Simulations of the Solar Atmosphere with MURaM

- From quiet Sun to Flares -

Matthias Rempel
HAO/NCAR

G. Chintzoglou, M.C.M. Cheung, D. Przybylski,
MURaM GPU Team, MUSE and CMEx Science teams

May 14 , 2025

NCAR

High Altitude Observatory

NSF

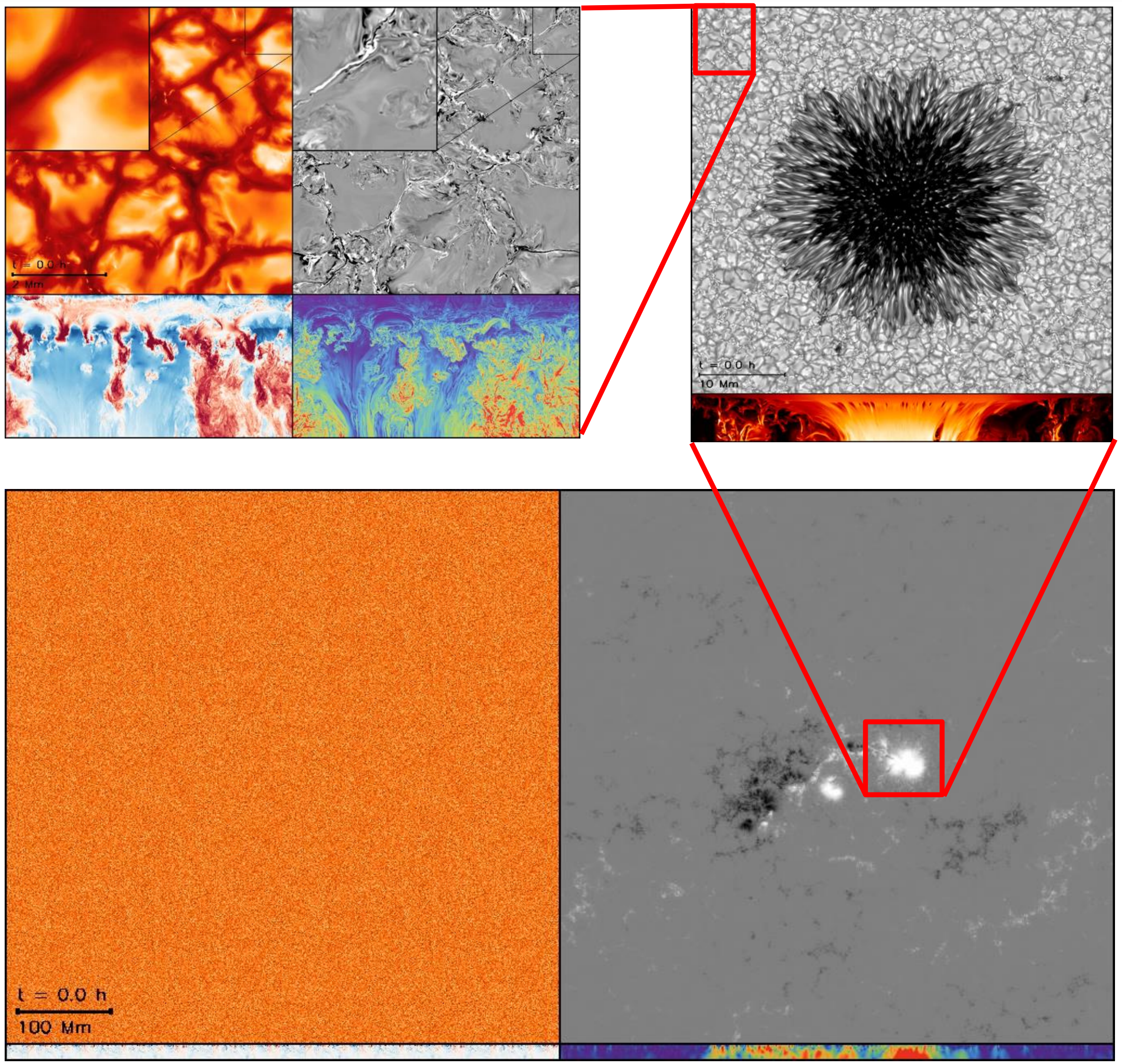
This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Motivation

- Focus of this Study: Comprehensive MHD treatment of the solar atmosphere from convection zone into corona
  – Consider relevant physics required for modeling of synthetic observables, such as EUV, X-ray
  – Consider a setup that produces a corona naturally through sub-photospheric dynamics

- Outline
  – Model
    - Realistic MHD simulations covering upper convection zone through corona
  – Some representative simulation examples
    - Quiet Sun, Open flux regions, Arcade, Active Regions, Flares
  – Data driving, data nudging approaches
    - ISWAT challenge

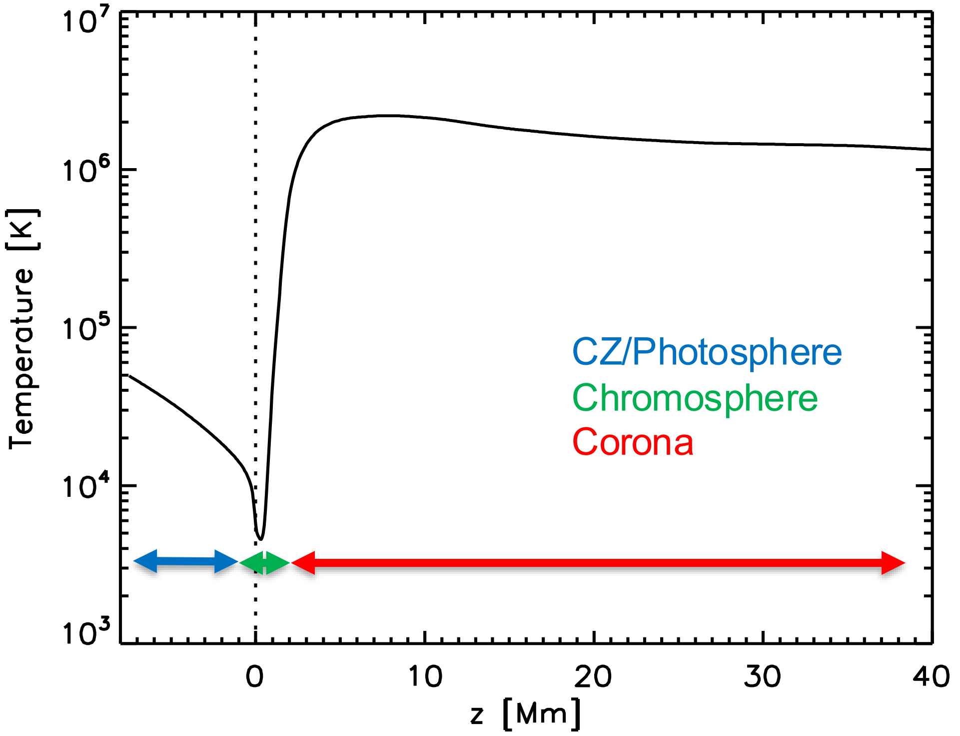
MURaM Code

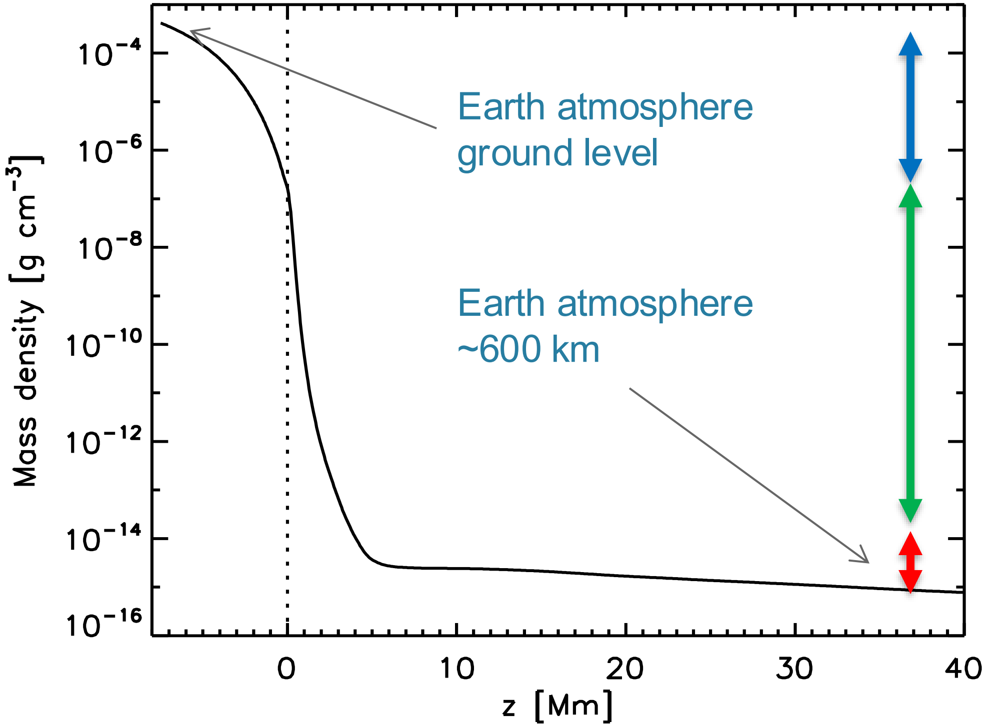


- 2000 – 2017:
  - Solar radiative MHD code that has been been applied to most solar magnetic environments:
    - Quiet Sun
    - Sunspots
    - Active regions
- Since 2017:
  - Added corona
  - simplified chromosphere
- Since 2020:
  - Chromospheric extension
  - NLTE treatment of chromosphere

The challenge

- The solar atmosphere is highly stratified





- Density contrast of $10^{12} – 10^{14}$

The challenge

- Highly stratified simulation domain
  - Density contrast of 10^{12} – 10^{14}
  - Transition from high to low beta regime
- Separation of time scales
  - Active region evolution on time-scales of hours to days
  - Short coronal time-scales due to high Alfven velocity (> 100,000 km/s) and very efficient heat conduction
- Energy storage and release
  - Slow injection of magnetic energy on time-scale of flux emergence
  - Release on time scales < minutes in flares
  - Built up of free magnetic energy requires sufficiently low magnetic diffusivity

Radiative MHD model

$$\frac{\partial \varrho}{\partial t} = -\nabla \cdot (\varrho \mathbf{v})$$

$$\frac{\partial \varrho \mathbf{v}}{\partial t} = -\nabla \cdot (\varrho \mathbf{v}\mathbf{v}) - \nabla P + \varrho \mathbf{g} + \mathbf{F_L} + \mathbf{F}_{SR}$$

$$\frac{\partial E_{\mathrm{HD}}}{\partial t} = -\nabla \cdot \left[\mathbf{v}\left(E_{\mathrm{HD}} + P\right) + q\hat{\mathbf{b}}\right] + \varrho \mathbf{v} \cdot \mathbf{g} + \mathbf{v} \cdot \mathbf{F_L} + \mathbf{v} \cdot \mathbf{F}_{SR} + Q_{\mathrm{rad}} + Q_{\mathrm{loss}}$$

$$\frac{\partial q}{\partial t} = \frac{1}{\tau}\left(-f_{\mathrm{sat}} \sigma T^{\frac{5}{2}} (\hat{\mathbf{b}} \cdot \nabla) T - q\right)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$\mathbf{F}_{SR} = -\left(1 - \frac{1}{\sqrt{1 + (\frac{v_A}{c})^4}}\right)\left[\mathcal{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}\right] - \left(-\varrho(\mathbf{v} \cdot \nabla)\mathbf{v} - \nabla p + \varrho \mathbf{g} + \mathbf{F_L}\right)$$

Boris correction and hyperbolic heat conduction save 2-3 order of magnitude in computing time!

- Coronal extension of MURaM code (Rempel 2017)
  - Realistic photosphere
  - Simplified (LTE) Chromosphere
  - Corona
    - Flux limited heat conduction
    - Optically thin radiative loss
- Numerical Treatment
  - Boris correction
    - Approximation of semi-relativistic MHD
    - Dynamically adjusted “speed of light”
  - Hyperbolic treatment of heat conduction
  - Numerical diffusivities emulate high Pm regime

Artificial limitation of Alfven and heat conduction speed

- Boris correction (Boris 1970, Gombosi et al 2002, Lyon et al 2004)
  - Semi-relativistic MHD with a reduced speed of light
  - Alfven velocity limited by reduced speed of light

$$\frac{\partial}{\partial t}\left(\varrho \mathbf{v} + \frac{\mathbf{E}\times\mathbf{B}}{4\pi\, c^2}\right) = -\nabla\cdot(\varrho \mathbf{v}\mathbf{v}) - \nabla p + \varrho \mathbf{g} + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} + \frac{1}{4\pi}(\nabla\times\mathbf{E})\times\mathbf{E}$$

  - Used in magnetospheric simulations for 40+ years
  - Energetically consistent (equations remain conservative)
  - **Reduction of V_A reduces also numerical diffusivities**

- Hyperbolic heat conduction (Telegraph equation) (e.g. Gombosi et al 1993, Snodin et al. 2006)

$$\frac{\kappa}{c^2}\frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \nabla\cdot[\kappa\hat{\mathbf{b}}(\hat{\mathbf{b}}\cdot\nabla)T]$$

  - Has well defined maximum wave speed (unlike heat conduction with formally infinite propagation speeds)
  - Explicit numerical integration without severe time step constraint possible (peak speeds set by free streaming limit, i.e. 1/6 electron thermal speed -> ~ 2 C_S)

- Dynamically adjust c in flare simulation
  - c = max(3|v|,2 C_S)

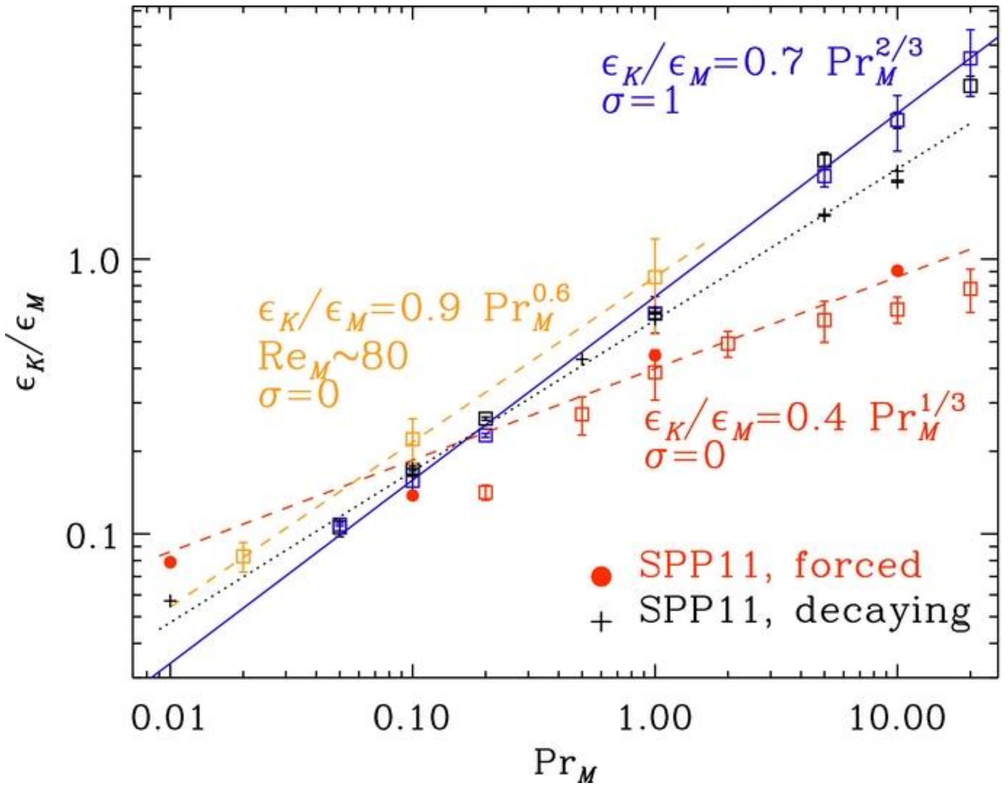
Numerical diffusivity

- Aims at emulating a high magnetic Prandtl number regime (Corona: Pm > 10^{10})
  - Minimize magnetic diffusivity (restricted to regions with a monotonicity change -> |j| has to exceed threshold)
  - Higher viscosity

$$\eta_{\rm eff} = 4\pi \frac{\int Q_{\rm res}^{\rm NUM} {\rm d}V}{\int |\mathbf{j}|^2 {\rm d}V} \sim 10^{11} - 10^{12} {\rm cm}^2/{\rm s}$$

$$\nu_{\rm eff} = \frac{\int Q_{\rm visc}^{\rm NUM} {\rm d}V}{\int \varrho \sum_{i,k} \frac{\partial v_i}{\partial x_k} \left[\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik} \nabla\cdot\mathbf{v} \right] {\rm d}V} \sim 10^{13} - 10^{14} {\rm cm}^2/{\rm s}$$

- Energy dissipation:
  - Ratio of resistive to viscous heating Pm dependent (similar to high-beta MHD turbulence Brandenburg (2011, 2014), Brandenburg & Rempel (2019))
  - Most energy is dissipated through viscosity, i.e. Lorentz force drives flows, which then dissipate
  - Direct Ohmic heating small



Brandenburg (2014)

MURaM implementation of the “transition region adaptive conduction (TRAC) method”

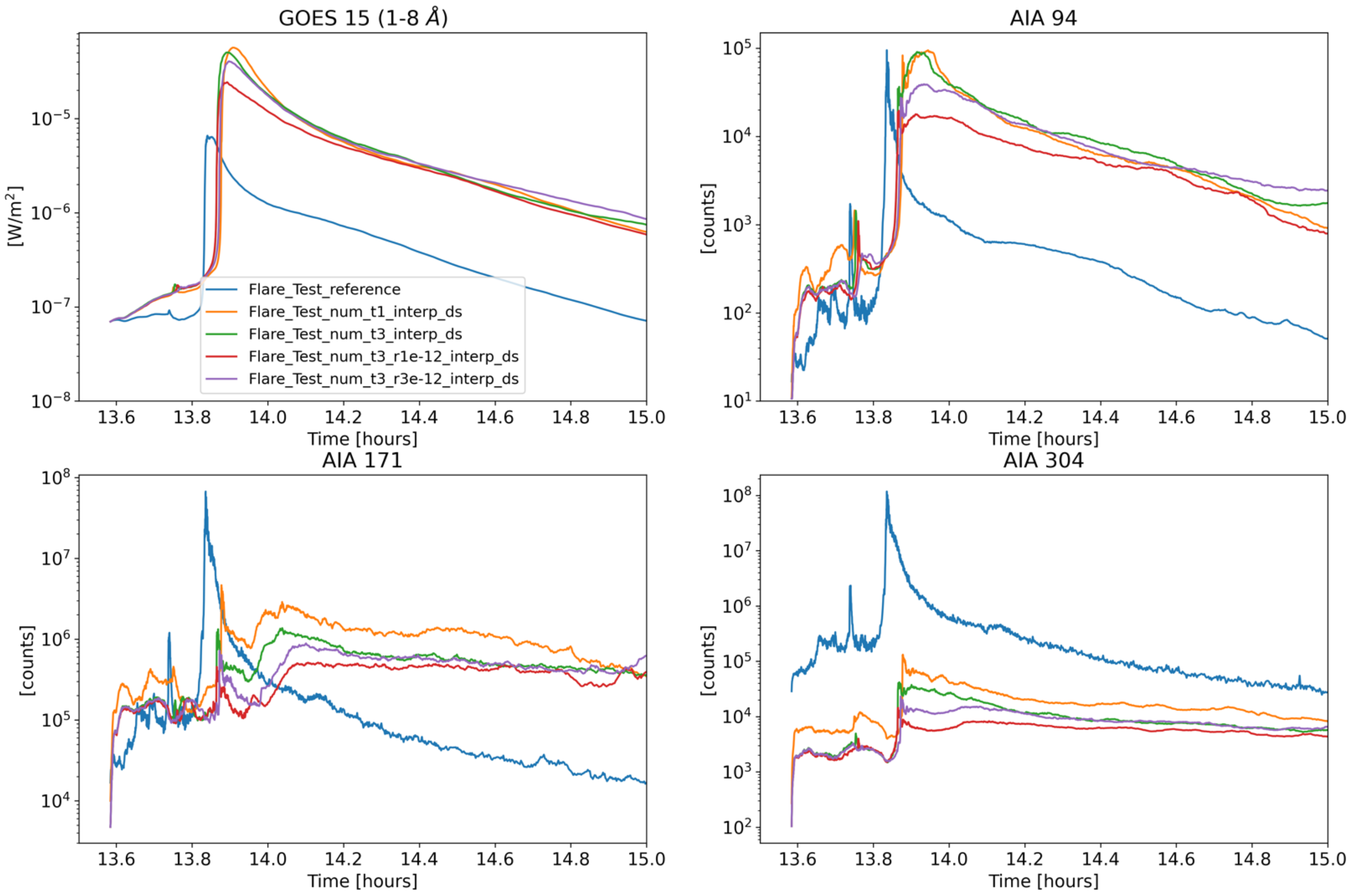
- Based on Johnston et al. 2021, but don’t follow all the steps in detail

“non-thermal enhancement”

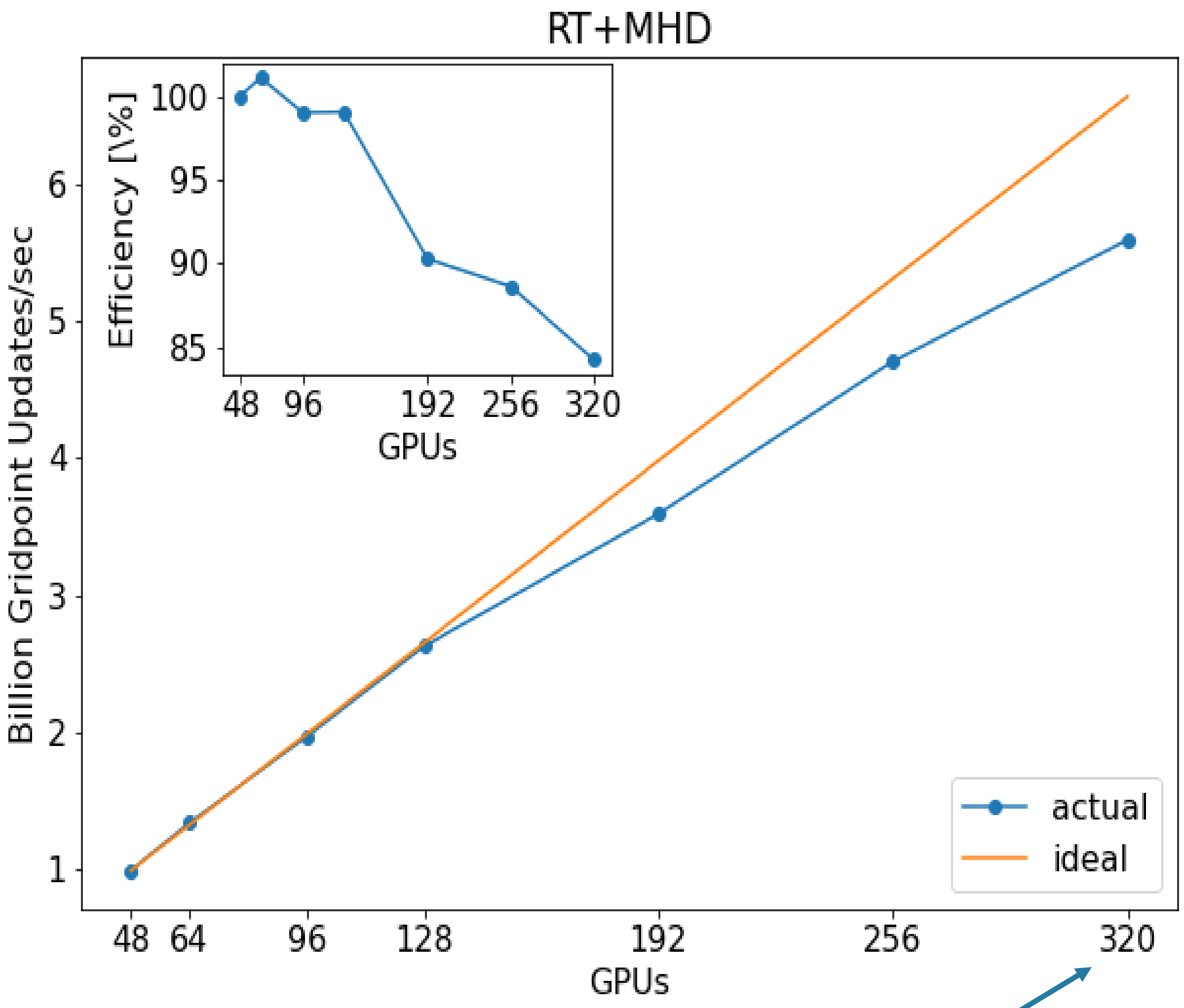
$$Q^* = Q \min\left[1, \frac{1}{s}\sqrt{\frac{\kappa_{\mathrm{Spitzer}} T}{Q}}\right]\left[1 + \left(\frac{\varrho}{\varrho_0}\right)^2\right]$$

$$EM^* = EM \min\left[1, \frac{1}{s}\sqrt{\frac{\kappa_{\mathrm{Spitzer}} T}{Q}}\right]$$

Disabled in quiet Sun regions!



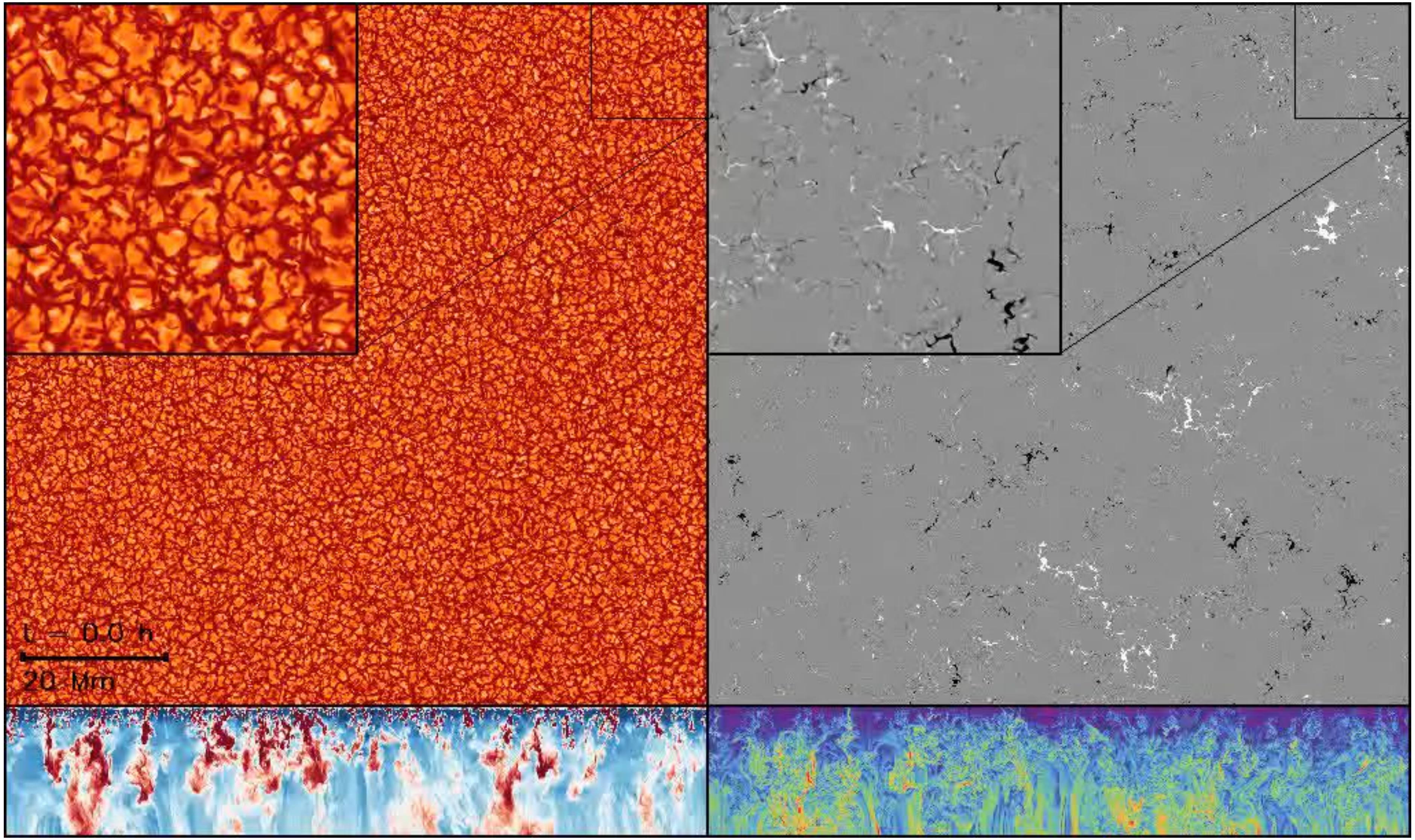
GPU Computing



Equivalent to about 50,000 CPU cores

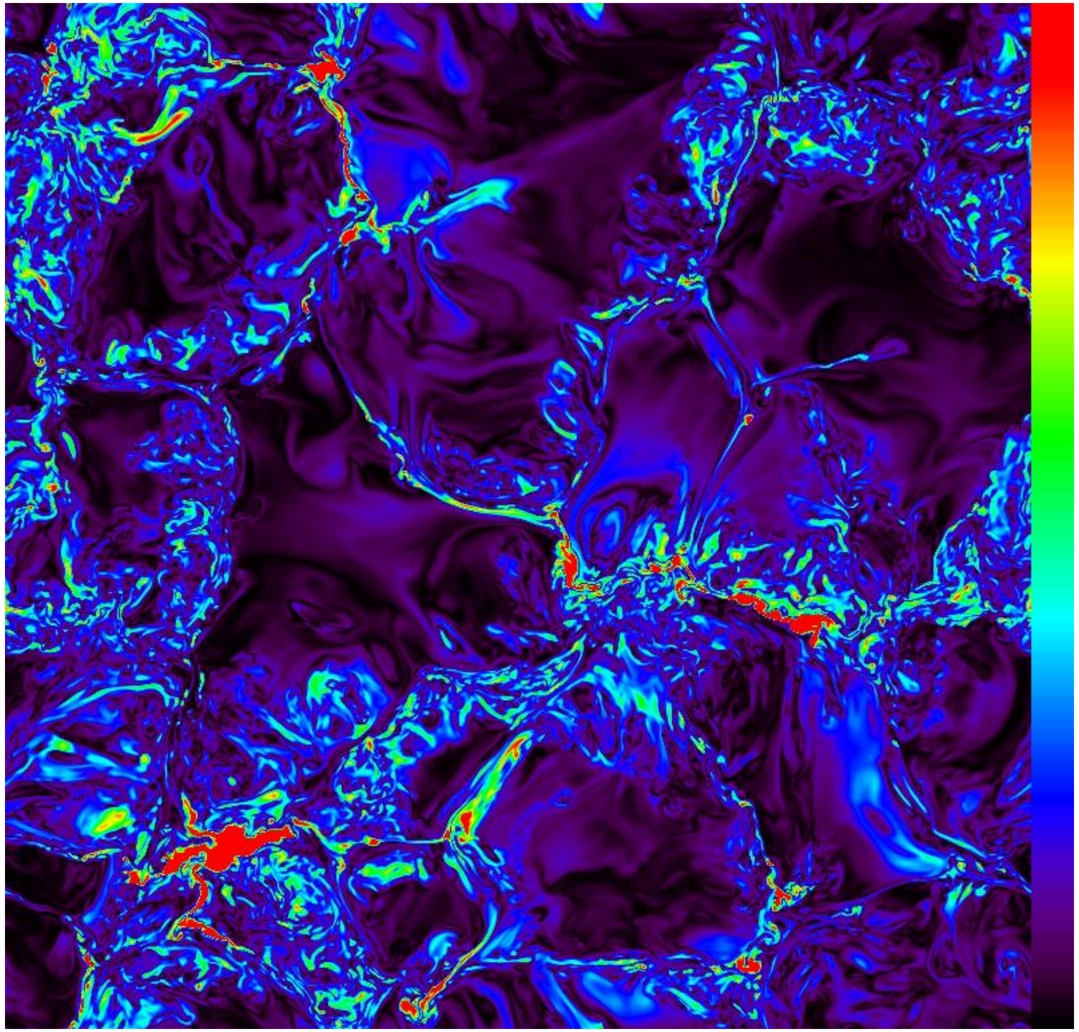
- NCAR (HAO, CISL), MPS, Univ. of Delaware collaboration
- OpenACC GPU code
  - Code runs on GPUs and CPUs
- Using GPUs reduces carbon footprint of simulations by about a factor of 4

The quiet Sun baseline



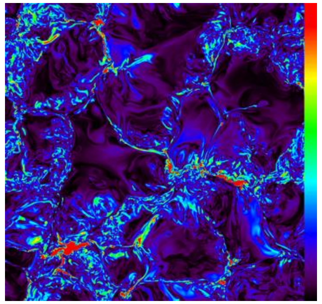
SSD can produce mixed-polarity network in sufficiently large domains, here 100x100x18 Mm

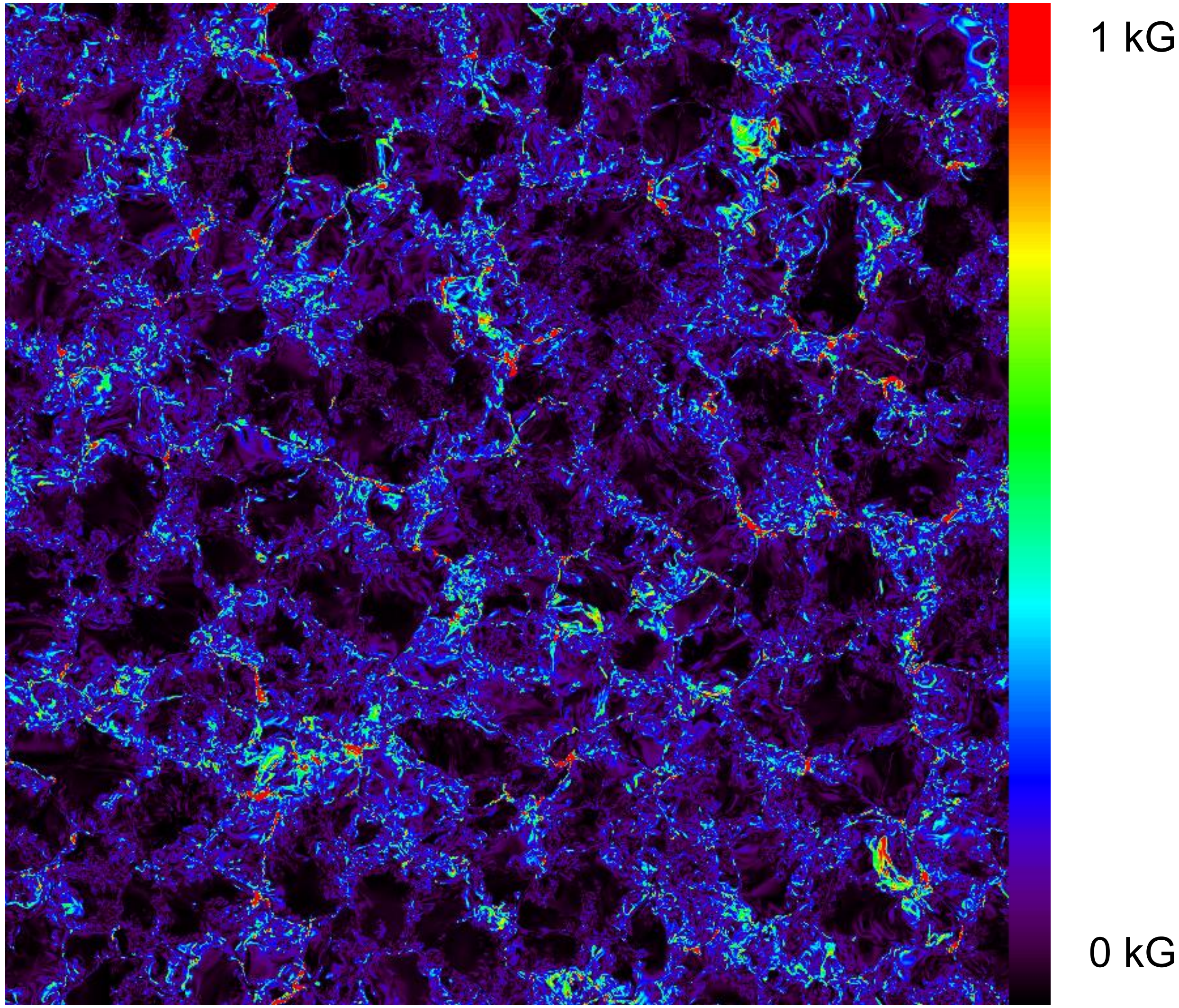
Larger scale organization and “voids”



6x6x2.3 Mm

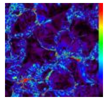
Larger scale organization and “voids”

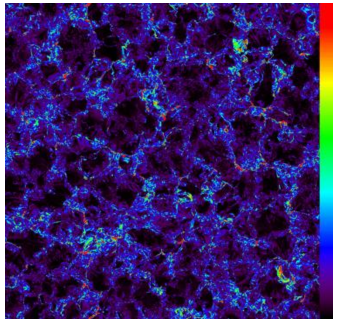


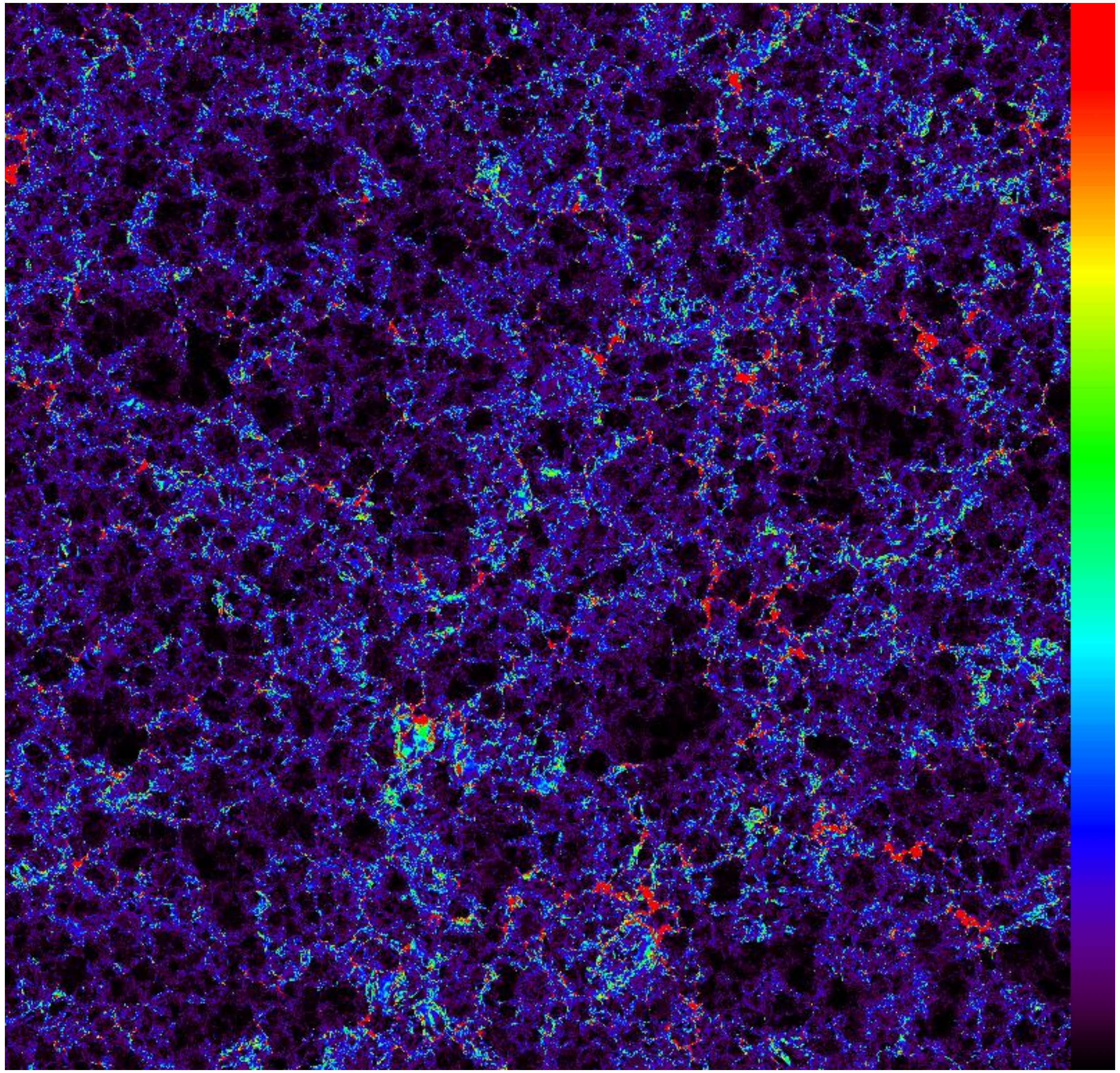


25x25x6.2 Mm

Larger scale organization and "voids"

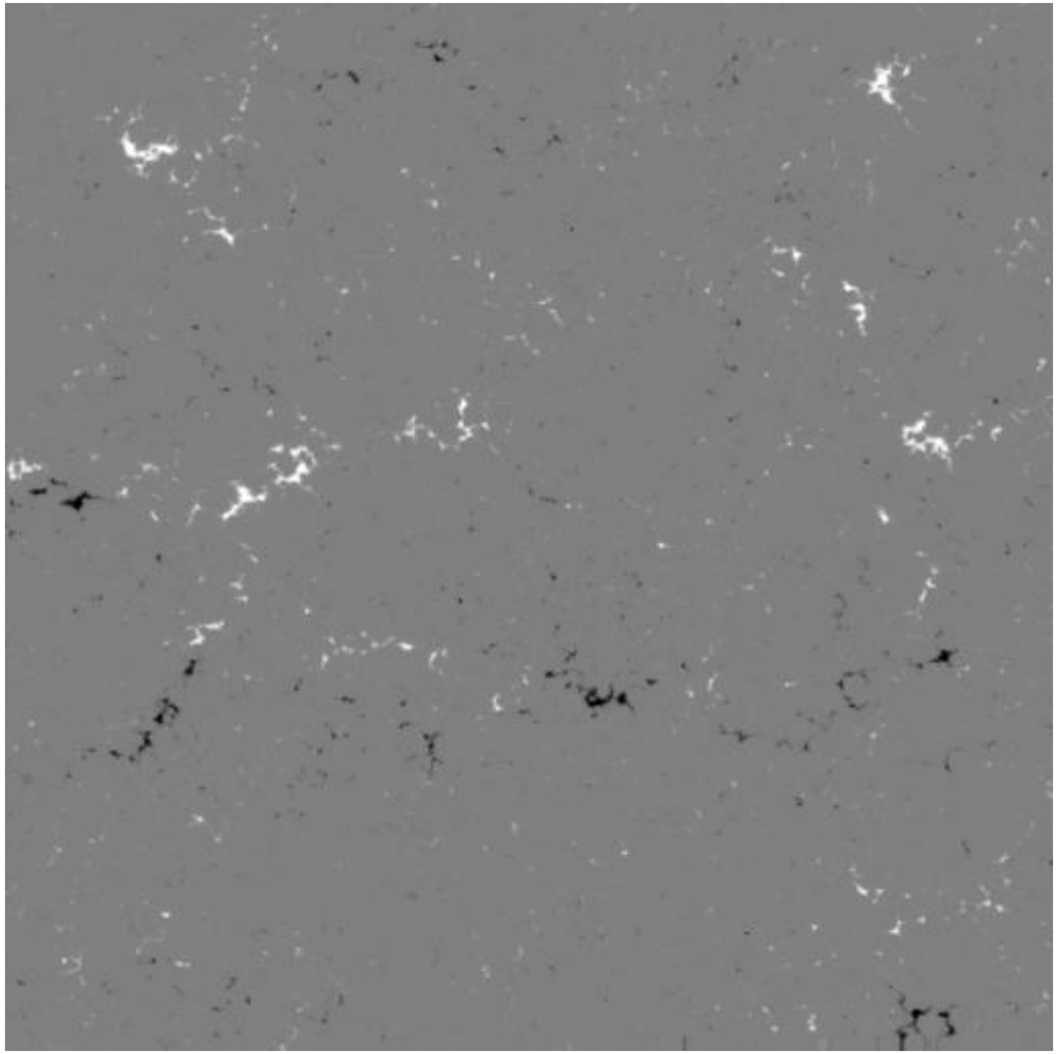


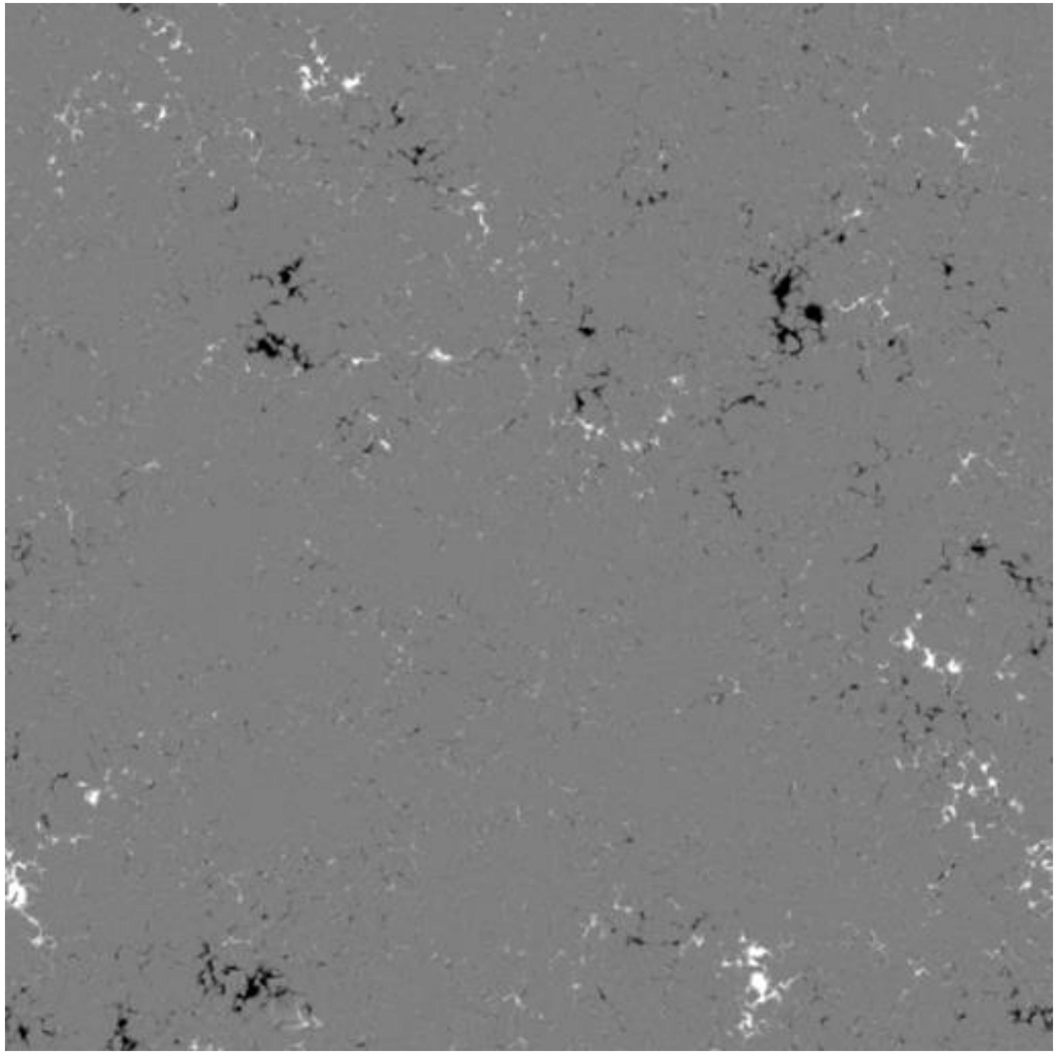




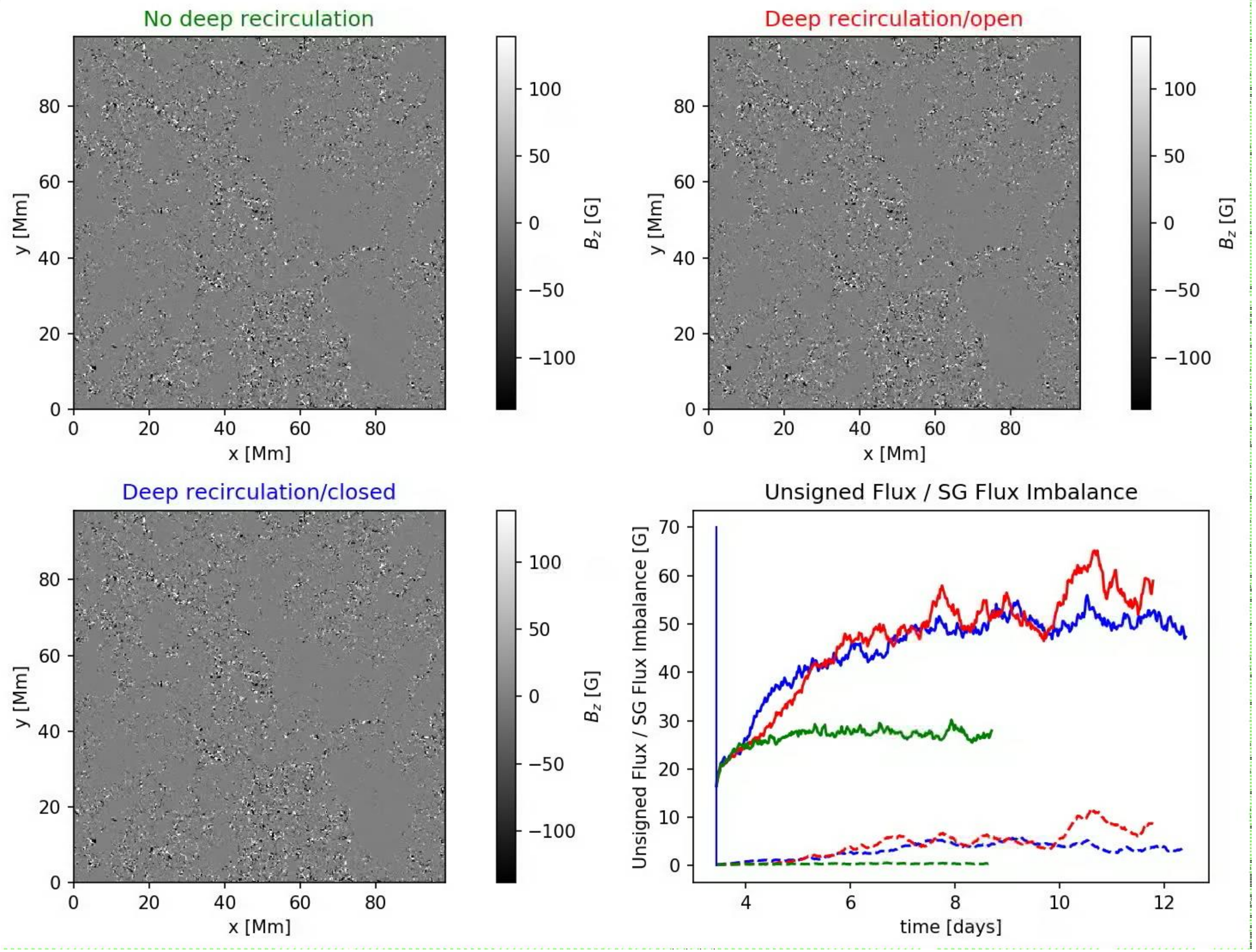
98x98x17.8 Mm

Quiz: Which map is an observation/simulation?

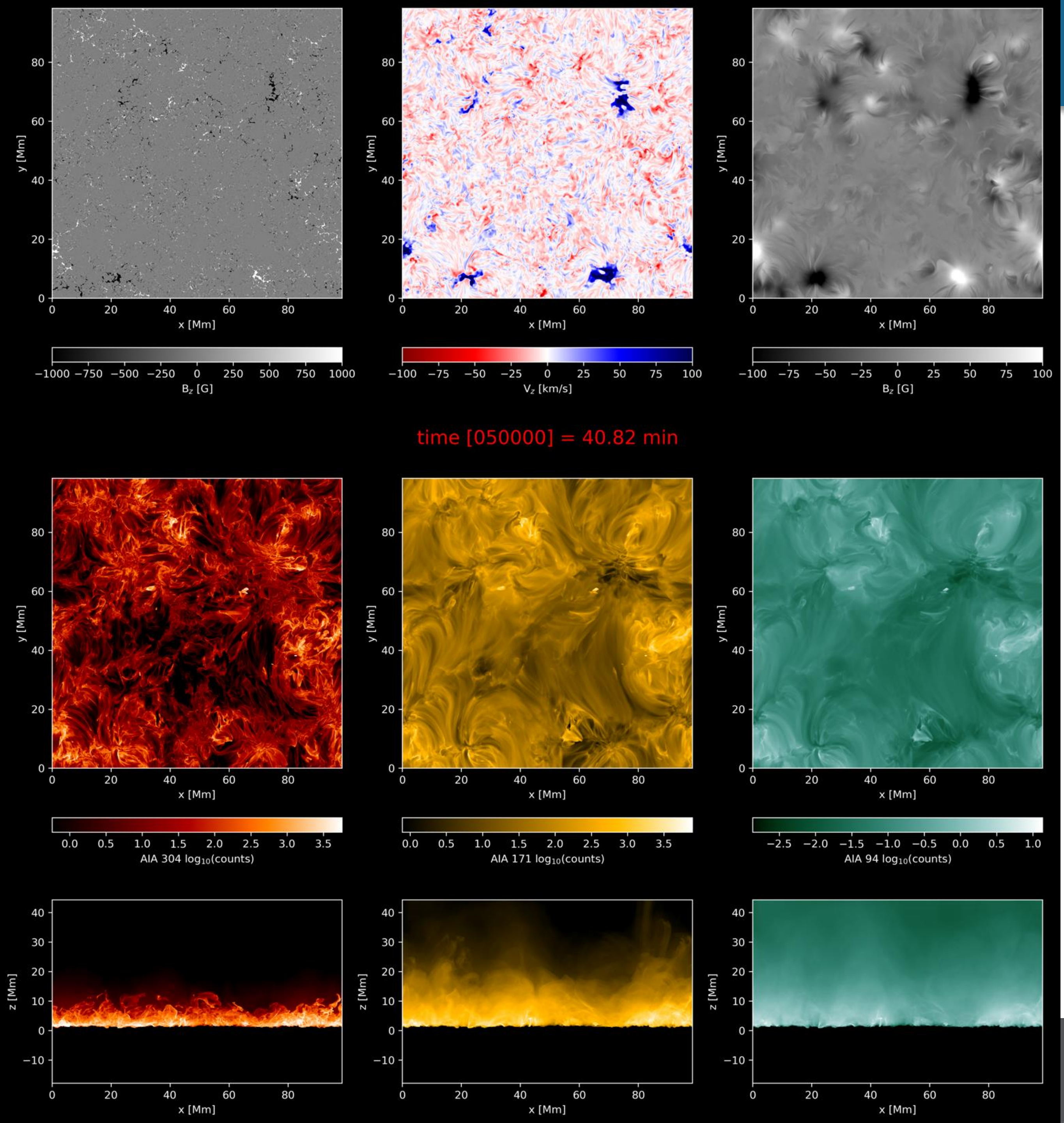




Deep recirculation and large-scale flux imbalance



- SSD in 98 Mm wide and 18 Mm deep domains
  - Lower resolution, longer time-scales
- Deep recirculation leads to large scale flux imbalance
  - Emergence of small bipoles in quiet sun "ephemeral active regions"
- Quiet sun super-granular network independent from active region decay
  - About 5-8 G average flux imbalance in 25x25 Mm^2 subdomains
- Flux imbalance required for maintaining a quiet Sun corona



Corona with deep recirculation

Total radiative loss

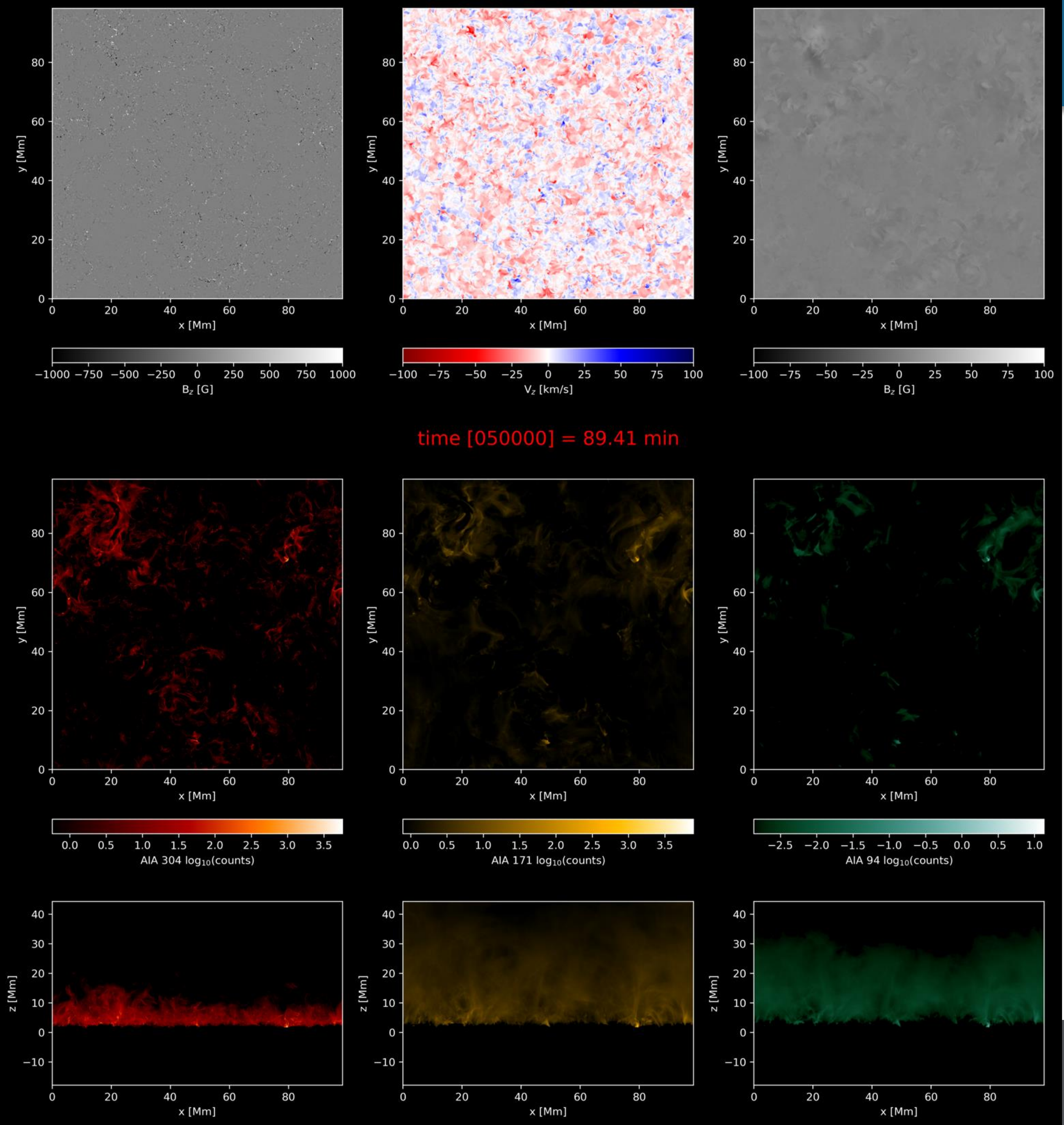
~6x10^5 erg/cm^2/s

Photospheric Poynting flux

~2x10^7 erg/cm^2/s

Withbroe & Noyes (1977)

~3x10^5 erg/cm^2/s



Corona without deep recirculation

Total radiative loss

~10^4 erg/cm^2/s

Photospheric Poynting flux

~$4x10^6$ erg/cm^2/s

A few simple setups

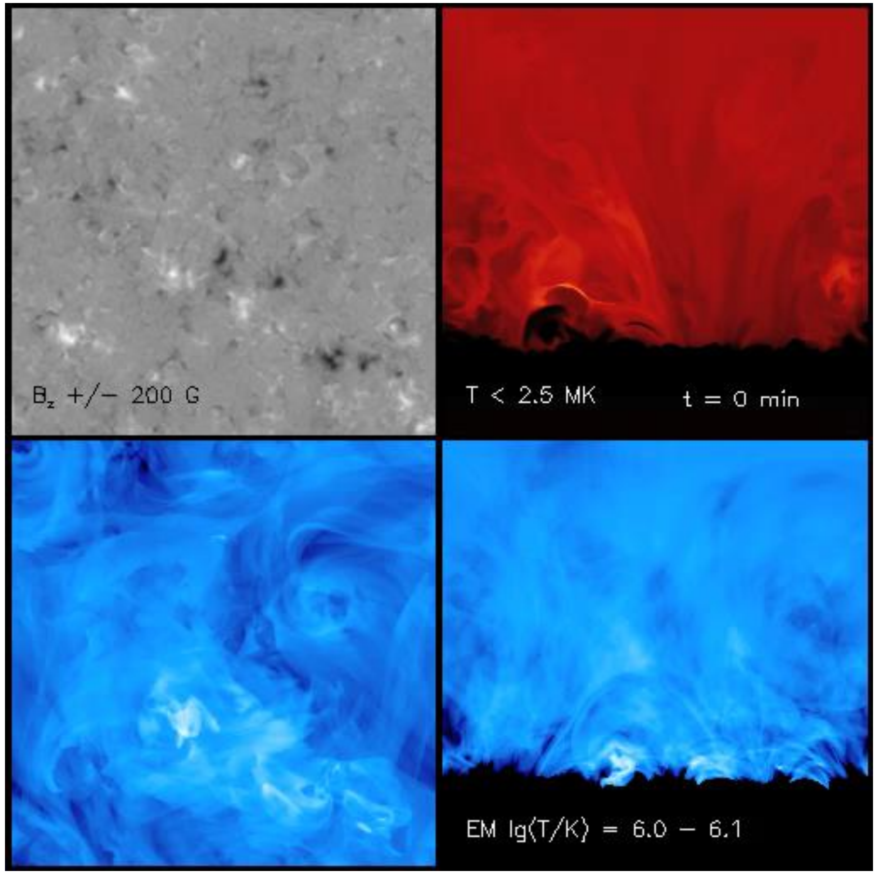
Heating is implicit, the primary factor that determines the type of corona is the magnetic environment in the photosphere

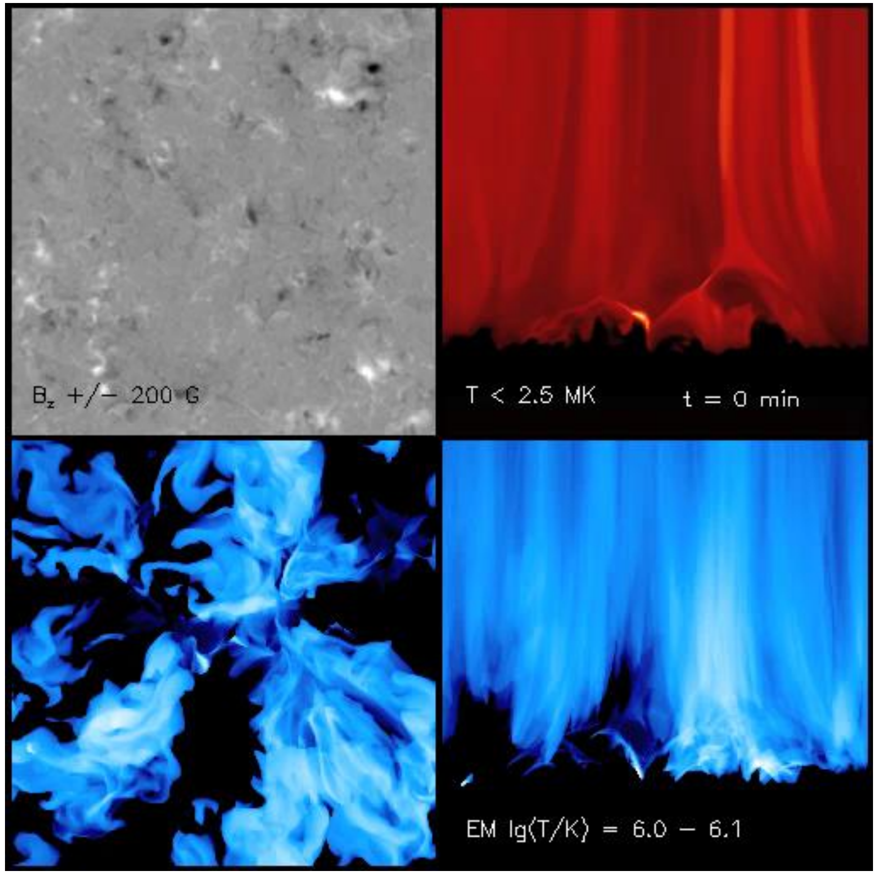
- Quiet Sun (49x49x49 Mm)
  - Small scale dynamo, zero net flux
- Open Flux (49x49x49 Mm)
  - Small scale dynamo + 3G
- Arcade (49x49x49 Mm)
  - Small scale dynamo +/- 50 G, zero net flux
- Active region (98x49x49 Mm)
  - Small scale dynamo + 3×10^{21} Mx pair of spots

- In all setups:
  - Lower 8 Mm -> convection zone
  - 192x64x192 km resolution
  - Top boundary (mostly) closed for all energy fluxes

- See Rempel 2017, ApJ 834,10

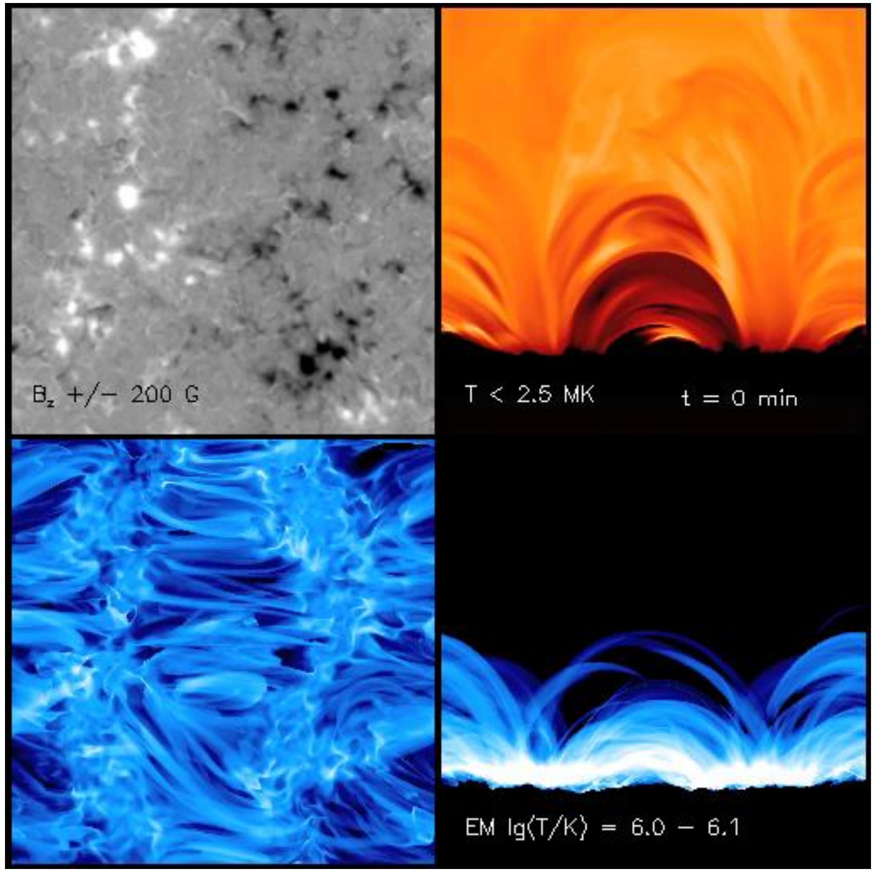
Quiet Sun, Open flux region

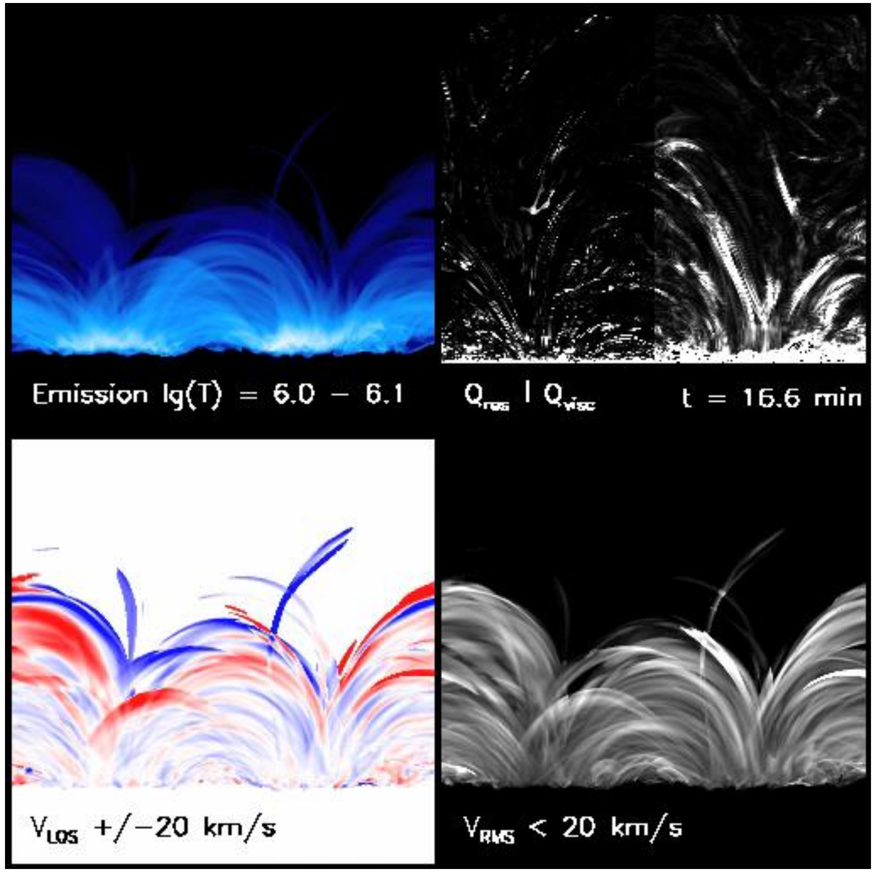




- Mixed polarity field maintained by small-scale dynamo
- 3G flux imbalance dominates in more than 10 Mm height

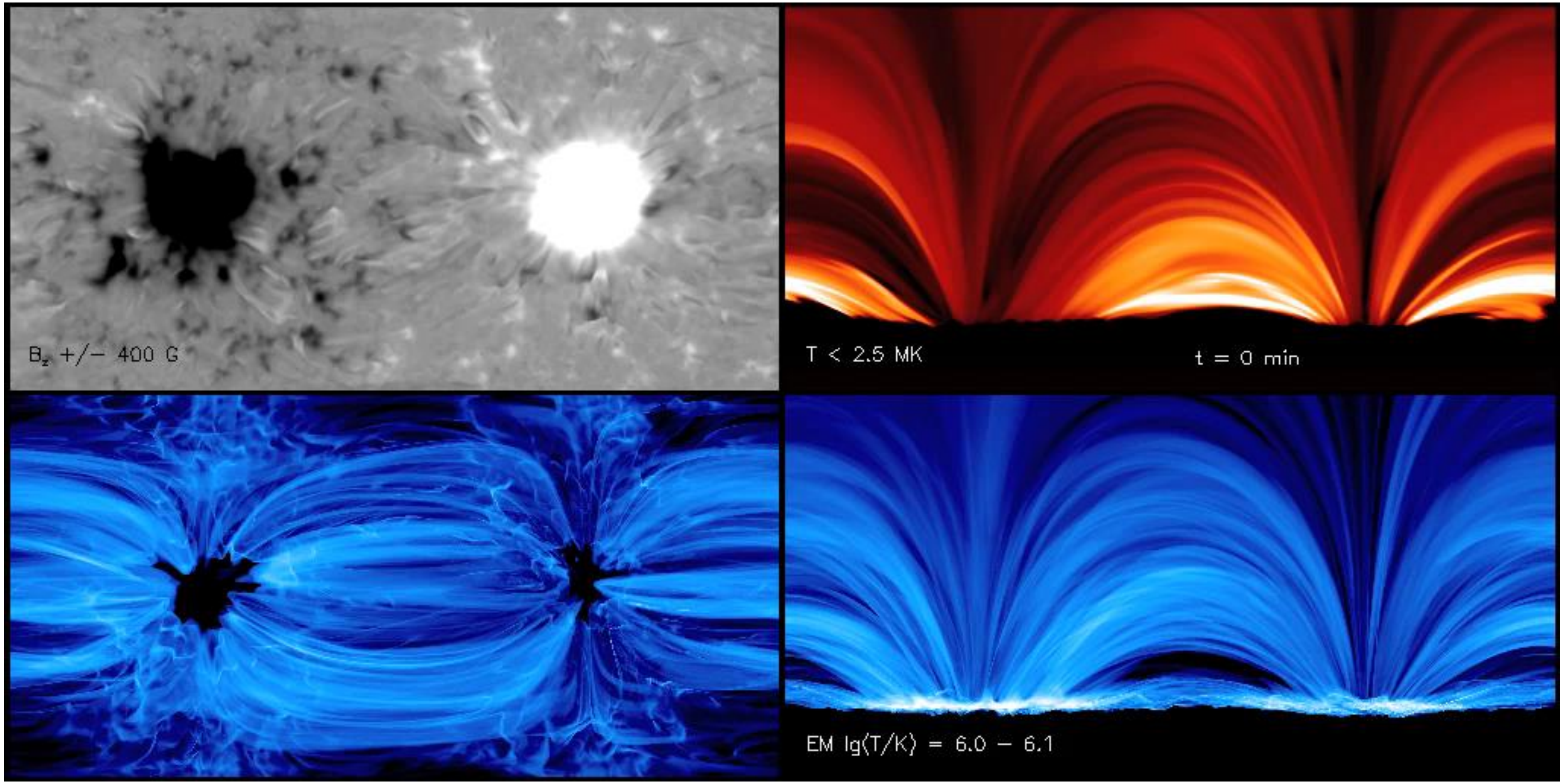
Arcade





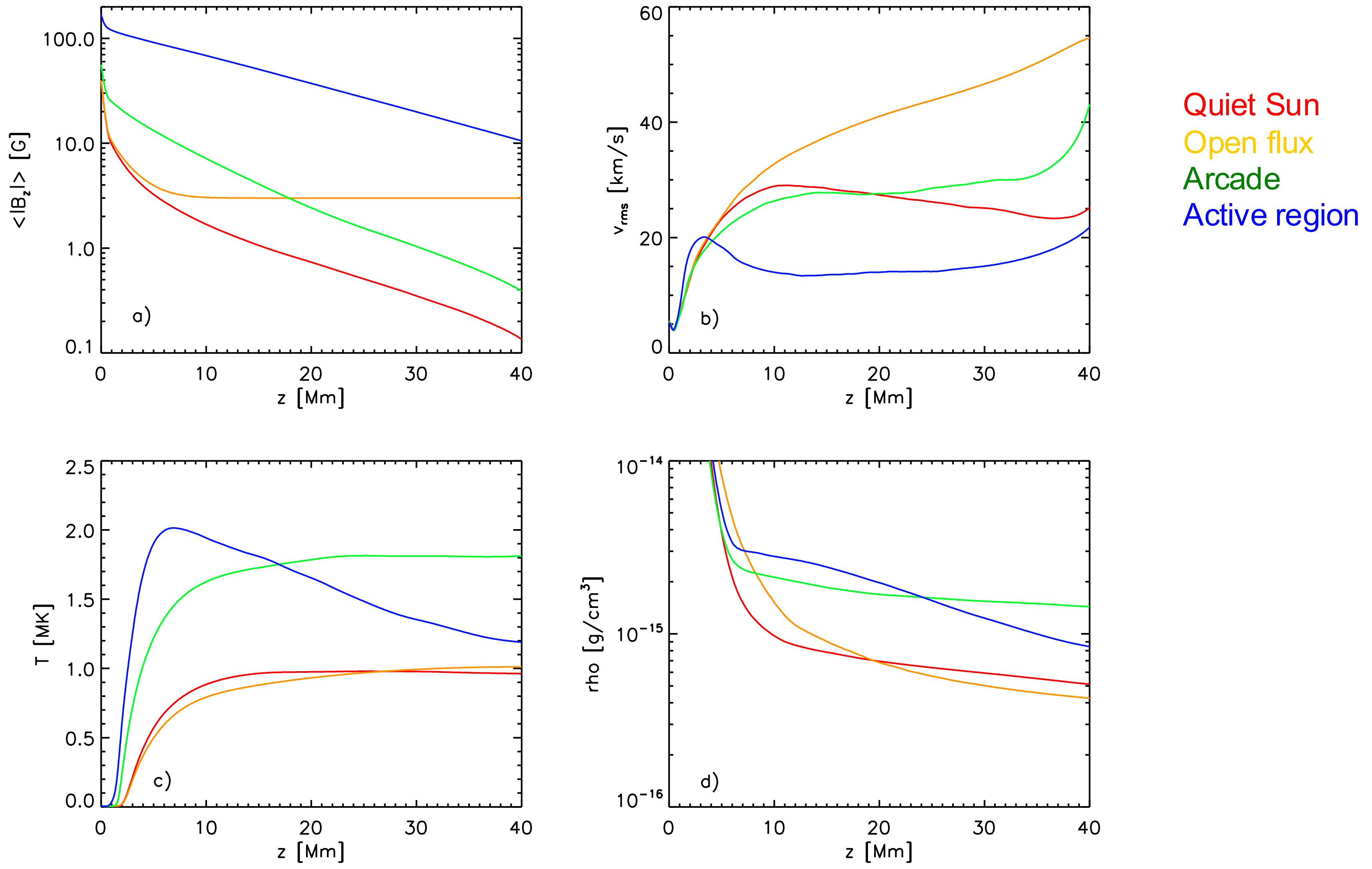
- SSD +/-50 G flux imbalance (left/right half)

Active Region



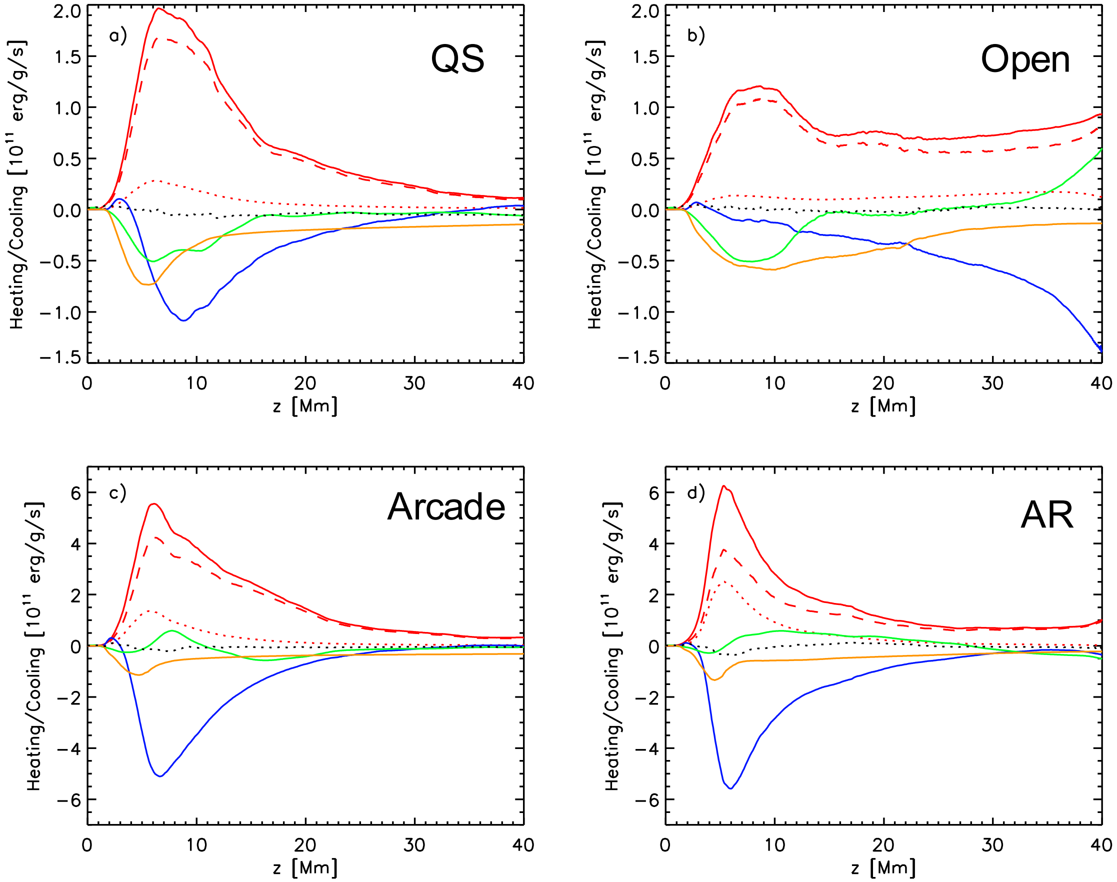
- Mixed polarity field from small-scale dynamo + a pair of 3×10^{21} Mx spots, slowly decaying

Mean state



100.0
10.0
1.0
0.1
$<|B_z|>$ [G]
a)
z [Mm]
60
40
20
0
v_{rms} [km/s]
b)
2.5
2.0
1.5
1.0
0.5
0.0
T [MK]
c)
10^{-14}
10^{-15}
10^{-16}
rho [g/cm^3]
d)
0
10
20
30
40
Quiet Sun
Open flux
Arcade
Active region

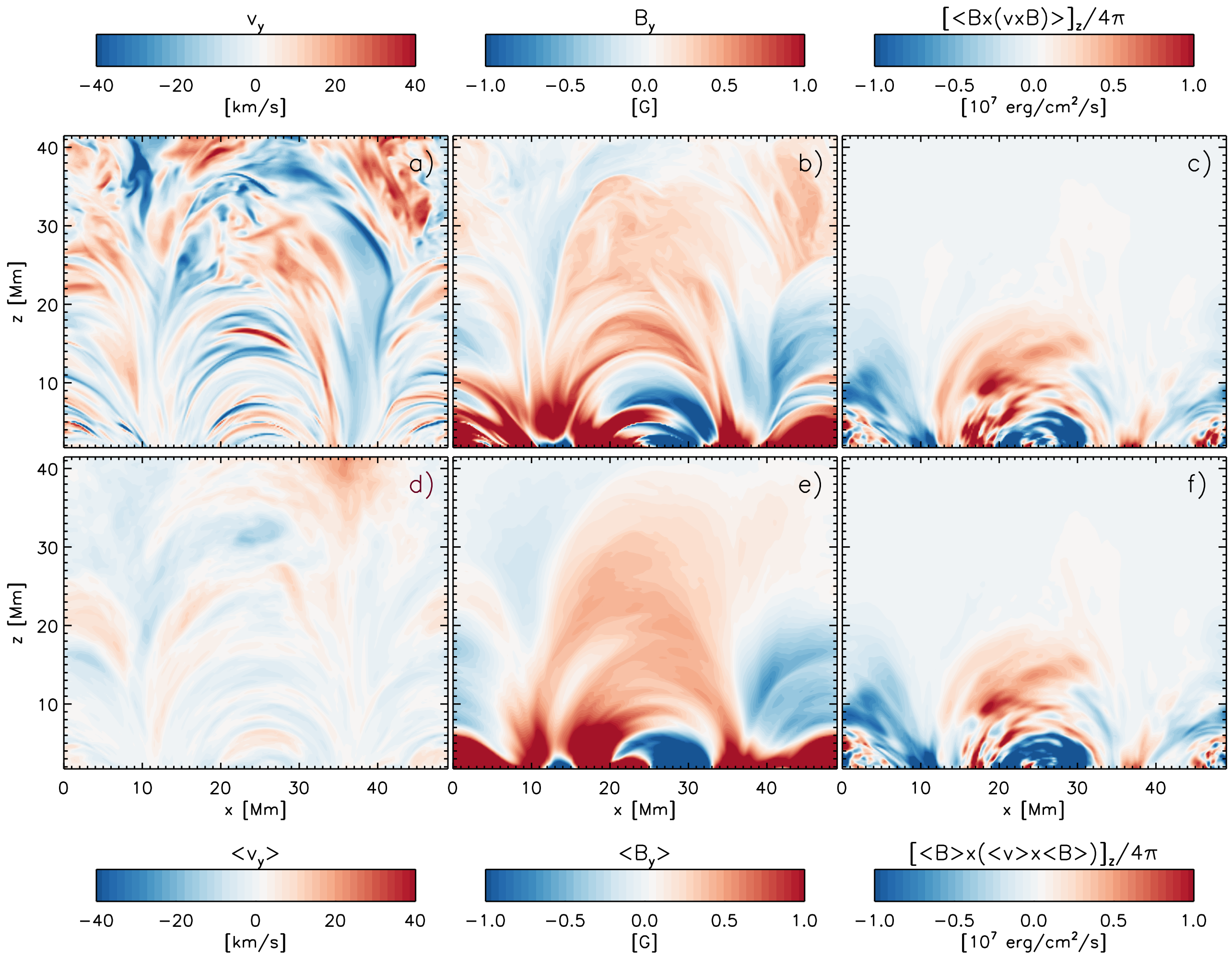
Coronal Energy balance



- Total Magnetic energy input
  - Resistive (dotted)
  - Lorentz force work (dashed)
- Divergence Advective energy flux
- Divergence Conductive energy flux
- Radiative loss
- Sum (dotted)

Total coronal energy inputs [erg/cm^2/s]: QS, OF 5x10^5, AC 2x10^6, AR 4x10^6

Time scales of coronal energy transport and energy release I



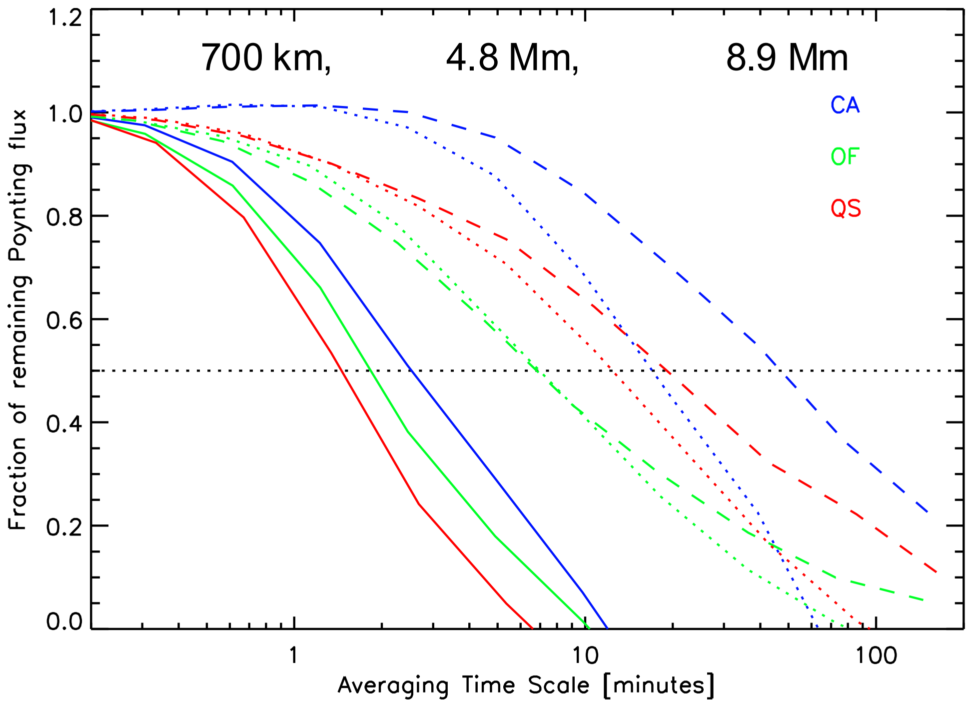
Snapshot of v and B

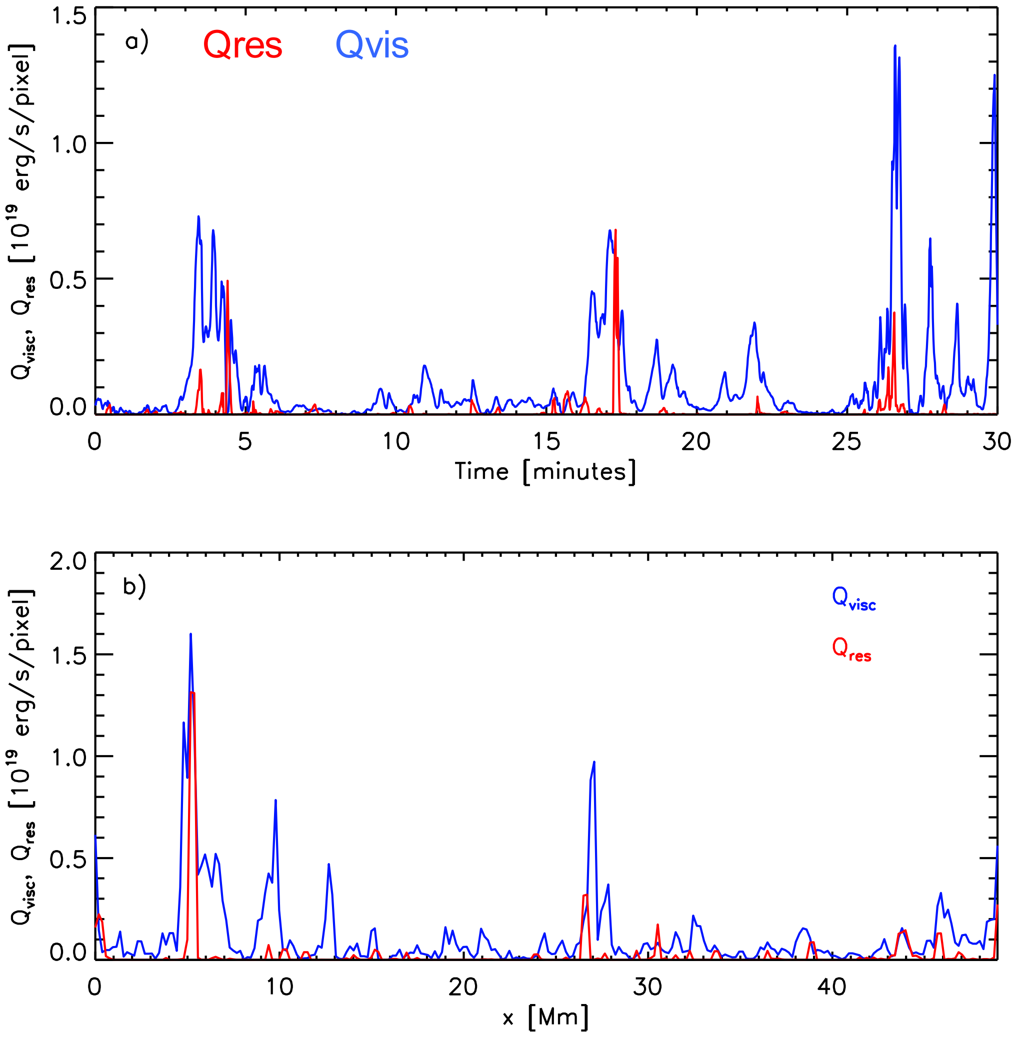
Time averaged (60 min) Poynting flux based on full v and B (including all wave contributions)

Temporally averaged v and B (60 min)

Poynting flux computed from averaged v and B (excluding most wave contributions)

Time scales of coronal energy transport and energy release II





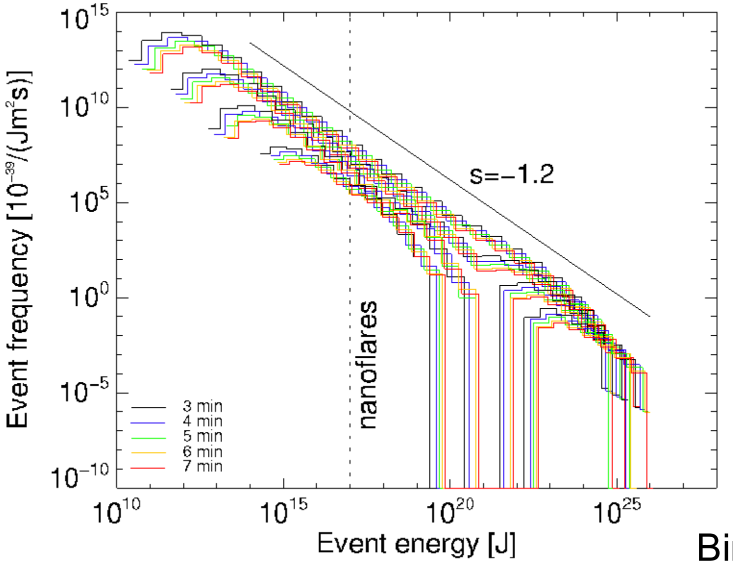
- Time scale of transport ~ 30-60 min, time scale of release ~ 1 min: Support for braiding of field lines + "nanoflare" heating (see also Bingert & Peter 2013)
- High Pm corona: Heating through viscous dissipation!

"Quantum of energy release"

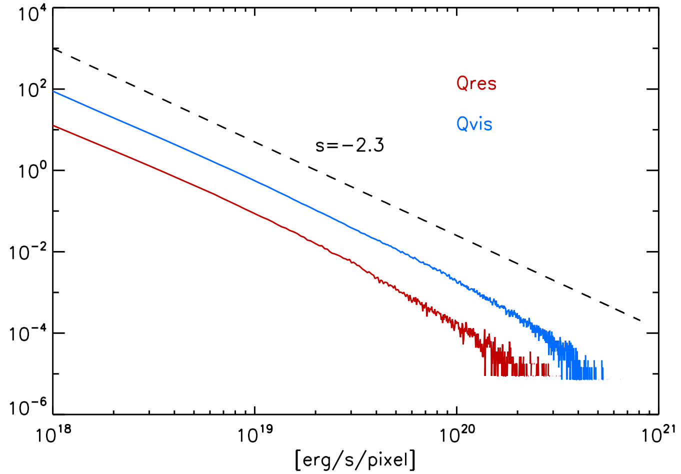
- Typical energy release
  - ~10^{19} erg/s/pixel
- Typical life time
  - 20 sec (Qres) to 80 sec (Qvis)
- Typical spatial extent
  - 500 km (Qres) to 1000 km (Qvis)
- Typical energy release
  - ~3×10^{23} erg

- Does this depend on resolution???

- Does this depend on the details of numerical dissipation???

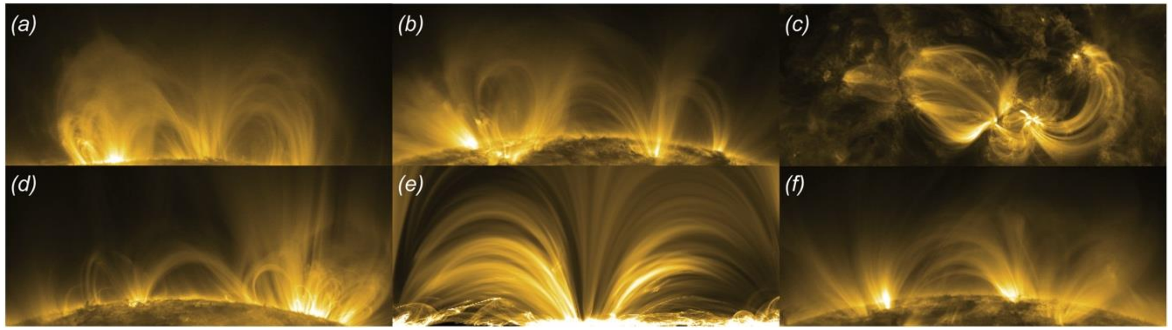


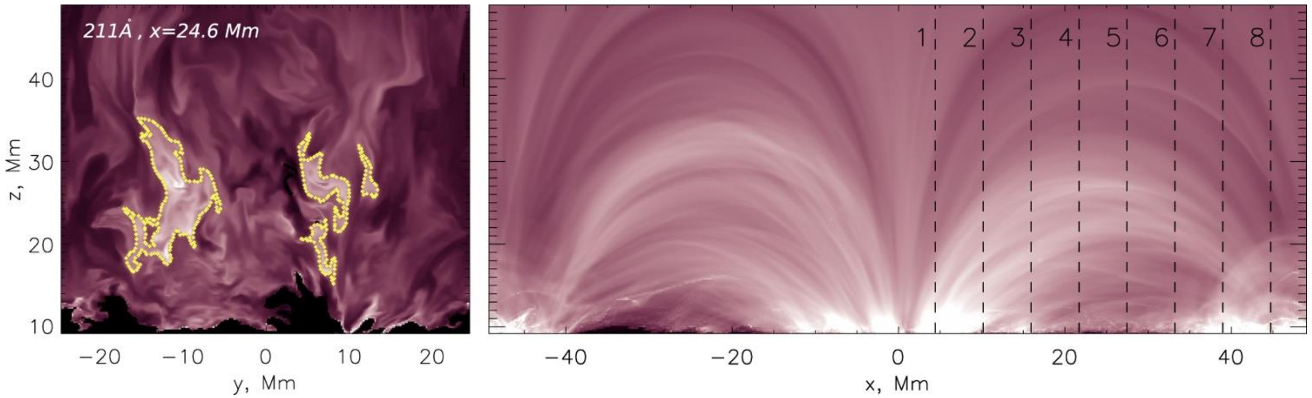
Bingert & Peter (2013)

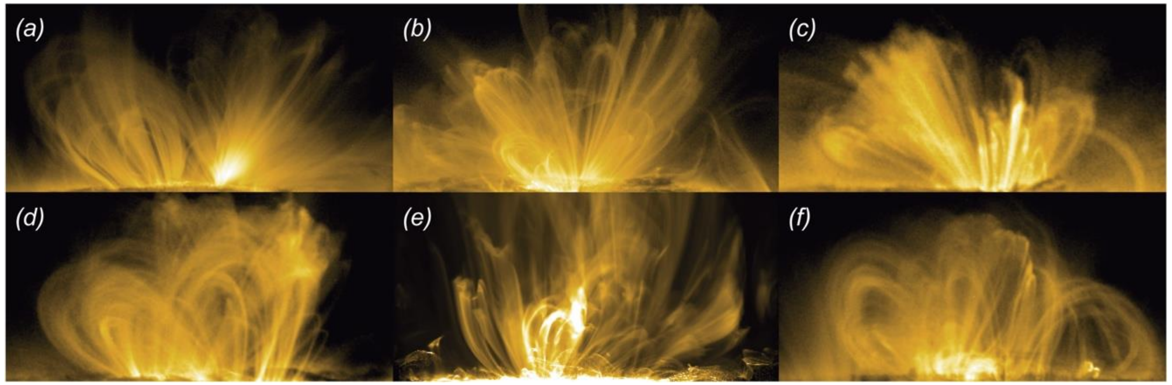


MURaM Simulation

Structure of “loops”



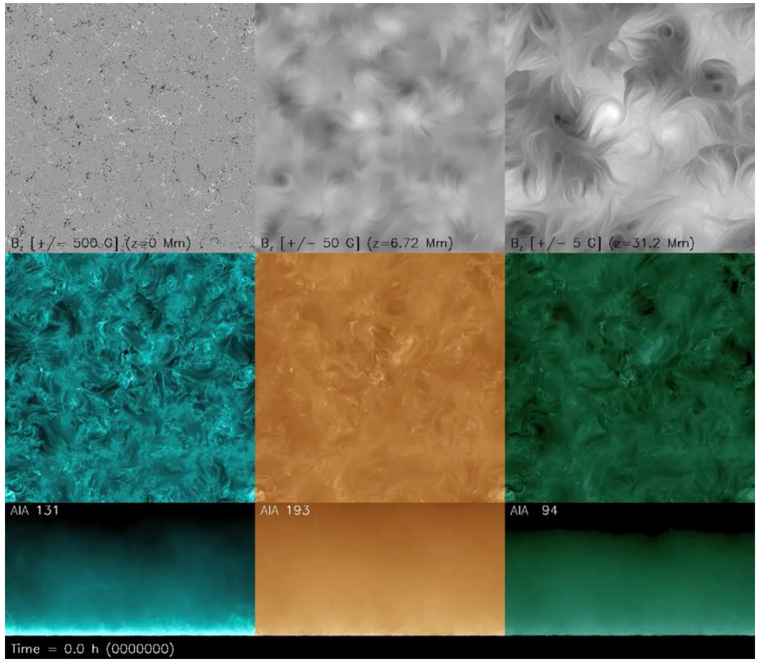




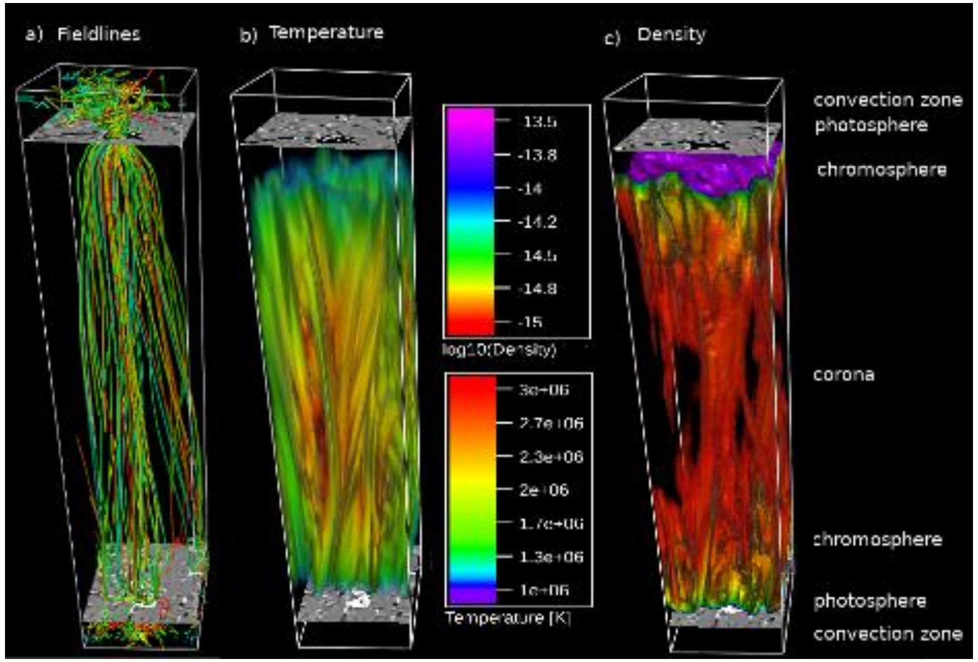
Malanushenko et al. (2022)

- Simulations show loop-like emission features qualitatively comparable to observations
- The 3D volume of emissivity does not show compact features that correspond to individual loops
- Loop-like appearance can result from line-of-sight integration

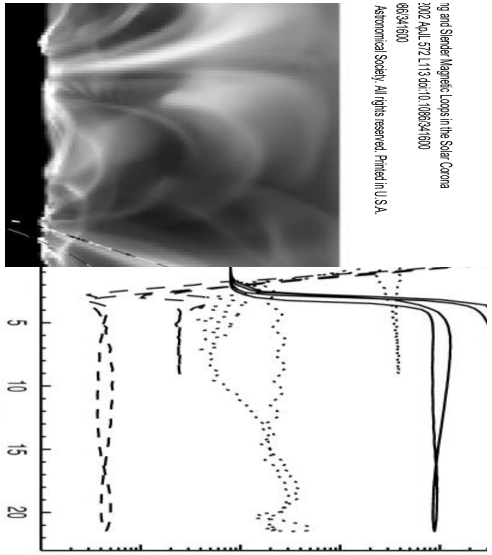
The “numerical robustness” of coronal heating?



From Chen et al. 2022



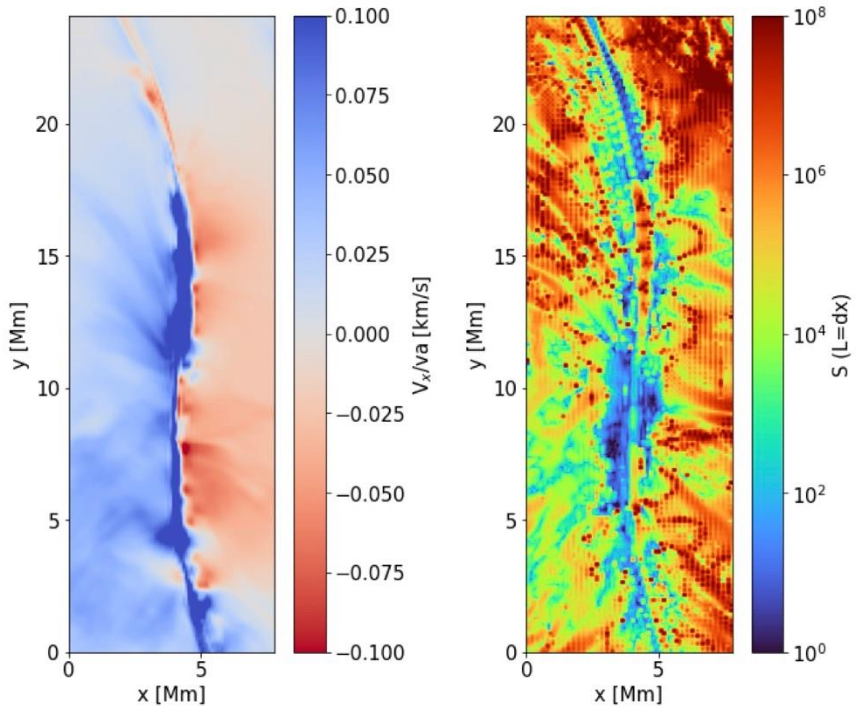
Breu et al (2022)

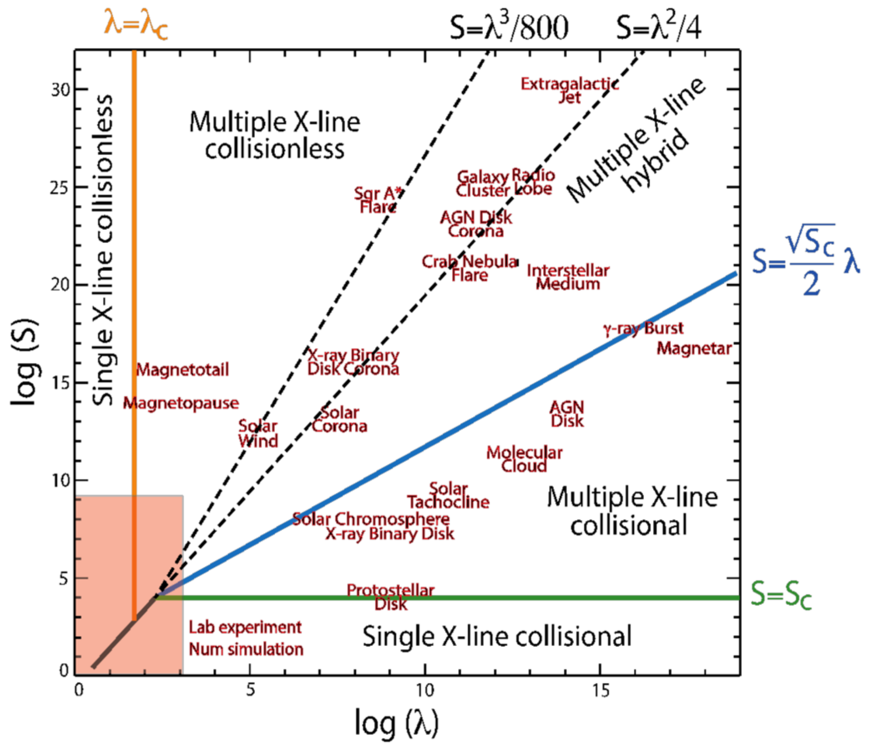


Gudiksen & Nordlund (2002)

- Are there any “failed” simulations of coronal heating that start from a “realistic” photosphere?
- Both low-res large-scale and high-res small-scale simulations provide roughly the “right” amount of heating
- What happens when we combine both? **Large, high-resolution setups**

Numerical treatment of reconnection?





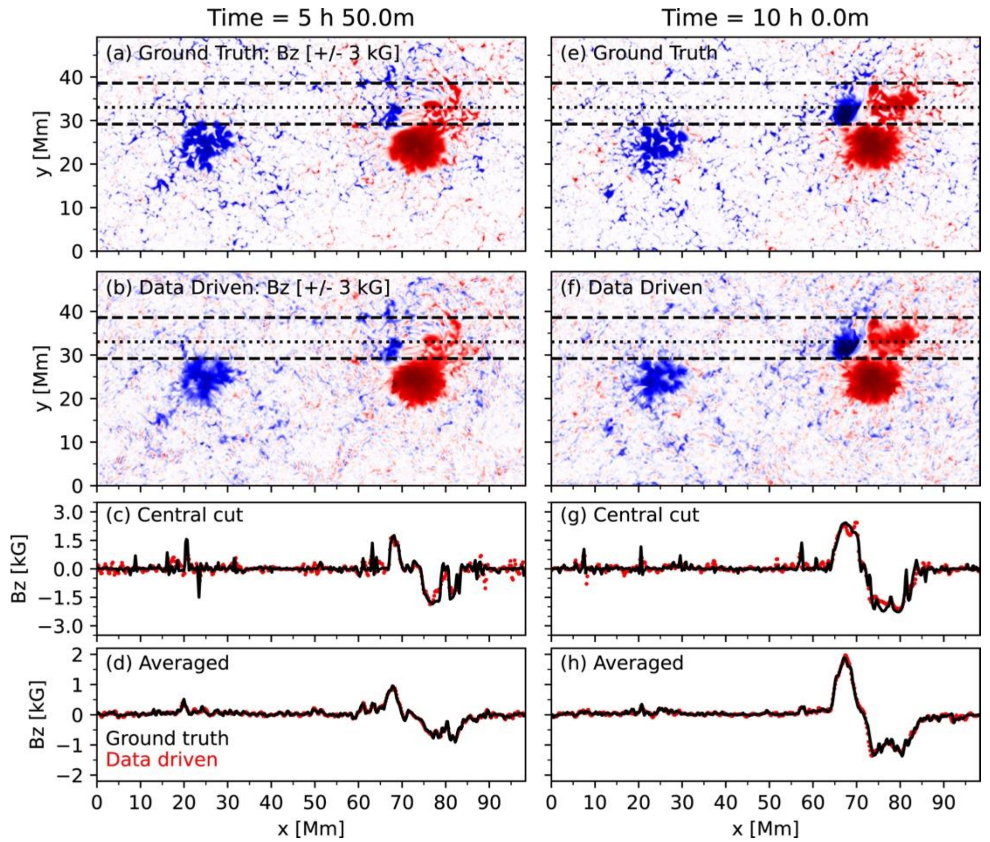
- Reconnecting current-sheet in MURaM Flare simulations
- Highly non-linear numerical resistivity results in spatially variable Lundquist number
- Reconnection rate near “typical finding” V~0.1 Va
- Mostly single X-point reconnection (due to lack of resolution)
- Most simulated flares have about a 10x shorter duration than observed

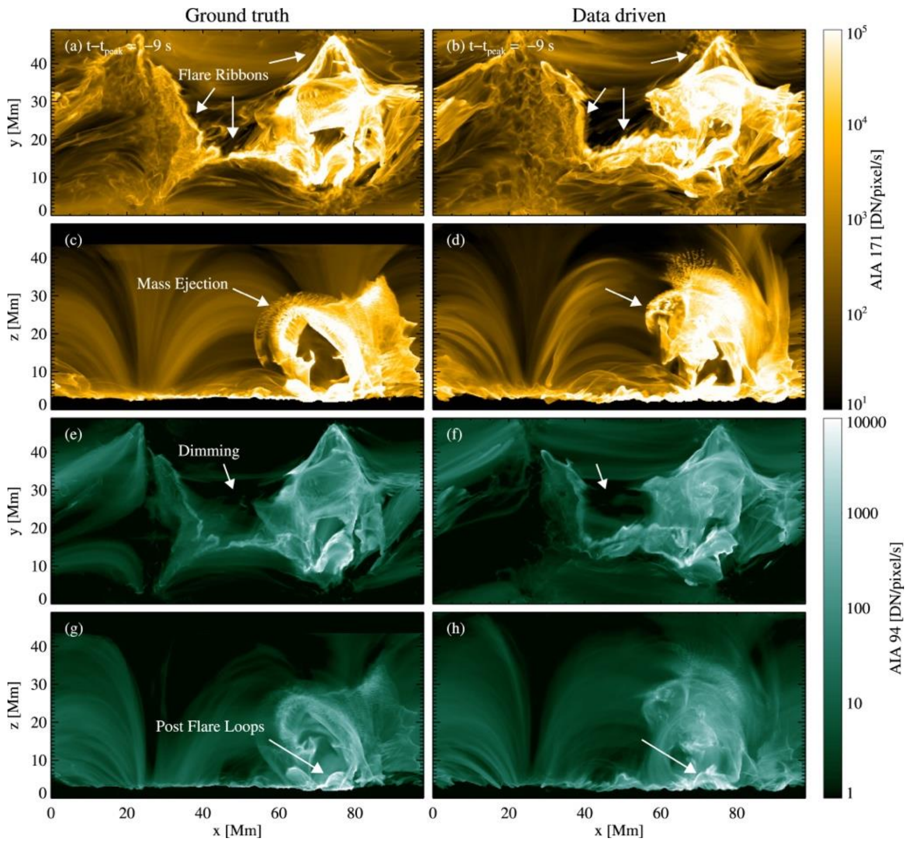
Towards data-driven simulations

- Current simulations are “data-inspired”
  - Initial condition and boundary driving aims to mimic a few observed key features

- Data-driven simulations
  - Boundary-driven (Chen et al. 2023)
    - Replace photosphere with data constrained boundary
    - Guarantees closest consistency with observations
    - No reliable treatment of photosphere and chromosphere
  - Data assimilative
    - Similar to to weather forecasting approaches
    - Run ensemble of simulations and evolve ensemble along observed path using Ensemble Kalman filters
    - Would include treatment of photosphere and chromosphere
    - Would allow probabilistic treatment
    - Currently mostly unproven in solar physics MHD simulations
    - Expensive
  - Data nudging
    - Evolve simulation with nudging terms that drive the simulation state towards an observed state “data assimilation with one ensemble member”
    - **Advantage: can switch off nudging and transition to free running MHD simulation**

Boundary driving



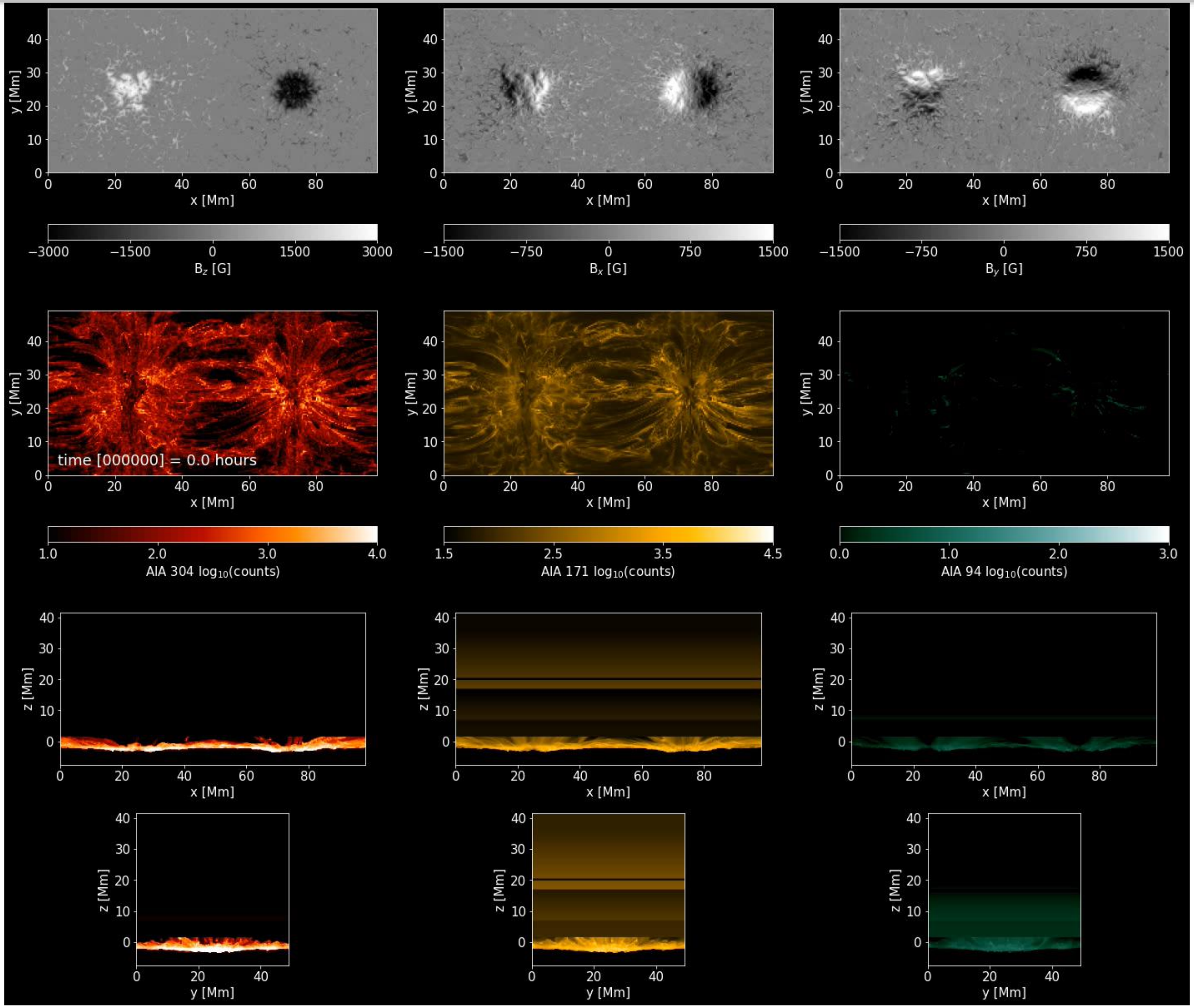


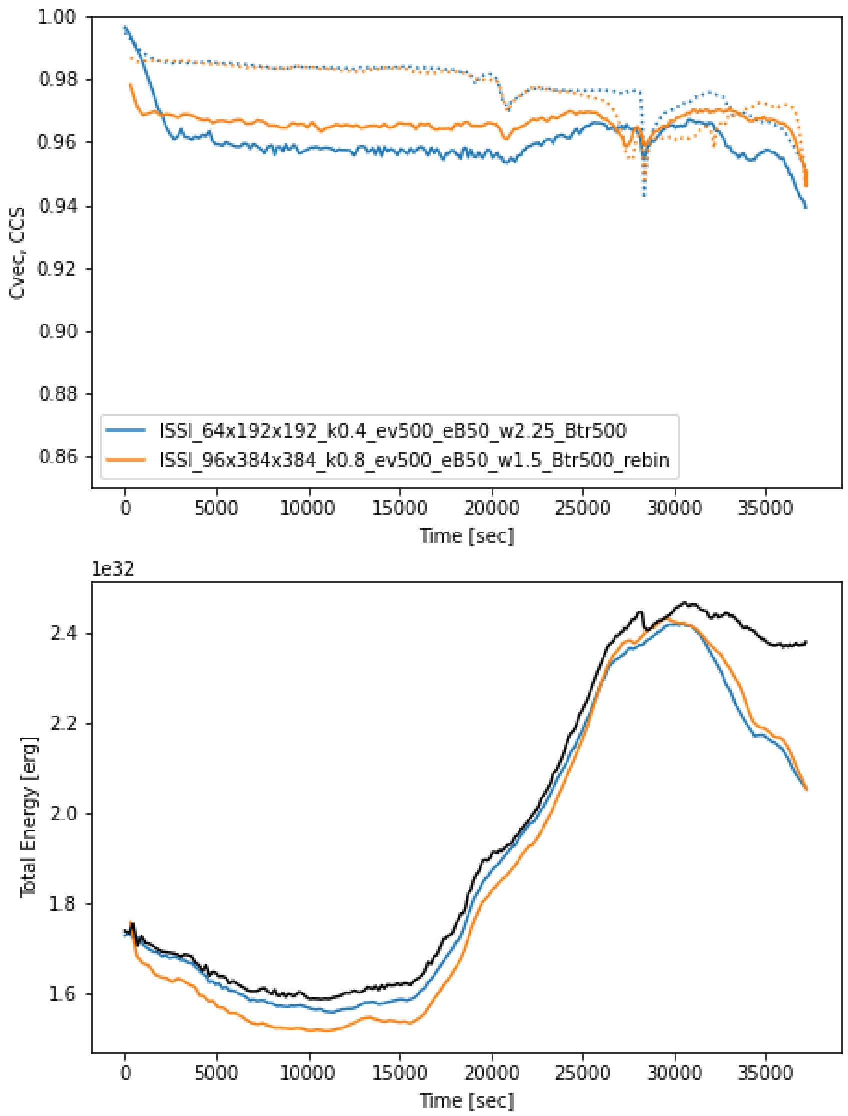
- Replace photosphere with data-driven boundary condition:
  - Use horizontal electric field in Induction equation
  - Relaxation terms of stratification

Data Nudging

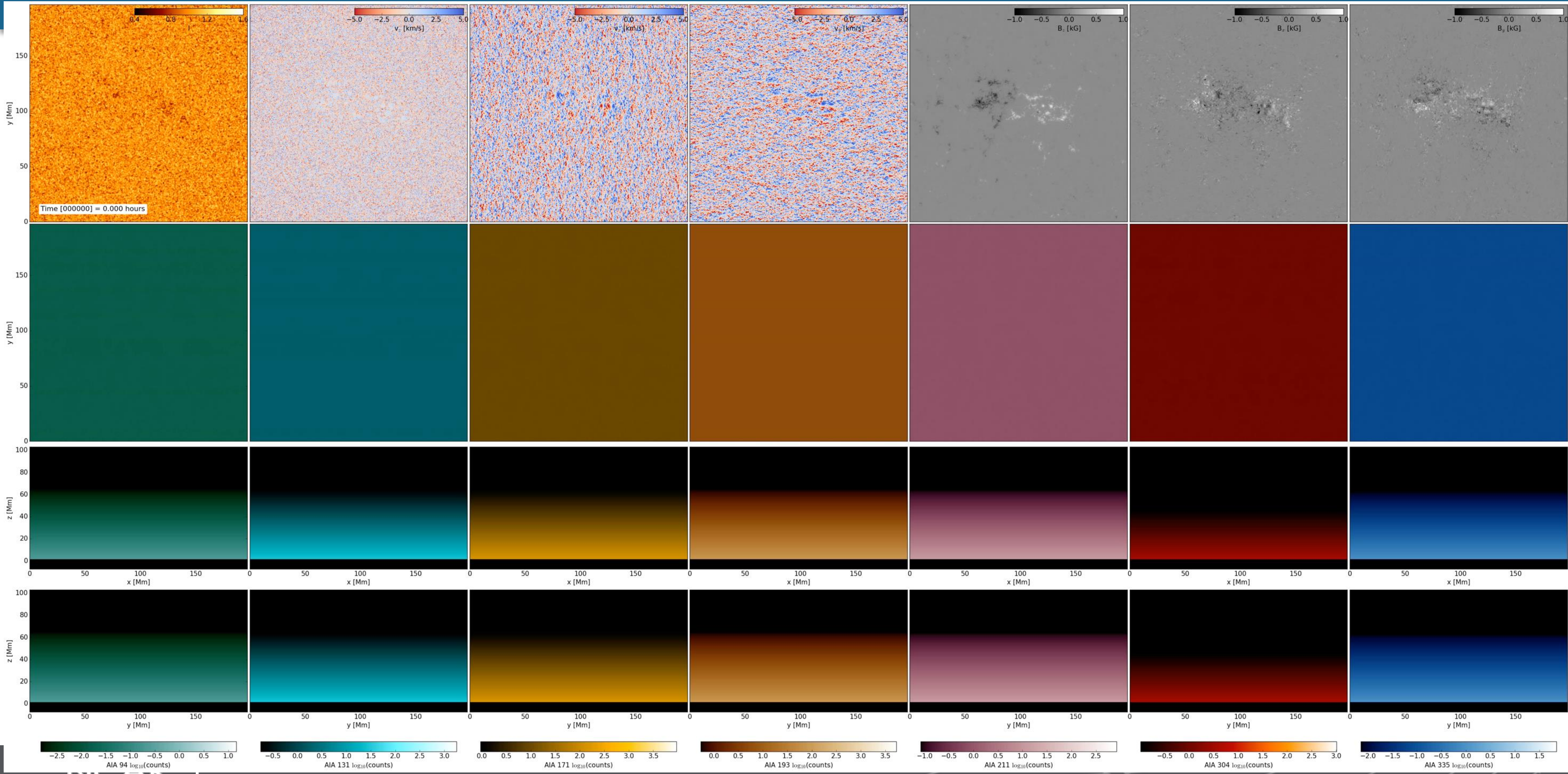
- Add forcing terms in momentum and induction equation
  - Limited to photosphere where observations are present
  - Nudge over a height range of about the numerical stencil width
- Nudging in wavenumber-space
  - Leave granulation to the code
  - Constrain larger scales (lambda > 3Mm) from observations
- Determine nudging time scale based on rms error
  - 500 m/s for flow
  - 50G for B-field
- Decompose velocity in parallel and perpendicular components to minimize crosstalk
  - B in simulation and input data will be slightly miss-aligned
  - Project v perp/parallel on new B direction
- Use hyperbolic divB cleaning algorithm on nudging terms (Dedner 2002)

Test on flux emergence simulation

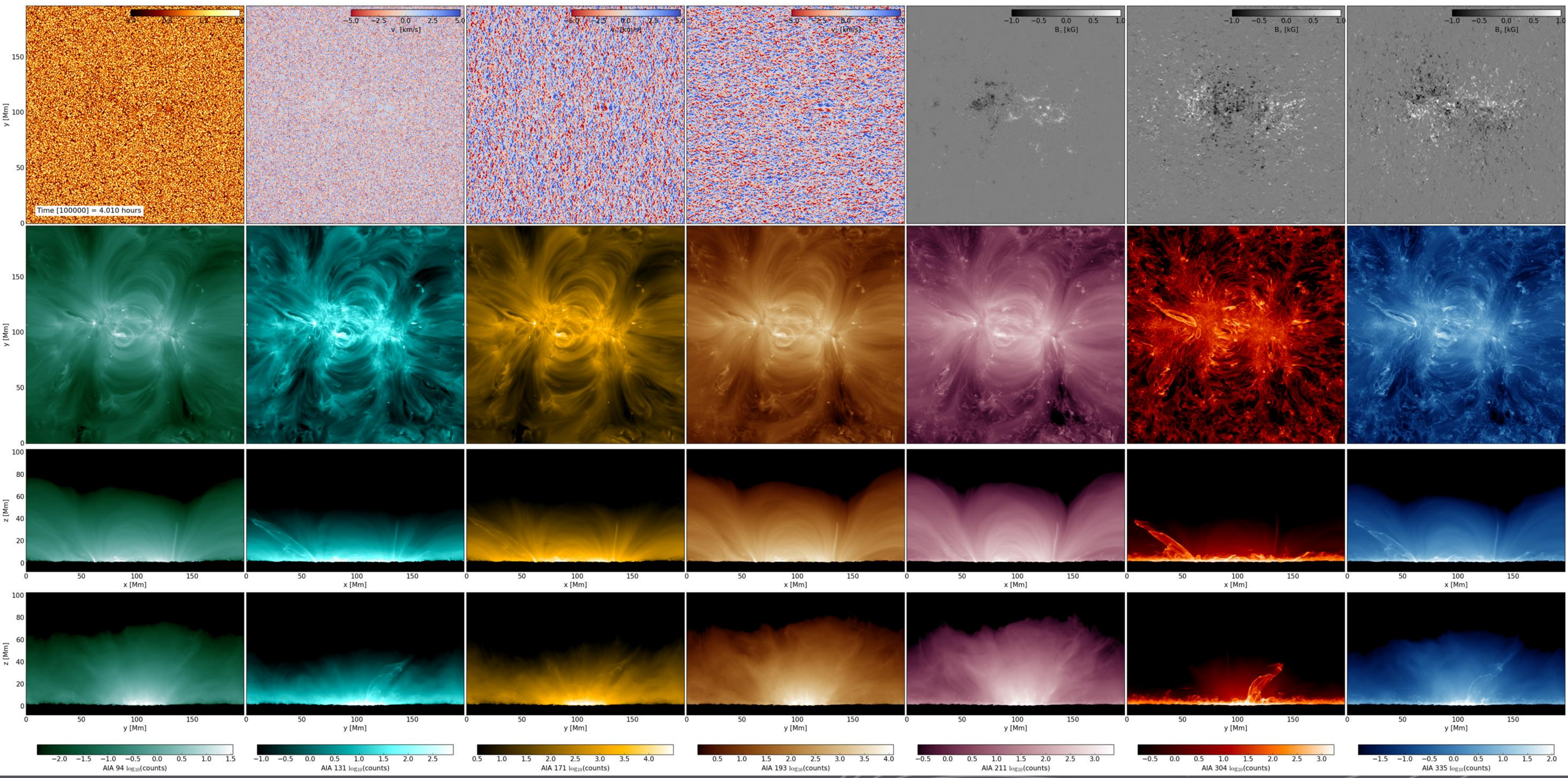




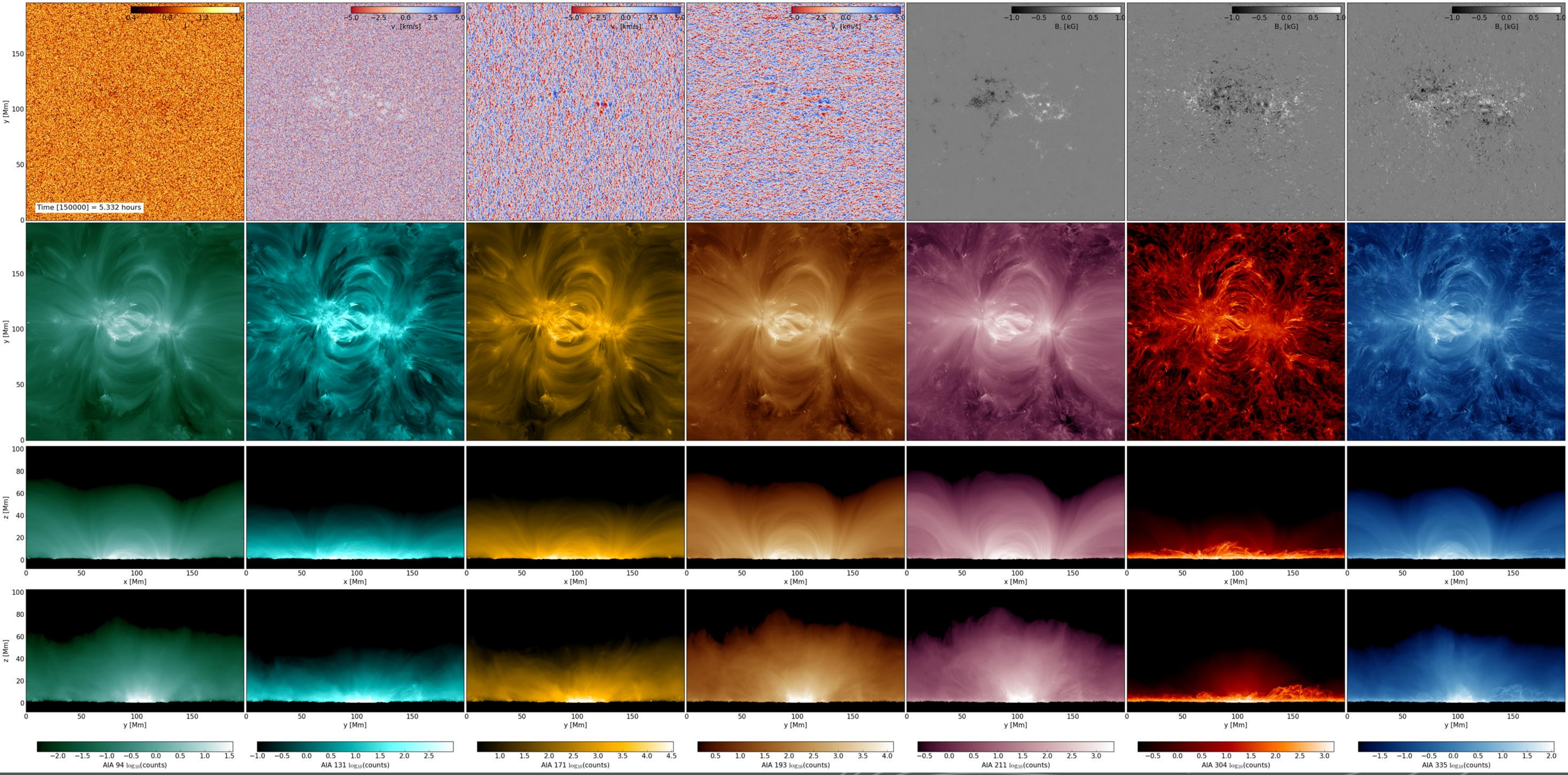
ISWAT Test case (AR 12760)



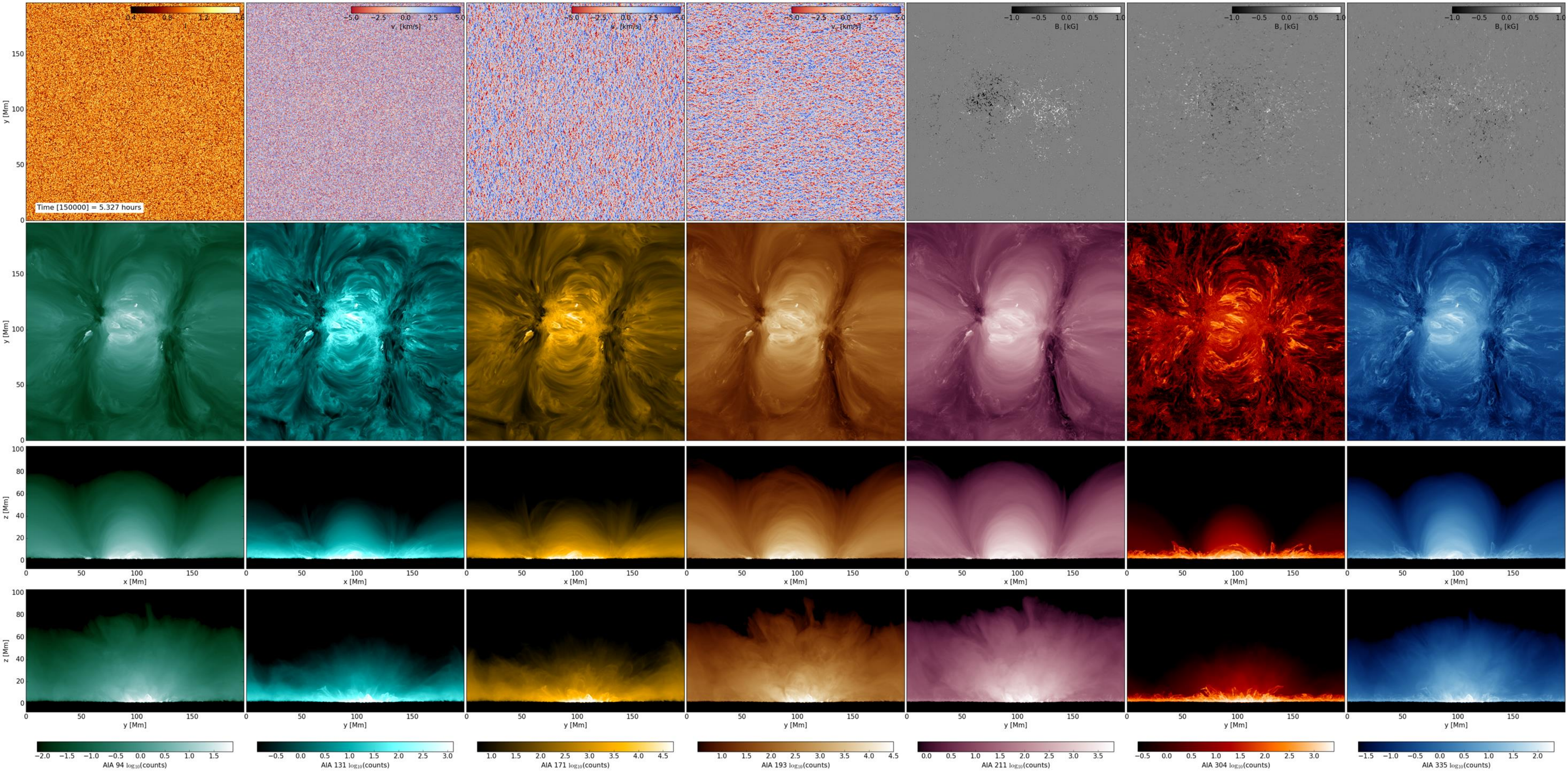
ISWAT Test case (AR 12760) – Low Resolution



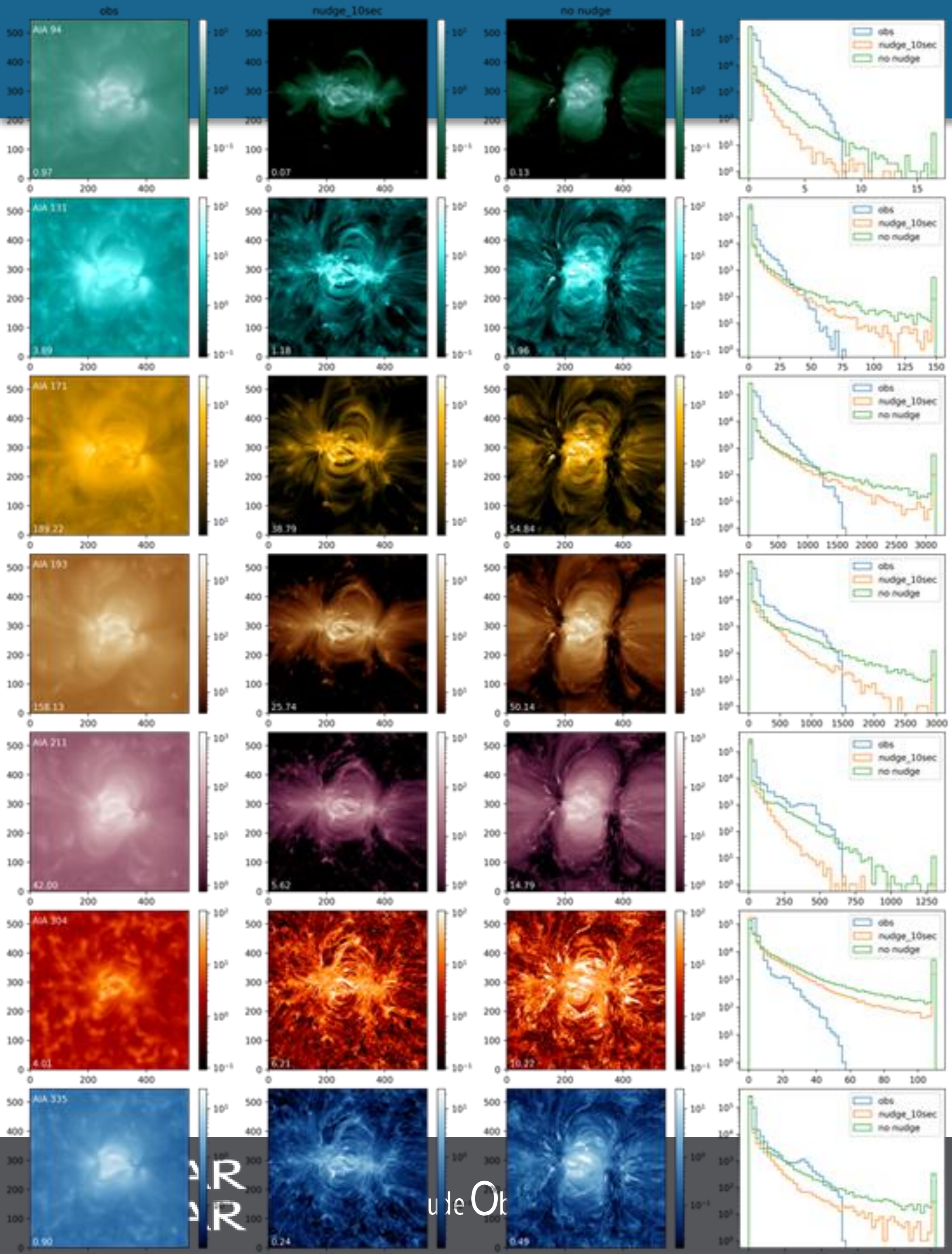
ISWAT Test case (AR 12760) – High Resolution



ISWAT Test case (AR 12760) – High Resolution, no nudging



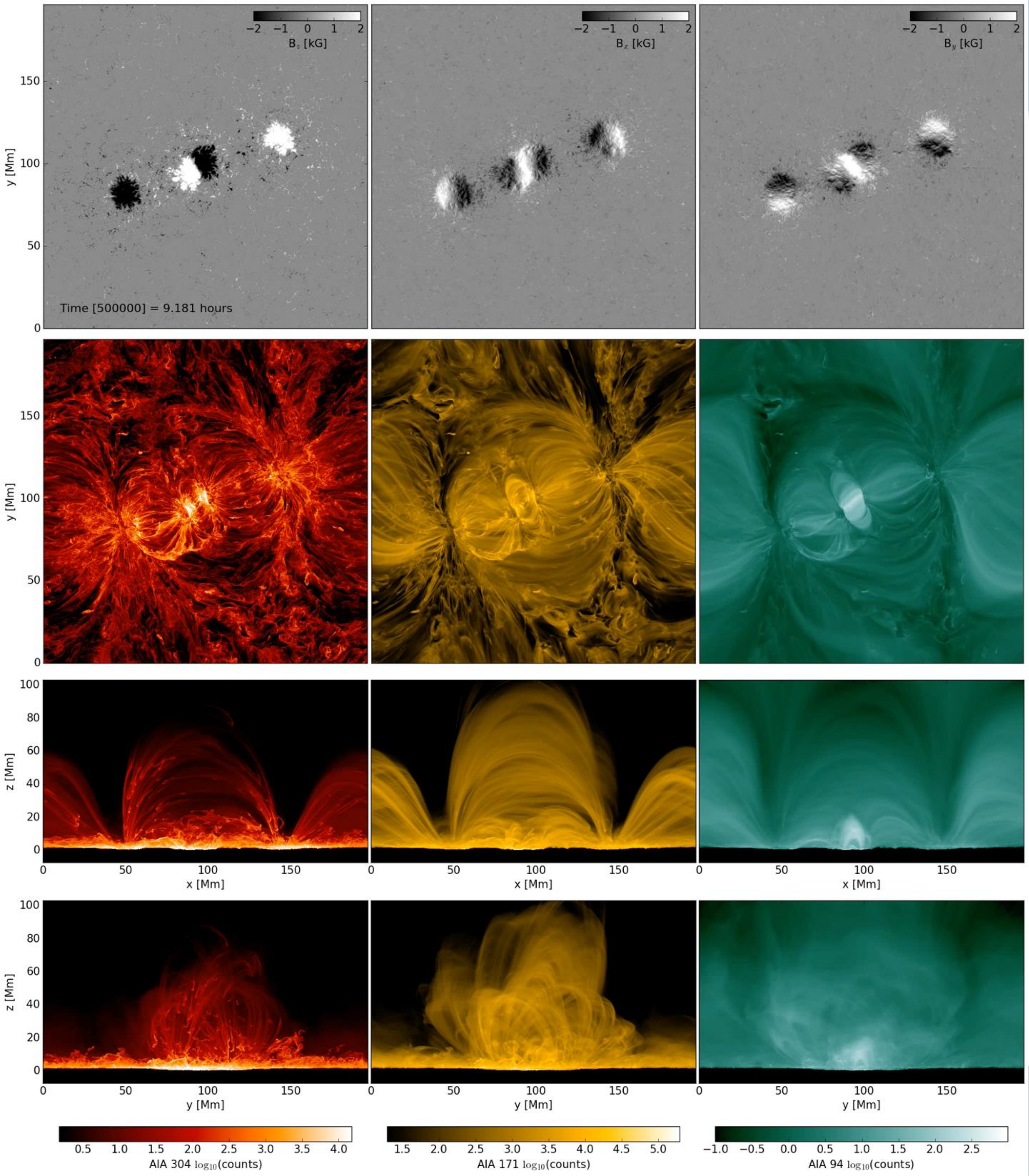
ISWAT Test case (AR 12760)

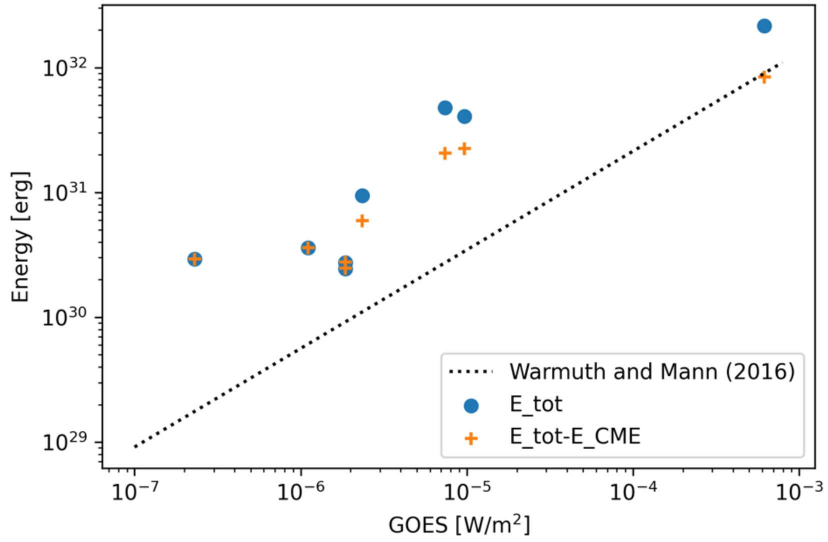


- Nudge on only Bz magnetogram (single time)
  - 10 sec nudging time scale
- Control run without nudging
  - Slightly higher Poynting flux
  - Less pronounced loop structure
- Comparison with observations:
  - Initial field is potential, different loop morphologies are in part due to different coronal field structure
  - Simulated corona has lower average counts in most AIA channels, put peak values are always higher
  - Corona outside AR too dim
    - HMI may be missing a lot of QS field

Flares!

- Setup inspired by AR 11158
  - No flux emergence
  - Collisional shearing
- Sequence of flares
  - 1 X-flare
  - Around 8 C-M flares
  - 4 CMEs





Summary

- Coronal extension of MURaM code has be widely applied to setups from quiet Sun to flaring Coronae
- In all cases the Poynting flux crated by photospheric magneto-convection maintains a corona that at least qualitatively compares to observed coronae, however:
  - Heating is implicit, i.e. due to numerical dissipation (resistive, viscous)
- Energy transport by Poynting flux dominated by 30-60 minute time scales
  - Braiding – nano-flare picture
- High Pm regime of corona suggest that dominant process of magnetic energy release is through the Lorentz-force driving flows (after reconnection)
  - Dominant heating comes from (numerical) viscosity
- Reconnection highly intermittent (due to high Pm setting)