On active latitudes and magnetic flux concentrations in convection simulations

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With

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Thanks: to many collaborators

Tool: Pencil Code (https://github.com/pencil-code)

NORDITA Program on stellar convection, 29 Aug 2024

Active Latitudes

Setup: Convecting Cartesian Box at Different Latitudes

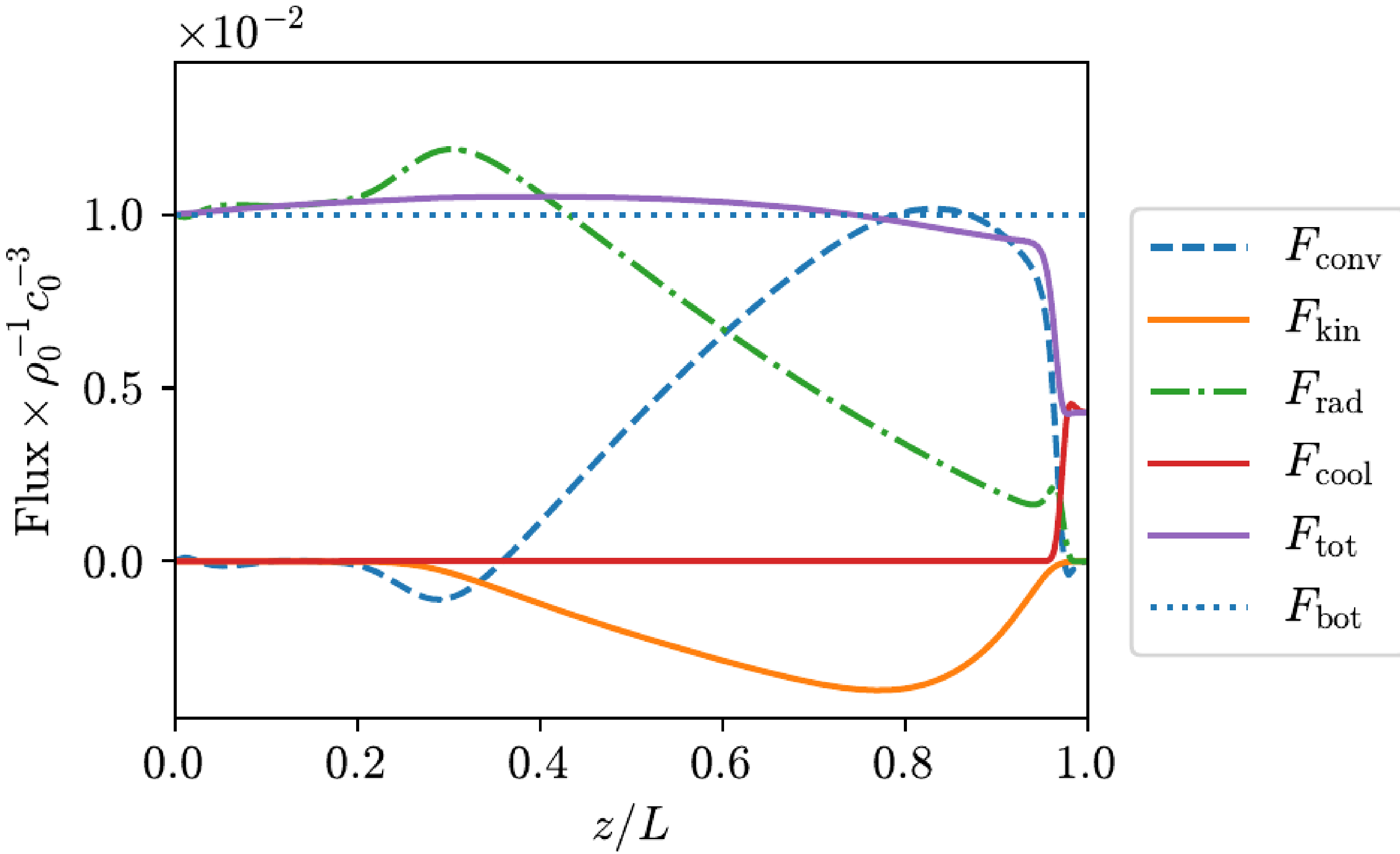
- Basic Equation:

$$
\begin{aligned}
\frac{\mathrm{D}\ln\rho}{\mathrm{d}t} &= -\nabla\cdot\boldsymbol{u} \\
\rho\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{d}t} &= -\nabla p - \rho g\hat{\boldsymbol{z}} + \boldsymbol{J}\times\boldsymbol{B} + 2\boldsymbol{\Omega}\times\boldsymbol{u} + \nabla\cdot\left(2\rho\nu\overleftrightarrow{S}\right) \\
\rho T\frac{\mathrm{D}s}{\mathrm{d}t} &= q + \nabla\cdot(\chi\nabla T) + 2\rho\nu S_{ij}S_{ij} \\
\frac{\partial\boldsymbol{A}}{\partial t} &= \boldsymbol{u}\times\boldsymbol{B} + \eta\nabla^2\boldsymbol{A}
\end{aligned}
$$

- Cooling function near the top:

$$
q = -\kappa\,\frac{(c_s^2 - c_0^2)}{c_0^2}\,\Theta\left(\frac{z - z_{\rm cool}}{w_{\rm cool}}\right)
$$

Fluxes



$$\boldsymbol{F}_{\mathrm{conv}} \equiv \langle \rho C_P \boldsymbol{u} T \rangle$$

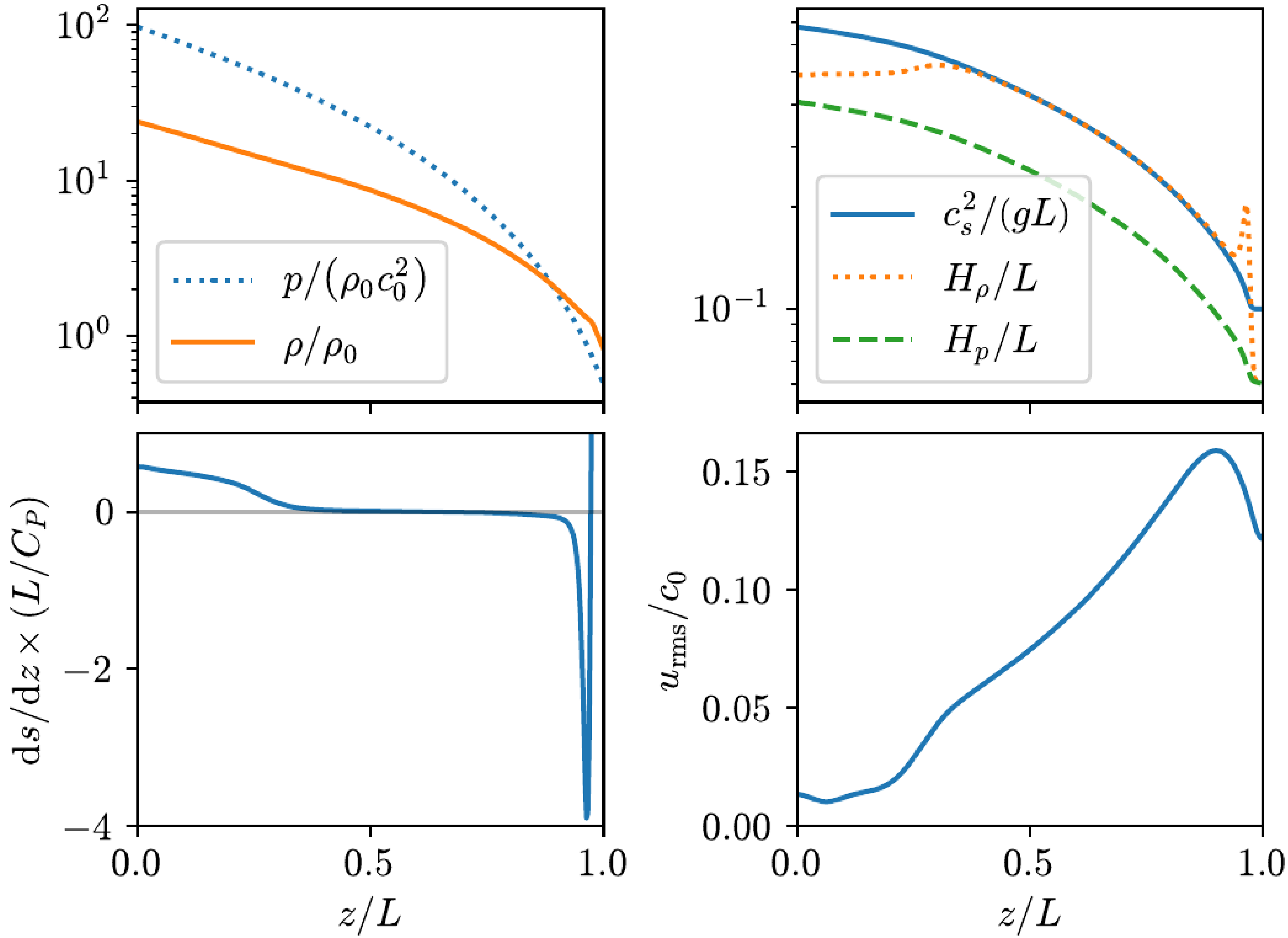
$$\boldsymbol{F}_{\mathrm{kin}} \equiv \langle \rho u^2 \boldsymbol{u}/2 \rangle$$

$$\boldsymbol{F}_{\mathrm{visc}} \equiv -\left\langle 2\rho\nu \boldsymbol{u} \cdot \overleftrightarrow{S} \right\rangle$$

$$\boldsymbol{F}_{\mathrm{cool}} \equiv -\hat{\boldsymbol{z}} \int_{z_{\mathrm{bot}}}^{z} \langle q \rangle \, \mathrm{d}z$$

$$\boldsymbol{F}_{\mathrm{rad}} \equiv -\chi \nabla T$$

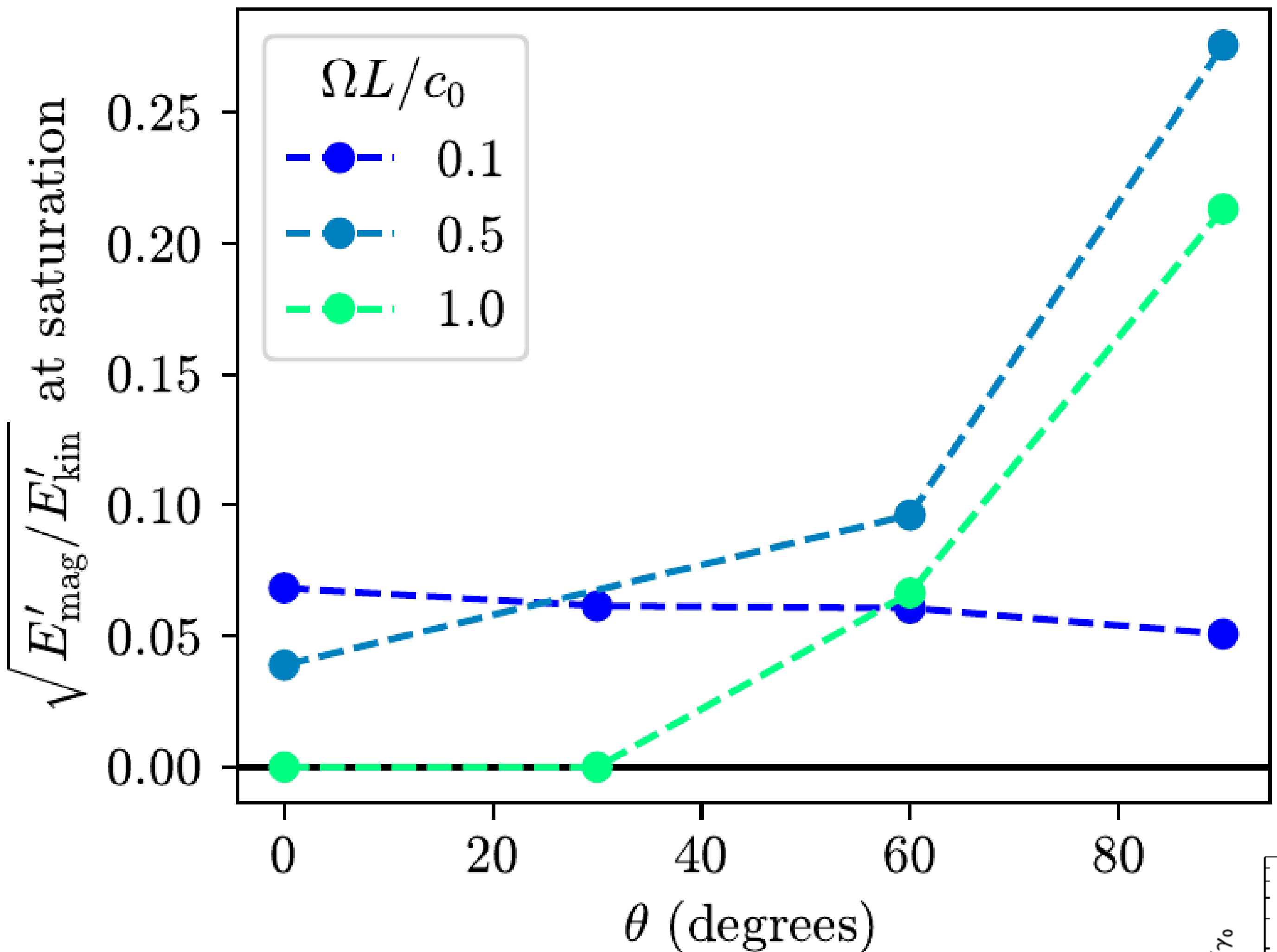
Background (NR case) and some parameters

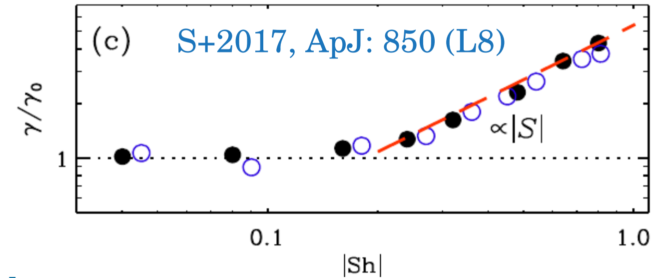


$\mathrm{Re}\ (\mathrm{Rm}) : 500 - 1000\ ; \mathrm{Co} : 0 - 2.5\ ; \mathrm{Ra} : (1 - 10) \times 10^6\ ; \mathrm{Ma} : 0.1 - 0.3$

Supercritical for Small Scale Dynamo

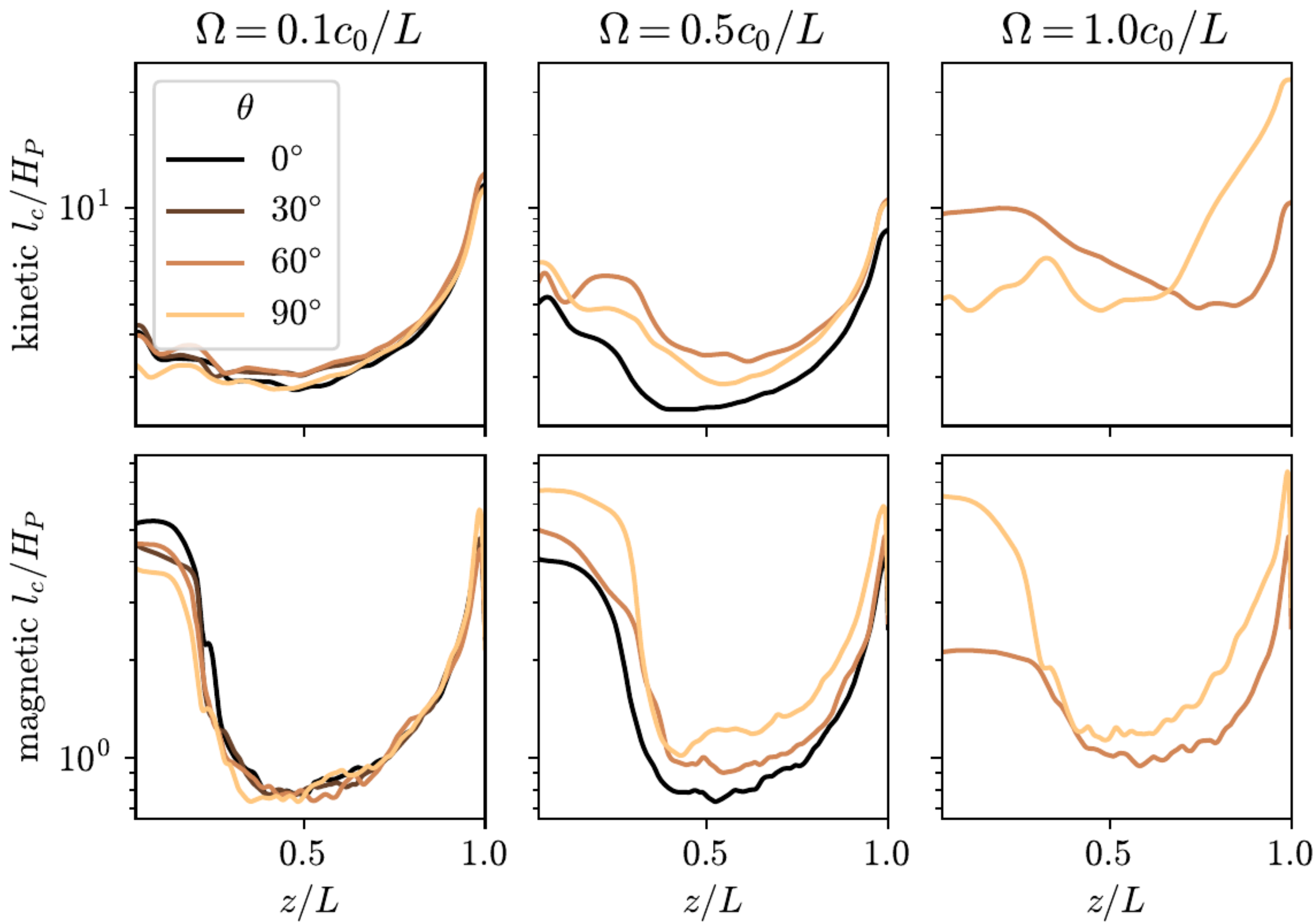
Magnetic Energy at Saturation





- Rotation suppresses the SSD
- Shear (induced by strong enough rotation) enhances it !

Integral Scales (from 2D spectra)



$l_c/L \lesssim 0.6$

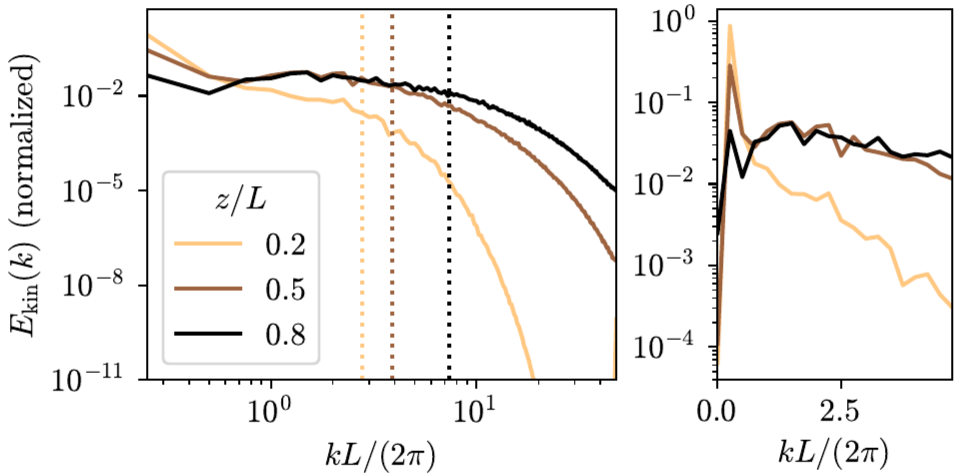
$l_c^M / l_c^K < 1$

Dominated by SSD

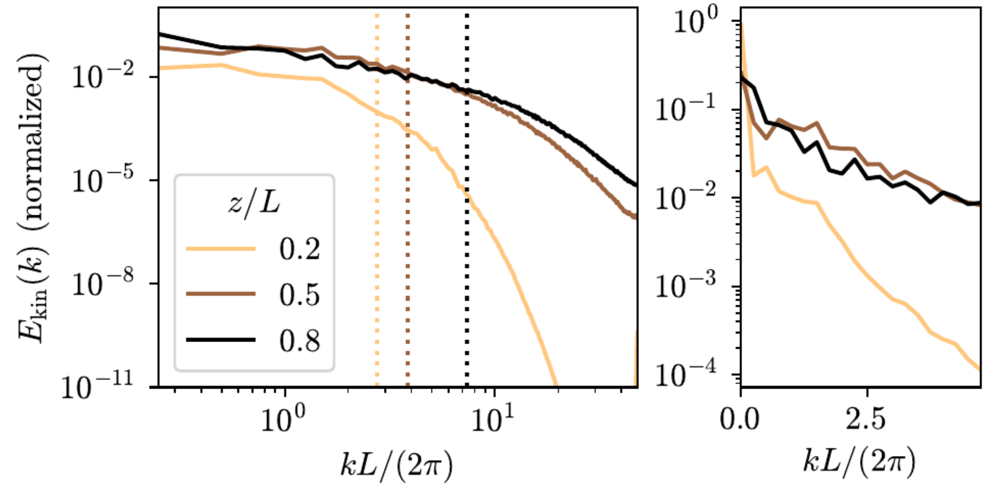
$$l(z) = \frac{2\pi}{\int_{+0}^{\infty} E(p,z)\,\mathrm{d}p} \int_{+0}^{\infty} \mathrm{d}p\, \frac{E(p,x_3)}{p}$$

Large scale flows/vortices: Shear

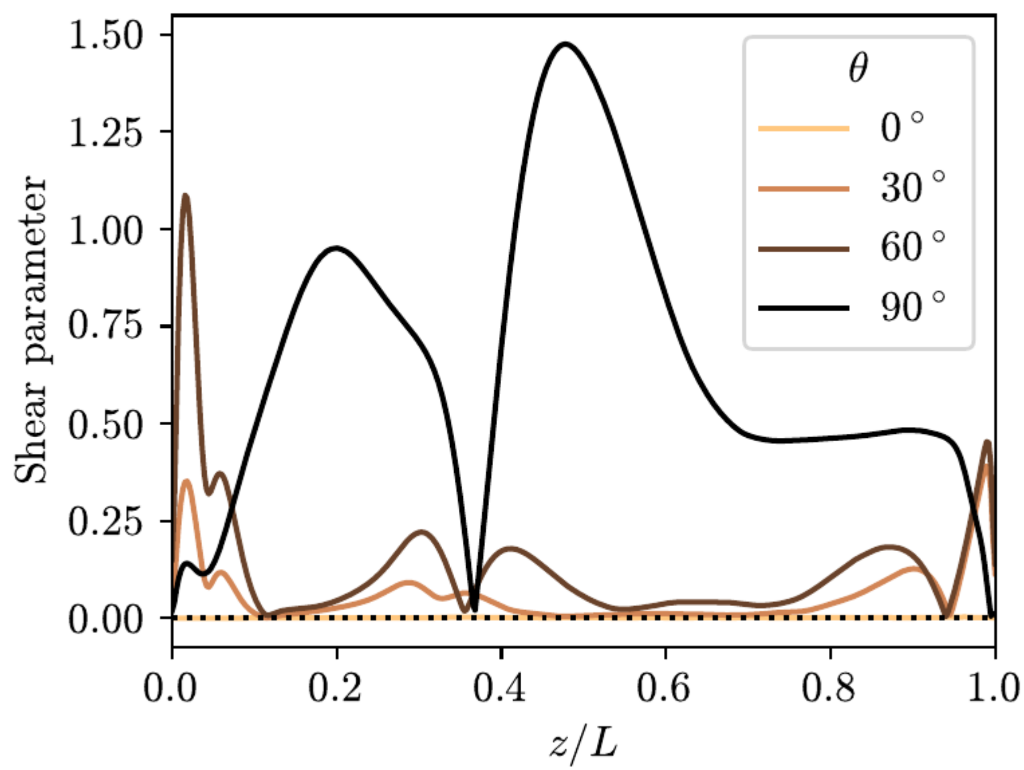
$\theta = 60^\circ$

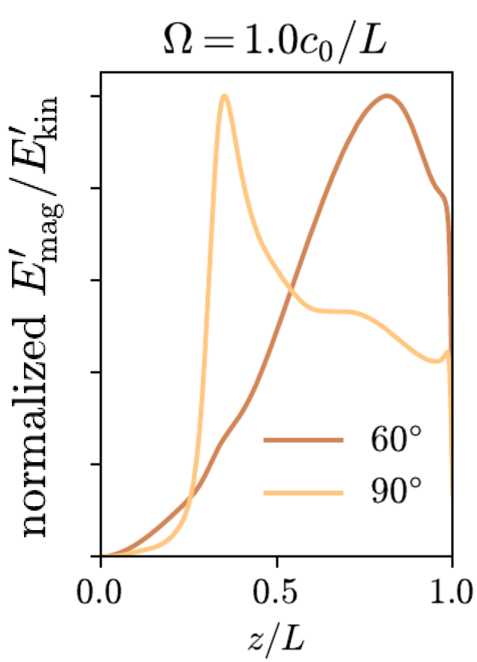


$\theta = 90^\circ$



$\Omega L / c_0 = 1$



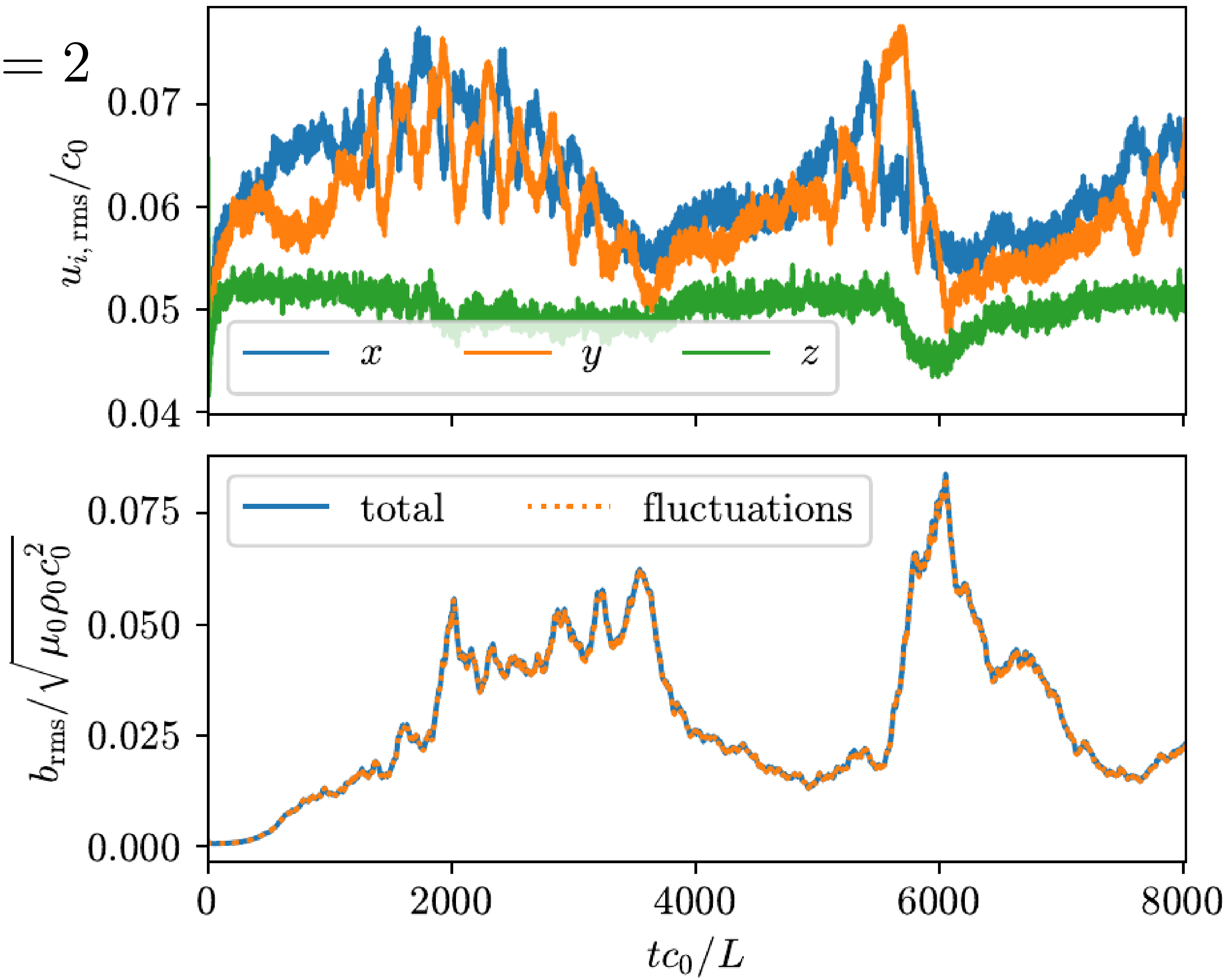


Cycles (nonlinear)

An interplay between LS flow/shear and magnetic fields

$\Omega L/c_0 = 2$

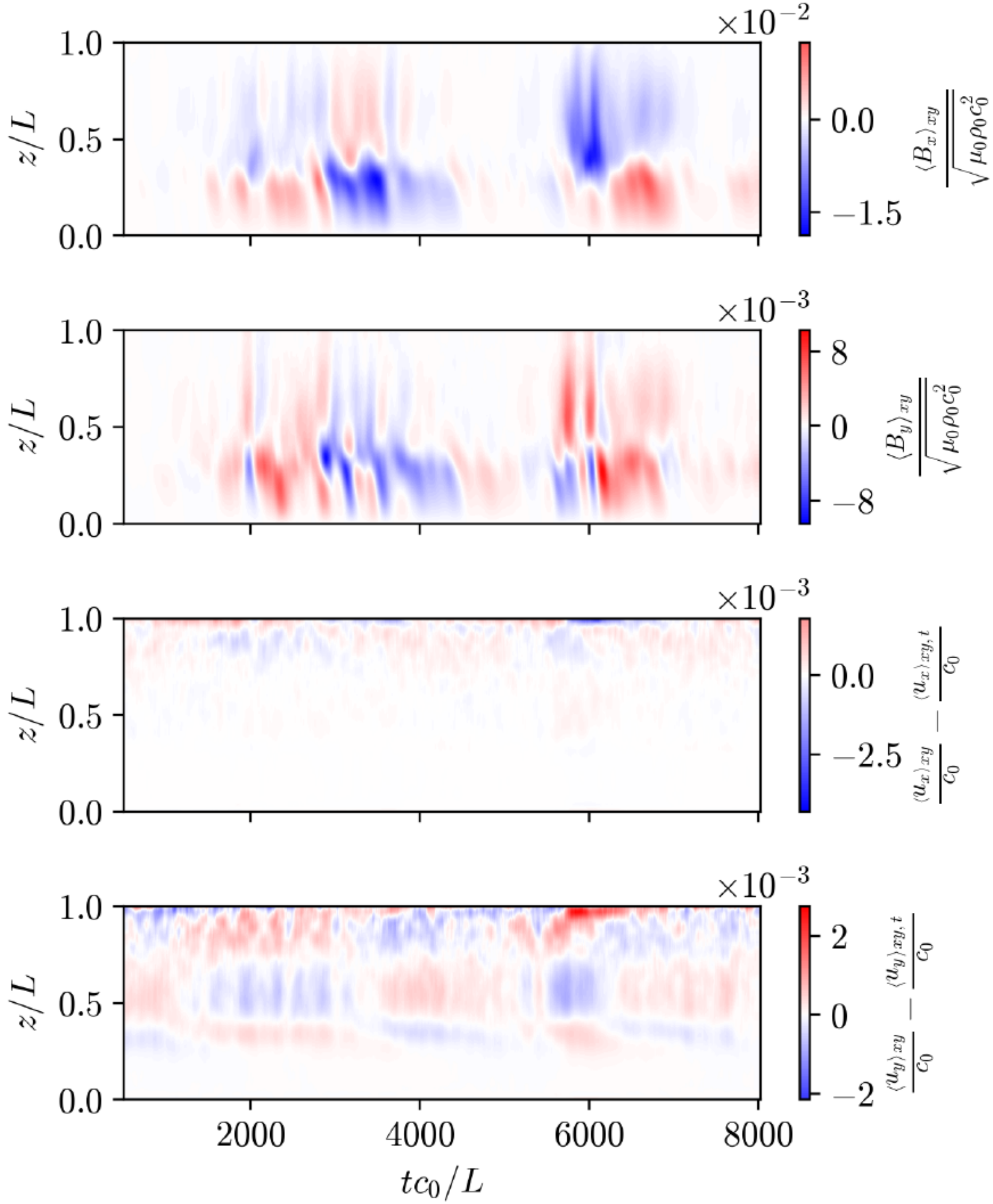
$\theta = 60^\circ$



Magnetic Cycles (nonlinear)

Butterfly diagrams of horizontally averaged fields (weak)

$\theta = 60^\circ$



Local Magnetic Fields
(concentrations)

Model: Turbulent Magneto-Convection

- Basic Equations:

See Käpylä et al 2016 for some details

$$\frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{u} \times \boldsymbol{B} - \eta \mu_0 \boldsymbol{J},$$

$$\frac{\partial \rho}{\partial t} = -\frac{1}{\xi^2} \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}),$$

$$\frac{D\boldsymbol{u}}{Dt} = \boldsymbol{g} + \frac{1}{\rho}\left[\boldsymbol{\nabla} \cdot (2\nu\rho\mathbf{S}) - \boldsymbol{\nabla} p + \boldsymbol{J} \times \boldsymbol{B}\right],$$

$$T\frac{Ds}{Dt} = \frac{1}{\rho}\left[\boldsymbol{\nabla} \cdot (K\boldsymbol{\nabla} T + \chi_{\mathrm{SGS}}\rho T \boldsymbol{\nabla} s) + \mu_0 \eta \boldsymbol{J}^2\right] + 2\nu\mathbf{S}^2 + \Gamma$$

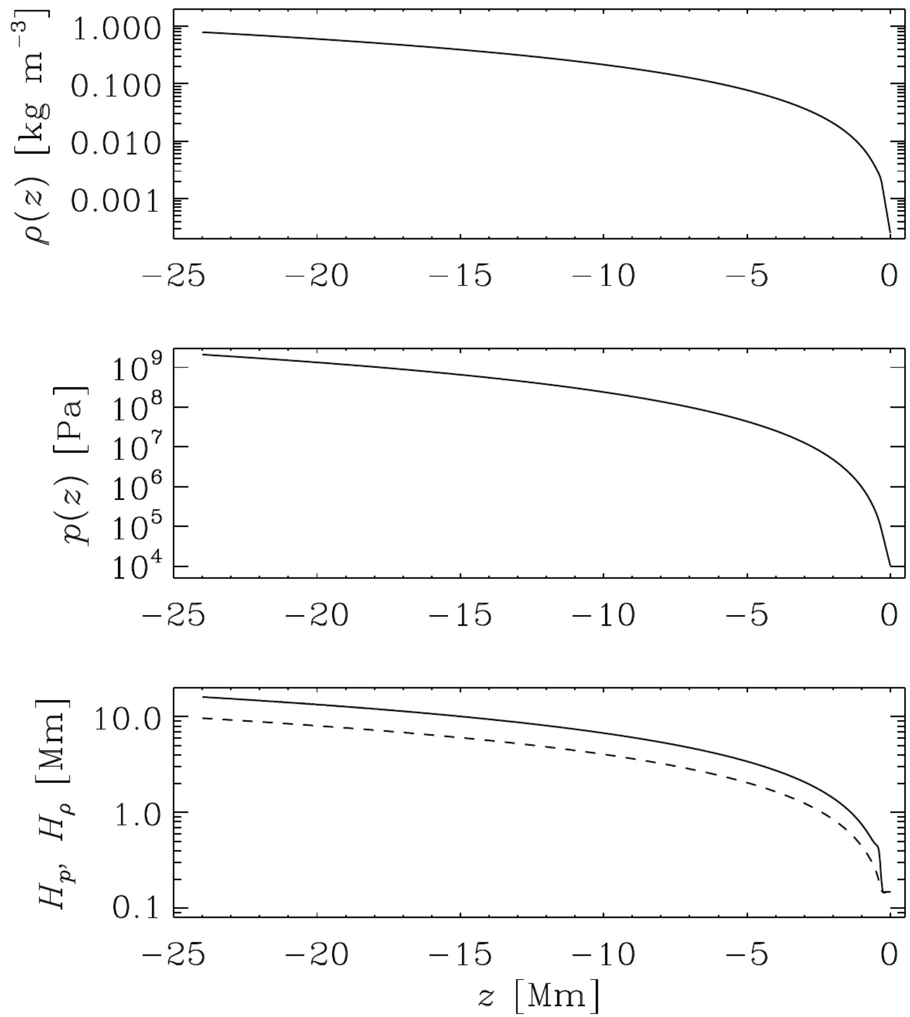
- Rayleigh Number: $\mathrm{Ra} = \frac{g d^4}{\nu \chi_{\mathrm{SGS}}}\left(-\frac{1}{c_{\mathrm{P}}}\frac{\mathrm{d}s}{\mathrm{d}z}\right)_{z_{\mathrm{m}}}$

- Large Eddy Simulations (Smagorinsky viscosity and magnetic diffusivity)

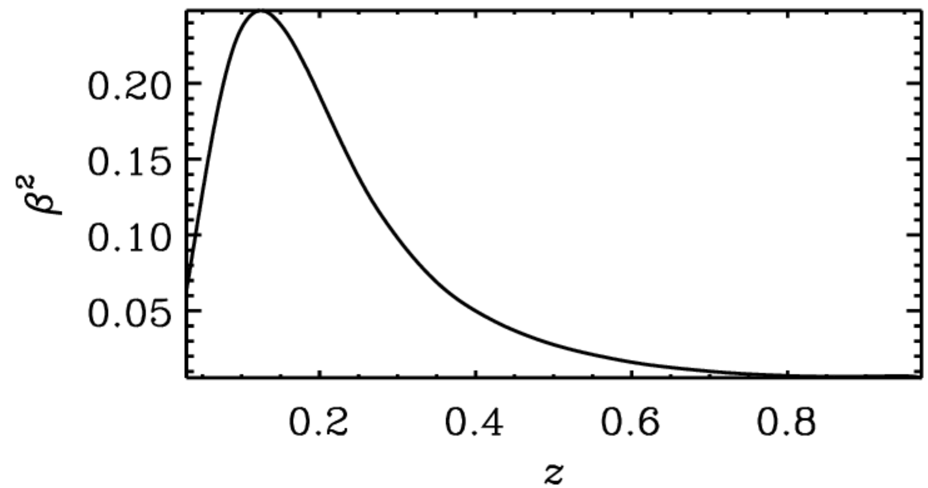
- 1024^3 simulations on 4096 cores

Model: Turbulent Magneto-Convection

Background state



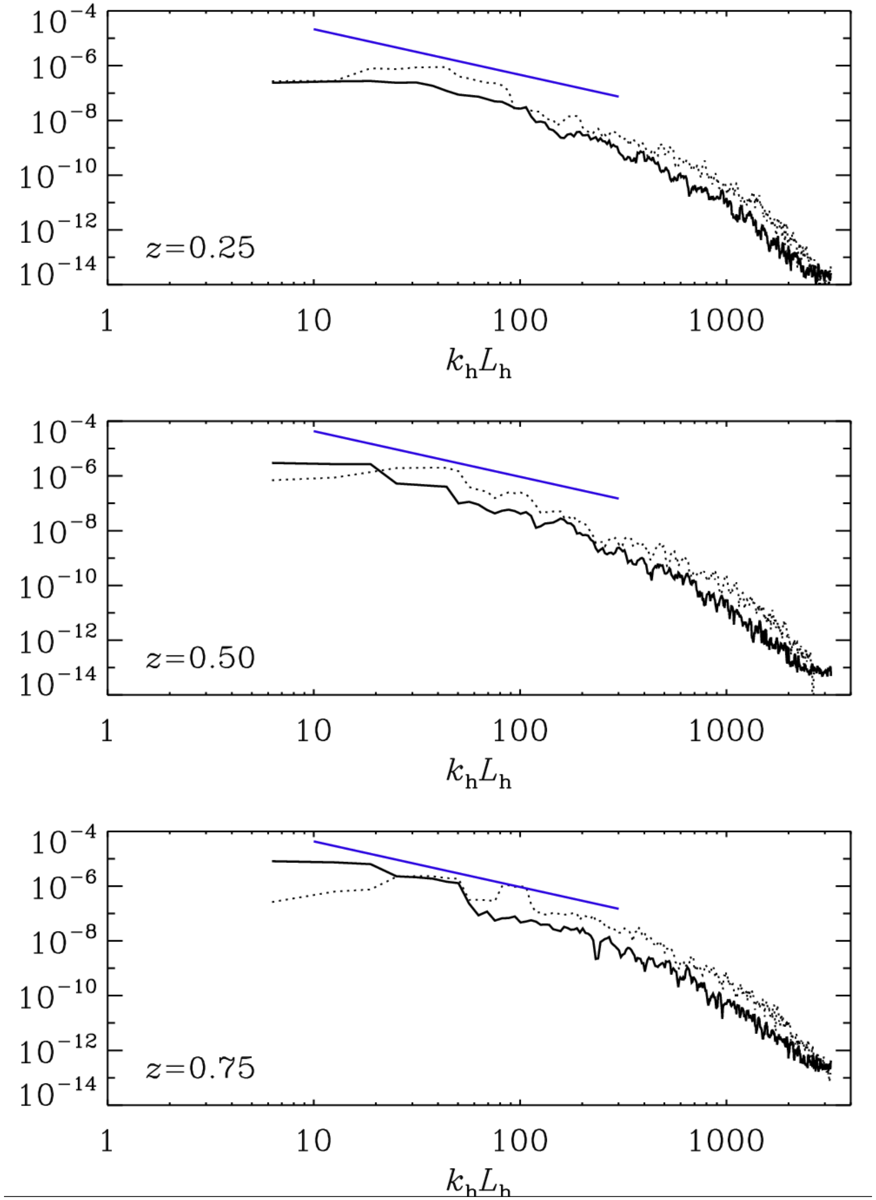
Magnetic field profile: imposed (strongest case)



- Scale height drops significantly close to the surface
- Domain: ~ 100 Mm x 100 Mm x 25 Mm
- Resolution: 0.09 Mm x 0.09 Mm x 0.02 Mm

Convective Flow Pattern

Velocity power spectrum



- Define a logarithmic gradient:

$$\nabla \equiv \frac{\mathrm{d}\log T}{\mathrm{d}\log P}$$

- For adiabatic stratification:

$$\nabla_{\mathrm{ad}} = \frac{\gamma - 1}{\gamma}$$

- Condition for convective instability:

$$\nabla > \nabla_{\mathrm{ad}} \quad \text{(superadiabaticity)}$$

- For a Polytrope: $P \propto T^{m+1}$

this yields, $$m < \frac{1}{\gamma - 1}$$

- It is equivalent to the Schwarzschild criterion for convection to set in:

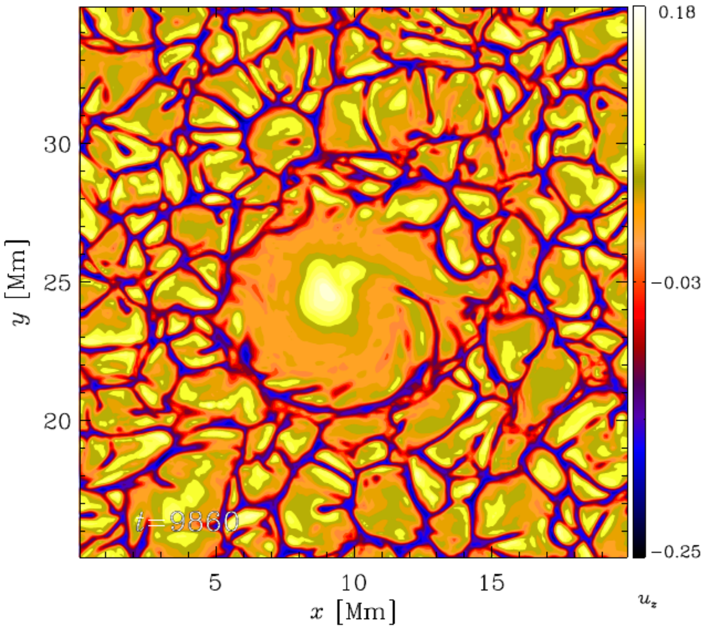
$$\mathrm{d}\,s/\mathrm{d}\,z < 0$$

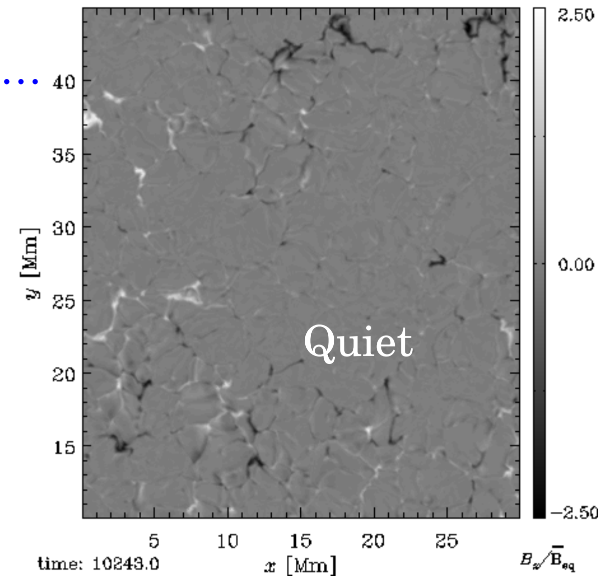
Magnetic flux concentrations

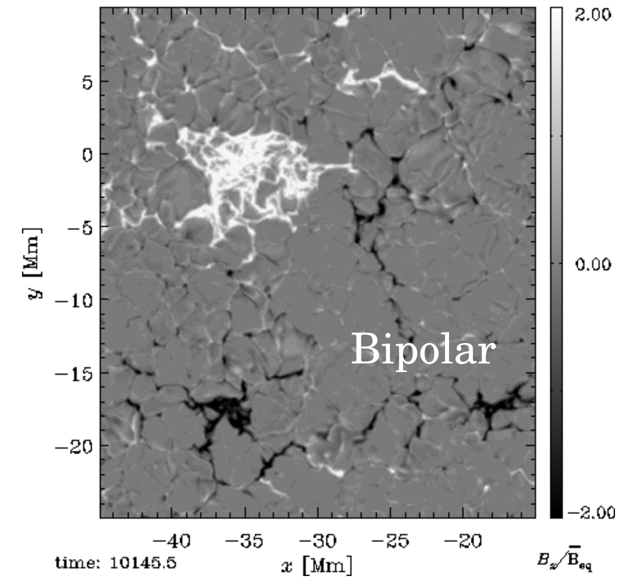
From high-resolution simulations of turbulent magneto-convection

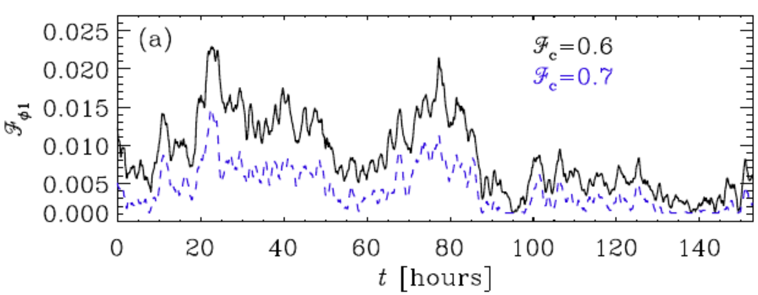
Some impressions from an ongoing work …

Vertical flow during flux emergence



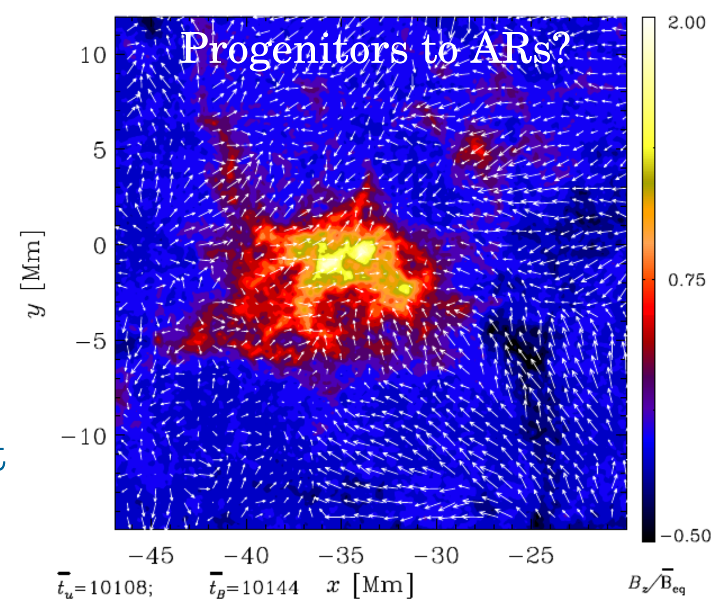






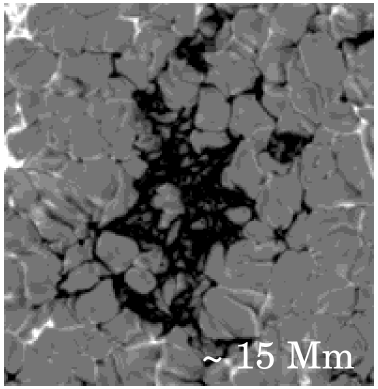
A linear in time process!

- ~ 1-5 kG field strengths are produced
- Stability ~ 20 hours
- Physical mechanism not yet fully understood



Questions

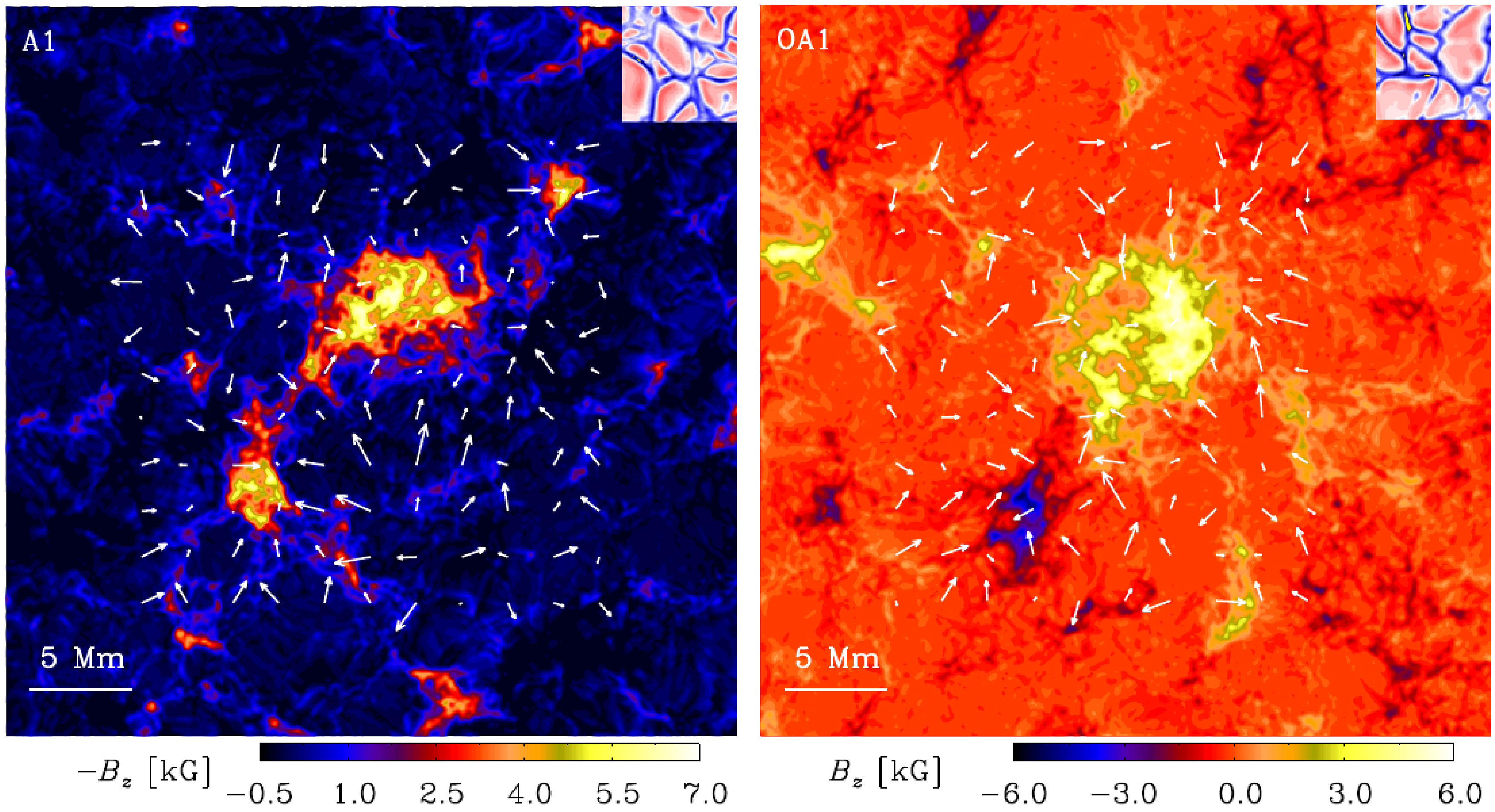
- What is the mechanism causing these concentrations?



- What determines their sizes?
- Is it due to NEMPI?
- What is the role of turbulent diamagnetism?

Magnetic flux concentrations

From high-resolution simulations of turbulent magneto-convection



$\Omega \neq 0$

- Structures survive rotation
- There is a SSD in all these cases

Turbulent Diamagnetism (pumping): a candidate

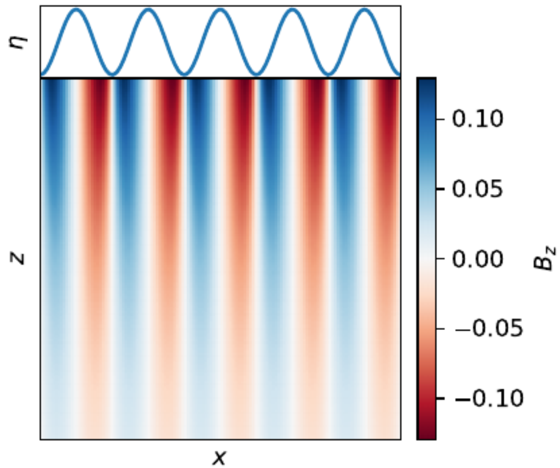
- Magnetic flux expulsion from regions of high turbulent intensity

$$\frac{\partial \overline{B}}{\partial t} = \nabla \times \left(-\frac{1}{2} \nabla \eta_t \times \overline{B} \right) - \nabla \times \left(\eta_t \nabla \times \overline{B} \right)$$

- A toy model:

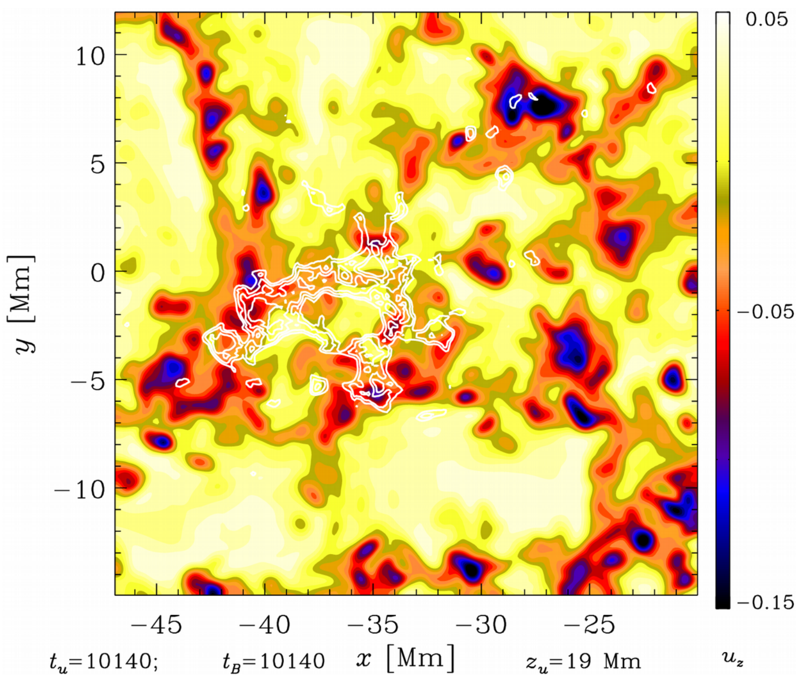
$$\eta_t(x, z) = \sin^2(x) \exp(-z)$$

Uniform Bx imposed at t=0



- Simulations:

- Convection pattern: complex and rich
- Clear example of an inhomogeneous turbulence
- Diamagnetic pumping seems plausible



Color: convection from a deeper layer (6 Mm below)

Contours: Bz from top (photosphere)

In preparation

Conclusions & Outlook

I: Active Latitudes

- Generation of large-scale flow/shear depends on latitude
- Cycles of diffuse LS fields seen in presence of SSD

II: Magnetic Spots

- Spontaneous magnetic flux concentrations seen in high resolution simulations of turbulent magneto-convection
- Turbulent diamagnetism appears to play a key role