Quantum Suppression of Alignment in Spinning Nanoparticles

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- **Davis-Greenstein Alignment by Magnetic Dissipation**
- **Suppression of Dissipation in Cold Nanoparticles**
- **Alignment vs. Grain Size**
- **Predicted Polarization vs. Frequency**

Davis-Greenstein Alignment by Magnetic Dissipation

- Grain spinning in static $\mathbf{B}_0$
  θ = angle beween $\mathbf{J}$ and $\mathbf{B}_0$
- Grain material tries to magnetize
- In grain frame:
  - Rotating component $\mathbf{B}_0 \sin\theta$
  - Magnetization $\mathbf{M}$ lags
- torque $\mathbf{M} \times \mathbf{B}_0$ on grain
  Reduces component of $\mathbf{J} \perp \mathbf{B}_0$
  Leaves component of $\mathbf{J} \parallel \mathbf{B}_0$ unchanged
  $\rightarrow$ alignment of $\mathbf{J}$ with $\mathbf{B}_0$
- If $\mathrm{Im}(\chi) = K\omega$, then
  Davis-Greenstein alignment time

$$\tau_{\rm DG} = \frac{2\rho a^2}{5KB_0^2} \propto \frac{a^2}{K}$$

vs. disalignment time (time to collide with own mass of gas)

$$\tau_{\rm M} \propto a$$

Hence:

$$\frac{\tau_{\rm DG}}{\tau_{\rm M}} \propto \frac{a}{K}$$

Naive DG theory:
for standard estimate of

$$K \approx \frac{1\times 10^{-13}\,{\rm s}}{T_{gr}/18\,{\rm K}}$$

small grains should be aligned.

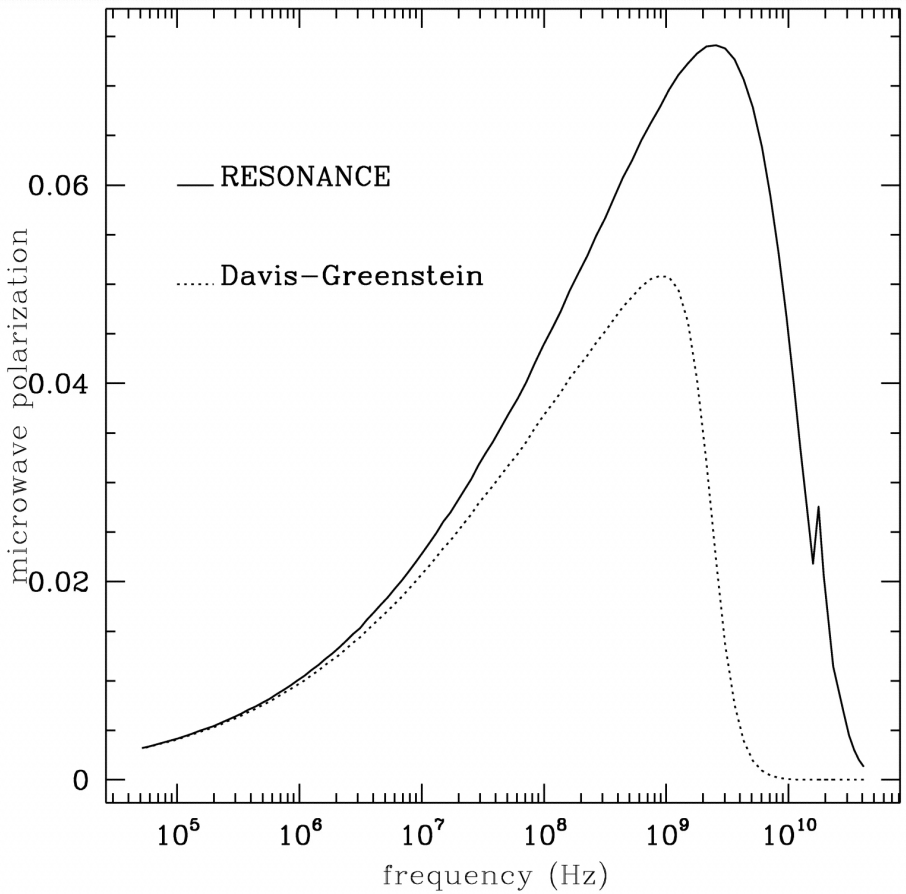
Alignment is result of *dissipation*:

J^2 is *reduced*:
rotational KE is converted to **heat**

Dissipation in Nanoparticles

Lazarian & Draine (2000):

- *Need to dissipate $\hbar\omega_{\rm rot}$ as heat.*
- *When nanoparticle is in very low vibrational level, there are no other vibrational states within $\Delta E = \hbar\omega_{\rm rot}$:*
- *Quantization of low-lying vibrational modes leads to suppression of paramagnetic dissipation in small nanoparticles.*



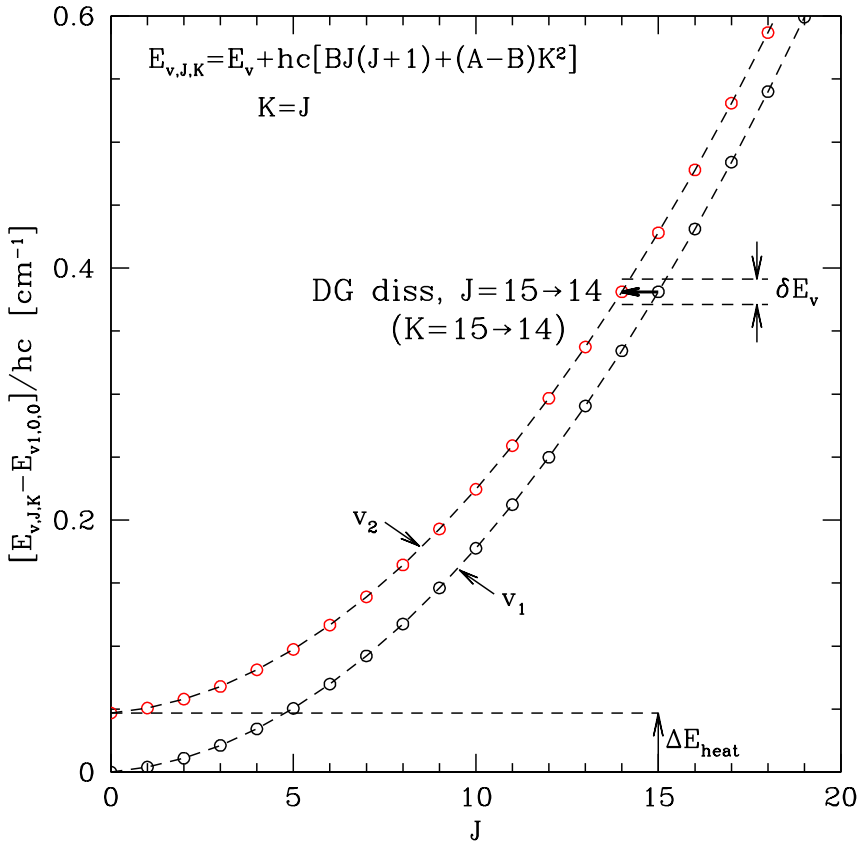
Prediction: $P \lesssim 4\%$ at $\nu > 10\,{\rm GHz}$

Fig. 1a from Lazarian & Draine (2000)

Draine & Hensley (2016): *quantum suppression of dissipation is more severe than estimated by Lazarian & Draine (2000).*

Dissipation in Nanoparticles

"heat" = vibrational KE in grain
Dissipation of rotational KE requires that there be a vibrational transition that can "accept" the energy.



The two energy levels must coincide to within energy level uncertainty δE_v

Energy level uncertainty δE_v from

- spontaneous emission
- collisions

For $T_{\rm vib} \lesssim 100\,{\rm K}$, δE_v is very small:

$$\frac{\delta E_v}{hc} \lesssim 10^{-12}\,{\rm cm}^{-1}$$

What is the probability that another energy level will exist within energy δE_v of the first level?

Vibrational Density of States in Nanoparticles

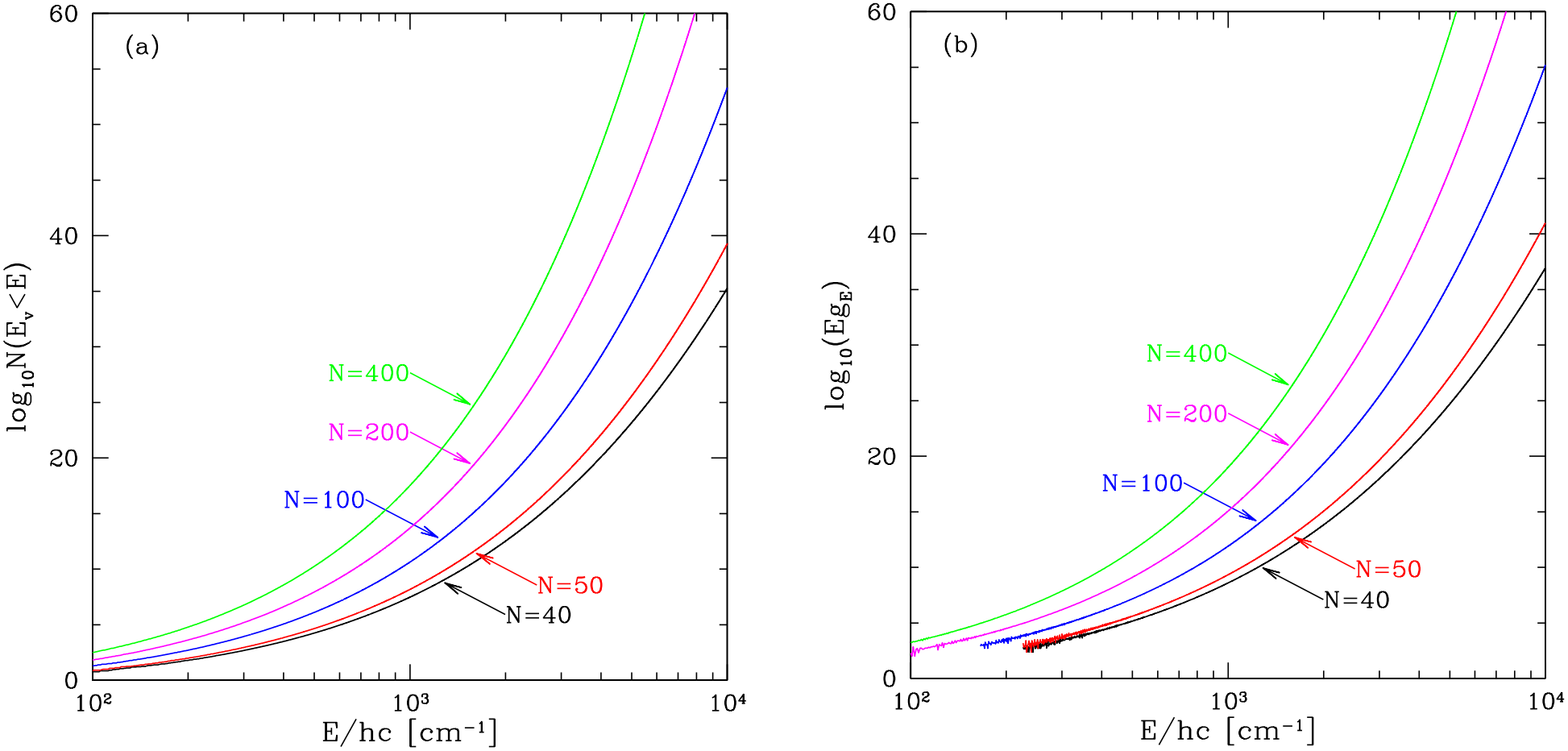
Nanoparticle with N atoms: $3N - 6$ vib. modes.

Each mode: harmonic oscillator with fundamental ω_j.

Directly calculate $N_v(E) \equiv$ number of *distinct* vibrational states with *total* vibrational energy $< E$.

Density of states $g_E \equiv dN_v/dE$

Plot of Eg_E



Examples assuming fundamental mode spectra for amorphous silicates

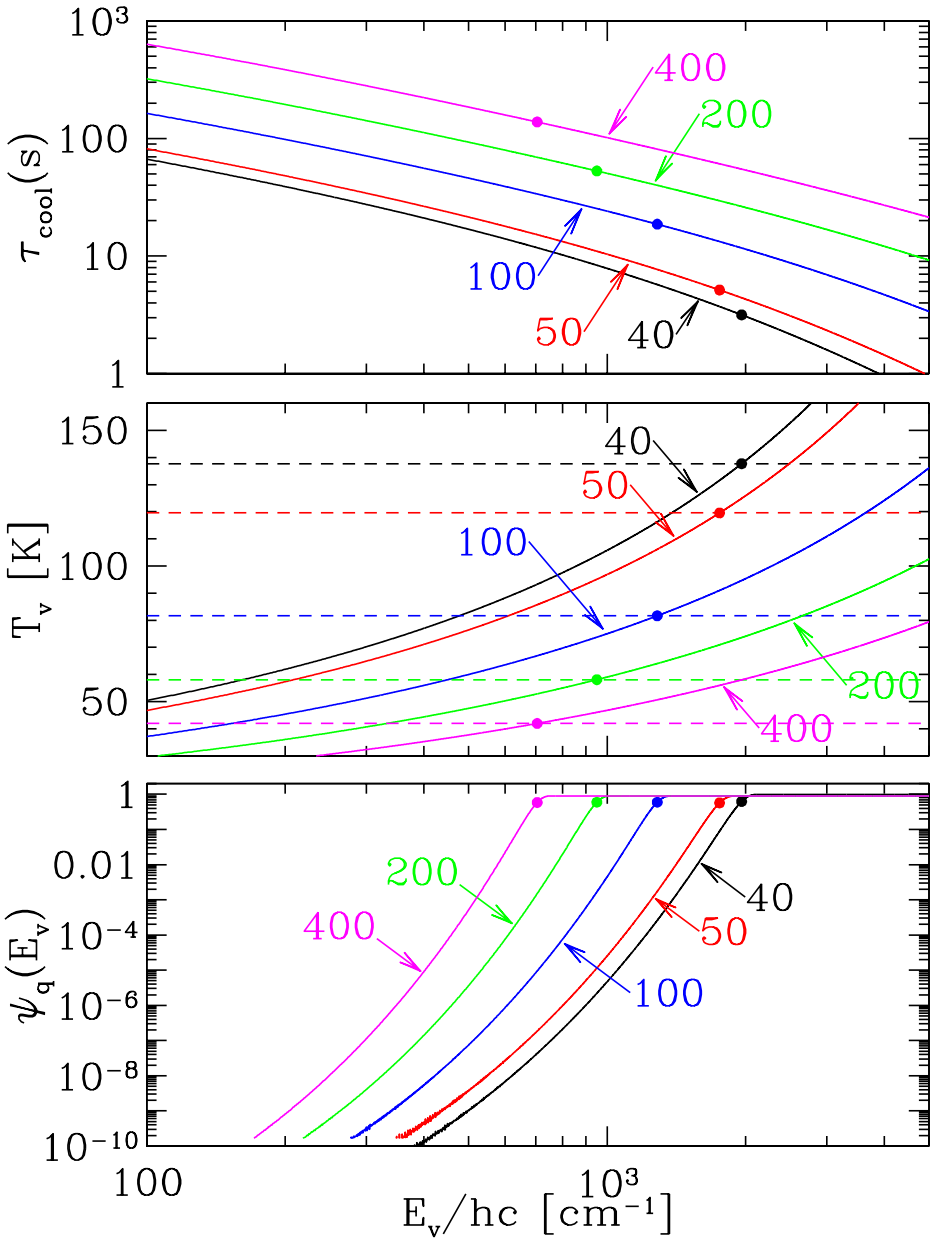
Quantum Suppression Factor ψ_q

Cooling time

Vibrational Temperature

Probability of one or more levels in interval δE

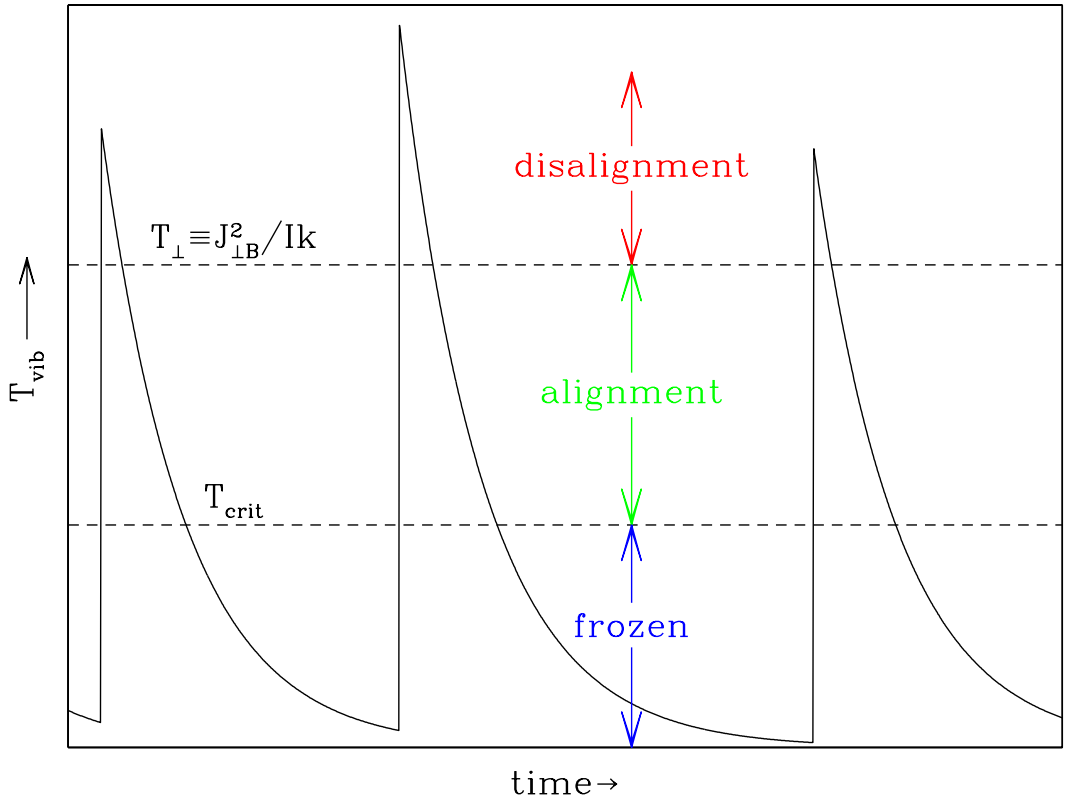
$$\psi_q(E) = 1 - \exp(-\delta E \times g_E)$$



$E_v \equiv$ vibrational energy

Time-Averaged Quantum Suppression Factor

- Stochastic heating by starlight: Fluctuating $T_{\rm vib}(t)$.
- When grain is "hot", magnetic **fluctuations** dominate magnetic dissipation: magnetic torques act to *increase* $\mathbf{J} \perp \mathbf{B}_0$
  $\rightarrow$ *disalignment*
- Intermediate $T_{\rm vib}$: magnetic **dissipation**: magnetic torques act to *decrease* $\mathbf{J} \perp \mathbf{B}_0$
  $\rightarrow$ *alignment*
- Low temperatures: dissipation suppressed: alignment is "frozen"



Steady-State Rotational Excitation and Alignment

Excitation and damping of grain rotation by

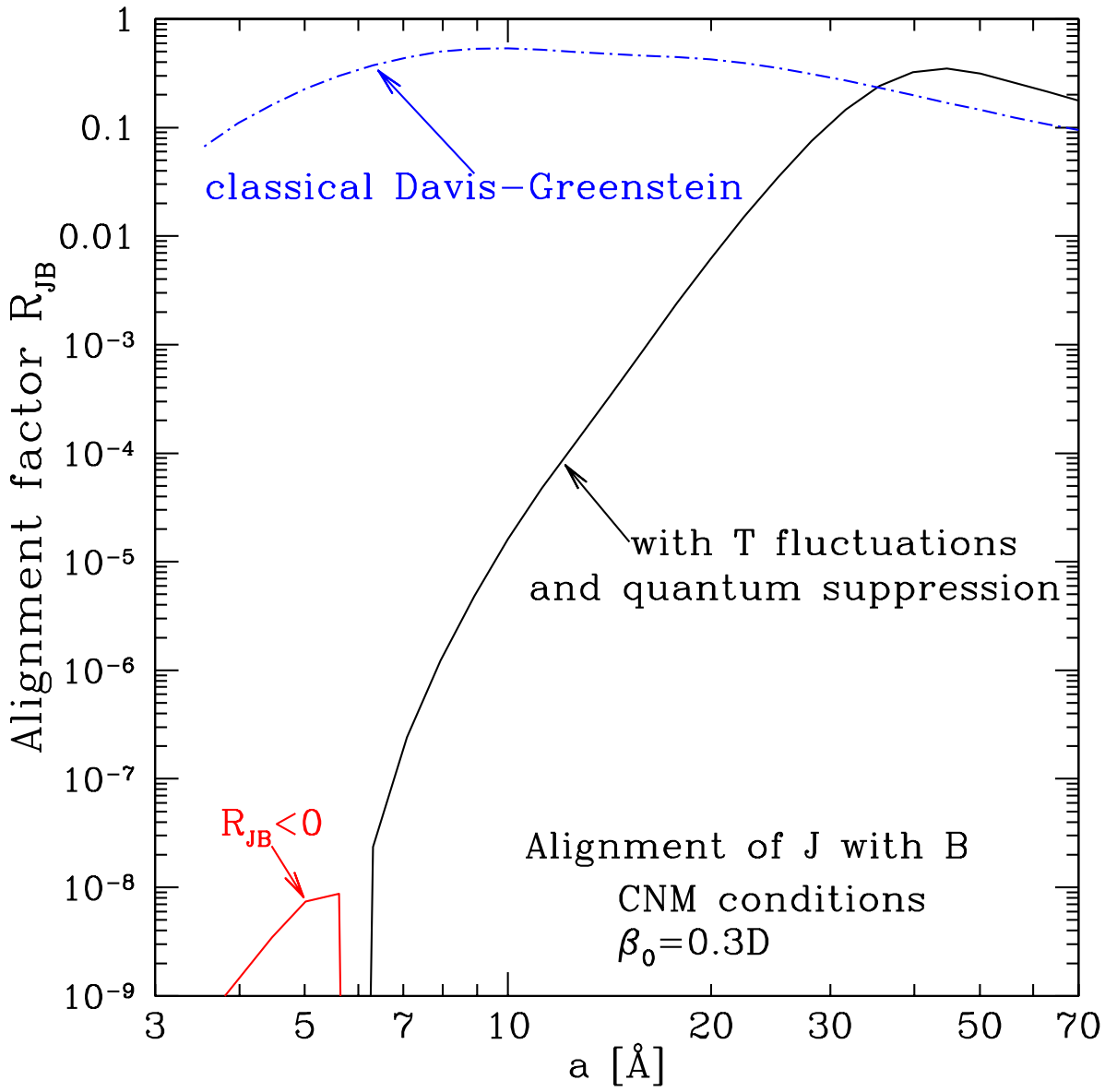
- collisions
- "plasma drag"
- absorption of starlight
- emission of IR photons
- rotational emission
- paramagnetic dissipation

Find rotation $\| \mathbf{B}_0$ and $\perp \mathbf{B}_0$:

$$\langle \cos^2\theta \rangle = \frac{\langle J_\parallel^2 \rangle}{(\langle J_\parallel^2 \rangle + \langle J_\perp^2 \rangle)}$$

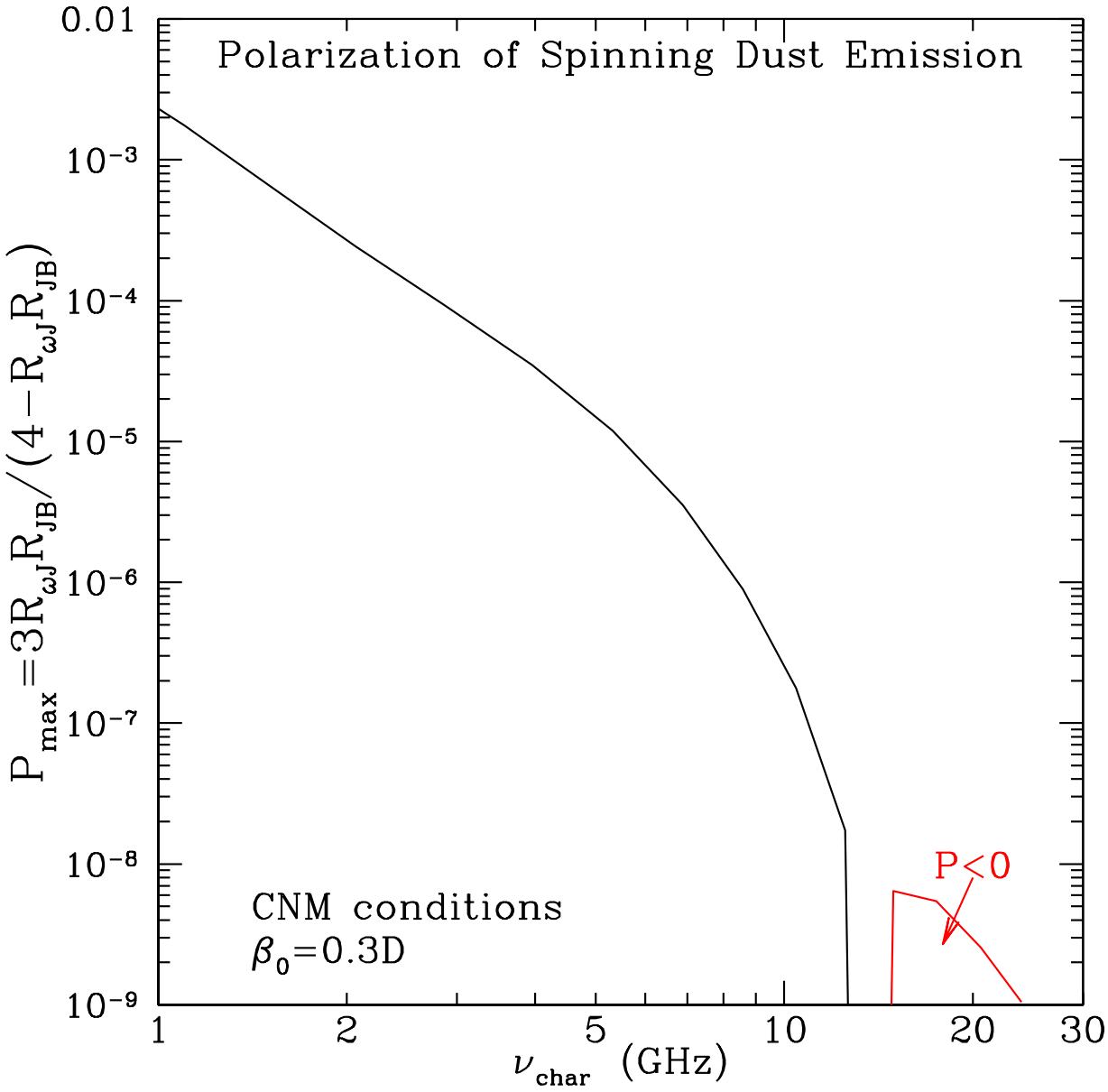
Alignment measure:

$$R_{\rm JB} \equiv {}^3\!/_2 \left(\langle \cos^2\theta \rangle - {}^1\!/_3 \right)$$

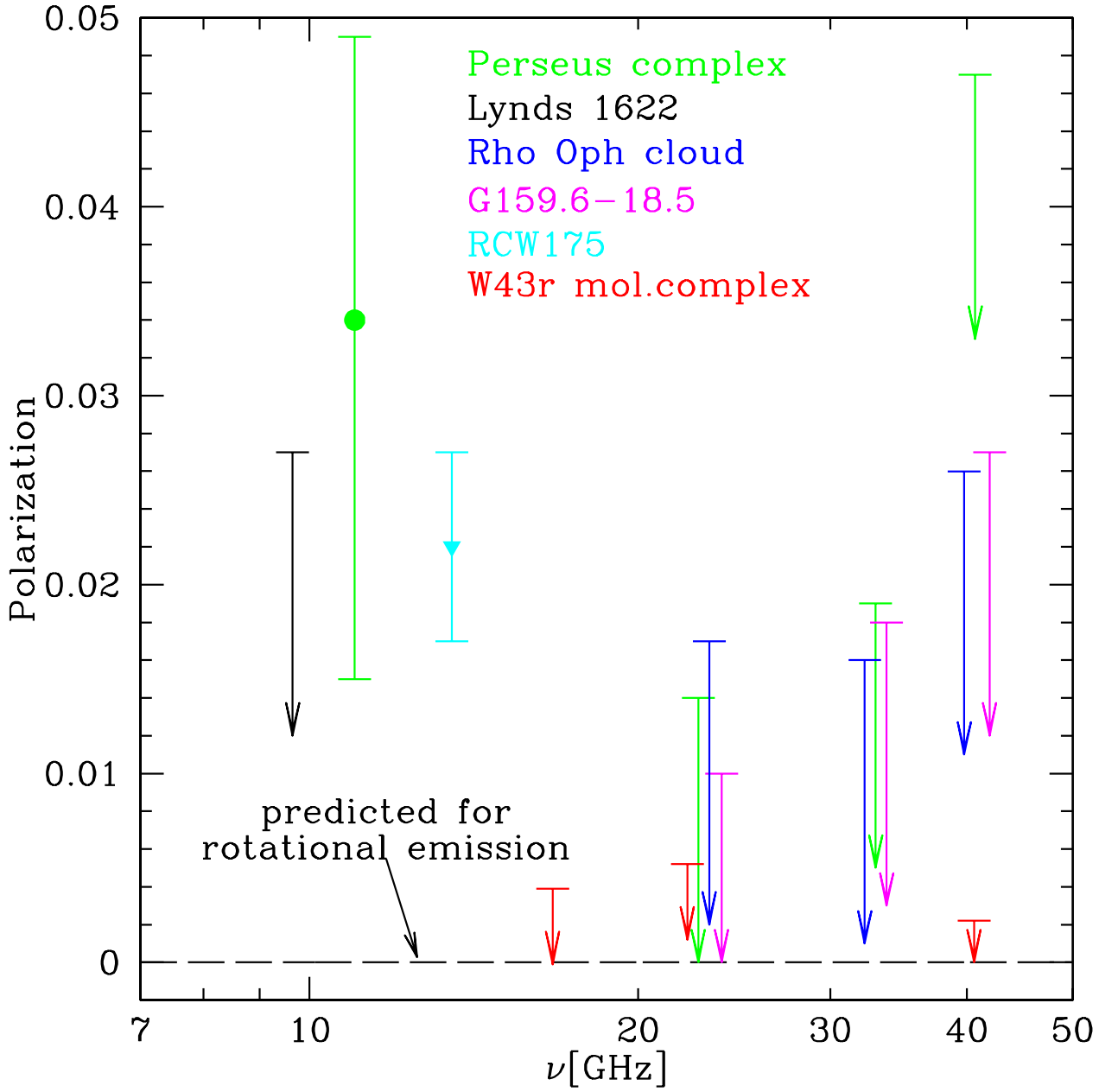


Polarization of Rotational Emission

- Observer's line-of-sight $\perp \mathbf{B}_0$
- Assume each size to spin at characteristic frequency $\langle\omega^4\rangle^{1/4}$
- Allow for imperfect alignment of $\boldsymbol{\omega}$ with $\mathbf{J}$ ($R_{\boldsymbol{\omega}\mathbf{J}} \approx 0.9$)



Observations



Perseus mol. complex: Battistelli et al. (2006), Dickinson et al. (2011)

Lynds 1622: Mason et al. (2009)

ρ Oph: Dickinson et al. (2011)

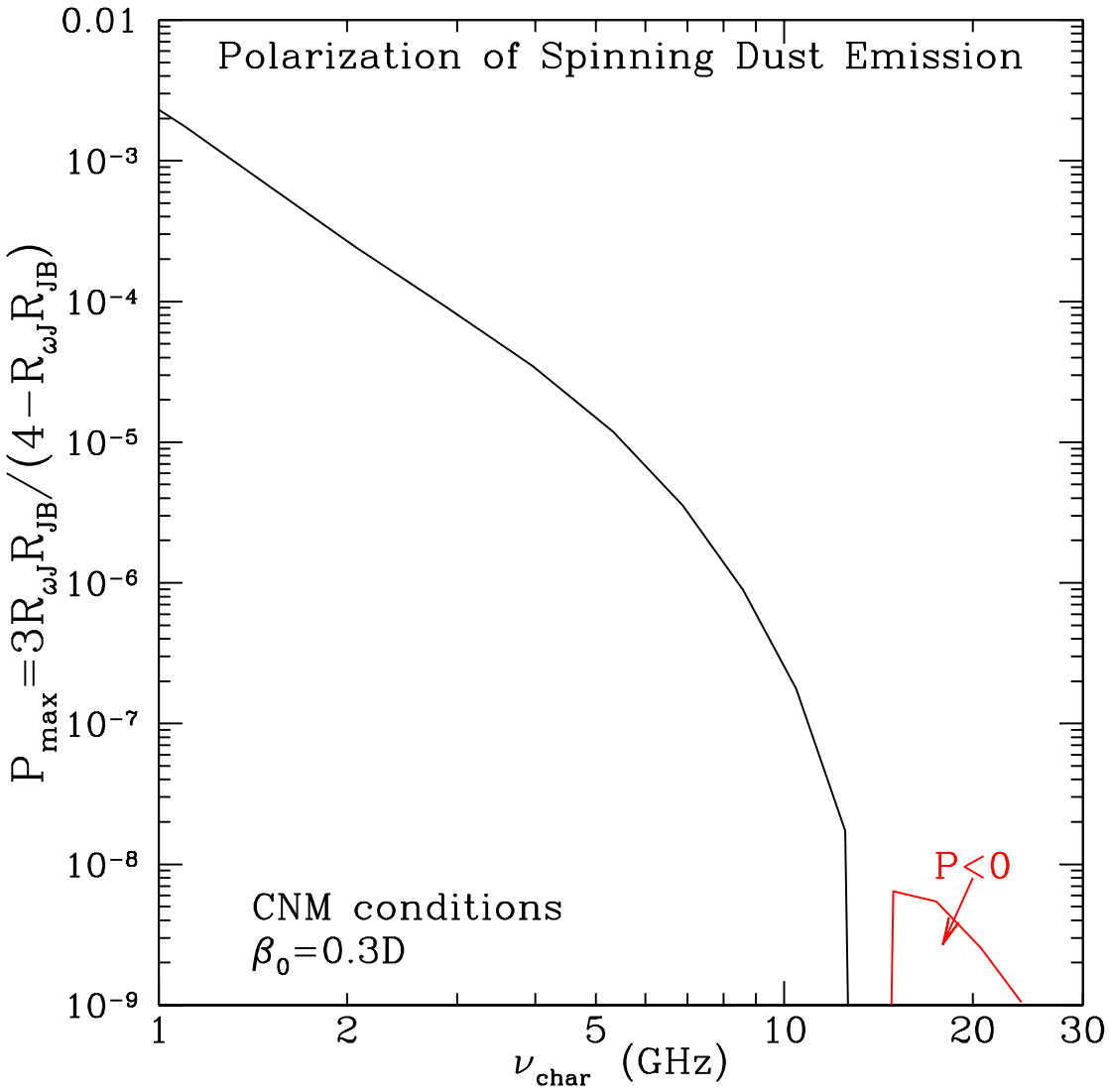
G159.6-18.5: López-Caraballo et al. (2011), Génova-Santos et al. (2016)

RCW175: Battistelli et al. (2015)

W43r mol. complex: Génova-Santos et al. (2016)

Summary

- Quantization of vibrational energy levels $\rightarrow$ suppression of dissipation in very small, cold nanoparticles.
- Suppression of dissipation $\rightarrow$ suppression of alignment of $\mathbf{J}$ with $\mathbf{B}_0$
- Emission from $a \lesssim 10\,\text{Å}$ nanoparticles will be negligibly polarized.




THANK YOU

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