# MHD Turbulence and Foreground for CMB and H21cm Studies

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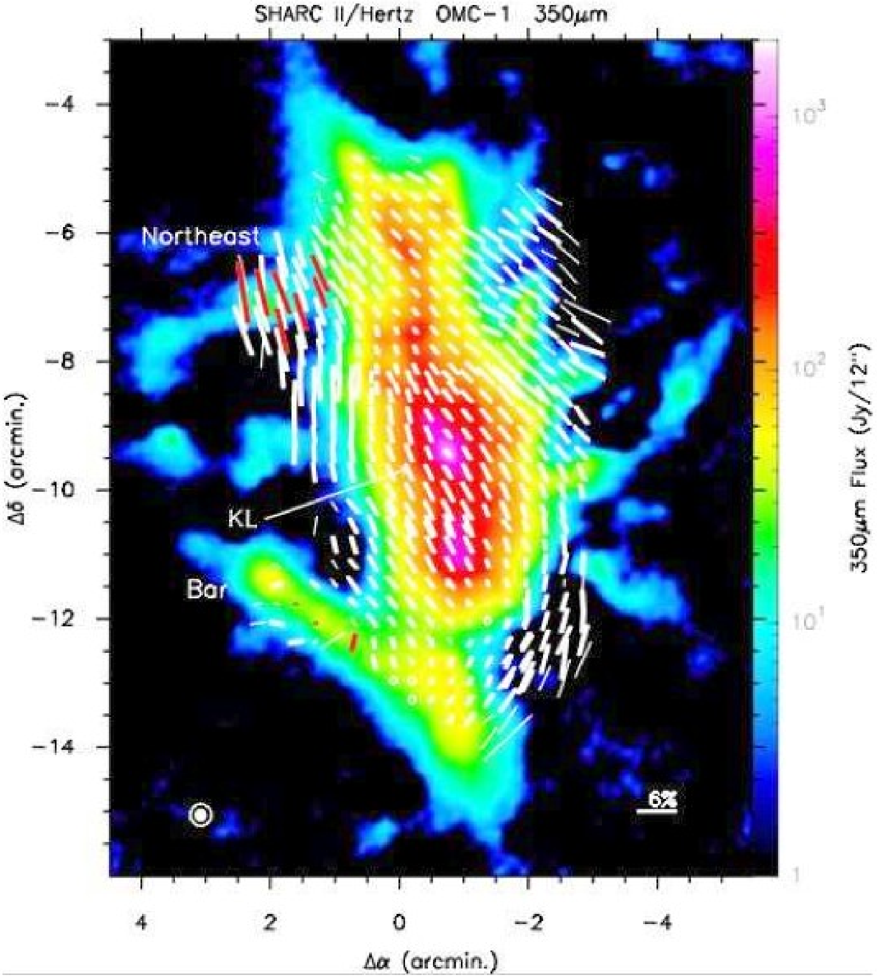
# Astrophysical fluids

Orion nebula




turbulence + B

System size > $l_{mfp}$

➔Fluid approximation seems to be OK

➔We can use MHD for astrophysical turbulence

# Example of MHD turbulence : ISM

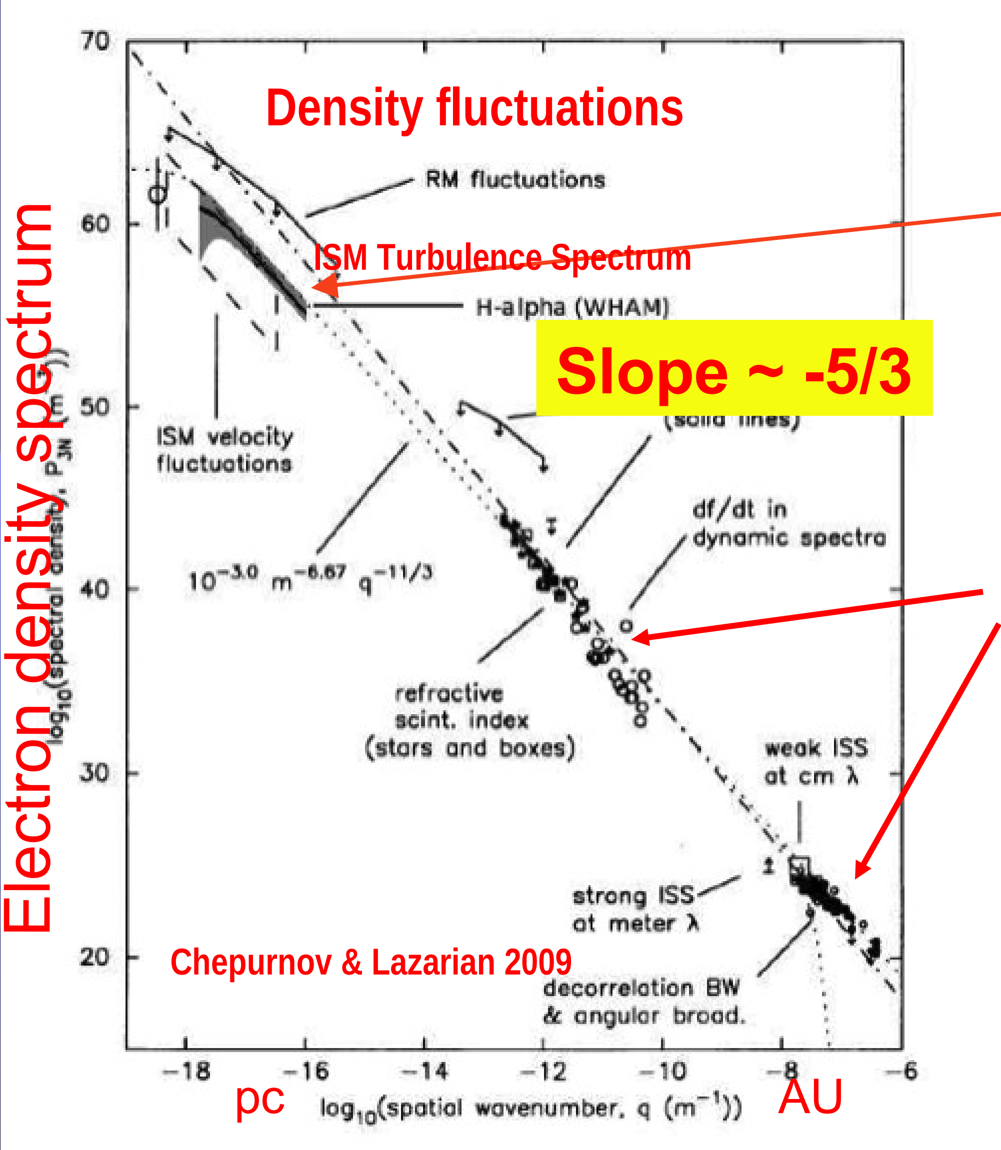
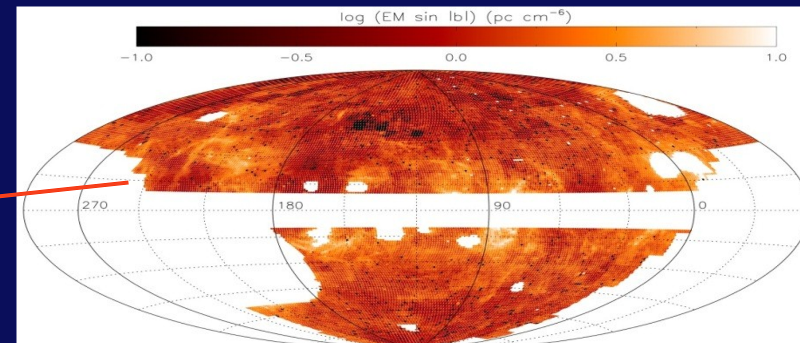



Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.




WHAM emission: density fluctuations

Chepurnov & Lazarian (2010)

Scincillations and scattering

From Armstrong, Rickett & Spangler(1995)

The ISM is filled with (MHD) turbulence!

➔ So is the Galactic halo!

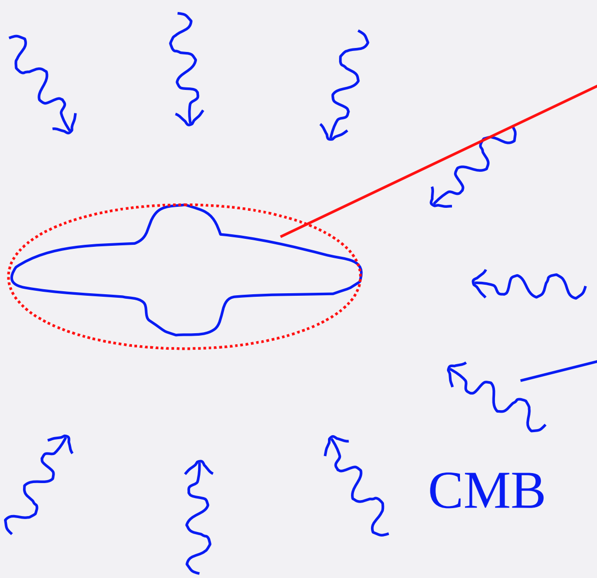
# Other examples of MHD turb. in diffuse media

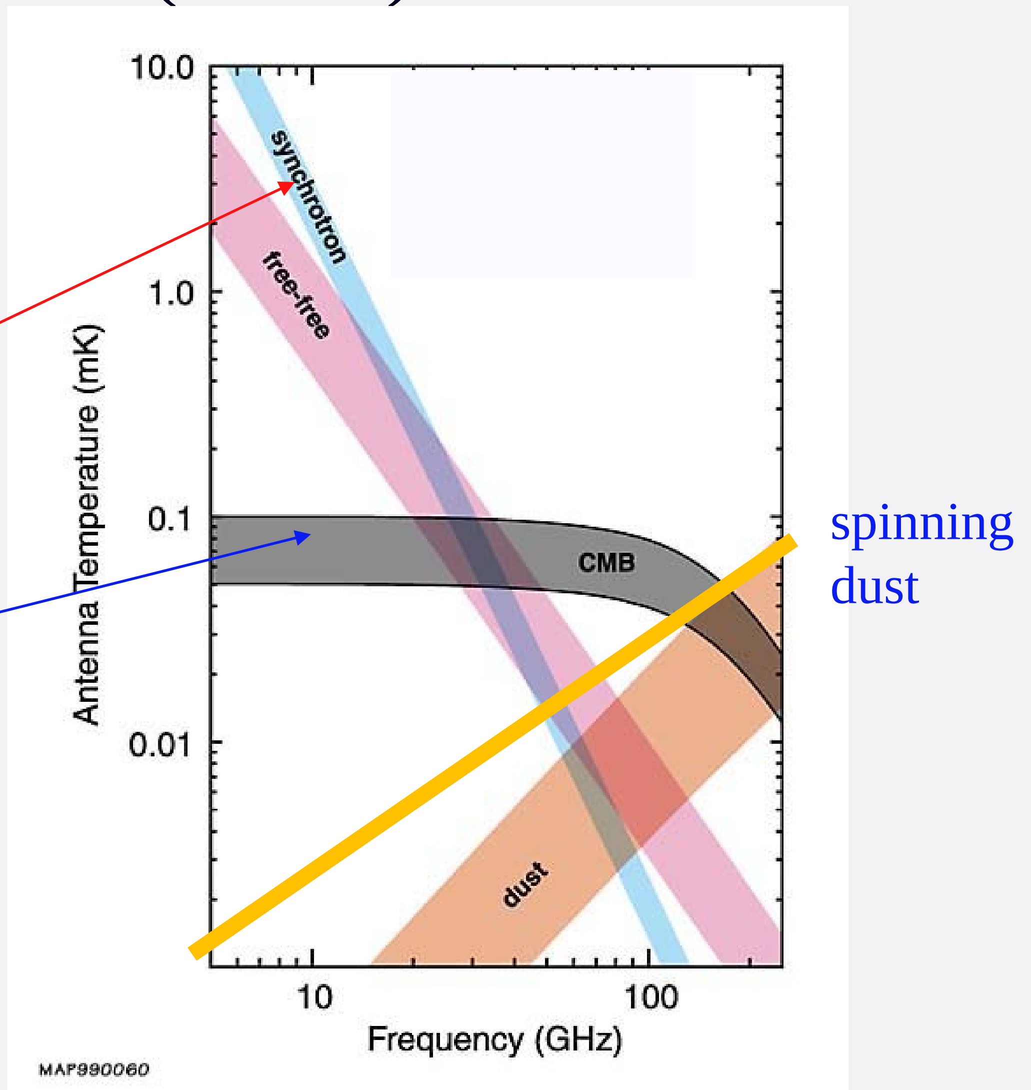
-ISM: Heiles & Troland (03, 05),…
talks by E. Falgarone, T. Inoue, D. Pogosyan
-Cores/Disks: talks by E. de Gouveia Dal Pino, M. Flock,
R. Banerjee, M. Leao, E. Vazquez-Semadeni,…
-Galaxies/ICM/IGM/etc: talks by M. Hanasz, T. Jaffe, M. Machida,
K. Otmiannowska-Mazur, T. Akahori, A. Beresnyak,
A. Esquivel, B. Burkhart, D. Elstner, K. Dolag, H. Yan,
R. Schlickeiser, D. Falceta-Goncalves, R. Santos-Lima,
D. Schleicher, …
-SMC: Stanimirovic & Lazarian (01)
← Vel. Channel Analysis (Lazarian & Pogosyan 00, 04):
Esquivel & Lazarian (05): ←Modified Vel. Centroid

MHD turbulence is ubiquitous!

# Foregrounds: do they matter?

## e.g.) CMB observations (~GHz)




map.gsfc.nasa.gov

# Topic 1: Foregrounds can be understood!

## ➔Example: synchrotron foreground

- Synchrotron emission:

  $$S(\mathbf{r}) \sim n_{cr} B^2(\mathbf{r})$$

  ➔ spatial spectrum of $S(\mathbf{r})$

  ~ spatial spectrum of $B^2(\mathbf{r})$

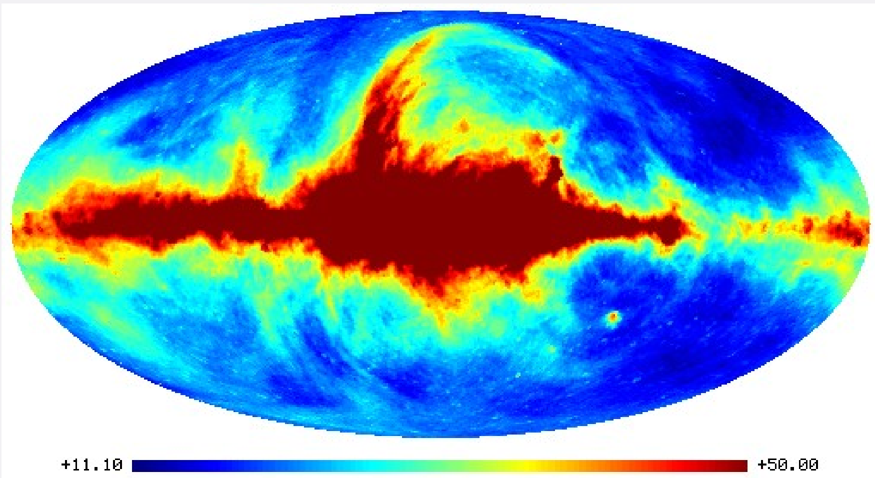
  ~ spatial spectrum of $\mathbf{B}(\mathbf{r})$ ← MHD turbulence

- We know MHD turbulence!.

  inside turb.: Goldreich & Sridhar (1995: incompressible);
  Lithwick & Goldreich (01: high β);
  Cho & Lazarian (02,03: low β)

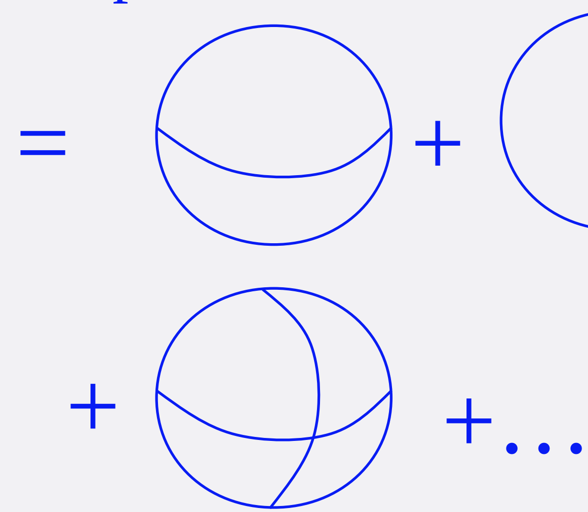
  outside turb.: For many problems, Kolmogorov is OK.

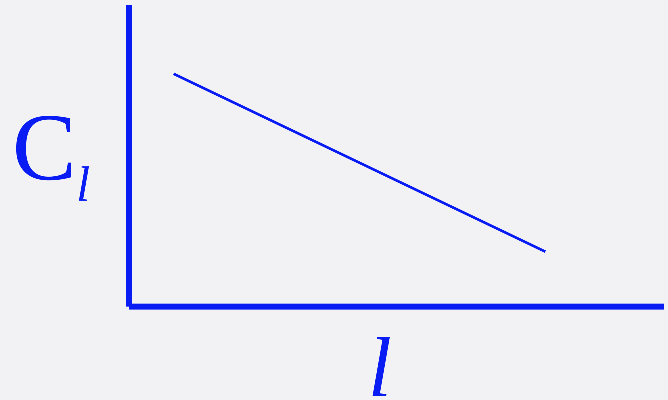
# Expected angular spectrum




Haslam et al (1982)

spherical harmonics $Y_{l,m}$



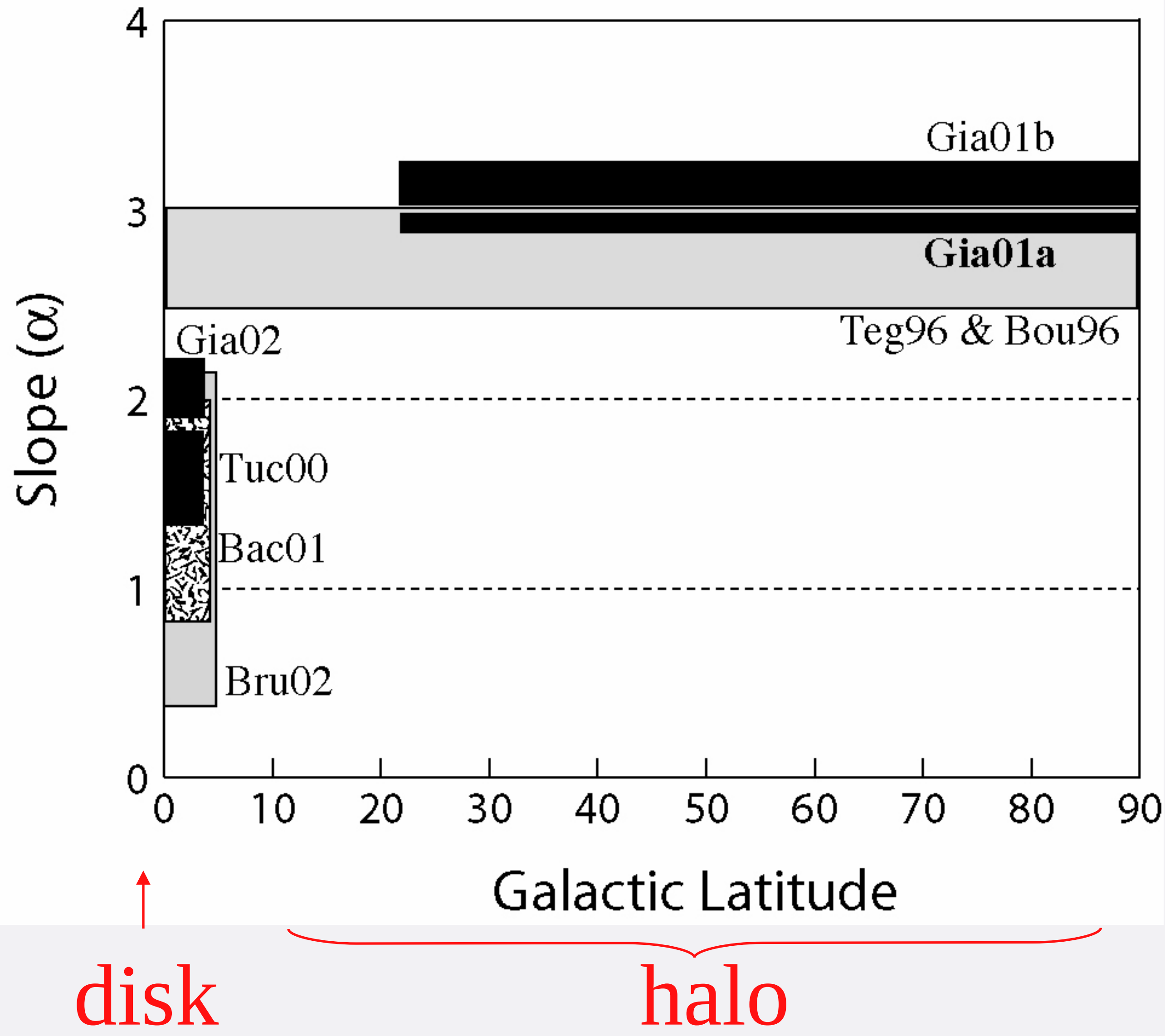




$l \sim 180^o/\theta^o$

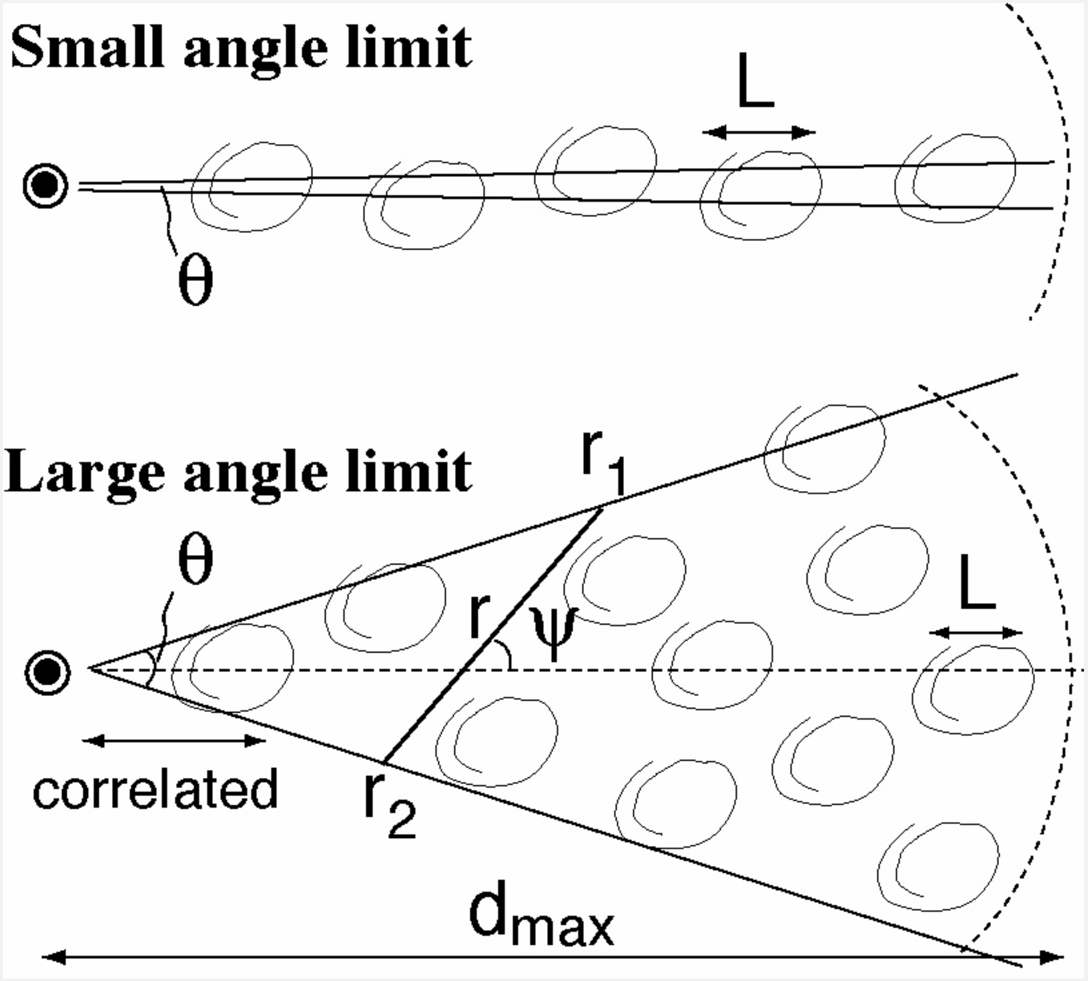
Note: $k \sim 2\pi/x$ in flat space.

So, $C_l \sim |f(k)|^2$ in flat sp.

# Observations ($C_l \sim l^{-\alpha}$)



# Our model




~flat geometry

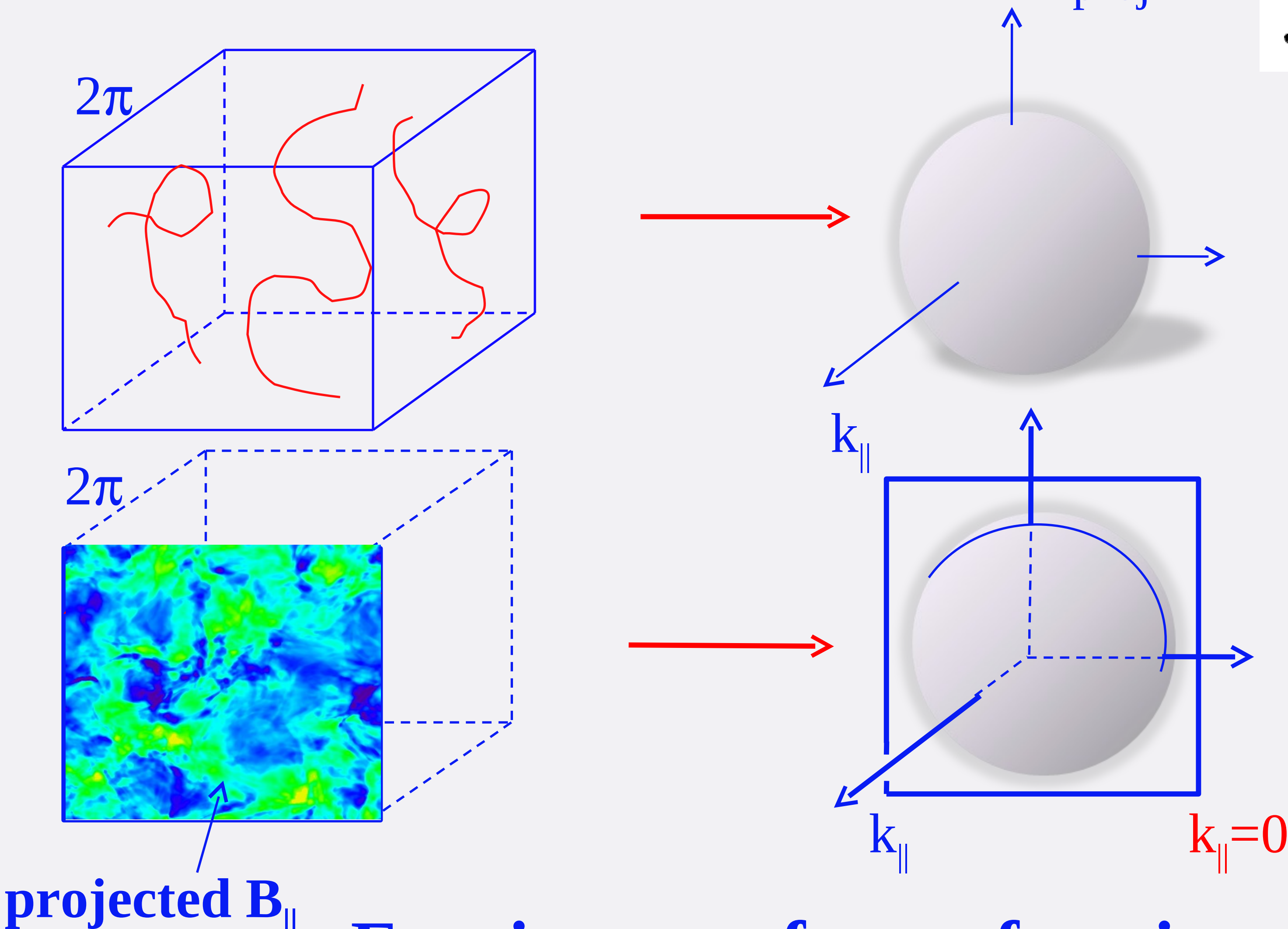
⇒$C_l \sim E_{3D}(k)$

⇒e.g. $\boldsymbol{l}^{-11/3}$ for Kolmogorov

$C_l \sim \boldsymbol{l}^{-1}$

Analytical studies:Lazarian & Shutenkov (1990)

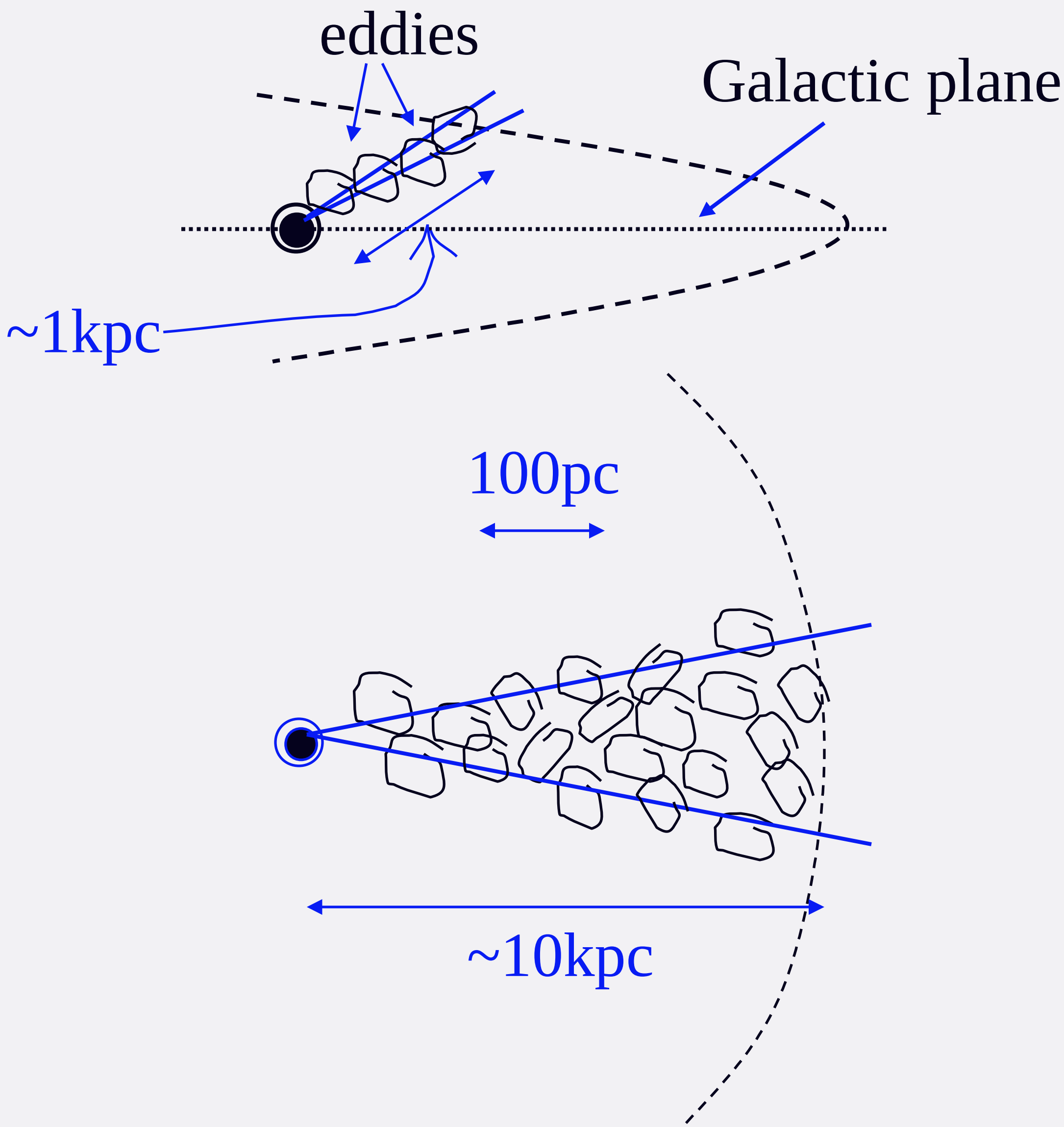
Spectrum of a projected quantity: e.g.) $B_{proj} = \int_0^{2\pi} B_{\parallel} ds$




# Fourier transform of projected B

$\propto$ $k_{\parallel}=0$ plane in **k** space ➔ $P(k) \propto k^{-11/3}$ if Kolmogorov

# Our model

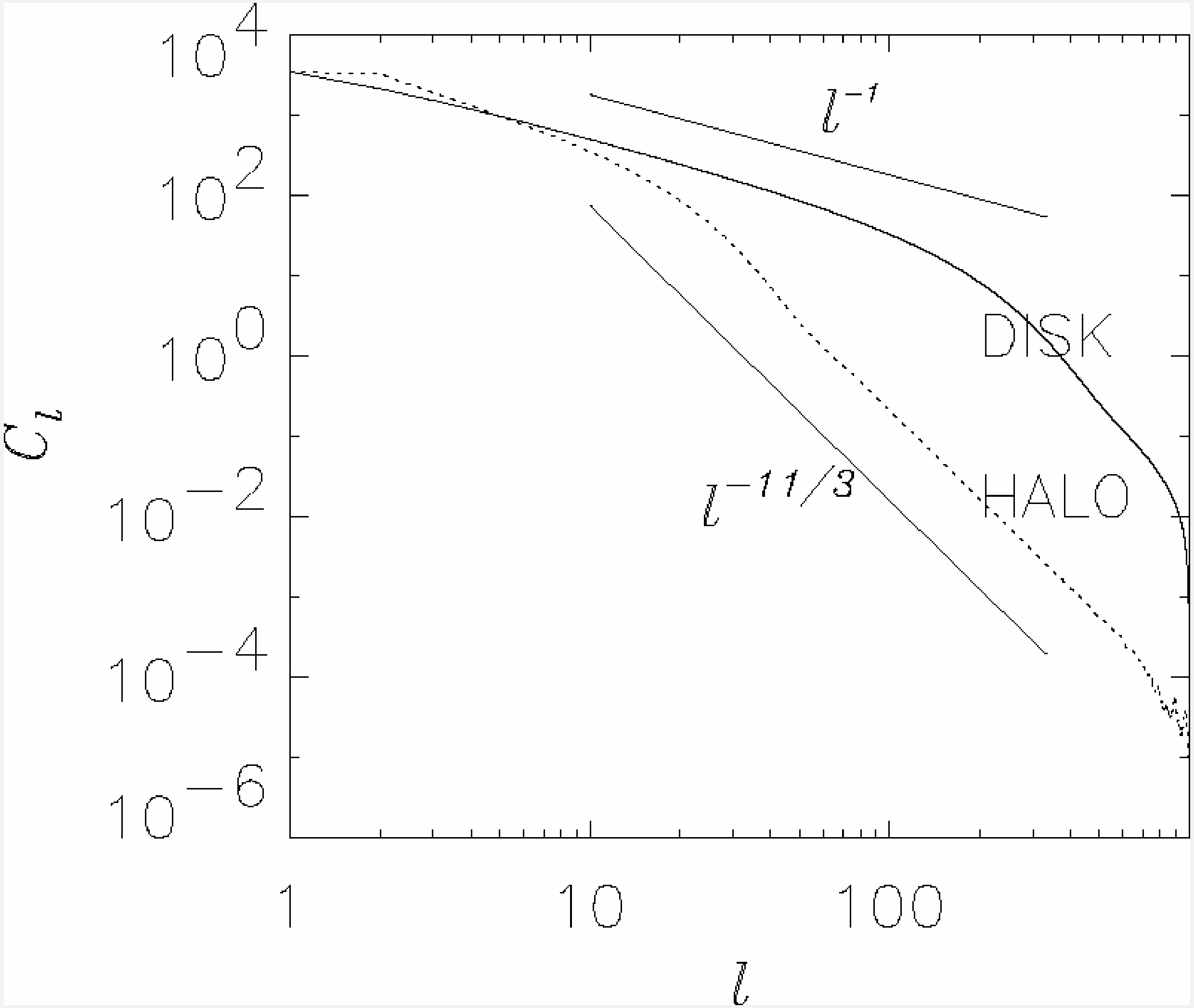



halo ~ small θ limit
(for θ < 6°; or *l*>30)

disk~ large θ limit

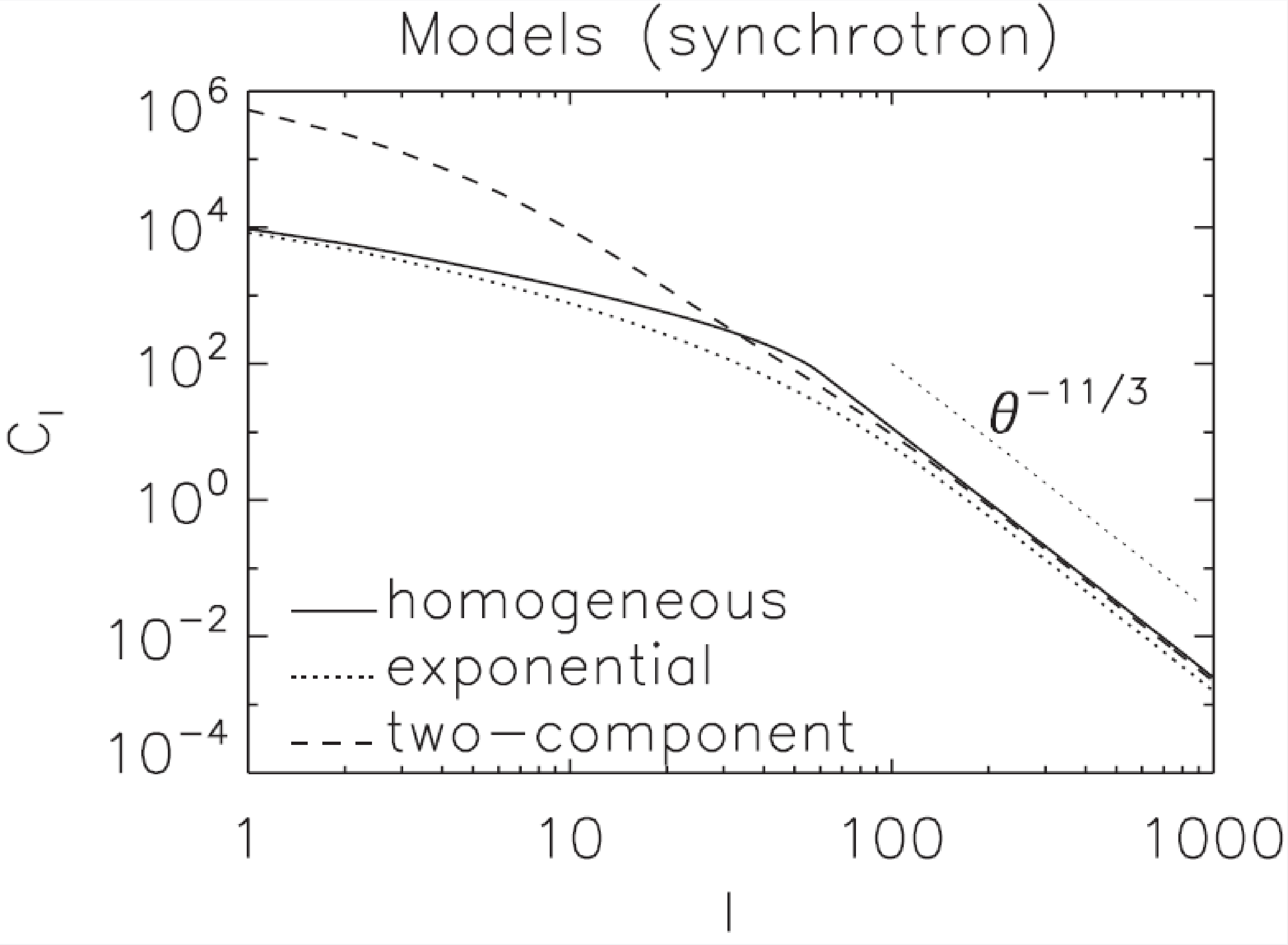
(for θ > 0.6°; or *l*<300)

# Result (simple model)




Cho & Lazarian 2002

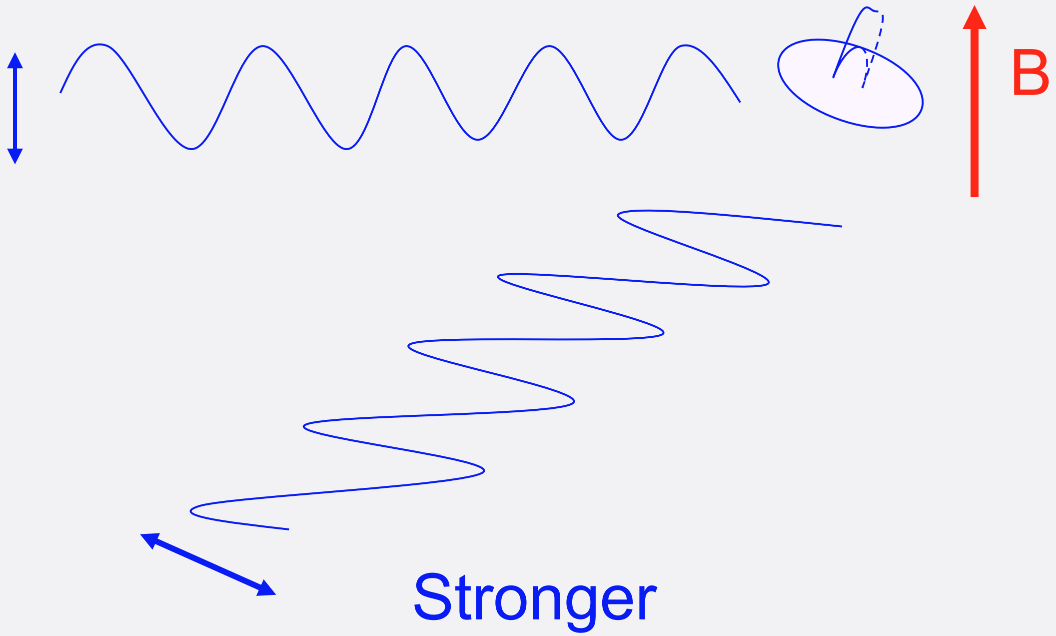
# More results (stratification effect, etc.)




Cho & Lazarian 2010

# Topic 2: Aligned dust and polarized CMB

Emission from aligned dust is the most strongest foreground for polarized CMB signals in K-band




Aligned grains emit polarized FIR/sub-mm.

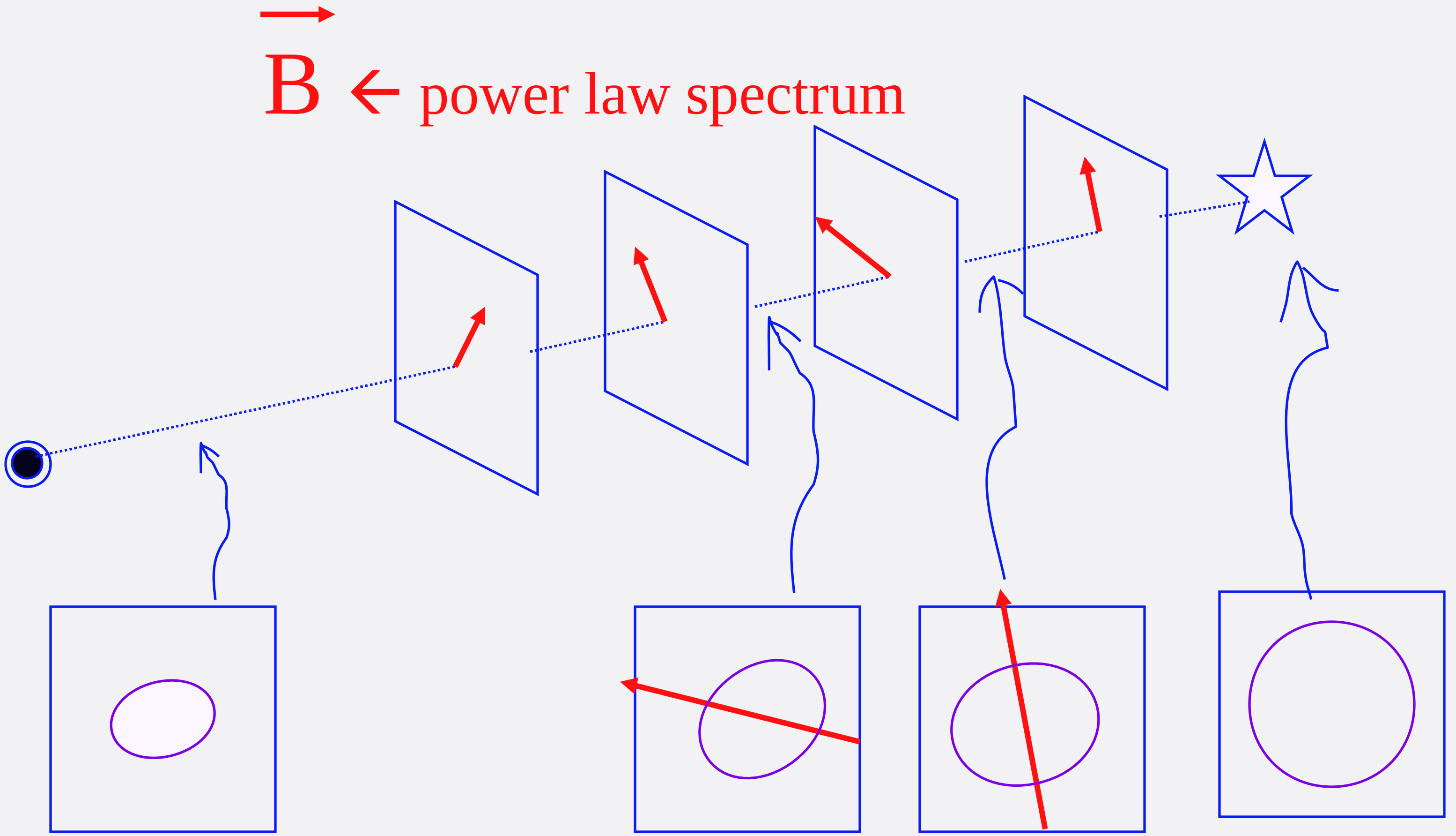
# Spectrum?

$$I_{pol,mm} = P_{em,mm}\ I_{mm} \propto P_{em,opt}\ I_{mm}$$
$$\approx (P_{abs,opt}/\tau)\ I_{mm}$$
$$\propto P_{abs,opt}.$$

⇐ $\tau \propto I_{mm}$

$C_l$ of $I_{pol,mm} \propto C_l$ of $P_{abs,opt}$

# Spectrum of starlight polarization: method



# Equations

$$I^{-1} dI/ds = -\delta + \Delta\sigma Q/I,$$
$$d(Q/I)/ds = \Delta\sigma - \Delta\sigma(Q/I)^2,$$
$$d(U/I)/ds = -\Delta\sigma(Q/I)(U/I)$$

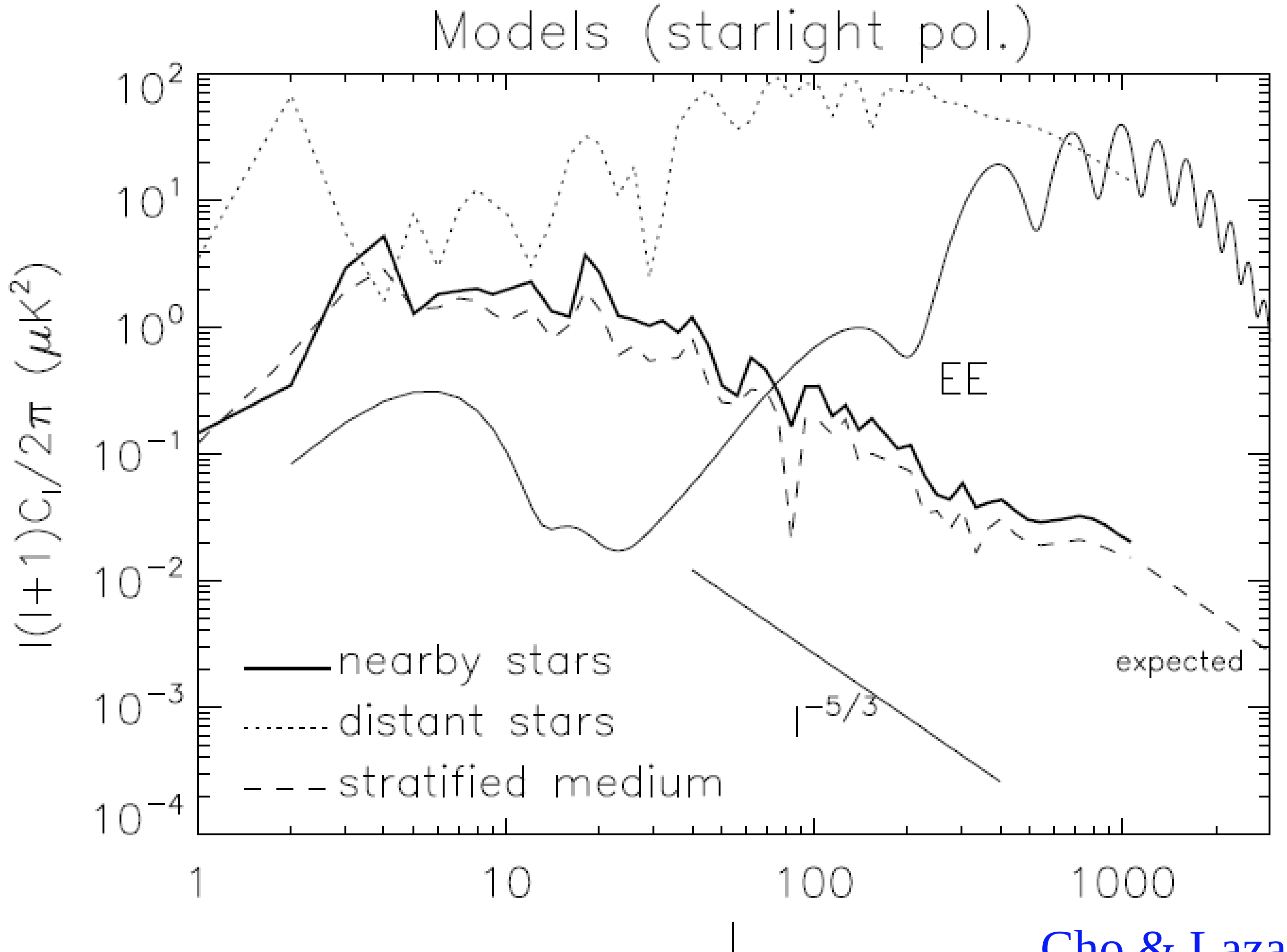
$$\delta = (\sigma_1 + \sigma_2),\ \Delta\sigma = (\sigma_1 - \sigma_2),$$

$$2\sigma_1 = \sigma_\perp,$$
$$2\sigma_2 = \sigma_\perp - (\sigma_\perp - \sigma_{||}) \cos\gamma$$

See, for example, Martin (1972)

# Result:

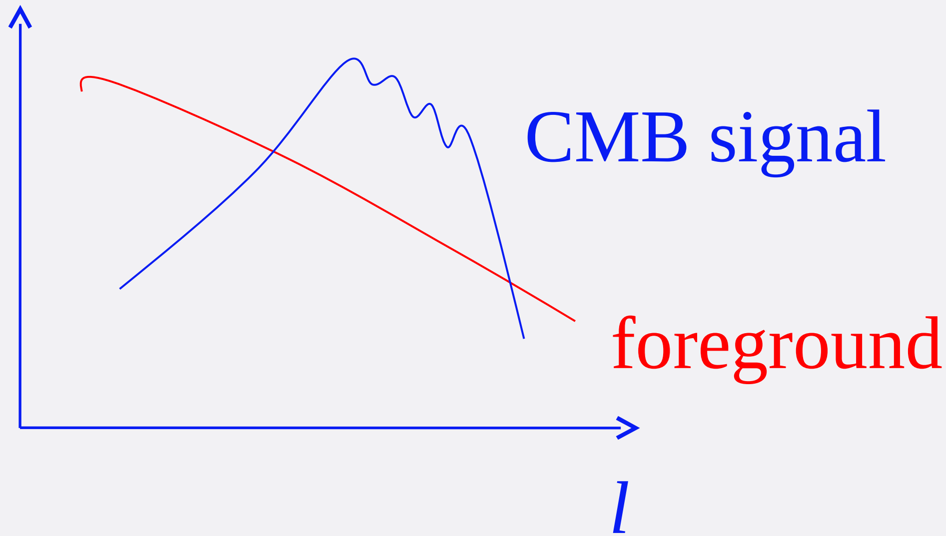
$C_l \propto l^{-11/3}$ for $l > 1000$

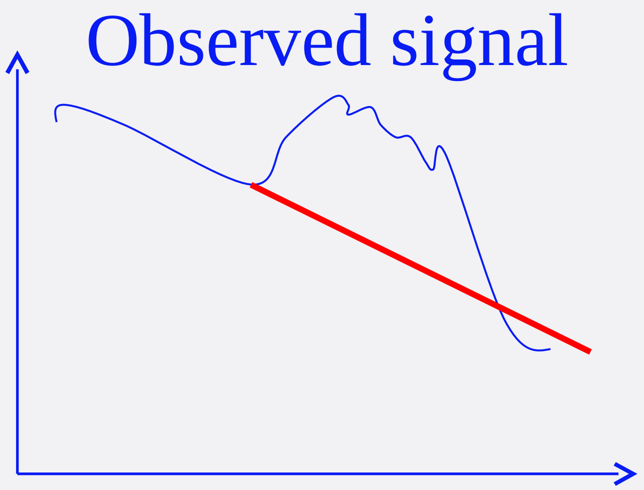



Cho & Lazarian (2010)

Note: EE signal > dust foreground for large *l*'s

# Topic 3: Removal of foregrounds

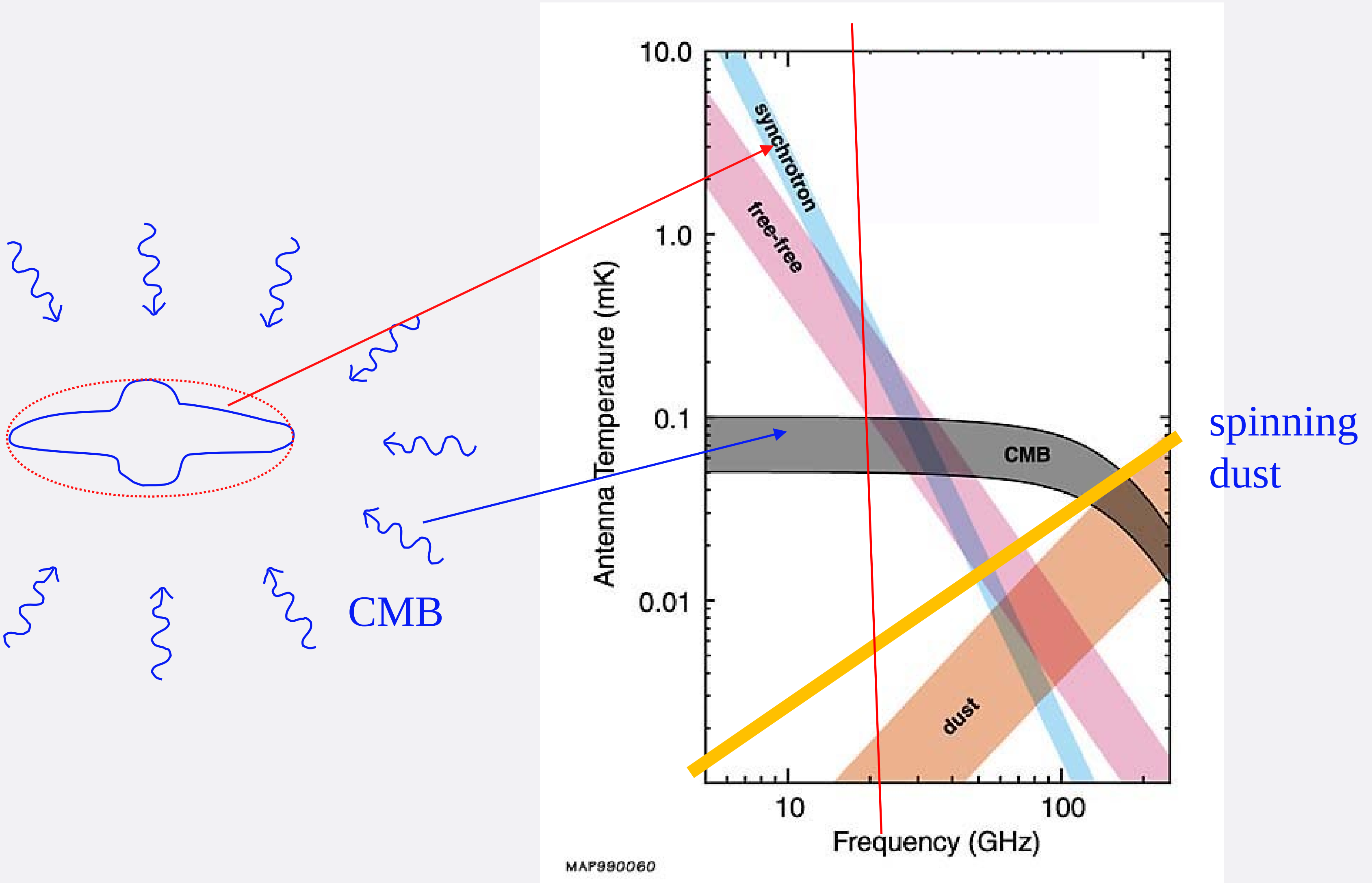



$$\langle (I_1^{\rm CMB} + I_1^{\rm F})(I_2^{\rm CMB} + I_2^{\rm F}) \rangle = \langle I_1^{\rm CMB} I_2^{\rm CMB} \rangle + \langle I_1^{\rm F} I_2^{\rm F} \rangle$$

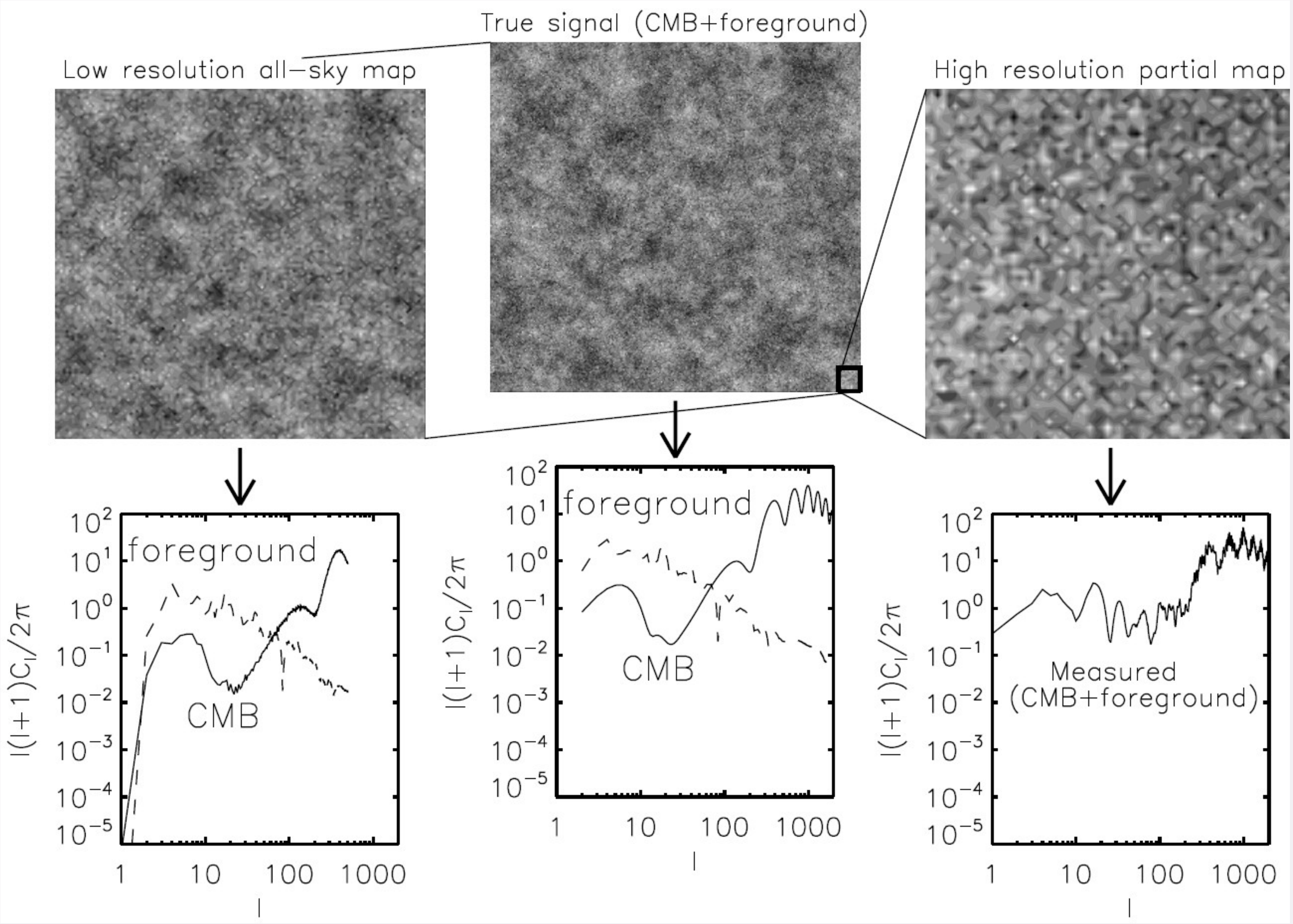
$$C_l^{\rm CMB} = C_l^{\rm measured} - C_l^{\rm F}$$

# "Foregrounds > CMB" doesn't mean that we cannot study CMB!

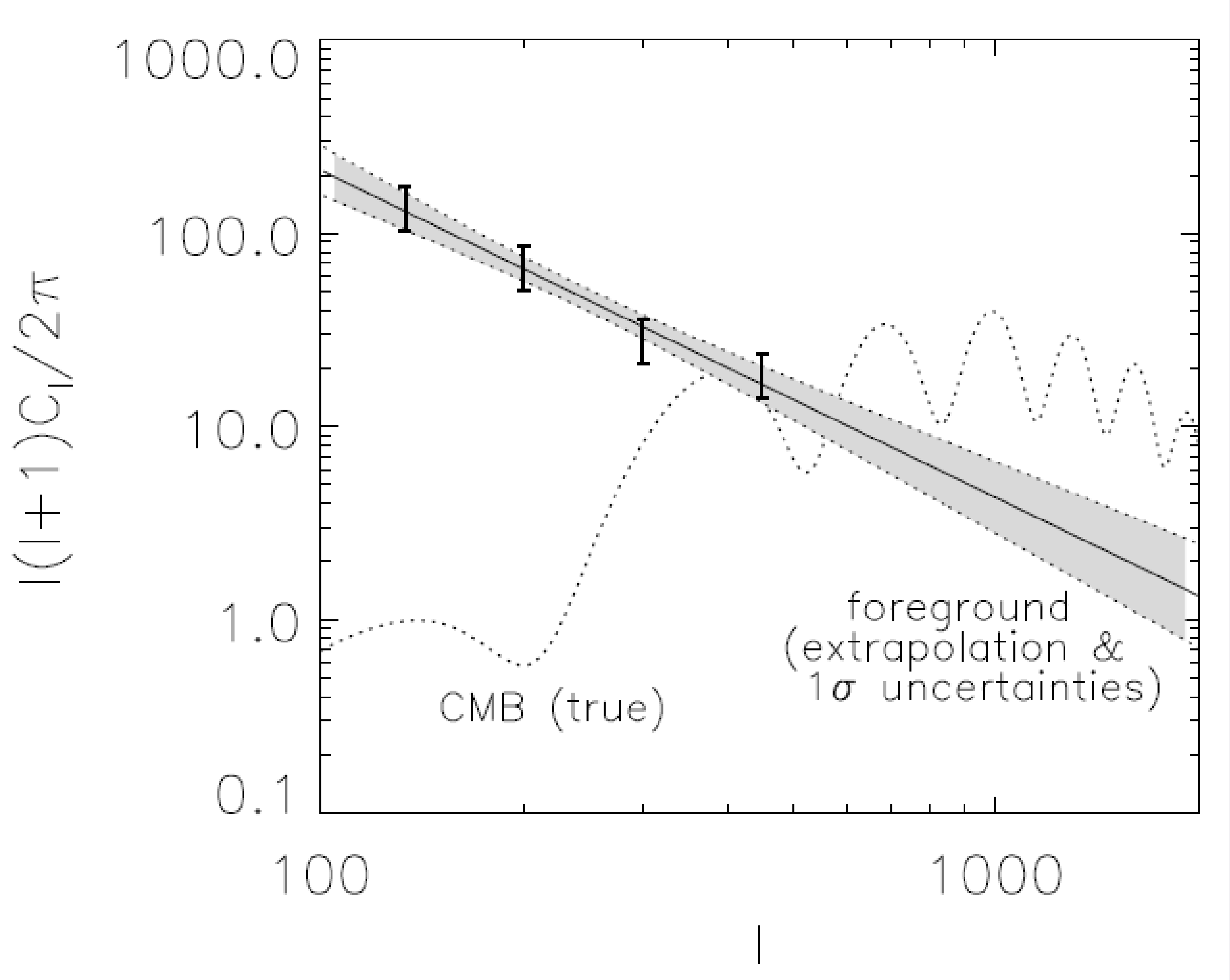



map.gsfc.nasa.gov

# Foreground removal: demonstration

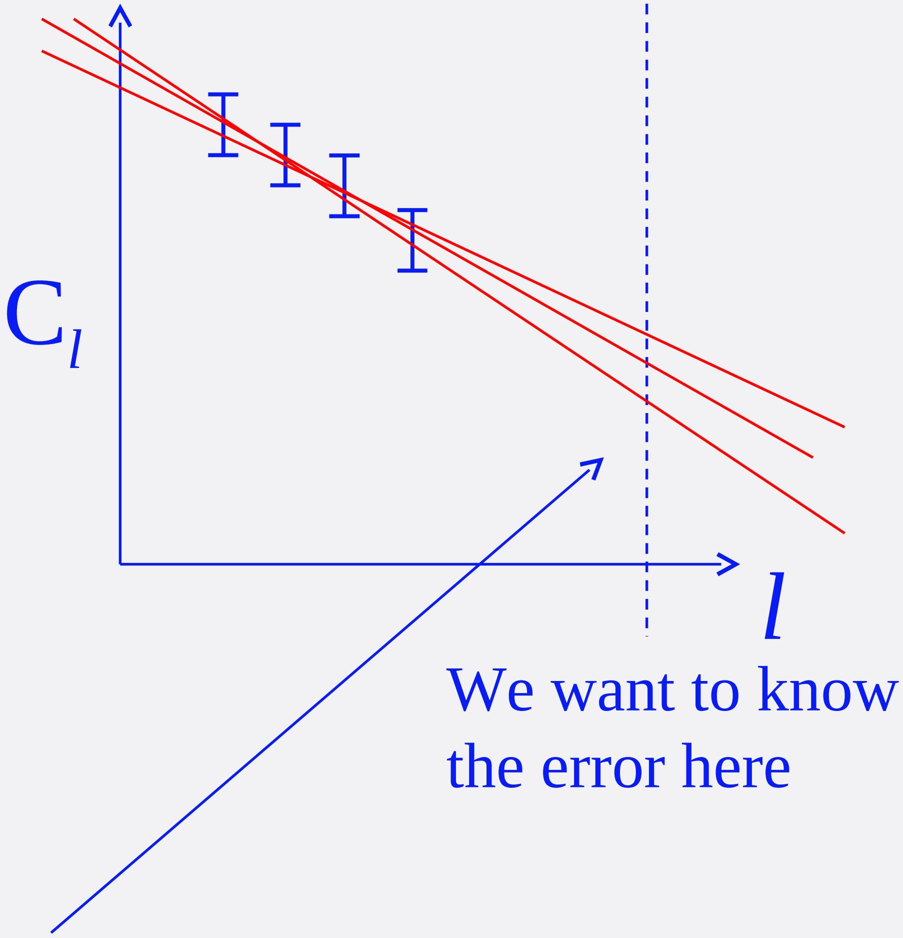


# Result



1000.0
100.0
10.0
1.0
0.1
100
1000
l
l(l+1)C_l/2π
foreground
(extrapolation &
1σ uncertainties)
CMB (true)

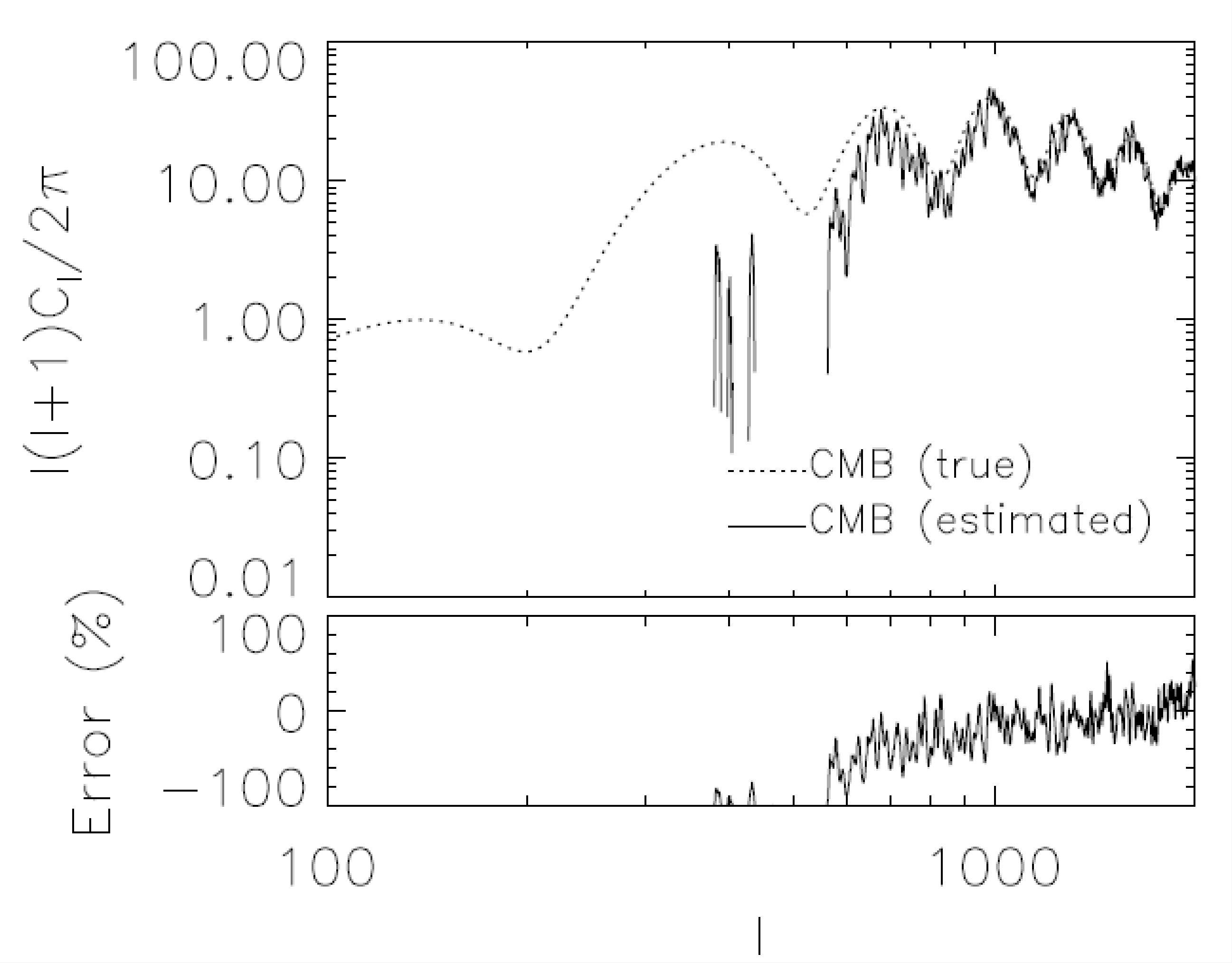
# Method: estimation of errors




We calculate all possible extrapolations here

➔ Then we calculate probabilities

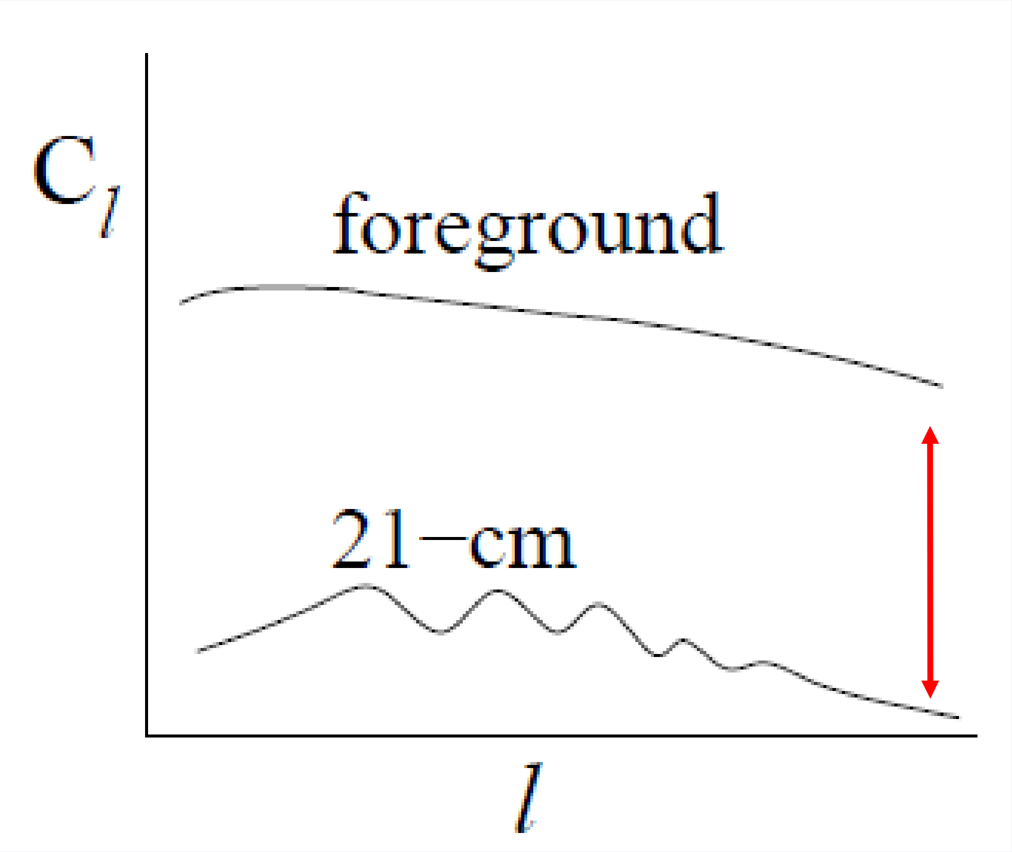
# Result: errors



# Topic 4. Removal of redshifted 21-cm foreground

||

synchrotron

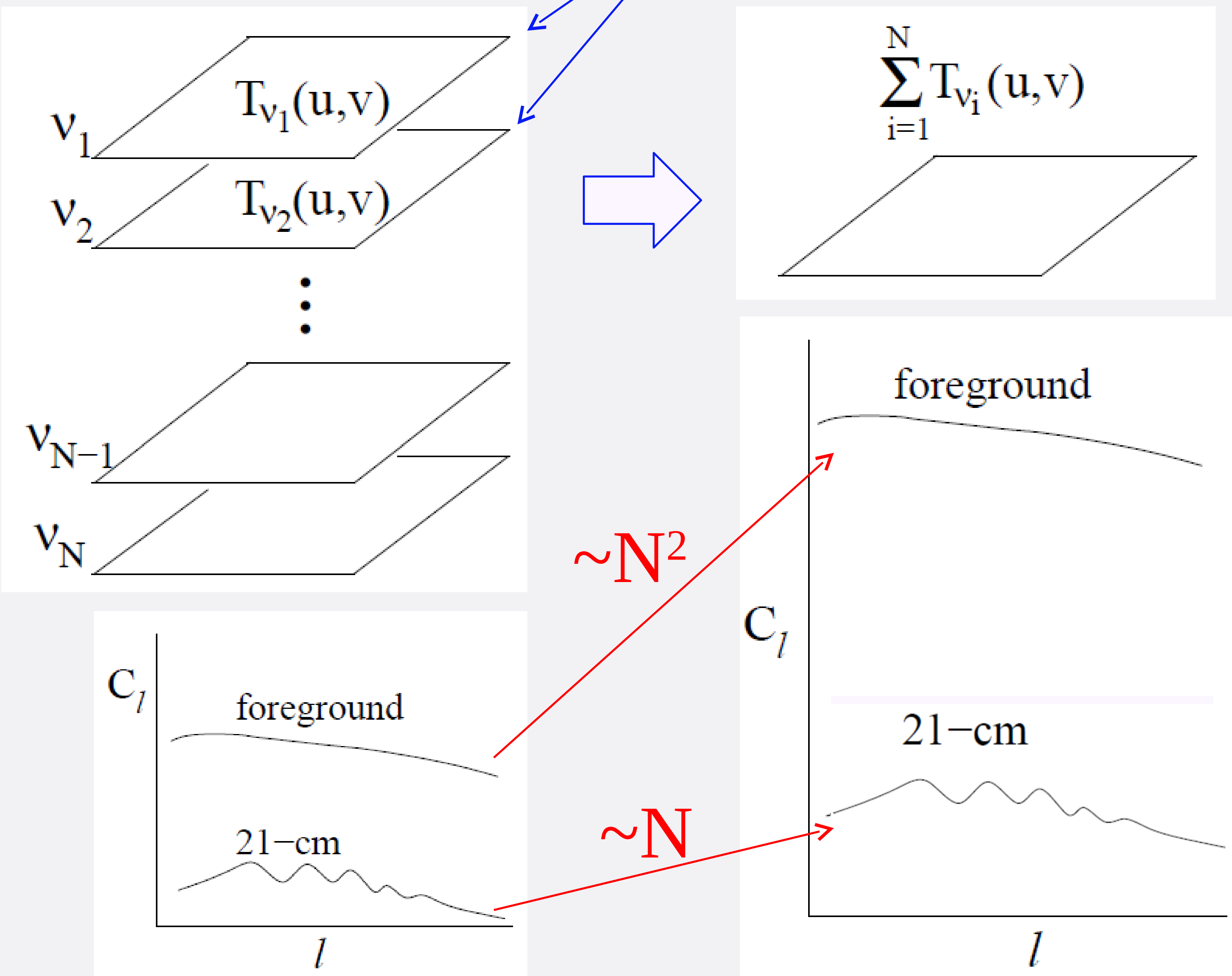



Q: How can we remove foreground?

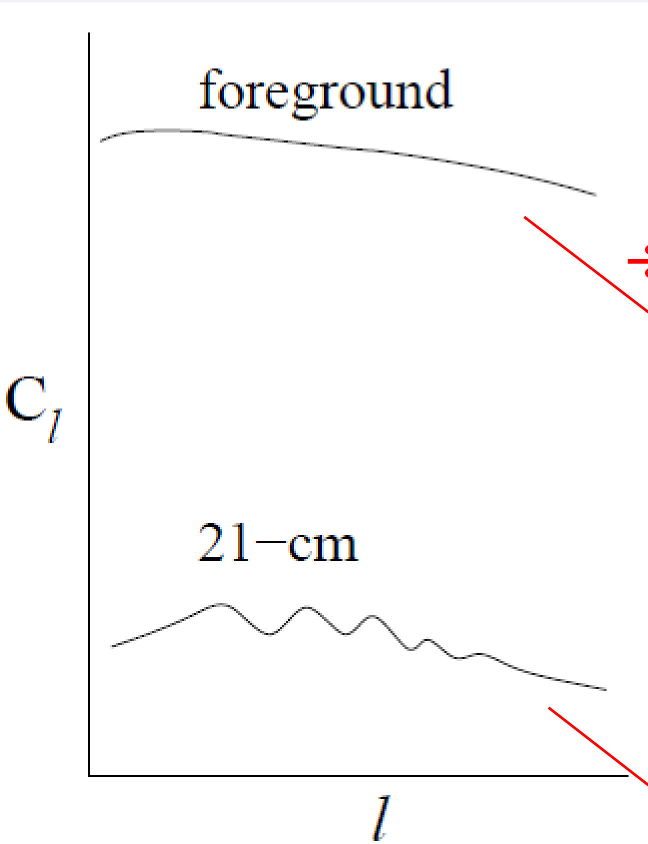
> $10^4$ times

# Our approach

Foreground: highly correlated
21-cm: not correlated

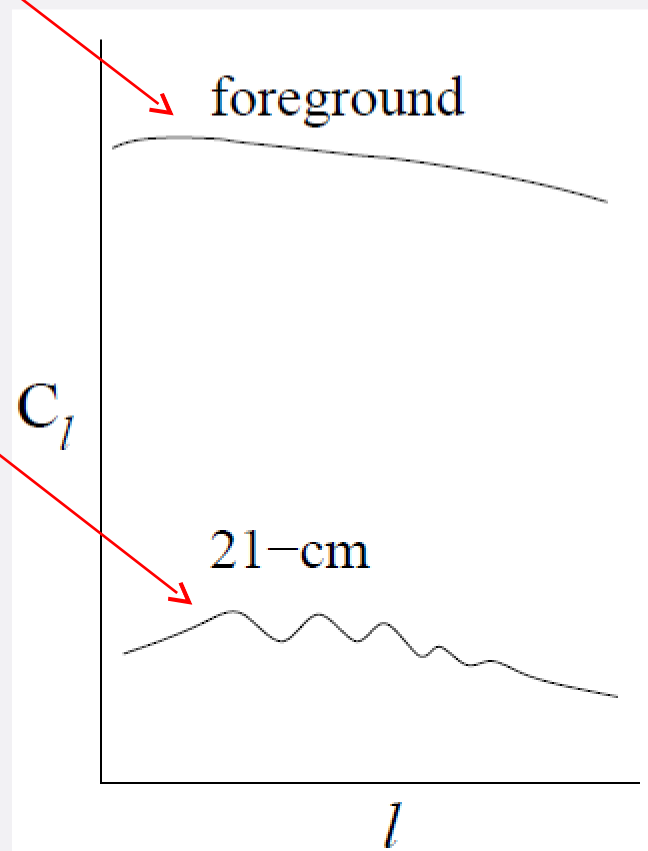


# Basic idea

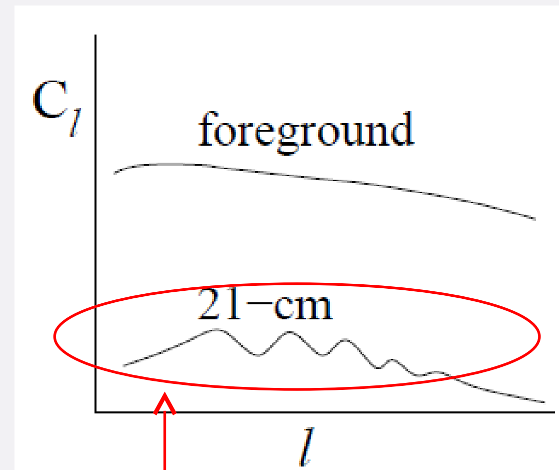



÷ $N^2$

$C_l^{avg}$

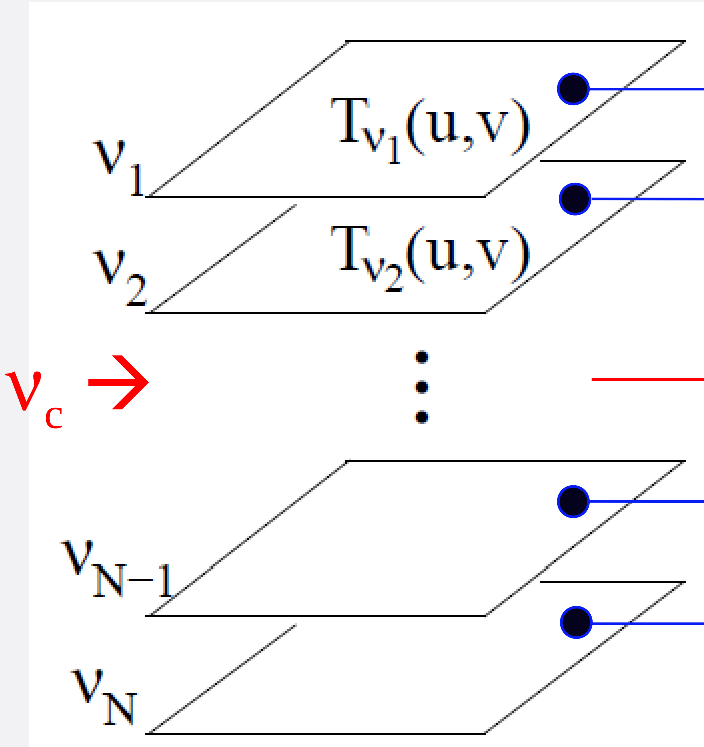



$C_l$ of each channel




$C_l$ of 21-cm
=combined $C_l$
- $C_l^{avg}$
???

# $C_l^{avg}$ : What is it?




$T_0 + a(\nu_1 - \nu_c)$

$T_0 + a(\nu_2 - \nu_c)$

$T_0$

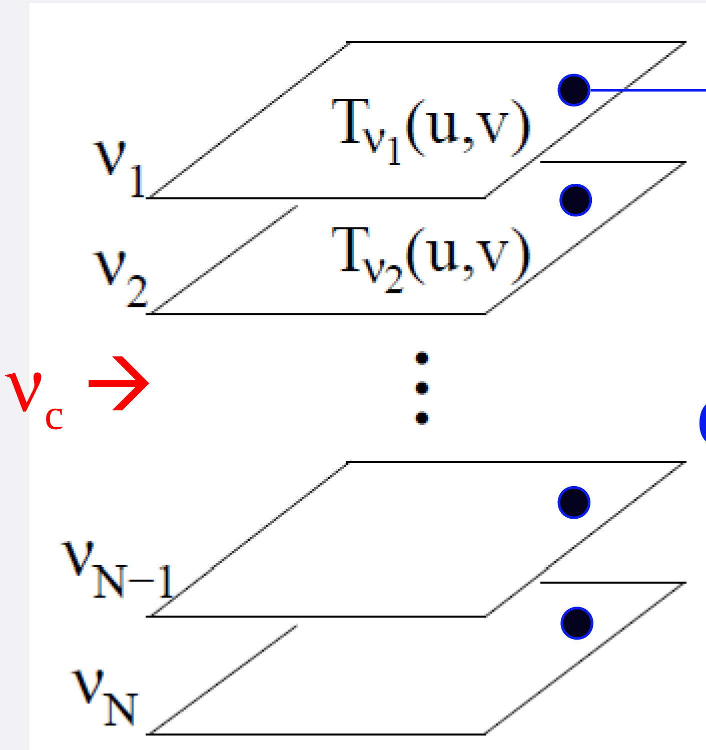
$T_0 + a(\nu_{N-1} - \nu_c)$

$T_0 + a(\nu_N - \nu_c)$

$$\frac{1}{N}\sum_{i=1}^{N} T_{\nu_i}(u,v) = T_0$$

$$C_l^{avg} = C_l^{\nu_c}$$

# Can we use $(C_l) - C_l^{avg}$ ?




$$T_0 + a(\nu_1-\nu_c) + T^{21}(\nu_1)$$

After some algebra,

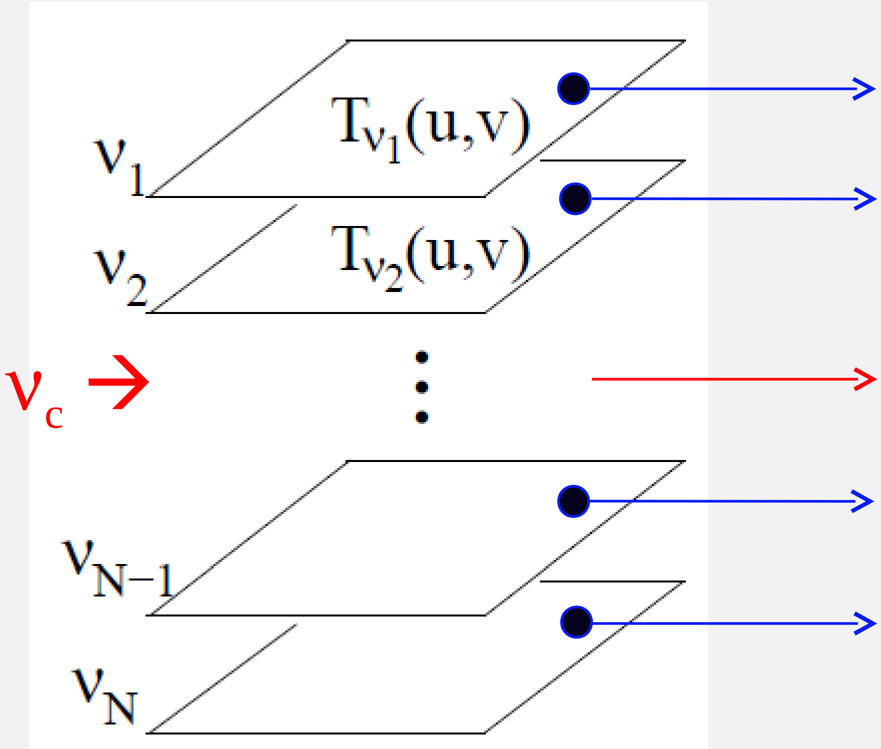
(Actually, $|T_0 + \ldots|^2$)

$$C_l(\nu_1)=|T_0|^2 + 2T_0\, a^*(\nu_1-\nu_c)+C_l^{21cm}(\nu_1)$$

$$|T_0|^2 = C_l^{avg}$$

$$C_l - C_l^{avg} \neq C_l^{21cm}$$

# Better expression:




$C_l = C_l^{avg} + 2T_0\, a^*(\nu_1 - \nu_c) + C_l^{21cm}$

$C_l = C_l^{avg} + 2T_0\, a^*(\nu_2 - \nu_c) + C_l^{21cm}$

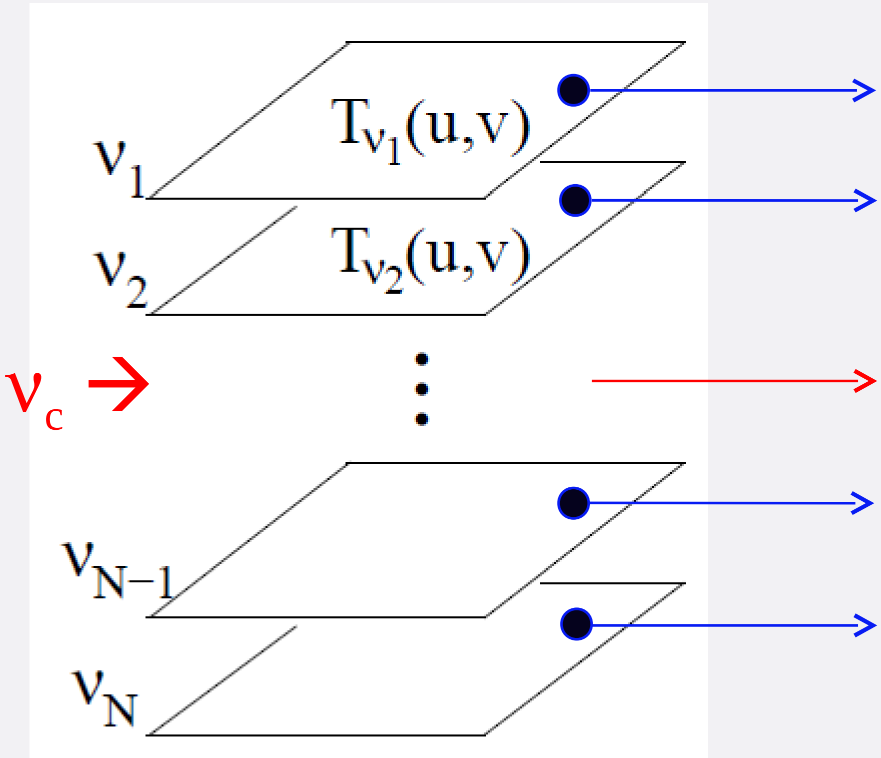
$C_l = C_l^{avg} + \qquad\qquad C_l^{21cm}$

$C_l = C_l^{avg} + 2T_0\, a^*(\nu_{N-1} - \nu_c) + C_l^{21cm}$

$C_l = C_l^{avg} + 2T_0\, a^*(\nu_N - \nu_c) + C_l^{21cm}$

$$\frac{1}{N}\sum_{i=1}^{N} C_l^{\nu_i,21cm} = \frac{1}{N}\left(\sum_{i=1}^{N} C_l^{\nu_i}\right) - C_l^{avg}$$

# Better expression:




$T_0 + a(\nu_1-\nu_c)+b(\nu_1-\nu_c)^2$

$T_0 + a(\nu_2-\nu_c)+b(\nu_2-\nu_c)^2$

$T_0$

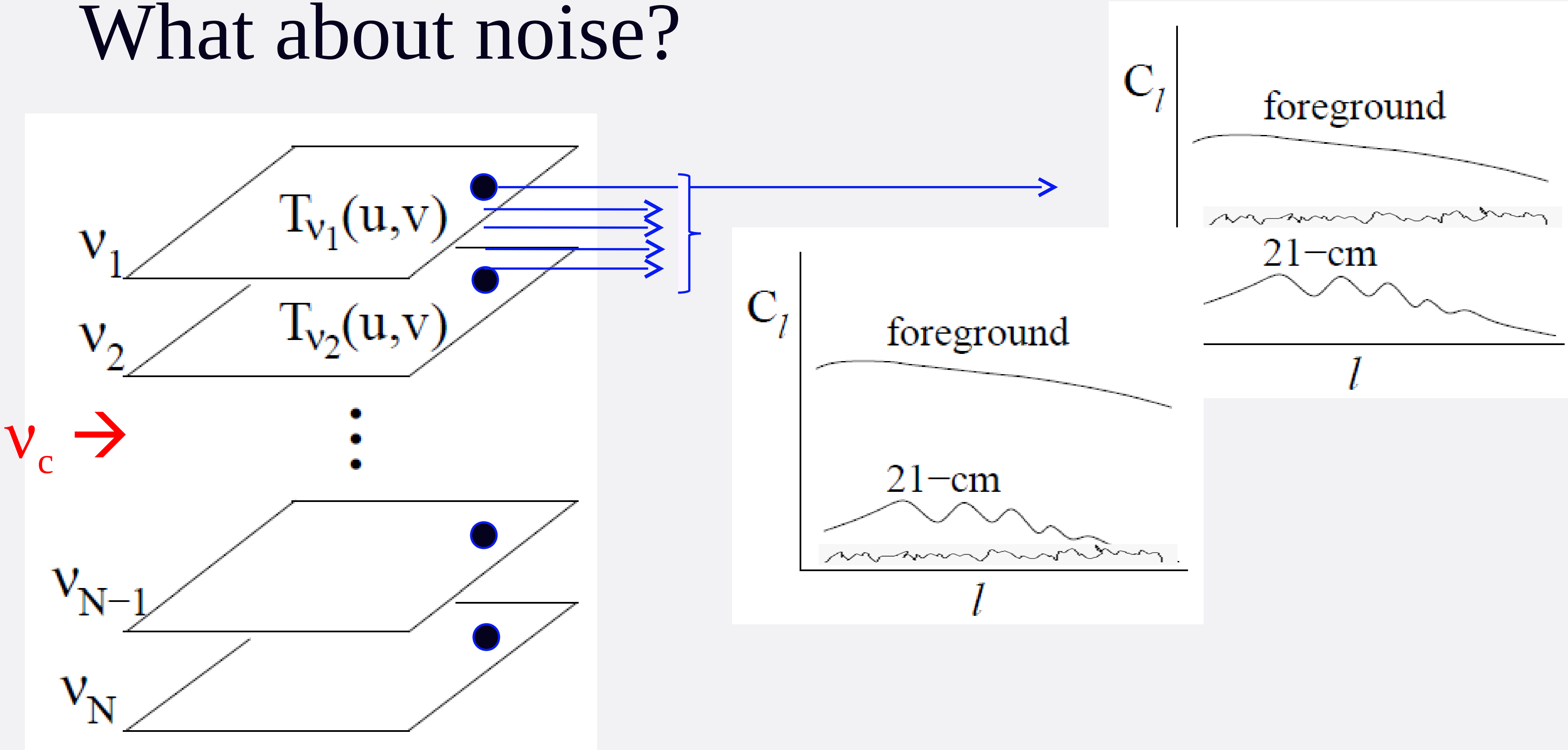
$T_0 + a(\nu_{N-1}-\nu_c)+b(\nu_{N-1}-\nu_c)^2$

$T_0 + a(\nu_N-\nu_c)+b(\nu_N-\nu_c)^2$

$$\frac{1}{N}\sum_{i=1}^{N} C_l^{\nu_i,21cm} = \frac{1}{N}\left(\sum_{i=1}^{N/2} D_l^{\nu_i}\right) - 2C_l^{avg}$$

spectrum of $T_{\nu_i}(u,v) + T_{\nu_{N-i+1}}(u,v)$

# What about noise?




➔Then we apply our method

# Conclusion

- Foregrounds can be understood
- With accurate foreground models, we can recover true CMB spectra
- We developed a new method for removing the foreground of red-shifted H21 signal