Turbulence simulations with ENZO and FLASH3

...

not yet

Adaptive-mesh simulations with FLASH

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Outline

ENZO vs. FLASH3
in turbulence simulations

- Turbulence in star formation
- 2D test case: Kelvin-Helmholtz-instability
- 3D test case: driven/forced turbulence
- Conclusions

Motivation for turbulence studies

Orion nebula M42 (HST 2006)

Random motion observed in molecular clouds

⇒

Supersonic compressible turbulence (typical rms Mach numbers are ~1-10)

⇒

Turbulence as key ingredient in star formation theory

(e.g., Mac Low & Klessen 2004; Elmegreen & Scalo 2004, Padoan & Nordlund 2002)

- Hierarchical structure
- Lifetime of molecular clouds
- Mass distribution (IMF)

Code comparison
ENZO vs. FLASH3

Turbulence code comparison

Features of ENZO and FLASH3 for turbulence simulations in star formation:

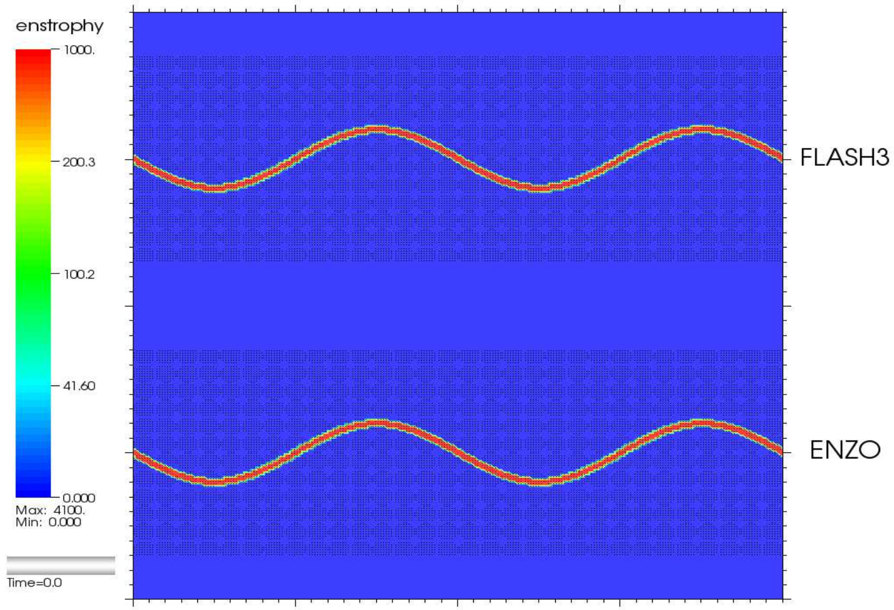
ENZO	FLASH3
Parallelized using MPI	Parallelized using MPI
AMR	AMR
HDF5 data output	HDF5 data output
PPM (shocks)	PPM (shocks)
Particles (passive/active)	Particles (passive/active)
Self-gravity	Self-gravity
(Cooling, Heating)	(Cooling, Heating)
	(Magnetic fields)

2 dimensional turbulence test case:
Kelvin-Helmholtz-instability

Turbulence code comparison

2D „turbulence“ test case:

Kelvin-Helmholtz-instability:



256x128 grid cells (no AMR)

Periodic BC in x, outflow BC in y

Uniform density

Upper half: velocity to the left

Lower half: velocity to the right

} + sinusoidal velocity perturbation in y

Isothermal equation of state (gamma = 1.001)

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units included in setup	Physics/hydro/HydroMain/split/PPM/PPMKernel	(piecewise parabolic method)
	physics/Eos/EosMain/Gamma	(gamma law equation of state)
	Particles/.../passive	(tracer particles (256x90))
	Grid/.../UG	(uniform grid)
	IO/.../hdf5/serial/UG	(HDF5 uniform grid output)
	Grid/.../Paramesh3/...	(paramesh3, but NO AMR)
	IO/.../hdf5/serial/PM	(HDF5 paramesh output)

FLASH3 vs. ENZO

enstrophy = vorticity^2 = (nabla x **v**)^2

FLASH3 uniform grid (UG) vs. FLASH3 paramesh3 (PM)

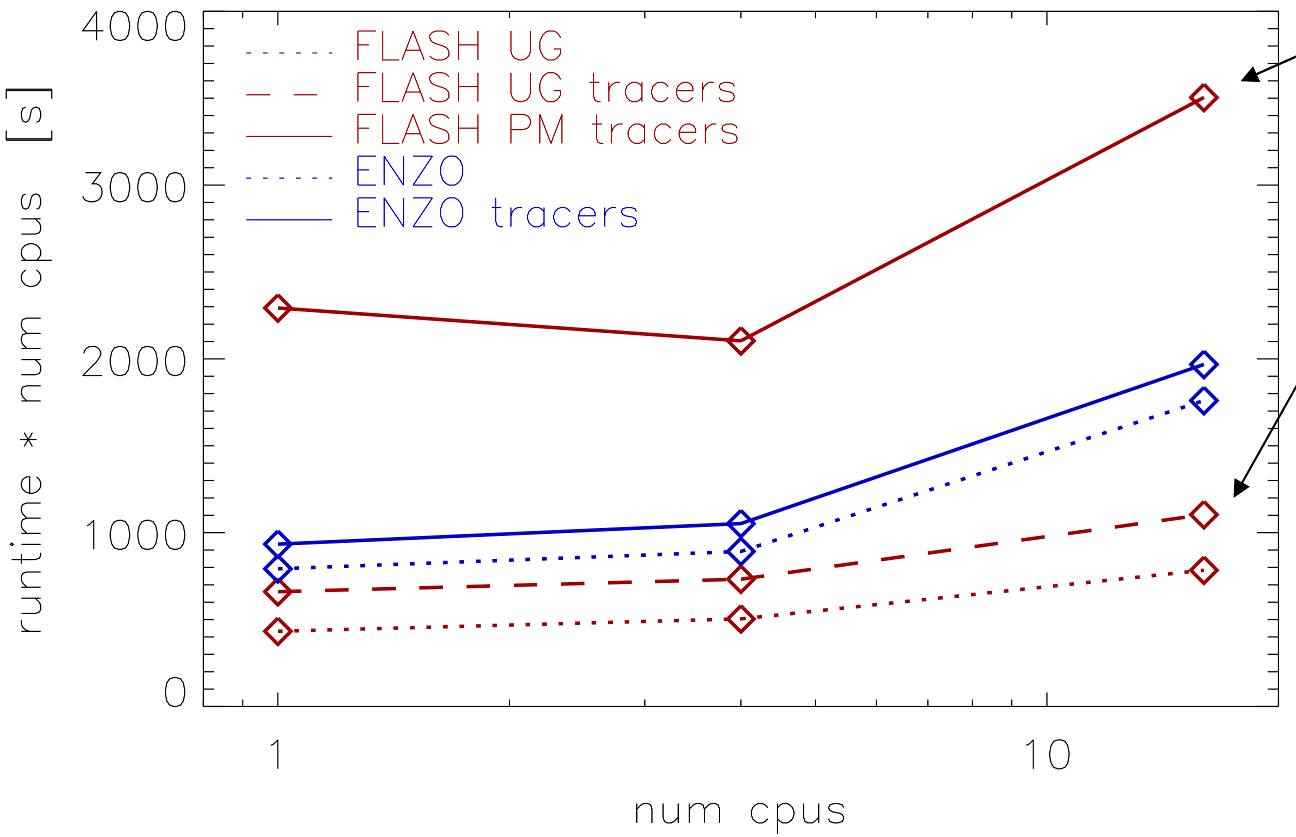
enstrophy = vorticity^2 = (nabla x $\mathbf{v}$)^2

Turbulence code comparison

2D „turbulence“ test case:

Kelvin-Helmholtz-instability: performance comparison

256x128 grid cells (no AMR)



Uniform grid is ~3x faster than paramesh3 and scales slightly better

Turbulence code comparison

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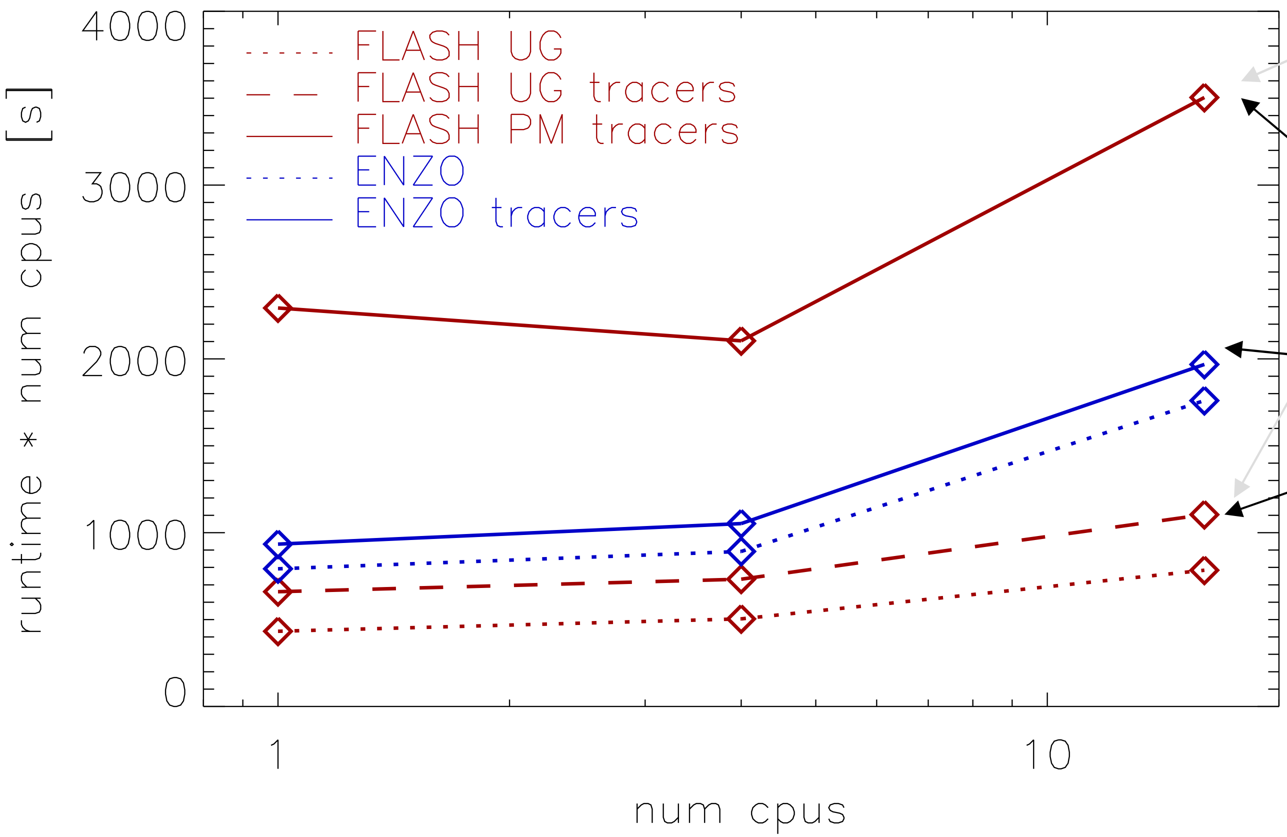

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ENZO lies in between FLASH3 UG and FLASH3 PM

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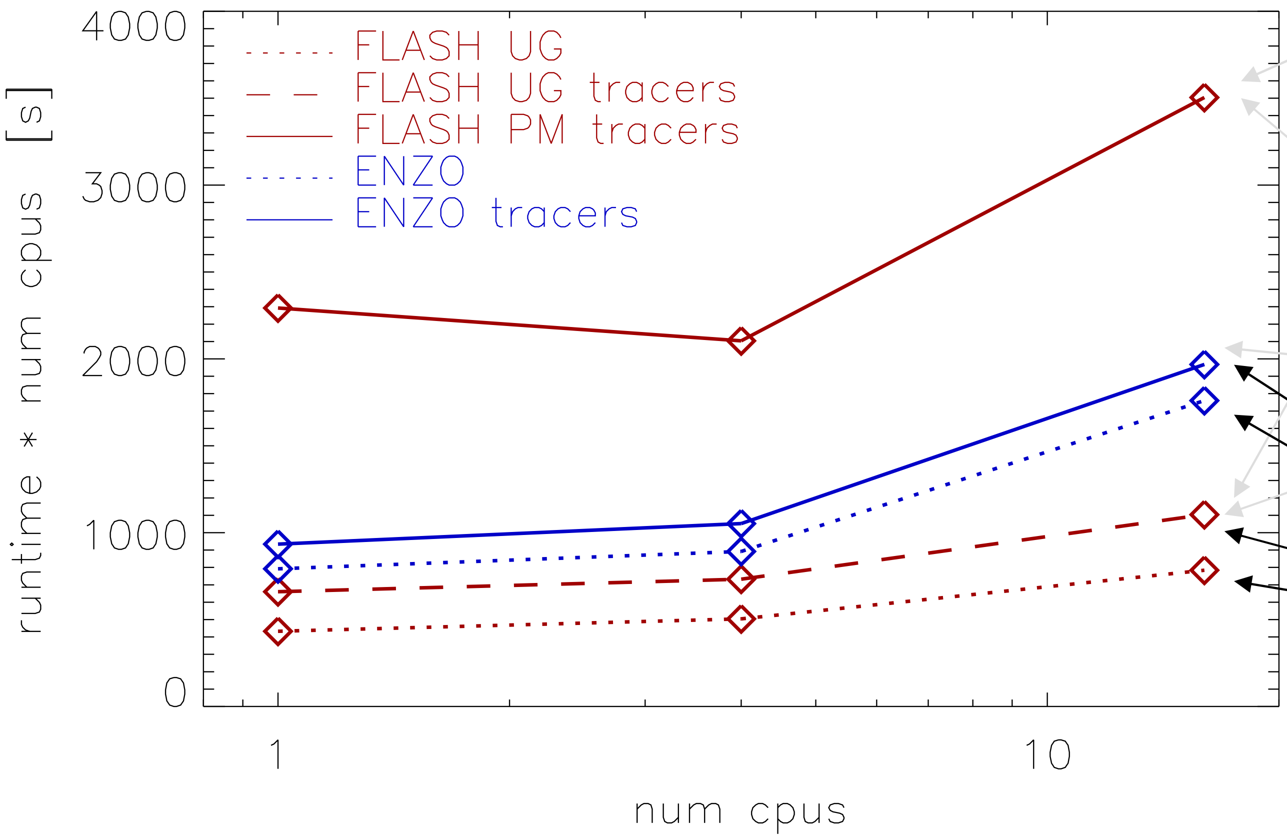

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Passive particles have minor effect on overall computational cost in both codes

3 dimensional turbulence test case: driven/stirred/forced turbulence

driven/stirred/forced turbulence

Turbulence code comparison

3D turbulence test case:

driven/stirred/forced compressible turbulence

Stochastic forcing term **f** as source term in equations of hydrodynamics:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla P + \mathbf{f}$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot \left[\mathbf{v}(\rho e + P)\right] = \rho \mathbf{v} \cdot \mathbf{f}$$

Physical force field **f** is constructed and evolved in Fourier space (typically only k=1,2,3 are driven) according to a 3D stochastic Ornstein-Uhlenbeck process with finite autocorrelation time (Eswaran & Pope 1988)

⇒ **f** varies smoothly in space and time !

Turbulence code comparison

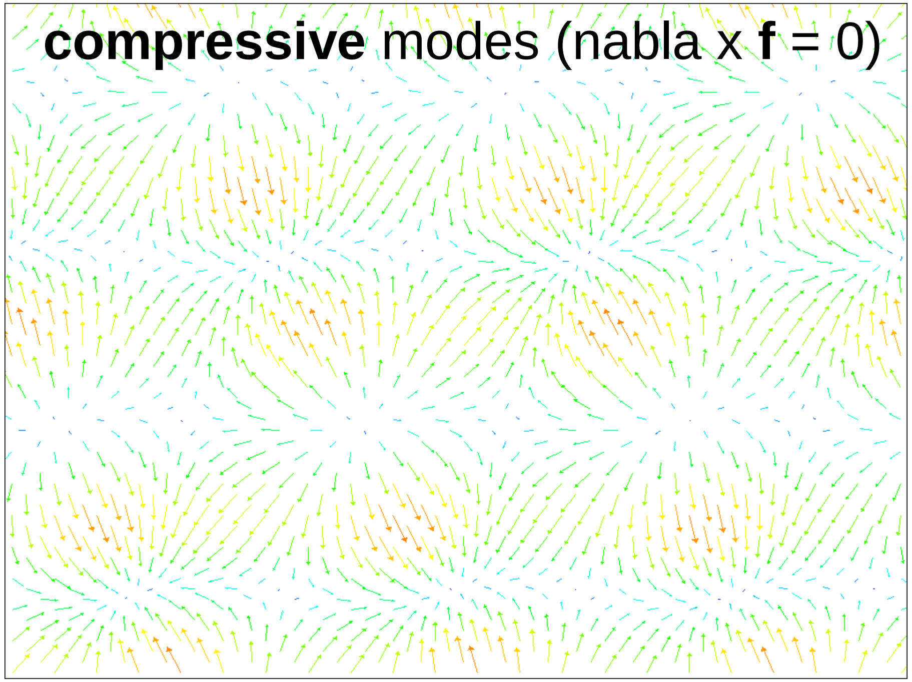
3D turbulence test case:

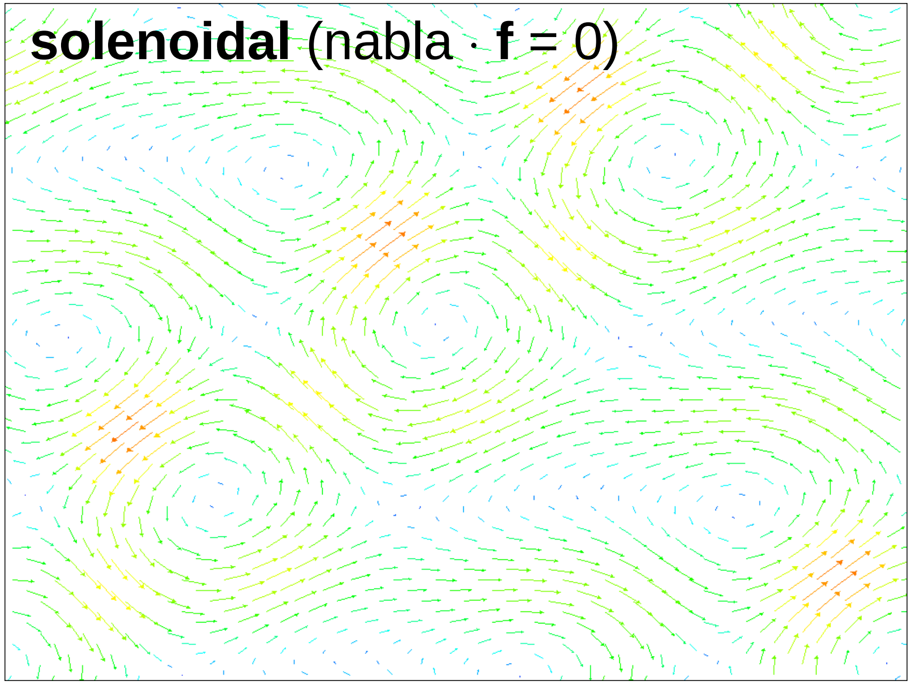
driven/stirred/forced compressible turbulence

Stochastic forcing term **f** as source term in equations of hydrodynamics:

Decomposition into

compressive modes (nabla x **f** = 0) and **solenoidal** (nabla · **f** = 0)





ENZO supports both compressive and solenoidal forcing, whereas FLASH3 currently only supports solenoidal forcing.

Turbulence code comparison

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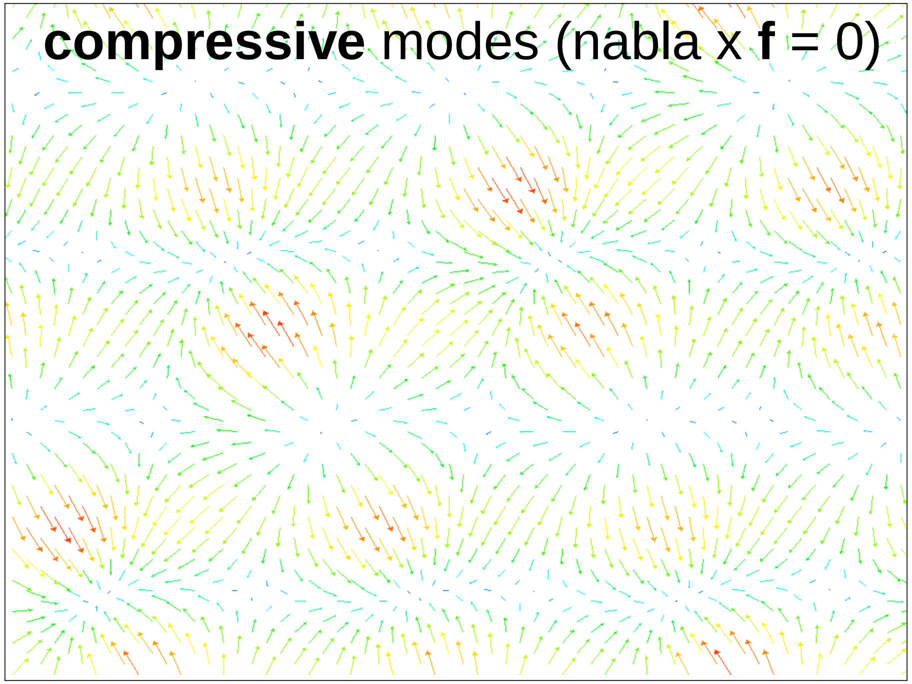

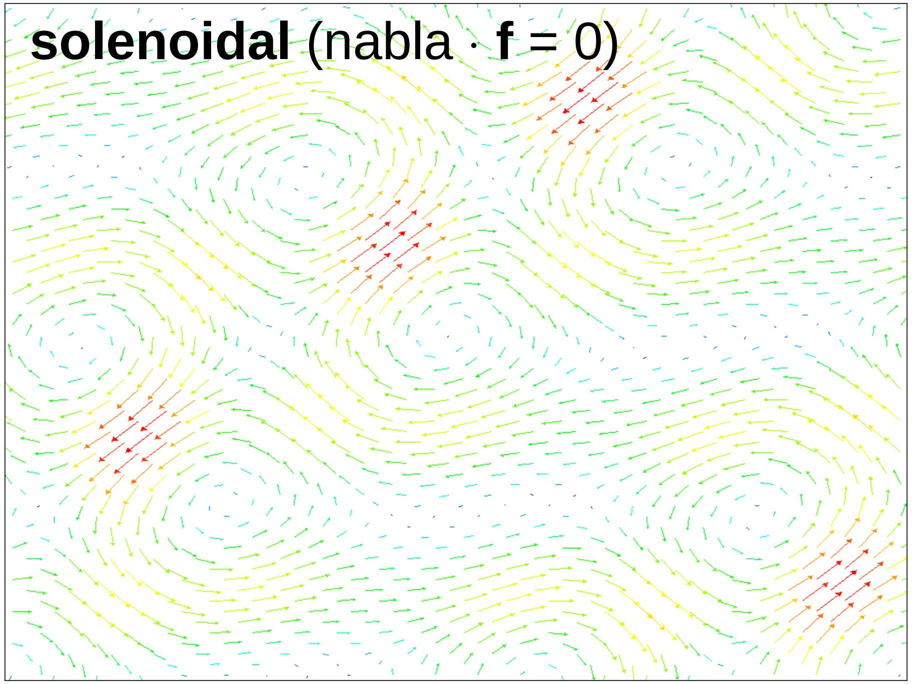

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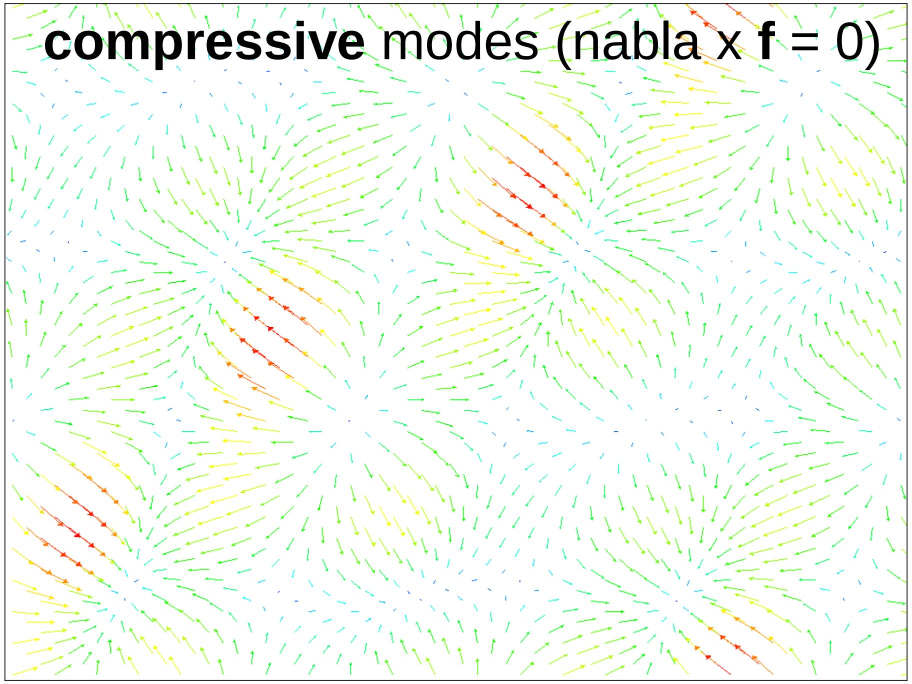

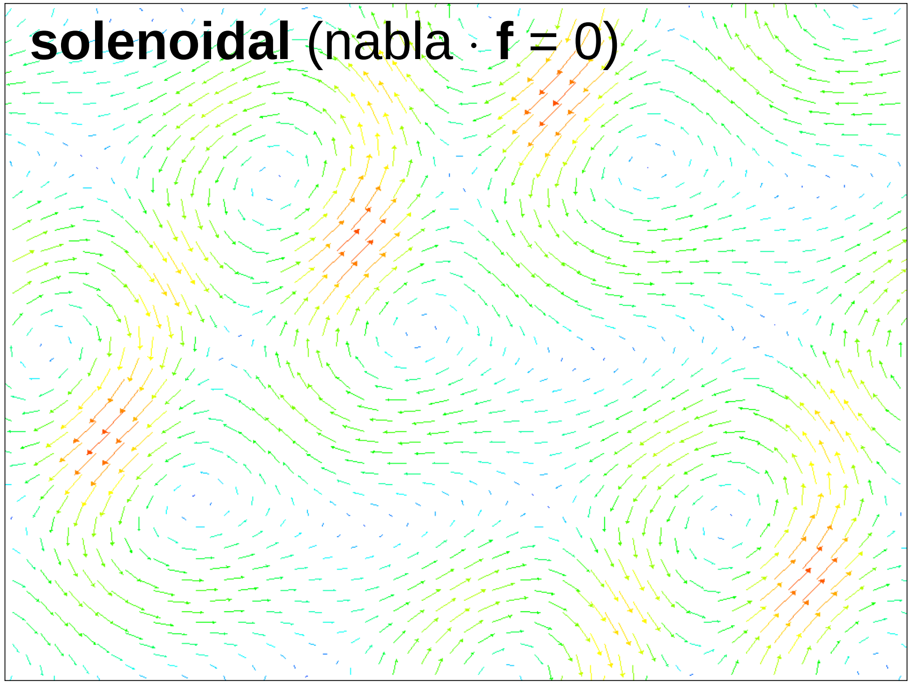

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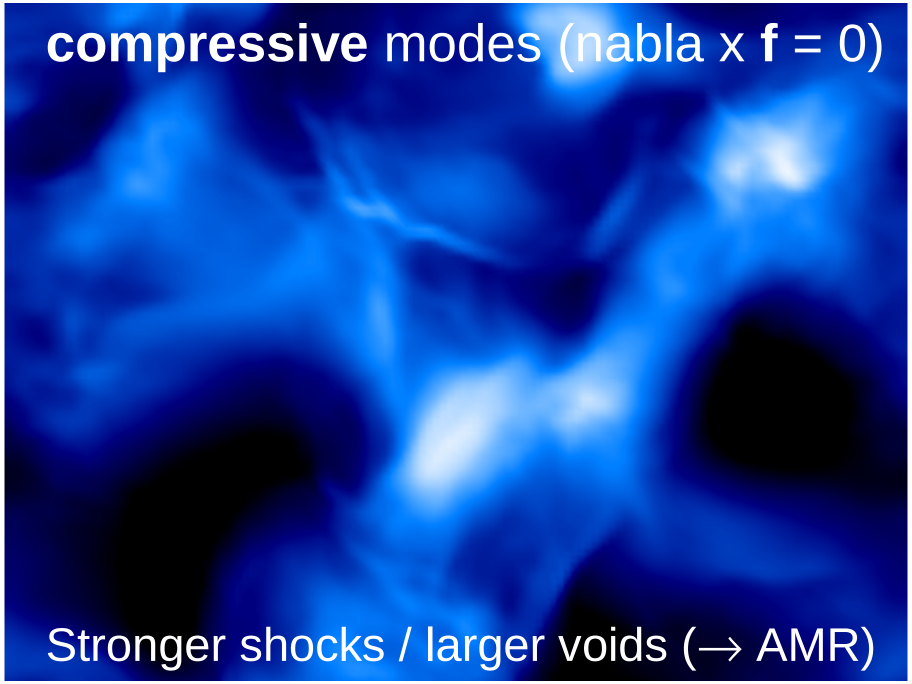
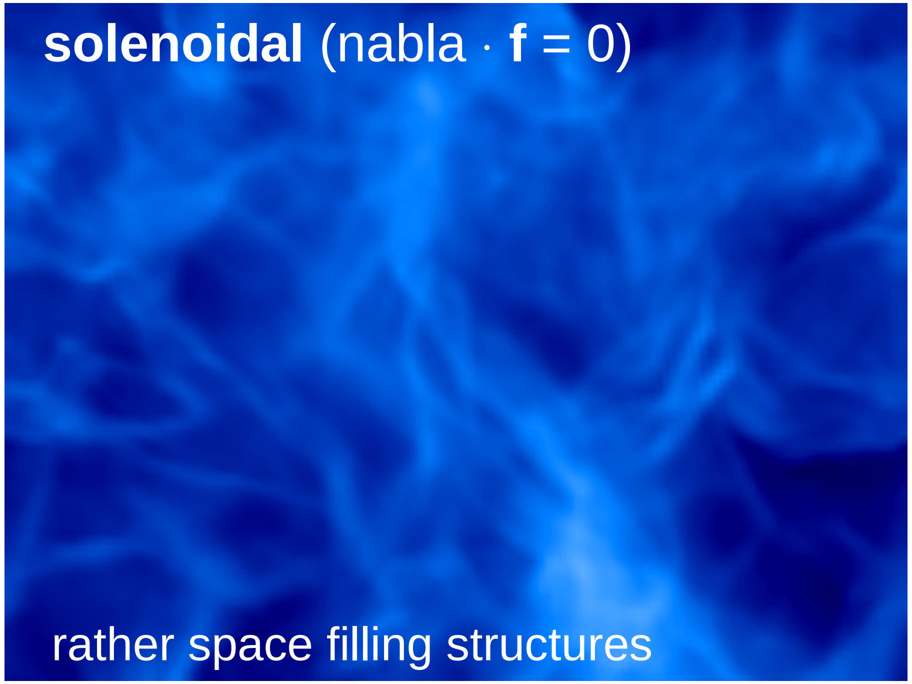


and



Compressive modes excited rather in the interstellar medium

(supernovae, gravitational instability, protostellar outflows, ... → converging flows)

Schmidt & Federrath 2007, PRE submitted
Federrath, Schmidt, Klessen 2007, ApJ submitted
Schmidt, Federrath, Hupp, Maier, Niemeyer 2007, in preparation

3 dimensional turbulence test case: driven/stirred/forced turbulence

Turbulence code comparison

3D turbulence test case:

driven/stirred/forced compressible turbulence

Resolution: 256^3; uniform grid (no AMR); periodic boundaries; uniform density, gas initially at rest; rms Mach number ~3.5; 128^3 tracer particles, **solenoidal forcing**

3 simulations

ENZO	FLASH3	FLASH3 visc
• Parabolic Fourier spectrum for force field on k=[1,3] • „cvisc“=0.0 • „use_steepening“=false	• Peak Fourier spectrum for force field on k=[1,2] • cvisc=0.0 • use_steepening=false	• Peak Fourier spectrum for force field on k=[1,2] • cvisc=0.1 • use_steepening=true

Additional modules included: physics/sourceTerms/Stir/StirMain

Turbulence code comparison

3D turbulence test case:

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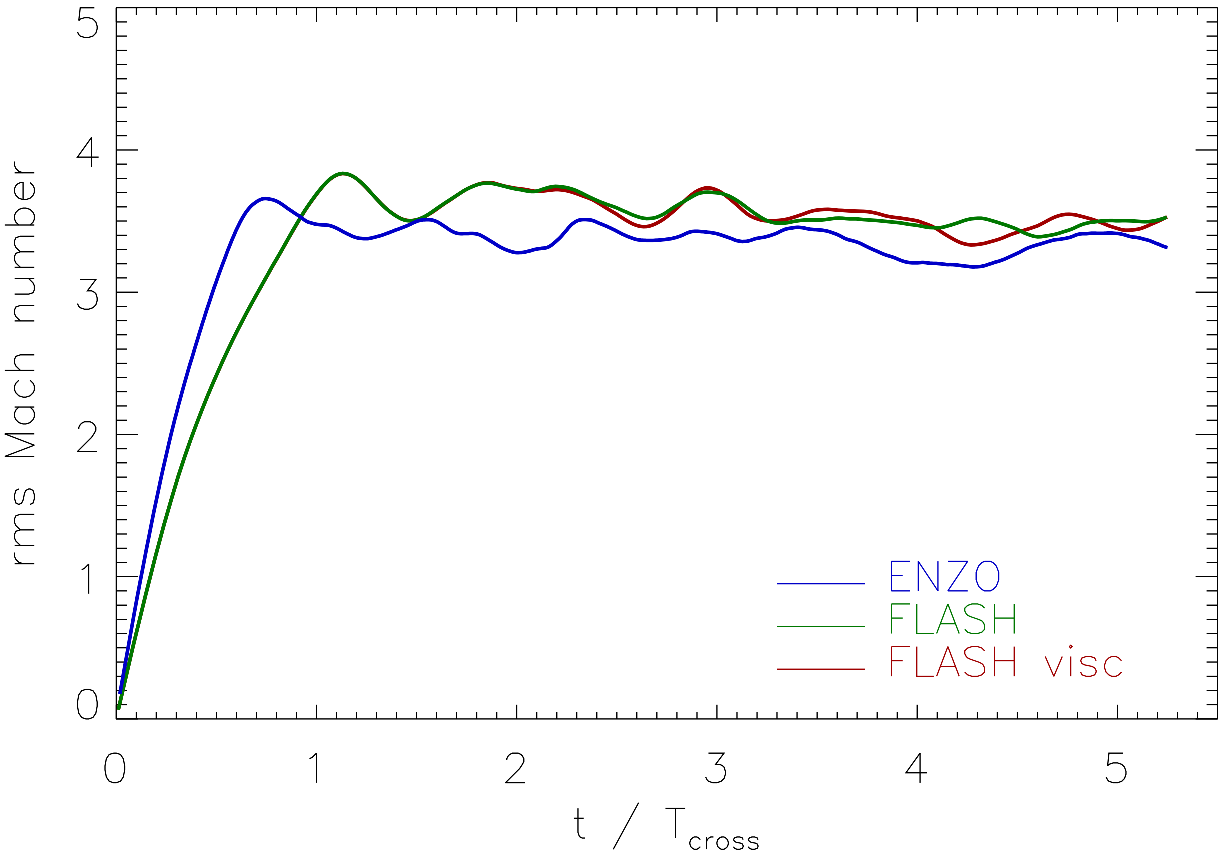
Temporal evolution of root mean squared Mach number:



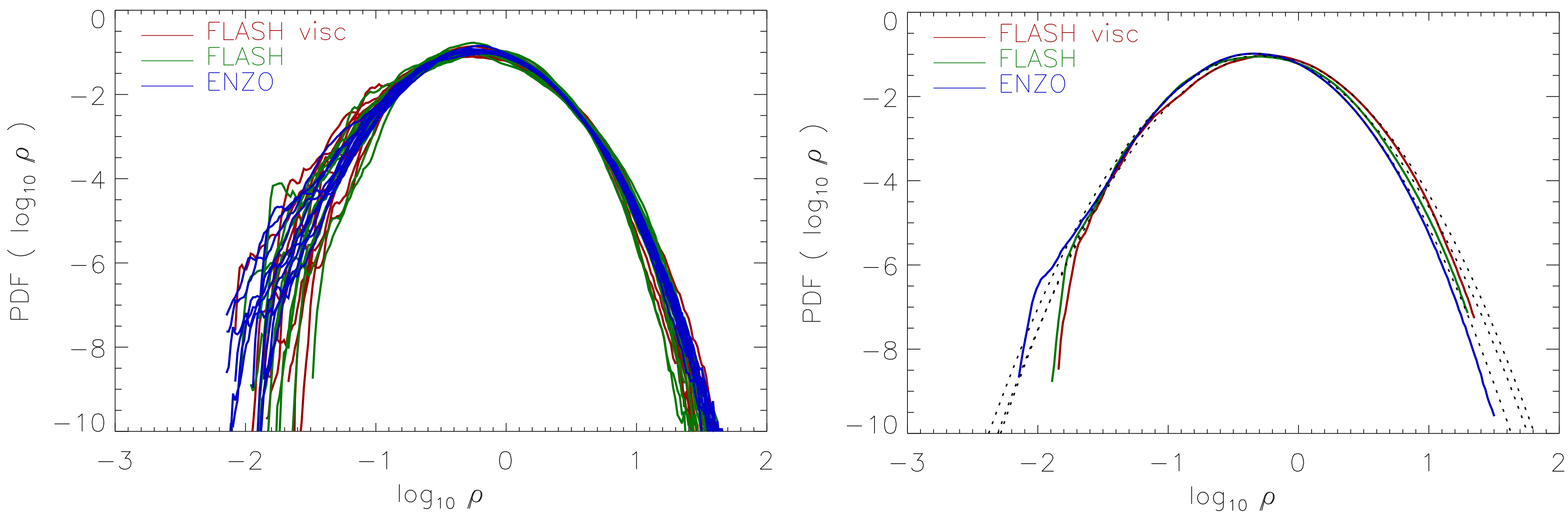
T_{cross} = box size / rms velocity

Turbulence code comparison

3D turbulence test case:

driven/stirred/forced compressible turbulence

Probability distribution function (PDF) of the density:



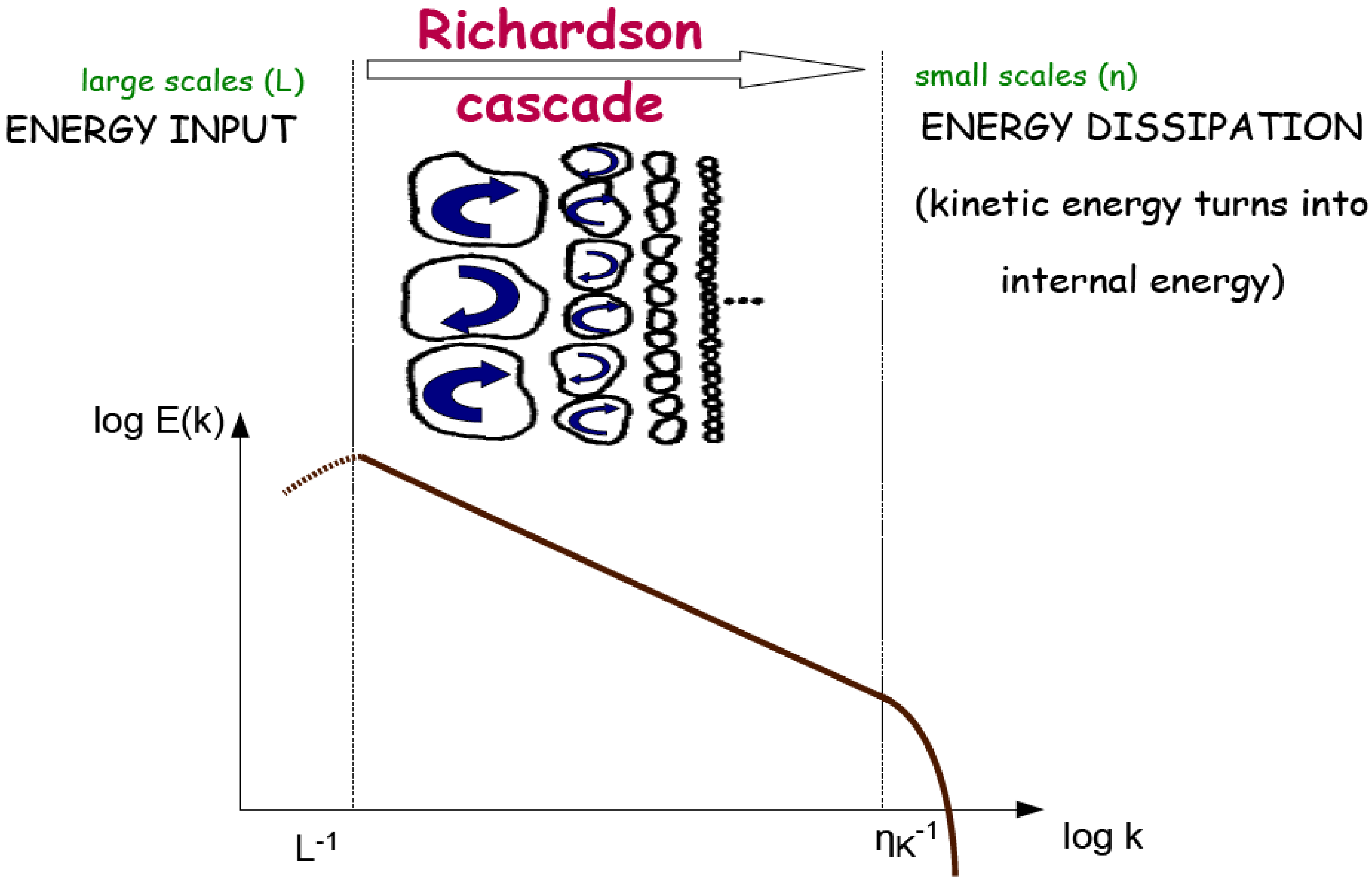
Log-normal-distribution

$$p_{v,m}(s)\,ds = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(s - s_{v,m})^2}{2\sigma^2}\right]ds$$

width of the distr.: $\sigma^2 = \ln\left(1 + \beta^2\,\mathrm{Ma}_{\mathrm{rms}}^2\right)$ (Padoan, Nordlund, Jones 1997)

Turbulence

- **Turbulence is random motion (Re>1000)**
- **Turbulence develops kinetic energy cascade**



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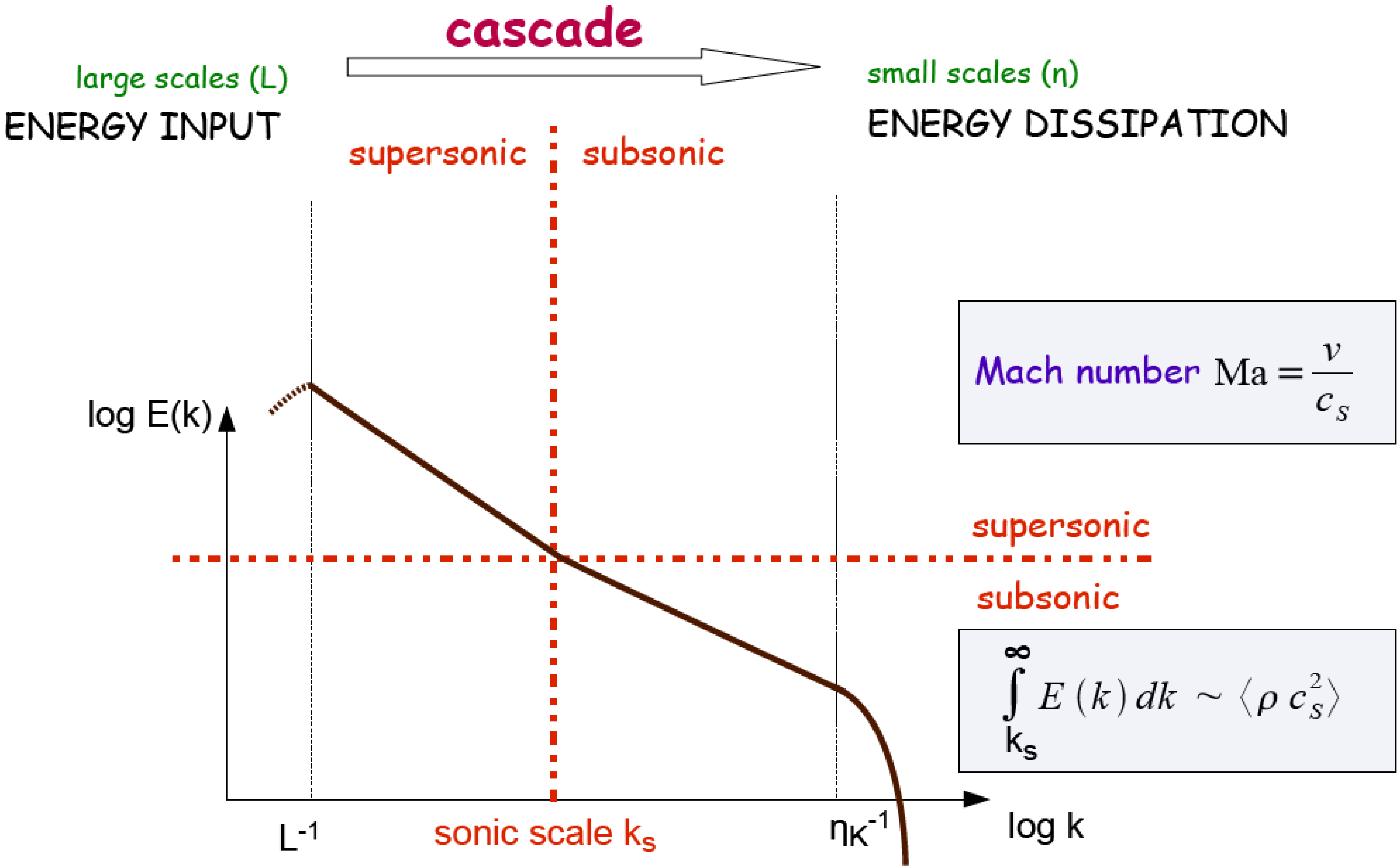

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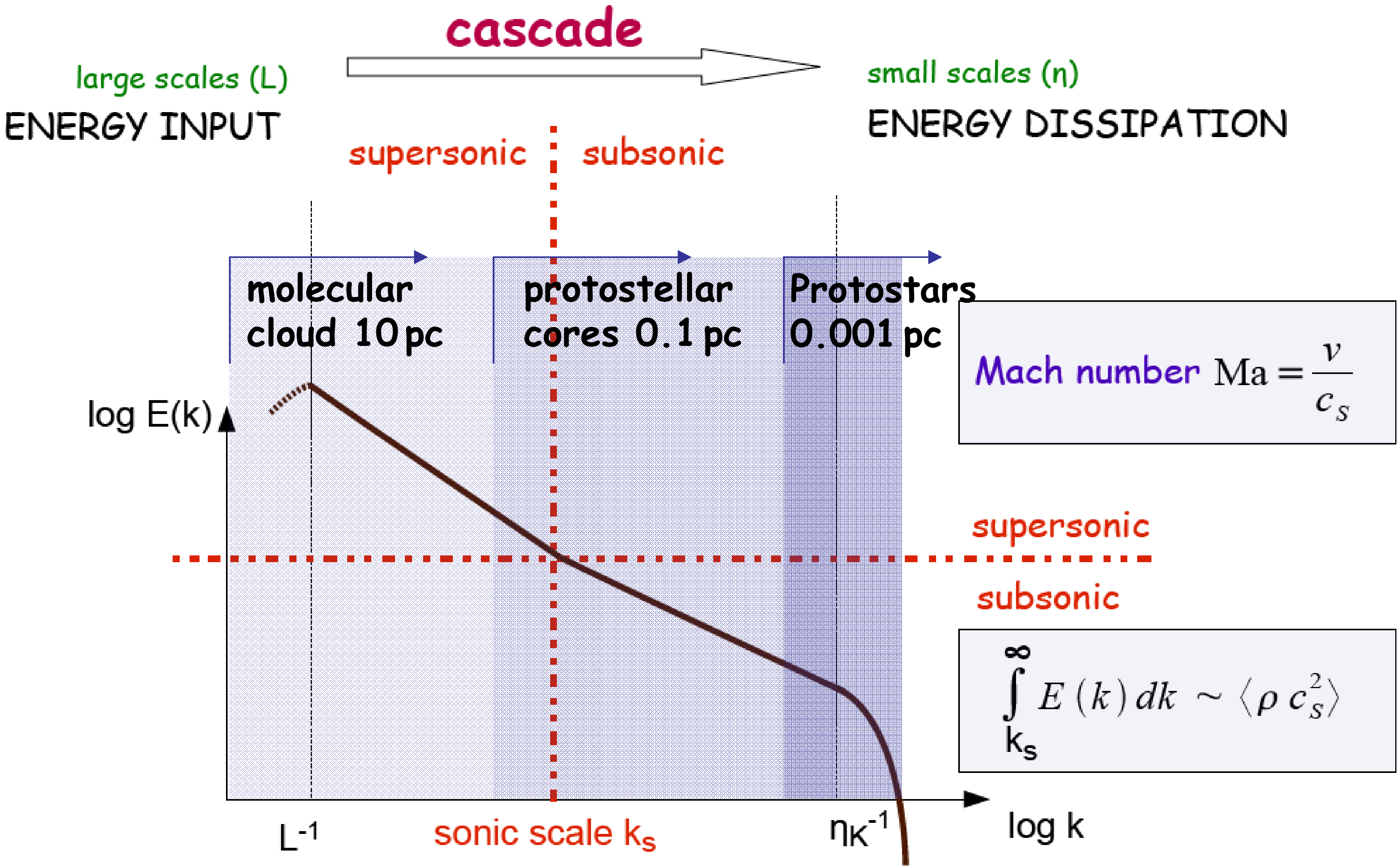

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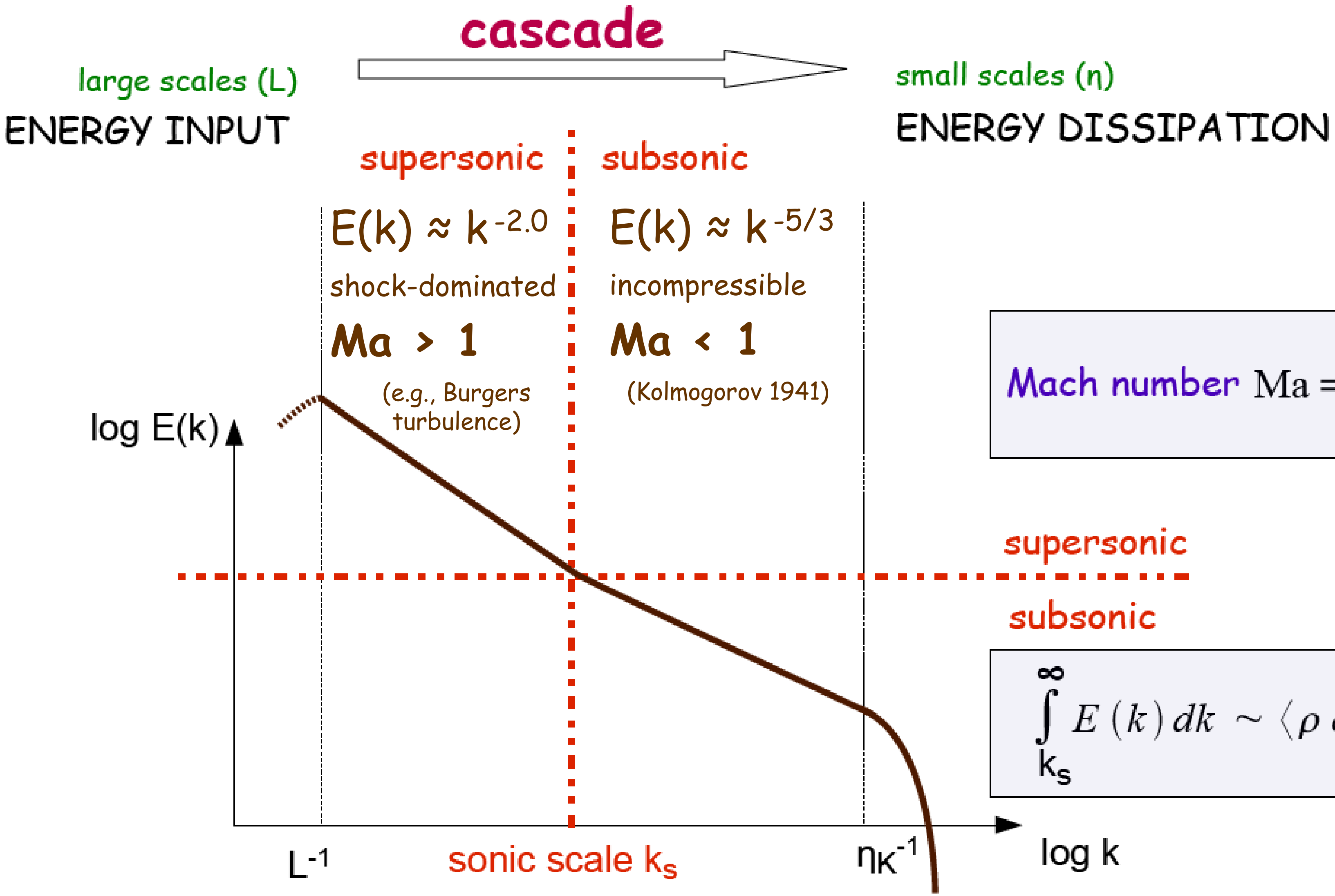


Mach number $\mathrm{Ma} = \frac{v}{c_S}$

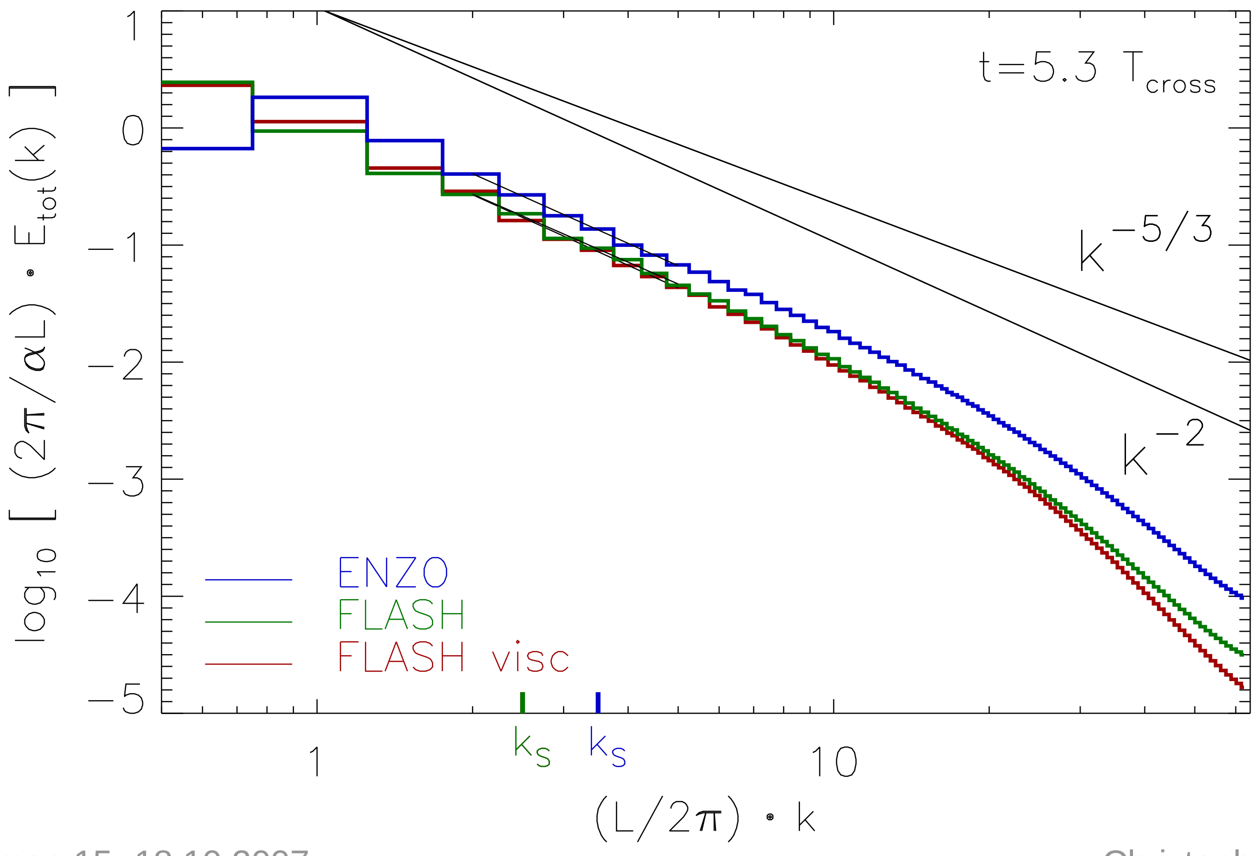
$$\int_{k_S}^{\infty} E(k)\, dk \sim \langle \rho\, c_S^2 \rangle$$

Turbulence code comparison

3D turbulence test case:

driven/stirred/forced compressible turbulence

Energy spectrum functions:



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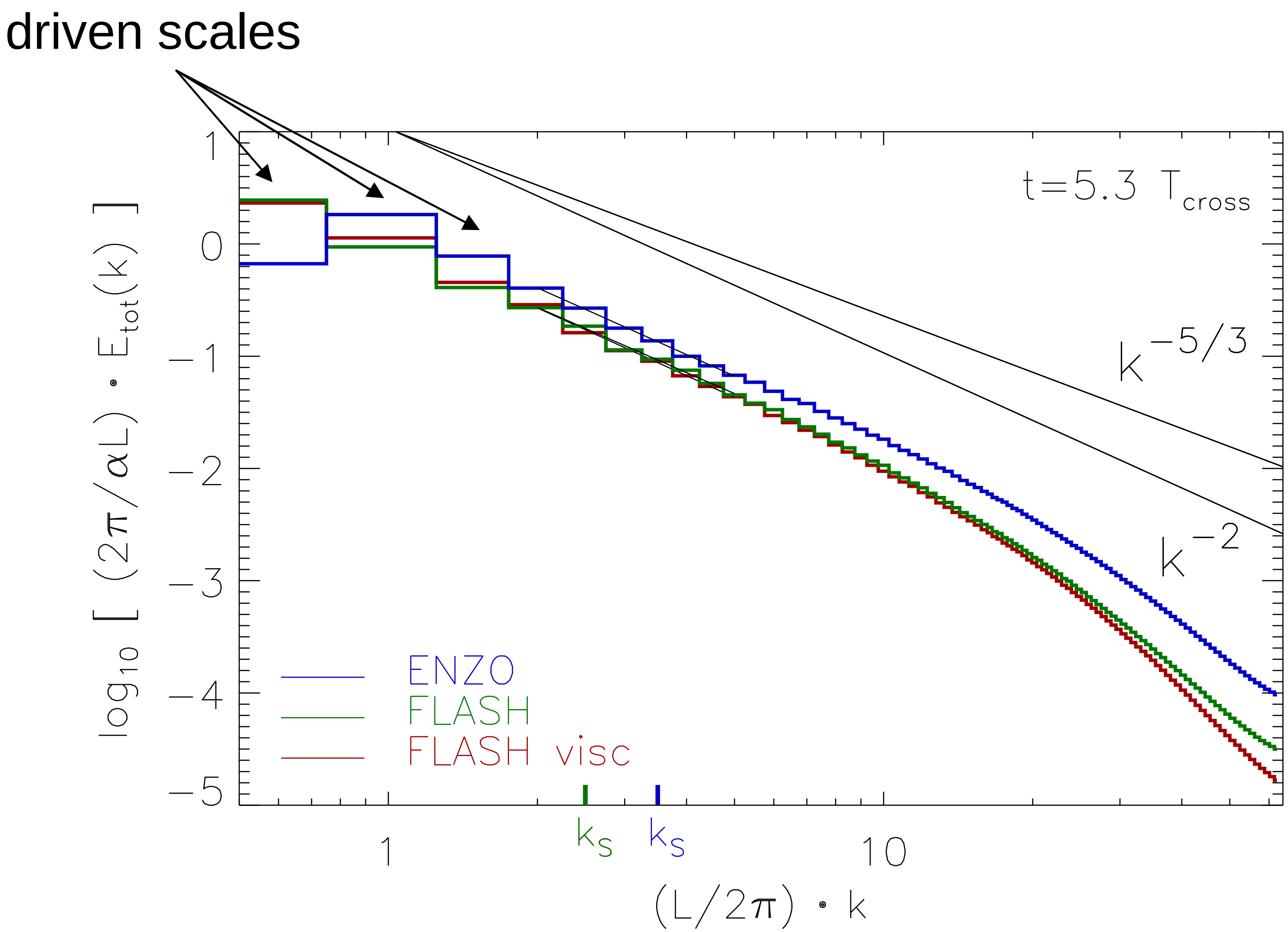

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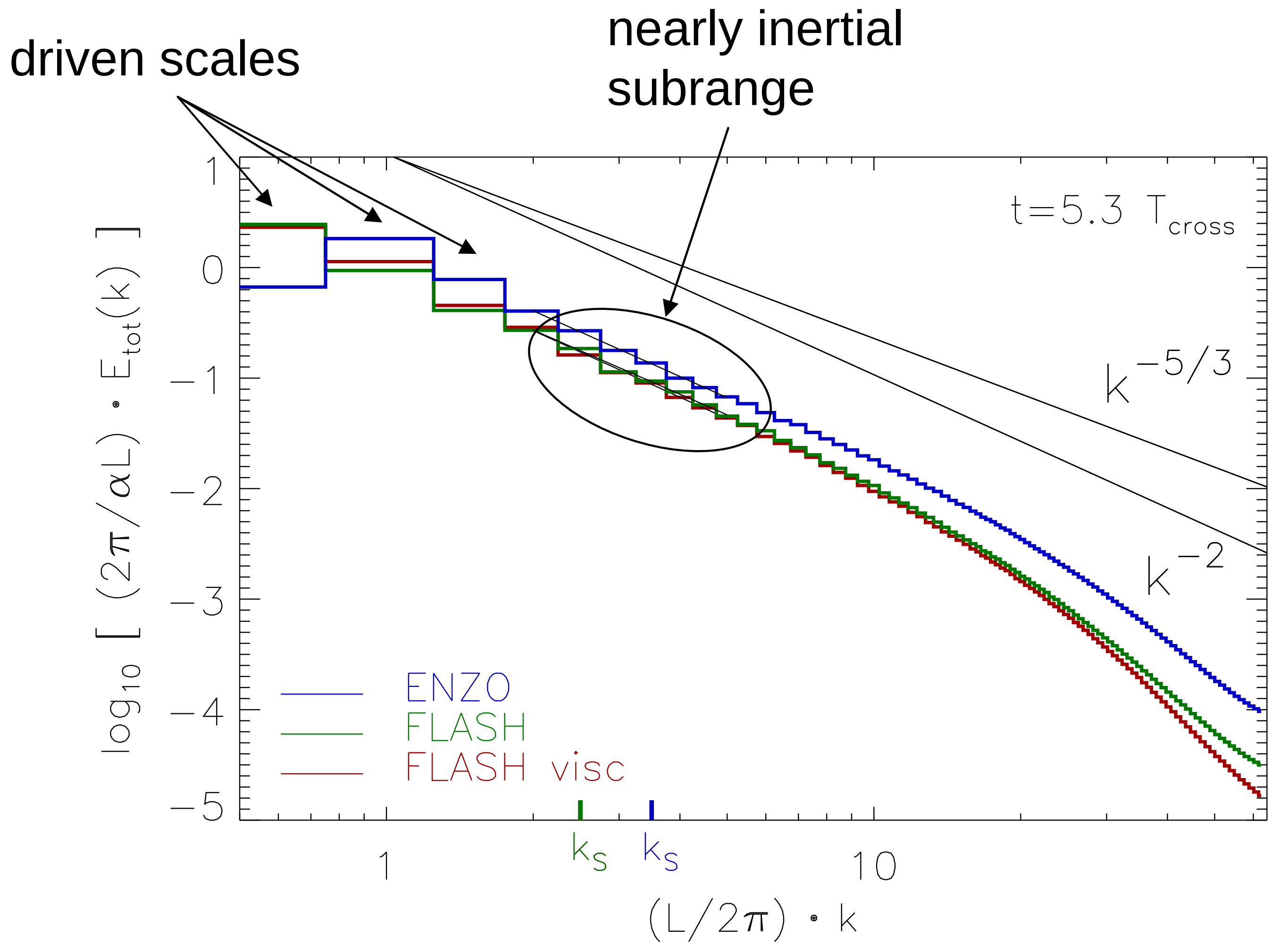

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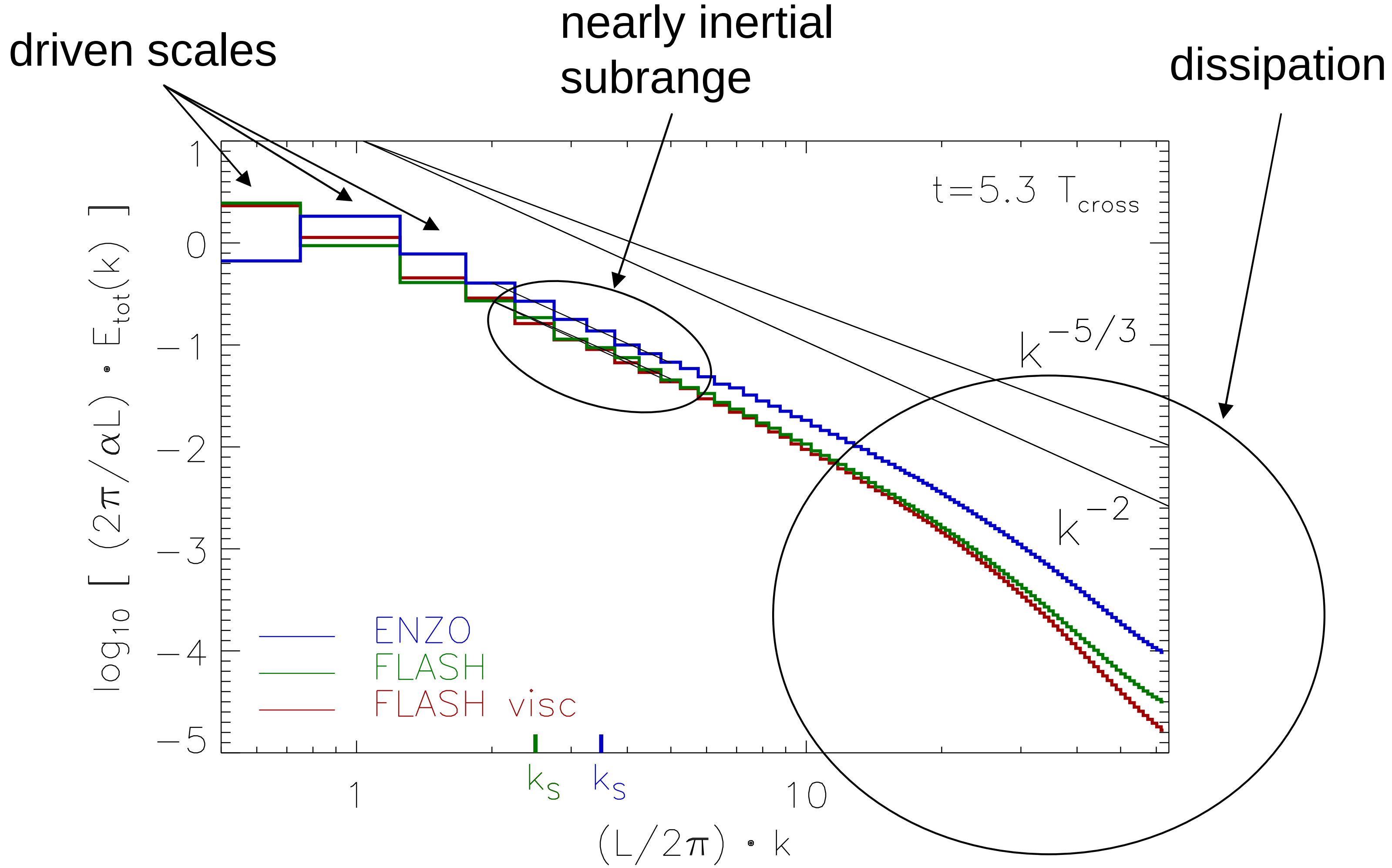

Turbulence code comparison

3D turbulence test case:

driven/stirred/forced compressible turbulence

performance: running on 64 cpus (Intel Itanium)

ENZO	FLASH3	FLASH3 visc
467 cpu-h	272 cpu-h	243 cpu-h
	(Uniform Grid mode)	(Uniform Grid mode)

Conclusions

- 2D test case: Kelvin-Helmholtz-instability
- 3D test case: forced compressible turbulence
  - FLASH3 and ENZO both produce robust and statistically similar results
  - FLASH3 Uniform Grid is ~2x faster than ENZO and ~3x faster than FLASH3 Paramesh3
  - Passive particles have minor effect on overall computatinal cost in both codes

Outlook

- Modify FLASH3 stirring implementation to account for *compressive forcing*
- include *self-gravity*, *smart sink particles*, *magnetic fields, AMR*