Ab Initio Models of Solar Activity

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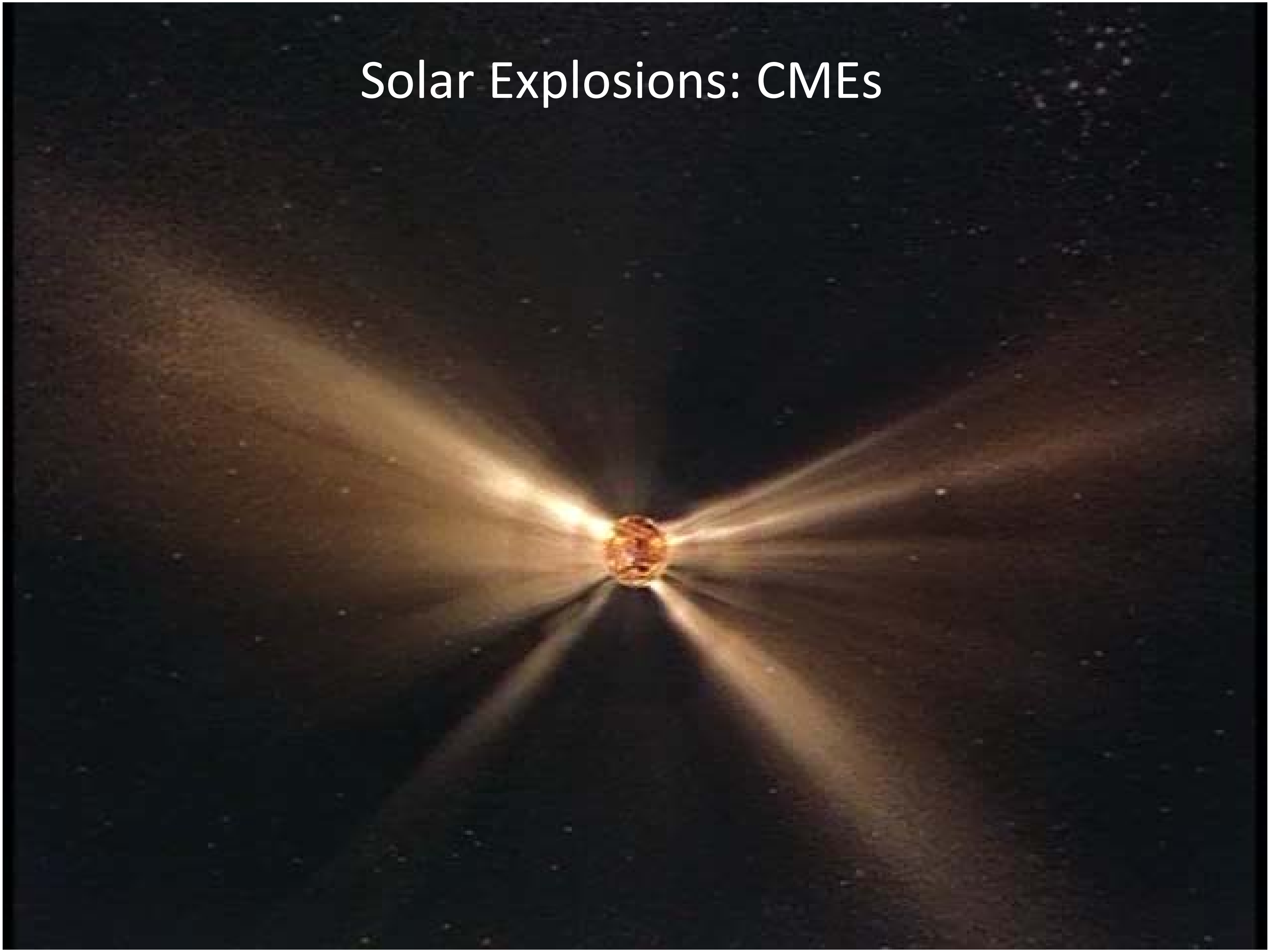
Solar Explosions: CMEs



GOAL: Understand Active Regions

- Magnetic fields are generated by dynamo action in solar convection zone
- Fields erupt through the visible solar surface to produce pores, sunspots and active regions
- New field interacts with existing field in the atmosphere to store and release magnetic energy which produces the explosions

Method: magneto-radiation-hydrodynamic simulations

Challenge

- Physics
  - Excitation and Ionization
  - Radiation energy transport
  - Turbulence
- Spatial & Temporal Range
  - DKIST will resolve 30 km
  - Convective structures 1-100 Mm
  - Surface convection – minutes, deep convection - days

Magneto-Hydrodynamic Equations

- Mass conservation

  $\partial\rho/\partial \mathrm{t} = -\nabla \cdot (\rho\mathbf{u})$

- Momentum conservation

  $\partial(\rho\mathbf{u})/\partial \mathrm{t} = -\nabla\cdot(\rho\mathbf{uu}) - \nabla P - \rho\mathbf{g} + \mathbf{J}\times\mathbf{B} - 2\rho\boldsymbol{\Omega}\times\mathbf{u} - \nabla\cdot\boldsymbol{\tau}_{\mathrm{visc}}$

- Energy conservation

  $\partial e/\partial \mathrm{t} = -\nabla\cdot(e\mathbf{u}) - P(\nabla\cdot\mathbf{u}) + Q_{\mathrm{rad}} + Q_{\mathrm{visc}} + \eta\mathbf{J}^2$

- Induction equation & Ohms law

  $\partial\mathbf{B}/\partial \mathrm{t} = -\nabla \times \mathbf{E}$, $\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \eta\mathbf{J} + (1/\mathrm{en_e})(\mathbf{J}\times\mathbf{B} - \nabla P_{\mathrm{e}})$,

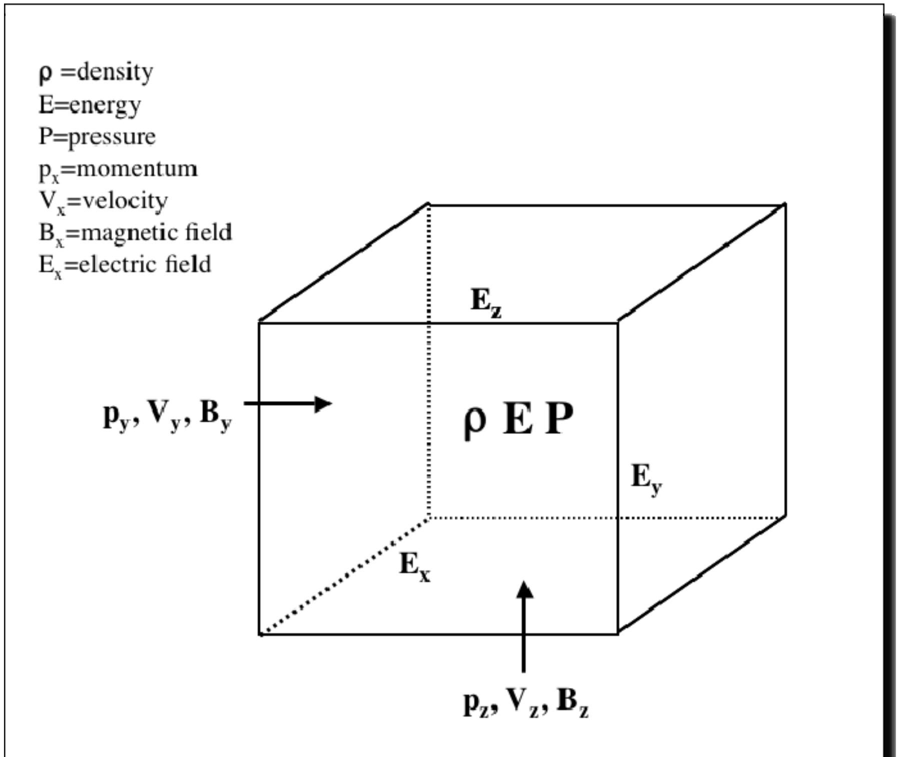
Numerical Method

- Spatial differencing
  - 6th-order centered finite difference.
- Time advancement
  - 3rd order, Runga-Kutta
- Equation of state
  - tabular
  - including ionization
  - H, He + abundant elements
- Radiative transfer
  - 3D, LTE
  - 4 bin opacity distribution function
- Diffusion

$$\left(\frac{\partial f}{\partial t}\right)_{diffisusion} = \left(\frac{\partial}{\partial x_i}\right)\left(\nu\alpha\left(\frac{\partial f}{\partial x_j}\right)\right)$$

$$\alpha = \Delta^3 / \max\left(\left|\Delta f\right|_{\{-2,-1,0,+1,+2\}}\right)$$

$$\nu_i = c_1(c_{sound}^2 + c_{Alfven}^2)^{1/2} + c_2\left|u_i\right| + c_3\left[\left(\Delta_3 u\right) < 0\right]\Delta x_i$$



Variables used in solving the governing equations and their staggering.

6th order Finite Differences

$$f'_{i+1/2,j,k} = \frac{a}{\Delta x}(f_{i,j,k} - f_{i+1,j,k}) + \frac{b}{\Delta x}(f_{i-1,j,k} - f_{i+2,j,k}) + \frac{c}{\Delta x}(f_{i-2,j,k} - f_{i+3,j,k}) \ ,$$

where

$$c = 3/640, \ b = -1/24 - 5c, \ a = 1 - 3b + 5c \, .$$

5th order Interpolation

$$f_{i+1/2,j,k} = a\left(f_{i,j,k} + f_{i+1,j,k}\right) + b\left(f_{i-1,j,k} + f_{i+2,j,k}\right) + c\left(f_{i-2,j,k} + f_{i+3,j,k}\right)$$

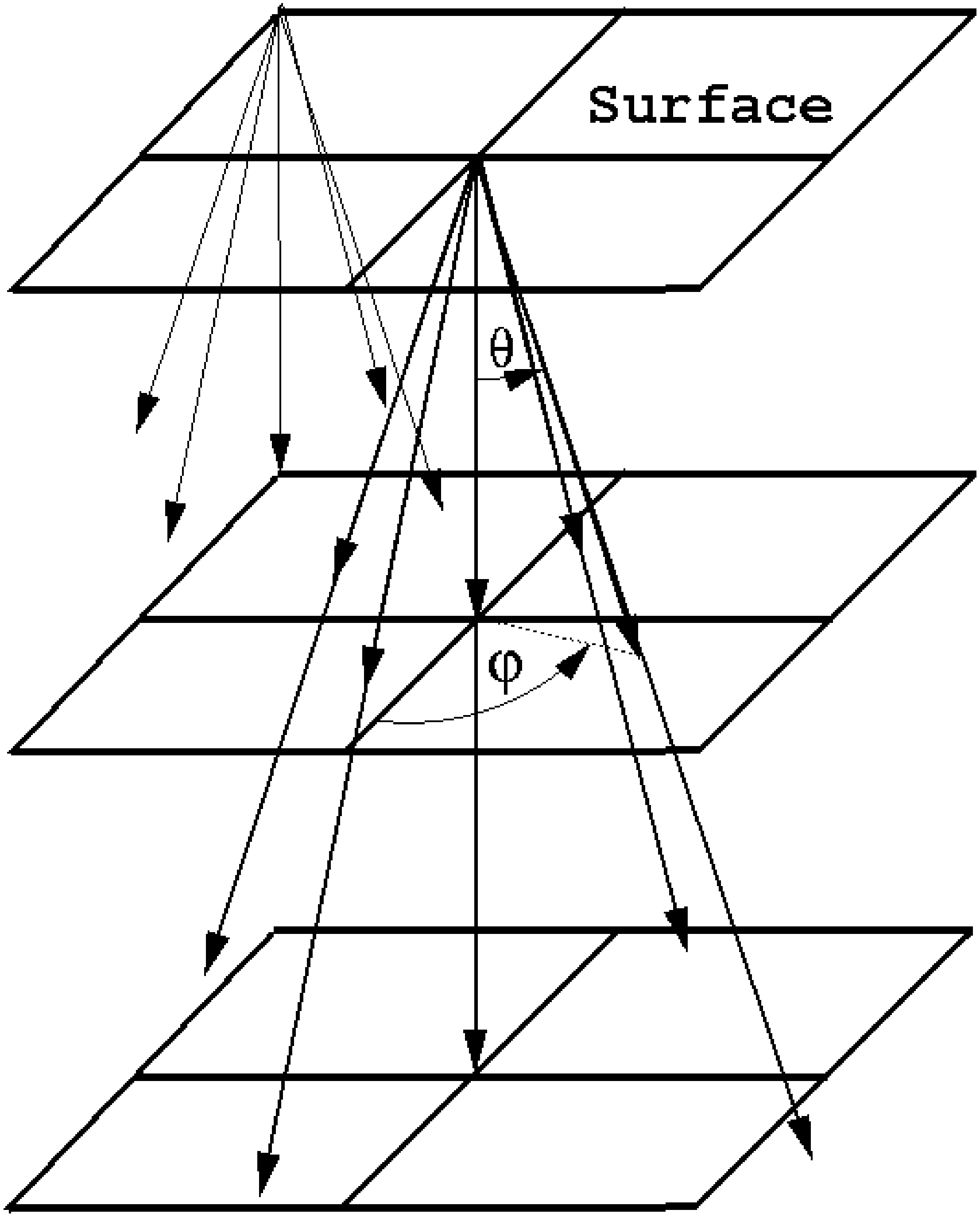
where

$$c = 3/256, \quad b = -25/256, \quad a = 0.5 - b - c$$

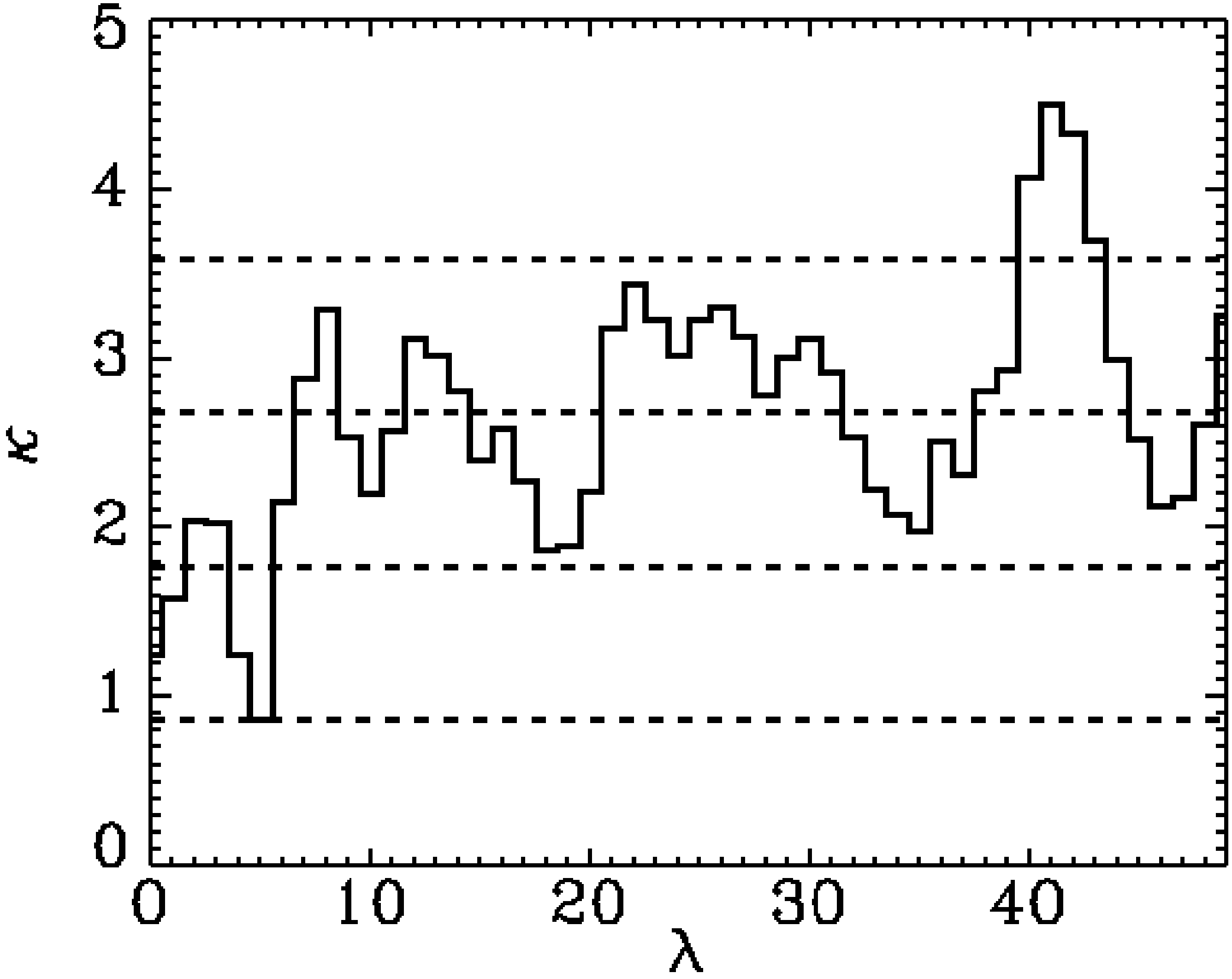
Key Challenge: Radiation Transport

- Radiation transport is inherently 3D & non-local. It couples distant regions ➔lots of communication. STAGGER uses long characteristics, filling the volume. Need to communicate volume data.
- Solution: restrict transfer calculation to only surface layers where it is important for the energy balance.
- Restrict number of frequencies (energies) and directions (rays).

Vertical and 4 angled rays
One through each surface cell
Angled rays rotate each time step,
   sweep out volume



Multigroup opacity and source function.
Bin frequencies according to opacity magnitude.
Use 4 bins, need 12 for precise agreement with observations



Boundary Conditions

- Vertical:
  - Density: Top extrapolate lnρ. Bottom-inflows fix rho, -outflows rho➔<rho>.
  - Velocity -> constant @ top, zero derivative @ bottom;
  - E=energy/mass Top: ➔ average value, Bottom: extrapolate <E> outflows, fix E inflows.
- B tends to potential field @ top,

B advected by Inflows @ bottom (20 Mm) --

Weak (1 kG) or Strong (5 kG), minimally structured (horizontal, uniform, untwisted) magnetic field .
Represents top of larger, rising flux concentration.

Imposed via specifying the horizontal electric field.

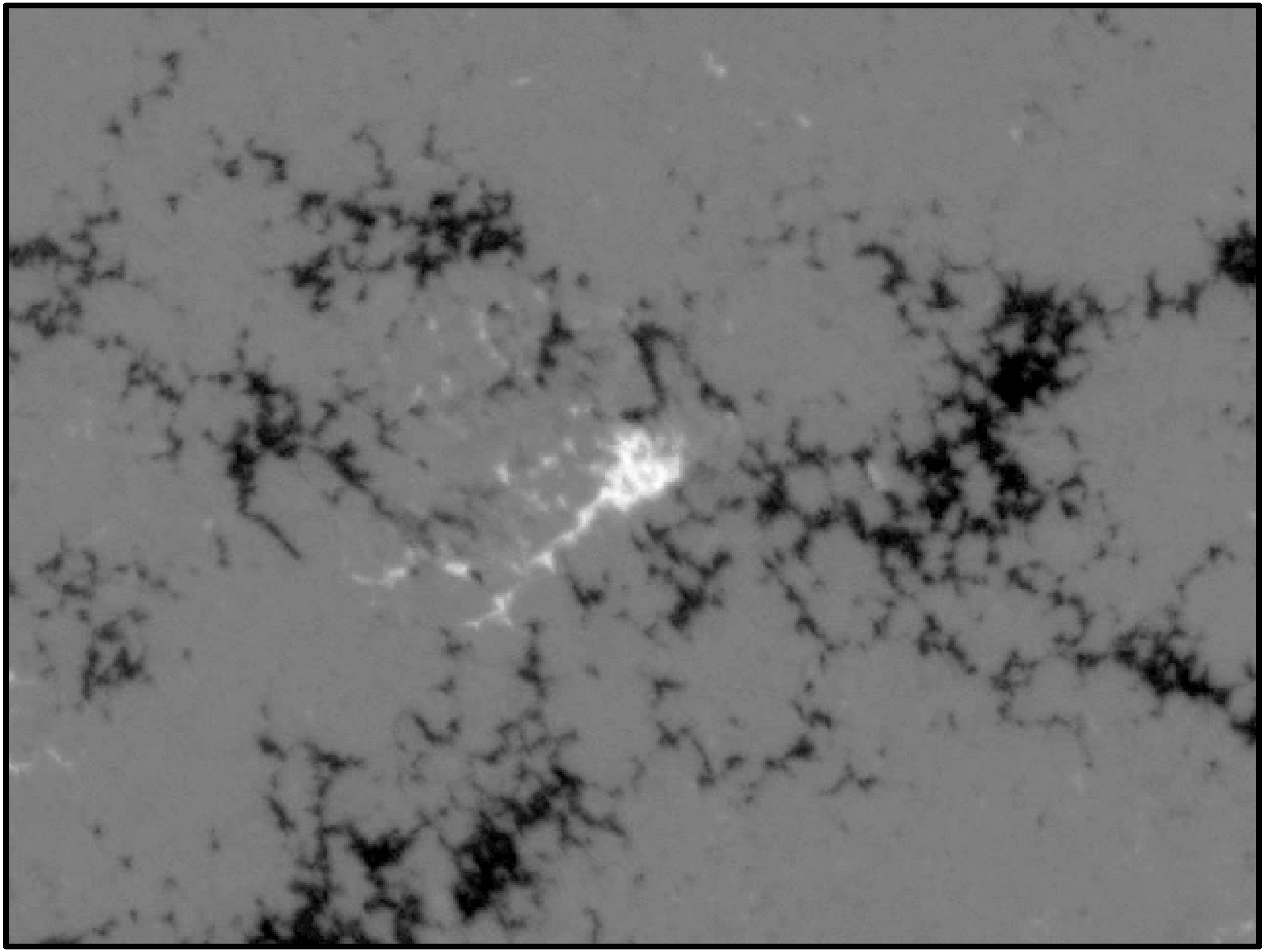
Simulations

- Variable is field strength and geometry (controlled by the convection, deeper ➔ larger).
- Project:

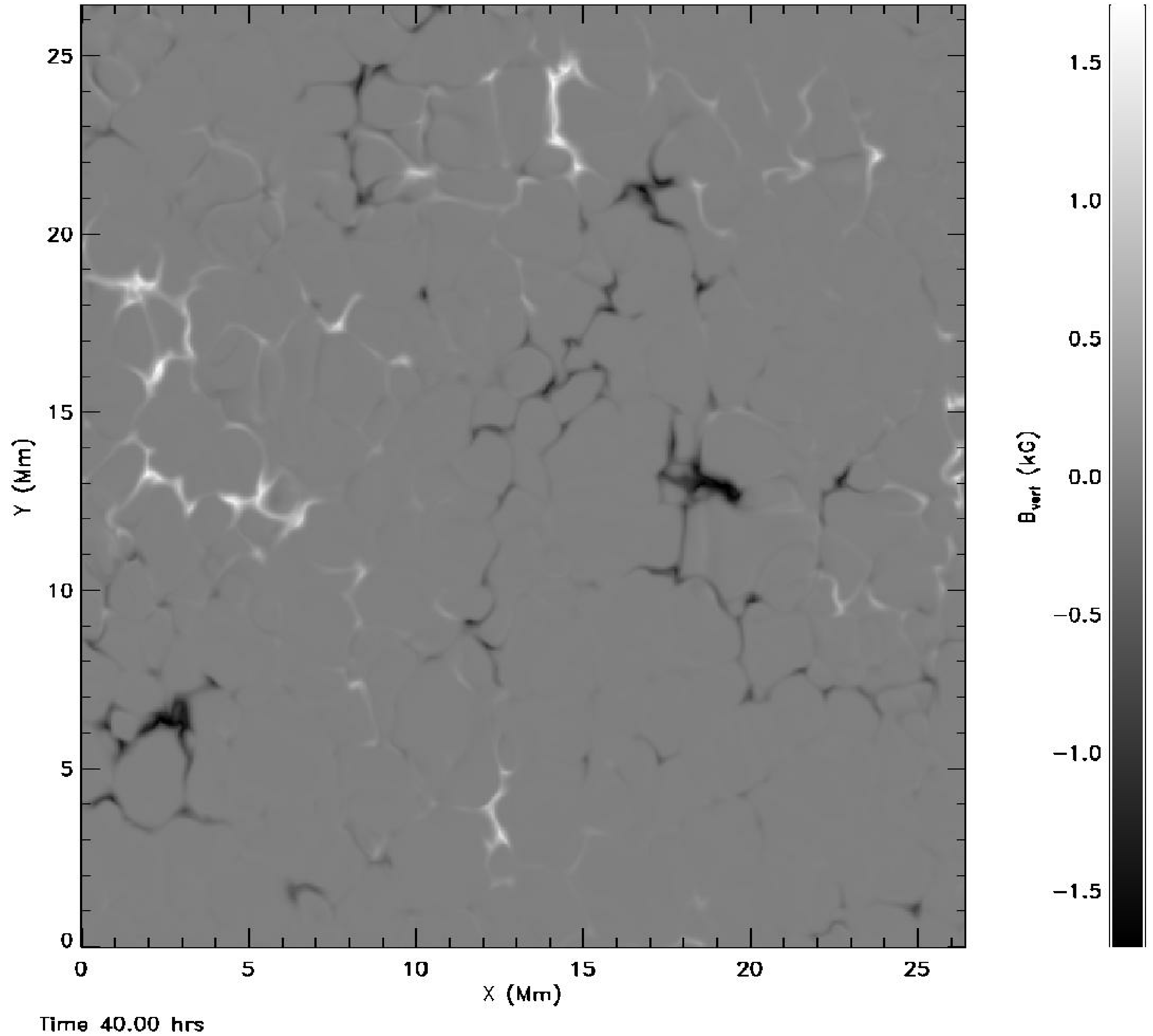
① Extend computational domain from 20 to 30 Mm depth so has larger convective cells and overlaps interior, global dynamo calculations.

② Use dynamo data ➔ spatially and temporally varying magnetic boundary condition.

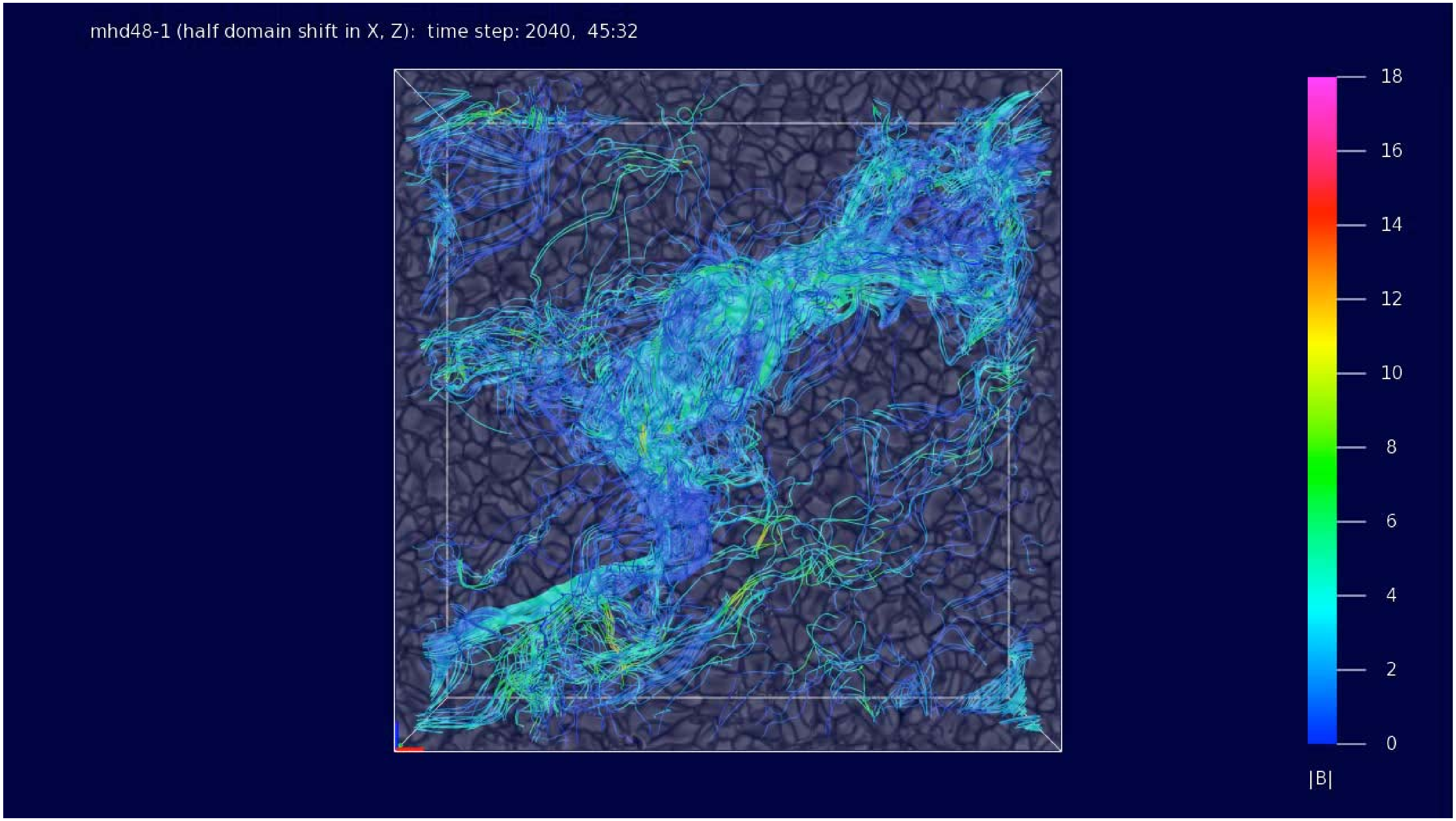
Observed AR Flux Emergence: Vertical Field



Simulated Vertical B

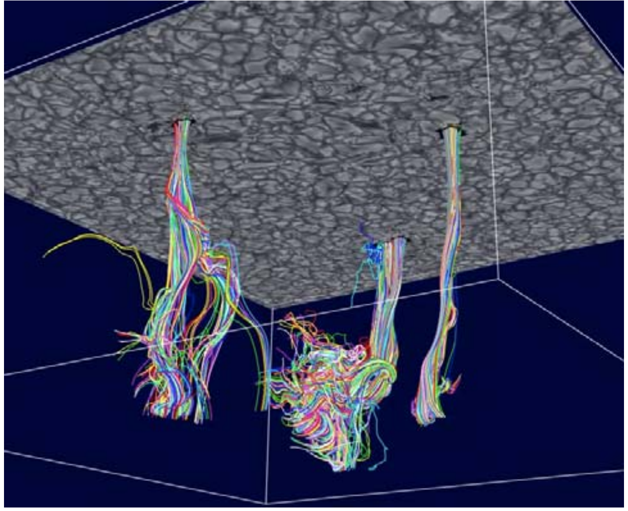


Tracking magnetic field lines: Rising Magnetic Loop



Summary

- Use BW 32-64K nodes to model AR formation by magneto-convection.
- Extending domain in depth and width to accommodate realistic solar AR.



- Provides synthetic data for improving & validating helioseismic inversions of magnetic regions.
- Provides synthetic data for analysis of observations from 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 192 Mm width.**