Turbulence in Molecular clouds : Observation versus Simulation

Hyunjin Cho, Hyesung Kang(PNU),
Dongsu Ryu(CNU), Jongsoo Kim(KASI)
& Jungyeon Cho(CNU)

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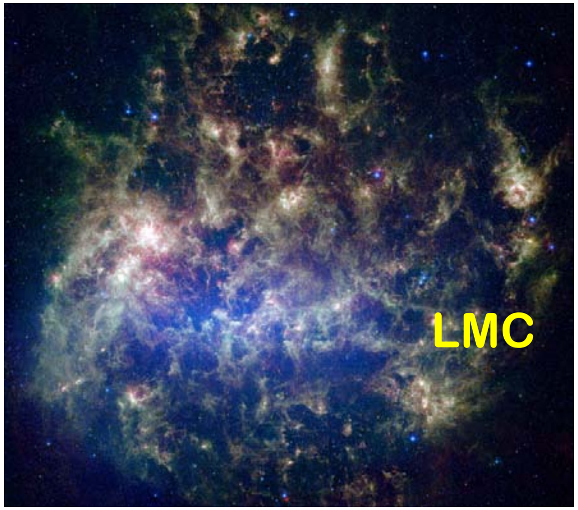
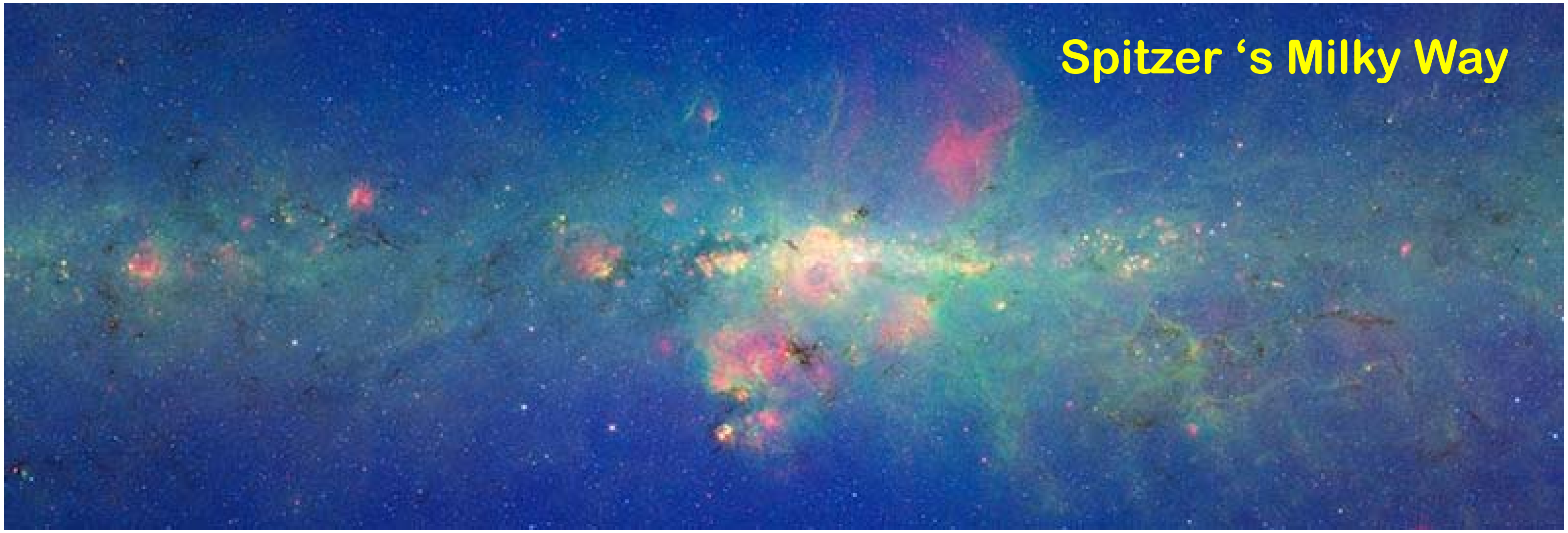
Interstellar Turbulence

❖ Observation and Numerical Simulation indicate ISM has turbulent structure.

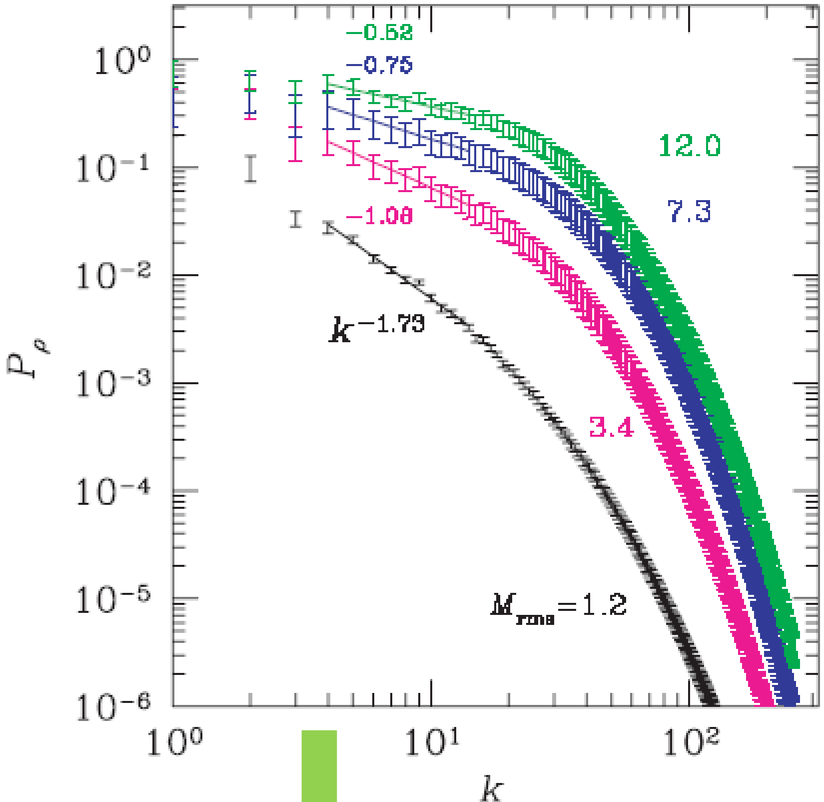
→ ISM turbulence plays an important role in star and galaxy formation.

→ Very complex, unpredictable environments PDF, SF, PS etc





Recent Studies of Astrophysical Turbulence Ⅰ



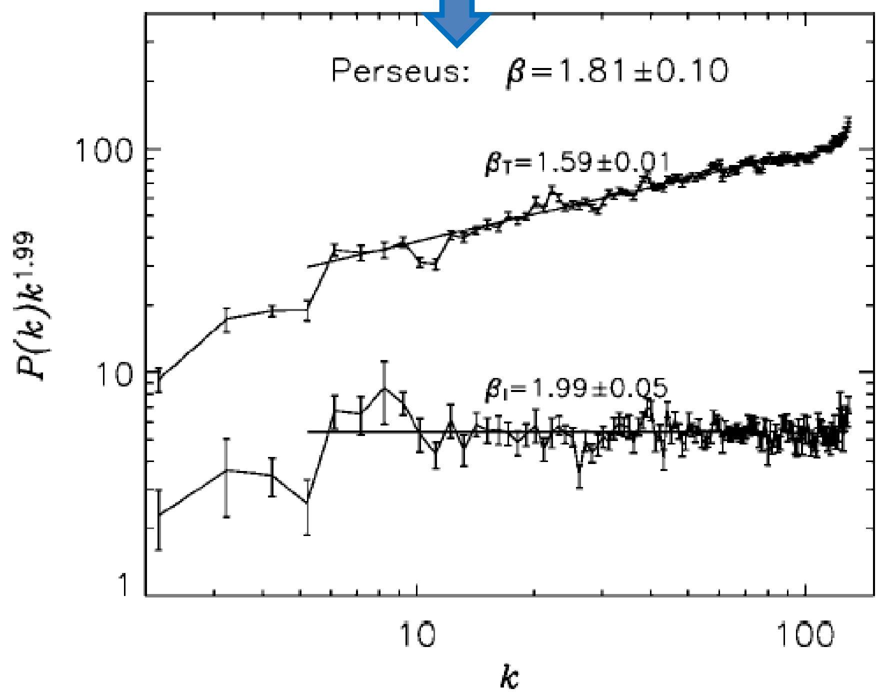
❖ Kim & Ryu (2005)

1d & 3d compressible HD turbulence simulations show the density power sp ectrum becomes shallower as the rms Mach number increases.

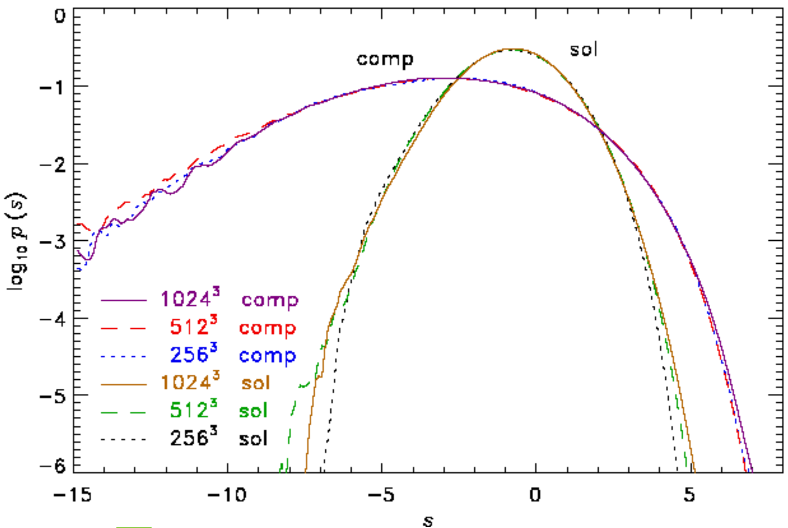
❖Padoan et. al. (2006)

Power Spectrum Study of Perseus Molecular Cloud based on VCA method.

Power spectrum is consistent with previous HI, CO studies , Super-Alfvenic turbulence simulations.



Recent Studies of Astrophysical Turbulence Ⅱ

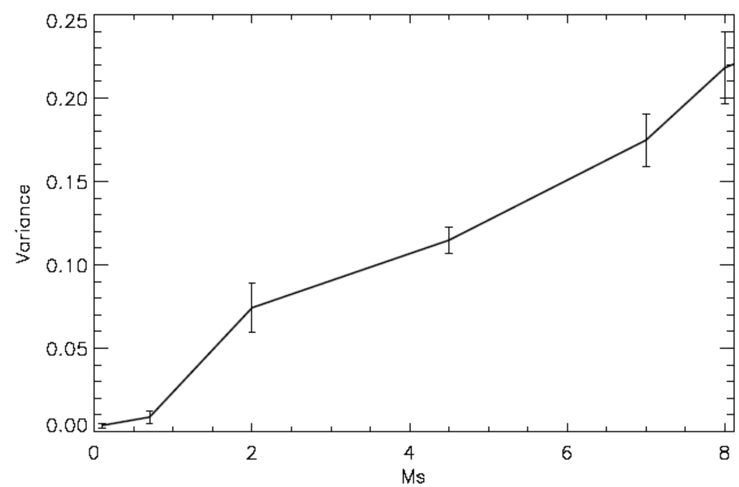


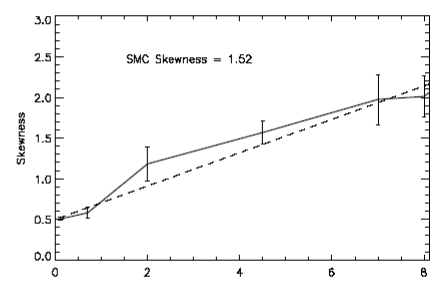
❖ Federrath et. al. (2010)

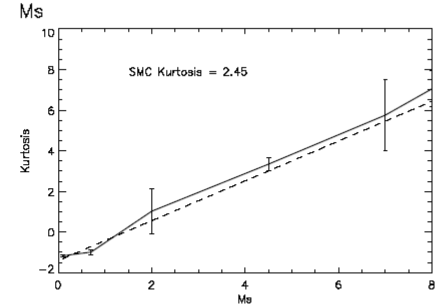
Compressive mode yields stronger turbulence than solenoidal mode, resulting in a three times larger standard deviation of volumetric and column density probability distributions (PDFs).

❖Burkhart et. al. (2009)

spatial variations of turbulence in the Small Magellanic Cloud (SMC) by applying several statistical methods







Purpose of This Study

- ❖ Many advances in both observations and numerical simulation models have provided new insights into the origins and evolution of the interstellar turbulence.

- ❖ Most of recent statistical methods require large datasets with large spatial or velocity range. However, there is still disagreements of these results.

- ❖ We attempt to improve statistical relation for various properties of turbulence using observational data. We also investigate the consistency of these result and the simulation result.

Galactic Ring Survey

Jackson et. al. (2006)

The Boston University - FCRAO Galactic Ring Survey (GRS) using 14m telescope, ^{13}CO (J=1→0) transition is 5kpc ring survey of the inner Galaxy

A Comparison of CO Surveys of the First Galactic Quadrant

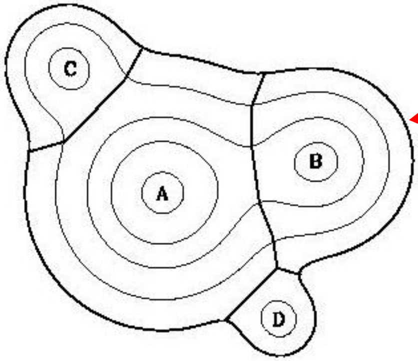
Survey	GRS	UMSB[a]	Bell Labs[b]	Columbia/CfA[c]
Dates	1998–2005	1981–1984	1978–1992	1980–
Transition ($J = 1 \rightarrow 0$)	^{13}CO	^{12}CO	^{13}CO	^{12}CO
T_R^* sensitivity per km s^{-1} channel (K)	0.27	0.40	0.1	0.18
Velocity resolution (km s^{-1})	0.21	1.0	0.68	0.65
Longitude coverage (deg)	18 to 55.7	8 to 90	−5 to 117	10 to 70
Latitude coverage (deg)	−1 to 1	−1.05 to 1.05	−1 to 1	−6 to 6
LSR velocity range (km s^{-1})	−5 to 135	−100 to 200	−250 to 250	−140 to 140
Angular resolution (arcsec)	46	45	103	450
Angular sampling (arcsec)	22	180	180	225–450
Number of spectra	1,993,522	40,551	73,000	54,000
Total survey region (deg^2)	75.4	172.2	244	660

[a] From Sanders et al. (1986).
[b] From Lee et al. (2001).
[c] From Dame et al. (2001).

Better Column density tracer
Excellent temperature sensitivity
Higher spectral resolution

Selection of Molecular Cloud in GRS survey

Rathborne et. al. (2009) identified 829 molecular clouds and 6124 clump s in Galactic Ring Survey using the CLUMFIND algorithm.



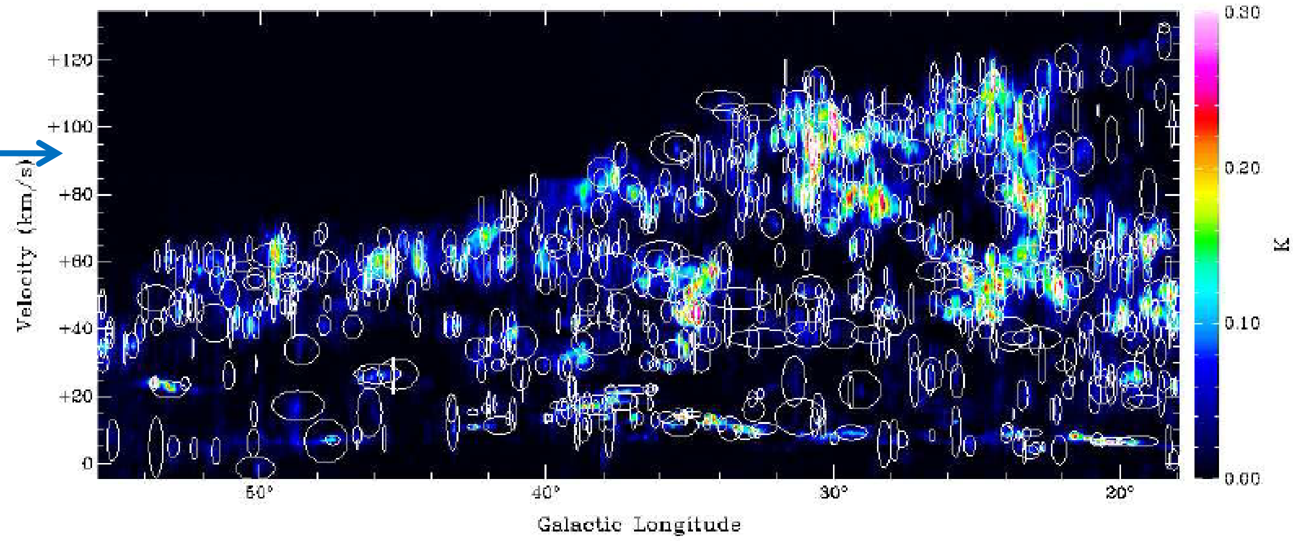
Initial condition parameter of CLUMPFIND

Lowest brightness (threshold) ~ 0.20K ~ 10σ

Contour increments ~ 0.20K

Algorithm concept by Williams et. al. (1994)

White ellipse :
l – v position of
829 molecular cloud



Molecular Cloud Catalogue in GRS survey

Table 2: Properties of the molecular clouds identified in the GRS.

Cloud GRSMC	Peak ℓ (°)	Peak b (°)	V_{LSR} (km s^{-1})	ΔV (km s^{-1})	T_{mb} (K)	Centroid ℓ (°)	Centroid b (°)	a (°)	b (°)	PA (°)	A (deg^2)	T_{av} (K)	I_{peak} (K km s^{-1})	I_{total} (K km s^{-1} deg^2)	$N(H_2)$ ($\times 10^{22}$ cm^{-2})	Flag
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
G053.59+00.04	53.59	0.04	23.7	1.99	5.75	53.69	0.01	0.52	0.19	16	0.27	1.90	36.5	0.95	1.8	-
G029.89−00.06	29.89	−0.06	100.7	5.09	5.46	29.99	−0.17	0.44	0.35	-46	0.46	2.49	87.6	3.12	4.3	-
G049.49−00.41	49.49	−0.41	56.9	9.77	5.25	49.57	−0.39	0.38	0.23	-21	0.18	2.18	193.2	1.64	9.5	Y
G018.89−00.51	18.89	−0.51	65.8	2.80	5.17	18.80	−0.56	0.31	0.31	-47	0.29	2.31	57.5	1.51	2.8	-
G030.49−00.36	30.49	−0.36	12.3	4.56	4.98	30.66	−0.39	0.47	0.24	-28	0.22	1.70	17.5	0.50	0.9	-
G035.14−00.76	35.14	−0.76	35.2	5.00	4.92	35.22	−0.78	0.31	0.22	-11	0.20	2.36	59.3	1.90	2.9	Y
G034.24+00.14	34.24	0.14	57.8	5.98	4.81	34.19	0.05	0.50	0.41	-3	0.52	1.46	80.5	3.15	4.0	-
G019.94−00.81	19.94	−0.81	42.9	2.81	4.58	19.97	−0.80	0.42	0.18	-7	0.22	1.76	32.1	1.00	1.6	Y
G023.44−00.21	23.44	−0.21	101.1	5.75	4.40	23.36	0.02	0.64	0.48	29	0.63	1.65	63.2	3.71	3.1	-
G038.94−00.46	38.94	−0.46	41.6	2.97	4.33	39.01	−0.51	0.36	0.28	-10	0.23	1.90	31.8	1.02	1.6	-
G023.44−00.21	23.44	−0.21	103.7	3.44	4.23	23.55	−0.27	0.35	0.23	28	0.12	2.13	51.7	0.49	2.5	-
G030.79−00.06	30.79	−0.06	94.7	6.12	4.23	30.86	−0.04	0.39	0.28	66	0.32	2.24	79.5	2.68	3.9	-
G030.29−00.21	30.29	−0.21	104.5	3.01	3.92	30.36	−0.18	0.39	0.23	66	0.26	1.66	40.0	0.98	2.0	-
G053.14+00.04	53.14	0.04	22.0	2.39	3.88	53.15	0.09	0.42	0.26	74	0.29	2.01	26.8	0.93	1.3	-
G022.44+00.34	22.44	0.34	84.5	2.81	3.62	22.51	0.30	0.41	0.23	32	0.14	1.52	29.0	0.42	1.4	-
G024.49+00.49	24.49	0.49	102.4	5.24	3.58	24.48	0.30	0.52	0.32	8	0.46	1.46	67.8	2.21	3.3	-
G049.39−00.26	49.39	−0.26	50.9	3.54	3.54	49.44	−0.23	0.30	0.18	63	0.15	1.93	54.1	0.90	2.7	-
G019.39−00.01	19.39	−0.01	26.7	3.88	3.48	19.53	0.02	0.42	0.26	-2	0.31	1.73	39.0	2.00	1.9	-
G034.74−00.66	34.74	−0.66	46.7	4.33	3.46	34.88	−0.63	0.42	0.34	51	0.34	1.91	35.3	2.27	1.7	Y
G023.04−00.41	23.04	−0.41	74.3	4.20	3.40	23.07	−0.45	0.50	0.31	7	0.45	1.54	45.9	2.31	2.3	-
G018.69−00.06	18.69	−0.06	45.4	3.86	3.33	18.77	−0.13	0.26	0.18	-22	0.13	1.87	32.8	0.85	1.6	-
G018.19−00.31	18.19	−0.31	50.1	4.15	3.29	18.20	−0.44	0.39	0.27	89	0.27	1.89	52.5	1.52	2.6	X
G025.64−00.11	25.64	−0.11	93.9	2.78	3.21	25.67	−0.26	0.36	0.30	12	0.29	1.64	24.8	1.06	1.2	Y
G024.79+00.09	24.79	0.09	110.4	3.25	3.17	24.62	0.17	0.48	0.37	4	0.48	1.50	50.3	1.79	2.5	-

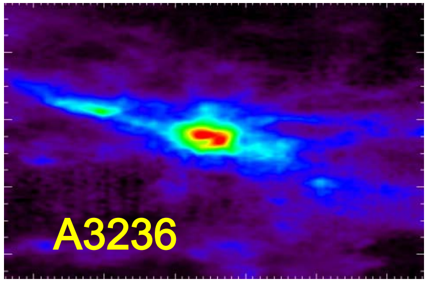
6 Molecular Cloud Information

We select 6 molecular clouds from the cloud information by Rathborne et. al. (2009)

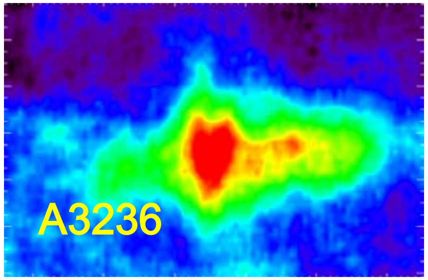
→ Consideration : resolution limits, velocity profile, more simple structure

Name	longitude	latitude	velocity	Δl	Δb	Δv
A2224	23.04	-0.41	74.30	0.50	0.31	7.20
A2426	25.64	-0.11	93.90	0.36	0.30	3.78
A3032	31.49	0.39	24.60	0.51	0.41	7.52
A3236	34.24	0.14	57.80	0.30	0.41	5.98
A4446	44.59	-0.41	61.00	0.45	0.45	7.59
A4850	49.44	-0.06	62.00	0.54	0.39	3.75

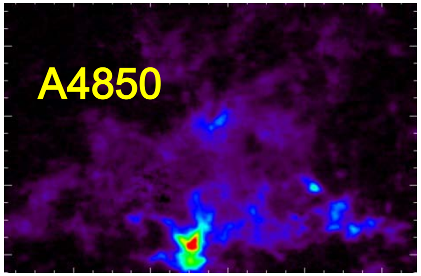
Examples of well defined molecular clouds



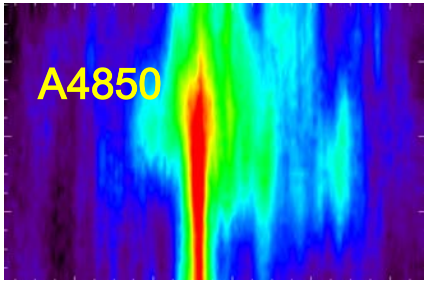
l – b diagram



l – v diagram



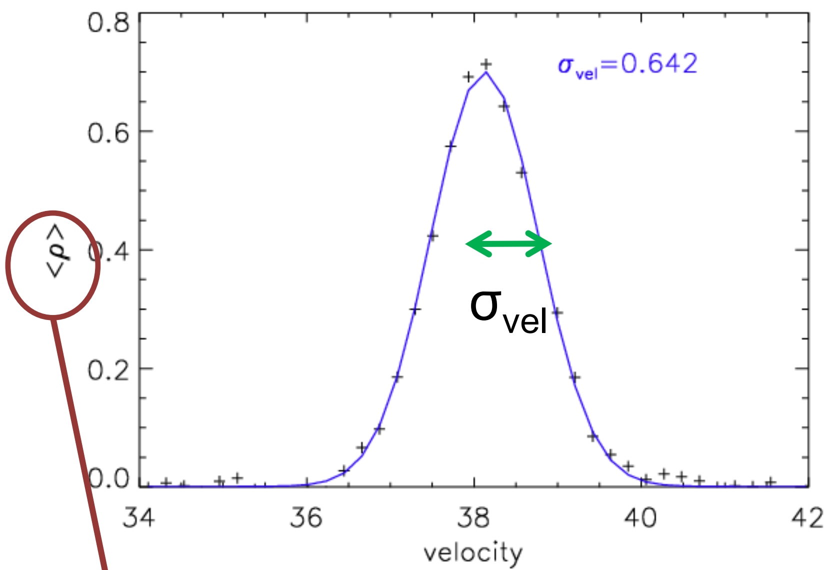
l – b diagram



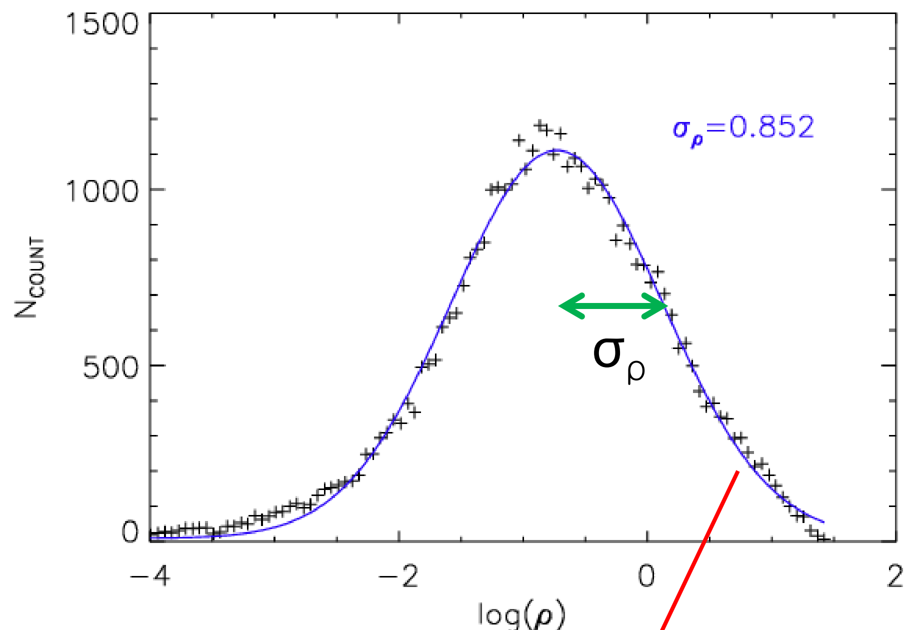
l – v diagram

Density & Velocity Distribution of each MC

Velocity Distribution



Density Distribution in (l,b,v) space



$$< \rho > (v) = \iint T(l,b,v)\,dl\,db$$

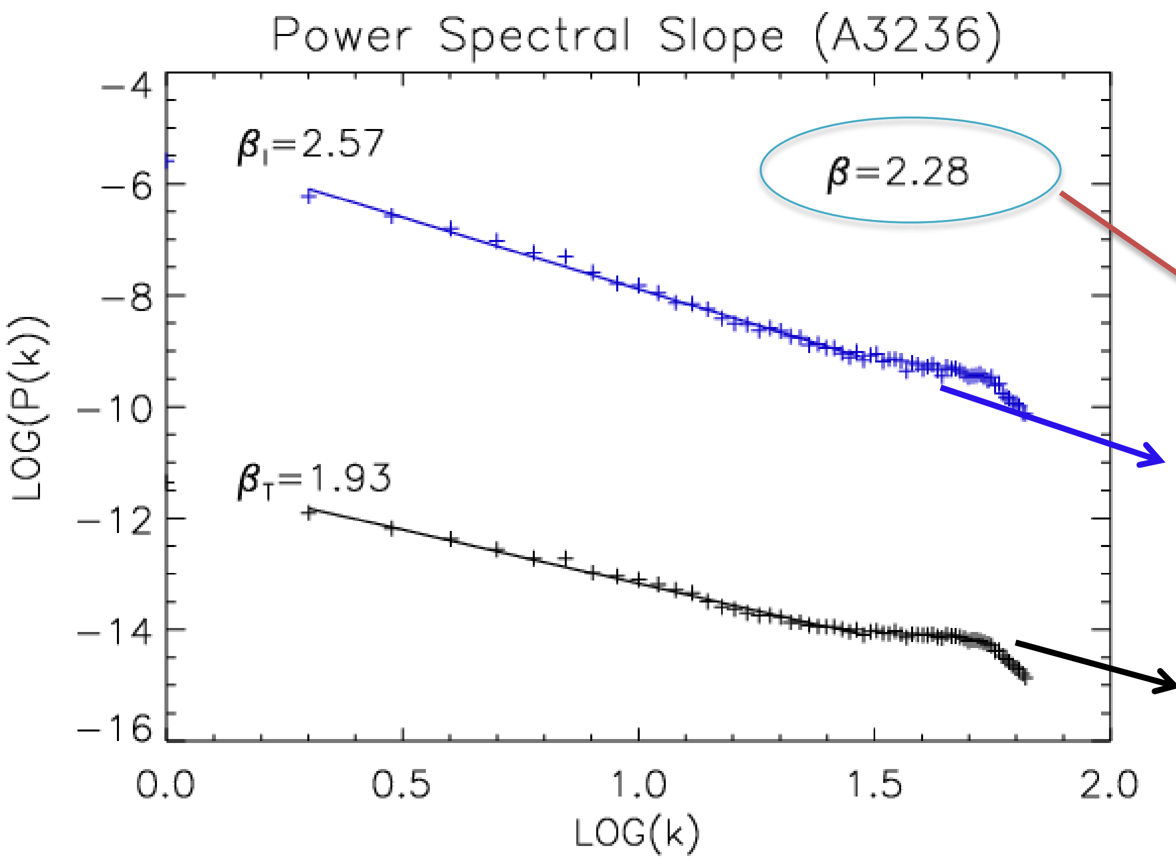
Integrated intensity along all of the Galactic longitude and latitude

σ_{vel} = velocity width = fcn(Ms)

Gaussian fitting
: Log-normal distribution

Density PDFs are consistent with numerical simulation of MHD turbulence

Power Spectrum on VCA method



Lazarian & Pogosyan (2000)

Velocity Power Spectrum slope

$$\beta = 1 + 2(\beta_I - \beta_T)$$

$$P_T(k) = \langle P_T(v,k) \rangle_v \propto k^{-\beta_T}$$

: **Averaged PS**

$$I(x) = \sum_v T(l,b,v)\Delta v$$

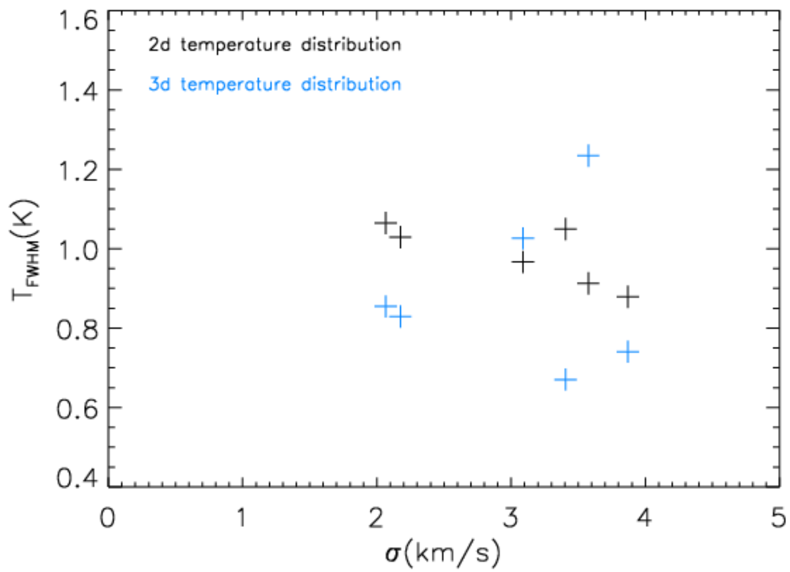
$$P_I(k) = k^{-\beta_I}$$

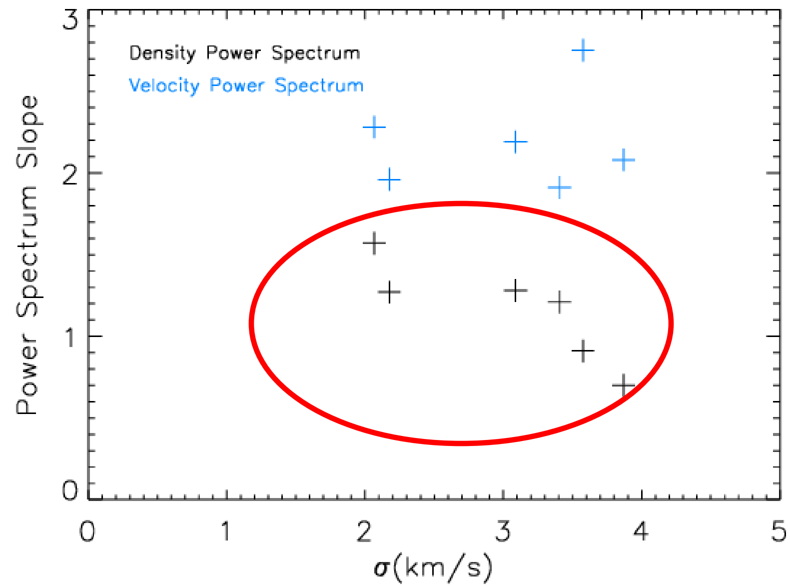
: **Integrated PS**

Integrated Power spectrum is related with the density power spectrum

$$\beta_\rho \sim \beta_I - 1$$

Properties of Turbulence in 6 MCs





σ = Velocity width = $V_{FWHM}/2(2\ln 2)^{1/2}$ is is related with sonic Mach number

Left : Velocity width & Density width
→ correlation ?

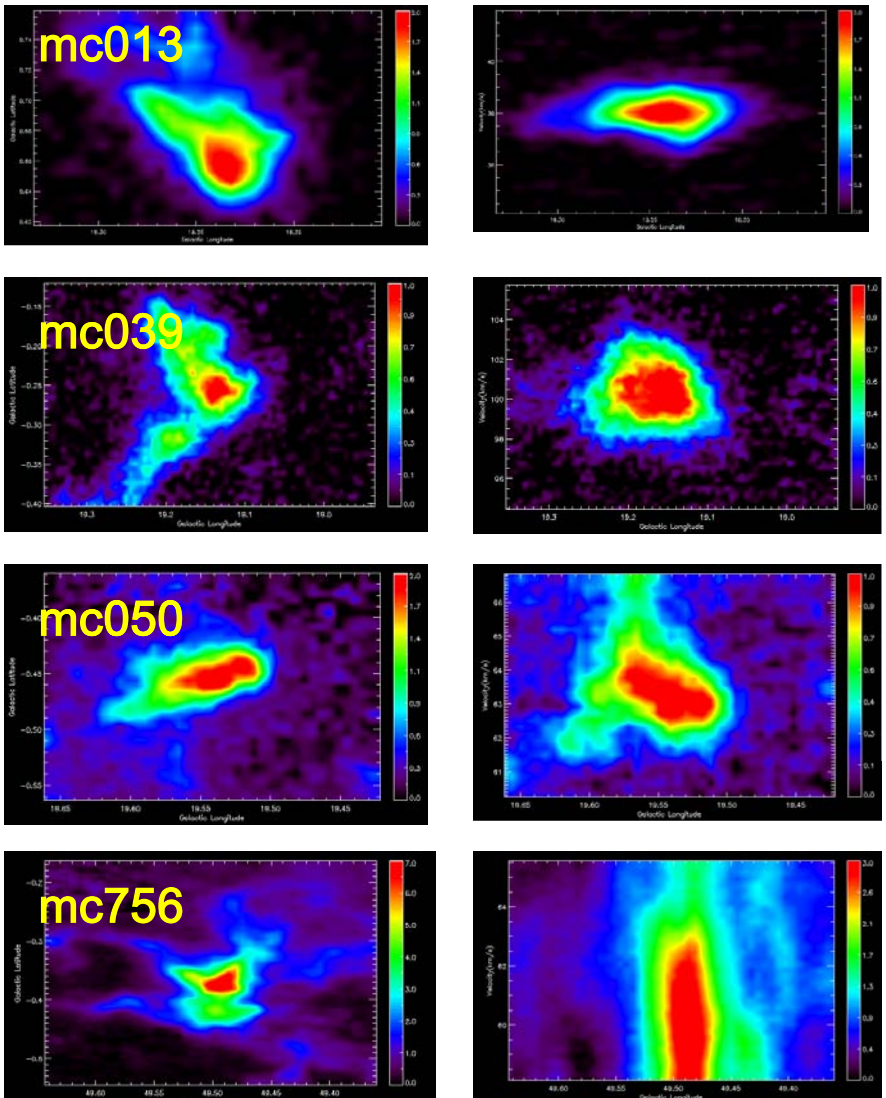
Right : Velocity width & Density, Velocity Power Spectrum Slopes
→ Reasonable correlation between density power spectrum and velocity profile

$$< \beta >= 2.20$$

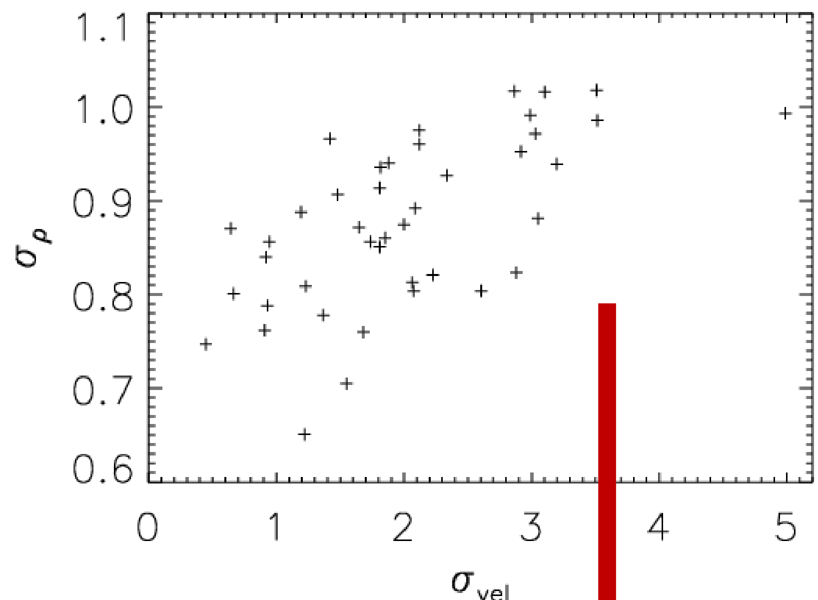
Properties of Turbulence in 50 MCs

l-b diagram

l-v diagram



density and velocity relation

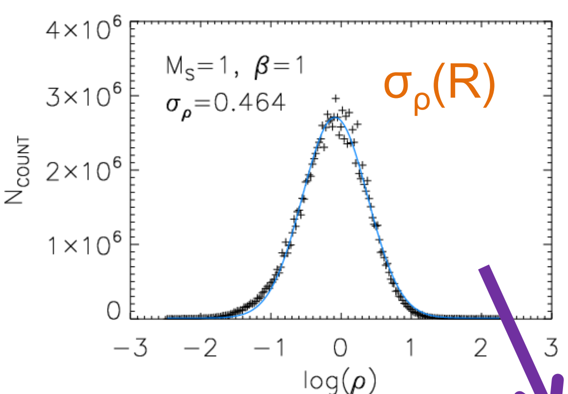


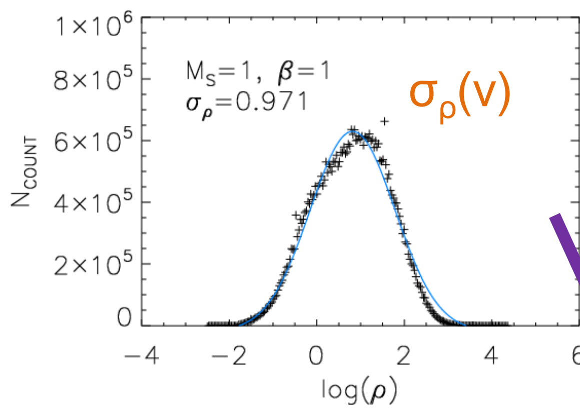
Turbulent velocity width σ_{vel} increases with density width.

MHD Turbulence Simulations

(Kim et. al 1999).
3-dimensional MHD simulation based on TVD scheme

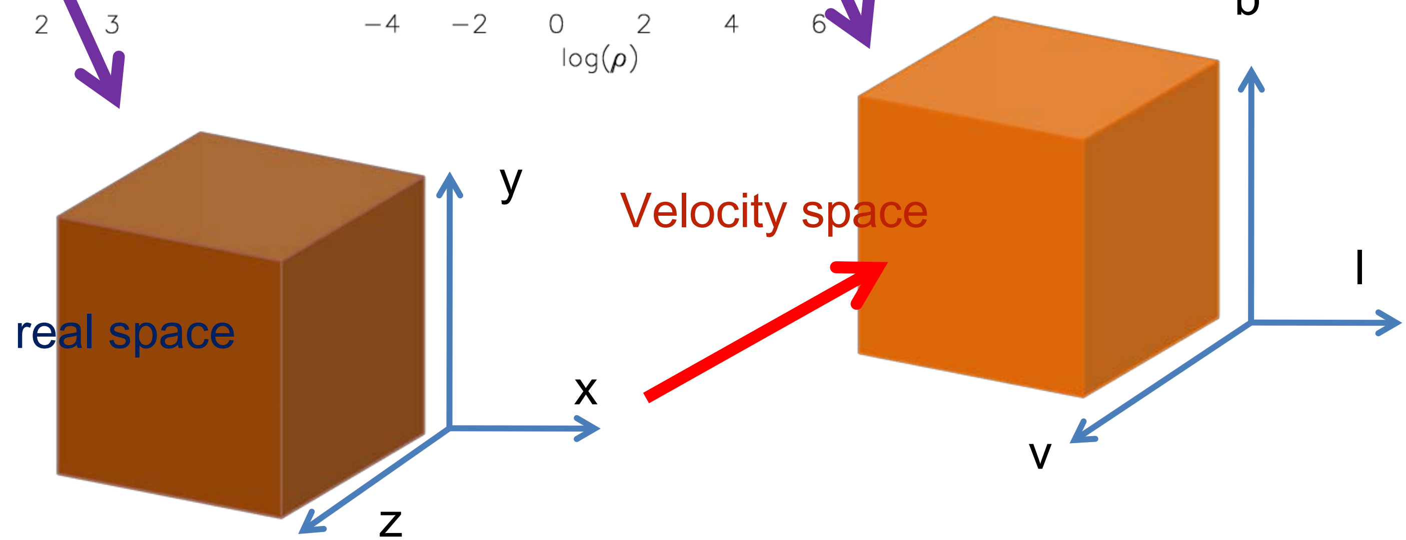
512^3 cube, isothermal gas
Various Mach number (Ms = 1, 2, 4, 7) & Magnetic field (β = 0.1, 1, 10)



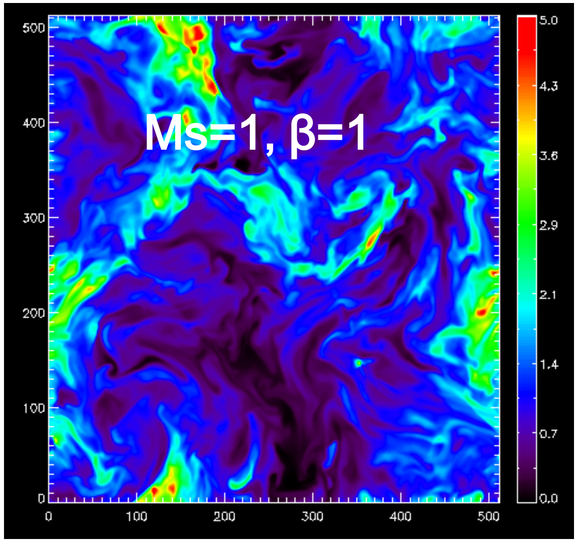


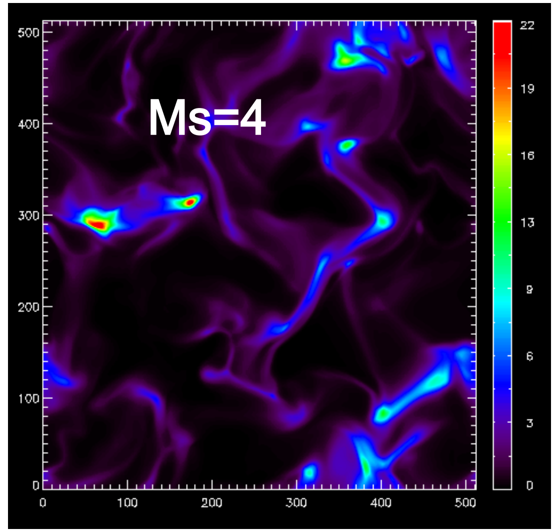
Averaged value of xyv_z, yzv_x, zxv_y space

$$M_s \approx \frac{\sigma_{vel}}{c_s}$$



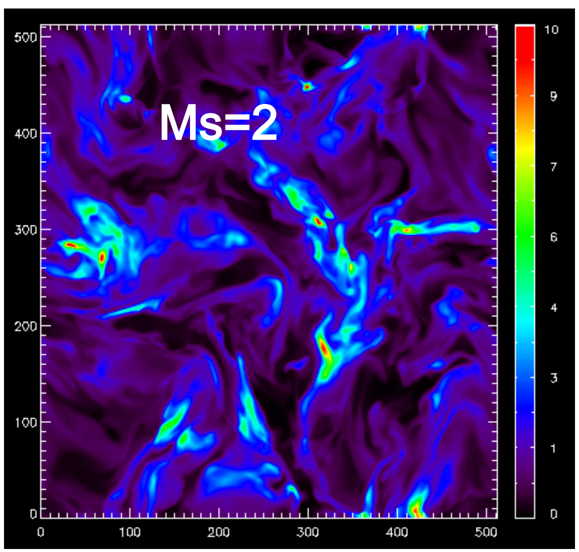
Density Images of MHD Turbulence Simulations

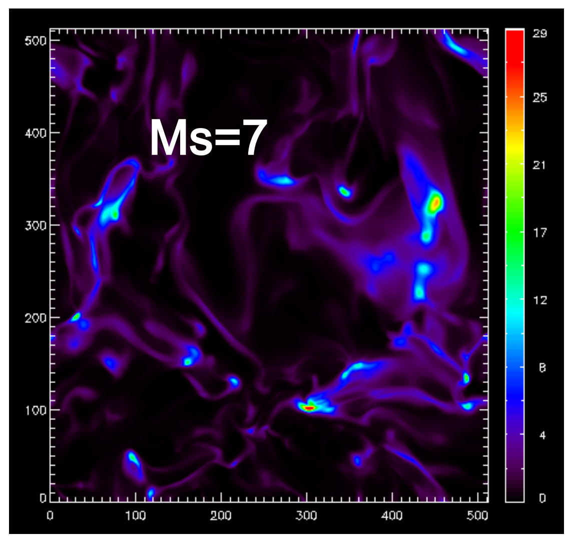




$$\beta = \frac{P_g}{P_B} = 1$$

Saturated Time



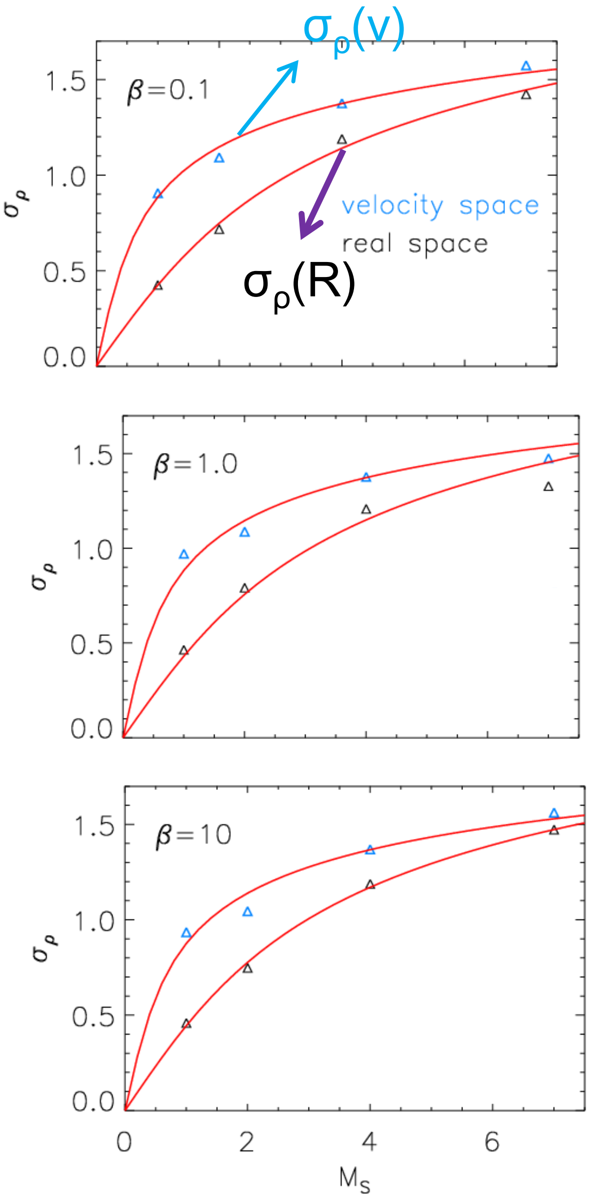


Supersonic turbulence

⇓

Dense core formation ↑

$\sigma_\rho(R)$ and $\sigma_\rho(v)$ in MHD turbulence simulation



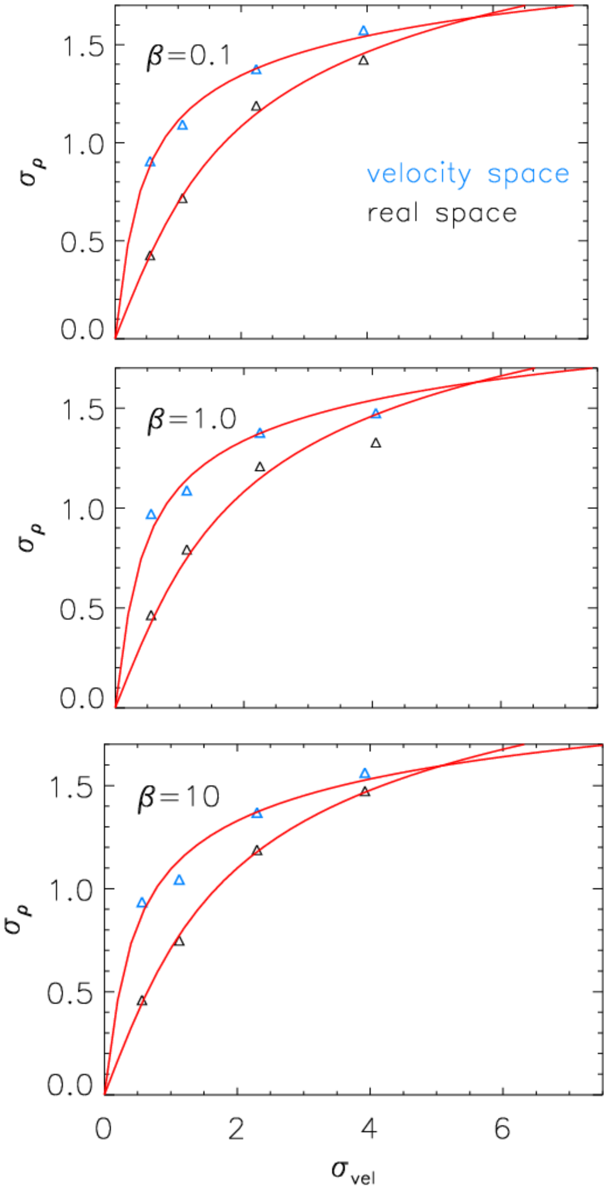
$$\sigma_\rho = a\sqrt{\ln(1+b^2 M_s^2)} \qquad a \sim 1.0, b \sim 0.5$$

$\beta = 0.1$
$\sigma_\rho(R)$: $a = 0.90$, $b = 0.50$
$\sigma_\rho(v)$: $a = 0.65$, $b = 2.32$

$\beta = 1.0$
$\sigma_\rho(R)$: $a = 0.90$, $b = 0.51$
$\sigma_\rho(v)$: $a = 0.65$, $b = 2.31$

$\beta = 10$
$\sigma_\rho(R)$: $a = 0.90$, $b = 0.53$
$\sigma_\rho(v)$: $a = 0.65$, $b = 2.27$

$\sigma_\rho(R)$ and $\sigma_\rho(v)$ in MHD turbulence simulation



$$\sigma_\rho = a\sqrt{\ln(1+b^2\sigma_{vel}^2)}$$

β = 0.1

$\sigma_\rho(R)$: a = 0.90, b = 0.90

$\sigma_\rho(v)$: a = 0.65, b = 4.20

β = 1.0

$\sigma_\rho(R)$: a = 0.90, b = 0.90

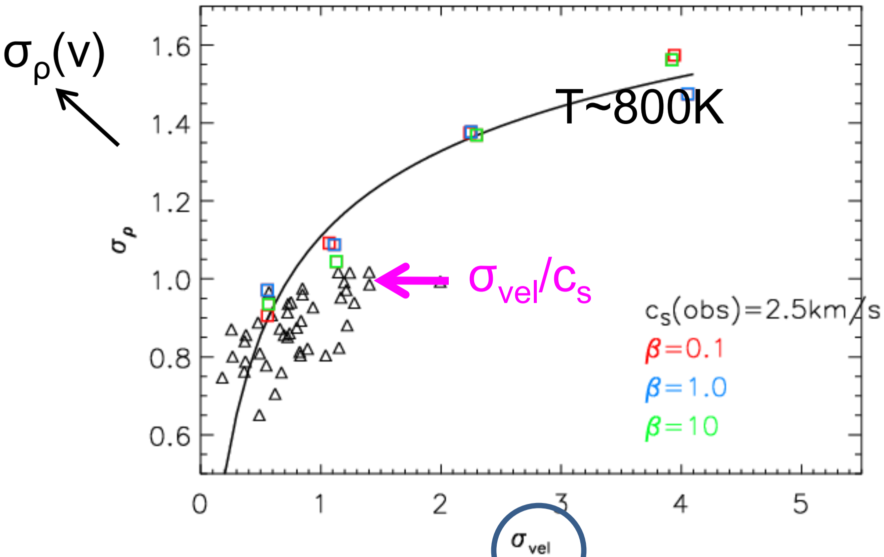
$\sigma_\rho(v)$: a = 0.65, b = 4.12

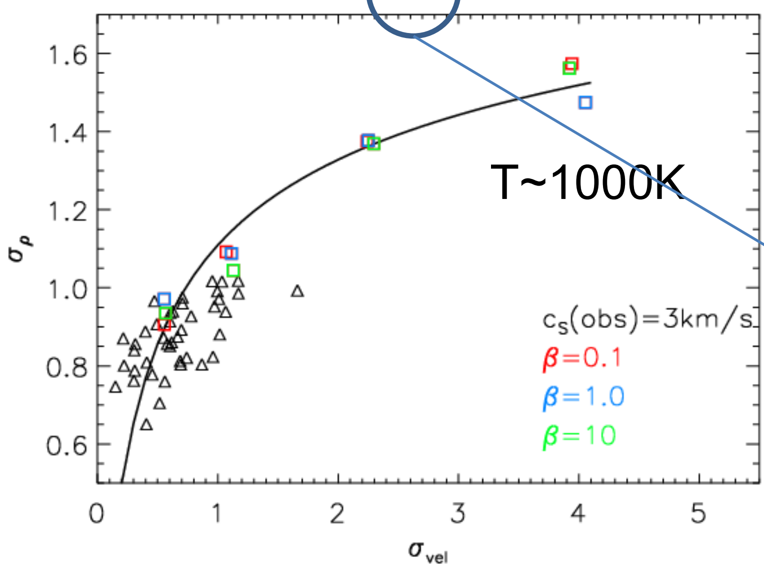
β = 10

$\sigma_\rho(R)$: a = 0.90, b = 0.92

$\sigma_\rho(v)$: a = 0.65, b = 4.01

Comparison of Observation and Simulation





$$c_s \sim 2km/s$$

$$c_s \sim \sqrt{\frac{P}{\gamma\rho}} \Rightarrow T \sim 1000K$$

It is too high temperature

→ Possible effects :

Molecular Cloud distribution
Optical depth

$$\sigma_{vel} \sim \frac{\sigma_{vel}}{c_s}$$

Conclusion

❖ Observation :

Molecular Clouds in GRS survey :

- complex and turbulent structures.
- Statistical analysis : log-normal density distribution
- correlation existence between the density PDF, velocity width, PS

❖ Simulation :

3-dimensional MHD turbulence simulation

- depends on the sonic Mach number
- conversion the real space into velocity space

❖ Comparison of observation & simulation :

- Cs (observed MCs) : 2~3 km/s
- Temperature of MCs ~ 1000 K
- consideration of effects for the spatial distribution, optical depth etc.