# Improved Model of Spinning Dust Emission and Implications

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in collaboration with

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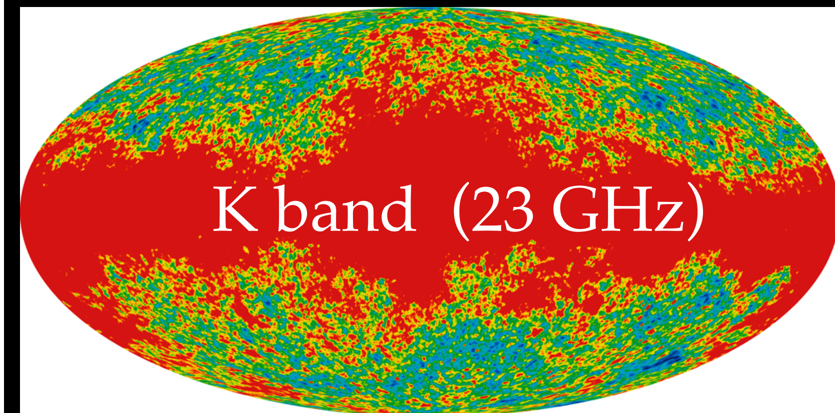
The Planck one-year all-sky survey

esa

# Outline

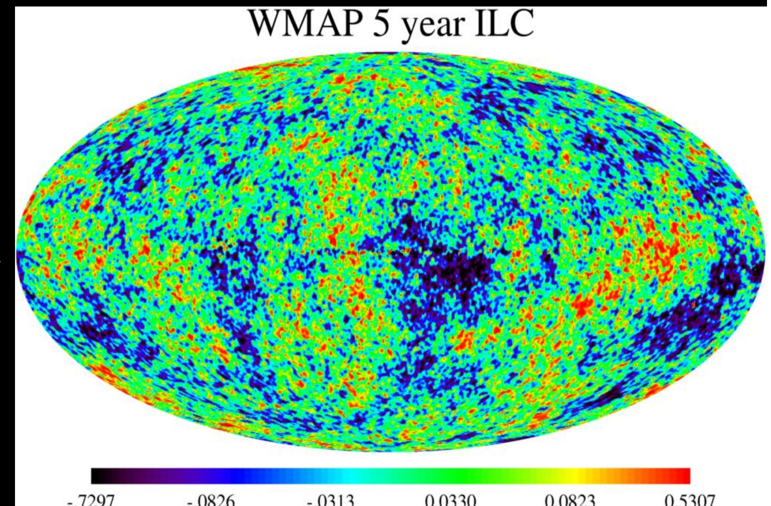
- Motivation
- Draine & Lazarian Model (DL98; Yacine's talk)
- Improved Model of Spinning Dust Emission
- Constraining Physical Parameters using WMAP data
- Summary and Future Works

# Precision Cosmology requires a Complete Model of Spinning Dust




LAMBDA

cleaning




Understanding

Galactic Foregrounds

| WMAP Cosmological Parameters<br>Model: lcdm<br>Data: wmap+sdss | |
|---|---|
| $10^2\Omega_b h^2$ | $2.230^{+0.071}_{-0.070}$ |
| $\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$ | $(24.1 \pm 1.3) \times 10^{-10}$ |
| $h$ | $0.710 \pm 0.026$ |
| $H_0$ | $71.0 \pm 2.6$ km/s/Mpc |
| $n_s(0.002)$ | $0.948^{+0.016}_{-0.015}$ |
| $\Omega_b h^2$ | $0.02230^{+0.00071}_{-0.00070}$ |
| $\Omega_\Lambda$ | $0.735 \pm 0.030$ |
| $\Omega_m$ | $0.265 \pm 0.030$ |
| $\Omega_m h^2$ | [illegible] |

*Spergel et al. 2003*

# Improved Model of Spinning Dust

**Step 1: Improving grain rotational dynamics**

- Grain wobbling, internal relaxation, transient spin-up

*(Hoang, Draine & Lazarian 2010, ApJ, 465, 1602)*

*Silsbee, Ali-Haimoud & Hirata 2011: no internal relaxation*

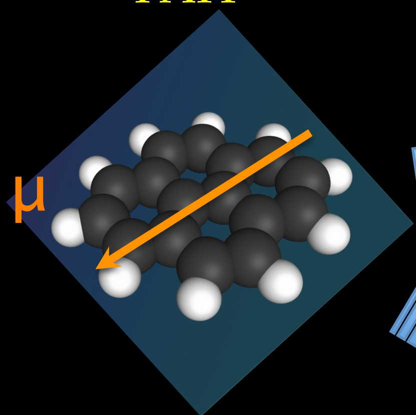
**Step 2: Dealing with realistic grain shapes**

- Triaxial ellipsoid (*irregular* shape)
- Probing physical properties of PAHs

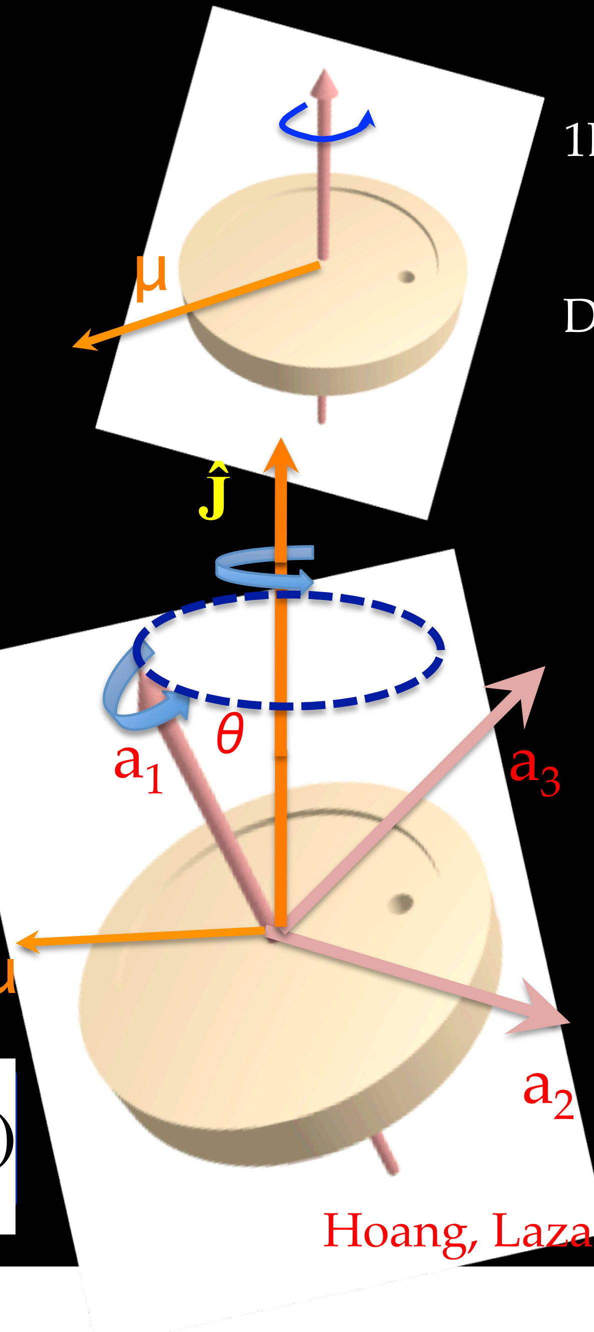
*(Hoang, Lazarian & Draine 2011, ApJ, 741, 87)*

# Step 1: Grain Wobbling

PAH




modeling




$$\frac{j_\nu}{n_H} \propto \int_{a_{\min}}^{a_{\max}} da \frac{dn}{da} 4\pi\omega^2 f_\omega 2\pi P_{\rm ed}(\omega)$$

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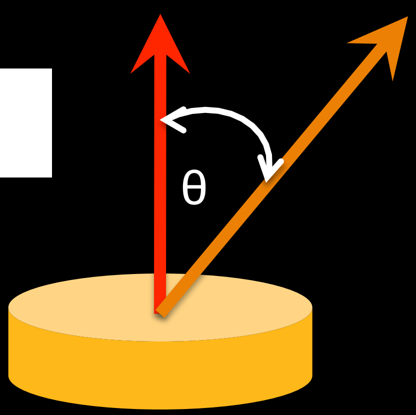
# Internal Fluctuations Induce Grain Wobbling

- Barnett effect: paramagnetic rotating body magnetized with magnetic moment **μ** ~ **ω** .

- Barnett effect results in the transfer of rotational energy:

$$E_{\mathrm{rot}}(\theta) = \frac{J^2}{2I_1}\left(1 + [h-1]\sin^2\theta\right)$$

Purcell 1979




to vibrational modes, i.e., $E_{\mathrm{rot}}$ decreases to minimum at θ=0

- Dissipation-Fluctuation Theorem:

$$f_{\mathrm{int}}(\theta)d\theta \propto \exp\left(\frac{E_{\mathrm{rot}}}{\mathrm{kT_{vib}}}\right)\sin\theta d\theta$$

Lazarian & Roberge 1997

# Spinning Dust: Power Spectrum

- Torque-free motion: Euler angles $\phi$, $\psi$, $\theta$, *and* rates

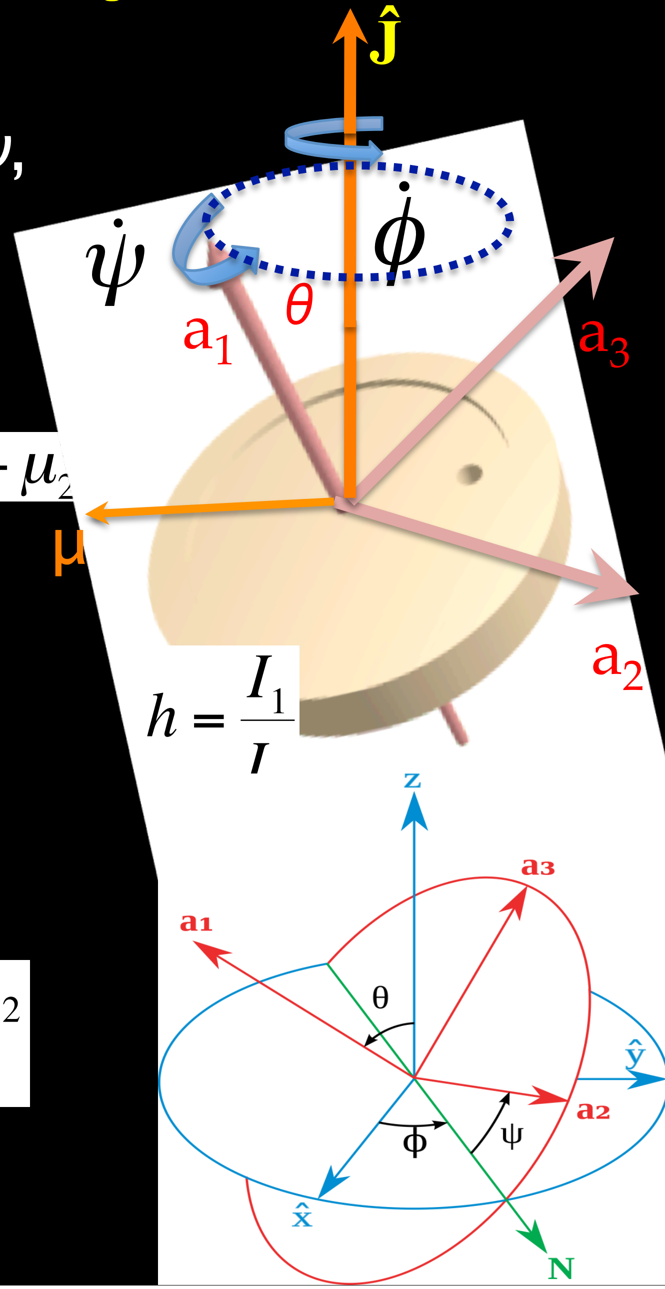
$$\dot{\theta}=0,\dot{\phi}=\frac{J}{I_2},\dot{\psi}=\frac{J\cos\theta(1-h)}{I_1}$$

- Electric dipole moment: $\vec{\mu}(J,\theta,t)=\mu_1\vec{a}_1+\mu_2$
- Fourier Transform: $\ddot{\vec{\mu}}(J,\theta,t)=\mu_1\ddot{\vec{a}}_1+\mu_2\ddot{\vec{a}}_2$

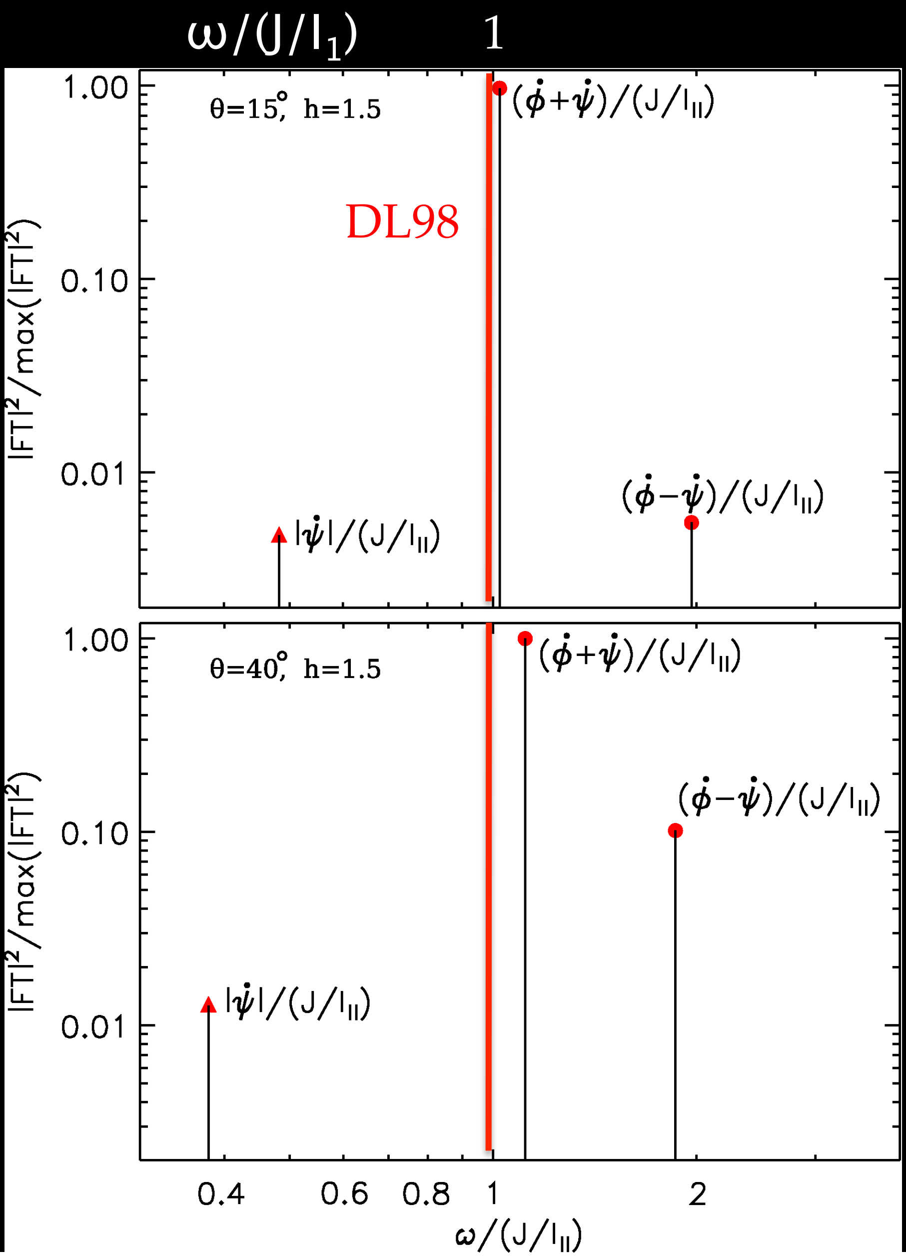
$$\ddot{\mu}_{i,k}=\int_0^\infty \ddot{\mu}_i(t)\exp(-i2\pi\nu_k t)dt, i=x,y,z$$

- Power Spectrum:

$$P_{\mathrm{ed},k}(J,\theta)=\frac{2}{3c^3}\sum_i(\ddot{\mu}_{i,k})^2$$



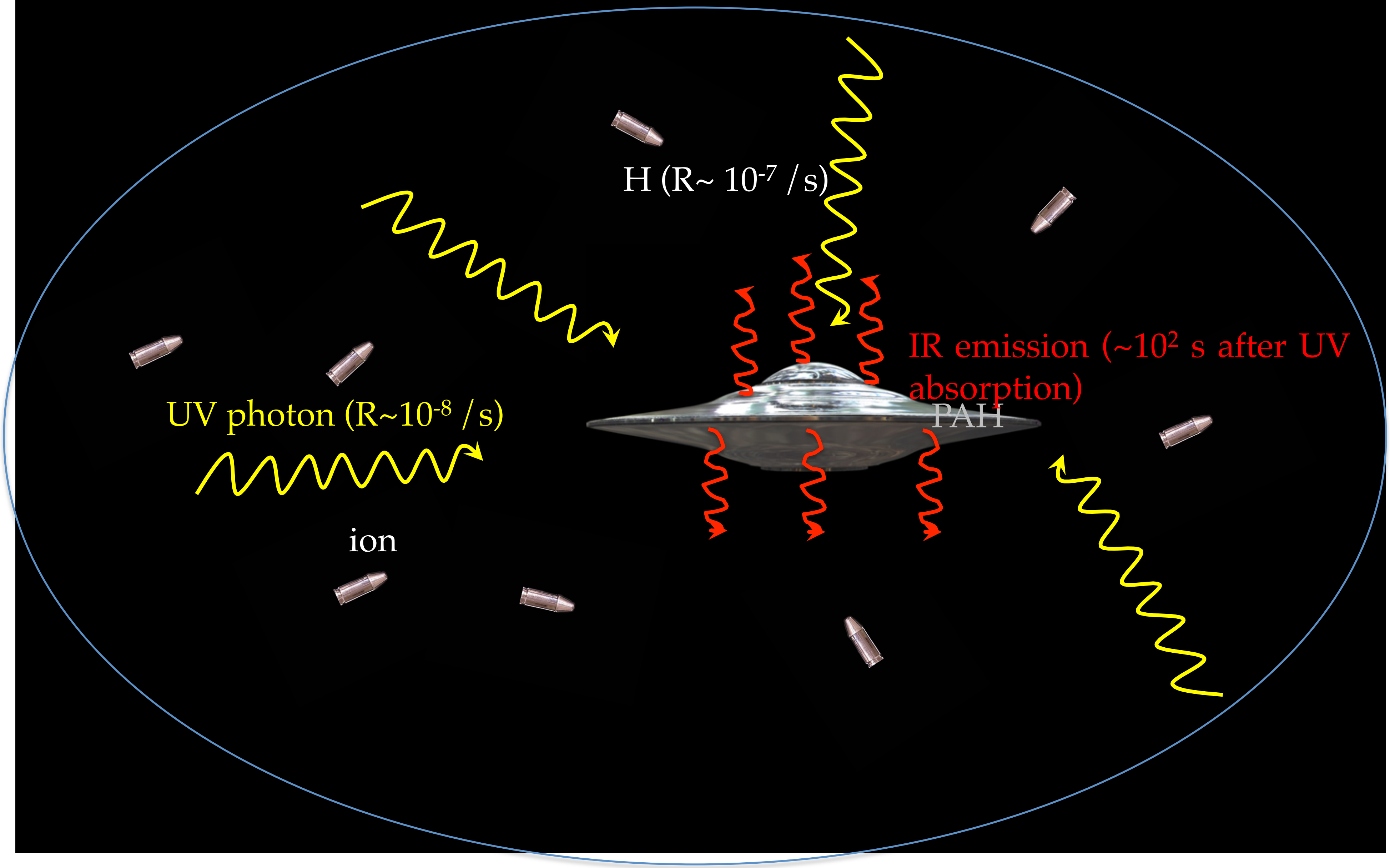
# Power Spectrum: Four Freq. Modes




- Precessing grain radiates at frequency modes: $\omega_k = \dot\phi, \dot\phi \pm \dot\psi, \dot\psi$
- Dominant modes: $\omega_k = \dot\phi \pm \dot\psi$

What induces grain rotation?

# Rotational Damping and Excitation



# Numerical Method: Langevin Equation

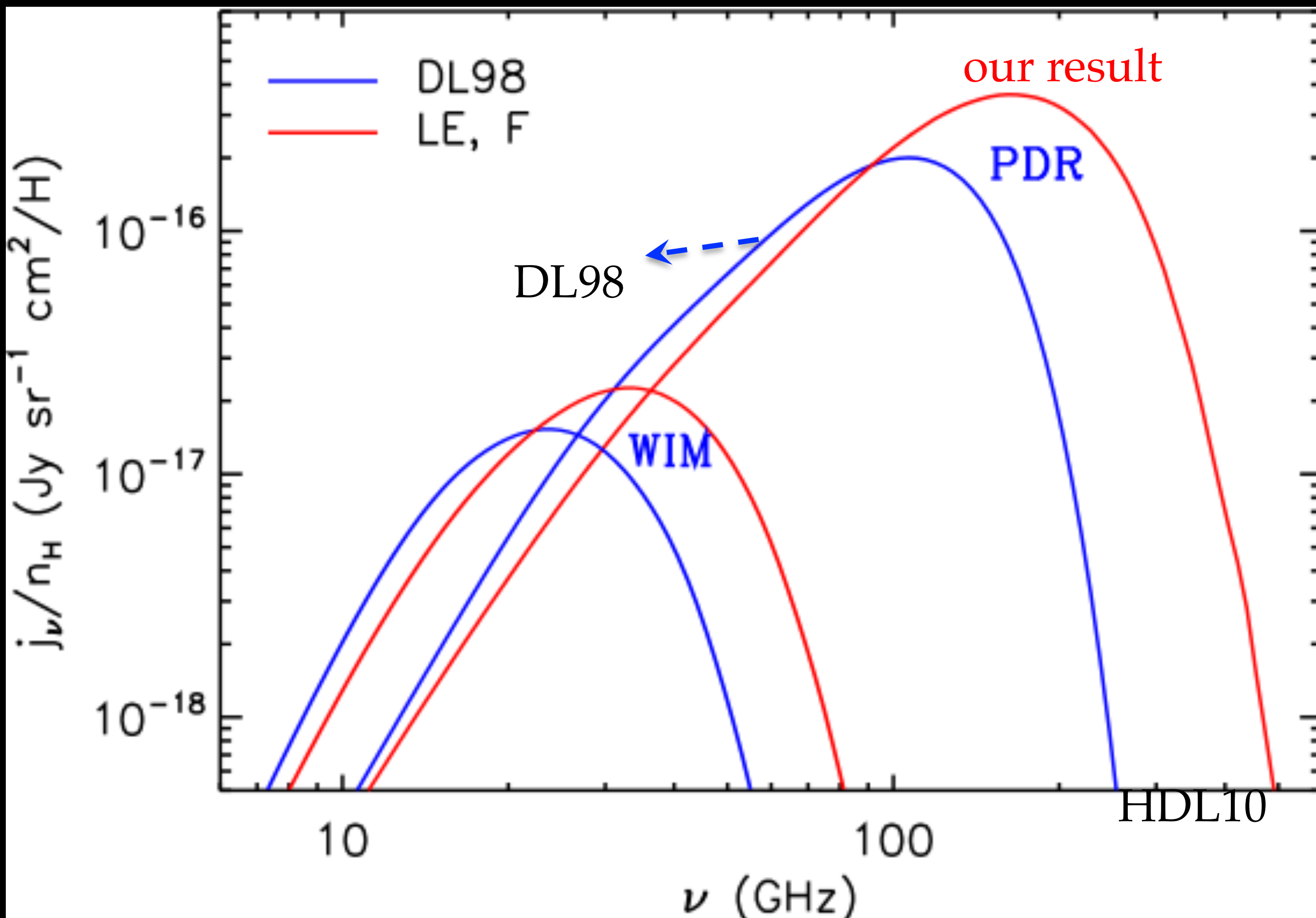
- Angular momentum **J** in the lab system is described by Langevin equations (LEs):

$$dJ_i = A_i dt + \sqrt{B_{ii}}dq_i\,,$$
$$A_i = \sum\left\langle \frac{\Delta J_i}{\Delta t}\right\rangle, B_{ii} = \sum\left\langle \frac{(\Delta J_i)^2}{\Delta t}\right\rangle, \langle dq^2\rangle = dt$$

- Integrate LEs to get J(t) and find momentum distribution $f_J$
- Emissivity per H atom:

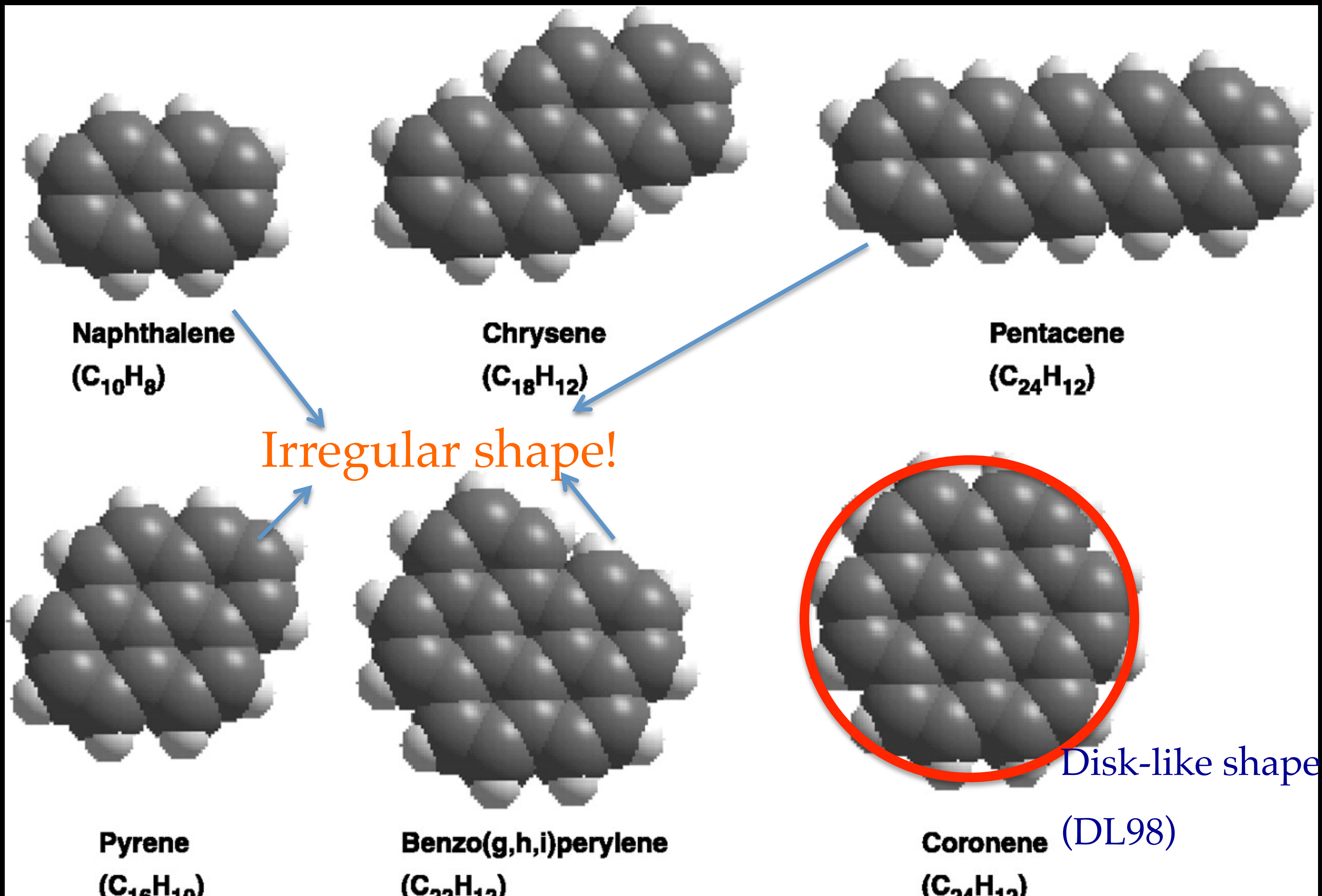
$$j_\nu^a = \int \sum_{\text{mod}} prob(\omega \mid J) P_{\text{ed}}(J) 2\pi f_J dJ \quad \Rightarrow \quad \frac{j_\nu}{n_{\text{H}}} = \frac{1}{4\pi}\frac{1}{n_{\text{H}}}\int da \frac{dn}{da} j_\nu^a$$

# Wobbling Grain Emits More Radiation

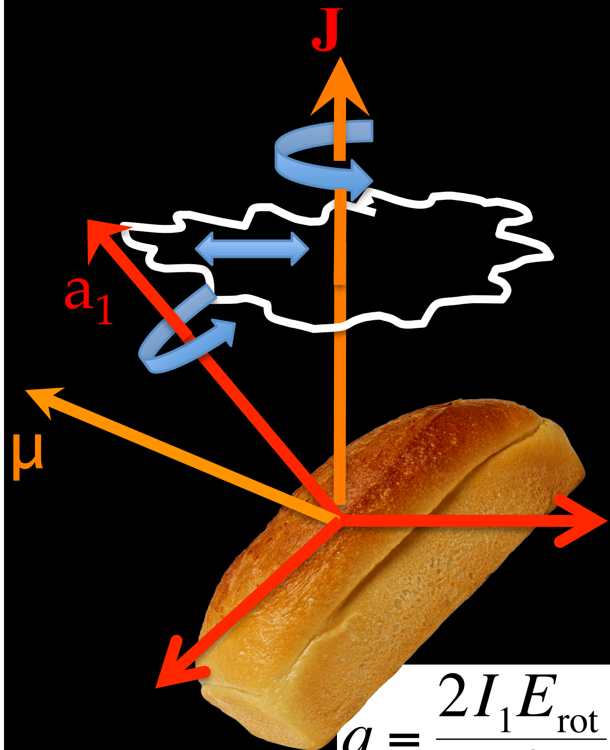



- Peak emissivity increases by a factor ~2 .
- Peak frequency increases by factors ~1.4 to 1.8.

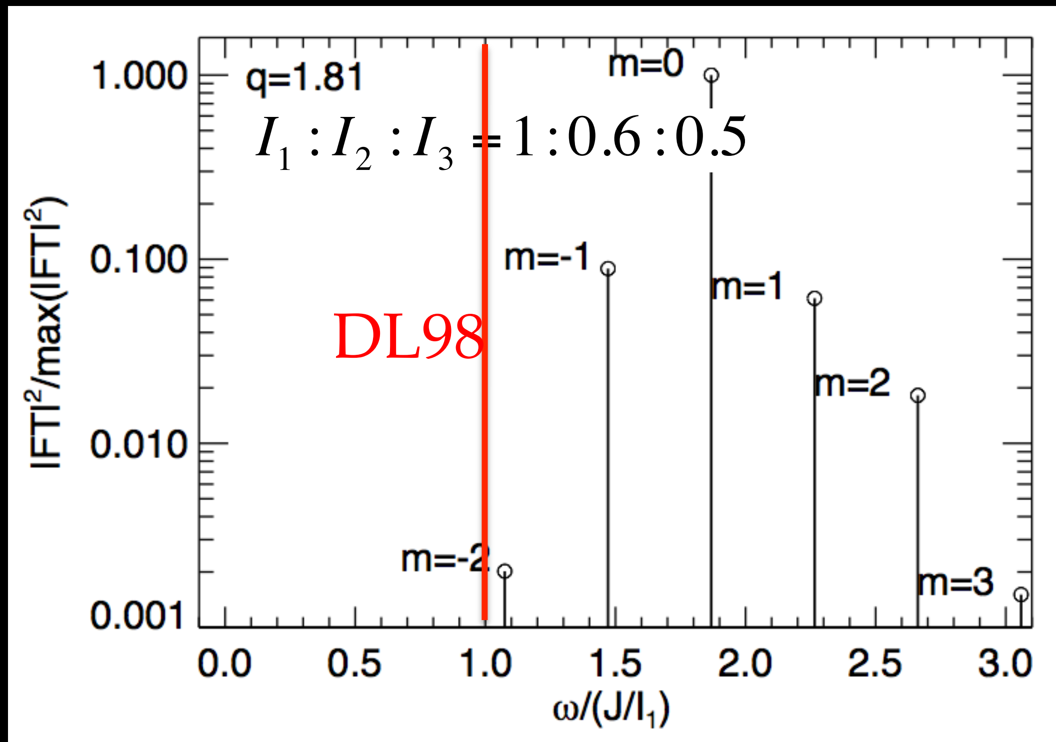
# Step 2: Irregular Grain Shape



# Power Spectrum: Multiple Freq. Modes




$$q = \frac{2I_1 E_{\text{rot}}}{J^2}$$




- Multiple frequency modes:

$$\omega_m = \langle \dot{\phi} \rangle + m\langle \dot{\psi} \rangle, m = 0, \pm 1, \pm 2 \ldots,$$
$$\omega_n = n\langle \dot{\psi} \rangle, n = 0, 1, 2$$

where <…> denotes time averaging.

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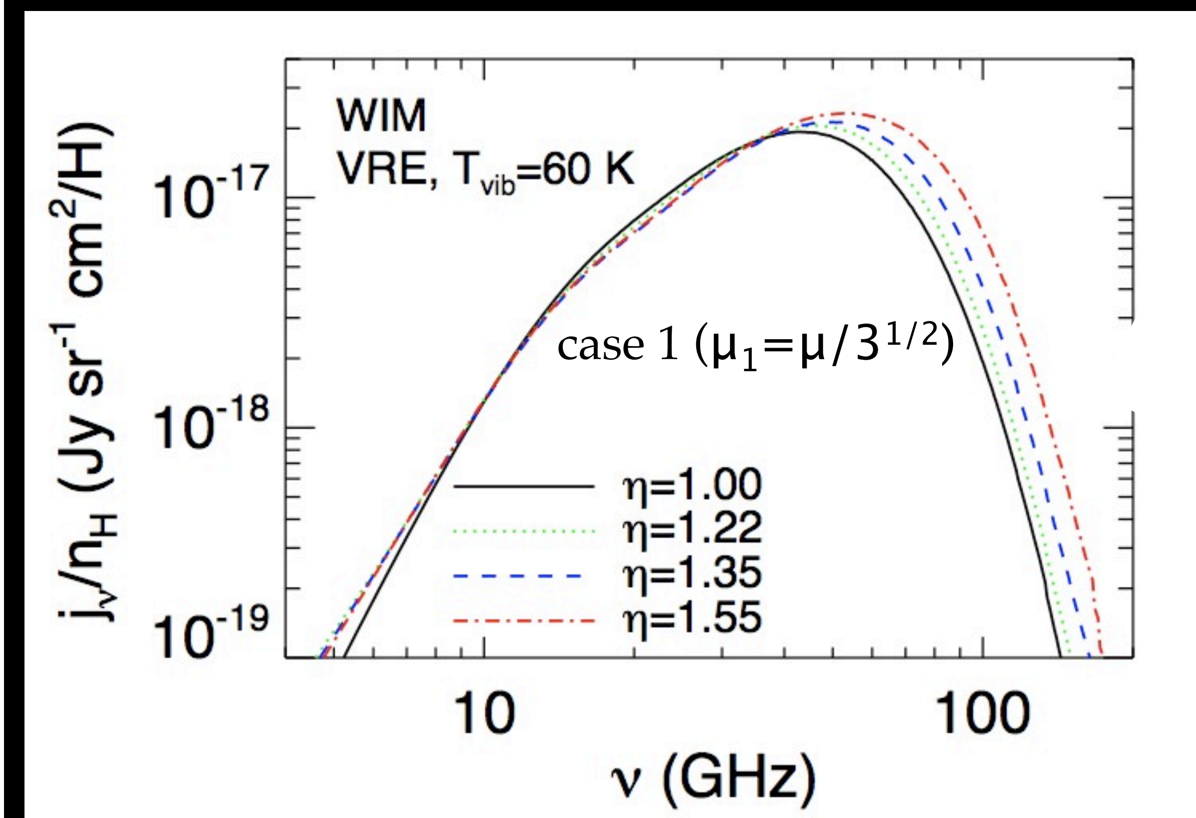
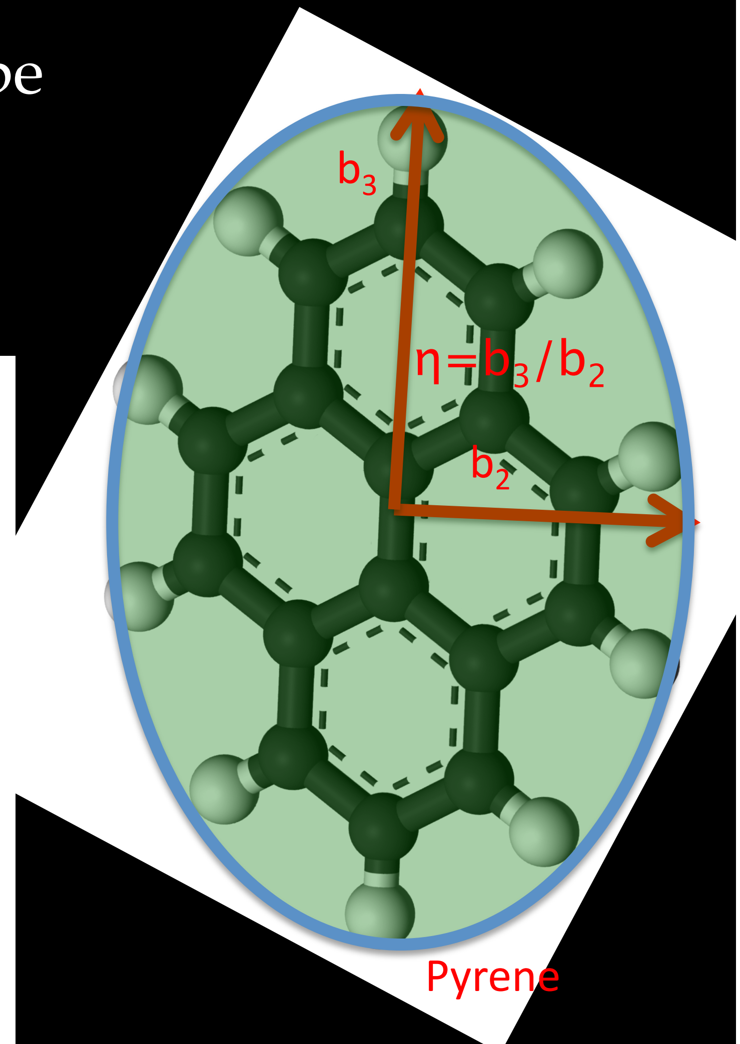
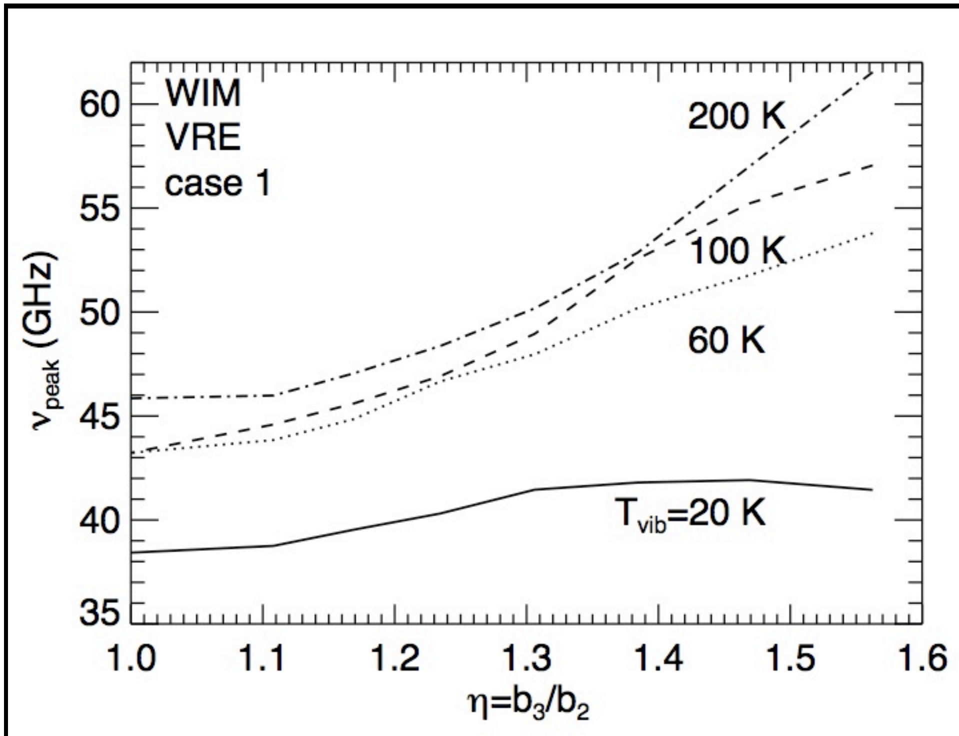
# Emissivity Increases with Grain Irregularity

- Working model: Simple irregular shape
- Irregularity: $\eta = b_3/b_2$

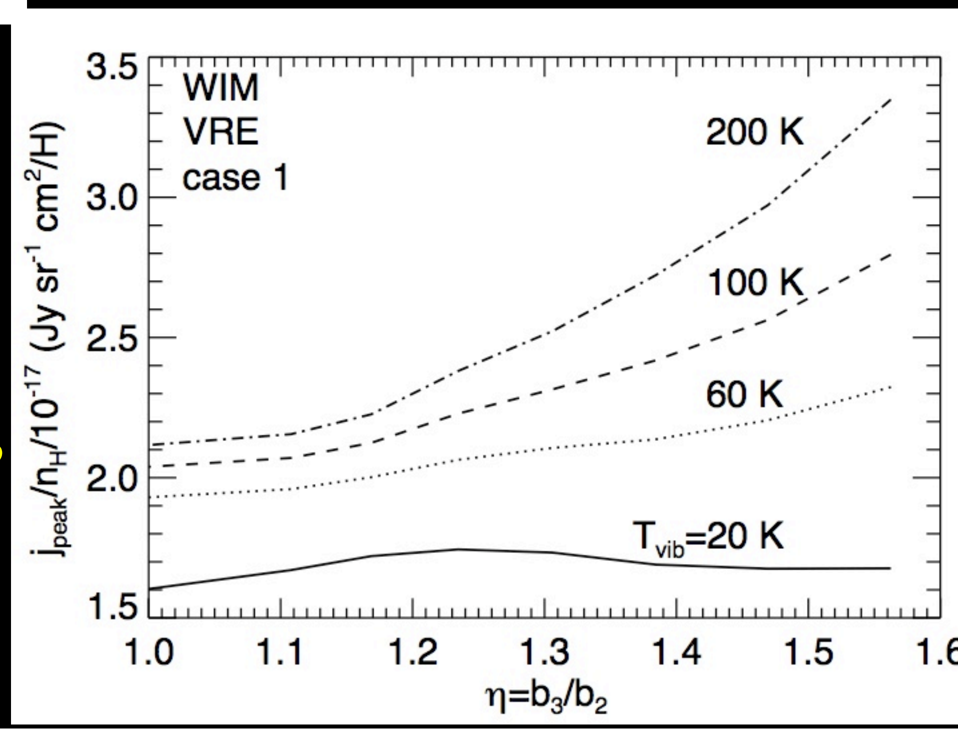


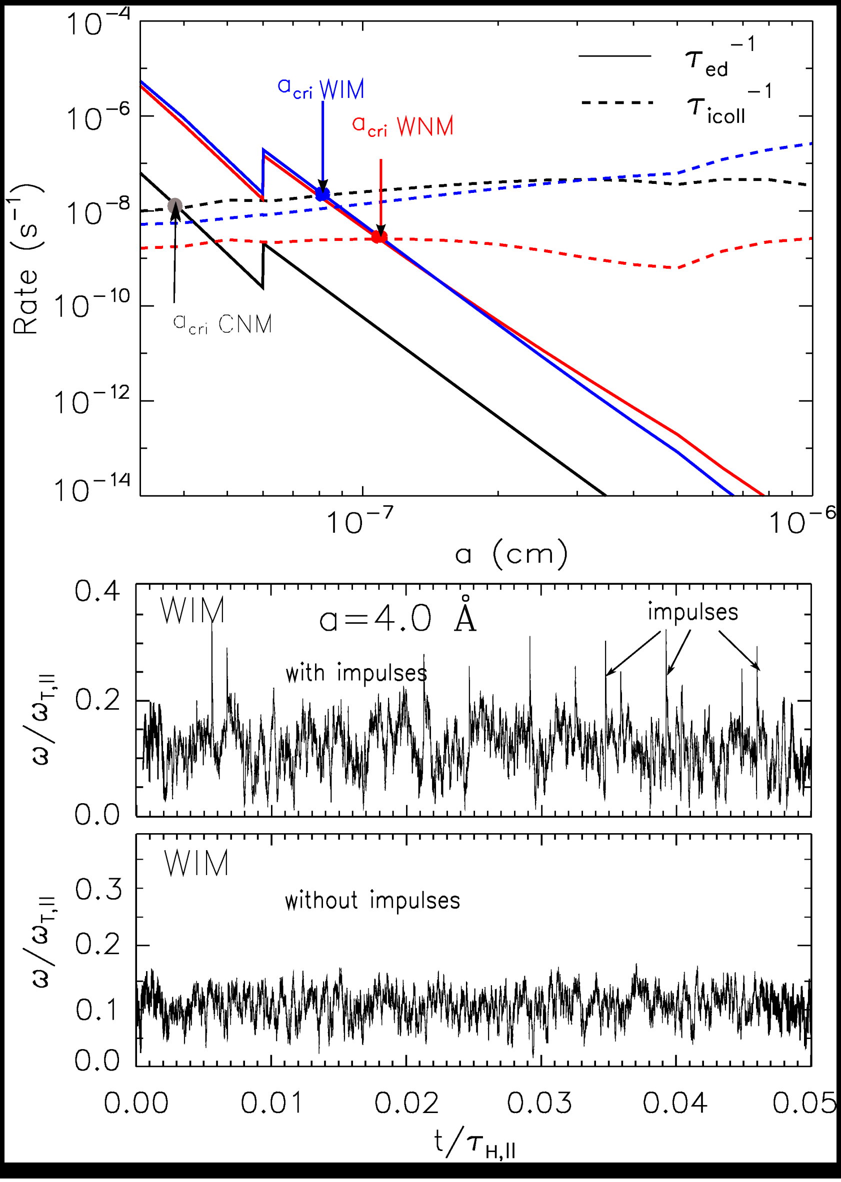


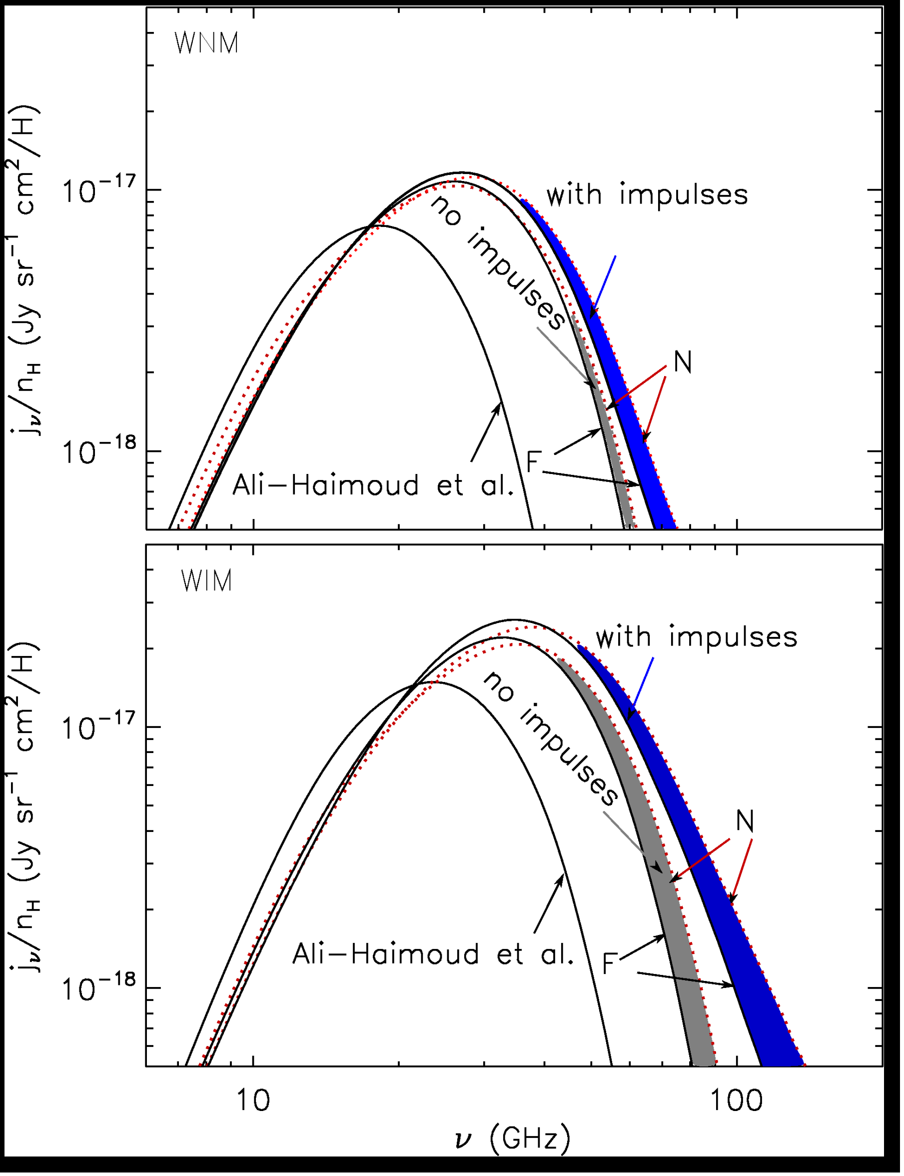

★ Emissivity increases with η

★ Emissivity increases with $T_{vib}$

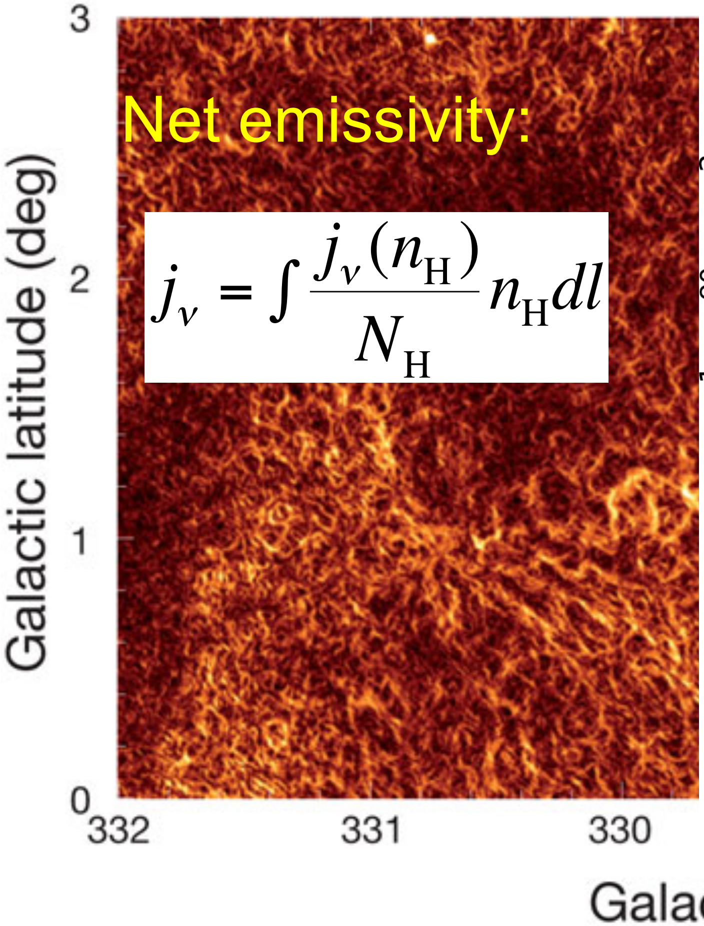


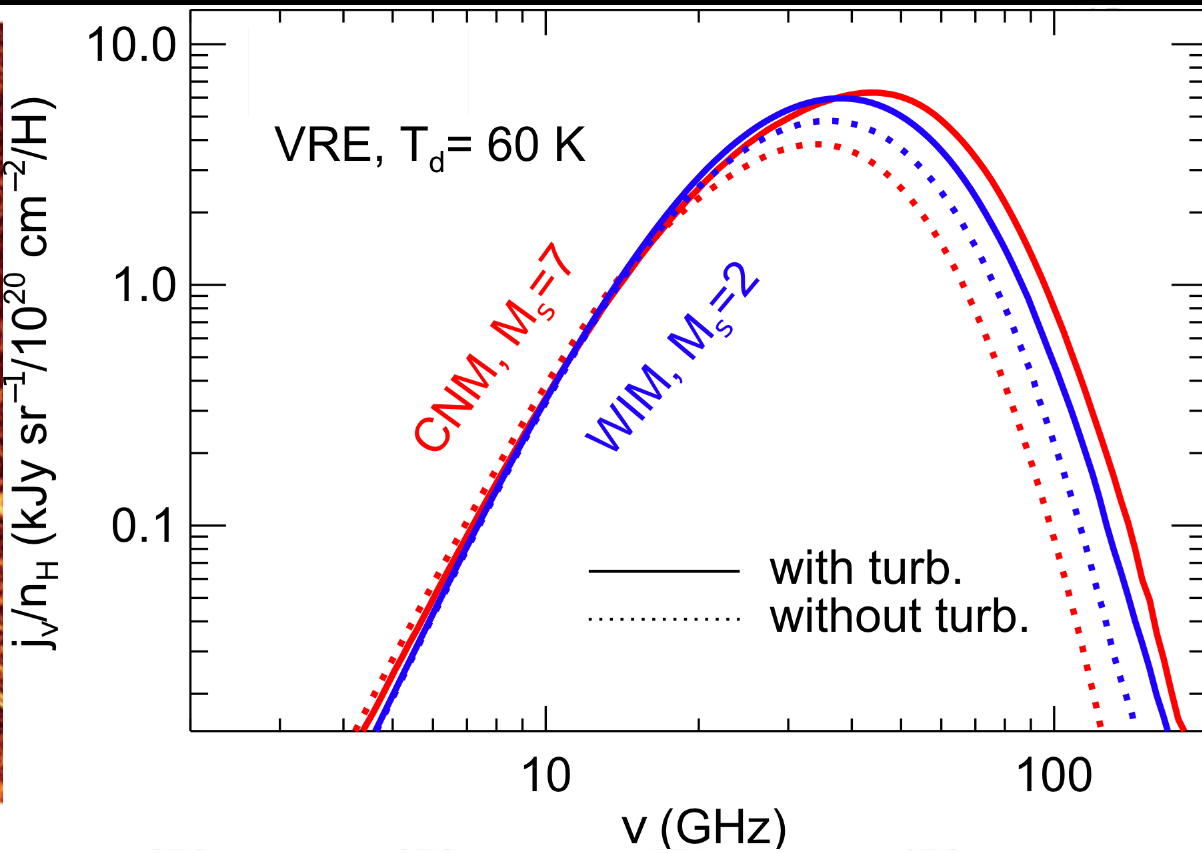
# Transient spin-up by single-ion collisions Extends Spectrum to High Frequency



# Compressible turbulence enhances emissivity

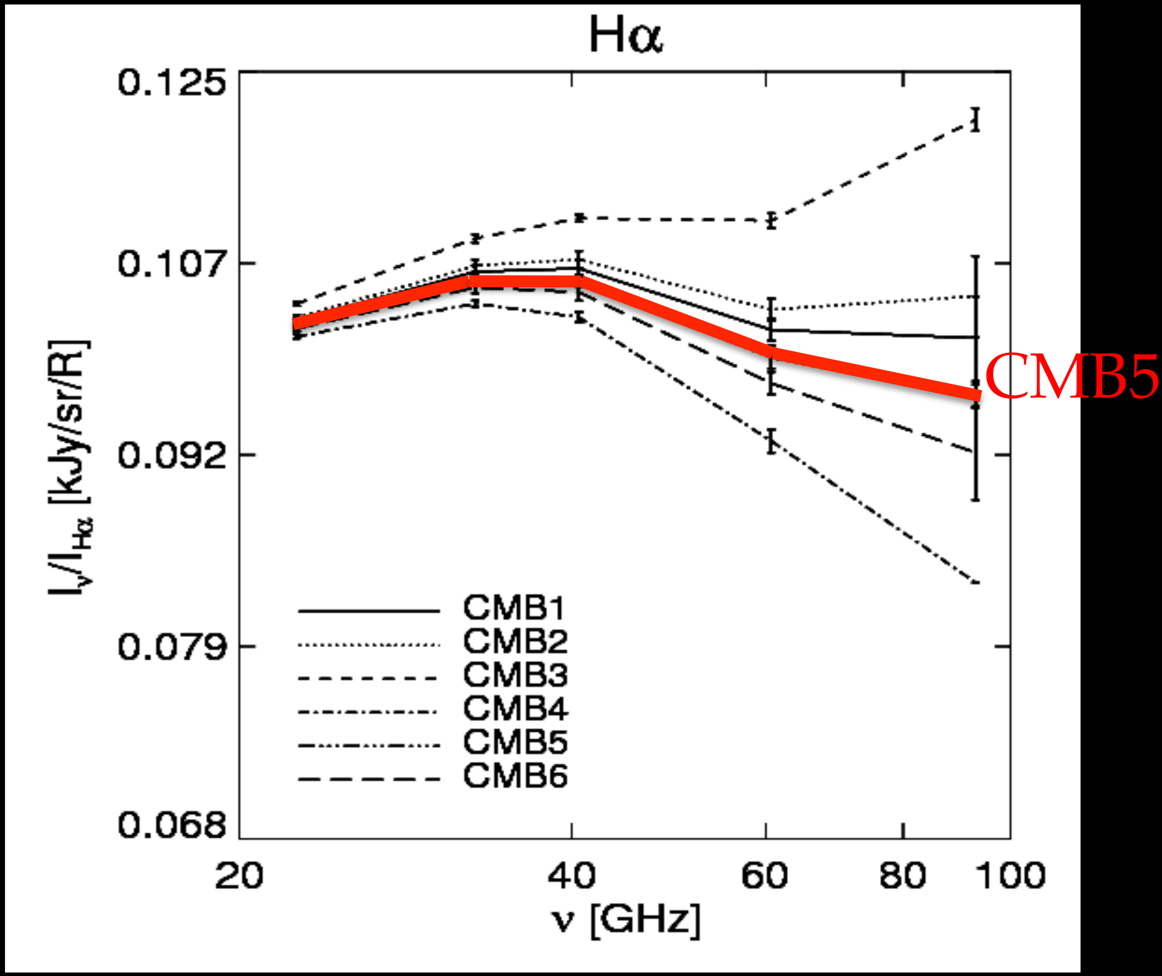



Gaensler et al. 2011, Nature

★ Emissivity increases with the amplitude of turbulence

# Probing Physical Parameters with Observation data




Dobler, Draine & Finkbeiner 2009

# Fitting WMAP Hα-correlated spectrum

- Model: $$I_\nu^{\rm mod} = F_0\left(\frac{\nu}{23{\rm GHz}}\right)^{-0.12} + Sd_0\left[\frac{I_\nu^{\rm sd}}{I_{\rm H\alpha}}\right]_{\rm WIM} + C_0\left(\frac{\nu}{23{\rm GHz}}\right)^2$$

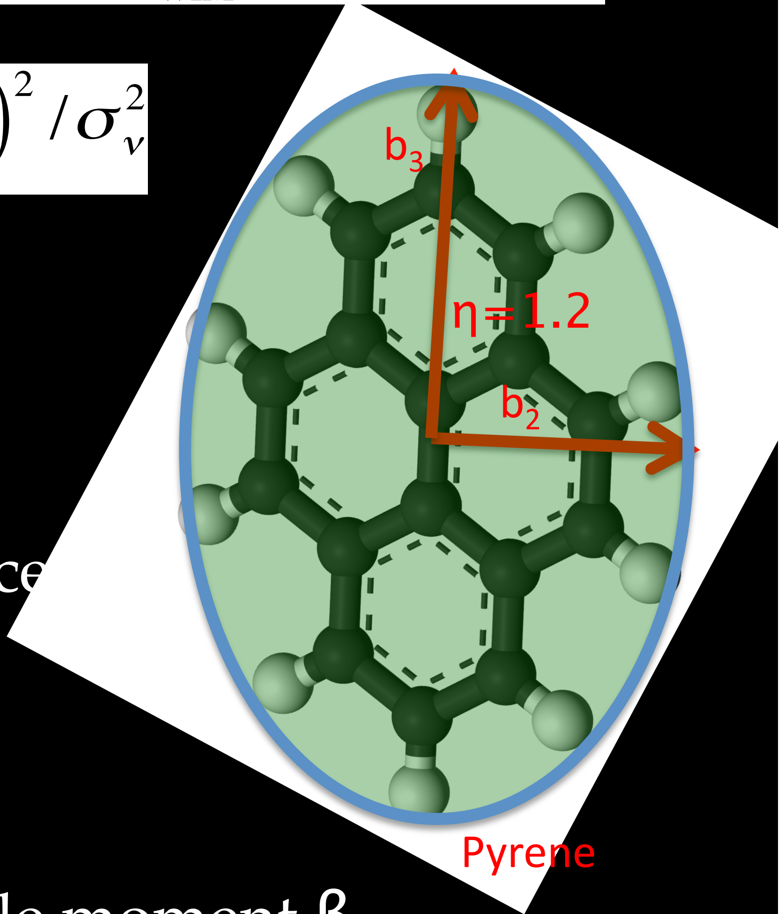
- Minimizing $$\chi^2 = \sum_\nu \left(I_\nu^{\rm mod} - I_\nu^{\rm obs}\right)^2/\sigma_\nu^2$$

- Fitting parameters:

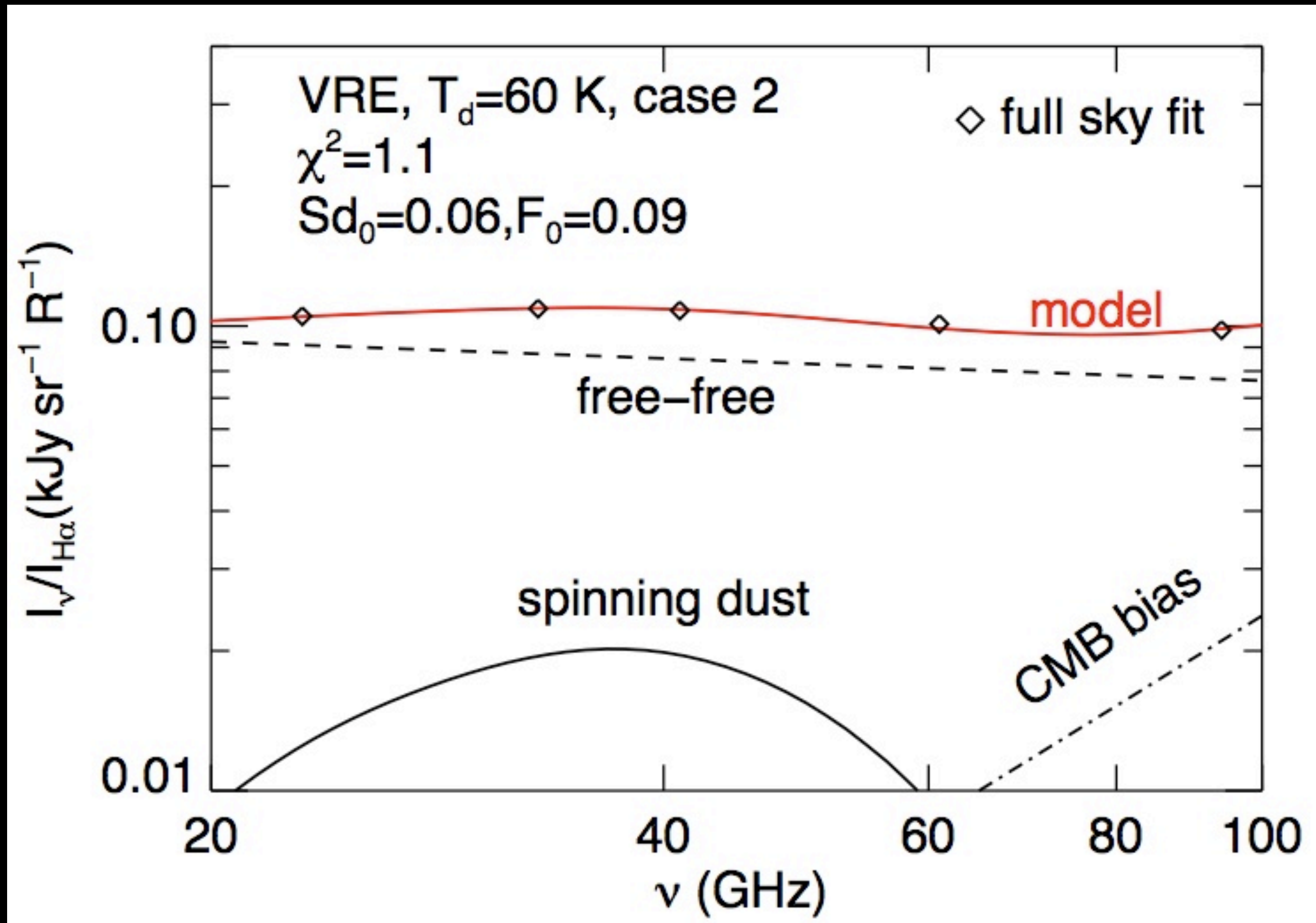
  $F_0$: e temperature

  $Sd_0$: variation of PAH abundance

  $C_0$: CMB estimator bias



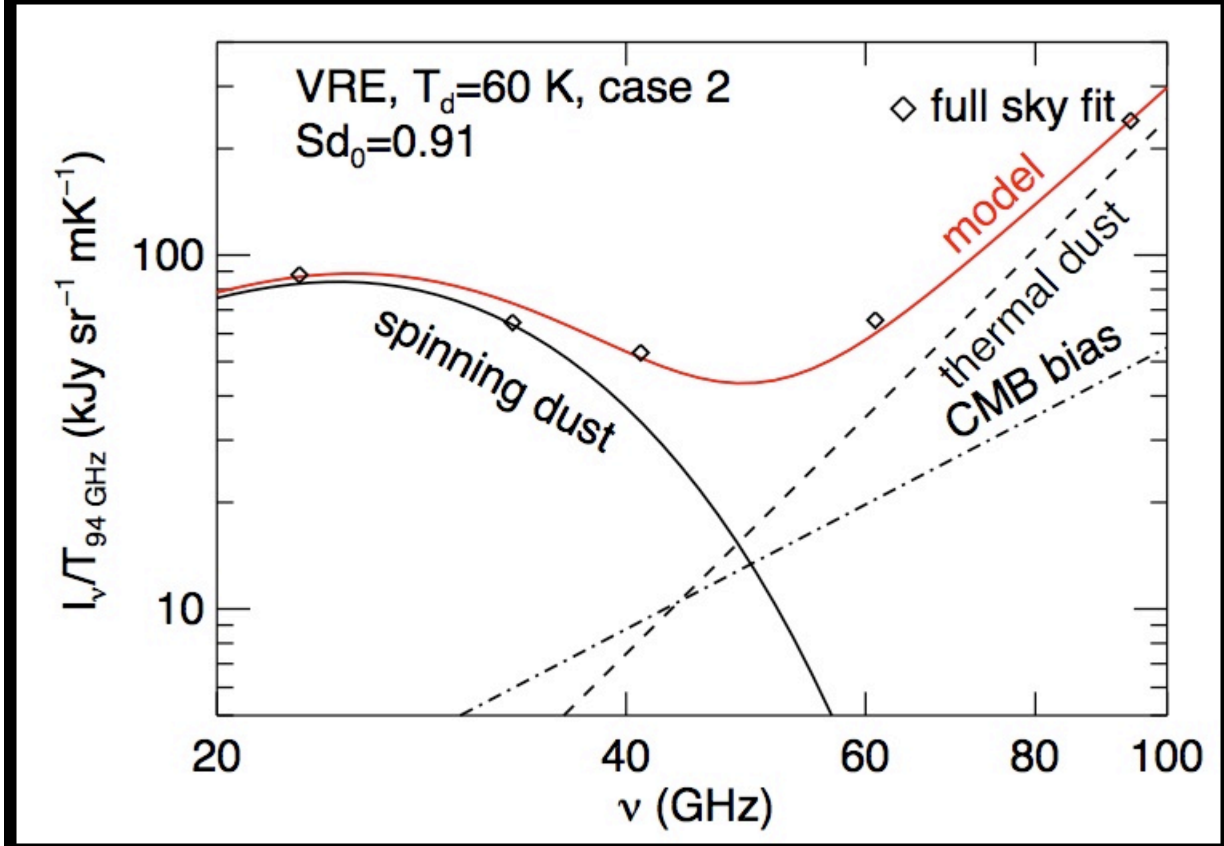

- Spinning dust parameters: $n_H$, dipole moment $\beta_0$




- ★ $F_0$=0.09 ➔$T_e$~ 2500K (Dong & Draine 2011 explain low $T_e$)
- ★ $Sd_0$=0.06 ➔PAH depleted in WIM
- ★ Dipole $\beta_0$~ 0.65 D, $n_H$ ~0.11 $cm^{-3}$

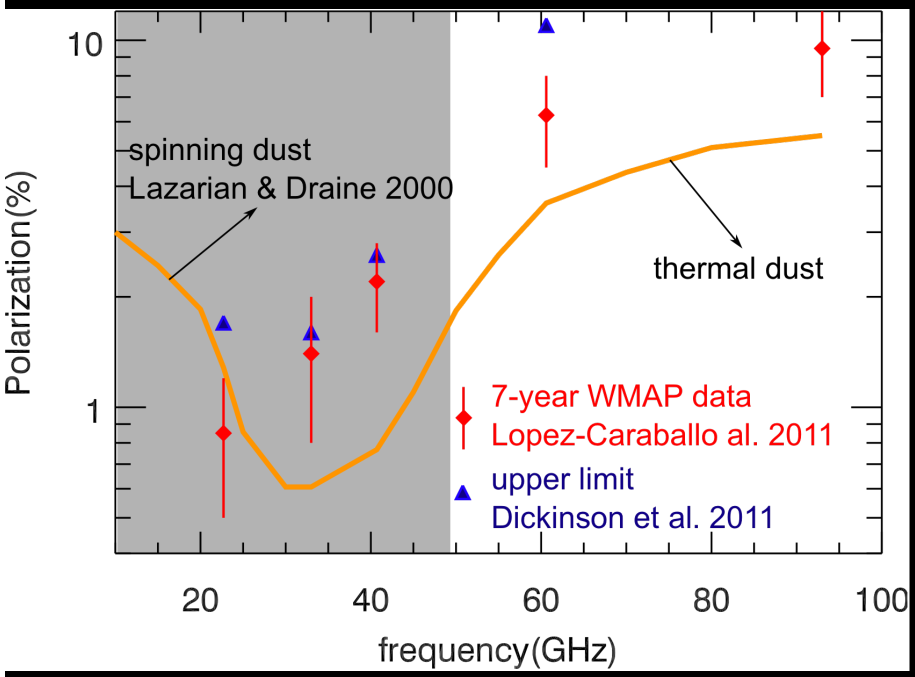
# Thermal Dust-Correlated Spectrum

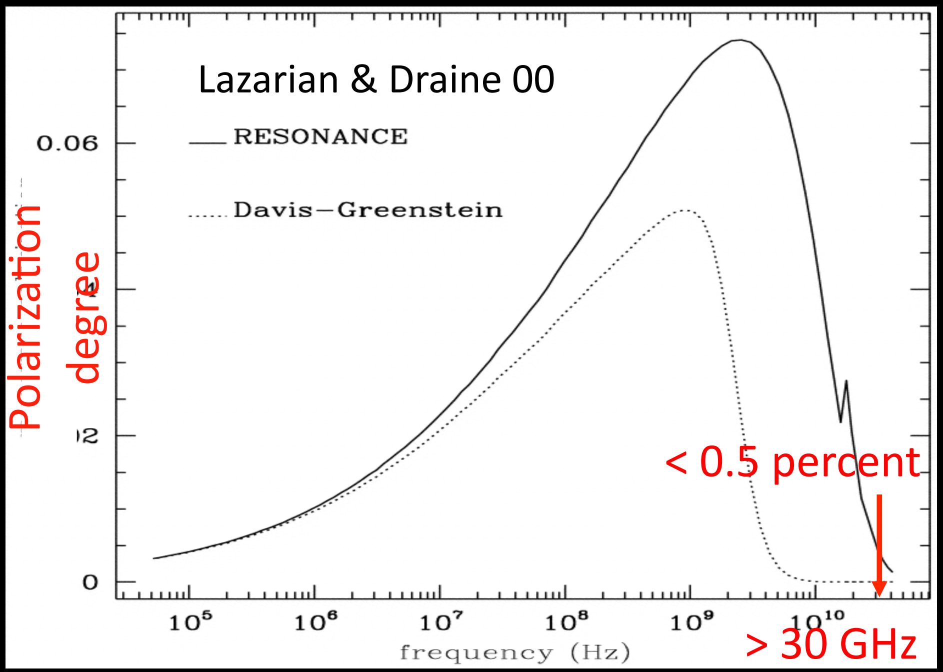
$$\frac{I_\nu^{\mathrm{mod}}}{T_{94\,\mathrm{GHz}}} = Sd_0 \frac{I_\nu^{\mathrm{sd}}(\mathrm{CNM})}{T_{94\,\mathrm{GHz}}} + T_0\left(\frac{\nu}{94\mathrm{GHz}}\right)^{3.8} + C_0\left(\frac{\nu}{23\mathrm{GHz}}\right)^{2}$$




- ★ $T_0$=0.8
- ★ $Sd_0$ ~ 0.9
- ★ $\beta_0$=0.95 D
- ★ $n_H$ ~10 cm$^{-3}$

# Spinning Dust Emission is Polarized!?




Recent studies: P ~ 1. - 5% for AME

Lazarian & Draine (2000): upper limit <observation data

*This difference should be clarified!*

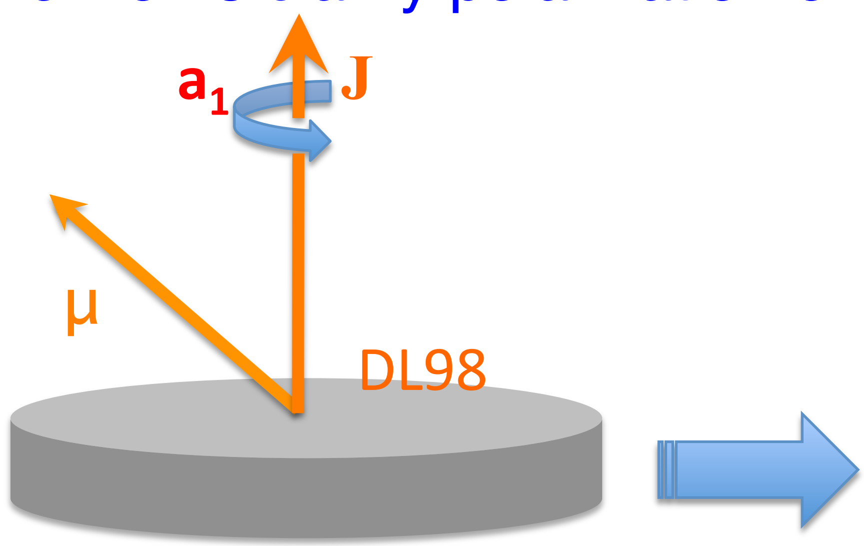
# Summary and Future Works

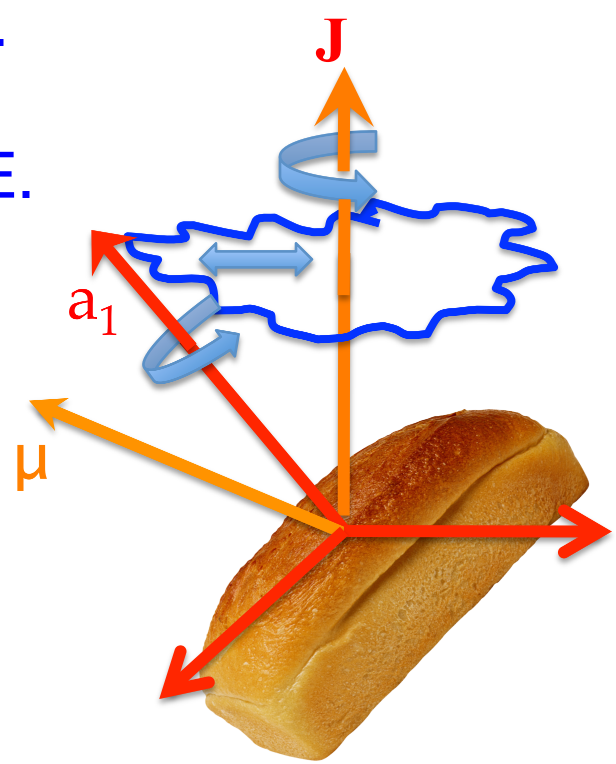
1. Improved model accounts for internal relaxation, grain wobbling, irregular shape, transient events, and turbulence.

2. Improved model can reproduce high peak frequency in Hα-correlated spectrum from WMAP data.

3. Improved model can be used to diagnose dust physical parameters using WMAP, Planck data.

4. Future works clarify polarization of AME.



# Thank You Very Much!