Outflow Driven Turbulence in Molecular Clouds: MHD Simulation Studies

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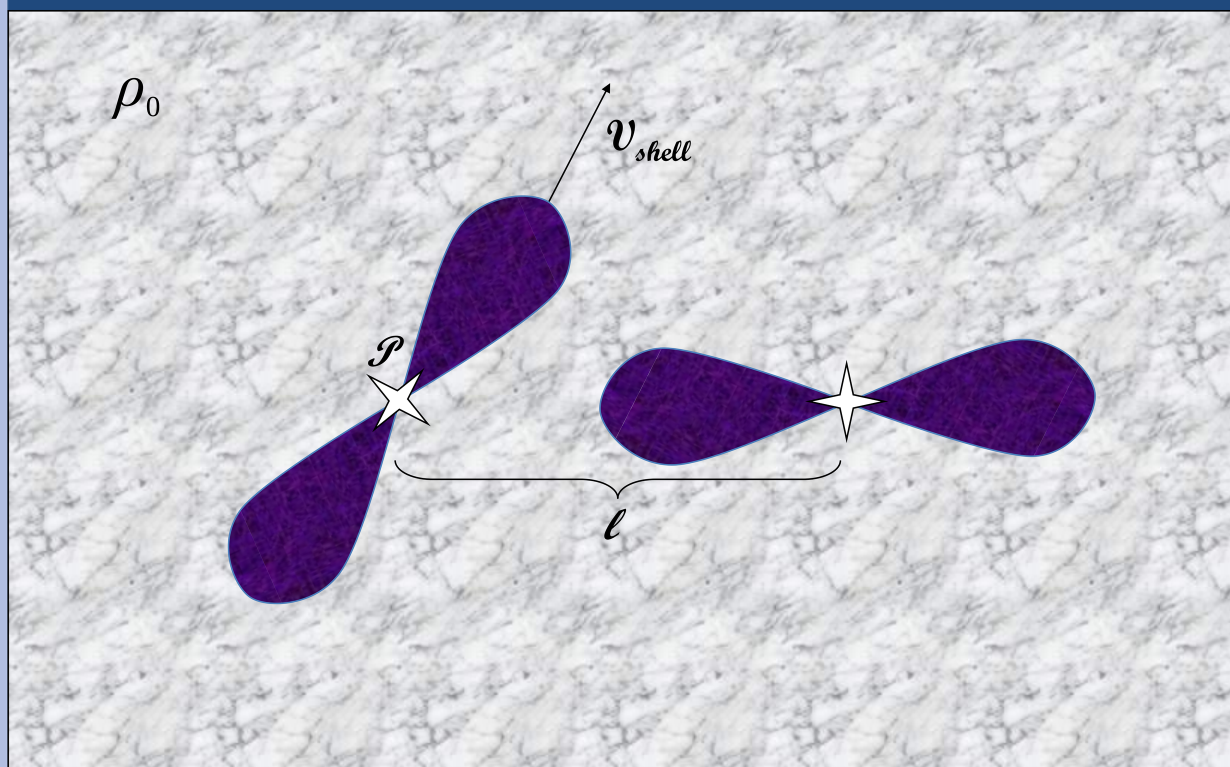
Theoretical Model



Given spherical outflows with momentum $\mathscr{P}$ in an environment with density ρ_0 occuring at a rate per volume S:

A given outflow will sweep up a shell of mass $m \approx \rho_0 \ell^3$ travelling at a velocity $v \approx \frac{\mathscr{P}}{m}$ over a period of time $t \approx \left(S\ell^3\right)^{-1}$ before encountering another outflow. Setting $vt = \ell$ gives:

$$\ell = \left(\frac{\mathscr{P}}{\rho_0 S}\right)^{1/7},\quad m = \frac{\rho_0^{4/7}\mathscr{P}^{3/7}}{S^{3/7}},\quad t = \frac{\rho_0^{3/7}}{\mathscr{P}^{3/7}S^{4/7}},\ \text{and}\ v = \frac{\mathscr{P}^{4/7}S^{3/7}}{\rho_0^{4/7}}$$

Parameters

Simulation parameters	
ρ_0	2.5e-20 g/cm^3
$\mathscr{P}$	21 $M_\odot$ km/s
S	59 pc^{-3}Myr^{-1}
ℓ	.37 pc
t	.34 Myr
m	19 $M_\odot$
L_{box}	1.5 pc
t_{run}	2.0 Myr
T	10 K

Run	β	Stirring	Outflows
I	-	N	Y
II	-	Y	Y
III	0.5	N	Y

Outflow Parameters	
ρ	2.5e-20 g/cm^3 (ρ_0)
v	66 km/s
t	25 kyr
r	6000 AU
θ	0°

Conclusions

- Outflows drive and sustain supersonic turbulence.
- Outflows produce a knee in the turbulent spectrum.
- Outflow driven turbulence has a steeper velocity spectrum than cascade models.
- Outflows are able to enhance magnetic fields initially present, though not to equipartition with kinetic energy.
- Further comparisons between simulation and observation are needed to understand the role of feedback and star formation.

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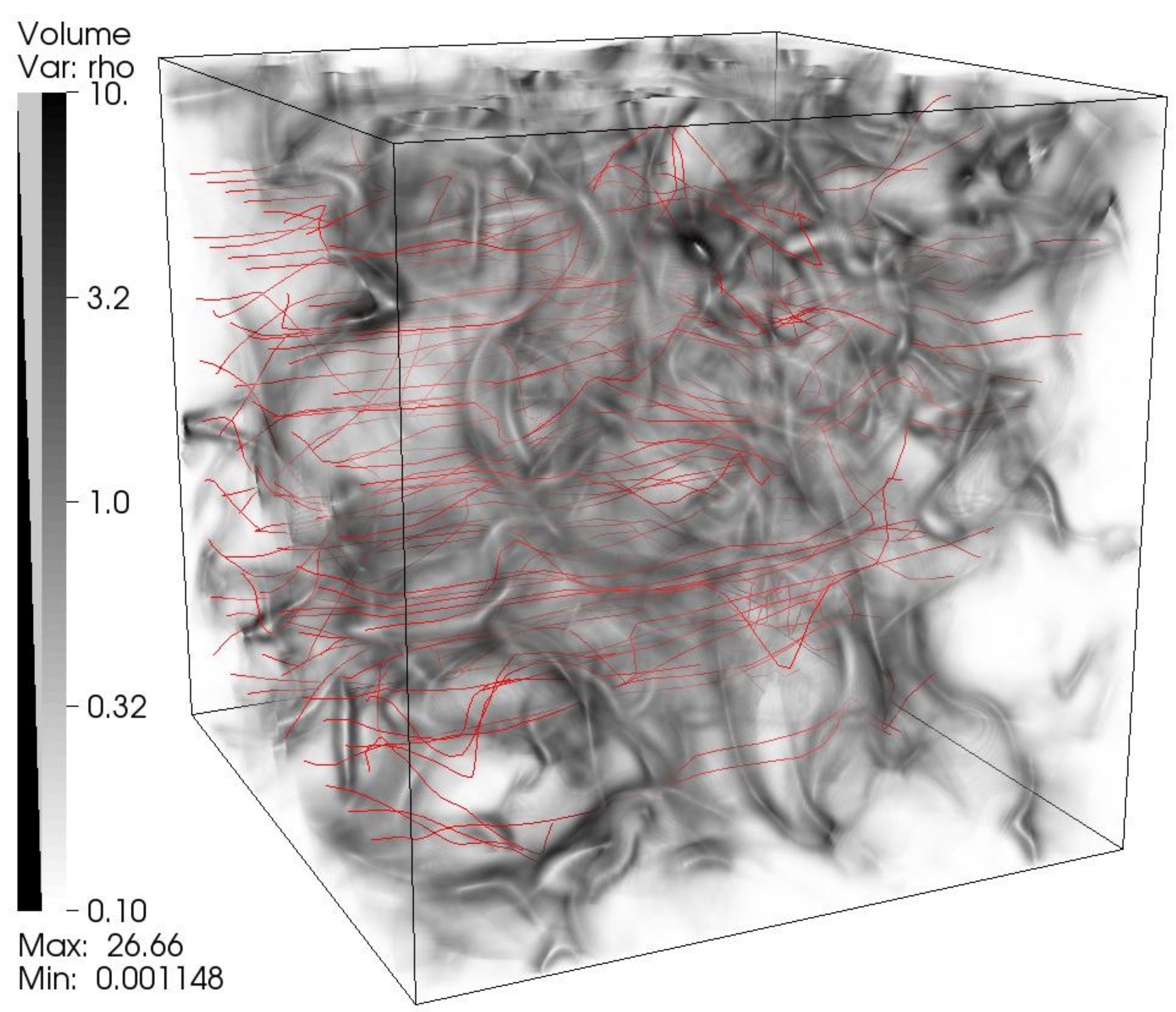
Abstract

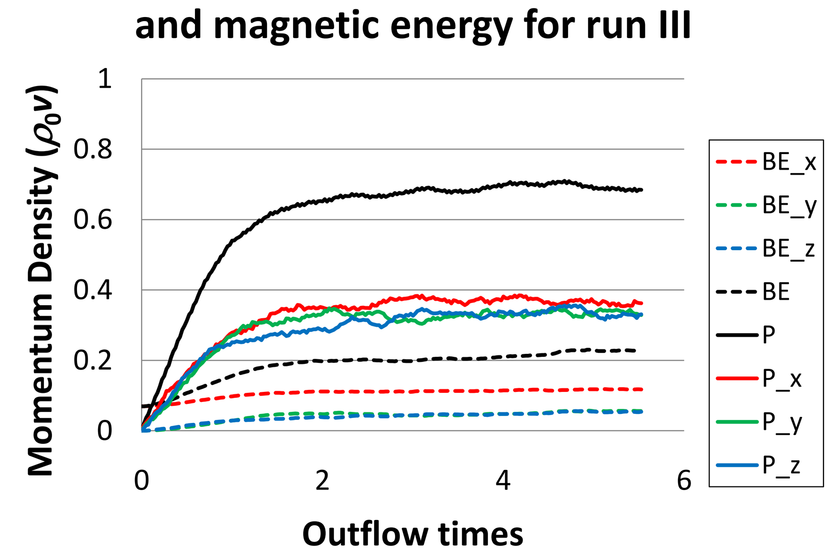
Protostellar outflows are ubiquitous in regions of star formation and inject sufficient momentum into their parent cloud to sustain supersonic turbulence. Here we present the results of 3-D MHD numerical simulations that demonstrate the capacity of multiple interacting outflows to both create and sustain supersonic turbulence. We discuss the differences between outflow driven turbulence and externally driven turbulence and the observational signatures of each. We also discuss the growth of magnetic fields from turbulent interactions with outflows.

Magnetic Fields and Outflows



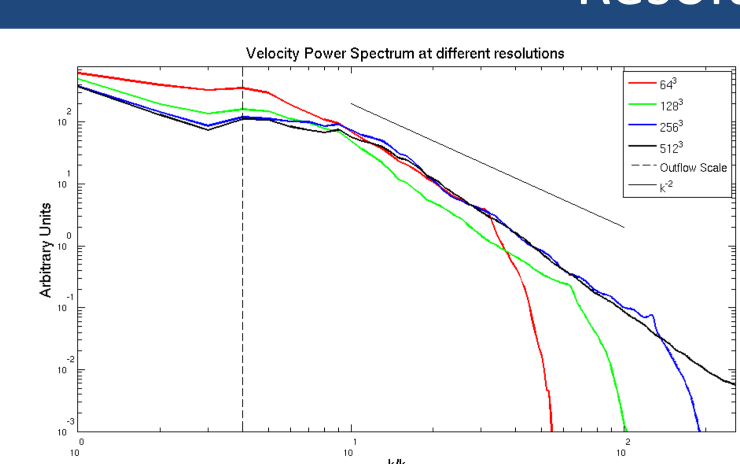
Volume plot of density with magnetic stream lines

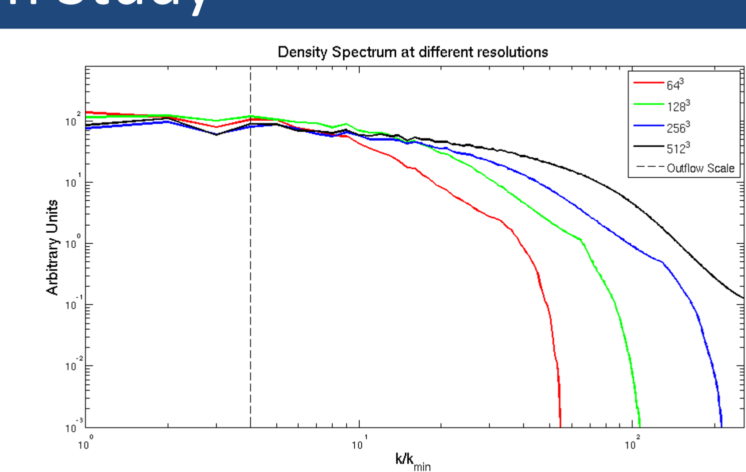
Time development of momentum and magnetic energy for run III



Note the saturation of the momentum after about 1 outflow time, and the saturation value is around $\rho_0 v$. Also note the slow growth of the magnetic field especially after 1 outflow time.

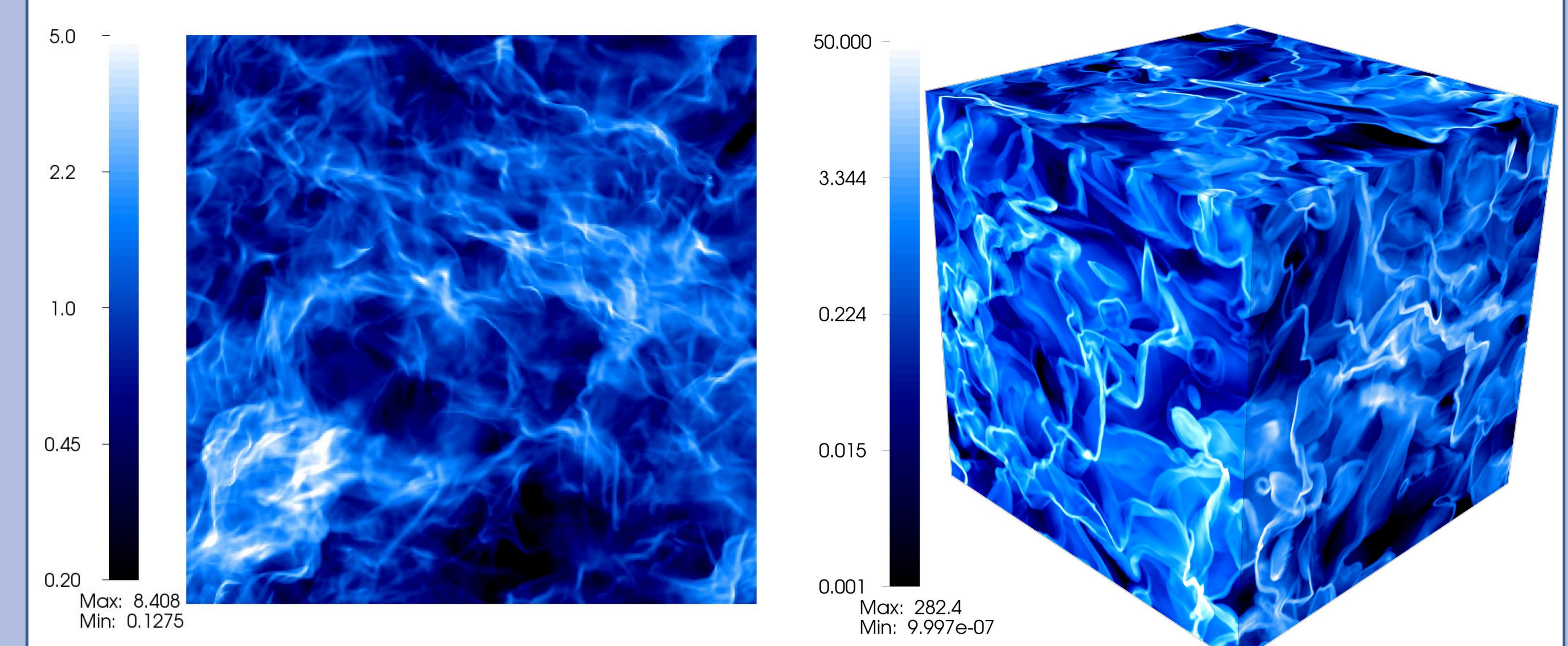
Resolution Study



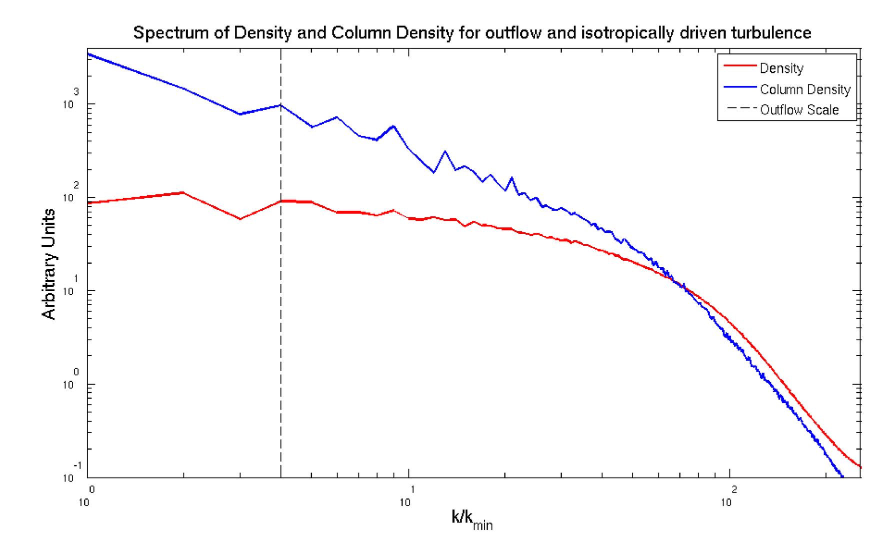


Note the steeper slope for the velocity spectrum (left) when outflows are present and the lack of a strong dependence on resolution. The density spectrum (right) however is fairly flat before turning downward at a wavelength strongly dependent on resolution at about $6\Delta x$ perhaps corresponding to the thickness of the isothermal shocks.

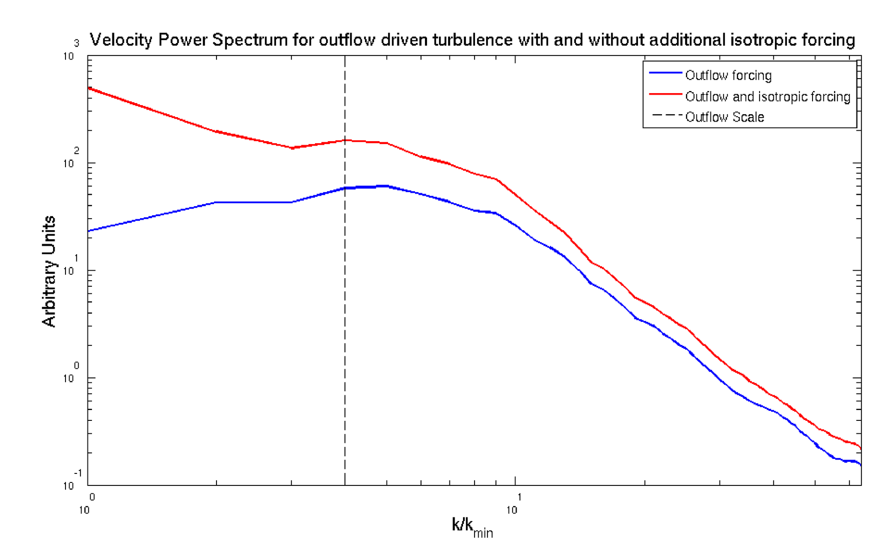
Density vs. Column Density



Log plots of column density (left) and density (right) for the isotropically forced/outflow driven case



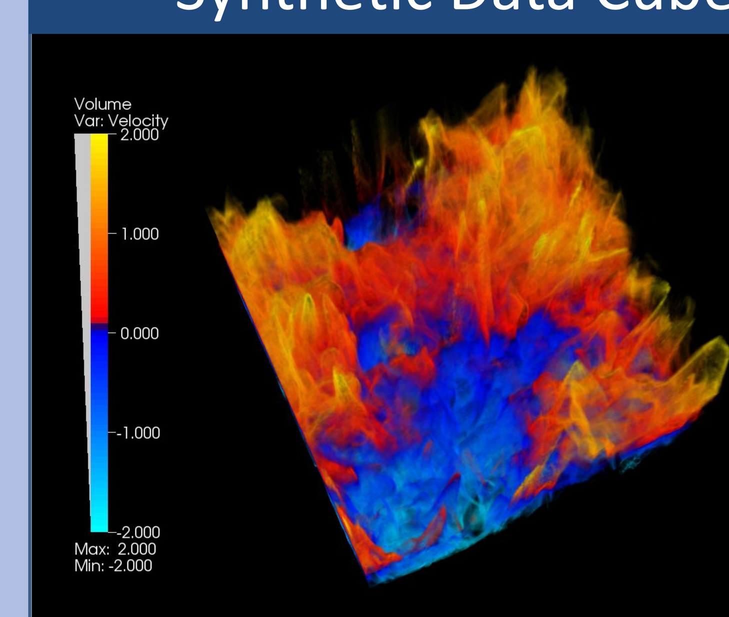
Note the difference in appearance between the column density and density. The large cavities visible in the density plot are obscured in the column density. Also notice the flat density spectra.

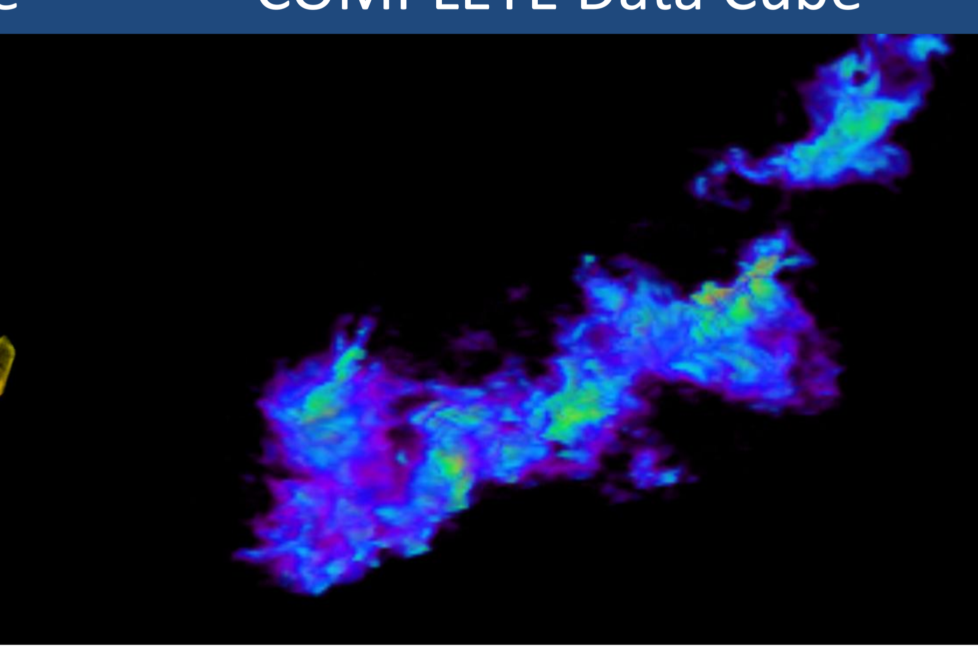


Note the knee and steep slope in the power spectrum due to outflows with and without external forcing. The strength of the isotropic forcing and the outflow forcing were comparable.

Synthetic Data Cube

COMPLETE Data Cube





The synthetic data cube (left) shows similar structures to the COMPLETE data cube (right). Note the holes and peaks in the data cubes from outflows and their cavities.