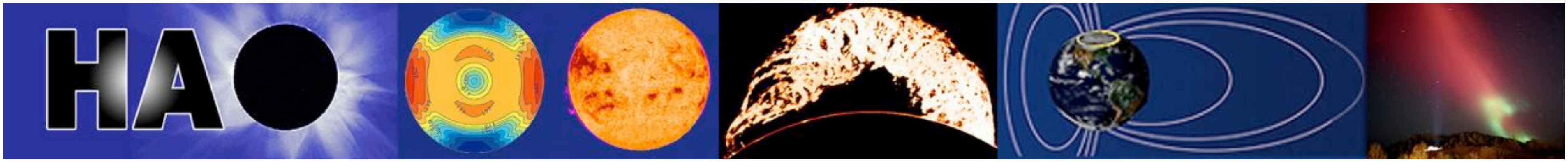

Quiet Sun magnetism

What does it tell us about small-scale dynamos and their contribution to solar activity?

Matthias Rempel, Hideyuki Hotta

HAO/NCAR

NCAR

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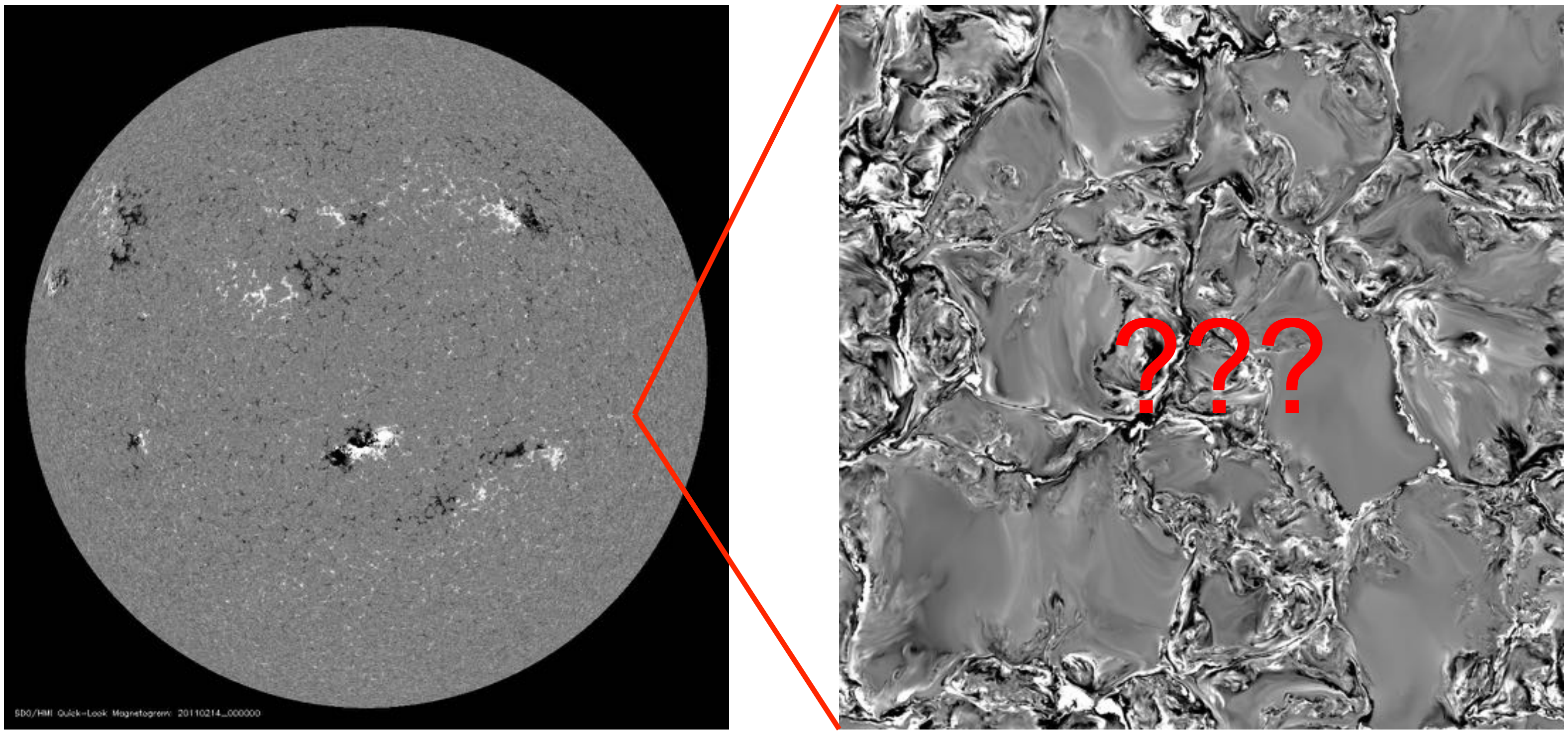
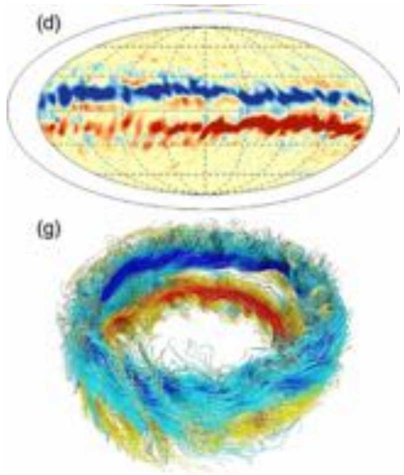
Quiet Sun magnetism



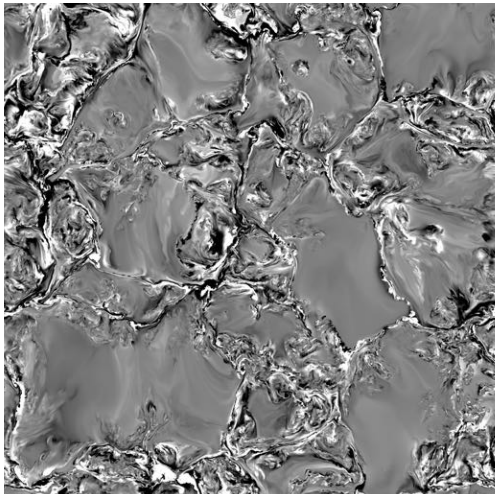
- Most of the solar surface is covered by “quiet Sun” at any time of the sunspot cycle
- Unsigned flux at $\tau=1$ is a few times 10^{24} Mx, i.e. comparable to the flux emerging in form of active regions throughout the cycle
- Where does this field come from and what does it tell us about the solar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



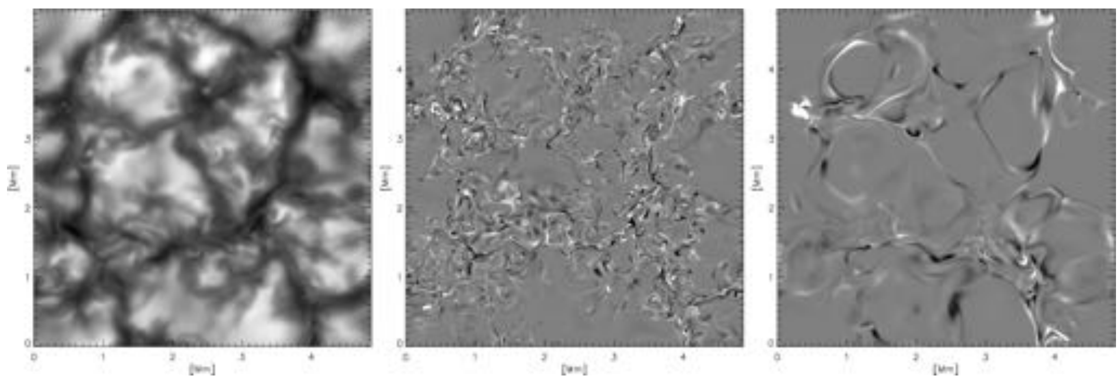
Rempel 2014

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



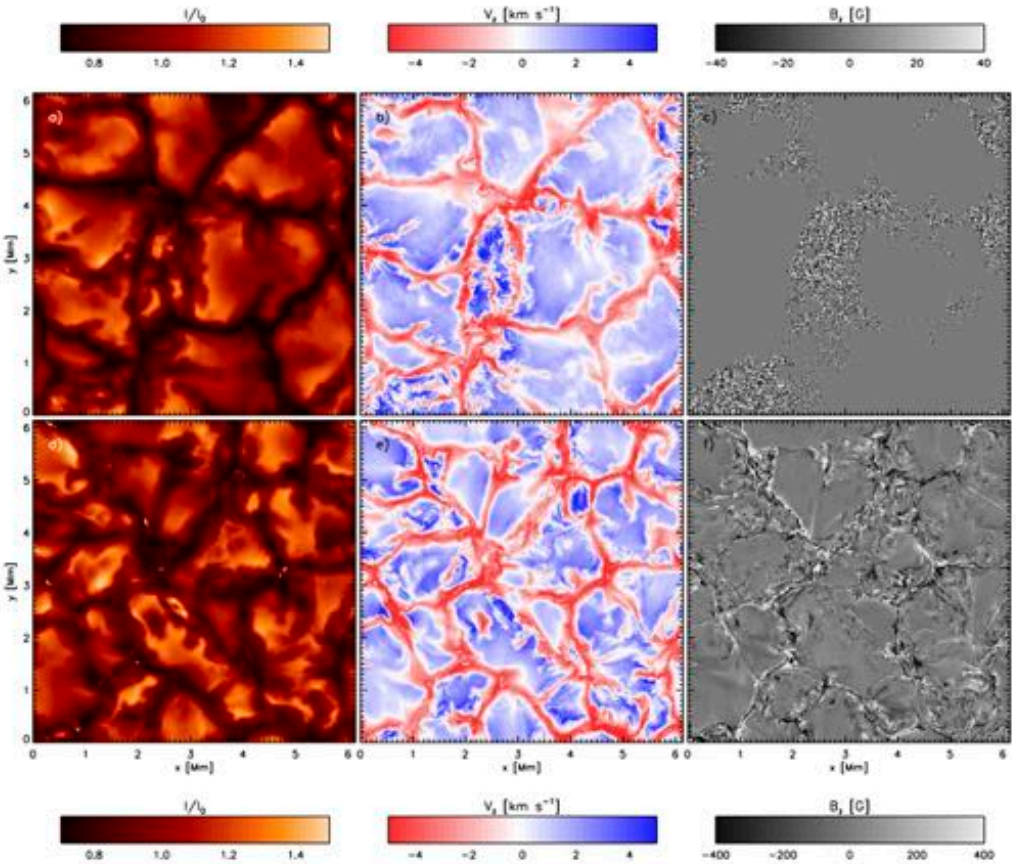
  - Moll et al. (2011)
    - Universal nature of SSD (“solar dynamo” similar to well studied idealized setups)
  - Danilovic et al. (2010)
    - Field strength falls short by a factor of 2-3 compared to Hinode observations

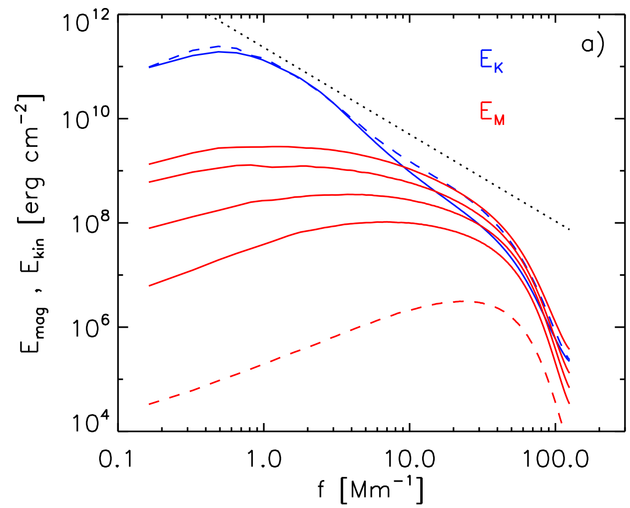
From idealized to “solar-like” dynamos

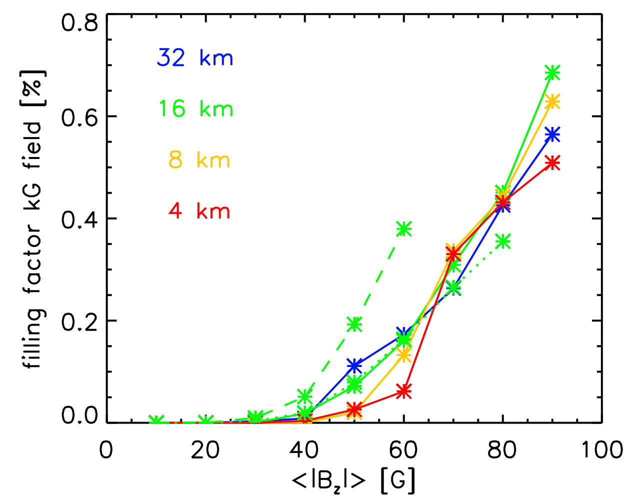
- What is required to the reach the observed quiet Sun levels?
  - Zeeman Stokes V (Danilovic 2010, 2014 priv. comm.)
    - $\langle|B_z|\rangle \sim 60$ G, $B_{RMS} \sim 170$ G (tau=1)
    - $\langle|B_z|\rangle \sim 20$ G, $B_{RMS} \sim 80$ G (tau=0.01)
  - Hanle effect (Trujillo Bueno et al. 2004, Shchukina, N., & Trujillo Bueno 2011)
    - B ~ 60 G (single value distribution), B ~ 130 G (exponential distribution)

- “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

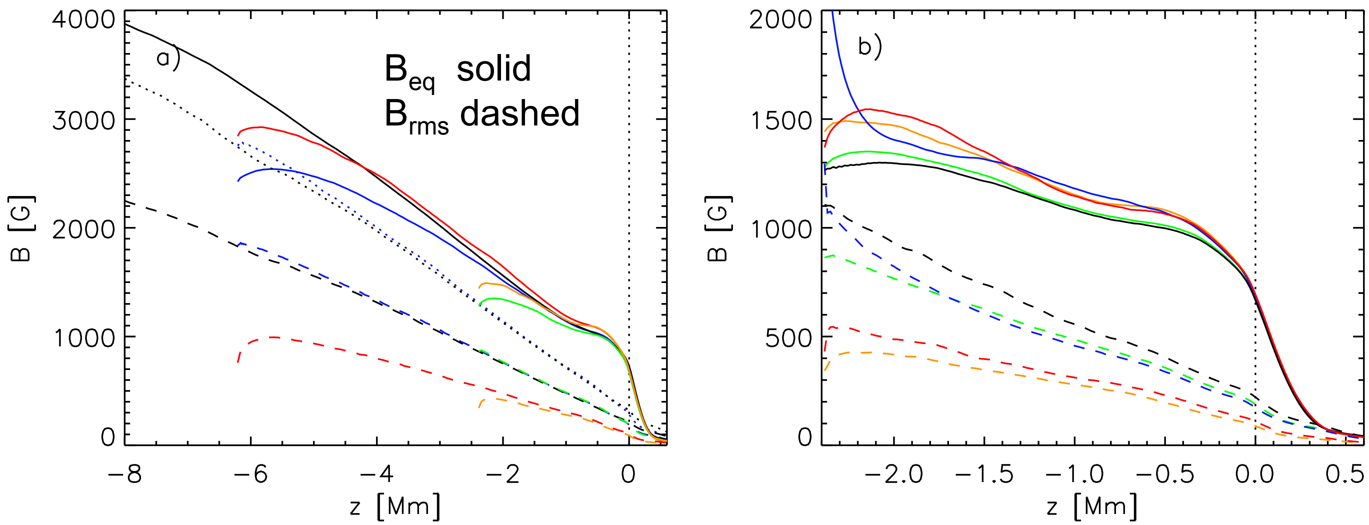






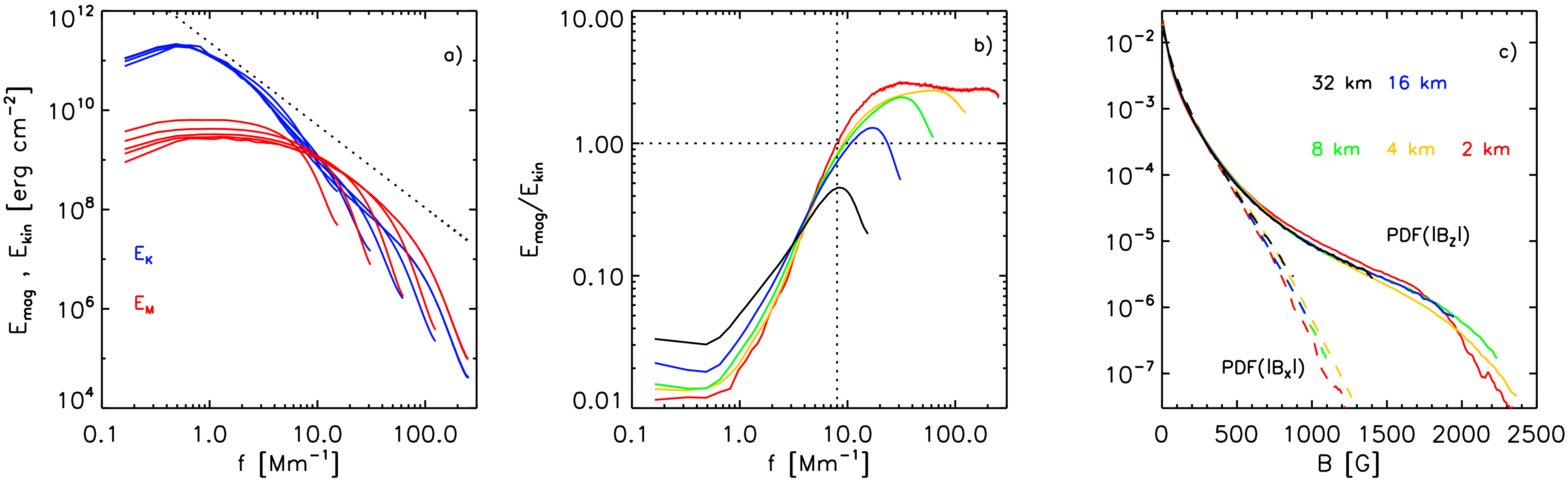
- Magnetic field organization changes dramatically during saturation
  - Non-linear saturation begins for $<|B_z|>\sim 10$ G in photosphere
  - Sheet like appearance instead of “salt and pepper”
  - Peak of magnetic energy near granular scales
  - kG flux concentrations, bright points appear starting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

Role of bottom boundary condition



- Bottom boundary sets overall field strength reached in the photosphere in the range
  - <|B$_z$|> ~ 30 – 85 G
- “Lower” bound (30 G):
  - B=0 in inflow regions, or vertical field boundary condition
  - Dynamo lives from local recirculation due to turbulent upflow/downflow mixing
  - Stronger field requires full recirculation (i.e. closed bottom boundary condition)
- “Upper” bound (85 G):
  - B_{rms} increases at same rate as B_{eq}

Resolution dependence 32 … 2 km

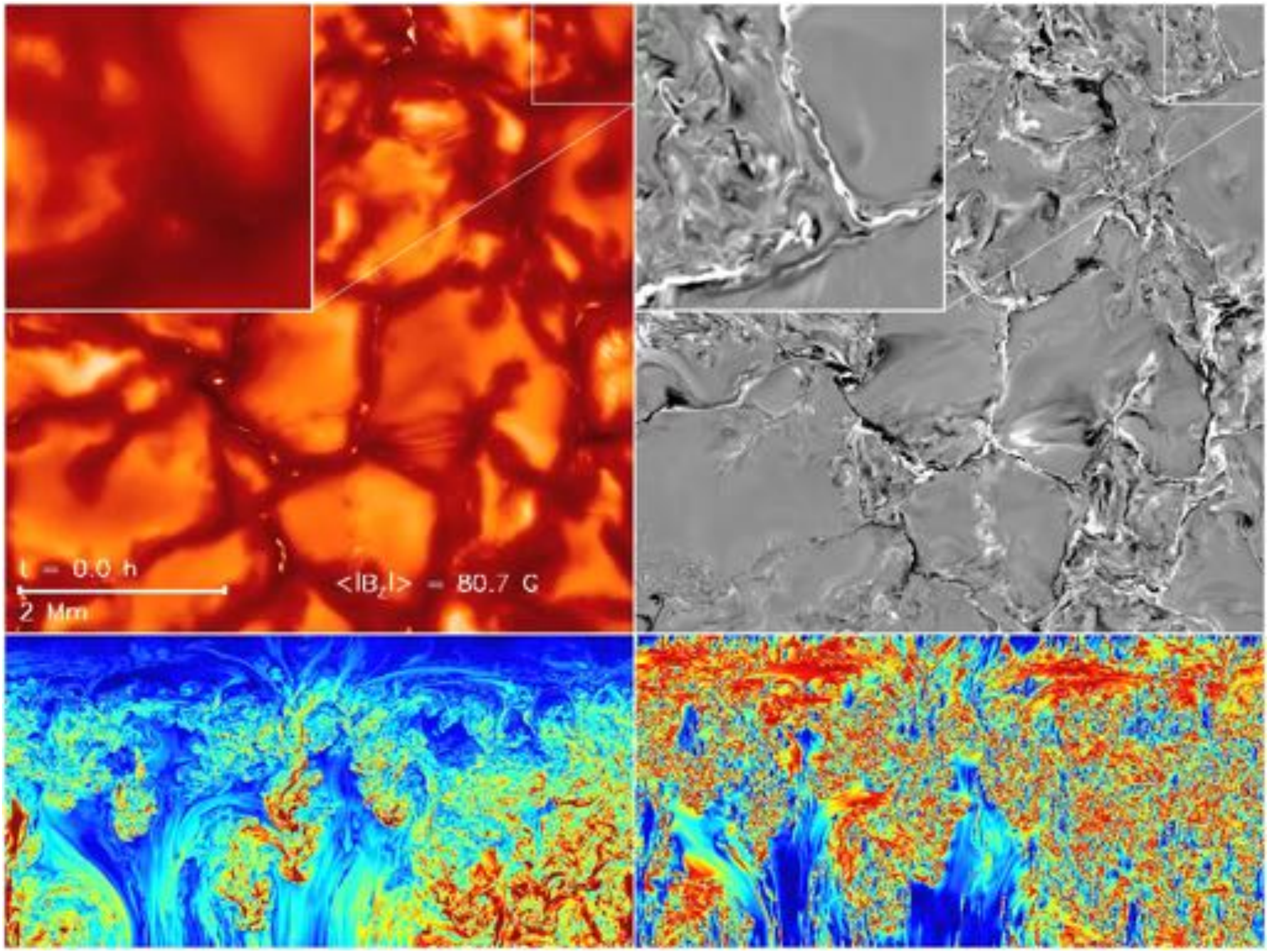


- Converged results using LES approach
  - No explicit viscosity or magnetic resistivity
  - Changing resolution by a factor of 16!
  - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
  - Implicit magnetic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

“Saturated” solution <|Bz|>~80G

Intensity

Bz (τ=1)

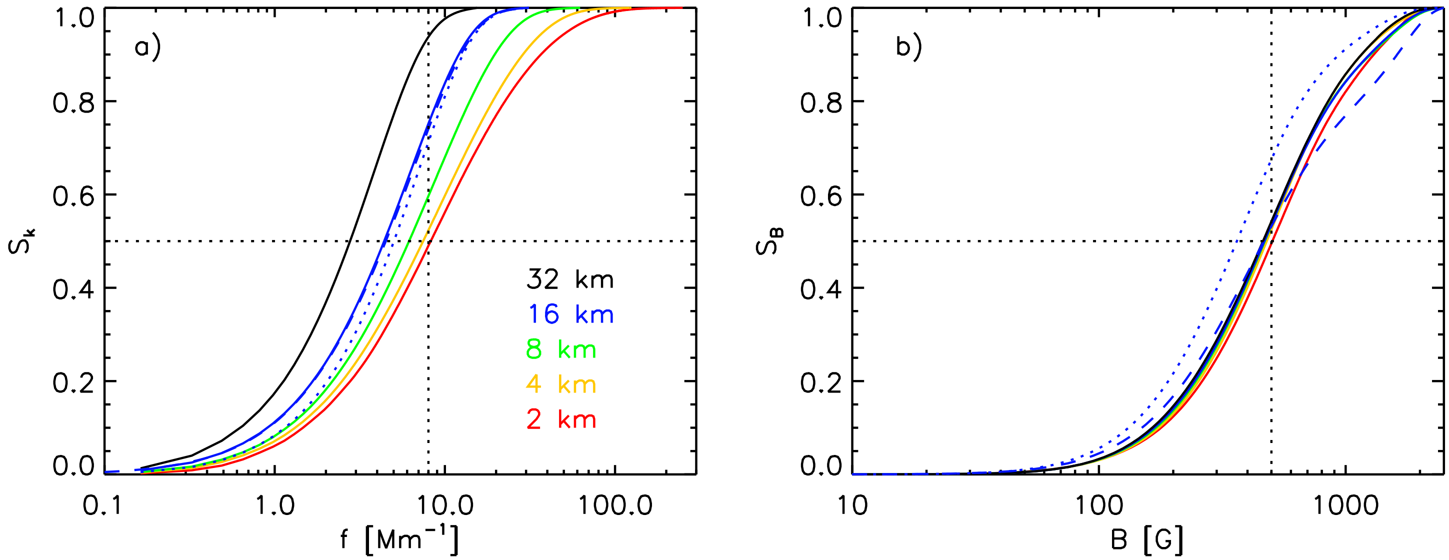


|B|

Inclination:
horizontal
vertical

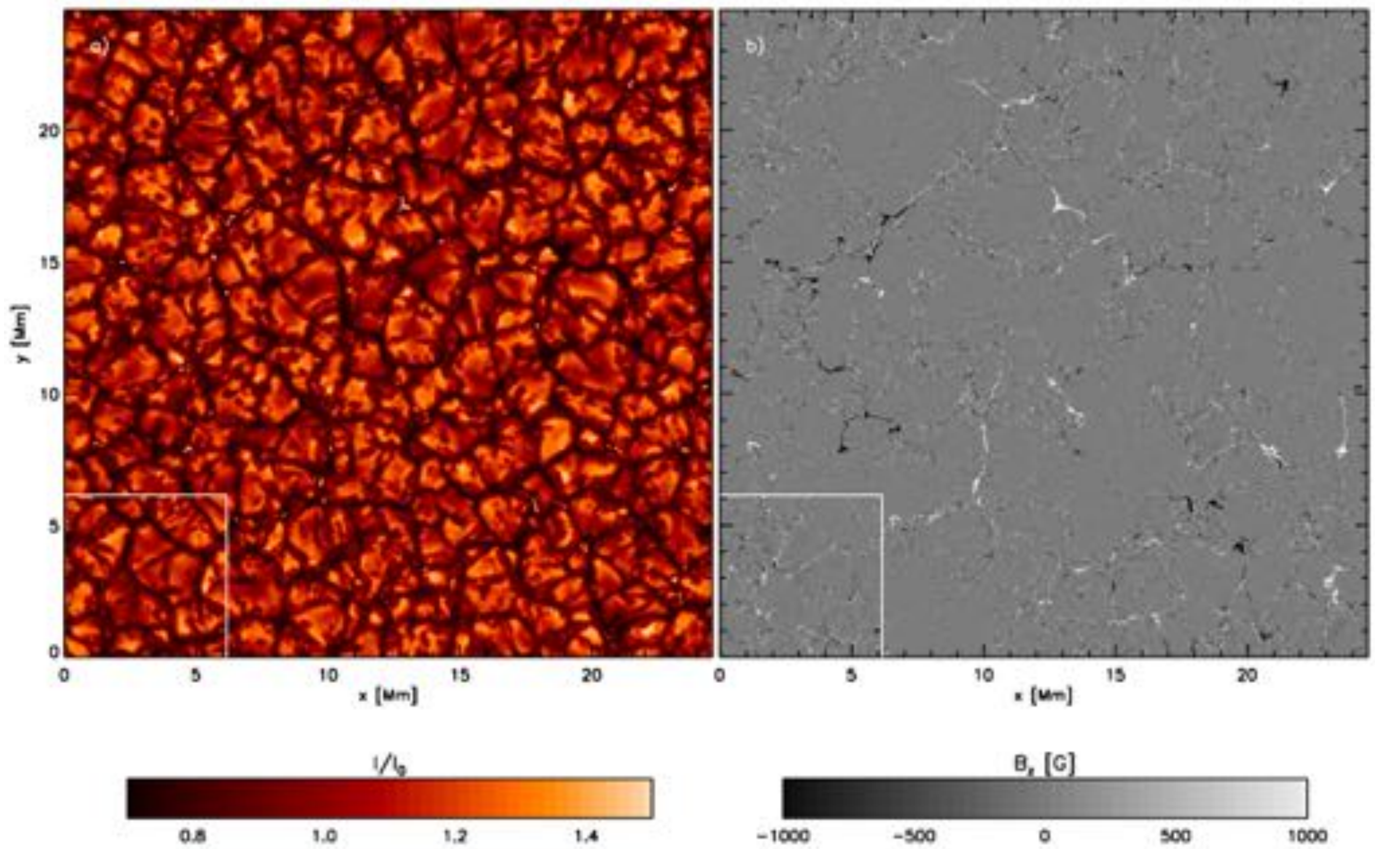
Domain: 6.144 x 6.144 x 3.072 Mm^3, 4km resolution

Energy distribution in photosphere



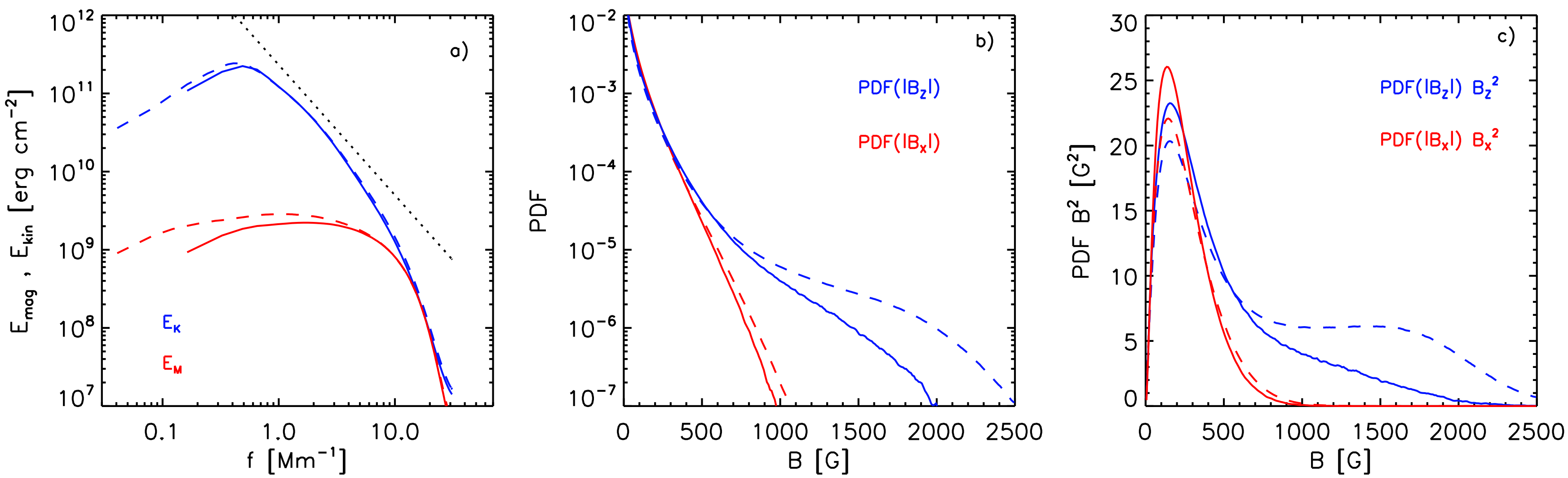
- ~50% of energy on scales smaller than 100 km
  - Need small (~8 km or smaller) grid spacing for properly resolving the spectral energy distribution
  - Hinode “sees” about 20% of the magnetic energy, DKIST could see more than 90%
- ~50% of energy from field weaker than 500 G
  - No resolution dependence, but domain size and overall field strength matters

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

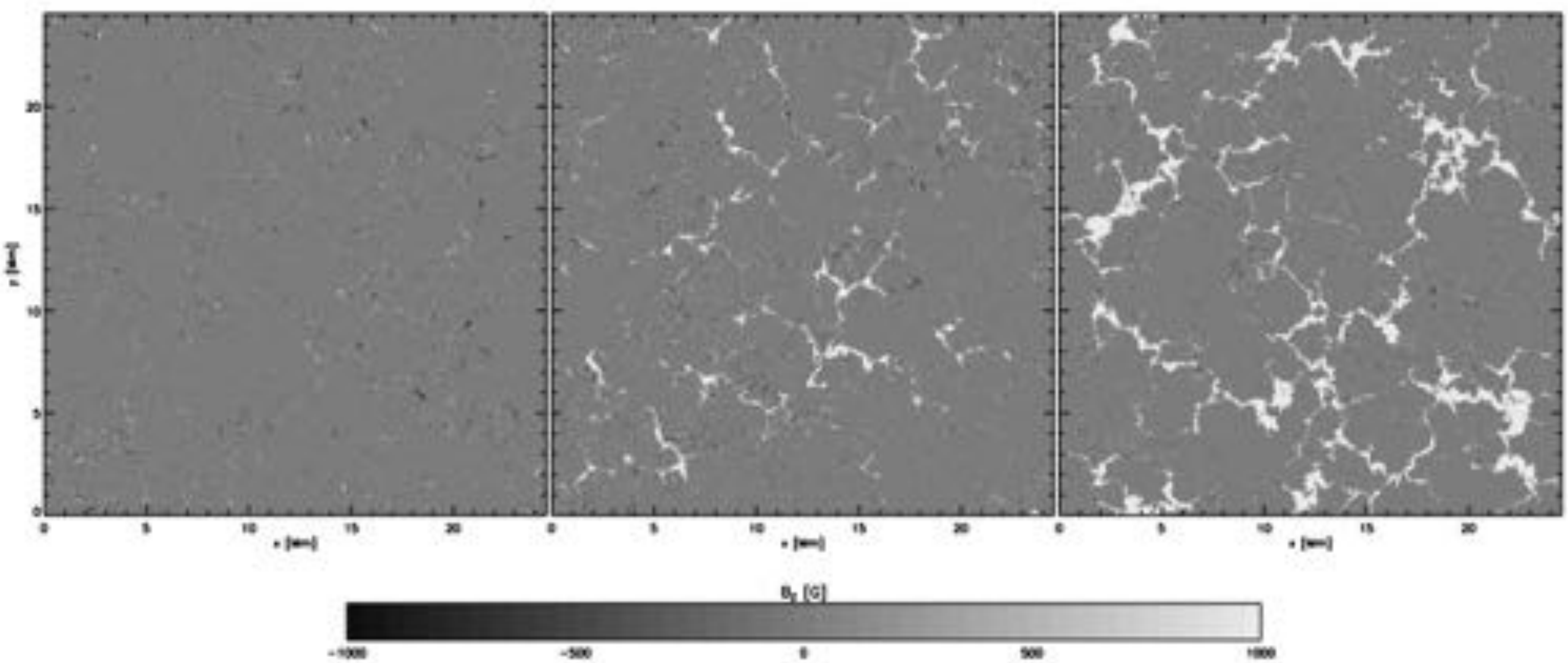
Meso-granular scales



- Increase of domain size leads to
  - Increase of magnetic power on large scale
  - Indication of a flat magnetic power spectrum on scales larger than granulation
  - Increase of kG field fraction, but no indication of a secondary peak in PDF (requires > 30 G flux imbalance)

Potential contribution from active region decay

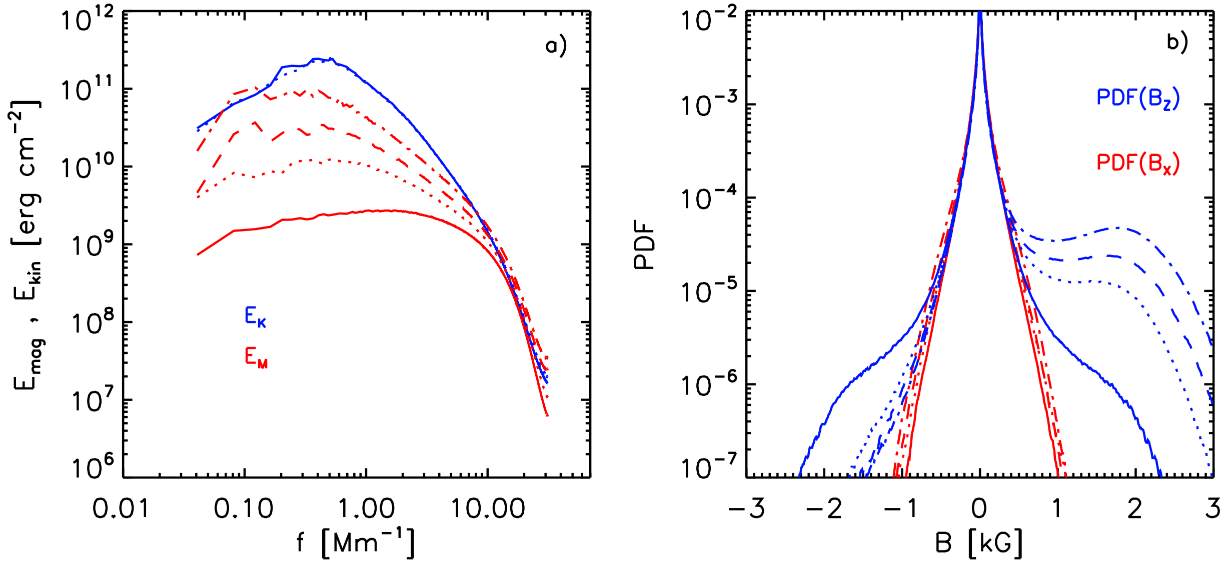
0G 30G 120G



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

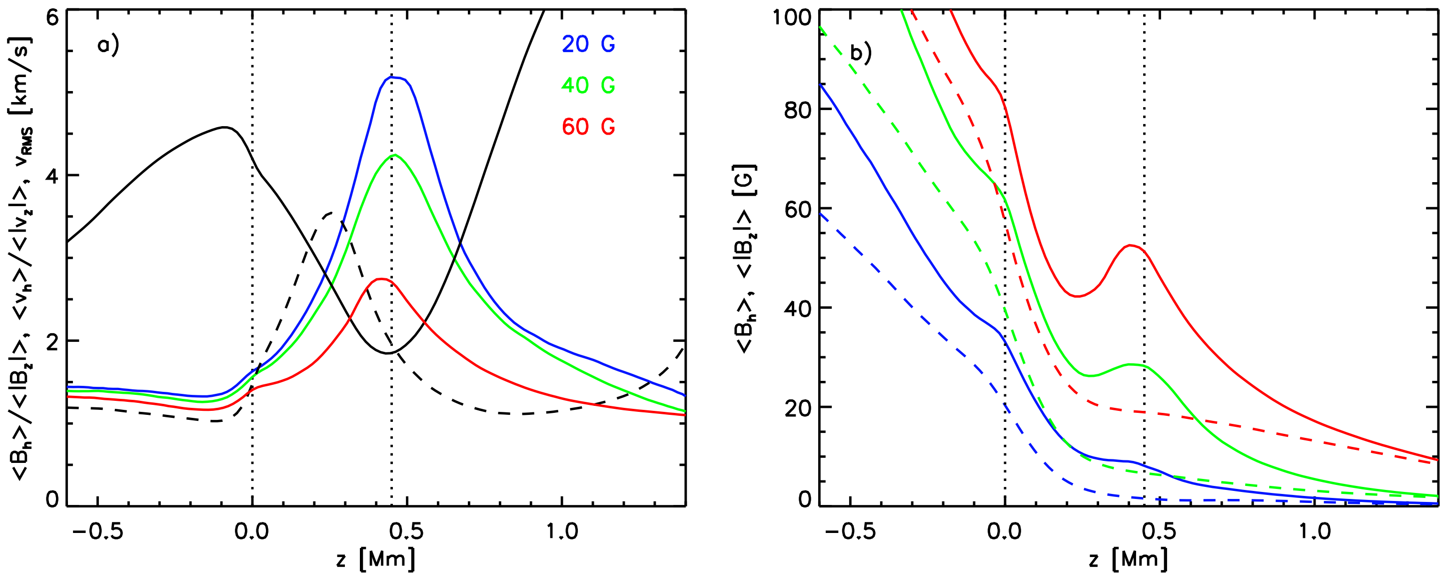
HAO

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

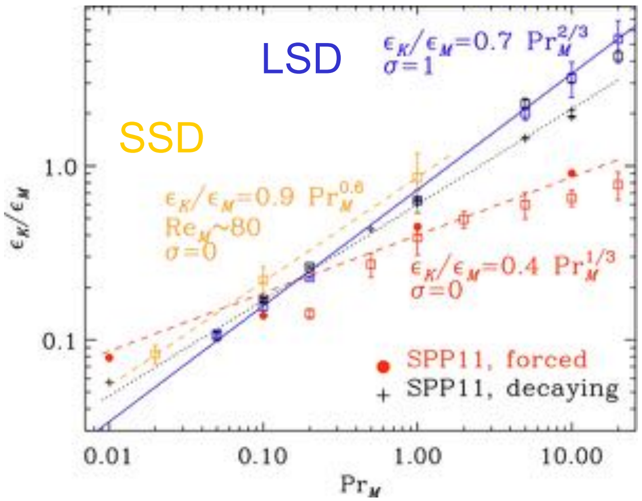


- Horizontal/vertical field ratio peaks ~450 km above tau=1
- Peak value strongly field strength dependent
  - Value of 2-3 expected for observed quiet Sun field strength
  - Hinode observations range from 3 (Orozco Suarez & Bellot Rubio 2012) to 5 (Lites et al 2011)
- Deep photosphere close to an isotropic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

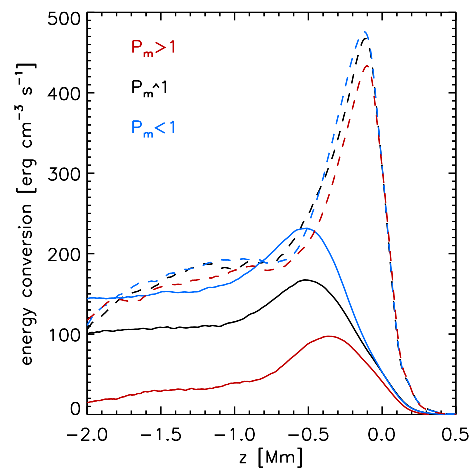
“Power/Efficiency” of dynamo?

- For most simulations presented here
  - $\langle v \cdot (j \times B) \rangle$ about 50% of $\langle v \cdot (\nabla P - \rho g) \rangle$
  - Integrated over the top 10 Mm of the convection zone this accounts to about 1 L_{Sun} of energy converted by the Lorentz force!
  - Note: This is not an energy sink, just a conversion rate. In the absence of a dynamo the energy would be dissipated through viscosity instead!
- Estimates for large scale dynamos
  - 0.001 – 0.01L_{Sun} extracted from mean shear of differential rotation (Rempel 2006, Nelson 2013)
- Energy conversion by SSD 1-2 orders of magnitude larger than LSD?
  - Difficult to draw the line between SSD and LSD!
- Why only 50%?
  - Potentially due to a P_m~1 (see e.g. Brandenburg 2011, 2014)

Role of Pm for saturated state



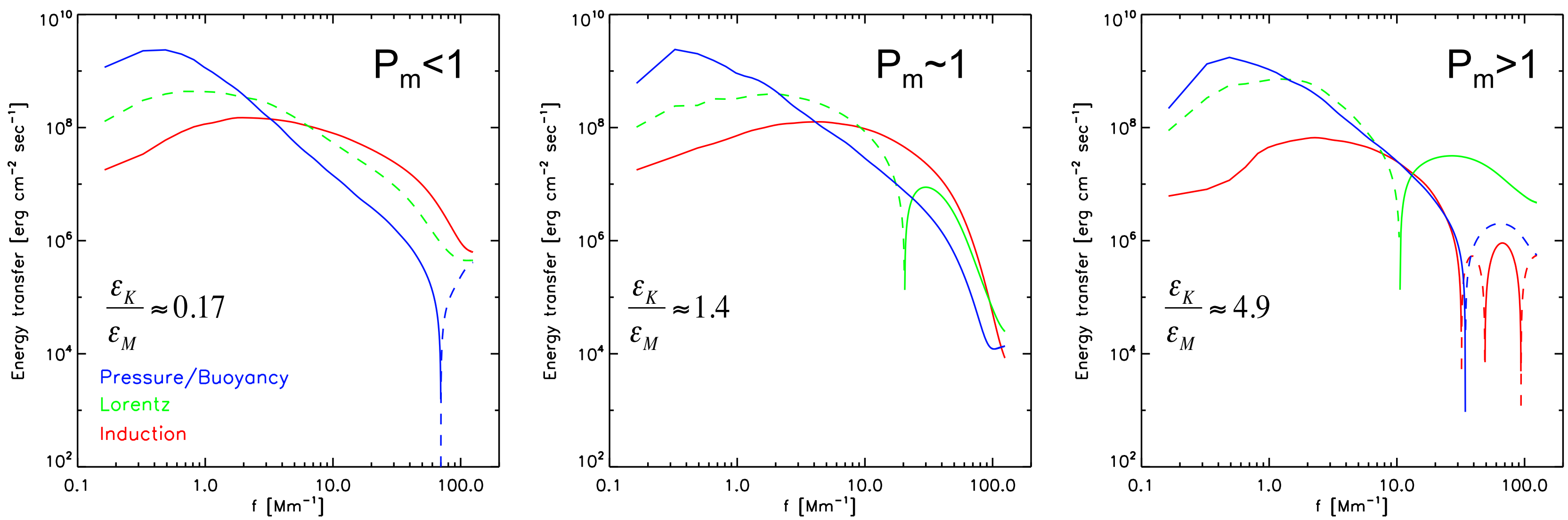
Brandenburg 2014



Experiments with “numerical P_m”

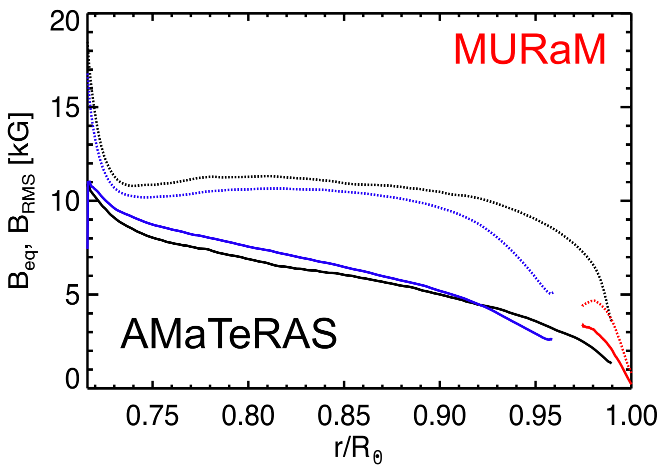
- Ratio of kinetic to magnetic energy dissipation depends on P_m
  - No universal scaling, but present for both SSD and LSD
  - Implies that dynamo efficiency $\langle v\cdot(j\times B)\rangle / \langle v\cdot(\nabla P-\rho g)\rangle$ depends on P_m
- Similar tendency found in experiments with “numerical P_m”
  - P_m<1: combination of more/less diffusive numerical scheme for B/v
    - Diffusivity of 2nd order TVDLF for B, only diffusivity at monotonicity changes for v
  - P_m>1: the other way round
  - P_m~1: TVDLF for B and v
- What does this mean?

Role of P_m for saturated state

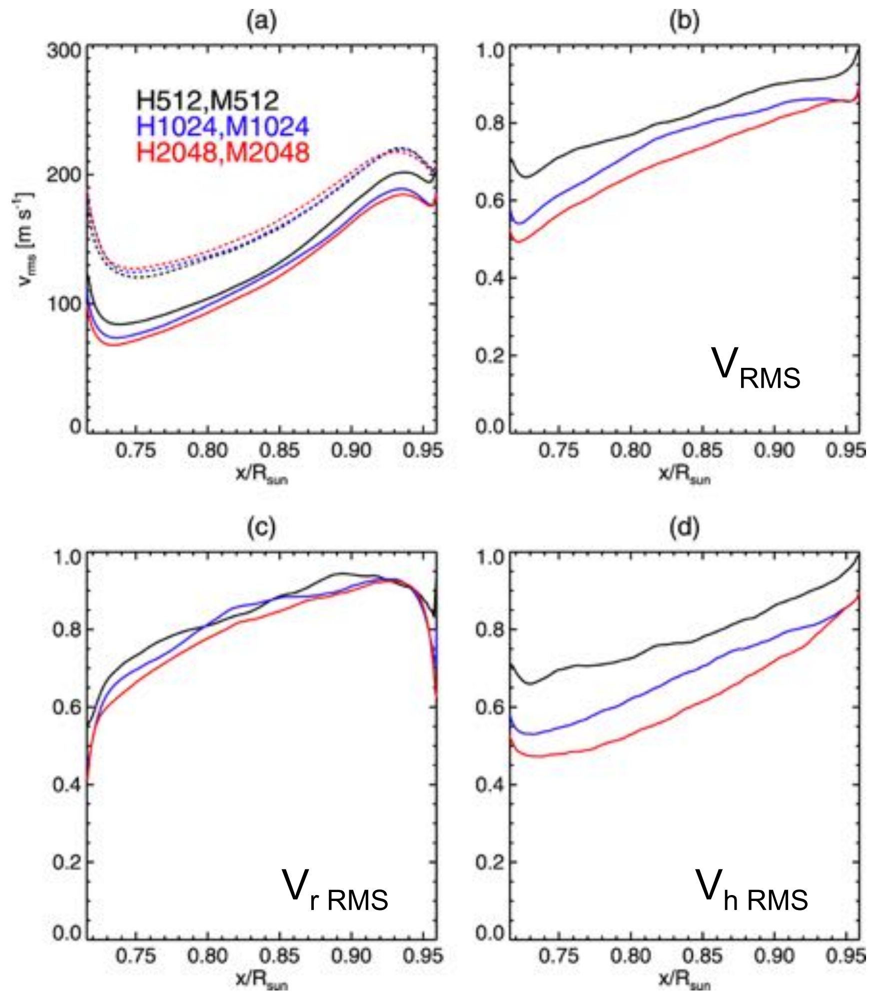


- P_m influences the k value at which the energy transfer by the Lorentz force changes sign:
  - Pm<1:
    - Negative transfer on all scales
    - This maximizes the net energy transfer
  - Pm>1:
    - Positive transfer on small scales returns most of the energy extracted at large scales
    - Induction on small scales suppressed since flows are driven by the Lorentz force

Implications for the convection zone

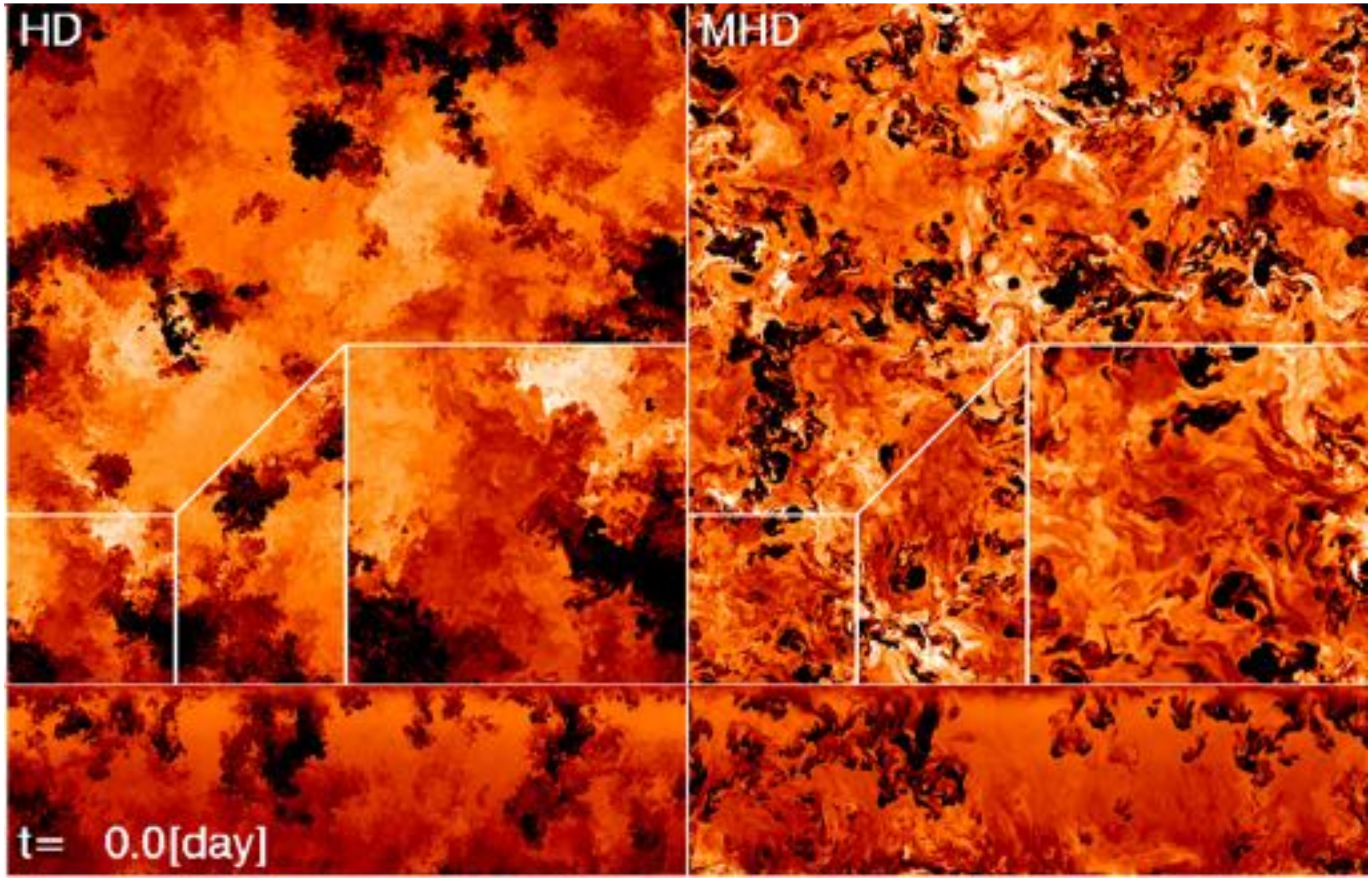


- SSD simulations in CZ (up 0.99 R) consistent with photospheric setups
  - Reach values ~ equipartition
- Dynamical feedback on convection:
  - Reduction of convective velocities by up to a factor of 2 near base of CZ
    - V_r converged
    - V_h not yet converged
  - Corresponds to a resolution of 600x6,000x12,000 in a global setting
  - Reduction of horizontal entropy mixing



Hotta et al. 2015

Implications for the convection zone



- 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
- Significant influence on convective dynamics and large scale dynamo action
  - Reduction of convective velocities by up to a factor of 2, reduction of upflow / downflow mixing, not fully converged yet
  - Capturing these effects in global simulations would require at least a factor 10 resolution increase
  - Coherent large-scale field possible in presence of efficient small-scale dynamo