# Estimation of B-field Strength in the WIM based on RM histograms

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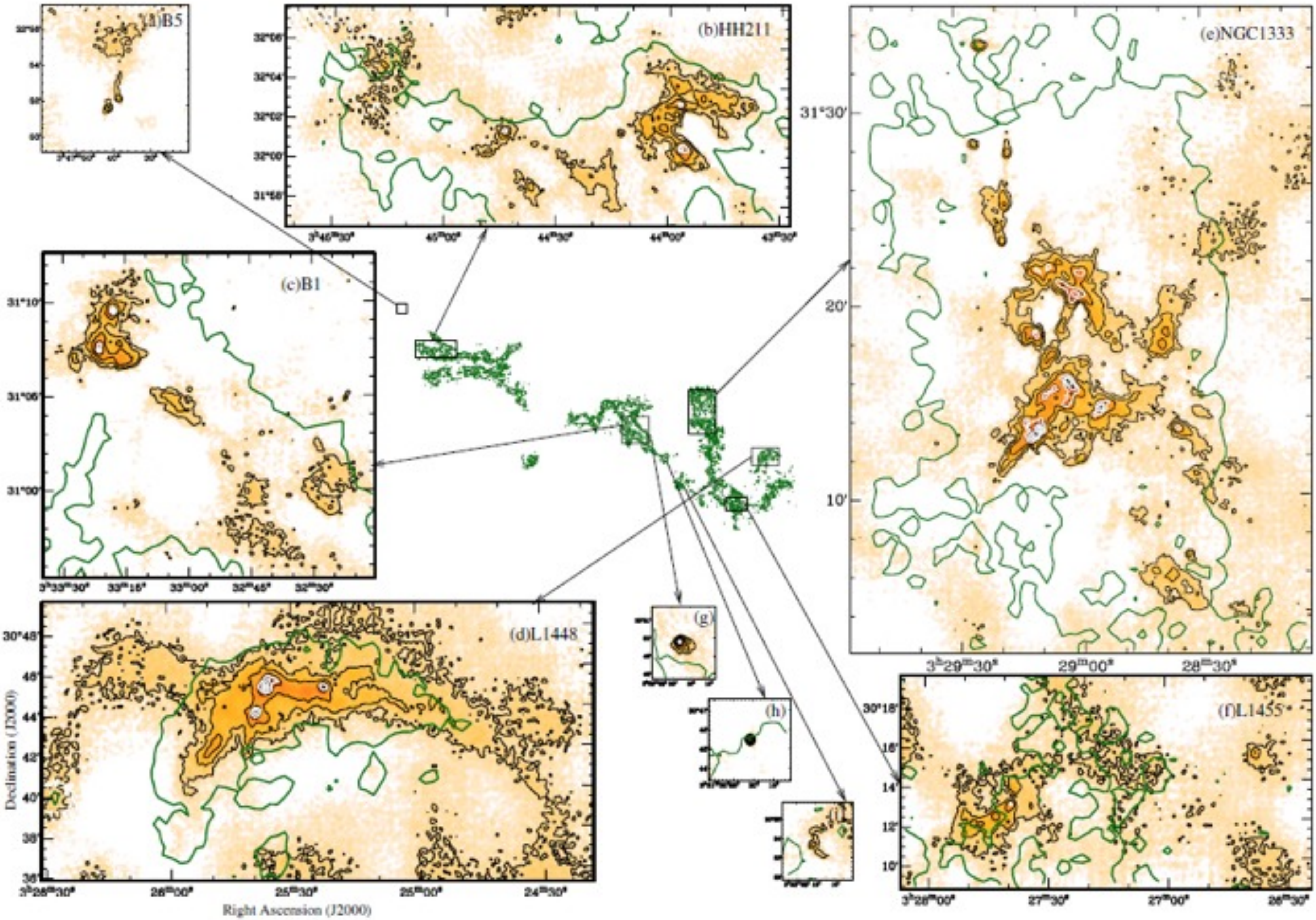
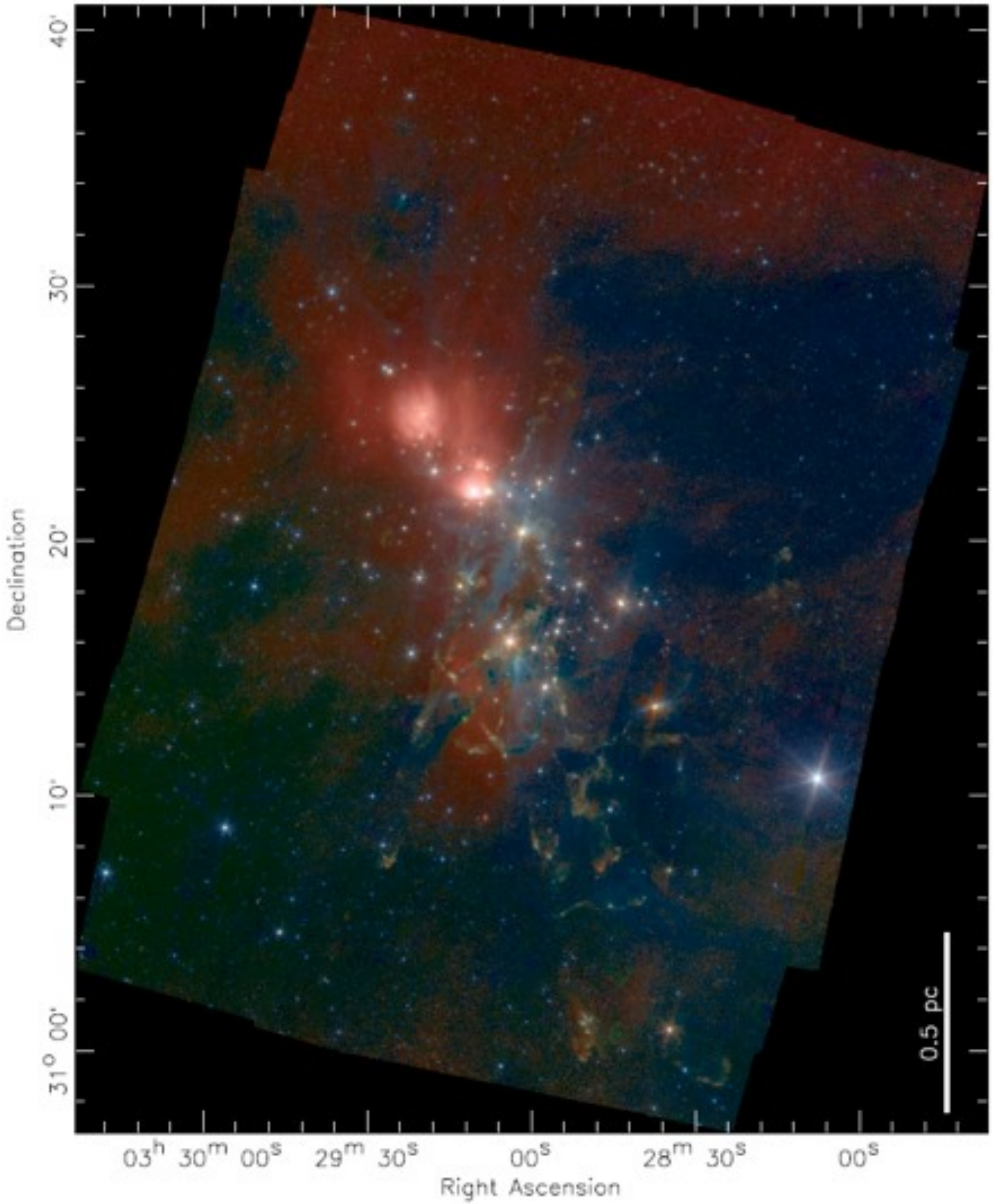
# Hatchell+ 2005






Gutermuth+ 2008
Spitzer
3.6,4.5, 8.0 micron
blue, green, red

# Reynolds number

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \mathbf{f}$$

$$\mathrm{Re} = \frac{\rho v L}{\mu} = \frac{v L}{\nu}$$

$$= \frac{vL}{v_T l}$$

$$\sigma n l = 1$$

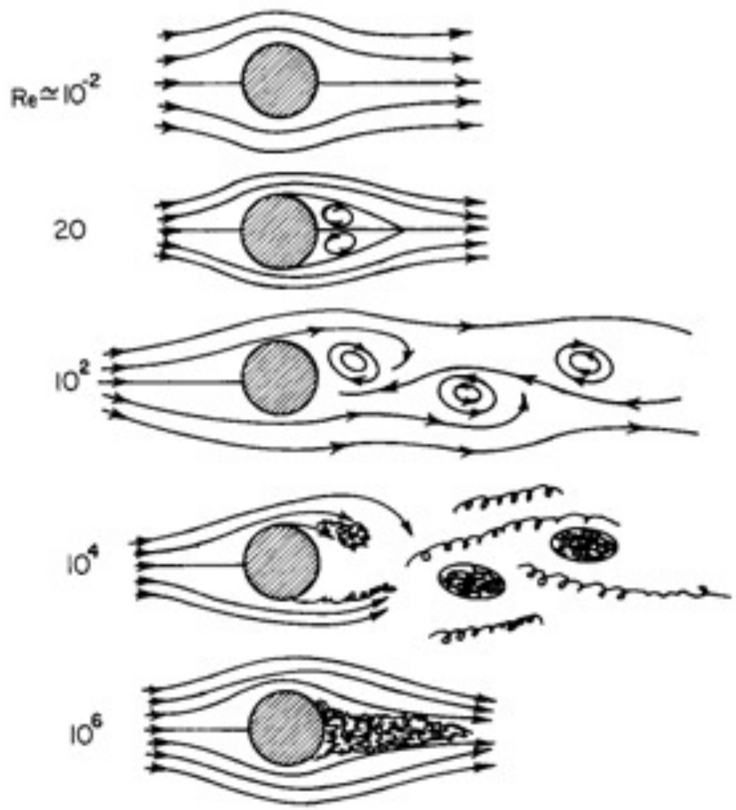
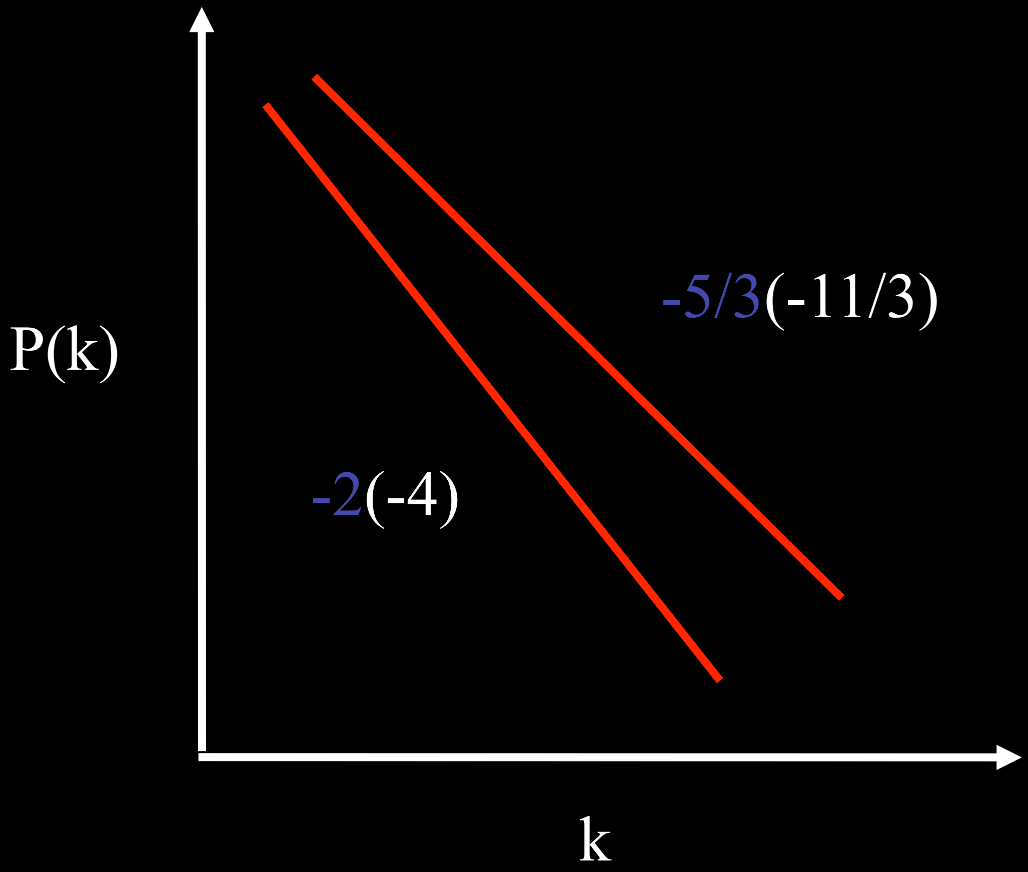
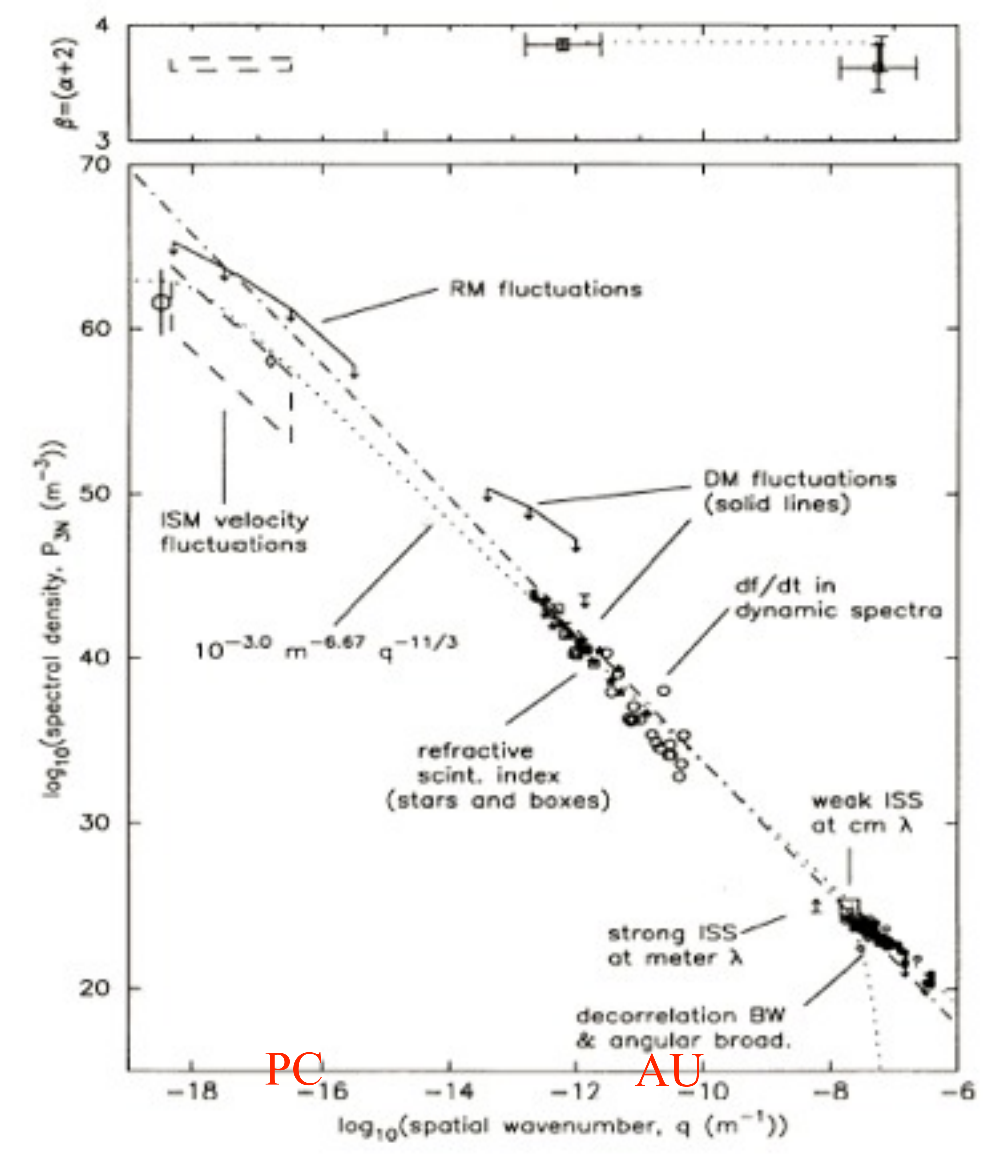



**Figure 1.1** Schematic picture of a fluid around a cylinder at different Reynolds numbers.

# Kolmogorov and Burgers Velocity Power Spectra



# Density Power Spectra

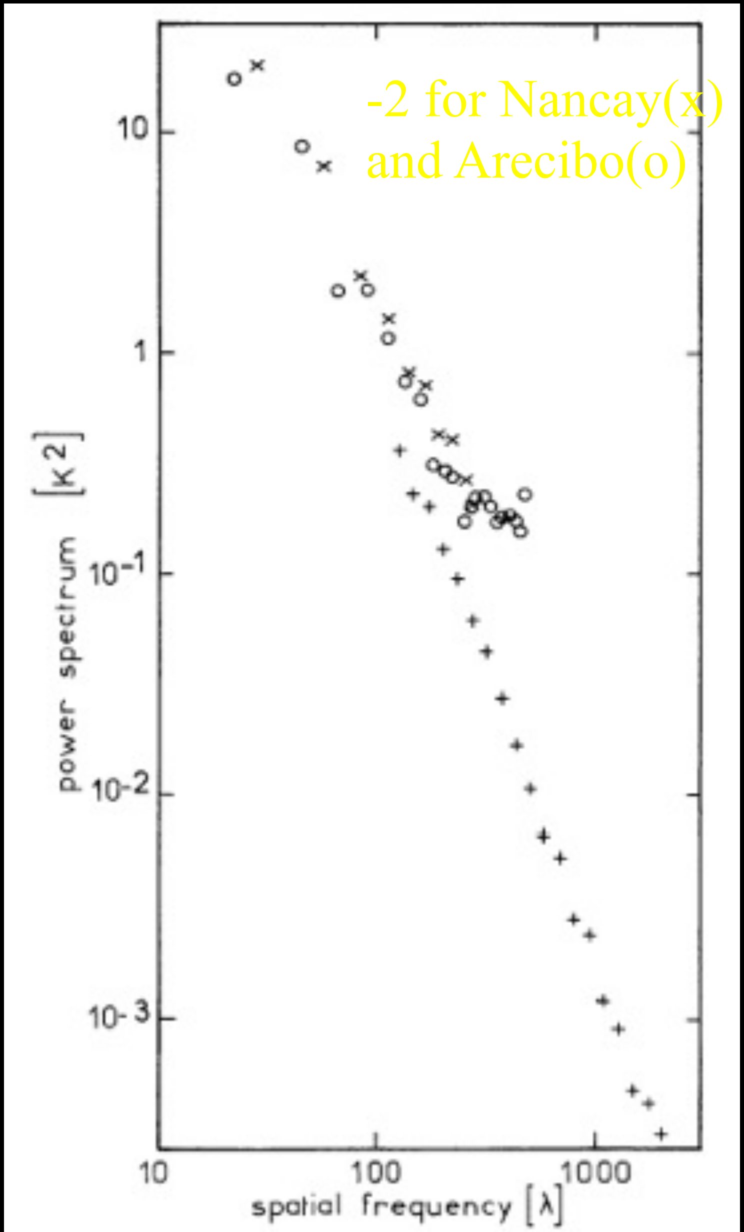



-5/3(-11/3) : the 3D (1D) slope of Kolmogorov PS

- Electron density PS (M~1)
- Composite PS from observations of ISM velocity, RM, DM, ISS fluctuations, etc.
- A dotted line represents the Kolmogorov PS
- A dash-dotted line does the PS with a -4 slope

Armstrong et al. 1995 ApJ, Nature 1981

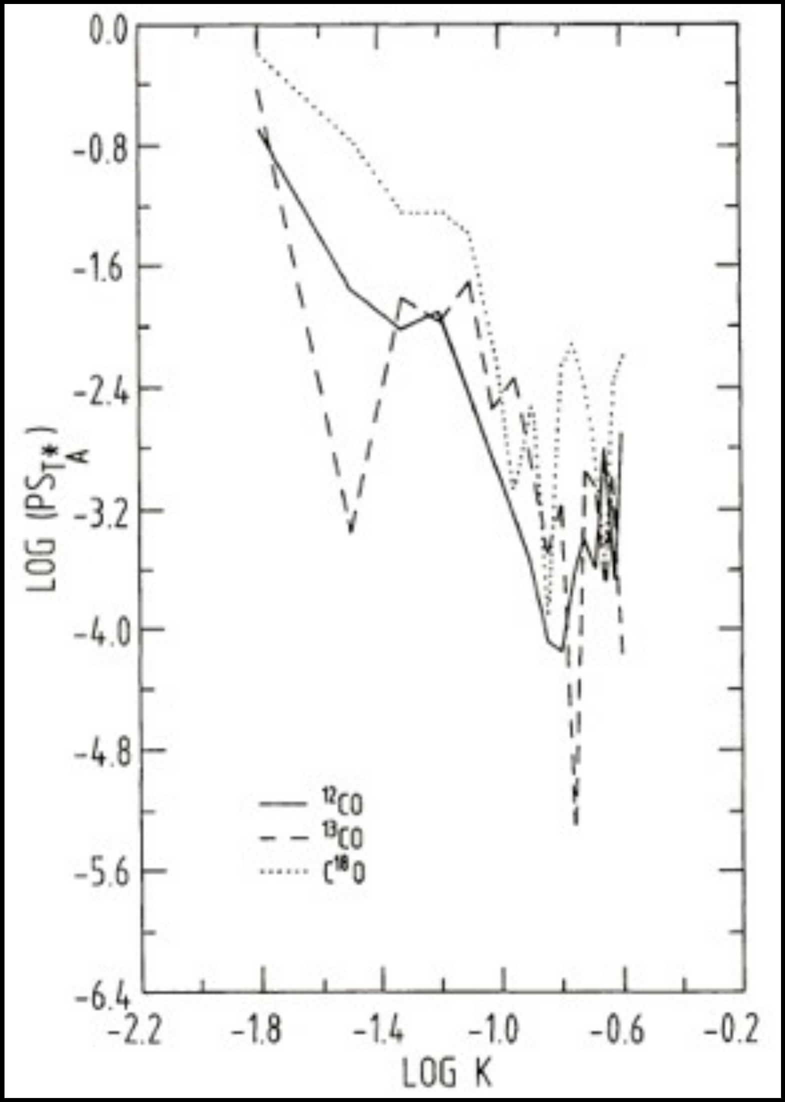
## Crovisier and Dickey 1983



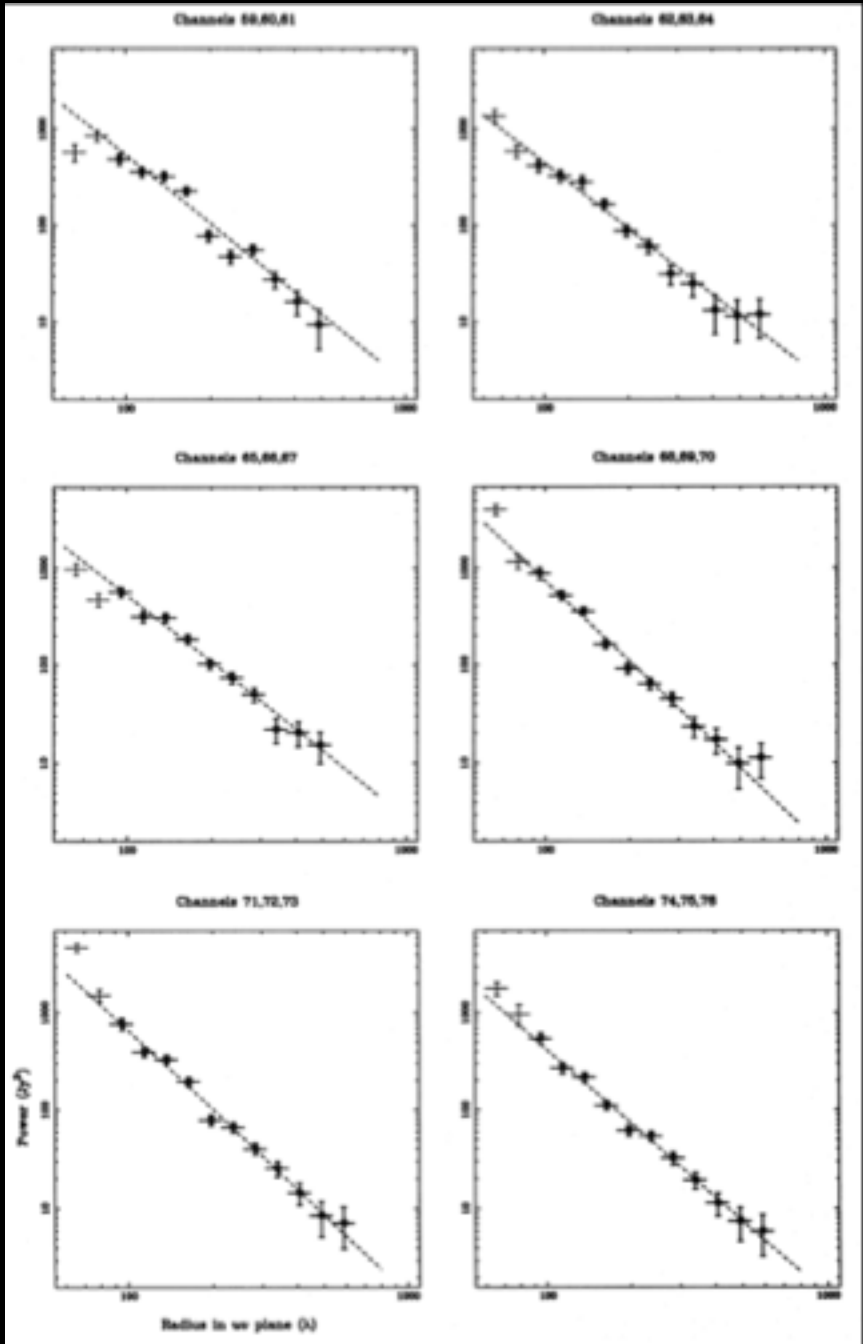

- PS of HI 21cm observations
- Observed with WSRT, Nancay and Arecibo
- l=52.5, b=0.0
- Easy to find PS from the visibility of interferometric observations
- The slopes of PS are -2(-3) for WSRT observations and -1 for single dish observations

-3: Westerbork(+)

## Stenholm 1984




- •B5, a molecular cloud
- •Power spectra of peak line temperatures along N-S scans
- •The mean spectral slope is around -1.67 (Komogorov type spectra)
- • density PS vs column-density PS.

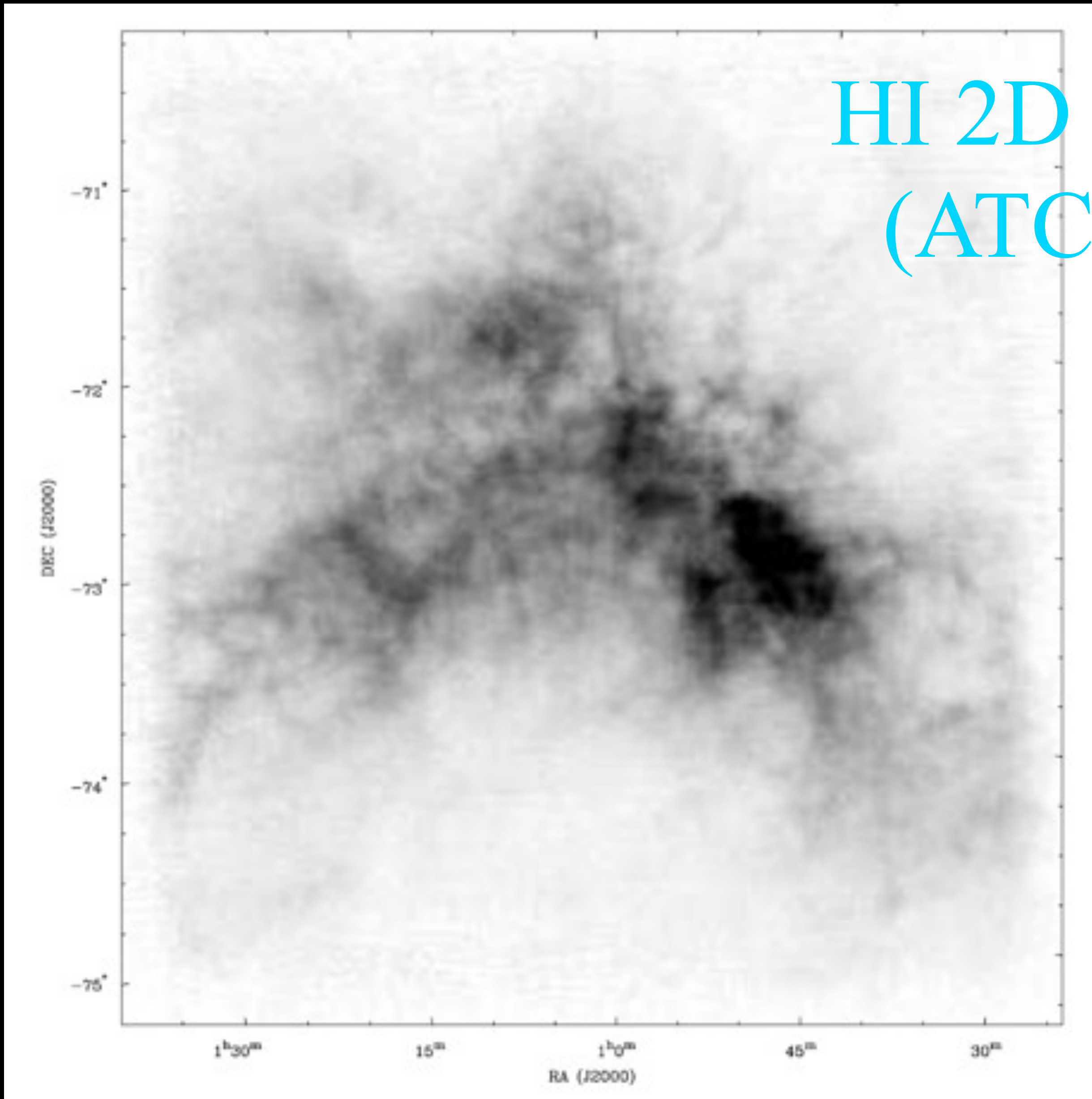


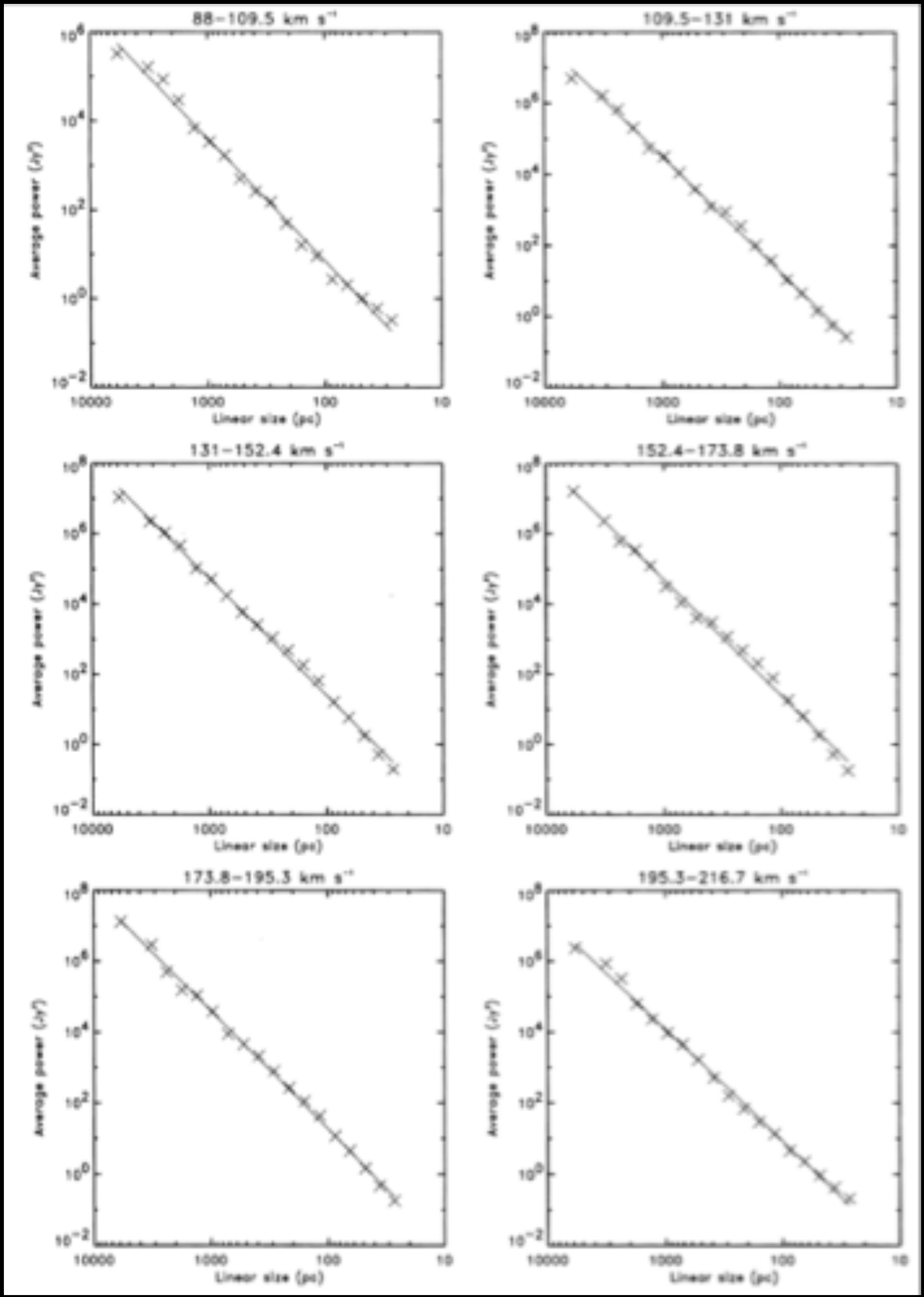
Green 1993

- PS of HI channel maps
- DRAO Galactic Plane Survey
- l=140 deg, b=0 deg
- Slope: -1.2~-2.0 (-2.2~-3.0)

Stanimirovic et al. 1999

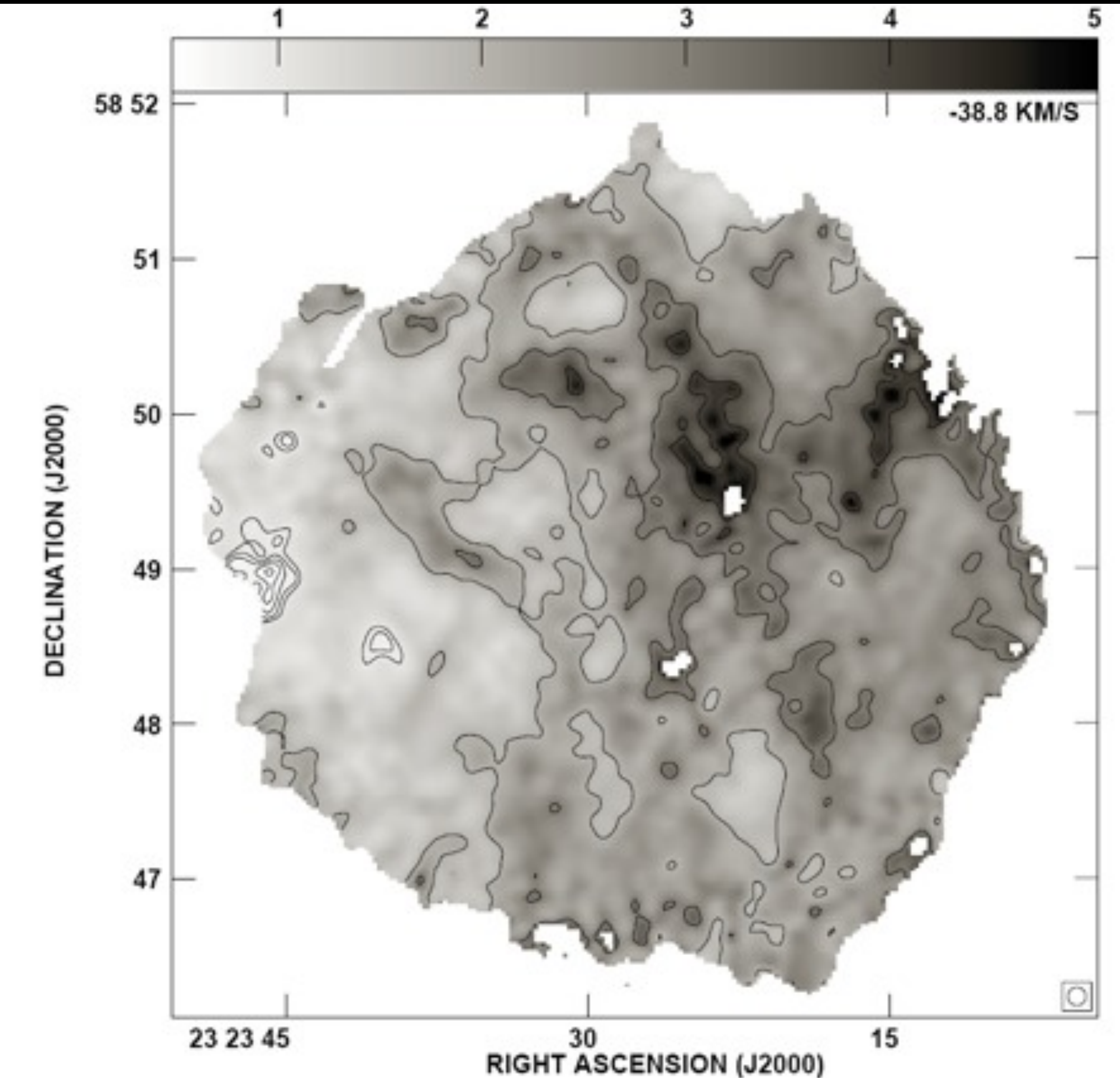
# HI 2D PS of SMC (ATCA+Parkes)






Slope: -2.04 (-3.04)

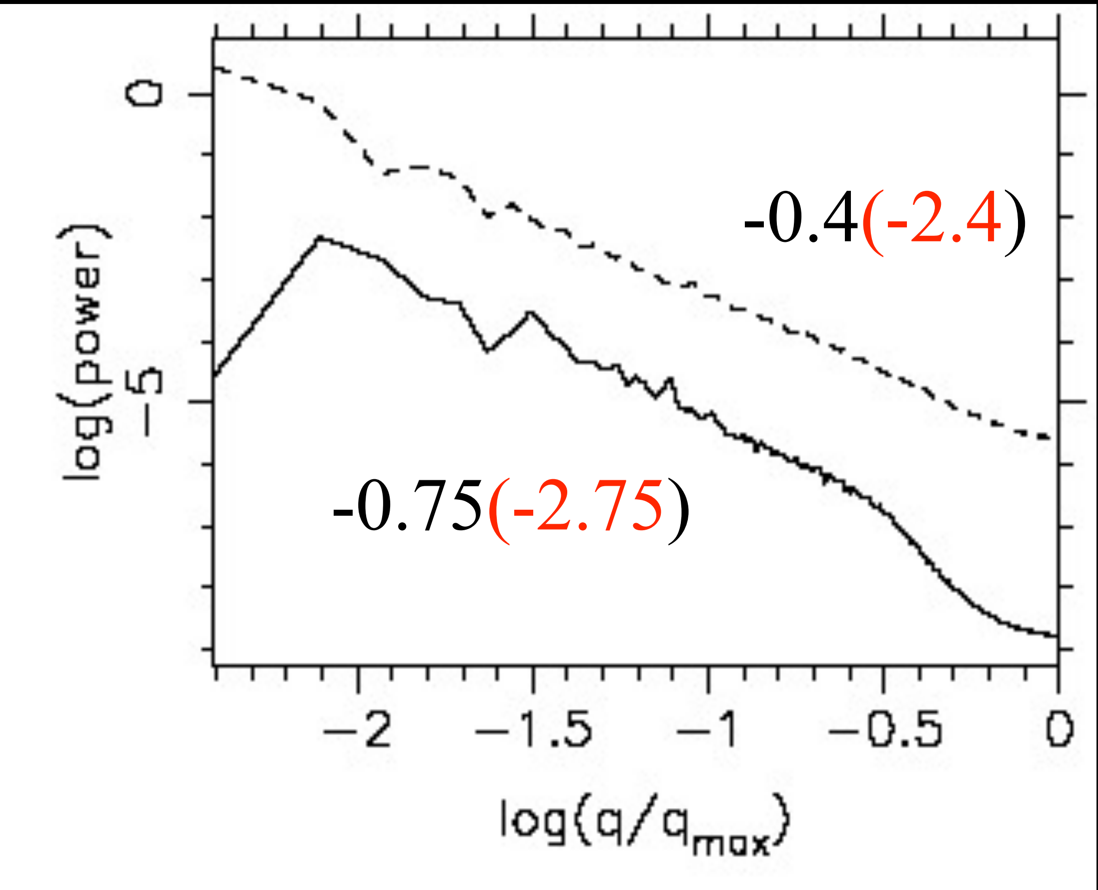
Deshpande et al. 2000




# HI optical depth image

- CAS A
- VLA obs.
- angular resol.: 7 arcsec
- sampling interval: 1.6 arcsec
- velocity reol.: 0.6km/sec

Deshpande et al. 2000




Density PS of cold HI gas (M~2-3 from Heiles and Troland 03)

-A dash line represents a dirty PS obtained after averaging the PW of 11 channels.

-A solid line represents a true PS obtained after CLEANing.

# Summary of observations

- Spectral slopes of most of observations are measured from density or column-density fields (compressible turbulence).
- The range of density spectral indexes are -0.4 ~ -2.0.

# Density PS of isothermal flows

Isothermal Hydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0; \qquad \rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}\right) = -\nabla(\rho a^2) + \vec{f}$$

- We adjust the amplitude of the velocity field in such a way that root-mean-square Mach number, Mrms, has a certain value.

$$M_{\rm rms} = \frac{v_{\rm rms}}{a} = 1 - 12;$$

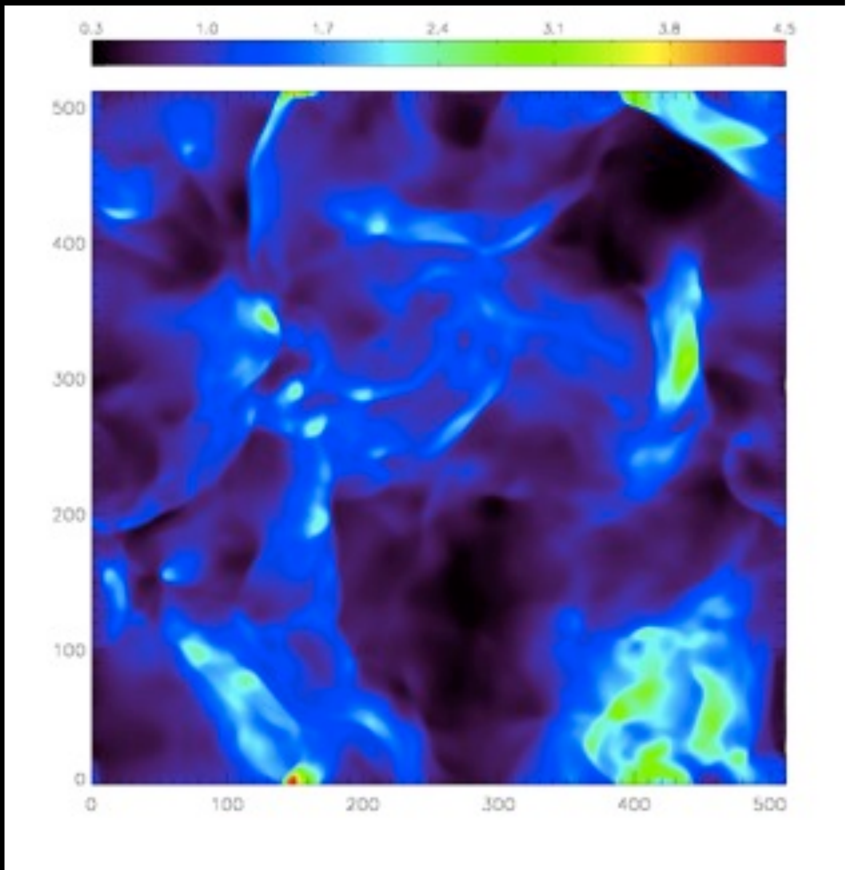
Initial Condition: uniform density

Periodic Boundary Condition

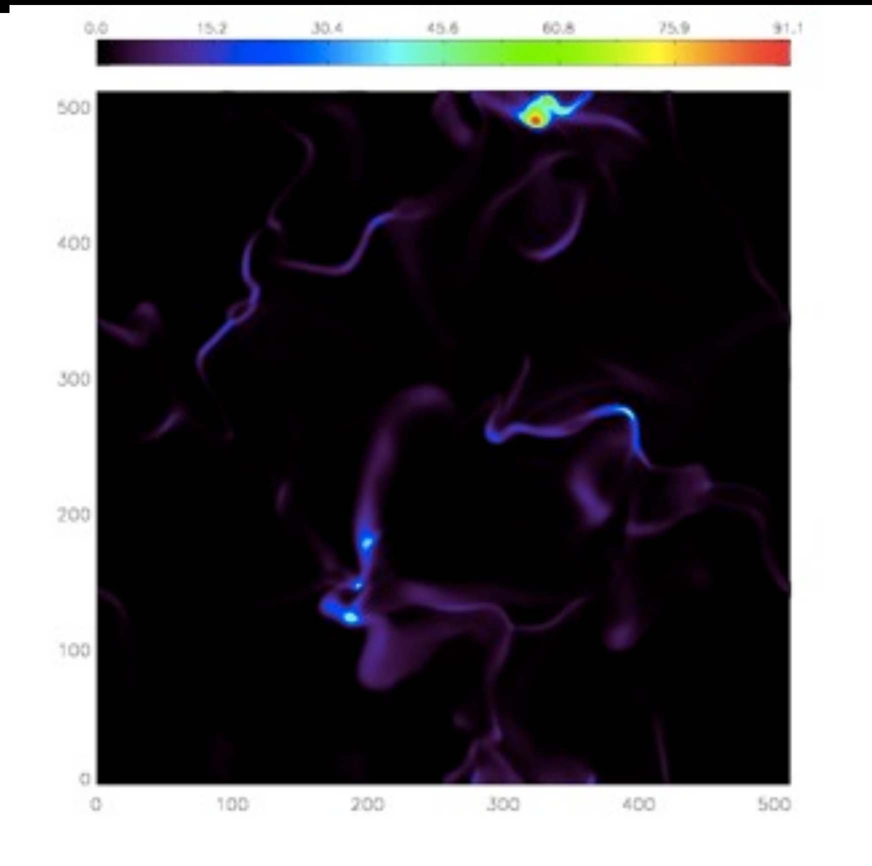
Isothermal TVD Code (Kim, et al. 99)

# Comparison of sliced density images from 3D simulations

Mrms=1.2



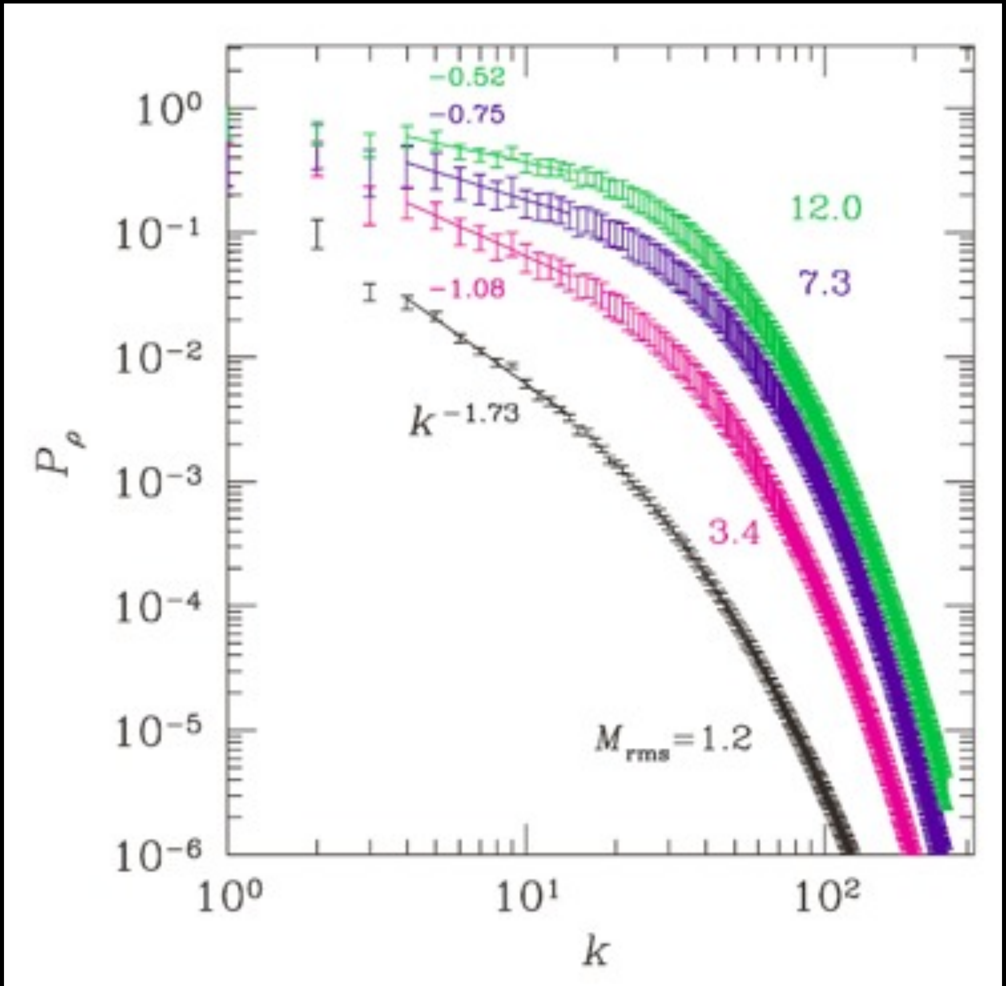

Mrms=12




- Large-scale driving in a wavenumber ranges $1<k<2$
- Resolution: $512^3$
- Filaments and sheets with high density are formed in a flow with Mrms=12.

Kim & Ryu 2005

# Density power spectra from 3D HD simulations




- Statistical error bars of time-averaged density PS
- Large scale driving in a wavenumber ranges $1<k<2$
- Resolution: $512^3$
- Spectral slopes are obtained with least-square fits over the ranges $4<k<14$
- As Mrms increases, the slope becomes flat in the inertial range.

# Density PS of thermally bi-stable flows

HD equations with cooling and heating terms

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

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot [\rho \vec{v}\vec{v} + p] = \vec{f}$$

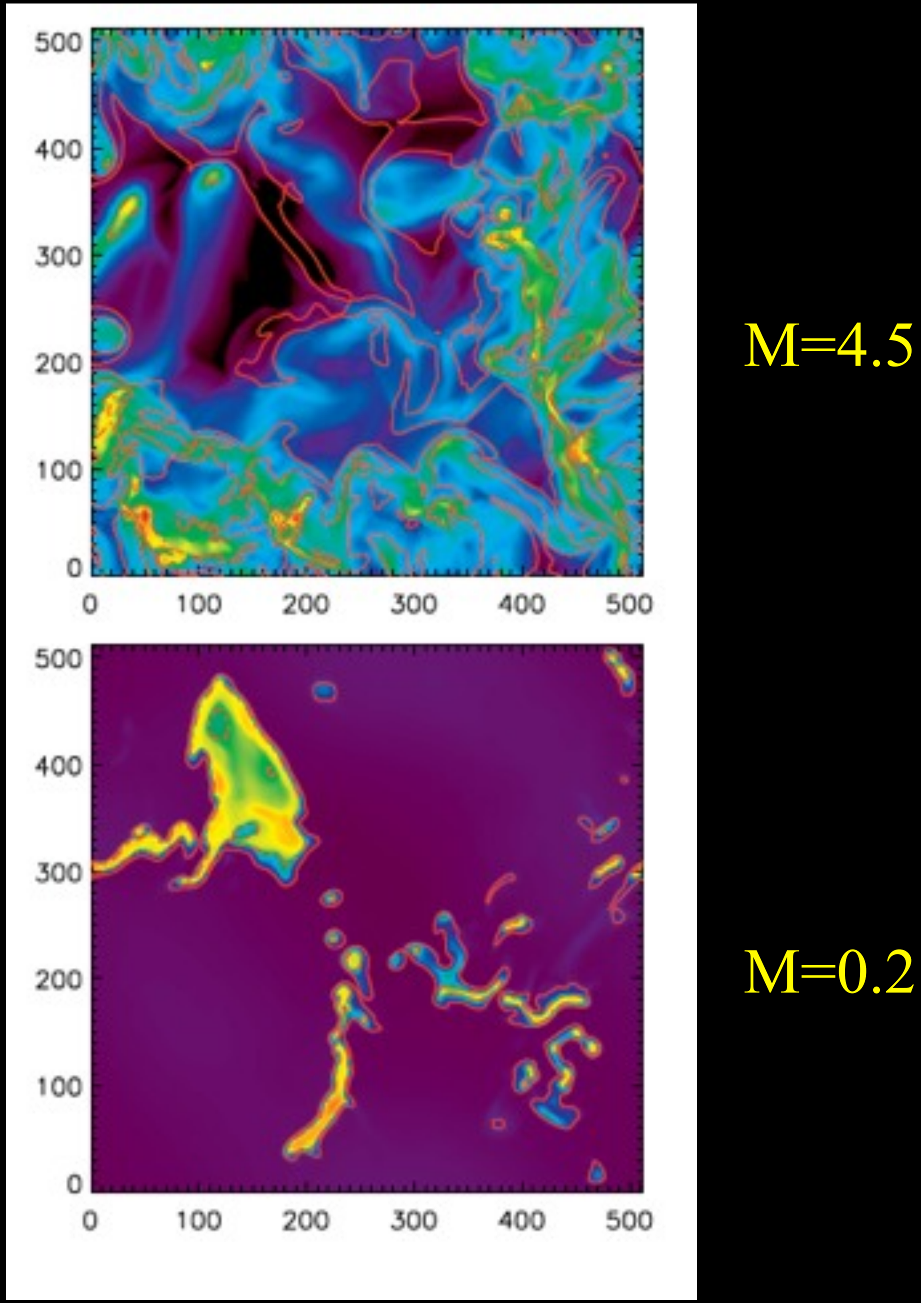
$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\vec{v}] = \Gamma - \Lambda$$

where

$$E = \frac{p}{\gamma - 1} + \frac{1}{2}\rho \vec{v}^{\,2}$$

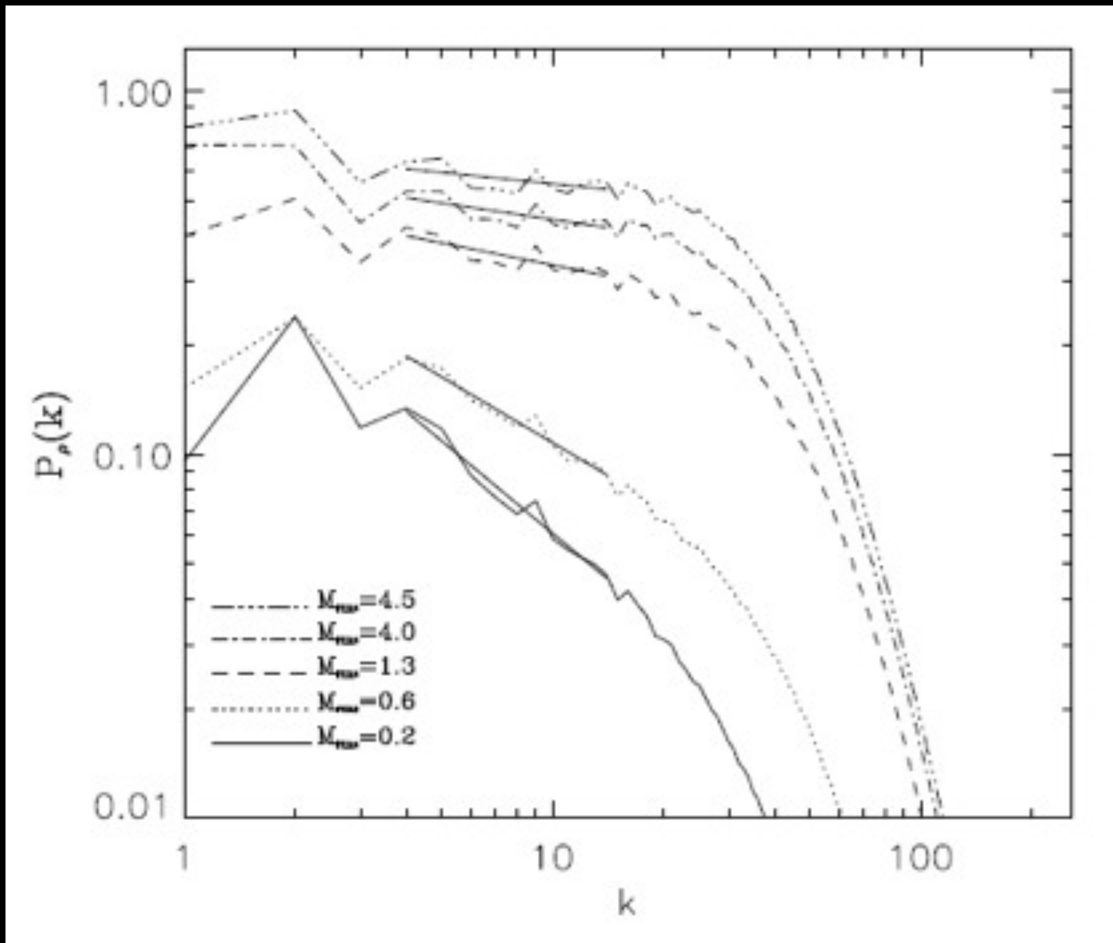
Gazol & Kim 2010

# Density PS in thermally bi-stable flows




Gazol & Kim 2010

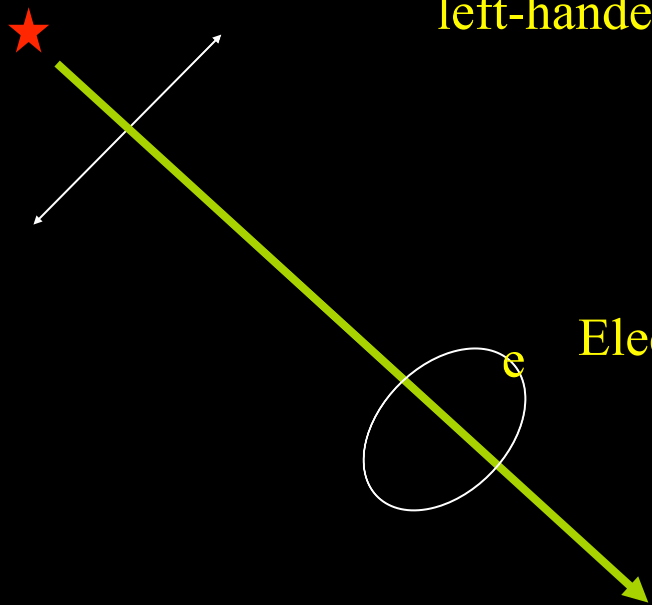
# Density PS




| $M$ | $P_\rho$ |
|---|---|
| 0.2 | -0.84 |
| 0.6 | -0.60 |
| 1.3 | -0.20 |
| 4.0 | -0.15 |
| 4.5 | -0.10 |

# Faraday Rotation

linearly polarized EM wave =
left-handed CP wave + right-handed CP wave




Electron gyrates with the gyrofrequency.

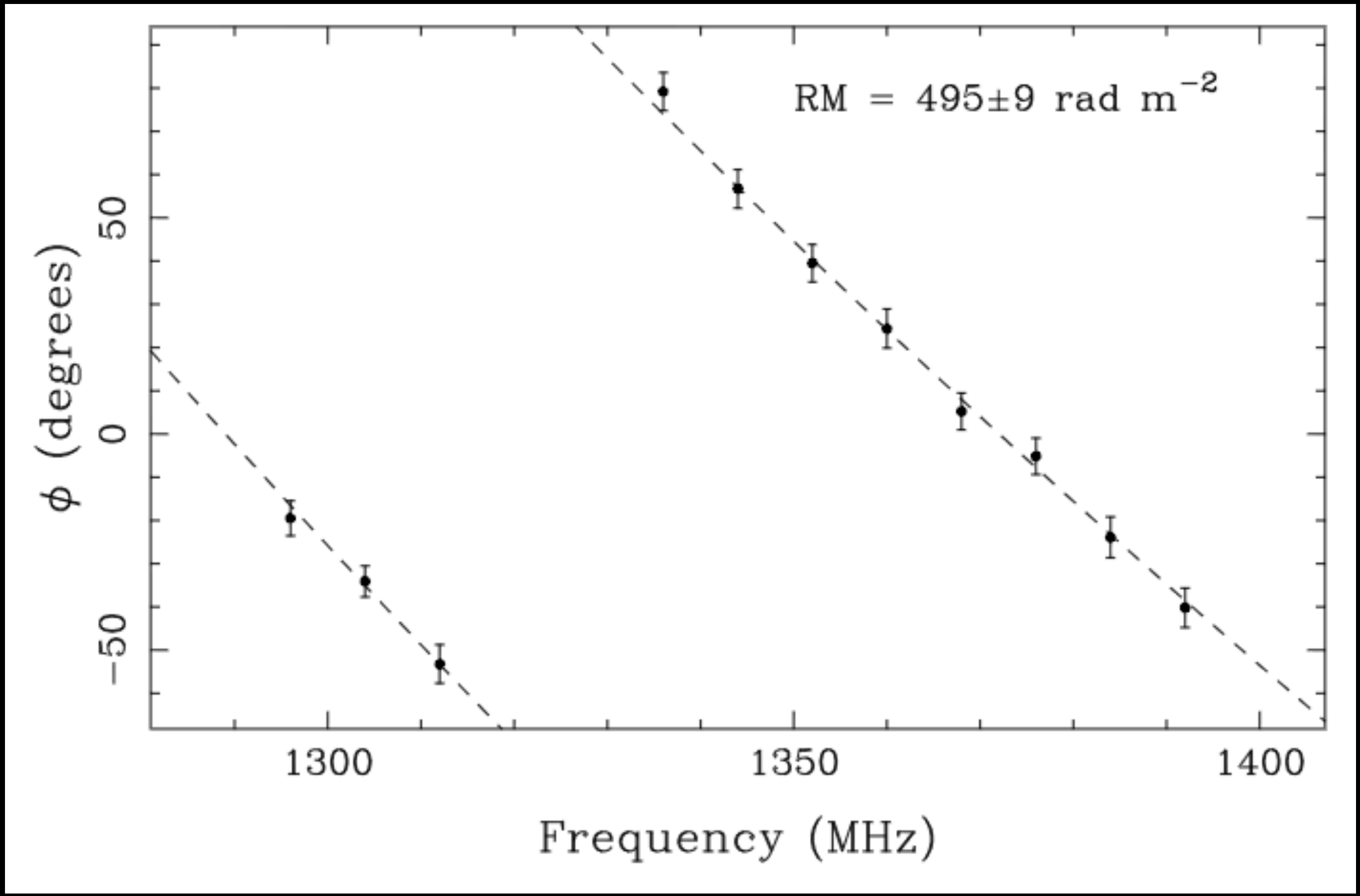
$$\varphi = \varphi_0 + \mathrm{RM}\,\lambda^2;$$

$$\mathrm{RM} = K \int_0^r n_e B_{\|}\, ds$$

$$K = 0.81\,\mathrm{rad\,m^{-2}\,pc^{-1}\,cm^{3}\,\mu G^{-1}}$$

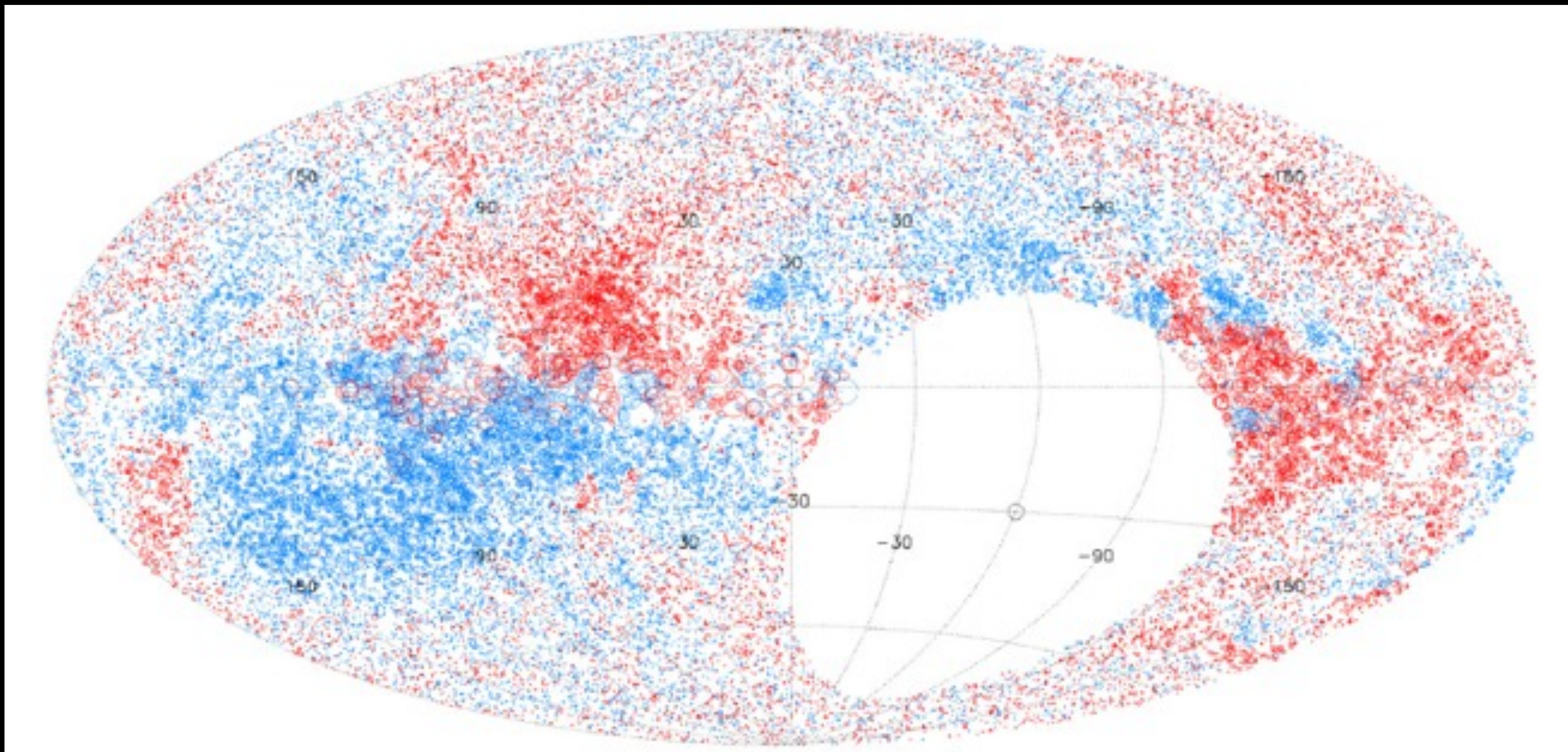
$$\langle B_{\|} \rangle = \frac{\mathrm{RM}}{\mathrm{DM}}$$

# Spectropolarimetry



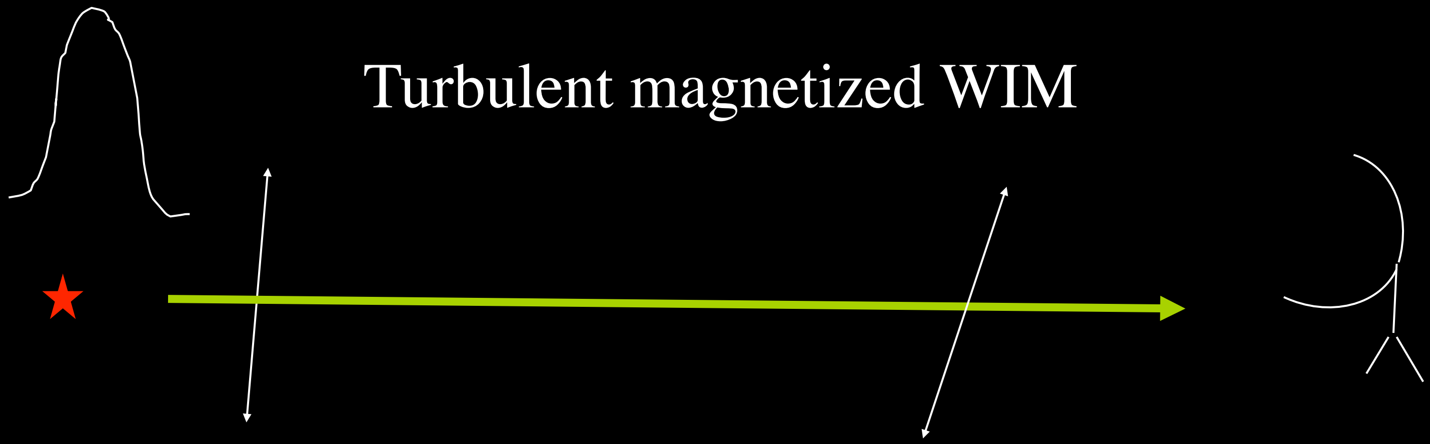
Taylor+ 2009

# RM Image of the Sky



- NRAO VLA Sky Survey, two bands around1.4GHz, 37543 radio sources(1 deg resolution), delta>-40,
- LOFAR, ASKAP, SKA (30 arcsec resolution)

# Motivation (I)




$$\langle B_{\parallel} \rangle = \frac{\mathrm{RM}}{\mathrm{DM}} = \frac{\int_0^r n_e B_{\parallel} ds}{\int_0^r n_e ds}$$

Basic assumption:
no correlation between
Bpara and ne

# Motivation (I)

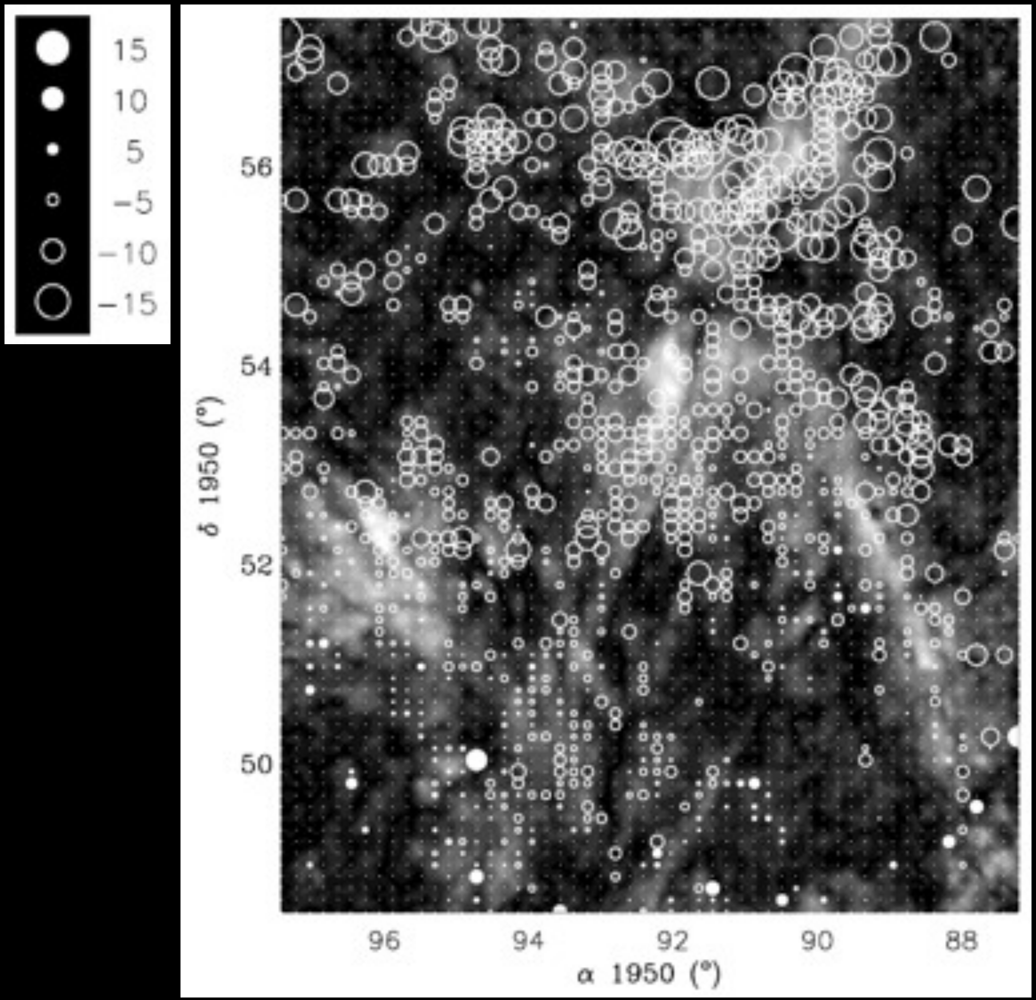
- Beck et al.(2003) : there may be anti-correlation between B and ne because total pressure of the WIM tents to be constant.

$$P_{\text{tot}} = P_{\text{gas}} + P_{\text{mag}} = \rho c_s^2 + \frac{B^2}{8\pi} = \text{const.}$$

- So the measured field strengths based on the RM/DM may be underestimated.
- Is there any correlation between B and ne in the WIM?

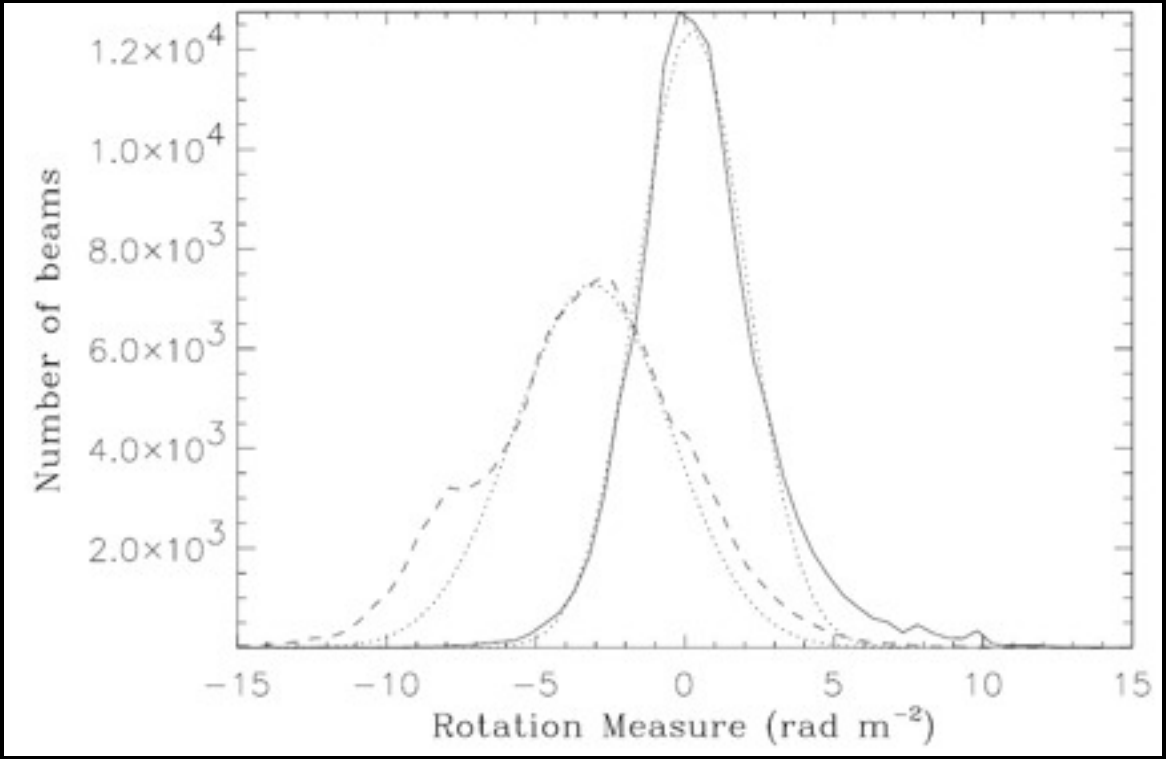
# Motivation (II)

Haverkorn et al. 2003




- WSRT, multi-frequency (341, 349, 355, 360 375MHz) pol. Obs. in the region of the Auriga constellation with diffuse synchrotron background
- Polarized Int. Map (349MHz)+ RMs

# Motivation (II)

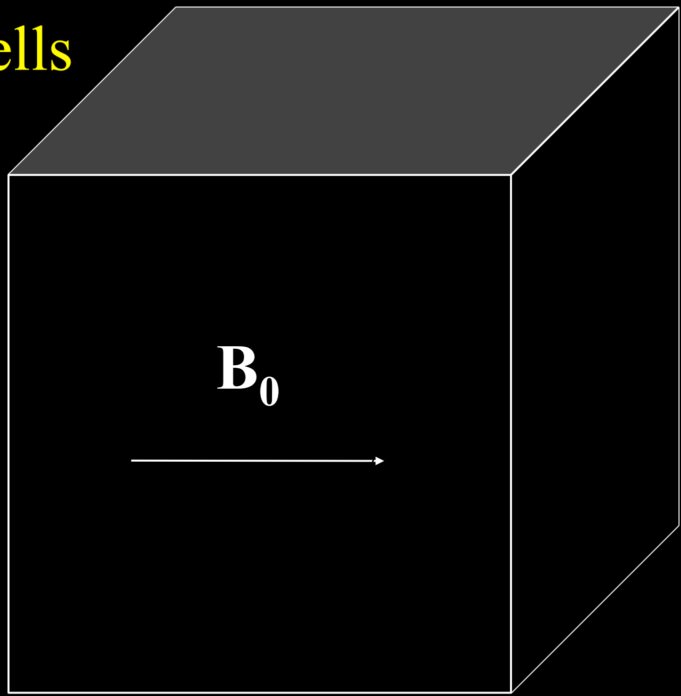



- Histograms of RMs
- Solid, dashed lines are from observations; dotted lines are from the Gaussian fitting
- Can we measure Bpara strength using the width of the Gaussian?

# Numerical Simulations

resolution: $512^3$ cells

driven
turbulent flow
with
$M$s = 1
(the magnetized
turbulent WIM)



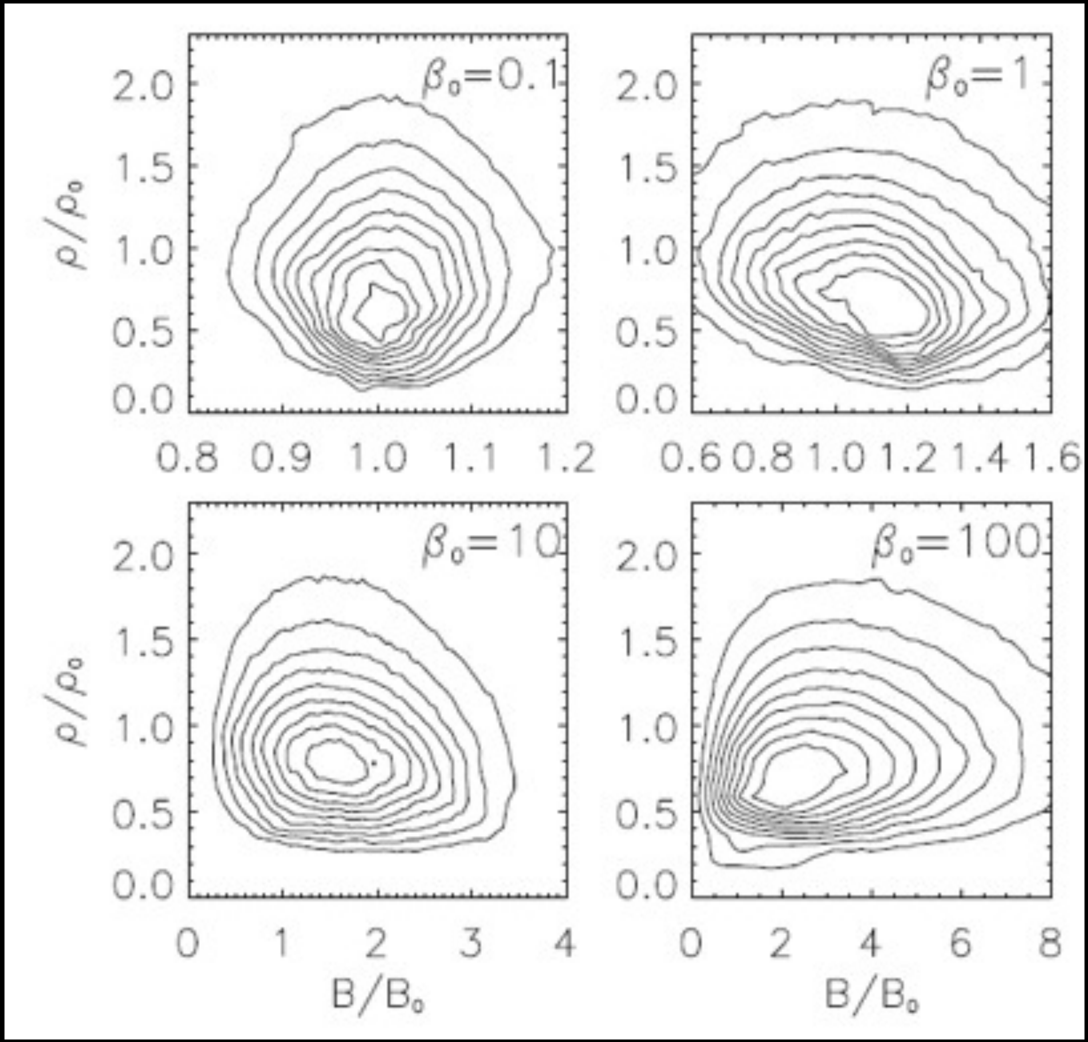

•periodic boundaries
•Solve isothermal MHD equation

$\beta_0$: ratio of gas pressure to magnetic pressure
$\beta_0$=0.1, 1, 10,100

$$B_0 = 1.3 \left(\frac{1}{\beta_0}\right)^{1/2} \left(\frac{T}{8000\mathrm{K}}\right)^{1/2} \left(\frac{n_e}{0.03\mathrm{cm}^{-3}}\right)^{1/2} \mu\mathrm{G}$$

$$RM_0 = 0.81 \int_0^L n_e B_0 ds = 0.81\ n_e B_0 L \quad \text{radians m}^{-2}$$

# 2D histogram on (rho, B) plane



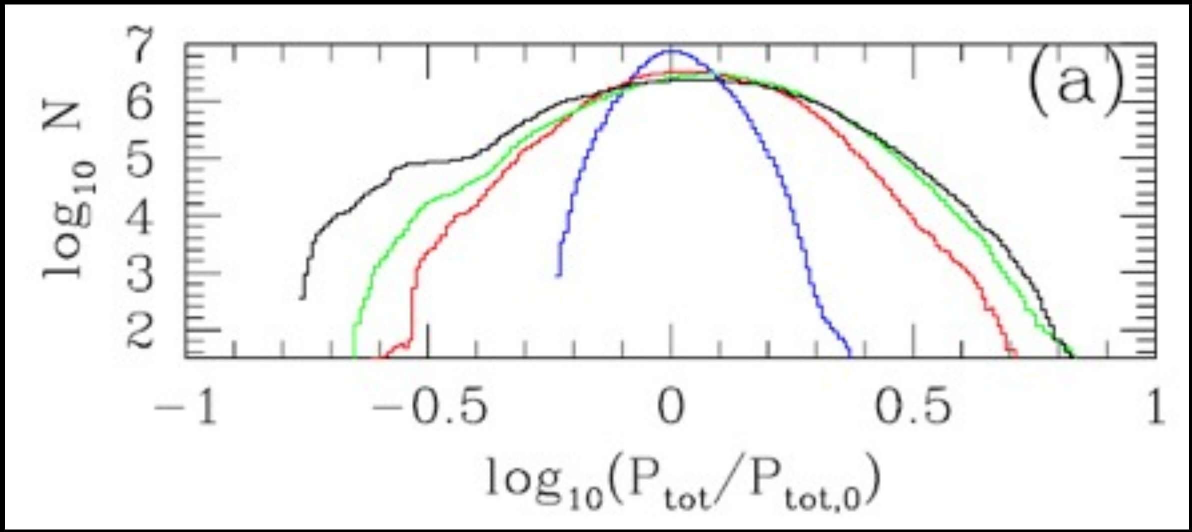

- Contour levels: from 10% to 90% of the peak value with 10% interval
- Almost no correlation between density and field strength

# Correlation Coefficients

$$C(\rho, B = |\vec{B}|) = \frac{\sum_{i,j,k} (\rho_{i,j,k} - \bar{\rho})(B_{i,j,k} - \bar{B})}{\sqrt{\sum_{i,j,k} (\rho_{i,j,k} - \bar{\rho})^2 \sum_{i,j,k} (B_{i,j,k} - \bar{B})^2}}$$

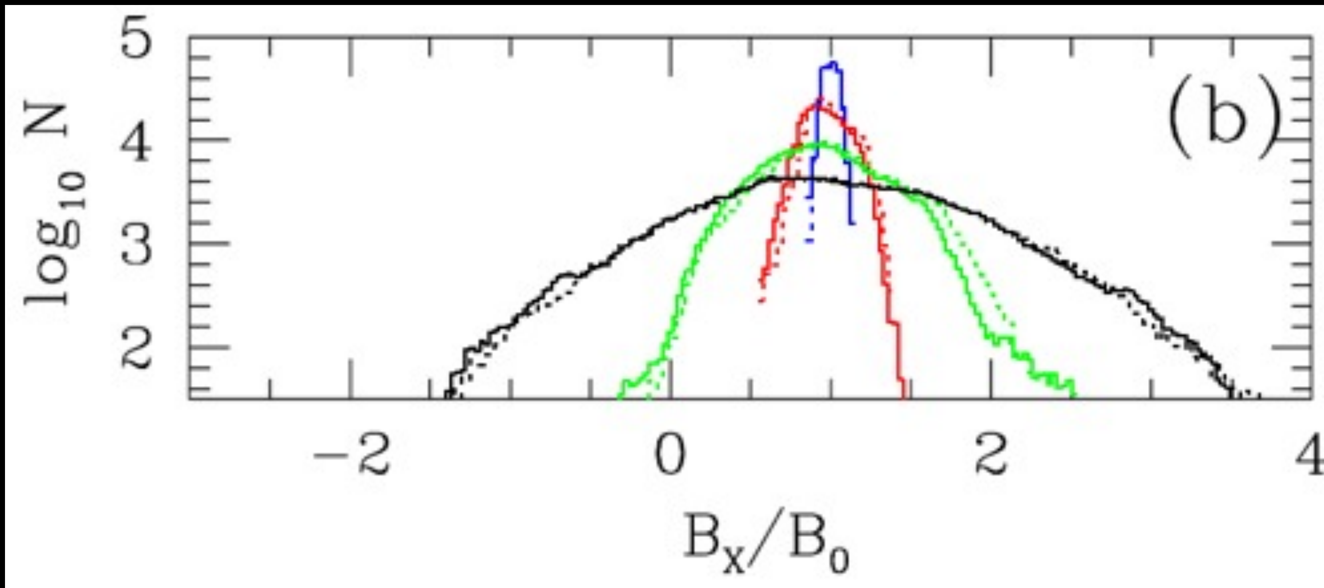
- C=1(-1); strong positive (negative) correlation
- C=0; no correlation
- $C(\beta_0=0.1,1,10,100) = 0.01,-0.12,-0.06,0.16$
- There is almost no correlation between density and B fields.

# Histograms of total pressure



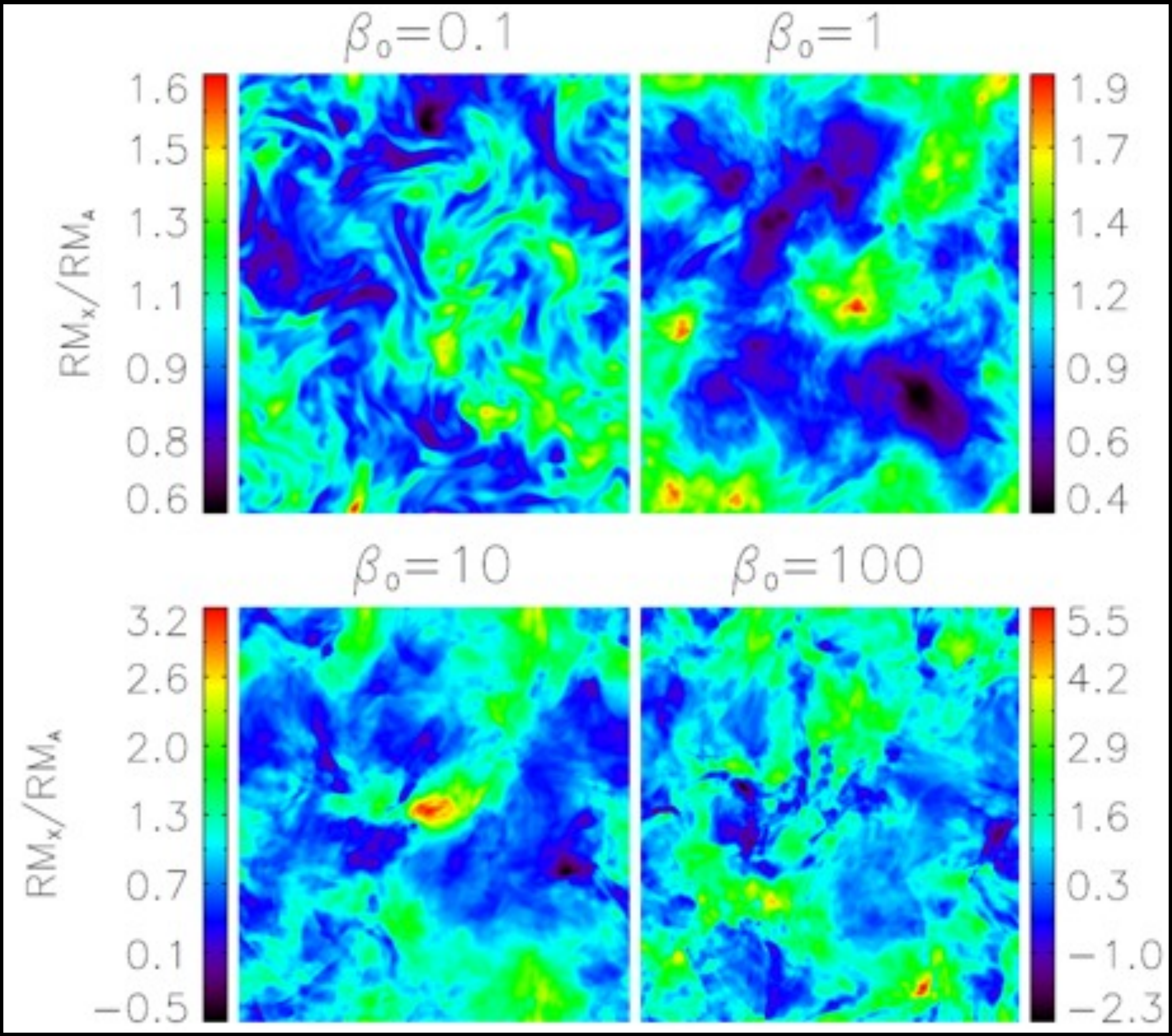

- blue $\beta_0$=0.1, red $\beta_0$=1, green $\beta_0$=10, black $\beta_0$=100
- Total (gas+magnetic) pressure is not a constant but distributes quite broadly.

# Intrinsic B-field strength vs. B-field strength from the ratio of RM to DM



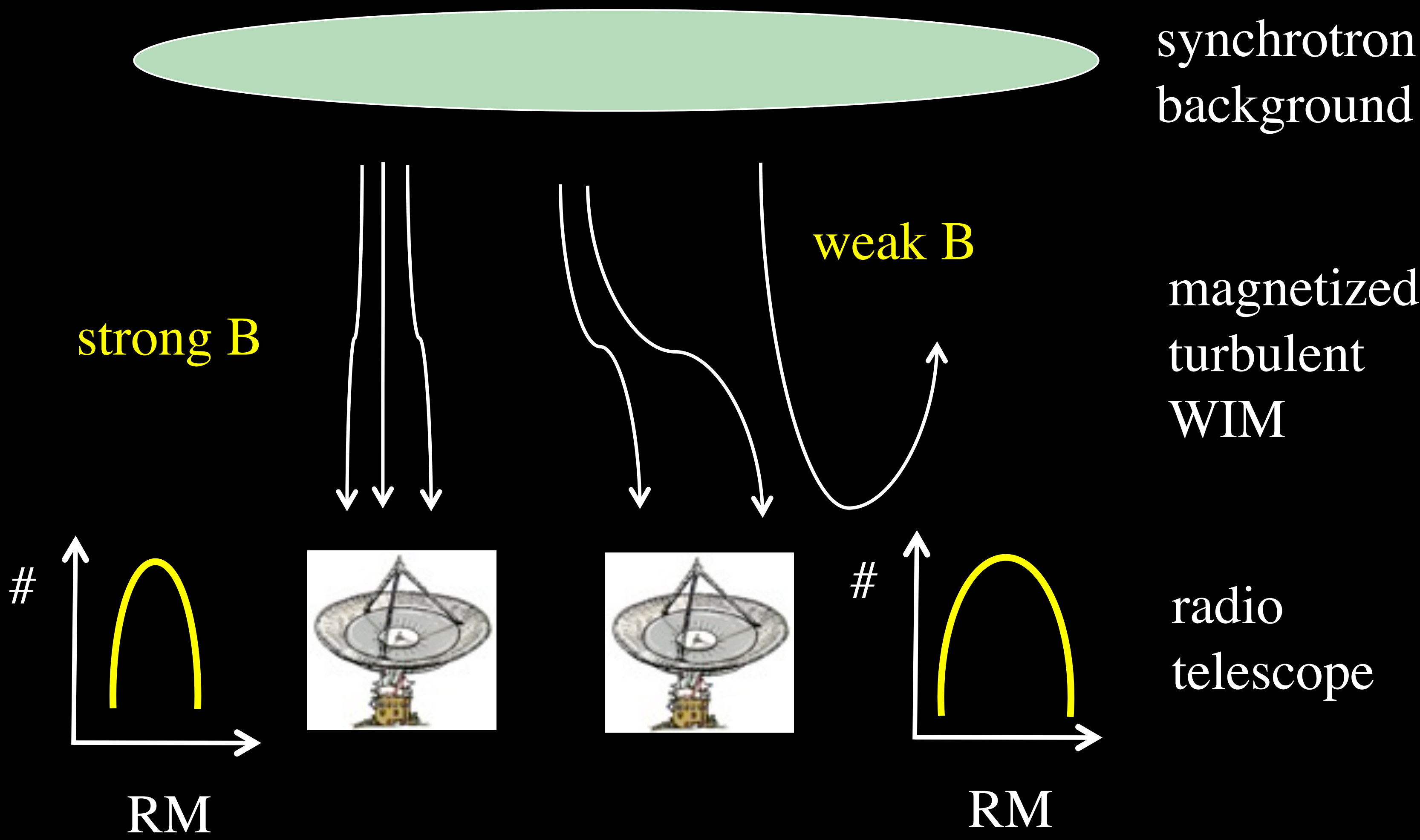

- blue $\beta_0$=0.1, red $\beta_0$=1, green $\beta_0$=10, black $\beta_0$=100
- Solid lines from Intrinsic B; dotted lines from the ratio
- They match very well.

# RM distributions

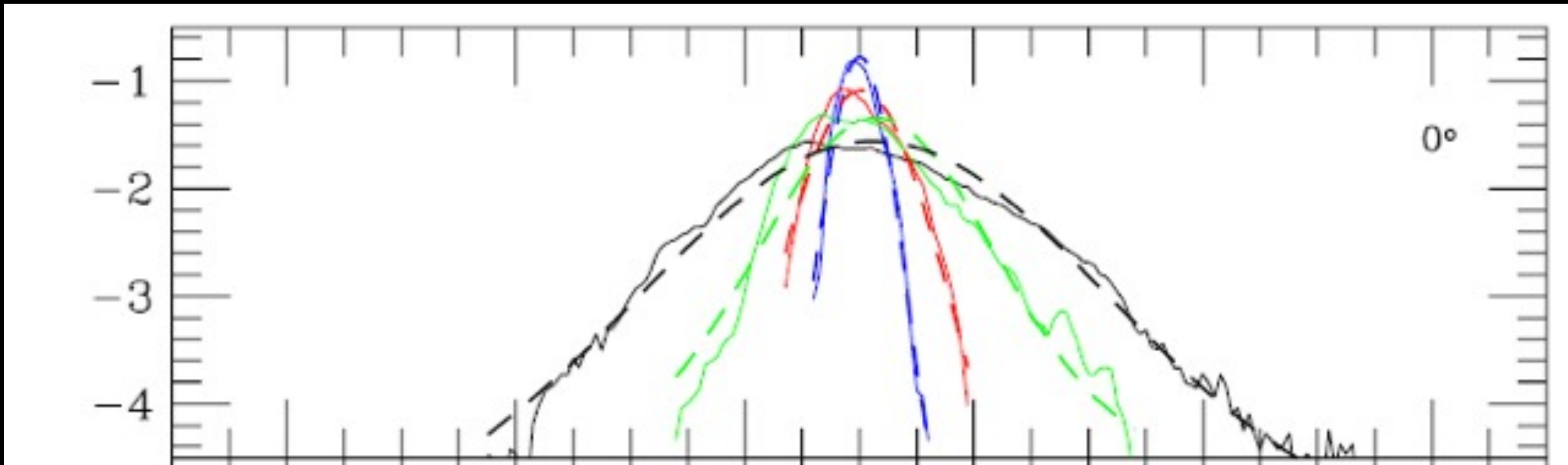



- Notice that the change of scales in color bars.
- As $\beta_0$ ($B_0$) increases (decreases), the dispersion of RMs increases (decreases).

# dispersion RM vs. B-field strength



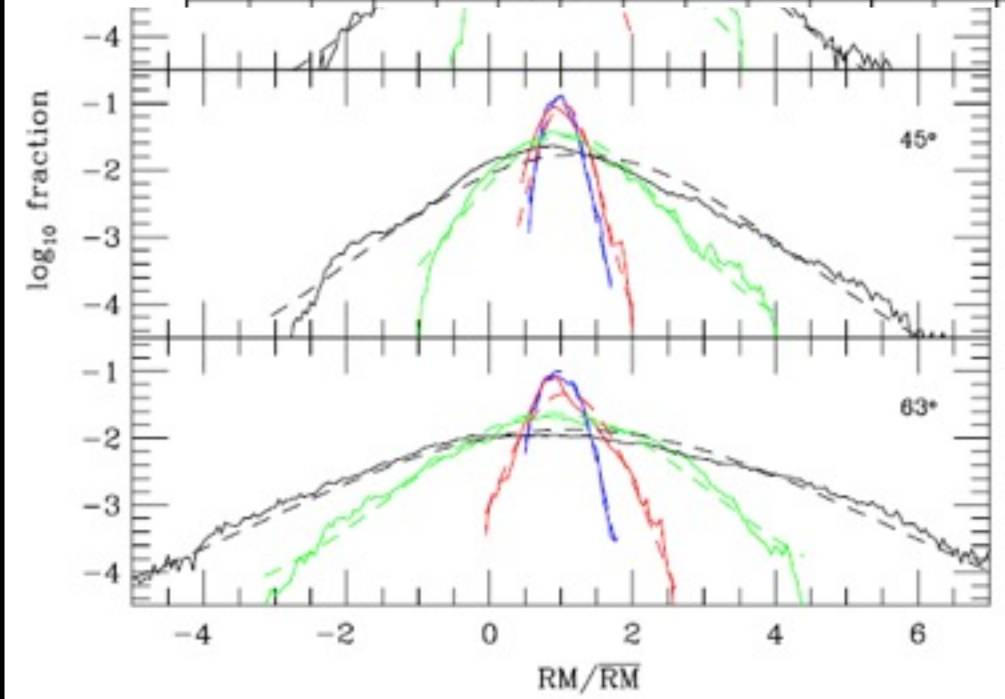
# Histograms of normalized RMs




, and

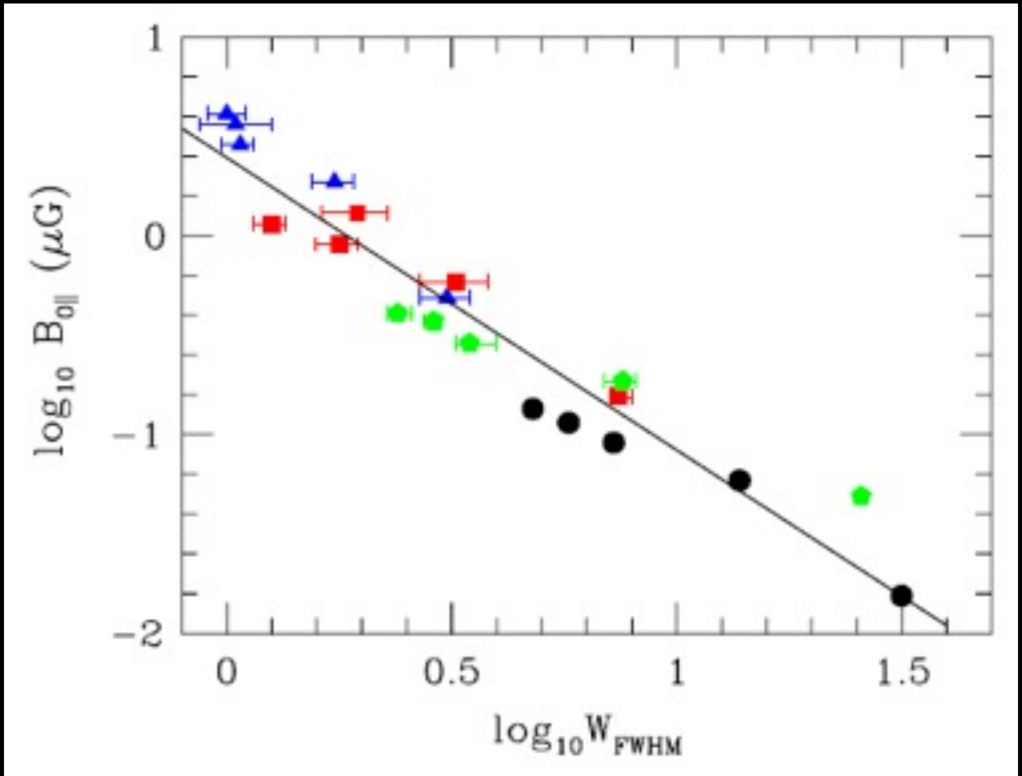
-

field direction




- solid lines: simulated RMs; dash lines: Gaussian fittings → match very well
- Indeed, the widths of Gaussian fittings become larger as the B-field strength is decreasing.

# B-field strength vs. width of RM distribution

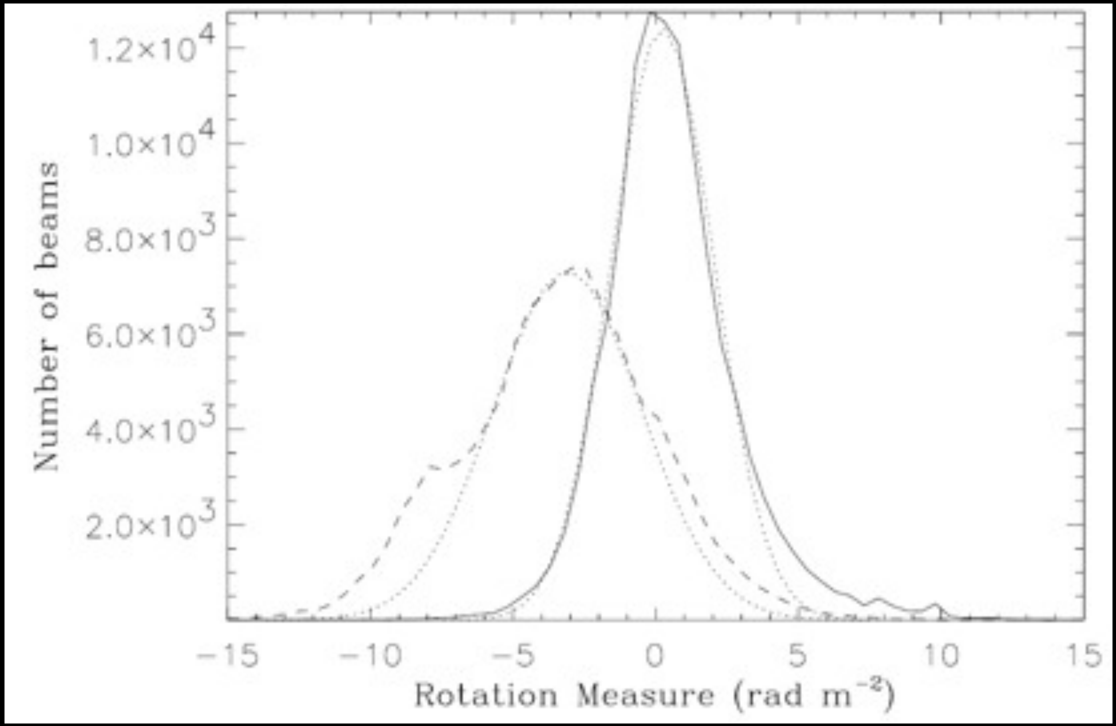



black: 0deg,
red: 27deg,
blue: 45deg,
green; 63deg,
pink: 83deg

- good correlation between the width and field strength.

$$B_{0\parallel} = (2.45 \pm 0.3) \times W_{\rm FWHM}^{-1.41 \pm 0.1}\ \mu{\rm G}$$

# Applications




Haverkorn et al. 2003

$$B_{0\parallel} = (2.45 \pm 0.3) \times W_{\text{FWHM}}^{-1.41 \pm 0.1} \,\mu\text{G}$$

- $W_{FWHM}$=2 → 0.6 μG

(~0.42 μG by Haverkorn+ 2003)

# Summary

- As the Mrms of compressible turbulent flow increases, the density power spectrum gradually becomes flat. This is due to density peaks (filaments and sheets) formed by shock interactions.
- The histogram of simulated RMs can be well fitted by the Gaussian function, which is consistent with observations.
- The width of the RM histogram is sensitive to the field strength, which provides a possible way to estimate the magnetic field strength in the WIM.