New Planck results:
A study of AME in Galactic clouds with Planck

Planck collaboration

Presented by

Clive Dickinson

Jodrell Bank Centre for Astrophysics (University of Manchester)

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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.

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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

AME papers!

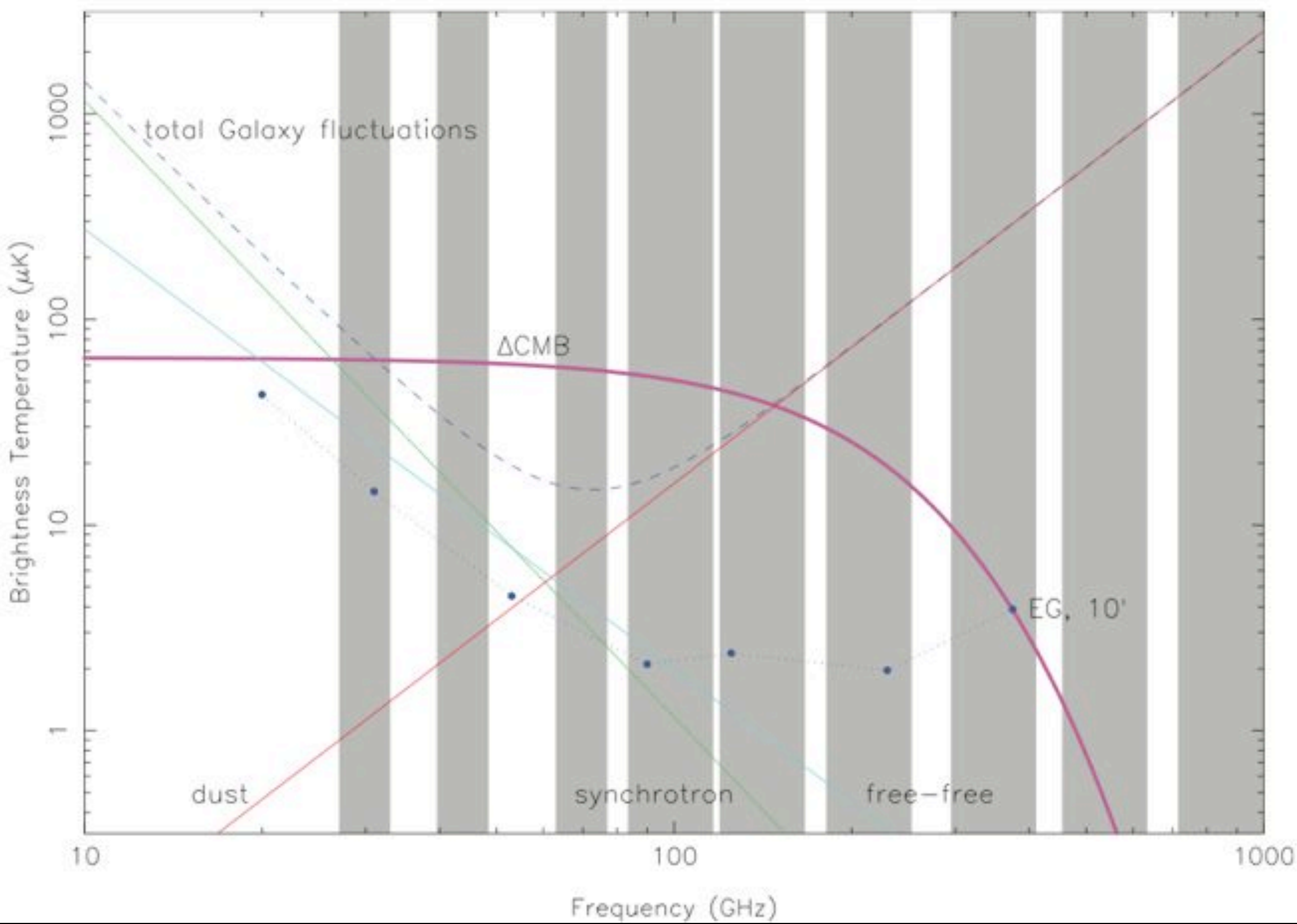
- A lot of evidence over the last 15 years - very active area of research, but still little is known about it! (lack of data!)
- Many papers, instruments, techniques, frequency ranges. E.g.:-
  - OVRO: Leitch et al. (1997)
  - COBE-DMR: Kogut et al. (1996), Banday et al. (2003)
  - Saskatoon: de Oliveira-Costa (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. (2009,2010,2011), Dickinson et al. (2009a, 2011), Lopez-Caraballo (2011), Genova-Santos et al. (2011), Peel et al. (2011)
  - Planck: Planck collaboration et al., Early papers XX, XXI (2011)
  - & now extragalactic as well! (Murphy et al. 2010; Scaife et al. 2010)

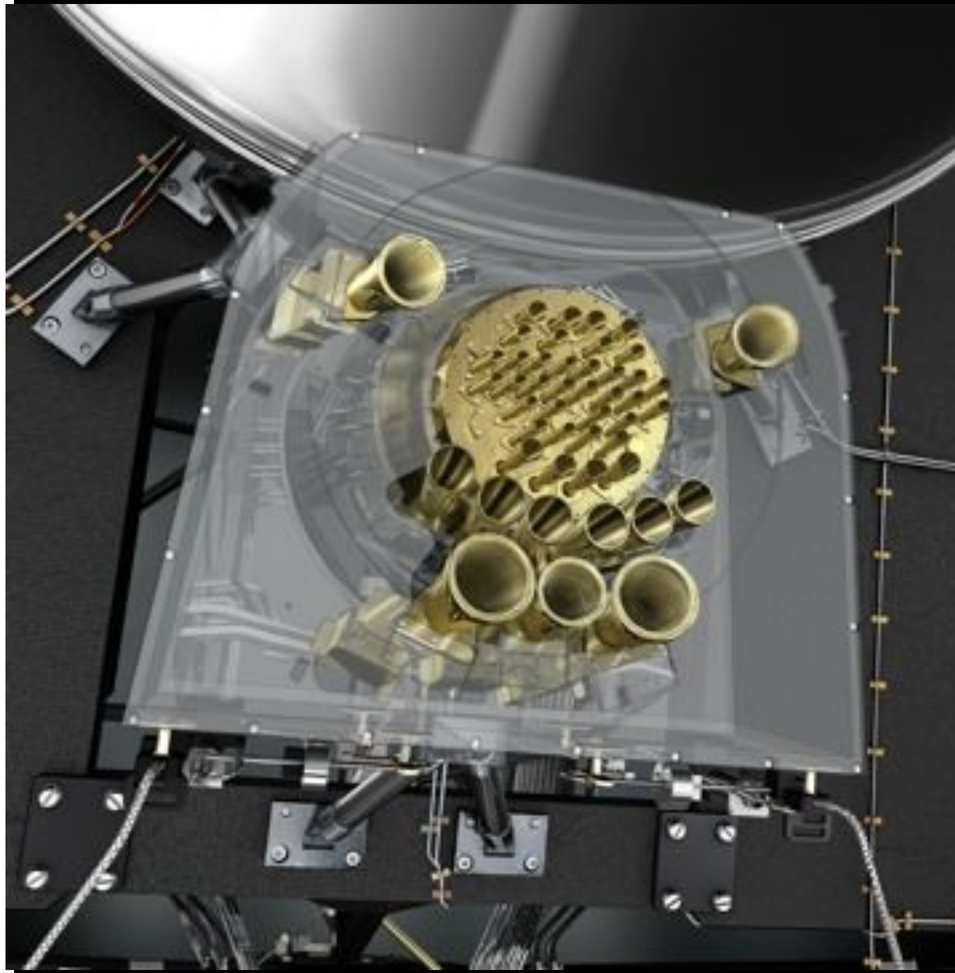
Planck instruments

SUMMARY OF PLANCK INSTRUMENT CHARACTERISTICS

INSTRUMENT CHARACTERISTIC	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q &U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".





Planck focal plane

Planck early paper XX

Planck collaboration et al., 2011, A&A, 536, A20

See also A21 (Galactic plane inversion)

Corresponding author: Clive Dickinson

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Astronomy & Astrophysics
Special feature

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)

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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

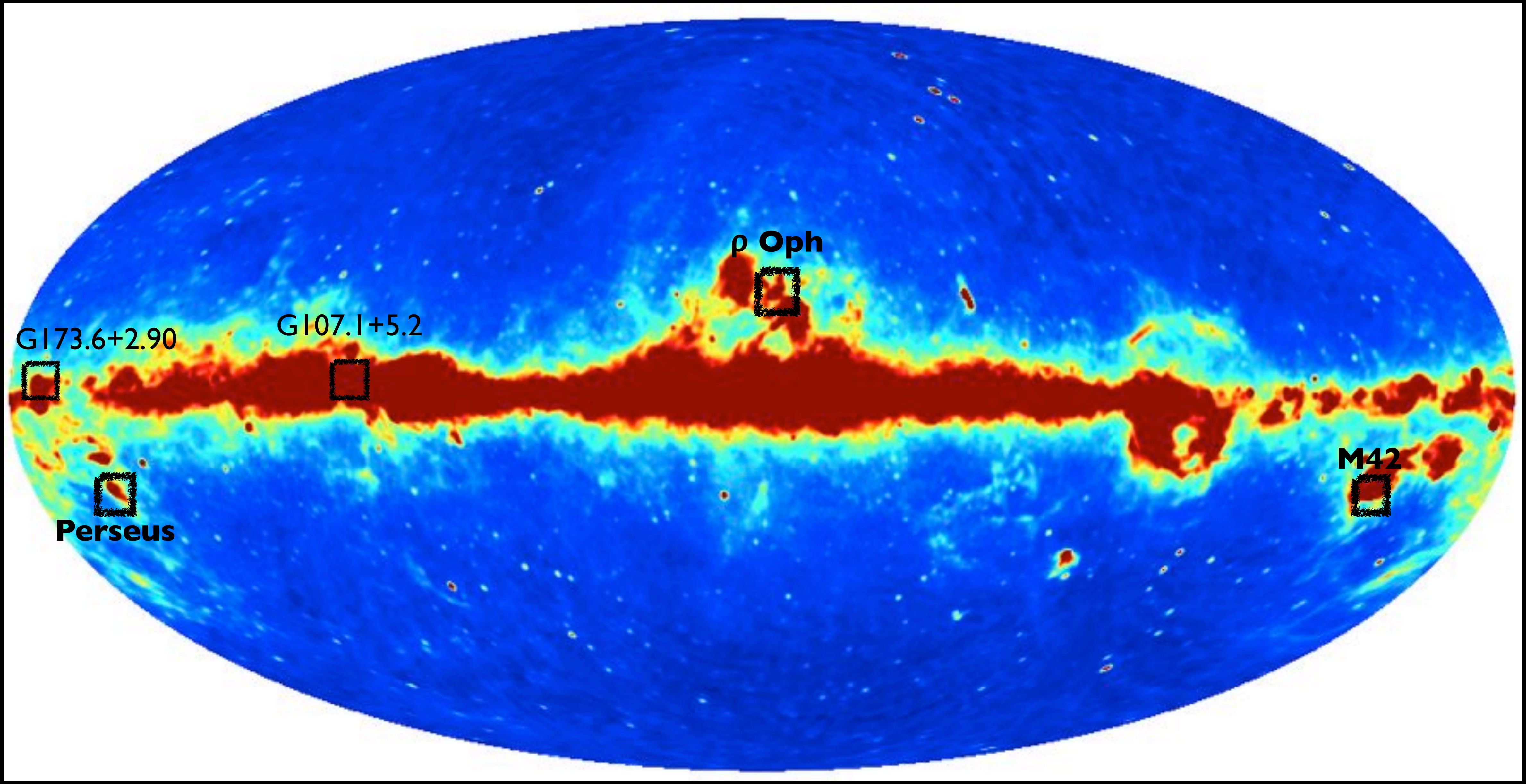
Anomalous microwave emission (AME) is an additional component of diffuse foreground emission that cannot be easily explained by synchrotron, free-free, or thermal dust emission. AME has been observed by numerous experiments over the frequency range ~10–60 GHz and is found to be very closely correlated 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;

* Corresponding author: C. Dickinson,
e-mail: Clive.Dickinson@manchester.ac.uk

AME regions studied in the early paper

Planck collaboration et al., 2011, A&A, 536, A20

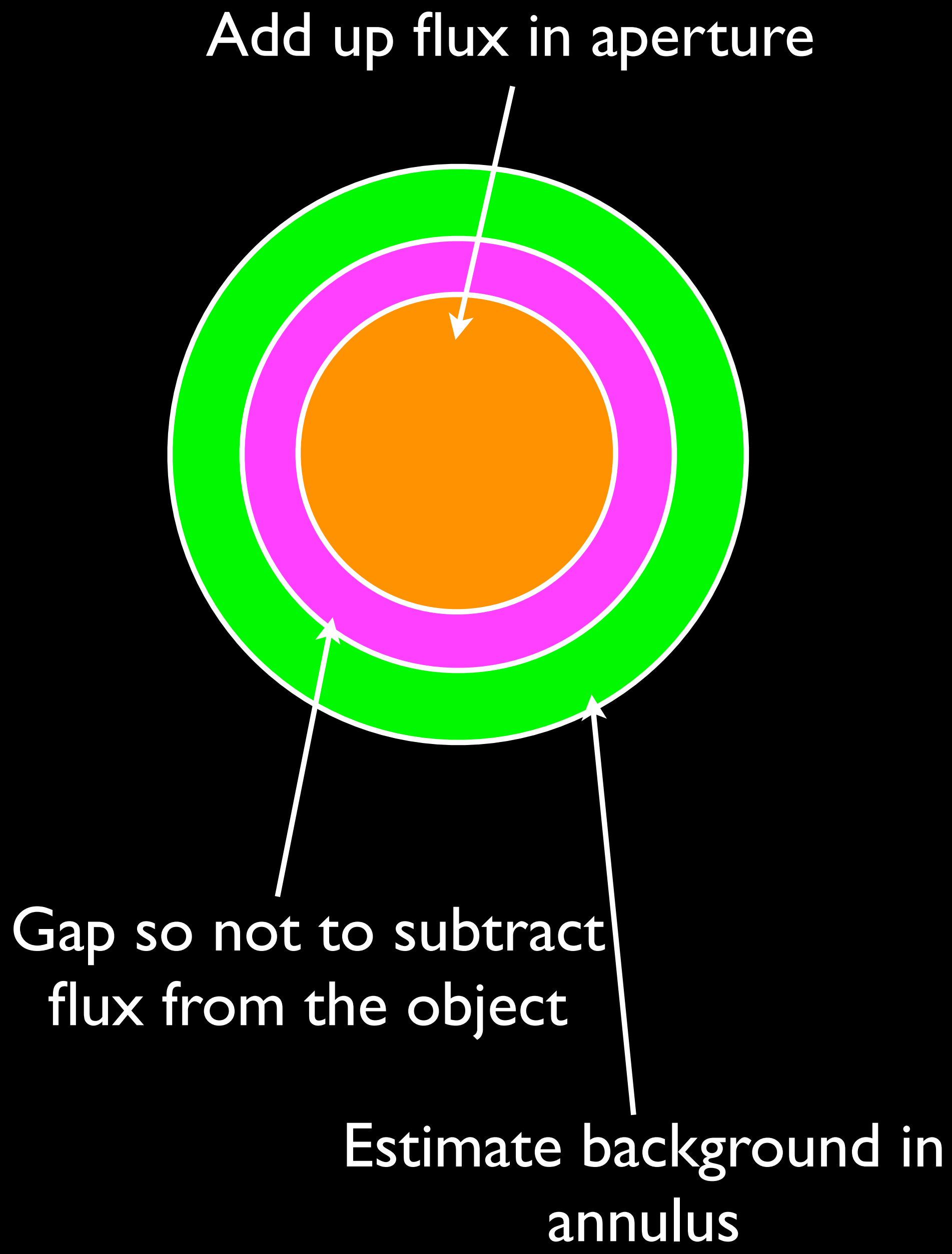
- 2 prime candidates (relatively bright, isolated, well known): Perseus and ρ Oph
- Identified new AME regions for further study: G173.6+2.90 and G107.1+5.2
- Control fields in Perseus and M42 (Orion nebula)



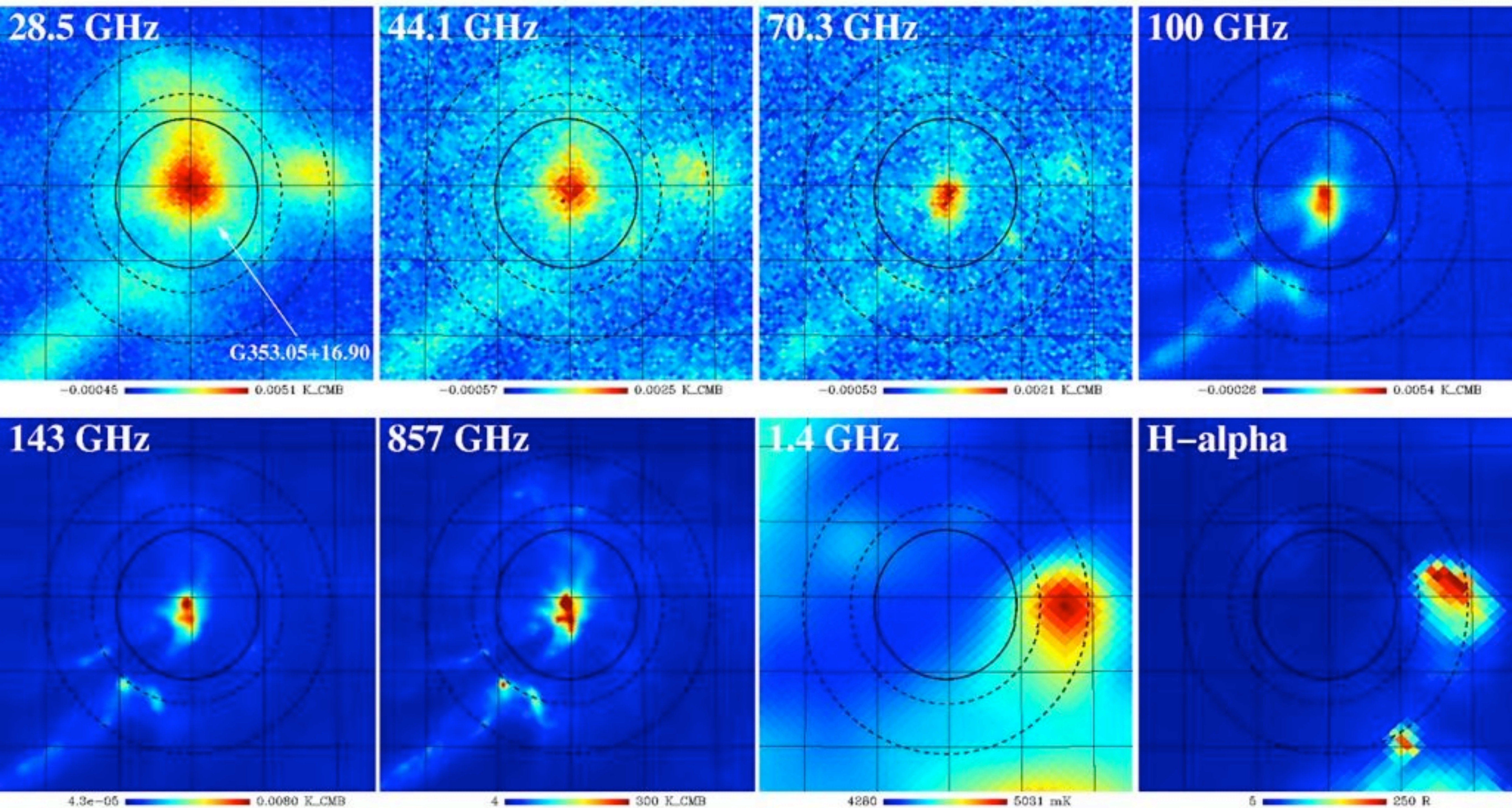
Planck 28.5 GHz DR2 map

Aperture photometry

- Smooth maps to common 1 deg resolution
    - Convert units (Jy/beam)
    - Do not use 100/217 GHz for fitting due to CO
- Simple analysis (e.g. aperture photometry)
- Uncertainties include
    - Absolute calibration errors (3%)
    - Noise/background errors from data
    - Residual spectrum includes modelling errors
- Fit simple models for free-free, CMB, thermal dust
    - Colour corrections applied based on model

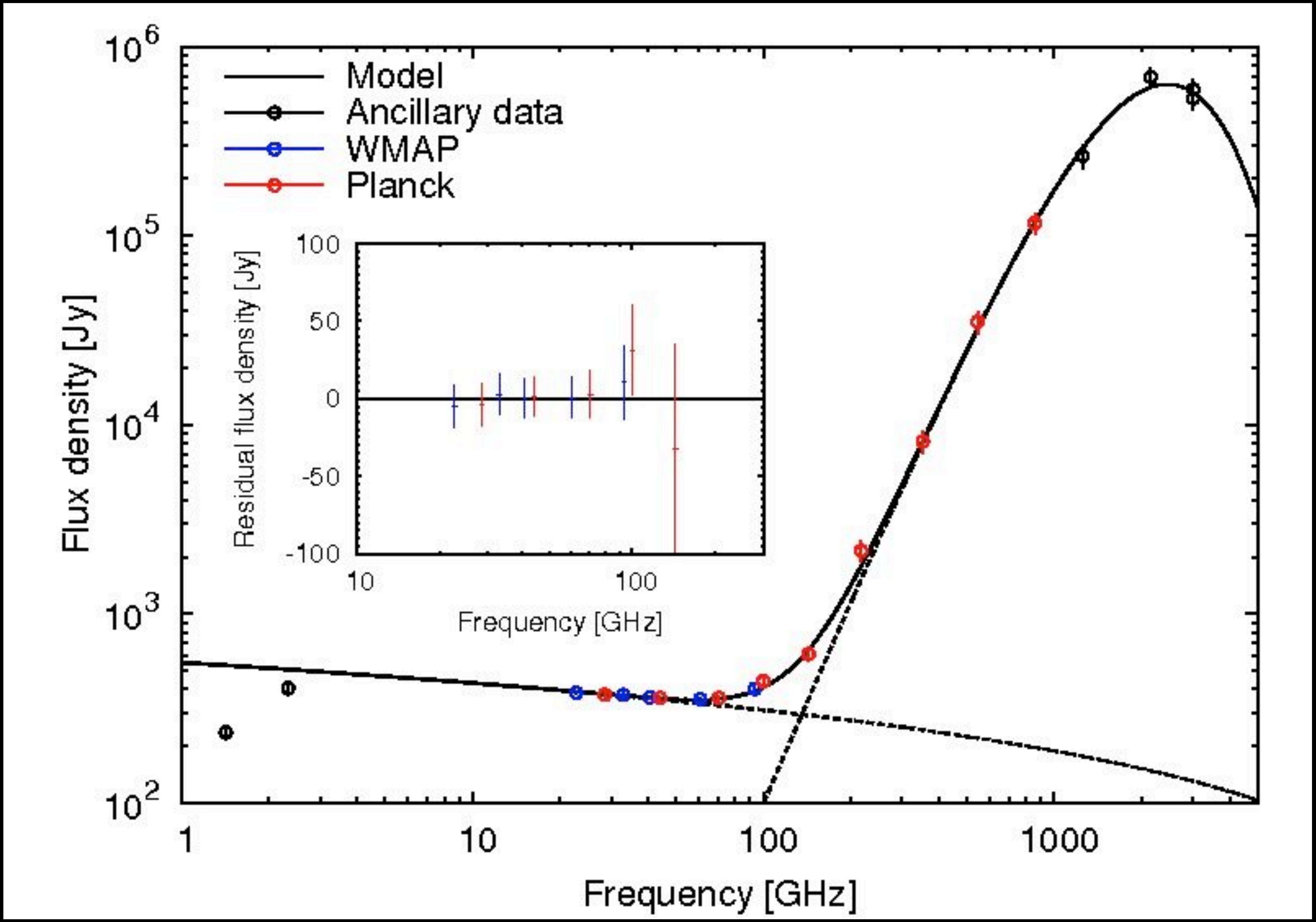


Maps: ρ Ophiuchi Molecular Cloud



Control field: M42

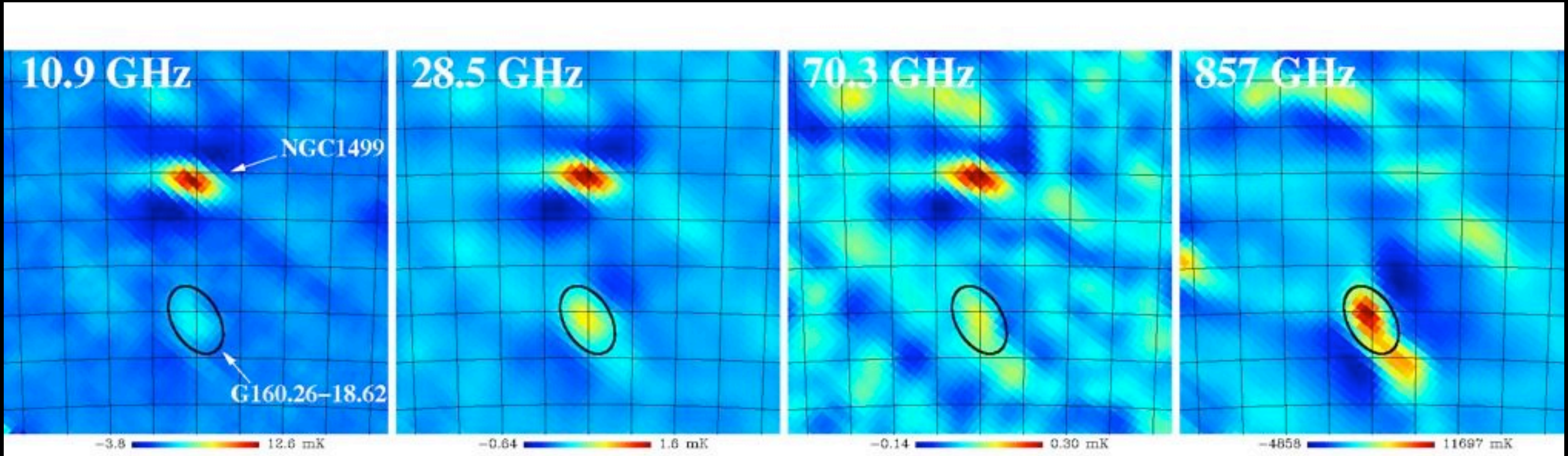
- WMAP/Planck consistent to ~1% or better



COSMOSOMAS data

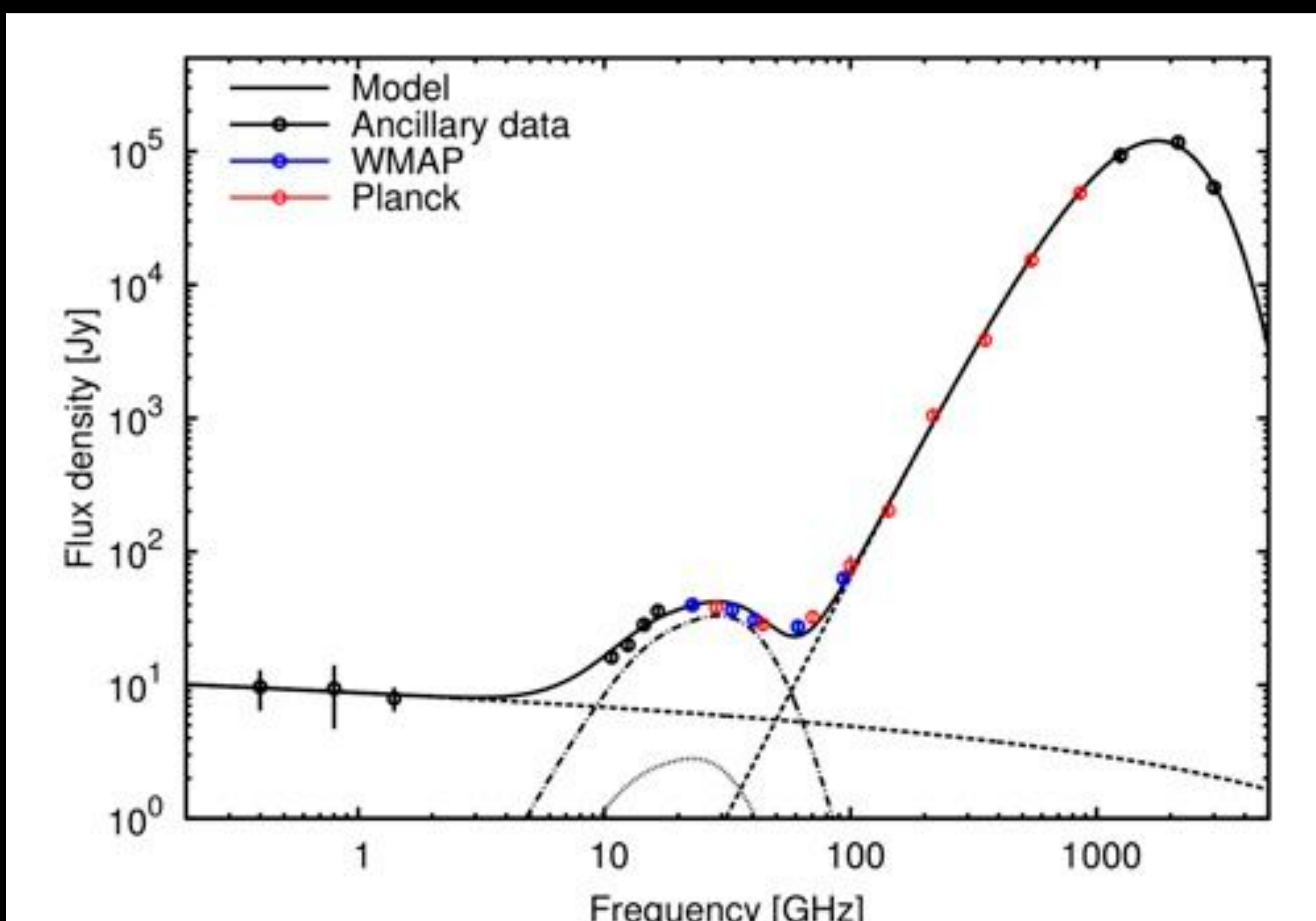
- Unique data @11-17 GHz (Watson et al. 2005) for ~1/4 sky
- BUT, filtering on large angular scales
  - Filter all data (including Planck) through same scanning/analysis pipeline

COSMOSOMAS instrument in Tenerife

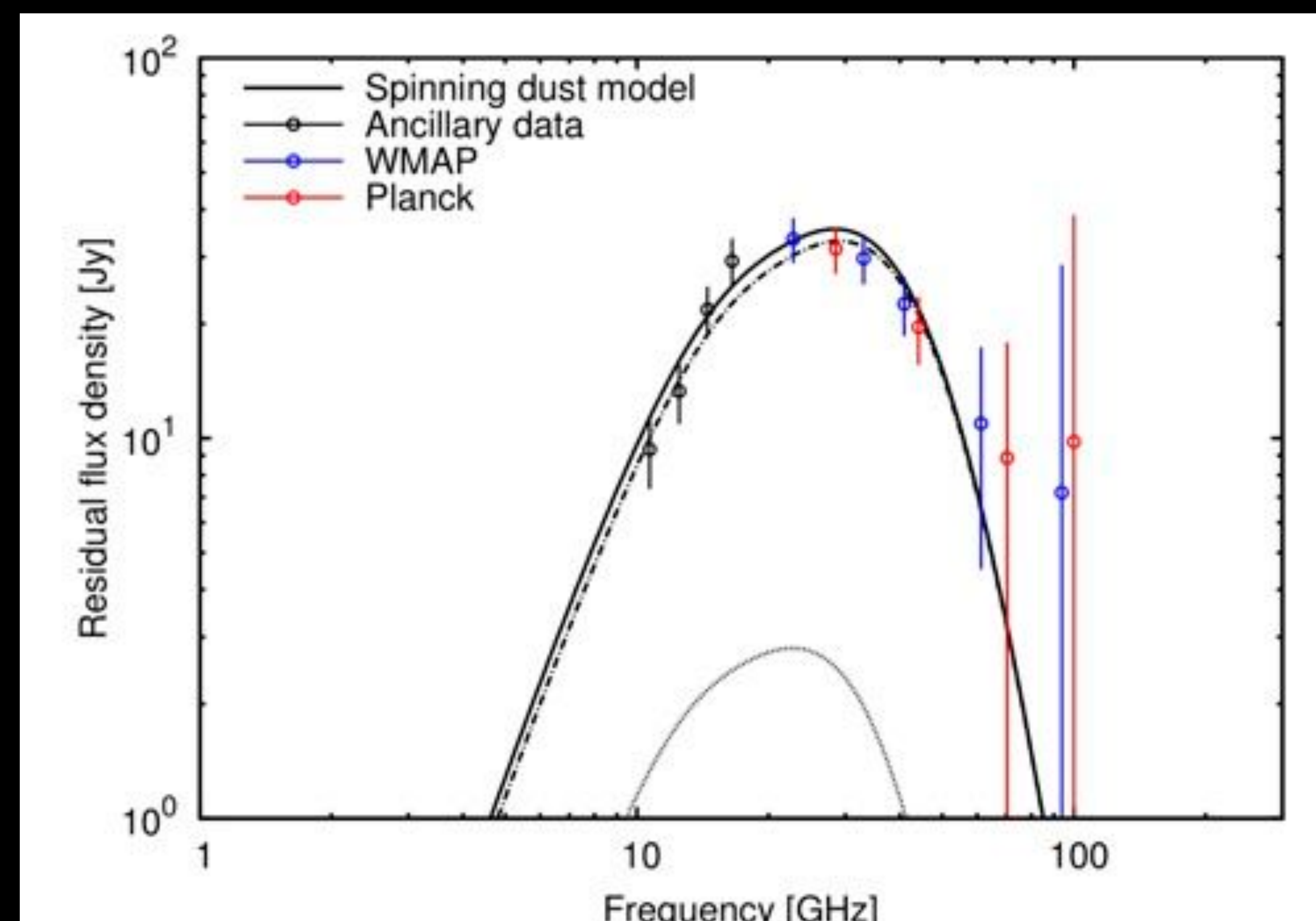


Spectra: Perseus

- Integrated spectrum well-fitted by optically thin free-free, CMB (negligible) and single component modified black-body function
- Residual spectrum has clearly peaked spectrum
  - Significant at 17σ



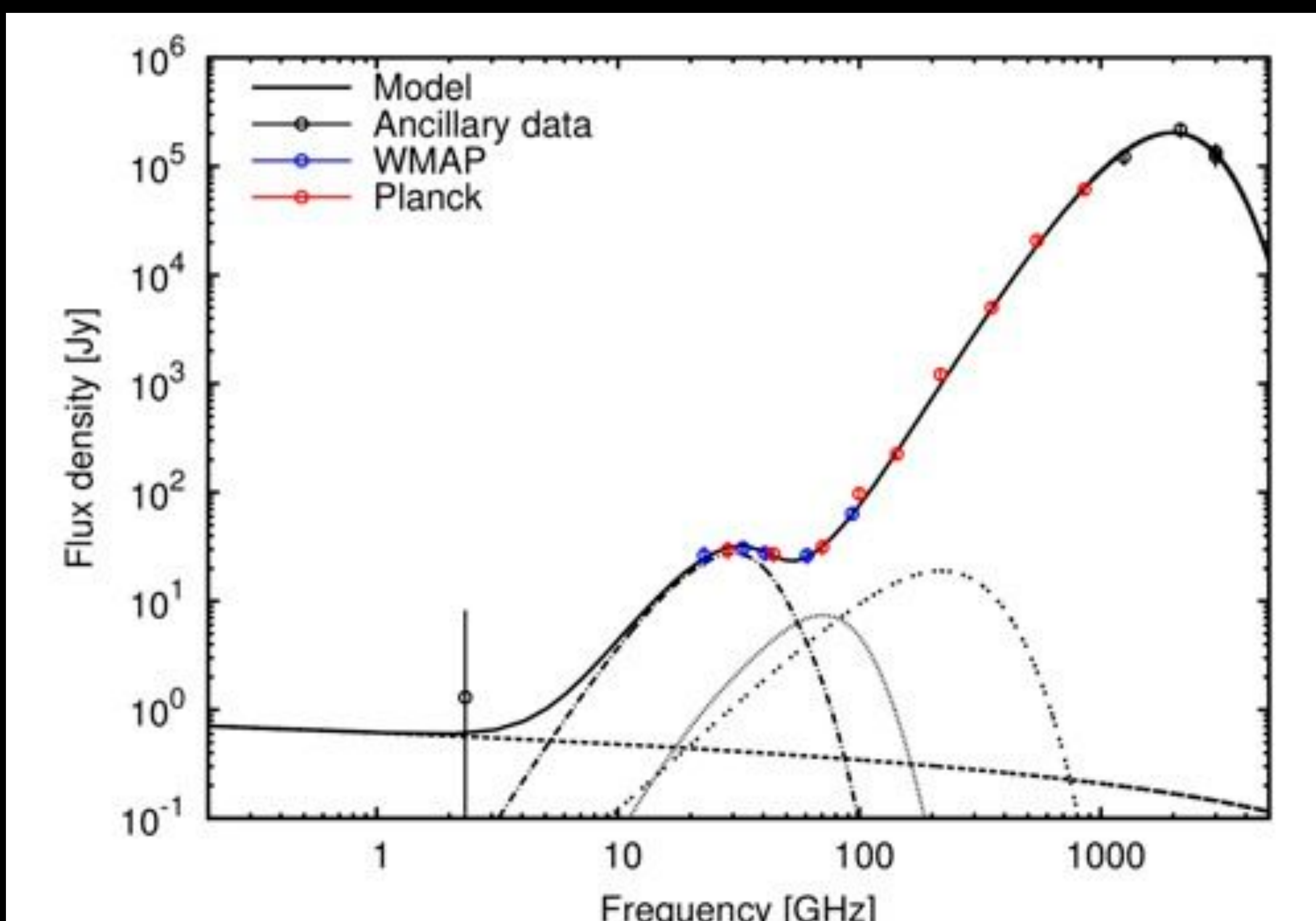
Perseus



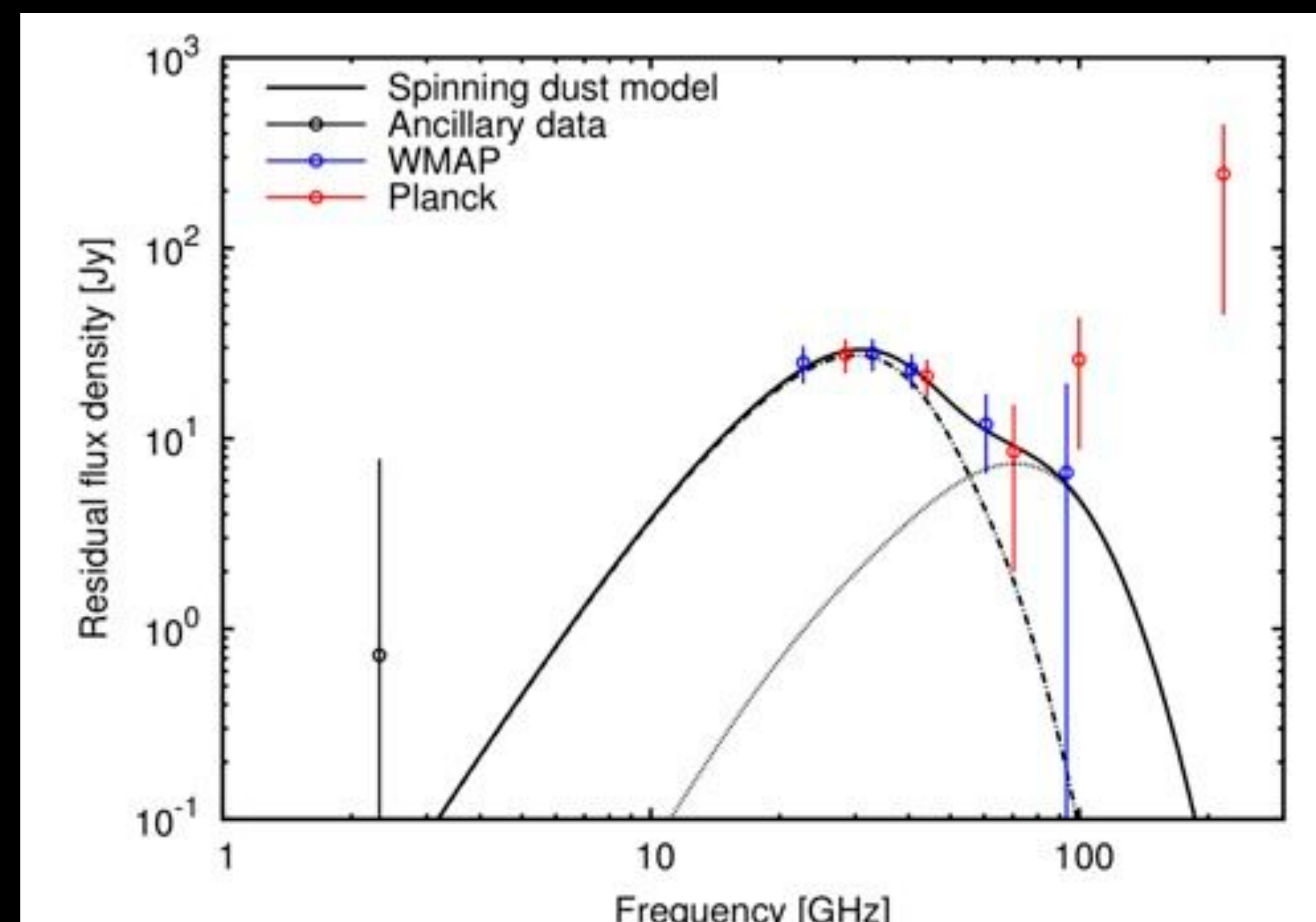
ρ Ophiuchus

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
  - Significant at 10σ



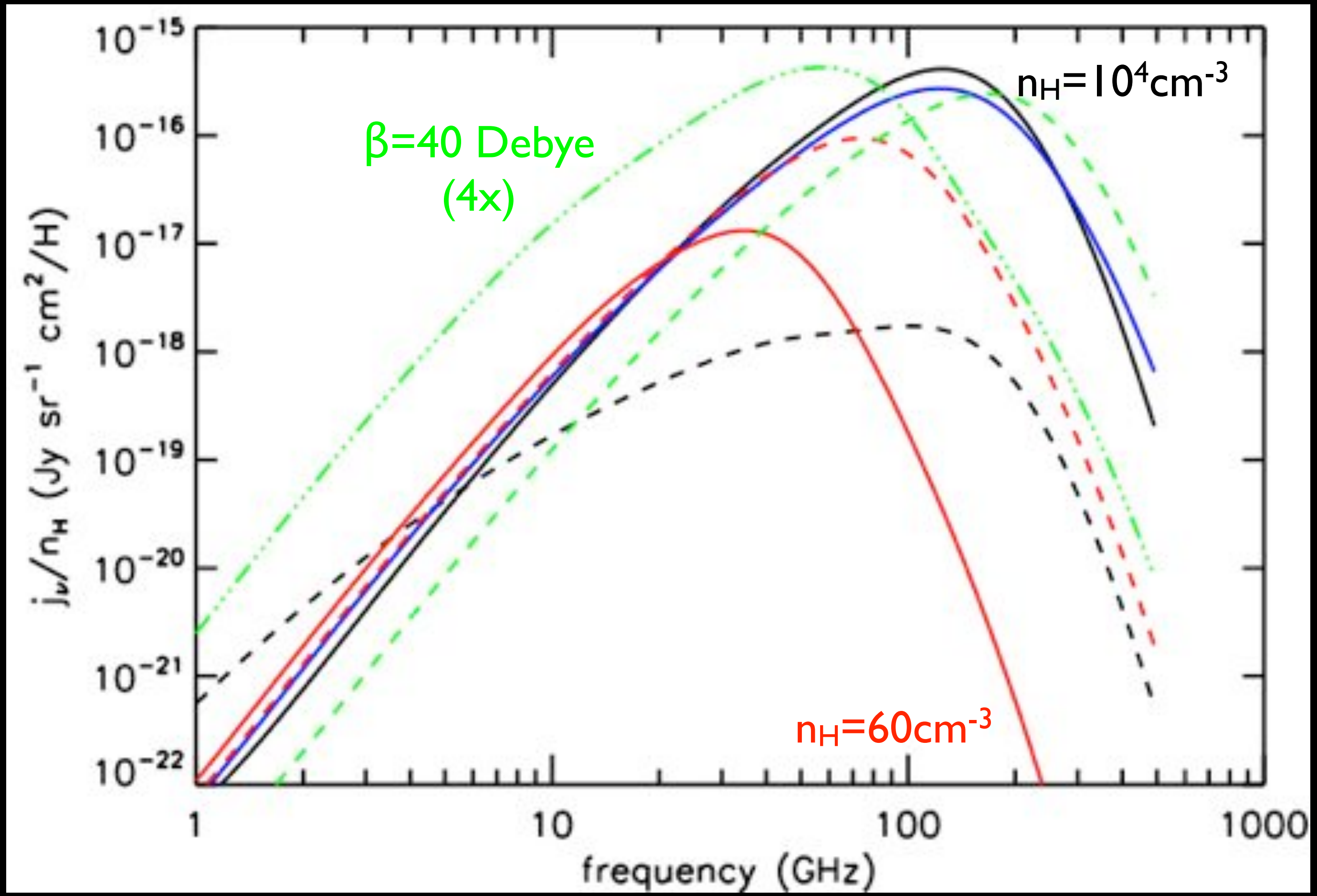
Perseus



ρ Ophiuchus

Modelling & Interpretation

- SPDUST code (Ali-Hamoud, Hirata, Dickinson 2009) provides spinning dust spectra for given parameters
  - ~10+ parameters to fit!
  - Strong degeneracies (e.g. a_0, n_H, G_0)
- CNM, WIM etc. can provide excellent fits, BUT, not necessarily physically plausible
  - CNM would give Perseus size > 100pc (should be ~10 pc or smaller)
  - Even worse for WIM
- Use a physically motivated model - not just make a nice plot
  - 1st go - not necessarily absolute best fit



Courtesy of Laurant Verstraete

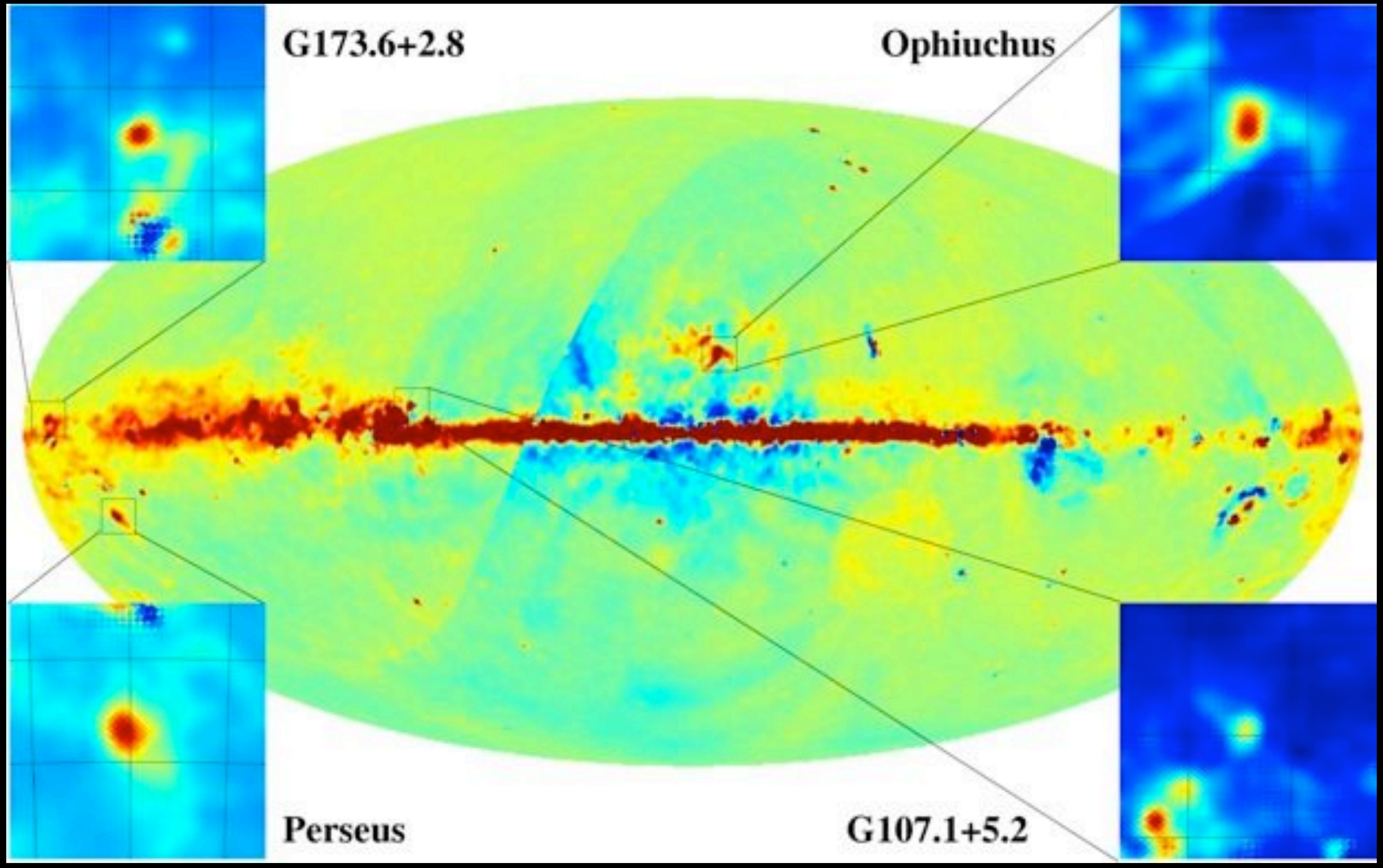
Spinning dust model

- 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) fitted for and agrees with 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	Ionised
		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 Ophiuchi	
N_H [10^{21} cm^{-2}]	18.2	0.4	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]	0.60	0.38	...
b_C [ppm]	65	50	...
β	...	1.75	...
T_d [K]	...	20.7	...
τ_{250}	...	3.2×10^{-3}	...

Early paper: Finding new AME regions (1)

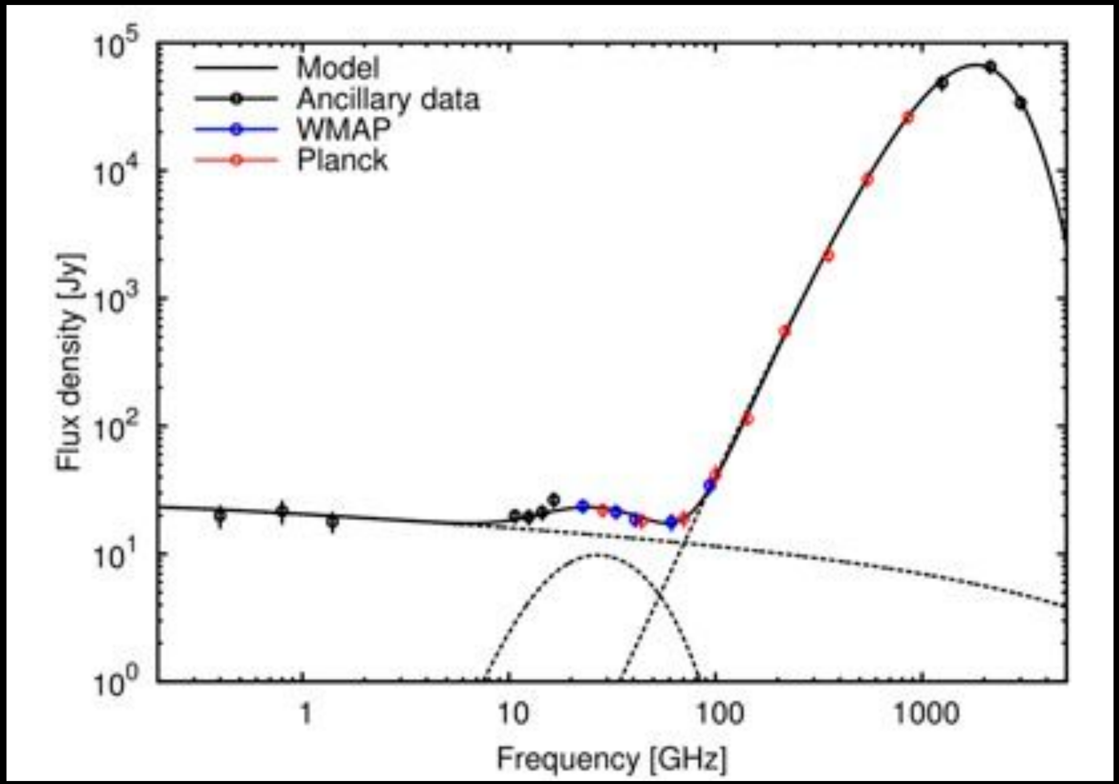
- Use simplistic approach to remove synchrotron, free-free, thermal dust from Planck 28.5 GHz map
    - Use templates and extrapolate!
- Residual map inspected in detail to find AME regions
    - ~50 candidates inspected for early paper (2 were chosen)

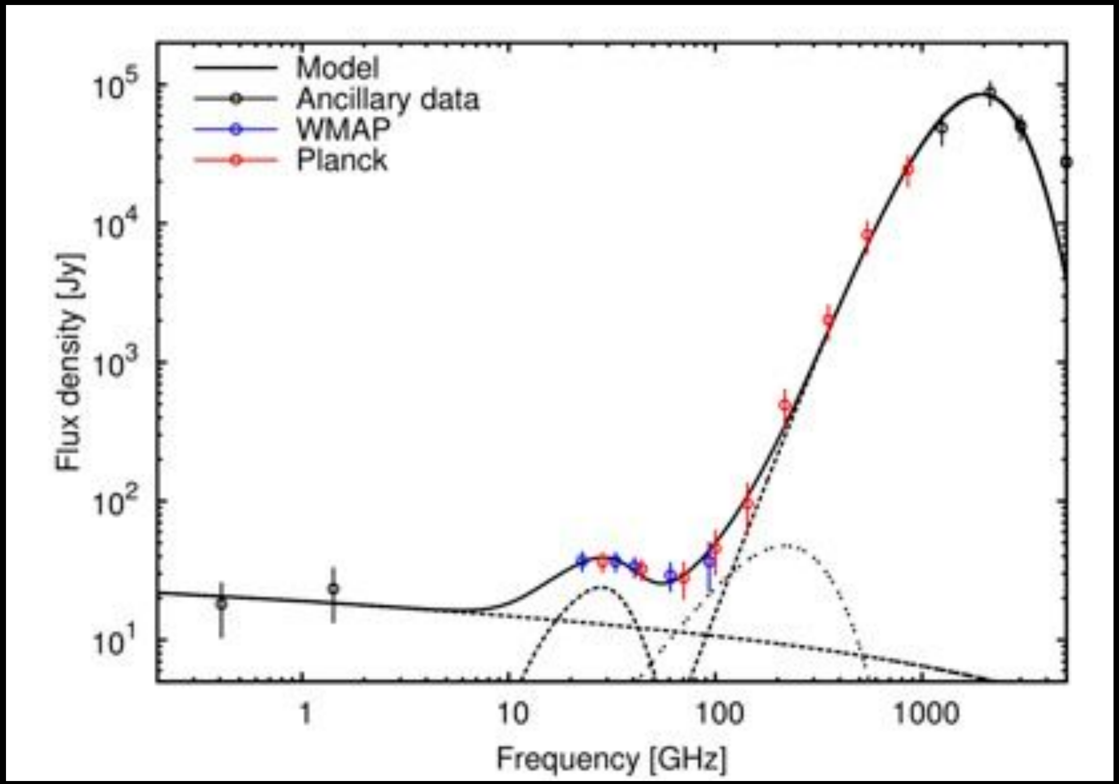


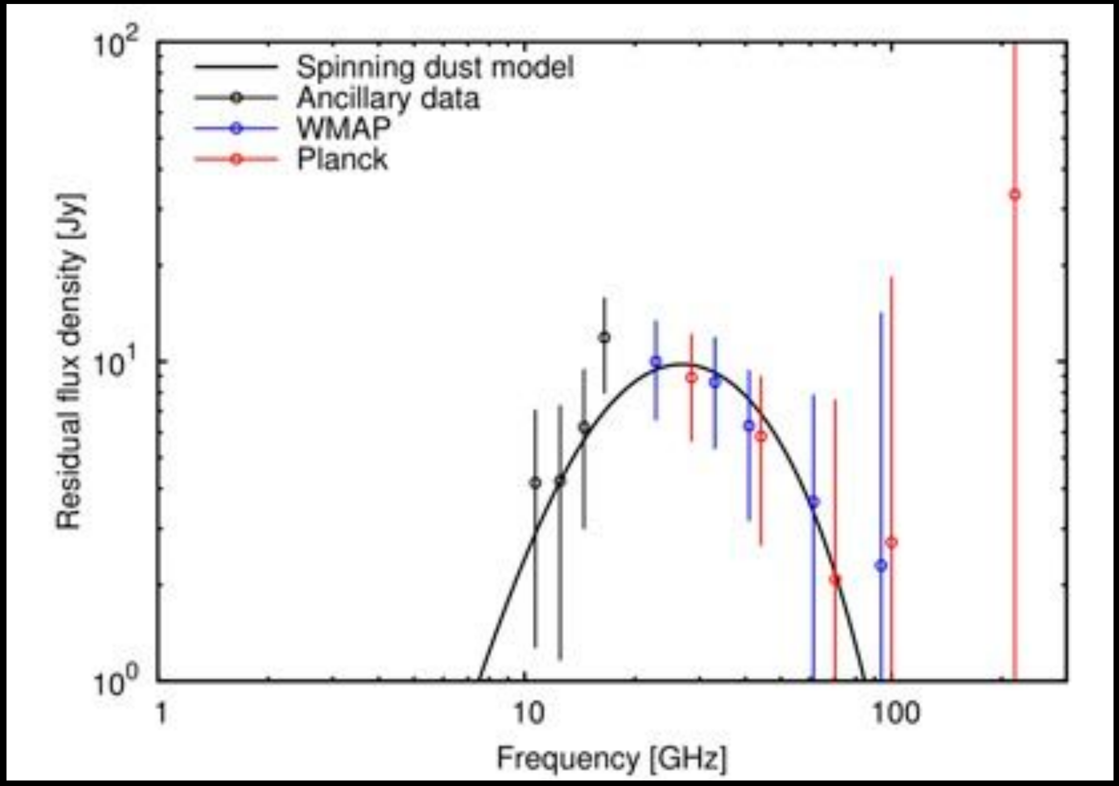
New AME regions spectra from early paper

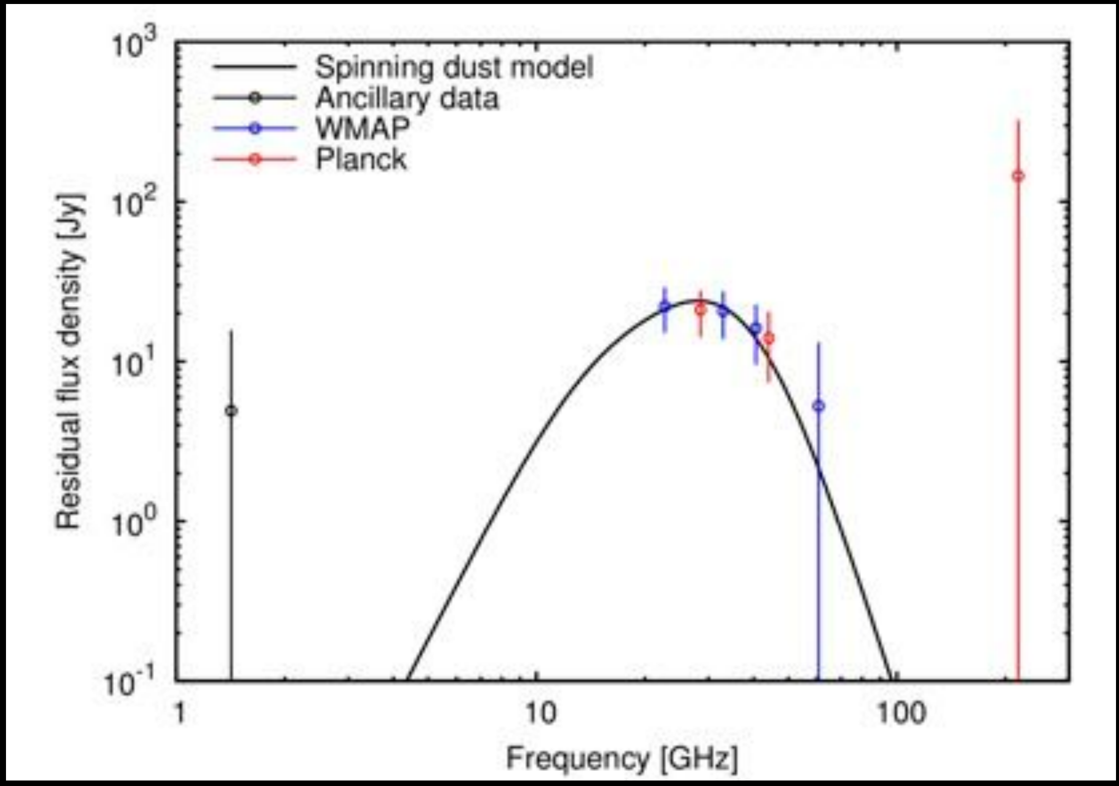
G173.6+2.80 (S235)

G107.1+5.20 (S140)









Planck intermediate paper (in prep.)

- Aim: Identify new AME candidates and make first statistical analysis
- Find reliable bright sources that are bright at all Planck frequencies
  - Typically HII regions!
  - Keep good non-AME HII regions to compare with AME regions!
- Source detection (SExtractor) at 70 GHz
  - Band-merge (cross-match) with 30 and 100 GHz
  - Remove extragalactic, SNRs, PNe etc.
  - 164 sources
- Remove sources that are not well-defined in the map or weak (<<10 Jy@30 GHz)...
  - 98 sources left (currently)

Some limitations & difficulties!

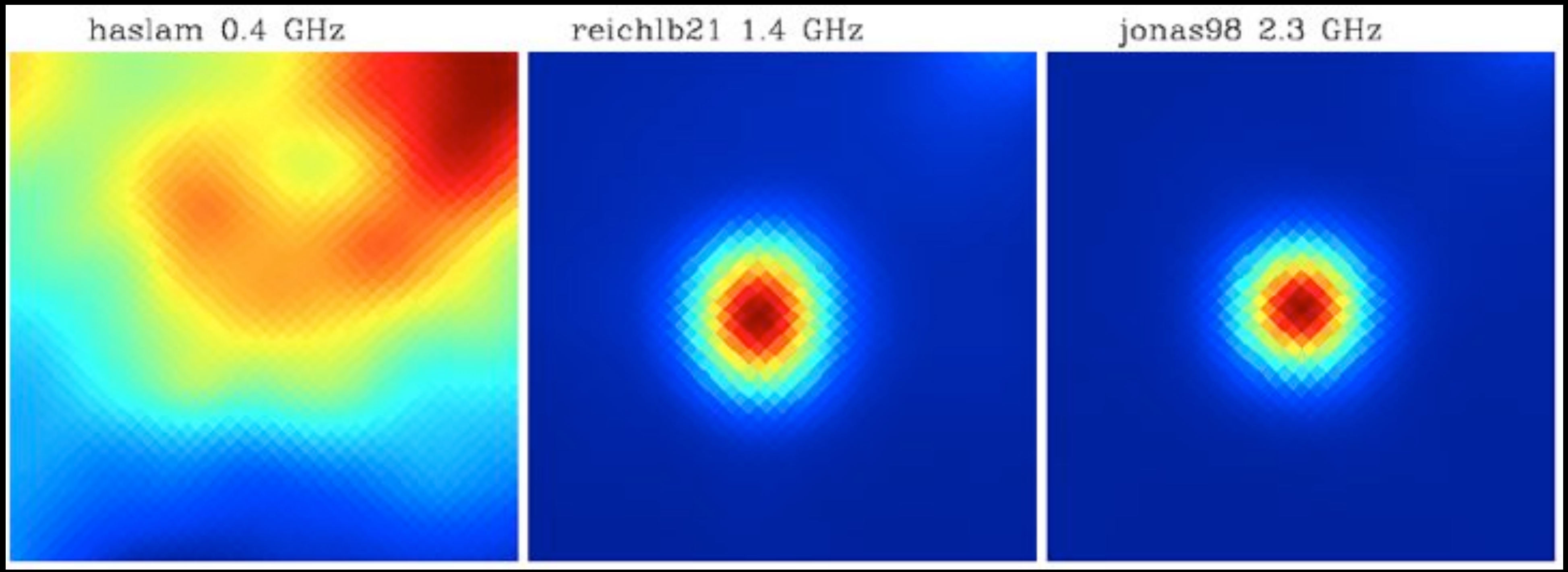
- 1 deg analysis (low frequency data)
    - Mix of sources / environments
    - Background can be very large / complex
- Calibration (particularly low frequencies)
    - Full-beam to main-beam calibration (can be several up to 50% from small to largest angular scales)
- SED fitting
    - Multiple thermal dust components
    - Flattening of thermal dust index at long wavelengths
    - Small CMB contribution
- Planck 100/217 GHz bands contaminated by CO
    - Can be corrected but uncertainties are increased
- Line/stellar contamination at shorter IRAS wavelengths
- ....

Haslam et al. 408 MHz map

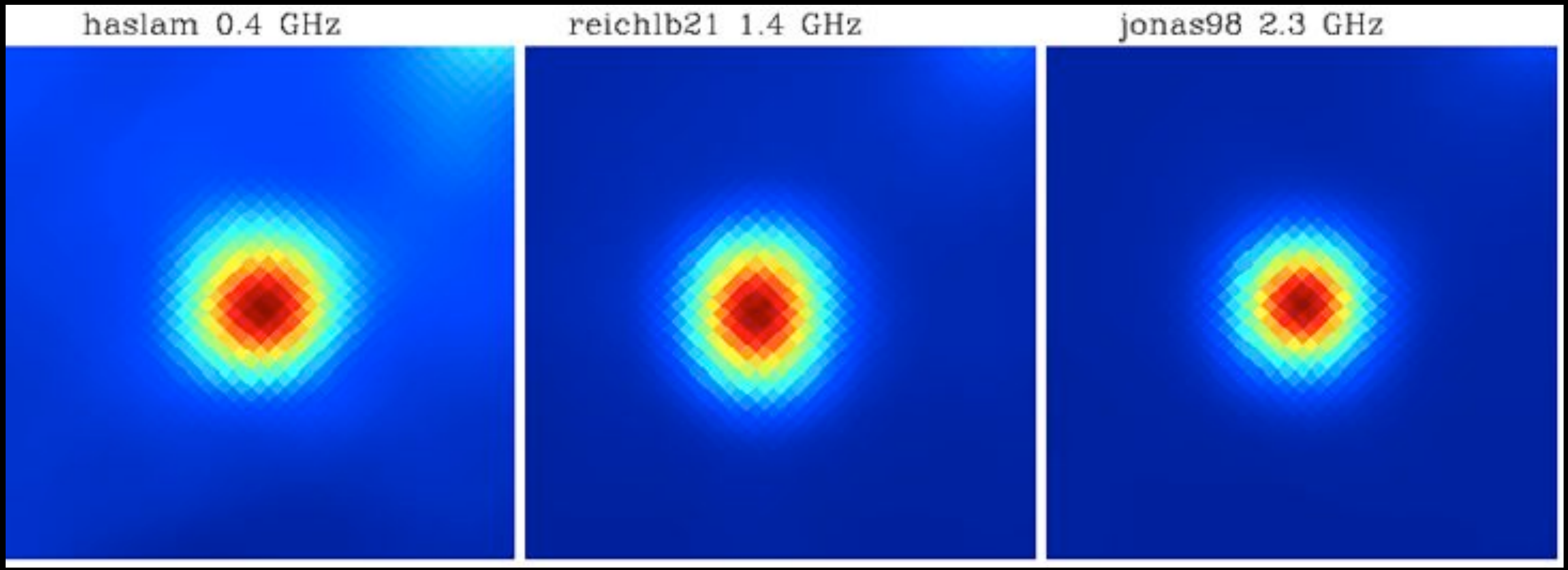
Radio maps must not be source-subtracted!

(Haslam et al. 408 MHz map on LAMBDA website no good for this)

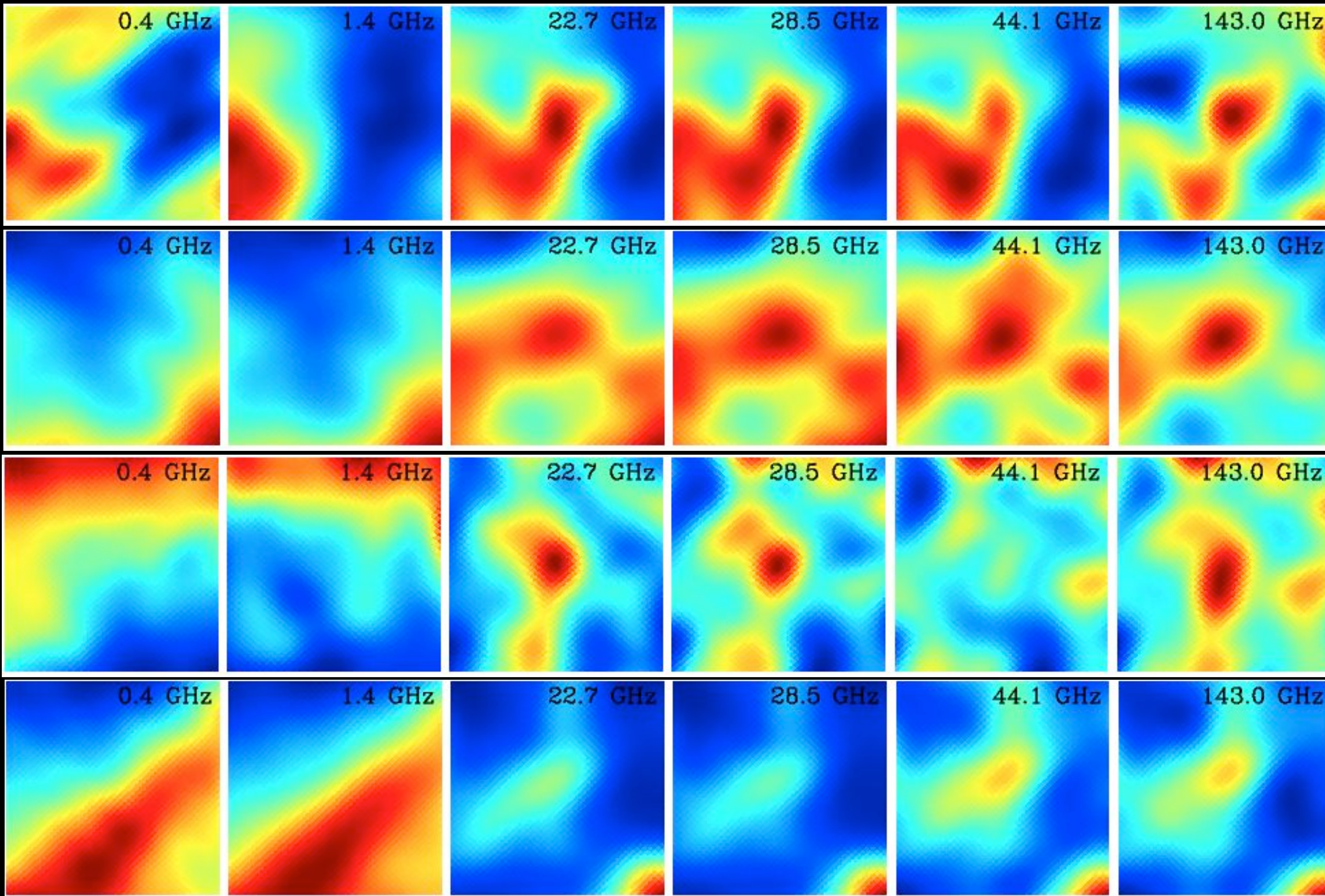
LAMBDA (NCSA)



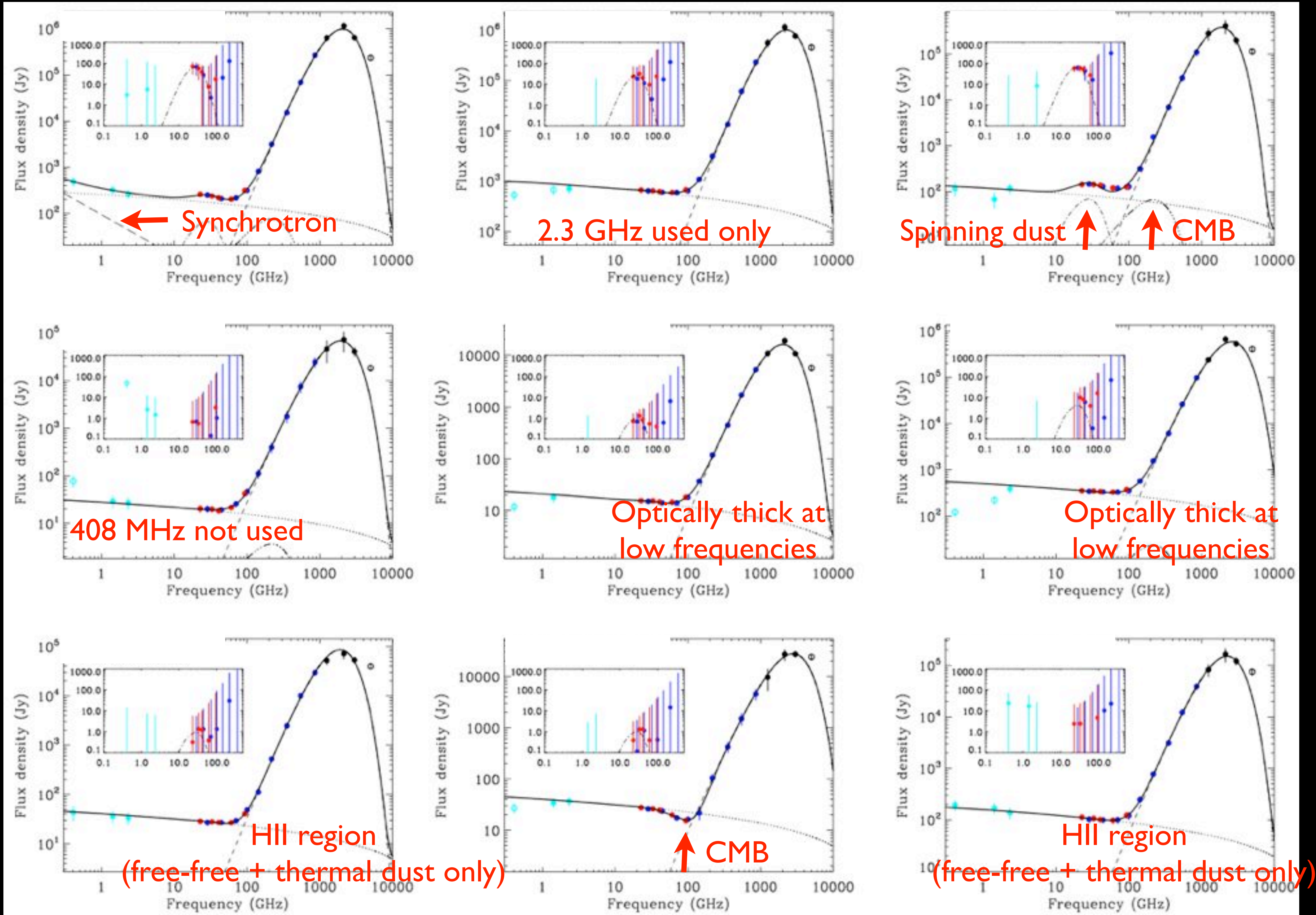
"Original"



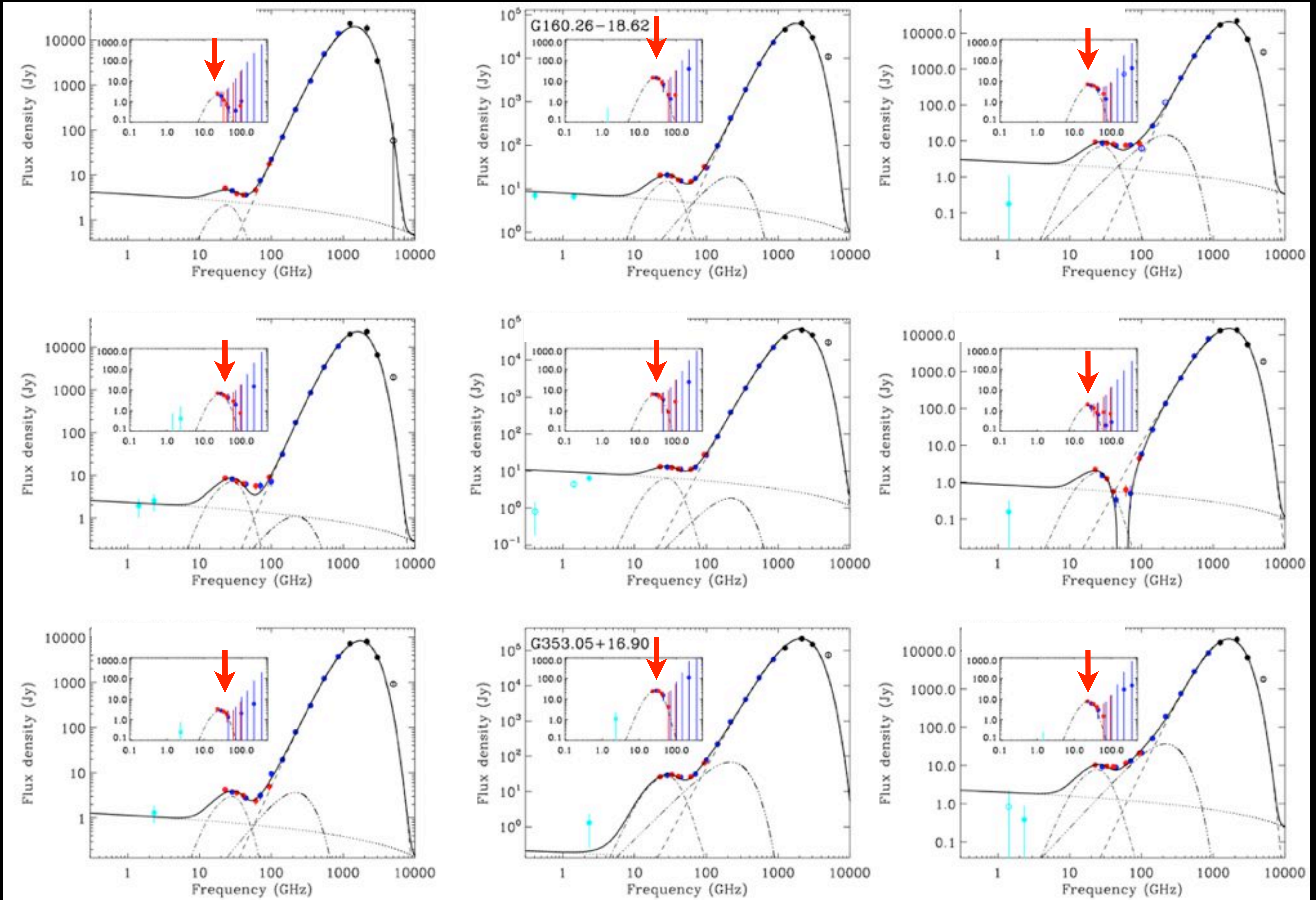
Maps of some new AME regions



Example spectra

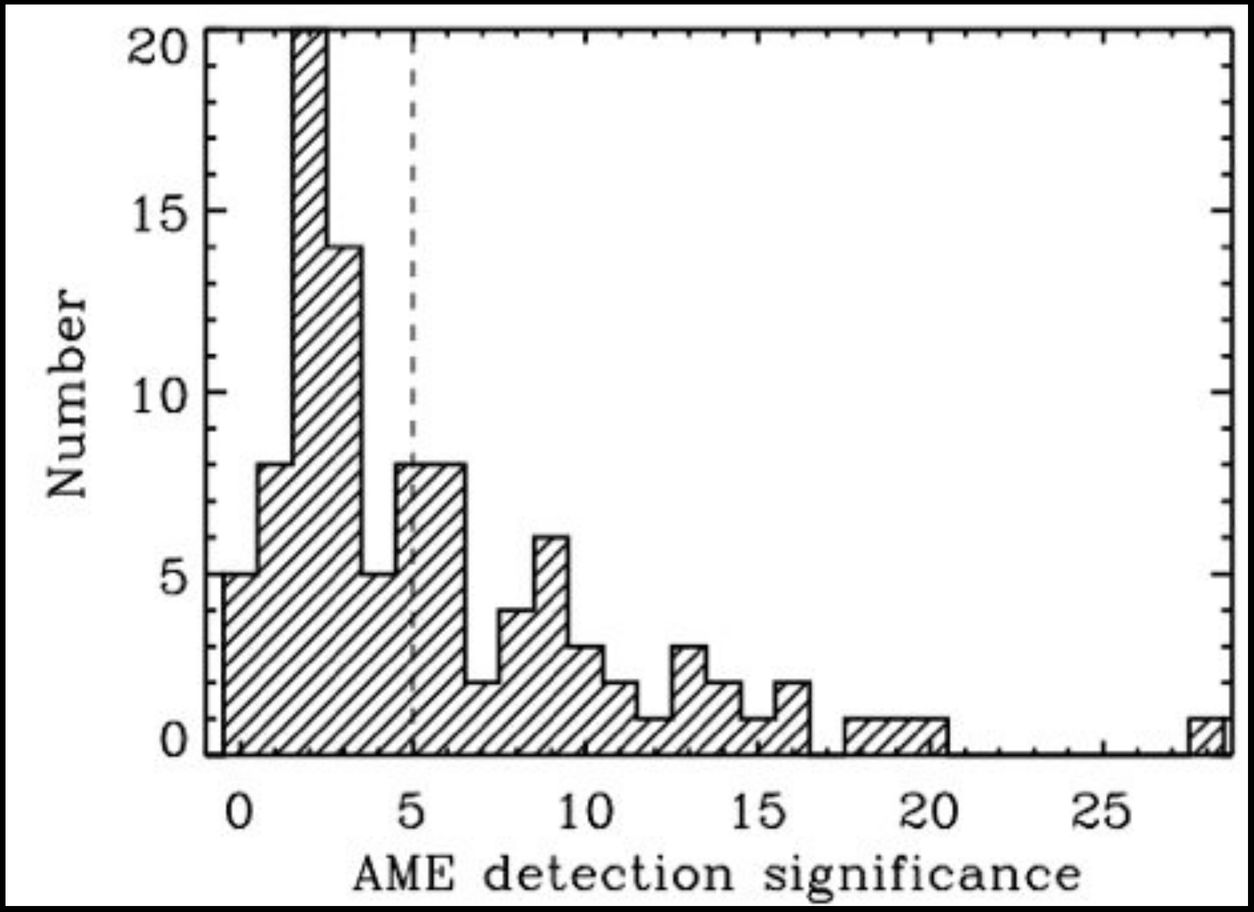


Example spectra with significant spinning dust



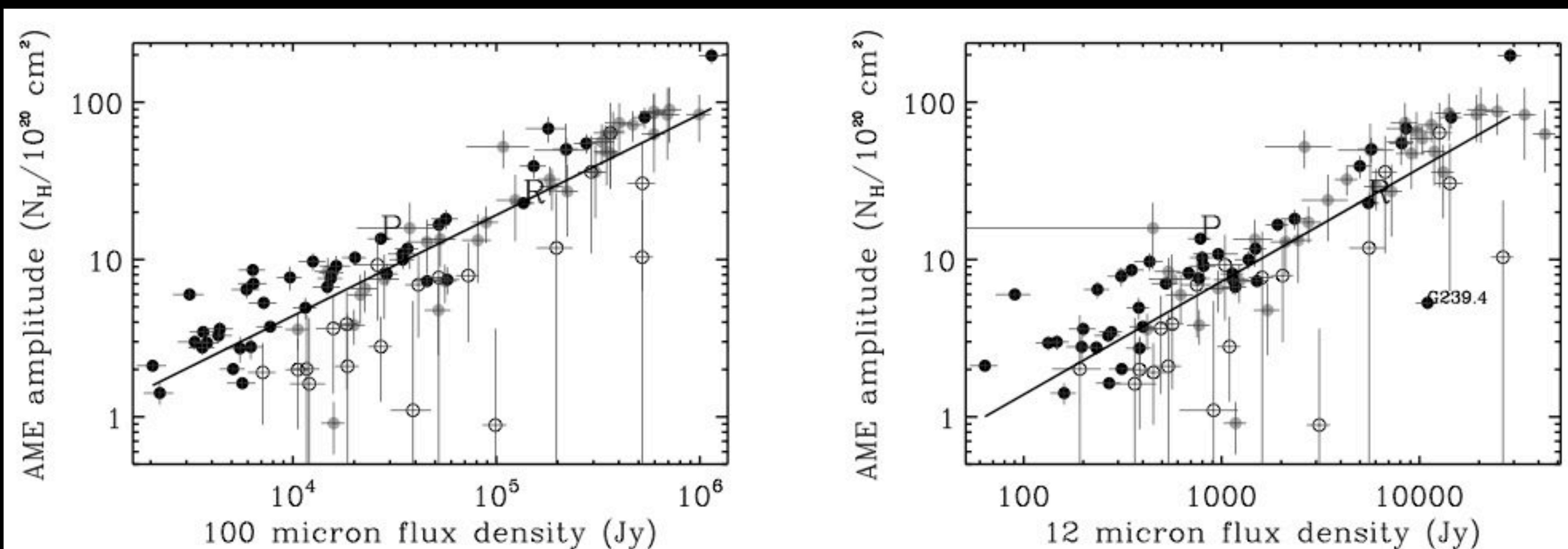
Significance

- Many sources show evidence of excess emission ~20-60 GHz
- ~40 (!) show high significance (>5σ at 20-60 GHz and >20% AME)
  - ~20 no significance (<1.5σ and <5% AME content)
  - ~40 number in between (possible AME contribution)
- Generally conservative due to difficulties (e.g. flattening of thermal dust tail, CMB, calibration of low frequencies , backgrounds etc.)



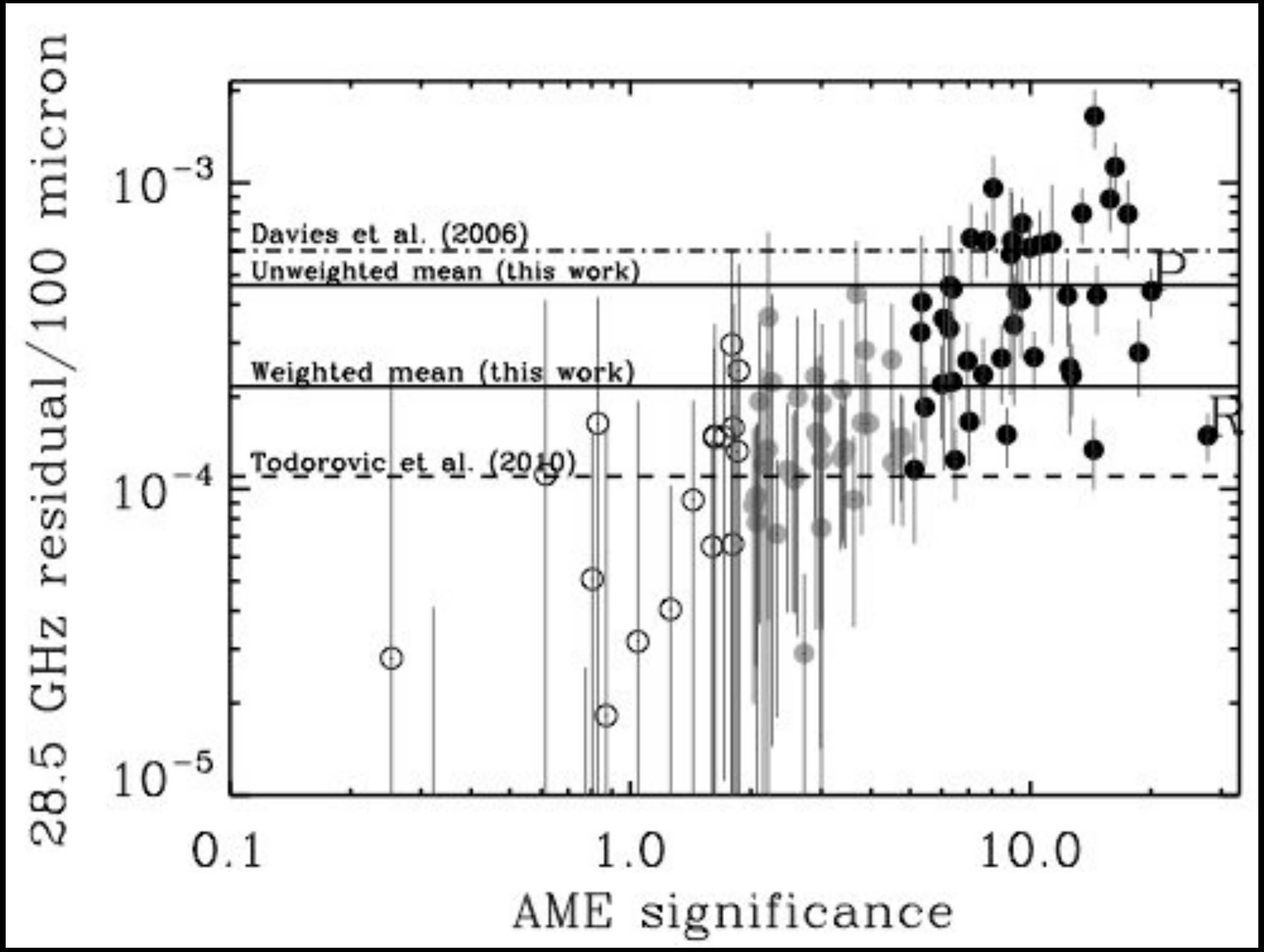
AME vs IR

- Strong correlation with thermal dust
  - AME objects show tighter correlation (as expected)
  - r~0.95 vs r~0.5
- Shorter wavelengths more difficult to interpret (line/stellar contamination?)



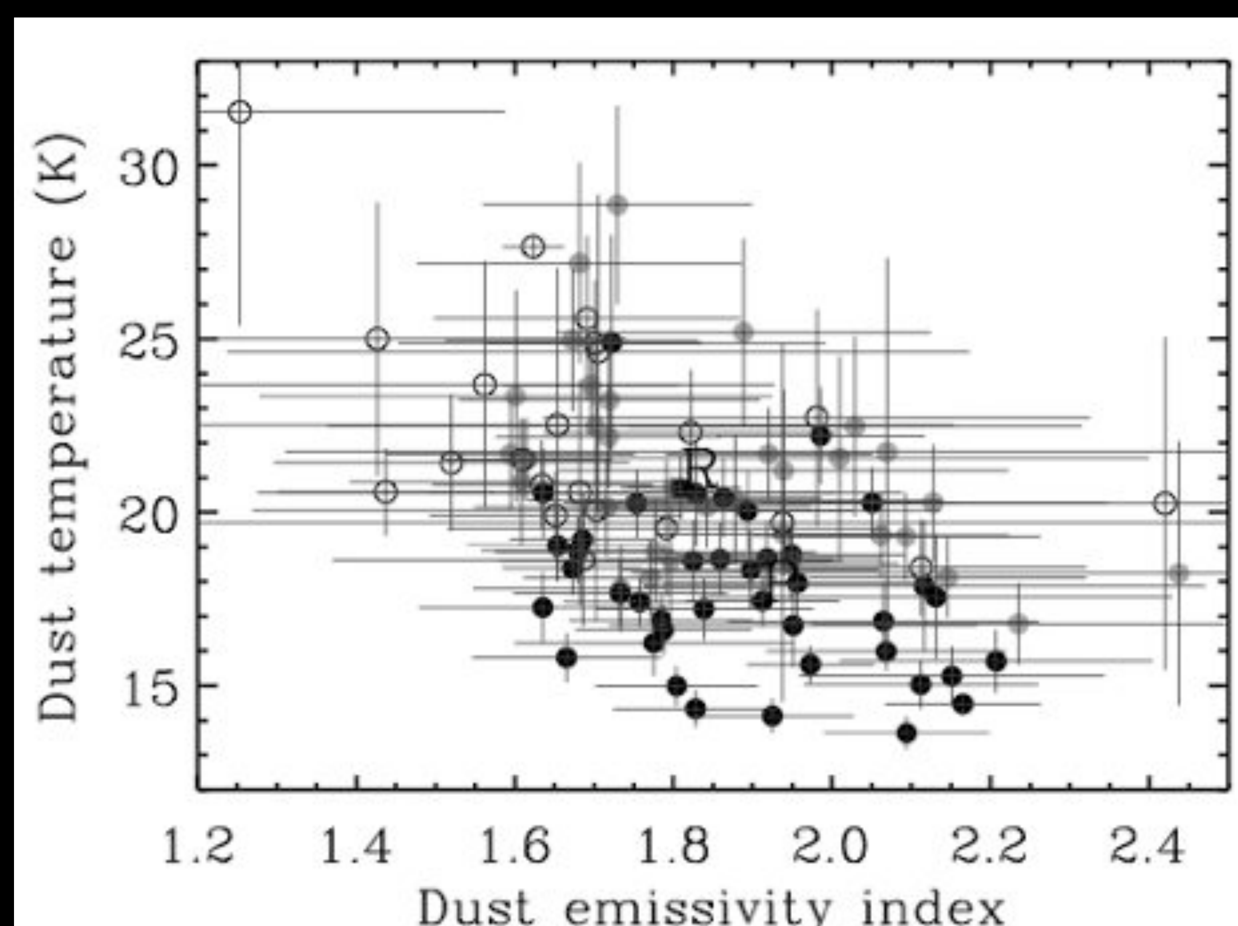
AME emissivity

- 100 um emissivity probably biased due to dust temperature
  - Level compatible to other clouds and high latitude AME
- Optical depth emissivity better - less biased! (not shown here)
  - Has a large range (factor of ~10)
  - AME emissivity comparable in most clouds!



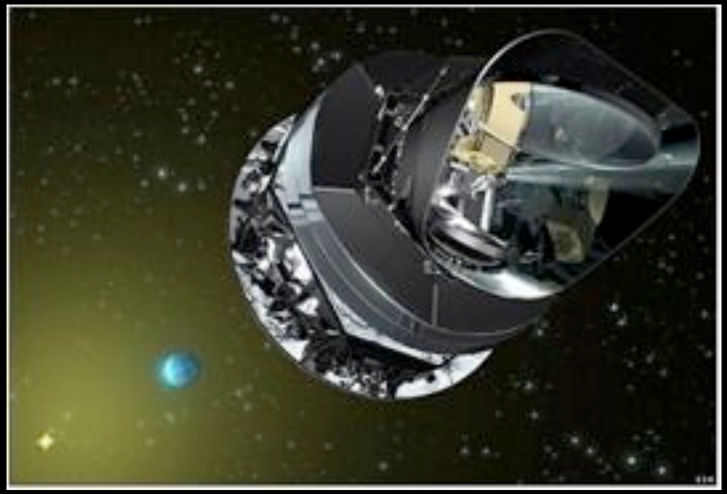
Some interesting trends...

- AME bright sources appear to be
  - More extended than non-AME regions
  - Slightly colder dust temperatures (on average)
    - Lower radiation fields (G_0)
    - Also higher 12/25 and 12/100 micron ratios
- Possible correlation with G_0 being investigated (c.f. Tibbs et al. 2012)



Conclusions

- Early paper: (Planck collaboration et al., 2011, A&A, 536, A20)
  - Planck + ancillary data have allowed us to produce precise spectra of AME with plausible physical model
  - Spinning dust is now generally accepted (at least for a few Galactic clouds)
- Intermediate paper (Planck collaboration, in prep.):
  - New sample of clouds with at least ~1/3 showing significant AME at 20-60 GHz
  - Spinning dust generally fits well with a wide range of emissivities
  - A few interesting trends are seen which may give us a hint to the nature of spinning dust and its environment (why do some regions not show AME at all?)
  - More detailed observations (~5 GHz, higher resolution etc) needed!
- Watch out for the published paper!



Special Issue on AME

Lead guest editor: Roberta Paladini
Guest editors: Clive Dickinson & Laurent Verstraete

Contributions wanted on all aspects of AME!
(theory, modelling, latest observations, extragalactic view, history...)

http://www.hindawi.com/journals/aa/si/962430/cfp/

Manuscript deadline: extended until July 18!!! (TBC)

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.

Spitzer IR maps

- Sub-sample of ~24 where Spitzer data available at 8 and 24 microns
- Bright emission nearly always seen
- Difficult to quantify trends with such small numbers