Statistics of isothermal compressible turbulence

: Single forcing versus Double forcing

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2010.12.17

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Outline

- Interstellar Medium & Turbulence
- Driving mechanism
- Purpose of this study
- Time evolution of energy density
- Energy spectrum
- Probability distribution function
- Summary
- Future work

Interstellar Medium and Turbulence

* Stars form in Cool / dense molecular clouds in ISM
* Turbulence, Gravity, Thermal process, Magnetic field
  ⇒ Influence on structure / dynamics of ISM
  ⇒ determine the modes of driving scale

* Turbulent magnetized ISM plays an important role in star formation and galaxy formation.

The Large Magellanic cloud ©E. Slawik

M83 ©NASA

Driving mechanisms

* Lack of energy injection (insufficient driving of flow)
  ⇒ turbulence will quickly dissipate
  ⇒ becomes laminar

* Driving mechanism can support turbulent motion
  ⇒ balance between turbulence and local density
  ⇒ determine star formation rate

Driving mechanisms

* Magnetorotational Instabilities

* Gravitational Instabilities

* Protostellar outflows

* Massive star
  - stellar wind
  - ionizing radiation
  - supernova explosion

Observed results

* Observed results about driving scale in the ISM
 - Han et al.(2004)
   : supernova explosion ~ 100 pc
 - Haverkorn et al.(2008)
   : protostellar outflow ~ few pc

* No settled-down issue about driving scale of ISM in our galaxy

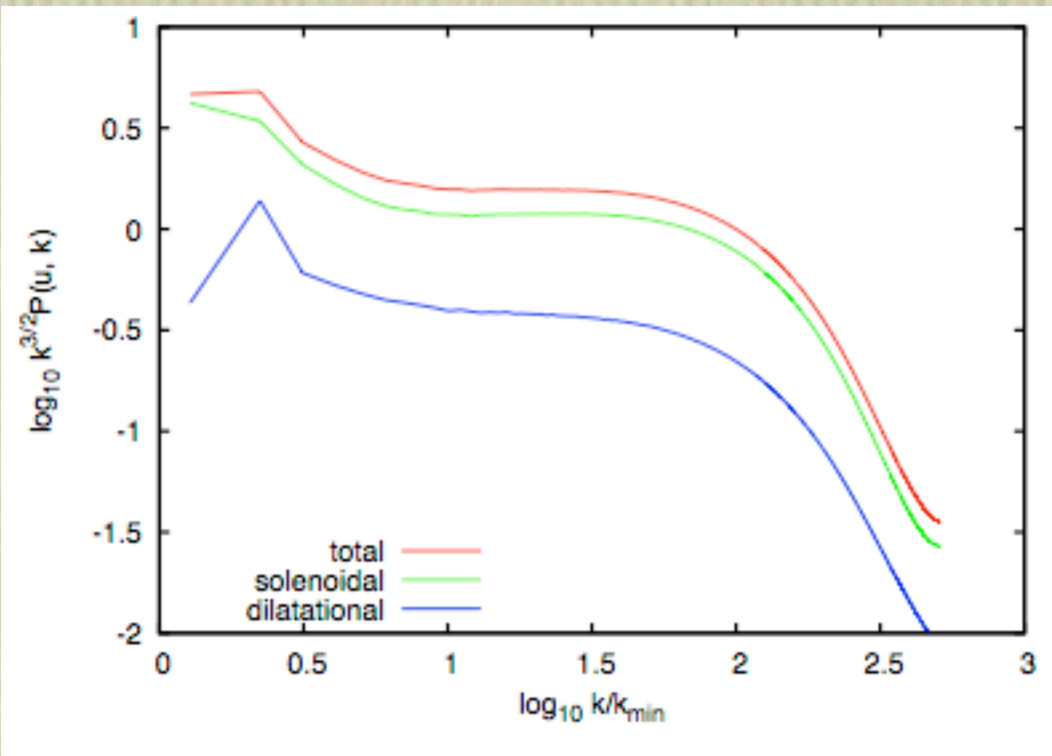
Other Simulations

* Many other turbulence simulations
  : energy injected at single k-number range
  (especially in large scale)
  (M.M.Mac Low et al.(1999), (2002) ..)

* Some simulations
  : comparing between incompressible(solenoidal)
  forcing and compressible(dilatational) forcing
  (A.G.Kritsuk et al.(2009), Federrath et al.(2008),
  M.Petersen et al.(2009) ..)

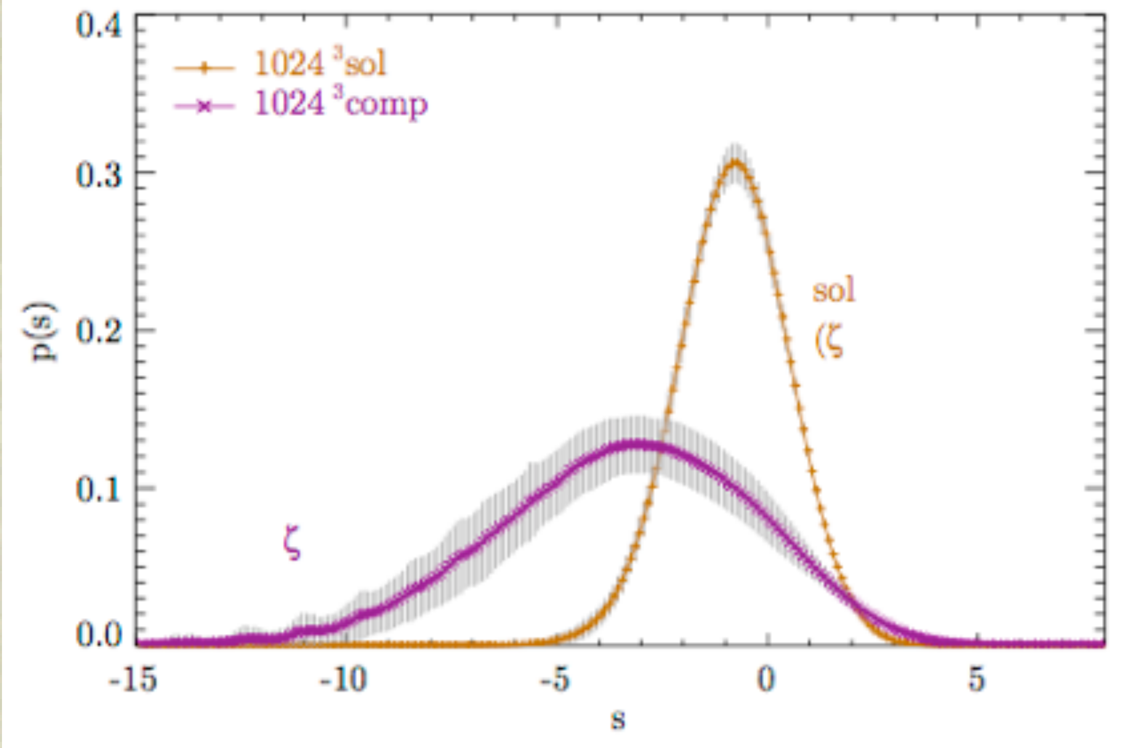
Informations

A. Krisuk et al.(2009)



Velocity power spectrum is dominated by the solenoidal component

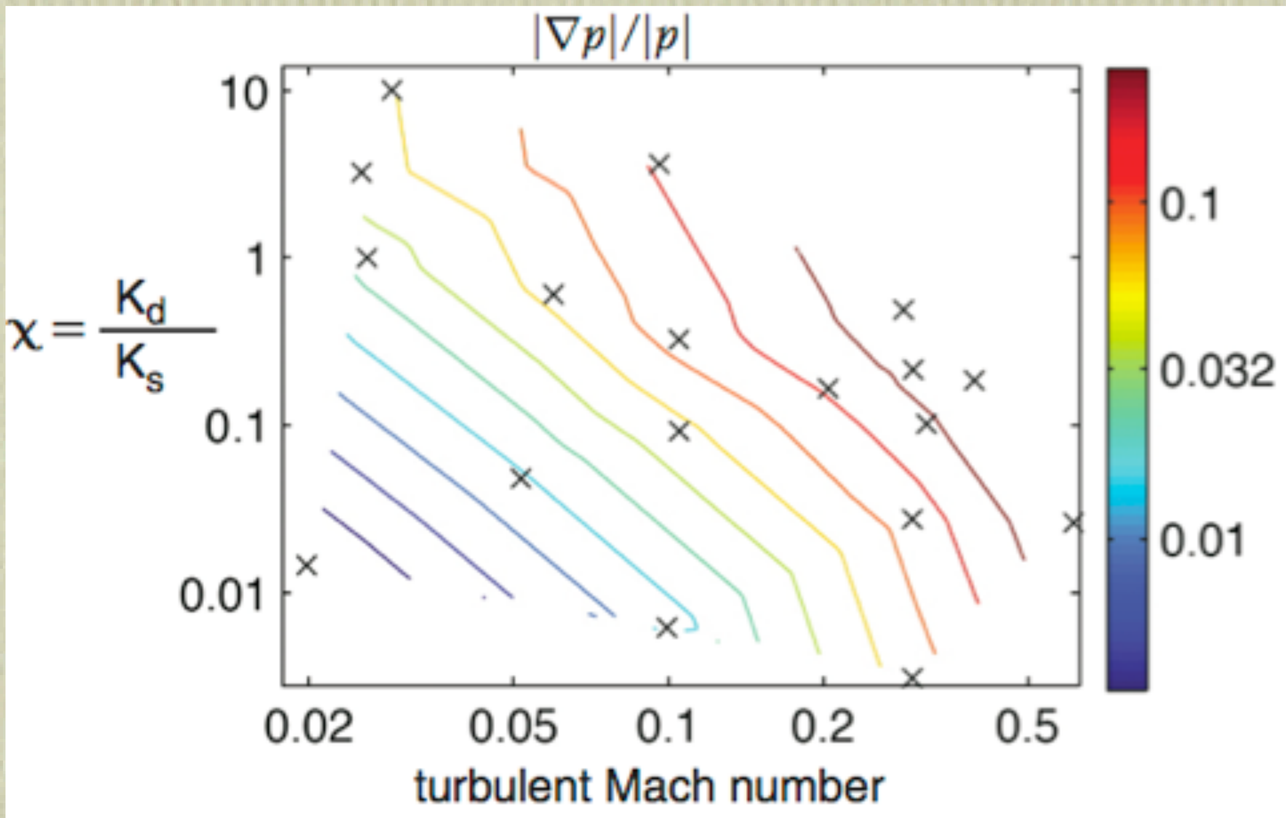
C.Federrath et al.(2008)



The standard deviation of the density PDF
-> compressive forcing is nearly 3 times larger than solenoidal forcing

Informations

M.Petersen et al. (2009)



The χ parameter shows the ratio of dilatational to solenoidal kinetic energy and it exhibit the effects of compressibility.

(e.g. Low χ / low Mach no.
⇒ incompressible)

Purpose of this study

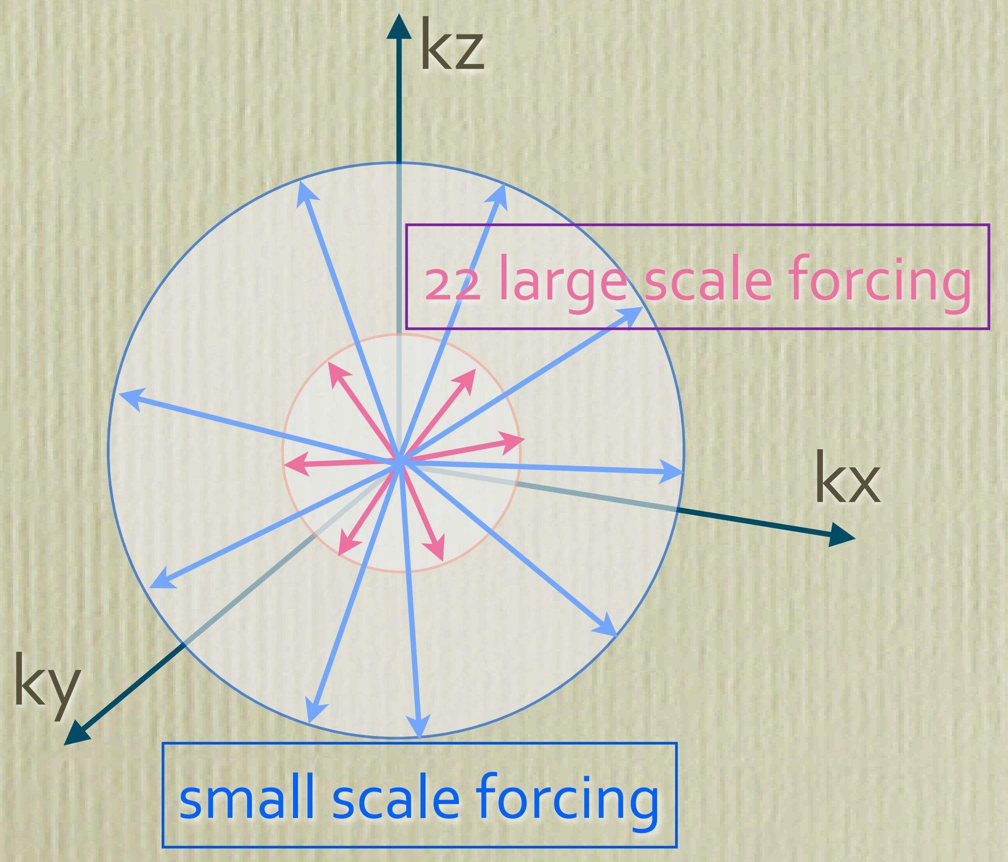
* ISM ⇐ energy input in several driving scales
  (no single)
* The characteristic of turbulence is depends on the driving scale which induced by different energy injection mechanism
* Making models with double forcing modes
  ⇒ Comparing with single forcing modes
  ⇒ Statistics
  ⇒ Suggest the driving scale in our galaxy

Initial conditions in simulation

* MagnetoHydroDynamic/HydroDynamic compressible turbulence
* 3-dimension (128x128x128)
* Periodic box size : 2π
* Isothermal (T is invariant)
* Ideal gas ($\gamma=1$ in EOS)
* Ignore self-gravitation / cooling effect
* Solenoidal forcing($\nabla \cdot v=0$; divergence-free)

Forcing modes

* Numerical turbulence - driven in Fourier space
* Number of small scale forcing modes
- controls the amount of energy injected into turbulence at small scale in double forcing simulation



k-space

*Single forcing
: 22 forcing only in large scale (k~2)

*Double forcing
: 22 forcing in large scale (k~2) + additional forcing in small scale (k~11)

Mach number

* Sound speed $C_s = \sqrt{\gamma \frac{P}{\rho}}$

Isothermal $\Rightarrow$ $\gamma = 1$

assume $\rho = 1$ (at t=0)

$\Bigg\}$ $C_s \propto \sqrt{p}$

* Mach number $M = \frac{<\upsilon>}{C_s}$

assume $<\upsilon>$ ~1

$\Rightarrow$ In this simulation, $\therefore M \propto \frac{1}{\sqrt{P}}$

Simulation conditions

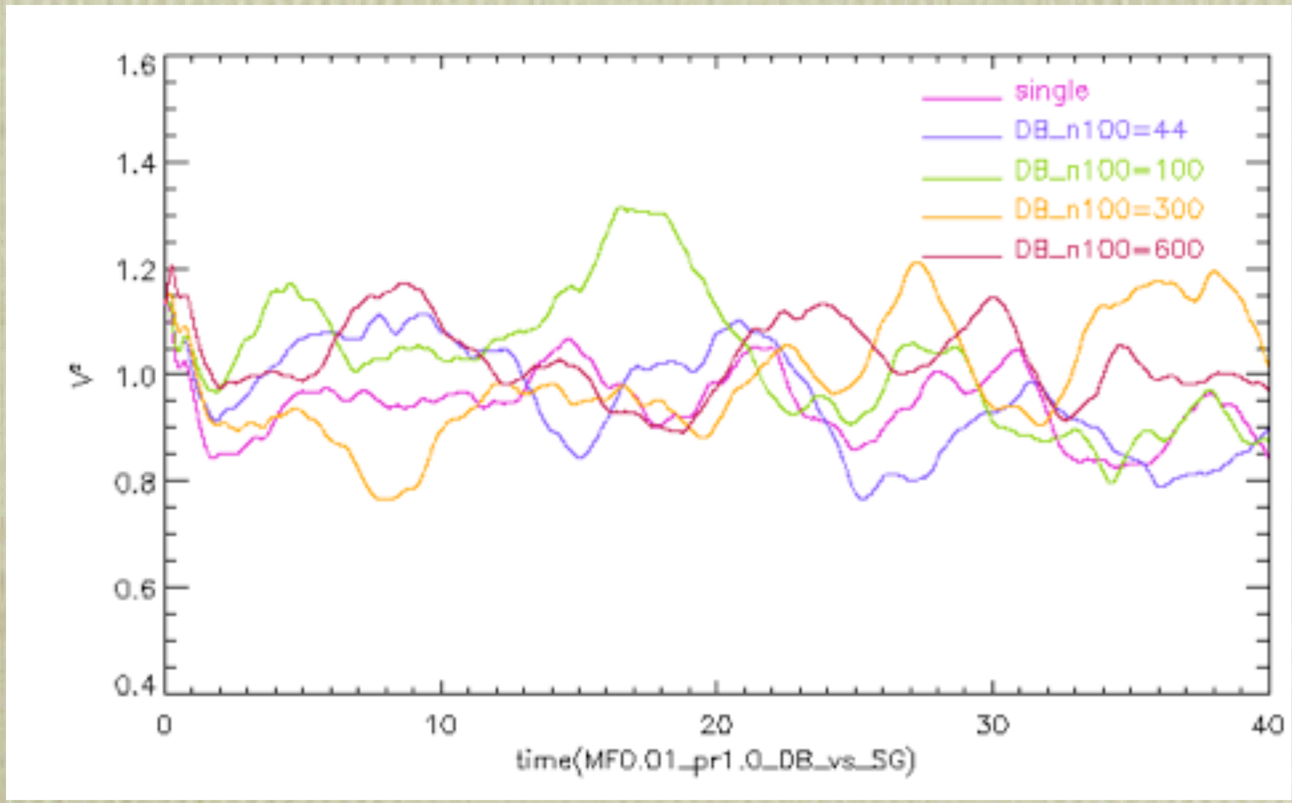
* Models with different pressure (i.e. Mach number)
  - P=0.1 $\Rightarrow$ M~3.16227766 (supersonic)
  - P=1.0 $\Rightarrow$ M~1 (sonic)
  - P=10.0 $\Rightarrow$ M~0.316227766 (subsonic)

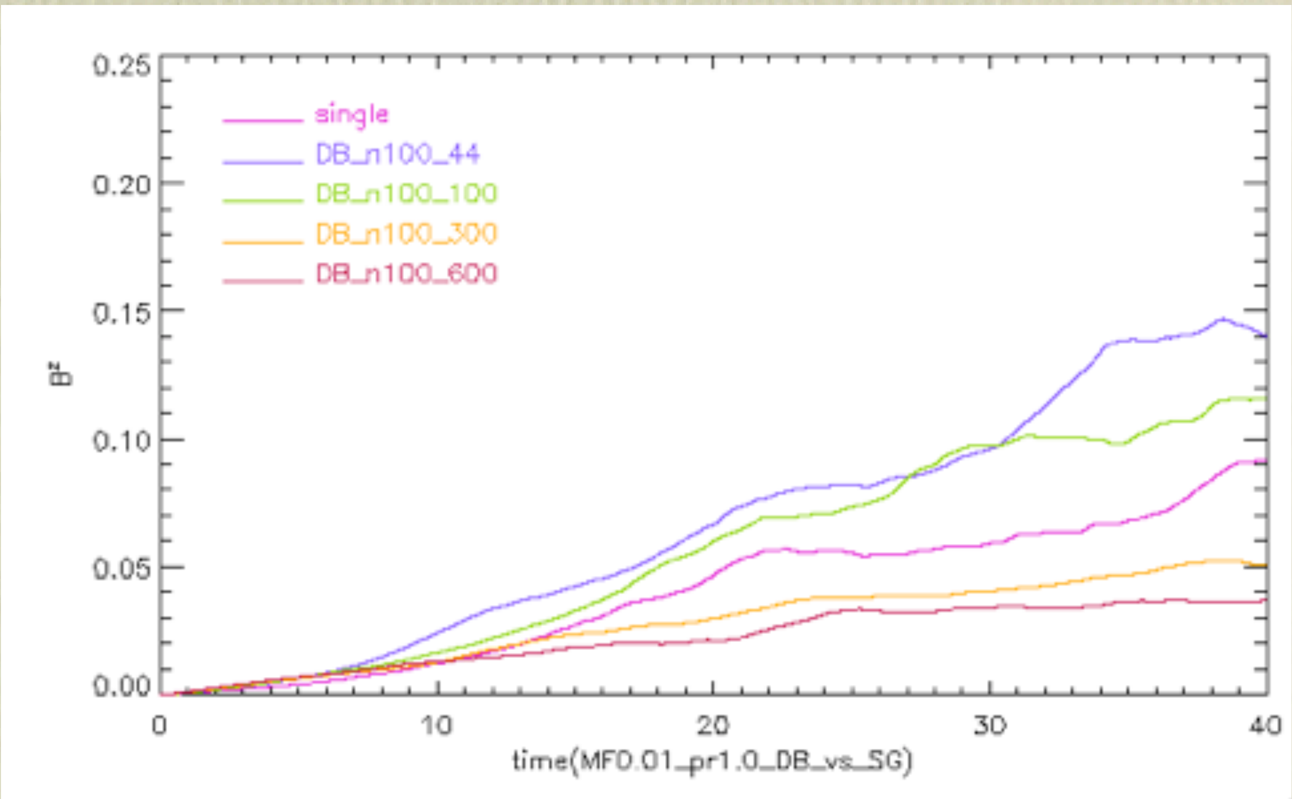
* External mean magnetic field (when t=0)
  : B_{ext}=0(HD), 0.01, 0.1(MHD)

Time evolution of energy density

* Time evolution of kinetic / magnetic energy density

- MHD (B_{ext}=0.01)

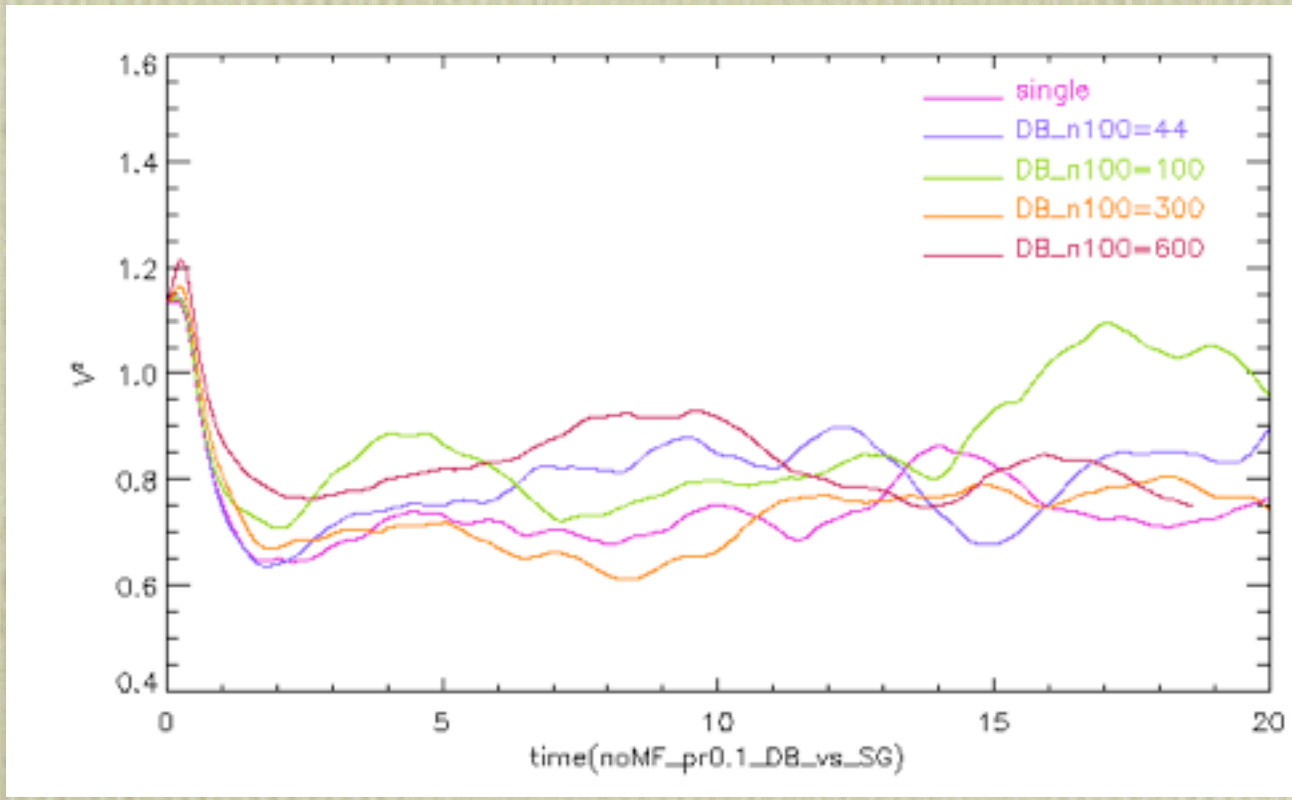




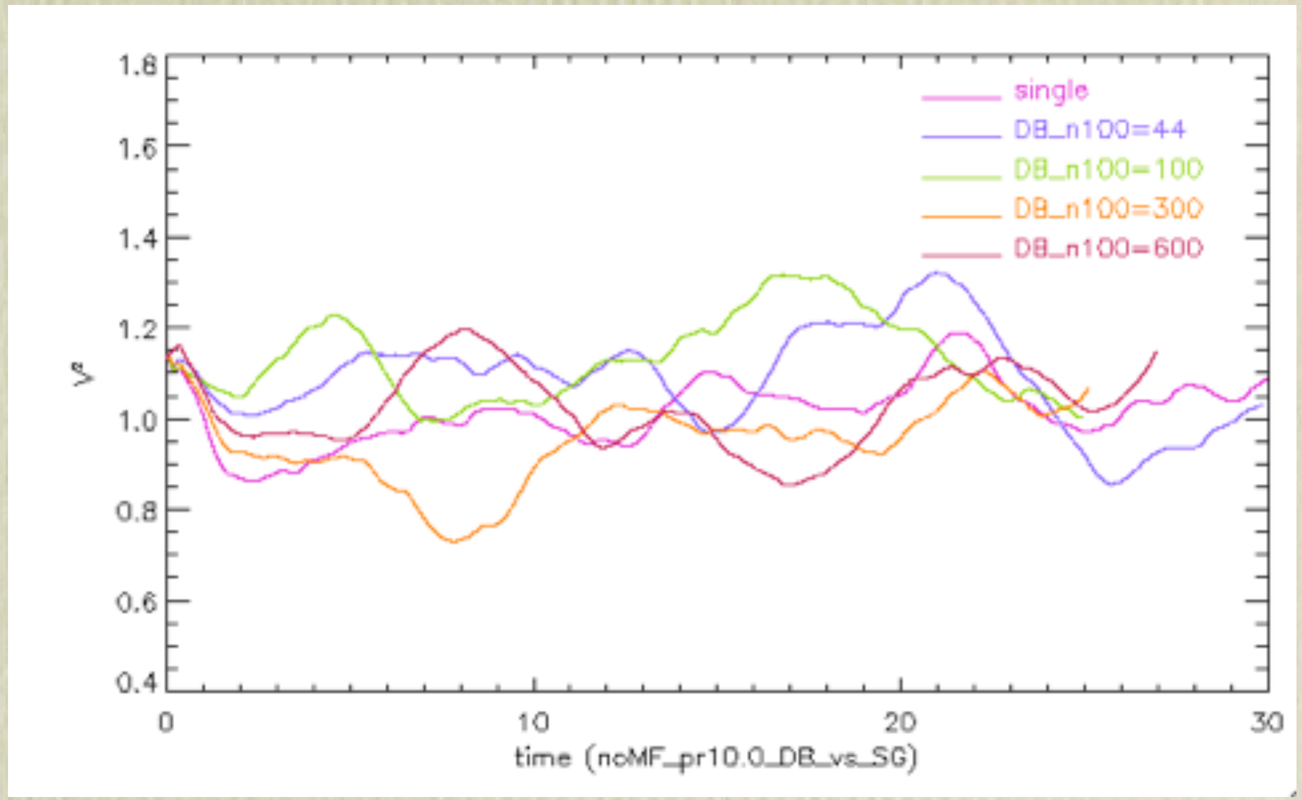
Sonic turbulence (M~0.316)

Time evolution of energy density

* Time evolution of kinetic energy density
- HD (B_{ext}=0)



Supersonic turbulence
M~3.16

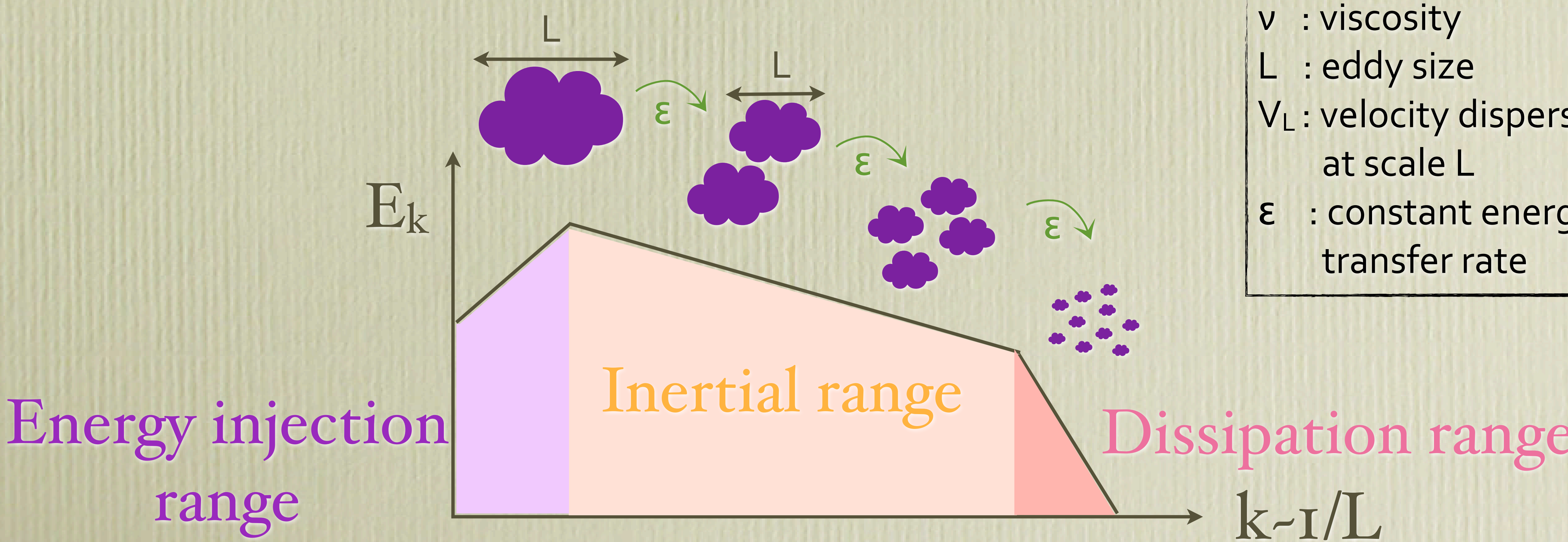


Subsonic turbulence
M~0.316

Turbulent energy cascade

* Turbulent energy cascade
: Energy is transferred along the power spectrum from largest scale to the dissipation scale

* Dissipation rate $\frac{\nu}{L^2}$ = Energy injection rate $\frac{V_L}{L}$

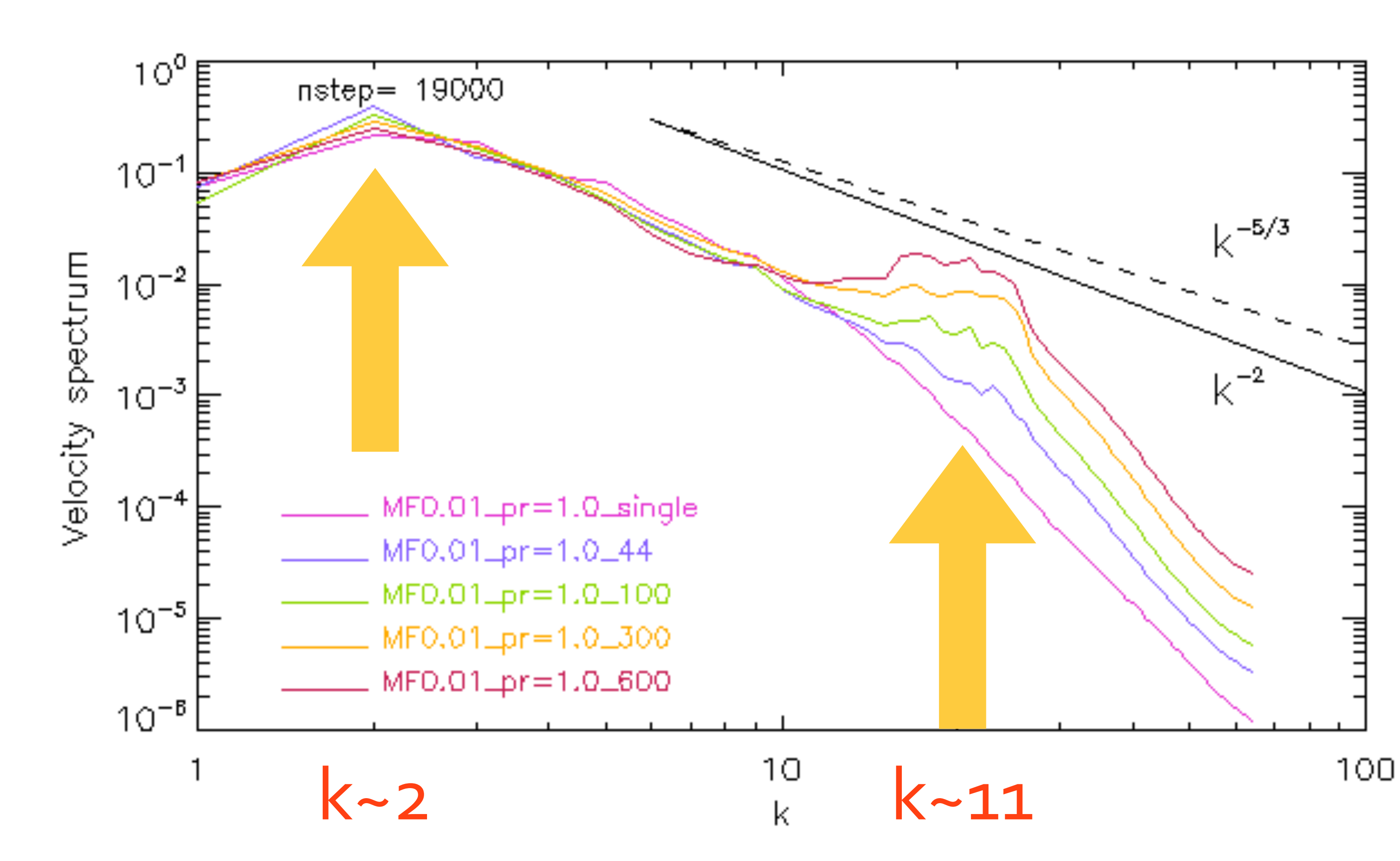


- ν : viscosity
- L : eddy size
- V_L : velocity dispersion at scale L
- ε : constant energy transfer rate

Kinetic spectrum

* Kinetic specrum

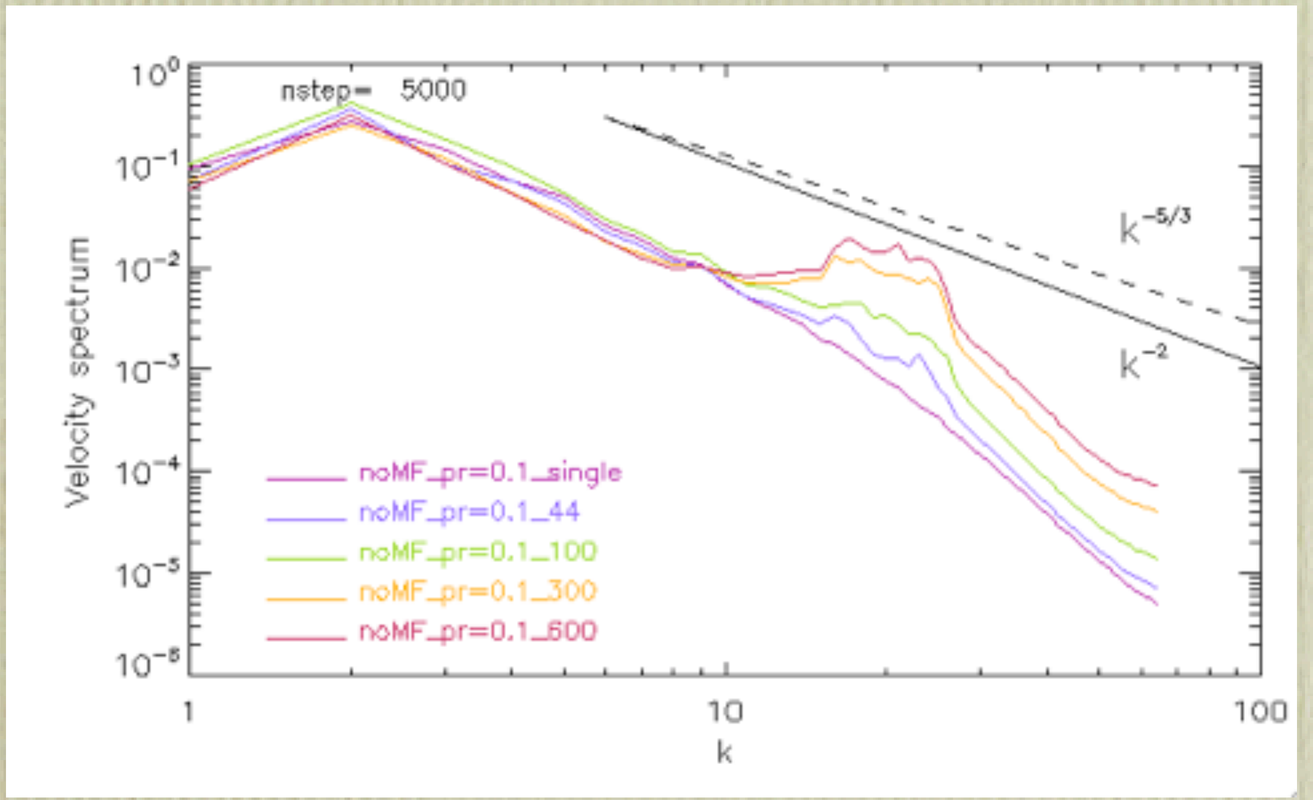
- MHD (B_{ext}=0.01)

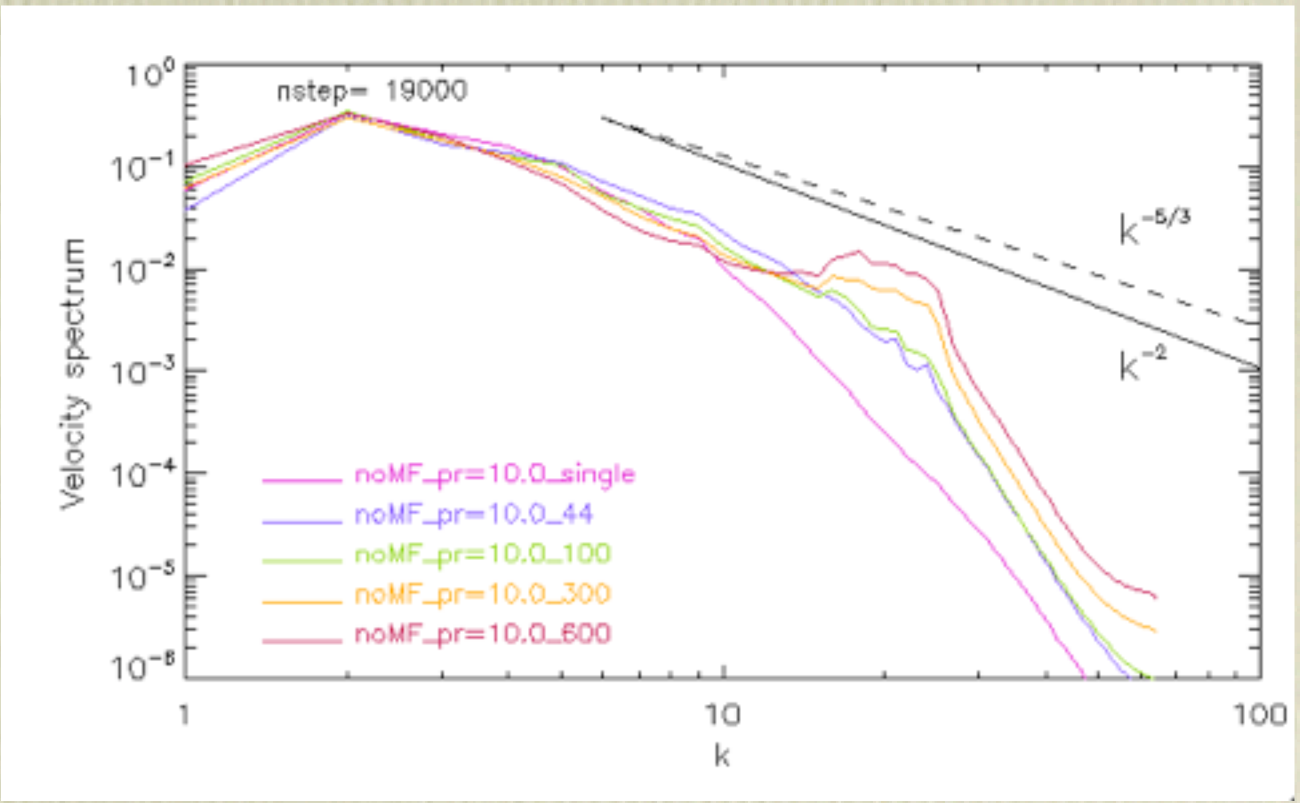


Sonic turbulence (M~1)

Kinetic spectrum

* Kinetic energy specrum
 - HD (B_{ext}=0)



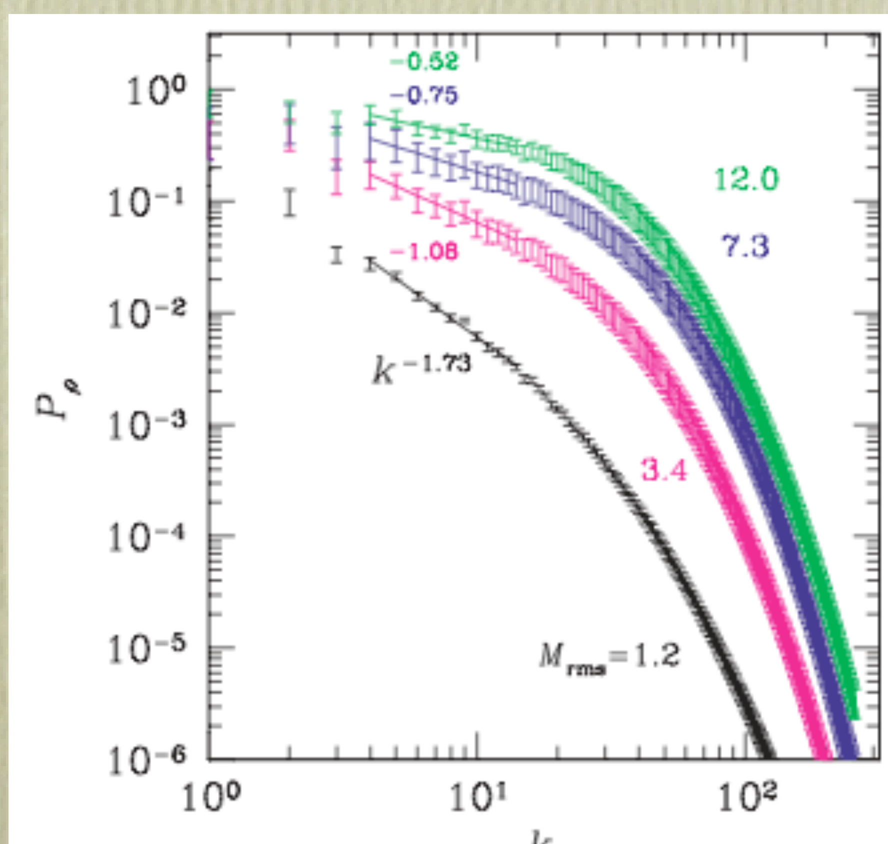


Supersonic turbulence
M~3.16

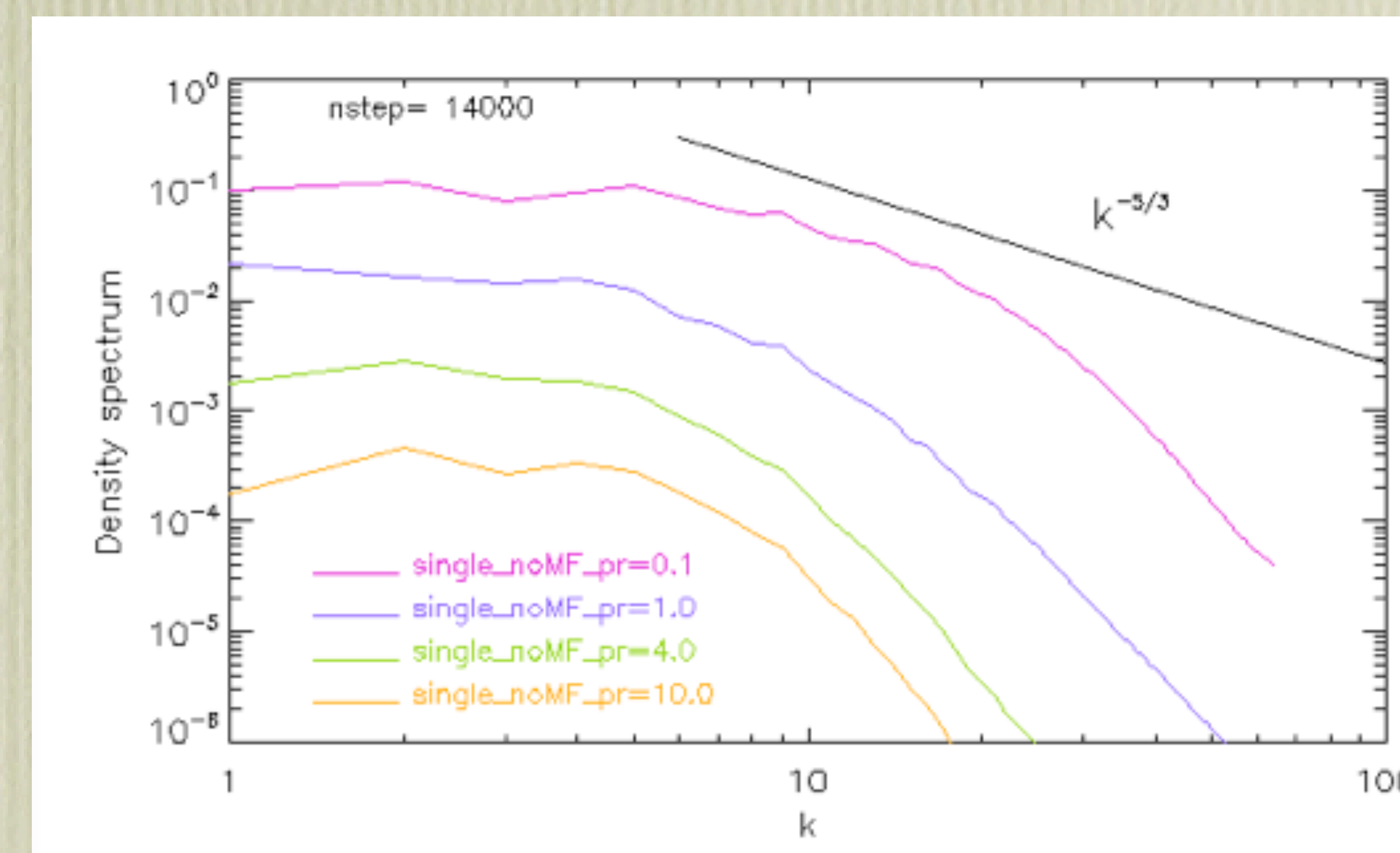
Subsonic turbulence
M~0.316

Density spectrum

* Kim & Ryu (2005)
* Mach number
  : important parameter that characterizes the density power spectrum
* higher Mach number
  -> slope of density spectrum flattens



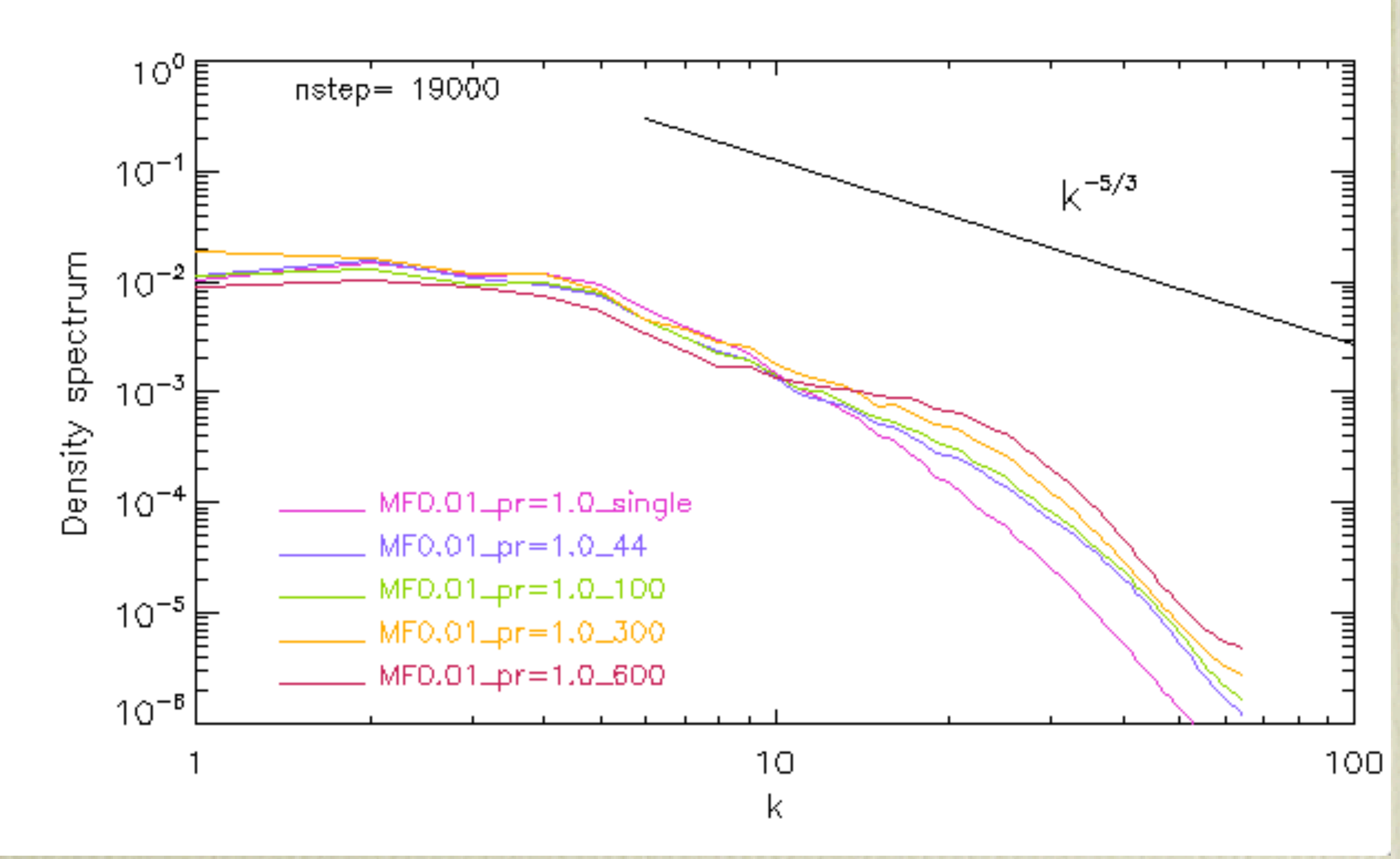
Kim & Ryu (2005)



Density spectrum

* Density specrum

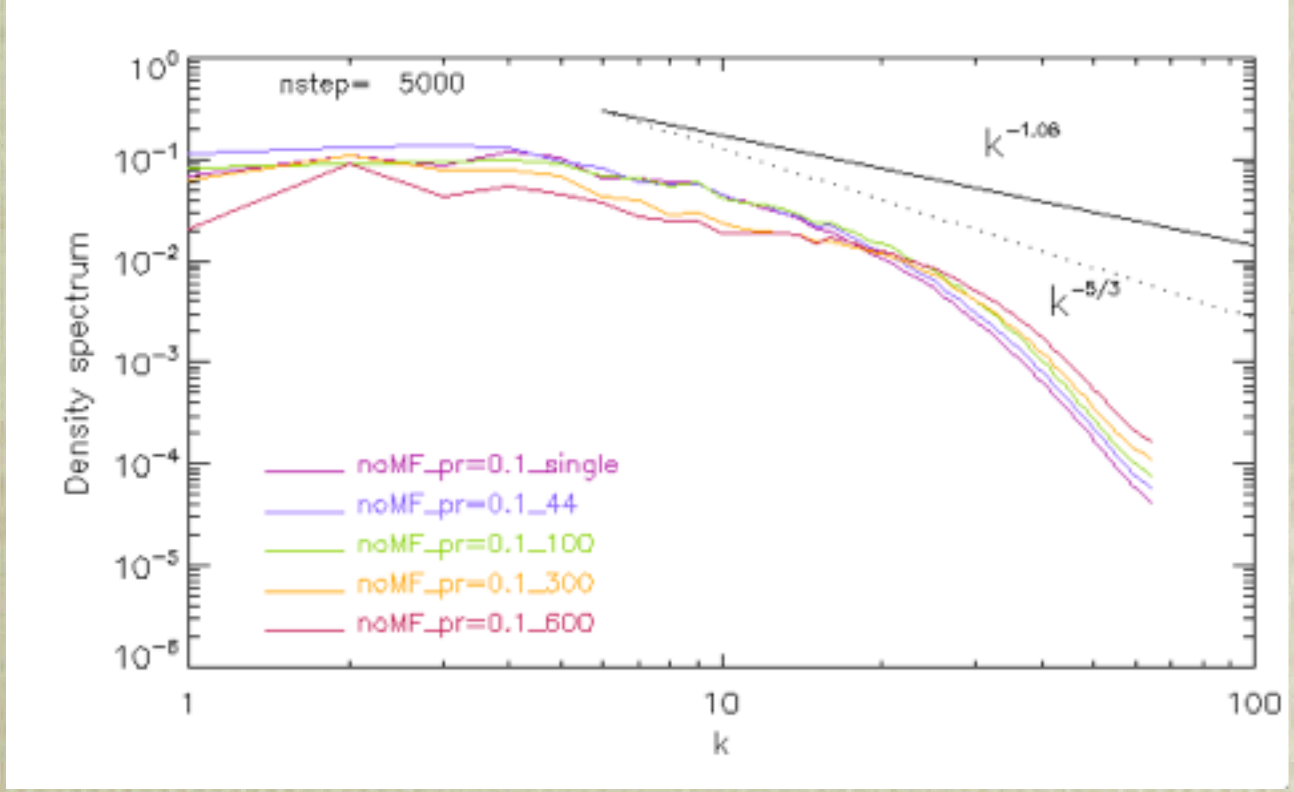
- MHD (B_{ext}=0.01)

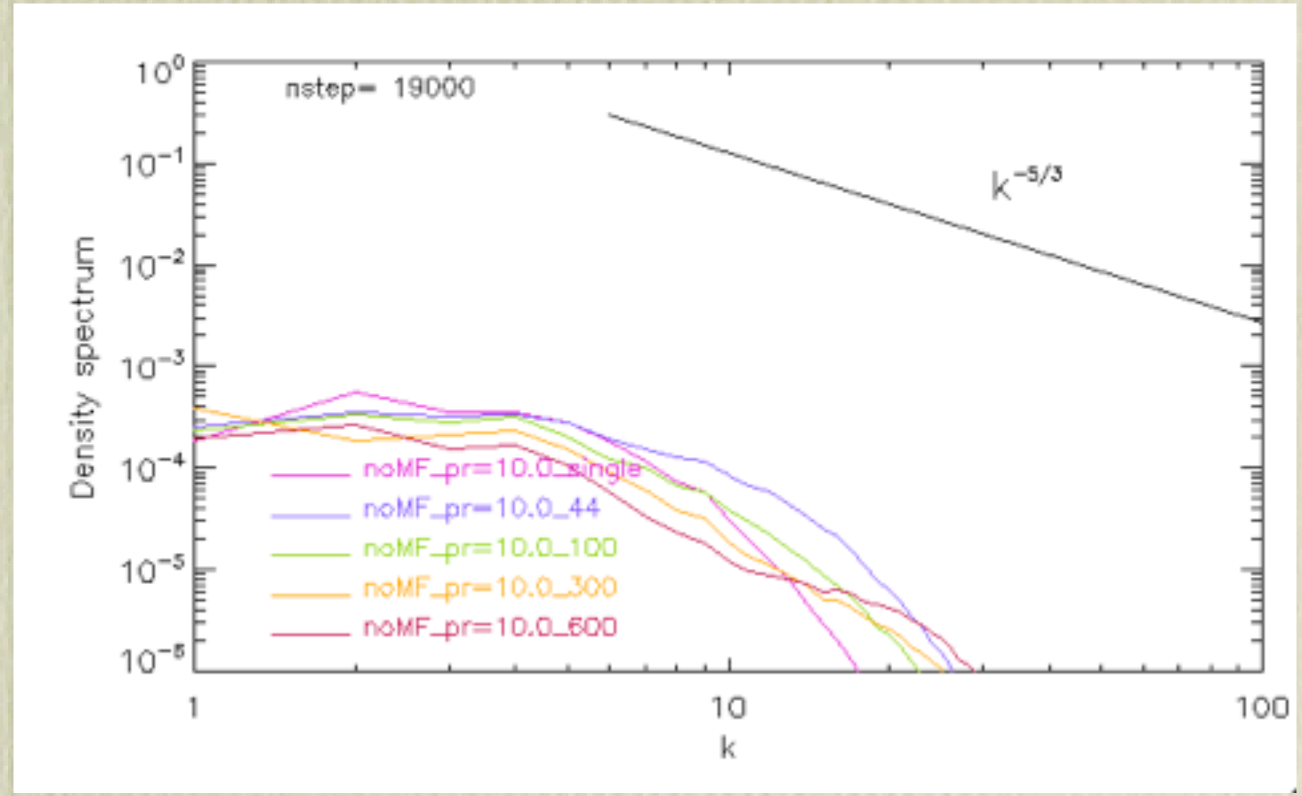


Sonic turbulence (M~1)

Density spectrum

* Density specrum
 - HD (B_{ext}=0)



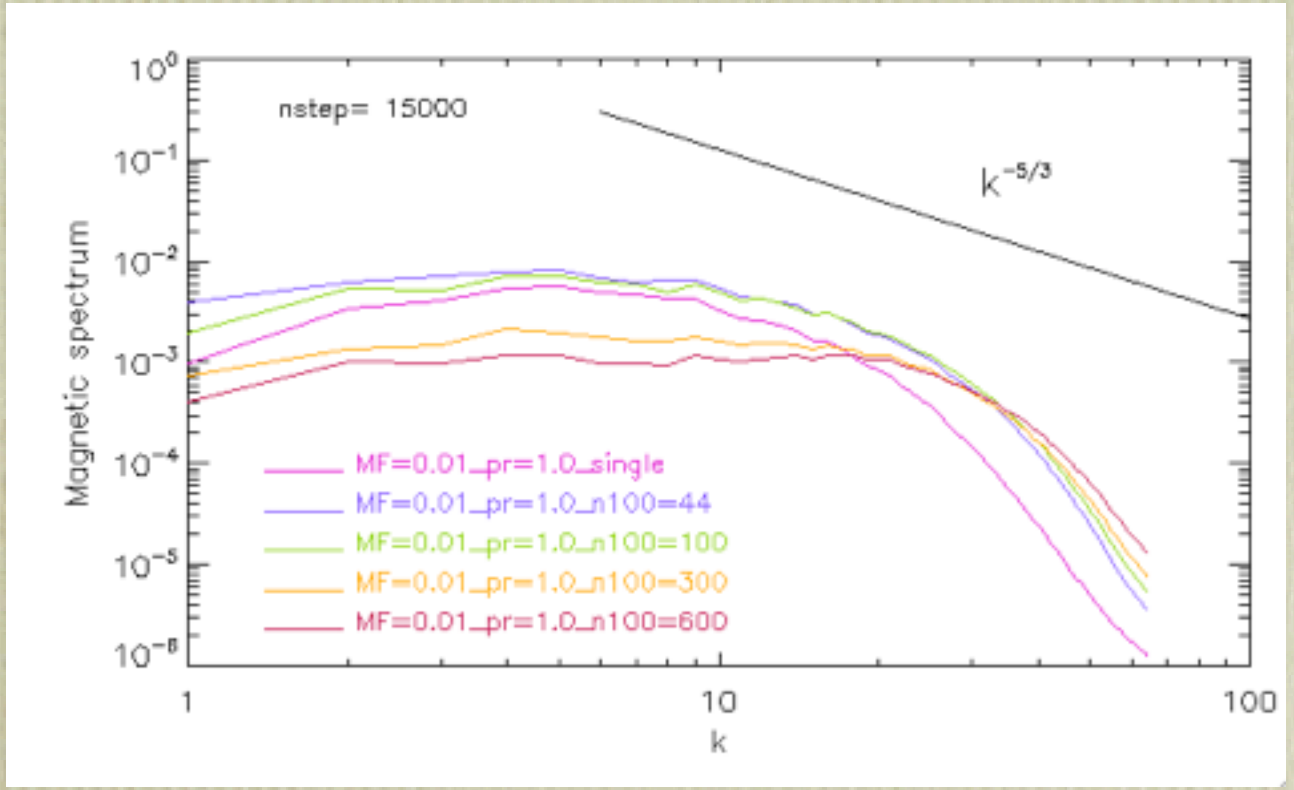


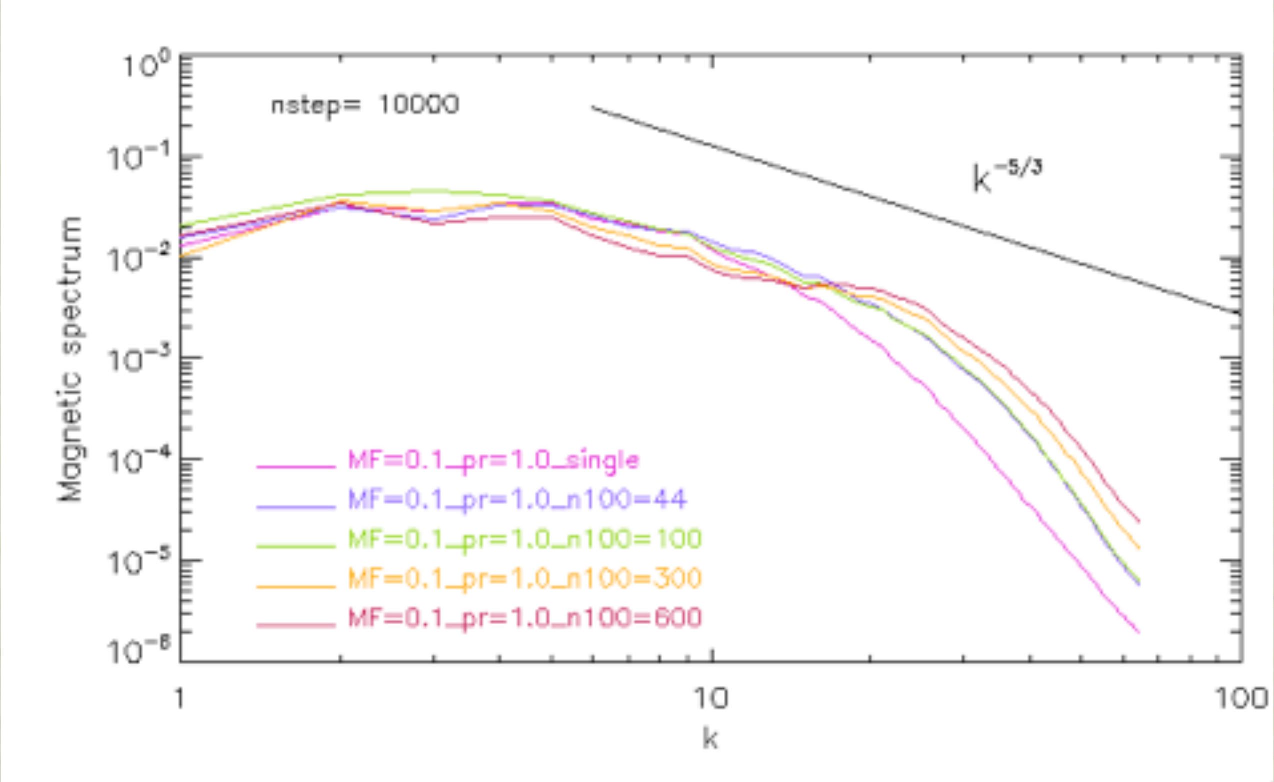
Supersonic turbulence
M~3.16

Subsonic turbulence
M~0.316

Magnetic spectrum

* Magnetic energy specrum
 - MHD

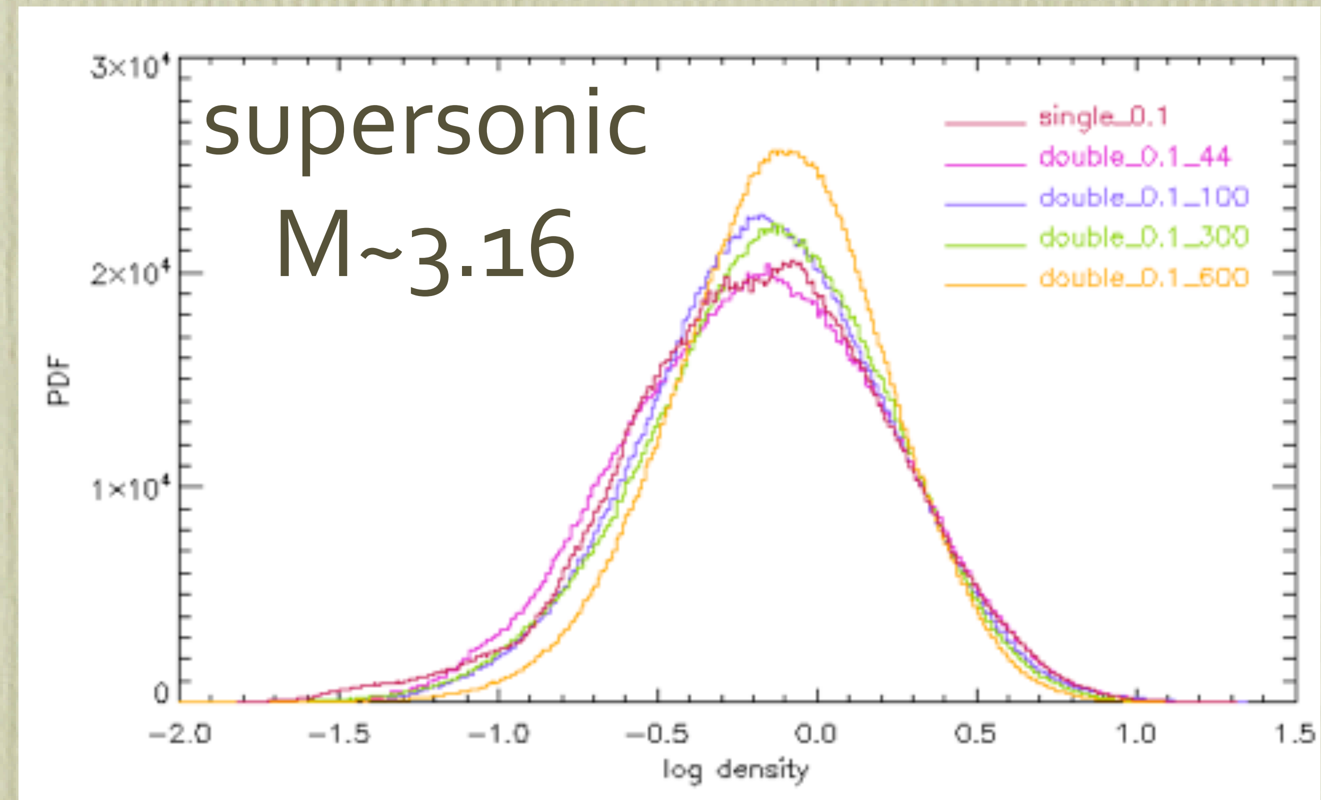


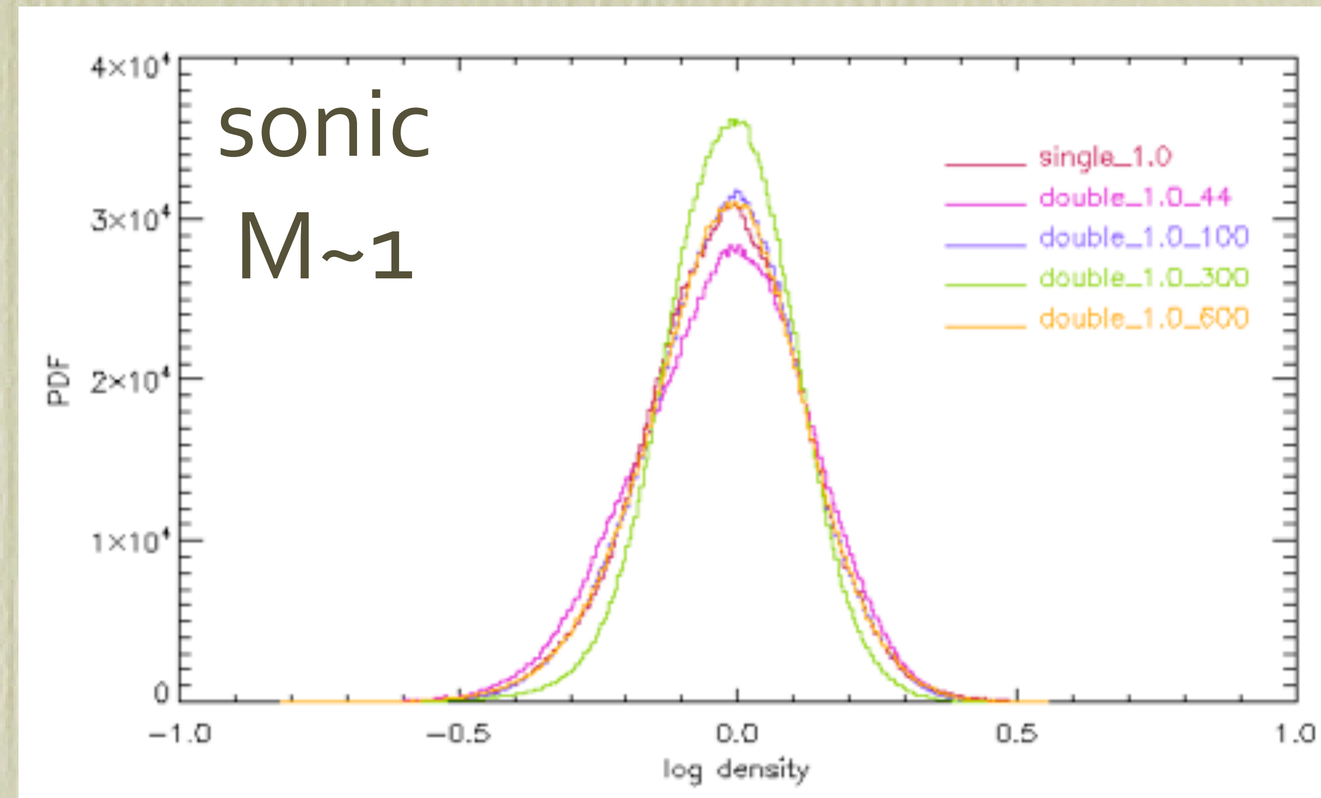


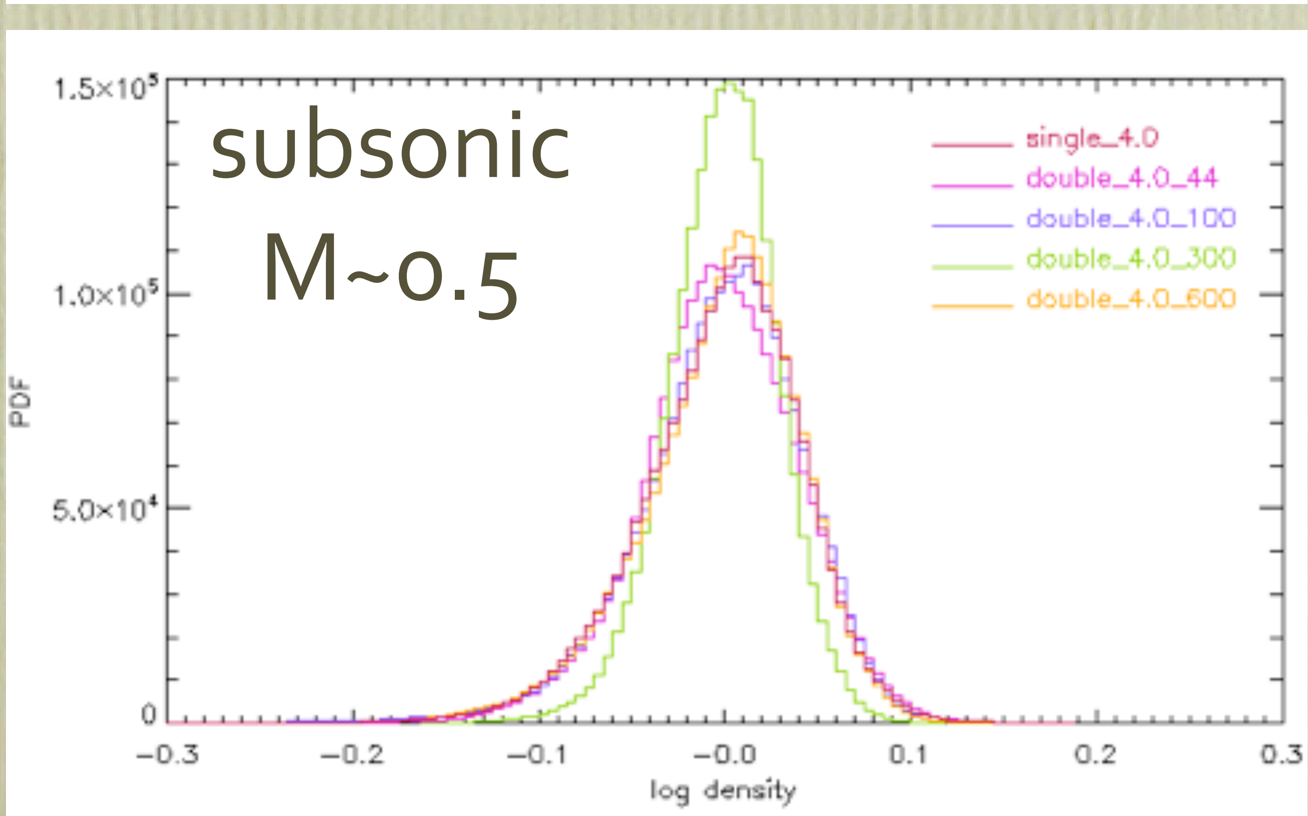
Sonic turbulence
M~1
(B_{ext}=0.01)

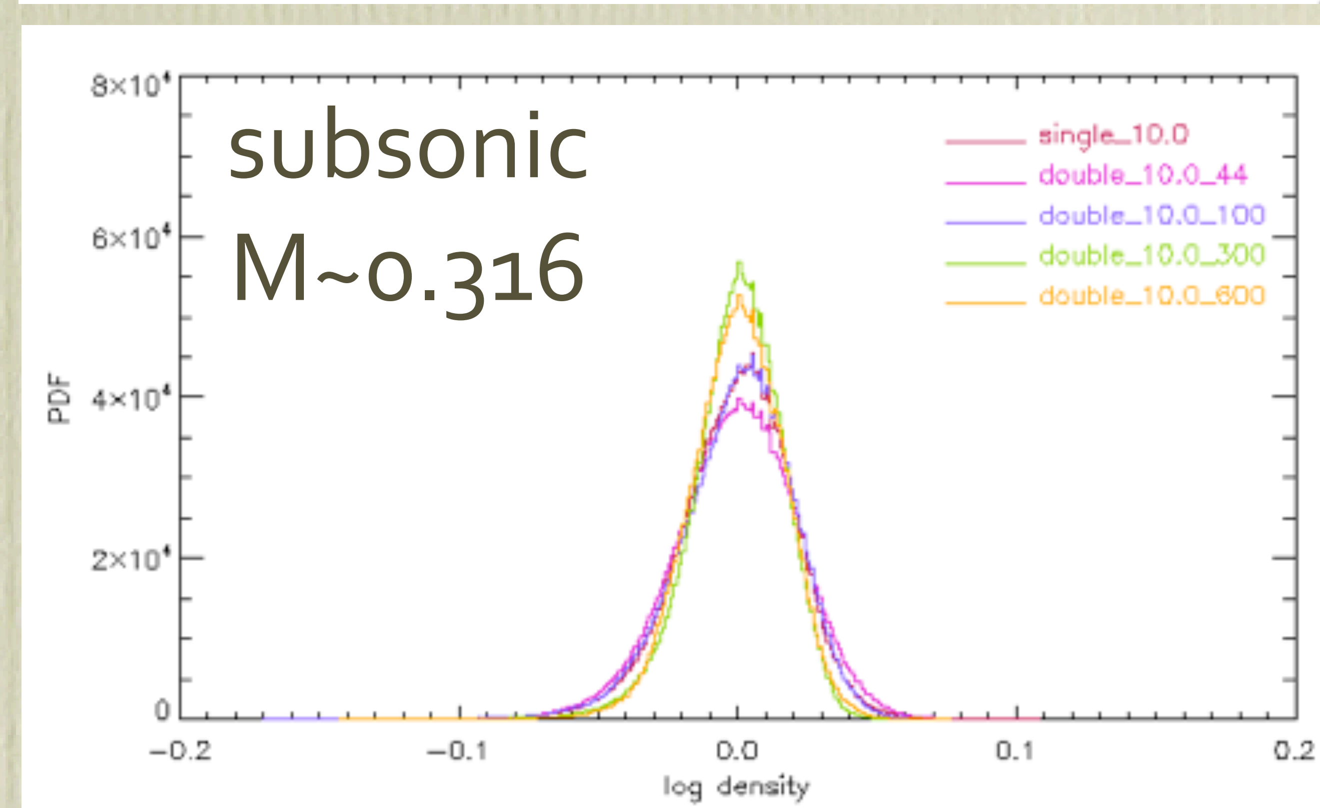
Sonic turbulence
M~1
(B_{ext}=0.1)

PDF


supersonic
M~3.16
single_0.1
double_0.1_44
double_0.1_100
double_0.1_300
double_0.1_600
PDF
log density
3×10⁴
2×10⁴
1×10⁴
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

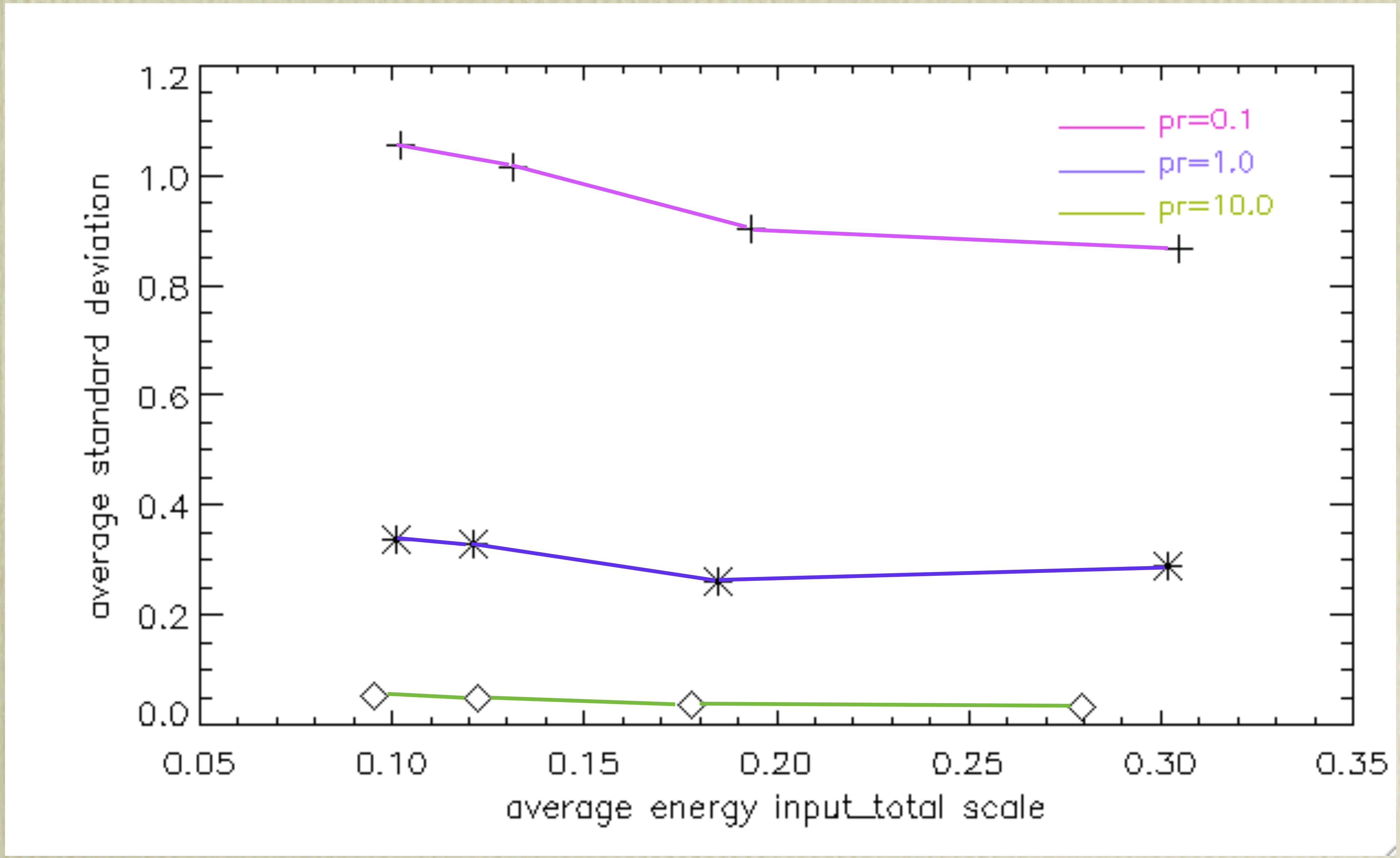

sonic
M~1
single_1.0
double_1.0_44
double_1.0_100
double_1.0_300
double_1.0_600
PDF
log density
4×10⁴
3×10⁴
2×10⁴
1×10⁴
0
−1.0
−0.5
0.0
0.5
1.0


subsonic
M~0.5
single_4.0
double_4.0_44
double_4.0_100
double_4.0_300
double_4.0_600
PDF
log density
1.5×10⁵
1.0×10⁵
5.0×10⁴
0
−0.3
−0.2
−0.1
−0.0
0.1
0.2
0.3


subsonic
M~0.316
single_10.0
double_10.0_44
double_10.0_100
double_10.0_300
double_10.0_600
PDF
log density
8×10⁴
6×10⁴
4×10⁴
2×10⁴
0
−0.2
−0.1
0.0
0.1
0.2

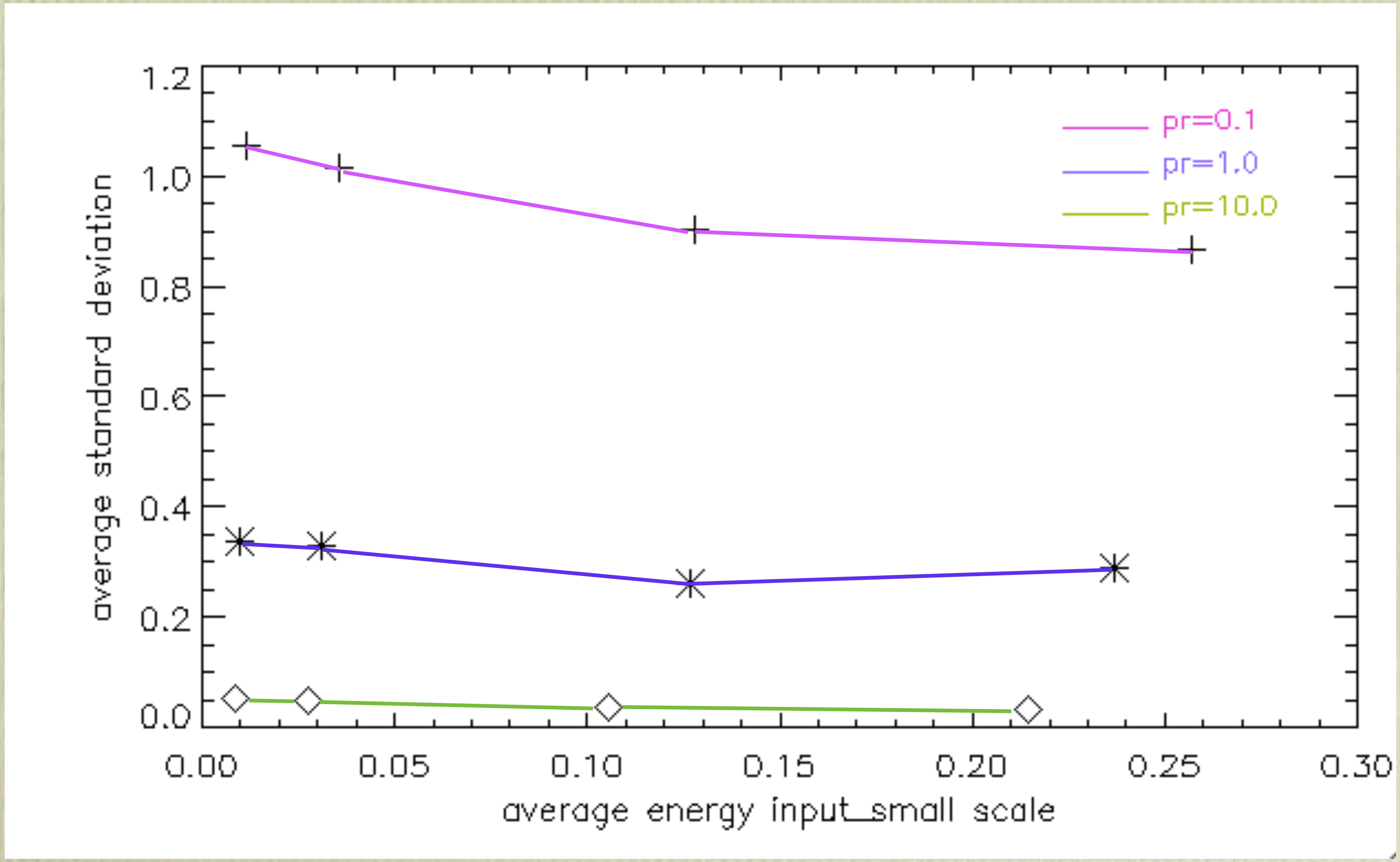
σ-energy input rate relation

* The relation between average standard deviation of density and average energy input rate (total scale)



σ-energy input rate relation

* The relation between average standard deviation of density and average energy input rate (small scale)



Summary

* Numerical simulations of driven MHD/HD turbulence with different forcing modes.
* The rate of kinetic energy density and magnetic energy density growth is decrease as energy input rate increase.
* In kinetic energy spectrum, the peak at small scale increase with more energy injection in small scale.
* Density spectrum is flatten as energy input in small scale increase.
* Magnetic energy spectrum is much flatter than the Kolmogorov spectrum.
* The standard deviation of density in higher mach number is larger than smaller one.

Future work

* Higher resolution simulation

* PDF comparison

* Visualization

* Clump-finding

Thank you :)