

Solar small-scale magnetic fields and their effect on convection and activity

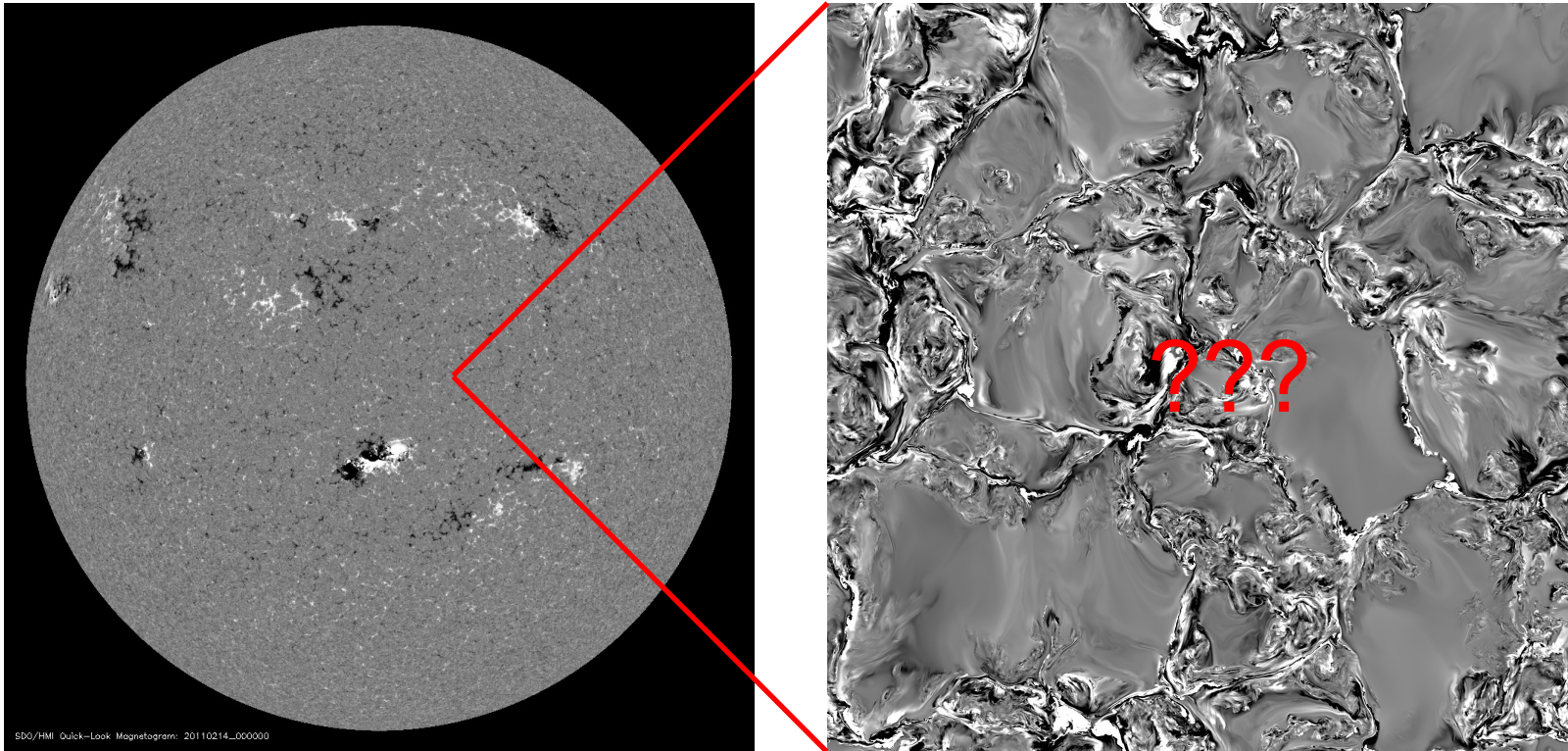
BBSO Summerschool

Matthias Rempel

July 30, 2024

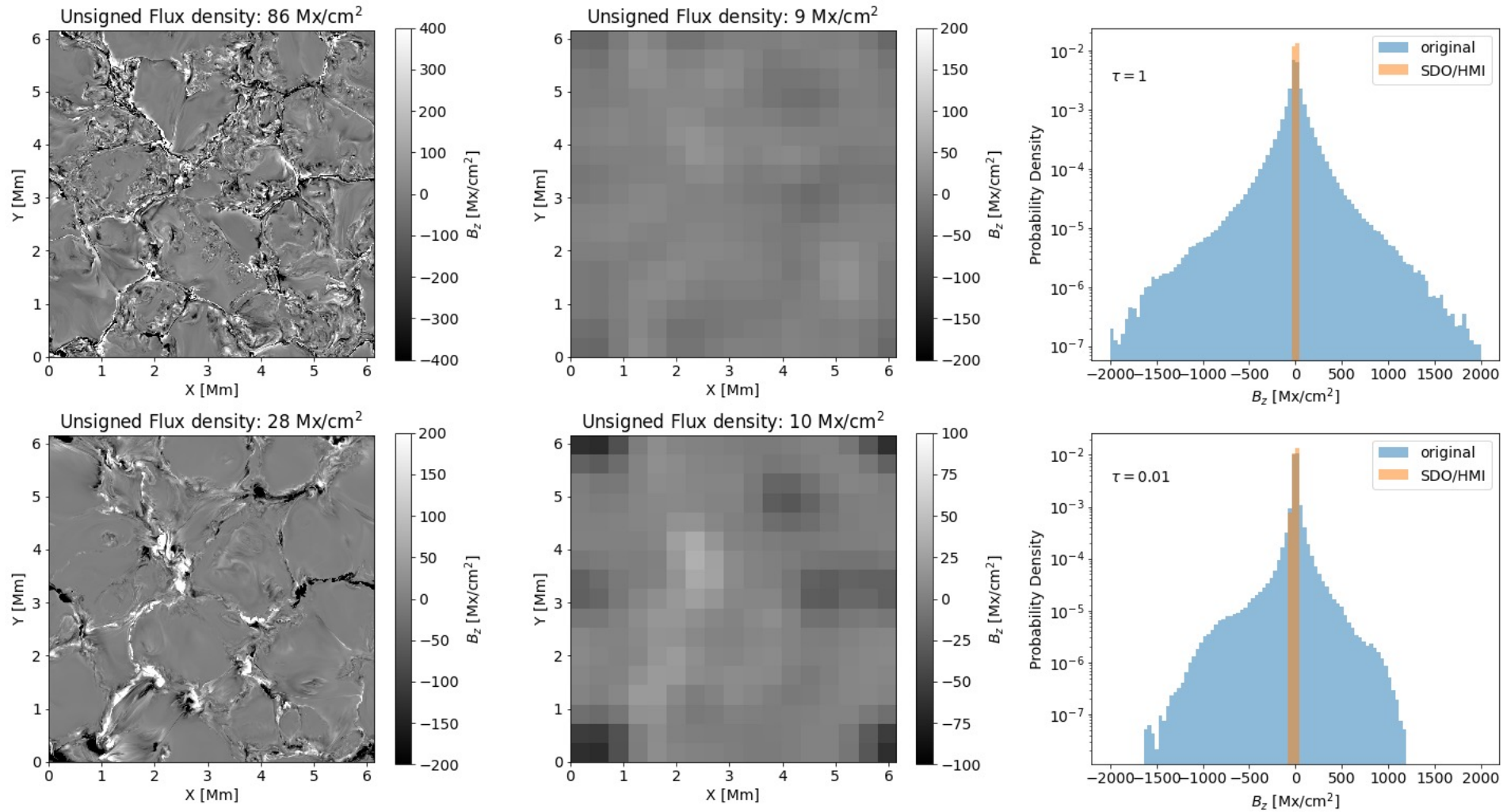


Quiet Sun magnetism

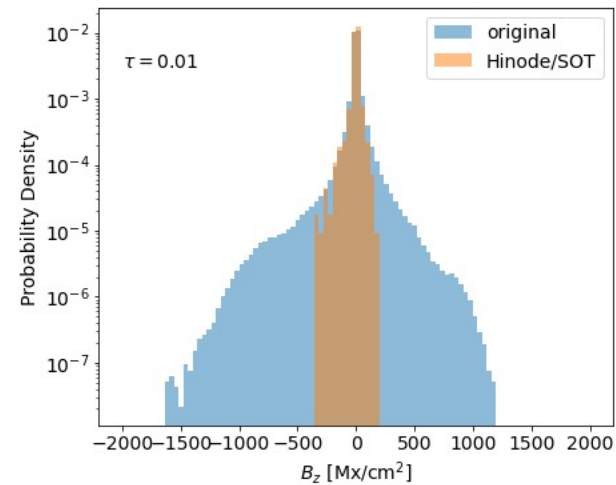
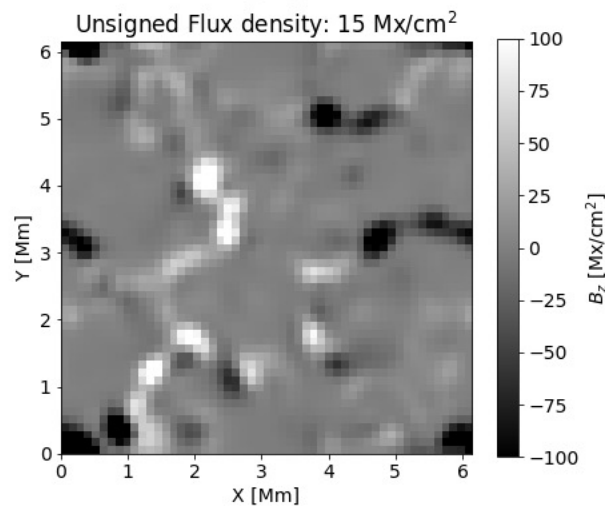
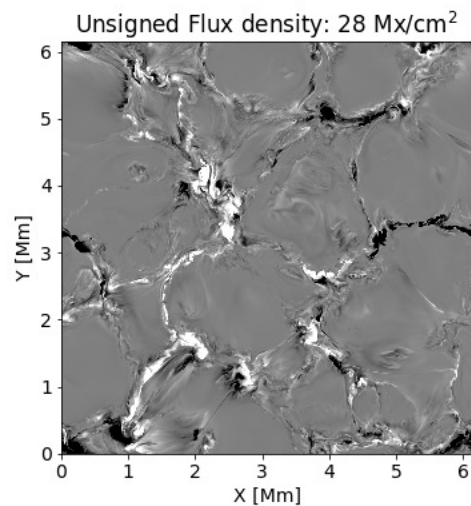
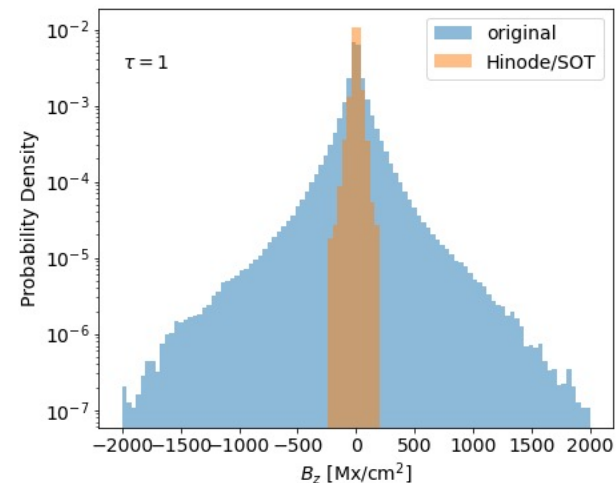
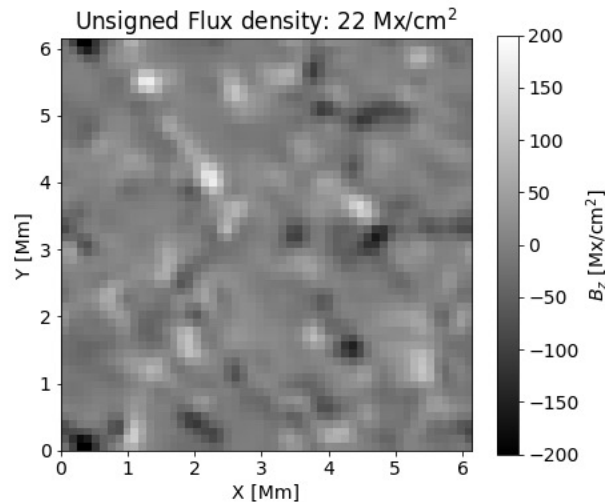
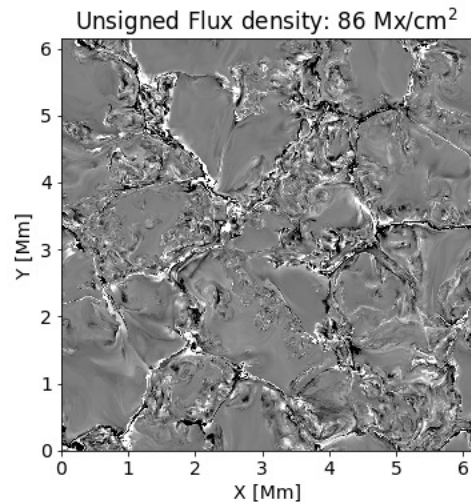


- Most of the solar surface is covered by “quiet Sun” at any time during the sunspot cycle!
- Where does this field come from?
- Does it have dynamic consequences for convection, differential rotation and the large scale dynamo?

How much flux is hiding in QS – HMI ?

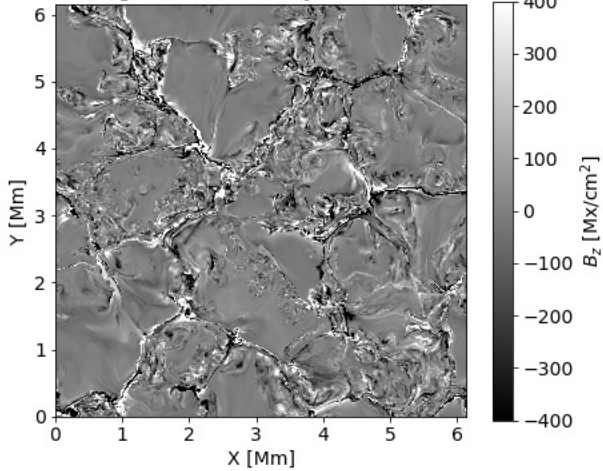


How much flux is hiding in QS - Hinode?

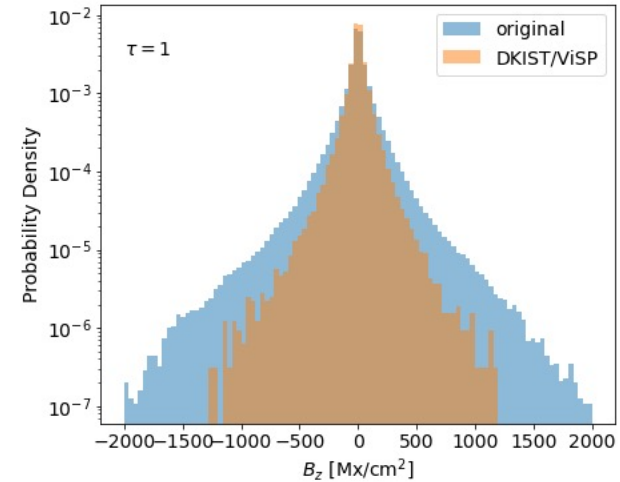
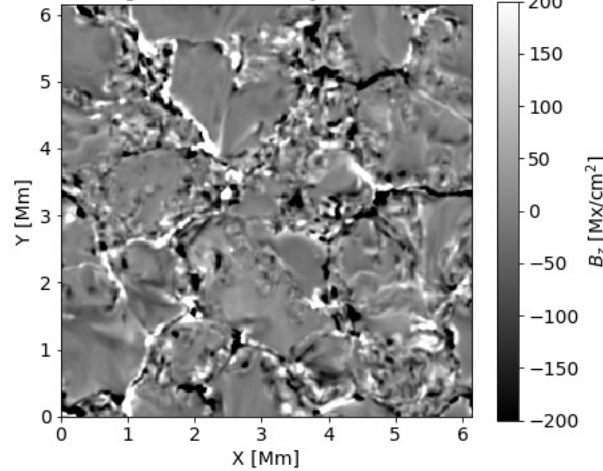


How much flux is hiding in QS – DKIST

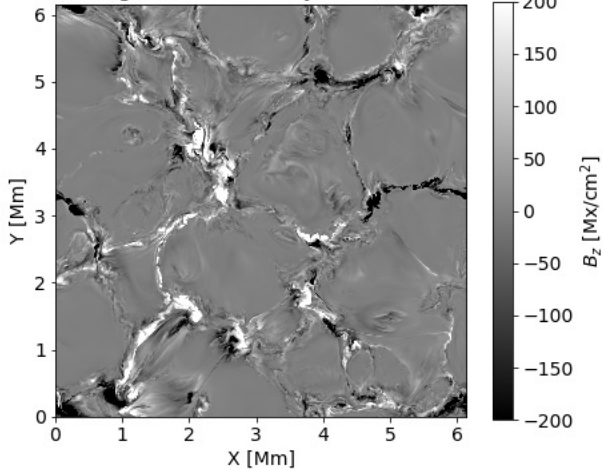
Unsigned Flux density: 86 Mx/cm²



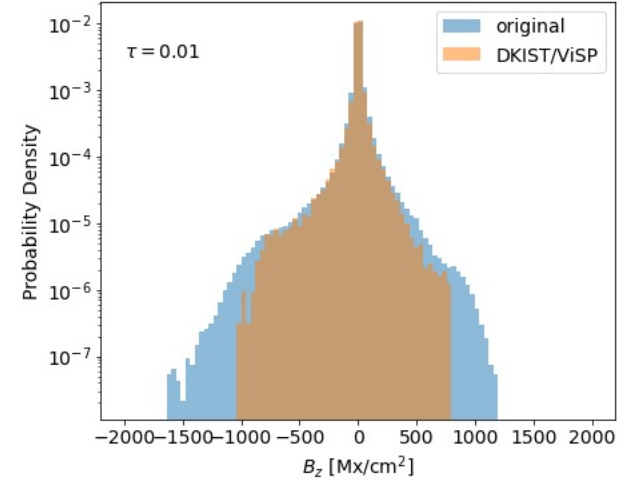
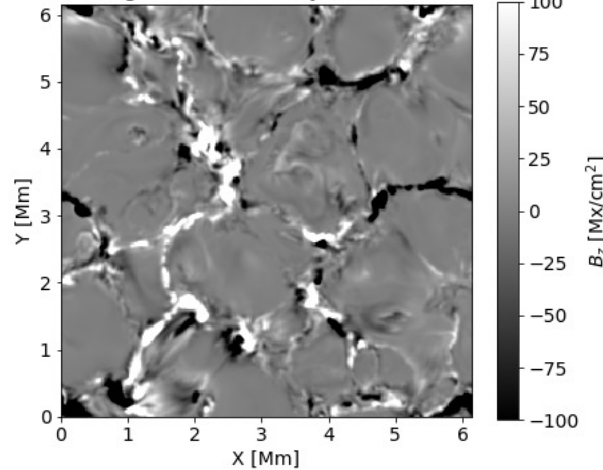
Unsigned Flux density: 53 Mx/cm²



Unsigned Flux density: 28 Mx/cm²

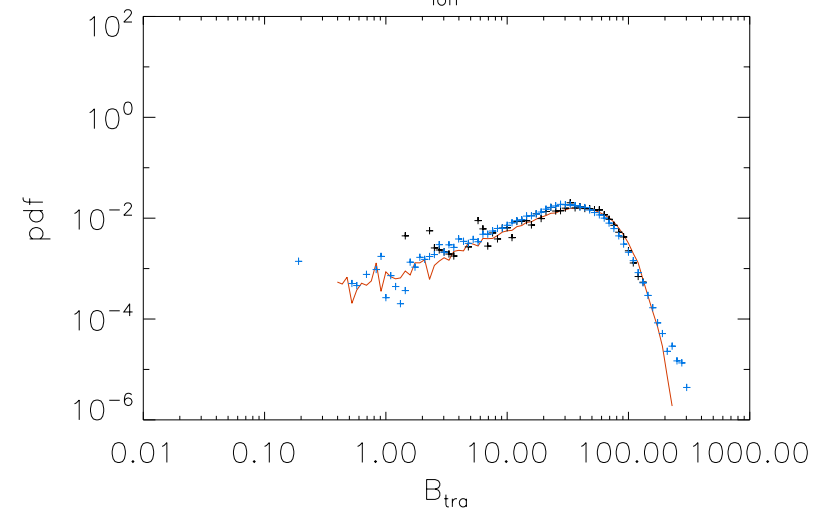
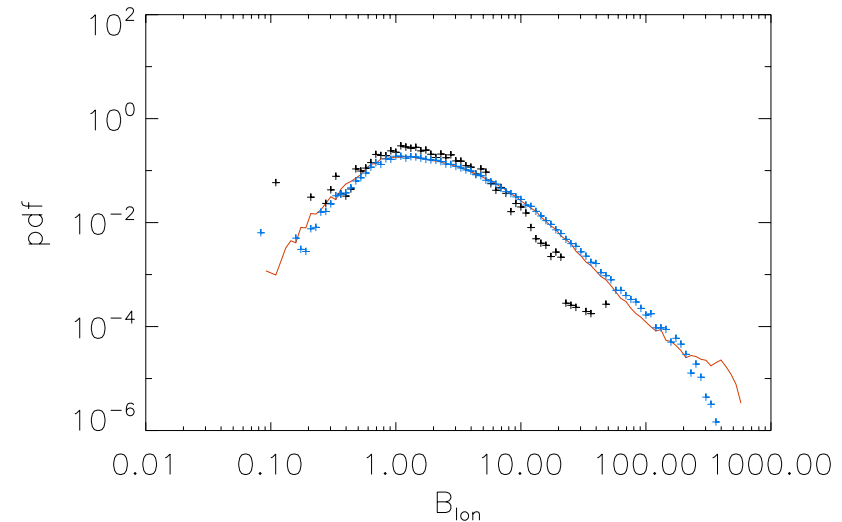


Unsigned Flux density: 23 Mx/cm²



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 $\langle |B_z| \rangle \sim 60 - 80 \text{ G}$ 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:
 - $\langle |B_z| \rangle \sim 60\text{-}80 \text{ G}$ at optical depth of unity
- Integrated over the entire solar surface:
 - $\sim 4 \times 10^{24} \text{ Mx}$
- 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!

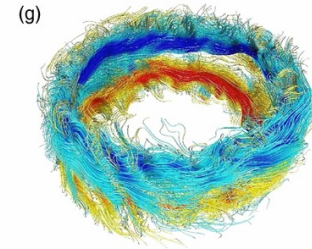
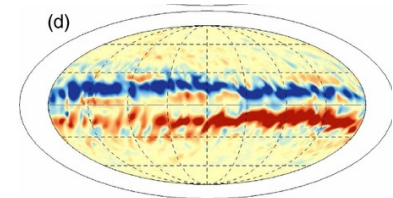


High Altitude
Observatory

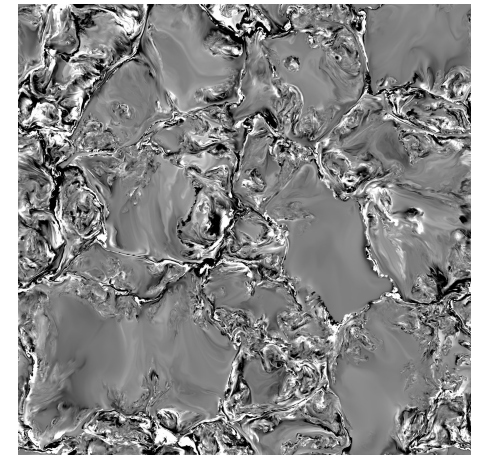
Operated by UCAR

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) $\mathbf{B} = \overline{\mathbf{B}} + \mathbf{B}'$:

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

- 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:

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

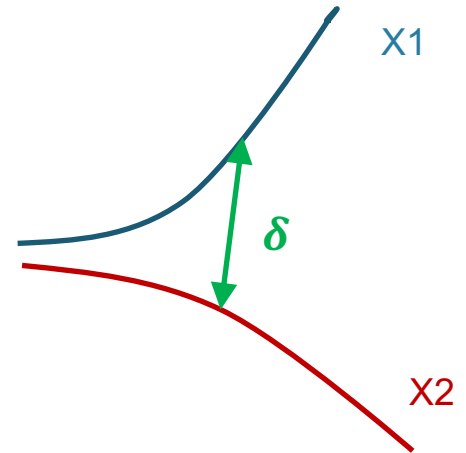
Small-scale dynamo

Lagrangian particle paths:

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

Consider small separations:

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



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

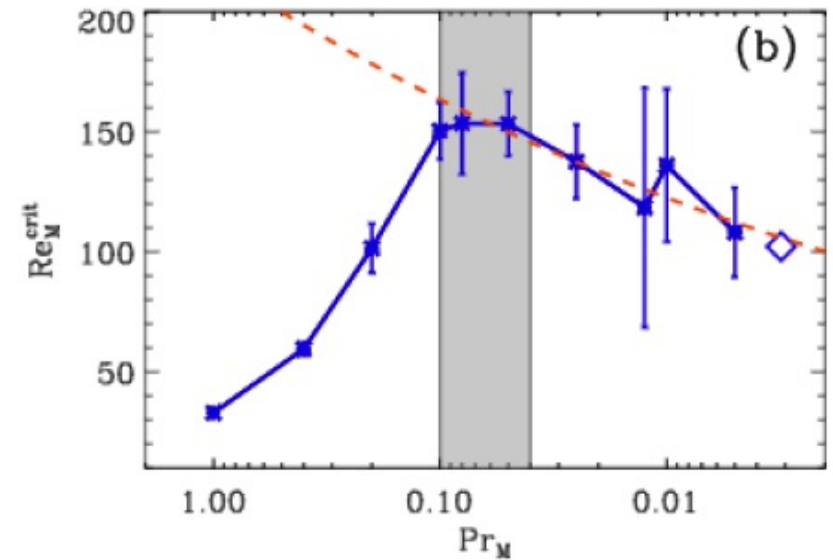
$$\frac{d\mathbf{B}}{dt} = \left(\frac{\mathbf{B}}{\varrho} \cdot \nabla \right) \mathbf{v}$$

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).



The Pm challenge

- Does a SSD exist at low Pm?
 - Increase of critical Rm as Pm decreases
 - How does this trend continue towards solar values of $Pm \sim 10^{-5}$?
- Recent idealized kinematic simulations:
 - SSD most difficult to excite around $Pm \sim 0.1 - 0.05$
 - Drop of critical Rm towards lower values



Warnecke et al. (2023)

- Operation of saturated solar dynamo at low Pm?

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



High Altitude
Observatory

Operated by UCAR

Modeling the solar photosphere

Fully compressible MHD

$$\begin{aligned}\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) \\ \frac{\partial \rho \mathbf{v}}{\partial t} &= -\nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \frac{1}{c} \mathbf{j} \times \mathbf{B} - \nabla P + \rho \mathbf{g} \\ \frac{\partial E_{\text{tot}}}{\partial t} &= -\nabla \cdot \left[\mathbf{v} (E_{\text{tot}} + P_{\text{tot}}) - \frac{1}{4\pi} \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) \right] + \rho \mathbf{v} \cdot \mathbf{g} + Q_{\text{rad}} \\ \frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B})\end{aligned}$$

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

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

Equation of state

$$\rho, E_{\text{int}} \longrightarrow P, T$$

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

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

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

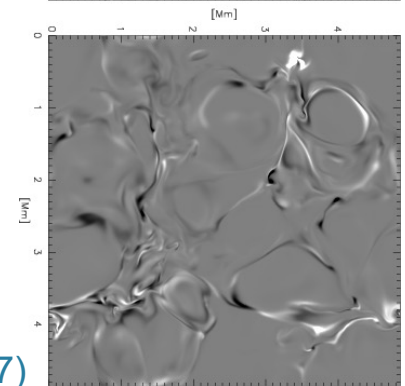
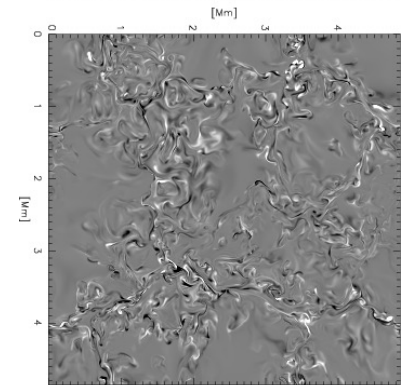
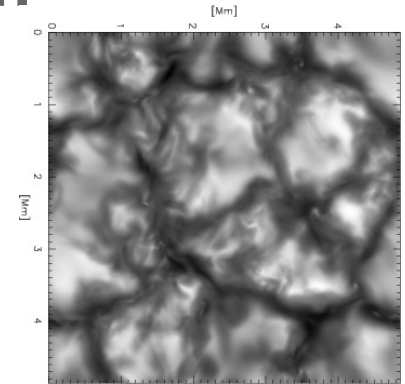
$$Q_{\text{rad}} = - \int_\nu (\nabla \cdot \mathbf{F}_\nu) d\nu = 4\pi \rho \int_\nu \kappa_\nu (J_\nu - S_\nu) d\nu$$

Numerical treatment

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

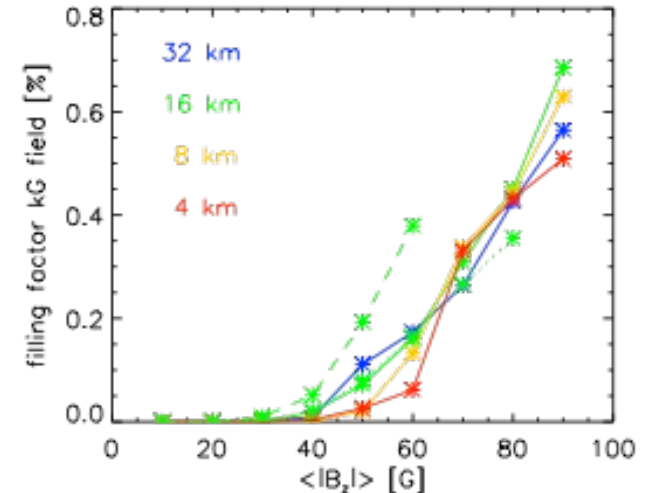
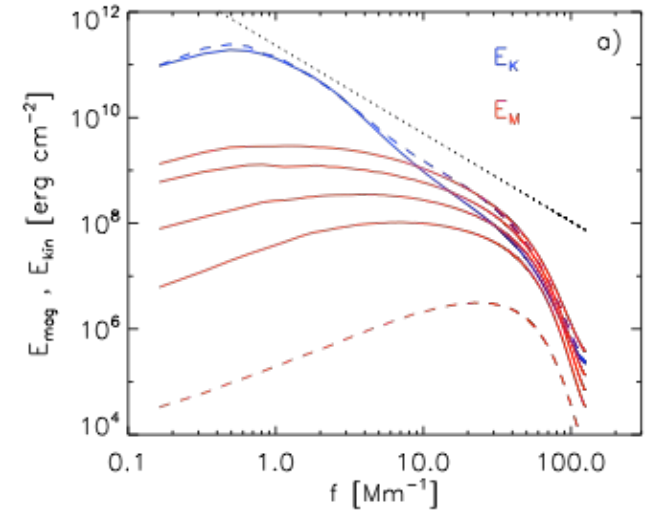
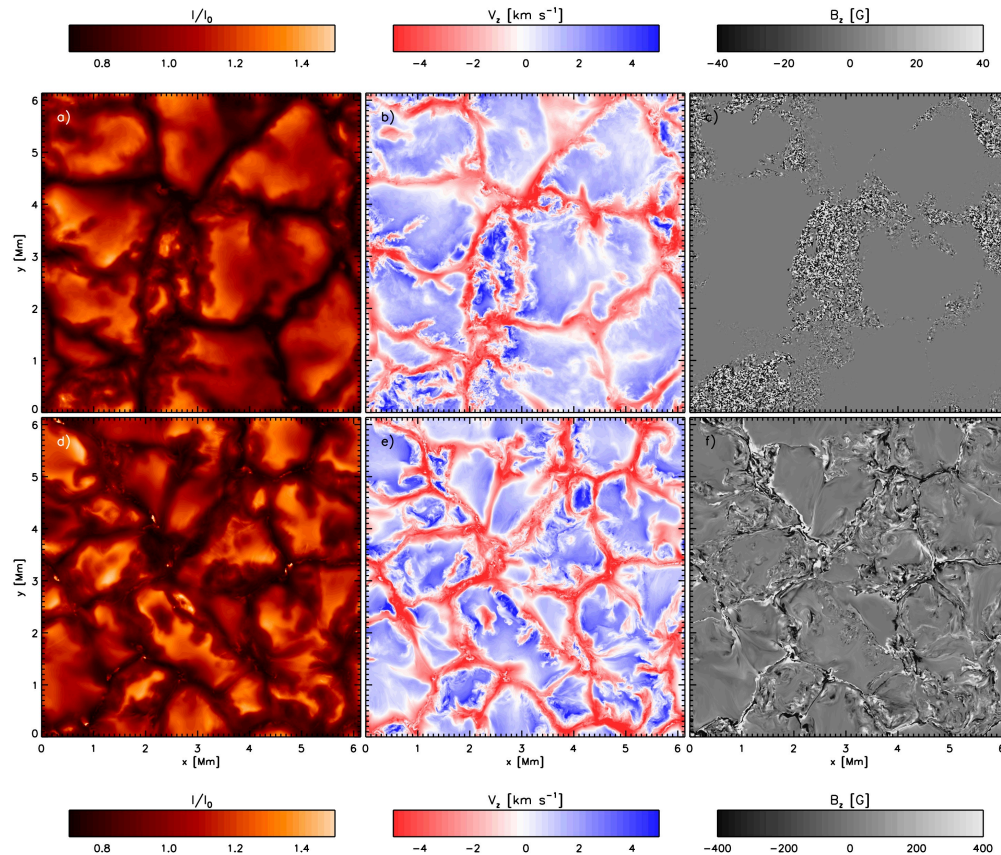
Solar simulations of the quiet Sun

- 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)
 - Magnetic field too weak, disagreement between Zeeman and Hanle inferences
- Many new recent models: Rempel (2014, 2018), Kitiashvili (2015), Khomenko (2017)
- Better agreement between simulations, Zeeman and Hanle observations: $\langle |B_z| \rangle \sim 60 - 80$ G (optical depth unity)
 - Danilovic et al. (2016) (Zeeman)
 - Del Pino Aleman et al (2018) (Hanle)
- Unsigned QS Flux:
 - 4×10^{24} Mx (comparable to all ARs of a 11 year cycle!)



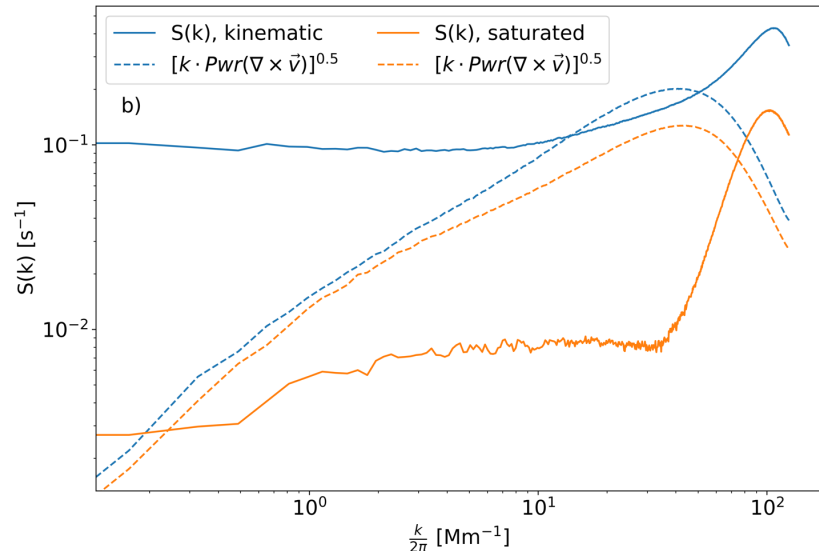
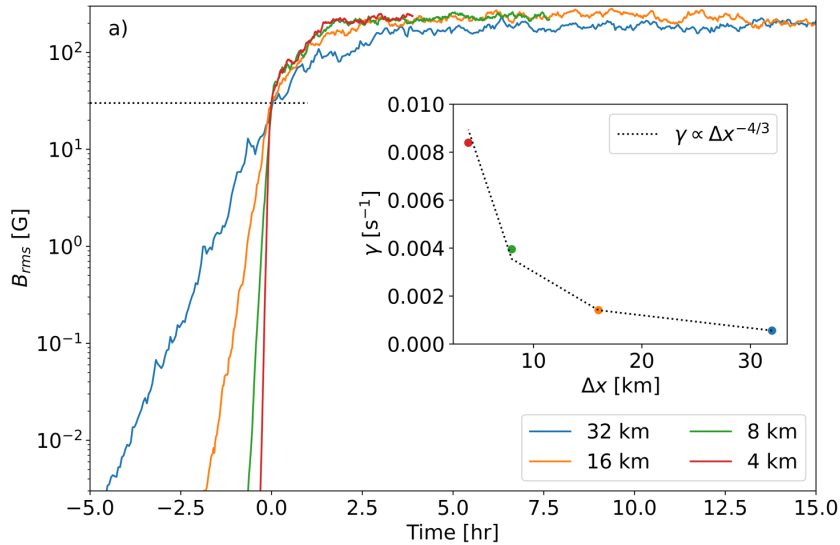
Vögler & Schüssler (2007)

Kinematic regime to saturation



- Magnetic field organization changes dramatically during saturation
 - Non-linear saturation begins for $\langle |B_z| \rangle \sim 10$ 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 $\langle |B_z| \rangle \sim 30$ G

Kinematic regime to saturation



- Kinematic regime
 - $B < 0.1 B_{QS}$ (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

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

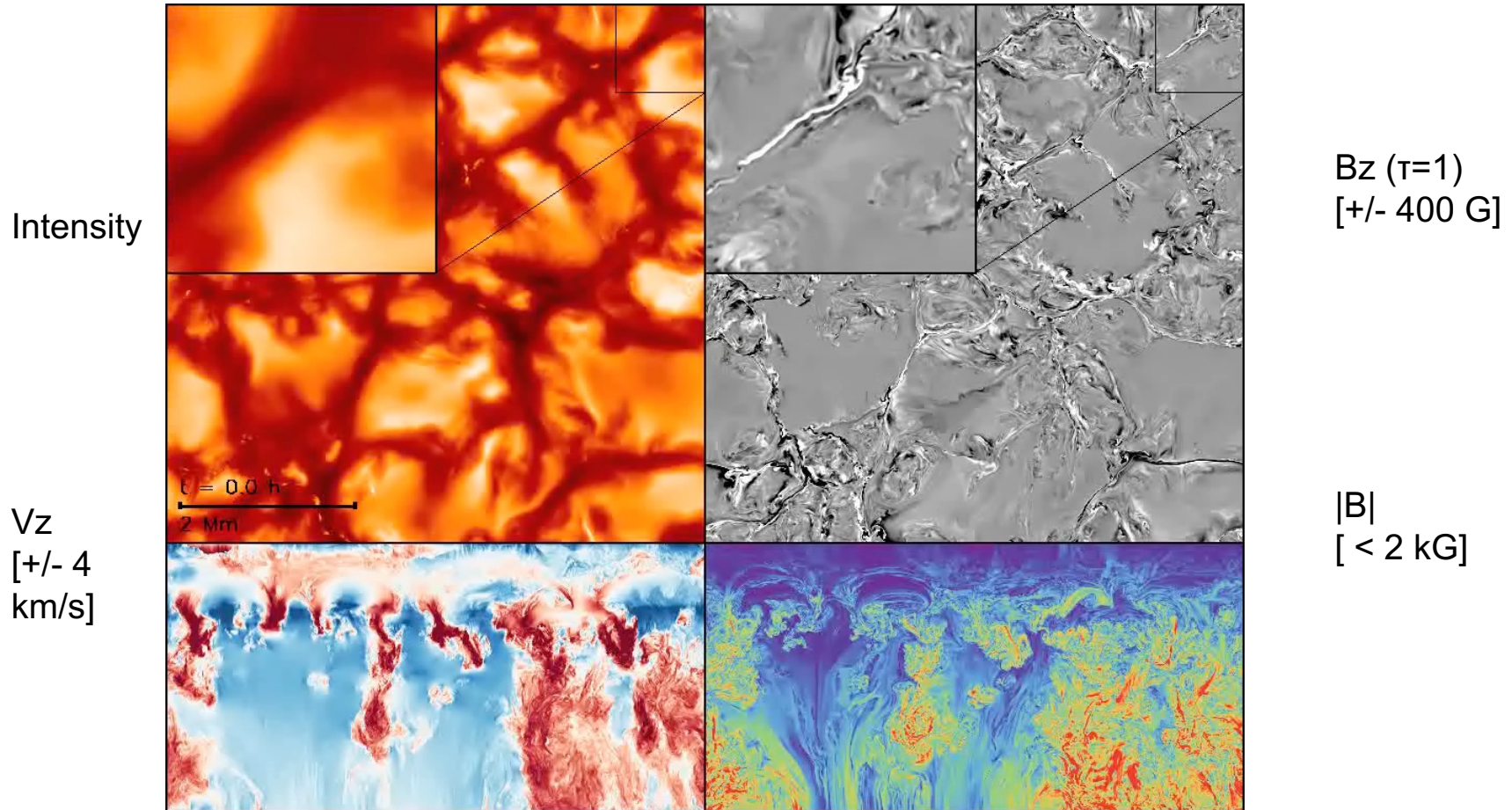
$$E_M(k) = \frac{1}{8\pi} \hat{\mathbf{B}}(k) \cdot \hat{\mathbf{B}}^*(k)$$

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

- Misalignment of velocity shear and magnetic field, misalignment of induced field with existing field

Saturated SSD solution consistent with observational constraints

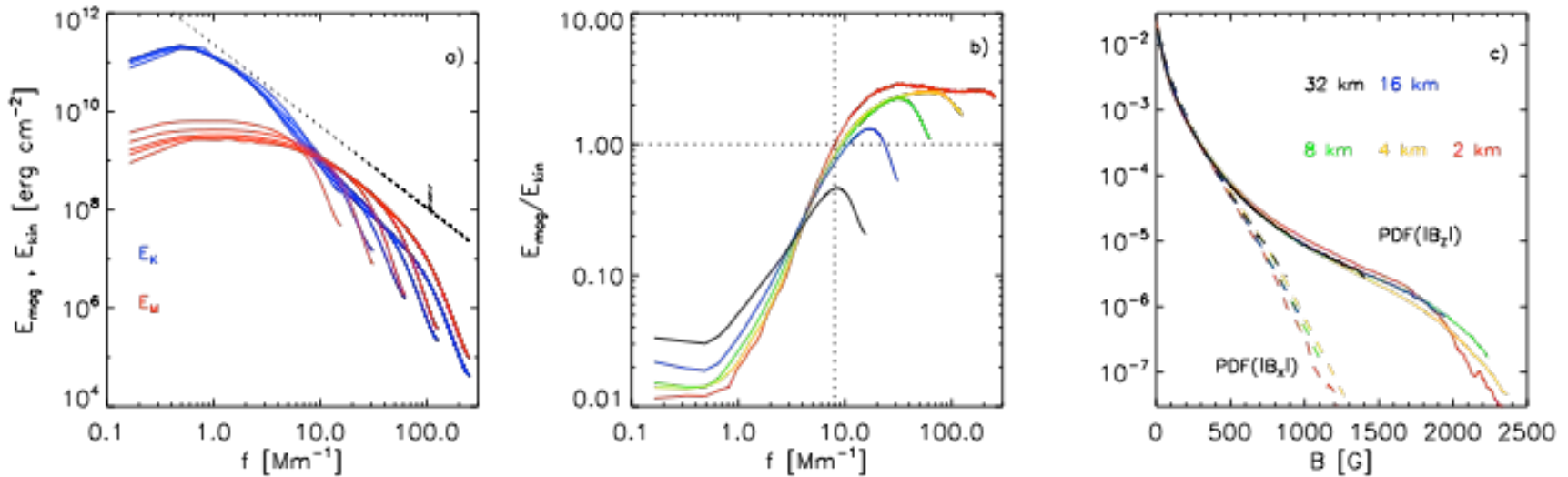
Domain: 6.144 x 6.144 x 3.072 Mm³ 4km grid spacing



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

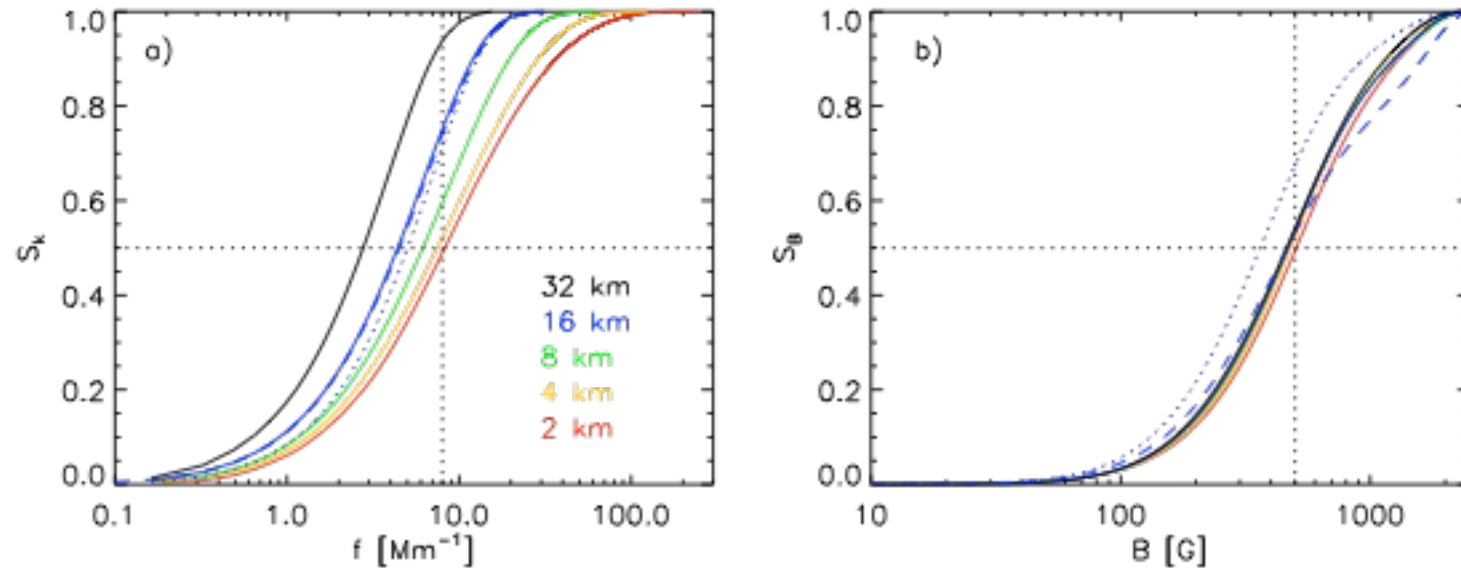
Rempel (2014)

Resolution dependence 32 ... 2 km



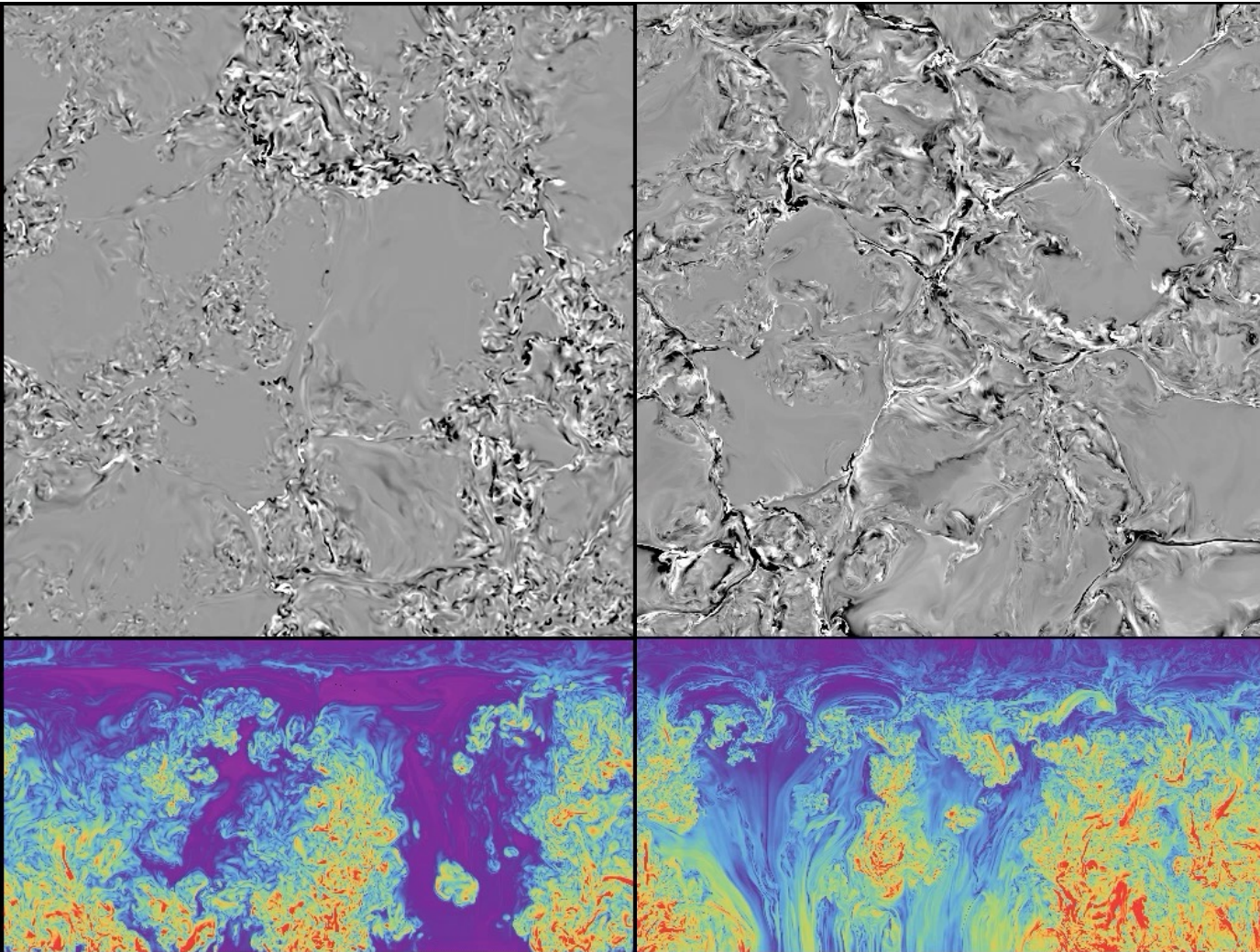
- Converged results using LES approach
 - No explicit viscosity or magnetic resistivity
 - Changing resolution by a factor of 16!
 - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
 - Implicit magnetic Prandtl 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

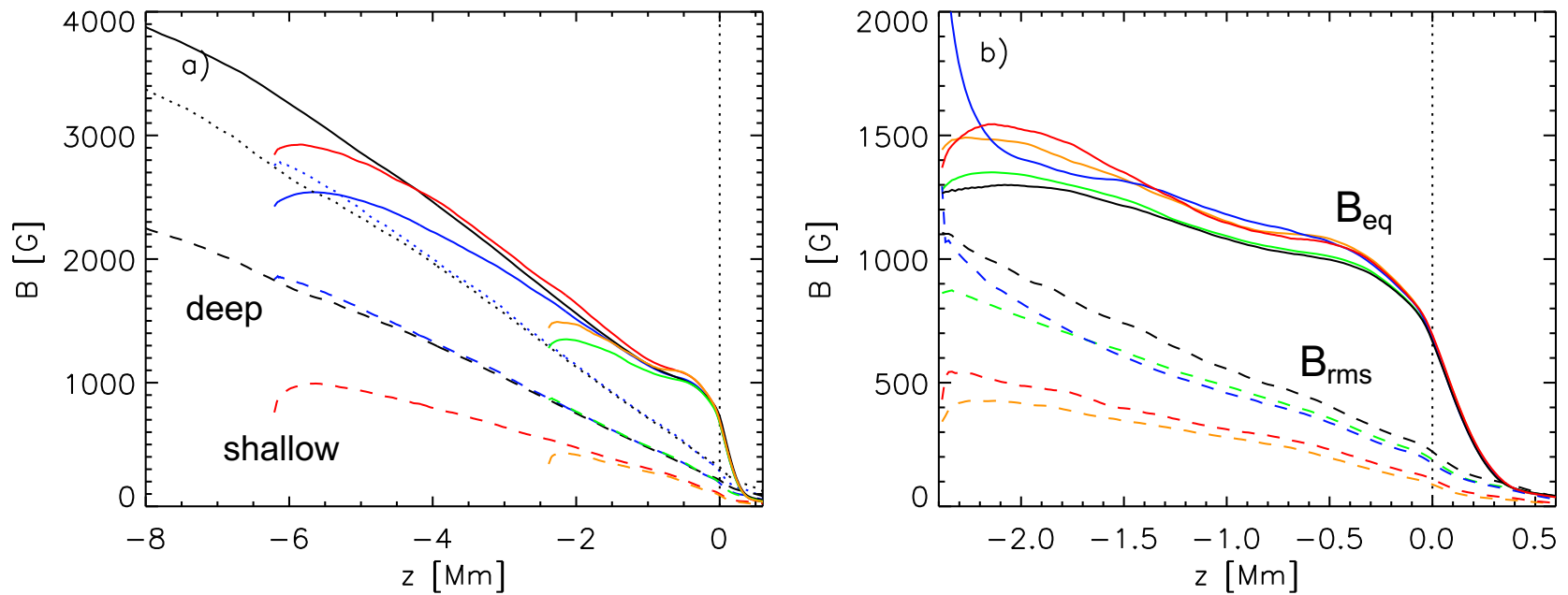
Local vs. global recirculation



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



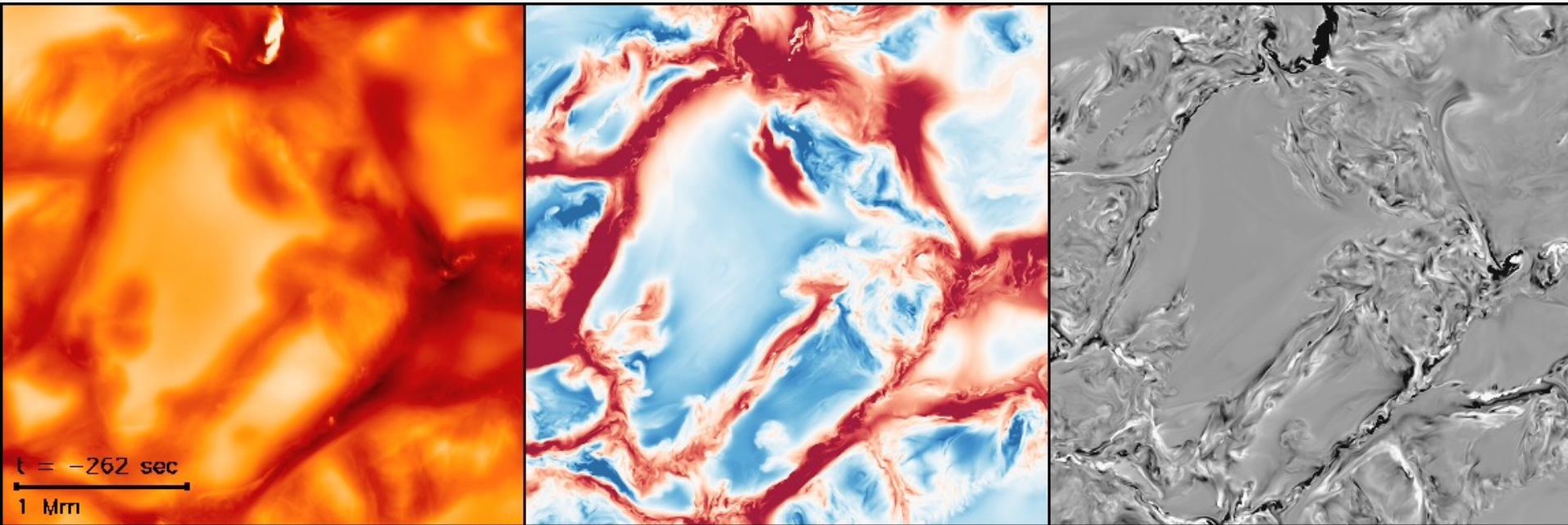
Saturation field strength vs bottom boundary condition



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

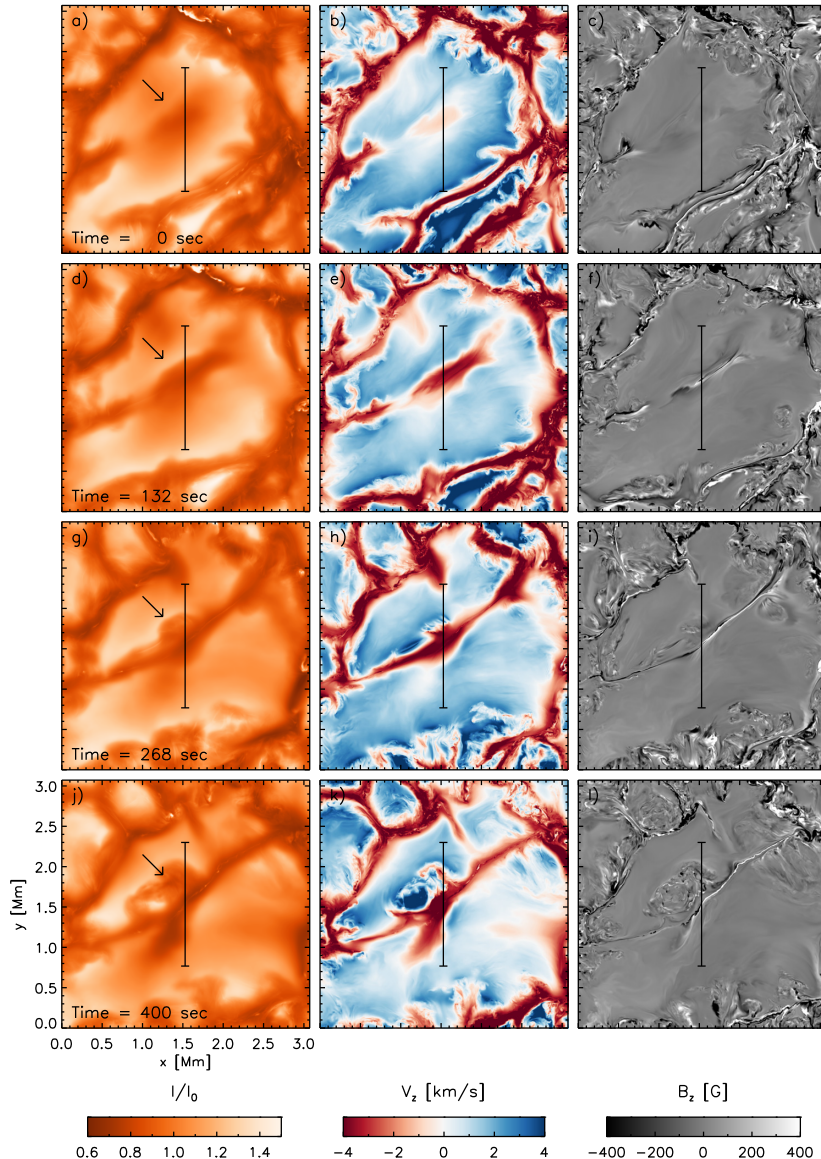


Rempel (2018)

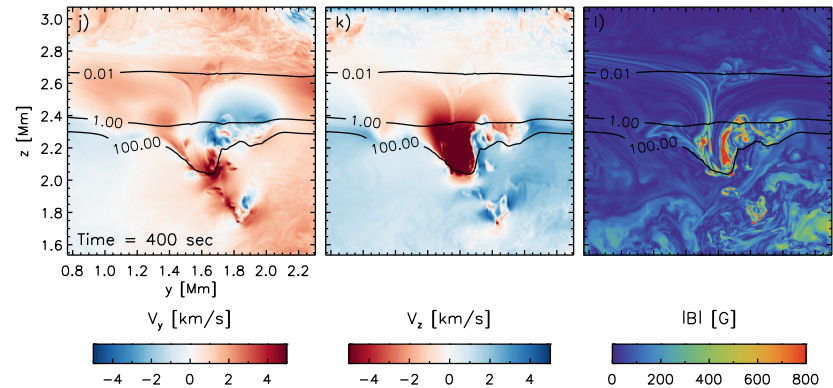
- Large granules form new downflow lanes in their interior
- Most “pristine” downflow lanes in solar photosphere
- Downflow lanes with weakest initial magnetization



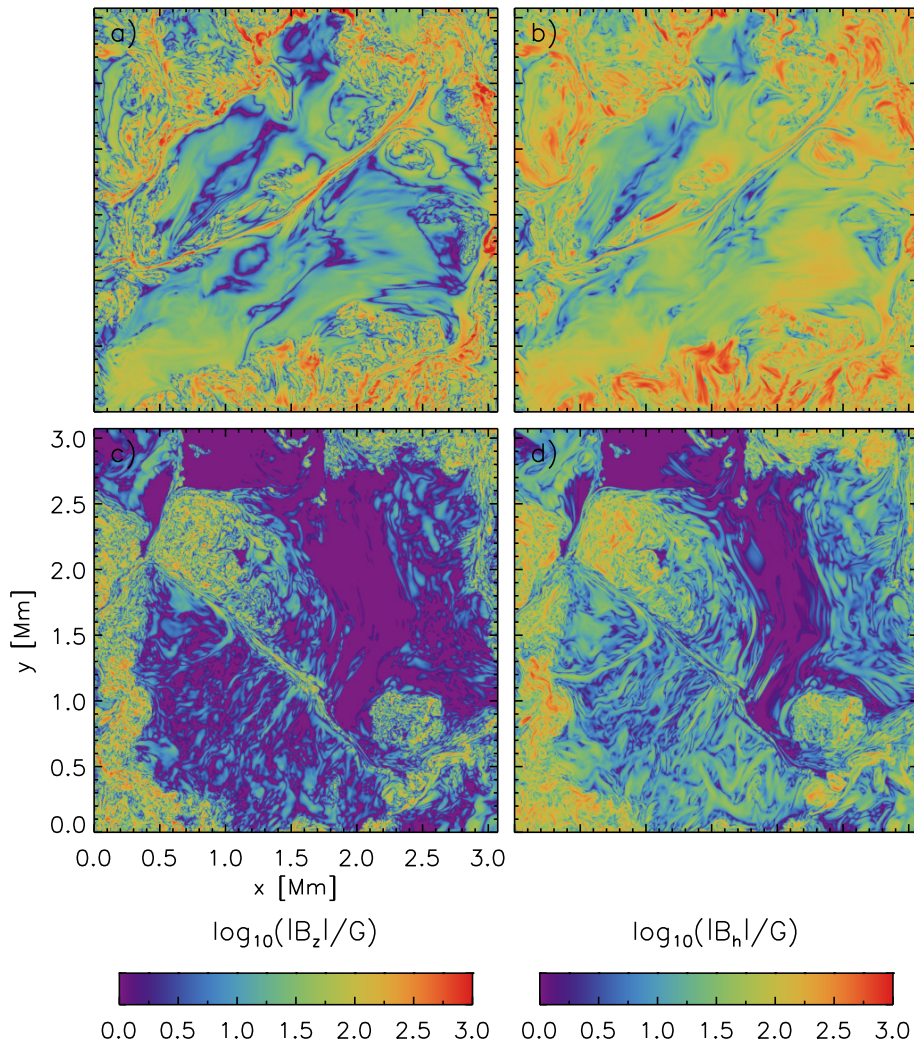
Magnetization of newly formed downflows



- Amplification of “granular seed field” by mostly **laminar** 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)
- **Turbulent** 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



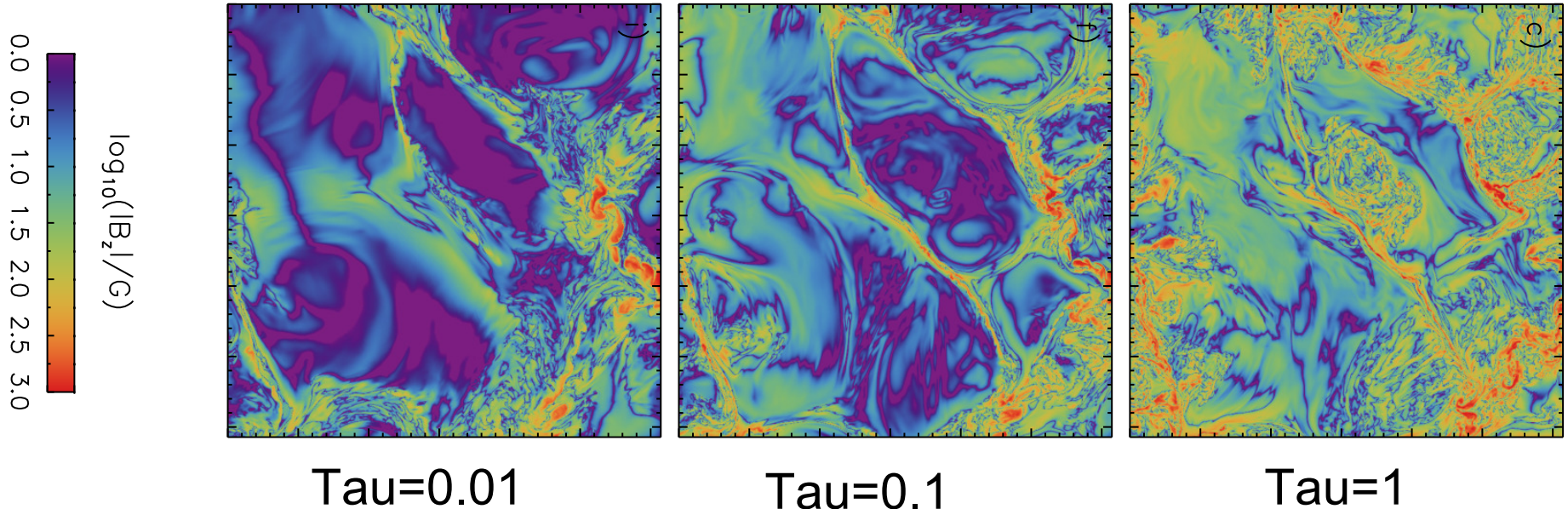
SSD with and without deep recirculation



- 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

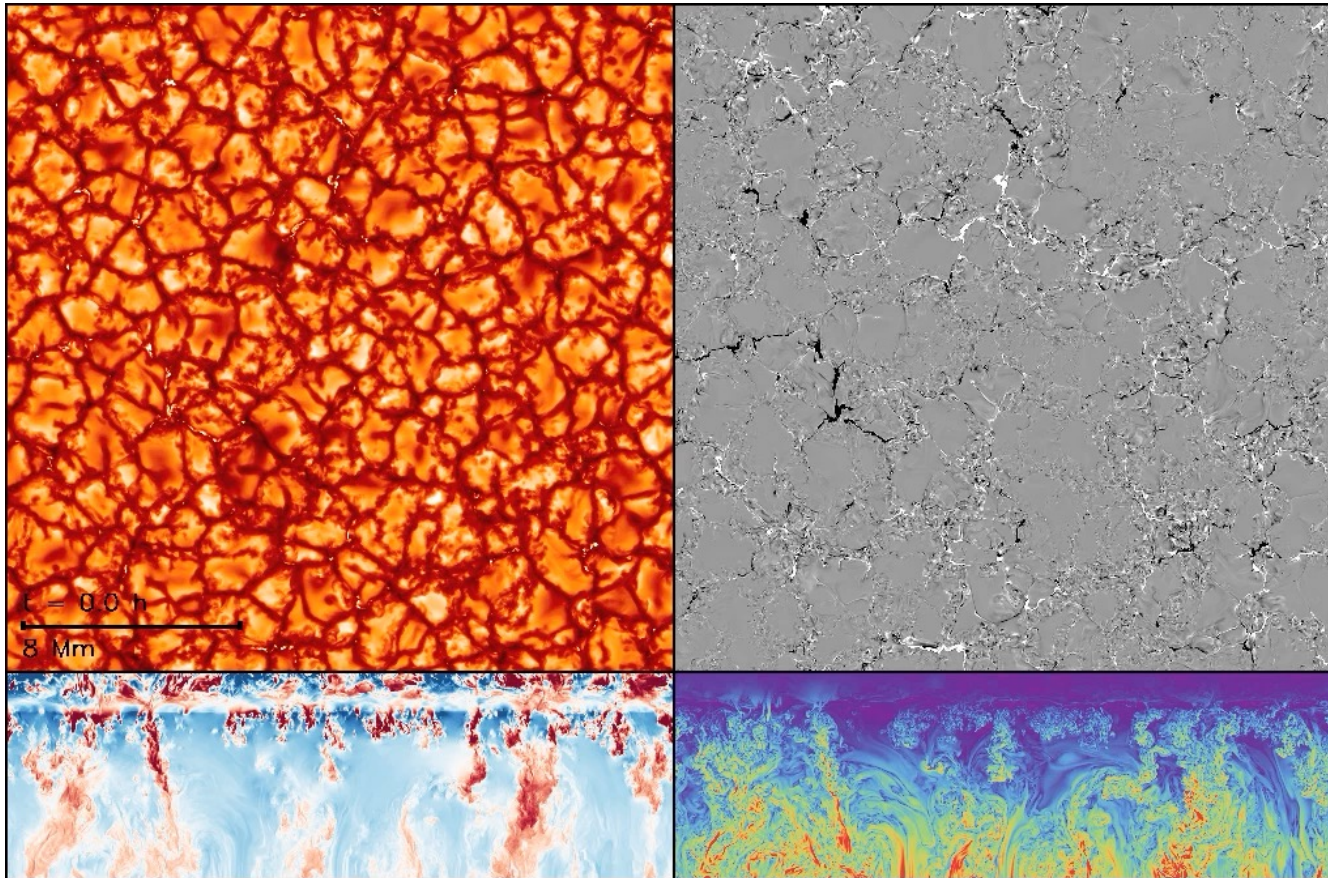


- Shallow and deep recirculation related field only visible in very deep photosphere ($\tau=1$)
- Already $\tau=0.1$ misses completely the turbulent field from shallow recirculation
- Observations at high resolution in deep photosphere required (\rightarrow DKIST @ 1600 nm)

Meso-granular scales

Intensity
0.5 – 1.5

V_z
+/- 4 km/s

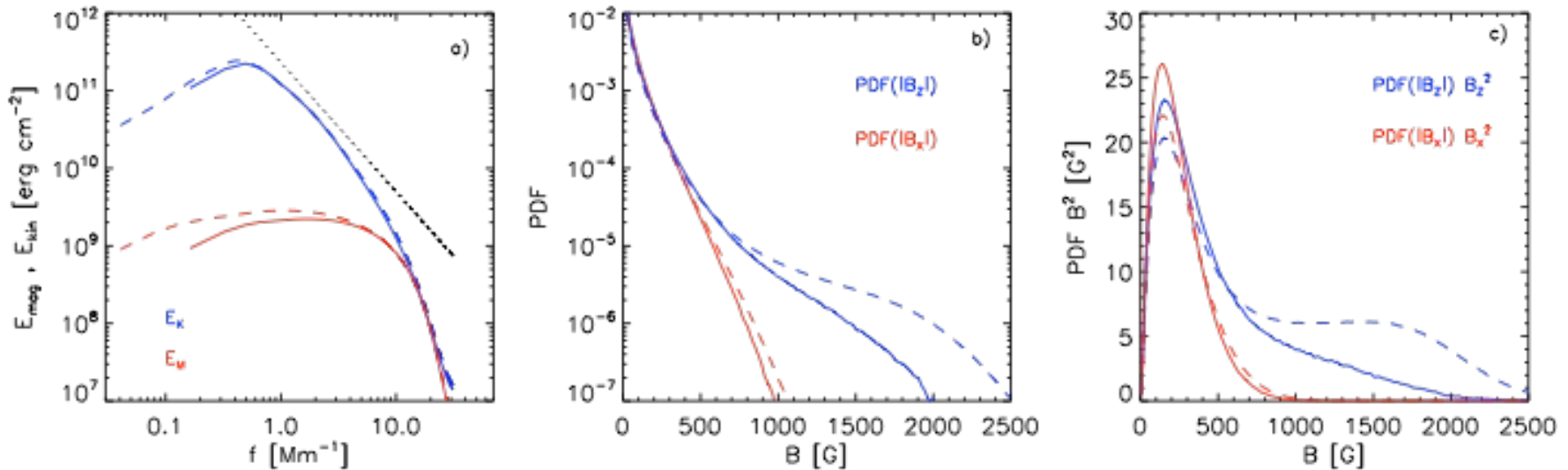


B_z ($\tau=1$)
+/- 400G

$|B|$
+/- 4kG

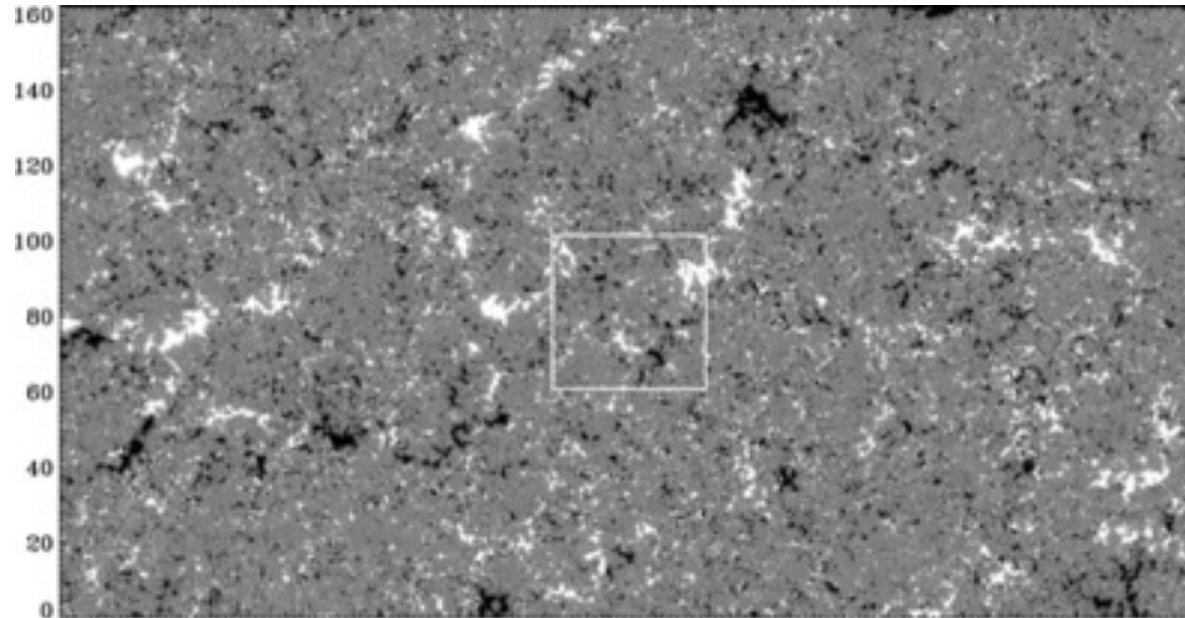
- Small-scale dynamo operating in a highly stratified domain
 - Dynamo operates over a wide range of scales at different depth, coupled through vertical transport
 - Can organize magnetic field on scales larger than granulation
 - Can lead to significant local flux imbalance

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

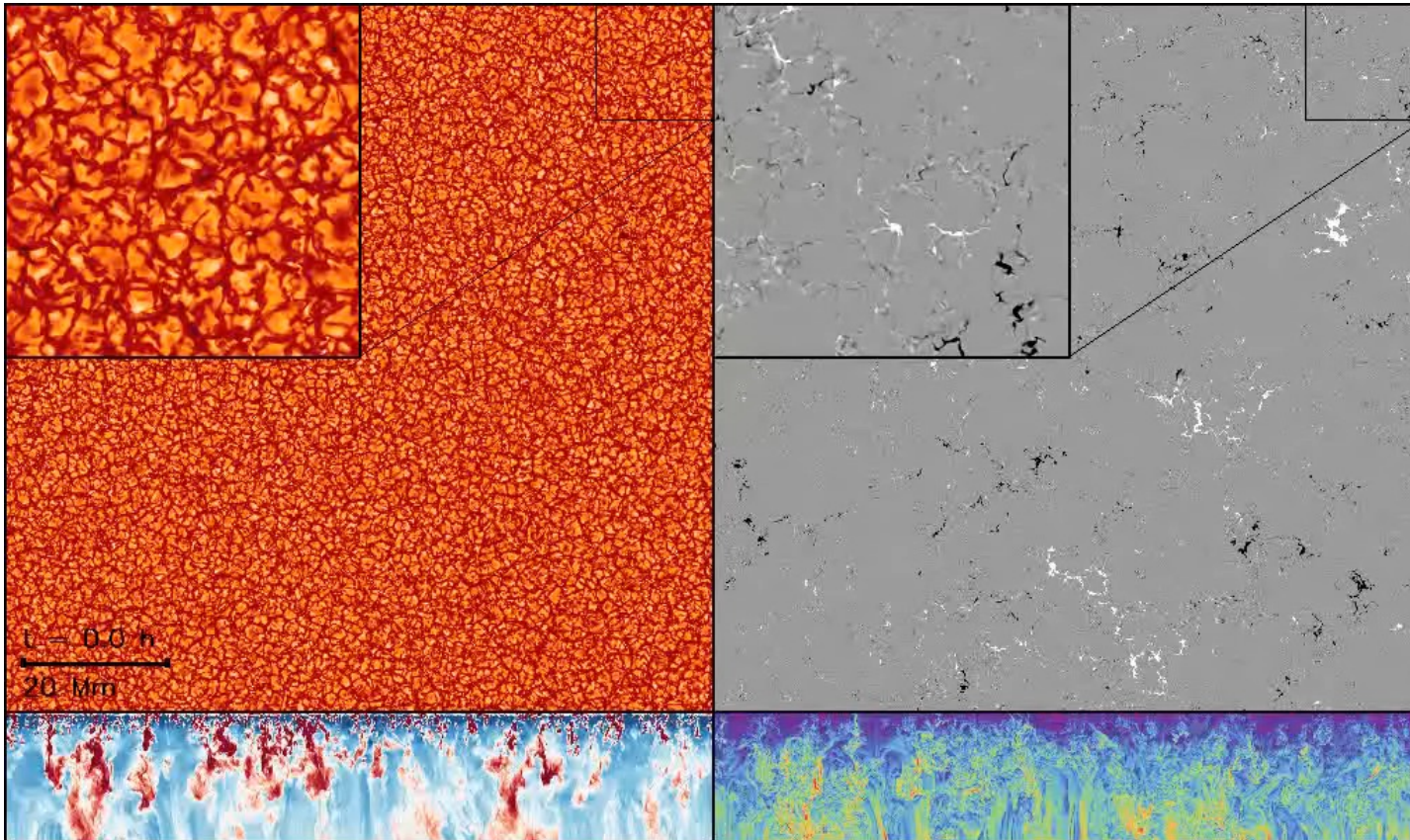


et From Lites al 2008

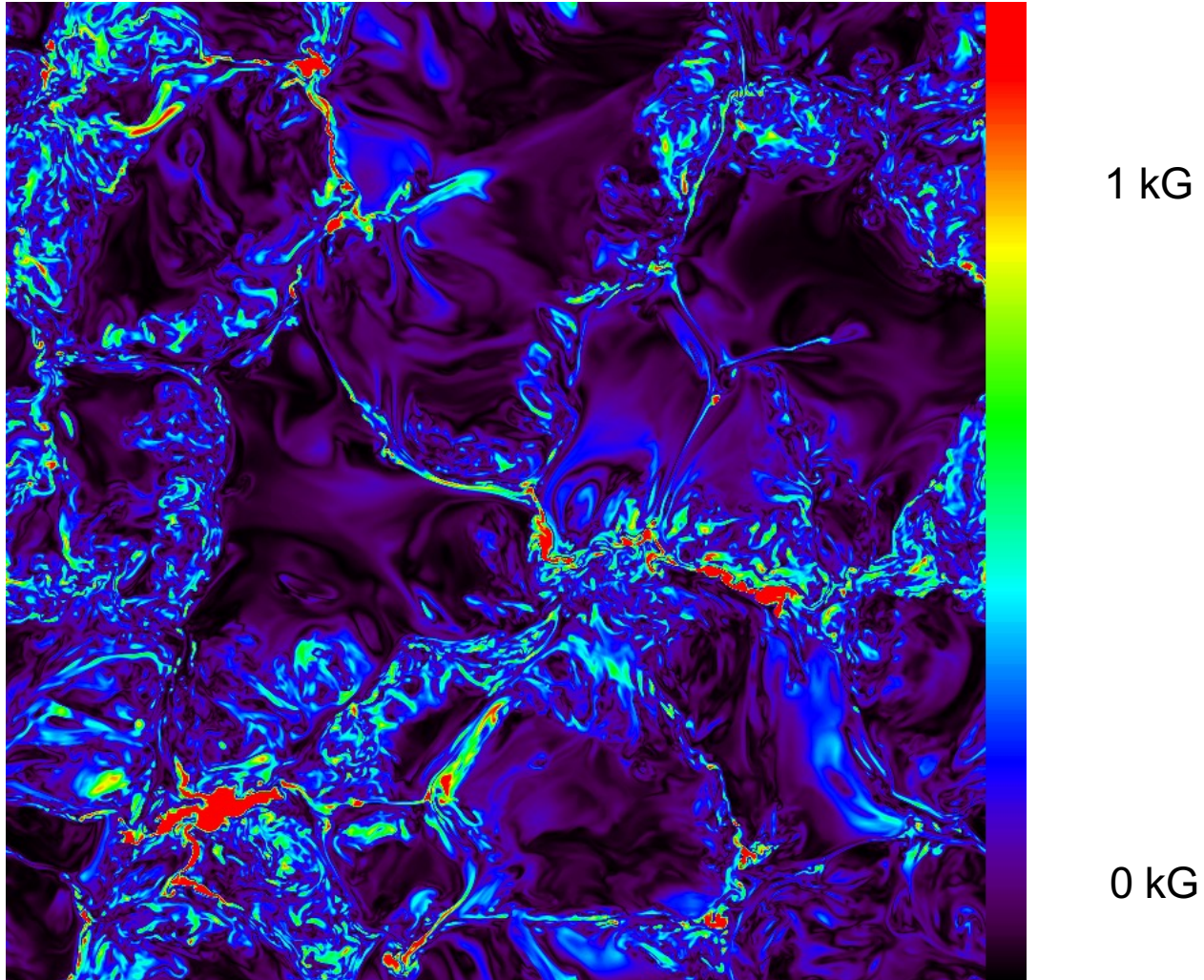
- What is the origin of the QS network field? Is it part of the quiet Sun or still a remnant of the solar cycle

Large scale flux imbalance

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



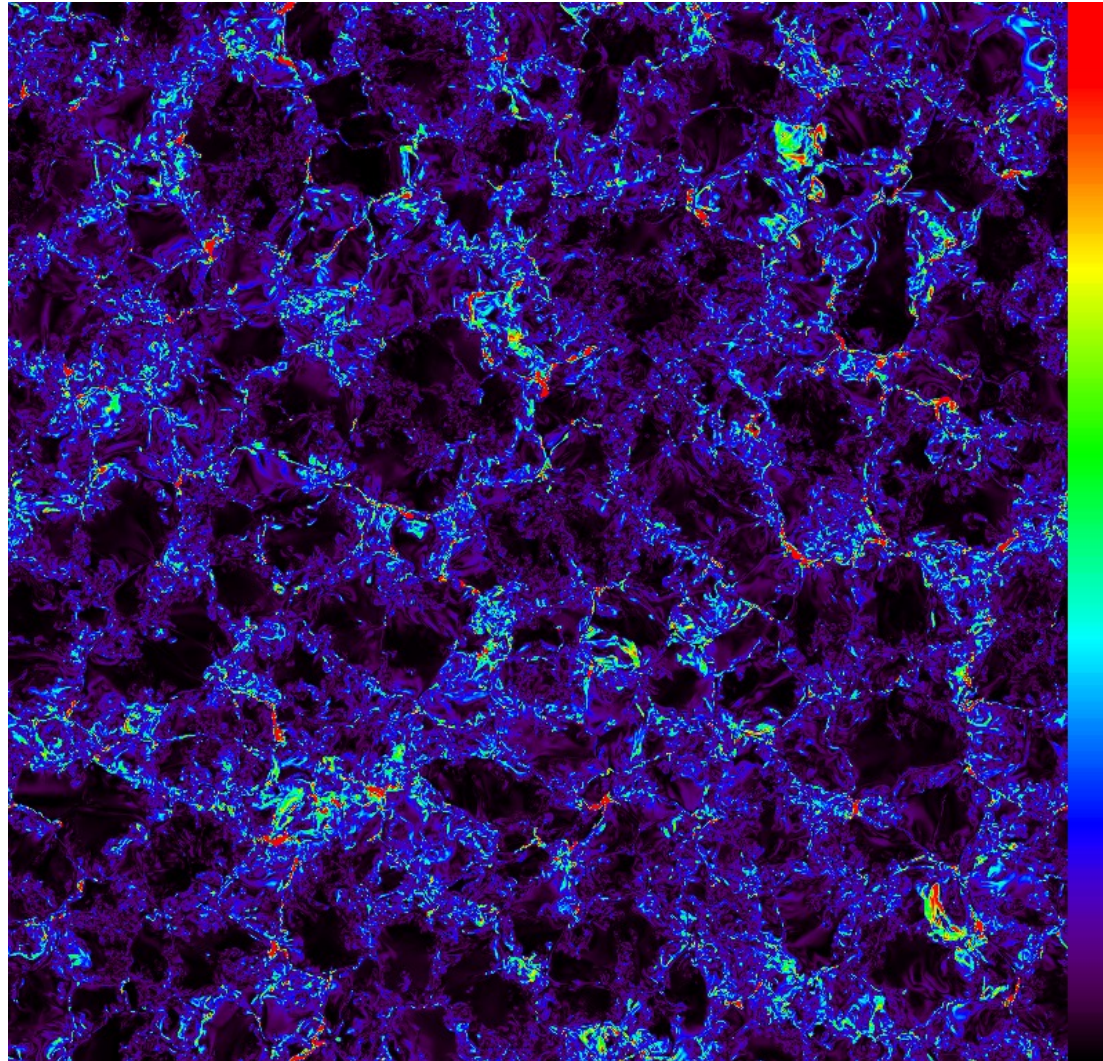
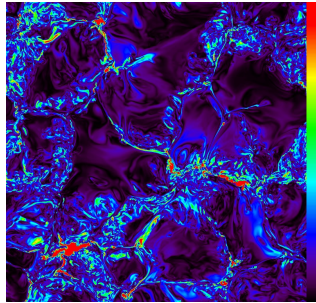
Larger scale organization and “voids”



6x6x2.3 Mm



Larger scale organization and “voids”

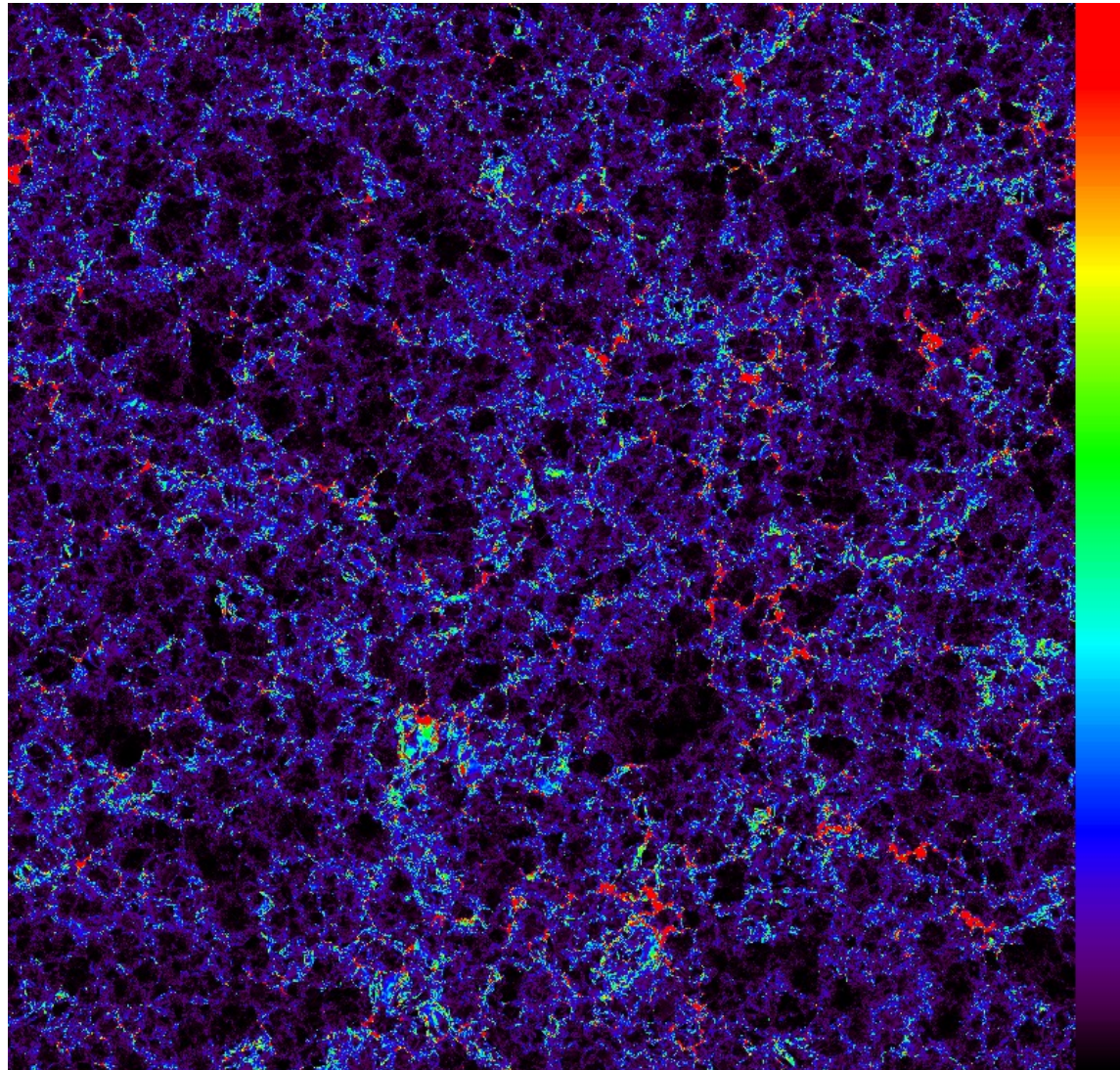
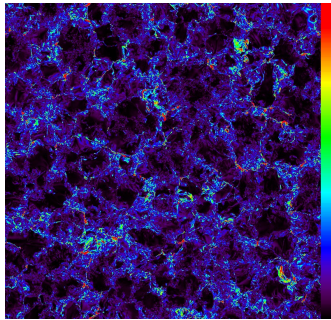
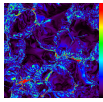


1 kG

0 kG

25x25x6.2 Mm

Larger scale organization and “voids”



1 kG

0 kG

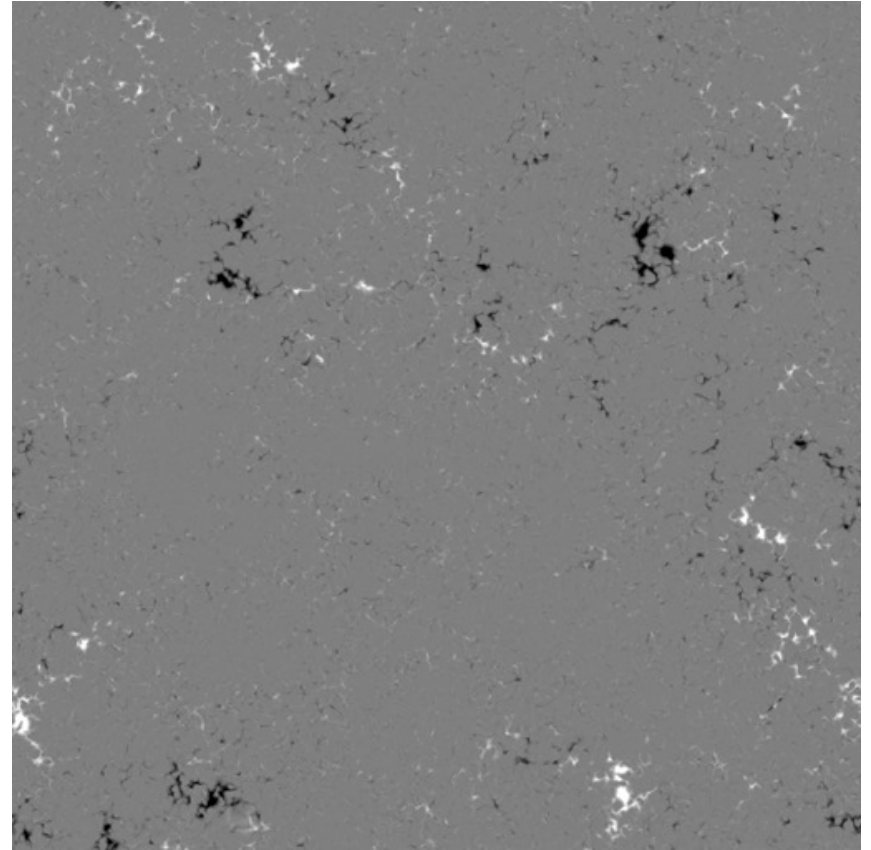
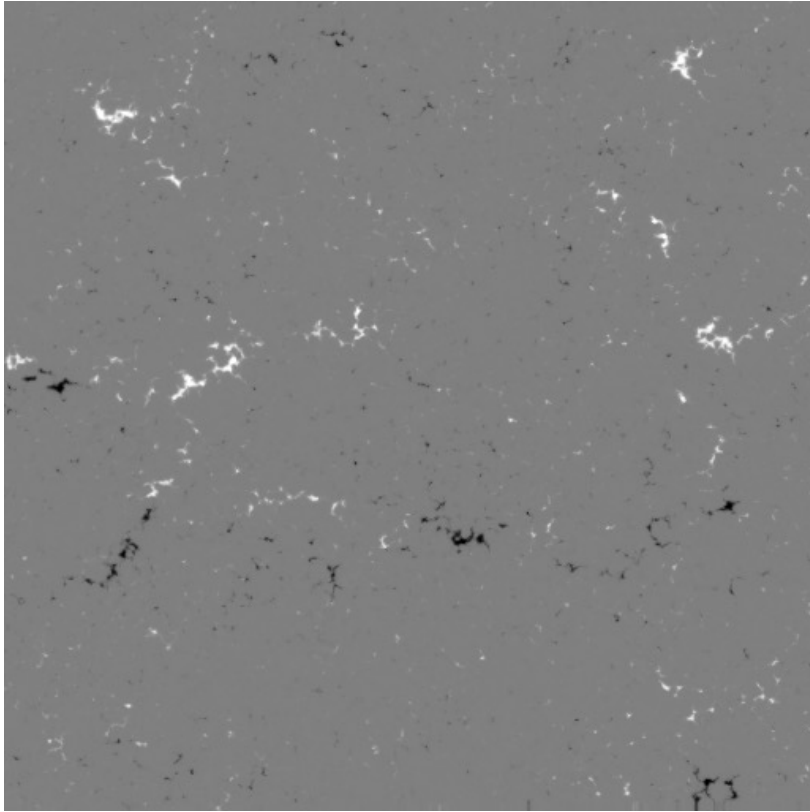
98x98x17.8 Mm



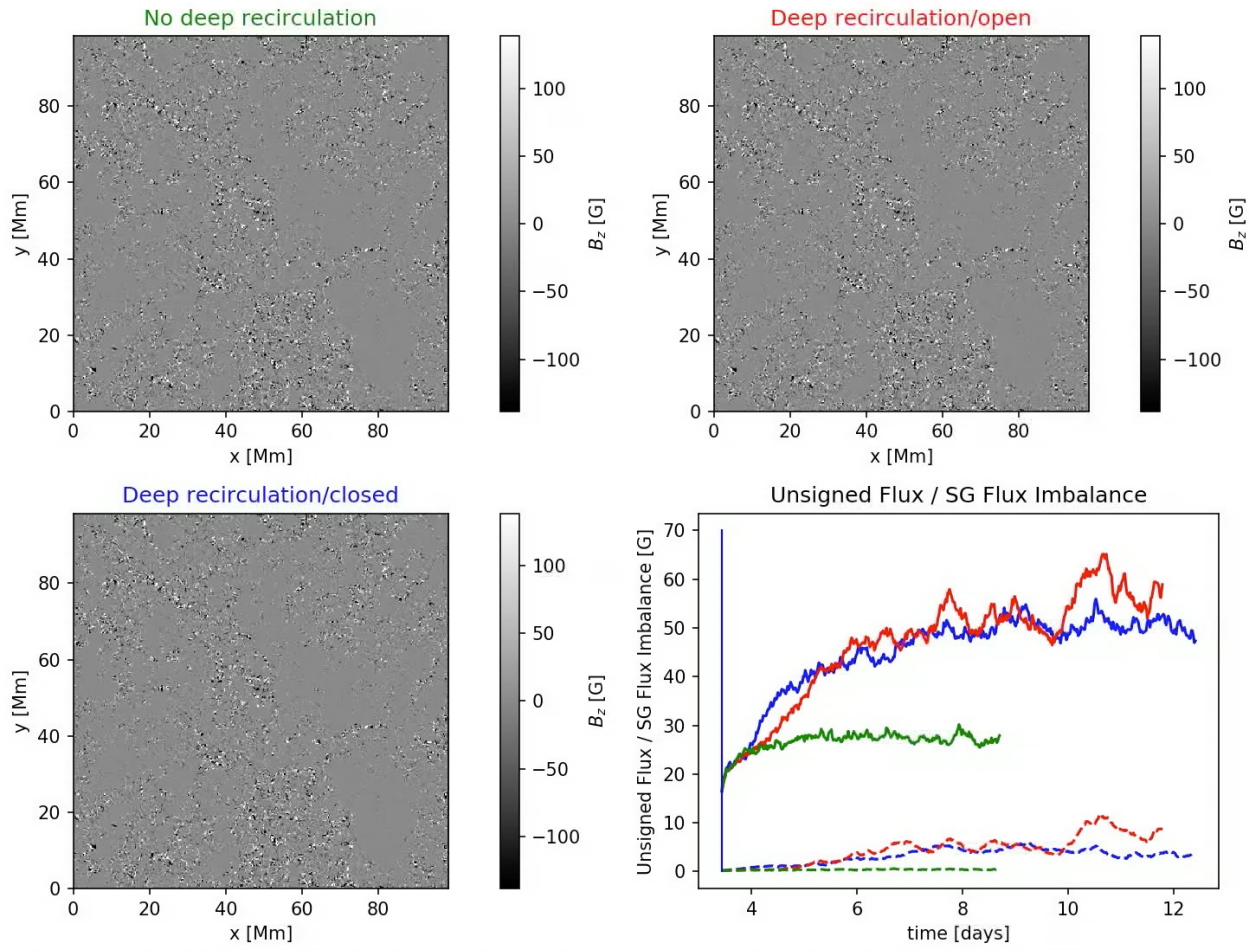
High Altitude
Observatory

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Quiz: Which map is an observation/simulation?



Deep recirculation and large-scale flux imbalance



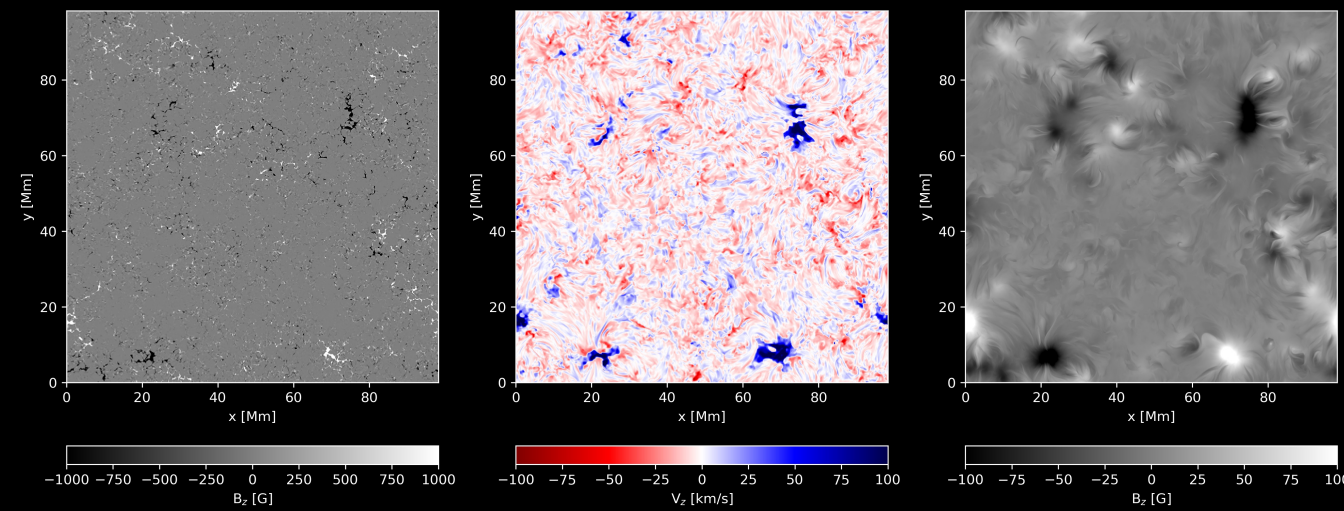
- SSD in 98 Mm wide and 18 Mm deep domains
 - Lower resolution, longer time-scales
- Deep recirculation leads to large scale flux imbalance
 - Emergence of small bipoles in quiet sun “ephemeral active regions”
- Quiet sun super-granular network independent from active region decay
 - About 5-8 G average flux imbalance in 25x25 Mm² subdomains
- Flux imbalance required for maintaining an quiet sun corona

Corona with deep recirculation

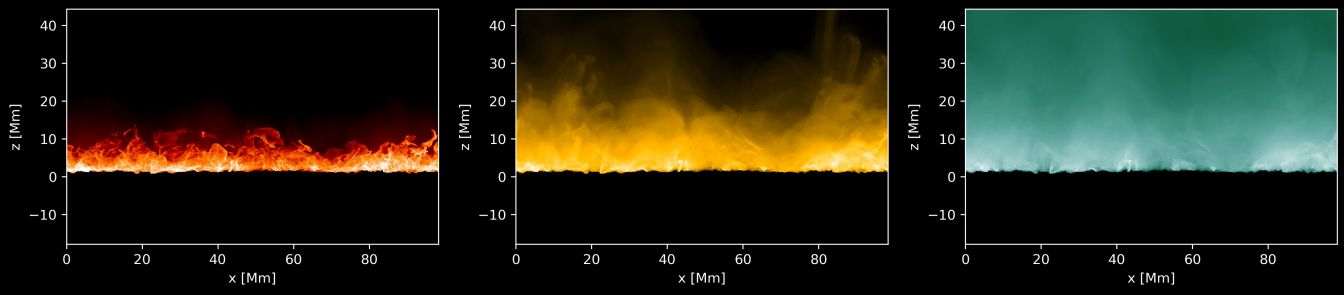
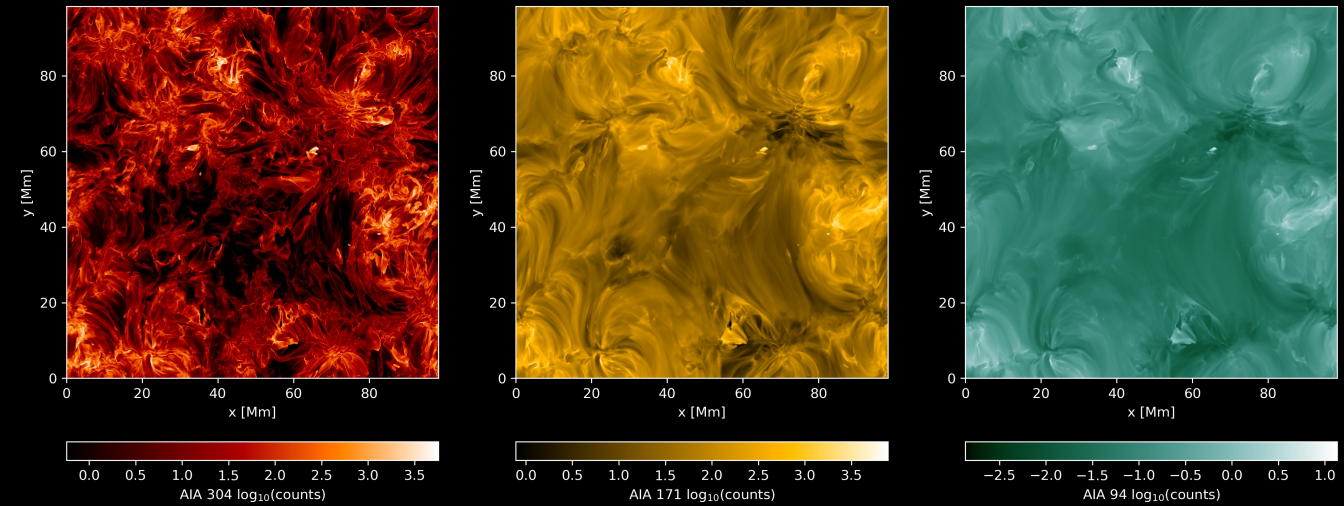
Total radiative loss
 $\sim 6 \times 10^5 \text{ erg/cm}^2/\text{s}$

Withbroe & Noyes
(1977)

$\sim 3 \times 10^5 \text{ erg/cm}^2/\text{s}$

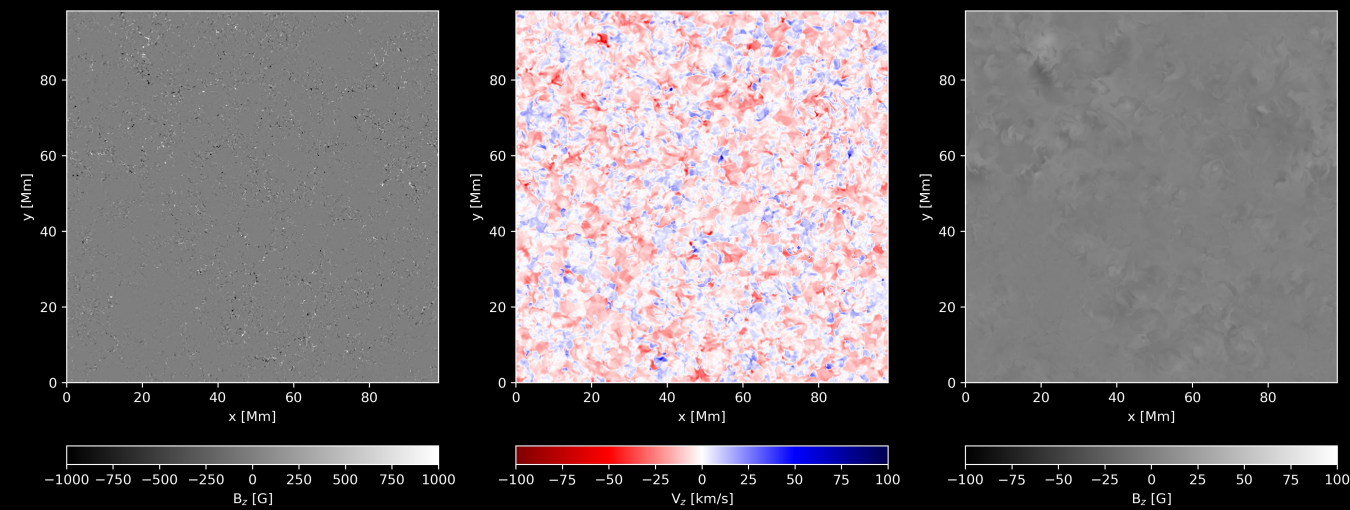


time [050000] = 40.82 min

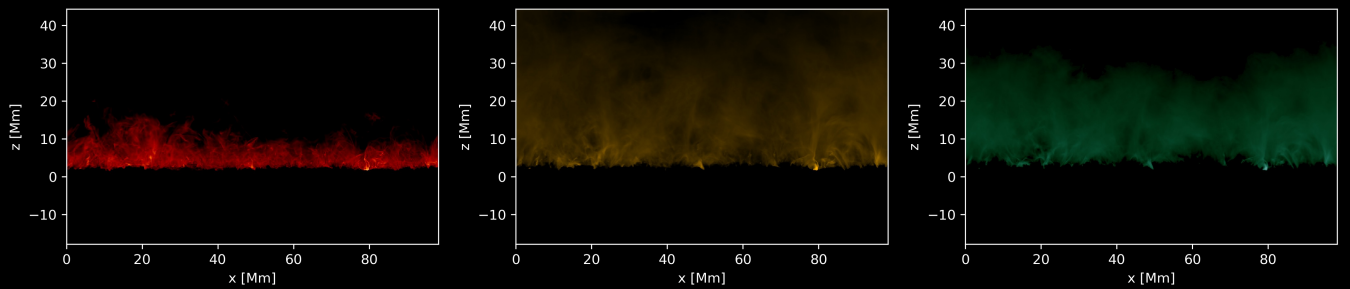
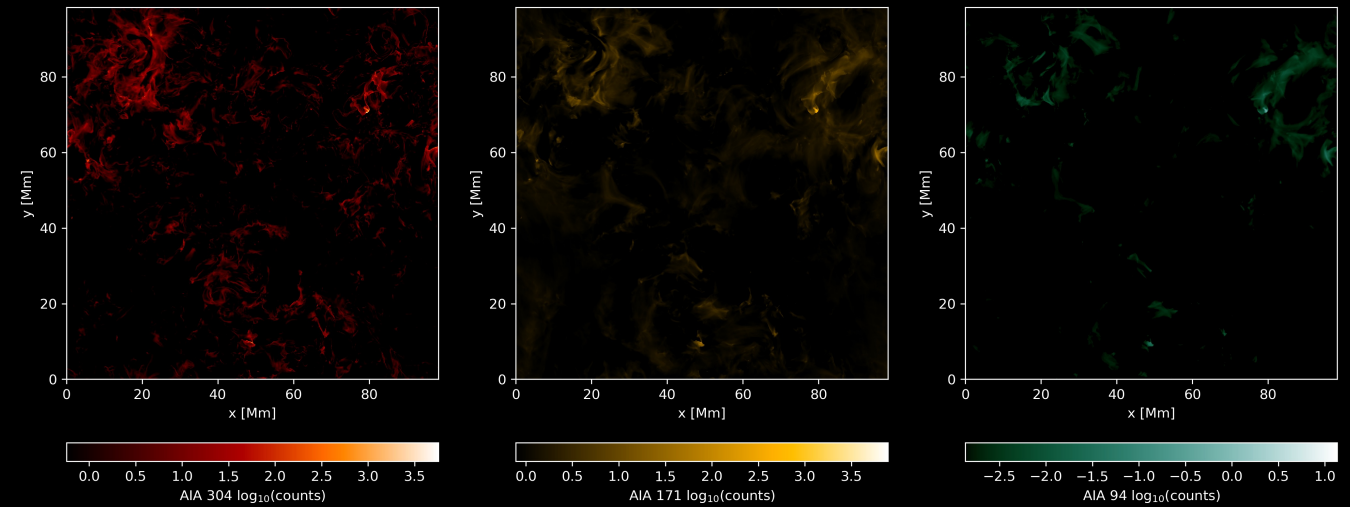


Corona without deep recirculation

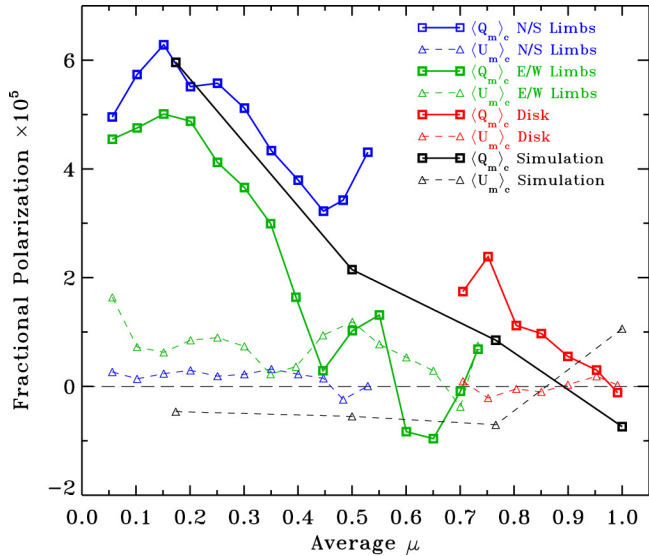
Total radiative loss
 $\sim 10^4$ erg/cm²/s



time [050000] = 89.41 min

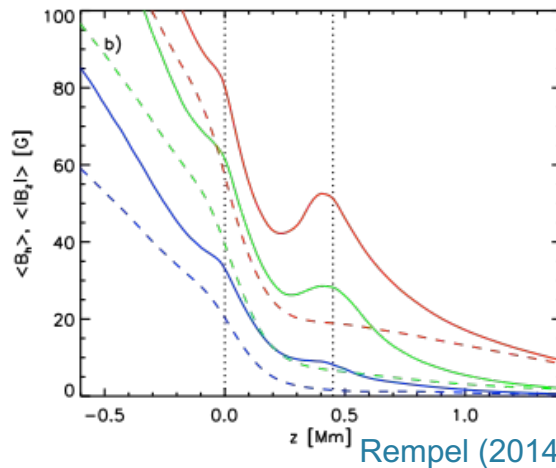
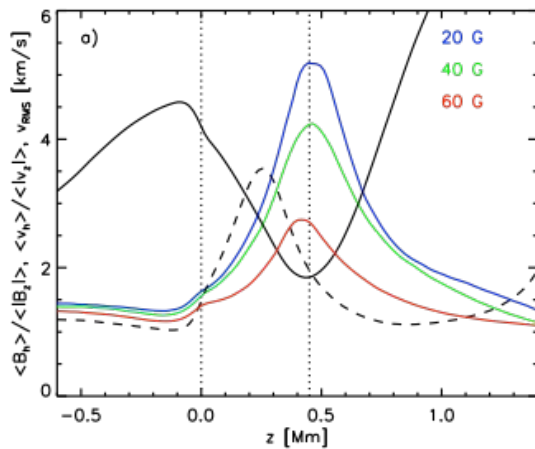


Horizontal magnetic fields



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



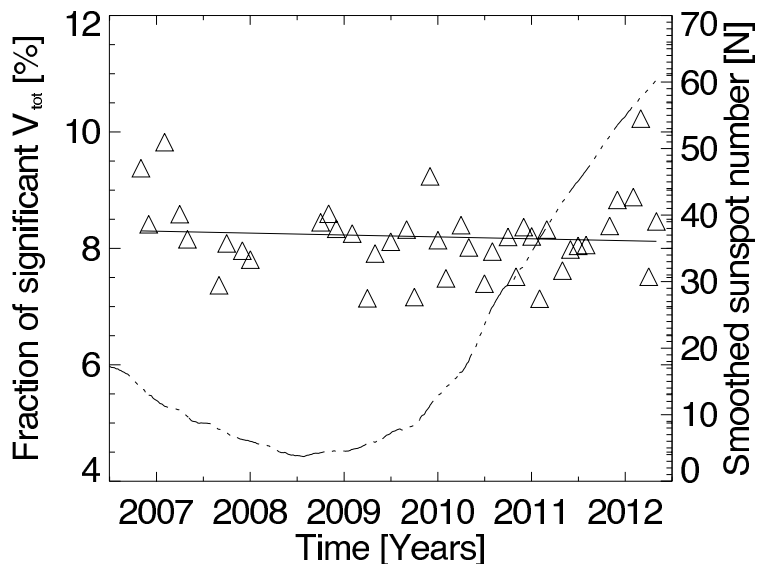
Rempel (2014)

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

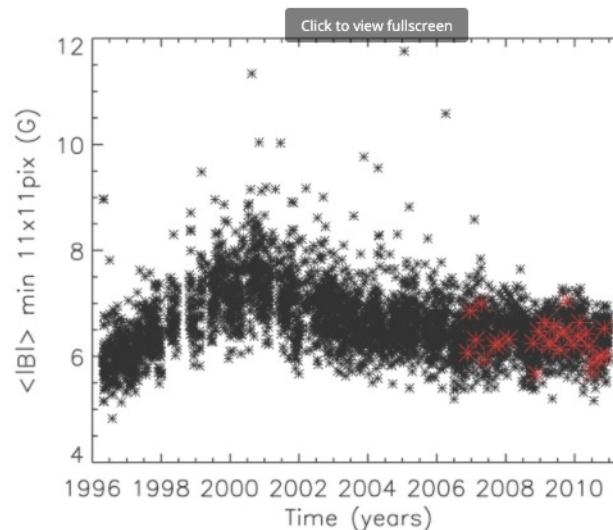
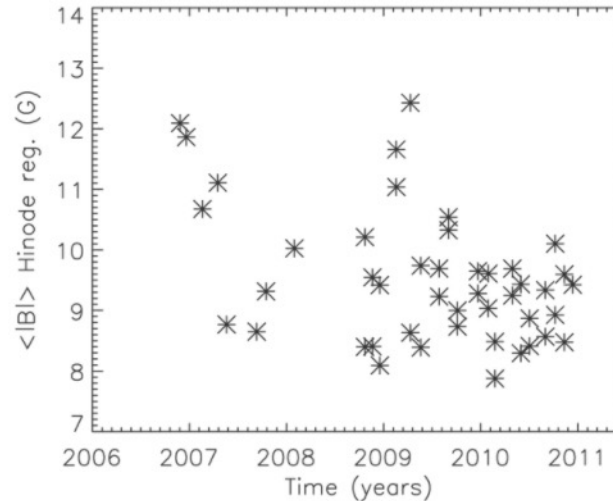
$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \nabla \times (\bar{\mathbf{v}} \times \bar{\mathbf{B}} + \gamma \times \bar{\mathbf{B}} \dots)$$

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

Does the QS vary with the solar cycle?



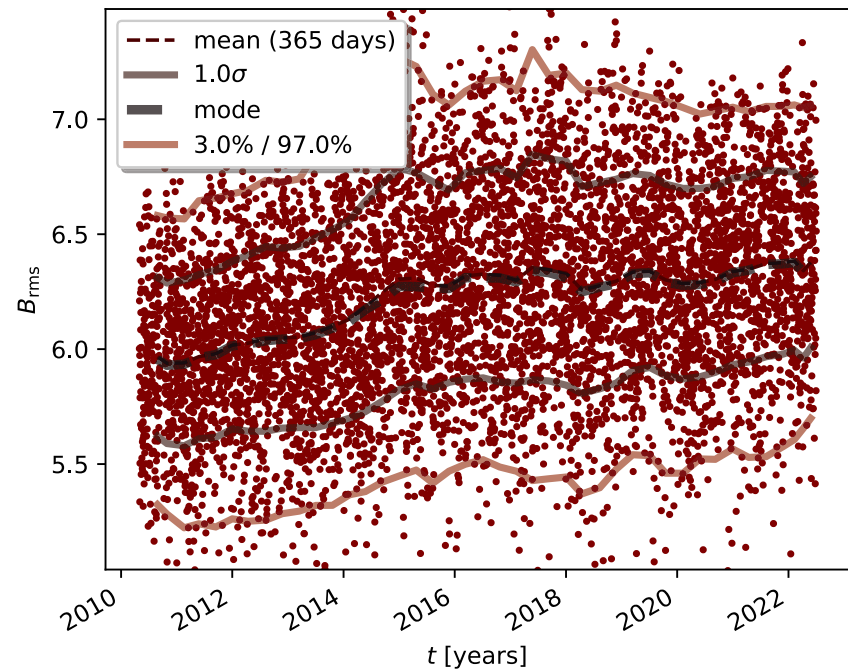
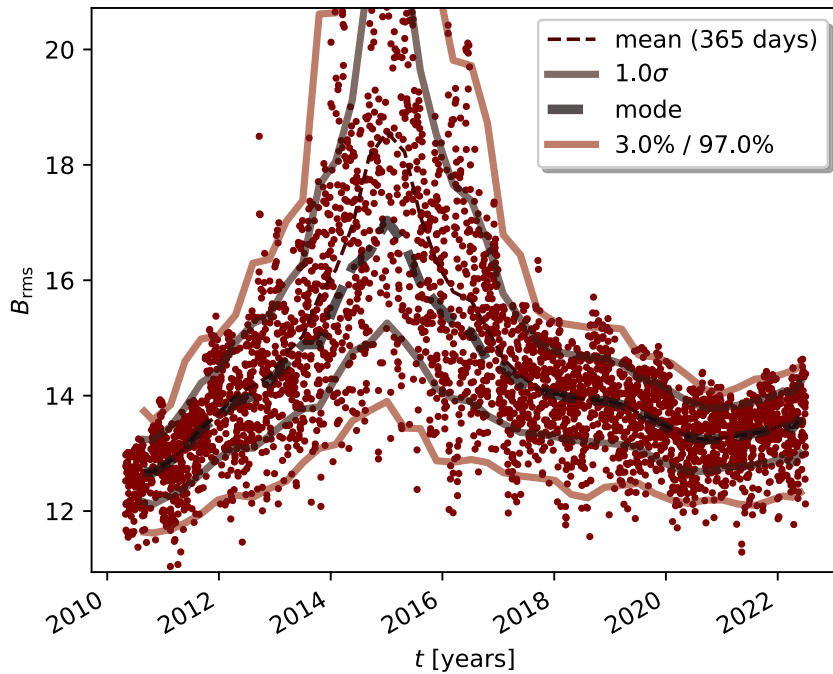
Bühler et al. (2013)
([Hinode](#))



Meunier (2018)
([MDI](#))

- 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?

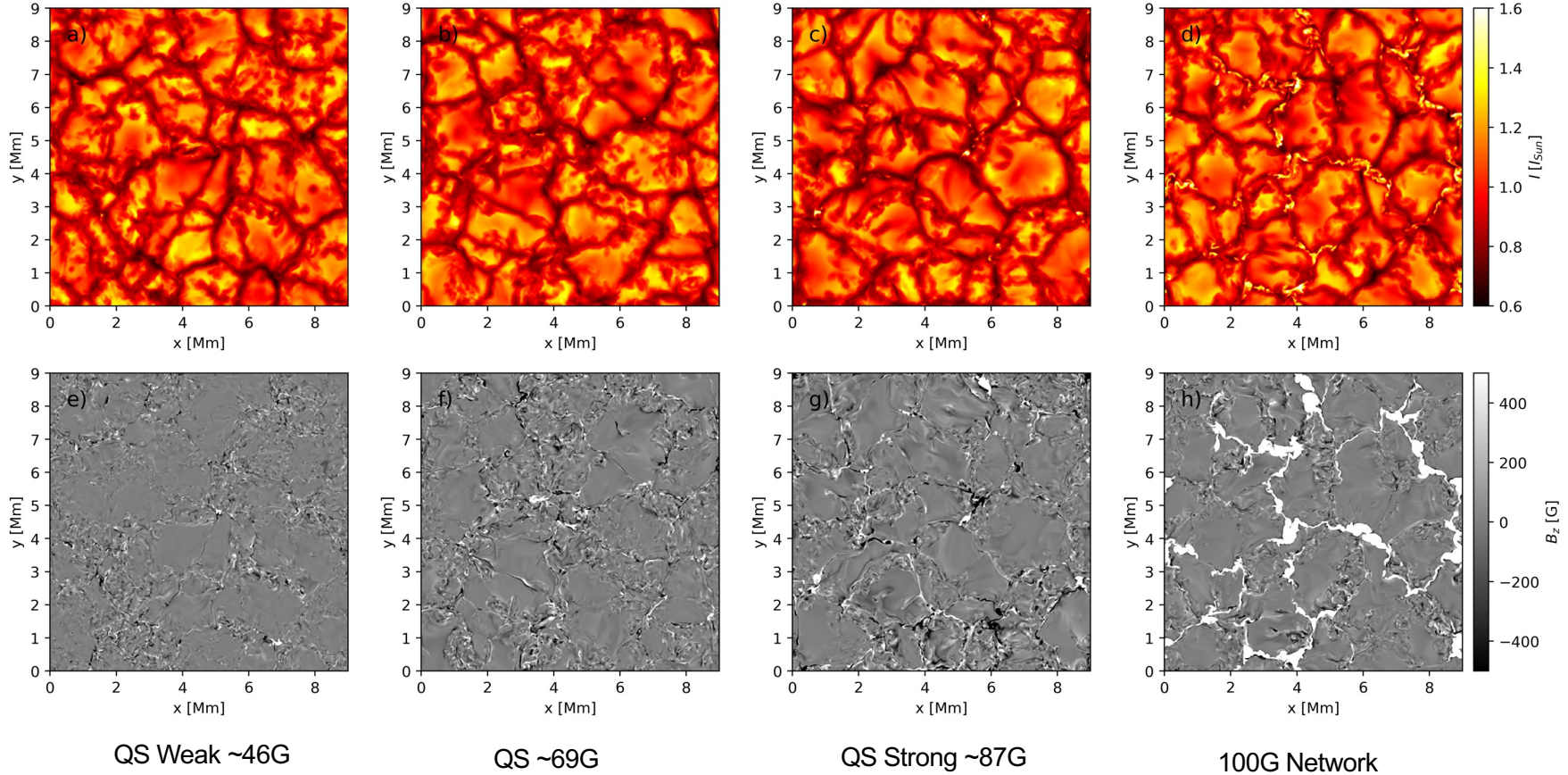
Does the QS vary with the solar cycle?



Korpi-Lagg et al. (2022)

- Solar cycle variation of quietest 15x15deg patches (includes network)
- No significant variation of quietest 1x1deg patches (excluding network)
- How much does the SSD contribute to the “quietest” network?
- Contribution to TSI from internetwork field?

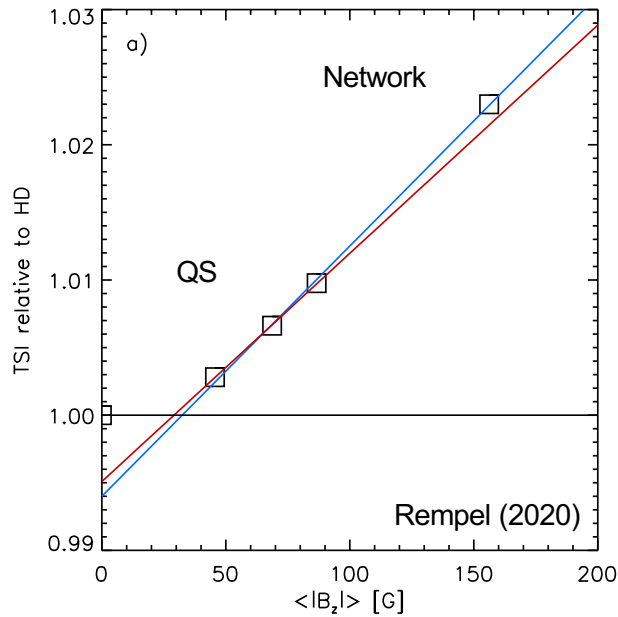
TSI sensitivity to the QS field strength



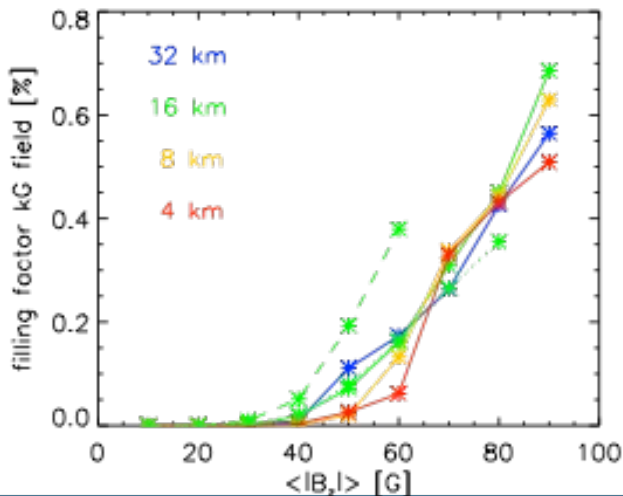
Zeeman and Hanle measurements (e.g. Danilovic et al. 2016, del Pino Alemán et al. 2018) suggest a QS field strength ($\langle |B_z| \rangle$ @ $\tau=1$) of 60 – 80 G

From Rempel (2020)

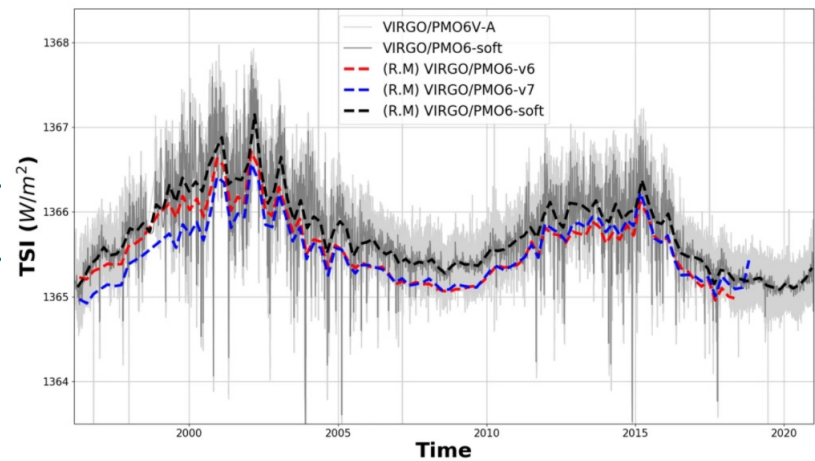
TSI sensitivity of quiet Sun



- 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

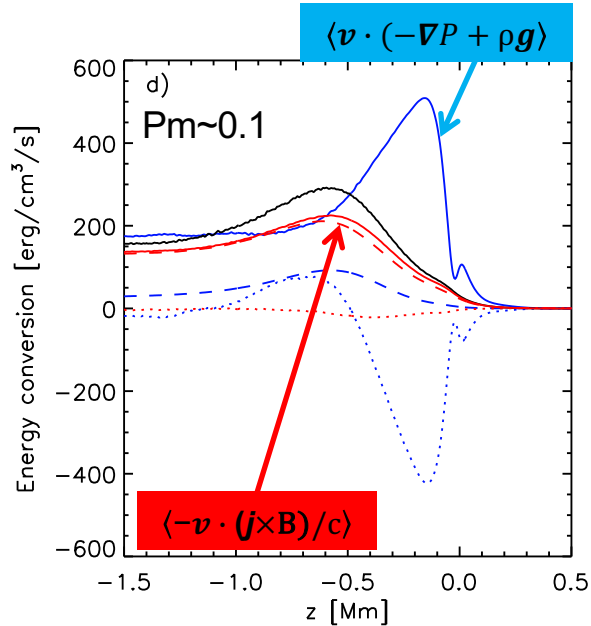
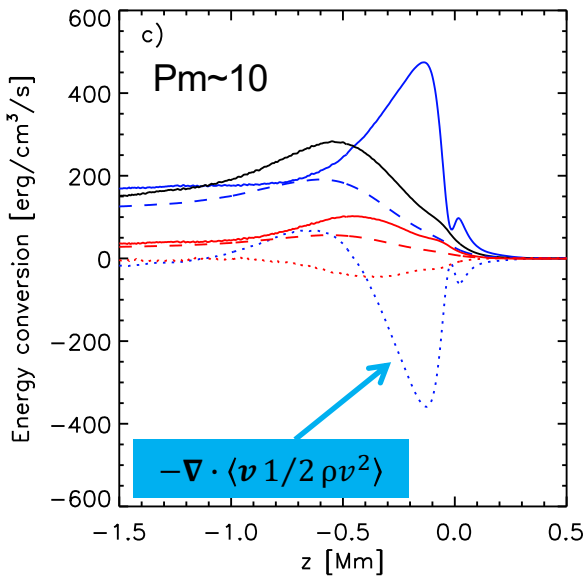


if the QS would vary by 10% (about 7G out of 70G)

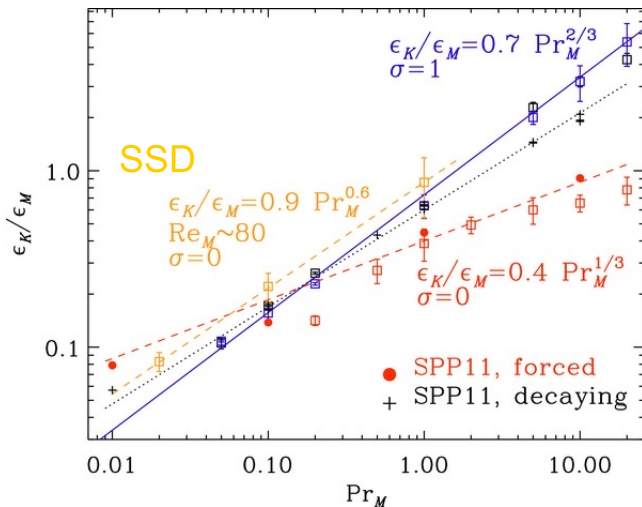


Finsterle et al. (2021)

SSD energetics

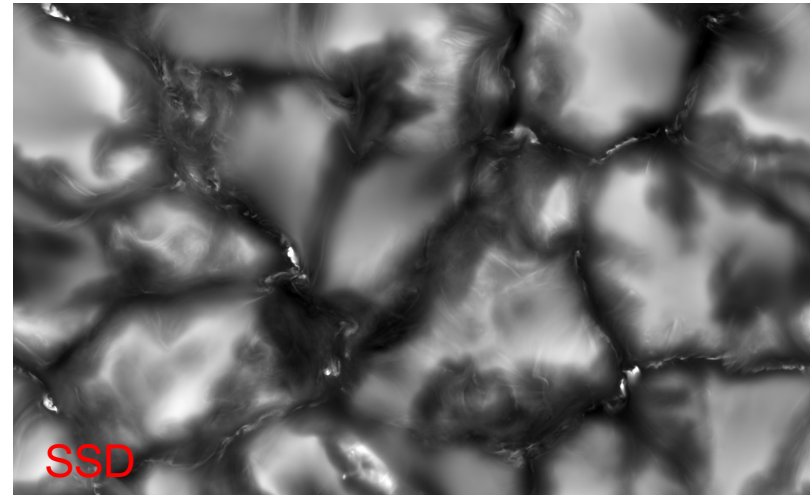
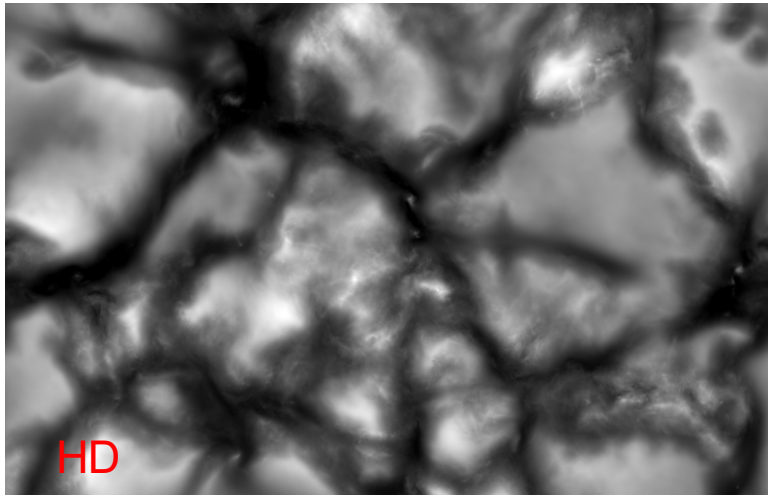


- About 150 erg/cm³/s “convective driving” available in upper CZ/photosphere to drive dynamo
- Energy transfer to magnetic energy strongly Pm dependent (Brandenburg 2011, 2014, Brandenburg & Rempel 2019)
- Most efficient dynamos (in terms of energy conversion) found for low Pm regime
- Uppermost 1.5 Mm of convection zone: About $>0.3 L_{\text{Sun}}$ converted to B
- Total pressure/buoyancy driving in CZ $\sim 3 L_{\text{Sun}}$

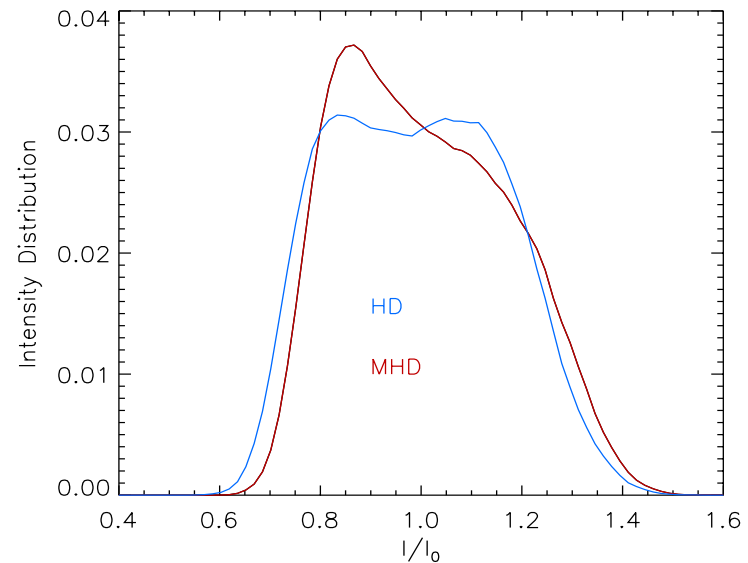


Brandenburg (2014)

Implications for granulation

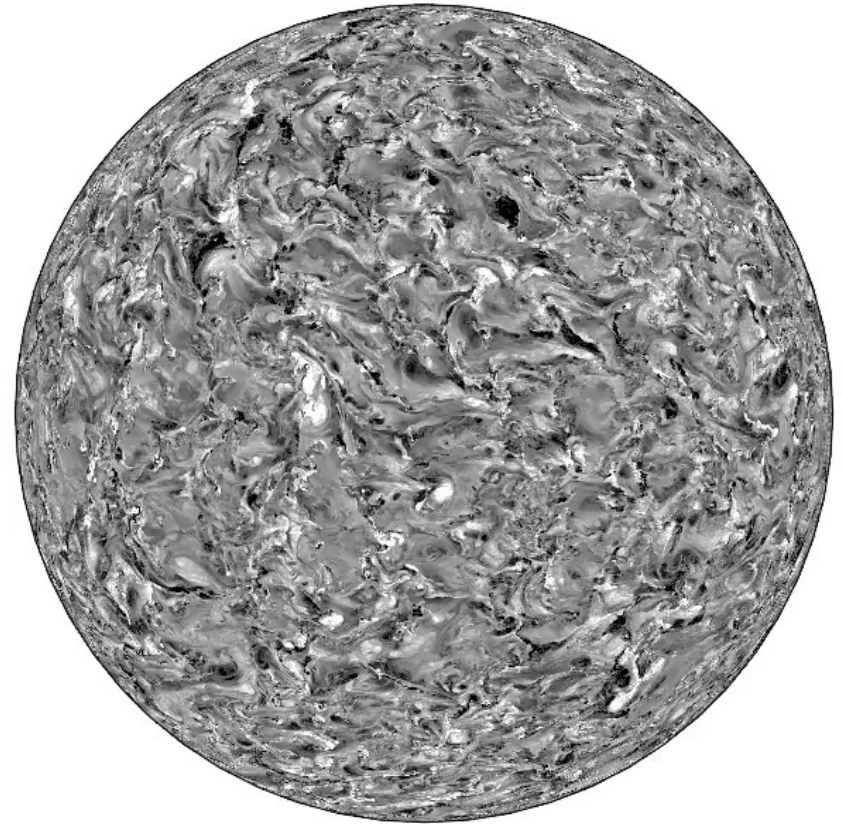
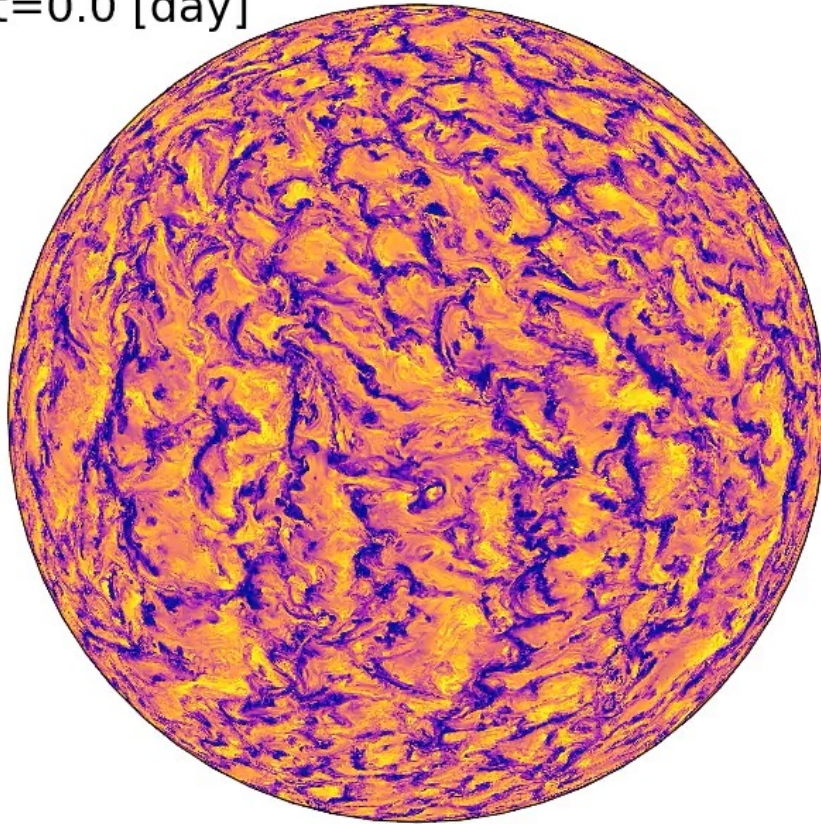


- Shape of intensity PDF strongly resolution dependent
 - Steiner 2017: Asymmetric double peak disappear for high resolution HD
- Asymmetric shape fingerprint of SSD!



Differential rotation/convective conundrum

t=0.0 [day]



From Hotta & Kusano (2021)

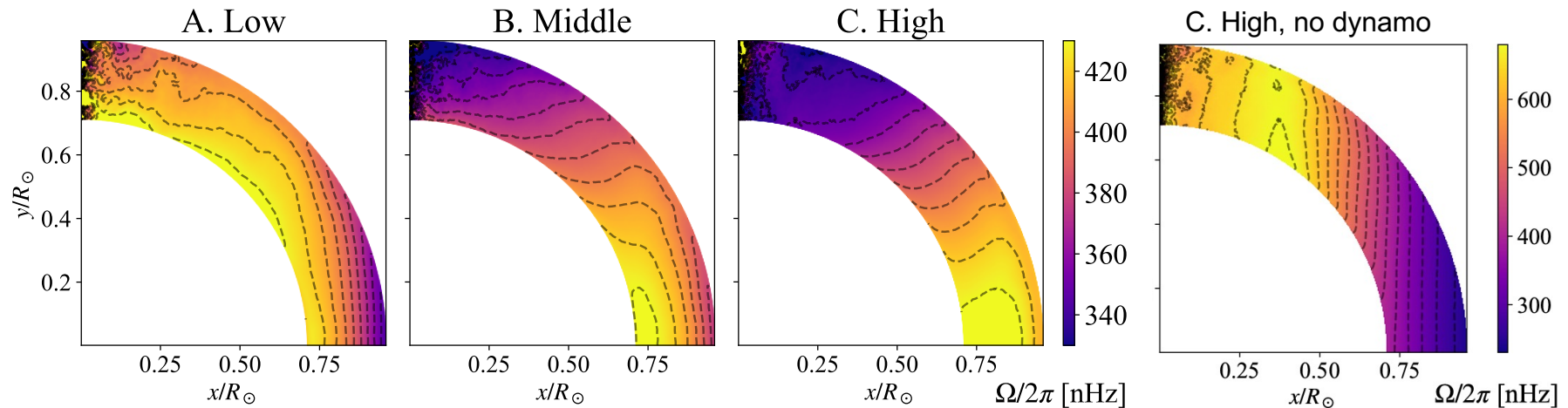


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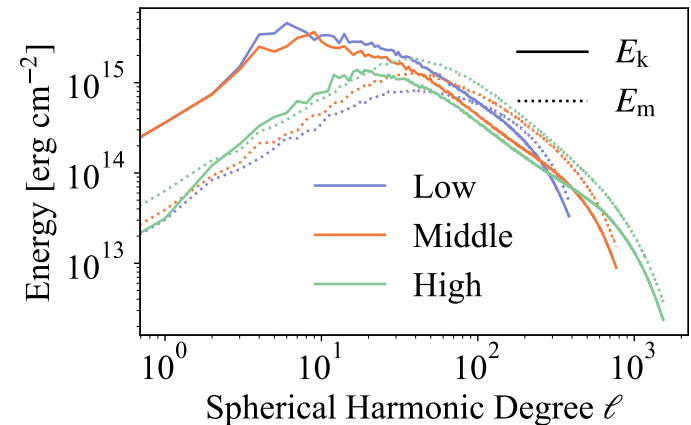
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Differential rotation/convective conundrum

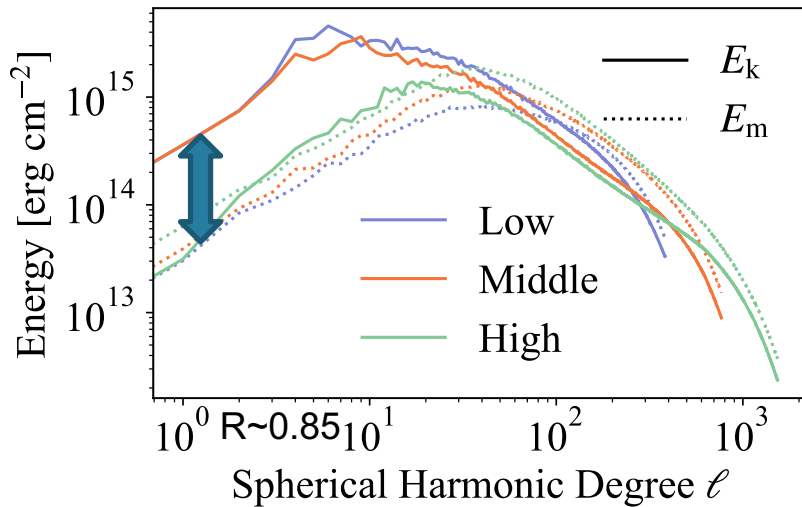


- Flip from fast pole to fast equator for high resolution simulation $\sim 384 \times 3072 \times 6144$, happens only in presence of magnetic field
- Suppression of flows on large scales, peak of power shifts from $l=6$ to $l=30$
- Did not (yet?) produce a large-scale field, possibly due to total simulation time (4000 days)

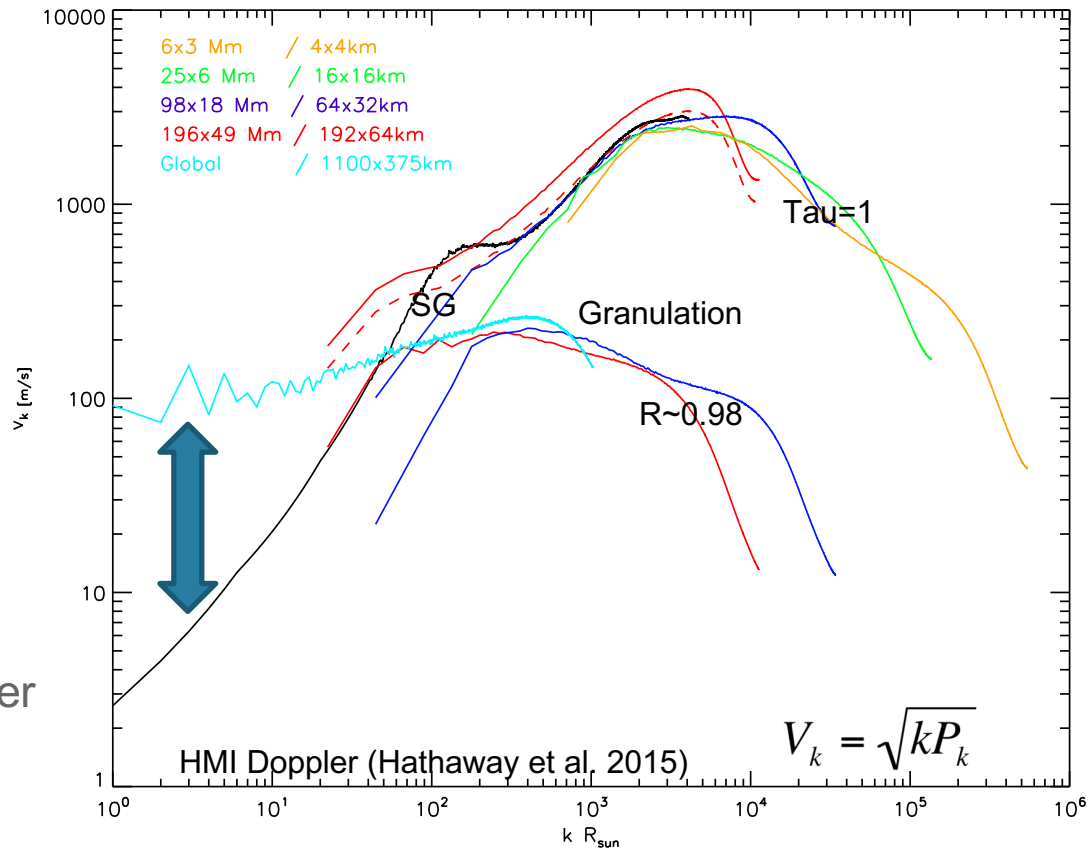


From Hotta & Kusano (2021, 2022)

Solar velocity spectrum at large scales



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



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

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



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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 R_m , 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**



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