Magnetic fields in quiet Sun and plage: results from Boussinesq simulations

Thierry Emonet

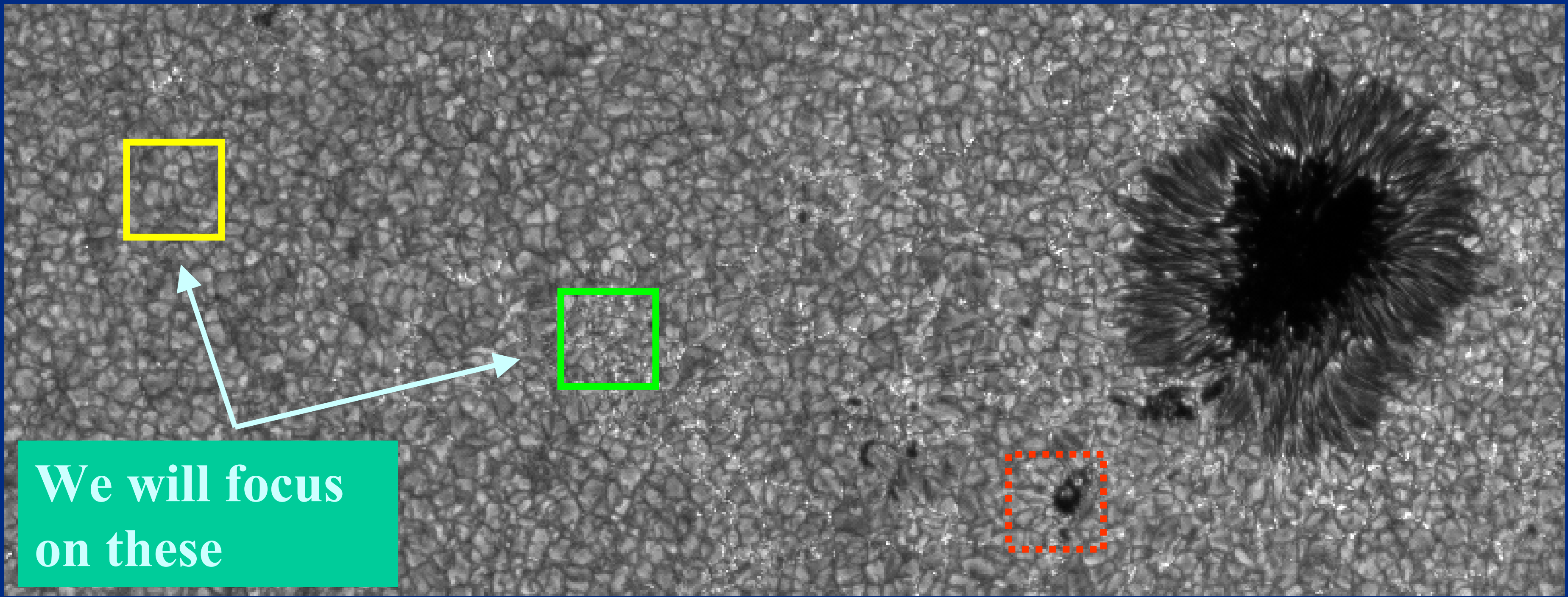
University of Chicago

with F. Cattaneo (*U Chicago*)

http://flash.uchicago.edu/~mhd

Quiet Sun and plages

- **Small** convective regions (granules, mesogranules), **not rotationally constraint**
- **Local** convective dynamics, influenced by mean magnetic field (plages)



T. Berger, SVST 12 May 1998, Obs. del Roque de los Muchachos

Quiet Sun – Plages – Pores

Magnetic flux →

← Horiz. scale of convection

← Convective transport

The observational picture

High resolution G-band observations (Berger & Title)

- Timescale for magnetic flux evolution in plage is ~ ***6-8 min***., morphological changes occur on timescales as short as ***100 sec.***
- ***No*** evidence of ***stable*** isolated subarcsecond flux tubes.

High resolution IR observations (Lin & Rimmele)

- Quiet Sun contains weak magnetic field (~ 1 G over 1 arcsec^2), mixed polarities.
- Evolves with the granular velocity field.

MDI/SOHO magnetograms (Hagenar, Schrijver, Title, ...)

- Ephemeral regions are generated by convection; are not recycled cancelled flux.
- Quiet, mixed-polarity network is generated locally.

Hanle effect (Landi Degl'Innocenti, Stenflo, Trujillo Bueno, ...)

- Solar photosphere contains a 5-15 G randomly oriented magnetic field.

MIcroStructured Magnetic Atmospheres, MISMA model (Sánchez Almeida)

- Consistent and unified reproduction of asymmetries in Stokes V profiles

The *fast* dynamo theory picture

- Any three-dimensional, turbulent (chaotic) flow with high magnetic Reynolds number is very likely to be a dynamo.

- Dynamo action associated with the granular and supergranular flows generates magnetic flux with the corresponding spatial scales:
  - Granular flow $\rightarrow$ intranetwork fields
  - Supergranular flow $\rightarrow$ ephemeral regions, network field

- The larger scale organization (active regions) is due to the effect of the rotation

Observations

Fast dynamo theory

Direct simulations

- interaction between turbulent convection and magnetic field
- simpler physics than reality (isolate physical processes)

- higher spatial resolution than observation: can be used to study the effects of limited resolution on inferred magnetic structures

Plan

- Direct numerical simulations (with F. Cattaneo and A. Dubey)
  - Formulation
  - Surface features
  - Statistics: PDF’s, filling factors, …
  - Structure of magnetic field
- “Observation” of the data
  - Effects of limited resolution on the inferred structure of photospheric magnetic fields
- Conclusion

Boussinesq numerical simulations

(with Fausto Cattaneo and Anshu Dubey)

Meneguzzi & Pouquet (1989); Cattaneo (1999); Emonet, Cattaneo & Weiss (2001)

Retain only essential ingredients:

• magnetic field and thermally driven turbulent convection

Forget about:

• NO Compressibility

• NO radiative transfer

• NO rotational effects: horizontal scale is smaller than Rossby number

Numerical power concentrated into:

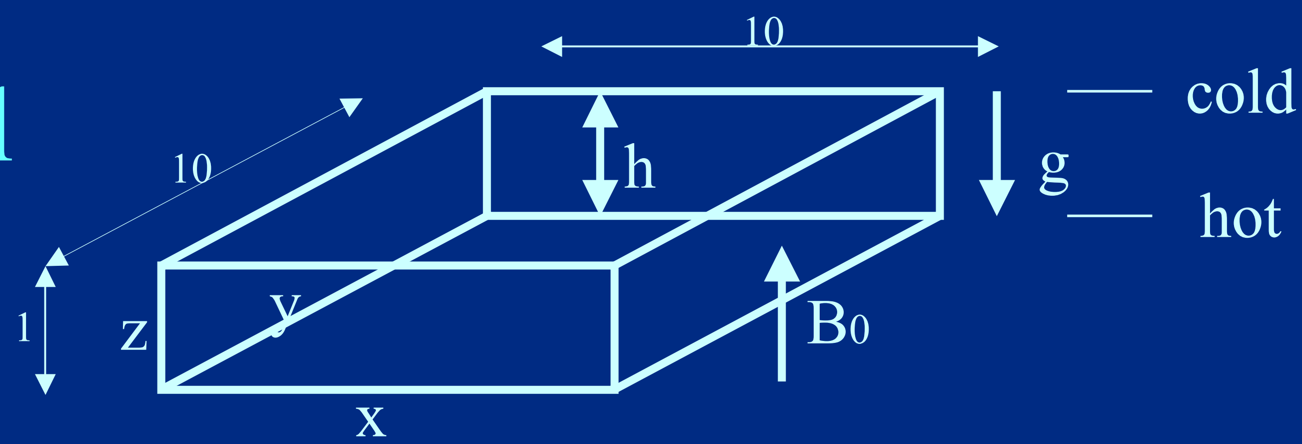
• VERY TURBULENT convective flow, thermally driven: $Ra = 5 \times 10^5$

• LARGE aspect ratio 3D box

How magnetic fields interact with such a flow?

What MHD tells us about the structure of the magnetic fields?

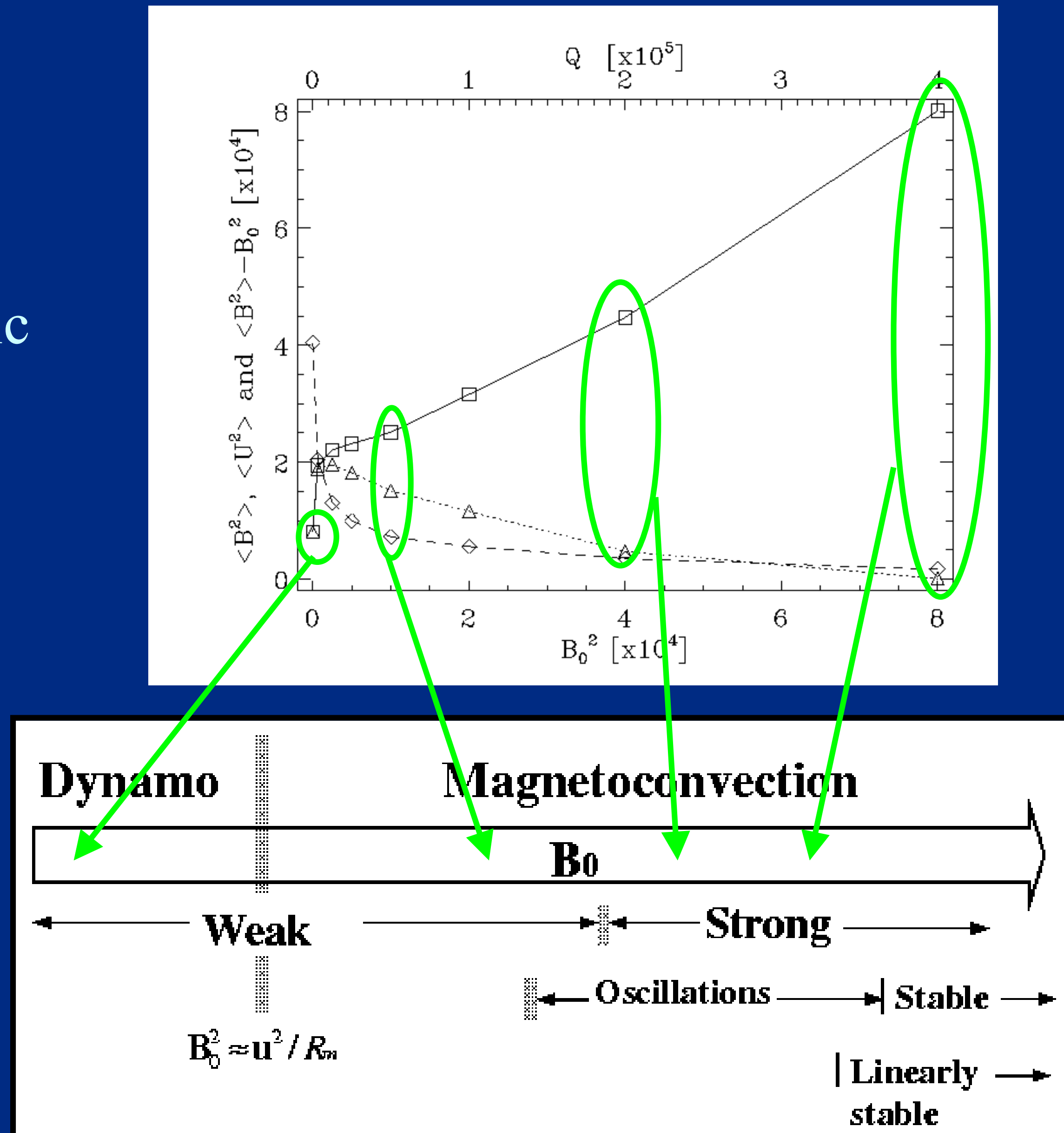
The model



- Geometry:
  - Large aspect-ratio box: 10 x 10 x 1
  - Resolution: 512 x 512 x 100
- Boussinesq Fluid:
  - Re=200, Rm=1000, $Ra = 5 \times 10^5$, $\sigma = \frac{\nu}{\kappa} = 1$, $\sigma_m = \frac{\nu}{\eta} = 5$
- Boundary Conditions:
  - constant temperature and stress free in z, periodic in x and y
- Runs:
  - Started from a fully turbulent convection
  - At t=0: we add a random seed field, or a uniform vertical field B_0
  - B_0 between zero and values strong enough to halt the convection

Which regimes do we have?

Asymptotic volume averages of the magnetic and kinetic energies



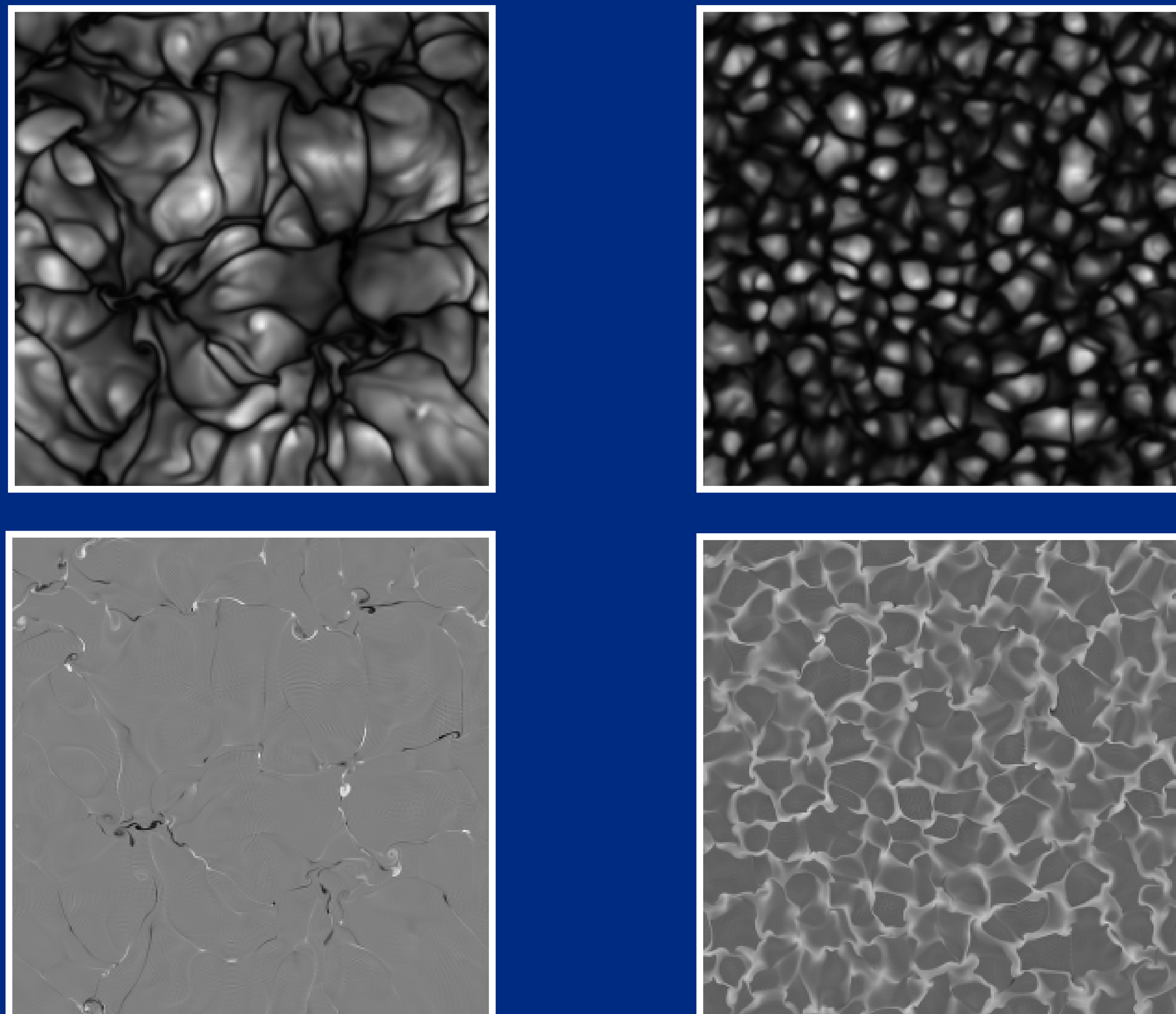
Regime transitions:

- Dynamo – magnetoconvection
- Weak – strong magnetic
- Non-oscillatory – oscillatory

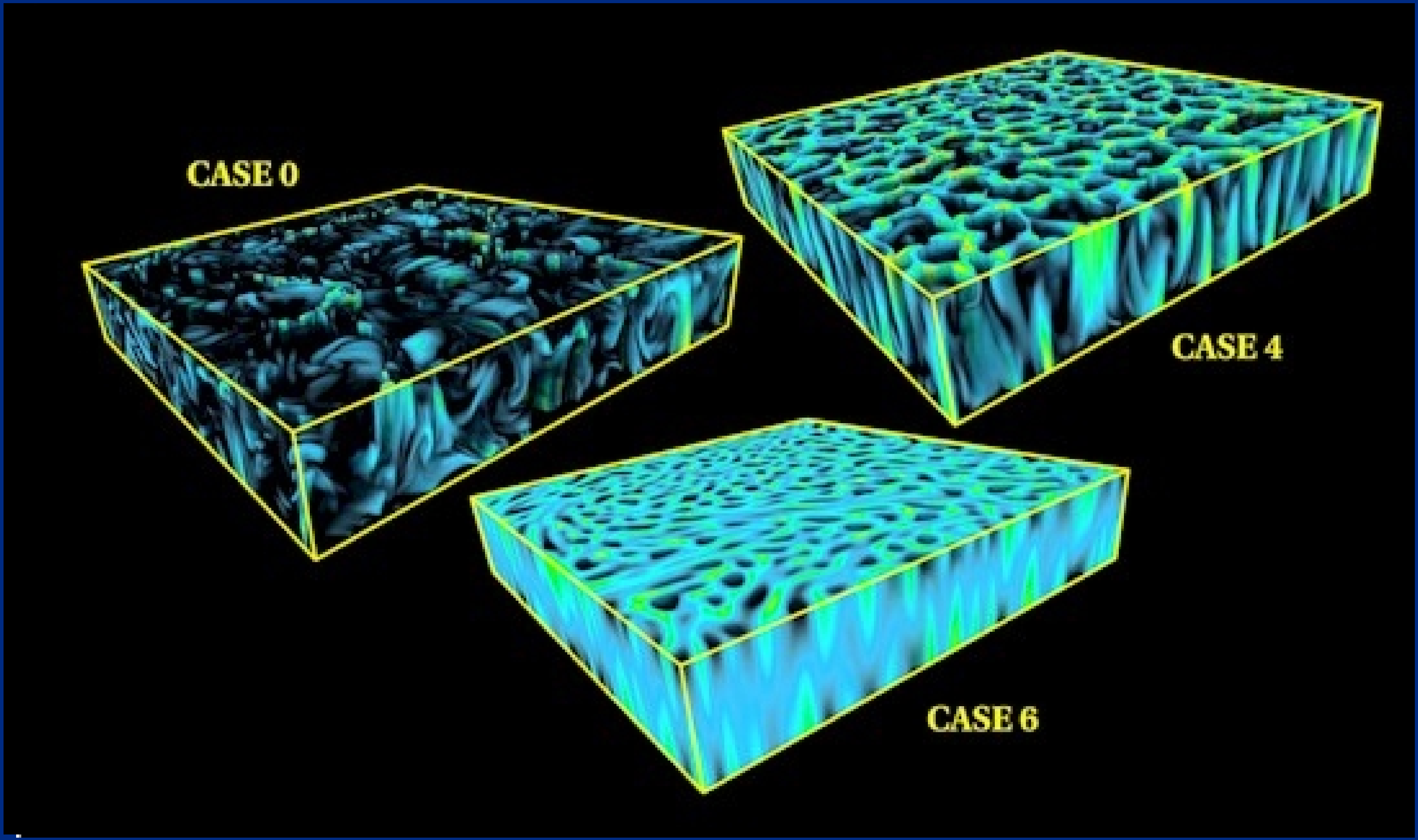
Dynamo (quiet Sun) | Mean flux (plage)

ΔT

Bz



Internal structure



Near surface PDFs

Assumes that Equipartition in the dynamo case is 400 G

Dynamo (zero mean):

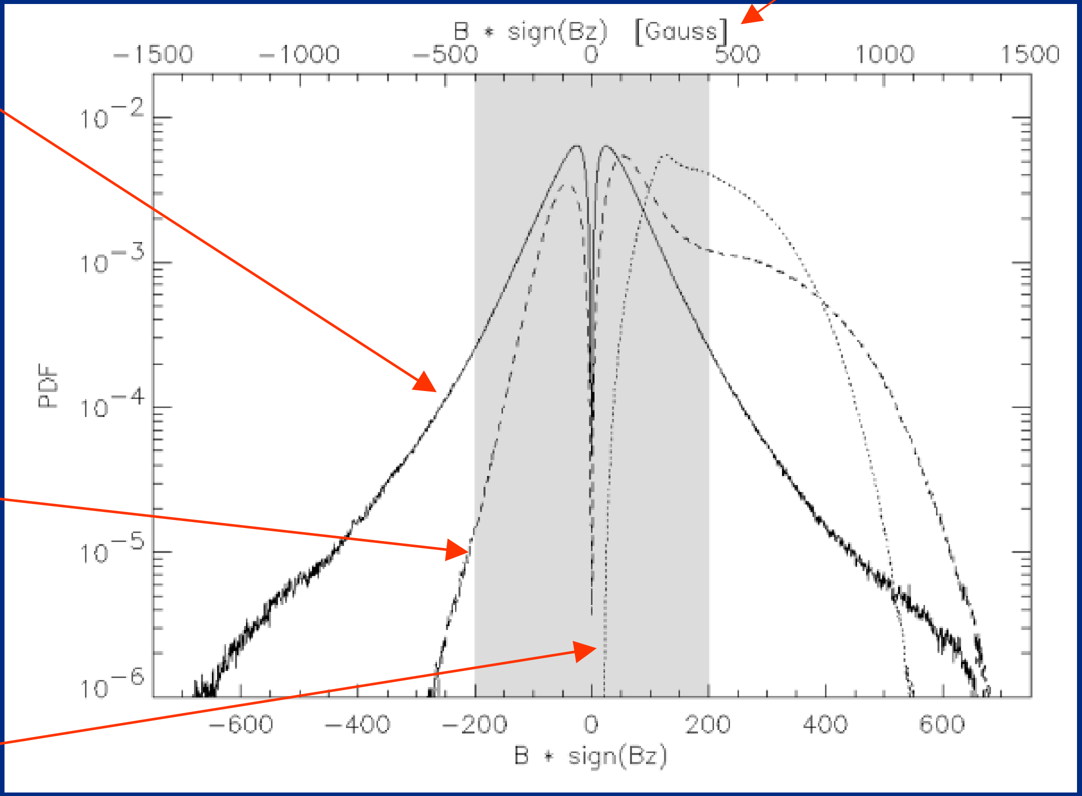
- stretched exponential
- strong fluctuations
- symmetric PDF
- most probable: weak fields
- ***flow able to concentrate field***

Weak mean field:

- stretched exponential + Gaussian
- most probable: weak fields
- ***flow still able to concentrate field***

Strong mean field:

- no exponential
- most probable: mean field
- ***flow not able to concentrate field***



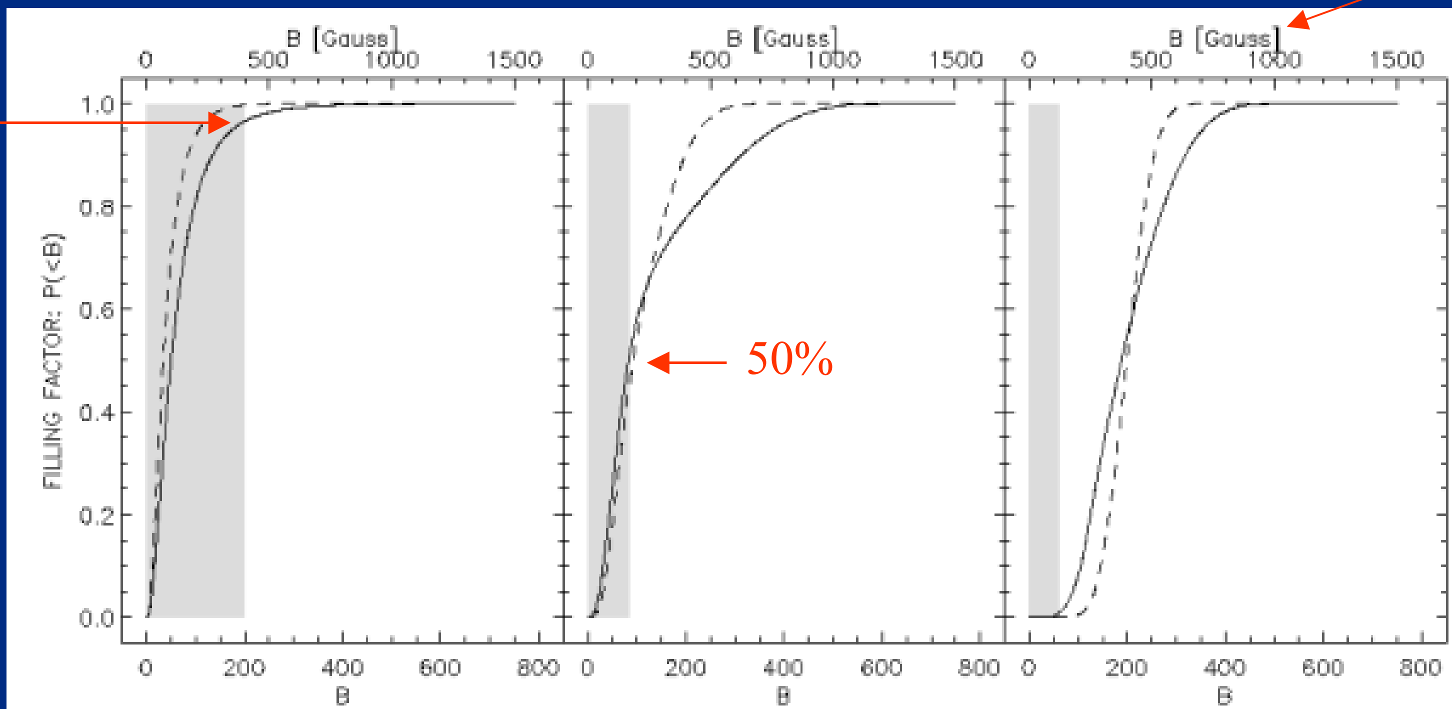
Dynamo process → exponential signature

Flux redistribution → Gaussian signature

Filling factors

Assumes that Equipartition in the dynamo case is 400 G

97%



50%

Dynamo (Quiet Sun)

The main contribution to the unsigned flux is due to the weak fields

Weak mean field

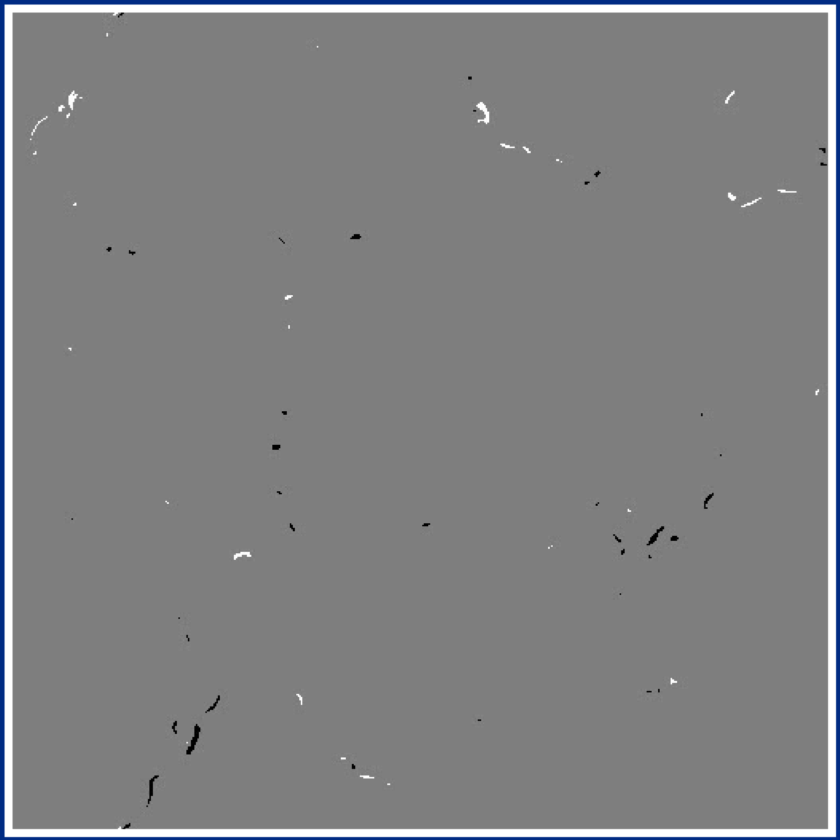
More than 50% of the unsigned flux is due to super-equipartition fields.

Strong mean field

Almost all the flux is due to strong fields.

Strong (> 2 Equipartition) magnetic concentrations dynamo case (quiet Sun)

Life time similar to overturning time
Mixed polarities
Small filling factor: 0.3 %

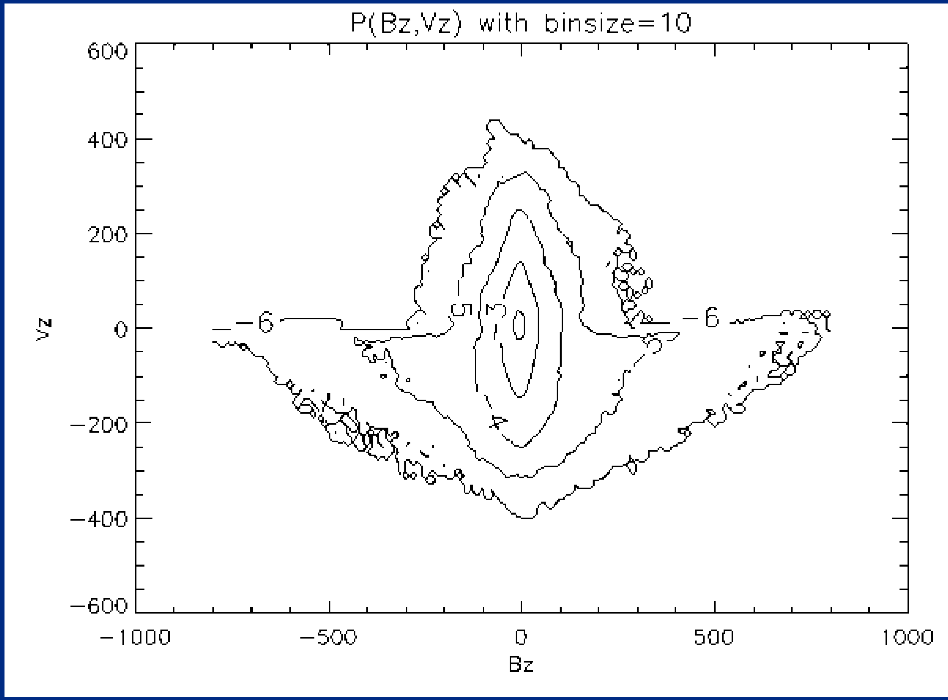


|Bz| > 2 equipartition   10 overturns

Highest magnetic fields are located:

- where the speeds are negative
- not where the speeds are the highest

i.e. near downdraft, but not in them.



Magnetic structures in the Boussinesq simulations

Weak mean field (plages)

- The magnetic field affects convection
  - kinetic energy < magnetic energy
  - smaller convection cells
- Strong fluctuations
  - filling factor 3 %
  - flow still able to concentrate magnetic flux
  - downdrafts around strong magnetic fields
  - less asymmetry between up and down flow

Dynamo, zero mean (quiet Sun)

- Flow dominates:
  - kinetic energy > magnetic energy
- Highly intermittent magnetic component:
  - weak mean: flux density ≅ 1/4 equipartition
  - permeates whole volume
- Strong fluctuations (> 2 equipartition):
  - small filling factor: 0.3 %
  - Mixed polarities
  - located near downdrafts, but not on them
  - very dynamic (lifetime ≅ 1 overturning time)

Strong mean field

- Convection almost halted
  - magnetic field dominates
  - vertical oscillations
  - turbulent horizontal flow: interchange

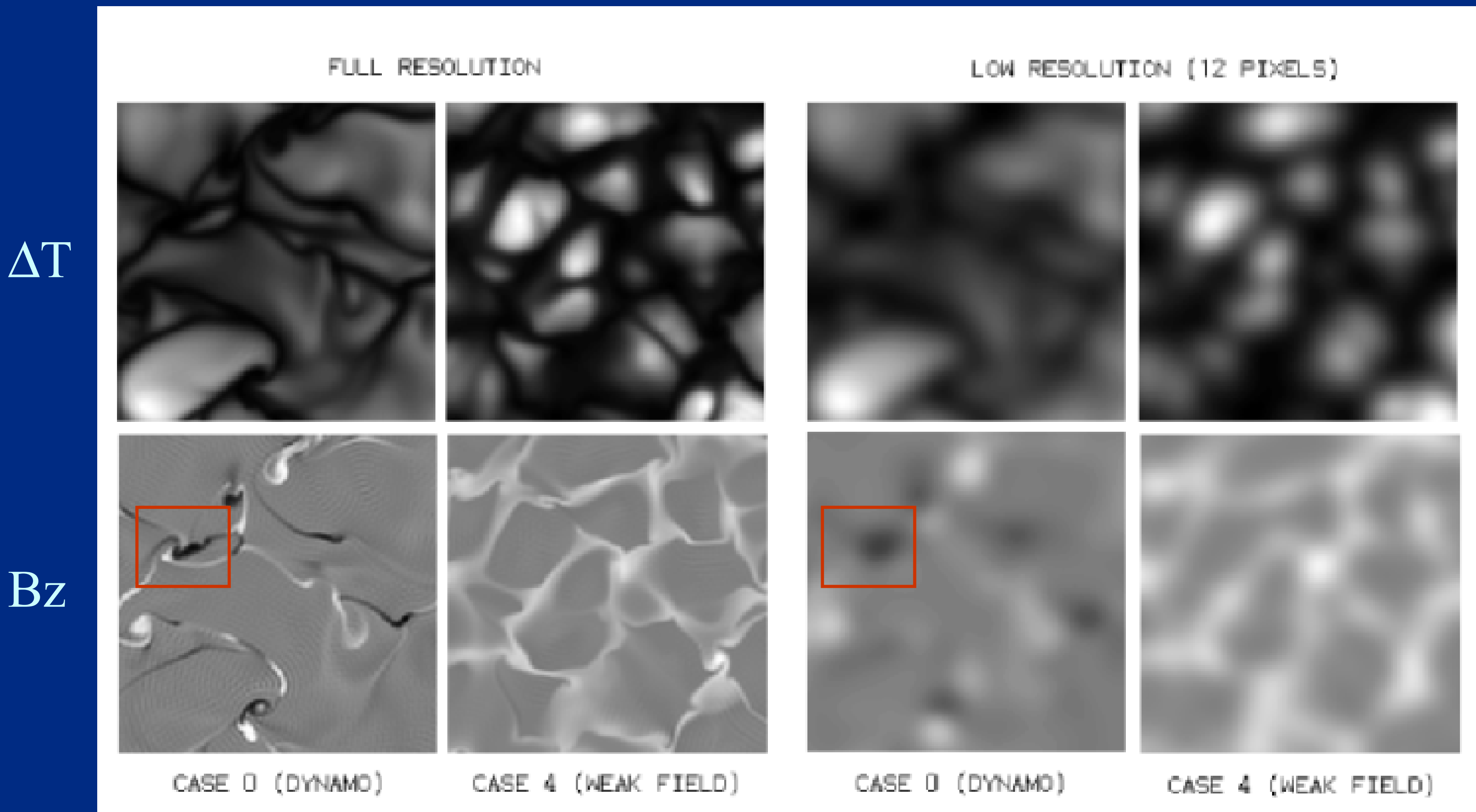
Effect of limited resolution on the inferred structure of magnetic fields

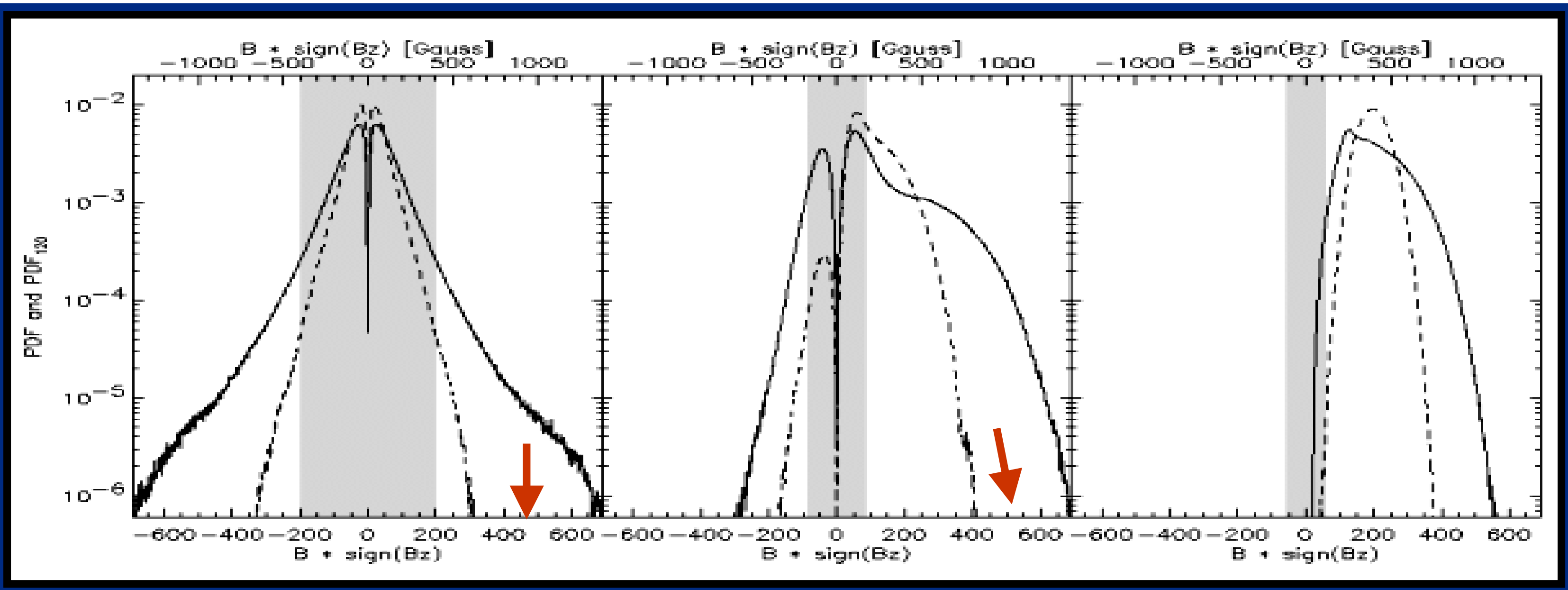
1. Take cube of data from the dynamo simulation
2. Make a convolution with a Gaussian filter
3. Redo the statistics
4. Compare with statistics for the fully resolved set of data

Scales in the numerical simulation

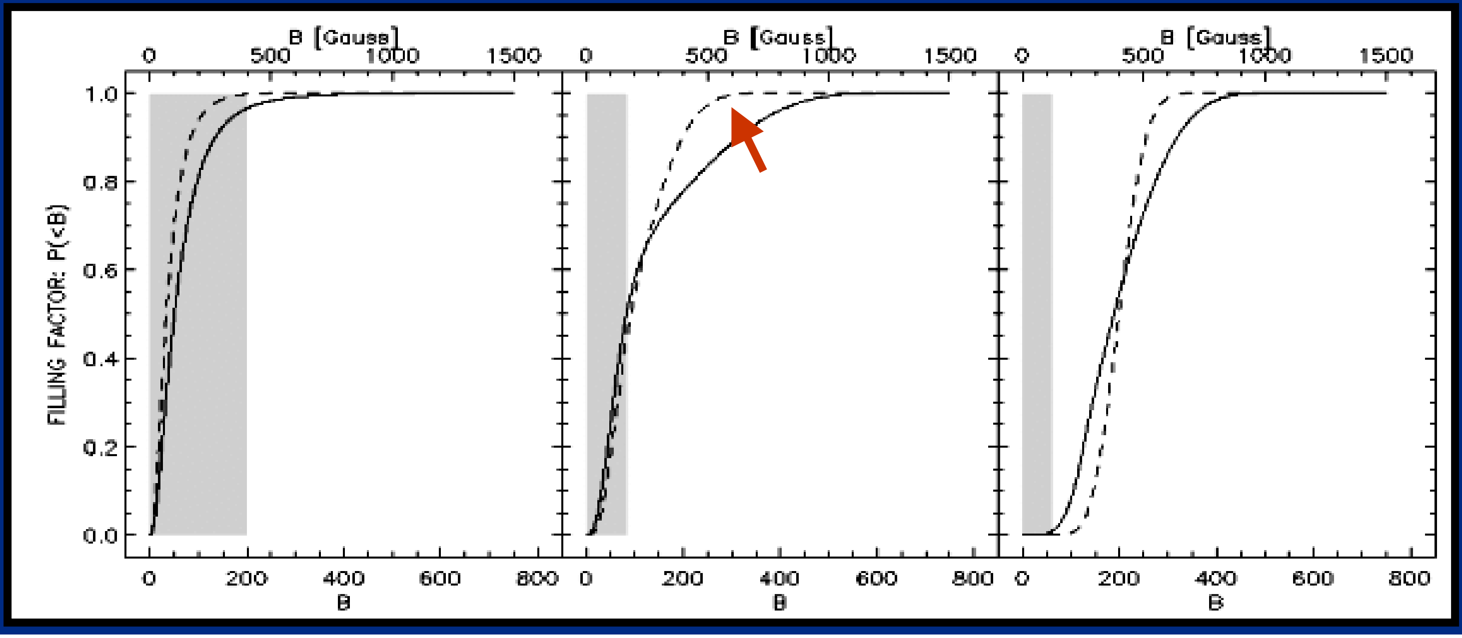
- assume that equipartition is 400 G or 2 km/s
- the domain is about 5000 km wide
- grid resolution is about 10 km
- Rm=1000 so the spatial scale of magnetic structures > 30 km

120 km FWHM filter

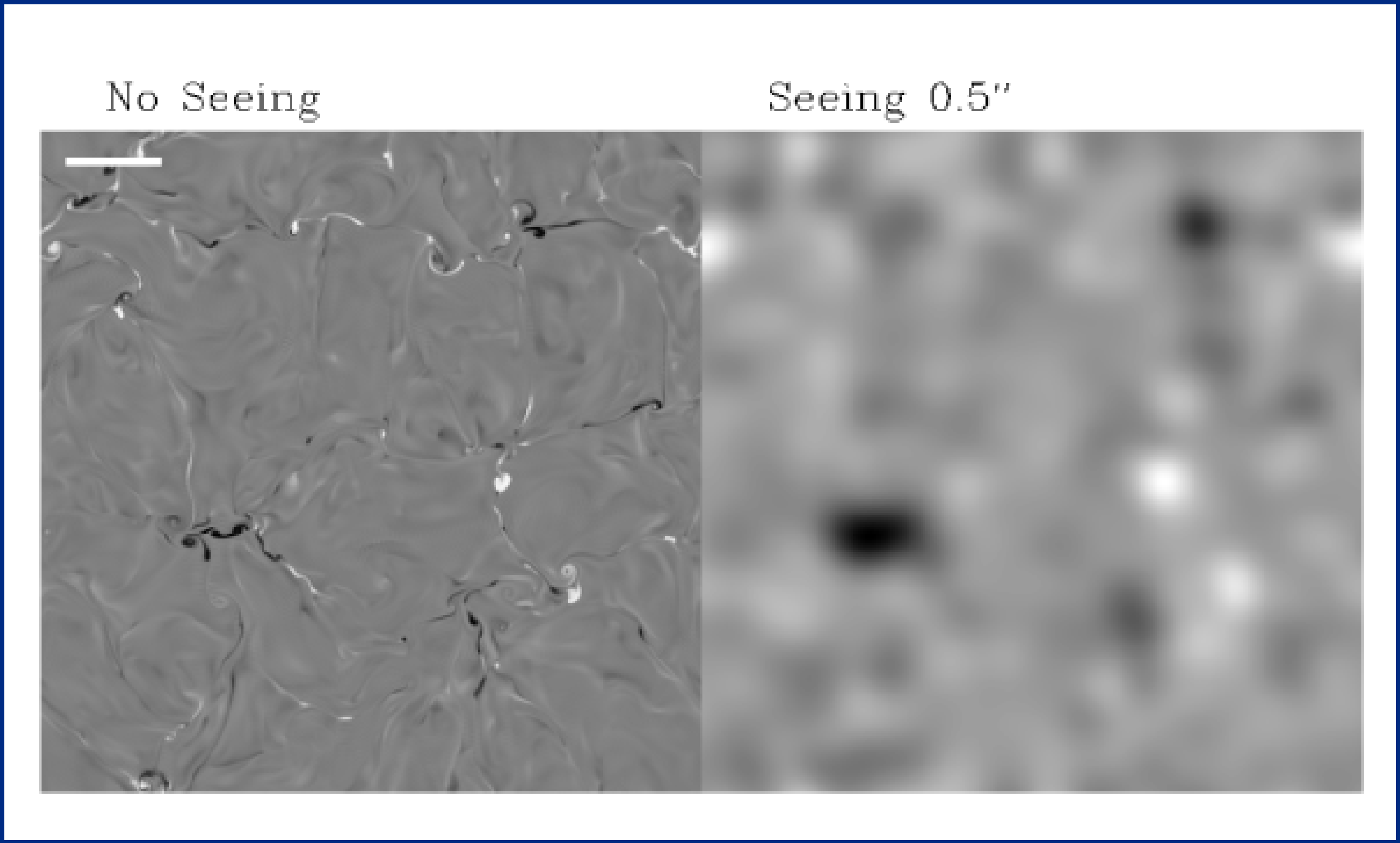




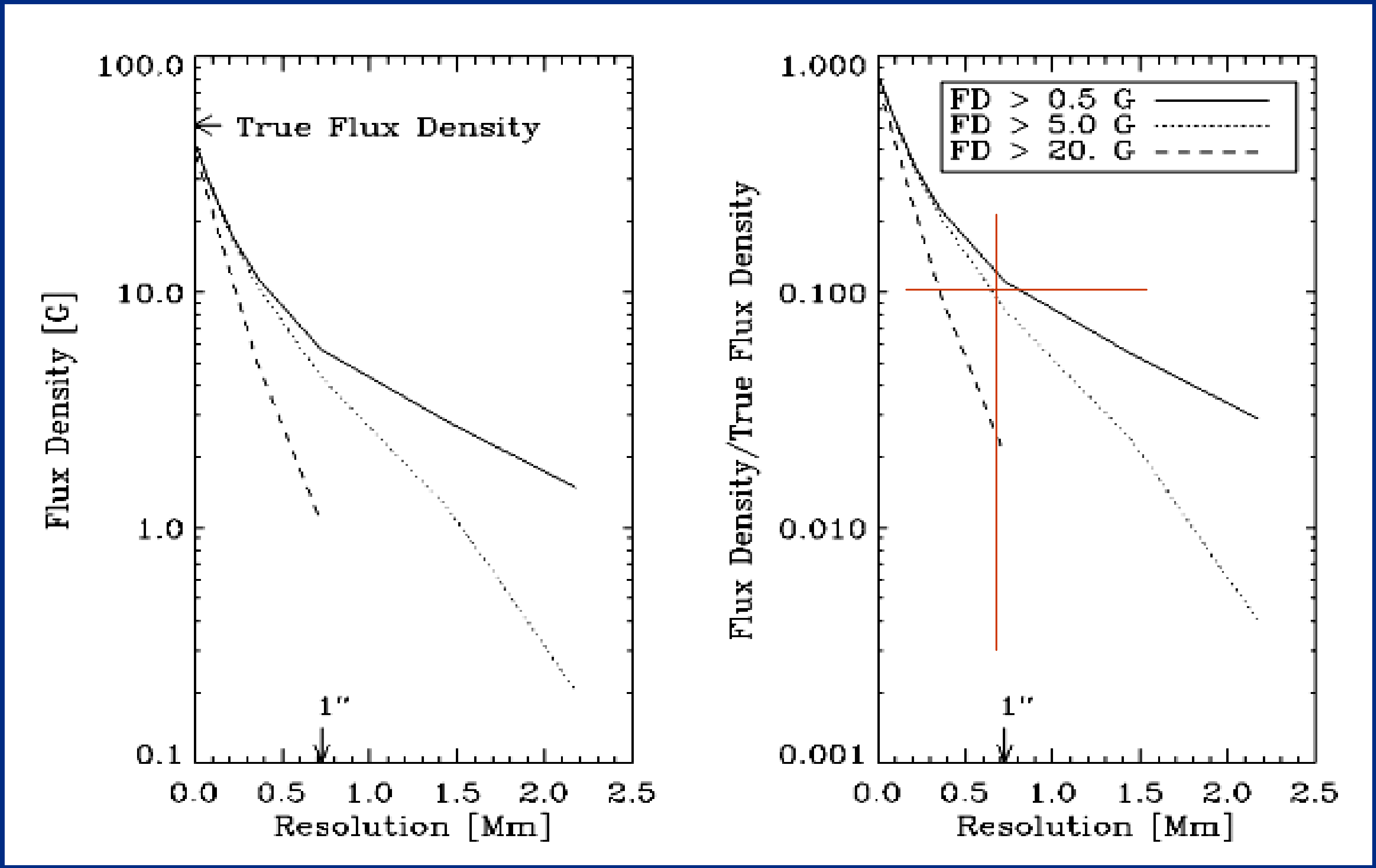
The strong magnetic fluctuations, the characteristic signature of dynamo action, are eliminated



Magnetogram



Flux density (angular resolution)



With 1" resolution and a good sensitivity, only 10 % of the actual flux is measured

Conclusion

The simulations agree with several observational results

• Existence of a very intermittent magnetic component with weak mean.
• Strong (> 2 B_{equ}) magnetic fluctuations near downdrafts, lifetime of few minutes.
• Strong magnetic structure are very dynamic.
• Decrease of the horizontal scale of convection with the amount of magnetic flux.
• Quiet, mixed-polarity network is generated locally.

The above features are obtained with VERY simple ingredients

• Incompressible (Boussinesq) fluid.
• NO ionization, NO radiative transfer, NO rotational effects.
• Strong fields (up to 3 times equipartition) generated by the dynamo, without the aid of convective collapse (will amplify still them).

Effect of limited resolution

• Eliminates wings from PDF, makes it more Gaussian (dynamo signature is exponential) i.e., the signature of strong magnetic fluctuations are eliminated.
• Mixed-polarity magnetic structures appear to be monopolar.
• At 1” resolution and good sensitivity about 90% of the flux density is lost.

Quick Summary

Simple model (Boussinesq) reproduce main observational features

– highly intermittent fields with weak mean
– strong fluctuations

How to observe this?

-- first study effect of limited resolution on the diagnostic techniques

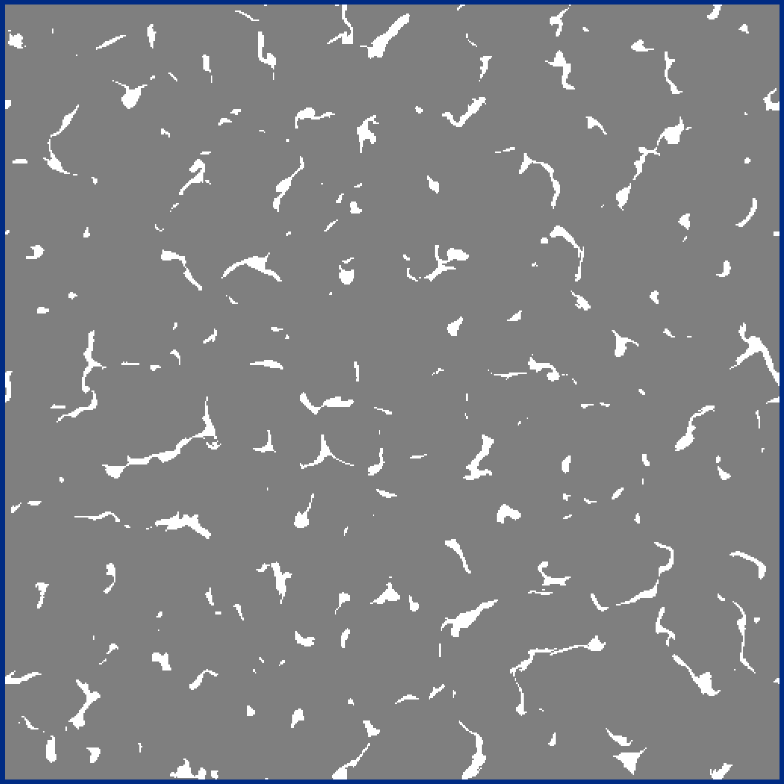
3D MHD numerical simulations achieve higher spatial resolutions than observations

– use solution to test effects of limited resolution
– use solution to test diagnostic techniques

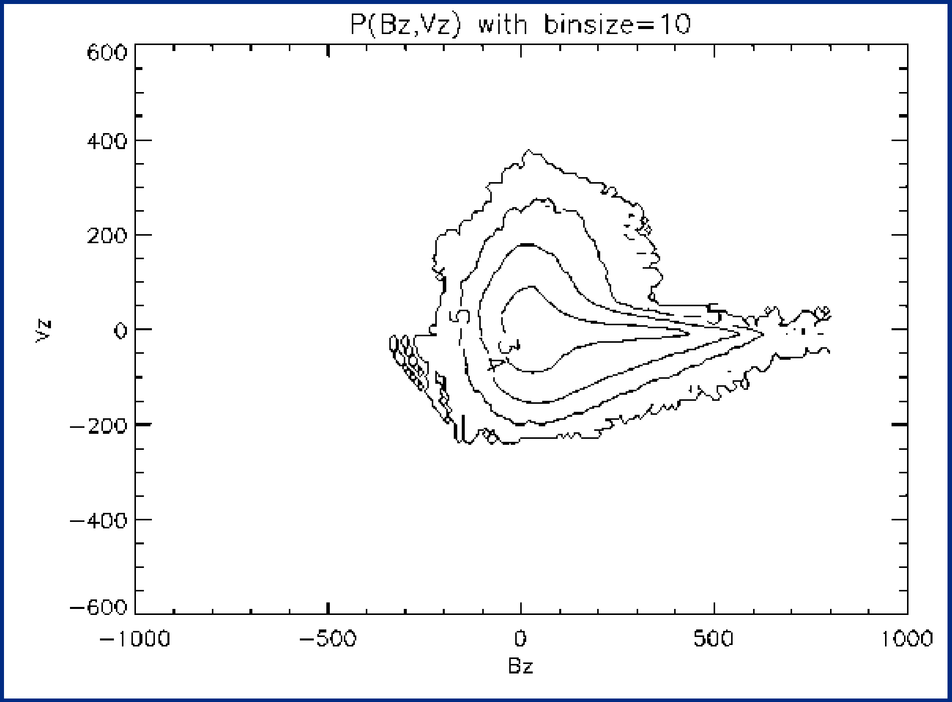
Strong (> 2 Equipartition) magnetic concentrations weak non-zero mean (plage)

Border of cells filled with strong field
Mostly same polarity
Still a small filling factor: 3 %

No more symmetric in Bz
Prefered position still near downdrafts BUT speed is almost zero near the strongest fields

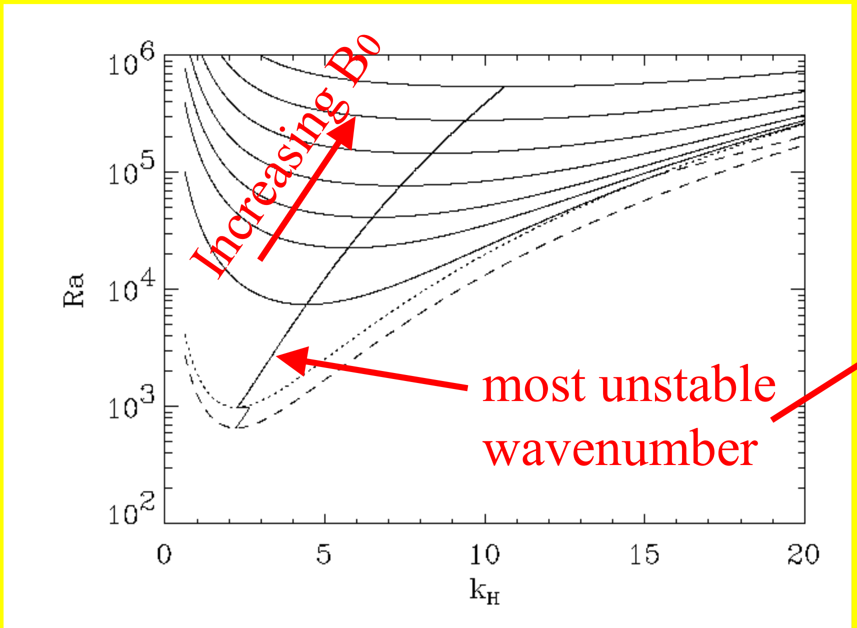


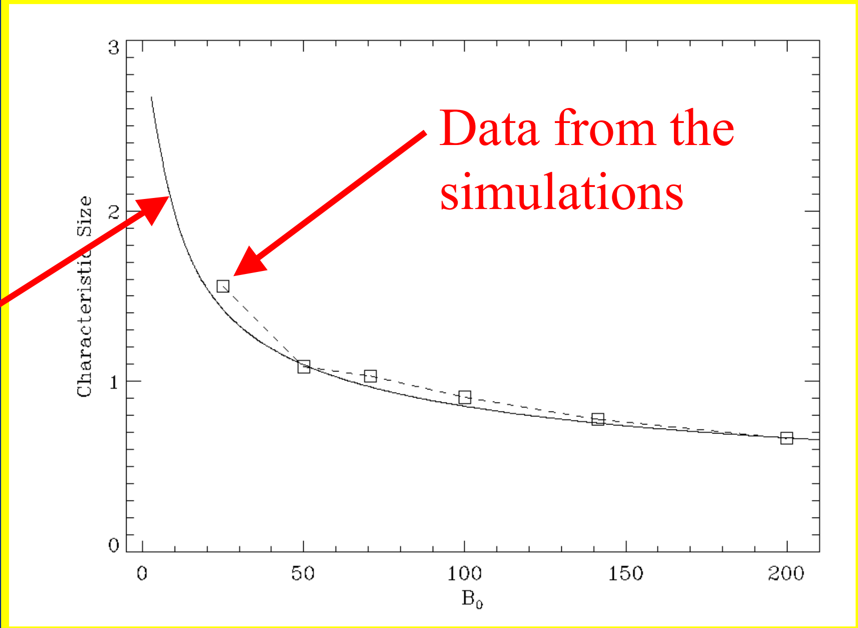
|Bz| > 2 equipartition



Horizontal scale of convection

<u>**Linear theory**</u>: the preferred horizontal scale of convection decreases for growing B_0.

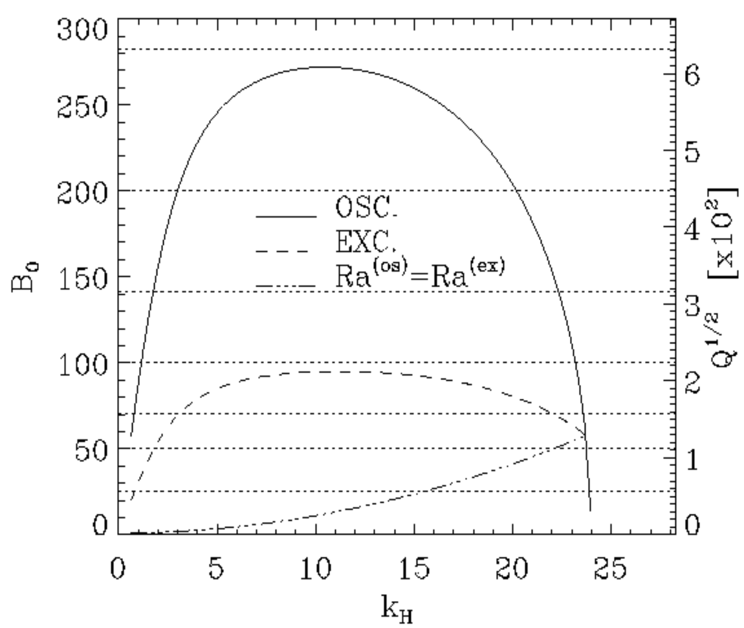




Variation of the critical Rayleigh number as function as the horizontal wavenumber for different values of B_0.

Characteristic size of the magnetic field configuration as measured from the power spectra of B_z in the top layer

Linear Analysis



- **Solid line**: critical value of B_0 or Q above which the system is linearly stable (Ra=5x10^5).
- **Dashed line**: critical value for which there exists a zero eigenvalue.
- **Dotted-dashed line**: critical value above which oscillatory modes exist.
- **The dotted lines** indicate the values of B_0 used in our simulations (cases 1 to 7).

Increasing B_0 from zero: first, all (unstable) linear modes are real (overturning convection), then oscillatory modes appear that coexist with the direct ones, then the direct ones disappear and the only form of (linear) instability is to oscillatory modes; finally the convection becomes stable in linear theory (e.g. case 7).

Equations

Boussinesq convection plus induction equation

$$(\partial_t - \nabla^2)\theta = -\partial_i (u_i \theta) + u_3$$

$$(\partial_\mathbf{t} - \sigma\nabla^2) u_i = \partial_j (B_i B_j - u_i u - p\delta_{ij}) + Ra\sigma\theta\delta_{i3}$$

$$(\partial_t - \sigma / \zeta\nabla^2) B_i = \partial_j (u_i B_j - u_j B_i)$$

$$\theta, u_3, B_1,\ B_2,\ \partial_3 u_1,\ \partial_3 u_2,\ \partial_3 B_3 = 0 \text{ at } z = 0,\ 1$$