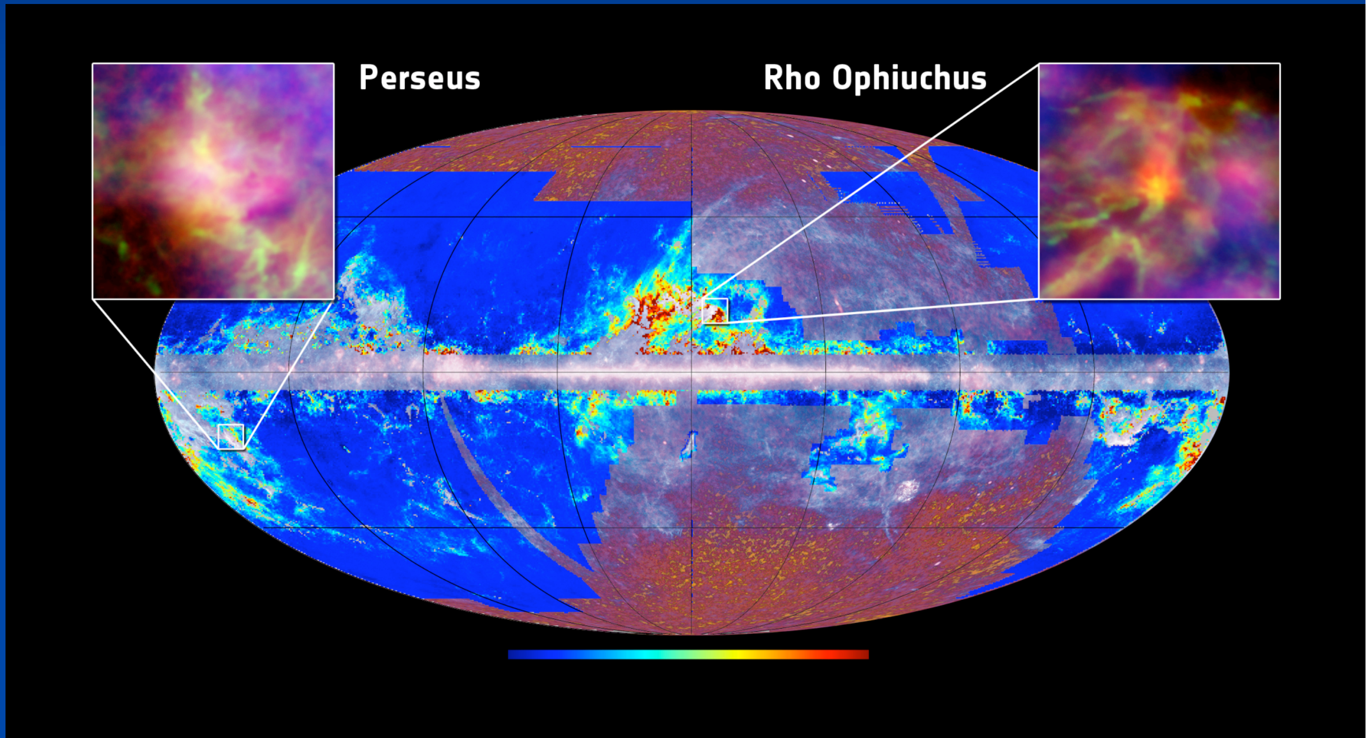
Spinning Dust: Past, Present and Future



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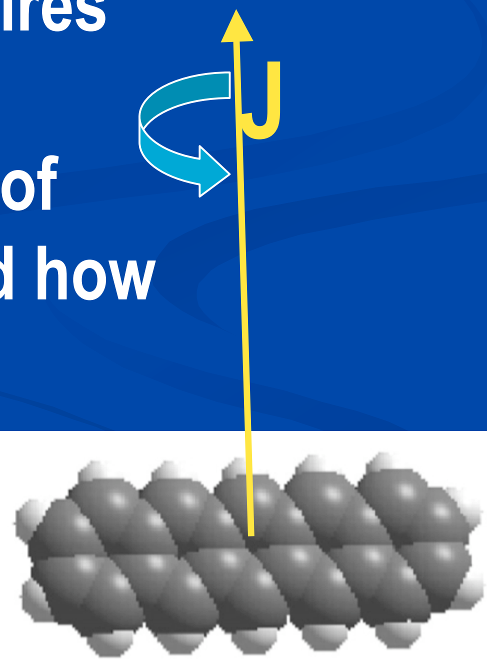
Special Thanks: Thiem Hoang and Bruce Draine

Alexander von Humboldt Stiftung/Foundation

THE UNIVERSITY of WISCONSIN MADISON

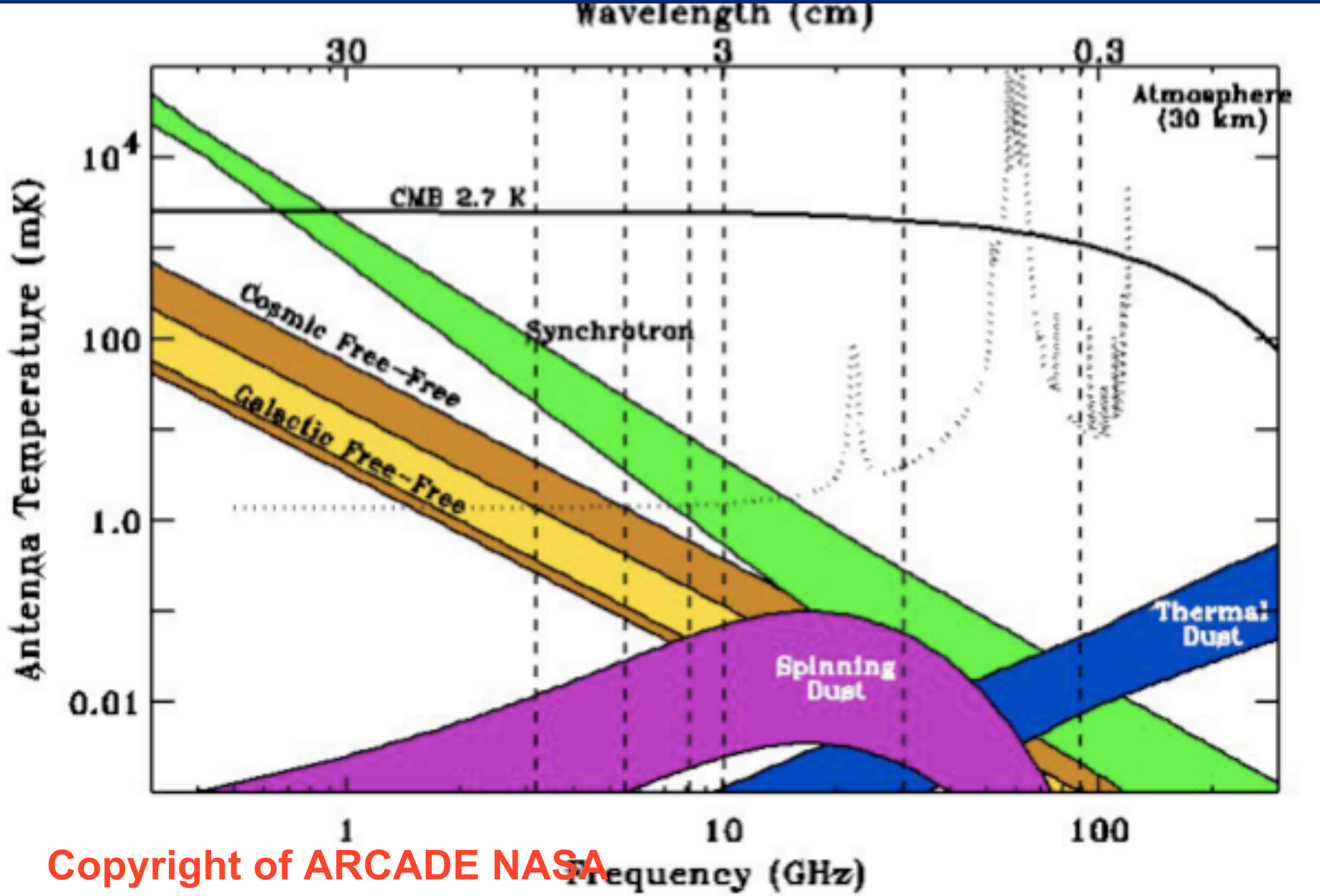
In the talk spinning dust model, its current state and outstanding questions are discussed

1. Anomalous galactic foreground emission originates from spinning dust.
2. New era of precision cosmology requires precise models of spinning dust.
3. There are still outstanding questions of whether the emission is polarized and how to weed it out.



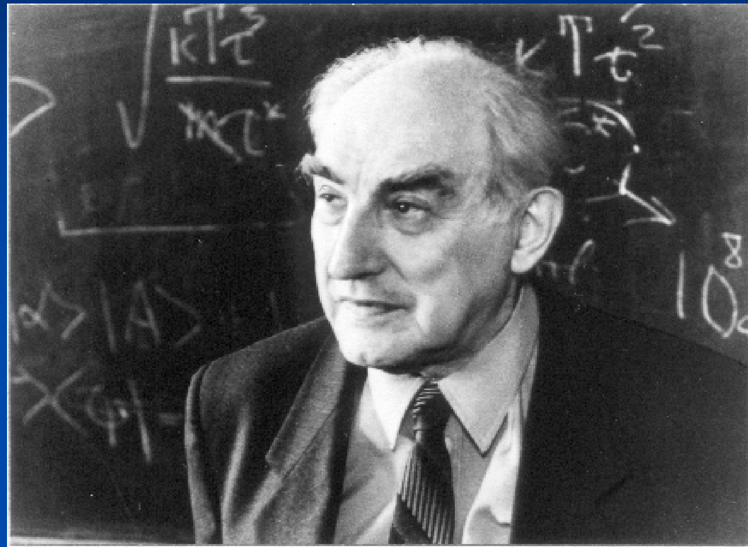
Pentacene
($C_{24}H_{12}$)

Spinning dust, i.e. spinning tiny PAHs with dipole moments, has become an accepted foreground



Past: Ideas of spinning dust emission can be traced through decades of astrophysical research

Erickson 1957
Ginzburg & Eidman 1959
Ferrara & Dettmar 1994



Two big changes from 50s:

1. Discovery of PAHs (Leger & Puget 1984)
2. Discovery of anomalous emission (Kogut et al. 1996, Leitch et al. 1997)

Small grains are better emitters:

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

David Spergel attracted my attention to the spinning dust, initiating our study of this phenomenon which resulted in Draine & Lazarian 1998 ab

Draine & Lazarian 98 model accounted for grain interacting with gas, plasma, ions and photons

Emission of a grain:

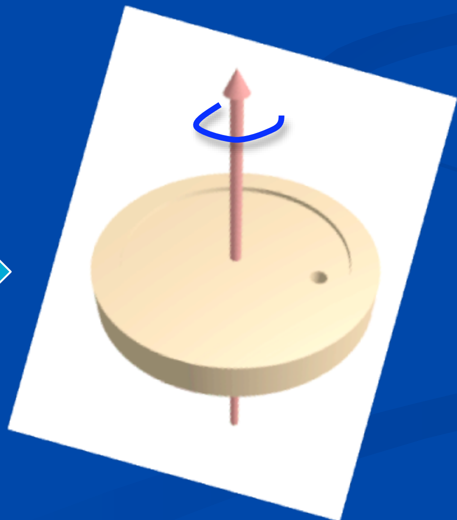
$$P_{ed}(\omega) = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}$$

μ is dipole moment, ω Is angular velocity

Dipole moment $\mu = N^{1/2}\beta_0$ is due to defects or intrinsic to polarized molecules

Collisions with gas atoms
Collisions with ions
Interaction with plasma
Emission of photons
....

→



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Microwave emission

The grain size distribution is constrained by the near infrared PAH emission.

Spinning dust was suggested about decade ago to account for the anomalous foreground emission

- Kogut et al. (1996) : dust correlated emision in 31 GHz.
- Leitch et al. (1997)

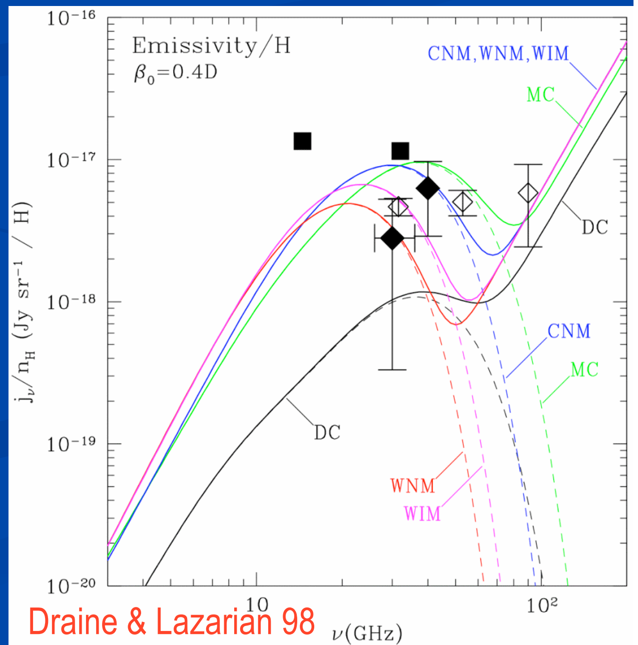
 - *an anomalous emission at 14.5 and 31 GHz*

 - Free-free emission from gas T≥10^6 K?

- Draine & Lazarian 1998

- cannot be free-free emission from 10^6 K gas

- electric dipole radiation of small dust grains

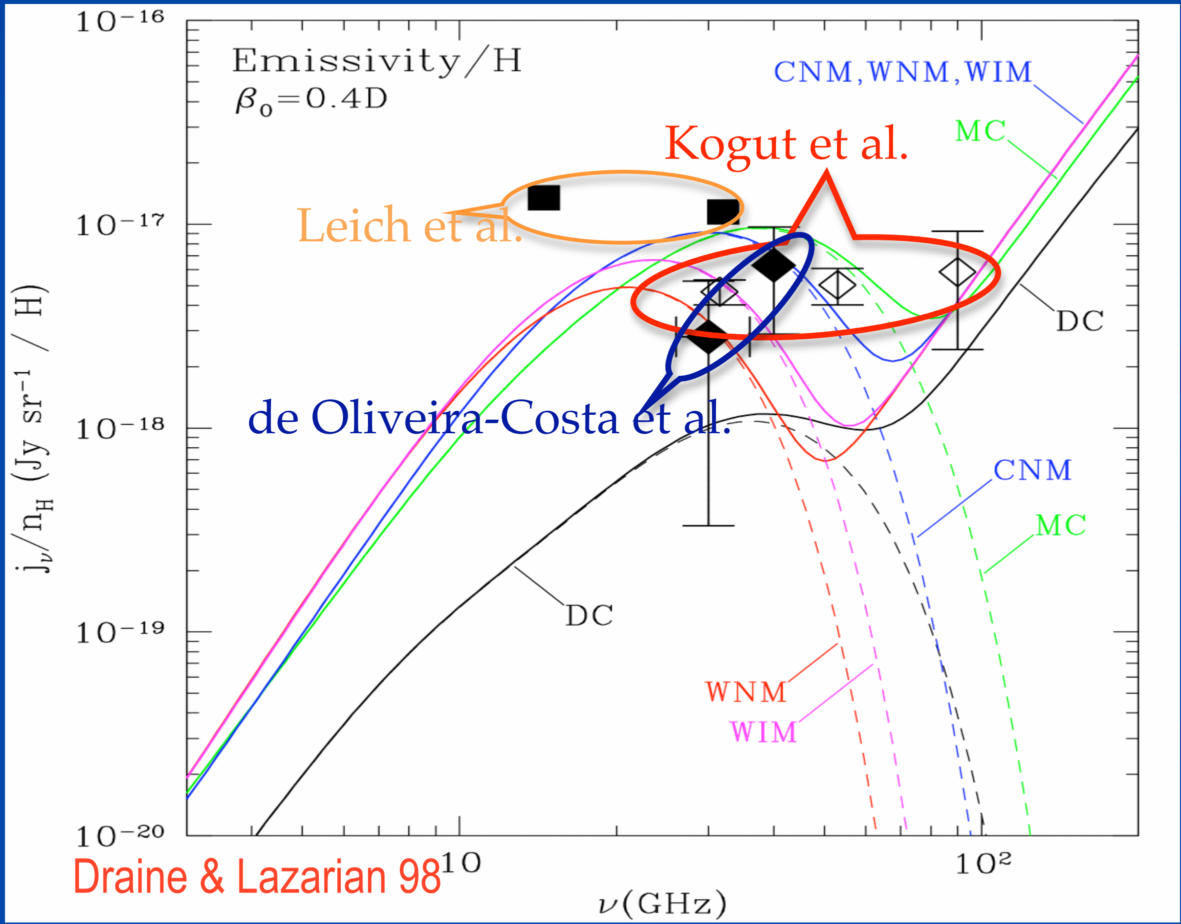


Initial fit was very easy to criticize

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

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

total emissivity integrated over grain size distribution *dn/da*



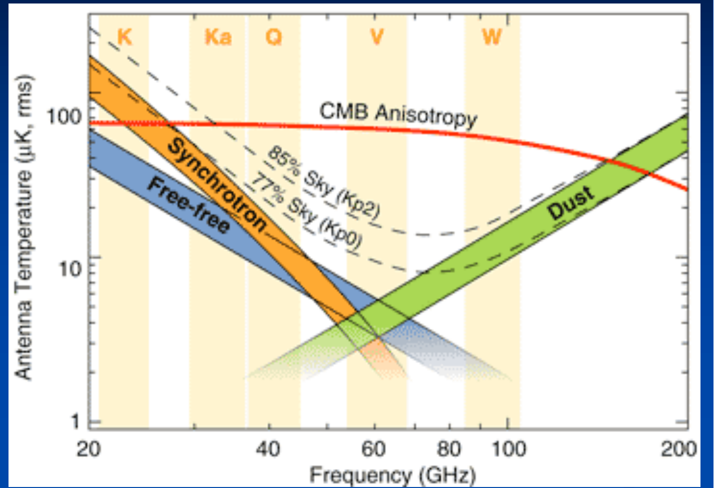
Draine & Lazarian 98

Testing has not supported alternative explanations of the anomalous emission

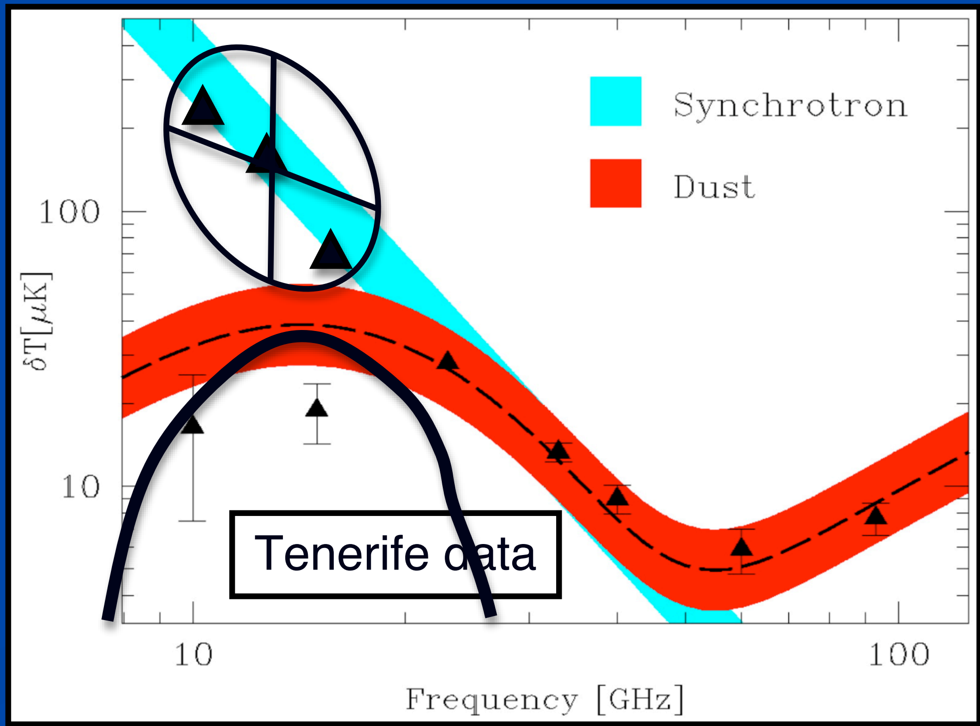
- The WMAP team (Bennett et al. 2003):

- emission excess for 20-40 GHz range

- suggested: new synchrotron component!



De Oliveira-Costa et al. (99, 00, 02, 04) showed that **spectrum is consistent with spinning dust prediction** and not with synchrotron emission.



Dickinson et al. 2006, 2007
Scaife et al. 2007, 2010

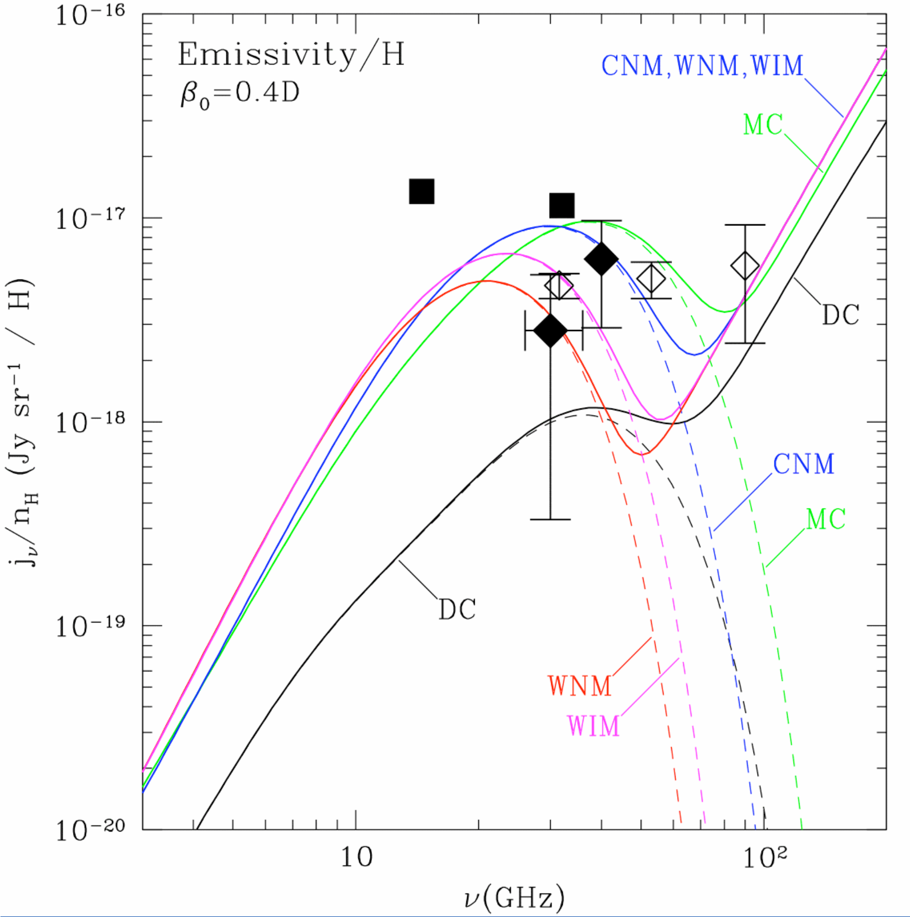
Tenerife data supports spinning dust emission

Simple model in DL 98 provided good fit to observational data, reproducing major features of observations

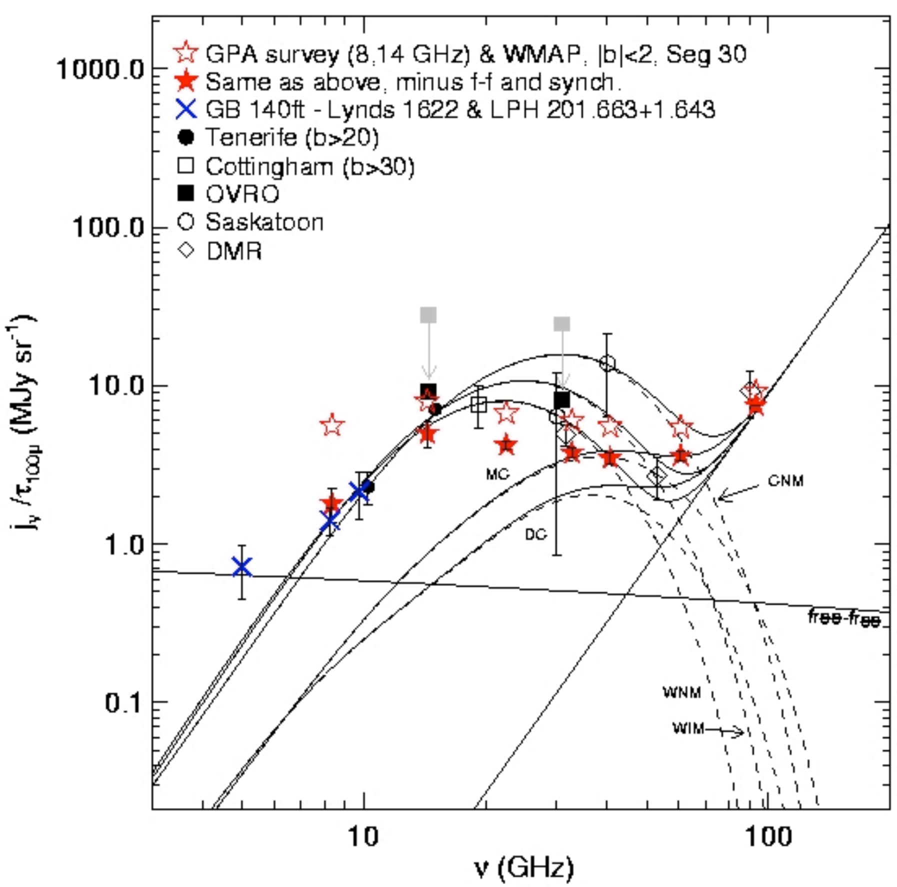
Emissivity:

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

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



Draine & Lazarian (1998)



Finkbeiner et al. (2004)

A lot of great work, galactic and extragalactic studies, many different objects are explored

Instruments used to study spinning dust: OVRO, COBE-DMR, Tenerife, Saskatoon, Green Bank, VCA, CBI WMAP etc.

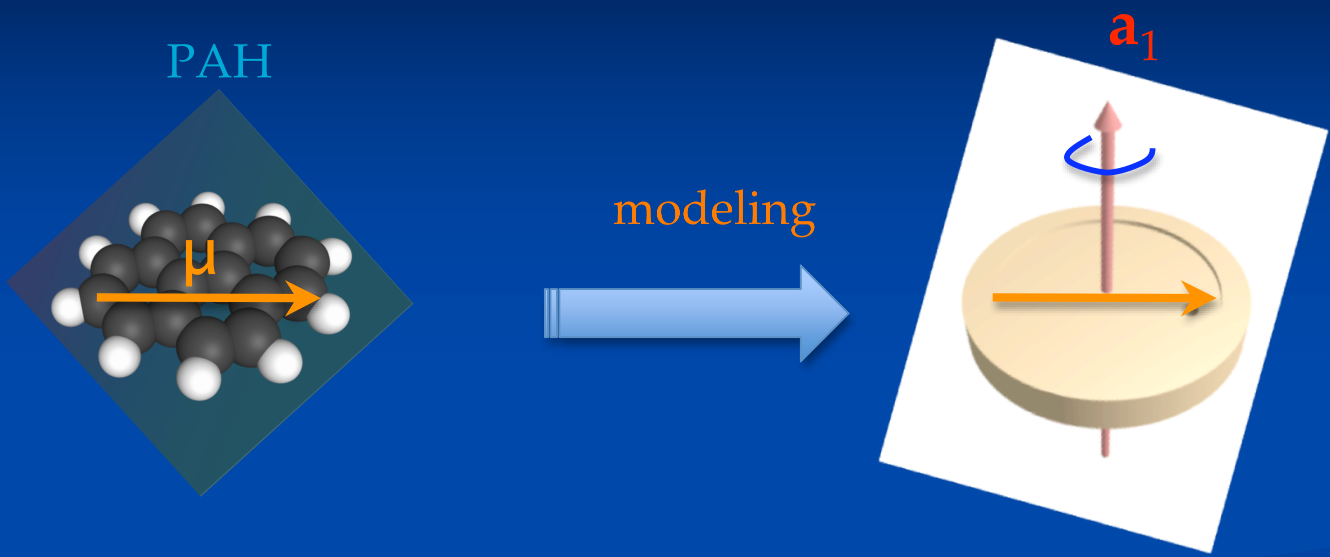
Measured in diffuse and molecular gas, associated with HII regions etc.

Measured in extragalactic environments (e.g. Murphy et al. 2010, Scaife et al. 2010)

Discussed as means of study ISM and dust distribution

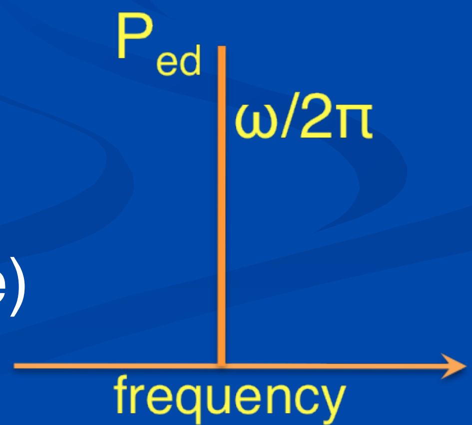
It is time to reconsider the assumptions in the initial DL98 model!!!

Original DL98 model involves simplifications



Grain of dipole moment μ, rotating with **ω** parallel to $\mathbf{a}_1$:

- Radiates at unique frequency $\nu = \frac{\omega}{2\pi}$
- Angular velocity distribution: $f_\omega \approx$ *Maxwellian*
- Idealized ISM phases are used (no turbulence)



Spinning dust has a complex spectrum: should know it better!

1. Free-Free emission:

$$T_{A,ff}(\nu) \propto \nu^{\beta}, \beta \sim -2.1$$

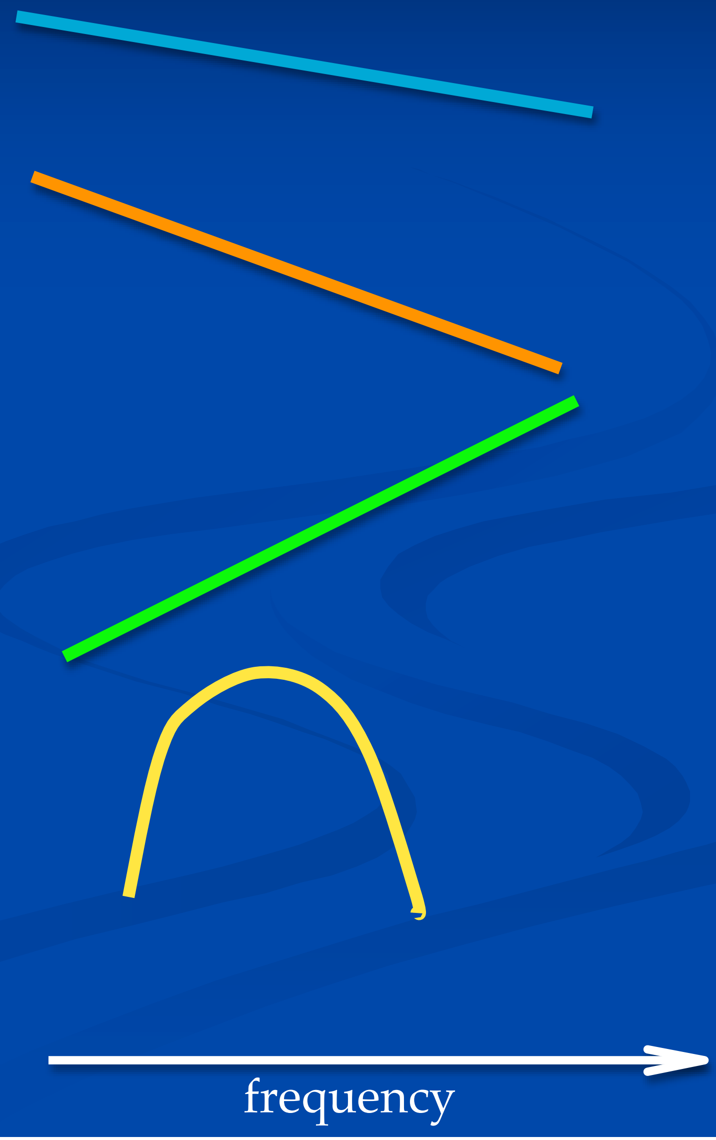
2. Synchrotron emission:

$$T_{A,syn}(\nu) \propto \nu^{\beta}, \beta \sim -2.7 : -3.2$$

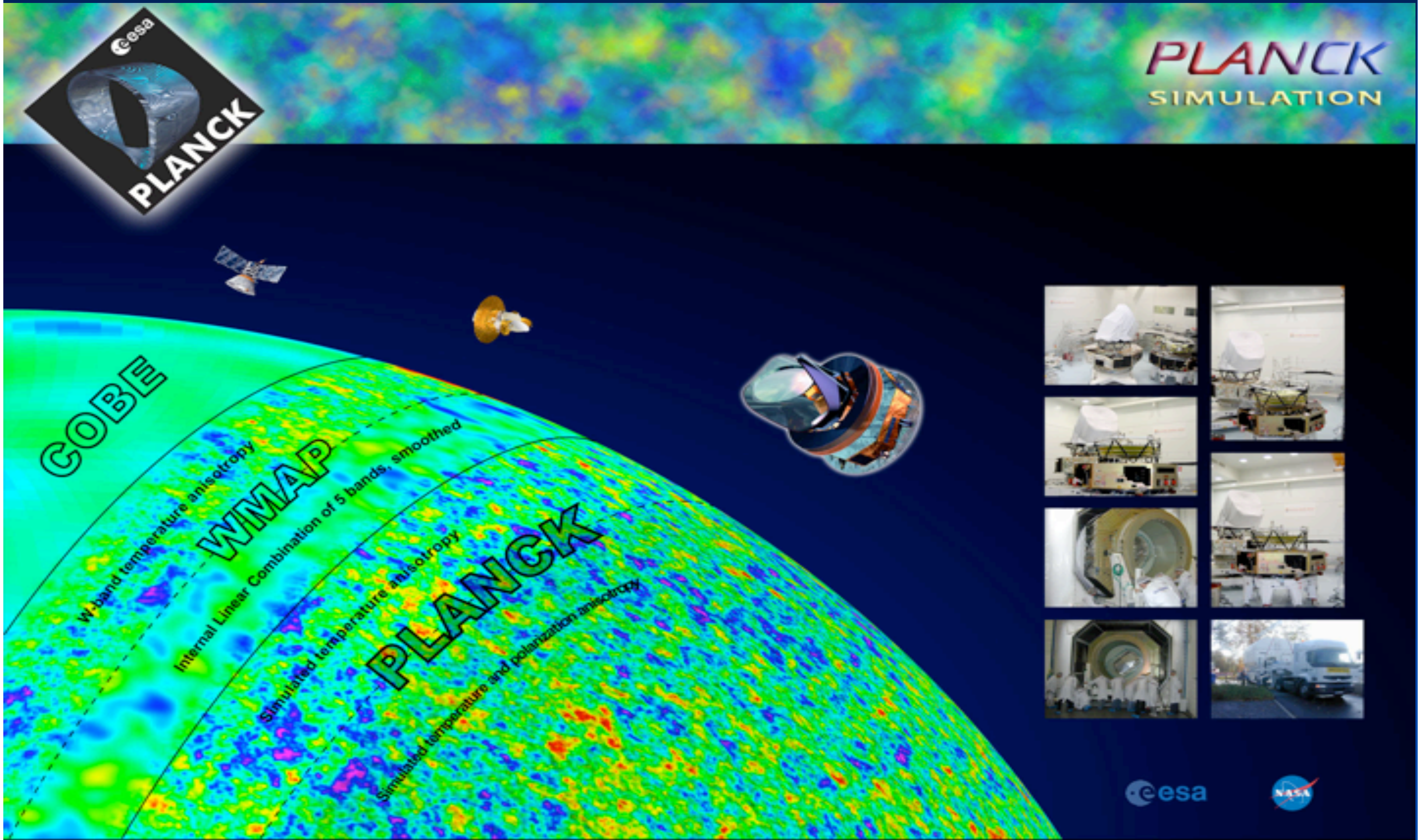
3. Thermal dust emission

$$T_{A,d}(\nu) \propto \nu^{-0.3} B_{\nu}(T_d)$$

4. **Spinning Dust Emission**

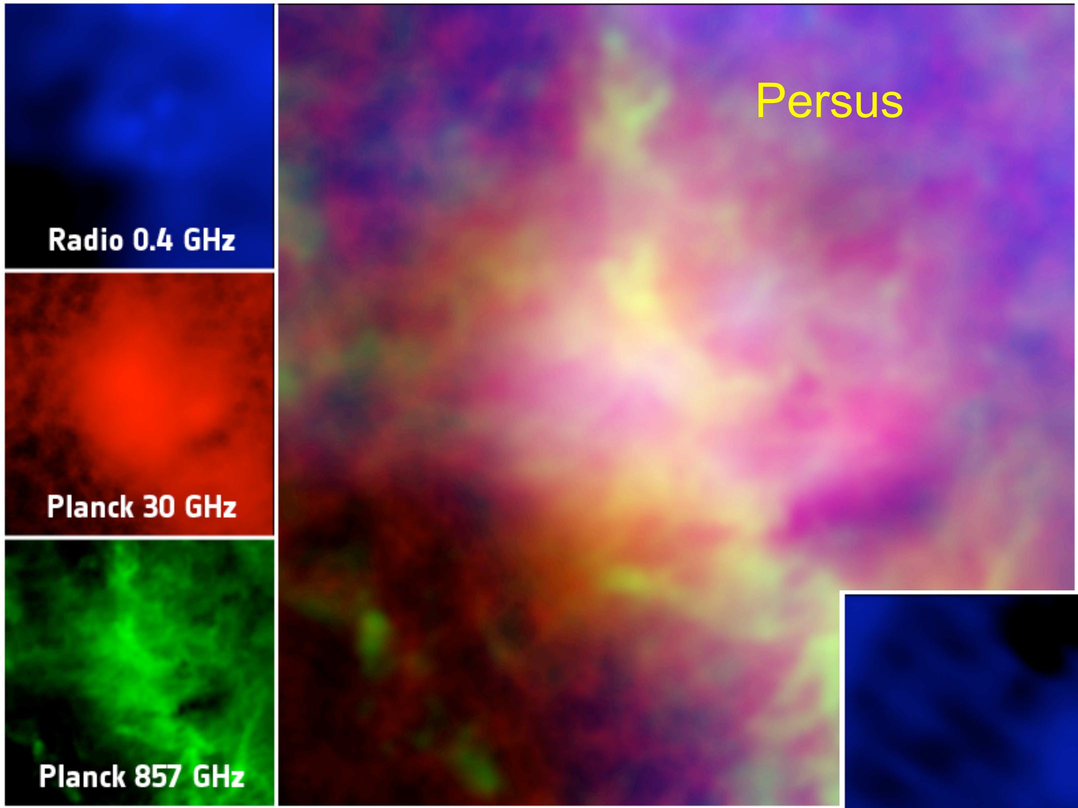


Present: Simplicity of DL 98 model is obvious in Planck era

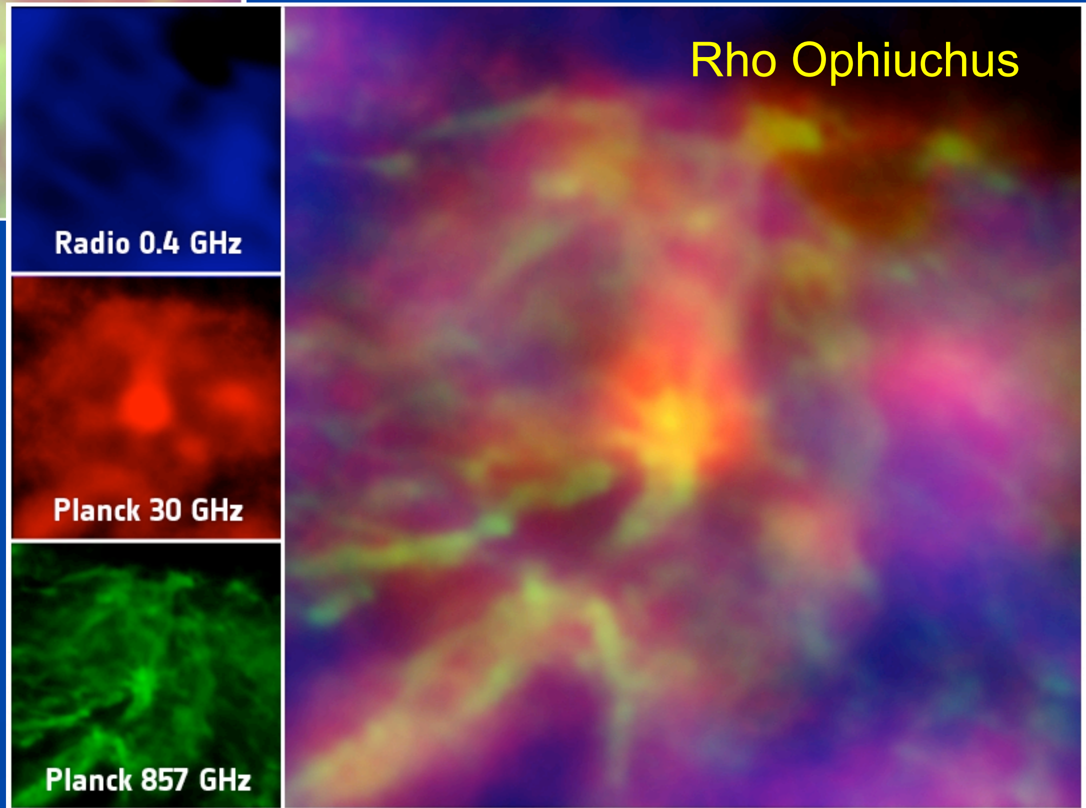


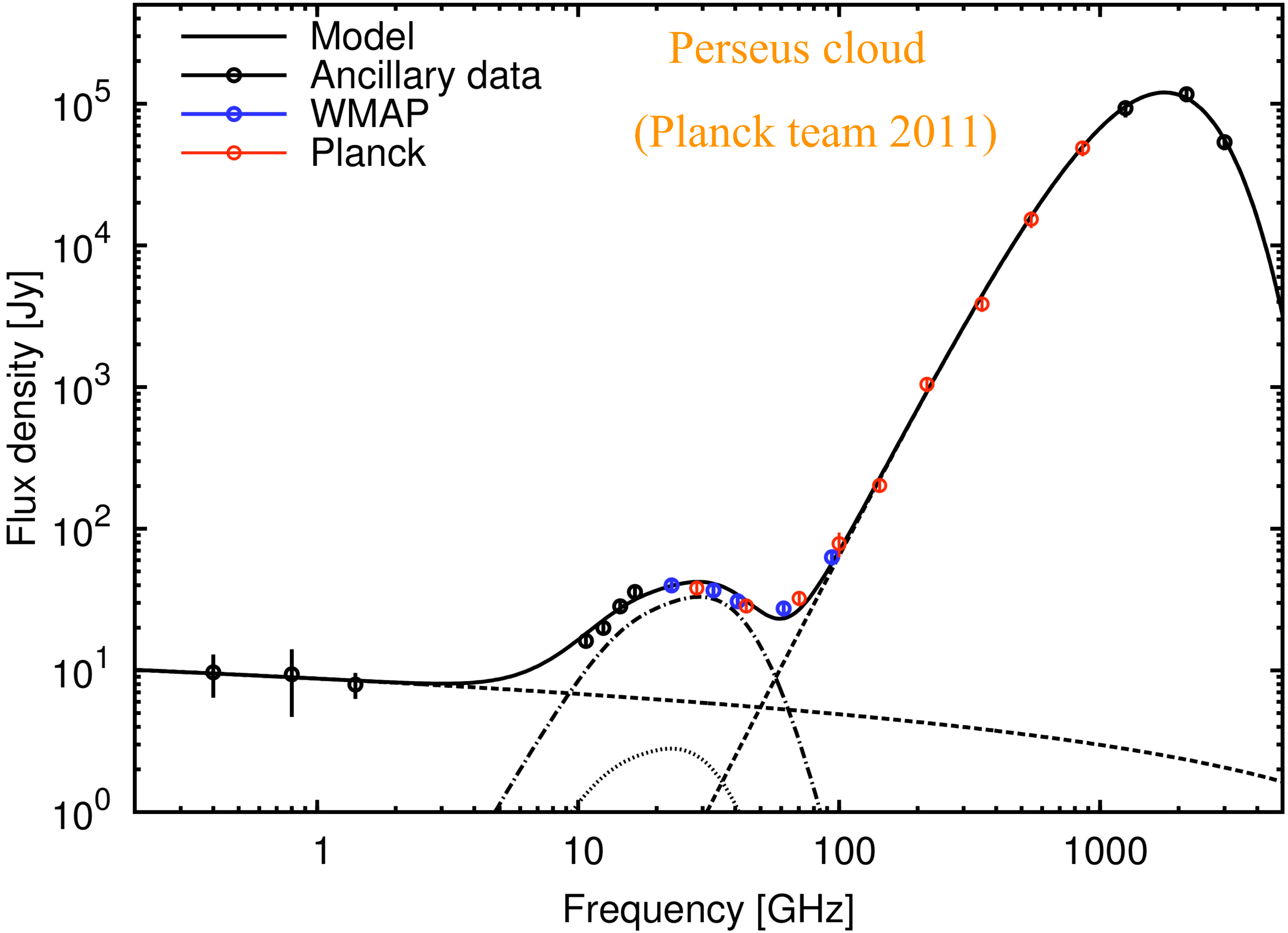
Credit: ESA, NASA

More regions with anomalous emissions are identified



More evidence for anomalous emission arising from fast spinning PAHs ($\sim 10^{10}$ rad/s).





Model
Ancillary data
WMAP
Planck
Perseus cloud
(Planck team 2011)
Flux density [Jy]
Frequency [GHz]
10^0
10^1
10^2
10^3
10^4
10^5
1
10
100
1000

Theoretical work to improve Draine & Lazarian 98 model

Ragot 2002 presented a different way of calculating plasma drag.
Should be consistent with DL98 model. I suspect that there are problems with treating the Debye radius.

Ali-Haimound et al. 2009 presented analytical Fokker-Plank treatment of the problem but disregarded the discrete nature of ion-grain interactions.
Improvement compared to the Maxwellian treatment in DL98. Final results are very similar to DL98.

Yasard & Verstraete 2010 provided quantum mechanical treatment in the Draine & Lazarian 98 model.
However, the rotational quantum numbers of smallest grains are larger than 100

$$J = \frac{I\omega}{\hbar} \approx 5.9 N^{5/6} \left(\frac{T_{rot}}{100\ \mathrm{K}} \right)^{1/2}$$

Thus their final results coincide with the classical treatment in DL98.

Present: improved spinning dust model

Hoang, Draine & Lazarian 2010 (HDL10) calculated:

1. Effect of ion-grain collisions with large J exchange
2. Emission of precessing oblate grain with internal relaxation.

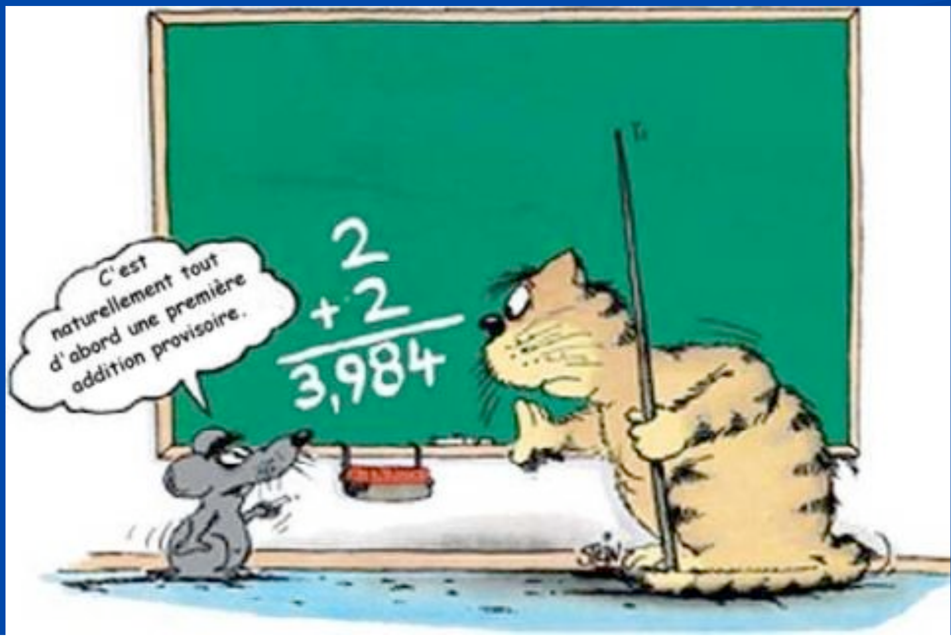
Silsbee, Ali-Haimond & Hirata 2011 calculated emission of oblate grains with precession analytically, but their treatments disregards internal relaxation and valid in the limit of infinite $T_{vibrational}$

Hoang, Lazarian & Draine 2011 (HLD11) calculated:

1. Emission from irregular wobbling grains
2. New effect of enhancing microwave emission due to transient heating
3. Effects of compressible turbulence on the emission.

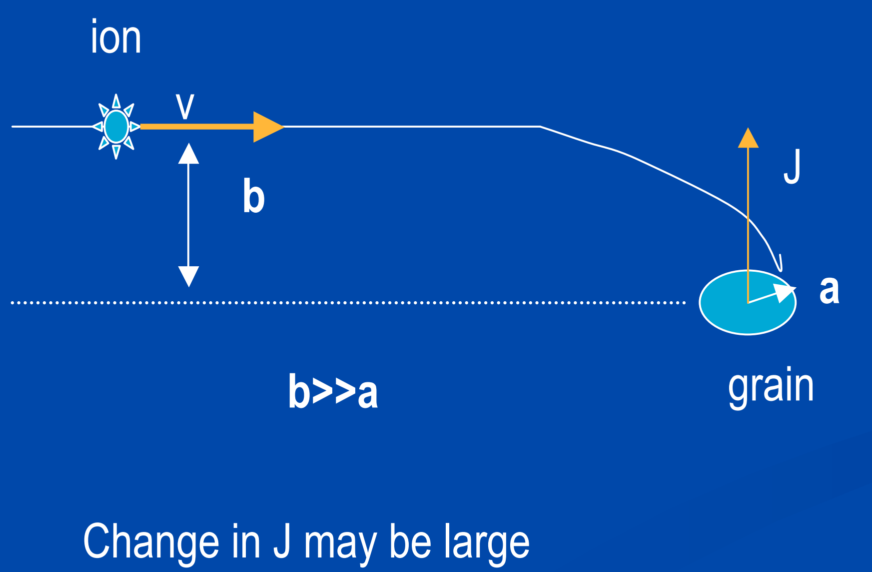
A number of effects have been added to DL98 model

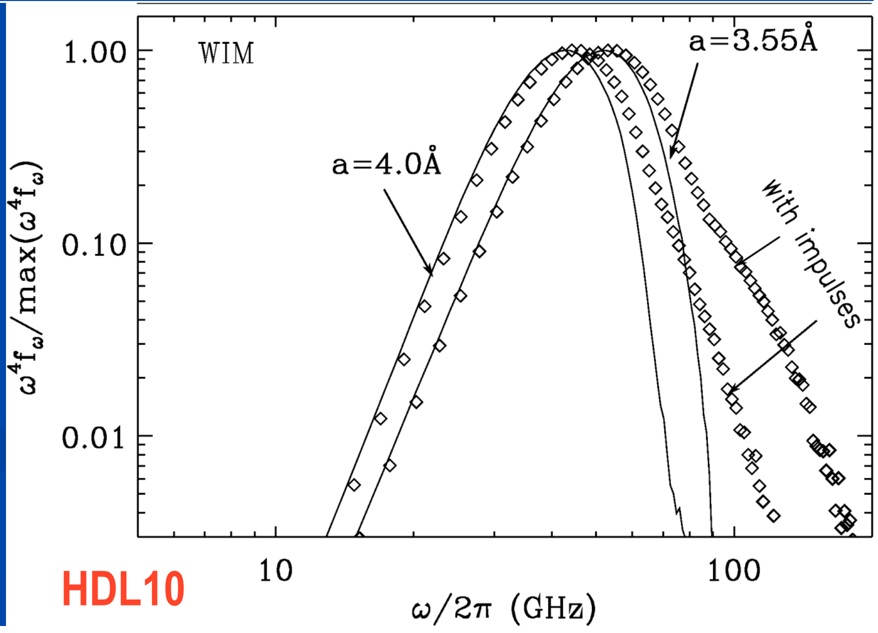
1. Wobbling of the irregular grains
2. Changes of wobbling due to absorption of UV photons
3. Compressible turbulence
4. Efficiency of internal relaxation of energy
5. Spin-up due to the interactions with individual ions



Individual ions colliding with PAHs can transfer momentum larger than the grain momentum

- Transient spin up is important for small grains which slow down between grain-ion collisions. It increases emissivity by 1.2 for WIM
- Tail of high frequency emissivity is created.



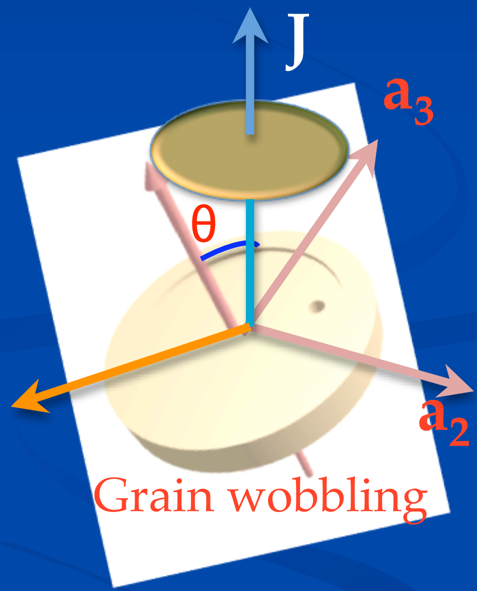


HDL10

Wobbling is determined by coupling of rotational and vibrational degrees of freedom

Energy of rotating body

$$E_{\rm rot}(\theta)=\frac{J^2}{2I_1}\left(1+[h-1]\sin^2\theta\right)$$



gets distributed according to Boltzman distribution if internal relaxation is fast enough

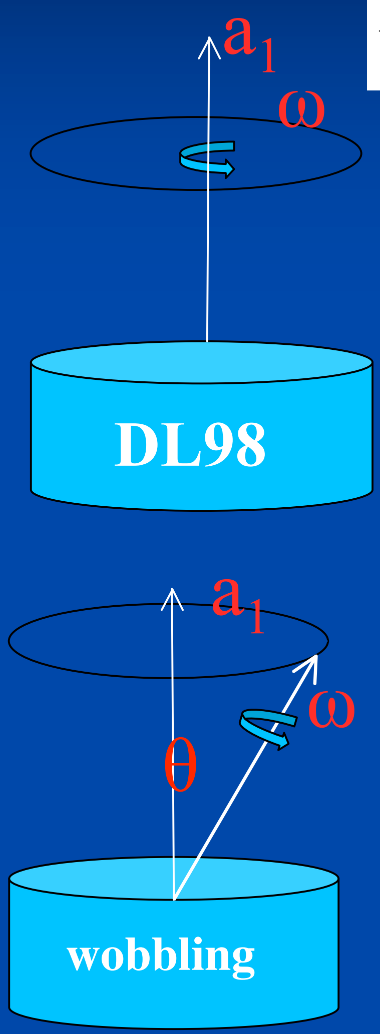
$$f_{\rm VRE}(\theta)=A\sin\theta\exp\left(-\frac{E_{\rm rot}(\theta)}{2I_1kT_{\rm vib}}\right)$$

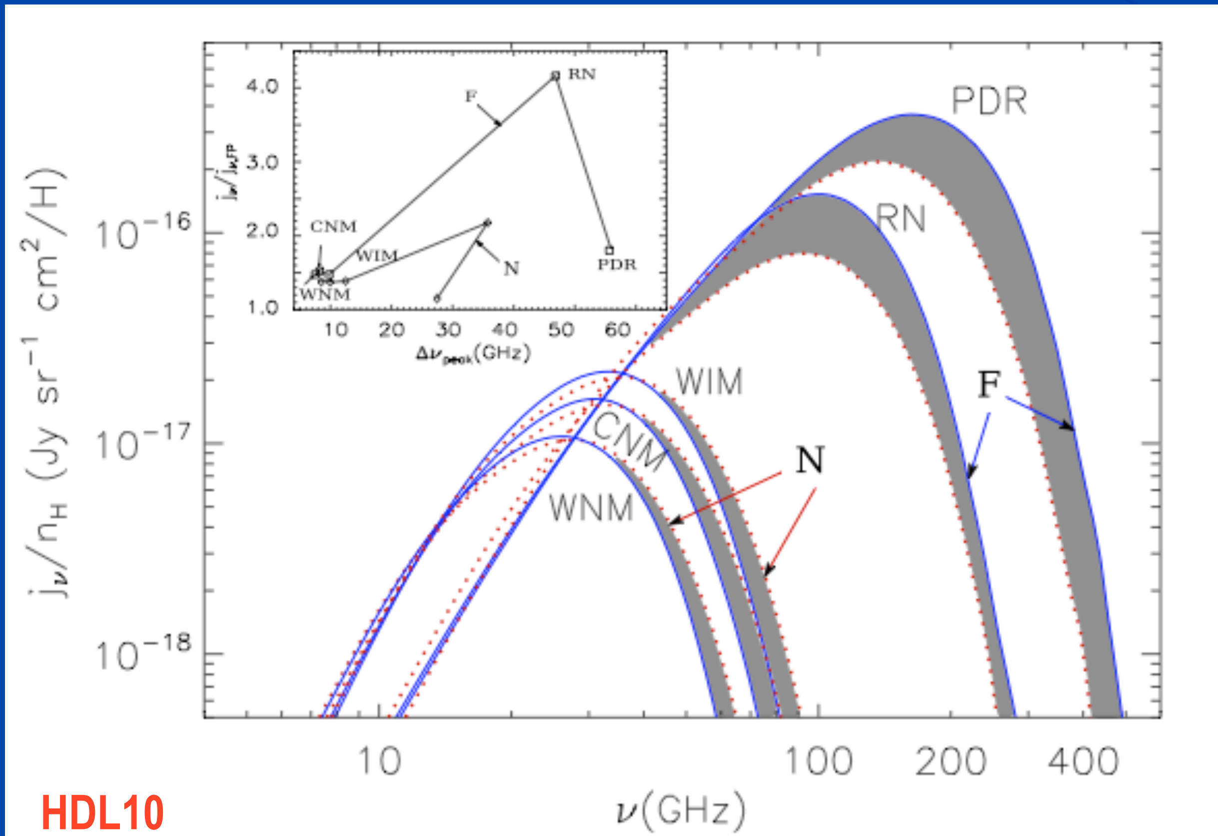
T_{vib} depends on UV photons absorption and V-R exchange

Lazarian & Roberge 19

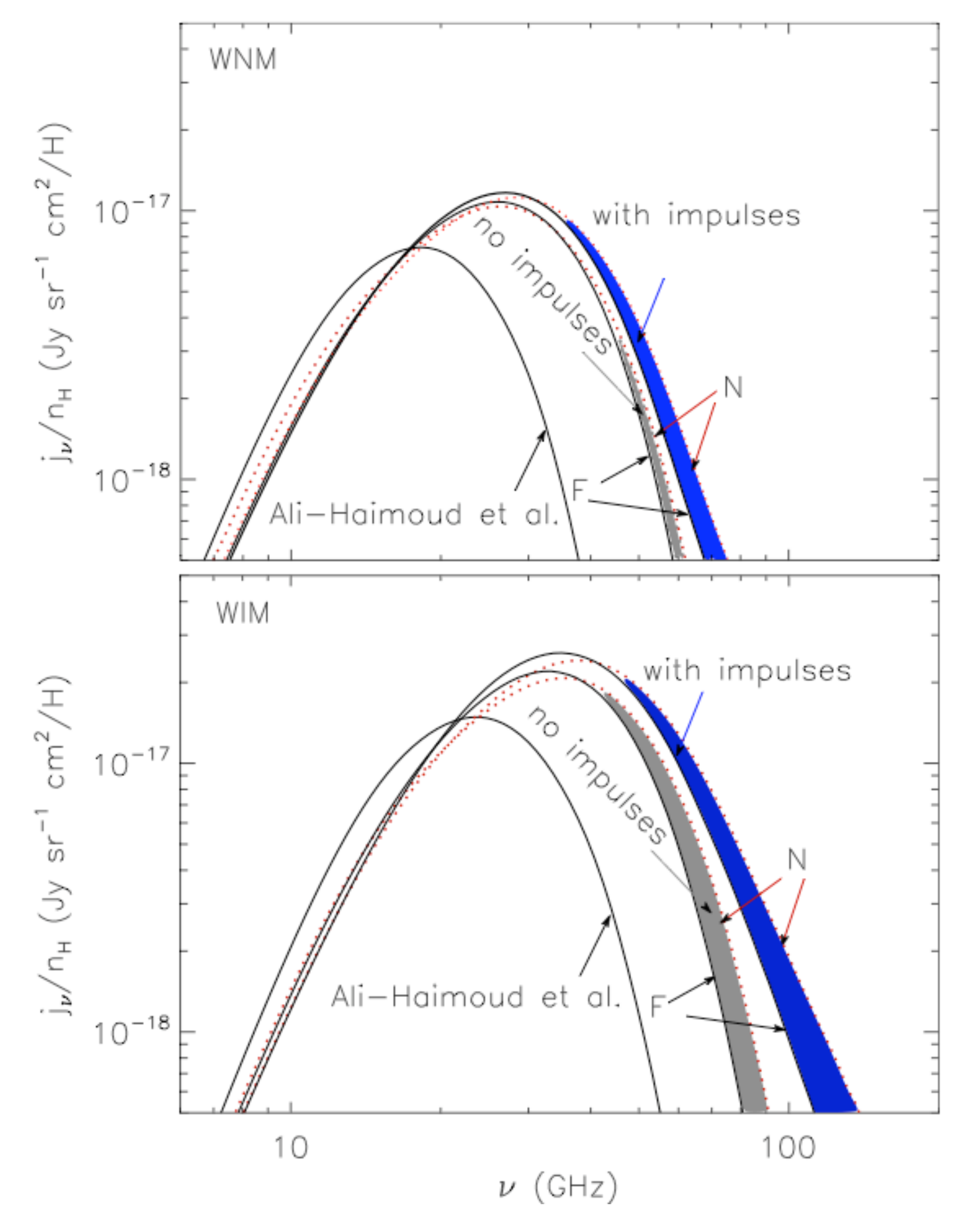
Due to thermal wobbling PAHs emit at multiple frequencies, increasing the spinning dust emission

$$P_{ed}(\omega) = \frac{2\mu^2\omega^4}{3c^3}$$



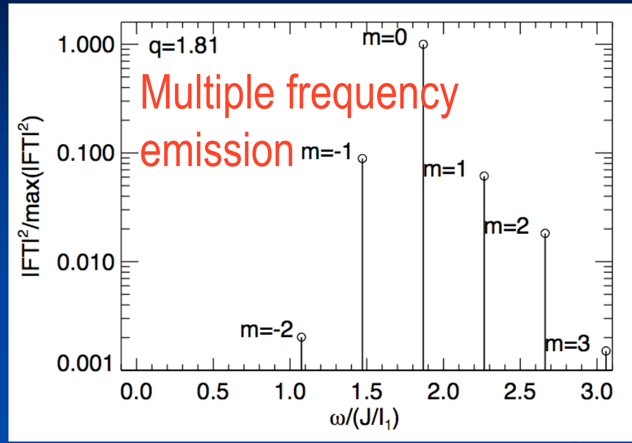


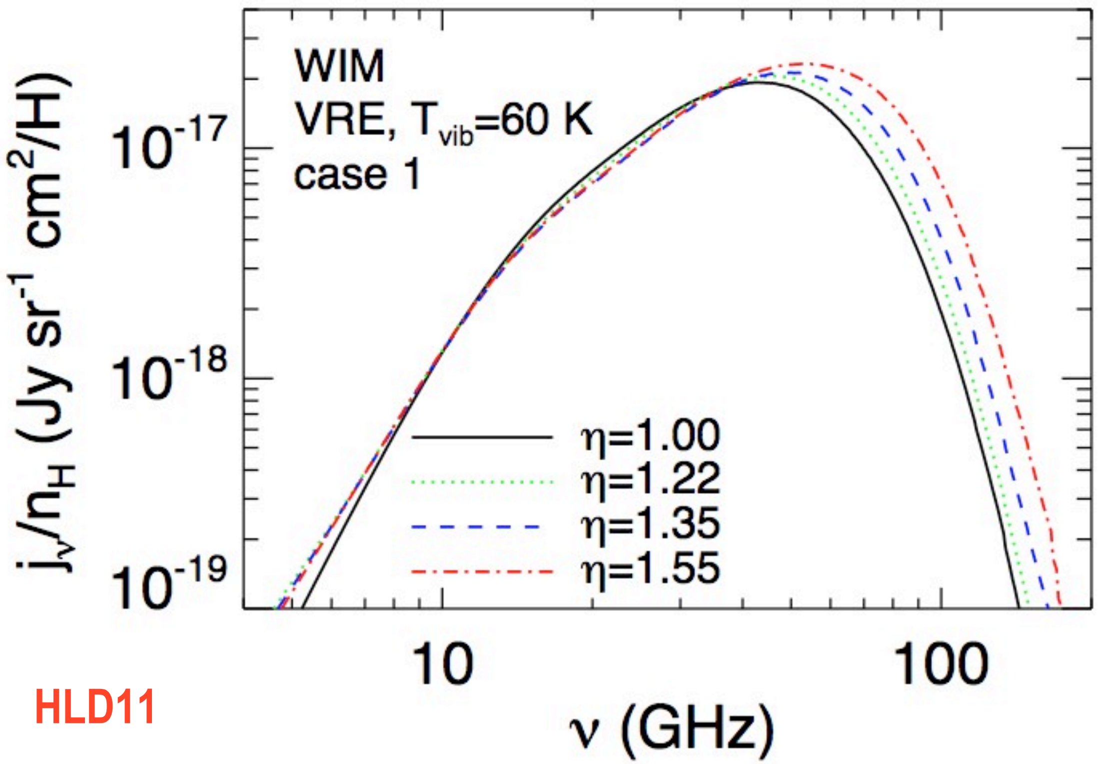
Results are rather different from the original DL98 model



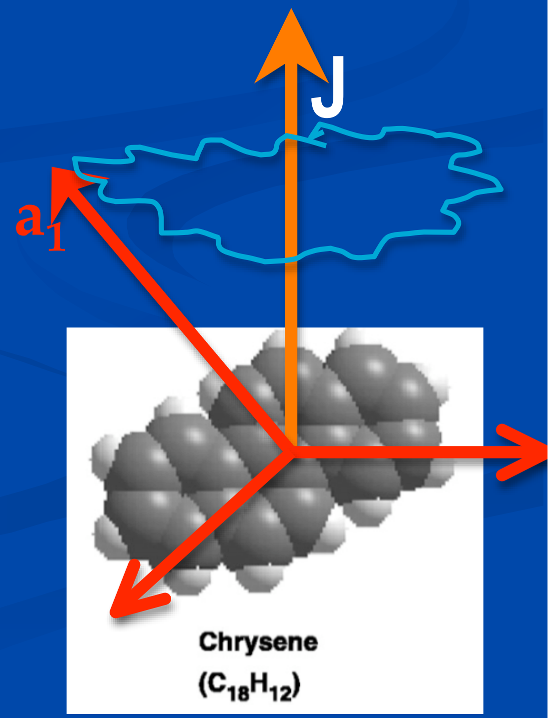
Irregular grains wobble violently, emit at higher frequencies and emit more energy

• Irregularity given by b_3/b_2

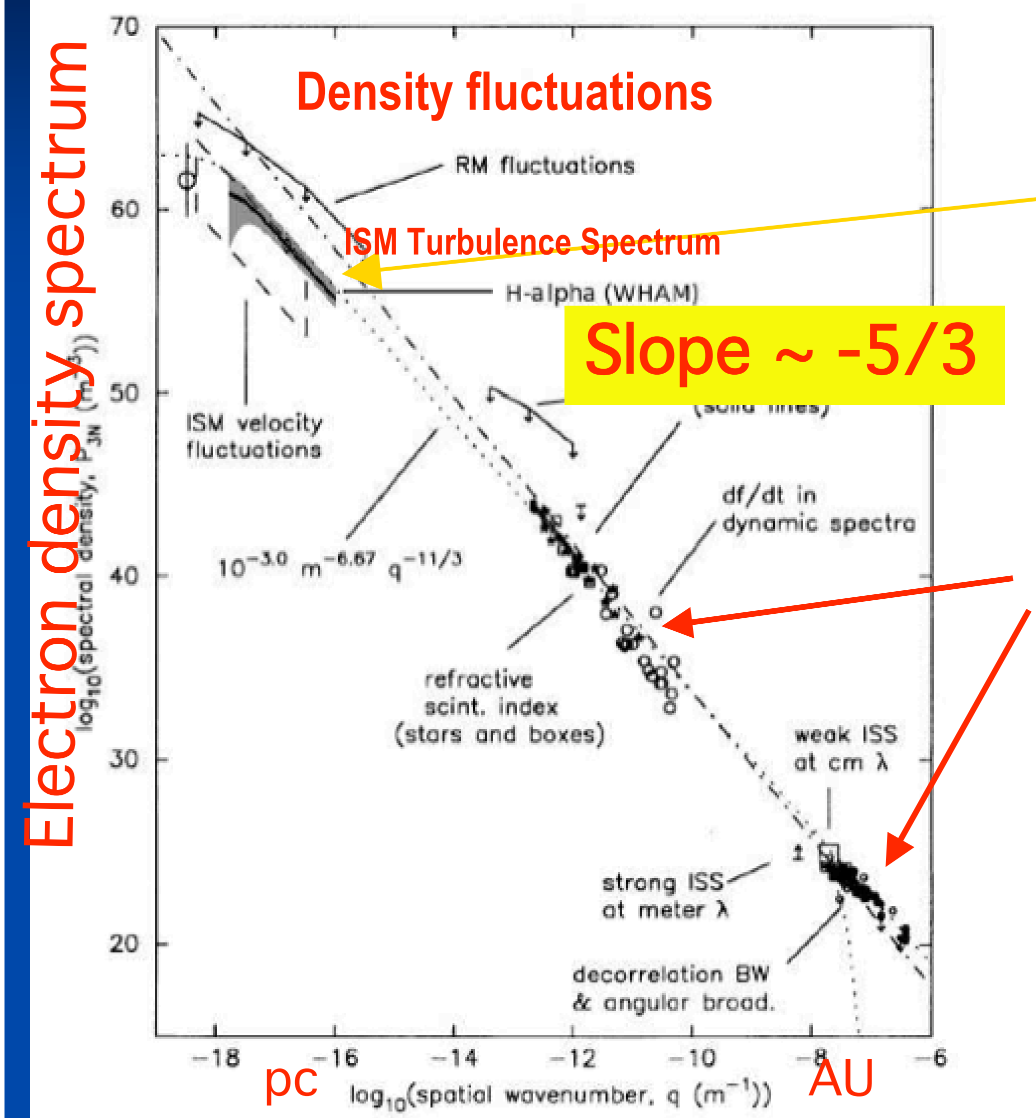




HLD11

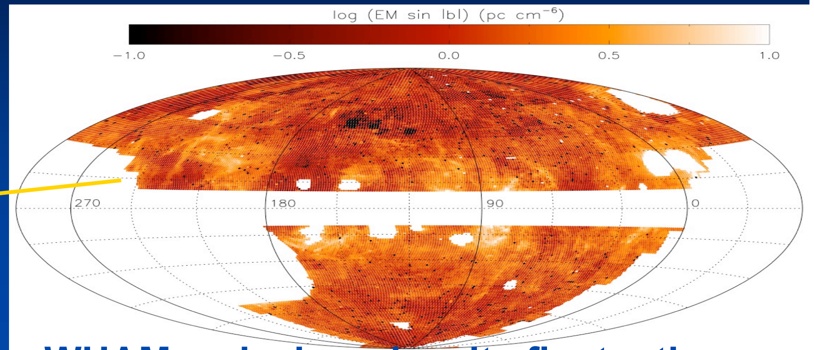


ISM reveals power-law spectrum of turbulent fluctuations



Chepurnov & Lazarian 2010

Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.



WHAM emission: density fluctuations

Scincillations and scattering

From Armstrong, Rickett & Spangler1995

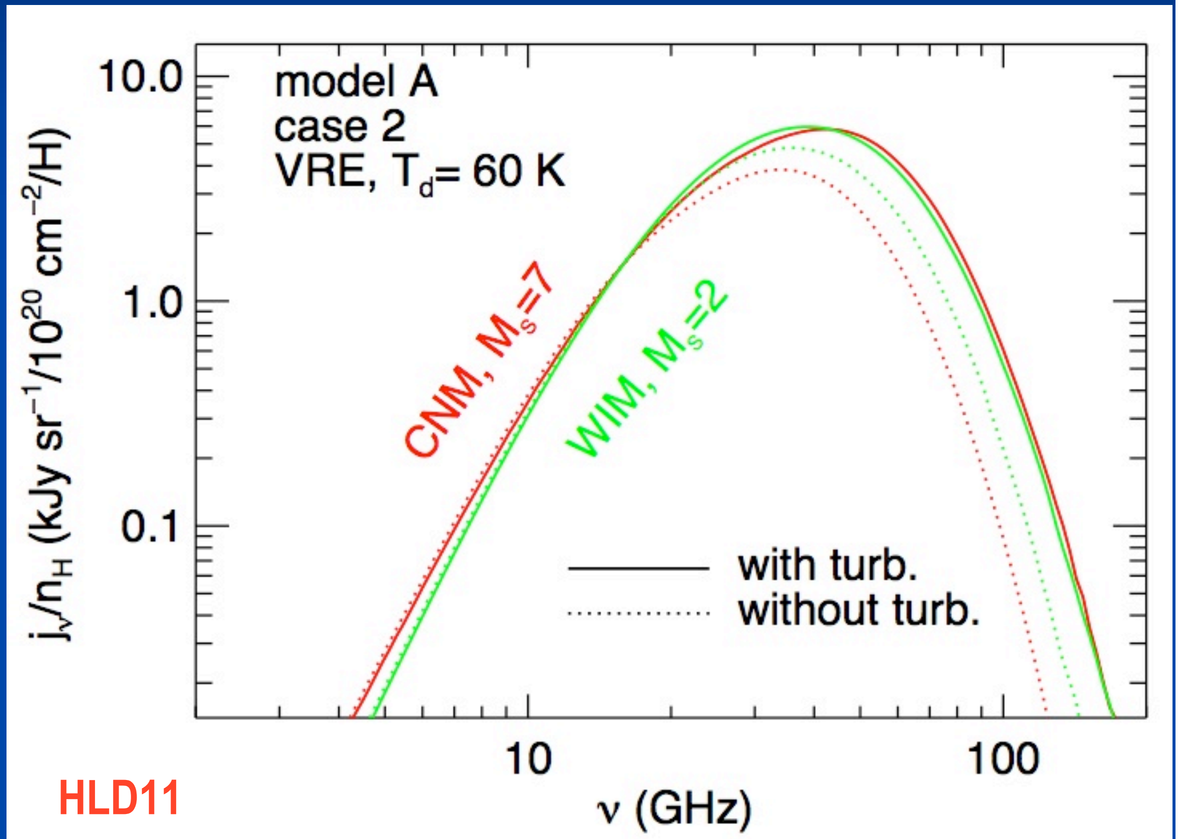
Turbulent fluctuation increase the coupling between gas and PAHs enhancing emission

Total emission intensity:

$$I_\nu = \int \left[\frac{j_\nu(n_H)}{n_H} \right] n_H dl$$

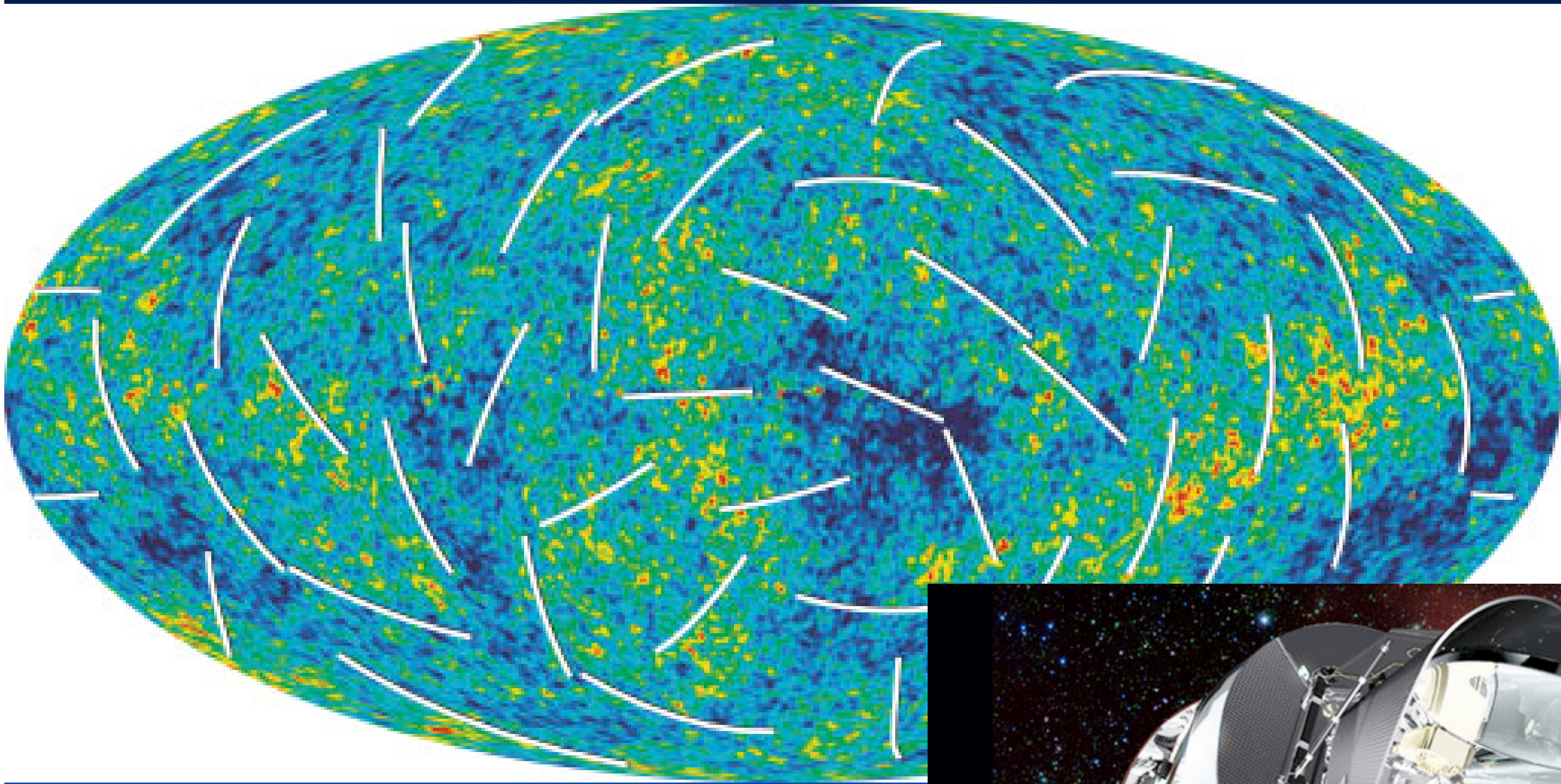
n_H from MHD simulations

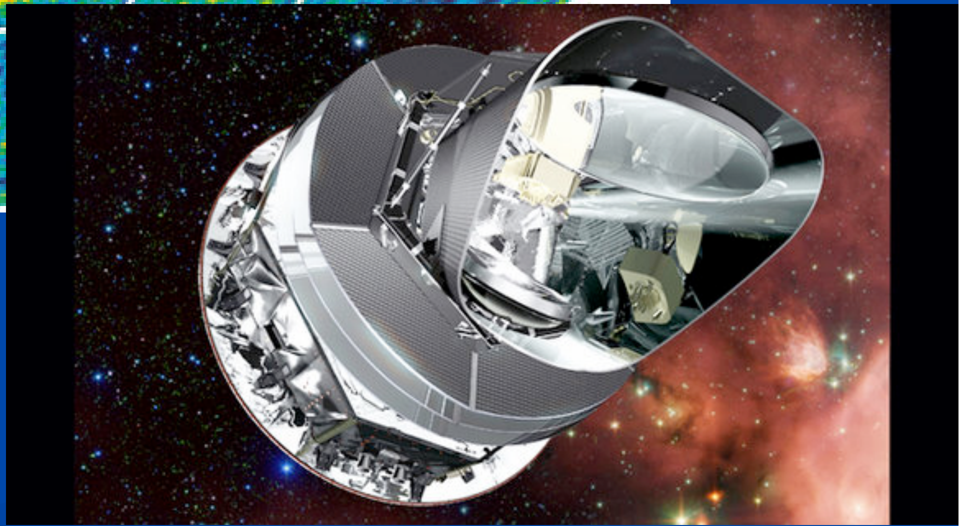
M_s: Mach sonic number



Sonic Mach number can be obtained from observations (see Lazarian & Pogosyan 00, Kowal et al. 07, Burkhard et al. 09, 10)

Future: What is the polarization of anomalous emission?



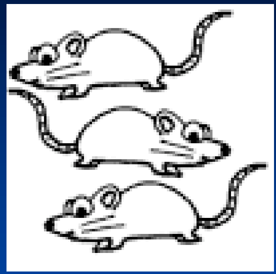


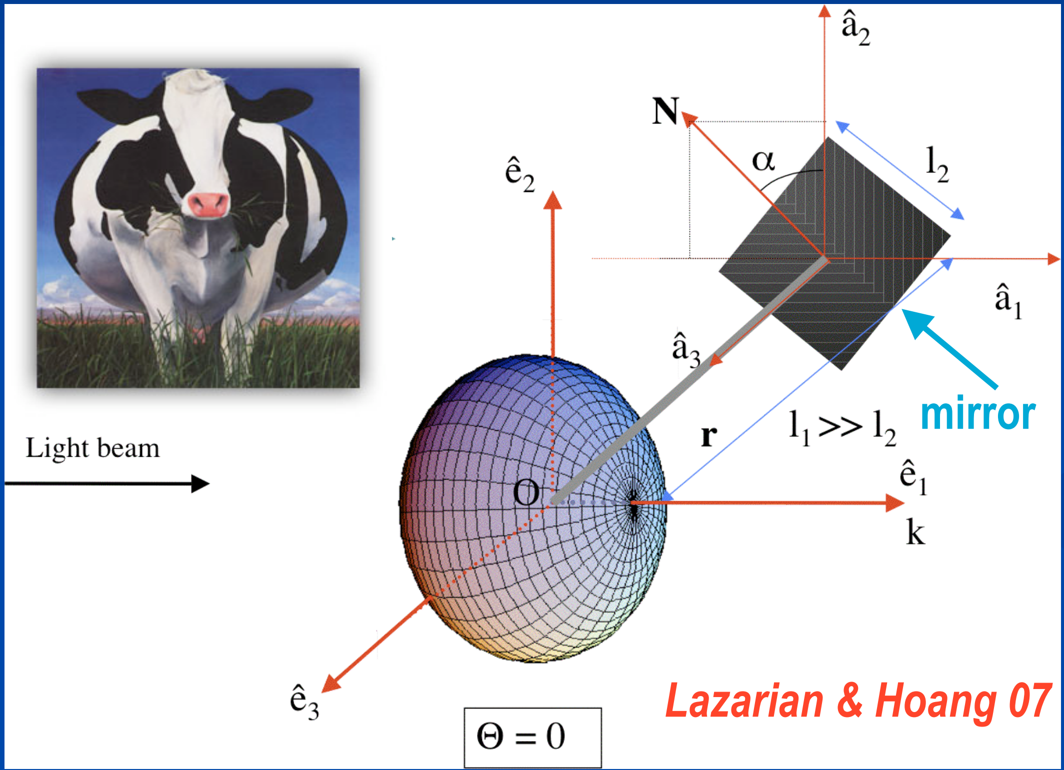
The absence of detection of the polarized infrared emission does not prove that spinning dust emission is not polarized. The internal randomization at the time of heating kills former but not later.

Future is so exciting because we do not know it!

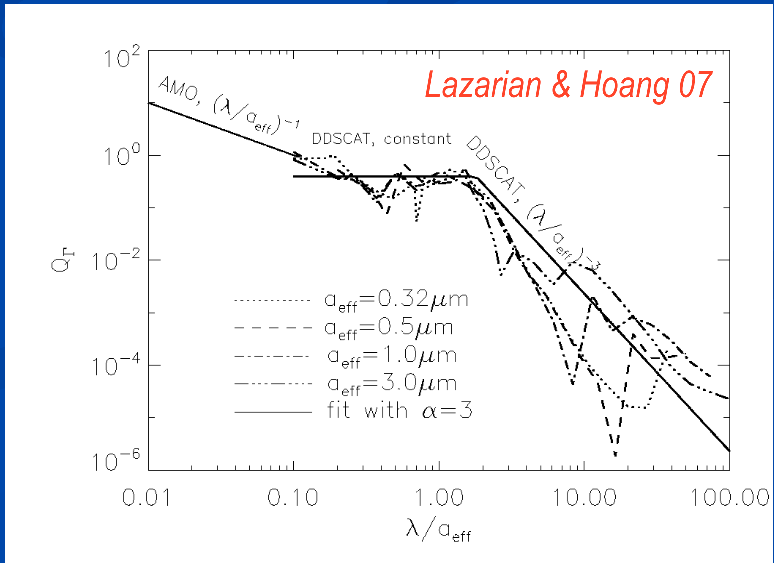
Winnie the Pooh found the search for the Eastern Pole so appealing because no one knew where it is!

Radiative torques (RATs) are the favorable model for large grain alignment, but inefficient for PAHs





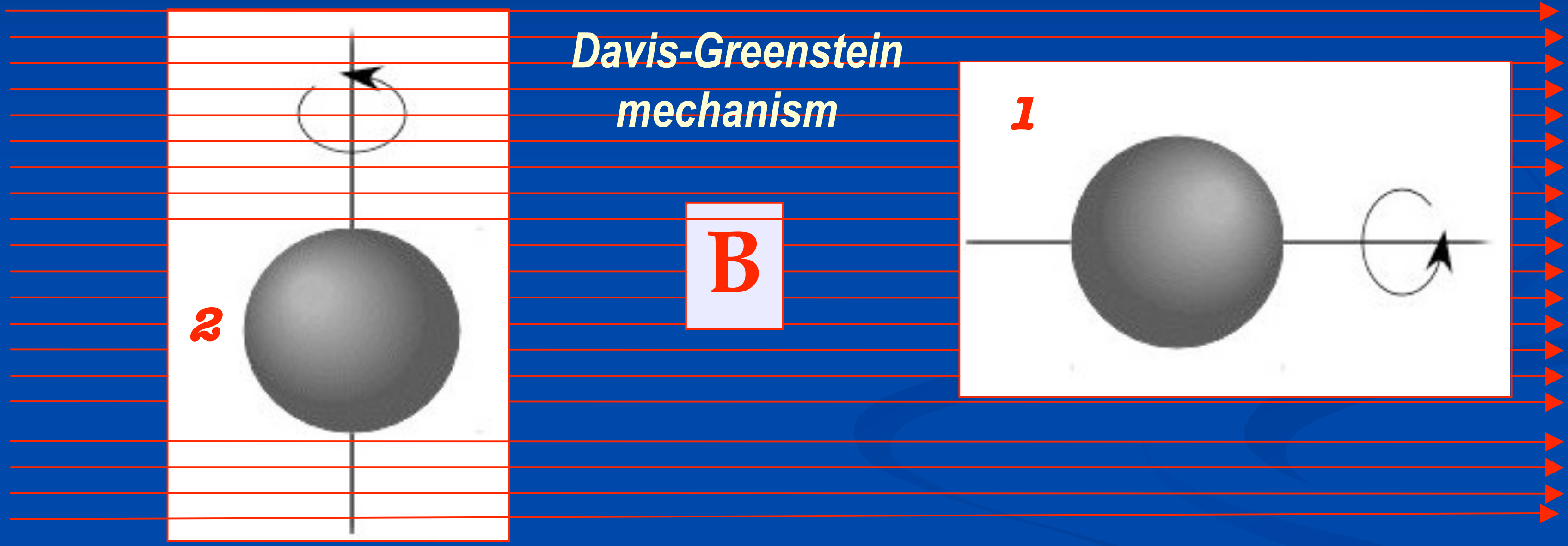
NOTICE to PLANCK EXPERTS:
Zodiacal light is polarized!



Introduced by Dolginov & Mytrophanov 76, ignored 20 years.
Draine & Weinarnter 96 calculated with DDSCAT;
Lazarian & Hoang 07 presented analytical model

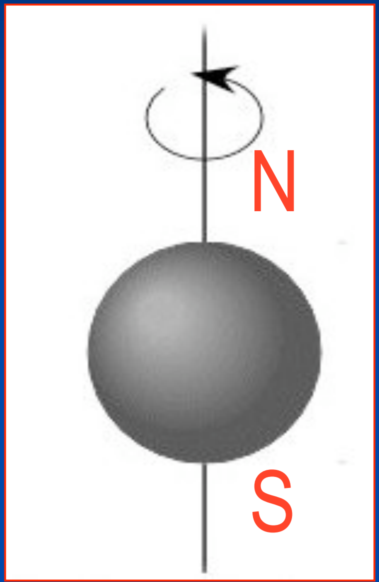
Textbook paramagnetic alignment is inefficient, but Lazarian & Draine 2000 identified a new mechanism of resonance relaxation

This is textbook solution

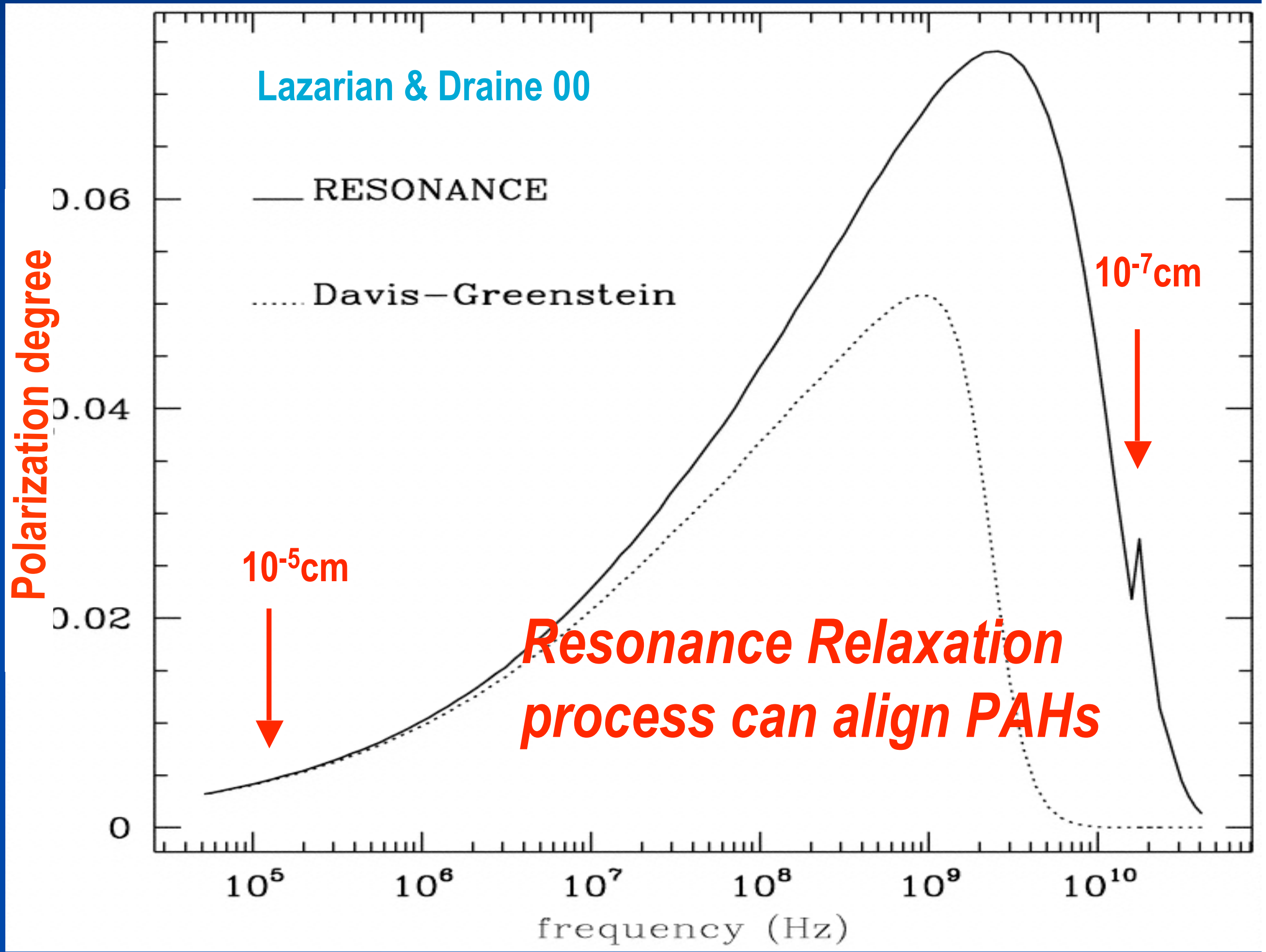


Grains get aligned with rotation axis parallel to B (grain 1)

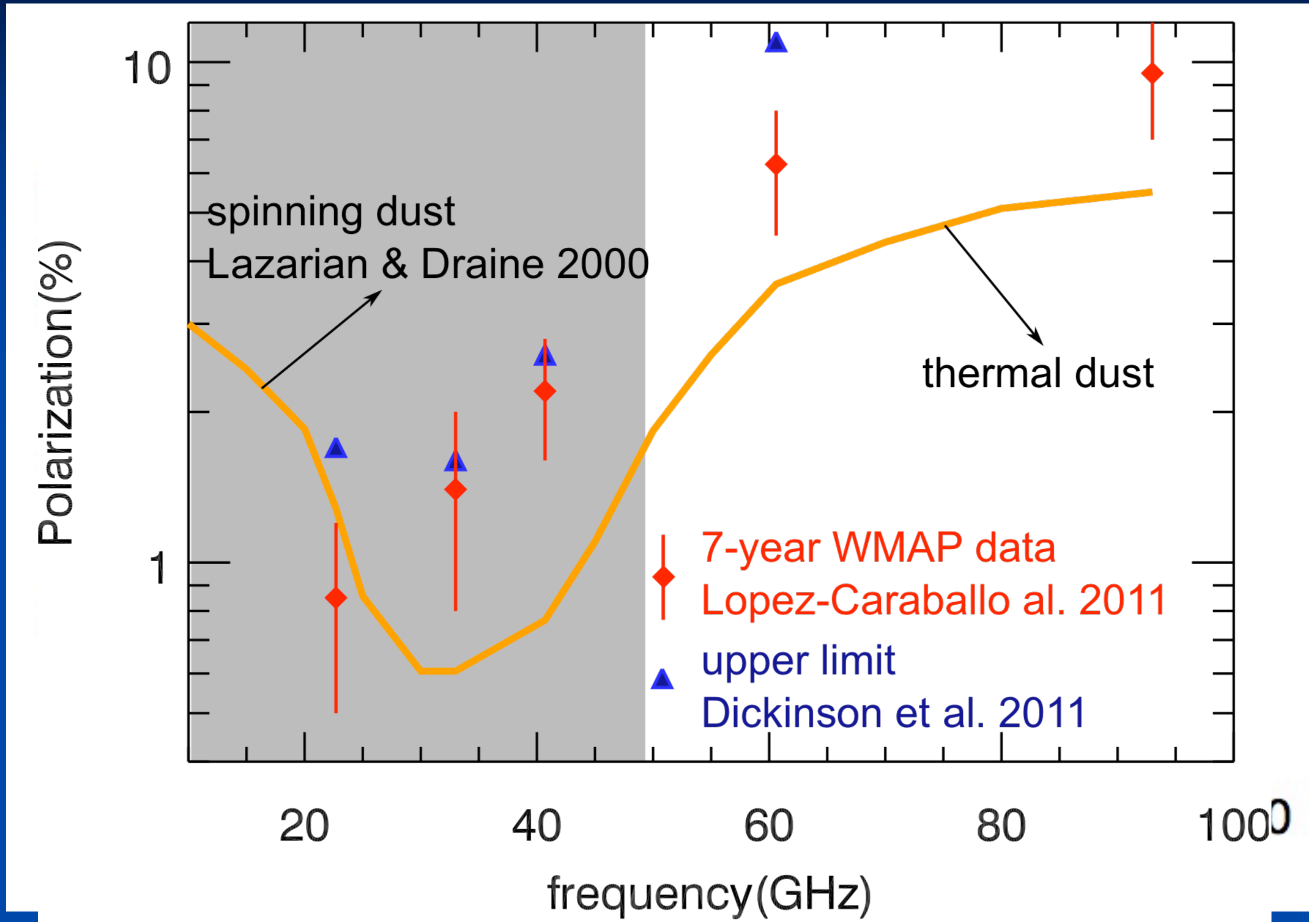
Grains get magnetized as they rotate and this results in efficient resonance relaxation



Lazarian & Draine 00 estimates of the magnetic response of realistic PAHs



We must better understand polarization from dust

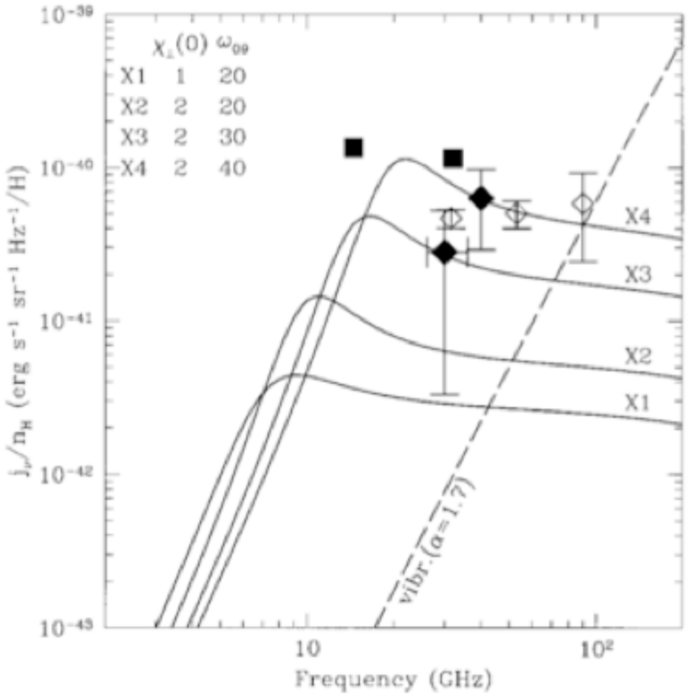


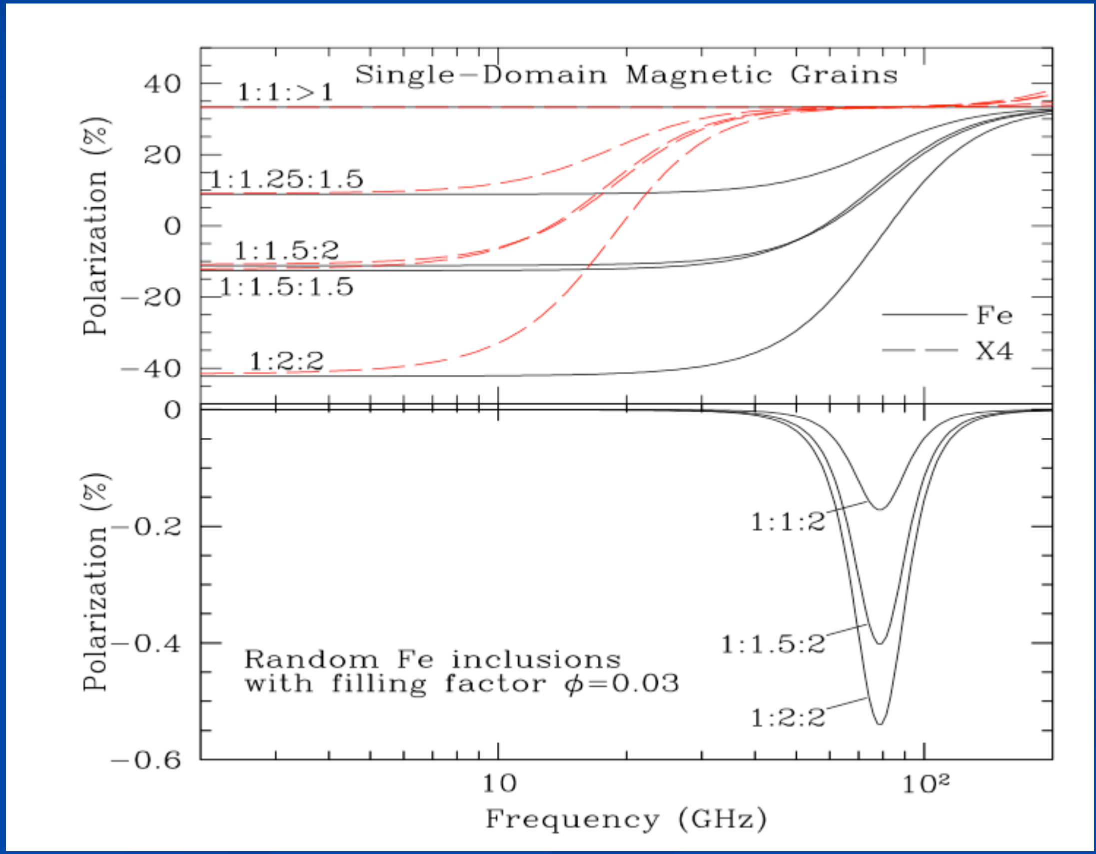
Kogut et al. 2007: P~1 %, recent studies: P~1.-5% for AME

Lazarian & Draine (2000): upper limit <observation data

This difference must be clarified for detecting B-mode

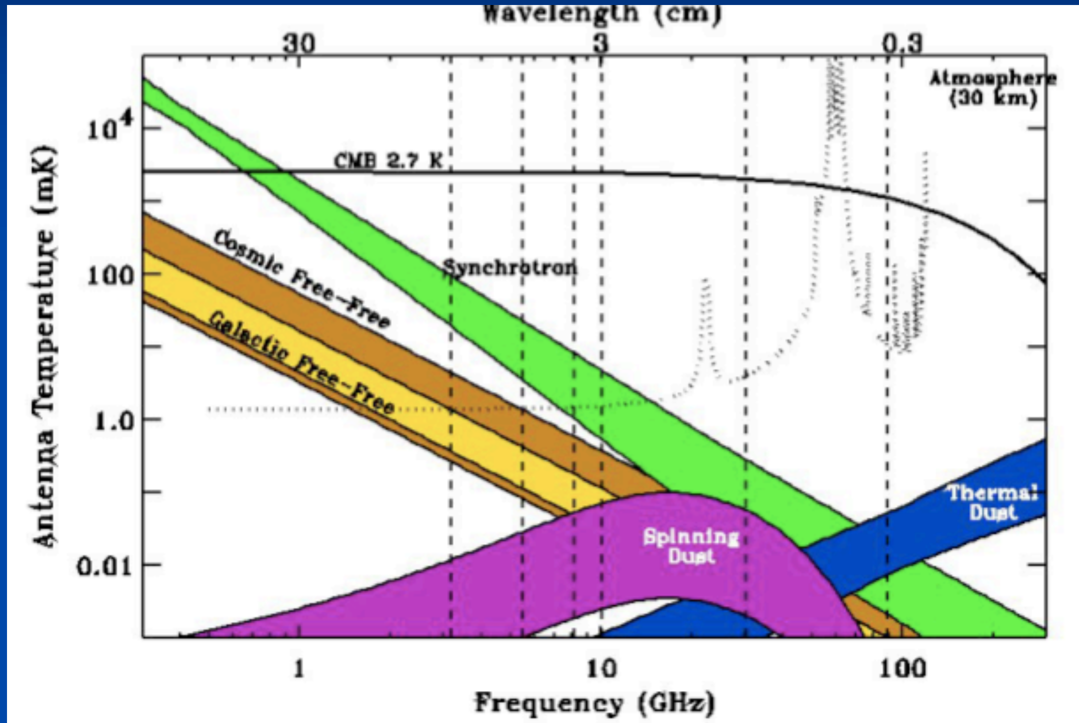
Polarization can also be due to another photon-based alignment of PAHs and also arise from aligned "magnetic grains"





Magnetic grains proposed in Draine & Lazarian 1999 may produce high polarization

Spinning dust is an important foreground emission and possible polarization from it must be accounted for

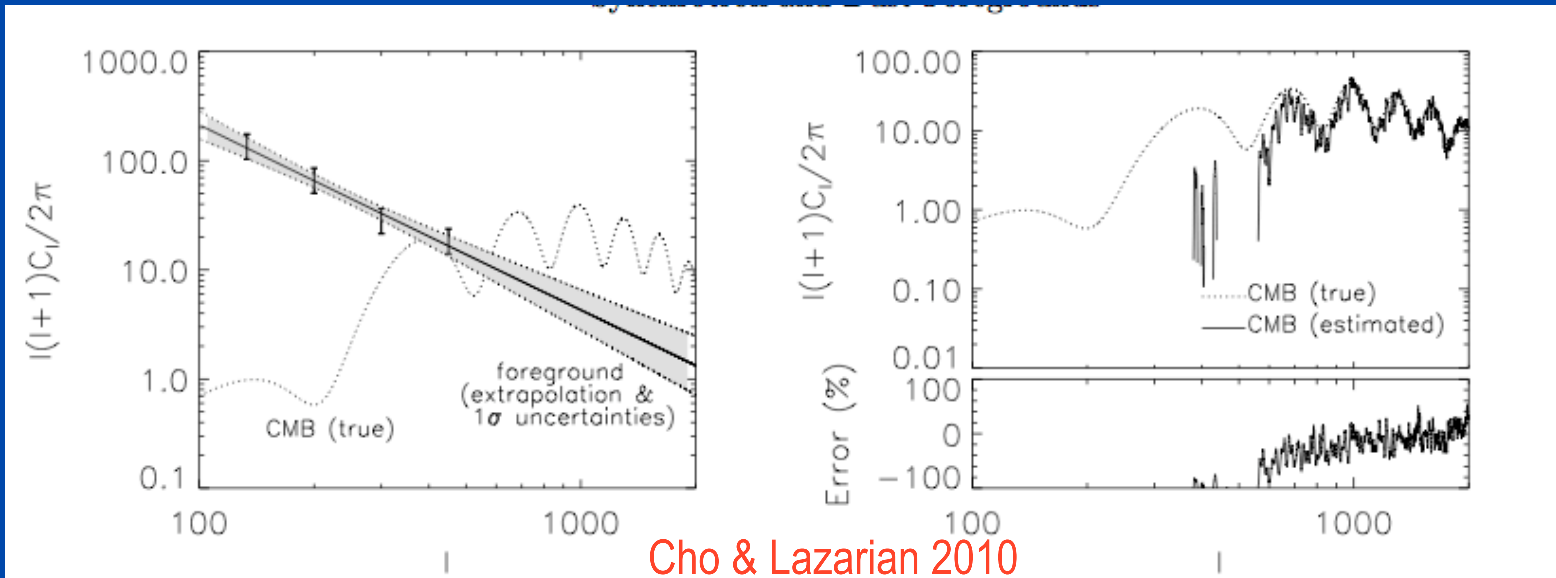


"What mysteries do lie beyond thy dust?"
H. Vaughan 1625-1695

This power-law nature of fluctuations can be used to provide spatial filtering of foregrounds

$$\langle (I_1^{CMB} + I_1^F)(I_2^{CMB} + I_2^F) \rangle = \langle I_1^{CMB} I_2^{CMB} \rangle + \langle I_1^F I_2^F \rangle$$

$$C_l^{CMB} = C_l^{measured} - C_l^F$$



Cho & Lazarian 2010

If we know foregrounds at low resolution, we can extrapolate them to high l.

Advertisement: We described synchrotron fluctuations for any spectrum of CR

STATISTICAL DESCRIPTION OF SYNCHROTRON INTENSITY FLUCTUATIONS: STUDIES OF ASTROPHYSICAL MAGNETIC TURBULENCE

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Draft version May 19, 2011

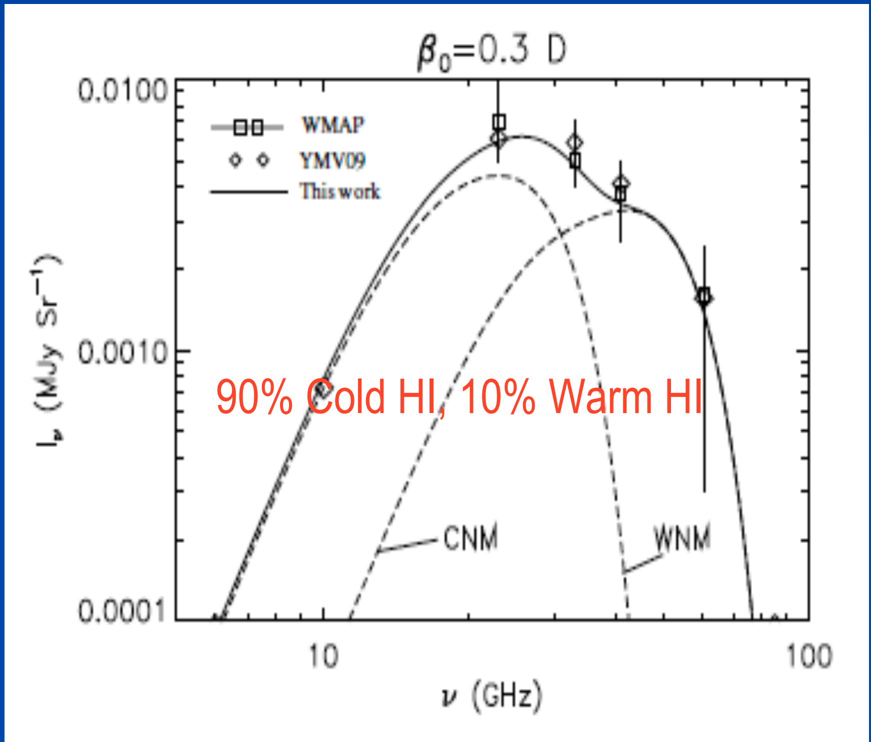
To appear on arXiv listing tomorrow May 25

$$\xi_{H_\perp^\gamma}(\mathbf{r}) \approx \mathcal{P}(\gamma)\xi_{H_\perp^2}(\mathbf{r}),$$

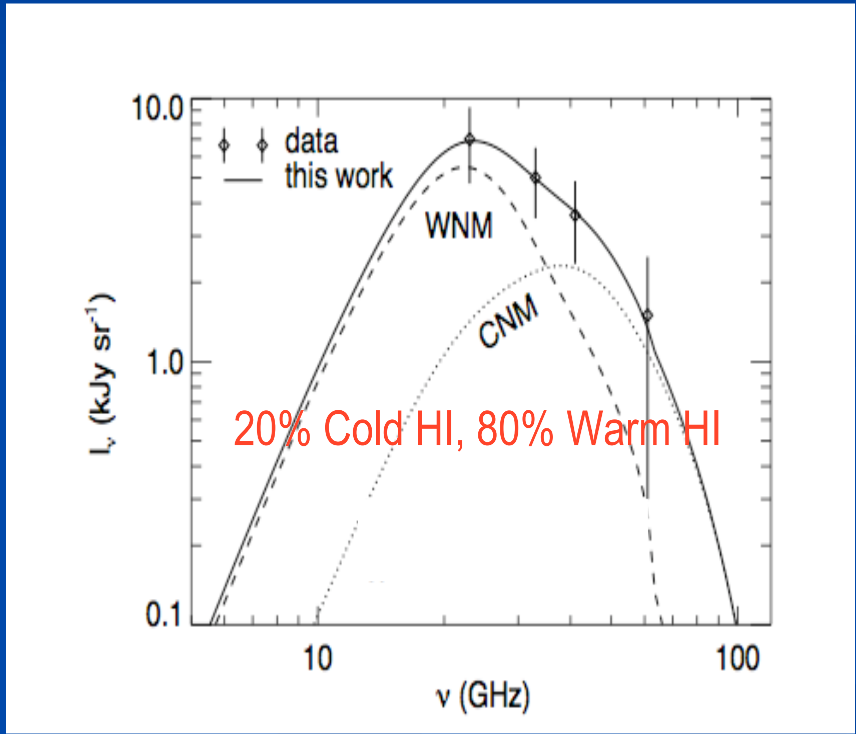
$\xi_{H_\perp^\gamma}(\mathbf{R}, z) = \langle H_\perp^\gamma(\mathbf{x}_1) H_\perp^\gamma(\mathbf{x}_2)\rangle$ Is correlation function of synchrotron for arbitrary γ

Allows to remove fluctuations / study magnetic turbulence

New models provide better correspondence to observations



DL98 and Ysard & Verstraete 2009



Hoang, Lazarian & Draine 2011

WMAP data from Ysard & 2010 can be well fitted for a realistic WNM to CMN ratio