Planck Early Results:
New light on Anomalous Microwave Emission from Spinning Dust Grains

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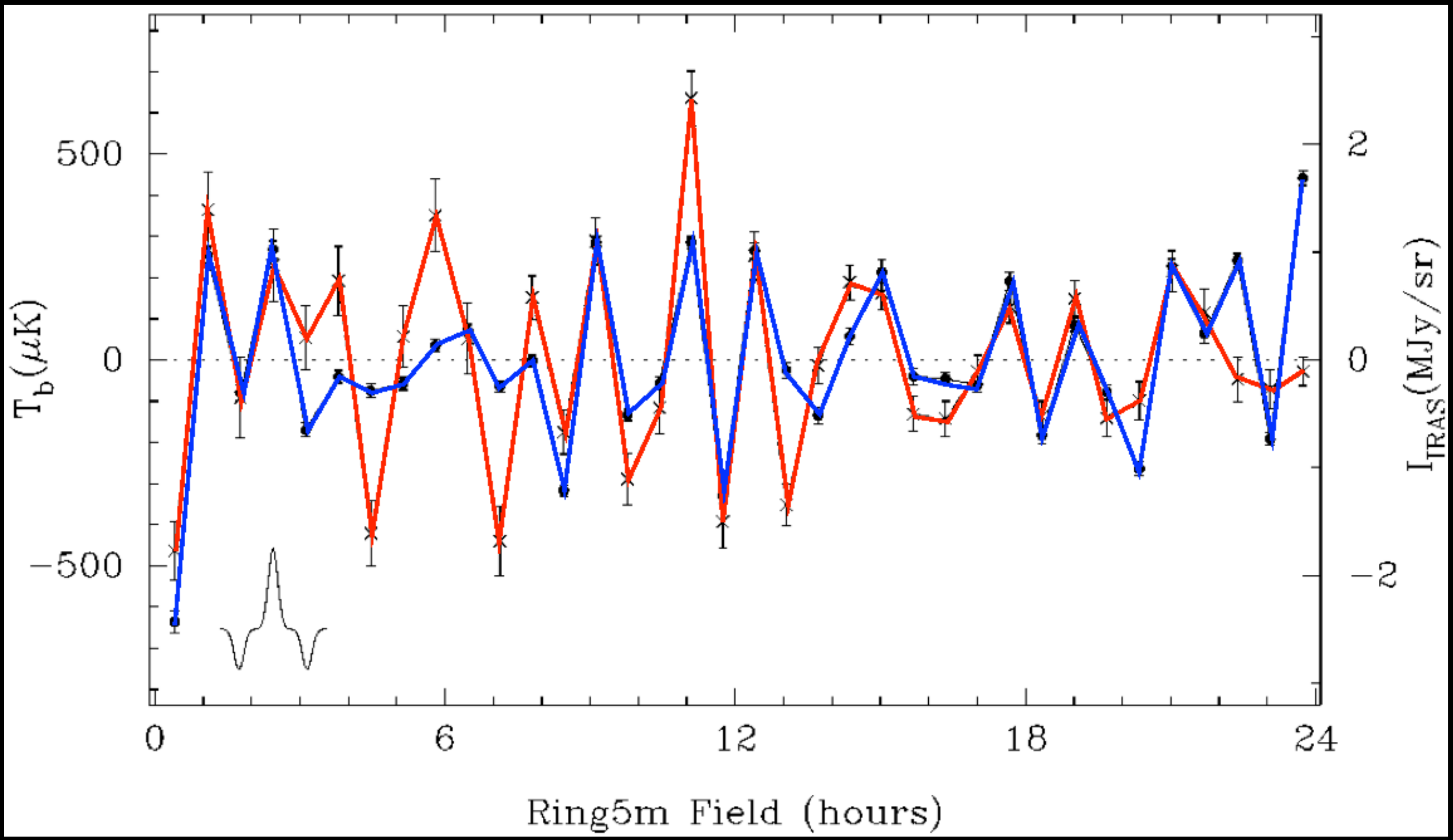
On behalf of the Planck Collaboration (arXiv:1101.2031)

Millimetre and Submillimetre Sky in the Planck Era, Cite des Sciences, Paris, 10-14 January, 20101

Discovery of Anomalous Microwave Emission



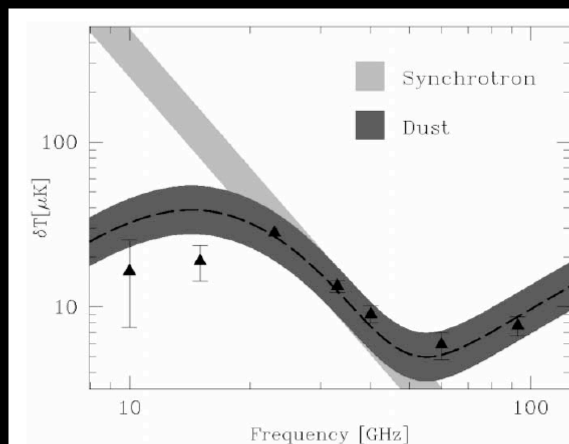
14.5/32 GHz OVRO (Leitch et al. 1997)

Evidence for anomalous emission

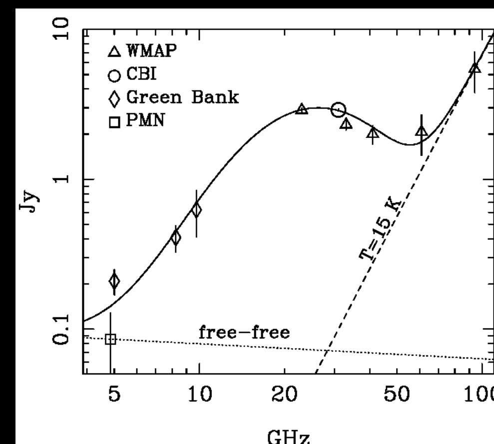
- A lot of evidence over the last 14 years - very active area of research, but still little is known about it! (lack of data!)
- Many papers, instruments, techniques, frequency ranges. E.g.:-
  - OVRO: Leitch et al. (1997)
  - COBE-DMR: Kogut et al. (1996), Banday et al. (2003)
  - Saskatoon: de Oliveira-Costa (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), Lopez-Caraballo (2011)
  - & now extragalactic as well! (Murphy et al. 2010; Scaife et al. 2010)

More data required!

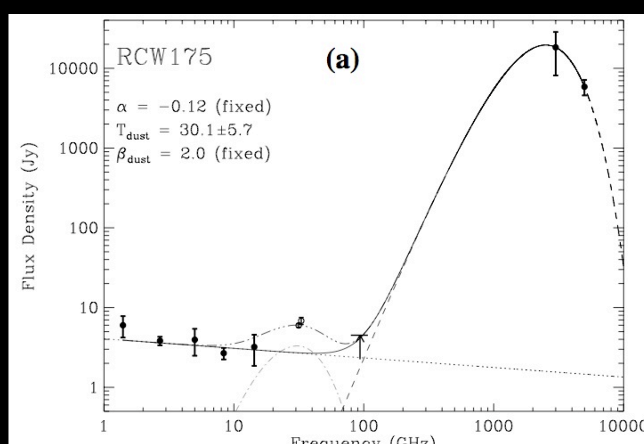
- High frequencies (>70 GHz) crucial in constraining the R-J tail from thermal dust grains and allow high frequency roll-off to be seen
- Accurate data near peak (~30 GHz) to complement WMAP data



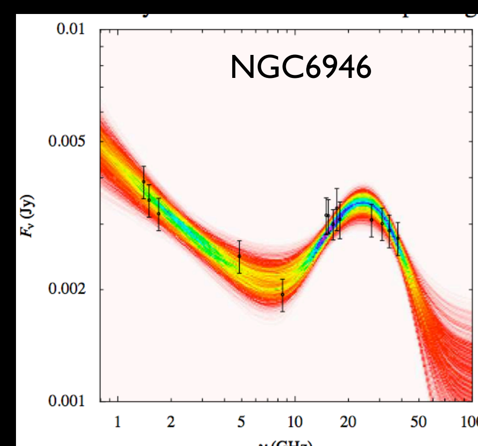
de Oliveira-Costa (2004)



Casassus et al. (2006)



Dickinson et al. (2009)

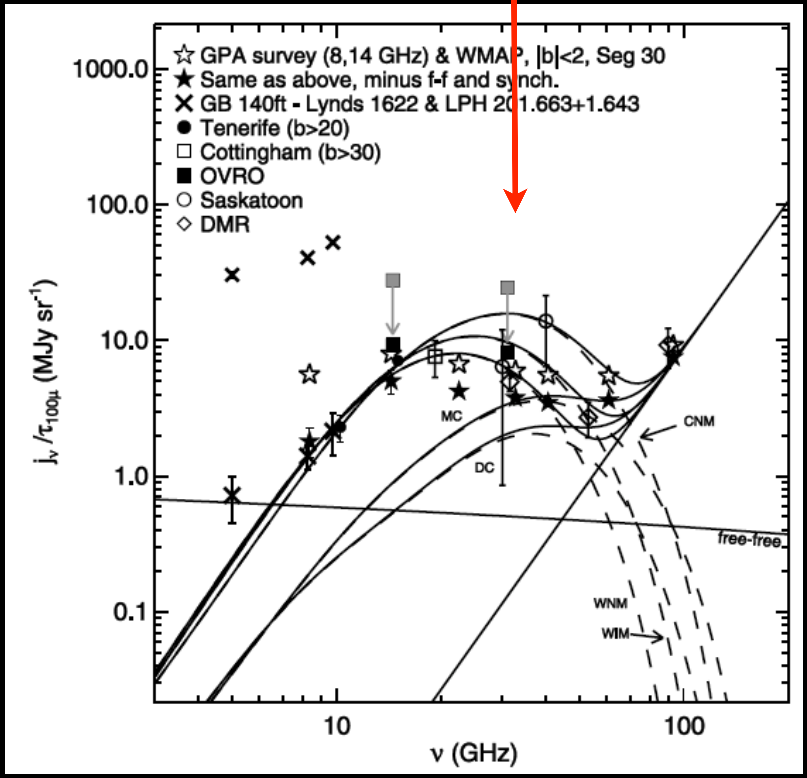


Scaife et al. (2010)

What is the anomalous emission?

Peaked spectrum over ~10-100 GHz

- 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")
- Planck now makes this much more solid!



Draine & Lazarian (1998)
Finkbeiner (2004)

A history lesson

A MECHANISM OF NON-THERMAL RADIO-NOISE ORIGIN*

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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}.

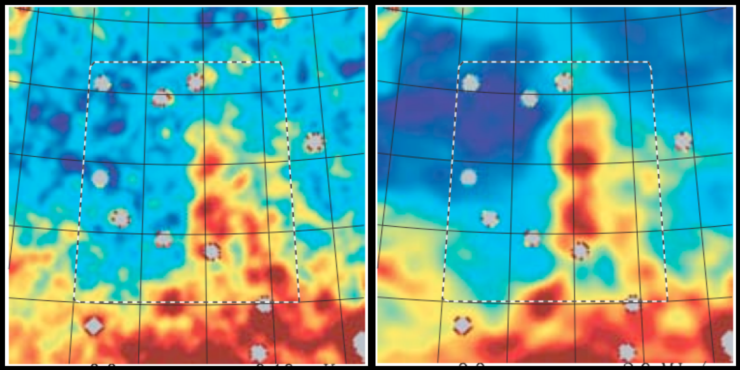
If interstellar grains exist in radio-source regions, collisions with the high-velocity gas will excite them to states of rapid rotation. In fact, it will be shown that they will rotate at radio frequencies. Thus, if an appreciable number of the grains possess electric or magnetic moments, they will 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.

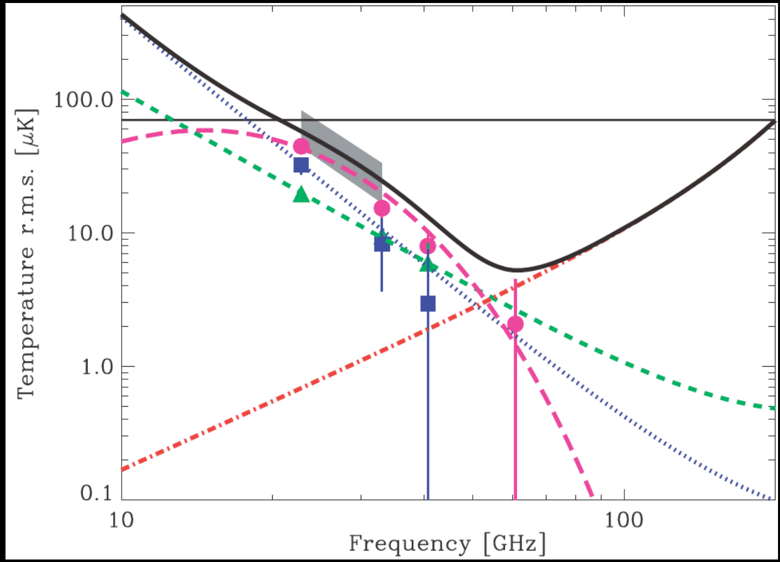
For calculational purposes, it will be assumed that the grains are spherical. The assumption of non-spherical grains requires a far more complex calculation than would

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

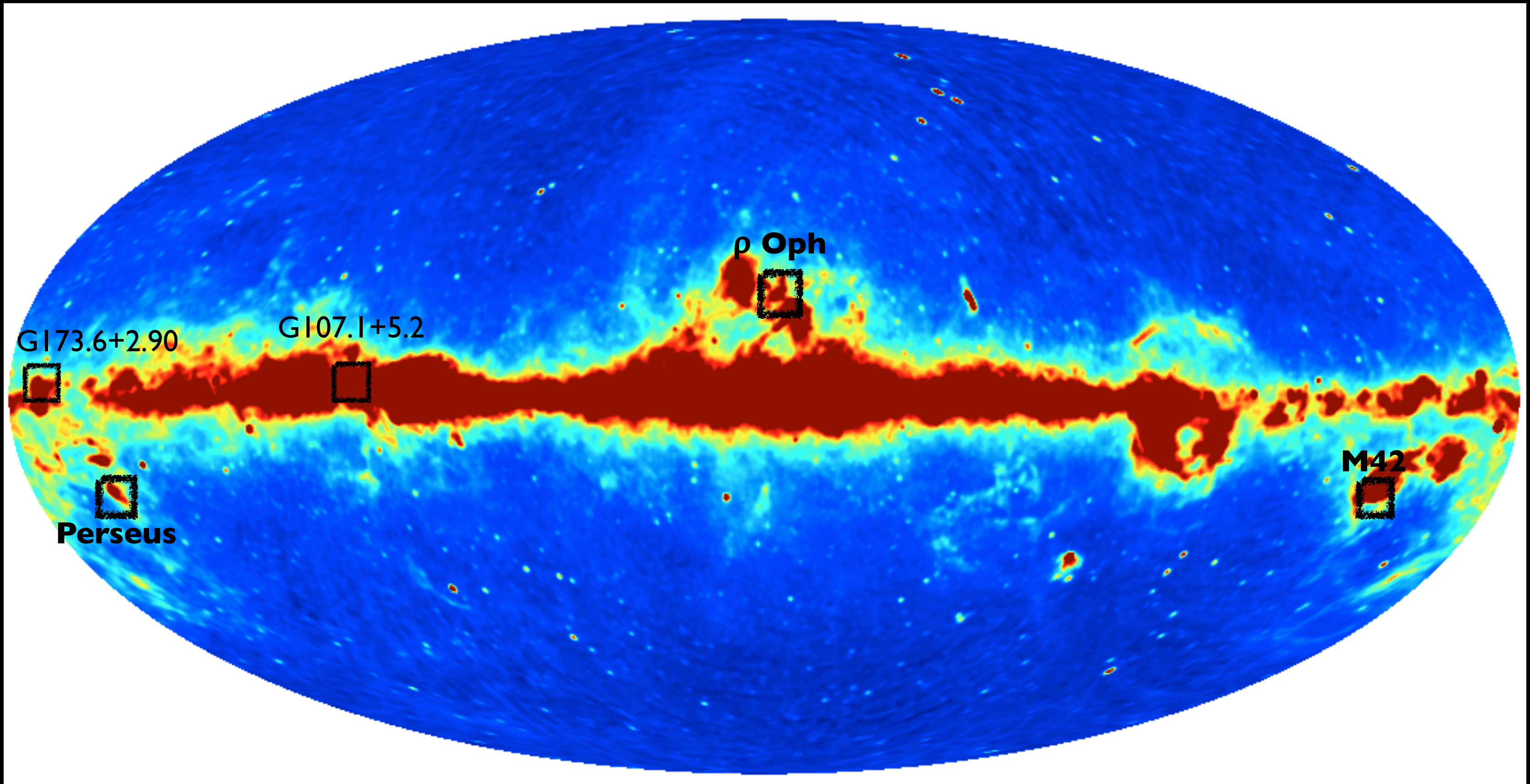




Davies et al. (2006)

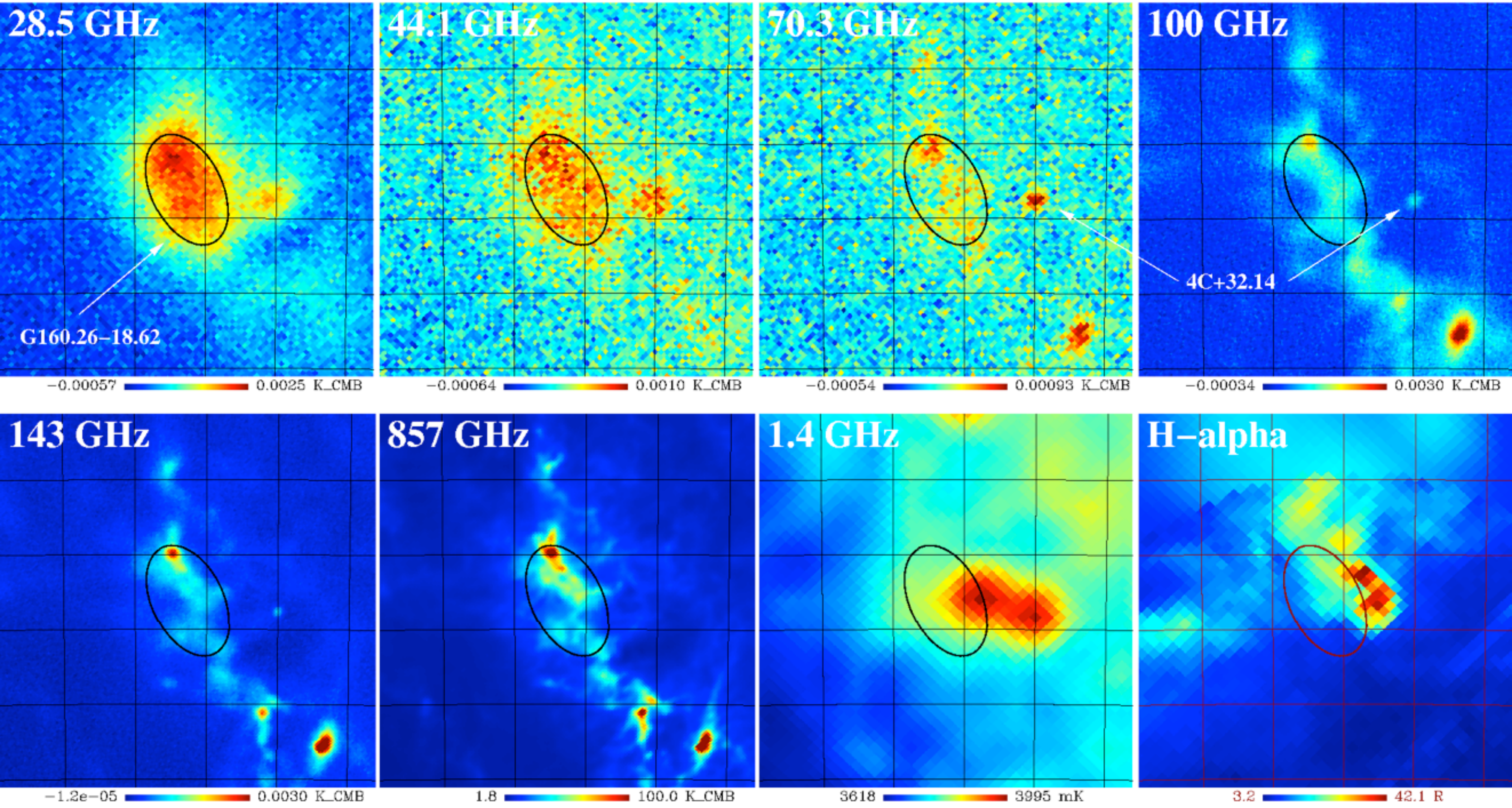
Regions studied in the early paper

- 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)

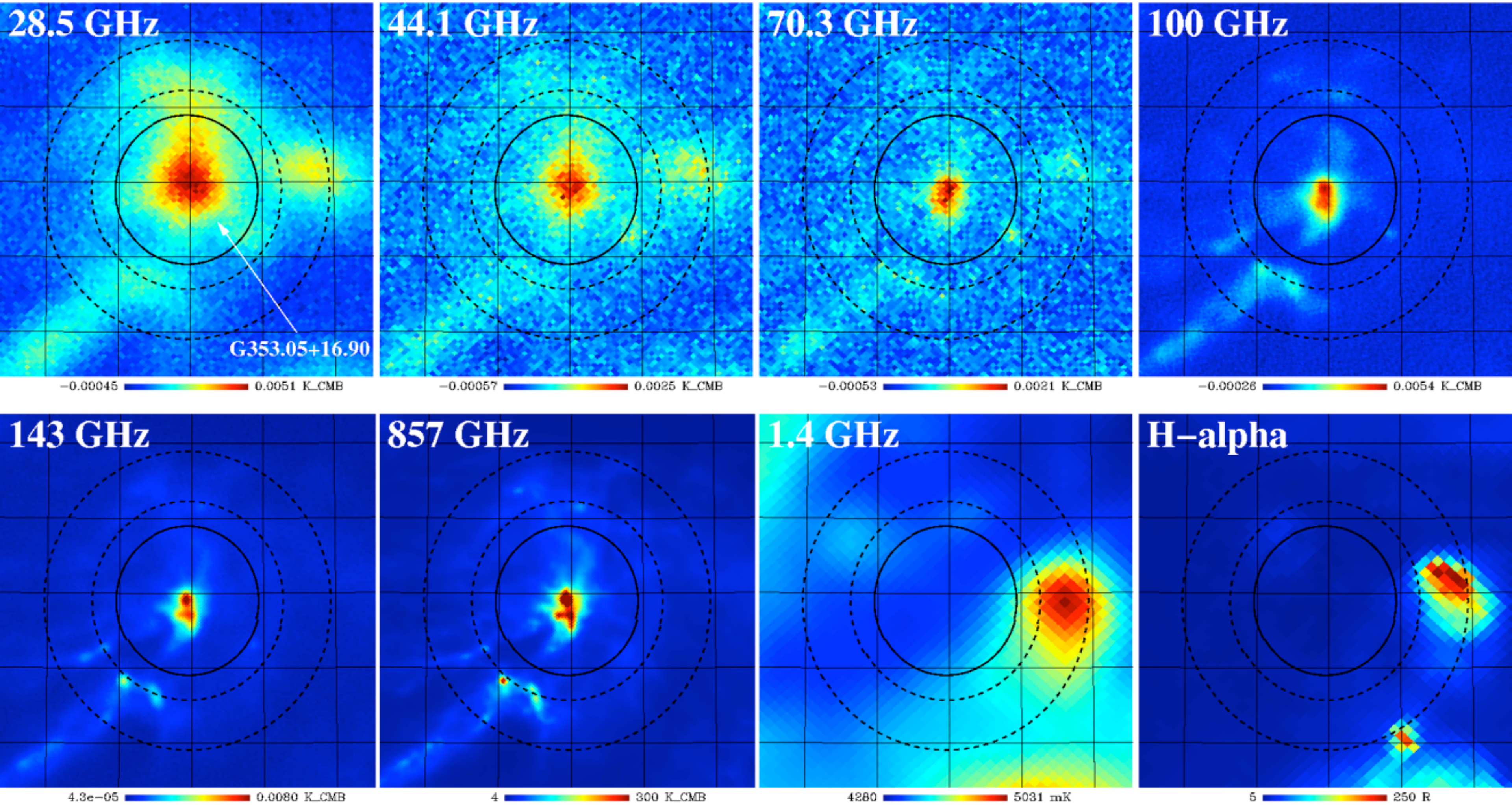


Planck 28.5 GHz DR2 map

Maps: Perseus Molecular Cloud

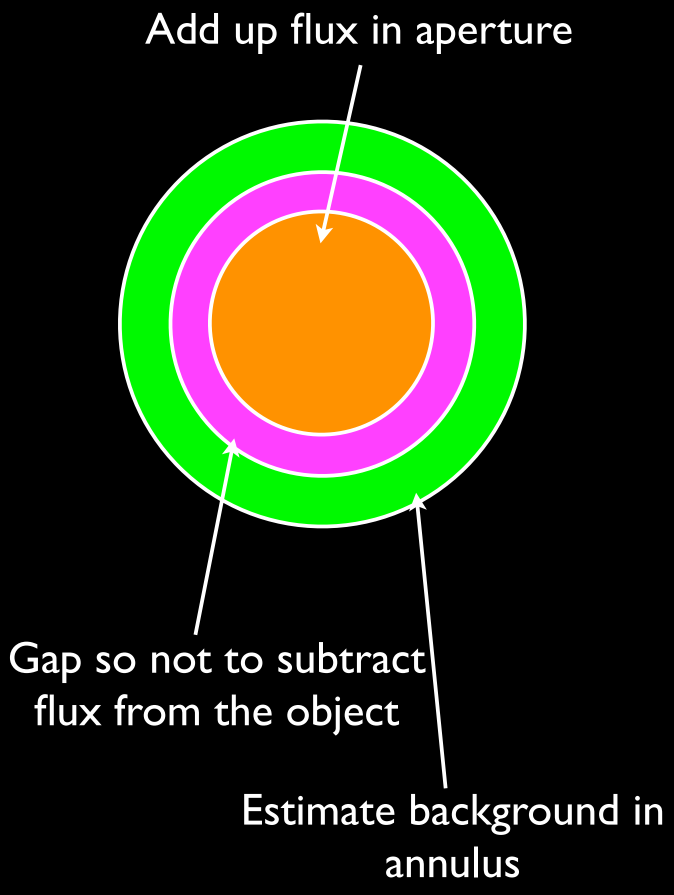


Maps: ρ Ophiuchus Molecular Cloud



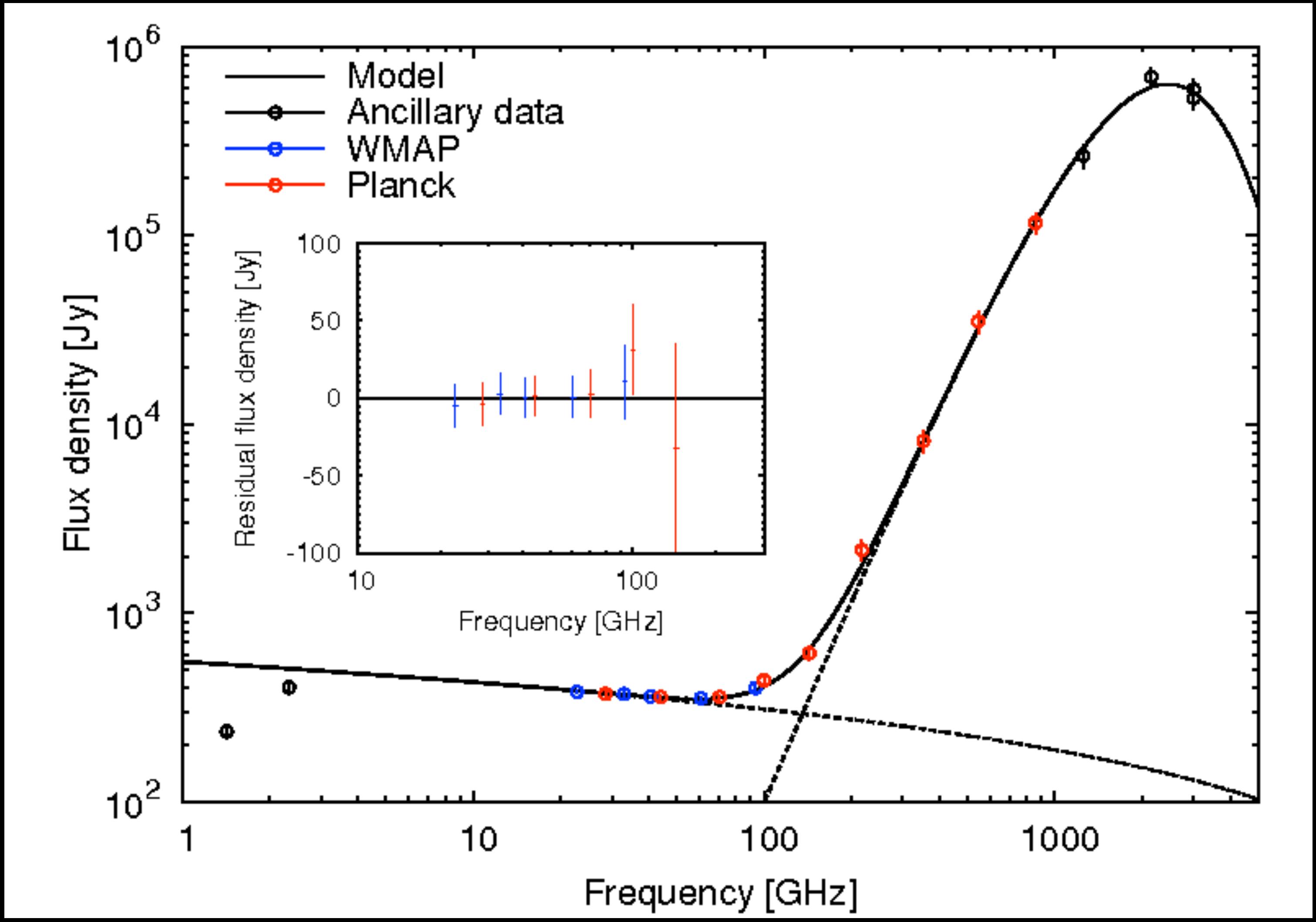
Data analysis

- Smooth maps to common 1 deg resolution
  - Convert units (Jy/beam)
  - Do not use 100/217 GHz for fitting due to CO
- Simple aperture photometry (2 regions) OR, fit simple elliptical Gaussian model when including COSMOSOMAS data (2 regions)
- 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



Control field: M42 (aperture photometry)

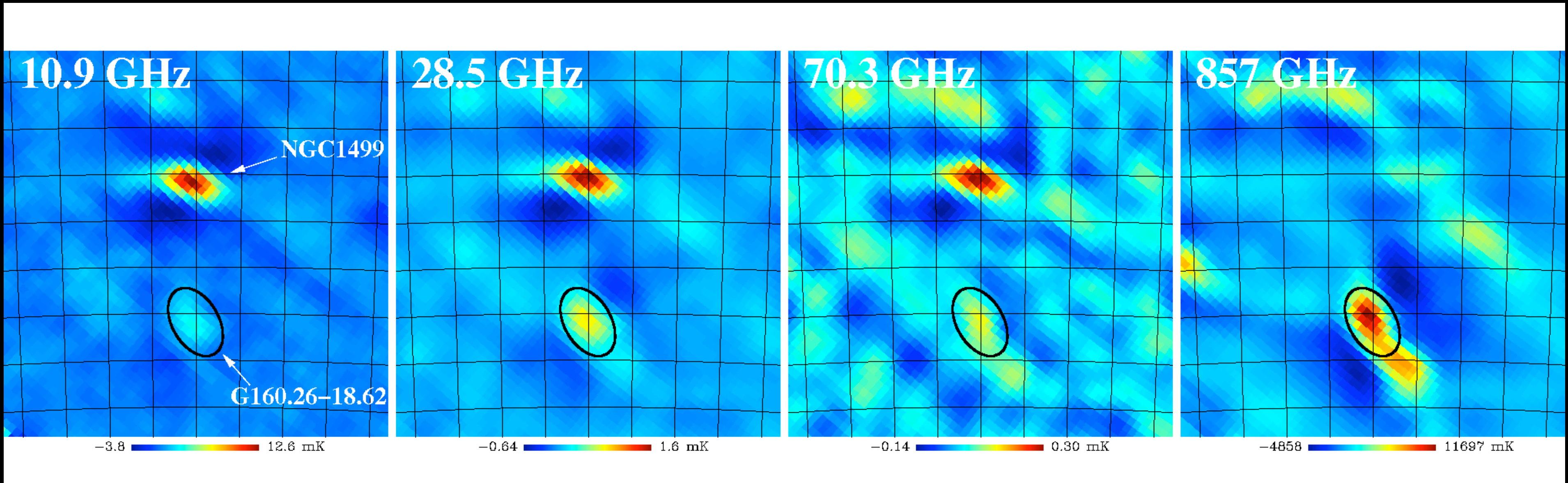
- WMAP/Planck consistent to ~1% or better



Including Cosmosomas data

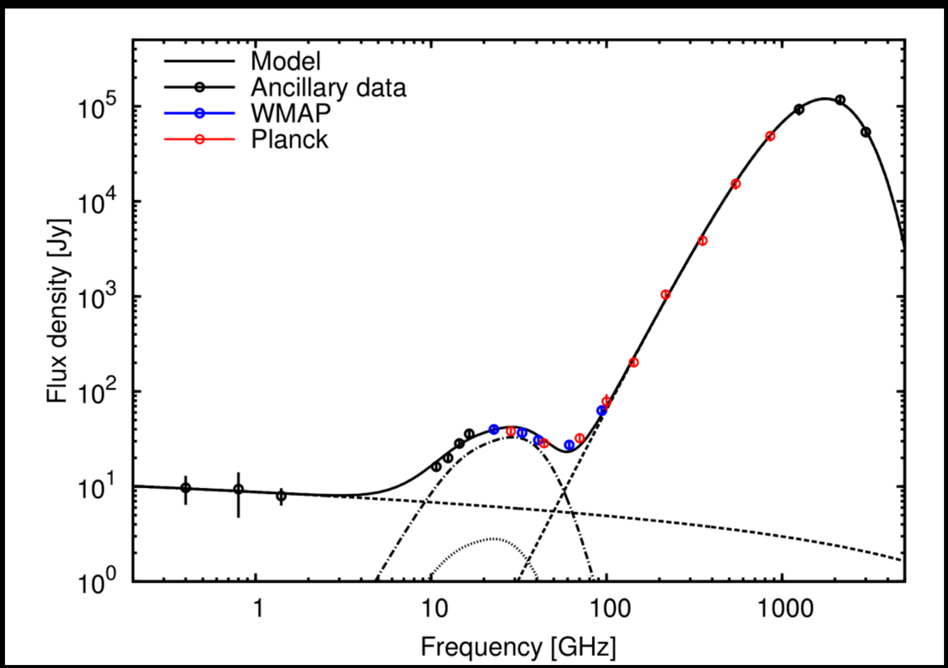
- Unique Cosmosomas data (11-17 GHz) (Watson et al. 2005)
  - ~1deg resolution at 11, 13, 15, 17 GHz covering ~10000 sq deg of Northern sky from Tenerife
  - Covers Perseus and one new region
  - Constrain low frequency part of spinning dust spectrum
  - BUT, filtering on large angular scales
- Filter all data (including Planck) through same scanning/ analysis pipeline

Cosmosomas instrument in Tenerife

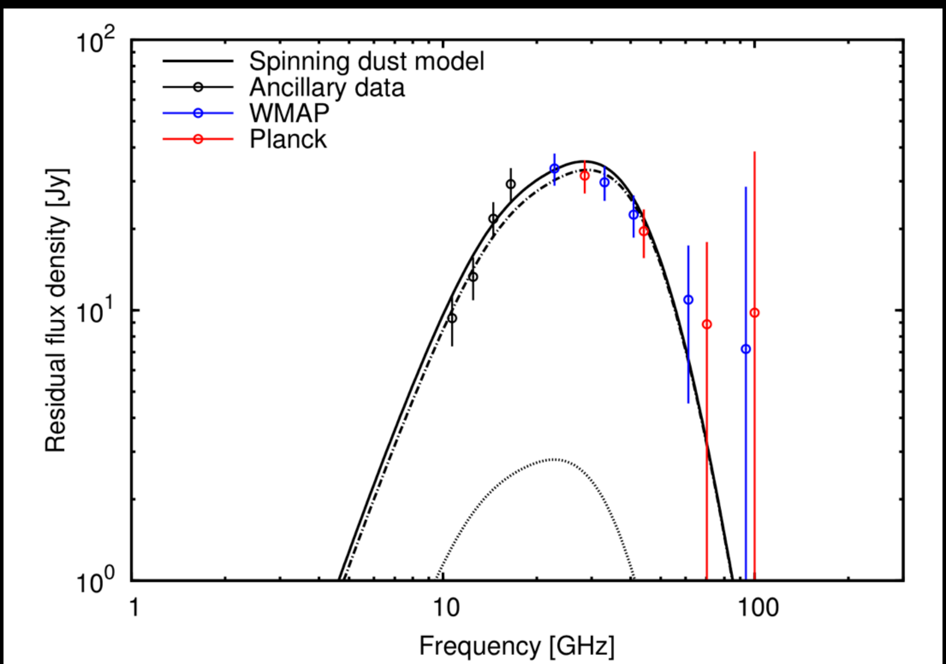


Spectra: Perseus

- 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



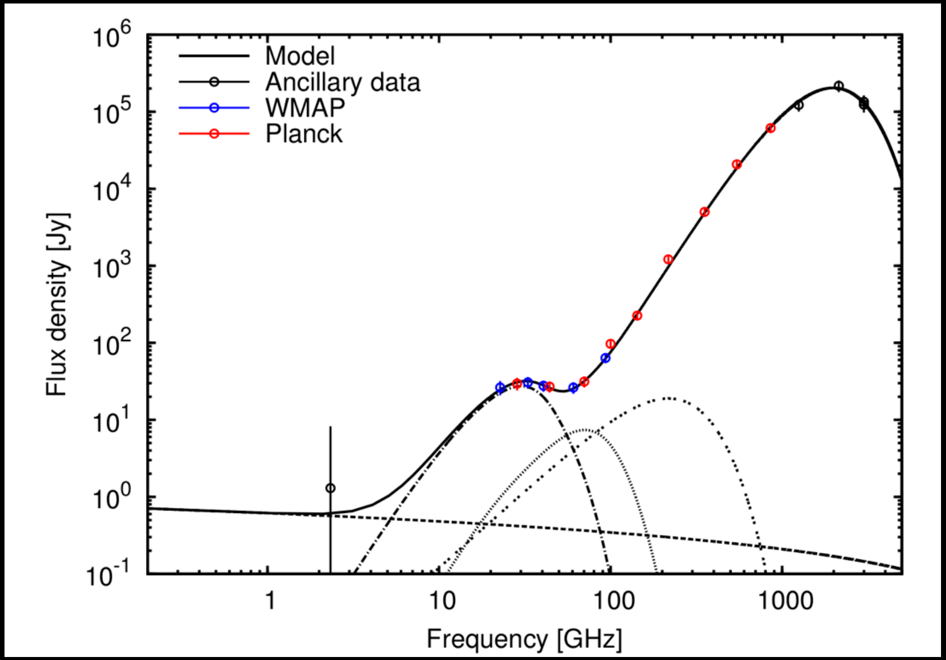
Perseus



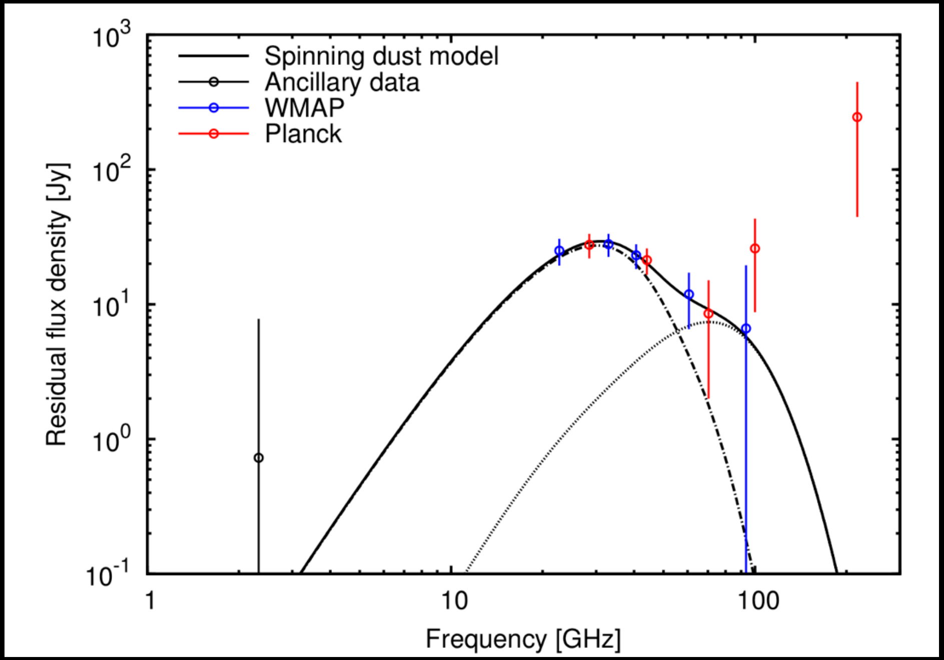
ρ Ophiuchus

Spectra: ρ Ophiuchus

- Integrated spectrum well-fitted by optically thin free-free, CMB (negligible) and single component modified black-body function
- Residual spectrum has clearly peaked spectrum
  - Significant at 10σ



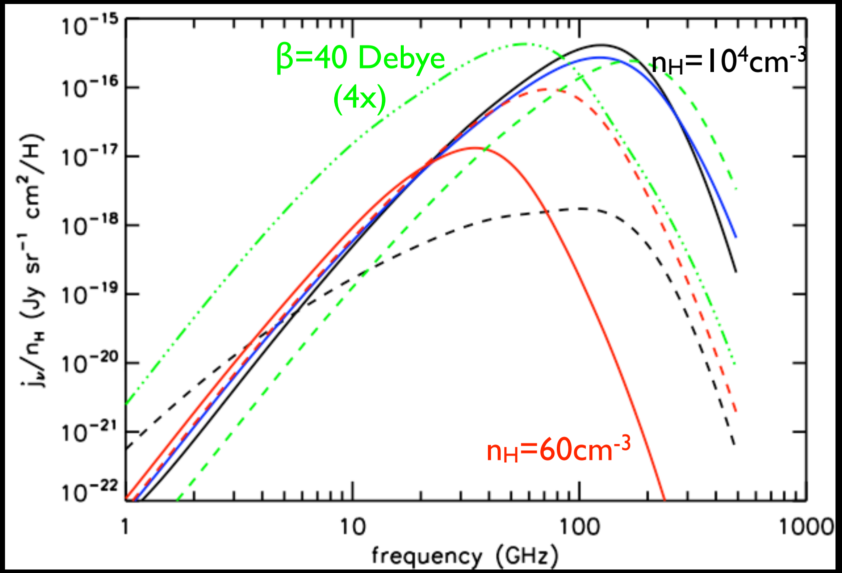
Perseus



ρ Ophiuchus

Modelling & Interpretation

- Spectral fits provide information on the material (ionized gas, dust grains) and on environment (ISRF, densities etc.)
- SPDUST code (Ali-Hamoud, Hirata, Dickinson 2009) provides spinning dust spectra for given parameters
  - Essentially an improved version of Draine & Lazarian (DL98)
- Can get very good fits but unphysical parameters (e.g. large dipole moments)
- 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

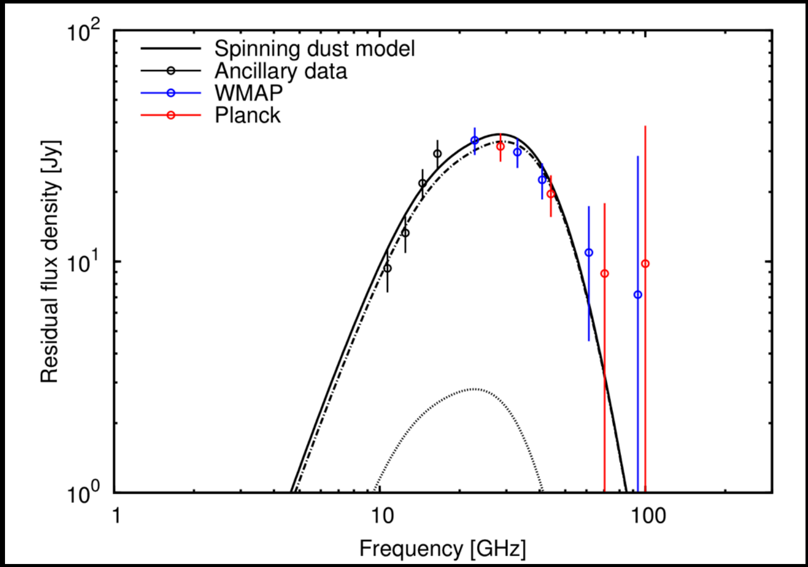


Spinning dust model

- We are not doing a full optimization of spinning dust models i.e. full fitting of all spinning dust parameters (future work!)
    - ~10 parameters to fit!
    - Strong degeneracies (e.g. a, n_H, G_0)
- Use a physically motivated model - not just make a nice plot
    - 1st go - not necessarily absolute best fit
- 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
    - WIM assumed to have no spinning dust (no PAHs)
    - ...(see paper for more details)

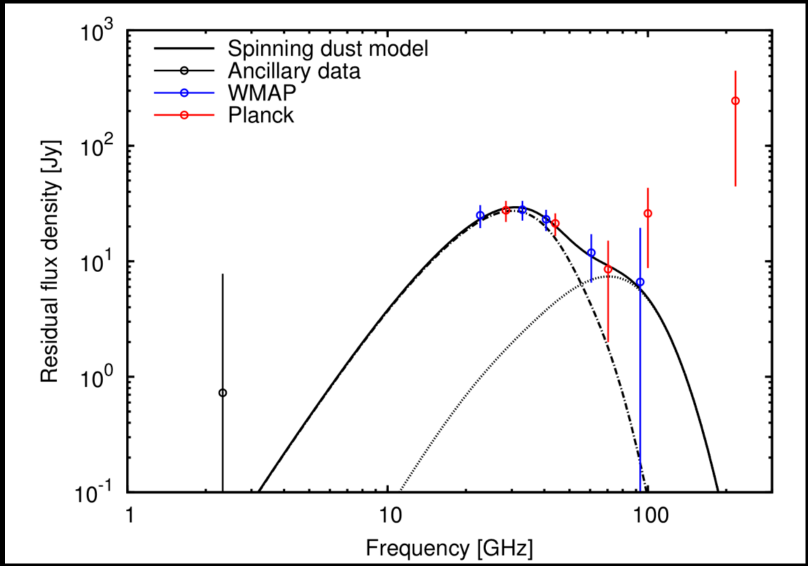
Gas state	Molecular	Atomic	Ionized
		Perseus	
N_H [10^{21} cm^{-2}]	11.7	1.3	0.4
n_H [cm^{-3}]	250	30	1
z [pc]	15.1	14.0	...
G_0	1	2	...
T [K]	40	100	8×10^3
x_H [ppm]	112	410	10^6
x_C [ppm]	<1	100	...
y	1	0.1	...
a_0 [nm]	0.58	0.53	...
b_C [ppm]	68	68	...
β	...	1.65	...
T_d [K]	...	18.5	...
τ_{250}	...	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}	...

Spinning dust spectra & conclusions



Perseus

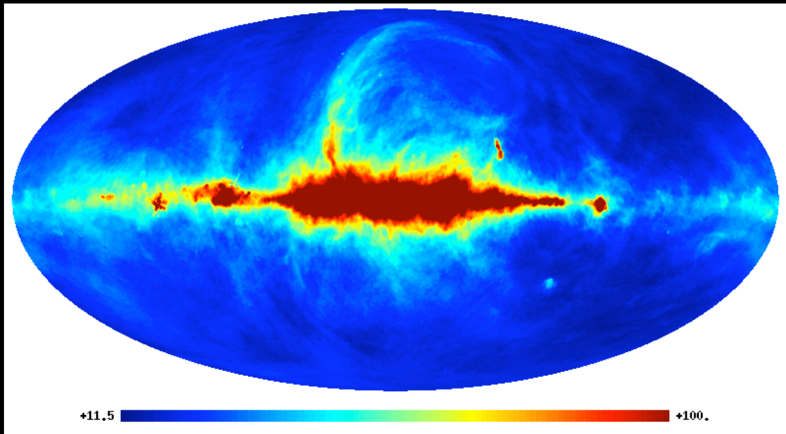
- Plausible physical models appear to fit the data
- Higher density molecular gas can account for most of AME
- Lower density atomic (neutral) gas appears to play only a minor role in Perseus
- Irradiated low density atomic gas can account for excess at ~60-90 GHz in ρ Ophiuchus



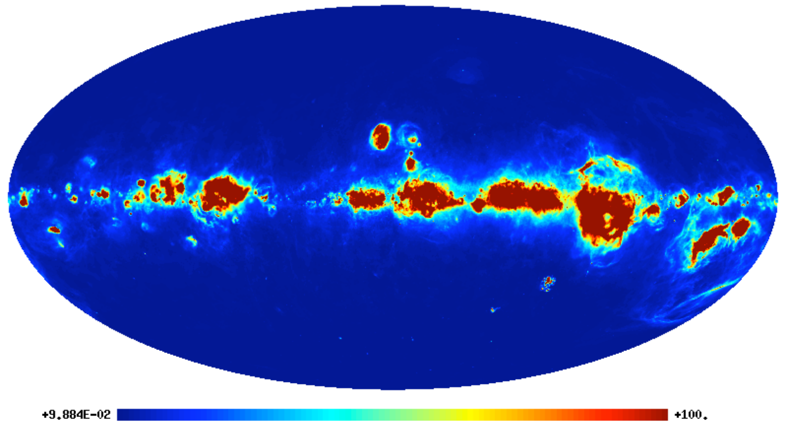
ρ Ophiuchus

New AME regions

- Use simplistic approach to remove synchrotron, free-free, thermal dust from Planck 28.5 GHz map
  - Haslam et al. 408 MHz map extrapolated using a power-law (1420/2326 MHz data, or -3.0 if no data)
  - Hα map map corrected for dust absorption assuming 30% of dust in front (Dickinson et al. 2003)
  - HFI (143/545 GHz) extrapolated using a power-law
- Far from perfect (!) but removes large fraction of non-AME
- Residual map inspected in detail to find regions only
  - ~50 candidates inspected for early paper (2 were chosen)
  - Spectra made from original Planck maps

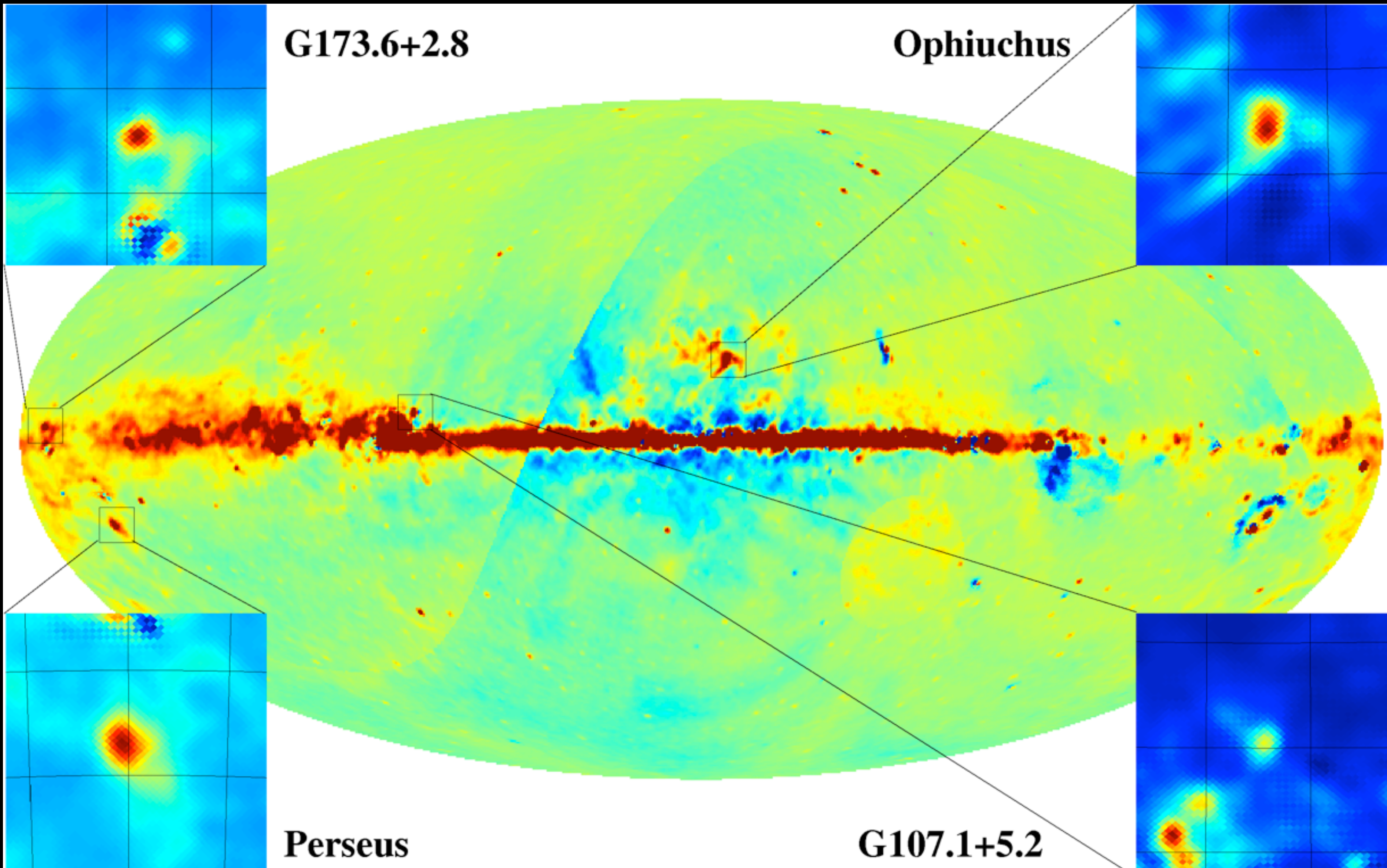


408 MHz (Haslam et al. 1982)



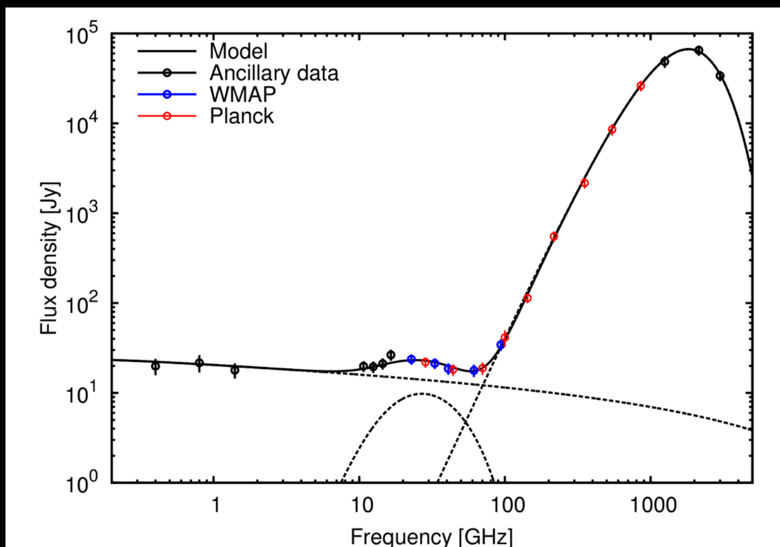
Hα (Dickinson et al. 2003)

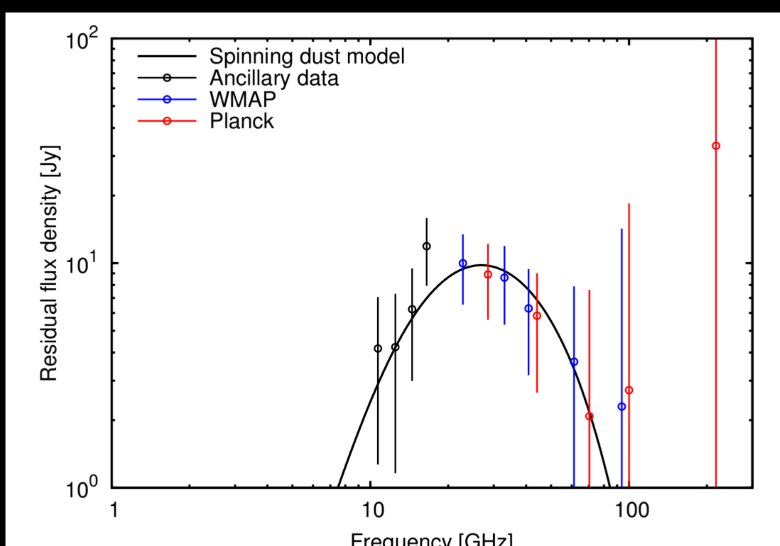
AME map at 28.5 GHz



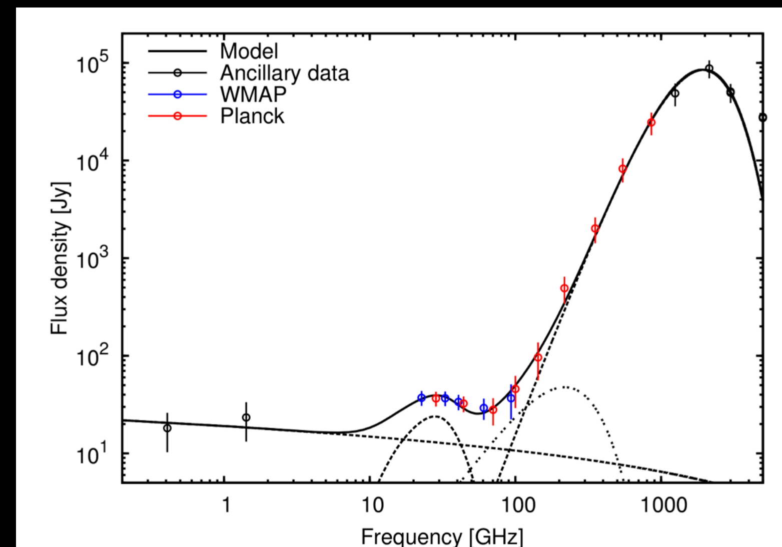
New AME regions spectra

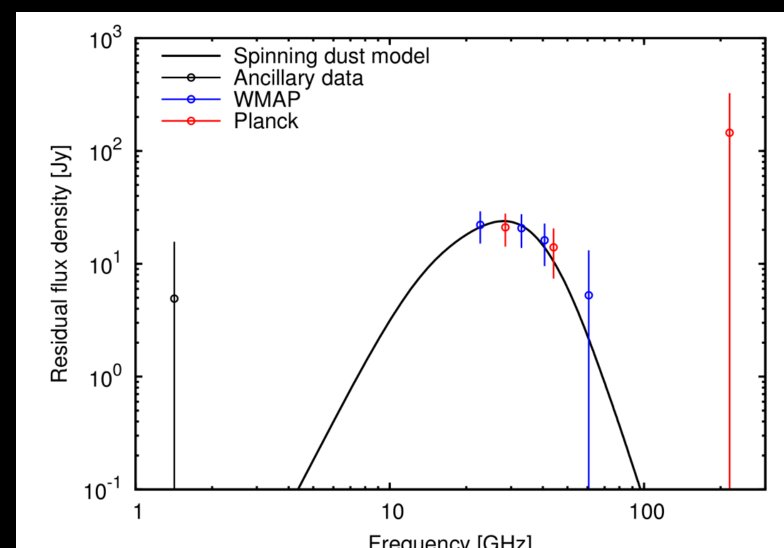
G173.6+2.80





G107.1+5.20





Conclusions

- Most accurate and comprehensive spectra of AME to date (Perseus & ρ Oph)
  - Very robust! (formally significant at 17 and 10σ !)
  - Modelling errors are not dominant
  - Convex shape as predicted by models of spinning dust emission
- Physical model for spinning dust is plausible and can account for the majority of the AME
  - Denser environment appears to dominate the AME
  - Low density atomic (neutral) gas appears to be play only a minor role
  - Indication of high frequency (60-90 GHz) contribution in ρ Oph from irradiated gas
- Search for new AME regions was successful
  - 2 new AME regions detected at >5σ
  - Shape looks like spinning dust (however, could be UCHII regions)
- Much more to look at!
  - More regions, including high latitude sky
  - Detailed modelling of the dust grains and environment, including IR data etc.
  - Polarization

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.