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Unsolved Problems in Modern Astrophysics: Anomalous Microwave Emission

Thematic Areas: ☐ Planetary Systems ☑ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: It has now been over 20 years since the initial discovery of Anomalous Microwave Emission (AME) as a major foreground contaminant in Cosmic Microwave Background (CMB) studies, yet its physical origin remains an unsolved problem in modern astrophysics. AME was first detected in 1996 as a component of diffuse Galactic radiation observed at frequencies spanning $\sim 10-60\,$GHz and has now been seen in a variety of environments in the Galaxy, as well in two extragalactic sources and three proto-planetary disks. These seemingly uncorrelated instances of strong detections indicate that AME is highly sensitive to interstellar medium conditions. The leading explanation for AME is rotational emission from ultra-small (radius $a \lesssim 1\,$nm) dust grains, first postulated in 1957, however current observations remain inconclusive. If correct, spinning dust emission provides a new window into the properties of interstellar dust grains and their environment. If AME is not understood and accounted for, it could have a major impact as a foreground for CMB experiments, as well for interpreting radio observations in extragalactic astronomy. Progress in this field requires new observations of large heterogeneous samples of AME detections covering $\sim 1-120\,$GHz with a combination of sensitivity and high-angular resolution that exceeds any extant facility. Precise polarization measurements are also required for understanding emission mechanisms and to inform sensitive CMB polarization experiments.

Introduction

Precise characterization and separation of foregrounds remain a major challenge for current and future Cosmic Microwave Background (CMB) experiments (e.g., BICEP2/Keck Collaboration et al. 2015; *Planck* Collaboration et al. 2016), which includes a prominent and enigmatic component of Anomalous Microwave Emission (AME). Although total-intensity foregrounds appear to be under control, polarized CMB foregrounds present a particularly difficult challenge. Any significant (i.e., $\sim$1%) polarization from AME would significantly complicate analyses aiming to detect faint B-modes (Dunkley et al. 2009; Remazeilles et al. 2016).

It has been over 20 years since the initial discovery of excess $\sim 30\,$GHz ($\sim 1\,$cm), dust-correlated emission in CMB experiments (e.g. Kogut et al. 1996; Leitch et al. 1997), yet our current understanding of the physical mechanism and environmental conditions powering AME remains highly incomplete (see Dickinson et al. 2018 for a review). The leading explanation for AME is "spinning dust," in which rapidly rotating ultrasmall (radius $a \lesssim 1\,$nm) grains, with a non-zero electric dipole moment, produce a peaked microwave emission spectrum in the frequency range spanning $\approx 10 - 60\,$GHz (Erickson 1957; Draine & Lazarian 1998; Ali-Haïmoud et al. 2009; *Planck* Collaboration, et al. 2011). Magnetic dipole radiation from thermal fluctuations in the magnetization of interstellar dust grains (e.g., Draine & Lazarian 1999; Hensley et al., 2016), may also be contributing to observed AME, particularly at higher frequencies ($\gtrsim$50 GHz).

Investigations within the Galaxy have uncovered strong detections of AME in molecular clouds (e.g., see Figure 1) along with discrete locations adjacent to larger H II complexes (e.g., Dickinson et al. 2009; Tibbs et al. 2011), consistent with the theoretical expectation that it is a ubiquitous emission component in the interstellar medium (ISM) of galaxies. Over the last 10 years, AME has now been detected in external galaxies, and most recently in proto-planetary disks. The first extragalactic detection of AME unexpectedly resulted from a multi-wavelength investigation of star formation activity towards H II region complexes in the nearby galaxy NGC 6946 (Murphy et al. 2010). Since this initial discovery, a number of searches for extragalactic AME have been undertaken with WMAP and *Planck* data (e.g., the Magellanic Clouds, Bot et al. 2010; NGC 4945, Peel et al. 2011; NGC 6946, Scaife et al. 2010, Hensley et al. 2015), all of which have been largely inconclusive. Only one additional (secure) extragalactic detection is known in the star-forming disk of NGC 4725, which appears consistent with a highly-embedded (A_V >5 mag) nascent star-forming region, in which young ($\lesssim 3\,$Myr) massive stars are still enshrouded by their natal cocoons of gas and dust, lacking enough supernovae to produce measurable synchrotron emission (Murphy et al. 2018a). Finally, the recent detection of AME towards three proto-planetary disks around Herbig Ae stars by Greaves et al. (2018) suggests that hydrogenated nano-diamands may be a potential carrier. These seemingly uncorrelated instances of strong detections demonstrate that AME is indeed a major tracer of ISM conditions and that a complete model could lead to significant changes in our understanding of the astrophysics of the ISM and even star and planet formation.

*Why is such strong AME found for certain Galactic regions (e.g., molecular clouds and near H*II *regions), proto-planetary disks, and in two discrete regions in the star-forming disks of NGC 4725 and NGC 6946? Is there something outstanding about the physical properties (e.g., chemistry, size) of the dust grains and/or the environmental conditions (e.g., density, temperature, radiation field) that drives AME? If so, how might these particular conditions affect star/planet formation, and could they be more common in the high-z Universe? How must extragalactic investigations of*

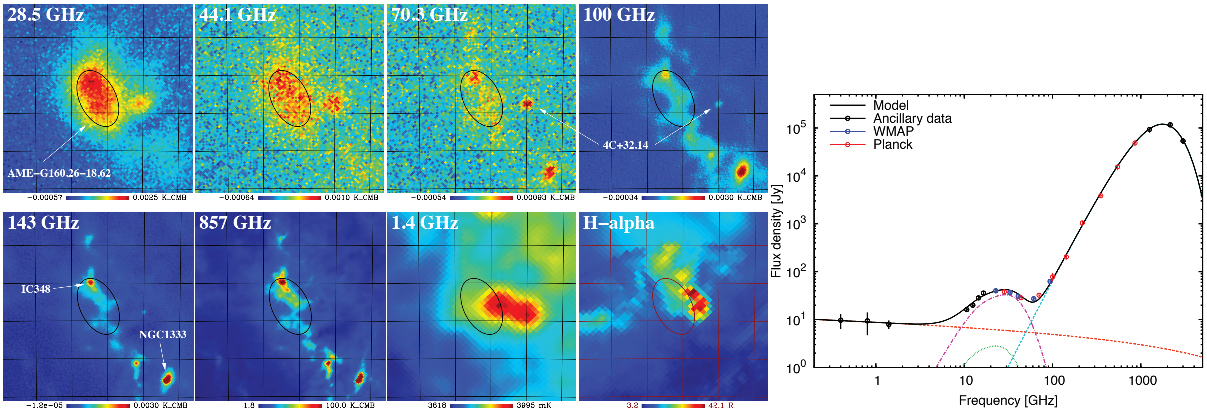

Figure 1: Taken from *Planck* Collaboration et al. (2011). **Left:** Maps of the Perseus molecular cloud region. From left to right – top row: *Planck* 28.5; 44.1; 70.3 and 100 GHz – bottom row: *Planck* 143 and 857 GHz; 1.4 GHz; and Hα. The maps cover 5° × 5° and have linear colour scales. The graticule has 1° spacing in Galactic coordinates. The FWHM of the elliptical Gaussian model used to fit the flux density for photometry is shown. The strong AME is evident at $30-70$ GHz. **Right**: Spectrum of AME-G160.26 – 8.62 in the Perseus molecular cloud. The best-fitting model consisting of free-free (orange dashed line), spinning dust, and thermal dust (light blue dashed line) is shown. The two-component spinning dust model consists of high density molecular gas (magenta dot-dashed line) and low density atomic gas (green dotted line).

star-formation and source counts for galaxy evolution studies take into account the possible presence of AME? Presently, existing observations have yet to uncover the smoking gun to explain the physical conditions responsible for powerful, compact AME detections, and it is almost certain that the next generation of facilities will be required to finally solve this astrophysical enigma.

Examples of Observed AME

Galactic Clouds: The most direct evidence of AME has come from dedicated observations of known dust clouds in the ISM (Finkbeiner et al. 2002; Casassus et al. 2006; Scaife et al. 2009; Dickinson et al. 2009, 2010). Perhaps the best example is that of the Perseus molecular cloud. *Planck* maps of the Perseus molecular cloud region, covering $30-857$ GHz, are shown in the left half of Figure 1, along with the 1.4 GHz and Hα maps (taken from *Planck* Collaboration et al. 2011). The strong dust-correlated AME at $30-70$ GHz is evident; it has no obvious counterpart at 1.4 GHz but correlates well with the higher ($>$100 GHz) *Planck* frequencies, which are dominated by thermal dust. In the right half of Figure 1 the spectrum of AME-G160.26 – 18.62 in Perseus is shown, together with the best-fitting model, and is consistent with free-free emission at low frequencies (<2 GHz), thermal dust emission at high frequencies ($>$100 GHz), and a strong excess at $\approx 10-70$ GHz with a convex spectrum peaking at $\approx$25 GHz. As is evident in Figure 1, AME is not always coincident with structures seen in the higher frequency dust maps; this is most likely due a combination of different environmental conditions and/or grain populations less favorable to powering strong AME. *However, given what little information exists to investigate these regions with the requisite sensitivity and frequency coverage at much higher ($\approx$10 pc) scale resolution, accurately predicting these exact (favorable) conditions that power AME remains out of reach.*

Extragalactic Detections: For two H II complexes (NGC 6946 E4 b & NGC 4725 B), excess 1 cm emission was found to be a factor of $\gtrsim$2 above what was expected given ancillary radio, mm, sub-mm, and infrared data (Figure 2; Murphy et al. 2010, 2018a). This excess emission has been attributed to AME, and another $\approx$25 regions (out of $\approx$ 300) have been identified as potential AME

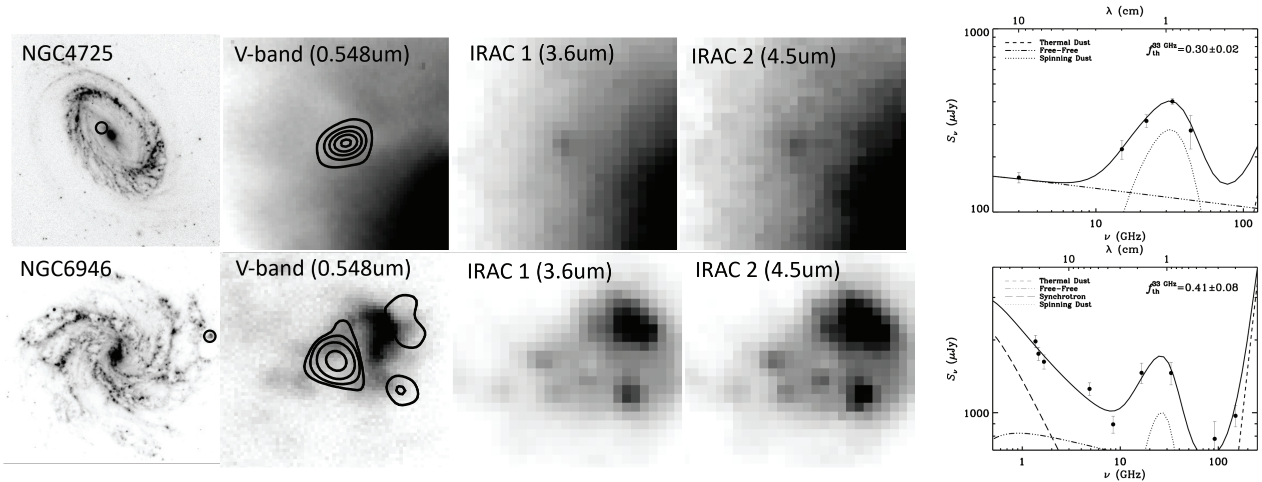

Figure 2: **Top:** An 8 μm image of NGC 4725 with the location of NGC 4725 B identified. The next three panels show a $15'' \times 15''$ zoom in at V (0.548 μm), IRAC 1 (3.6 μm) and IRAC 2 (4.5 μm) bands. The 33 GHz contours are shown on the V-band image. The final panel shows the radio spectrum of NGC 4725 B, indicating AME from a discrete, likely nascent star-forming region in this galaxy's inner disk (Murphy et al. 2018a). In the top right corner of each panel the thermal (free-free) emission fraction is given, and is less than the AME. **Bottom:** Same as for the top row, but instead for NGC 6946 E4 b. In both cases there is no identifiable optical counterpart, however distinct counterparts are seen at both 3.6 and 4.5 μm. The final panel shows the radio spectrum of NGC 6946 E4 b, exhibiting excess 1 cm emission, and identified as the first extragalactic detection of AME (adapted from Murphy et al. 2010).

candidates requiring additional follow-up observations (S. Linden et al. 2019, in prep.). If spinning dust in indeed responsible for these observations, models (e.g., Draine & Lazarian 1998; Ali-Haïmoud et al. 2009) suggest that there should be a significant amount of small grains ($a \lesssim 1$ nm). The interpretation of spinning dust is consistent with the inferred extinction of $A_V \gtrsim 5$ mag for NGC 4725 B based on the measured free-free emission and Hα upper limit. Both extragalactic detections are optically opaque, but detected by *Spitzer*/IRAC at 3.6 and 4.5 μm (see Figure 2), indicating a significant amount of small dust grains. Contradictory to these observations, there is no strong spatial coincidence observed between the AME and 8 μm PAH or very small grain 24 μm emission for these two sources, similar to results from Galactic investigations (e.g., Tibbs et al. 2012; Hensley et al., 2016), as would be expected if PAHs were the carriers. This suggests that the radiation field may play a pivotal role, and/or that the 8 μm PAH carriers are not sampling the correct grains that power AME. *The detailed nature of the associated grains and environmental conditions remain a critical and largely unconstrained aspect of these sources.*

Proto-planetary Disks: AME has also been recently detected in three proto-planetary disks (Greaves et al. 2018), which is shown in Figure 3. What is most striking about these findings is that AME was only detected in those disks around Herbig A-type emission-line objects hosting hydrogenated nano-diamands (Acke & van den Ancker 2006), where C-H bonds can provide suitable electric dipole moments. This is in stark contrast to the much more commonly detected PAHs, suggesting that nano-diamonds might indeed be the AME carrier.

JWST will provide routine access to the 3.3 and 3.4 μm PAH features, which are the shortest wavelength PAH features, and thus probes the abundance and chemical composition of the smallest grains. The 3.3 μm feature is associated with aromatic structures in grains with fewer than ~ 30 carbon atoms (Draine & Li 2007), while the 3.4 μm feature arises from aliphatic (chain-like) structures. *JWST* will also be able to detect the 3.43 and 3.53 μm features associated with hydrogenated nano-diamonds (Guillois et al. 1999). A strong association between any of these feature and the

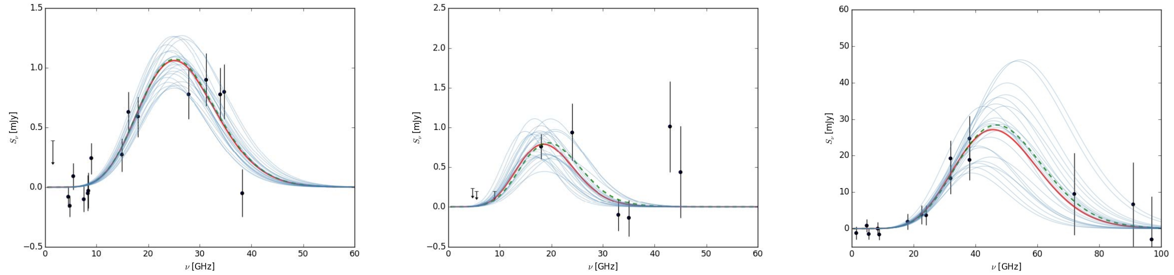

Figure 3: Taken from Greaves et al. (2018): AME data points with dust and wind model subtracted to leave the AME residual for V892 Tau (**meft**), HD 97048 (**middle**) and MWC 297 (**Right**). Overlaid is the Maximum Likelihood fit (dashed line), a model using the parameters' expectation values (solid line), and 24 samples randomly drawn from the posterior distribution (thin lines).

AME detections would shed light on the precise molecular nature of the AME carriers, but the few cases discussed here are the only ones known, and therefore may be the exception rather than the rule. Lower luminosity stars, as well as Galactic and extragalactic sources in general, could still host AME carriers at similar abundances as those discussed here, but simply be un-detectable in the microwave regime given the sensitivity limits of extant facilities. *Achieving an understanding of AME in proto-planetary disks on AU-scales may help constrain models of grain growth that feed into to estimating the timescales for the formation of the rocky cores of planets, which are completely at odds with current observations.*

Impact of future AME research

While AME research is of significant interest in its own right, it also impacts other areas of astrophysics. Below we highlight some of the potential key impacts of AME research:

Emission mechanisms. To most it is unacceptable to have widespread emission that we do not understand. Although electric dipole radiation from small spinning dust grains is the favoured explanation, there are a number of unanswered questions and discrepancies. For example, what is the carrier of AME (PAHs, small silicate grains; see e.g., Hensley & Draine 2017). We must also be aware of other potential contributions such as from magnetized dust grains which could be highly polarized (Draine & Lazarian 1999, Draine & Hensley 2013, Hoang & Lazarian 2016).

Physics of dust grains and dust grain properties. Following on from above, if spinning dust is the main mechanism, it can be used as a direct tracer of interstellar dust grains. In particular, it is highly sensitive to the grain size distribution and distribution of electric dipole moments. In combination with IR diagnostics, spinning dust studies can yield the abundance of nanoparticles in environments such as cold cores (Tibbs et al. 2016) and protoplanetary disks (Greaves et al. 2018).

ISM environment. AME has the potential to constrain environmental properties of the ISM. If AME is due to spinning dust, the spectrum is sensitive to the environment due to the effects of spinning up or damping down the rotational velocities of grains. Detailed spectral measurements can constrain parameters such as the density and interstellar radiation field strength. The degree of alignment of nanoparticles is sensitive to the magnetic field strength, although the alignment physics remains controversial (Lazarian 2003, Hoang et al. 2014,2018; Draine & Hensley 2016). Recent works have also identified additional uses such as tracing the velocity of interstellar shocks (Hoang & Tram 2019) and as a test of dust destruction mechanisms (Hoang et al., 2019).

CMB foregrounds. The search for primordial B-mode fluctuations in the CMB is one of the "holy grails" of modern cosmology. However, foreground contamination must be carefully understood and subtracted. Any significant polarization from AME would complicate the picture by adding an additional foreground component at frequencies below ~ 100 GHz, with a different distribution from the already polarized synchrotron and thermal dust emissions. Future CMB experiments are aiming at sensitivities of sub-μK over a range of frequencies and thus even a small level ($\sim 1\%$) of AME polarization could be important (e.g., Remazeilles et al. 2016, 2018).

Extragalactic continuum measurements. Understanding the potential ubiquity of AME from extragalactic sources, along with its ability to bias radio free-free emission star formation rate estimates, is of critical value given that future radio surveys at $\lambda \lesssim 3$ cm (perhaps using a next-generation VLA and/or the Square Kilometre Array), will measure rest-frame $10 - 60$ GHz emission from high-z galaxies (e.g., Murphy 2009). This might be important given that high-z galaxies have been modeled to have grain properties that are similar to that of the SMC (e.g., Perley et al., 2010; Maiolino et al. 2004), a system that appears to contain a significant amount of AME arising from a combination of spinning and magnetized nano-grains (Draine & Hensley, 2012).

A Pathway Forward

The occurrence of AME remains highly unpredictable due to our lack of understanding of the carrier(s) and physical conditions favorable for triggering this emission mechanism. Progress in this field requires that we be able to build samples of AME sources for a large, heterogeneous set of physical conditions both within and outside of our Galaxy on the linear scales for which the emission is operating. To achieve this requires, in prioritized order:

- Sensitive radio observations spanning $\sim 1 - 120$ GHz to highly sample AME for spectral modeling purposes. For extragalactic sources, high (i.e., $0\rlap{.}''1$) angular resolution is needed to map AME at ~10's of pc in galaxies out to $d_L \approx 20$ Mpc. For proto-planetary disks, ≈ 5 mas angular resolution is needed to map AME on AU-scales in nearby systems (i.e., <140 pc). This could be achieved with a next-generation ground-based interferometer like the next-generation VLA (ngVLA: Bolatto et al. 2017; Murphy et al. 2018b).
- Precise polarization measurements are required both for understanding the emission mechanisms and environment and to inform ultra-sensitive CMB polarization experiments that aim to detect faint B-modes from the epoch of inflation. Large-scale diffuse emission will require dedicated instruments such as C-BASS (Jones et al., 2018) or low frequency instruments as part of CMB-S4. Small-scale measurements can be achieved with ngVLA and ALMA.
- Spectroscopic mapping capabilities in the mid-infrared ($\sim 3 - 25\,\mu$m) range to access spectral features that are sensitive to a range of grain size distribution and chemistry that may directly trace the AME carrier. This should be realized by *JWST*.
- Far-infrared ($\sim 40 - 160\,\mu$m) mapping capabilities on (sub-)arc-second resolution to correlate the dust emissivity with AME detections on the physical scales for which the emission is operating. This requires a next-generation far-infrared telescope from space with an extremely large aperture (≈ 15 m) along with fast, multi-band mapping capabilities.
- Laboratory work is important both to study the alignment of nanoparticles and to explore the magnetic response of the candidate particle materials for the purpose of exploring different mechanisms of producing emission and polarization that can be responsible for the AME.

References • Acke, B., & van den Ancker, M. E. 2006, A&A, 457, 171 • Ali-Haïmoud Y., et al. 2009, MNRAS, 395, 105; • BICEP2/Keck Collaboration et al. 2015, PhRvL, 114, 101301 • Bolatto A., et al. 2017, arXiv:1711.09960.; • Bot C., et al. 2010, A&A, 523, 20; • Casassus A., et al. 2006, ApJ, 639, 951; • Dickinson, C., et al. 2009, ApJ, 690, 1585; • Dickinson, C., et al. 2010, MNRAS, 407, 2223; • Dickinson, C., et al. 2018, 2018, NewAR, 80, 1; • Draine B. T., & Lazarian A. 1998, ApJ, 508, 157; • Draine B. T., & Lazarian A. 1999, ApJ, 512, 740; • Draine B. T., & Li , A. 2007, ApJ, 657, 810; • Draine B. T., & Hensley B., ApJ, 2012, 757, 103; • Draine, B. T., & Hensley, B. 2013, ApJ, 765, 159; • Draine, B. T., & Hensley, B. S. 2016, ApJ, 831, 59; • Dunkley, J., et al., 2009, AIPC, 1141, 222; • Erickson W. C., 1957, ApJ, 126, 480; • Finkbeiner, D. P., et al. 2002, ApJ, 566, 898; • Guillois, O. et al. 1999, ApJ, 521, L133; • Greaves, J. S., et al. 2018, Nature Astronomy, 2, 662 • Hensley B. S., et al. 2015, MNRAS, 449, 809; • Hensley B. S., et al. 2016, ApJ, 827, 45; • Henlsey B. S., & Draine B. T. 2017, ApJ, 836, 179; • Hoang, T., et al., 2014, ApJ, 790, 6; • Hoang, T., & Lazarian, A. 2016, ApJ, 821, 91; • Hoang, T., & Lazarian, A. 2018, ApJ, 860, 158; • Hoang, T., & Tram, L. N. 2018, arXiv:1810.12007; • Hoang, T., et al., 2019, arXiv:1810.05557; • Jones, et al. 1994, ApJ, 433, 797; •, Jones, M. E., et al., 2018, MNRAS, 480, 3224; • Kogut, A., et al. 1996, ApJ, 460, 1; • Lazarian, A., & Draine, B. T. 2000, ApJ, 536, L15 • Lazarian, A. 2003, JQSRT, 79, 881; • Leitch E. M., et al. 1997, ApJ, 486, L23; • Maiolino, R., et al. 2004, Nature, 43, 533; • Murphy E. J., 2009, ApJ, 706, 482; • Murphy E. J., et al. 2010, ApJL, 709, 108; • Murphy E. J., et al. 2018a, ApJ, 862, 20; • Murphy E. J., et al. 2018b, ASPC, 517, 3; • Peel M., et al. 2011, MNRAS, 416, L99; • Perley D. A., et al. 2010, MNRAS, 406, 2473; • *Planck* Collaboration, et al. 2011, A&A, 536, A20; • *Planck* Collaboration, et al. 2016, A&A, 586, A133; • Remazeilles, M., et al., 2016, MNRAS, 458, 2032; • Remazeilles, M., et al., 2018, JCAP, 4, 023; • Scaife, A. M. M., et al. 2009, MNRAS, 400, 1394; • Scaife A. M. M., et al., 2010, MNRAS, 406, L45; • Tibbs, C. T. et al. 2012, ApJ, 754, 94 • Tibbs, C. T., et al., 2016, MNRAS, 456, 2290;