Ab Initio Models of Solar Activity

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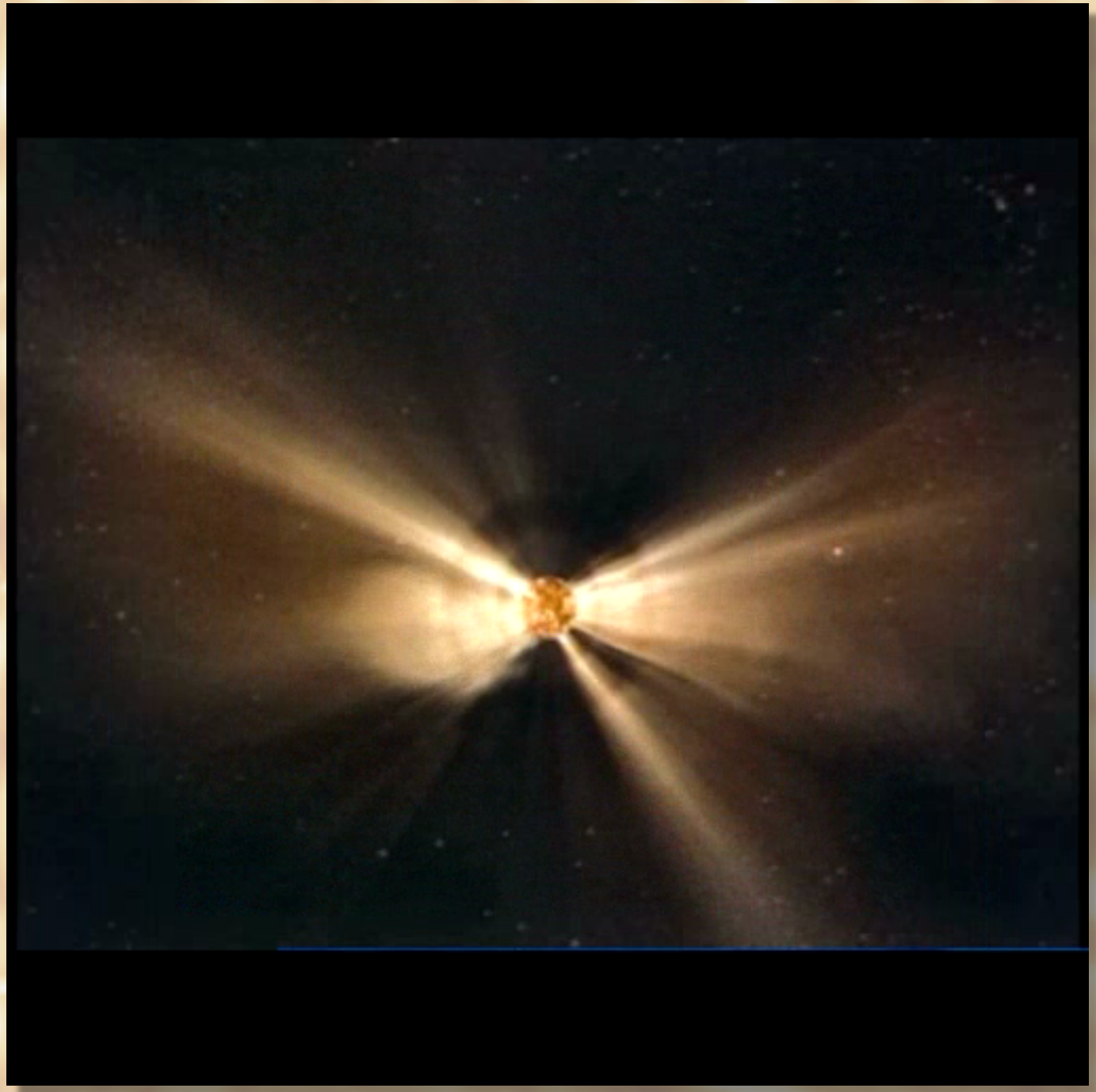
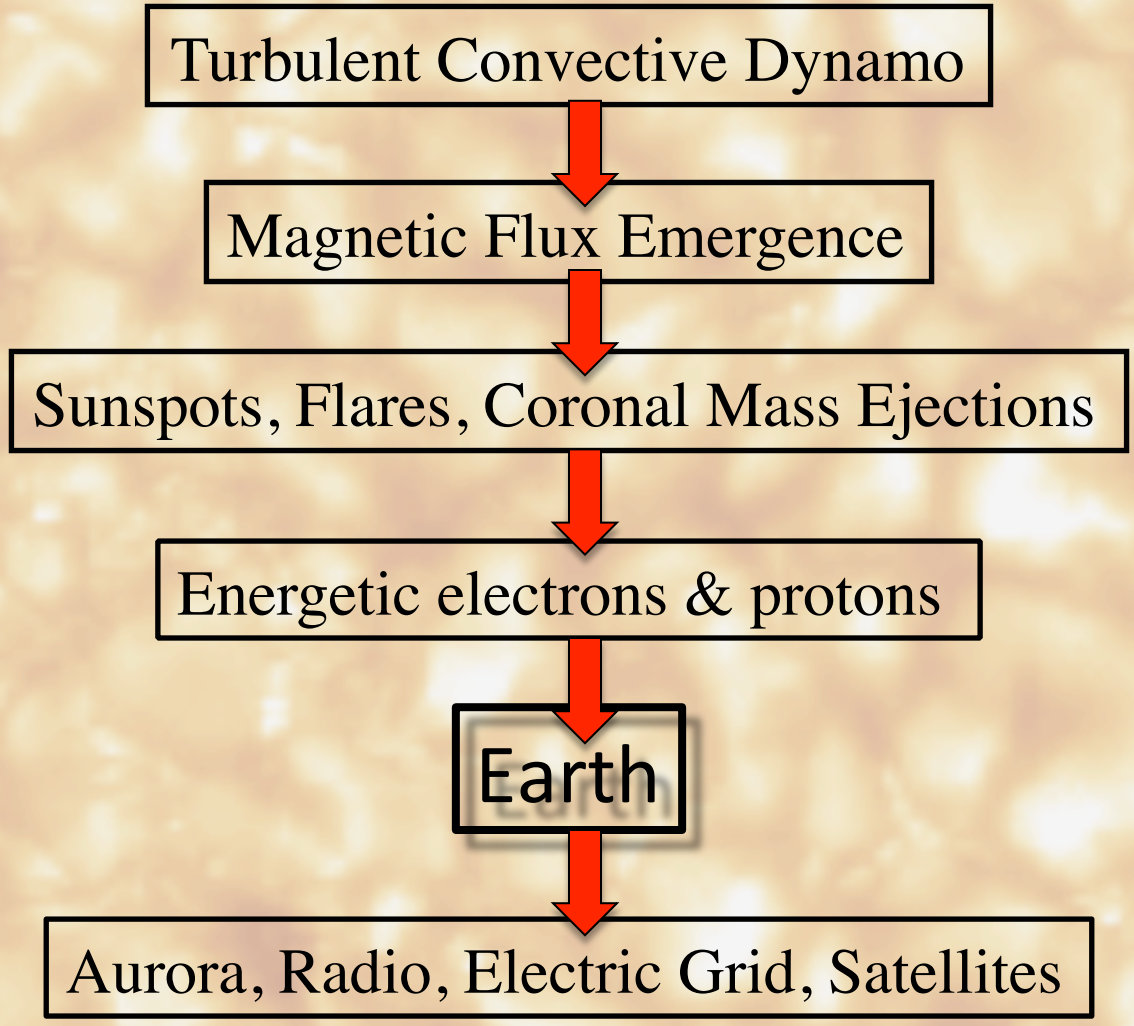


Coronal mass ejections from the Sun

Why It Matters



The Project:
Origin & Role of Active Regions

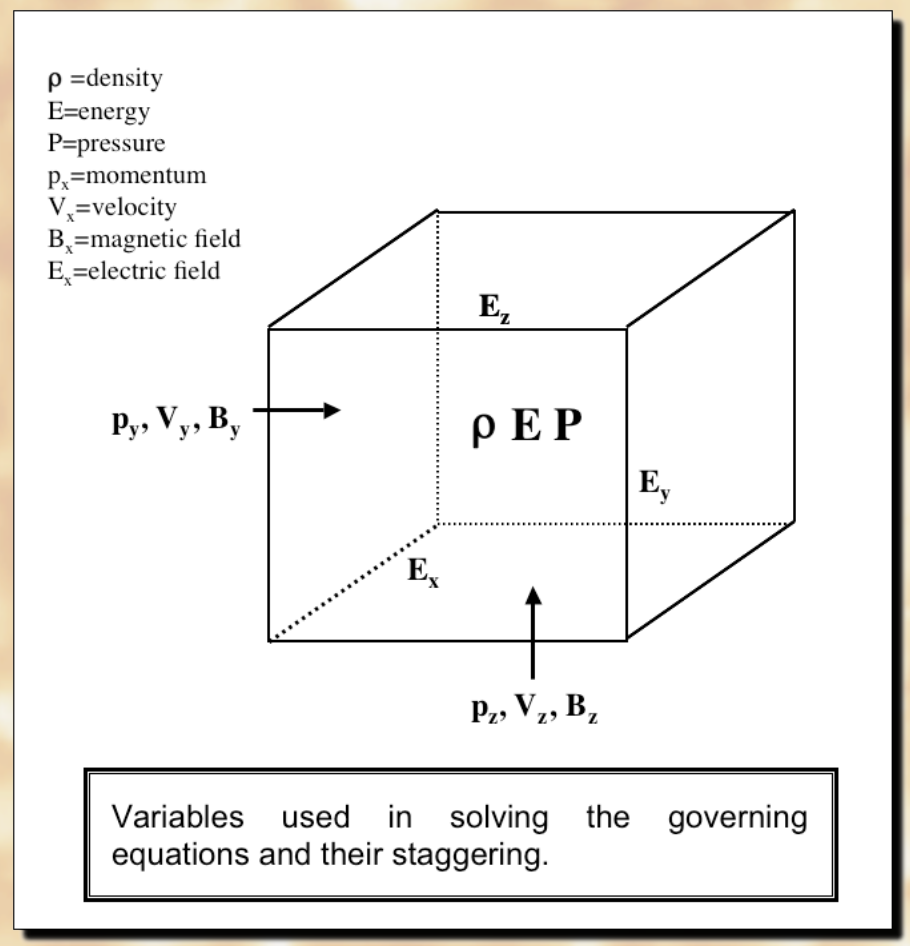
Magnetic field (dynamo)

Surface Magneto-Convection (STAGGER)

Chromosphere & Corona (BIFROST, RADMHD, PHOTON_PLASMA)

STAGGER

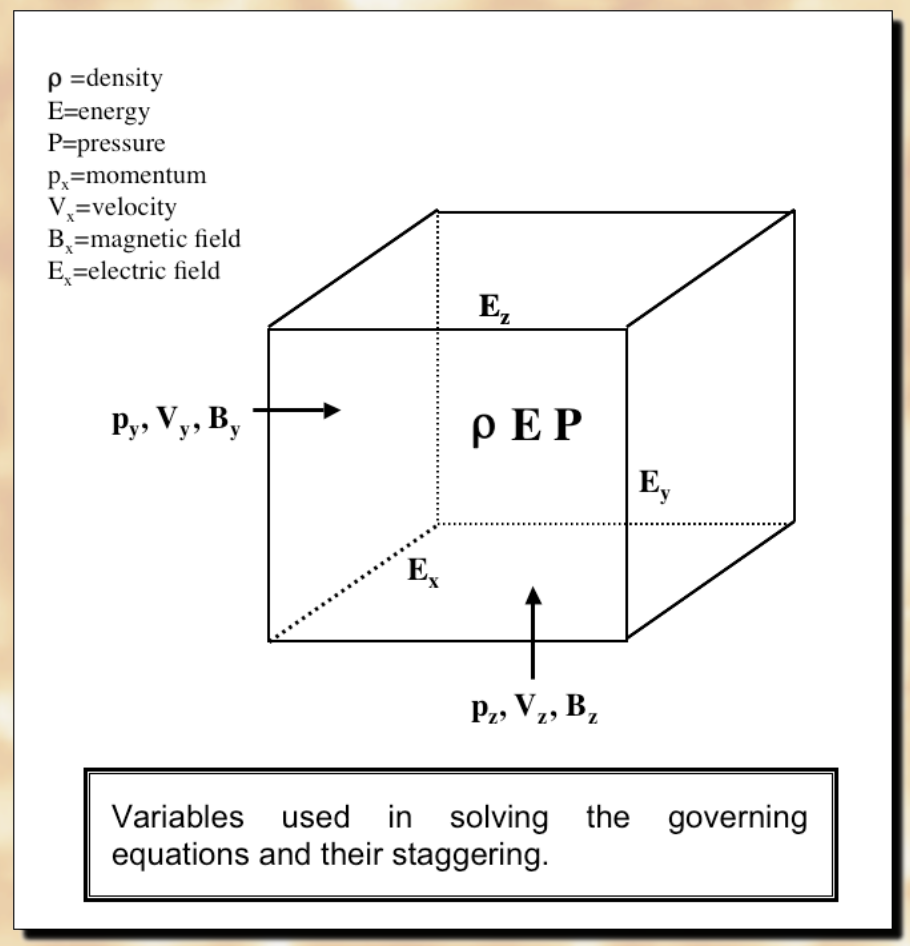
- Spatial differencing
  - 6^{th}-order centered finite difference.
  - Staggered variables
  - Stretched vertical grid
- Time advancement
  - 3^{rd} order Runga-Kutta
- Equation of state
  - tabular LTE
  - ionization & excitation
  - H, He + abundant elements
- Radiative transfer
  - 3D, LTE, long characteristics
  - 4 bin multi-group
- Quenching



Variables used in solving the governing equations and their staggering.

BIFROST

- Spatial differencing
  - 6th-order centered finite difference.
  - Staggered variables
  - Stretched vertical grid
- Time advancement
  - 3rd leapfrog
- Equation of state
  - Non-LTE, time-dependent H ionization
  - Tabular LTE EOS other elements
- Radiative transfer
  - 3D, short characteristics
  - Multi-group, scattering
- Quenching
- Conduction
- Hall currents



Variables used in solving the governing equations and their staggering.

Other 2 Codes

- RADMHD (convection zone - corona is stiff system)
  - Semi-implicit
    - NL terms: explicit 3rd order non-oscillatory fluxes
    - source terms: implicit, Jacobian-free, Newton-Krylov
  - Non-uniform mesh
  - Escape probability radiation
- PHOTON-PLASMA
  - PIC, relativistic, electron-ion
    - 6th order space, 2nd order implicit time advance
    - Coulomb interactions
  - Calculates emitted radiation spectrum

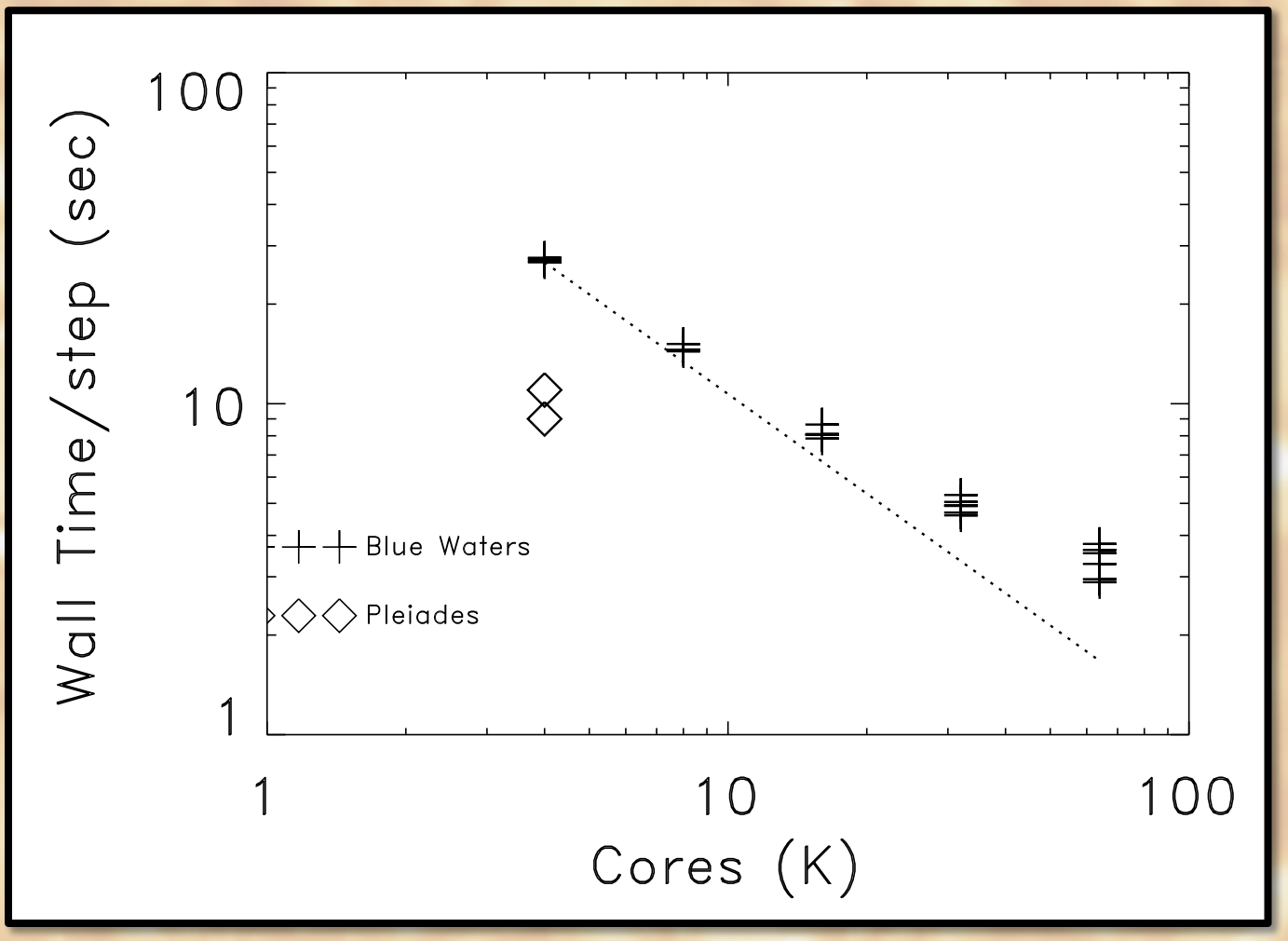
Key Challenge: Radiation Transport

- Radiation transport is inherently 3D & non-local, so it couples distance regions ➔lots of communication. STAGGER uses long characteristics covering the entire volume.
- Solution: restrict transfer calculation to only those layers where it is important for the energy balance.
- Future: do MHD & radiation on different processors on the same node ➔ Larger domains ➔ less communication.

Why BW?

- BW is 1/2.5 the speed of Pleiades (Ivy Bridge), but can use 4-8 as many processors on BW ➔ significant speedup for evolutionary calculations needing many time steps to evolve.

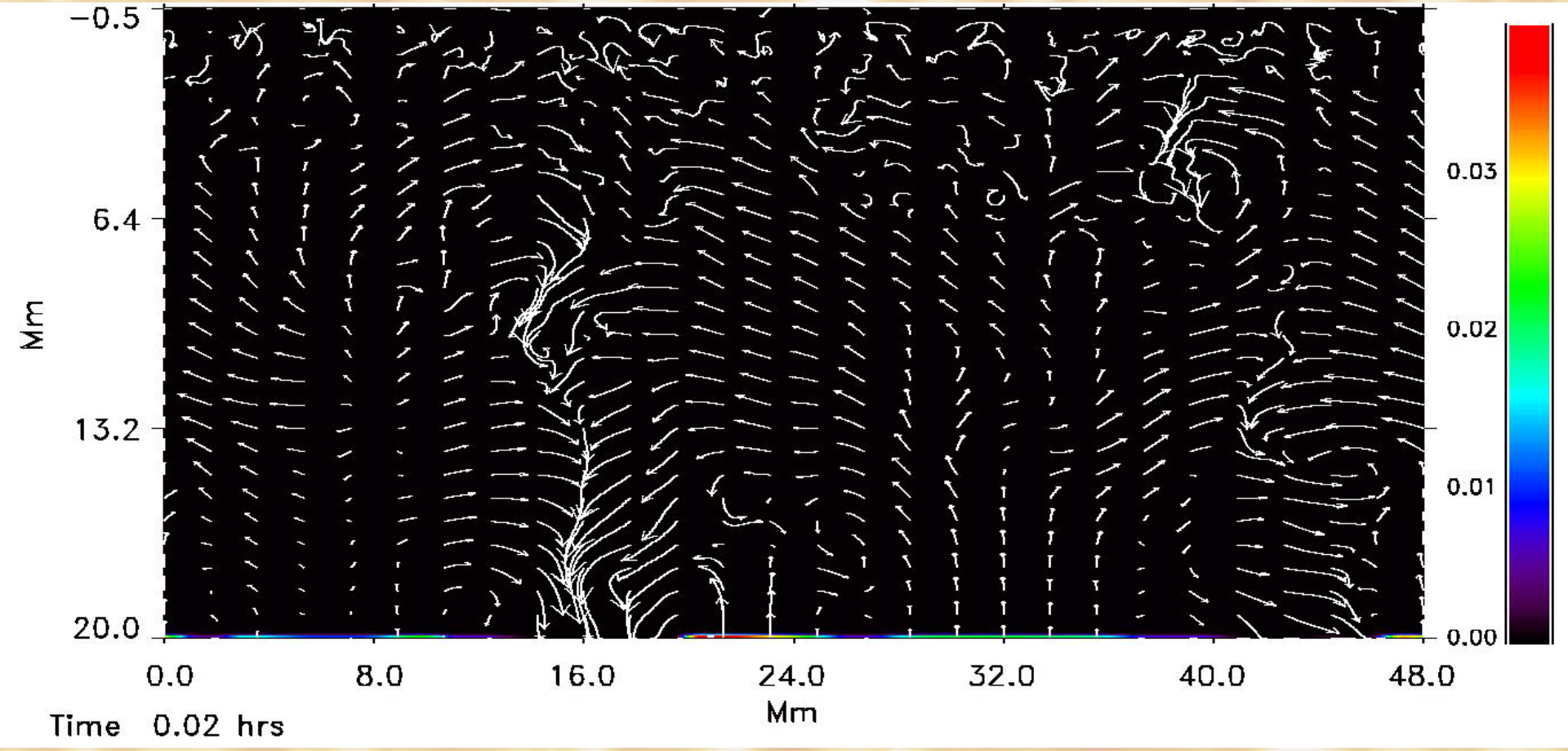
Strong Scaling



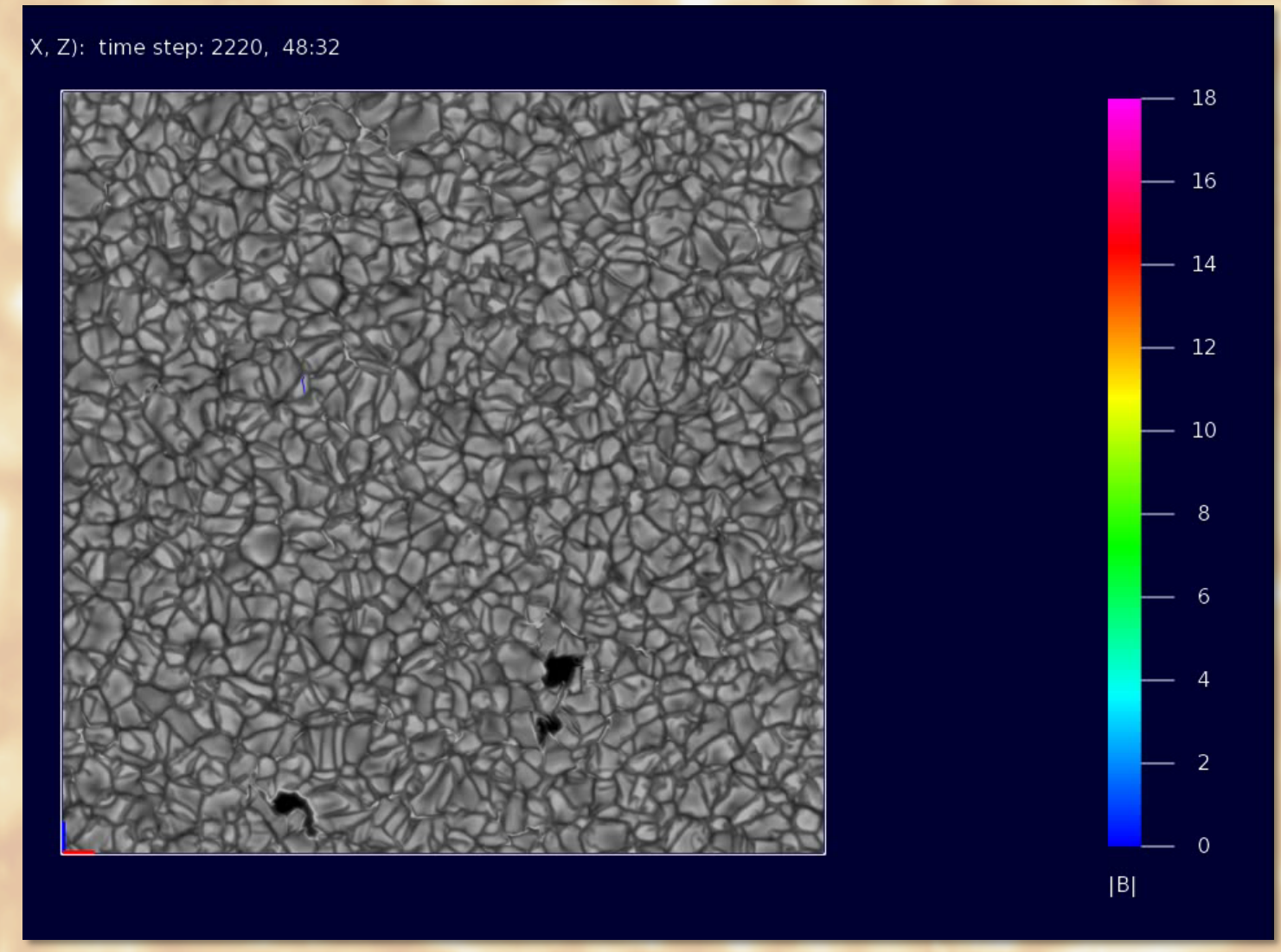
4032 x 500 x 4032 grid

Simulations

- Surface magneto-convection simulations are the foundation of the chain of calculations.
- Magnetic field is advected into the computational domain by inflows at the bottom boundary. Variable is field strength and area of inflow cells (controlled by the convection, deeper ➔ larger)
- Two simultaneous calculations:
  1. Extending computational domain from 20 to 30 Mm depth so larger cells and can improve magnetic boundary condition by using data from interior flux emergence calculations.
  2. Modeling suface dynamo action to determine its role in AR formation.

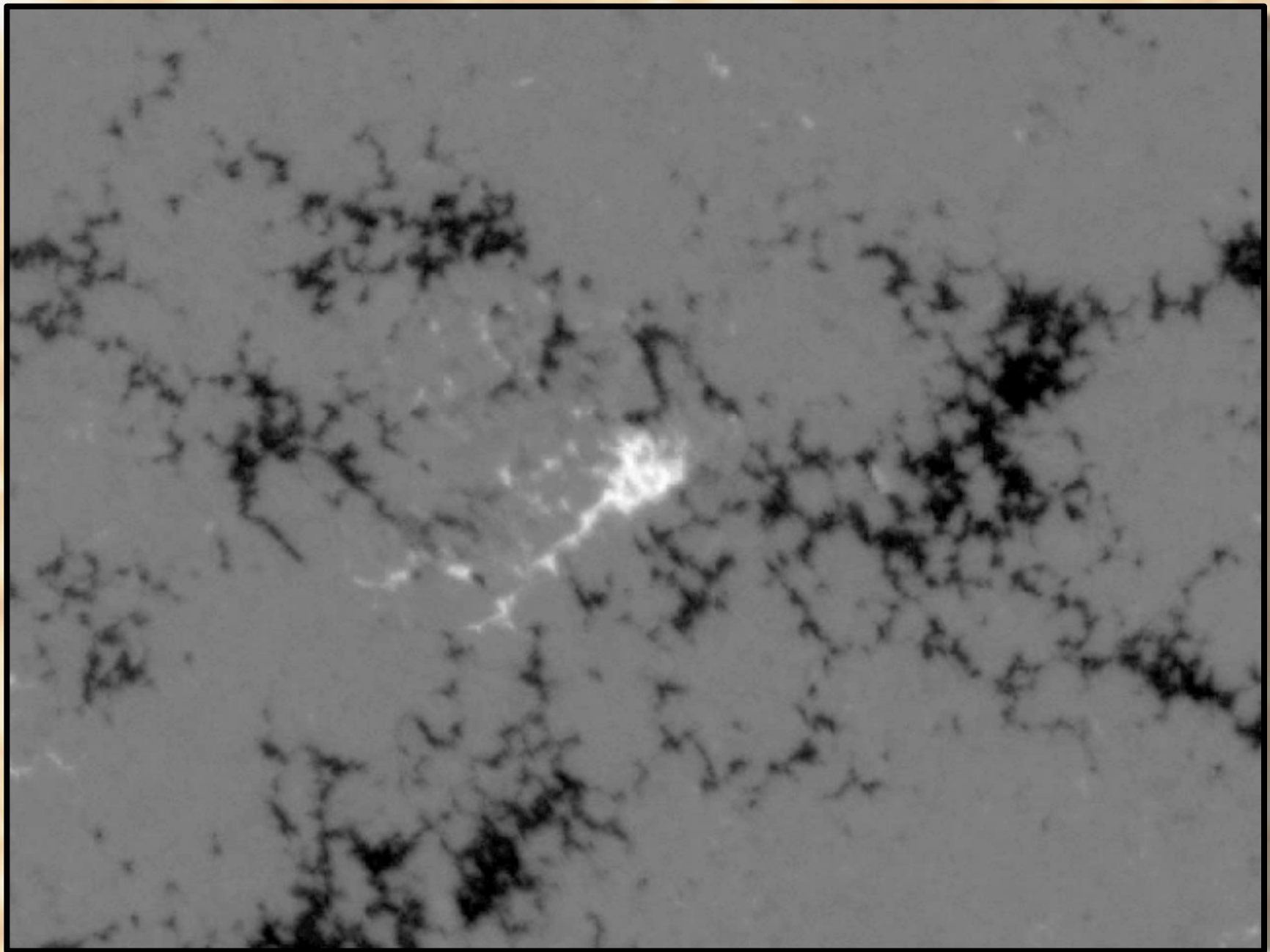


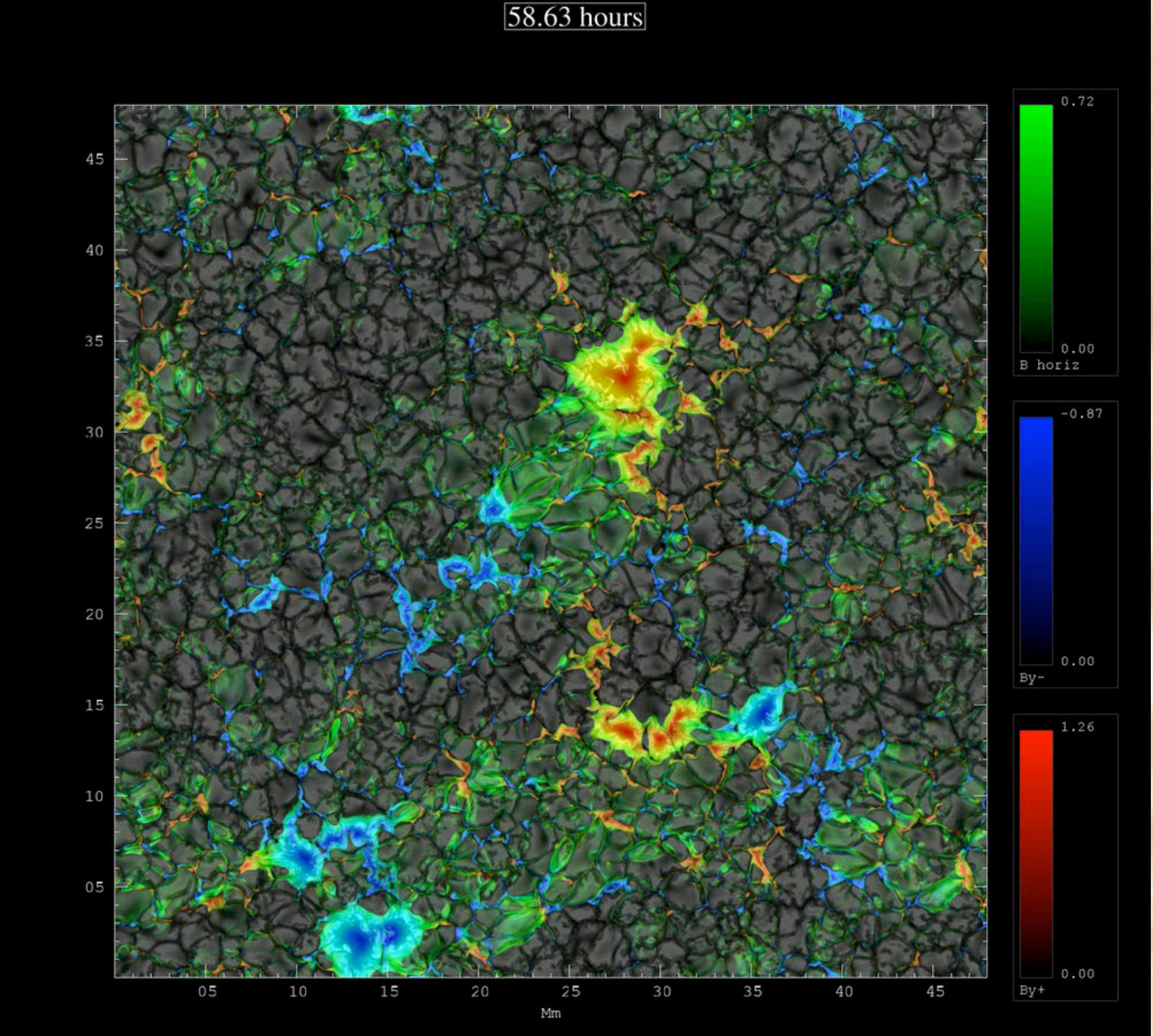
Horizontal magnetic field is advected into the computational domain. It rises due to upflows and buoyancy. Downflows hold the field down. The combination of up- and down- flows produces magnetic loops.



Convection confines, shreds, collects and advects magnetic field. Shredded field emerges first , then coherent legs.

AR Flux Emergence (Hagenaar)





B_V: red,blue
B_H: green

B emerges in localized patches. B_H emerges over granules, B_V at ends in lanes

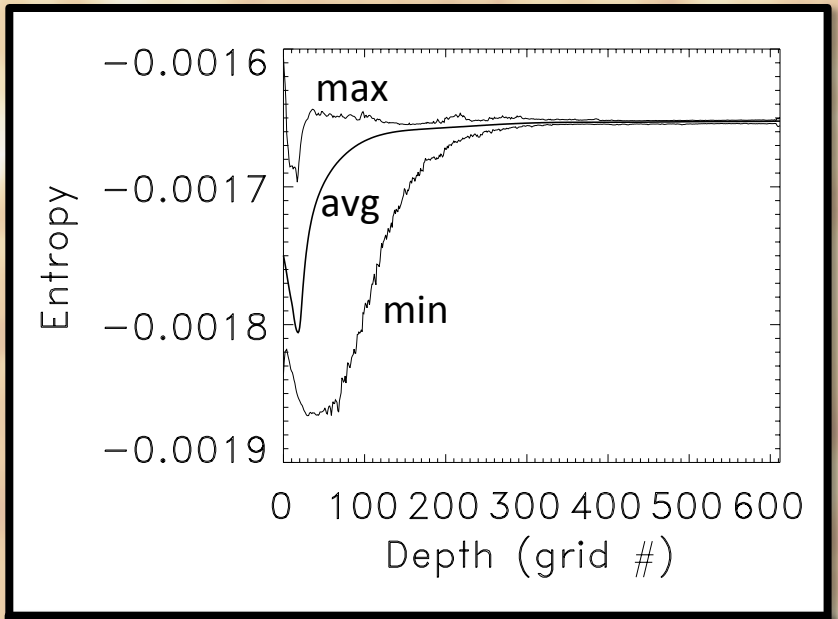
Extension to 30 Mm depth

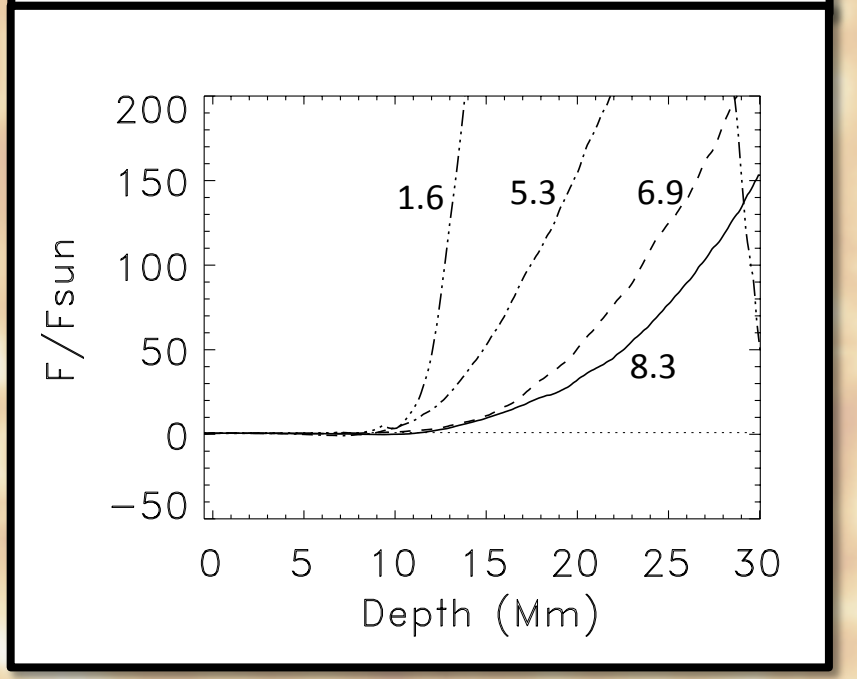
- Initiated with quiescent, constant entropy, hydrostatic extension.
- Convective motions penetrate from above.
- Must relax to constant convective flux. Has completed 8 hrs. so far.
- Will then double horizontal extent form 96 to 192 Mm to encompass size of observed solar active regions.

Currently

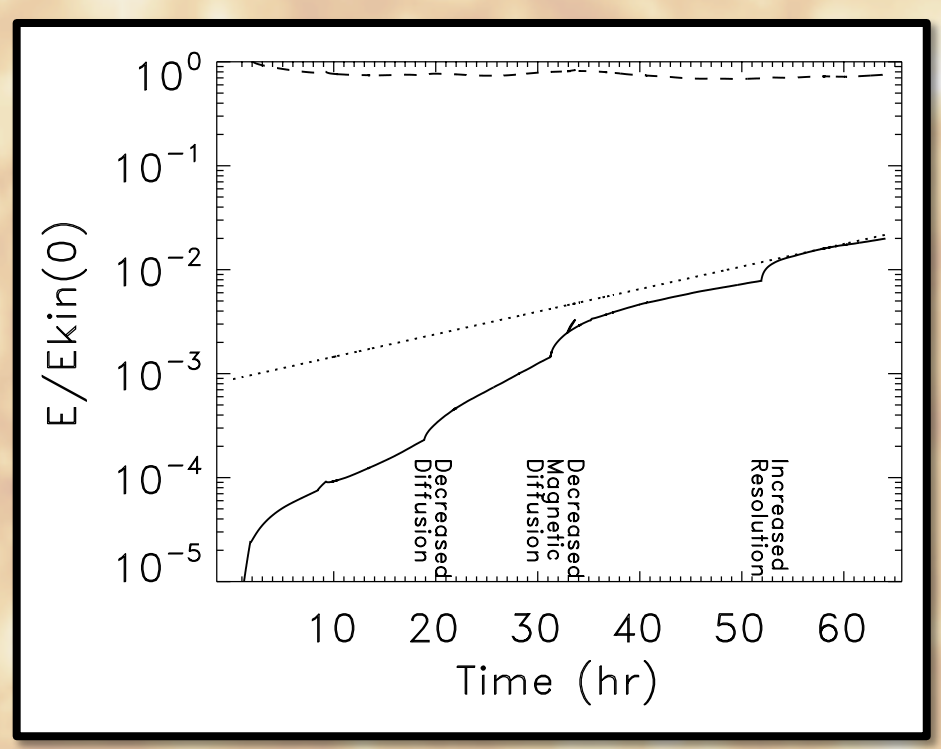
- Constant entropy

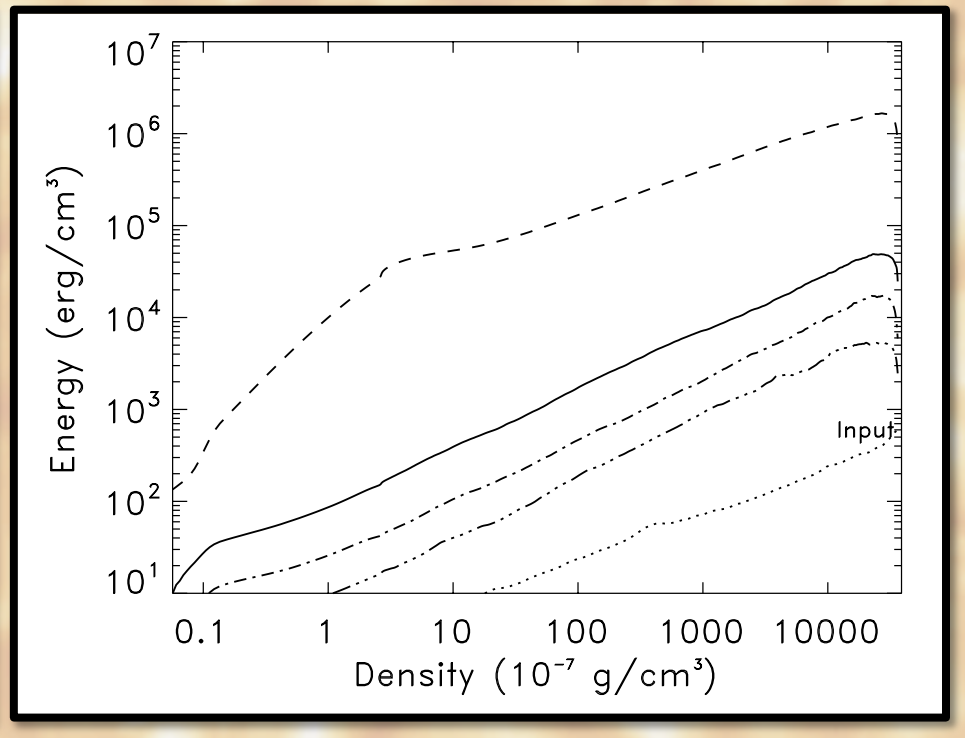
- Relaxing convective flux





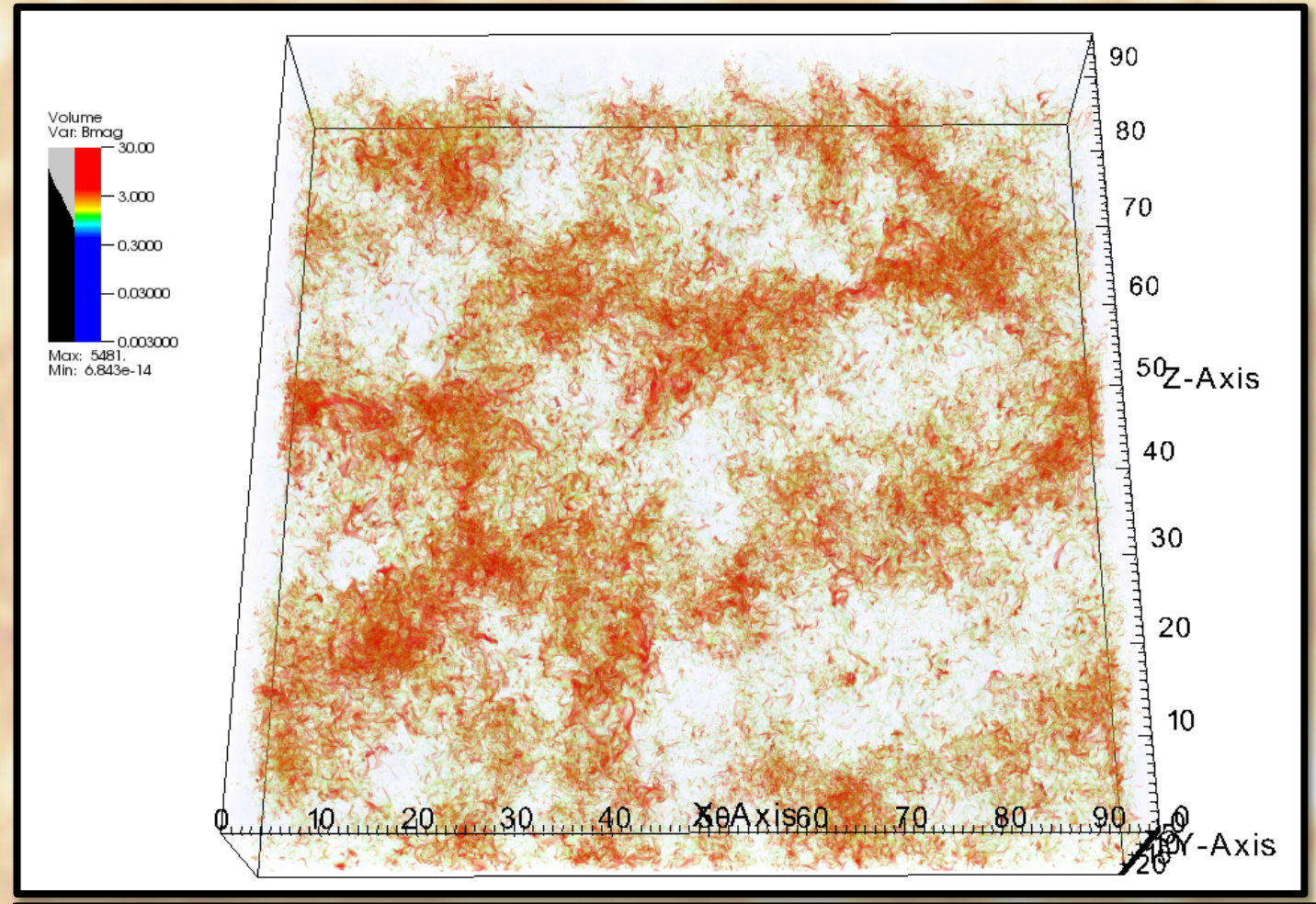
Surface Dynamo





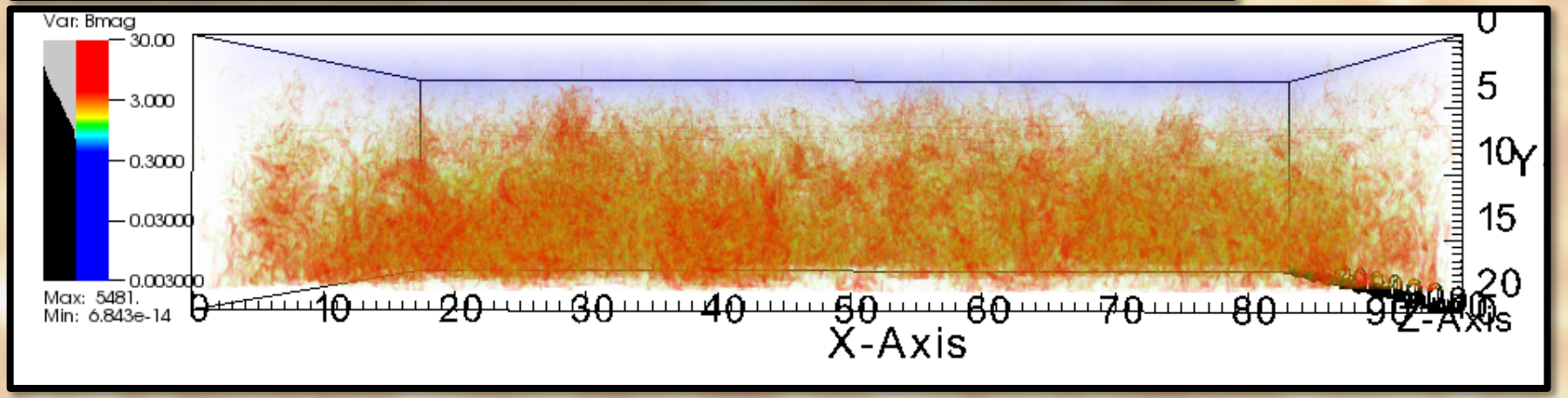
Dynamo has run 64 hrs, or 1.3 turnover times so far. Magnetic energy has reached 2.6% of kinetic energy. It is starting to saturate at this resolution (24 km horizontally, 12-78 vertically). May need to increase resolution / decrease diffusion.

Both kinetic and magnetic energies are power laws in the density and nearly proportional to one another except near the surface.

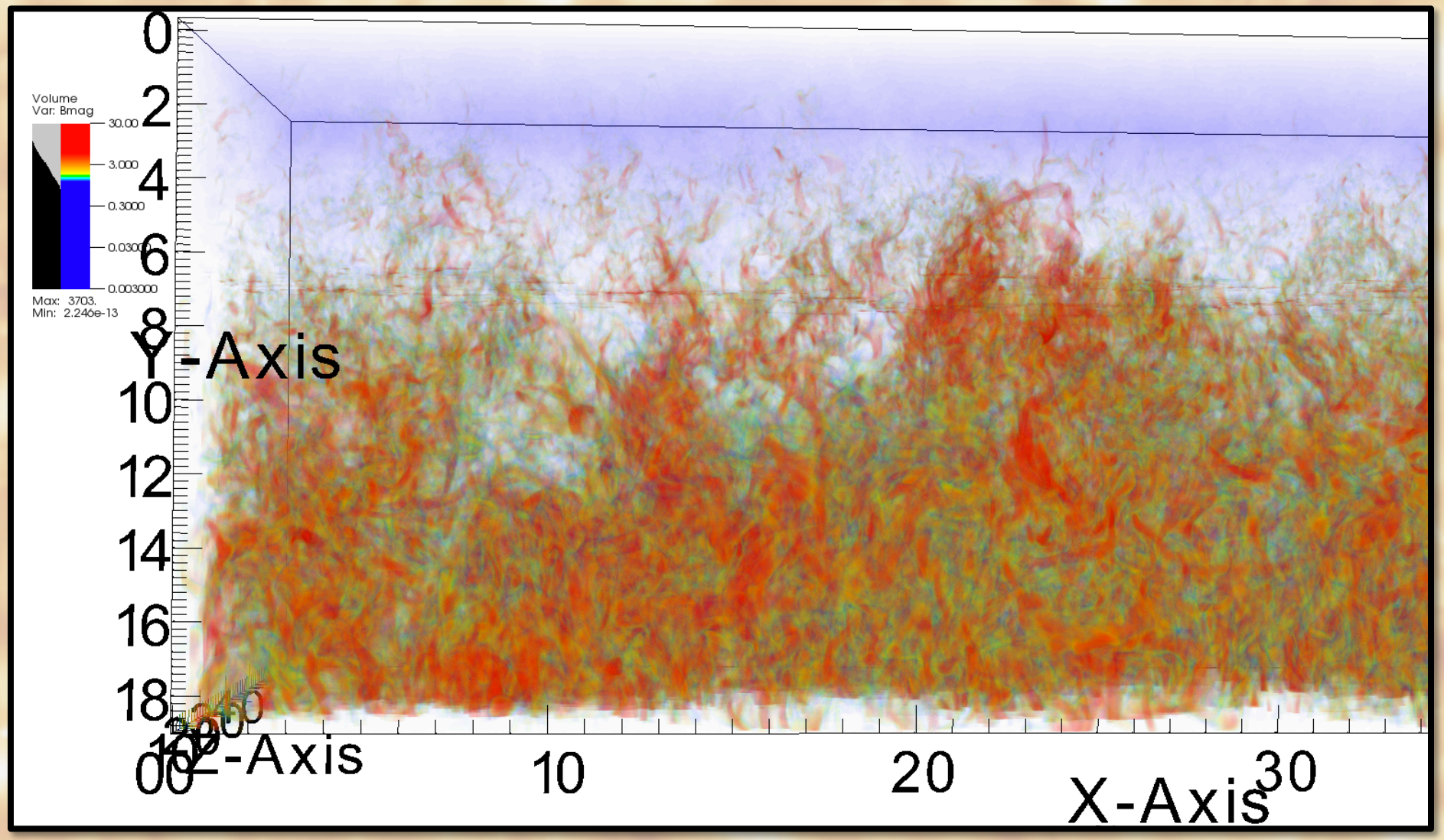


Magnetic Field:

Structured as convective downflows, Stronger at depth.

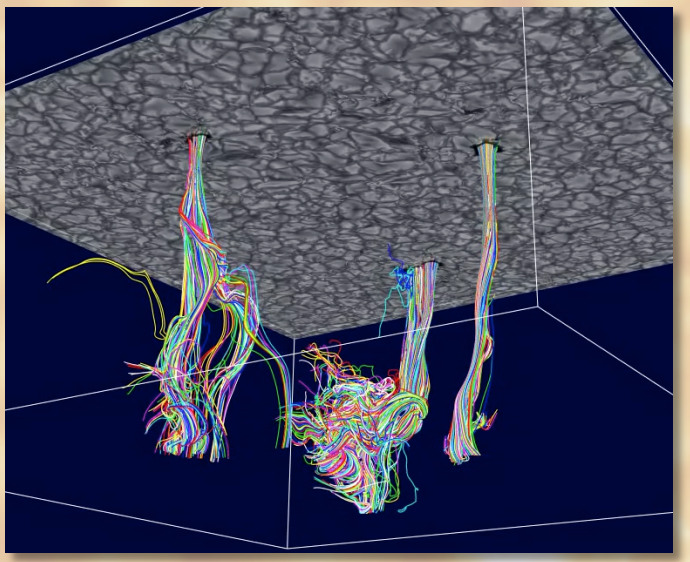


Zooming in on B



Summary

- Use BW 32-64K nodes to model AR formation by magneto-convection.
- Extending domain in depth and width to accommodate realistic solar AR.
- Synthetic data for improving and validating helioseismic inversions of magnetic regions.
- Synthetic data for analysis for new solar telescopes: NST, Daniel K. Inouye Solar Telescope (DKIST, formerly ATST)



- **Other parts of project await completion of extension to 30 Mm depth x 96 Mm width. Codes have been tested successfully on B.**