AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Summer jobs

- Possibility for summer jobs at RoCS (ITA does not have summer jobs anymore, only RoCS!)
- 4-6 weeks during summer break
- B.Sc. / M.Sc. can apply
- More information will follow (or ask Boris Gudiksen)

Rosseland Centre for Solar Physics

Assignments

First mandatory assignment

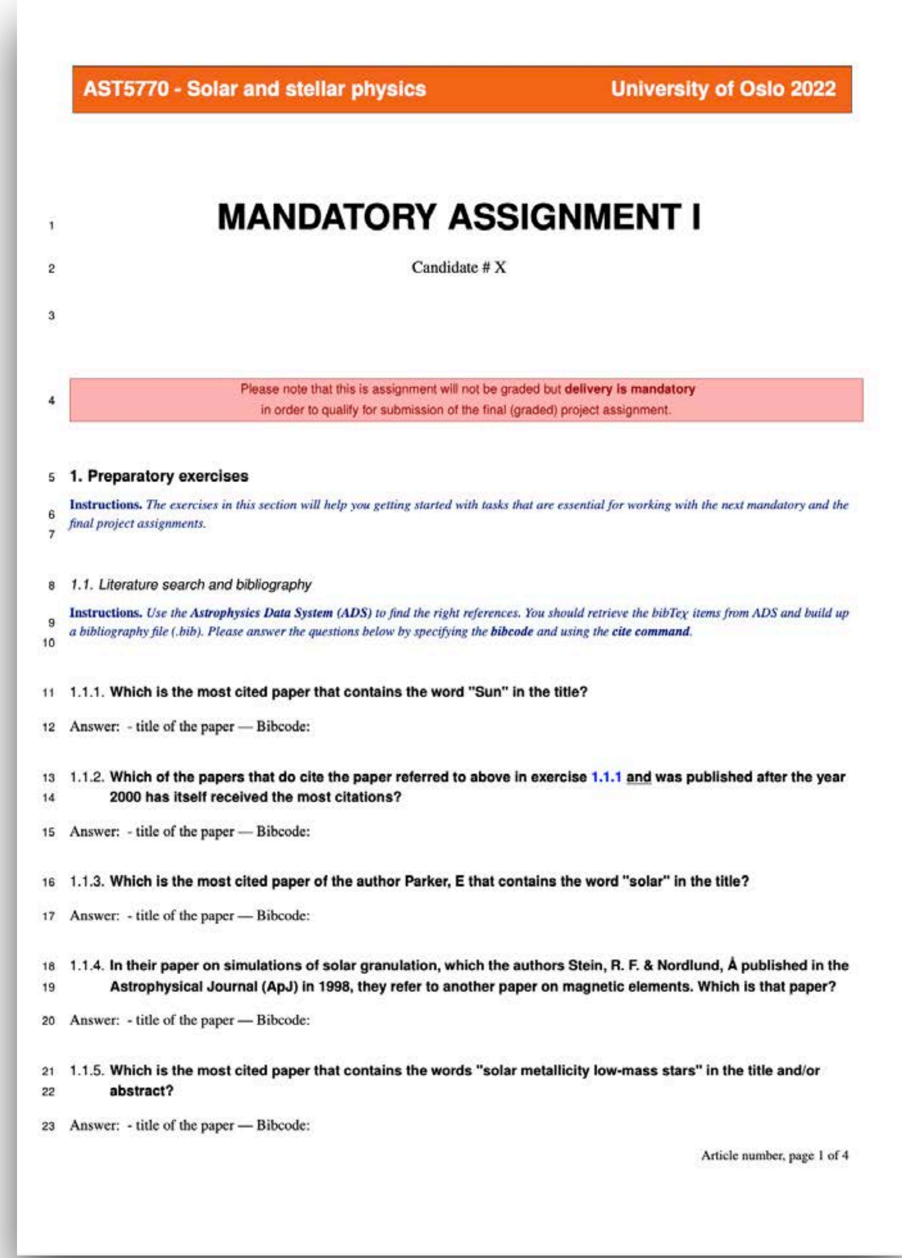
- Delivery via devilry (more information soon)
- Assignments to prepared using the provided latex templates:

`/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/assignment/assign1/`

- **Preparatory exercises for training**

  1. Literature research with ADS
     - Download bibtex items and use them in latex
  2. Loading and plotting a reference model (VALC)
  3. Use the helioviewer tool
  4. First look at the provided observation and simulation data

- **First steps towards the final project assignment**
  - Tentative science question, work plan, and reading list
  - Important: Just to get started! Can be updated!



AST5770 - Solar and stellar physics University of Oslo 2022

MANDATORY ASSIGNMENT I

Candidate # X

Please note that this is assignment will not be graded but **delivery is mandatory** in order to qualify for submission of the final (graded) project assignment.

1. Preparatory exercises

Instructions. *The exercises in this section will help you getting started with tasks that are essential for working with the next mandatory and the final project assignments.*

1.1. Literature search and bibliography

Instructions. *Use the **Astrophysics Data System (ADS)** to find the right references. You should retrieve the bibTeX items from ADS and build up a bibliography file (.bib). Please answer the questions below by specifying the **bibcode** and using the **cite command**.*

1.1.1. **Which is the most cited paper that contains the word "Sun" in the title?**

Answer: - title of the paper — Bibcode:

1.1.2. **Which of the papers that do cite the paper referred to above in exercise 1.1.1 and was published after the year 2000 has itself received the most citations?**

Answer: - title of the paper — Bibcode:

1.1.3. **Which is the most cited paper of the author Parker, E that contains the word "solar" in the title?**

Answer: - title of the paper — Bibcode:

1.1.4. **In their paper on simulations of solar granulation, which the authors Stein, R. F. & Nordlund, Å published in the Astrophysical Journal (ApJ) in 1998, they refer to another paper on magnetic elements. Which is that paper?**

Answer: - title of the paper — Bibcode:

1.1.5. **Which is the most cited paper that contains the words "solar metallicity low-mass stars" in the title and/or abstract?**

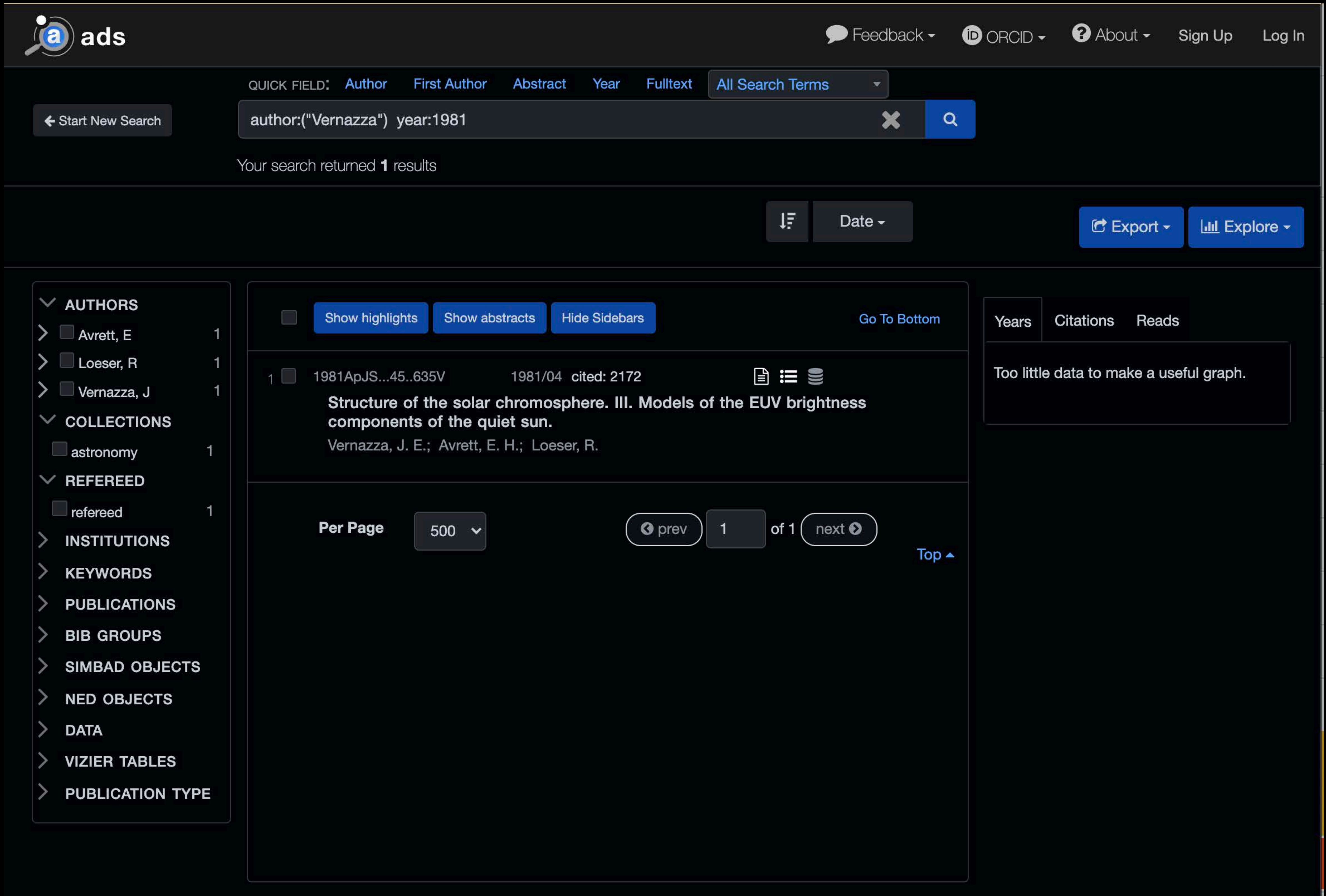
Answer: - title of the paper — Bibcode:

Article number, page 1 of 4

Literature research

https://ui.adsabs.harvard.edu/

Introduction to the Astrophysics Data System (ADS)



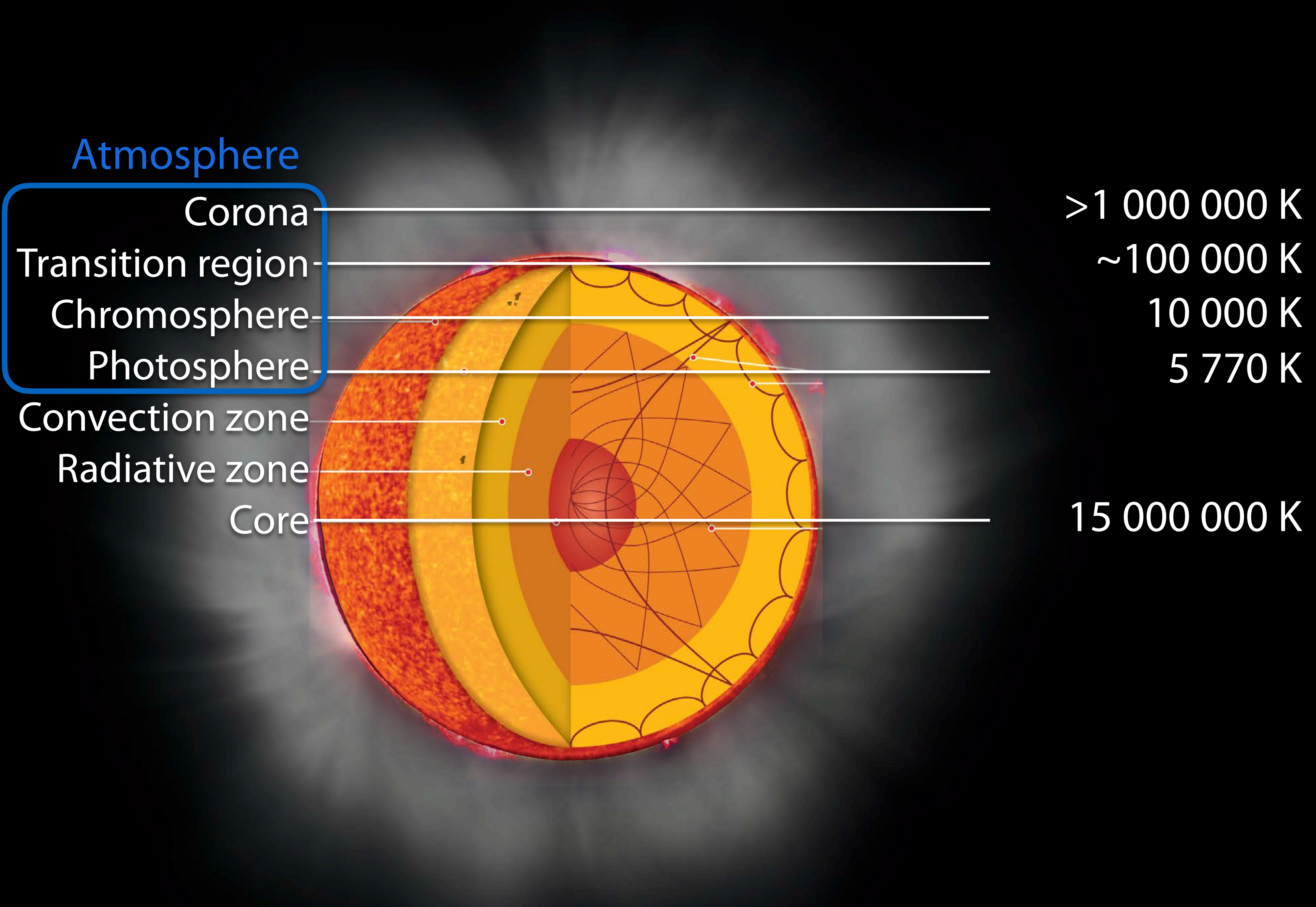
Practical information

Data / material for assignments

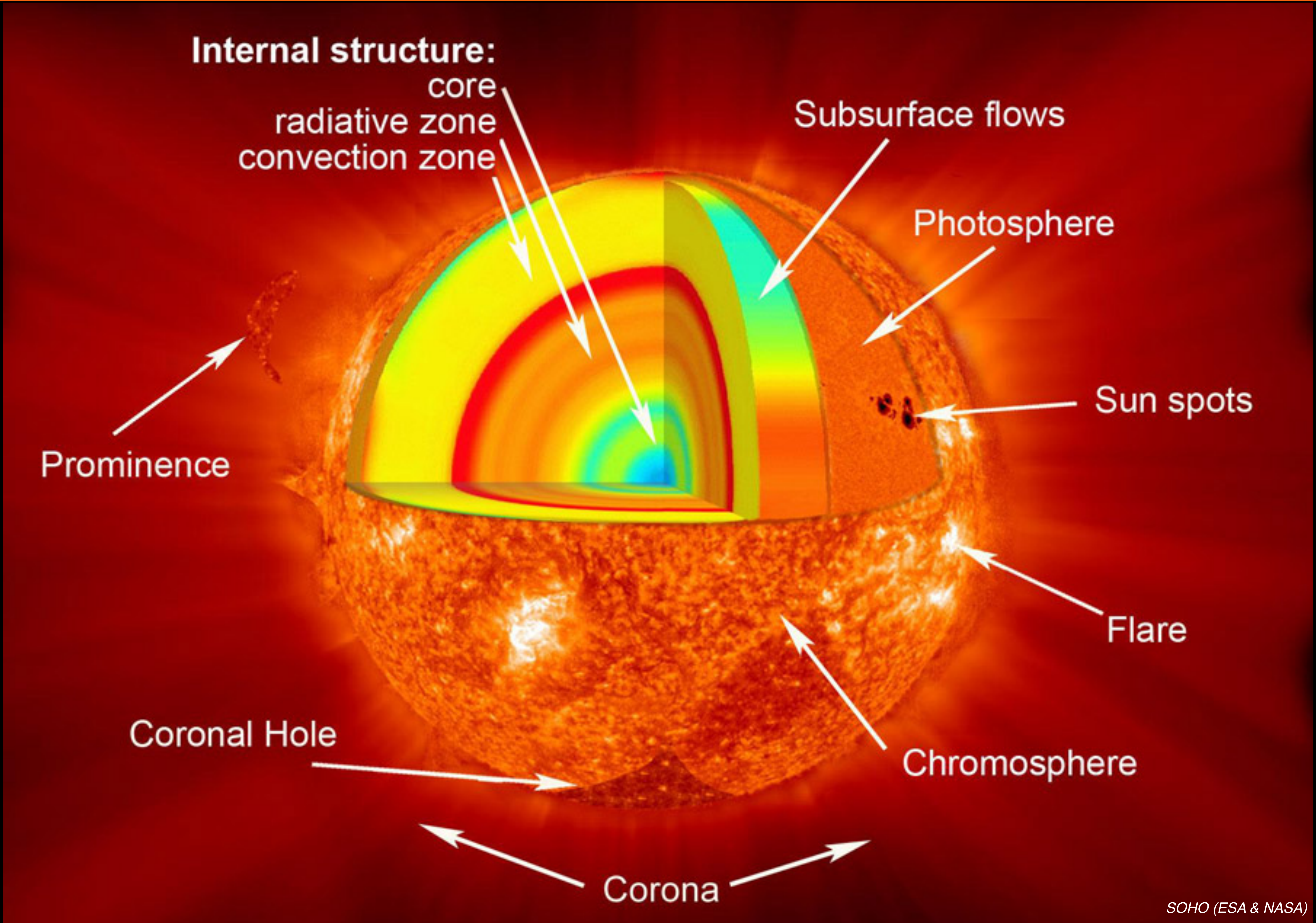
- Main directory: `/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/`
- Sub-directories/content:
    - Data: `data/`
  - Templates 4 assignments: `assignment/`
    - First assignment: `assignment/assign1/`
    - Latex: `assignment/latex/`
  - Further information: `AST5770_manual.pdf`

- Who uses python? Who IDL?
- Note that order of dimensions in data cubes can be flipped!

Stellar structure — The Sun



The solar atmosphere



SOHO (ESA & NASA)

The solar atmosphere

Solar "zoology"

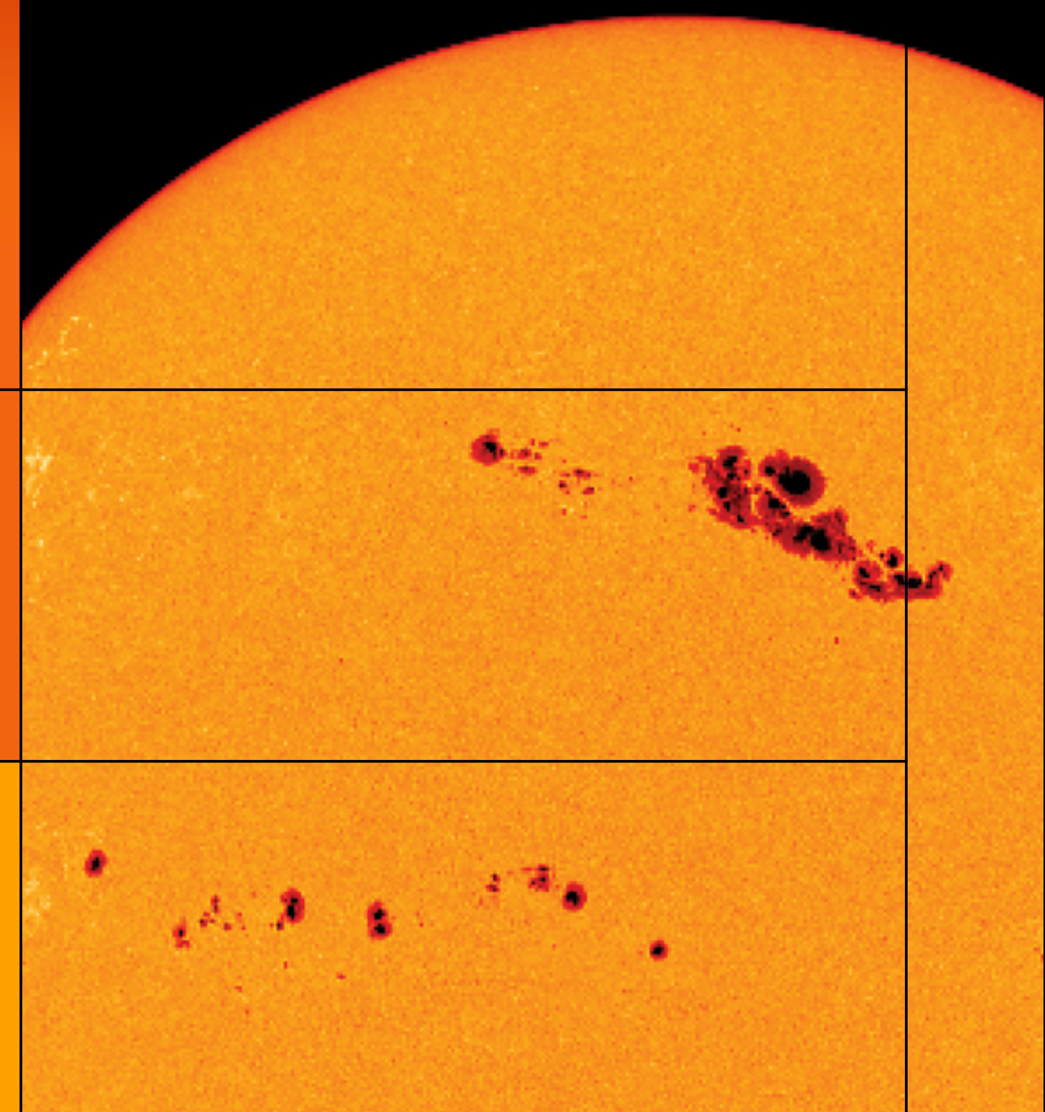
- A plethora of phenomena with different names
- Names often depend on the **region/layer** where phenomenon occurs (if known/limited to that) or the **wavelength** domain in which it is observed
- Names are often given upon discovery without understanding the physical mechanism behind — names not always meaningful
- Careful: Sometimes different names just refer to different aspects of the same phenomenon or observable imprints in different parts of the spectrum

The solar atmosphere

Different regions — photosphere

(Average) magnetic field strength ↓

Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Faculae bright (filamentary) areas	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	

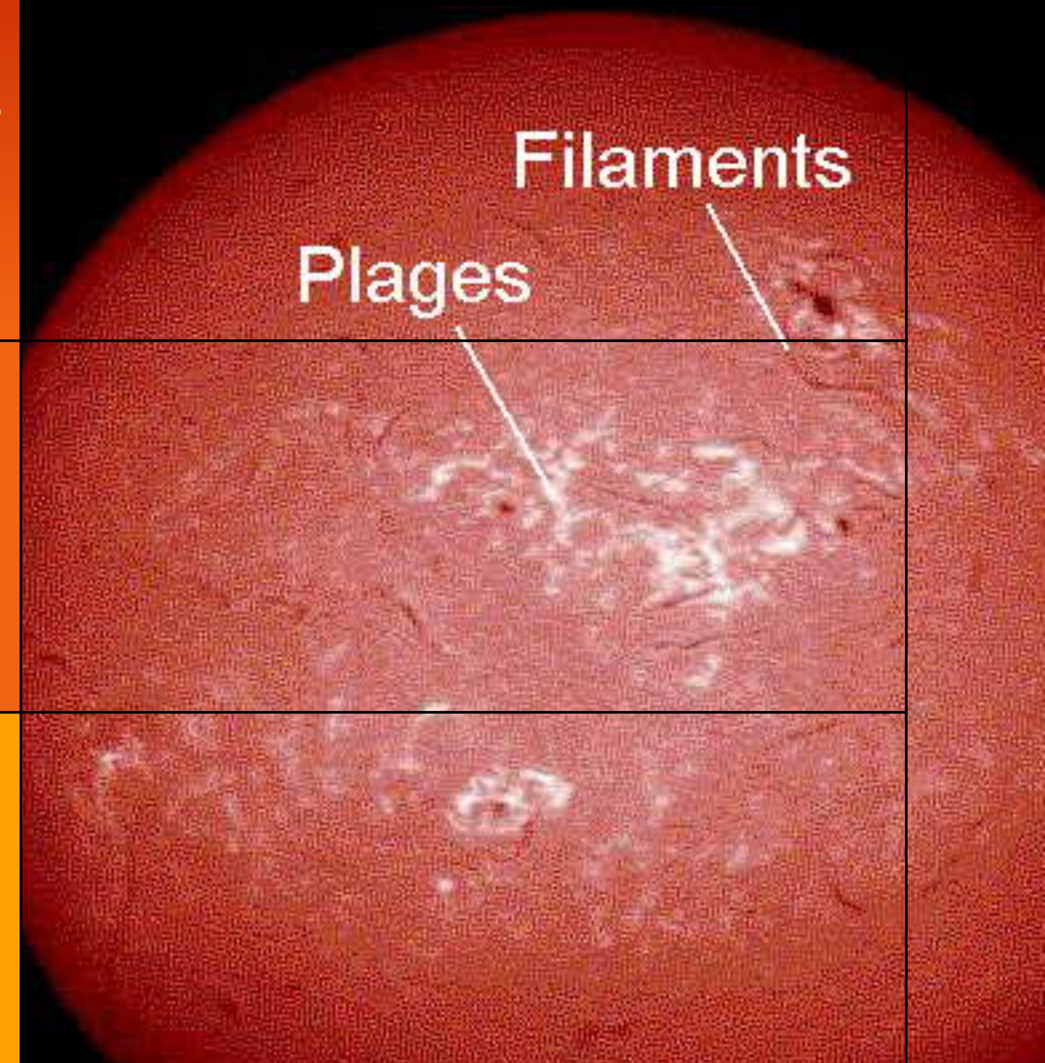


The solar atmosphere

Different regions — chromosphere

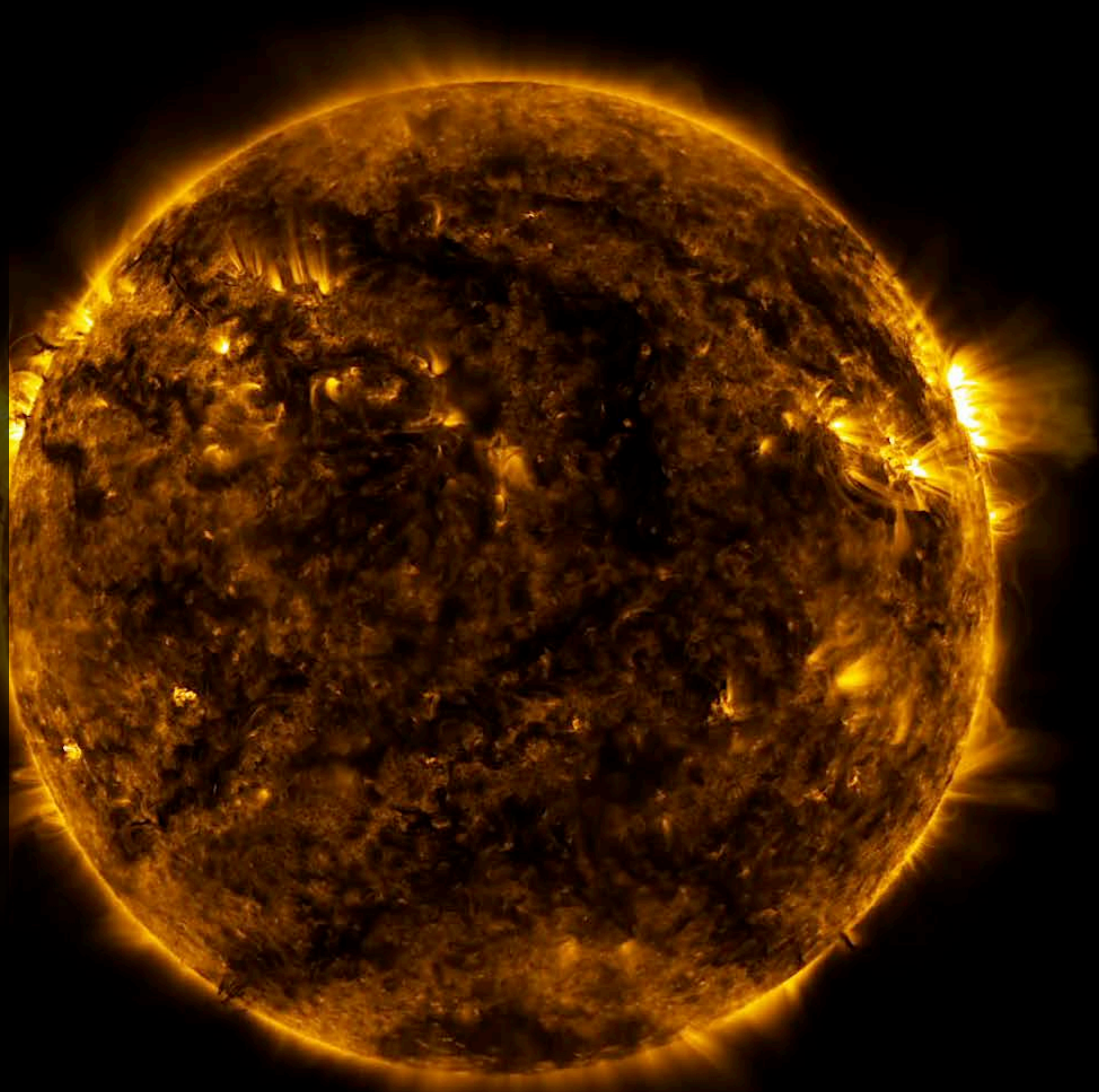
(Average) magnetic field strength ↓

Active Region (Large) area with strong magnetic field	**Sunspot** Areas of concentrated very strong field, appear dark	**Umbra** Central compact part, dark **Penumbra** Surrounding, filamentary
	Plage bright area, higher temperature, often proceeds formation of sunspots	
Quiet Sun Outside Active Regions, weaker magnetic field	**Network** Concentrations of strong magnetic field, filamentary/ mesh-like	
	Inter-network Areas with weak magnetic field inside network cells	



The solar atmosphere

- Solar atmosphere
  highly dynamic
  intermittent
  dynamically coupled
- Structured on large range of spatial scales, down to (at least) 0.1 arcsec
- The Sun is dynamic on short timescales (down to seconds)
- Plethora of processes.
- Great plasma physics "laboratory"

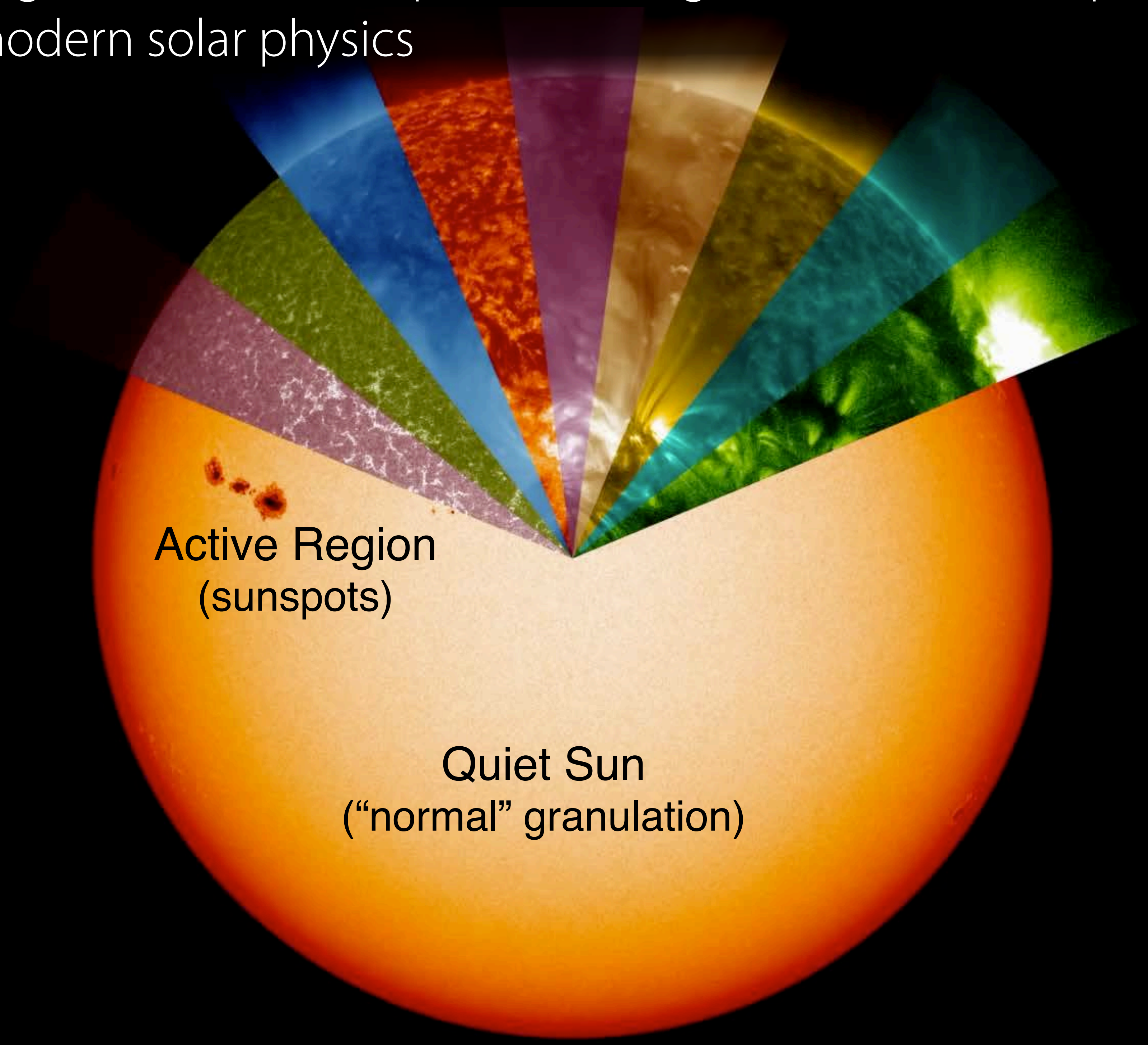


Solar Dynamics Observatory SDO/NASA

HOW TO OBSERVE THE SUN?

- Different continua and spectral lines probing different plasma properties in different domains/layers

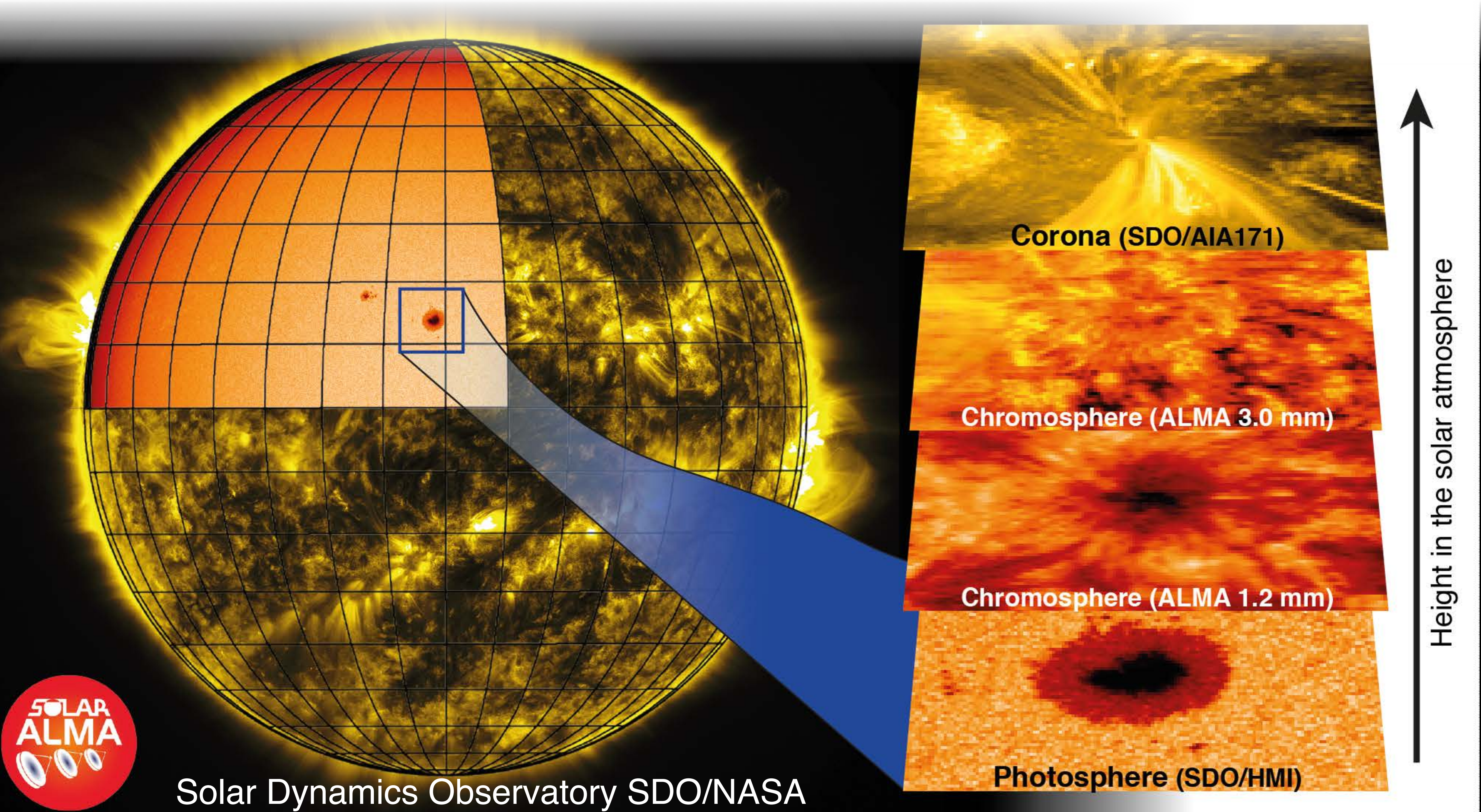
➡ Multi-wavelength co-ordinated space-borne/ground-based campaigns as standard in modern solar physics



Solar Dynamics Observatory SDO/NASA

The solar atmosphere

- ➡ Multi-wavelength co-ordinated space-borne/ground-based campaigns as standard in modern solar physics



The solar atmosphere

Solar Dynamics Observatory (SDO)

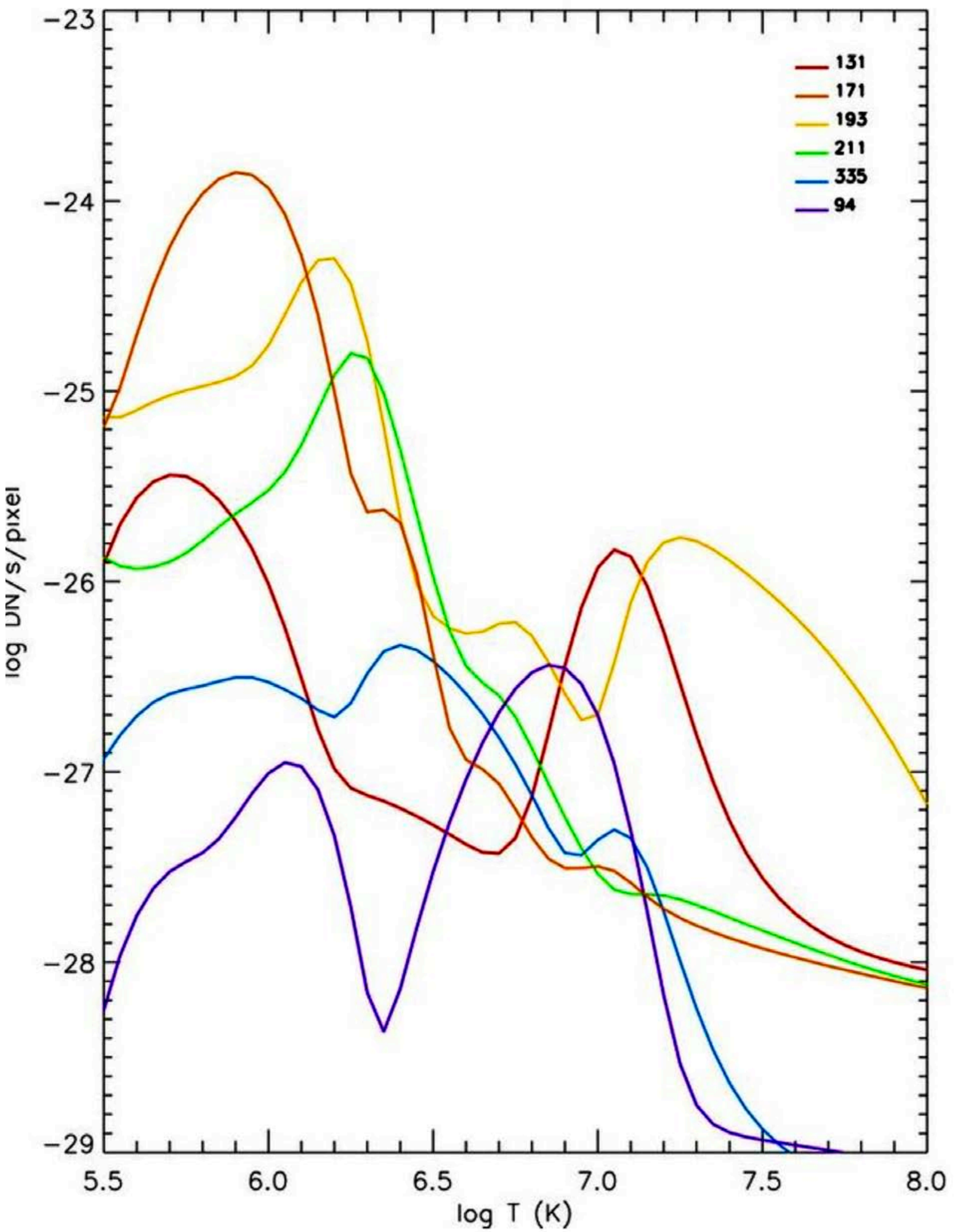
- Space telescope(s) with several instruments (since 2010)
- Helioseismic and Magnetic Imager (**HMI**)
  - Provides magnetograms
- Atmospheric Imaging Assembly (**AIA**)
  - Many different filters (distributed over 4 telescopes) that map different layers (or more precisely temperature ranges) in the solar atmosphere
  - 12s cadence

The solar atmosphere

Solar Dynamics Observatory (SDO)

- Atmospheric Imaging Assembly (**AIA**)
- Maps effectively different layers in the chromosphere and corona

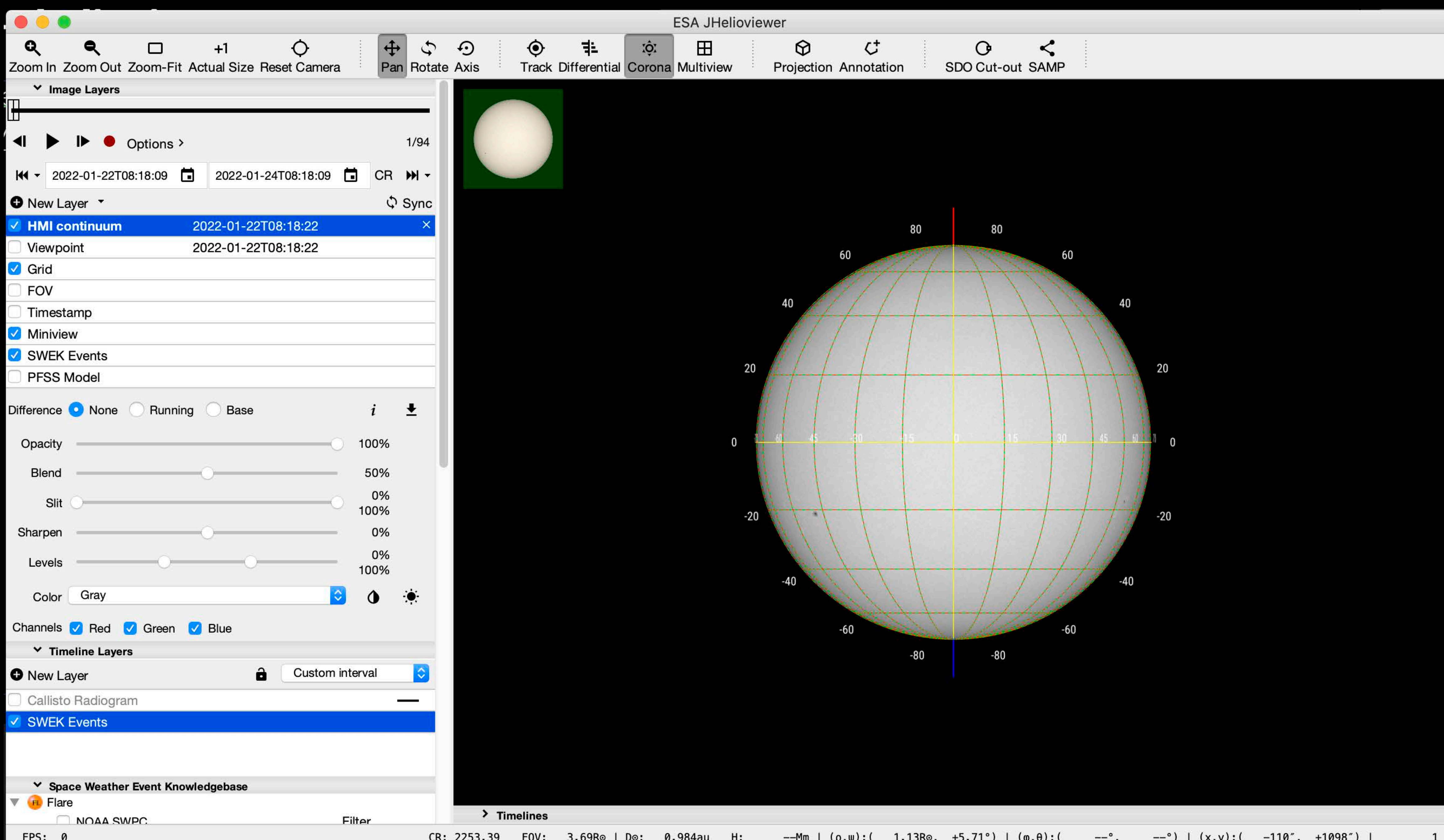
Filter	Ions	Log T
131	Fe VIII, XX, XXIII	5.6, 7.0, 7.2
171	Fe IX	5.8
193	Fe XII, XXIV	6.1, 7.3
211	Fe XIV	6.3
335	Fe XVI	6.4
94	Fe XVIII	6.8



Preview - The solar atmosphere

Interactive exploring — helioviewer

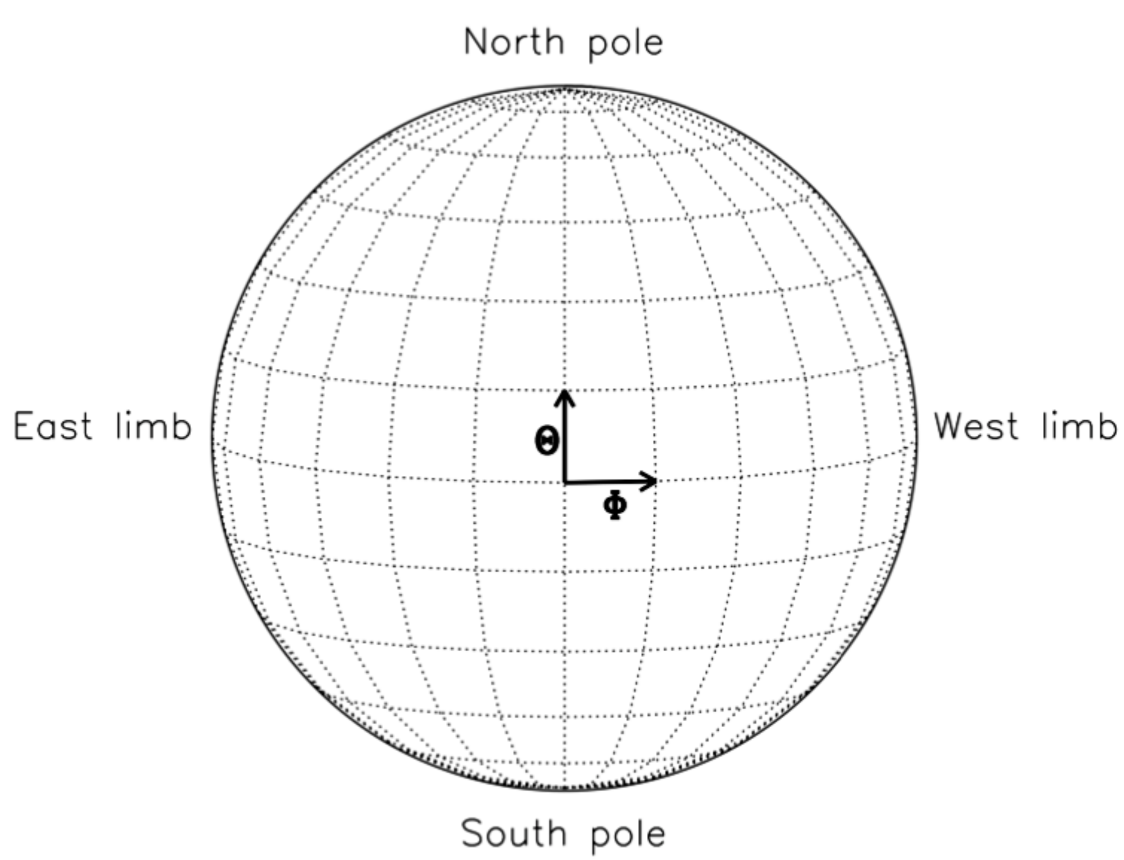
- web-based version: https:// helioviewer.org/
- downloadable application: https://www.jhelioviewer.org/ (has more functions)



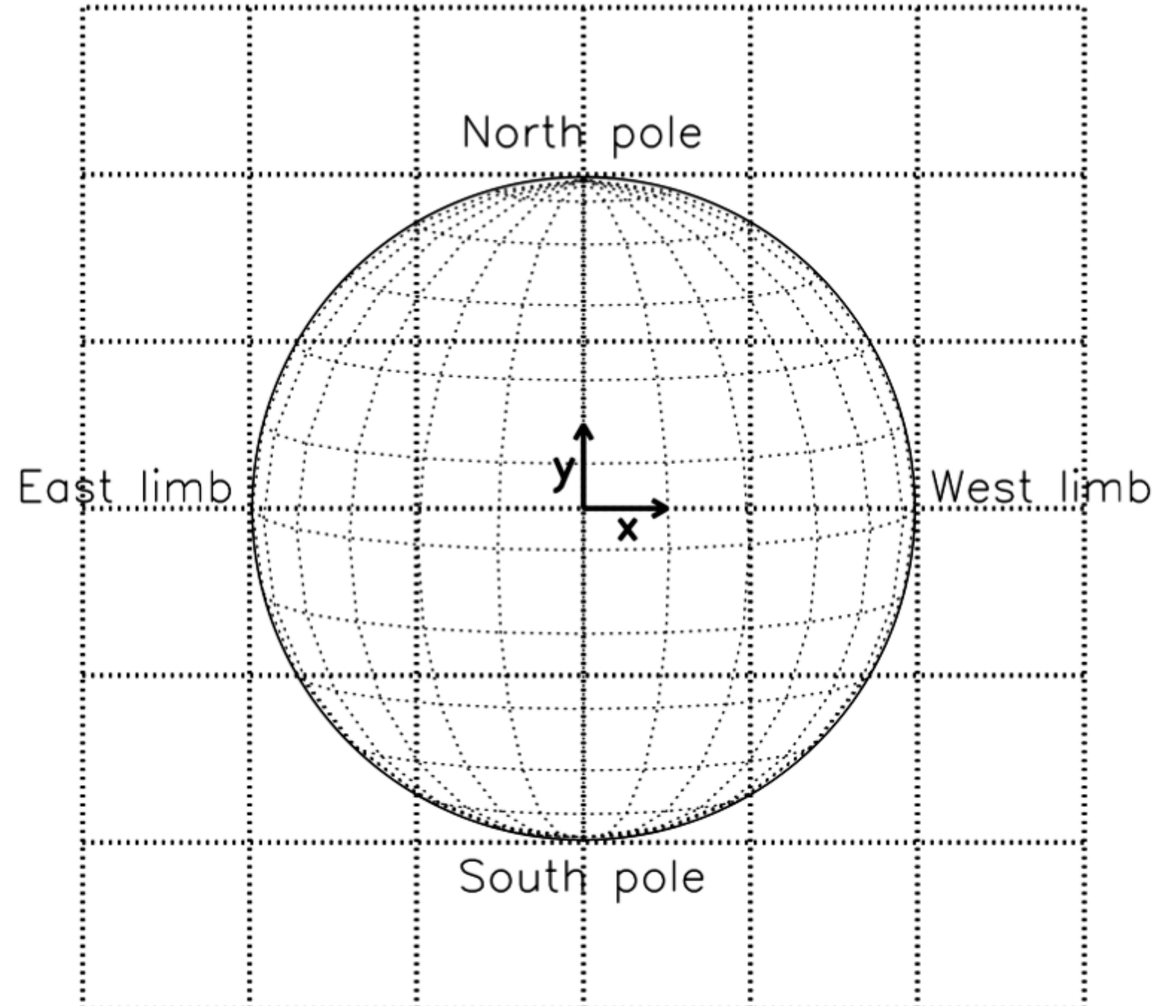
Solar coordinate systems

- RA/Dec does not make sense for relative coordinates on the Sun as the Sun itself is moving with respect to the sky background
- Relevant coordinates for the Sun shown at the bottom of the helioviewer window!

Heliographic coordinates (Stonyhurst)



Heliocentric coordinates (Cartesian)



See https://fits.gsfc.nasa.gov/wcs/coordinates.pdf

Solar coordinate systems

Helioprojective Cartesian Coordinates

- Observations are projected against the celestial sphere
- Observer-centric system with projective angles and solar disc-centre as origin

This is the projected equivalent of heliocentric-cartesian coordinates, where the distance parameters x and y are replaced with the angles θ_x and θ_y, where θ_x is the longitude, and θ_y is the latitude. Close to the Sun, where the small angle approximation holds, the heliocentric-cartesian and helioprojective-cartesian are related through the equations

$$x \approx d(\frac{\pi}{180°})\theta_x \approx D_\odot(\frac{\pi}{180°})\theta_x, \quad (4)$$

$$y \approx d(\frac{\pi}{180°})\theta_y \approx D_\odot(\frac{\pi}{180°})\theta_y,$$

where d is the distance between the observer and the feature, and $D_\odot$ is the distance between the observer and Sun center.

See https://fits.gsfc.nasa.gov/wcs/coordinates.pdf

The solar atmosphere

Semi-empirical model atmosphere

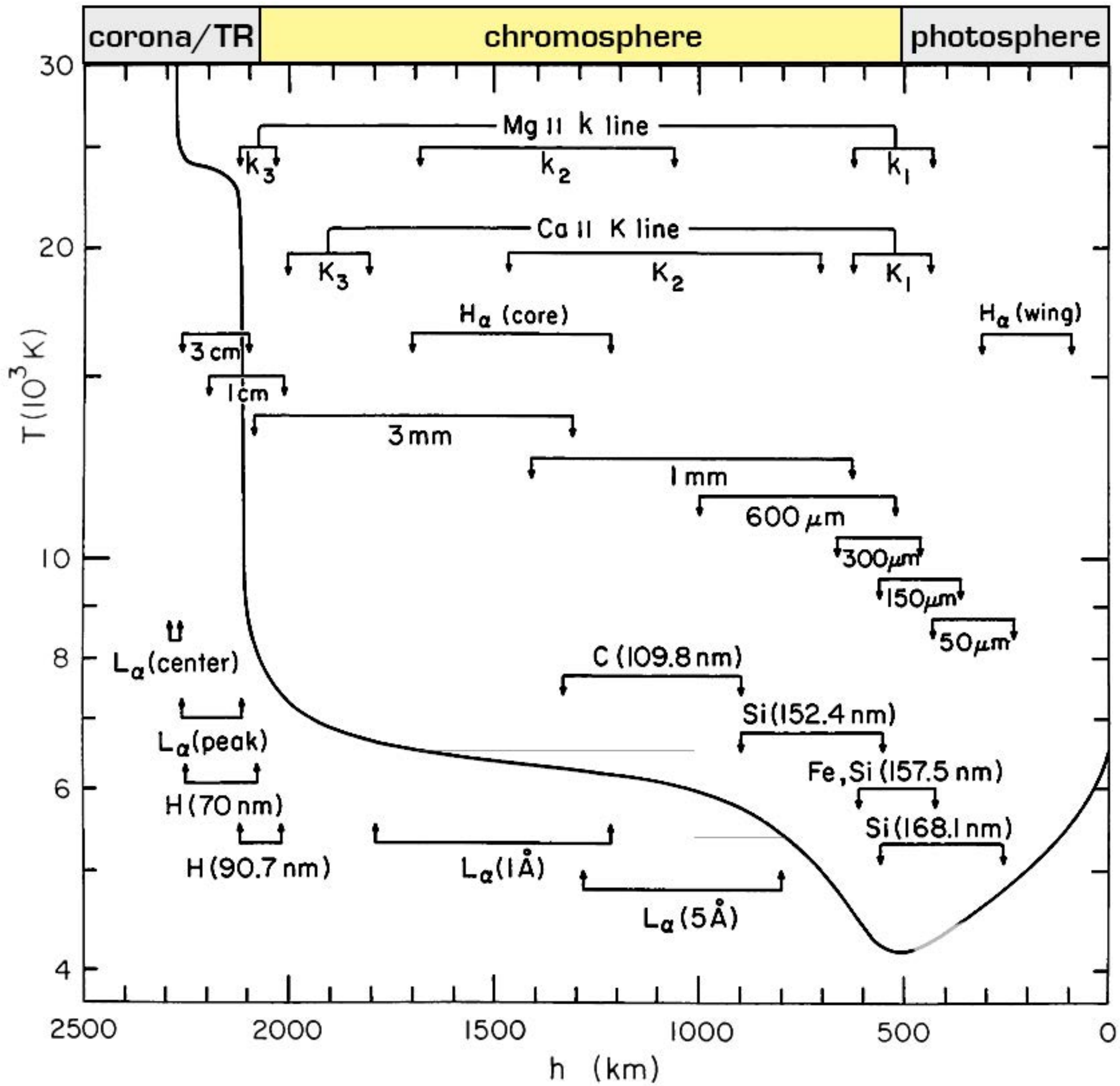
- Semi-empirical models
  - Starting with a model atmosphere that describes the stratifications of relevant properties such gas temperature, density etc.
    - Calculate the emergent intensity for different continua and spectral lines
    - Compare to observations
    - Adjust the model atmosphere
  - Repeat until the observations are (overall) reproduced as accurately as possible

- **Very well known: VAL: Vernazza, Avrett, Loeser (1981)**
  - One-dimensional!
  - Several models and updates/modifications
  - Widely used as a reference

The solar atmosphere

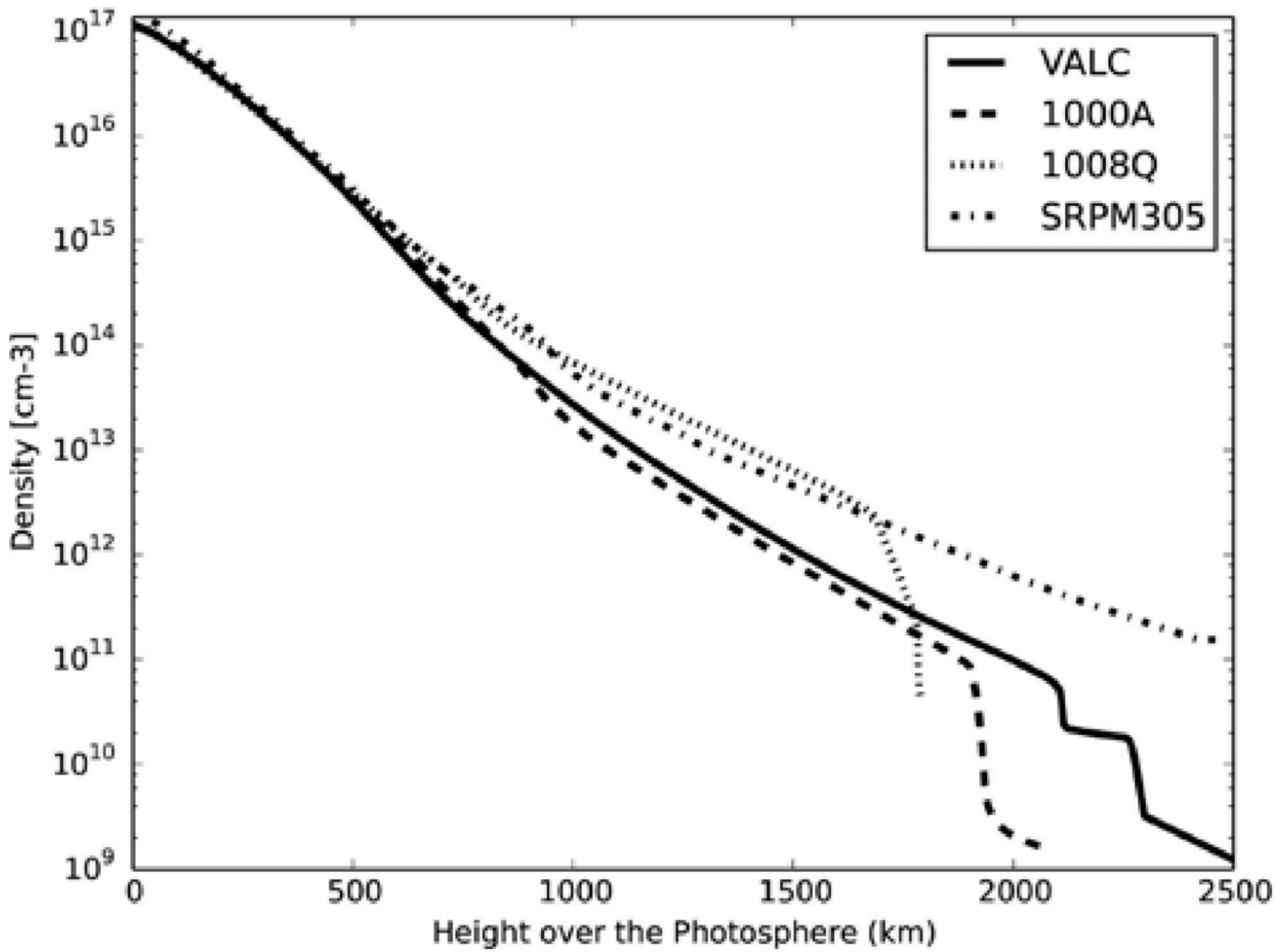
Semi-empirical model atmosphere

VAL: Vernazza, Avrett, Loeser (1981)



The solar atmosphere

Semi-empirical model atmosphere

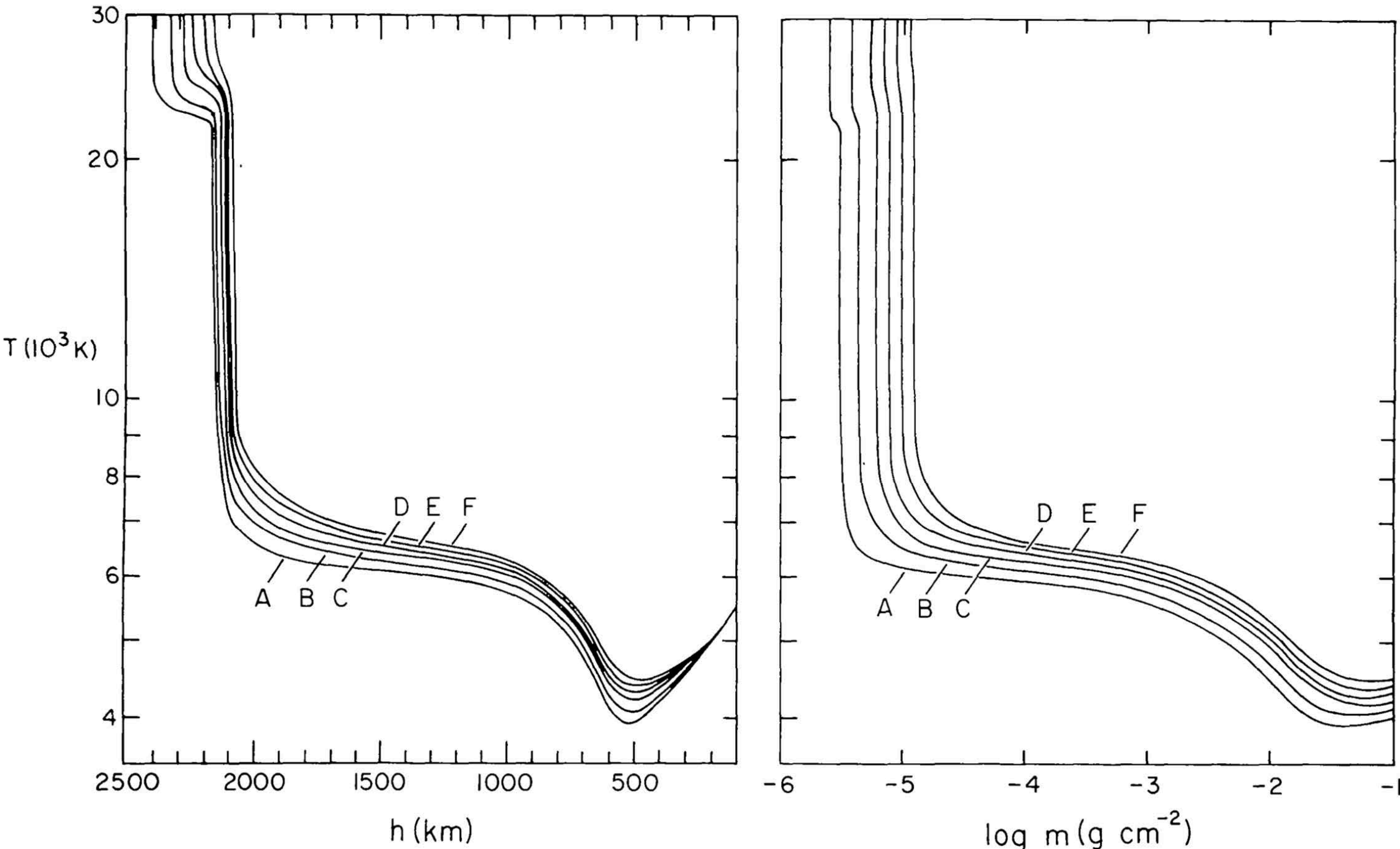


VAL: Vernazza, Avrett, Loeser (1981)

The solar atmosphere

Semi-empirical model atmosphere

VAL: Vernazza, Avrett, Loeser (1981)



The solar atmosphere

Semi-empirical model atmosphere

TABLE 12
ATMOSPHERIC PARAMETERS FOR MODEL C

VAL Model C (1981)

	h (km)	m (g cm^{-2})	τ_{500}	T (K)	V (km s^{-1})	n_H (cm^{-3})	n_e (cm^{-3})	P_{total} (dyn cm^{-2})	P_{gas}/P_{total}	σ (g cm^{-3})
1	2543	5.257-06	0.	447000	11.28	1.005+09	1.205+09	1.440-01	.9896	2.349-15
2	2298	5.365-06	3.712-08	141000	9.87	3.205+09	3.839+09	1.470-01	.9752	7.494-15
3	2290	5.373-06	3.969-08	89100	9.82	5.041+09	5.961+09	1.472-01	.9614	1.179-14
4	2280	5.389-06	4.491-08	50000	9.76	9.038+09	9.993+09	1.477-01	.9318	2.113-14
5	2274	5.404-06	4.952-08	37000	9.73	1.201+10	1.318+10	1.481-01	.9102	2.808-14
6	2271	5.413-06	5.234-08	32000	9.71	1.378+10	1.498+10	1.483-01	.8976	3.222-14
7	2267	5.427-06	5.657-08	28000	9.70	1.567+10	1.677+10	1.487-01	.8840	3.665-14
8	2263	5.443-06	6.124-08	25500	9.68	1.718+10	1.812+10	1.491-01	.8738	4.017-14
9	2255	5.476-06	7.110-08	24500	9.64	1.797+10	1.881+10	1.500-01	.8698	4.203-14
10	2230	5.583-06	1.030-07	24200	9.49	1.862+10	1.943+10	1.530-01	.8718	4.355-14
11	2200	5.716-06	1.426-07	24000	9.33	1.932+10	2.009+10	1.566-01	.8645	4.517-14
12	2160	5.902-06	1.977-07	23500	9.08	2.051+10	2.120+10	1.617-01	.8778	4.795-14
13	2129	6.055-06	2.427-07	23000	8.87	2.163+10	2.219+10	1.659-01	.8801	5.058-14
14	2120	6.101-06	2.562-07	22500	8.81	2.231+10	2.276+10	1.672-01	.8789	5.216-14
15	2115	6.128-06	2.640-07	21000	8.78	2.403+10	2.402+10	1.679-01	.8710	5.619-14
16	2113	6.140-06	2.674-07	18500	8.77	2.732+10	2.620+10	1.682-01	.8539	6.390-14
17	2109	6.172-06	2.754-07	12300	8.74	4.092+10	3.306+10	1.691-01	.7839	9.569-14
18	2107	6.193-06	2.801-07	10700	8.72	4.673+10	3.535+10	1.697-01	.7552	1.093-13
19	2104	6.228-06	2.877-07	9500	8.71	5.239+10	3.705+10	1.706-01	.7277	1.225-13
20	2090	6.416-06	3.243-07	8440	8.60	6.127+10	3.799+10	1.758-01	.6986	1.433-13
21	2080	6.564-06	3.507-07	8180	8.55	6.541+10	3.780+10	1.798-01	.6891	1.530-13
22	2070	6.722-06	3.770-07	7940	8.50	6.960+10	3.783+10	1.842-01	.6808	1.628-13
23	2050	7.066-06	4.299-07	7660	8.42	7.705+10	3.792+10	1.936-01	.6701	1.802-13
24	2016	7.732-06	5.203-07	7360	8.22	9.075+10	3.811+10	2.118-01	.6616	2.122-13
25	1990	8.322-06	5.903-07	7160	8.01	1.033+11	3.858+10	2.280-01	.6600	2.417-13
26	1925	1.015-05	7.717-07	6940	7.63	1.380+11	4.028+10	2.780-01	.6620	3.227-13
27	1785	1.647-05	1.212-06	6630	6.92	2.601+11	4.771+10	4.511-01	.6772	6.082-13
28	1605	3.407-05	1.958-06	6440	5.85	6.386+11	6.005+10	9.334-01	.7262	1.493-12
29	1515	5.144-05	2.420-06	6370	5.26	1.048+12	6.456+10	1.409+00	.7595	2.450-12
30	1380	1.012-04	3.286-06	6280	4.51	2.273+12	7.600+10	2.774+00	.8051	5.315-12
31	1280	1.747-04	4.084-06	6220	3.92	4.200+12	7.486+10	4.786+00	.8423	9.822-12
32	1180	3.112-04	5.075-06	6150	3.48	7.865+12	8.108+10	8.527+00	.8694	1.839-11
33	1065	6.299-04	6.861-06	6040	2.73	1.711+13	9.349+10	1.726+01	.9136	4.000-11
34	980	1.098-03	9.148-06	5925	2.14	3.147+13	1.041+11	3.008+01	.9440	7.359-11
35	905	1.840-03	1.239-05	5755	1.70	5.546+13	1.049+11	5.043+01	.9628	1.297-10
36	855	2.632-03	1.553-05	5650	1.53	8.135+13	1.064+11	7.210+01	.9691	1.902-10
37	755	5.577-03	2.537-05	5280	1.23	1.864+14	8.838+10	1.528+02	.9784	4.358-10
38	705	8.333-03	3.288-05	5030	1.09	2.935+14	7.664+10	2.283+02	.9821	6.864-10
39	655	1.276-02	4.452-05	4730	.96	4.794+14	8.085+10	3.495+02	.9852	1.121-09
40	605	2.013-02	7.022-05	4420	.83	8.119+14	1.112+11	5.516+02	.9881	1.899-09
41	555	3.270-02	1.456-04	4230	.70	1.382+15	1.733+11	8.958+02	.9912	3.232-09
42	515	4.878-02	3.014-04	4170	.60	2.096+15	2.495+11	1.336+03	.9934	4.902-09
43	450	9.378-02	1.017-03	4220	.53	3.989+15	4.516+11	2.569+03	.9949	9.327-09
44	350	2.481-01	5.626-03	4465	.52	9.979+15	1.110+12	6.798+03	.9954	2.334-08
45	250	6.172-01	2.670-02	4780	.63	2.315+16	2.674+12	1.691+04	.9936	5.413-08
46	150	1.433+00	1.117-01	5180	1.00	4.917+16	6.476+12	3.926+04	.9854	1.150-07
47	100	2.118+00	2.201-01	5455	1.20	6.866+16	1.066+13	5.804+04	.9801	1.606-07
48	50	3.056+00	4.395-01	5840	1.40	9.203+16	2.122+13	8.274+04	.9748	2.152-07
49	0	4.279+00	9.953-01	6420	1.60	1.166+17	6.433+13	1.172+05	.9702	2.727-07
50	-25	4.991+00	1.683+00	6910	1.70	1.261+17	1.547+14	1.368+05	.9688	2.949-07
51	-50	5.747+00	3.338+00	7610	1.76	1.317+17	4.645+14	1.575+05	.9697	3.080-07
52	-75	6.534+00	7.445+00	8320	1.80	1.365+17	1.204+15	1.790+05	.9711	3.192-07

Data for assignments

Overview

- Data: `/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/data`

`ref`	Reference model, solar atmosphere (Vernazza et al. 1981), model C
`obs_sunspec`	Observed spectrum of the Sun (Neckel & Labs 1994)

`obssun_sst1`
`obssun_sst2`
`obssun_sst3`
`obssun_sst4`
	Observations of the Sun with the Swedish 1-m Solar Telescope (SST)

`obs_starcat` `obs_starcat/SED`	Catalogue with stellar parameters Spectral Energy Distribution for different stars

`simsts_F5V`
`simsts_K2V`
`simsts_K8V`
`simsts_G2V`
`simsts_K5III`
`simsts_M3V`
	3D numerical simulations for different stellar types, 1 snapshot each
	• Volume data
	• Continuum intensity
	• Spectral line data

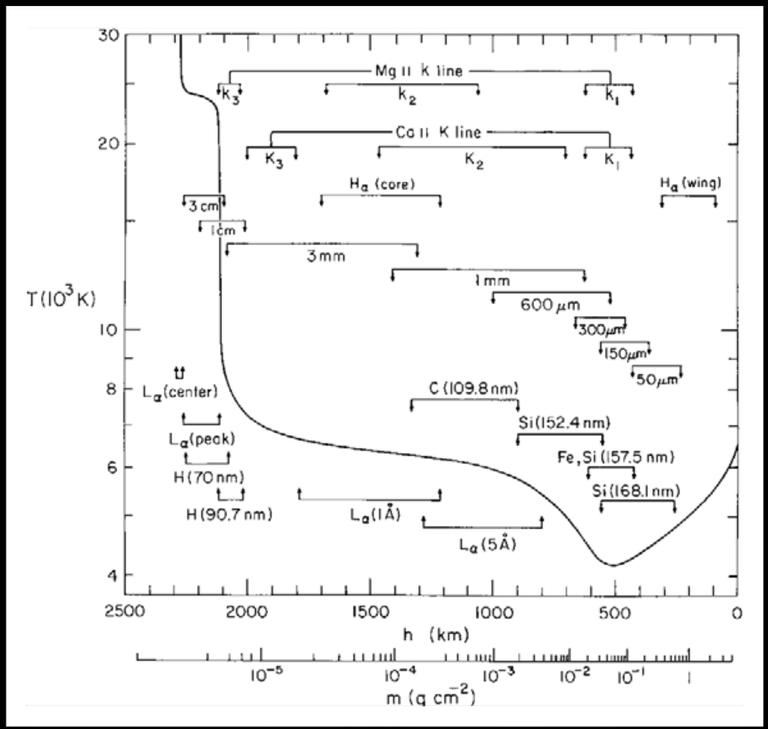
`simsut_G2V`	Time series of 2D slices extracted from a 3D numerical simulations of the Sun

Data for assignments

Reference model

- Semi-empirical atmospheric model of the Sun by Vernazza, Avrett, and Loeser (1981)
- Provided: Model C for Quiet Sun conditions (referred to as **VAL C**)
- For comparison and/or as reference for observational and simulation data sets.
- `/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/data/ref/ val81c.h5`
- HDF5 the following tags:

```
DESCRIPTION ─┬─ H ── _data      z: Geometrical height above the photospheric
H            ├─ ...             level with h=0km where the continuum optical
I            └─ ...             depth tau_500=1
M
N_E
N_H
P_TOTAL
PFRAC
RHO
T
TAU500
UNIT ────────┬─ H ── _data      km
V            ├─ ...
H            └─ ...
```



Data for assignments

Reference model

- Semi-empirical atmospheric model of the Sun by Vernazza, Avrett, and Loeser (1981)
- Provided: Model C for Quiet Sun conditions (referred to as **VAL C**)
- For comparison and/or as reference for observational and simulation data sets.
- `/mn/stornext/d9/svenwe/lecture/AST5770/data/ref/val81c.h5`

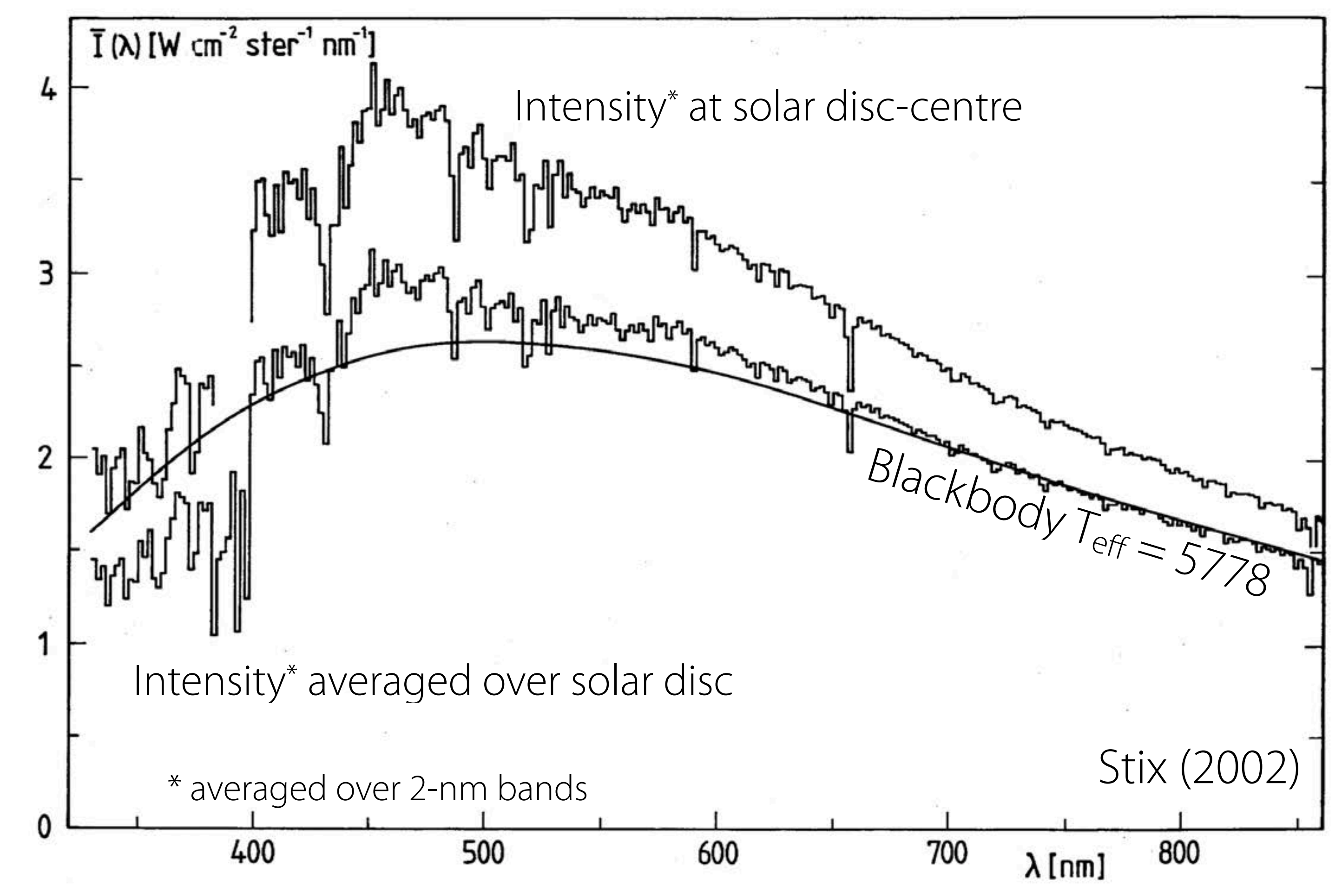
- For the beginning only VAL C is provided.
- More models (VAL A — F) and others can be added soon

Data for assignments

Solar spectrum

- Data from Neckel and Labs (1984) - measurement spectrum of the Sun (function of wavelength)
- Flux: at solar disc-centre (**FC**) and averaged over the solar disc (**F**), wavelength (**LC**)
- Intensity: at solar disc-centre (**IC**) and averaged over the solar disc (**I**), wavelength (**LC**)
- `/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/data/obssun_spec/obssun_spec_NL94.h5`
- HDF5 the following tags:

```
DESCRIPTION
F
FC
I
IC
LF
LI
TAGS
TLF
TLI
```



Data for assignments

Data / material for assignments — solar observations

Solar observations with Swedish 1-m Solar Telescope (SST)/CRISP, time series of images		
obssun_sst1	Quiet Sun, photospheric spectral line Fe I 617.3 nm 2015-Oct-11 08:44:29 - 09:18:16 UT ($\mu = 0.78$, $[x,y] = [-590", 47"]$)	$[x, y, \lambda, t]$
obssun_sst2	Quiet Sun, chromospheric spectral line Ca II 854.2 nm 2015-Oct-11 08:44:15 - 09:18:01 UT ($\mu = 0.78$, $[x,y] = [-590", 47"]$) Note: Data contains some weak artefacts that need to be dealt with.	$[x, y, \lambda, t]$
obssun_sst3	Sunspot (AR12533), chromospheric spectral line Hα 29-Apr-2016 09:43:09 - 11:13:07 UT, ($\mu = 0.75$, $[x,y] = [623", 8"]$) Drews and L. Rouppe van der Voort (2020), L. H. M. Rouppe van der Voort et al. (2021)	$[x, y, \lambda, t]$
obssun_sst4	Sunspot (AR12770), photospheric spectral line Fe I 617.3 nm 2020-Aug-07 08:22:21 - 08:59:58 UT, ($\mu = 0.83$, $[x,y] = [-446", 279"]$)	$[x, y, \lambda, t]$

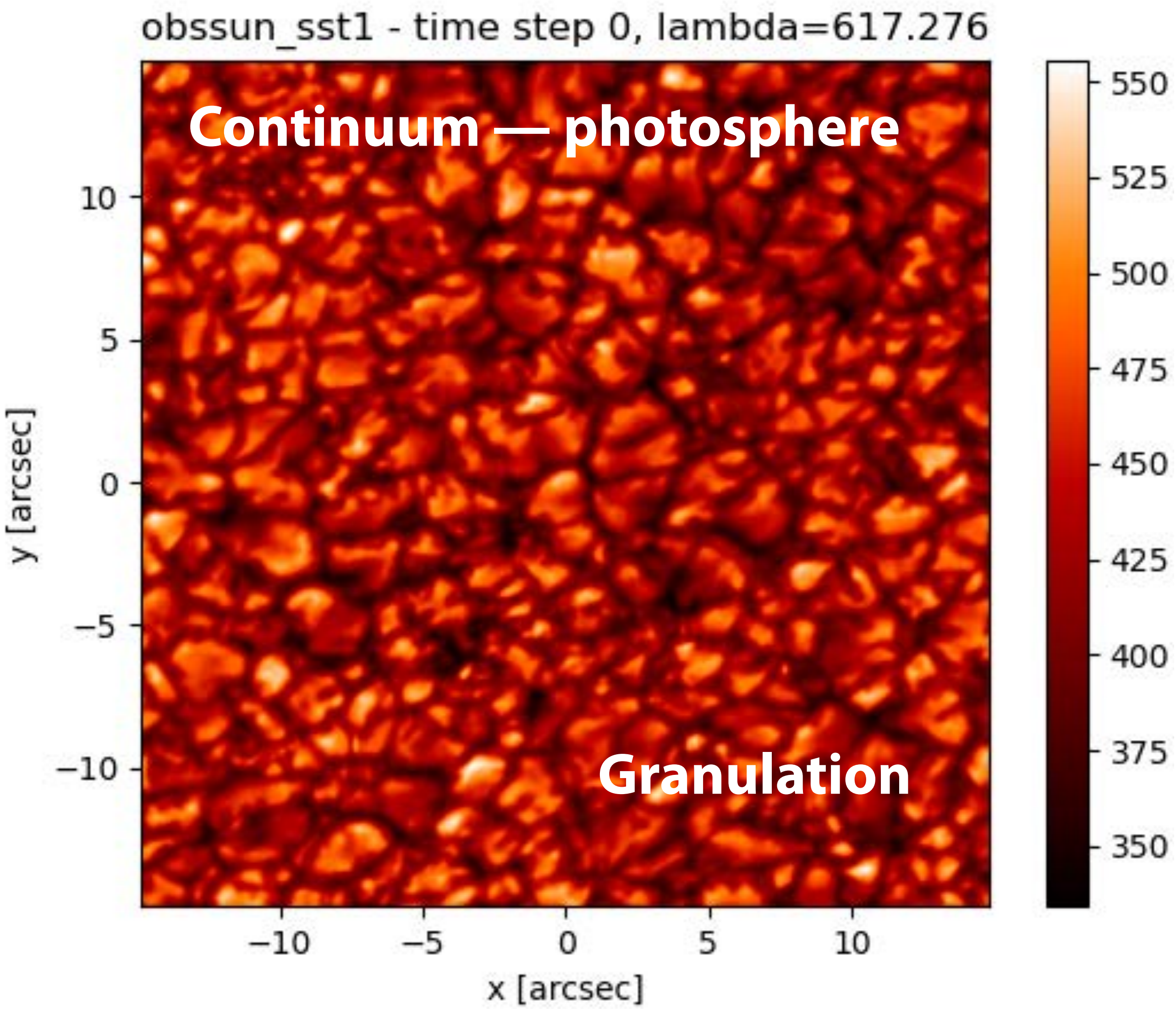
- Swedish 1-m Solar Telescope (SST)
- Time series for different continua and spectra are offered for different solar targets.
- Intensity in units of instrumental counts (no absolute physical units!)
- Files are in HDF5 format and contain a **description**, coordinates (relative within the provided field of view), wavelengths, and time.

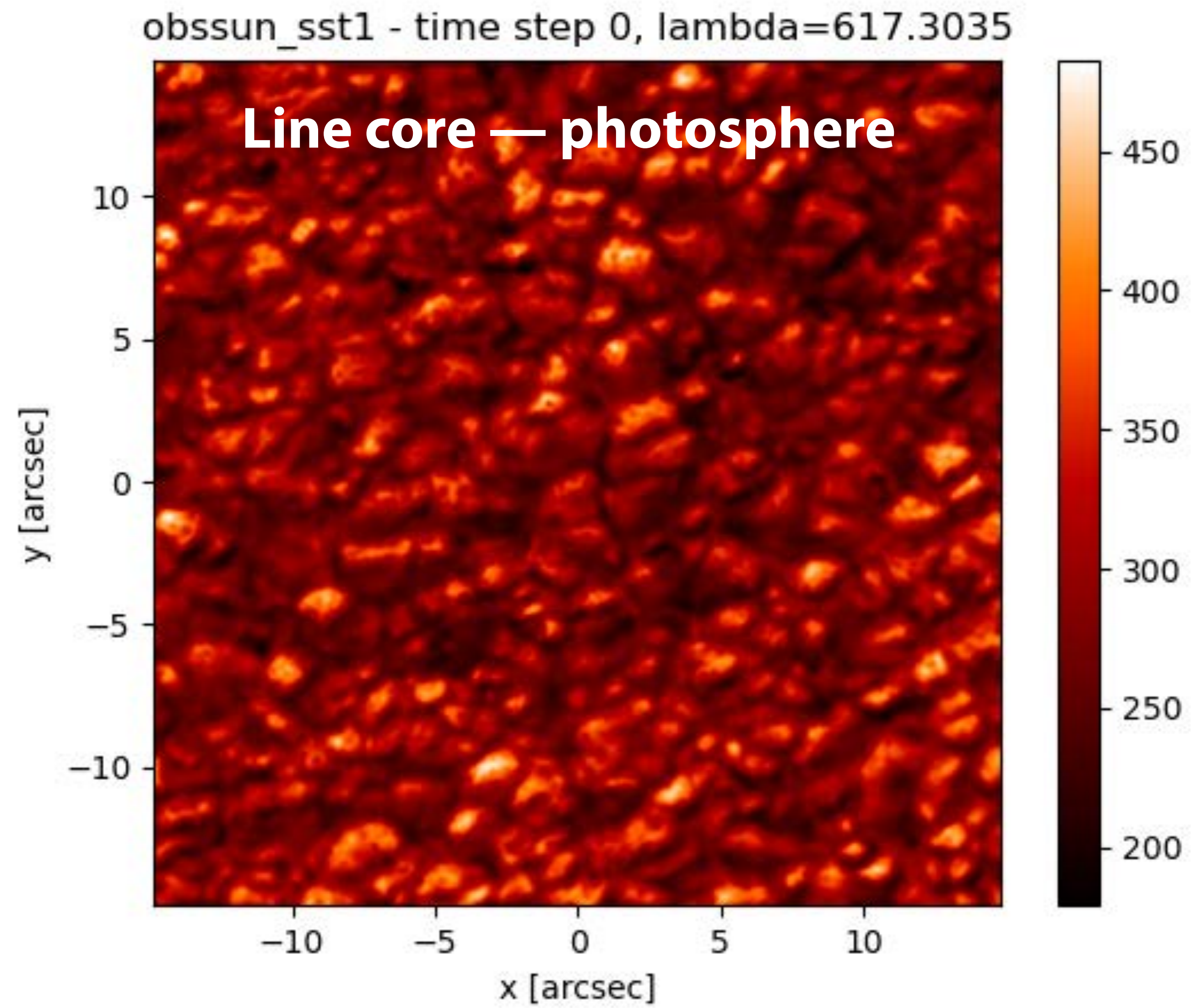
Data for assignments

Solar observations (SST) — obssun_sst1

obssun_sst1	Quiet Sun, photospheric spectral line Fe I 617.3 nm 2015-Oct-11 08:44:29 - 09:18:16 UT ($\mu = 0.78$, $[x,y] = [-590'', 47'']$)	$[x, y, \lambda, t]$

- Simultaneous with dataset obssun_sst2!



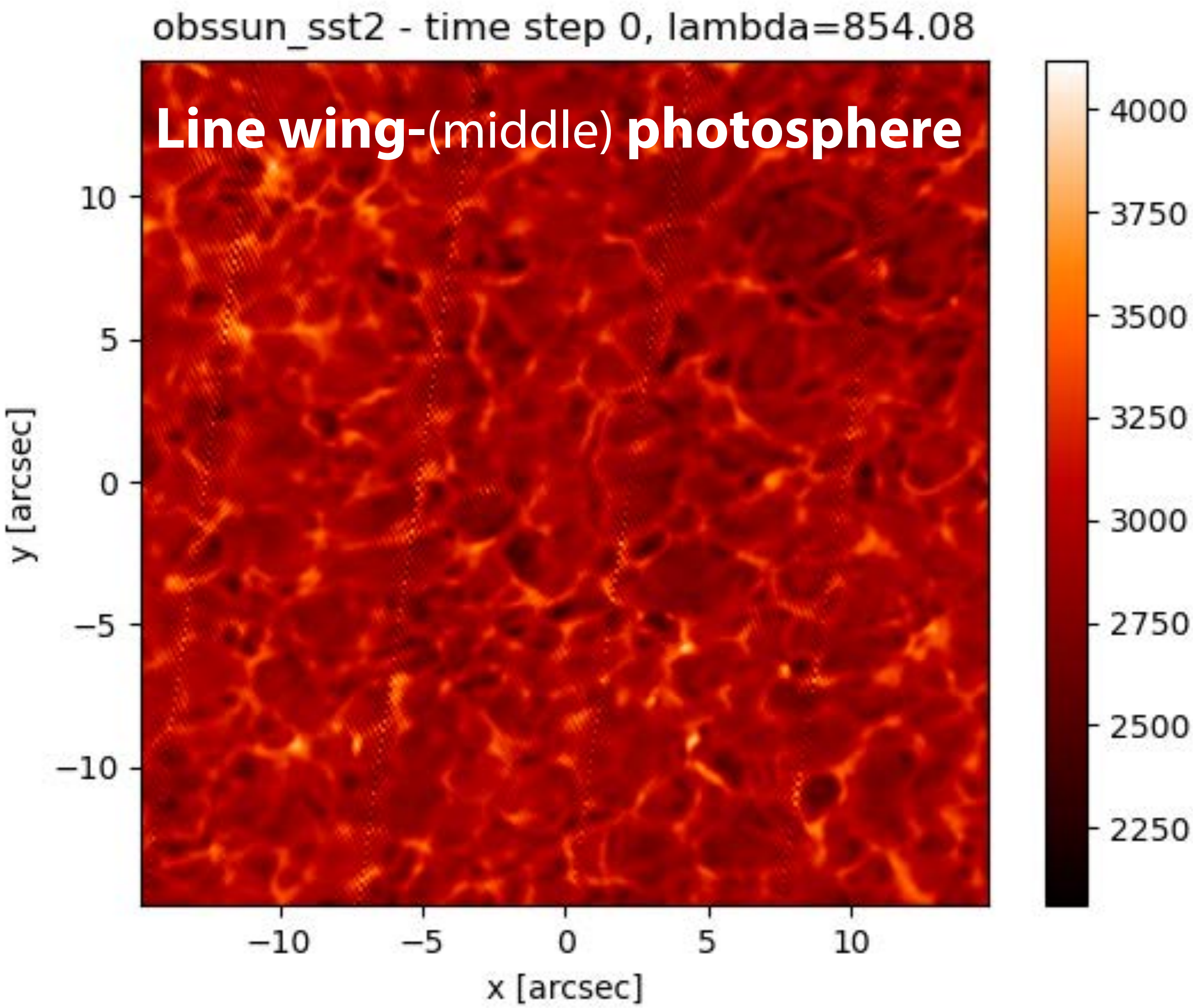


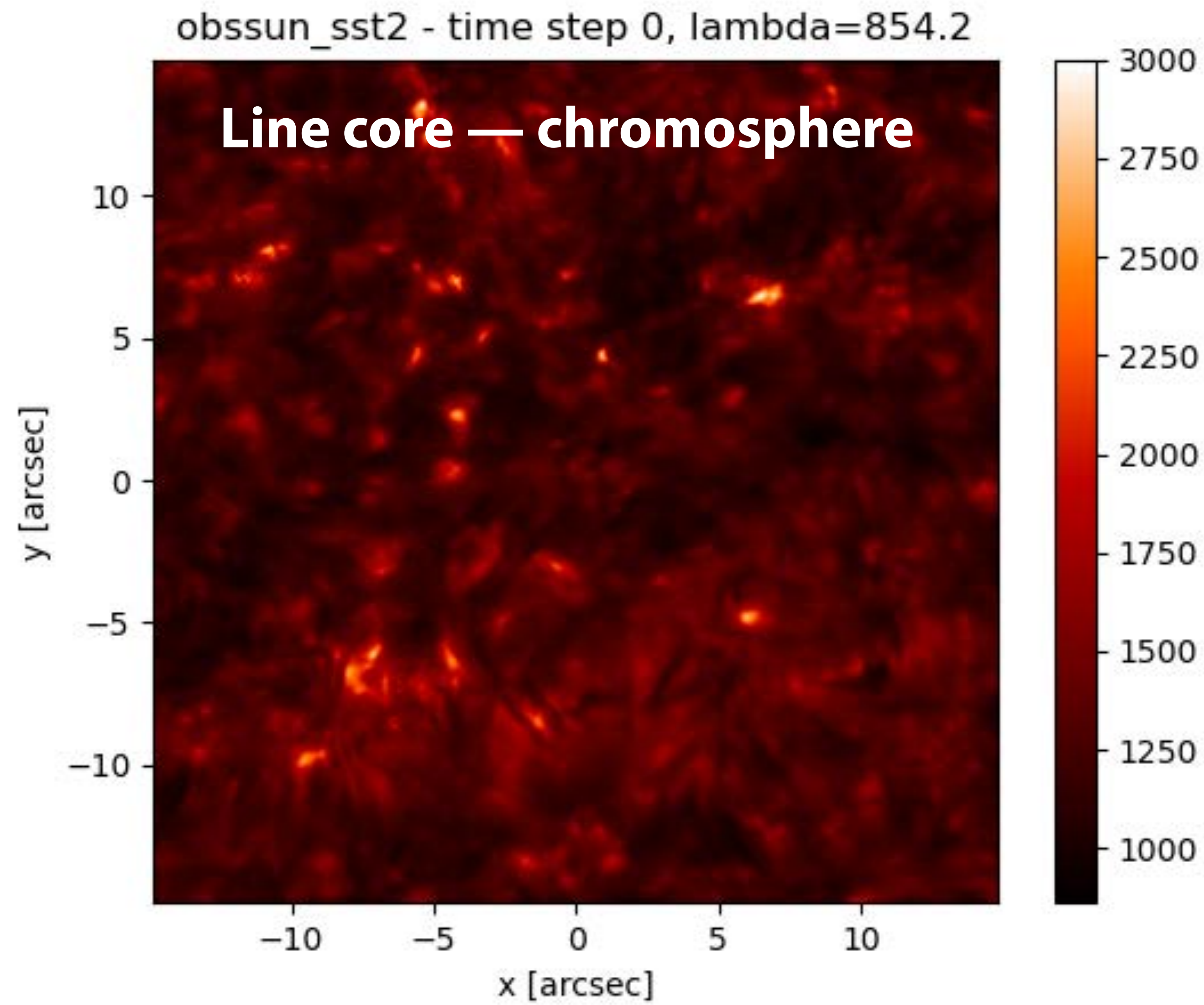
Data for assignments

Solar observations (SST) — obssun_sst2

obssun_sst2	Quiet Sun, chromospheric spectral line Ca II 854.2 nm 2015-Oct-11 08:44:15 - 09:18:01 UT ($\mu = 0.78$, $[x,y] = [-590'', 47'']$) Note: Data contains some weak artefacts that need to be dealt with.	$[x, y, \lambda, t]$

- Simultaneous with dataset obssun_sst1!

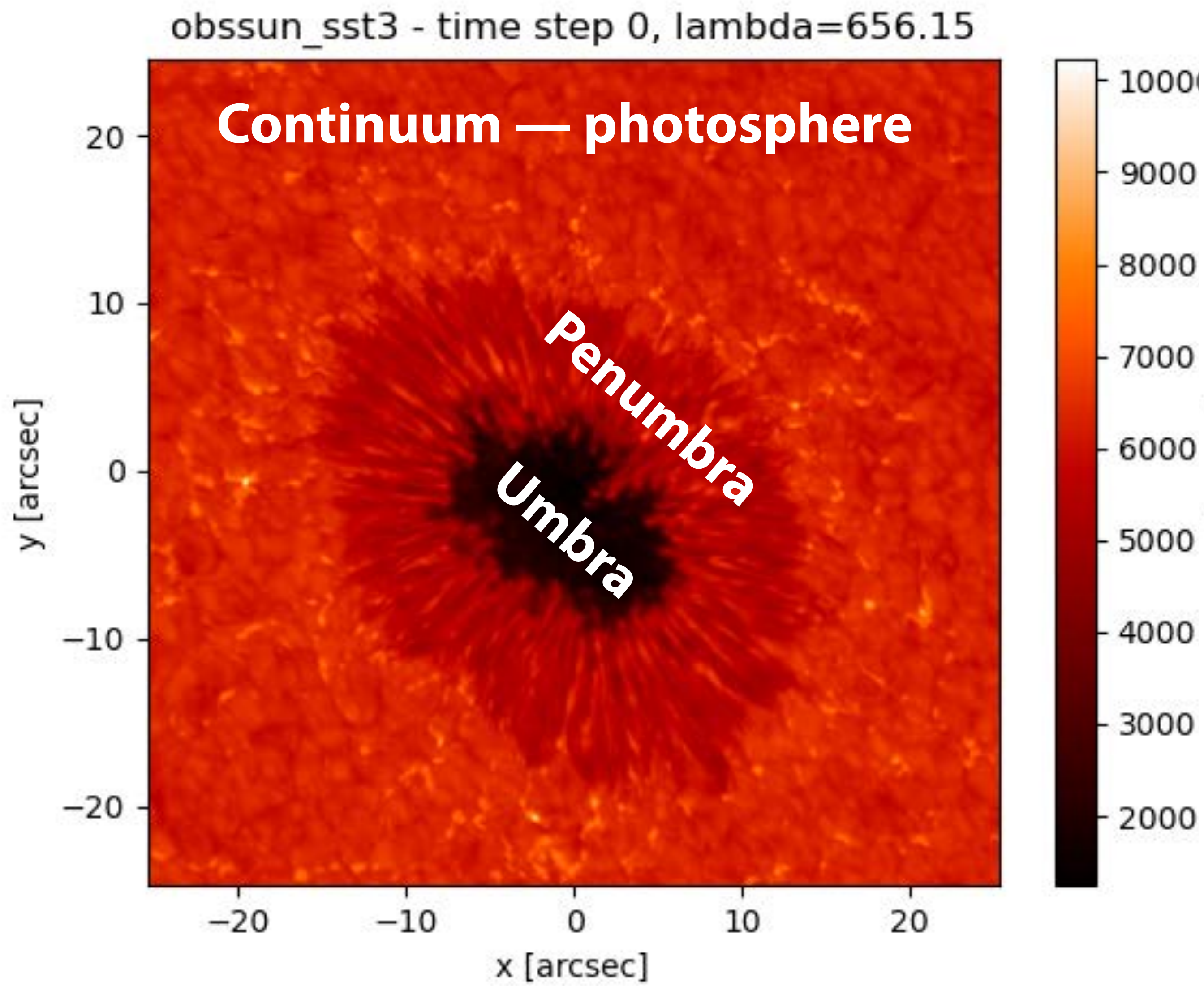


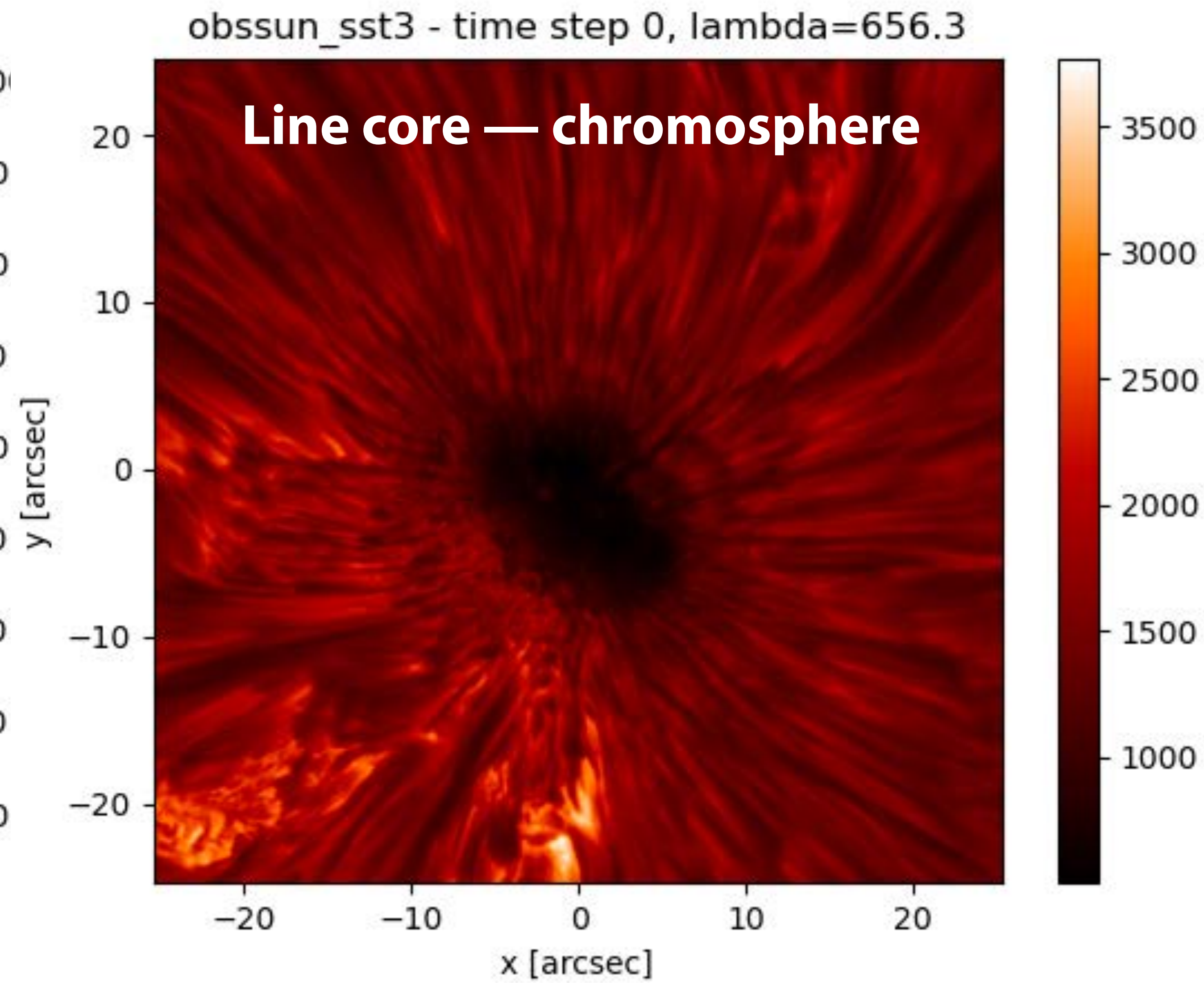


Data for assignments

Solar observations (SST) — obssun_sst3

obssun_sst3	Sunspot (AR12533), chromospheric spectral line Hα 29-Apr-2016 09:43:09 - 11:13:07 UT, ($\mu = 0.75$, $[x,y] = [623'', 8'']$) Drews and L. Rouppe van der Voort (2020), L. H. M. Rouppe van der Voort et al. (2021)	$[x, y, \lambda, t]$

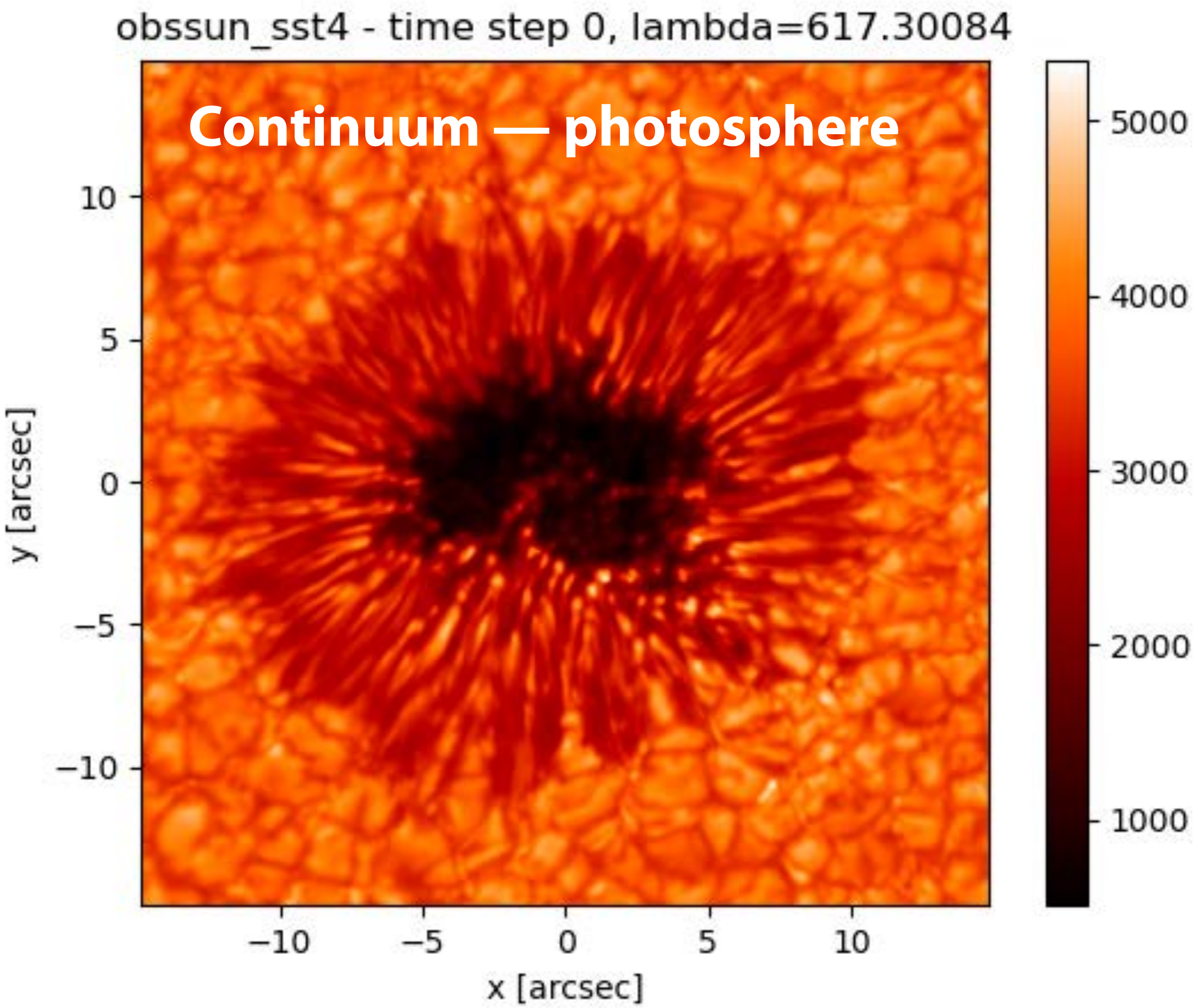


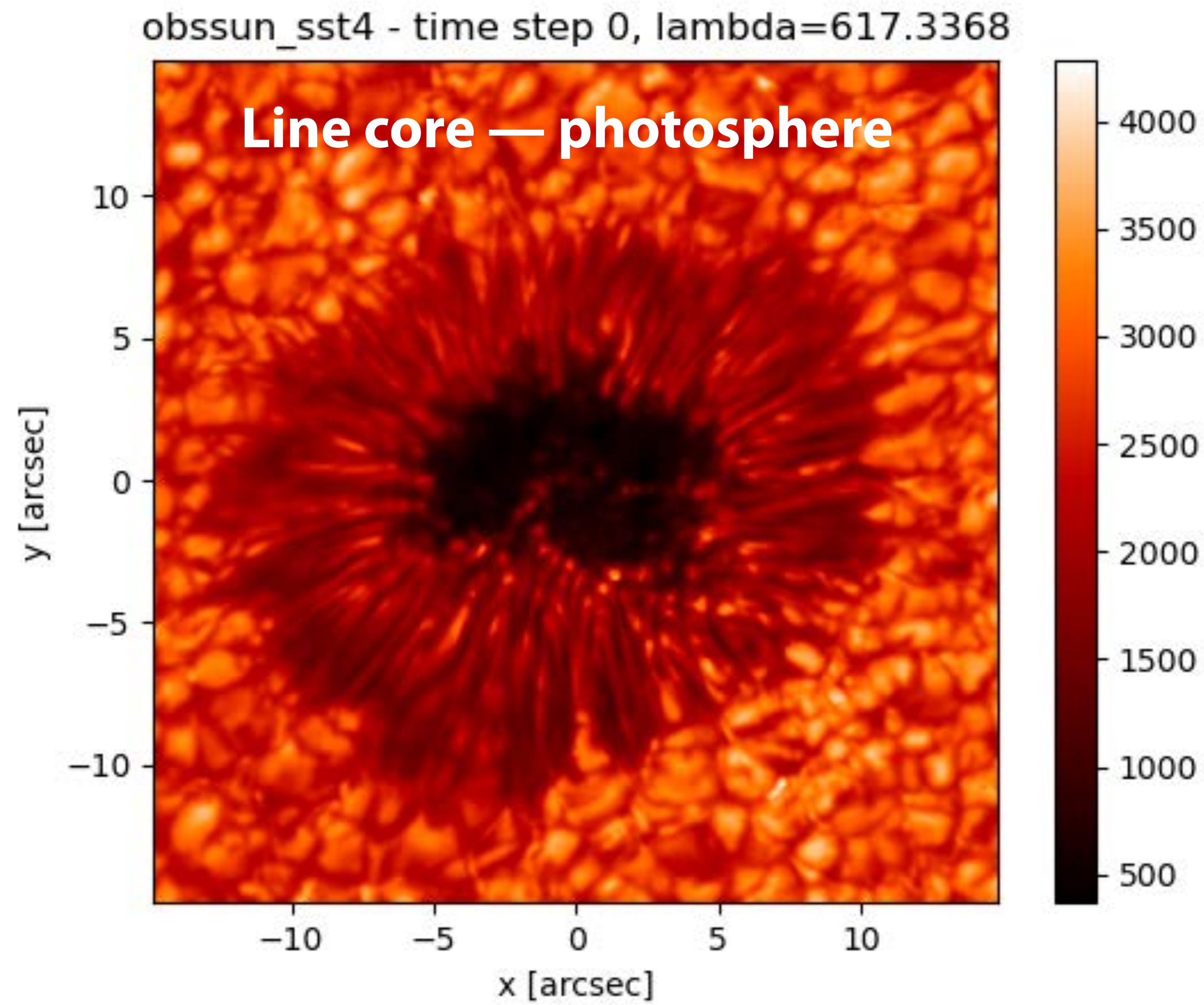


Data for assignments

Solar observations (SST) — obssun_sst4

obssun_sst4	Sunspot (AR12770), photospheric spectral line Fe I 617.3 nm 2020-Aug-07 08:22:21 - 08:59:58 UT, ($\mu = 0.83$, $[x,y] = [-446", 279"]$)	$[x, y, \lambda, t]$



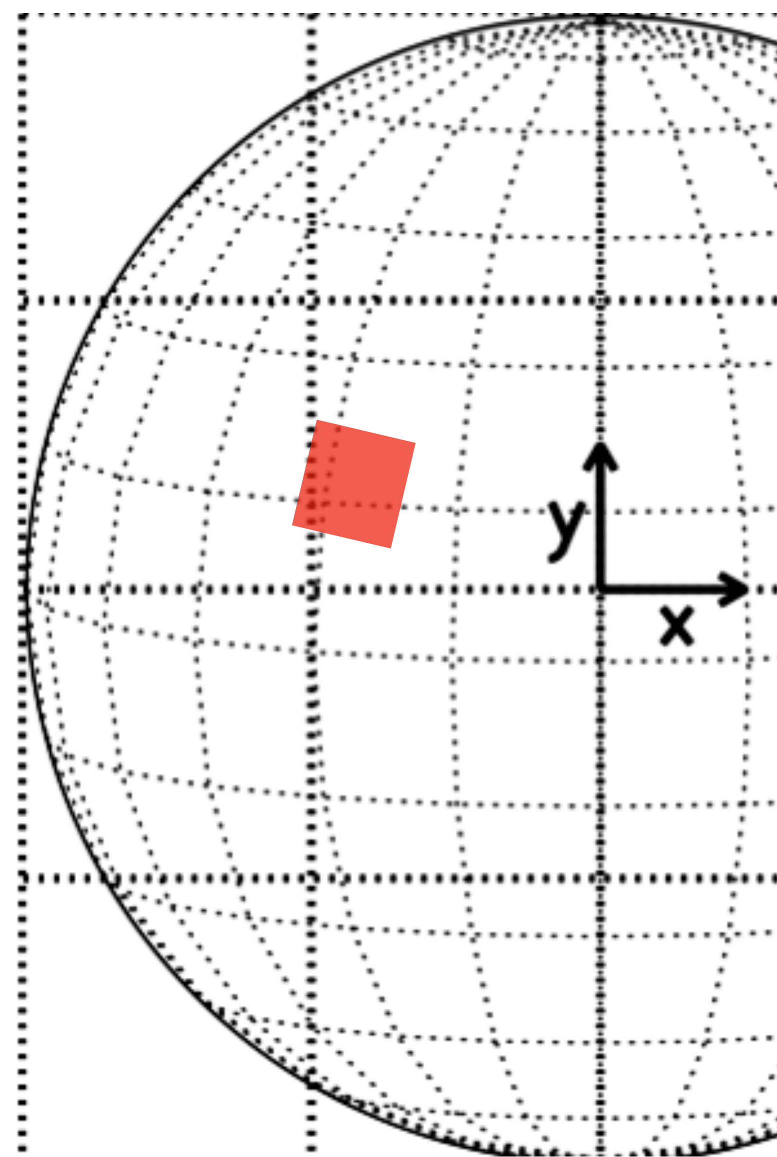


Data for assignments

Solar observations — coordinates

- **Caution: Coordinates and rotation!**
- The coordinates are approximate for the telescope pointing
- Typically near the centre of the field of view (FOV)
- Typically at the beginning of the observation
- Can **differ** from the correct(ed) helioprojective coordinates by a **few arcseconds**!
- The FOV can be **rotated** with respect to the helioprojective coordinate frame
- Usually: FOV is **co-aligned** with a reference image, e.g. SDO
  - SDO coordinates are corrected
  - Co-alignment easier if there are prominent features in both images (e.g. a sunspot)
  - Co-alignment can be hard and unreliable in absence of prominent features!
  - **“Fun” experiment:** Compare the SST FOVs with SDO
  - Correct co-alignment is not expected for the project assignment!

[−590”,47”])



Data for assignments

Solar observations — coordinates

- **Caution: Coordinates and rotation!**
- The coordinates are approximate for the telescope pointing
- Typically near the centre of the field of view (FOV)
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- Can **differ** from the correct(ed) helioprojective coordinates by a **few arcseconds**!
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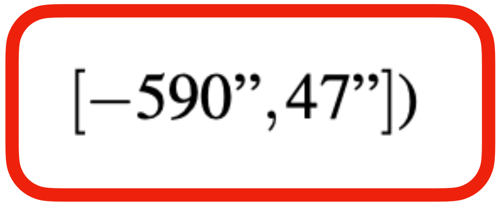
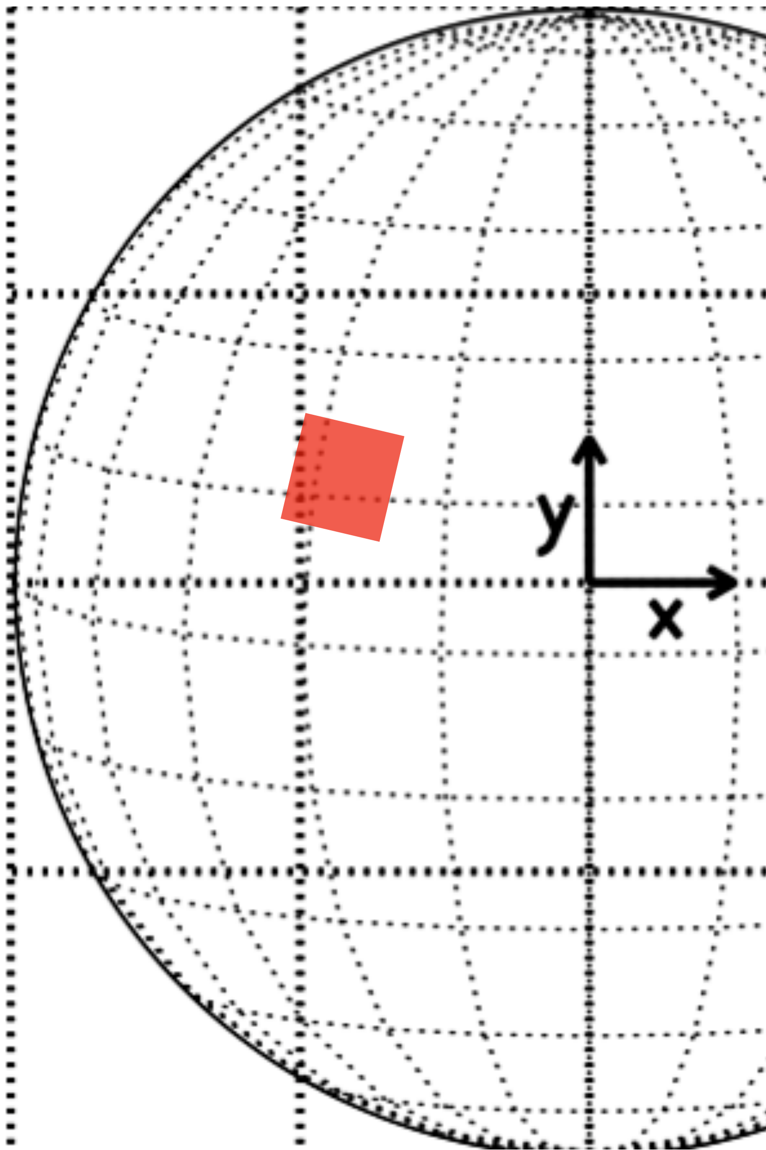


- In addition:
  - The FOV of different telescopes vary
  - SST ~60” x 60” (Note: smaller close-up regions are provided for the assignments)
  - Sun rotates! Following the same feature on the Sun needs following of the solar rotation (slow but notable after 1h)
  - The quality of images can vary over time (“seeing” due to Earth’s atmosphere)



Data for assignments

Stellar catalogue

- `obs_starcat/obs_starcat.p` contains catalogue with (mostly empirical) parameters for 79 stars
- Can be loaded as a table in python. Some hints: `AST5770_manual.pdf`

Name	Sp Type	SIMBAD MAIN ID	RA	DEC	Distance	B-V	Mass	Radius	Teff	L_bol	Period	Vsini	Age	Log R'HK	[Fe/H]	Log L_X	Log Rx	log g	|B_V|	R0	U	V	R	I	J
			deg	deg	pc		Msun	Rsun	K	Lsun	d	Km/s	Myr			Erg/s		cgs	G						
GJ 1111	M6	G 51-15	127.4556042	26.7760389	3.5805	2.066	0.1	0.11	3293	0.0013	0.46	7.3	200		-0.12	27.61	-2.75	3.36	51.5	0.005		14.81	14.736		8.235
Proxima Cen	M5.5V	NAME Proxima Centauri	217.43	-62.68	1.3	1.886	0.12	0.15	2990	0.003	89.8	2.7	4850	-4.29	-0.07	26.82	-3.98	3.17	200	0.63	14.21	11.13	9.45	7.41	5.357
GJ 1156	M5	V* GL Vir	184.7474811	11.1260831	6.4722	1.83	0.14	0.16	3467.33	0.0021	0.49	8.7	5000		0.11	27.69	-3.29	3.18	64.9	0.005		13.9	13.55		8.525
EQ Peg B	M4.5	BD+19 5116B	352.9693164	19.9371906	6.2477	1.65	0.25	0.25	3309	0.0077	0.4	28.5	950	-4.5		28.19	-3.25	3.04	364	0.005		10.44	12.165		7.101
V374 Peg	M4	V* V374 Peg	330.3046894	28.3069075	9.1041	1.718	0.28	0.28	3432.62	0.01	0.45	39.1			-1.83589	28.36	-3.2	2.99	493	0.006		11.99	11.602		7.635
EV Lac	M3.5	V* EV Lac	341.7072156	44.3339881	5.0502	1.412	0.32	0.3	3742.19	0.0115	4.37	6.9	300	-3.97	0	28.37	-3.32	2.99	406	0.068		10.26	9.89		6.106
YZ CMi	M4.5	V* YZ CMi	116.1673917	3.5524542	5.9874	1.62	0.32	0.29	3542.23	0.011	2.77	6.5		-4.26	0.29	28.33	-3.33	3.02	480	0.042	13.761	11.225	9.958	8.263	6.581
V2247 Oph	M1	EM* SR 12	246.8313	-24.6945528	112.3166	1.545	0.36	2	3828.93	0.236	3.5	19.874675	1.4		-0.254	30.11	-3.14	1.39	142	0.016		13.28	12.15	10.855	9.424
EQ Peg A	M3.5	BD+19 5116A	352.9673833	19.9372944	6.2614	1.52	0.39	0.35	3585	0.018	1.06	17.5	950	-4.18		28.83	-3.02	2.94	282	0.02		10.173	9.946		6.162
AD Leo	M3	BD+20 2465	154.9011708	19.8700361	4.966	1.544	0.42	0.38	3859.05	0.0192	2.24	3.34	25	-4.33	0.2	28.73	-3.18	2.9	152	0.047		9.52	9.19		5.449
CE Boo	M2.5	BD+16 2708	223.6218214	16.1010631	9.9324	1.5	0.48	0.43	3806.34	0.0335	14.7	3.5	130	-4.319	-0.15	28.4	-3.7	2.85	91.6	0.288	12.86	10.15	9.116	7.872	6.633
TYC6349-0200-1	K6	HD 358623	314.0114111	-17.1816122	45.9306	0.978	0.54	0.54	4270	0.244	3.39	15.6	21		-0.1			2.71	34.1			10.625	10.18	8.847	7.849
OT Ser	M1.5	V* OT Ser	230.4705439	20.9777589	11.4445	1.3629	0.55	0.49	3802.66	0.017	3.4	4.8	70	-4.27	-0.1	28.8	-3.4	2.8	81	0.097	12.662	10.003	8.993	7.843	6.61
GJ_2006A	M3.5Ve	GJ 2006 A	6.96	-32.55	34.8	1.5	0.552	0.558	3150	0.046	3.9	6.2	6		-0.5	29.53	-2.72	2.69	4.02			12.95	11.79	10.29	8.88
GJ 49	M1.5	BD+61 195	15.6619519	62.3450481	9.8556	1.463	0.57	0.51	3777	0.048	18.6	2.49	1200	-4.668	0.49	28	-4.3	2.78	16.3	0.352		9.6	8.7	7.88	6.23
DS Leo	M0	V* DS Leo	165.6597572	21.9671392	11.9365	1.437	0.58	0.52	3911.91	0.056	14	2.89	710	-4.37	0.03	28.3	-4	2.77	23.9	0.267	12.246	9.572	8.638	7.634	6.522
HIP 12545	K6	BD+05 378	40.3578681	5.9884503	44.4373	1.25	0.58	0.57	4166.67	0.262	4.83	40	21		0.3			2.69	78.5			10.271	9.88	9.3	7.904
DT Vir	M0.5	BD+13 2618	195.1940975	12.3757311	11.5132	1.45	0.59	0.53	3965.42	0.051	2.85	9.75	600	-3.994	-0.339	28.92	-3.4	2.76	76.6	0.092	12.314	9.75	8.785	7.653	6.437
HIP 76768	K6	HD 139751	235.1182958	-18.6961711	38.1494	1.24	0.61	0.6	4572.53	0.162	3.64	8	120		0.3			2.67	54.2			10.07	9.953	8.637	7.73
DN Tau	M0	V* DN Tau	68.8640625	24.2497028	128.2199	1.36	0.65	1.9	3964	0.534	6.32	12.3	1.7		-1.005	30.08	-3.41	1.7	317	0.027	13.56	12.32	11.79	10.95	9.139
TYC6878-0195-1	K4	CD-26 13904	287.936125	-26.069125	59.0713	1.05	0.65	0.64	4566.78	0.367	5.72	9.8	21		-0.371			2.64	31.7			10.2	9.55	9.09	8.081
HD 201091A	K5V	* 61 Cyg A	316.7248019	38.7494403	3.4972	1.069	0.66	0.62	4327	0.164	34.2	1.1	3600	-4.704	-0.03	28.22	-4.53	2.67	2.68	0.786	7.5	5.21	4.19	3.54	3.12

Data for assignments

Stellar catalogue

- `obs_starcat/obs_starcat.p` contains catalogue with (mostly empirical) parameters for 79 stars
- Can be loaded as a table in python. Some hints:

    `AST5770_manual.pdf`

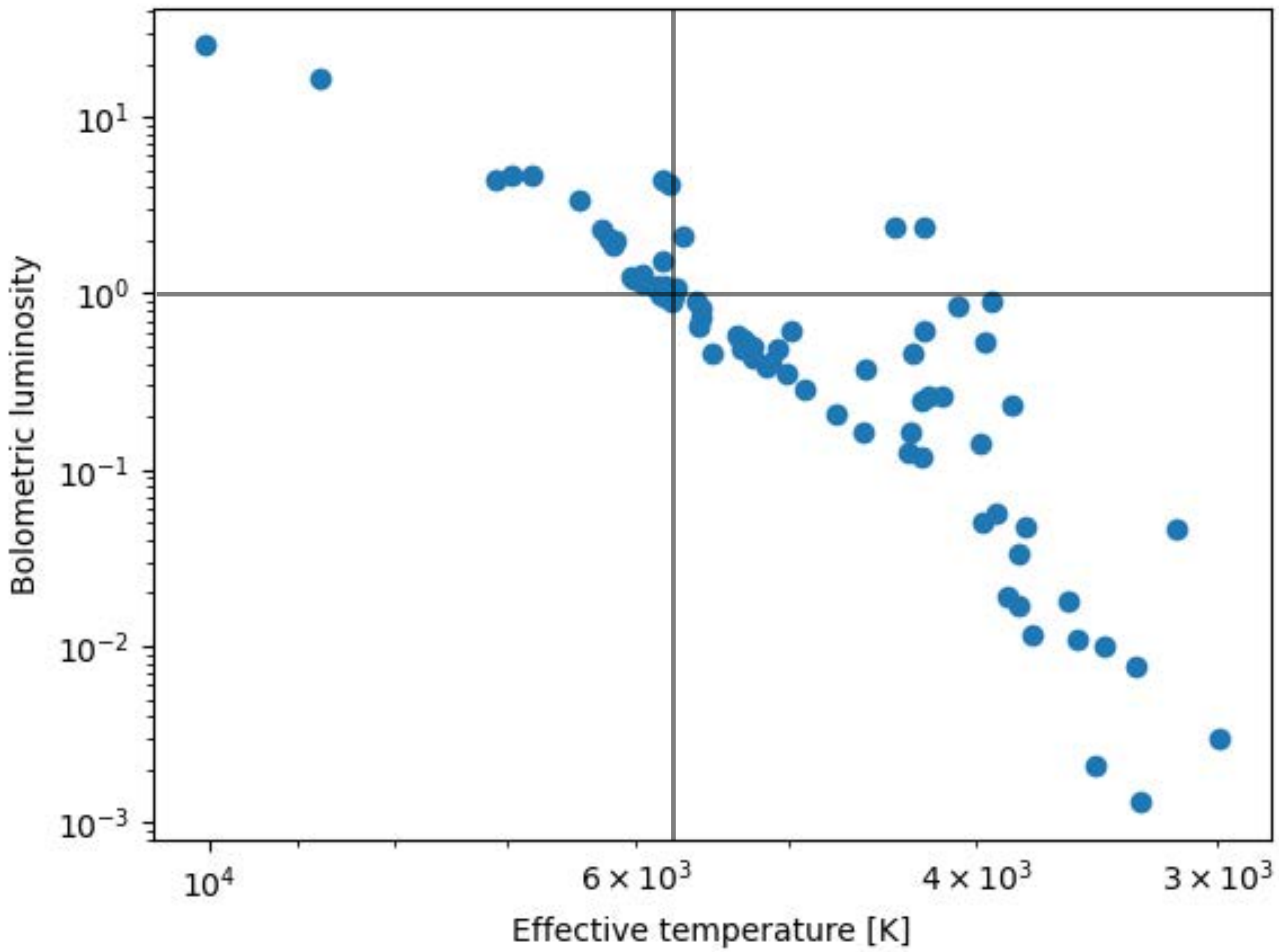
- For some stars fluxes at selected frequencies (mm-radio range)

S (10 GHz)	S (15 GHz)	S (33 GHz)	S (45 GHz)	S (98GHz)	S (150 GHz)	S (200 GHz)	S (230 GHz)	S (344 GHz)	S (400 GHz)	S (680 GHz)
mJy	mJy	mJy	mJy	mJy	mJy	mJy	mJy	mJy	mJy	mJy

Data for assignments

Stellar catalogue

- `obs_starcat/obs_starcat.p` contains catalogue with (mostly empirical) parameters for 79 stars
- Can be loaded as a table in python. Some hints: `AST5770_manual.pdf`
-



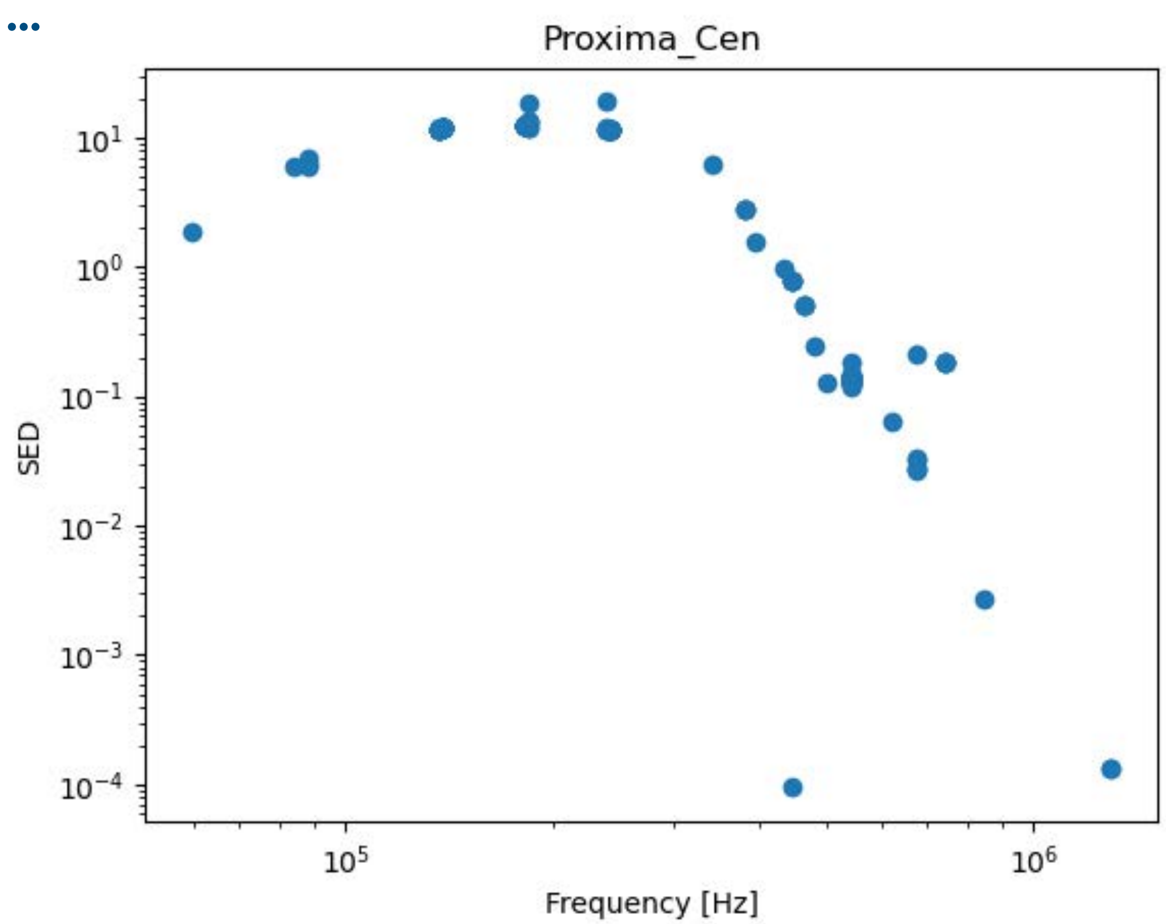
Data for assignments

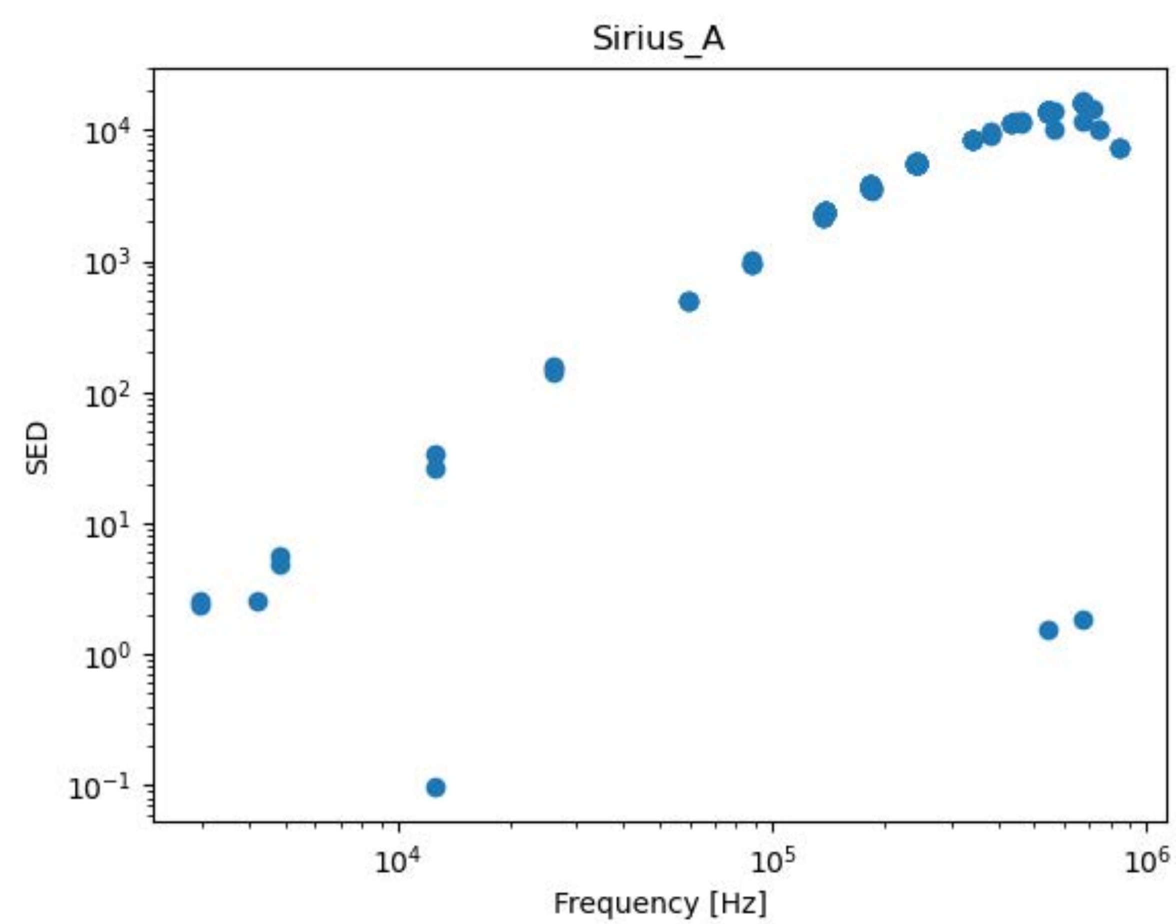
Stellar observations — Spectral Energy Distribution (SED)

- `obs_starcat/SED` contains files for all 79 stars with SEDs
- Can be loaded in python. Some hints: `AST5770_manual.pdf`

```
from astropy.io.votable import parse_single_table
sed = parse_single_table(datafile).to_table()
list(sed.columns)
freq=sed['sed_freq']
flux=sed[‘sed_flux']
error=sed[‘sed_eflux']
...
```

★ See also: `obs_starcat_SED_info.txt`

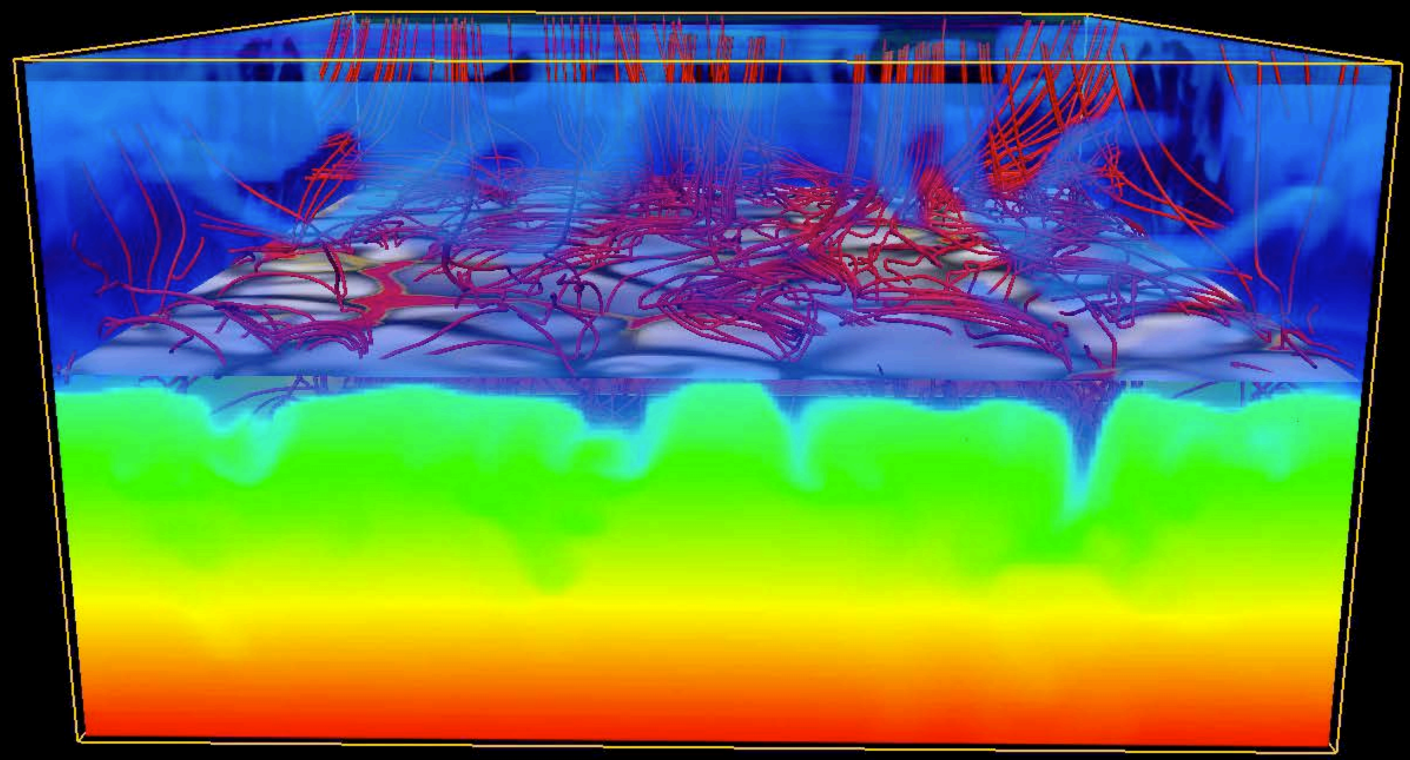




Numerical simulation

3D radiation magnetohydrodynamics

- Complicated spatial structure of the solar atmosphere requires modelling in 3D
- Small part of the atmosphere plus upper convection zone to drive dynamics self-consistently
- Computational grid, advanced time step by time step
- Solving equations of (magneto)hydrodynamics with "realistic" equation of state plus radiative transfer (simplified with pre-calculated opacity look-up tables)

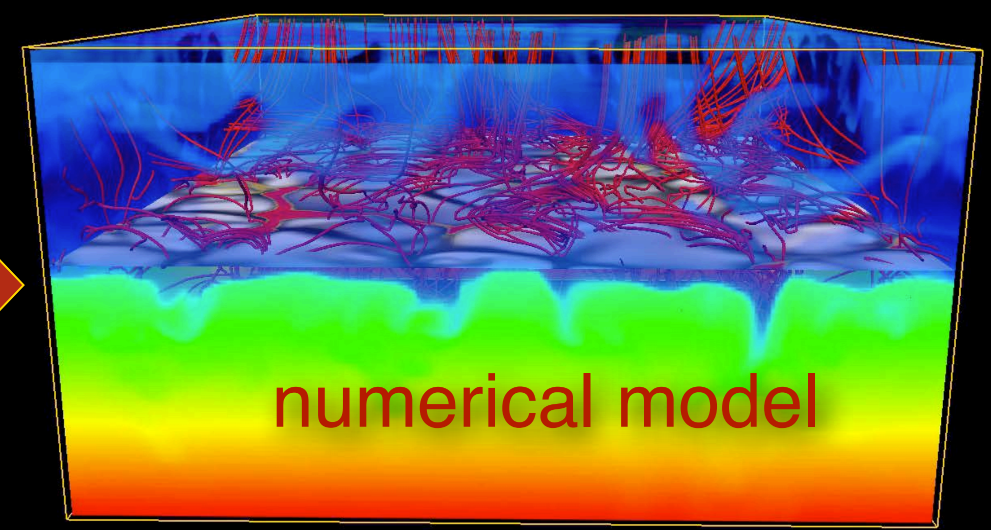


The solar atmosphere

Synthetic observations — radiative transfer

- Predictions by means of synthetic intensity maps calculated from 3D radiation magnetohydrodynamic simulations

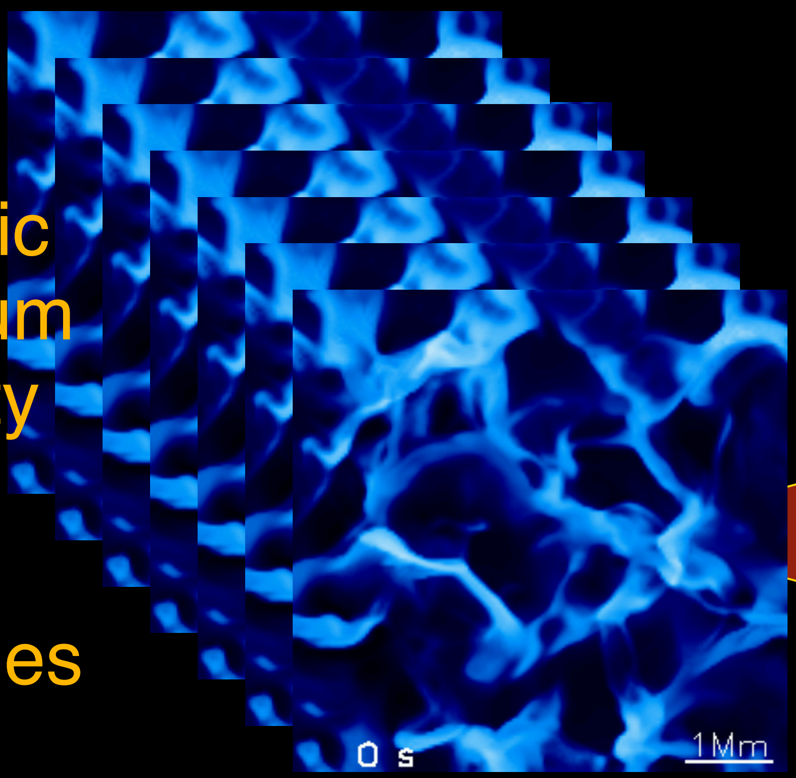
3D radiation magneto-hydrodynamic code



intensity synthesis code

3D radiative transfer calculations

synthetic continuum intensity maps
+
time series



Numerical simulations

Overview

- Different 3D simulation data for different spectral types are available
- names starting with simsts, only one snapshot per model is available.
- For most spectral types: two models for same spectral type but with different initial magnetic field strength B_0
- See `AST5770_manual.pdf`

ID	Spectral type	T_{eff} [K].	$\log g$	$\lvert B_0 \rvert$ [G]	Description	Ref.
MHD simulations for different stellar types, single snapshots only						
simsts_F5V	F5V	6500	4.5	0, 50		S18
simsts_G2V	G2V	5770	4.44	0, 50	Sun	S18
simsts_K2V	K2V	5000	4.5	0, 50		S18
simsts_K8V	K8V	4000	4.5	0, 50		S18
simsts_M3V	M3V	3240	4.5	100	Red dwarf star, similar to AD Leo	W13a
simsts_K5III	K5III	4010	1.5	0	Red giant star, equivalent to Aldebaran (α Tau); Data: 1 time step,	W17
MHD simulations for the Sun, short time series						
simsut G2V	G2V	5770	4.44	50	Sun, time series ($\Delta t = 10\,\mathrm{s}$)	W13b

Numerical simulations

Overview

- HDF5 files

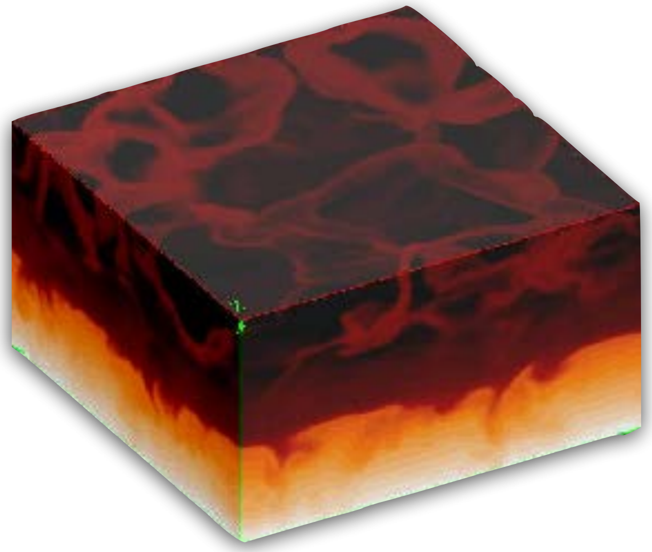


Table A.4: Quantities contained in the simulation data files.

Entry	Description	Unit	Dimension
X	x axis	cm	1D
Y	y axis	cm	1D
Z	z axis	cm	1D
DZ	z extent of grid layer	cm	1D
TIME	time	s	1D or scalar
RHO	Mass density	g/cm^3	3D
TGAS	Gas temperature	K	3D
PGAS	Gas pressure	dyn/cm^2	3D
KAPPA	Absorption coefficient		3D
VX	Velocity x-component	cm/s	3D
VY	Velocity y-component	cm/s	3D
VZ	Velocity z-component	cm/s	3D
The following entries are only available for MHD models.			
BX	Magnetic field x-component	G	3D
BY	Magnetic field y-component	G	3D
BZ	Magnetic field z-component	G	3D
In addition, all files contain the following useful information.			
DESCRIPTION	Description of the data entries		
UNIT	Physical units of the data entries		

Numerical simulations

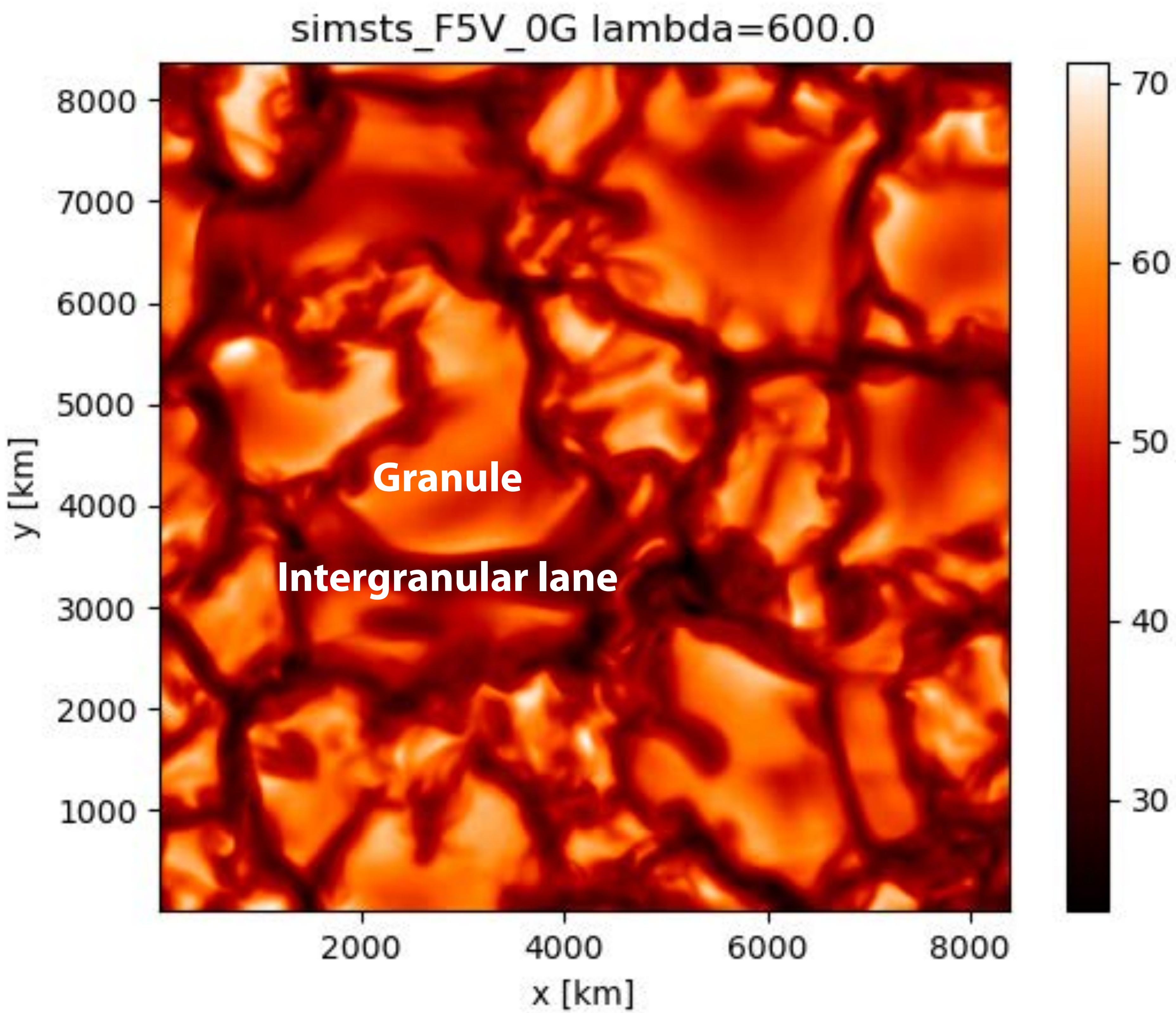
Overview

- Synthetic observables in each folder:

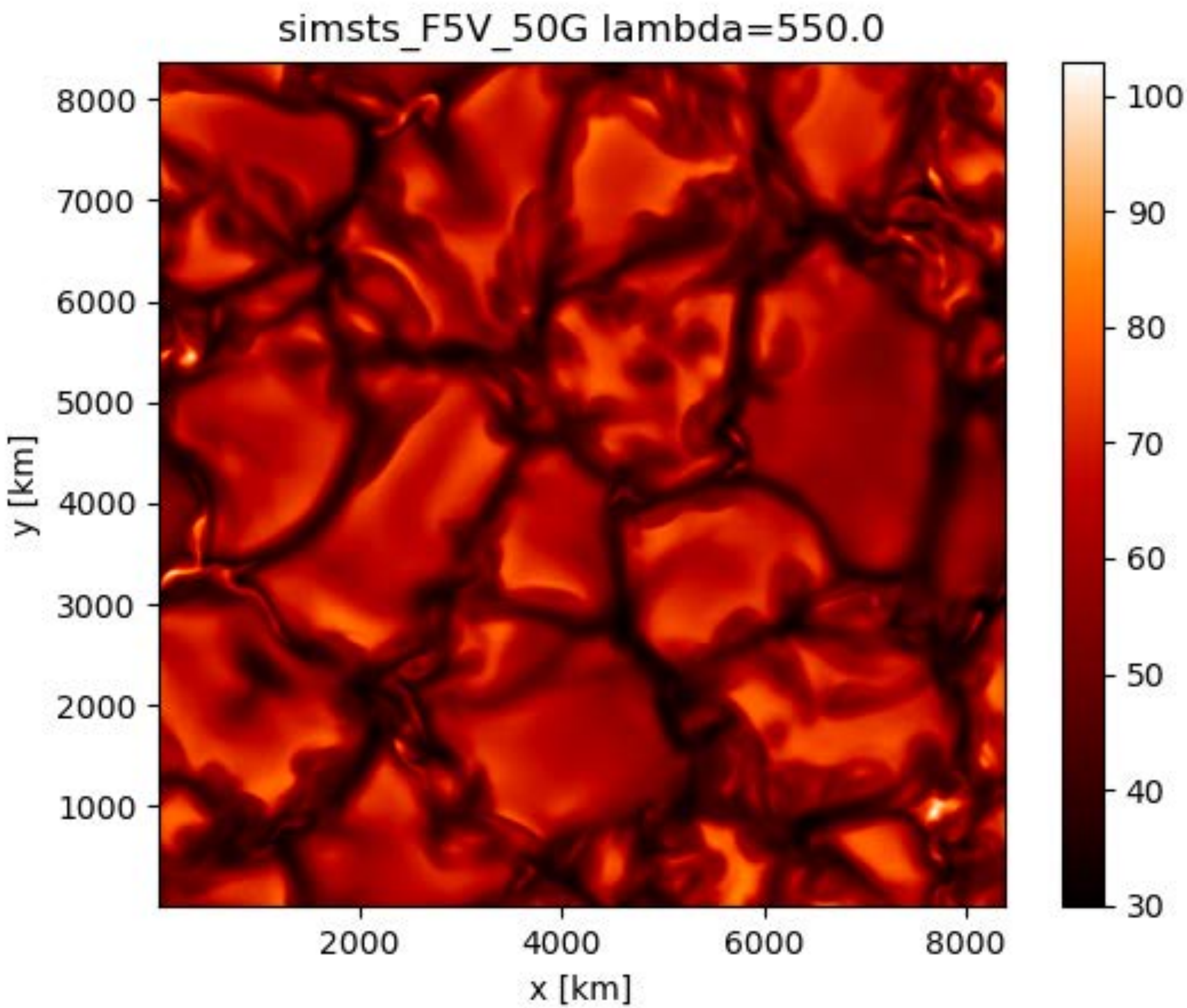
  - **`*_continuumintensity.h5`**: continuum intensity for wavelengths 300 nm — 5.0 μ m
    - theoretical continuum: under assumption of local thermodynamic equilibrium, no spectral lines.
    - ➡ Differences with respect to real observations should be expected
    - intensity data provided as function horizontal coordinates (x and y, identical to those in the files described above) and wavelength λ .
    - See the description and unit tags.

  - **`*_lineintensity_FeI6173.h5`**: intensity for the Fe I 6173 line (neutral iron, 617.3 nm)
    - difference with respect to the continuum intensity files: spectral line files contain intensity as function of wavelength across a narrow region around the nominal central wavelength λ_0 of the line.
    - In addition, the theoretical continuum at λ_0 (calculated as if there was no line)

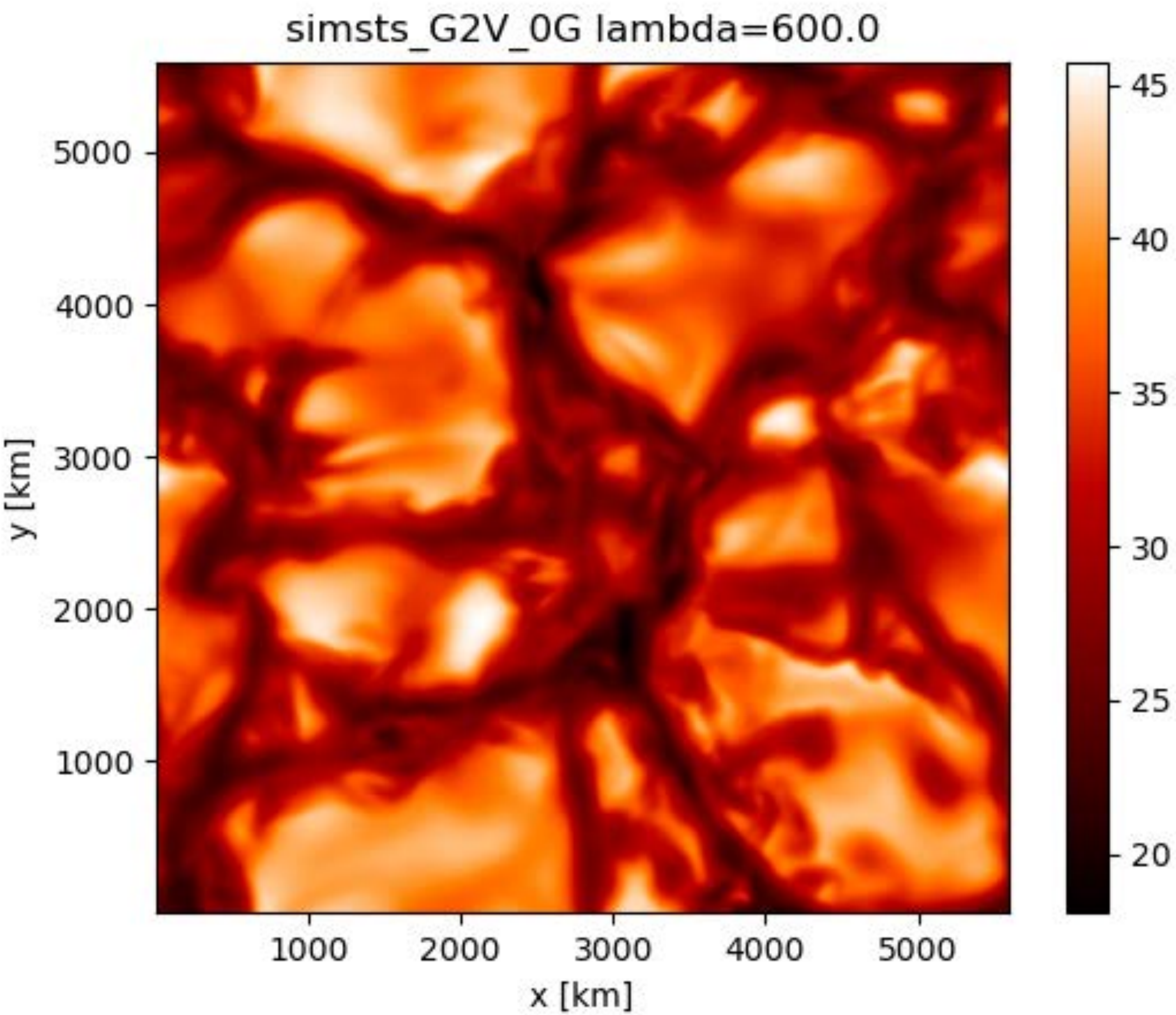
Numerical simulations



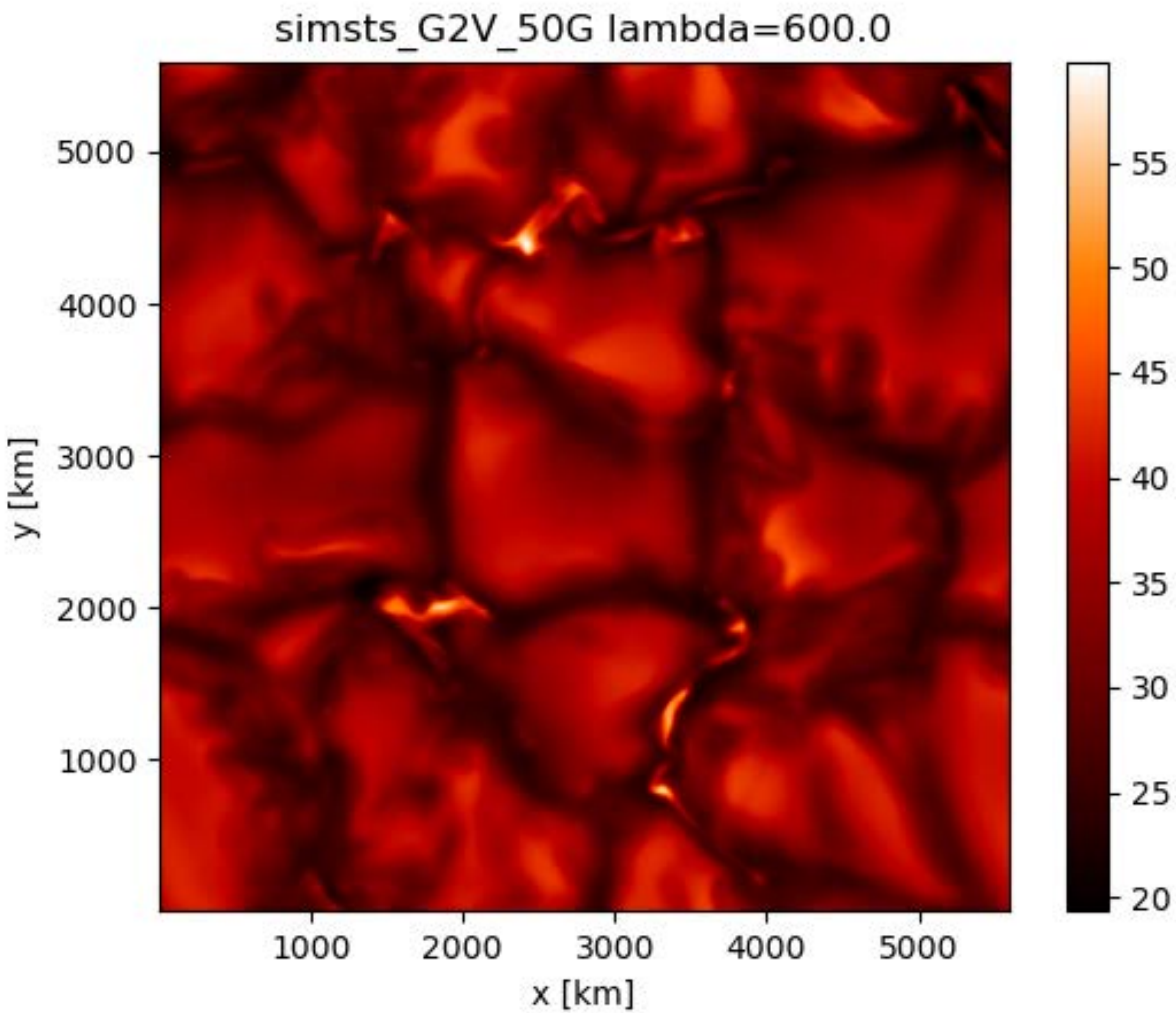
Numerical simulations



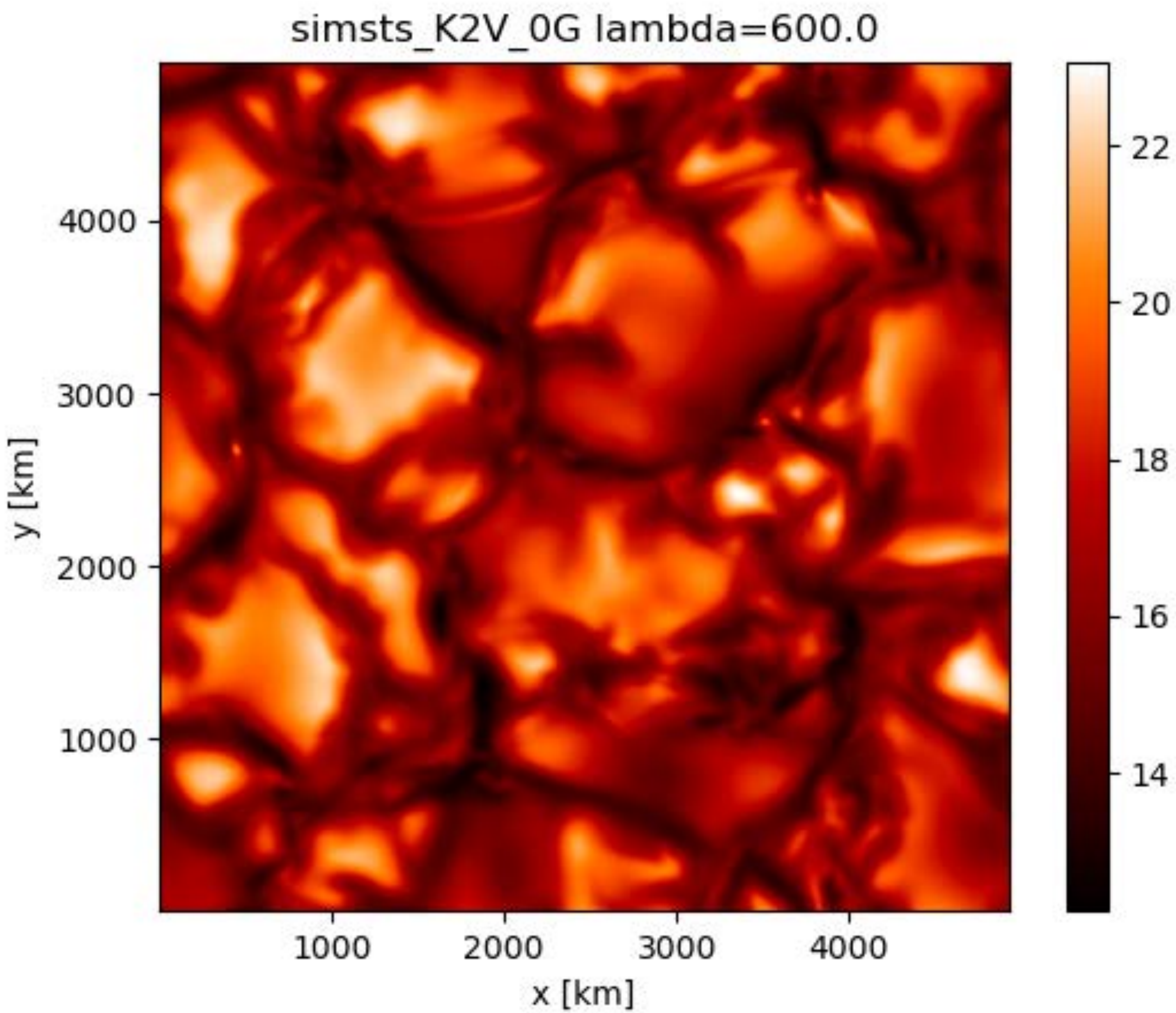
Numerical simulations



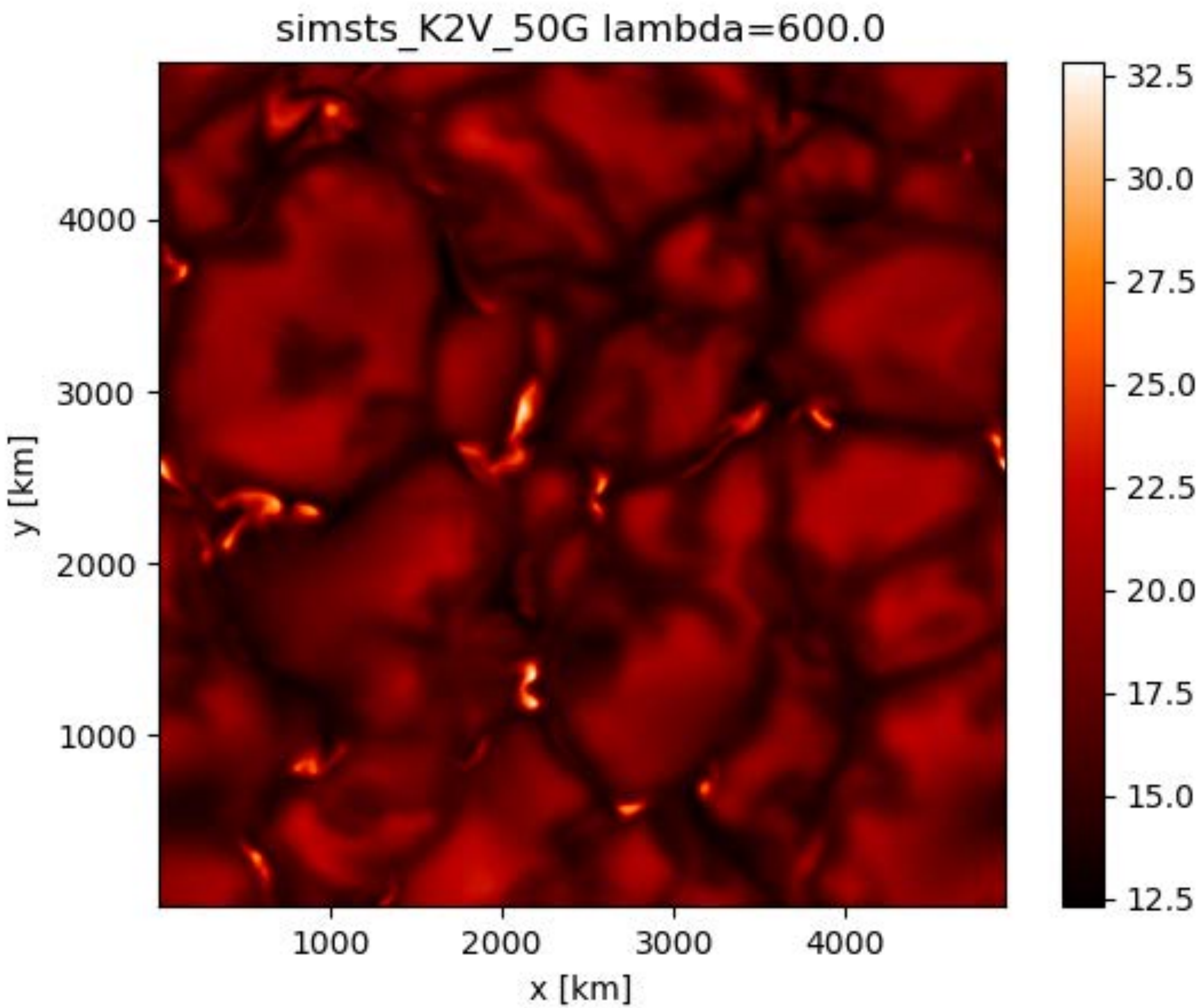
Numerical simulations



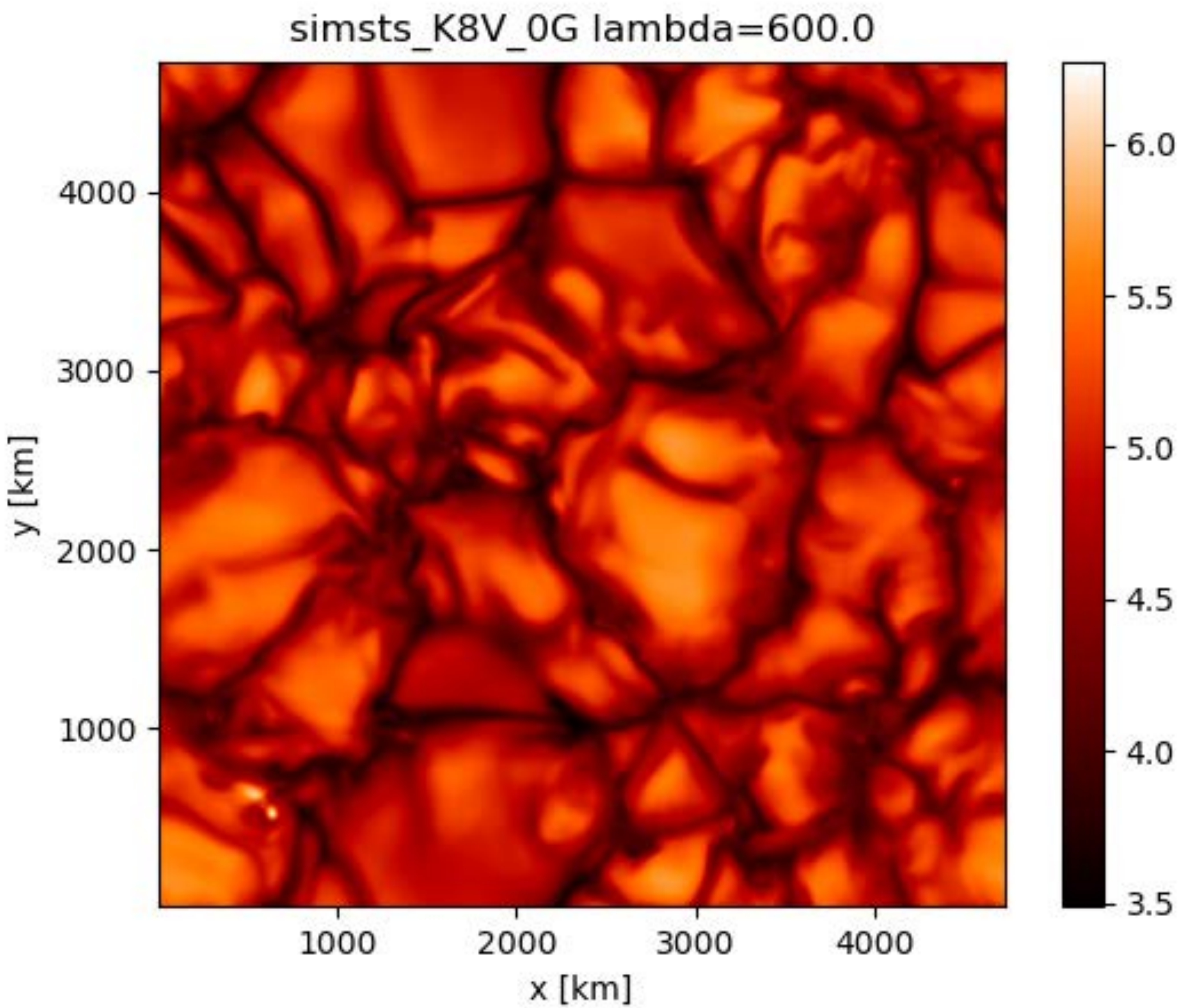
Numerical simulations



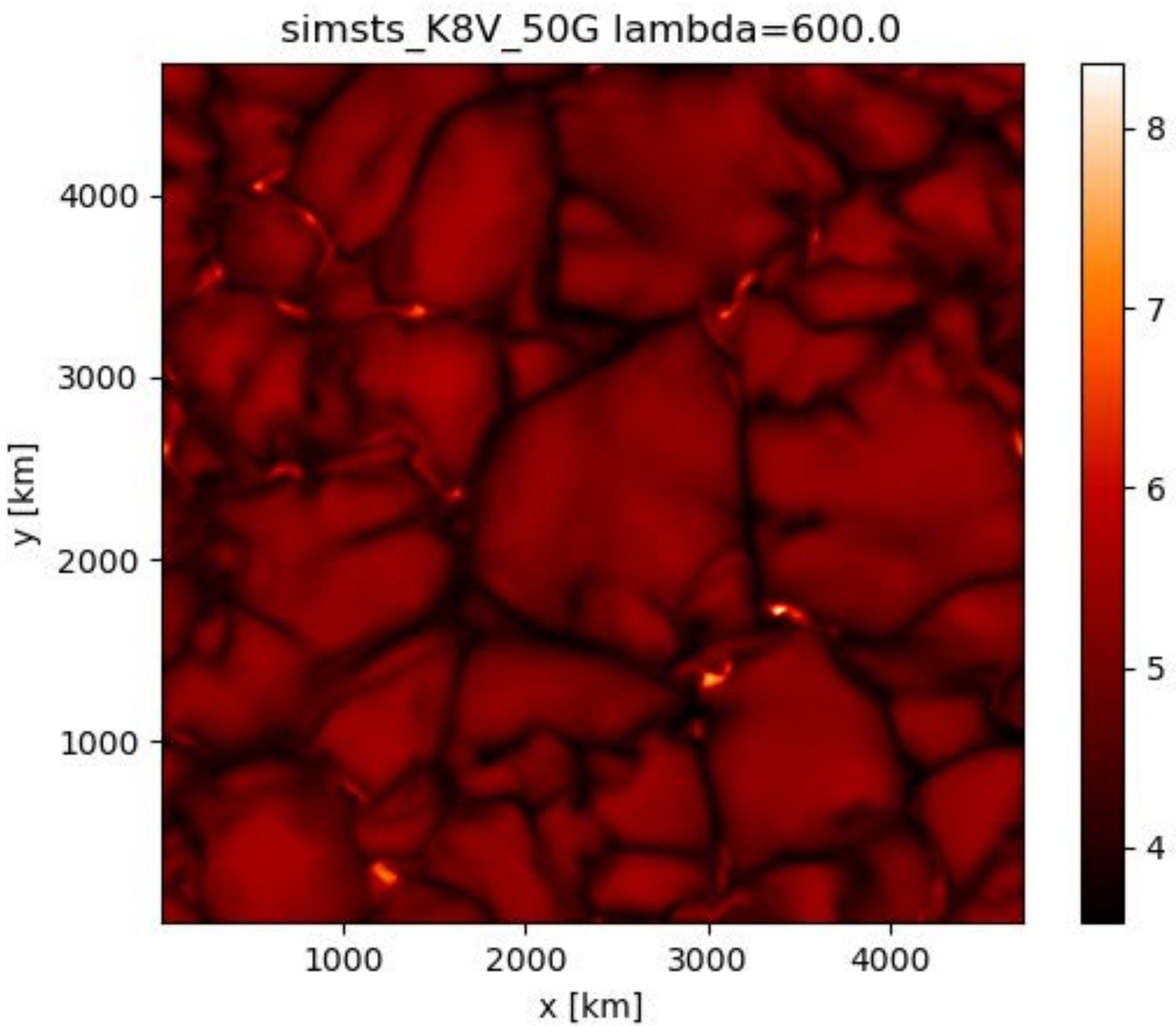
Numerical simulations



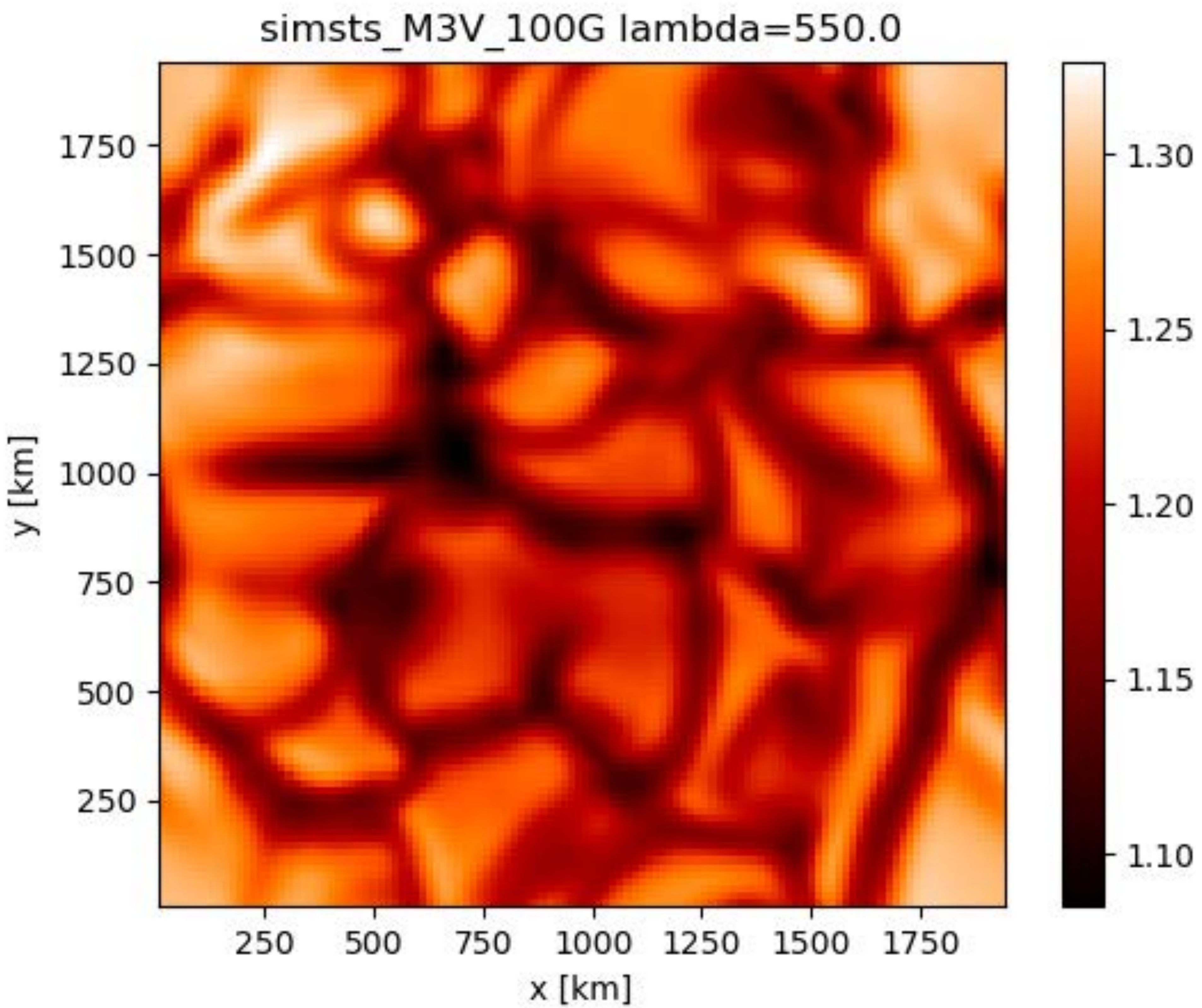
Numerical simulations



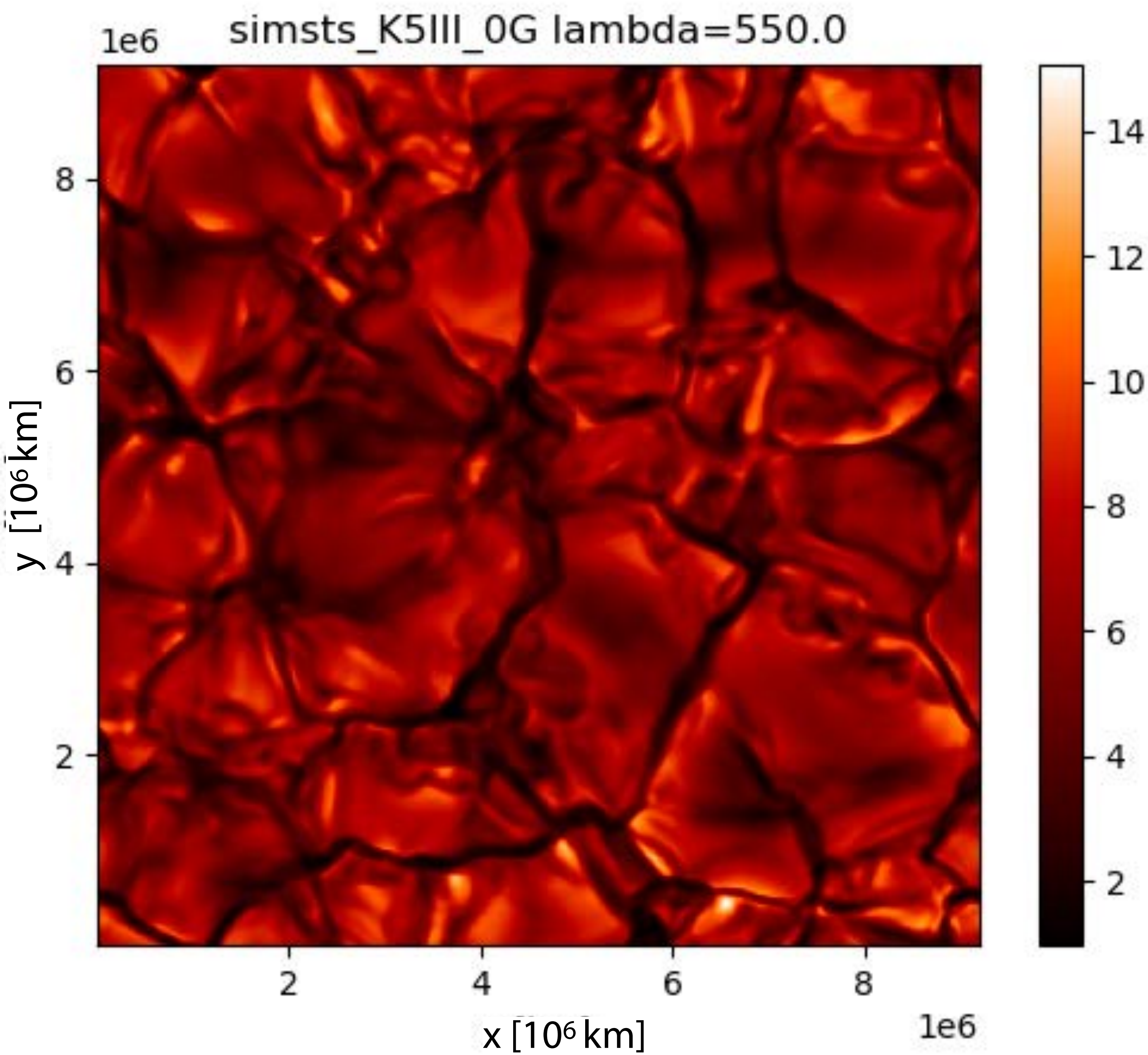
Numerical simulations



Numerical simulations

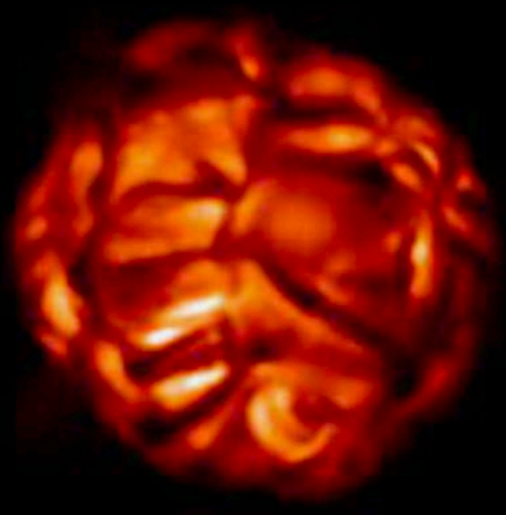


Numerical simulations

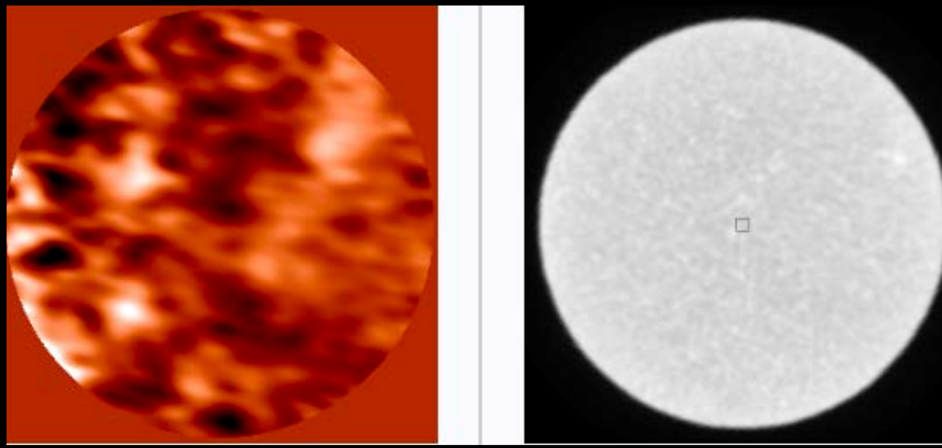


Data for assignments

More …



- **Currently more data in preparation**
  - Global 3D model of a giant star
  - ALMA observations of the Sun (SALSA - http://sdc.uio.no/salsa/)



- **Own ideas for projects? Need other data?**

  ➡ Talk to us!

- When using computers at ITA:
  - Do not store large data sets in your home directory, use data directories
  - Do not compute on the login servers (login, tsih2), use other machines such as beehive