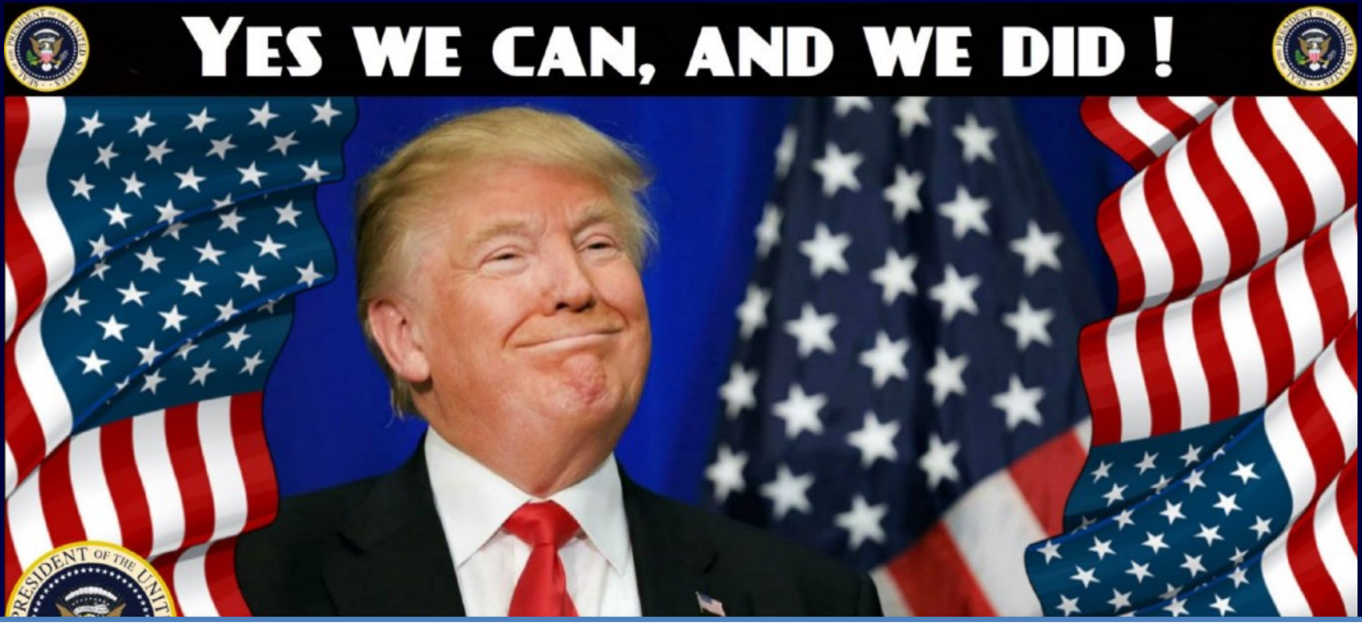
Can we trace magnetic fields via polarized emission by PAHs?

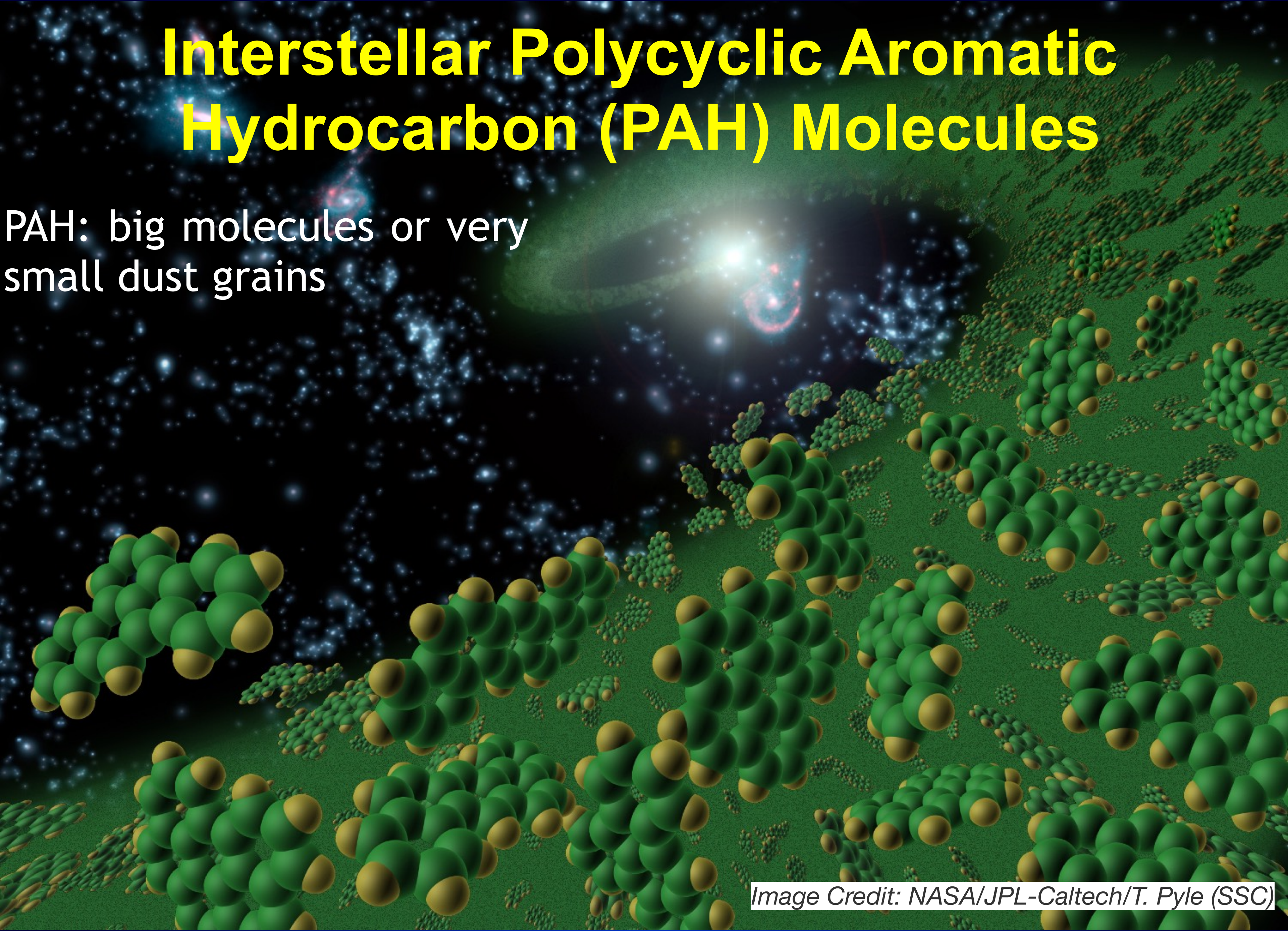


Thiem Hoang, 2017, ApJ, 838, 112 (theory)

H Zhang, CW Telesco, Thiem Hoang et al., 2017, ApJ, 844, 6 (observation)

SFDE17, Quy Nhon, August 6-11, 2017

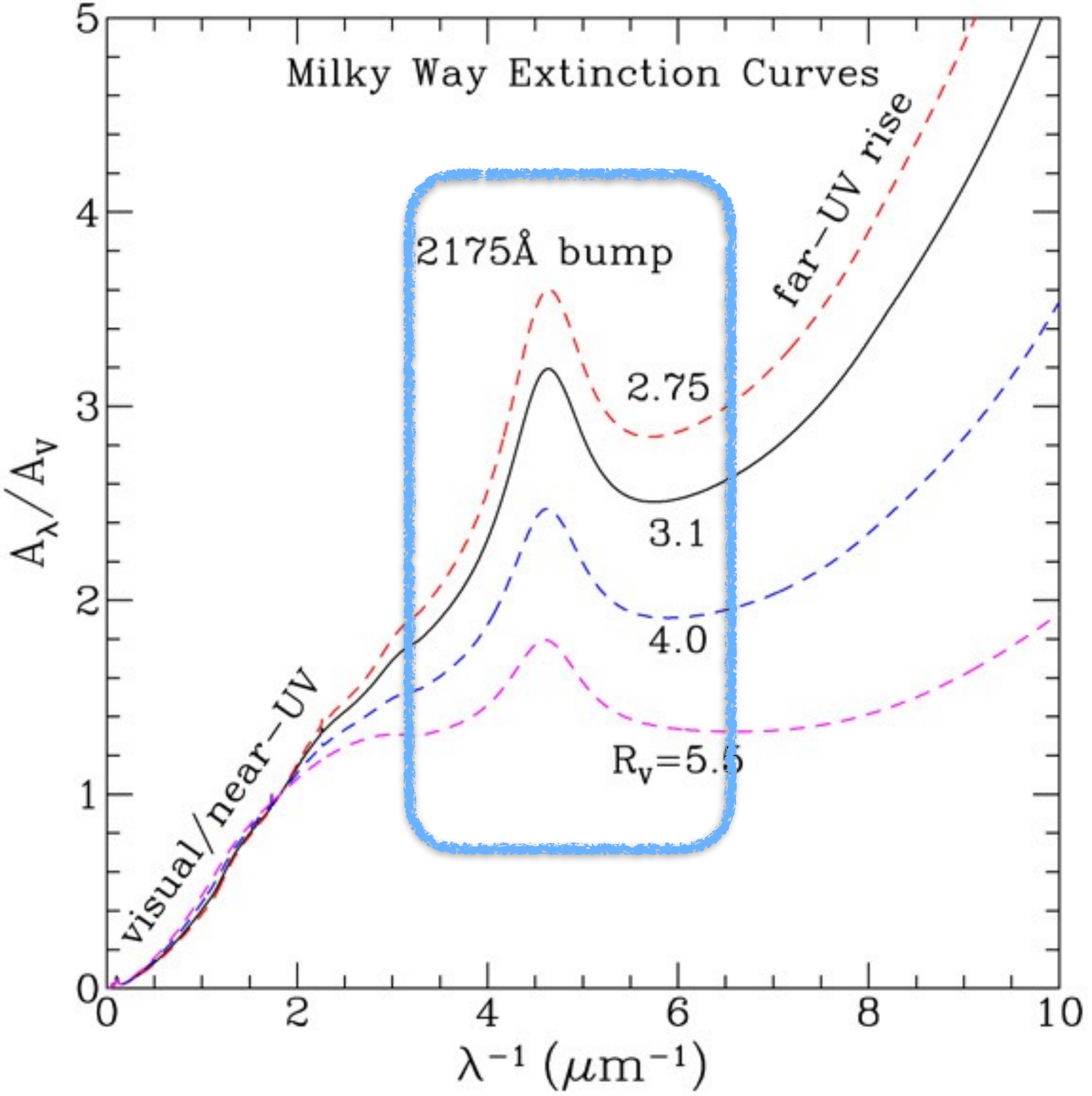
Interstellar Polycyclic Aromatic Hydrocarbon (PAH) Molecules



PAH: big molecules or very small dust grains

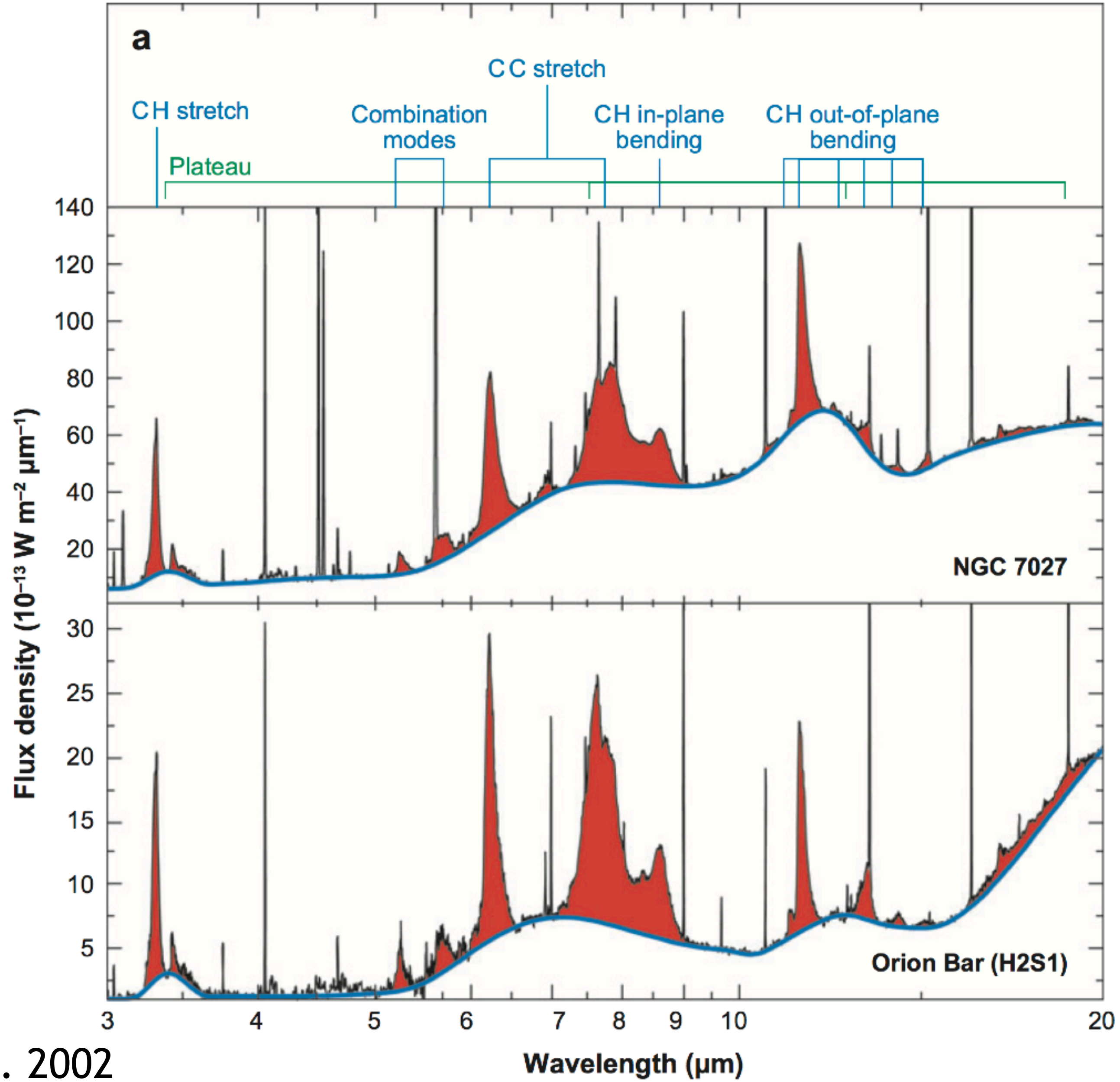
Image Credit: NASA/JPL-Caltech/T. Pyle (SSC)

PAH Absorption and UV Extinction Bump



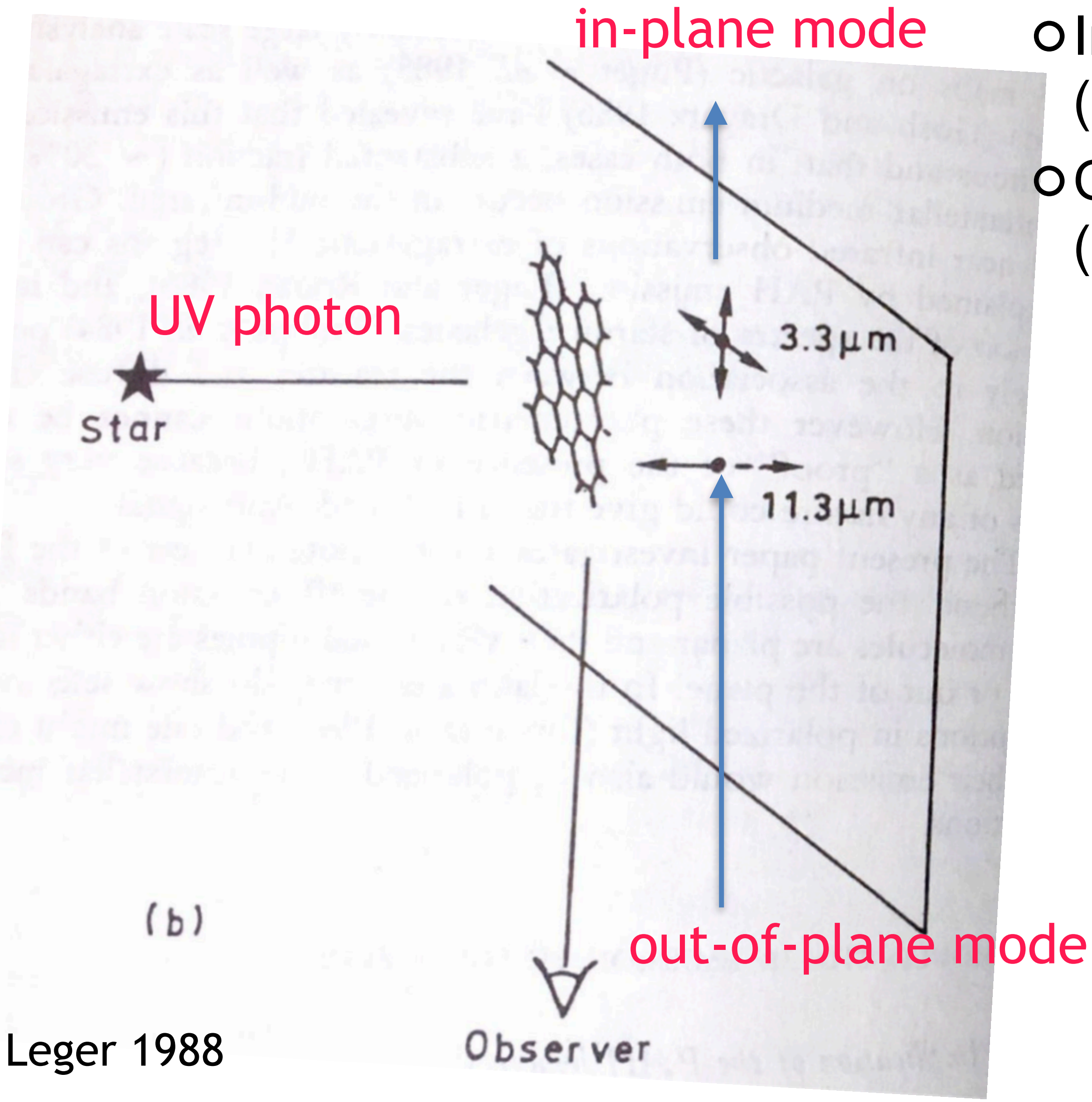
Draine 2003

Mid-IR Emission from PAHs



Peeters et al. 2002

Physics of IR Emission by PAHs



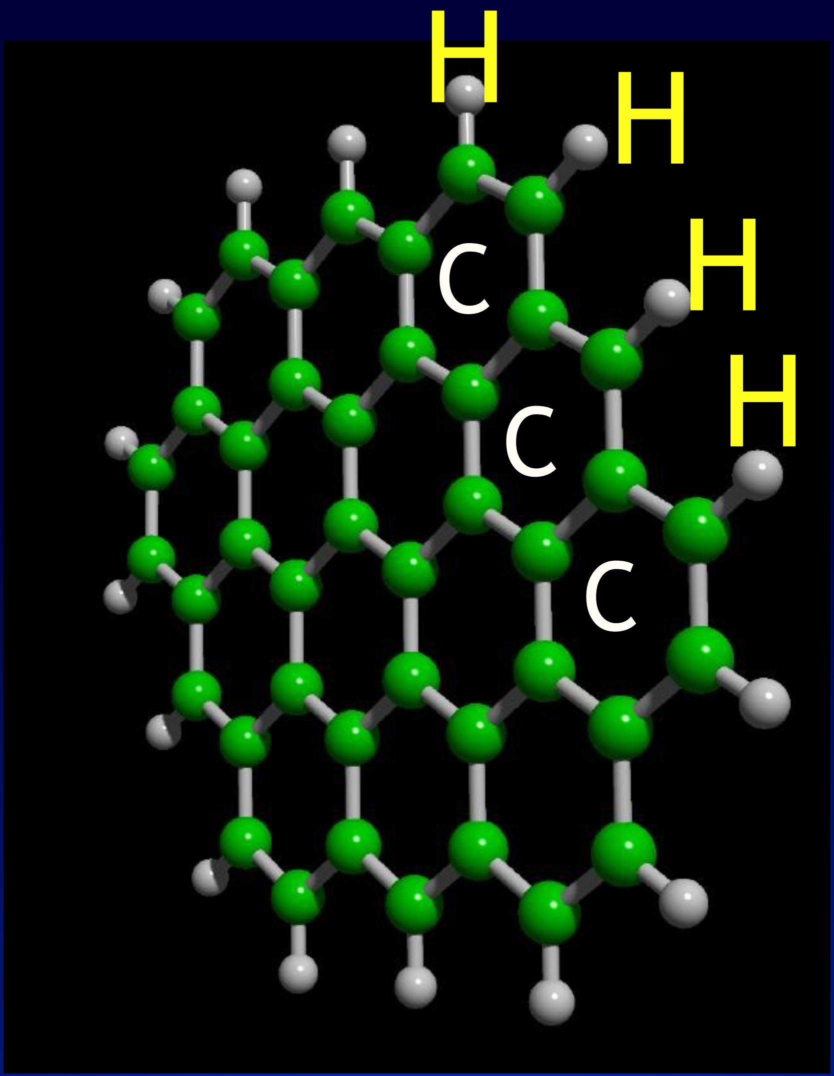
Leger 1988

- In-plane stretching modes (C-C, C-H)
- Out-of-plane bending modes (C-H)

Is Emission by PAHs Polarized?

1. Can PAHs be aligned?
2. What is the polarization of PAH emission?

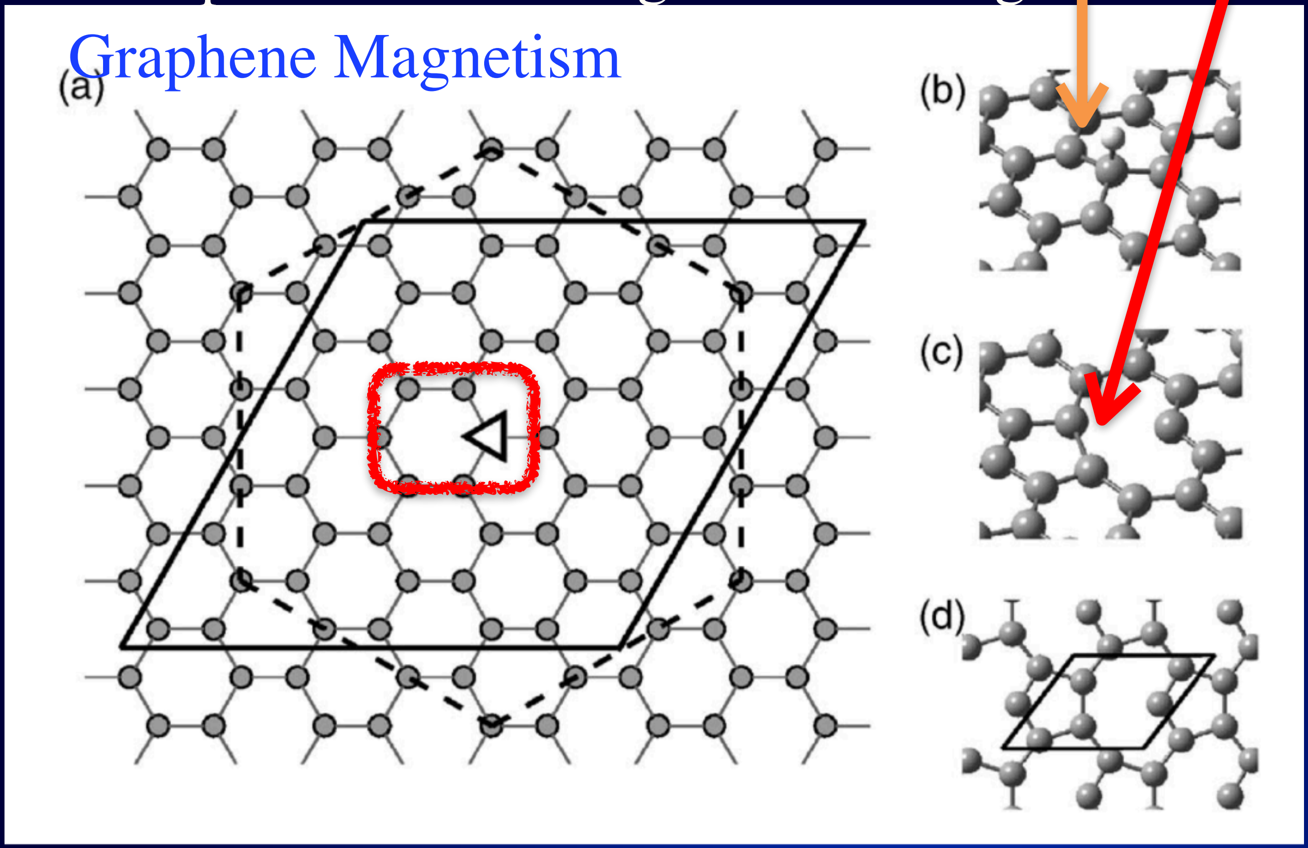
PAH magnetism: ideal PAH are not paramagnetic

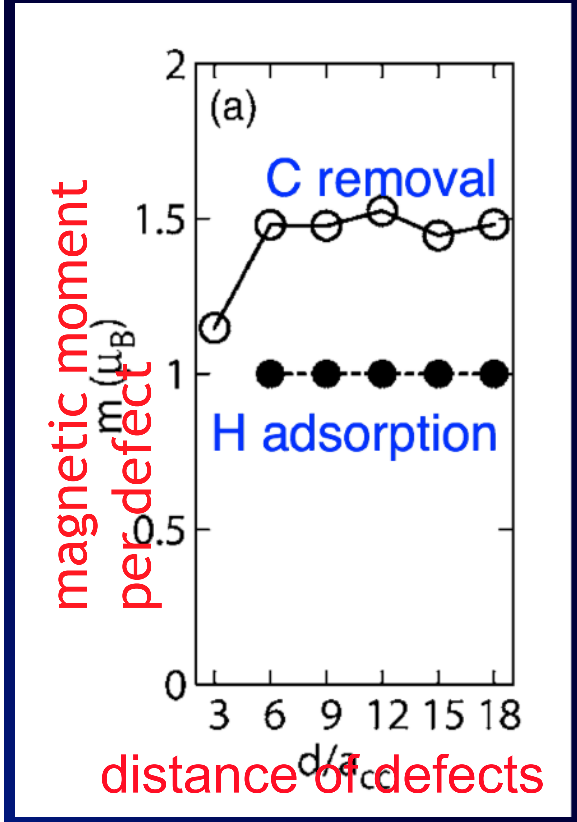


Astrophysical PAHs can get magnetized due to defects

C vacancy creates unpaired electrons

H adsorption incudes magnetic ordering





Yazyev & Helm 2007

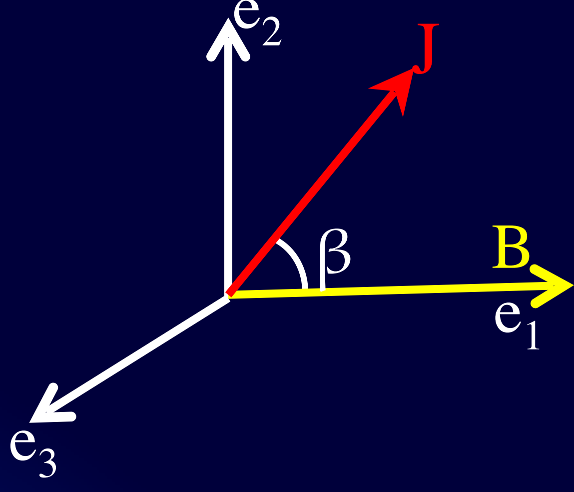
Paramagnetic PAHs can be aligned by resonance paramagnetic relaxation (Lazarian & Draine 2000)

Simulations of PAH Alignment

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

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

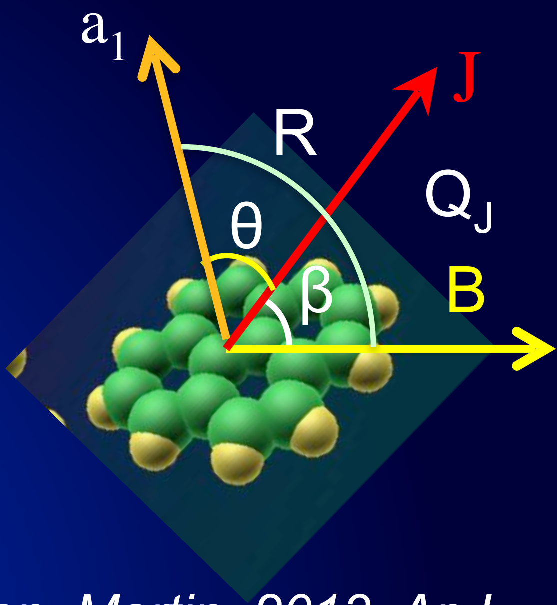
$$A_i = \sum_k \left\langle \frac{\Delta J_i^k}{\Delta t} \right\rangle, B_{ii} = \sum_k \left\langle \frac{(\Delta J_i^k)^2}{\Delta t} \right\rangle, \langle dq^2 \rangle = dt$$



- Damping and excitation coefficients (A_i & B_{ii})
  - resonance paramagnetic relaxation
  - grain-neutral collision
  - grain-ion collisions
  - infrared emission
  - plasma drag by passing ions
- Degrees of alignment:

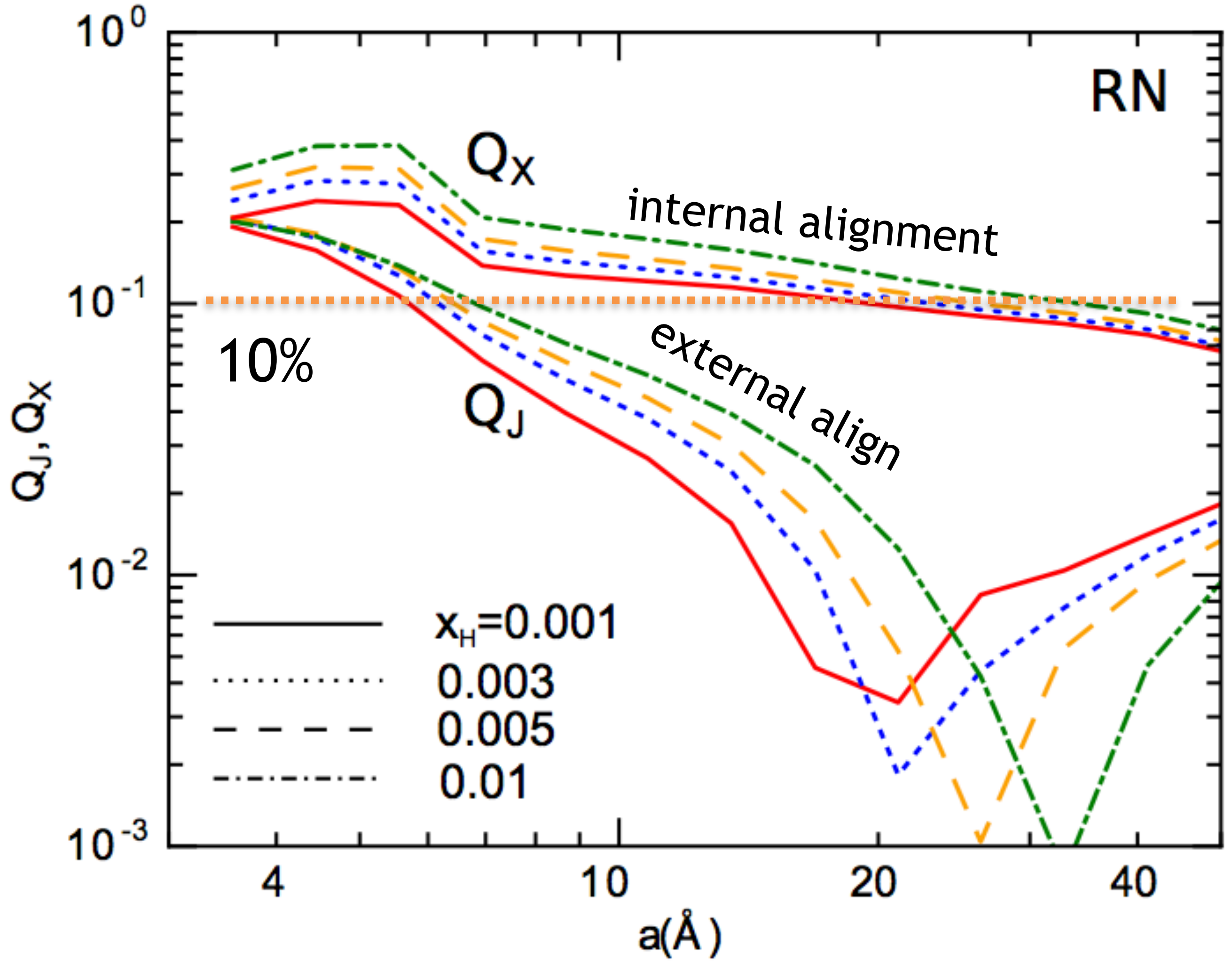
$Q_J(J,B) = \langle G_J \rangle$, $Q_X(a_1,J) = \langle G_X \rangle$, $R = \langle G_X * G_J \rangle$

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



Hoang, Lazarian, Martin, 2013, ApJ

Alignment of PAHs in Reflection Nebula



- ○ Degree of PAH alignment increases with increasing x_H
- ○ Alignment degree rises toward smaller sizes

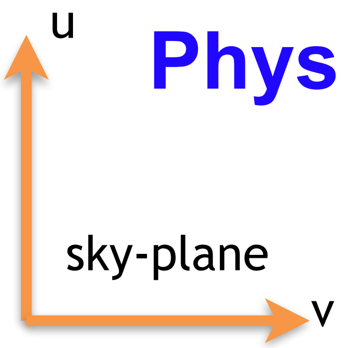
New Model of Polarized IR Emission by PAHs

References:

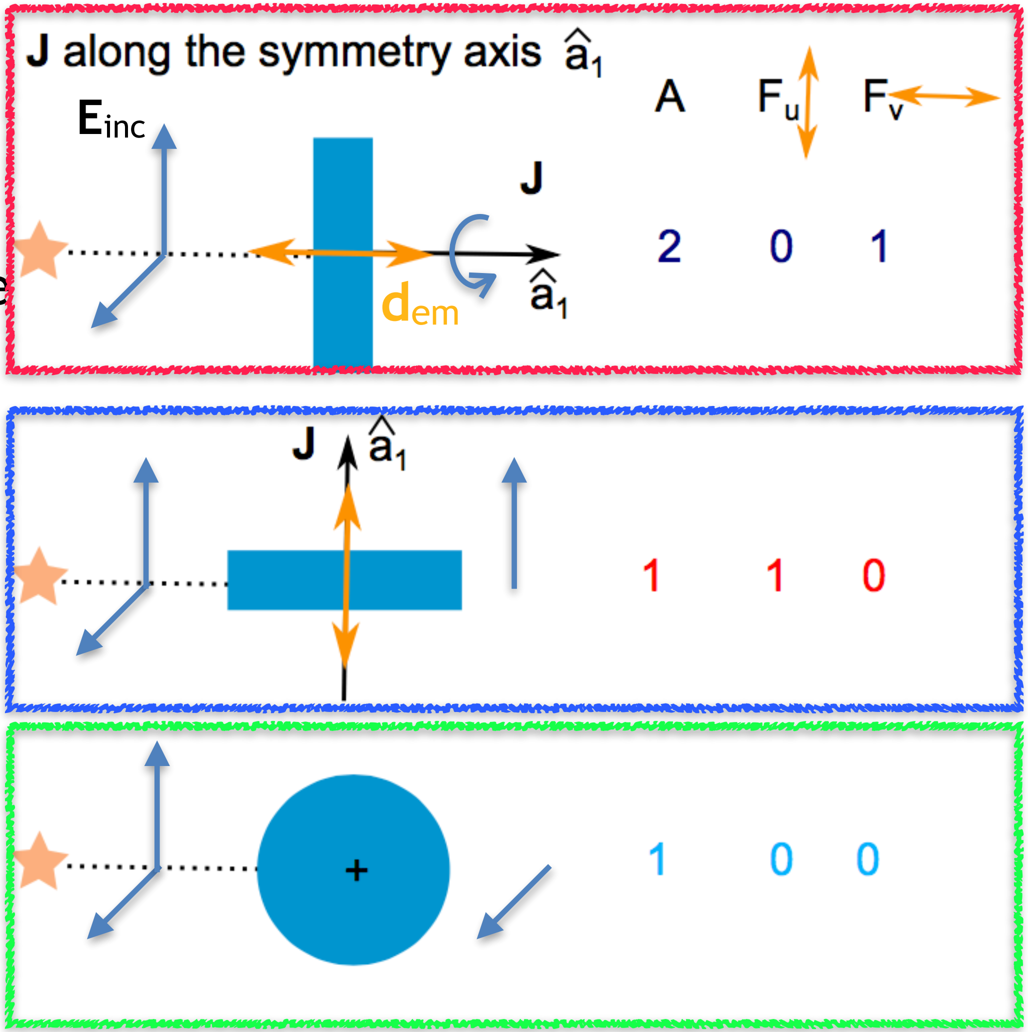
Hoang Thiem, 2017, ApJ, 838, 112 (theory)

Han Zhang, Charles Telesco, Hoang Thiem, et al., ApJ, 844, 6 (observation)

Physics of Polarized IR Emission by PAH



Out-of-plane emission mode



Absorption cross-section

A = <$\mathbf{E}_{inc}$.$\mathbf{d}_{abs}$>,

$\mathbf{d}_{abs}$ absorption dipole on PAH plane

Emission cross-section

F_w = <$\mathbf{w}$.$\mathbf{d}_{em}$>, w= u, v

Case 1: J parallel to a_1

$$I_{u,\|} = \sum_{i=1}^{3} W_i A_i F_u = \frac{1}{3},$$

W_i=1/3 for iso J

$$I_{v,\|} = \sum_{i=1}^{3} W_i A_i F_v = \frac{1}{3}2,$$

Polarization degree

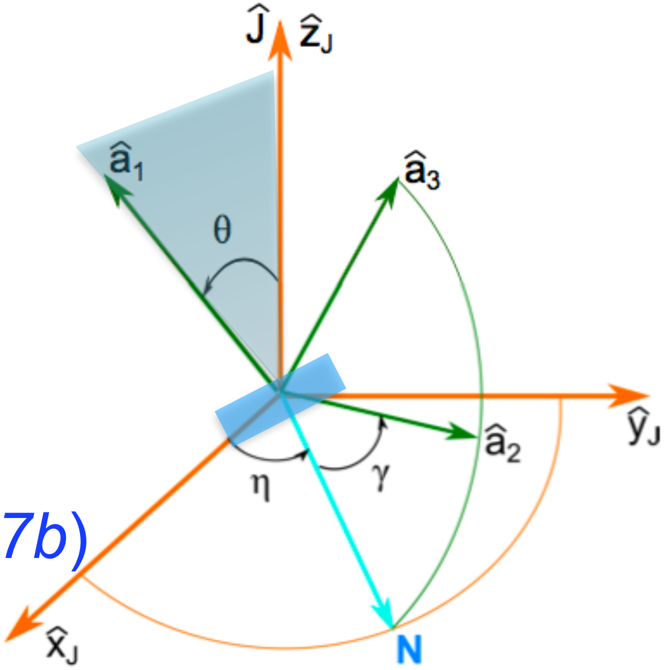
p = (I_u-I_v)/(I_u+I_v) = -1/3 ~ -33%. Too large

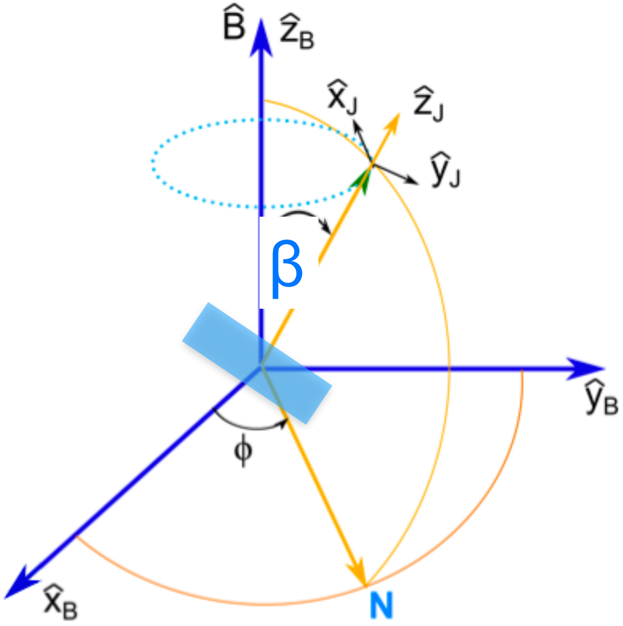
A general Model of Polarized PAH Emission

○ **Two main physical effects:**

1. Thermal fluctuations, before and after UV absorption. PAH axes not tied to **J** (*Leger 1988, Sironi & Draine 2009*).

2. Alignment of **J** with **B**-field (*Hoang 2017b*)





New Model: Effect of PAH alignment with B-field

Total emission intensity:

before UV absorb., fixed **J**

$$I^{\|,\perp}_{\star,w}(\alpha,\psi)=\int f_J(\mathbf{J})d\mathbf{J}\left[\int_0^{\pi} f_0(\theta_0,J)d\theta_0\int_0^{\pi} f_{ir}(\theta,J)d\theta \times A_\star(\beta,\theta_0)F^{\|,\perp}_{w}(\beta,\varphi,\theta,\alpha)\right], \qquad (2)$$

during IR emission, fixed **J**

J-distribution

Ergodic Approximation:

$$I^{\|,\perp}_{\star,w}=\int f_J(\mathbf{J})d\mathbf{J}\times\mathcal{I}^{\|,\perp}_{w}=\frac{1}{N}\sum_{\{J,\beta,\varphi\}_i;i=1}^{i=N}\mathcal{I}^{\|,\perp}_{w}(J_i,\beta_i,\varphi_i)$$

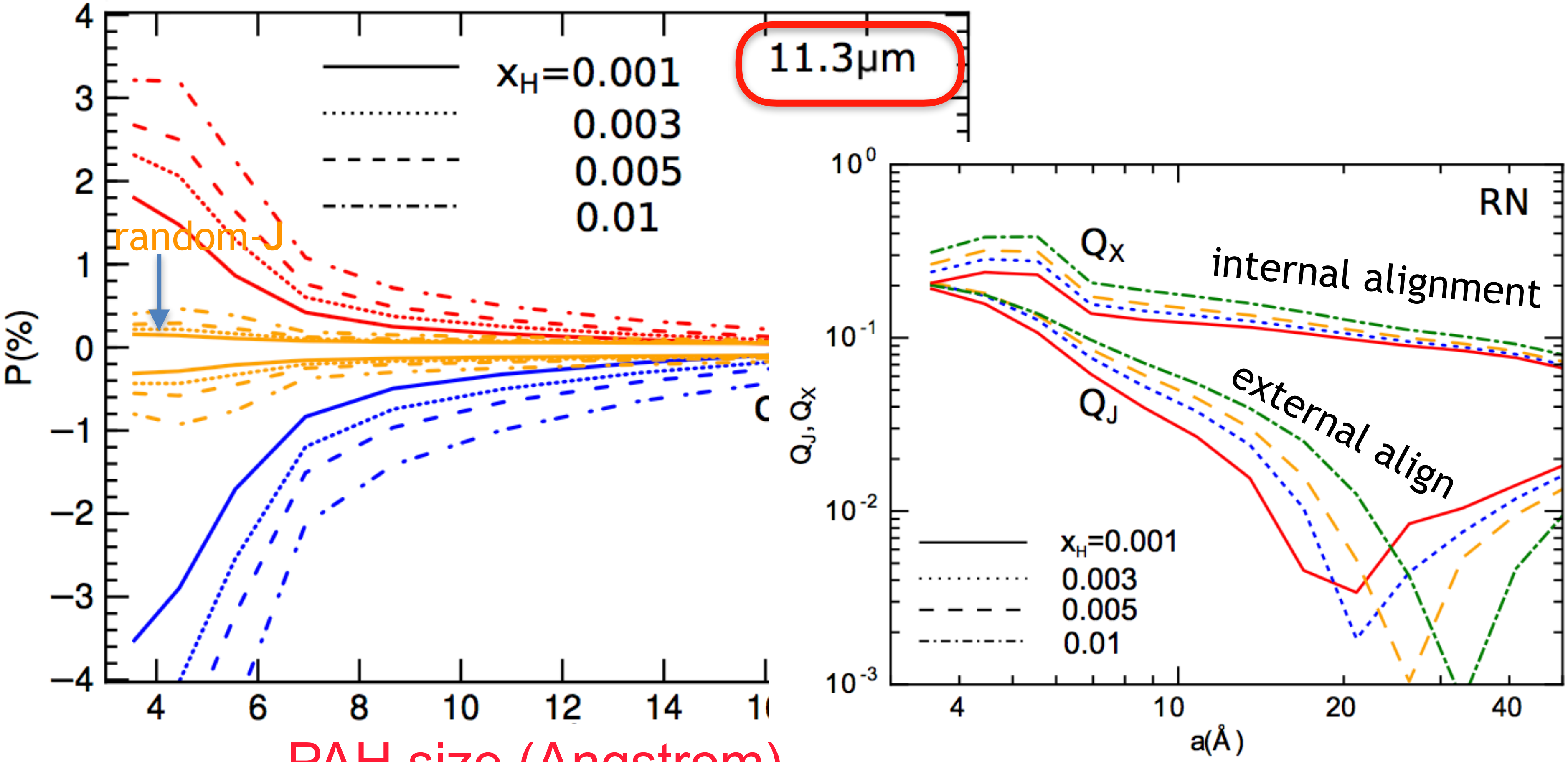
$\{J\}_i$: $N=10^7$ orientation of **J** from simulations

Polarization degree

$$p^{\|,\perp}(\alpha,\psi)=\frac{I^{\|,\perp}_{u}(\alpha,\psi)-I^{\|,\perp}_{v}(\alpha,\psi)}{I^{\|,\perp}_{u}(\alpha,\psi)+I^{\|,\perp}_{v}(\alpha,\psi)}, \qquad (3)$$

Hoang Thiem 2017, ApJ, 838, 112

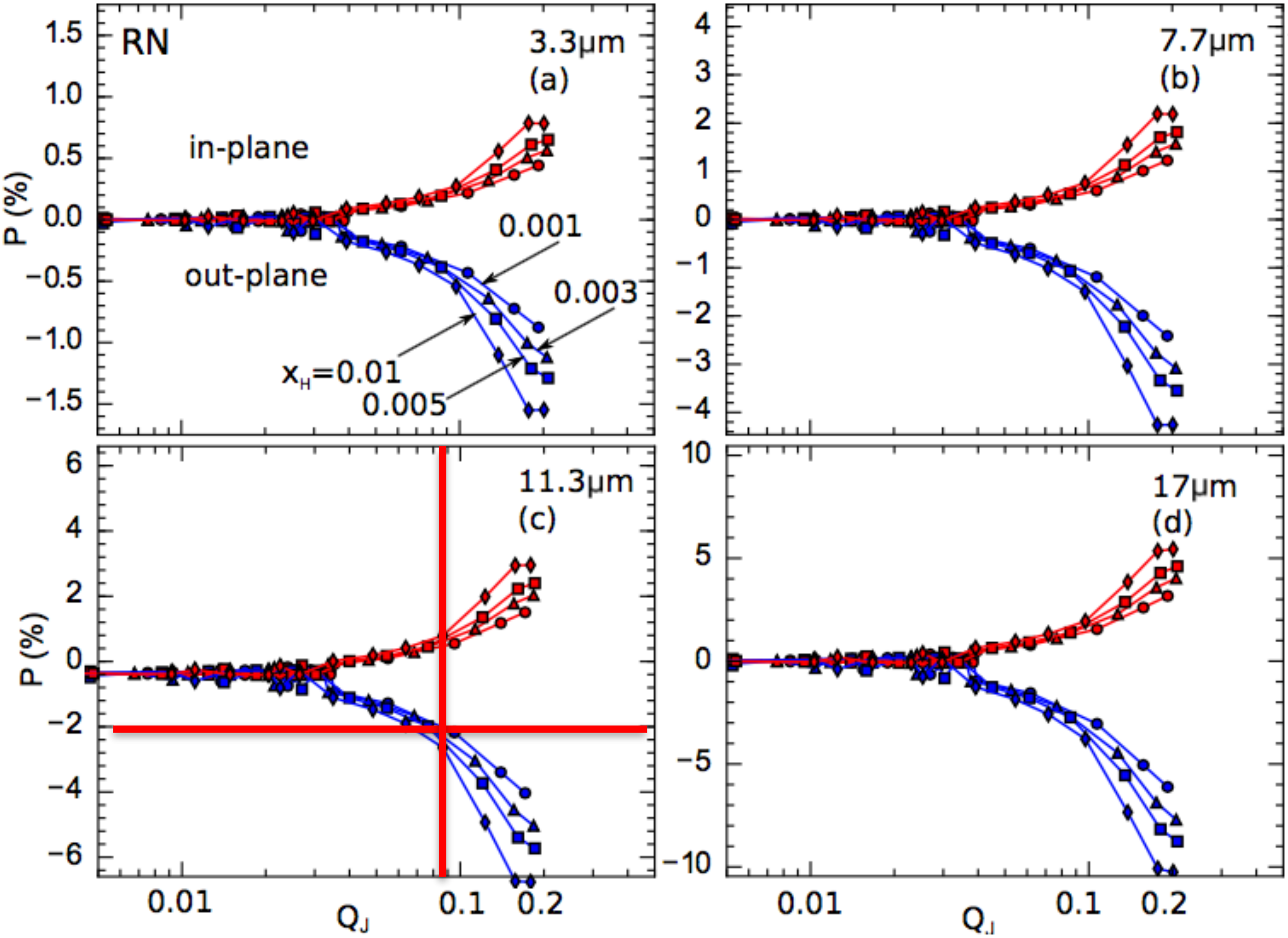
Polarized Mid-IR Emission from Reflection Nebula



PAH size (Angstrom)

- Degree of polarization increases with increasing x_H
- Polarization rises toward smaller PAHs
- At typical $x_H=10^{-3}$, P ~ 4%

Polarization degree vs. PAH alignment

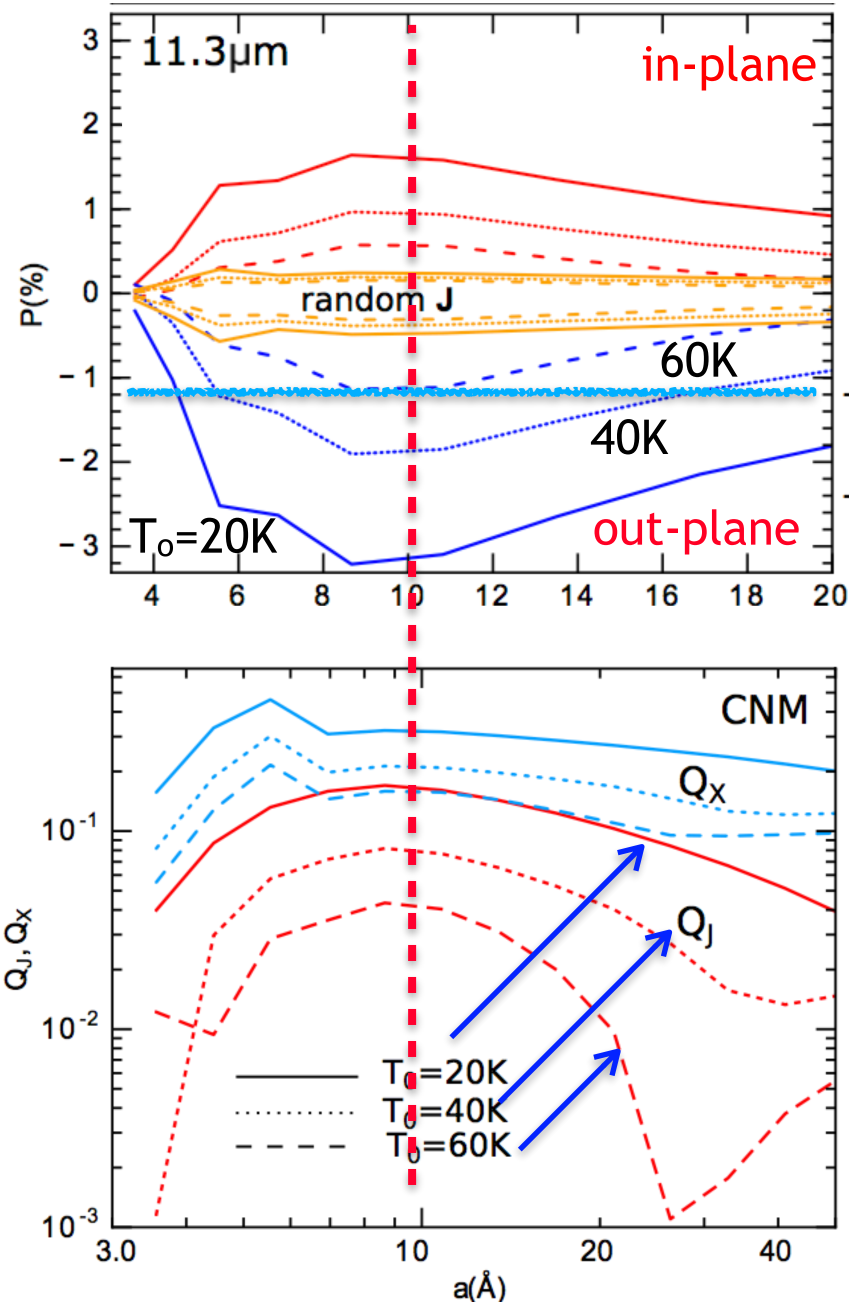


Alignment Degree

- Polarization increases with the alignment degree
- Pol increases with the emission wavelength

Hoang Thiem 2017, ApJ, 838, 112

Polarized IR emission from the diffuse ISM

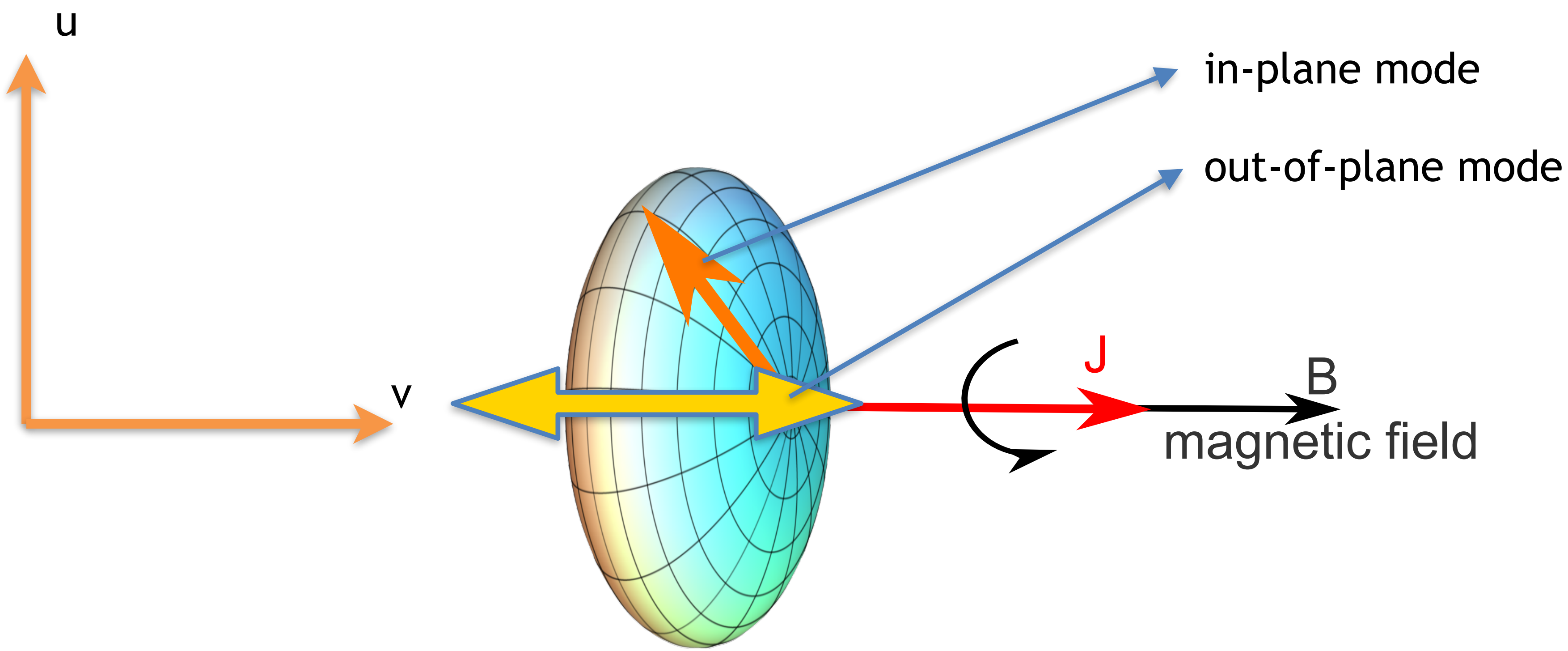


- **Model:** Dust temperature T_o changes, gas density and ionization x_H constant

- Degree of polarization increases with decreased T_o
- Peak polarization occurs at a ~ 10 A
- At typical T_o=60K, P < 1%
- Our P is much larger than the result from Sironi & Draine (2009) model with random **J**

- Degree of PAH alignment increases with decreasing T_o
- Peak alignment degree at a ~ 10 A

Polarization angle and B-field direction



- In-plane emission mode: **P** perp. to **B**-field
- Out-of-plane emission mode: **P** along **B**-field

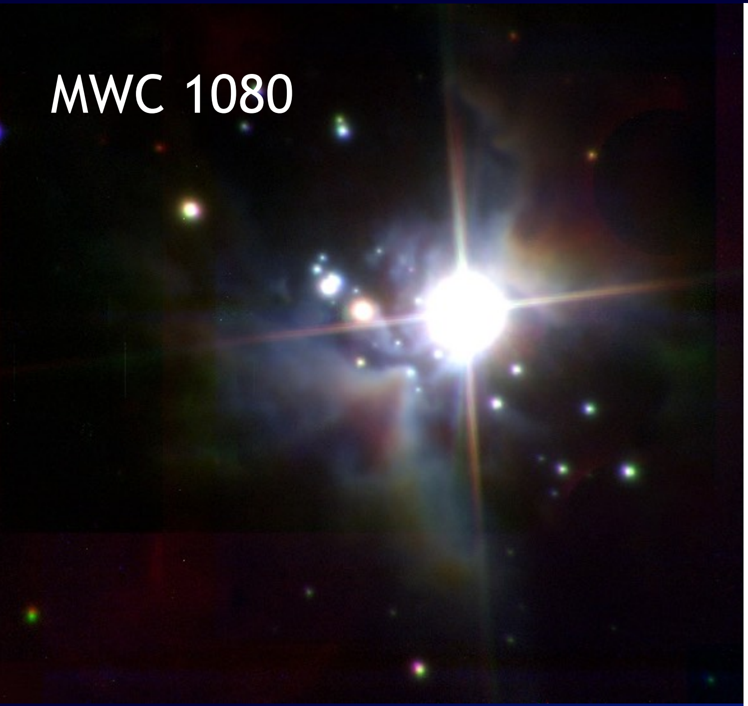
First Detection of Polarized Emission at 11.3 micron

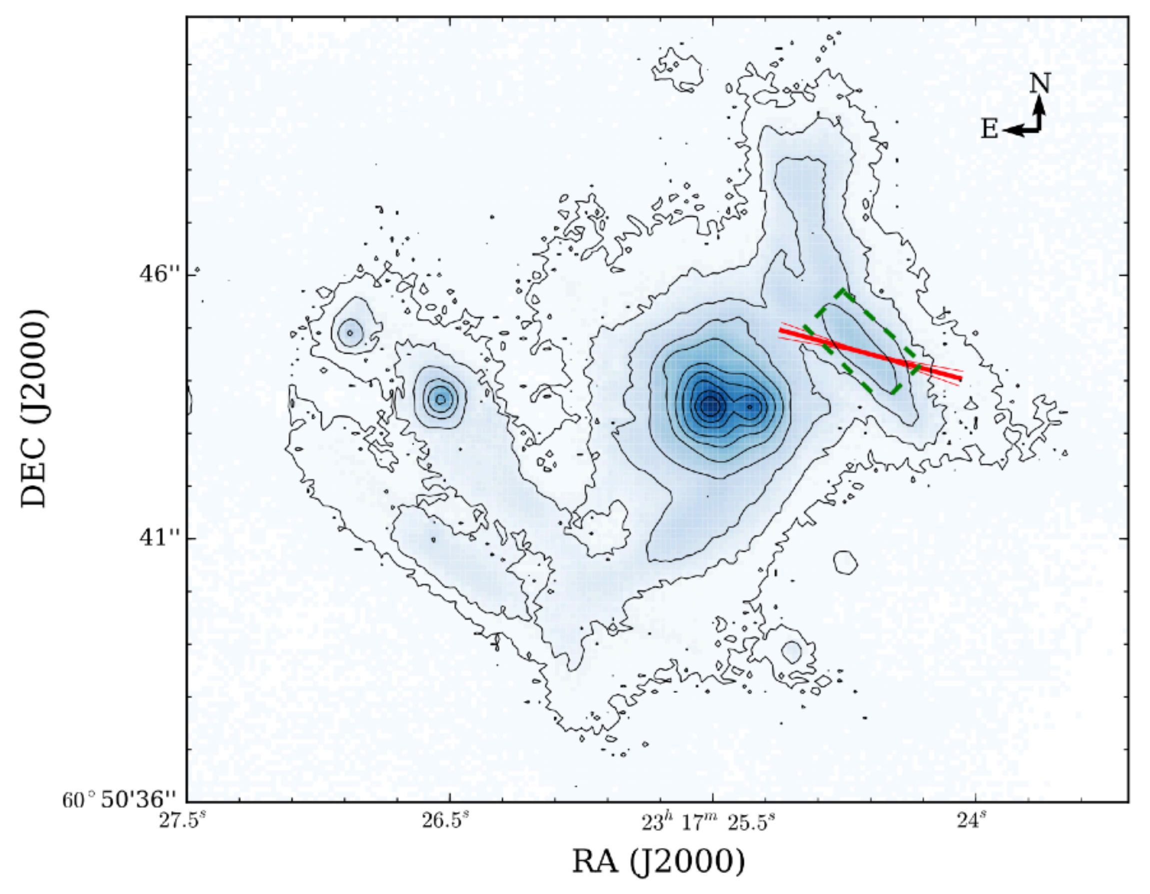
Confirmation of PAH alignment with B-field

H Zhang, CW Telesco, Hoang Thiem et al., 2017, ApJ, 844, 6

Polarized PAH Emission from MWC 1080

Out-of-plane (C-H) mode: 11.3um

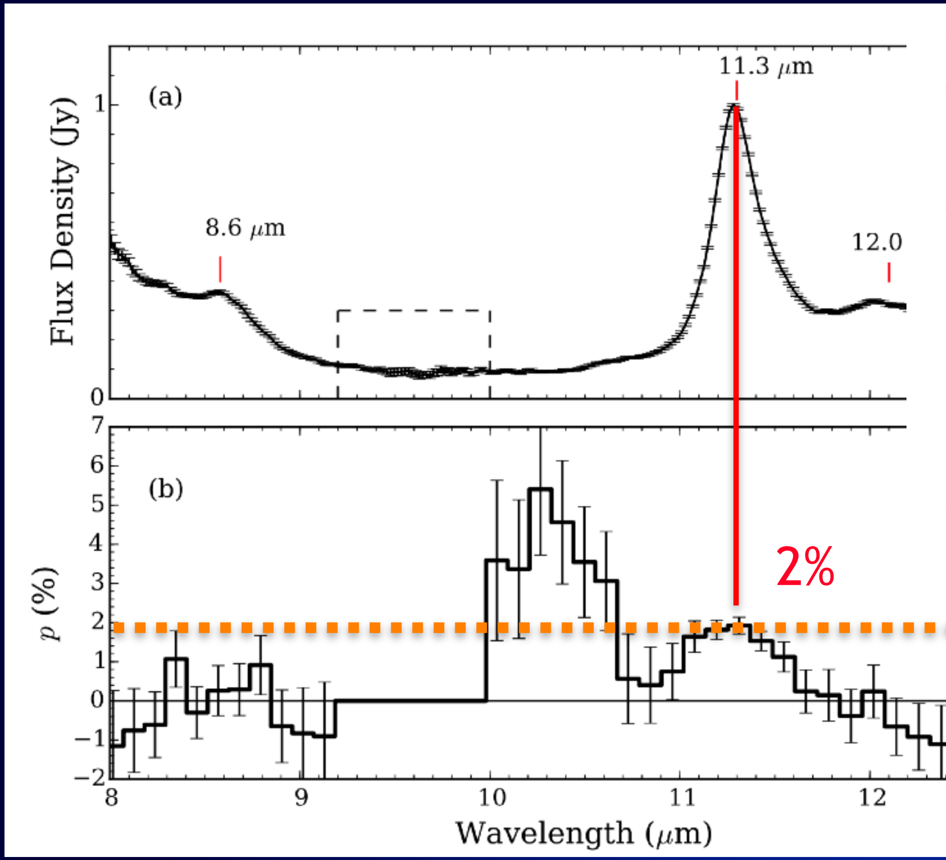




Han, Telesco, Hoang, et al. 2017
Using CanariCam/GTC telescope

Pol degree consistent with our predictions

Theoretical Predictions



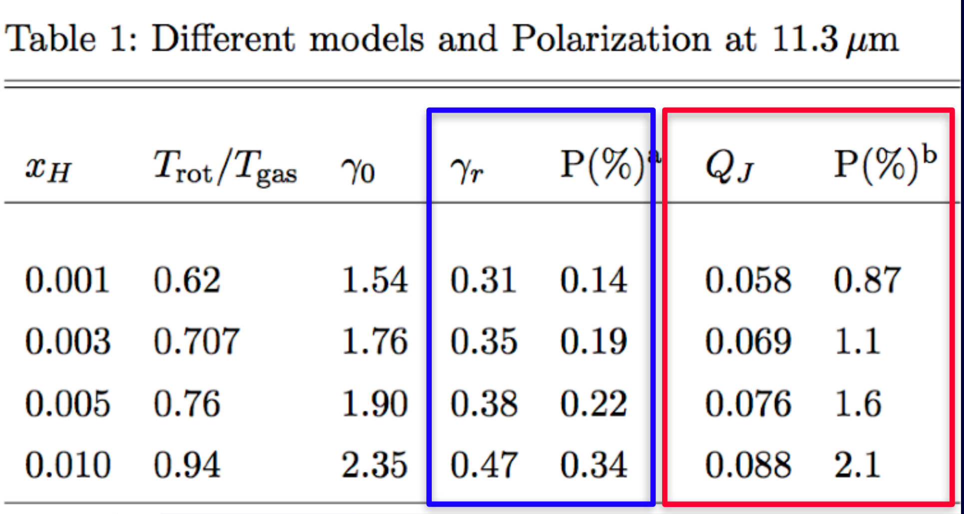
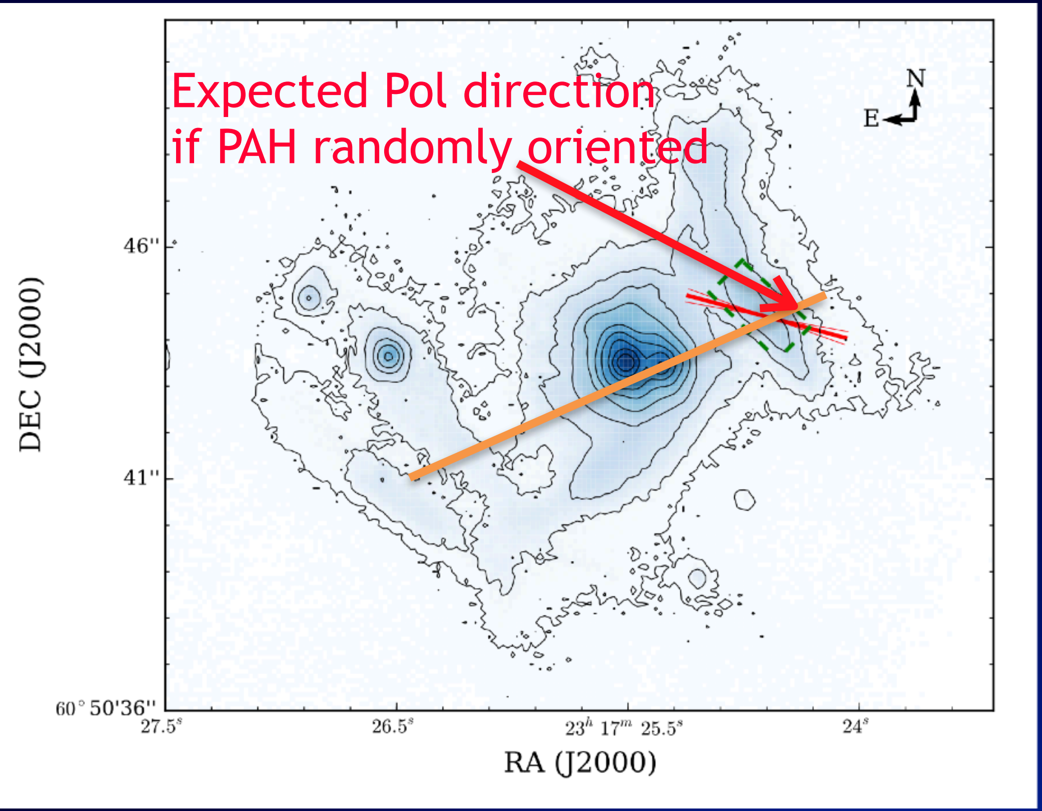
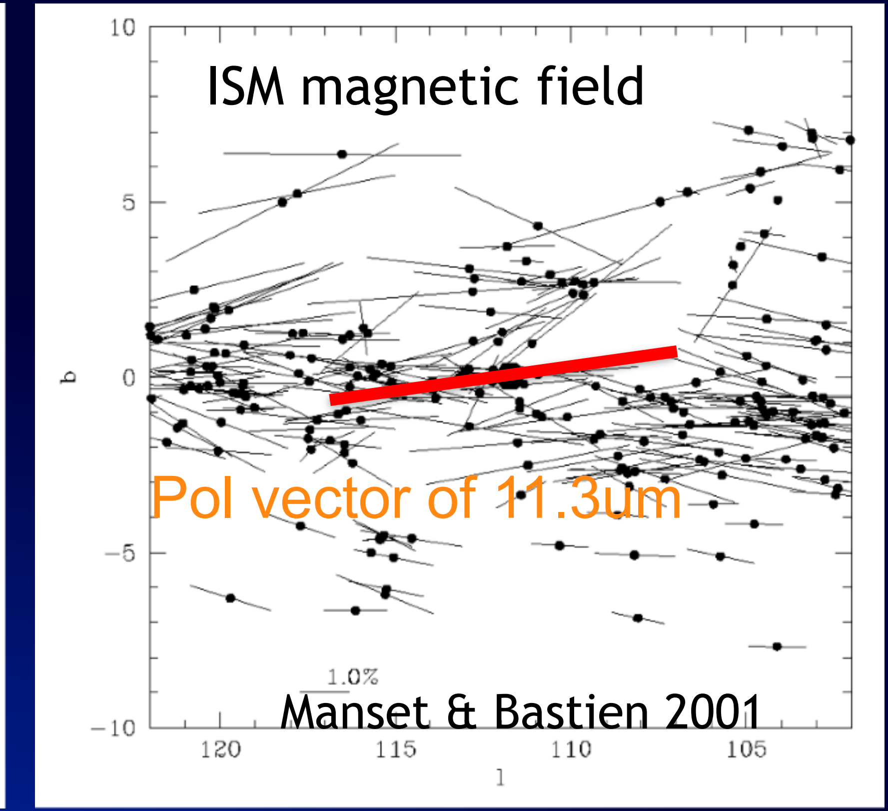


Table 1: Different models and Polarization at 11.3 μm

x_H	$T_{\rm rot}/T_{\rm gas}$	γ_0	γ_r	P(%)^a	Q_J	P(%)^b
0.001	0.62	1.54	0.31	0.14	0.058	0.87
0.003	0.707	1.76	0.35	0.19	0.069	1.1
0.005	0.76	1.90	0.38	0.22	0.076	1.6
0.010	0.94	2.35	0.47	0.34	0.088	2.1

Pol angle along B-field, as predicted

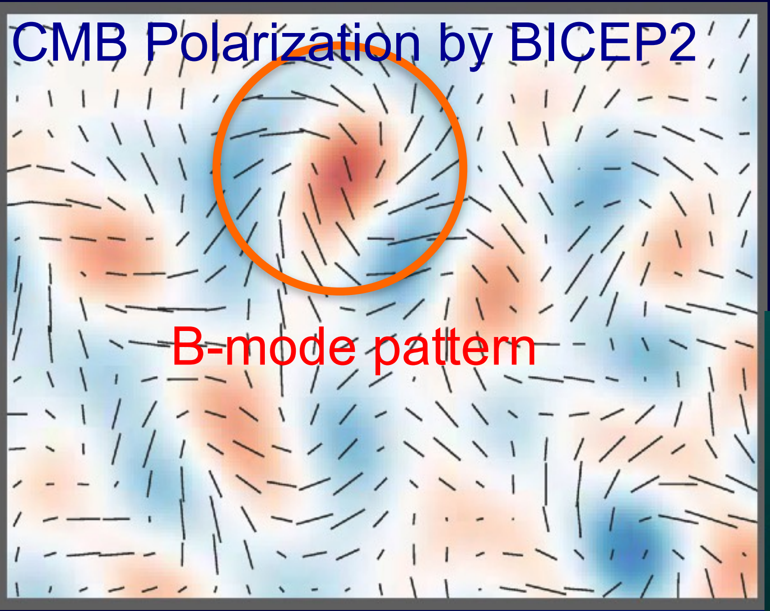




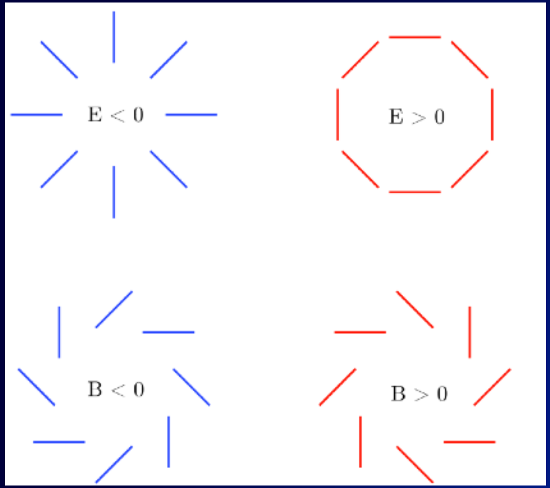
- ★ Polarization vector is along the ambient magnetic field as predicted
- ★ Evidence for PAH alignment with the B-field

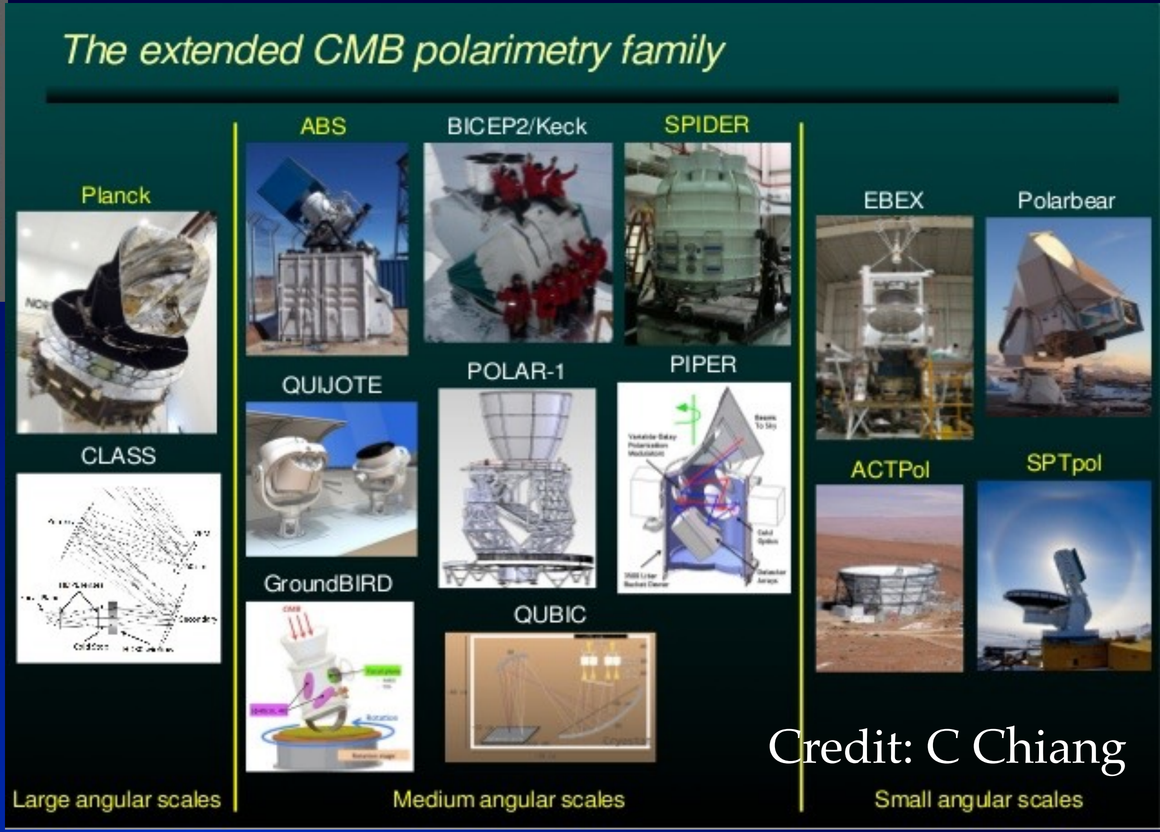
Golden Age of CMB Polarimetry:

Measuring Gravitational Waves with CMB B-Modes



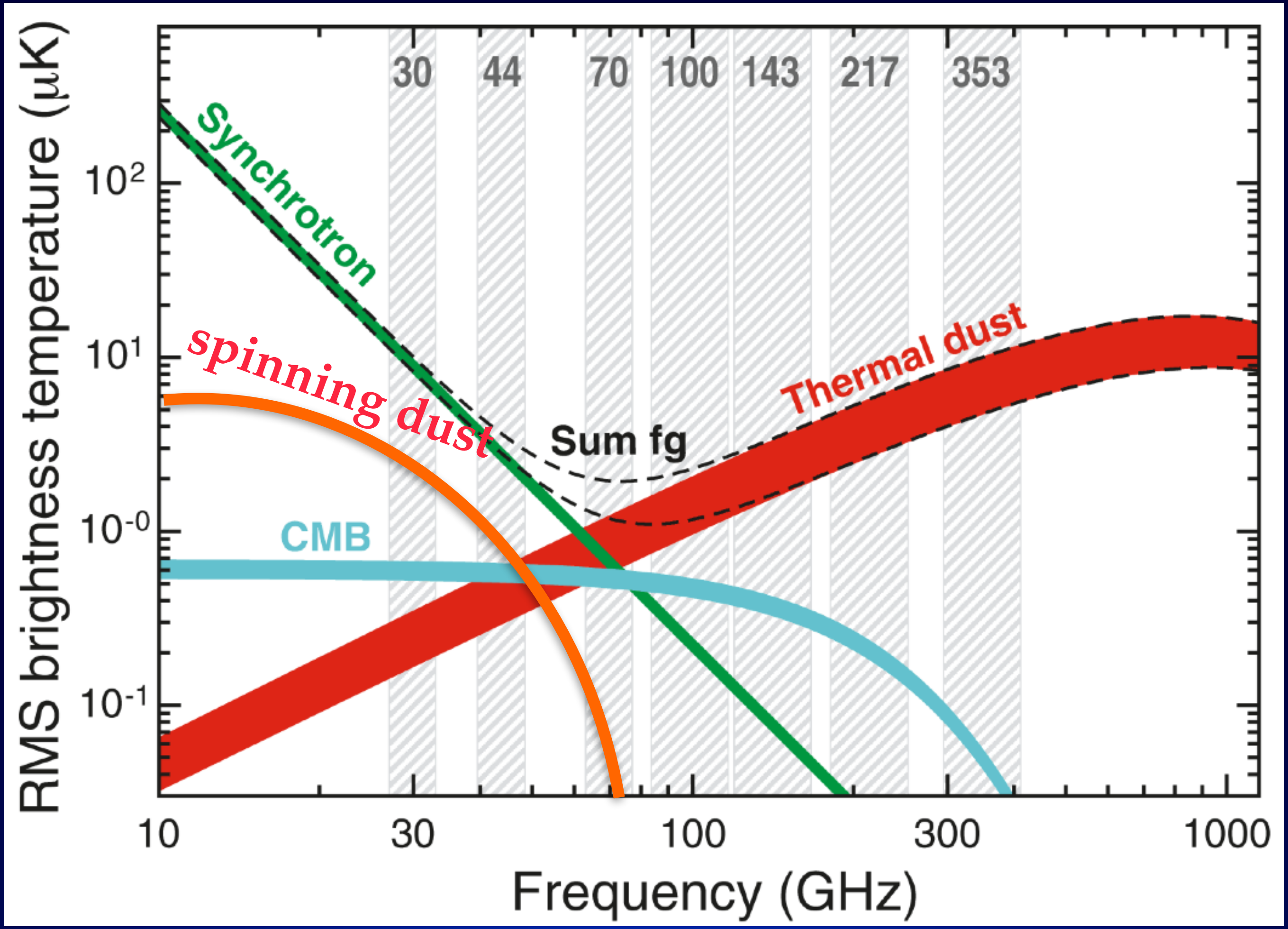
CMB: Cosmic Microwave Background





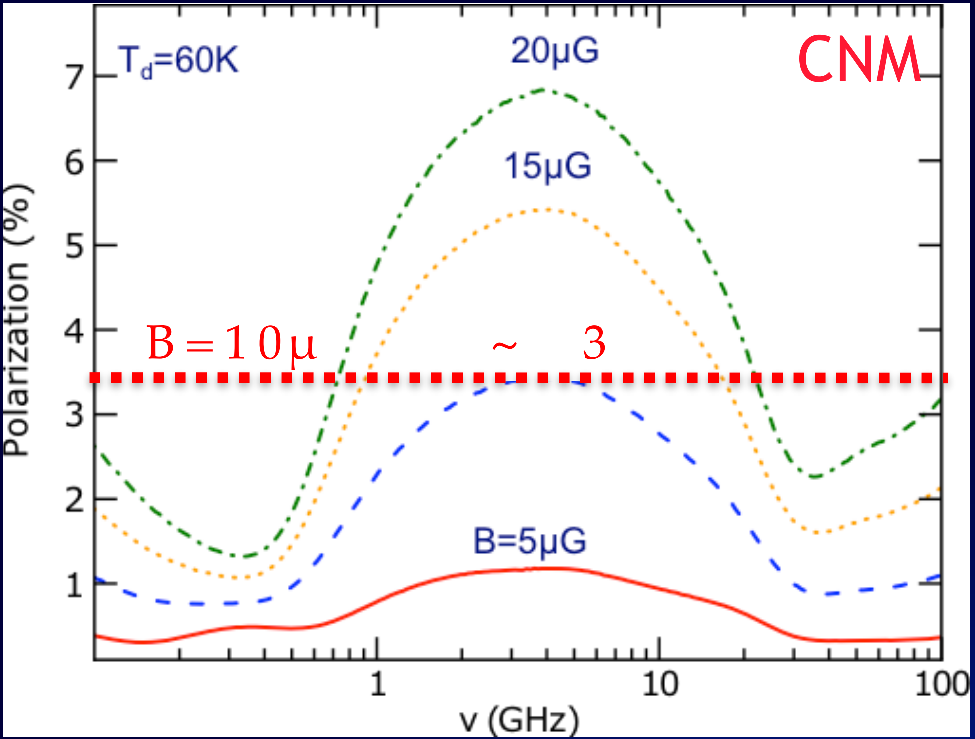
Credit: C Chiang

Spindust polarization: a challenge for CMB B-modes detection

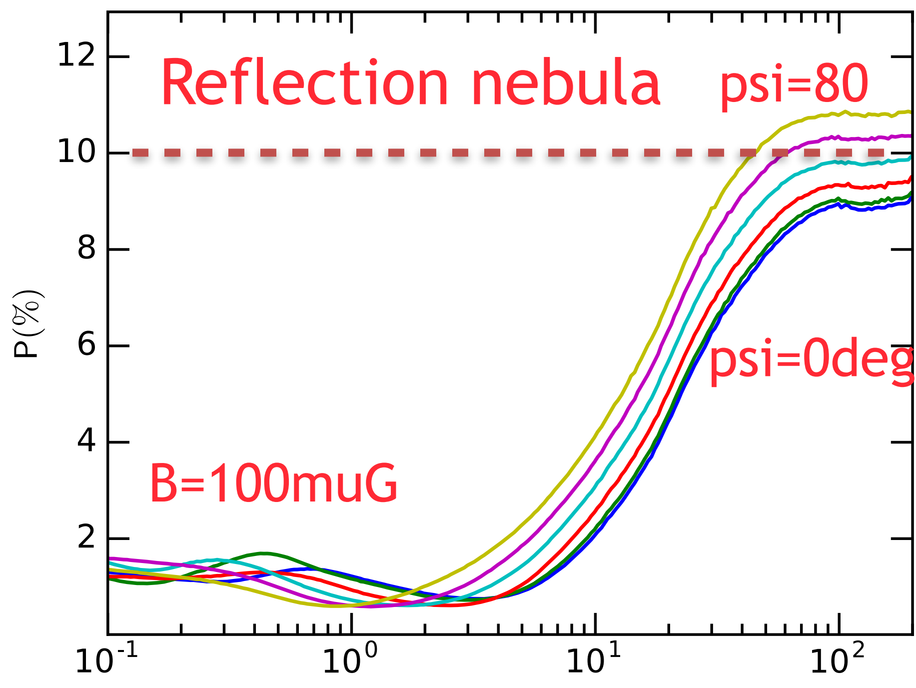


Polarized intensity (Planck Collaboration et al. 2016, I. Overview of products and scientific results, lu: 73-93% sky)

Polarization of spinning PAH Emission

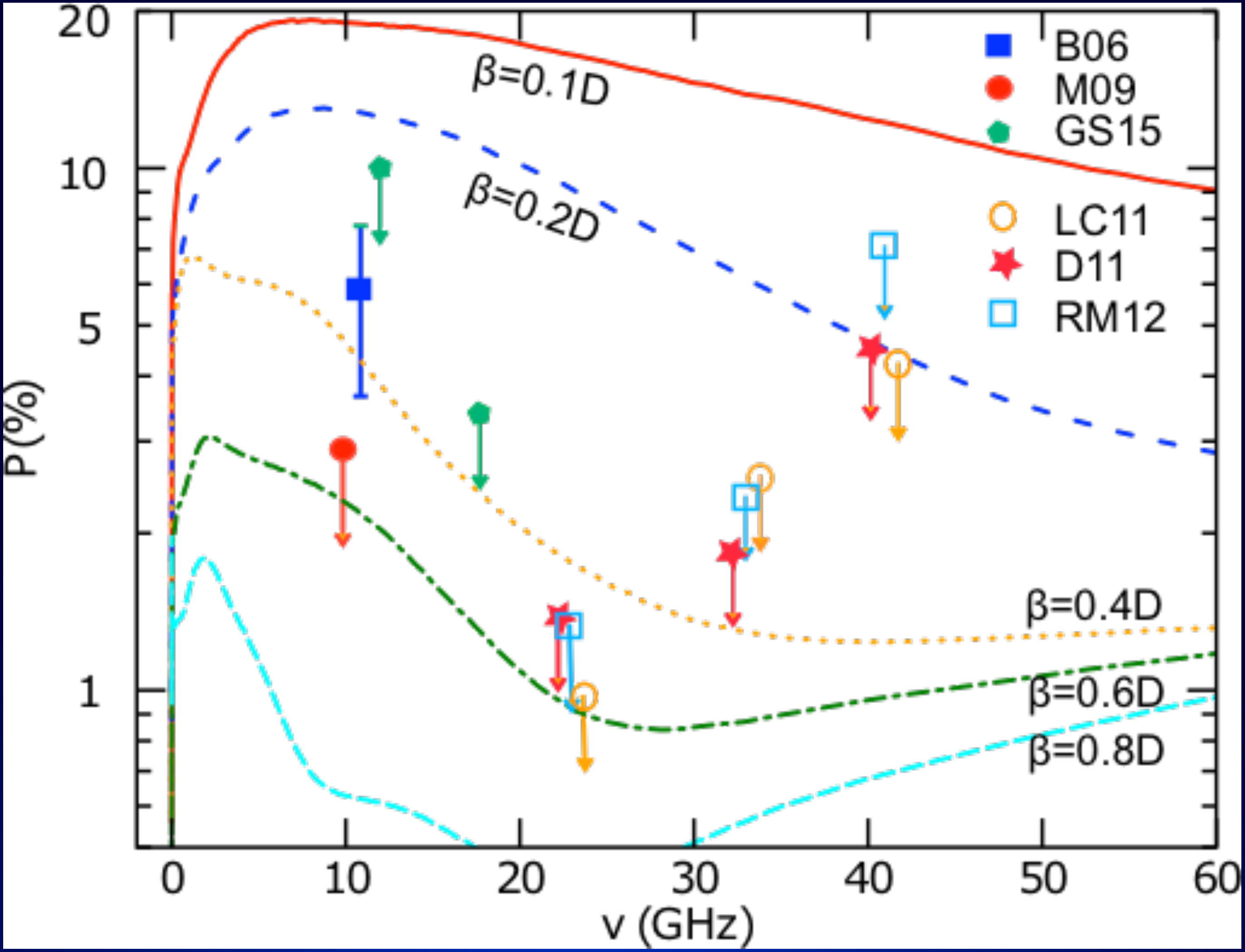


Polarization increases with the magnetic field strength, ranging from 1-10 %



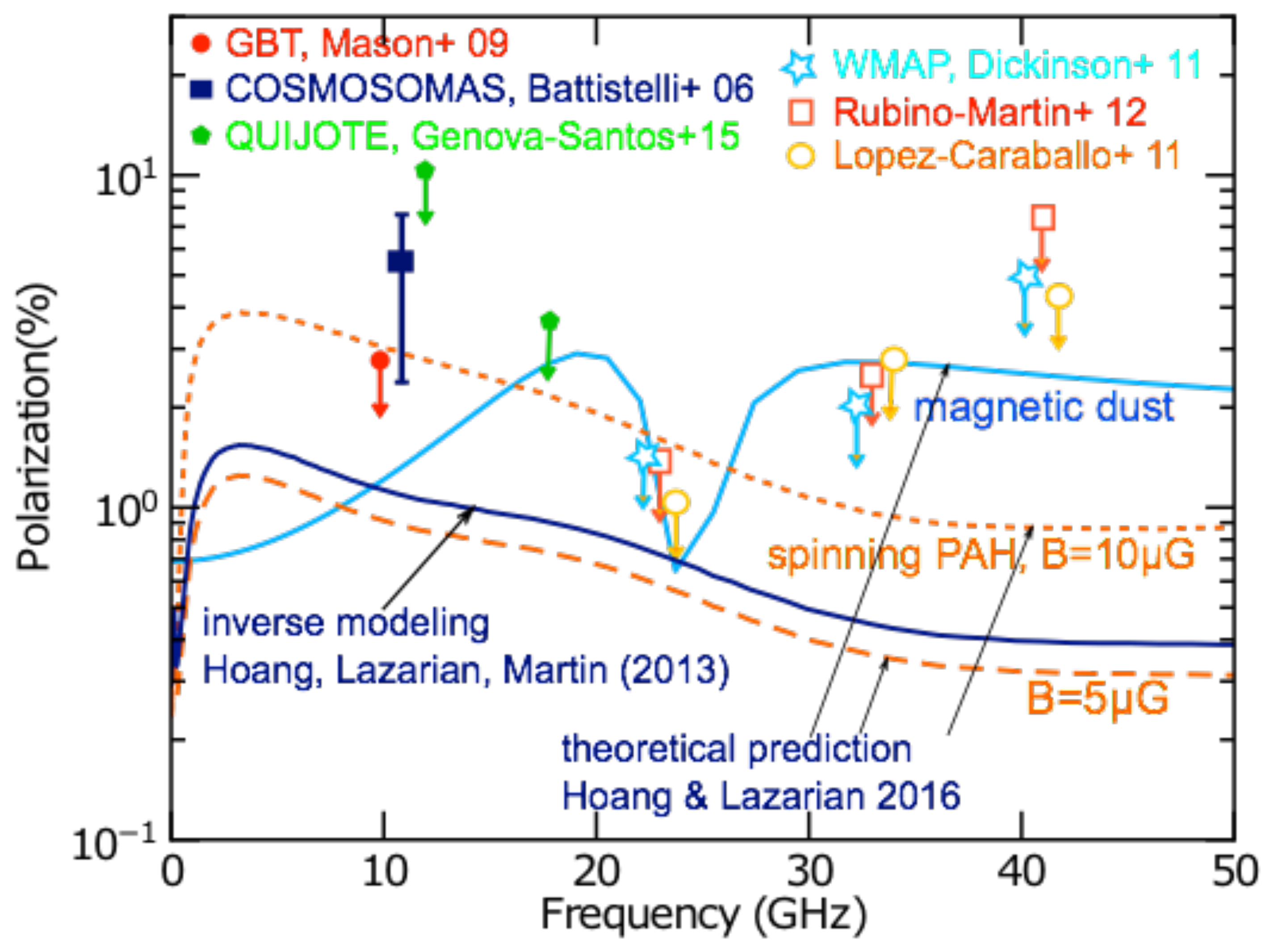
Hoang and Lazarian (in prep)

Polarization of spinning nanosilicate emission



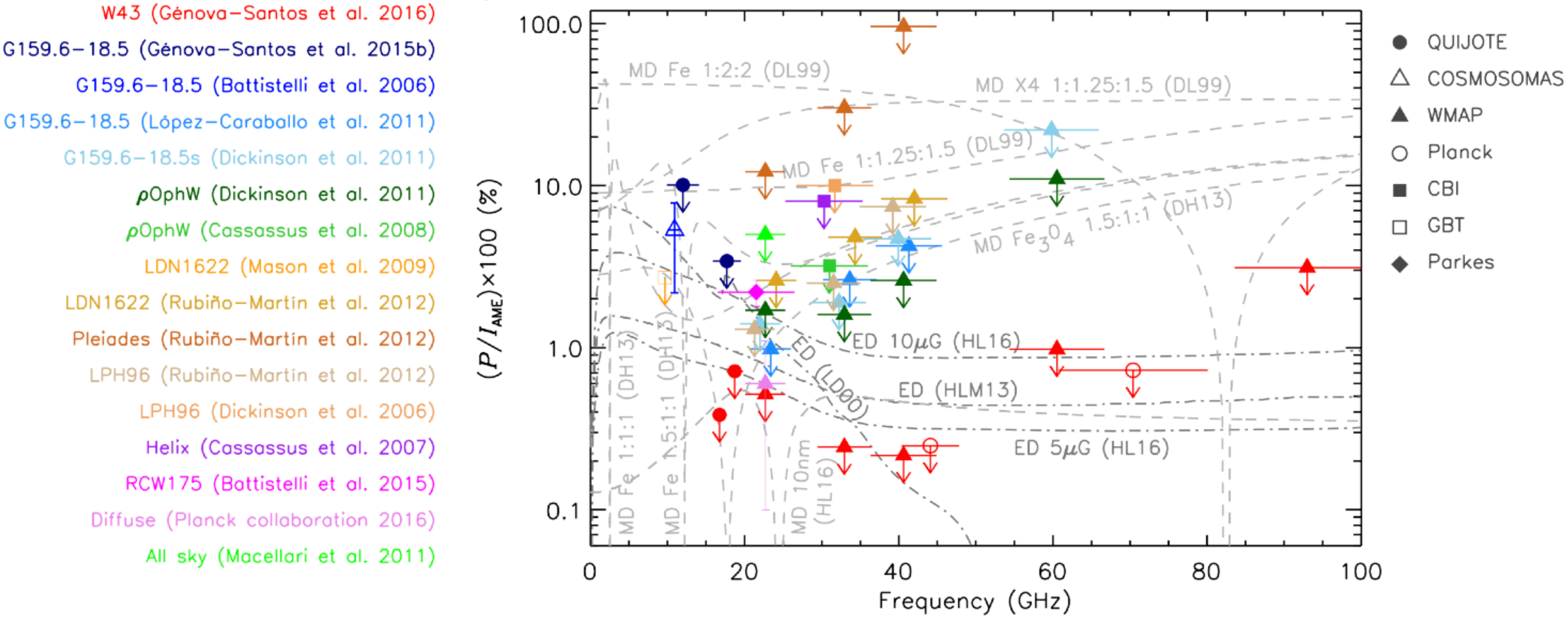
Hoang, Vinh, & Lan 2016, ApJ, 824, 18

Spinning PAH and Magnetic Dust can reproduce the AME polarization



Theoretical predictions vs. Observations

Dickinson et al., incl Hoang (2017)

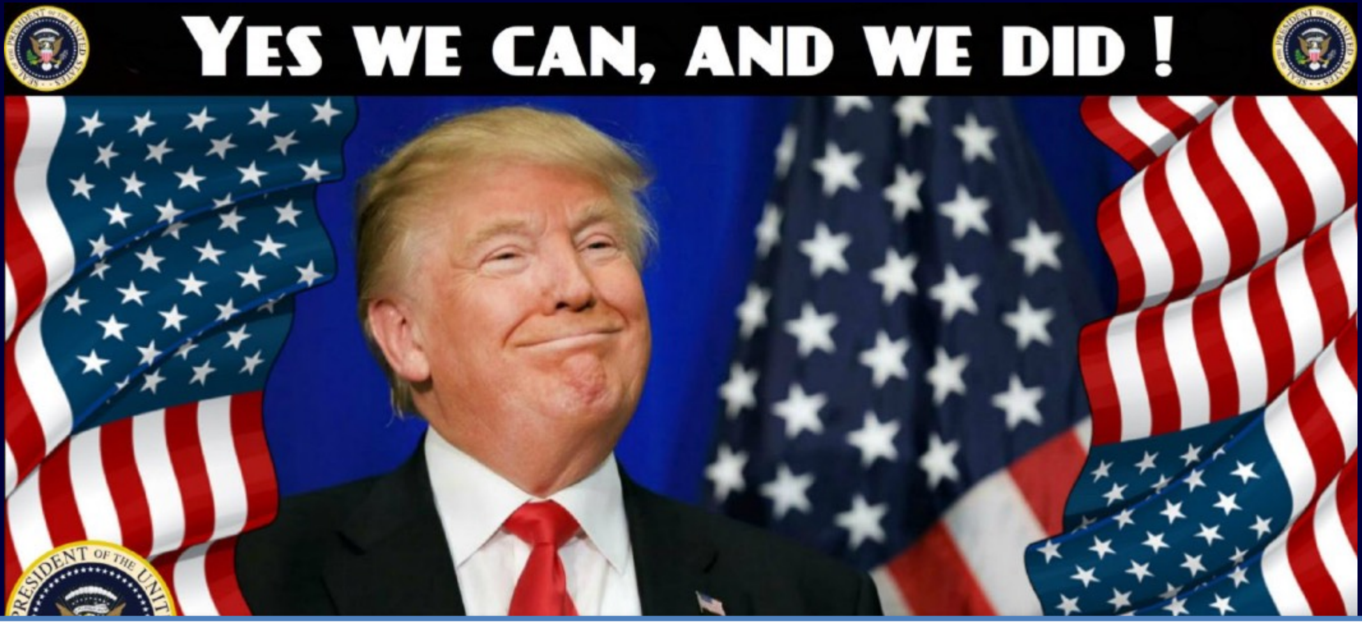


ratio by more than 1σ. For sensitive CMB experiments, omitting in the foreground modelling a 1% polarized spinning dust component may induce a non-negligible bias in the estimated tensor-to-scalar ratio.

Simulations by Dickinson's group

Summary

- PAHs are important for IR emission, UV bump, and AME
- PAHs can be aligned by paramagnetic relaxation
- A new model of polarized PAH emission is developed, incorporating PAH alignment with the magnetic field
- First detection of polarized PAH emission, consistent with theoretical predictions by PAH alignment with B-field
- A new way to trace magnetic fields via Mid-IR Pol, good in RNe and and circumstellar disks
- Polarization of AME by PAHs and nanoparticles cannot be negligible, a serious challenge for CMB B-mode detection.

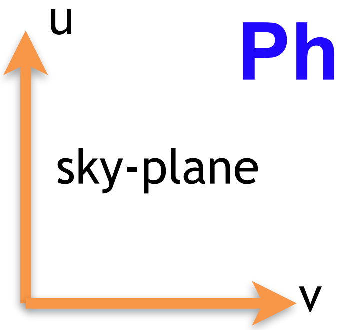


Thiem Hoang, 2017, ApJ, 838, 112 (theory)

H Zhang, CW Telesco, Thiem Hoang et al., 2017, ApJ, 844, 6 (observation)

Thank You Very Much!

Physics of Polarized Mid-IR Emission



Case 2: J perp to a_1 (i.e.,parallel to a_2)

$$I_{u,\perp} = \sum_{i=1}^{3} W_i \langle A_i \rangle \langle F_u \rangle = \frac{1}{3}(1/2 + 3/4) = \frac{5}{12},$$

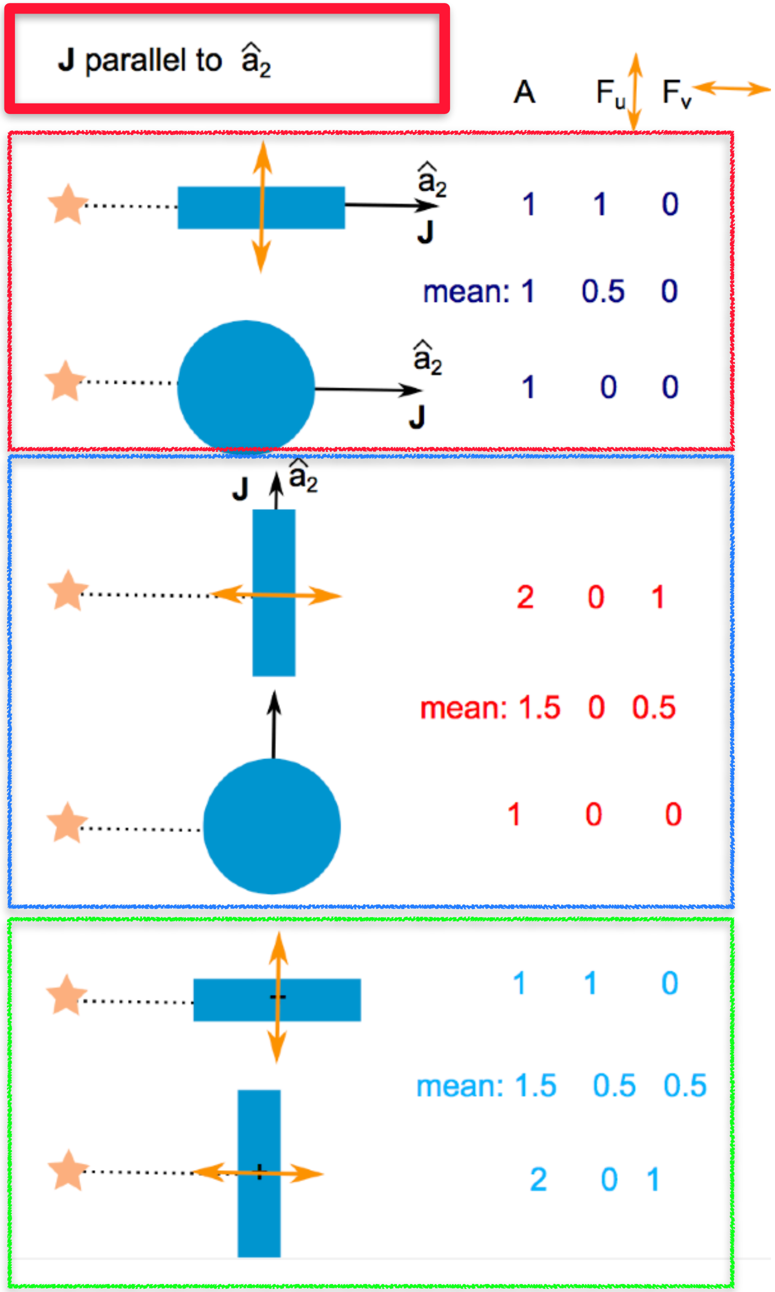
$$I_{v,\perp} = \sum_{i=1}^{3} W_i \langle A_i \rangle \langle F_v \rangle = \frac{1}{3}(3/4 + 3/4) = \frac{6}{12},$$

Polarization degree

$p = (I_u - I_v)/(I_u + I_v) = -1/11 \sim -9.1\%$

$p>0$: p along u-direction

$p<0$: p along v-direction



J parallel to $\hat{a}_2$

A F_u F_v

1 1 0

mean: 1 0.5 0

1 0 0

2 0 1

mean: 1.5 0 0.5

1 0 0

1 1 0

mean: 1.5 0.5 0.5

2 0 1

Original Model of Polarized Emission: Leger (1988)

Model assumptions:

- ○ Randomly oriented J $$f(J) \propto \delta(J - \bar{J})$$
- ○ Damping and excitation by gas collisions and IR emission only

Results:

$<J^2> \, > J^2_{th}$, large Pol

Sellgren+1988: No Detection

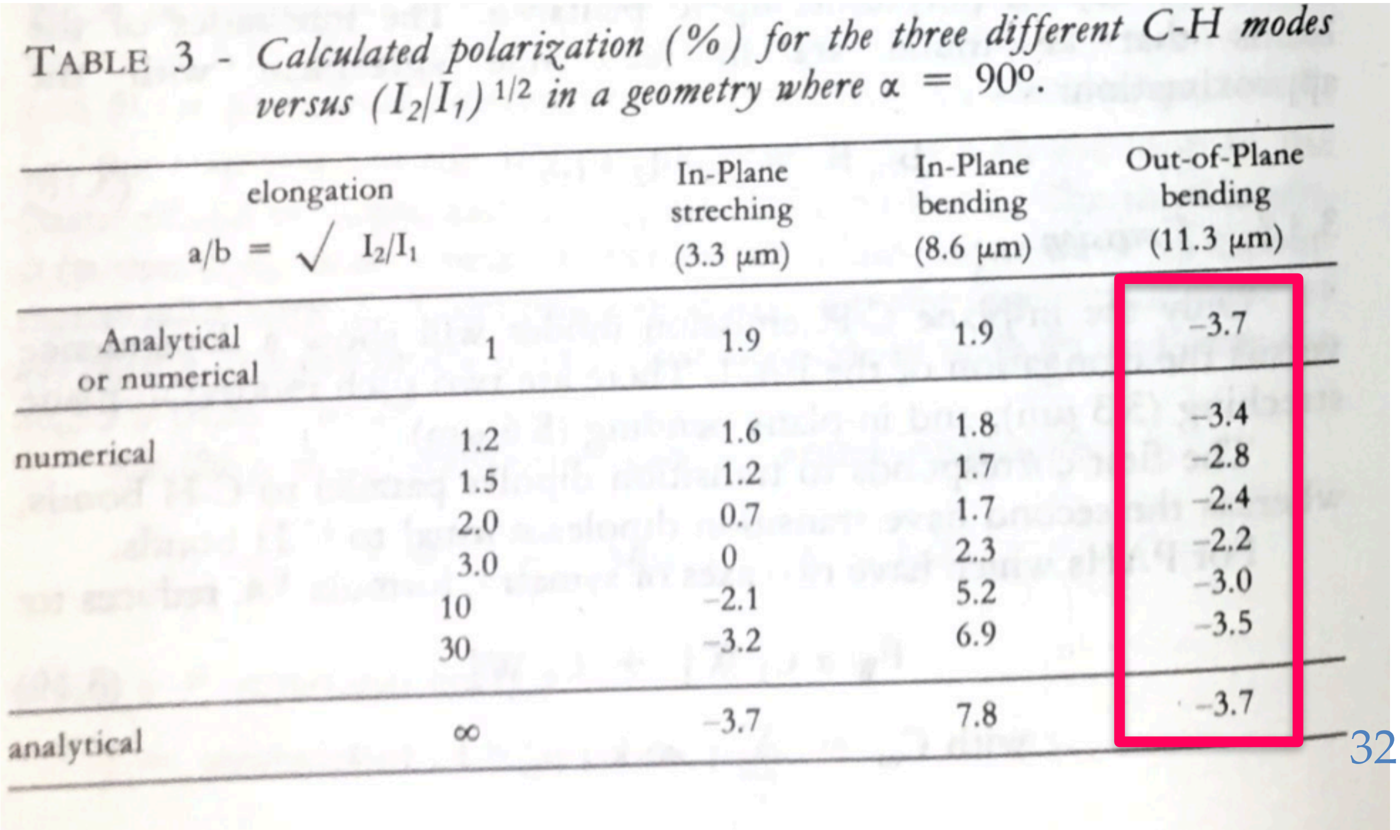


TABLE 3 - *Calculated polarization (%) for the three different C-H modes versus* $(I_2/I_1)^{1/2}$ *in a geometry where* $\alpha = 90°$.

elongation	$a/b = \sqrt{I_2/I_1}$	In-Plane streching (3.3 µm)	In-Plane bending (8.6 µm)	Out-of-Plane bending (11.3 µm)
Analytical or numerical	1	1.9	1.9	−3.7
numerical	1.2	1.6	1.8	−3.4
	1.5	1.2	1.7	−2.8
	2.0	0.7	1.7	−2.4
	3.0	0	2.3	−2.2
	10	−2.1	5.2	−3.0
	30	−3.2	6.9	−3.5
analytical	∞	−3.7	7.8	−3.7

Revisited Model of Sironi & Draine (2009)

Model assumptions:

- Randomly oriented **J**
- Damping and excitation by collisions, IR, **rotational emission damping**

Results: Much lower pol

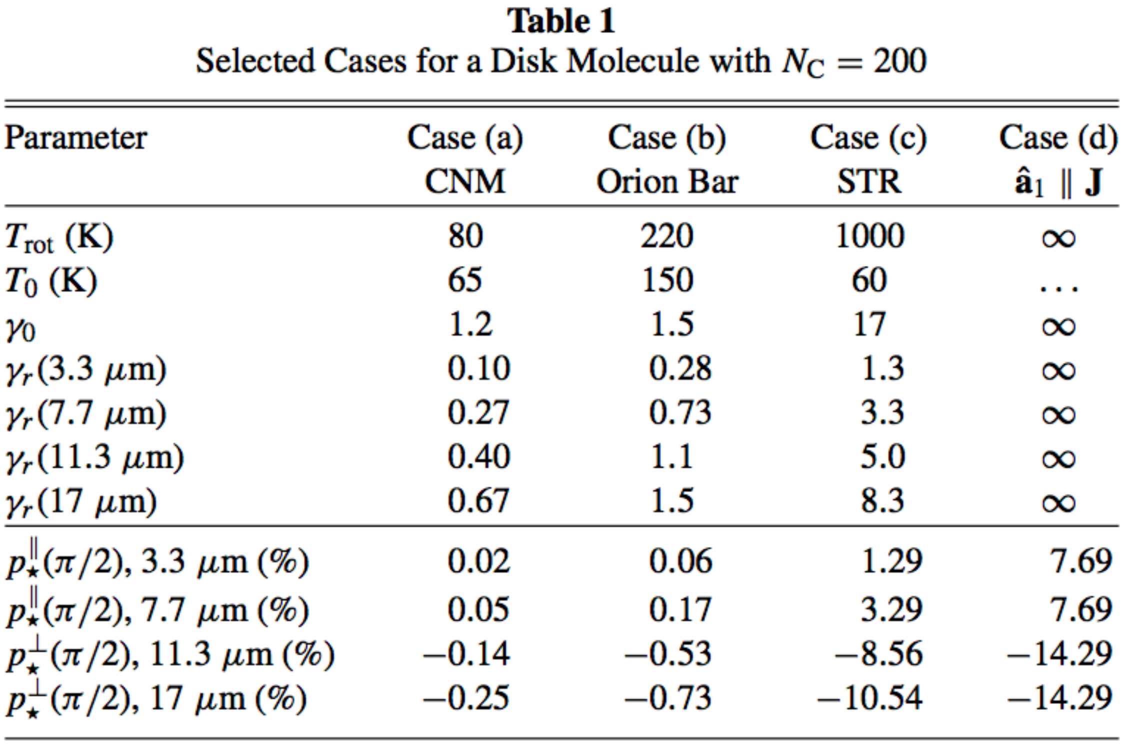
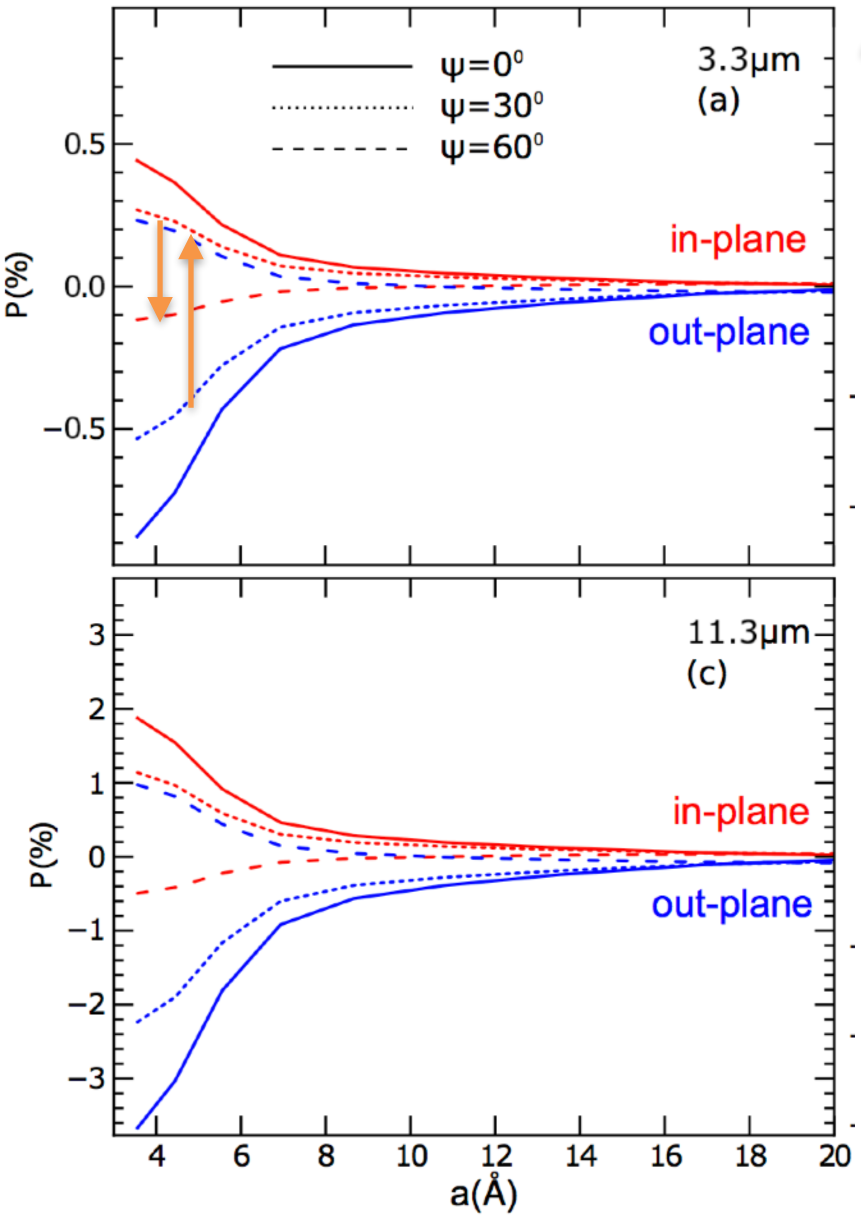
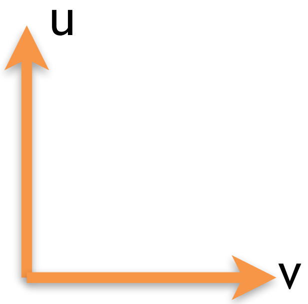


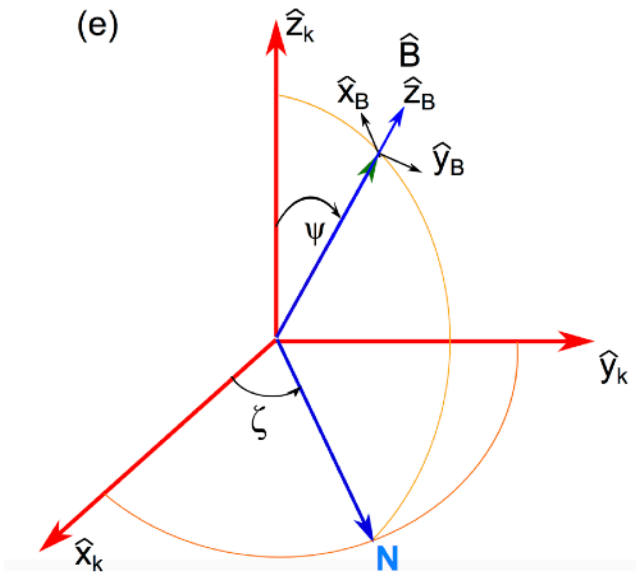
Table 1
Selected Cases for a Disk Molecule with $N_C = 200$

Parameter	Case (a) CNM	Case (b) Orion Bar	Case (c) STR	Case (d) $\hat{\mathbf{a}}_1 \parallel \mathbf{J}$
T_{rot} (K)	80	220	1000	∞
T_0 (K)	65	150	60	...
γ_0	1.2	1.5	17	∞
$\gamma_r(3.3\ \mu m)$	0.10	0.28	1.3	∞
$\gamma_r(7.7\ \mu m)$	0.27	0.73	3.3	∞
$\gamma_r(11.3\ \mu m)$	0.40	1.1	5.0	∞
$\gamma_r(17\ \mu m)$	0.67	1.5	8.3	∞
$p_\star^{\parallel}(\pi/2)$, 3.3 μm (%)	0.02	0.06	1.29	7.69
$p_\star^{\parallel}(\pi/2)$, 7.7 μm (%)	0.05	0.17	3.29	7.69
$p_\star^{\perp}(\pi/2)$, 11.3 μm (%)	−0.14	−0.53	−8.56	−14.29
$p_\star^{\perp}(\pi/2)$, 17 μm (%)	−0.25	−0.73	−10.54	−14.29

Polarization vs. Magnetic Field Direction





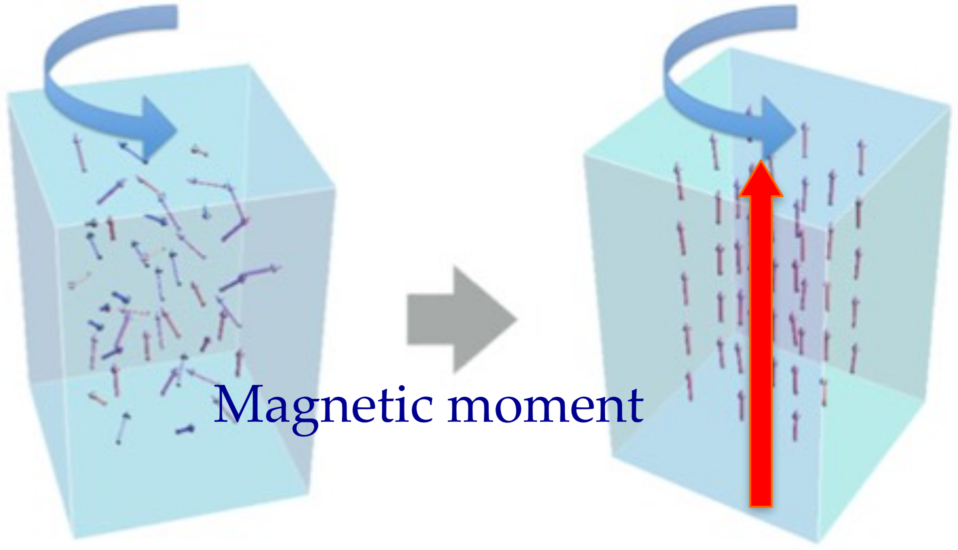


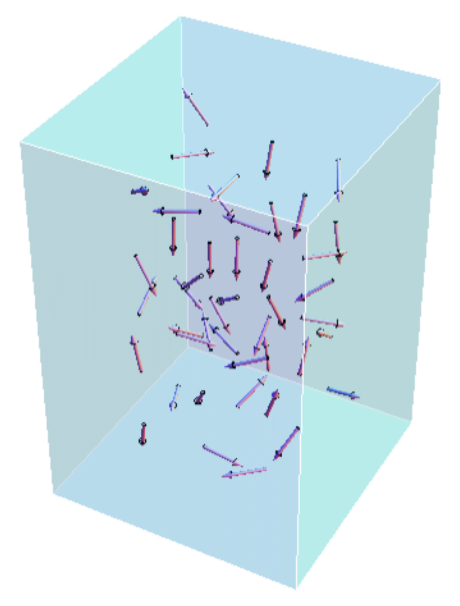
- Polarization decreases with the B-field angle
- Pol vector changes its direction between u- and v- direction if B-field angle is large.

Magnetic Alignment of PAH with Magnetic Fields

- ★ PAHs are paramagnetic material, with unpaired electron spins
- ★ PAHs get magnetized via spinning: Barnett effect

(inverse of Einstein de-Hass effect)

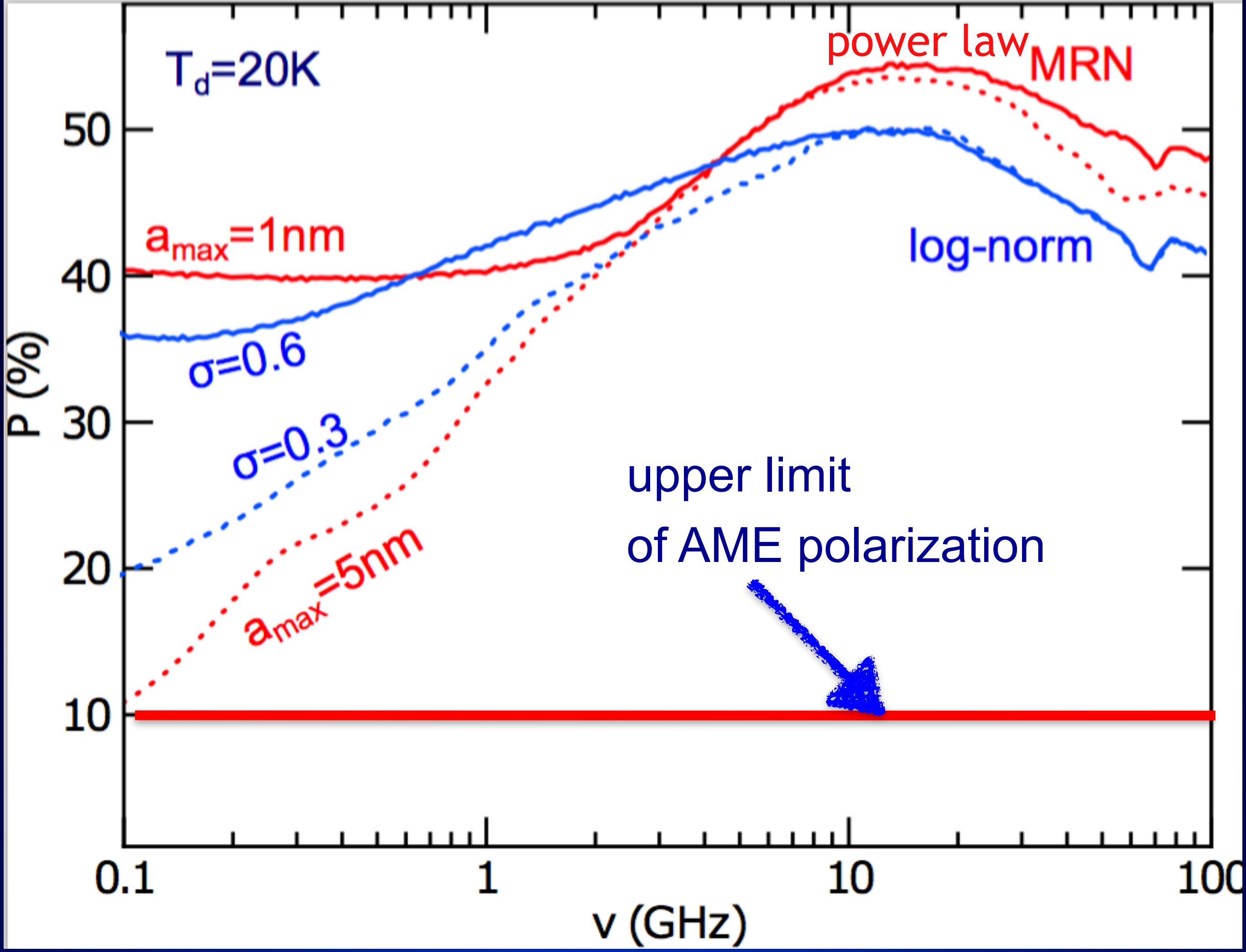




Credit: Mamoru Matsuo

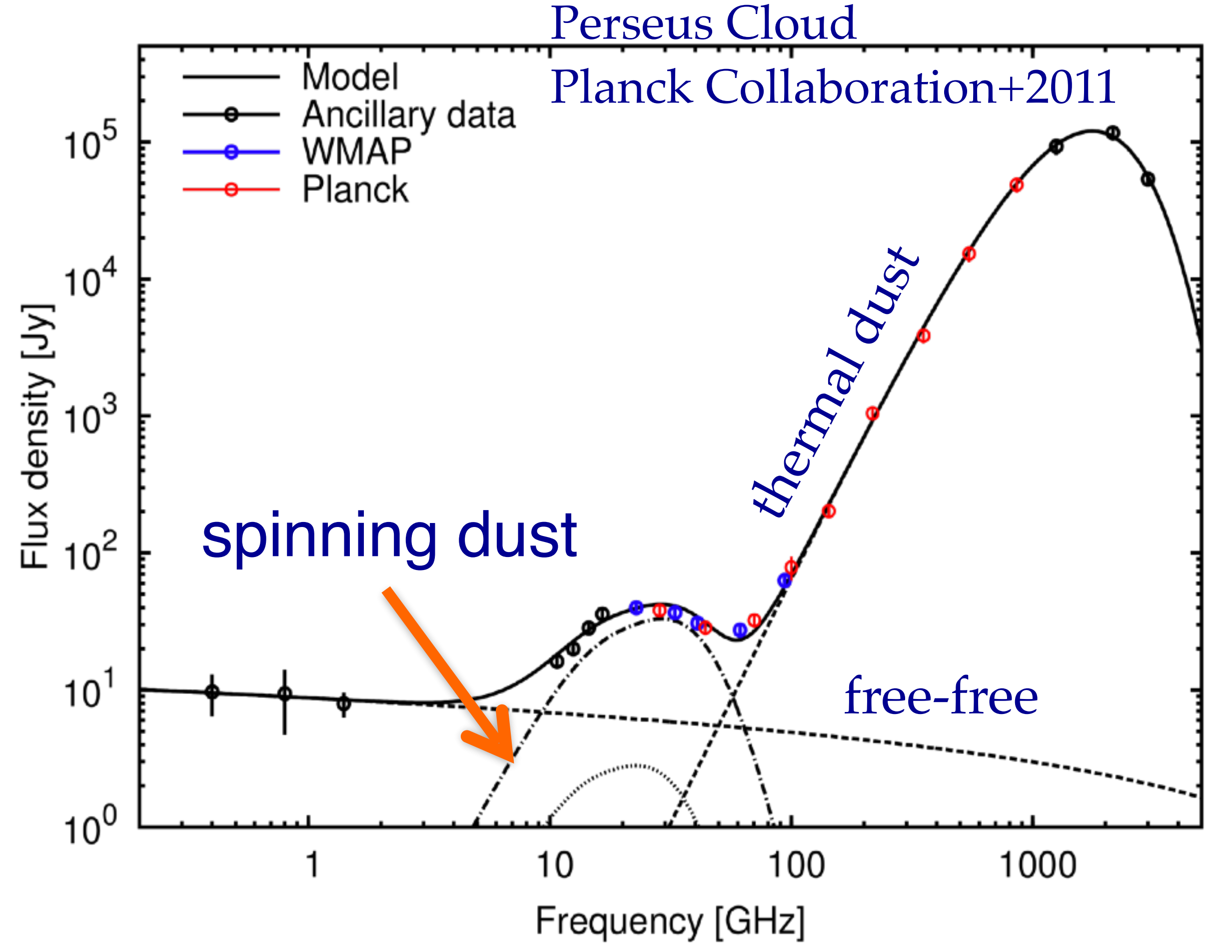
- ★ PAHs can be weakly aligned with the B-field via resonance paramagnetic relaxation (Lazarian & Draine 2000)

Polarization of spinning iron emission too high



Hoang & Lazarian 2016, ApJ, 821,91

PAHs as a carrier of Anomalous Microwave Emission: Spinning Dust



Perseus Cloud

Planck Collaboration+2011

spinning dust

thermal dust

free-free

AME & Spinning dust:

Kogut et al. 1996, Leitch et al. 1997, Draine & Lazarian 1998, de-Oliveira Costa et al., Finkbeiner et al., Hoang et al., Dickinson et al

Nanosilicates are likely an important carrier of the AME (Hoang et al 2016, Hensley & Draine 2017)