A global picture of active regions: models meet observables

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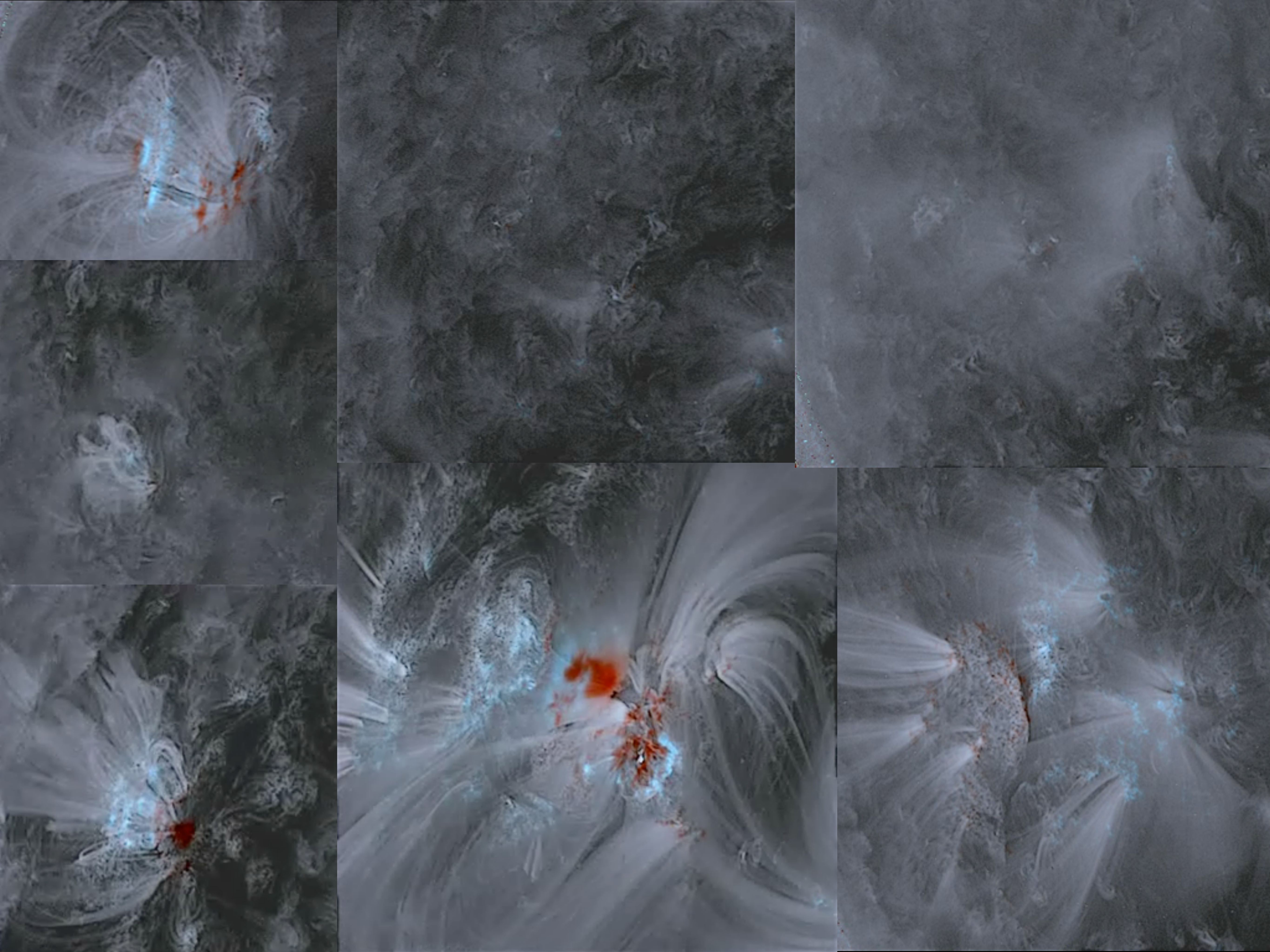
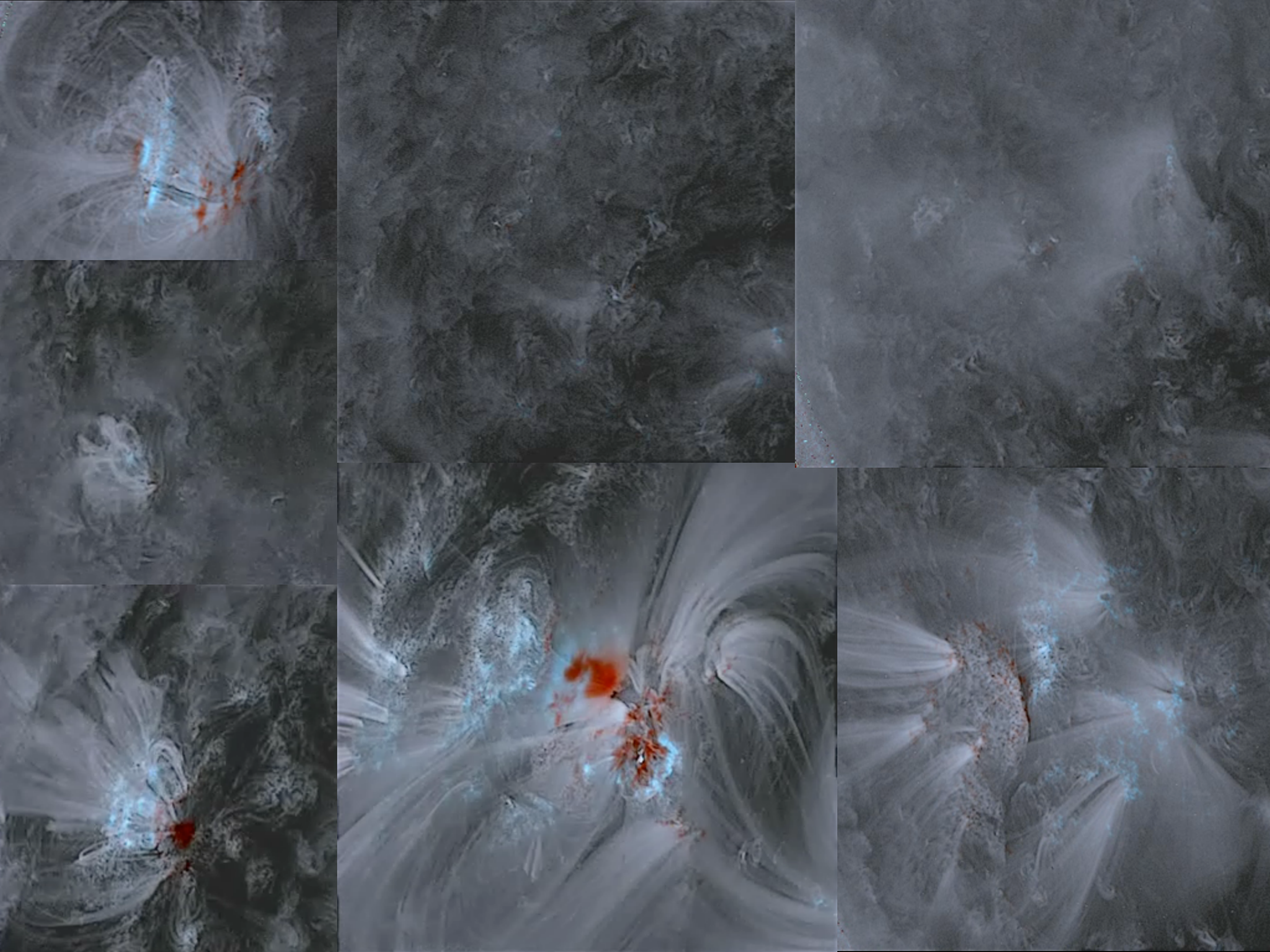
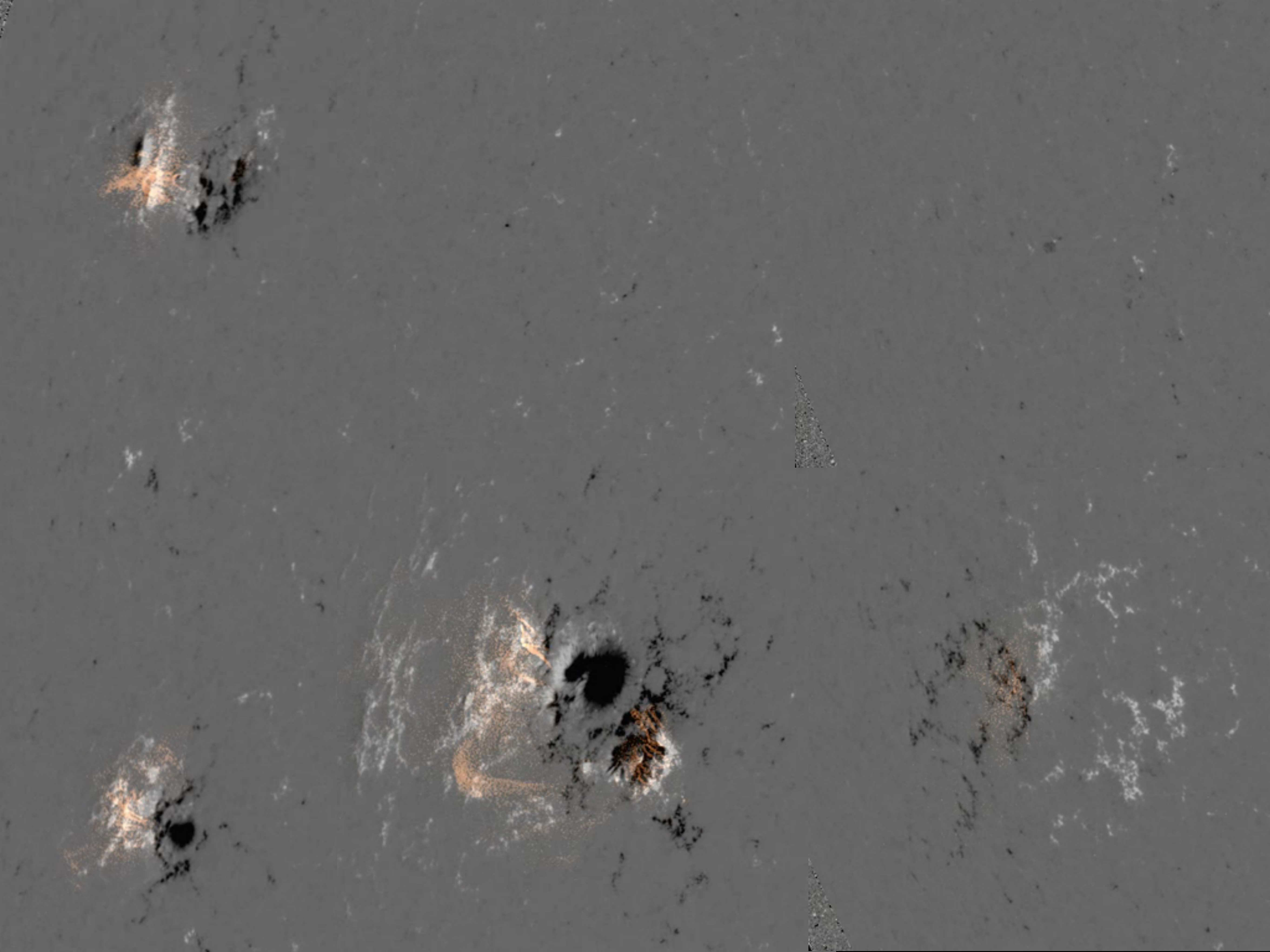
Coronal Loops Workshop VII - University of Cambridge - July 21st 2015

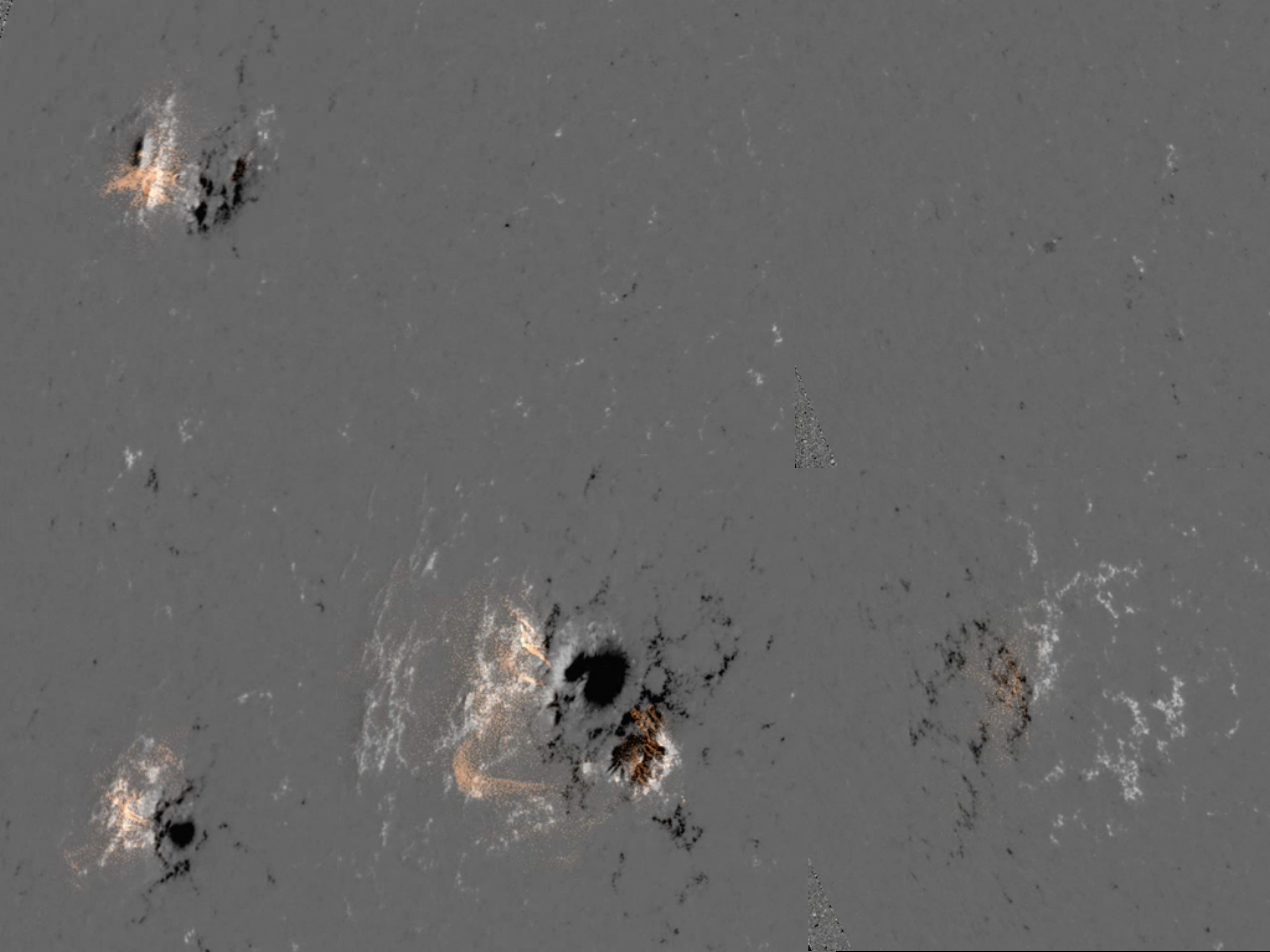
Global models

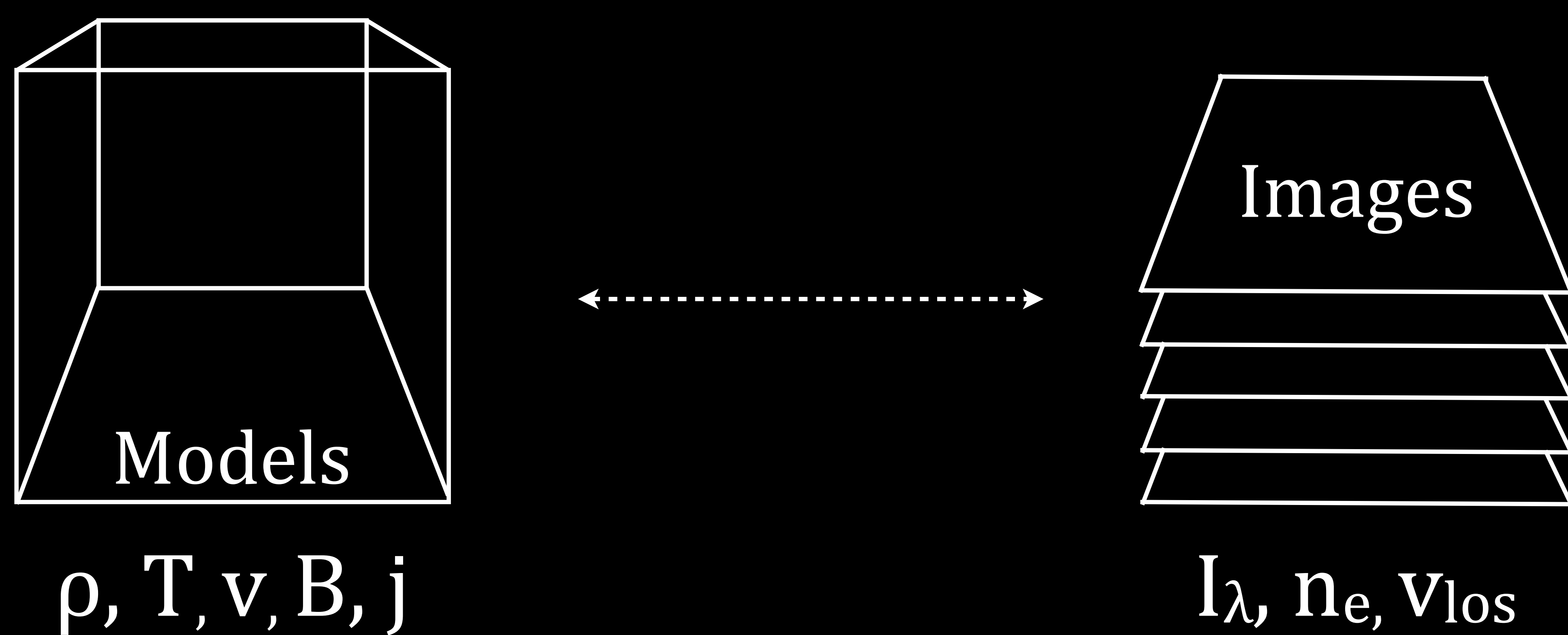
What is an active region?



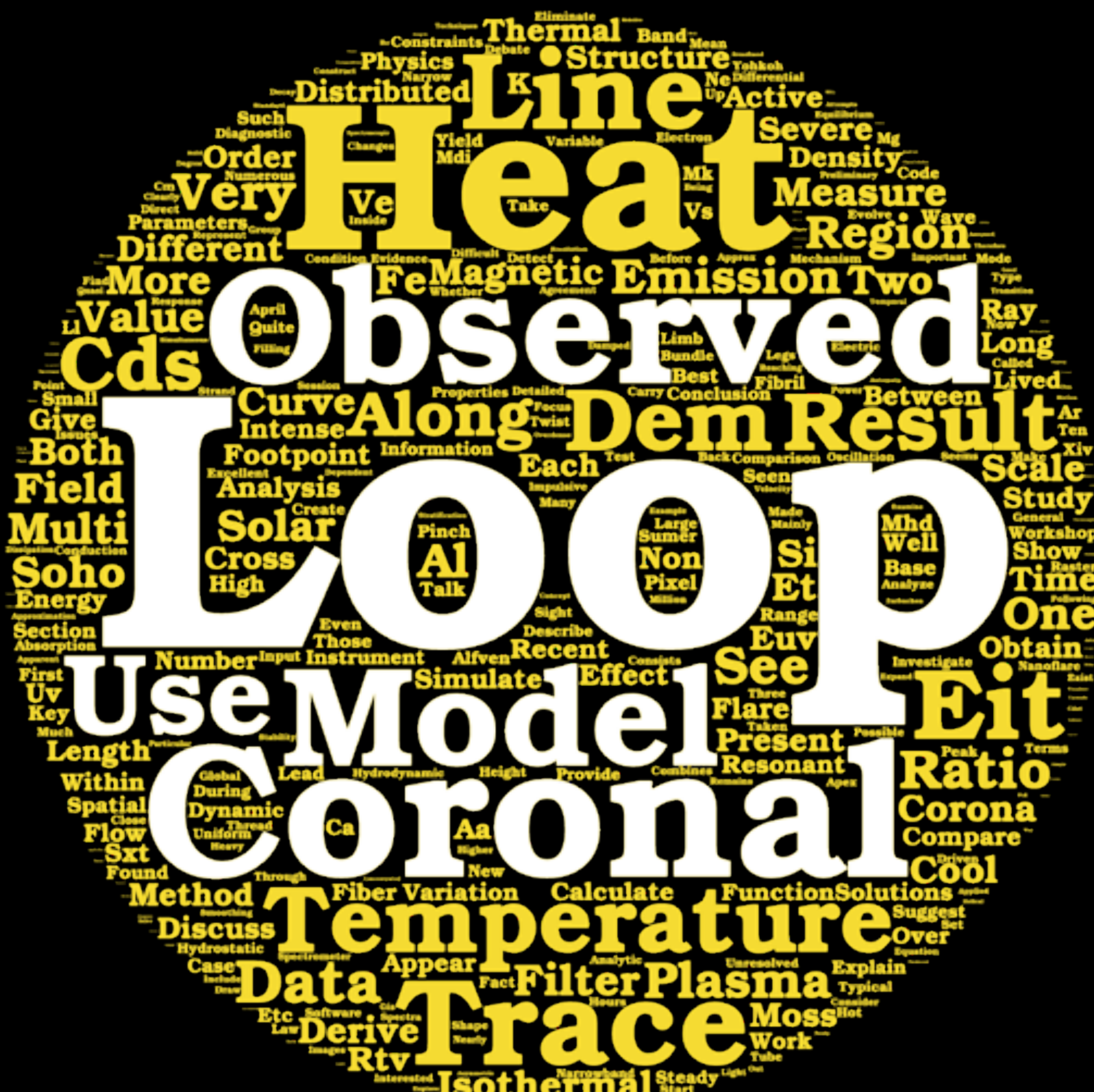




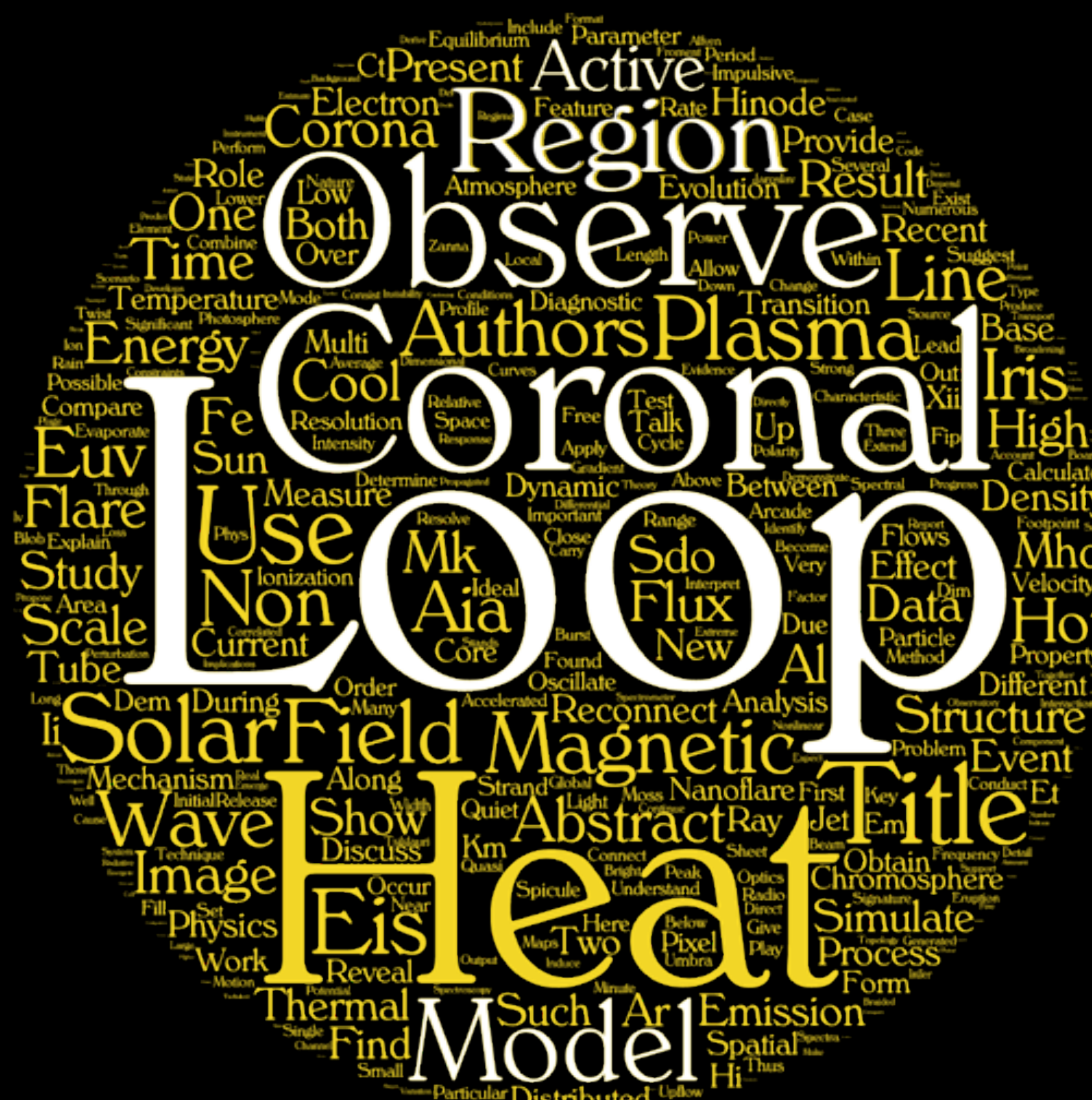



Models
ρ, T, v, B, j
Images
Iλ, ne, vlos

Coronal Loops Workshop I,
Paris, November 2002



Coronal Loops Workshop VII,
Cambridge, July 2015



3D volume
Fixed topology
0D/1D hydro **static** **dynamic**

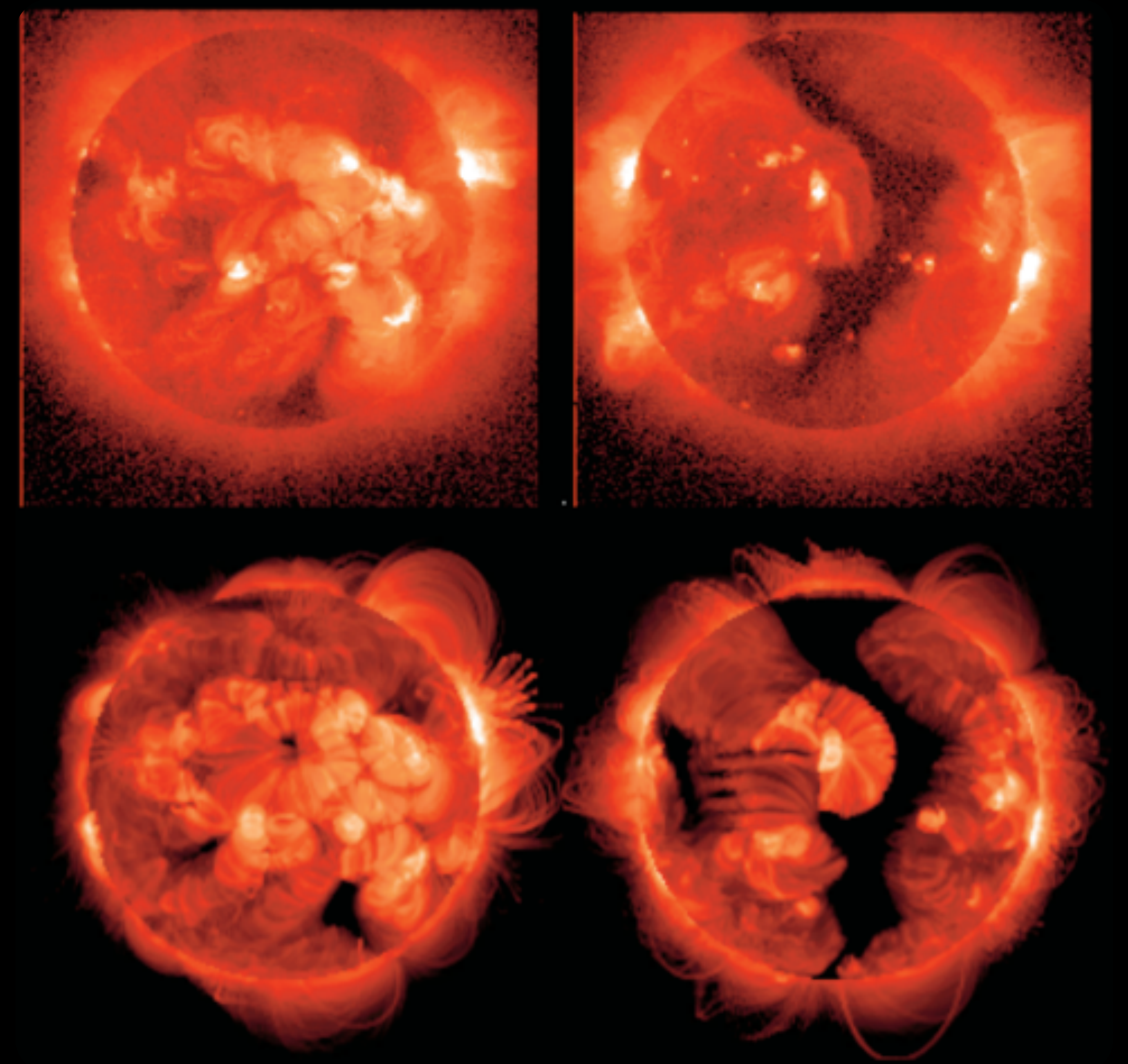
3D volume
3D MagnetoHydroDynamics

1. Observables in the corona
2. Comparisons with data

Schrijver et al. (2004)

- Full Sun (2 datasets)
- Magnetic configuration: flux transport
- Extrapolation: PFSS (46,000 field lines)
- Loops modeled in 0D
  - Ad hoc heating: $F_H = \alpha B_f^{\beta} L^{\gamma} f(B_f)$

    $0.0 \leq \beta \leq 2.0 \quad -1.7 \leq \gamma \leq 0.3$
  - Uniform, Non-uniform
  - Hydrostatic solutions (Serio et al. 1981)



Data comparisons

- SXT/Yohkoh (Al/Mag), EIT/SoHO (171,284)
- Qualitative: visual
- Quantitative: intensities
- Quantitative: full Sun emission measures simulated vs historical DEMs

Results / Conclusions

- Best fit: $F_H \approx 4 \times 10^{14} \frac{B^{1.0\pm0.3}}{L^{1.0\pm0.5}} f(B)$
  - Uniform heating
- Quasi-hydrostatic equilibrium for T > 2MK

Identified problems

- Lack of cool relatively bright loops.
- Excessive contrast in simulated 171 and 195
- No faint and compact sources (PFSS resol.)

Warren & Winebarger (2006)

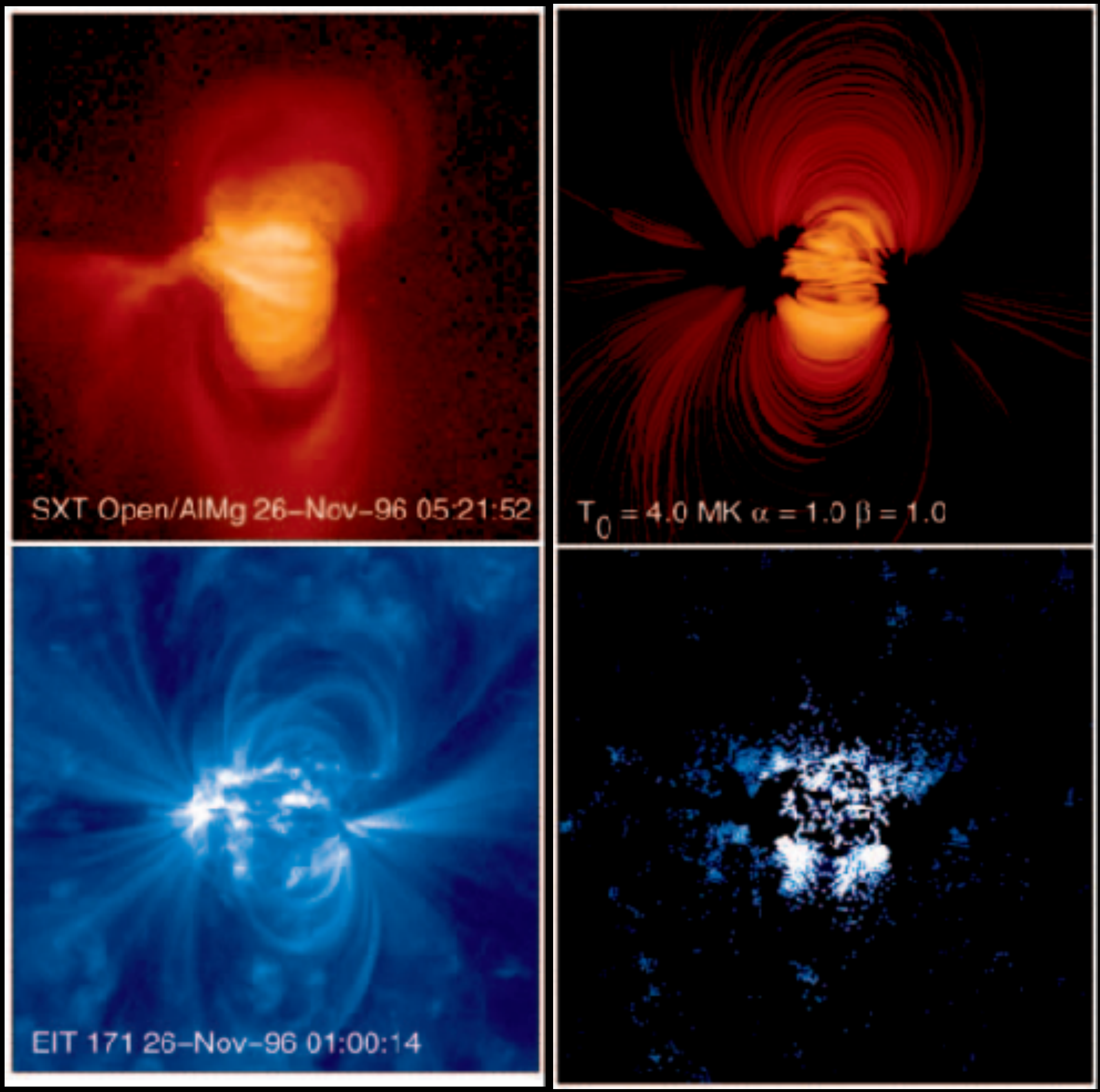
- Active region size (26 regions)
- Magnetic configuration: MDI los magnetog.
- Extrapolation: Potential
- Loops modeled in 1D
  - Hydrostatic solutions (van Ballegooijen)
  - Ad hoc heating: Uniform

$$E_H \propto \frac{\bar{B}^\alpha}{L^\beta}$$

$$\alpha, \beta \in [0, 1, 2]$$

Data comparisons

- SXT/Yohkoh (AlMg, Al.1)
  EIT/SoHO (171, 195, 284)
- Qualitative: visual (morphology)
- Quantitative: $\log \mathrm{I} = \mathrm{b} \log \Phi$
  (correlation & slopes)



Results / Conclusions

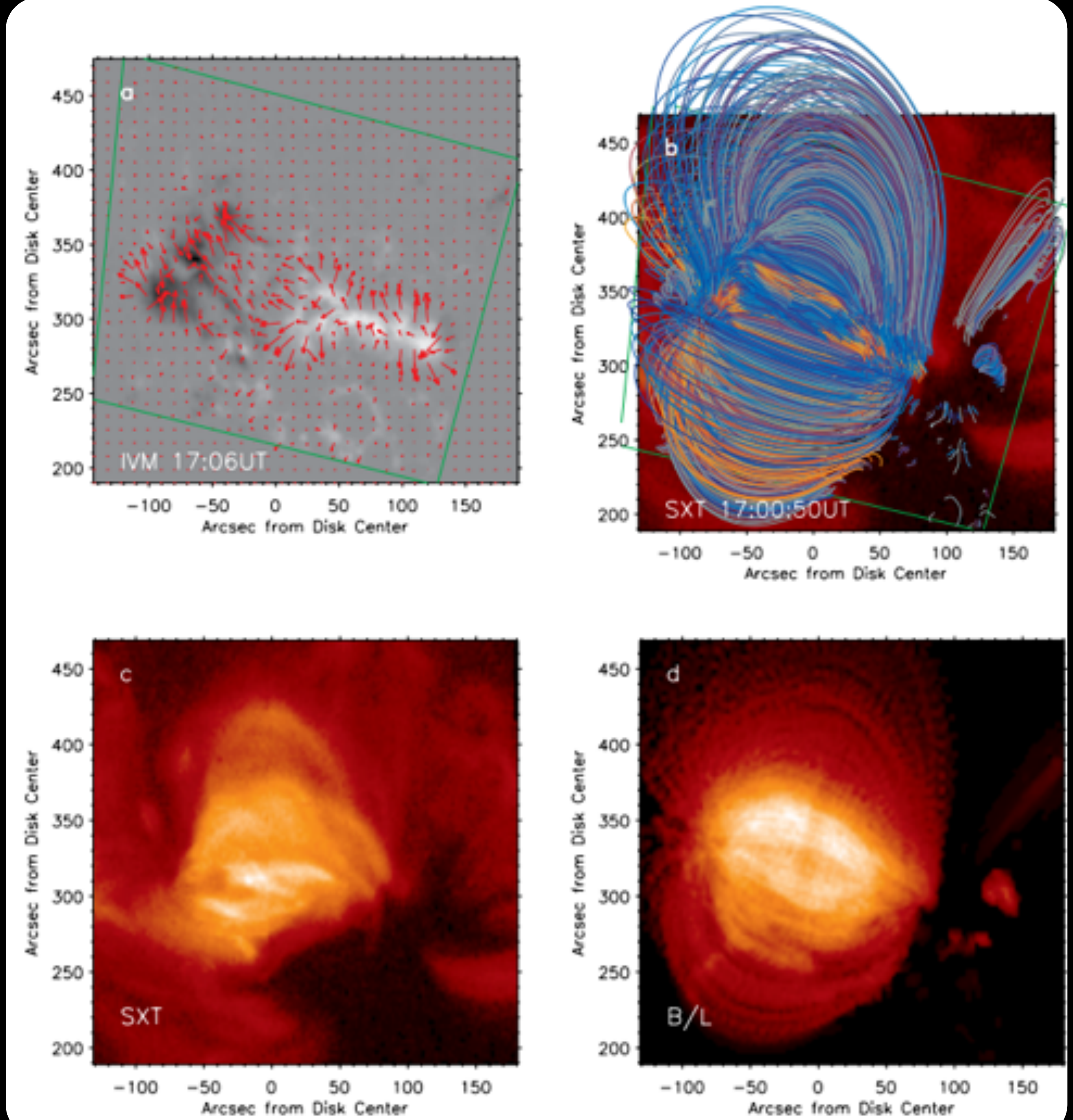
- Static models adequate to reproduce high T
- Most consistent (qual + quant): $E_H \propto \frac{\bar{B}}{L}$
- Same as Schrijver : $E_H \sim \frac{F_H}{L} \sim \frac{B_0}{L^2} \sim \frac{\bar{B}}{L}$

Identified problems

- Significant differences in cool emission:
  - EIT simulated images dominated by moss
  - Moss is too bright
- Filling factors needed to match intensities

Lundquist et al. (2008a, 2008b)

- Active region size (10 regions)
- Magnetic configuration: vector magnetogram
- Extrapolation: NLFF
- Loops modeled in 1D
  - Steady state energy balance model
  - Ad hoc heating:
    Uniform $$E_H \propto \frac{\bar{B}}{L}; \frac{\bar{B}}{L^2}; \frac{\bar{B}^2}{L}; \frac{\bar{B}^2}{L^2}$$



Data comparisons

- SXT/Yohkoh (AlMg, Al1)
- Qualitative: visual
- Quantitative: intensities (correl., distrib.)
- Quantitative: single T filter ratio

Results / Conclusions

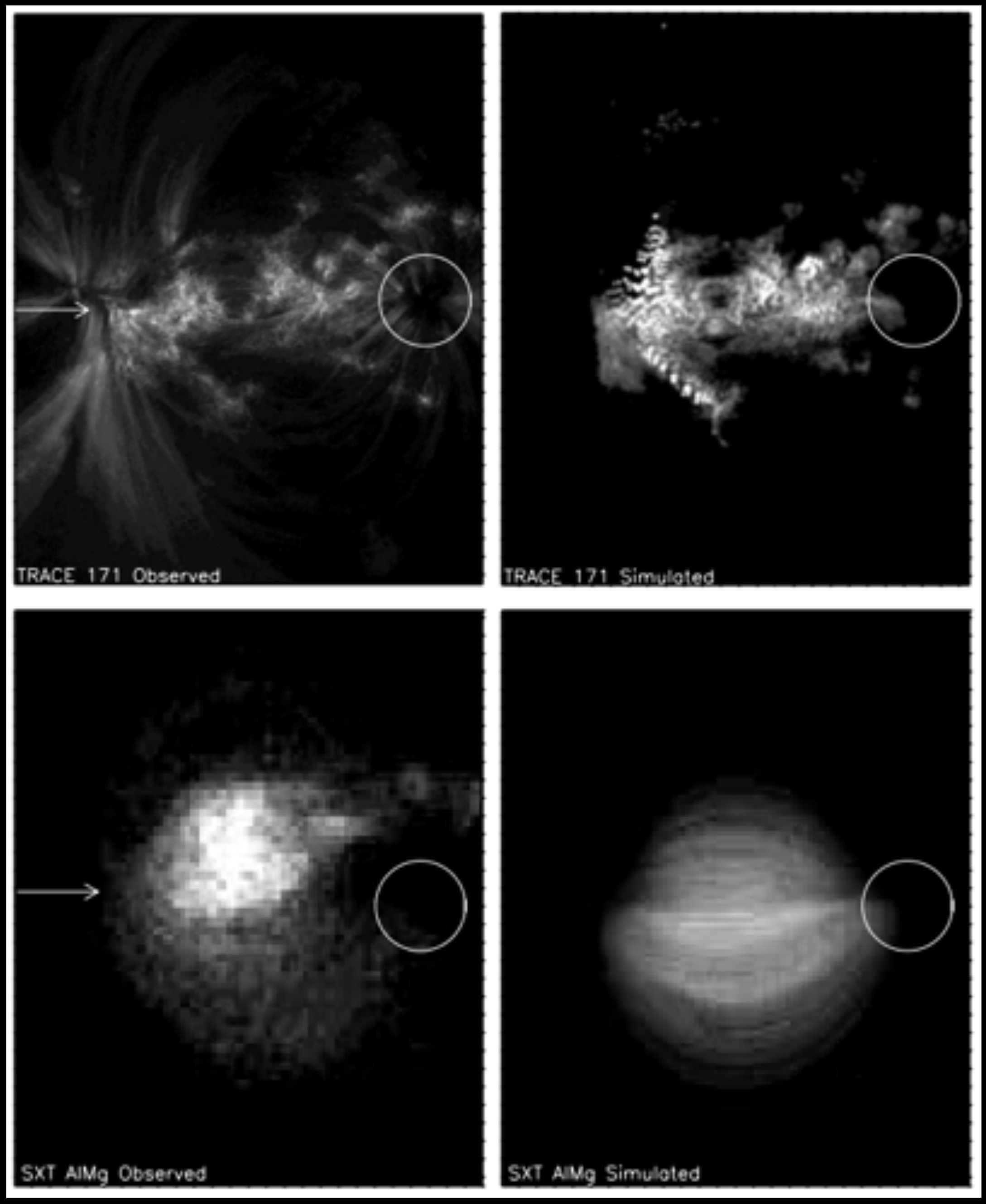
- Visually and quantitatively best predictor is: $$E_H \propto \frac{\bar{B}}{L}$$
- Pixel intensities disagree by 200% (best case)
- Filter ratio: non-conclusive

Identified problems

- Major factors:
  - Topology from NLFF
  - Steady-state equilibrium approximation

Winebarger et al. (2008)

- Active region size (1 region)
- Magnetic configuration: MDI los magnetog.
- Extrapolation: Potential
- Loops modeled in 1D
  - Steady heating
  - E_H guess: 171 moss + Martens + Rosner
  - Hydrostatic solutions (van Ballegooijen)
  - Find E_H that matches moss and total SXT
  - Regression E_H vs B vs L



Data comparisons

- SXT/Yohkoh (AlMg, Al12)
- TRACE (171)
- Quantitative:
  - 171 moss intensities at field line footpoint
  - SXT total intensities

Results / Conclusions

- Intensities can be matched to steady uniformly heated loops within 2 stdev.
- Best match:
  - Filling factor 8%
  - Expanding loop

$$E_H \propto \frac{\bar{B}^{0.29}}{L^{0.95}}$$

Identified problems

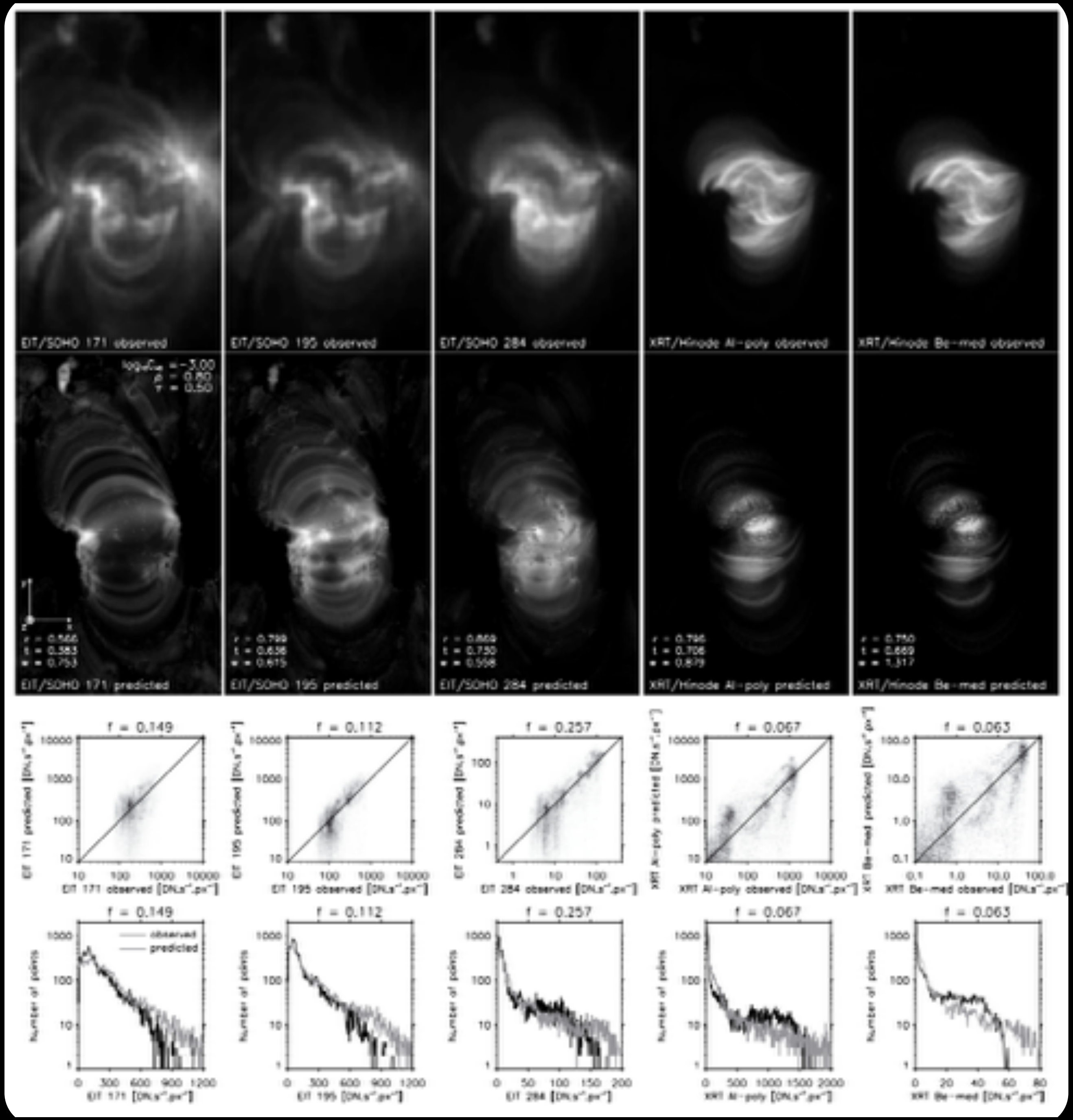
- Morphological discrepancies

Dudik et al. (2011)

- Active region size (1 region)
- Magnetic configuration: MDI los magnetog.
- Extrapolation: Potential
- Loops modeled in 1D
  - Hydrostatic solutions
  - Ad hoc heating: Non-uniform

$$E_H \propto \frac{B_f^{\alpha}}{L^{\beta}} f(s)$$

$$0.5 \leq \alpha \leq 1.0$$
$$0.0 \leq \beta \leq 2.0$$



Data comparisons

- XRT/Hinode (Al-,C-,Ti-poly,Be-thin,Be-med)
- EIT/SoHO (171, 195, 284)
- Qualitative: visual
- Quantitative:
  - T filter ratio
  - Intensity correlation and histograms

Results / Conclusions

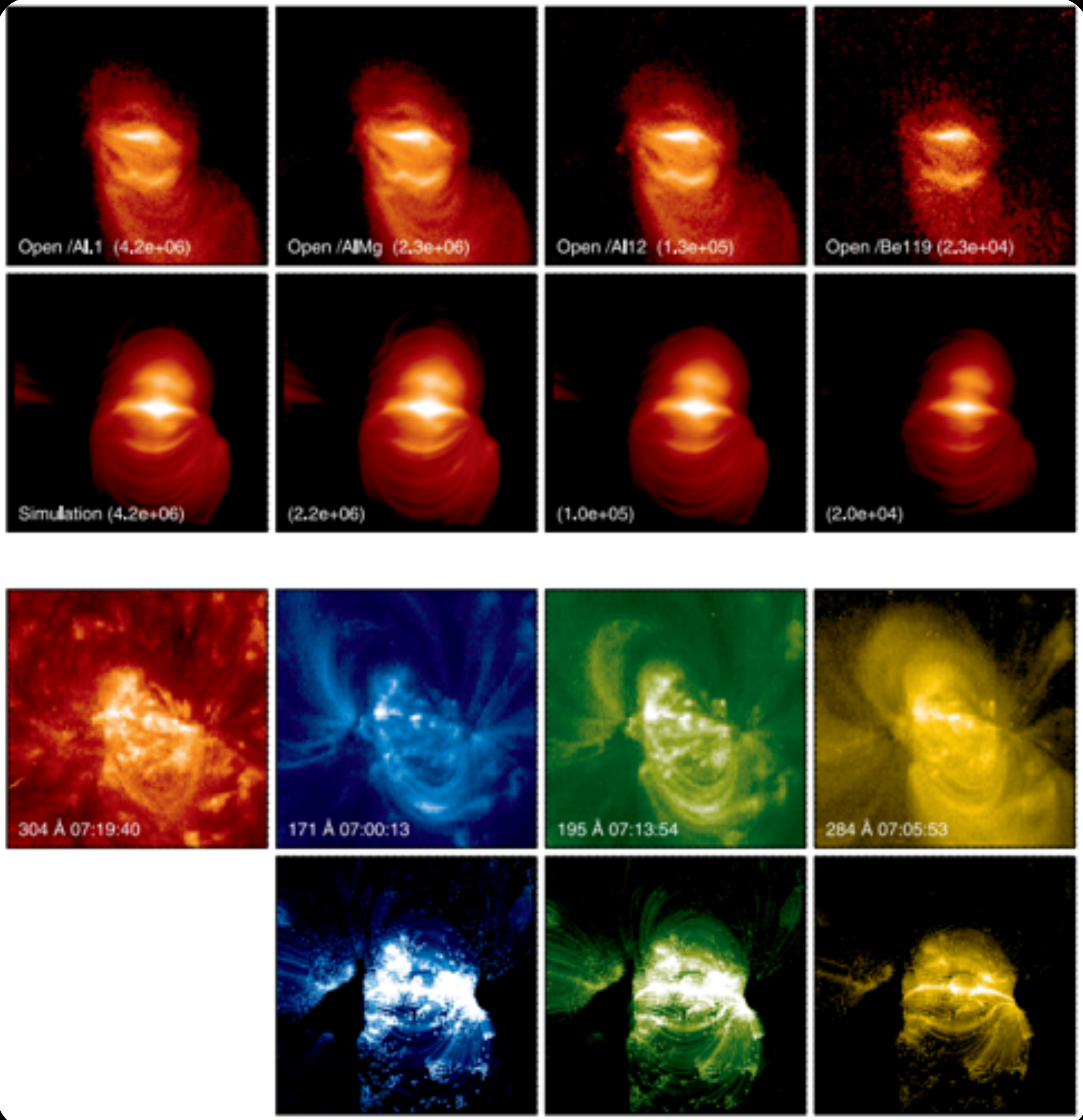
- Best fit solution: $E_H \propto \frac{B_f^{0.8}}{L_f^{0.5}}$
- X-ray emission: large heating scale lengths
- EUV loops: only with short heating scale L

Identified problems

- Synthetic emission higher than observed: filling factor?
- Unable to find a steady heating model that reproduces X-ray and EUV without unstable EUV loops.

Warren & Winebarger (2007)

- Active region size (1 region)
- Magnetic configuration: MDI los magnetog.
- Extrapolation: Potential (2000 field lines)
- Loops modeled in 1D
  - a) Hydrostatic solutions
  - b) Hydrodynamics (NRL Solar FT Model)
    Ad hoc heating: $E_D(t) = g(t)\,R\,E_S + E_B$
    Uniform $E_S \propto \frac{\bar{B}}{L}$



Data comparisons

- SXT/Yohkoh (Be119,Al12,AlMg, Al.1)
  EIT/SoHO (304,171, 195, 284)
- Qualitative: visual (morphology)
- Quantitative: I_{tot} and intensity histograms

Results / Conclusions

- Static: reproduces SXT I_{tot} and morphology
- Impulsive: reproduces SXT
- Impulsive: significant loop emission in EUV

Identified problems

- The morphology of EUV does not agree.
- EUV intensities at the core are too bright

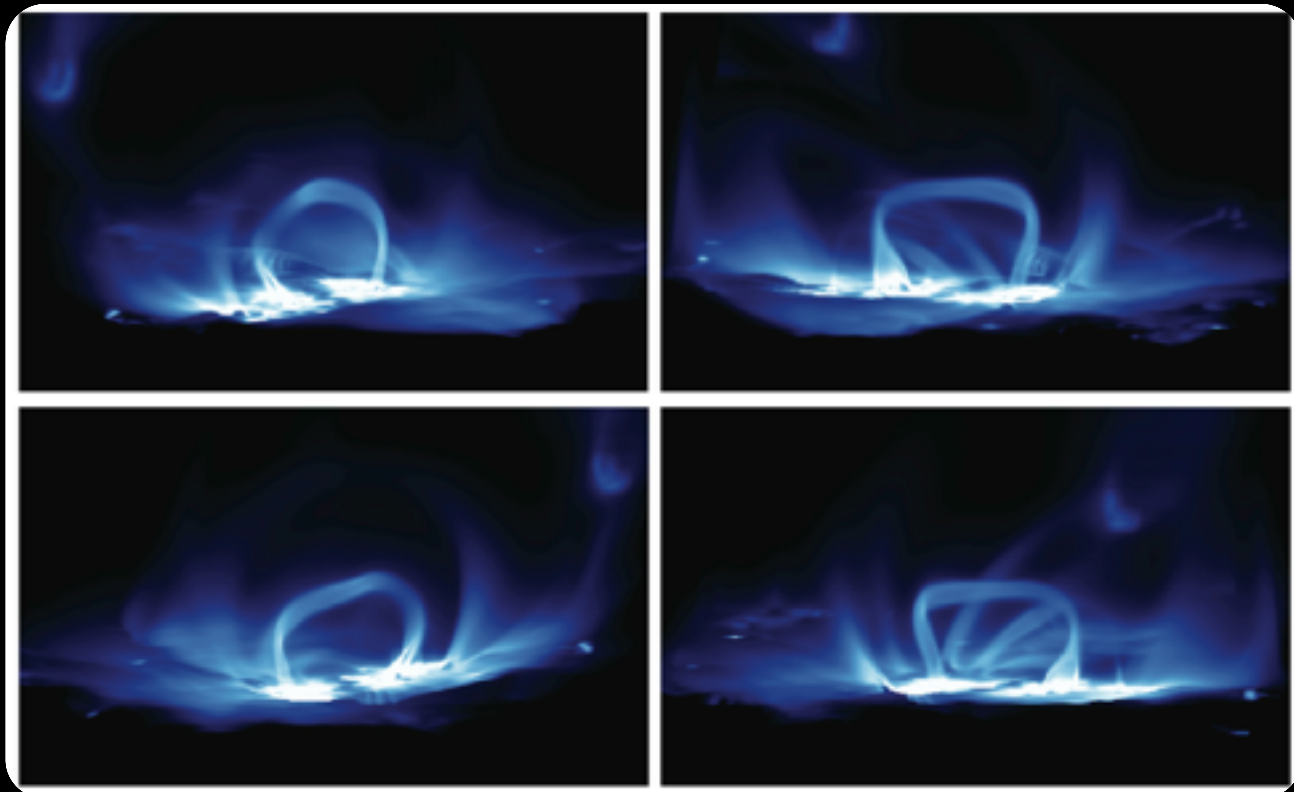
3D volume
Fixed topology
0D/1D hydro **static** **dynamic**

Schrijver et al. (2004)
Warren & Winebarger (2006)
Warren & Winebarger (2007)
Winebarger et al. (2008)
Lundquist et al. (2008a,b)
Dudik et al. (2011)

Full Sun, AR size
1500 km< Pixel size < 10,000 km
Ad-hoc parameterized heating
Static and dynamic heating
Uniform and non-uniform
Constant and expanding cross-sections

Visual (morphology)
Intensities
Intensity-flux relationship
Filter ratio temperatures

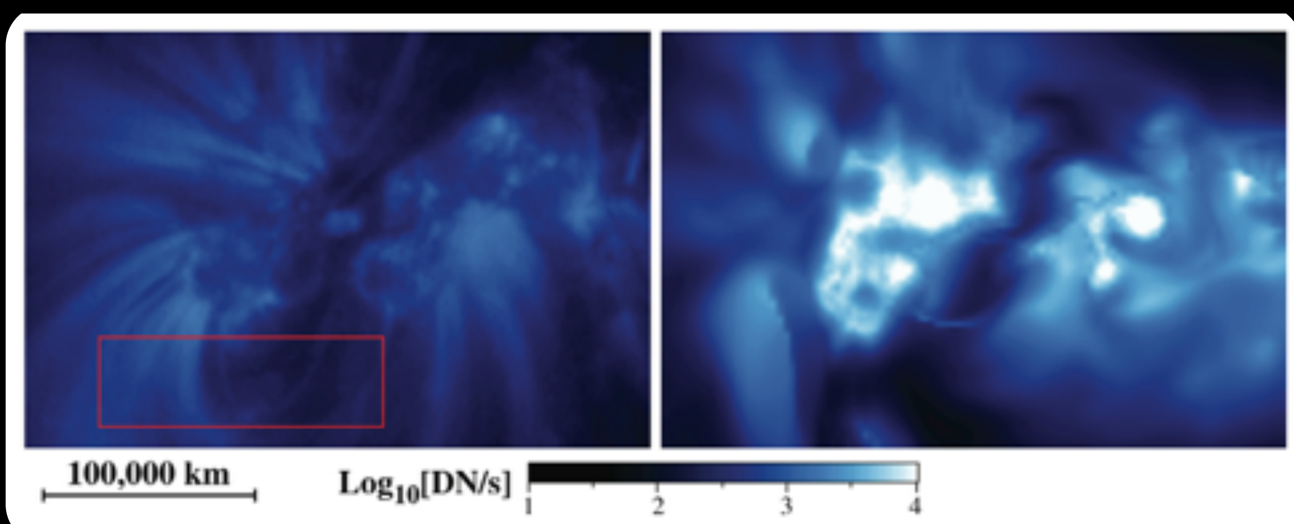
3D volume
3D MagnetoHydroDynamics



Mok et al. (2005, 2008)

- Active region size (127x91x137 mesh)
- Magnetic configuration: MDI los magnetog
- Topology: Potential ⇒ NLFF
- 3D MHD code
  - static magnetic field
  - thermodynamics along the field
  - Ad-hoc steady heating:

$$E_H(x) = cB(x')^\alpha \rho(x)^\beta$$



Data comparisons

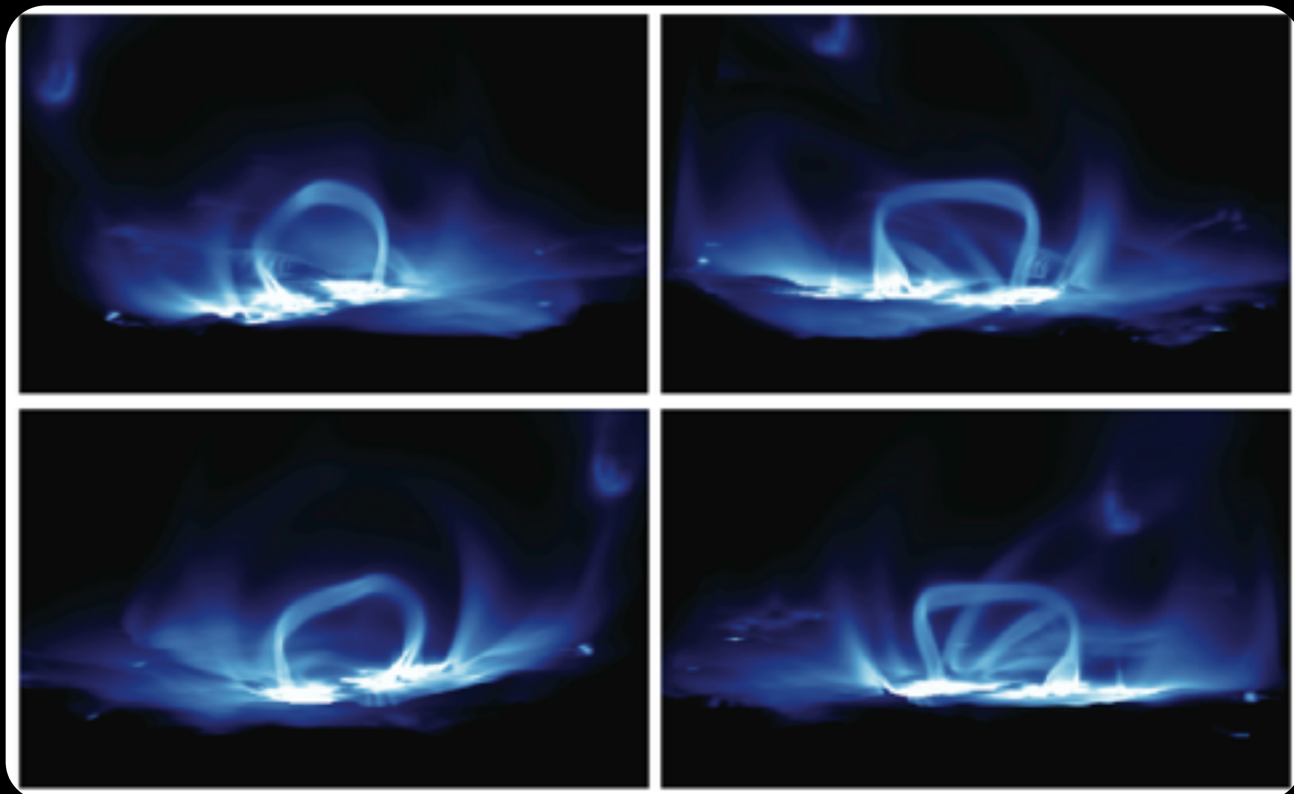
- TRACE 171, 195 , 284
- SXT
- Quantitative:
  - match SXT intensity
  - compare: intensity ranges in EUV

Identified problems

- Only diffuse corona <2 MK for small heating: no loops
- Excessive EUV emission of ‘moss’

Results / Conclusions

- Thermally unstable loops for stronger heat with time-dependency (steady heating)
- SXT intensities matched and EUV (171, 195, 284) intensities in observed range



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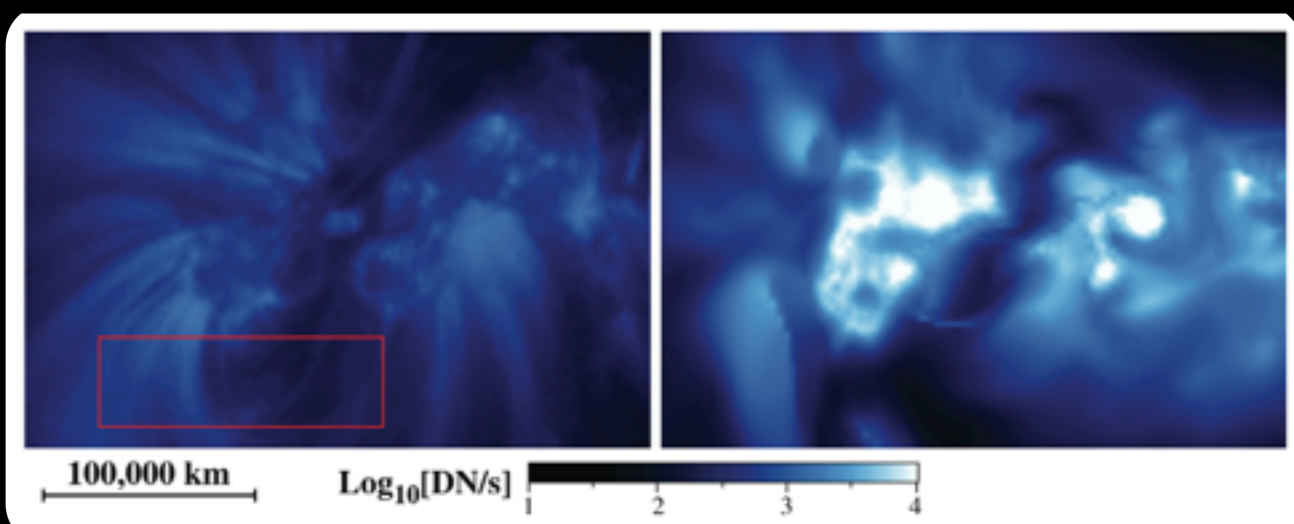

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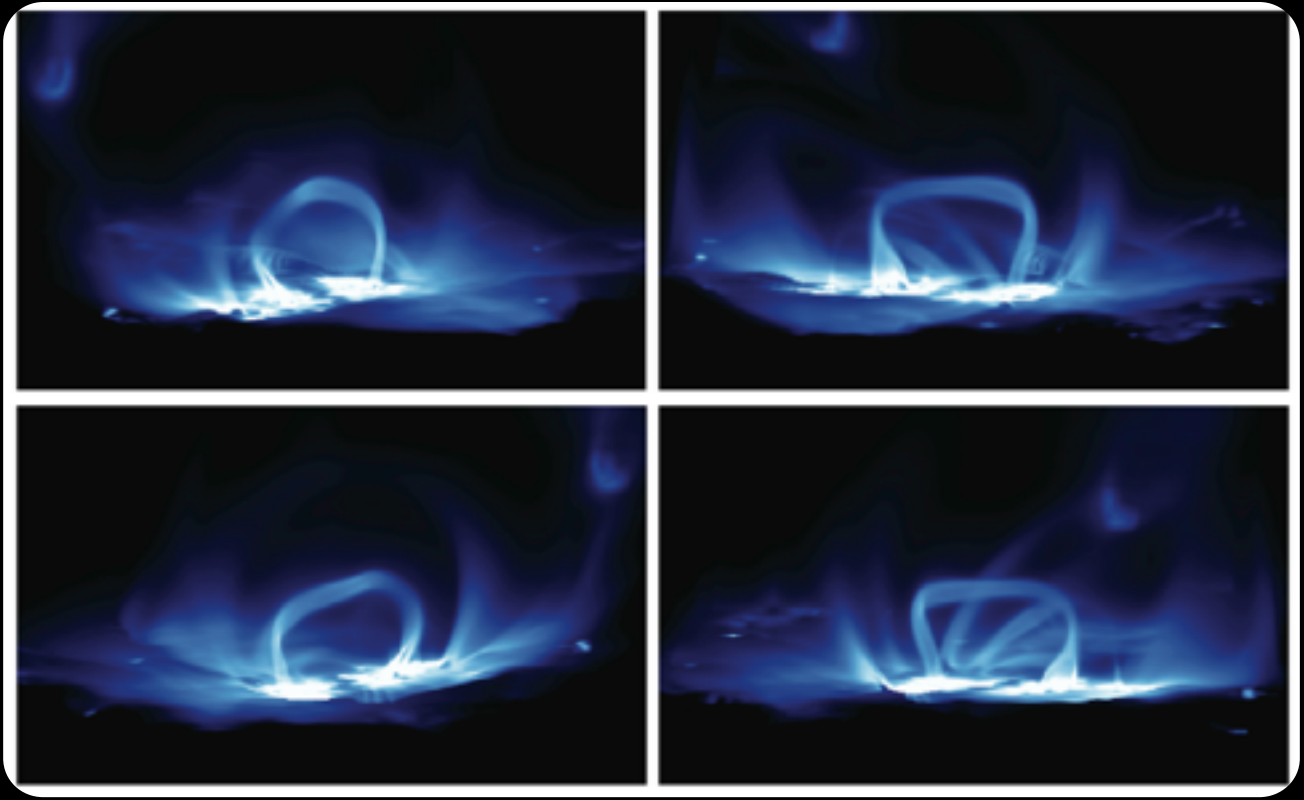

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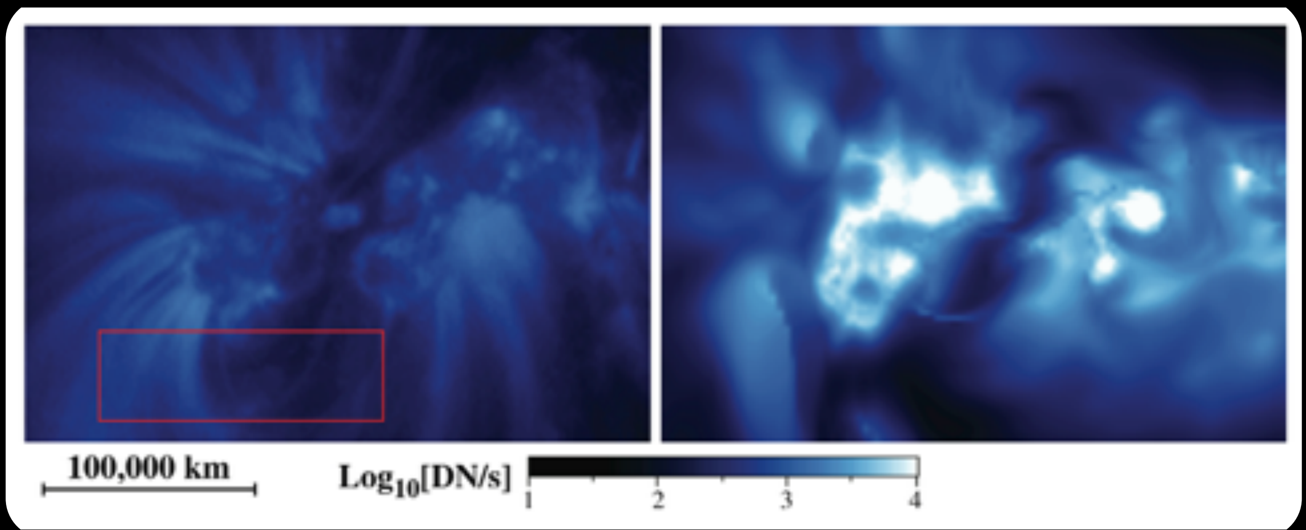

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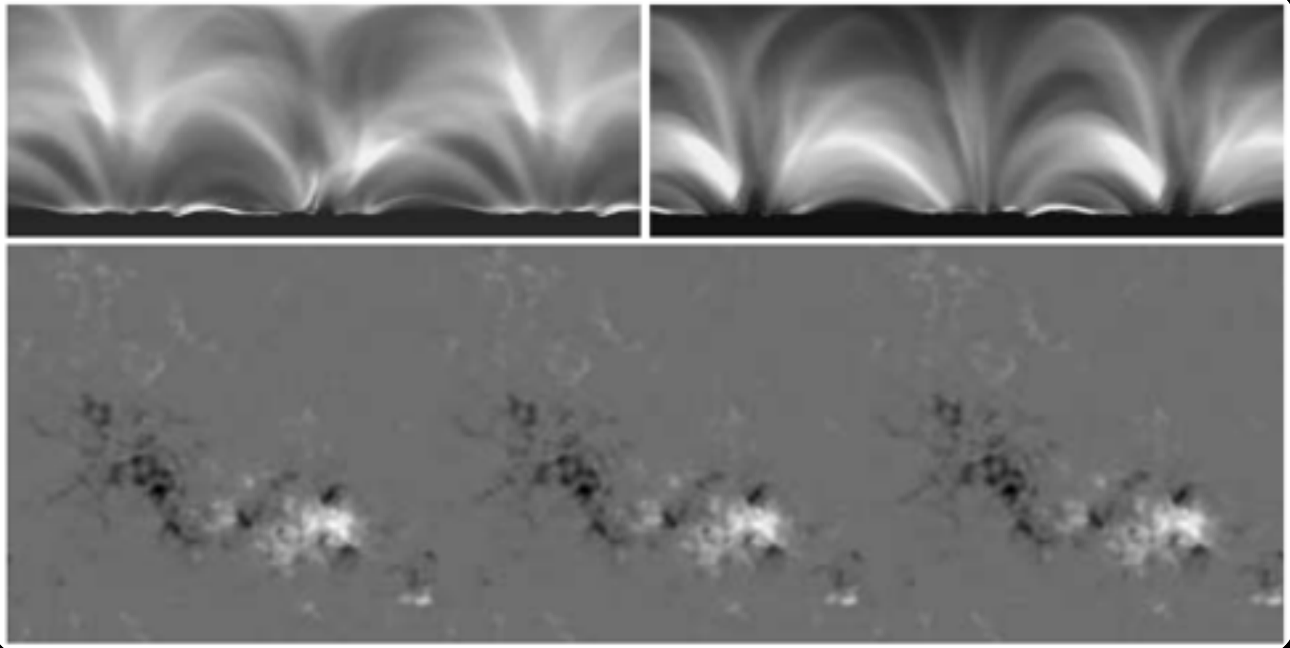
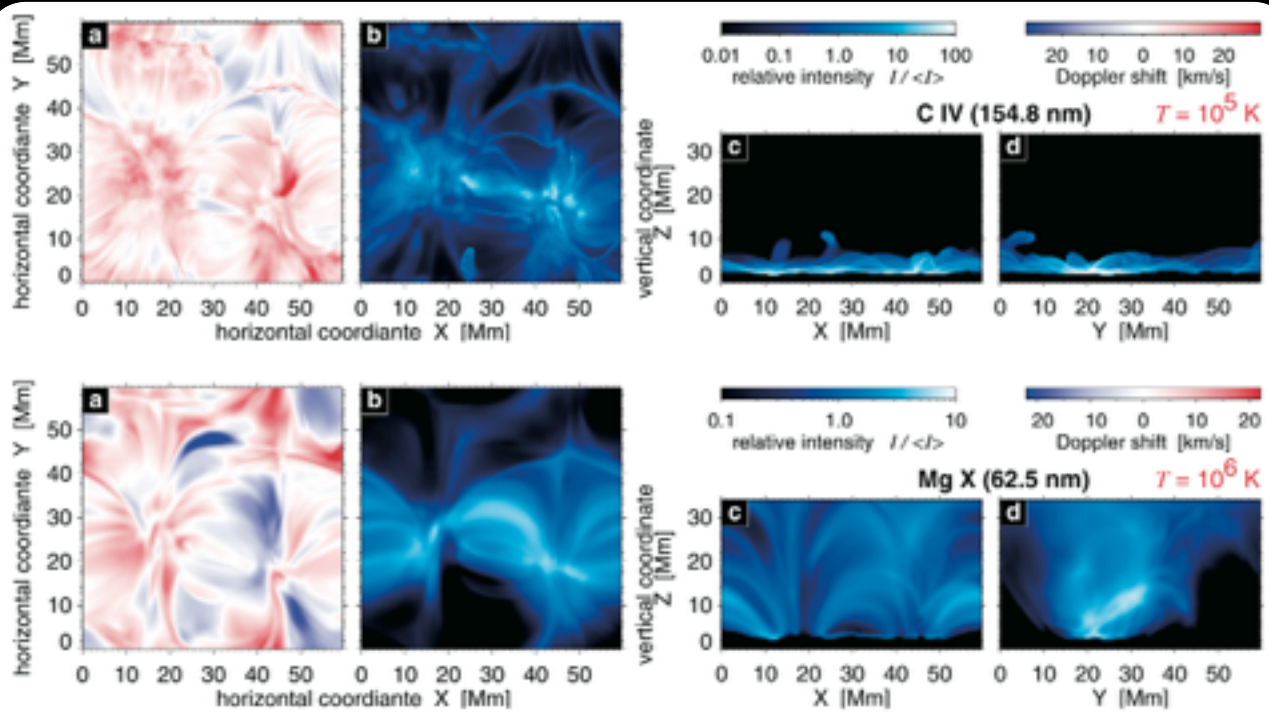


Gudiksen & Nordlund (2005)
Peter et al. (2004)

- 60 x 60 x 37 Mm^3 (150x150x150 mesh)
- Magnetic configuration:
  MDI los magnetogram scaled down
- Topology: potential (t=0)
- Field advected by prescribed velocity field
- 3D compressible MHD code
  - thermal conduction along field



Data comparisons

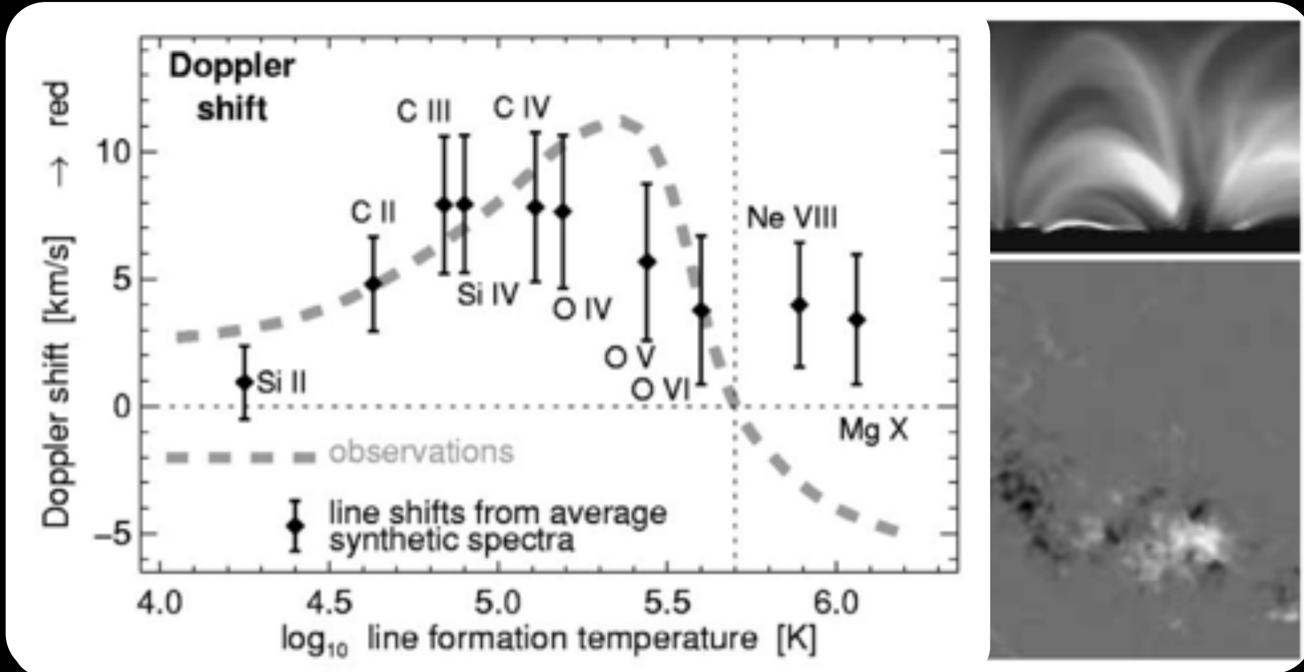
- TRACE 171, 195 intensities
- SUMER/SoHO Doppler shifts and DEM
- Qualitative: visual impression
- Quantitative:
  - intensities in EUV images
  - avg. Doppler shifts as a function of λ
  - DEM (avg. intensities time and space)

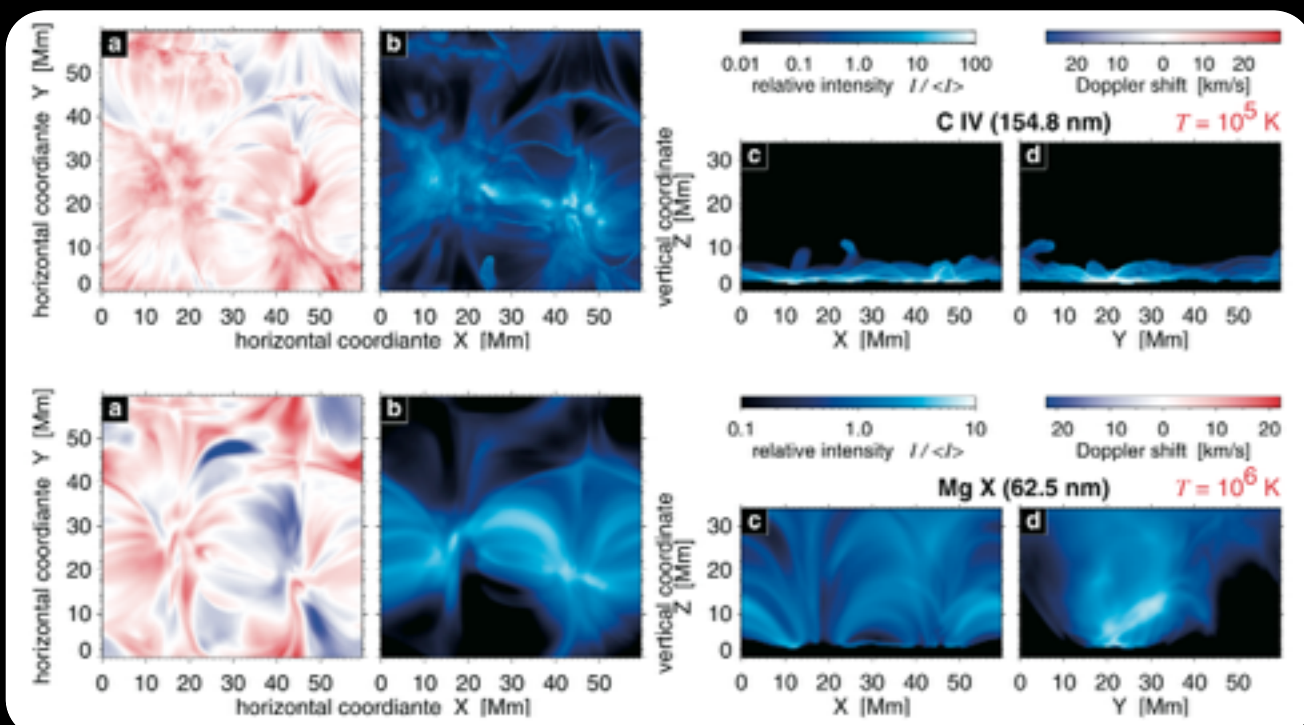
Identified problems

- TRACE intensities too high: factor 3-10
- T distribution too cool for Yohkoh loops
- Doppler shifts not reproduced at high T

Results / Conclusions

- ne ~ 10^8-10^{10} cm^{-3} ; T_e ~ 10^4-$3x10^6$ K
- Energy dissipated: 10^6-10^8 erg cm^{-2} s^{-1}
- Doppler shifts as a function of λ reproduced
- Quiet Sun DEM shape reproduced





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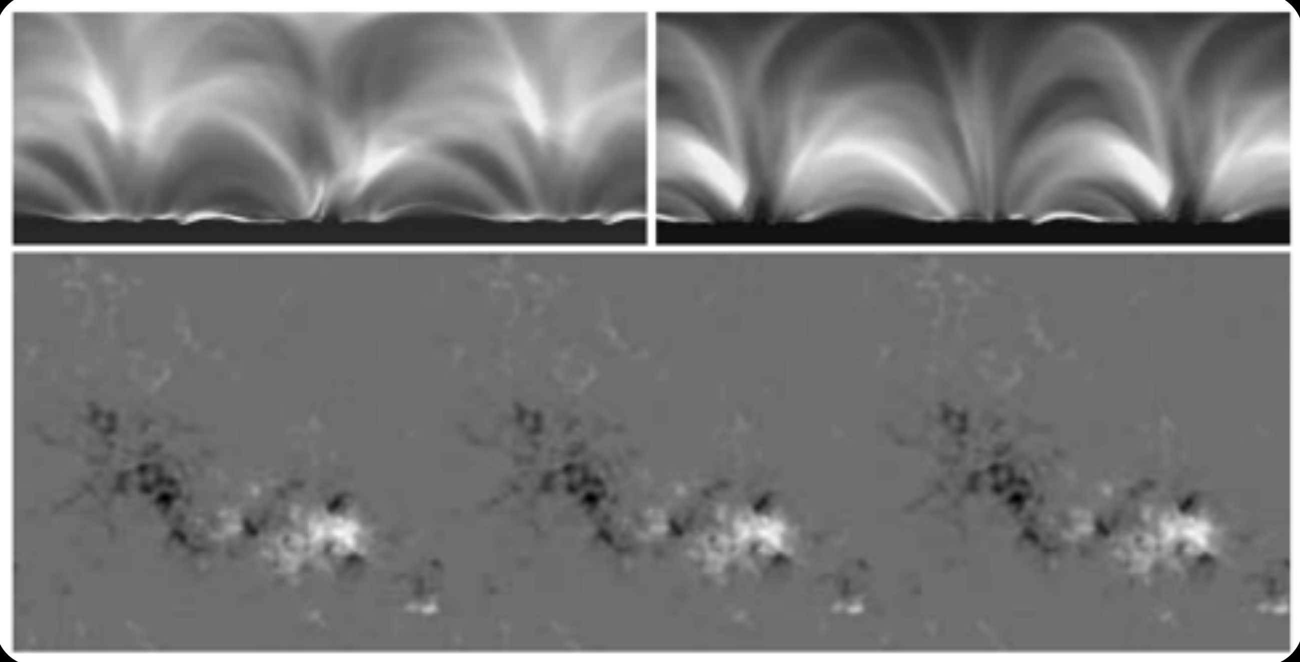

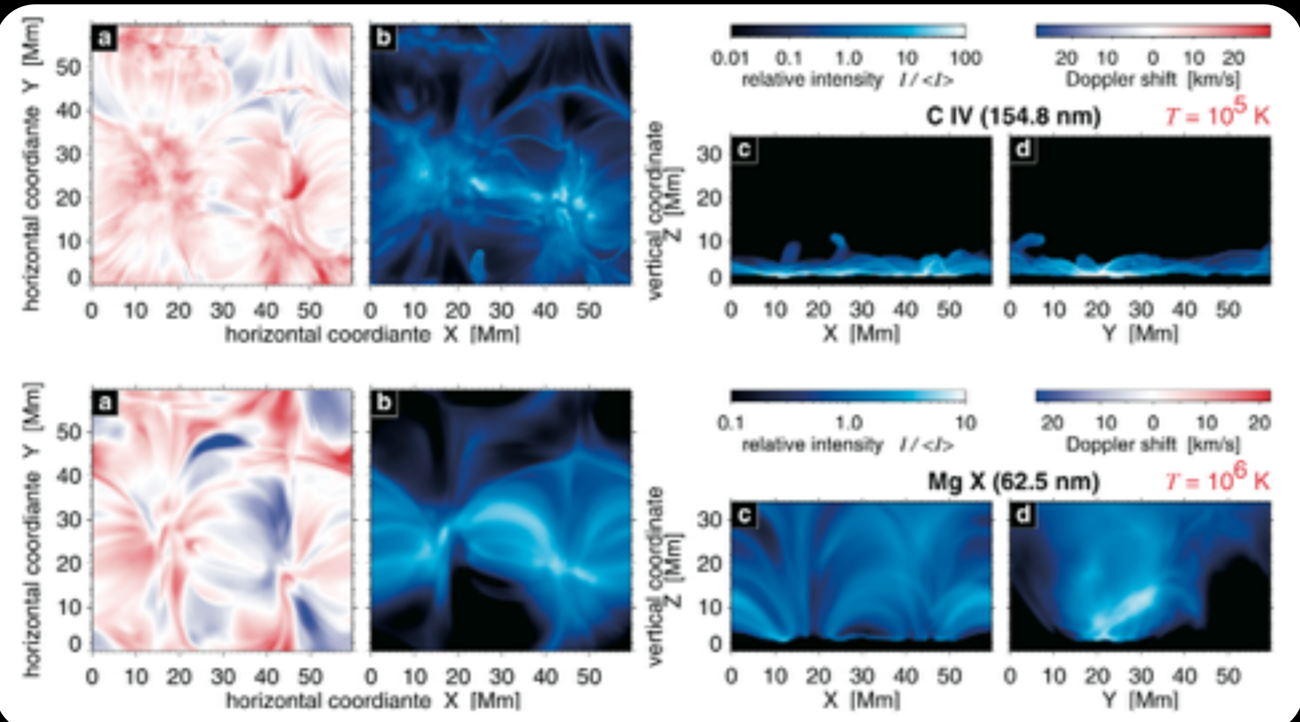

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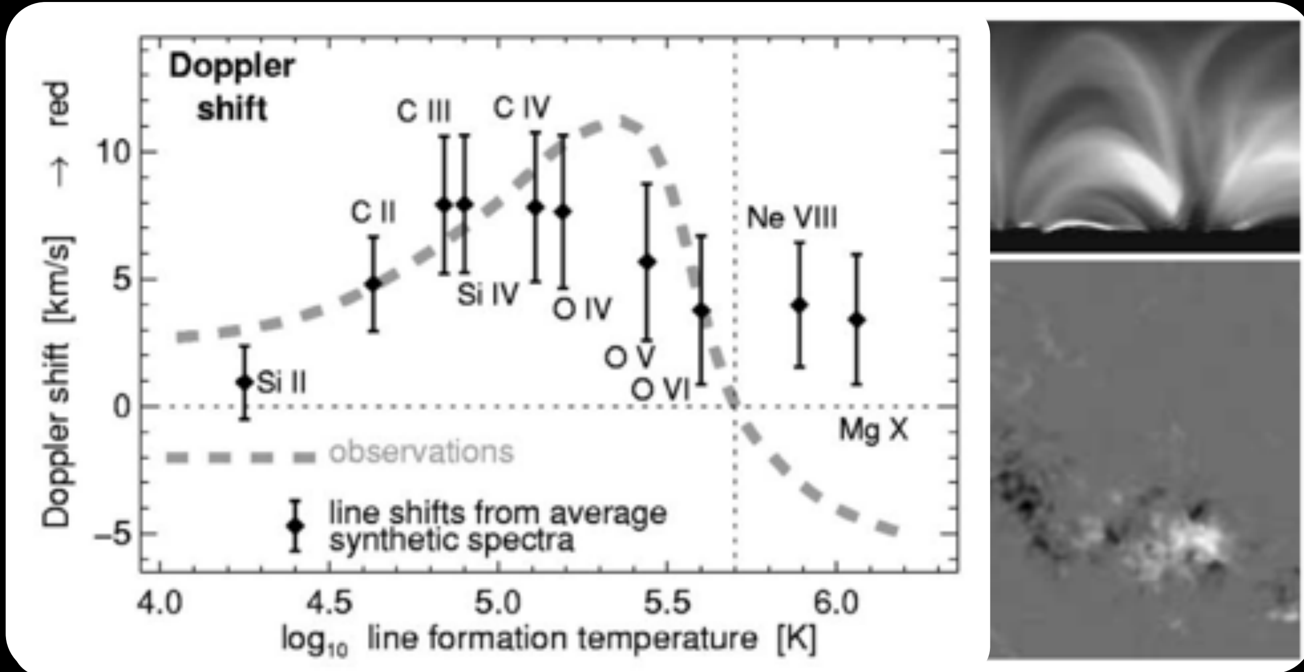

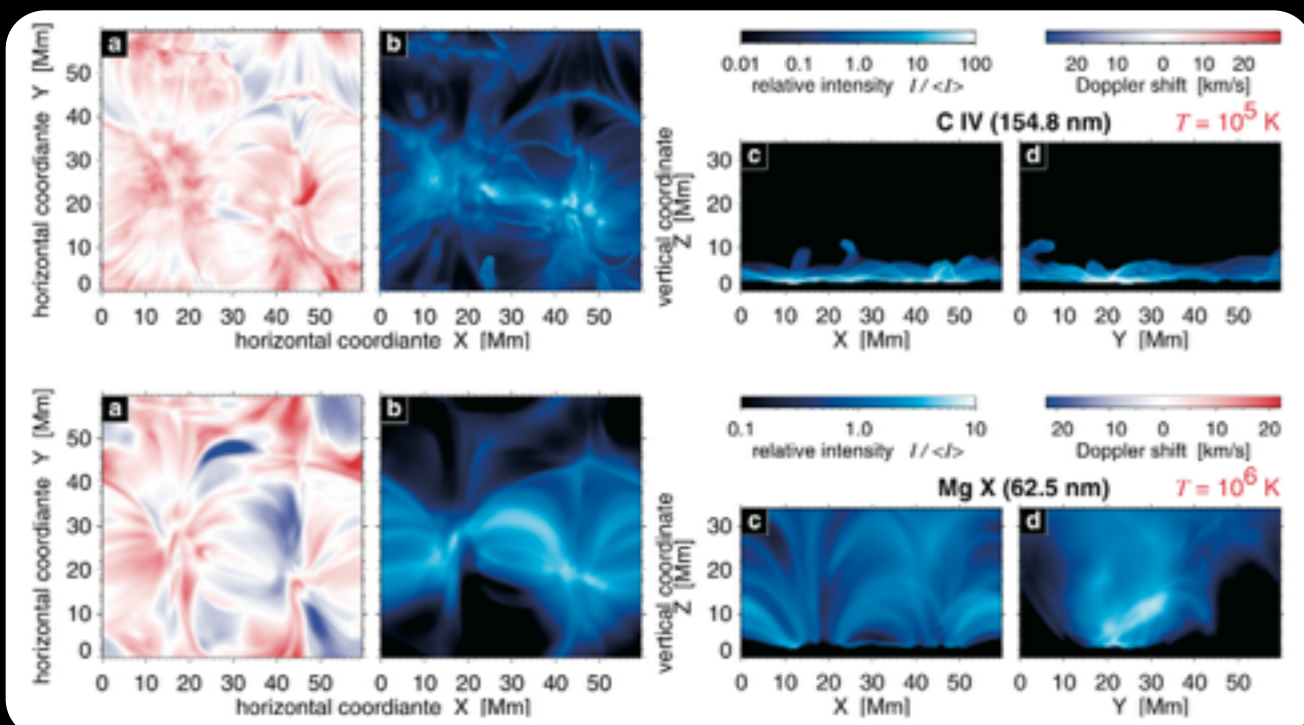

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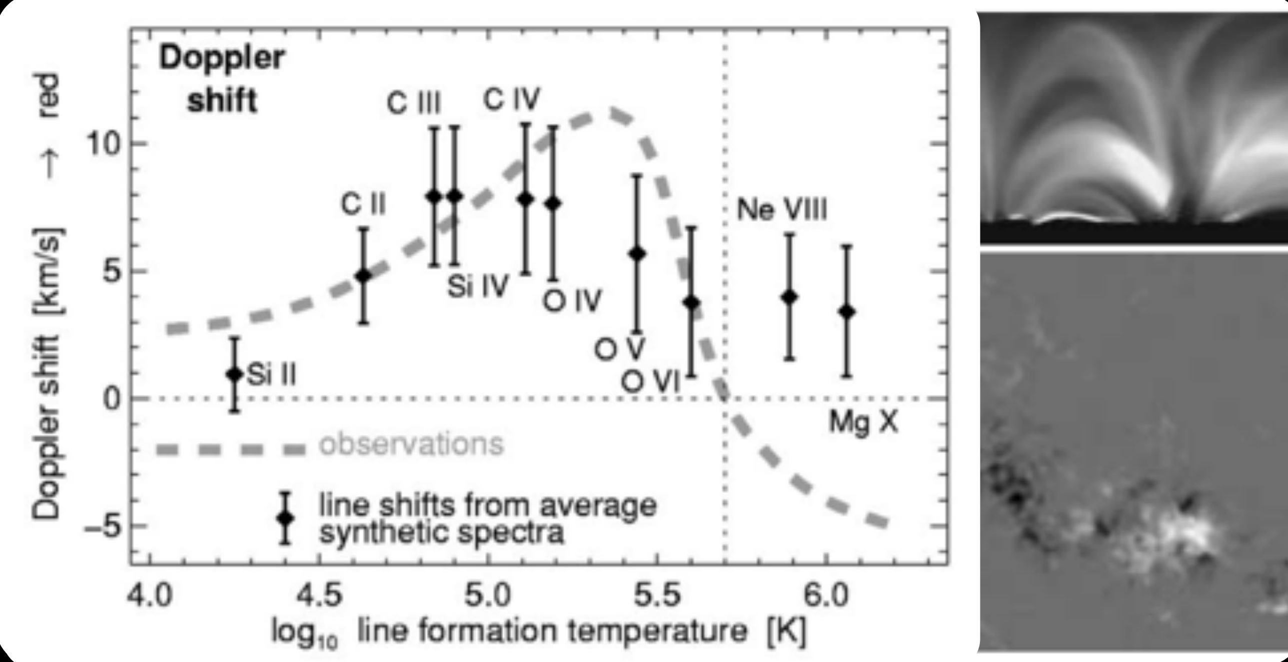

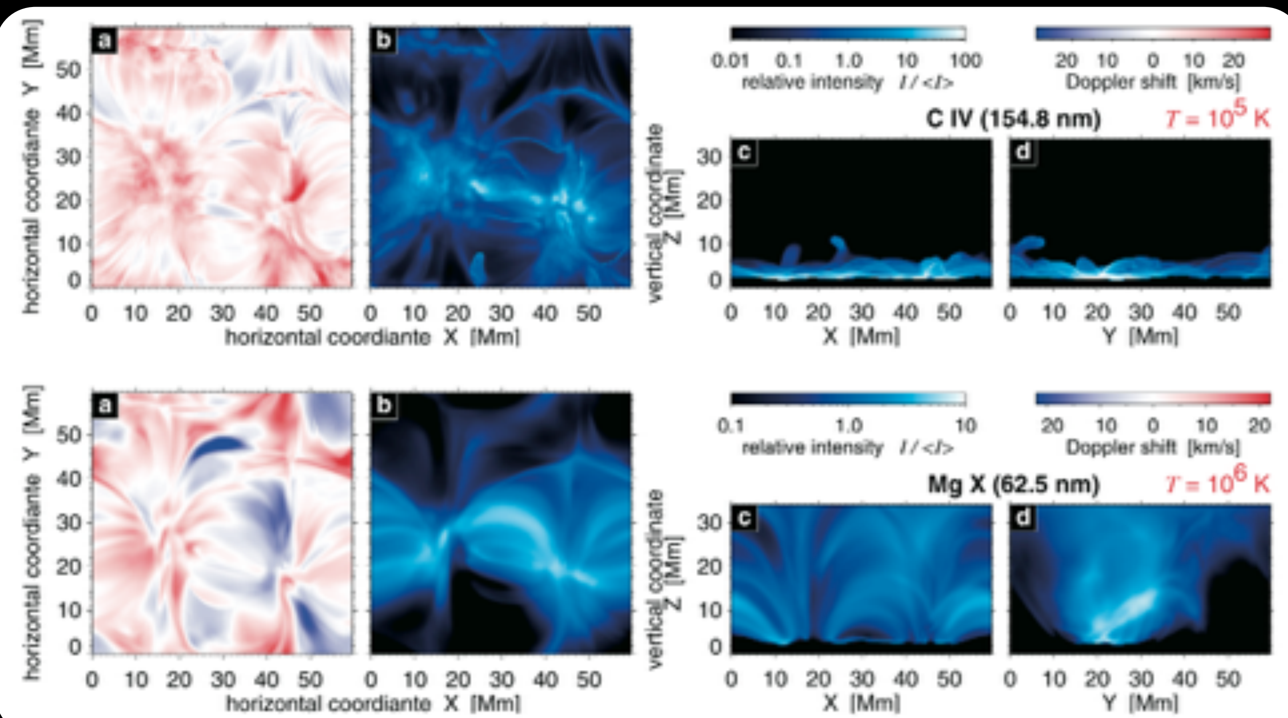

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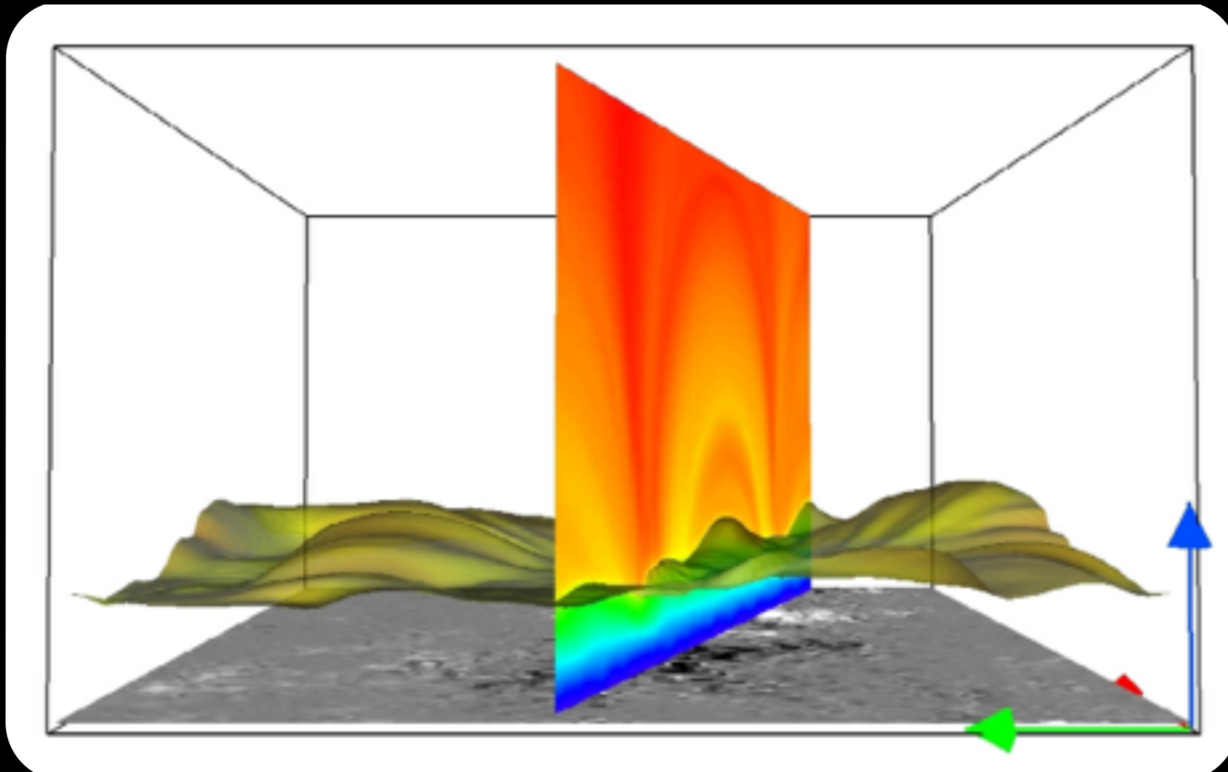
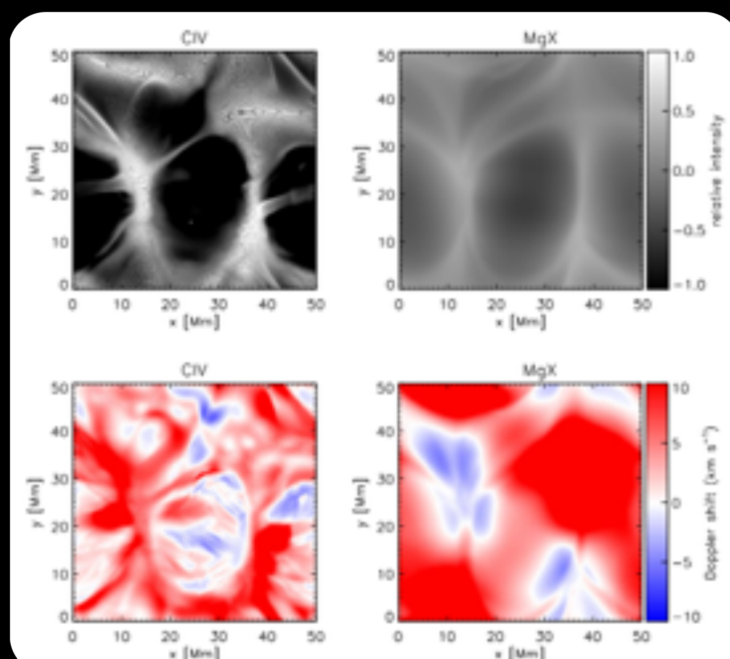


Zacharias et al. (2009, 2011)
Bingert & Peter (2011)

- 50 x 50 x 30 Mm^3 (256x256x256 mesh)
- Magnetic configuration:
  Gudiksen magnetogram + QS network (x5)
- Topology: potential (t=0)
- Field advected by prescribed velocity field
- 3D compressible MHD code (Pencil code)
  - thermal conduction along field



Data comparisons

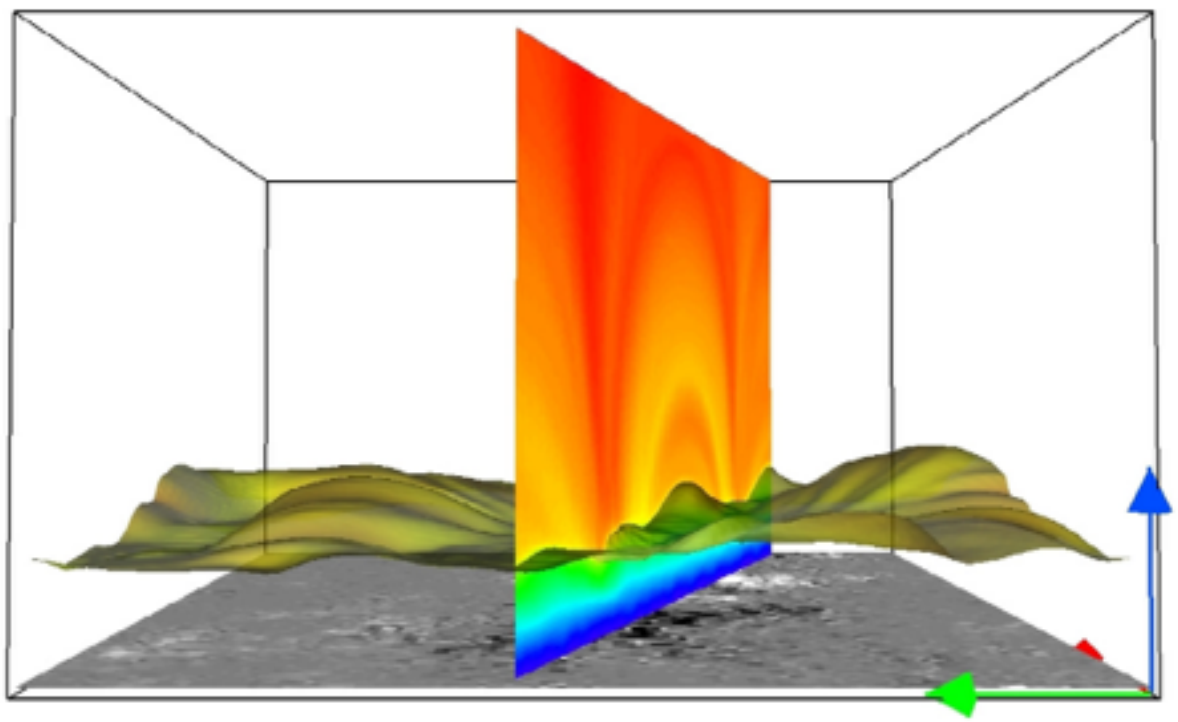
- SUMER/SoHO Doppler shifts
- Qualitative: visual impression
- Quantitative:
  - avg. Doppler shifts as a function of λ
  - intensity fluctuations (rms) as funct. of λ
  - Doppler shifts rms as a function of λ

Identified problems

- Doppler shifts not reproduced at log T > 5.7
- Some discrepancies in the fluctuations distributions as a function of λ

Results / Conclusions

- Coronal emission diffuse and continuous
- Cool lying loops in the transition region
- Doppler shifts as a function of λ (log T < 5.7)



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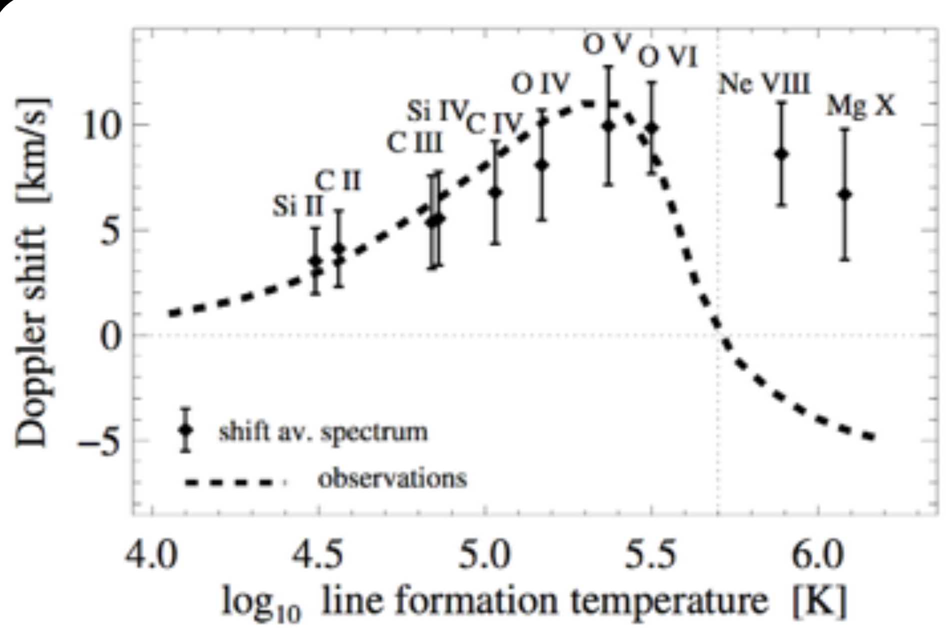

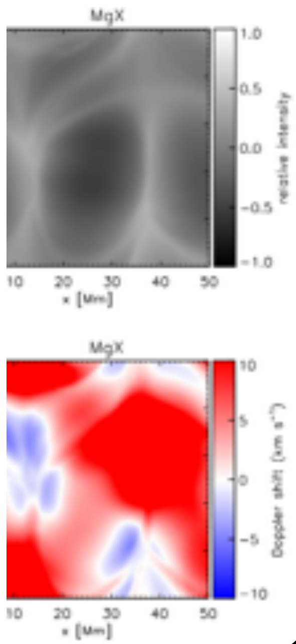

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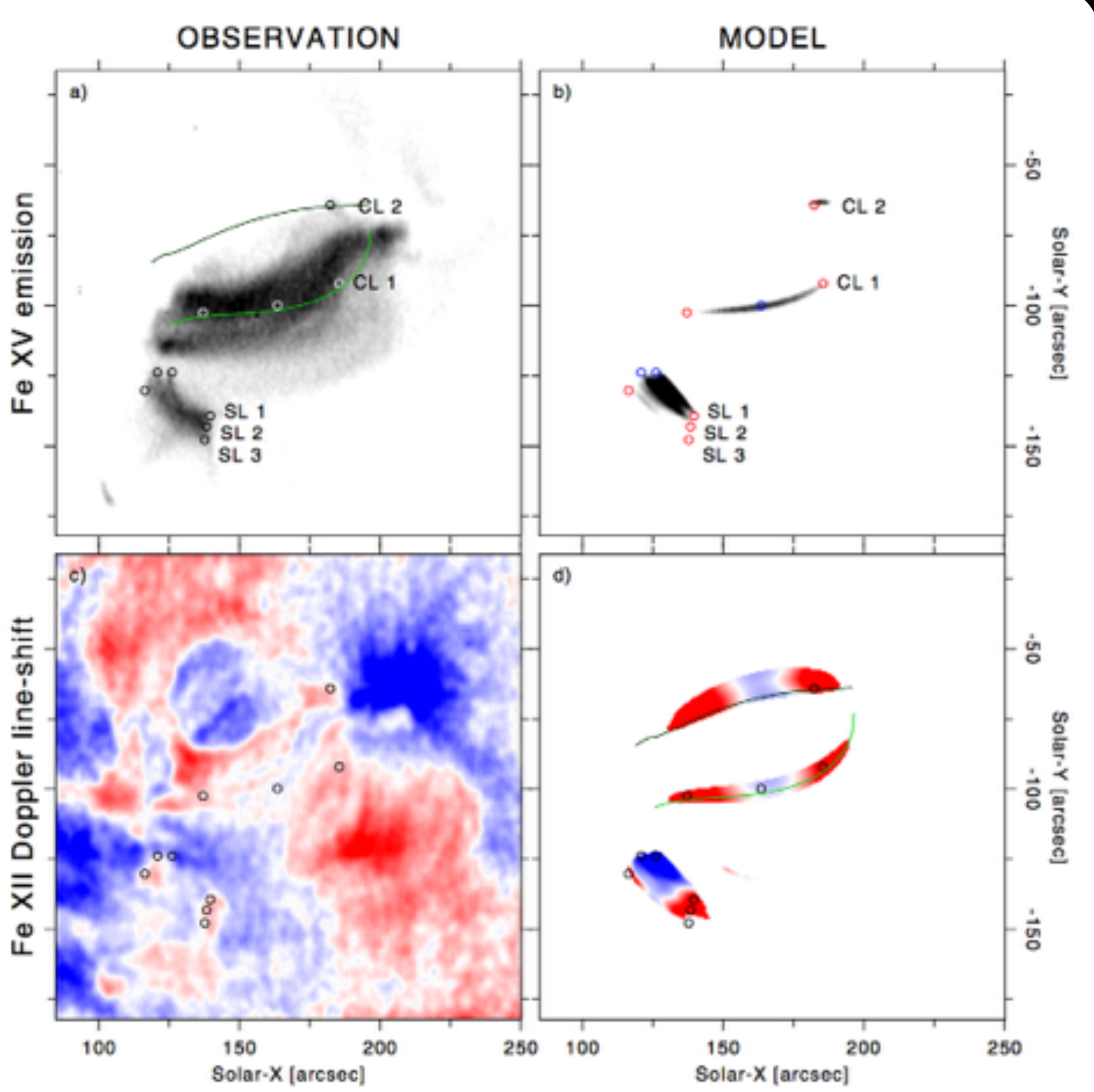
  - avg. Doppler shifts as a function of λ
  - intensity fluctuations (rms) as funct. of λ
  - Doppler shifts rms as a function of λ

Identified problems

- Doppler shifts not reproduced at log T > 5.7
- Some discrepancies in the fluctuations distributions as a function of λ

Results / Conclusions

- Coronal emission diffuse and continuous
- Cool lying loops in the transition region
- Doppler shifts as a function of λ (log T < 5.7)



Bourdin et al. (2013)
Bingert & Peter (2011)

- 235 x 235 x 156 Mm^3 (1024x1024x256 grid)
- Magnetic config.: SOT vector/los magnetog.
- Topology: potential (t=0)
- Field advected by prescribed velocity field:
  - correlation tracking: supergranulation
  - Gudiksen granulation
- 3D compressible MHD code (Pencil code)
  - thermal conduction along field

Data comparisons

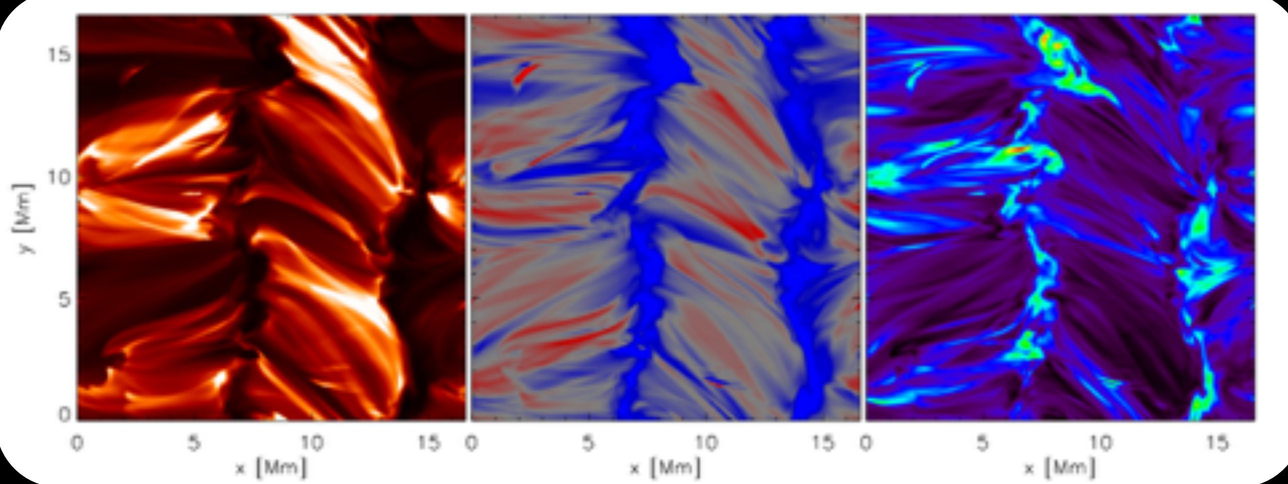
- EIS/Hinode (Fe XV 284 Å, Fe XII 195 Å)
- EUVI/STEREO 284 Å
- Qualitative: visual impression (morphology)
- Quantitative:
  - EUV intensities & Doppler shifts
  - reconstructed geometry in 3D

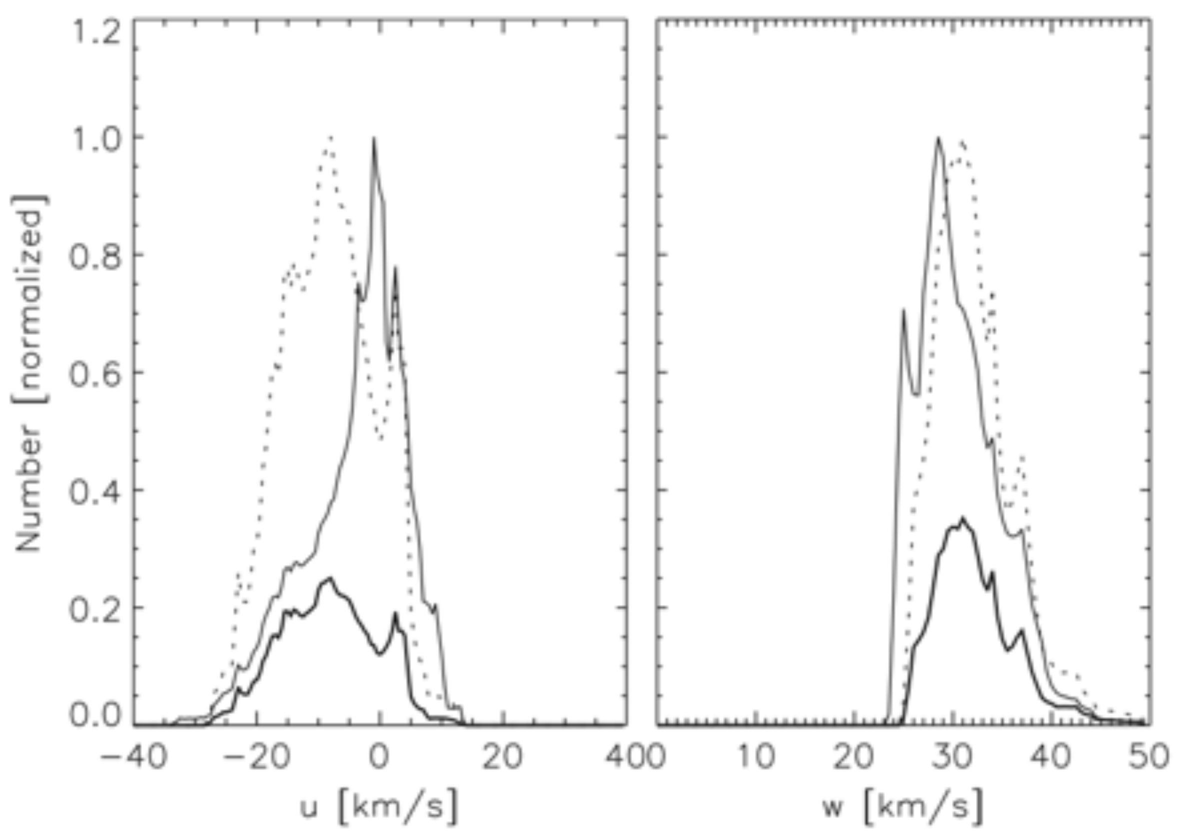
Identified problems

- Long loops: synthetic emission weaker
- Certain short loops not observed

Results / Conclusions

- Long loops: good agreement location & shape
- Good correspondance in Doppler along loops
- Geometry: synthetic emission located within 3D reconstruction





Hansteen et al. (2010)
Gudiksen et al. (2011)

- 16 x 16 x 16 Mm^3 (512x512x325 grid)
- Magnetic configuration: prescribed field
- Optically thick radiative losses ⇒ convection
- Magnetic field advected with flow
- 3D MHD compressible code
  - thermal conduction along field

Data comparisons

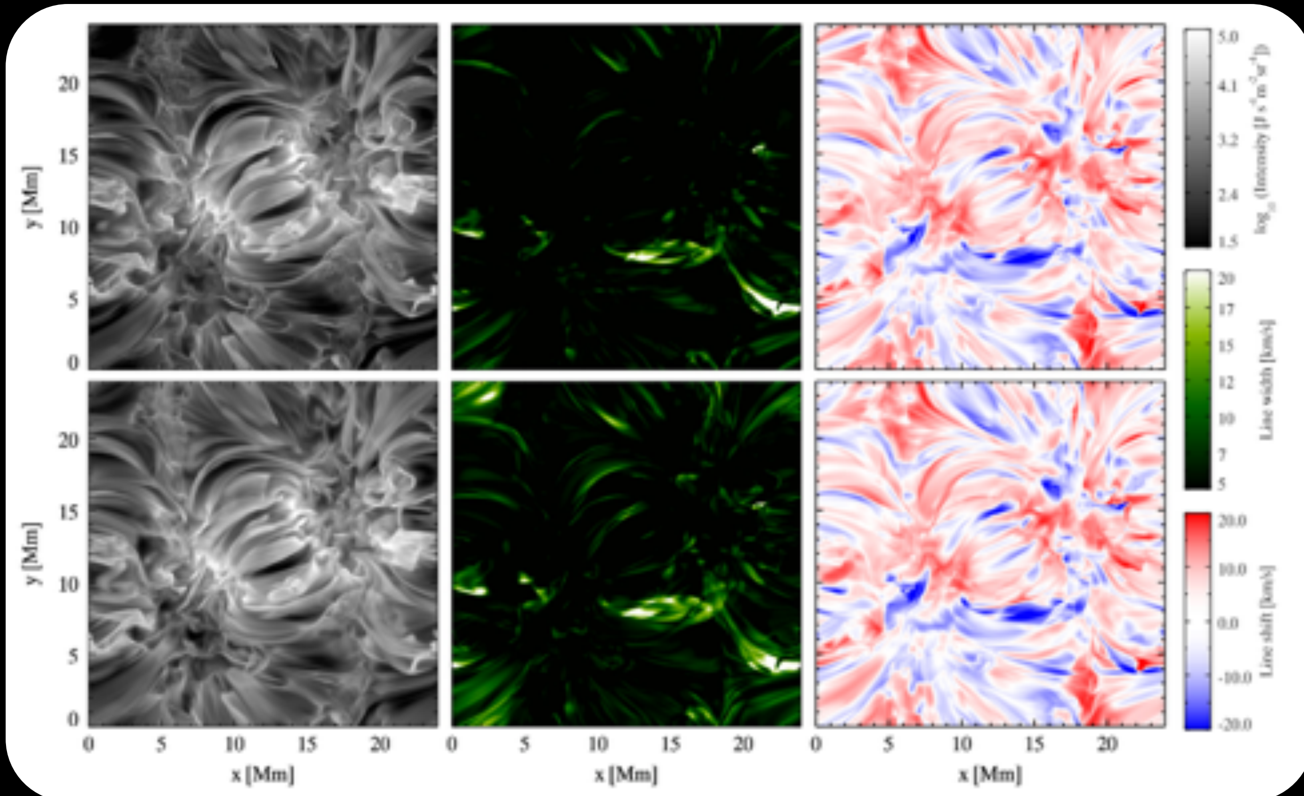
- EIS/Hinode Fe XIV 274 Å
- Quantitative:
  - Doppler shift histograms (Fe XIV)
  - Line width histograms (Fe XIV)

Identified problems

- Fe XIV line widths in simulation are smaller than observed

Results / Conclusions

- Simulation is able to produce red shifts in TR lines (C IV) and blue shifts in the corona .
- Simulated coronal blue shifts match observed by EIS at loop and footprints



Olluri et al. (2015)

- Size: 24 x 24 x 17 Mm^3 (512x512x496 grid)
- Magnetic configuration: prescribed field
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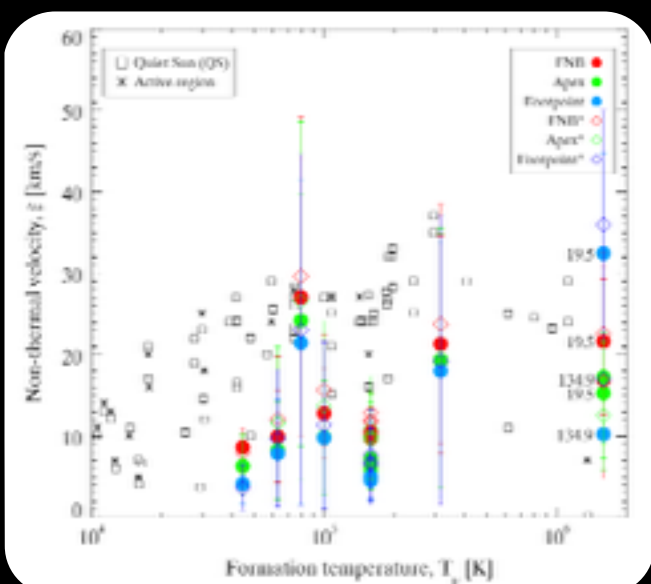
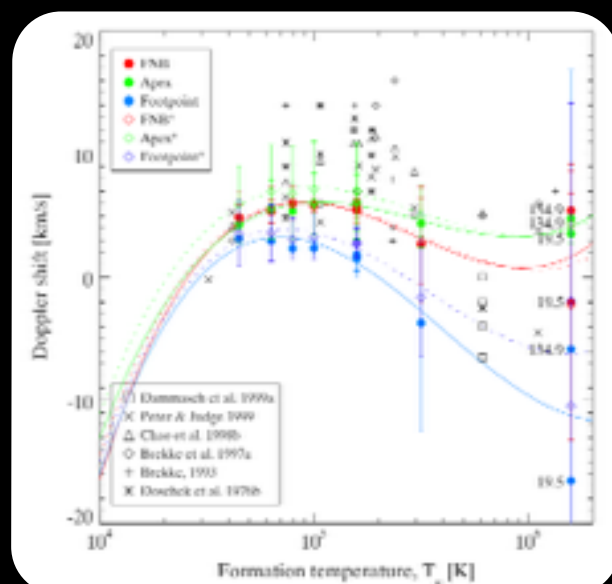
- Magnetic field advected with flow
- 3D MHD compressible code
  - thermal conduction along field





Data comparisons

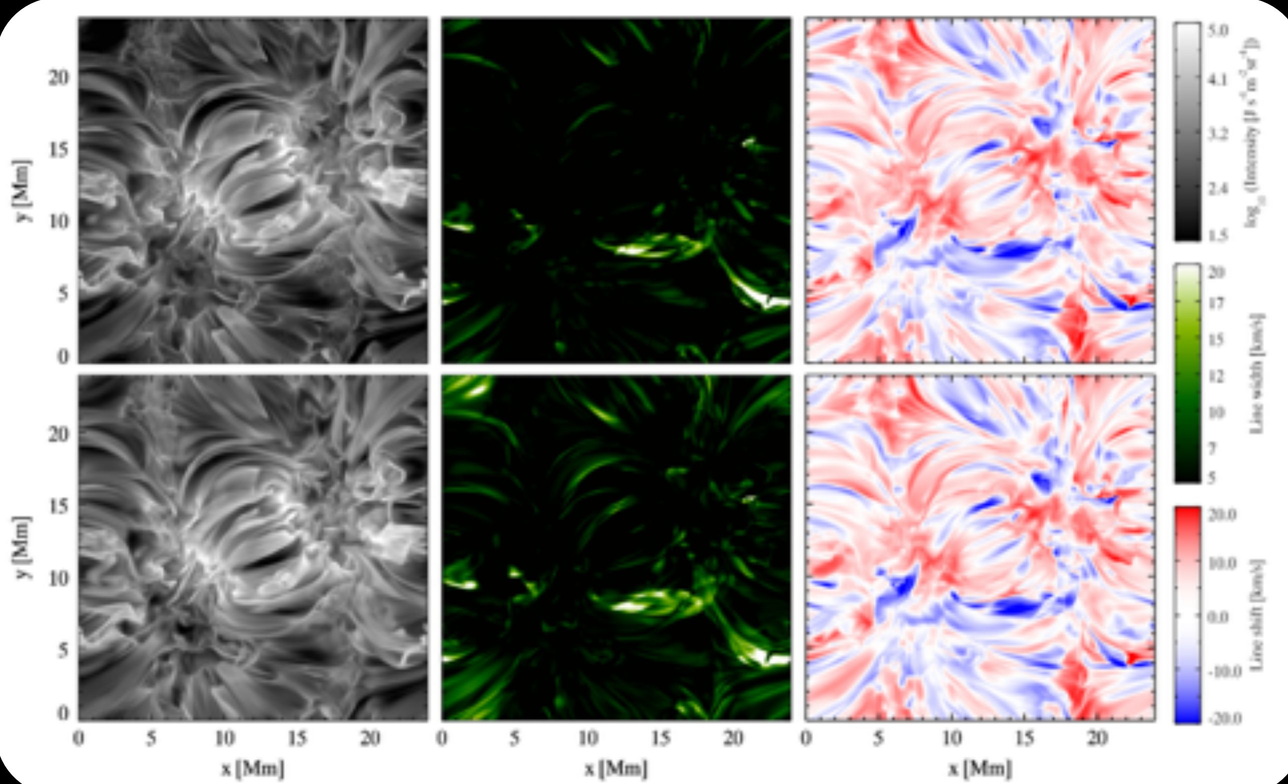
- HRTS atlas (QS, AR)
- SUMER/SoHO atlas (QS)
- EIS/Hinode (QS, AR)
- Quantitative:
  - line intensities: He II, C II, Si IV, O IV, O VI, Fe XII
  - line widths
  - Doppler shifts

Identified problems

- Observed EIS Fe XII and He II QS intensities much larger than synthetic.
- Non-thermal widths below QS observations

Results / Conclusions

- Intensities for TR lines reproduced (factor 2)
- Doppler shifts as a function of λ
- Able to produce Doppler shift correlations:
  - decreasing correlation with T in TR lines
  - anticorrelation of Doppler shifts vs non-thermal widths in Fe XII



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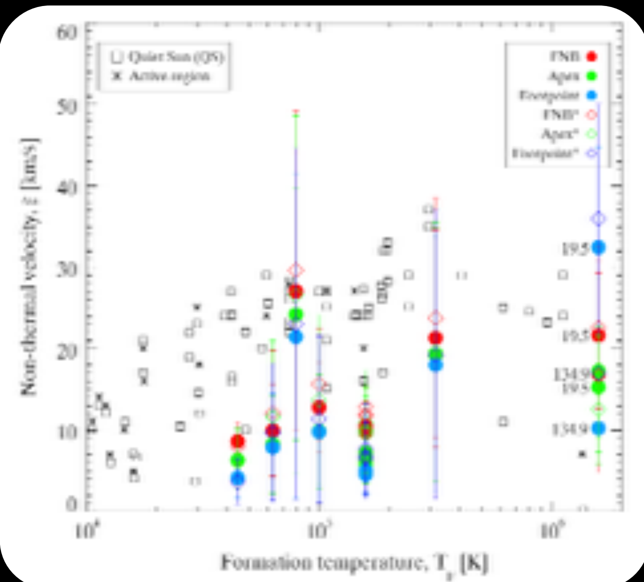

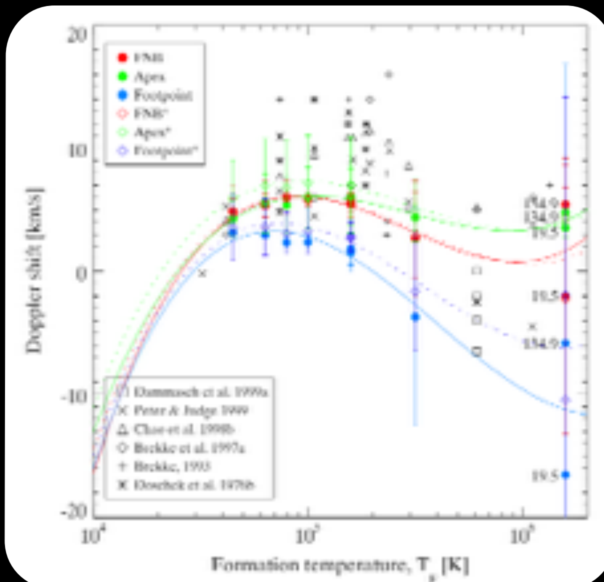

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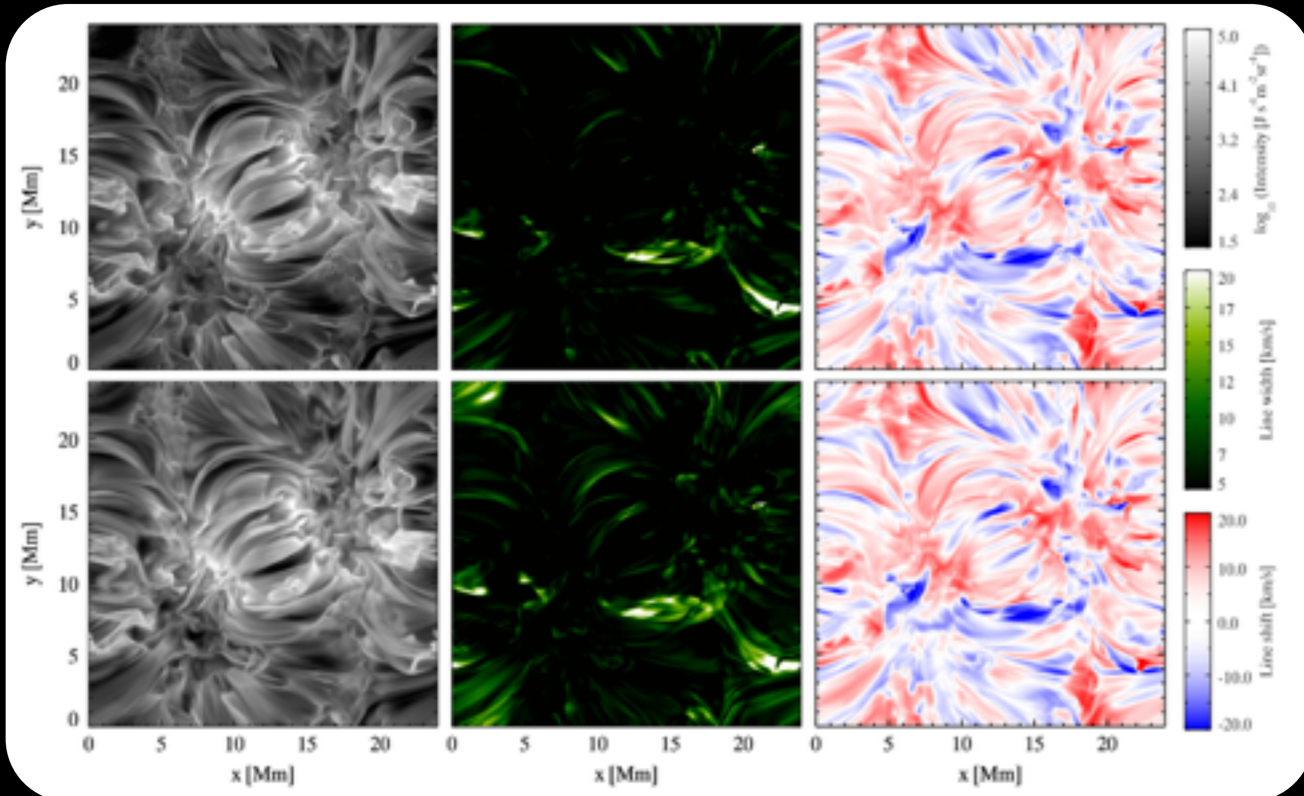

Olluri et al. (2015)

Testa et al. (2012)

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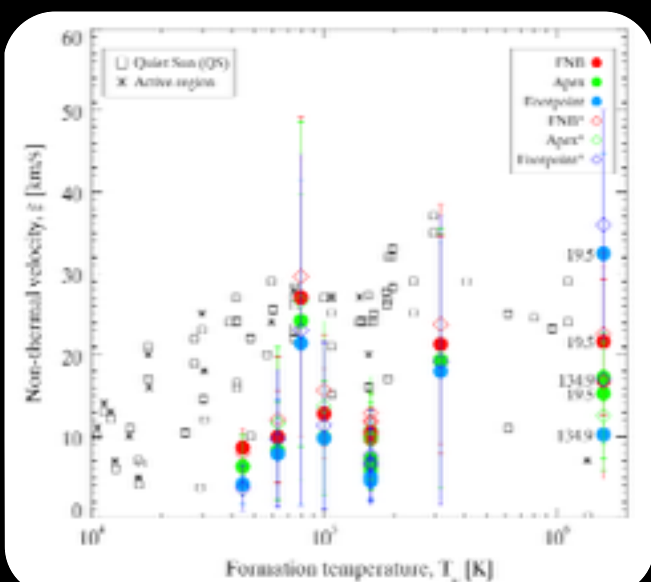

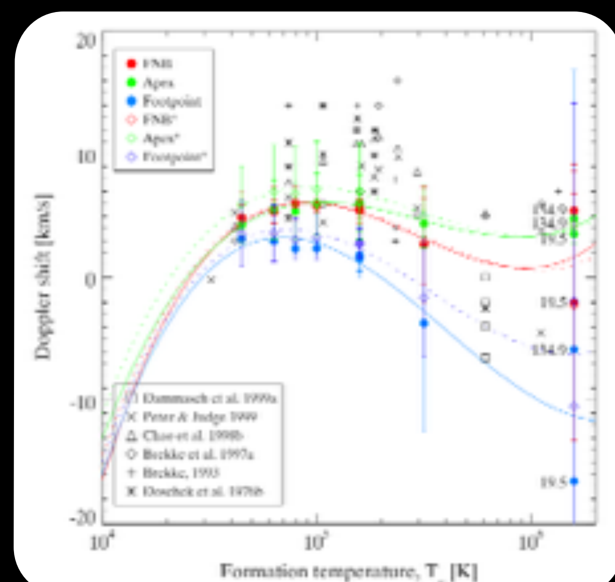

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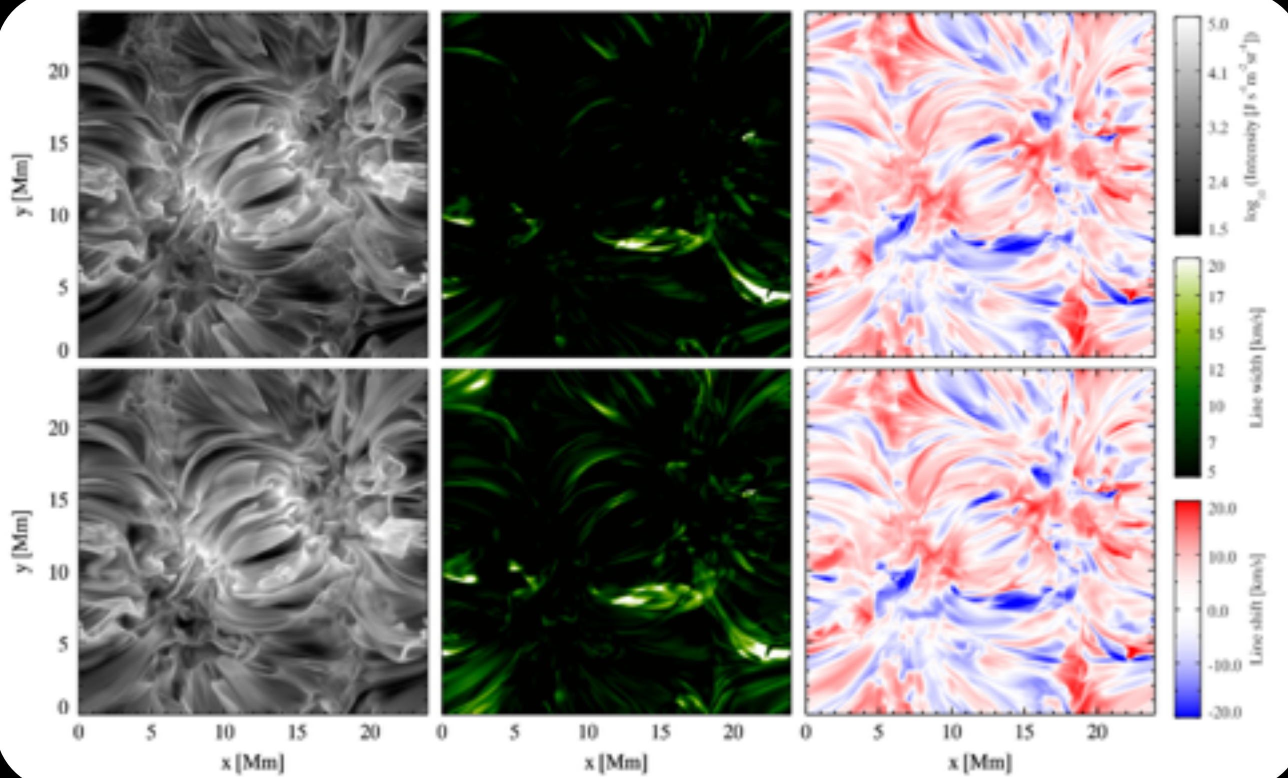

Olluri et al. (2015)

Testa et al. (2012)

Martínez-Sykora et al. (2011)

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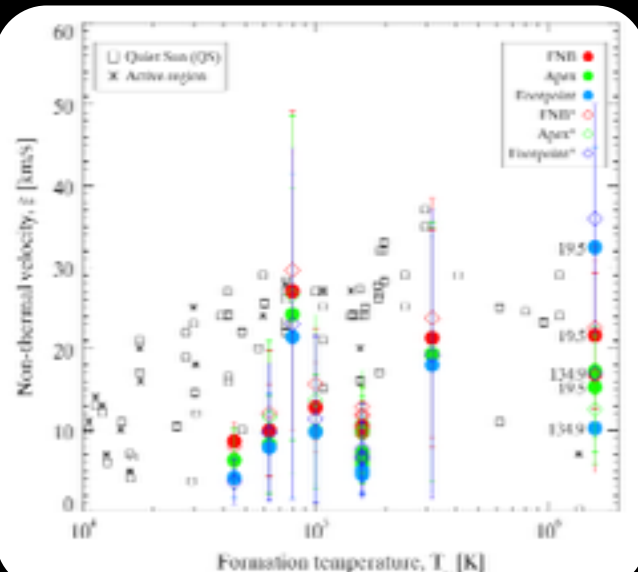

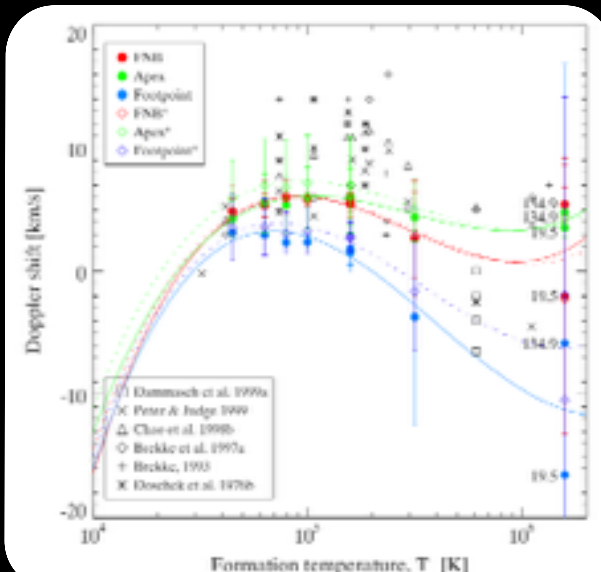

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3D volume
Fixed topology
0D/1D hydro static / dynamic

Schrijver et al. (2004)
Warren & Winebarger (2006)
Warren & Winebarger (2007)
Winebarger et al. (2008)
Lundquist et al. (2008a,b)
Dudik et al. (2011)

Full Sun, AR size
1500 km< Pixel size < 10,000 km
Ad-hoc parameterized heating
Static and dynamic heating
Uniform and non-uniform
Constant and expanding cross-sections

Visual (morphology)
Intensities
Intensity-flux relationship
Filter ratio temperatures
DEM

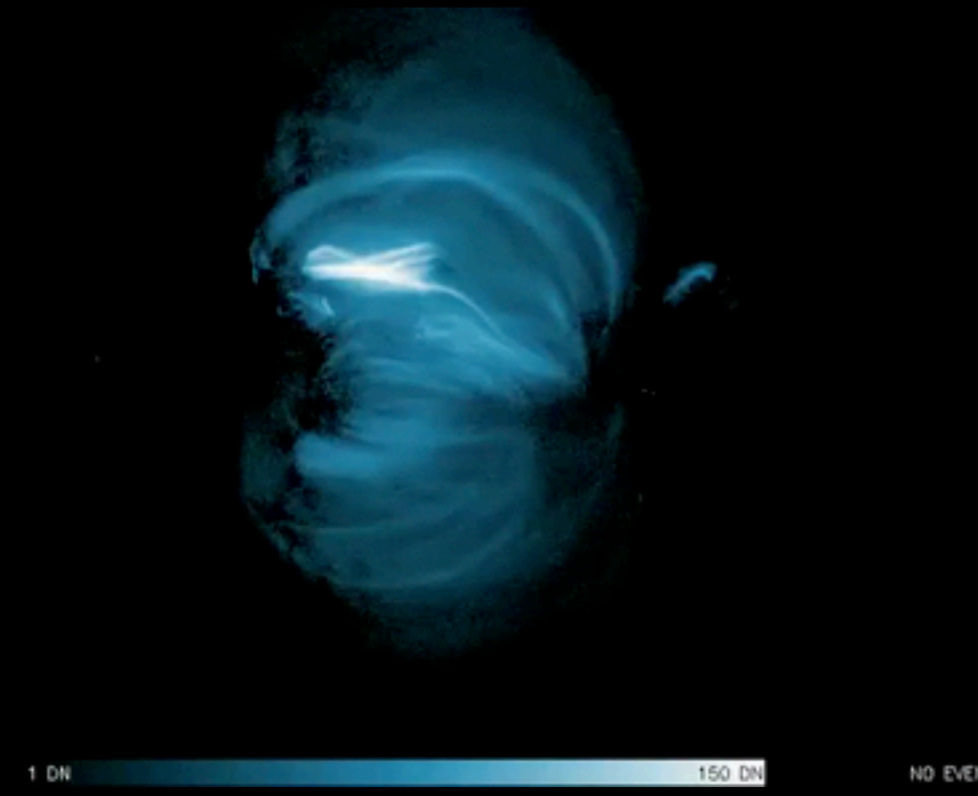
3D volume
3D MagnetoHydroDynamics

Mok et al. (2005,2008)
Peter et al. (2004, 2006)
Gudiksen & Nordlund (2005)
Zacharias et al. (2009, 2011)
Bingert & Peter (2011)
Bourdin et al. (2013)
Hansteen et al. (2010)
Gudiksen et al. (2011)
Martinez-Sykora et al. (2011)
Olluri et al. (2015)
Testa et al. (2012)

16Mm - 250 Mm
Rigid topology / advection mag. field
Ad-hoc steady heating /
Intermittent Ohmic heating
Prescribed velocity fields /
Convection simulation
Visual (morphology)
Intensities (total, fluctuations)
Doppler shifts
DEM
3D geometry
Line widths

Warren & Ugarte-Urra (TBD)

- Active region size (15 regions)
- Magnetic configuration: HMI los magnetog.
- Extrapolation: NLFF (10,000 field lines)
- Loops modeled with EBTEL (0D)
  - Hydrodynamics
  - Ad hoc heating: $E_H \propto \frac{\bar{B}}{L}$
    Uniform
    Frequency: $dt \propto E_{i-1}$



Data comparisons

- AIA/SDO (Fe XVIII, 195, 171)
- EIS/Hinode
- Qualitative: visual
- Quantitative:
  - Flux-luminosity relationship
  - Statistics on event detection
  - DEM

Results / Conclusions

- Time-dependent quantitative comparisons are possible
- B/L works for high T
- Best match: intermediate frequencies

Identified problems

- Topology ⇔ Morphology
- 1 MK emission: too much on small loops
- Temporal variability is spatially correlated
- Inferring unknown heating function is hard
- Solar corona is not 0D

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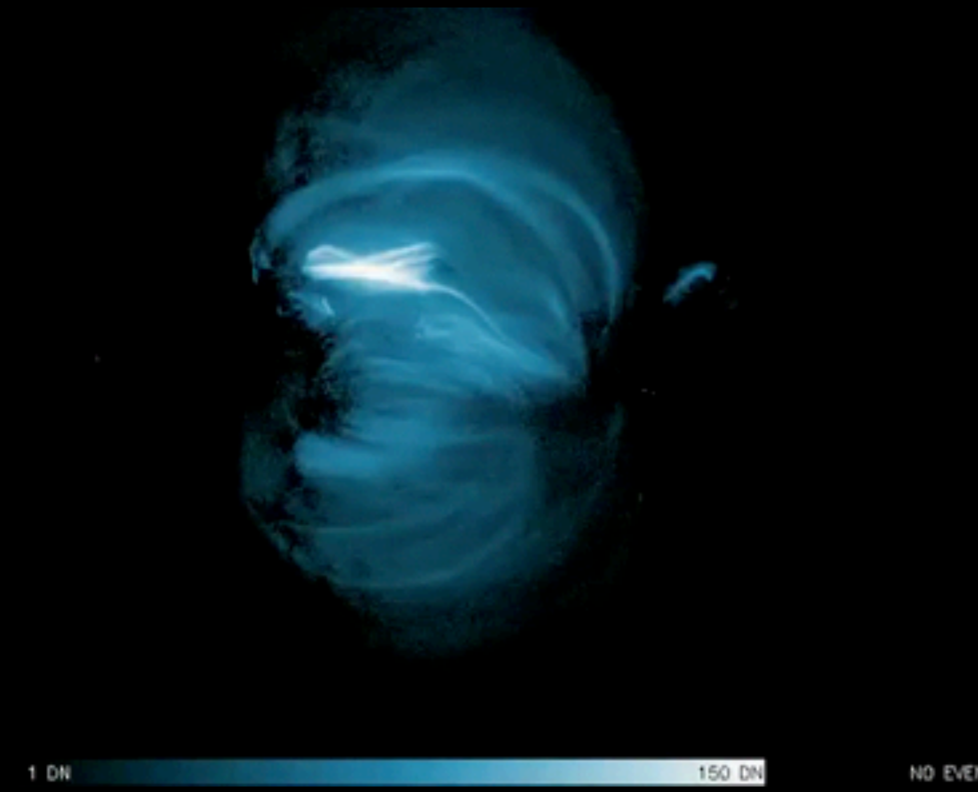

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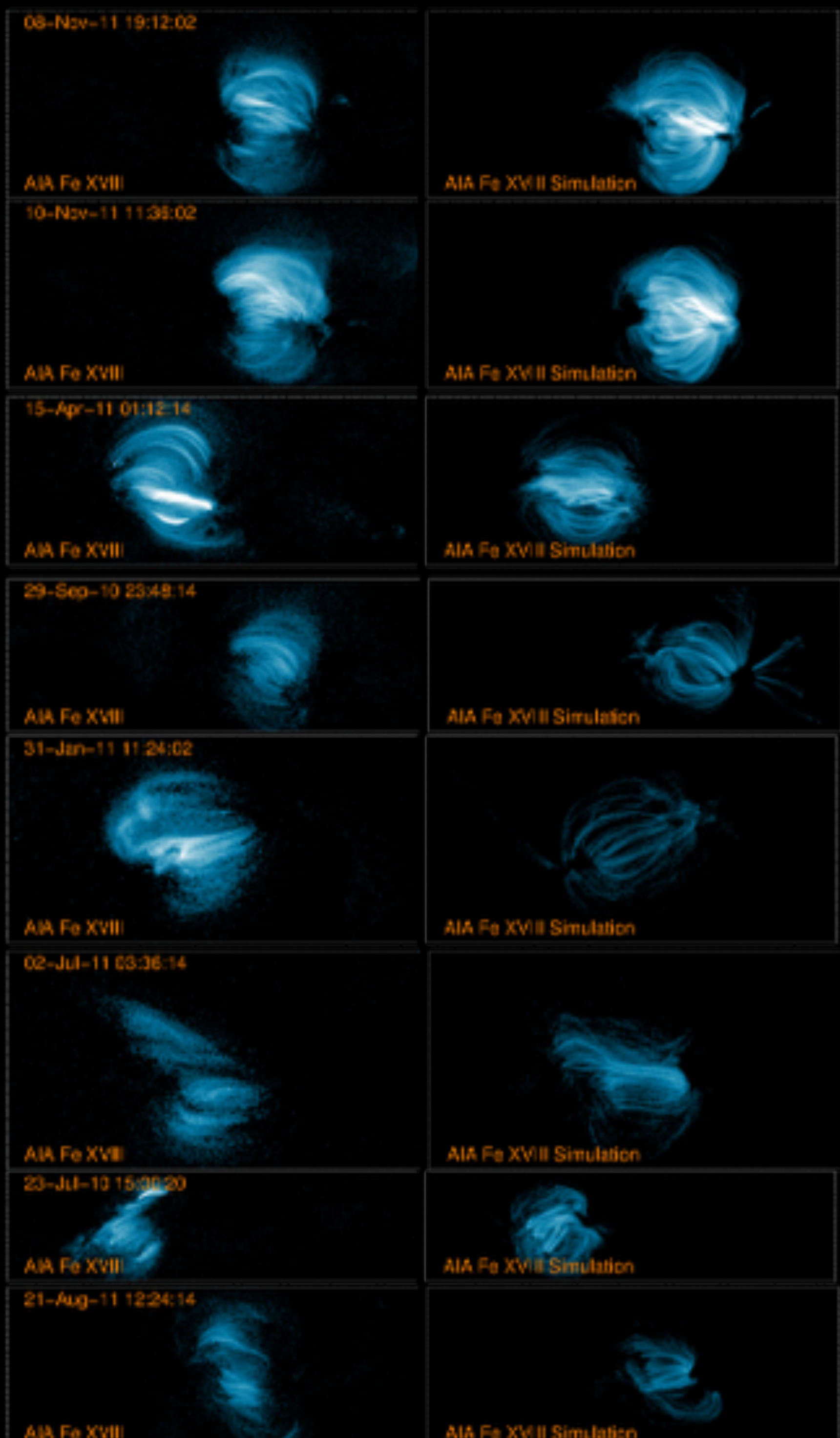
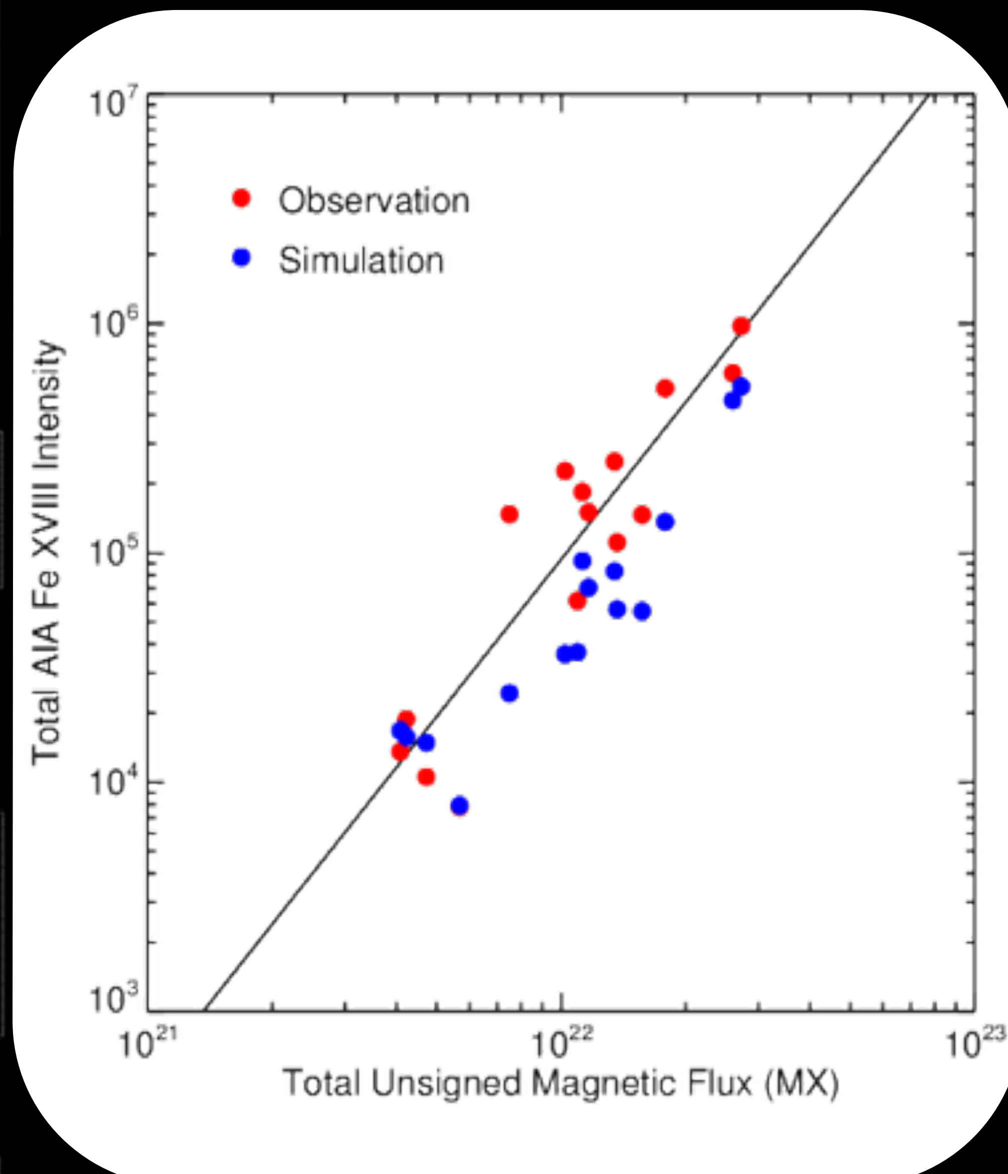
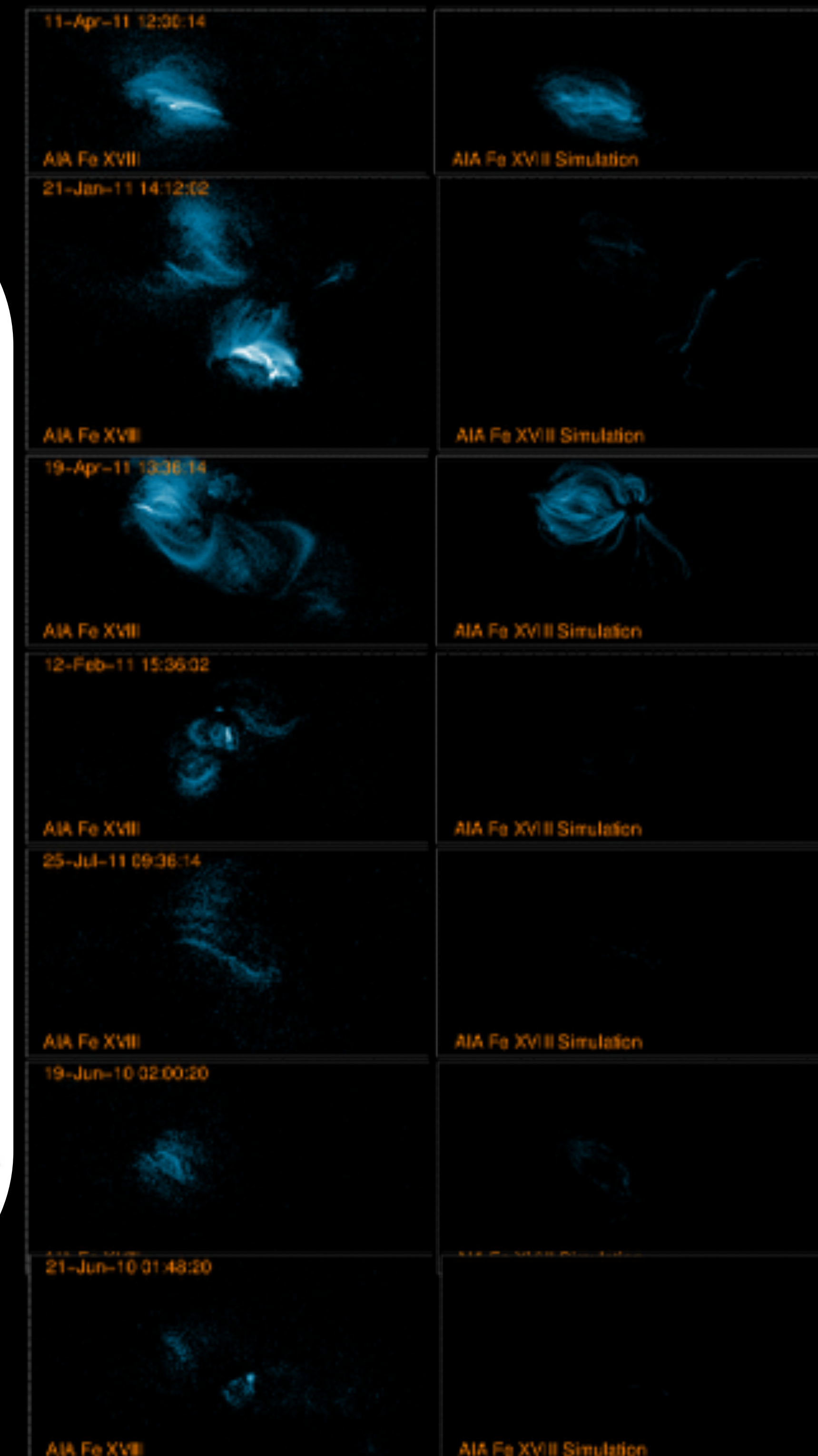

08-Nov-11 19:12:02
AIA Fe XVIII
AIA Fe XVIII Simulation
10-Nov-11 11:36:02
AIA Fe XVIII
AIA Fe XVIII Simulation
15-Apr-11 01:12:14
AIA Fe XVIII
AIA Fe XVIII Simulation
29-Sep-10 23:48:14
AIA Fe XVIII
AIA Fe XVIII Simulation
31-Jan-11 11:24:02
AIA Fe XVIII
AIA Fe XVIII Simulation
02-Jul-11 03:36:14
AIA Fe XVIII
AIA Fe XVIII Simulation
AIA Fe XVIII
AIA Fe XVIII Simulation
21-Aug-11 12:24:14
AIA Fe XVIII
AIA Fe XVIII Simulation


Observation
Simulation
Total AIA Fe XVIII Intensity
Total Unsigned Magnetic Flux (MX)
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{21}
10^{22}
10^{23}


11-Apr-11 12:00:14
AIA Fe XVIII
AIA Fe XVIII Simulation
21-Jan-11 14:12:02
AIA Fe XVIII
AIA Fe XVIII Simulation
19-Apr-11 13:36:14
AIA Fe XVIII
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12-Feb-11 15:36:02
AIA Fe XVIII
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25-Jul-11 09:36:14
AIA Fe XVIII
AIA Fe XVIII Simulation
19-Jun-10 02:00:20
21-Jun-10 01:48:20
AIA Fe XVIII
AIA Fe XVIII Simulation

3D volume
Fixed topology
0D/1D hydro static / dynamic

Successful at reproducing the high T emission

Difficulty in reproducing EUV (impulsive?)

Hints about the timescales of heating:
quasi-steady or not too infrequent

Difficult to get at the source

3D volume
3D MagnetoHydroDynamics

Successful at reproducing the
TR-low corona emission (QS)

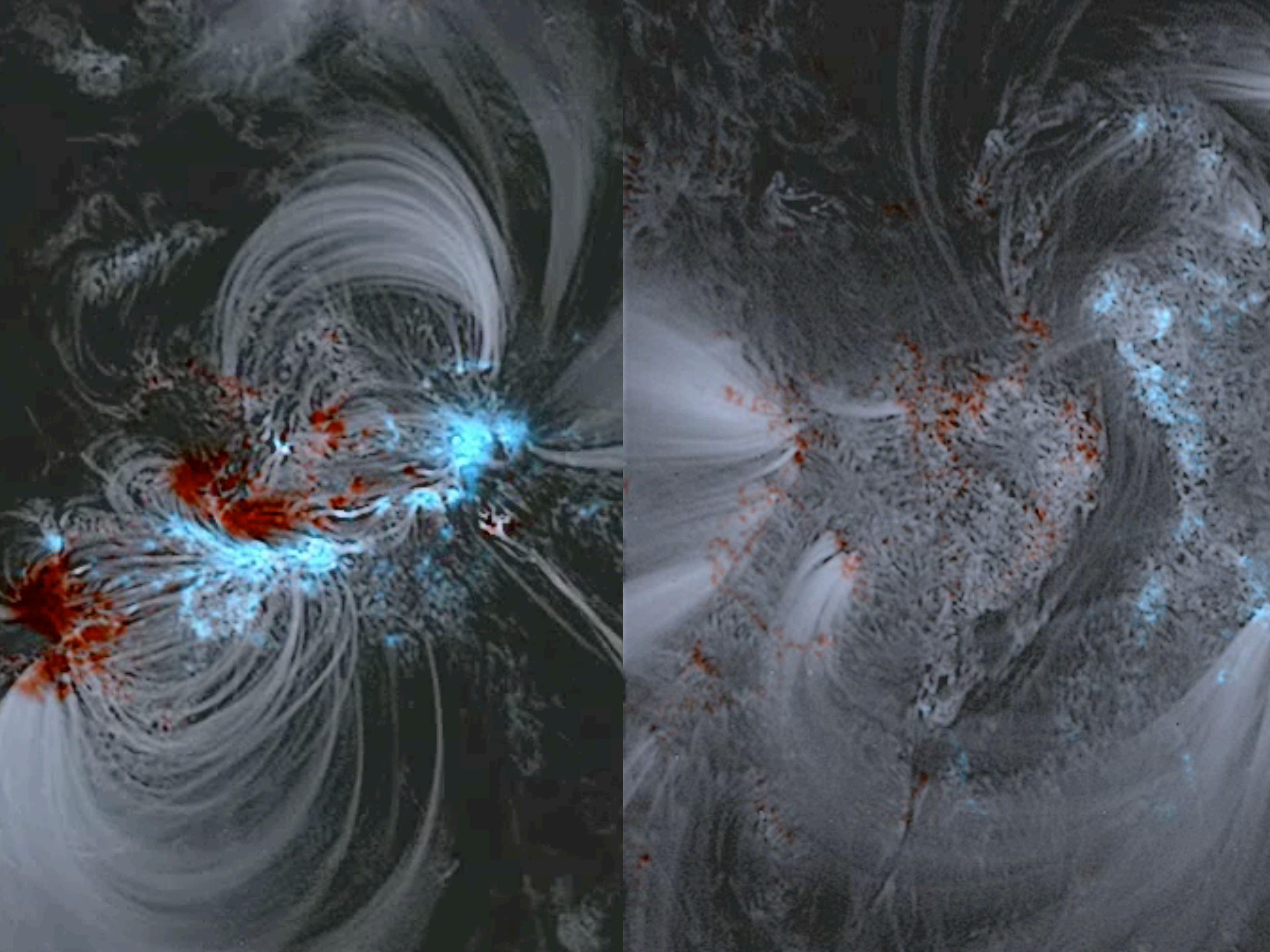
Too cool for the high T core emission in AR

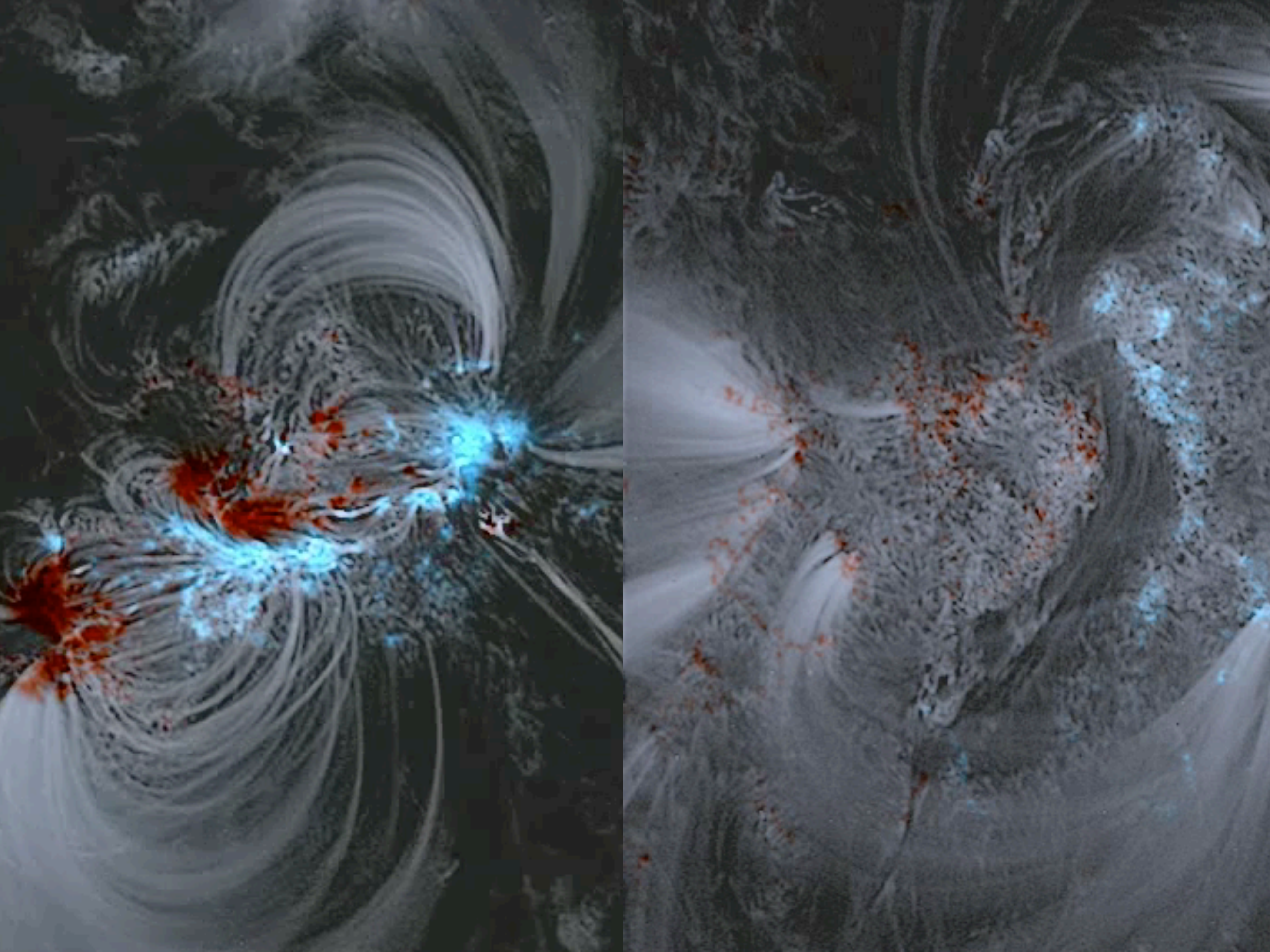
Intermittency of heating

Source is everywhere, 90% near footpoints

Final thoughts

- Significant progress since 2002
- The coronal heating problem is not just about producing 1-2 MK
- Model to data comparisons are very specific with several successes
- Challenges:
  - Scaling with total flux
  - Properties of different loop populations
  - Temperature distributions (DEM)
  - Time dependency
  - Evolutionary timescales





EXTRAS

Dahlburg et al. (Submitted to ApJ)