Planck Early Results Paper XX: New Light on Anomalous Microwave Emission

Clive Dickinson

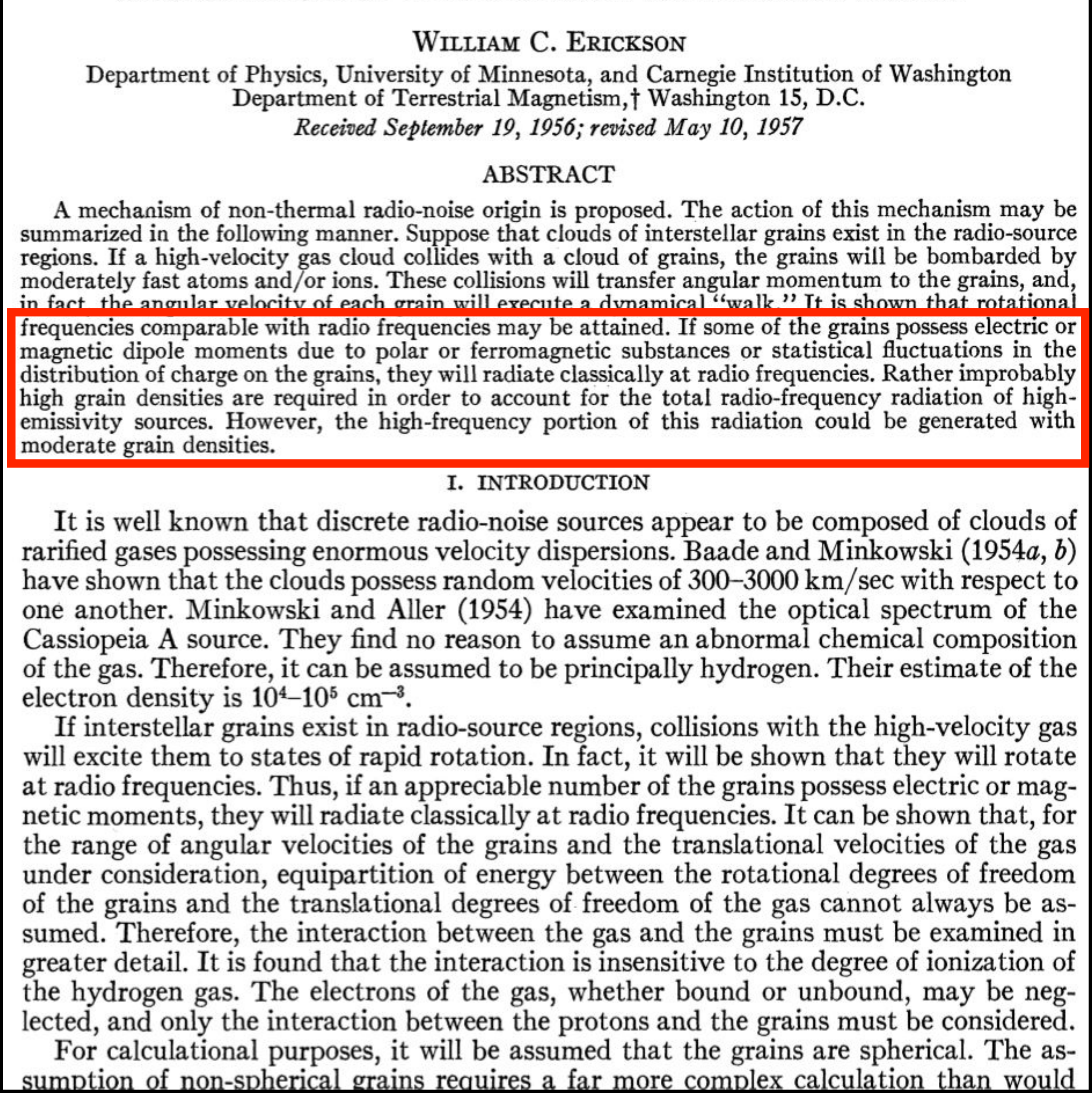
Jodrell Bank Centre for Astrophysics (University of Manchester)

NAM 2012, Manchester, 27 March 2012

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

A bit of history...



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

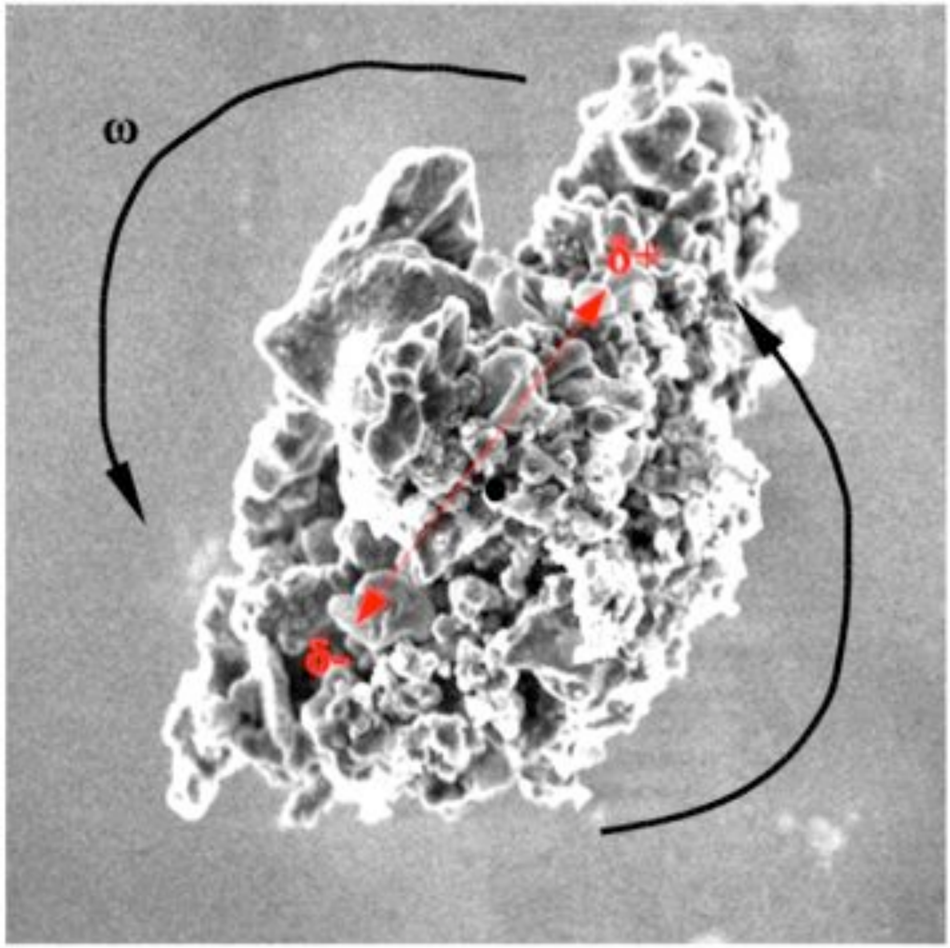
A mechanism of non-thermal radio-noise origin is proposed. The action of this mechanism may be summarized in the following manner. Suppose that clouds of interstellar grains exist in the radio-source regions. If a high-velocity gas cloud collides with a cloud of grains, the grains will be bombarded by 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.

I. INTRODUCTION

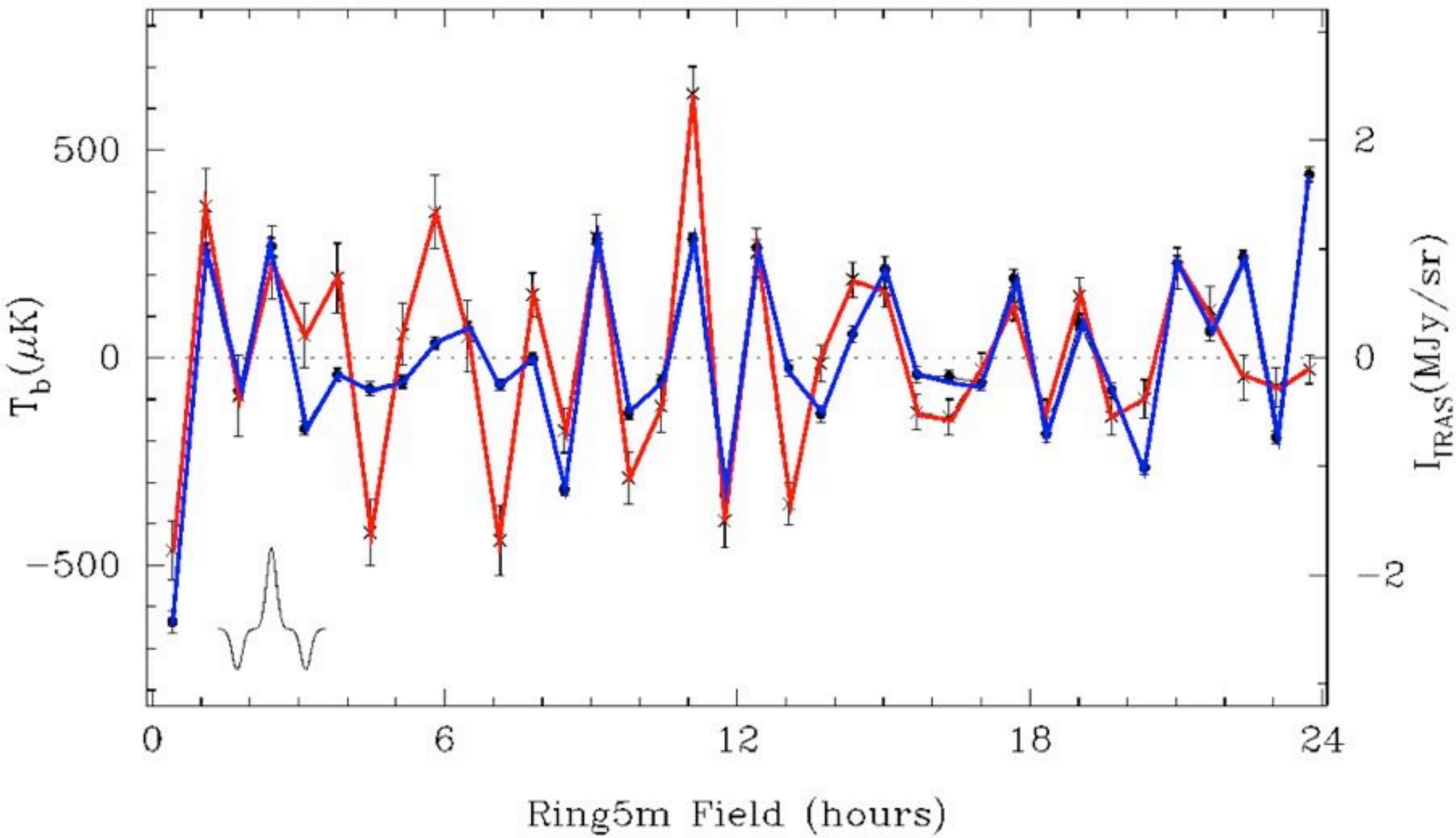
It is well known that discrete radio-noise sources appear to be composed of clouds of rarified gases possessing enormous velocity dispersions. Baade and Minkowski (1954*a*, *b*) have shown that the clouds possess random velocities of 300–3000 km/sec with respect to one another. Minkowski and Aller (1954) have examined the optical spectrum of the Cassiopeia A source. They find no reason to assume an abnormal chemical composition of the gas. Therefore, it can be assumed to be principally hydrogen. Their estimate of the electron density is 10^4–10^5 cm^{-3}.

If interstellar grains exist in radio-source regions, collisions with the high-velocity gas will excite them to states of rapid rotation. In fact, it will be shown that they will rotate at radio frequencies. Thus, if an appreciable number of the grains possess electric or magnetic moments, they will radiate classically at radio frequencies. It can be shown that, for the range of angular velocities of the grains and the translational velocities of the gas under consideration, equipartition of energy between the rotational degrees of freedom of the grains and the translational degrees of freedom of the gas cannot always be assumed. Therefore, the interaction between the gas and the grains must be examined in greater detail. It is found that the interaction is insensitive to the degree of ionization of the hydrogen gas. The electrons of the gas, whether bound or unbound, may be neglected, and only the interaction between the protons and the grains must be considered.

For calculational purposes, it will be assumed that the grains are spherical. The assumption of non-spherical grains requires a far more complex calculation than would



Discovery of Anomalous Microwave Emission

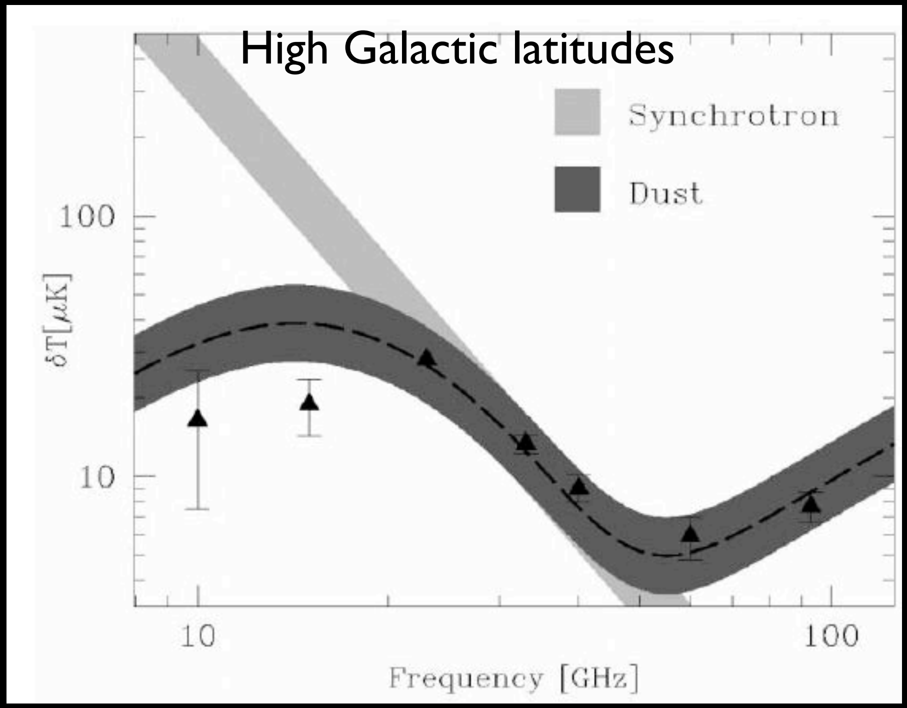


14.5/32 GHz OVRO (adapted from Leitch et al. 1997)

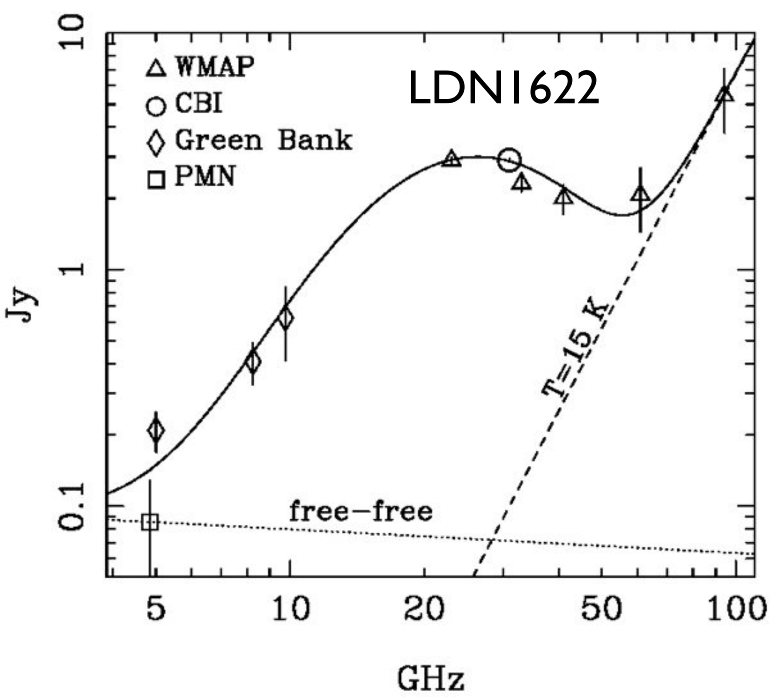
Quite a bit of evidence over the years...

- A lot of evidence over the last 14 years - very active area of research, but still little is known about it! (lack of data!)
- Many papers, instruments, techniques, frequency ranges. E.g.:-
    - OVRO: Leitch et al. (1997)
    - COBE-DMR: Kogut et al. (1996), Banday et al. (2003)
    - Saskatoon: de Oliveira-Costa (1997)
    - Tenerife: Mukherjee et al. (2001), de Oliveira-Costa et al. (2002, 2004)
    - Python V: Mukherjee et al. (2003)
    - Green Bank: Finkbeiner (2002), Finkbeiner et al. (2004)
    - Cosmosomas: Watson et al. (2005), Battistelli et al. (2006), Hildebrandt et al. (2007)
    - VSA: Scaife et al. (2007), Tibbs et al. (2009), Todorovic et al. (2010)
    - CBI: Casassus et al. (2004,2006,2007,2008), Dickinson et al. (2006,2007,2009a,2010), Castellanos et al. (2011), Vidal et al. (2011)
    - AMI: Scaife et al. (2008), Scaife et al. (2009a,b), Scaife et al. (2010)
    - WMAP: Bennett et al. (2003), Lagache et al. (2003), Davies et al. (2006), Bonaldi et al. (2007), Miville-Deschenes et al. (2008), Gold et al. (2009), Dobler & Finkbeiner (2009), Ysard et al. (2009), Dickinson et al. (2009a, 2011), Lopez-Caraballo (2011), Peel et al. (2011), Macellari et al. 2011, Ghosh et al. (2011), Genova-Santos et al. (2011)
    - & now extragalactic as well! (Murphy et al. 2010; Scaife et al. 2010)

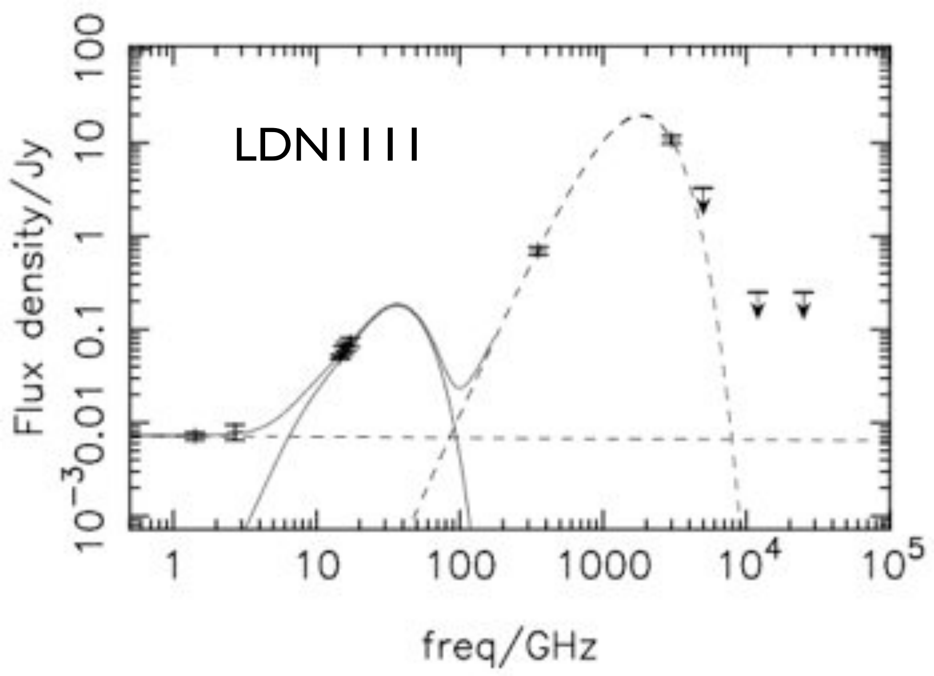
Example detections (need more data!)



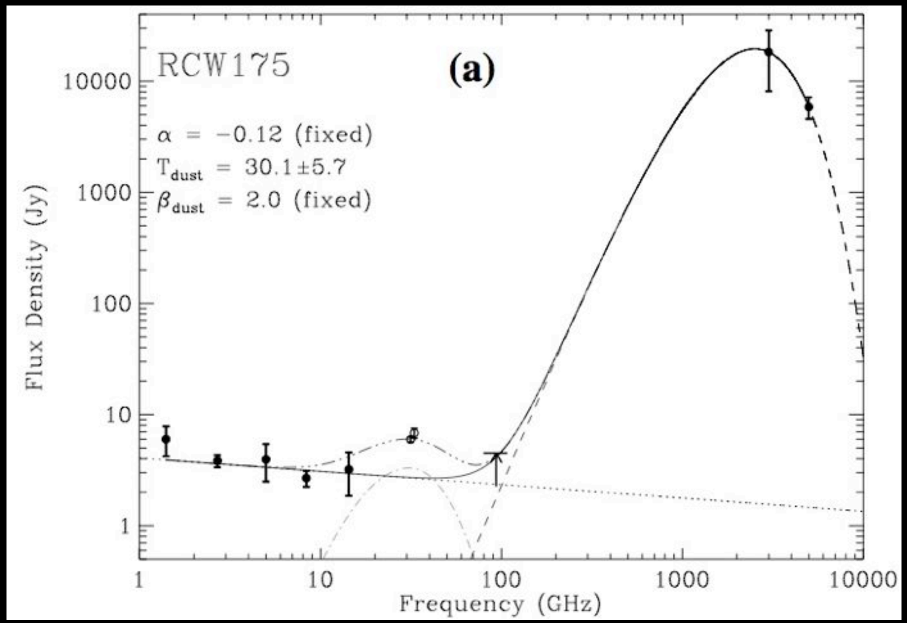
de Oliveira-Costa (2004)



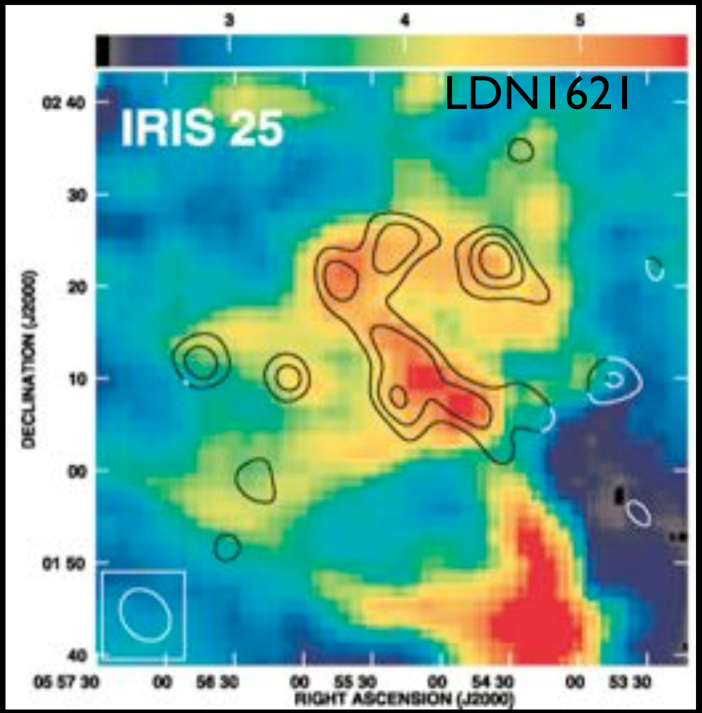
Casassus et al. (2006)



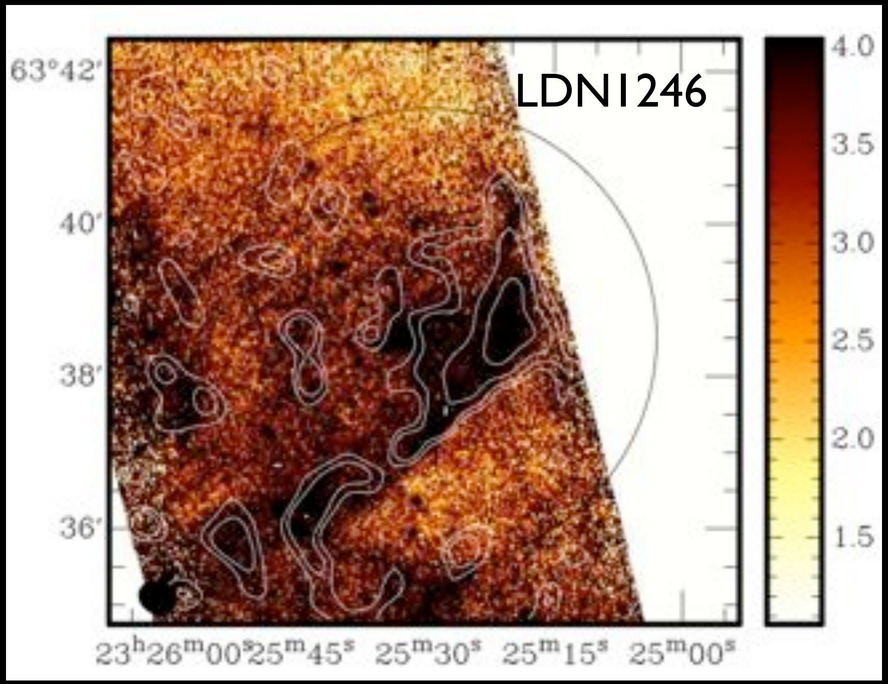
Scaife et al. (2009a)



Dickinson et al. (2009)



Dickinson et al. (2010)

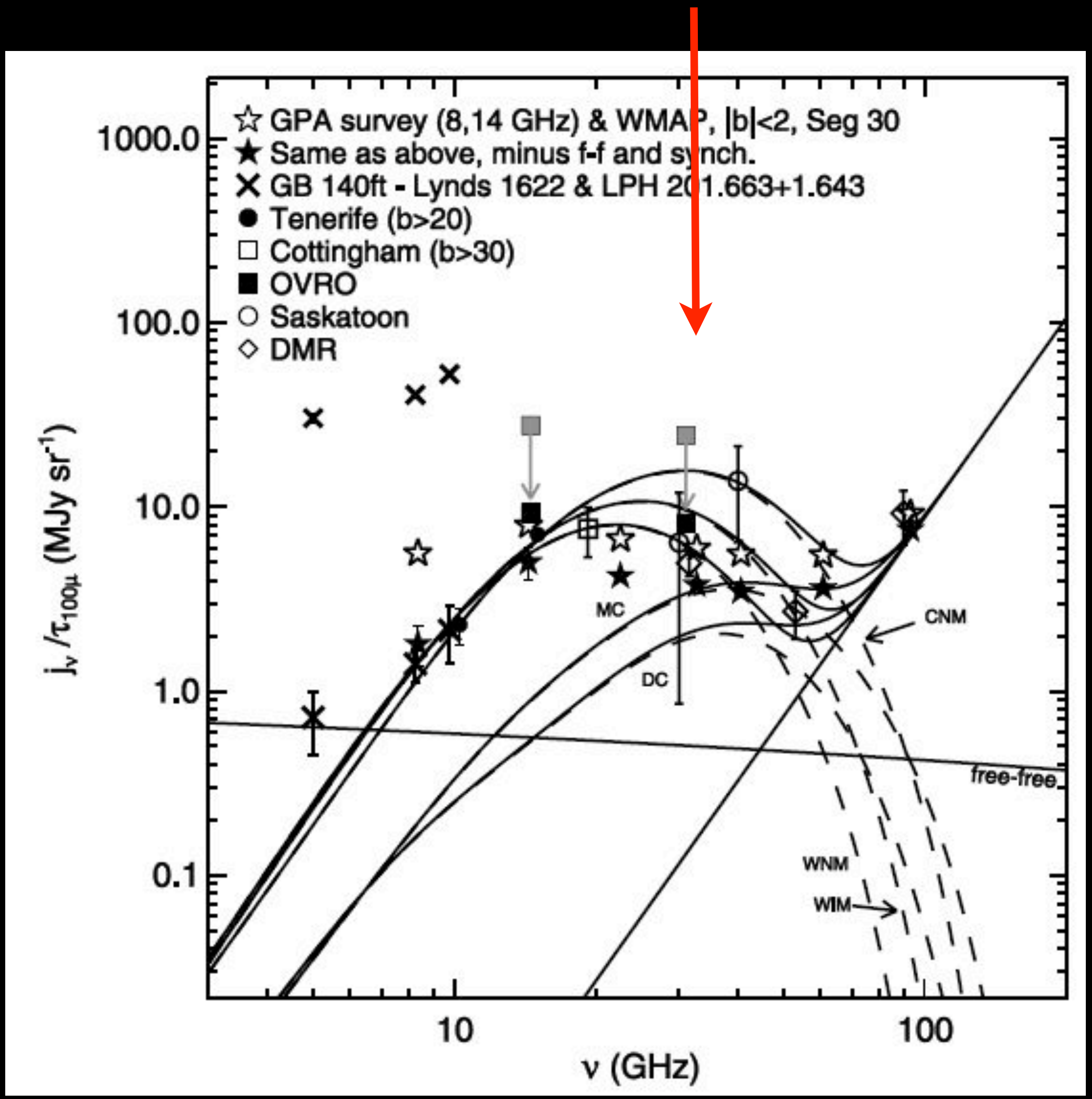


Scaife et al. (2009b)

What is the anomalous microwave emission?

- Lots of possibilities have been considered
  - Warm (T~10000 K) free-free
  - Hot (T~10^6 K) free-free
  - Absorbed free-free from UCHII regions
  - Flat spectrum (β~-2.5) synchrotron emission
  - Magneto-dipole radiation
  - Cold dust / emissivity variations
  - & others!
- Best explanation is electro-dipole radiation from small spinning dust grains (“spinning dust”)
  - Basic theory understood (Draine & Lazarian 1998a,b and more recent enhancements)

Peaked spectrum over ~10-100 GHz



Draine & Lazarian (1998)
Finkbeiner (2004)

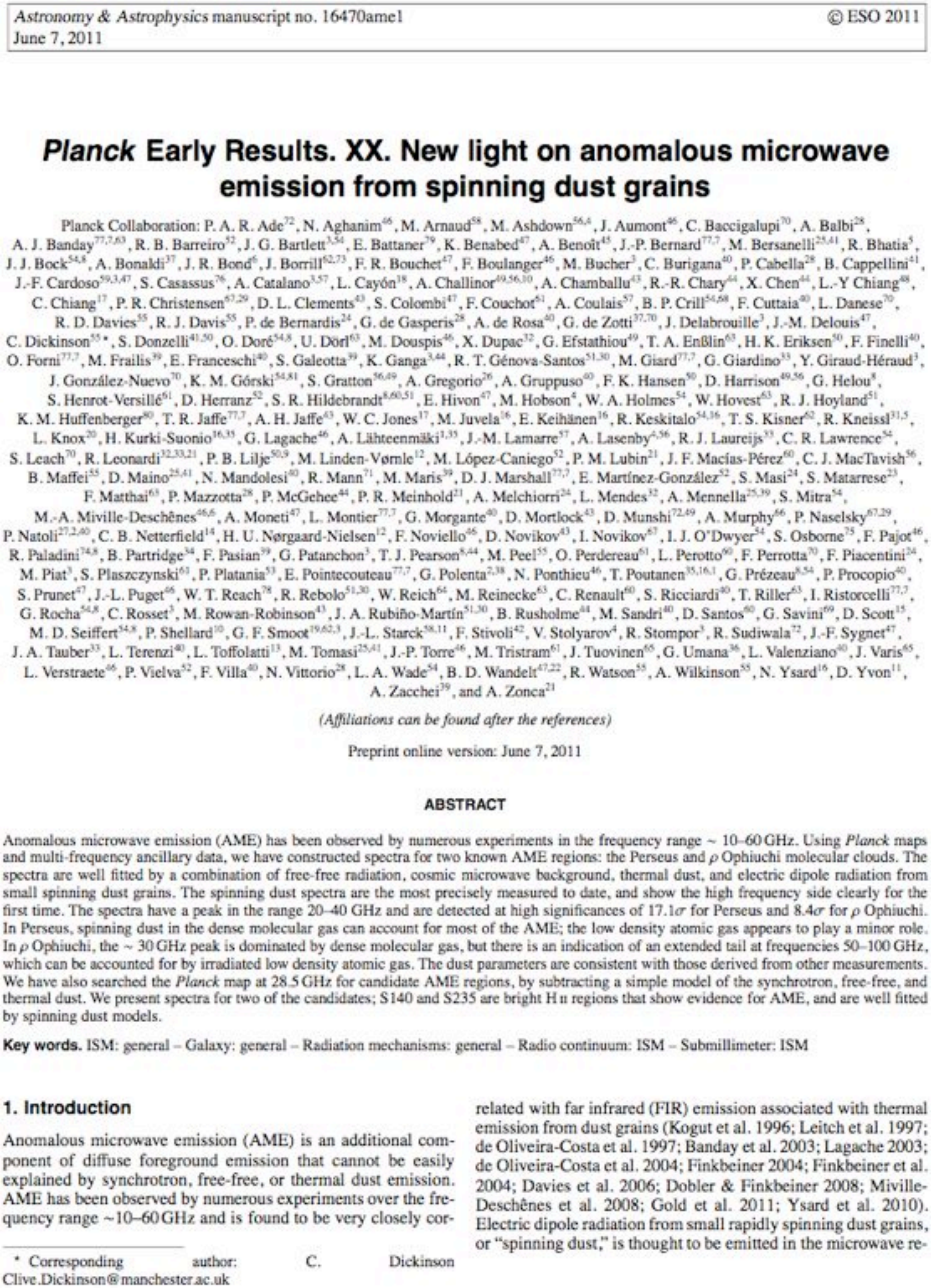
Early Planck paper on AME

Paper XX

Planck collaboration et al.,
2012, A&A, 536, A20 (arXiv:1101.2031)

Corresponding author: C. Dickinson

Very strong support for spinning dust model



Astronomy & Astrophysics manuscript no. 16470ame1
June 7, 2011

Planck Early Results. XX. New light on anomalous microwave emission from spinning dust grains

Planck Collaboration: P. A. R. Ade[72], N. Aghanim[46], M. Arnaud[58], M. Ashdown[56,4], J. Aumont[46], C. Baccigalupi[70], A. Balbi[28], A. J. Banday[77,7,63], R. B. Barreiro[52], J. G. Bartlett[3,54], E. Battaner[79], K. Benabed[47], A. Benoît[45], J.-P. Bernard[77,7], M. Bersanelli[25,41], R. Bhatia[5], J. J. Bock[54,8], A. Bonaldi[37], J. R. Bond[6], J. Borrill[62,73], F. R. Bouchet[47], F. Boulanger[46], M. Bucher[3], C. Burigana[40], P. Cabella[28], B. Cappellini[41], J.-F. Cardoso[59,3,47], S. Casassus[76], A. Catalano[3,57], L. Cayón[18], A. Challinor[49,56,10], A. Chamballu[43], R.-R. Chary[44], X. Chen[44], L.-Y Chiang[48], C. Chiang[17], P. R. Christensen[67,29], D. L. Clements[43], S. Colombi[47], F. Couchot[61], A. Coulais[57], B. P. Crill[54,68], F. Cuttaia[40], L. Danese[70], R. D. Davies[55], R. J. Davis[55], P. de Bernardis[24], G. de Gasperis[28], A. de Rosa[40], G. de Zotti[37,70], J. Delabrouille[3], J.-M. Delouis[47], C. Dickinson[55]*, S. Donzelli[41,50], O. Doré[54,8], U. Dörl[63], M. Douspis[46], X. Dupac[32], G. Efstathiou[49], T. A. Enßlin[63], H. K. Eriksen[50], F. Finelli[40], O. Forni[77,7], M. Frailis[39], E. Franceschi[40], S. Galeotta[39], K. Ganga[3,44], R. T. Génova-Santos[51,30], M. Giard[77,7], G. Giardino[33], Y. Giraud-Héraud[3], J. González-Nuevo[70], K. M. Górski[54,81], S. Gratton[56,49], A. Gregorio[26], A. Gruppuso[40], F. K. Hansen[50], D. Harrison[49,56], G. Helou[8], S. Henrot-Versillé[61], D. Herranz[52], S. R. Hildebrandt[8,60,51], E. Hivon[47], M. Hobson[4], W. A. Holmes[54], W. Hovest[63], R. J. Hoyland[51], K. M. Huffenberger[80], T. R. Jaffe[77,7], A. H. Jaffe[43], W. C. Jones[17], M. Juvela[16], E. Keihänen[16], R. Keskitalo[54,16], T. S. Kisner[62], R. Kneissl[31,5], L. Knox[20], H. Kurki-Suonio[16,35], G. Lagache[46], A. Lähteenmäki[1,35], J.-M. Lamarre[57], A. Lasenby[4,56], R. J. Laureijs[33], C. R. Lawrence[54], S. Leach[70], R. Leonardi[32,33,21], P. B. Lilje[50,9], M. Linden-Vørnle[12], M. López-Caniego[52], P. M. Lubin[21], J. F. Macías-Pérez[60], C. J. MacTavish[56], B. Maffei[55], D. Maino[25,41], N. Mandolesi[40], R. Mann[71], M. Maris[39], D. J. Marshall[77,7], E. Martínez-González[52], S. Masi[24], S. Matarrese[23], F. Matthai[63], P. Mazzotta[28], P. McGehee[44], P. R. Meinhold[21], A. Melchiorri[24], L. Mendes[32], A. Mennella[25,39], S. Mitra[54], M.-A. Miville-Deschênes[46,6], A. Moneti[47], L. Montier[77,7], G. Morgante[40], D. Mortlock[43], D. Munshi[72,49], A. Murphy[66], P. Naselsky[67,29], P. Natoli[27,2,40], C. B. Netterfield[14], H. U. Nørgaard-Nielsen[12], F. Noviello[46], D. Novikov[43], I. Novikov[67], I. J. O'Dwyer[54], S. Osborne[75], F. Pajot[46], R. Paladini[74,8], B. Partridge[34], F. Pasian[39], G. Patanchon[3], T. J. Pearson[8,44], M. Peel[55], O. Perdereau[61], L. Perotto[60], F. Perrotta[70], F. Piacentini[24], M. Piat[3], S. Plaszczynski[61], P. Platania[53], E. Pointecouteau[77,7], G. Polenta[2,38], N. Ponthieu[46], T. Poutanen[35,16,1], G. Prézeau[8,54], P. Procopio[40], S. Prunet[47], J.-L. Puget[46], W. T. Reach[78], R. Rebolo[51,30], W. Reich[64], M. Reinecke[63], C. Renault[60], S. Ricciardi[40], T. Riller[63], I. Ristorcelli[77,7], G. Rocha[54,8], C. Rosset[3], M. Rowan-Robinson[43], J. A. Rubiño-Martín[51,30], B. Rusholme[44], M. Sandri[40], D. Santos[60], G. Savini[69], D. Scott[15], M. D. Seiffert[54,8], P. Shellard[10], G. F. Smoot[19,62,3], J.-L. Starck[58,11], F. Stivoli[42], V. Stolyarov[4], R. Stompor[3], R. Sudiwala[72], J.-F. Sygnet[47], J. A. Tauber[33], L. Terenzi[40], L. Toffolatti[13], M. Tomasi[25,41], J.-P. Torre[46], M. Tristram[61], J. Tuovinen[65], G. Umana[36], L. Valenziano[40], J. Varis[65], L. Verstraete[46], P. Vielva[52], F. Villa[40], N. Vittorio[28], L. A. Wade[54], B. D. Wandelt[47,22], R. Watson[55], A. Wilkinson[55], N. Ysard[16], D. Yvon[11], A. Zacchei[39], and A. Zonca[21]

(Affiliations can be found after the references)

Preprint online version: June 7, 2011

ABSTRACT

Anomalous microwave emission (AME) has been observed by numerous experiments in the frequency range ~ 10–60 GHz. Using *Planck* maps and multi-frequency ancillary data, we have constructed spectra for two known AME regions: the Perseus and ρ Ophiuchi molecular clouds. The spectra are well fitted by a combination of free-free radiation, cosmic microwave background, thermal dust, and electric dipole radiation from small spinning dust grains. The spinning dust spectra are the most precisely measured to date, and show the high frequency side clearly for the first time. The spectra have a peak in the range 20–40 GHz and are detected at high significances of 17.1σ for Perseus and 8.4σ for ρ Ophiuchi. In Perseus, spinning dust in the dense molecular gas can account for most of the AME; the low density atomic gas appears to play a minor role. In ρ Ophiuchi, the ~ 30 GHz peak is dominated by dense molecular gas, but there is an indication of an extended tail at frequencies 50–100 GHz, which can be accounted for by irradiated low density atomic gas. The dust parameters are consistent with those derived from other measurements. We have also searched the *Planck* map at 28.5 GHz for candidate AME regions, by subtracting a simple model of the synchrotron, free-free, and thermal dust. We present spectra for two of the candidates; S140 and S235 are bright H II regions that show evidence for AME, and are well fitted by spinning dust models.

Key words. ISM: general – Galaxy: general – Radiation mechanisms: general – Radio continuum: ISM – Submillimeter: ISM

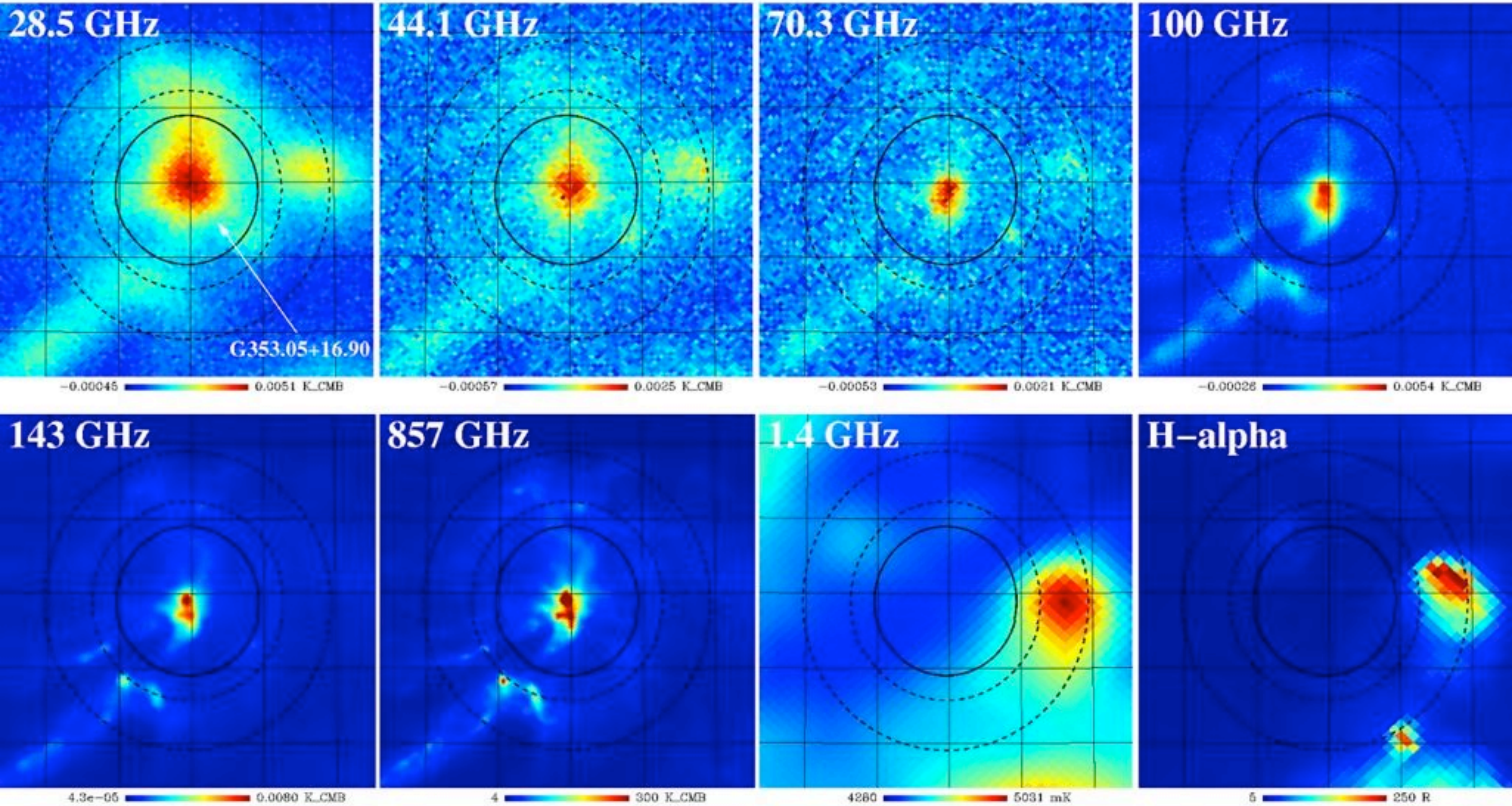
1. Introduction

Anomalous microwave emission (AME) is an additional component of diffuse foreground emission that cannot be easily explained by synchrotron, free-free, or thermal dust emission. AME has been observed by numerous experiments over the frequency range ~10–60 GHz and is found to be very closely correlated with far infrared (FIR) emission associated with thermal emission from dust grains (Kogut et al. 1996; Leitch et al. 1997; de Oliveira-Costa et al. 1997; Banday et al. 2003; Lagache 2003; de Oliveira-Costa et al. 2004; Finkbeiner 2004; Finkbeiner et al. 2004; Davies et al. 2006; Dobler & Finkbeiner 2008; Miville-Deschênes et al. 2008; Gold et al. 2011; Ysard et al. 2010). Electric dipole radiation from small rapidly spinning dust grains, or "spinning dust," is thought to be emitted in the microwave re-

---

* Corresponding author: C. Dickinson Clive.Dickinson@manchester.ac.uk

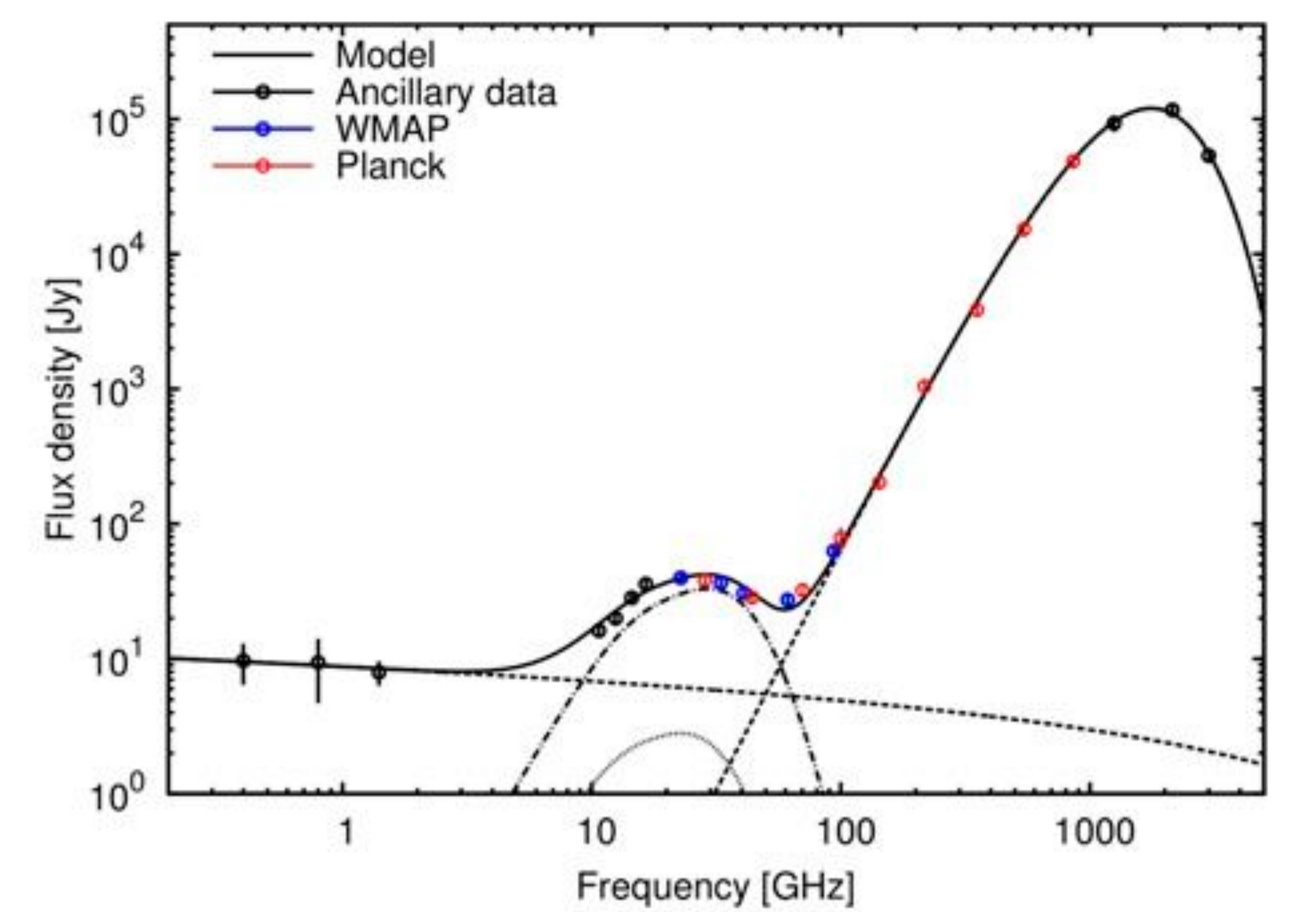
Maps: ρ Ophiuchi Molecular Cloud

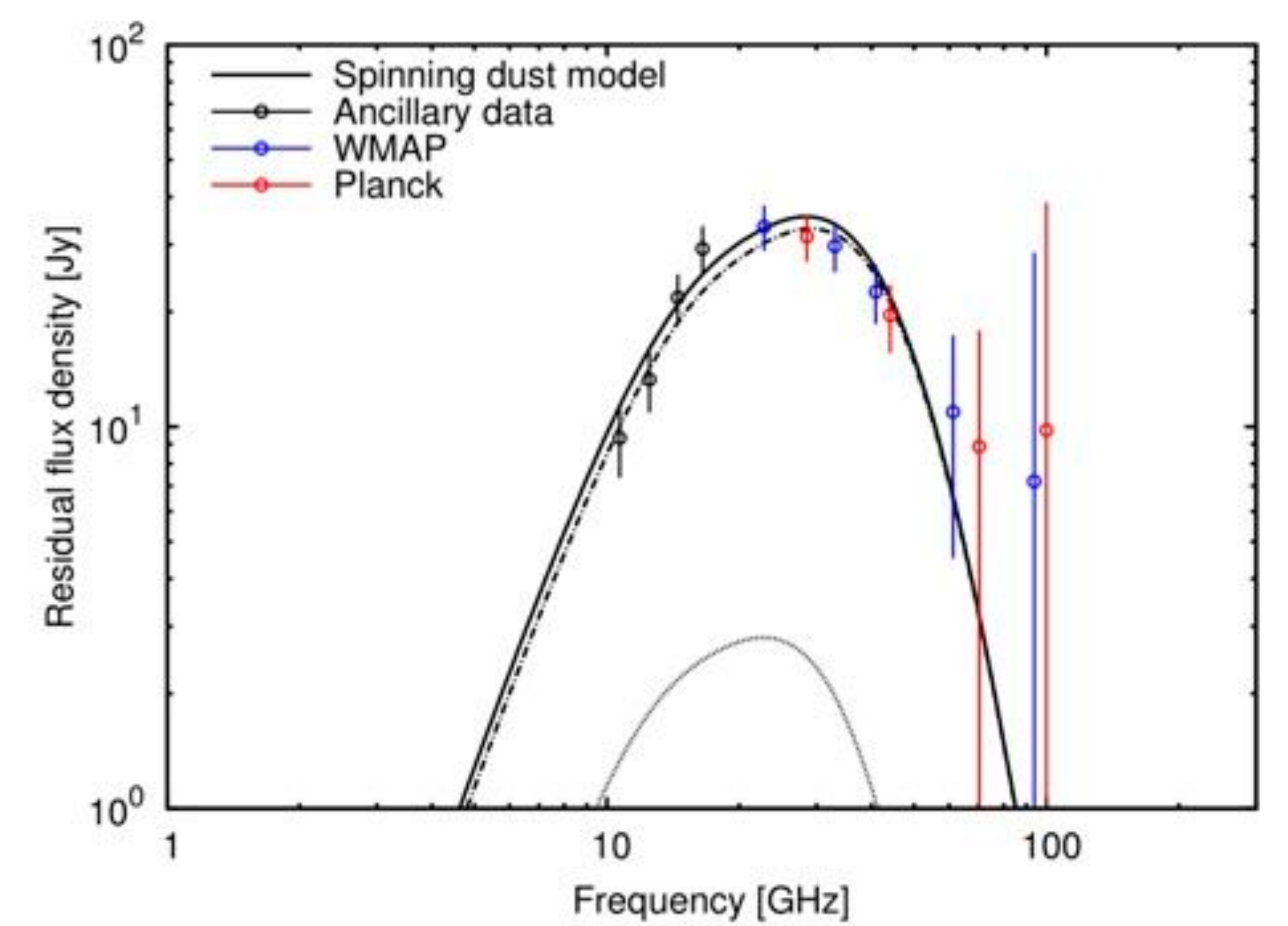


Originally detected by Casassus et al. (2008) using the CBI at 31 GHz

Spectra: Perseus

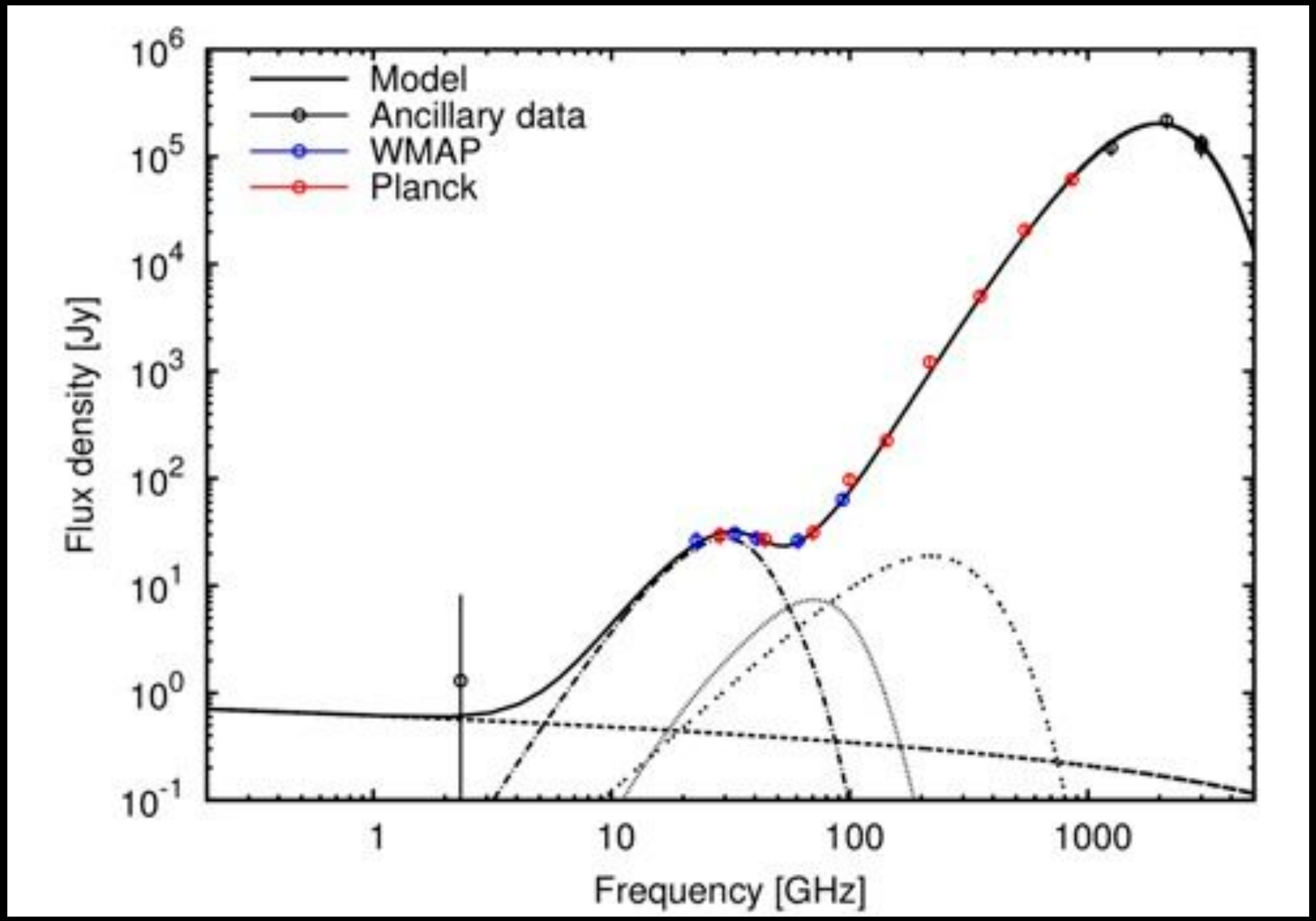
- Integrated spectrum well-fitted by optically thin free-free, CMB (negligible) and single component modified black-body function
- Residual spectrum has clearly peaked spectrum
- Plausible physical model for spinning dust fits the data well
  - Denser molecular component appears to dominate

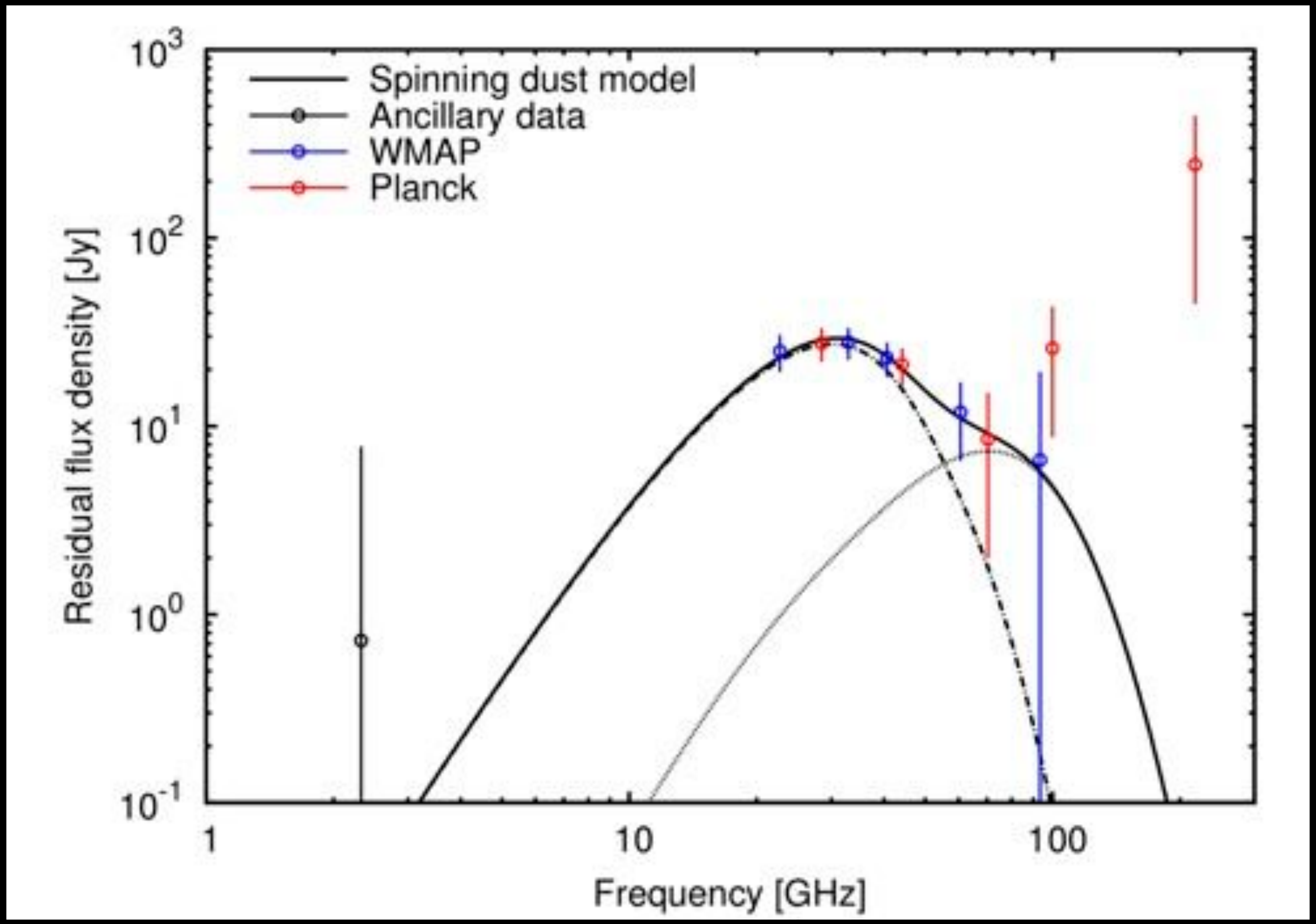




Spectra: ρ Ophiuchus

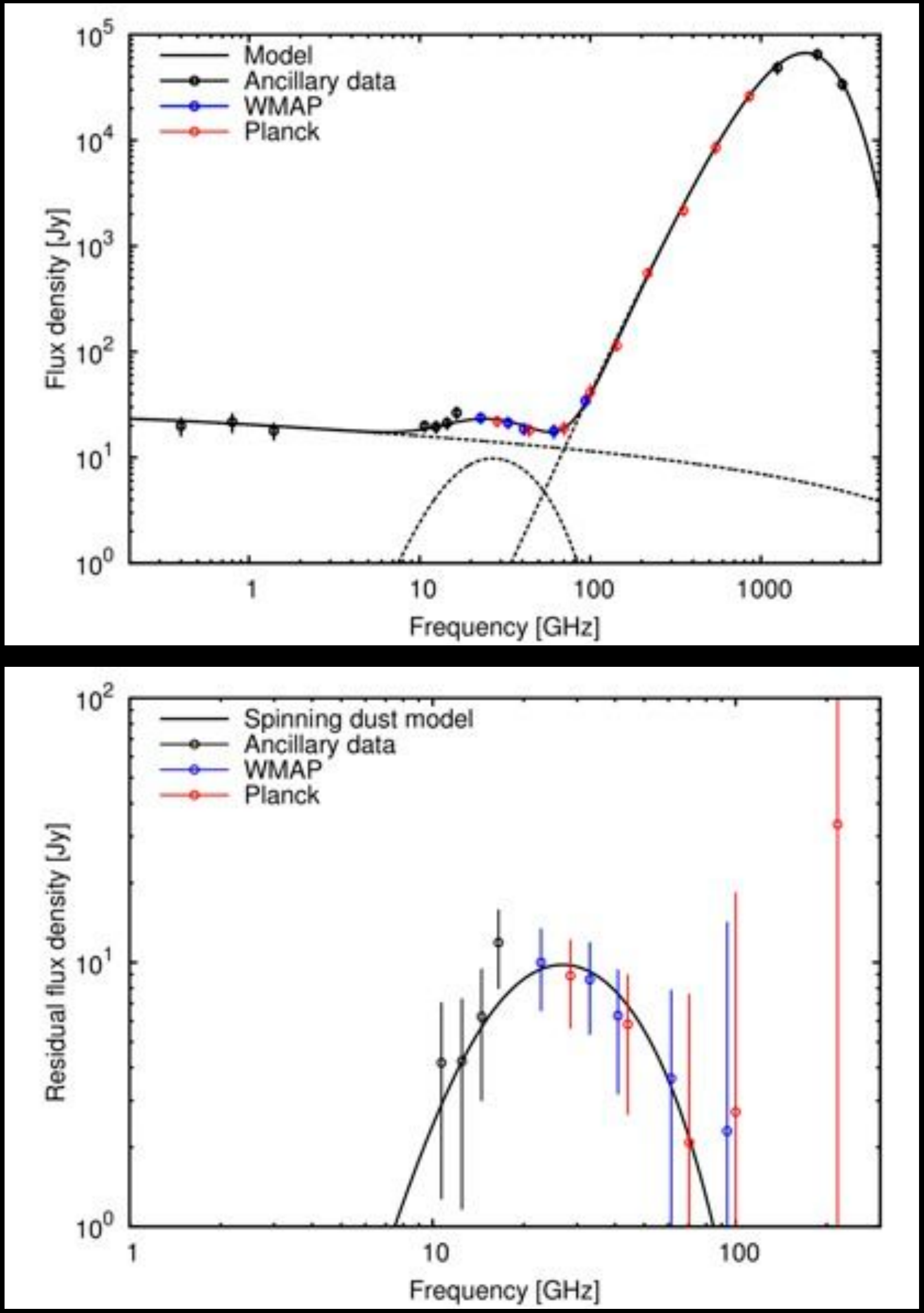
- Integrated spectrum well-fitted by optically thin free-free, CMB (small) and single component modified black-body function
- Residual spectrum has clearly peaked spectrum
    - Denser molecular component dominates
    - Irradiated atomic gas may contribute at frequencies ~60-90 GHz



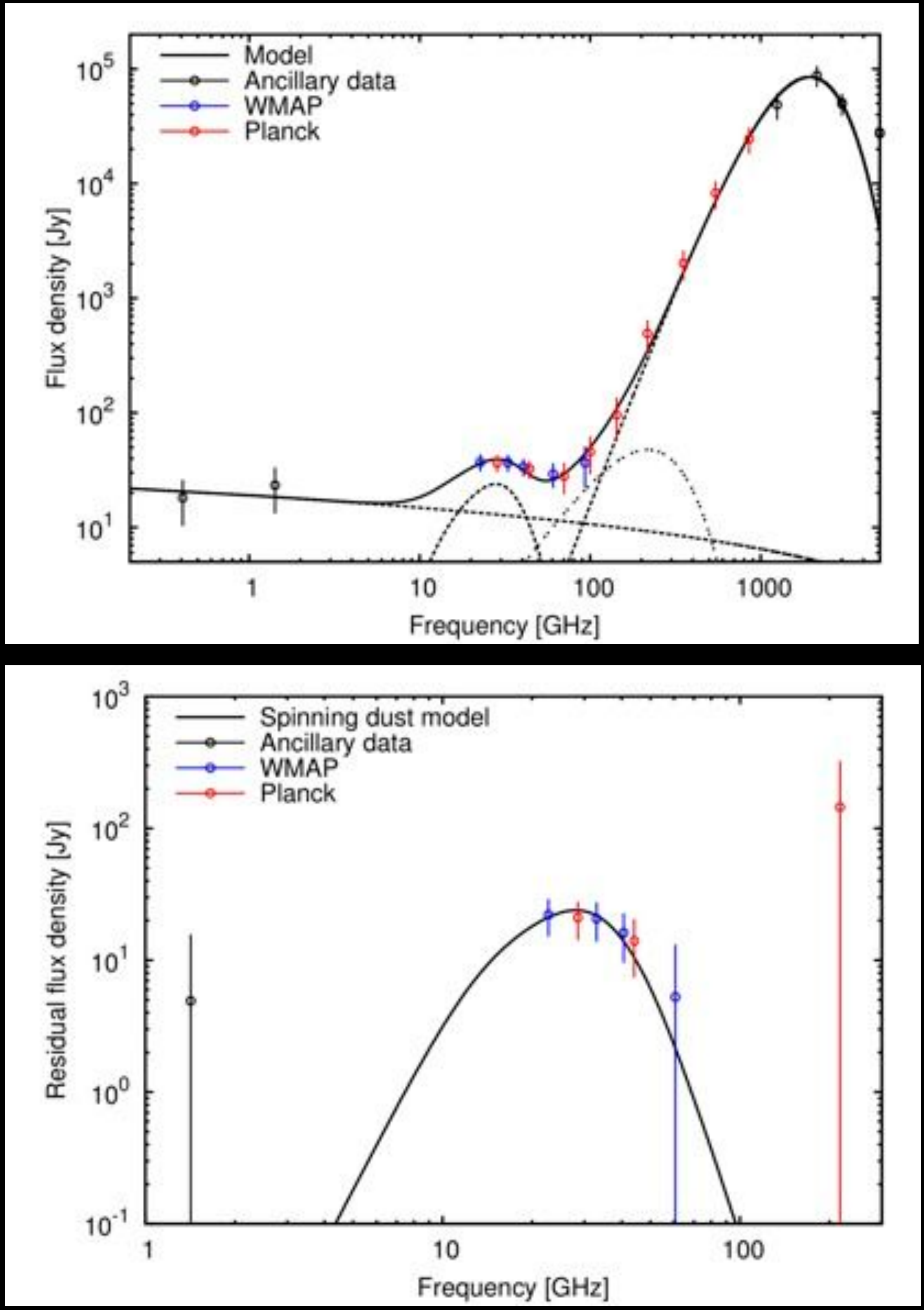


New AME regions spectra from Planck

G173.6+2.80



G107.1+5.20



Conclusions

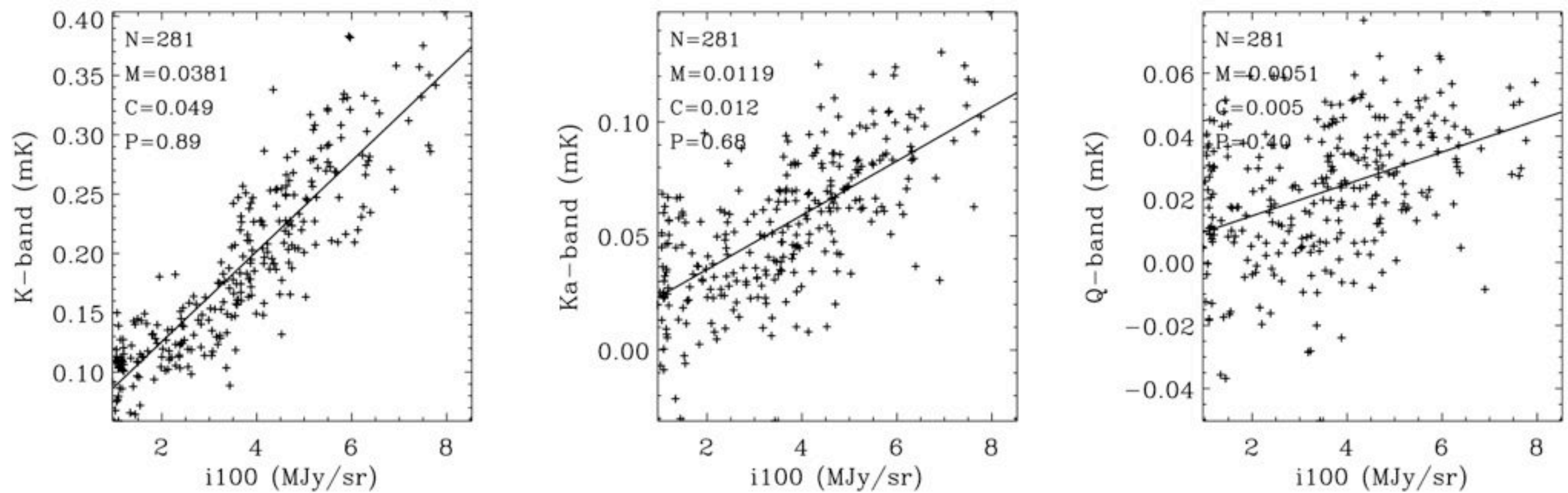
- Planck data are beautiful!
  - Learn a lot about radio/microwave/sub-mm foregrounds as well as CMB!
- Very strong evidence for the spinning dust model in Perseus and Ophiuchus
  - Plausible physical model fits the data well (see paper for details)
  - Spectrum (amplitude, peak frequency, shape) can help to constrain the conditions, grain properties etc.
  - New diagnostic tool for studying small dust grains
- Watch out for upcoming Planck intermediate paper (expected later this year)
  - Statistical study of a sample of new AME regions

AME is <u>almost</u> everywhere!

(at least as seen from our position)

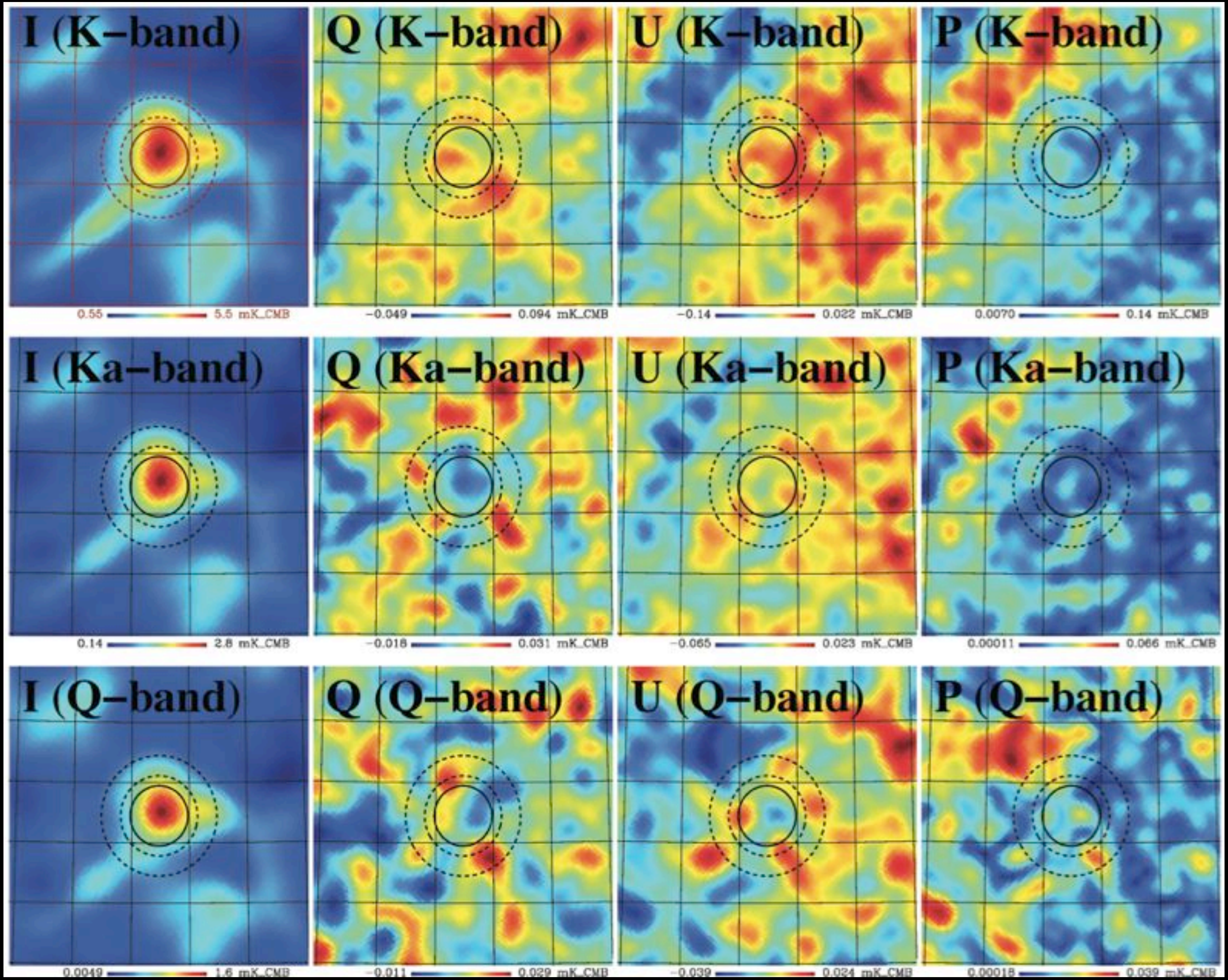
WMAP vs IRAS 100 microns:
AME is dust-correlated emission at ~20-60 GHz

23 GHz 33 GHz 41 GHz



Davies et al. (2006)
Peel et al. (2011a) show that addition of 2.3 GHz does not change this picture

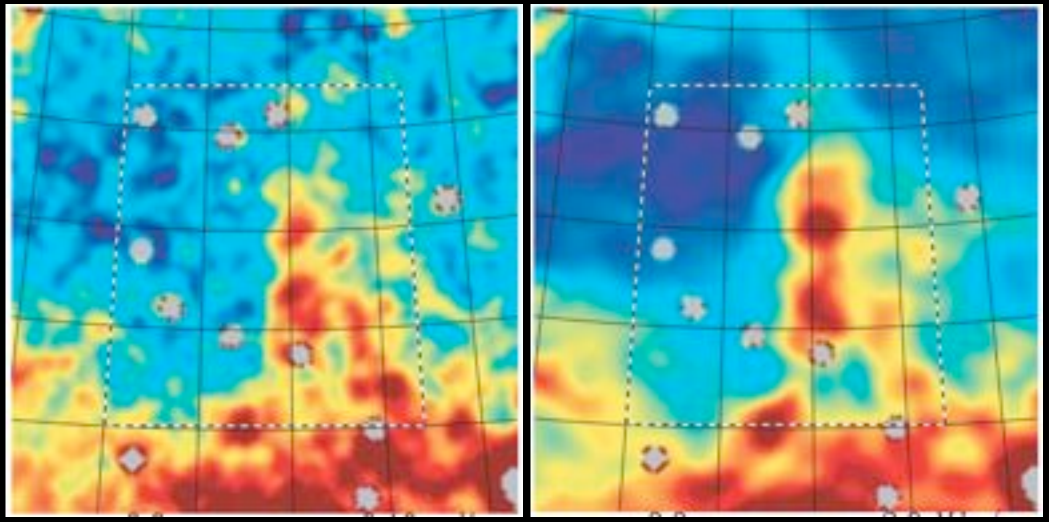
AME polarization appears to be small



No more than a few % polarized, probably < 1% (Dickinson et al. 2011)

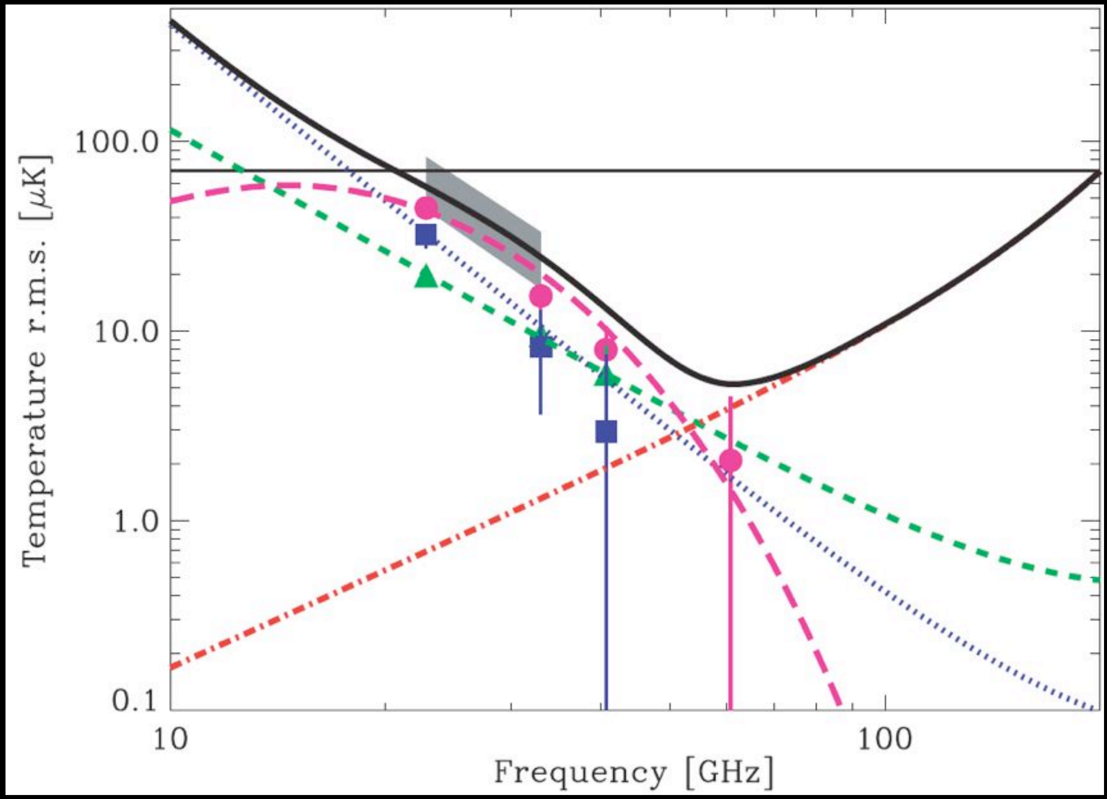
Why is spinning dust important?

- Important foreground for CMB studies
  - Strong in total-intensity (possibly dominant ~20-60 GHz?)
  - May be significant foreground for CMB polarization (even if only ~few % polarized)
- Important new constituent of the ISM
  - Dust important in star formation, planet formation, chemistry of interstellar clouds etc.
- New diagnostic for dust grains and ISM environment
  - Spectrum depends on many parameters (esp. grain size distribution, column density, ISRF, electric dipole moment)
  - Complementary to IR data



WMAP 23 GHz

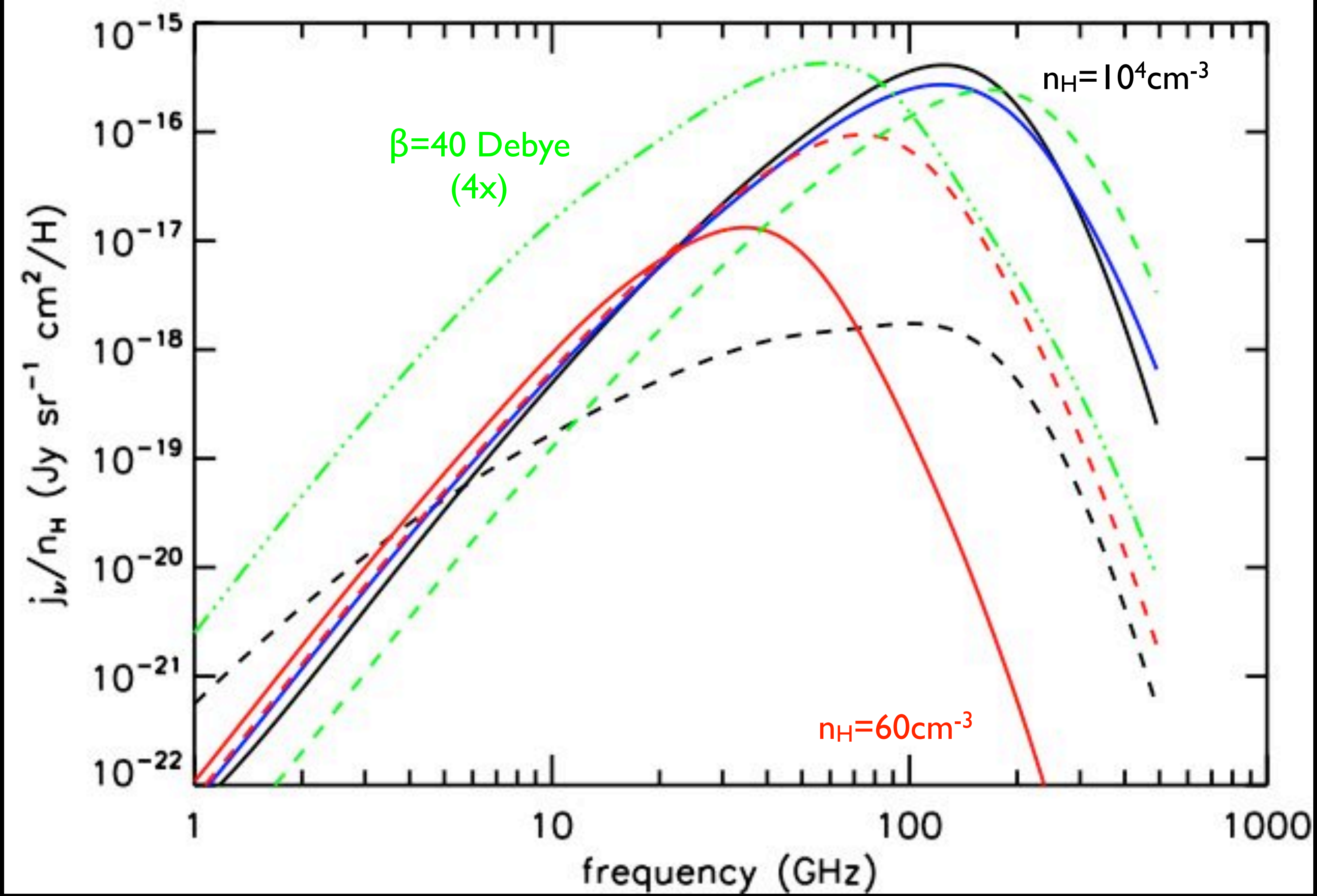
IRAS 100 microns



Davies et al. (2006)

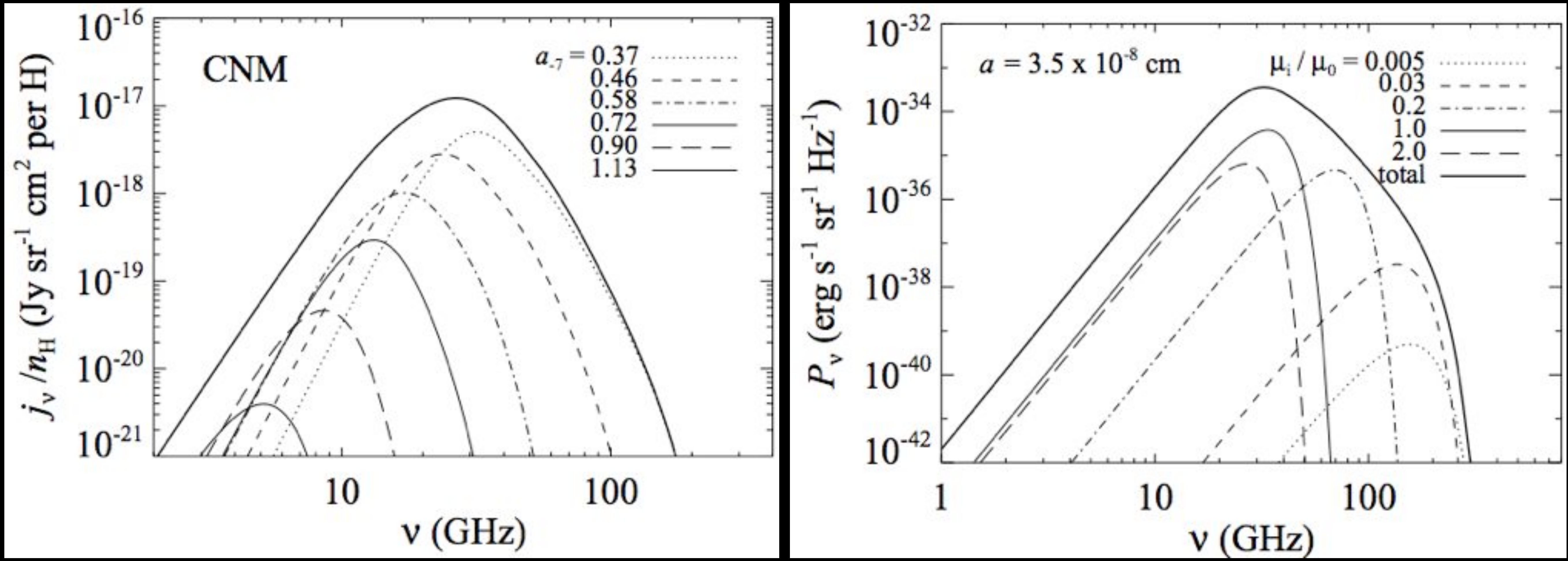
Modelling with spinning dust

- Basic theory is understood but the details are complicated!
- Also, significant degeneracies given limited information content in the smooth spectra
  - Needs to be combined with IR continuum/spectra, optical lines/absorption etc.



Contributions to spinning dust spectrum

It is complicated! Spectrum depends on a lot of parameters!
Grain size distribution, electric dipole moments, densities, ISRF, ion fractions etc

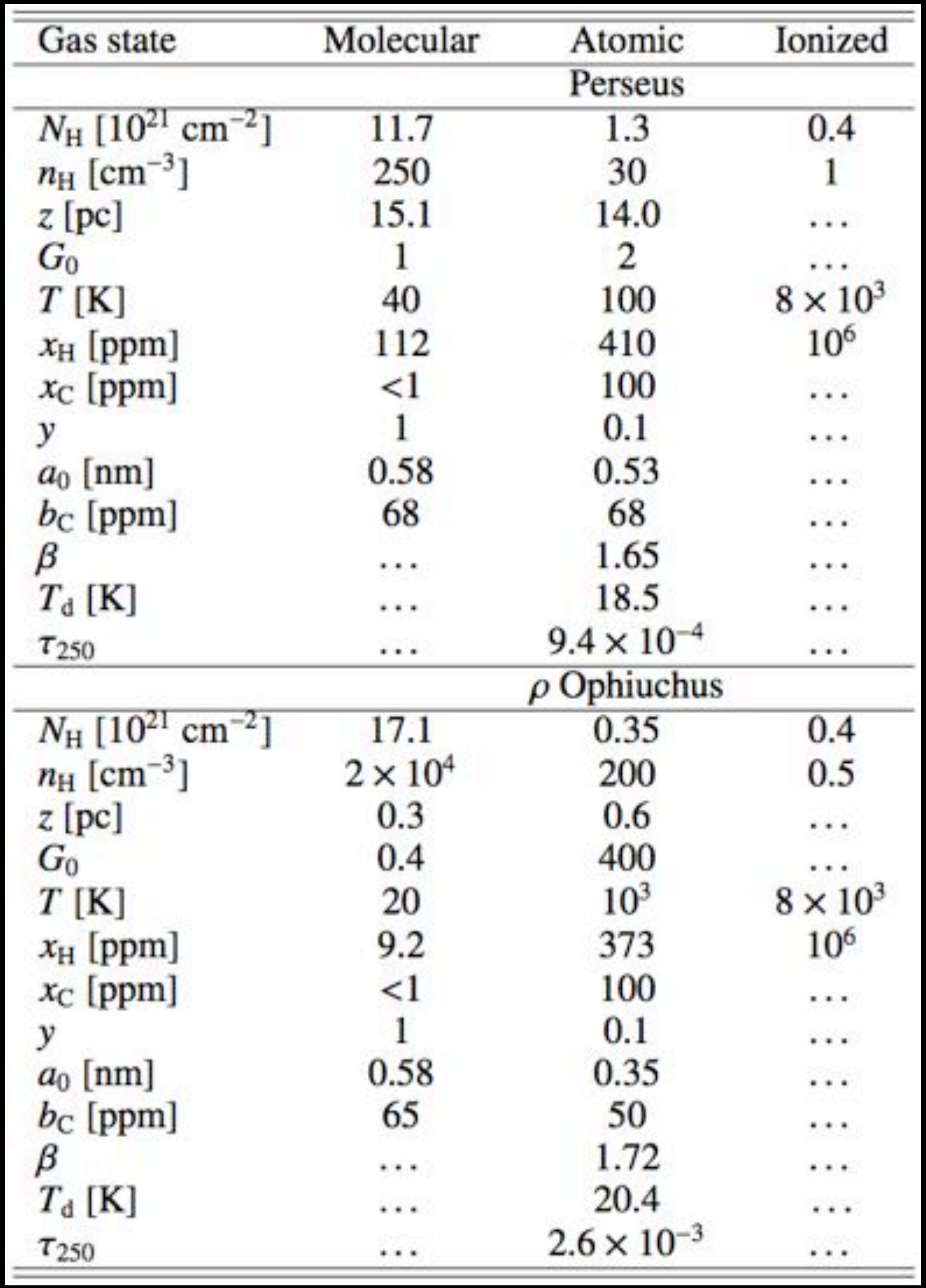


$P \propto \omega^4$

SPDUST code (Ali-Hamoud, Hirata, Dickinson, 2009)

Spinning dust model

- Low and high density components
- Fix parameters where possible!
    - e.g. for Perseus, use molecular n_H from C_2 lines (Iglesias-Groth 2010), depth (z) from Ridge et al. (2006) etc...
    - T_d, τ_{250} from thermal dust fit
    - H+ ions x_H determined by ionization balance
    - C+ ions x_C more difficult - leave as free parameter
    - Grain size set by a_0 with σ=0.4
    - PAH abundance set by C in PAHs b_c
    - Dipole moment β from DL98 prescription (~0.4 debye)
    - WIM assumed to have no spinning dust (no PAHs)
    - ...(see paper for more details)

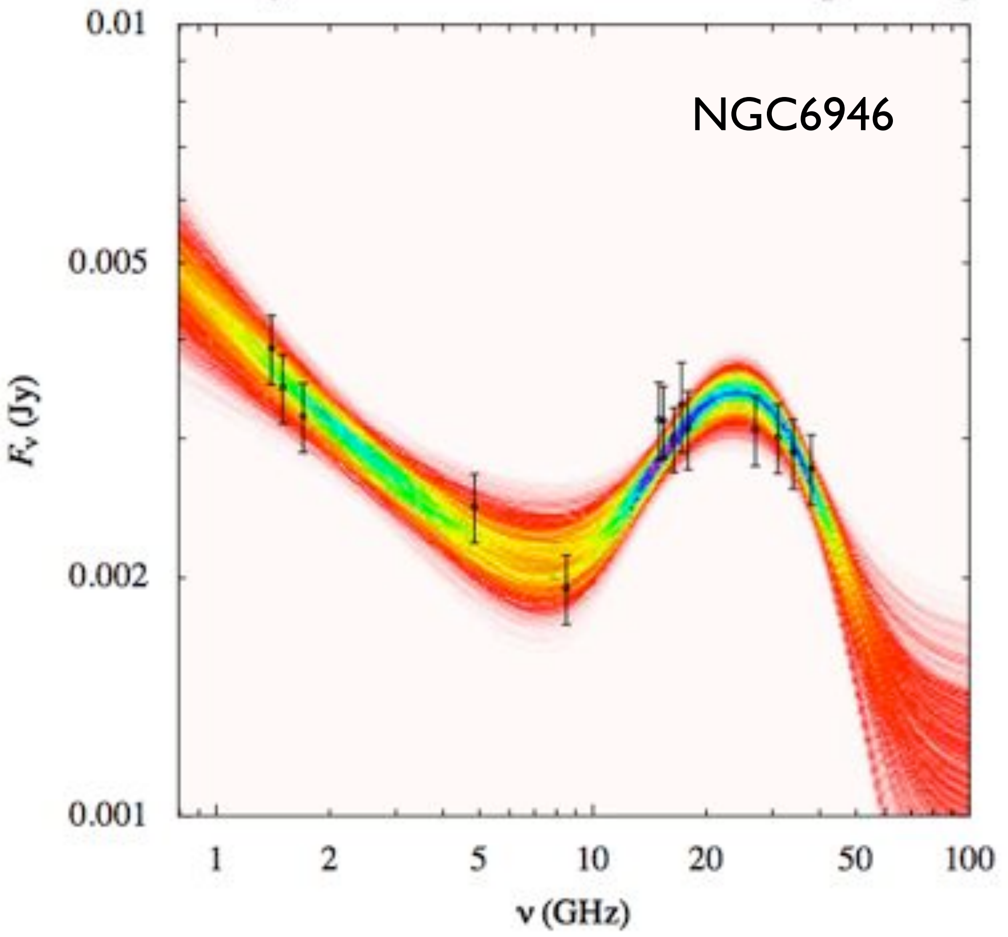


Gas state	Molecular	Atomic	Ionized
		Perseus	
N_H [10^{21} cm^{-2}]	11.7	1.3	0.4
n_H [cm^{-3}]	250	30	1
z [pc]	15.1	14.0	…
G_0	1	2	…
T [K]	40	100	8×10^3
x_H [ppm]	112	410	10^6
x_C [ppm]	<1	100	…
y	1	0.1	…
a_0 [nm]	0.58	0.53	…
b_C [ppm]	68	68	…
β	…	1.65	…
T_d [K]	…	18.5	…
τ_{250}	…	9.4×10^{-4}	…
		ρ Ophiuchus	
N_H [10^{21} cm^{-2}]	17.1	0.35	0.4
n_H [cm^{-3}]	2×10^4	200	0.5
z [pc]	0.3	0.6	…
G_0	0.4	400	…
T [K]	20	10^3	8×10^3
x_H [ppm]	9.2	373	10^6
x_C [ppm]	<1	100	…
y	1	0.1	…
a_0 [nm]	0.58	0.35	…
b_C [ppm]	65	50	…
β	…	1.72	…
T_d [K]	…	20.4	…
τ_{250}	…	2.6×10^{-3}	…

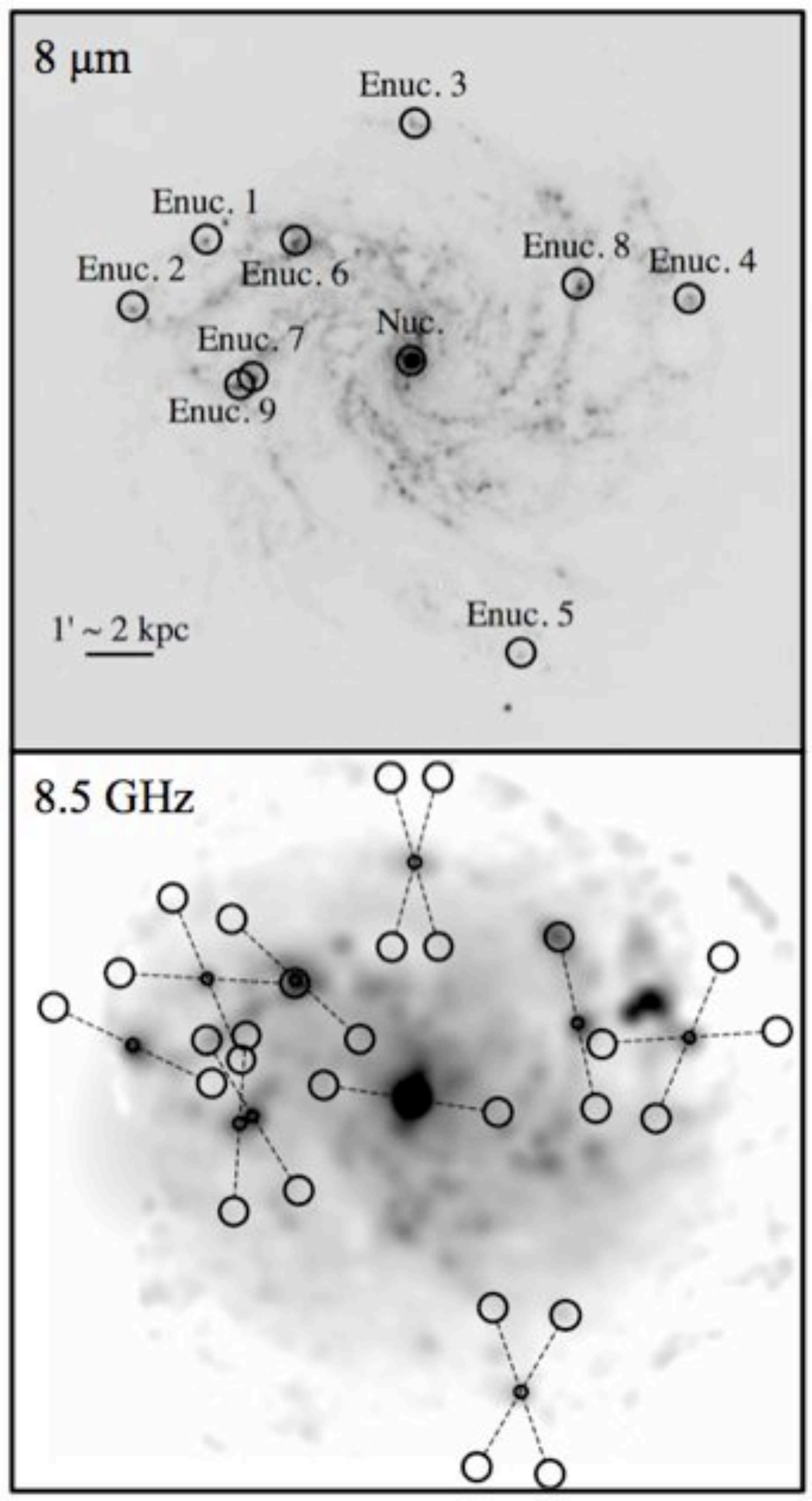
arXiv:1101.2032

How about in other galaxies?

NGC6946 has 1-2 regions that show AME
(region 4 the most clear detection)



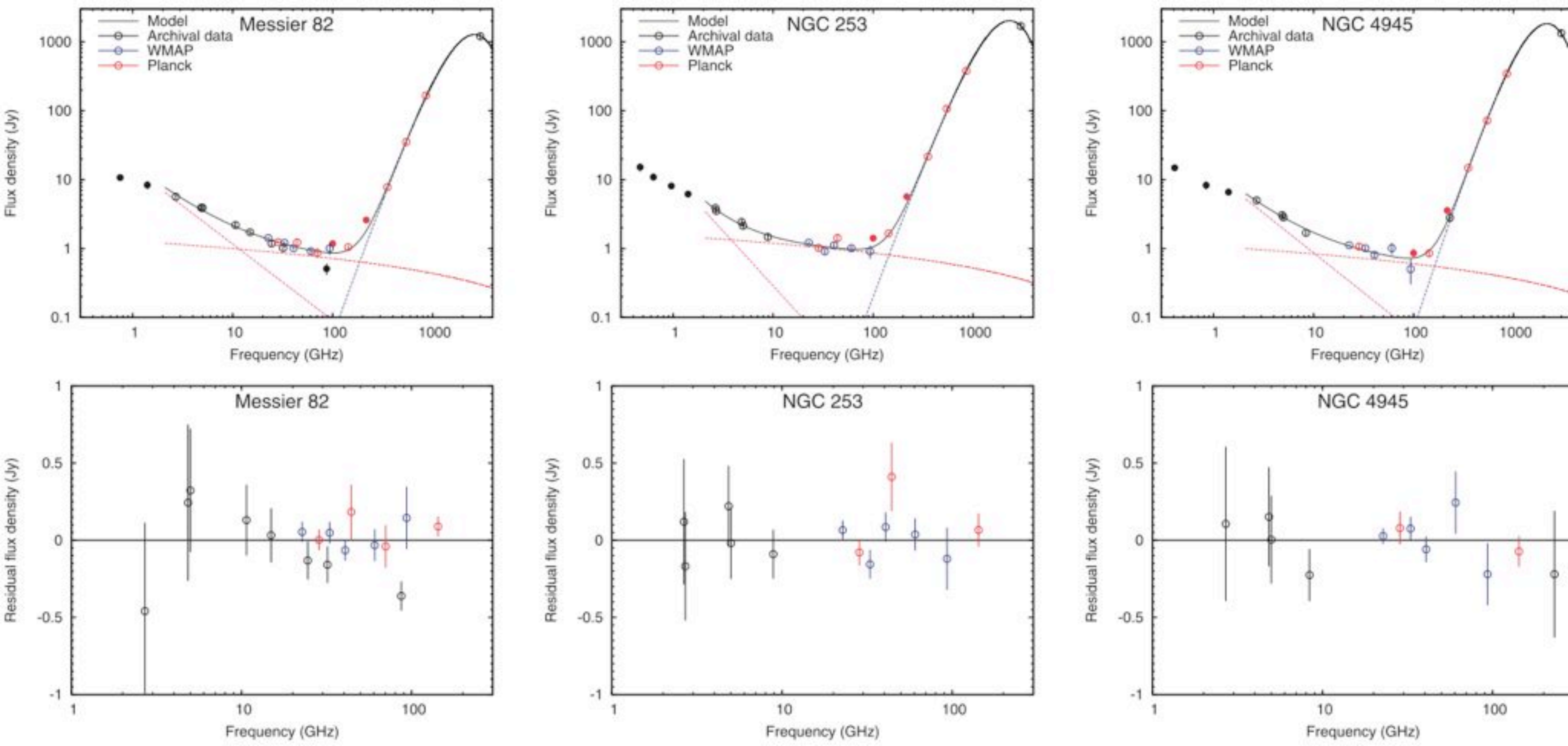
Scaife et al. (2010)



Murphy et al. (2010)

Limits on AME in other galaxies

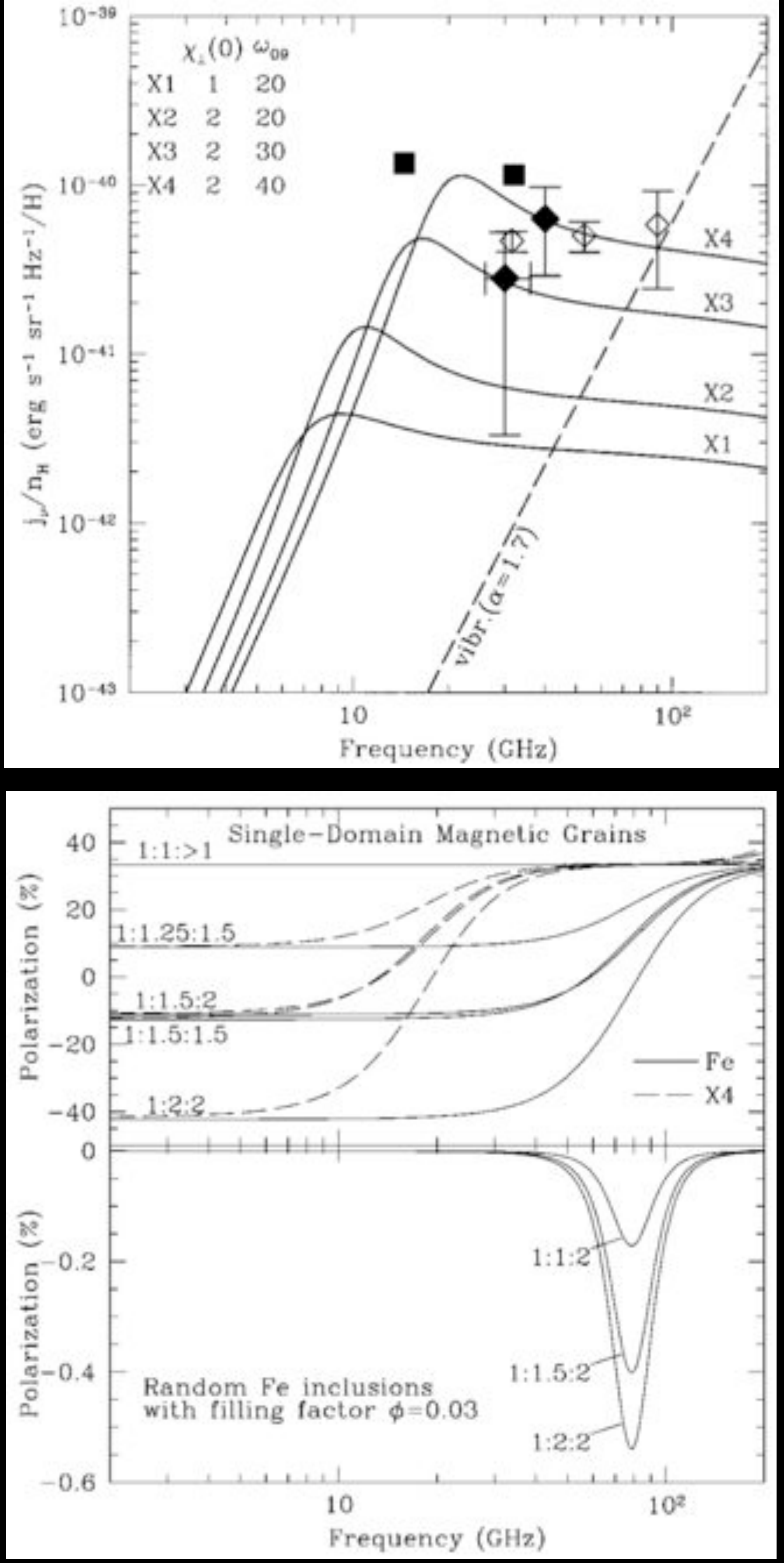
However, generally speaking, AME doesn't seem to be a dominant part of the integrated spectrum of galaxies
(but only a few have been measured so far!)



Peel et al. (2011b)

Magnetic dust?

- Recent discussions with Bruce Draine has complicated matters!
  - Still a possibility for magnetic thermal fluctuations
- Theory not well understood!
  - (I will stick with spinning dust for now!)



Draine & Lazarian (1999)