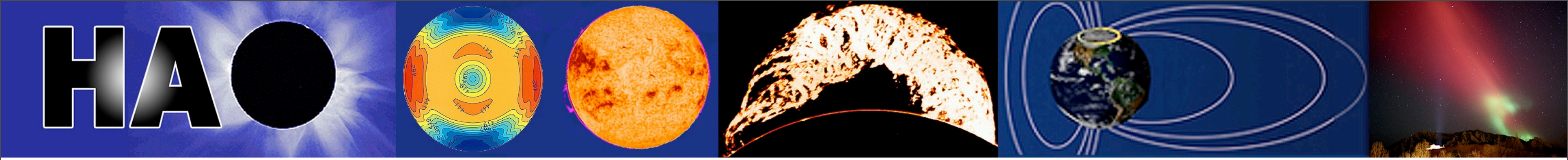

LES Simulations of Quiet Sun Magnetism

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The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Quiet sun magnetism

- Origin and spatial distribution of quiet sun field
  - Small scale dynamo?
  - Remnant field from large scale dynamo?
- Vögler, Schüssler (2007)
  - Upper most few Mm of CZ act as dynamo despite small recirculation
  - Field strength falls short by a factor of 2-3 compared to Hinode observations (Danilovic et al. 2010)
- Approach here:
  - Only numerical diffusivities based on monotonicity constraints
    - Does this make sense for small scale dynamo simulation?
    - Robustness of results:
      - Resolution, "numerical Pm"
      - Comparison with physical η and real sun
  - Bottom boundary conditions
    - Open (try to mimic the deep CZ):
      - saturation field strength depends on assumptions in inflow regions
      - $<|B_z|> \sim 30 \ldots 80$ G
      - Observations (Hinode) best reproduced for $<|B_z|> \sim 60$ G
    - Closed (better defined dynamo problem, but not the Sun):

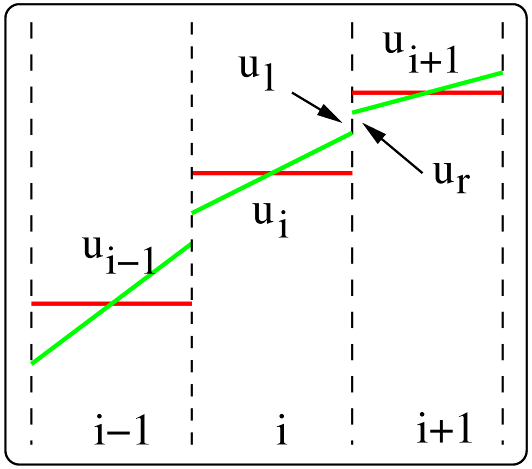
Numerical diffusivities

- Starting point: 4th order scheme (RK4 + centered 5 point stencil in space, MURaM radiative MHD code)
  - Stable for linear waves, need additional diffusivity for discontinuities
- Diffusive flux required for shock capturing:

$$F_{i+1/2} = -\frac{1}{2}c(u_{i+1} - u_i) \;\rightarrow\; D = \frac{1}{2}c\Delta x \;\rightarrow\; t_{diff} = \frac{1}{2}\frac{(\Delta x)^2}{D} = \frac{\Delta x}{c} = t_{adv}$$

- High order scheme to reduce diffusivity in “smooth” regions:
  - Piecewise linear reconstruction of solution using a limited slope (i.e. disable reconstruction if there is a monotonicity change

$$S_i = \mathrm{Slope\_Limiter}(u_{i+1} - u_i, u_i - u_{i-1})$$



  – Extrapolated values at cell interfaces:

$$u_l = u_i + 0.5\ S_i$$

$$u_r = u_{i+1} - 0.5\ S_{i+1}$$

  – Jumps at interfaces:

$$\Delta u_{CC} = u_{i+1} - u_i$$

$$\Delta u_{EX} = u_r - u_l$$

Numerical diffusivities

- 2^{nd} order diffusive flux (e.g. 2^{nd} order TVD Lax-Friedrichs):

$$F_{i+1/2} = -\frac{1}{2}\, c\, \Delta u_{EX}$$

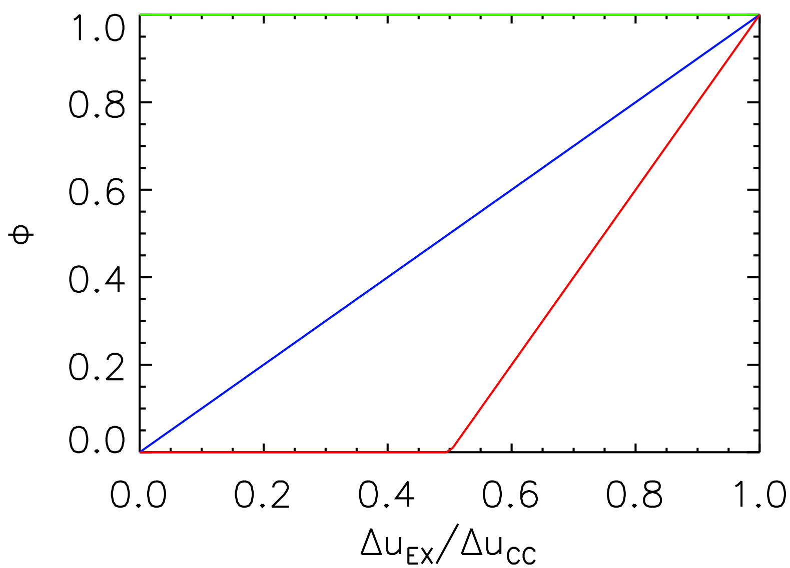
- Further reduction of diffusivity

$$F_{i+1/2} = -\frac{1}{2}\, c\, \Phi\left(\frac{\Delta u_{EX}}{\Delta u_{CC}}\right) \Delta u_{EX}$$

$$\Phi(x<0) = 0 \text{ (no anti-diffusion)}$$

$$\Phi(x=1) = 1 \text{ (keep max schock diffusivity)}$$

$$\Phi \text{ monotonically increasing}$$



- Additional ingredients:
  - $c=v+v_{alfven}$ (sound speed not required: low diffusivity for small Ma)

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"Sun" at 4 km resolution

Intensity

Bz(tau=1)

|B|

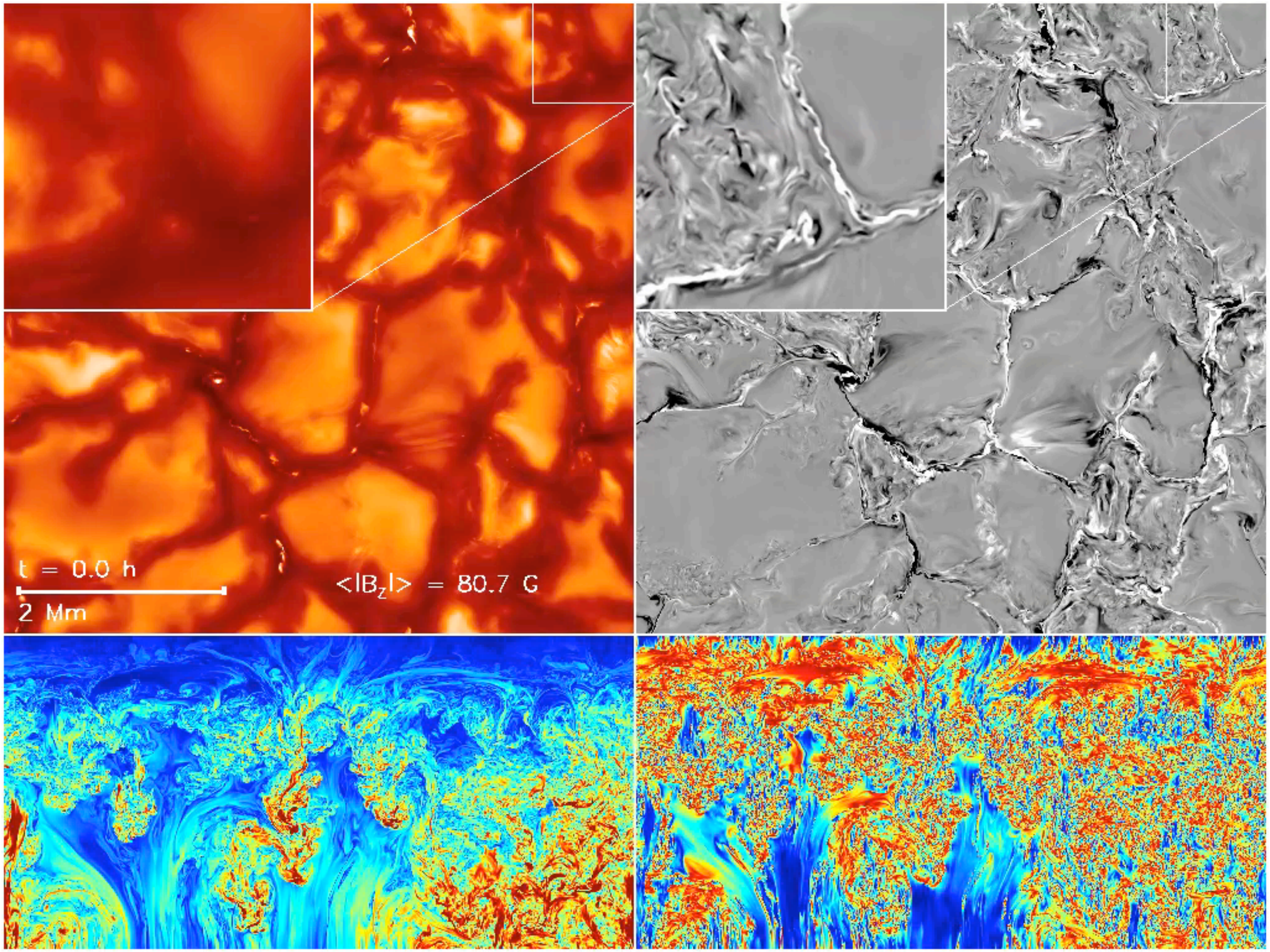
Inclination
horiz./vert.

- Simulation domain: 6.144 x 6.144 x 3.072 Mm^3
- Grid size: 1536 x 1536 x 768

“Sun” at 4 km resolution

Intensity

Bz(tau=1)



|B|

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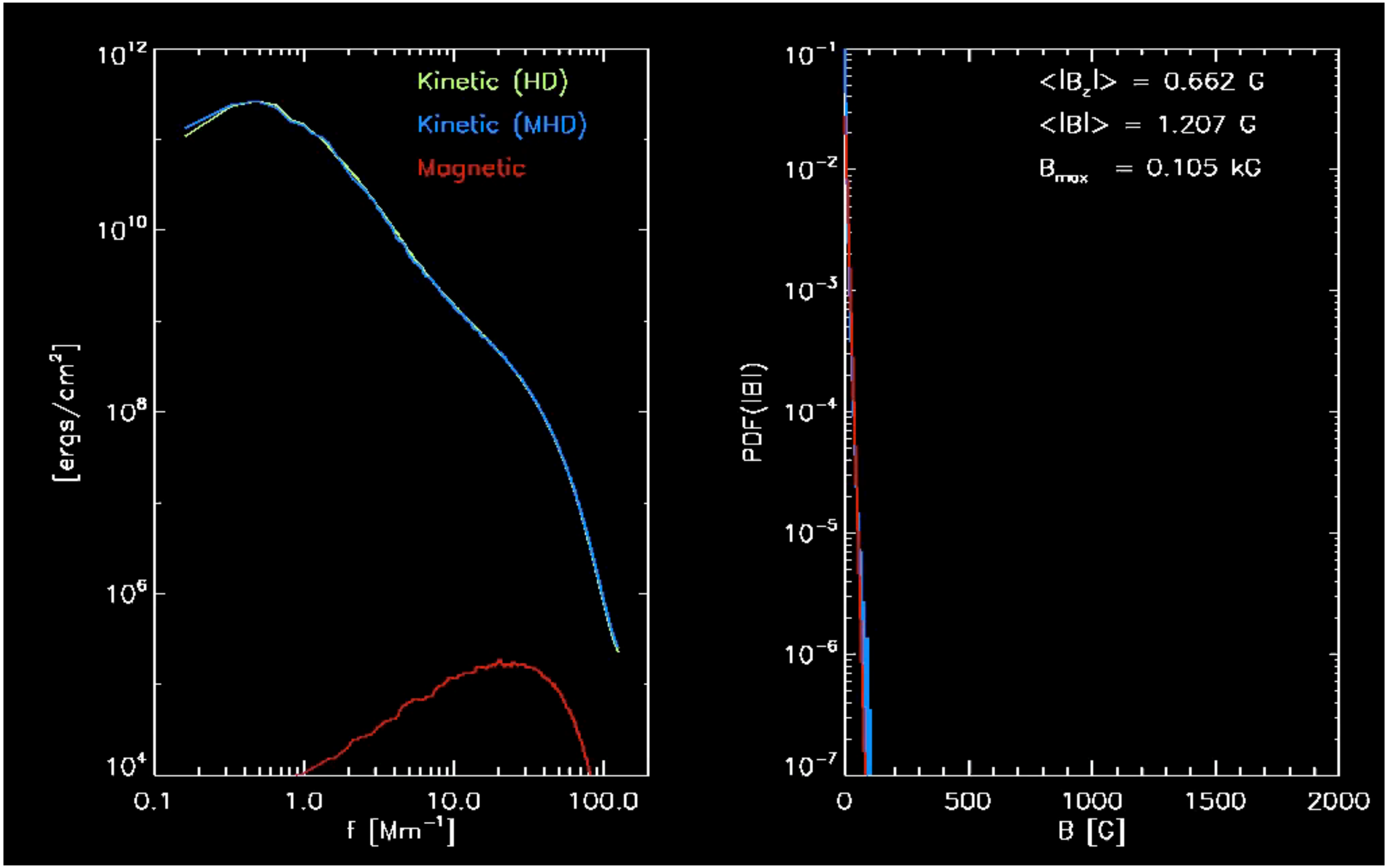
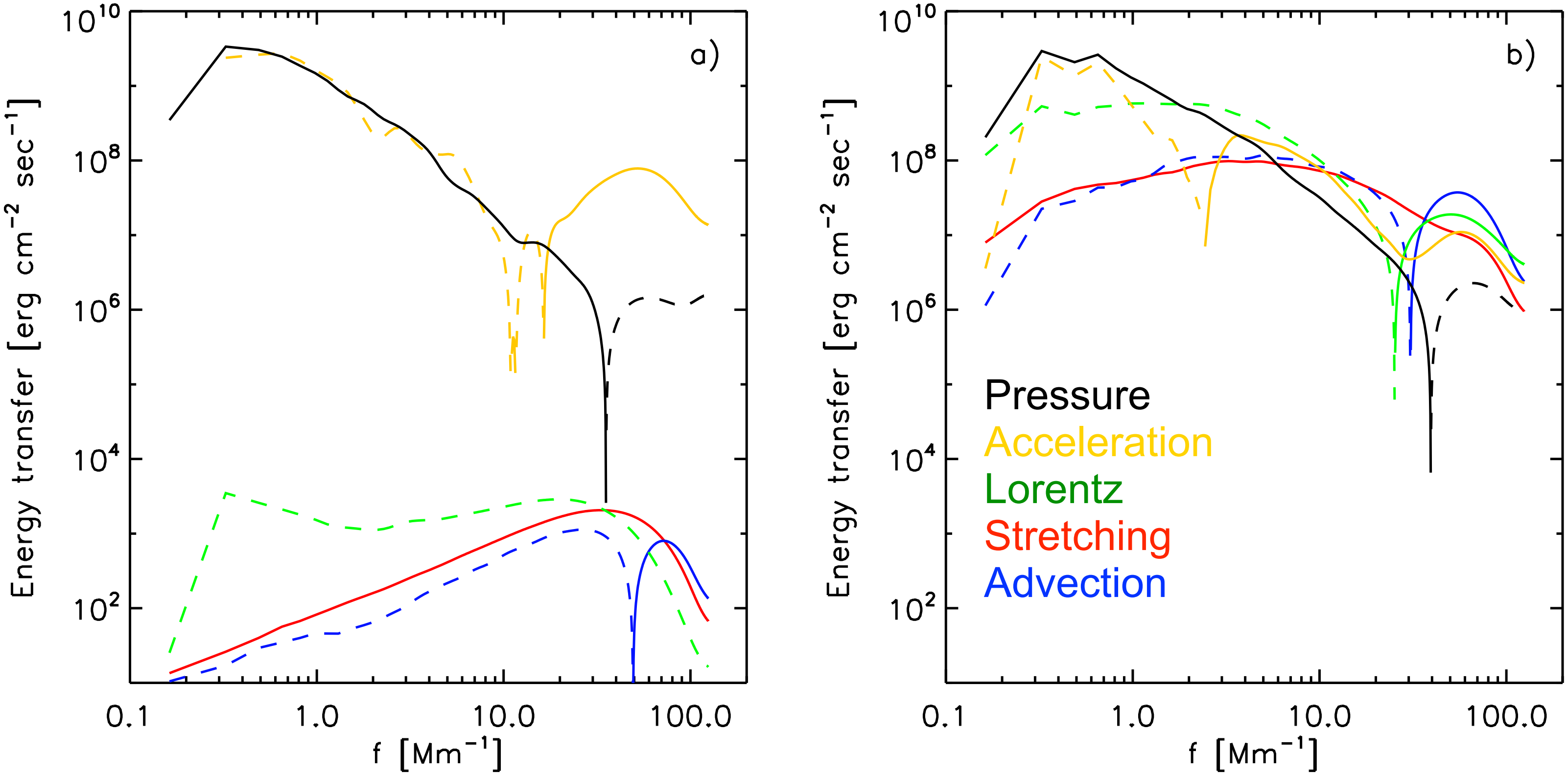
Kinematic to saturated regime

Kinematic to saturated regime



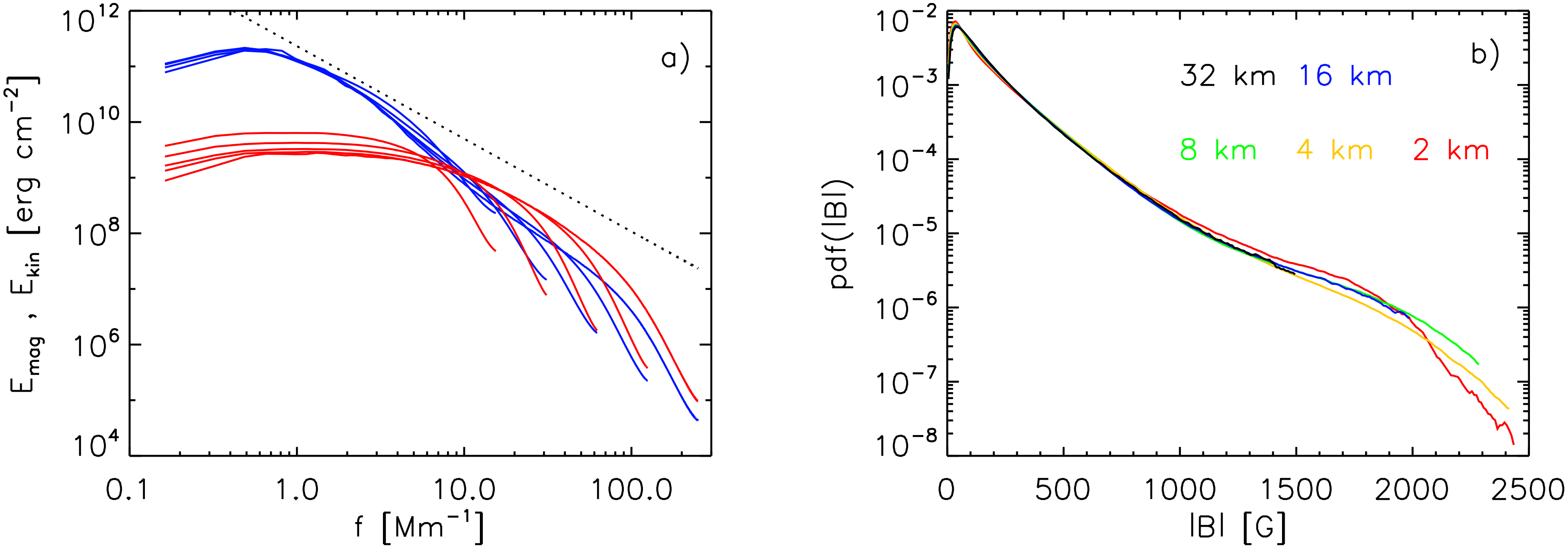
Kinematic to saturated regime

Kinematic to saturated regime: Transfer functions



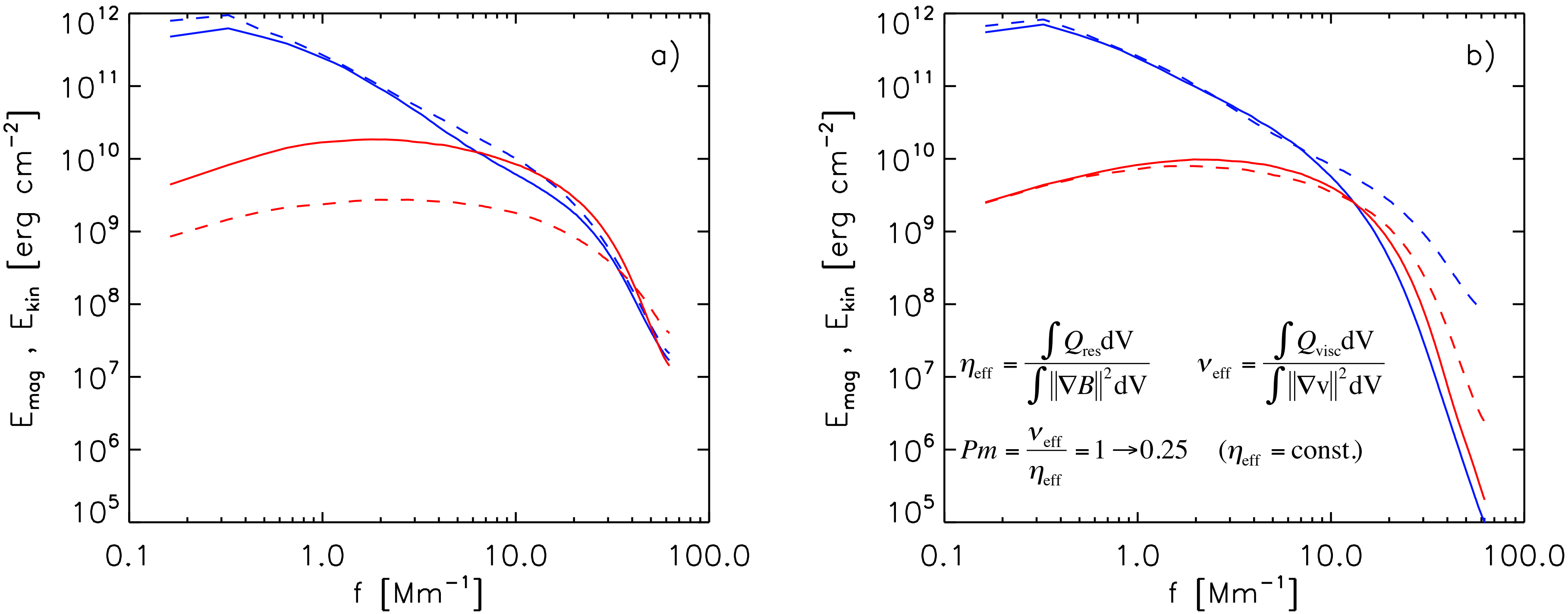
- Kinematic phase:
  - Energy exchange at L ~ 6-8 Δx
  - Depends on resolution
- Saturated phase:
  - Energy exchange at L ~ 250 km (downflow lanes)
  - Does not depend on resolution

Resolution dependence 32 ... 2 km



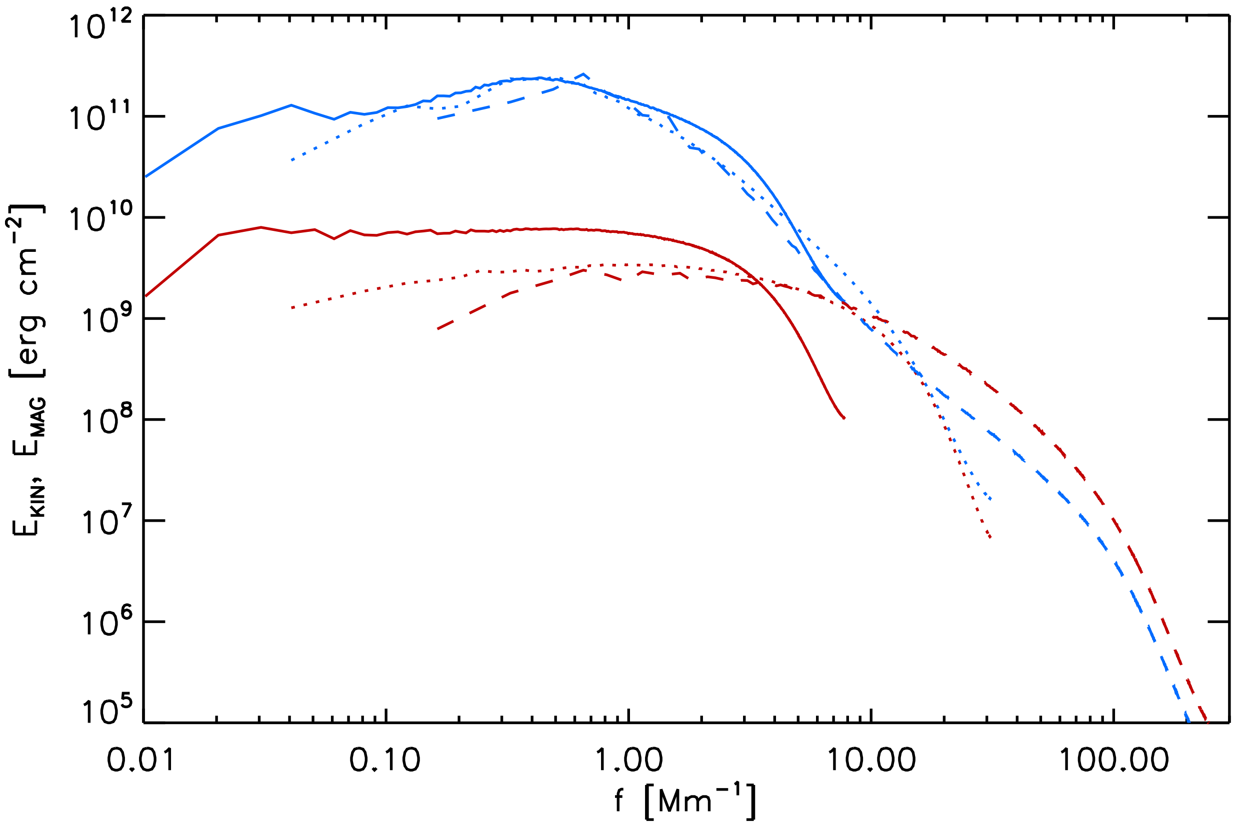
- Converged results using LES approach
  - No explicit viscosity or magnetic resistivity
  - Changing resolution by a factor of 16!
  - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
  - Implicit magnetic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

Physical vs. numerical diffusivity, magnetic Pm (experiments with closed bnd)



- Solutions with physical η similar to pure numerical diffusivity
  - Similar transfer functions, but
  - reaches only 25% of magnetic energy ($\eta = 10^{10}$ cm^2/sec)
- Moderate dependence on “numerical Pm”

From granulation to supergranulation

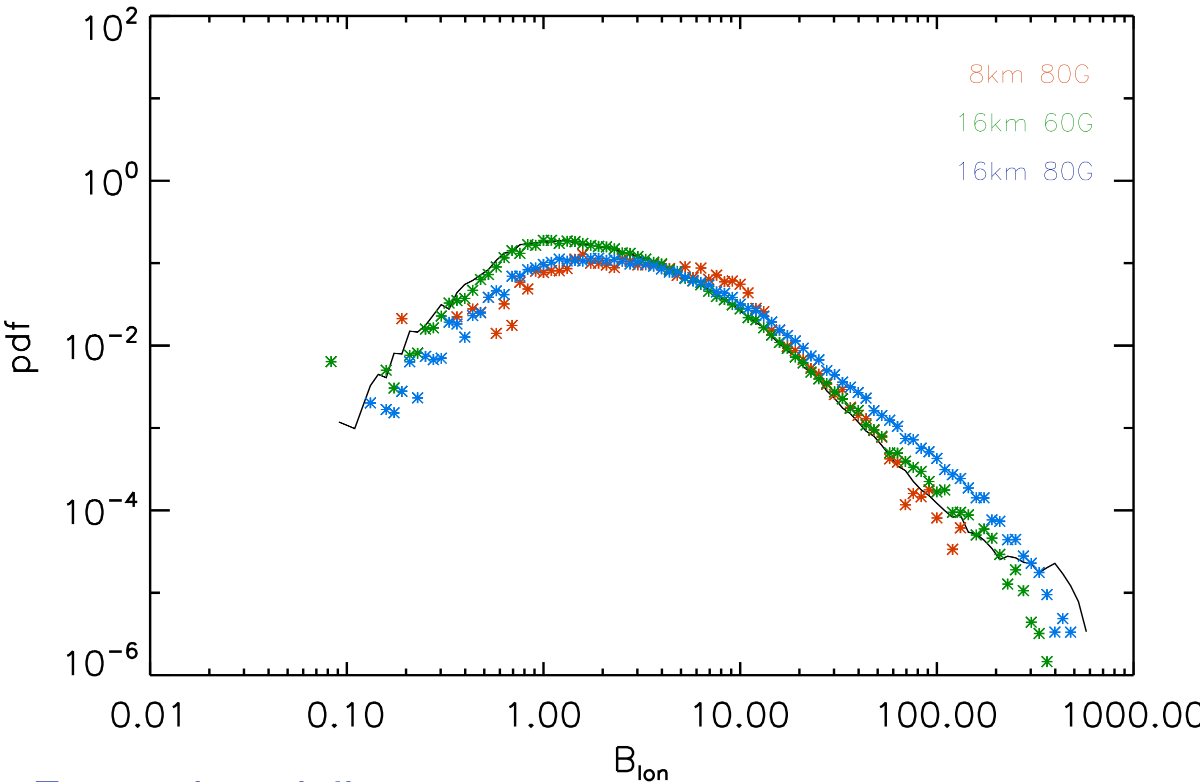


- Domains from 6x6x3 Mm^3 to 100x100x20 Mm^3
- Photospheric power spectrum (E_{mag})

Flat on scales larger than granulation

E_{mag} ~ 2 E_{kin} on scales smaller than 100 km

Comparison with Hinode



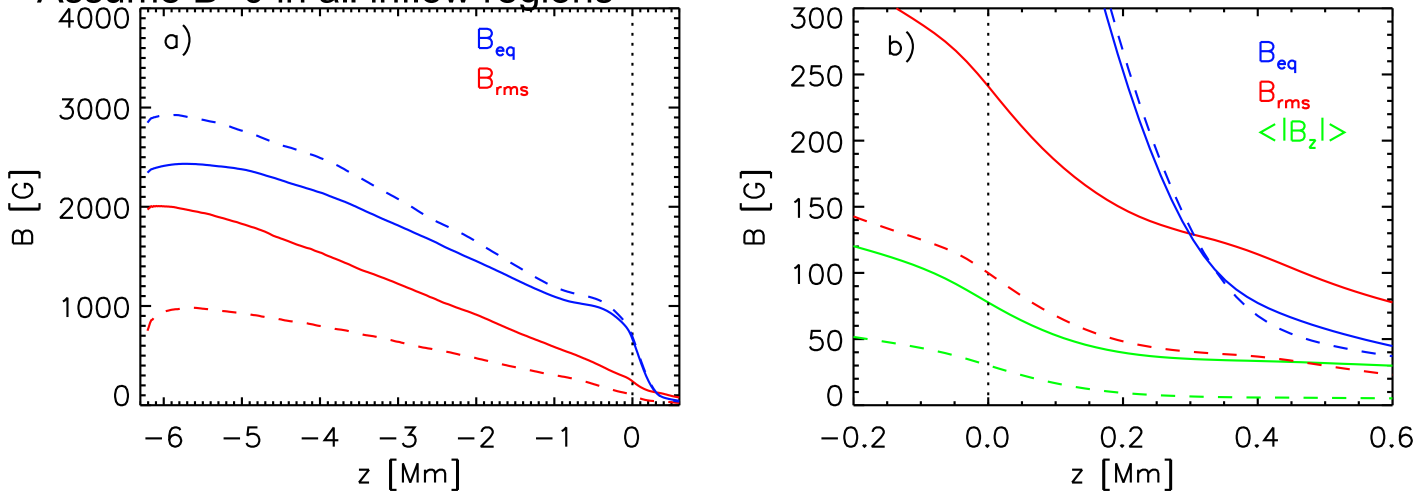
- Forward modeling:
  - Simulation with non-grey RT
  - Stokes profiles for Fe 6301/6302
  - Convolution with PSF of Hinode
  - Addition of noise
  - Analysis identical to observed data

Conclusions

- LES Small scale dynamo
  - Used modified slope-limited diffusion scheme
    - No “physcial” SGS, monotonicity constraints on solution
  - Results converged with respect to resolution (for saturated regime, kinematic growth rate strongly resolution dependent)
  - No substantial difference to case with physical resistivity, except for saturation level
  - No strong dependence on “numerical Pm”, although explored here only moderate variation from 1 to 0.25
- Quiet Sun magnetic field
  - Observed flux density indicates solar convection zone close to equipartition in a few Mm depth
  - Saturated dynamo operates on scale of downflow lanes (250 km), 3 orders of magnitude away from dissipation scale
    - Might be the reason why LES is OK for saturated case
  - Magnetic powerspectrum flat for L > 1 Mm, super-equipartition (factor ~ 2) for L < 100 km
  - Agrees well with observations (only constraint on scales > 200 km)

Field strength of quiet sun?

- Depends on bottom boundary condition
  - B=0, B vertical, B isotropic …?
- Upper limit:
  - B_{rms} should not increase faster with depth than B_{eq}
- Lower Limit:
  - Assume B=0 in all inflow regions



- Field strength range: <|Bz|> ~30-80 G
  - Best match with Hinode data <|Bz|>~60 G (Danilovic & Rempel in prep.)