Penetration, Overshooting, Magnetic Field Transport and Shear Barriers in Turbulent Compressible Convection

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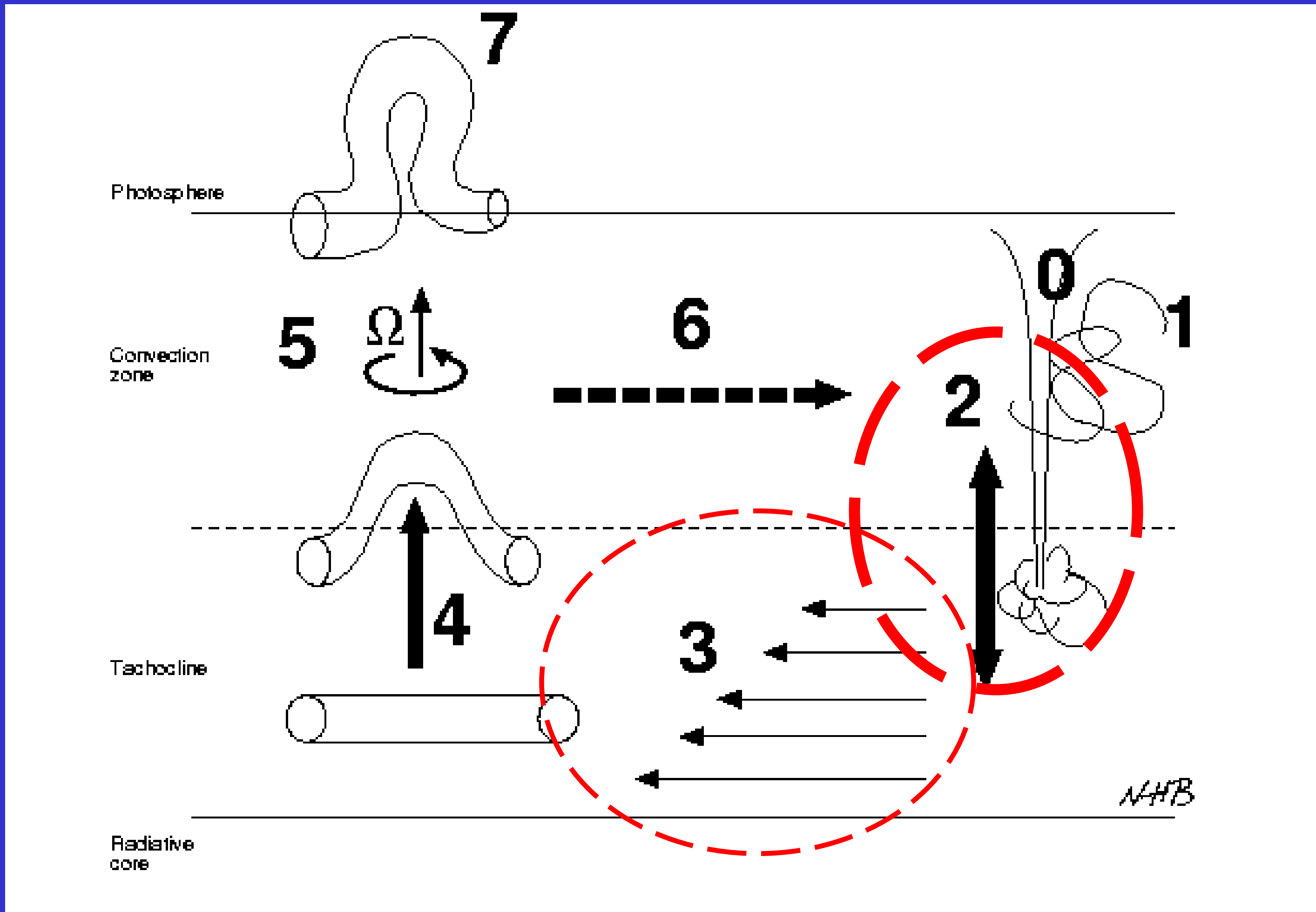
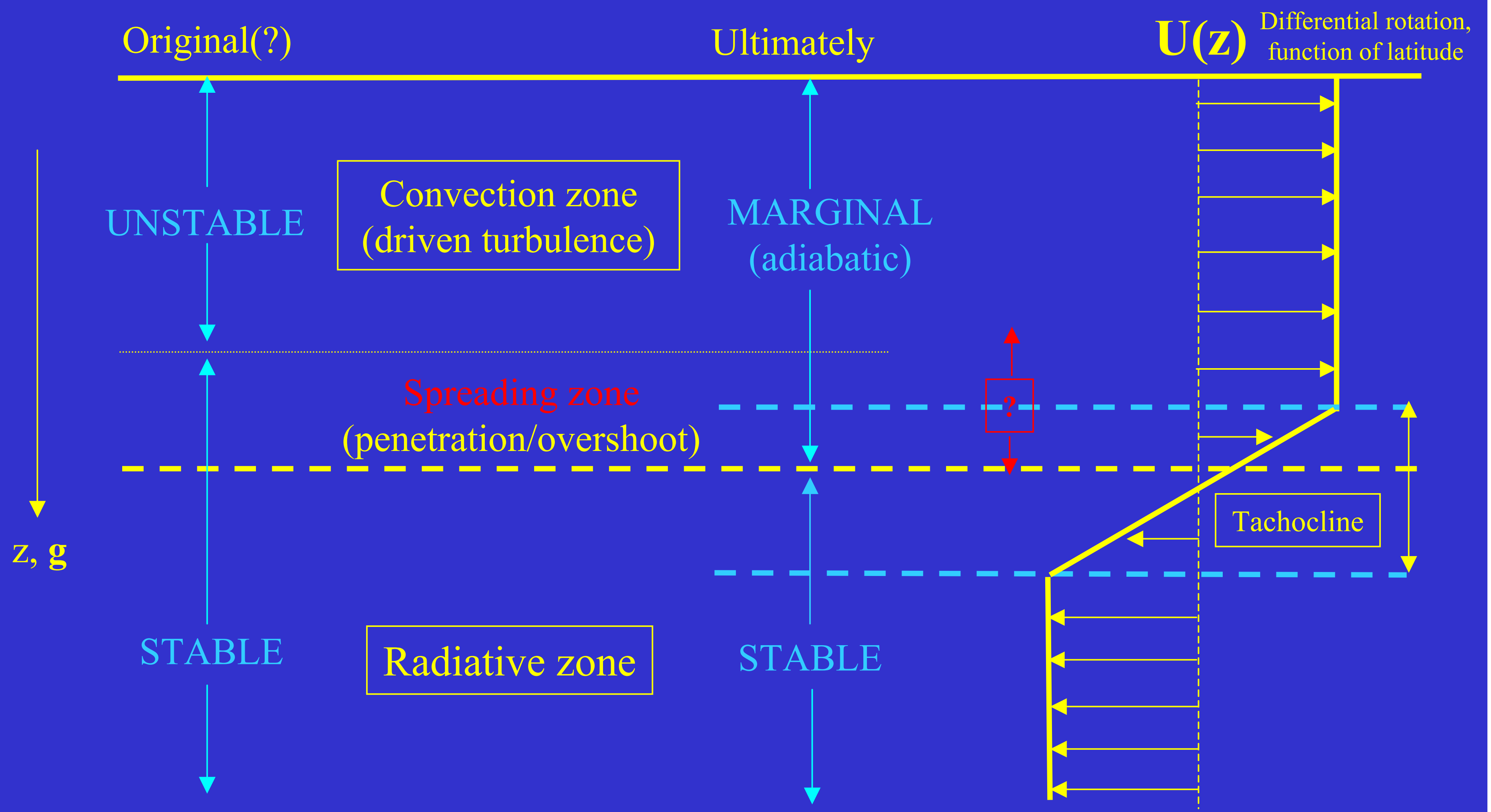
Why are solar physicists interested in penetrative convection?

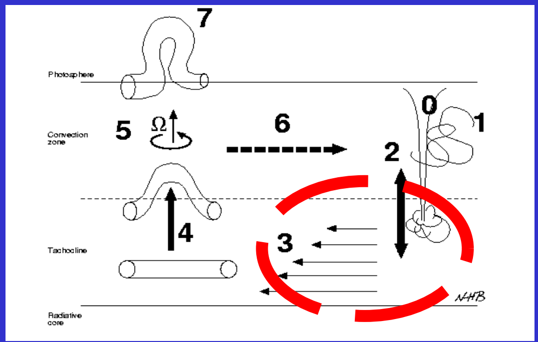
Large-scale solar dynamo: intuitive picture



OR … a turbulent spreading system with a transport barrier

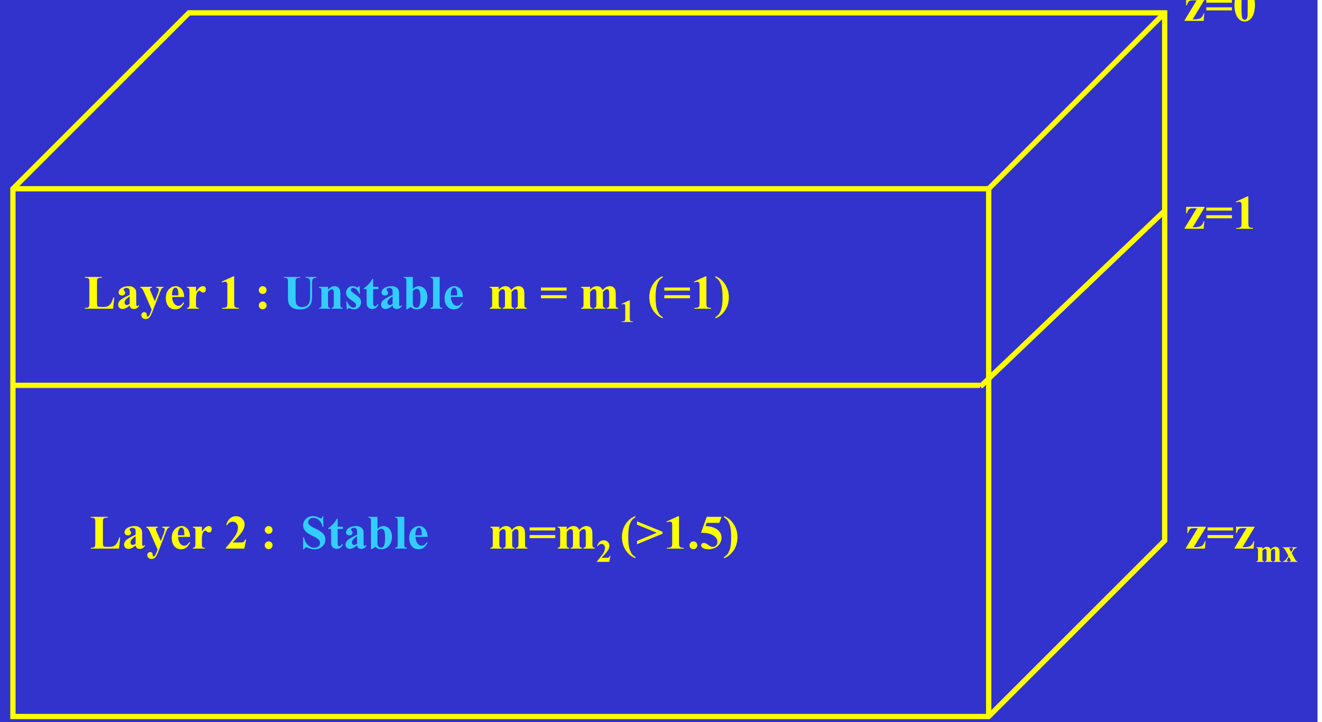


Penetrative compressible convection



- *Compressible MHD (poloidal/toroidal)*
- *DNS*
- *Cartesian*
- *Pseudospectral / finite-difference*
- *Semi-implicit*

Simulation of the base of the convection zone:



Thermal diffusivity $\kappa=\kappa(z)$ (not $\kappa(\rho,T:x,y,z)$) :

C_k(layer1)/C_k(layer2)=$(m_2+1)/(m_1+1)$

"Stiffness", $S = (m_2-m_{ad})/(m_{ad}-m_1)$

Penetrative compressible convection

High Peclet number,

S=3

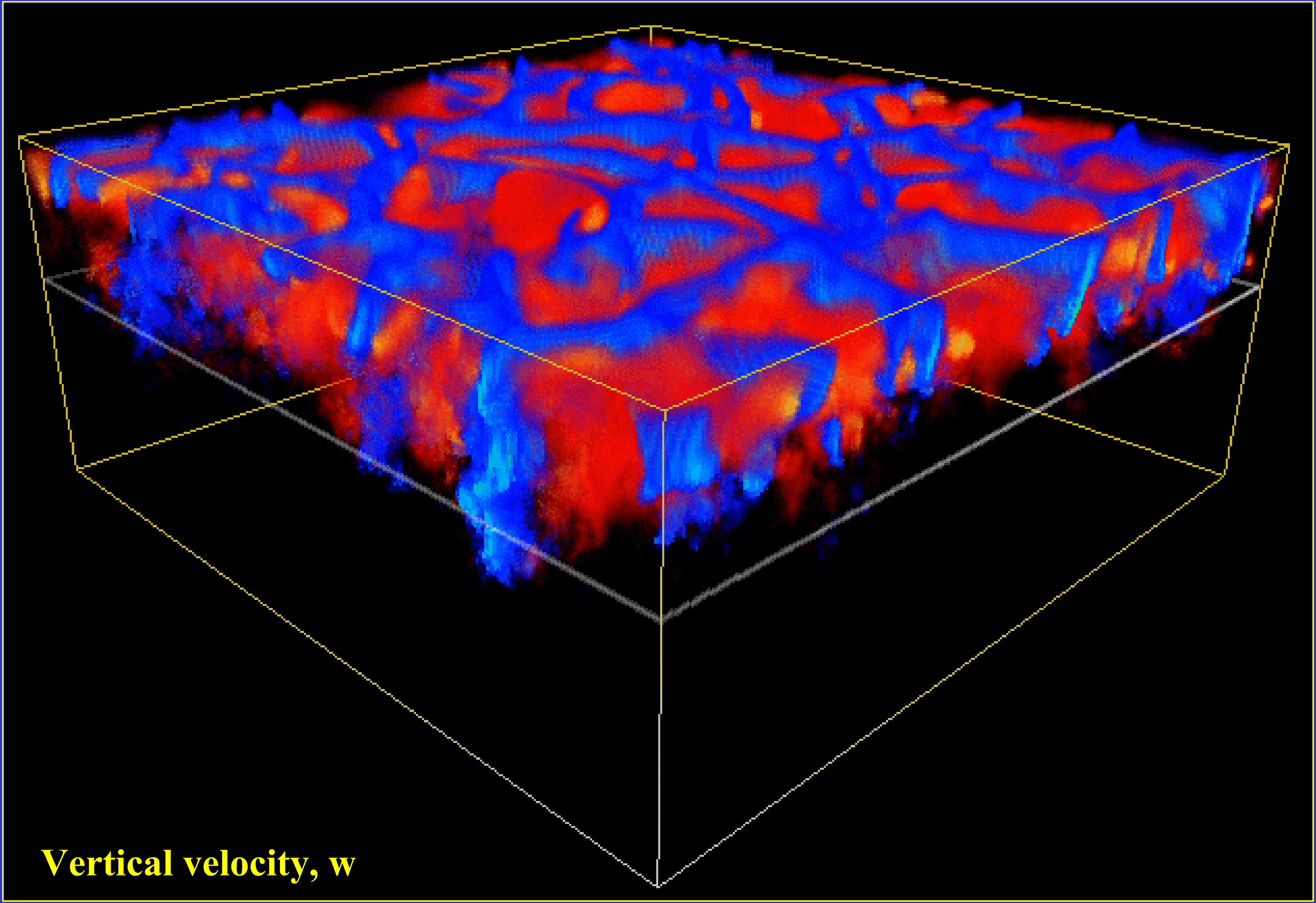
512x512x575

$Re_{rms} \sim 1800$

$Re_{\lambda} \sim 20$

$Ra = 4x10^7$

$Pe_{down} \sim 200$



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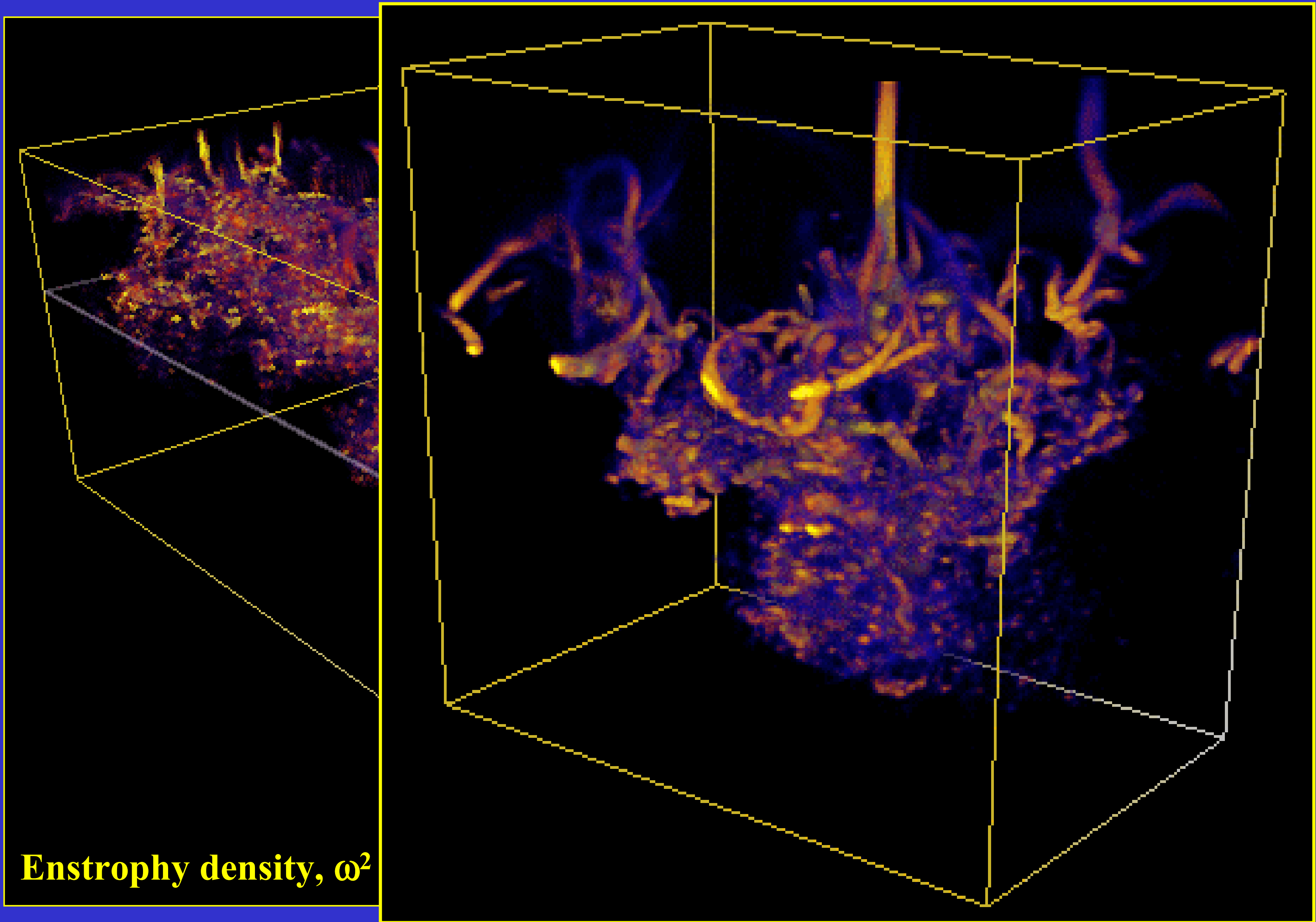
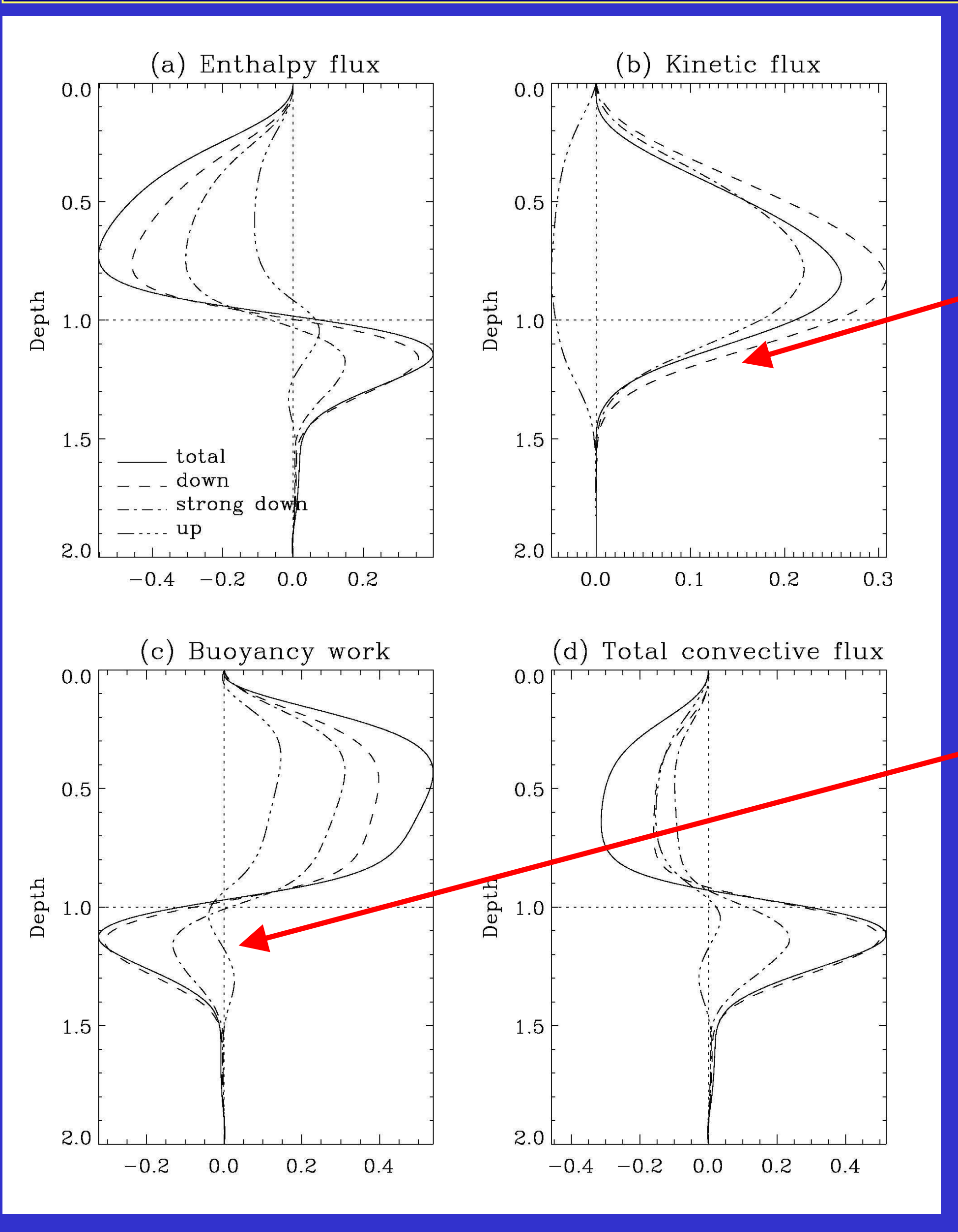
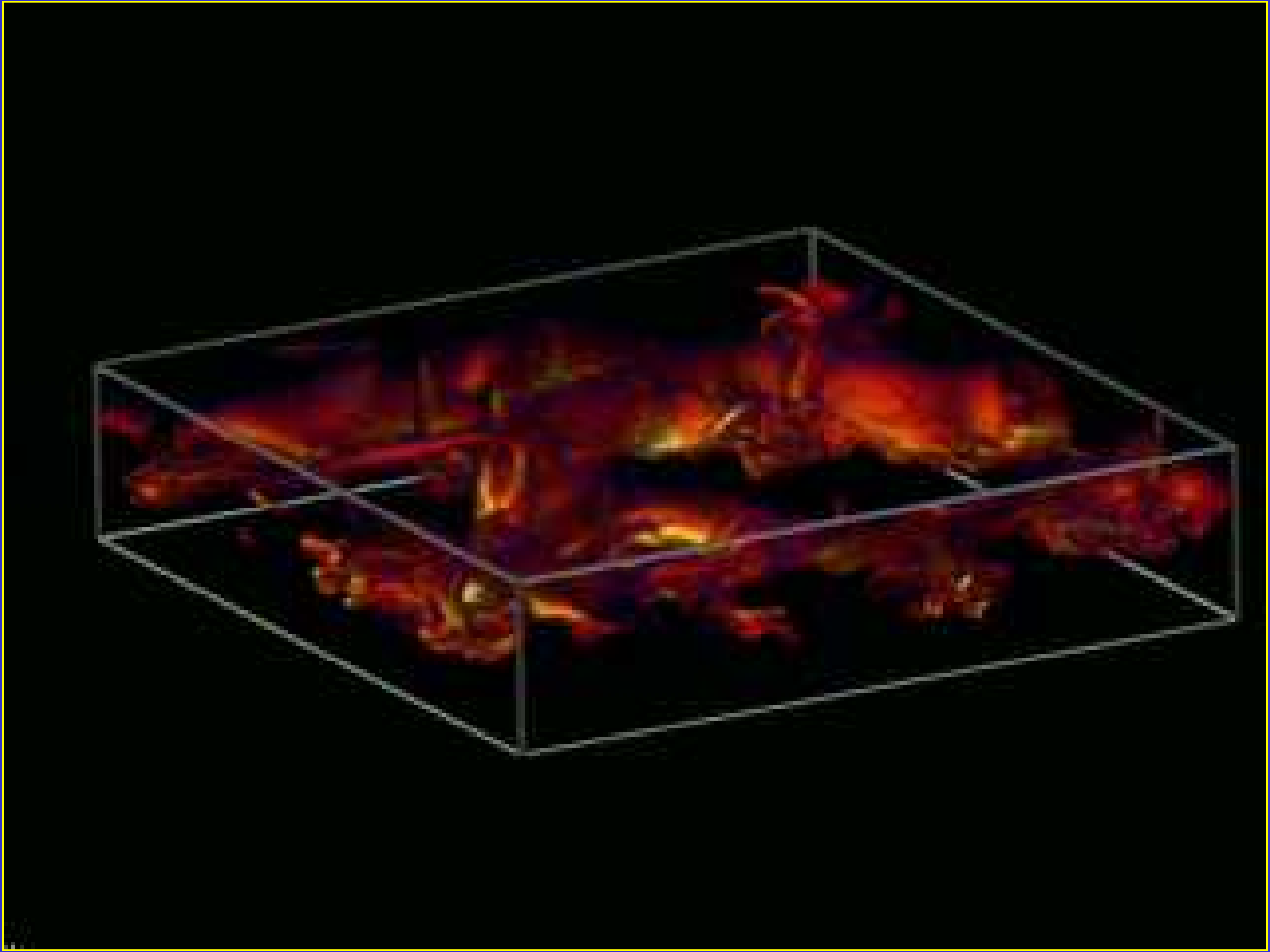


Penetrative convection: Fluxes



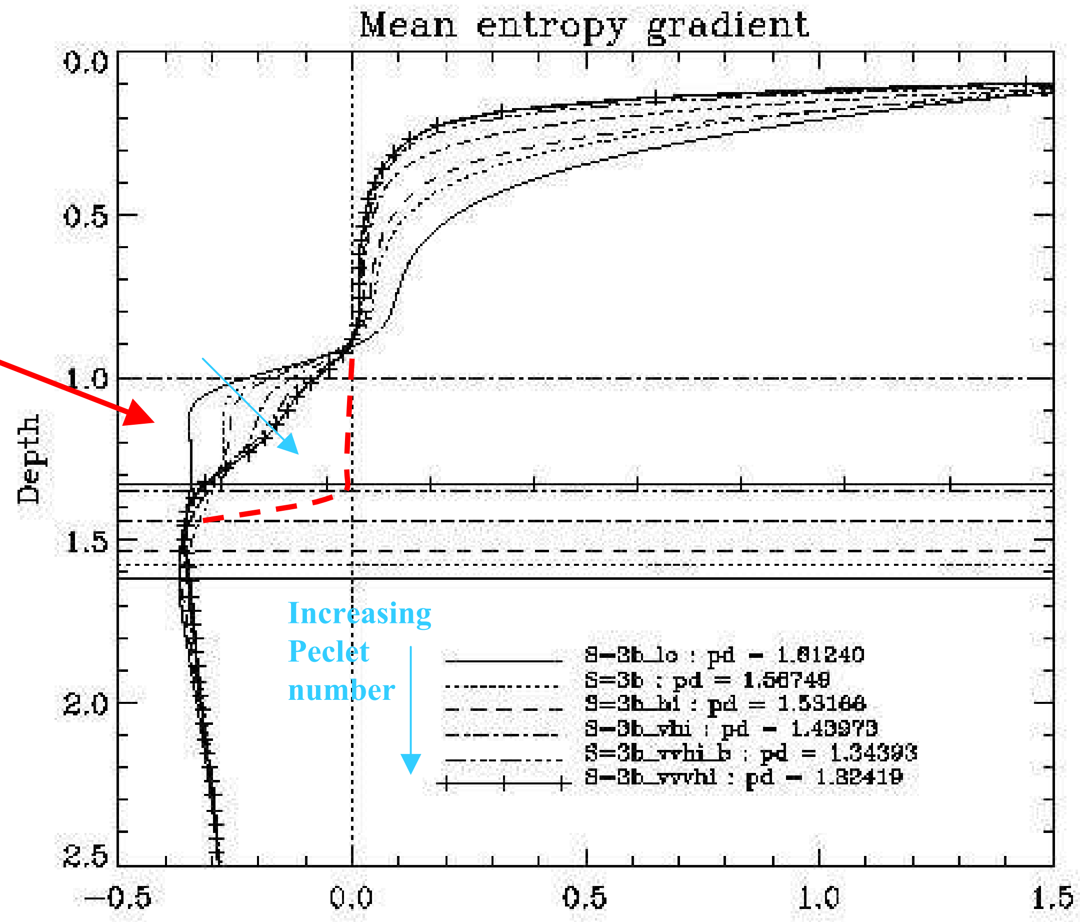
- **Overshooting or penetrating motions: motions extend below the interface.**
- **Large downwards (+ve) kinetic flux due to the strong downflows.**
- **Bouyancy braking decelerates the motions in the stable region.**

Penetrative convection movie



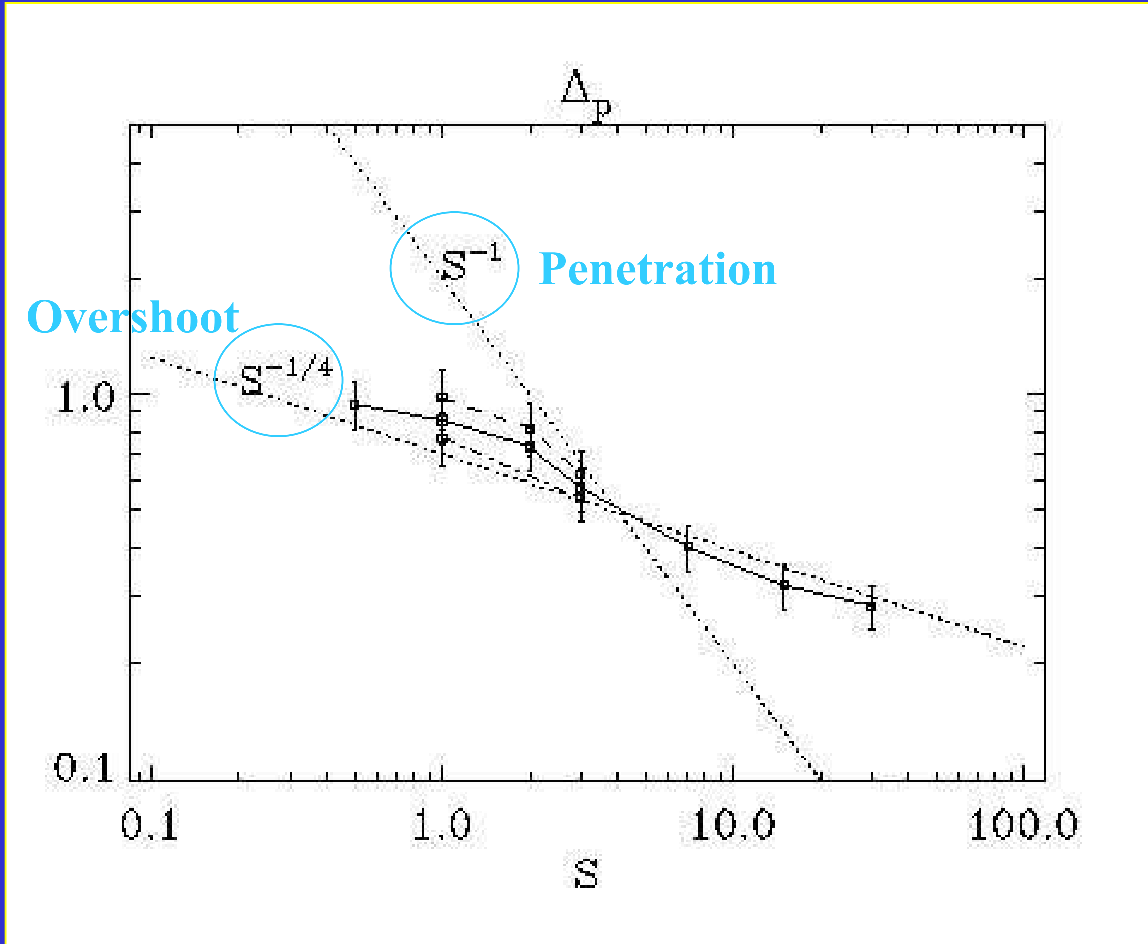
Main penetrative convection results: 1

- 3-D penetrative convection does not really penetrate, only overshoot.
- No extension of the adiabatically mixed region due to low filling factor of 3-D plumes.
- Even at highest Peclet numbers simulated.
- Possibly not high enough Pe! (Matthias Rempel : semi-analytic model)

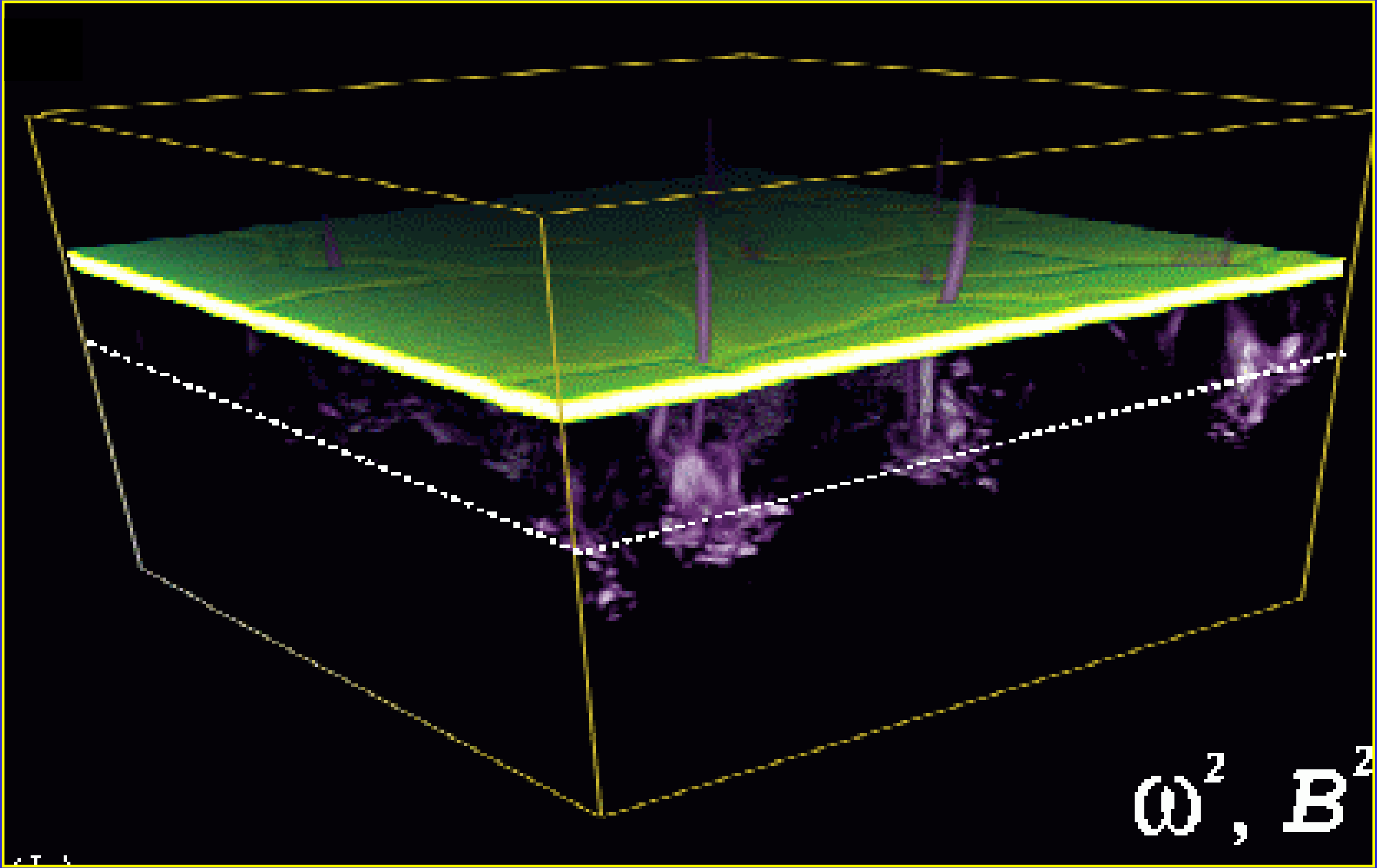


Main penetrative convection results: 2

- 3-D penetrative convection therefore has a different scaling with the relative stability of the lower layer than 2-D (Zahn, 1991), reflecting the lack of true penetration even at low S.
- So all following stuff is OVERSHOOTING convection, whether you like it or not!

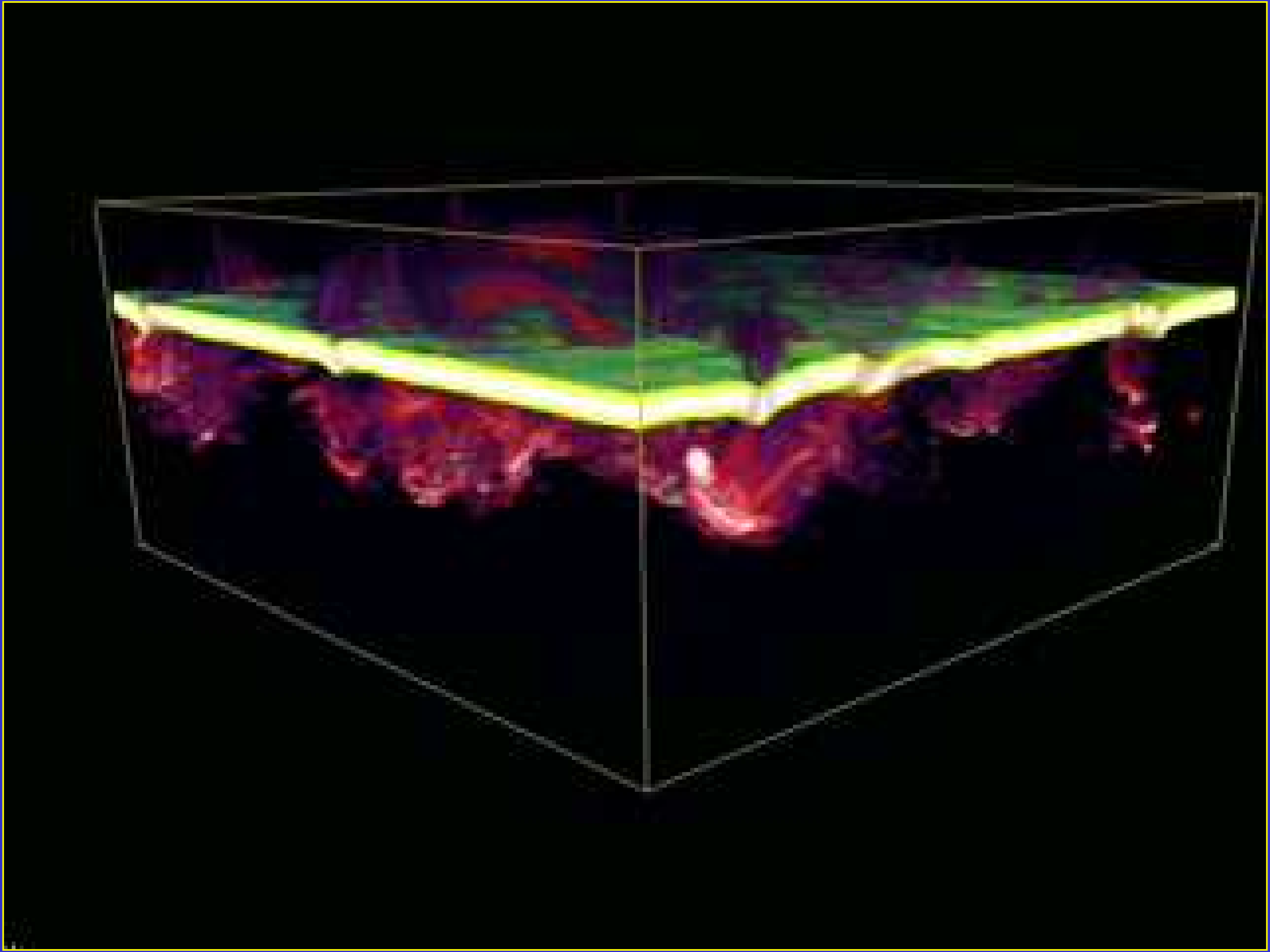


Magnetic flux transport – "Pumping"

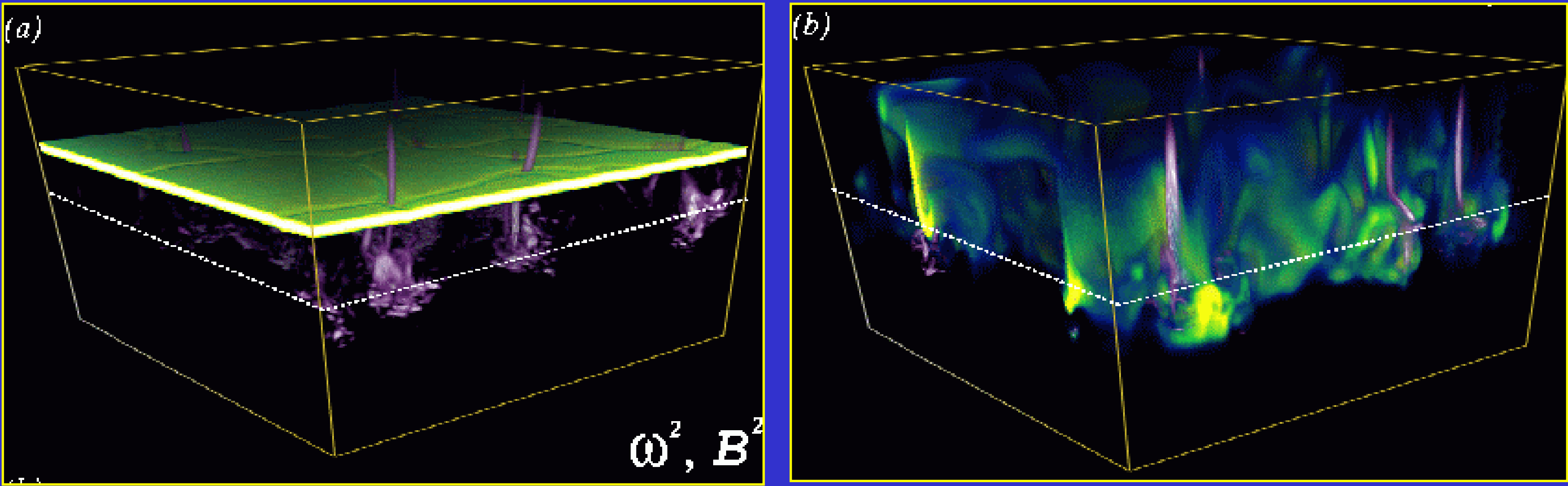


What happens if we add magnetic field
to the penetrative convection?

Magnetic pumping movie

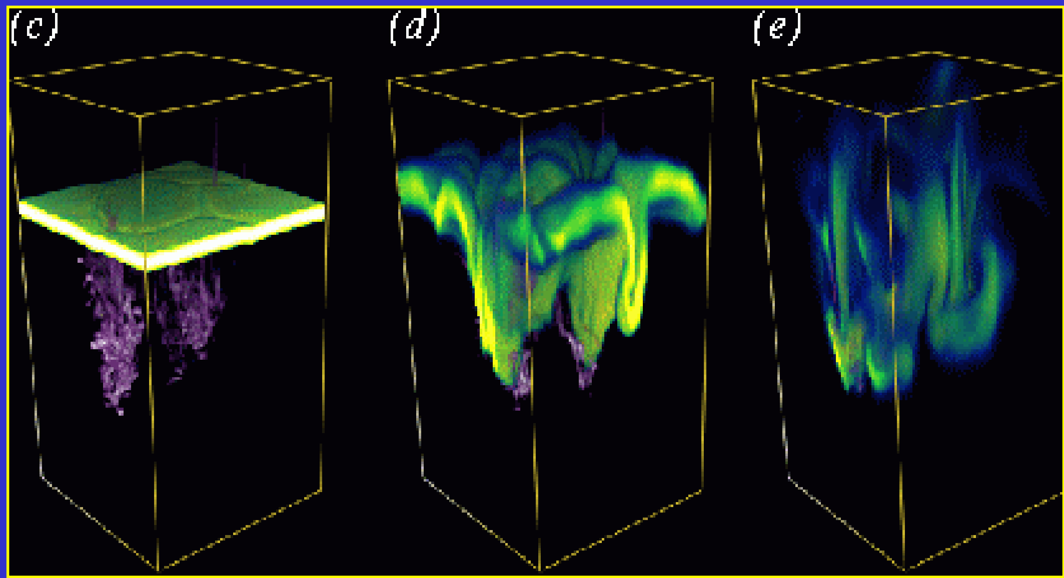


Magnetic pumping

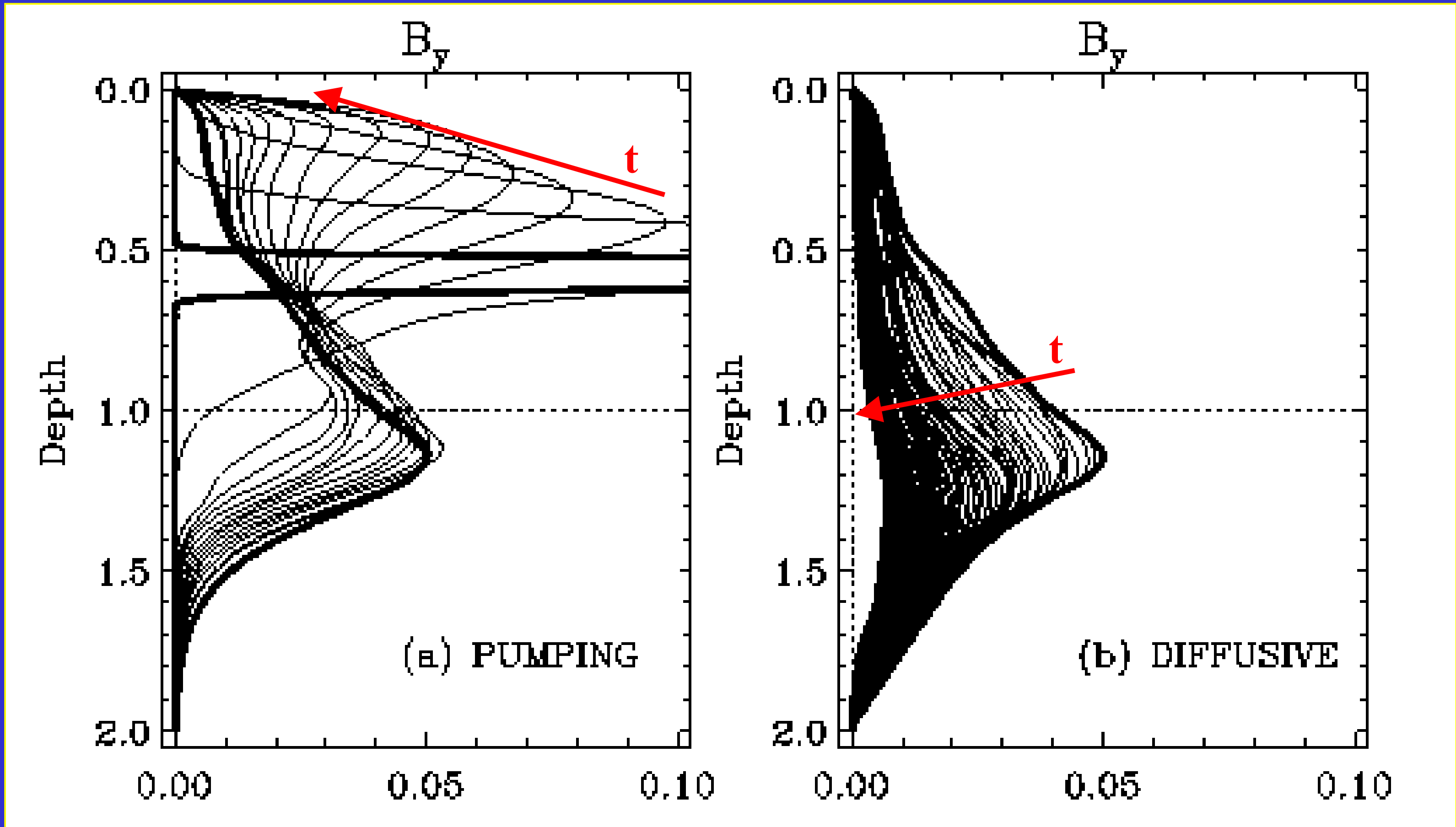


- Magnetic flux is transported, or "pumped" out of the convection zone into the stable overshoot layer by advective action of plumes.

- Local amplification of the magnetic field everywhere but particularly in overshoot layer (although most of energy in CZ is fluctuating component)



Magnetic pumping

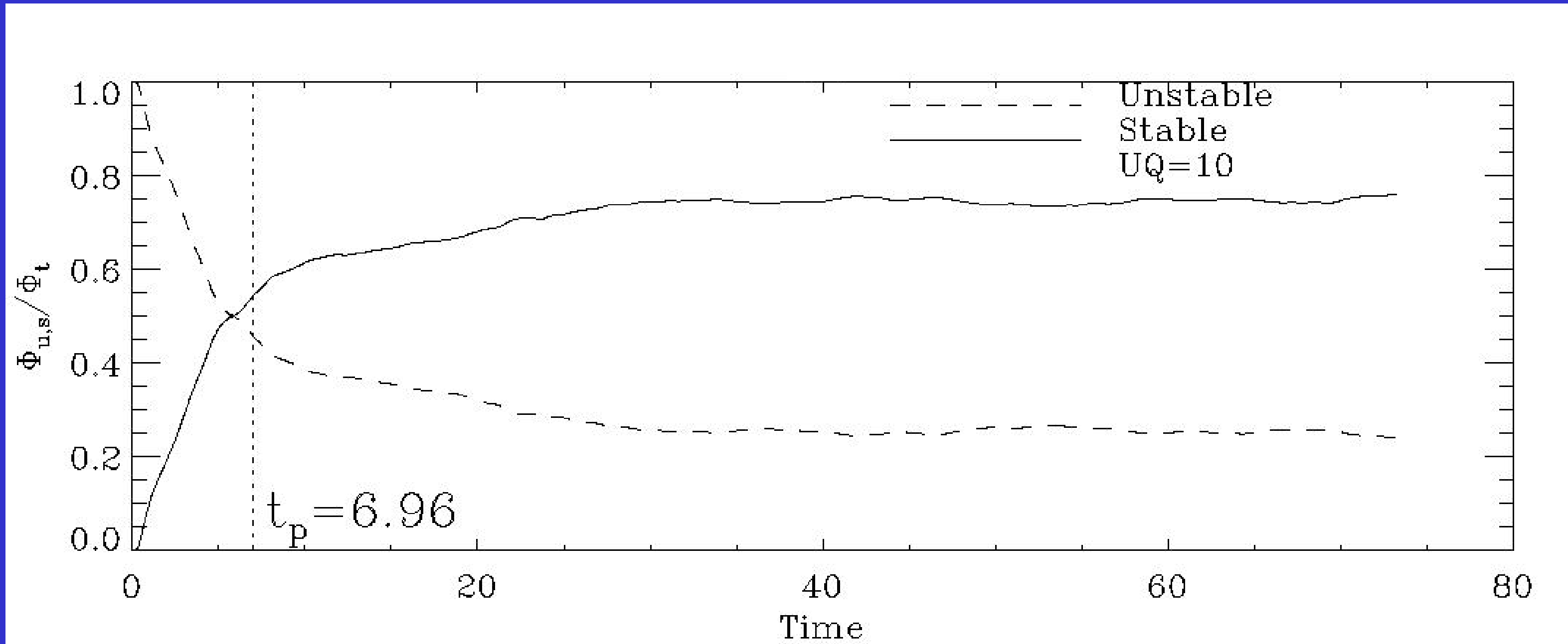


Pumping stage: Flux rises initially, then is redistributed to the lower region

Diffusive stage: Diffusion then tries to erode profile (depends on bcs)

Magnetic pumping

Flux fraction in unstable and stable regions



Significant fraction of flux ends up in lower layer ~ 70%

Can define measures such as pumping time, pumping depth etc.

Main magnetic pumping results: 1

Storage of > 70% of the magnetic flux in the overshoot zone.

Magnetic pumping is very robust:

- **Works for weak to moderately strong magnetic fields**

  (max plasma β studied ~ 0.03; structure sims => much stronger)

- **Works for ANY initial distribution of the magnetic field**

  (convection zone layer, overshoot zone layer, everywhere)

- **Works for variety of boundary conditions**

  (B=0, No Flux)

- **Works for wide variety of other parameters**

  (notably S, including S negative => sunspot penumbrae!)

Doesn't look like a turbulent diffusion! **(not isotropic; doesn't need B gradients)**

Main magnetic pumping results: 2

Two possible transport effects operating:

- **Transport due to asymmetry of motions – net downward advective flux (w^3)**
  - Compressibility enforces asymmetry (but could be e.g. Bouss with depth-dependent viscosity)
  - Stable layer enhances asymmetry
- **Transport due to turbulent intensity gradient – transition from turbulence to quiescent region**

Not obvious how to discern which is responsible here

Main magnetic pumping results: 3

- It should be noted that

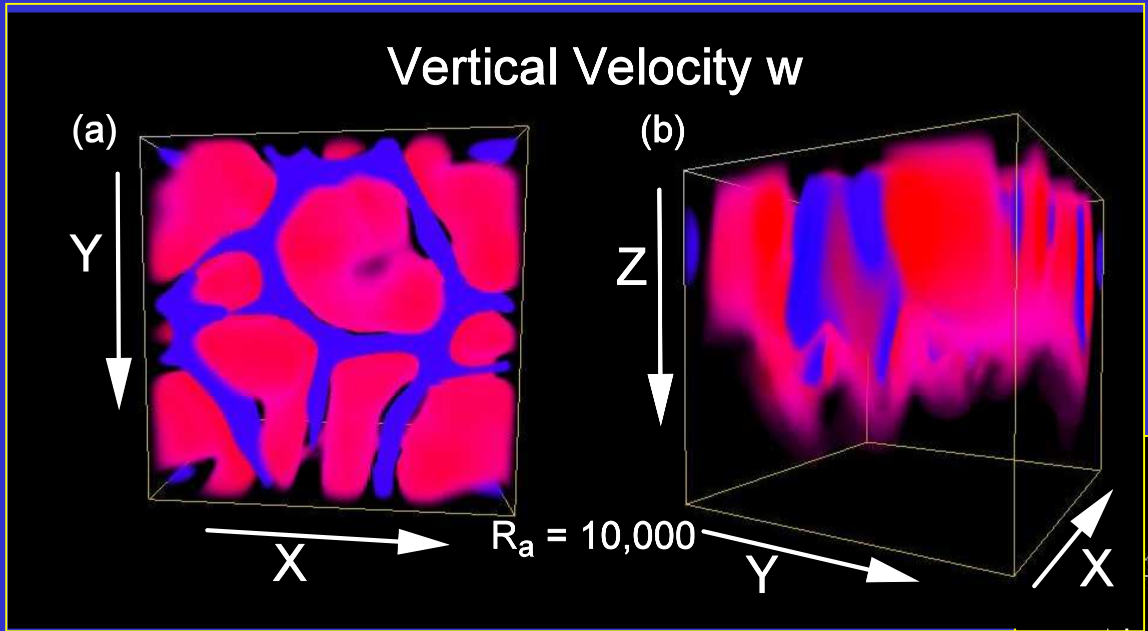
PUMPING is a MEAN effect

and is not a static equilibrium state.

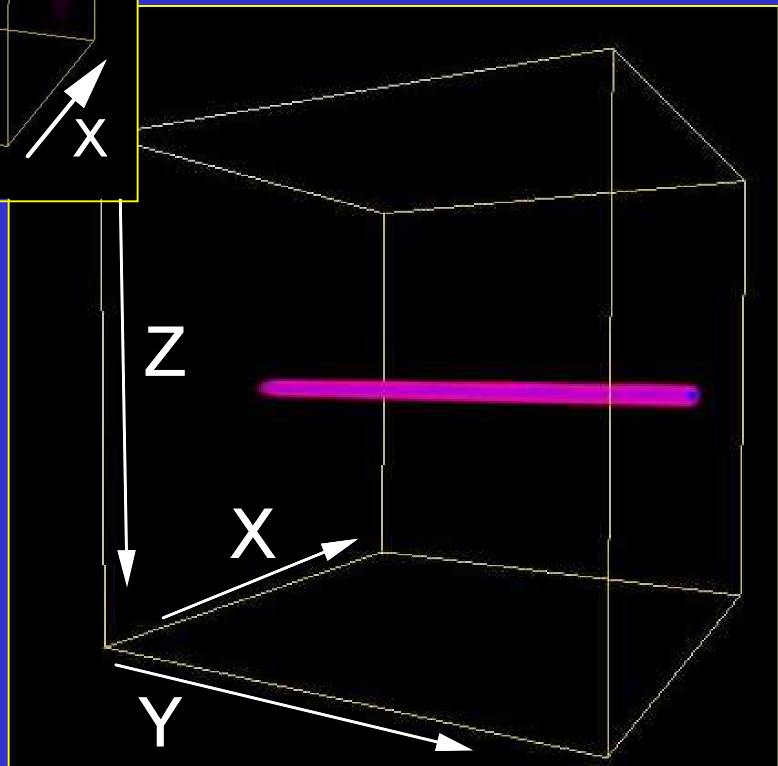
- **Magnetic field is constantly arriving and departing from the overshoot zone.**

- **Strongest, most concentrated elements selected to rise?**

Rise of magnetic structures



Penetrative, S=3,
$Ra=10^4$, Pr
Pm=100, 6x6x2.5,
$z_p \sim 1.75$



Idealised twisted tube, centred at (x_0, z_0):

$$B_y(r) = 1 - r^2/r_0^2$$

$$B_r(r) = -2q(z-z_0)/r_0\, B_y(r)$$

$$B_z(r) = +2q(x-x_0)/r_0\, B_y(r)$$

where

$r<r_0$, $r^2 = (x-x_0)^2 + (z-z_0)^2$, $r_0^2 = x_0^2 + z_0^2$

Twist angle ❑ ▪ $\tan^{-1}(2q)$

Rise of magnetic structures

Weak magnetic field: $E_b \ll E_k$

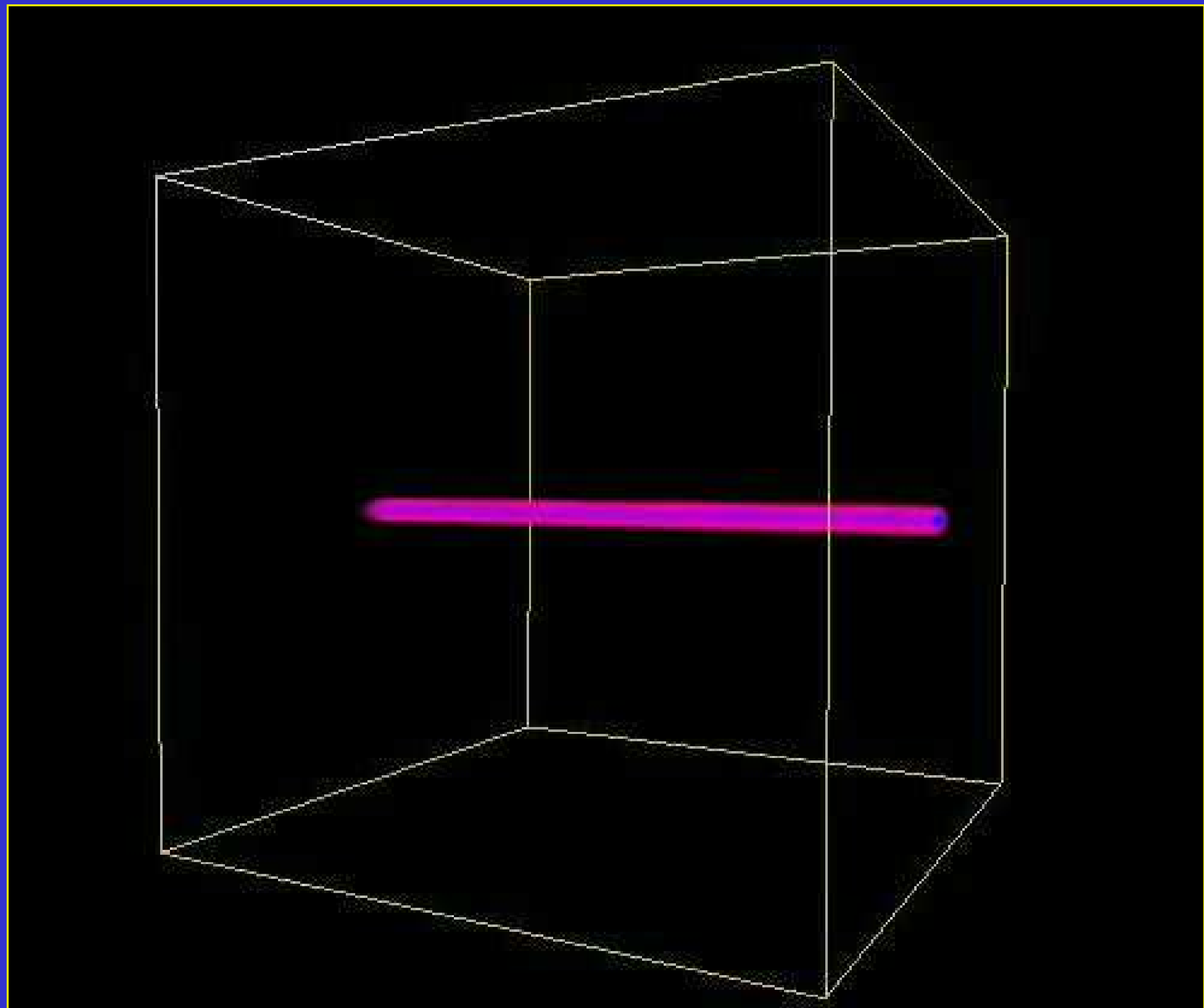
E_b=♋$_m|B|^2/2$

E_k=❐$|u|^2/2$

E_k (rms) ~ 0.6

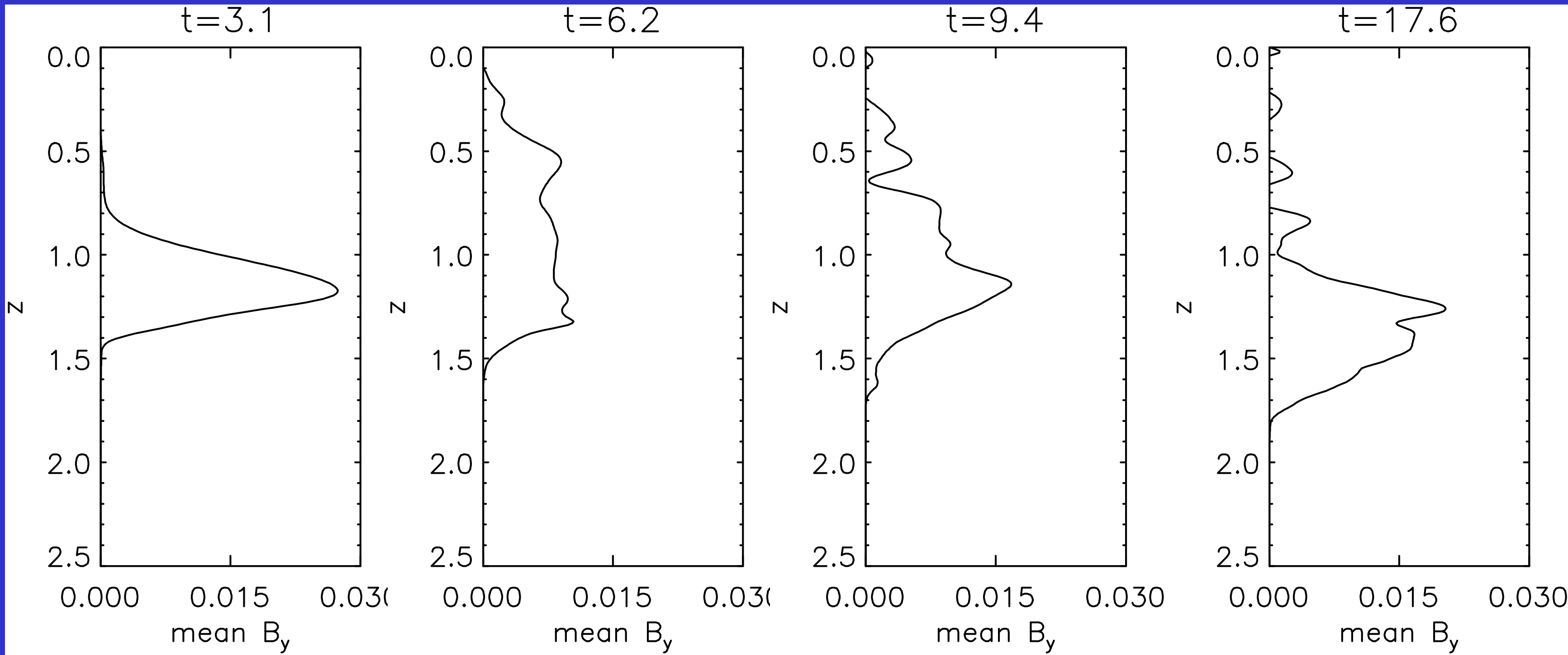
E_k (max) ~ 9.5

E_b (max) ~ 0.026



Rise of magnetic structures

<u>Weak magnetic field</u>: $E_b << E_k$



Field is disrupted, then <u>pumped</u>.

Rise of magnetic structures

Strong magnetic field: $E_b \sim E_k$

E_b=♋$_m|B|^2/2$

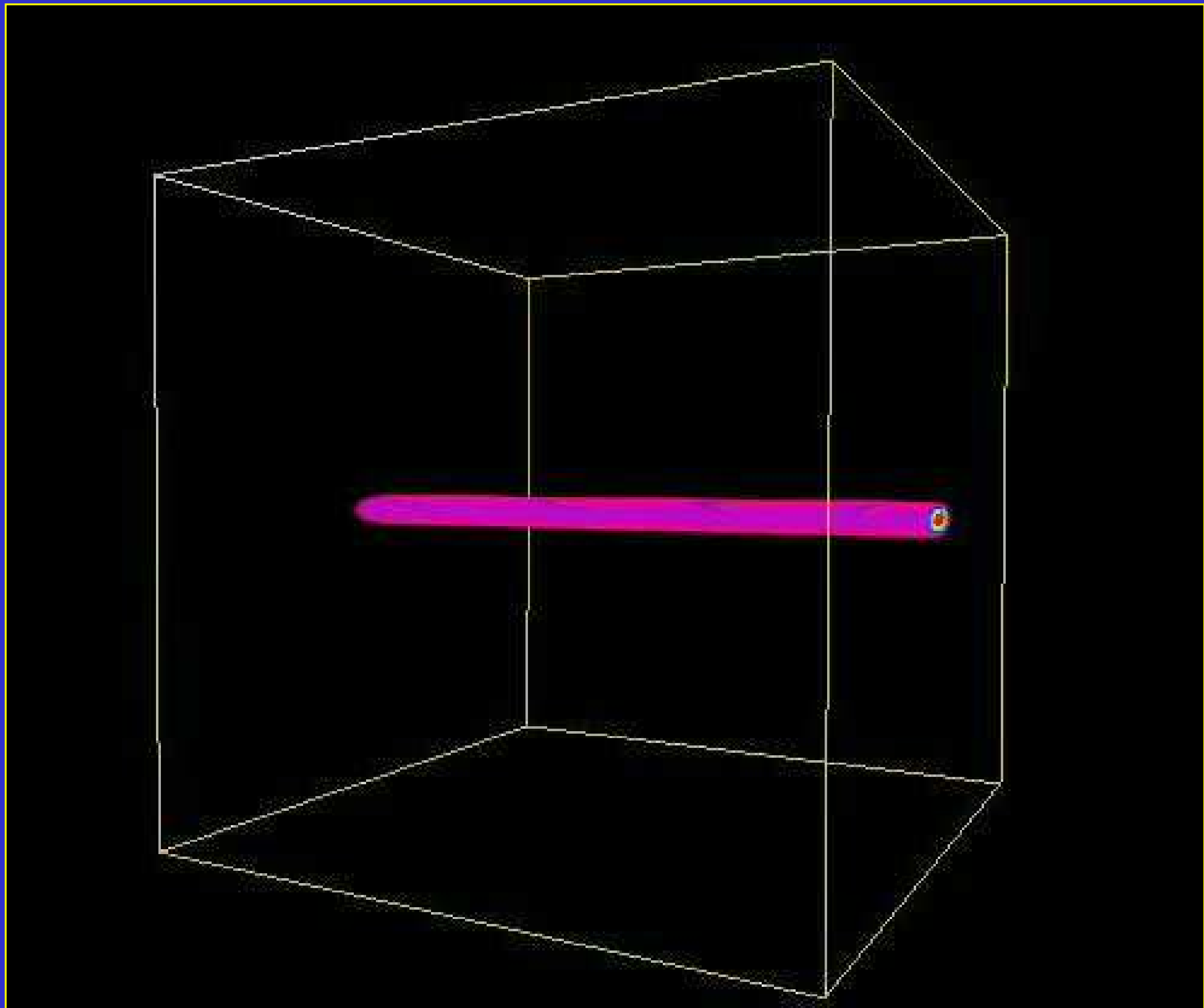
E_k=❒$|u|^2/2$

E_k (rms) ~ 0.6

E_k (max) ~ 9.5

E_b (max) ~ 13

Same fate: tube is shredded and pumped!



Rise of magnetic structures

<u>Very strong magnetic field</u>: $E_b > E_k$

E_b=♋$_m|B|^2/2$

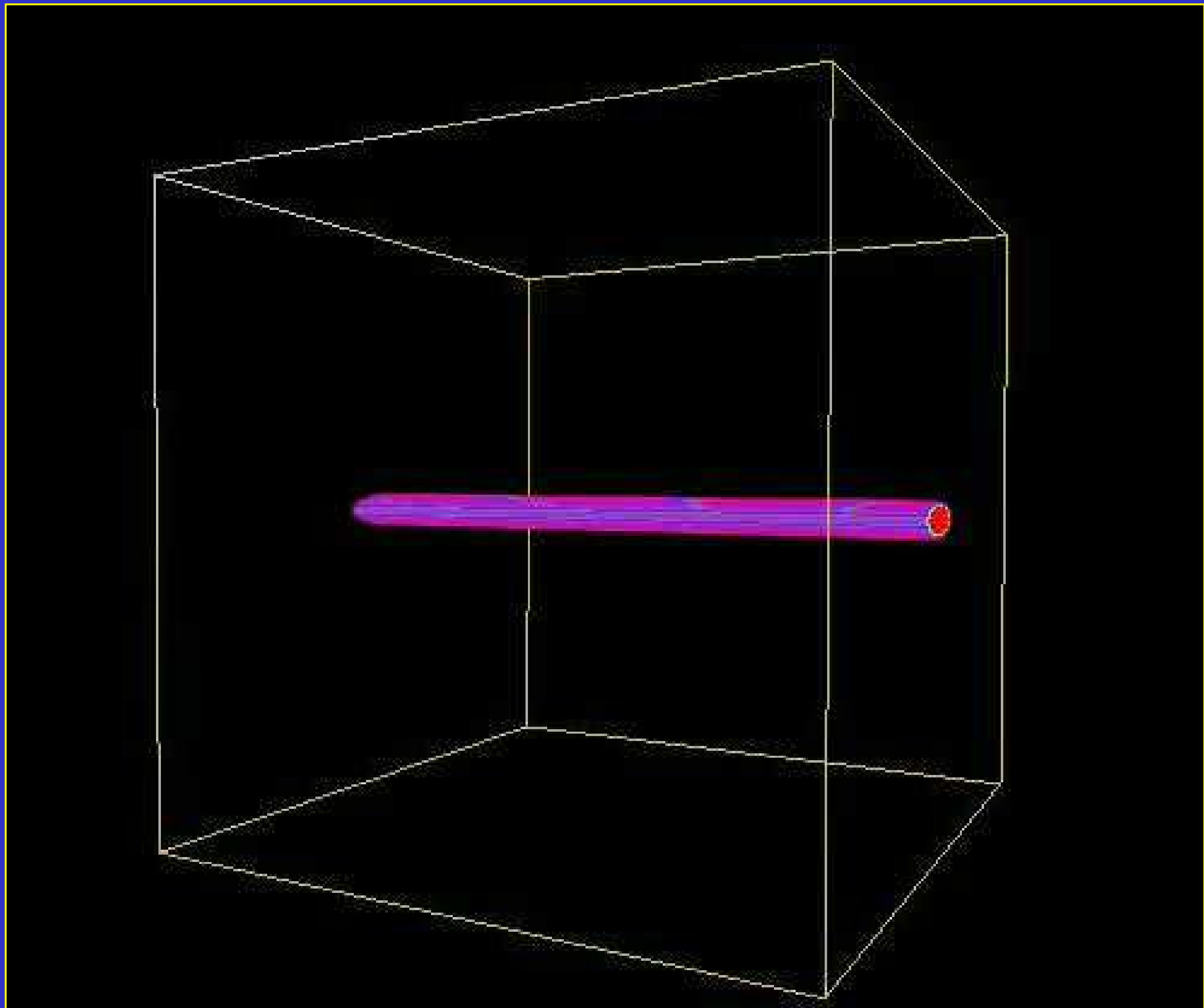
E_k=❐$|u|^2/2$

E_k (rms) ~ 0.6

E_k (max) ~ 9.5

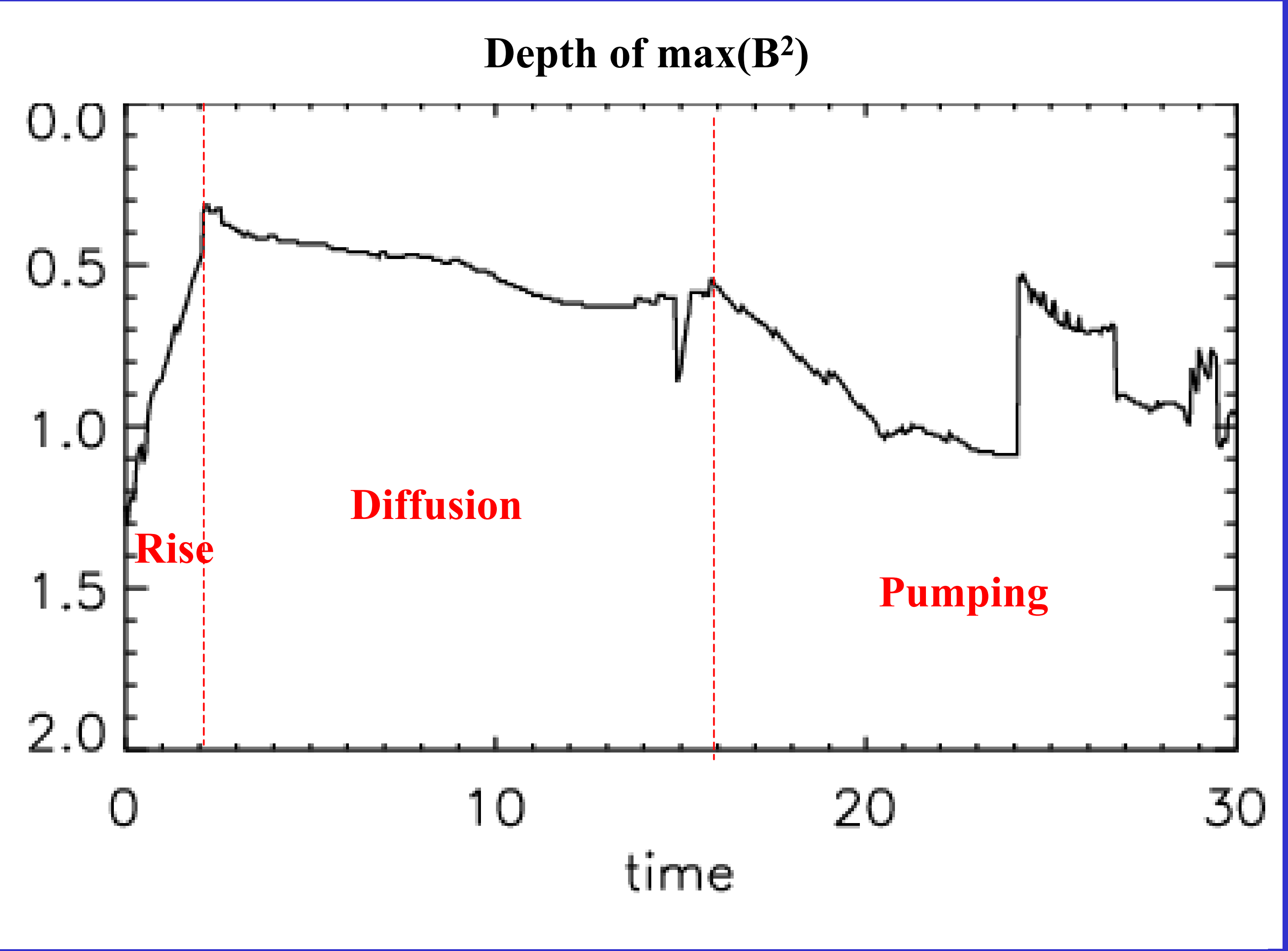
E_b (max) ~ 30

Tube survives!
Coherent rise; only gets pumped when diffuses sufficiently



Rise of magnetic structures

Very strong magnetic field: $E_b > E_k$



Rise of structures: main results

Structure must be surprising strong to survive

- If does not survive, gets pumped
- There are no other outcomes (pumped coherently, or shredded rise)

Variation with parameters:

- Higher Ra => pumps harder => harder to rise
- Lower resistivity => less disruption of structure
- Less twist => faster disruption
- Stronger density contrast => harder to rise

Note that these are truly isolated tubes (idealised). Less isolated (more realistic?) tubes may encounter more difficulty with rise due to anchoring.

Conclusions

Turbulent transport of magnetic fields and pumping important for a lot of solar MHD problems.

Where else could pumping be important?

(i.e. what are we doing next!)

Transport barriers: Shear

Basic questions: How do the presence of shear (and other magnetic fields) affect this transport mechanism?

First: What is the interaction between overshooting convection and shear?

- **Does shear "cut off" penetration and pumping? (quenching, barrier mechanisms)**

OR

- **Does convection deal with the shear?**

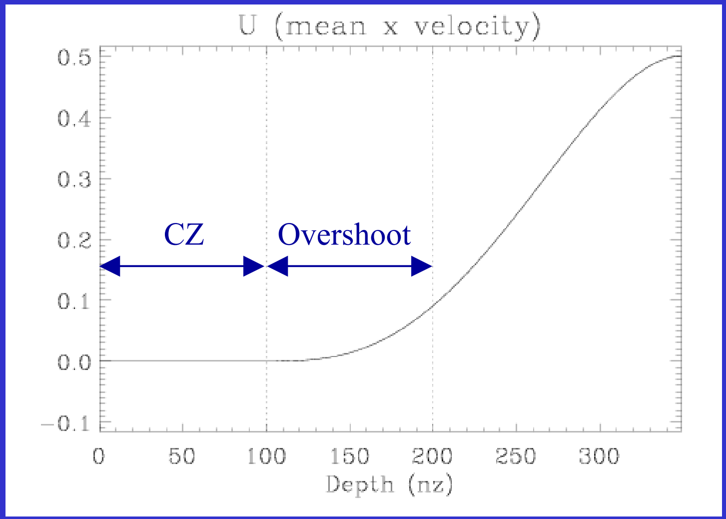
Add forced shear layer below

Add forcing function that provides desired shear in absence of other effects

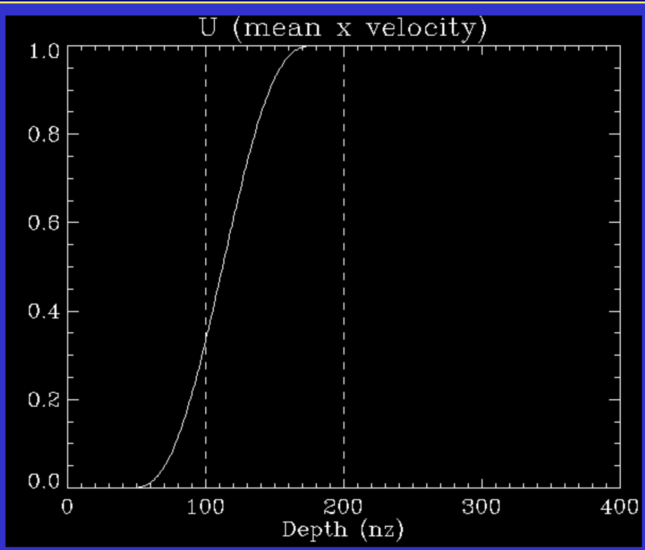
Parameterisation:

- **Strength of shear**
- **Location of shear**

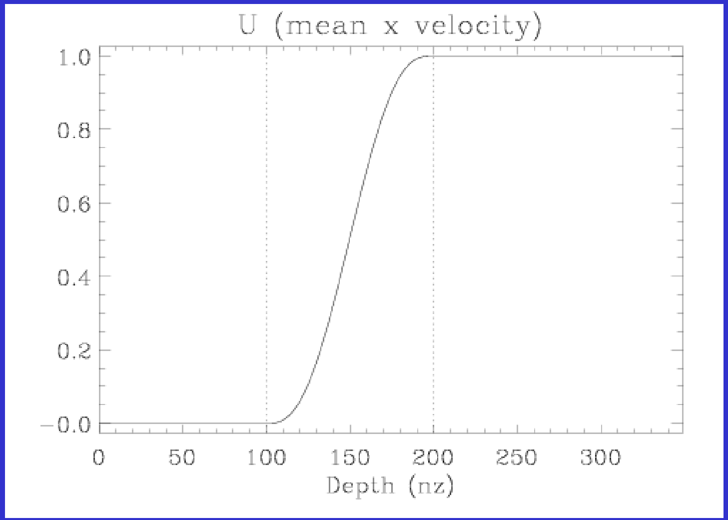
Base cases run:



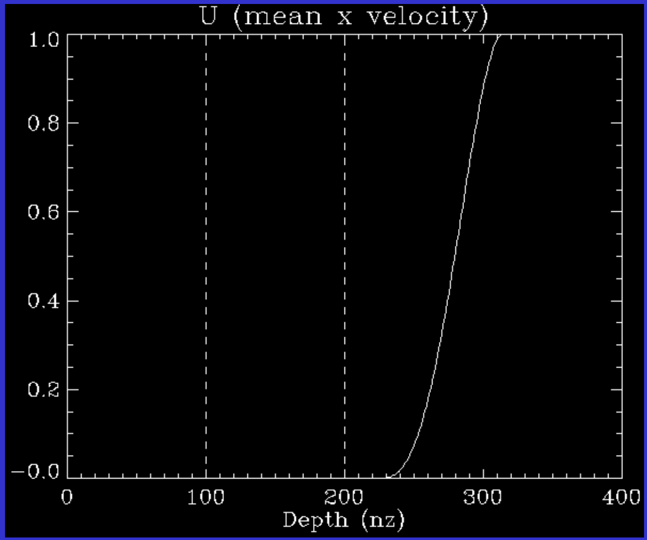
Weak shear, weak overlap



Strong shear, CZ strong overlap

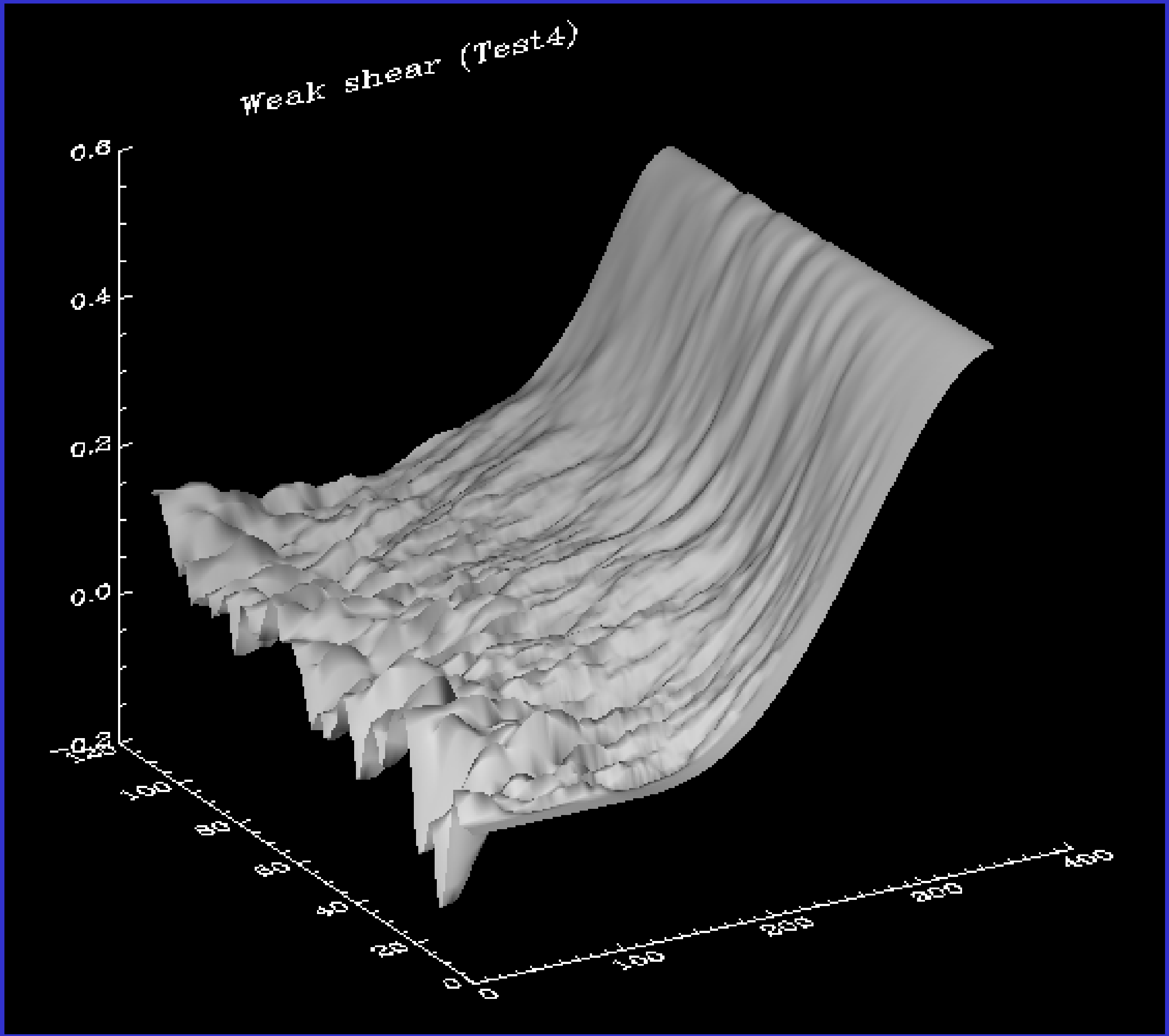


Strong shear, strong overlap

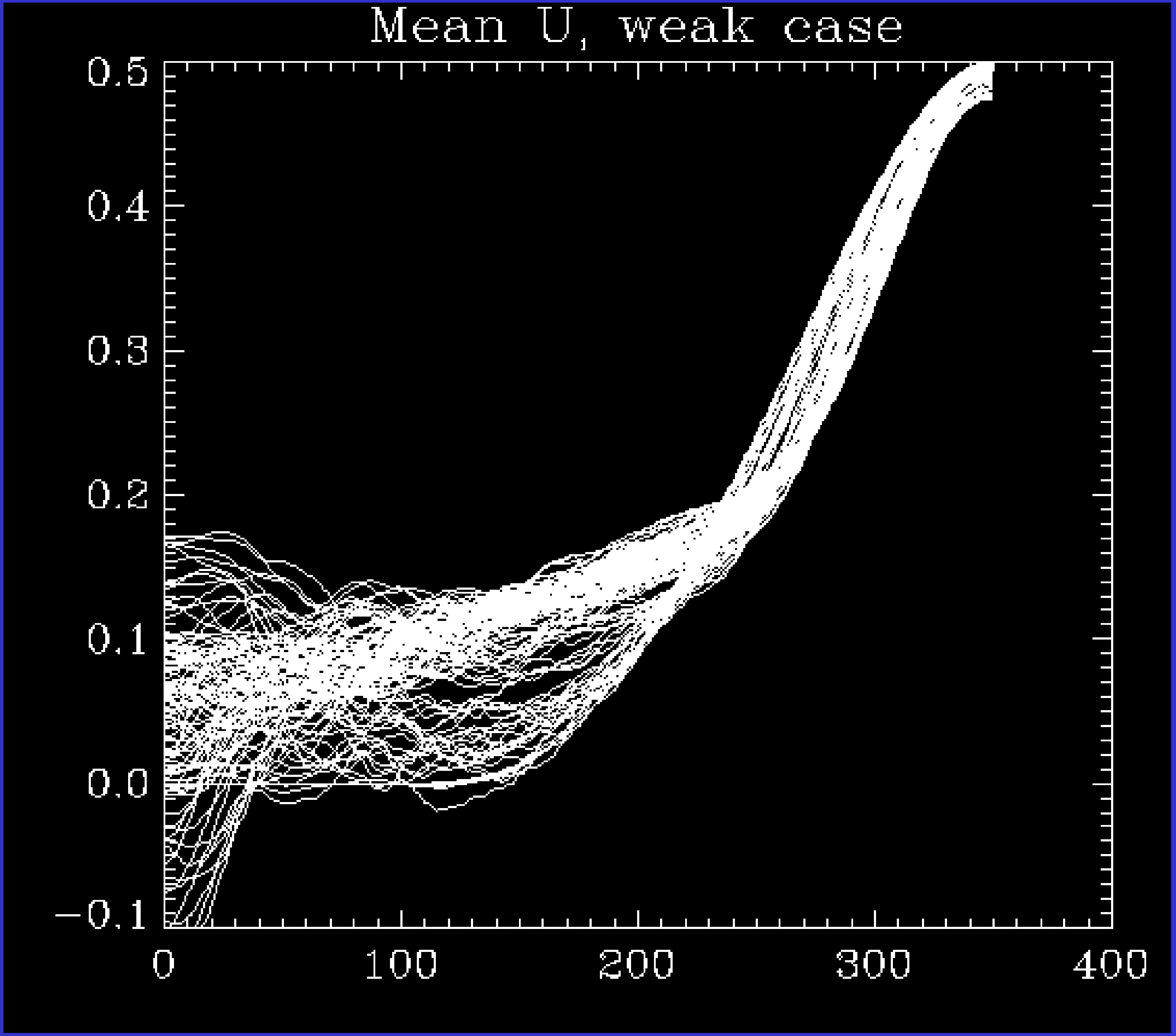


Strong shear, no overlap

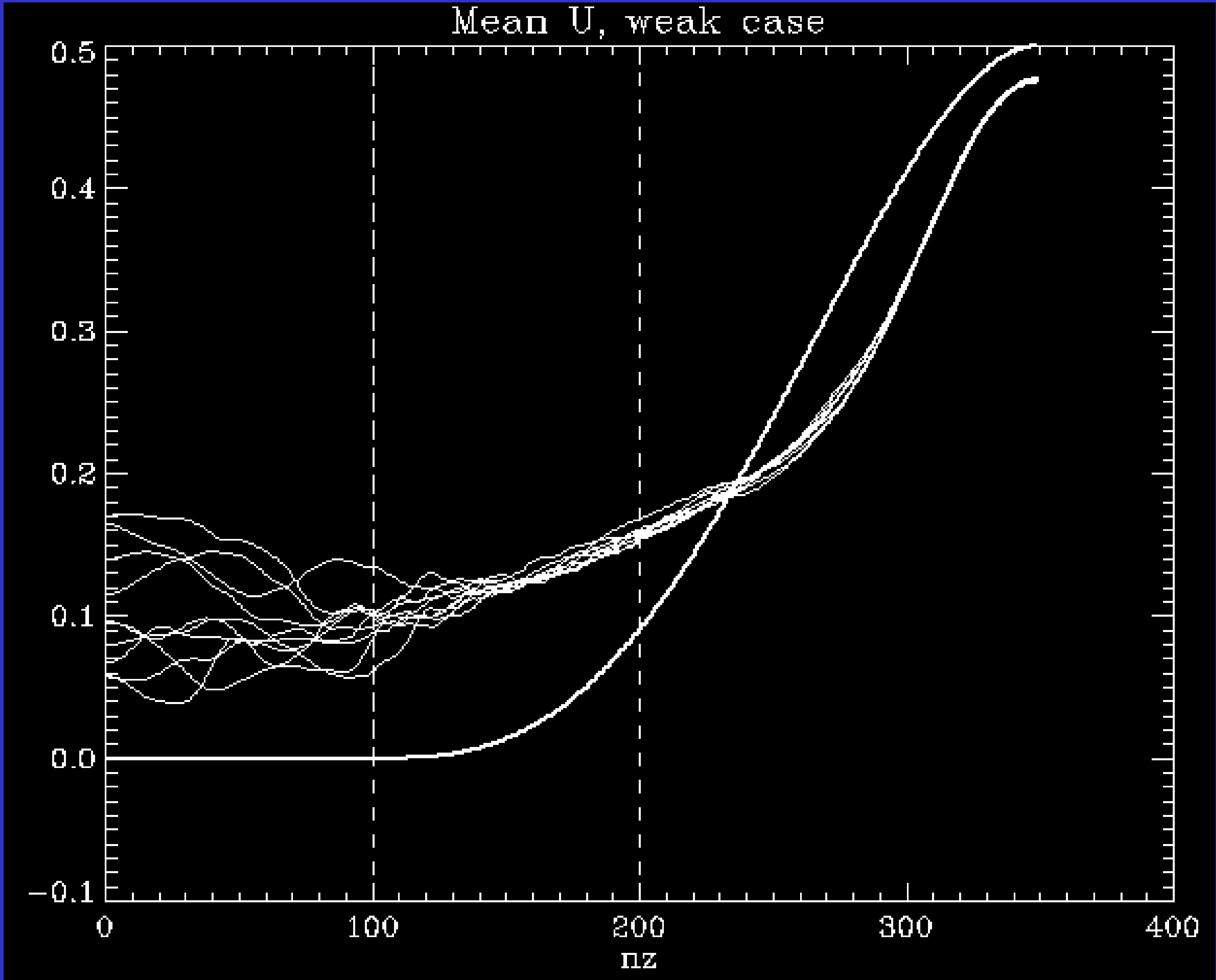
Weak shear : time dependence



Weak shear

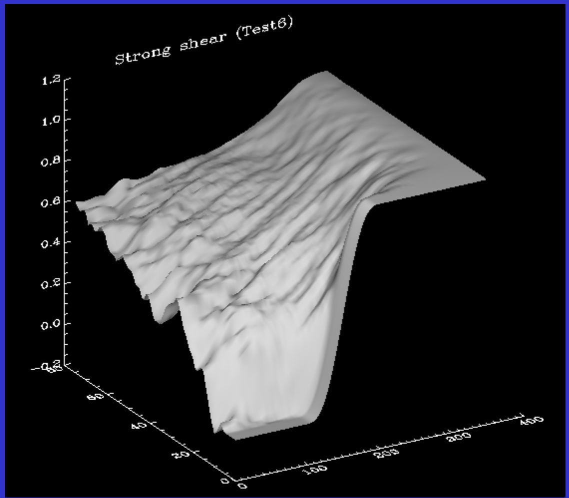


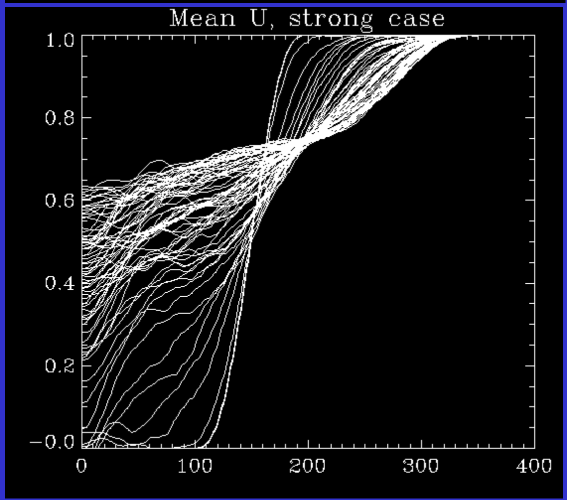
Weak shear : beginning & end

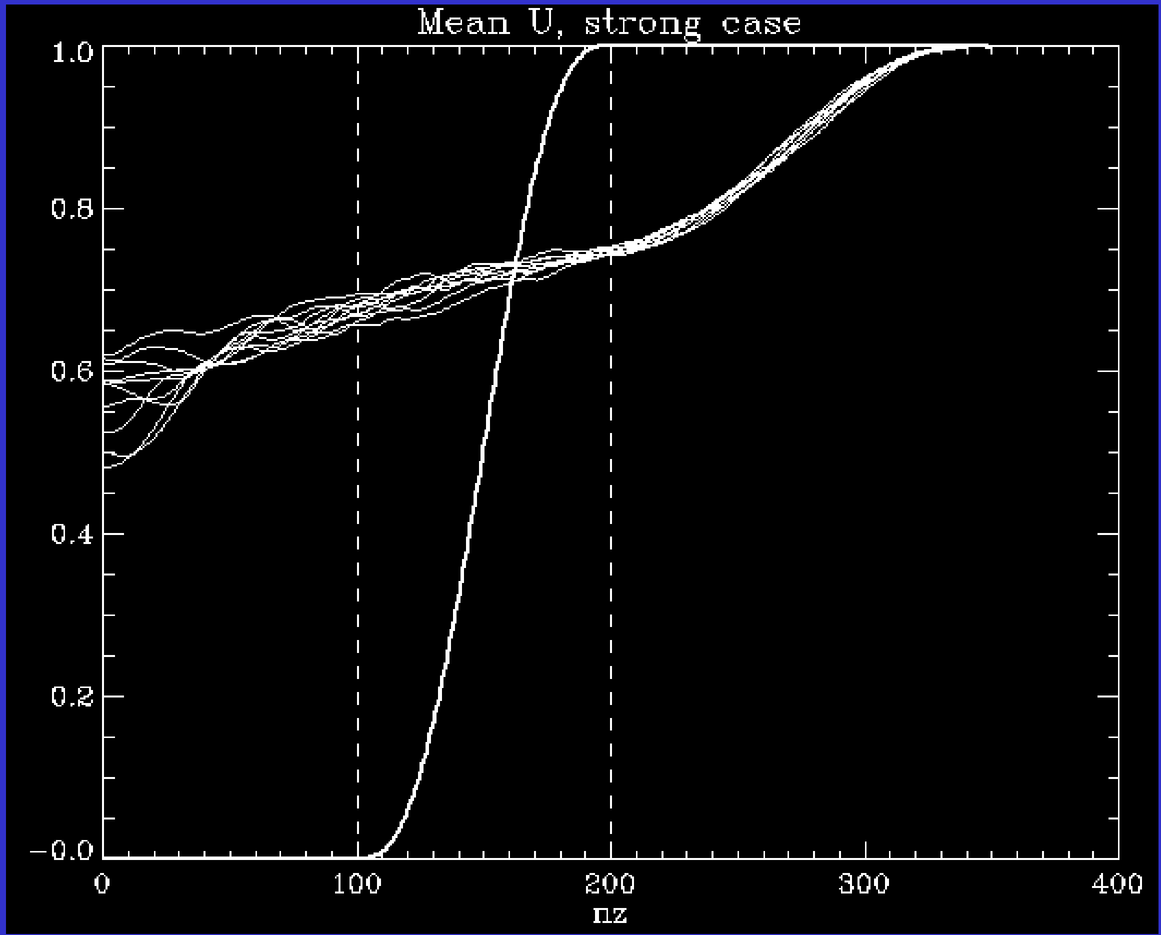


Stronger shear?

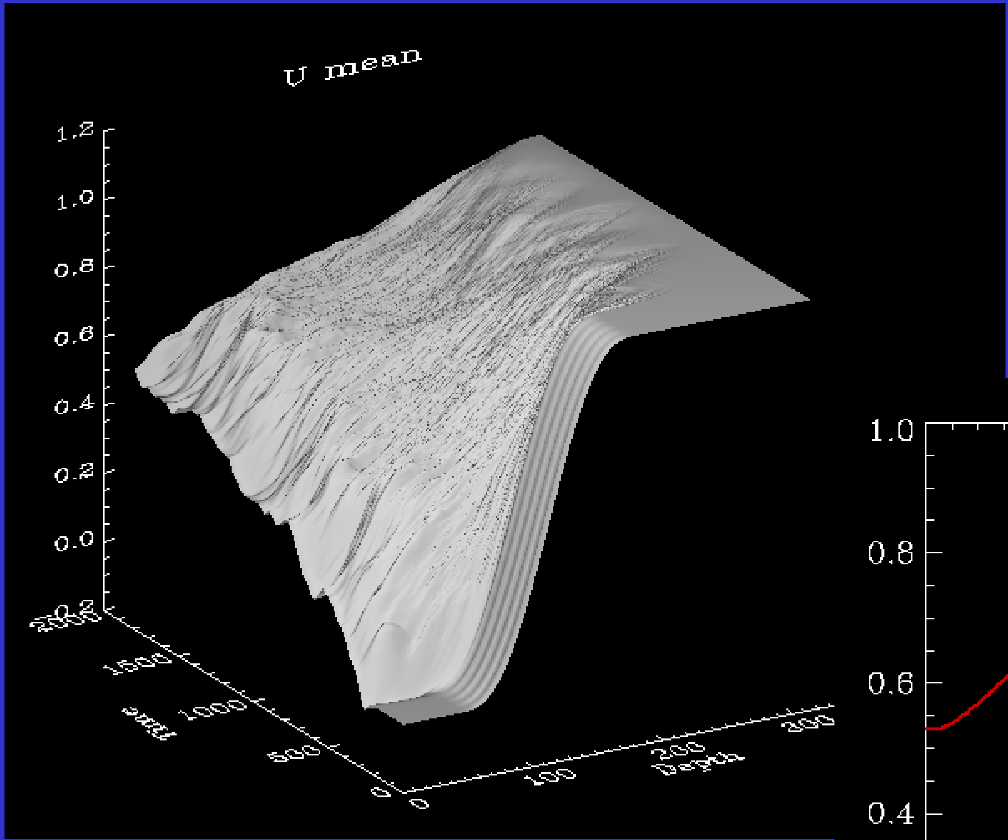
Surely a stronger shear won't experience this?

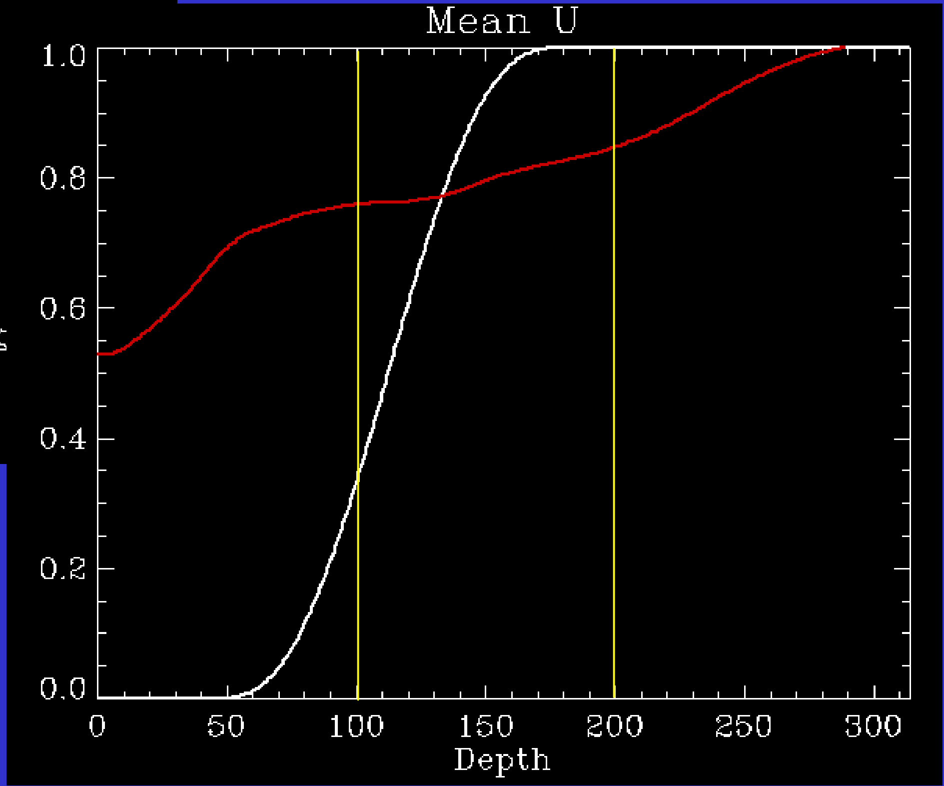




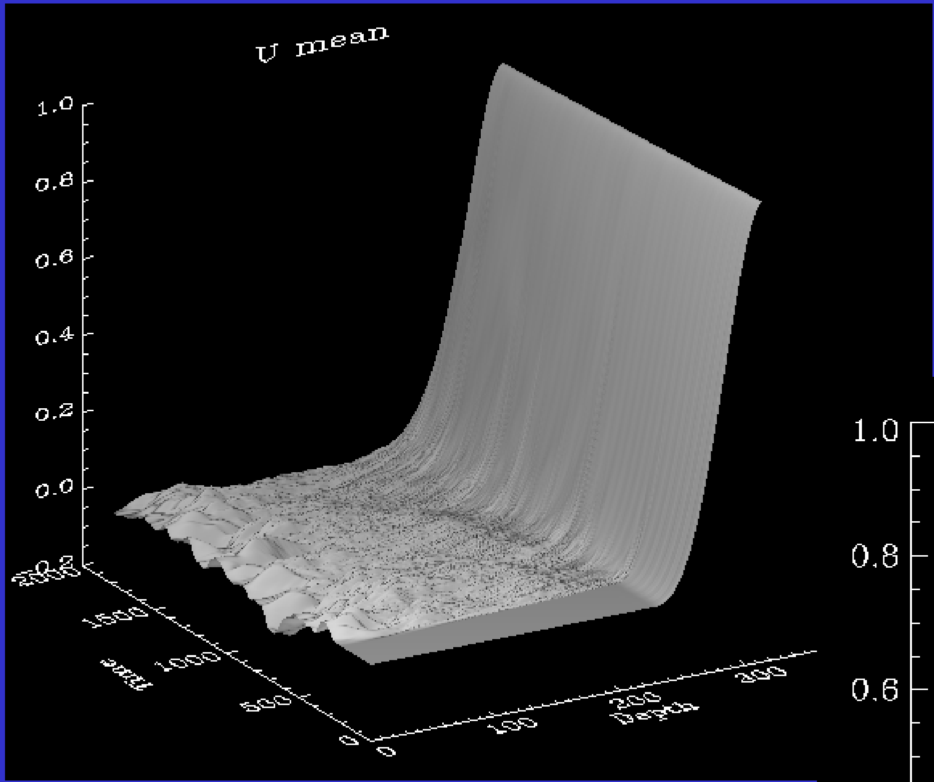


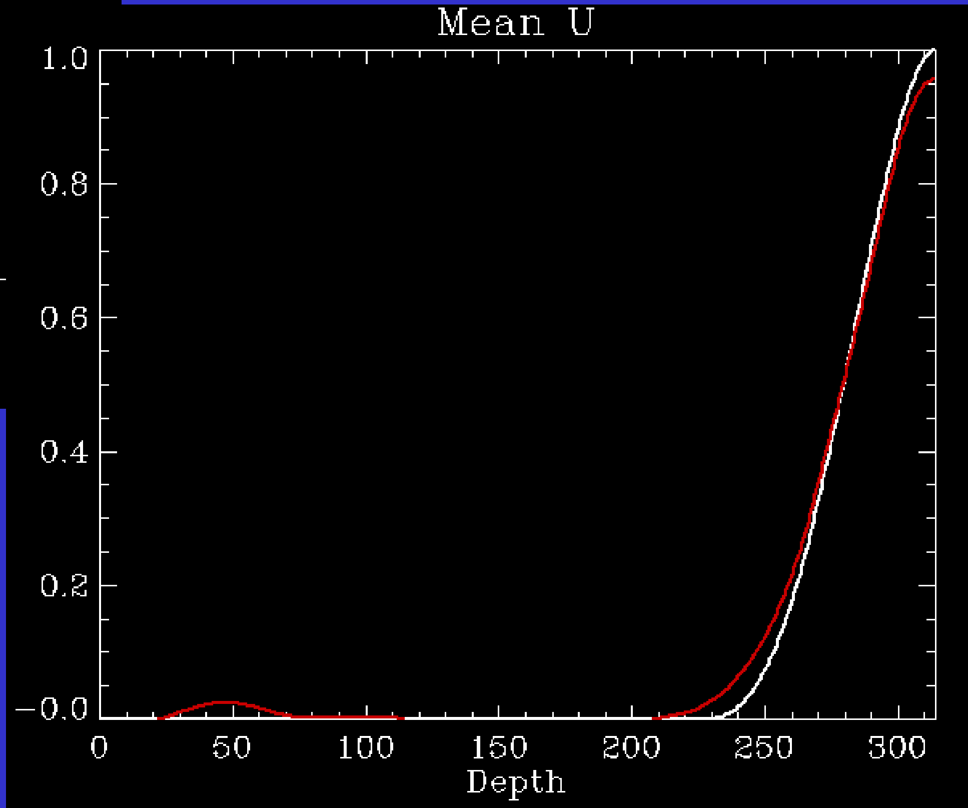
Strong shear, CZ overlap?





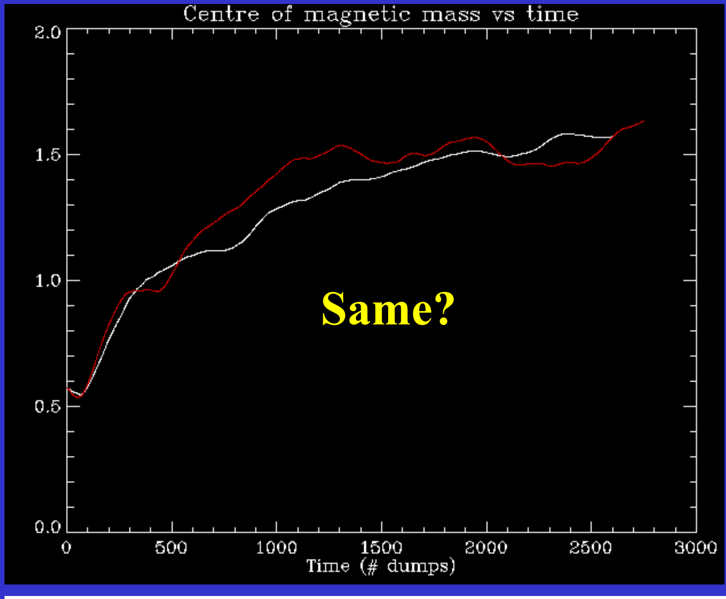
Strong shear, no overlap (control)?



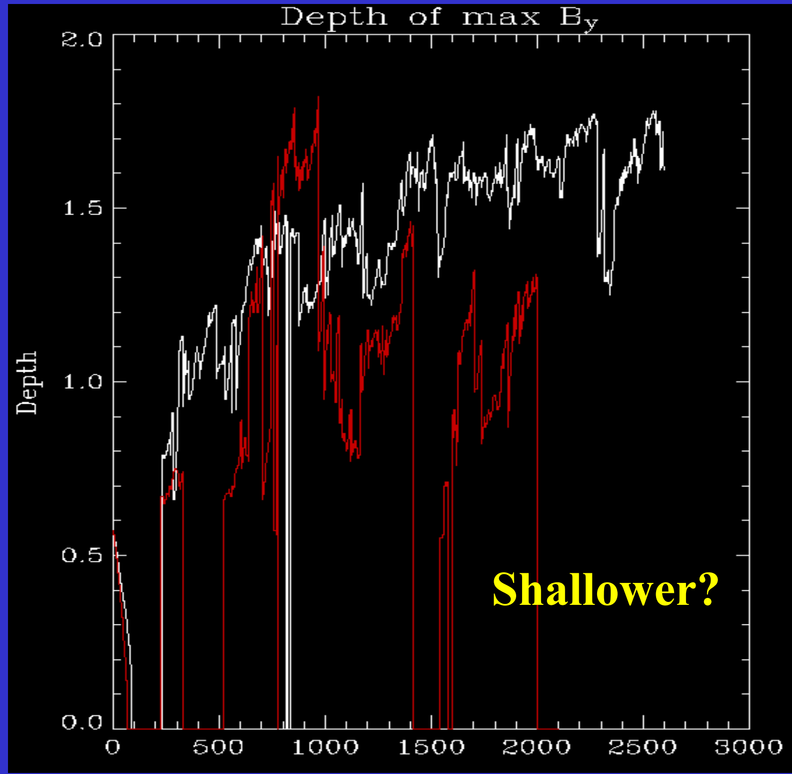


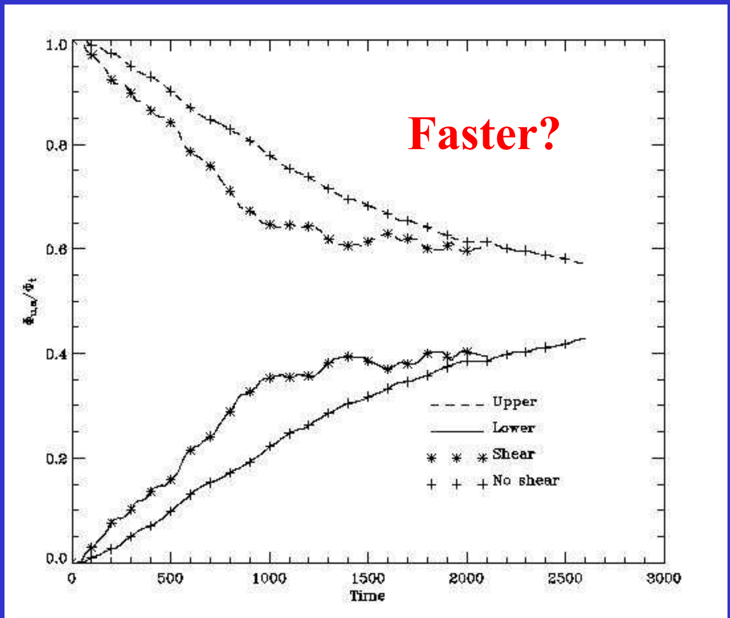
Some slight rearrangement, but generally forcing function maintains shear.

Pumping with (weak) shear?



Red=+shear



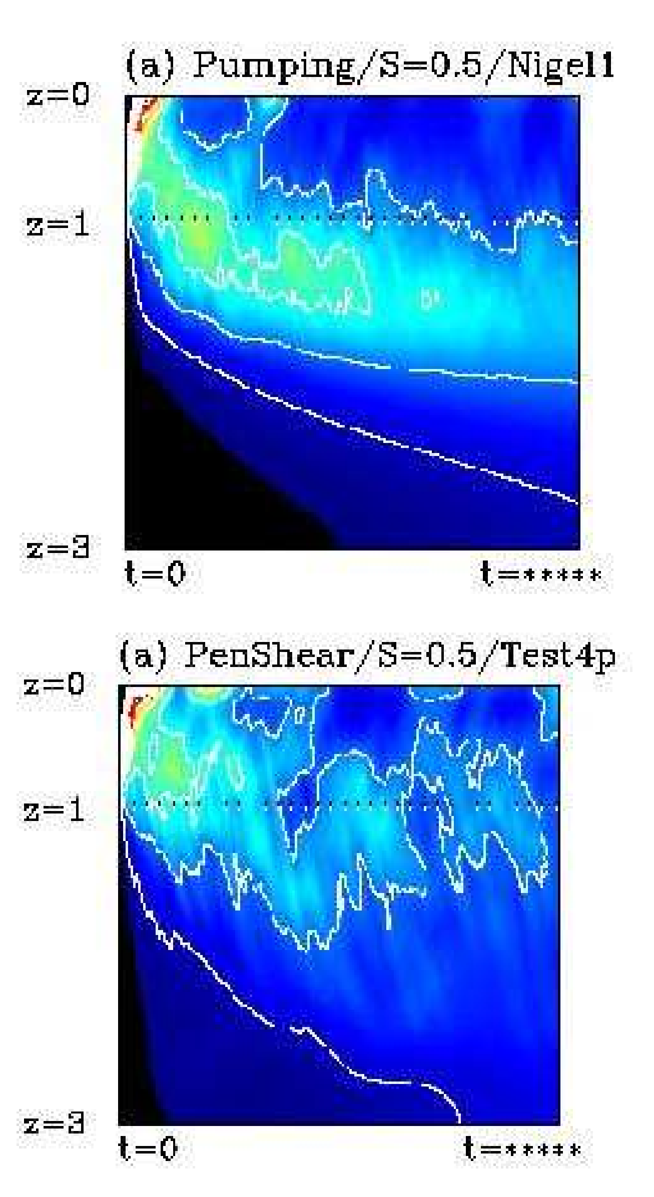


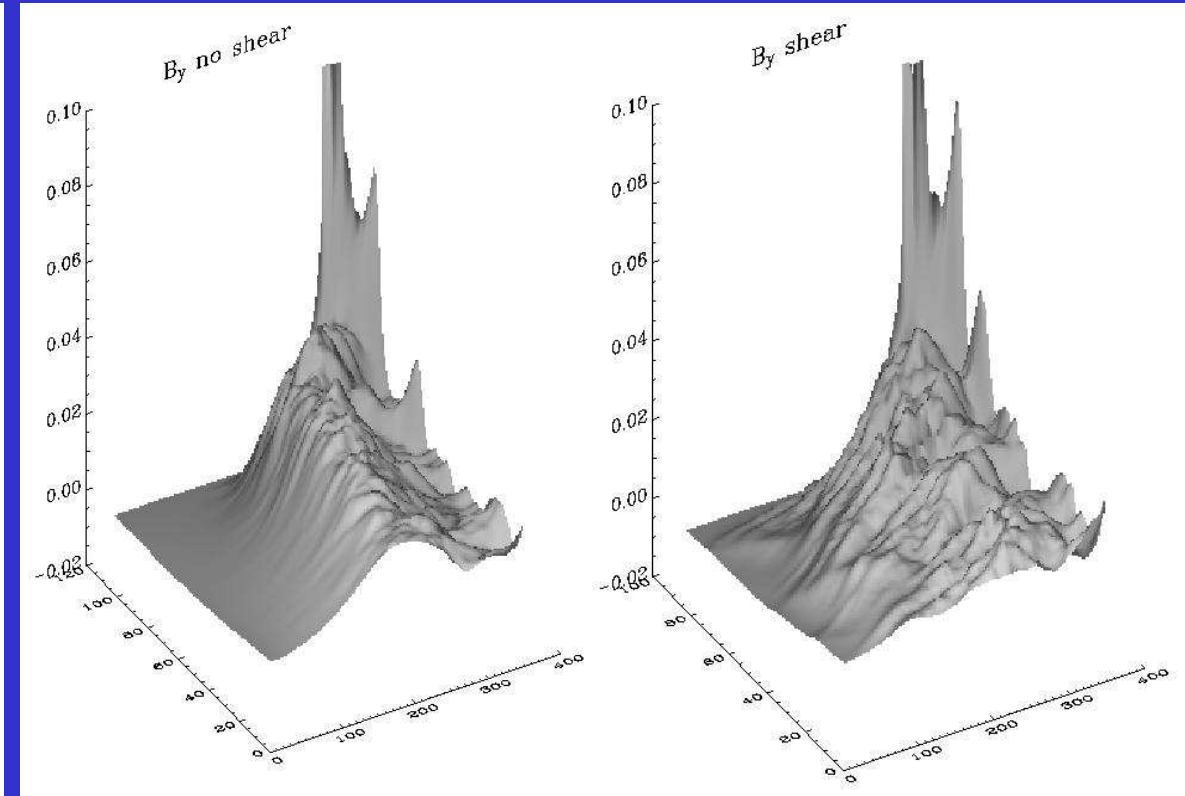
Pumping with (weak) shear:

- **Similar fraction pumped**
- **Same or shallower (NOT deeper at least!)**
- **Faster**

Due to shear spreading of flux in interior?

Pumping with (weak) shear





Pumping with (weak) shear:

- **Less well-defined pumping**

Thoughts 1 …

Can convection and shear ever overlap?

In absence of convection, shear is maintained => this effect is a turbulent diffusion :

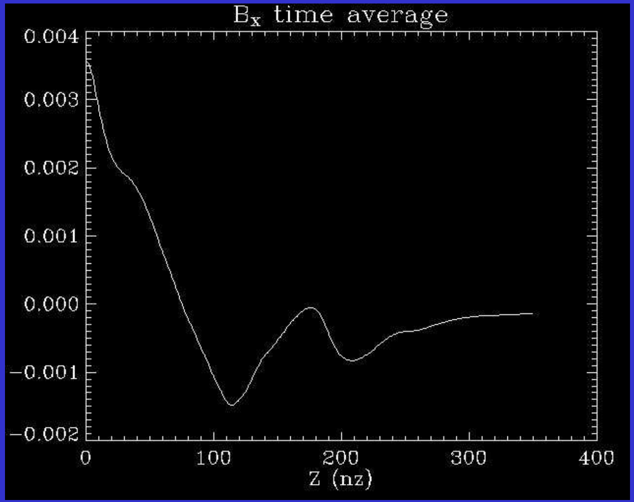
$$\nu_t \ \delta^2 U_{final}(z)/\delta z^2 = \text{Forcing}(z)$$

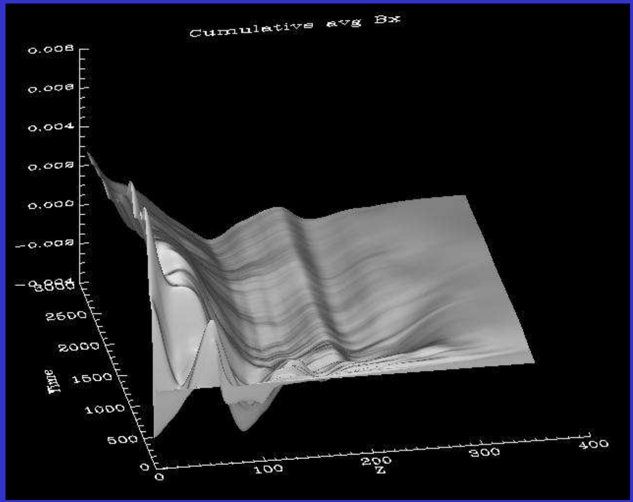
⇒ What is this as a function of Re? Rm? Applied B_0? (quenching)

Shear not self-consistent here. Do in a different manner?

⇒ Rotation? U=0 bottom boundary?

B_x (toroidal field):





Thoughts 2 : Chicken/egg problems …

We are always tempted to take what we see (from helioseismology) and use this to try and produce what we need.

However, what we see is final saturated state of nonlinear process that produces everything.

It is all **back-asswards**!

Need to guess the right initial condition that gives the correct nonlinear saturated state – very difficult.

Very difficult because it means you need to include all nonlinear effects.

The End

Thoughts 3 :Another example …

Here is another example:

A radial shear in the tachocline will stretch a poloidal field to produce a toroidal field, right?

We see a radial shear so the idea is to use this to create the strong confined toroidal field that we also (eventually) "see".

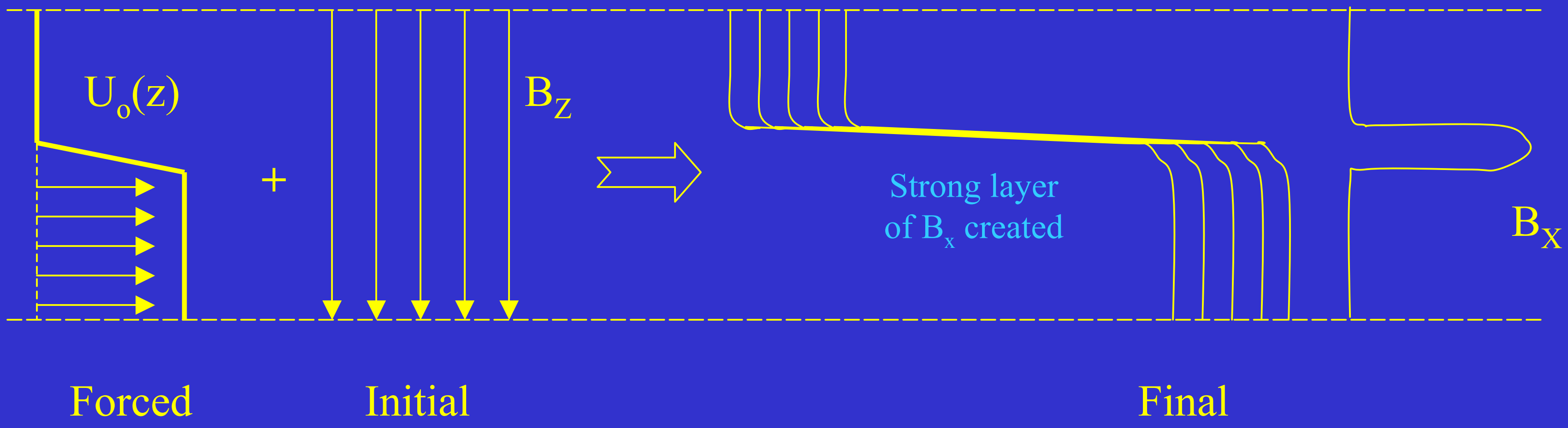
BUT …

A steady net shear and a confined magnetic layer are not necessarily compatible!

1D, steady: Forced shear and B …

Vasil & Brummell (2005)

One might expect …



… but actually answer depends on how diffusive the situation is …

1D, steady: Forced shear and B (2) …

B_x eqn:

$$D\,[B_z U + \eta\, D\, B_x] = 0$$

$$\Rightarrow \qquad U = -\,(\eta / B_z)\, DB_x$$

U eqn:

$$D[\,(B_z/\mu_0\rho_0)\, B_x + \nu\, DU - \nu\, DU_0\,] = 0$$

$$\Rightarrow \qquad \lambda^2 B_x - D^2 B_x = (\mu_0\rho_0\sigma_m)^{1/2}\, \lambda\, DU_0$$

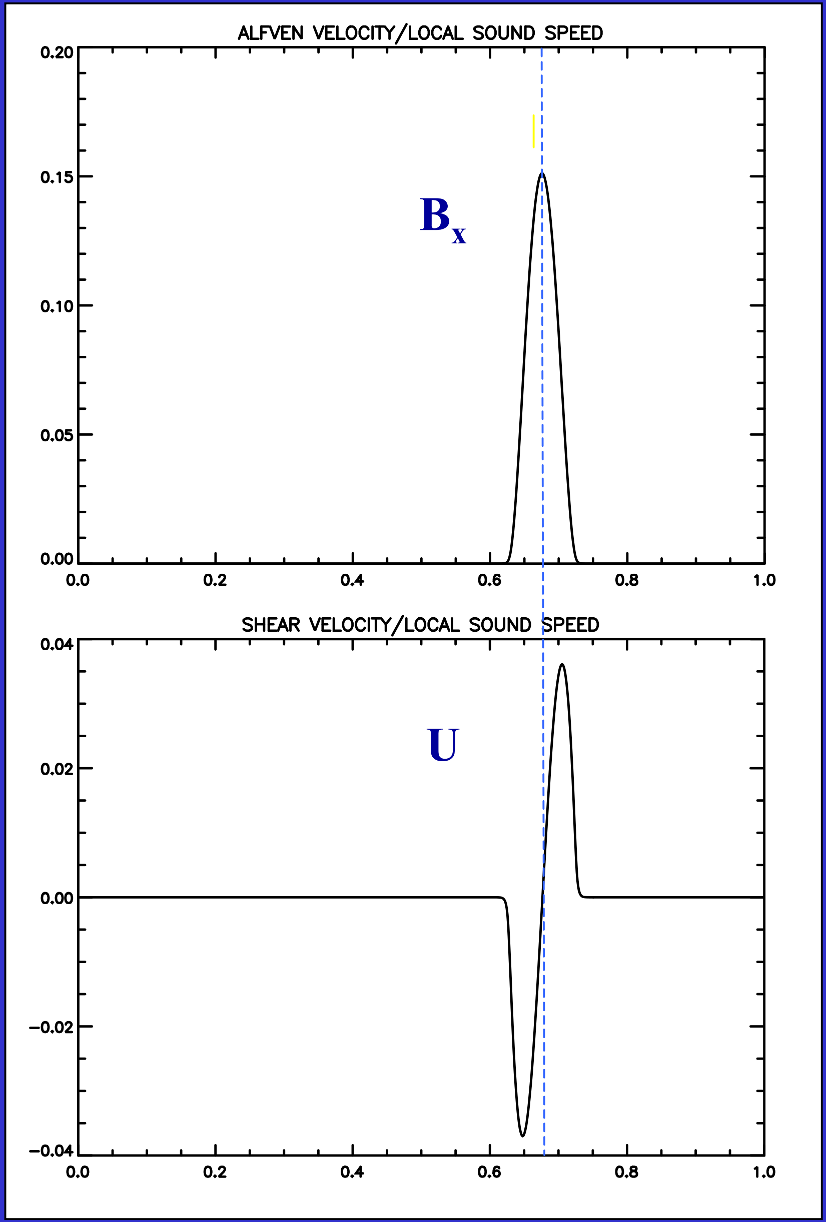
where $\lambda = B_z/(\mu_0\rho_0\nu\eta)^{1/2}$

$\sigma_m = \nu/\eta$

Thermal eqns:

$$-c_p\kappa D^2T = (\eta/\mu_0\rho_0)\,(DB_x)^2 + \nu\,(DU)^2$$

$$D[P + B_x^{\,2}/(2\mu_0)] = g\rho$$



1D, steady: shear and B …

(In this diffusive case, not necessarily applicable to the Sun …)

Strong localised layer of magnetic field is compatible with no net velocity shear, even though a forcing function that produces a large net shear in the absence of magnetic fields was applied.

Strong magnetic field can be produced where there is no "apparent" shear!

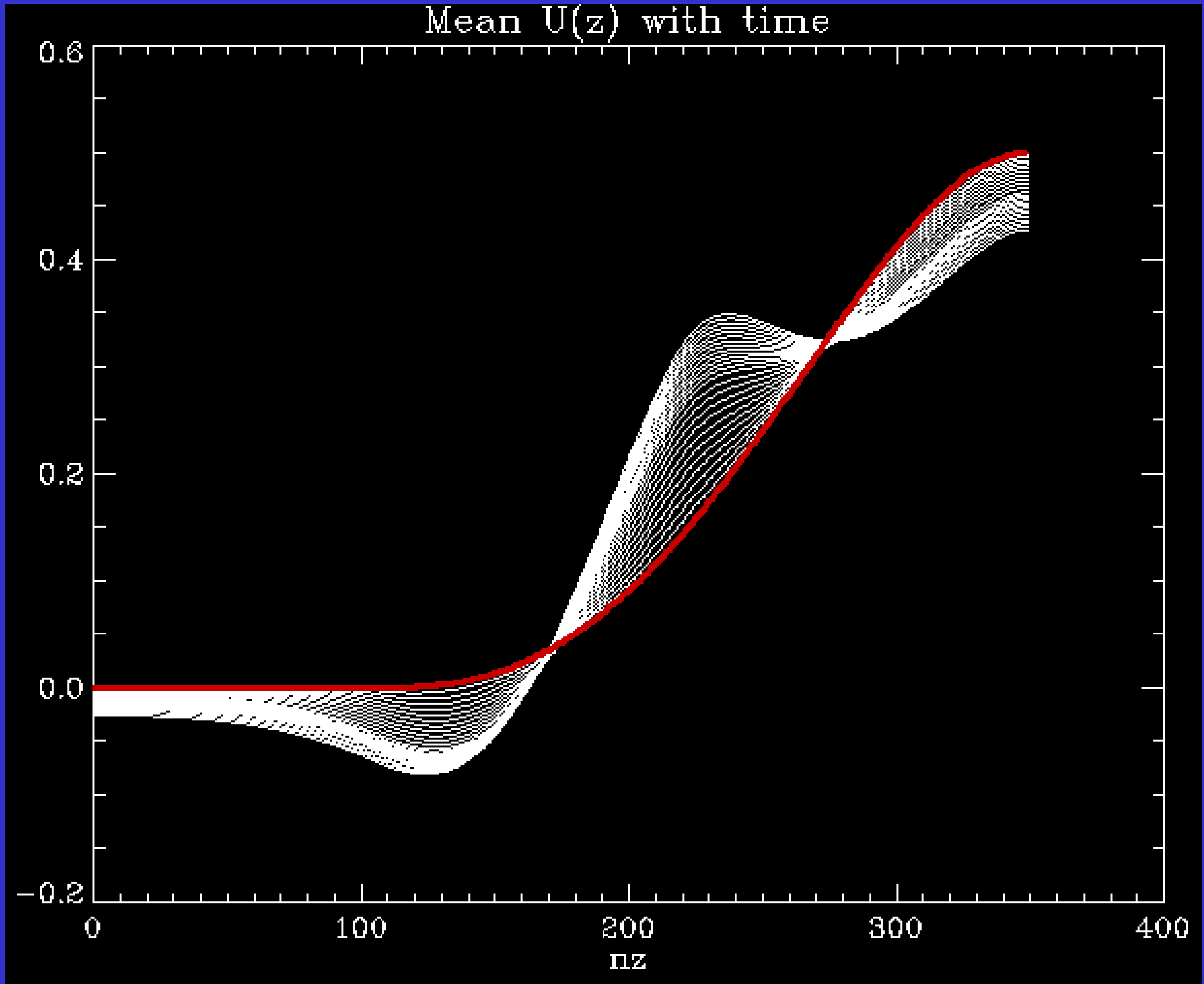
For an "apparent" net shear, magnetic field is non-localised (more distributed).

Solar conclusion: most field could be produced at mid-latitudes in the tachocline.

What is this?

Some sort of (polytrope) readjustment?

Run with no convection to test:



Uh-oh!

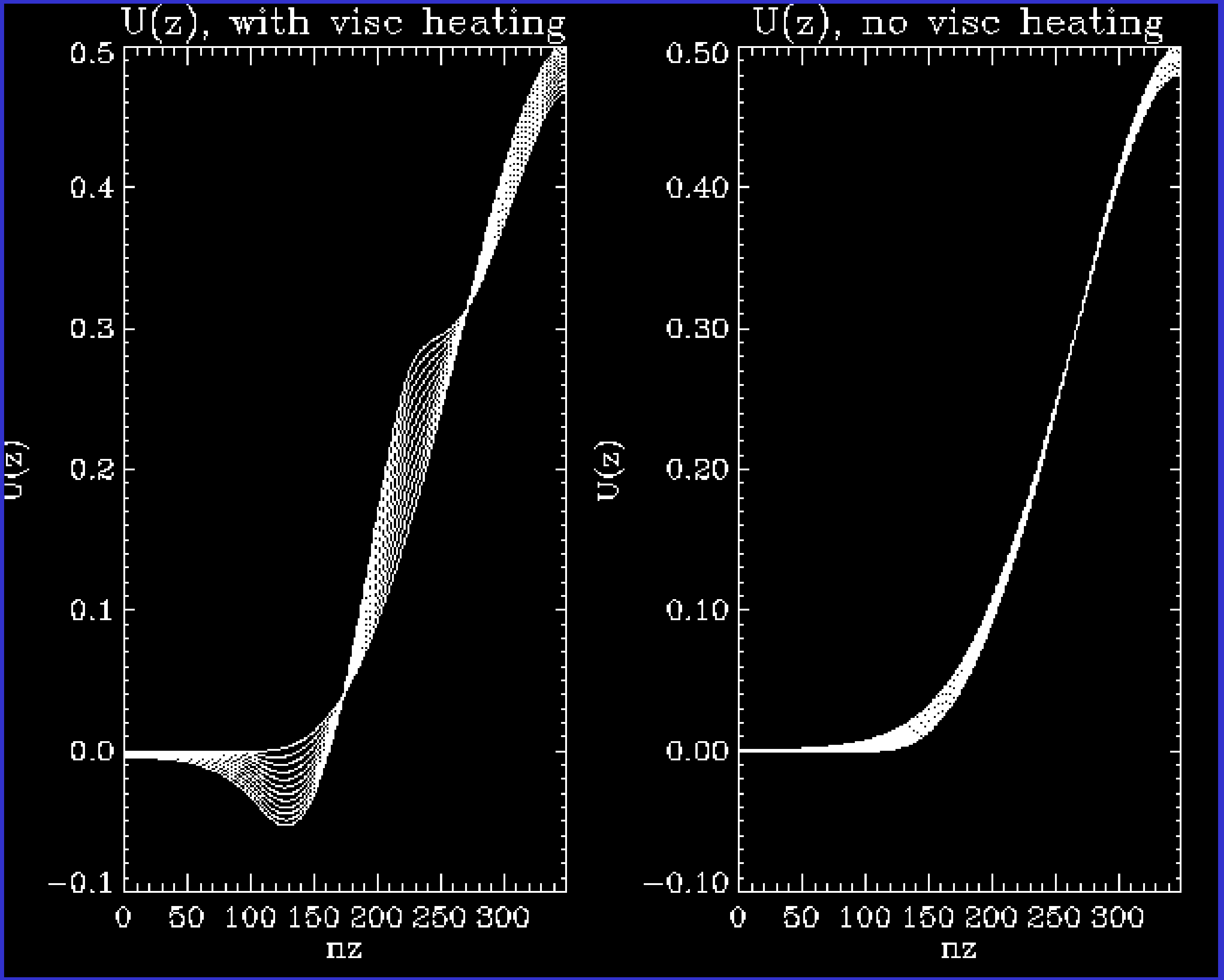
Not what we saw!

ASIDE:

What is this?

Instability?

ASIDE: Viscous heating instability!

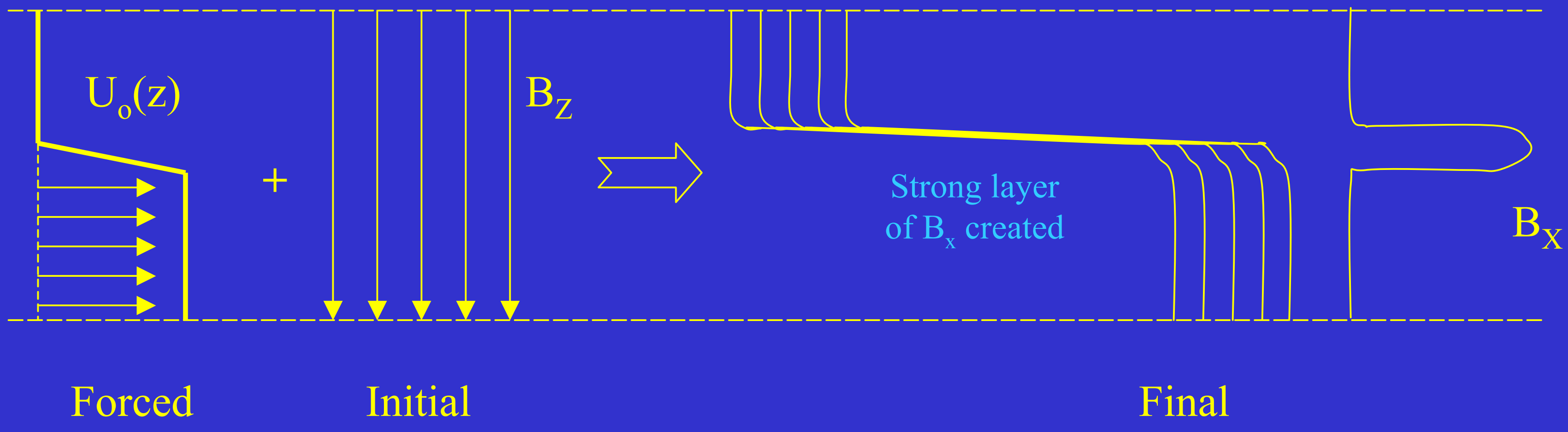


Instability **Diffusion**

1D, steady: Forced shear and B …

Vasil & Brummell (2005)

One might expect:



Final solutions actually end up as:

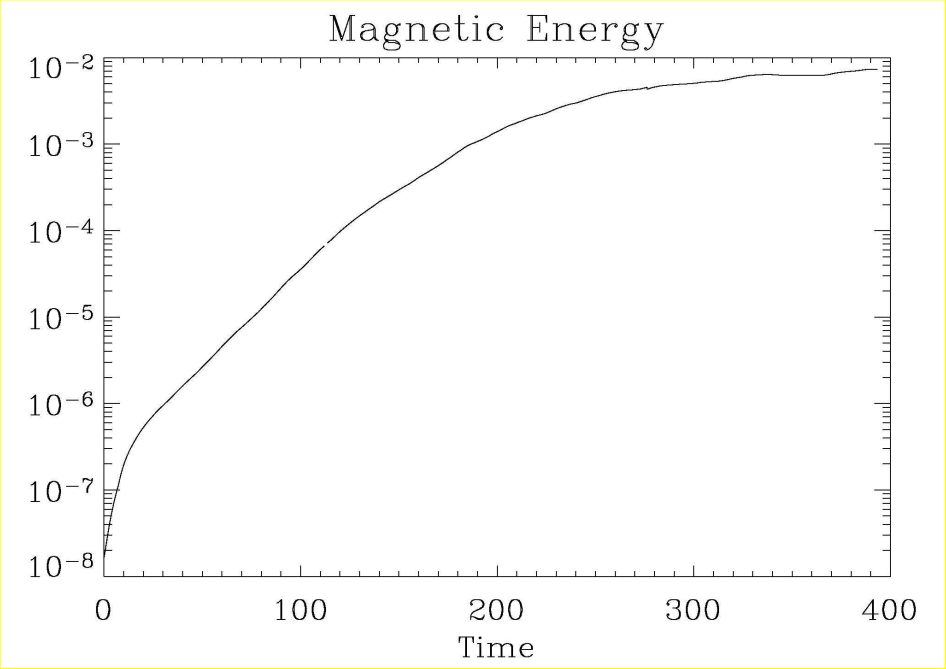
Compressible small-scale dynamo

Small-scale dynamo action driven by convection in compressible convection?

Different from Boussinesq – density effects (magnetic buoyancy), asymmetry effects (pumping)

(High Pm, of course!)

Who wins the competition of pumping and dynamo action in the penetrative case?



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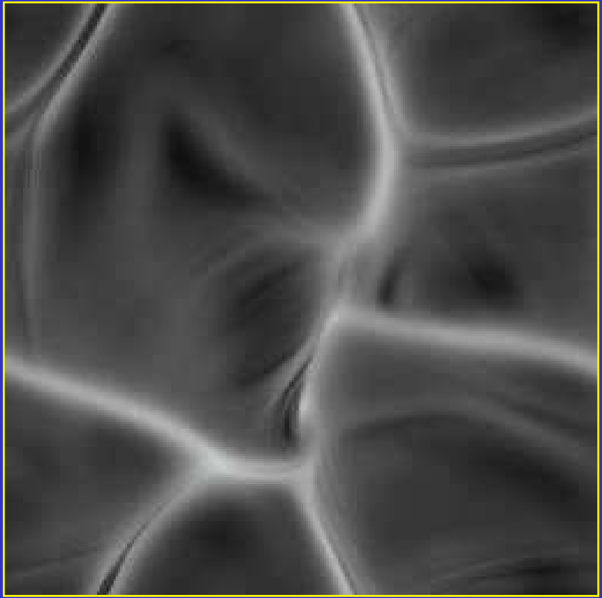
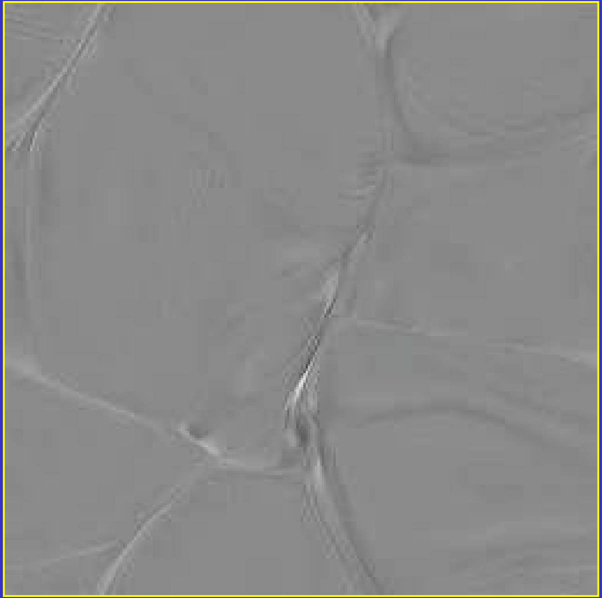


B_z



512x512x256

Compressible small-scale dynamo

512x512x256

The full majesty of large numerical simulations!