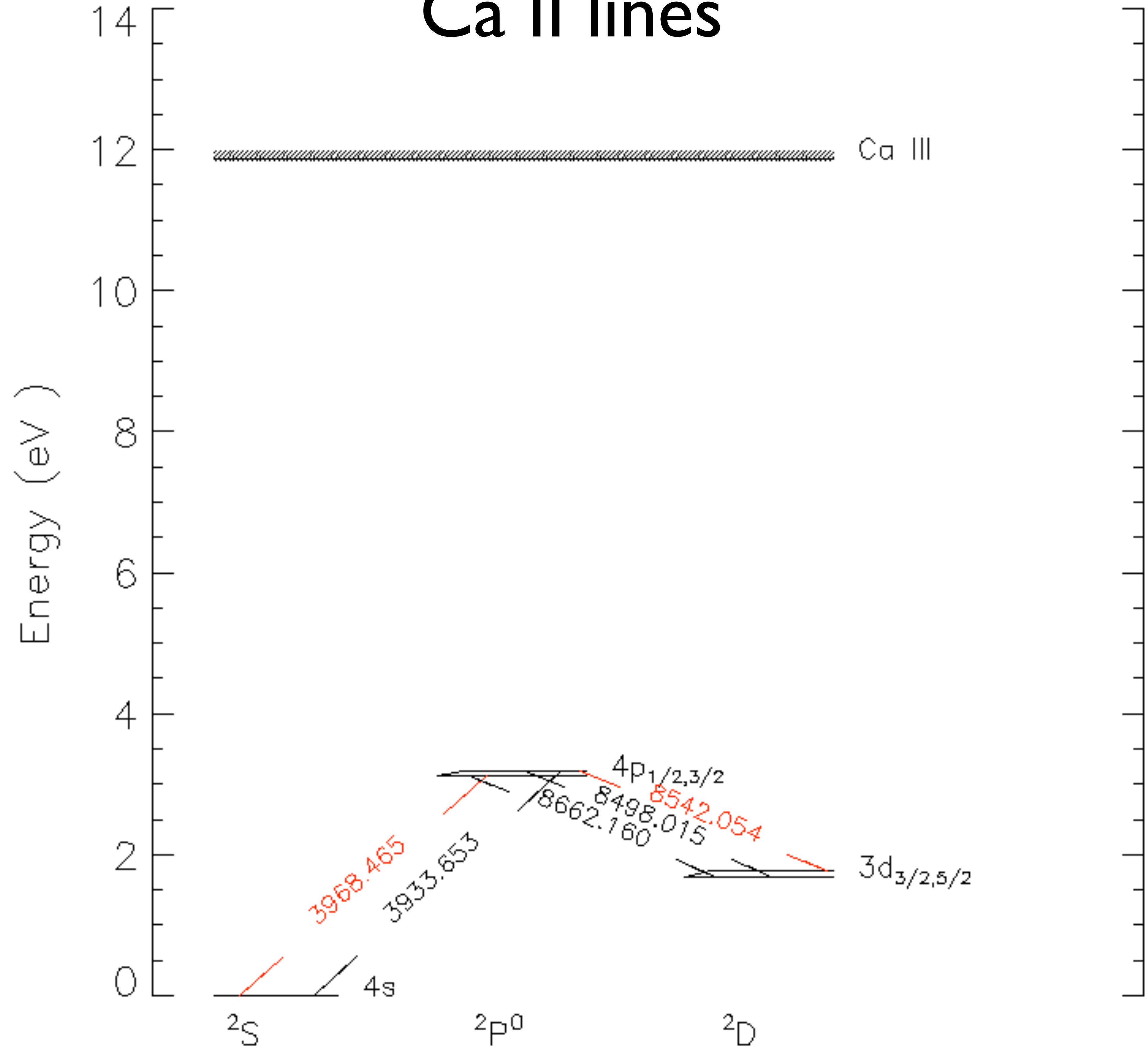



| K | H | h | G | | f | e | d | F | c | $b_4$ | | $b_2$ | $b_1$ | E | $D_2$ | $D_1$ | a | C | B | | A | Z | y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ca+ | Ca+ | Hδ | Ca | Fe | H | Fe | Fe | Hβ | Fe | Mg | Fe | Mg | Mg | Fe | Na | Na | $O_2$ | Hα | $O_2$ | $H_2O$ | $O_2$ | $O_2$ | $O_2$ |
| 393.368 | 396.847 | 410.175 | 430.774 | 430.790 | 434.0 | 438.355 | 466.814 | 486.134 | 495.761 | 516.733 | 516.891 | 517.270 | 518.362 | 527.0 | 588.995 | 589.592 | 627.661 | 656.281 | 686.719 | 720.0 | 759.370 | [redacted] | 898.765 |

# Identified Fraunhofer Spectrum ~ 1850



# Ca II lines



Ca III
4p1/2,3/2
3d3/2,5/2
4s
3968.465
3933.653
8662.160
8498.015
8542.054
Energy (eV)
0
2
4
6
8
10
12
14
2S
2P0
2D

# Energy balance

- Radiation in strong lines from H, Ca, Mg, He
  - non-LTE 6-12 levels per element
  - incident coronal radiation field
- Radiation in very many weak lines
  - many frequencies needed
  - non-LTE Fe: many levels needed

- Radiative transfer in energy balance in 3D simulations
  - non-locality - parallelization
  - frequency integration
  - scattering

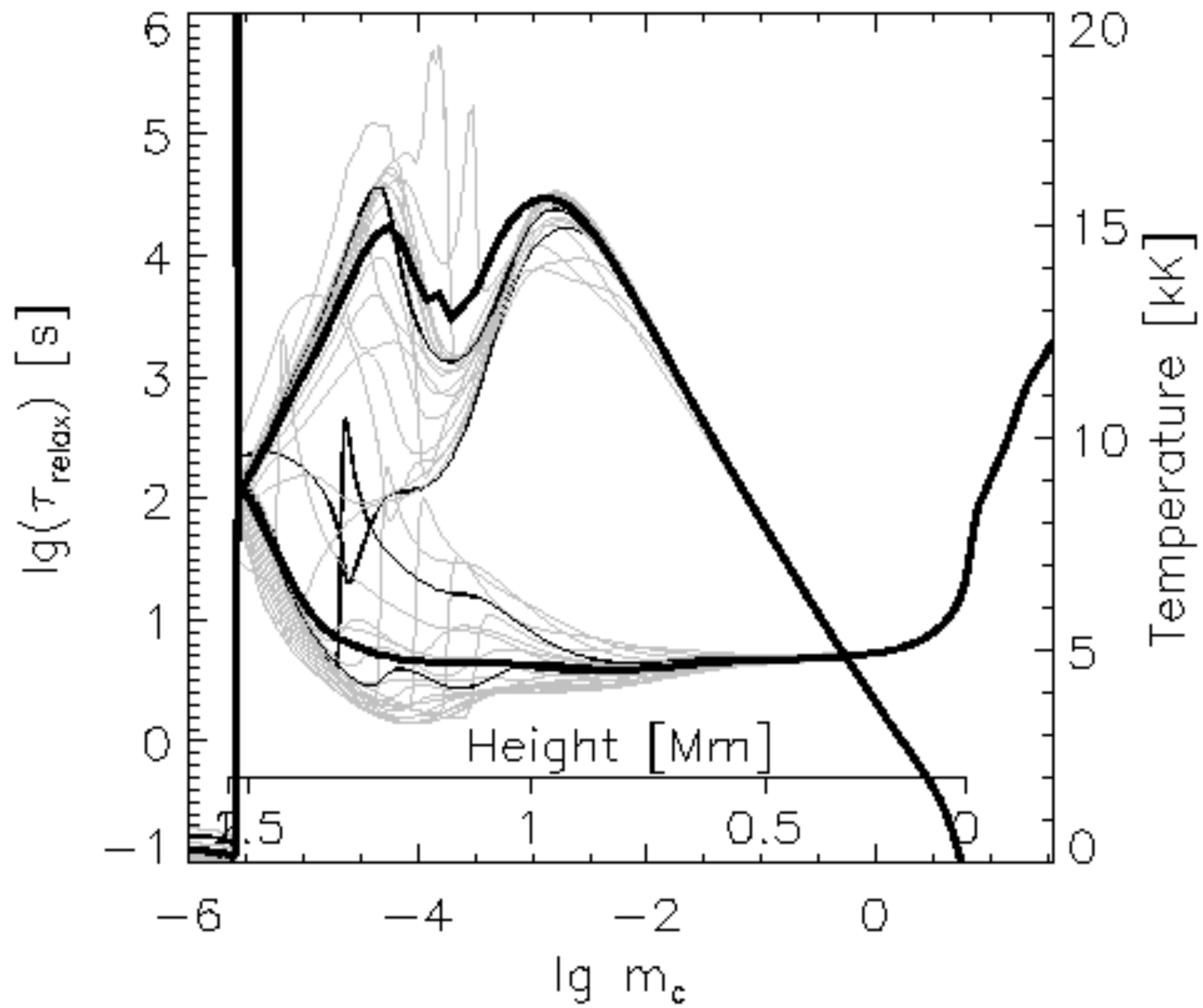
$$\Phi = \int_0^\infty \chi_\nu (S_\nu - J_\nu) d\nu$$

$$\Phi = \int_0^\infty \epsilon_\nu \chi_\nu (B_\nu - J_\nu) d\nu$$

# Energy balance

- Shock dissipation
    - high spatial resolution
- Conduction
    - time-scales short
- Magnetic field
    - reconnection
    - high wave speeds: time-scales short
- Particle beams

# Ionization equilibrium




- Timescales for hydrogen ionization balance long
  - need to solve rate equations for hydrogen

# MHD?

- Chromosphere mostly neutral
  - ion-neutral effects
- non-Maxwellian distribution functions
  - kinetic modelling

# Can we do this?

- In principle, yes
- 20 km resolution, 50 Mm box, NLTE H+Ca+He+Mg:
- 6 million years on 5000 CPUs for one hour of solar time
- In practice, no

# The MHD equations

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

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) + p\nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + \eta j^2 + Q_{visc}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + \tau) = -\nabla p + \mathbf{j} \times \mathbf{B} - g\rho$$

with some equation of state... $T_g, p_g = \mathrm{EOS}(e, \rho)$


Bifrost

# BIFROST

Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007, Sykora, Hansteen, Carlsson 2008,
**Gudiksen et al 2011**

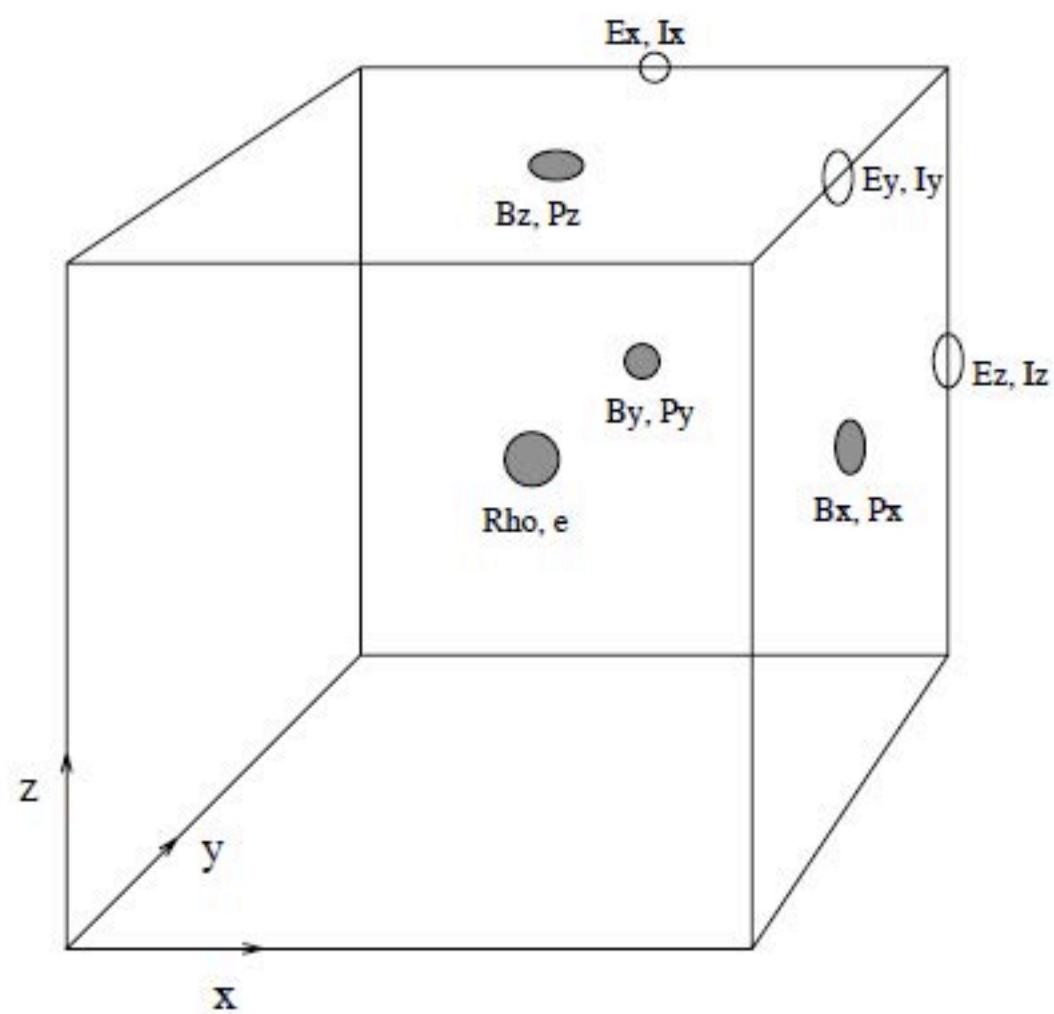
- 6th order scheme, with "artificial viscosity/diffusion"
- Open vertical boundaries, horizontally periodic
- Possible to introduce field through bottom boundary

- "Realistic" EOS
- Detailed radiative transfer along 48 rays
  - Multi group opacities (4 bins) with scattering
- NLTE losses in the chromosphere, optically thin in corona

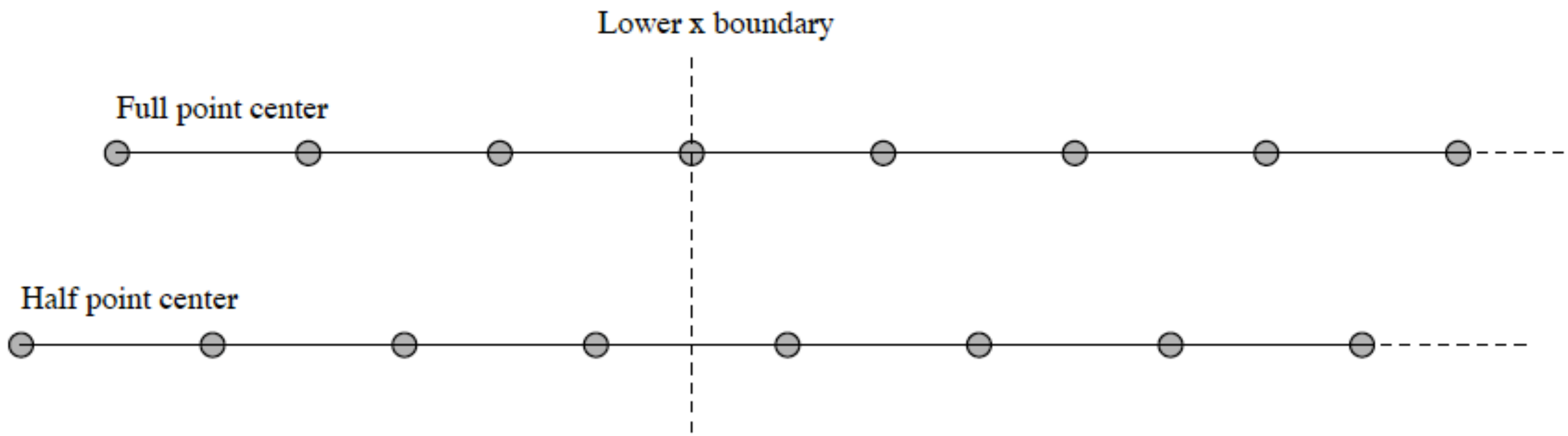
- Conduction along field lines
  - Operator split and solved by using multi grid method

- Time dependent Hydrogen ionization
- Generalized Ohm's Law

# Centering of variables



# 6'th order differential operator




$$
\begin{aligned}
\frac{\partial f_{+\frac{1}{2}}}{\partial \vec{x}} \quad = \quad & a_{\vec{x}} \left[ f_{+1} - f_{0} \right] + \\
& b_{\vec{x}} \left[ f_{+2} - f_{-1} \right] + \\
& c_{\vec{x}} \left[ f_{+3} - f_{-2} \right]
\end{aligned}
$$

# Diffusion coefficients and the hyperdiffusive operator

$$\nu_x = v_1 \Delta x c_f + v_2 \Delta x |u_x| + v_3 \Delta x |\nabla \cdot u|_-$$

with $\quad c_f = \left( \frac{B^2 + \gamma p}{\rho} \right)^{1/2}$

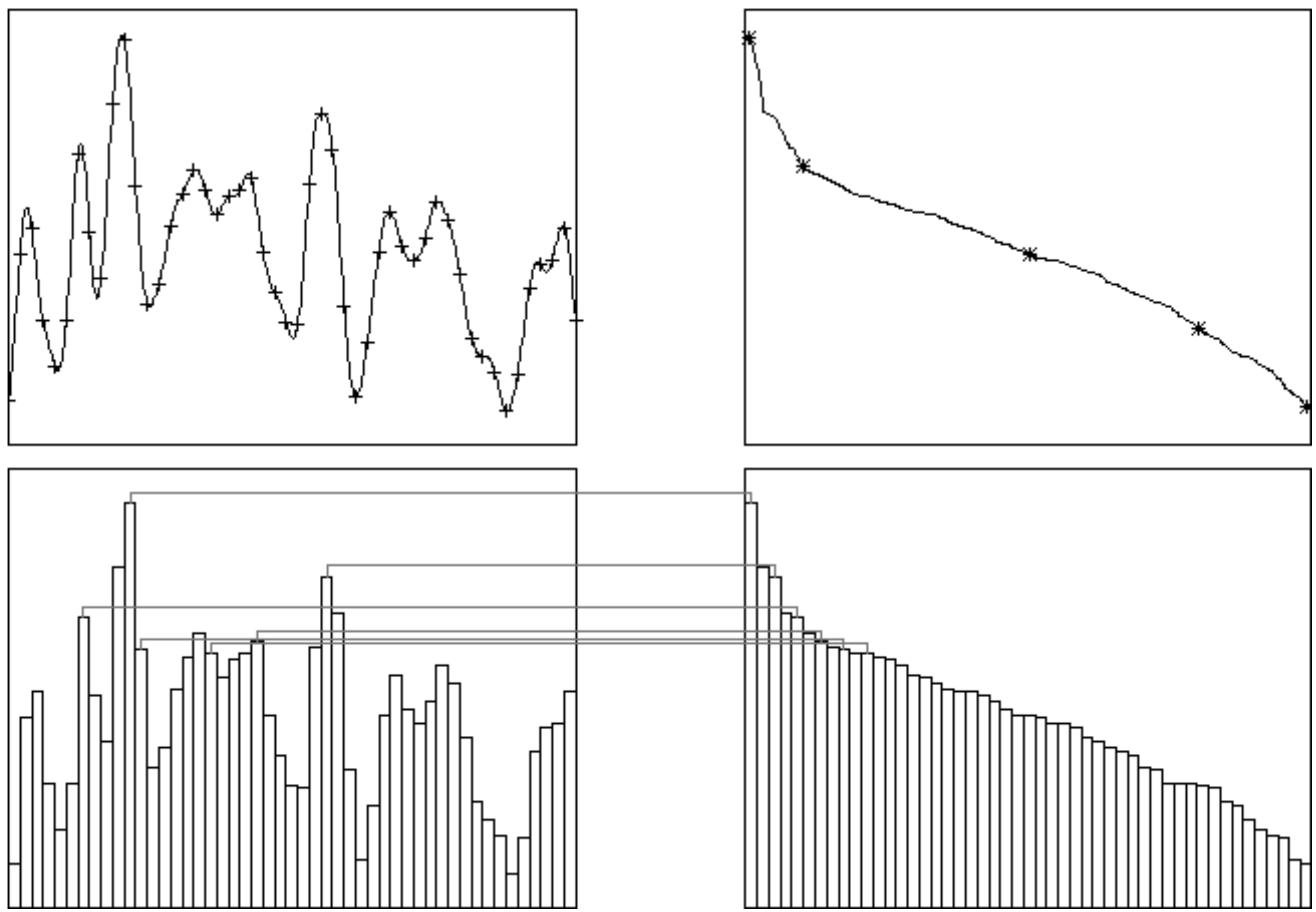
appears in equations with terms such as

$$\frac{\partial(\rho u_x)}{\partial t} = \ldots - \frac{\partial}{\partial x}\left(-\rho \nu_x \frac{\partial u_x}{\partial x}\right) + \ldots$$

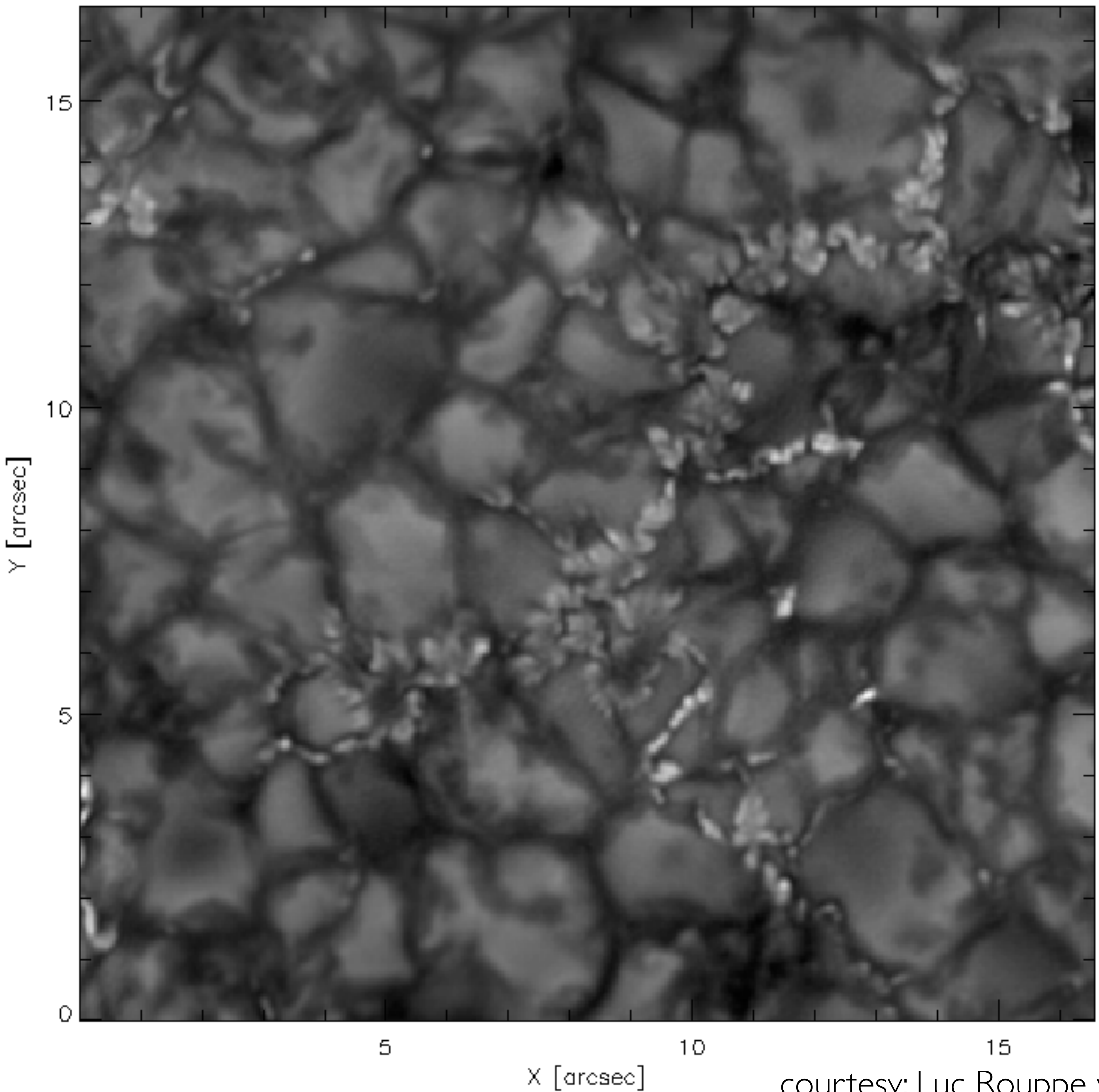
etc... where the first derivative is replaced by

$$d^+_{,x}(f) = \frac{\max_{x\pm1}|\Delta^3 f|}{\max_{x\pm1}|\Delta f|} \partial^+_{,x}(f)$$

$$\Phi = \int_0^\infty \chi_\nu (S_\nu - J_\nu) d\nu$$

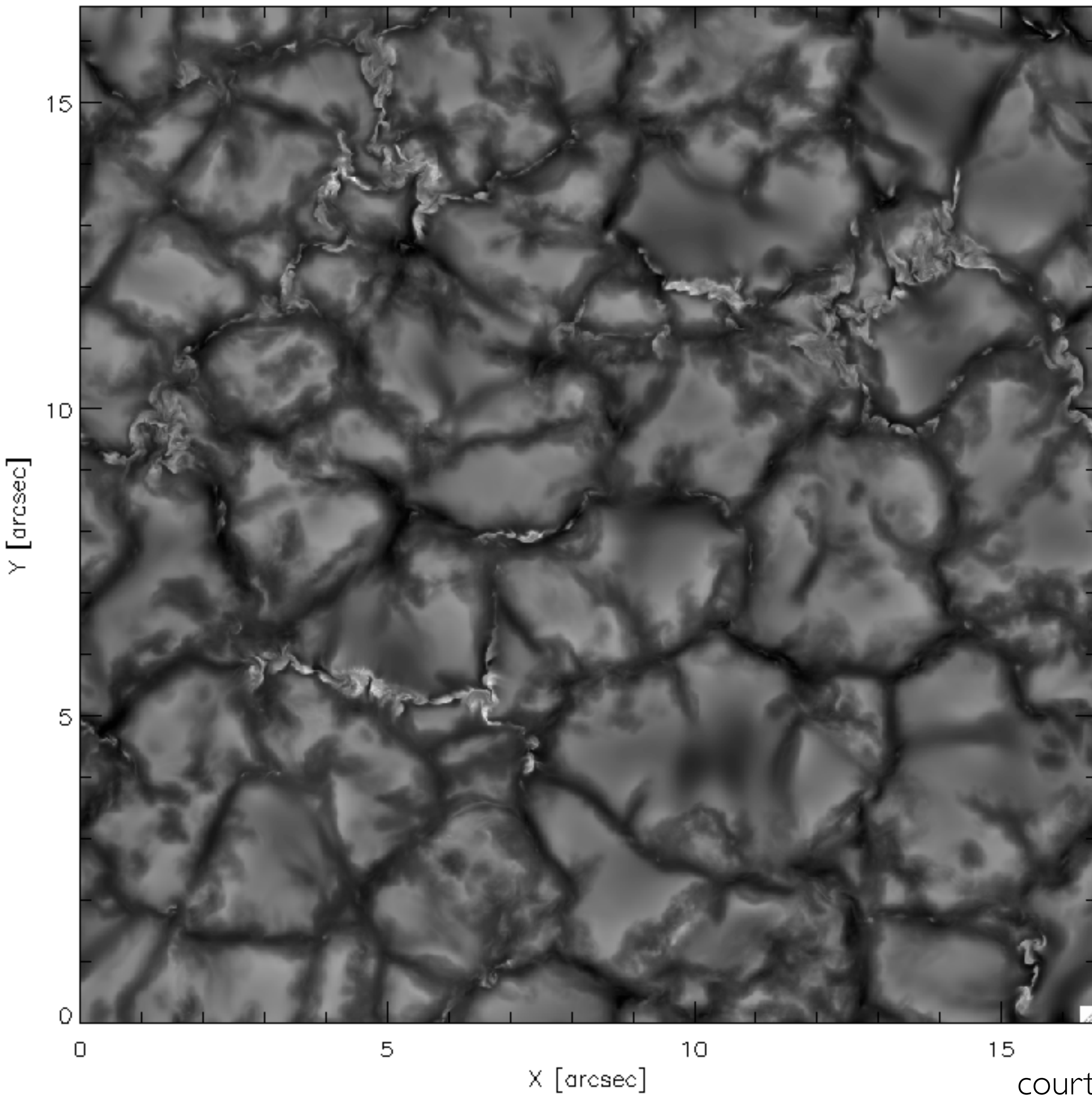


SST
G-band



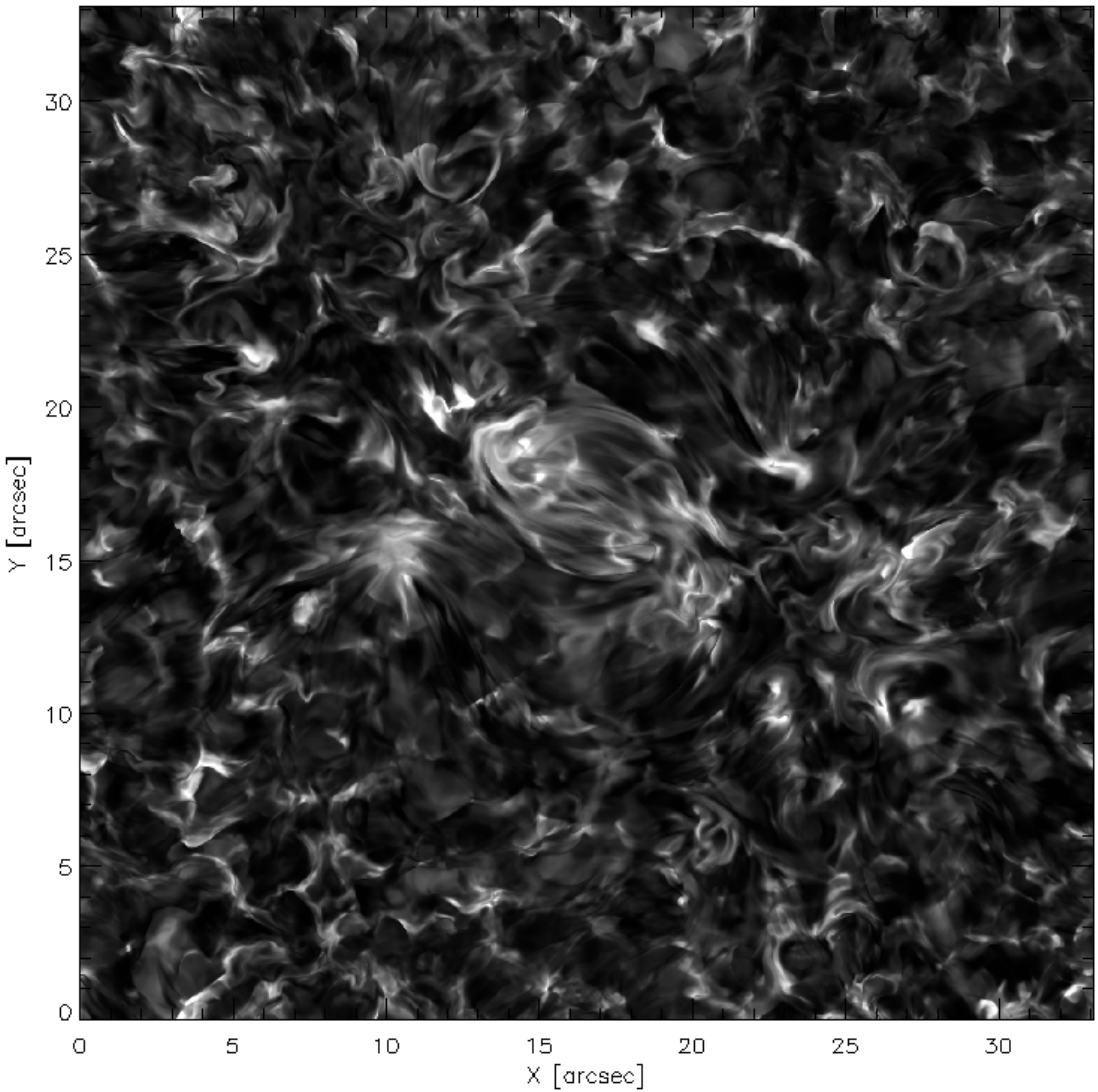

courtesy: Luc Rouppe van der Voort

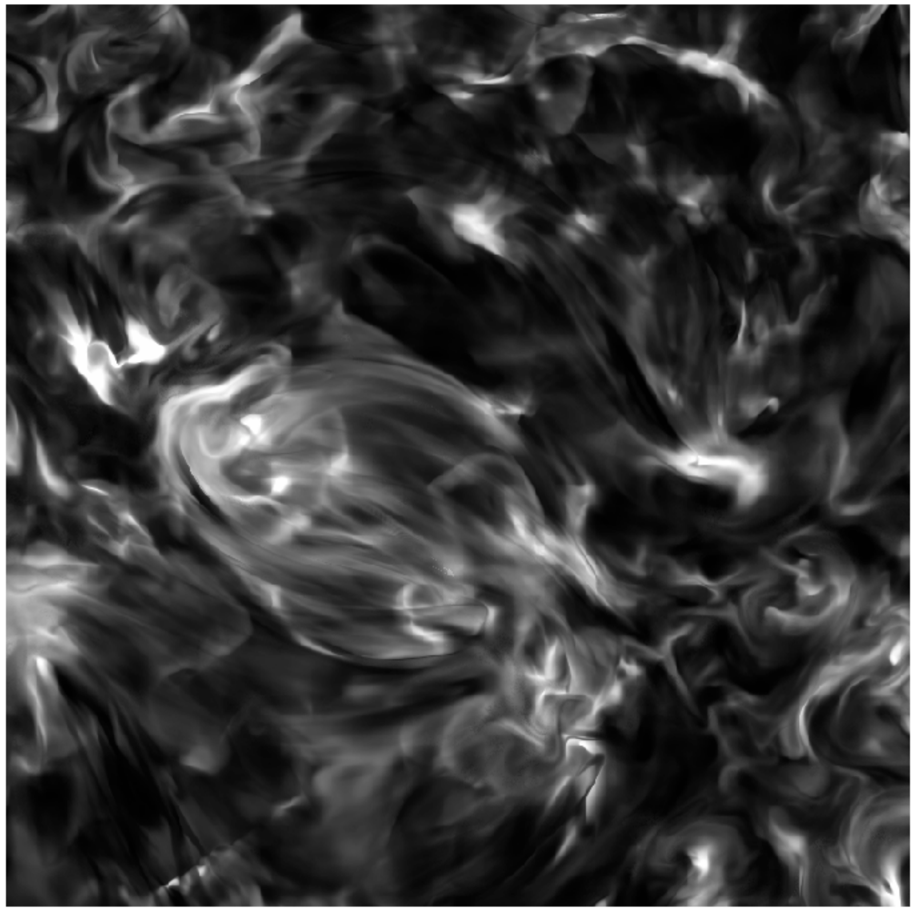
$\Delta x$=6 km
$\langle B_z \rangle$=60 G

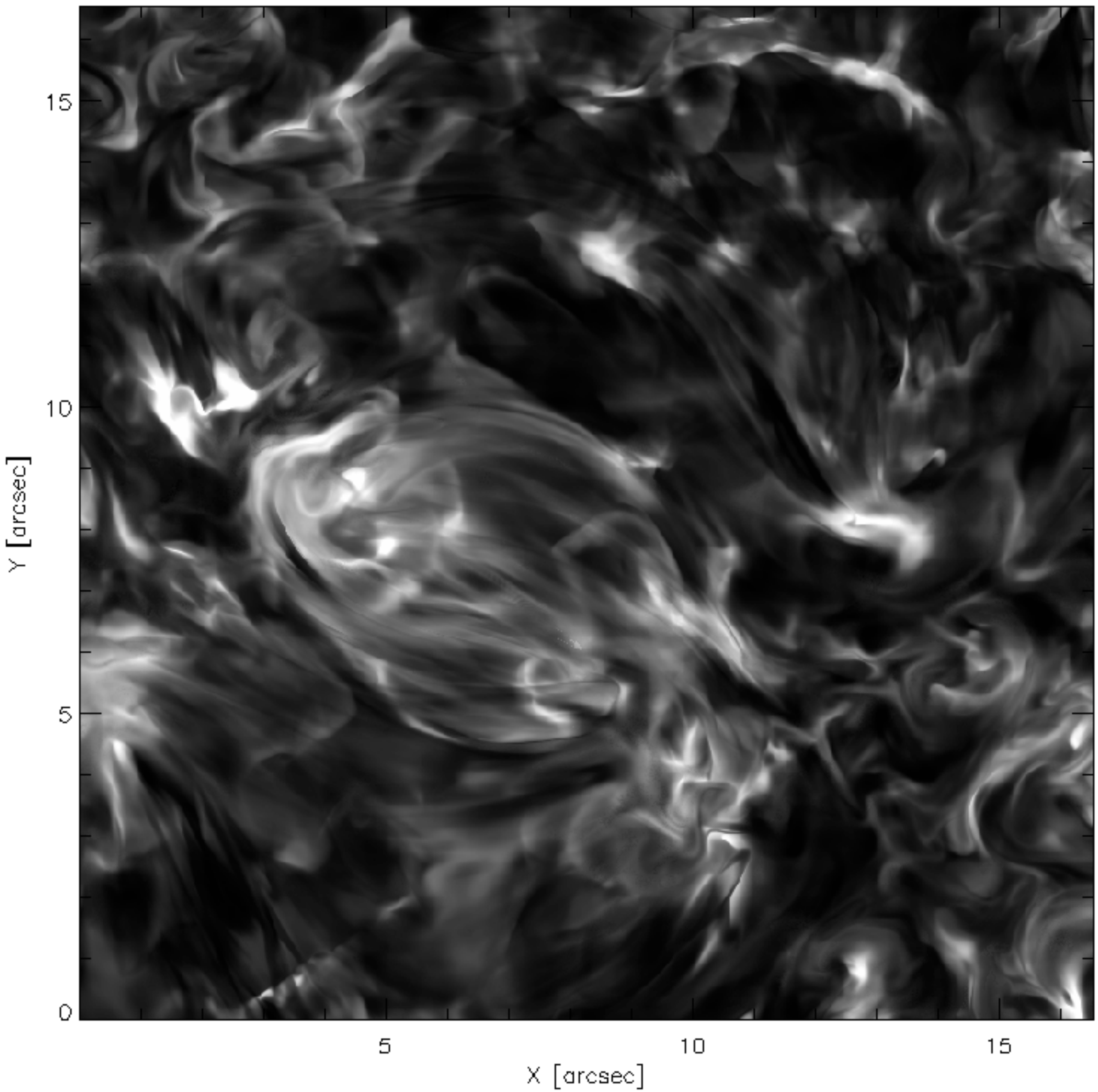



courtesy: Bob Stein

Ca II 8542
core
Δx=15 km



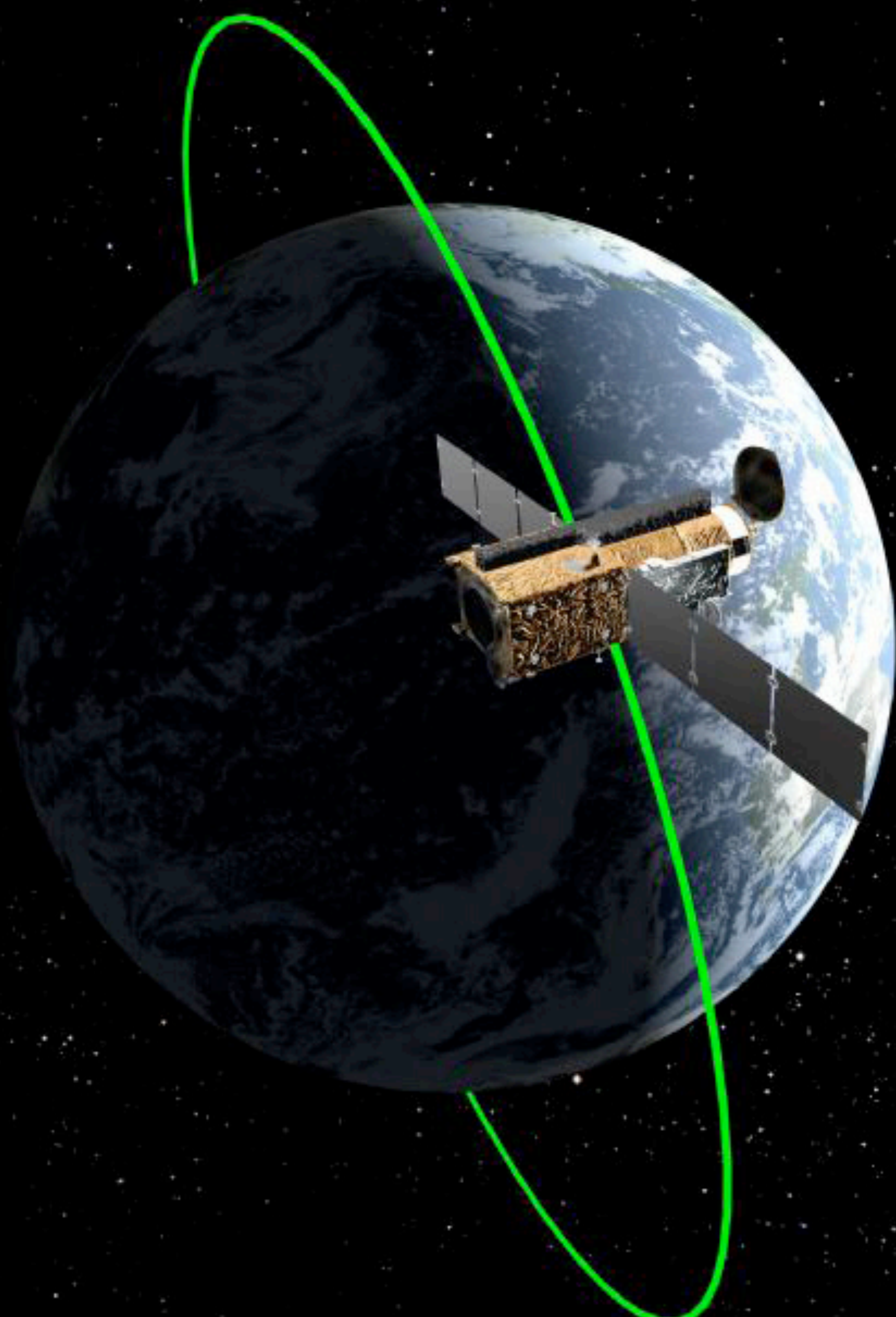




15
10
5
0
Y [arcsec]
5
10
15
X [arcsec]

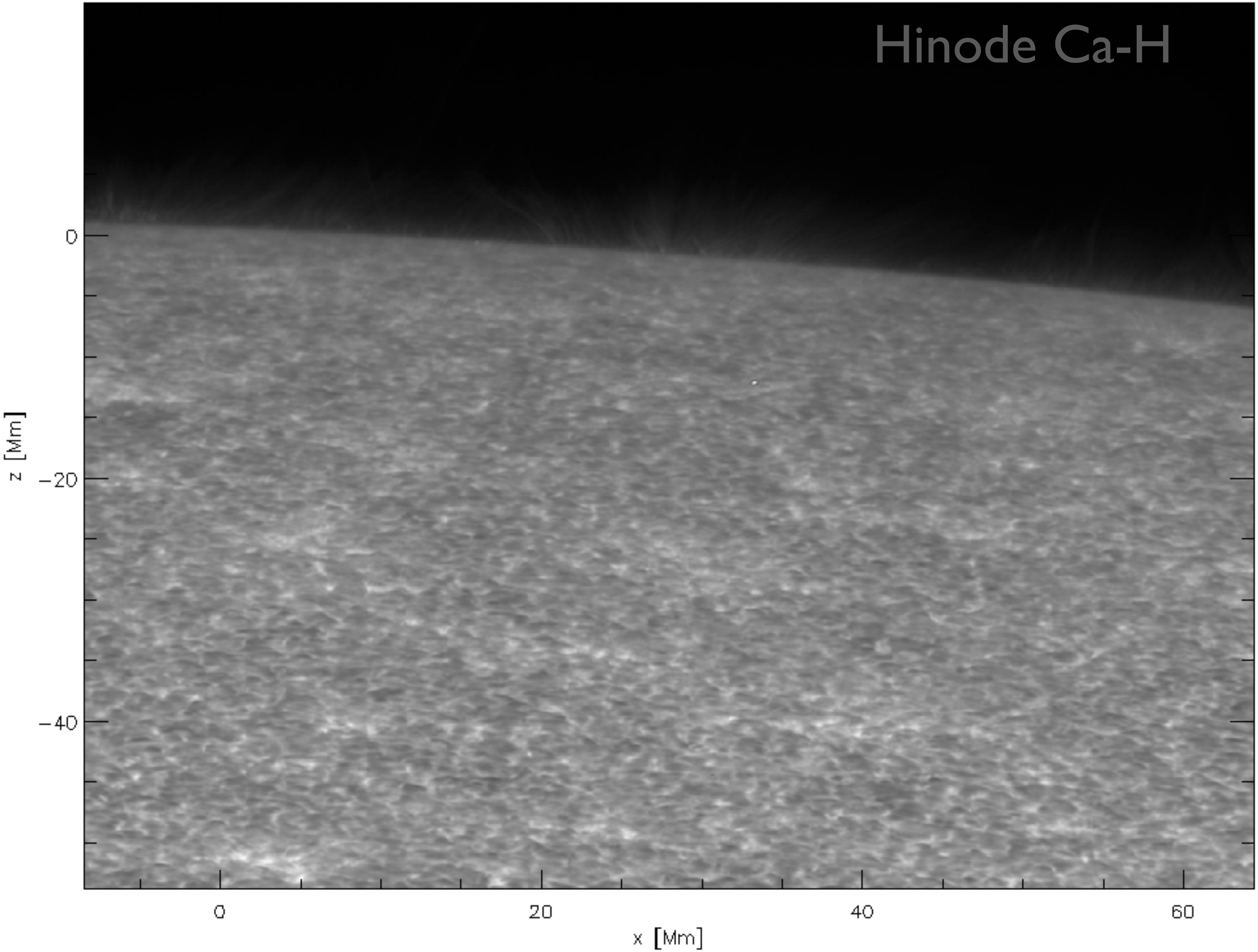

# How Is The Solar Corona Filled with Hot Plasma?

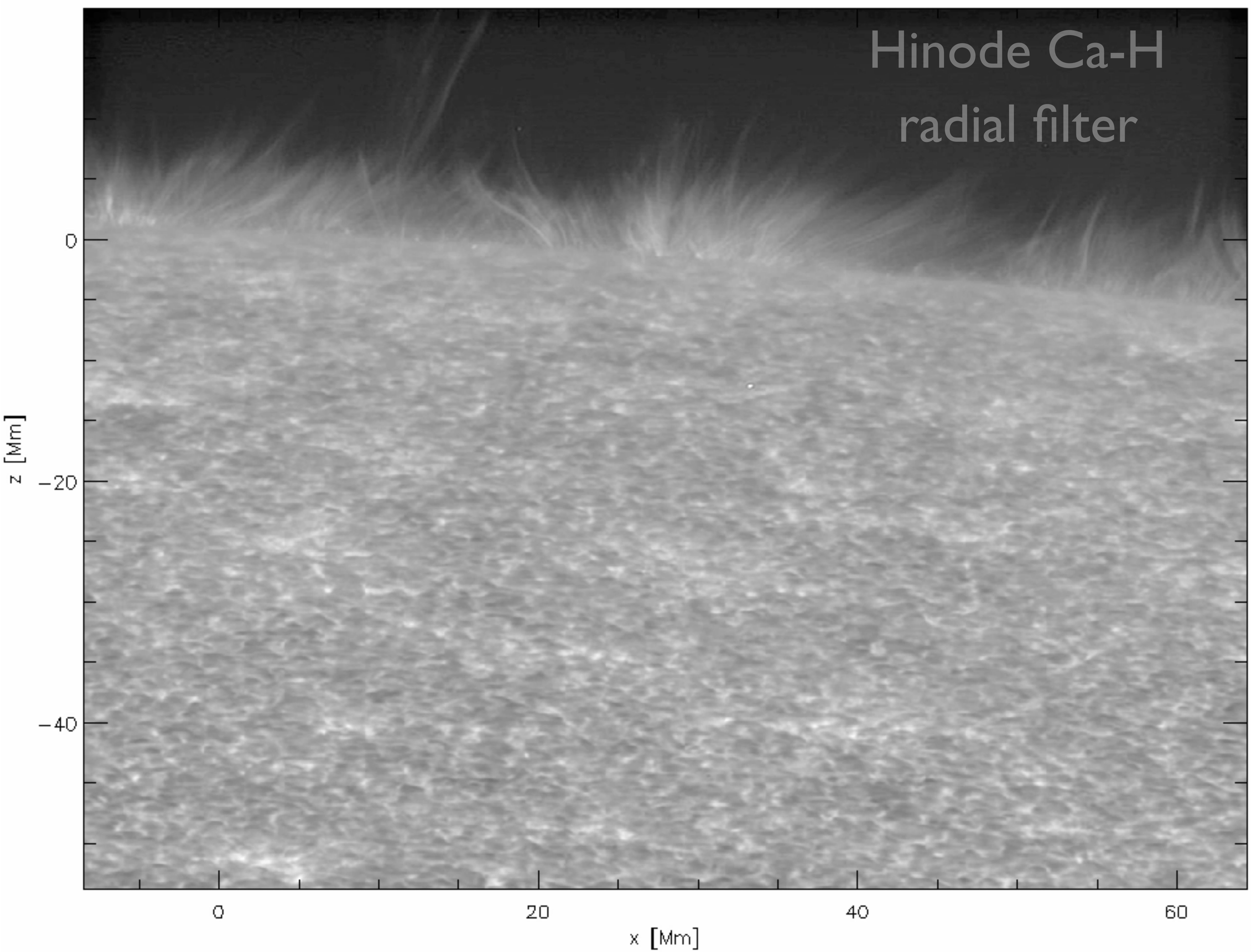
# Hinode



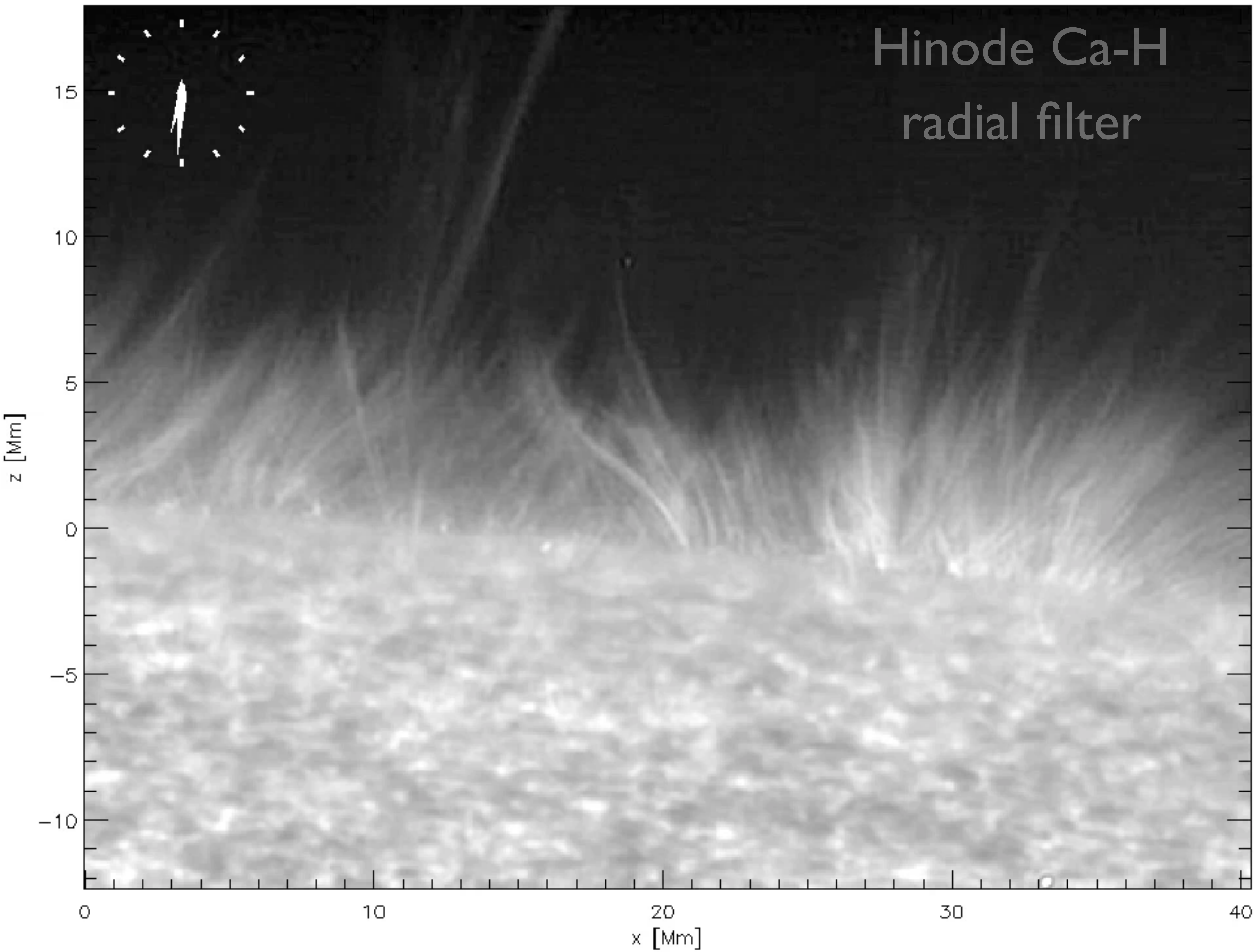
Launch September 2006
50cm optical telescope
X-ray telescope
UV spectrograph (EIS)

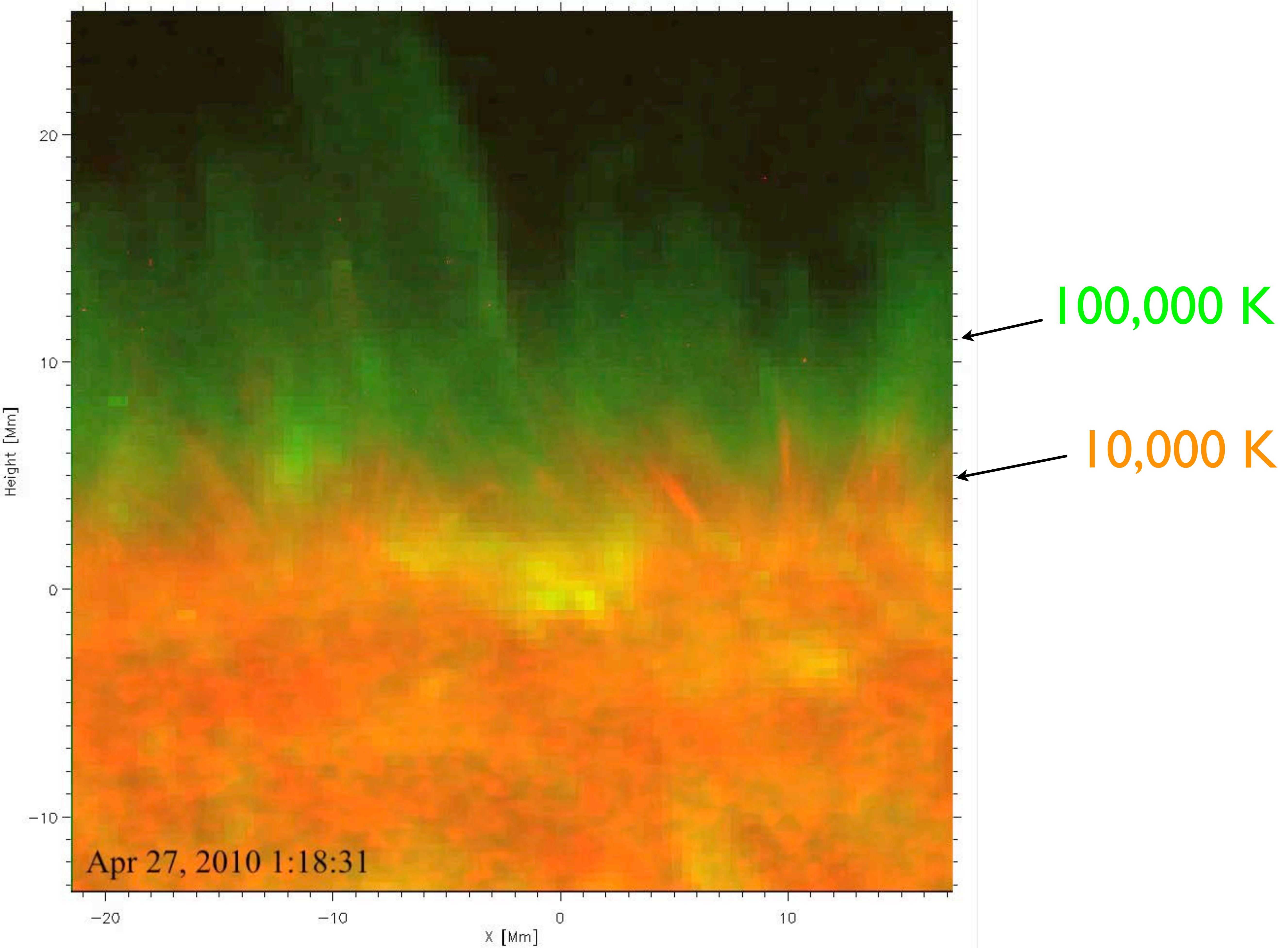
Norway:
- EIS software
- Svalbard downlink
- European datacenter


Hinode Ca-H
0
−20
−40
z [Mm]
0
20
40
60
x [Mm]

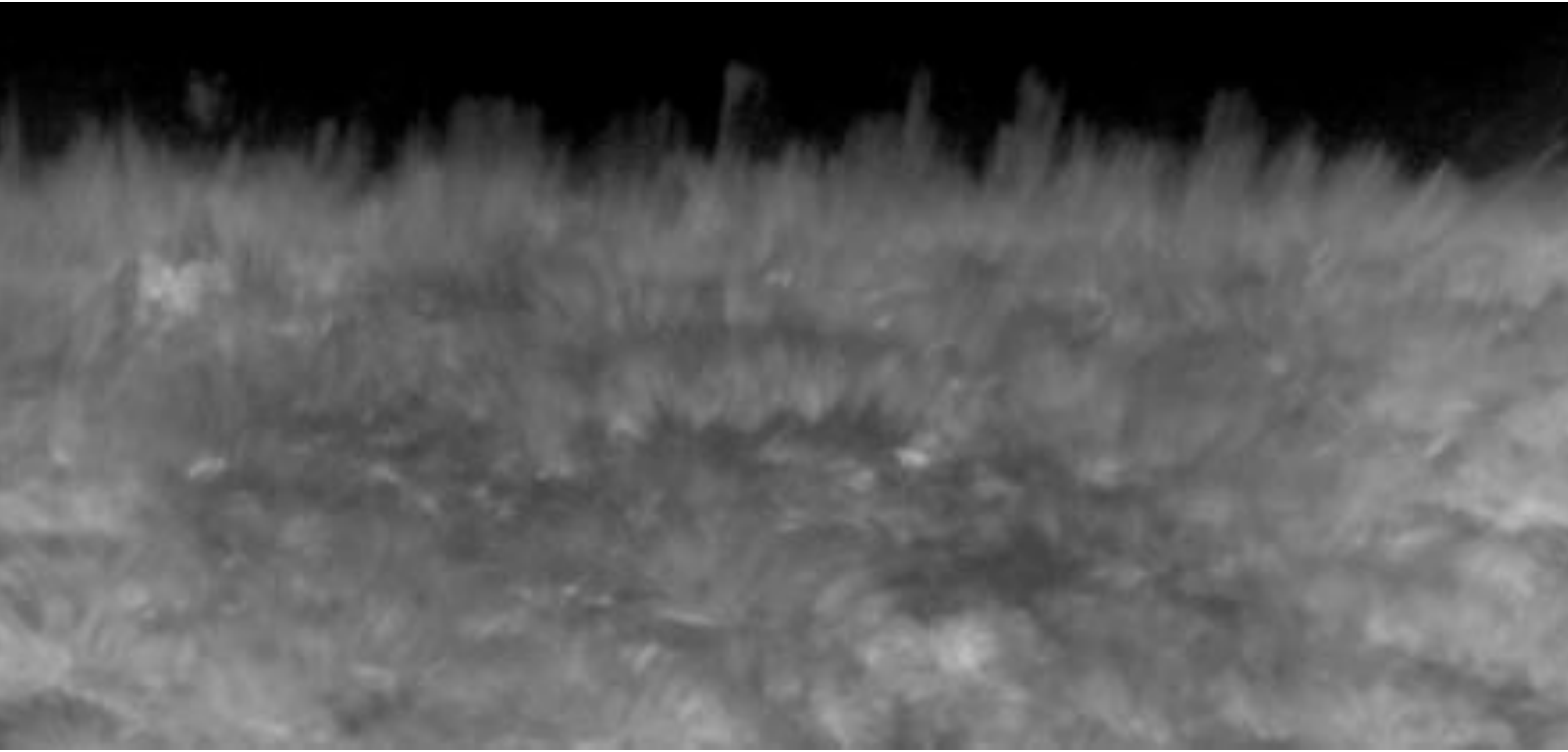


Hinode Ca-H
radial filter
0
−20
−40
z [Mm]
0
20
40
60
x [Mm]


Hinode Ca-H
radial filter
z [Mm]
x [Mm]
15
10
5
0
−5
−10
0
10
20
30
40

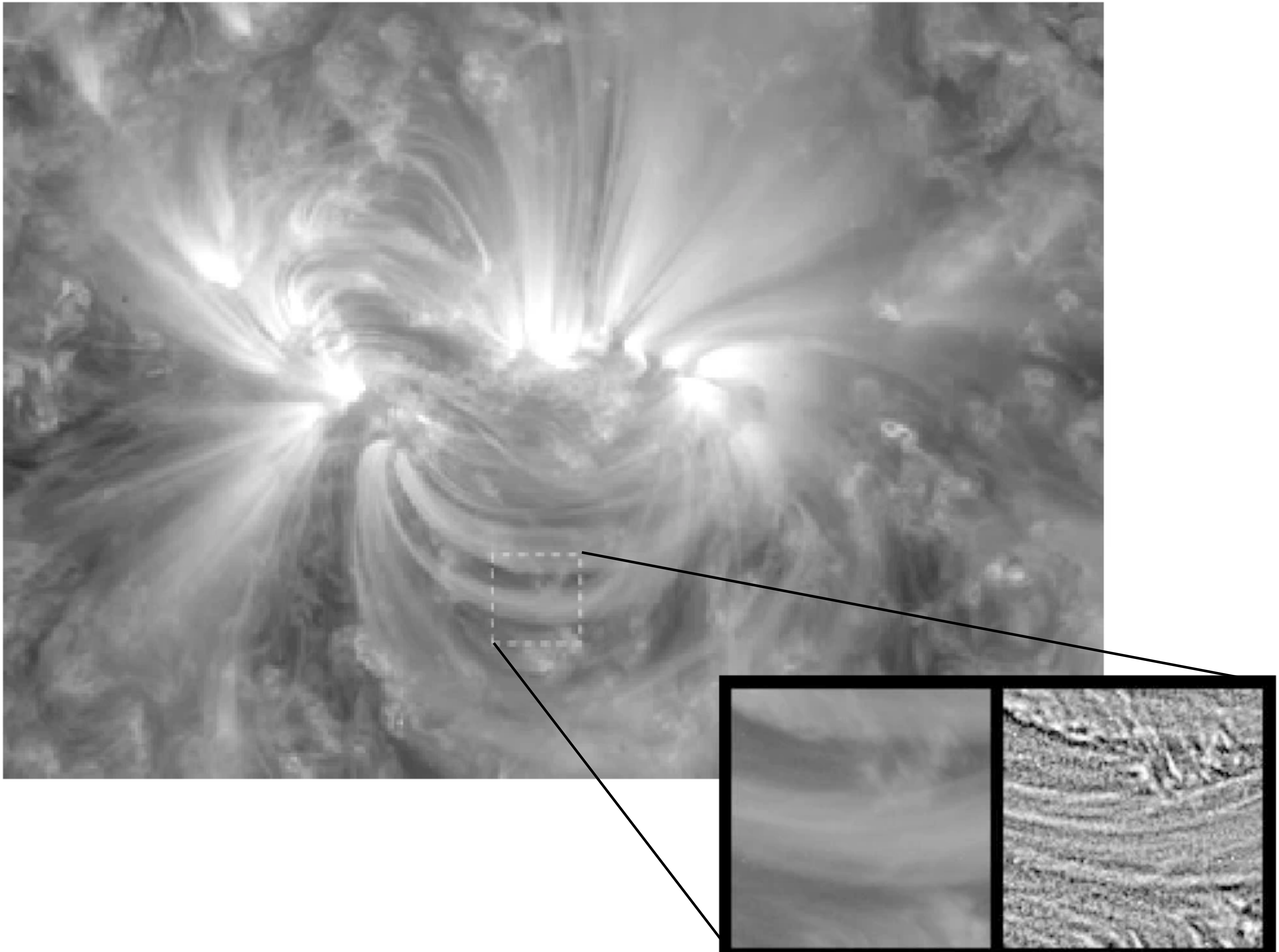


20
10
0
−10
Height [Mm]
−20
−10
0
10
X [Mm]
Apr 27, 2010 1:18:31
100,000 K
10,000 K



Alfvénic waves with sufficient energy to power the quiet solar corona and fast solar wind

Nature, July 27 2011



# Computational setup

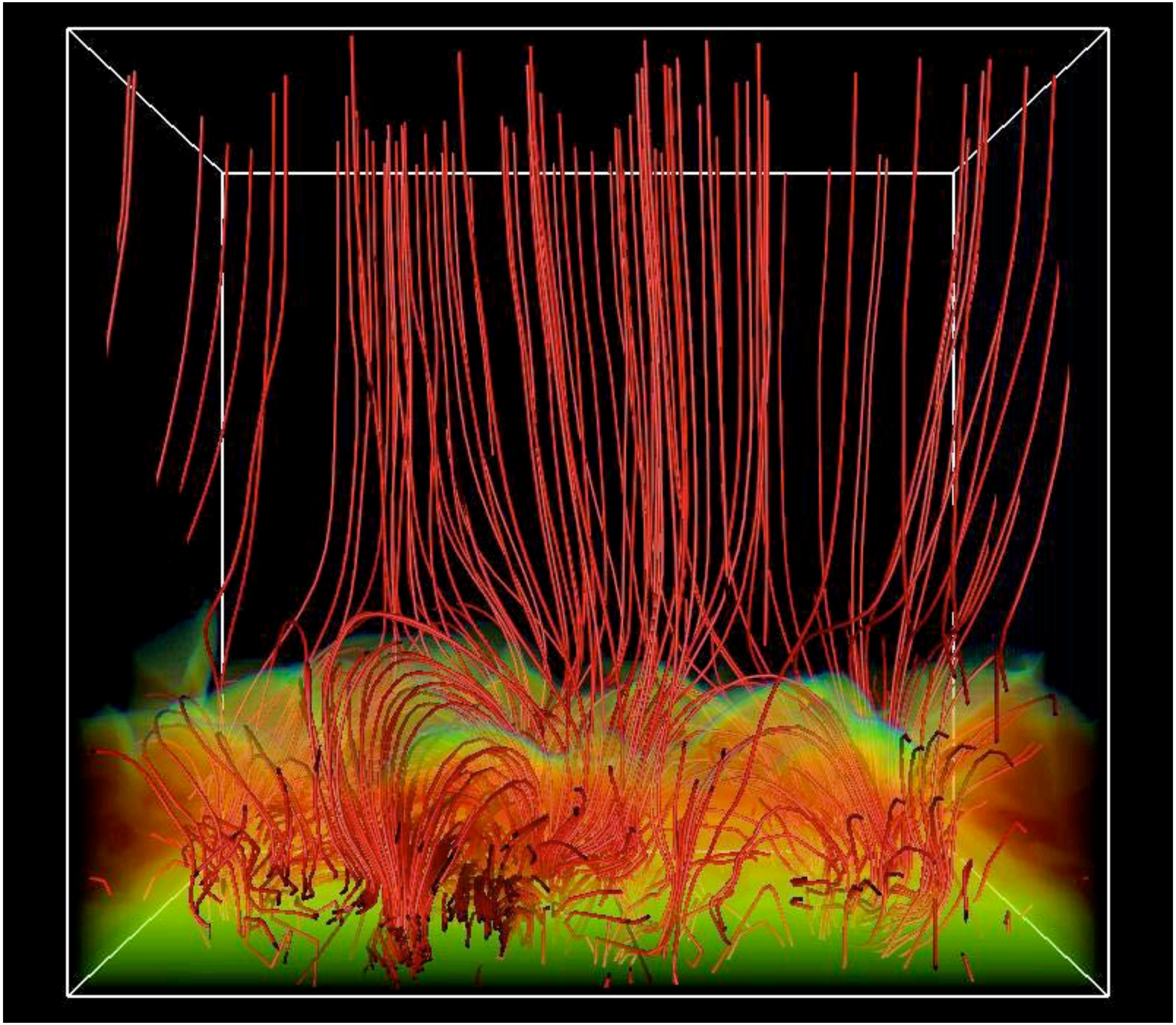
- 24x24x17 Mm (2.5 Mm below, 14.5 Mm above z=0)
- 504x504x496 (768x768x768) (1536x1536x768)
- 48 km horizontal, 19-97 km vertical (31, 12-82) 16
- polarities separated by 8 Mm
- <|B|>=30-50 G

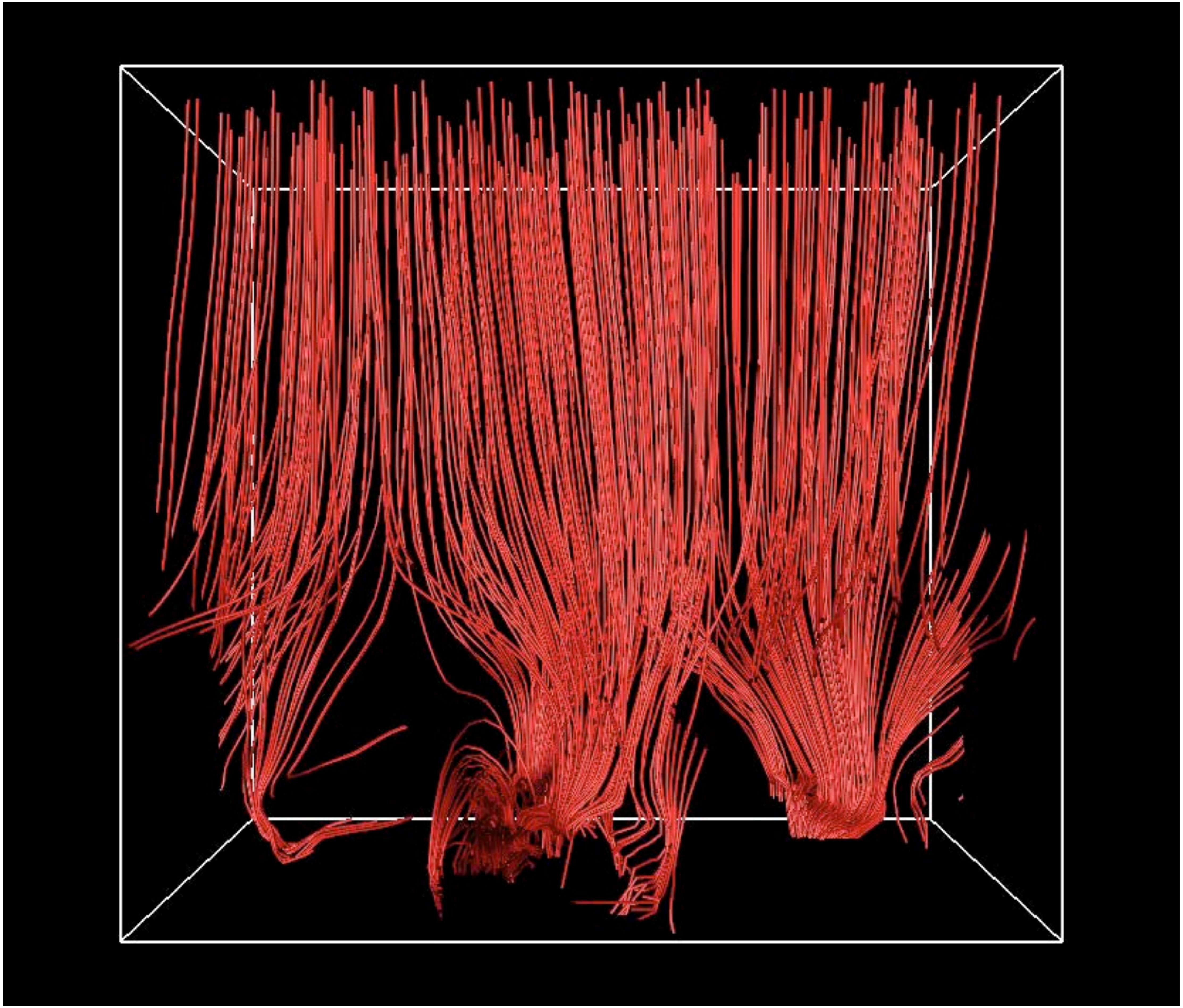
3ms timesteps, 5s/timestep on 512 cores = 70 days, 0.8 Mh for one hour solar time

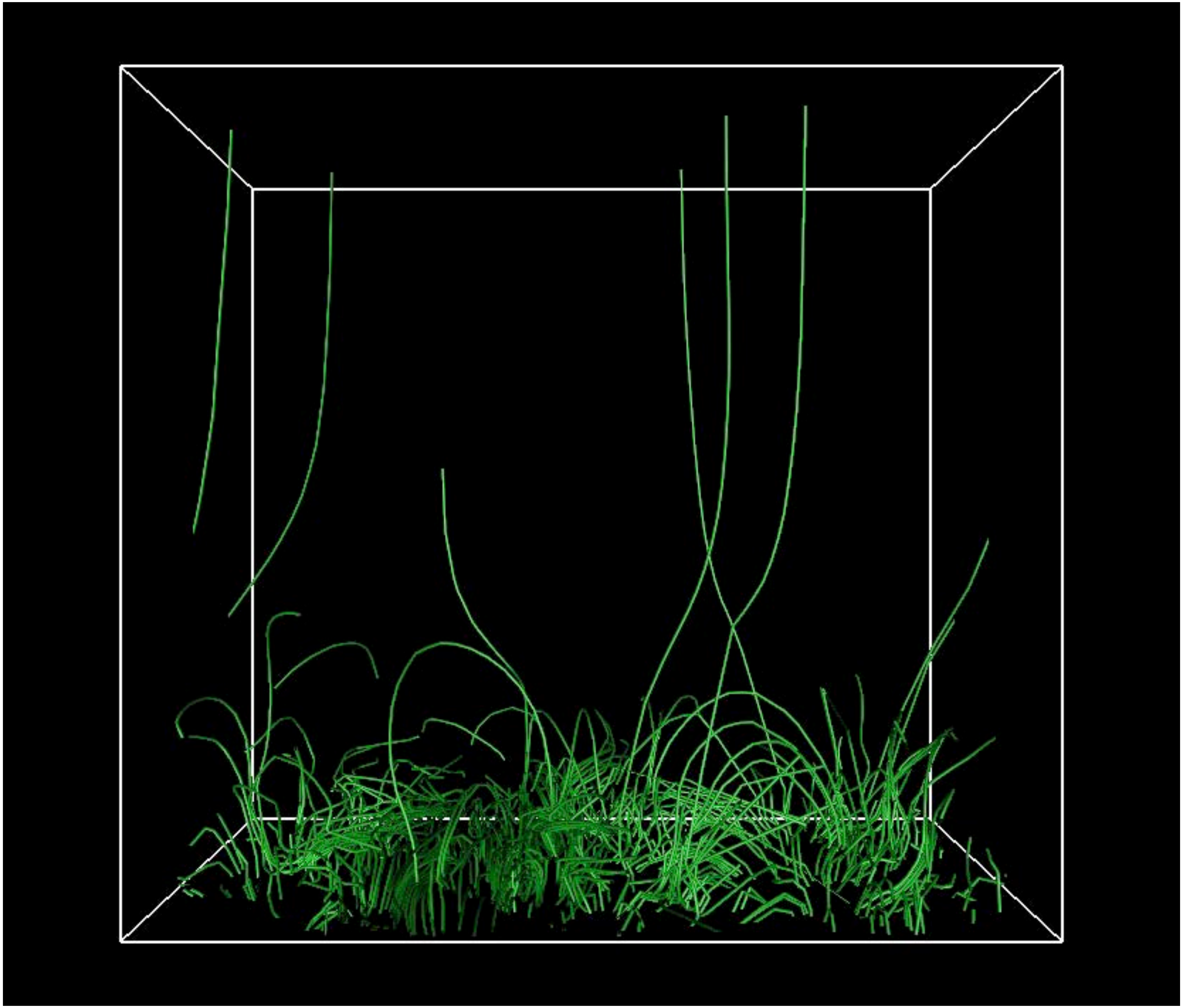
1728 cores = 70 days, 2.7 Mh

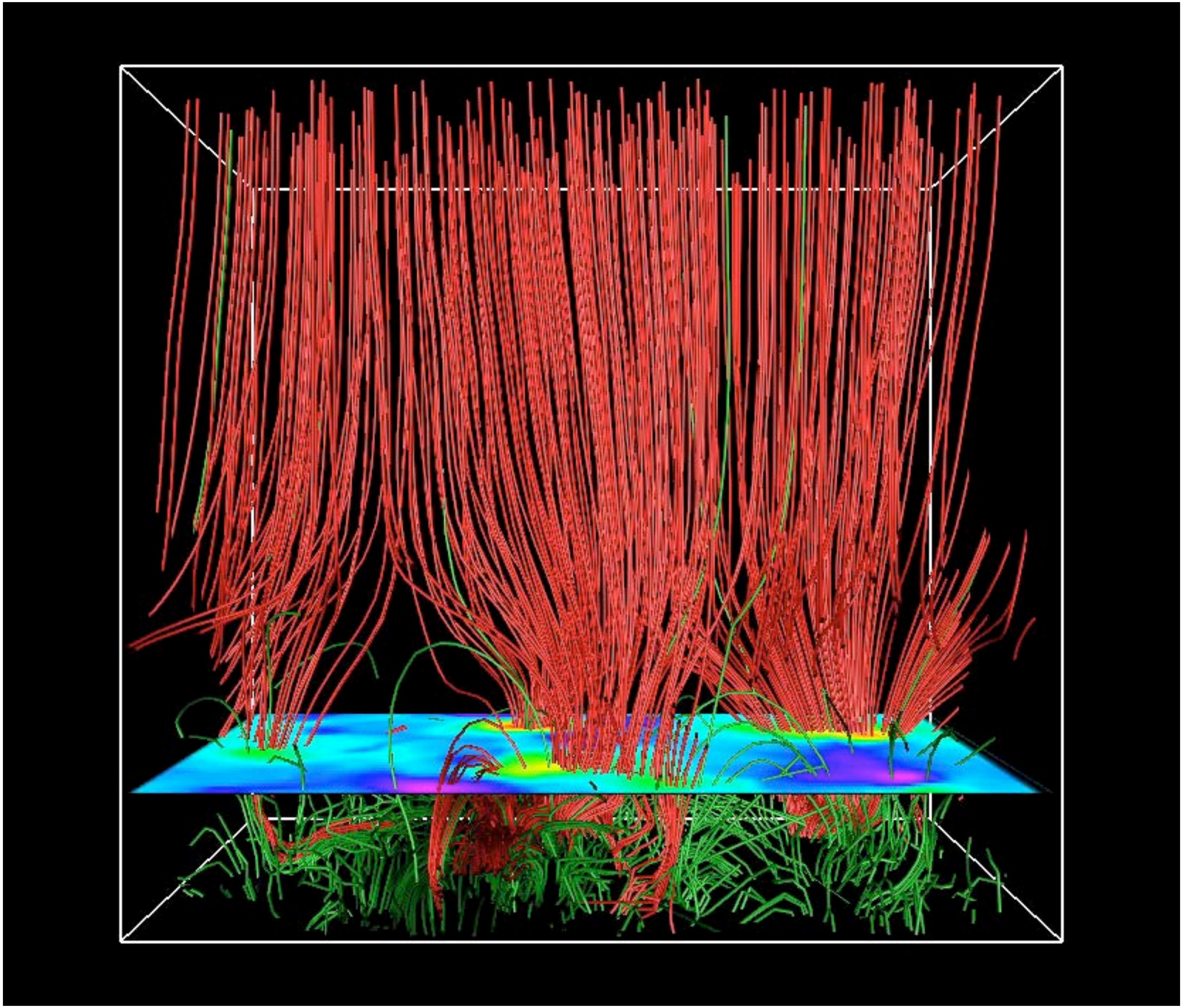
6912 cores = 70 days, 11 Mh

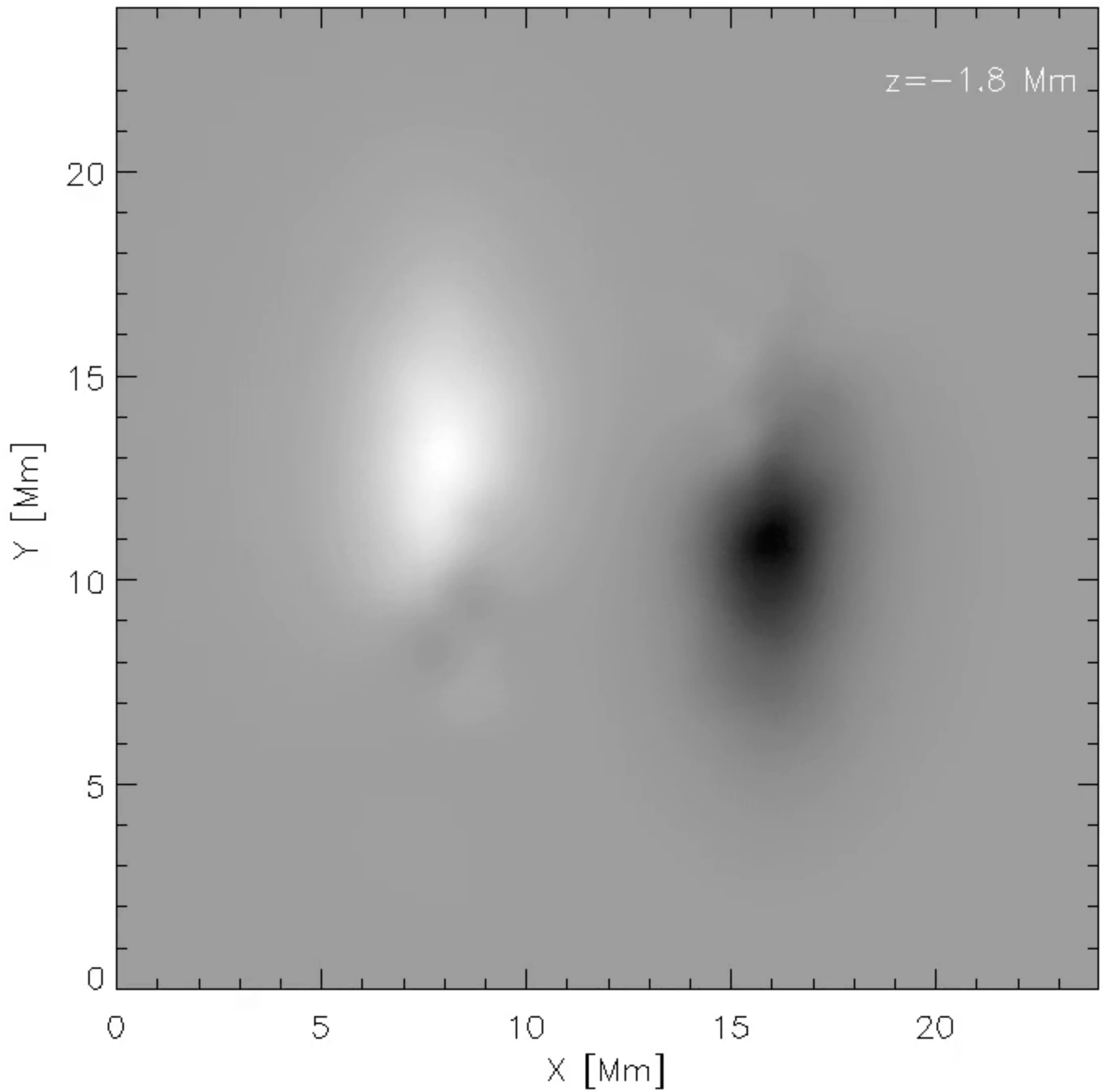
3D diagnostics: 2000 days
1.5D diagnostics: 10 days



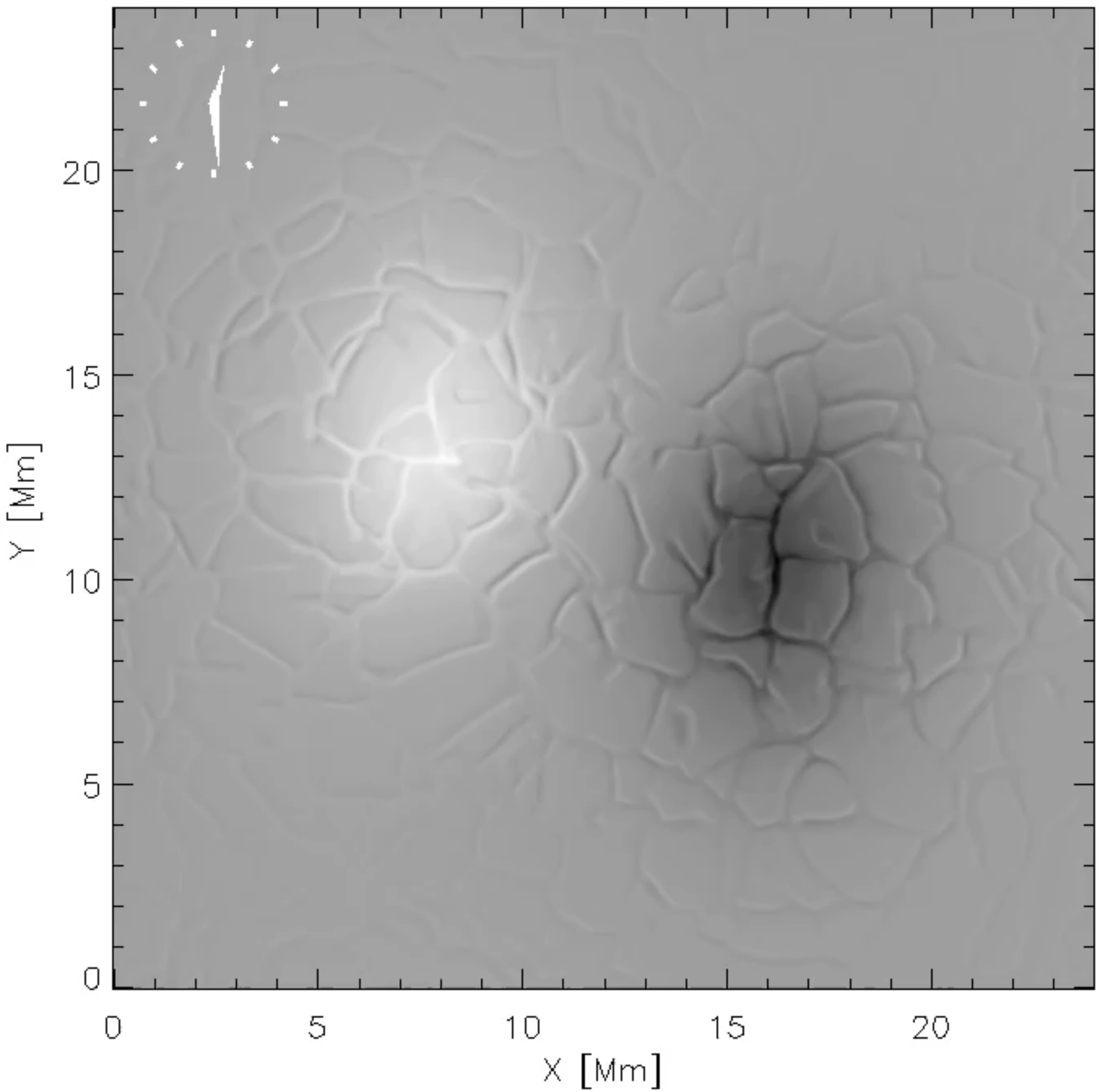




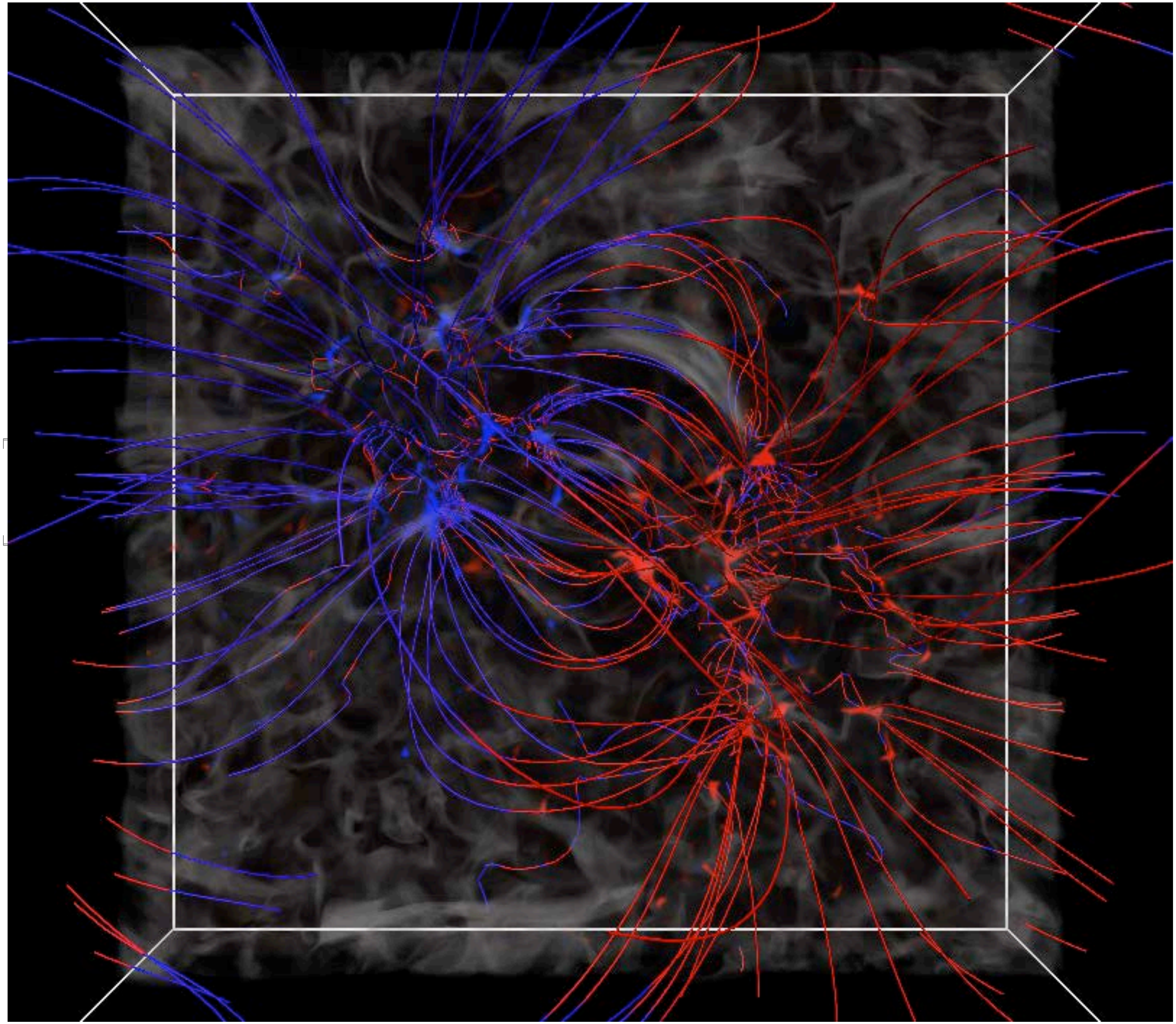


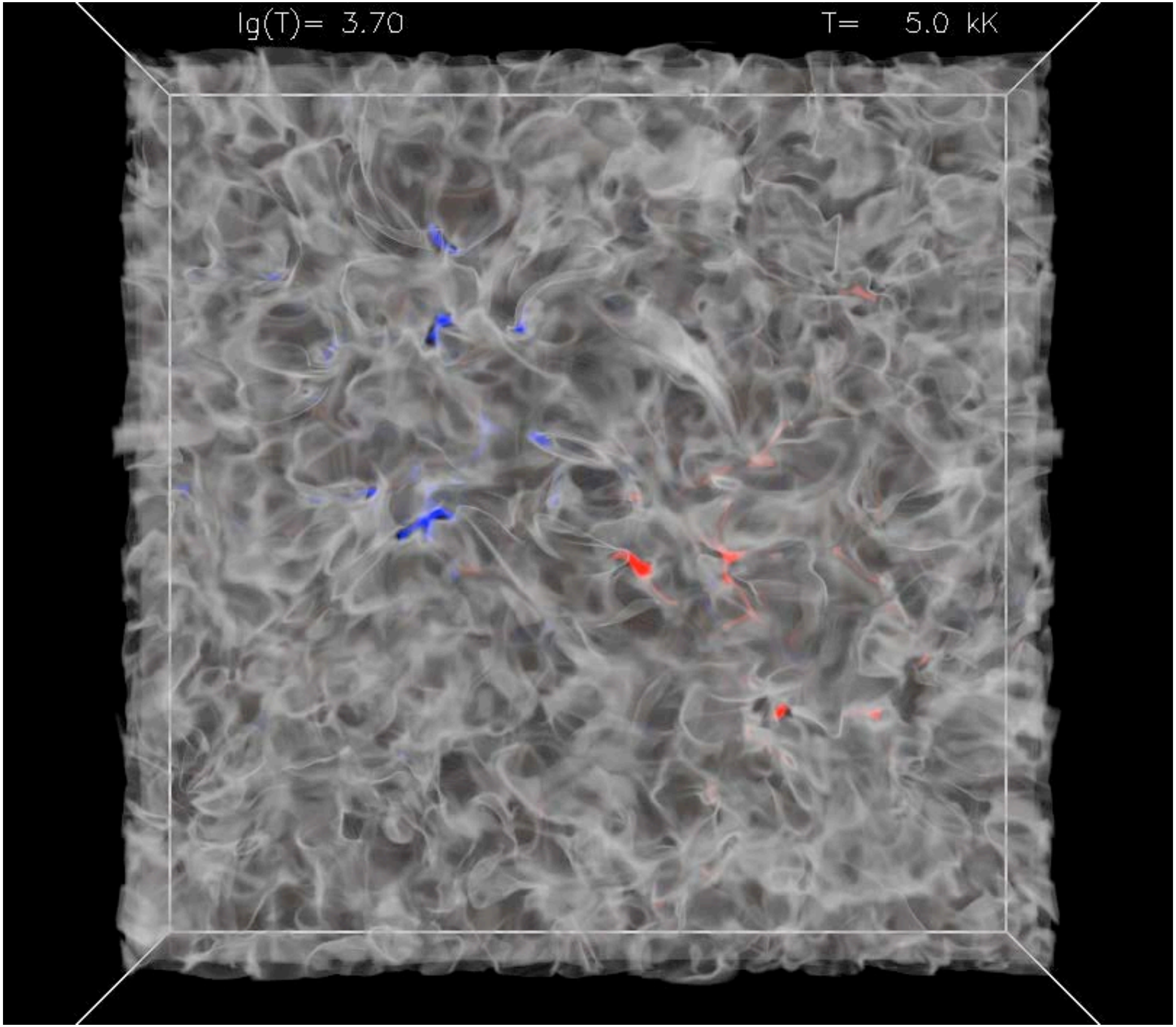


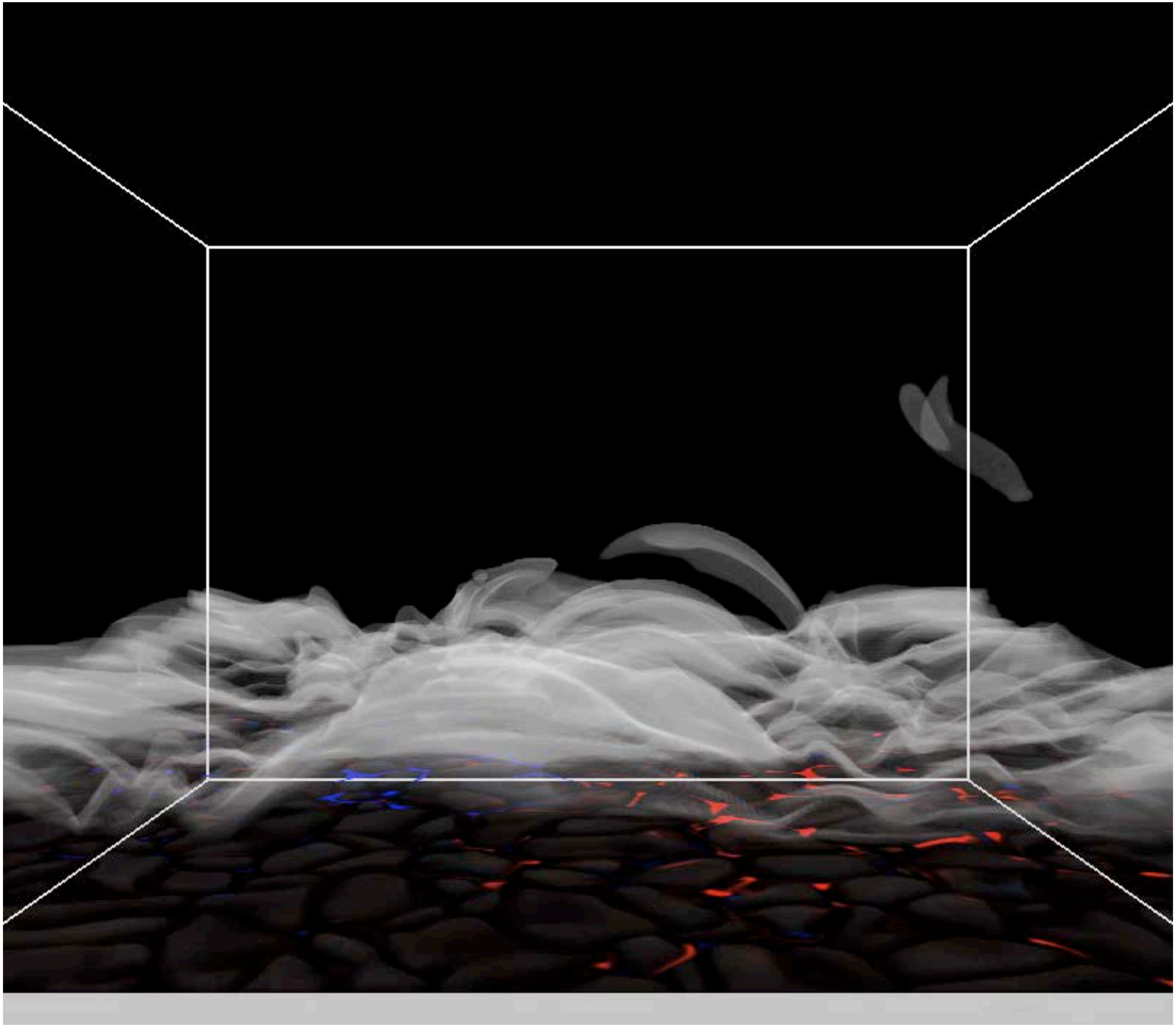
z=−1.8 Mm
20
15
10
5
0
Y [Mm]
0
5
10
15
20
X [Mm]



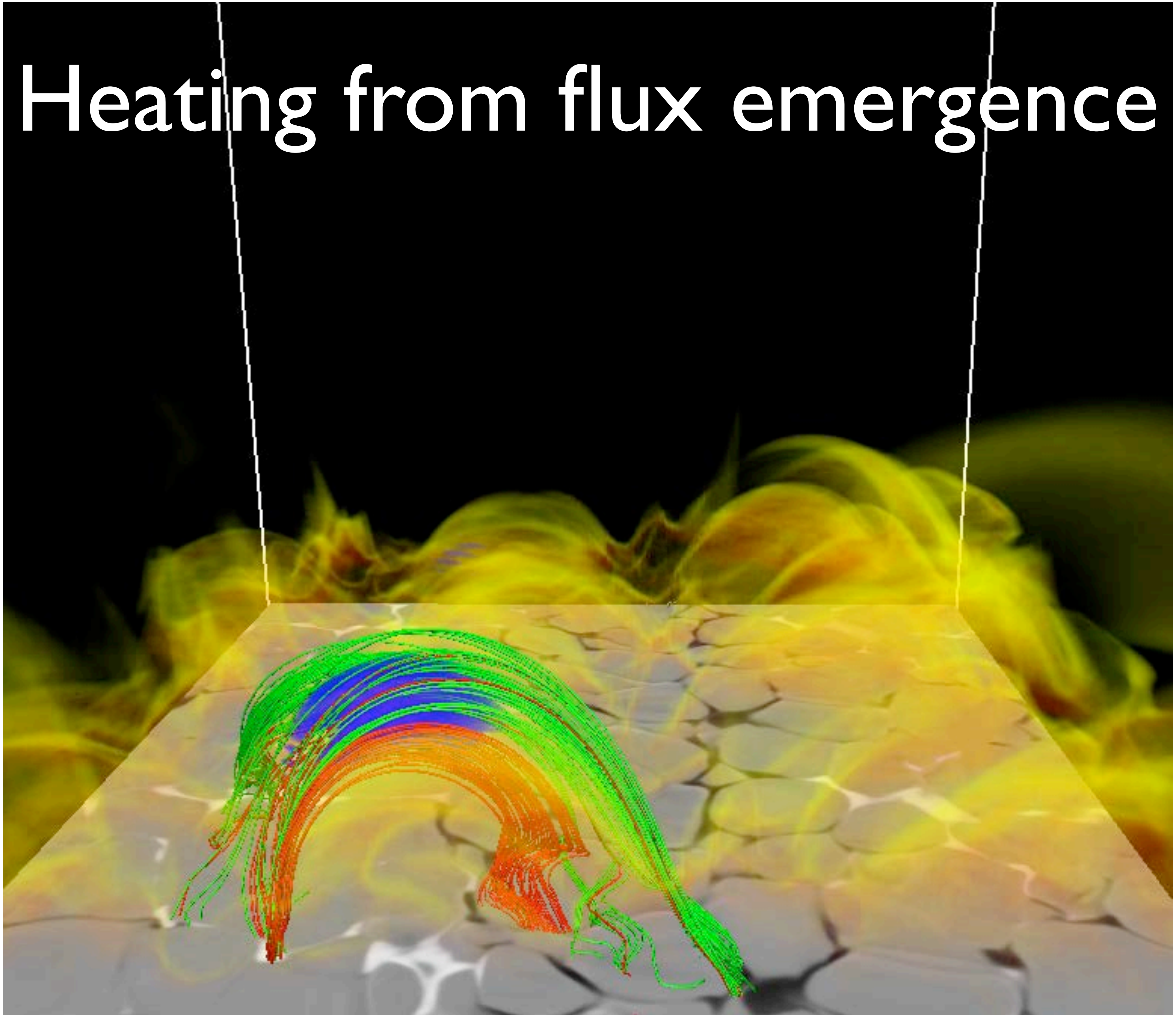
0
5
10
15
20
X [Mm]
Y [Mm]


X [Mm]

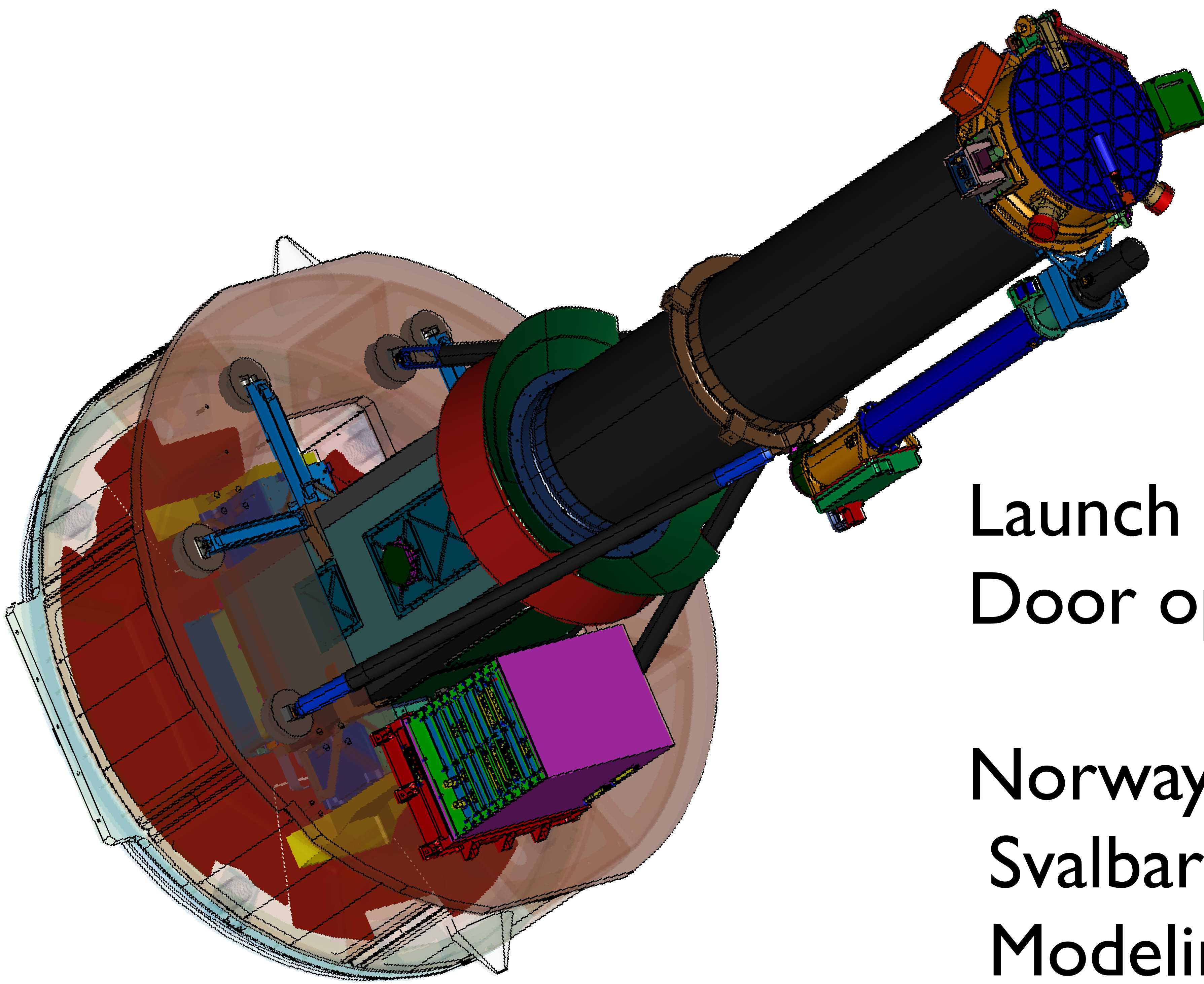

lg(T)= 3.70
T= 5.0 kK



# Heating from flux emergence

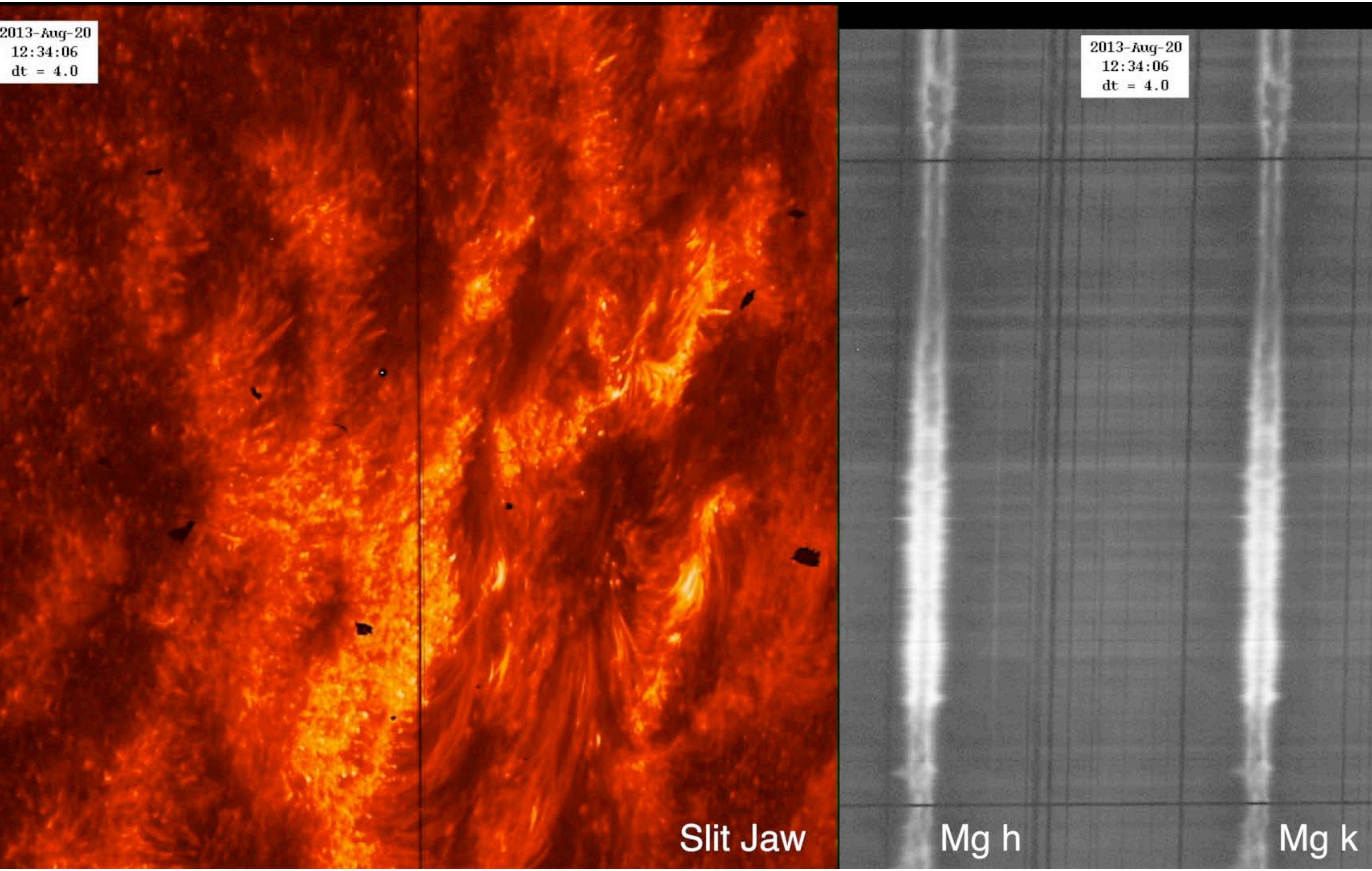


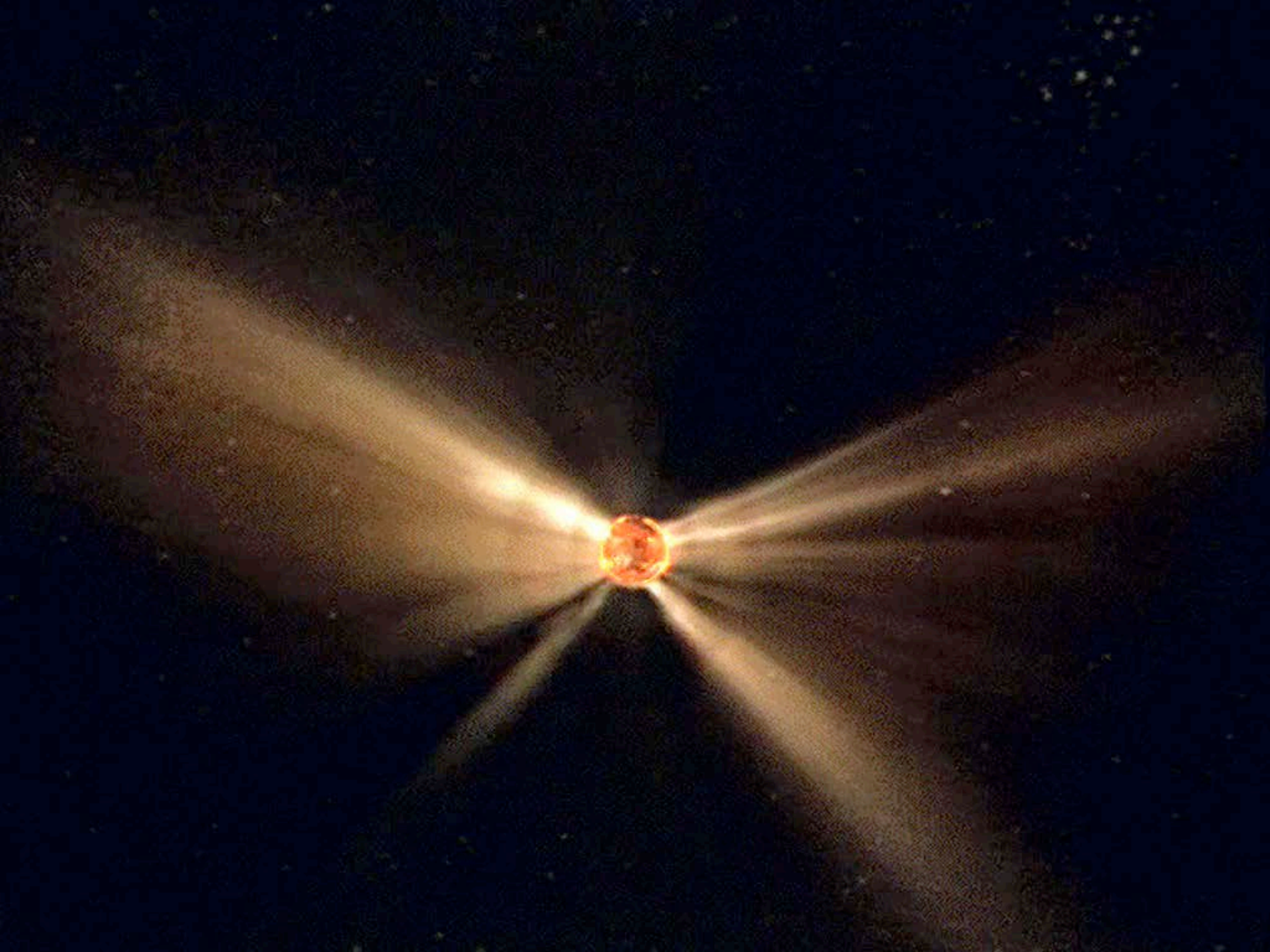
# Interface Region Imaging Spectrograph (IRIS)

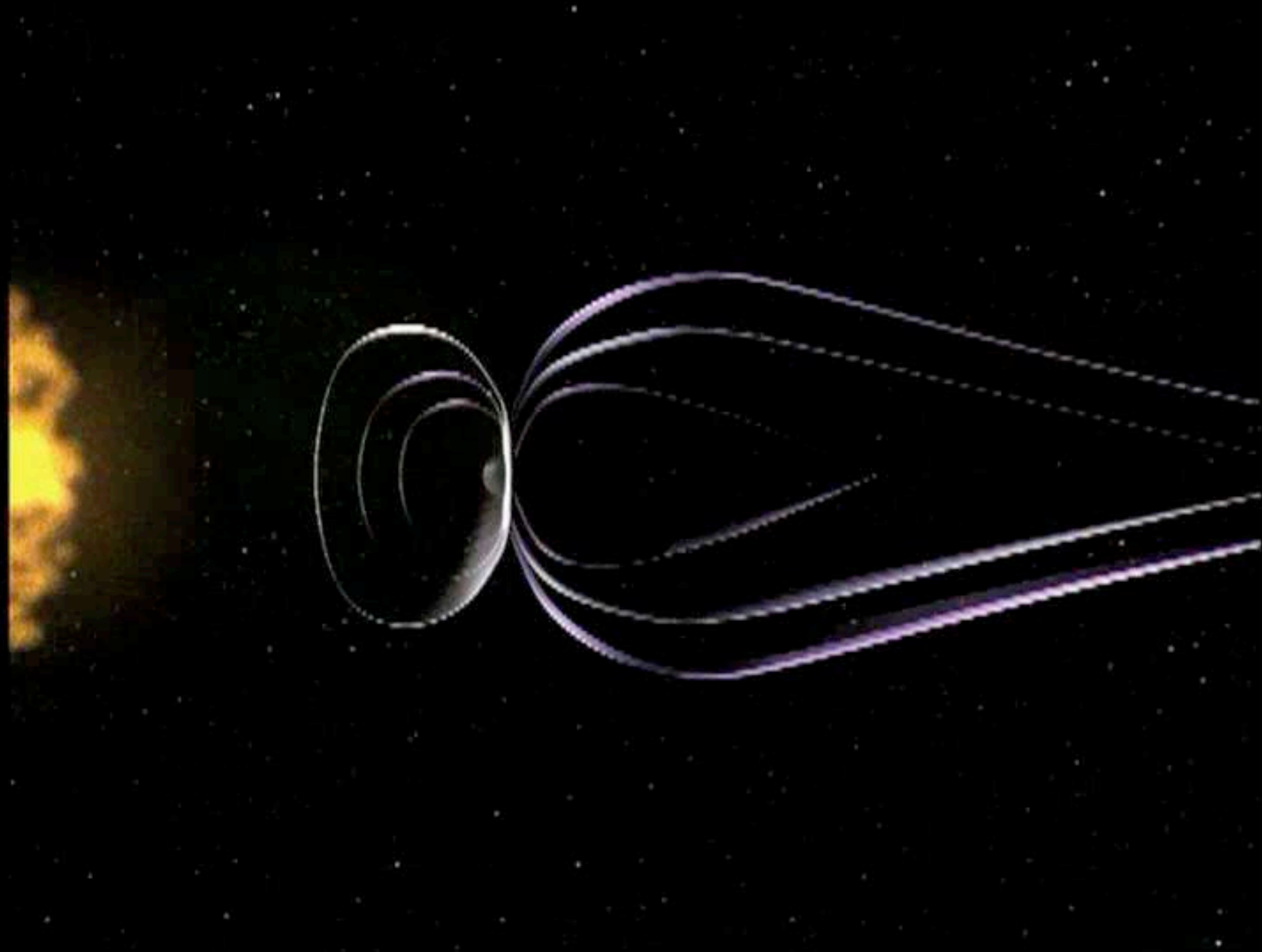


Launch 28 June 2013
Door opened 17 July

Norway:
- Svalbard downlink
- Modeling
- Datacenter


2013-Aug-20
12:34:06
dt = 4.0
2013-Aug-20
12:34:06
dt = 4.0
Slit Jaw
Mg h
Mg k





Aurora seen from the International Space Station from a CME that occurred 19 January 2012.

*NASA/ISS*

# Conclusions

- Solar atmosphere highly dynamic
- Magnetic fields play a dominant role
- New missions (SDO, IRIS) and large aperture ground based telescopes (ATST, EST) combined with numerical modeling crucial for the understanding of our active Sun