Jas Fest – 5 December, 2018

Radio Surveys, Cosmology and Statistics

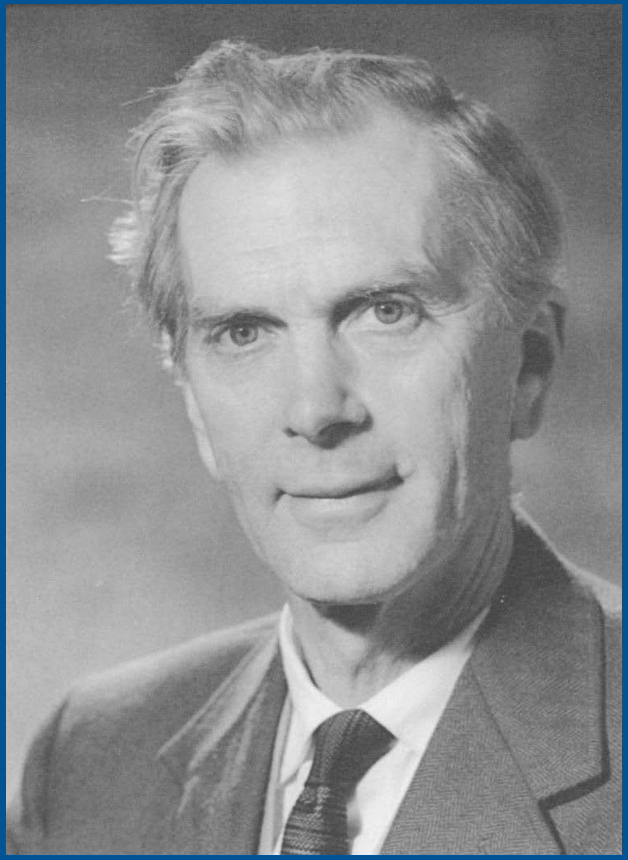
Tim Pearson

Mullard Radio Astronomy Observatory, Cambridge 1972-1977

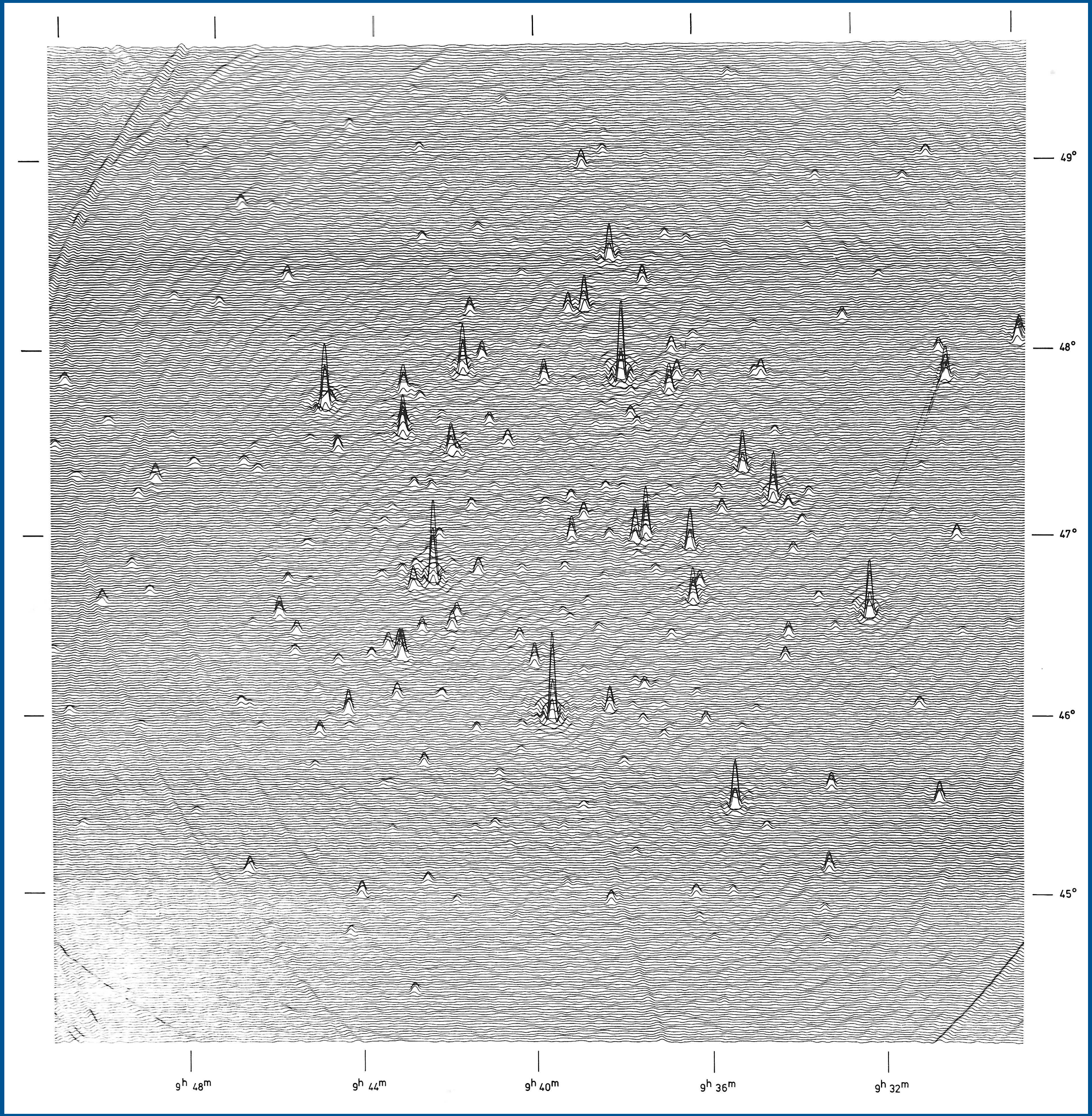
Owens Valley Radio Observatory, Caltech 1977-2018

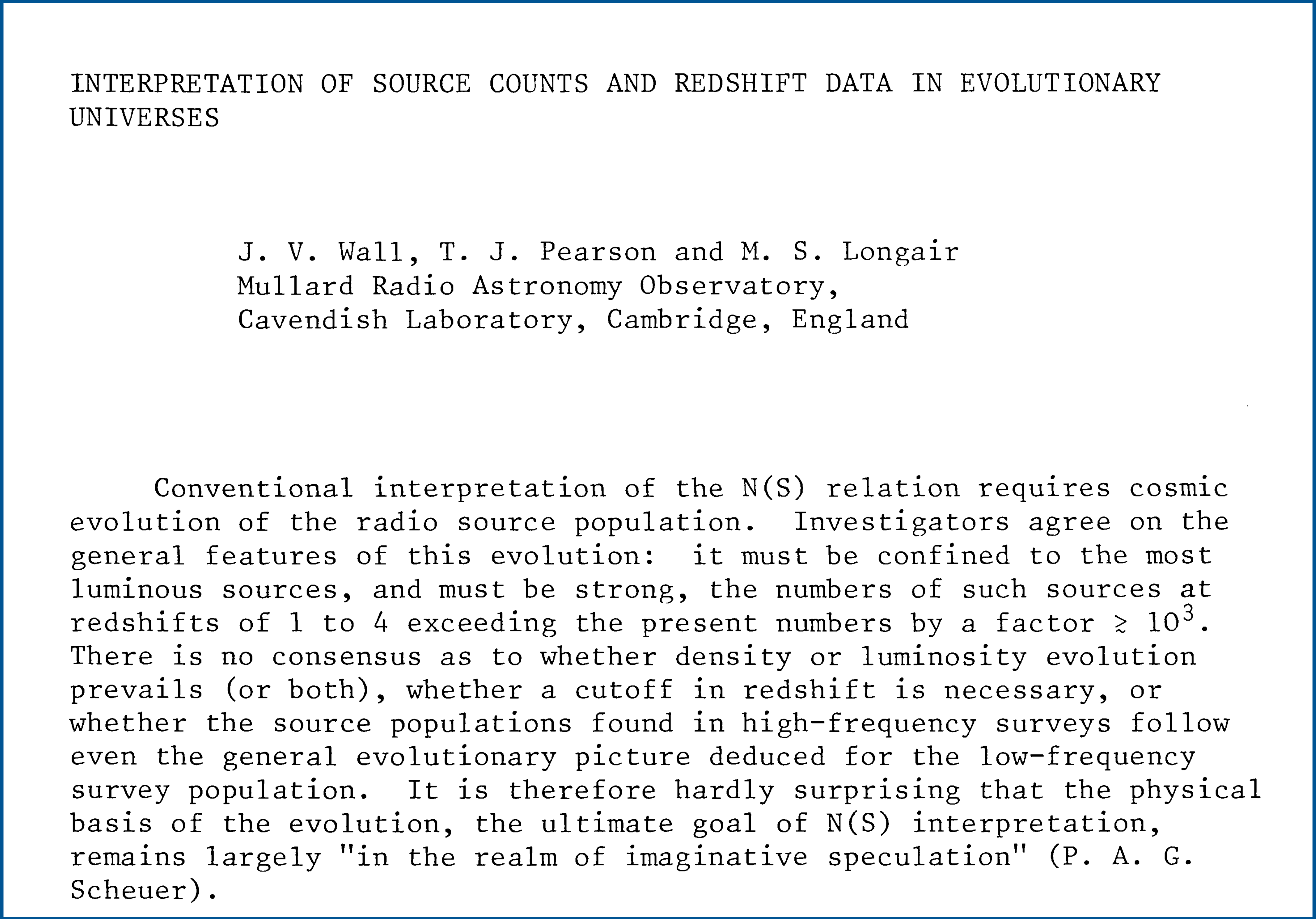
The problem of the physics of radio galaxies and quasars and the cosmological problem are strangely linked; we appear to be living in an evolving Universe, so that very distant sources which, due to the signal travel time, we observe as they were when the Universe was younger, may be systematically different from a sample of nearby sources.

Martin Ryle, Nobel Lecture, 1974



5C5 survey (One-Mile Telescope, 1973)





INTERPRETATION OF SOURCE COUNTS AND REDSHIFT DATA IN EVOLUTIONARY UNIVERSES

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Conventional interpretation of the N(S) relation requires cosmic evolution of the radio source population. Investigators agree on the general features of this evolution: it must be confined to the most luminous sources, and must be strong, the numbers of such sources at redshifts of 1 to 4 exceeding the present numbers by a factor $\gtrsim 10^3$. There is no consensus as to whether density or luminosity evolution prevails (or both), whether a cutoff in redshift is necessary, or whether the source populations found in high-frequency surveys follow even the general evolutionary picture deduced for the low-frequency survey population. It is therefore hardly surprising that the physical basis of the evolution, the ultimate goal of N(S) interpretation, remains largely "in the realm of imaginative speculation" (P. A. G. Scheuer).

IAU Symposium 74, Radio Astronomy and Cosmology, 1976, Cambridge
and two papers in MNRAS

Interpreting source counts and redshift data

Jasper's approach:

(1) a simple numerical technique which makes efficient use of the data,

(2) the comparison of models with observations using appropriate statistical procedures, and

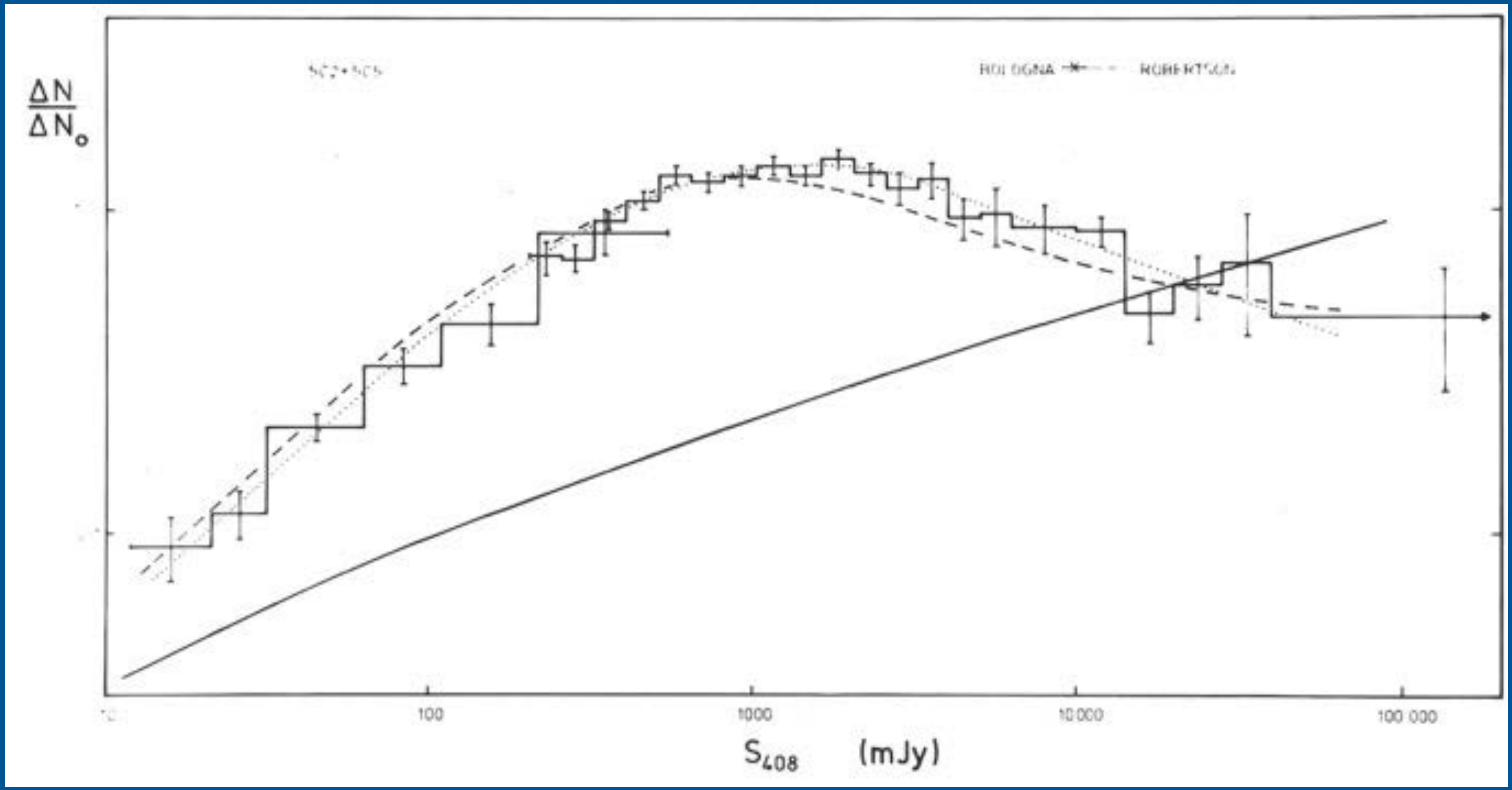
(3) the determination of which new observations are most important in defining the cosmological evolution with greater precision.

We want to know the **generalized radio luminosity function**

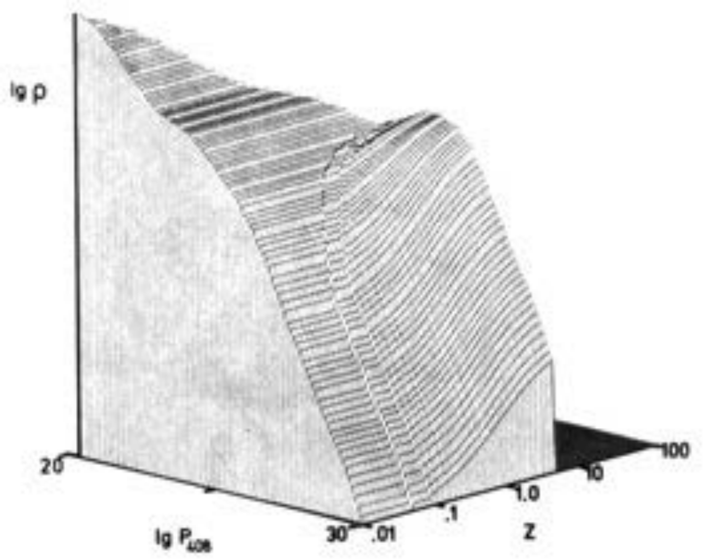
$$\rho\,(P,\, z,\, \textit{radio source type})$$

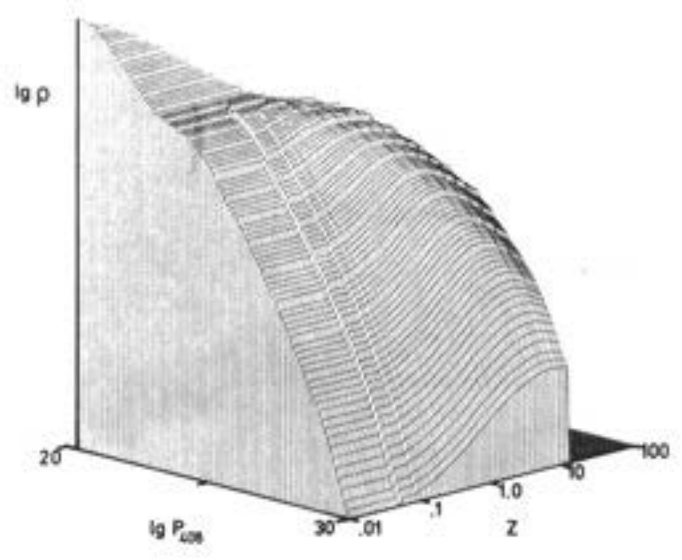
which describes the comoving space density of radio sources as a function of radio power P, redshift z (i.e. epoch — we assume that redshifts are cosmological distance indicators), and radio source type.

408 MHz source counts and 3 models



Dependence of luminosity function in redshift in 2 models





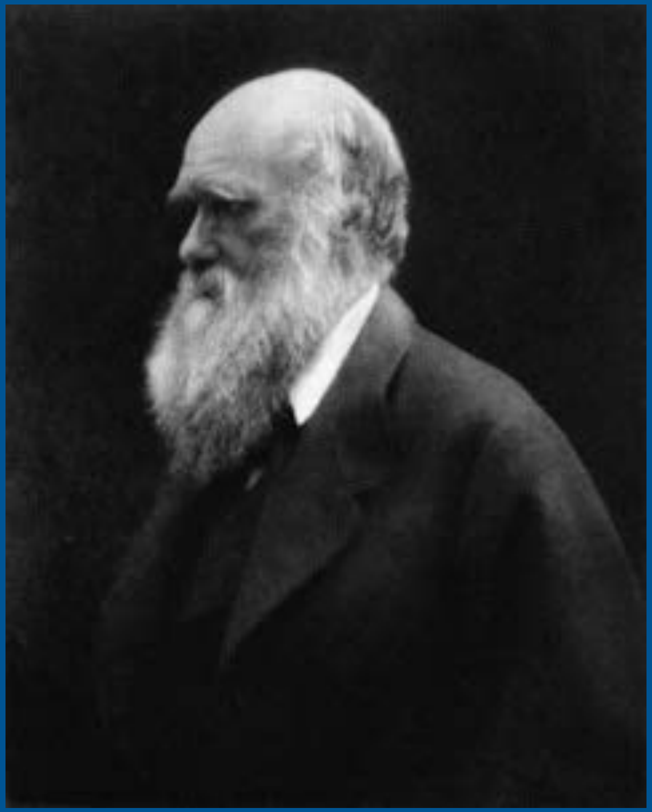
Ever since radio sources were first identified with optical sources (galaxies and quasars), of moderate and high redshift, it has been obvious that the radio source population was quite different at early cosmological times than at present (Pooley & Ryle 1967; Schmidt 1968; Rees 1971). As beautifully shown by Wall et al. (1977), when source counts, local radio luminosity function, and redshift data are combined, it is clear that it is the bright (FR II) end of the luminosity function that was much more populous in the past. At the present epoch powerful radio sources and quasars are rather rare.

Roger Blandford, David Meier, and Tony Readhead: "Relativistic Jets in Active Galactic Nuclei", to appear in ARAA

About 30 years ago there was much talk that Geologists ought only to observe & not theorise; & I well remember some one saying, that at this rate a man might as well go into a gravel-pit & count the pebbles & describe their colours. How odd it is that every one should not see that all observation must be for or against some view, if it is to be of any service.

—

Charles Darwin, Letter to Henry Fawcett, 18 September 1861



CBI: cosmologizing in Chile

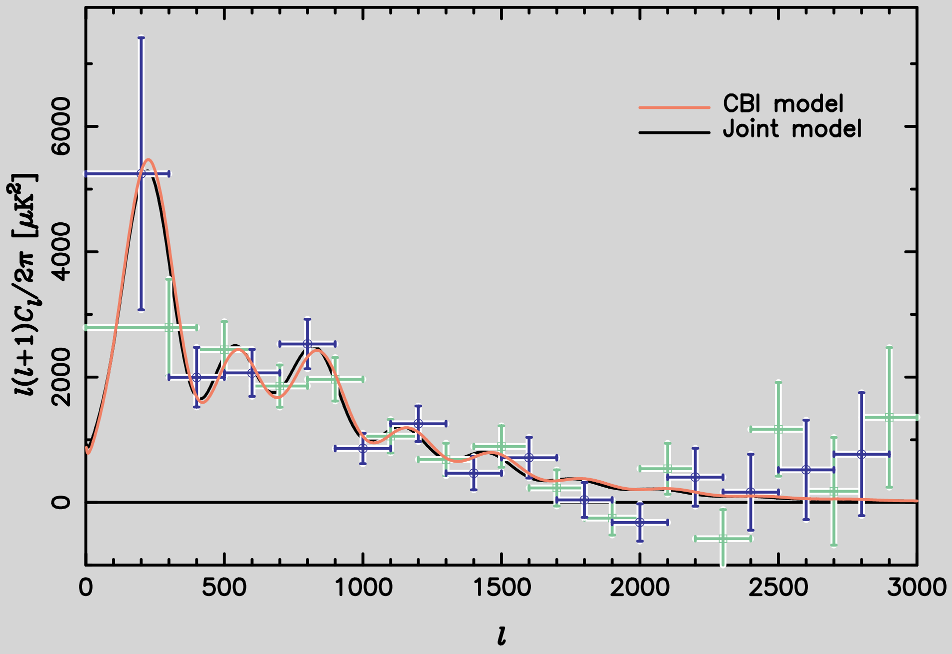
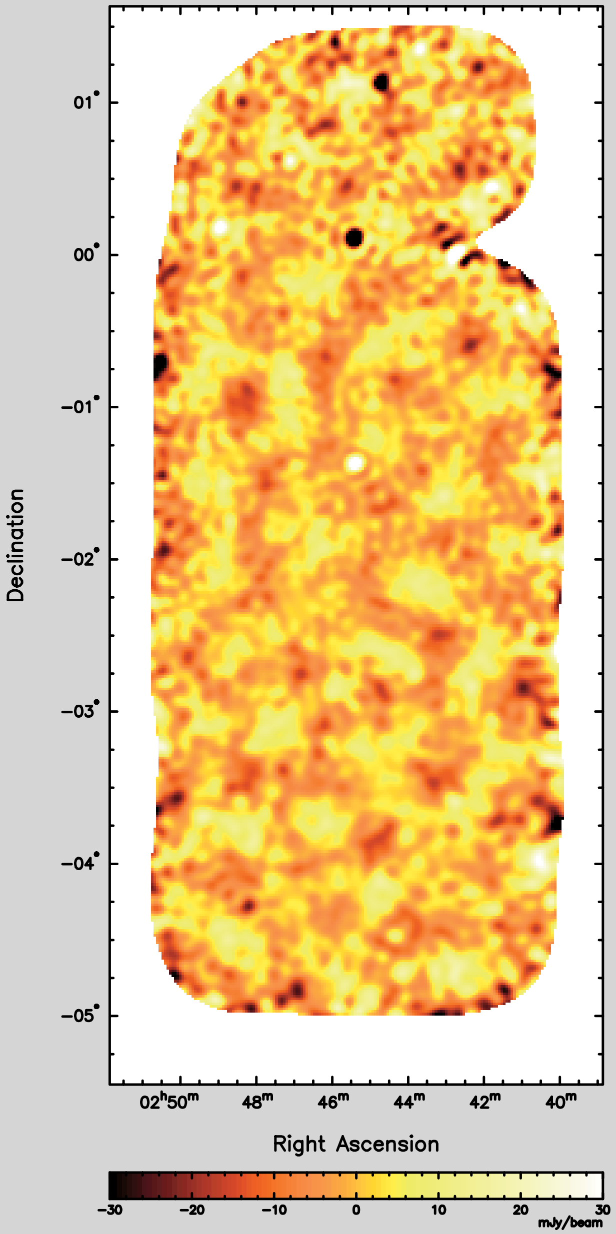
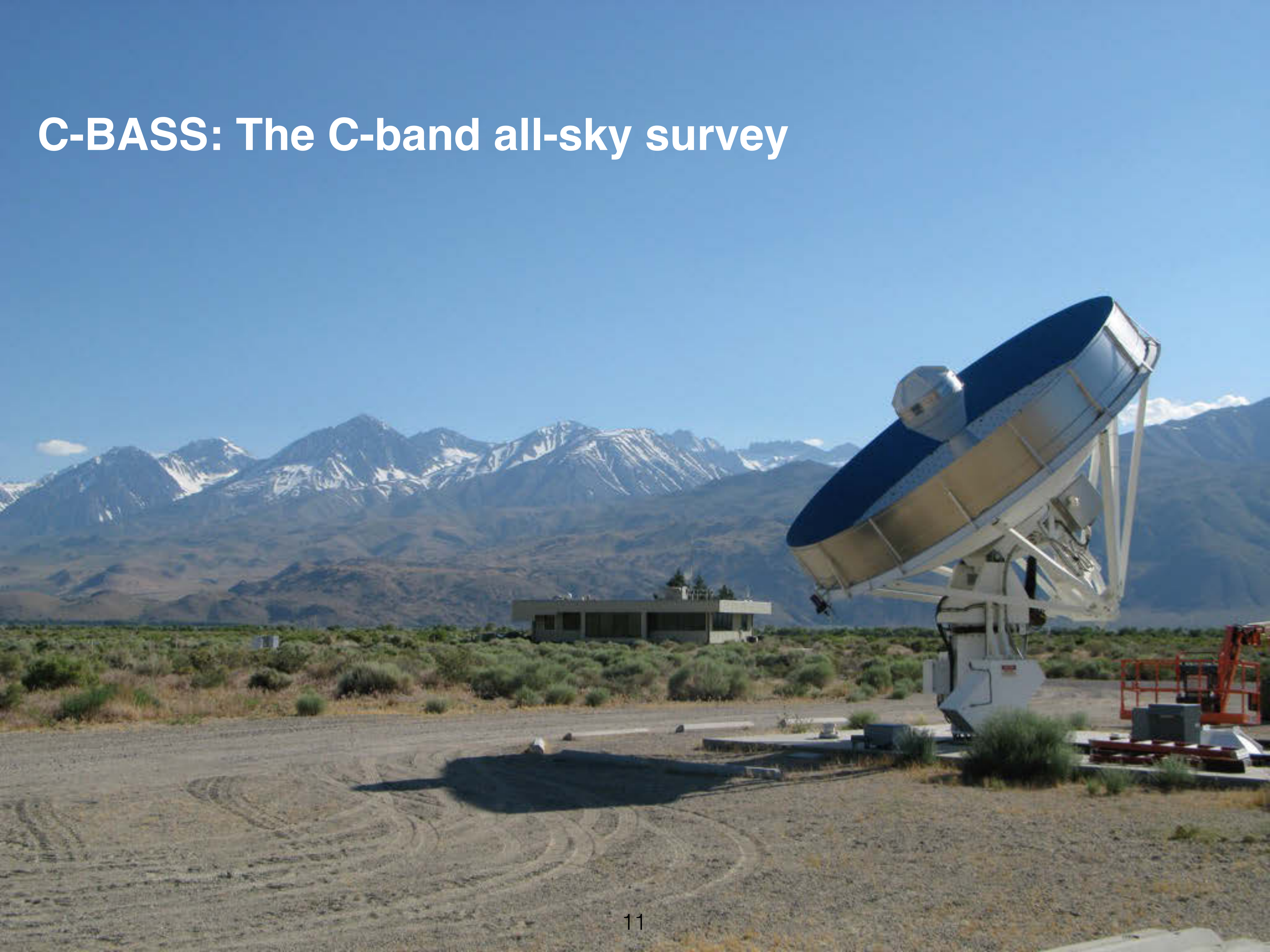


FIG. 10.—Joint power spectrum estimates for the three CBI mosaics. Band power estimates have been made for two alternate divisions of the l range into bins: "even" binning (*green squares*) and "odd" binning (*blue circles*). The error bars show $\pm 1\ \sigma$ uncertainties from the inverse Fisher matrix. Two minimal inflation–based models are shown. *Red:* Fit to CBI plus *COBE* DMR; $\Omega_{\rm tot} = 1.0$, $\Omega_b h^2 = 0.0225$, $\Omega_{\rm cdm} h^2 = 0.12$, $\Omega_\Lambda = 0.6$, $n_s = 0.95$, $\tau_c = 0.025$, $\mathcal{C}_{10} = 786$ μK^2. *Black:* Joint fit to CBI, DMR, DASI, BOOMERANG-98, VSA, and earlier data; $\Omega_{\rm tot} = 1.0$, $\Omega_b h^2 = 0.02$, $\Omega_{\rm cdm} h^2 = 0.14$, $\Omega_\Lambda = 0.5$, $n_s = 0.925$, $\tau_c = 0$, $\mathcal{C}_{10} = 887$ μK^2. For details, see Paper V.



C-BASS: The C-band all-sky survey



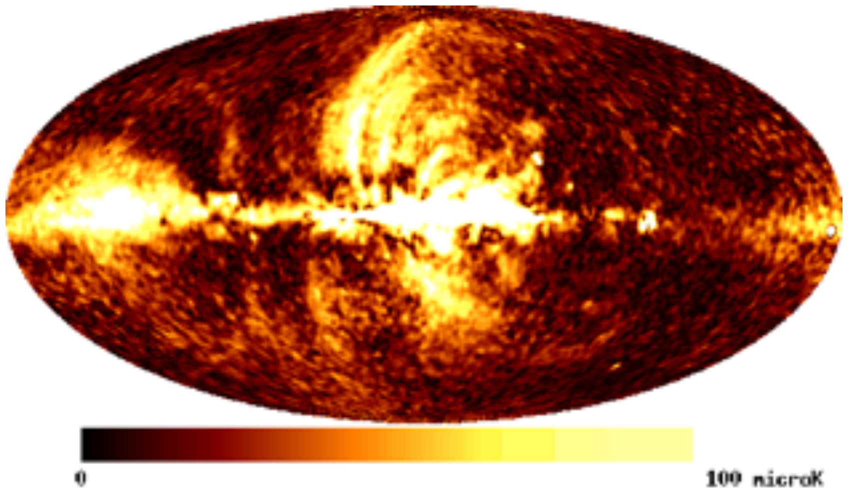
C-BASS: The C-band all-sky survey

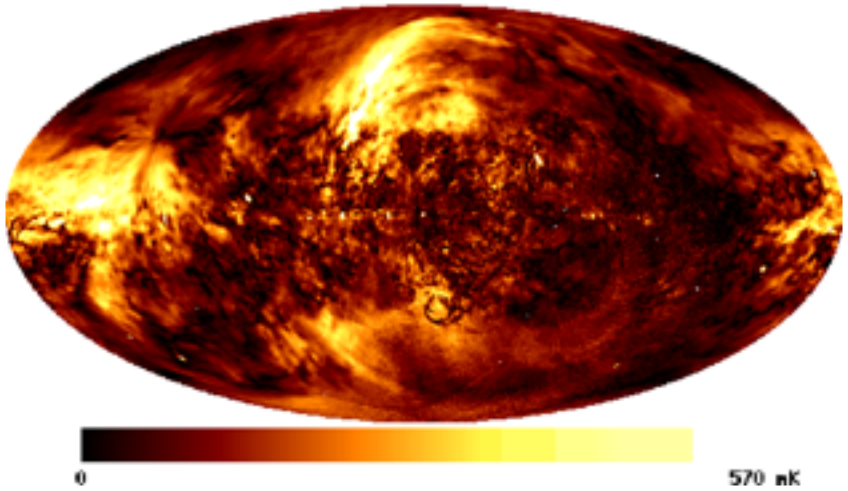
- The C-Band All-Sky Survey (C-BASS) is a project to produce high signal-to-noise all-sky maps at a central frequency of 5 GHz in intensity and linear polarization (Stokes *I*, *Q*, and *U*).
- C-BASS uses two telescopes, one in the northern hemisphere at the Owens Valley Radio Observatory in California, and one close to the South African SKA site. Angular resolution 0.73°.
- Novel optical design to minimize sidelobes.
- Nominal bandwidth 1 GHz.
- Thermal noise sensitivity is ~3 mK√s in *I* and ~2 mK√s in *Q/U*, with a target survey thermal noise level of 0.1 mK.
- Maps at this frequency are dominated by synchrotron radiation and largely uncorrupted by Faraday rotation.

Motivation

- The CMB *B*-mode polarization signal is confused by foregrounds at all frequencies, even in clean regions of sky, so foregrounds must be subtracted with high accuracy.
- Low-frequency foregrounds (synchrotron, free-free, and AME “spinning dust”) have complicated spectra.
- Foreground modeling needs ground-based observations below the “space microwave band”, i.e., < 20 GHz
- Polarization must be corrected for Faraday rotation and depolarization
- 5 GHz is trade-off between sensitivity and Faraday rotation

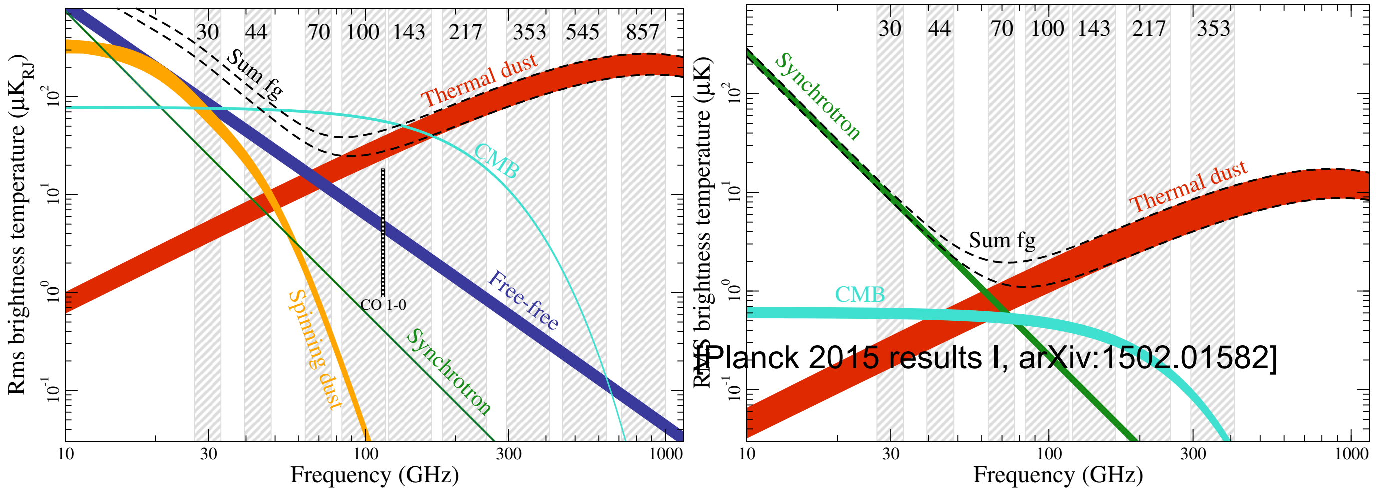
WMAP 23 GHz polarized intensity





DRAO/Villa Elisa 1.4 GHz

Sun et al. A&A 477, 573–592 (2008)



[Planck 2015 results I, arXiv:1502.01582]

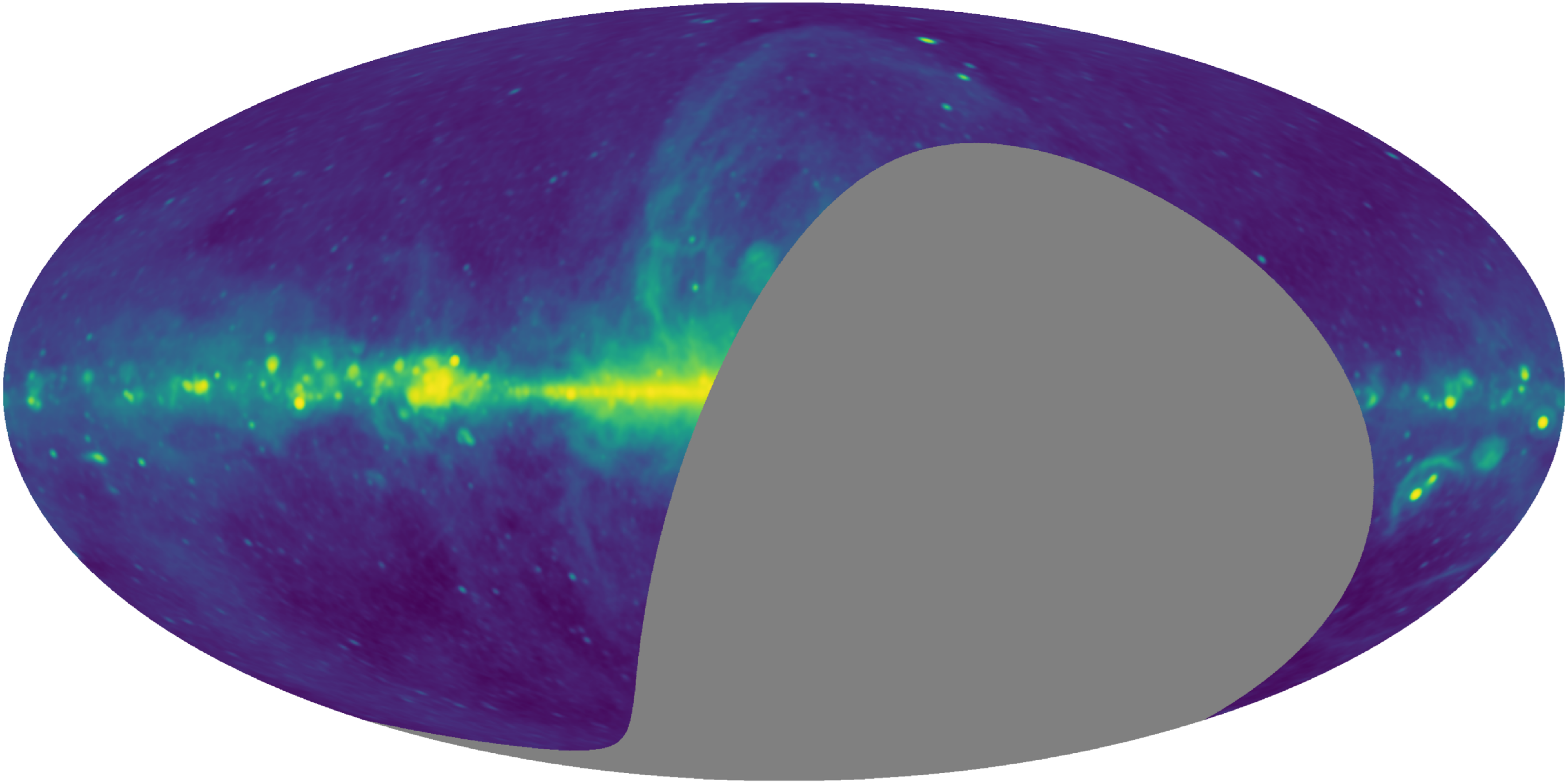
Fig. 18. Brightness temperature rms of the high-latitude sky as a function of frequency and astrophysical component for temperature (*left*) and polarization (*right*). For temperature, each component is smoothed to an angular resolution of 1° FWHM, and the lower and upper edges of each line are defined by masks covering 81 and 93 % of the sky, respectively. For polarization, the corresponding smoothing scale is 40′, and the sky fractions are 73 and 93 %.

Two Telescopes

OVRO California

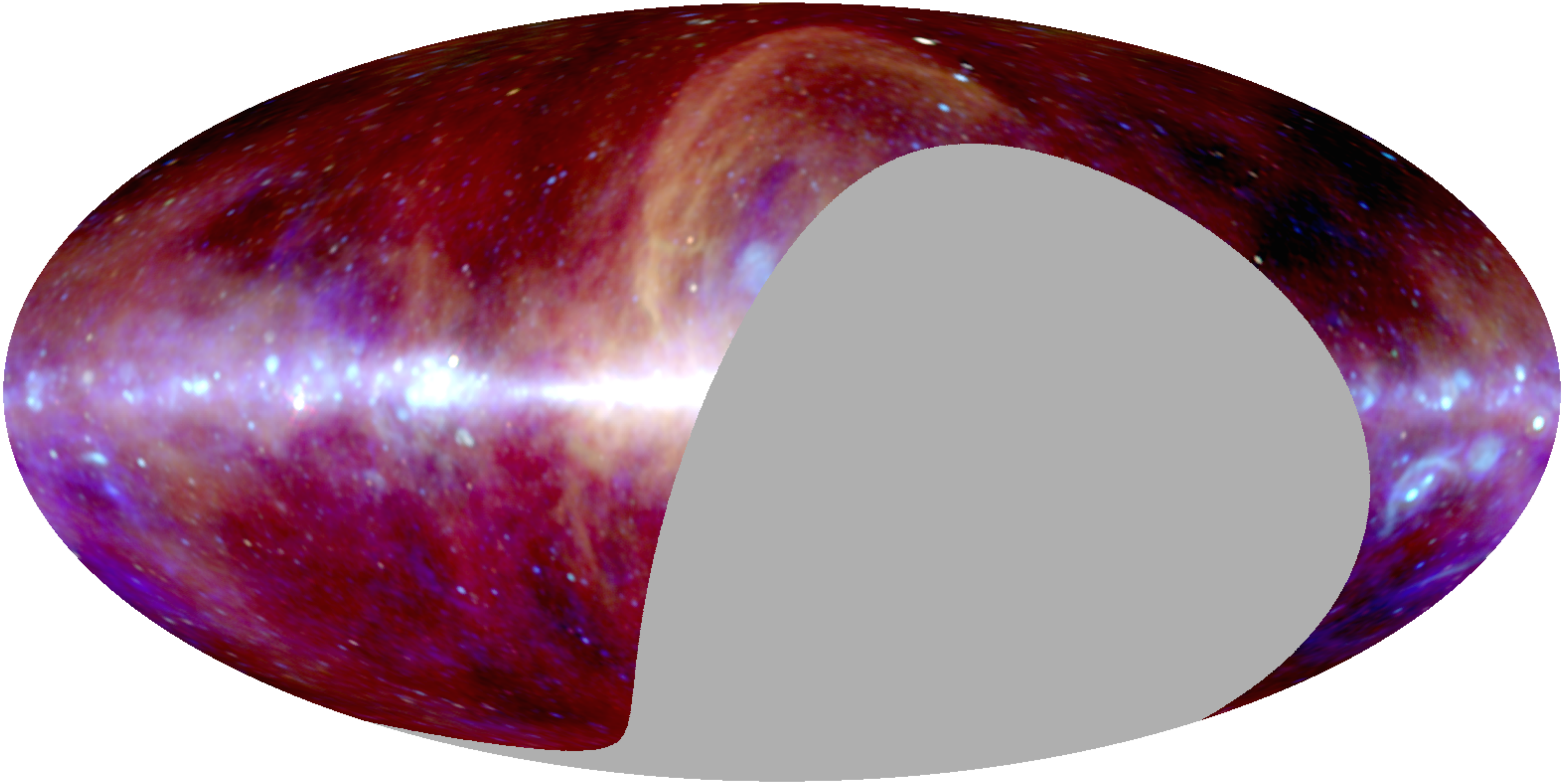
Klerefontein South Africa (SKA site)

CBASS-N intensity



CBASS-north: sky map of total intensity. Night-time only data, all elevations (37, 47, 67, and 77 deg), non-linear color scale.

408 MHz – 5 GHz – 23 GHz



CBASS-north: three-color image : RED: Haslam et al 408 MHz map; GREEN: C-CBASS 5-GHz map; BLUE: WMAP K-band with the CMB removed. Colors balanced such that a temperature spectrum of index −2.7 would appear white. Synchrotron emission appears as red or orange, free-free as white or light blue; AME as dark blue.

NCP

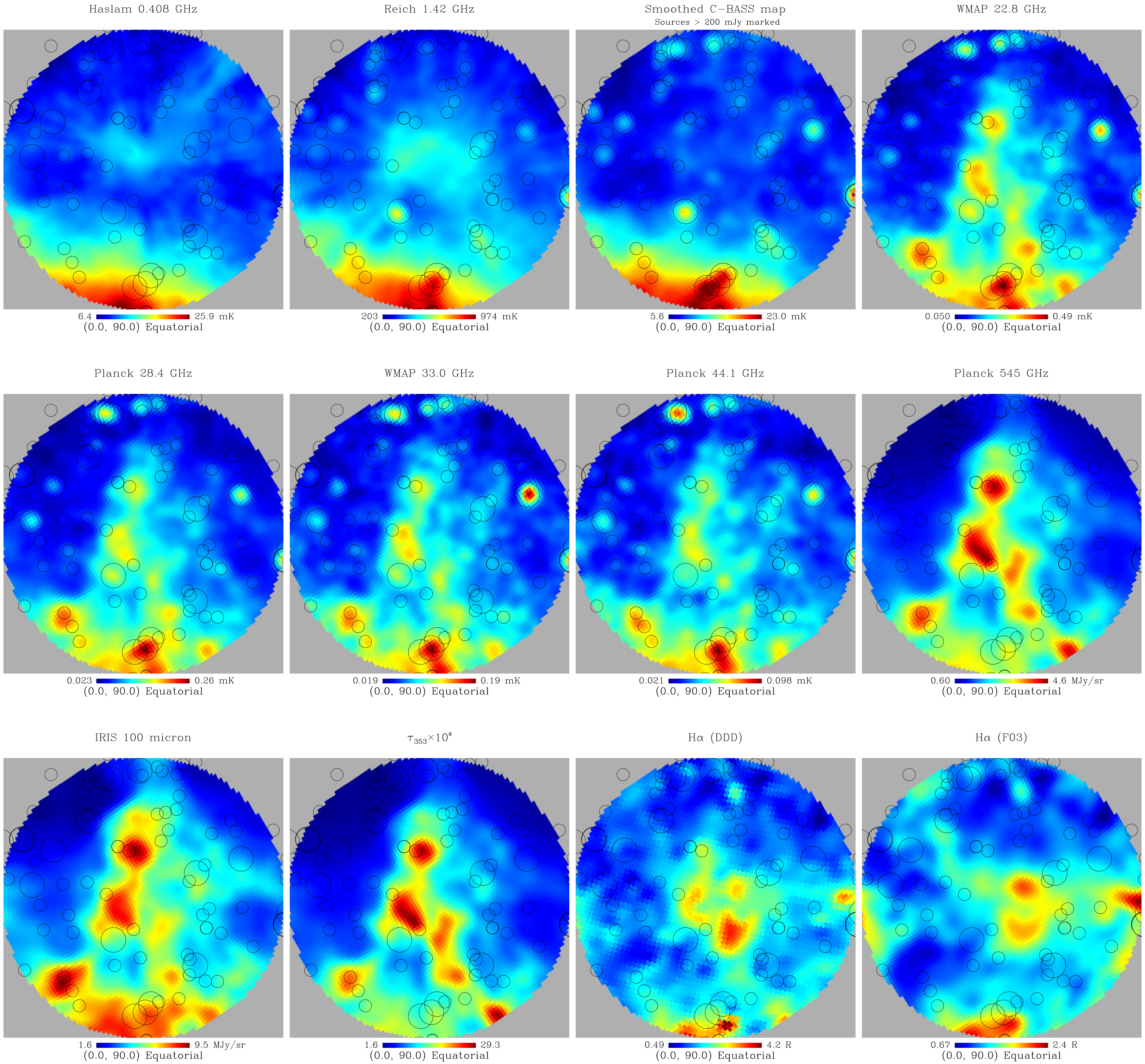
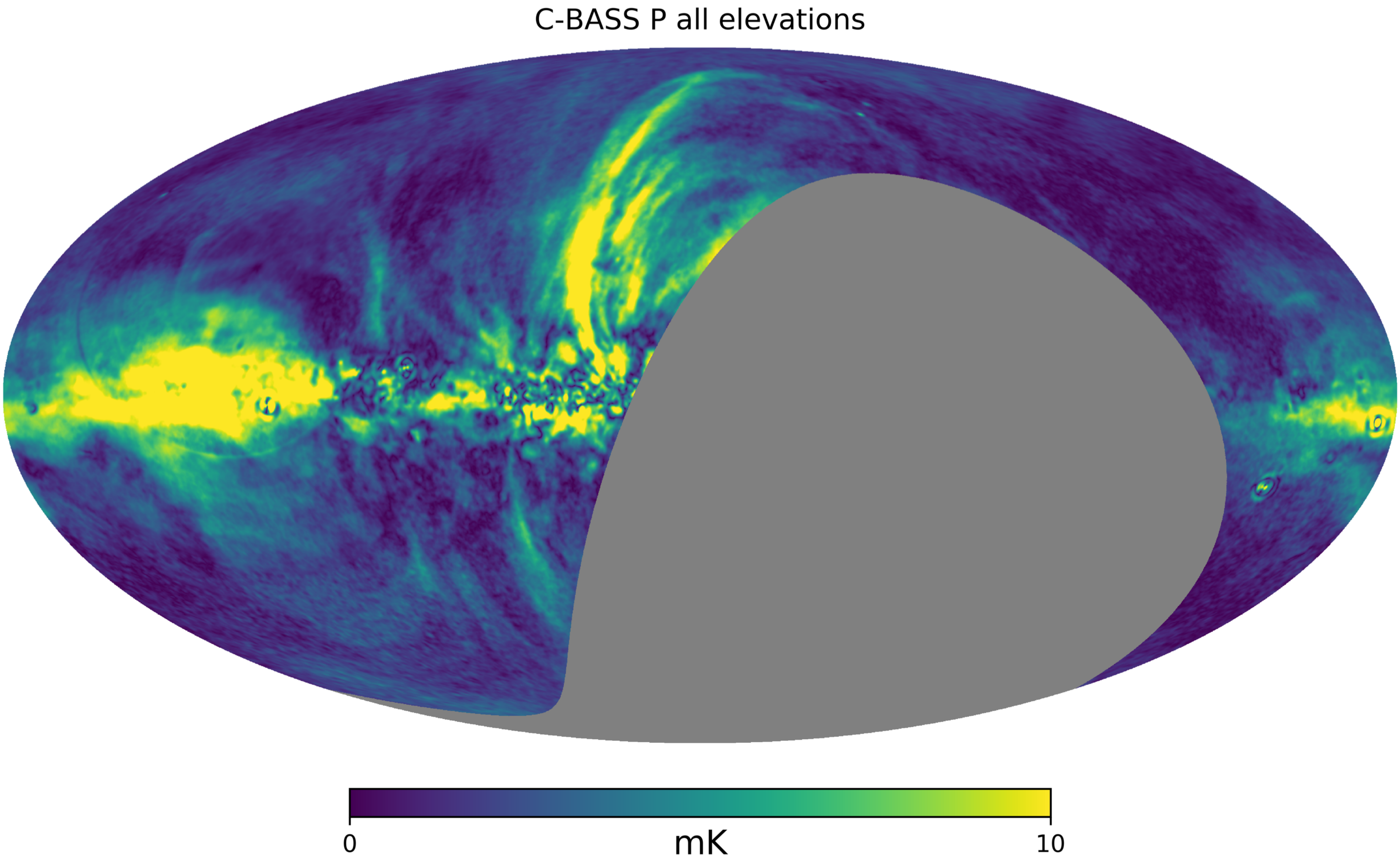
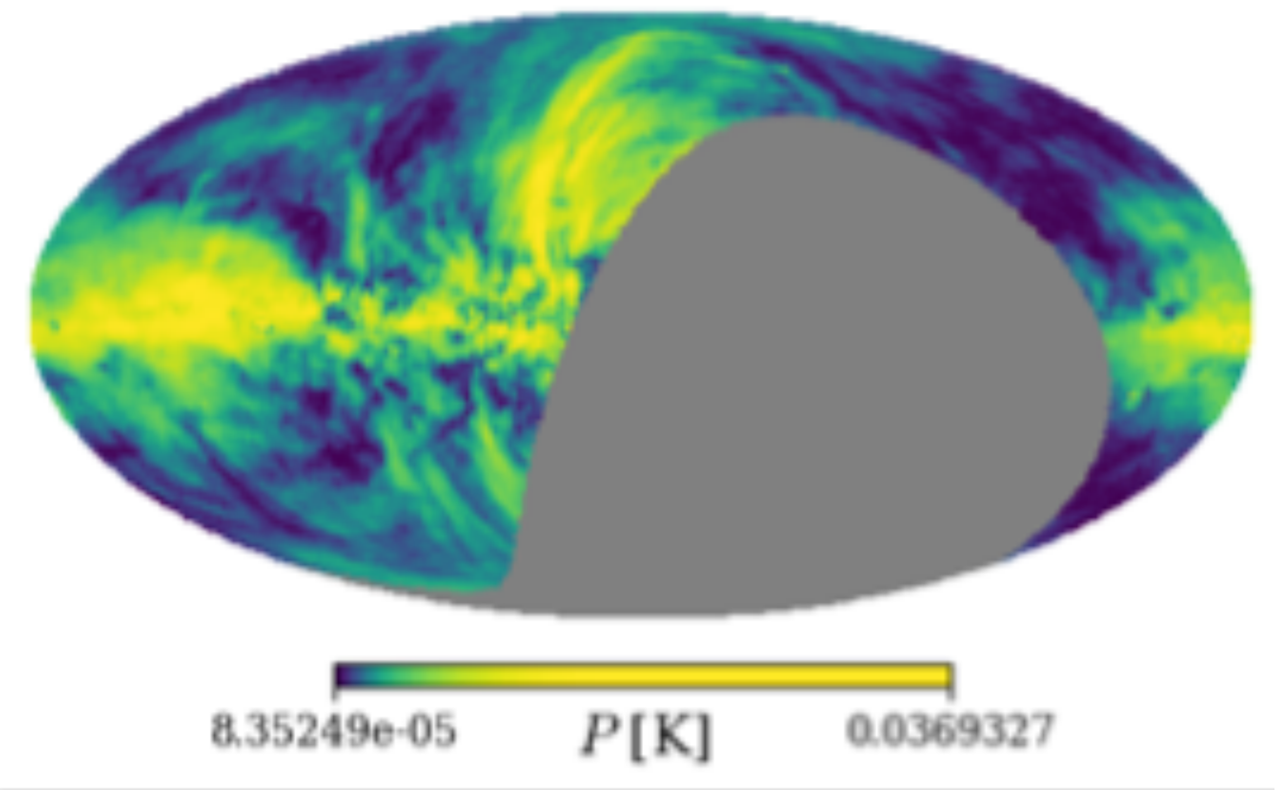


Figure 3. Multi-frequency maps of the NCP region at a common resolution of 1° (see Table 2 for details). The panels are arranged in increasing frequency order: 0.4, 1.42, 4.7, 22.8, 28.4, 33.0, 41.0, 545, 3000 GHz (100 μm). The last three panels are τ_{353}, followed by two versions of the Hα map (D03 and F03). The colour scales are all on a linear stretch. Radio sources are indicated by circles as in previous figures. The dust-correlated AME structure (e.g., at 545 GHz, 100 μm, τ_{353}) is clearly visible at 22.8 and 28.4 GHz but not at 4.7 GHz. Striations and other artifacts are also visible in the 0.408/1.42 GHz maps that are not seen in the C-BASS data.

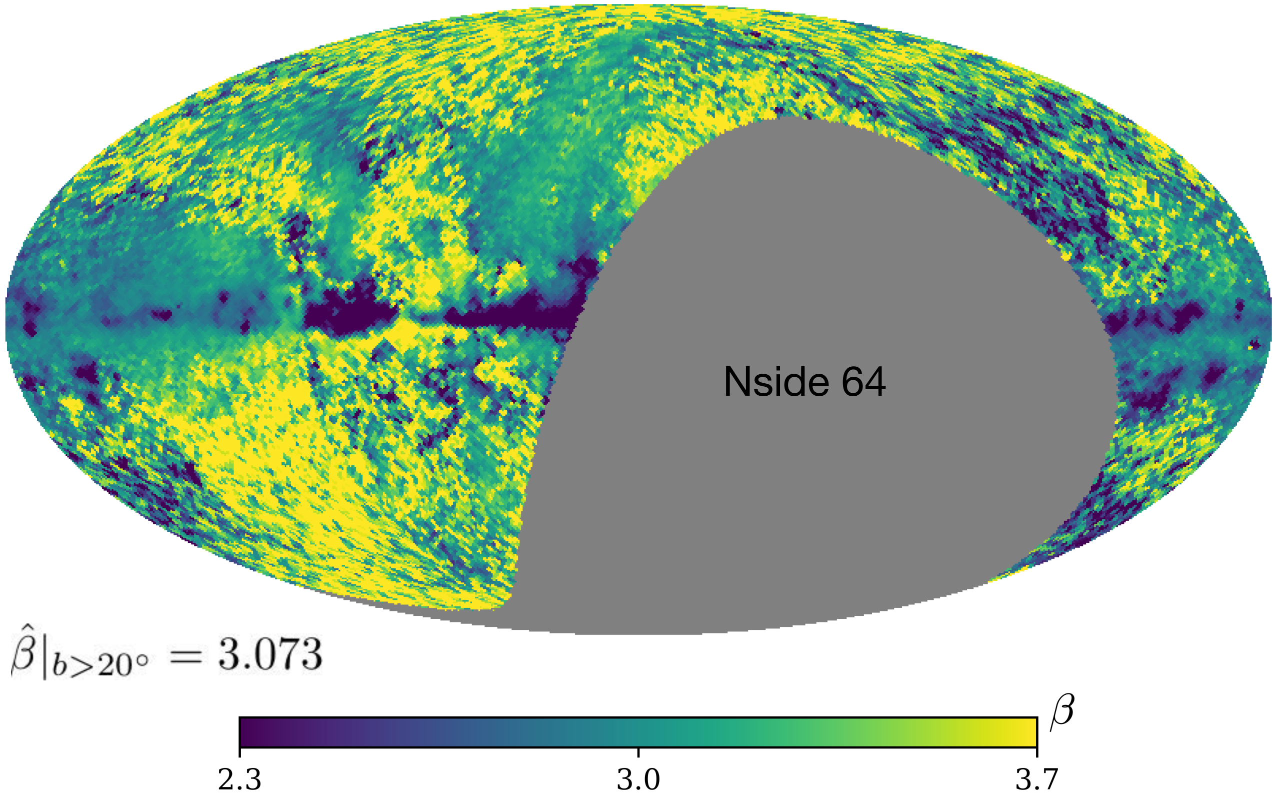
CBASS-N polarized intensity



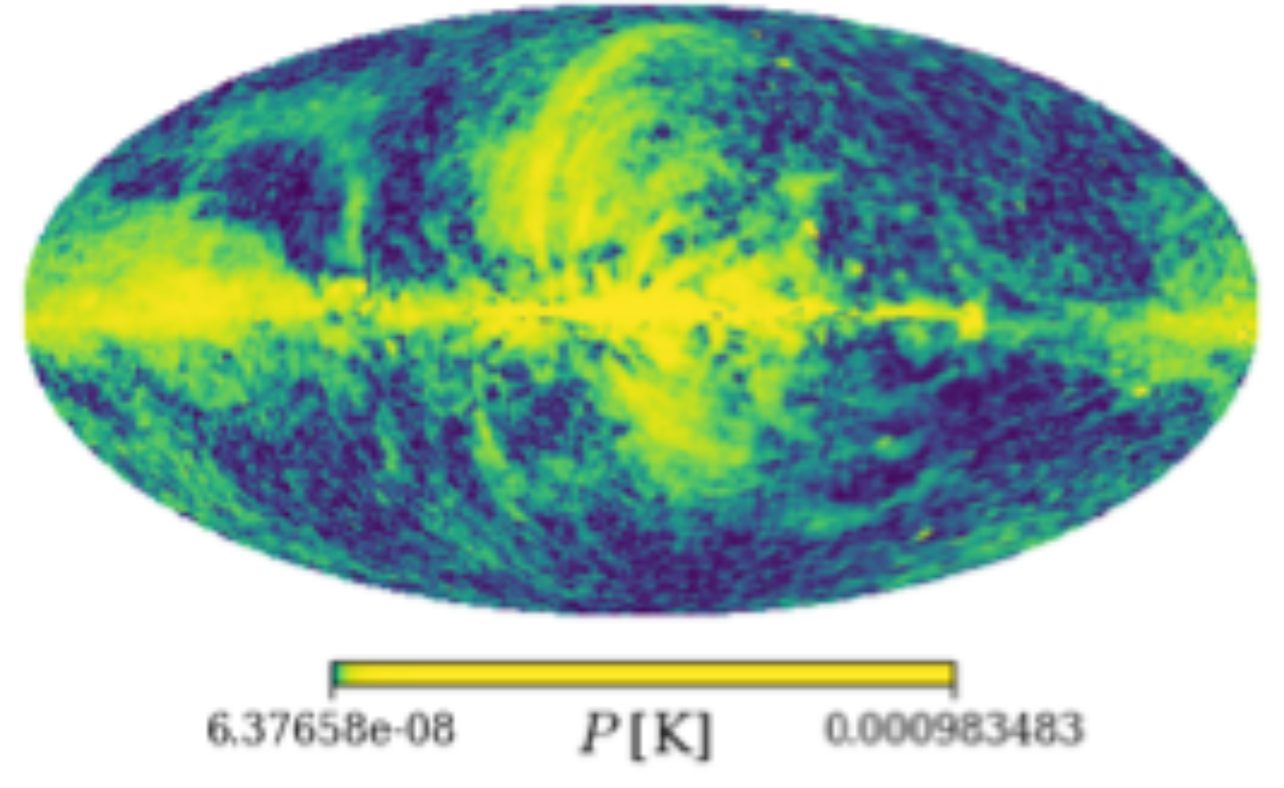
Polarized spectral indices 5 – 30 GHz



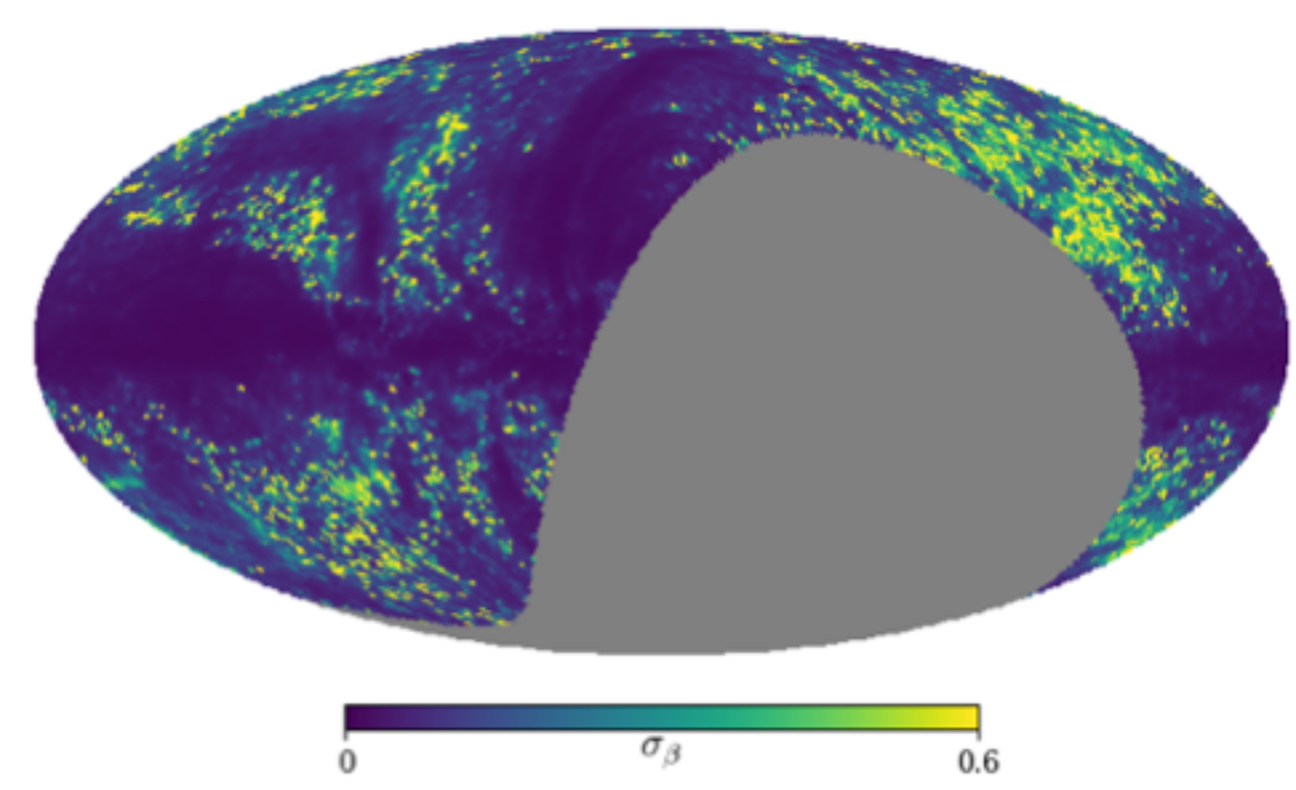
(a) C-BASS *P* map



Spectral index map

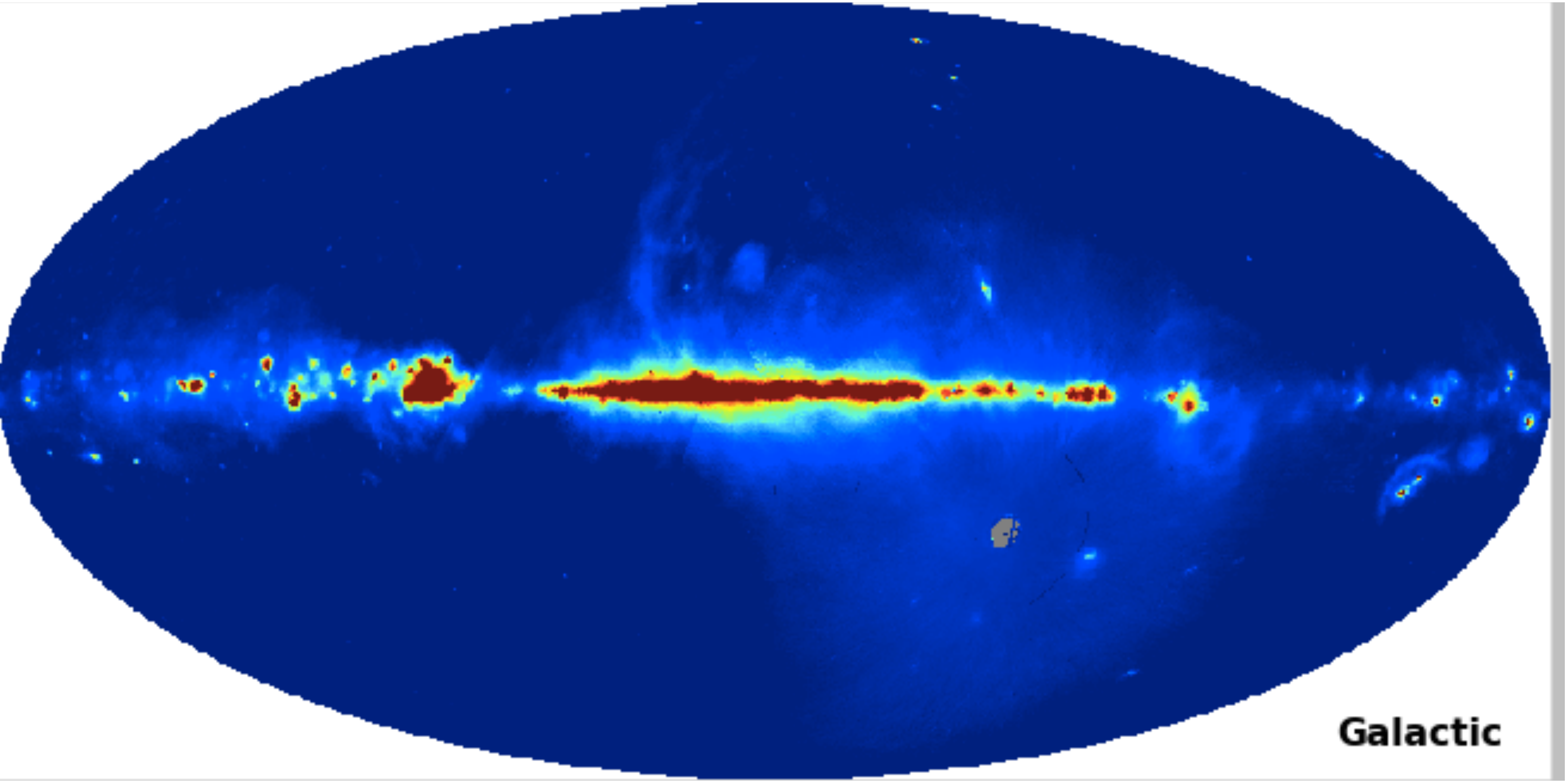


(c) *Planck* 30 GHz *P* map



Spectral index error map

First full-sky C-BASS map



Uncalibrated intensity map

Issues for the future

- We need maps at many frequencies to fully characterize foregrounds even in the cleanest areas of sky
- We will need maps like C-BASS, only better, at multiple frequencies, with higher resolution than C-BASS, and (ideally) matched beams
- Problems to be tackled:
    - Ground pickup (need good ground screens)
    - RFI (radio frequency interference) – getting worse
    - Sun and other sources in far sidelobes
    - Instrumental stability (easier in space?) and control of systematics
    - Polarization calibration (C-BASS is tied to Tau A, which is uncertain at ~ 1% or 1 deg)
    - Zero level (cf. ARCADE)

C-BASS: The C-band all-sky survey

- *C-BASS is a collaborative project between:*
- Oxford University (UK) *supported by Oxford University, STFC, and the Royal Society*
    - Angela Taylor, Mike Jones, Jamie Leech, Luke Jew, Richard Grummit
- Manchester University (UK)
    - Clive Dickinson, Paddy Leahy, Stuart Harper, Adam Barr, Mel Irfan, Rod Davies, Richard Davis, Mike Peel, Joe Zuntz
- California Institute of Technology (USA) + OVRO + JPL *supported by NSF and NASA*
    - Tim Pearson, Stephen Muchovej, Tony Readhead, Oliver King, Erik Leitch, Matthew Stevenson, Sebastian Kiehlmann
- South Africa *supported by the Square Kilometre Array project*
    - Justin Jonas, Charles Copley, Cynthia Chiang, Jon Sievers, Moumita Aitch, Heiko Heiligendorff
- KACST: King Abdulaziz City for Science and Technology (Saudi Arabia)
    - Yaser Hafez