Anomalous Microwave Emission from Spinning Dust and Polarization Spectrum

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Stiftung/Foundation

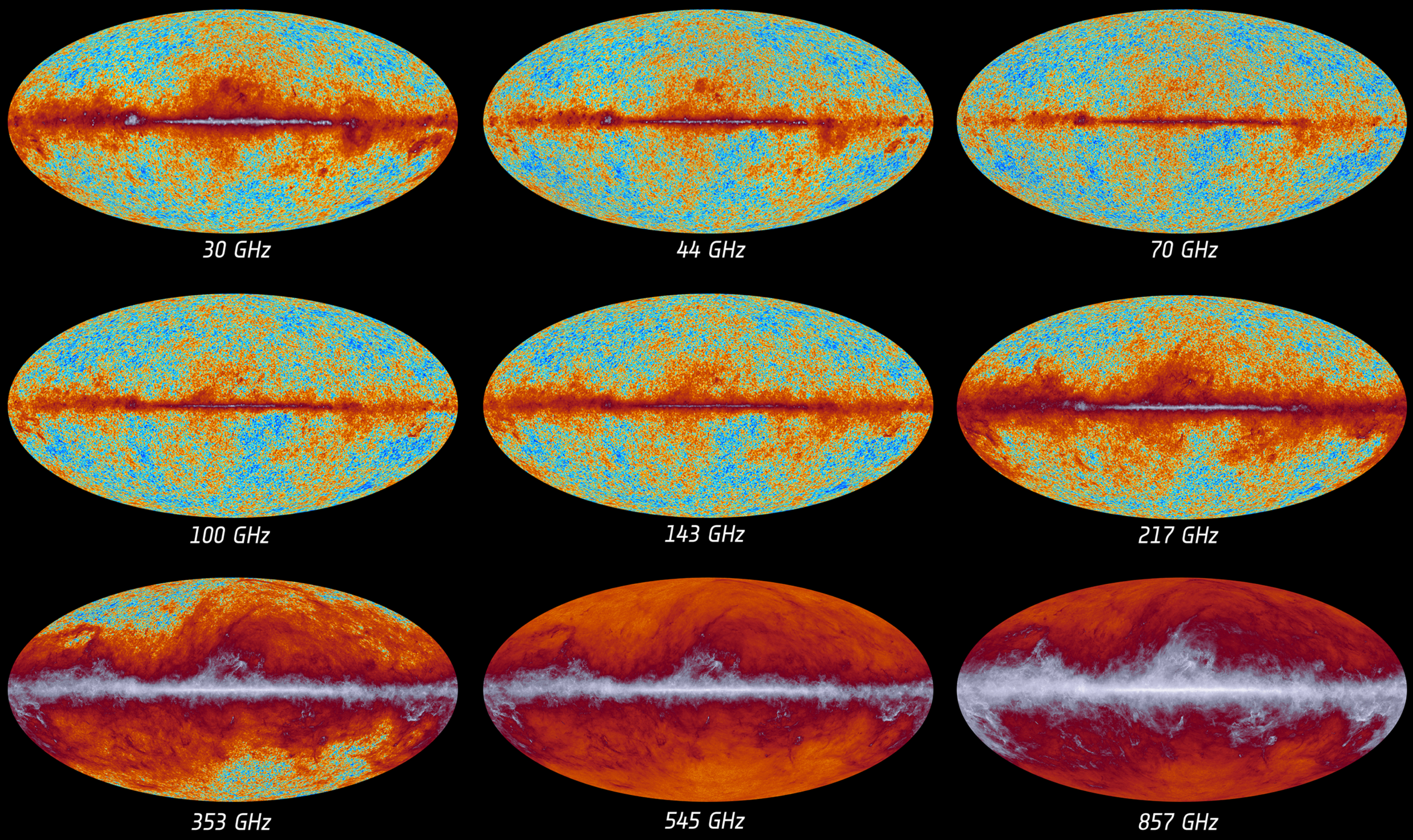
Outline

- Motivation: From Dust to Dawn
- Anomalous Microwave Emission and Spinning Dust
- Original Model, Modern Model, and Observations
- Polarization: Theory and Observations
- Summary

AME = Anomalous Microwave Emission

Full Sky seen by Planck

The sky as seen by Planck



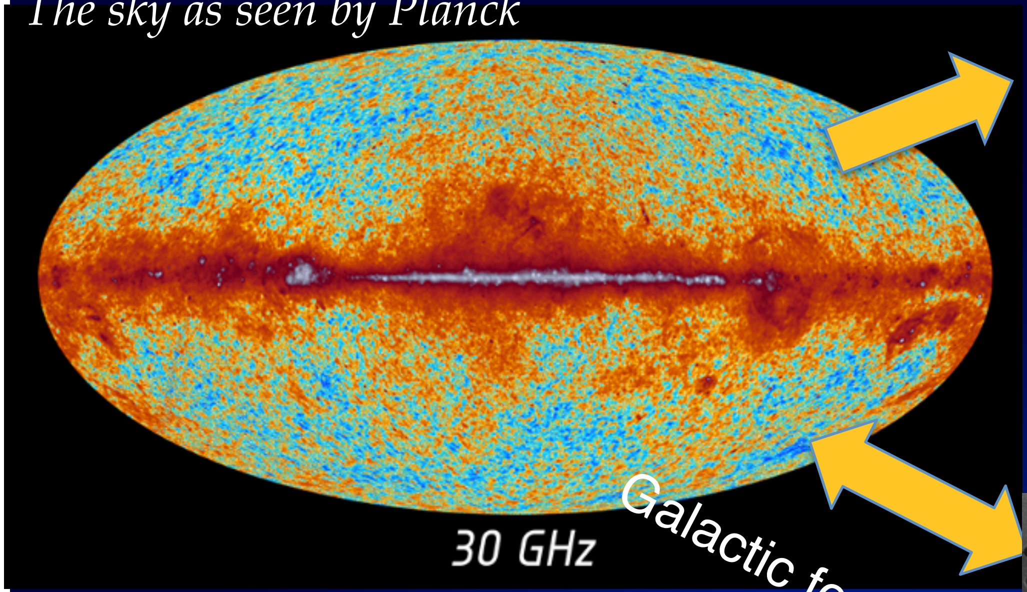
30 GHz 44 GHz 70 GHz

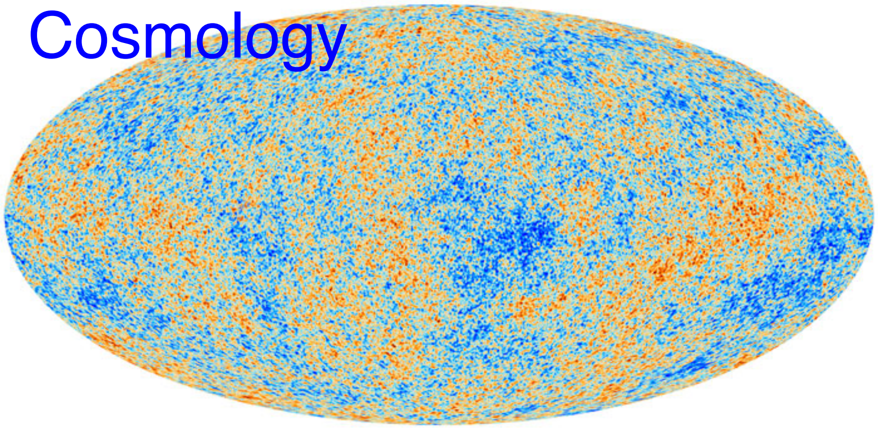
100 GHz 143 GHz 217 GHz

353 GHz 545 GHz 857 GHz

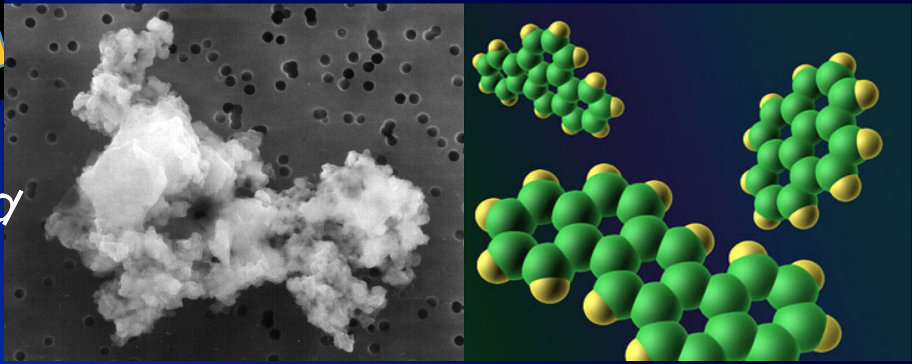
From Dust to Dawn

The sky as seen by Planck



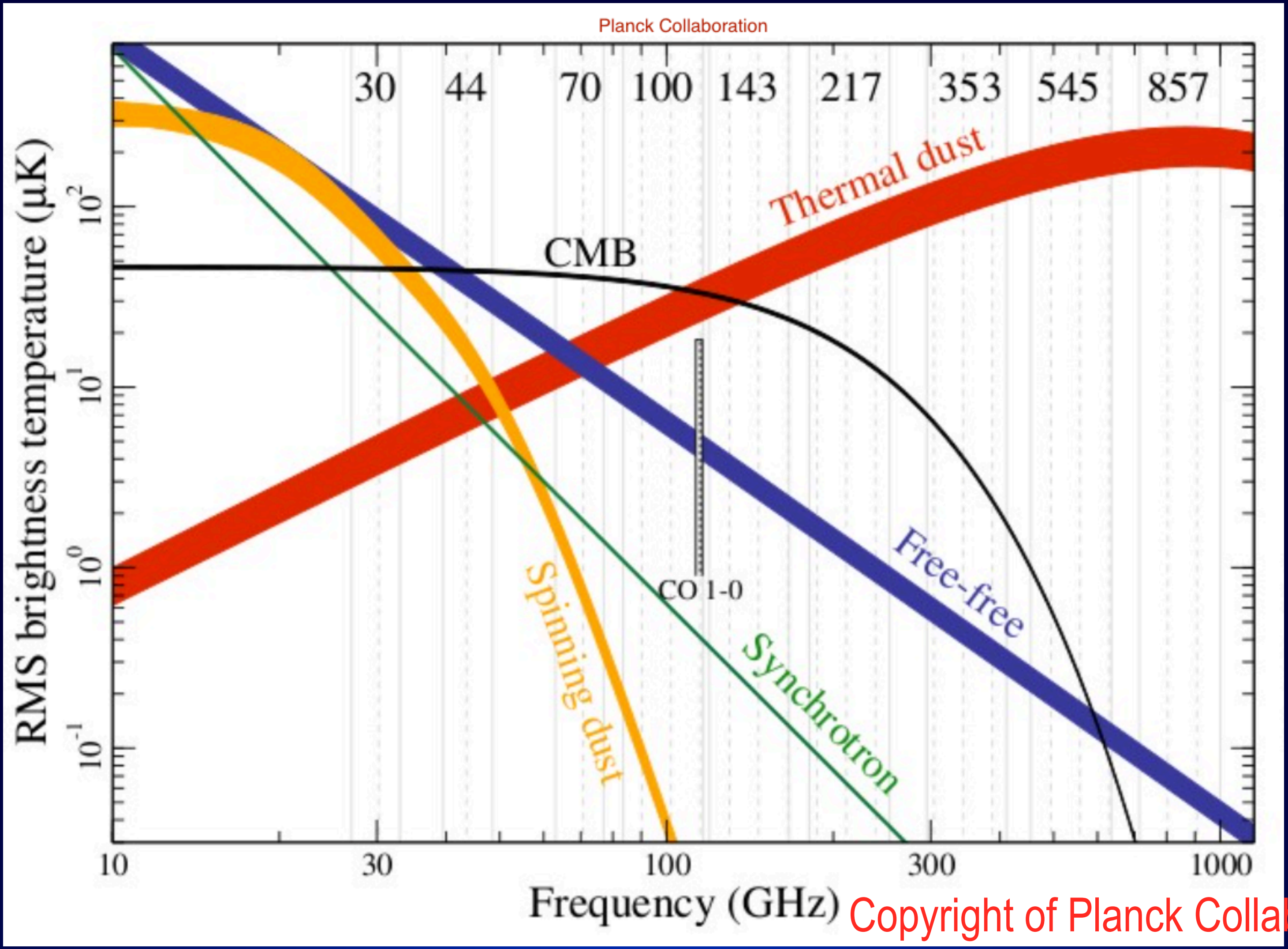


Galactic science



Galactic foreground

Galactic Foreground Components



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New component: Spinning dust emission

Discovery of Anomalous Microwave Emission

- 1996 Kogut et al. found emission excess at 31 GHz.

- 1997 Leitch et al.:
  - *emission excess at 14.5 and 32 GHz*
  - *explained by free-free emission from very hot gas*

- 1998 Draine & Lazarian suggested:
  - Electric dipole emission by spinning ultrasmall grains—PAH (Polycyclic Aromatic Hydrocarbon)

Discovery of Polycyclic Aromatic Hydrocarbon

Leger & Puget 1984

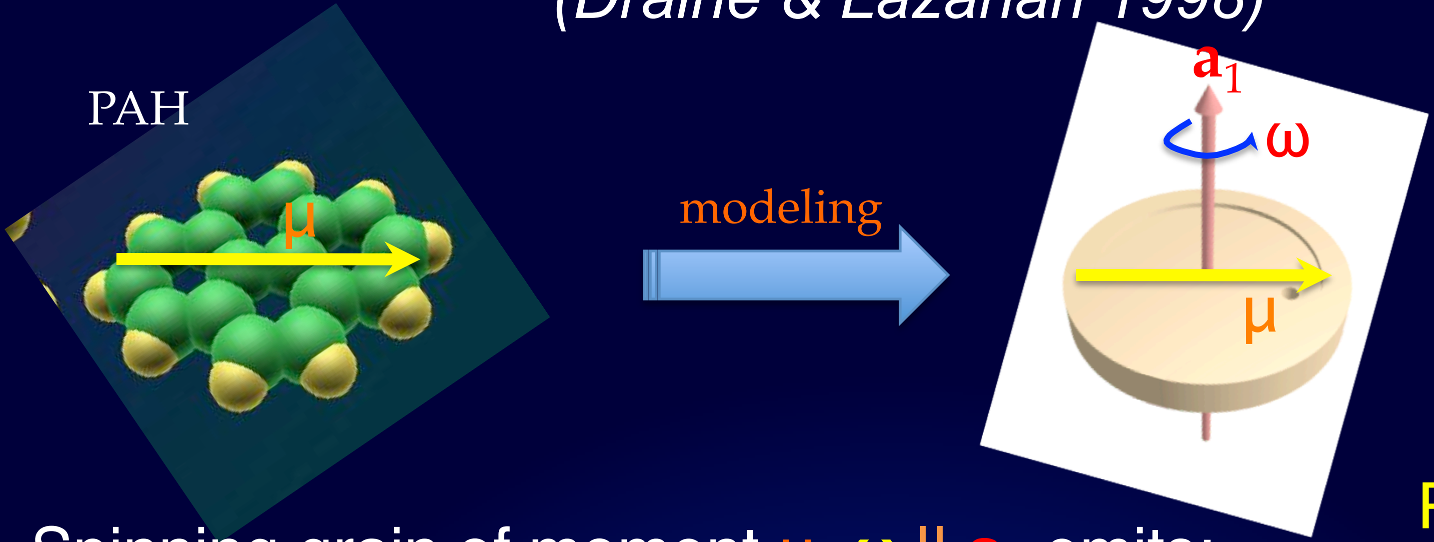
Credit: NASA

PAH: polycyclic aromatic hydrocarbon

PAHs produced by honeycomb coal stove
in Vietnam

Original Spinning Dust Model

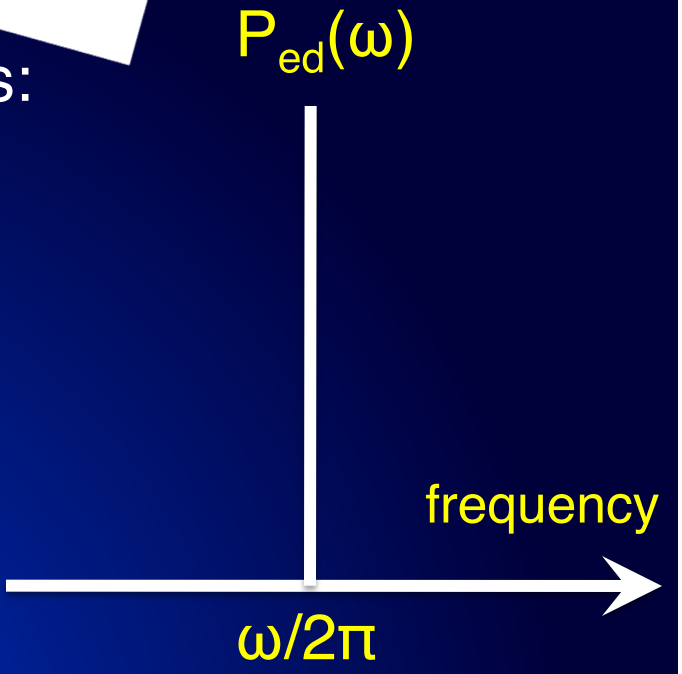
(Draine & Lazarian 1998)



1. Spinning grain of moment μ, **ω** || **$\mathbf{a}_1$** emits:

- unique frequency mode: $$\nu = \frac{\omega}{2\pi}$$

- emission power: $$P_{\mathrm{ed}}(\omega) = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}$$

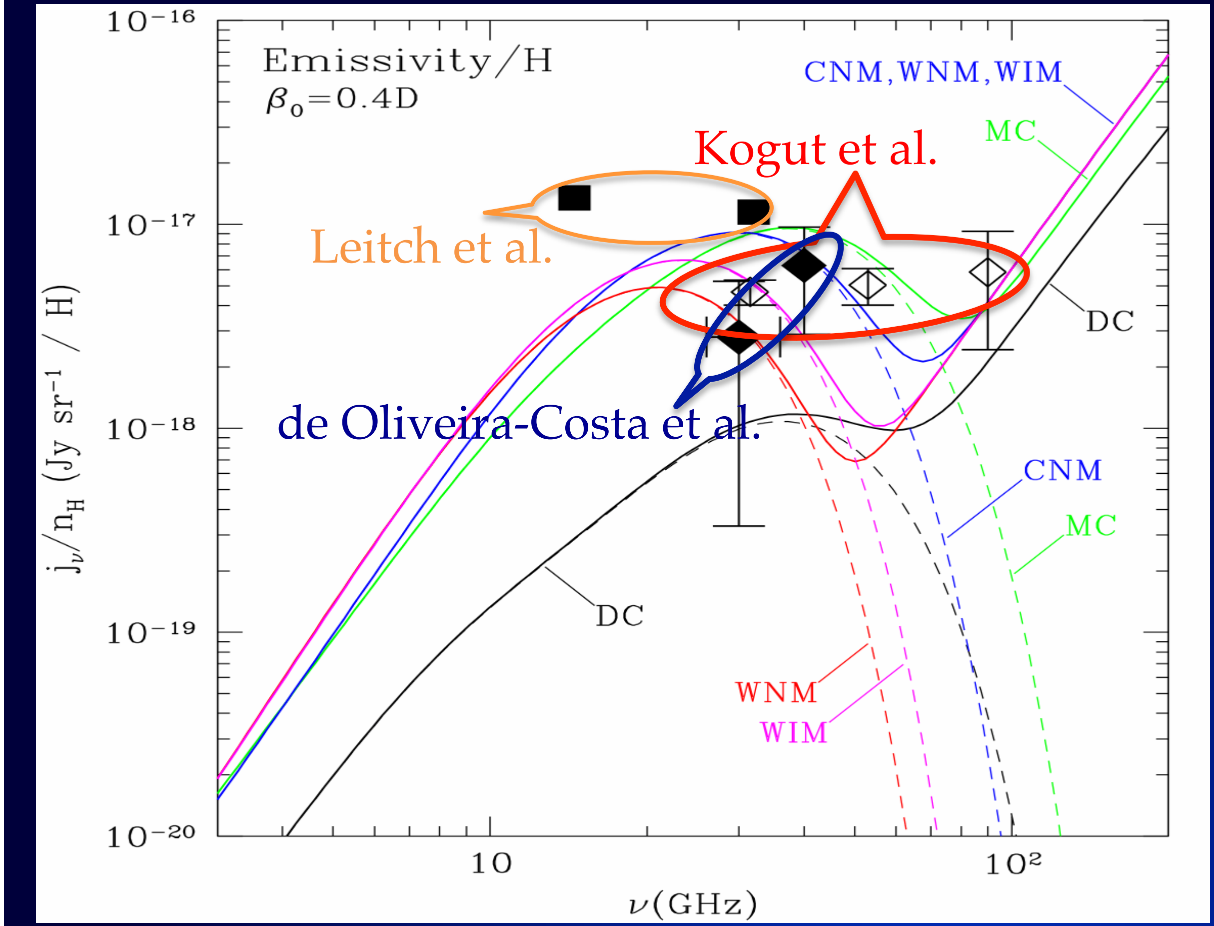


2. ω follows Maxwellian distribution f_ω

Total spinning dust emissivity:

$$\frac{j_\nu}{n_H} = \frac{1}{4\pi}\int_{a_{\min}}^{a_{\max}} da \, \frac{1}{n_{\rm H}}\frac{dn}{da} 4\pi\omega^2 \boxed{f_\omega} 2\pi \boxed{P_{\rm ed}(\omega)}$$

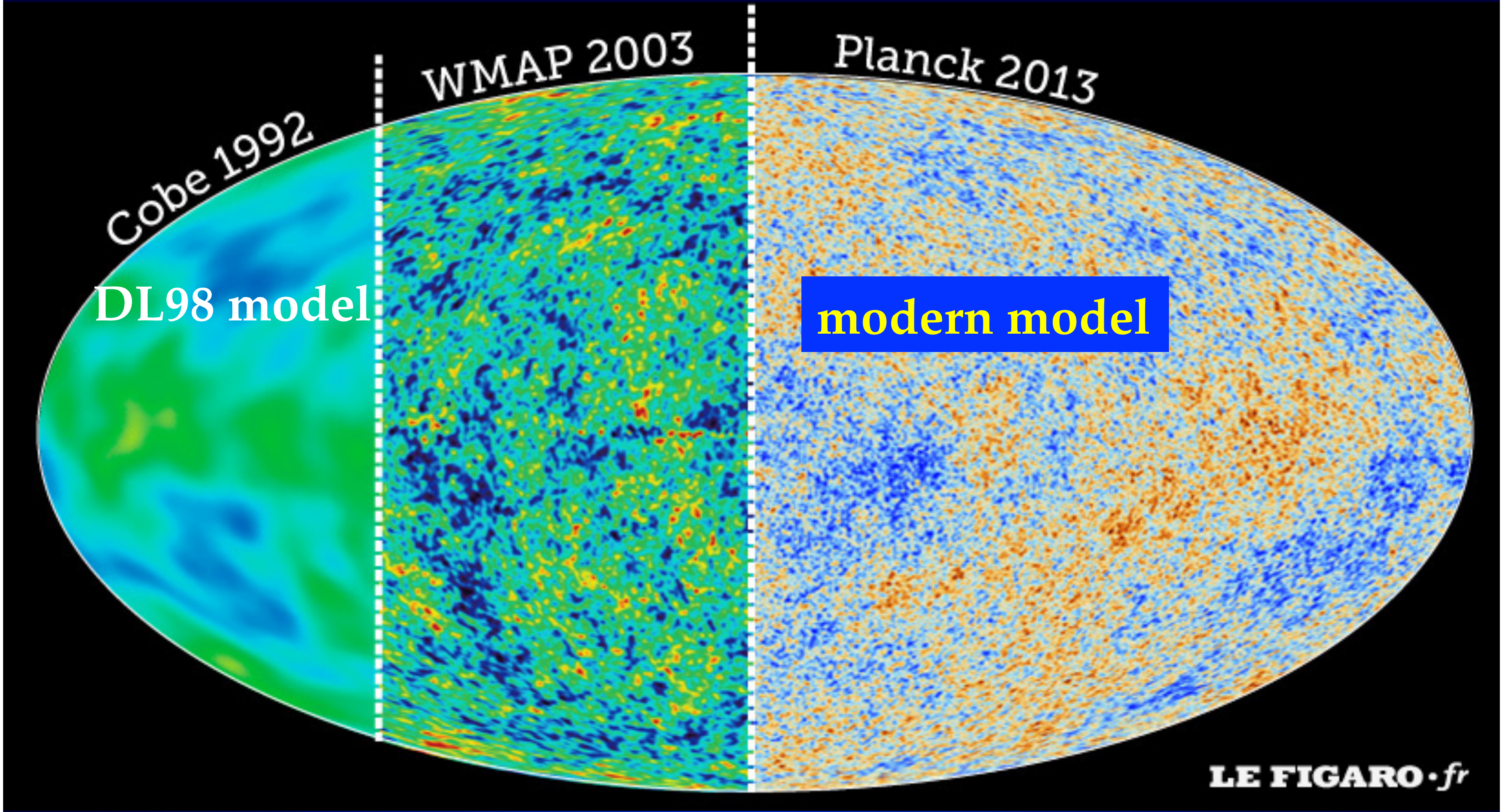
$$\left(\mathrm{erg\,s^{-1} cm^2 sr^{-1} Hz^{-1}/H}\right)$$



Draine & Lazarian (1998)

1997-2004 Numerous observations led by Angela de Oliveira Costa, Doug Finkbeiner consistent with spinning dust

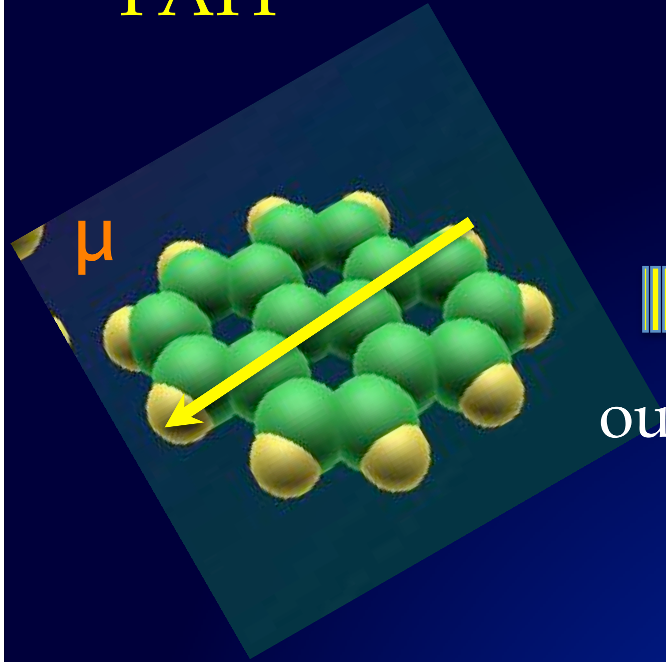
Precision Cosmology Requires Reliable Model of Spinning Dust



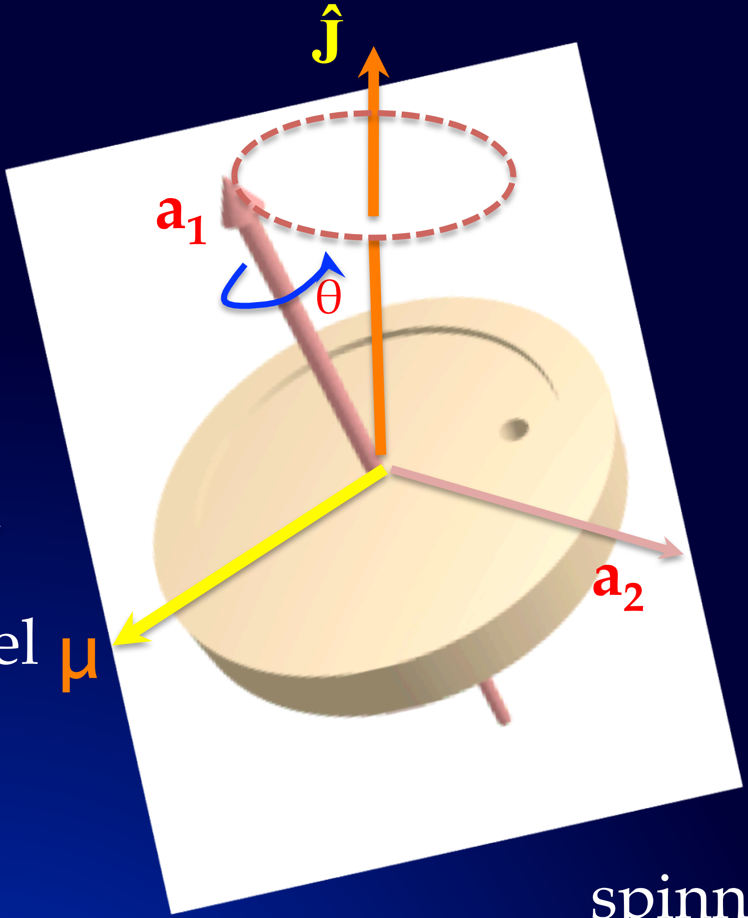
Papers	Internal Alignment	Grain Shape	Treatment	Single ion collisions	Transient heating	Turbulence
DL98 model	Perfect J / / a	disk	Classical	Identified, not quantified		
Ali-Haimoud et al. 09	Perfect	disk	classical			
Ysard & Verstraete 10	Perfect	disk	quantum			
Hoang et al. 10	not perfect: Precession +wobble	disk	classical	quantified		
Silsbee et al. 11	Not perfect, precession	disk	classical			
Hoang et al. 11	Not perfect Precession +wobble	triaxial	classical	quantified	quantified	quantified

Modern Model: Emission from Wobbling Grain

PAH

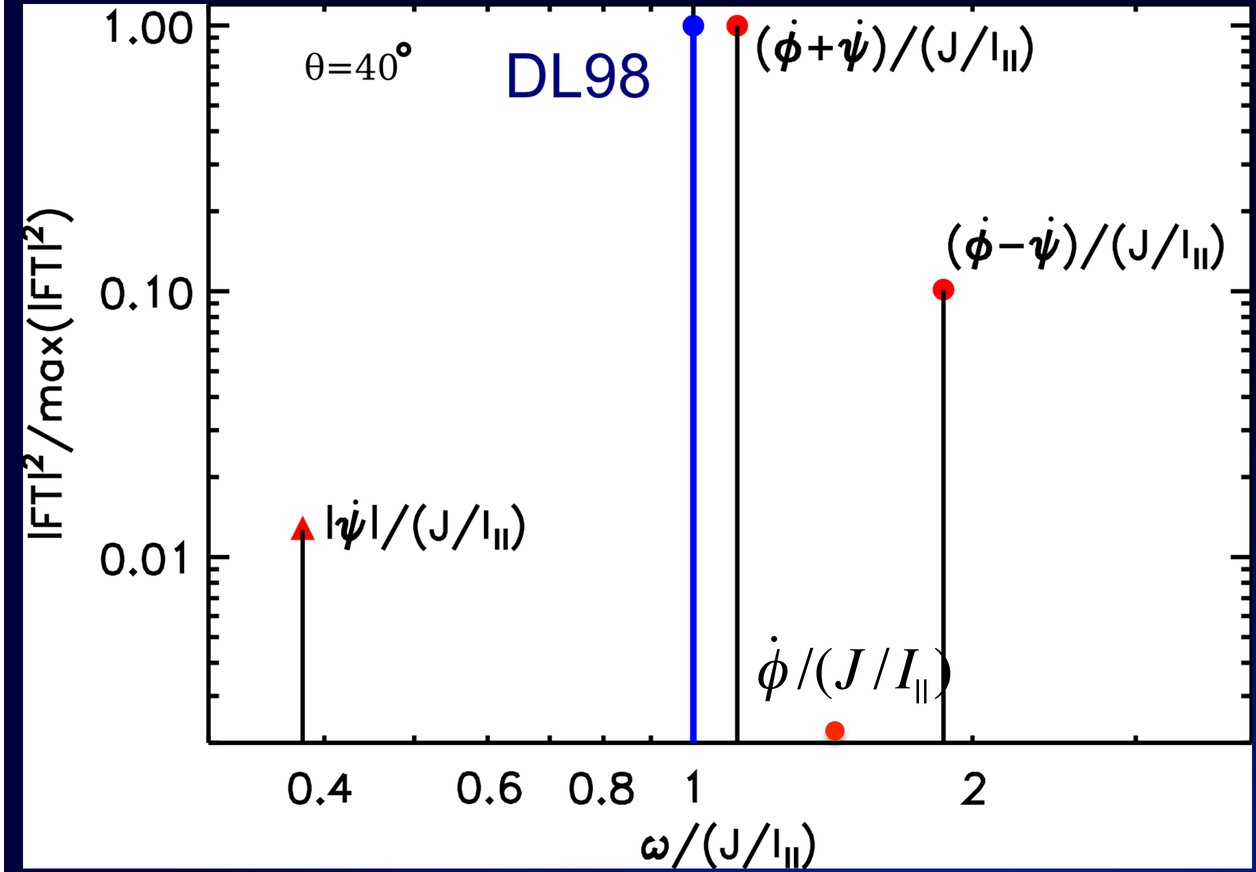


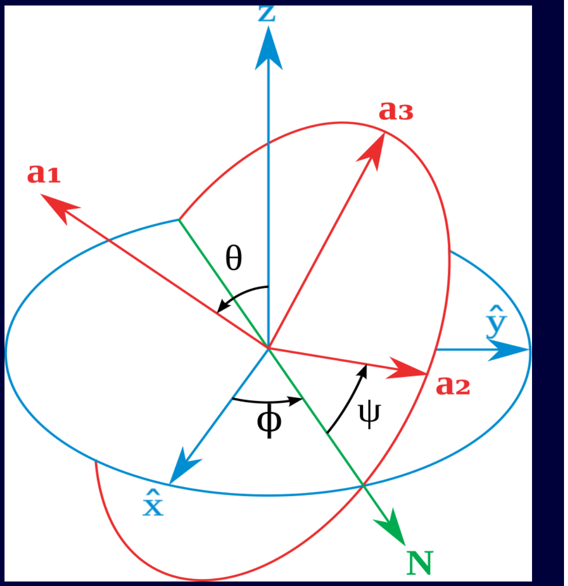
our new model

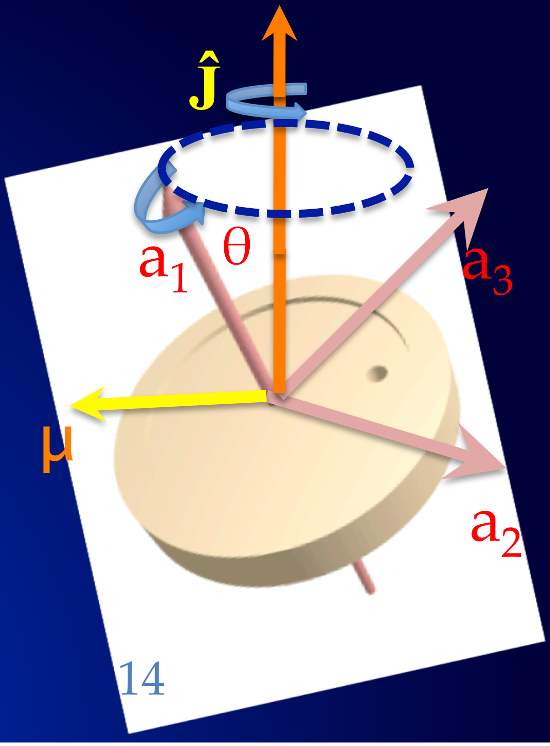


spinning +
wobbling

A precessing axisymmetric grain emits at 4 frequency modes

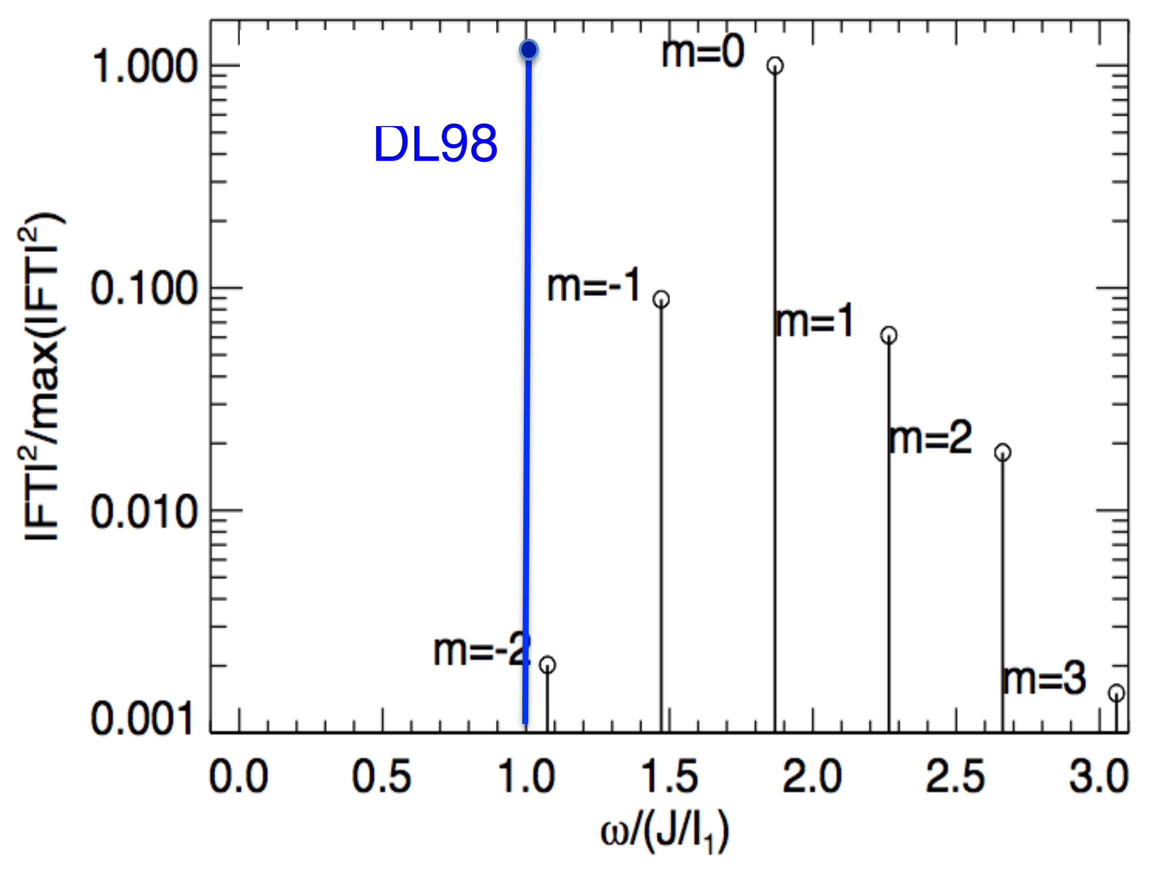


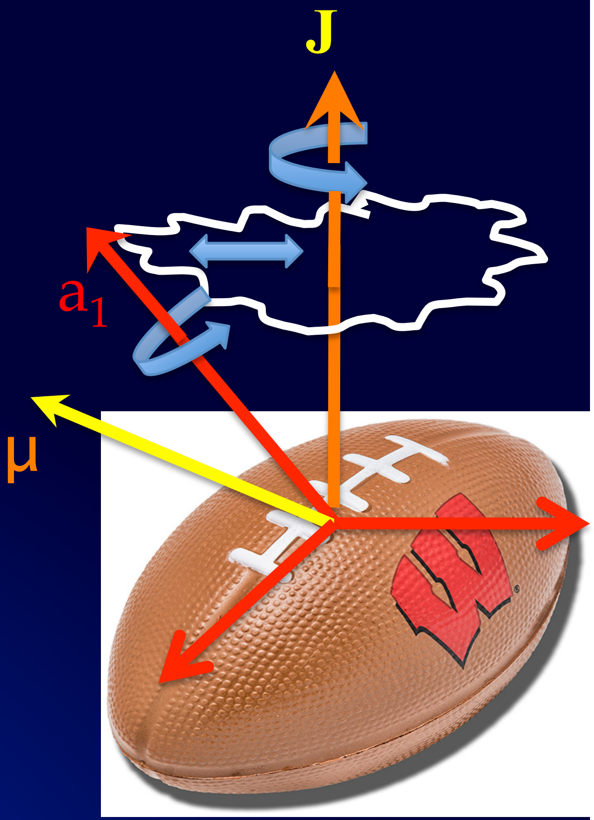




Hoang et al. 2011

A wobbling irregular grain emits at multiple frequency modes





- Multiple modes:

$$\omega_m = \langle\dot{\phi}\rangle + m\langle\dot{\psi}\rangle, m = 0, \pm1, \pm2...,$$

$$\omega_n = n\langle\dot{\psi}\rangle, n = 0,1,2$$

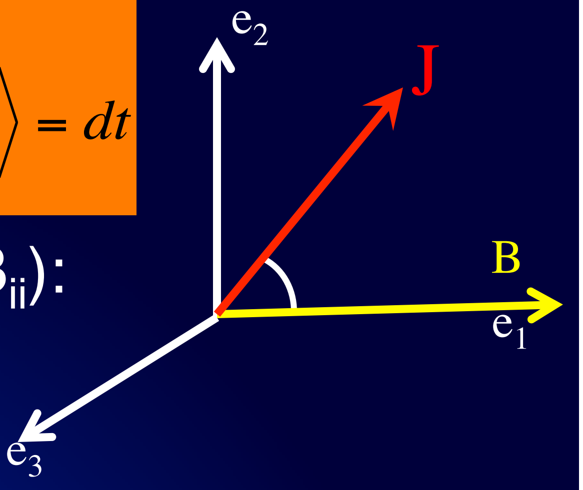
Hoang, Lazarian, & Draine 11

Angular Momentum Distribution Function

- Angular momentum J in the lab system is described by stochastic differential equations (SDEs -Langevin equation):

$$dJ_i = A_i dt + \sqrt{B_{ii}}\, dq_i,\ i = 1,2,3$$

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



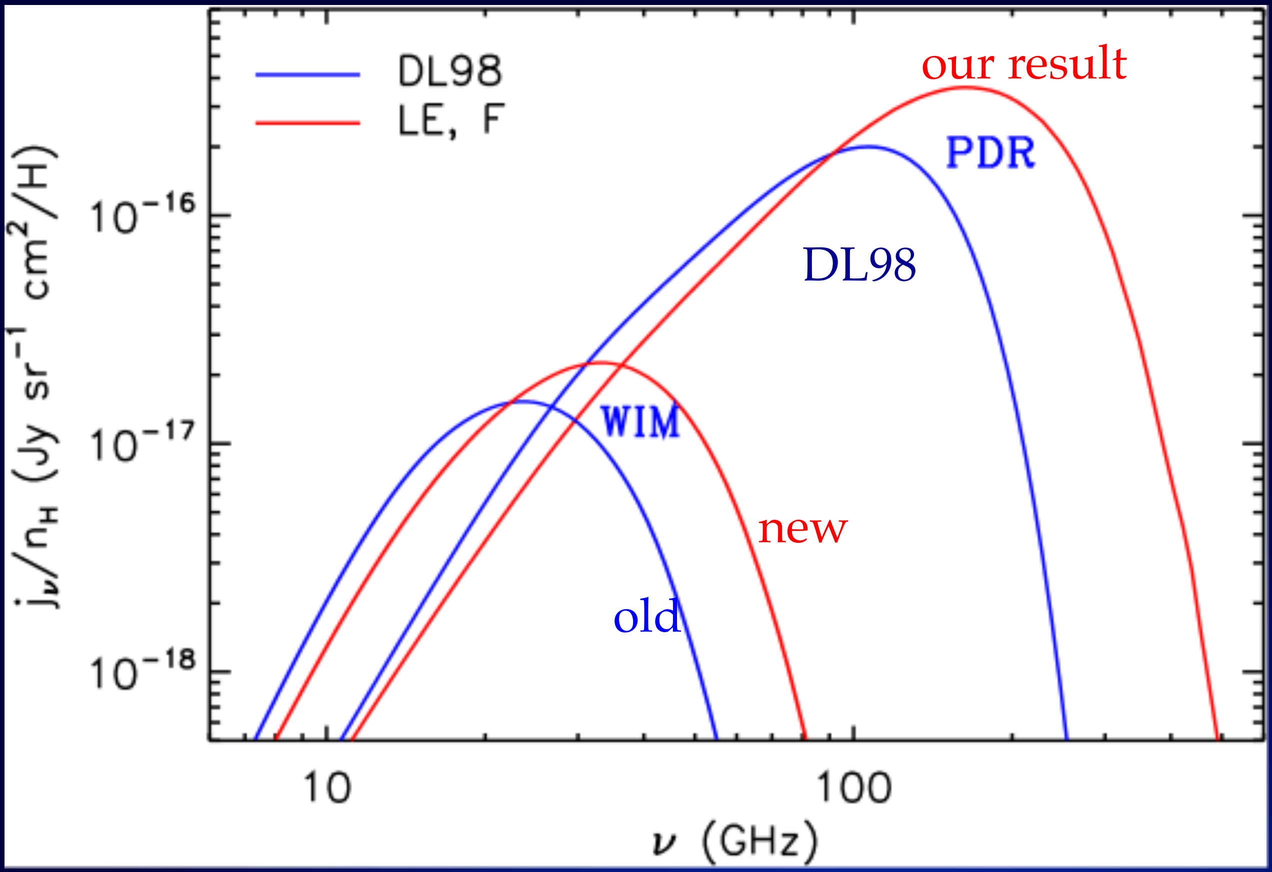
- Damping and excitation coefficients (A_i and B_{ii}):
  - grain-neutral and grain-ion collisions
  - photon absorption and infrared emission
  - plasma drag (passing ions)

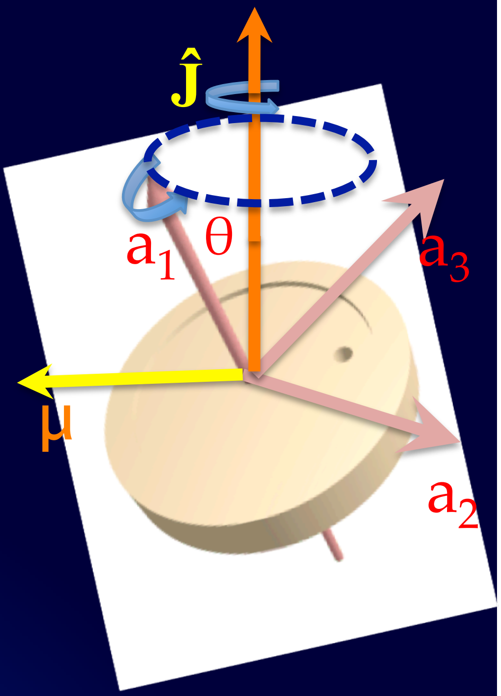
- Integrate SDEs to get J(t) and find momentum distribution f_J

- Emissivity per H atom:

$$\frac{j_\nu}{n_{\mathrm{H}}} = \frac{1}{4\pi}\frac{1}{n_{\mathrm{H}}}\int da \frac{dn}{da} j_\nu^a \qquad j_\nu^a = \int \mathrm{pdf}\left(\omega \mid J\right) P_{\mathrm{ed}}(J) 2\pi f_J\, dJ$$

Emission Spectrum

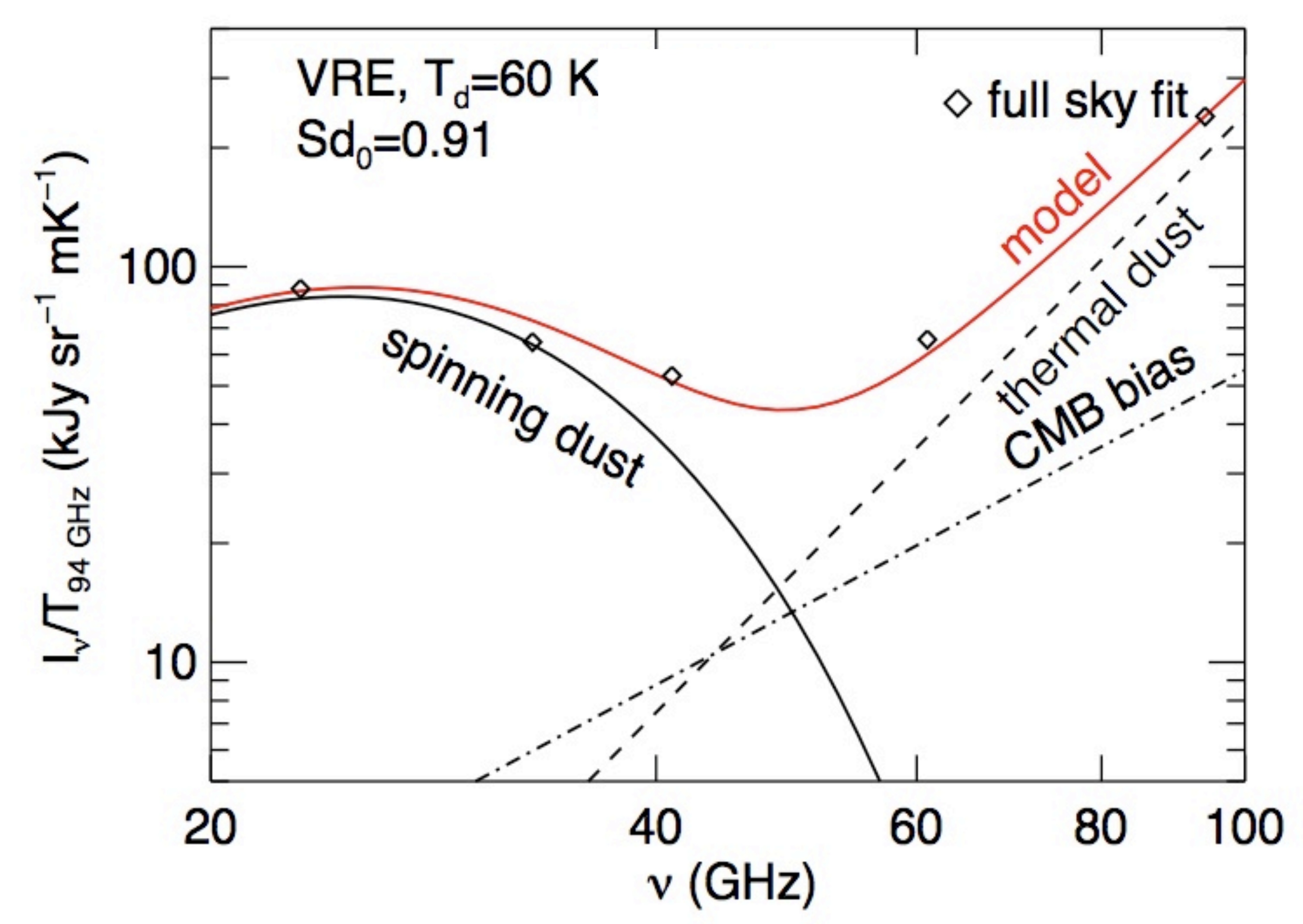




Hoang, Draine & Lazarian 10

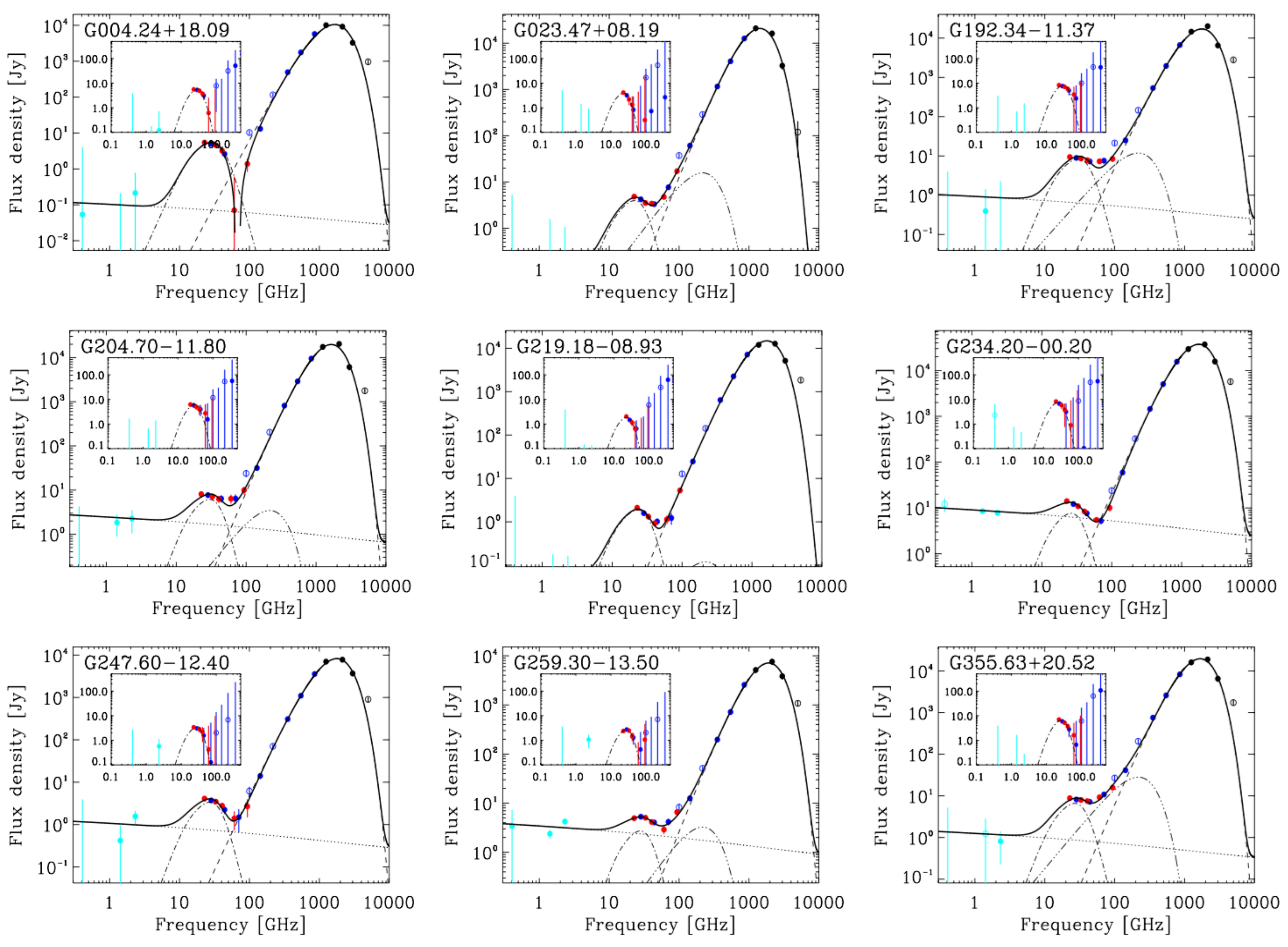
- Peak emissivity increases by a factor ~ 2.
- Peak frequency increases by a factor ~1.4 to 1.8.

New Spinning Dust Model Fits well to WMAP data

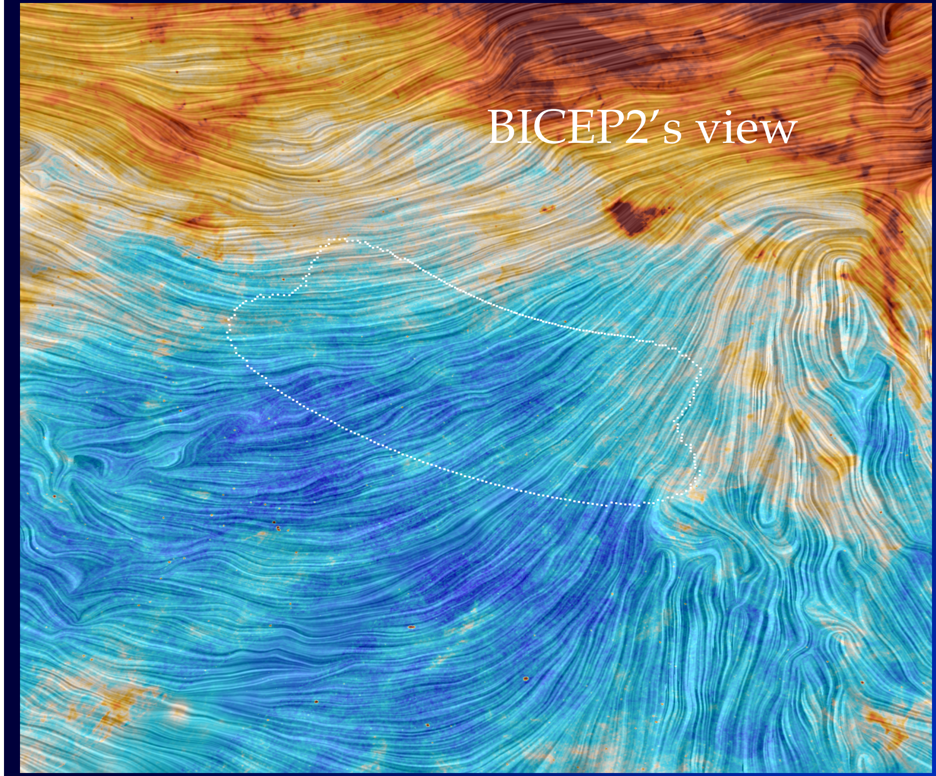


Hoang, Lazarian, & Draine 11

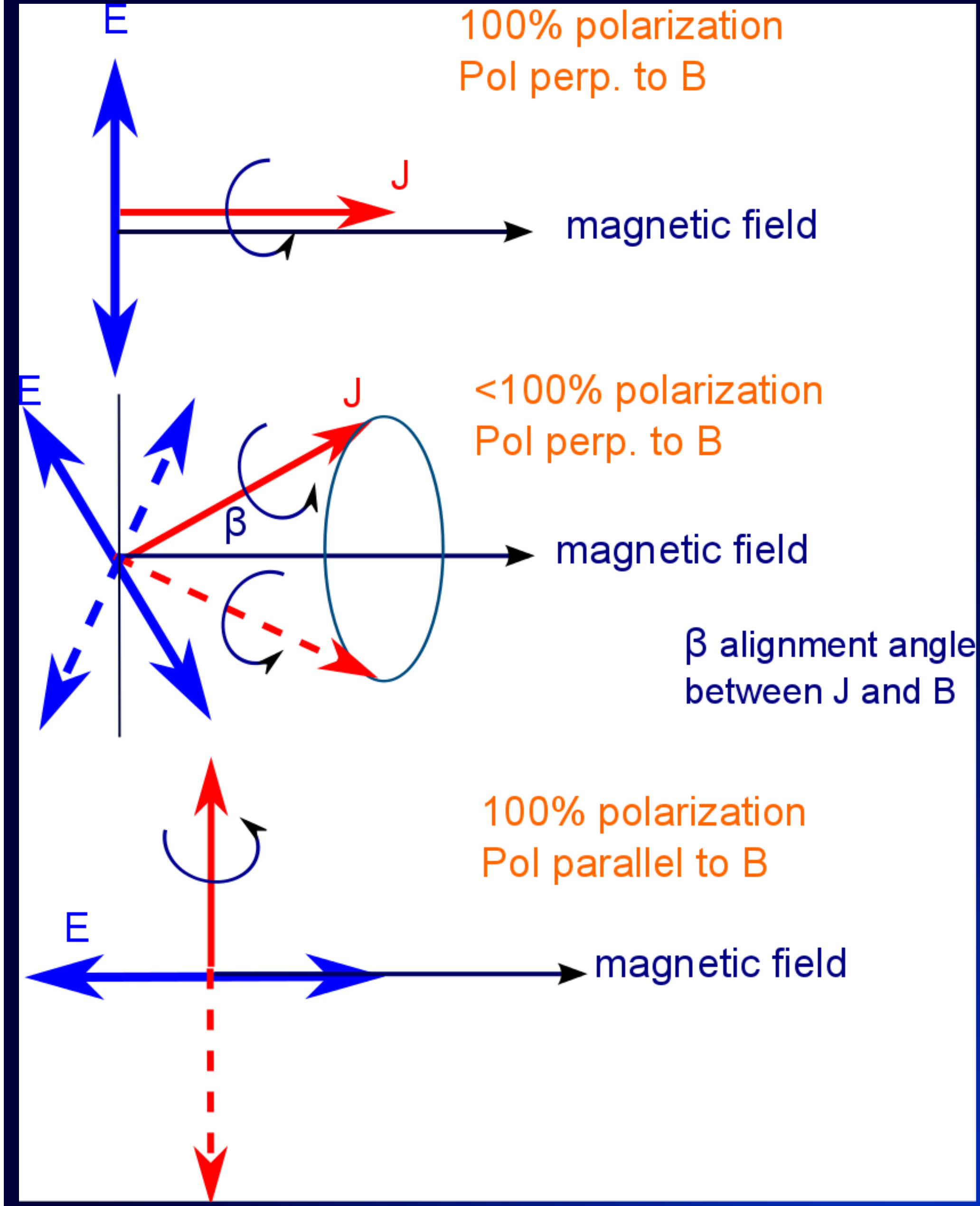
98 regions with AME discovered by Planck 2013, and 28 regions are well fitted by spinning dust



Polarization of Spinning Dust: Theory and Observational Constraints



PAHs must be aligned to emit polarized radiation

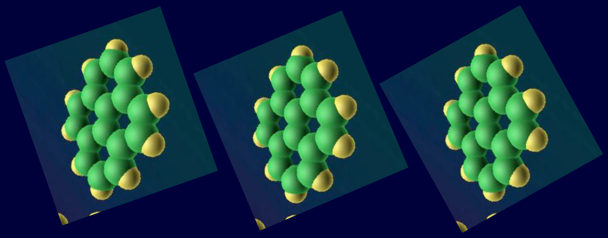


100% polarization
Pol perp. to B

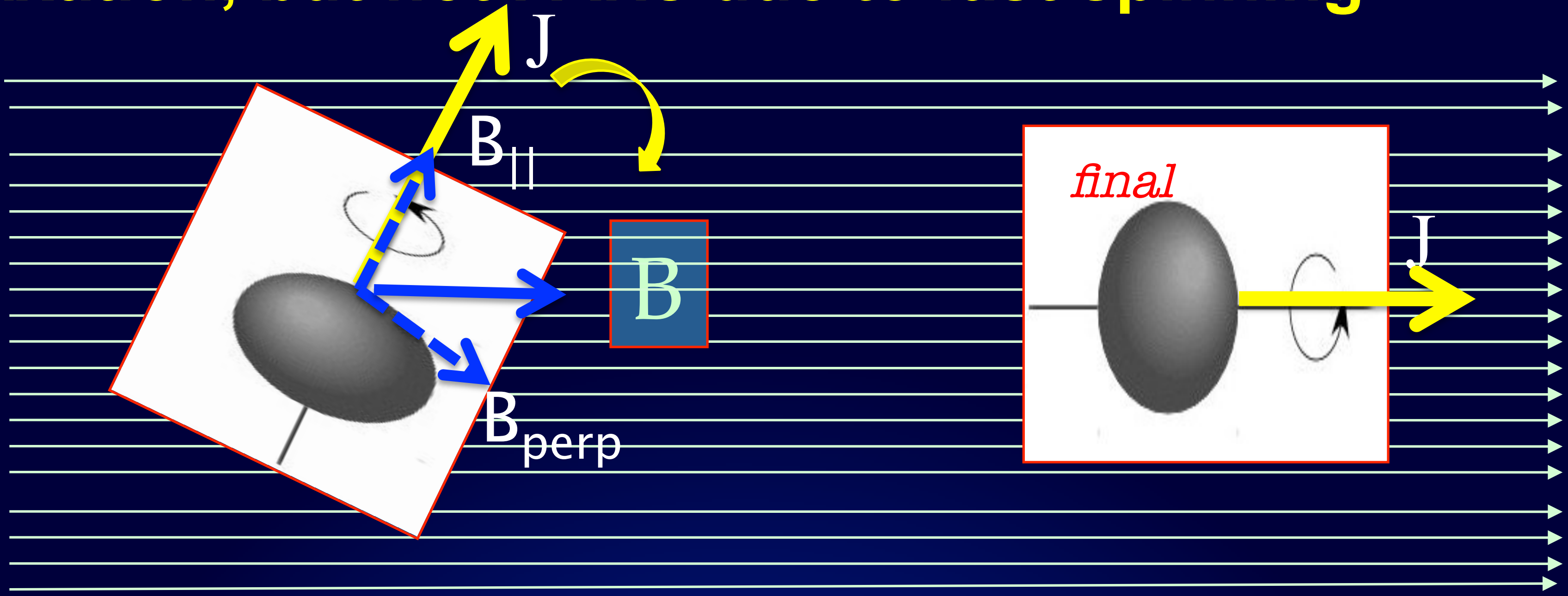
<100% polarization
Pol perp. to B

β alignment angle
between J and B

100% polarization
Pol parallel to B



Small grains weakly aligned by paramagnetic relaxation, but not PAHs due to fast spinning



Davis & Greenstein (1951)

magnetic susceptibility

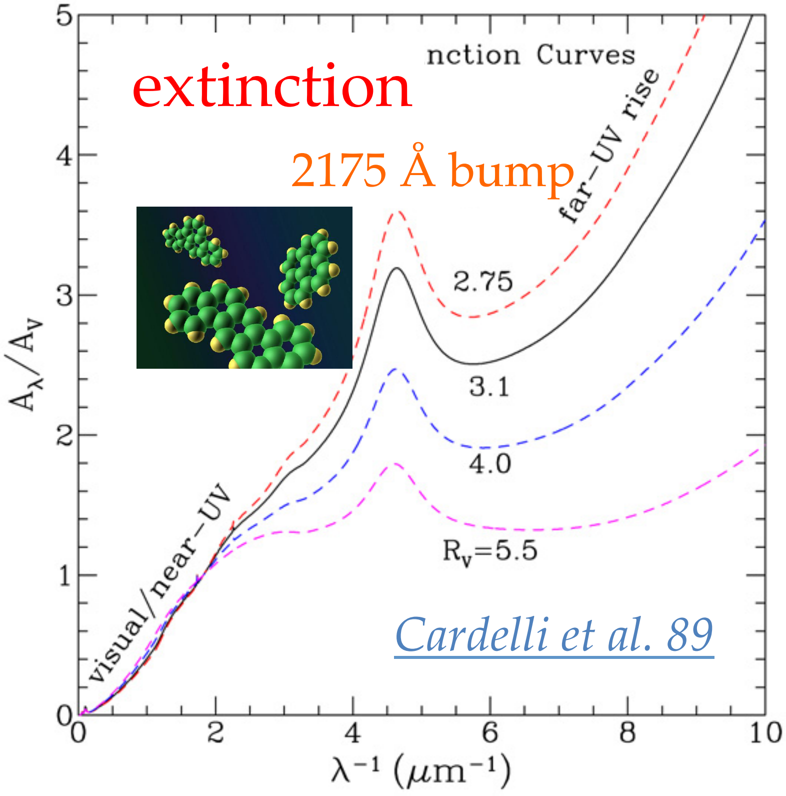
$$K_{\rm sil}(\omega) \approx 1.2 \times 10^{-13} \left(\frac{T_{\rm d}}{15\,{\rm K}}\right)^{-1} \frac{1}{[1+(\omega\tau_2/2)^2]^2}\ {\rm s}.$$

K goes to zero when $\omega \gg 1/\tau_2$

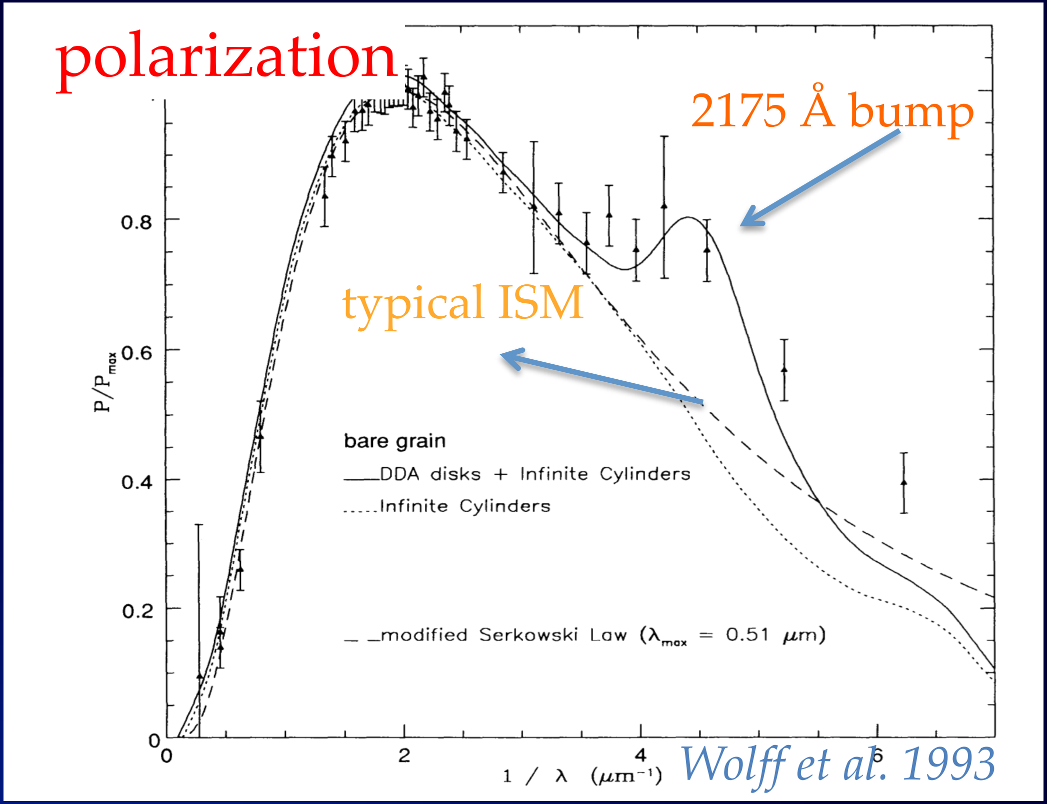
τ_2 spin-spin relaxation time ~ 1e-9 s

Resonance relaxation can help PAHs to be aligned (Lazarian & Draine 2000)

Constraints by Starlight Extinction and Polarization



Cardelli et al. 89



Wolff et al. 1993

- Two stars exhibit 2175 Å polarization bump.
- PAHs produce 2175 Å bump and radiate microwave emission.
- How efficient are PAHs aligned?

Inversion Technique

- Adopting a model of dust: silicate & carbonaceous compositions
- Constructing a model (Kim & Martin 95, Draine & Fraisse 09):

$$A_{\mathrm{mod}}(\lambda_k) \propto \sum_{\mathrm{m=sil,carb}} \sum_{i=0}^{Na-1} n_d(a_i)\pi a_i^2 Q_{\mathrm{ext}}(a_i,\lambda_k)$$

$$P_{\mathrm{mod}}(\lambda_k) \propto \sum_{\mathrm{m=sil,carb}} \sum_{i=0}^{Na-1} f(a_i) n_d(a_i)\pi a_i^2 Q_{\mathrm{pol}}(a_i,\lambda_k)$$

Model parameters:

$n_d\,(a)$: grain size distribution

$f\,(a)$: alignment function

- Minimizing an objective function:

$$\chi^2_{\mathrm{ext}} = \sum_{k=0}^{N_\lambda -1} w_{\mathrm{ext}}\left[A_{\mathrm{mod}}(\lambda_k) - A_{\mathrm{obs}}(\lambda_k)\right]^2$$

$$\chi^2_{\mathrm{pol}} = \sum_{k=0}^{N_\lambda -1} w_{\mathrm{pol}}\left[P_{\mathrm{mod}}(\lambda_k) - P_{\mathrm{obs}}(\lambda_k)\right]^2$$

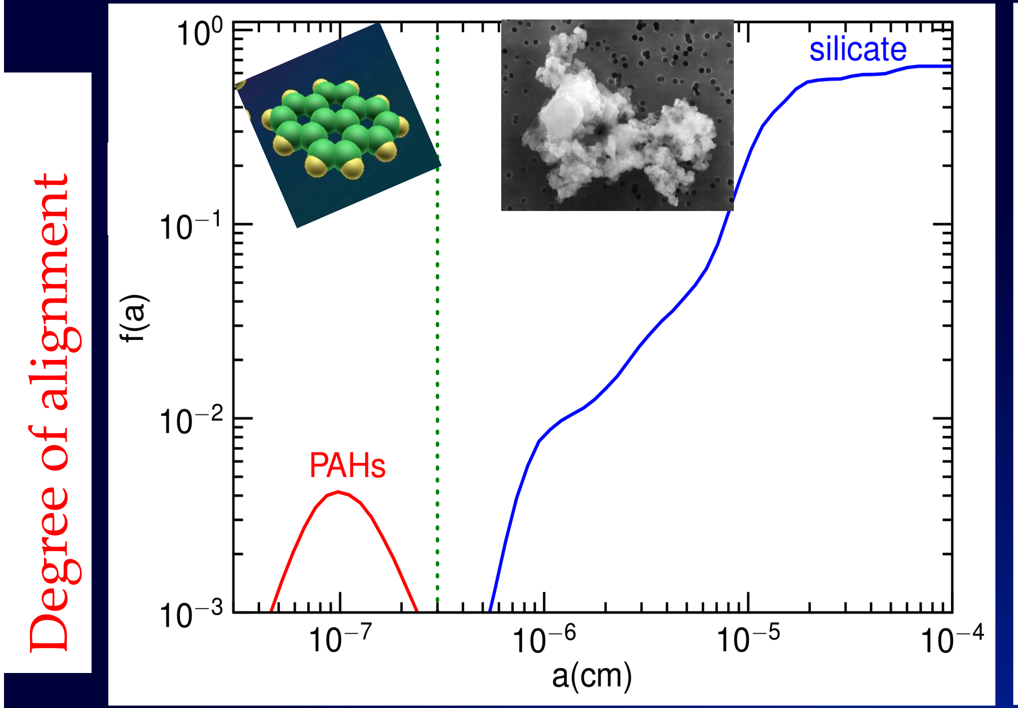
$$\chi^2 = \chi^2_{\mathrm{ext}} + \chi^2_{\mathrm{pol}} + \chi^2_{\mathrm{constraints}}$$

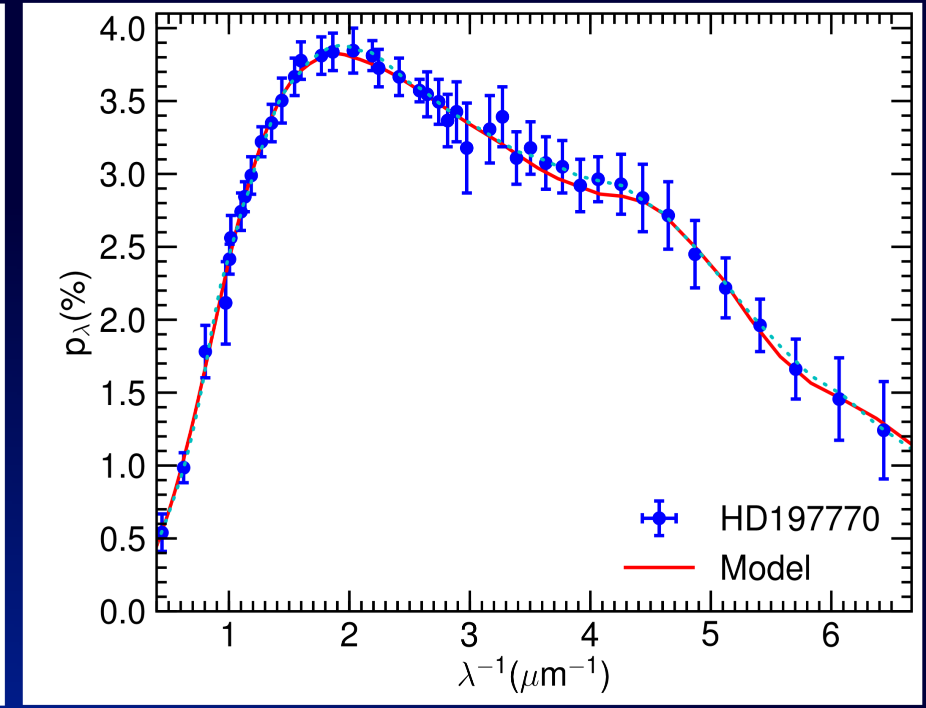
w_{ext}, w_{pol}: fitting weights

- Nonlinear Chi-square fitting: ~ $N_a{*}N_\lambda$ free parameters
- Monte Carlo search method for global minimization

Hoang et al. 2014a

Best-fit Model Parameters

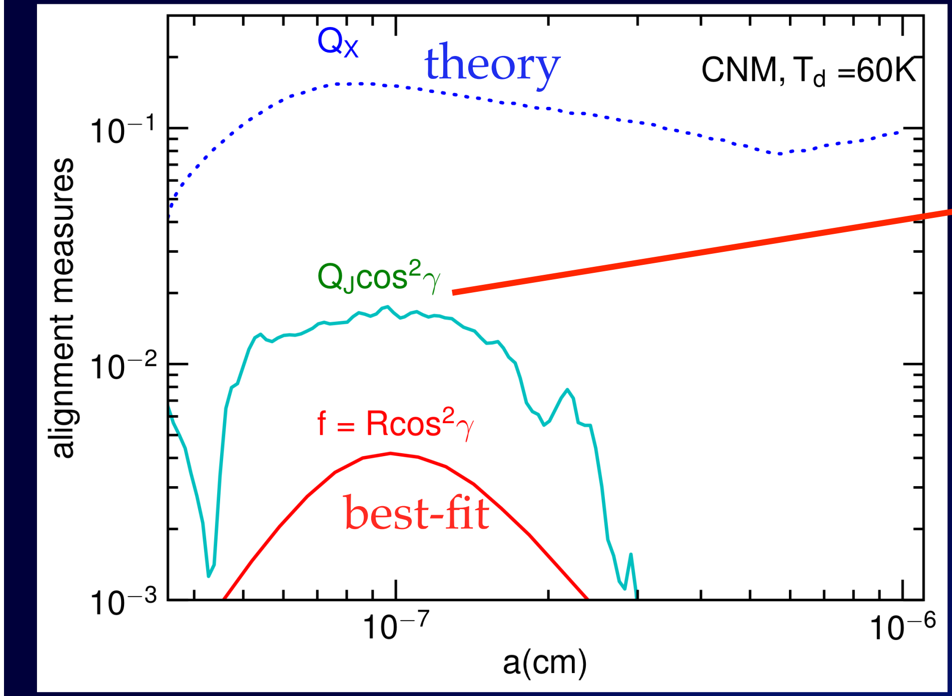




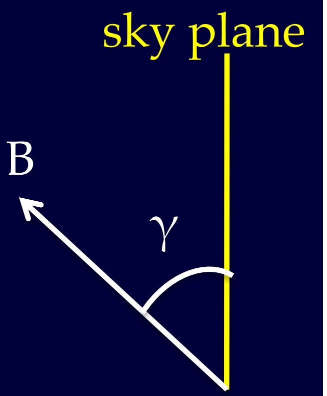
- PAHs are very weakly aligned
- Big silicates are efficiently aligned

Hoang et al. 2013

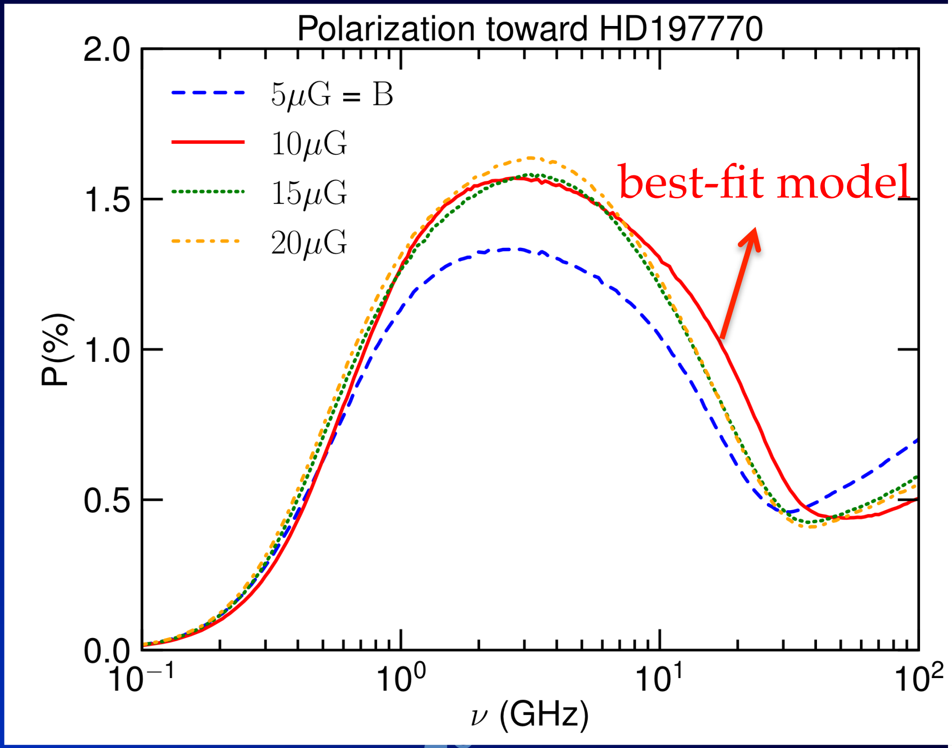
HD 197770: Peak polarization of spinning dust ~ 1.6 percent



$$P \propto Q_J \cos^2 \gamma$$



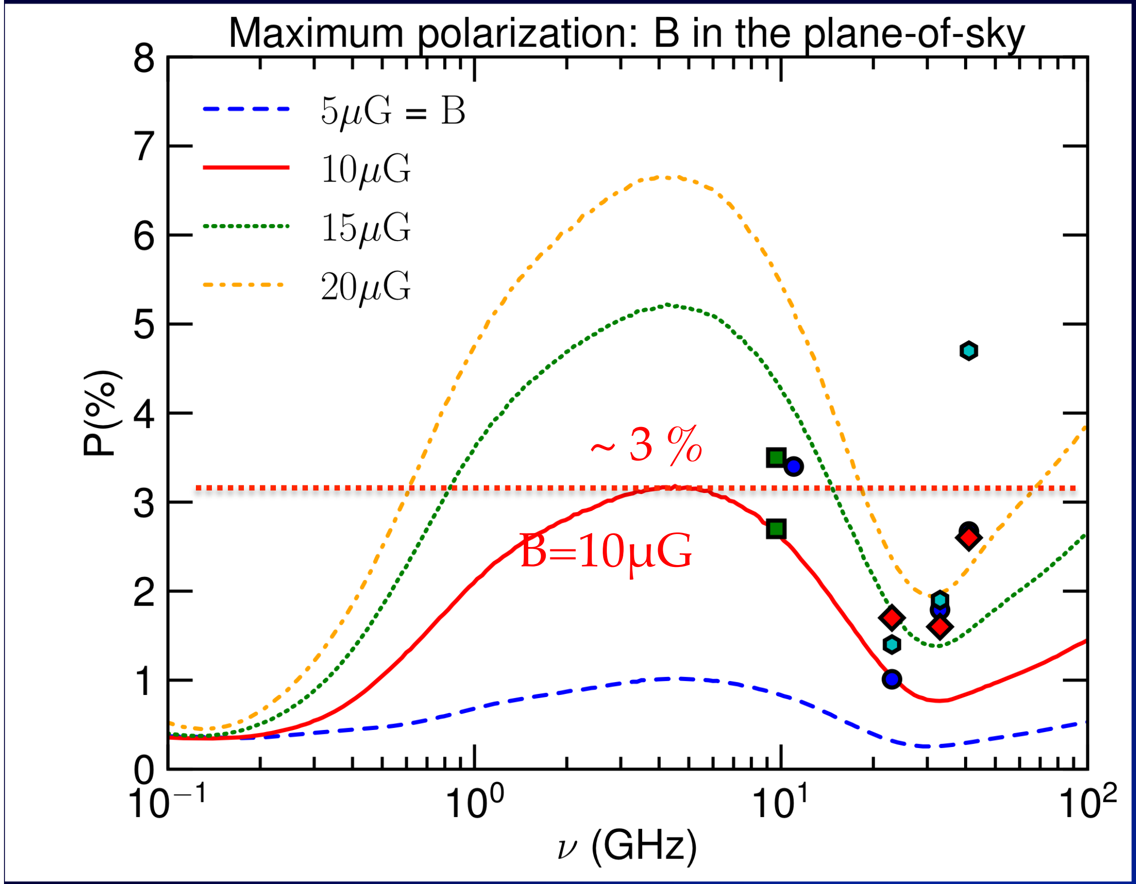
Polarization



Hoang et al. 2013

Theory vs. Observations

Theory: maximum polarization ~ 3 % for typical ISM field.



Upper limits from observations:

Battisteli + 2006 (•)

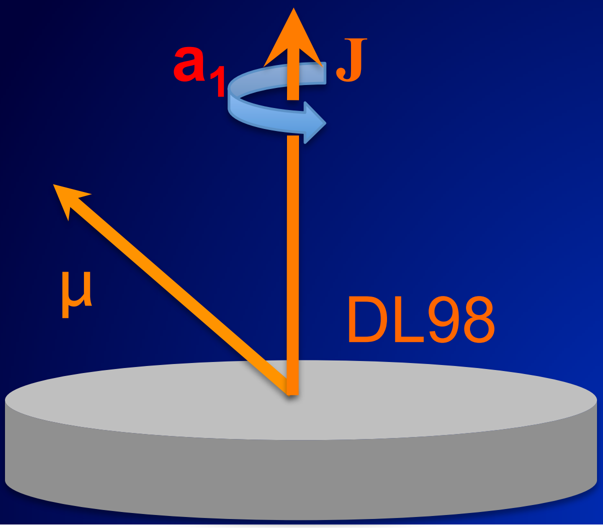
Mason + 2009 (■)

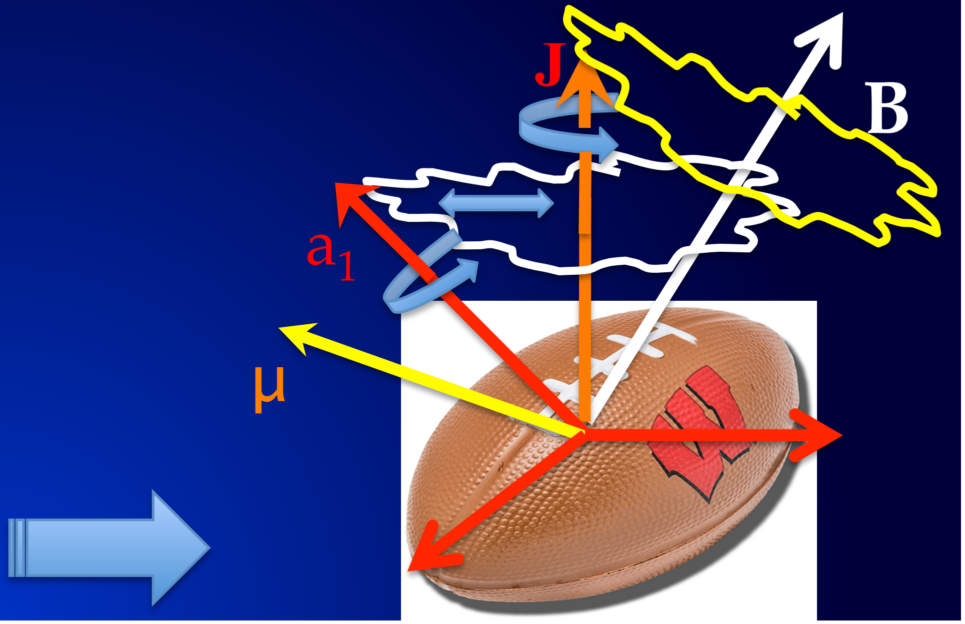
Dickinson + 2011(◆)

Hoang et al. 2015c

Summary and Discussion

- Modern spinning dust model accounts grain precession, irregular shape, transient events, and turbulence
- Spinning dust as AME is further supported by Planck data and becomes a diagnostic tool for dust properties (Tibbs + 15)
- Dipole emission by spinning iron nanoparticles may be considerable (Hoang et al. 2015d, submitted)
- Polarization of spinning dust is low and consistent with upper limits of observations

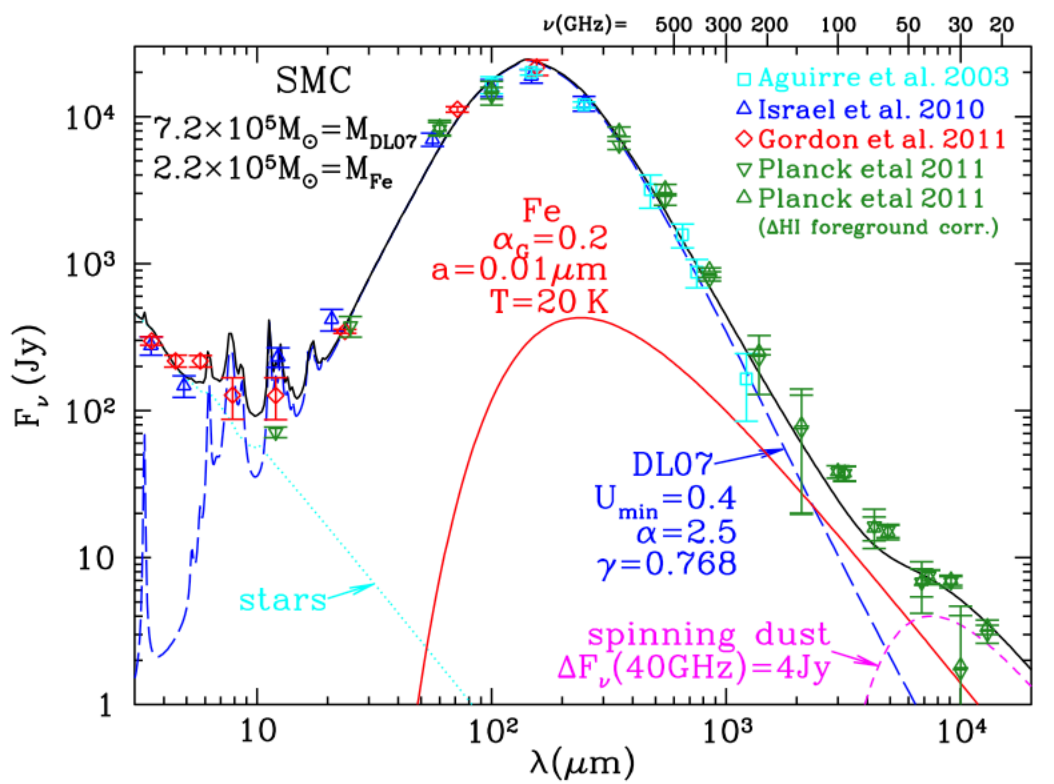


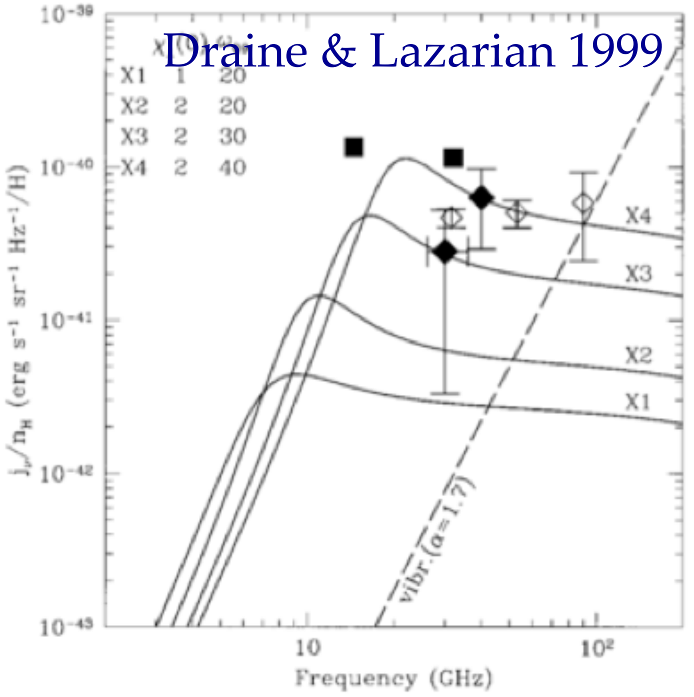


Magnetic dust: Emission from Magnetic Dipole Fluctuations

- Draine & Lazarian (1999) proposed magnetic dipole microwave emission as an alternative to spinning dust

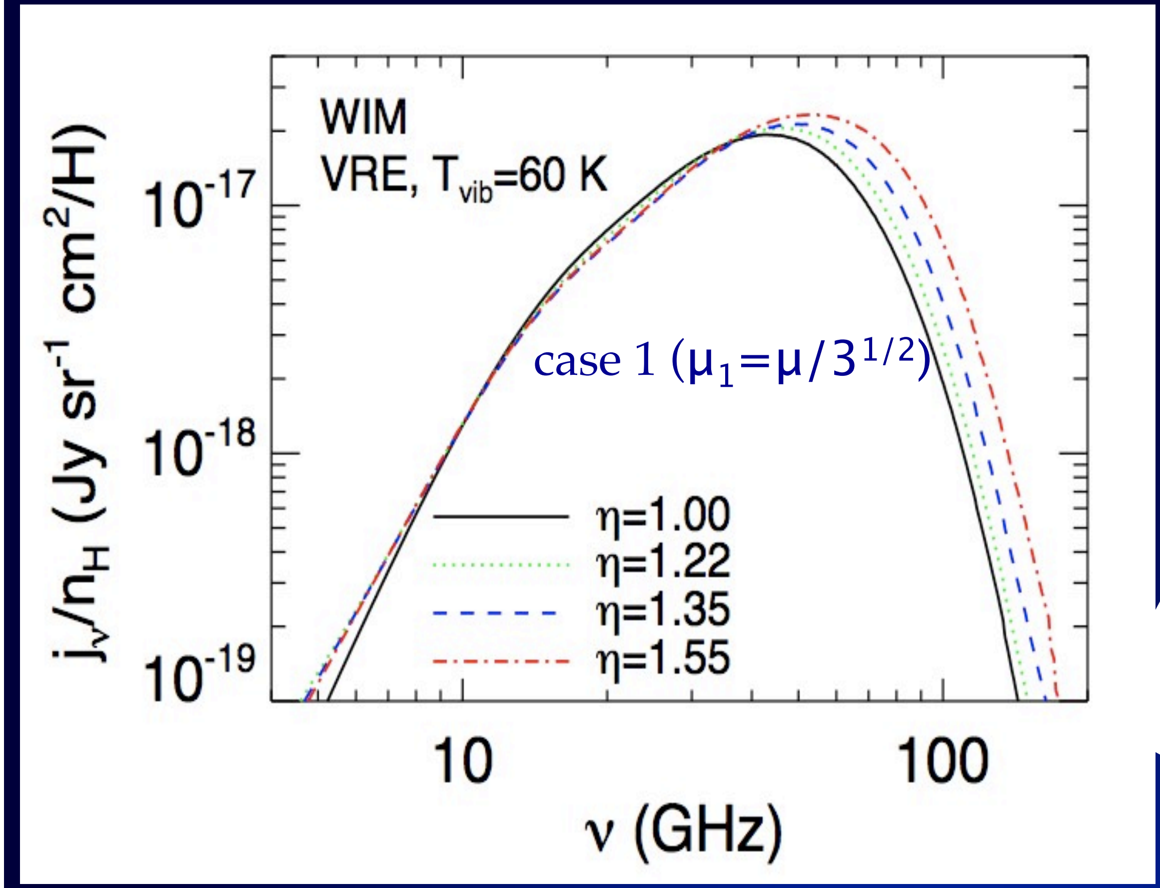
- Draine & Hensley (2012, 2013) extended and improved the DL99, successfully explain submm excess



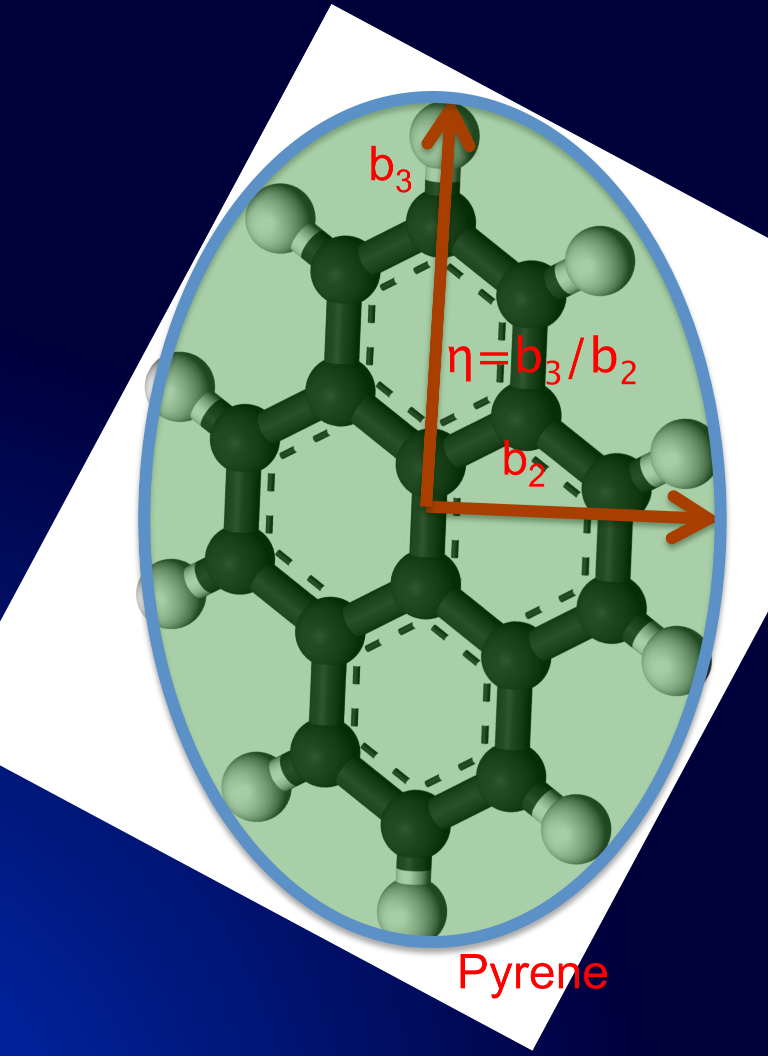

Draine & Lazarian 1999

Draine & Hensley 2012

Emissivity Increases with Grain Irregularity



case 1 ($\mu_1=\mu/3^{1/2}$)



Pyrene

Lots of observations supporting DL98 model of spinning dust

- Instruments used to study spinning dust: OVRO, COBE-DMR, Tenerife, Saskatoon, Green Bank,VCA, CBI, COBE WMAP (de Oliveira Costa et al., Finkbeiner et al)

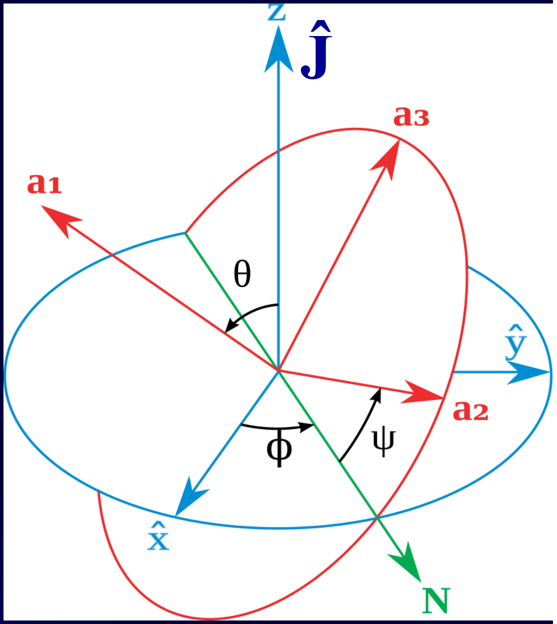
- Measured in diffuse and molecular gas, HII regions (Dickinson et al. 13, Tibbs et al. 13), supernova remnants, etc

- Measured in extragalactic environments (Murphy et al. 2010, Scaife et al. 2010, Hensley et al. 2014)

Power spectrum of an isolated grain

- Torque-free motion: Euler angles ϕ, ψ, θ, *and* rates

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

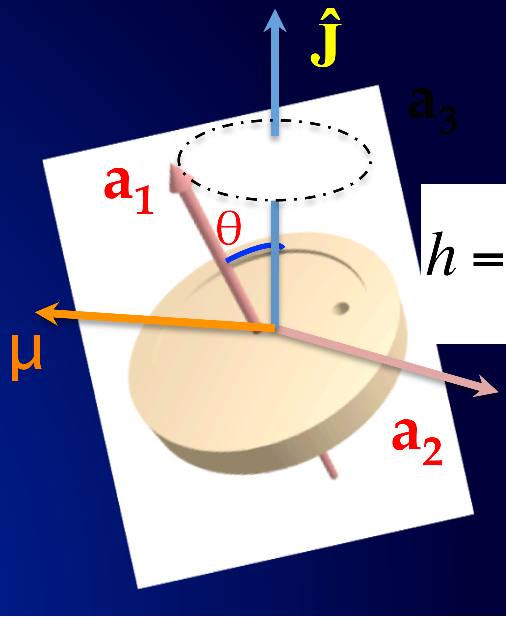


- Electric dipole moment: $\mu(J,\theta,t) = \mu_1 a_1 + \mu_2 a_2$
- Fourier Transform: $\ddot{\mu}(J,\theta,t) = \mu_1 \ddot{a}_1 + \mu_2 \ddot{a}_2$

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

- Power Spectrum:

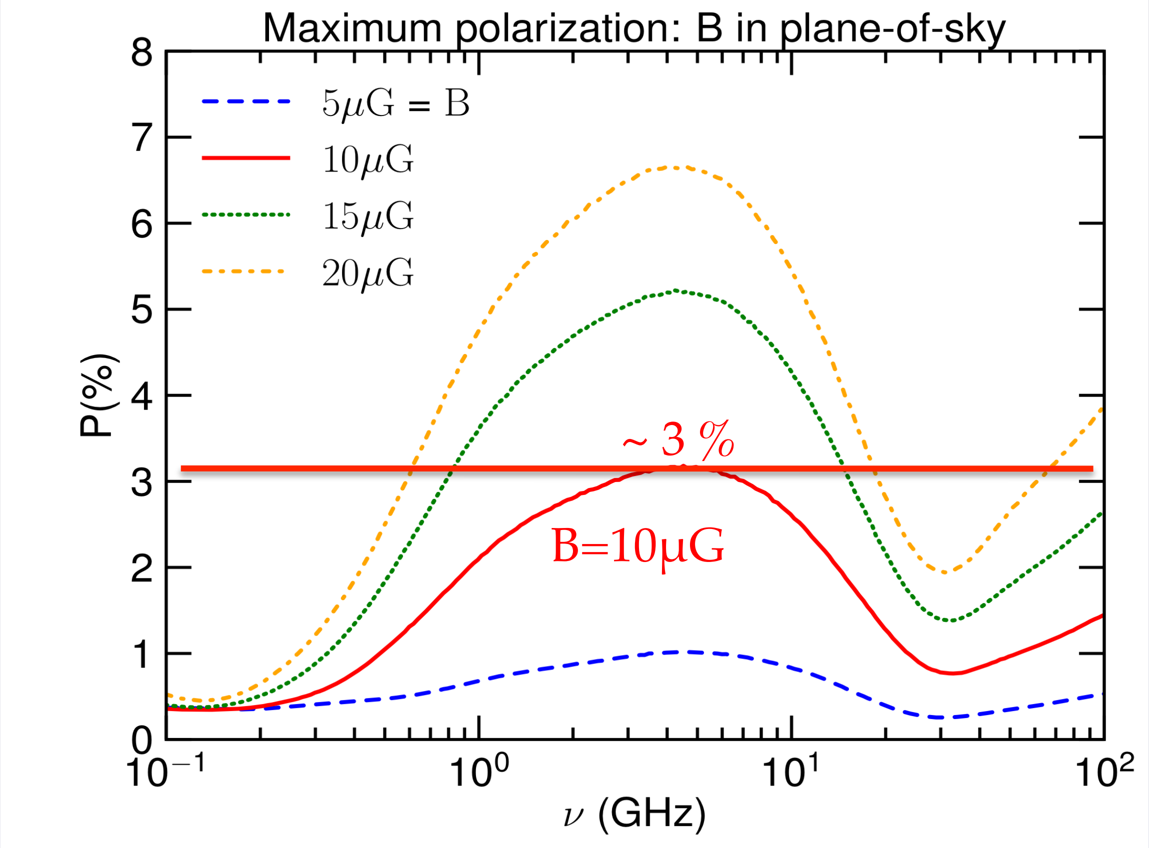
$$P_{\mathrm{ed},k}(J,\theta) = \frac{2}{3c^3}\sum_i (\ddot{\mu}_{i,k})^2$$

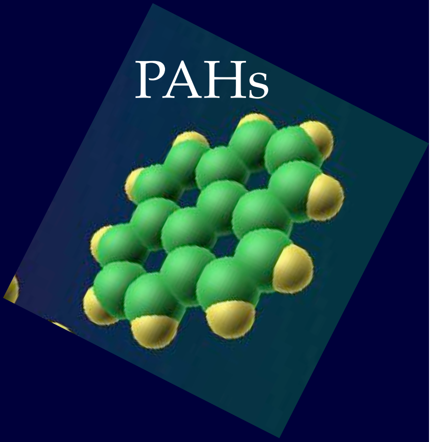


$$h = \frac{I_1}{I_2}$$

Hoang, Draine & Lazarian 10

Theory: maximum polarization ~ 3 % for typical ISM field.

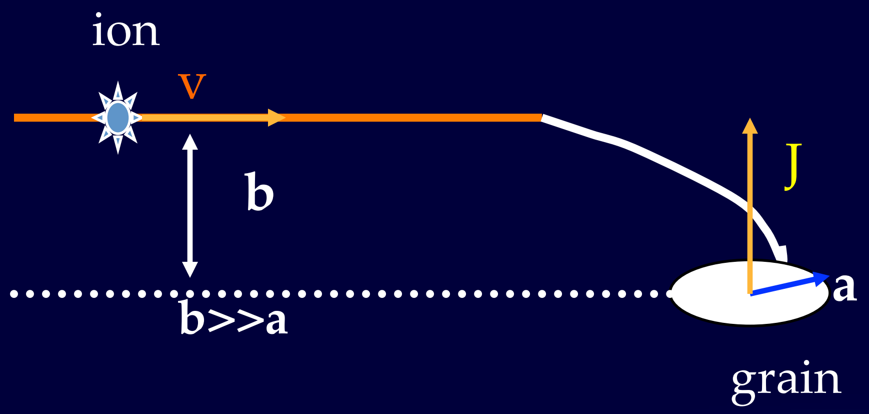




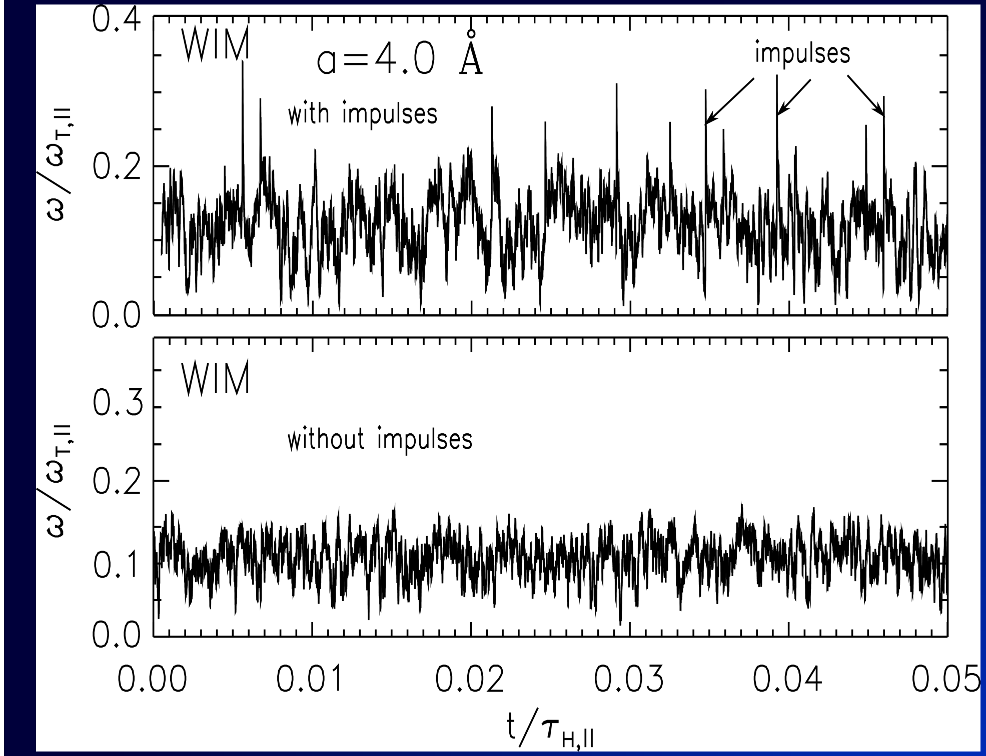
- Maximum polarization increases with increasing B strength.

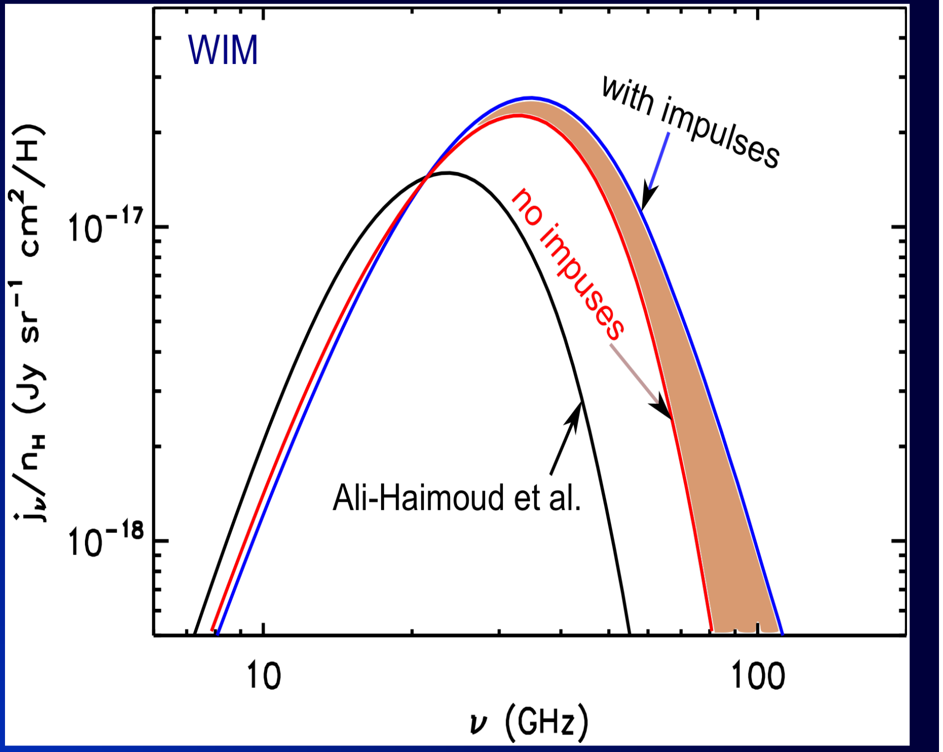
Hoang et al. 2015

Impulsive excitation by single-ion collisions

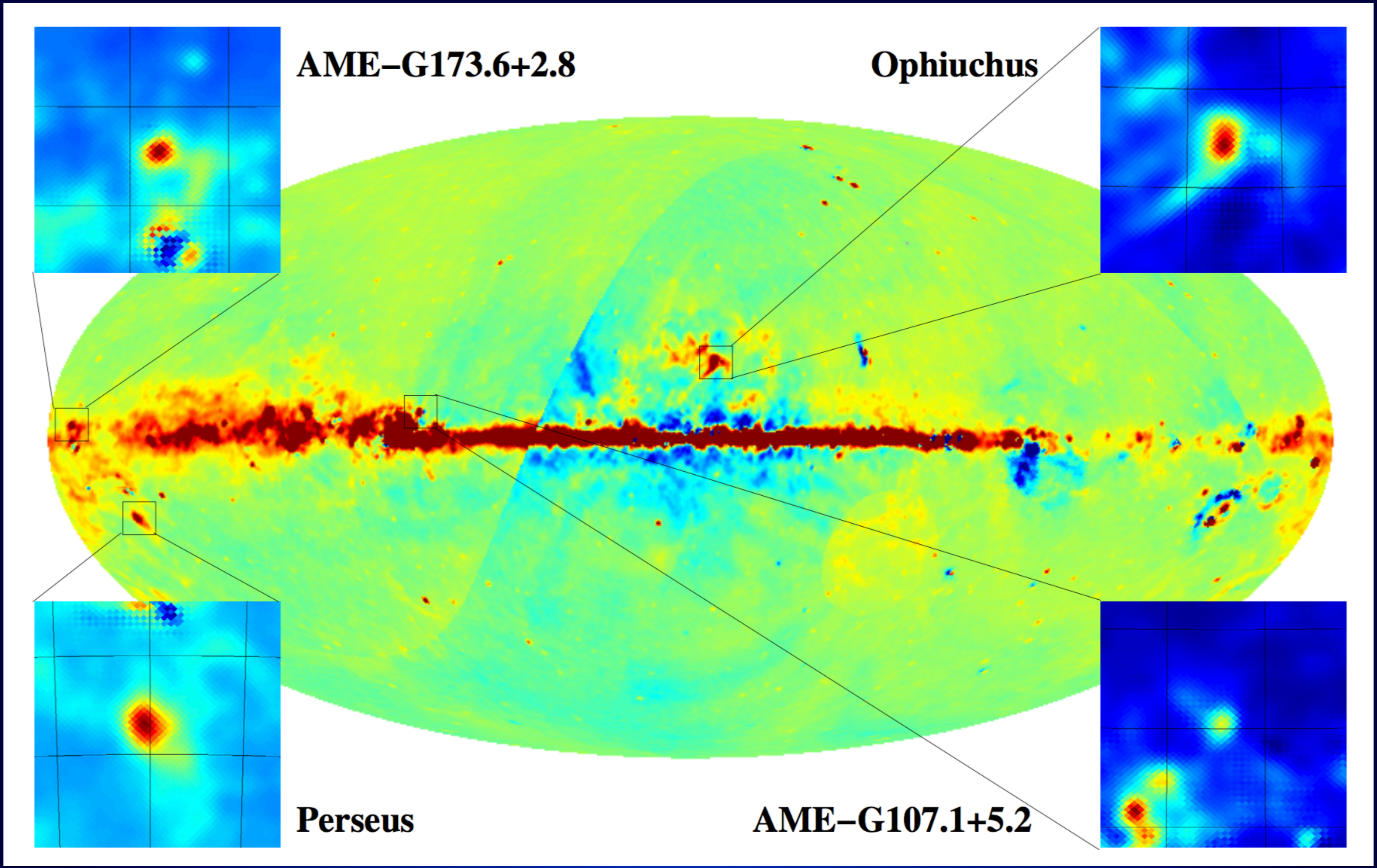


Change in J may be large



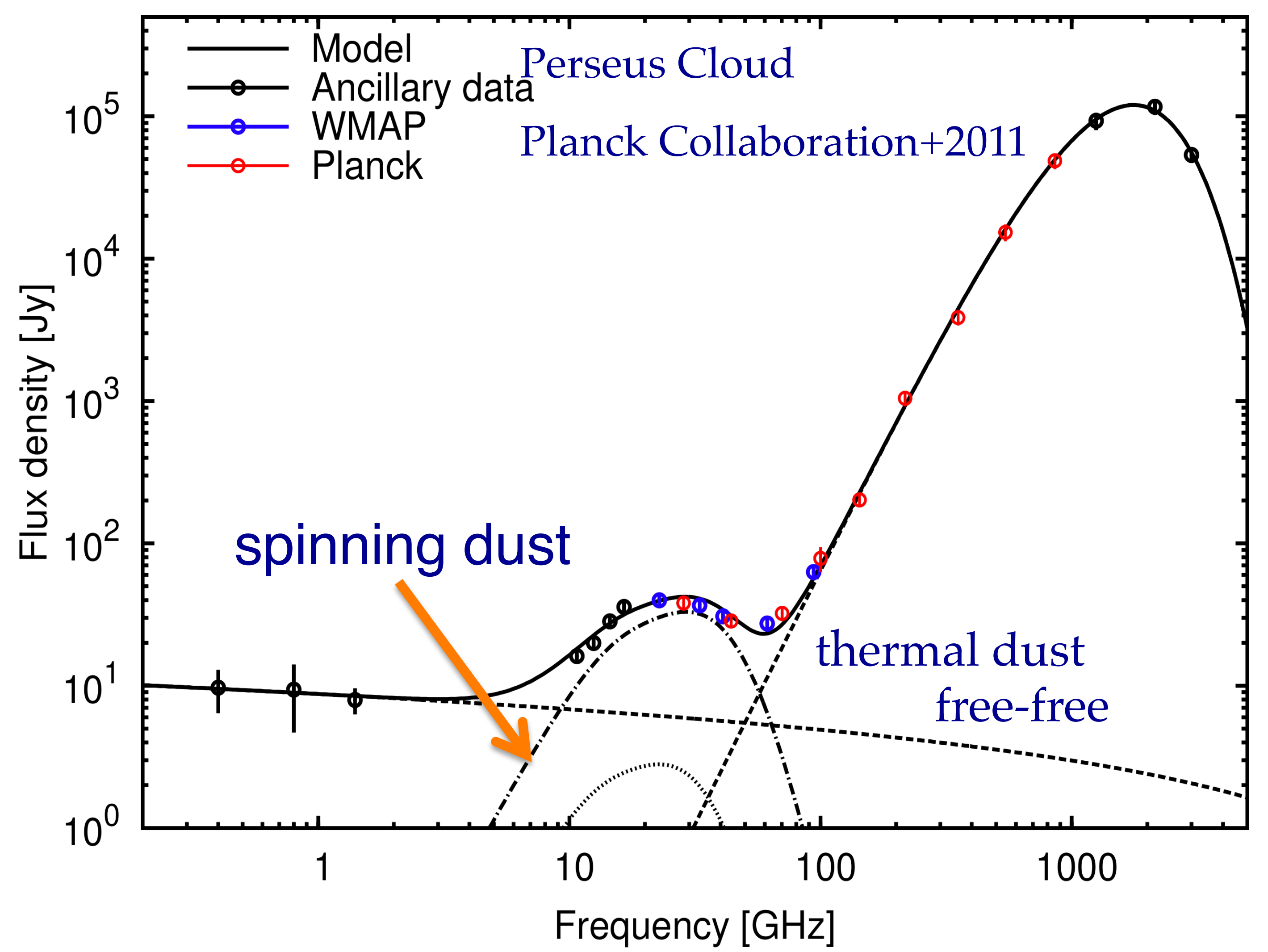


New AME regions discovered by Planck 2011

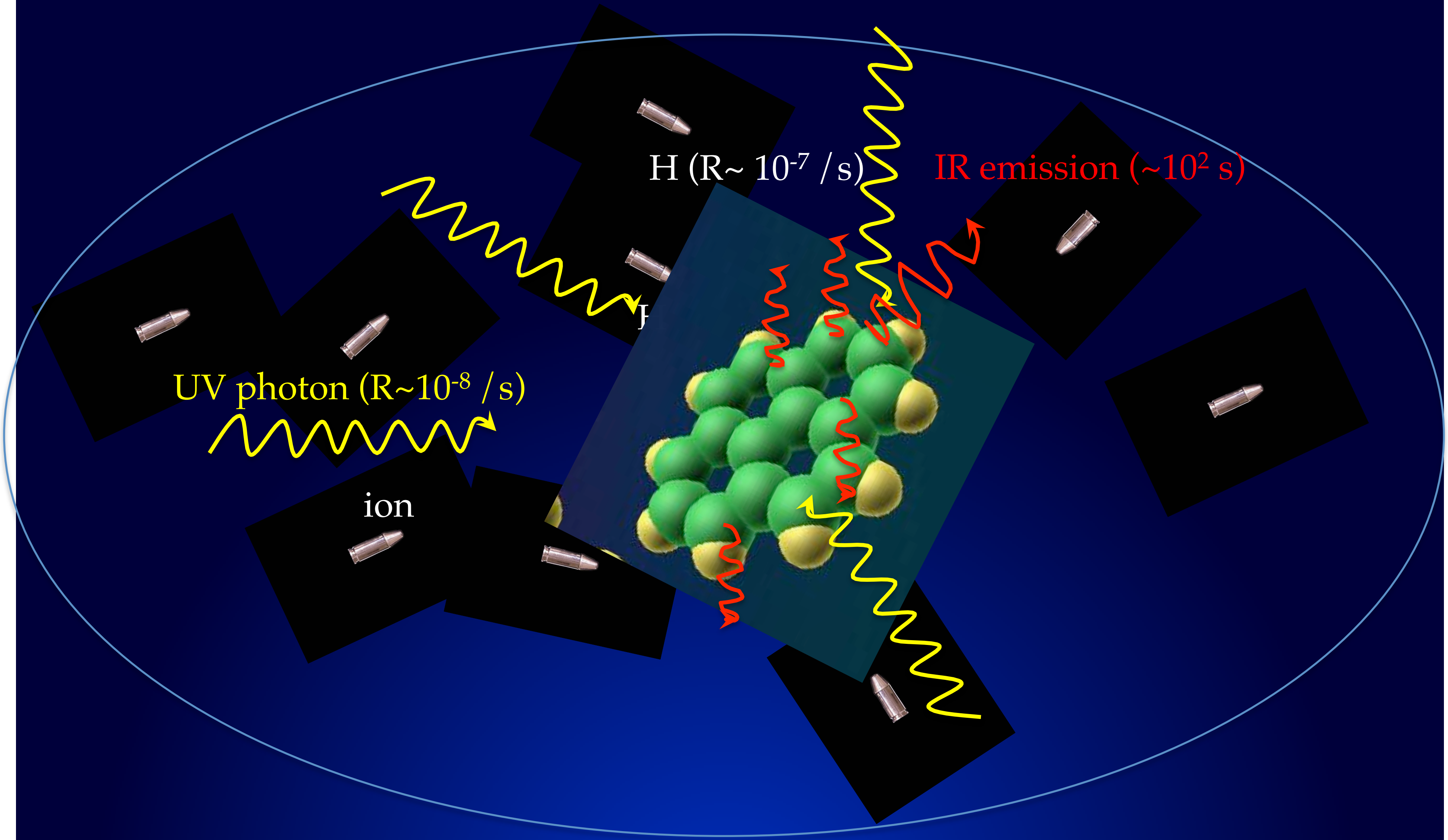


Planck Collaboration 2011, A20

Spinning dust gives great fit to AME seen by Planck



Rotational Damping and Excitation Processes



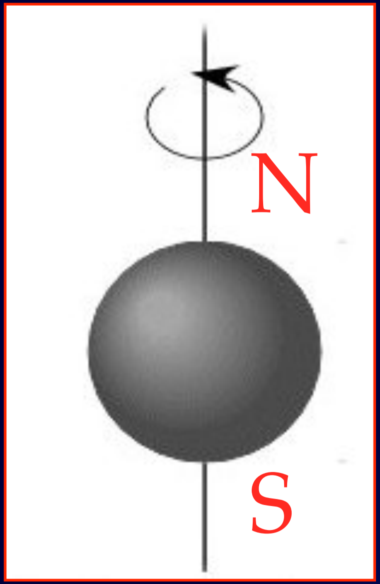
H (R~ 10^{-7} /s)

IR emission (~10^{2} s)

UV photon (R~10^{-8} /s)

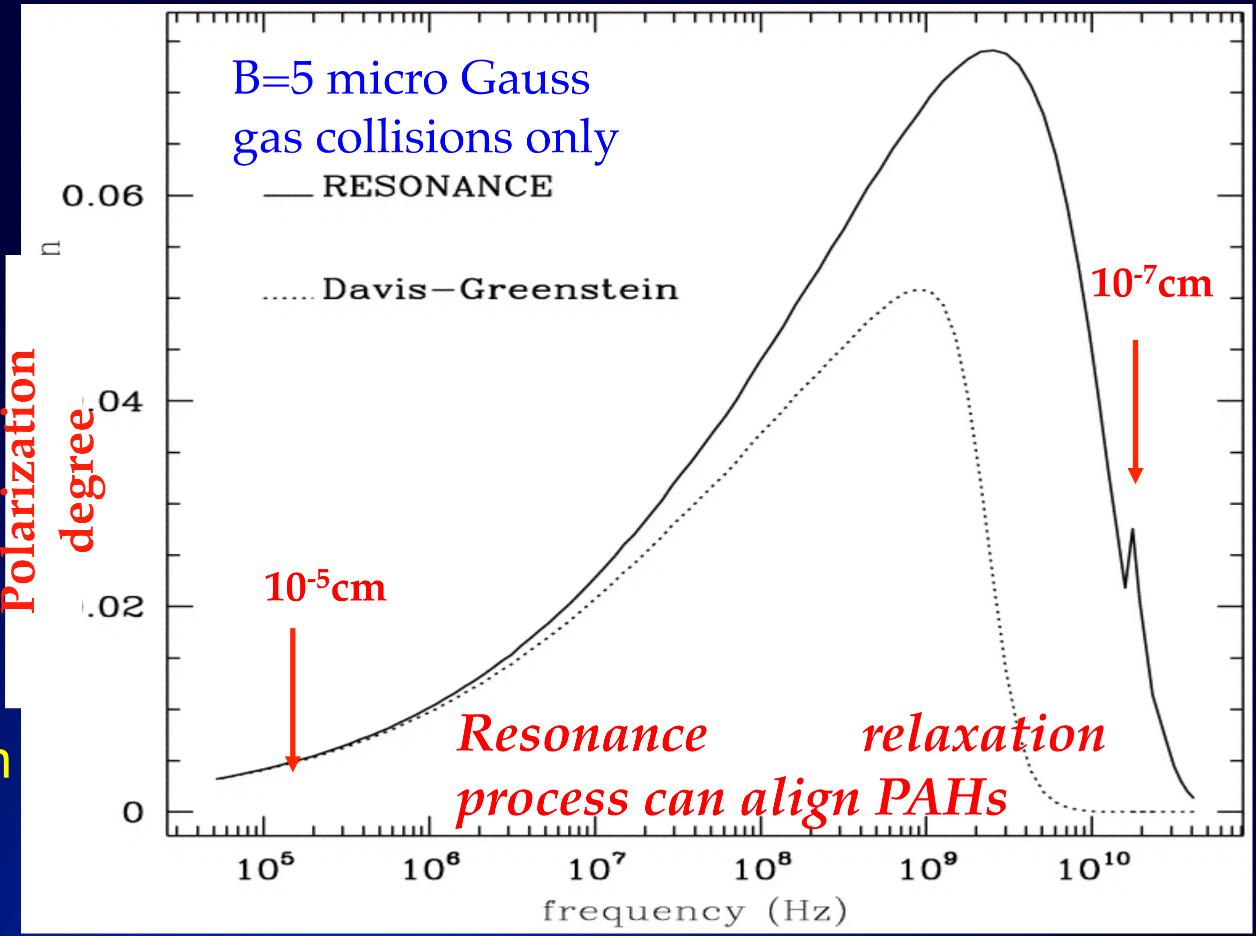
ion

Grains get magnetized as they rotate and this results in resonance paramagnetic relaxation



Magnetization by rotation

(Barnett effect)



B=5 micro Gauss
gas collisions only

Resonance relaxation process can align PAHs

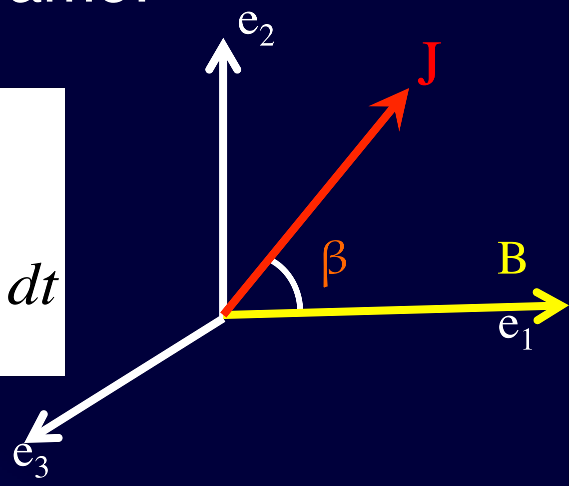
Lazarian & Draine 2000

Theoretical calculations of paramagnetic alignment

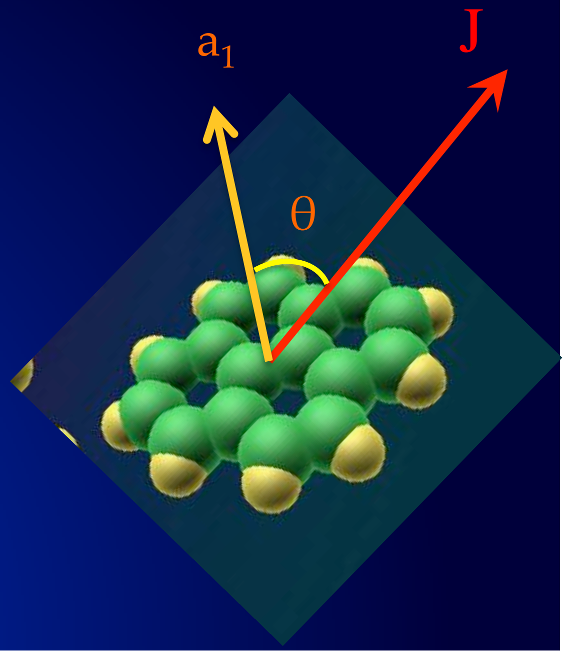
- Evolution of angular momentum **J** in the lab frame:

$$dJ_i = A_i dt + \sqrt{B_{ii}}\, dq_i,\ i = 1 - 3$$

$$A_i = \sum_k \left\langle \frac{\Delta J_i^{\,k}}{\Delta t} \right\rangle, B_{ii} = \sum_k \left\langle \frac{(\Delta J_i^{\,k})^2}{\Delta t} \right\rangle, \left\langle dq^2 \right\rangle = dt$$



- Damping and excitation coefficients (A_i and B_{ii}):
  - dust-neutral and dust-ion collisions
  - infrared emission
  - plasma drag
  - paramagnetic relaxation, i.e., $\tau_{DG}(B)$



- Degrees of alignment:

$R = \langle G_X{}^*G_J \rangle$, $Q_J(J,B) = \langle G_J \rangle$, $Q_X(a_1,J) = \langle G_X \rangle$

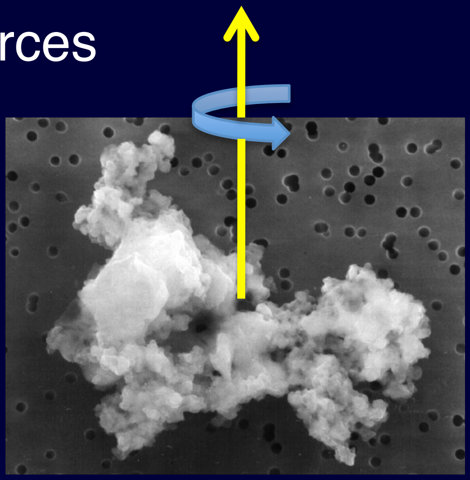
with $G_J = [3\cos^2\beta - 1]/2$, $G_X = [3\cos^2\theta - 1]/2$

Spinning Dust Emission before COBE

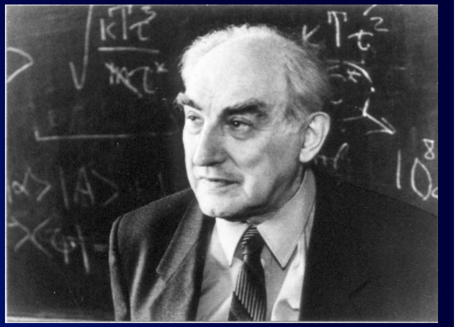
- 1957 Erickson:
  - spinning dust emission as non-thermal radio-noise sources

Dipole Emission from a Spinning Grain:

$$P \sim \omega^4 \qquad \omega \sim r^{-5/2} \qquad P \sim r^{-10}$$



- 1959 Ginzburg & Eidman
- 1970 Hoyle & Wickramasinghe:
  - spinning dust as radio sources in HII regions
- 1994 Ferrara & Dettmar:
  - radio sources in free electron layers of galaxies



Nobel Laureate V.L. Ginzburg

Two radical changes from 80s