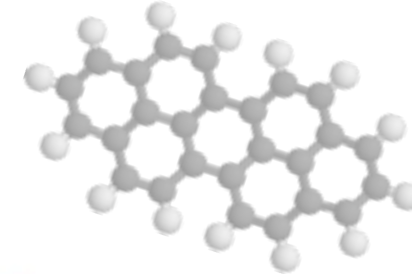

Foregrounds and secondary science: Spinning dust radiation

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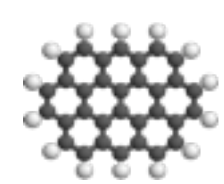
Caltech

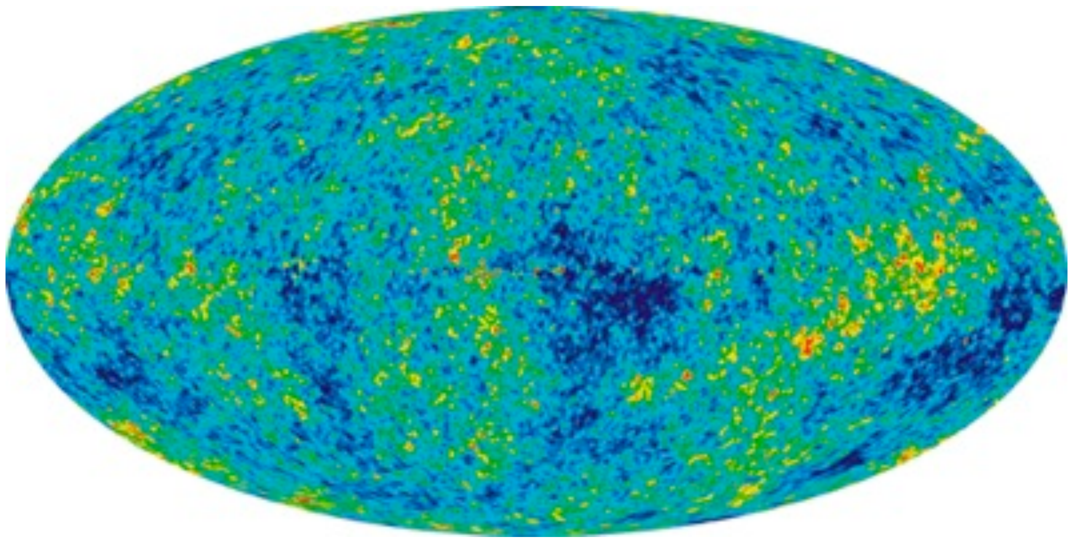
Collaborators: Chris Hirata, Clive Dickinson, Kedron Silsbee

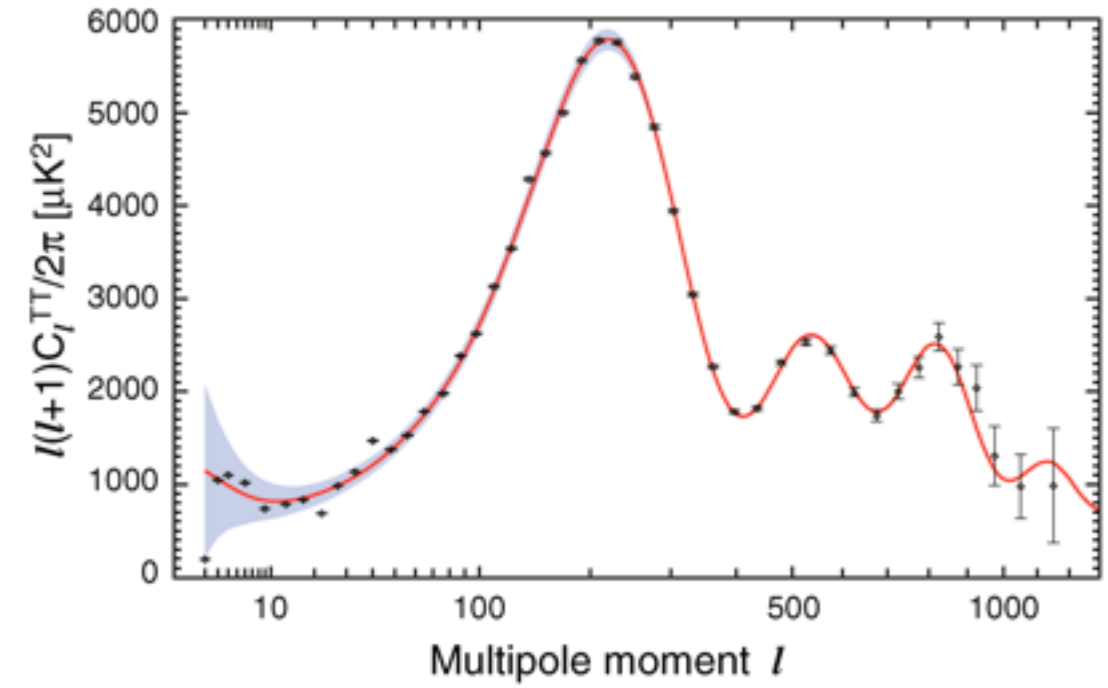
KISS workshop *The First Billion Years*
August 19th 2010

Outline

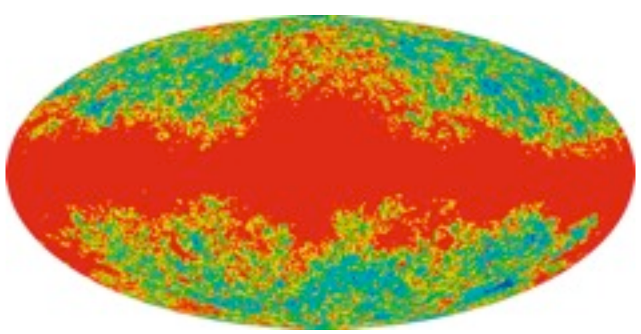
- Spinning dust as a new, “anomalous” CMB foreground
- Ingredients of the theory
- Spinning dust radio lines: how bad is the contamination of Recombination lines?
- Secondary science: PAHs 

- What cosmologists want:

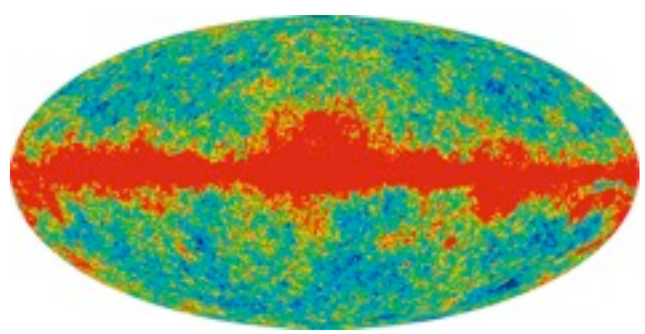




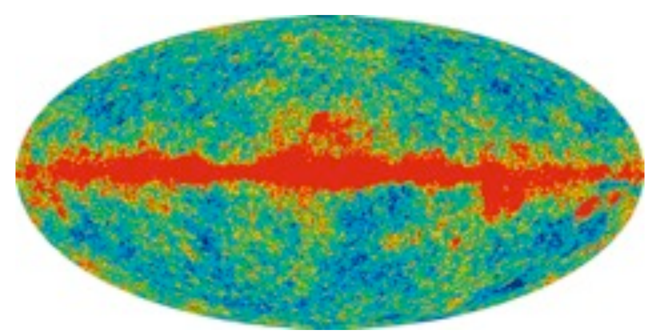
- What the Galaxy gives us:



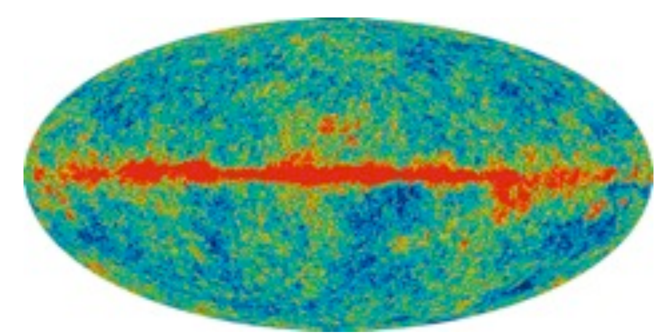
WMAP 23 GHz



WMAP 33 GHz



WMAP 41 GHz



WMAP 61 GHz

- Need to understand Galactic foreground emission.

The standard Galactic foregrounds

- Synchrotron Radiation

$$T_\nu \propto \nu^{-\alpha} \sim \nu^{-3}$$

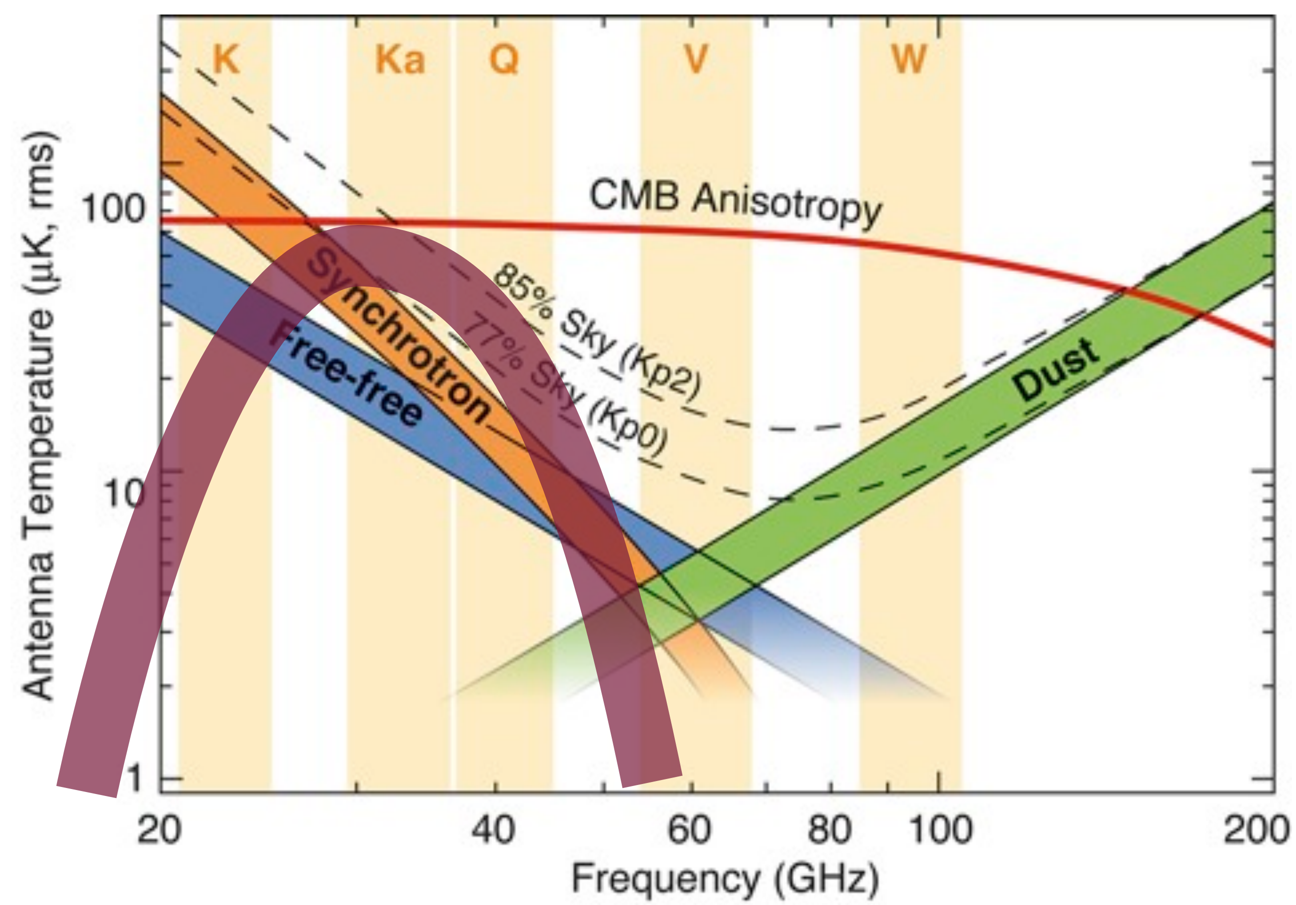
$$N(E) \propto E^{-(2\alpha-3)}$$

- Thermal Bremsstrahlung (Free-Free)

$$T_\nu \propto n_e n_p e^{-\frac{h\nu}{kT_e}} \nu^{-2} g(\nu, T_e)$$

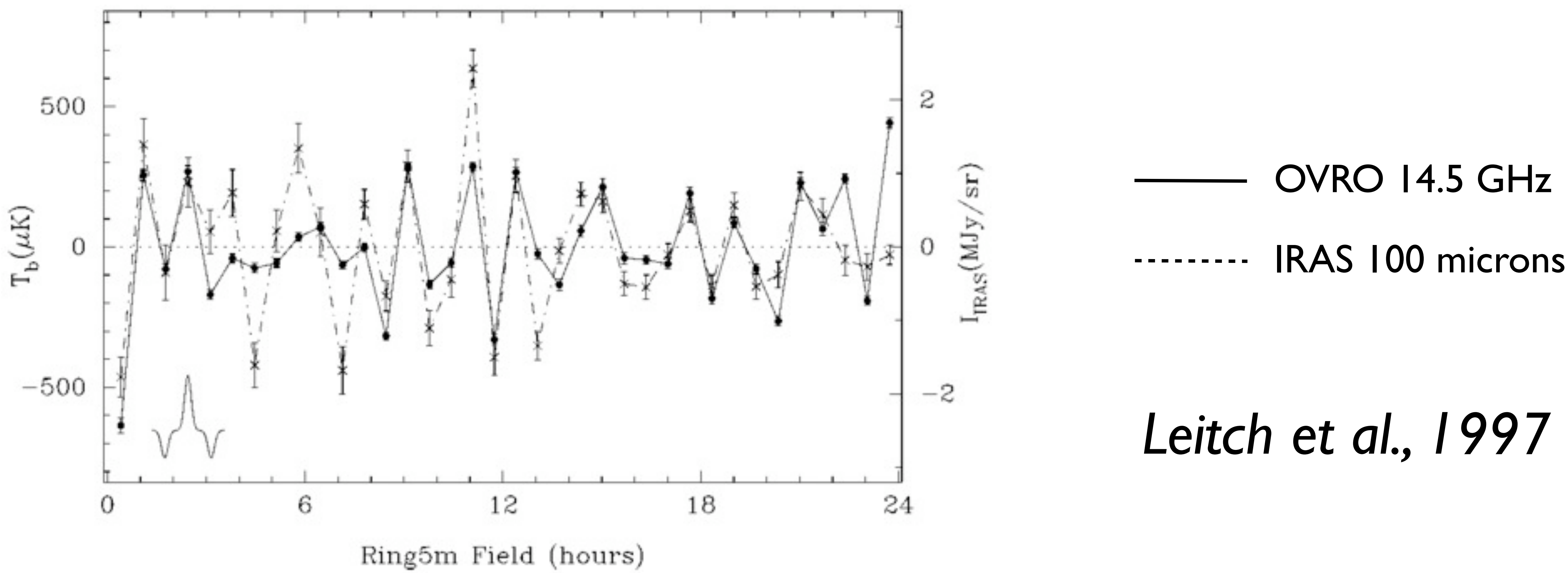
- "Thermal" (vibrational) dust

$$T_\nu \propto \nu^2$$



- Recently, an additional "anomalous" emission was detected

First detection of the "anomalous emission"



Leitch et al., 1997

Extremely good spatial correlation, despite the large frequency difference (two orders of magnitude !)

Also: Kogut et al. 1996, de Oliveira-Costa et al. 1997

The free-free hypothesis

- Leitch et al. (1997) find $\epsilon_\nu \sim \nu^{-0.2}$ very similar to free-free radiation $\epsilon_\nu^{ff} \propto n_e n_p T^{-1/2} e^{-\frac{h\nu}{kT}} \bar{g}_{ff}(T,\nu)$
- Hα emission : subsequent to the recombination of ionized Hydrogen.

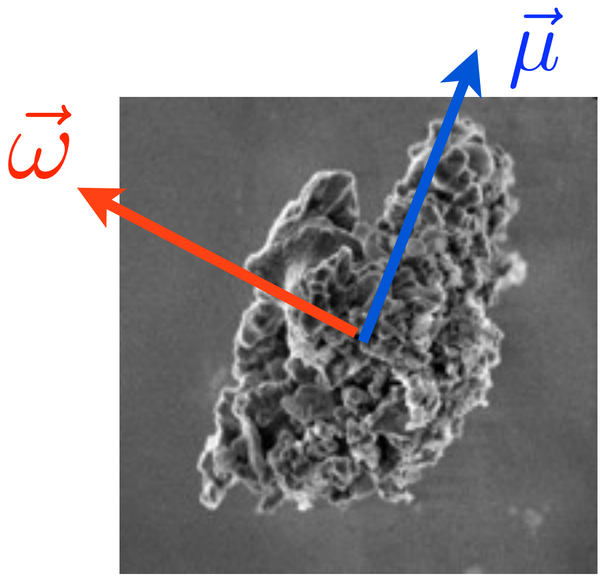
e + p → H* + γ → H(n=3) + γ → H(n=2) + **γ** → H(1s) + γ

$$\epsilon_\nu^{\mathrm{H}\alpha} \propto n_e n_p T^{-1.2}$$

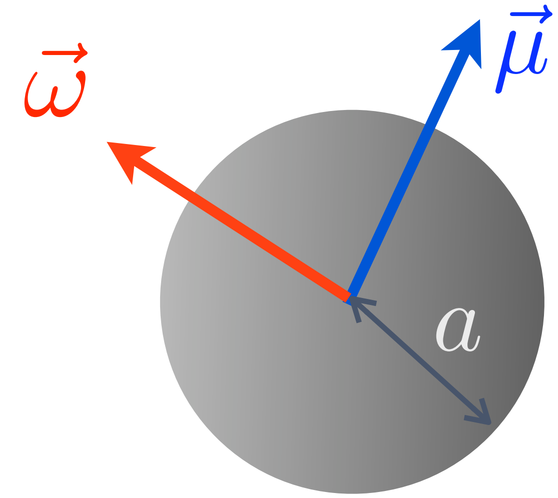
- Upper bounds on Hα imply $T > 10^6$ K to explain the anomalous emission
- Heating enough gas to reproduce anomalous emission to $T > 10^6$ K requires ~ 100 times the energy input from supernovae. ⇒ ***Not free-free***

Spinning dust emission.

Draine & Lazarian, 1998



$$P = \frac{2\ddot{\vec{\mu}}^2}{3c^3}$$



For a spherical grain: $P(\omega) = \frac{2}{3c^3}\omega^4\mu^2_{\perp,a}$ emitted at $\nu = \omega/2\pi$

- Emissivity : $$\epsilon_\nu = 2\pi \int \mathrm{d}a \boxed{\frac{\mathrm{d}n_{gr}}{\mathrm{d}a}} \boxed{4\pi\omega^2 f_a(\omega)} P(\omega)$$

grain abundance (from IR emission and extinction)

Rotation rate probability distribution

The Fokker-Planck equation for $f_a(\omega)$

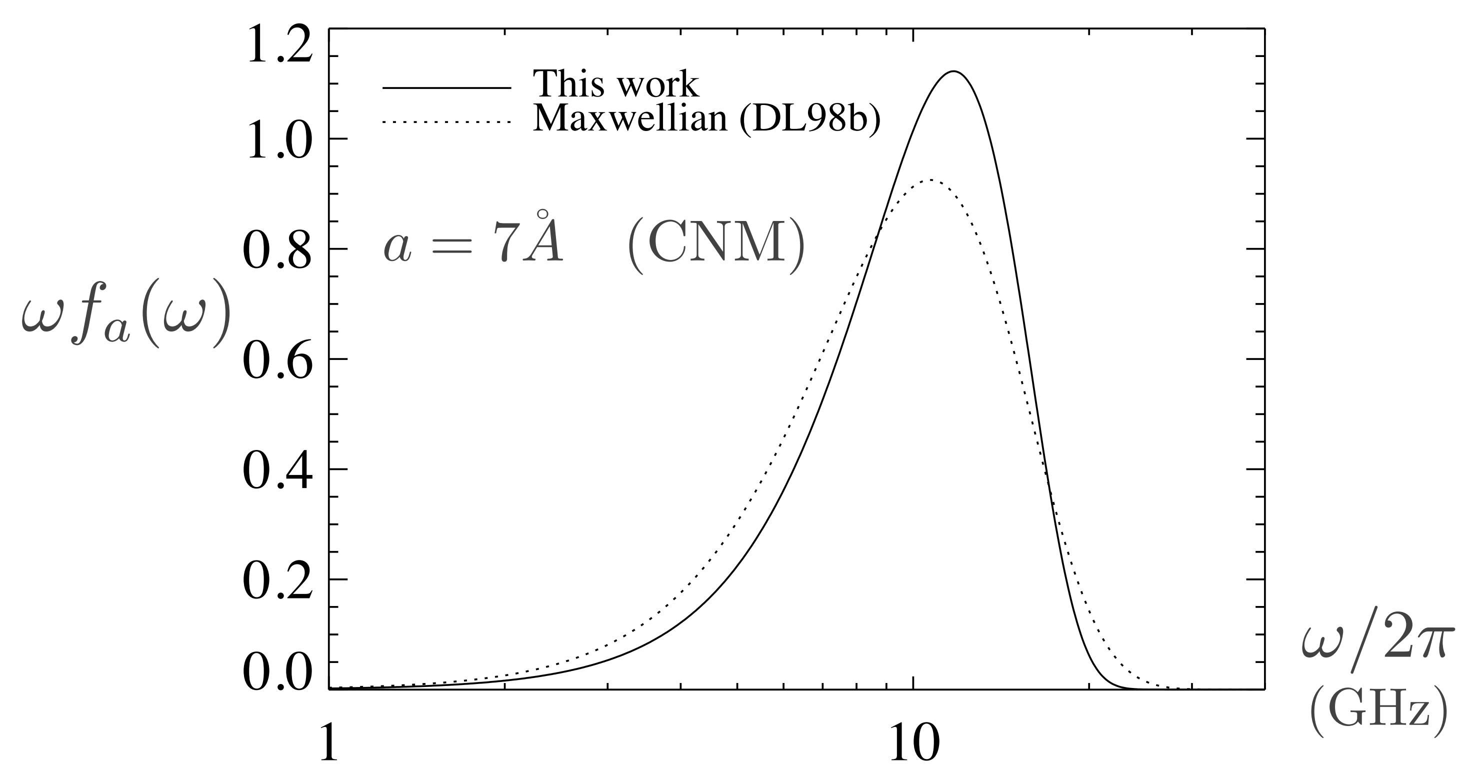
$$\boxed{\cancel{\frac{\partial f_a}{\partial t}} = \frac{\partial}{\partial \omega}\left[D(\omega) f_a(\omega)\right] + \frac{1}{2}\frac{\partial^2}{\partial \omega^2}\left[E(\omega) f_a(\omega)\right]}$$

= 0 (steady-state)

$$D(\omega) = -\lim_{\delta t \to 0} \frac{\langle \delta\omega \rangle}{\delta t}$$ rotational damping (drift) rate

$$E(\omega) = \lim_{\delta t \to 0} \frac{\langle \delta\omega^2 \rangle}{\delta t}$$ rotational excitation (diffusion) rate

Non thermal,
non Maxwellian
distribution function



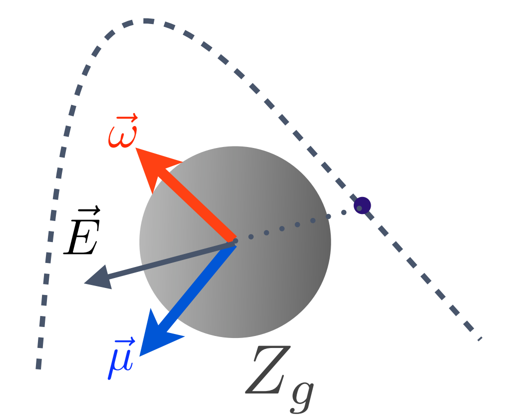
Ali-Haïmoud, Hirata & Dickinson, 2009

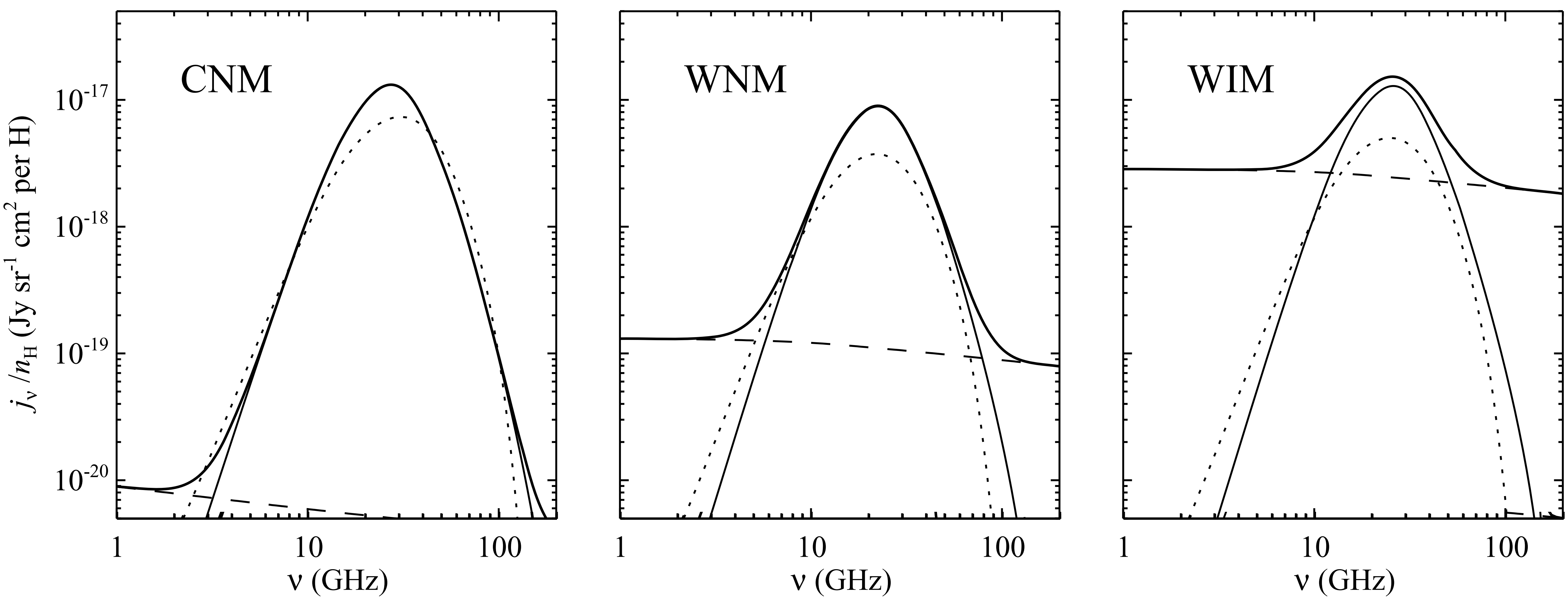
Rotational excitation and damping mechanisms

- Collisions with ions/atoms
- Interaction with the stochastic plasma electric field
- Infrared emission
- Less important (?), harder to quantify: H_2 formation
- Spectrum depends on multiple parameters:

  environment: n_H, T, u_{ν}, x_{H+}, x_C, x_{H2} (environment)

  grain properties: $\mu(a)$, $n_{gr}(a)$



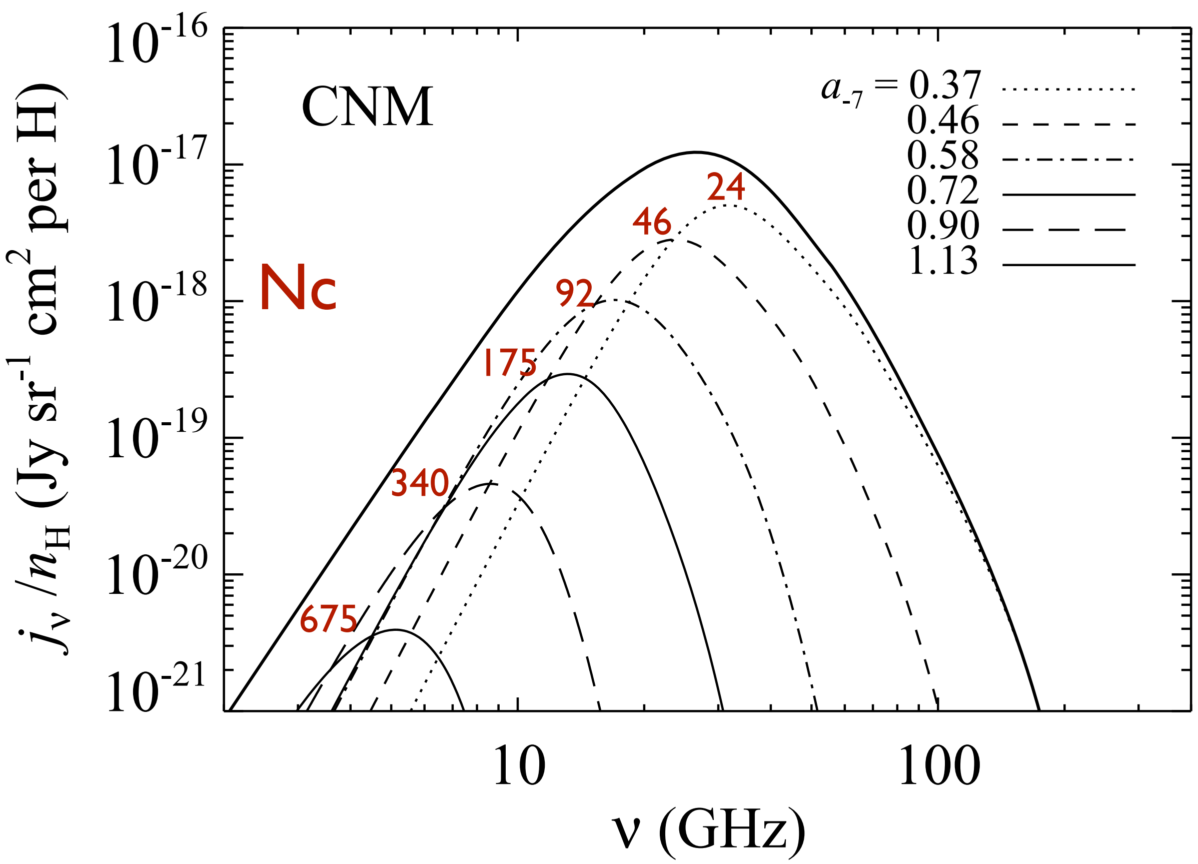


free-free

Draine & Lazarian 1998

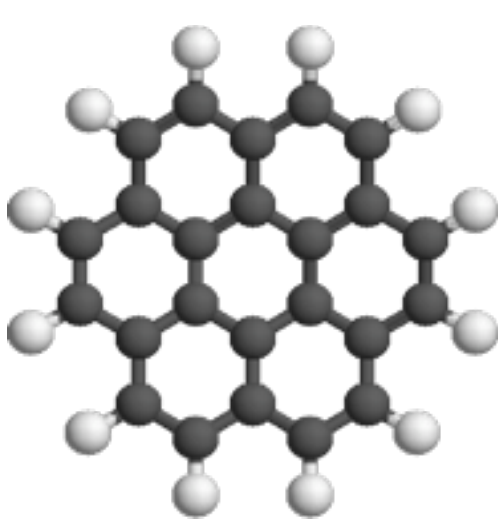
SpDust (Ali-Haïmoud, Hirata & Dickinson, 2009)

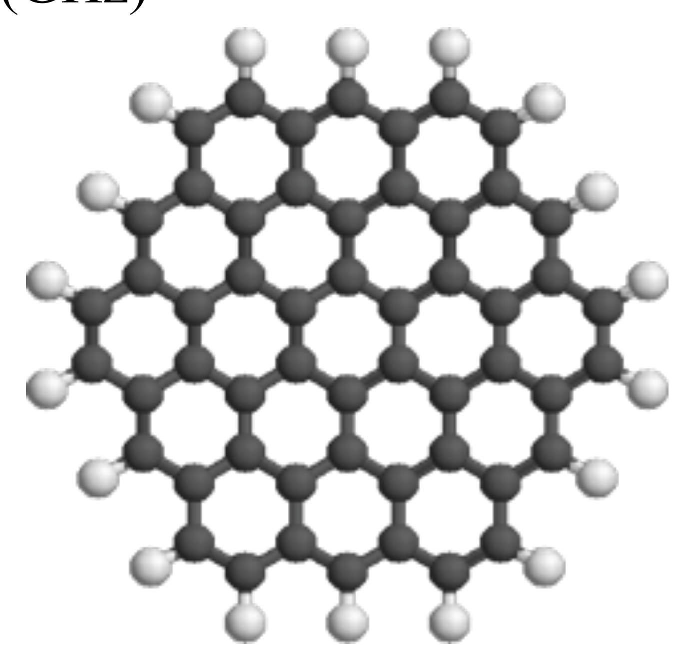
Emission dominated by the smallest dust grains: PAHs

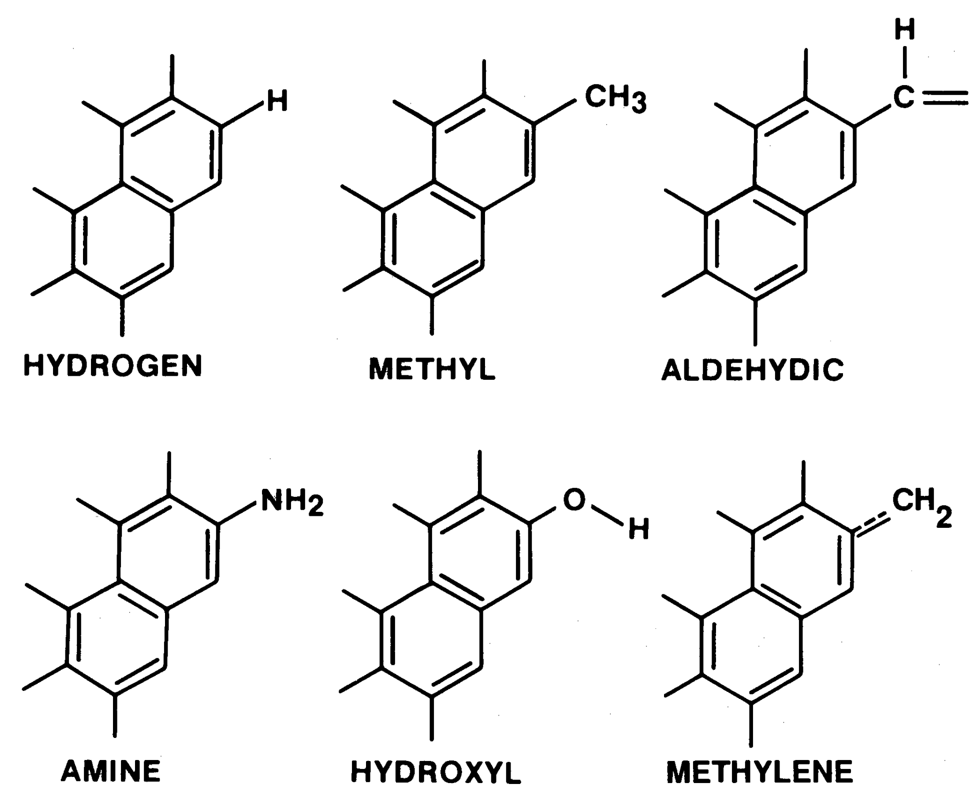


Dipole moment:

- Dehydrogenation
- Super-hydrogenation
- Substitution
- PAH-metal complexes

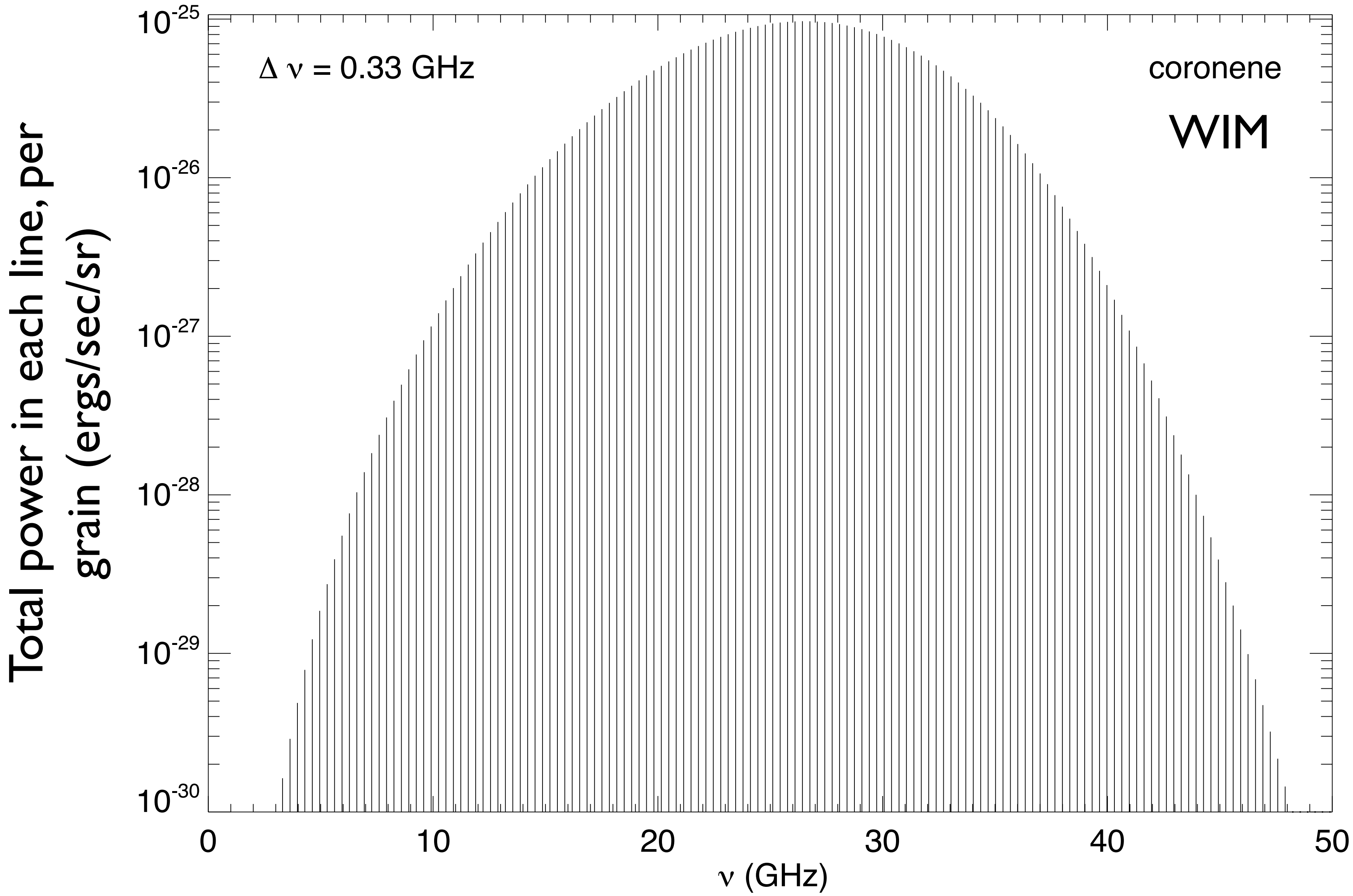


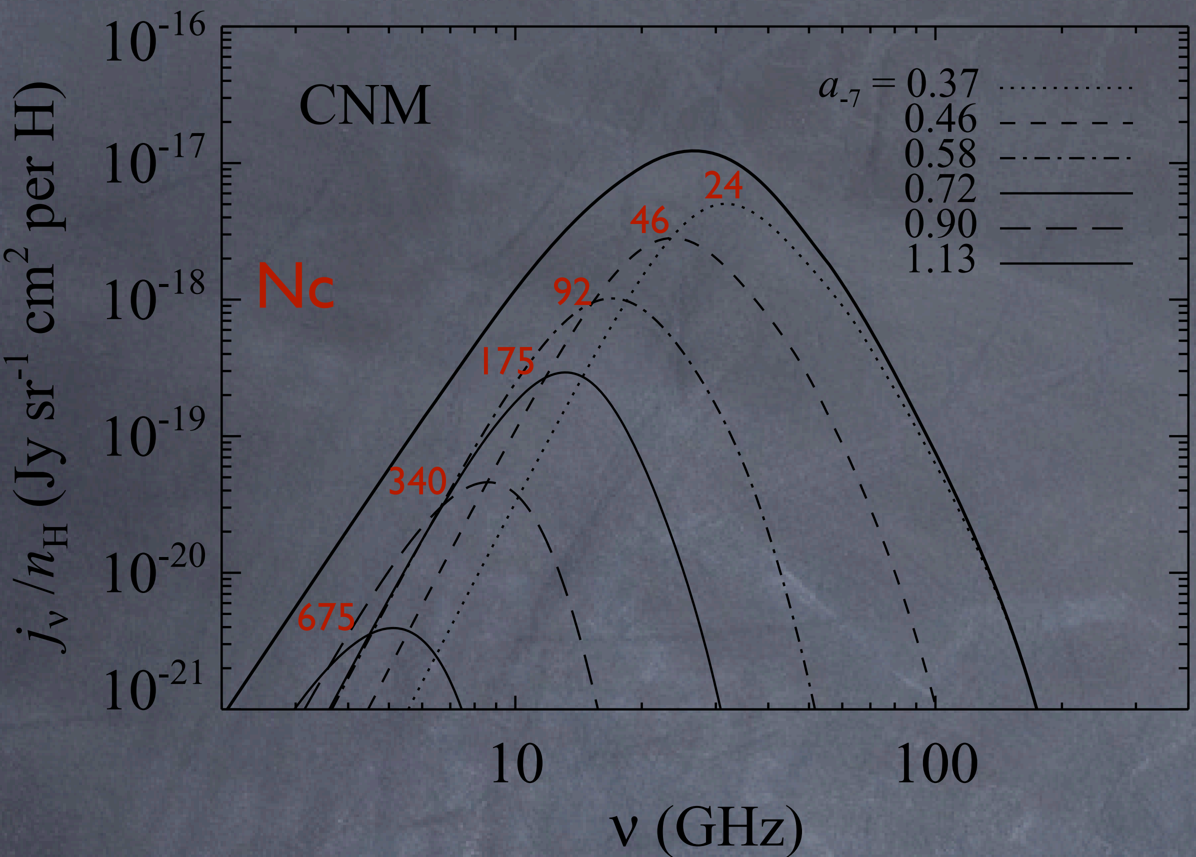




Geballe et al. 1989

Example spectrum

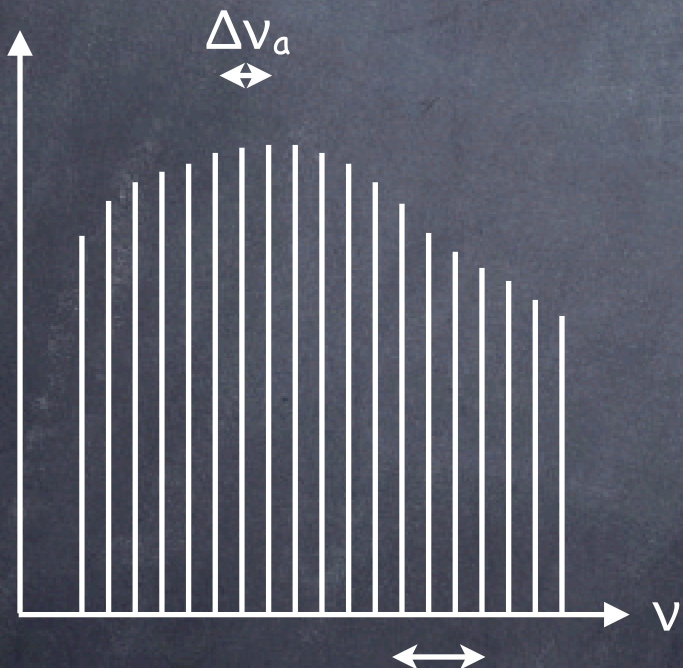




$$\Delta\nu_a = \hbar/(2\pi\ I_a) = 2B_a$$

Nc	24	46	92	175	340	675
$\Delta\nu_a$ (MHz)	330	90	20	20	7	2

Disklike Spherical

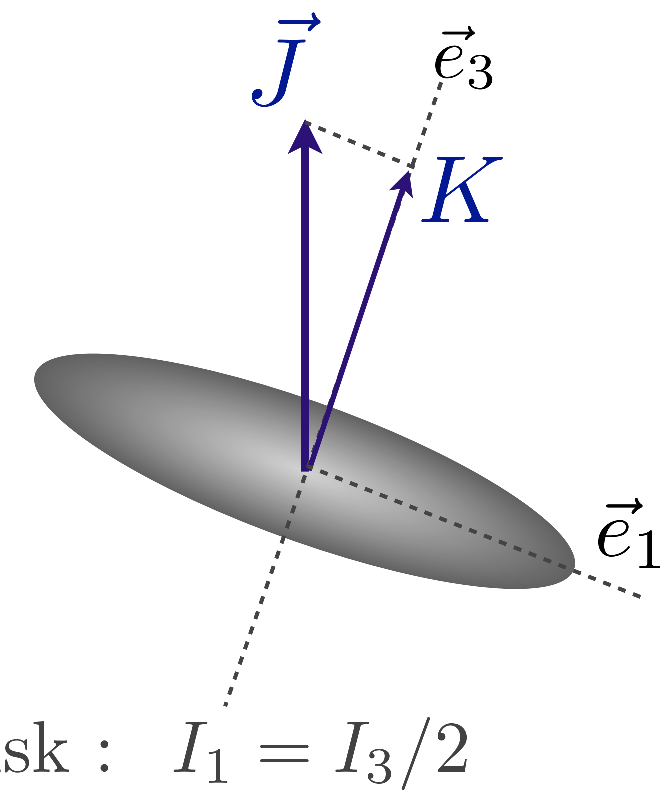


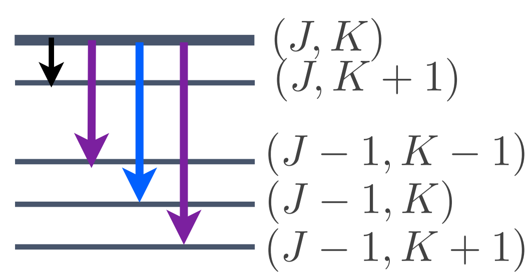
- If only one type of grains: $\Delta T_\nu/T_\nu \approx \Delta\nu_a/\Delta\nu_{obs}$
- If several types of grain: [☢ hand-wavy ☢]
  $\Delta T_\nu/T_\nu \approx \Sigma_a\ \Delta\nu_a/\Delta\nu_{obs}\ j_{\nu(a)}/j_{\nu(tot)}$
- With the above numbers, for $\Delta\nu_{obs} \approx$ 500MHz at $\nu_{obs} \approx$ 10GHz: $\Delta T_\nu/T_\nu \approx$ 1-10 %.
- With $T_\nu \approx$ 0.1 mK this is $\Delta T_\nu >$ μK (?)
- Issue for CO studies ?

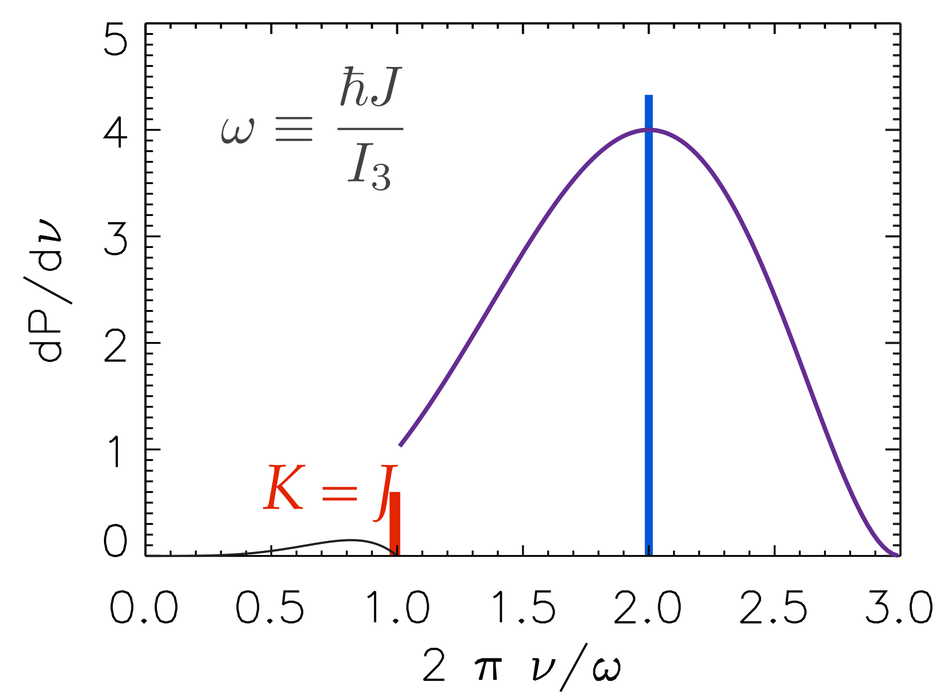
Complications and subtleties

- Grains are not spherical, not rotating about the axis of greatest inertia.

  E.g., for disk-like grains $$E = \frac{\hbar^2}{2}\left[\frac{J(J+1)}{I_1} - K^2\left(\frac{1}{I_1} - \frac{1}{I_3}\right)\right]$$







- For given conditions, total angular momentum ~0.7 lower, peak frequency ~1.4 higher. (*Silsbee, Ali-Haïmoud & Hirata, 2010*)
- A different forest of lines. Does it help or not ... ?

Secondary science: learning about PAHs and the ISM

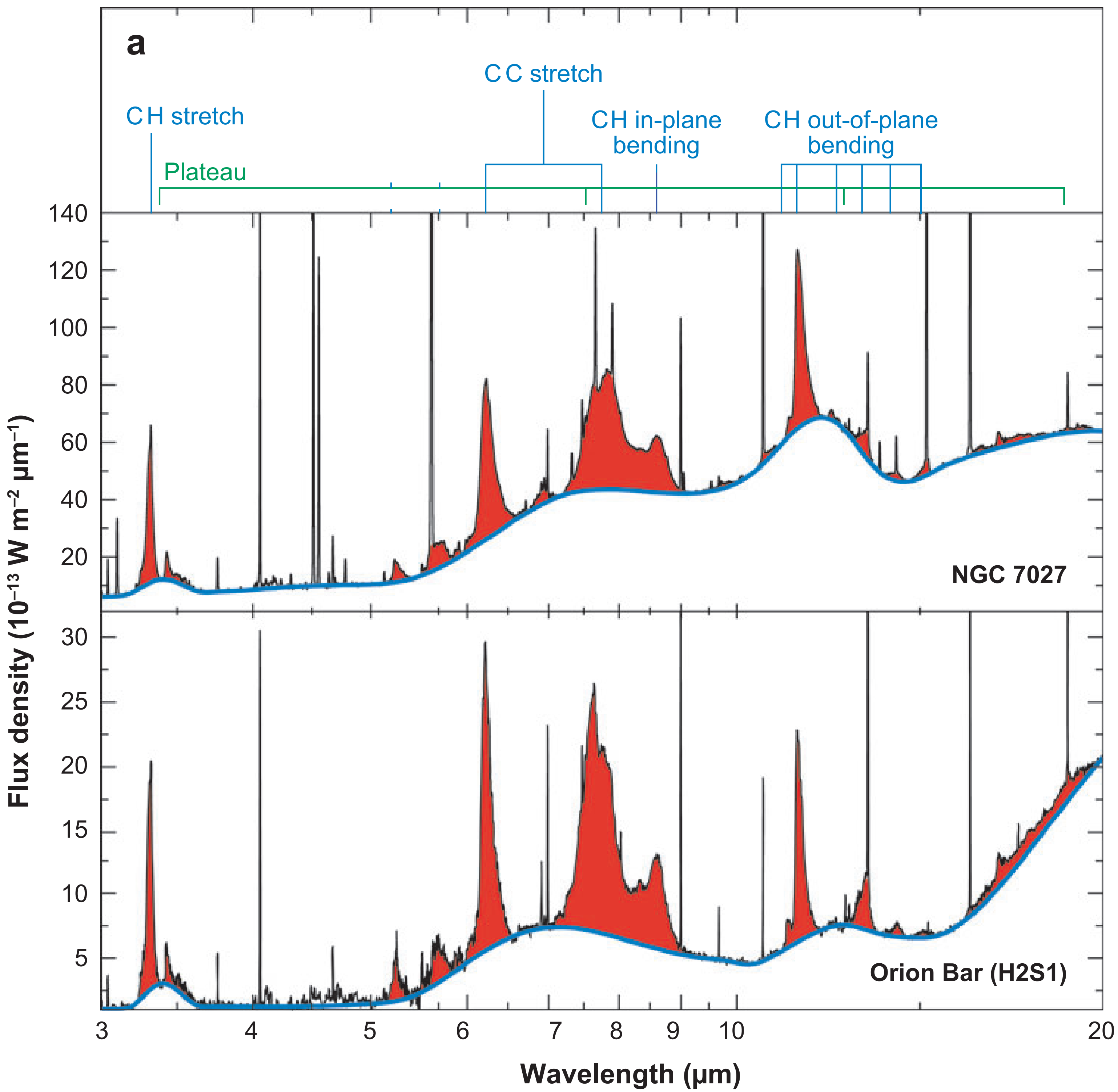
- Why are PAHs important:
- PAHs are a significant source of heating

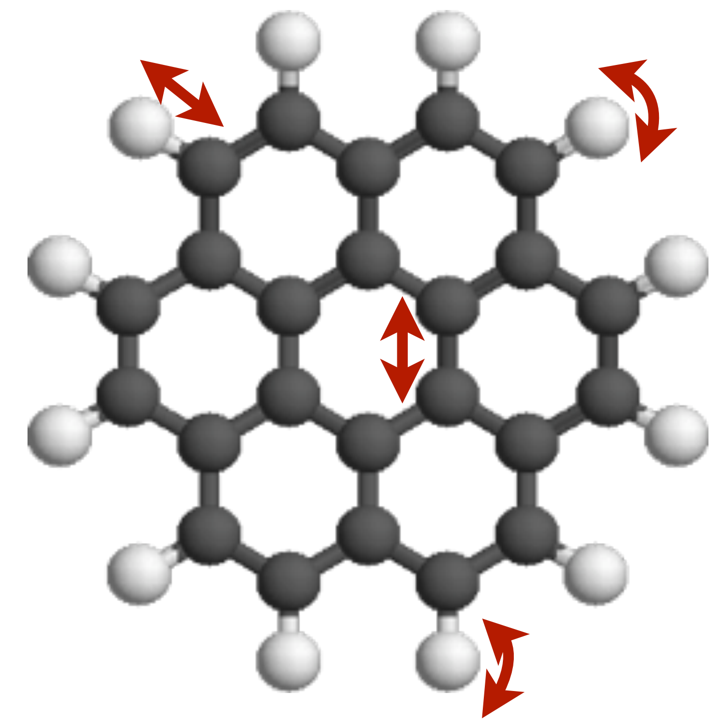
  $PAH + \Upsilon \rightarrow PAH^{+} + e^{-}$

- They contribute to the ionization balance of the ISM

  $PAH^{-} + C^{+} \rightarrow PAH + C$

PAHs: current picture

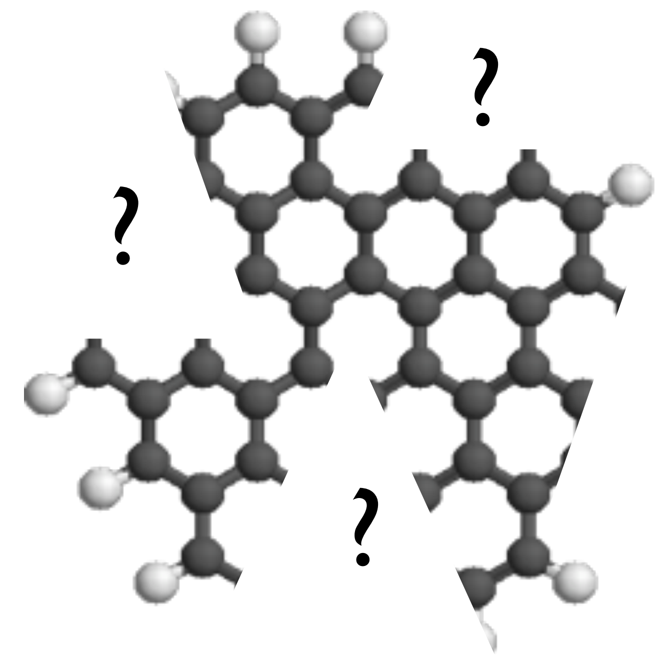




Generally agreed upon picture. Some weak bands are controversial: super-hydrogenated molecules ?

PAHs: current picture

Tielens, 2008



- C-H out of plane bending modes:

  11.2 µm: lone C-H groups ⇒ long edges

  12.7 µm: duos/trios ⇒ corners

  Circumstellar PAHs in PNes: more compact

  ISM PAHs: more corners (⇒ smaller or more irregular)

- 15-20 µm region: skeleton vibrations, more molecule-specific

  Less experimental data

  ISM PAHs seem to be dominated by *a few classes* of molecules

- Lots of progress in observations and theory, but somewhat blurry picture... Fits require messing up with line positions, widths and strengths

Learning from rotational lines

- Can compute rotational constants and dipole moments from DFT (e.g., PANHs *Hudgins, Bauschlicher, & Allamandola, 2005)*

- Basics of rotation dynamics theory in place (if you trust us...)

- mid-IR bands are indicators of physical conditions in the ISM: 6.2/11.3 indicator of degree of ionization of PAHs => $G_0 T^{1/2}/n_e$

- Could use the rotational lines as probes of the ISM

- Spinning dust absorption against strong background radio sources?

TABLE 5

Calculated Dipole Moments for the Singly Substituted Isomers of the N-coronene, N-ovalene, N-circumcoronene, and N-circum-circumcoronene Cations

Species	Dipole Moments μ_a (D)	μ_b (D)	$\boldsymbol{\mu}$ (D)
N-coronene Cations			
1N	5.48	0.19	5.49
2N	3.69	0.00	3.69
3N	2.67	0.00	2.67
N-ovalene Cations			
1N	7.10	0.98	7.17
1′N	5.38	4.81	7.21
1″N	4.92	4.26	6.51
1‴N	0.00	3.47	3.47
2N	5.25	1.19	5.38
2′N	1.59	3.65	3.98
3N	4.32	1.02	4.44
3′N	1.29	1.99	2.37
4N	0.00	1.56	1.56
N-circumcoronene Cations			
1N	9.23	0.23	9.23
1′N	6.99	0.00	6.99
2N	6.77	0.47	6.79
3N	5.30	1.20	5.43
4N	4.55	0.00	4.55
5N	1.32	0.00	1.32

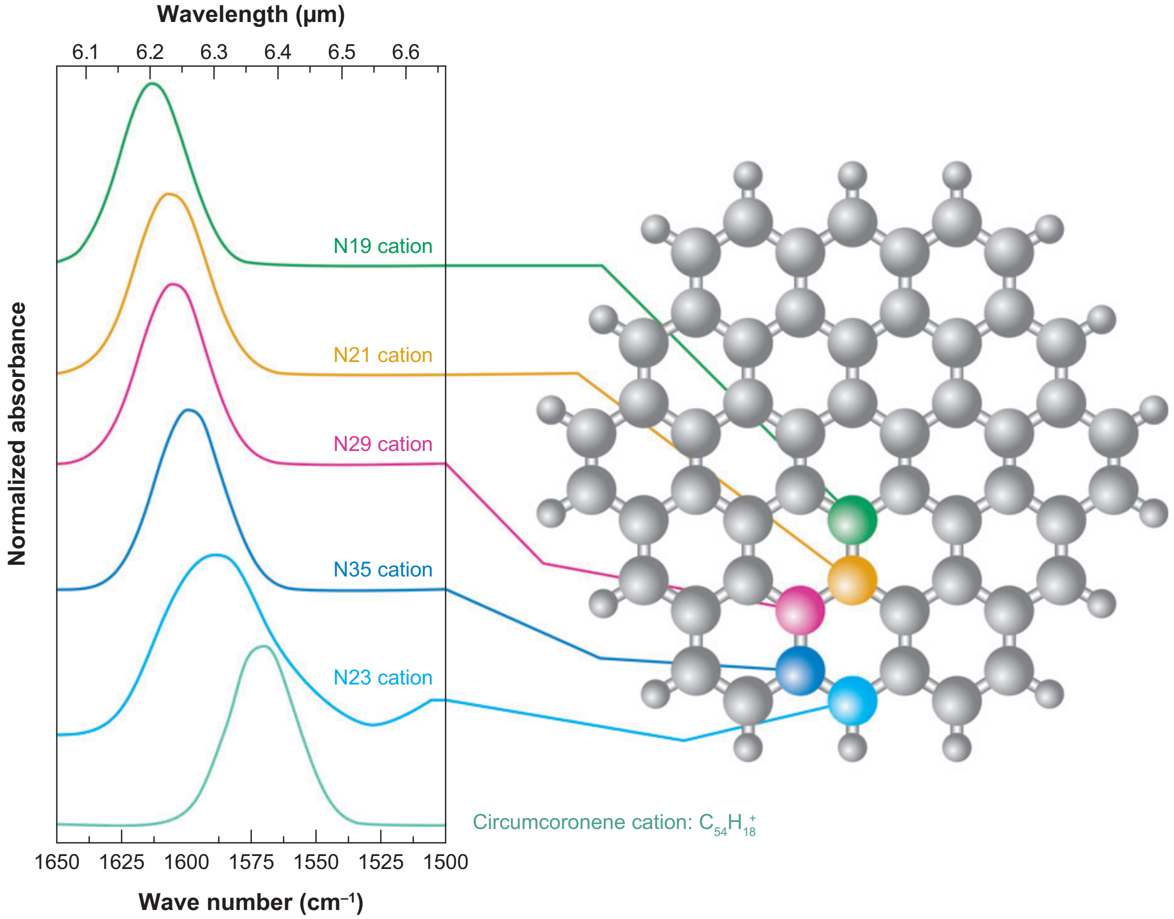


TABLE 6

Calculated Rotational Constants for the Singly Substituted Isomers of the N-coronene, N-ovalene, N-circumcoronene, and N-circum-circumcoronene Cations

Species	Rotational Constants *A* (GHz)	*B* (GHz)	*C* (GHz)
N-coronenes	0.334–0.337	0.331–0.336	0.166–0.168
N-ovalenes	0.238	0.148	0.091
N-circumcoronenes	0.066	0.066	0.033
N-circum-circumcoronenes	0.021	0.021	0.011

Hudgins, Bauschlicher, & Allamandola, 2005