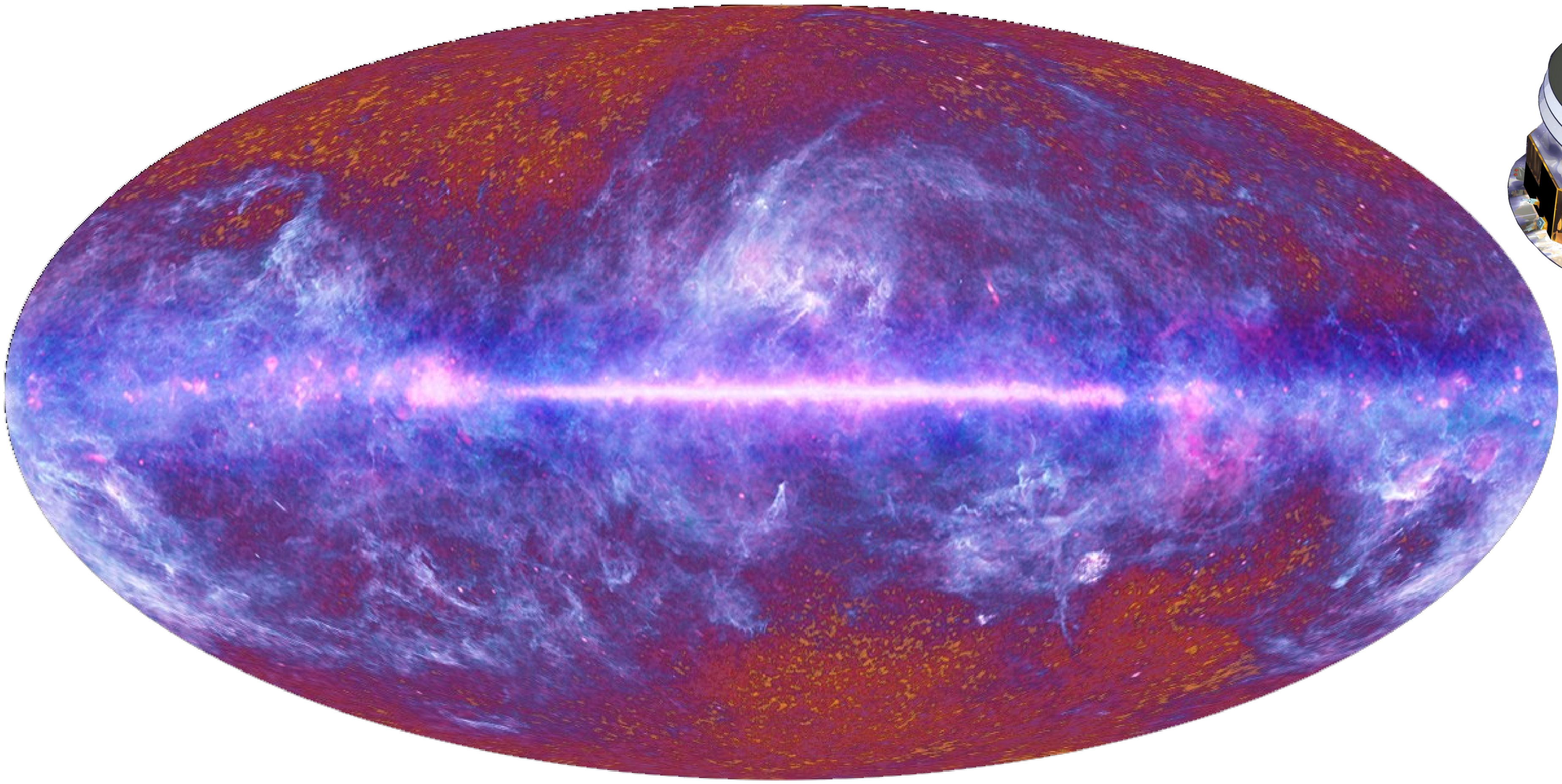
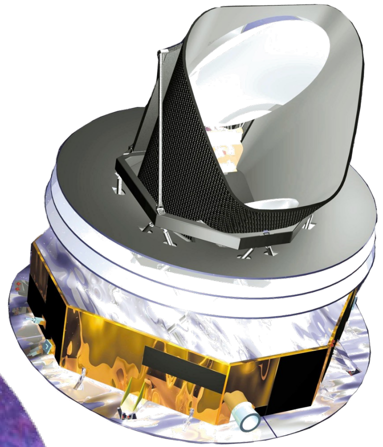
CMB Foregrounds:
Just how bad are they?



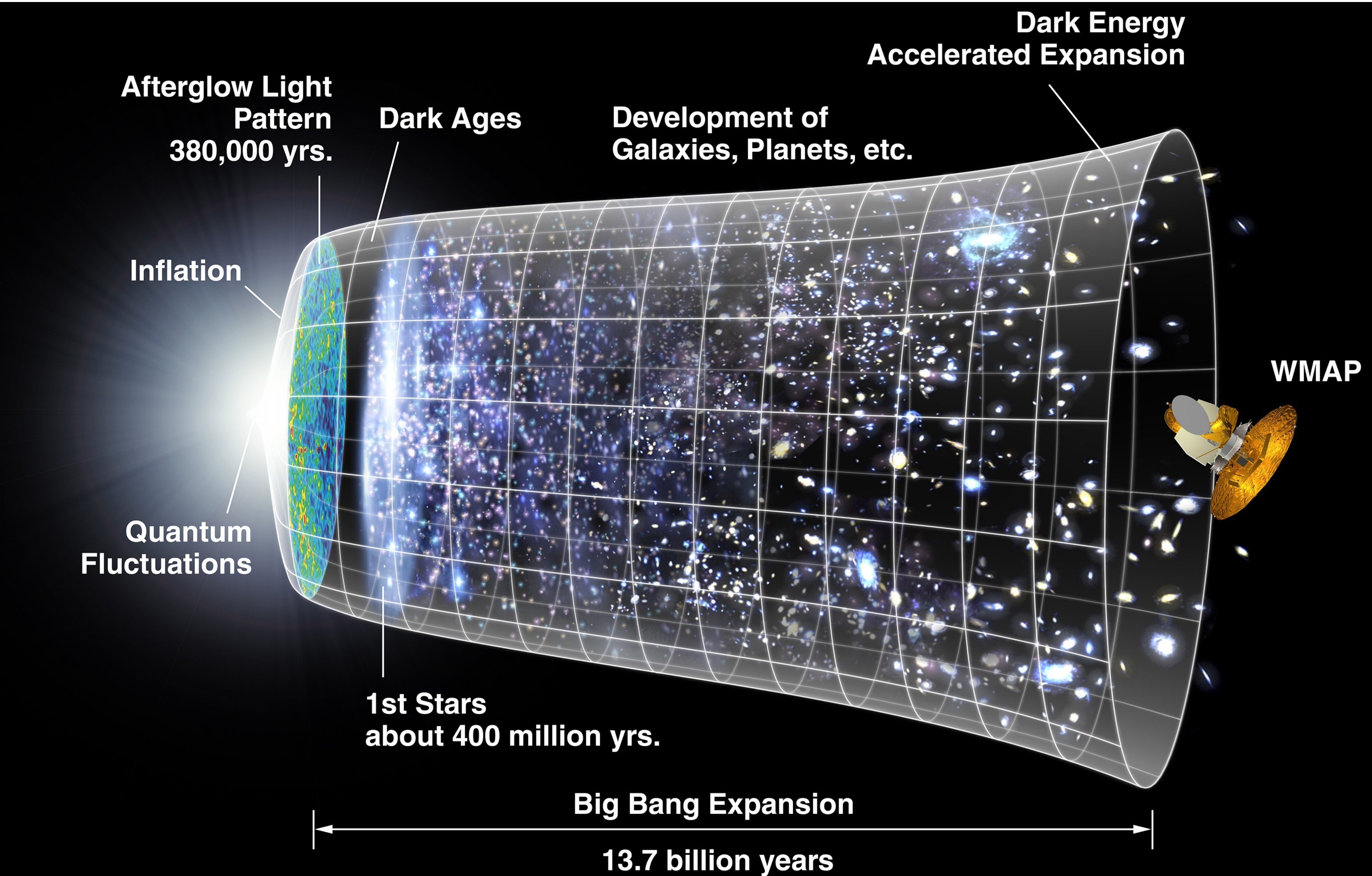


Clive Dickinson
Jodrell Bank Centre for Astrophysics
The University of Manchester

Towards a next space probe for CMB observations and cosmic origins exploration, CERN, 17-20May 2016

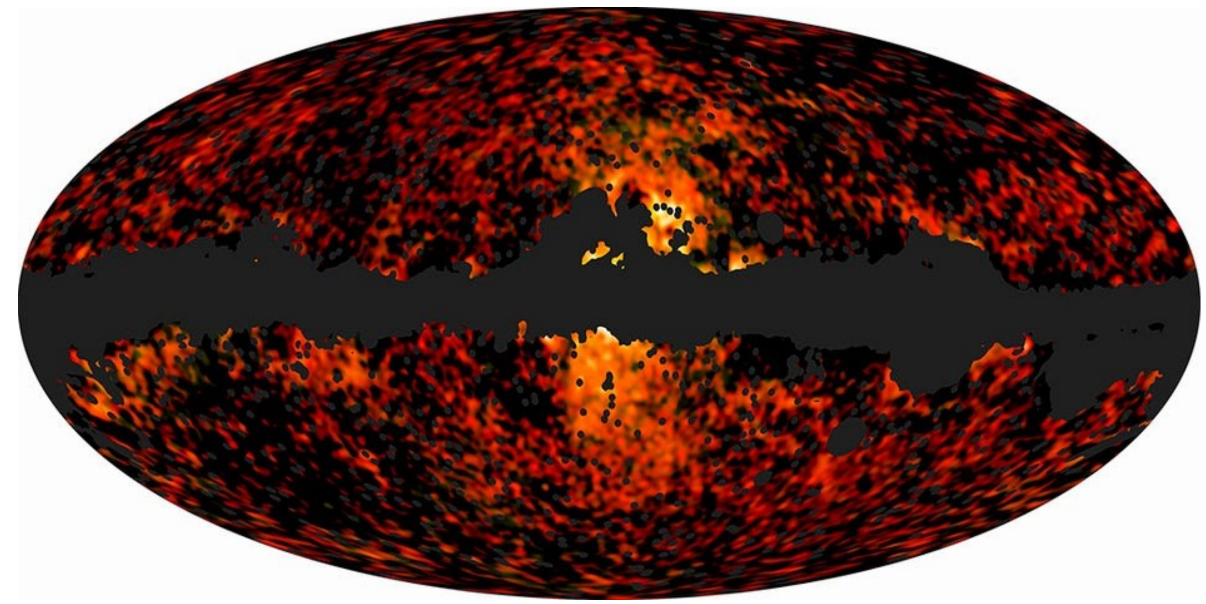
CMB foregrounds

Foregrounds are everything between the CMB (last scattering surface at z=1090) and the detectors!

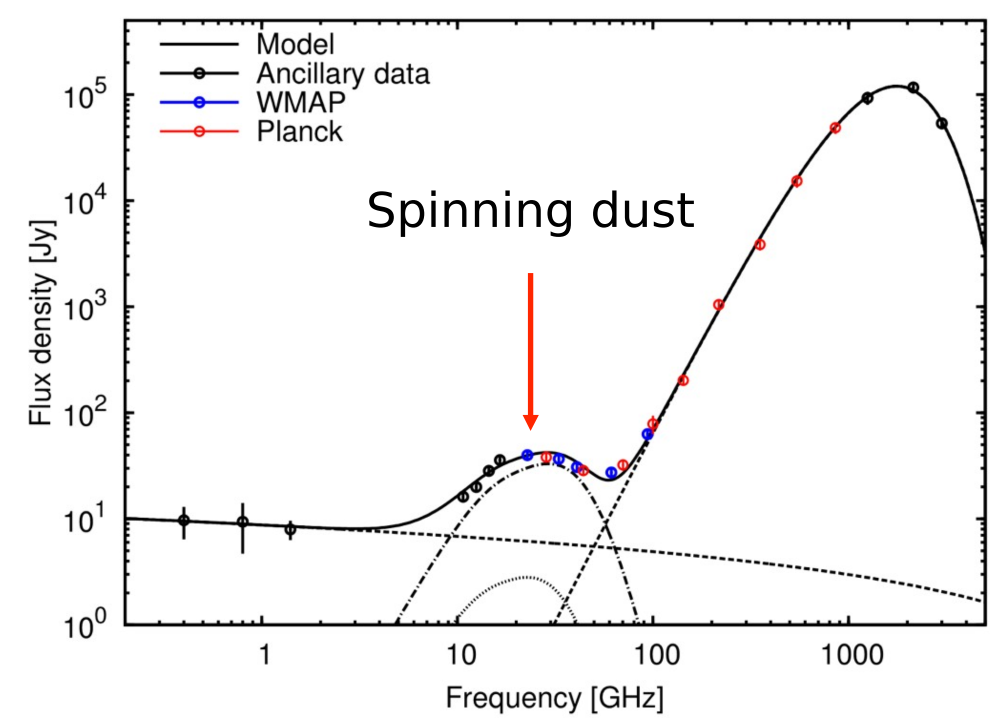


Foregrounds are fun! (for some of us)

- **Foregrounds are interesting in themselves - astrophysics!**
  - Physical emission mechanisms
  - Galactic structure
  - Galactic magnetic field
  - Interstellar medium (density, temperature...)
  - Star formation
  - Extinction
  - Astrochemistry
  - Galaxy formation
  - Large-scale structure
  - ...
- **Astrophysical knowledge can inform CMB component separation**

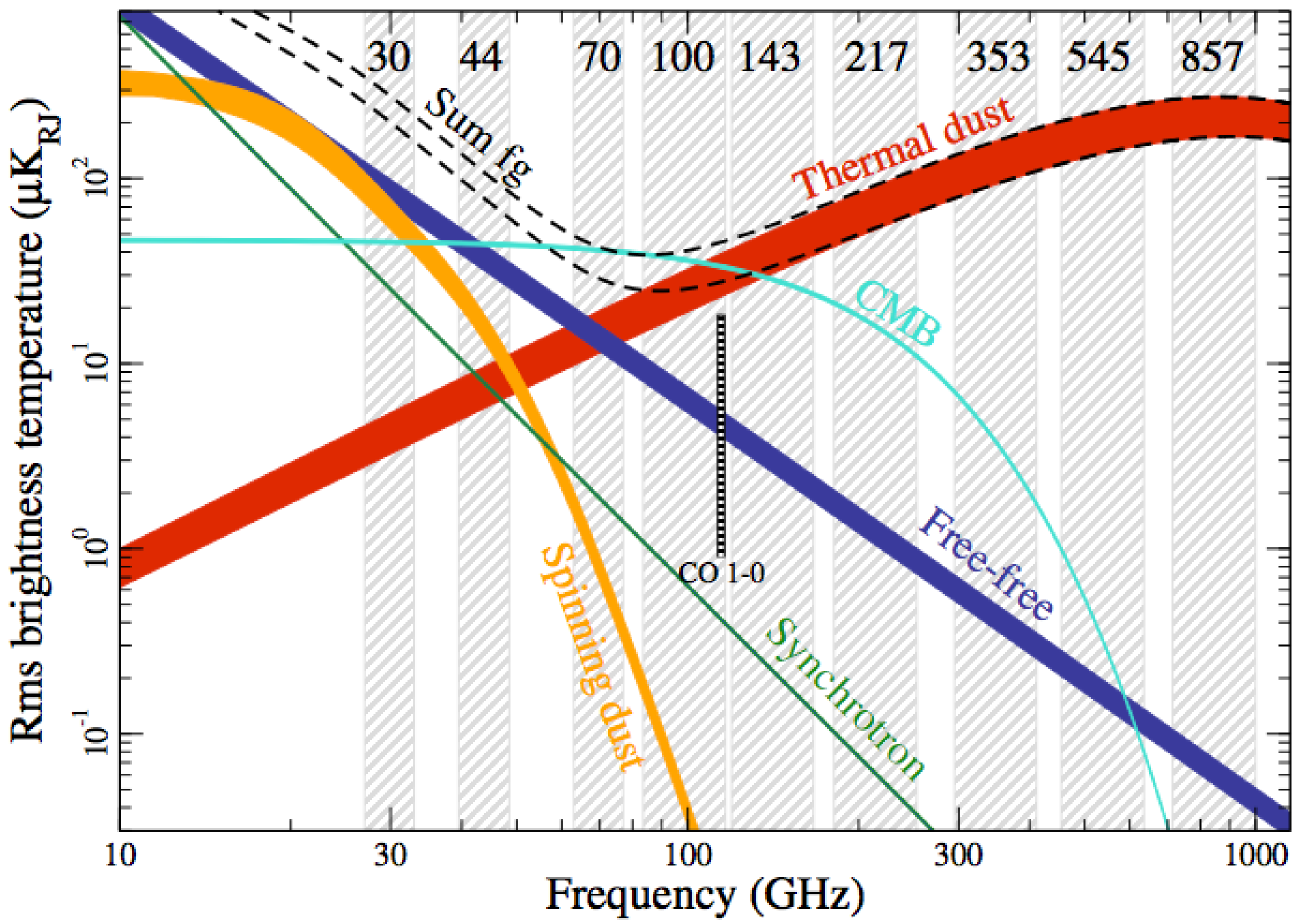


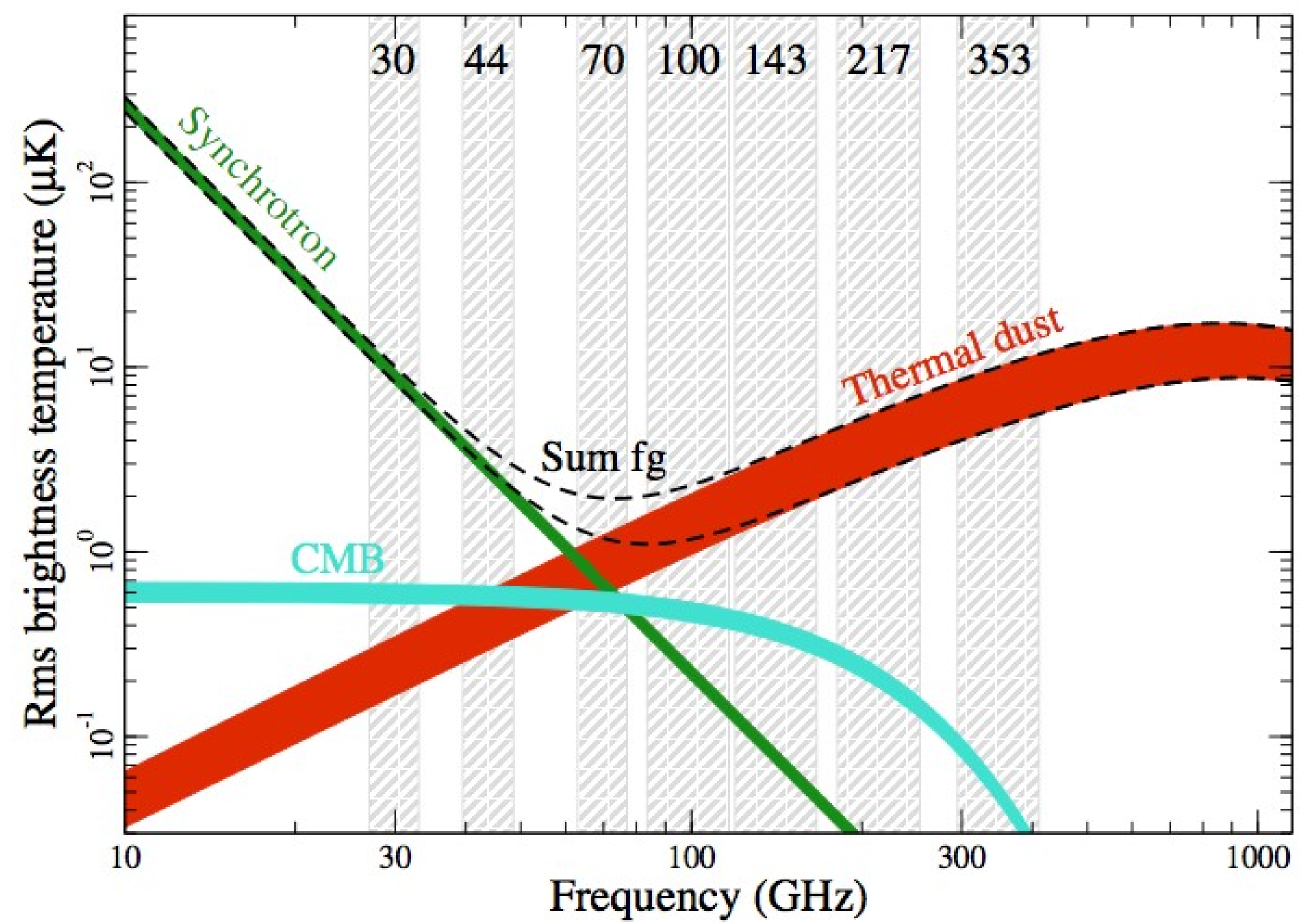
The WMAP/Planck Microwave haze:
Relativistic electrons outflowing from the Galactic Centre
Planck Collaboration, 2013, Int results, XI



Detection of spinning dust grains
Planck Collaboration, 2011, A&A, 534, A20 (XX)

Galactic foregrounds

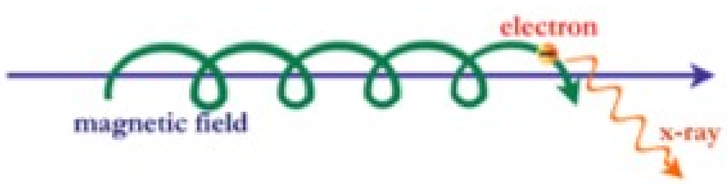




Planck Collaboration, 2015, arXiv:1502.01588

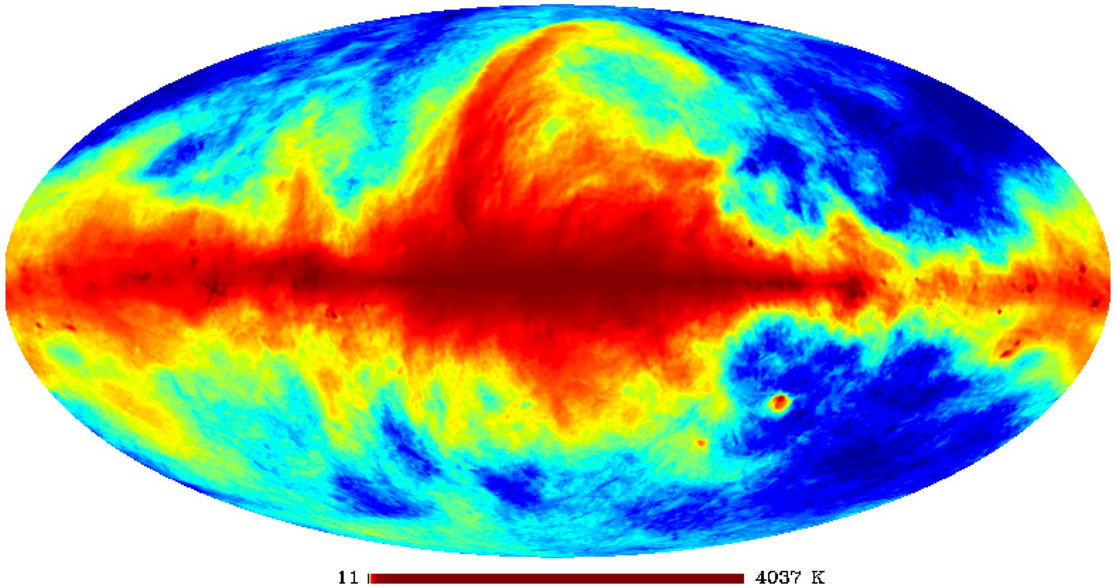
- **Galactic foregrounds dominate on large angular scales (>~1 deg)**
- Total intensity appear to be more complicated than polarisation!
  - BUT, CMB window at ~40-200 GHz range for some areas of sky and on medium (~1 deg) scales
  - **Foreground minimum at ~80 GHz**
- Polarization might be less complicated but requires higher precision (CMB weaker)
  - **Foreground minimum at ~70 GHz**

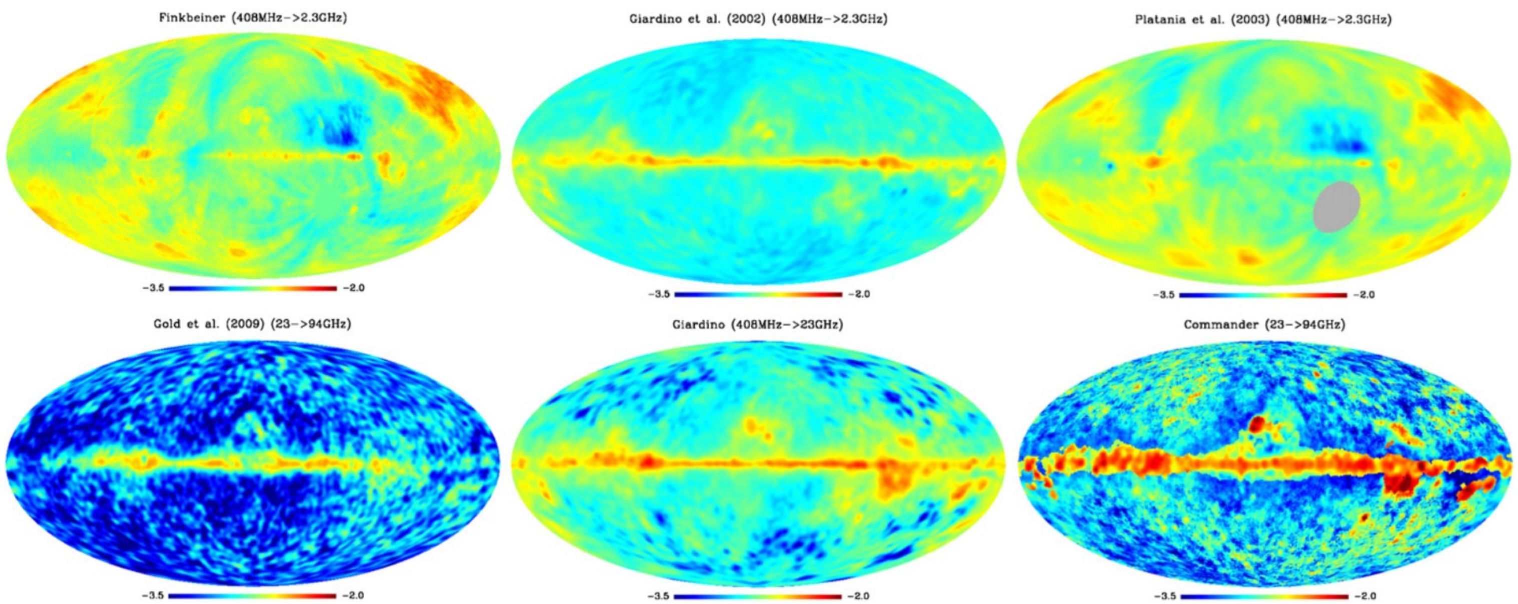
Synchrotron radiation



- Relativistic cosmic ray electrons accelerating in Galactic magnetic field
  - CR energy spectral index p~3.0 at GeV energies
- Integration of power-law distribution of Larmor law gives another power-law
  - Synchrotron spectral index **β~-2.7 +/- 0.2 at ~1 GHz**
- Synchrotron radiation dominates at **low frequencies**

Dickinson et al. (2009)



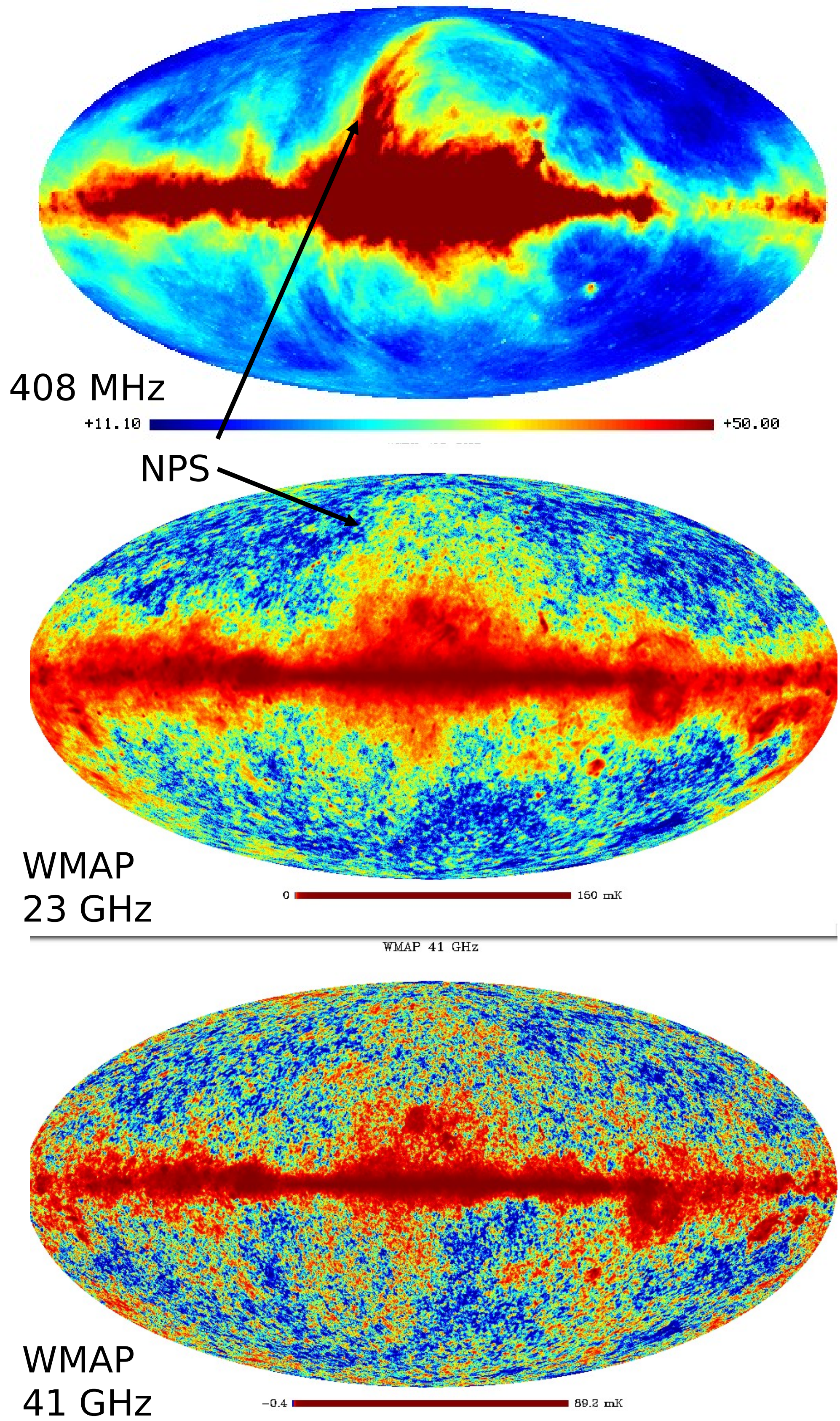


408 MHz all-sky map (Haslam et al. 1982)
Remazeilles et al. (2015): new version with better destriping & desourcing

Synchrotron spectral indices are not very accurate
Low freqs: data quality (systematics)
High freqs: component separation

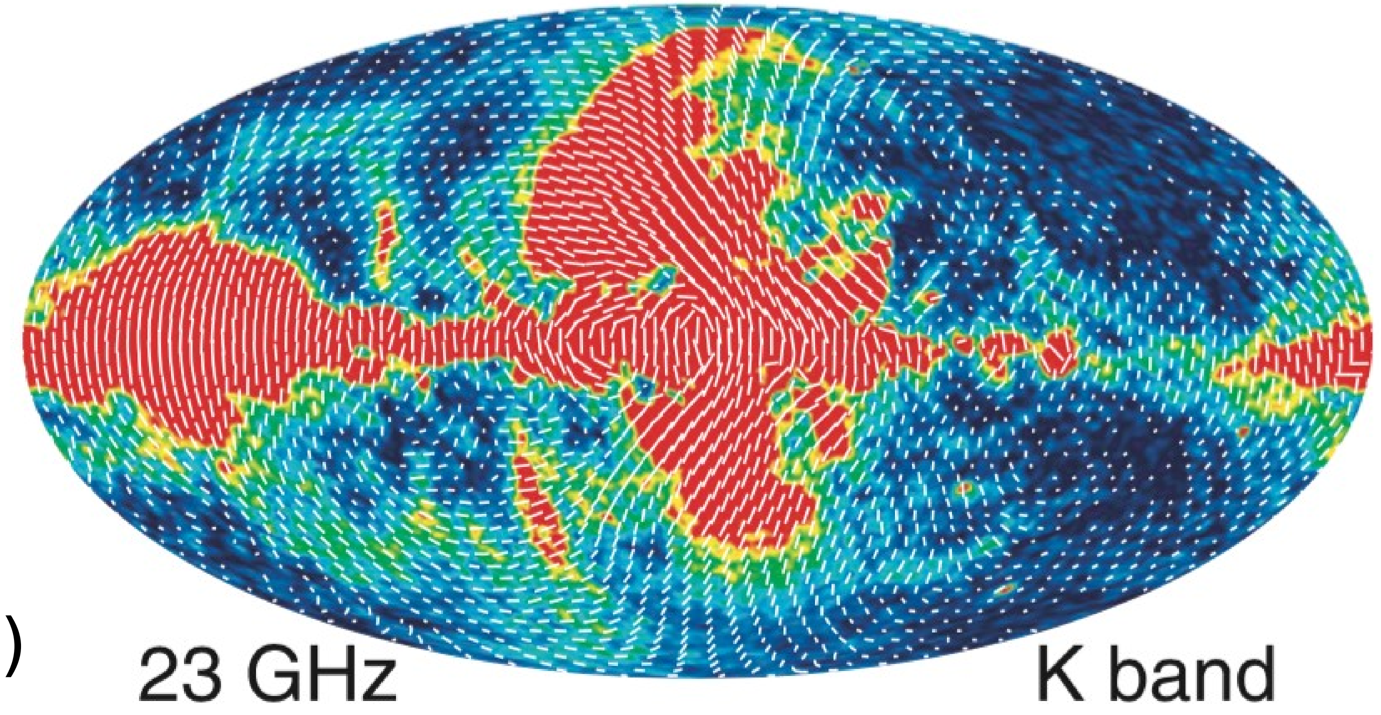
Synchrotron at CMB frequencies

- High energy electrons lose energy more quickly (spectral ageing):
  - **β~-3.0 +/- 0.1 above ~5 GHz**
  - -> **Curved synchrotron spectrum**
- Relatively weak at frequencies above ~30 GHz
  - Except bright supernova remnants and radio galaxies (bright up to 100+ GHz)
- No strong hard (β~-2.5) synchrotron emission outside of Galactic plane/centre region
- **But requires high sensitivity and high fidelity ~5-15 GHz data to be sure!…**
  - **Accurate spectral index extrapolation**
  - **Flat spectrum components at high frequencies?**

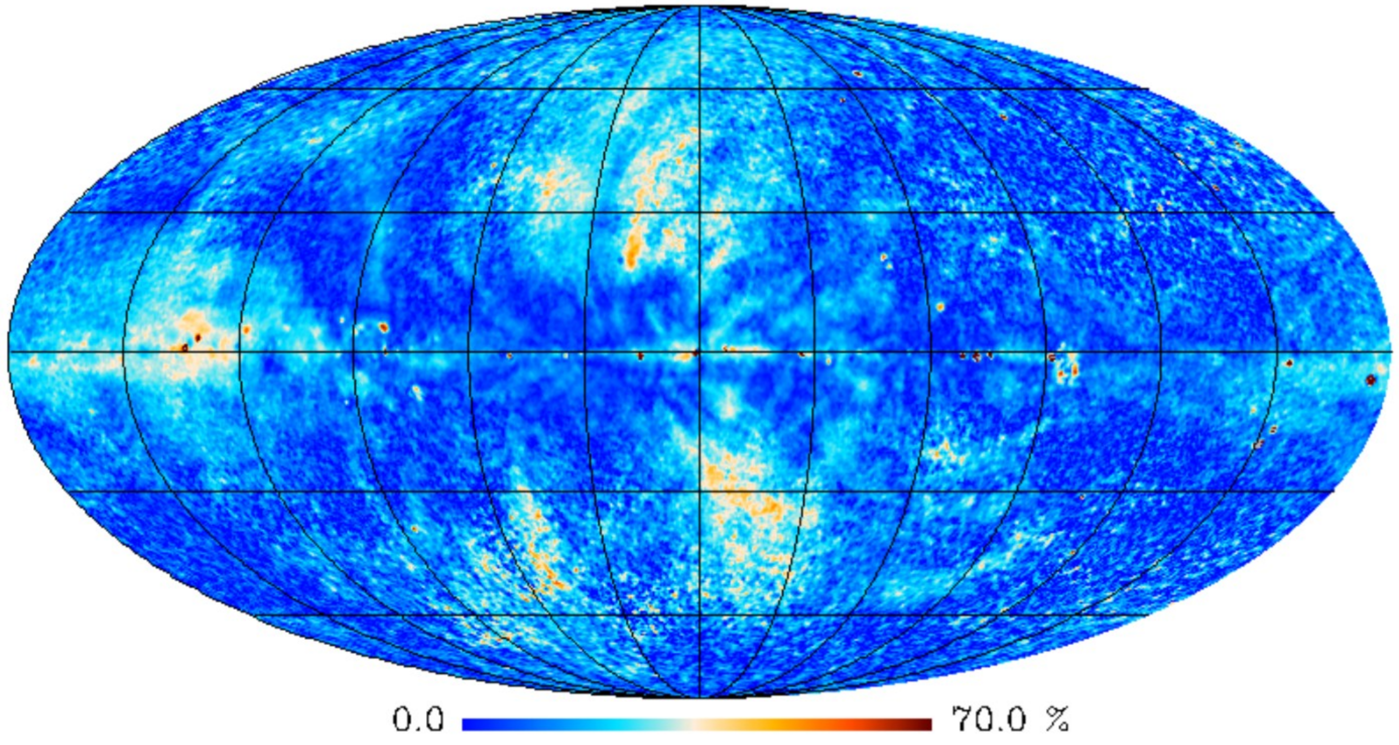


Polarised synchrotron radiation

- Dominates polarised sky up to ~70 GHz !
- Up to 70% polarised (theoretically)
  - **~40-50% max observed**
  - **~20% typical**
- Steep spectrum **β~-3.05+/-0.1**
- Low frequencies (< few GHz) corrupted by Faraday Rotation
- WMAP 23 GHz/Planck 28.5 GHz only good templates so far



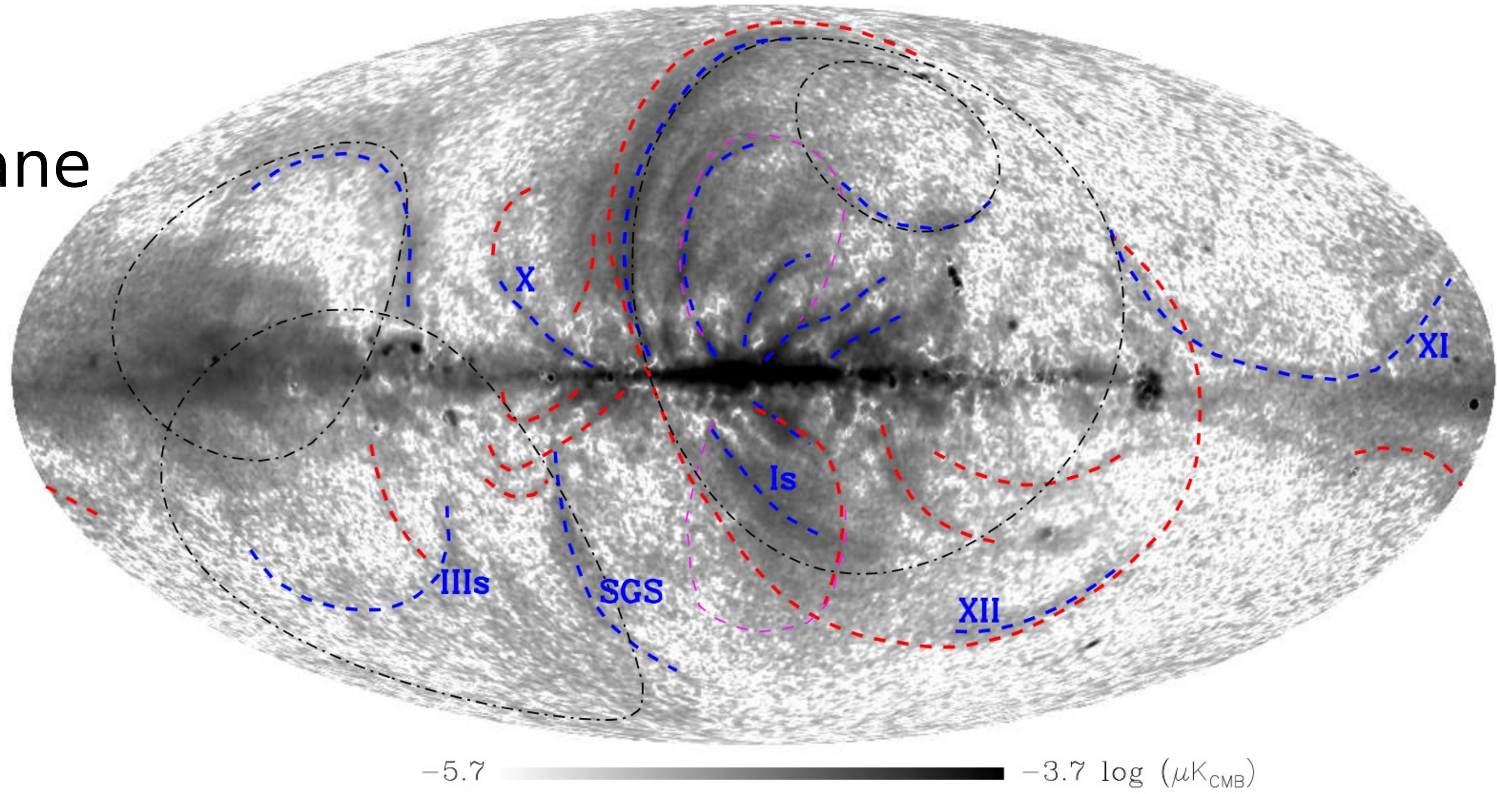
WMAP 9-year 23 GHz polarised intensity
(Bennett et al. 2013)

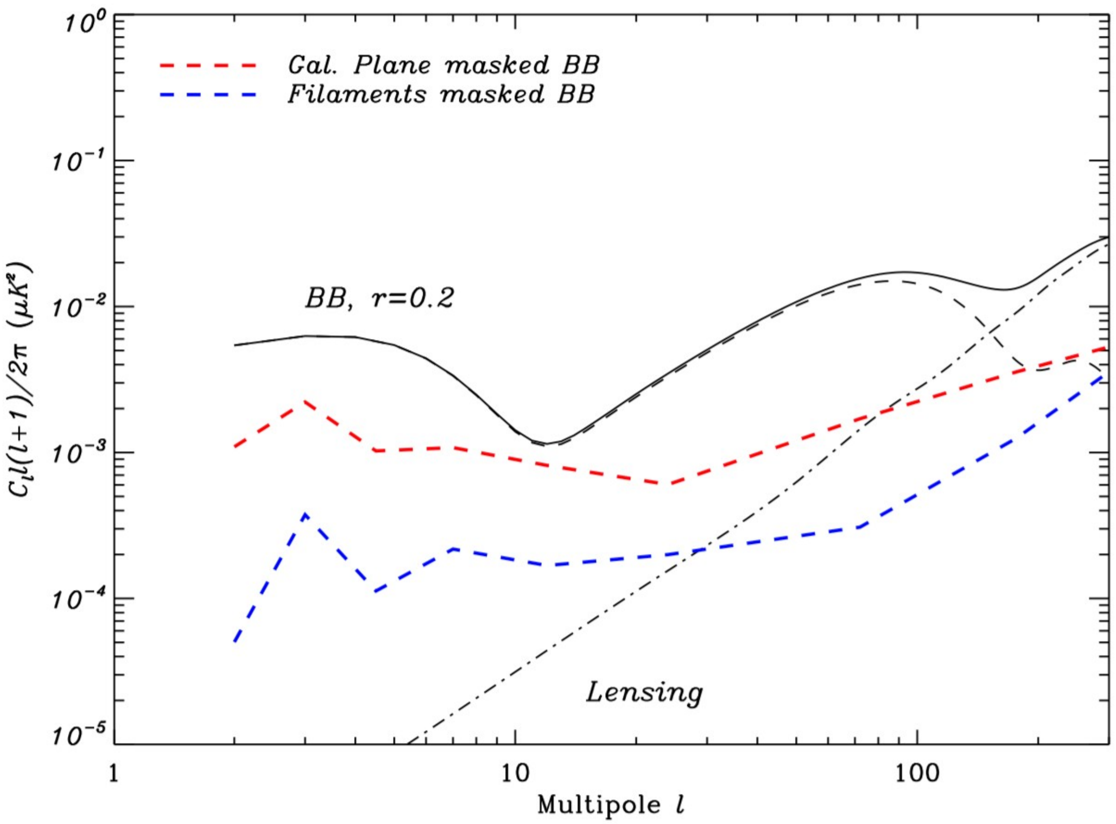


Synchrotron polarisation fraction
(Planck Collaboration, 2015, arXiv:1506.06660)

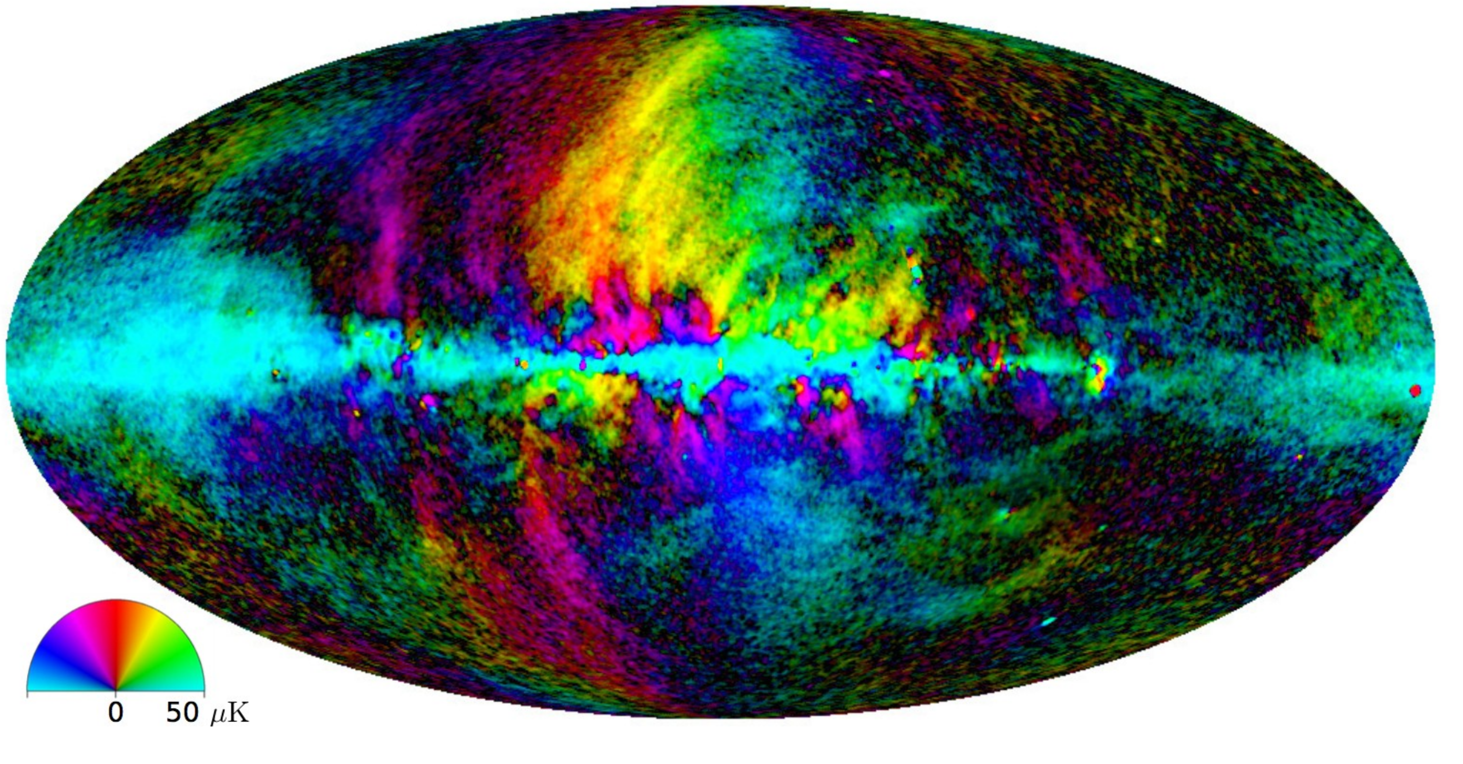
Polarised synchrotron radiation

- Large-scale power from Galactic plane and several “loops/spurs”
  - Highly polarised
  - Cover large fraction of the sky!
  - May be responsible for bulk of synchrotron radiation!





Vidal et al. (2015)



Planck Collaboration, 2015, arXiv:1506.06660

C-BASS

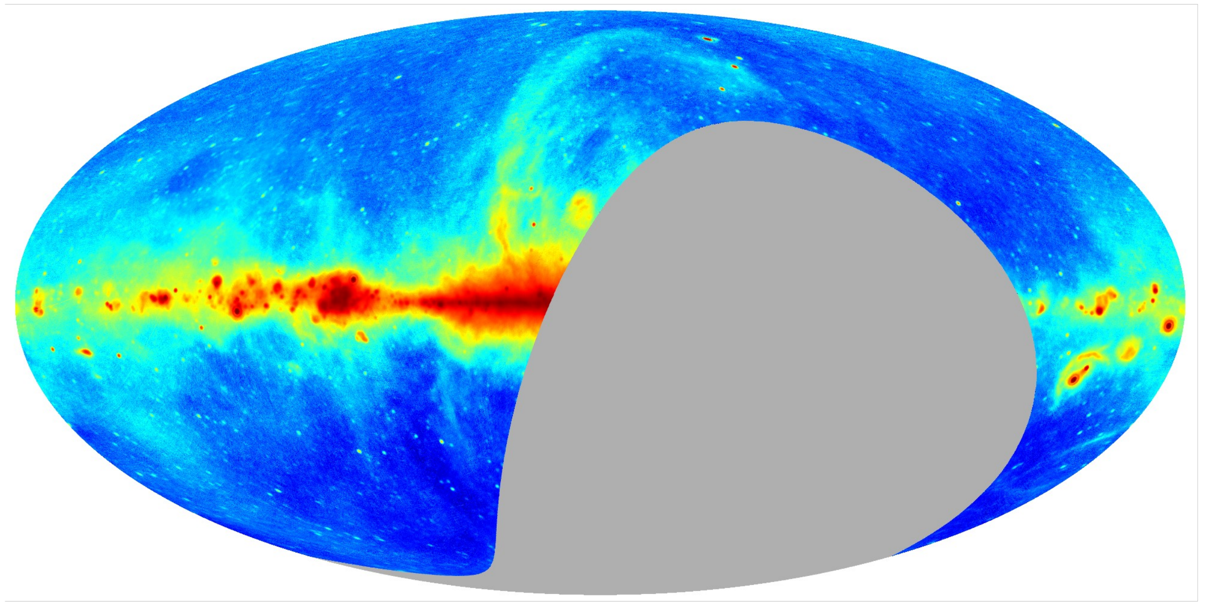
- Collaboration:
  UK (Manchester/Oxford),
  U.S. (Caltech/JPL),
  South Africa (Rhodes, UKZN),
  Saudi Arabia (KACST)
- **Full-sky 5 GHz I/Q/U survey at 45 arcmin resolution, <0.1mK rms noise, with good calibration and minimal systematics**
- Careful attention to design details
  - Carefully balanced correlation receiver to reduce 1/f noise
  - Lowest noise C-Band low noise amplifiers
  - RFI notch filters
  - Foam cone support to reduce scattering
  - Under-illuminated low sidelobe matched beams
  - Absorbing baffles around reflectors
  - Fast scanning (4deg/s)
  - Digital spectral backend (Southern instrument)
  - …

California

South Africa

Sky-coverage	All-sky
Angular resolution	0.73 deg (43.8 arcmin)
Sensitivity	< 0.1mK r.m.s
Stokes coverage	I, Q, U, (V)
Tsys	~20K, including sky
Frequency	1 (0.7) GHz bandwidth, centered at 5 GHz
Northern site	OVRO, California Latitude, 37.2 deg
Southern site	MeerKAT site, Karoo, South Africa Latitude -30.7 deg

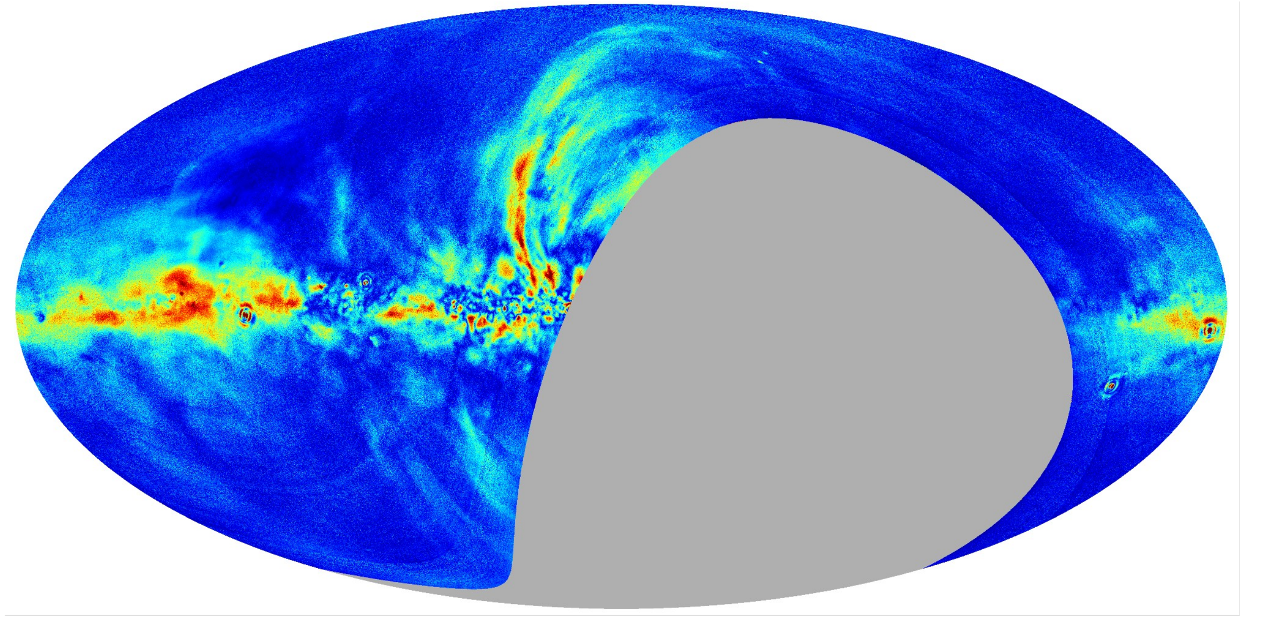
<u>Preliminary</u> C-BASS maps



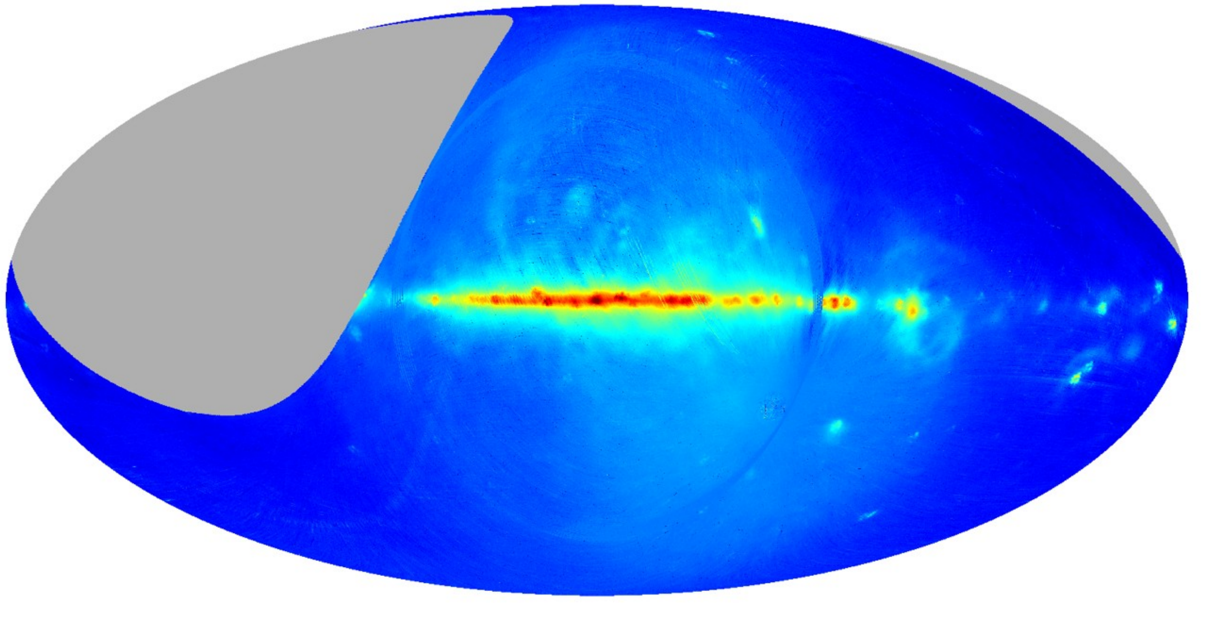
Stokes I map

For first results on the Galactic plane see Irfan et al. (2015), arXiv:1501.06069

More results coming soon!



Polarised intensity map



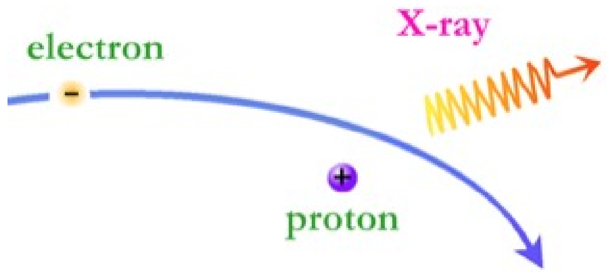
C-BASS South now coming online!

(delays due to lightning storm damage, compressor failure, local RFI...)

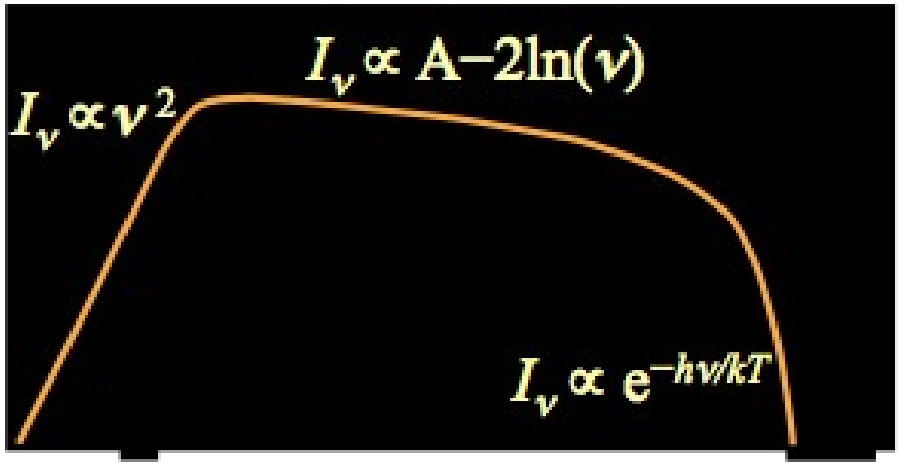
VERY raw and preliminary I map

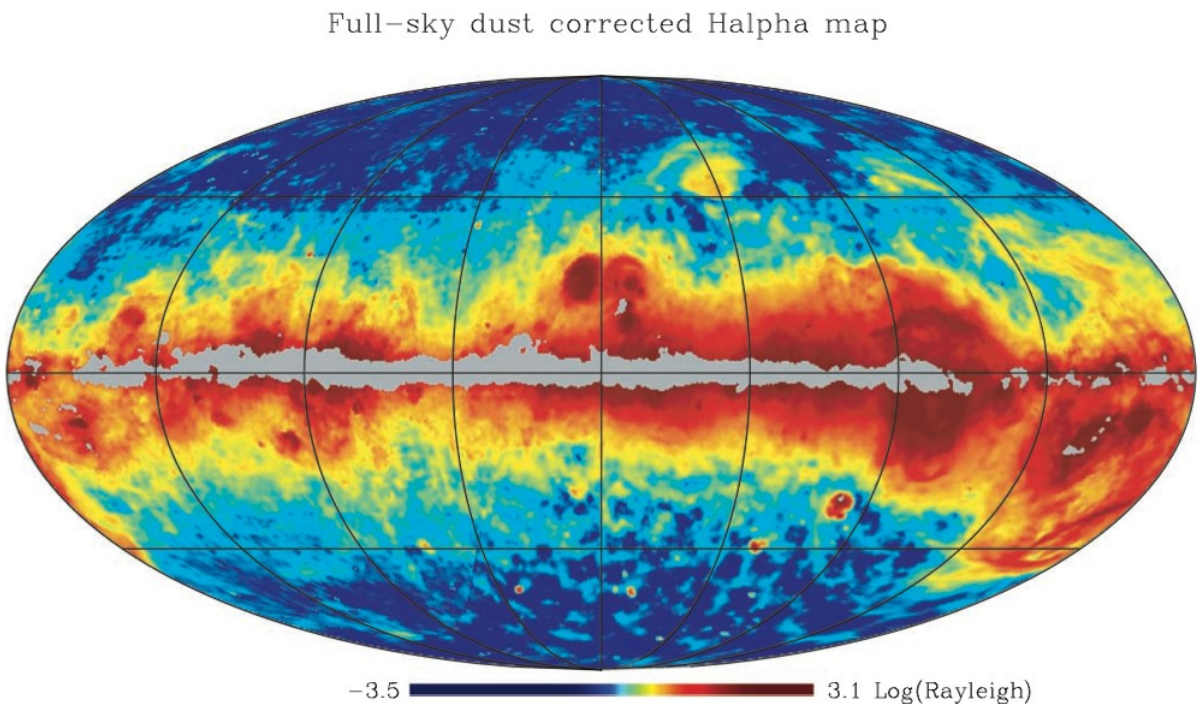
(virtually no calibration/data editing)

Free-free radiation



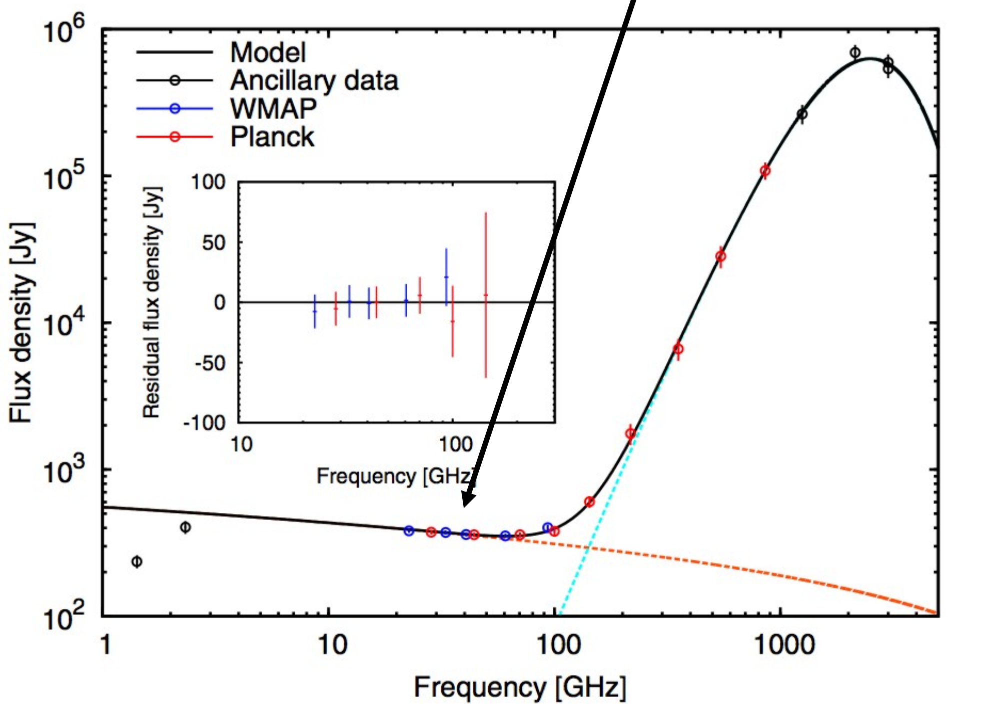
- Electrons accelerating in ionised gas by Coulombic interactions (thermal bremsstrahlung)
- At radio/microwave/sub-mm frequencies, very close to power-law with flatter spectrum: **β=-2.1 +/- 0.02**
- H-alpha maps used as template/predictor
  - Weak at high latitudes: ΔT ~10-20 μK at 30 GHz
- **Intrinsically unpolarised**





Full-sky Hα map corrected for dust extinction (Dickinson, Davies, Davis 2003)

Free-free spectrum α≈-0.1 across CMB frequency band

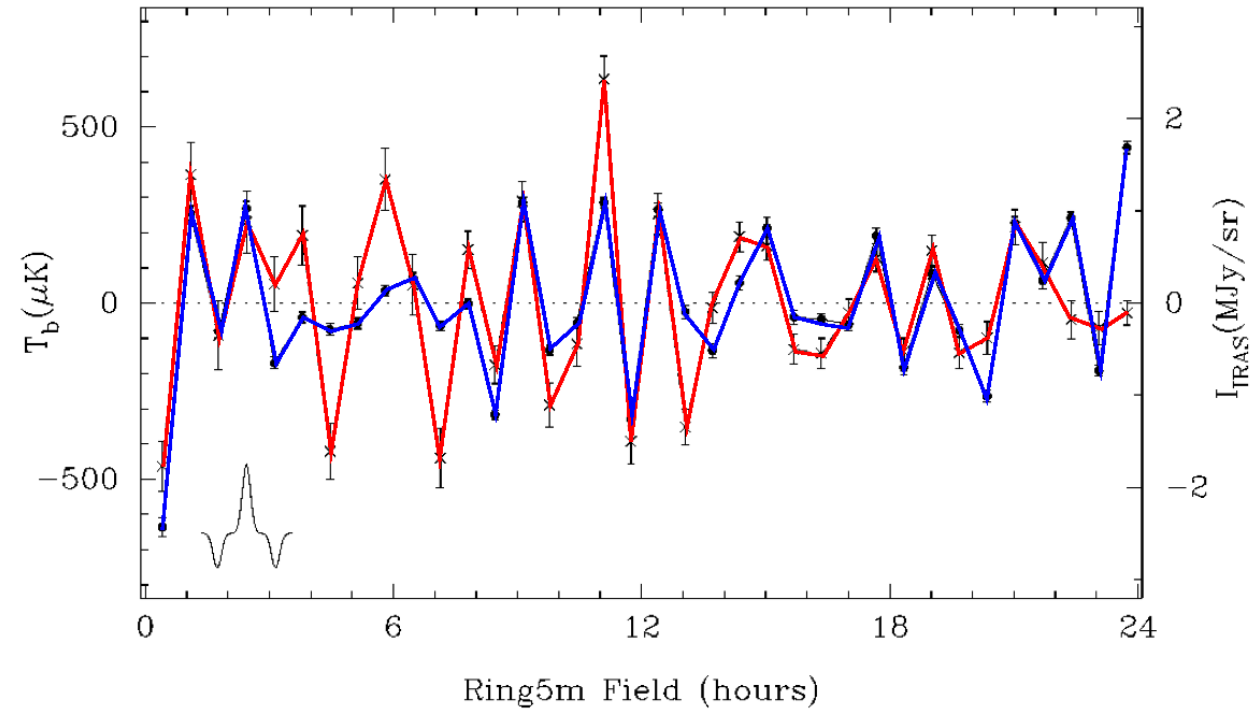


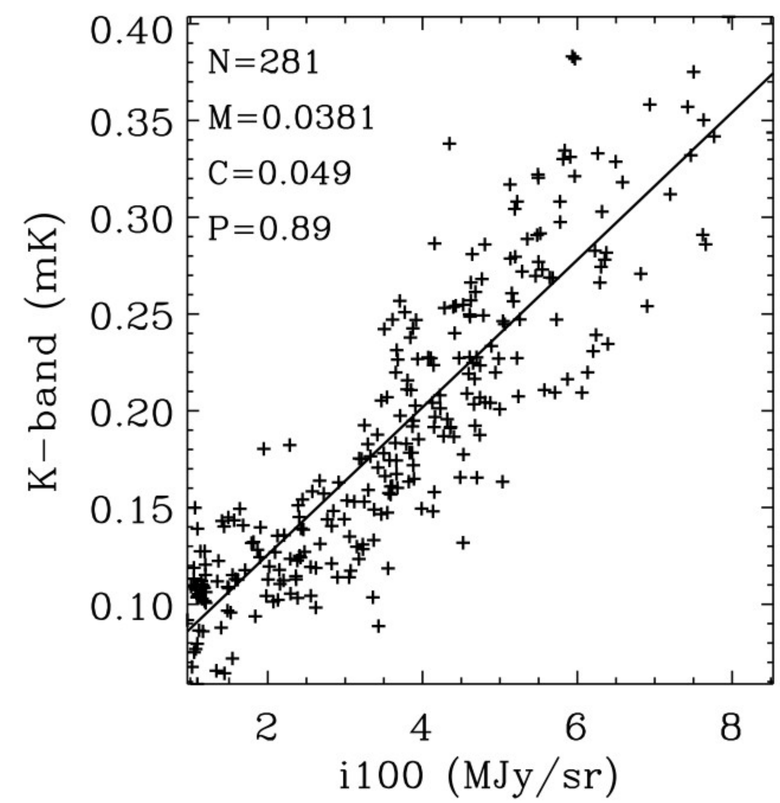
M42 Orion Nebula spectrum (Planck Collaboration, 2011, Early Paper XX)

Anomalous Microwave Emission (AME)

- Additional foreground detected at frequencies ~10-60 GHz (Kogut et al. 1996; Leitch et al. 1997)
  - Cannot easily be explained by synchrotron/free-free/CMB emission mechanisms
  - Strongly correlated with far-IR (~100μm) thermal dust emission
  - Steeply falling spectrum above ~30 GHz
  - Relatively low level of polarisation (few % or less)
- AME has been detected by many experiments

Adapted from Leitch et al. (1997)

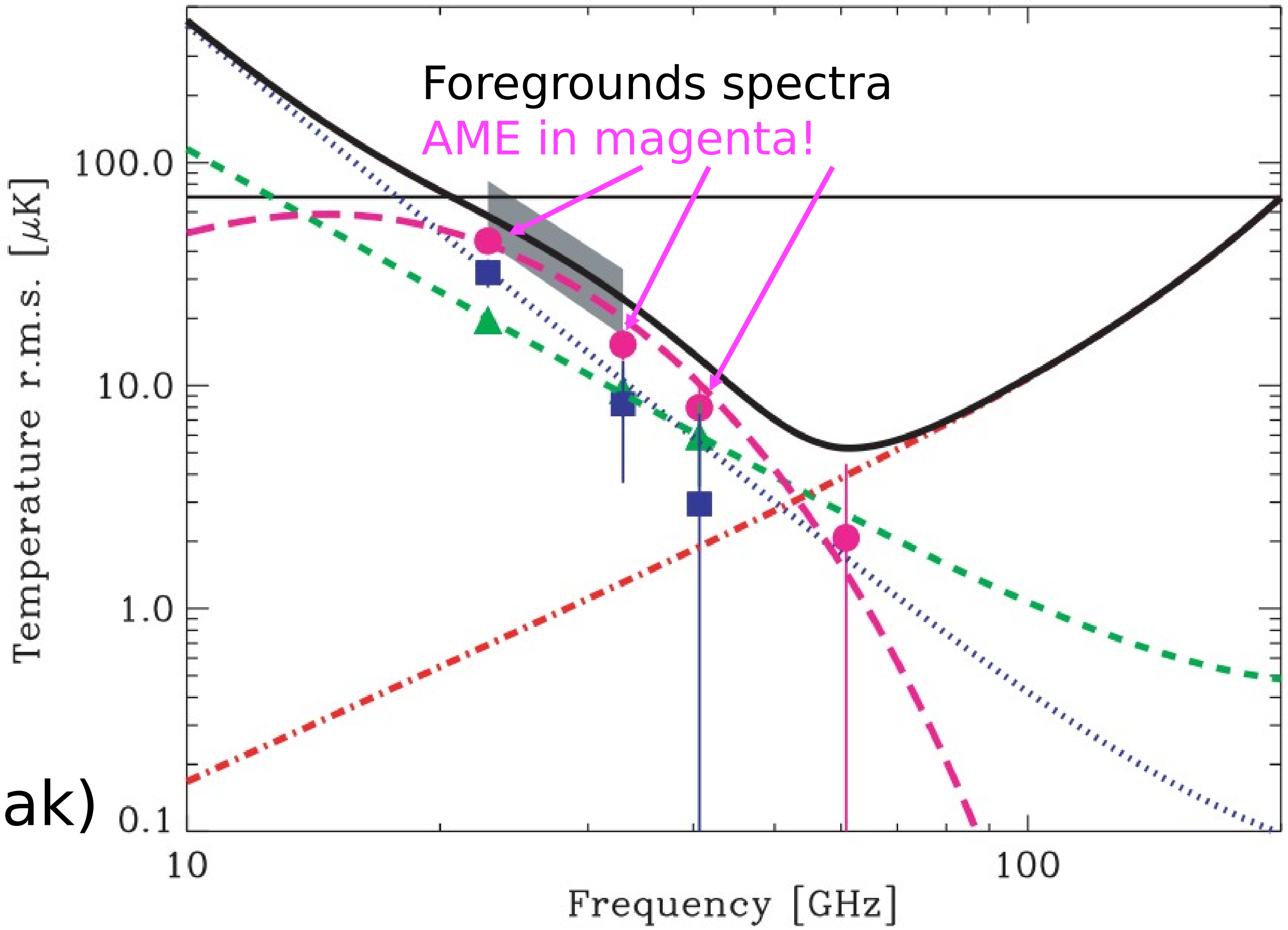




Correlation plot of 23 GHz and 100 μm (Davies et al. 2006)

AME at high Galactic latitudes

- Still debate about diffuse AME at high Galactic latitudes
  - Spinning dust?
  - Flat spectrum synchrotron?
  - Magnetic dust?
  - Hot bremsstrahlung
  - Quantum dust
  - ....
- Difficult to separate the (relatively weak) diffuse components and CMB!
  - **N.B. AME may be the dominant foreground at 20-60 GHz !**
- Best explanation is **electric dipole radiation from ultra-small rapidly <u>spinning dust</u> grains (Draine & Lazarian 1998)**

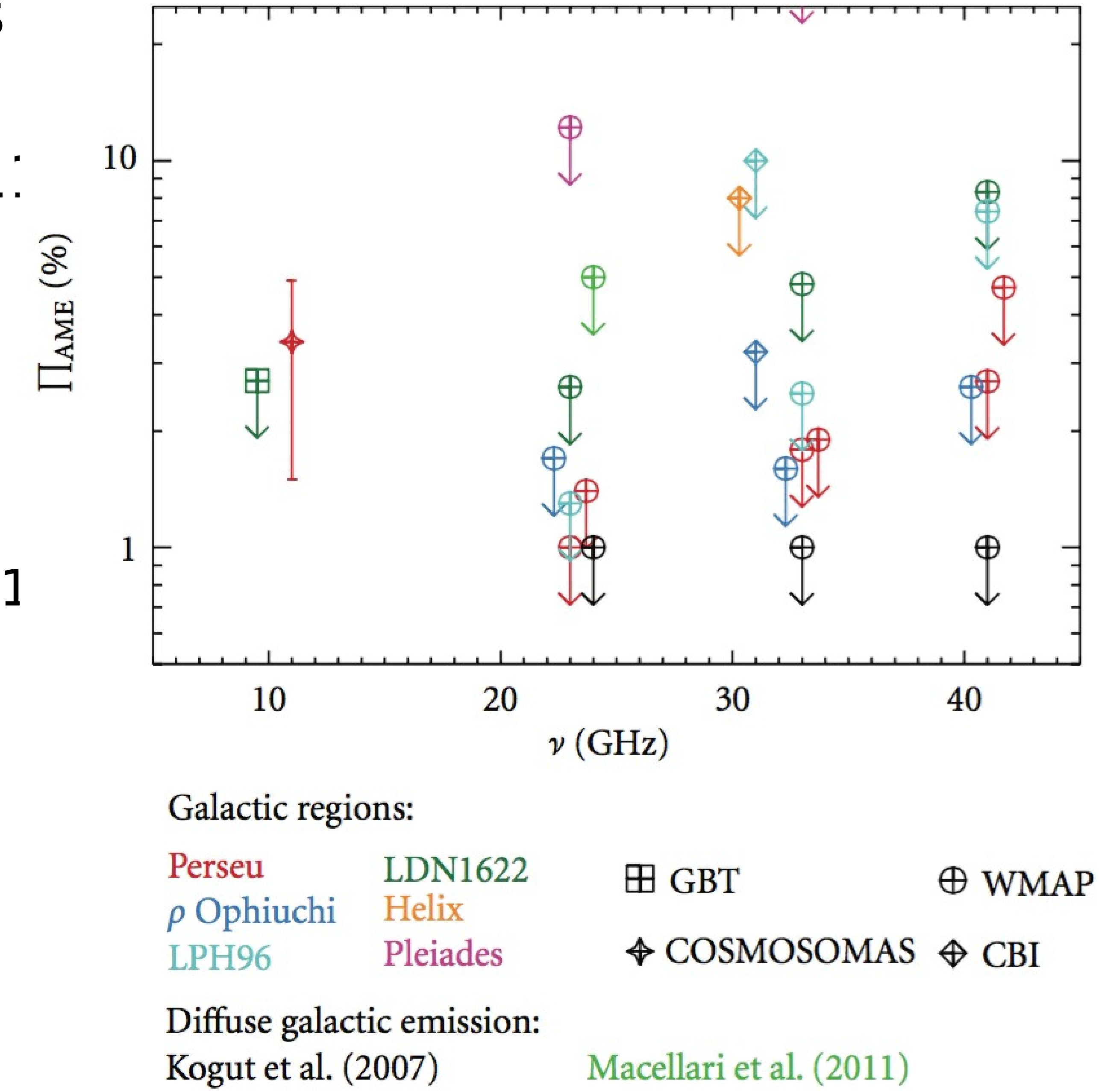


Foreground template component separation of WMAP data
Davies et al. (2006)

AME polarization constraints

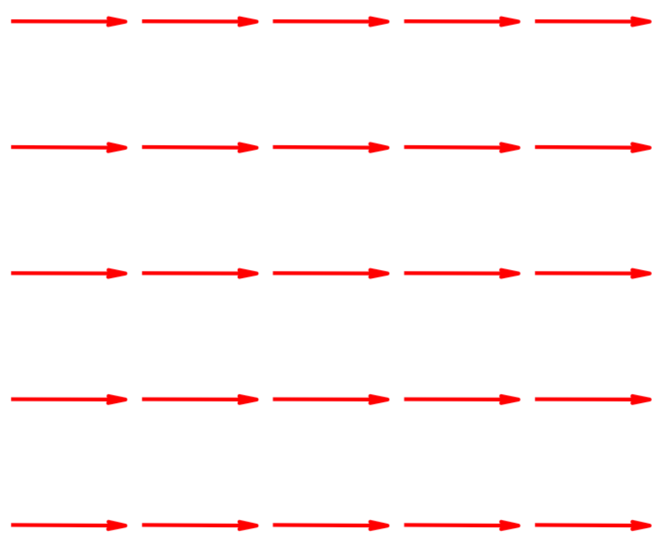
- Observations of Galactic AME clouds
- **Upper limit of a few % at 30 GHz**
  (e.g. Dickinson, Peel, Vidal et al. 201
- Diffuse AME more difficult
  due to component separation and
  weak signals
  - Appears to be similar (<~5%)
  - Kogut et al. (2007); Macellari et al. (2011
    Planck Collaboration 2015 XXV
    arXiv:1506.06660)

Rubino-Martin et al. (2012)

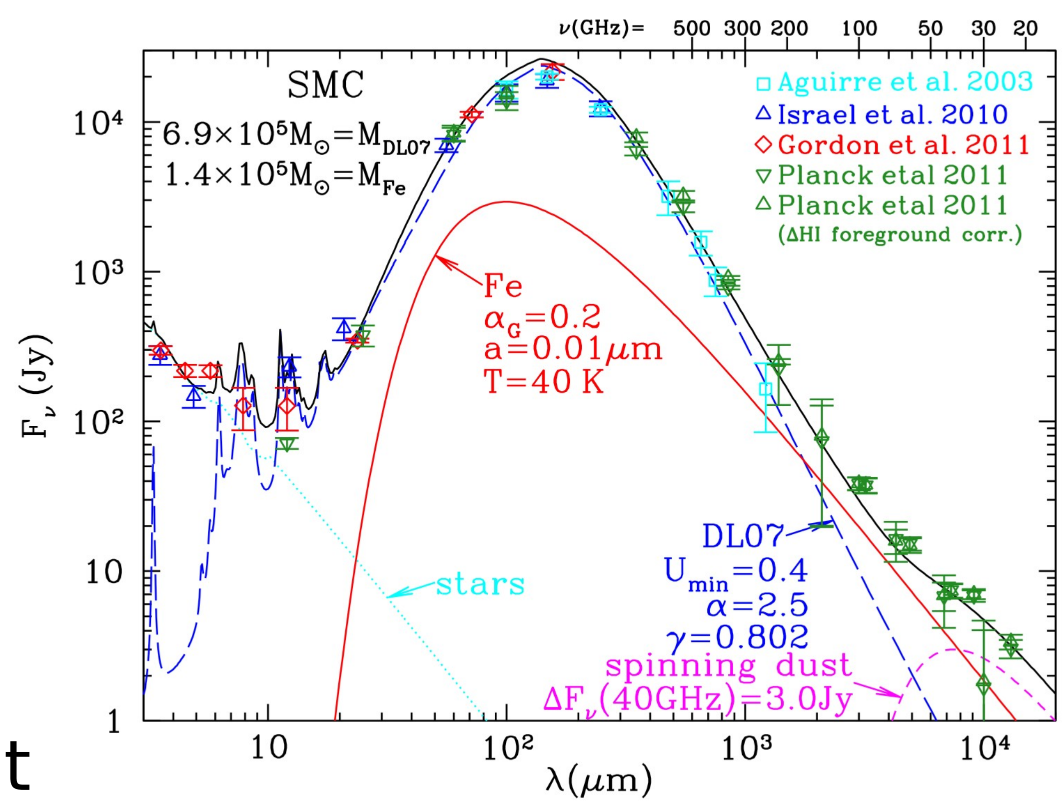


Thermal fluctuations of magnetic dust

- Much of Fe could be in magnetic material (metallic Fe, magnetite, maghemite etc.)
- Oscillations in magnetization -> magnetic dipole radiation
- Finite temperature -> **thermal magnetic dipole (MD) emission**
- Detailed predictions depend very much on form of Fe
  - Draine & Lazarian (1999), Draine & Hensley (2013)
- Black-body-like spectrum
- **No hard evidence for MD although several hints!**
  - Flattening of sub-mm index
  - Excellent fit to SMC with plausible physics
  - Slight decrease in dust polarisation at ~100 GHz and below



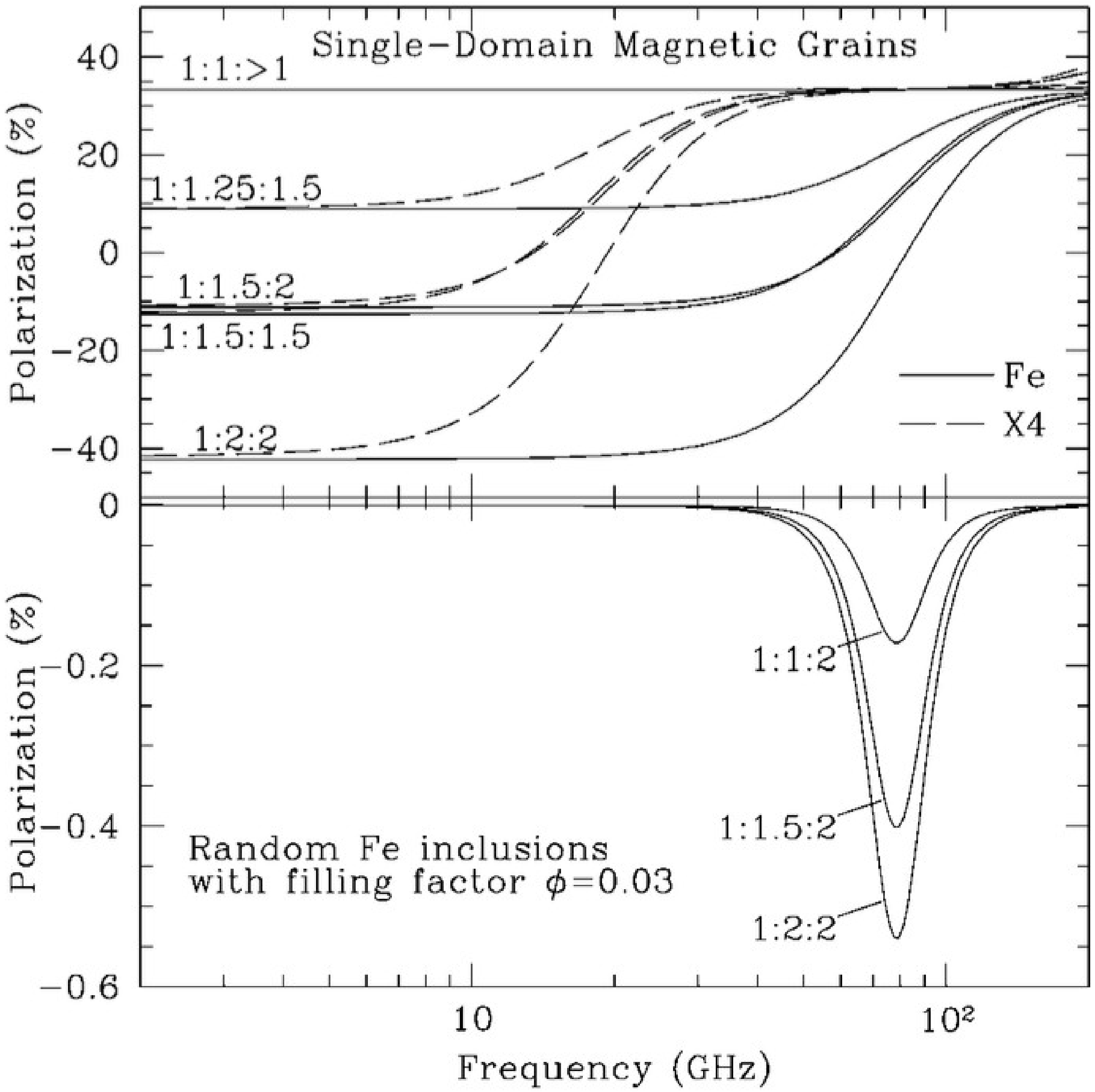
Ferromagnetic lattice with spins aligned
Thermal fluctuations will move them away
producing dipole radiation



Draine & Hensley (2013)

Magnetic dust polarization

- MD could be highly polarised (up to 35%)!
- Several hints of MD being significant in both intensity and polarisation



35% polarised at high frequencies!

But see updated models with reduced polarisation Hoang & Lazarian 2016 (arXiv:1511.03691)

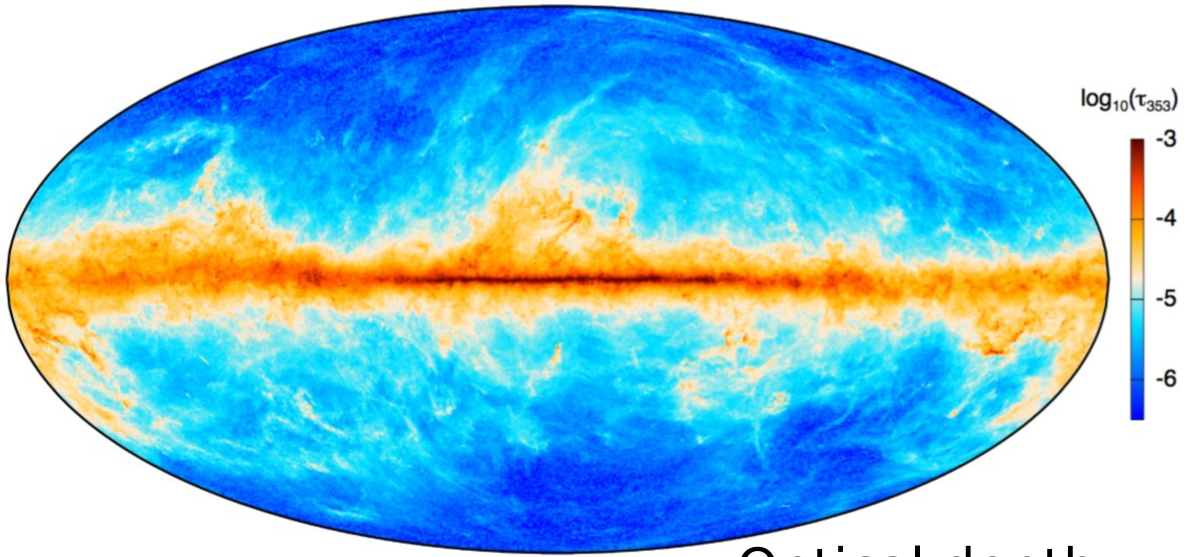
Draine & Lazarian (1999)

Thermal dust radiation

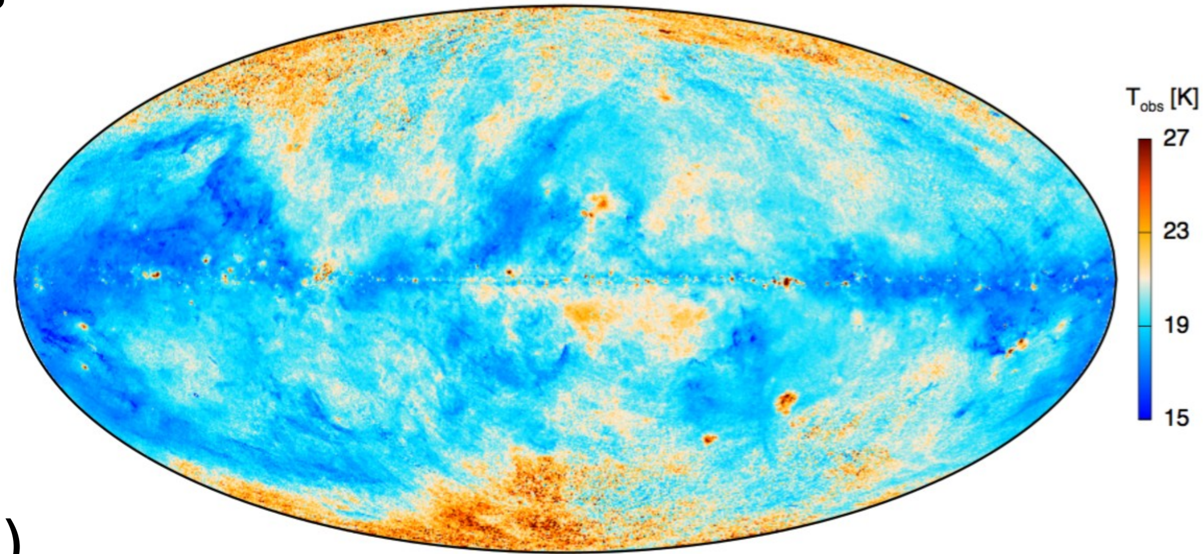
- Dust grains ubiquitous throughout interstellar medium, absorbing UV
  - T~10-100K
- Black-body radiation but with opacity effects at lower frequencies
  - Often modelled as a modified black-body radiation

$$I_\nu = \tau_{\nu_0} B_\nu(T_{\text{obs}}) \left(\frac{\nu}{\nu_0}\right)^{\beta_{\text{obs}}}$$

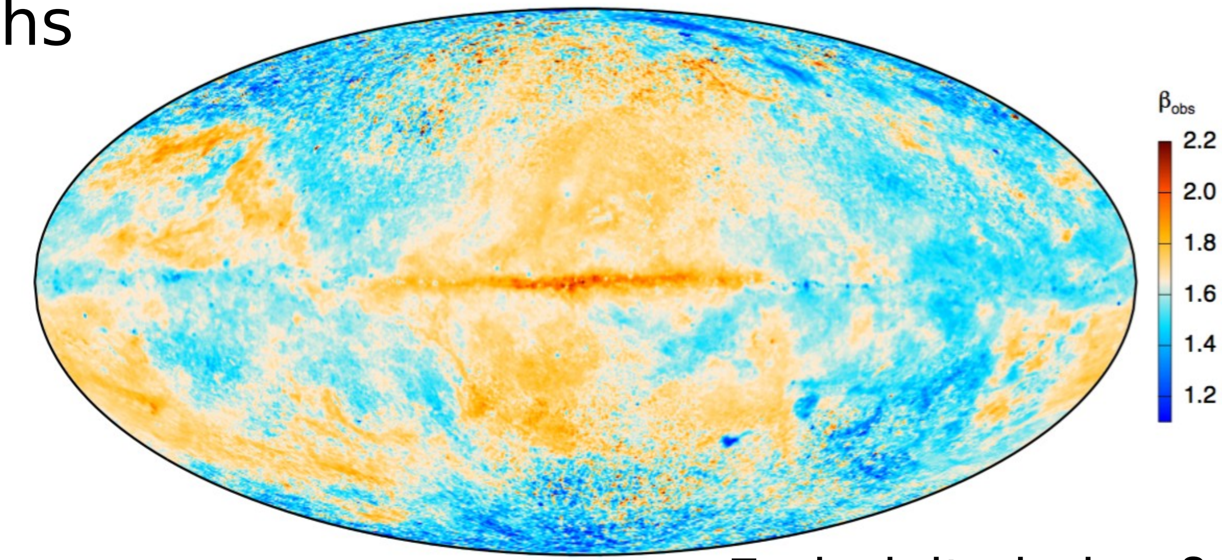
- Spectrum peaks in far-IR (~100um/3000GHz)
  - Rayleigh-Jeans tail at sub-mm wavelengths (hundreds of GHz)
  - T~15-30K, <T>=19.6 K
- **Dominant foreground above ~100 GHz**
- Theory/lab analyses suggests β~+2.0
  - Planck data strongly prefers β~+1.5-1.6 with significant variations



Optical depth τ



Dust temperature T



Emissivity index β

Planck all-sky thermal dust model
(Planck Collaboration 2013 results XI)

Polarized Dust

- Dust grains are aspherical, charged and rotating
- **Magnetic field aligns the grains -> polarization**
- Until Planck, very few observations
- Archeops balloon experiment found ~3-5% polarisation on average at 353 GHz (but very noisy and limited sky area)

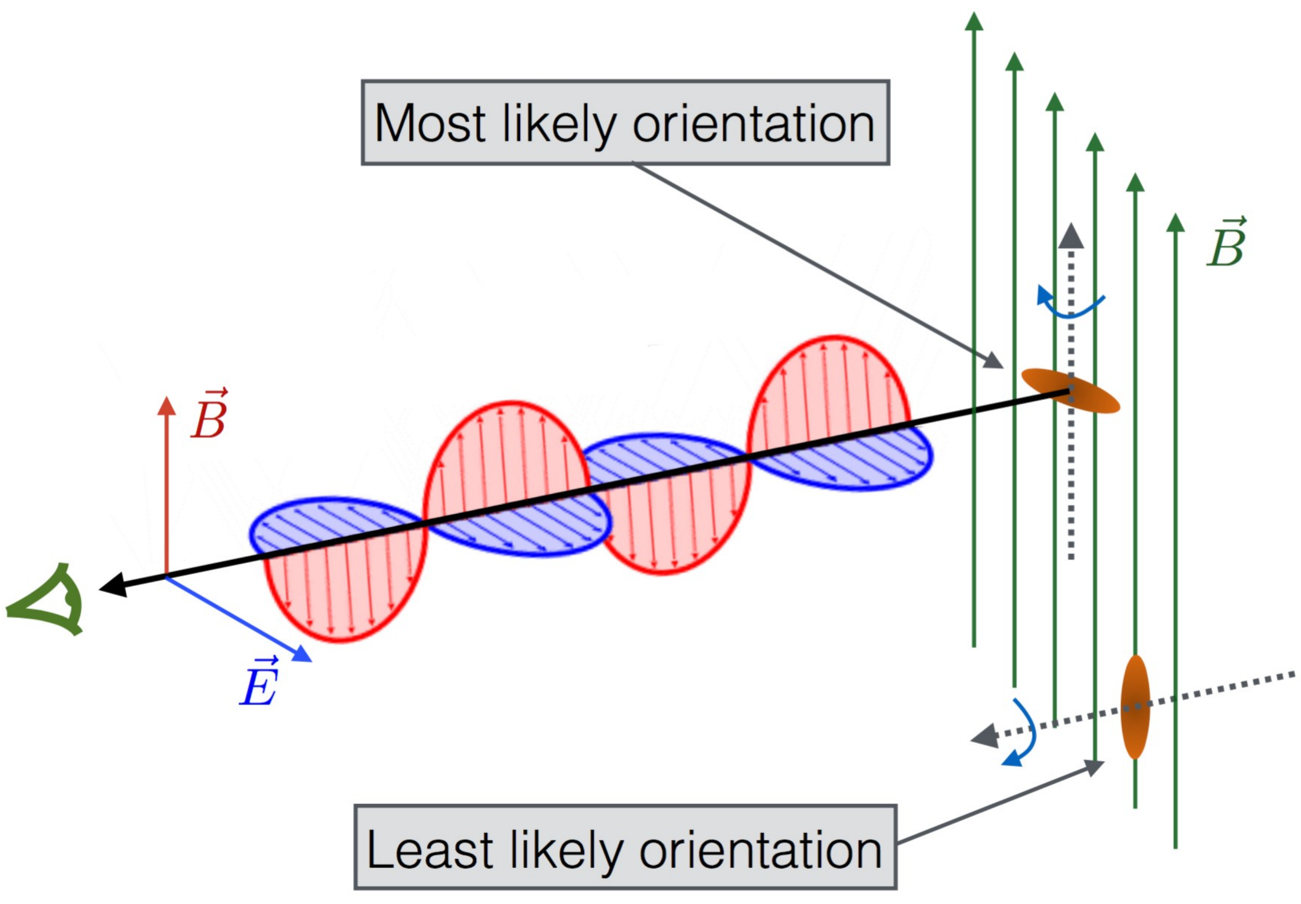
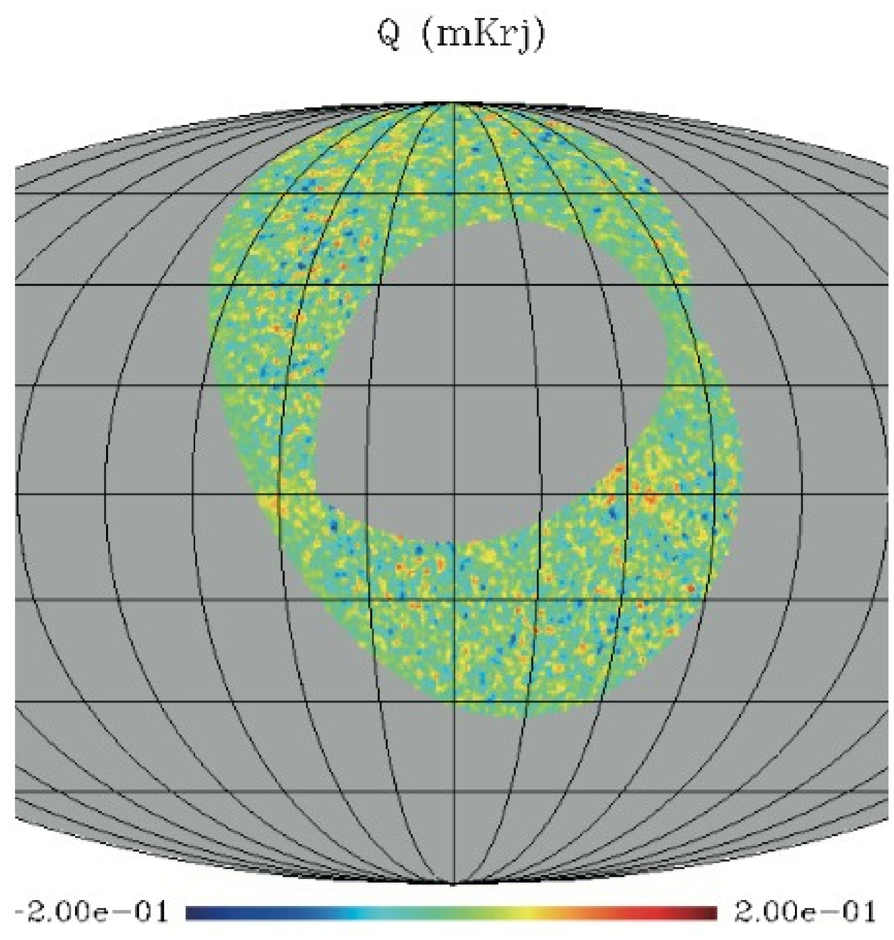
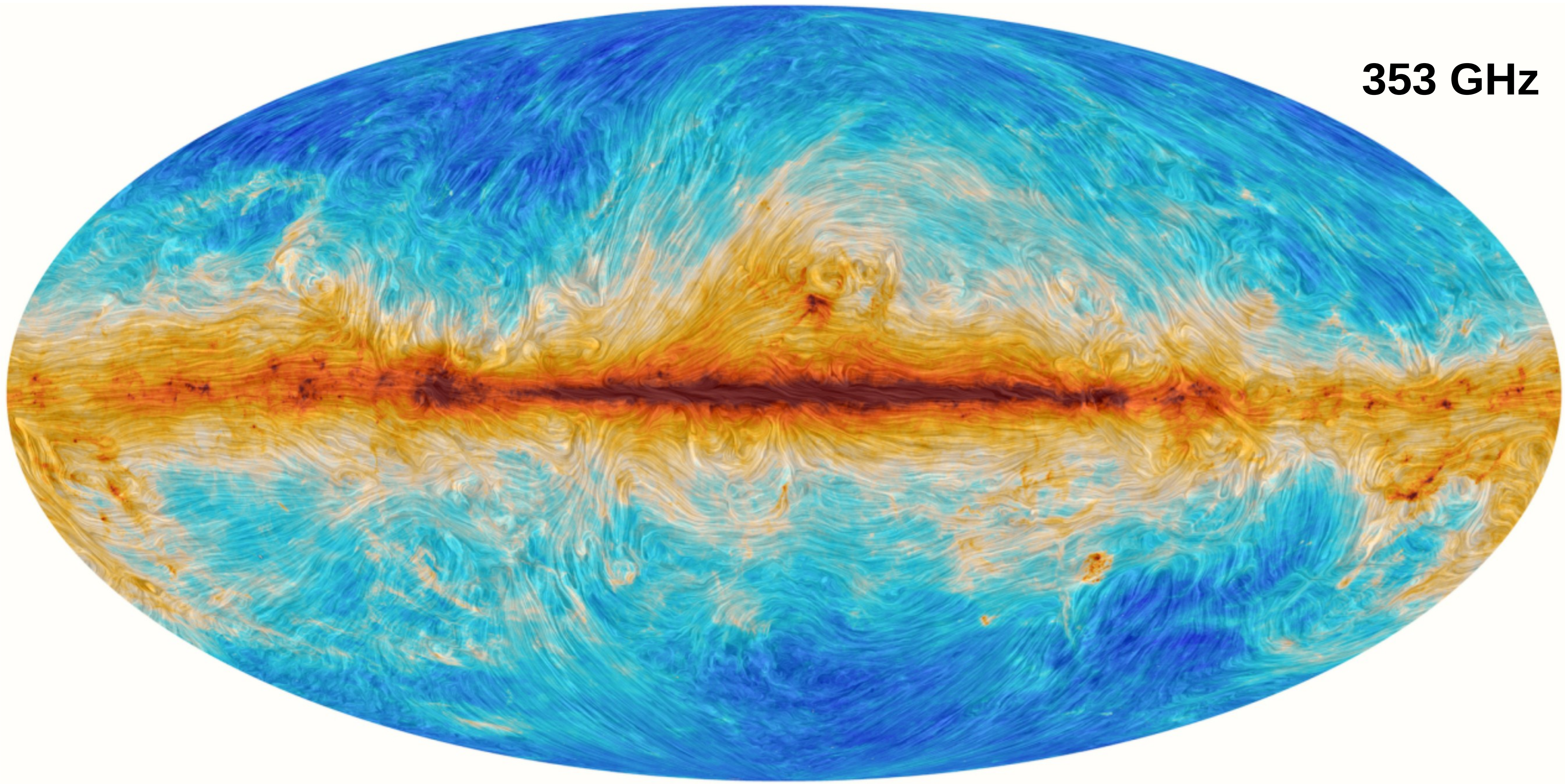


Image courtesy of F. Boulanger



Archeops polarisation (Q) map
Benoit et al. (2004); Ponthieu et al. (2005)

Planck thermal dust polarisation map

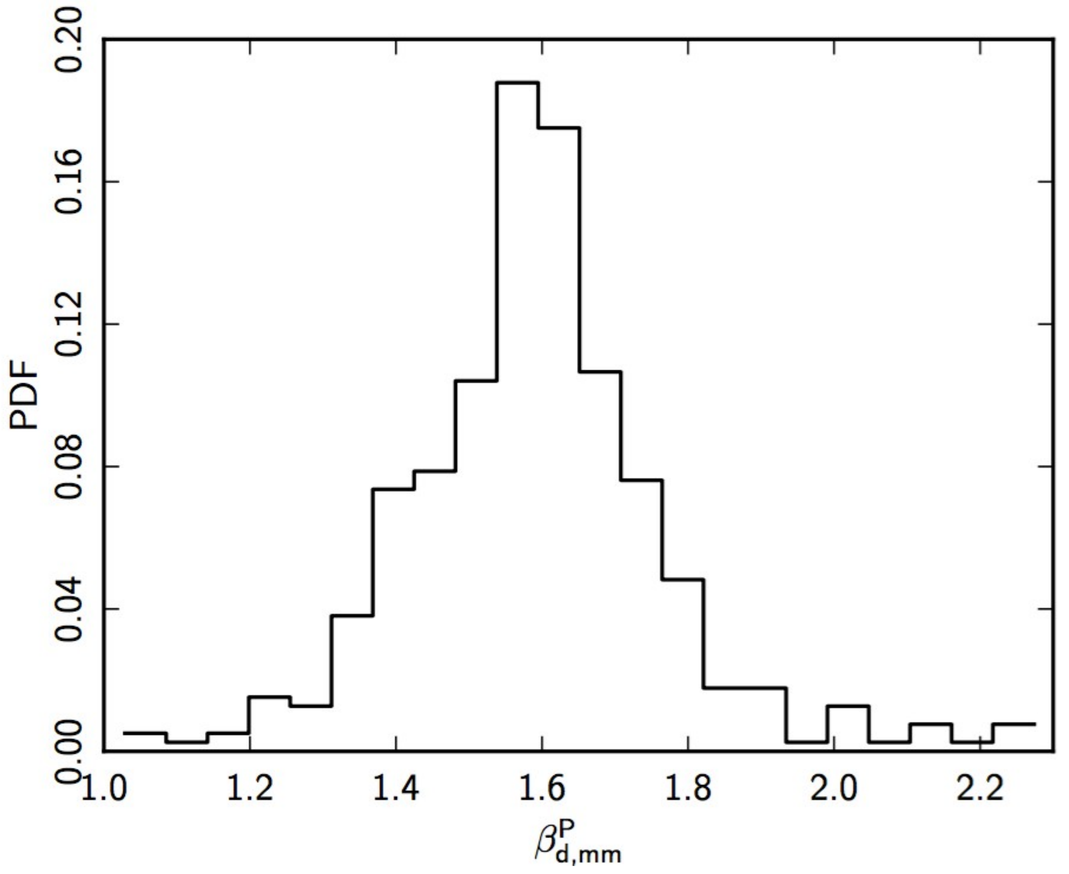


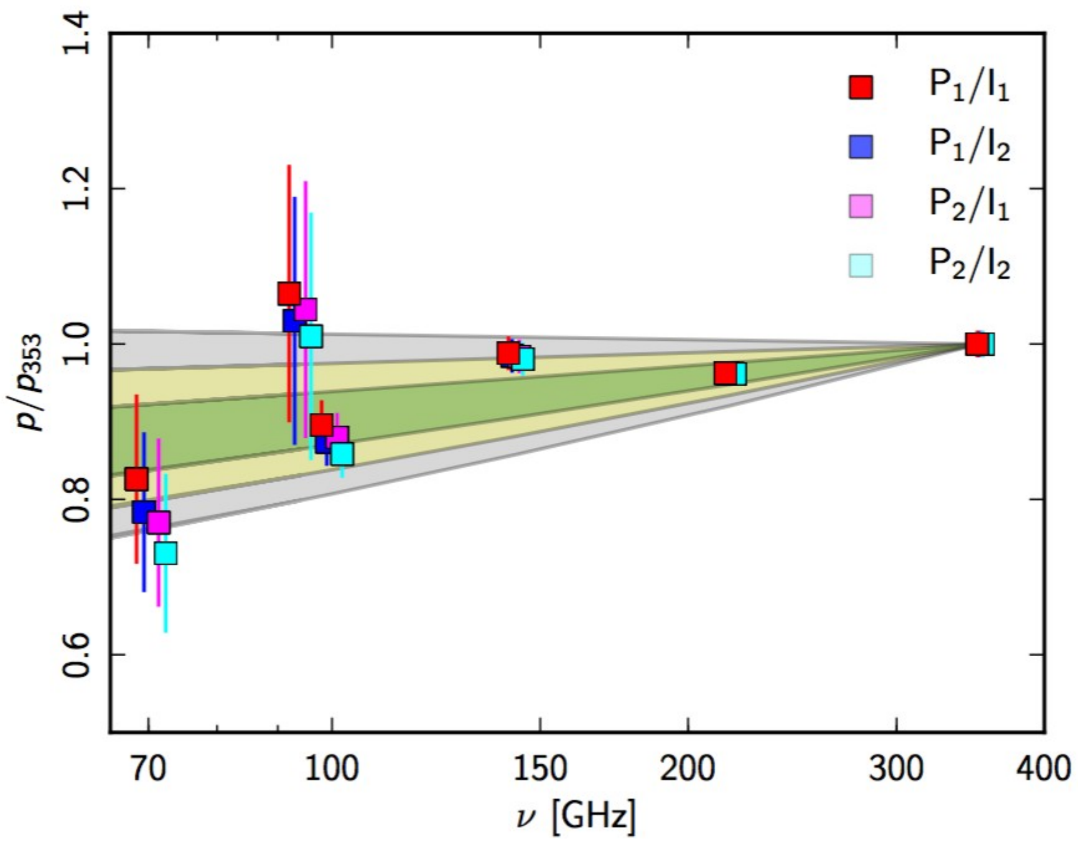
Planck Collaboration 2015 results

Line Integration Convolution algorithm used to show intensity and magnetic field direction
Very complicated! (magnetic field, depolarization, turbulence...)

Polarized Dust

- Planck has mapped large-scale dust polarisation **but limited S/N at high latitudes**
- Emissivity index similar (but not the same) as total-intensity: **β~+1.6** with significant variations
- Tentative evidence of flattening at sub-mm frequencies (70-350GHz)
- Also slight reduction in polarisation fraction at ~70-100 GHz ?
  - Multiple dust components/decorrelation or magnetic dipole radiation at ~100 GHz ?
  - **Could be a problem for sensitive CMB polarisation measurements**

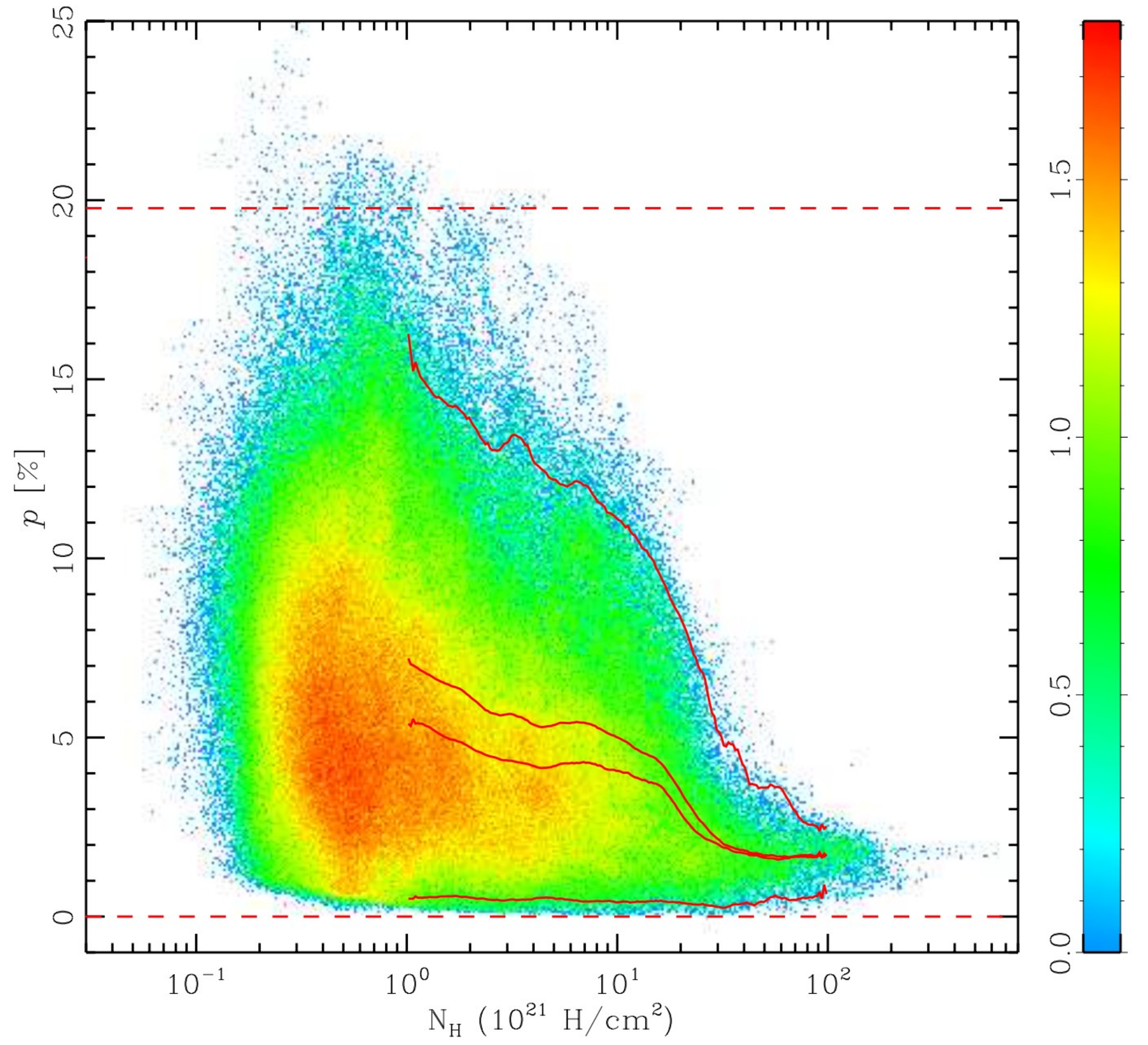




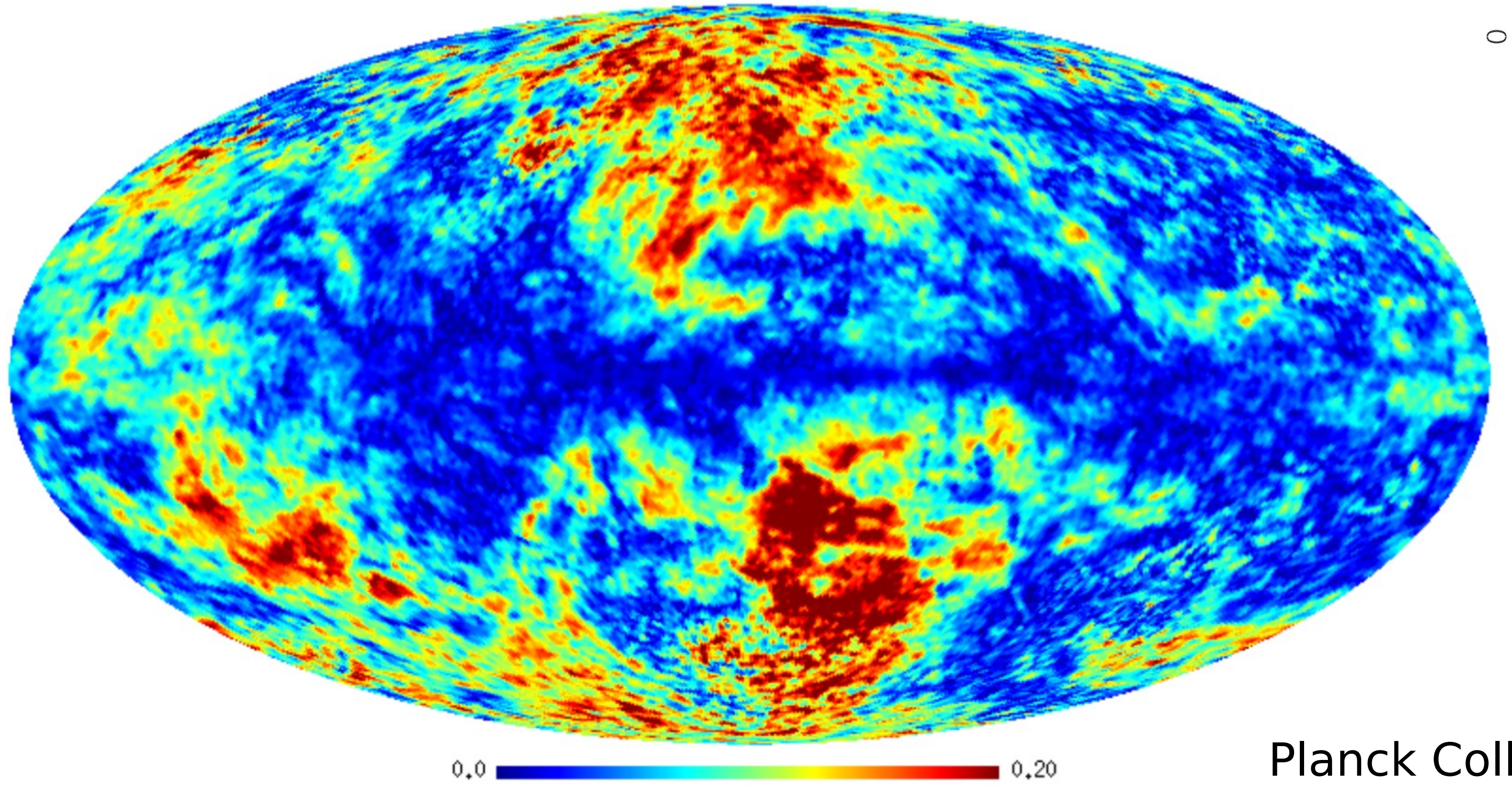
Planck Collaboration, 2015, Int. Results XXII, A&A, 576, A107

Polarization fraction of thermal dust

- Polarization fractions generally higher than previously thought
- **Up to ~20+% in some areas**
- **Average value ~10% at high latitudes**
- Lower column density lines-of-sight (high latitude) typically higher!
  - **Bad for CMB studies!**

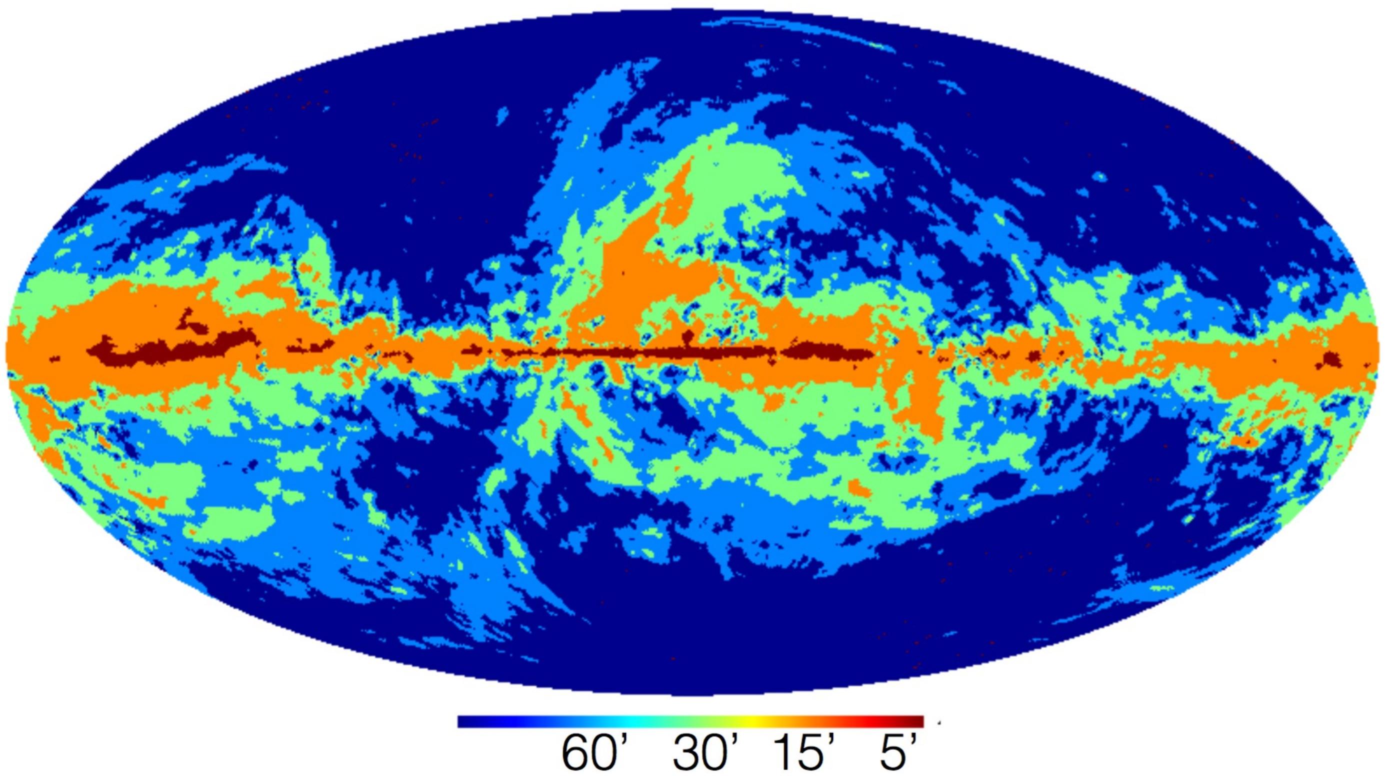


Polarization Fraction

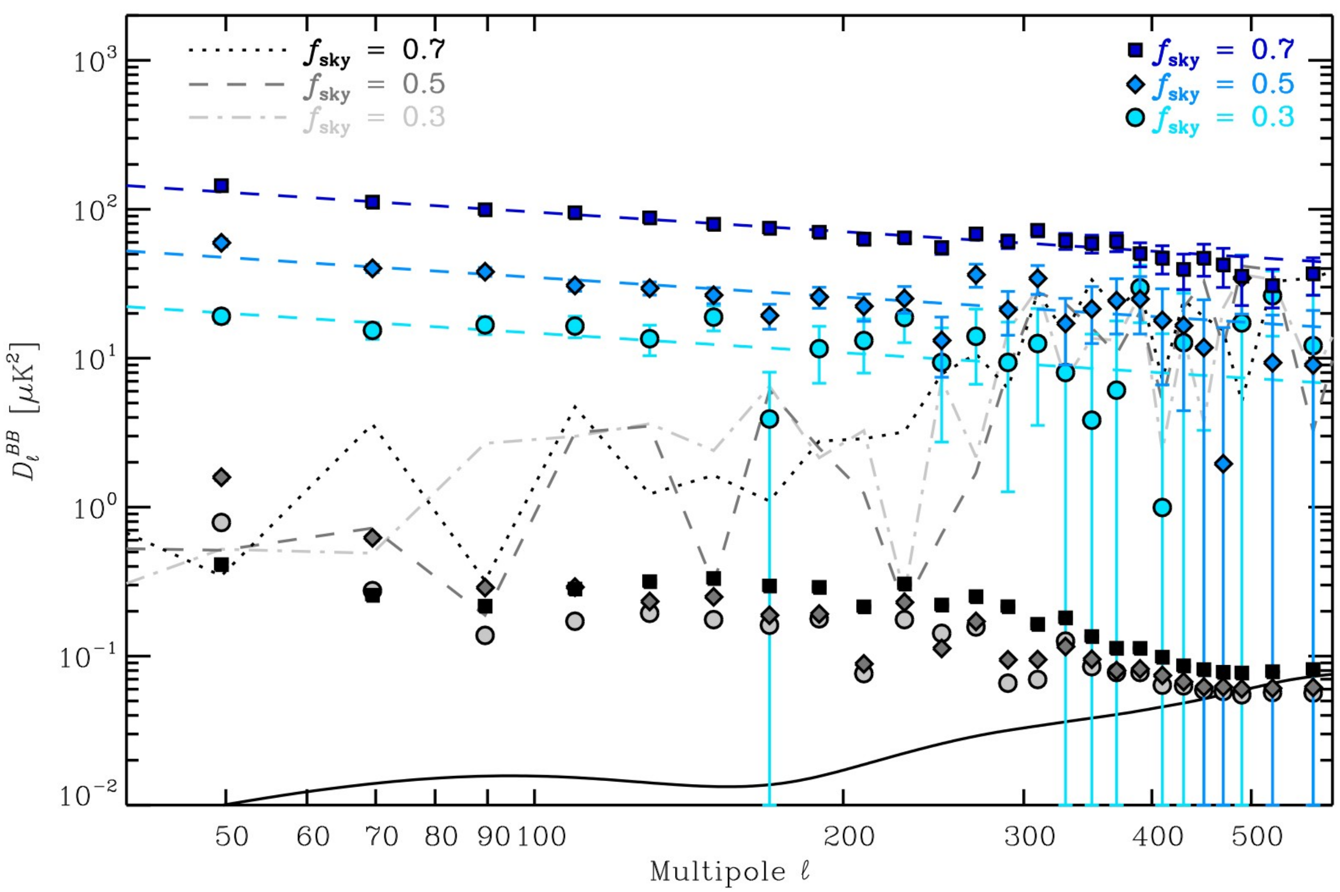


Planck Collaboration, 2015, Int. paper, A&A, 576, A104

Polarized Dust power



Angular scale where
EE dust power = Planck noise

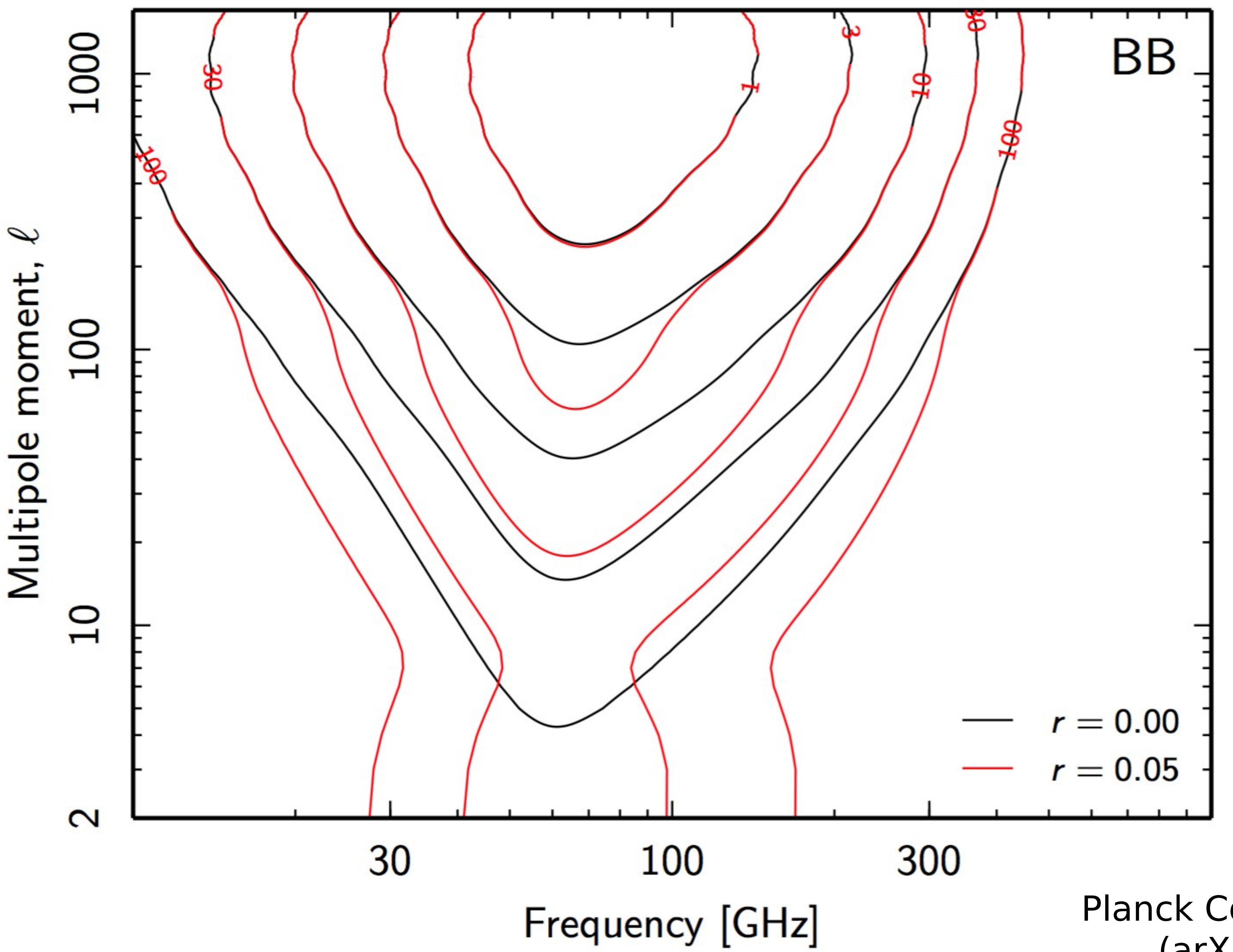


Power spectrum well-described by
power-law with **slope=-0.42**

Planck Collaboration, Int. results, 2015, A&A, paper XXX

Large-scale B-modes vs foregrounds

Foregrounds/CMB amplitude ratio (73% sky coverage)



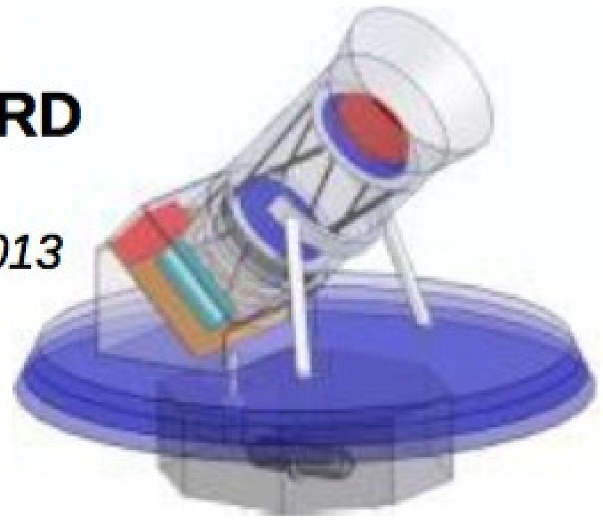
Planck Collaboration 2015 X
(arXiv:1502.01588)

- Minimum at ~60-100 GHz depending on angular scale
- **Minimum at ~70 GHz for large-scale B-modes**

B-mode satellite concepts all aiming for $r\sim10^{-3}$

LiteBIRD

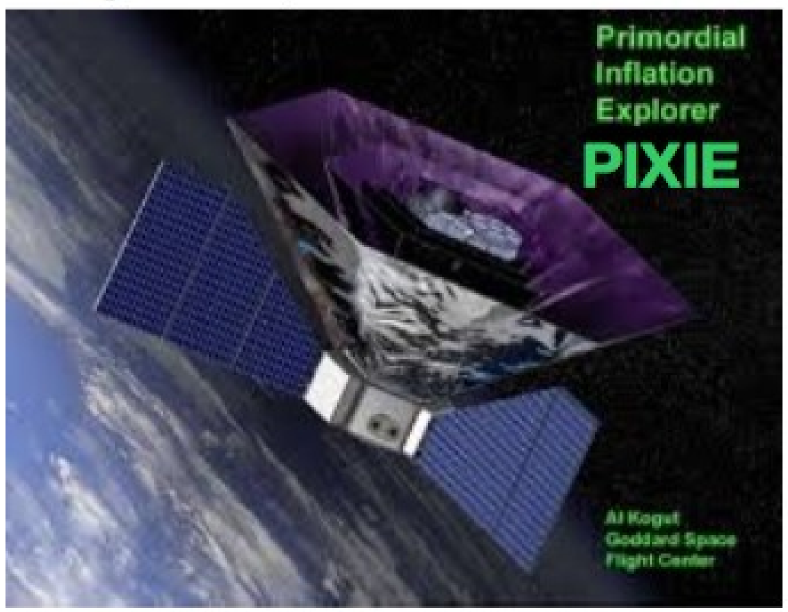
Matsumura et al., 2013



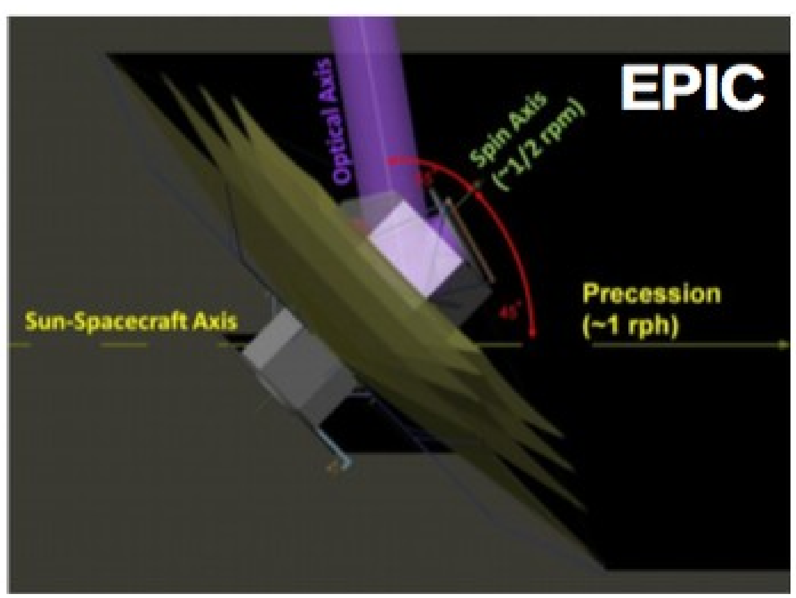
COrE

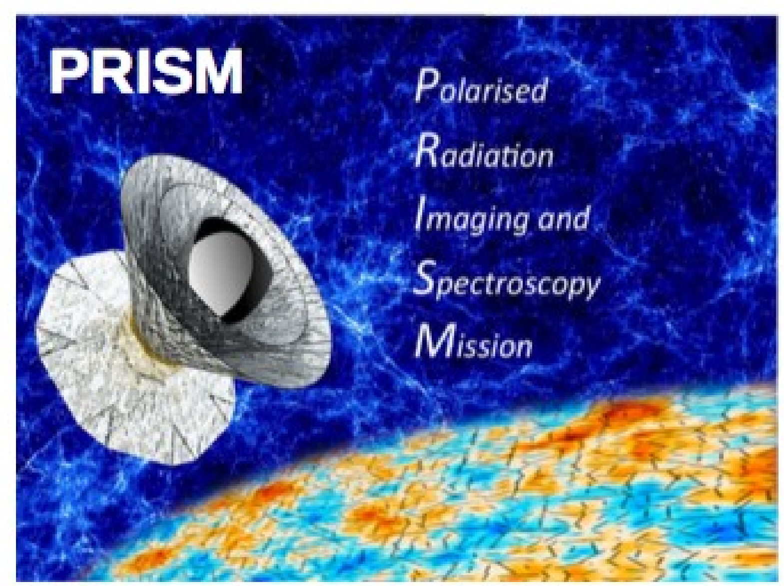
COrE Collaboration et al., 2011

Kogut et al., 2011



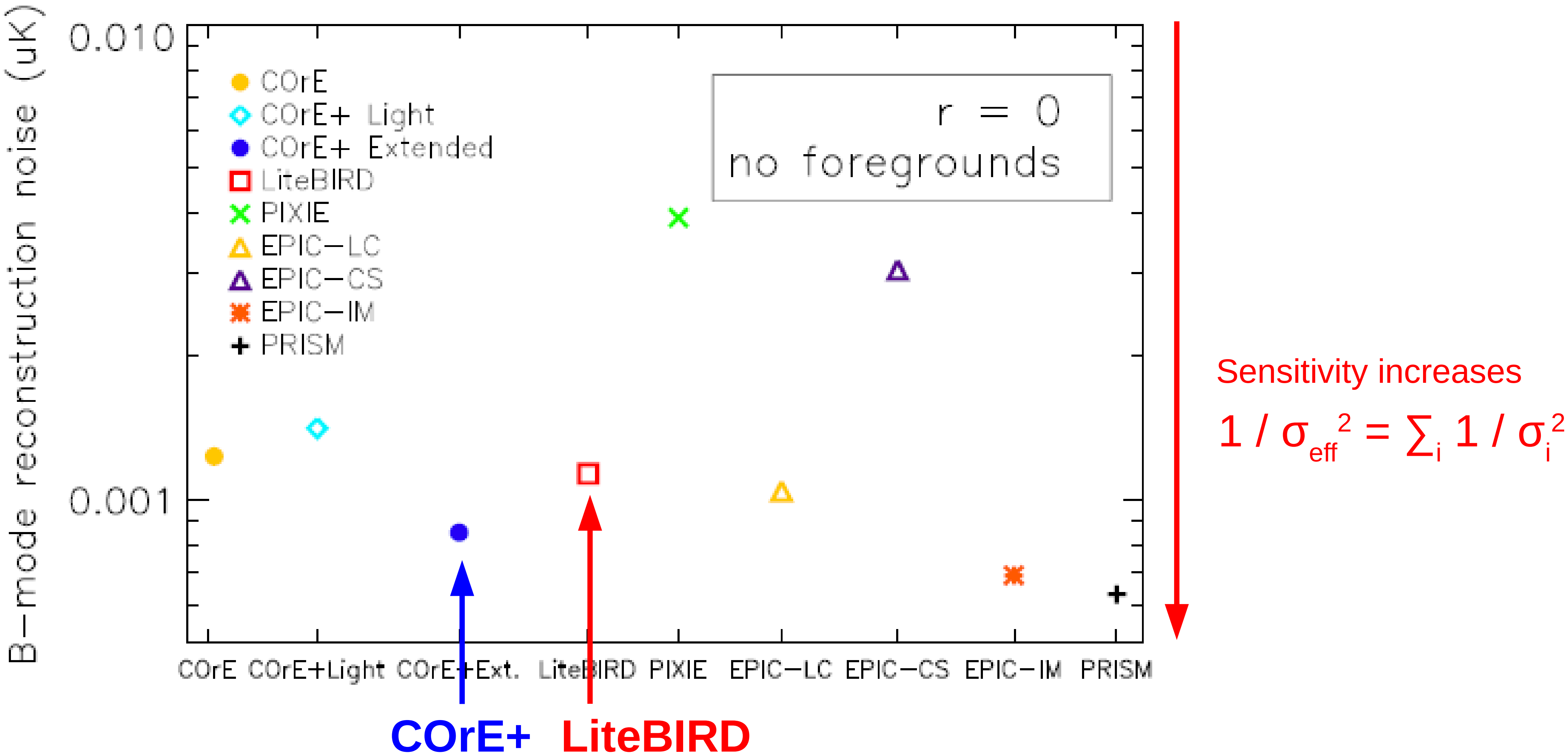
Bock et al., 2008





André et al., 2014

Sensitivity of B-mode satellite concepts



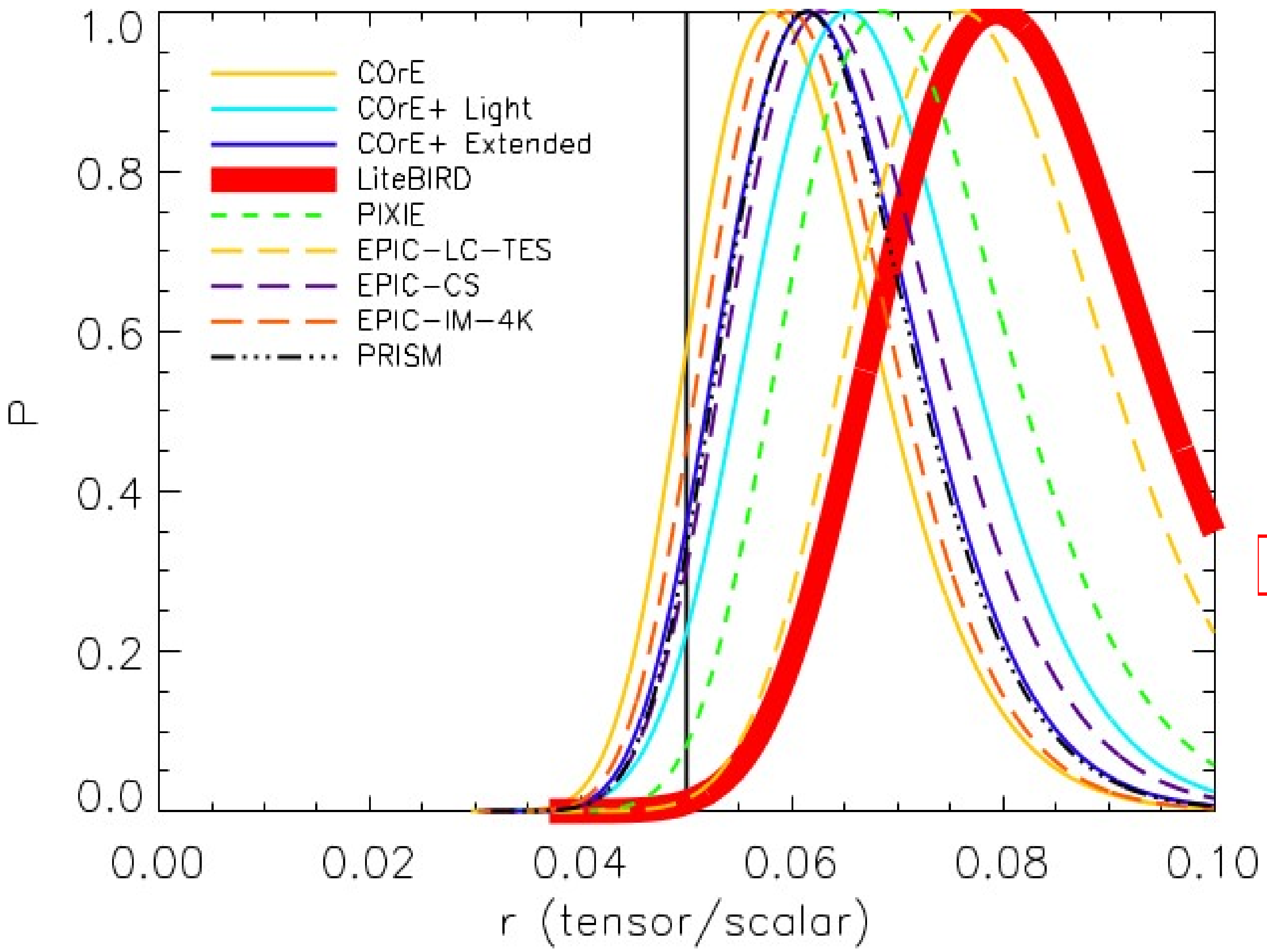
« Because of much larger sensitivity of future CMB space mission, the estimation of the tensor-to-scalar ratio will be much more sensitive to imperfect foreground modelling »

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

See also Errard et al. (arXiv:1509.06770)

Impact of mis-modelling synchrotron: neglecting index curvature

r = 0.05



LiteBIRD original

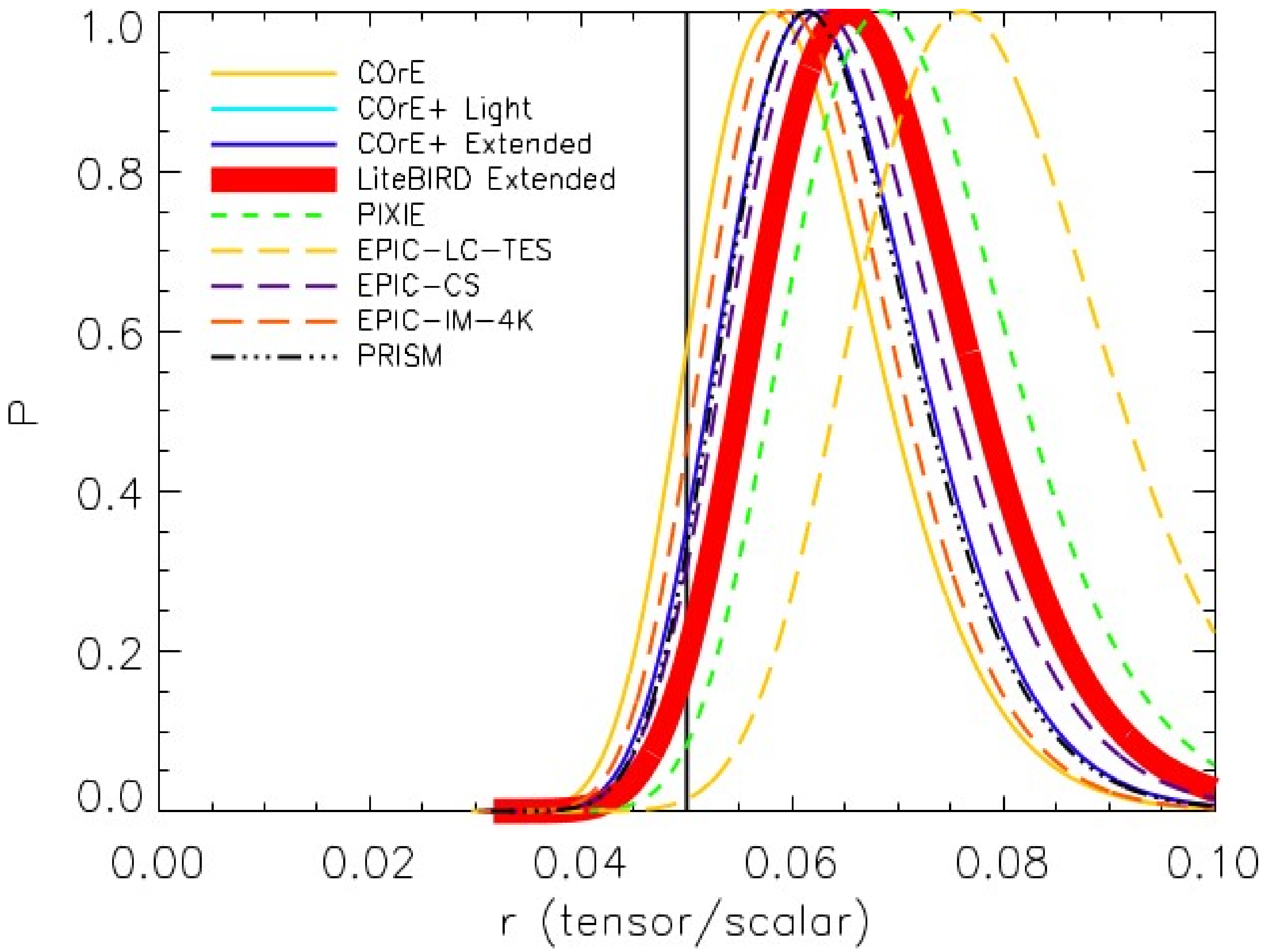
χ^2	r	
1.00	0.06756 ± 0.01027	COrE+ Light
1.01	0.06390 ± 0.00946	COrE+ Extended
1.01	0.06074 ± 0.00920	COrE
1.01	0.07988 ± 0.01027	LiteBIRD
1.01	0.07122 ± 0.01027	PIXIE
1.09	0.07769 ± 0.01029	EPIC-LC-TES
0.99	0.06558 ± 0.01004	EPIC-CS
1.30	0.06205 ± 0.00906	EPIC-IM-4K
1.12	0.06386 ± 0.00925	PRISM

extra bias:
false r detection with no χ^2 evidence !
→ lack of low-frequency channels

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Impact of mis-modelling synchrotron: neglecting index curvature

r = 0.05

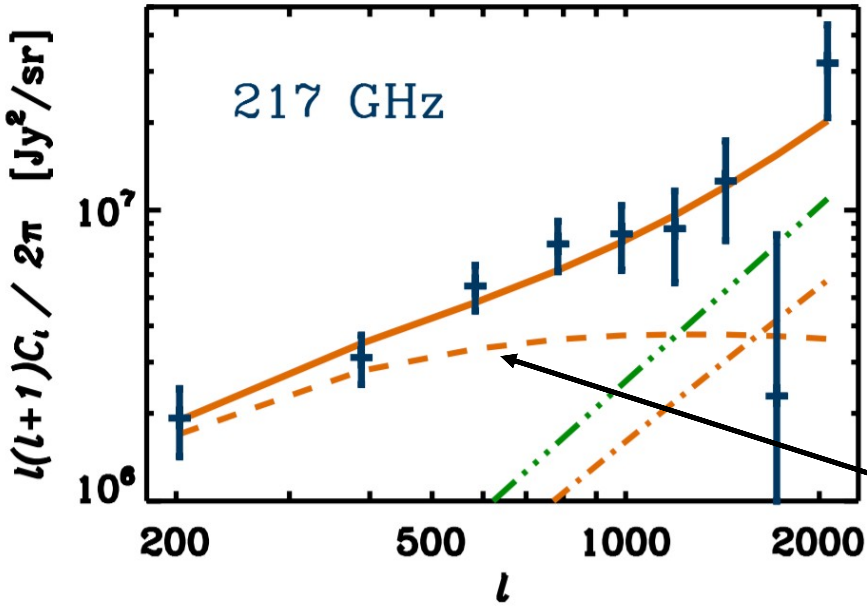


LiteBIRD extended

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

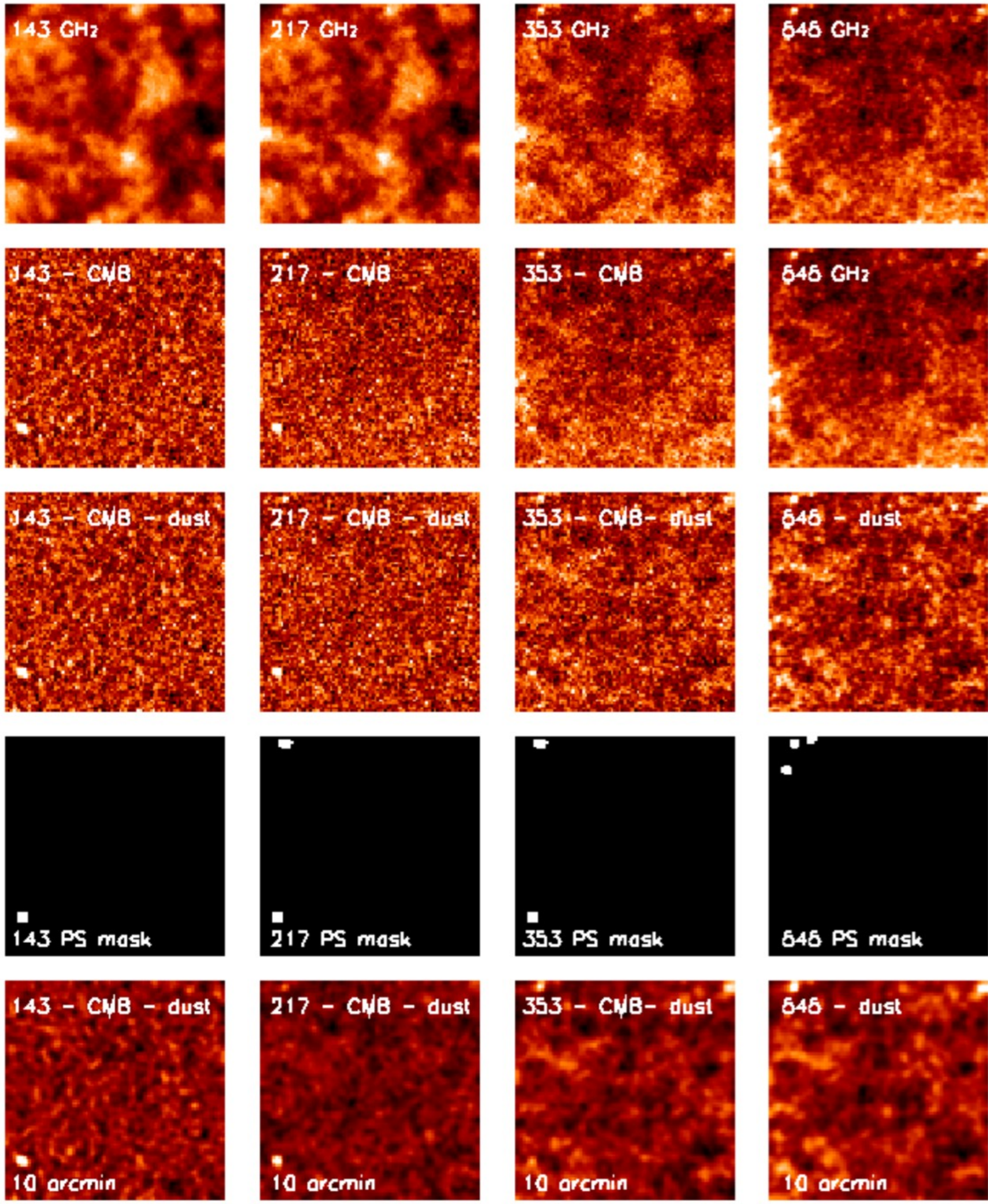
CIB polarization

- Cosmic Infrared Background (CIB) - dusty IR galaxies across the Universe (mostly z~1-4)
  - Correlated by large-scale structure (clustering)
  - Significant power on deg scales
- Thermal dust polarisation very small for individual galaxies (~1% ?)
  - e.g. Arp 220 upper limit (Seiffert et al. 2007)
- Expect polarisation to largely cancel out on average (random orientations)
- **BUT, variance will not cancel!**
  - **Polarised CIB could be important for future CMB polarisation missions!**



CIB (clustering contribution)

Planck Collaboration 2013 Results XXX (arXiv:1309.0382)



Maps of CIB

Planck Collaboration (2011), 536, A18

Conclusions

- **CMB TT**: foregrounds generally not a major issue any more, except possibly at very high-l
- **CMB TE/EE**: foregrounds an issue, but under control with careful masking and fitting
- **CMB BB: foregrounds definitely an issue.**
  - How far we can go depends on details of polarised foreground characteristics
  - **Utilise as many frequency channels and range as possible**
  - **Minimum is at ~70 GHz (on large scales)**
  - **Low frequencies (<~20 GHz) can be done from the ground (e.g. C-BASS)**
  - **Future CMB polarisation space mission will need flexibility -> lots of frequency channels!**
- Component separation will be even more critical for many areas of cosmology in the future!
  - Similar problem for HI/CO intensity mapping