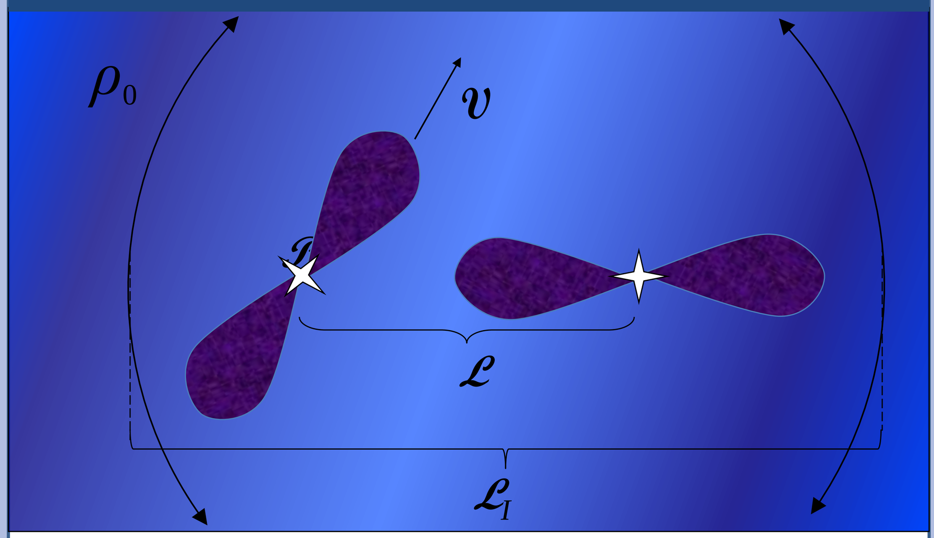
Isotropically Driven vs. Outflow Driven Turbulence in Molecular Clouds

Jonathan J. Carroll[1], Adam Frank[1], Eric G. Blackman[1]

[1] University of Rochester, Rochester, NY

Theoretical Model



Given spherical outflows with momentum $\mathcal{P}$ in an environment with density ρ_0 occuring at a rate per volume $\mathcal{S}$, a given outflow will sweep up a shell of mass $\mathcal{M} \approx \rho_0 \mathcal{L}^3$ travelling at a velocity $\mathcal{V} \approx \frac{\mathcal{P}}{\mathcal{M}}$ over a period of time $\mathcal{T} \approx \left(\mathcal{S}\mathcal{L}^3\right)^{-1}$ before encountering another outflow. Setting $\mathcal{V}\mathcal{T} = \mathcal{L}$ gives characteristic scales of length, mass, time :

$$\mathcal{L} = \left(\frac{\mathcal{P}}{\rho_0 \mathcal{S}}\right)^{1/7}, \mathcal{M} = \frac{\rho_0^{4/7}\mathcal{P}^{3/7}}{\mathcal{S}^{3/7}}, \mathcal{T} = \frac{\rho_0^{3/7}}{\mathcal{P}^{3/7}\mathcal{S}^{4/7}}$$

Combining these defines the velocity $\mathcal{V} = \frac{\mathcal{L}}{\mathcal{T}}$ and acceleration $\mathcal{A} = \frac{\mathcal{L}}{\mathcal{T}^2}$ scale. If we include a background isotropic forcing of similar strength $(\mathcal{A}_I = \mathcal{A})$, but on a larger scale $(\mathcal{L}_I = 4\mathcal{L})$, then this isotropic forcing will have a larger characteristic time scale $(\mathcal{T}_I = 2\mathcal{T})$ and a larger characteristic velocity $(\mathcal{V}_I = 2\mathcal{V})$.

Forcing Parameters

	Outflow Forcing	Isotropic Forcing
ρ_0	2.5e-20 g/cm^3	ρ_0
$\mathcal{P}$	21 $M_\odot$ km/s	128 $\mathcal{P}$
$\mathcal{S}$	59 pc^{-3}Myr^{-1}	$\mathcal{S}$/128
$\mathcal{L}$	.37 pc	4$\mathcal{L}$
$\mathcal{T}$	.34 Myr	2$\mathcal{T}$
$\mathcal{M}$	19 $M_\odot$	64$\mathcal{M}$
$\mathcal{V}$	1.07 km/s	2$\mathcal{V}$

Jet Parameters

Outflow Parameters	
ρ	2.5e-20 g/cm^3
v	65.5 km/s
t	2.34 kyr
r	5960 AU
θ	0
$\dot{M}$	1.3e-4 $M_\odot$ yr^{-1}

The high velocity of the outflows compared to the induced turbulent velocity makes the computation difficult. Each turbulent crossing time is ~60 outflow crossing times so each 512^3 simulation requires the resources of a typical 1400^3 simulation

Conclusions

- Outflows are able to sustain supersonic turbulence at levels consistent with the scaling relations from Matzner 2007.
- Outflow driven turbulence is characterized by a steeper velocity spectra and flatter density spectra than for isotropically driven turbulence.
- Velocity and density structures on sub-outflow scales are dominated by the presence of outflows and seem fairly unaffected by the presence of an external cascade.
- On larger scales, outflows have the potential to disrupt large scale coherent flows and density structures from forming leading to a flatter density and velocity spectra.
- The different density and velocity distributions produced by outflows leads to a bias in PCA that may mask the signature of outflow driving in molecular clouds.

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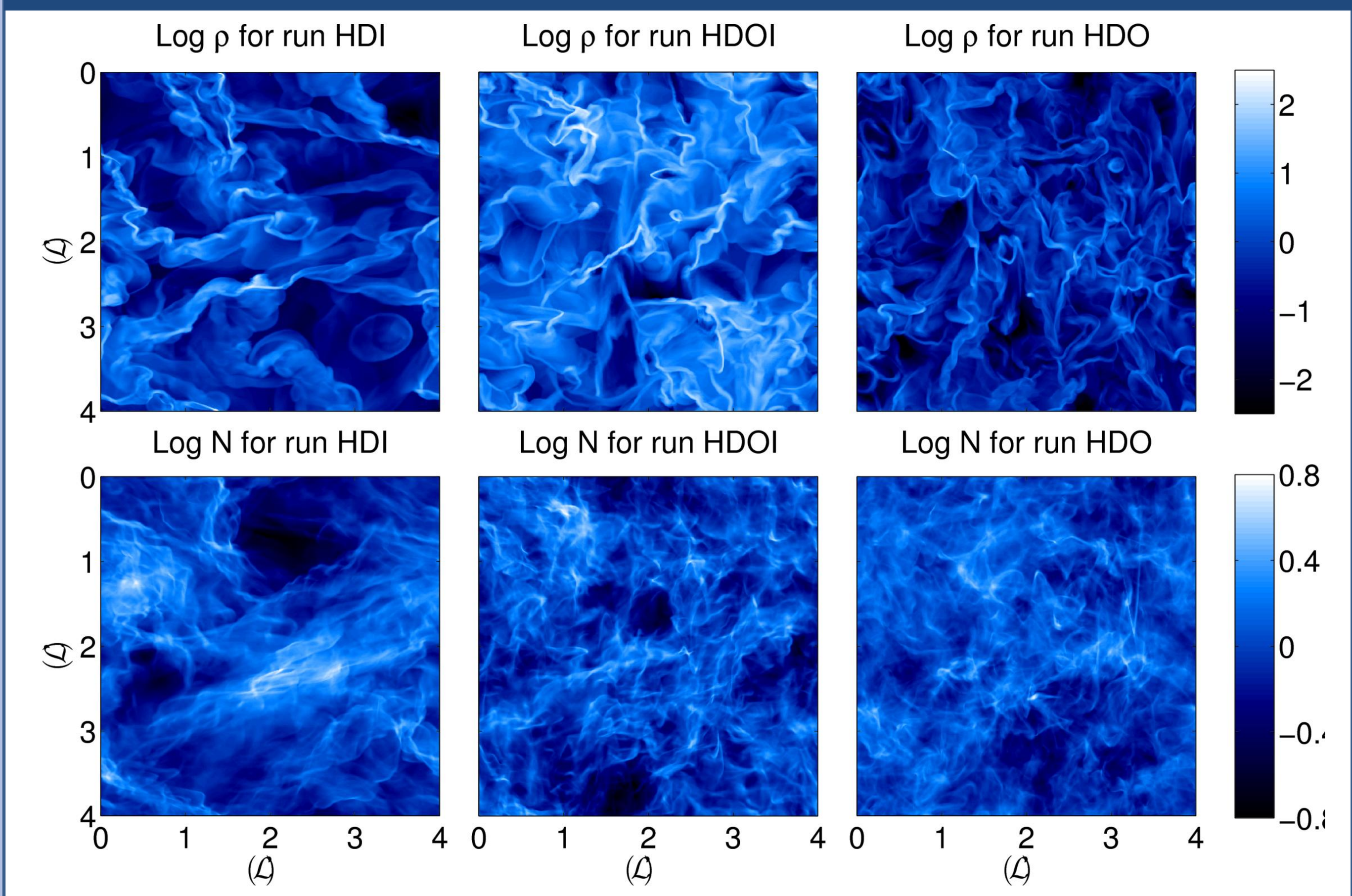
Abstract

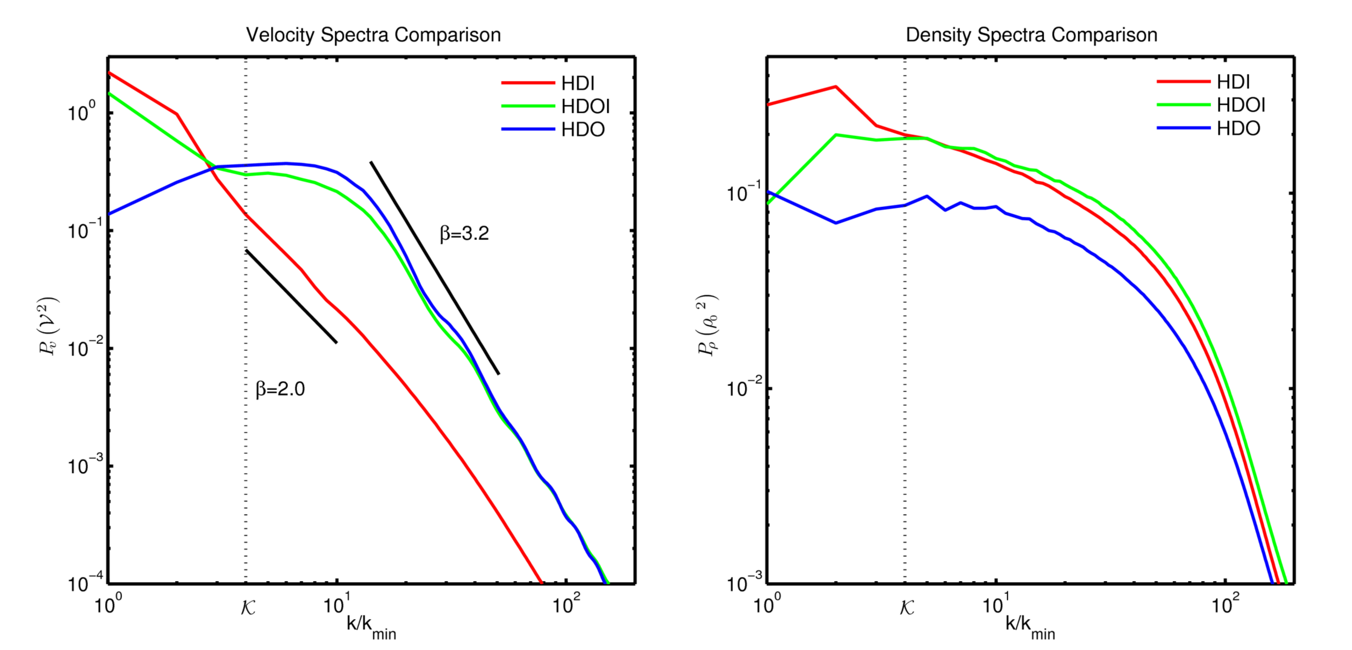
Feedback from protostellar outflows can influence the nature of turbulence in star forming regions even if they are not the primary source of velocity dispersion for all scales of molecular clouds. For the rate and power expected in star forming regions, we previously (Carroll et al. 2009) demonstrated that outflows could drive supersonic turbulence at levels consistent with the scaling relations from Matzner (2007) although with a steeper velocity power spectrum than expected for an isotropically driven supersonic turbulent cascade. Here we perform higher resolution simulations and combine simulations of outflow driven turbulence with those of isotropically forced turbulence. We find that the presence of outflows within an ambient isotropically driven turbulent environment produces a knee in the velocity power spectrum at the outflow scale and a steeper slope at sub-outflow scales than for a purely isotropically forced case. We also find that the presence of outflows flattens the density spectrum at large scales effectively reducing the formation of large scale turbulent density structures. These effects are qualitatively independent of resolution. We have also carried out Principal Component Analysis (PCA) for synthetic data from our simulations. We find that PCA as a tool for identifying the driving scale of turbulence has a misleading bias toward low amplitude large scale velocity structures even when they are not necessarily the dominant energy containing scales. This bias is absent for isotropically forced turbulence but manifests strongly for collimated outflow driven turbulence.

Comparing Two Types of Forcing



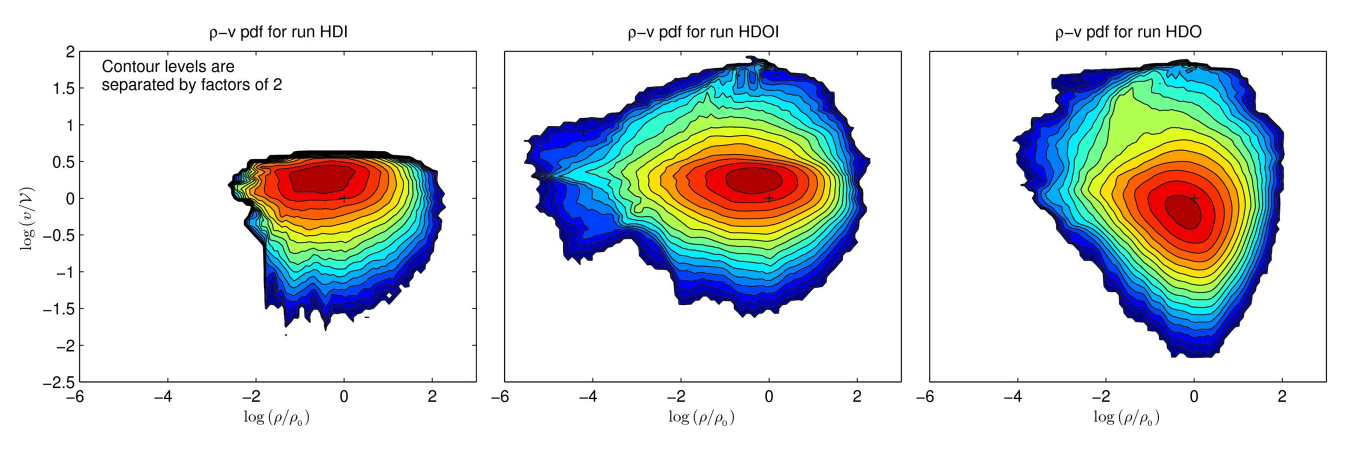
We performed 3 simulations with just isotropic forcing (HDI), just outflow forcing (HDO) and with both types of forcing (HDOI). The presence of outflows in run HDOI leads to the disruption of smooth large scale structures normally produced by large scale isotropic forcing as seen in run HDI.

Velocity and Density Spectra



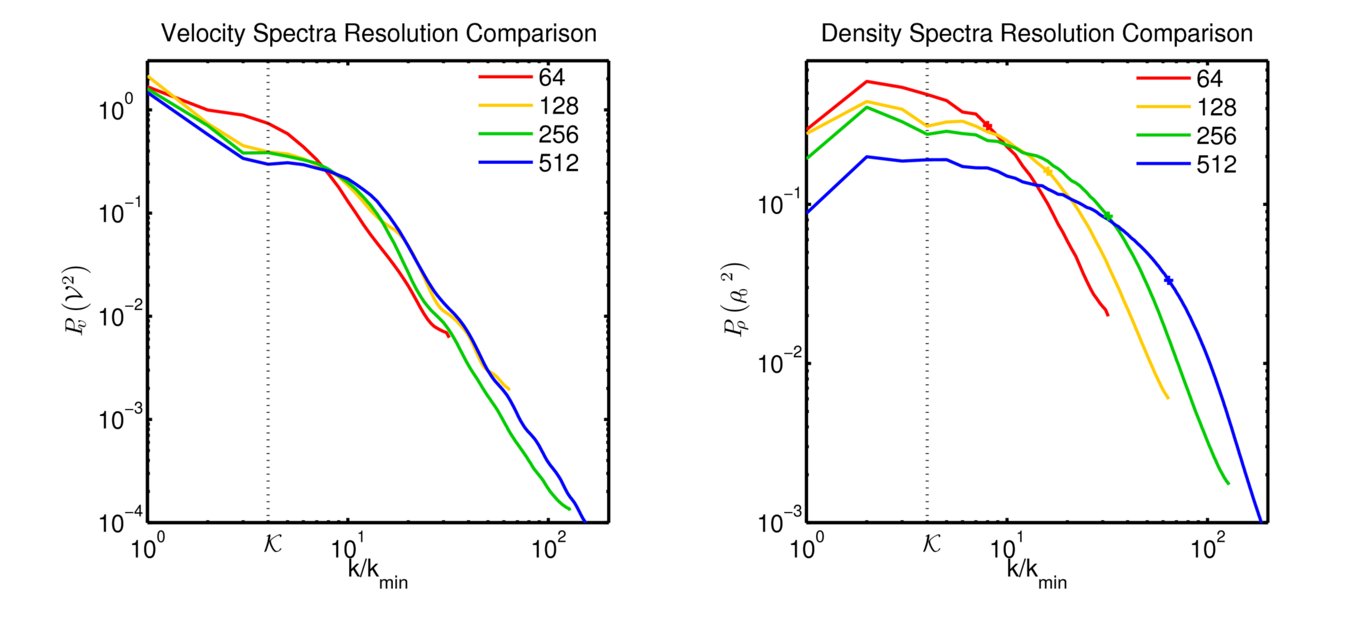
The velocity spectra for runs with outflow forcing (HDOI and HDO) show a clear bump at approximately the outflow scale and a steeper spectra at smaller scales. In addition the disruption via outflows of large scale motions and structures leads to a flatter density spectra, and reduced power at large scales.

Joint Density Velocity Distributions



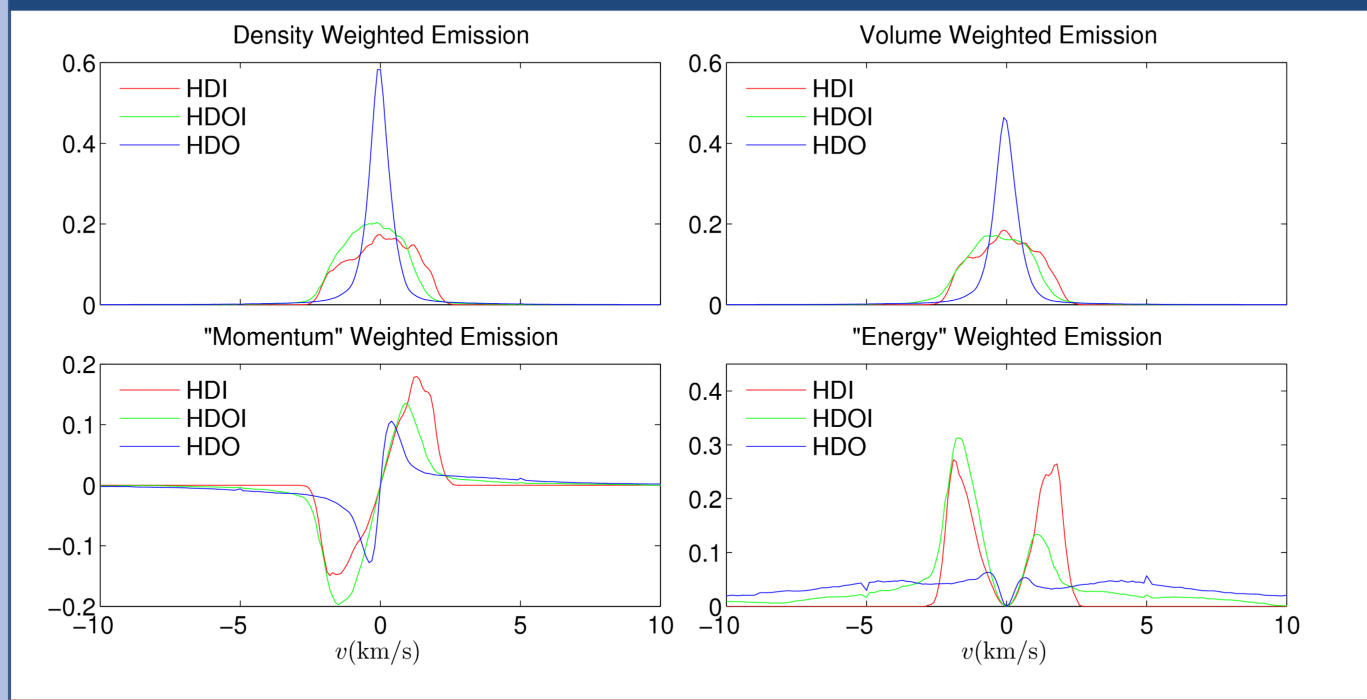
Outflow driven turbulence produces quite different density-velocity distributions than isotropically driven turbulence. In particular runs with outflows have a high velocity component which contributes significantly to the actual velocity spectra. However, since emission is density dependent, and the material is distributed over a large range in velocities, this high velocity component produces only a faint signal in the synthesized line profiles.

Resolution Study



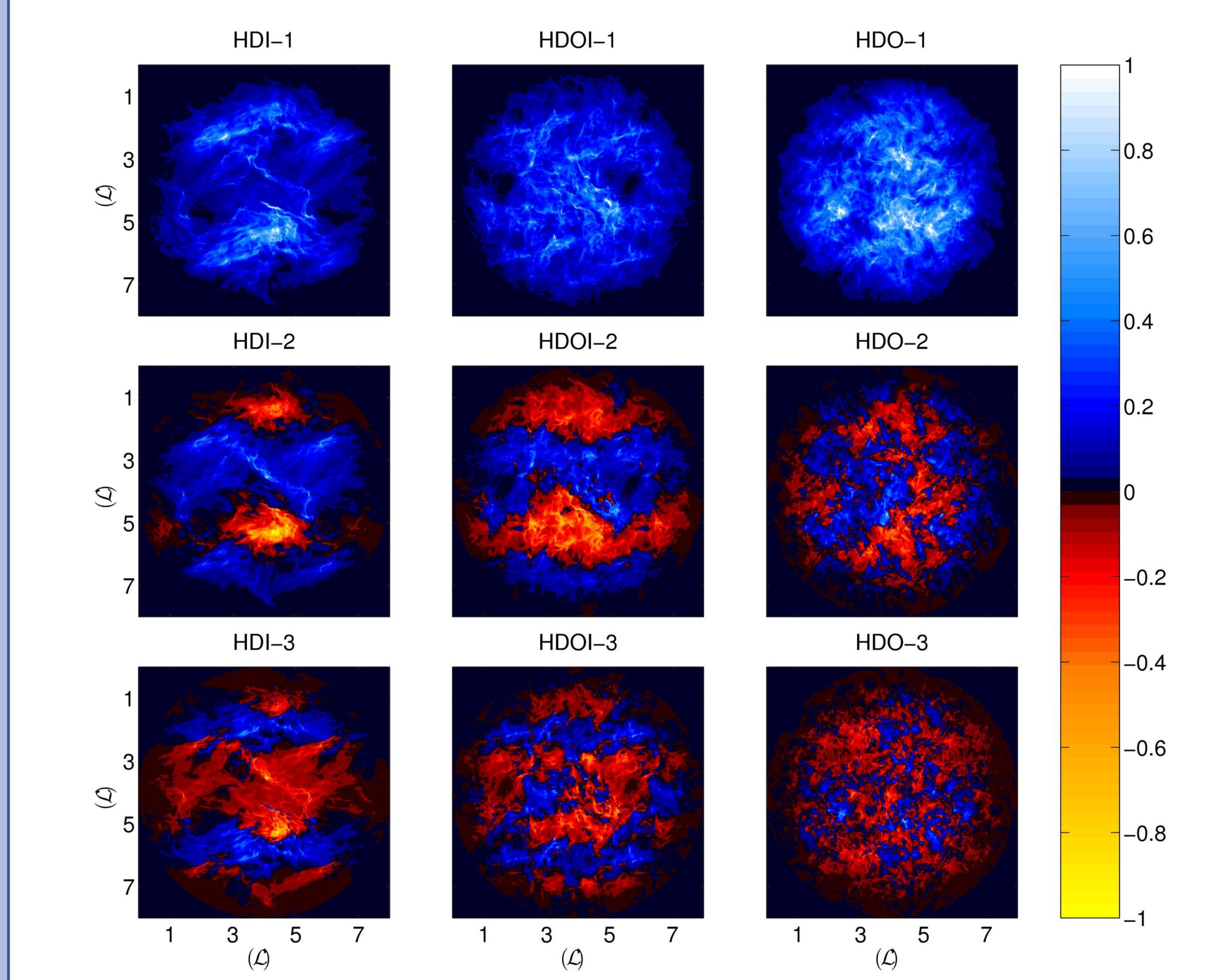
We completed run HDOI at different resolutions to determine what role numerical dissipation might be playing. The velocity spectra is fairly insensitive to resolution since outflows themselves provide the primary means of dissipation. (Outflows sweep over areas in the same time required for the resulting turbulence to cascade.) The density spectra flatten at higher resolutions and turn over at a resolution dependent scale of about 8Δx.

Observational Implications



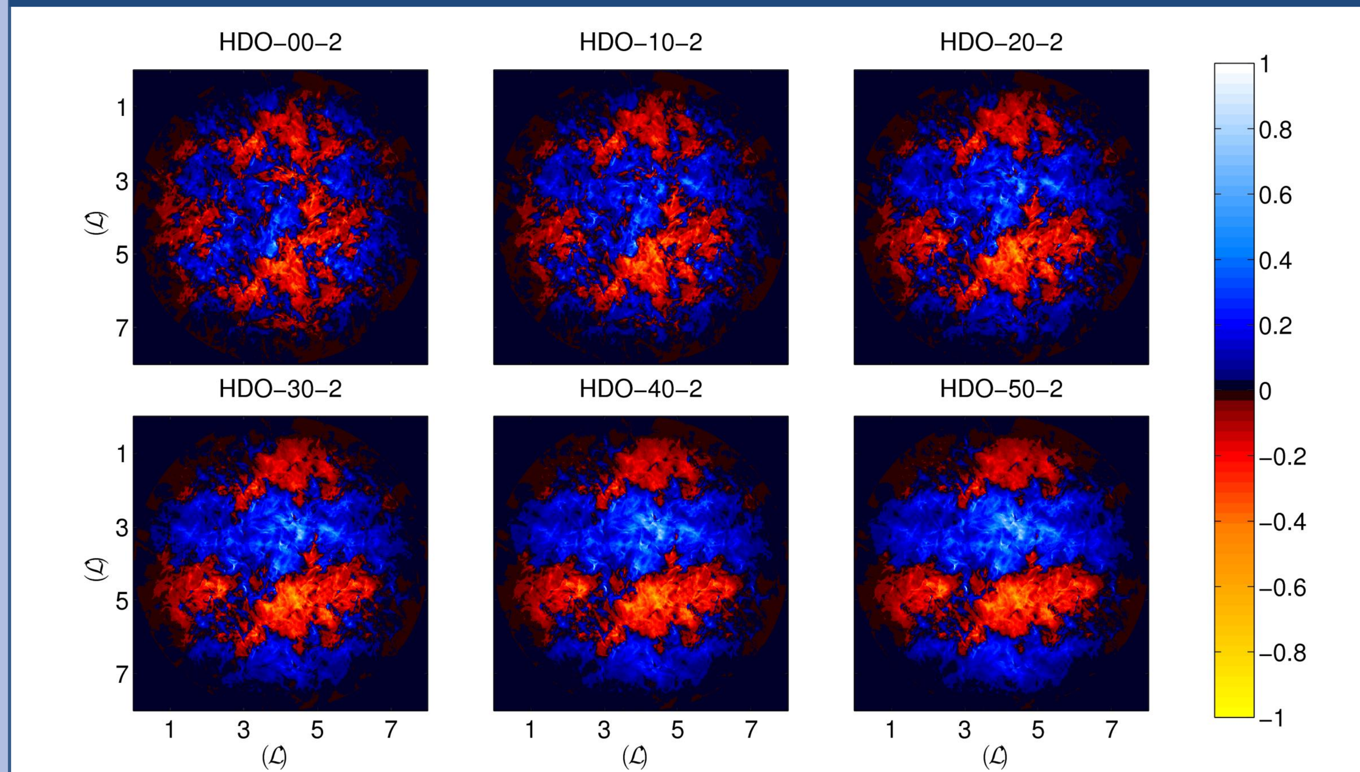
Note the contribution of the high velocity material present in runs with outflows is non-evident in the density-weighted emission, although its contribution to the momentum and energy is apparent in the lower two velocity weighted panels.

Application of Principal Component Analysis

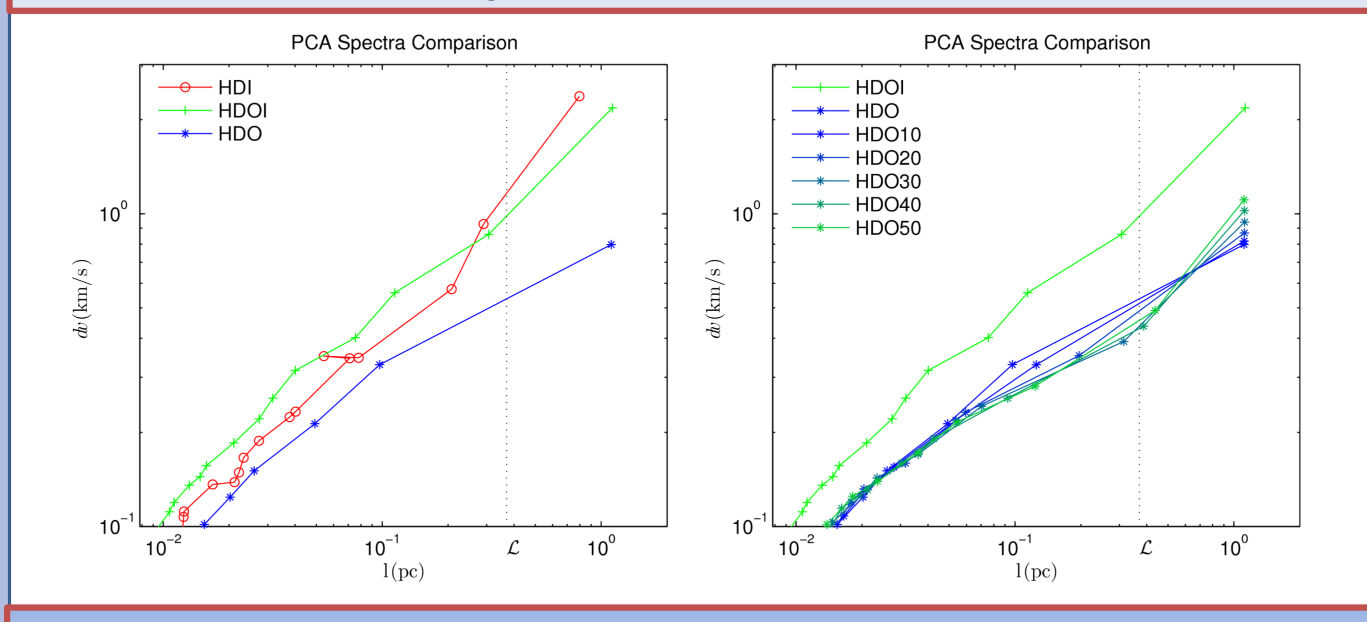


Projections of synthetic data cubes onto the first three principal eigen-spectra. The first principal eigen-image for each run (top row) mimic the column density plots, while the second principal eigen-image reveals the ***primary*** driving scale.

Potential Bias of Principal Component Analysis



To investigate the potential bias in PCA towards large scale - low velocity driving, we added a sinusoidal velocity perturbation of varying strength to the results from run HDO. We found that a small $(dv = .3\mathcal{V})$ perturbation was enough to significantly mask the evidence of outflow driving.



Note the differences between the line-width size relationships derived from PCA and the true velocity spectra. Also that the small velocity perturbation present in run HDO30 produces a line-width size relation similar to run HDOI.