UNIVERSIDAD AUTONOMA DE CHILE

Dust and PAH emission at cm-wavelenghts.

Matías Vidal Navarro.

Simon Casassus, Carla Arce-Tord, Adolf Witt, Brandon Hensley, Bruce Draine, Clive Dickinson, Natalia Inostroza.

III Chilean Astrochemistry School

Dust

The rich 1%...

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Small particles (0.1nm—1um) with complex chemistry and physics

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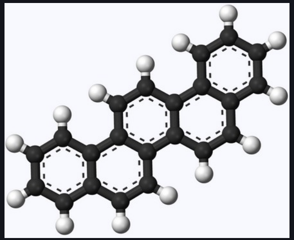
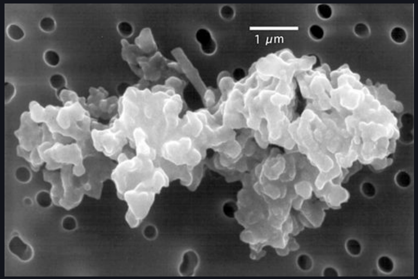
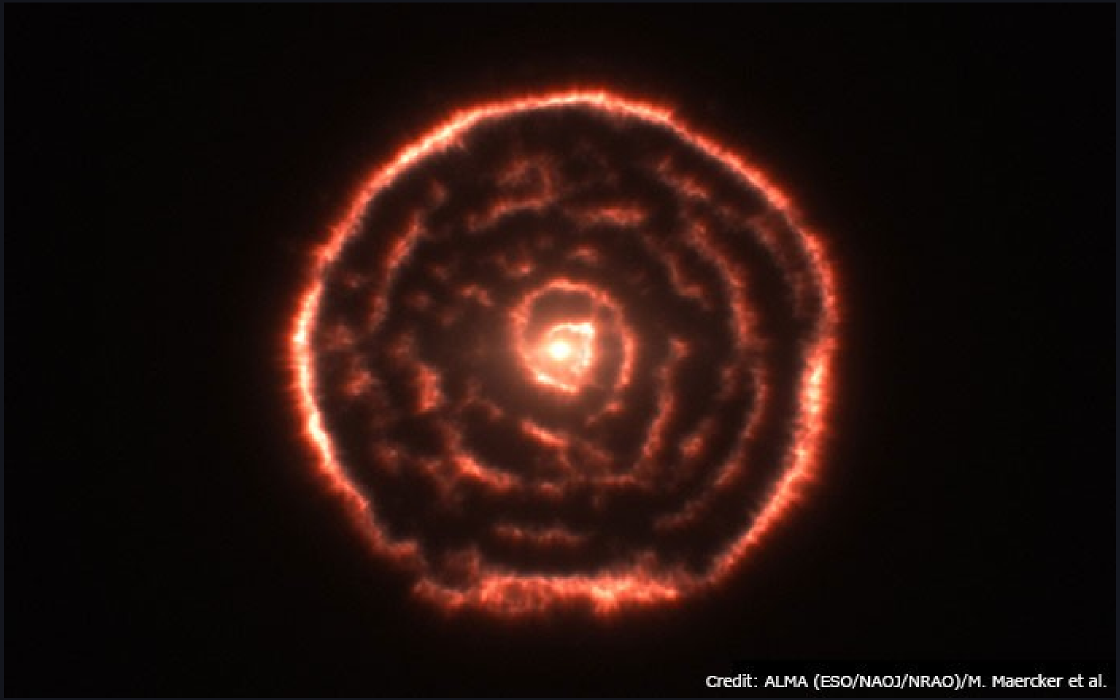




Fundamental in astrophysical processes...

Dust



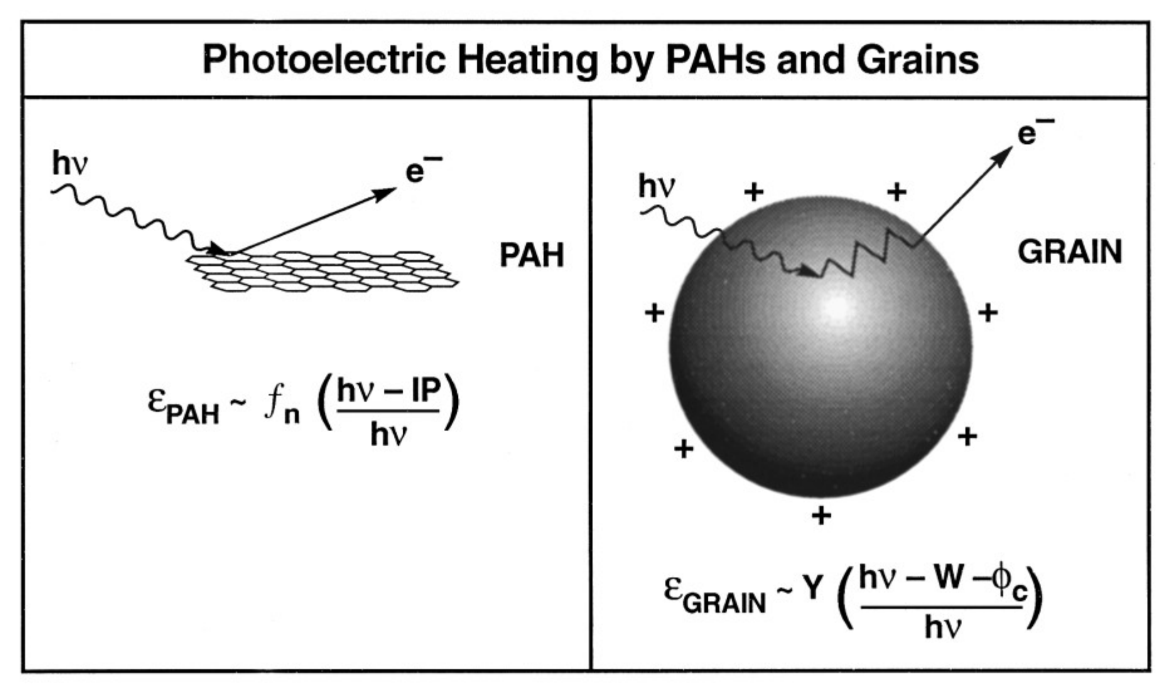
Dust is formed in the external layers of evolved stars. The relatively high density and low temperature permit the formation of refractory dust molecules.

Dust from stellar winds from the R Sculptoris star. Thermal emission observed by ALMA.

Small grains are very important component of the ISM

Only ~0.1% by mass, ***but***

- They heat the gas
- They bound to magnetic fields.
- Control radiative transfer in galaxies
- Shield molecular clouds from far-UV photons
- Form H_2, and host grain surface chemistry
- Forms rocky planets…
- …
- Very interesting emission properties.



Dust grains heat the gas, being the smallest grains the most effective.

Dust couples to magnetic fields

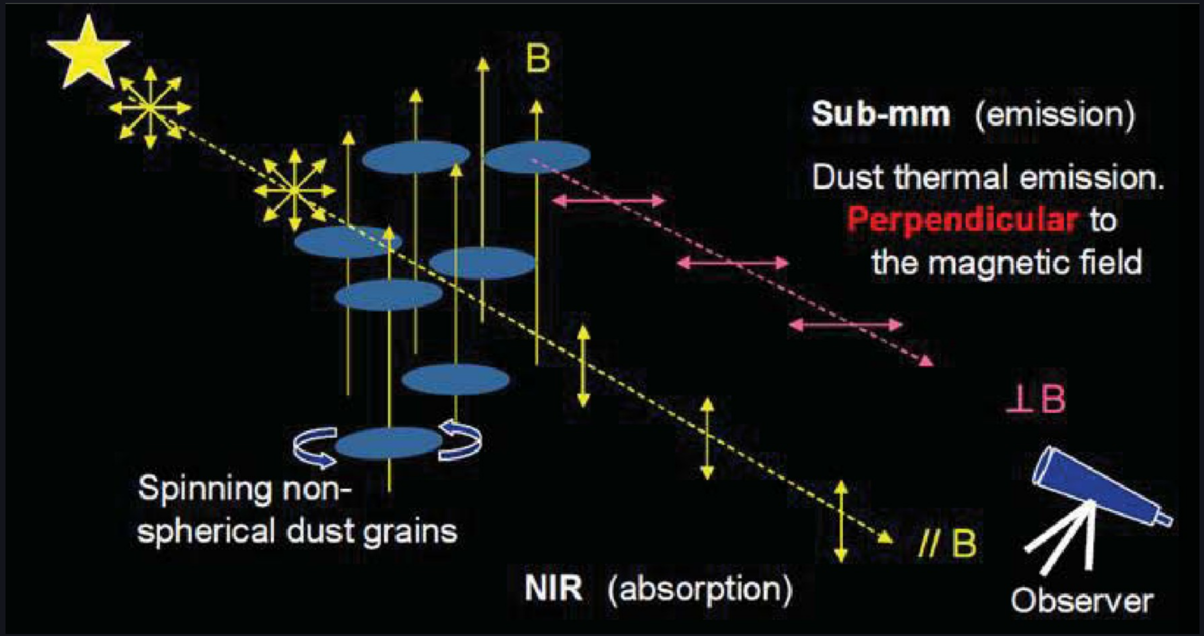
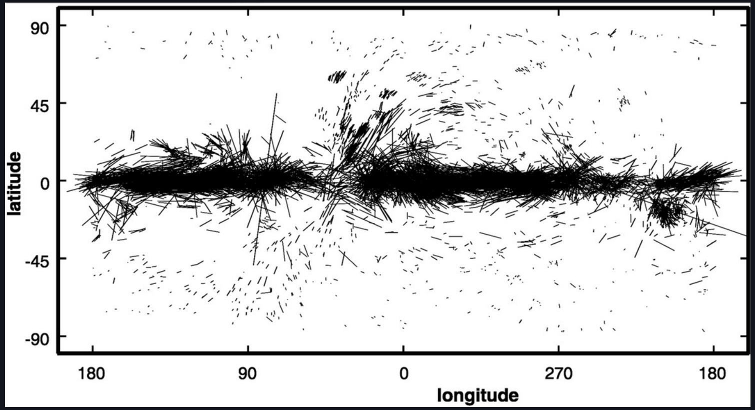
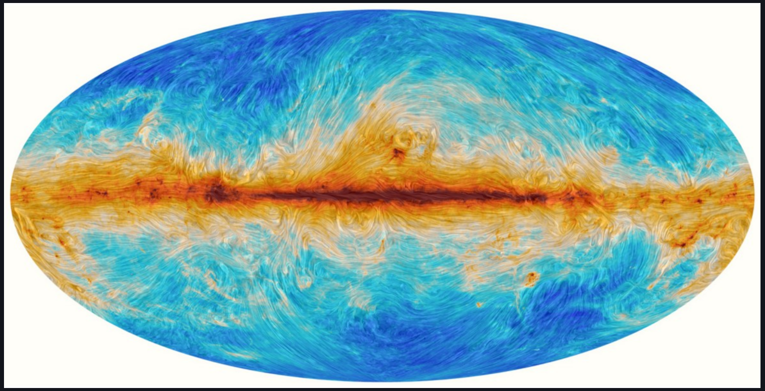


Figure from B. H. Su (AIP Conf. Proc. 1543,)

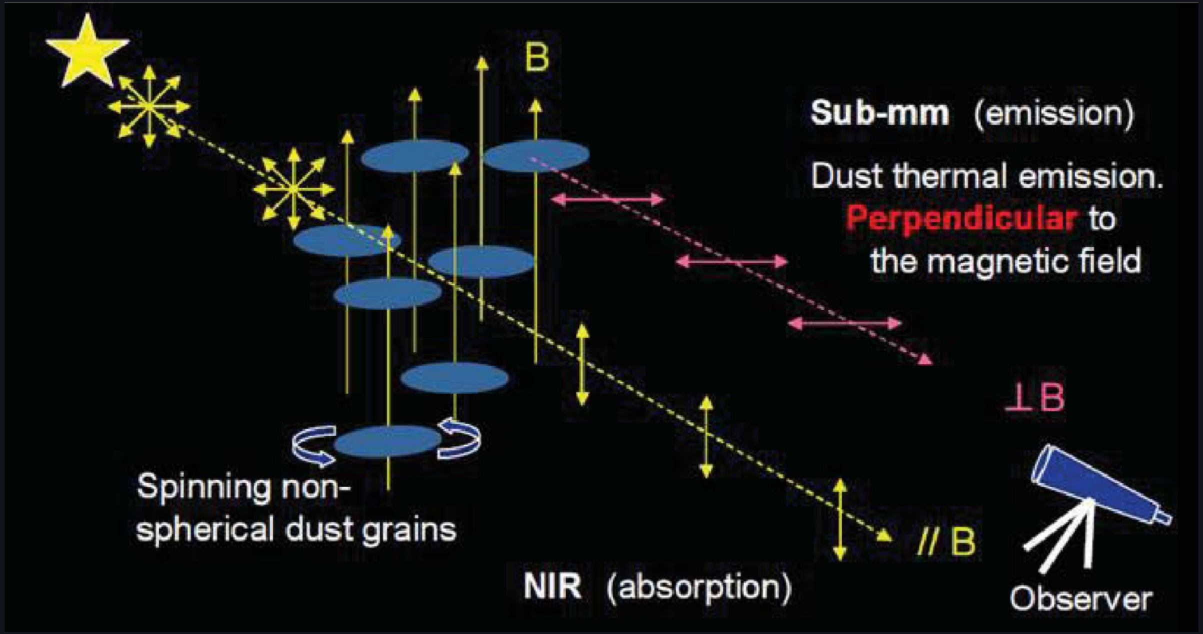
Dust couples to magnetic fields



Starlight polarisation



Dust Pol. at 353 GHz



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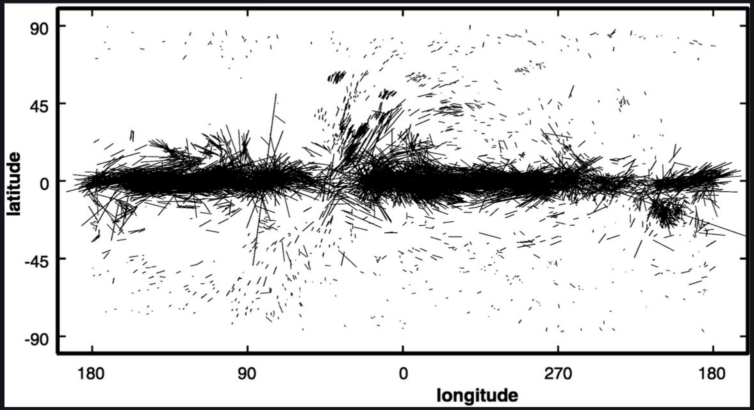
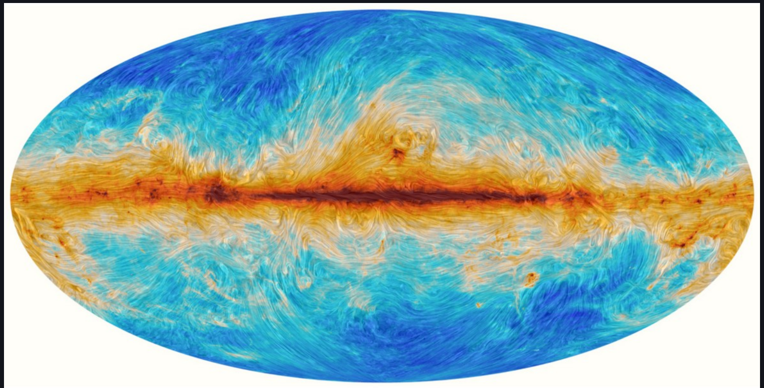
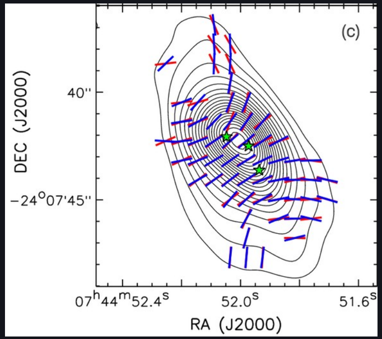
Dust couples to magnetic fields



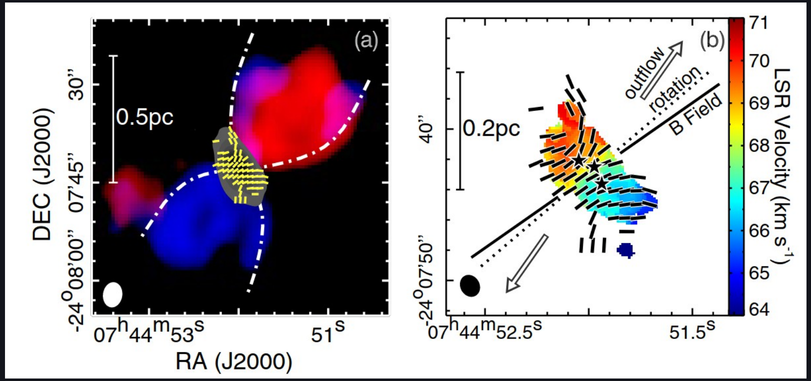
Starlight polarisation



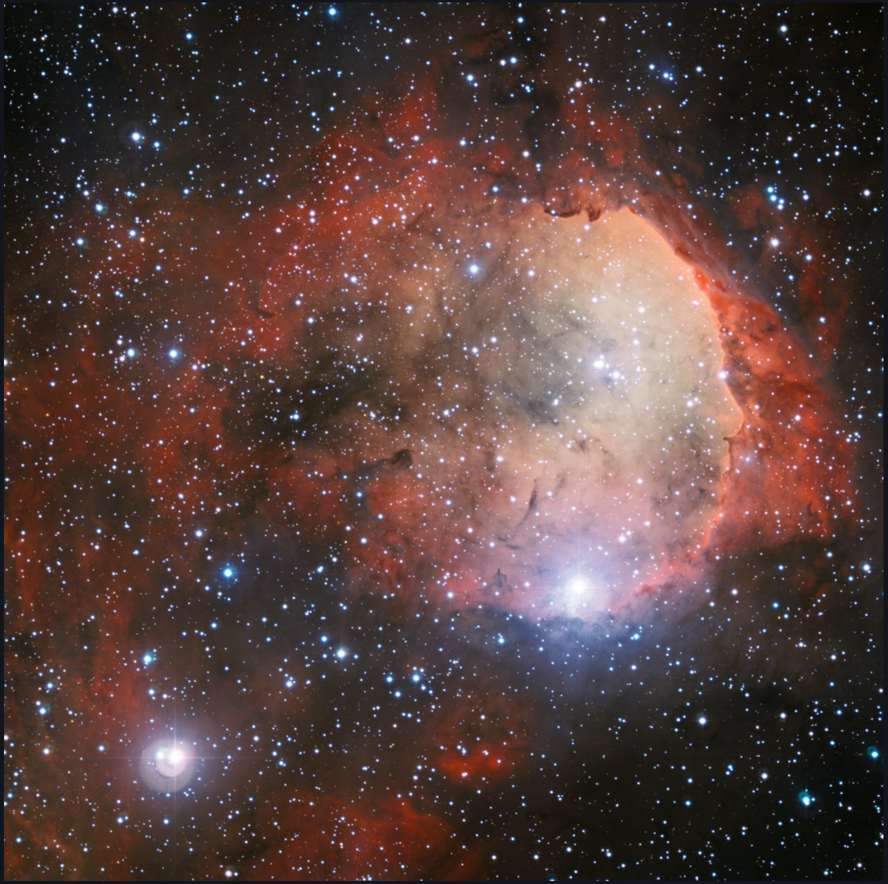
Dust Pol. at 353 GHz



Sub-pc observations of high mass star-forming region.



Qiu et al. 2014



NGC 3324 (2.2-metre MPG/ESO telescope at La Silla Observatory)

Dust shields molecular clouds from far-UV photons

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“Gabriela Mistral Nebula”. Literature Nobel Price from Vicuña

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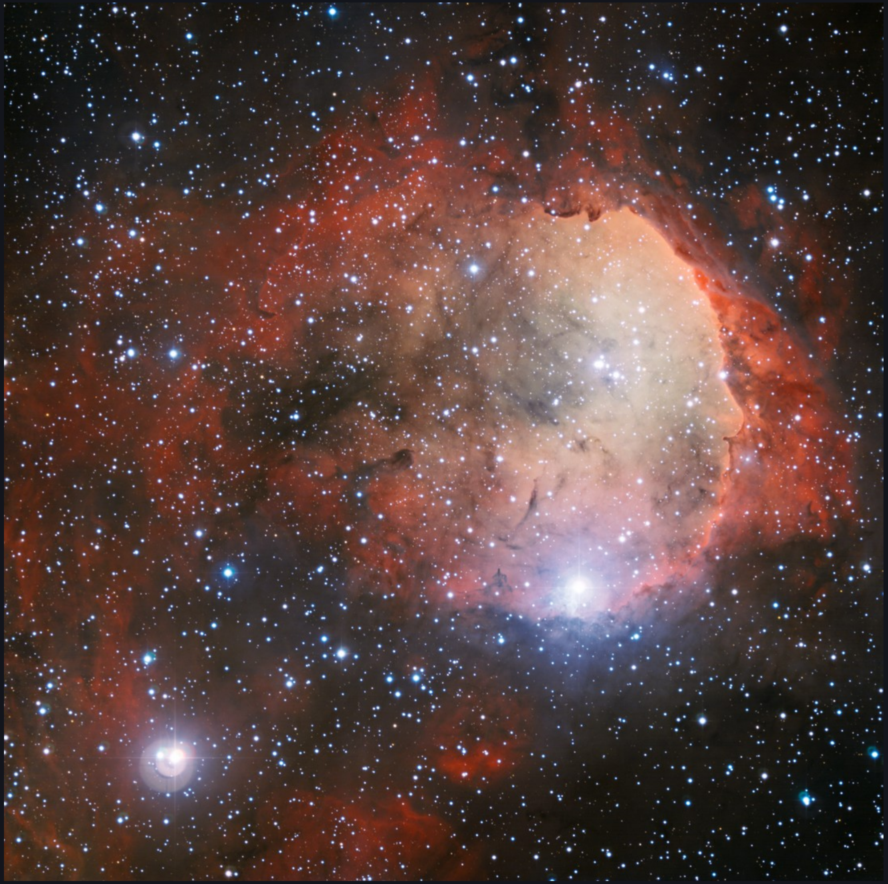

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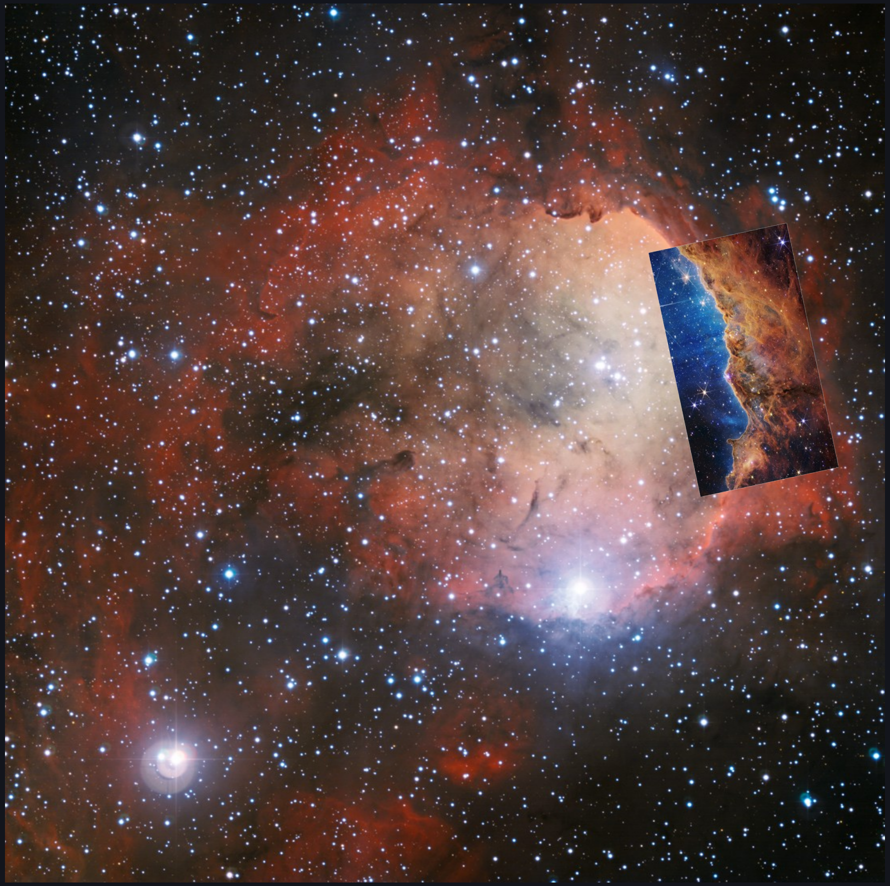


NGC 3324 (2.2-metre MPG/ESO telescope at La Silla Observatory)

Dust shields molecular clouds from far-UV photons

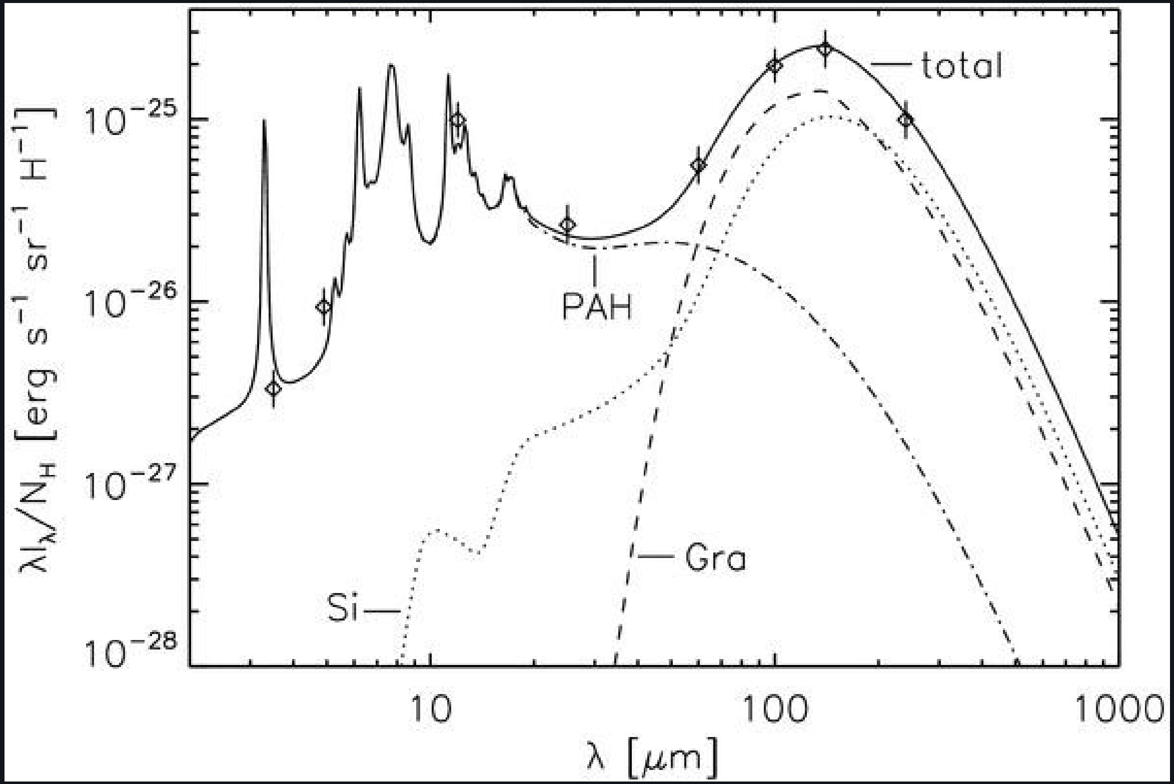
NGC 3324 (James Webb Space Telescope)

Dust shields molecular clouds from far-UV photons

Dust shields molecular clouds from far-UV photons

NGC 3324 (James Webb Space Telescope)

Dust observation: complex spectrum



Dust emission from diffuse ISM

C. C. Popescu et al. 2010

Thermal emission with a modified black body spectrum

$$I(\nu) \propto \nu^{\alpha} B_{\nu}(T_{BG})$$

+

Modeling of PAH emission.

Dust models

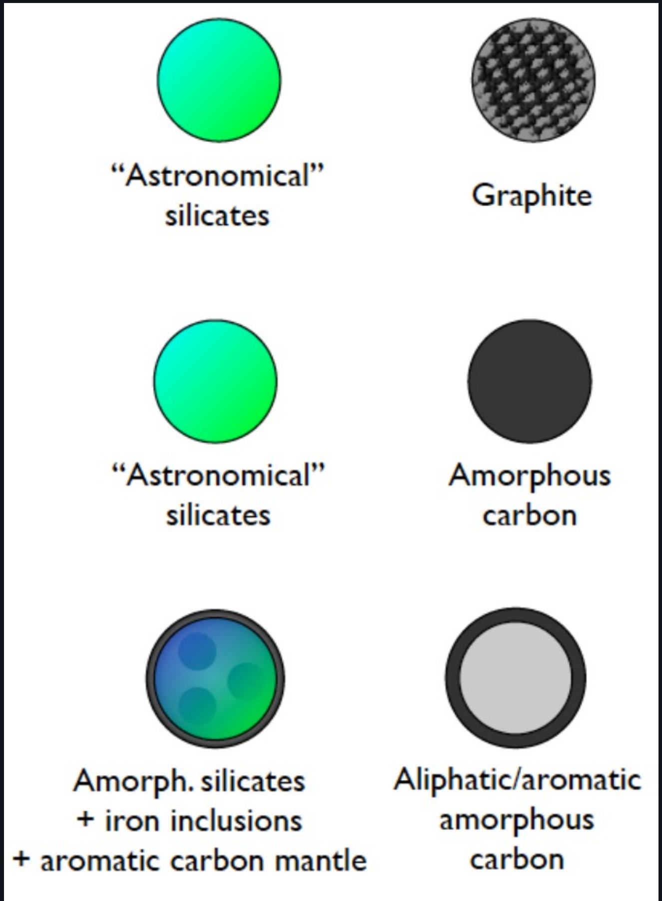
Draine & Fraisse 2009

Draine & Hensley 2013

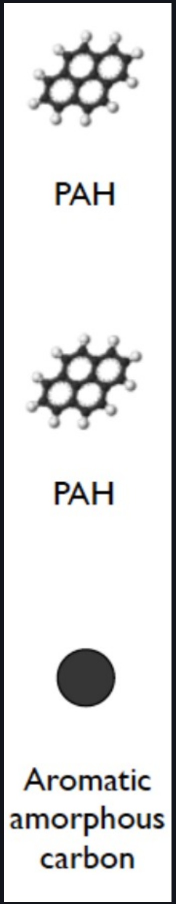
Compiegne et al. 2011

Guillet et al. 2018

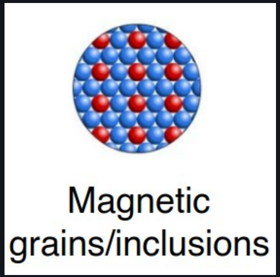
Jones et al. 2013



Large dust grains, Dust polarization

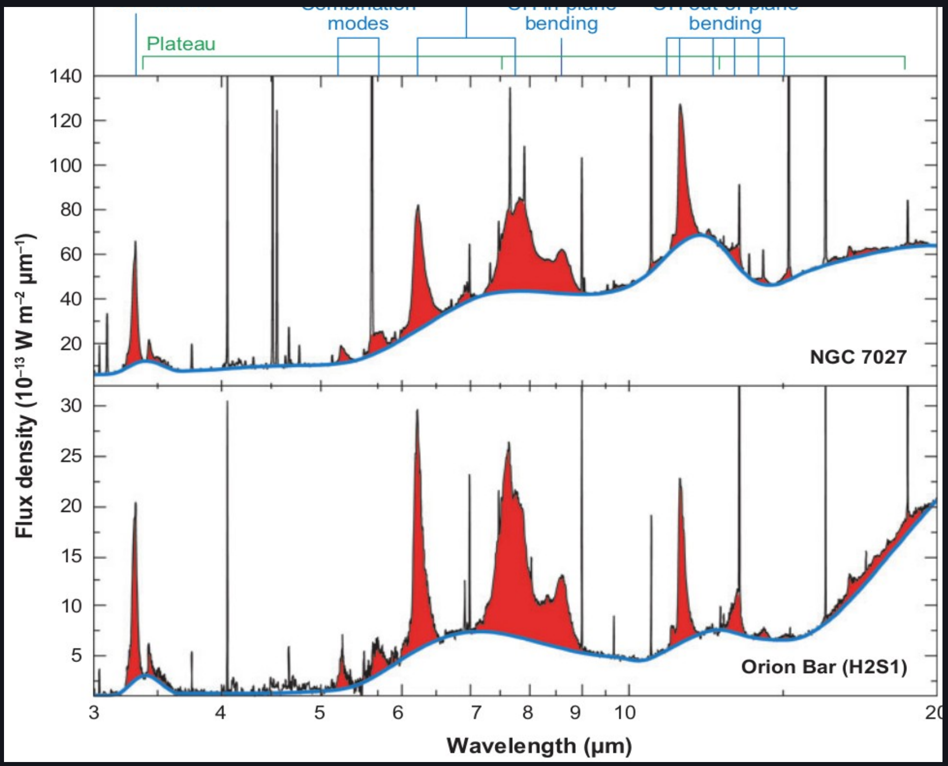


NIR emission
and microwave



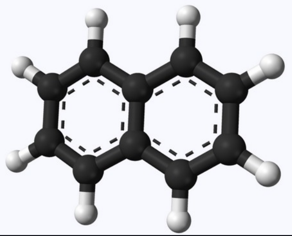
Magnetic Dipole Emission

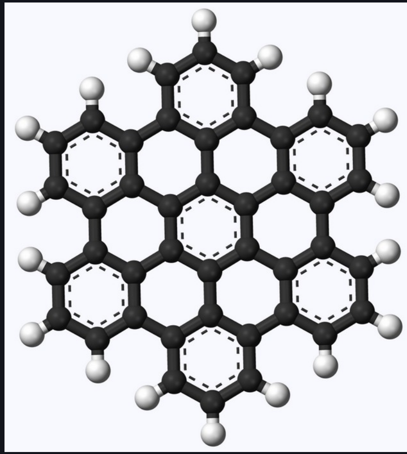
Polycyclic aromatic hydrocarbon (PAH)



Tielens 2008, ARAA

Planar molecules that can account for the rich mid-IR spectrum observed from the ISM.





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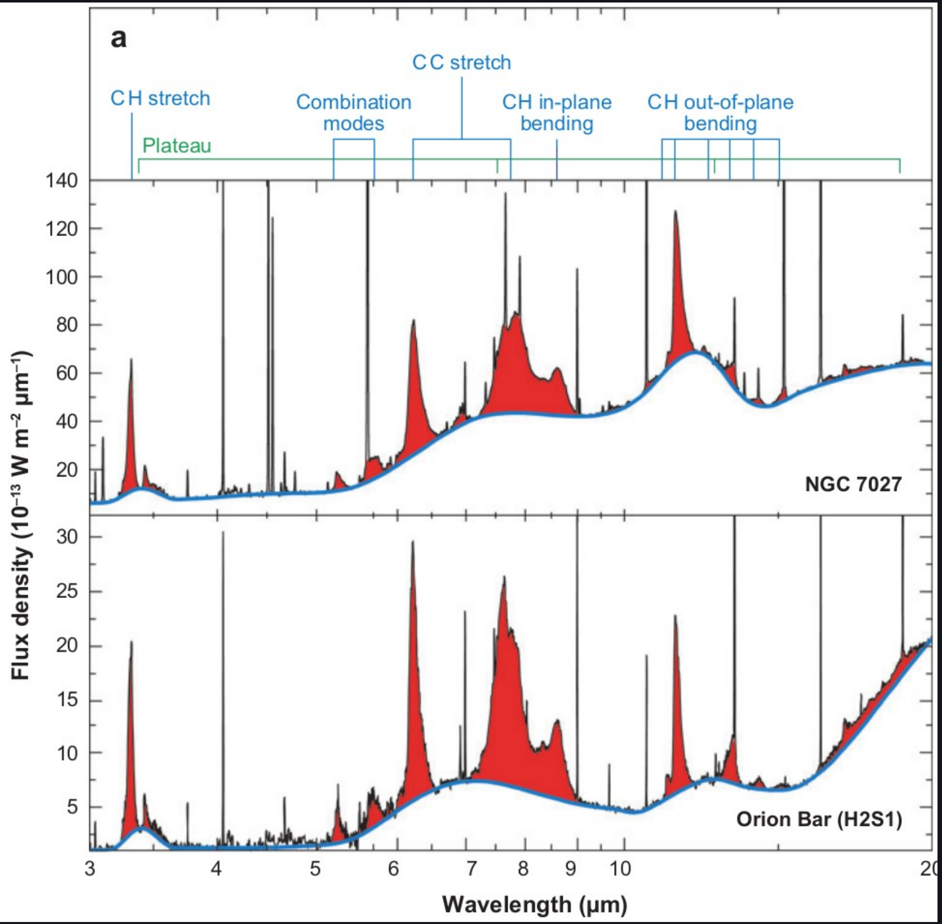

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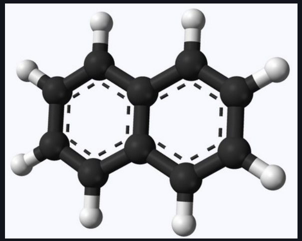

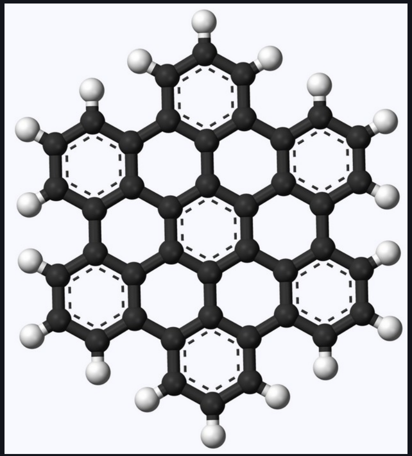

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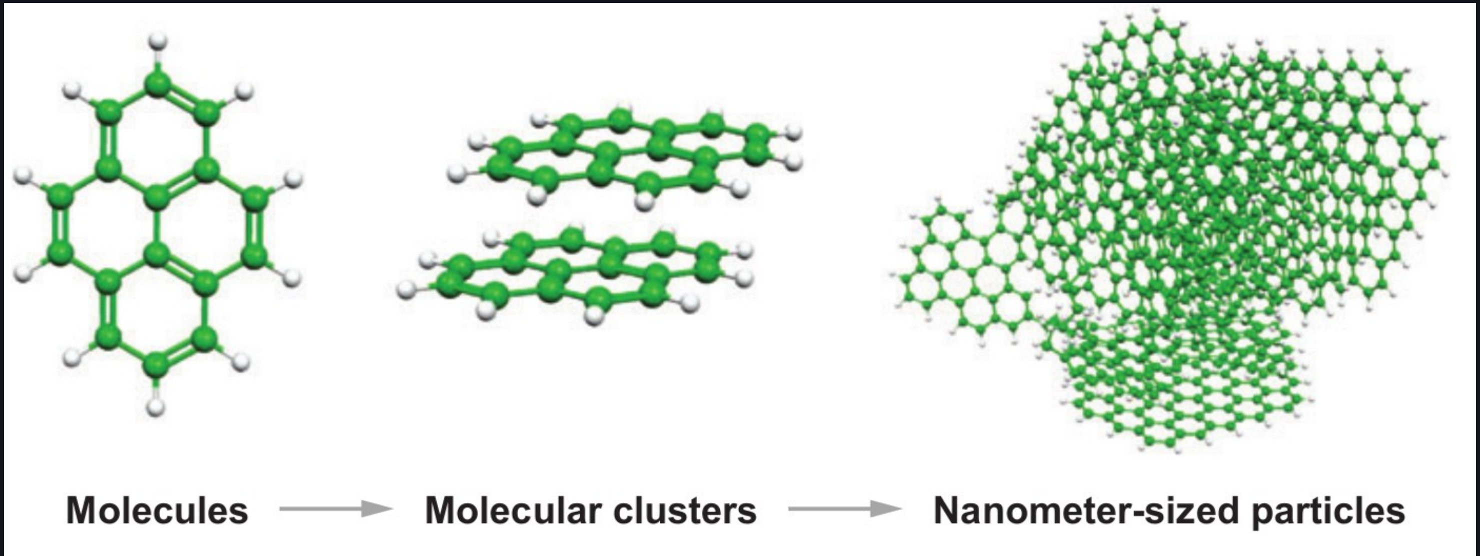
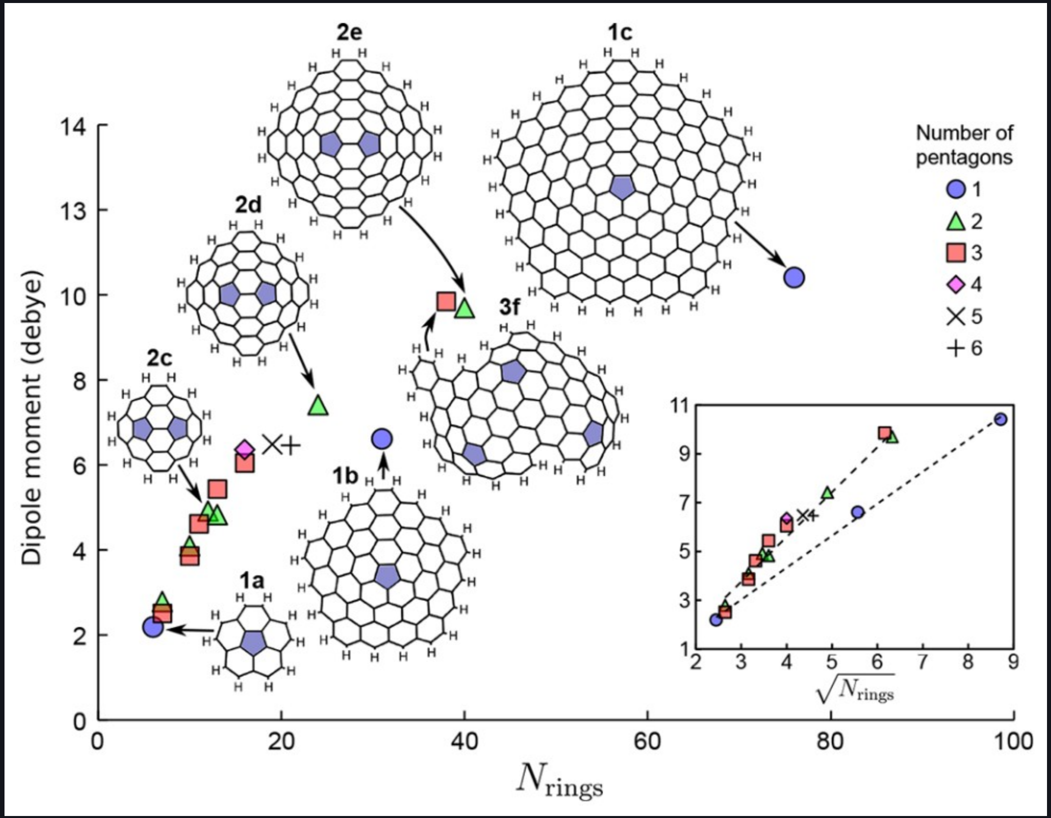


Tielens 2008, ARAA

From PAH molecules, larger particles can be formed (they are quite sticky)

Polycyclic aromatic hydrocarbon (PAH)

The introduction of curvature into a hexagonal carbon lattice through a pentagonal defect produces a considerable molecular dipole moment.



Martin et al. 2019

What about the rotational spectrum?

→ Spinning Dust.

Spinning dust

A MECHANISM OF NON-THERMAL RADIO-NOISE ORIGIN*

WILLIAM C. ERICKSON
Department of Physics, University of Minnesota, and Carnegie Institution of Washington Department of Terrestrial Magnetism,† Washington 15, D.C.

Received September 19, 1956; revised May 10, 1957

ABSTRACT

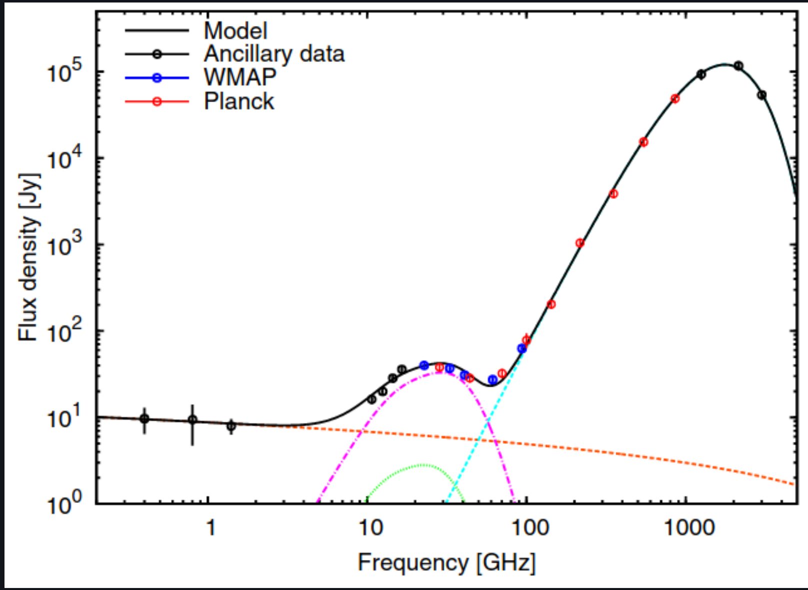
A mechanism of non-thermal radio-noise origin is proposed. The action of this mechanism may be summarized in the following manner. Suppose that clouds of interstellar grains exist in the radio-source regions. If a high-velocity gas cloud collides with a cloud of grains, the grains will be bombarded by moderately fast atoms and/or ions. These collisions will transfer angular momentum to the grains, and, in fact, the angular velocity of each grain will execute a dynamical "walk." It is shown that rotational frequencies comparable with radio frequencies may be attained. If some of the grains possess electric or magnetic dipole moments due to polar or ferromagnetic substances or statistical fluctuations in the distribution of charge on the grains, they will radiate classically at radio frequencies. Rather improbably high grain densities are required in order to account for the total radio-frequency radiation of high-emissivity sources. However, the high-frequency portion of this radiation could be generated with moderate grain densities.

Spinning dust

An updated model was proposed by Draine & Lazarian 1998

It produces a concave spectrum that peaks around 30GHz

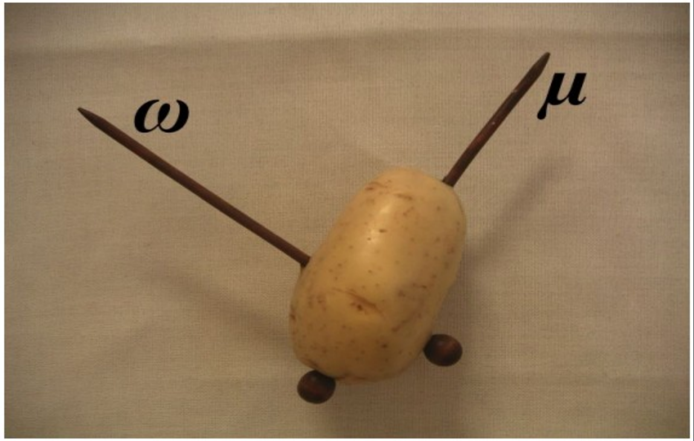
Great success explaining the dust-correlated excess of emission observed at that frequency range by CMB experiments.



Radio spectrum of Perseus Molecular cloud

Planck Collaboration. 2011

Spinning dust



Credit: Yacine Ali-Haïmoud

Very small grains can get spun up by gas collisions, radiative torques and other processes.

If grains have a dipole moment, this rotation causes them to radiate.

Power radiated given by Larmor formula:

$$P = \frac{2}{3}\frac{\omega^4 \mu^2 \sin^2 \theta}{c^3}$$

Frequency of emission:

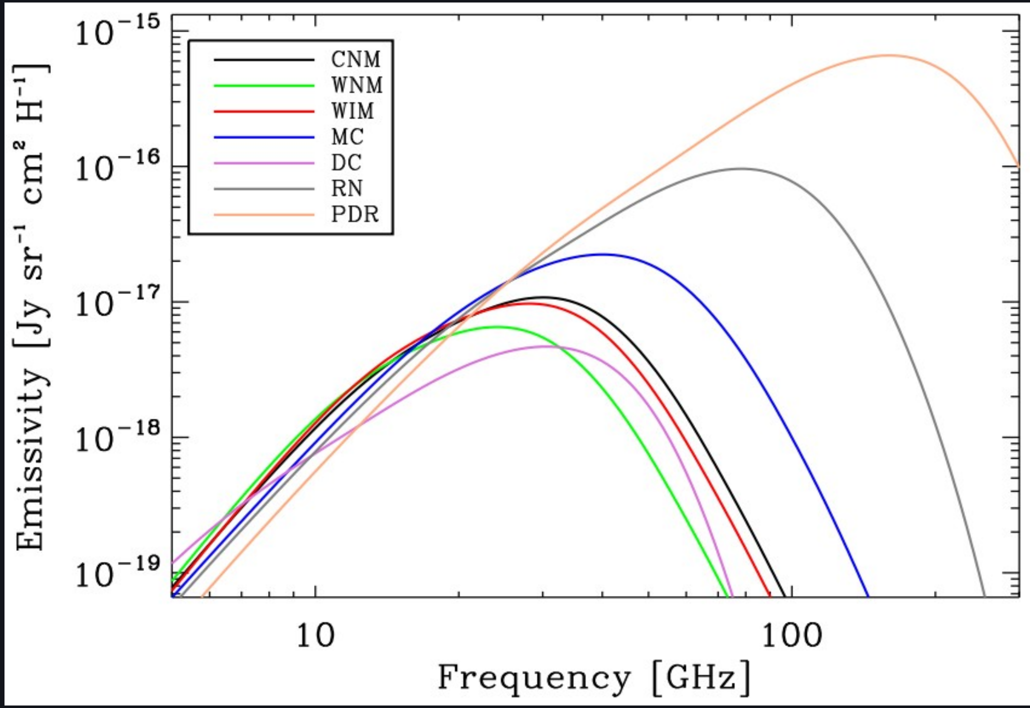
$$\nu = \frac{\omega}{2\pi} = 21\,\mathrm{GHz}\left(\frac{T}{100\,\mathrm{K}}\right)^{1/2}\left(\frac{\rho}{3\,\mathrm{g\,cm^{-3}}}\right)^{-1/2}\left(\frac{a}{5\,\text{Å}}\right)^{-5/2}$$

To get 20-30 GHz spinning dust emission, grains have to be ***very*** small, < 1 nm.

=>Macromolecules.

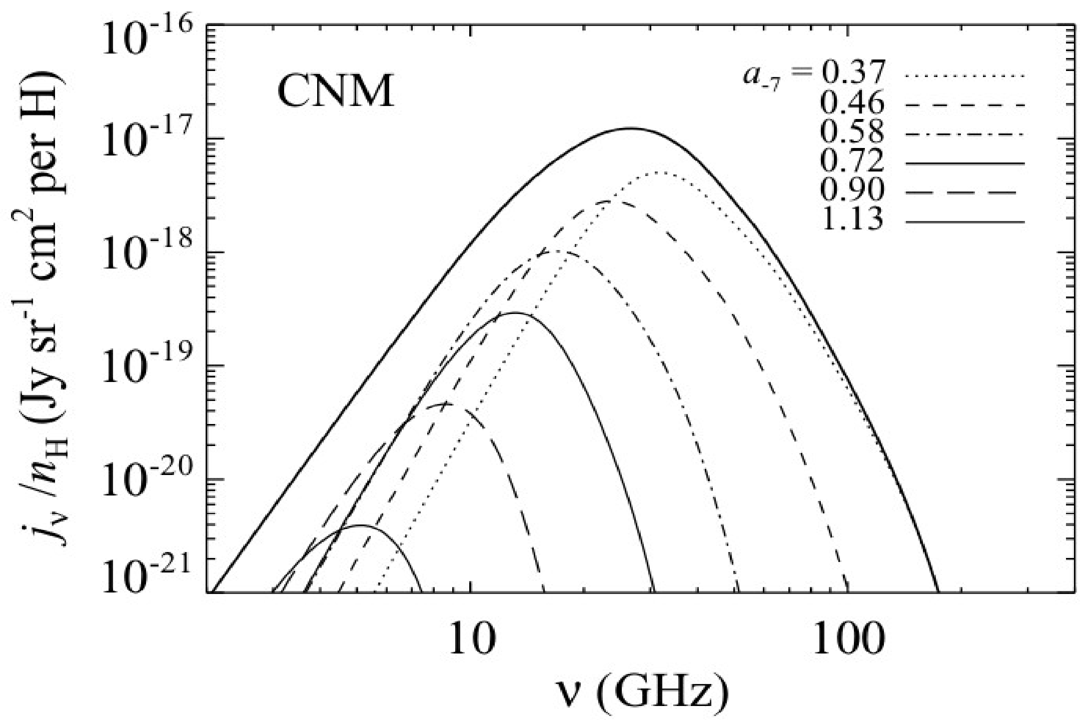
Detailed theoretical models have been constructed that include all the known relevant effects.

The SD Spectral energy distribution is expected to vary with environment…



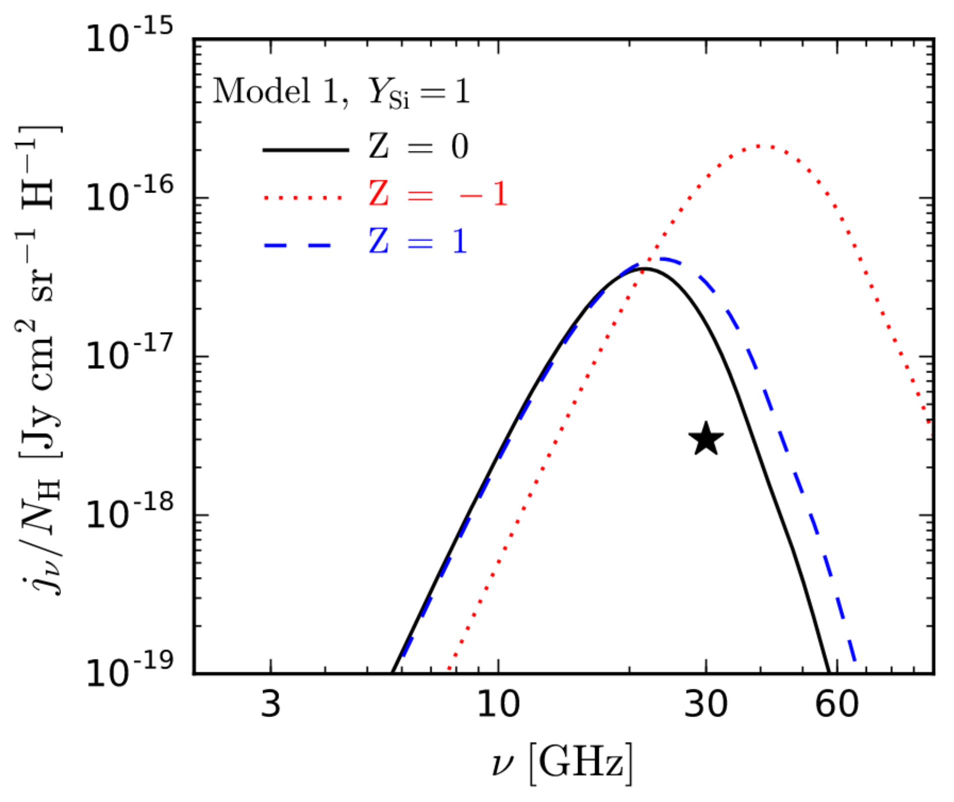
Different astrophysical environments

… and nanoparticle sizes…



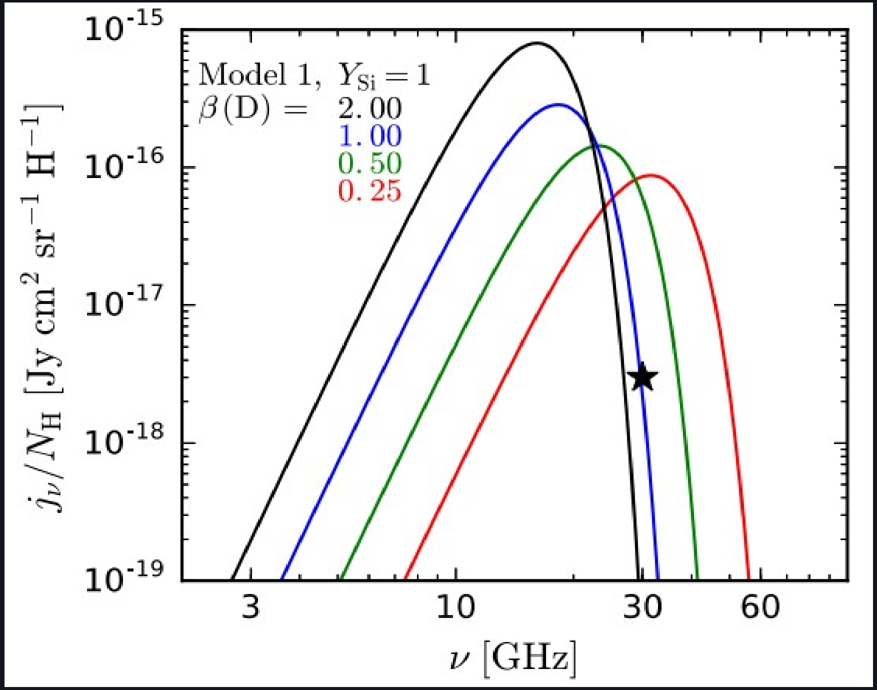
Ali-Haimoud+ 2009

… and charge state…



Hensley & Draine 2017

… and dipole moments. => Complex problem.

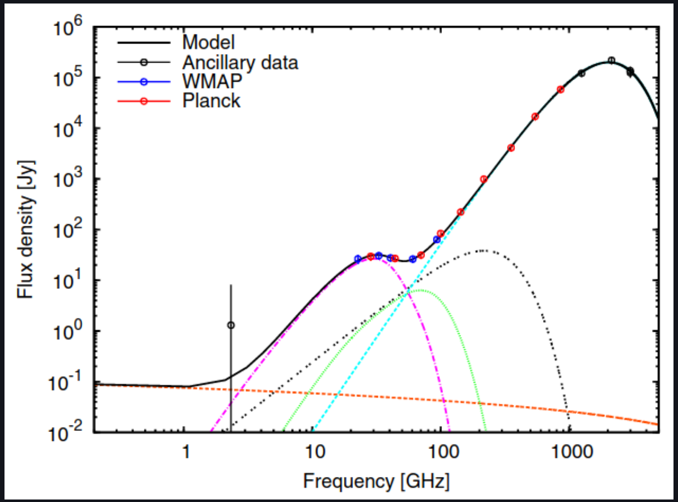


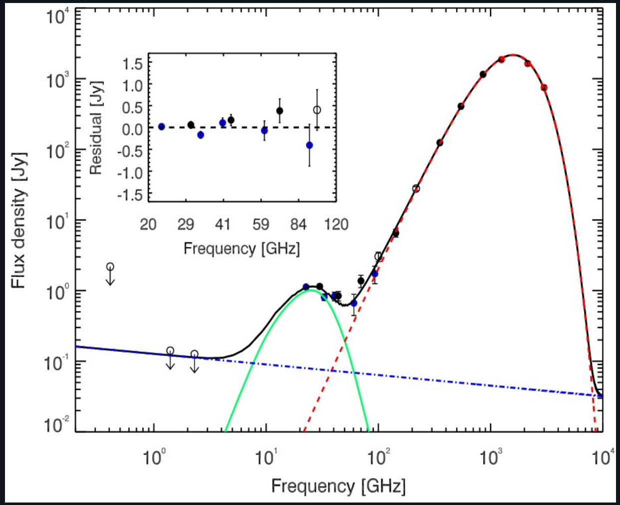
Hensley & Draine 2017

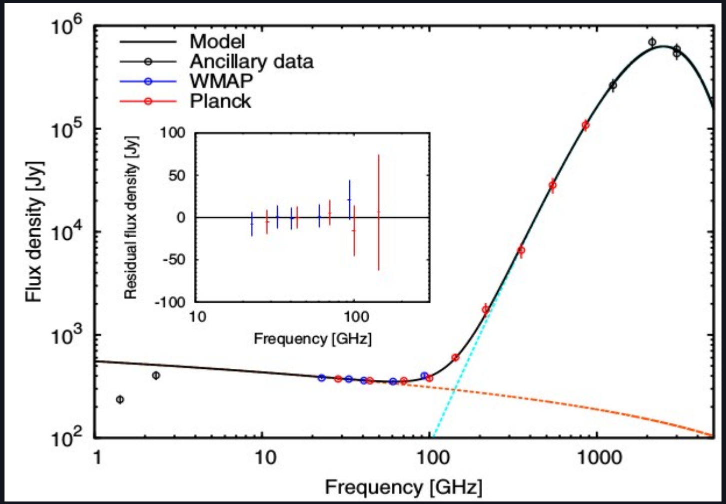
Spinning/damping mechanisms

- Collisions with neutral atoms
- Collisions with ions
- Interaction of charged grain with plasma (“plasma drag”)
- Interaction of grain dipole moment ~μ with plasma
- Absorption of optical photons (electronic transitions)
- Emission of IR photons (vibrational transitions)
- Emission of microwave photons (rotational transitions)
- Emission of photoelectrons
- Formation of H2

Spinning dust examples: interstellar clouds



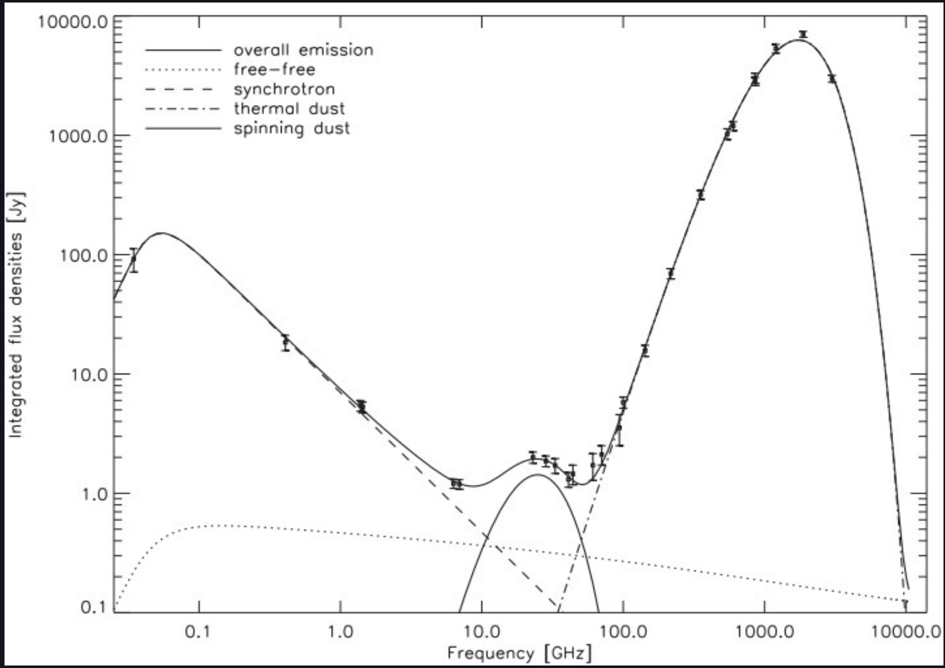




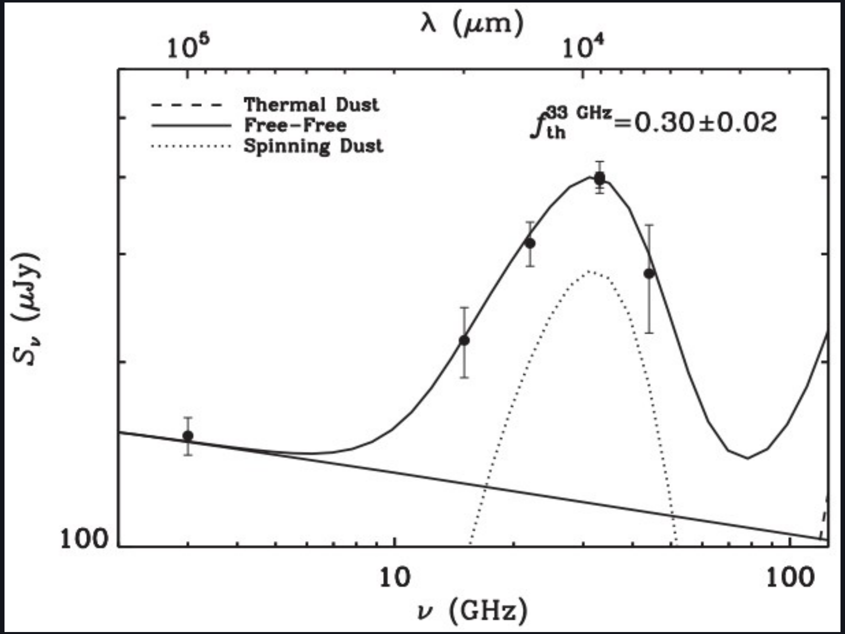
rho Oph, LDN 1780, and Orion molecular clouds

Spinning dust examples: extragalactic

M31
Battistelli+ 2019

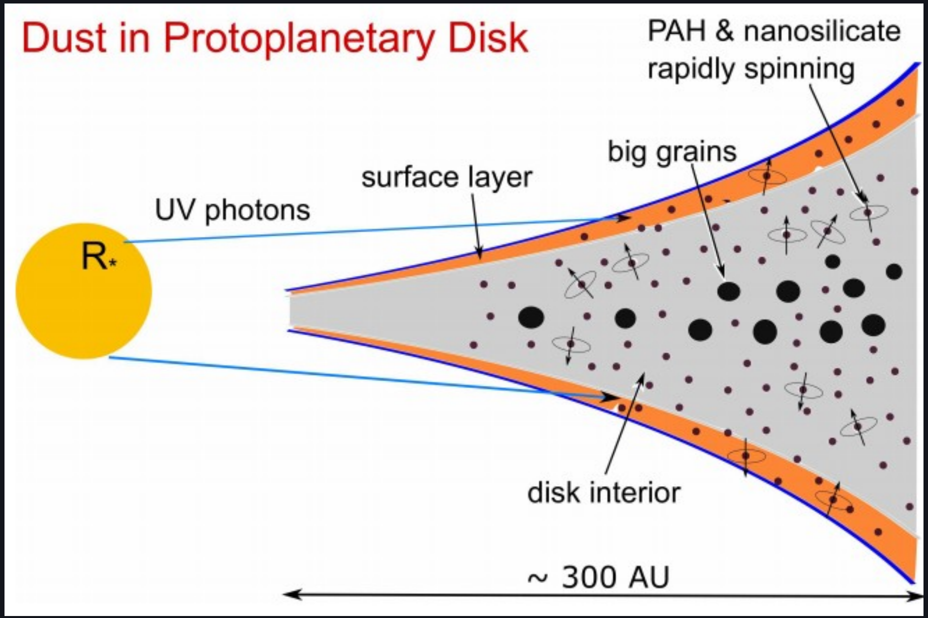


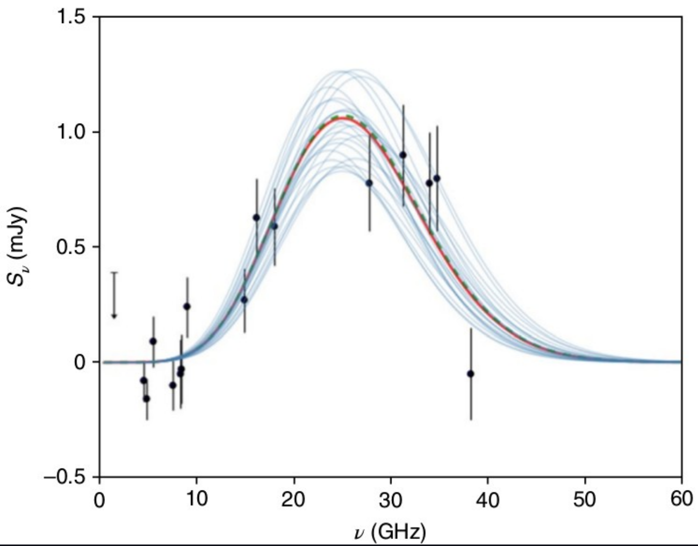
NGC 4725
Murphy+ 2018



Spinning dust examples: PPD

Emission from spinning PAHs or nanosilicates dominates over thermal dust at frequencies ν < 60 GHz, even in the presence of significant grain growth. (Hoang et al. 2018)





Spinning nano-diamonds from the circunstellar disk **V892 Tau**

- (Greaves+ 2018, Nature)

Carriers?

- Smaller grains are more susceptible to the spun up/damping mechanisms

- Polycyclic aromatic hydrocarbons (PAH) are a well known small grains population of the ISM

- Some SD/PAHs correlations have been observed (Casassus+ 2008; Scaife+2010)

- As well as lack of correlation in individual clouds: Tibbs+ 11, Vidal+ 11, Battistelli+15 and also full sky: Hensley+ 2016, Vidal+ 2020.

Progress in identification and understanding of excitation mechanisms has been slow due to lack of high angular resolution radio observations.

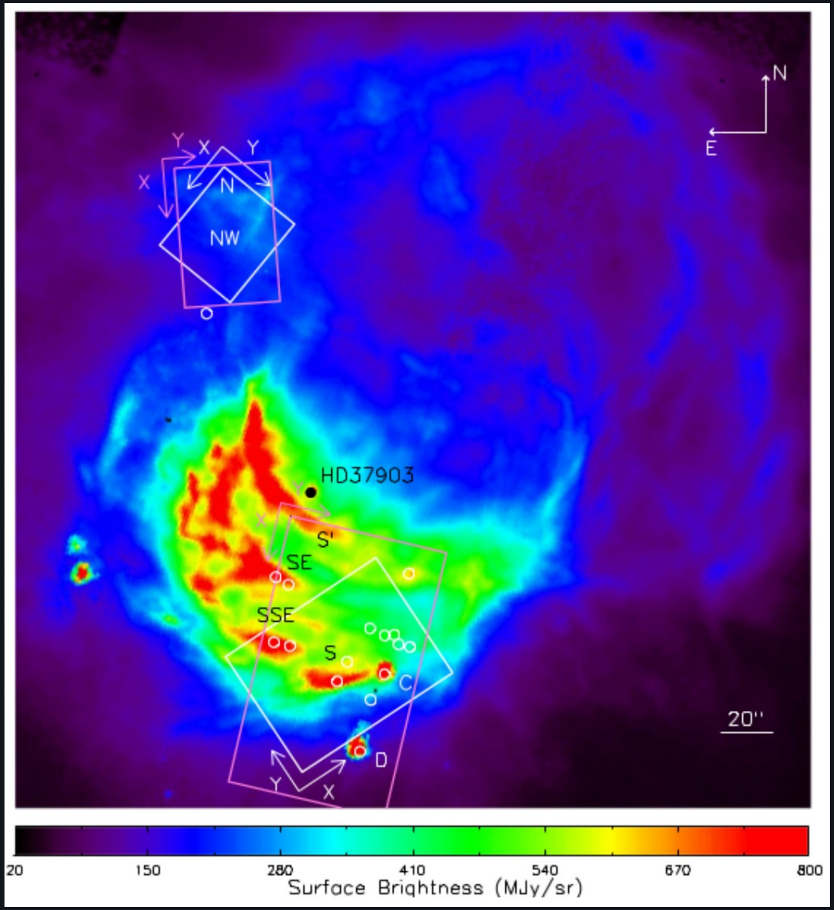
NGC 2023

Credit: ESO, HLA, Robert Gendler

Well studied reflection nebula/edge-on PDR.

- Conspicuous PAH emission.
- Shows Extended Red Emission.
- Central B1.5 star excites the gas and dust.
- 475 pc.

NGC 2023 mid-IR data

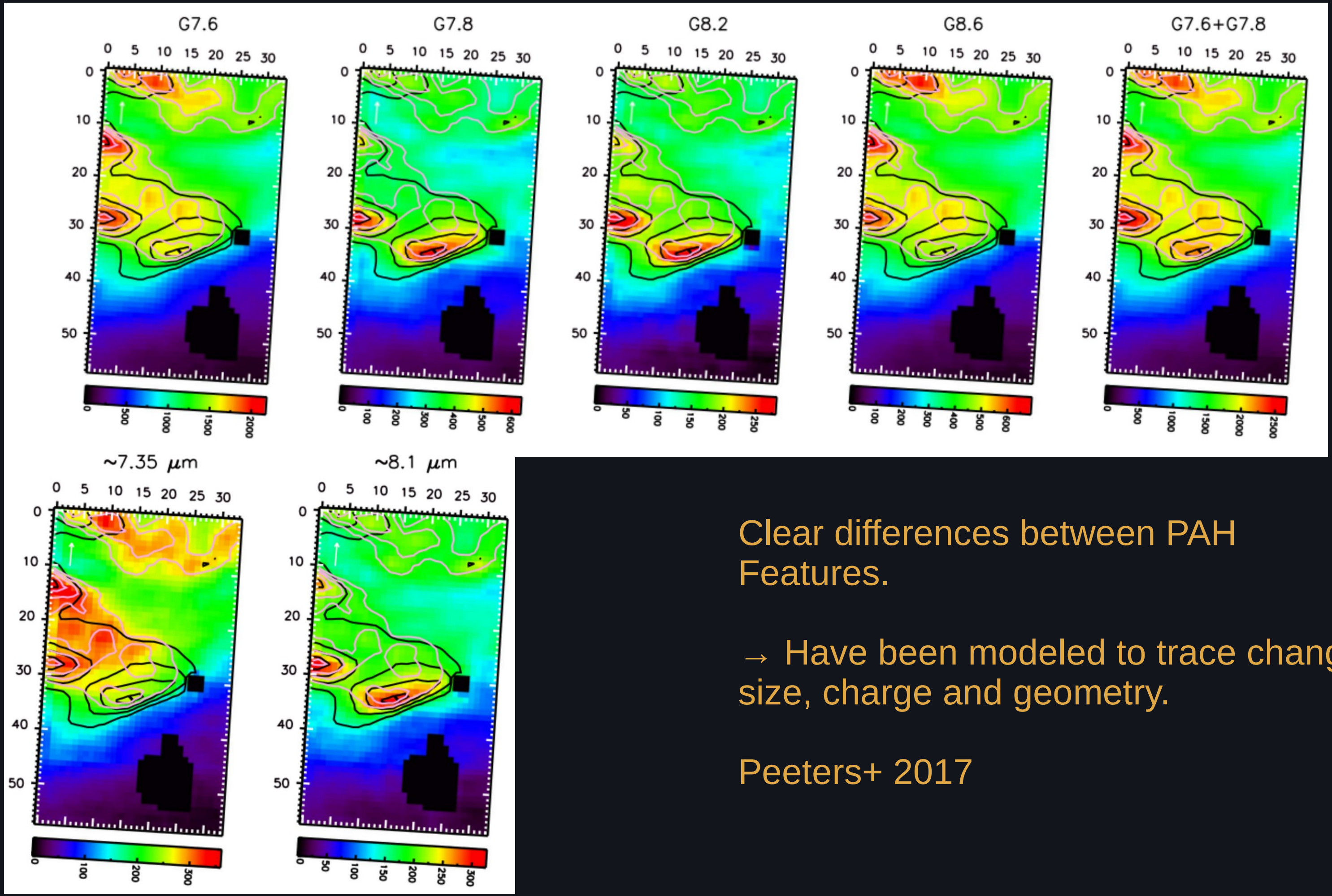


Well characterized mid-IR emission with Spitzer spectra: PAH, H2, C60

Complememtary datasets: C-RRL, HCO+, HCN, CN...

Peeters+ 2017

NGC 2023 mid-IR data

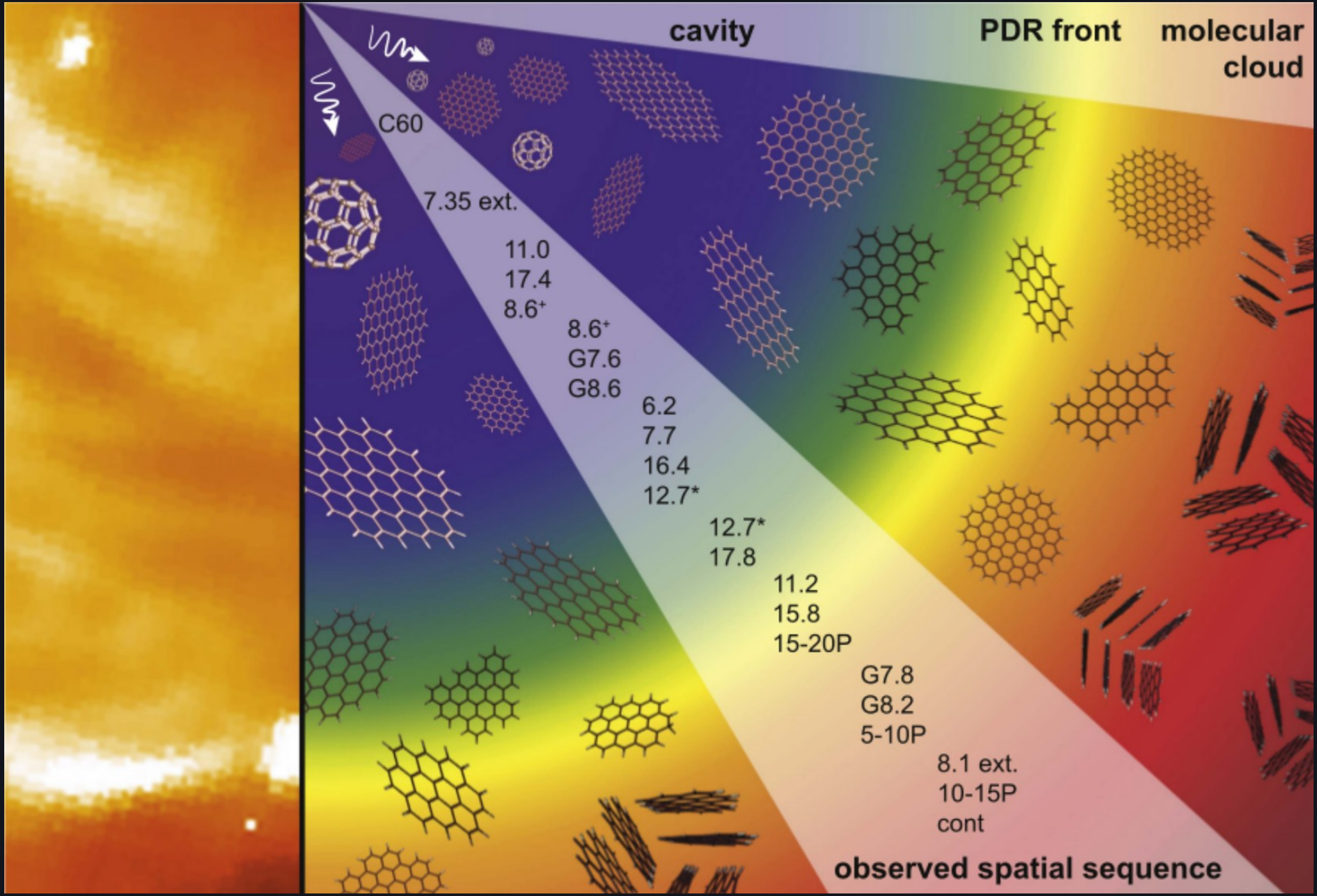


Clear differences between PAH Features.

→ Have been modeled to trace changes in PAH size, charge and geometry.

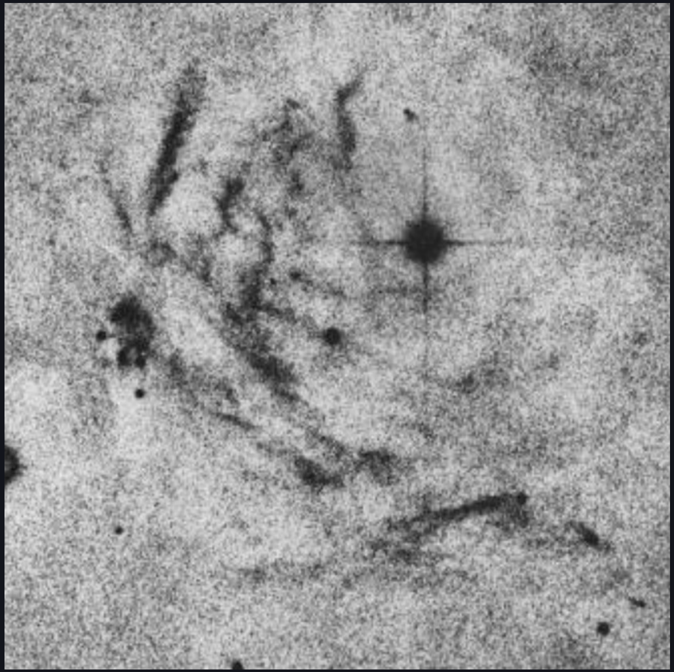
Peeters+ 2017

NGC 2023 PAH model



Peeters+ 2017

NGC 2023 ERE



Unsharped-masked ERE map.
Witt and Malin 1989.

First detection of Extended red emission (Gorodetskii & Roshkovskii 1978).

ERE → Excess of diffuse intensity in the optical R and I bands from reflection nebulae.

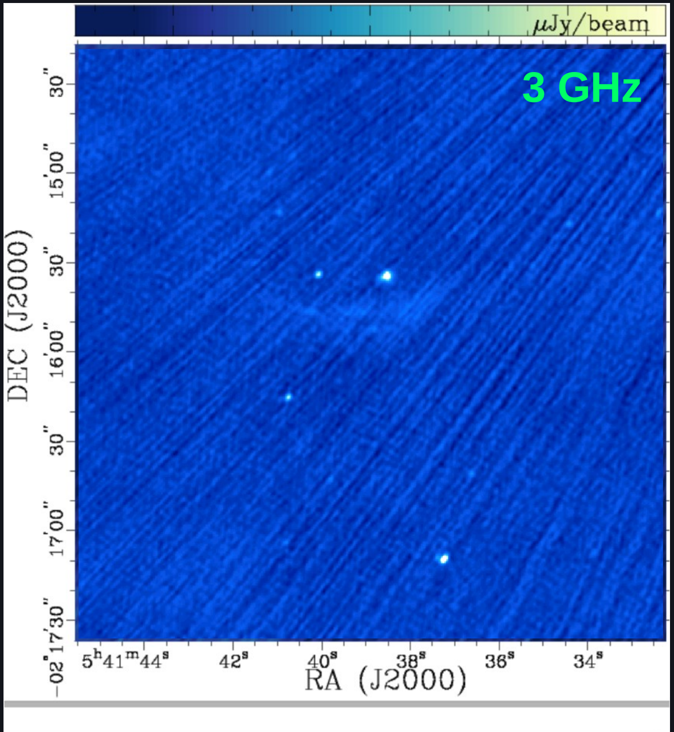
Likely due to luminiscence of carbonaceous nanograins exposed to UV (e.g. Witt+ 2006).

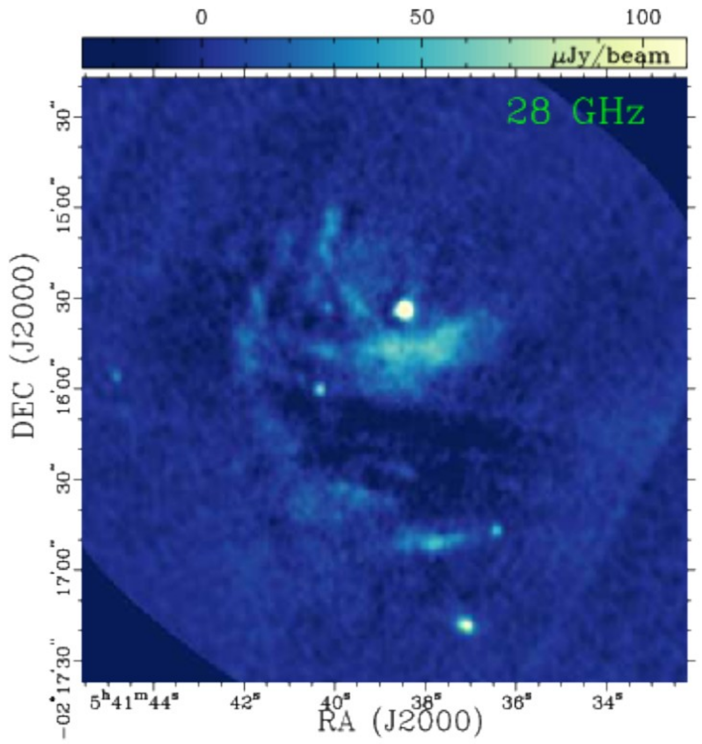
Does it relates with spinning dust?

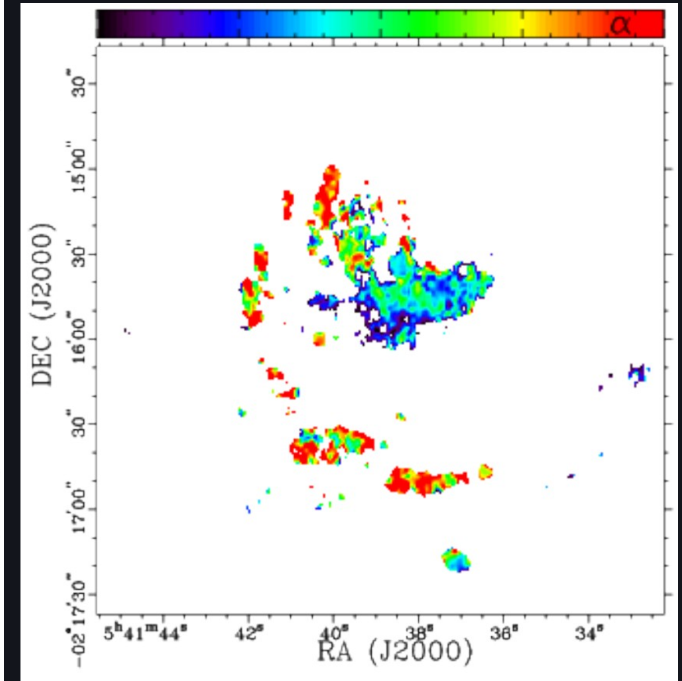
VLA observations of NGC 2023

Recent VLA continuum observations at K, Ka bands (18 to 36 GHz) and also S band (2 to 4) GHz.

- ≈ 2 arcsec synthesized beam.
- Filamentary emission without counterpart at 3 GHz.

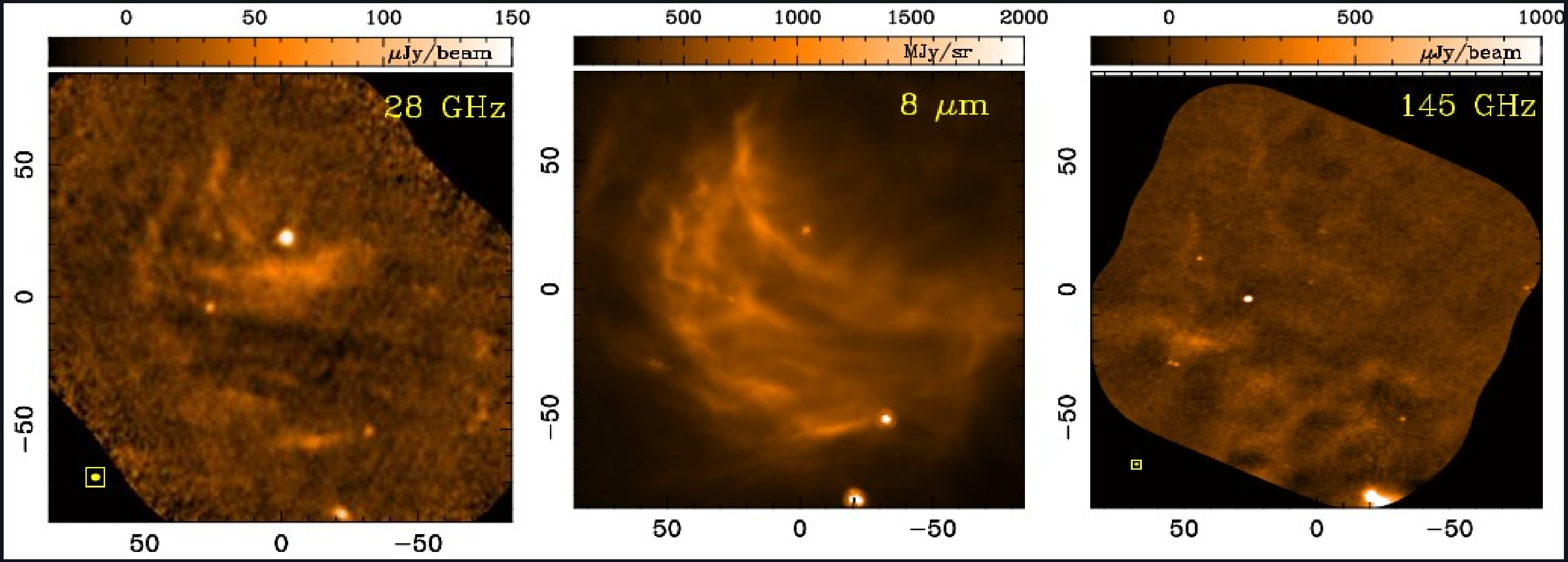






18-36 GHz spectral index

VLA observations of NGC 2023

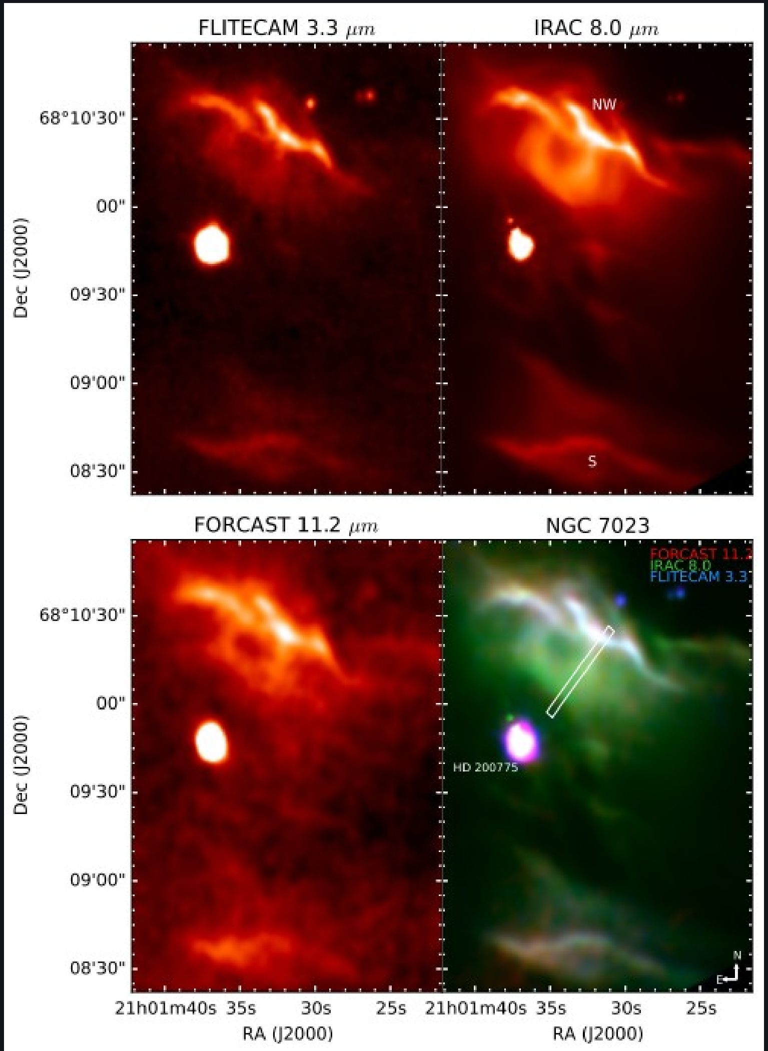


Radio

PAH

ALMA data at 145 GHz confirms that the emission is consistent with SD

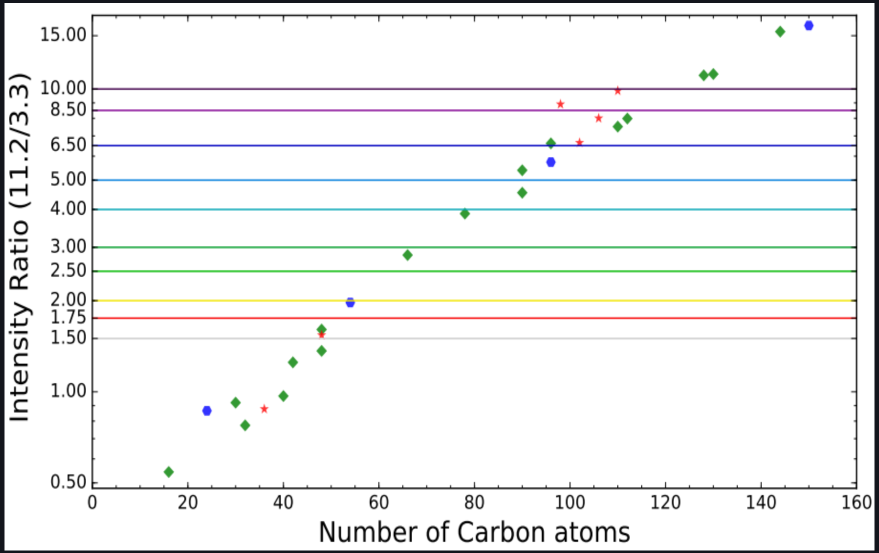
NGC 7023



Another well studied PDR with strong PAH emission

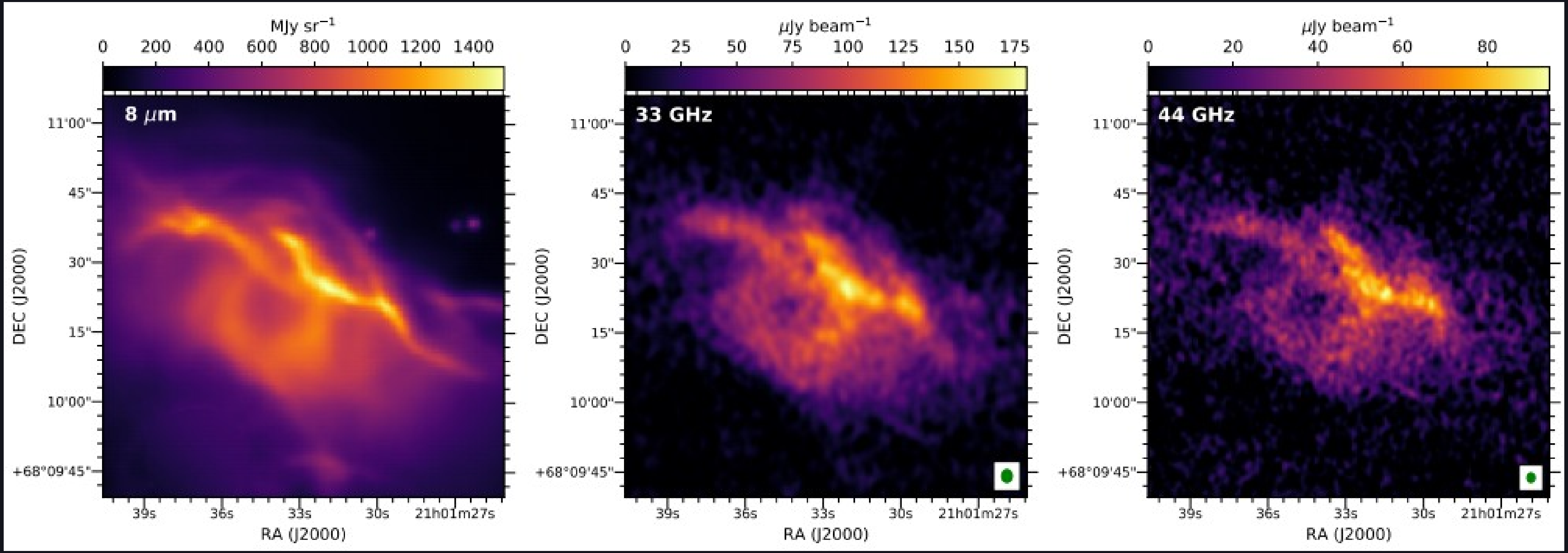
Measurements of IR ratios probe the morphology of the PAH size distribution and ionization: smallest PAH concentrate on the PDR surface.

Excellent target to study spinning dust!



Croiset+ 2016

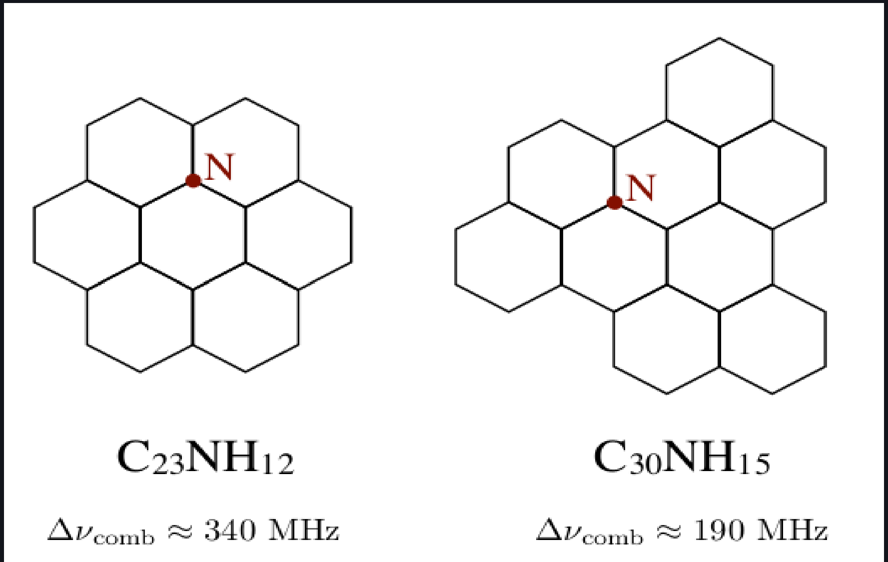
NGC 7023



Obtained VLA data to map NGC7023 from 5 to 50 GHz. We are measuring spectral variations and compare the grain size distribution with what is inferred from IR ratios.

Project lead by PhD student Carla Arce-Tord.

PAH rotational spectroscopy

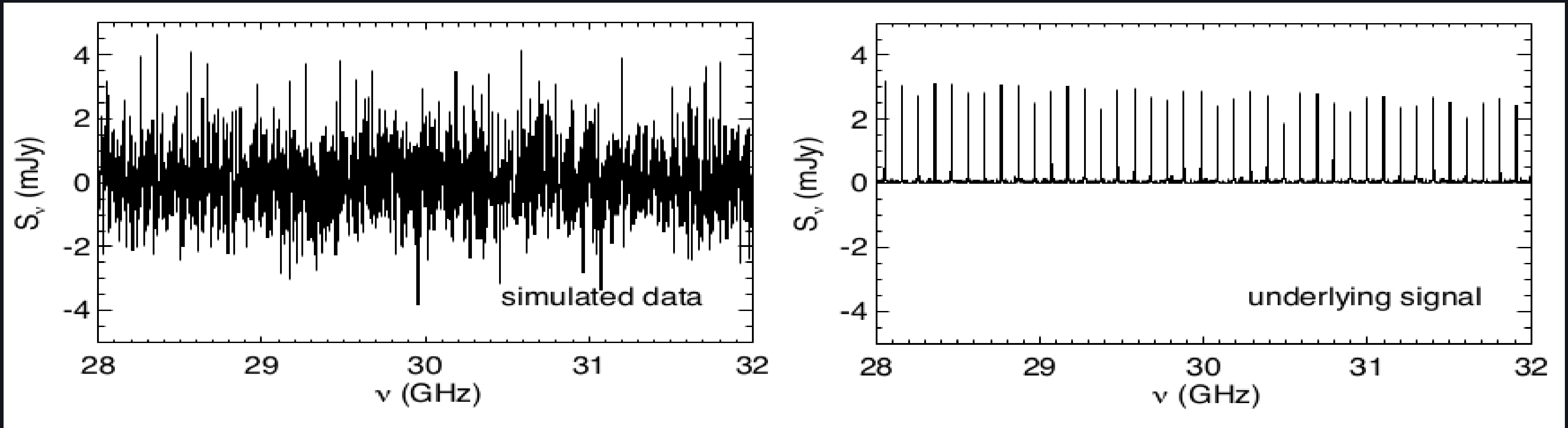


Quasi-symmetric planar PAHs should have a comb-like rotational spectrum

Quasi-symmetric PAHs nitrogen-substituted are common on the ISM

This could allow for unambiguous detection of individual PAH

PAH rotational spectroscopy



One attempt to detect the patter with the GBT on the Perseus molecular cloud.
Only upper limits (Ali-Haïmoud+ 2015)

ALMA Band 1 might be better suited for this search.

Summary

- Dust is fundamental in (most) astrophysical processes.

- Spinning dust hypothesis offer a new window to study ISM, although we don’t know for sure the carriers (PAHs? nano-silicates? Nano-diamons? Probably all.)

- SD observations can be used to trace the smallest grains when other tracers (IR) are not available (e.g. due to the lack of UV photons).

- New facilities such as ALMA Band 1, ngVLA, SKA will offer great observations in the 10–50 GHz range. It is necessary the understanding of the dominant radiative processes (spinning dust, magnetic dust?) and the possibilities they offer.

Gracias!