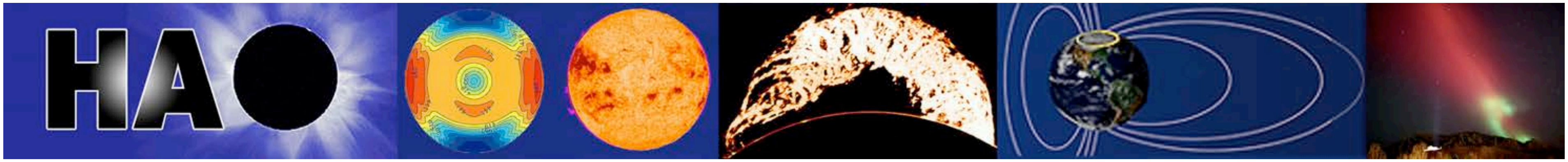

# Magneto-Convection, the Small-scale and the Large-Scale Dynamo

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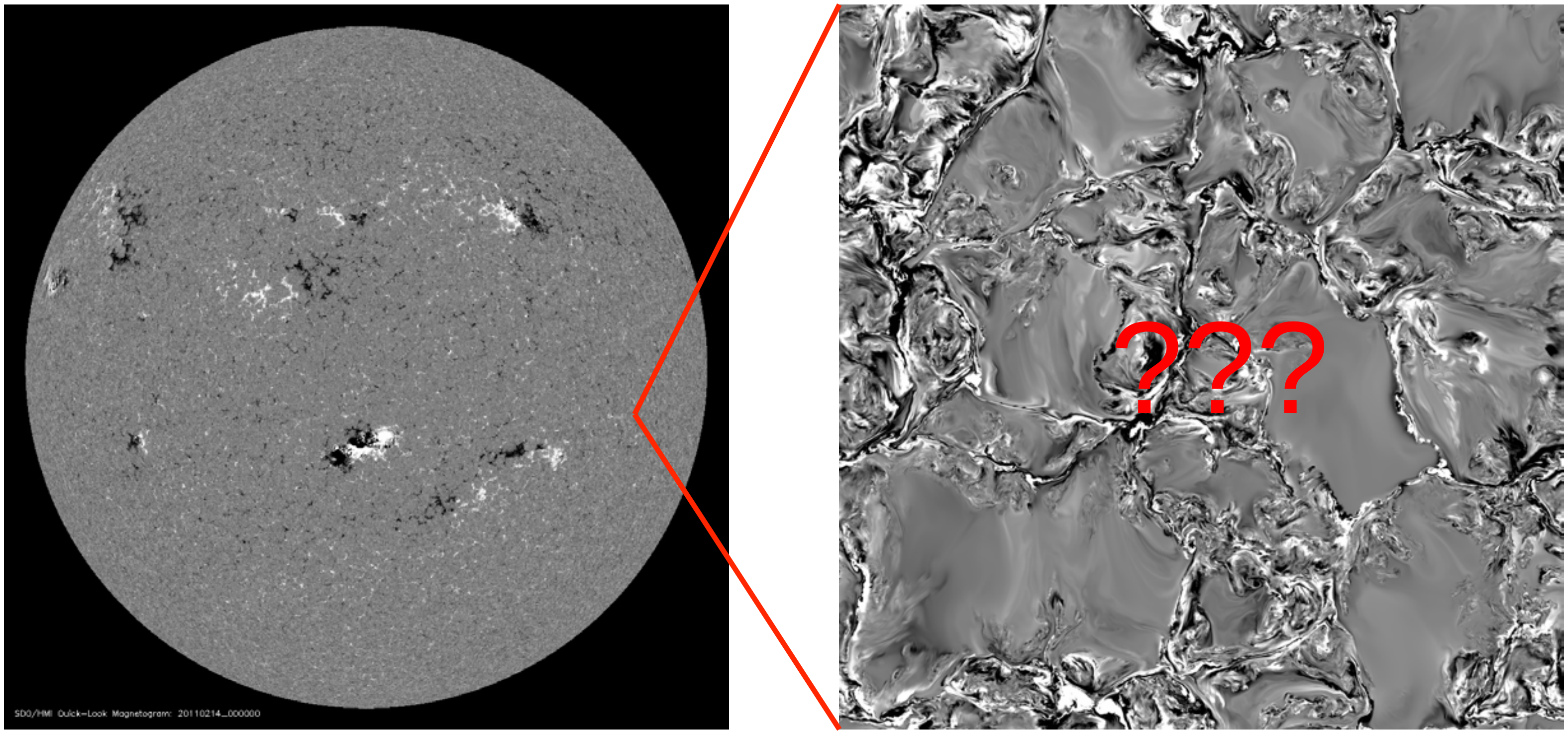
# Outline

- Quiet Sun Magnetism and the role of a small scale dynamo
  - What is a small-scale dynamo?
  - What are the challenges?
  - Recent progress
- Implications for the upper solar atmosphere
  - Horizontal field in upper photosphere
  - Upward Poynting flux, heating of the upper atmosphere
- Implications for the deep convection zone
  - Dynamical feedback from small scale field on convection

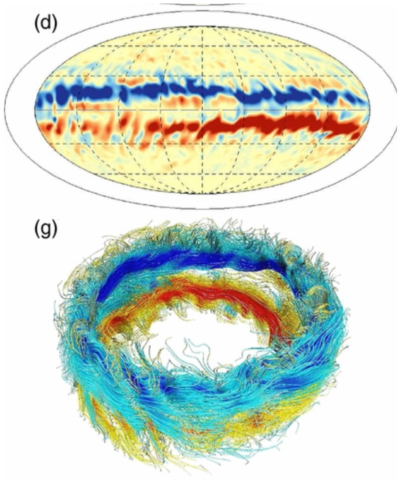
# Quiet Sun magnetism



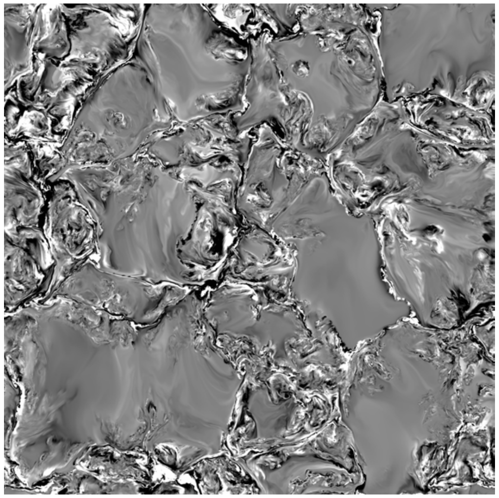
- Most of the solar surface is covered by “quiet Sun” at any time of the sunspot cycle
- Unsigned flux at τ=1 is a few times $10^{24}$ Mx, i.e. comparable to the flux emerging in form of active regions throughout the cycle
- Where does this field come from and what does it tell us about the solar dynamo(s)?

# What is a small-scale dynamo?

- Large-scale dynamo
  - Maintains a “meanfield” on scales larger than the energy carrying scale of convection
  - Requires rotation and large-scale shear
  - Operates on an “intermediate” time scale (shorter than diffusive, longer than time scales of turbulence)
- Small-scale dynamo
  - No “meanfield”, maintains a mixed polarity magnetic field on scales similar or smaller than the energy carrying scale of convection
  - Does not require rotation or large-scale shear
  - Lives from the chaotic nature of convective flows
  - Operates on a short time scale (during kinematic phase near fastest eddy turnover time scale of the system)
- In most astrophysical systems both dynamos co-exist
  - Not trivial to draw a line in-between



Nelson et al 2013



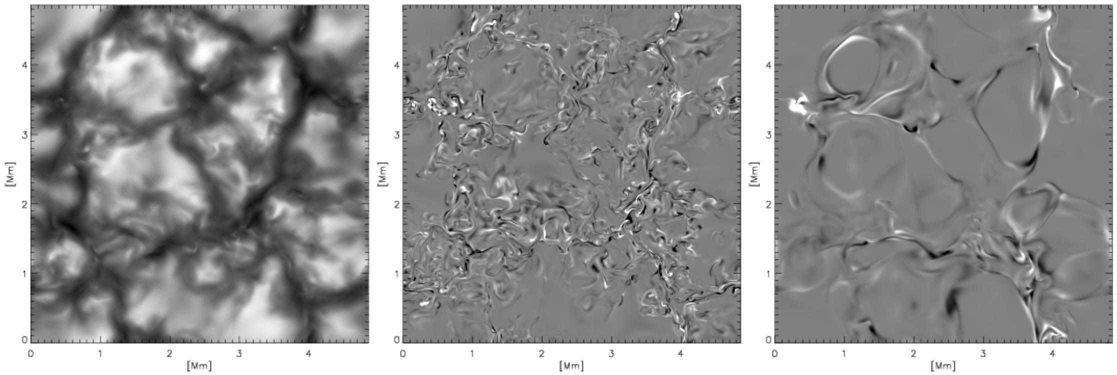
Rempel 2014

# The challenge

- Origin of quiet sun field
  - Small scale dynamo
  - Remnant field from large scale dynamo
- Challenges
  - Low recirculation of mass in upper convection zone (Stein 2003)
    - Raises dynamo threshold, substantial amount of energy loss due to convective transport
    - Network field “stuck” in downflows, little feedback on internetwork field
  - Low magnetic Prandtl number (Pm=viscosity/resistivity)
    - Low Pm implies a “rough” velocity field near resistive scale
    - Kinematic phase:
      - Raises dynamo threshold, can be problem for lab experiments and simulations (only moderate Rm reachable), likely not a problem for astrophysical systems with Rm >> 1 (e.g. Tobias et al 2011)
    - Saturated phase:
      - Controls energy dissipation (almost all energy is dissipated through resistivity for Re>>Rm>>1 regime (Brandenburg 2011, 2014)

# From idealized to “solar-like” dynamos

- Idealized small-scale dynamo simulations:
  - Brandenburg 1996 (compressible), Cattaneo 1999 (Boussinesq), Bercik et al. 2005 (anelastic)
- “Solar-like” small-scale dynamo simulations:
  - Vögler, Schüssler 2007 (compressible + realistic EOS + RT + open bottom)
    - Upper most few Mm of CZ act as dynamo despite small recirculation

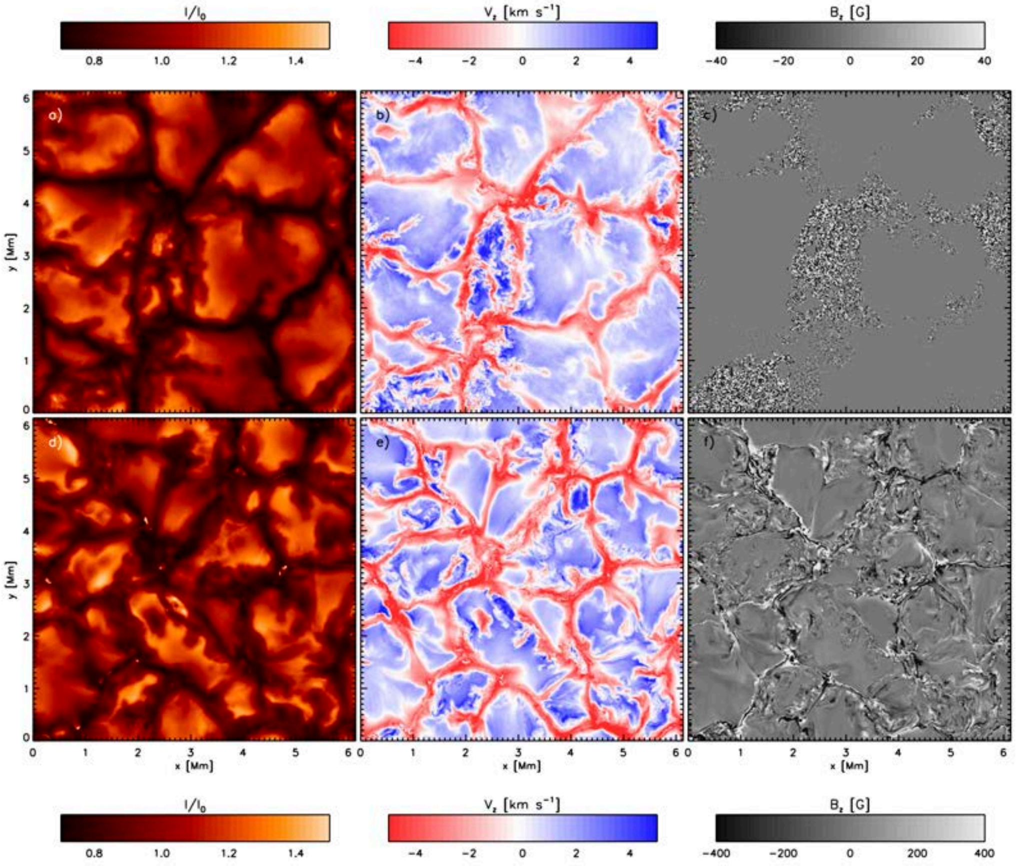


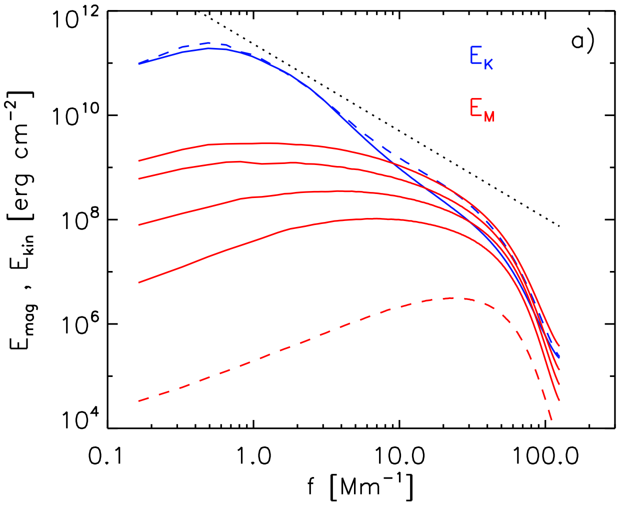
  - Moll et al. (2011)
    - Universal nature of SSD (“solar dynamo” similar to well studied idealized setups)
  - Danilovic et al. (2010)
    - Field strength falls short by a factor of 2-3 compared to Hinode observations

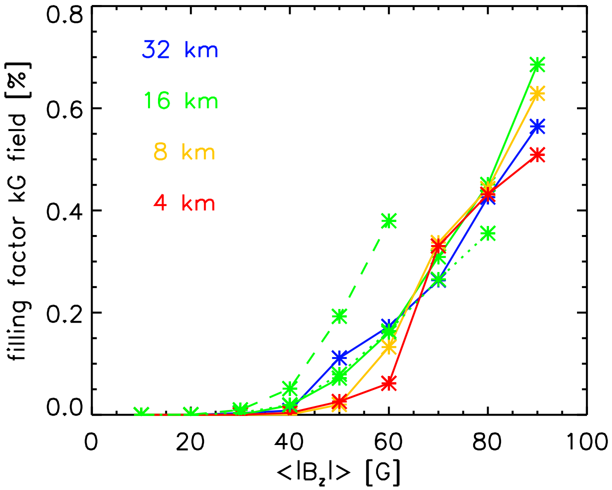
# From idealized to “solar-like” dynamos

- What is required to the reach the observed quiet Sun levels?
  - Rough target (Danilovic 2010)
    - $<|B_z|> \sim 60 \ldots 80$ G, $B_{RMS} \sim 200$ G (tau=1)
- “Degrees of freedom in models”
  - Resolution/Treatment of small scales:
    - Magnetic Reynolds number and dynamo efficiency
  - Boundary conditions:
    - What are the (magnetic) conditions of upflows reaching the photosphere?
    - How strongly is the photosphere coupled to the rest of the convection zone?
    - Vögler, Schüssler 2007 used a “conservative setup”, i.e. no Poynting flux in upflow regions (minimal coupling to rest of CZ)
- Models presented here:
  - Large Eddy Simulations (LES), only numerical diffusivities
  - Less “conservative” bottom boundary conditions

# Kinematic regime to saturation

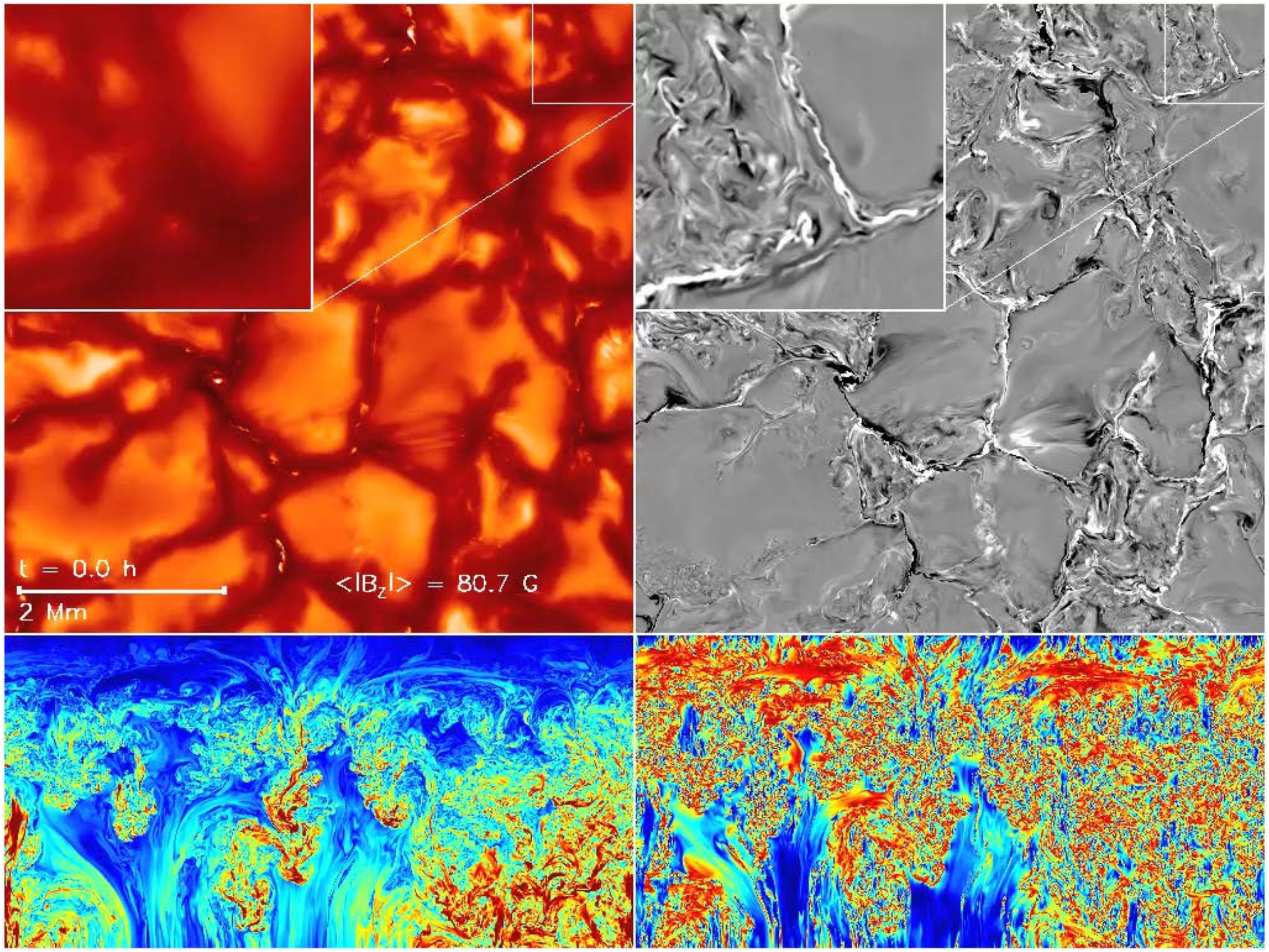






- Magnetic field organization changes dramatically during saturation
  - Non-linear saturation begins for $<|B_z|>\sim 10$ G in photosphere
  - Sheet like appearance instead of “salt and pepper”
  - Peak of magnetic energy near granular scales
  - kG flux concentrations, bright points appear starting from $<|B_z|>\sim 30$ G

# “Saturated” solution <|Bz|>~80G



Intensity

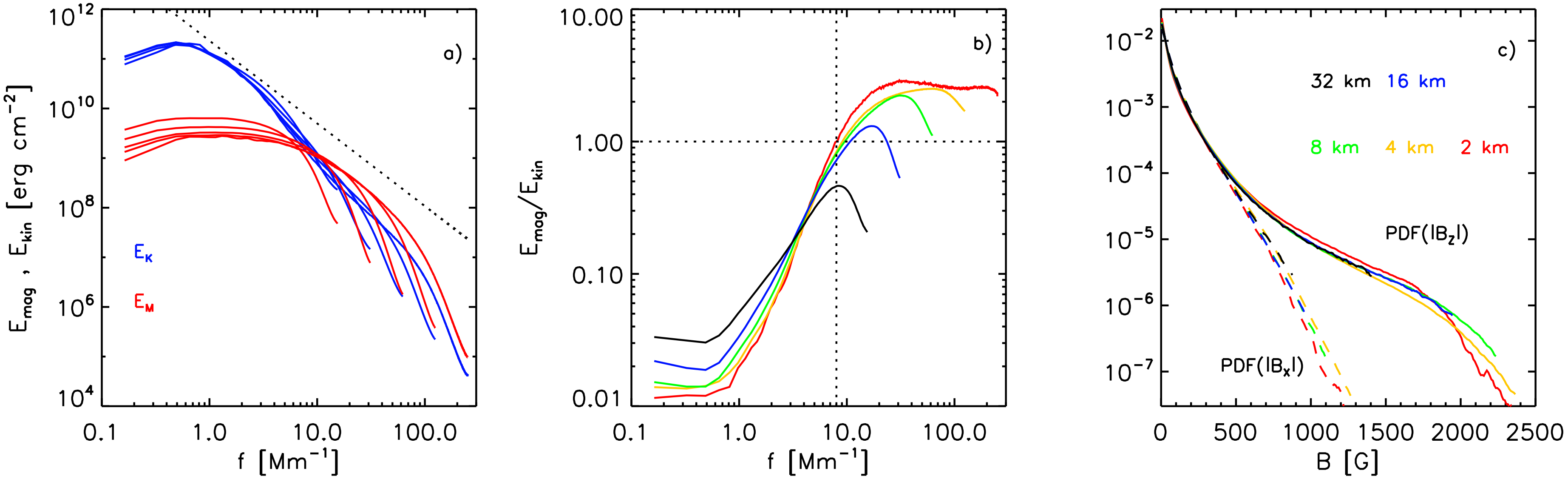
Bz (τ=1)

|B|

Inclination:
horizontal
vertical

Domain: 6.144 x 6.144 x 3.072 Mm$^3$, 4km resolution

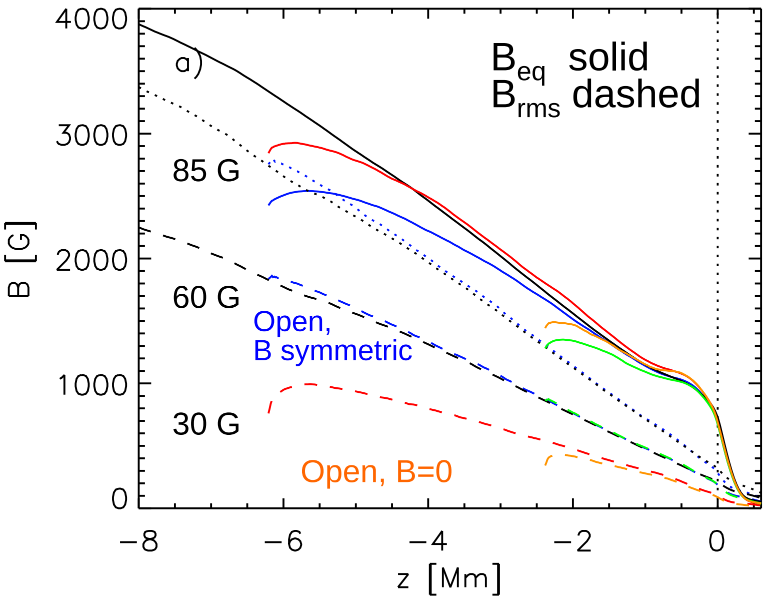
# Resolution dependence 32 ... 2 km

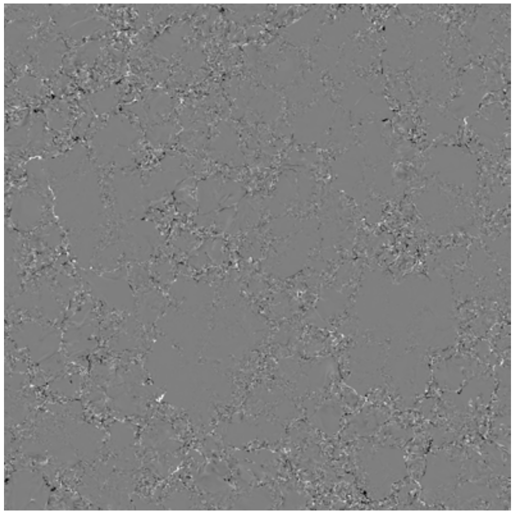


- Converged results using LES approach
  - No explicit viscosity or magnetic resistivity
  - Changing resolution by a factor of 16!
  - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
  - Implicit magnetic Prandtl number ~1
  - Sun (photosphere): $P_m$~$10^{-5}$
- Need either high resolution DNS or high resolution observations to confirm

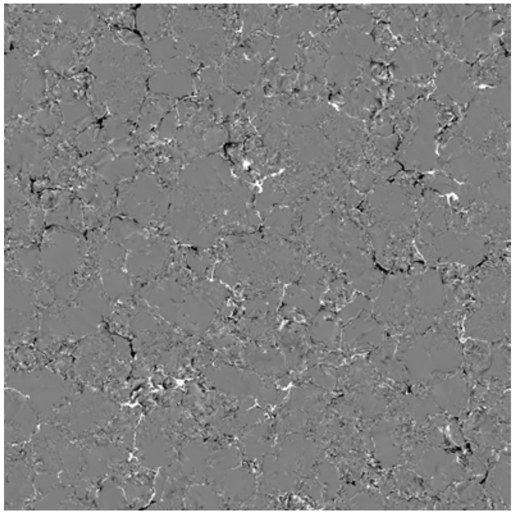
# Role of bottom boundary condition

- Bottom boundary sets overall field strength reached in the photosphere in the range
  - $\langle|B_z|\rangle \sim 30 - 85$ G
- Lower bound:
  - B=0 in inflow regions, or vertical field boundary condition
  - Saturates around $\langle|B_z|\rangle \sim 30$ G in photosphere
- “Upper” bound (85 G):
  - $B_{rms}$ increases at same rate as $B_{eq}$
- Bottom boundary matters!
  - Photosphere strongly coupled to rest of CZ!
  - We cannot determine the saturation level of the quiet sun without knowing what the CZ is doing!
  - The observed quiet Sun field strength implies a CZ magnetized close to equipartition!



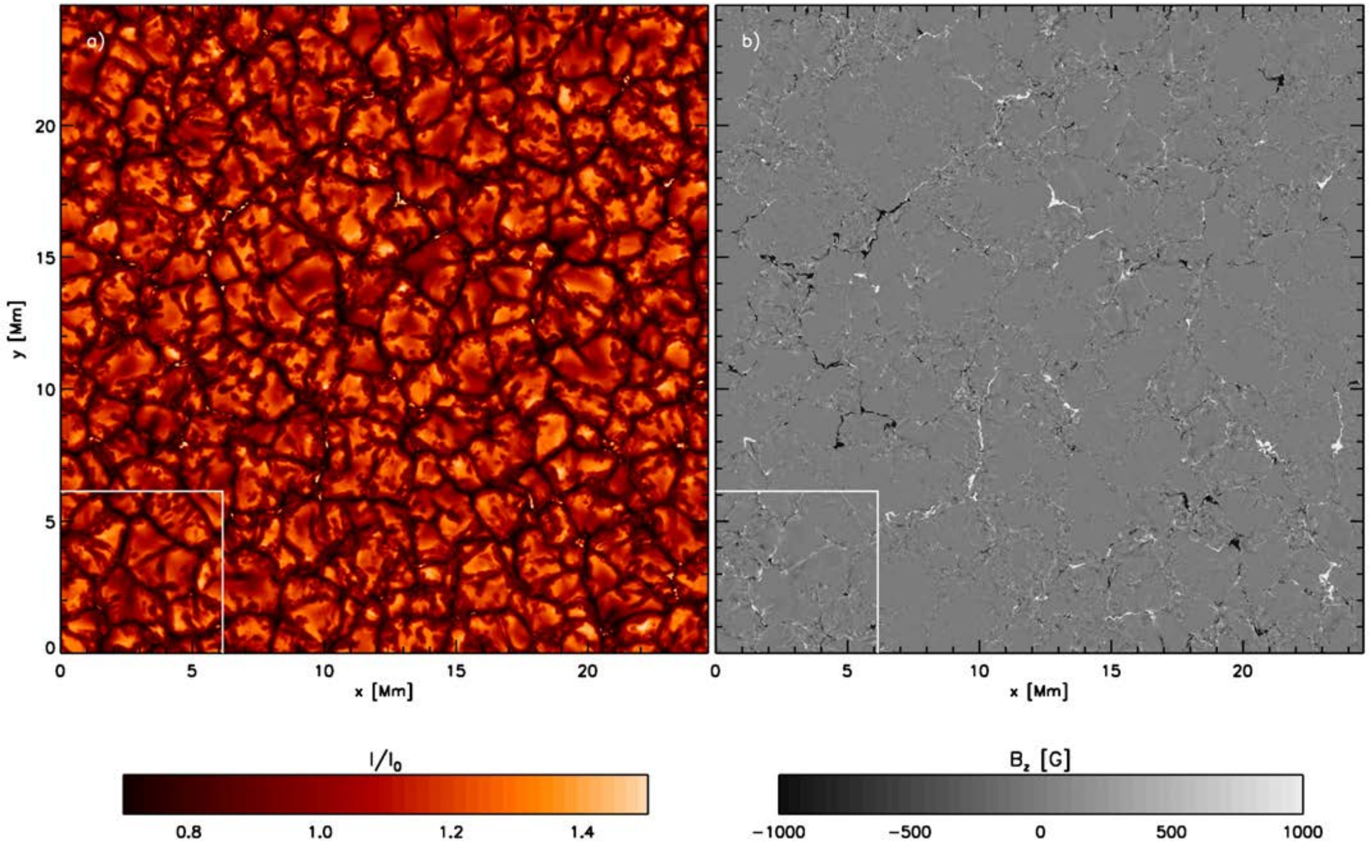


30 G



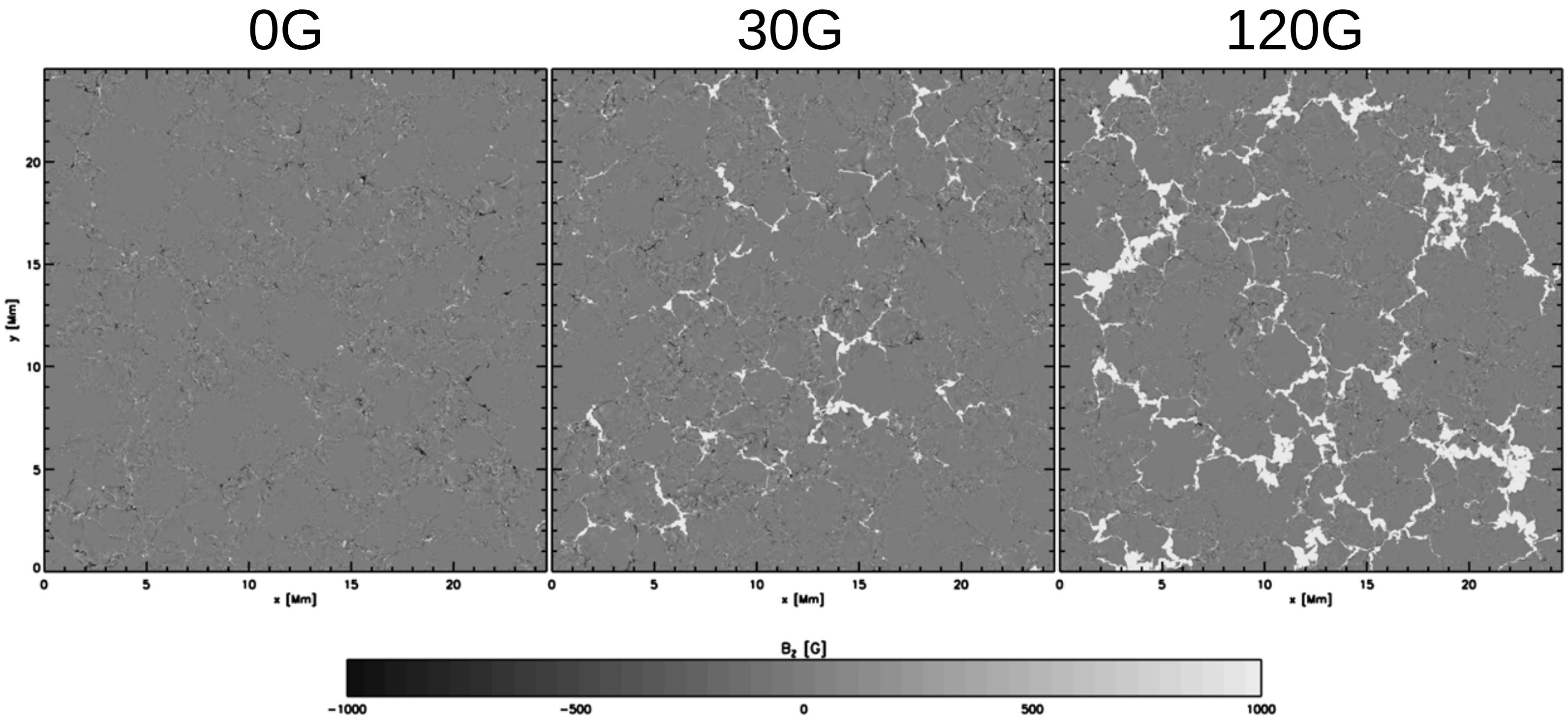
60 G

# Meso-granular scales



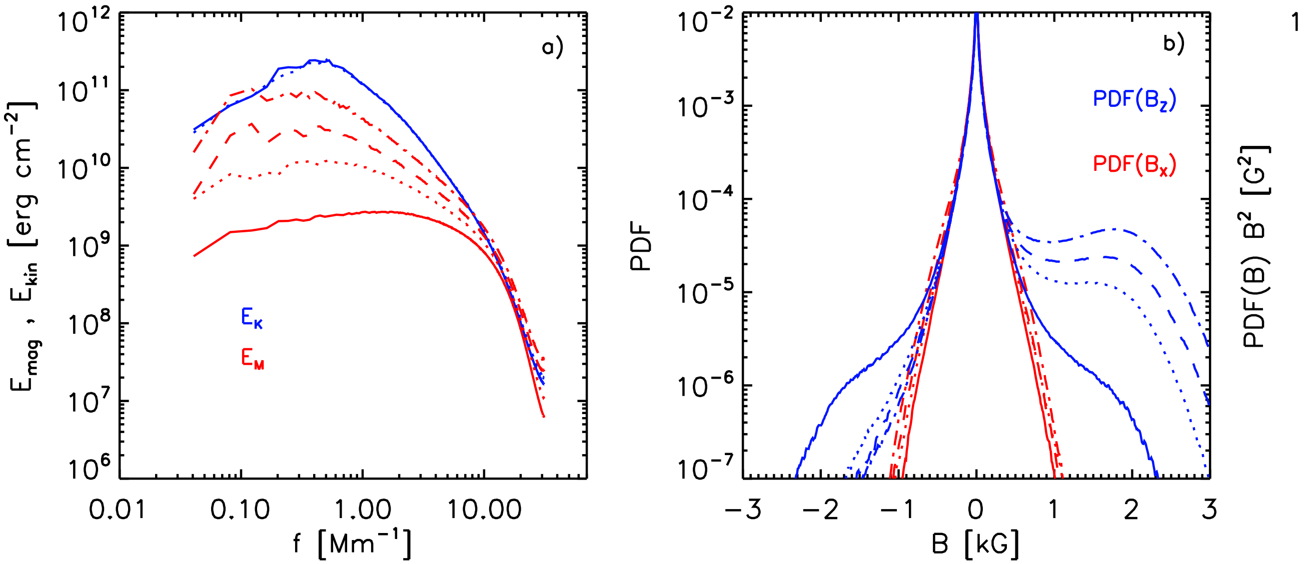
- Small-scale dynamo operating in a highly stratified domain
  - Dynamo operates over a wide range of scales at different depth, coupled through vertical transport
  - Can organize magnetic field on scales larger than granulation
  - Can lead to significant local flux imbalance

# Potential contribution from active region decay



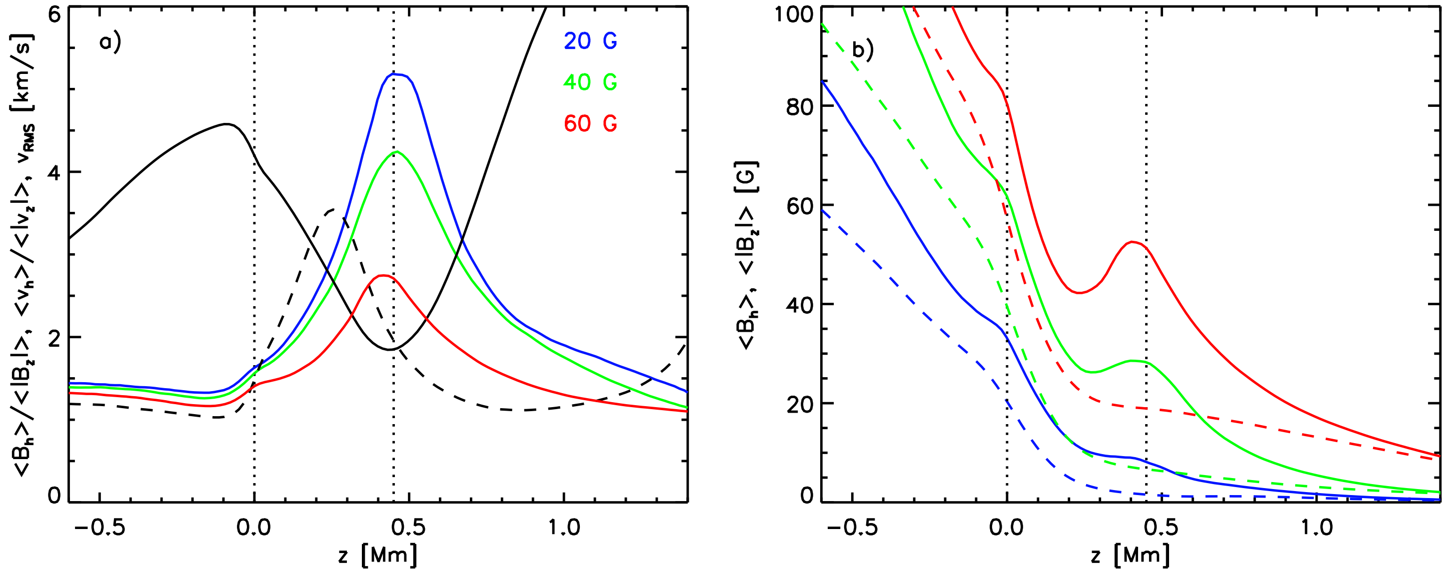
- Small scale dynamo + added net flux
  - 0G, 30G, 60G, 120G
  - Magnetic “network” on meso-granular scales

# Potential contribution from active region decay



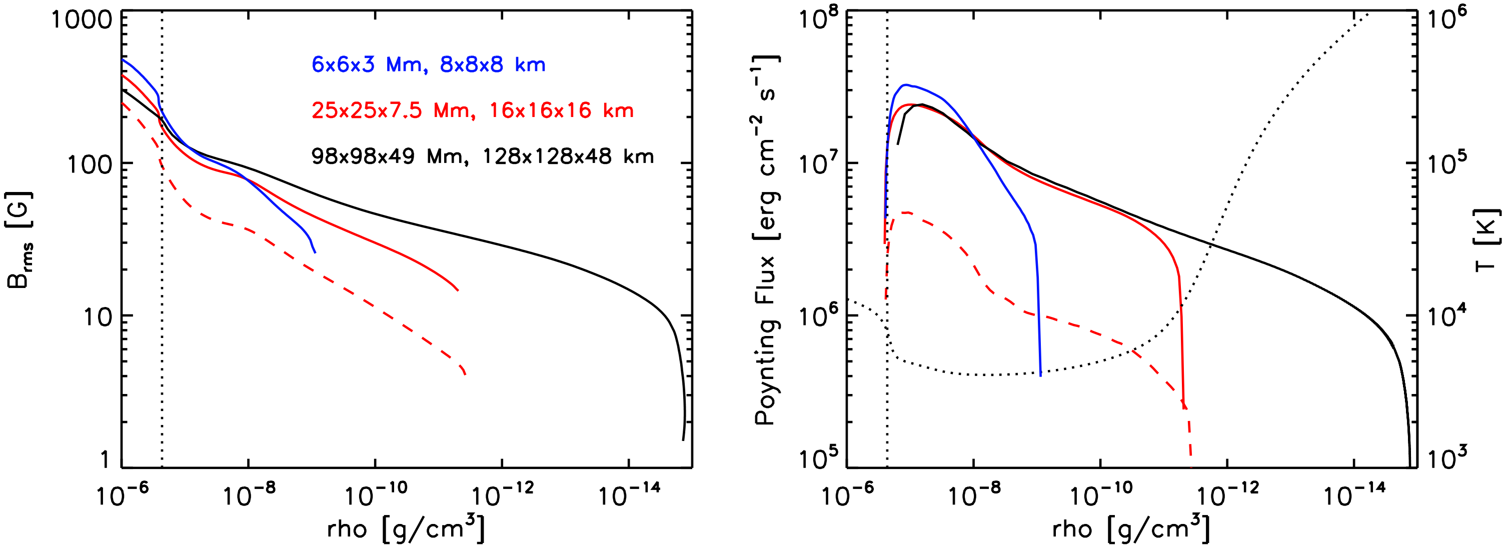
- Most of the additional energy on large scales
- No significant change of PDFs for B<500 G
- Strong network at 2 kG, suppression of kG opposite polarity flux
- Only weak overall increase in horizontal field strength
  - Small recirculation in the top few Mm of the CZ prevents network field from influencing the internetwork regions
- Indication from observations
  - Lites 2011 (only weak dependence of QS on netflux imbalance)
  - Buehler 2013 (no cycle variation)
  - Lamb 2014 (network field does not influence statistical properties of internetwork field)

# Magnetic field inclination in photosphere



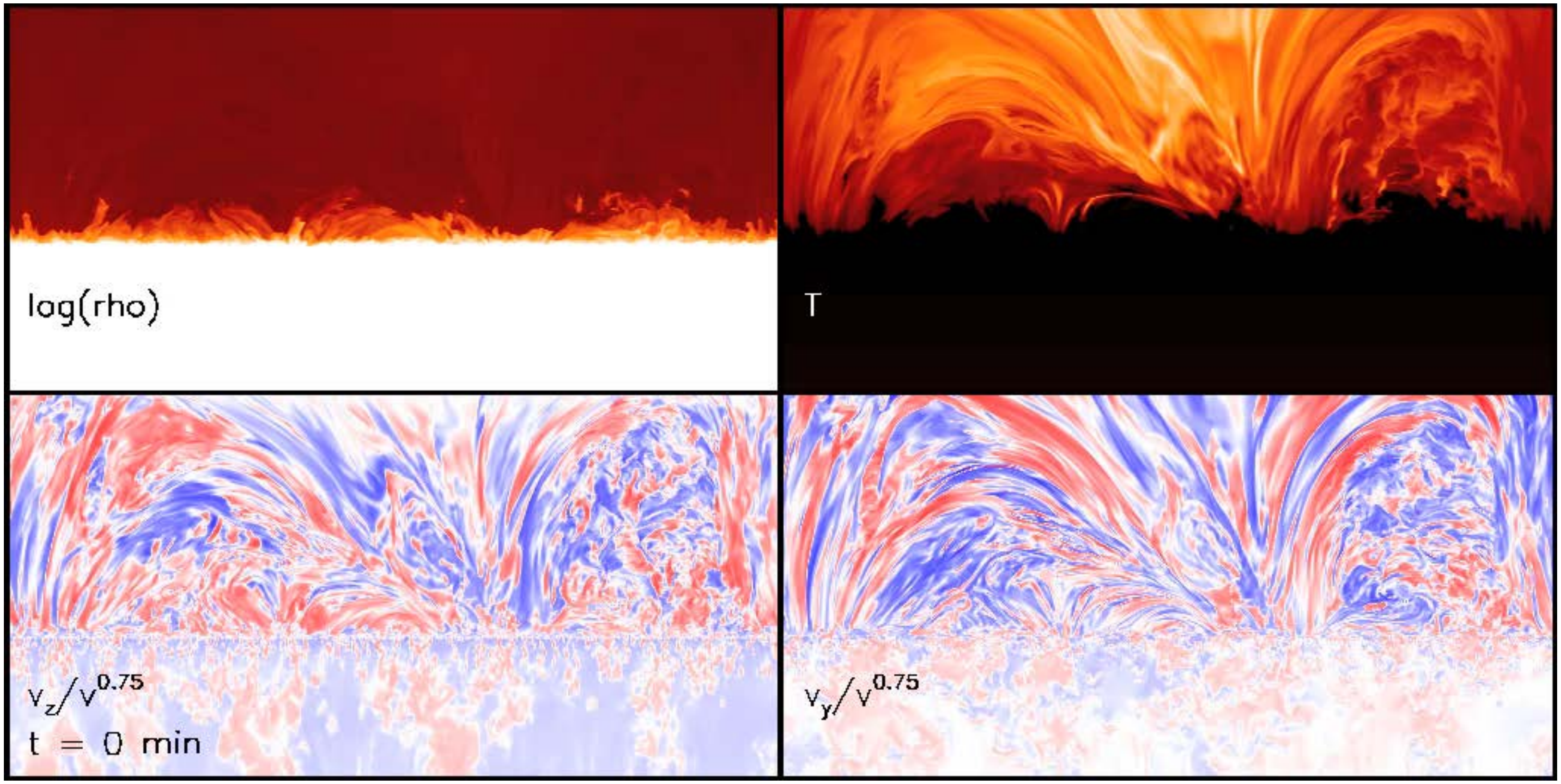
- Horizontal/vertical field ratio peaks ~450 km above tau=1
- Peak value strongly field strength dependent
  - Value of 2-3 expected for observed quiet Sun field strength
  - Hinode observations range from 3 (Orozco Suarez & Bellot Rubio 2012) to 5 (Lites et al 2011)
- Deep photosphere close to an isotropic distribution
  - Found in infrared lines (Martinez Gonzalez et al 2008)
- Peak located in minimum of turbulent RMS velocity

# Poynting flux expected from quiet Sun



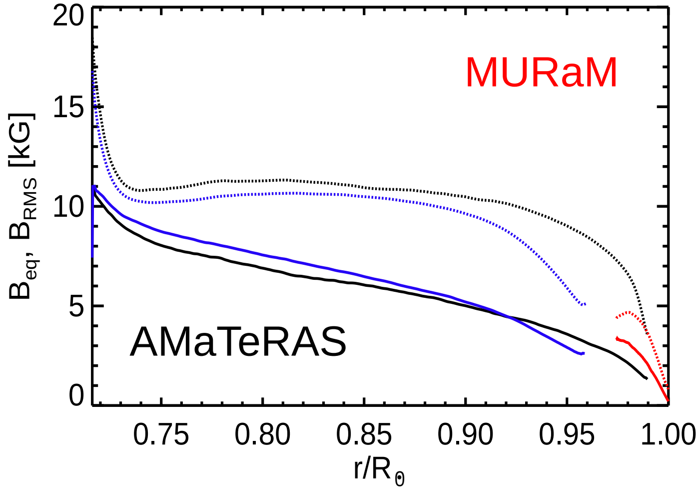
- Poynting flux in (upper) photosphere
  - Around $3\times10^7$ erg cm$^{-2}$ s$^{-1}$
  - Mostly field strength dependent, rather insensitive to numerical resolution (explored 8 to 128 km grid spacing)
  - About $10^6$ erg cm$^{-2}$ s$^{-1}$ reach “base of corona”
    - Can maintain an ~1-2 MK corona
  - Quiet sun models that agree with photospheric observations can also maintain a quiet Sun corona

# Small-scale dynamo with “Corona”

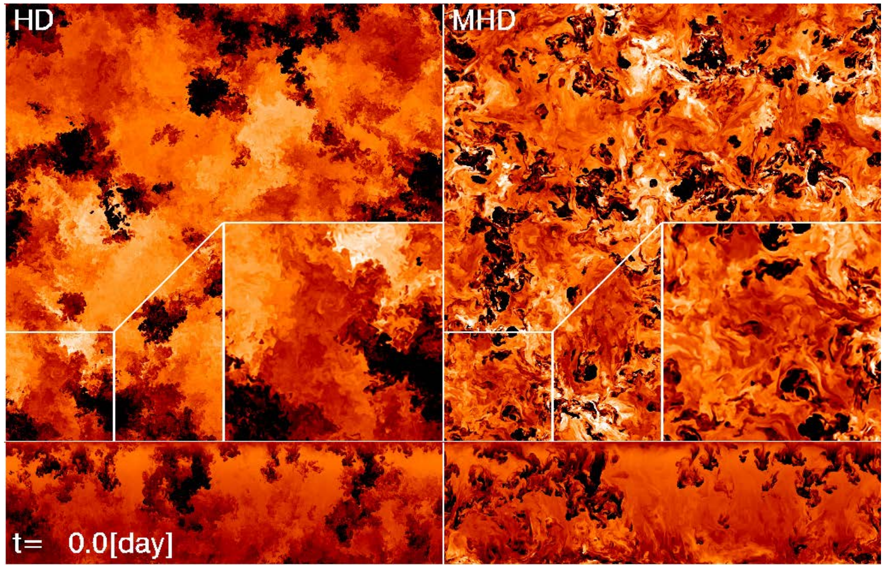


- Domain:
  - 98x98x49 Mm domain, 128x128x48 km resolution
- Lower 18 Mm:
  - SSD maintaining field + source of upward Poynting flux above photosphere
- Upper 31 Mm:
  - Balance between “magnetic heating”, heat conduction, optically thin radition loss

# Implications for the convection zone



Hotta et al. 2014



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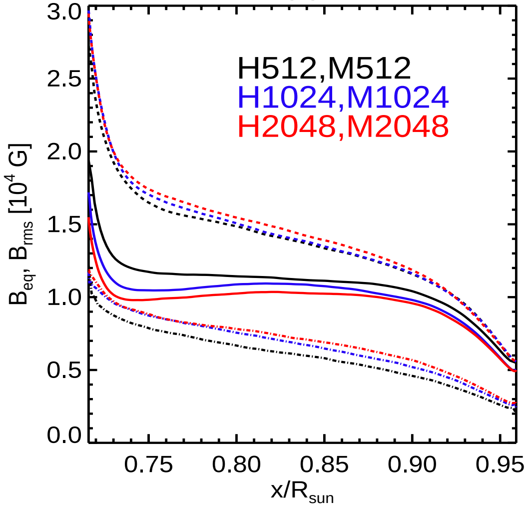

- SSD simulations in CZ (up 0.99 R) consistent with photospheric setups
  - Reach values ~ equiparition
- Dynamical feedback on convection:
  - Reduction of convective velocities by up to a factor of 2 near baseof CZ
  - Reduction of horizontal entropy mixing
  - More narrow and cooler downflow plumes
  - Somewhat similar to high thermal Prandtl number convection, i.e. the Maxwell stress mimics viscous stresses

# Summary

- Small-scale dynamo restricted to photosphere is not enough
  - Would saturate at about half the observed field strength
- Need dynamo action throughout CZ over a wide range of scales
  - Small-scale and large-scale dynamo are likely inherently coupled
  - Magnetic field shows organization over a wide range of scales
  - Local field generation and non-local transport from deeper layers are of equal importance
- Quiet Sun convection zone has to be magnetized close to equipartition
  - Observed quiet Sun field is the “tip of the iceberg” of a rather strong (dynamically relevant) field throughout the convection zone
- Photospheric quiet Sun field can be modulated in strength by 2 processes:
  - Flux imbalance from active region decay: minor effect, mostly influences network
  - Convective Poynting flux in upflow regions: strong (up to a factor of 2) effect
- Quiet Sun produces enough Poynting flux to heat the upper atmosphere
- Many of these findings are numerically very robust!
  - Changing grid spacing by a factor of 8-16 does not change the outcome!
  - Numerical robustness does not imply correctness, results can be systematically wrong! Need observations over a wide range of length- and time-scales to tell us!