Small-scale dynamos on the Sun

The different spatio-temporal scales of the solar magnetism

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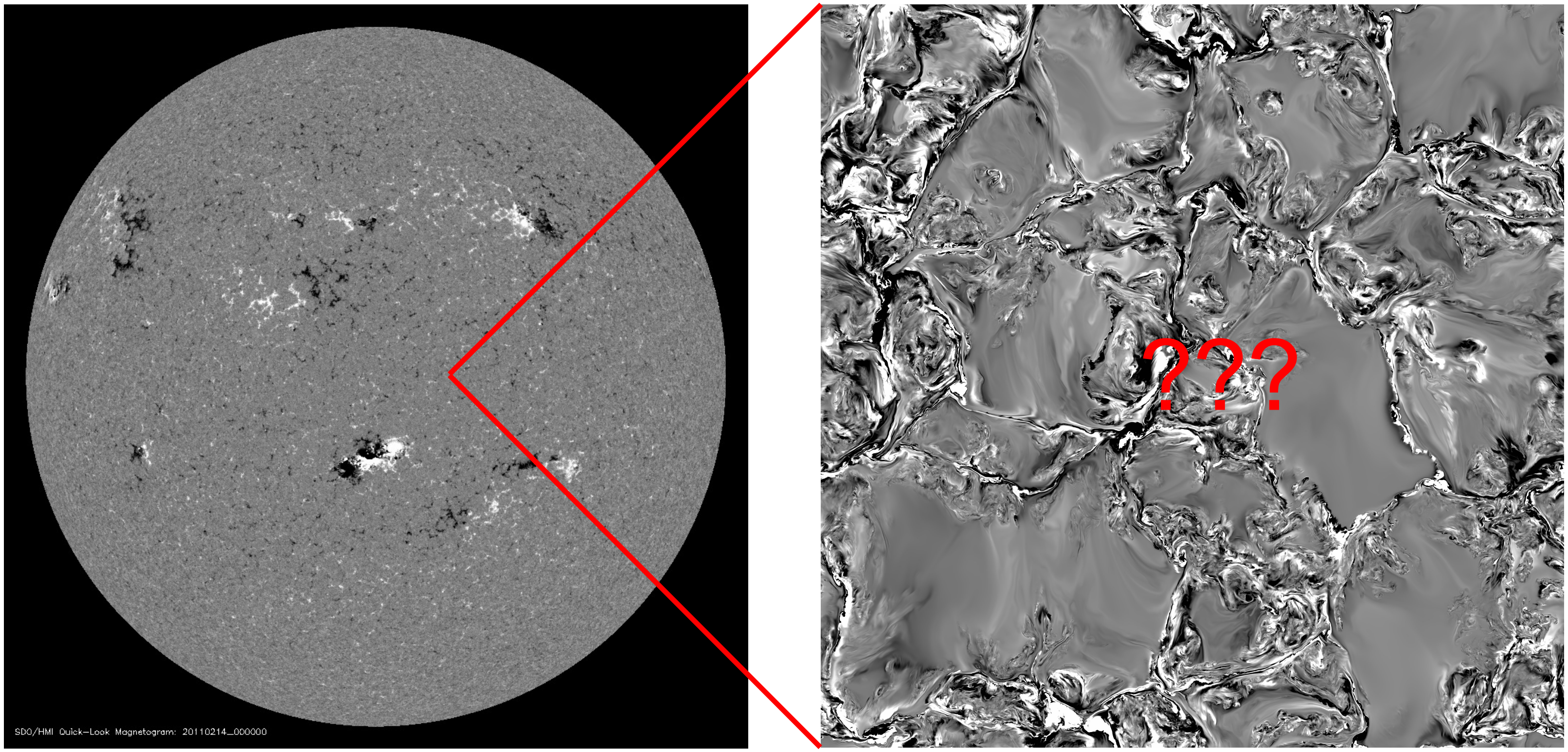
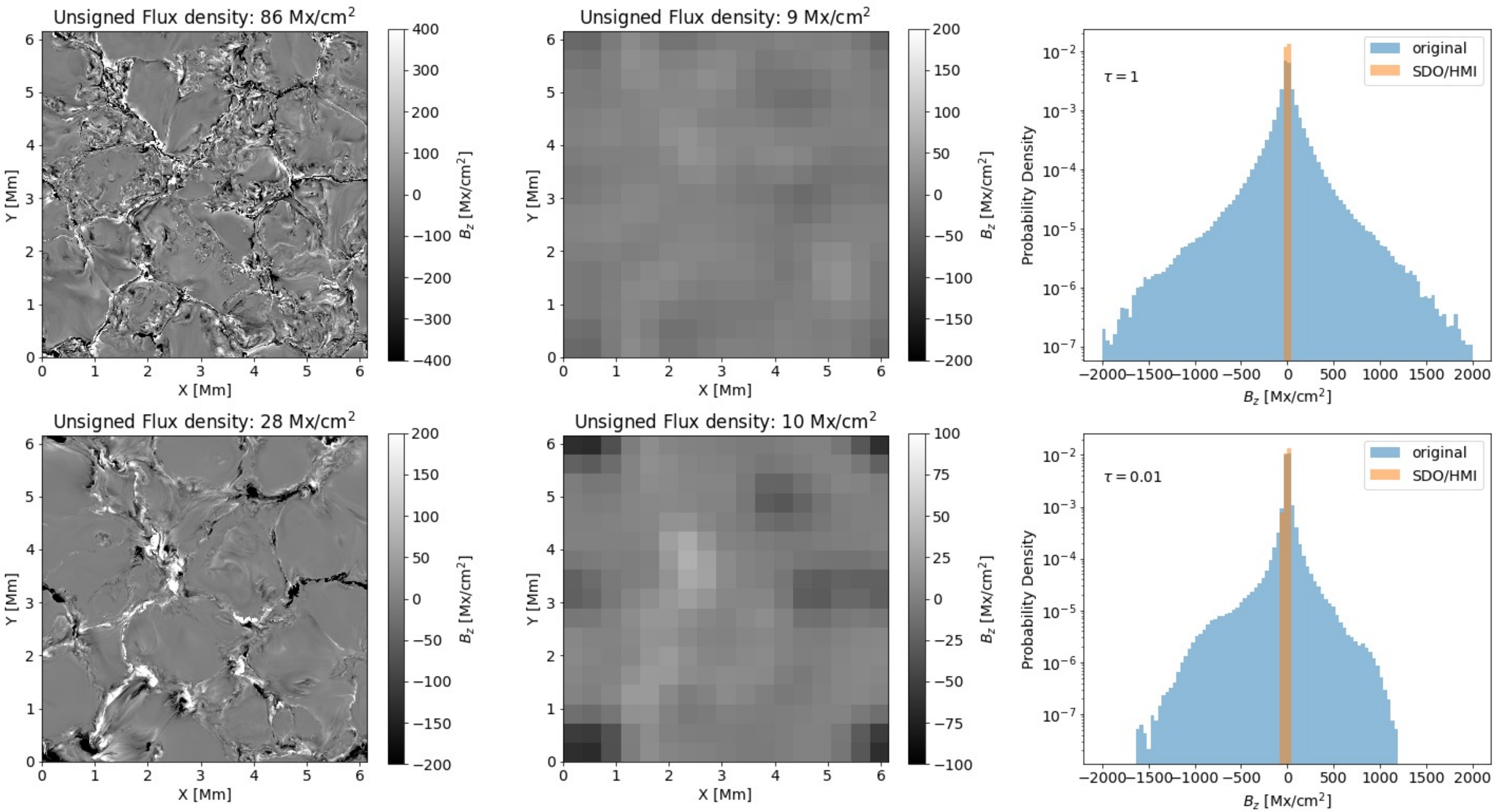
Quiet Sun magnetism

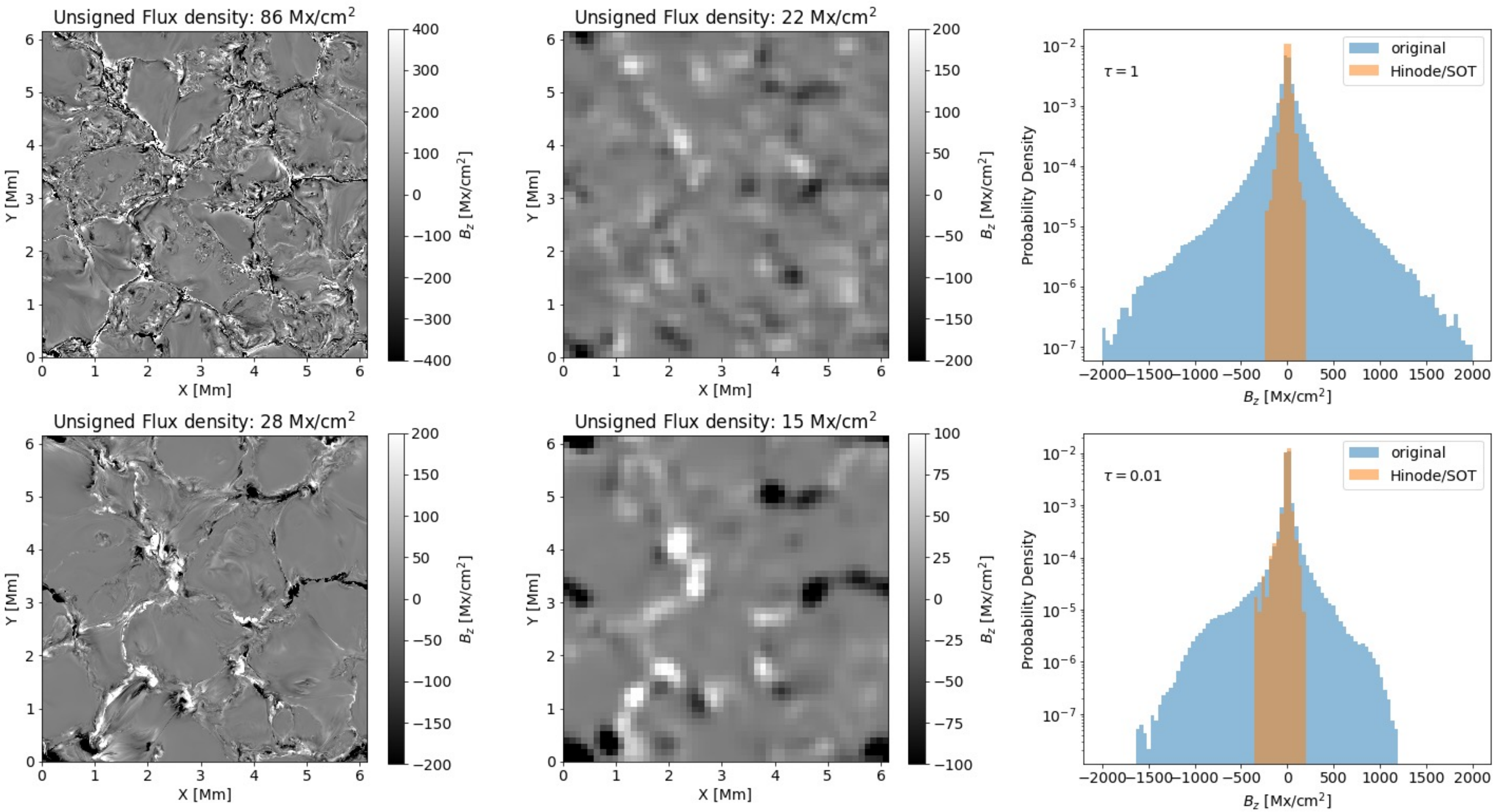


- Most of the solar surface is covered by “quiet Sun” at any time during the sunspot cycle!
- Where does this field come from?
- Does it have dynamic consequences for convection, differential rotation and the large scale dynamo?

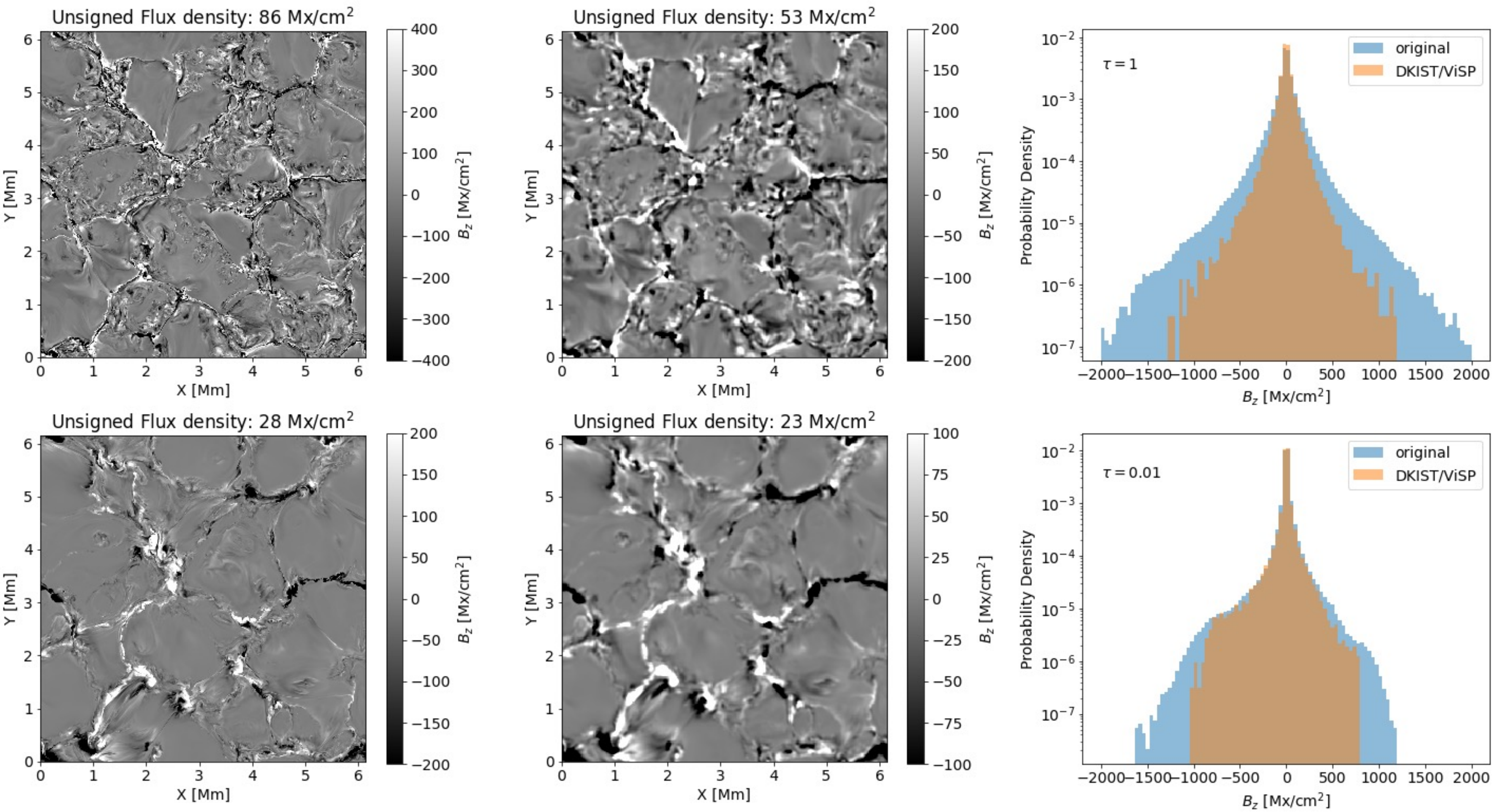
How much flux is hiding in QS – HMI ?



How much flux is hiding in QS - Hinode?



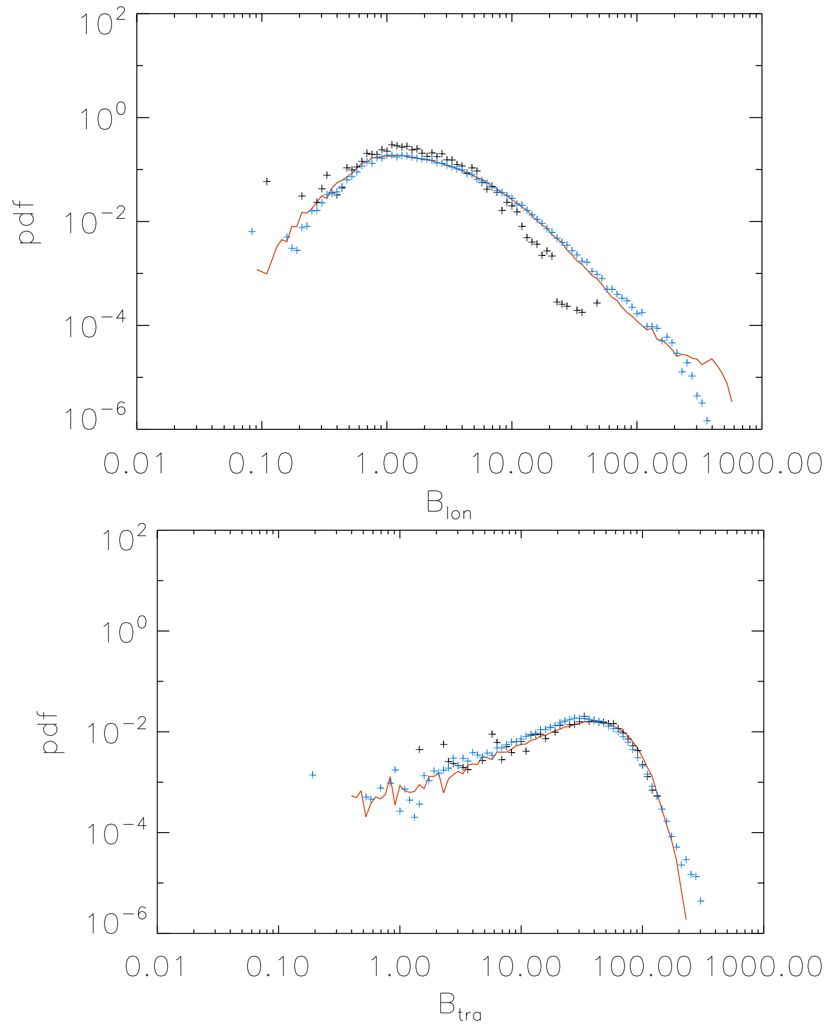
How much flux is hiding in QS – DKIST (not yet observed)?



Models and Observations of quiet Sun Magnetism

- Proper interpretation of observations needs to take into account instrumental effects
  - Start from MHD simulation
  - Forward synthesis
  - Degradation to observation resolution (spatial/spectral)
  - Addition of noise
  - Use of same data analysis pipeline

- Good agreement between simulations, Zeeman and Hanle observations requires $\langle|B_z|\rangle \sim 60 - 80$ G at optical depth unity
  - Danilovic et al. (2016) (Zeeman)
  - Del Pino Aleman et al (2018) (Hanle)



Danilovic et al. (2016)

Hidden unsigned flux in QS

- Comparison of observations and simulations suggests:
  - <|Bz|> ~ 60-80 G at optical depth of unity
- Integrated over the entire solar surface:
  - ~ 4 x 10^{24} Mx
- Typical solar active region:
  - 10^{22} Mx

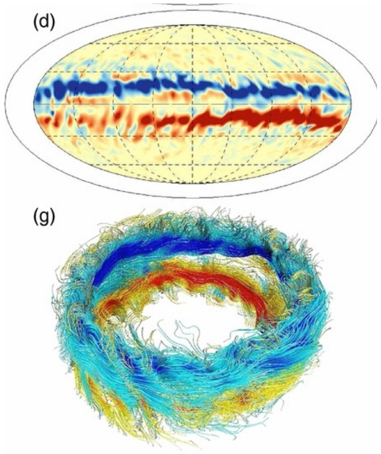
- ***Unsigned*** flux content of QS comparable to that of all the active regions in an entire 11 solar cycle at any given time!

  - It is very unlikely that this is a remnant of the solar cycle!

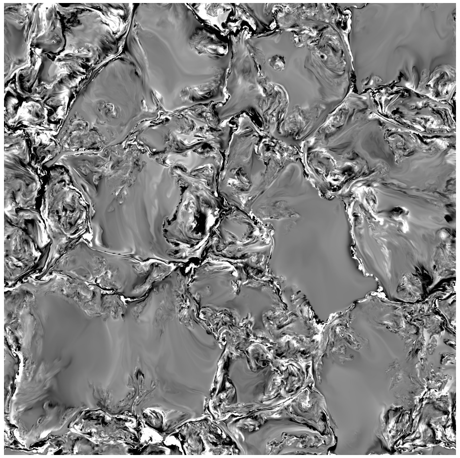
  - We need an independent dynamo process that maintains the small-scale field!

Small-scale vs large-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

Small-scale vs large-scale

Decompose the magnetic field into large scale part and small scale part (energy carrying scale of turbulence) $\mathbf{B} = \overline{\mathbf{B}} + \mathbf{B}'$:

$$E_{\rm mag} = \int \frac{1}{2\mu_0}\overline{\mathbf{B}}^2\, dV + \int \frac{1}{2\mu_0}\overline{\mathbf{B}'^2}\, dV\ .$$

- Small scale dynamo: $\overline{\mathbf{B}}^2 \ll \overline{\mathbf{B}'^2}$
- Large scale dynamo: $\overline{\mathbf{B}}^2 \geq \overline{\mathbf{B}'^2}$

Almost all turbulent (chaotic) velocity fields are small scale dynamos for sufficiently large R_m, large scale dynamos require additional large scale symmetries.

Alternate form of induction equation:

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

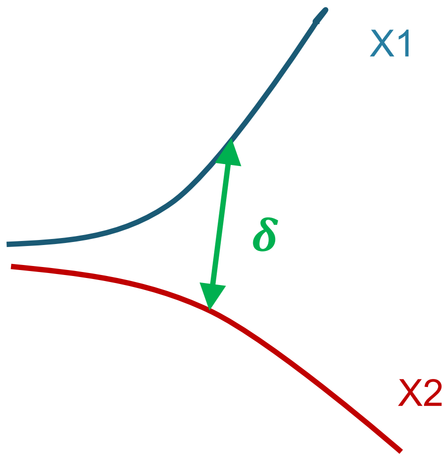
Combination with equation of continuity leads to:

$$\frac{d}{dt}\frac{\mathbf{B}}{\varrho} = \left(\frac{\mathbf{B}}{\varrho}\cdot\nabla\right)\mathbf{v}$$

Small-scale dynamo

Lagrangian particle paths:

$$\frac{d\mathbf{x}_1}{dt} = \mathbf{v}(\mathbf{x}_1, t) \qquad \frac{d\mathbf{x}_2}{dt} = \mathbf{v}(\mathbf{x}_2, t)$$



Consider small separations:

$$\delta = \mathbf{x}_1 - \mathbf{x}_2 \qquad \frac{d\delta}{dt} = (\delta \cdot \nabla)\mathbf{v}$$

Chaotic flows have exponentially growing solutions. Due to mathematical simularity the equation:

$$\frac{d}{dt}\frac{\mathbf{B}}{\varrho} = \left(\frac{\mathbf{B}}{\varrho} \cdot \nabla\right)\mathbf{v}$$

has exponentially growing solutions, too. We neglected here η, exponentially growing solutions require $R_m > \mathcal{O}(100)$ (forced, non-stratified turbulence), $R_m > \mathcal{O}(2000)$ (solar granulation).

Modeling the solar photosphere

- Key ingredients:
  - MHD
  - Radiative transfer
    - 3D, i.e. angular dependence resolved
    - Frequency dependence of opacity (capture by a few opacity bins)
  - Equation of state with partial ionization
- Open bottom boundary condition
  - Cannot afford simulation the entire convection zone
  - Use open bottom boundary conditions:
    - Convective energy flux across boundary
    - Downflows exit the domain with their thermal properties
    - Upflows have a prescribed fixed entropy

Modeling the solar photosphere

Fully compressible MHD

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

$$\frac{\partial \varrho\mathbf{v}}{\partial t} = -\nabla\cdot(\varrho\mathbf{v}\mathbf{v}) + \frac{1}{c}\mathbf{j}\times\mathbf{B} - \nabla P + \varrho\mathbf{g}$$

$$\frac{\partial E_{\rm tot}}{\partial t} = -\nabla\cdot\left[\mathbf{v}\,(E_{\rm tot}+P_{\rm tot}) - \frac{1}{4\pi}\mathbf{B}(\mathbf{v}\cdot\mathbf{B})\right] + \varrho\mathbf{v}\cdot\mathbf{g} + Q_{\rm rad}$$

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

$$E_{\rm tot} = E_{\rm int} + \frac{1}{2}\varrho v^2 + \frac{B^2}{8\pi}$$

$$P_{\rm tot} = P + \frac{B^2}{8\pi}$$

Equation of state

$$\varrho, E_{\rm int} \longrightarrow P, T$$

Radiative transfer equation (I specific intensity, $\hat{\mathbf{n}}$ unit vector in ray direction)

$$\frac{dI_\nu}{ds}(\hat{\mathbf{n}}) = \kappa_\nu\varrho(S_\nu - I_\nu(\hat{\mathbf{n}}))$$

Source function $S_\nu = B_\nu(T)$ in local thermodynamic equilibrium (LTE)

Radiative energy flux

$$\mathbf{F}_\nu = \int_{4\pi} I_\nu(\hat{\mathbf{n}})\hat{\mathbf{n}}\,d\Omega$$

Average intensity

$$J_\nu = \frac{1}{4\pi}\int_{4\pi} I_\nu(\hat{\mathbf{n}})\,d\Omega$$

Radiative heating/cooling

$$Q_{\rm rad} = -\int_\nu (\nabla\cdot\mathbf{F}_\nu)d\nu = 4\pi\varrho\int_\nu \kappa_\nu(J_\nu - S_\nu)d\nu$$

Numerical treatment

- Compute a discrete number of rays, typically 24 - 48
- Compute a discrete number of frequency bins, typically 1 - 12

Solar simulations of the quiet Sun

- Before 2000, mostly HD granulation simulation
- Idealized SSD simulations, Cattaneo (1999) (Boussinesq) Bercik et al. (2005) (anelastic)
- Vögler & Schüssler (2007), first "realistic" SSD simulation (compressible, EoS, RT)
- Discrepancy between simulations and observations
  - Danilovic et al. (2010): Zeeman, simulations 2-3 too weak
  - Trujillo-Bueno (2011): Hanle, stronger than Zeeman, simulation needs to be scaled up 12x in upper photosphere
- Many new recent models: Rempel (2014, 2018), Kitiashvili (2015), Khomenko (2017)
  - Higher resolution
  - Improved boundary conditions
- Good agreement between simulations, Zeeman and Hanle observations requires $<|B_z|>\sim 60 - 80$ G at optical depth unity
  - Danilovic et al. (2016) (Zeeman)
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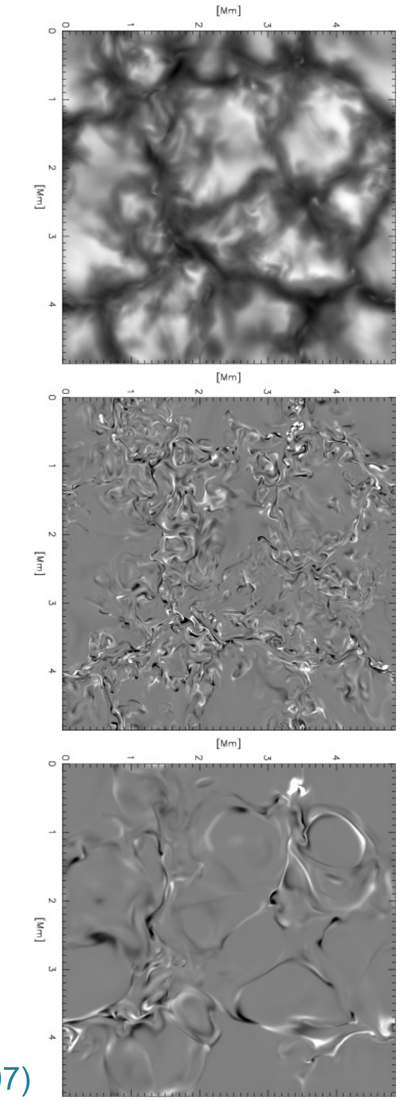
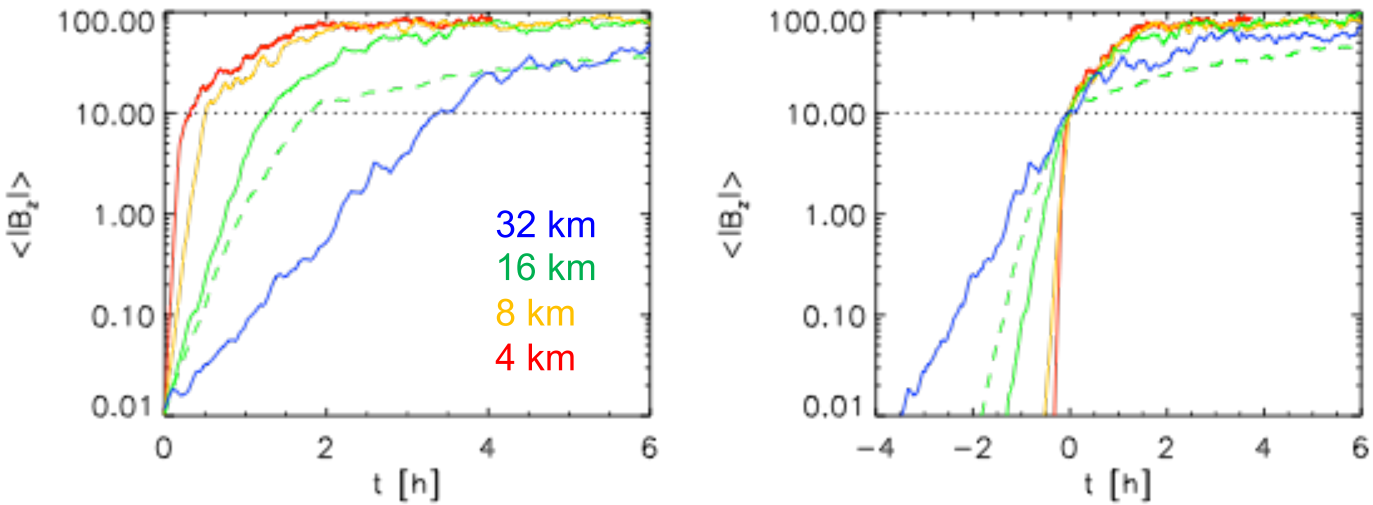
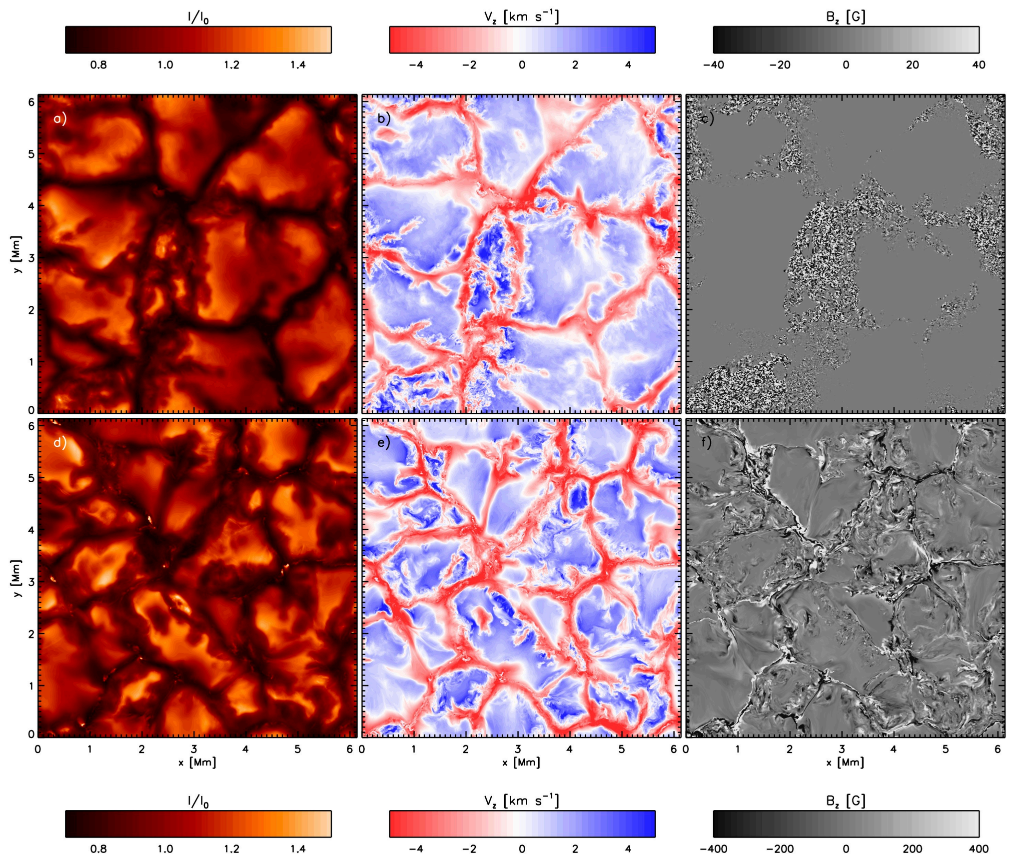


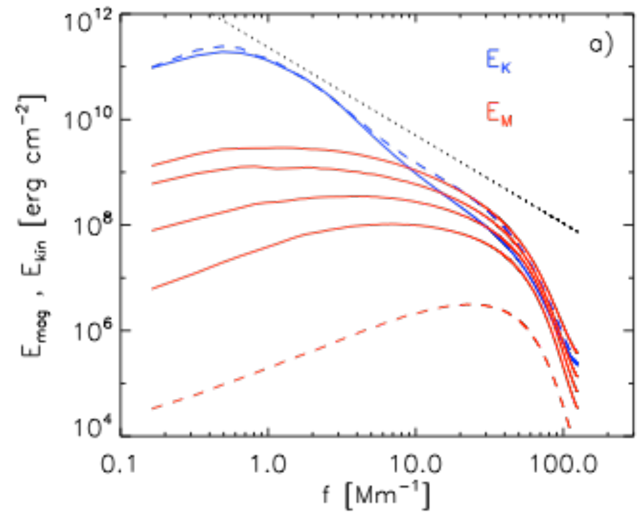
Vögler & Schüssler (2007)

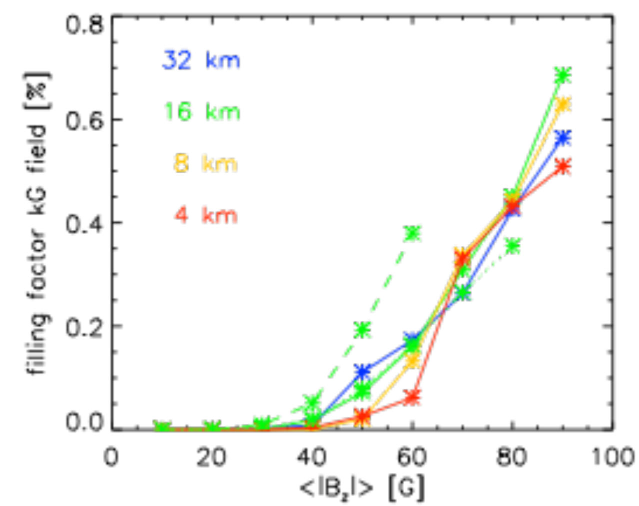


- Kinematic regime
  - $B<0.01\ B_{QS}$ (current simulations)
  - Equipartition with E_{kin} near magnetic dissipation scale
- $B>0.1\ B_{QS}$
  - Slow growth on a typical convective time scale
  - Organization of QS field on meso to supergranular scales expected
- Observable quiet sun
  - Saturated regime of a small scale dynamo

Kinematic regime to saturation







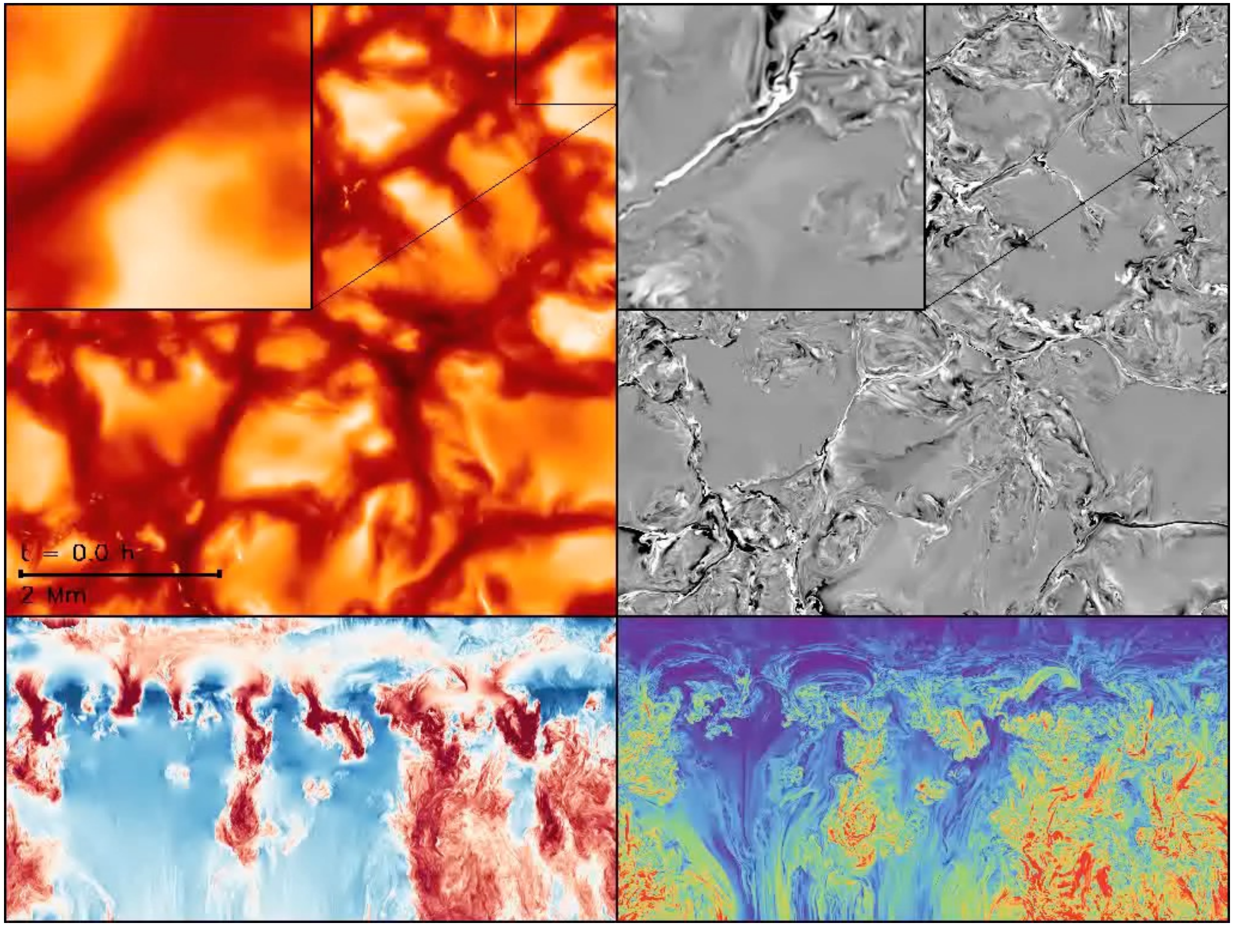
- Magnetic field organization changes dramatically during saturation
  - Non-linear saturation begins for <|B_z|>~10 G in photosphere
  - Sheet like appearance instead of "salt and pepper"
  - Peak of magnetic energy near granular scales
  - kG flux concentrations, bright points appear starting from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

Saturated SSD solution consistent with observational constraints

Domain: 6.144 x 6.144 x 3.072 Mm^3 4km grid spacing

Intensity

Bz (τ=1)
[+/- 400 G]



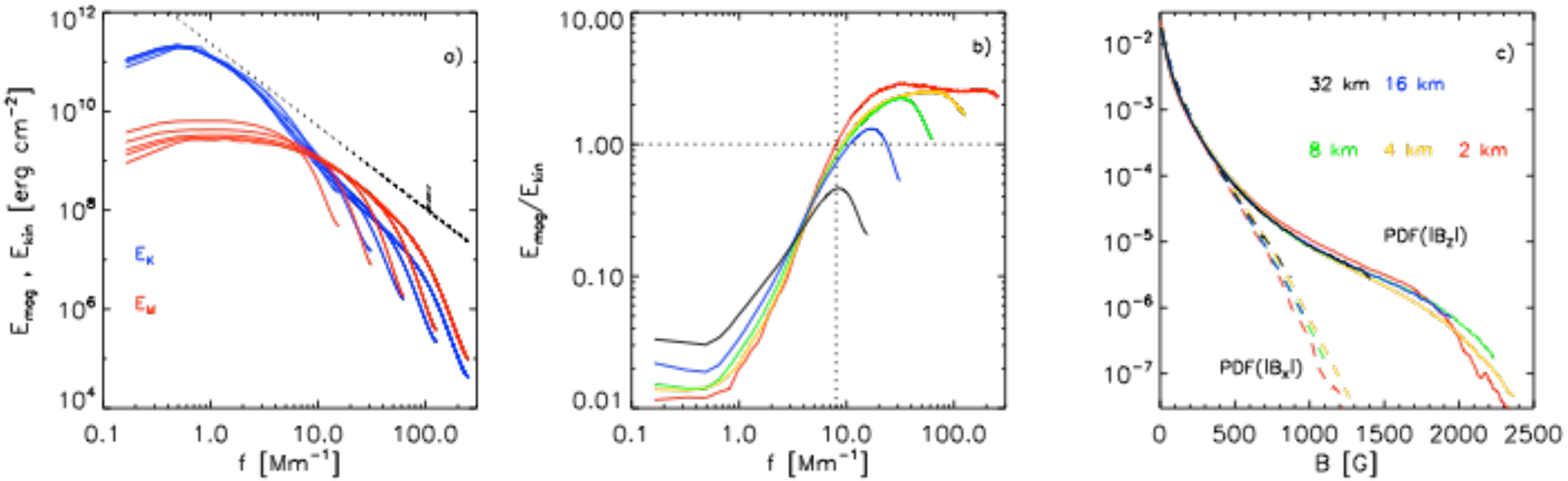
Vz
[+/- 4
km/s]

|B|
[< 2 kG]

Open bottom boundary mimics the presence of a deep magnetized convection zone

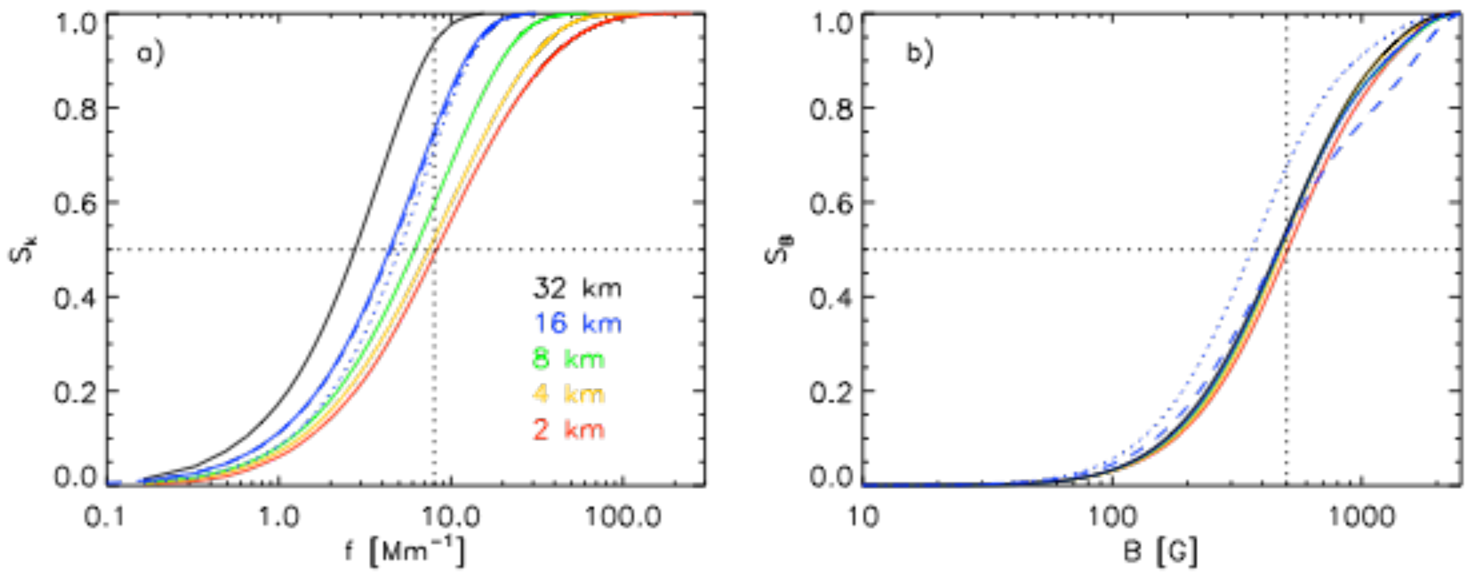
Rempel (2014)

Resolution dependence 32 … 2 km



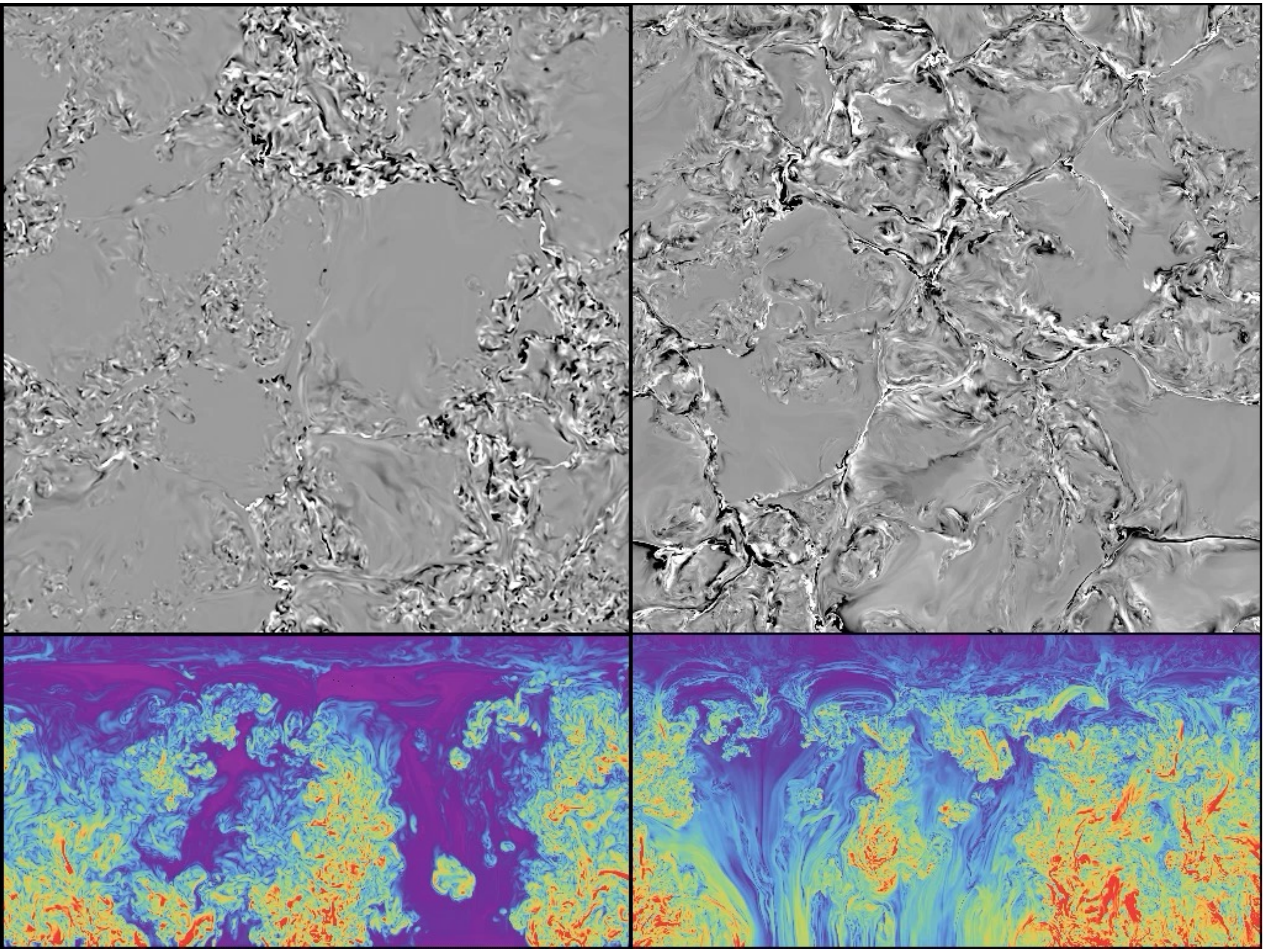
- Converged results using LES approach
  - No explicit viscosity or magnetic resistivity
  - Changing resolution by a factor of 16!
  - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
  - Implicit magnetic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

Energy distribution in photosphere

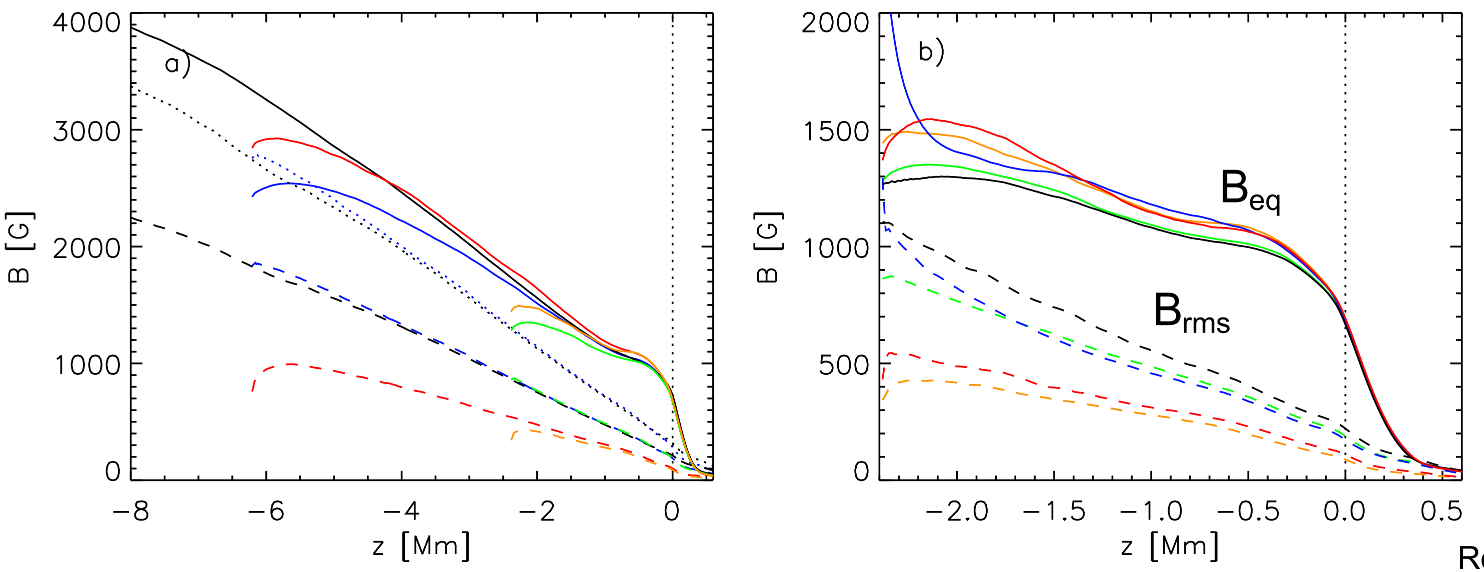


- ~50% of energy on scales smaller than 100 km
  - Need small (~8 km or smaller) grid spacing for properly resolving the spectral energy distribution
  - Hinode “sees” about 20% of the magnetic energy, DKIST could see more than 90%
- ~50% of energy from field weaker than 500 G
  - No resolution dependence,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

Local vs. global recirculation



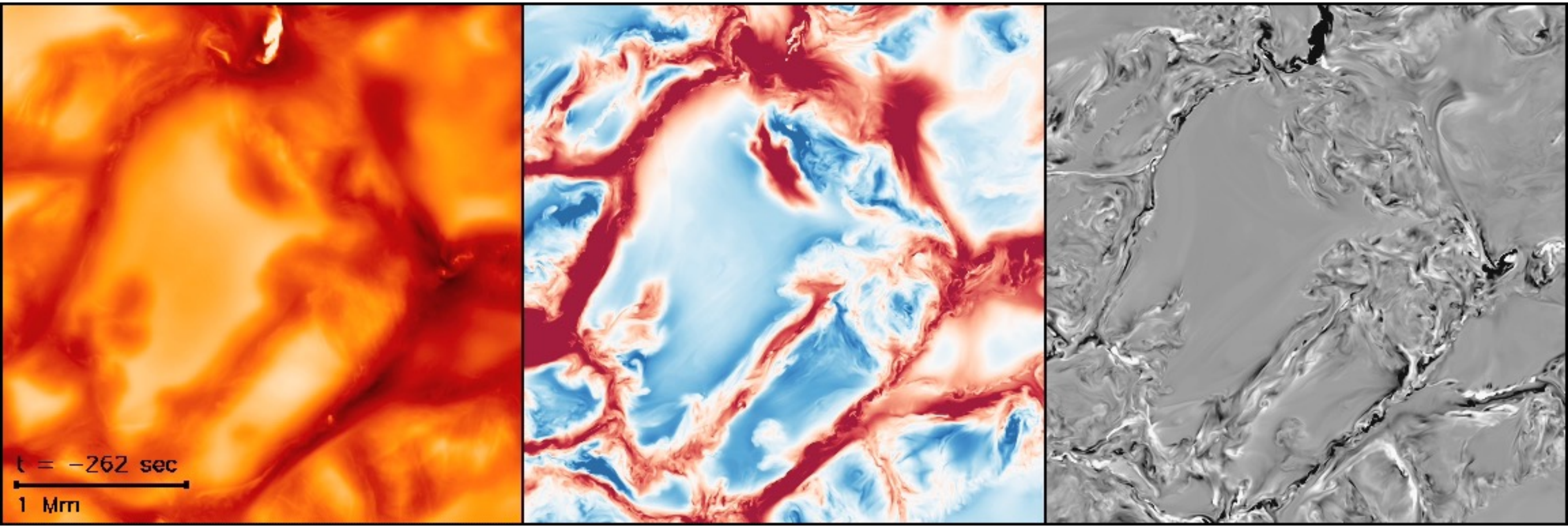
- Left:
  - B=0 in inflow regions
- Right
  - B symnmetric across boundary
  - Similar to closed boundary with full recirculation



Rempel (2014)

- Presence of deep recirculation leads to about 2x saturation field strength
  - Closed BND with full recirculation
  - Open BND with horizontal field emergence

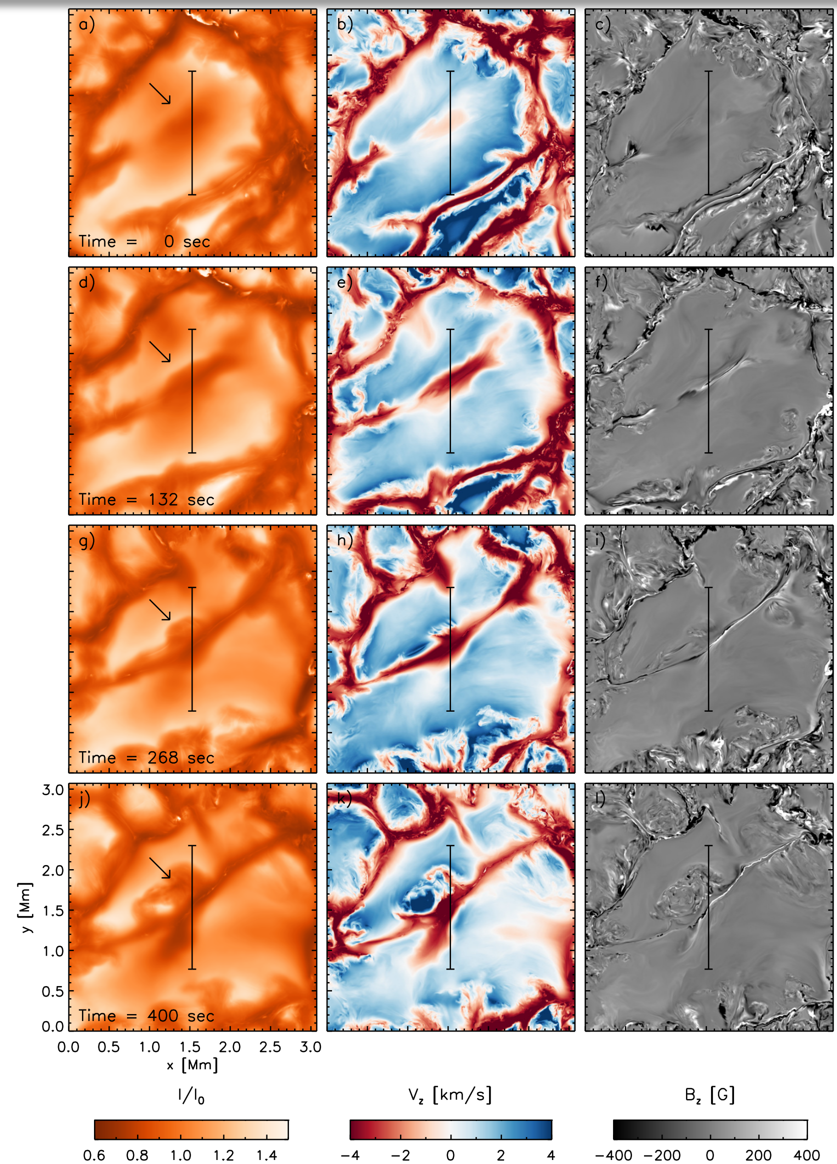
Exploding granules



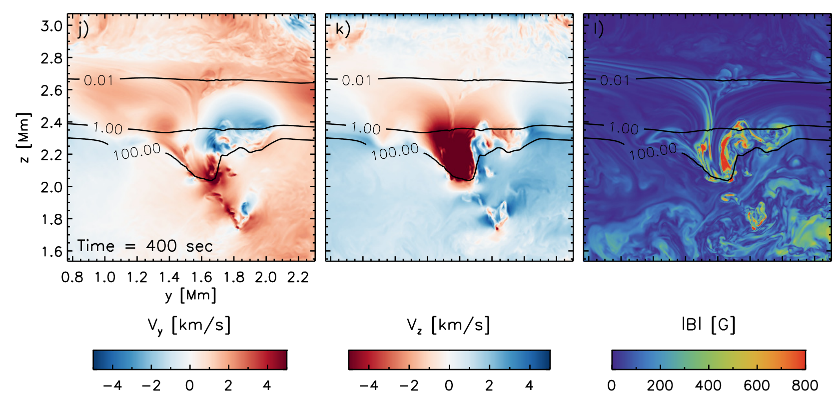
Rempel (2018)

- Large granules form new downflow lanes in their interior
- Most “pristine” downflow lanes in solar photosphere
- Downflow lanes with weakest initial magnetization

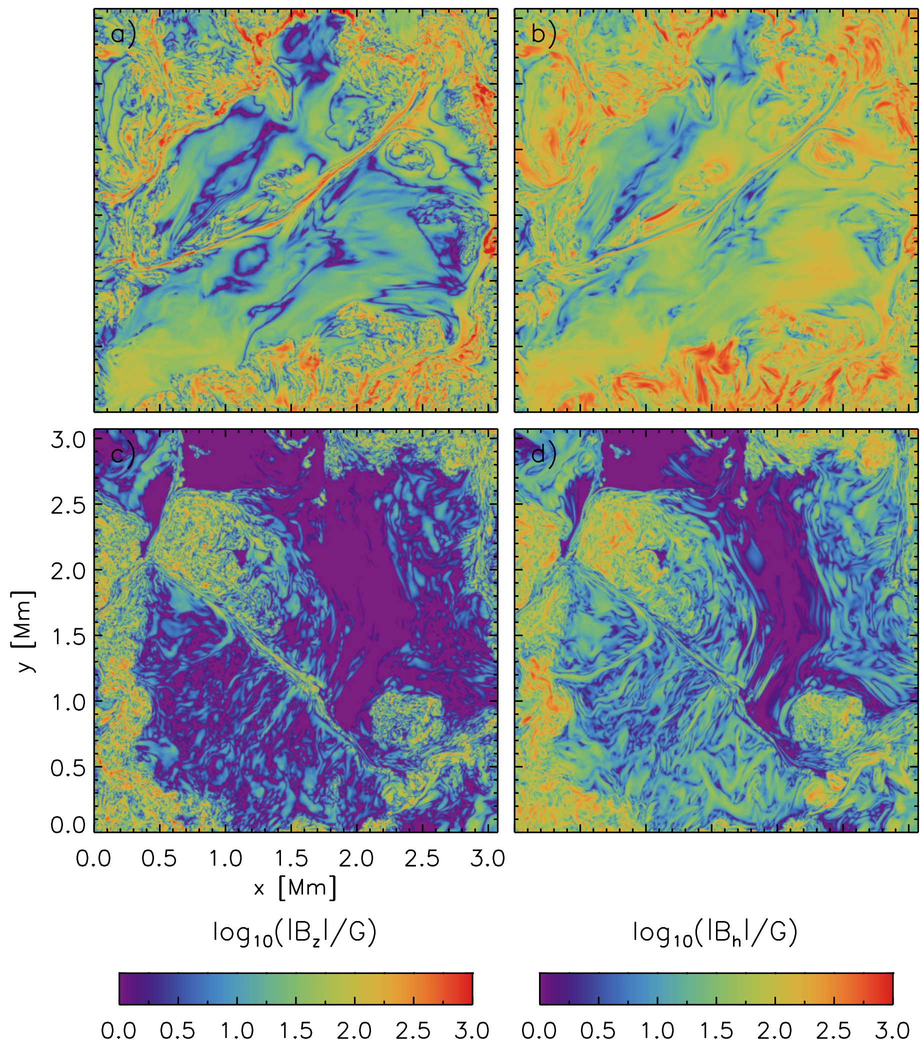
Magnetization of newly formed downflows



- Amplification of "granular seed field" by mostly ***lamina***r horizontally converging flows
  - Thin sheet of magnetic field
  - Reflects structure of granular seed field
- Indication of asymmetric horizontal vorticity
  - Sharp edge in intensity (Steiner et al. 2010)
- ***Turbulen***t field appears first in upflows at the edge of the downflow lane
  - Indication of shallow recirculation
  - Newly formed downflow reaches only a few 100 km deep

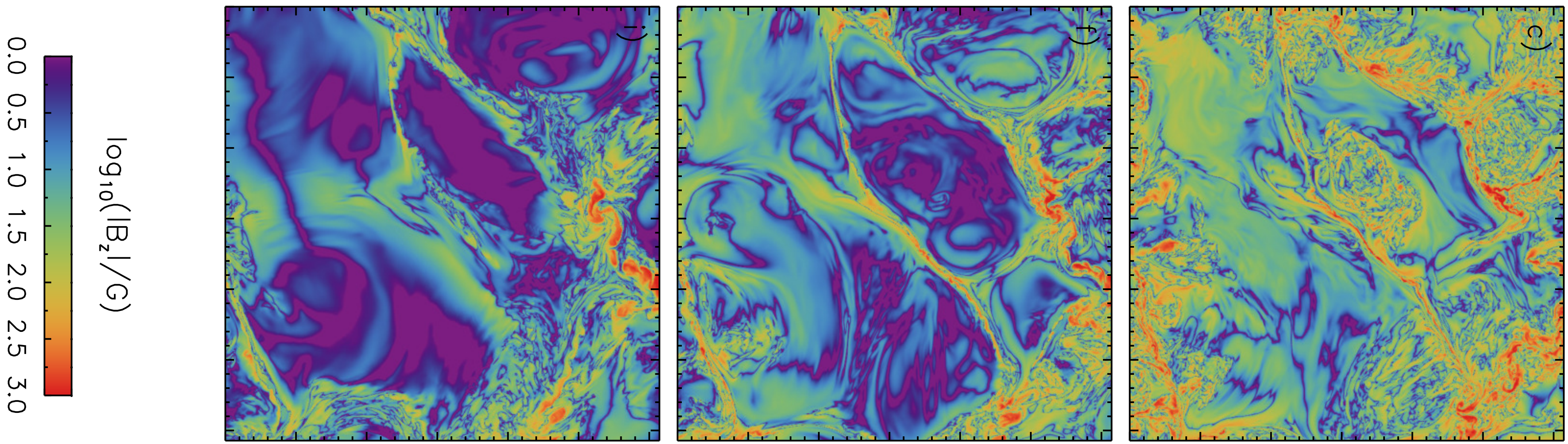


SSD with and without deep recirculation



- Amount of granular "seed field" heavily dependent on deep recirculation
  - Center of granules close to field free without deep recirculation
- Less turbulent, organized on larger scales
  - Consequence of horizontal expansion due to stratification
- Deep recirculation leads to strong magnetic sheets in downflow lanes

Visibility of turbulent field in photosphere



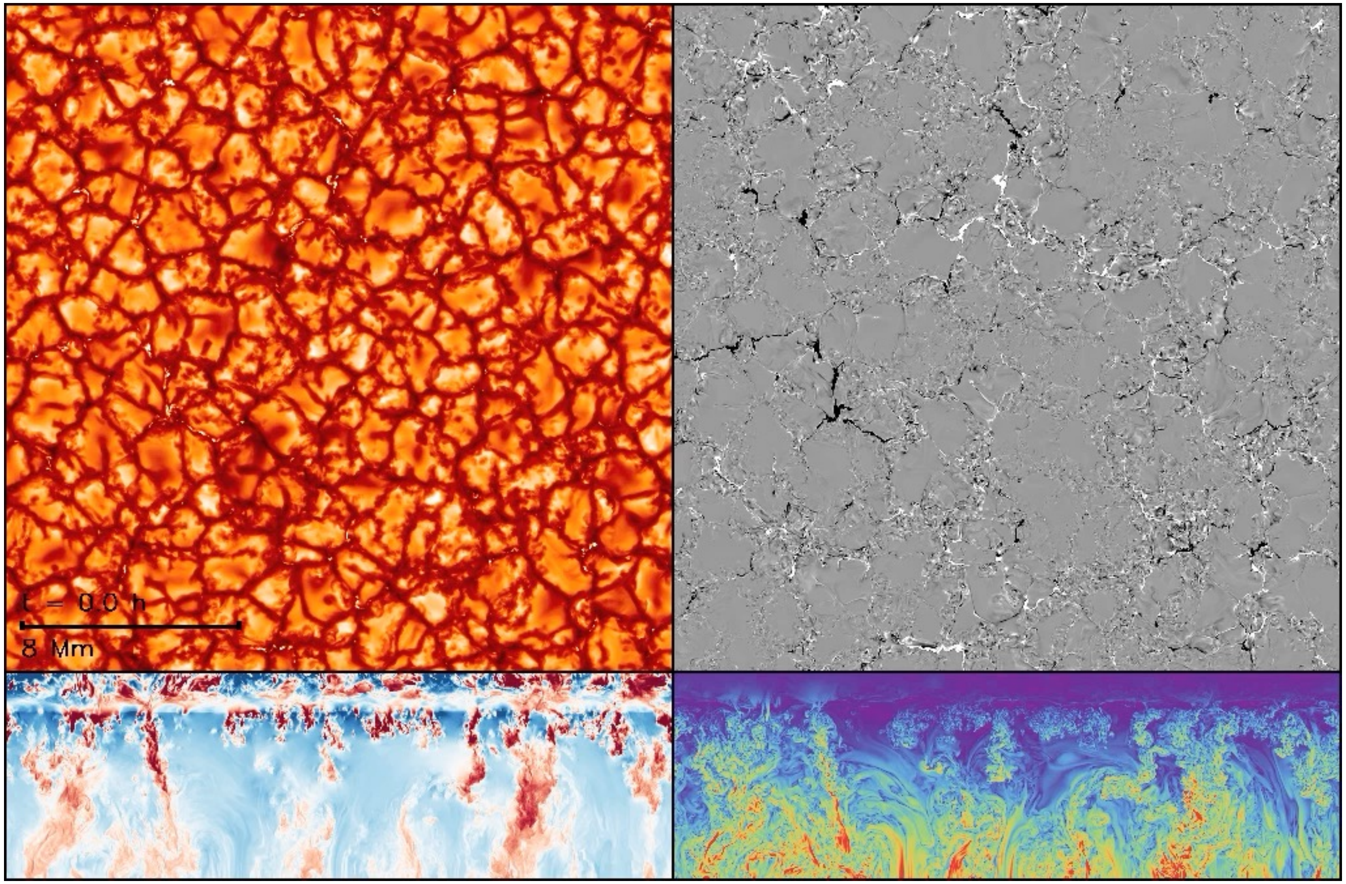
Tau=0.01 | Tau=0.1 | Tau=1

- Shallow and deep recirculation related field only visible in very deep photosphere (tau=1)
- Already tau=0.1 misses completely the turbulent field from shallow recirculation
- Observations at high resolution in deep photosphere required (→ DKIST @ 1600 nm)

Meso-granular scales

Intensity
0.5 – 1.5

Vz
+/- 4 km/s

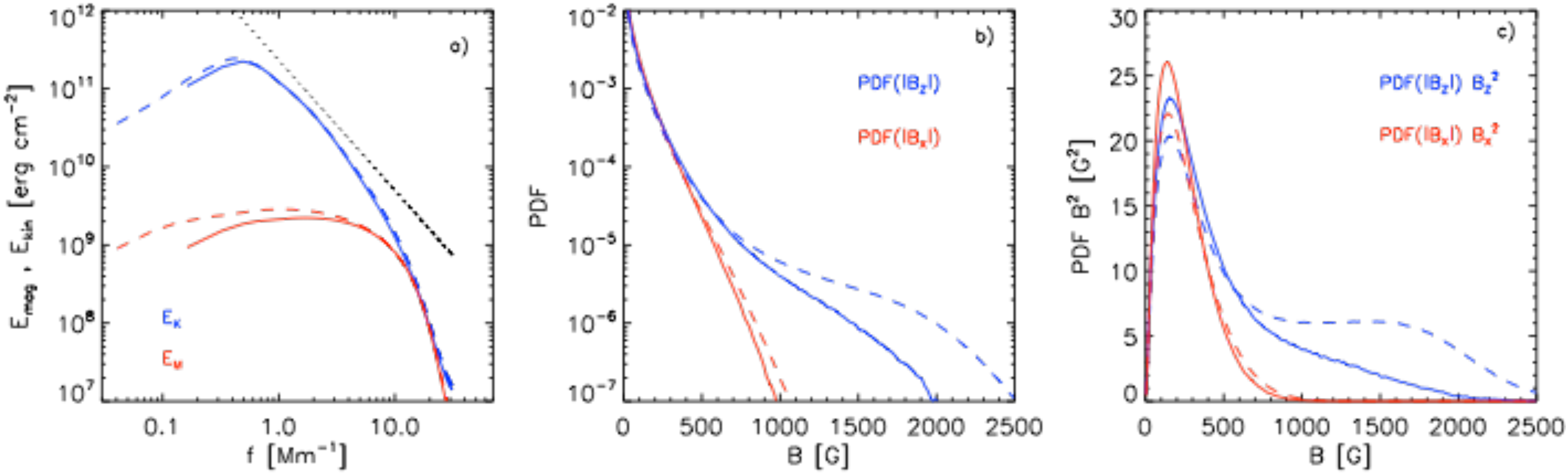


Bz (τ=1)
+/- 400G

|B|
+/- 4kG

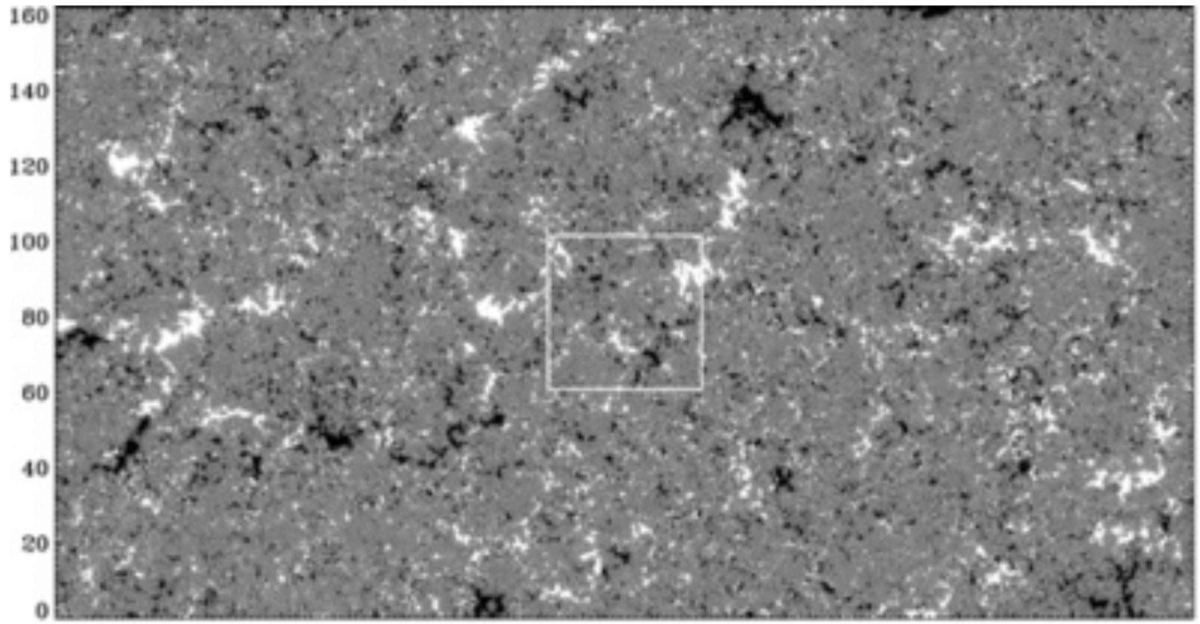
- Small-scale dynamo operating in a highly stratified domain
  - Dynamo operates over a wide range of scales at different depth, coupled through vertical transport
  - Can organize magnetic field on scales larger than granulation
  - Can lead to significant local flux imbalance

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)

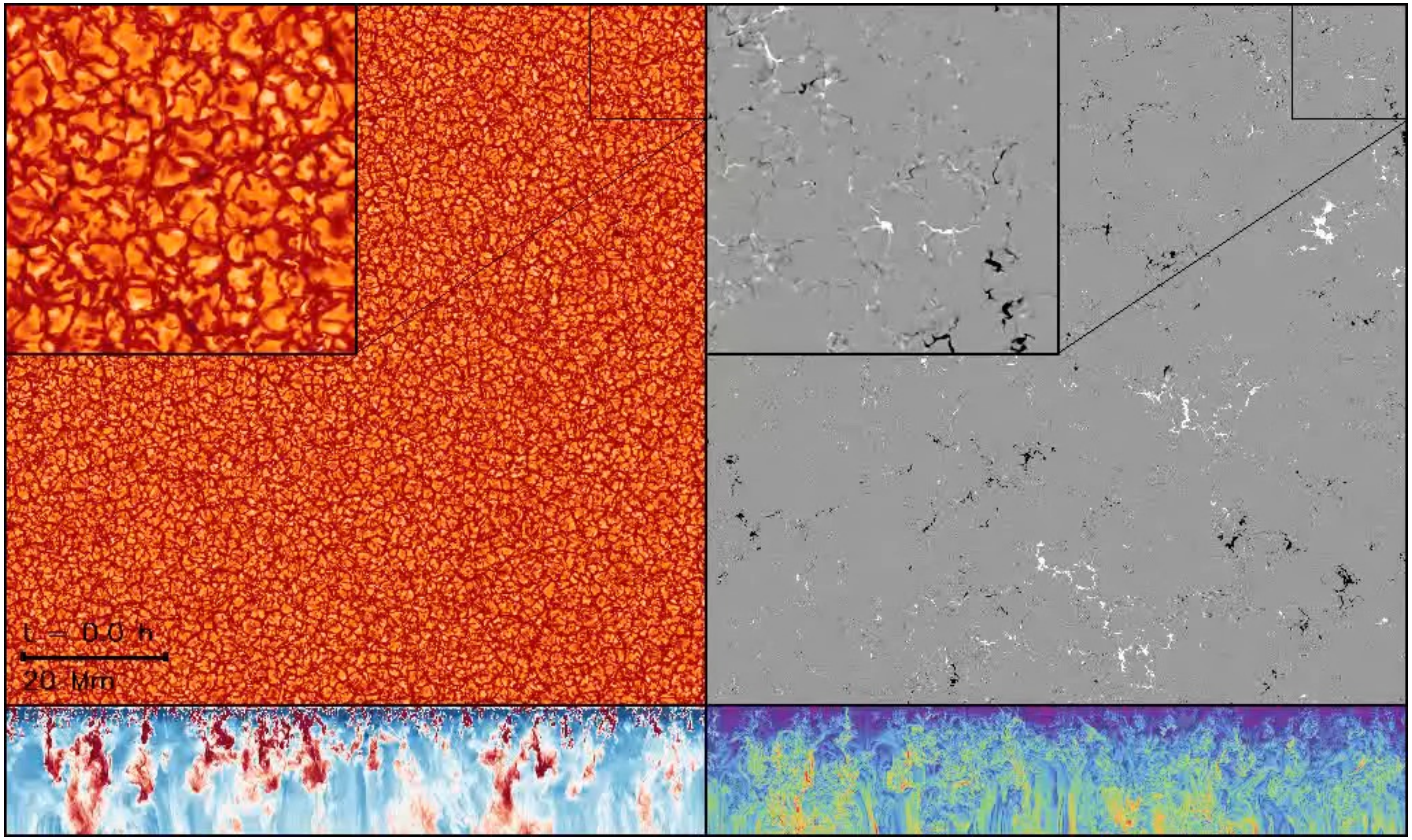
Origin of Quiet Sun Network field



et From Lites al 2008

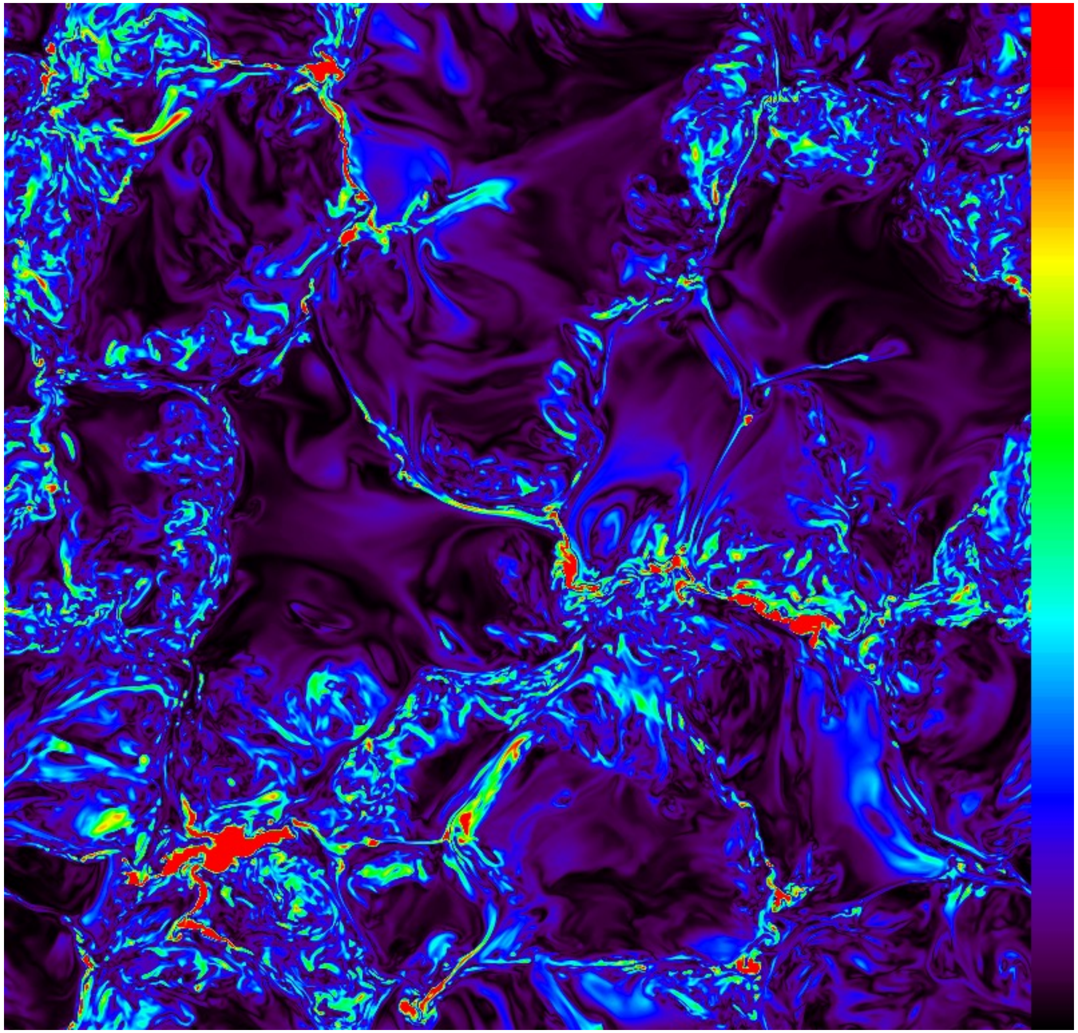
- What is the origin of the QS network field? Is it part of the quiet Sun or still a remnant of the solar cycle

Large scale flux imbalance



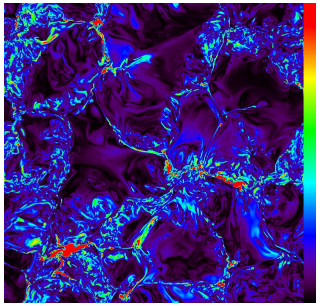
SSD can produce mixed-polarity network in sufficiently large domains, here 100x100x18 Mm

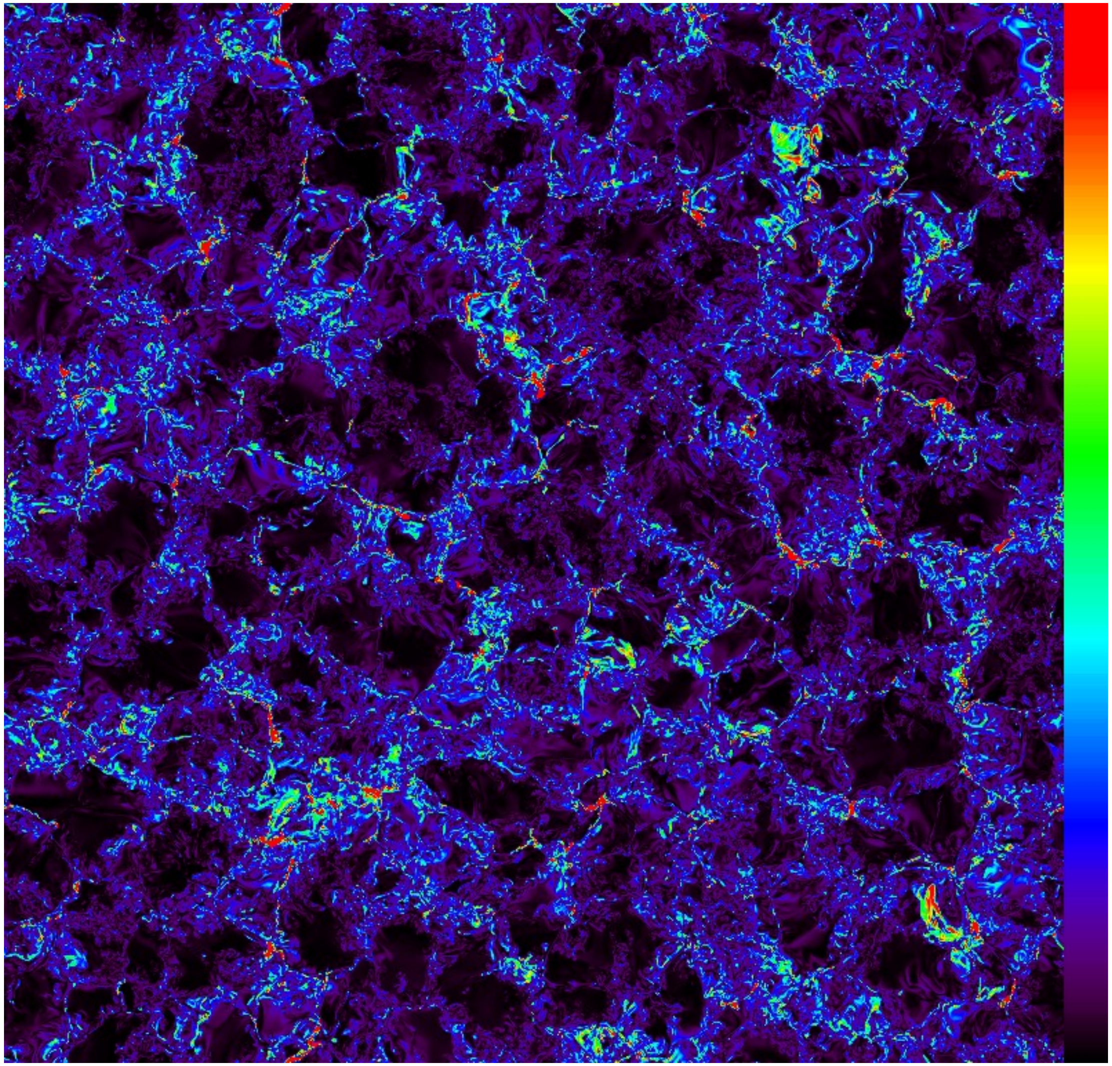
Larger scale organization and "voids"



6x6x2.3 Mm

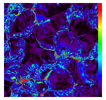
Larger scale organization and “voids”

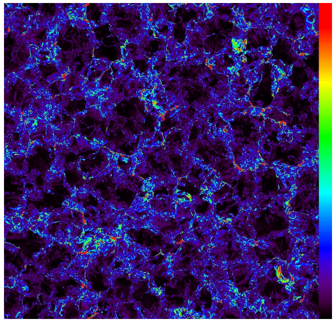


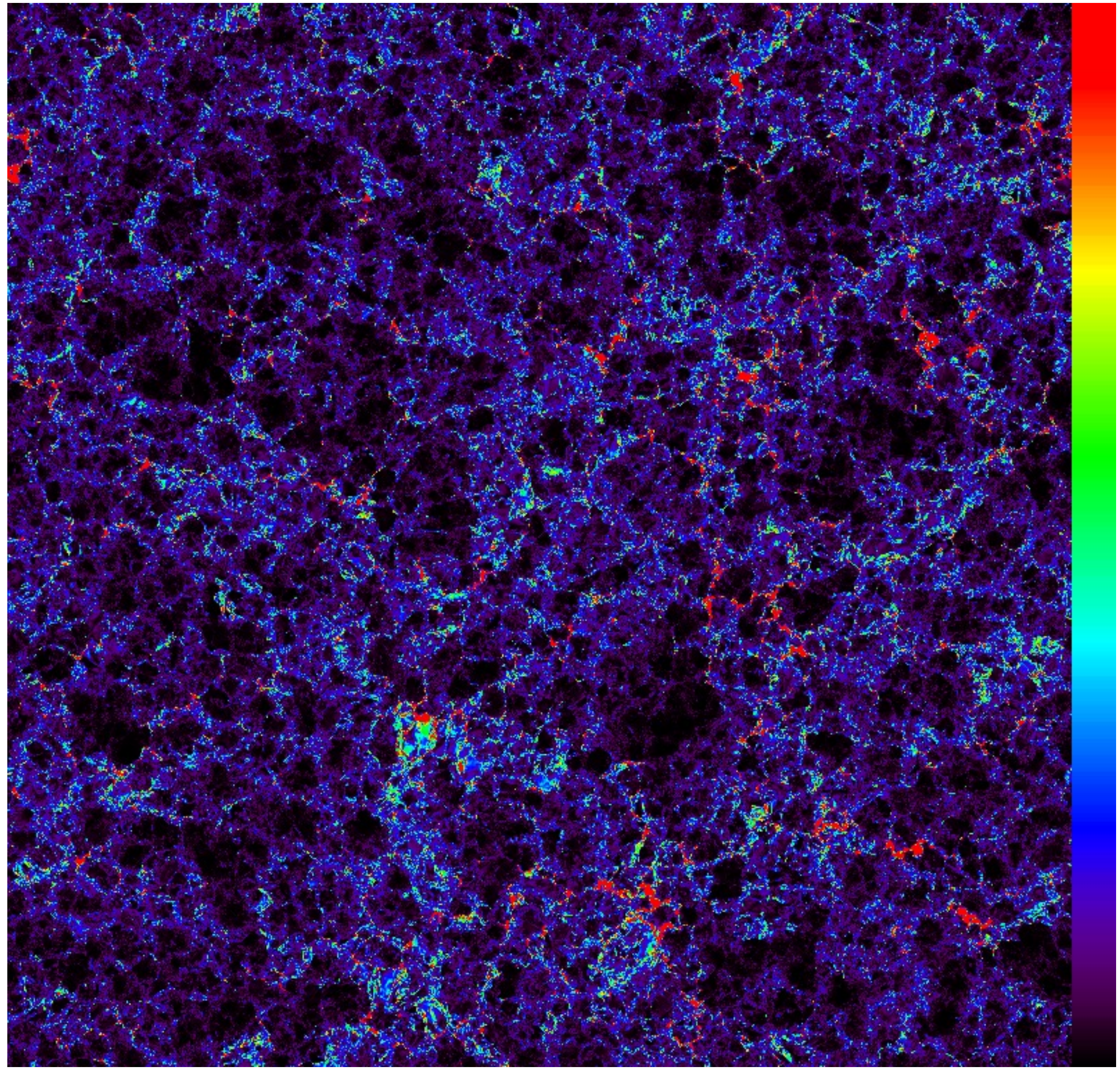


25x25x6.2 Mm

Larger scale organization and "voids"





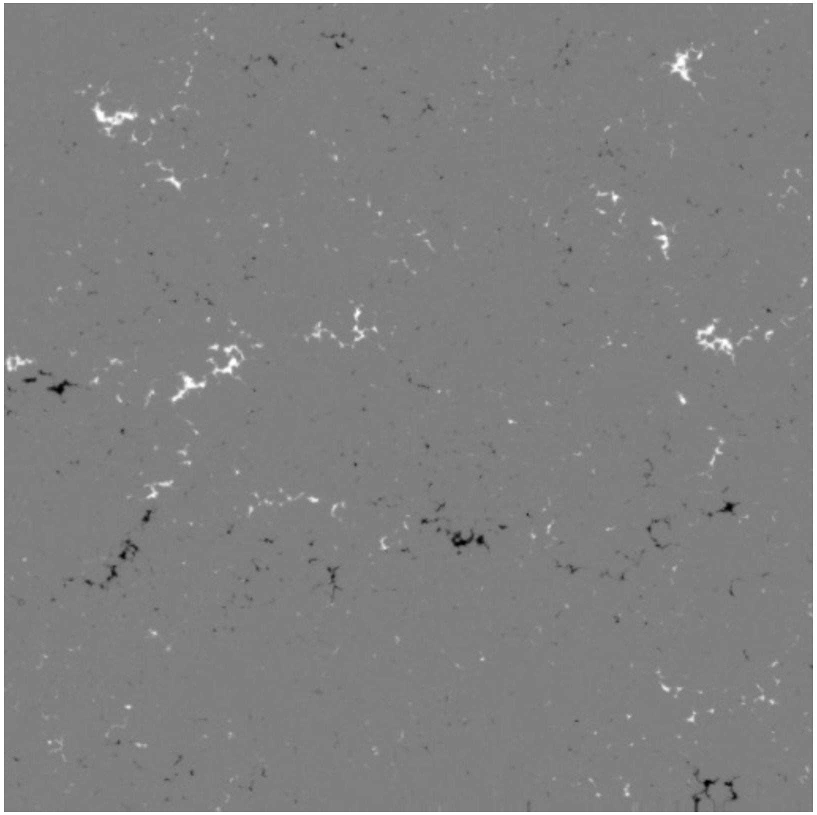


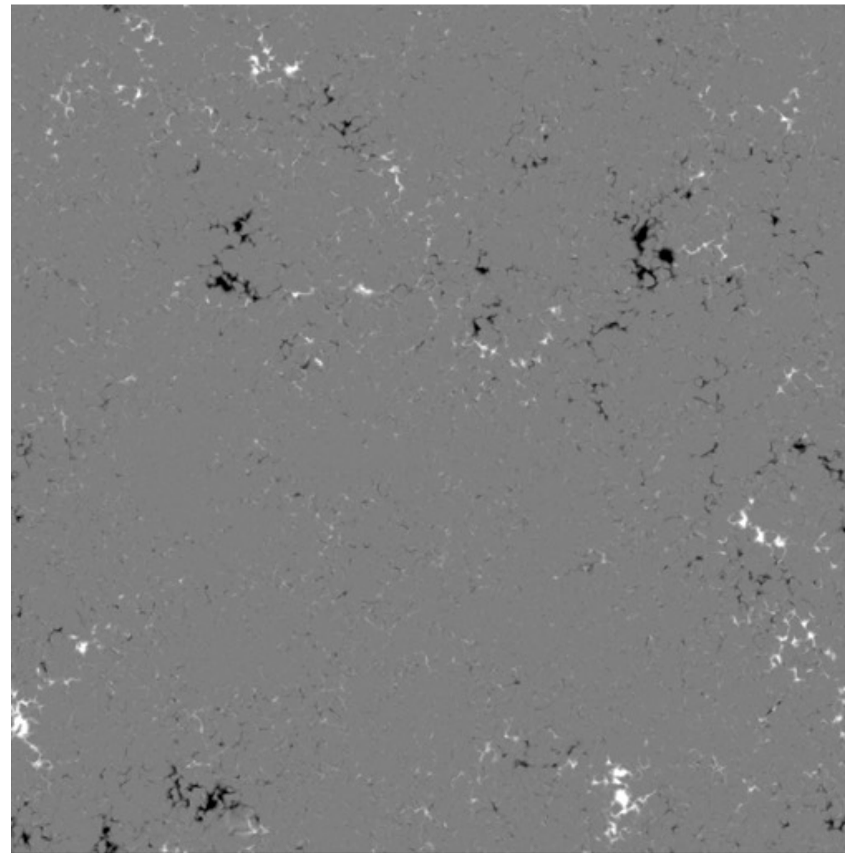
1 kG

0 kG

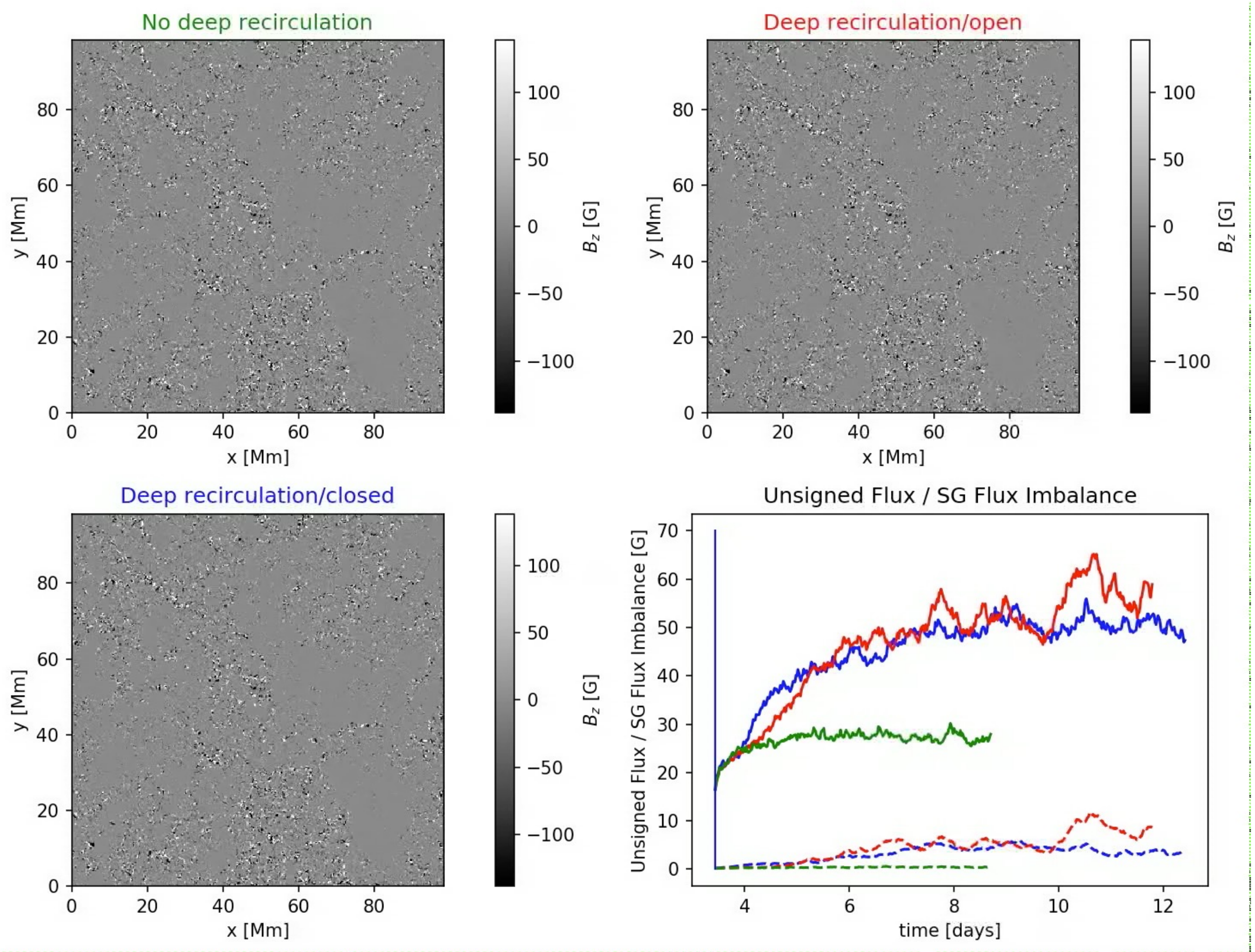
98x98x17.8 Mm

Quiz: Which map is an observation/simulation?

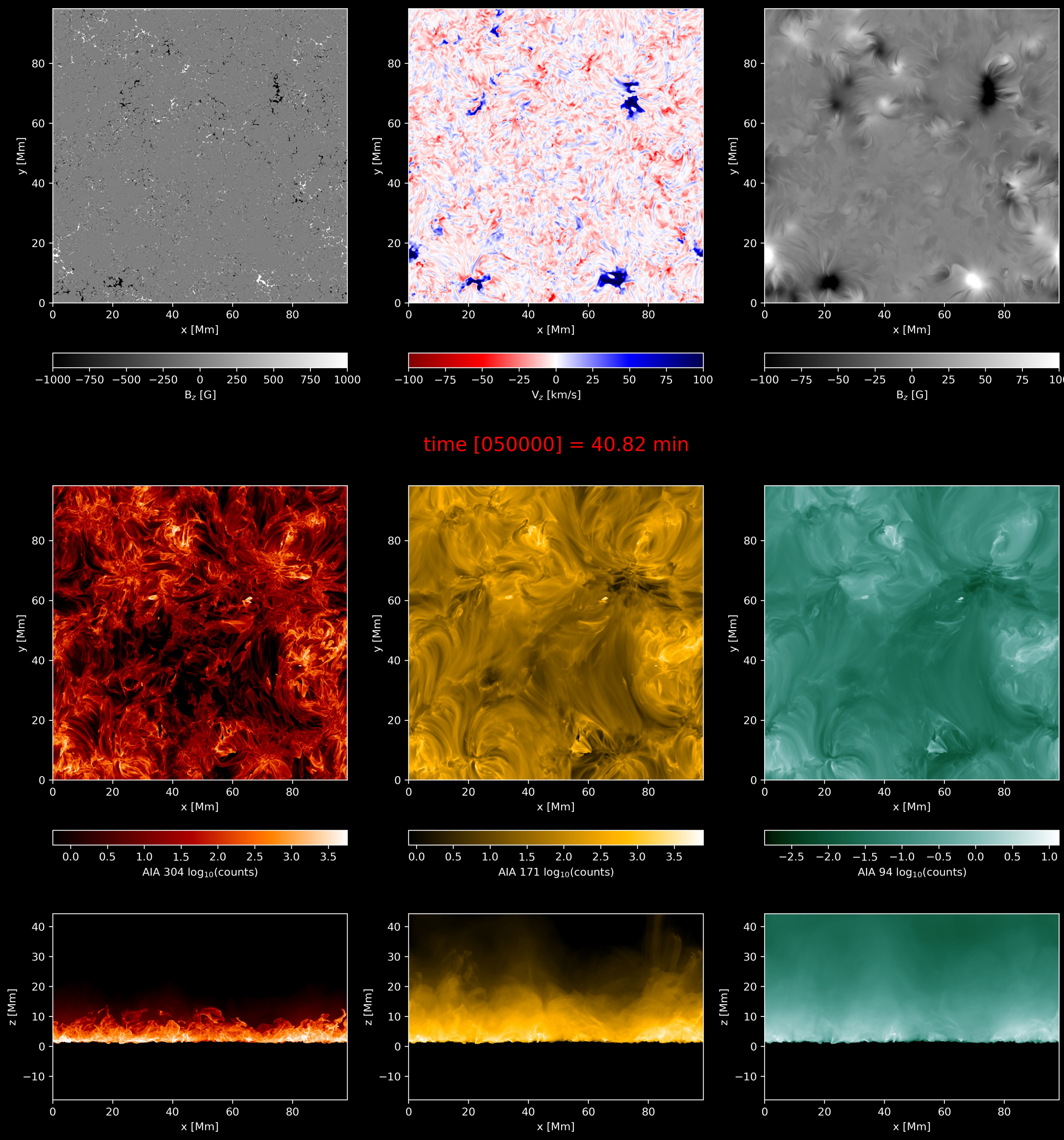




Deep recirculation and large-scale flux imbalance



- 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 an quiet sun corona



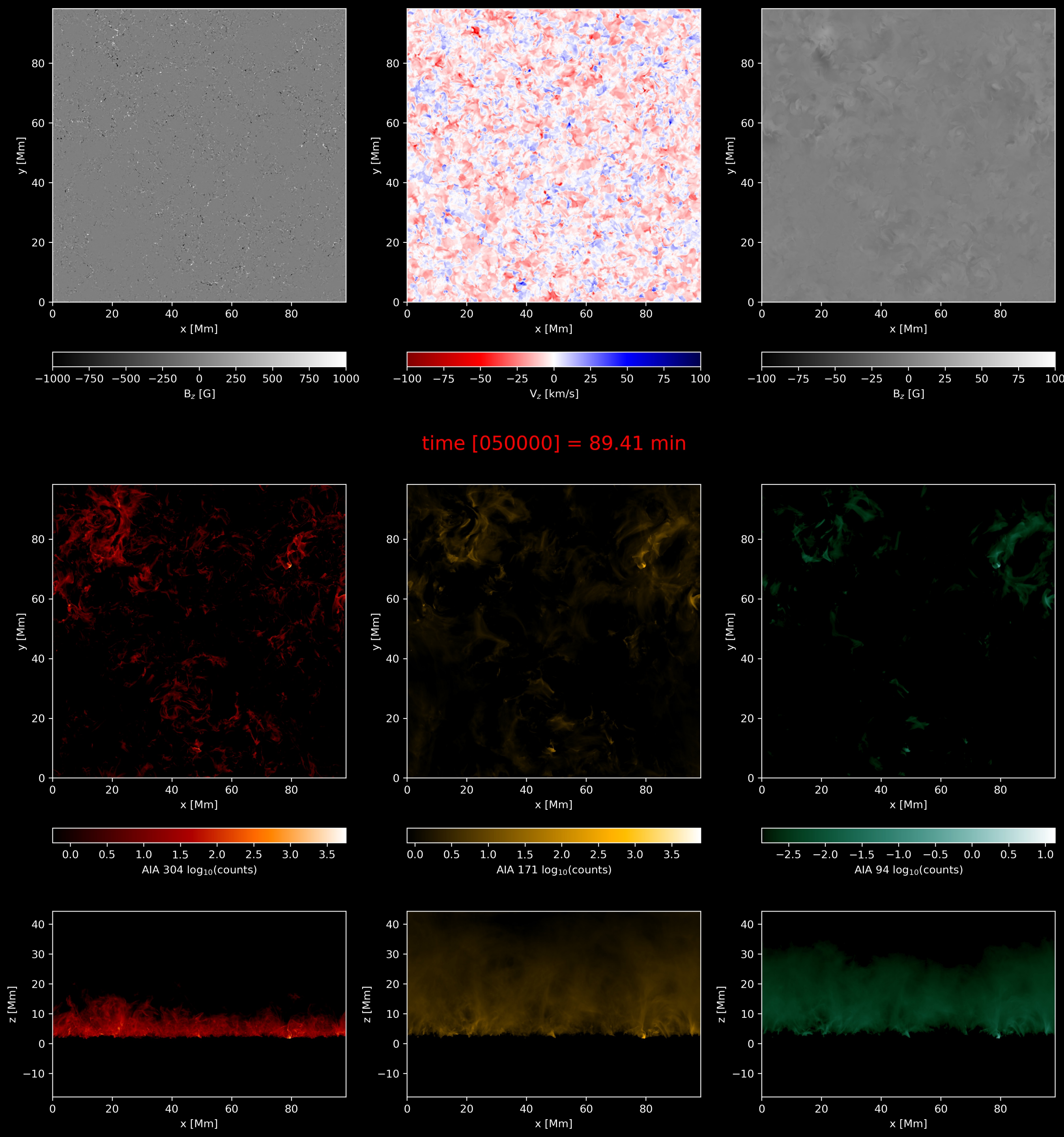
Corona with deep recirculation

Total radiative loss

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

Withbroe & Noyes (1977)

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

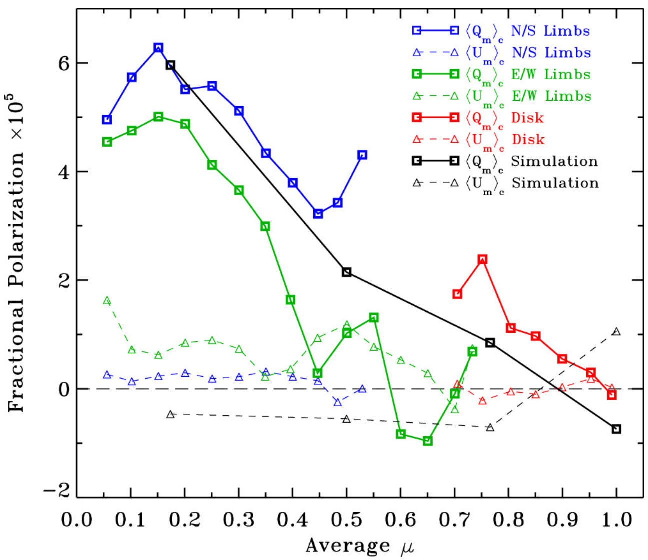


Corona without deep recirculation

Total radiative loss

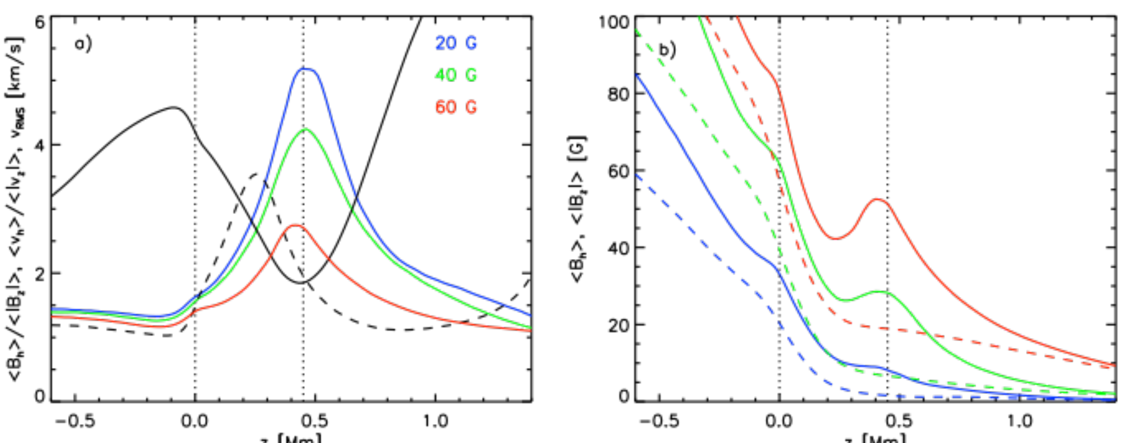
$\sim 10^4$ erg/cm^2/s

Horizontal magnetic fields



Lites et al. (2017)

- Orosco Suárez et al. (2007), Lites et al. (2008, 2011), Orosco Suárez & Bellot Rubio (2012)
  - Ratio of horizontal to vertical field strength in Hinode observations around 3-5
- Schüssler & Vögler (2008)
  - Dominance of horizontal field above photosphere
  - Ratio about 4-6 over formation height of Hinode lines
- Rempel (2014)
  - Peak around 450 km above tau=1, field strength dependent
- Lites et al. (2017)
  - CLV of Q & U agrees well with simulations



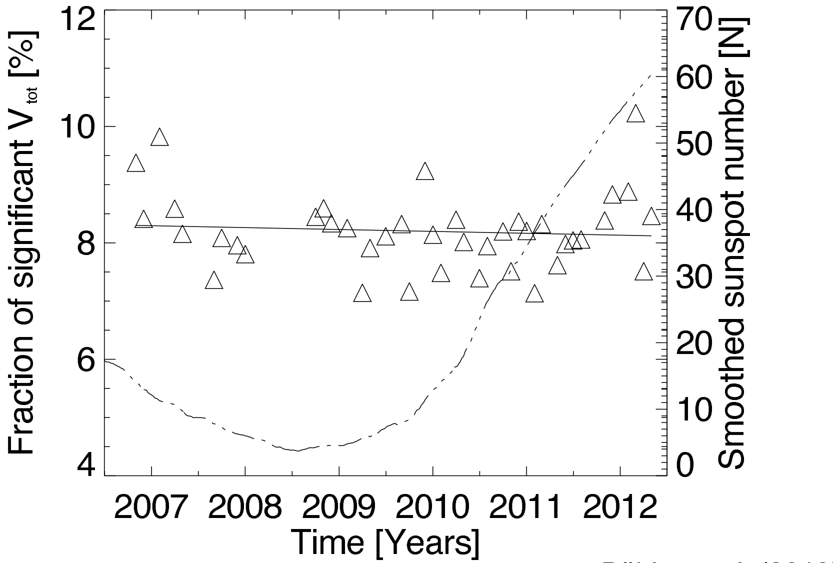
Rempel (2014)

Field anisotropy coincides with the minimum of turbulent RMS velocity in solar atmosphere. Potential explanation: Turbulent diamagnetism!

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times \left(\overline{\mathbf{v}} \times \overline{\mathbf{B}} + \gamma \times \overline{\mathbf{B}} \ldots\right)$$

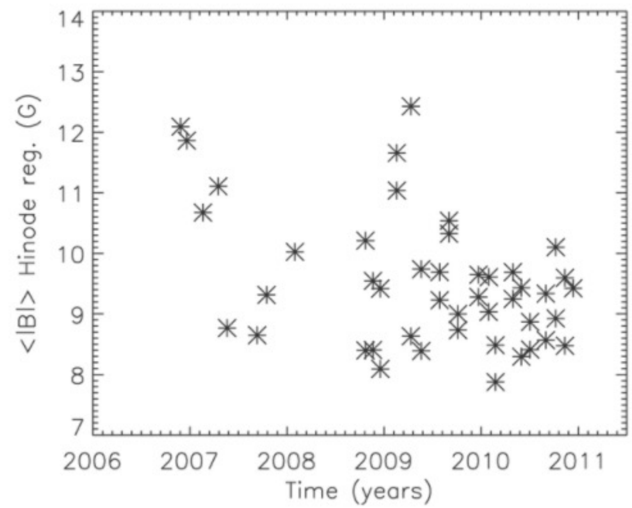
$$\gamma = -\frac{1}{6}\tau_c \nabla \overline{\mathbf{v}'^2}$$

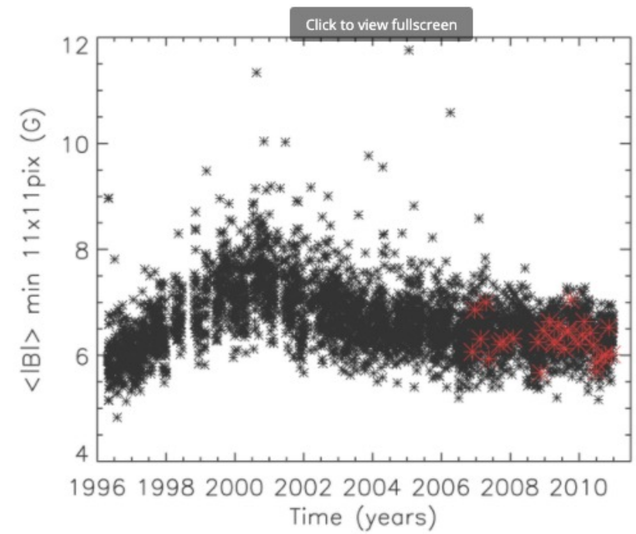
Does the QS vary with the solar cycle?



Bühler et al. (2013)
(Hinode)

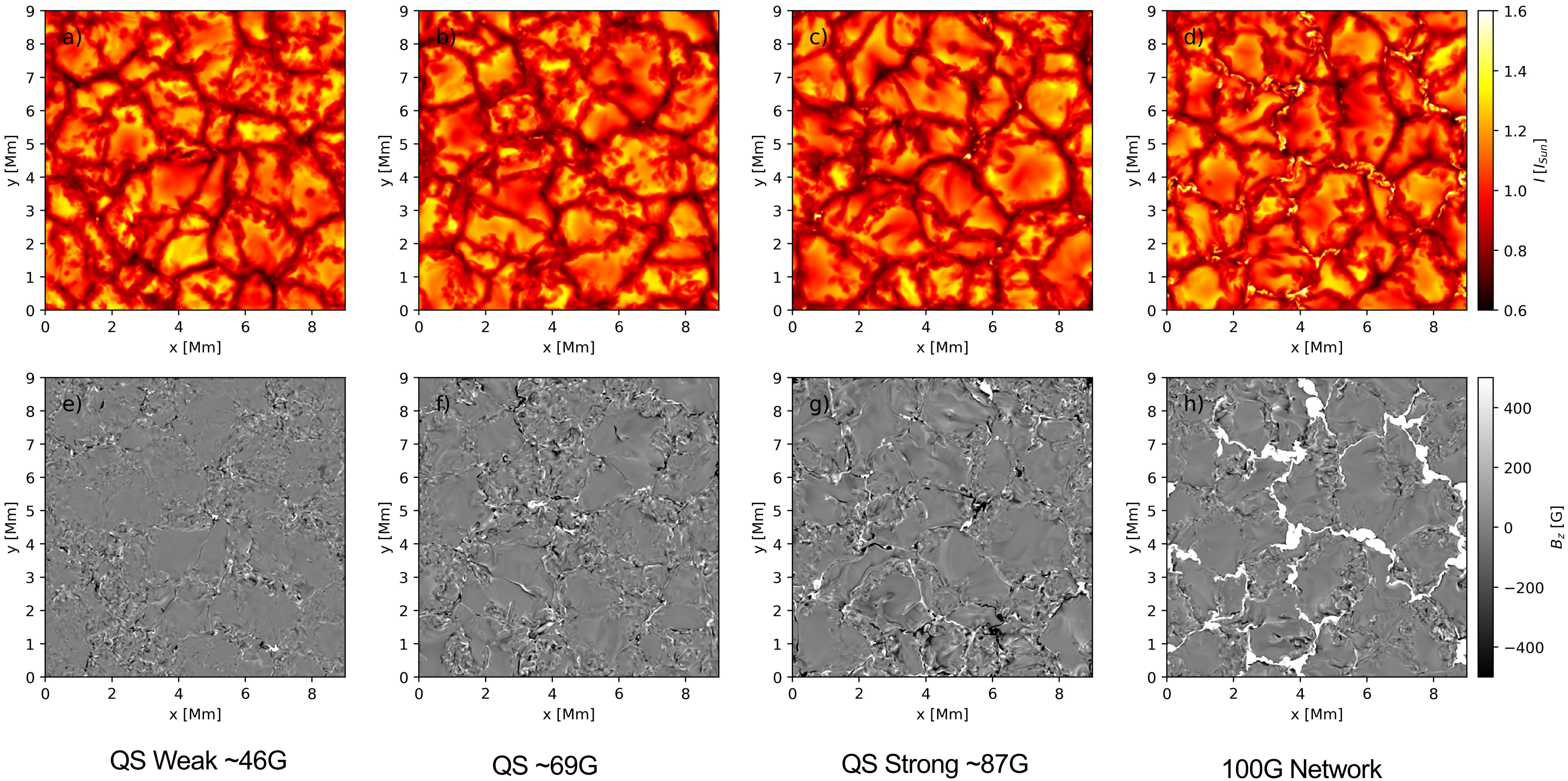
- Results from direct field measurements are debated
- Need perhaps a longer Hinode analysis (another 9 years of data)
- Can we use TSI to constrain the QS variation?





Meunier (2018)
(MDI)

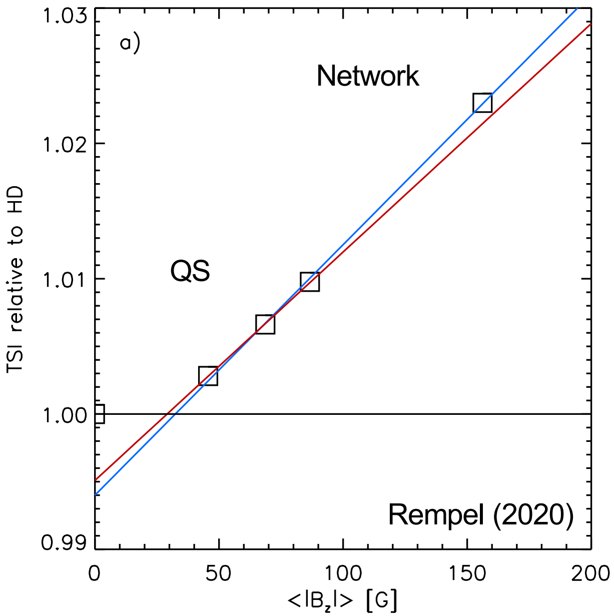
TSI sensitivity to the QS field strength

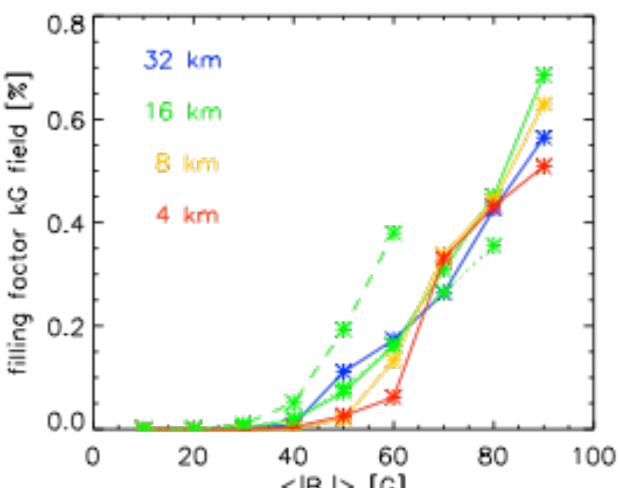


Zeeman and Hanle measurements (e.g. Danilovic et al. 2016, del Pino Alemán et al. 2018) suggest a QS field strength (<|B_Z|> @ tau=1) of 60 – 80 G

From Rempel (2020)

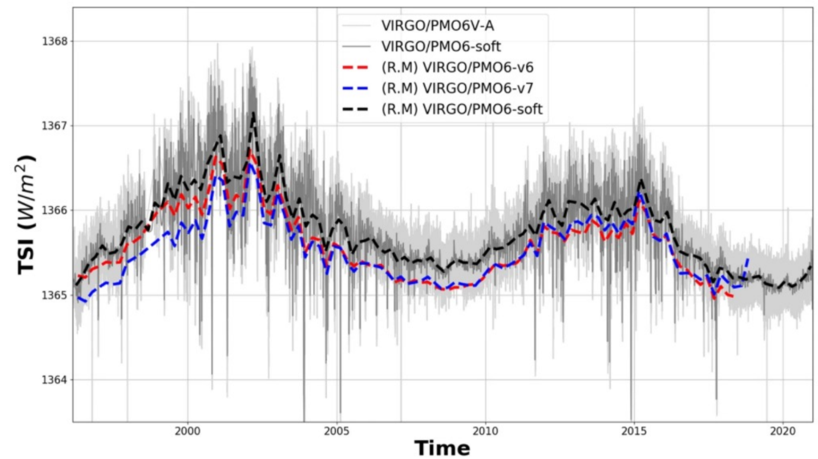
TSI sensitivity of quiet Sun





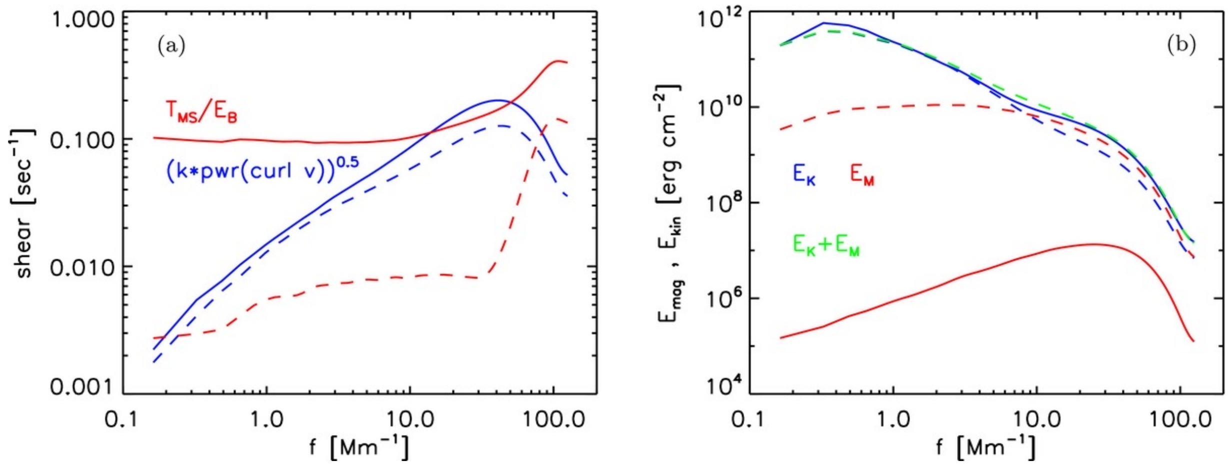
- QS and (weak) network models show similar overall trend:
  - 0.14% TSI increase per each 10G of mean vertical field strength at tau=1
  - Net flux imbalance has secondary effect
- Consequence:
  - Variation of QS with regular solar cycle has to be ***very*** small: 10% variation would lead to 0.1% TSI variation alone

if the QS would vary by 10% (about 7G out of 70G)



Finsterle et al. (2021)

Dynamo saturation



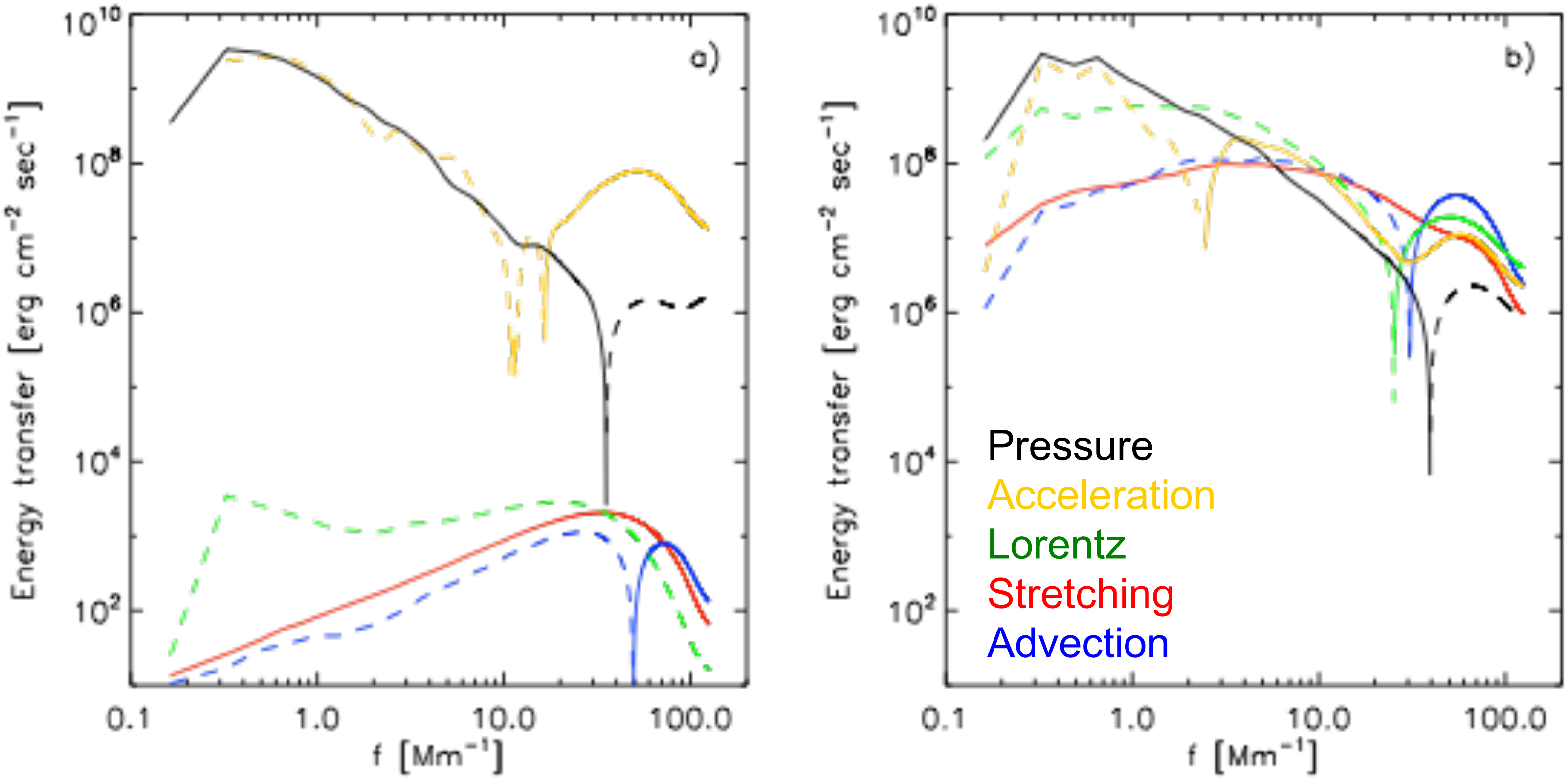
- Naïve picture of saturation:
  - Lorentz force feedback reduces flow amplitudes until dynamo growth rate approaches zero
- Does not work for SSD
  - SSD is fundamental property of turbulent flow and the flow of a saturated dynamo remains turbulent
- Misalignment of velocity shear and magnetic field, misalignment of induced field with existing field

$$T_{MS}(k) = \frac{1}{8\pi}\widehat{\mathbf{B}}(k)\cdot\widehat{[(\mathbf{B}\cdot\nabla)\mathbf{v}]}^{*}(k) + c.c.$$

$$E_M(k) = \frac{1}{8\pi}\widehat{\mathbf{B}}(k)\cdot\widehat{\mathbf{B}}^{*}(k)$$

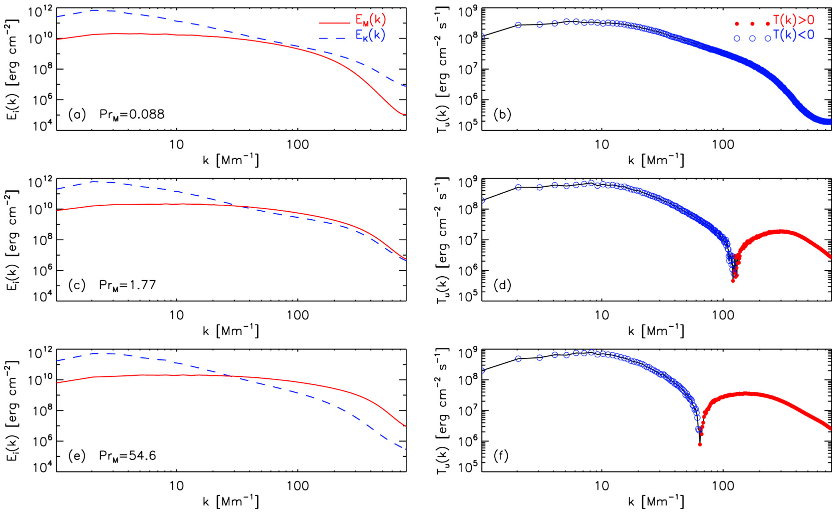
$$S(k) = T_{MS}(k)/E_M(k)$$

Kinematic to saturated regime: Transfer functions

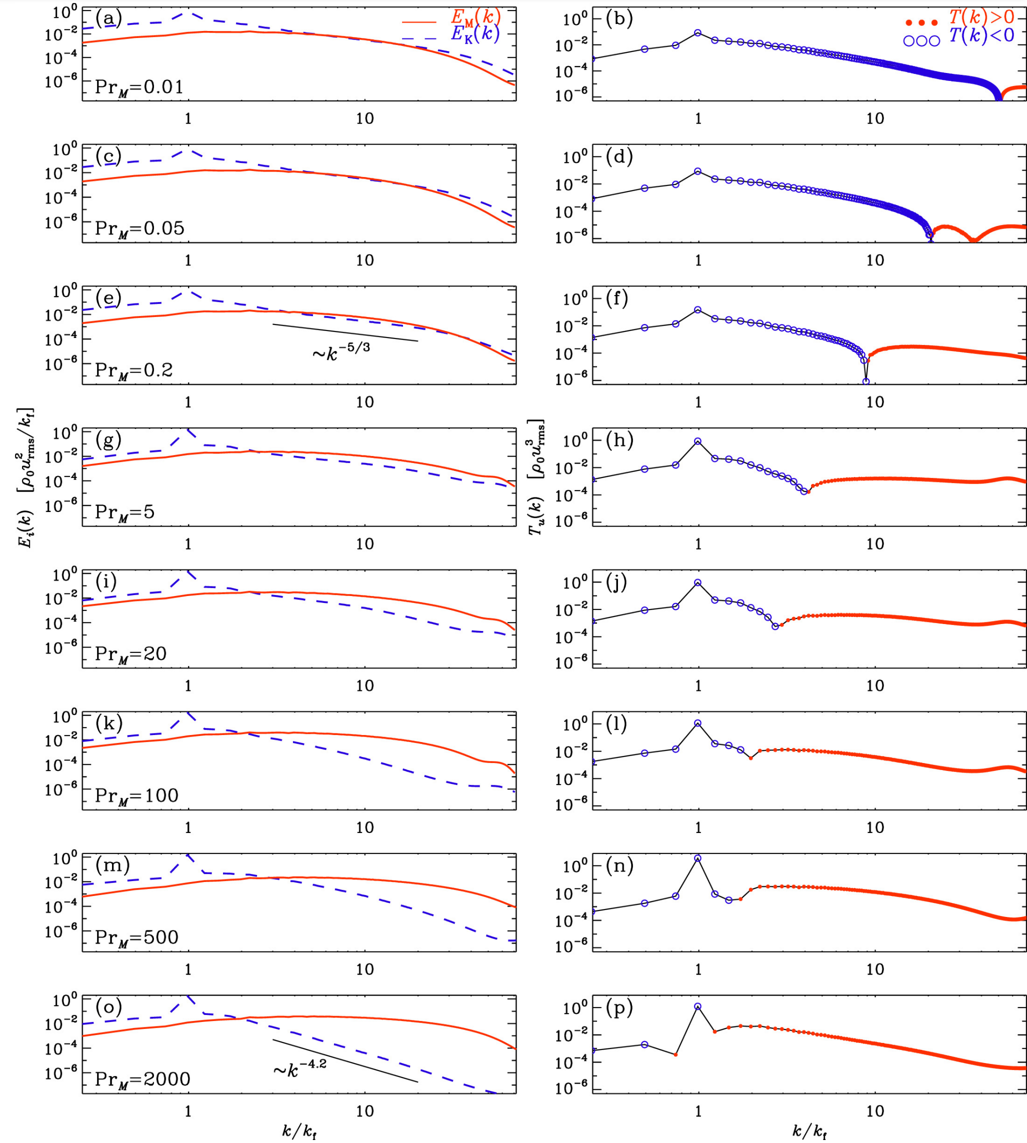


- Kinematic phase:
  - Energy exchange at L ~ 6-8 Δx
  - Depends on resolution
- Saturated phase:
  - Energy exchange at L ~ 250 km (downflow lanes)
  - Does not depend on resolution

Pm dependence of energy transfers

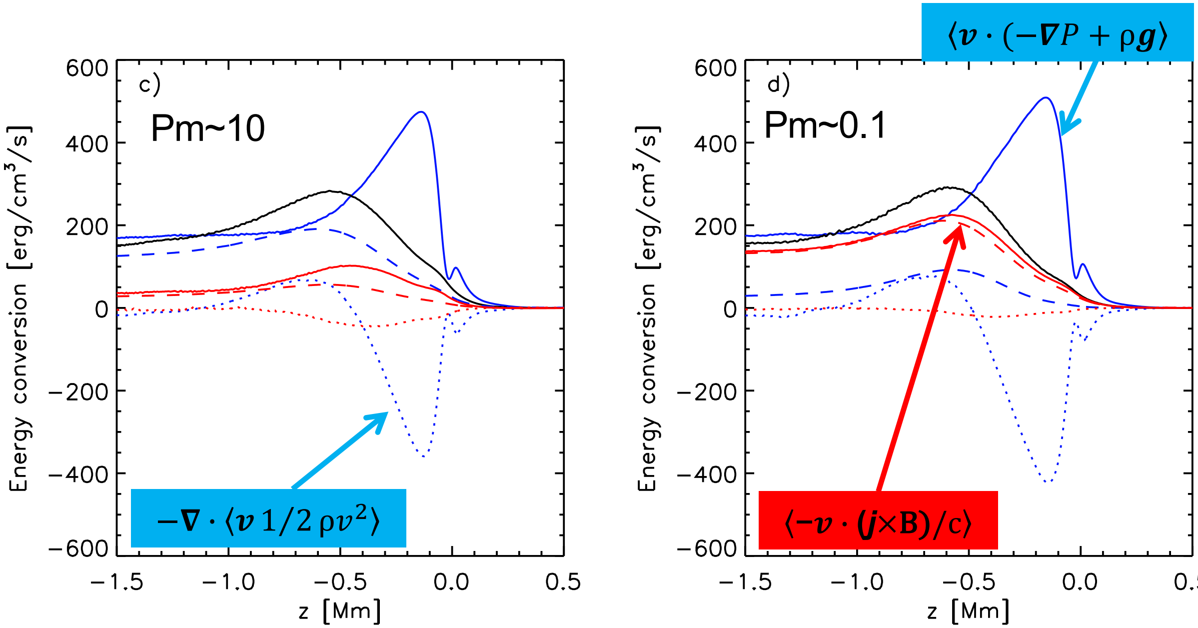


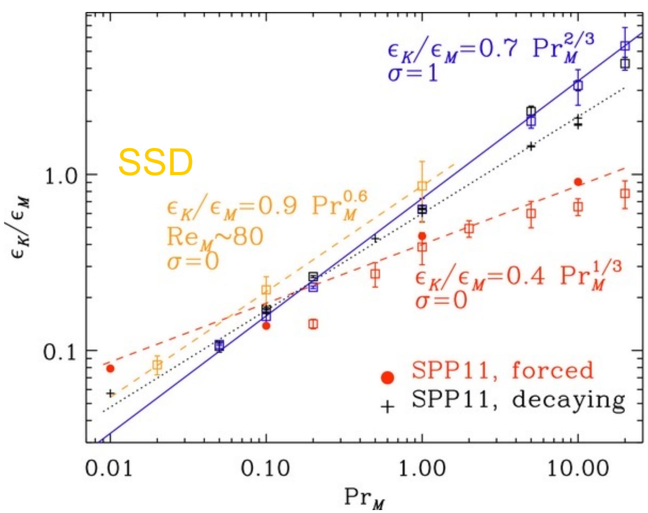
- High Pm regime has a "reversed dynamo" on small-scales, i.e. Lorentz force drives flows
- Robust result realized in both LES and DNS simulations
- Reversed dynamo reduces total Lorentz force work
- Ratio of viscous to resistive heating depends on Pm



From Brandenburg & Rempel (2019)

SSD energetics

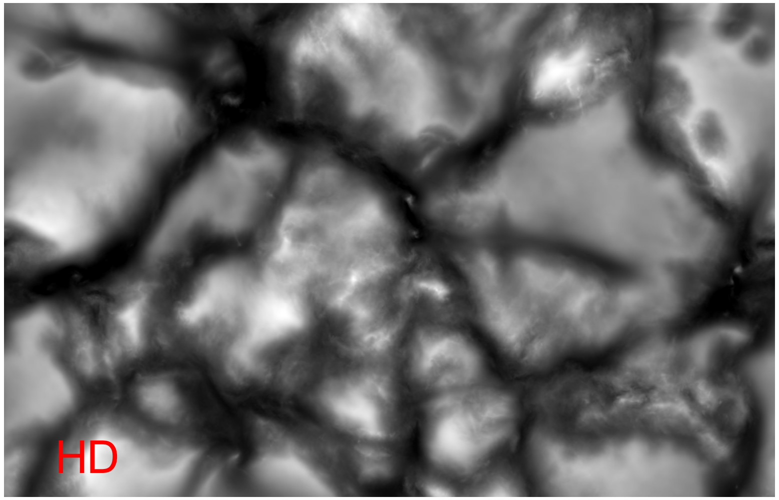


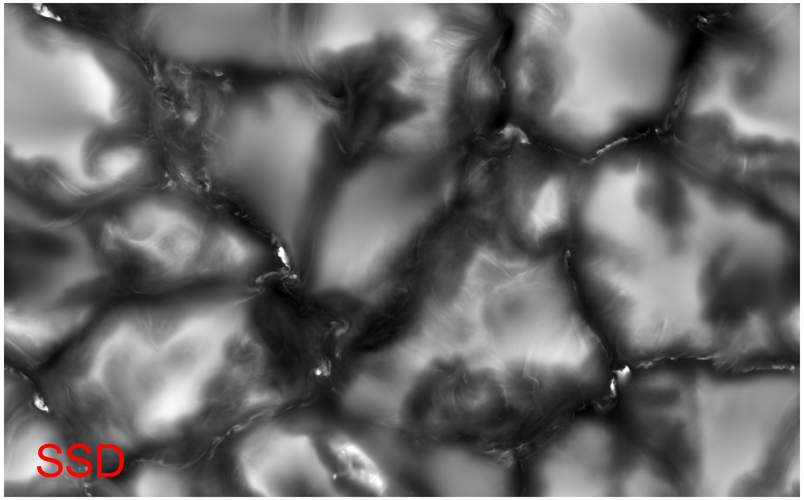


Brandenburg (2014)

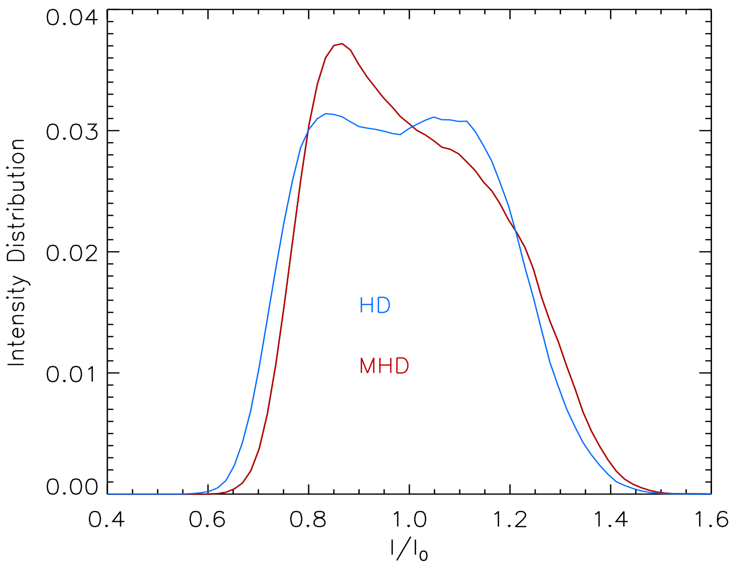
- About 150 erg/cm^3/s "convective driving" available in upper CZ/photosphere to drive dynamo
- Energy transfer to magnetic energy strongly Pm dependent (Brandenburg 2011, 2014, Brandenburg & Rempel 2019)
- Most efficient dynamos (in terms of energy conversion) found for low Pm regime
- Uppermost 1.5 Mm of convection zone: About >0.3 L_{Sun} converted to B
- Total pressure/buoyancy driving in CZ ~ 3 L_{Sun}

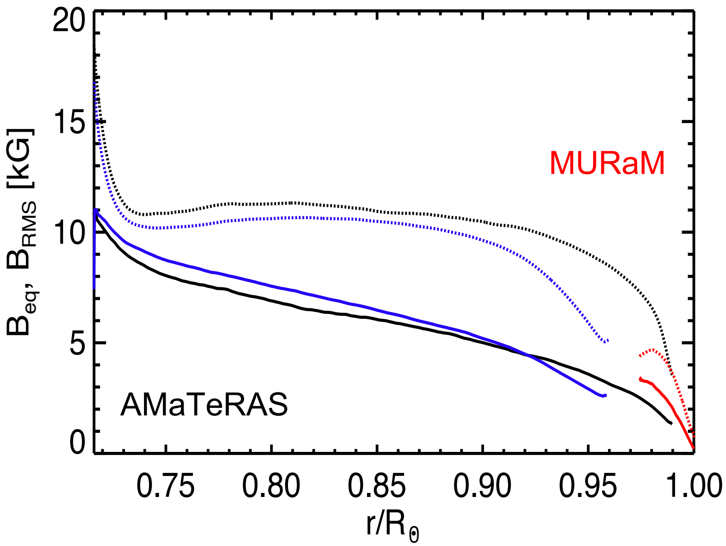
Implications for granulation





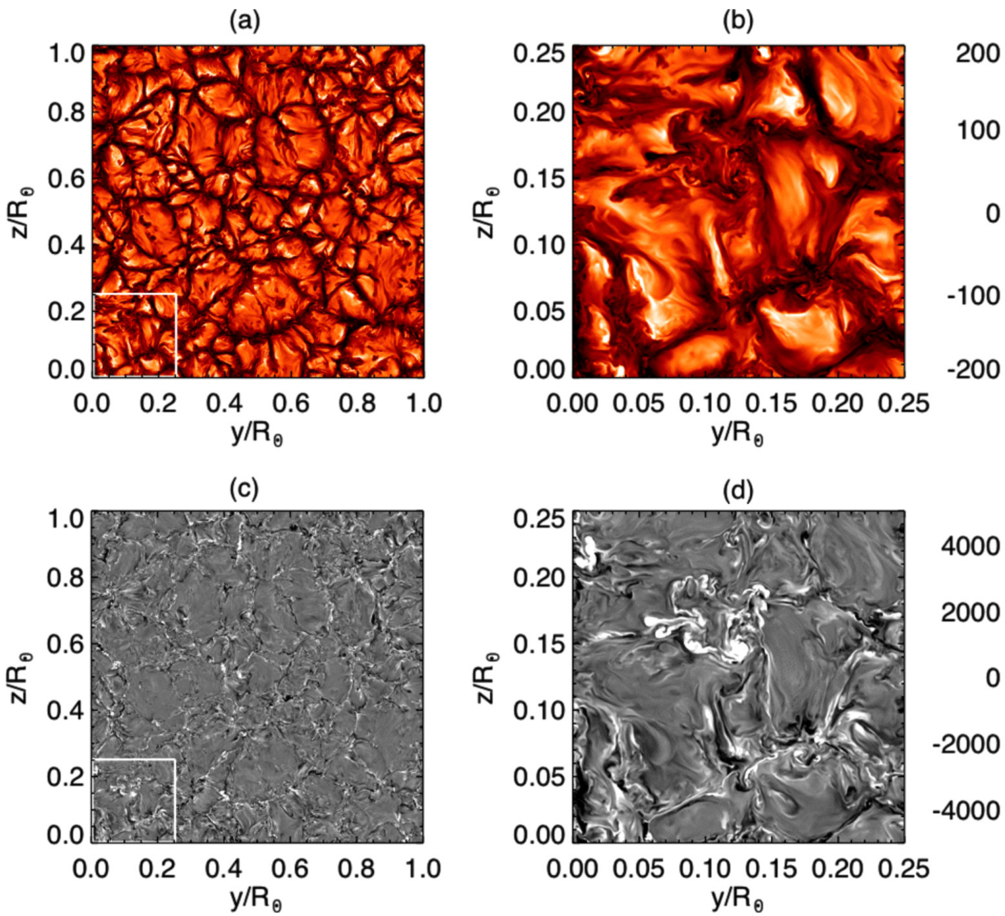
- Shape of intensity PDF strongly resolution dependent
  - Steiner 2017: Asymmetric double peak disappear for high resolution HD
- Asymmetric shape fingerprint of SSD!





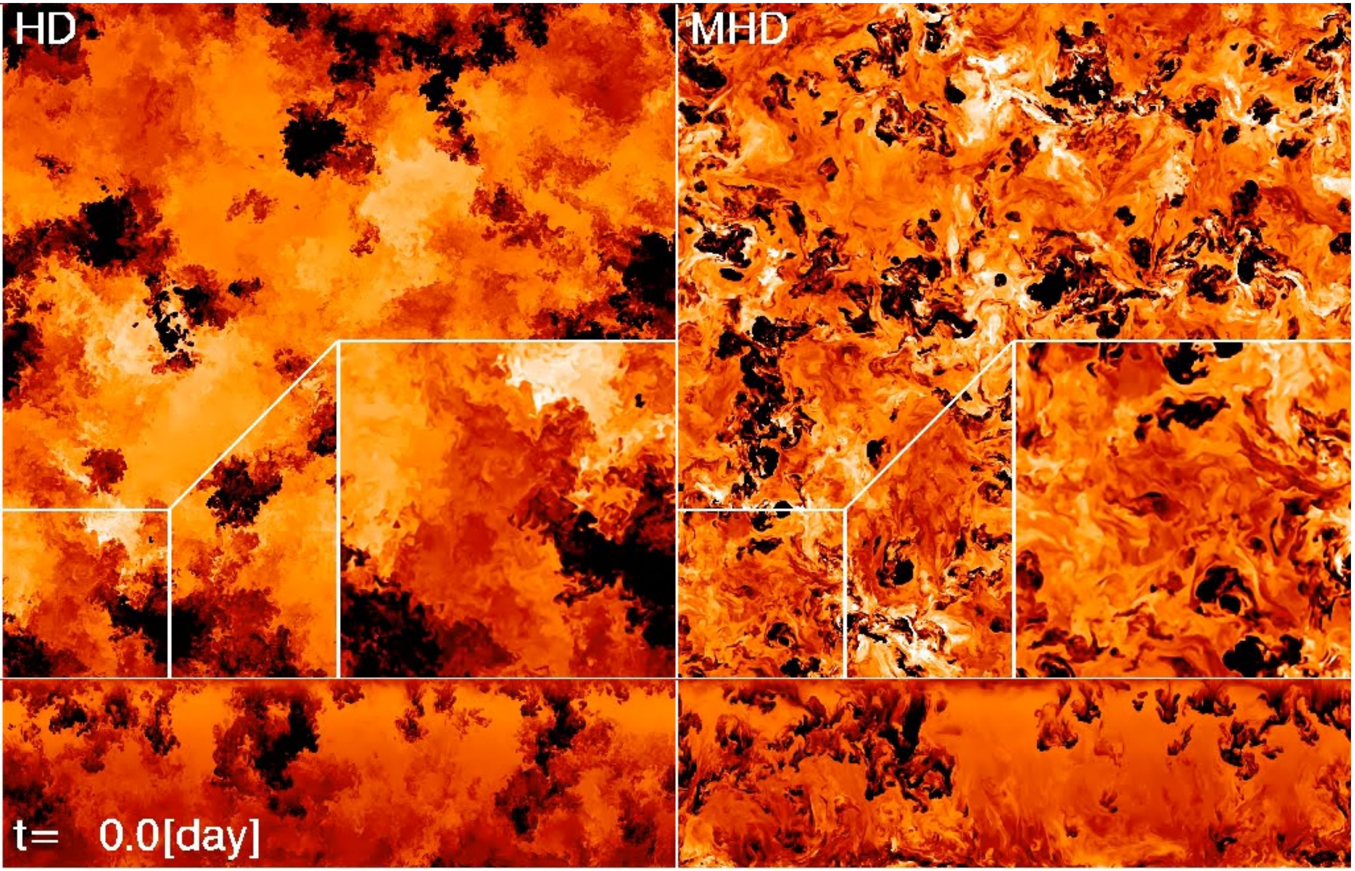
Observed strength of quiet sun magnetic field implies a strength close to equipartition
throughout most of the convection zone!

Is the small-scale field dynamically relevant?



Hotta et al. 2015

Implications for the deep convection zone

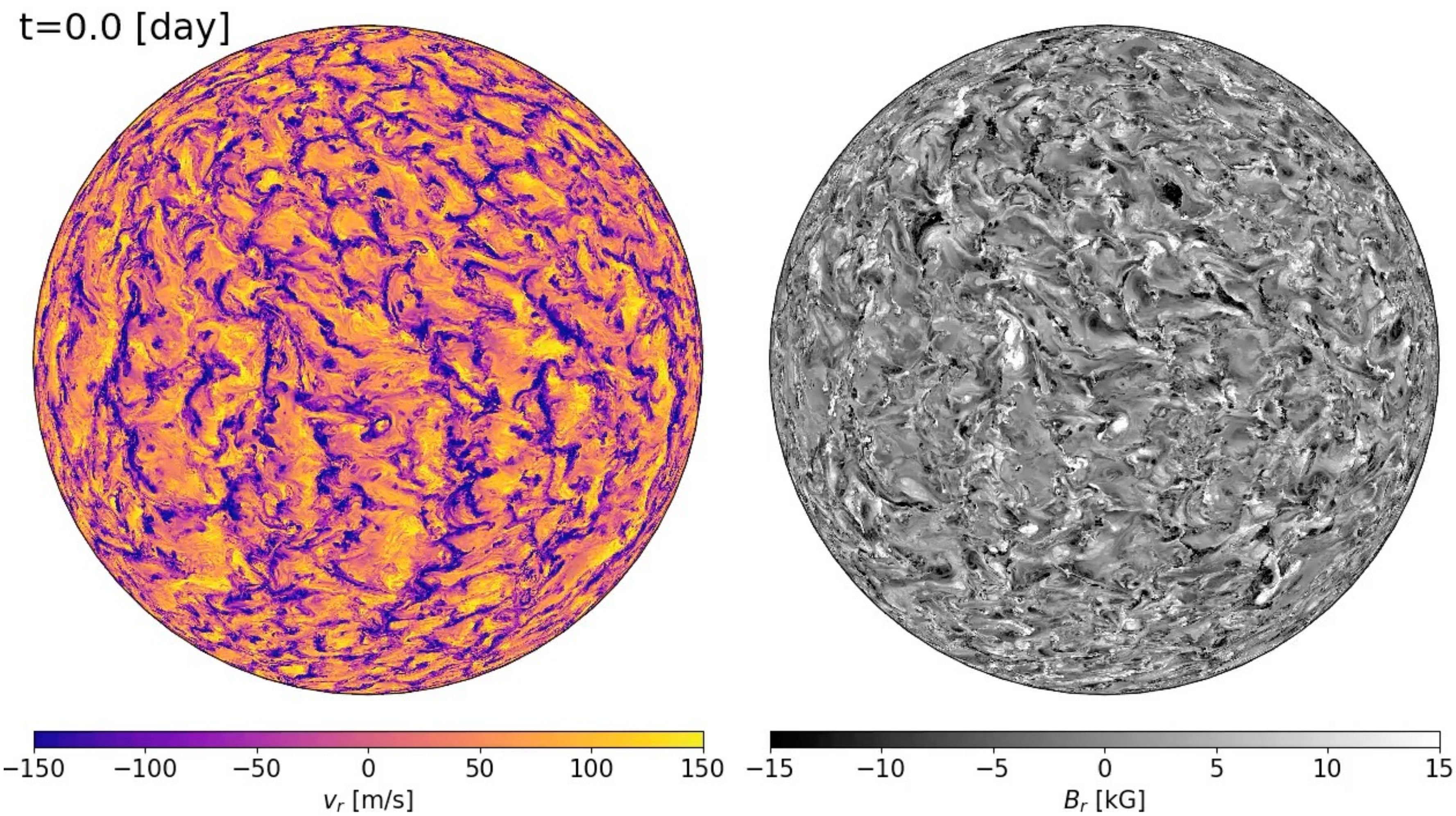


Hotta et al. 2015

Convection with efficient SSD shows more narrow and cooler downflow plumes, similar to expectation in high thermal Prandtl number convection

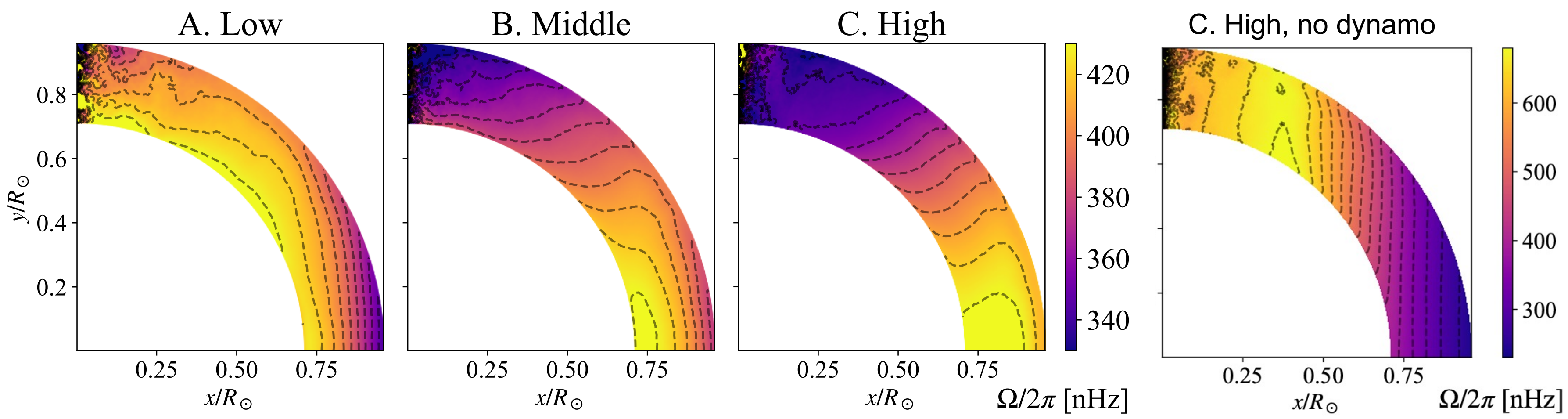
Maxwell stress mimics viscous stresses, i.e. MHD system behaves like a more viscous HD system

Differential rotation/convectice conundrum

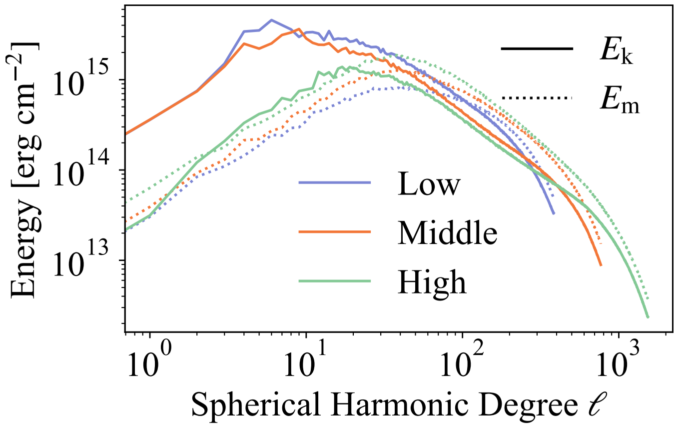


From Hotta & Kusano (2021)

Differential rotation/convectice conundrum

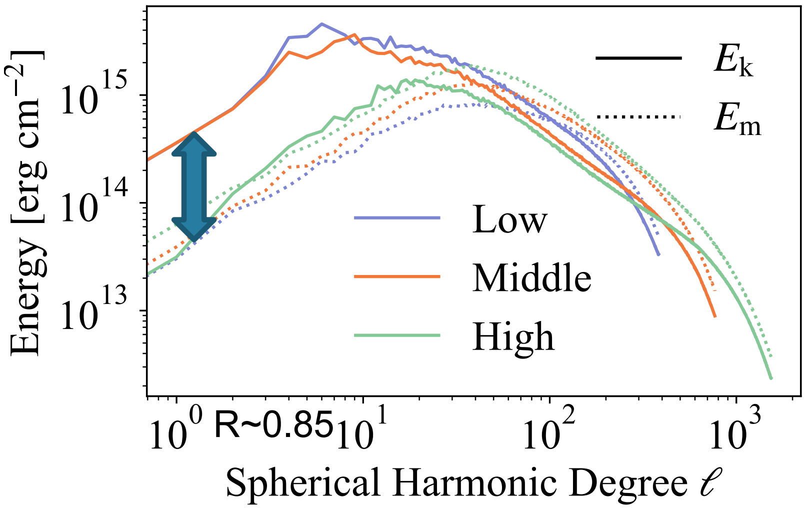


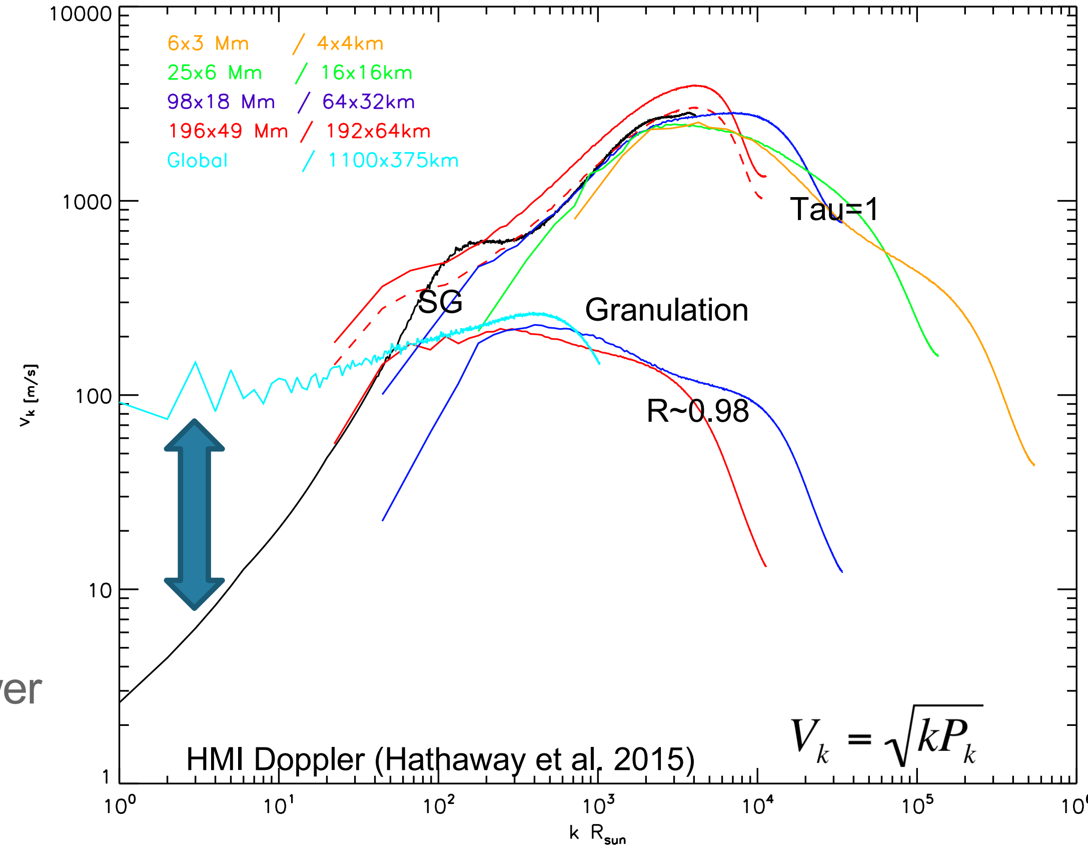
- Flip from fast pole to fast equator for high resolution simulation ~384x3072x6144, happens only in presence of magnetic field
- Suppression of flows on large scales, peak of power shifts from l=6 to l=30
- Did not (yet?) produce a large-scale field, possibly due to total simulation time (4000 days)



From Hotta & Kusano (2021, 2022)

Solar velocity spectrum at large scales

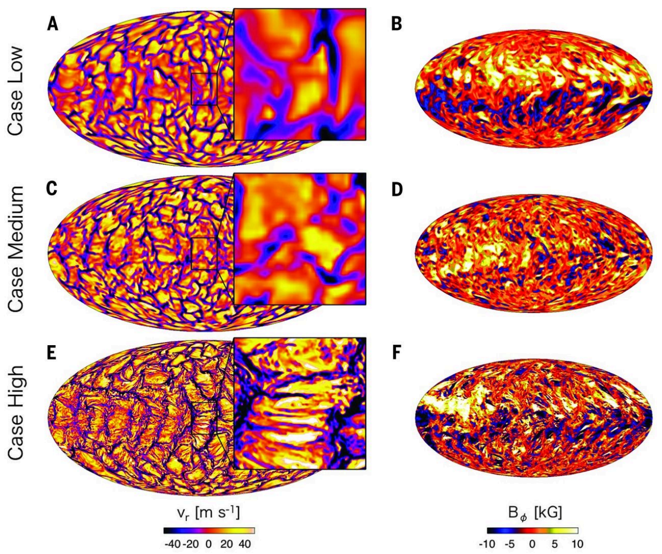




On scales larger than SG (~30Mm, l~120) simulations have too much power compared to observations!

Is there something very fundamental about highly stratified convection we do not understand?

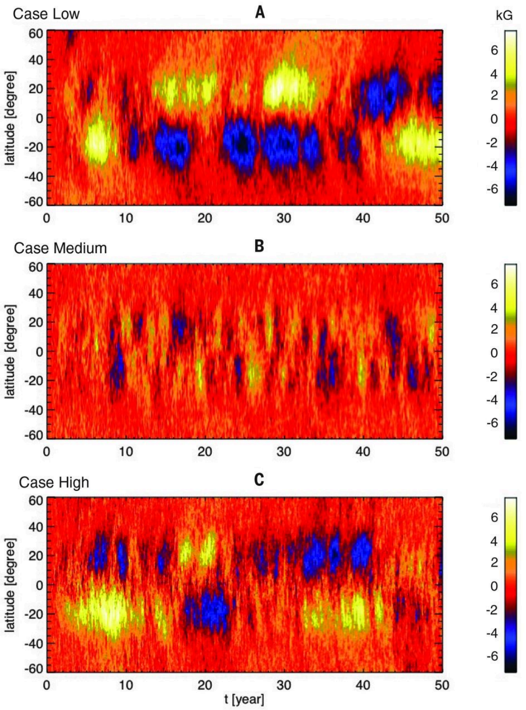
Large-scale dynamo action in presence of small-scale field



- Increasing resolution leads to reduced coherence of large-scale field
- Coherence of large-scale field is regained in presence of efficient small-scale dynamo

- Detailed mechanism at work not fully understood

- See also:
  Väisälä et al. (2021)



From Hotta et al. (2016)

Remarks on nomenclature: local, small-scale

- The community uses the terms “small-scale”, “local” and sometimes even “local in the photosphere” as synonyms, but they can be misleading:
- Small-scale
  - The dynamo is small-scale in the turbulence sense during the kinematic growth phase, when the eddies at the smallest scales of the magnetic field determine the dynamics
  - The quiet Sun is always a nearly saturated dynamo, most energy transfers happen at the scale of granular downflow lanes, which is the driving scale of turbulence. This is no longer small-scale in the turbulence sense, but still much smaller than the system scale
- Local
  - The dynamo action is local during the fast kinematic growth phase, but the dynamo slows down significantly during saturation and non-local transport becomes important. The saturated dynamo is distributed over a wide range of scales and depths of the convection zone
- Local in the photosphere
  - The photosphere is the least favorable place for this dynamo to operate, due to a combination of (relatively) low Rm, fast overturning and a low degree of turbulence right in this boundary layer.
  - The dynamo action reaches full speed about 500 km beneath optical depth unity and the photospheric field is to a significant degree the consequence of non-local transport from deeper layers
- Alternative: Turbulent fluctuation dynamo

Summary

- Unsigned magnetic flux in the QS comparable to flux in active regions that emerge during 11 year sunspot cycle
  - Independent origin from large scale dynamo is required
- Most of the magnetic energy is maintained on small scales (50% below 100km in the solar photosphere)
  - SSD independent from large-scale dynamo
  - Dominant dynamo in terms of energy conversion rate
- The dynamo is distributed over a wide range of scales and depths in the convection zone
  - The photosphere is the tip of the iceberg
- Small-scale field is dynamically relevant!
  - Understanding convection, angular momentum transport and large-scale dynamos may require capturing the SSD component
  - Potential solution for "convective conundrum"
- This is likely an issue for most sun-like stars!
  - The Sun is the only star where we can study the SSD in detail