

Estimation of Magnetic Field Strength in Molecular Clouds through a **Modified Chandrasekhar- Fermi Method**

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Related paper:
Cho & Yoo (2016, ApJ)

Chandrasekhar-Fermi method

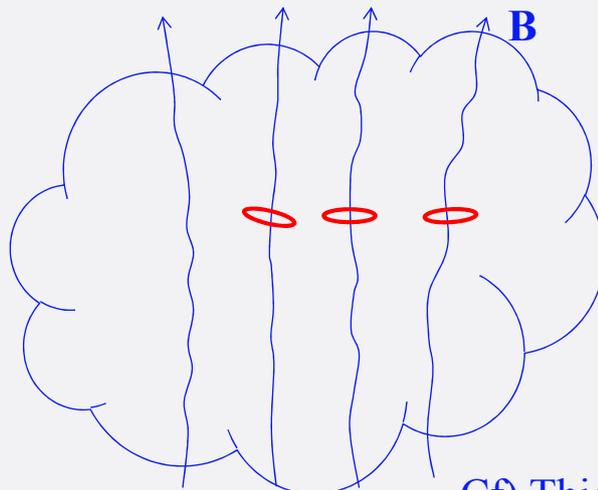
Magnetic field plays important roles in star formation

→ Strength of B?

Observation of dust polarization

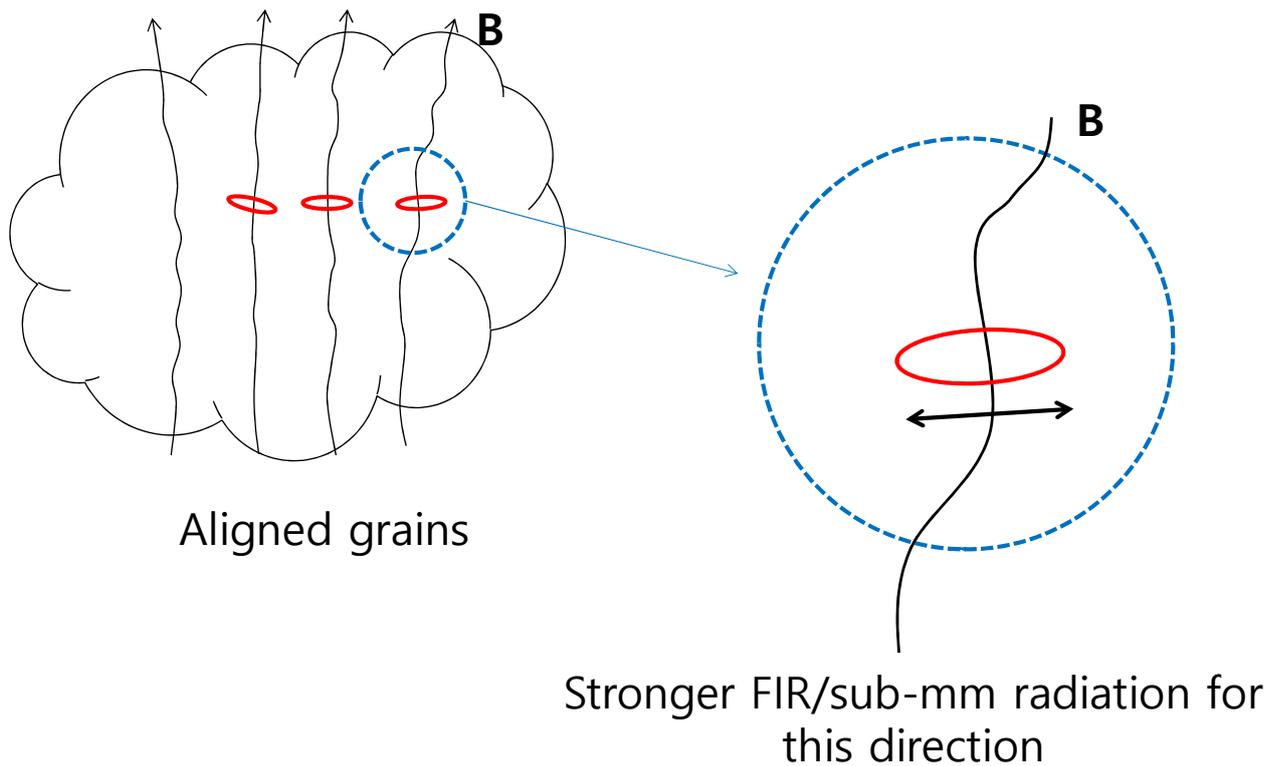
→ Strength of the mean field on the plane of the sky ($B_{0,sky}$)

Grains are aligned ← long axis \perp **B**

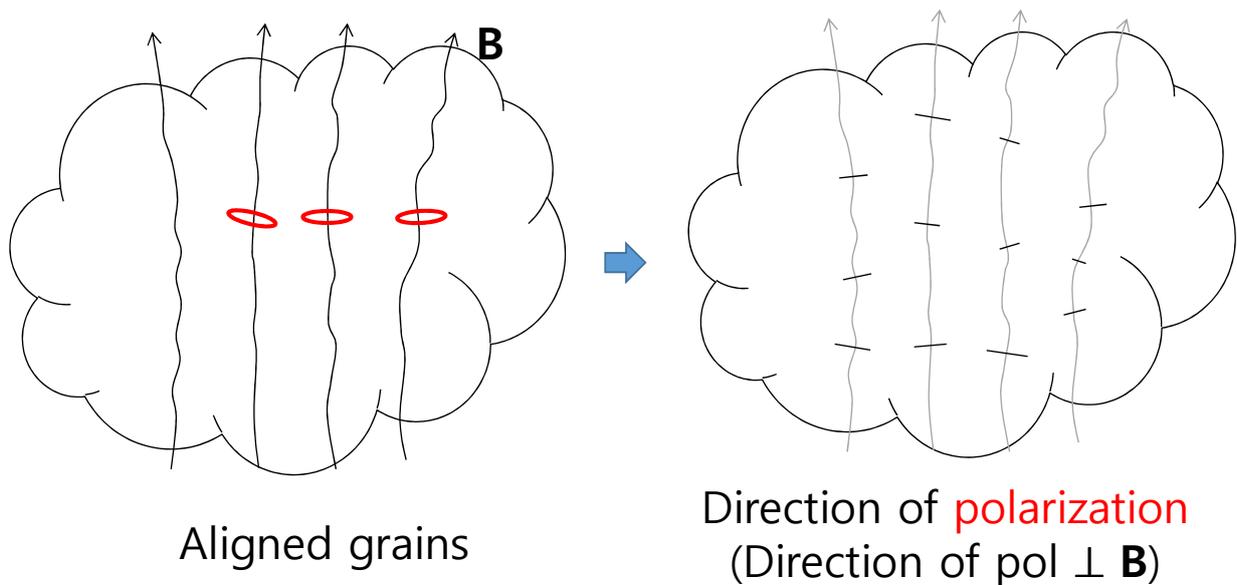


Cf) Thiem Hoang's talk

Radiation from **elongated grains**

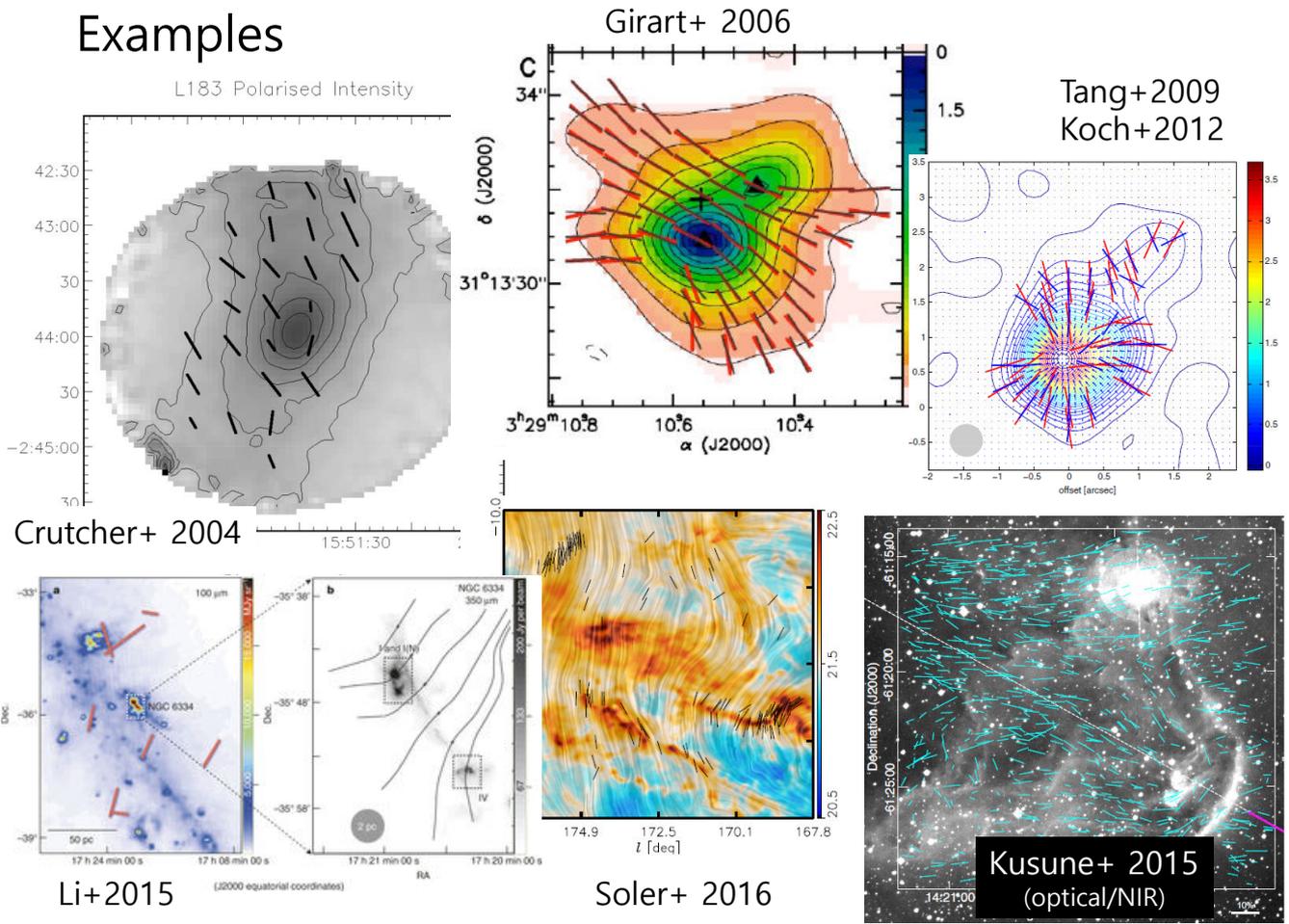


Observations of polarized FIR/sub-mm emission:

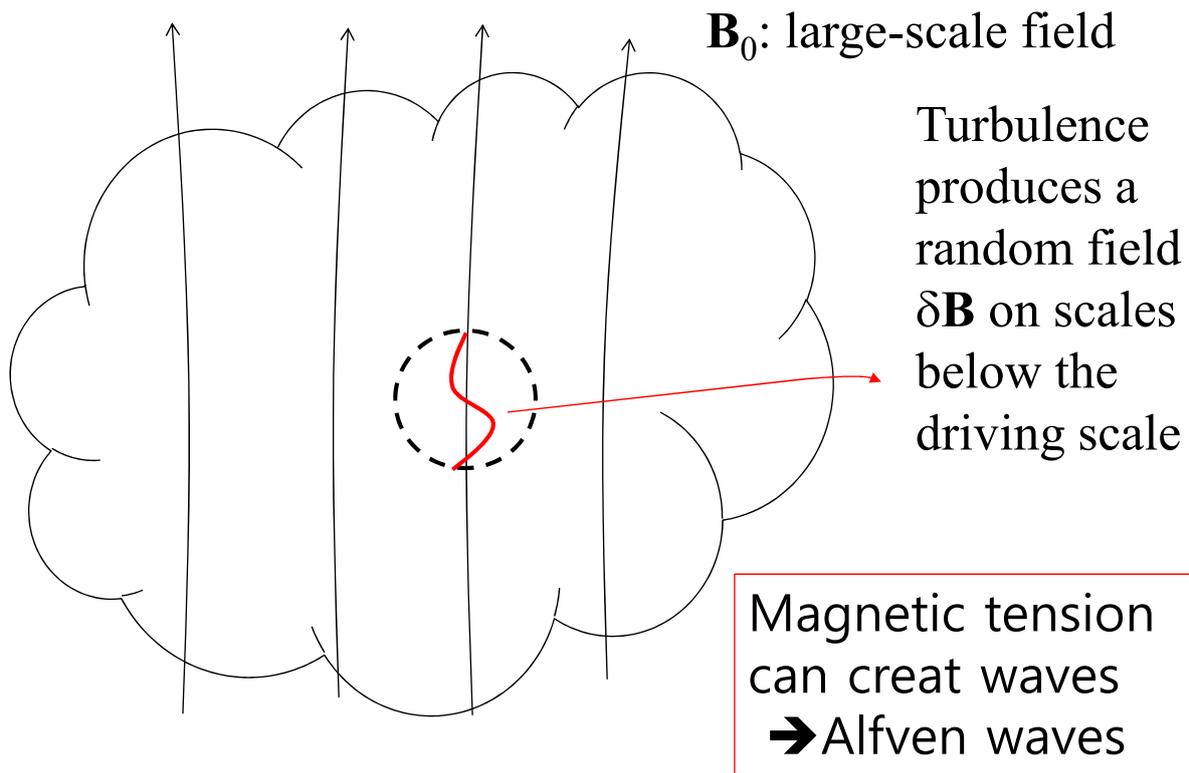


Review: Crutcher 2012, Heiles & Haverkorn (2012)
See also Gonatas+ 1990; Di Francesco+ 2001; Lai+ 2001;
Crutcher+ 2004; Girart+ 2006; Curran & Chrysostomou 2007;
Heyer+ 2008; Mao+ 2008; Tang+ 2009; Sugitani+ 2011;
Kwon+ 2011; Li, McKee & Klein 2012, ...

Examples



Turbulence produces a small-scale magnetic field $\delta\mathbf{B}$

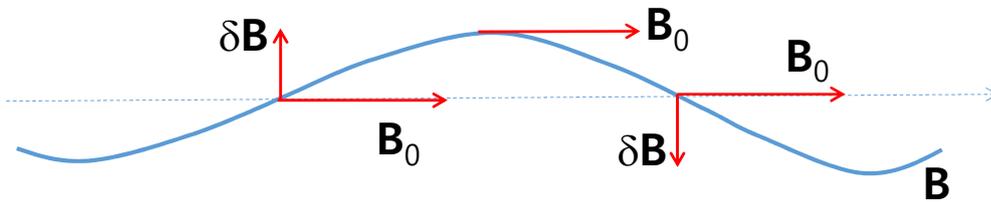


Alfven waves

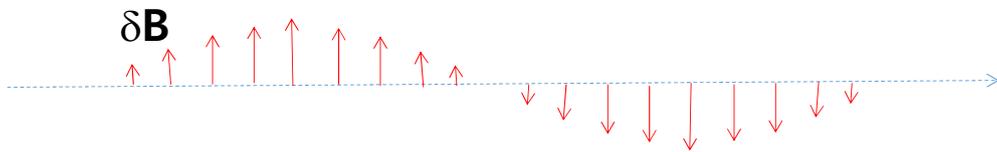
Suppose that we have a mean magnetic field \mathbf{B}_0



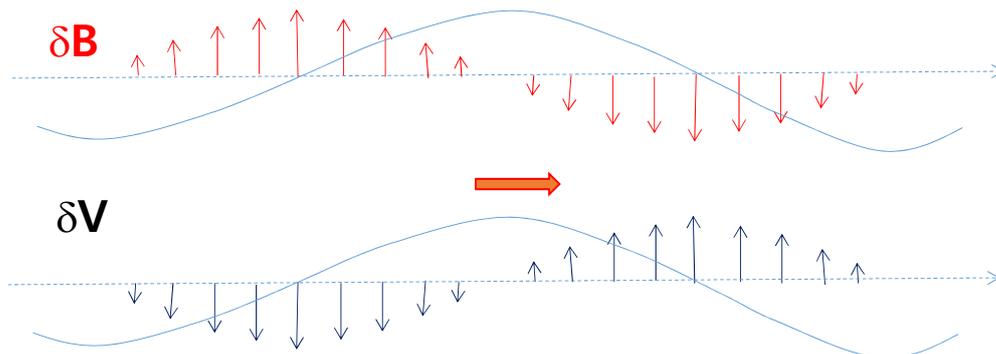
Let's consider an Alfven wave..



Then, what does $\delta\mathbf{B}$ look like?



We can also obtain $\delta\mathbf{V}$:



Summary) For an Alfven wave moving to the right,

$$\delta\mathbf{B} \propto -\delta\mathbf{V}$$

$$\rightarrow \text{In fact, } \frac{\delta B}{\sqrt{4\pi\rho}} = -\delta V$$

CF method

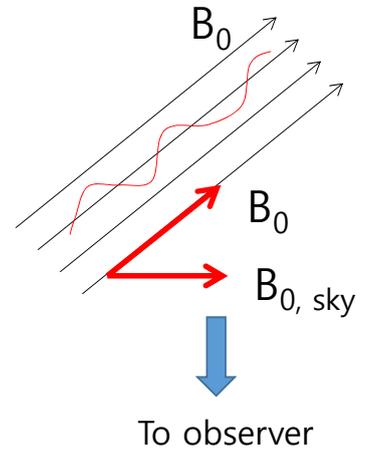
For Alfvén waves,

$$\frac{\delta B}{\sqrt{4\pi\rho}} = \delta V \quad \text{or} \quad 1 = \frac{\delta V}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right)}$$

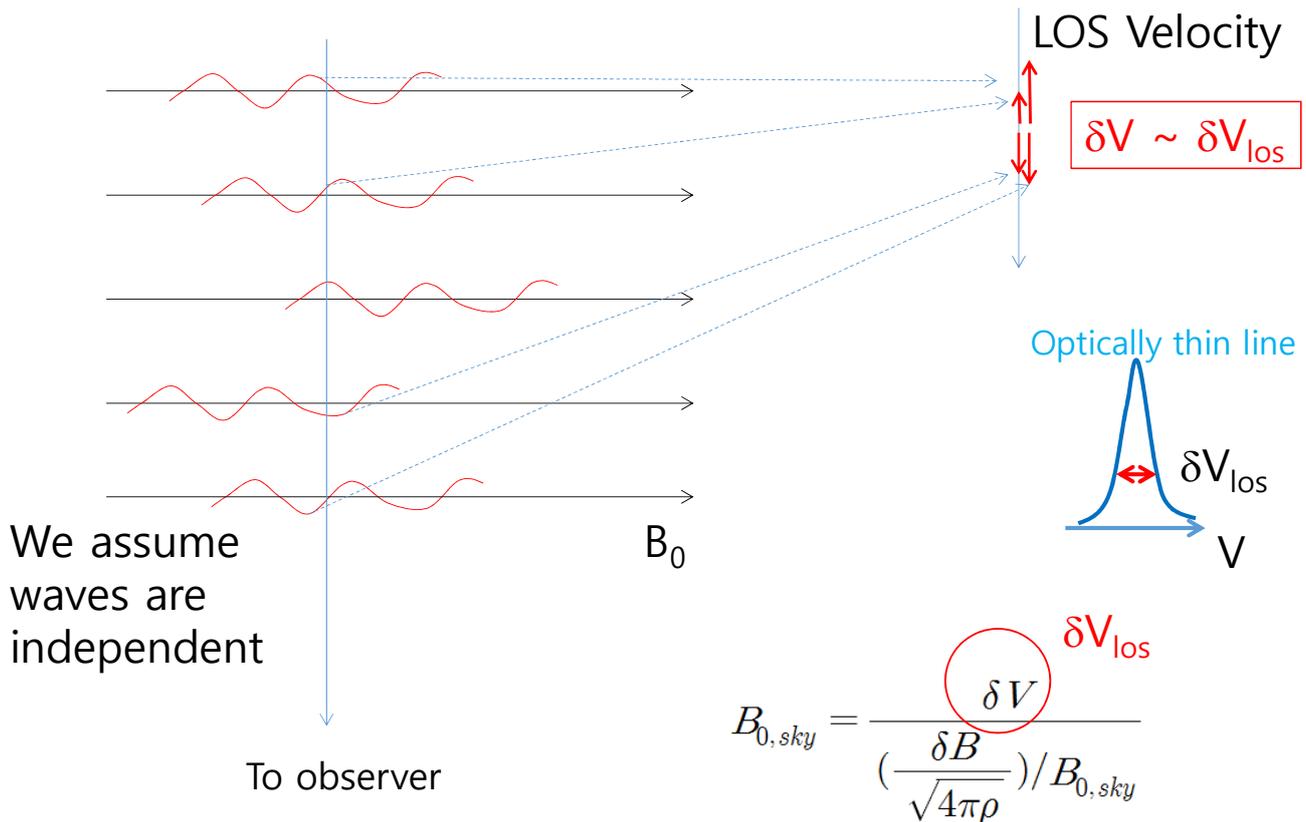
If we multiply $B_{0, sky}$ on both sides,

$$B_{0, sky} = \frac{\delta V}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right) / B_{0, sky}}$$

→ How can we get δV and δB ?

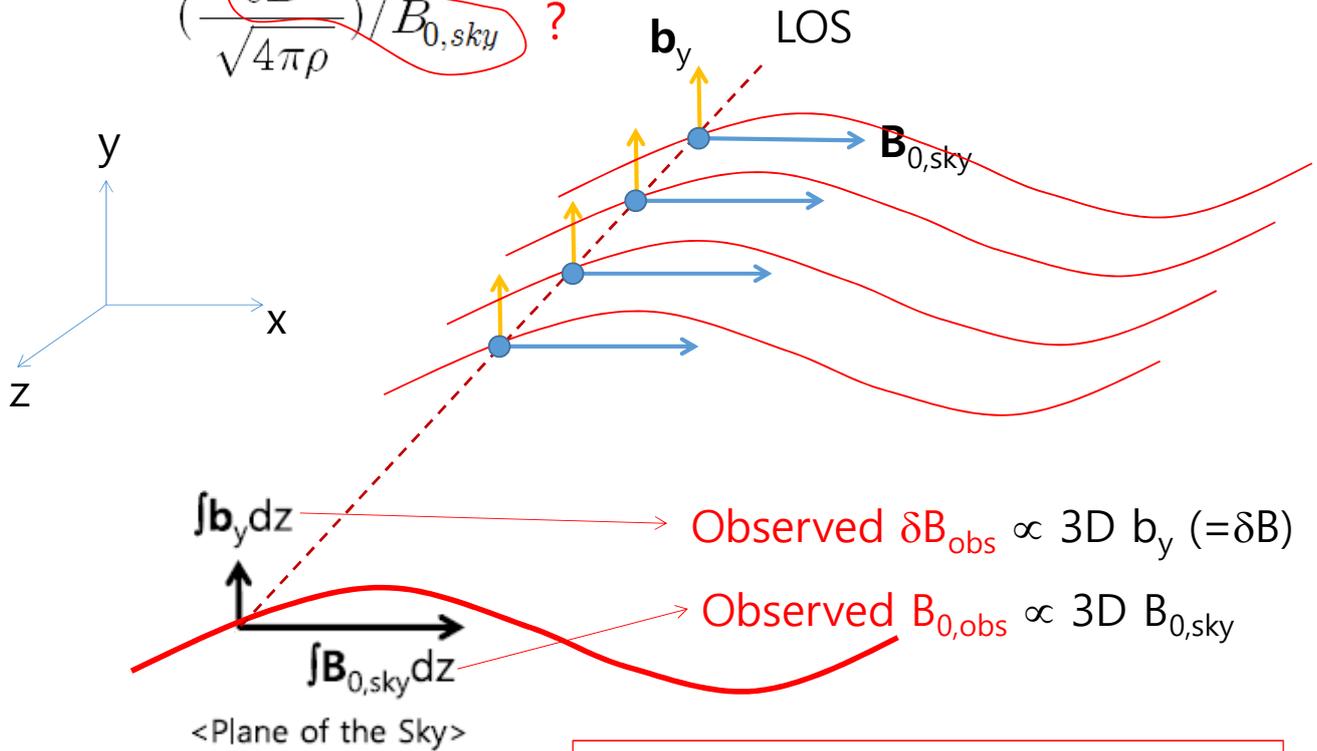


For simplicity, let's assume that $B_0 \perp$ LOS



$$B_{0,sky} = \frac{\delta V_{los}}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right)/B_{0,sky}} \quad ?$$

Suppose that we have coherent waves



$$\rightarrow \delta B/B_{0,sky} = \delta B_{obs}/B_{0,obs}$$

$$B_{0,sky} = \frac{\delta V}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right)/B_{0,sky}} \quad \rightarrow \quad B_{0,sky} = \frac{\delta V_{los}}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right)/B_{0,sky}} \quad ?$$

→ CF assumed that $\delta B/B_{0,sky} = \delta B_{obs}/B_{0,obs}$



In this case we have $\delta B_{obs}/B_{0,obs} \approx \tan \phi \approx \phi$

$$\begin{aligned} \rightarrow B_{0,sky} &= \frac{\delta V_{los}}{\left(\frac{\delta B_{obs}}{\sqrt{4\pi\rho}}\right)/B_{0,obs}} = \sqrt{4\pi\rho} \frac{\delta V_{los}}{\left(\frac{\delta B_{obs}}{B_{0,obs}}\right)} \\ &= \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta(\tan \phi)} \approx \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta \phi} \end{aligned}$$

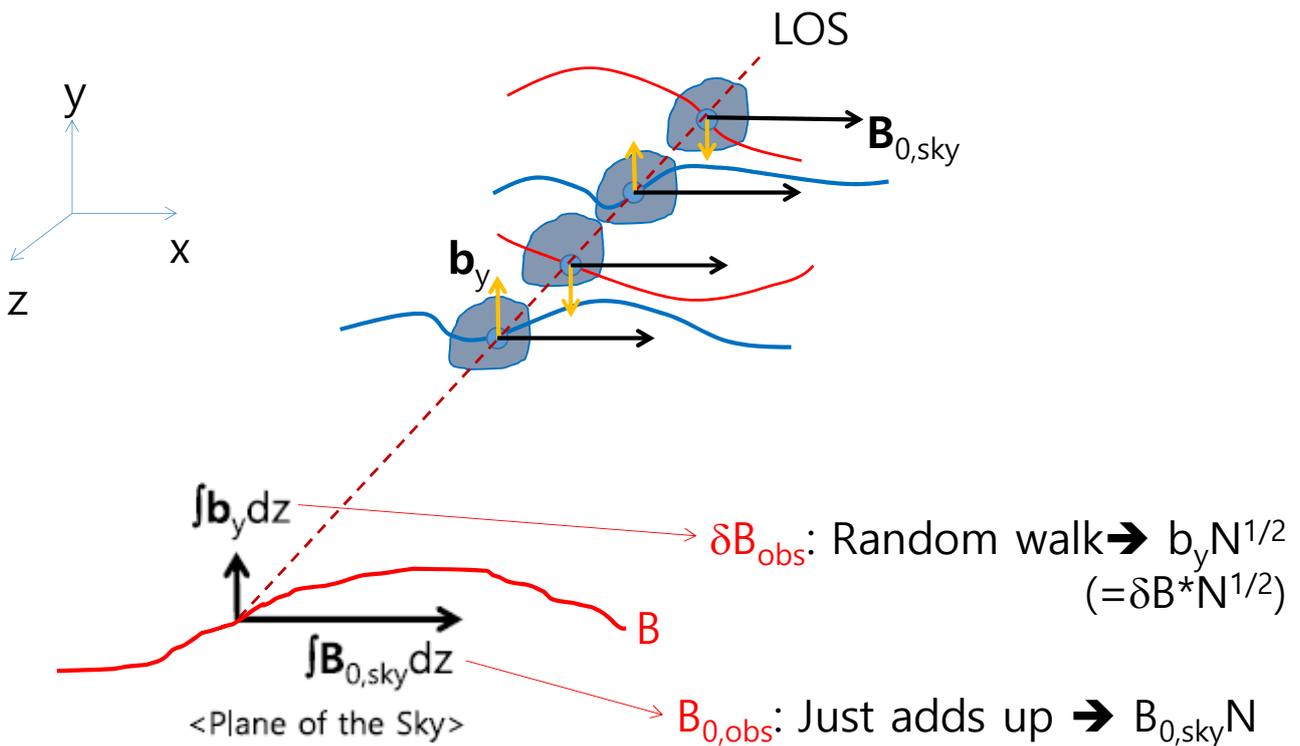
Original CF method (C & F 1953):

$$B_{0,sky} \approx \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta\phi}$$

Numerical Simulations (e.g. Ostriker et al. 2001):

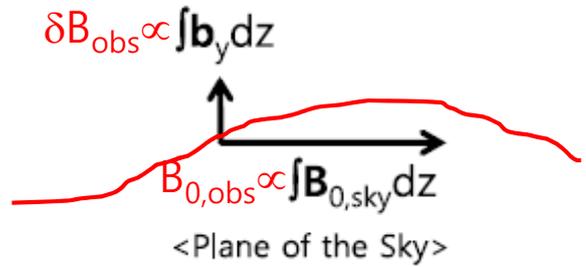
$$B_{0,sky} \approx \frac{1}{2} \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta\phi}$$

Q) Is $\delta B/B_{0,sky} = \delta B_{obs}/B_{0,obs}$? → No!



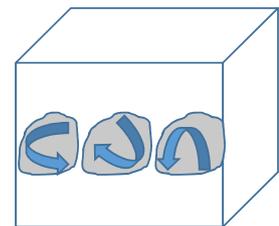
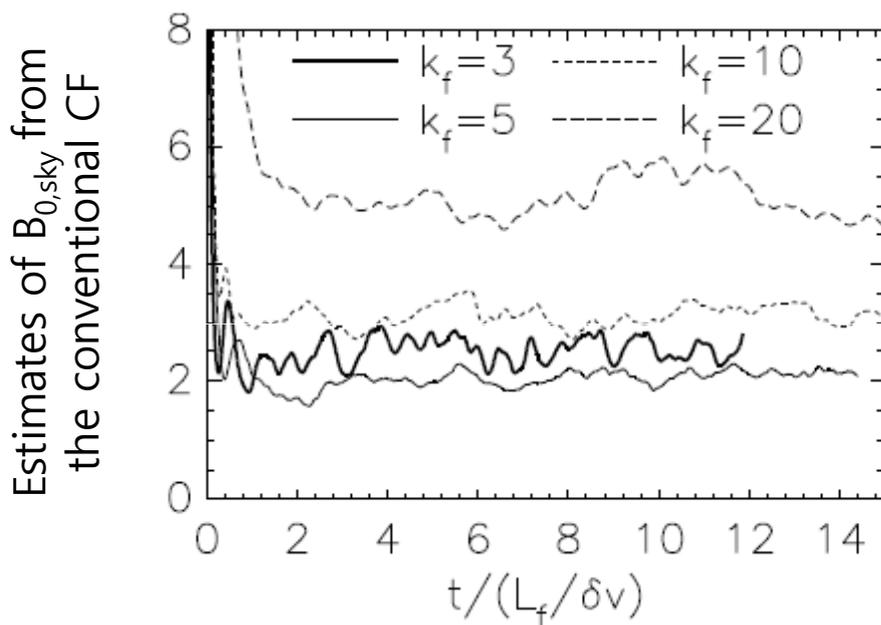
→ The conventional CF-method overestimates $B_{0,sky}$ by $\sim N^{1/2}$!

$$B_{0,sky} = \frac{\delta V}{\left(\frac{\delta B}{\sqrt{4\pi\rho}}\right)/B_{0,sky}}$$
~~$$= \sqrt{4\pi\rho} \frac{\delta V_{los}}{\left(\frac{\delta B_{obs}}{B_{0,obs}}\right)}$$~~



See earlier discussions in Myers & Goodman 1991, Zweibel 1996, Houde et al 2009.

Conventional CF indeed overestimates $B_{0,sky}$

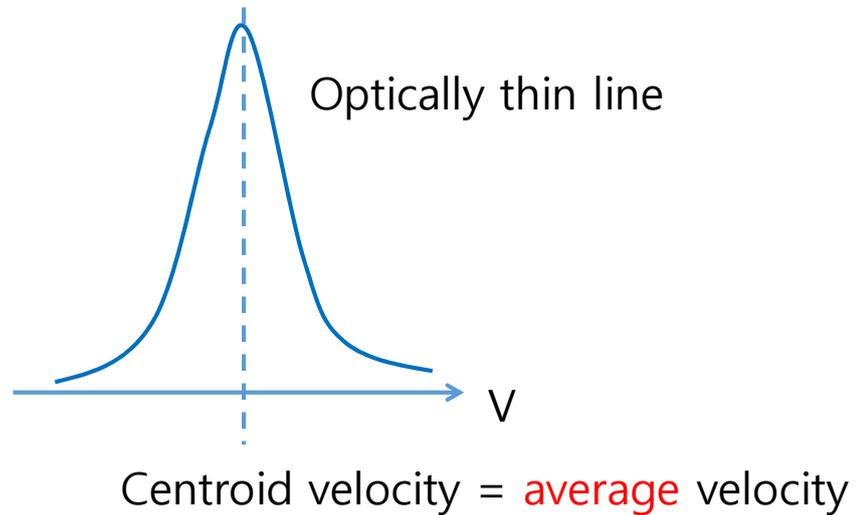


* $N = 1/k_f$

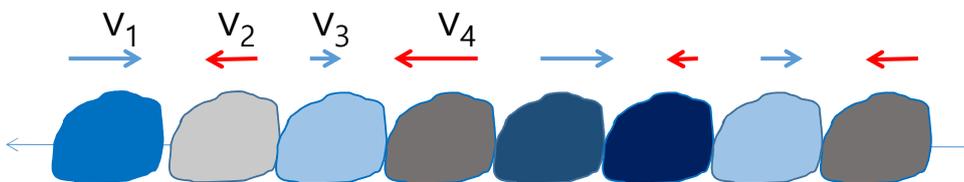
* In our simulations, $B_{0,sky} = 1$

Then, how to fix it?

- We need to know N!
(N=number of independent eddies along the LOS)
- We can get N from the standard deviation of centroid velocities



δV_C has something to do with $N^{1/2}$



V shows a random walk → Let's consider $(V_1 + V_2 + V_3 + \dots)$

St Dev of $(V_1 + V_2 + V_3 + \dots) \sim N^{1/2} |V|$
 → St Dev of $(V_1 + V_2 + V_3 + \dots)/N \sim N^{-1/2} |V|$

→ $\delta V_C \sim N^{-1/2} |V|$

→ $\delta V_C / |V| \sim 1/N^{1/2}$

$\delta V_C / \delta V_{los} \propto 1/N^{1/2}$

Standard deviation
of cent. vel.

Average width of an
optically thin line

Our new CF-method

= conventional CF-method * $\delta V_C / \delta V_{los}$

$$\rightarrow B_{0,sky} = \sqrt{4\pi\rho} \frac{\delta V_{los}}{\left(\frac{\delta B_{obs}}{B_{0,obs}}\right)} \otimes \delta V_C / \delta V_{los}$$

Conventional CF

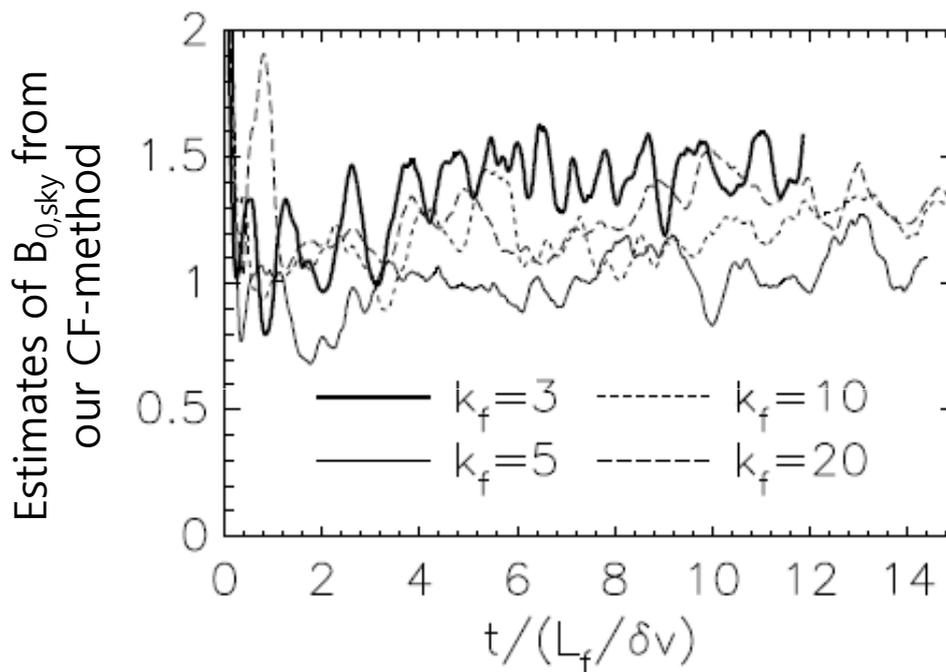
Our correction factor

$$= \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta(\tan\phi)} \otimes \delta V_C / \delta V_{los}$$

$$\approx \sqrt{4\pi\rho} \frac{\delta V_{los}}{\delta\phi} \otimes \delta V_C / \delta V_{los}$$

$$= \xi' \sqrt{4\pi\rho} \frac{\delta V_c}{\delta\phi}$$

Our simulations show that $\xi' \approx 1$



* In our simulations $B_{0,sky} = 1$

Summary

- If there are N independent eddies along the line of sight, the traditional CF method overestimates the $B_{0,sky}$ by a factor of $N^{1/2}$
- We found that standard deviation of centroid velocity is proportional to $1/N^{1/2}$
- Our modified CF-method performs better when the driving scale of turbulence is small