Heating of the solar chromosphere

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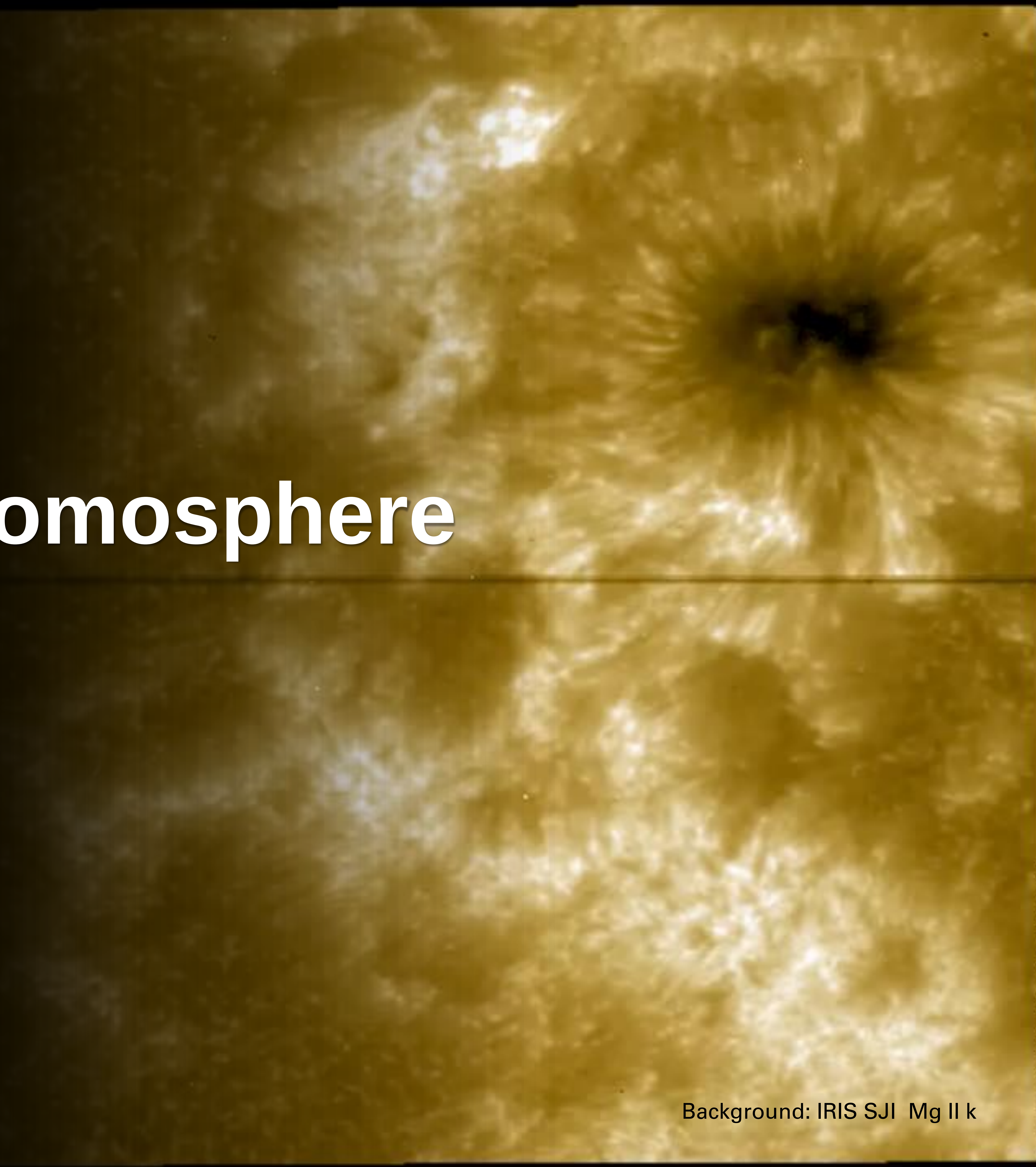
X. Zhu, S. White, G. Vissers & M. Rempel



Background: IRIS SJI Mg II k

Radiative energy losses [kW m^{-2}]

compiled by Withbroe & Noyes (**1977**)

	Lower chromosphere	Upper chromosphere	Total
QS	2	0.3	4
AR	≥10	2	20

Heating mechanisms

compiled by Withbroe and Noyes (**1977**)

QS	**acoustic shocks**, reconnection, Joule heating
AR	**MHD waves**, reconnection, Joule heating

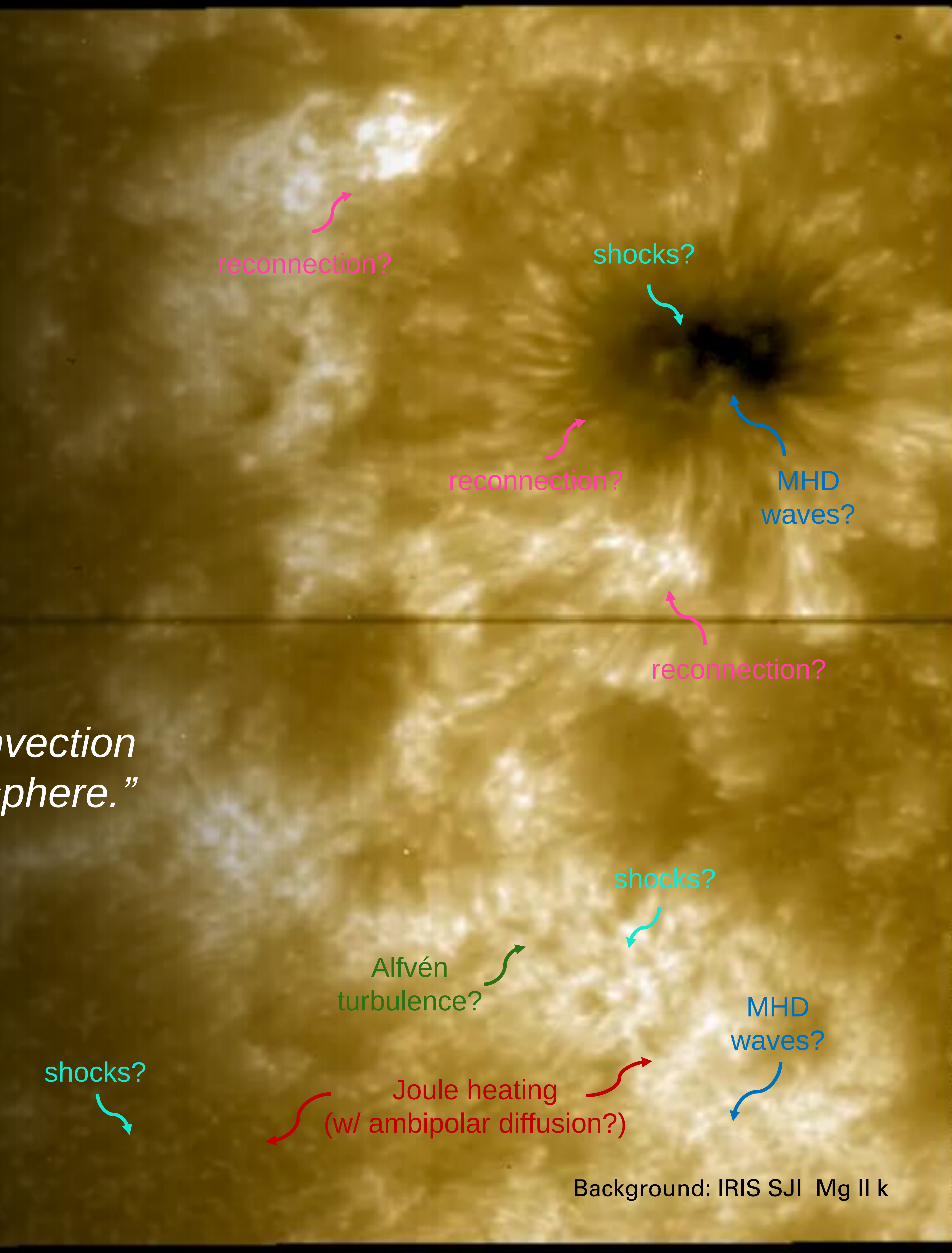
other: mass flows and thermal conduction from above

“(…) dissipation of energy carried by waves generated in the convection zone is the most likely source of the energy heating the chromosphere.”

Heating mechanisms

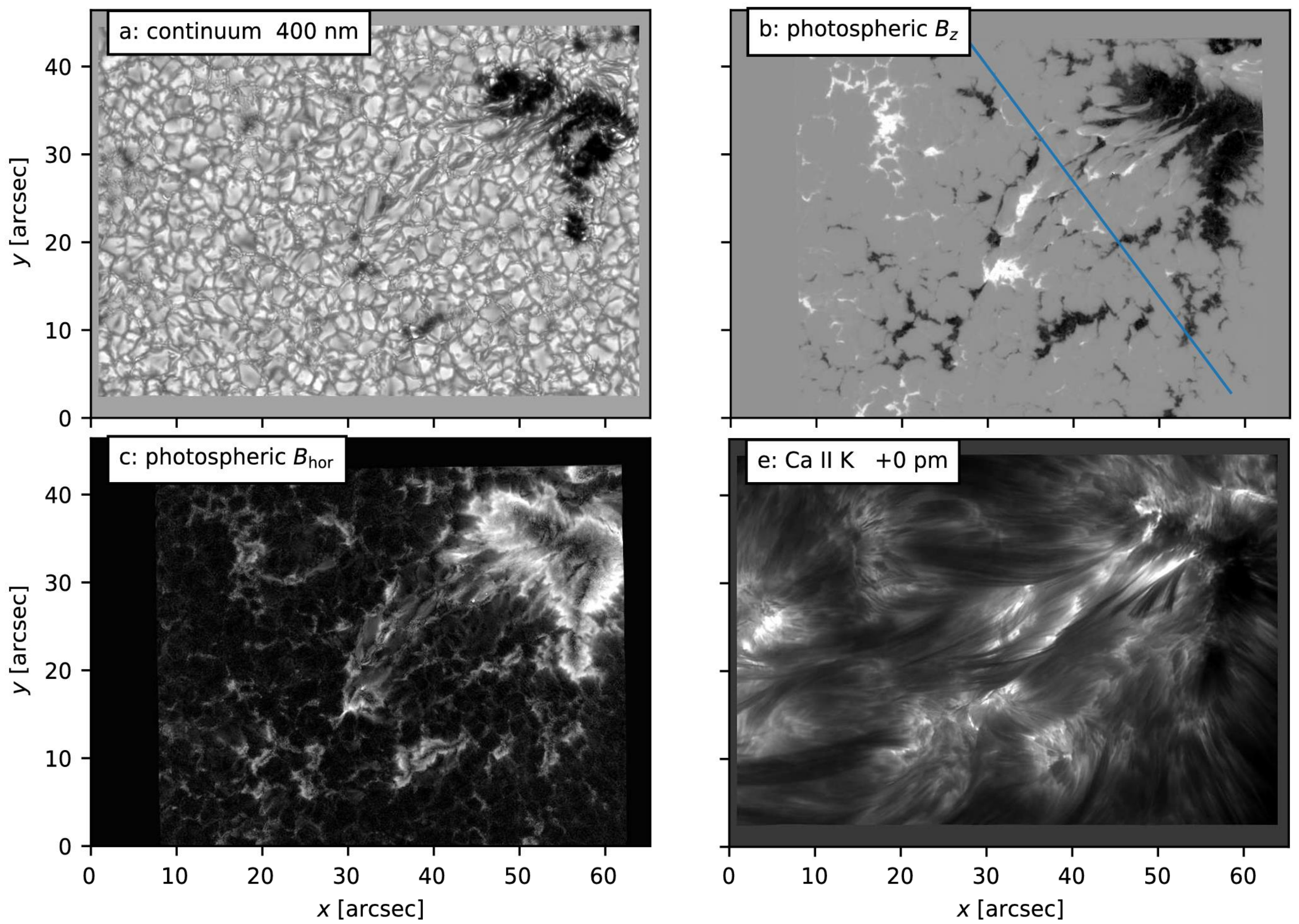
compiled by Carlsson, De Pontieu & Hansteen (**2019**)

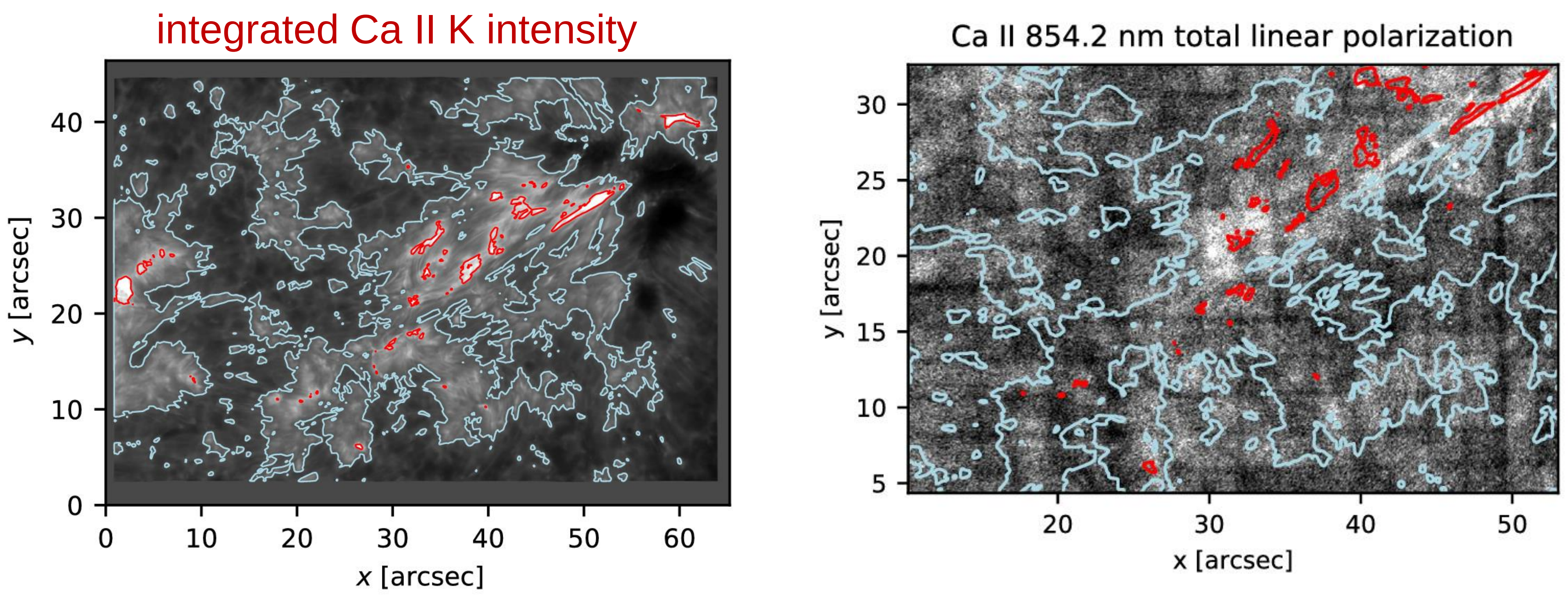
QS	acoustic shocks, reconnection, Joule heating, ion-neutral effects
AR	magnetoacoustic shocks, reconnection, Joule heating, Alfvén turbulence, MHD waves, ion-neutral effects



High-resolution proxies for chromospheric heating

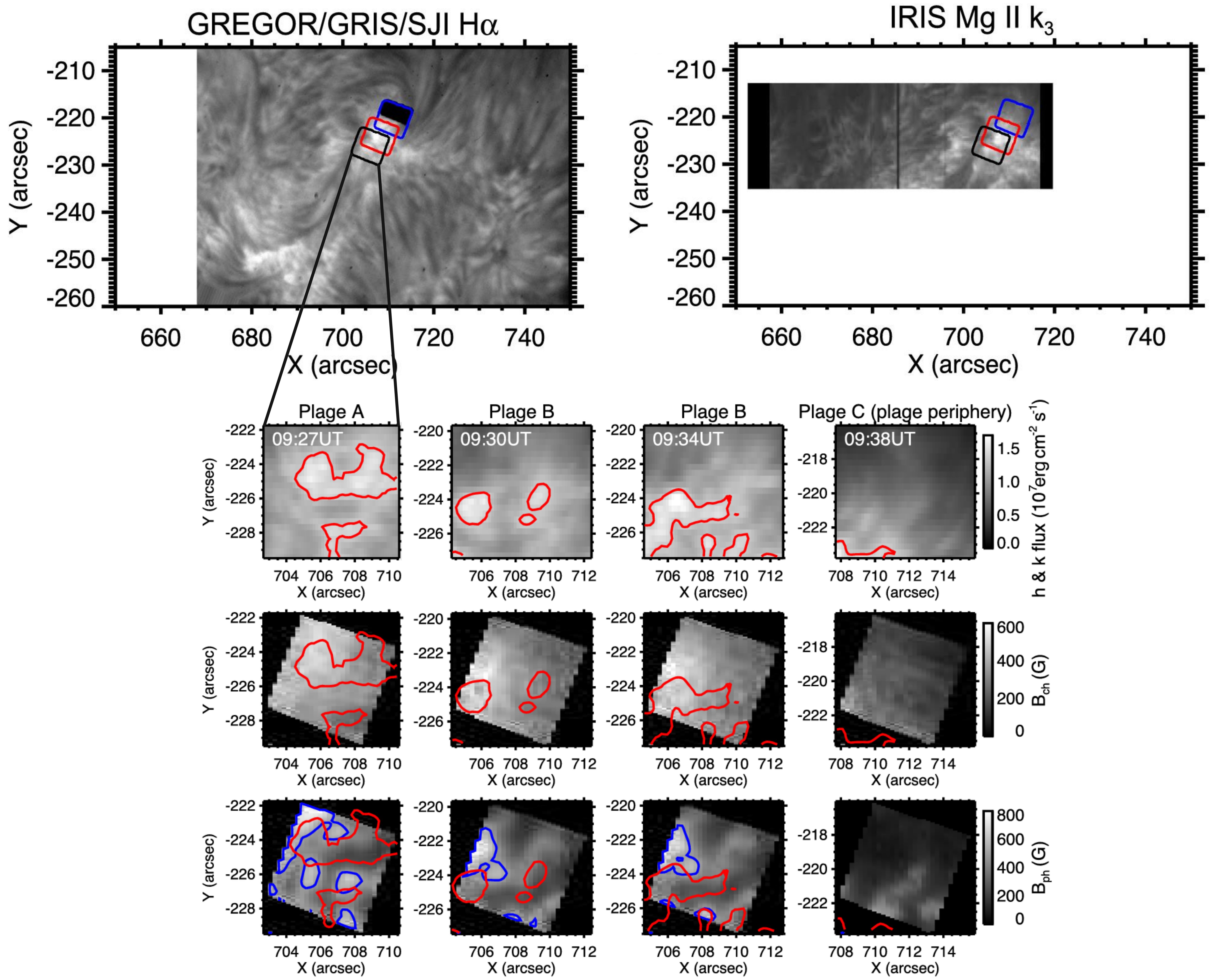
SST/CRISP and CHROMIS observations





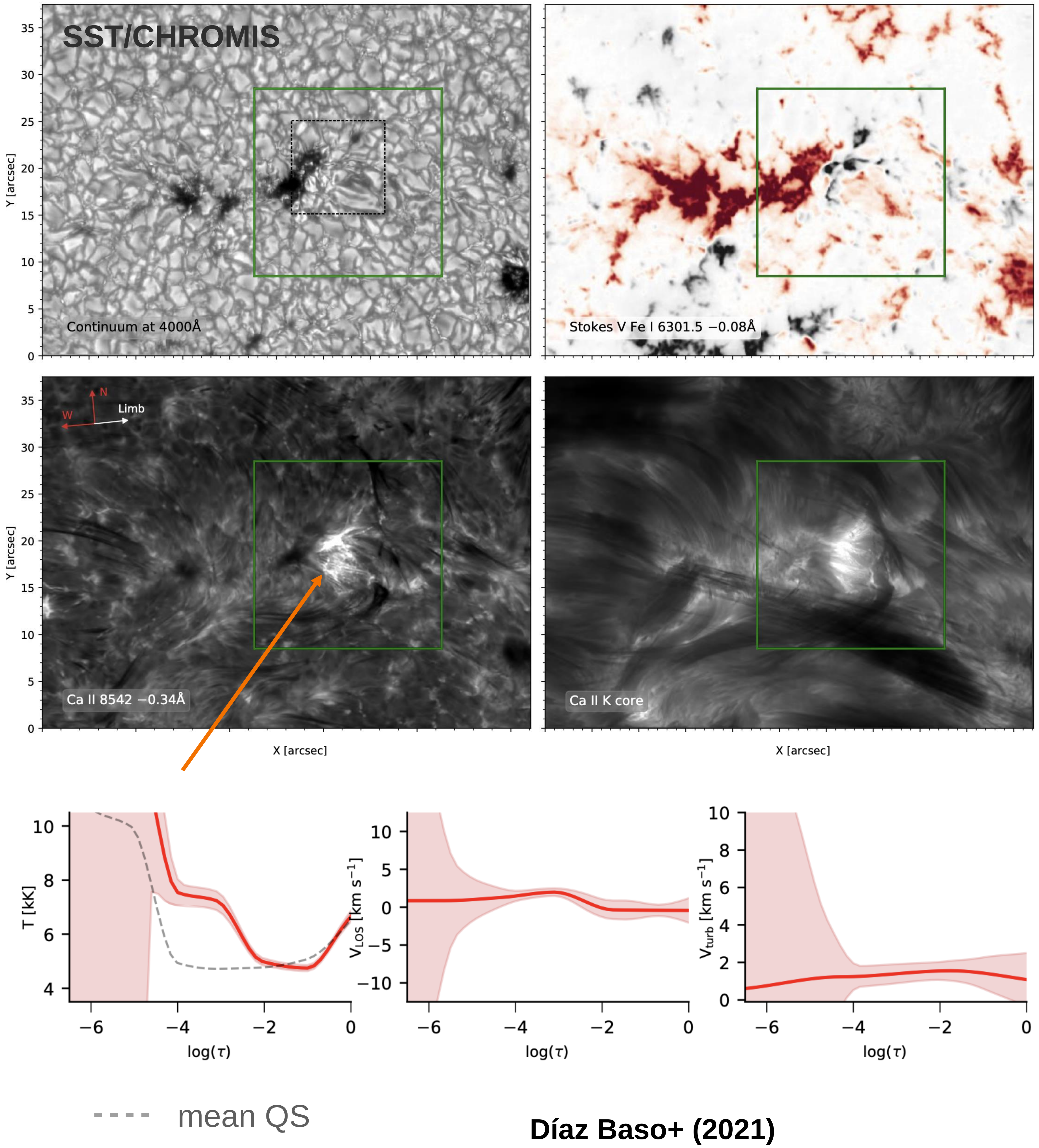
Leenaarts+ (2018)

GREGOR/GRIS and IRIS observations

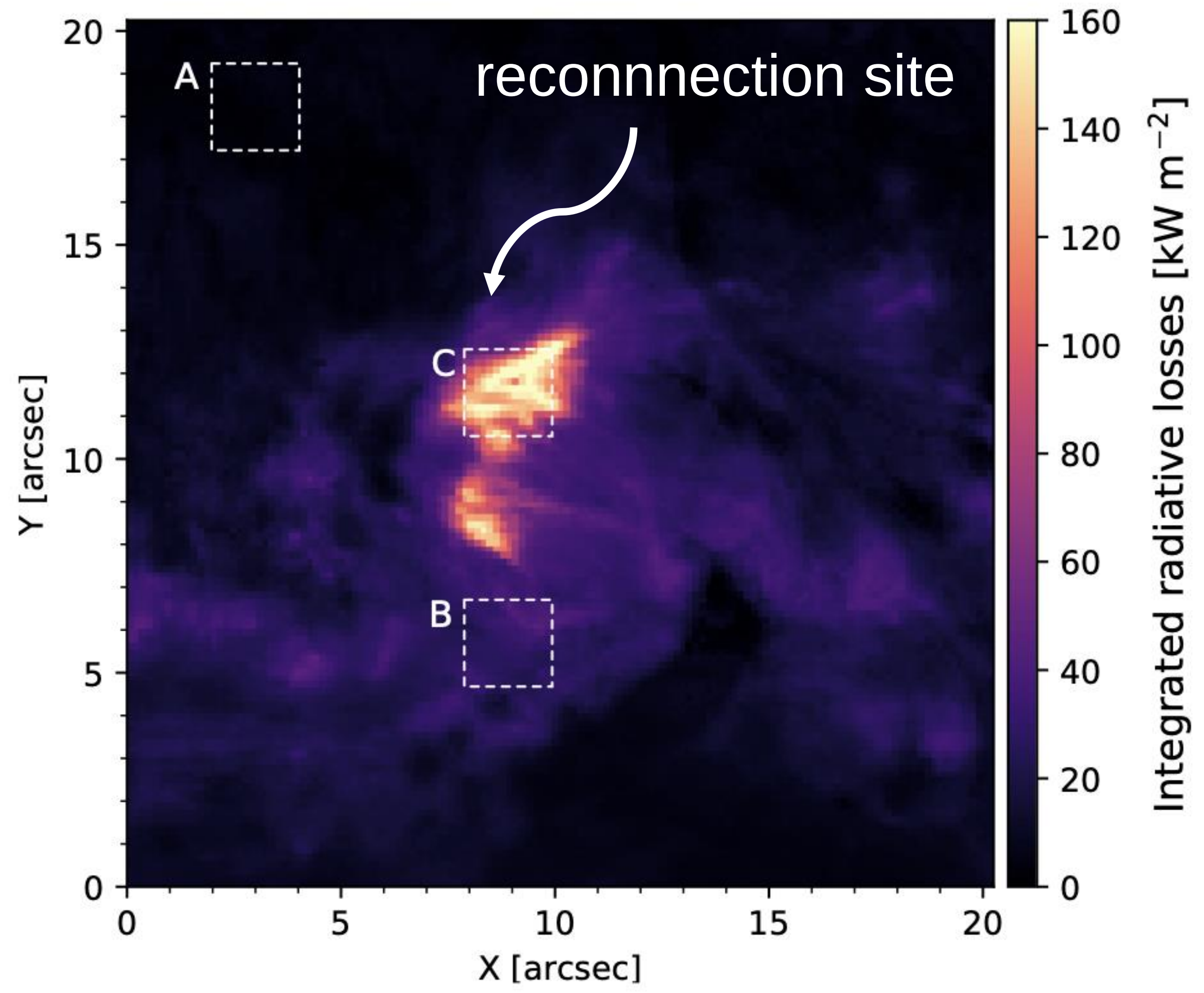


Anan+ (2021)

Spatially resolved chromospheric radiative losses



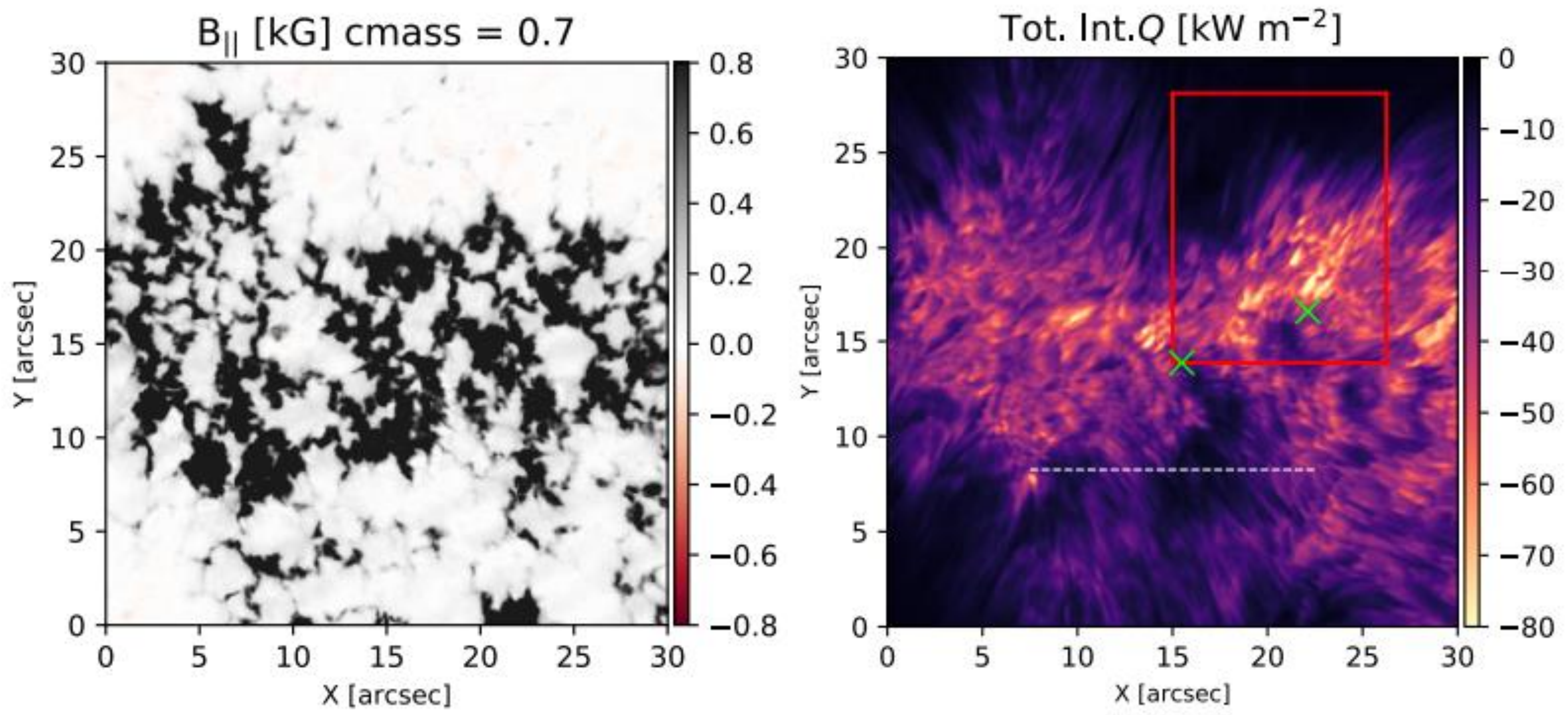
Díaz Baso+ (2021)



“<QS>”: 4.5 kW m^{-2}
AR: 20-50 kW m^{-2}
burst: up to 160 kW m^{-2}

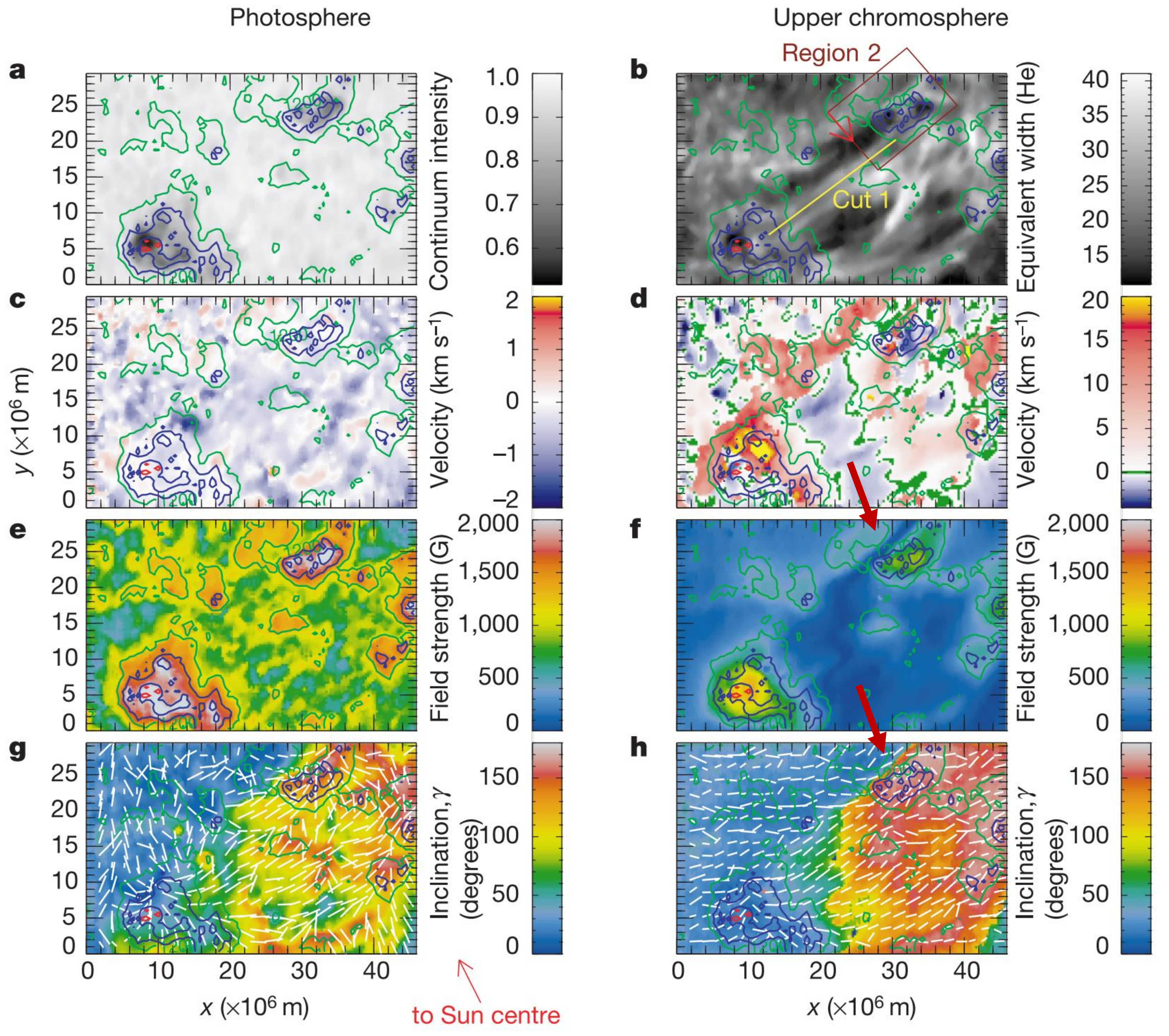
(total) dominated by the low chromosphere

Morosin+ (2022)



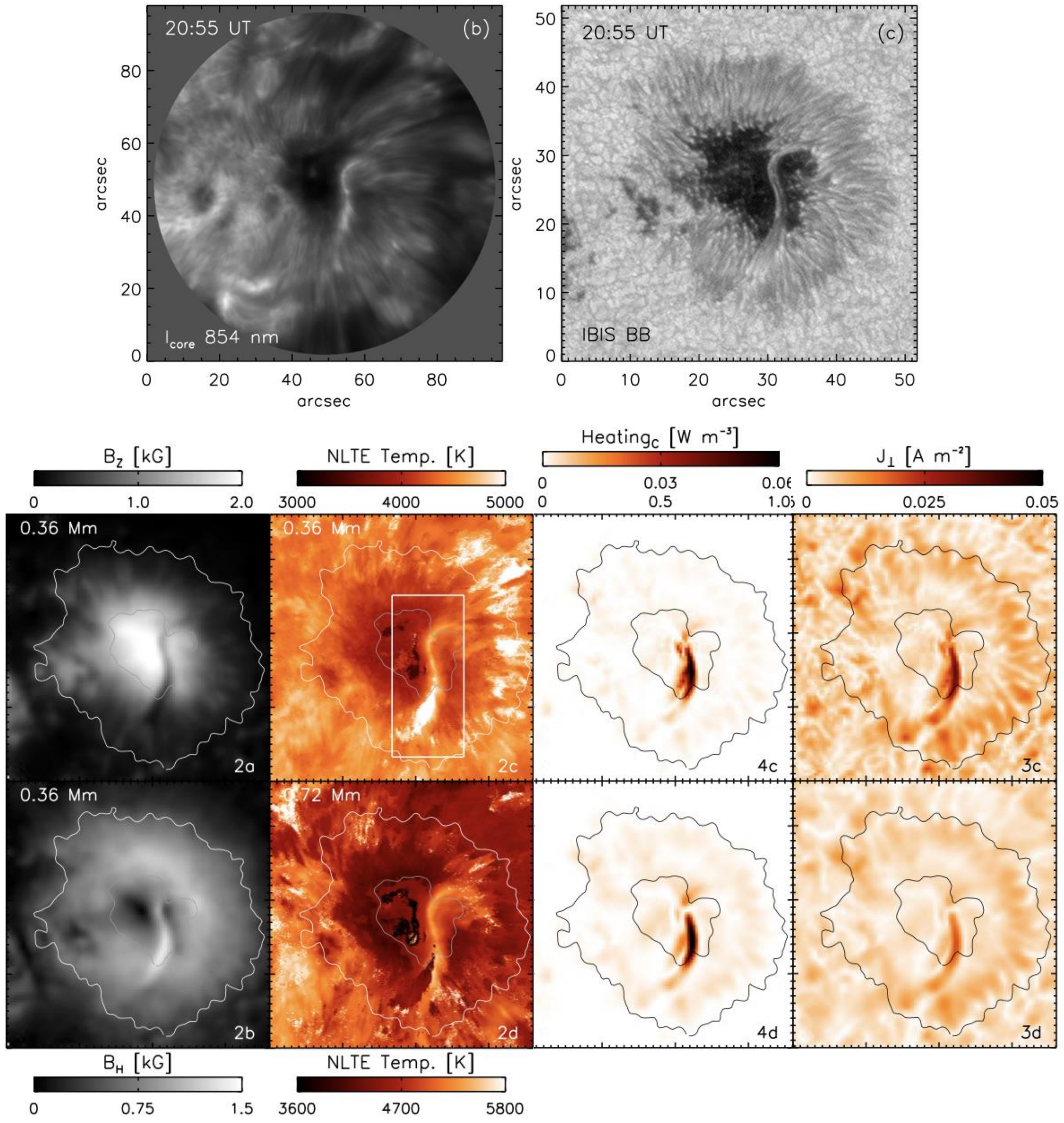
Electric currents in the chromosphere are poorly understood

He I 10830, VTT observations



Solanki+ (2003)

Ca II 8542, Dunn/IBIS observations

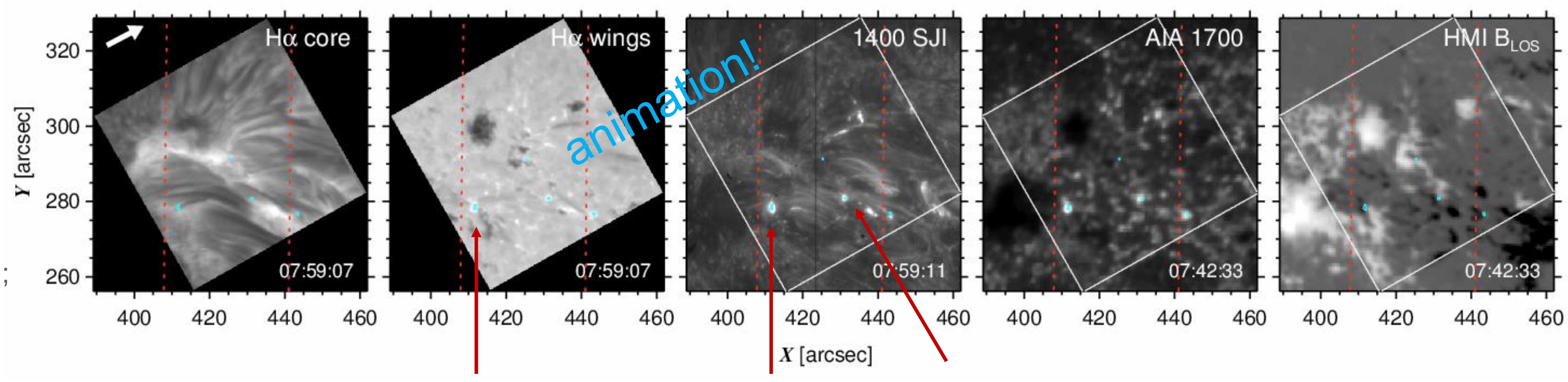


Louis+ (2021)

Heating in chromospheric current sheets: UV-bursts

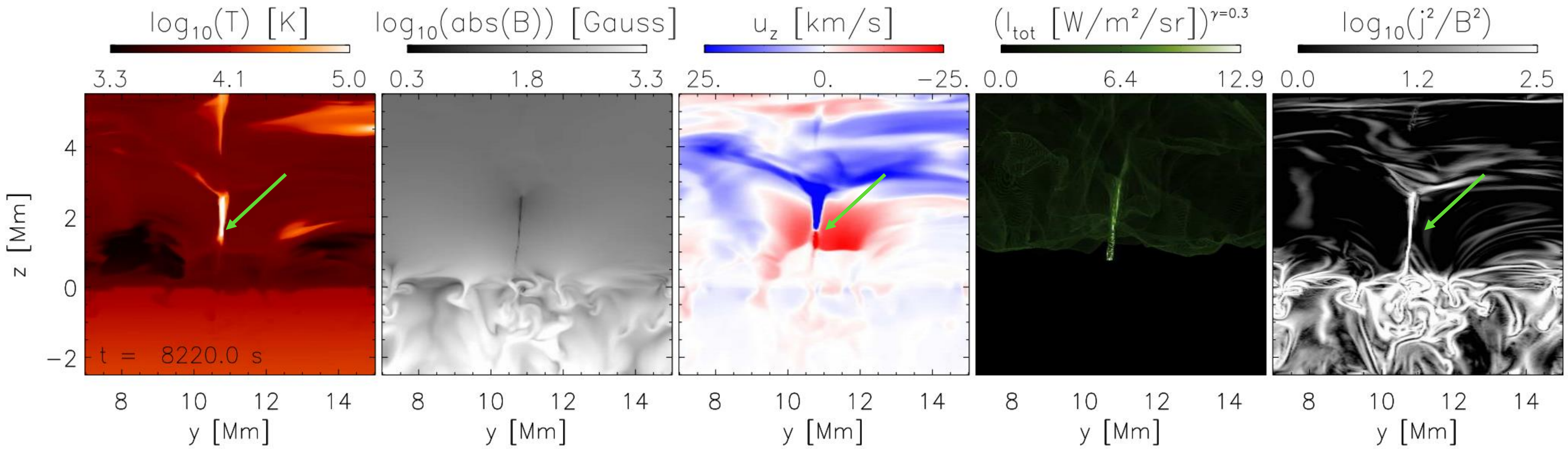
IRIS, AIA, SST observations
Vissers+ (2015)

see also, e.g., Peter+(2014); Guglielmino+(2018) Tian++(2018)



Ellerman bombs **UV-bursts** **Flaring active region fibrils**

2D cut of a 3D Bifrost simulation



Hansteen+ (2019)

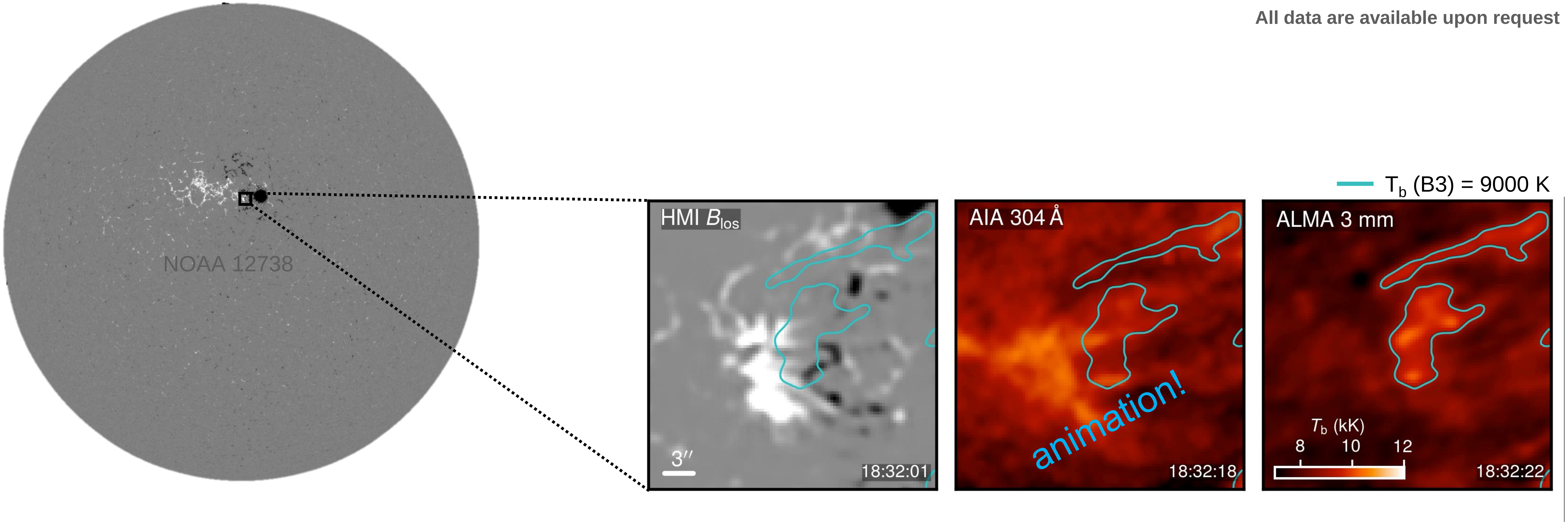
see also, e.g., Nobrega-Siverio+ (2017); Priest+ (2018); Peter+ (2019)

Joint observations with ALMA and the 1-m SST in 2019

da Silva Santos+ (2020, 2022a, 2022b)

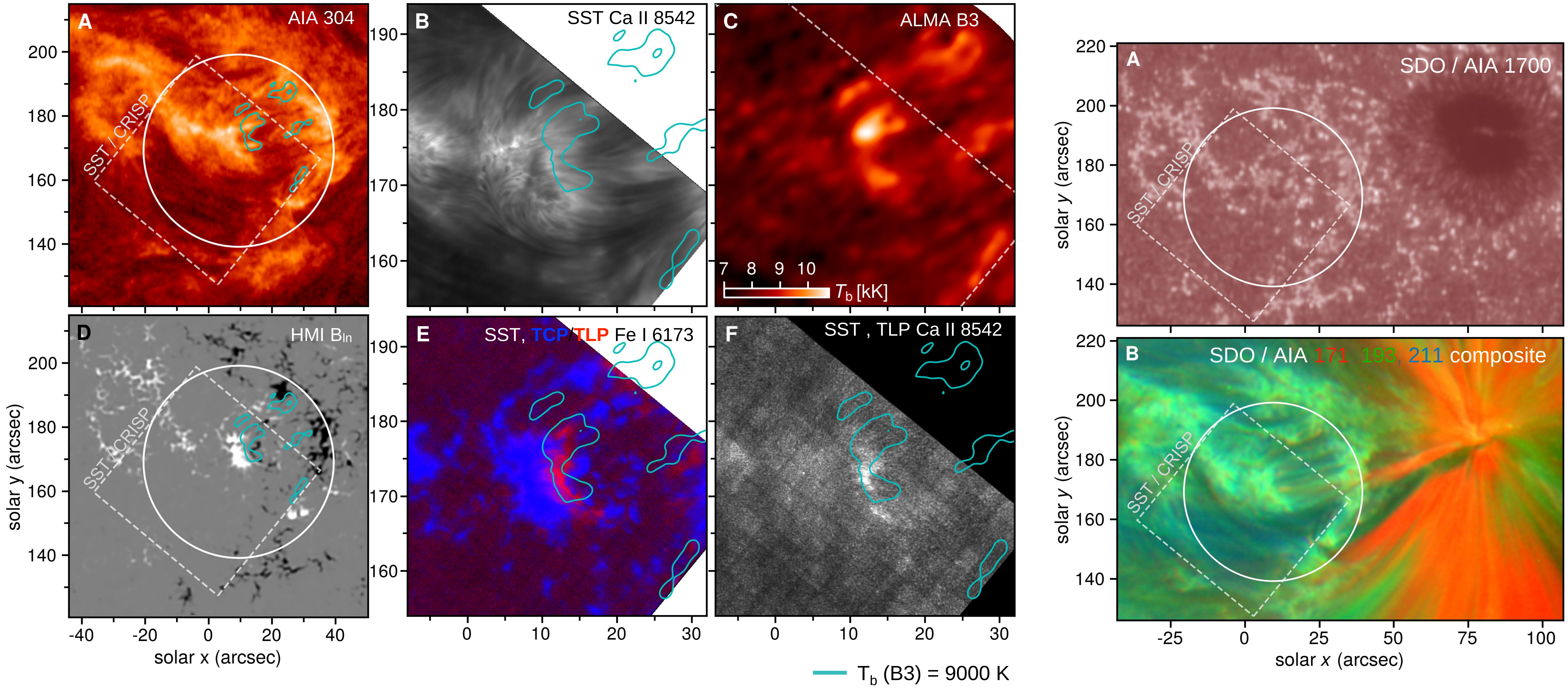
14:15 … 17:50 UT	**IRIS:** NUV (e.g. Mg II h and k), FUV (e.g. Si IV, C II) passbands, dense raster **Hinode/SOT/SP and EIS:** Fe I 6301 magnetograms and EUV lines **ALMA:** Band 6 (1.25 mm continuum), baselines up to 700 m – 0.6 arcsec, mosaic
18:50 UT	**SST/CRISP:** Ca II 8542 and Fe I 6173 (polarimetry), single scan **ALMA:** Band 3 (3 mm continuum), baselines up to 700 m – 1.2 arcsec, 2sec cadence

All data are available upon request



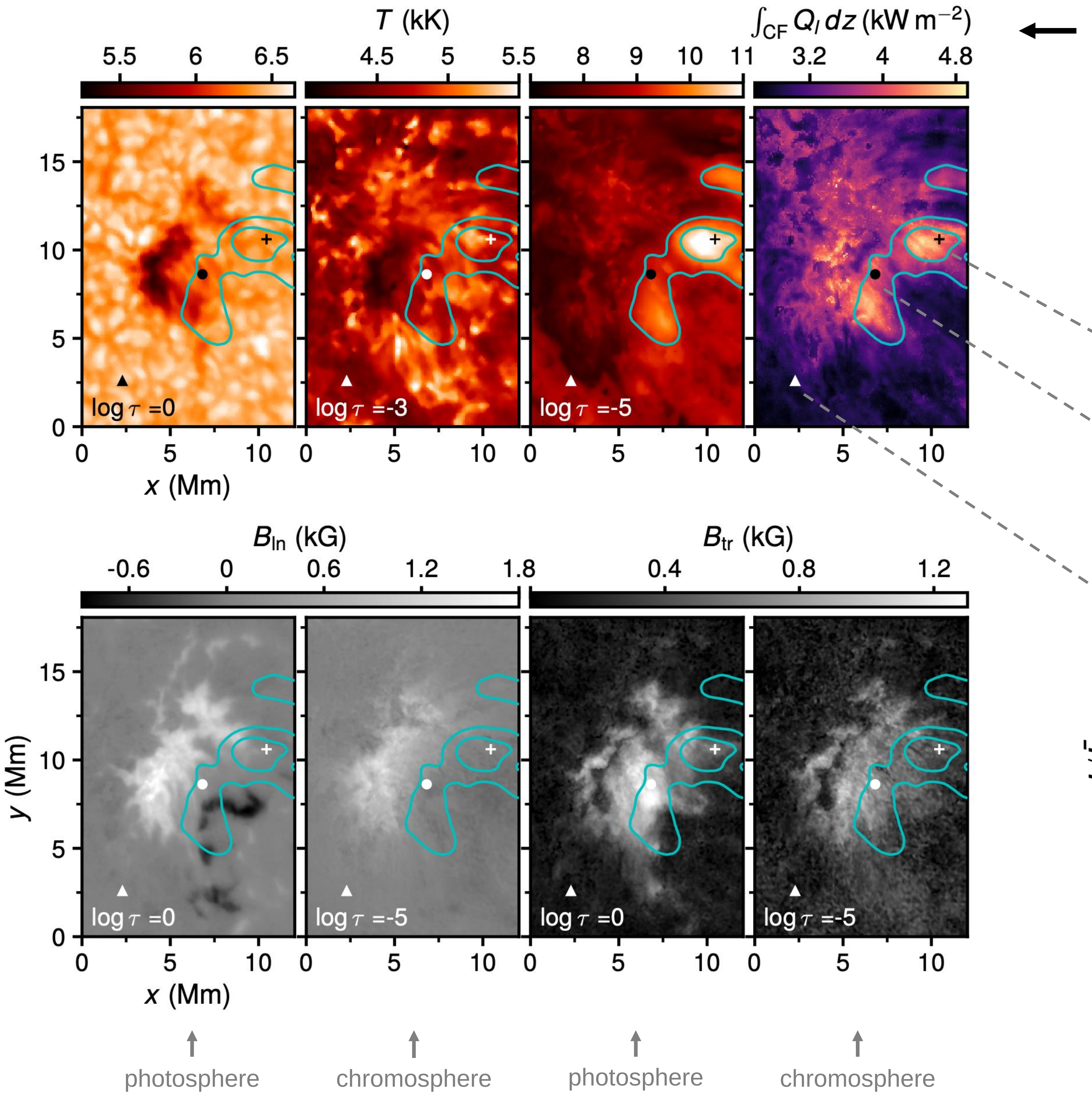
Flux emergence and chromospheric heating

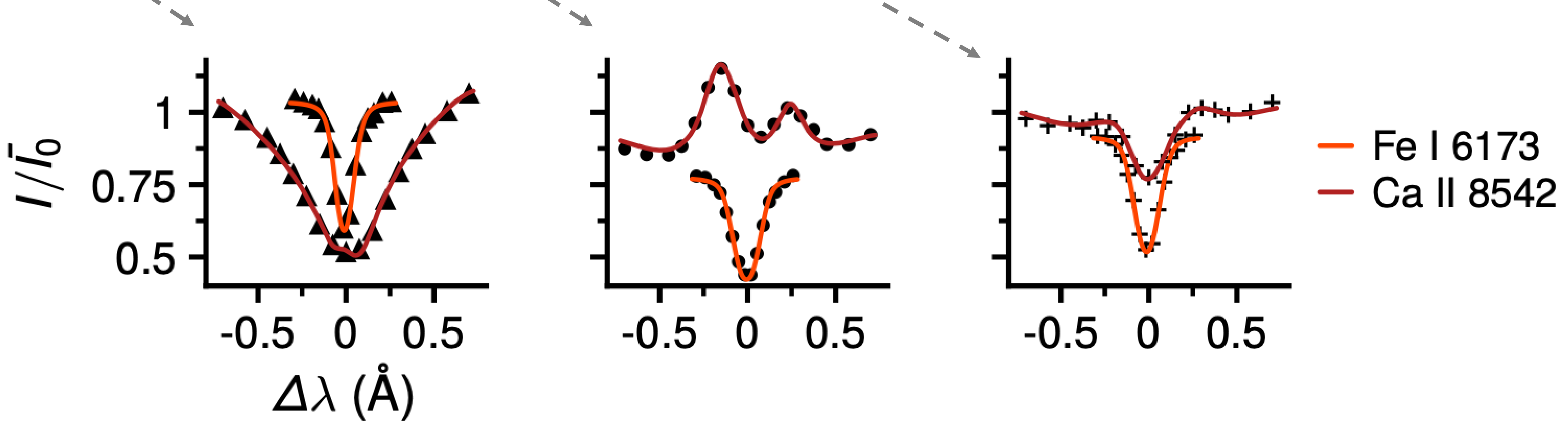
da Silva Santos+ (2022, *A&A, 661, A59*)



Non-LTE inversions of SST/CRISP+ALMA 3 mm data

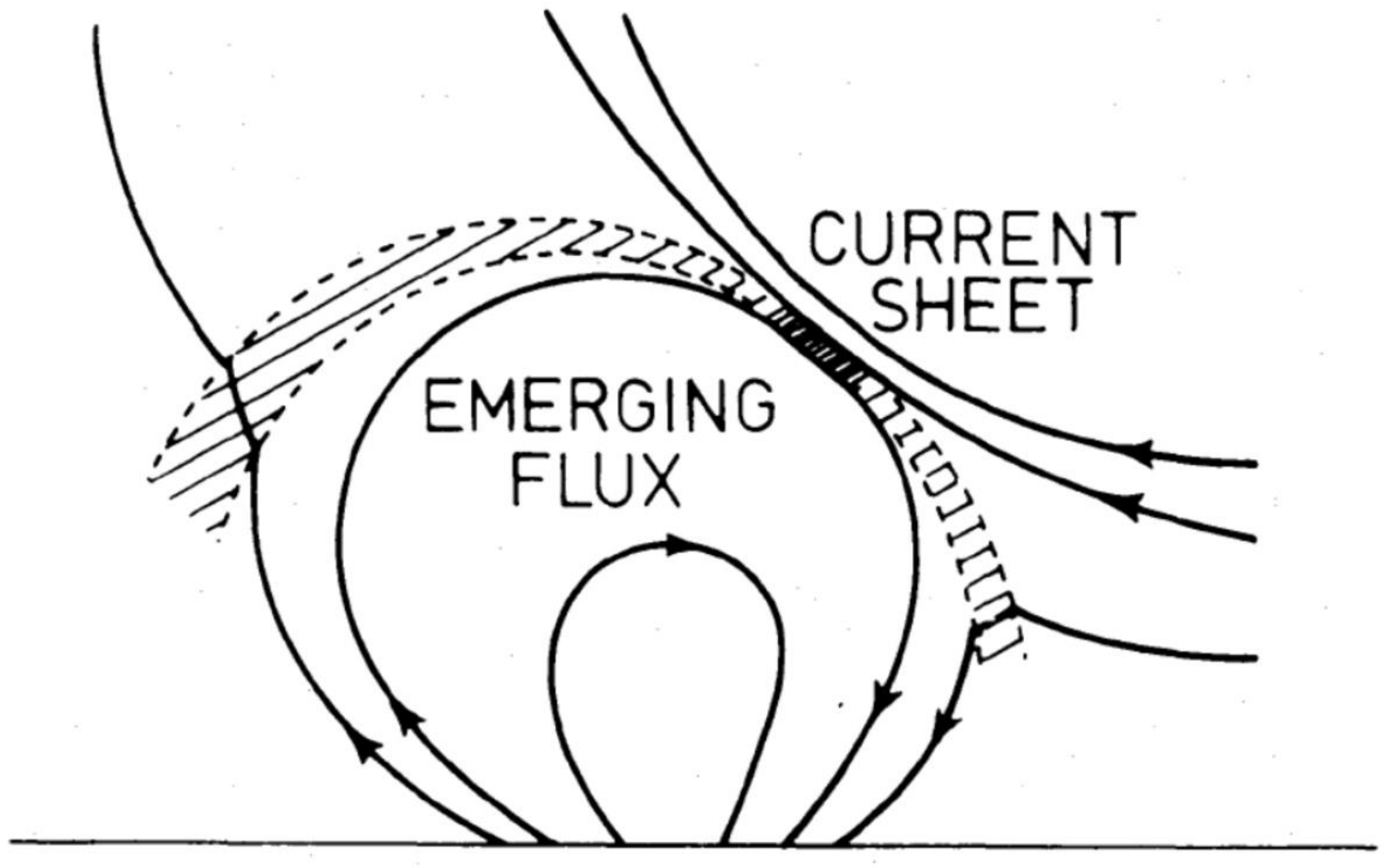
Radiative losses (Ca II, Mg II, HI) within the contribution function of the 3 mm continuum (upper chromosphere T ~ 10,000 K)





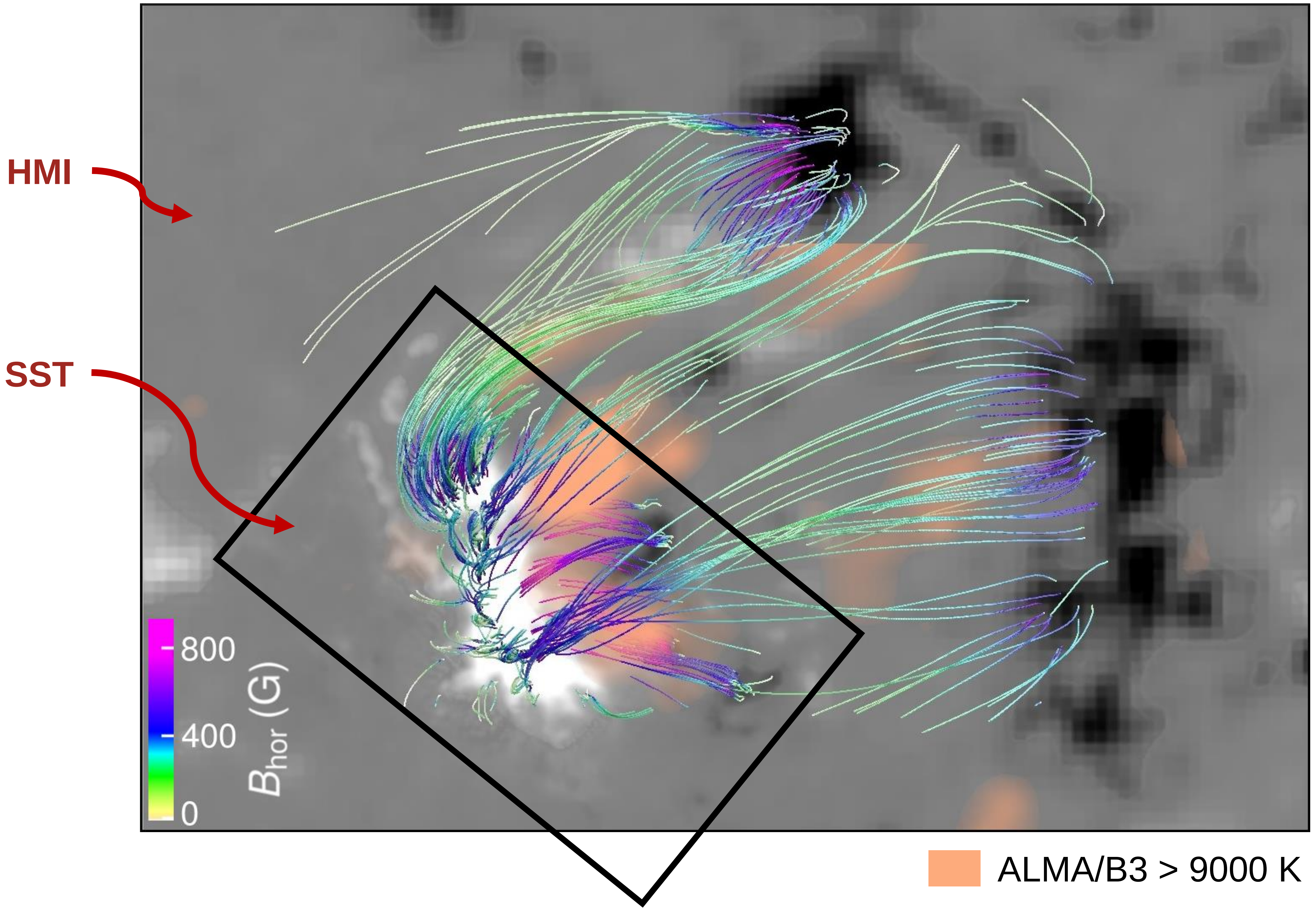
example fits at different locations

Magnetohydrostatic extrapolation based on the SST+HMI (composite) vector magnetogram



Heyvaerts+ (1977)

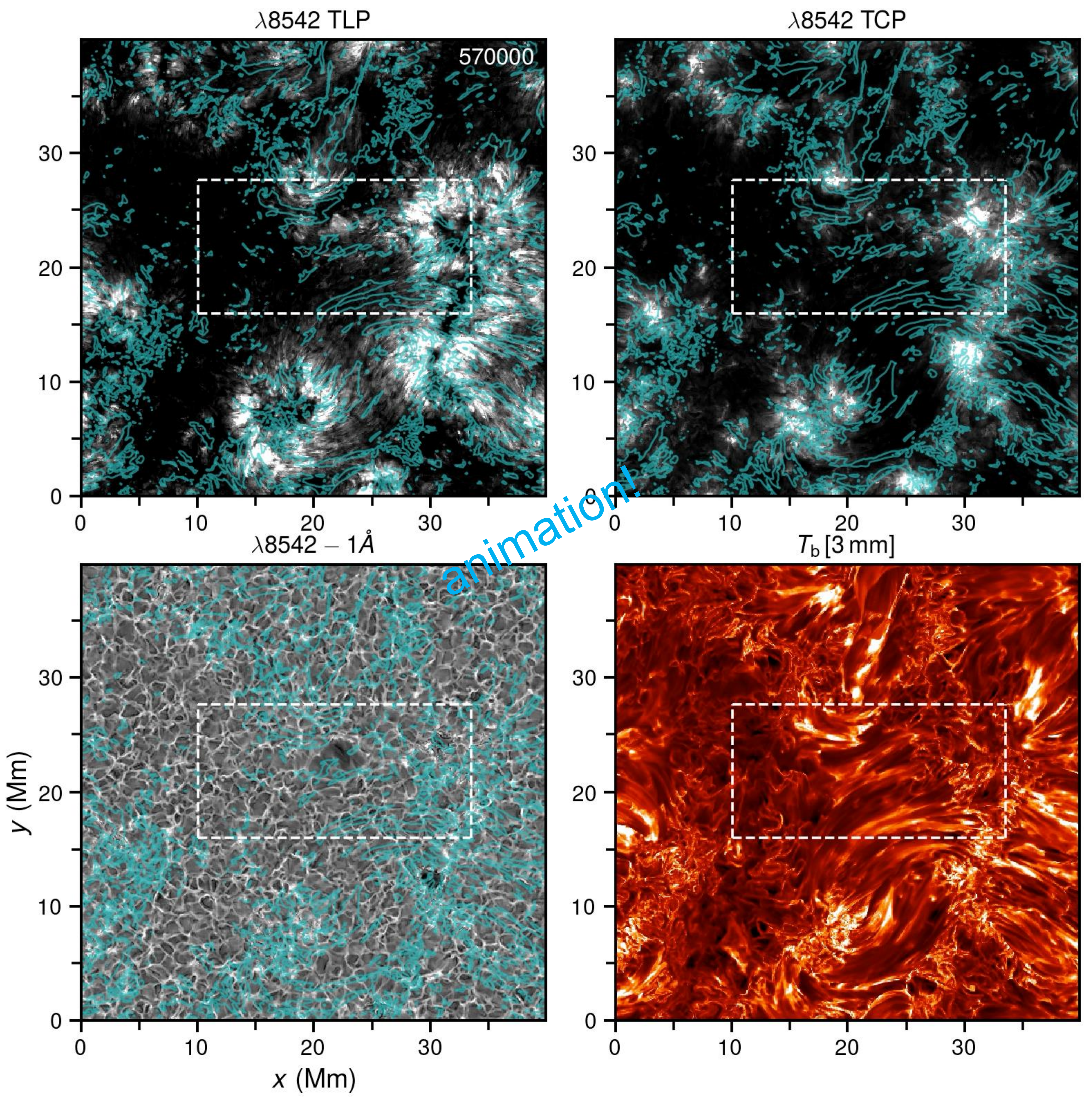
see also, e.g., Galsgaard+ (2007)
Cheung & Isobe (2014)
Archontis & Hansteen (2014)
Ortiz+ (2016)

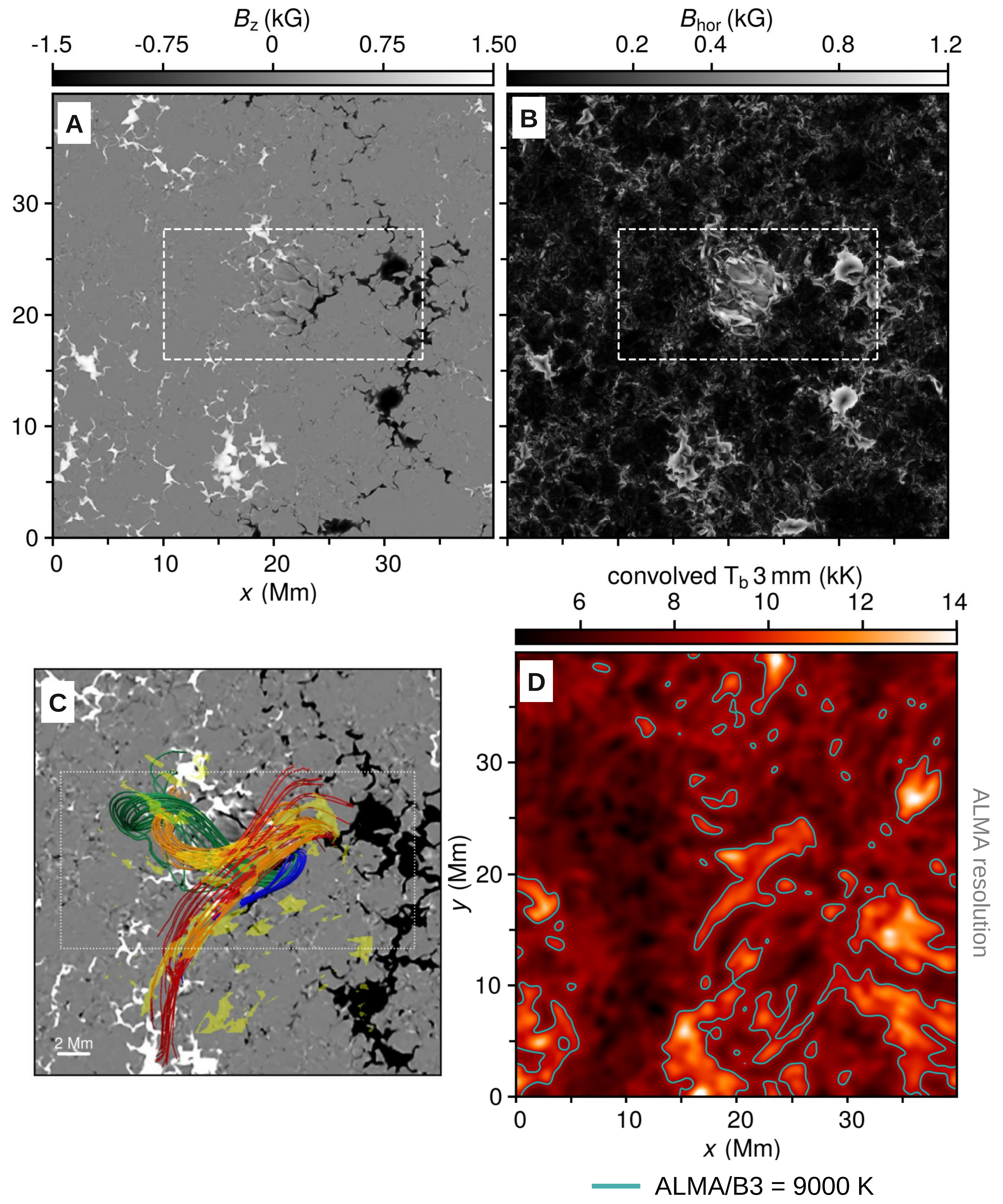


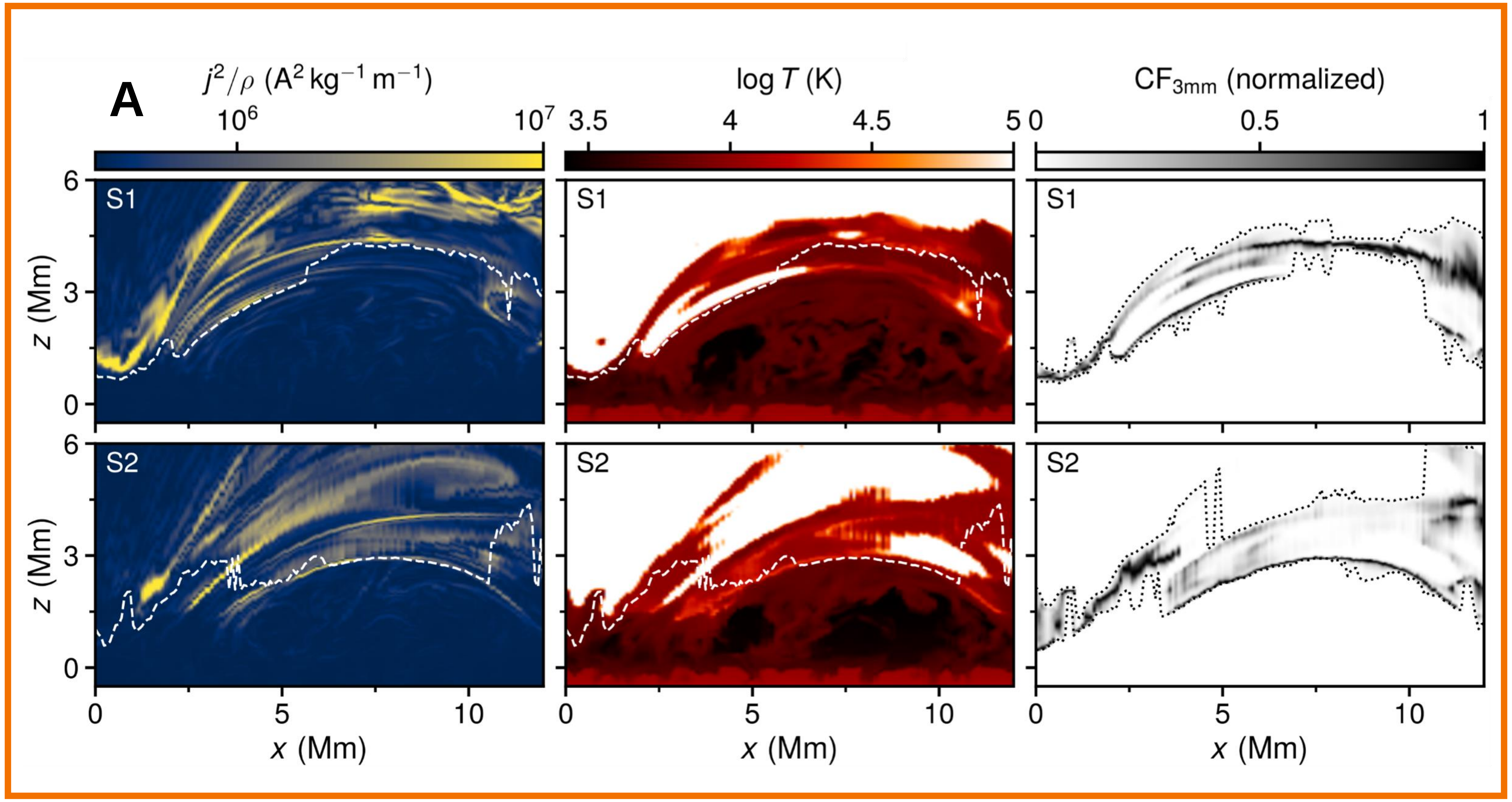
da Silva Santos+ (2022)

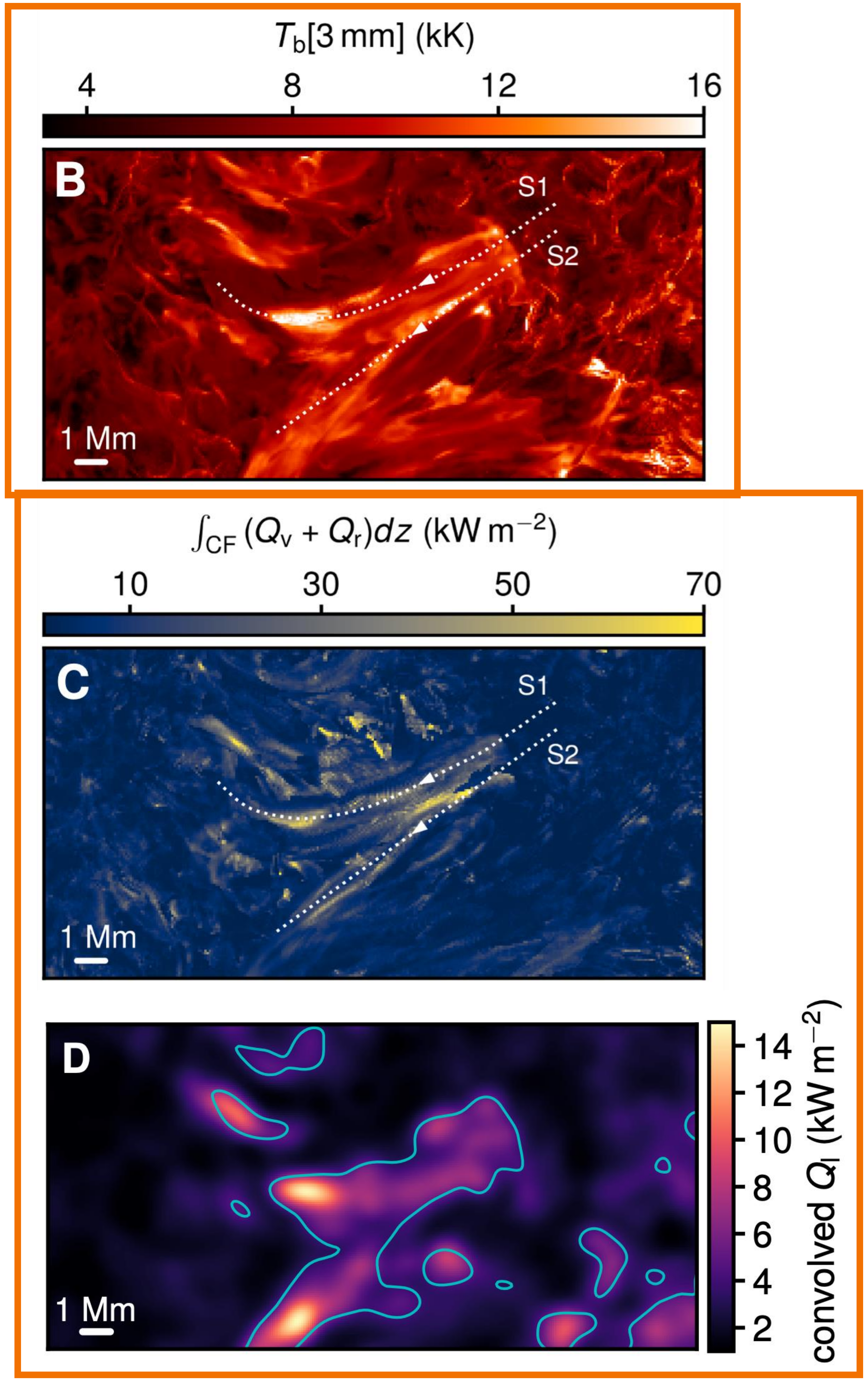
see e.g., Zhu & Wiegelmann (2018); Zhu+ (2020) on the extrapolation algorithm

3D MURaM simulation of flux emergence → selected snapshot for analysis









A Vertical slices of the MURaM atmosphere

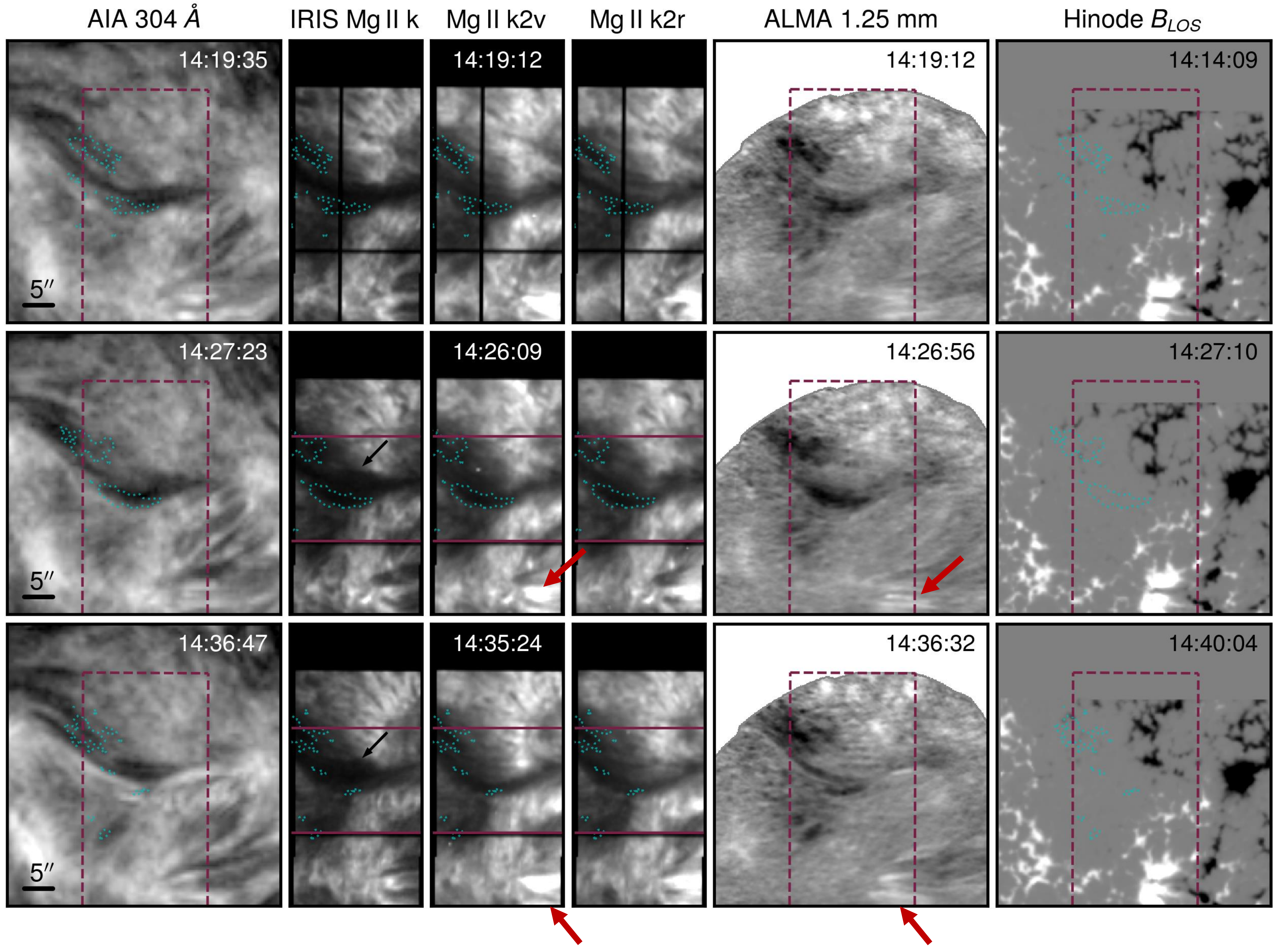
B 3 mm brightness temperature

C Total heating rates within the 3 mm formation range (**capped**)

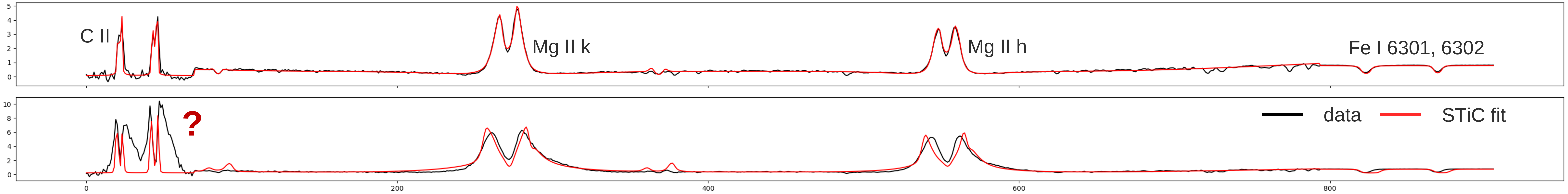
D Chromospheric radiative losses within the 3 mm formation range

IRIS / Hinode / ALMA observations of the AR hours earlier

da Silva Santos+ (2022b, Front. Ast. Space Sci.)



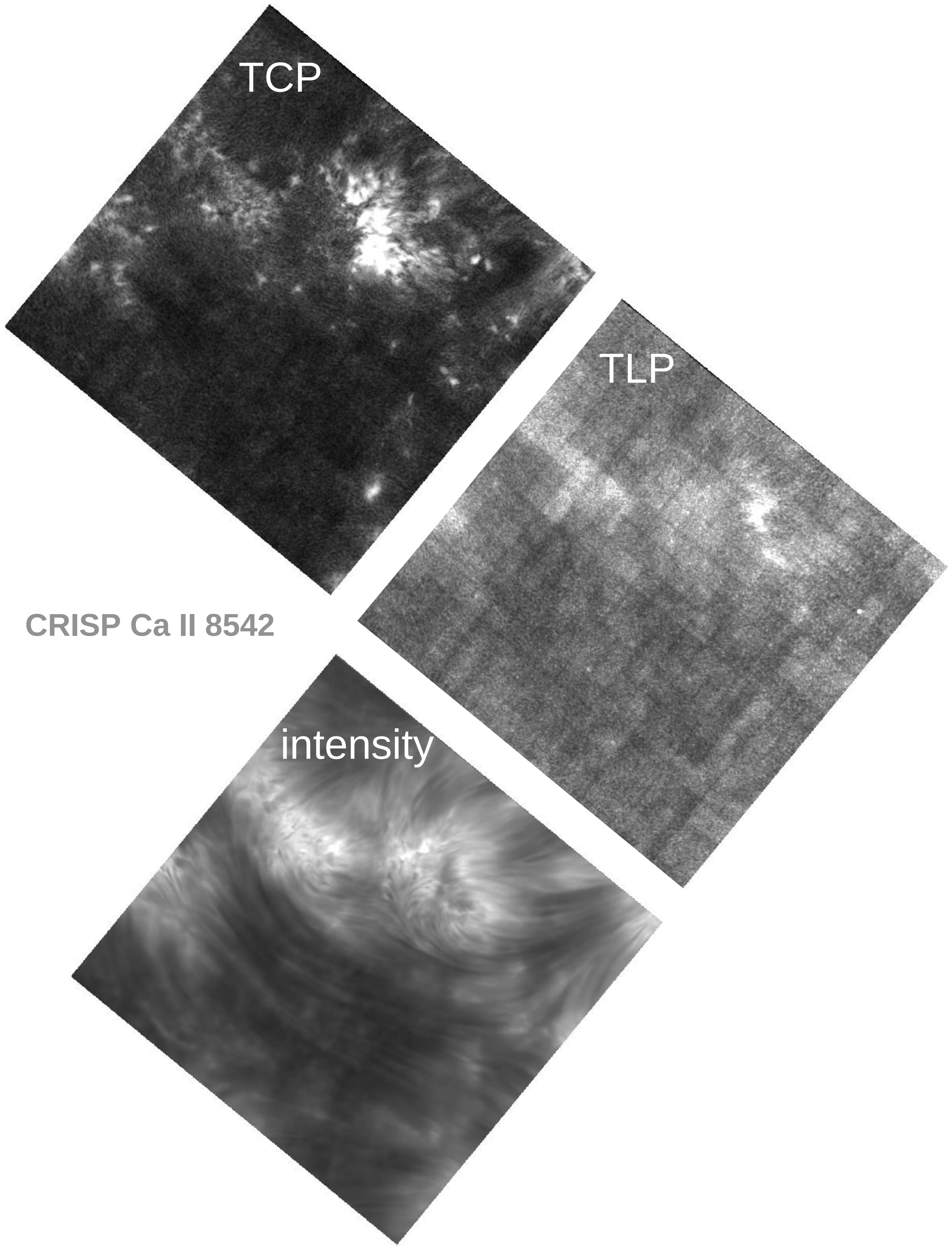
Attempting to invert IRIS + Hinode + ALMA spectra of a UVB (using STiC)



plage

UVB

da Silva Santos, Sainz Dalda, in progress



Conclusions

- Persistent, enhanced chromospheric temperatures are associated with the interaction of **low-lying magnetic loops** and the **canopy in an AR**.
- **Radiative cooling rates** (upper chromosphere ~10,000 K) up to ~5 kW m^{-2} — a factor >2 higher than in the surroundings.
- The main observables are reproduced by **MURaM simulation**.

Impact of NEQHION on the mm continuum during flux emergence?