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Turbulence in Planet Formation:
Does it help or hurt?

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Turbulence in Planet Formation:
Does it help or hurt?

- Background
- MHD simulations of disk turbulence
- Important things we don’t understand…

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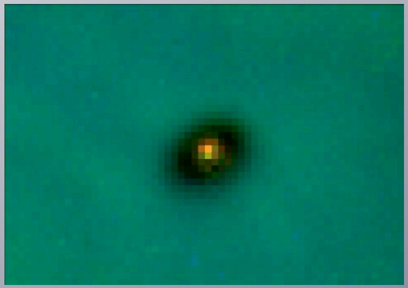
Environment for planet formation

Protoplanetary disks



- scales ~100 AU (~10^{15} cm)
- masses 10^{-3} to 10^{-1} M_*
- density ~10^{-9} g cm^{-3}
- T ~ 1000 - 20 K
- lifetime ~Myr (10^3 to 10^7 t_{dyn})

Gas + dust / condensible solids (~1% by mass)

Hydrostatic equilibrium vertically: $h = \frac{c_s}{\Omega} \sim 0.05$

Rotation balances radial gravity: $\frac{v_\phi^2}{r} = \frac{GM_*}{r^2} + \mathcal{O}\left(\frac{h}{r}\right)^2$

Why does turbulence matter?

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Source of angular momentum transport

$$l = r^2 \Omega \propto \sqrt{r}$$

To accrete gas, need angular momentum redistribution or loss

Molecular viscosity $\nu_m \sim 2.5 \times 10^7 \ \mathrm{cm}^2 \ \mathrm{s}^{-1}$

Evolution time: $t_\nu \simeq \dfrac{r^2}{\nu_m} \sim 3 \times 10^{13} \ \mathrm{yr}$

Require a large "effective viscosity" from turbulence to explain observed evolution

Why does turbulence matter?

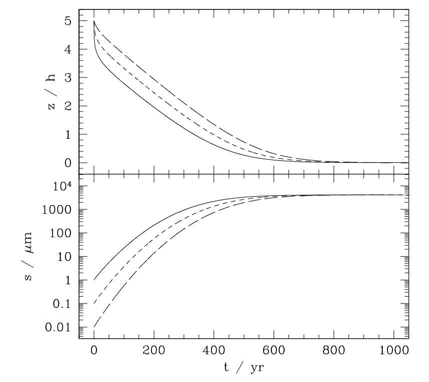
Settling / coagulation / growth of small particles

Laminar disk: particles will settle to midplane rapidly

$$|F_{\rm drag}| = \frac{4\pi}{3}\rho a^2 v_{\rm th} v \qquad |F_{\rm grav}| = m\Omega^2 z$$

$$v_{\rm settle} = \frac{\rho_m}{\rho}\frac{a}{v_{\rm th}}\Omega^2 z$$

Time scale ~10^5 yr for a ~ micron at 1 AU



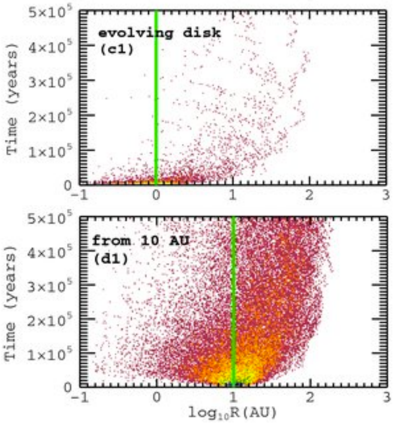
Overestimate: small particles stick on collision, grow and sediment to midplane on ~10^3 yr time scale

Why does turbulence matter?

Settling / coagulation / growth of small particles

Gas is intrinsically turbulent: turbulence inhibits settling depending on D(a), mixes particles radially

Stardust: Brownlee et al. 06

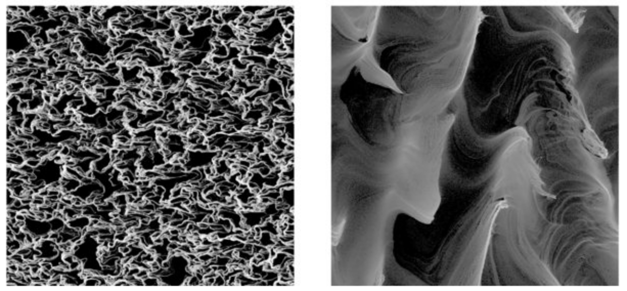


Hughes & Armitage (2010)

Why does turbulence matter?

Settling / coagulation / growth of small particles

Gas is weakly turbulent, particles settle until their density ~ gas density: 2 fluid instabilities set in



Bai & Stone (2010): likely that *concentration* in turbulence is important for forming ~km scale planetesimals from cm scale pebbles that are largest sizes to coagulate easily

Main questions:

- what are sources of intrinsic turbulence?
- how efficient at transporting angular momentum?

$$\alpha \equiv \left\langle \frac{\delta v_r \delta v_\phi}{c_s^2} - \frac{B_r B_\phi}{4\pi \rho c_s^2} \right\rangle$$

- how diffusive?
- do we generate large-scale structure?
- are conditions for 2-fluid instabilities met?
- what is their non-linear outcome?

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Kris Beckwith, Armitage & Simon (2011)
Jake Simon, Armitage & Beckwith (in prep)

MHD Turbulence in Disks

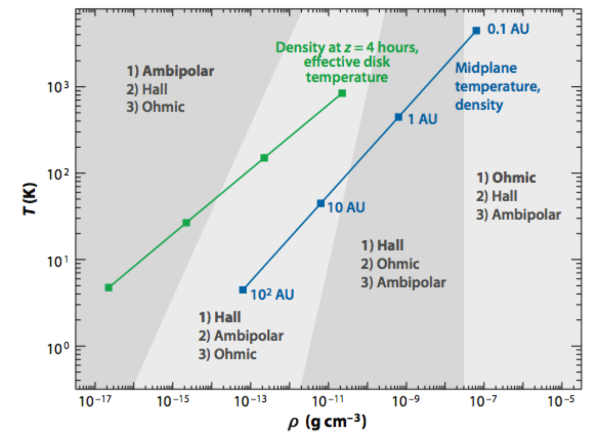
- driven by magnetorotational instability (MRI): local, linear instability of weak fields that taps free energy of shear if:

$$\frac{\mathrm{d}\Omega^2}{\mathrm{d}r} < 0$$

- very fast growth rate ~dynamical
- most unstable scales ~fraction of h
- likely dominant driver of turbulence unless disk is very massive - self-gravitating

MHD Turbulence in Disks

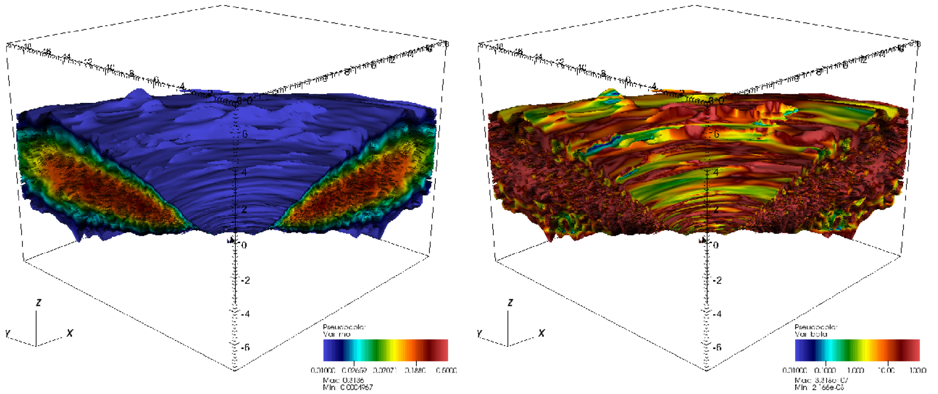
Non-ideal MHD is important except at small scales



...only ideal MHD case is ~moderately well-understood

Global simulations

Beckwith, Armitage & Simon (2011)

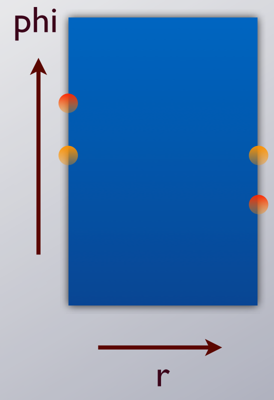


Density

Plasma beta

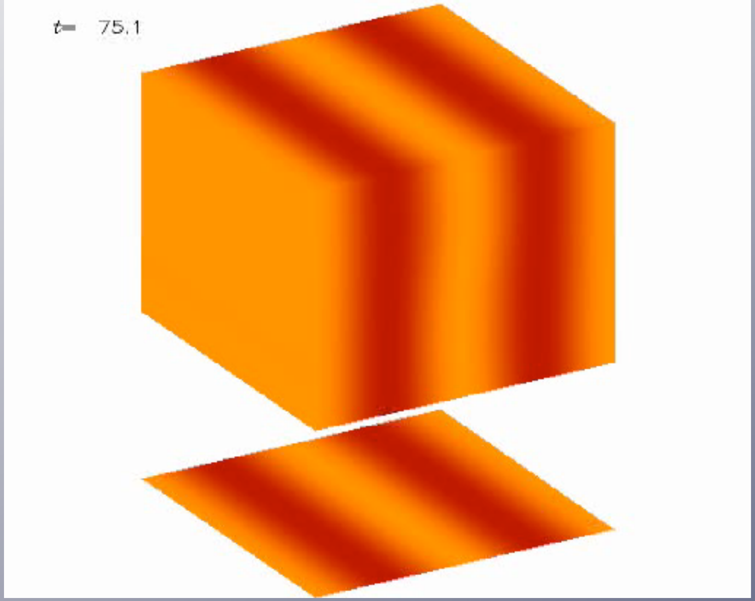
Resolution is a challenge: obtained 32 / h only in a core regions of the disk close to the midplane

Local simulations



Local cartesian volume: up to 16h x 32h x 8h
Linear shear + Coriolis force
Azimuthally periodic, radially “shearing” periodic, vertically open boundaries
Vertical stratification under gravity

Local simulations

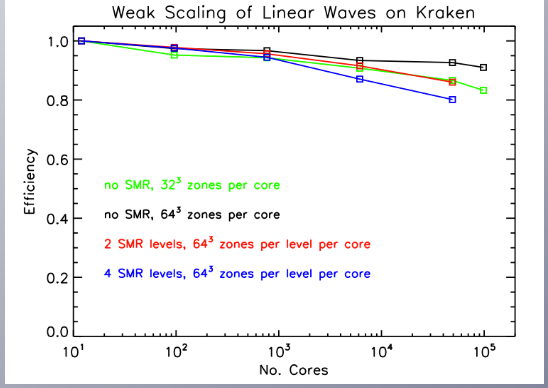


Local simulations

Athena code for compressible MHD (Stone et al. 1998)

Godunov-type finite volume scheme, using constrained transport for B

Parallelized with MPI



Convergence

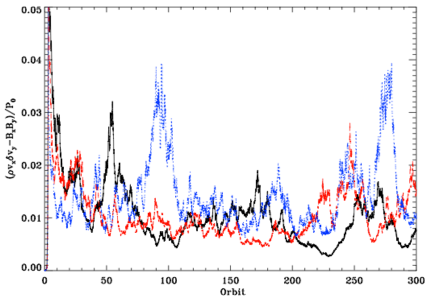
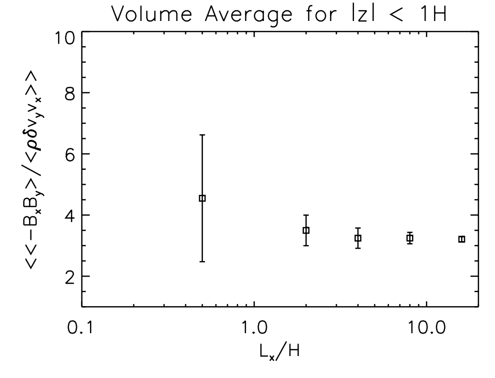


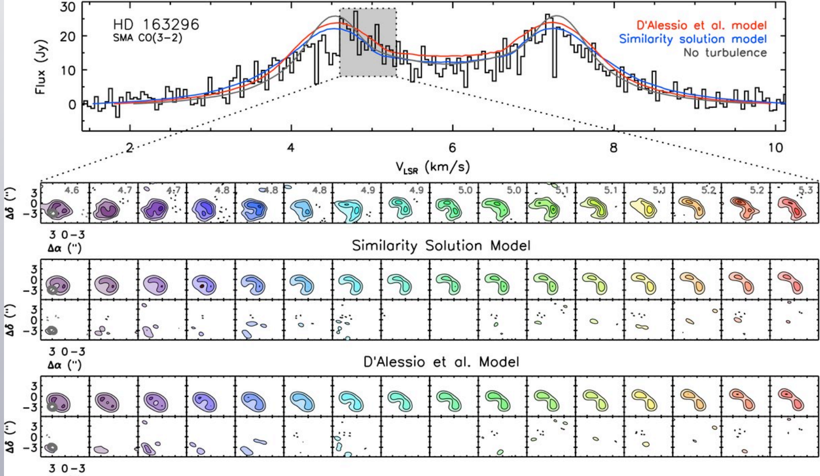
Figure 2. Sum of integrated Reynolds and Maxwell stresses as a function of time in stratified shearing boxes with $H \times 4H \times 4H$. The curves represent stresses obtained in simulations with resolutions of $128/H$ (black, solid), $64/H$ (red, dashed), and $32/H$ (blue, dotted).

Resolution (fixed domain):
Davis, Stone & Pessah (2010)



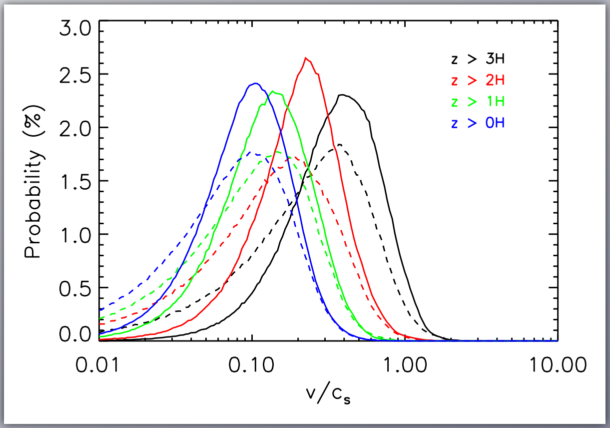
Domain (fixed resolution):
Simon et al. (2011)

Comparison with observations



Moderately significant detection of turbulent velocities in upper layers of protoplanetary disks by *Hughes et al. (2011)*: implies v ~ 0.4 c_s

Comparison with observations



Roughly consistent with ideal MHD prediction...
Expect much improved observations with *ALMA*

Things we don’t understand...

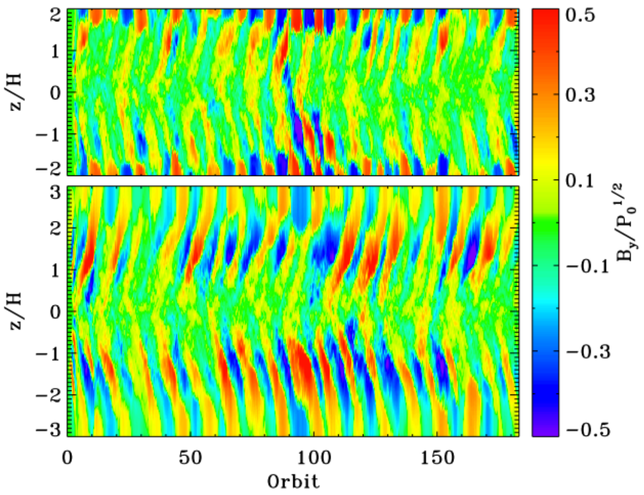
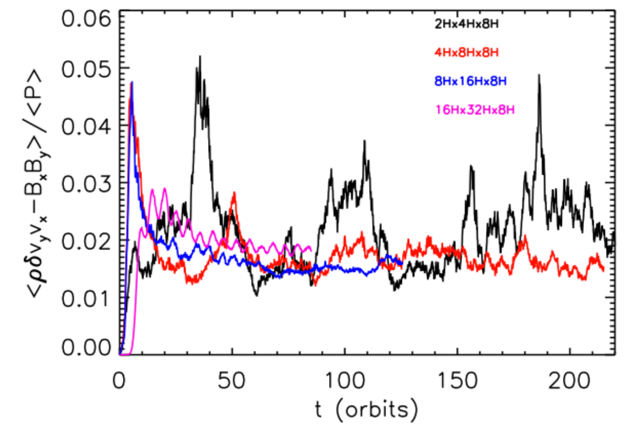


Figure 8. Spacetime plot comparing the horizontal average of the toroidal component of the magnetic field as a function of time in stratified shearing boxes with $32/H$ resolution. The top and bottom panels show simulations with four and six scale height vertical extent (respectively).

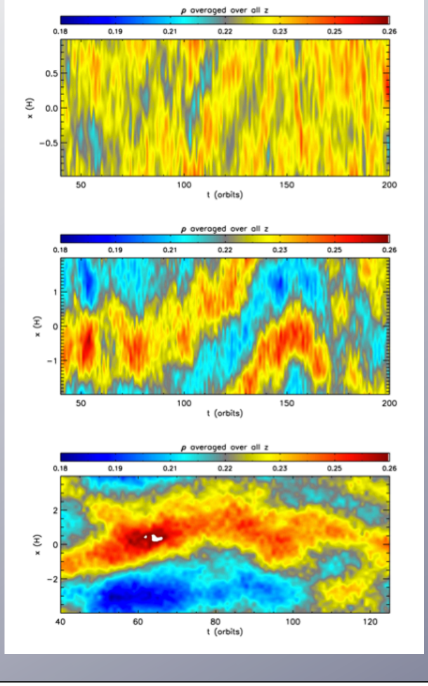
Davis, Stone & Pessah (2010)

Things we don't understand...



Temporal variability does not converge well with increasing domain size, even though stress and net toroidal field do appear to converge...

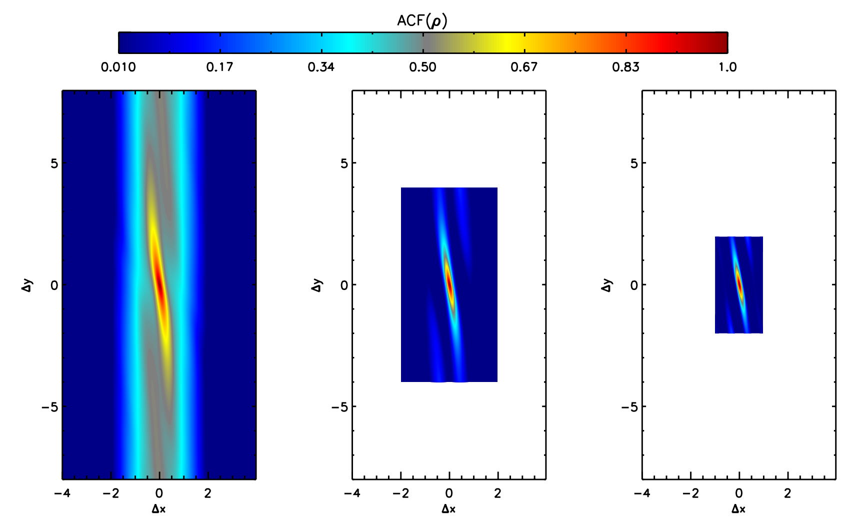
Things we don't understand...



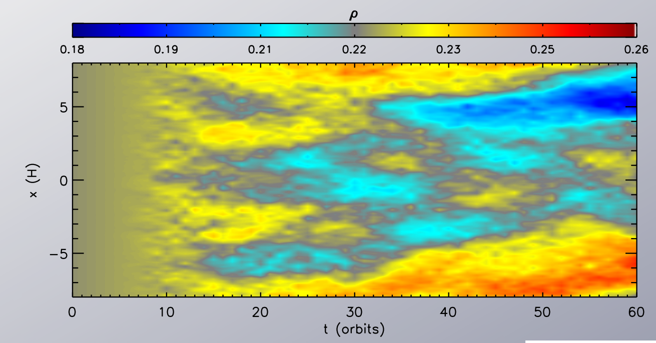
Spontaneous formation of near axisymmetric large-scale perturbations in azimuthal velocity and density

"Zonal flows": *Johansen et al. (2009)*

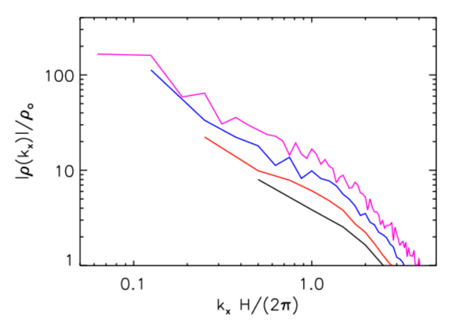
Things we don't understand...



Things we don't understand...



Hints in largest simulation (16h x 32h x 8h; 512 x 1024 x 256) that we are seeing physical scale



Do zonal flows avert radial drift problem?

Gas in disks orbits slightly sub-Keplerian (at O(h/r)^2) - net headwind felt by particles

$$v_r = \frac{\tau_{\rm fric}^{-1} v_{r,{\rm gas}} - \eta v_K}{\tau_{\rm fric} + \tau_{\rm fric}^{-1}}$$

Problem because predicted time scale is far too fast

Do zonal flows avert radial drift problem?

Gas in disks orbits slightly sub-Keplerian (at $O(h/r)^2$) - net headwind felt by particles

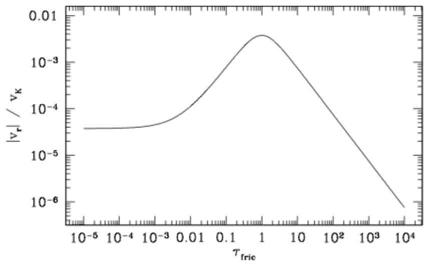


Fig. 4.2. The radial drift velocity of particles at the midplane of the protoplanetary disk is plotted as a function of the dimensionless stopping time $\tau_{\rm fric} = t_{\rm fric}\Omega_K$. The model plotted assumes that $\eta = 7.5 \times 10^{-3}$ and that $v_{r,\rm gas}/v_K = -3.75 \times 10^{-5}$. These values are approximately appropriate for a disk with $h/r = 0.05$ and $\alpha = 10^{-2}$ at 5 AU.

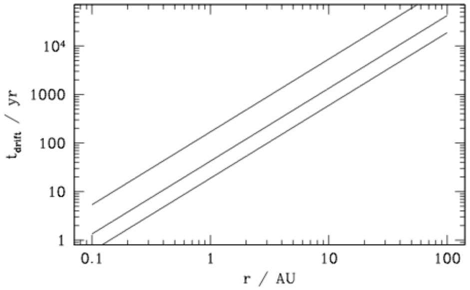
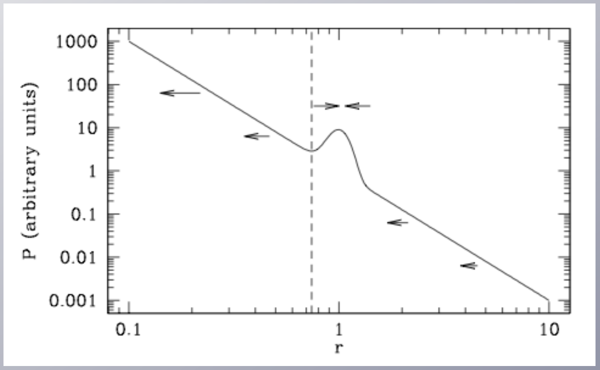


Fig. 4.3. The *minimum* time scale for the radial drift of solid particles as a function of radius, for disk models in which $\Sigma \propto r^{-1}$ and $h/r = 0.025$ (uppermost line), $h/r = 0.05$ or $h/r = 0.075$ (bottom line).

One explanation: never have particles in the disk that are critically coupled aerodynamically, "jump over" size scale (~1 m) where radial drift is catastrophic

Do zonal flows avert radial drift problem?



Alternative: turbulence develops local axisymmetric pressure maxima that trap inflowing particles aerodynamically

Summary

Turbulence likely central to understanding *early* phases of planet formation (from micron - km scales), and secular evolution of protoplanetary disks

MHD turbulence with non-ideal effects thought to be most relevant regime

Some interesting problems:

- particle-fluid coupling (2 fluid instabilities leading to turbulence)
- development of large scale density, velocity, B field structure