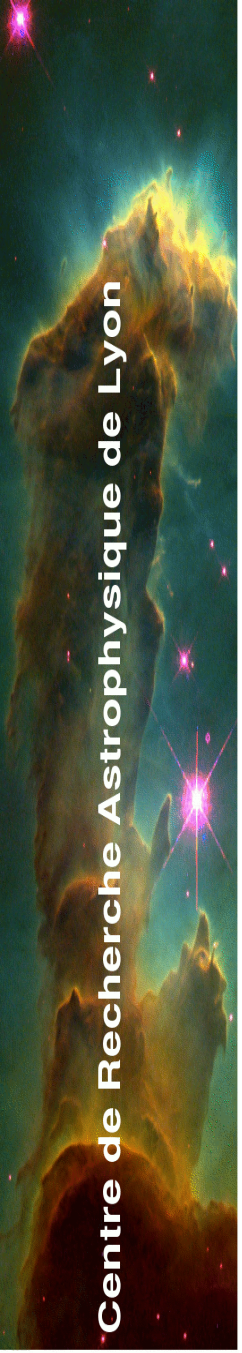
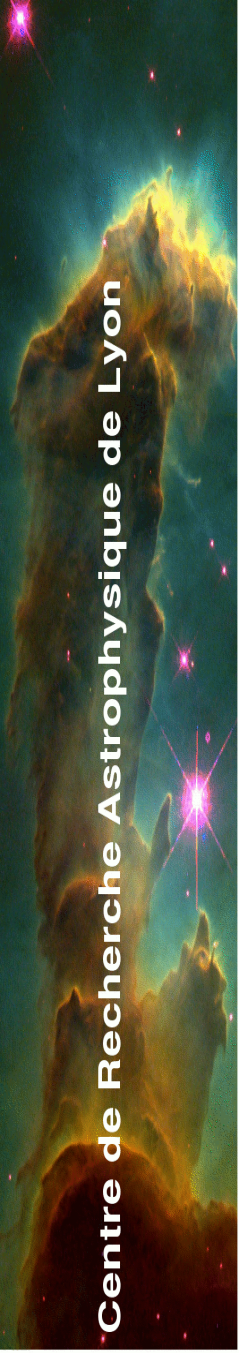


Supersonic Turbulence in Shock Bound Slabs

Doris Folini and Rolf Walder, CRAL, ENS Lyon, France

Visualization by Jean Favre, CSCS Manno, Switzerland

ECOLE NORMALE SUPERIEURE DE LYON



Outline

- shock bound slabs: why study?
- plane parallel isothermal shock bound slabs
  - boundary of slab $\leftrightarrow$ turbulence in slab
  - self-similarity
  - structure functions, modeled $\leftrightarrow$ observed
- summary / conclusions

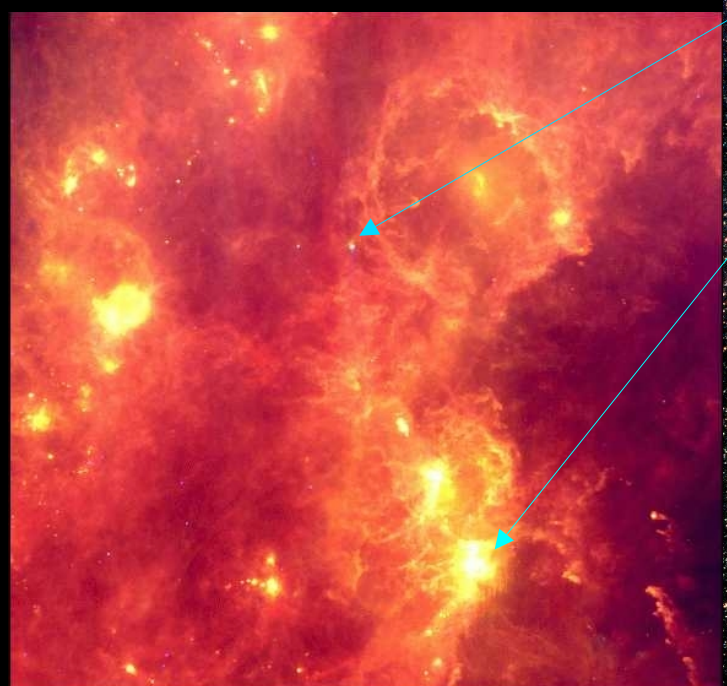
ECOLE NORMALE SUPERIEURE DE LYON

Shock Bound Slabs: another toy model for molecular clouds?

- cloud formation?
- star formation (IMF)?
- (driven) turbulence within cloud?

Orion: a giant molecular cloud

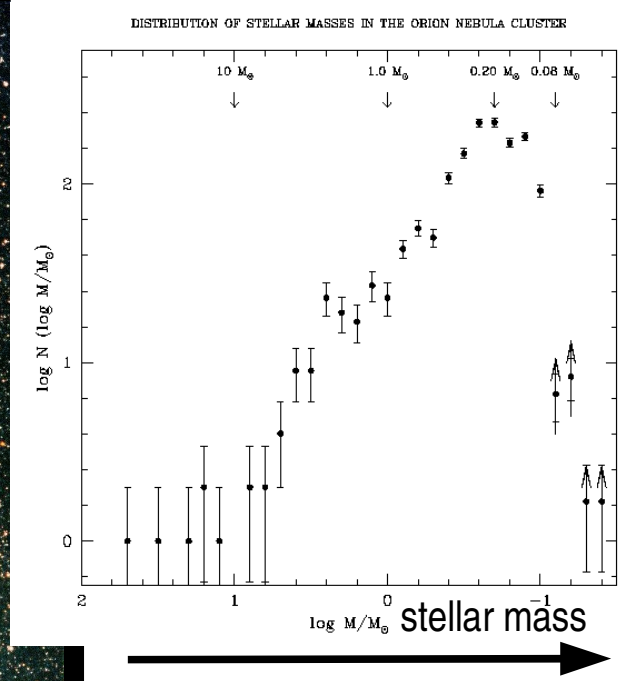
Distance: ~ 470pc
Mass: ~ 10^5 $M_\odot$
Diameter: ~ 30pc



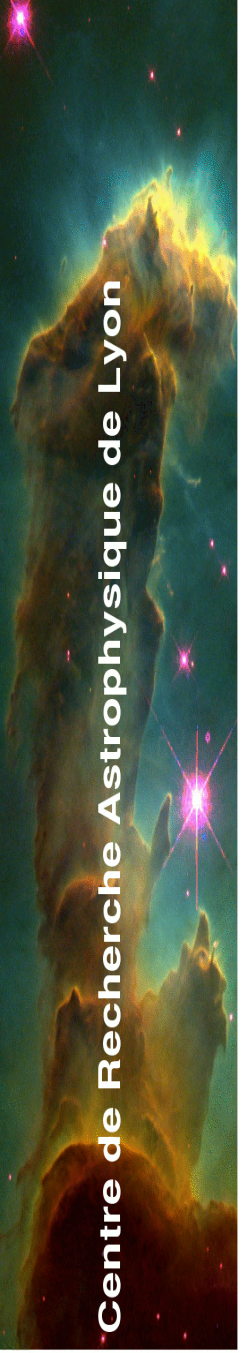
IRAS (12, 60, 100μ; 30°x24° ~240x200 pc)

Visible (S.Kohle & T.Credner)

Orion: stellar mass distribution



(L. Hillenbrand, Caltech)



From observations and (3D periodic box) simulations

- **molecular clouds are supersonically turbulent:**

  observations $\longrightarrow$ supersonic rms-velocities

- **the turbulence must be driven:**

  if not $\longrightarrow$ decay within a sound crossing time

  $\longrightarrow$ higher star formation rate than observed

- **the driving occurs at large scales:**

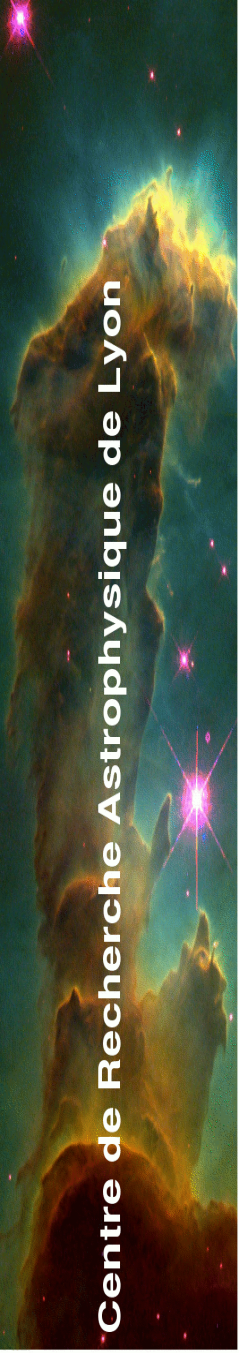
  observations $\longrightarrow$ large scales dominate velocity field and structure of low-density gas

  3D box models $\longrightarrow$ driving wavelength sets structure size

Our focus, somewhat complementary to 3D box:

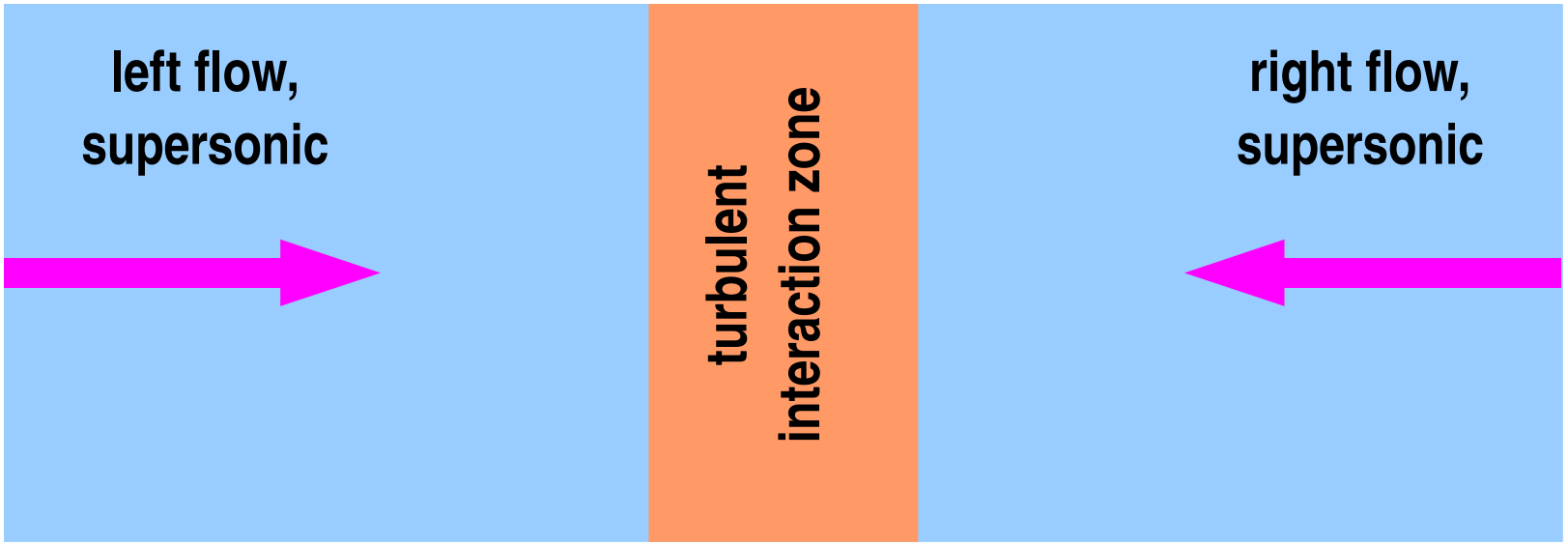
- study one possibility of a more natural forcing
- study interplay confining shocks $\longleftrightarrow$ turbulence

ECOLE NORMALE SUPERIEURE DE LYON



Model problem:

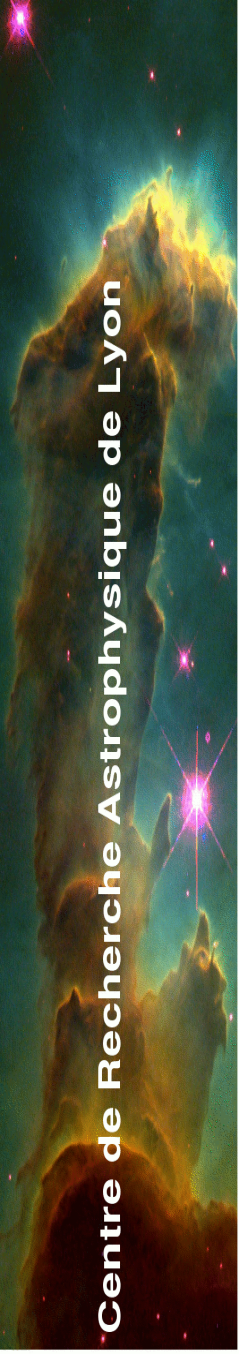
2D (3D) plan parallel isothermal colliding flows



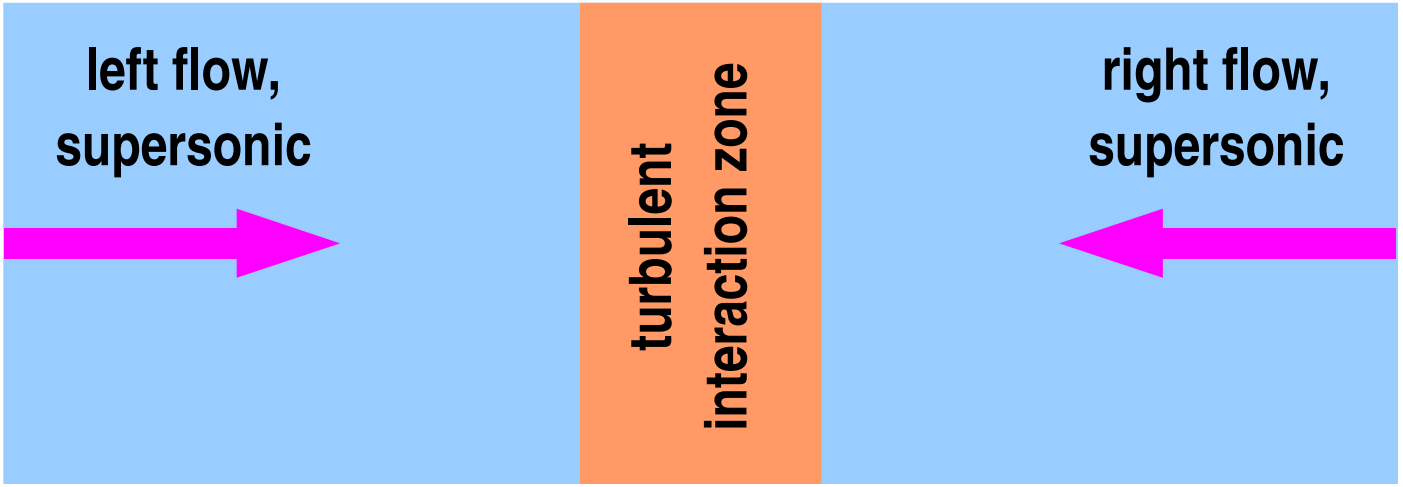
Computations done with A-MAZE:

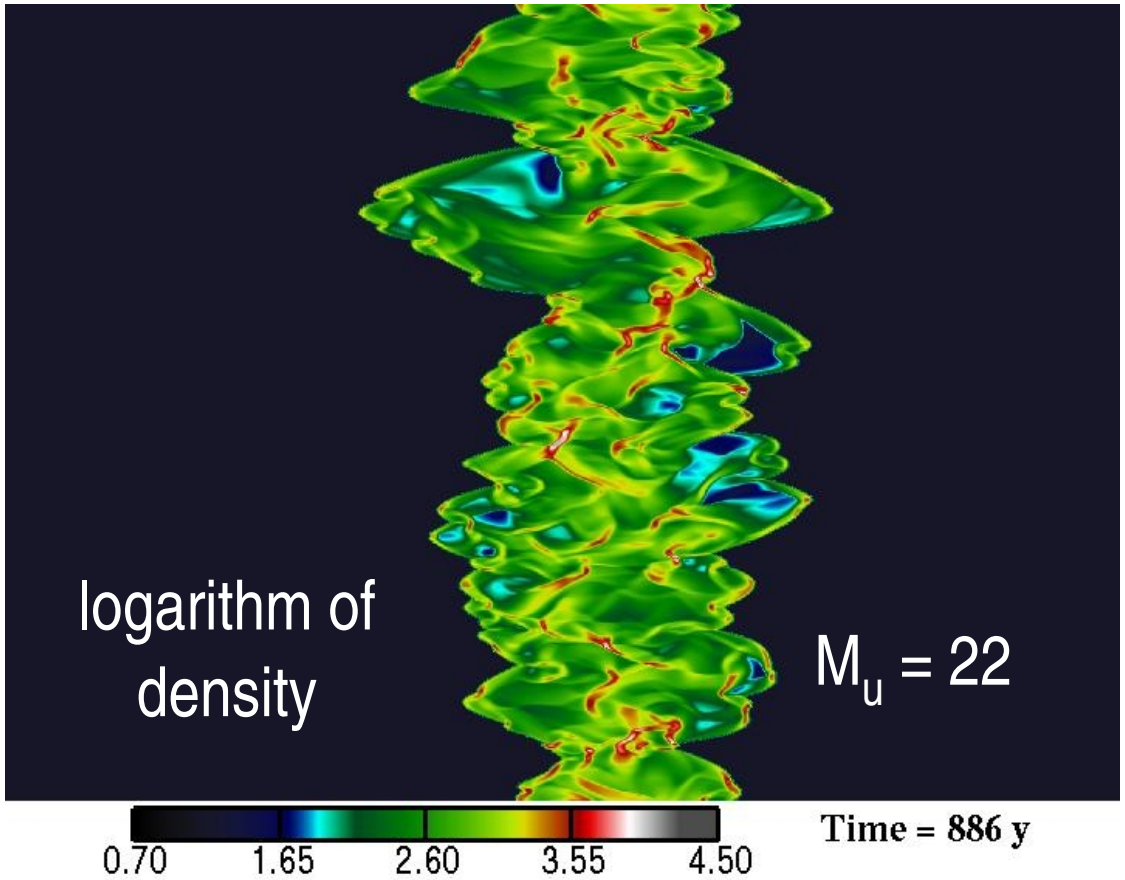
- ideal hydro
- AMR following evolution of growing interaction zone

ECOLE NORMALE SUPERIEURE DE LYON



2D plan parallel isothermal colliding flows





Interplay:

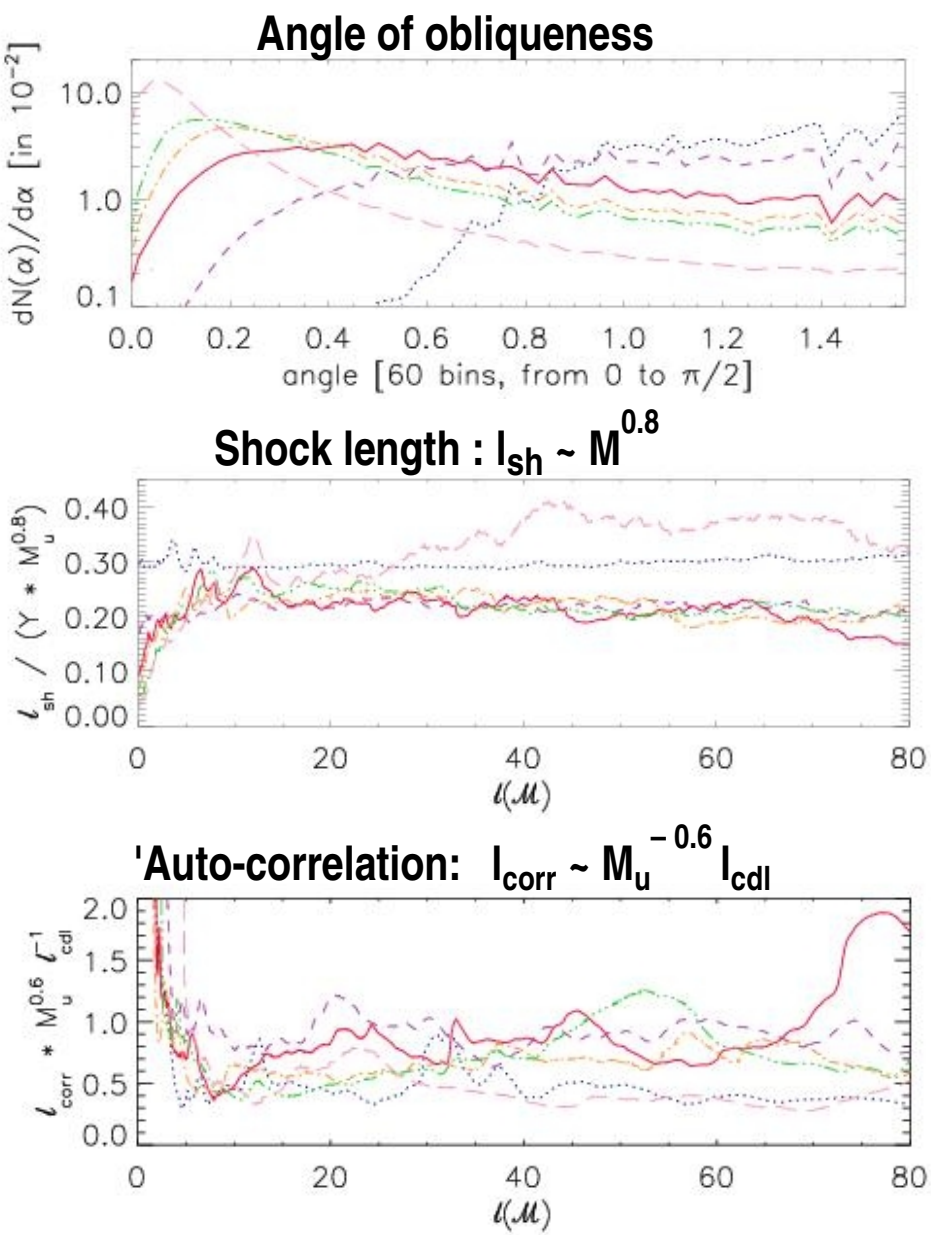
Oblique confining shocks force turbulence

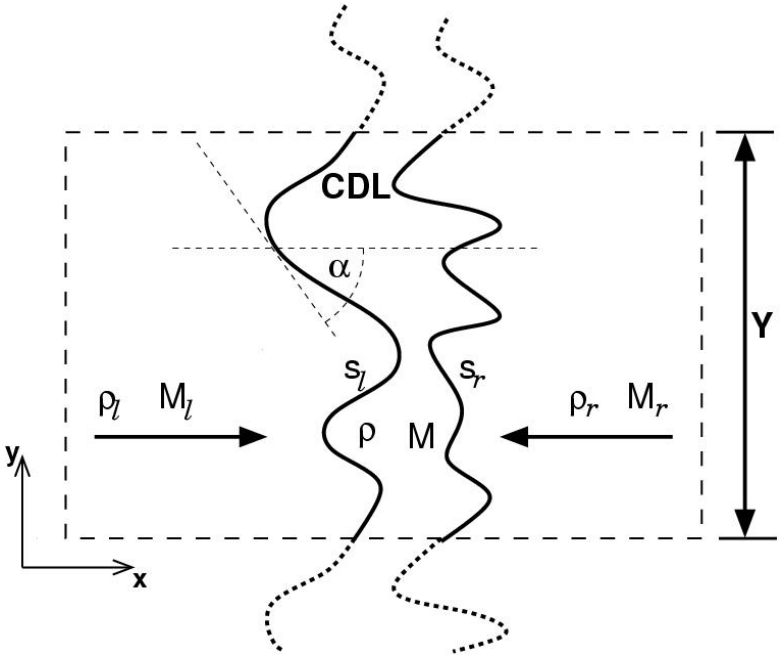
$\leftrightarrow$

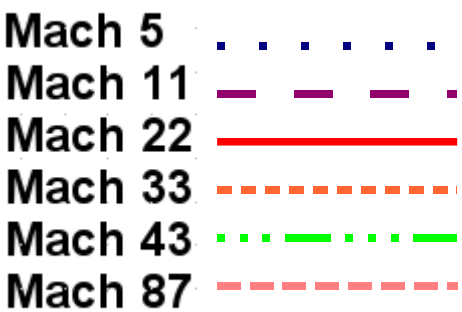
turbulence forces shocks to be oblique

ECOLE NORMALE SUPERIEURE DE LYON

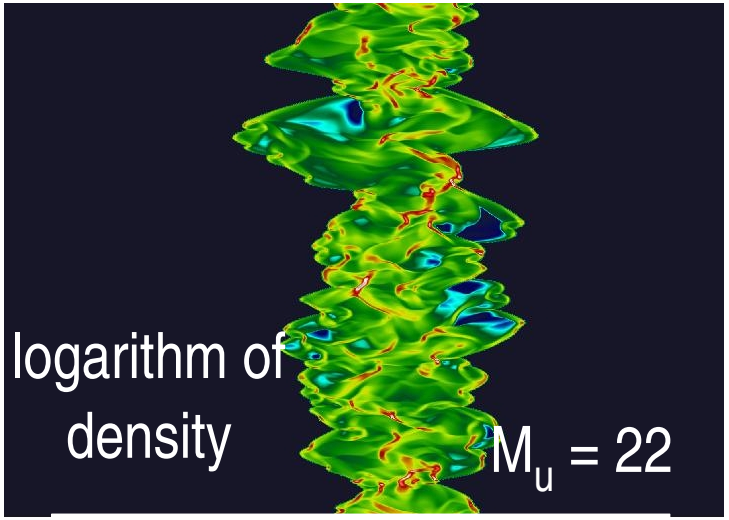
Higher upstream Mach number ⇒ confining shocks have more narrow, steeper wiggles with larger amplitude







(Folini & Walder, A&A, 2006)



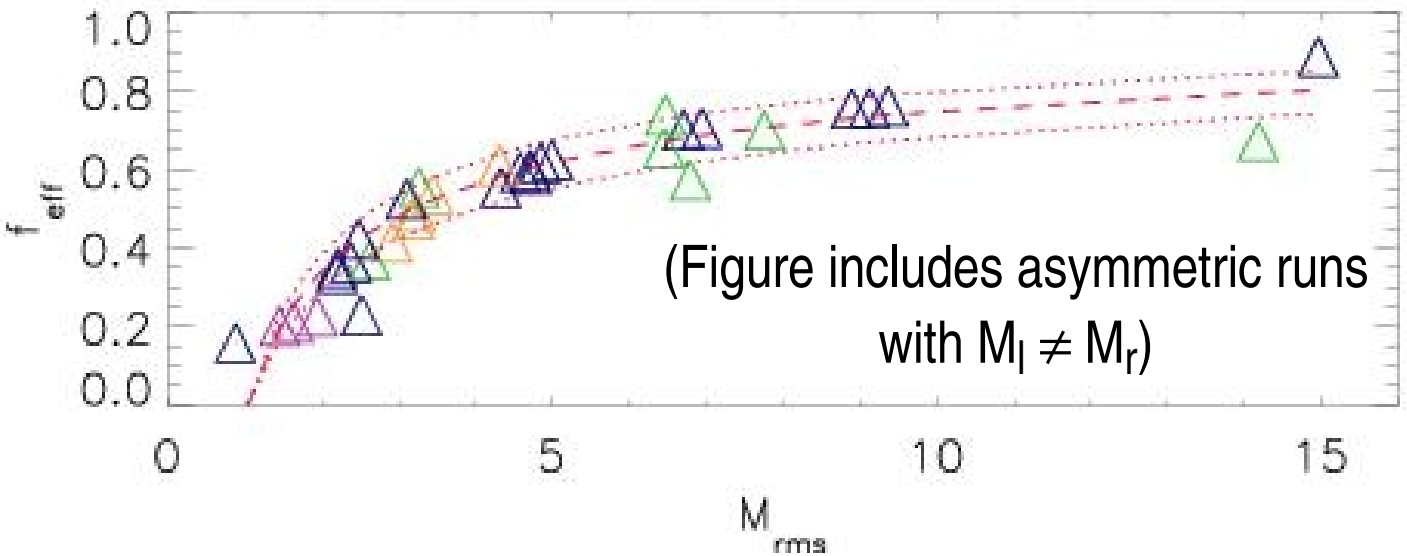
upstream kinetic energy flux

$$\mathcal{F}_{\mathrm{e_{kin},u}} = \rho_{\mathrm{u}} v_{\mathrm{u}}^3$$

kinetic energy flux entering slab

$$\dot{\mathcal{E}}_{\mathrm{drv}} = f_{\mathrm{eff}}(M_{\mathrm{u}}) \mathcal{F}_{\mathrm{e_{kin},u}}$$

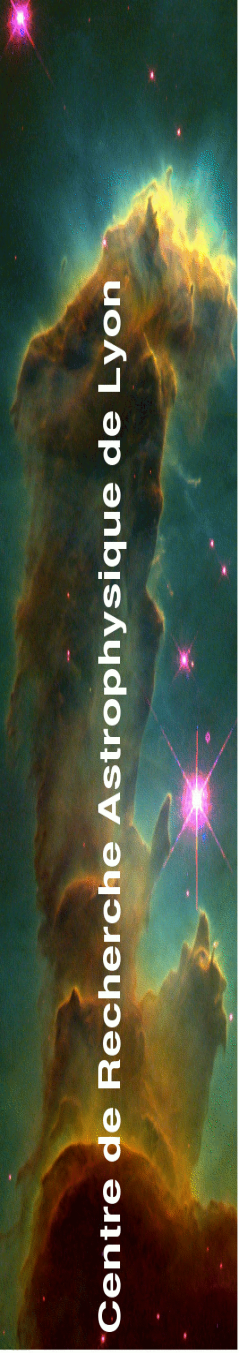
$$f_{eff} = f_{eff}(M_{rms}) = 1 - M_{rms}^{-0.6}$$



driving efficiency f_{eff} goverened by M_{rms},

indicating back-coupling of driving and turbulence

"turbulence forces shocks to be oblique"



scaling laws for mean quantities (like M_{rms}): dimensional analysis suggests self-similarity

Dimensional considerations:

$$
\begin{aligned}
(1) \qquad \rho_{\mathrm{m}} &= \eta_1 \rho_{\mathrm{u}} M_{\mathrm{u}}^{\beta_1} = \eta_1 \rho_{\mathrm{u}} \\
(2) \qquad M_{\mathrm{rms}} &= \eta_2 M_{\mathrm{u}}^{\beta_2} = \eta_1^{-1/2} M_{\mathrm{u}} \\
(3) \qquad \kappa_{2\mathrm{d}} &= \ell_{\mathrm{cdl}}/\tau = 2\eta_1^{-1} a M_{\mathrm{u}} \\
(4) \qquad \mathcal{E}_{\mathrm{drv}} &= \rho_{\mathrm{u}} a^3 M_{\mathrm{u}}^3 \boxed{(1 - \eta_3 M_{\mathrm{u}}^{\beta_3})} \quad f_{eff} \\
(5) \qquad \mathcal{E}_{\mathrm{dis}} &= \rho_{\mathrm{u}} a^3 M_{\mathrm{u}}^3 (1 - 2\eta_2^2 - \eta_3 M_{\mathrm{u}}^{\beta_3}).
\end{aligned}
$$

Numerical simulations confirm:

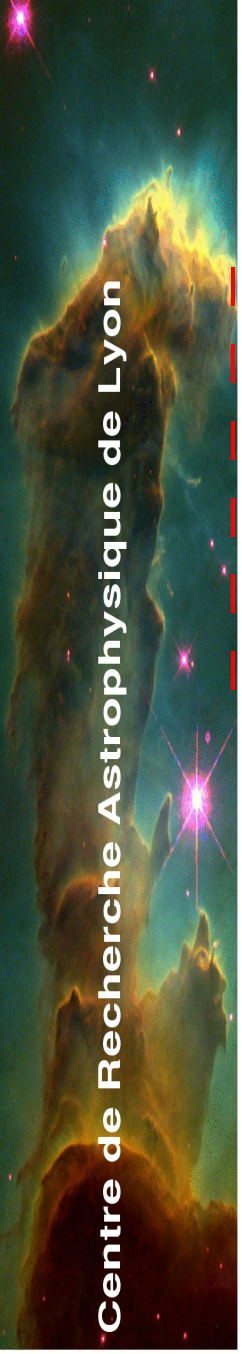
$\beta_1 = 0$ $\quad$ $\beta_2 = 1 - \beta_1 = 1$

Numerical simulations yield (2D):

$\eta_1 = 30$ $\quad$ $\eta_2 = (1/\eta_1)^{1/2} = 0.2$

$\beta_3 = -0.7$ $\quad$ $\eta_3 = 3.3$

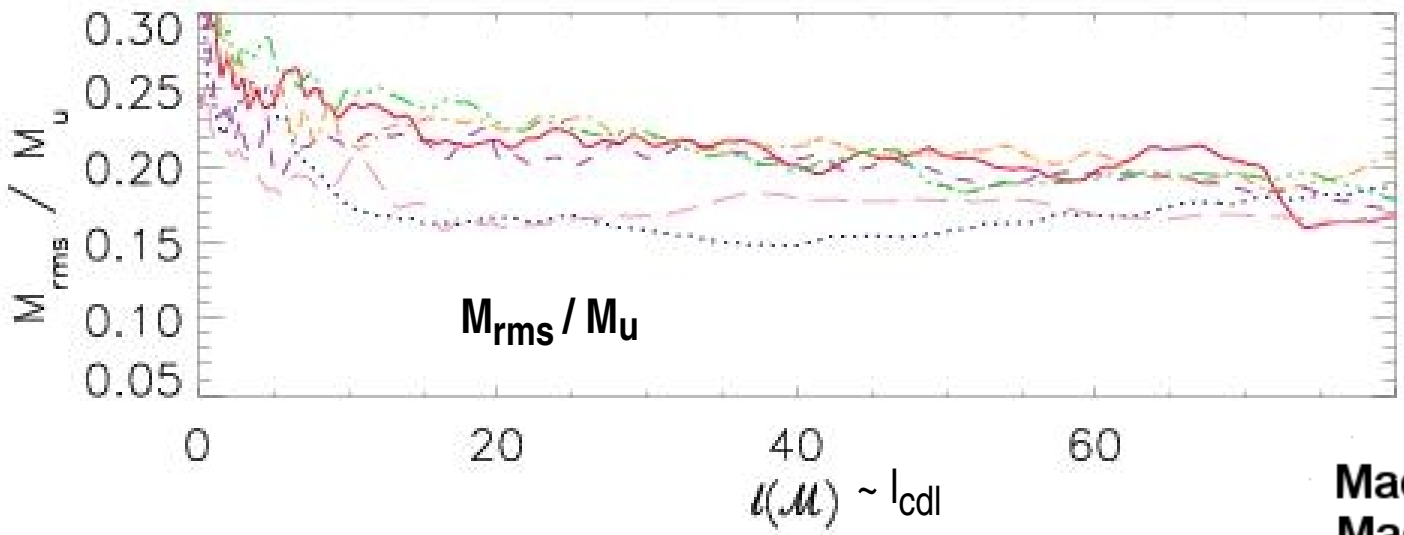
ECOLE NORMALE SUPERIEURE DE LYON

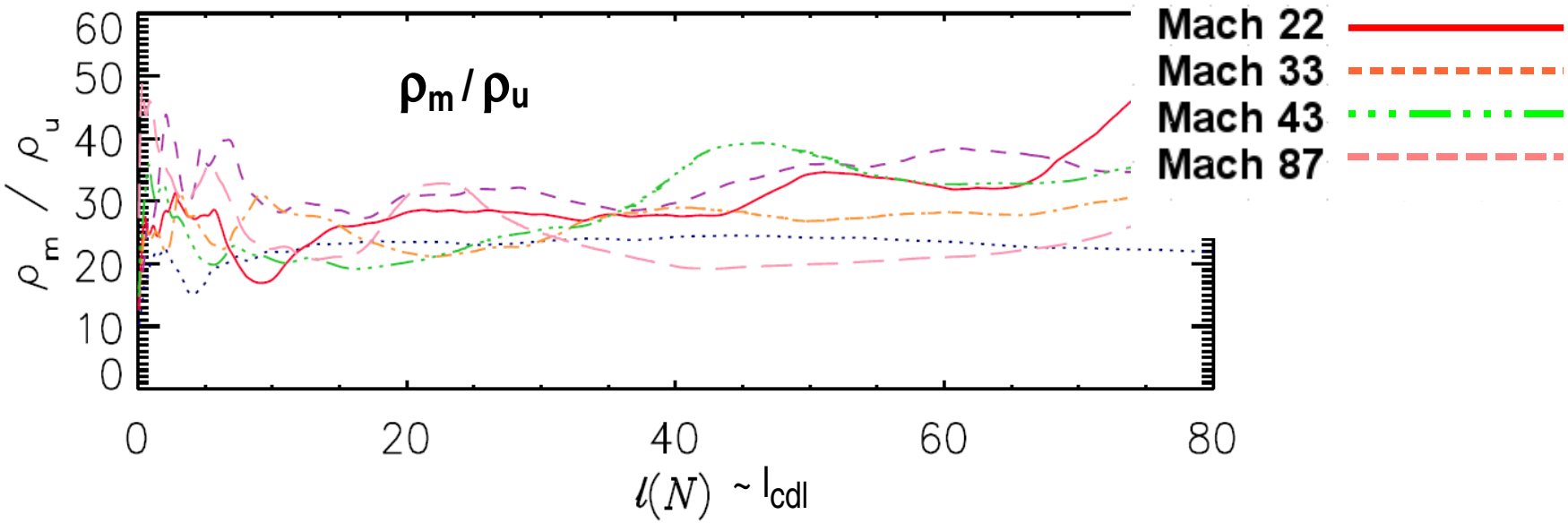


Numerical simulations, Mach number and density (2D):

Predicted : M_{rms} / M_u = const.

ρ_m / ρ_u = const. (independent of M_u !)



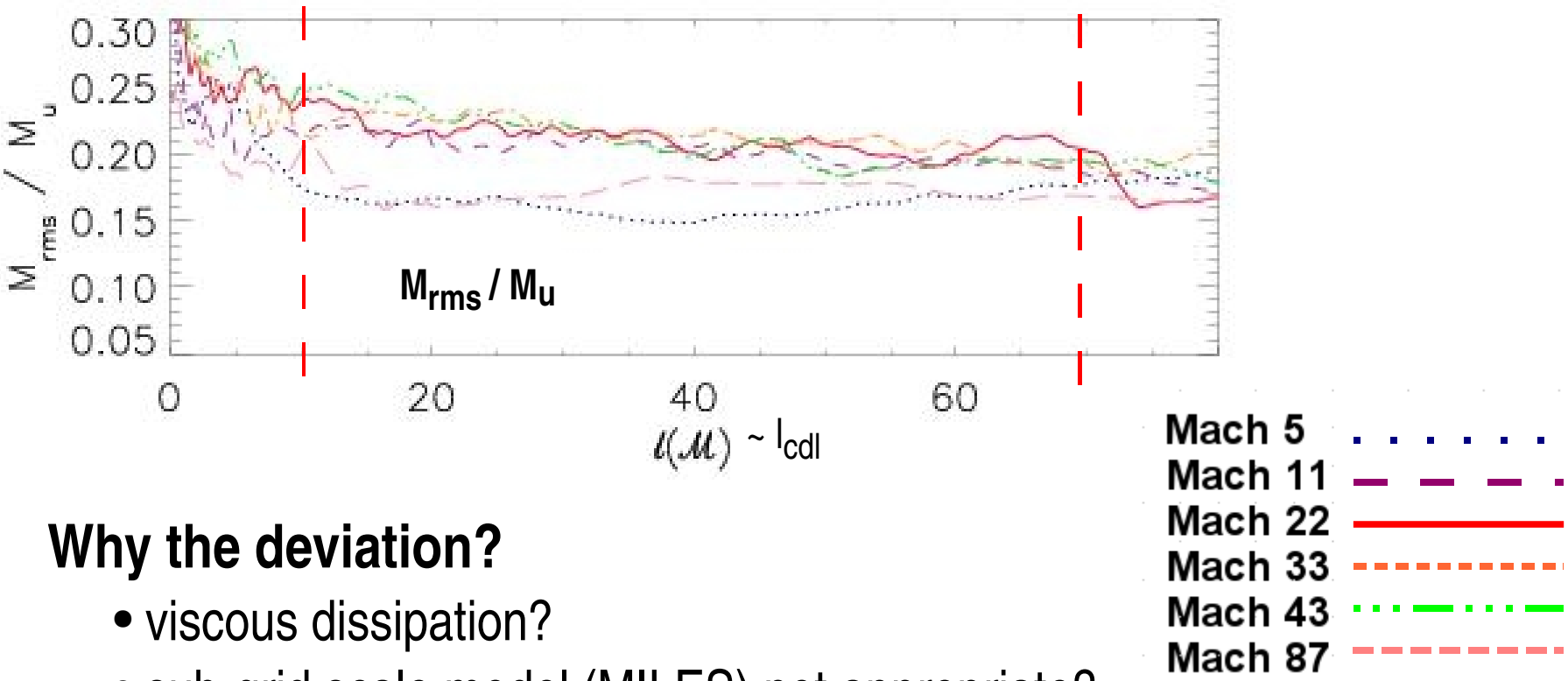


ECOLE NORMALE SUPERIEURE DE LYON

Second order effects I: slight decrease in M_{rms}

Predicted : M_{rms} / M_u = const.

Observed : 15% decrease as l_{cdl} goes from 10 to 70

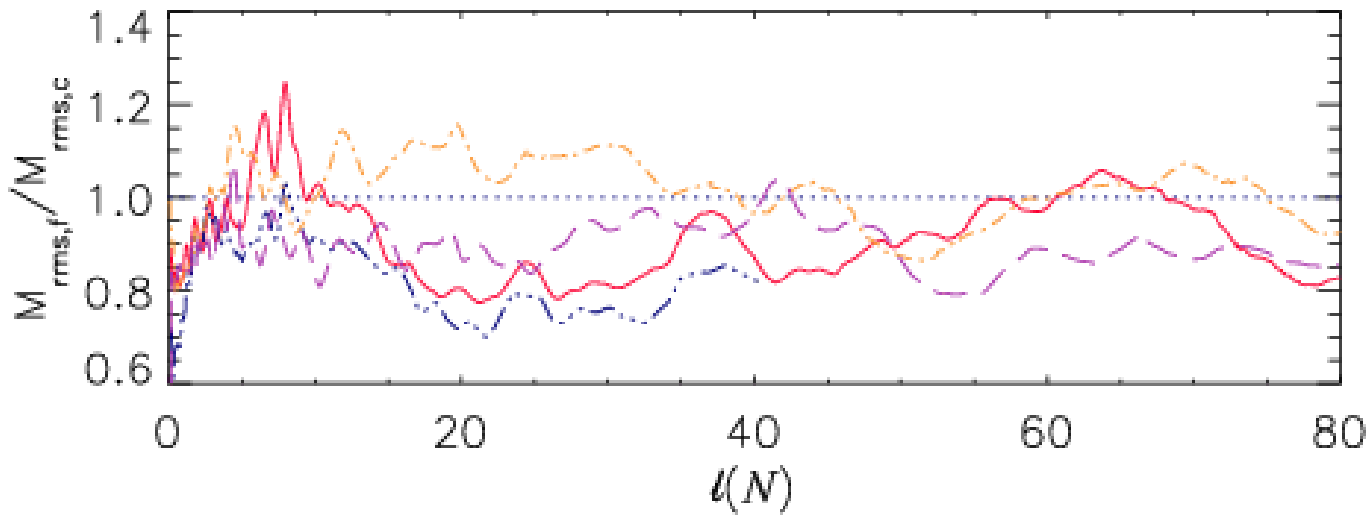


Why the deviation?

- viscous dissipation?
- sub-grid scale model (MILES) not appropriate?
- time scale of turbulence decay

'non-culprits' : y-extent of domain and spatial discretization

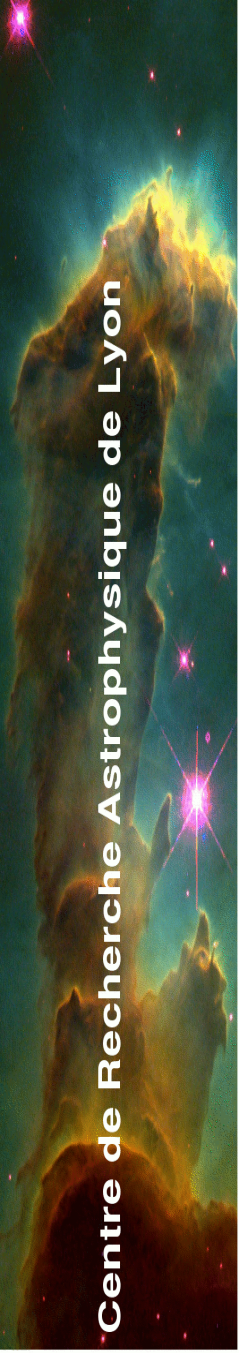
Second order effects II: no convergence so far



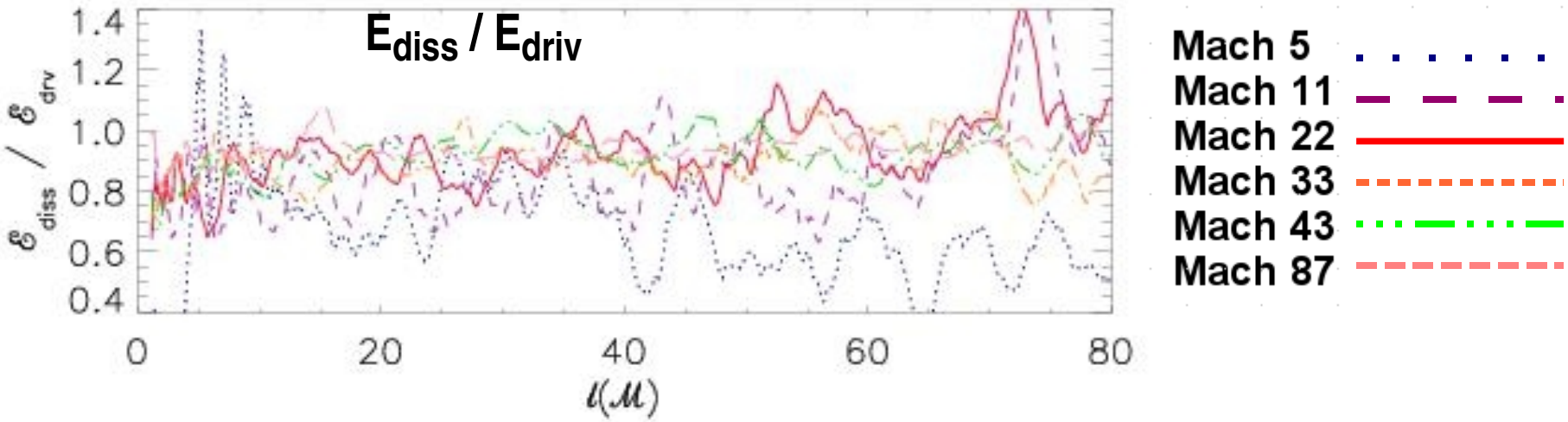
finer grids (factor 2) → smaller (15%) M_{rms}

Possible reasons?

- finer grids → more / better resolved shocks
  → enhanced total dissipation in shocks
- back coupling between M_{rms} and f_{eff} amplifies effect
- sub-grid scale model (MILES) sensitive to grid spacing?
  [MILES, monotone integrated large eddy simulation;
  Boris et al. 1992; Porter et al. 1992, 1994; Garnier et al. 1999]



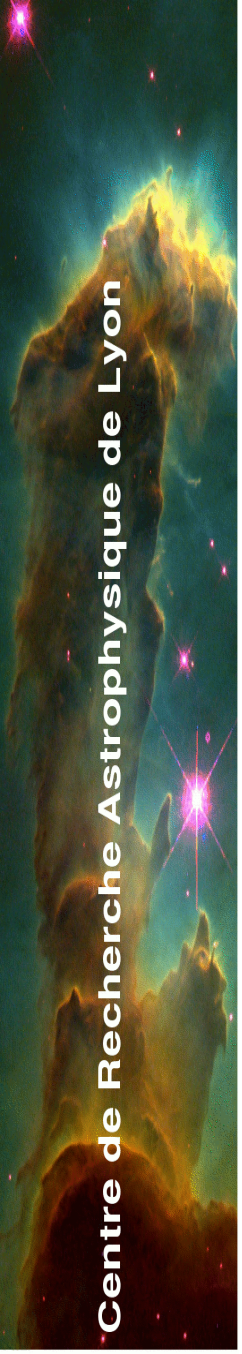
predicted by self-similarity & confirmed by simulations: column integrated dissipation independent from l_{cdl}

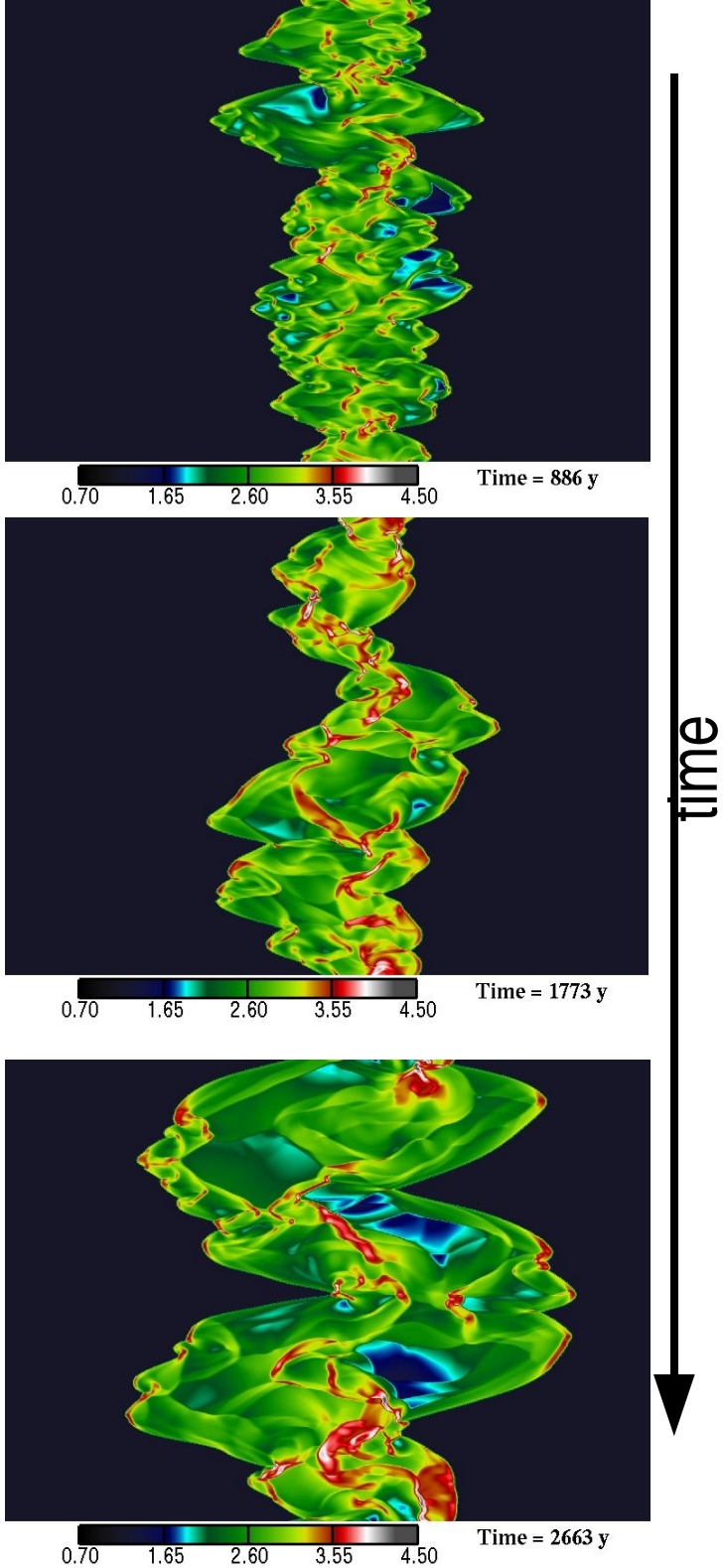


Possible explanation:

if self-similar, all length scales proportional to each other →
distance between shocks proportional to l_{cdl} →
number of shocks within CDL column constant →
column integrated dissipation (by shocks) constant

ECOLE NORMALE SUPERIEURE DE LYON





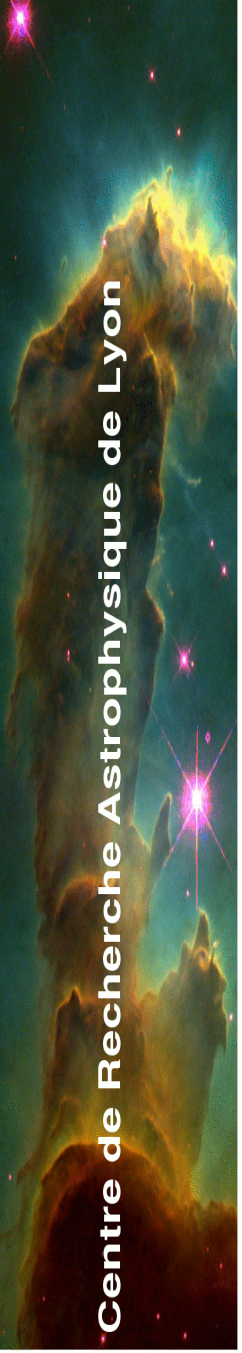
Density for three different times, three different shell sizes l_{cdl}

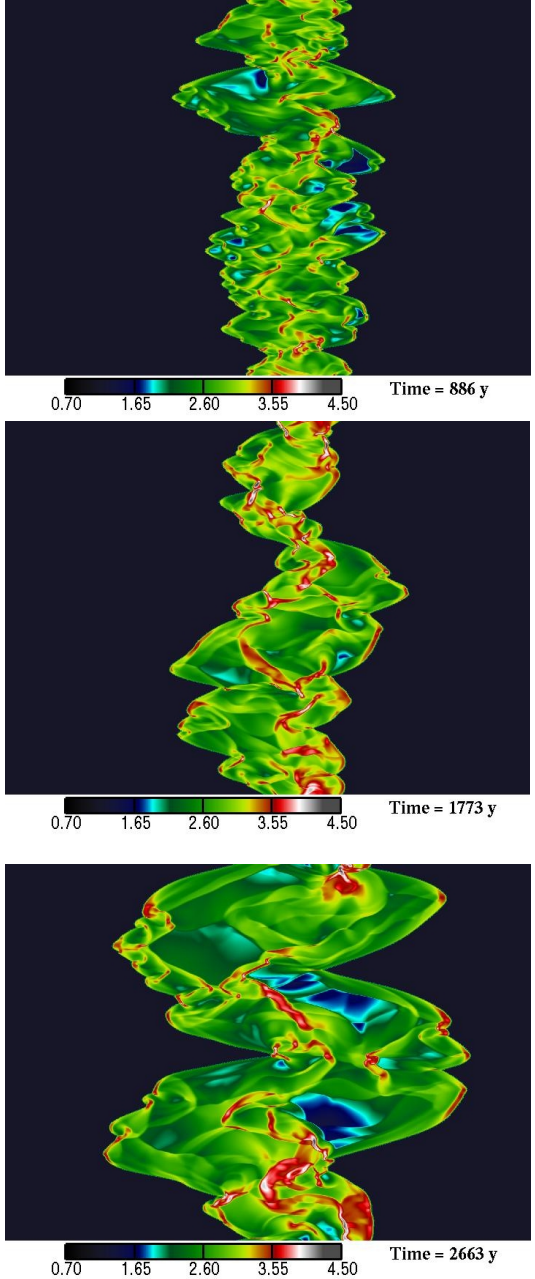
→ **Structure size increases with l_{cdl}**

hypothesis A:
wiggling of shocks →
effective driving wave-length →
scale of turbulence
(Mac Low, 1999, 3d box)

hypothesis B:
small scale structures decay first →
larger structures in center of CDL
(Smith et al., 2000)

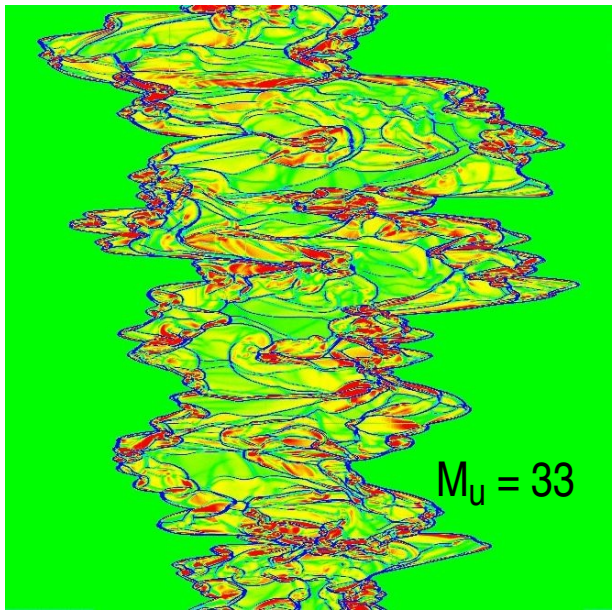
ECOLE NORMALE SUPERIEURE DE LYON

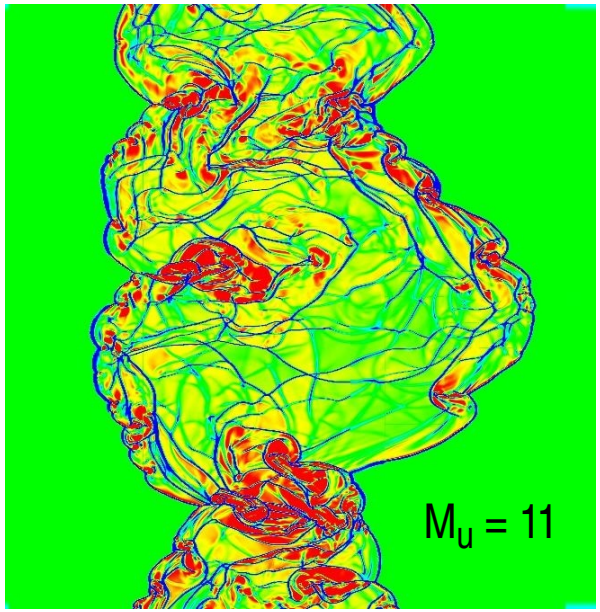




Structure size increases with l_{cdl}

Divergence for two different Mach numbers, same l_{cdl}

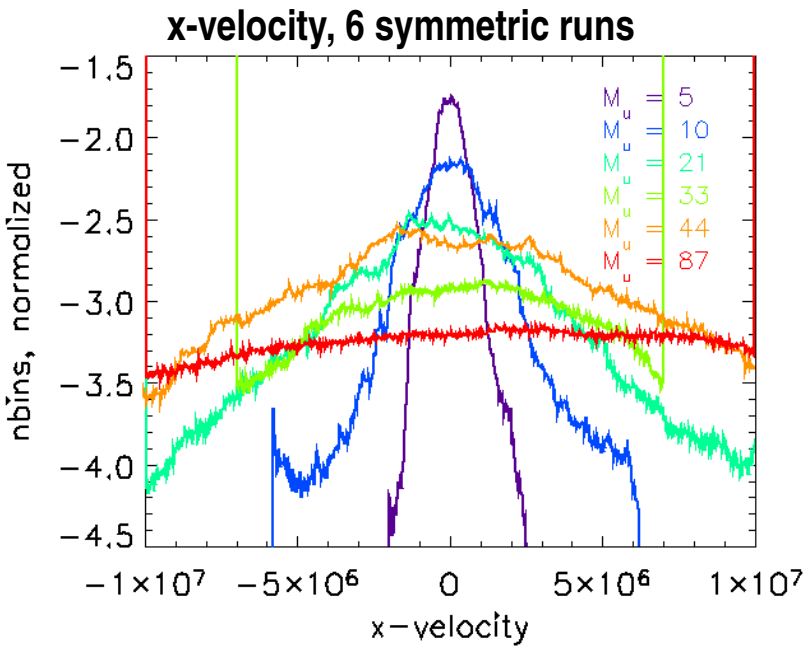


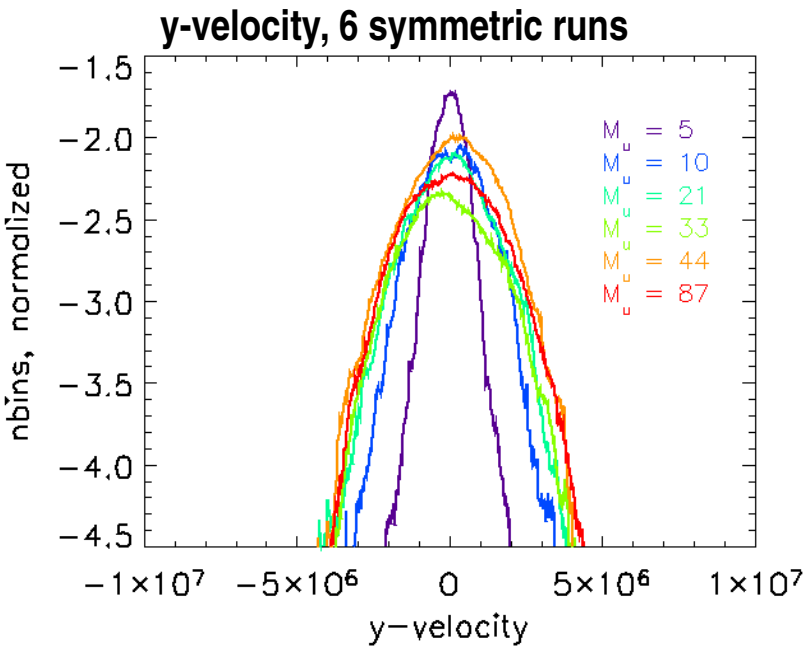


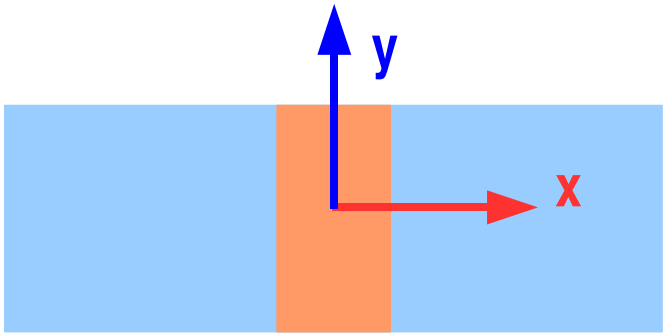
Structure size increases with decreasing upstream Mach number

ECOLE NORMALE SUPERIEURE DE LYON

velocity in slab clearly anisotropic



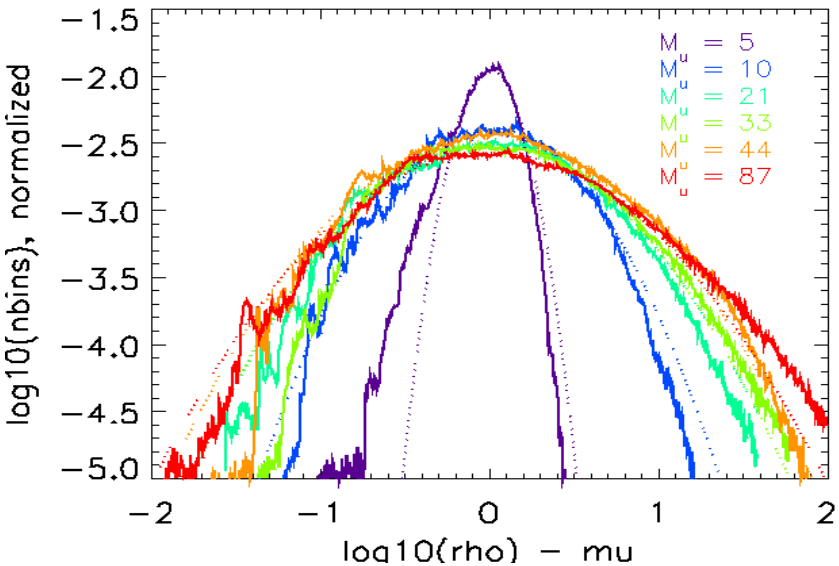


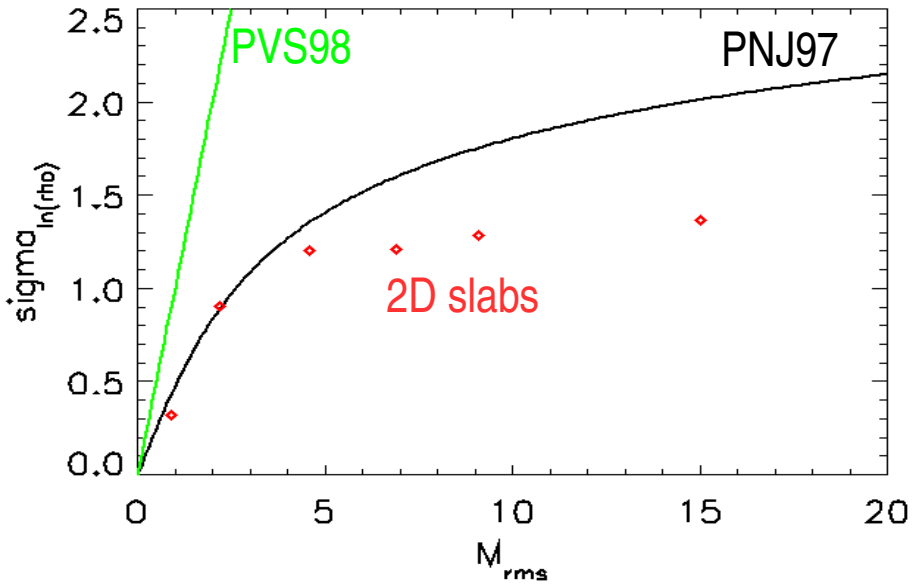


(Walder & Folini, 2000, ApSS, 274)

sound speed ~ $8 \cdot 10^5$ cm/s

width of density pdf levels off with large M_{rms}

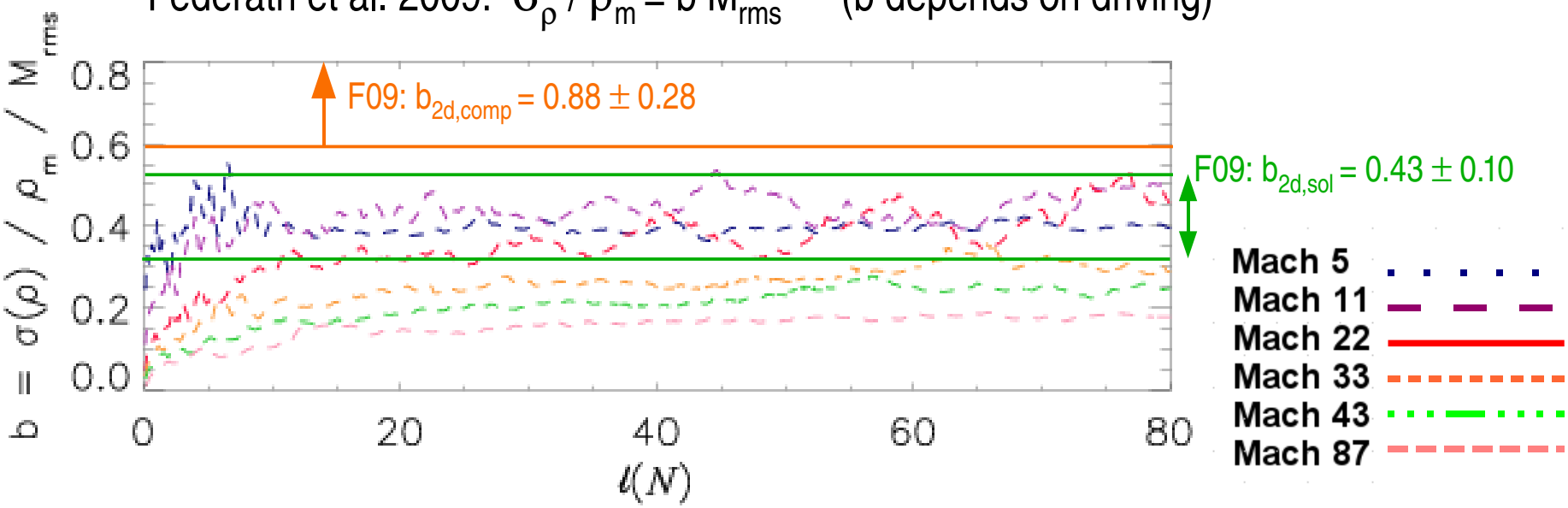




Passot & Vázquez-Semadeni, 1998, 1d data: $\sigma^2_{\ln(\rho)} \approx M^2_{rms}$

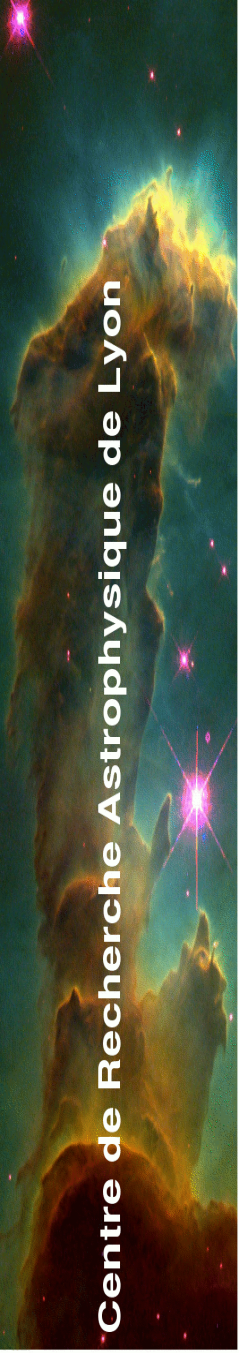
Padoan, Nordlund, & Jones, 1997, 3d data: $\sigma^2_{\ln(\rho)} \approx \ln(1 + M^2_{rms}/4)$

Federath et al. 2009: $\sigma_\rho / \rho_m = b\, M_{rms}$ (b depends on driving)



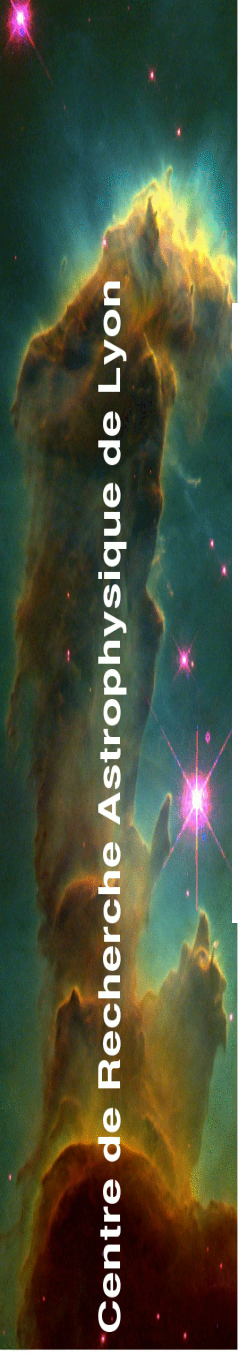
Centre de Recherche Astrophysique de Lyon

ECOLE NORMALE SUPERIEURE DE LYON



2D slabs ↔ 3D slabs?

ECOLE NORMALE SUPERIEURE DE LYON

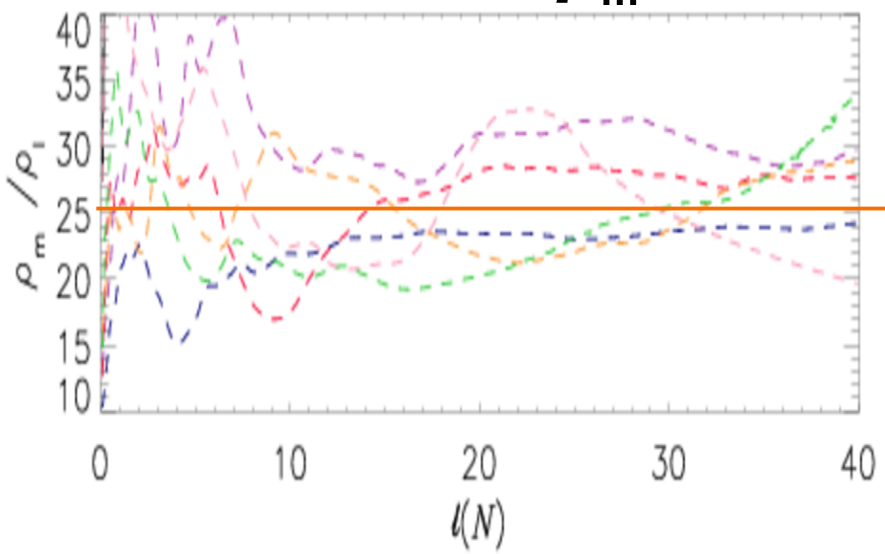


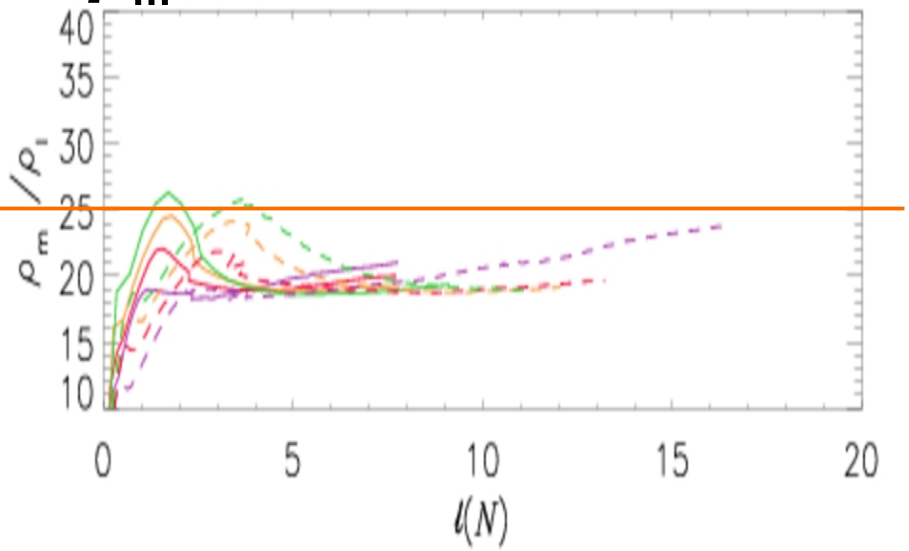
same upstream Mach number: 3D more turbulent

2D

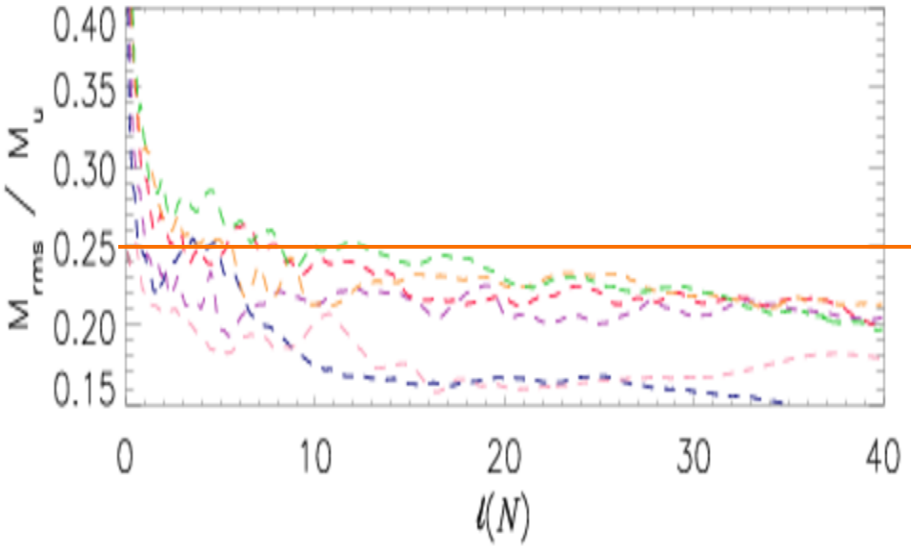
$\rho_m(2D) \approx 3/2\ \rho_m(3D)$

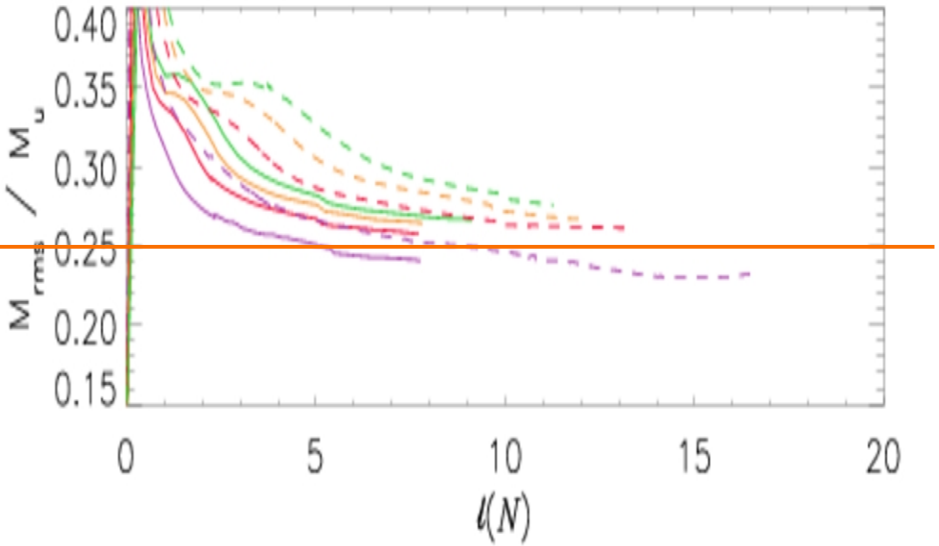
3D





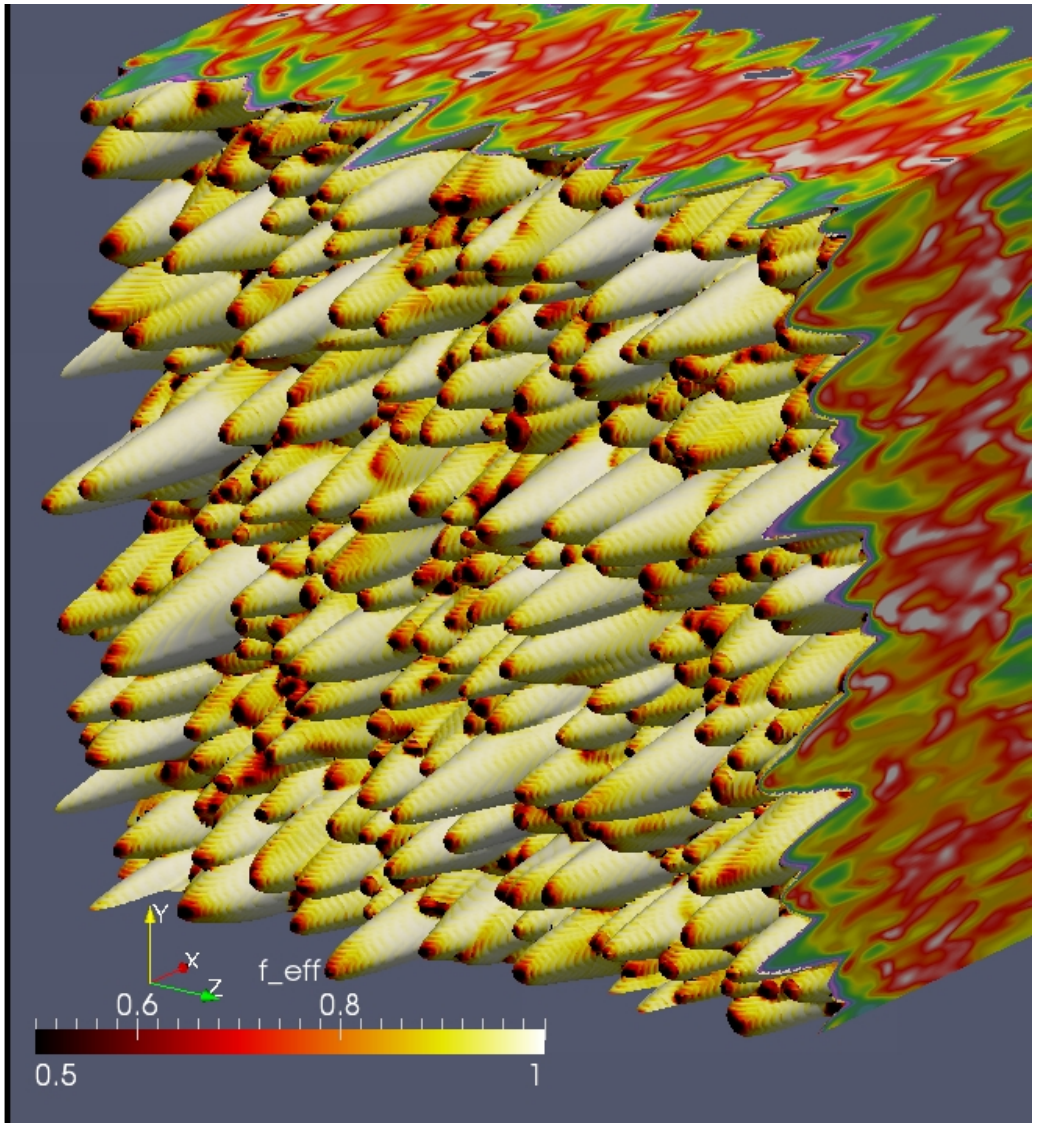
$M_{rms}(2D) \approx 0.8\ M_{rms}(3D)$





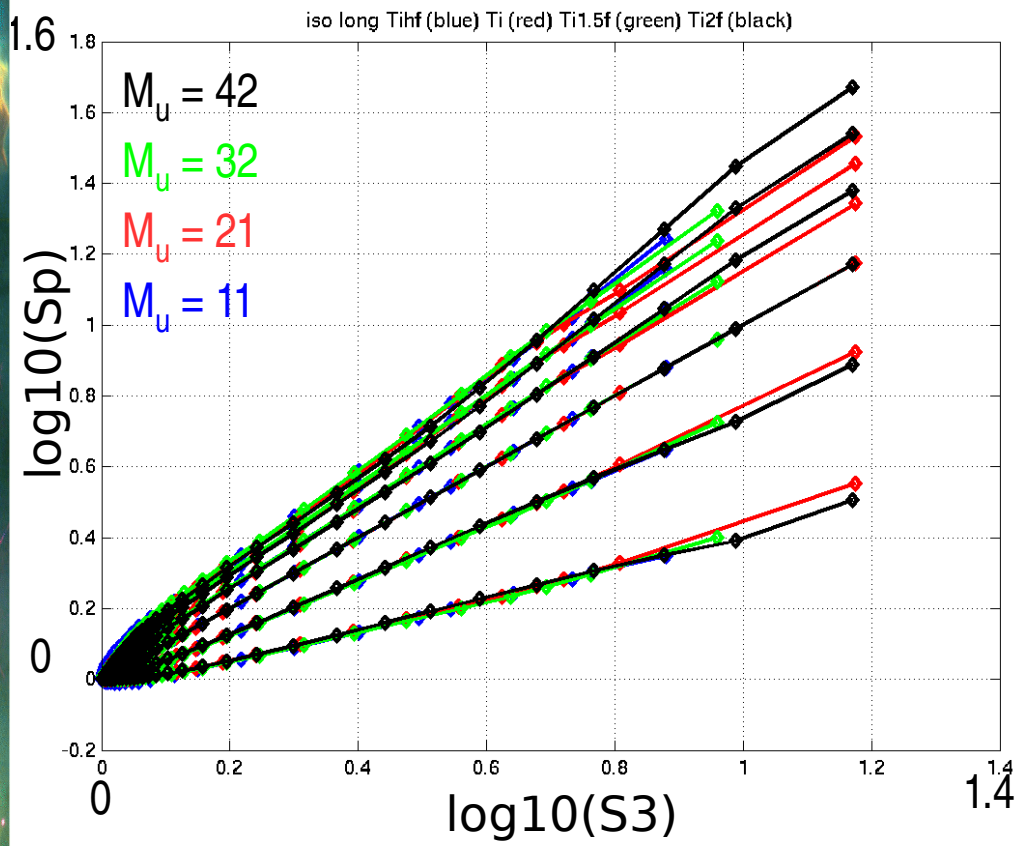
ECOLE NORMALE SUPERIEURE DE LYON

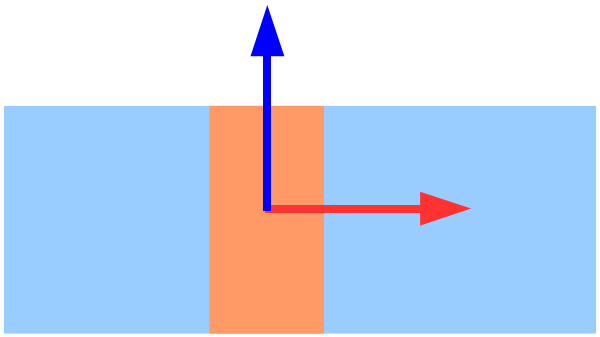
3D slabs: plane parallel isothermal symmetric



$$\dot{\mathcal{E}}_{\mathrm{drv}} = f_{\mathrm{eff}}(M_{\mathrm{u}})\mathcal{F}_{\mathrm{e_{kin},u}}$$

velocity structure functions (3D)

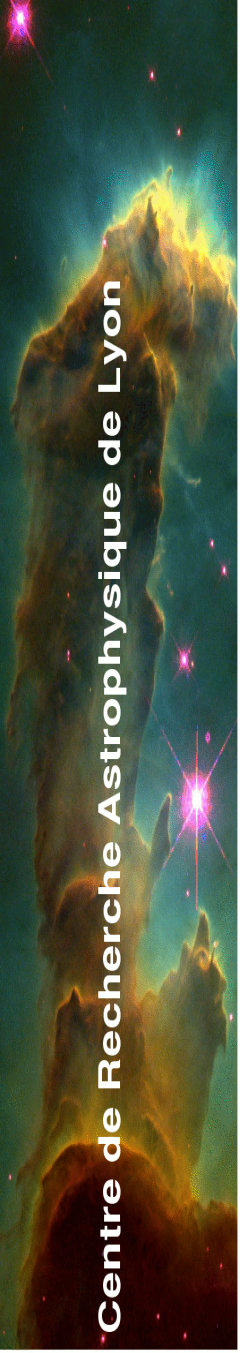




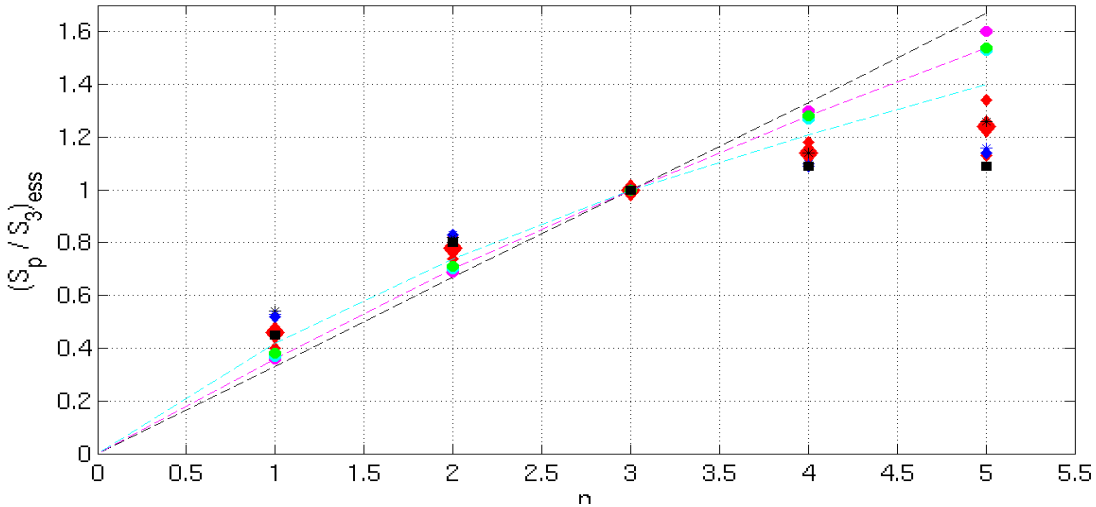
longitudinal & transverse directions:
no clear difference

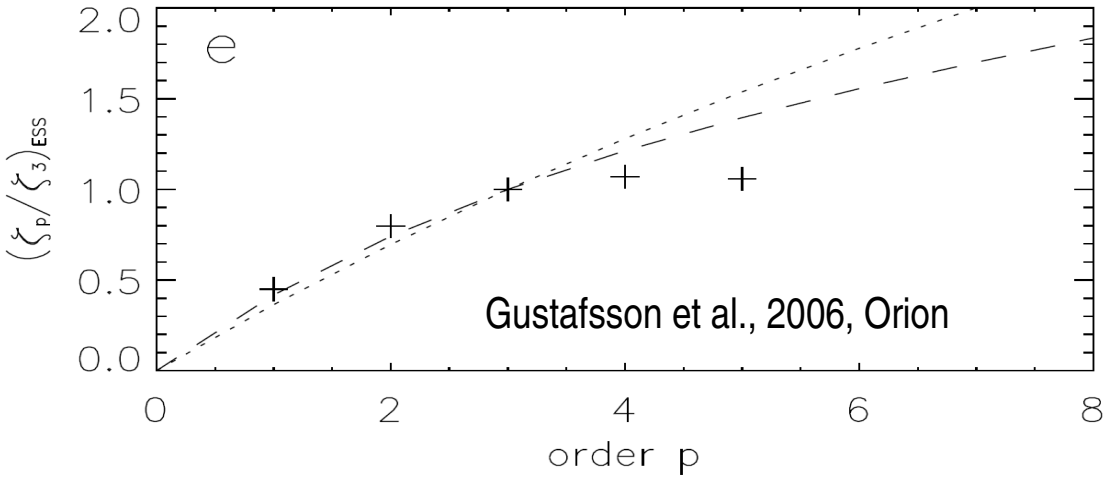
best agreement with
- Schmidt et al. 2009
- Dubrulle 1994

	3D slabs	Schmidt et al. 09	SL94	B02	K41
p=1:	0.40 / 0.52	0.52	0.36	0.42	0.33
p=2:	0.74 / 0.82	0.83	0.70	0.74	0.67
p=3:	1	1	1	1	1
p=4:	1.10 / 1.18	1.09	1.28	1.21	1.33
p=5:	1.12 / 1.33	1.14	1.54	1.40	1.67



red diamonds:
3D slabs
black squares:
Gustafsson et al. 2006 (Orion)
magenta/green circles:
Hily-Blant et al. 2008
(Polaris / Taurus)
blue diamonds:
Schmidt et al. 2009
blue/black stars:
Dubrulle 1994

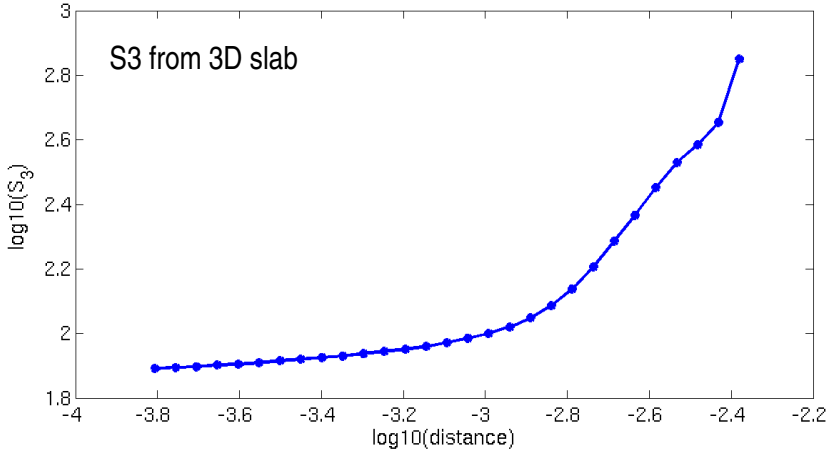


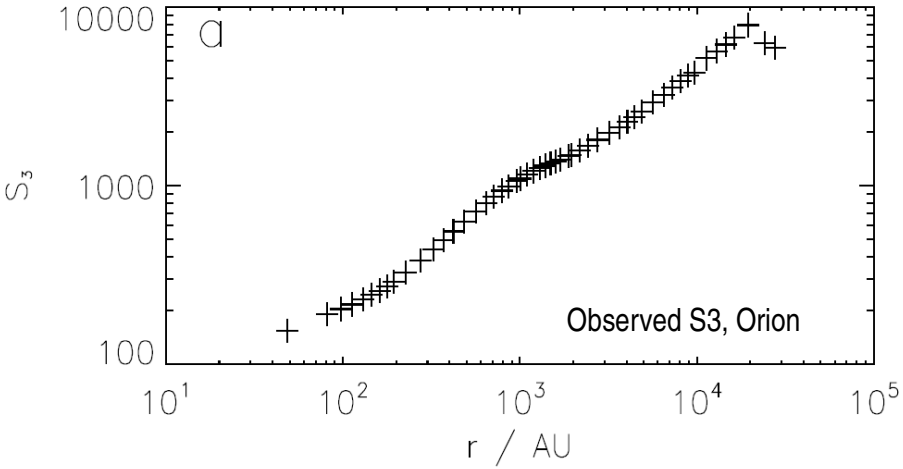


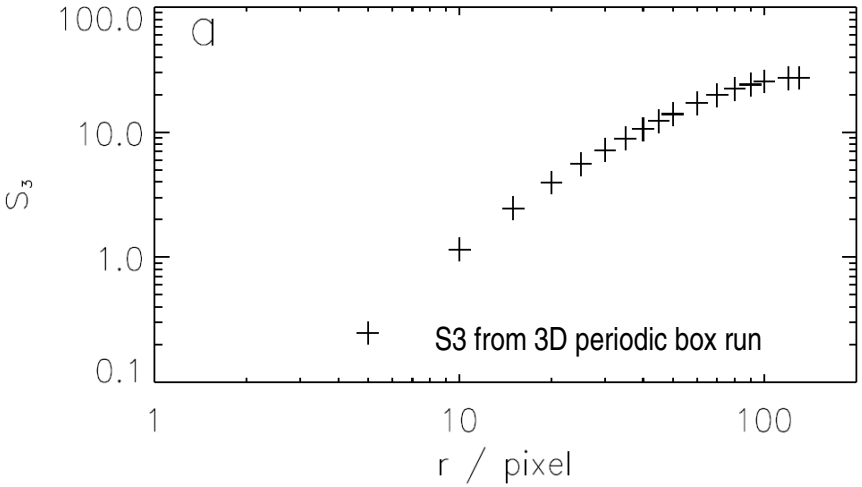
	3D slabs	Schmidt et al. 09	SL94	B02	K41
p=1:	0.40 / 0.52	0.52	0.36	0.42	0.33
p=2:	0.74 / 0.82	0.83	0.70	0.74	0.67
p=3:	1	1	1	1	1
p=4:	1.10 / 1.18	1.09	1.28	1.21	1.33
p=5:	1.12 / 1.33	1.14	1.54	1.40	1.67

ECOLE NORMALE SUPERIEURE DE LYON

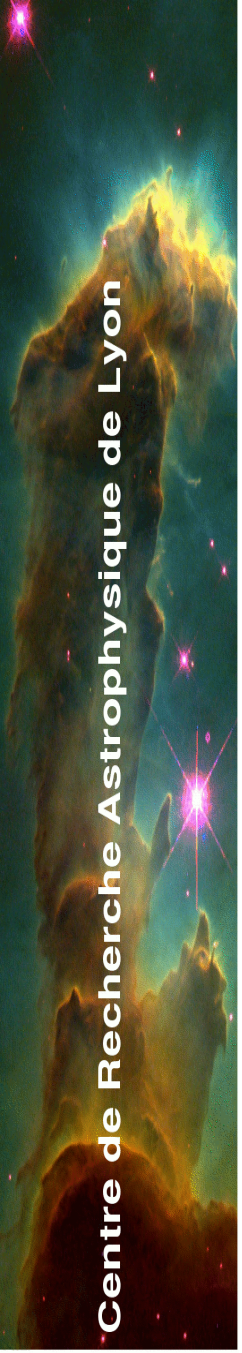
S3 not well represented by single power law in 3D slabs and Orion (Gustafsson et al, 2006)







Gustafsson et al., 2006



Summary / Conclusions

- confining shocks (driving) $\longleftrightarrow$ M_{rms} interior turbulence
  - driving more efficient in 3D and for larger M_u
  - thicker slab / smaller $M_u \rightarrow$ larger scale interior structure
  - mean quantities: self-similar, governed by M_u
- density pdf: width levels off with increasing M_{rms}
- S_p: no single power law, small exponents
- implications for molecular clouds?
  - velocities of colliding flows $M_u \geq 4\ M_{rms}$
  - naturally obtain “non-single-power-law” structure functions

ECOLE NORMALE SUPERIEURE DE LYON