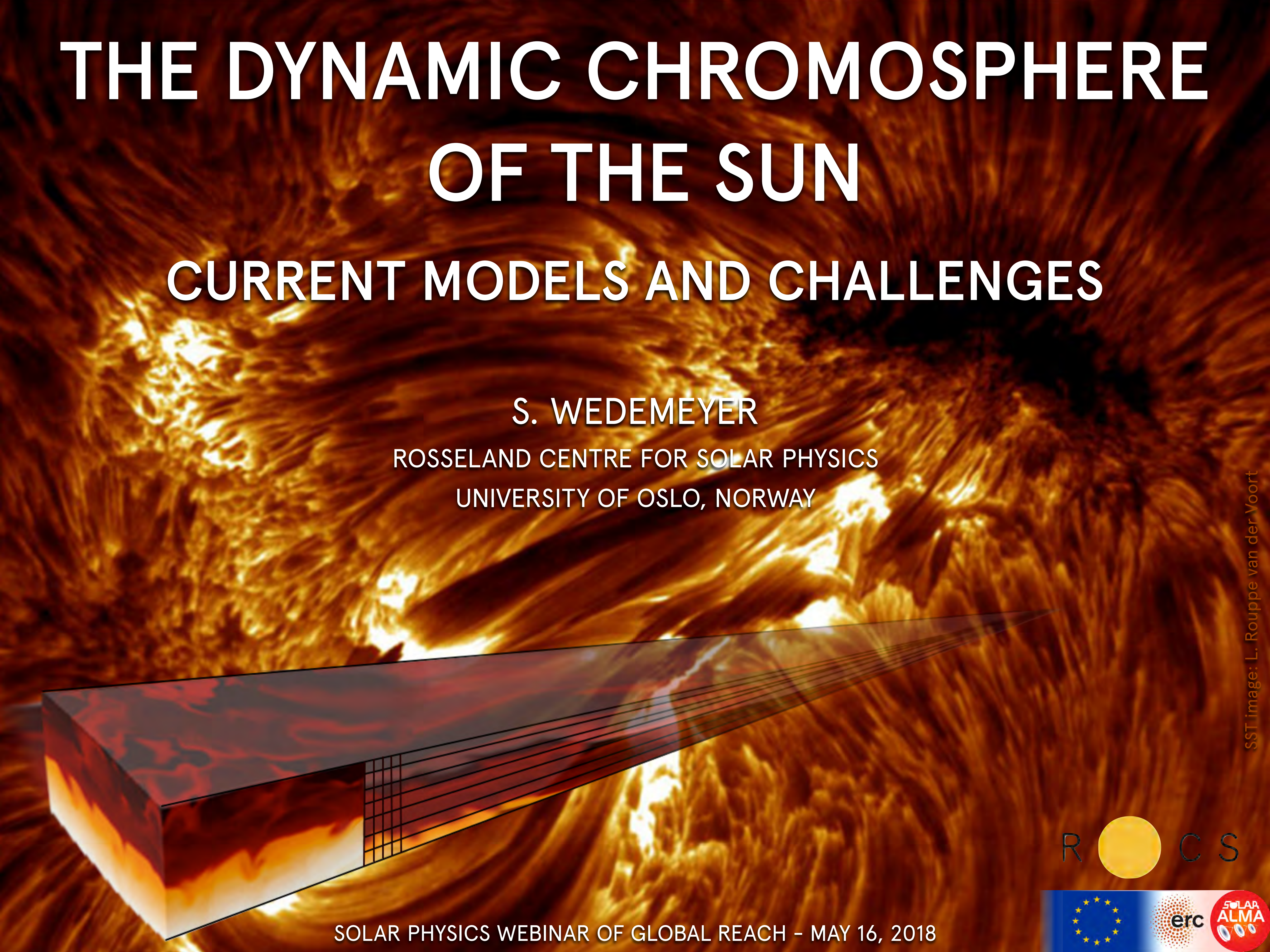

THE DYNAMIC CHROMOSPHERE OF THE SUN

CURRENT MODELS AND CHALLENGES

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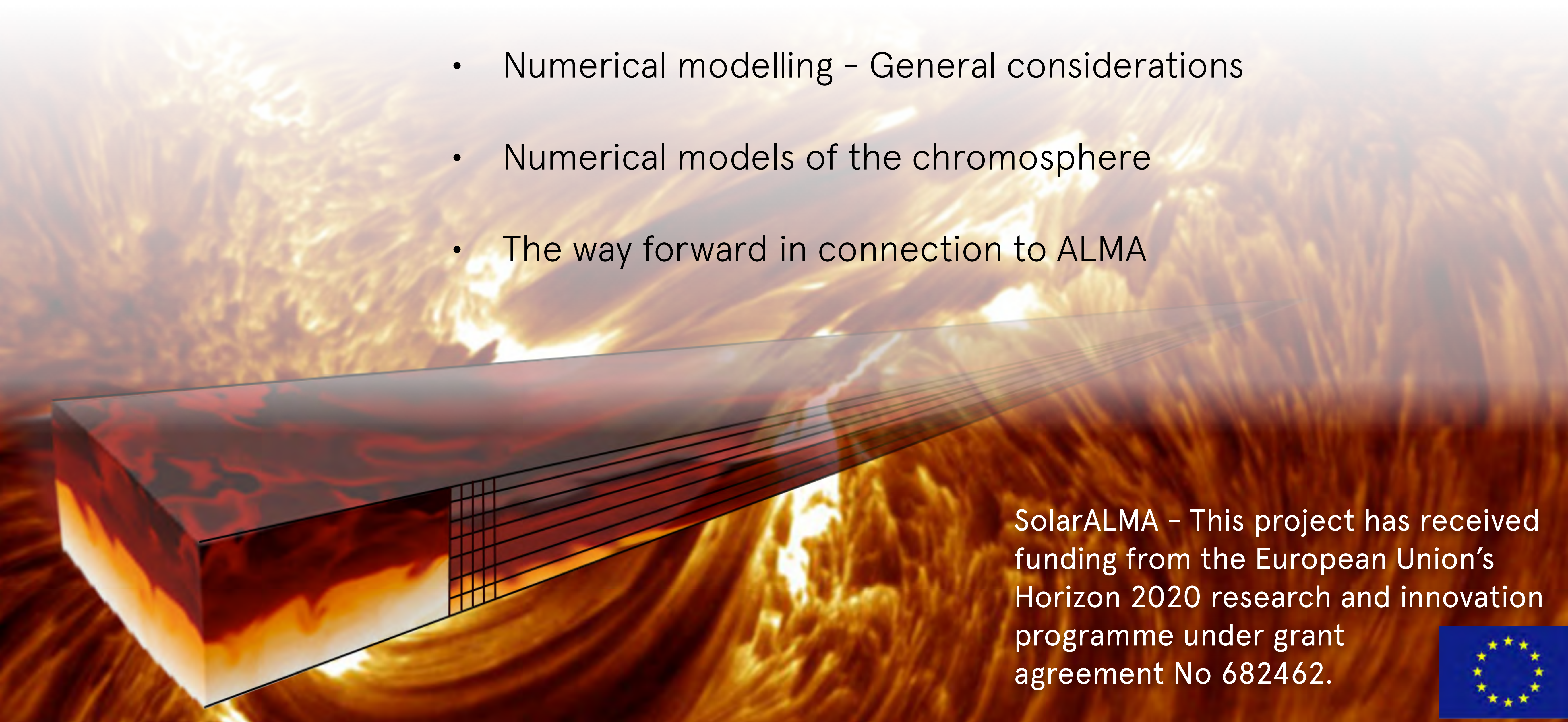
SOLAR PHYSICS WEBINAR OF GLOBAL REACH - MAY 16, 2018

SST image: L. Rouppe van der Voort

OVERVIEW

- Introduction
  - What is the chromosphere?
  - What do we observe?
  - What are the challenges?
- Numerical modelling – General considerations
- Numerical models of the chromosphere
- The way forward in connection to ALMA



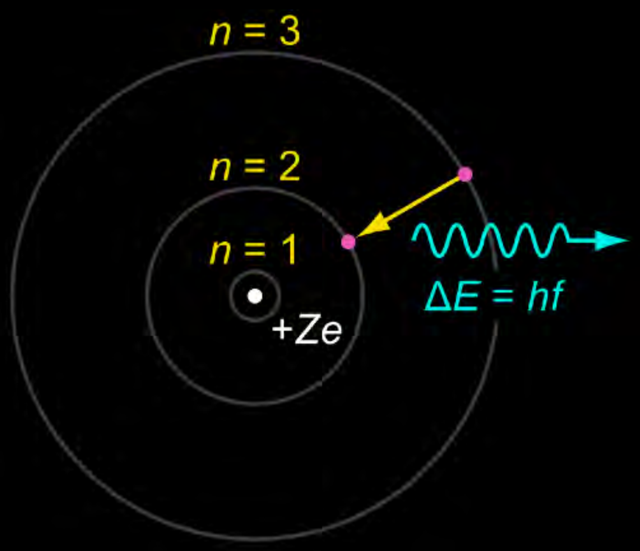
SolarALMA – This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 682462.

INTRODUCTION - WHAT IS THE CHROMOSPHERE?

- Literal definition from Greek "χρωμα" *(color)* and "σφαιρα" *(ball)*: Coloured thin rim seen at solar eclipse.

  - Mainly Balmer Hα line emission.

  ➡ Chromosphere = Layer where Hα emission originates



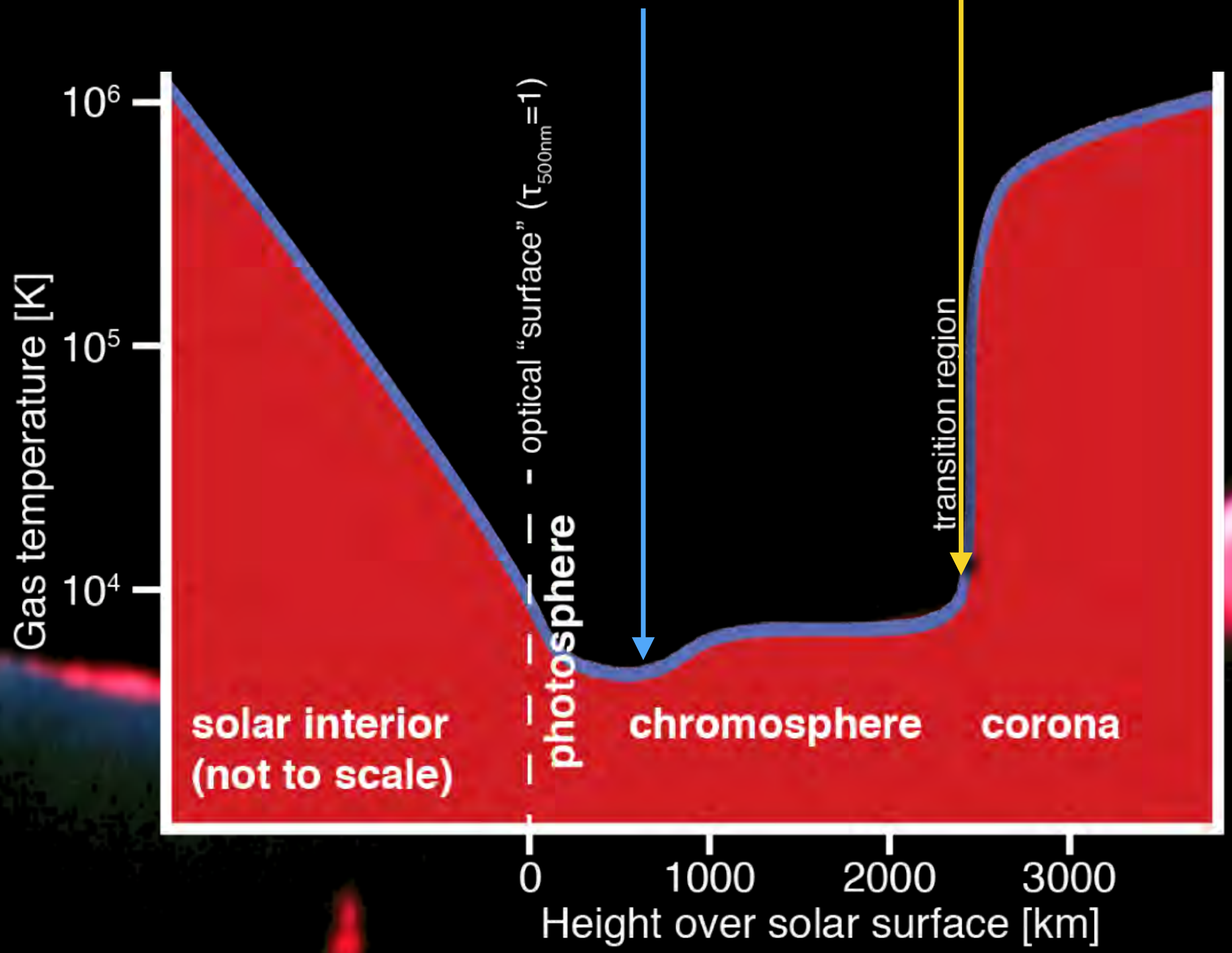
INTRODUCTION - WHAT IS THE CHROMOSPHERE?

- Definition based on average temperature stratification:

Atmospheric layer

above the photosphere and the temperature minimum

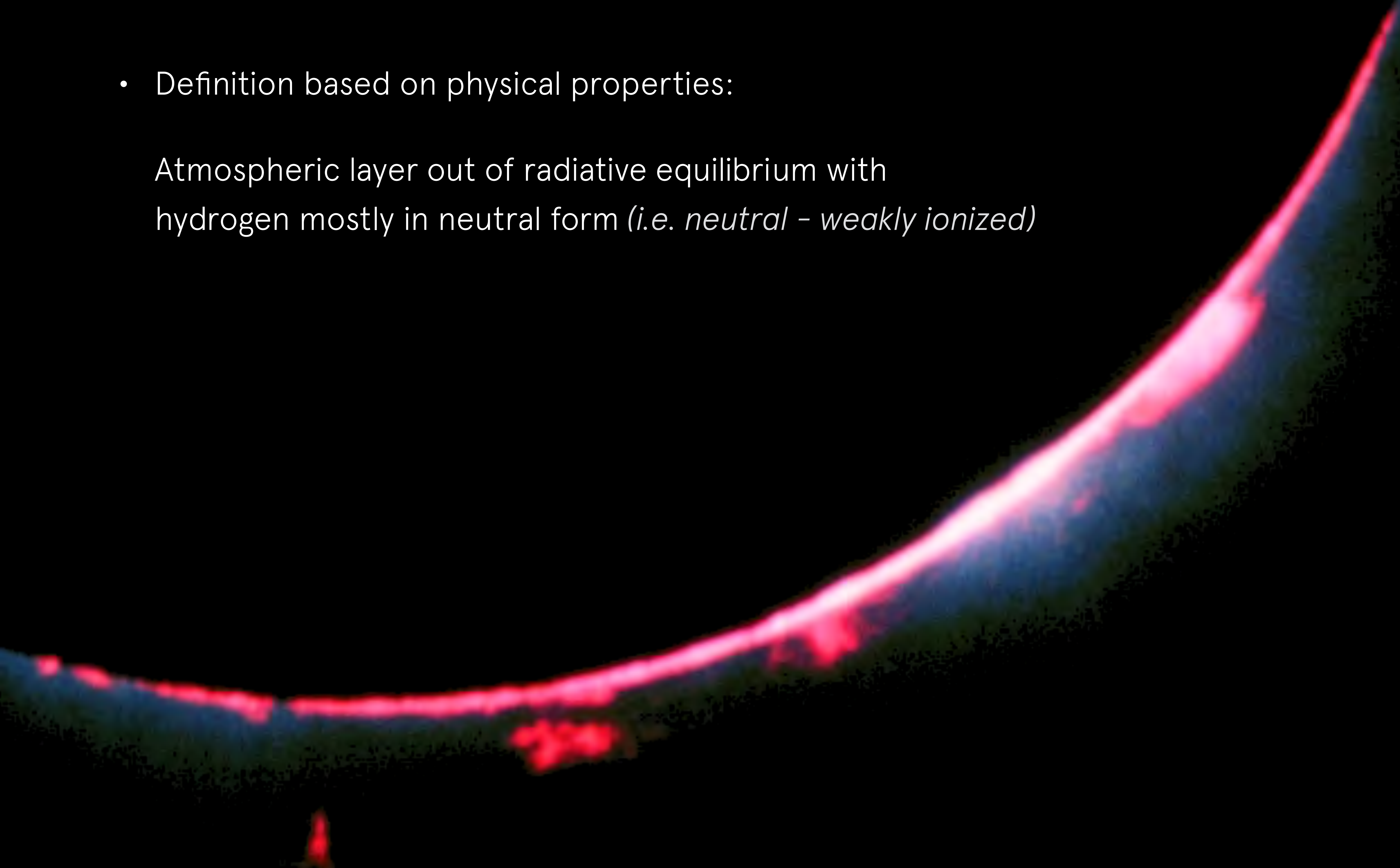
below the transition region with its sharp temperature rise to coronal values



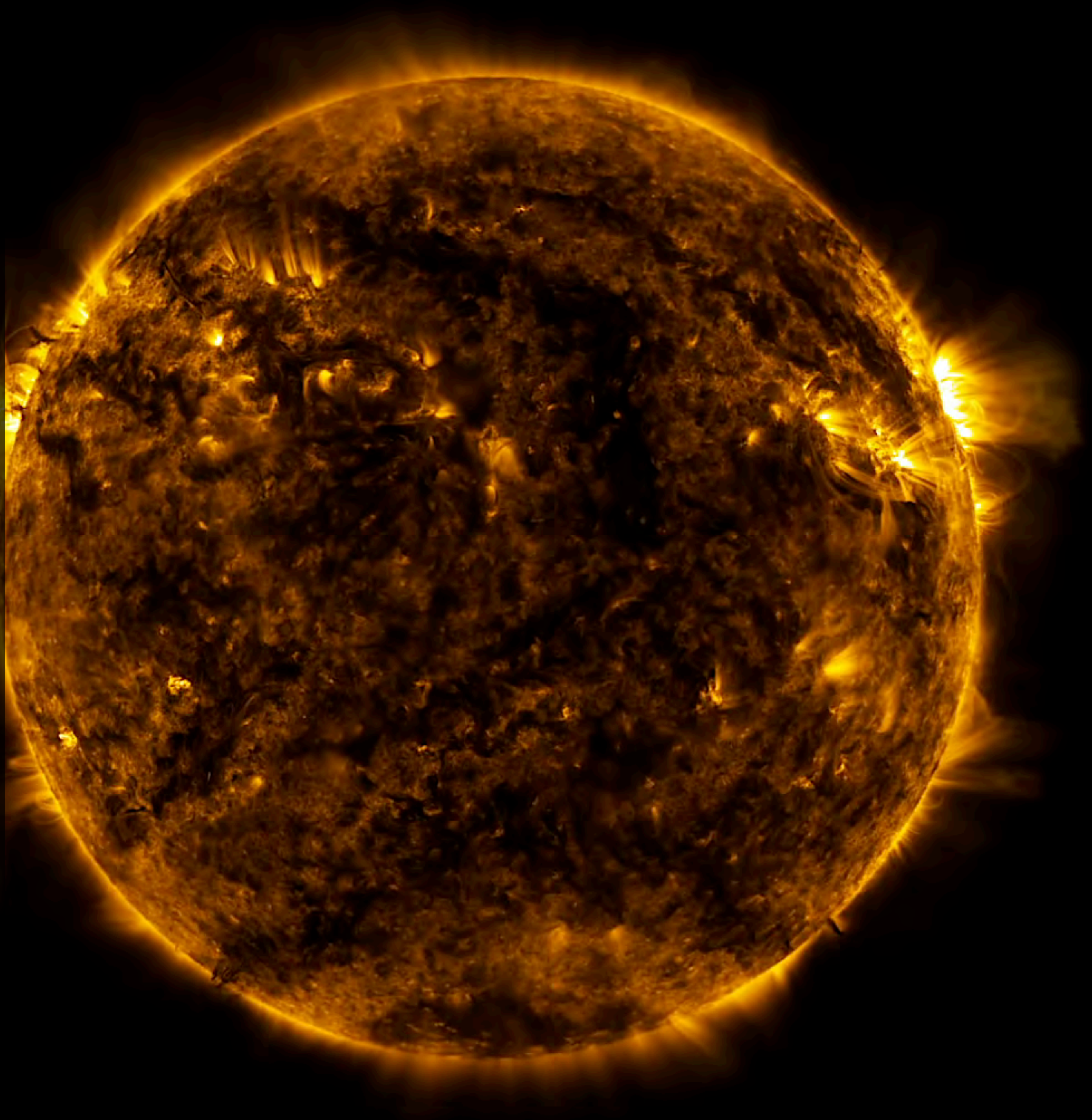
INTRODUCTION - WHAT IS THE CHROMOSPHERE?

- Definition based on physical properties:

  Atmospheric layer out of radiative equilibrium with hydrogen mostly in neutral form *(i.e. neutral - weakly ionized)*



- 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"

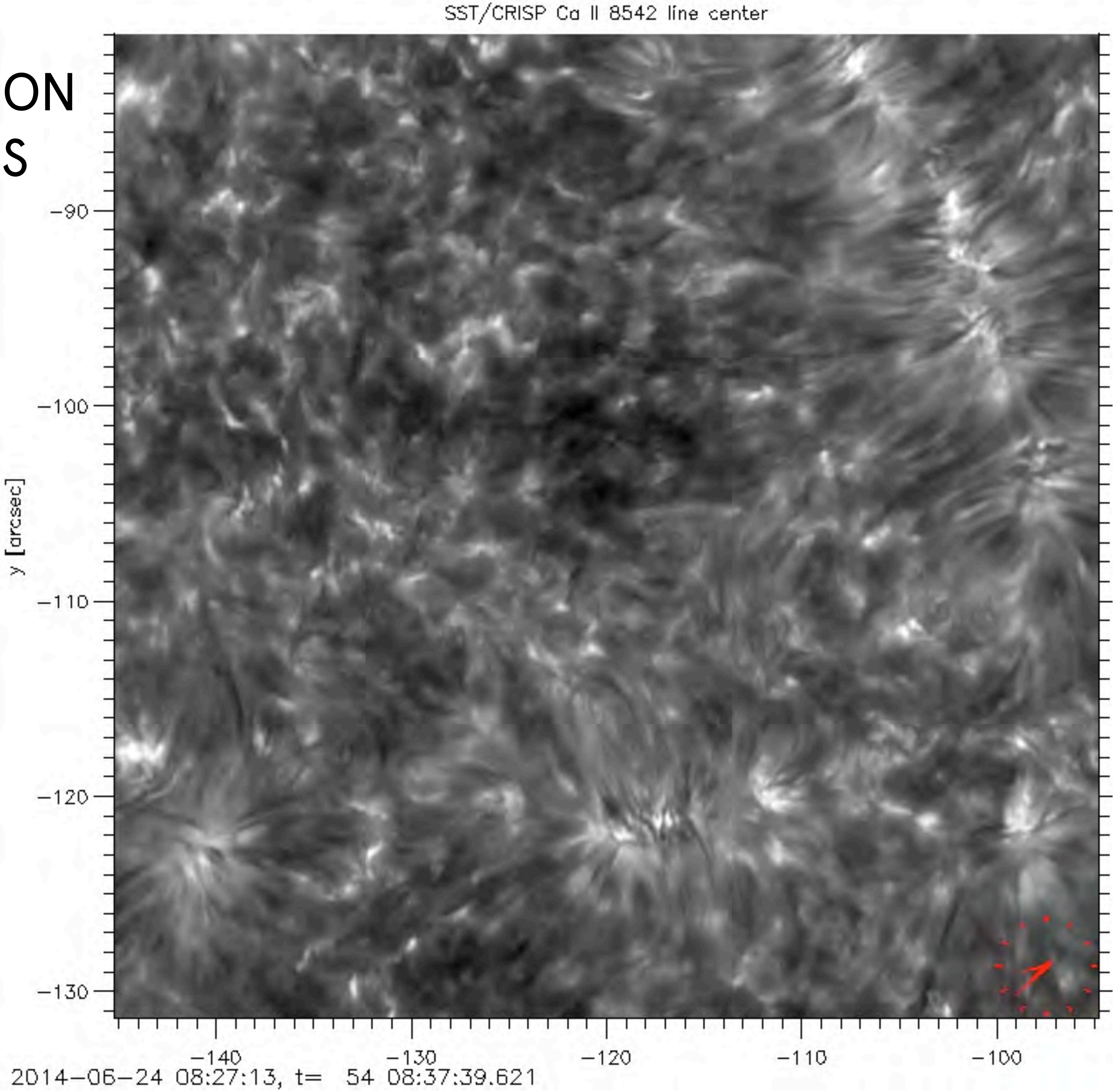


Solar Dynamics Observatory SDO/NASA

RECENT HIGH-RESOLUTION OBSERVATIONS

Ca II
854.2 nm
Line center

Highly dynamic.
Complicated
structure

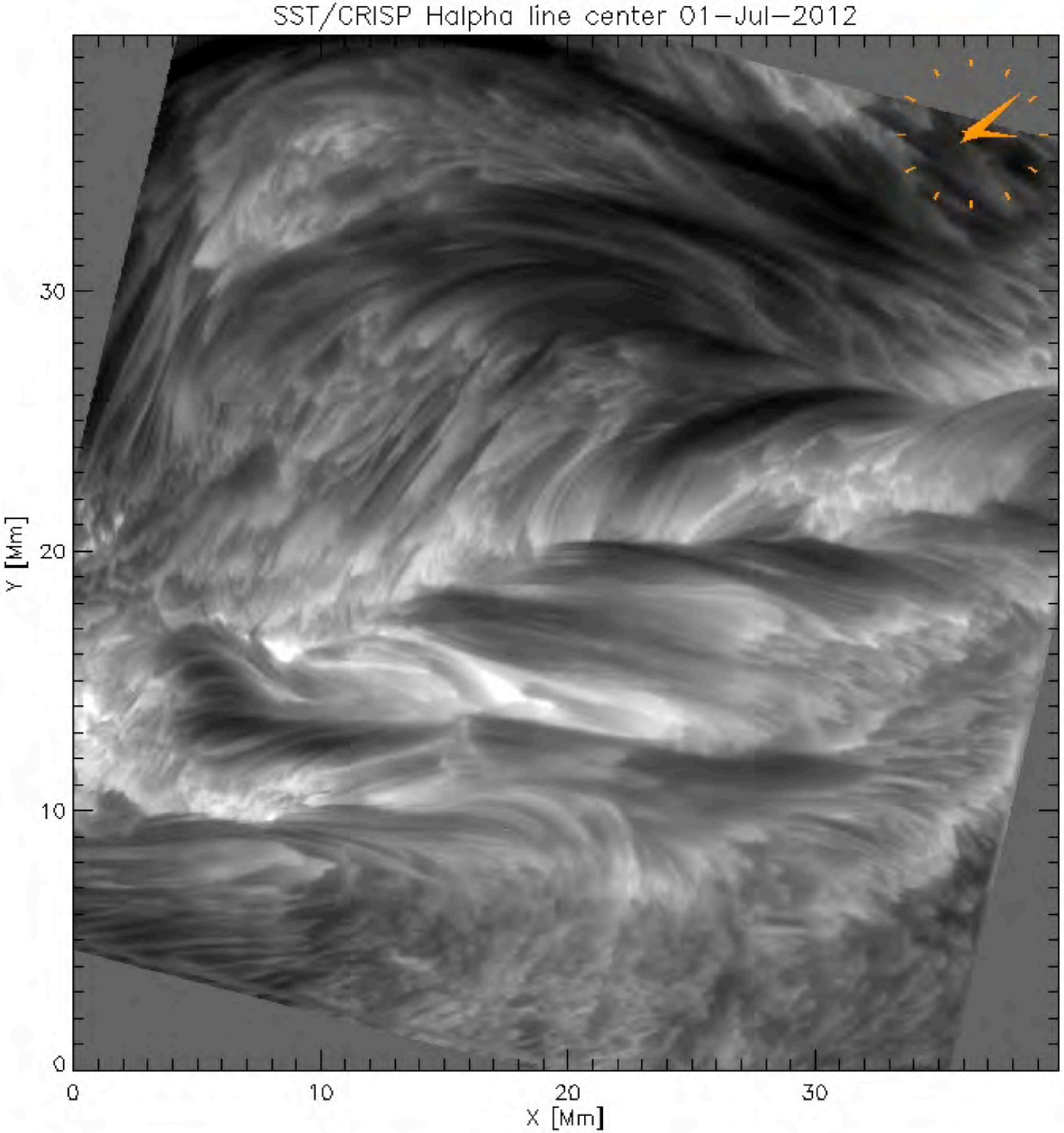


Courtesy: L. Rouppe van der Voort

RECENT HIGH-RESOLUTION OBSERVATIONS

Hα
656.3 nm
Line center

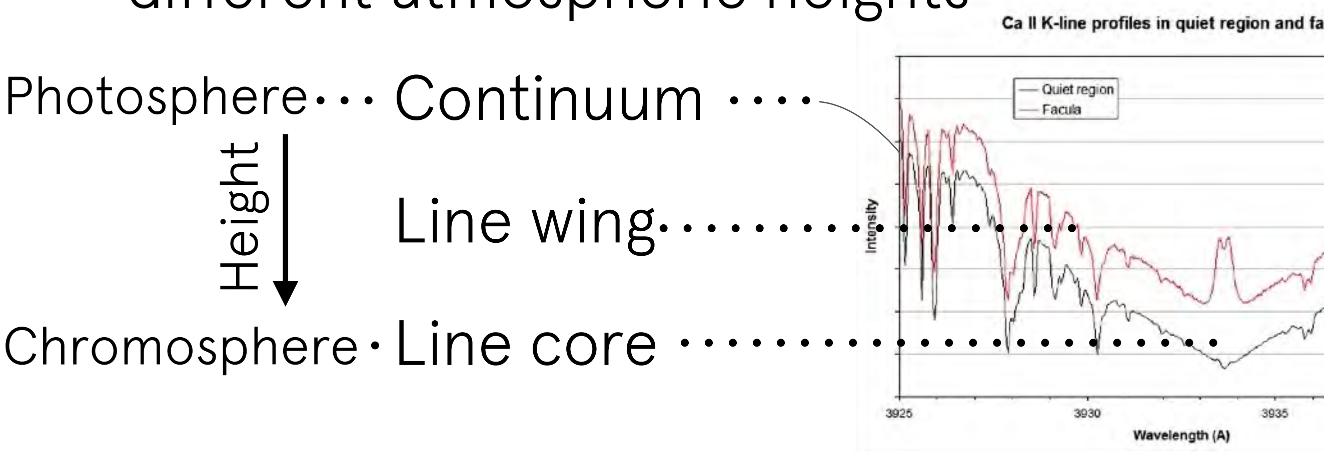
Highly dynamic. Complicated structure. Magnetic fields are clearly important.



Courtesy: L. Rouppe van der Voort

RECENT HIGH-RES. OBSERVATIONS

- Different parts of spectral formed at different atmospheric heights



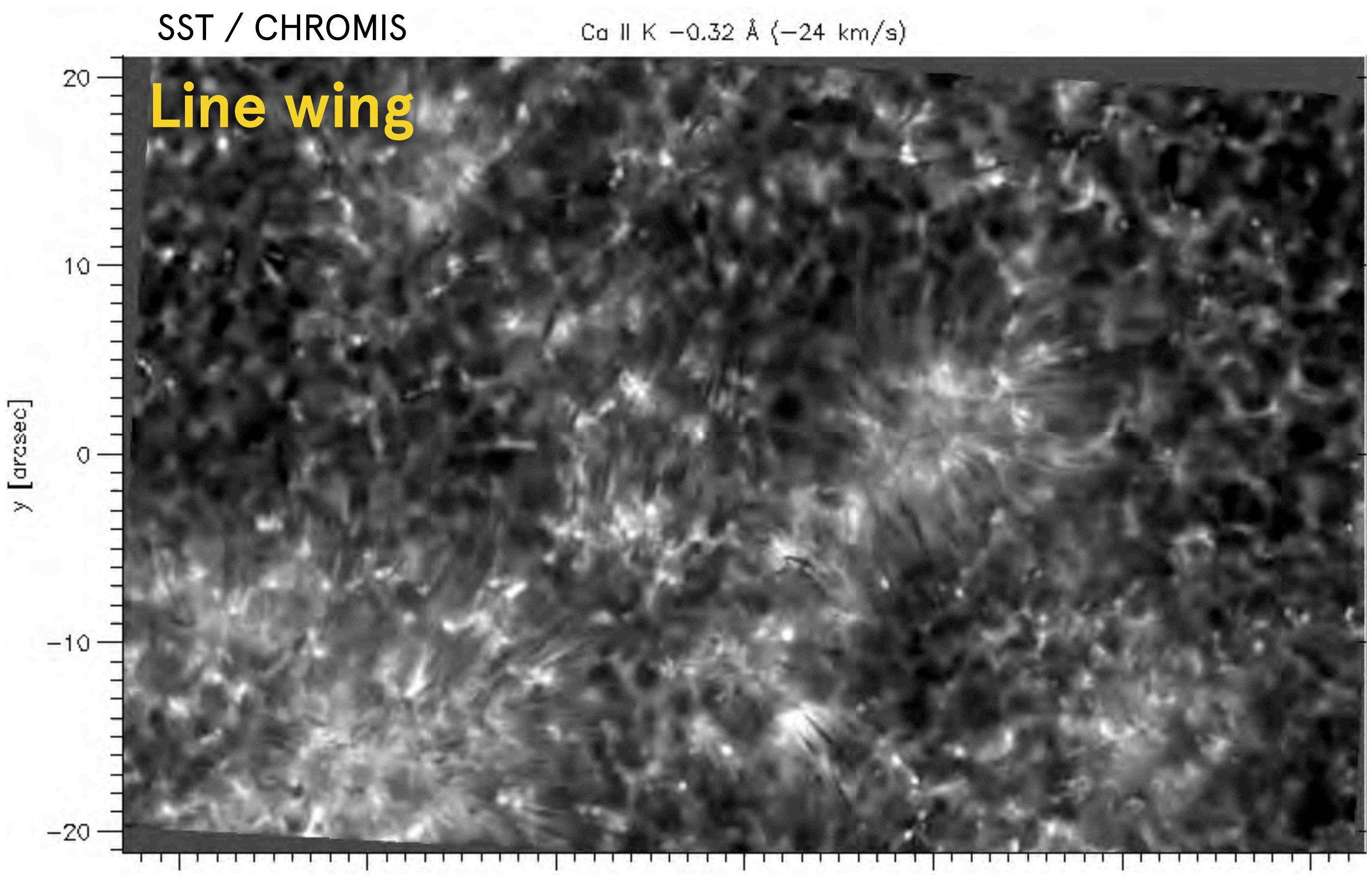
Photosphere··· Continuum ····

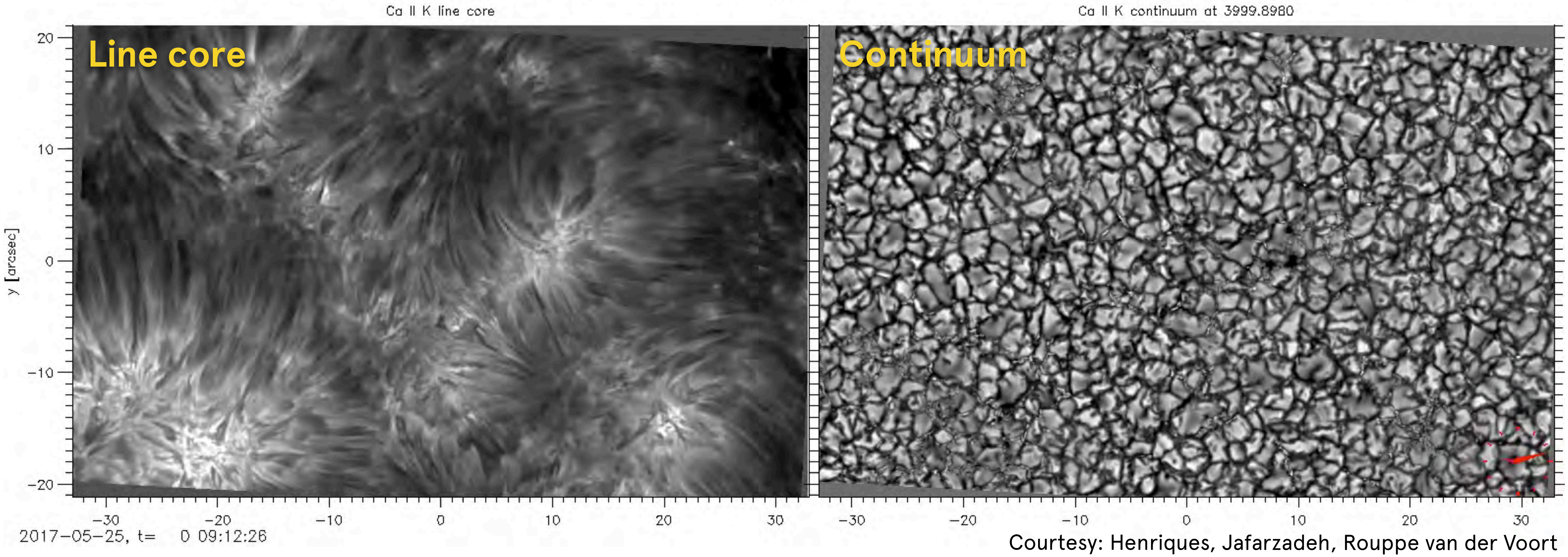
Height

Line wing·········

Chromosphere · Line core ···········

Ca II K 393 nm





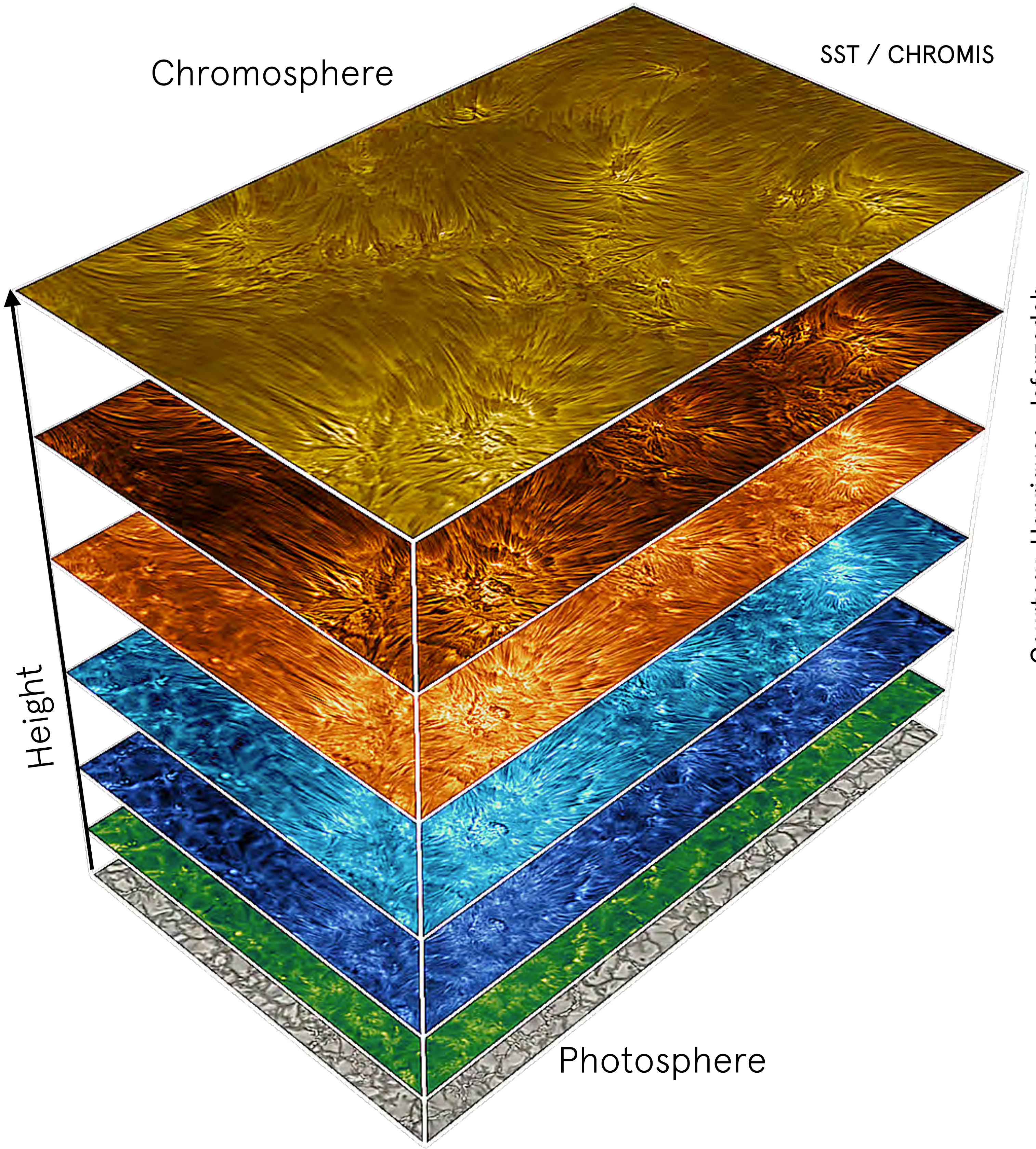
Courtesy: Henriques, Jafarzadeh, Rouppe van der Voort

RECENT HIGH-RESOLUTION OBSERVATIONS

- Combining information from different spectral indicators

➡ Qualitative change with height in the chromosphere

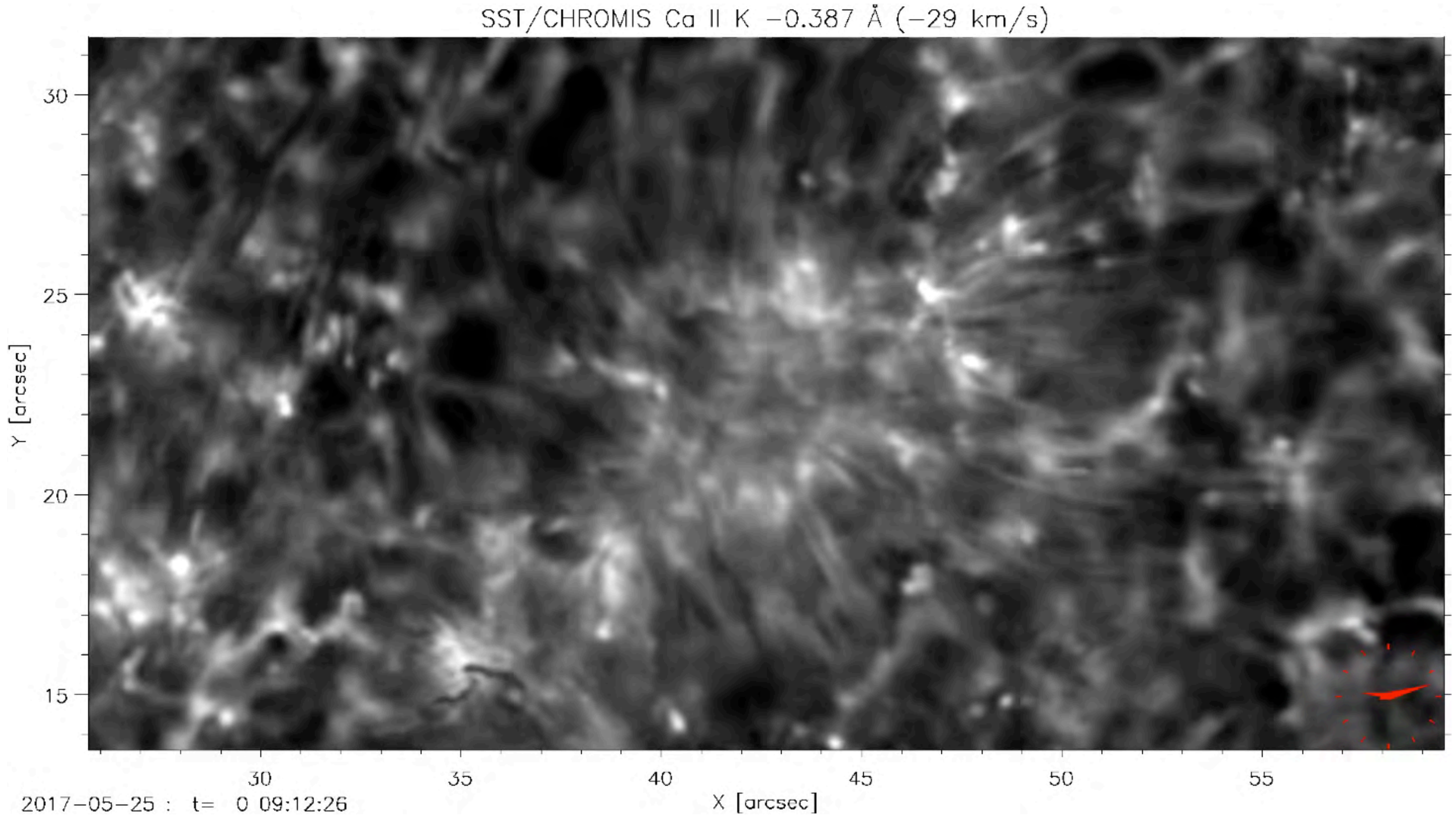
NOT a stack of flat layers!



Courtesy: Henriques, Jafarzadeh

RECENT HIGH-RESOLUTION OBSERVATIONS

- Partially opaque / transparent
- Different parts of the atmosphere coupled by radiation (non-local!)
- Extended formation height ranges of spectral features
- Challenging to interpret from a "integrated" observable!



Courtesy: Henriques, Jafarzadeh, Rouppe van der Voort

“THE DIAGNOSTIC PROBLEM”

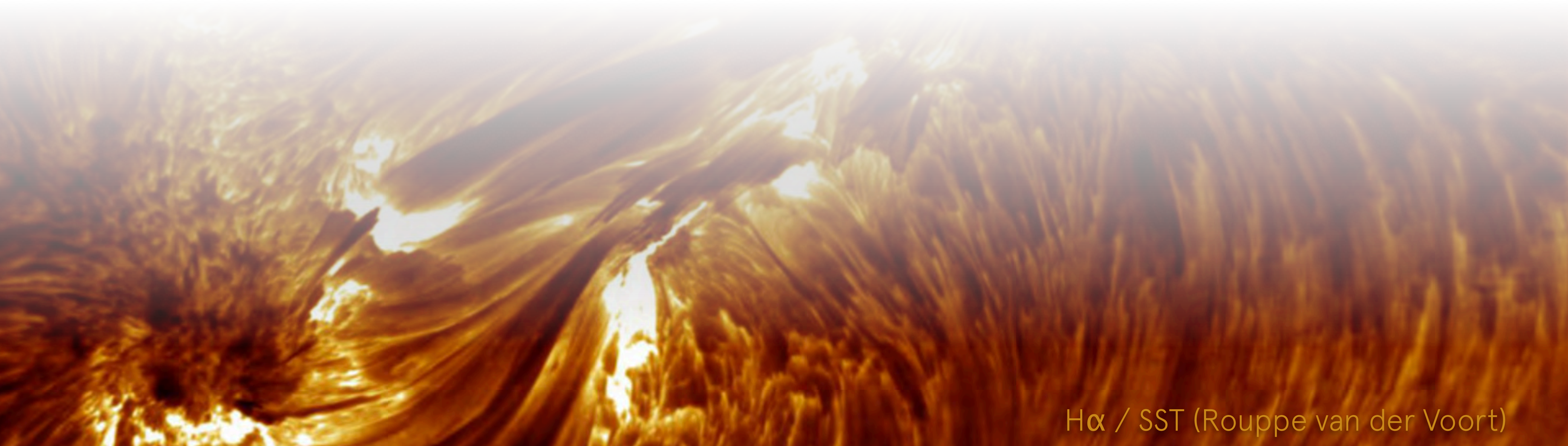
- Existing diagnostics for the chromosphere in the UV/visible/IR:
  - Few suitable diagnostics accessible
  - Complicated formation mechanisms and non-equilibrium effects (e.g., ionisation, non-LTE (non-local thermodynamic equilibrium))

➡ Non-linear relation between observables and plasma properties

➡ Uncertainties for the derived chromospheric plasma properties!

➡ **Interpretation difficult.**

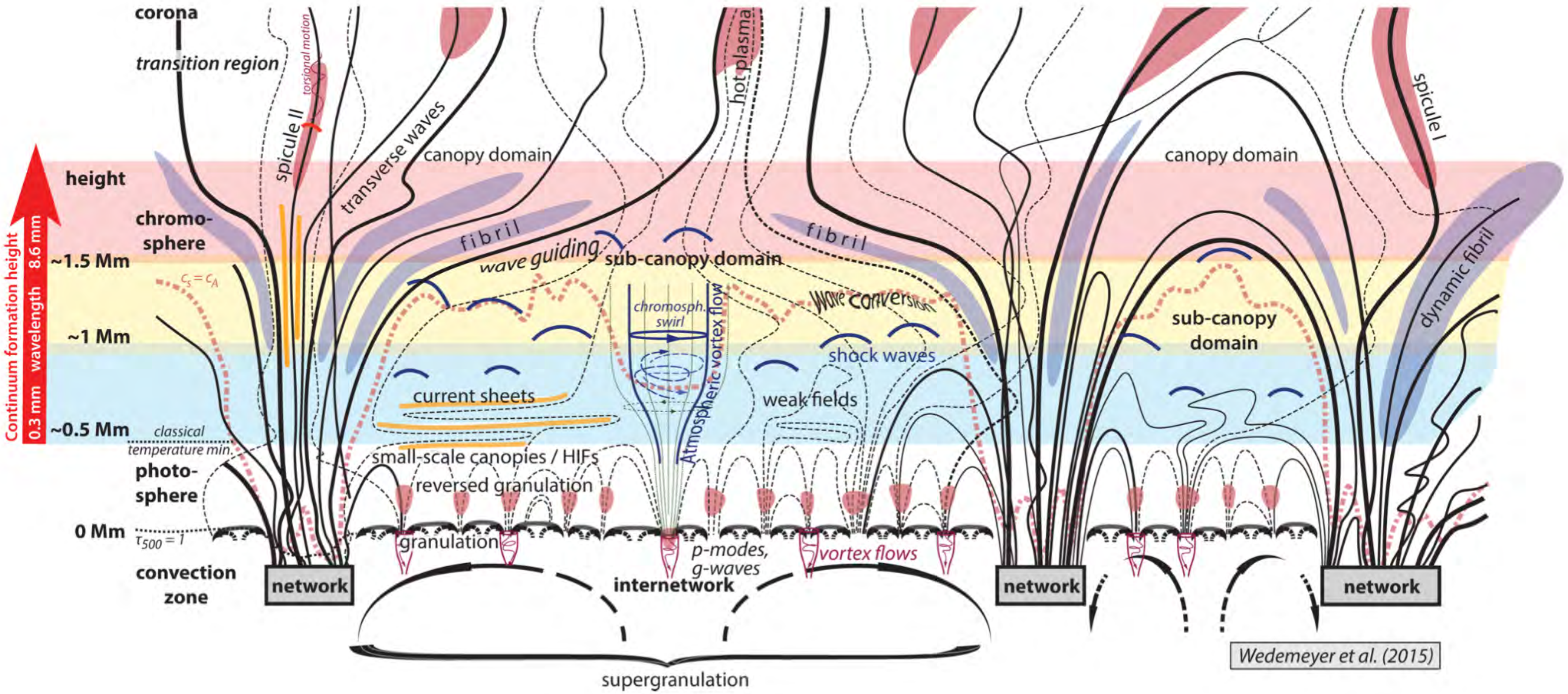
➡ **Should be supported by best possible numerical models.**



Hα / SST (Rouppe van der Voort)

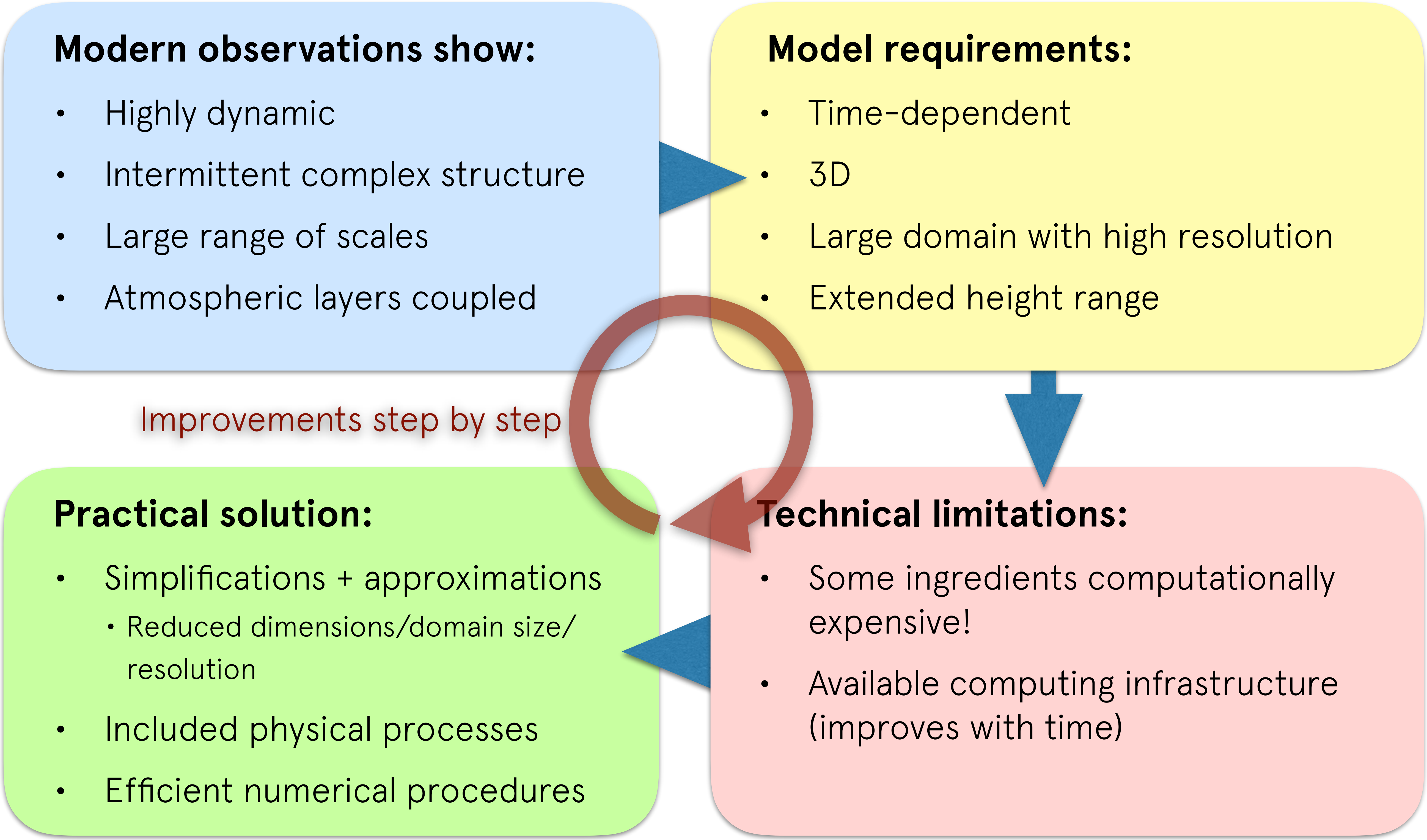
TRYING TO MAKE SENSE ...

- Important region between photosphere and corona
- Still many open questions despite many decades of research



Wedemeyer et al. (2015)

OBSERVATIONS AND MODELLING



Modern observations show:

- Highly dynamic
- Intermittent complex structure
- Large range of scales
- Atmospheric layers coupled

Model requirements:

- Time-dependent
- 3D
- Large domain with high resolution
- Extended height range

Technical limitations:

- Some ingredients computationally expensive!
- Available computing infrastructure (improves with time)

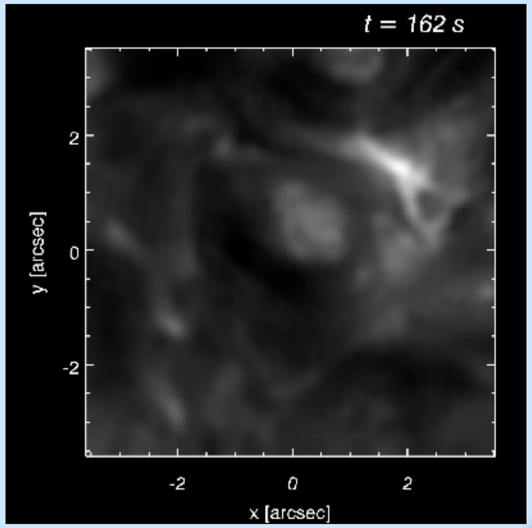
Practical solution:

- Simplifications + approximations
  - Reduced dimensions/domain size/ resolution
- Included physical processes
- Efficient numerical procedures

Improvements step by step

OBSERVATIONS AND MODELLING

Observations

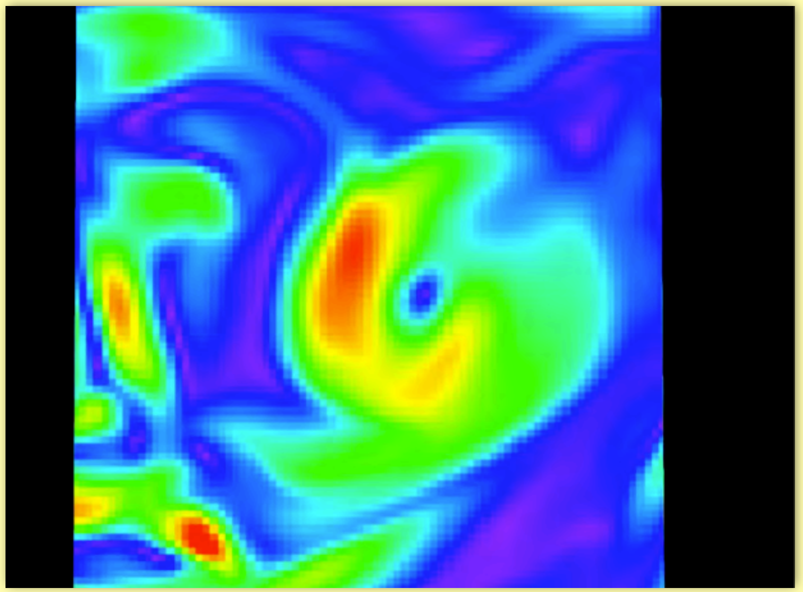


Observational constraints
Interpretation

COMPARISON

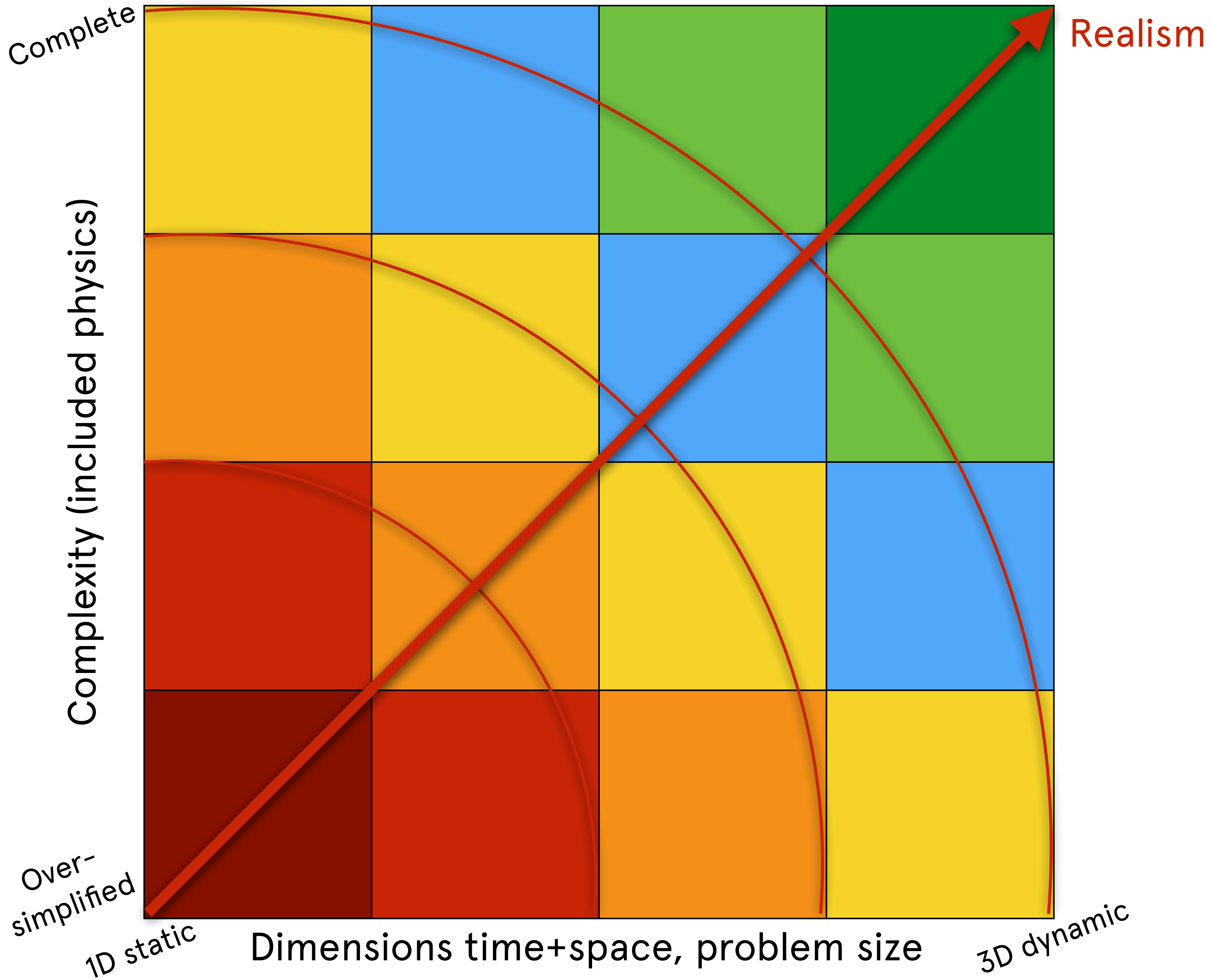
Tests: validation and discrepancies
Predictions

Models



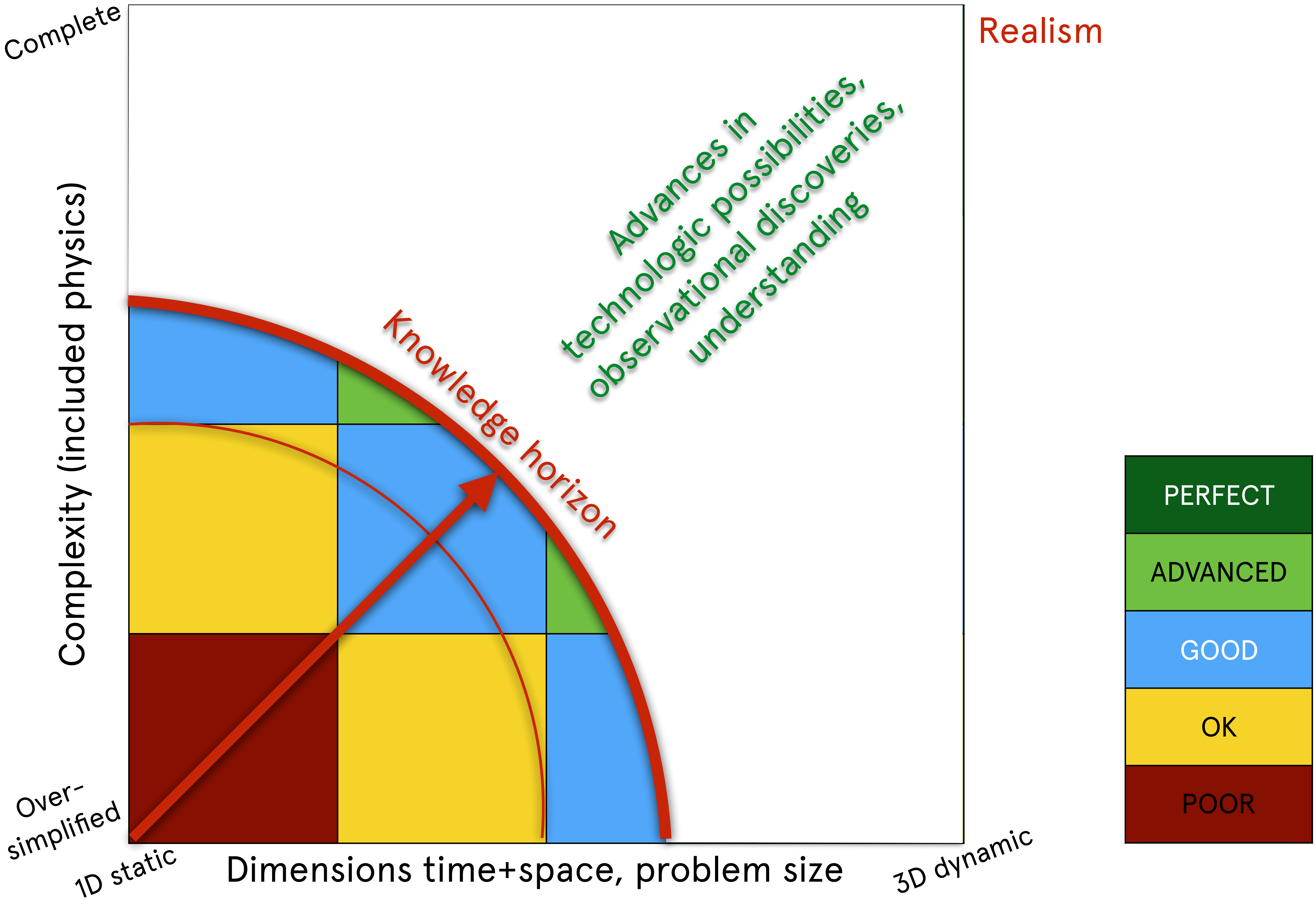
Wedemeyer et al. 2012 (Nature)

YOU CAN'T HAVE IT ALL …



- PERFECT
- ADVANCED
- GOOD
- OK
- POOR

YOU DON'T KNOW IT ALL ...



Realism

Complete

Complexity (included physics)

Over-simplified

1D static

Dimensions time+space, problem size

3D dynamic

Knowledge horizon

Advances in technologic possibilities, observational discoveries, understanding

PERFECT

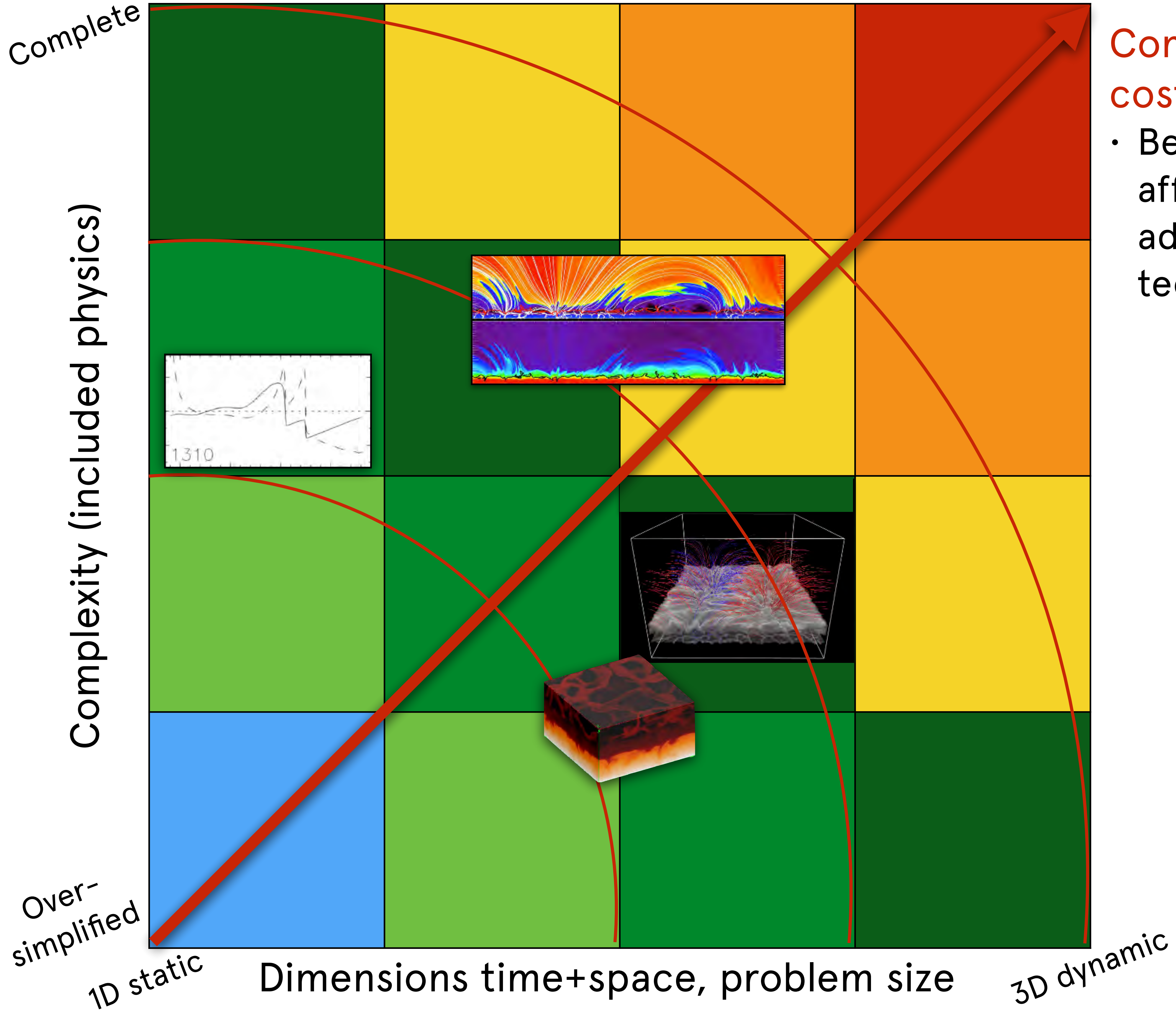
ADVANCED

GOOD

OK

POOR

YOU CAN'T AFFORD IT ALL (YET) ...



Computational costs

- Becomes more affordable with advancing technology

🟥 FUTURE
🟧 CHALLENGE
🟨 FRONTIER
🟩 DOABLE
🟩 ROUTINELY DONE
🟩 FAST & EASY
🟦 TOO SIMPLE

ADVANCES IN MODELLING

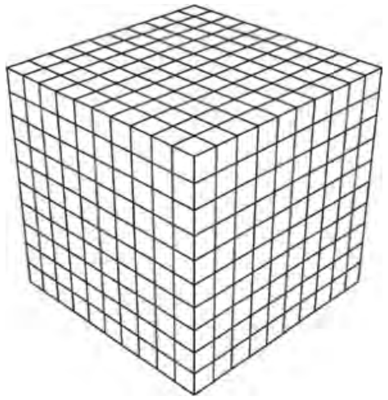
1980

Affordable complexity (time)

2020

	Theoretical modelling	Observation-driven modelling
TOO SIMPLE	1D hydrostatic	1D hydrostatic semi-empirical
FAST & EASY	2D/3D radiation hydrodynamics	1D hydrostatic semi-empirical
ROUTINELY DONE	3D ideal radiation magnetohydrodynamics (RMHD)	Data inversion (“pixel-by-pixel”)
DOABLE	3D ideal RMHD + ionisation	Data inversion (“pixel-by-pixel”)
FRONTIER	3D RMHD with ion-neutral effects: · Generalized Ohm's law (GOL) · Multi-fluid / multi-species	Advanced spatially coupled (3D) data inversion
CHALLENGE	3D RMHD with ion-neutral effects and coupled with particle-in-cell description (in sub-domains)	Advanced tempospatially coupled (“4D”) data inversion based on very many observational data points
FUTURE	. . .	

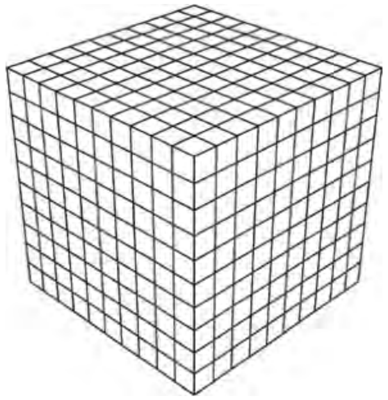
CHALLENGES - DOMAIN SIZE VS. RESOLUTION



SPATIAL DIMENSIONS

- Smallest spatial scales that need to be resolved?
  - Currently down ~1 - 10 km scale
- Largest spatial scales to be included in computational domain?
  - Currently ~10 000 km up to supergranulation scale (a few 10 000 km)
- Current 3D model sizes 512^3 - 1024^3 cells
- Unresolved scales - Sub-grid modelling

CHALLENGES - DOMAIN SIZE VS. RESOLUTION



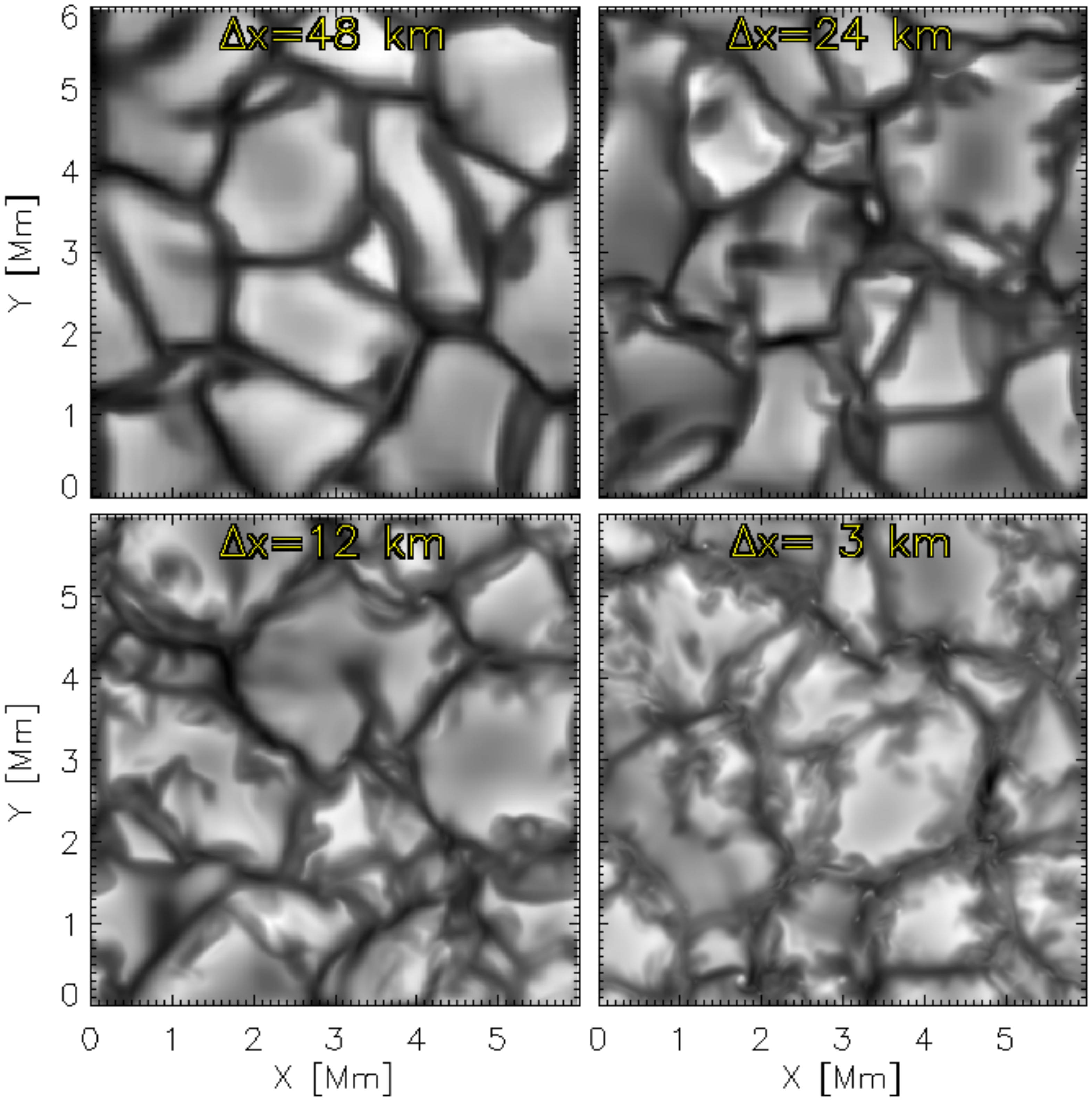
TEMPORAL DIMENSION

- Dynamic simulations advance time step by time step Δt
- Courant–Friedrichs–Lewy condition: $C = \frac{u\,\Delta t}{\Delta x} \leq C_{\max}$
  - Maximum time step Δt depends on grid cell size Δx and highest speed
    - ➡ Higher spatial resolution with smaller grid cells
    - ➡ Shorter time step Δt
    - ➡ More time steps needed to cover same simulation time span
  - ~0.1 s for typical HD photosphere models
  - Down to ~1 ms for MHD (depending on field strength or rather wave speeds)
  - In most codes: Global time steps
    - A single grid cell (with extreme conditions) can set Δt for whole domain!
- Extended domains require often simulation time span of many hours!
(Especially for relaxing from initial conditions in the convection zone)

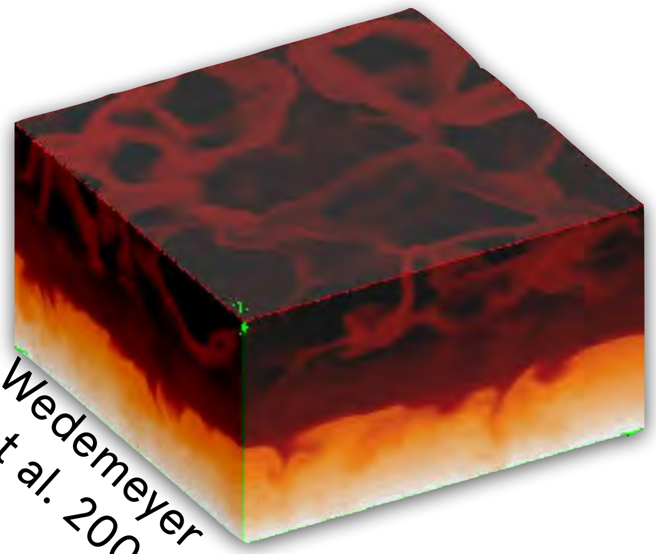
EFFECTS OF NUMERICAL RESOLUTION

Bifrost

Gudiksen et al. 2011



Bifrost - Courtesy: M. Carlsson

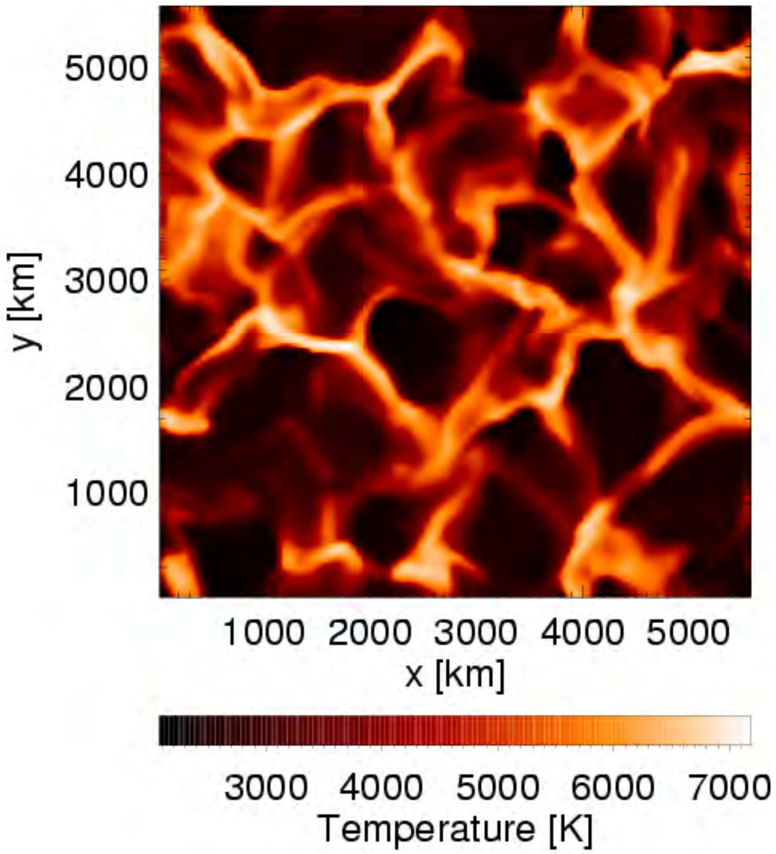


Wedemeyer et al. 2004

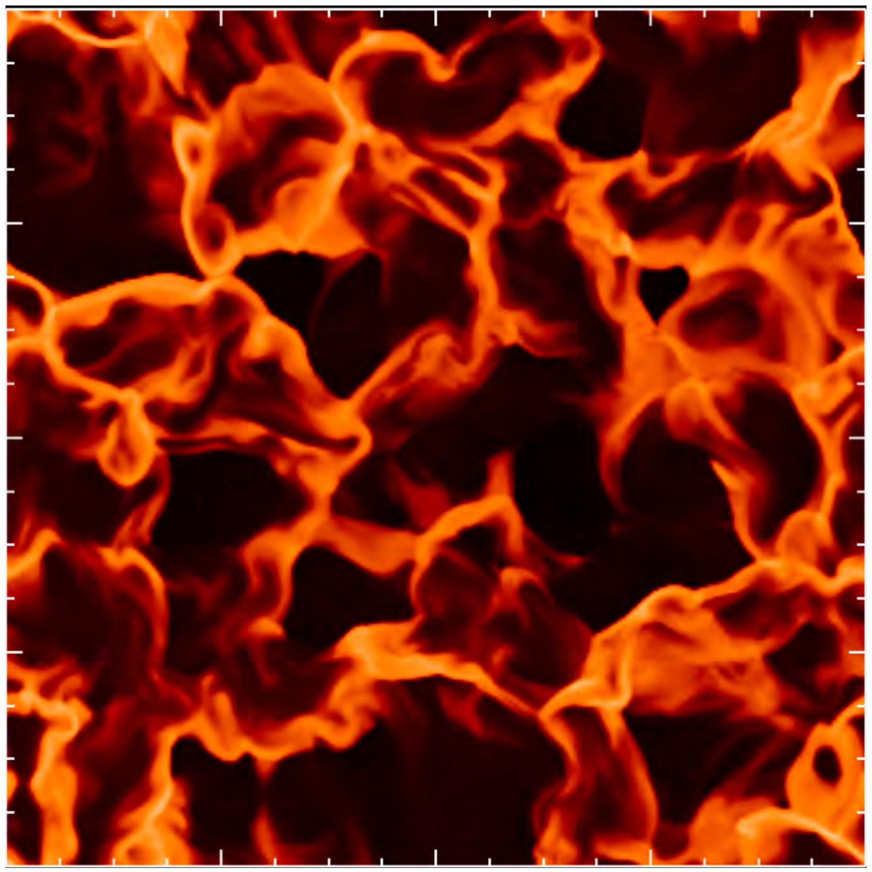
CO^{5}BOLD

Freytag et al. 2012

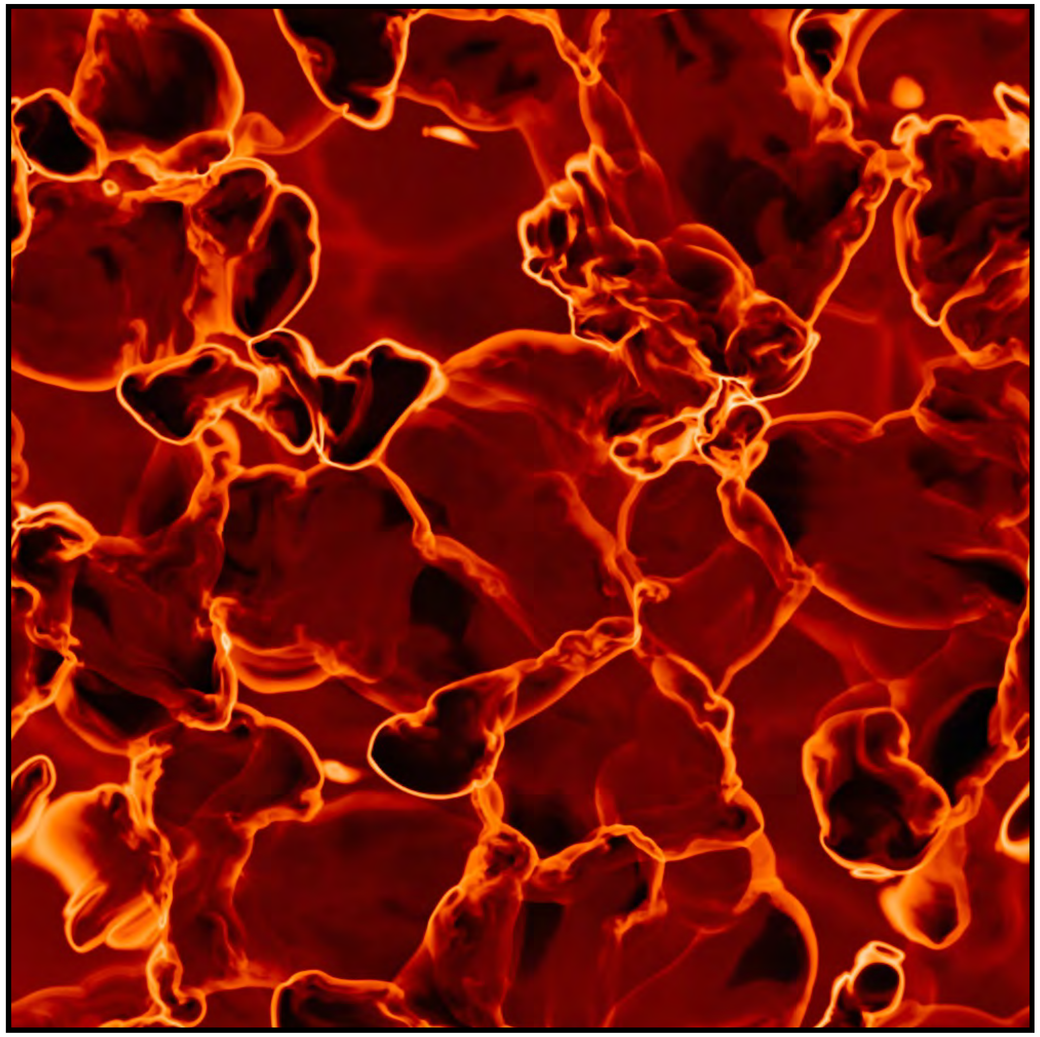
2002
5.6 Mm
140 cells



2006
8.0 Mm
286 cells



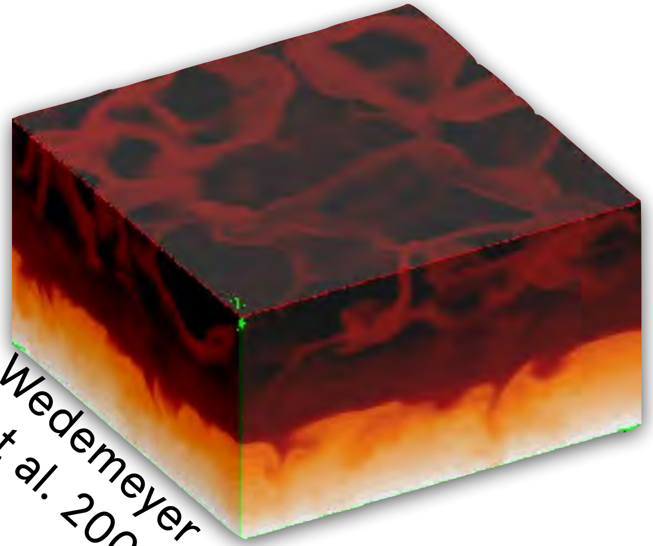
2017
9.6 Mm
960 cells



Courtesy: O. Steiner

Gas temperature in horizontal cut at height 1000 - 1200 km

EFFECTS OF NUMERICAL RESOLUTION



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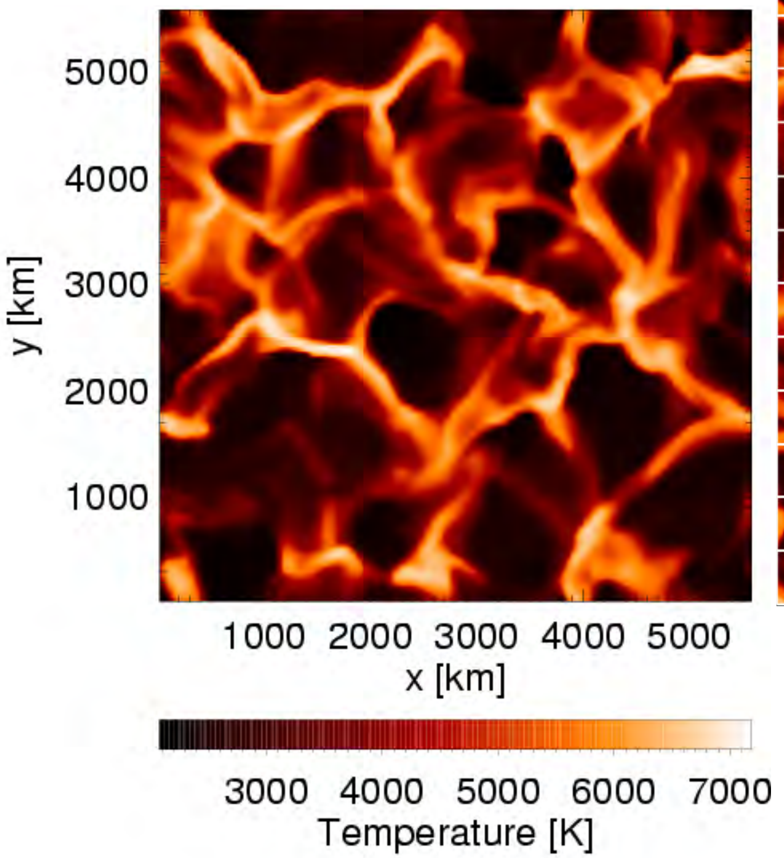

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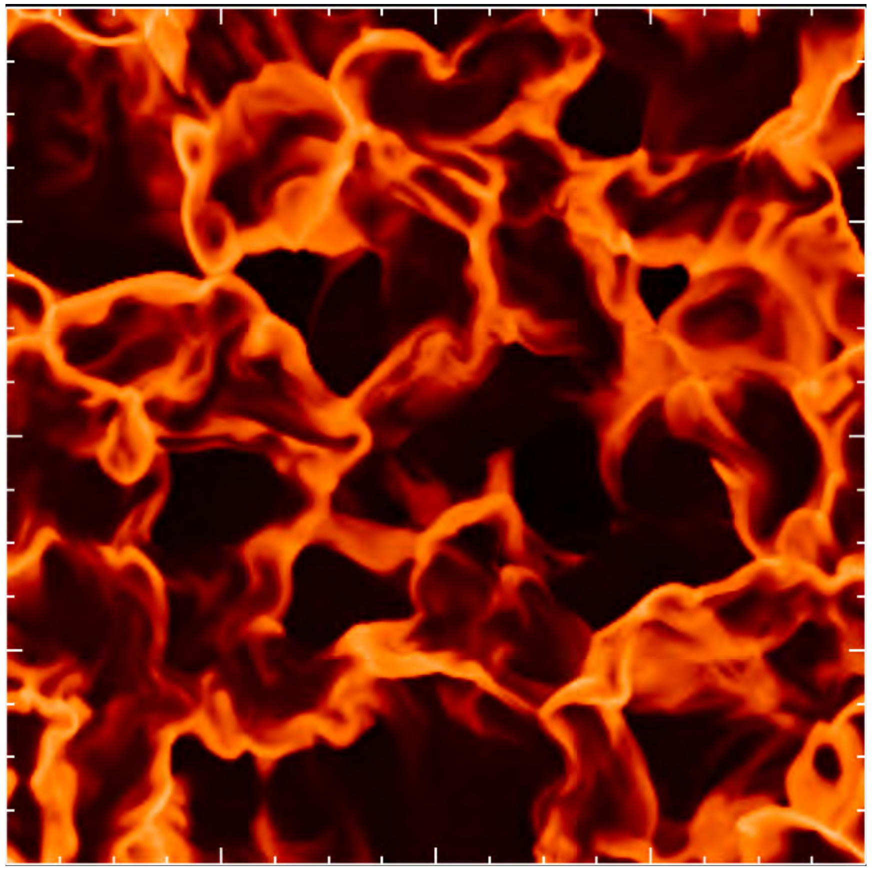
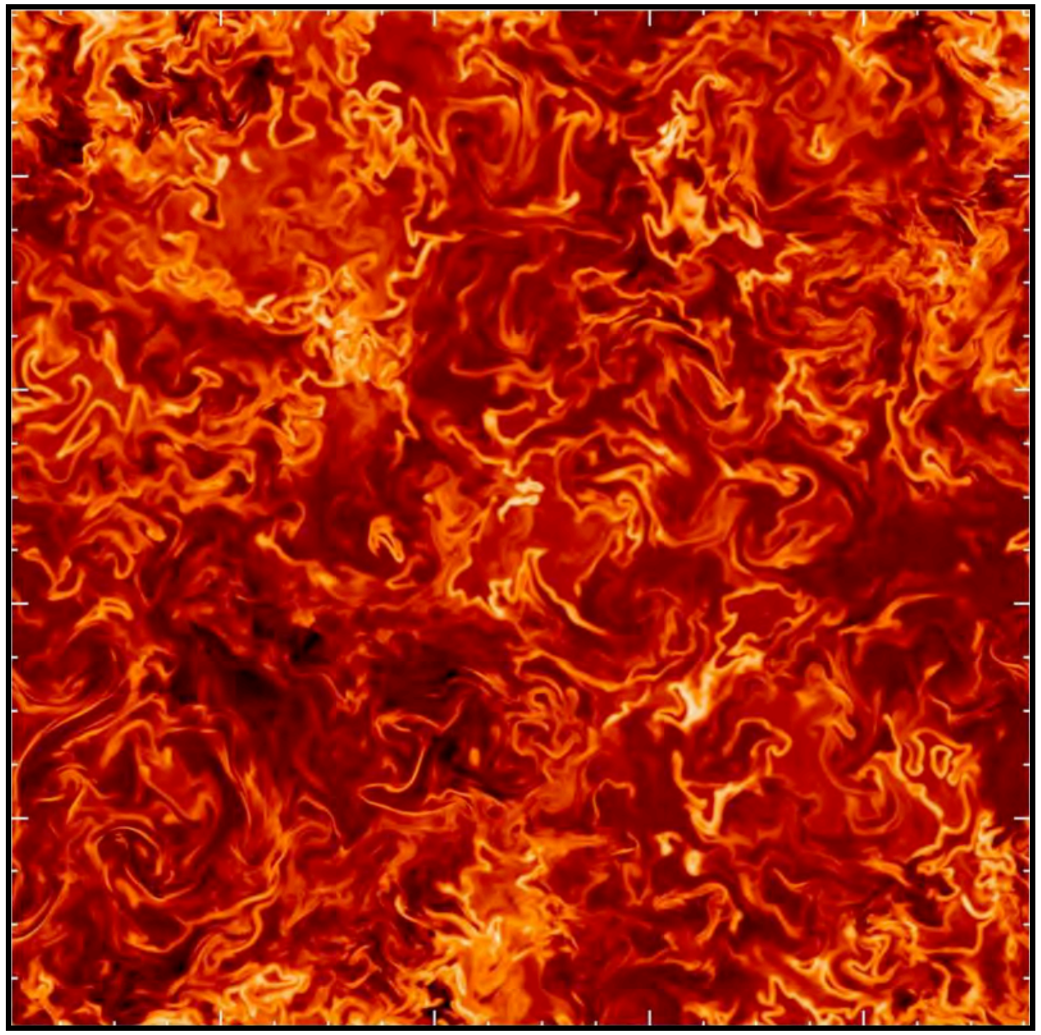


2017
9.6 Mm
960 cells

Initial magnetic field:
Homogeneous, vertical
50 G



Courtesy: O. Steiner

Gas temperature in horizontal cut at height 1000 - 1200 km

MODELLING: PHYSICAL PROCESSES

- Radiative transfer
- (Magneto-)hydrodynamics
- Thermodynamics (equation of state)
- Gravity
- Ionisation
- Conduction
- Chemistry
- Ion-neutral effects
- …

- **Deviations from equilibrium conditions:**
  - Ionisation degree
  - Atomic level populations (non-LTE)
  - Molecules …

RADIATIVE TRANSFER IN THE CHROMOSPHERE

- Neither fully transparent nor full opaque.

  ➡ Detailed description with wavelength dependence needed.

- Mean free path of photons:
  - Diffusion approximate in opaque media (convection zone)
  - In (partially) transparent regions radiation can couple far apart regions.

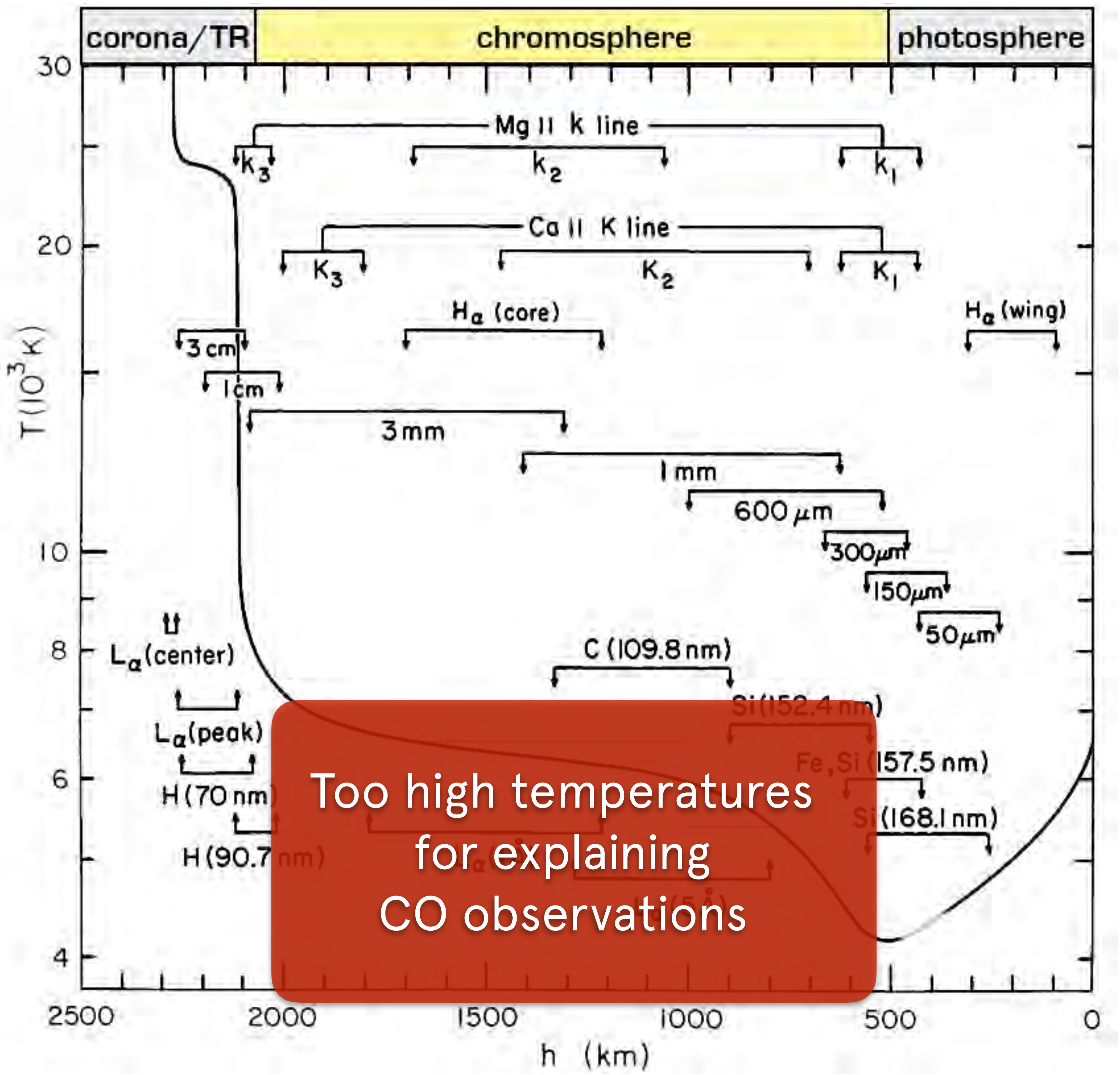
    ➡ Non-locality!
  - Back radiation from corona

- **What exactly is needed from the RT for the intended modelling?**
  - Reproduction of realistic spectral line profiles?
  - Or only the approximate impact on the atmospheric energy balance?

- **Two stages**
  1. Numerical simulations with focus on realistic plasma properties (energy balance)
  2. Radiative transfer codes producing detailed synthetic observables

1D SEMI-EMPIRICAL

- Vernazza, Avrett, Loeser (1981, VAL)
- Many more, e.g.: FAL, Anderson & Athay 1989, …
- Adjusting a hydrostatic stratification to match a large range of observations (spectral lines & continua)
- Advanced physics (non-LTE)
- Models for different types of region on the Sun
- Limits:
  - 1D
  - Static



Too high temperatures for explaining CO observations

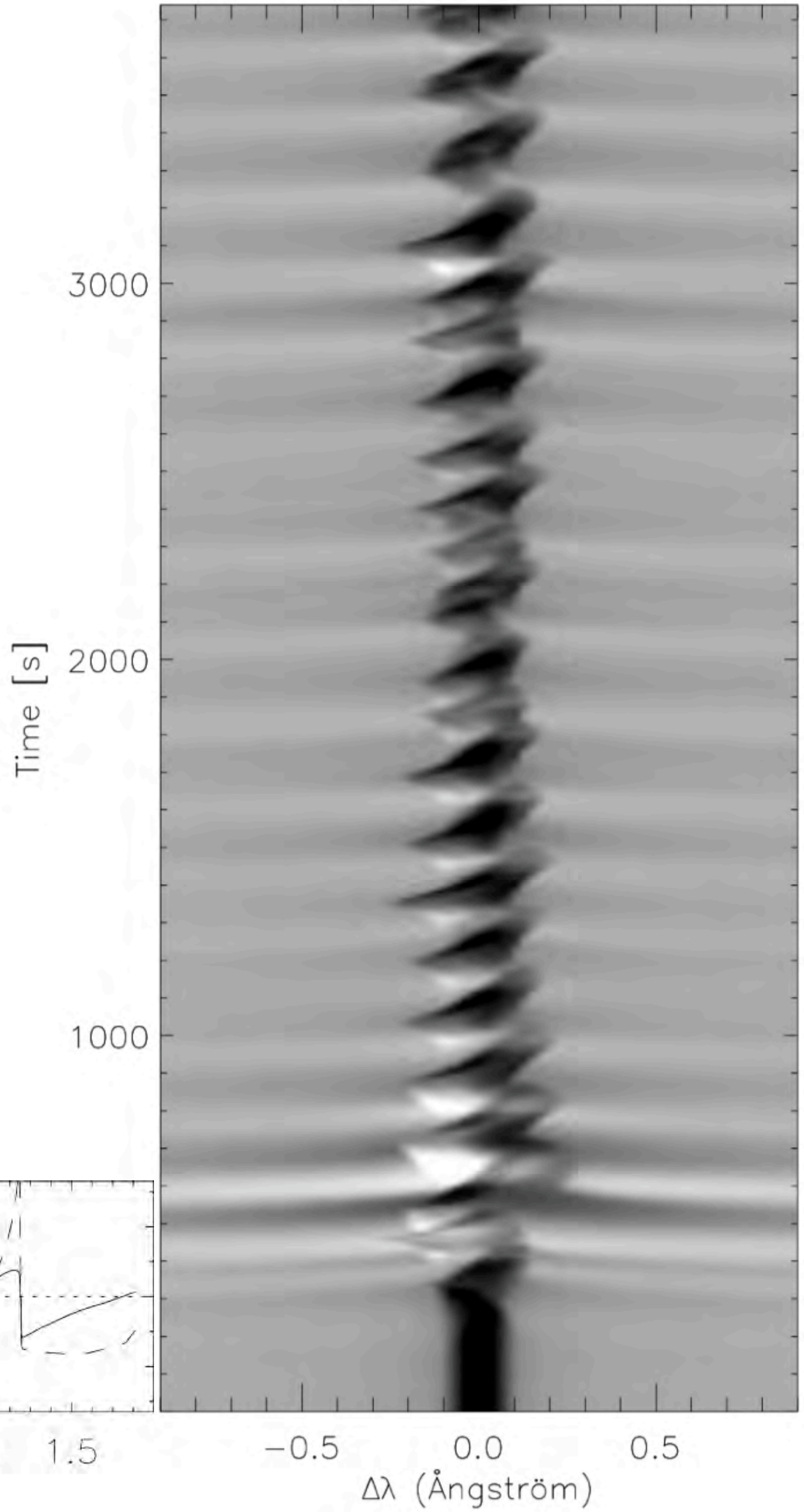
1D THEORETICAL

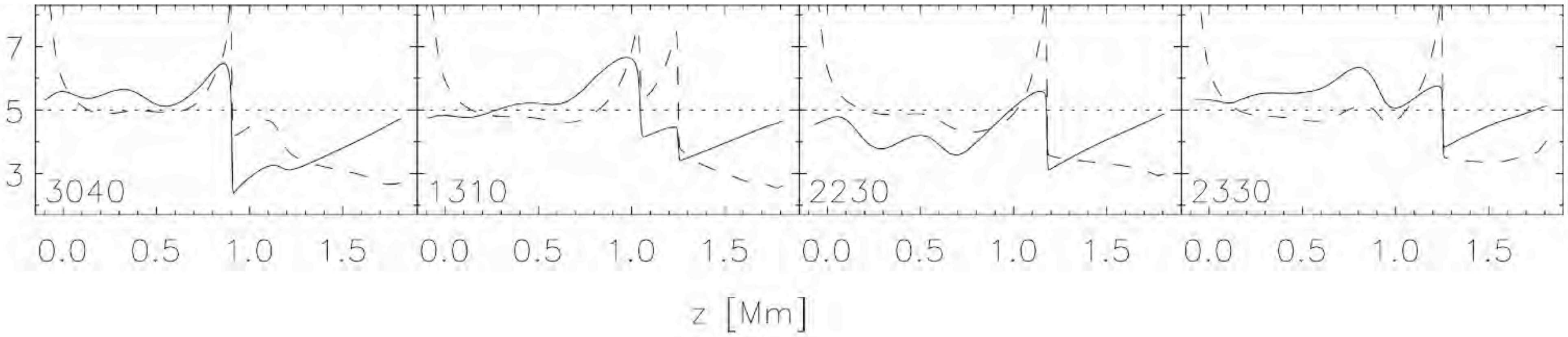
- RADYN (Carlsson & Stein 1992-1997)
  - **Dynamic** - time-dependent approach
  - Detailed treatment of physics (e.g., non-LTE, ionisation - uses model atoms)
  - Driven by empirical piston at the bottom
  - Produces observables that can be tested

➡ Explains observations of bright grains in Ca II H as result of propagating shock waves in the chromosphere

- Many other theoretical models (Ulmschneider 1971, etc)
- Limit: 1D only

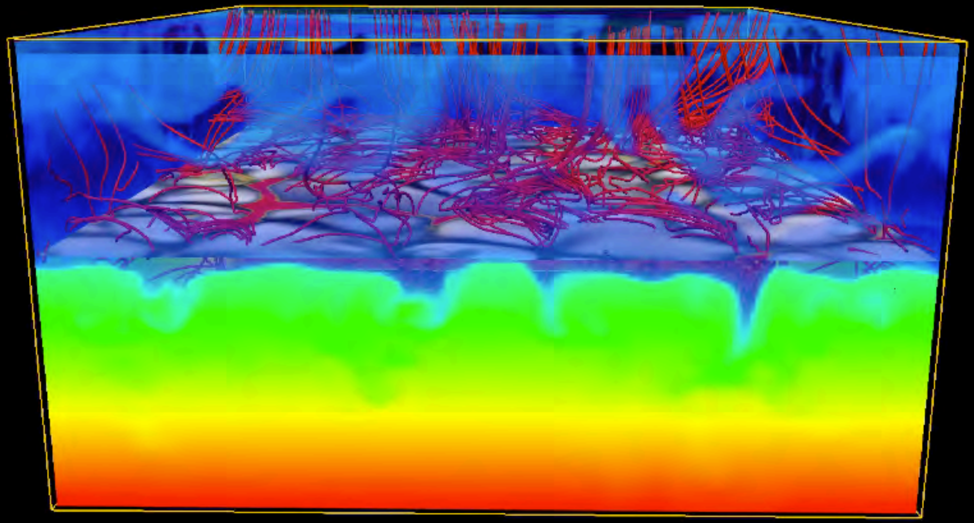
Ca II H





3D IDEAL RADIATION MAGNETOHYDRODYNAMICS

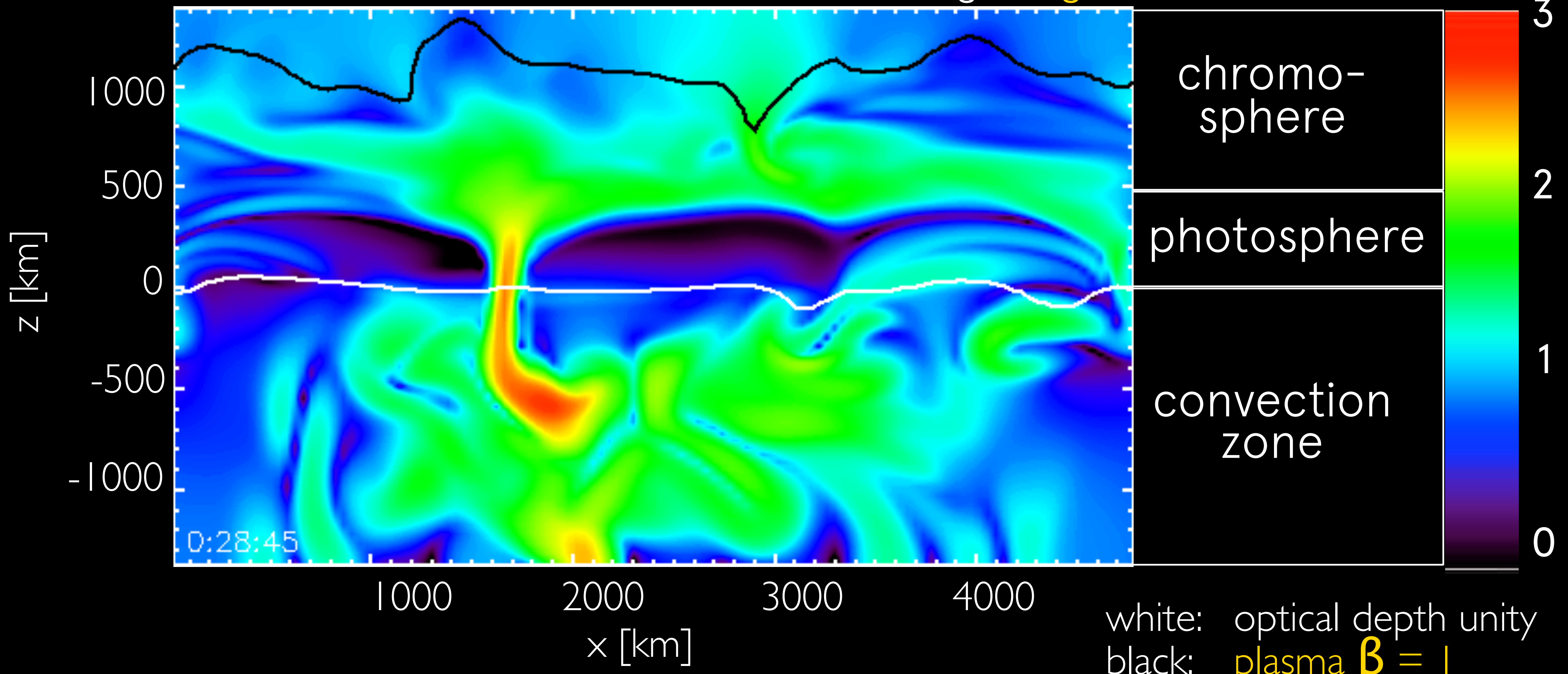
- Spatially structure requires modelling in 2D/3D
- Small part of the atmosphere plus upper convection zone to drive dynamics self-consistently
- Computational grid, advanced time step by time step
- Solving equations of (magneto)hydrodynamics with "realistic" equation of state plus radiative transfer (simplified with pre-calculated opacity look-up tables)



MAGNETIC FIELD STRUCTURE AND DYNAMICS

- Magnetic field in chromosphere is highly dynamic
  - Propagating shock waves compress magnetic field
  - Fast moving filaments of enhanced field

vertical cross-section: absolute field strength log |B|



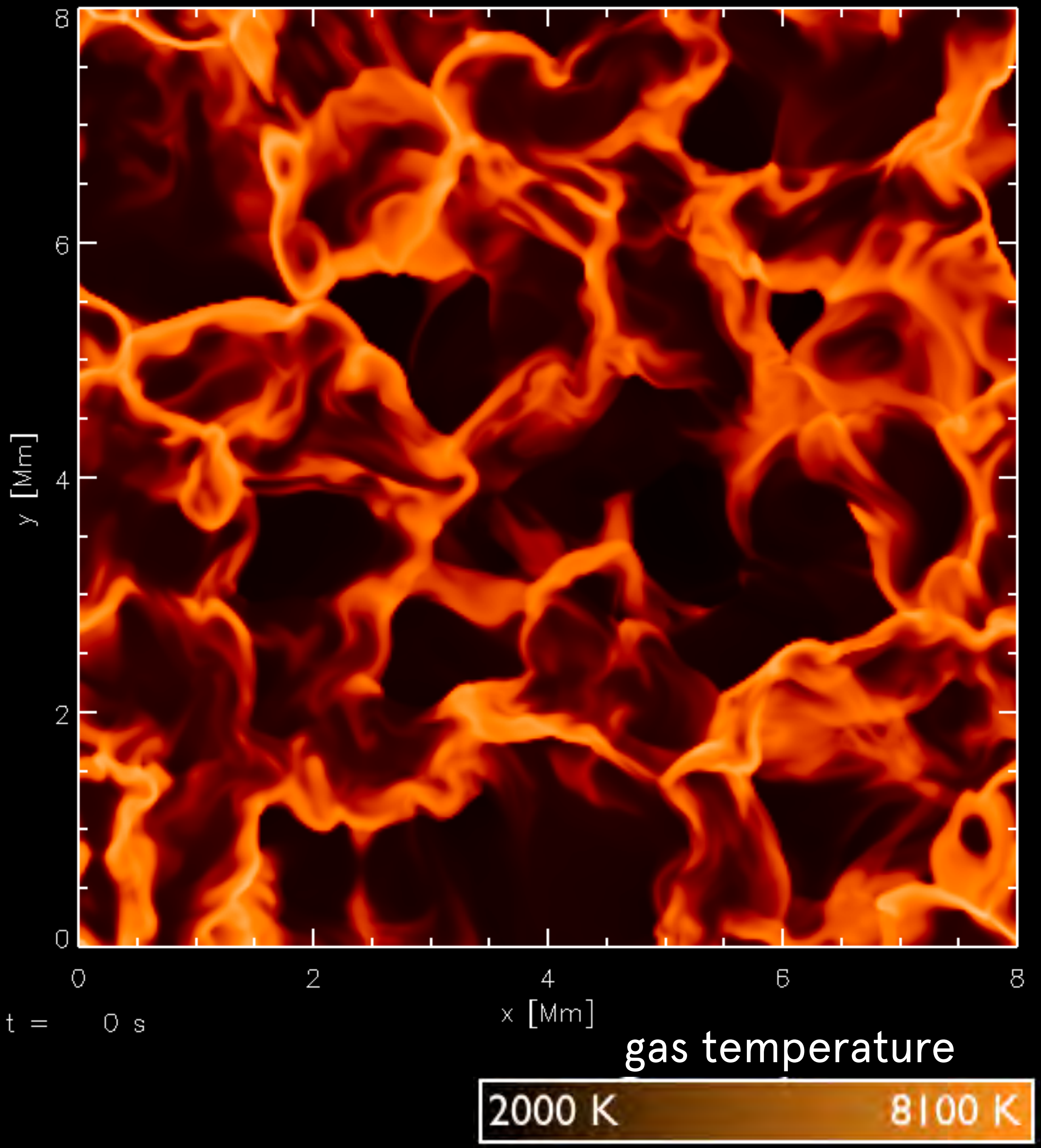
white: optical depth unity
black: plasma $\beta = 1$

$|B_0| = 10$ G

Schaffenberger, Wedemeyer, Steiner, Freytag (2005)

CHROMOSPHERE IN (VERY) QUIET SUN REGIONS

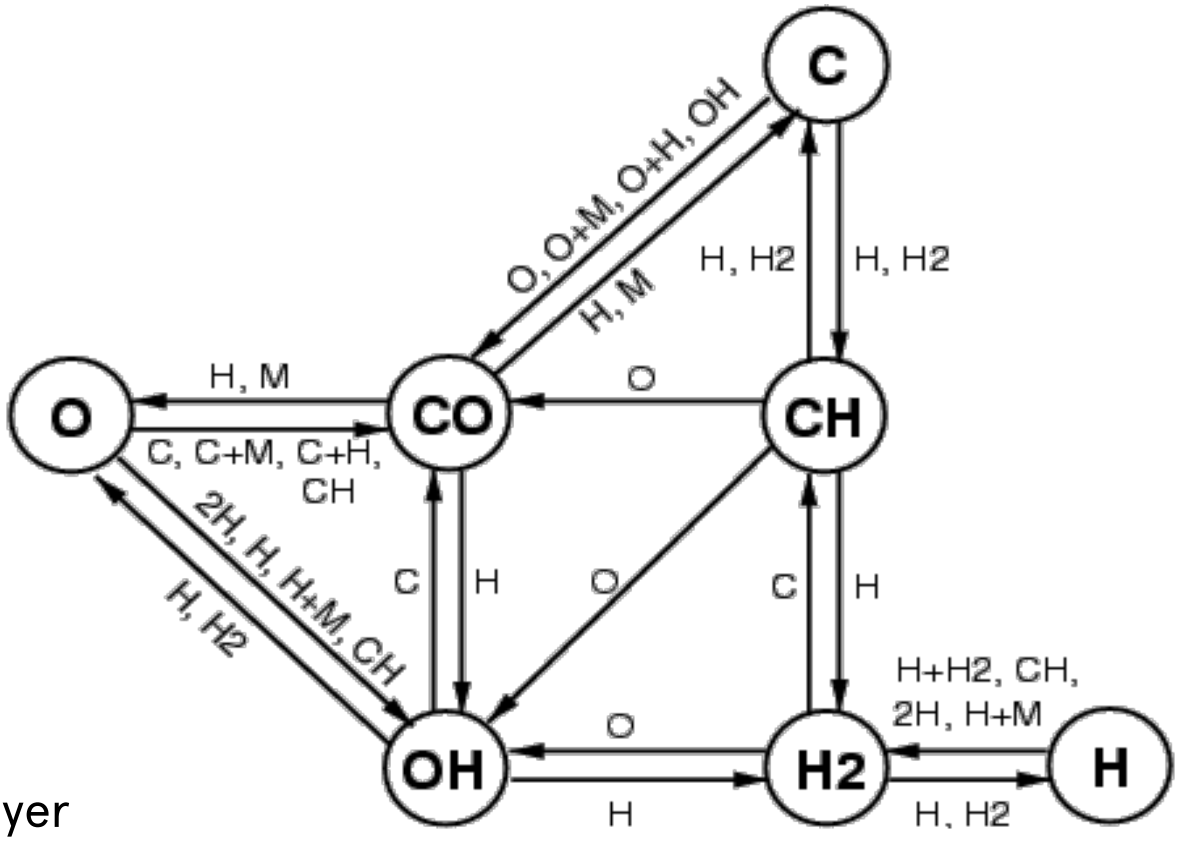
- Horizontal cut through model chromosphere at z=1000 km, gas temperature
- Hot shock fronts (~7000 - 8000 K) and cool post-shock regions (down to ~2000 K)
- Mean T_{gas} ~ 4000 K
- Pattern produced by interaction of shock fronts
- Typical length scale ~1000 km (1.3")
- Timescales of 20 -30 s



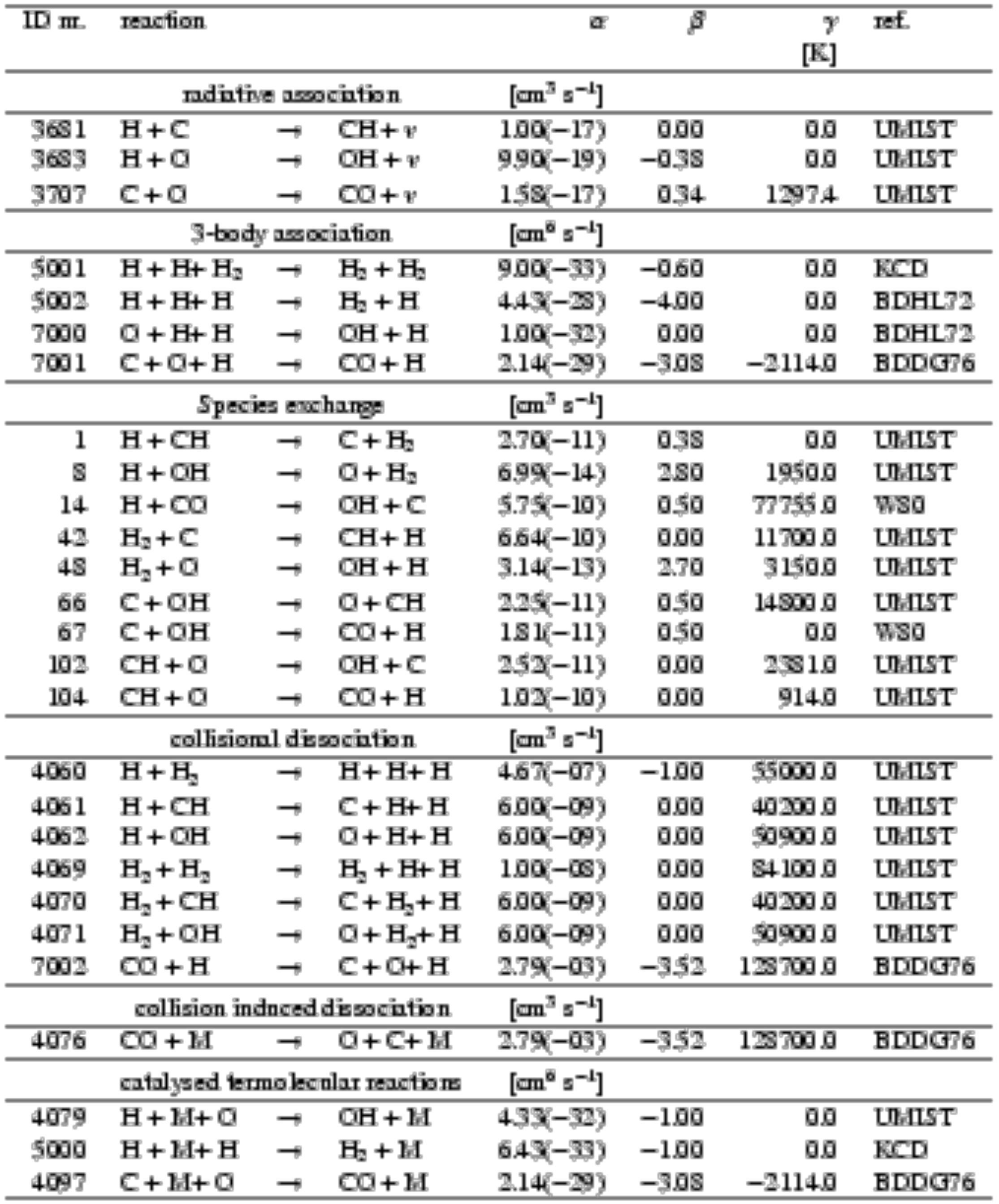
CARBON MONOXIDE

How does CO fit in?

- Simulations with time-dependent treatment of a chemical reaction network + advection of particles + radiative cooling
- chemical reaction network:
  - 7 chemical species plus representative metal (≥He): H, H_2, C, O, CO, CH, OH, M
  - 27 chemical reactions



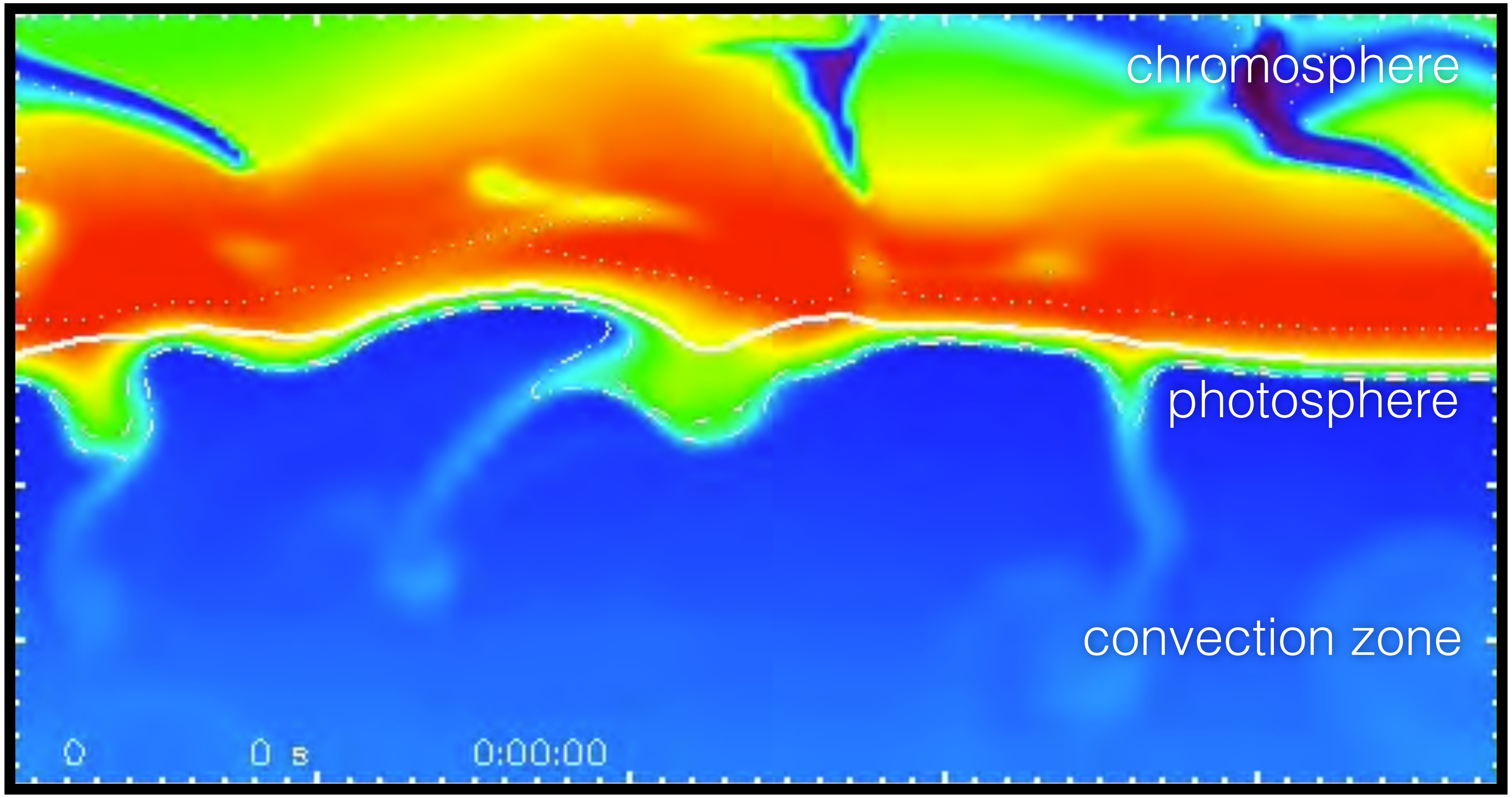
Wedemeyer et al. 2006



ID nr.	reaction			α	β	γ [K]	ref.
	radiative association			[$cm^3\ s^{-1}$]			
3681	H + C	→	CH + ν	1.00(−17)	0.00	0.0	UMIST
3683	H + O	→	OH + ν	9.90(−19)	−0.38	0.0	UMIST
3707	C + O	→	CO + ν	1.58(−17)	0.34	1297.4	UMIST
	3-body association			[$cm^6\ s^{-1}$]			
5001	H + H + H_2	→	H_2 + H_2	9.00(−33)	−0.60	0.0	KCD
5002	H + H + H	→	H_2 + H	4.43(−28)	−4.00	0.0	BDHL72
7000	O + H + H	→	OH + H	1.00(−32)	0.00	0.0	BDHL72
7001	C + O + H	→	CO + H	2.14(−29)	−3.08	−2114.0	BDDG76
	Species exchange			[$cm^3\ s^{-1}$]			
1	H + CH	→	C + H_2	2.70(−11)	0.38	0.0	UMIST
8	H + OH	→	O + H_2	6.99(−14)	2.80	1950.0	UMIST
14	H + CO	→	OH + C	5.75(−10)	0.50	77755.0	W80
42	H_2 + C	→	CH + H	6.64(−10)	0.00	11700.0	UMIST
48	H_2 + O	→	OH + H	3.14(−13)	2.70	3150.0	UMIST
66	C + OH	→	O + CH	2.25(−11)	0.50	14800.0	UMIST
67	C + OH	→	CO + H	1.81(−11)	0.50	0.0	W80
102	CH + O	→	OH + C	2.52(−11)	0.00	2381.0	UMIST
104	CH + O	→	CO + H	1.02(−10)	0.00	914.0	UMIST
	collisional dissociation			[$cm^3\ s^{-1}$]			
4060	H + H_2	→	H + H + H	4.67(−07)	−1.00	55000.0	UMIST
4061	H + CH	→	C + H + H	6.00(−09)	0.00	40200.0	UMIST
4062	H + OH	→	O + H + H	6.00(−09)	0.00	50900.0	UMIST
4069	H_2 + H_2	→	H_2 + H + H	1.00(−08)	0.00	84100.0	UMIST
4070	H_2 + CH	→	C + H_2 + H	6.00(−09)	0.00	40200.0	UMIST
4071	H_2 + OH	→	O + H_2 + H	6.00(−09)	0.00	50900.0	UMIST
7002	CO + H	→	C + O + H	2.79(−03)	−3.52	128700.0	BDDG76
	collision induced dissociation			[$cm^3\ s^{-1}$]			
4076	CO + M	→	O + C + M	2.79(−03)	−3.52	128700.0	BDDG76
	catalysed termolecular reactions			[$cm^6\ s^{-1}$]			
4079	H + M + O	→	OH + M	4.33(−32)	−1.00	0.0	UMIST
5000	H + M + H	→	H_2 + M	6.43(−33)	−1.00	0.0	KCD
4097	C + M + O	→	CO + M	2.14(−29)	−3.08	−2114.0	BDDG76

CARBON MONOXIDE

- Vertical cross-section - CO abundance
- CO dissociated by moving hot shock waves in chromosphere, builds up again in cold post-shock regions
- CO as integral part of a highly dynamic environment
- CO observations (cold gas) and UV observations (hot gas) explained with same model



Wedemeyer et al. 2006

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 24 rays
  - Multi group opacities (4 bins) with scattering
- NLTE losses in the chromosphere, optically thin in corona

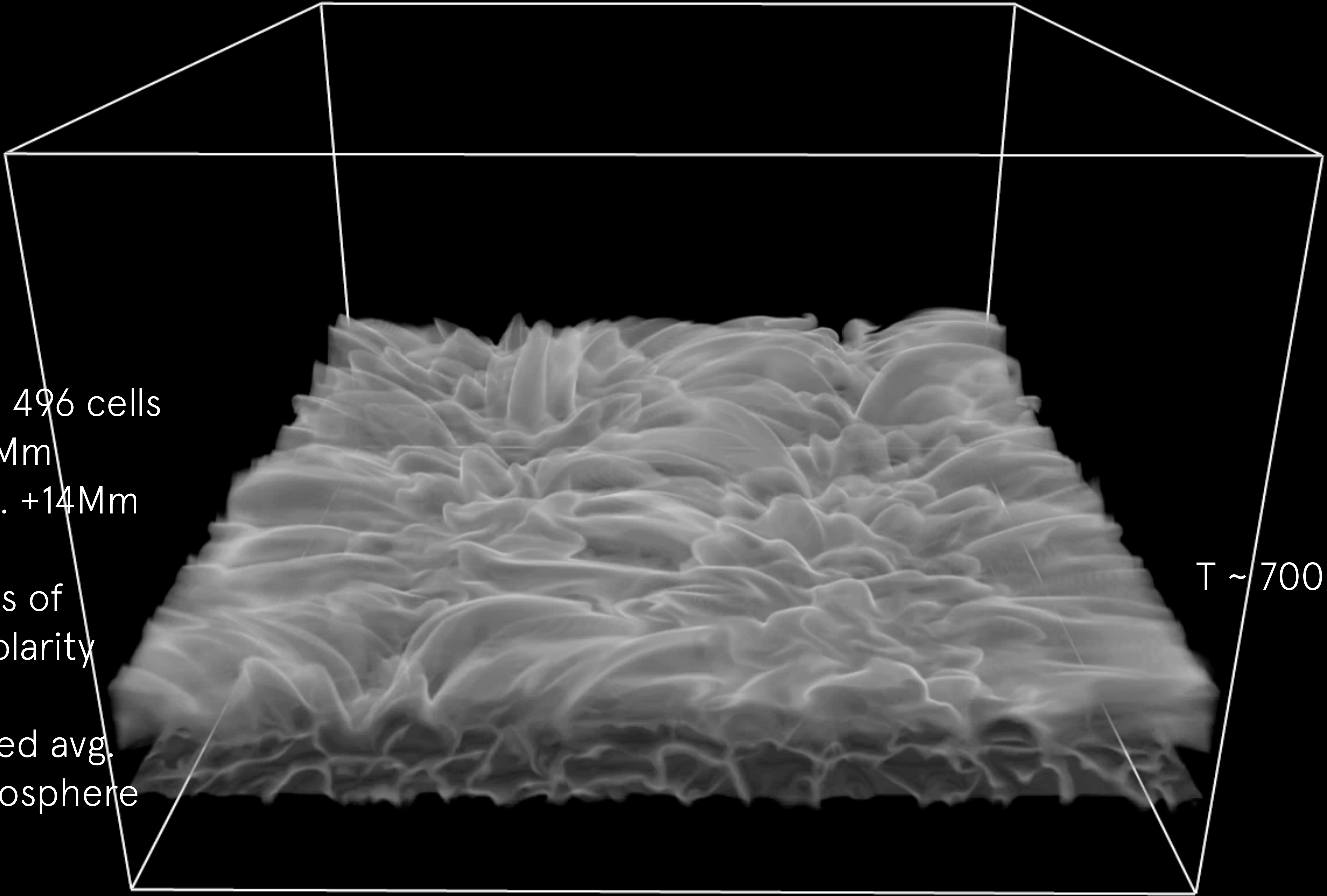
- Conduction along field lines
  - Operator split and solved by using multi grid method

- Non-equilibrium Hydrogen/Helium ionization
- Generalized Ohm’s Law

“ENHANCED NETWORK” SIMULATION

http://sdc.uio.no/search/simulations
IRIS Technical Note 33; Carlsson et al 2016

Bifrost



504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

Two patches of
opposite polarity

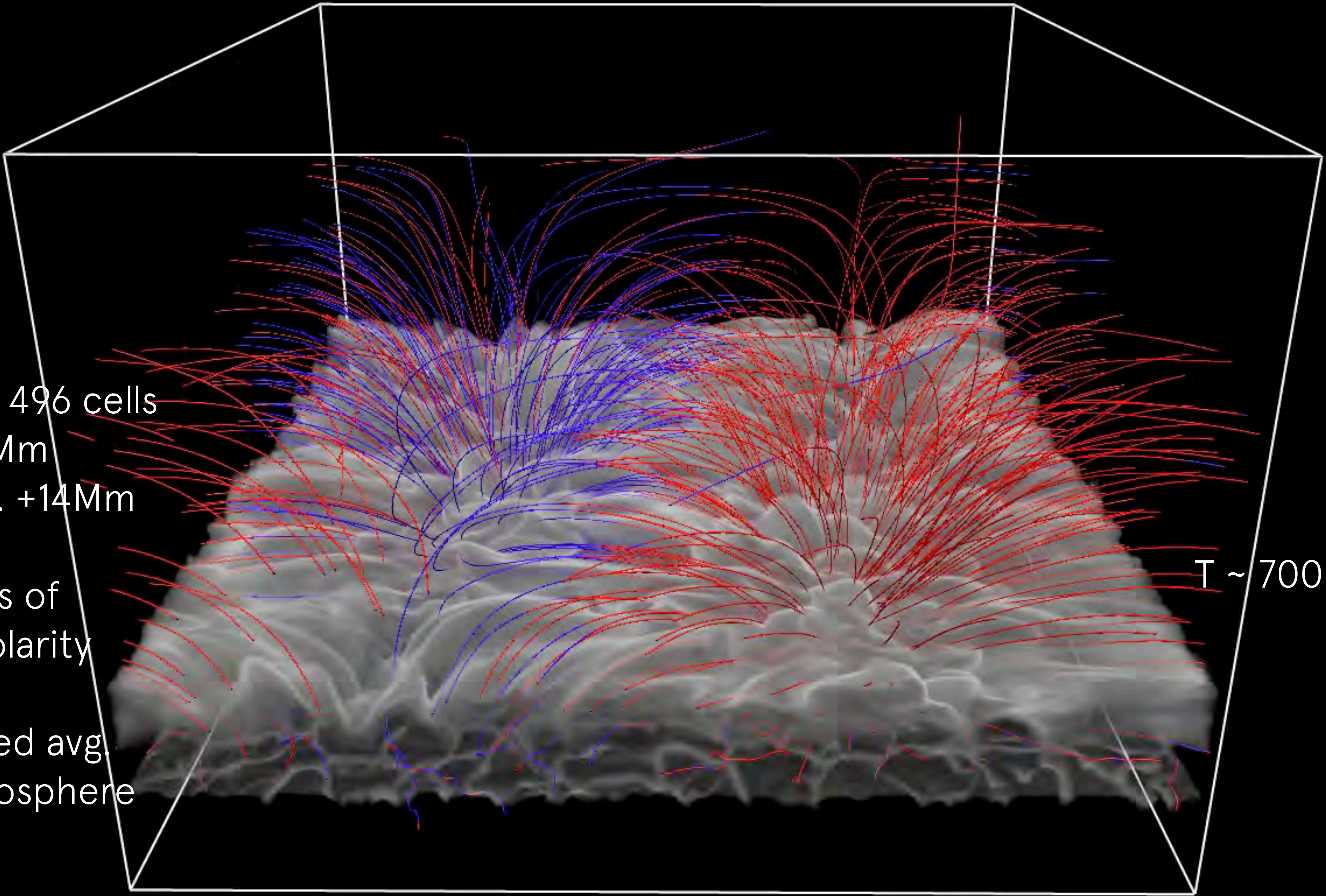
50G unsigned avg.
flux in photosphere

T ~ 7000 K

“ENHANCED NETWORK” SIMULATION

http://sdc.uio.no/search/simulations
IRIS Technical Note 33; Carlsson et al 2016

Bifrost



504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

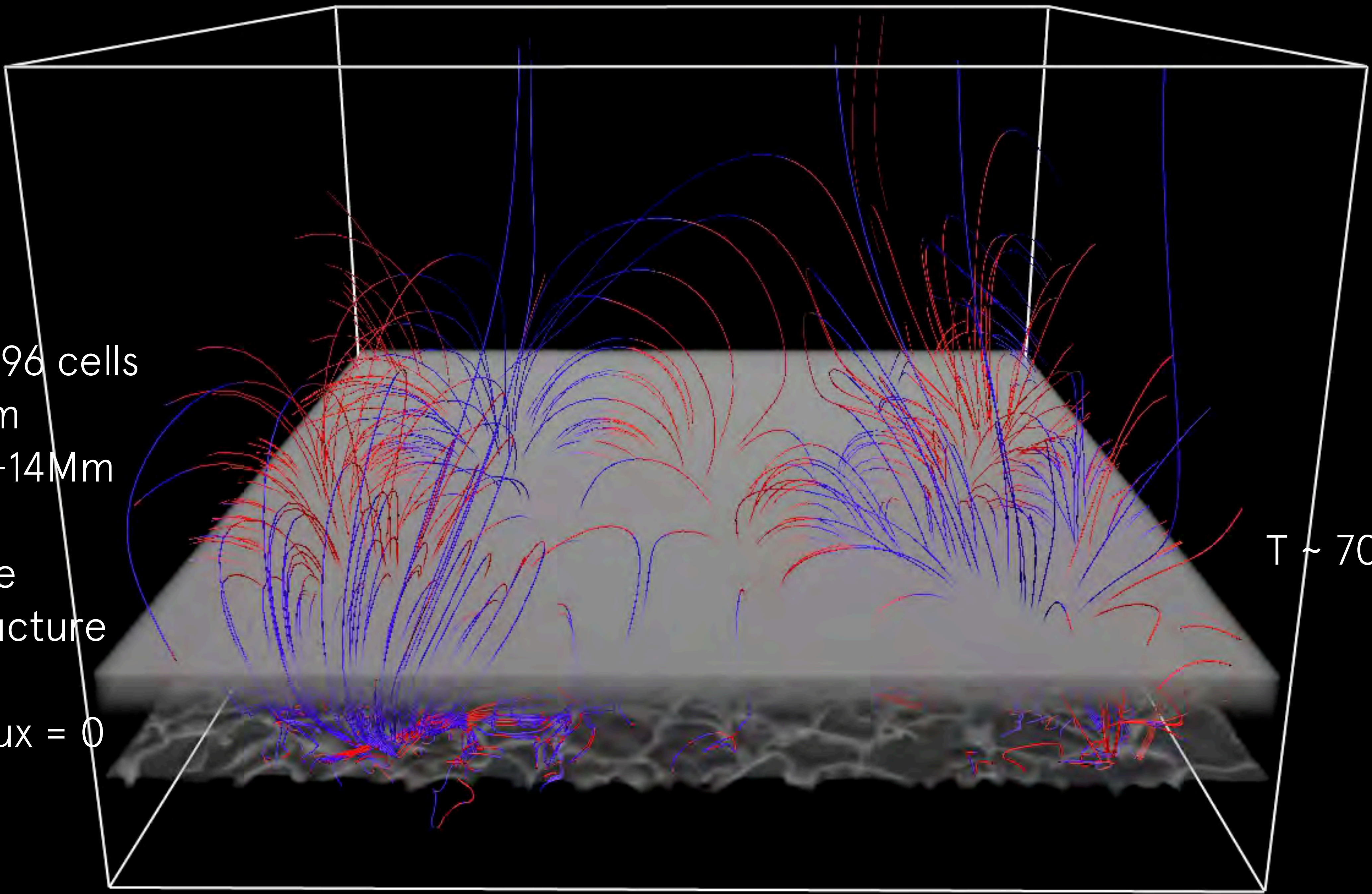
Two patches of
opposite polarity

50G unsigned avg.
flux in photosphere

T ~ 7000 K

QUIET SUN

Bifrost



504 x 504 x 496 cells
24Mm x 24Mm
z: -2.4Mm .. +14Mm

No large-scale
magnetic structure

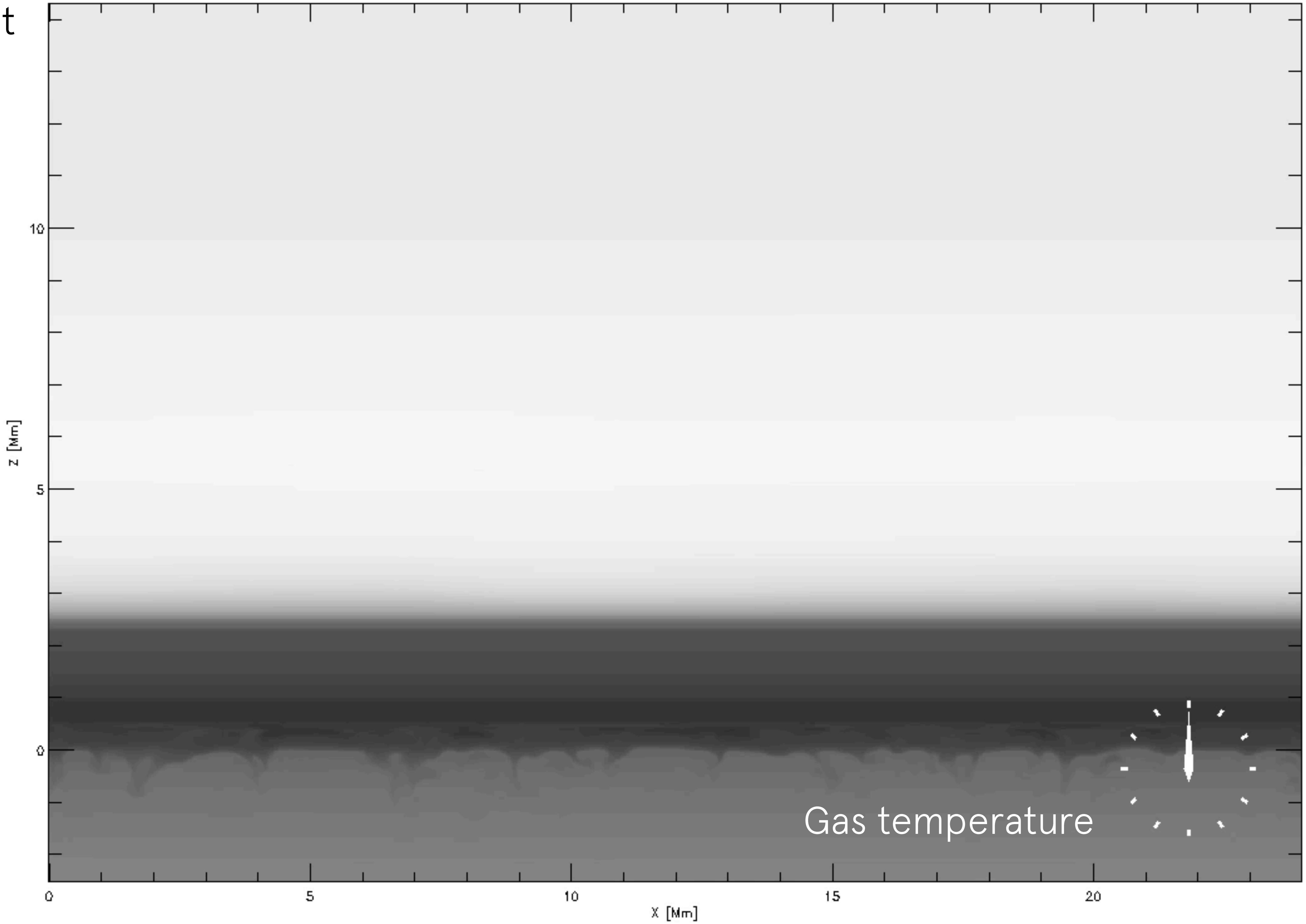
Avg. signed flux = 0

T ~ 7000 K

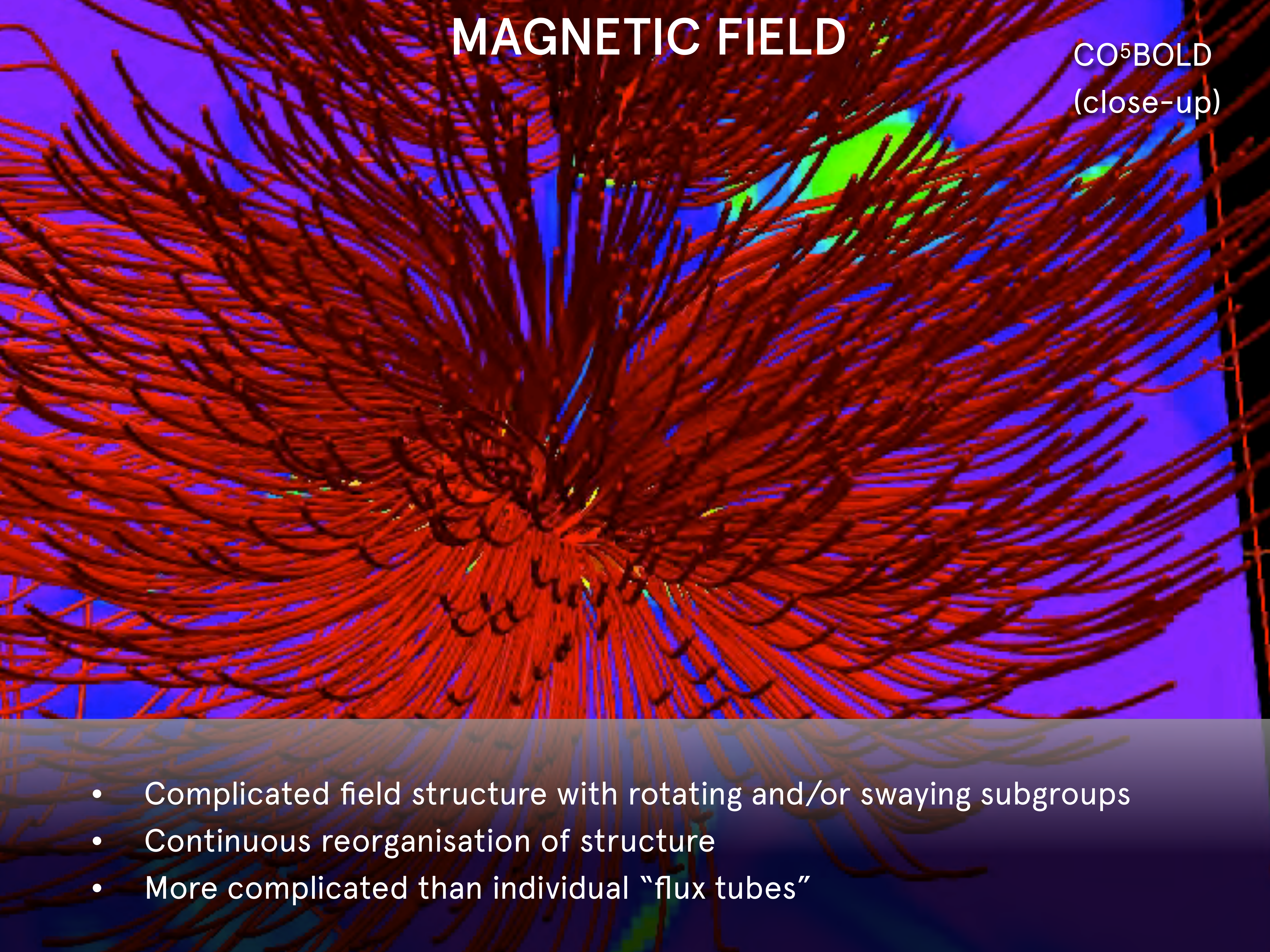
QUIET SUN

- Propagating waves
- High-beta regions in upper atmosphere (realistic?)

Bifrost



MAGNETIC FIELD

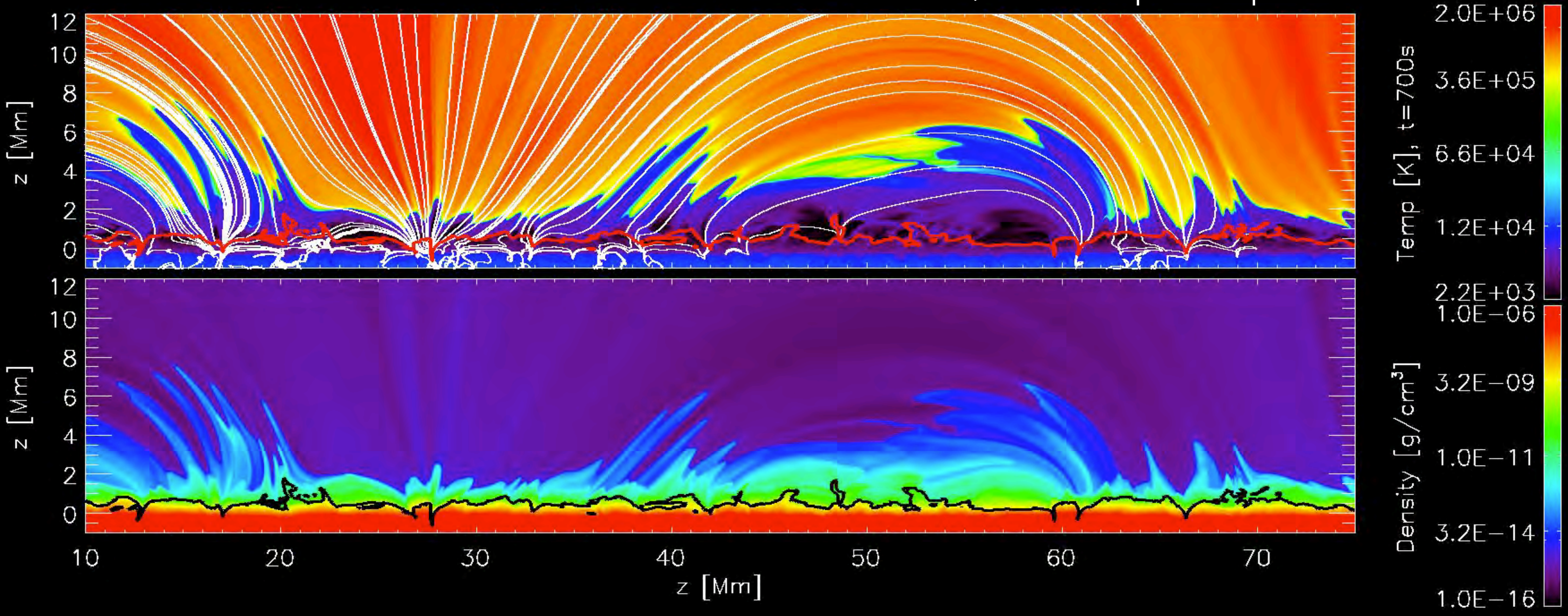

CO^{5}BOLD
(close-up)

- Complicated field structure with rotating and/or swaying subgroups
- Continuous reorganisation of structure
- More complicated than individual “flux tubes”

ION-NEUTRAL INTERACTIONS

- So far ideal MHD but chromosphere partially ionized
- Next step: Single fluid MHD + Generalized Ohm's Law
  - Good approximation as long as collision times are short

Bifrost simulation (90 Mm x 43 Mm at 16 km resolution, 190 G in photosphere)



Martínez-Sykora et al. 2017 (Science 356, 1269)

MULTI-FLUID / MULTI-SPECIES

- Chromosphere (weakly) ionized

  ➡ Thermodynamics affected by interaction between ionized and neutral particles

- Next step: multi-fluid / multi-species 3D radiative MHD code
  - Hall and ambipolar diffusion in the electric field
  - Different modes:
    - 2-fluids (e.g., ions + neutrals or ions+free electrons)
    - 3-fluids (ions + neutrals + free electrons)
    - Multi-species (ions and neutrals for each species, e.g., H and He)

- Code in the testing / early production stage

Martínez-Sykora, Szydlarski et al. (in prep.)

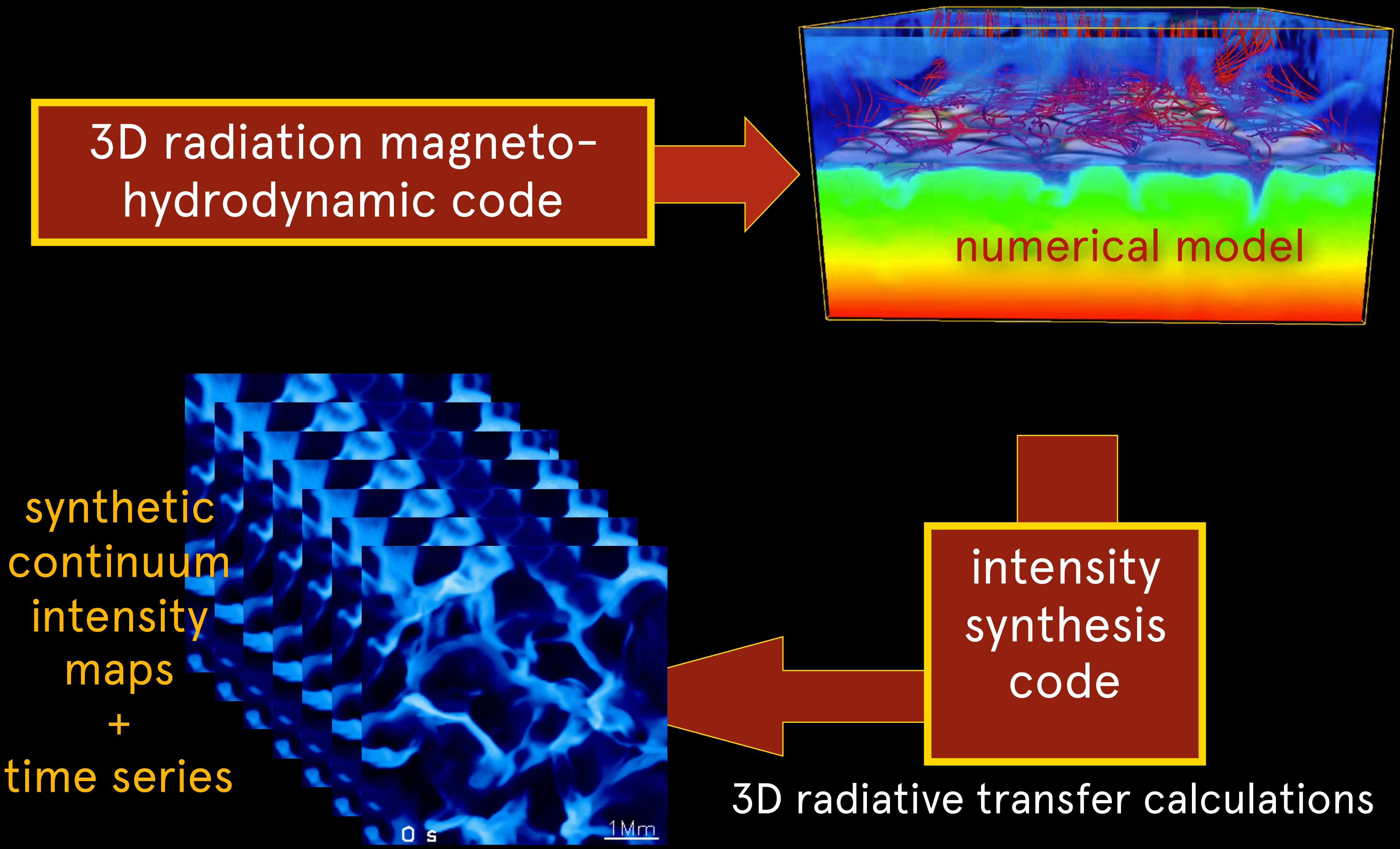
DISPATCH

- Wanted: Detailed "self-consistent" simulations of regions with strong magnetic field incl. flares
  - Effects like particle acceleration to be included properly (e.g., particle-in-cell approach)
  - Computationally prohibitive to do for a large computational domain (otherwise needed for modelled region and needed resolution)

- Simulation framework DISPATCH (Nordlund et al. 2018)
  - Can combine different modelling approaches for different regions
  - Different regions can run on different grids, resolution, time steps

PREDICTING ALMA OBSERVATIONS

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



3D radiation magneto-hydrodynamic code

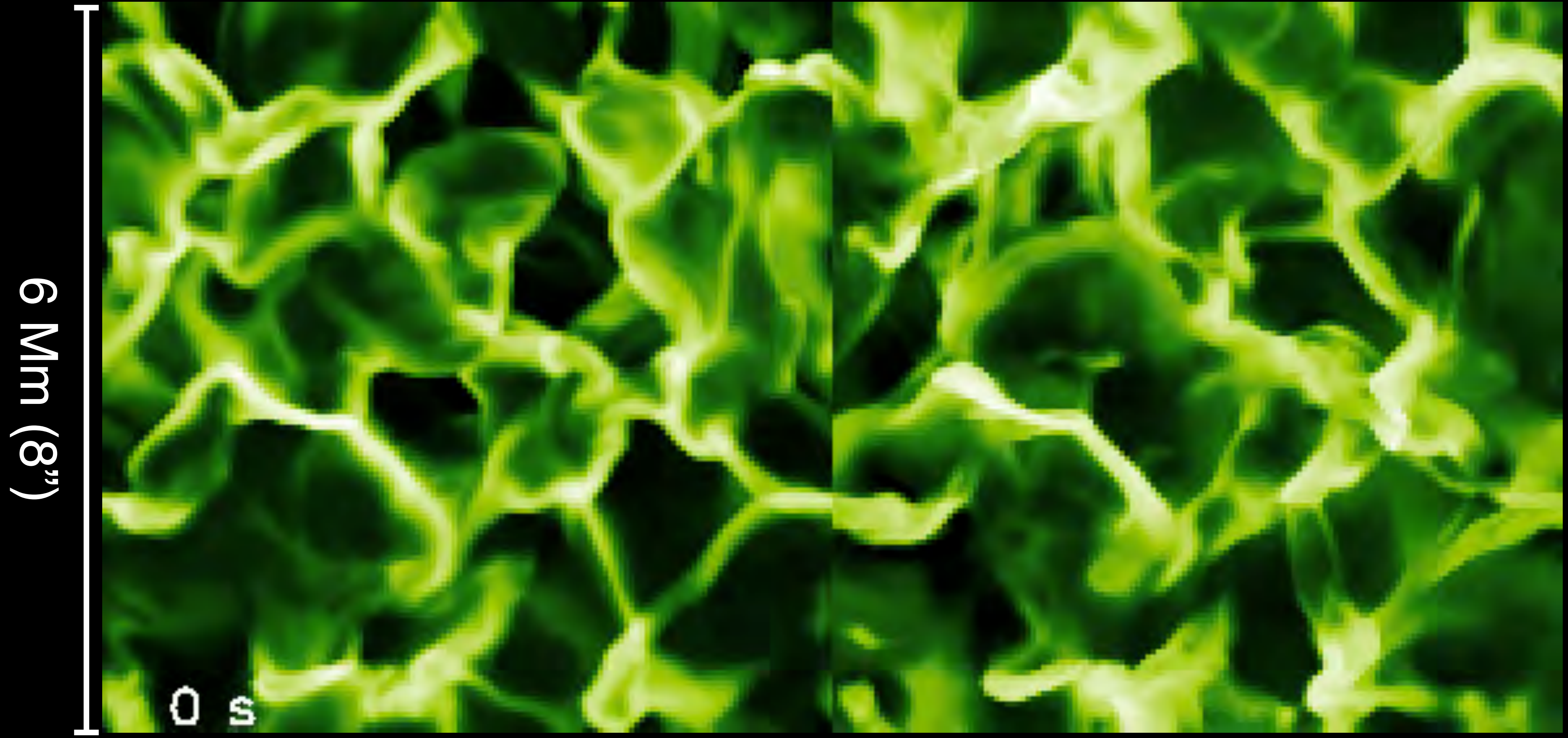
numerical model

intensity synthesis code

3D radiative transfer calculations

synthetic continuum intensity maps
+
time series

PREDICTING ALMA OBSERVATIONS



Wedemeyer et al. (2007)

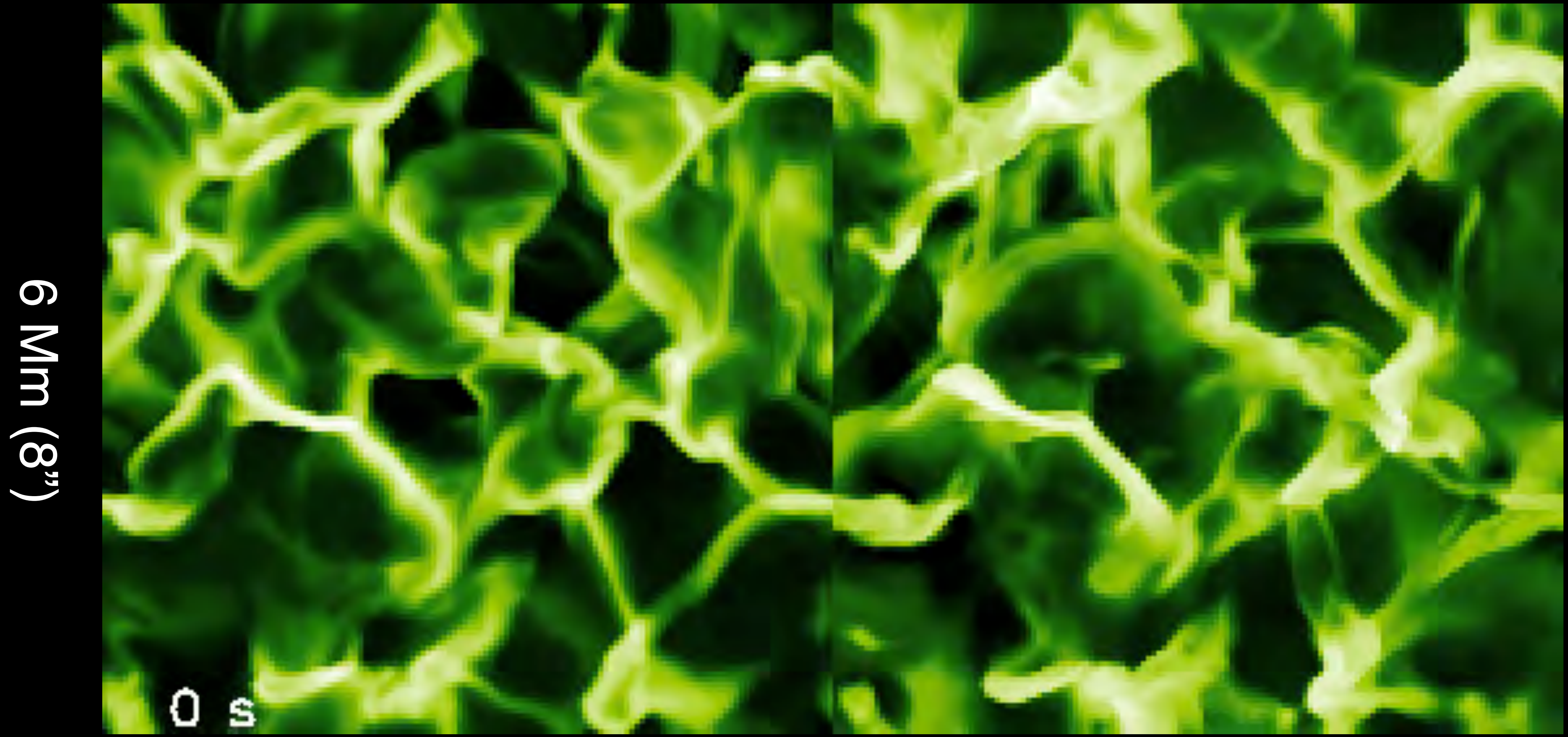
What is what?

gas temperature
at z=1000km

continuum intensity at
λ=1mm

3D hydrodynamical model
pattern produced by
the interaction of
propagating shock waves

PREDICTING ALMA OBSERVATIONS



Wedemeyer et al. (2007)

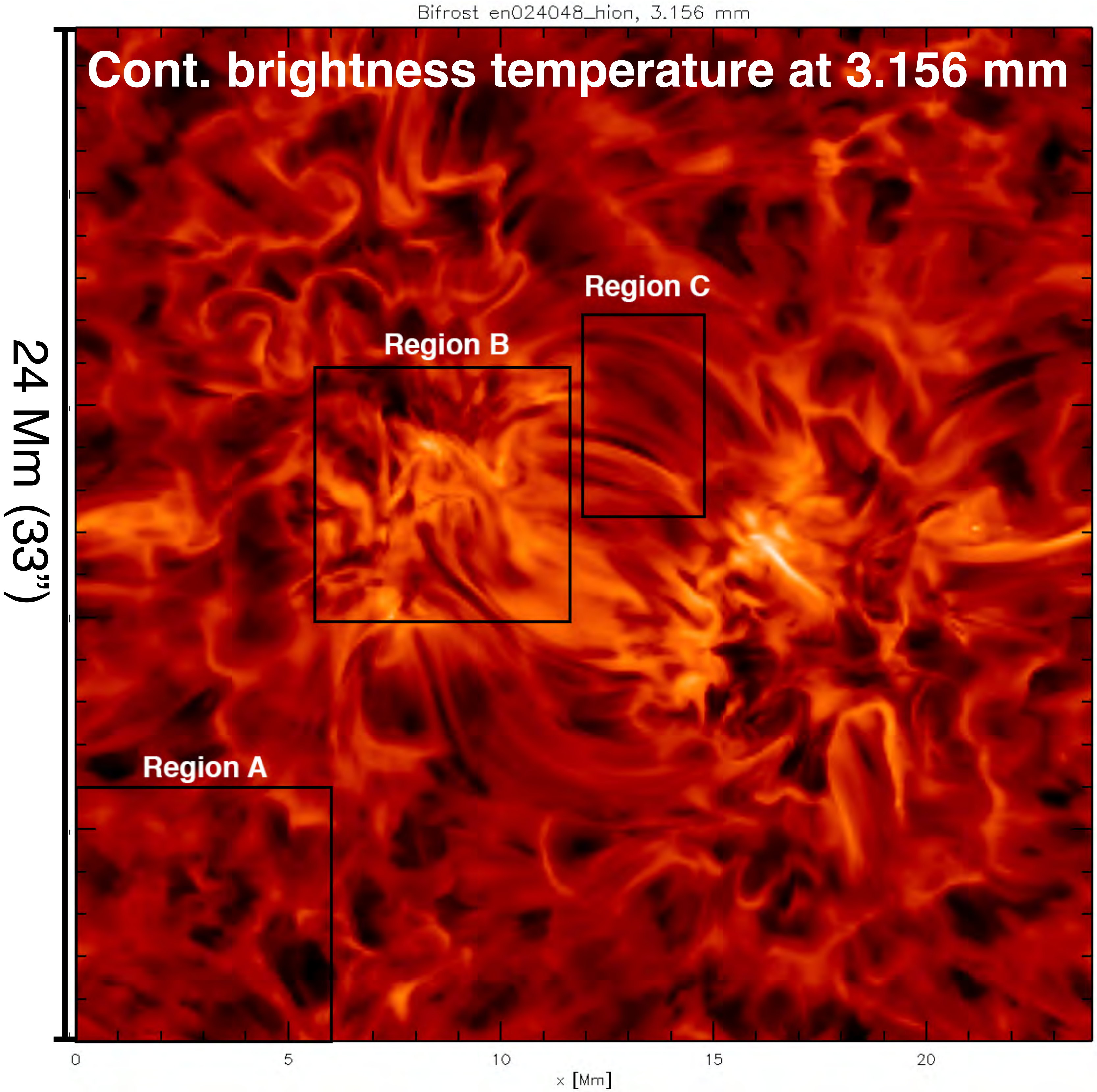
gas temperature
at z=1000km

continuum intensity at
λ=1mm

ALMA as linear thermometer for the chromospheric plasma!

➡ Gas temperature in chromosphere closely mapped

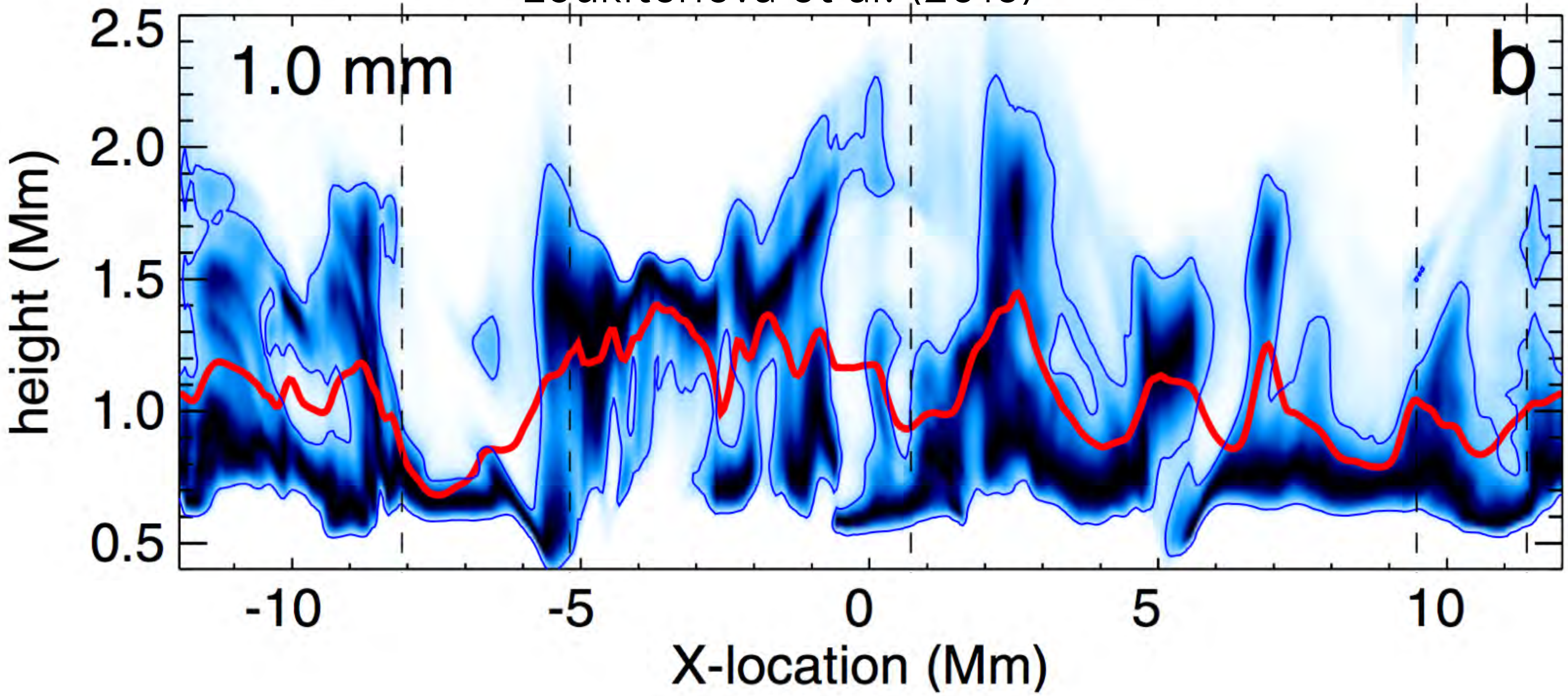
PREDICTING ALMA OBSERVATIONS



- **Bifrost snapshot** (Carlsson et al. 2016; cf. Loukitcheva et al. 2015)
- **Enhanced magnetic network:** patches of opposite polarity, coronal loops
- Used as benchmark for RT code comparison by SSALMON
    A. "Quiet Sun"
    B. Above magnetic field concentration
    C. Coronal loops

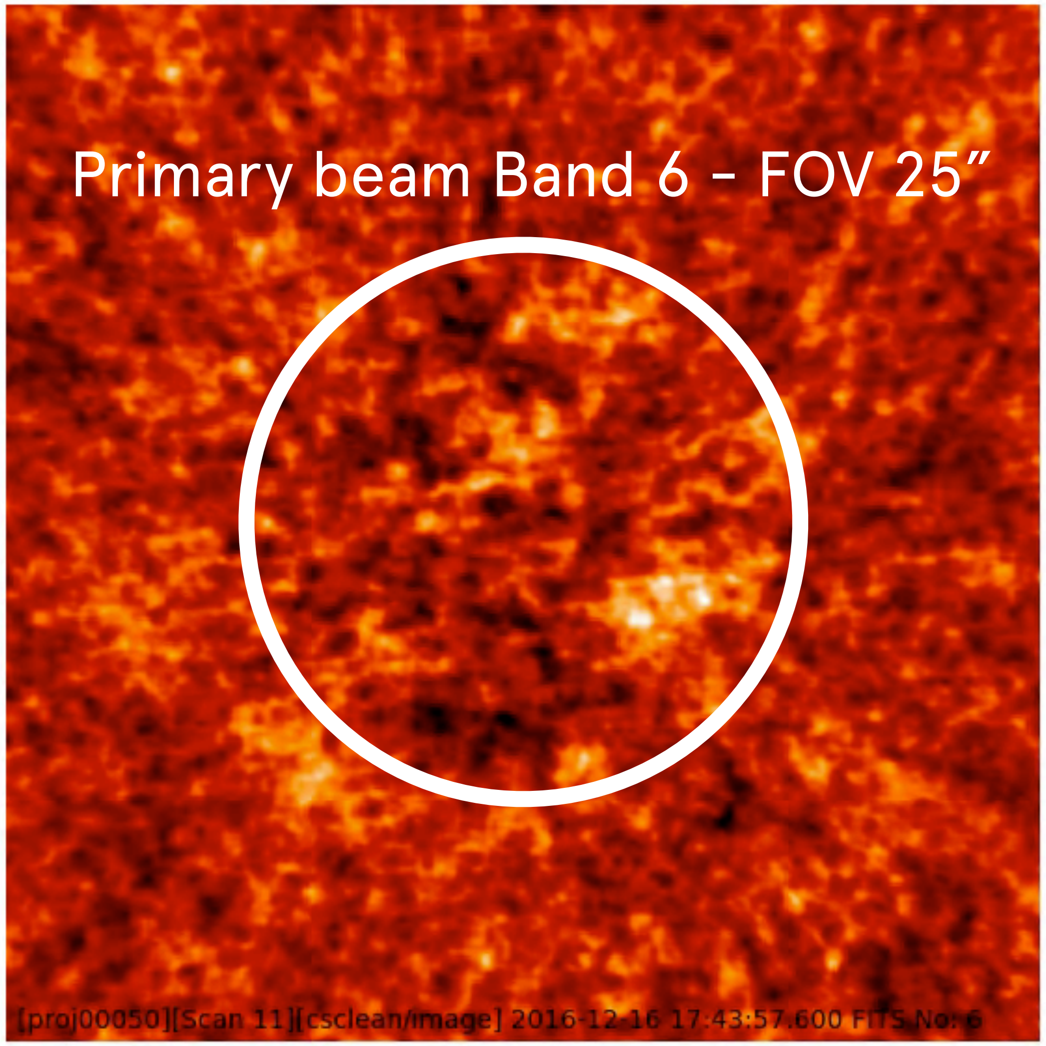
PREDICTING ALMA OBSERVATIONS

Loukitcheva et al. (2015)



- Taking into account non-equilibrium hydrogen ionisation reduces spread in height

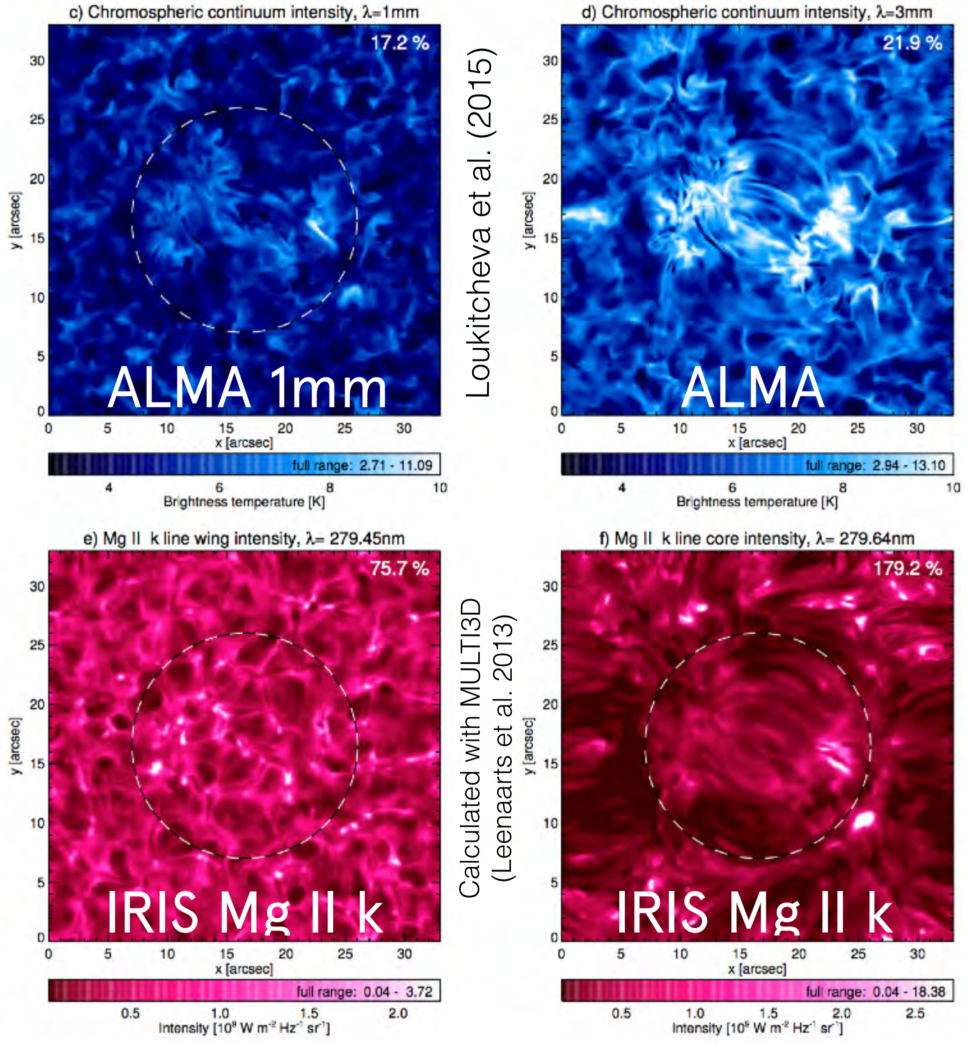
ALMA AS NEW DIAGNOSTIC TOOL



Cycle 4 (12/2016), Quiet Sun, Band 6

- ALMA: In future several 1000 spectral channels at 1s cadence
- Rich data sets for advanced data inversions
- Models of 3D dynamic structure of the chromosphere

- RT calculations: ALMA and IRIS providing complementary information



Wedemeyer et al. 2016

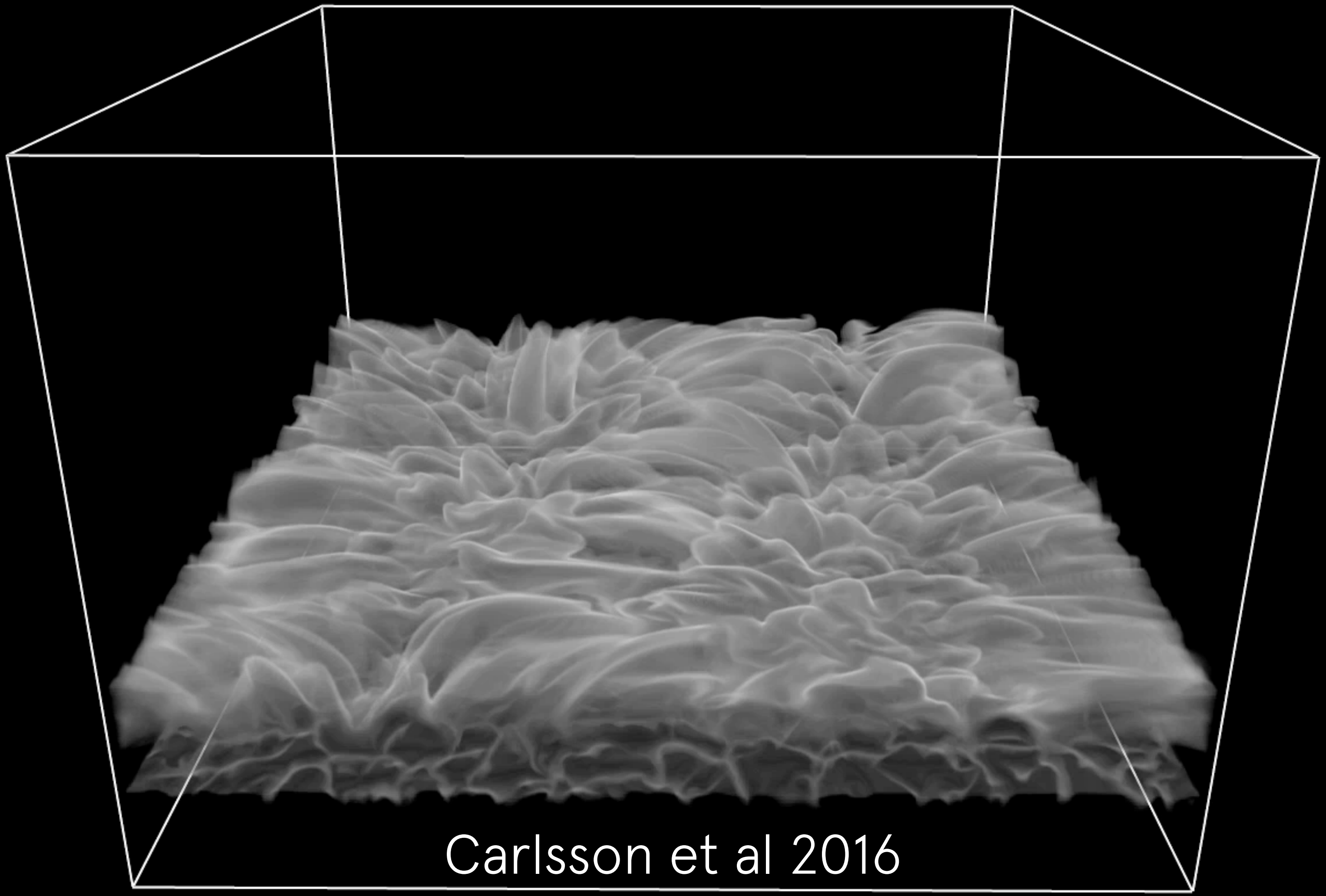
Loukitcheva et al. (2015)

Calculated with MULTI3D (Leenaarts et al. 2013)

Credits: ALMA (ESO/NAOJ/NRAO)

SUMMARY AND OUTLOOK

- Chromosphere still a challenging object to model
- Provides though tests for numerical simulation codes
- Numerical models with increasing degree of realism
- Still a lot to do …



Carlsson et al 2016

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