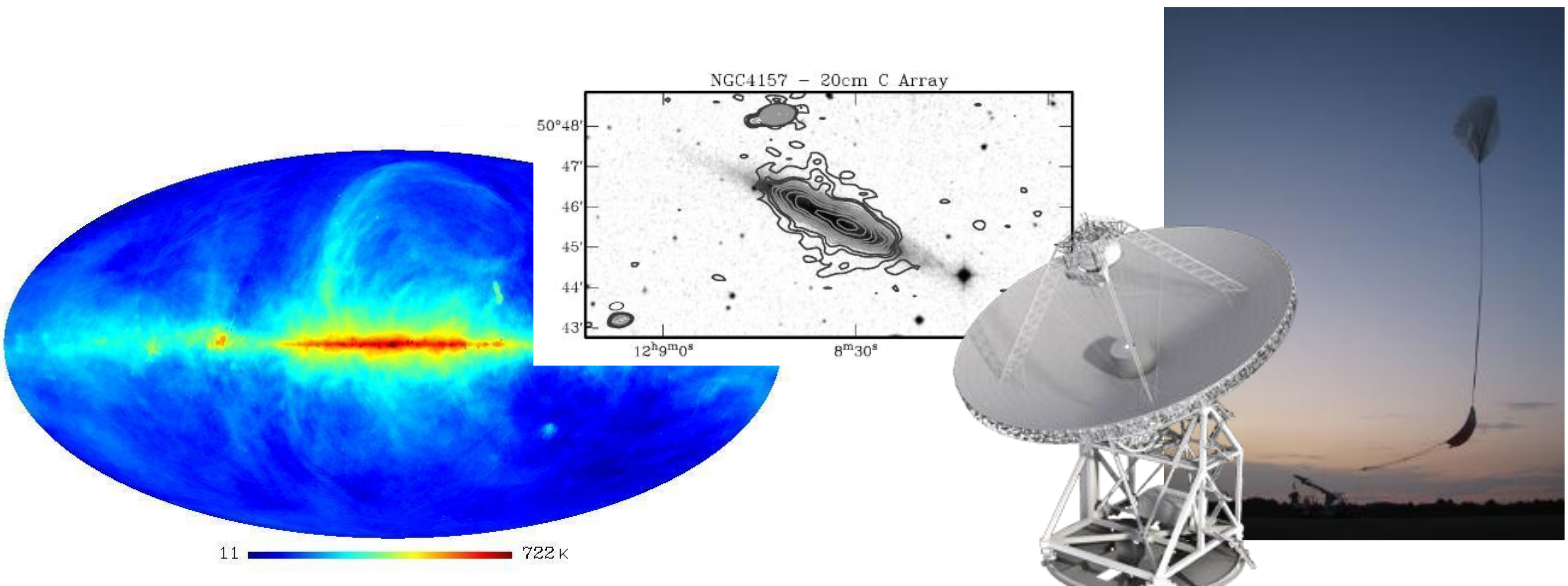
Jack Singal
University of Richmond

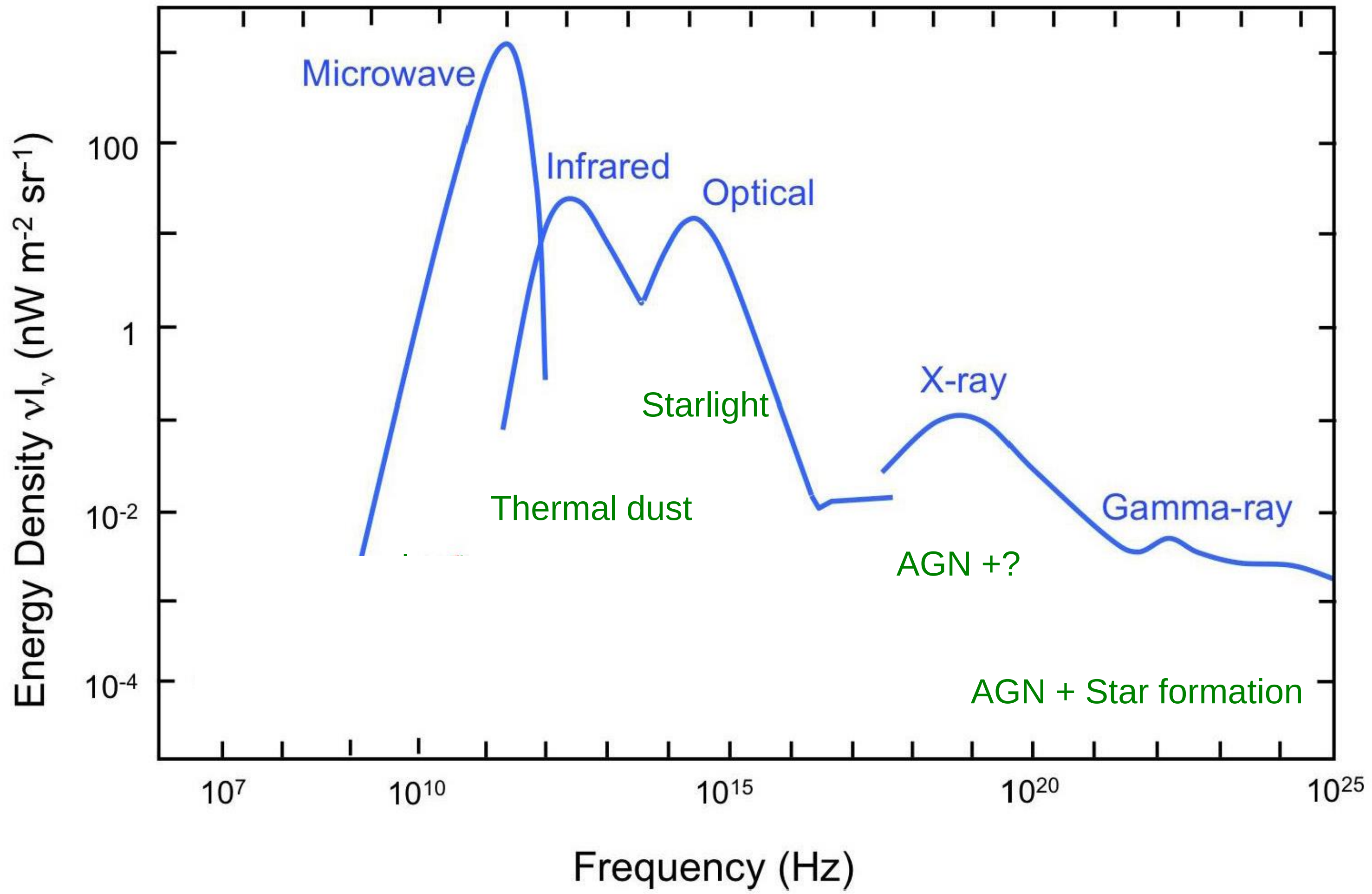
BAM! Anisotropic Universe Workshop
September 4, 2018

# The Radio Background and Its Anisotropies



# The Radio background???

What about over here?



# The Isotropic Radio Sky

An isotropic component of the diffuse radio emission was identified as early as the 1960s

- Costain, 1960, *MNRAS*, 120, 248 “The spectrum of the galactic radio emission.”

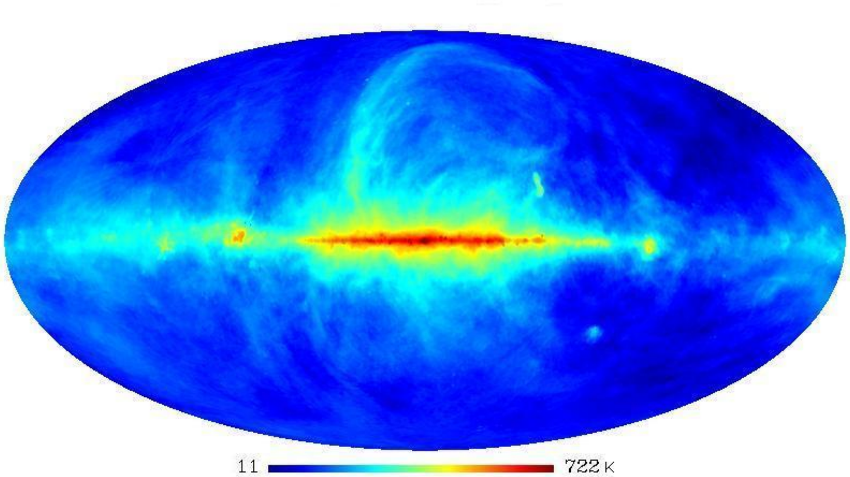
- Bridle, 1967, *MNRAS*, 136, 219 “The spectrum of the radio background between 13 and 408 MHz.”

# The Isotropic Radio Sky

The Haslam survey results from the early 1980s were clear about the existence of the radio isotropic component

- Phillips et al., 1981, *A&A*, 103, 405 "Distribution of Galactic Synchrotron emission II."

- Beuermann et al., 1985, *A&A*, 153, 17 "Radio Structure of the Galaxy – Thick and Thin Disk at 408 MHz."



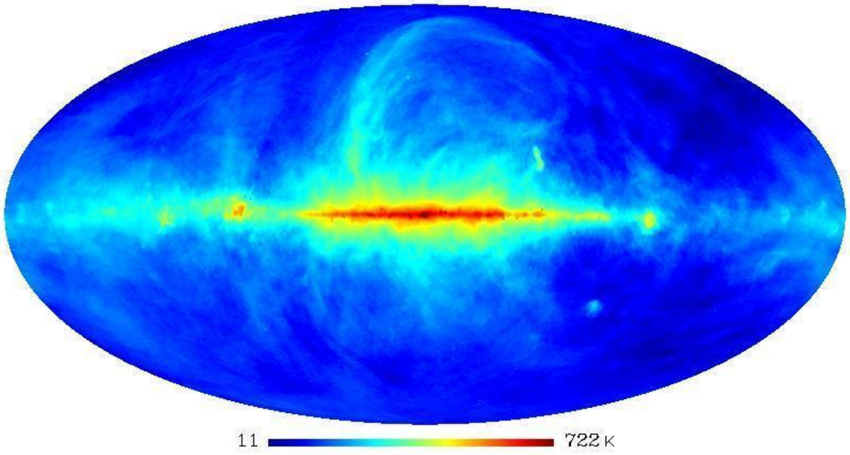

Haslam 408 MHz all-sky map

# The Isotropic Radio Sky

- **In the 60s-80s, the radio isotropic signal was assumed to be some combination of extragalactic point sources and/or a Galactic halo, neither of which were well constrained**

- **So no particular mystery then…**

What about at higher frequencies?




Haslam 408 MHz all-sky map

# ARCADE

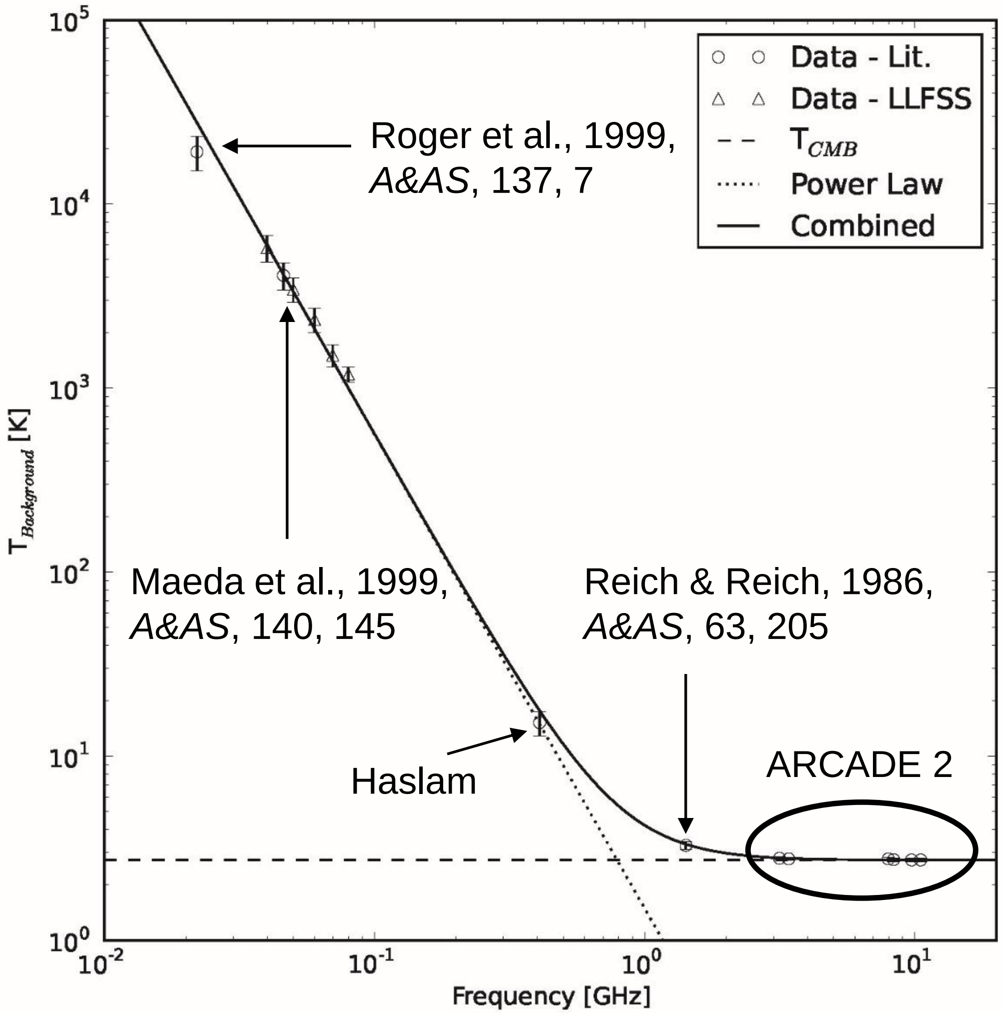
- mK-level absolute uncertainties and sub mK-level fractional uncertainties from 3-90 GHz

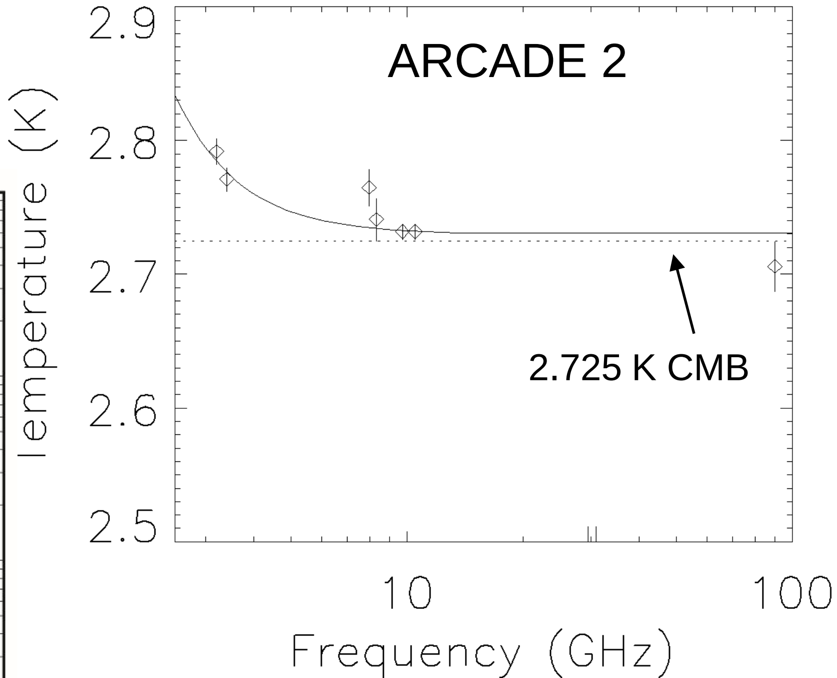
- Radiation from sky compared to large (~2ft. across) external microwave blackbody calibrator. Calibrator temperature is adjusted until its emission intensity matches the sky emission. That is then the radiometric temperature of the sky.

- Systematic errors are minimized by:
  - **no windows between the sky and the receivers**
  - **keeping everything cold** (at the top of a 7ft tall open dewar at 120,000 ft)

# Radio Background Temperature Results

Dowell & Taylor, 2018, *ApJL*, 858, 9



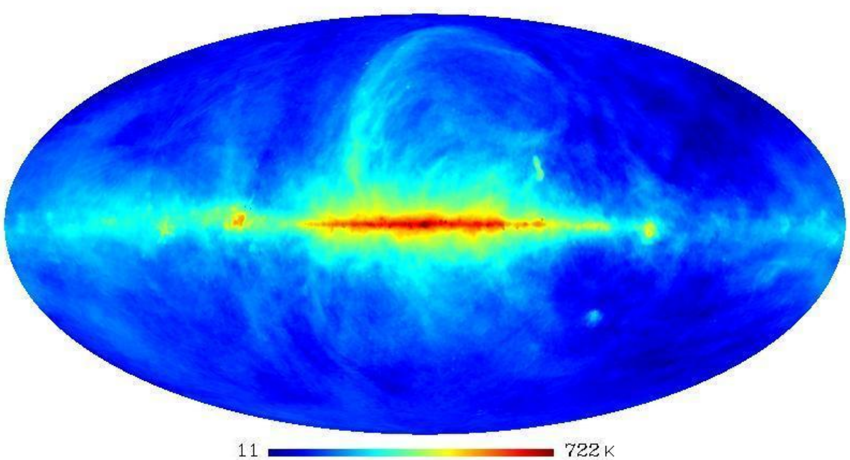

$$T_{bgnd}(\nu) = 28.5 \pm 1.7\ K \left(\frac{\nu}{310\ MHz}\right)^{-2.66\pm0.04}$$

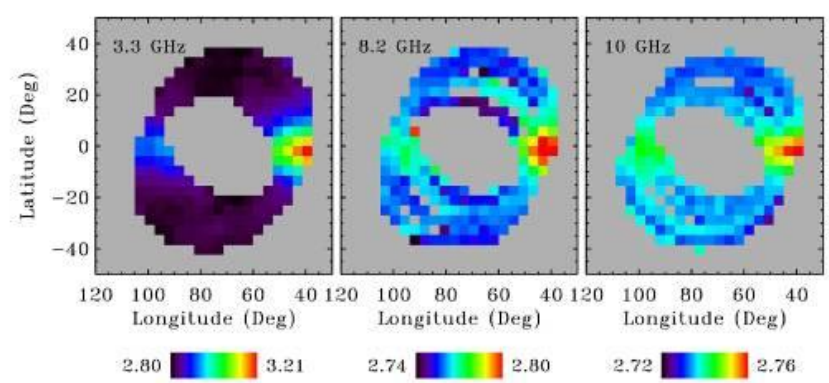
# Summary: The Isotropic Radio Sky

- Absolutely calibrated single dish all-sky maps at low frequencies (e.g. Haslam et al., 1982, *A&A*, 47, 1) and ARCADE 2 measurements at higher frequencies (Fixsen et al., 2011, *ApJ*, 734, 5) both indicate that there is a significant radio isotropic component

- The radio emission has a synchrotron spectrum

- It is isotropic on >1 deg scales



Ok, we have measured this level of background radio surface brightness…

*But nowadays the possible extragalactic and Galactic sources are much better constrained*

They do not agree!

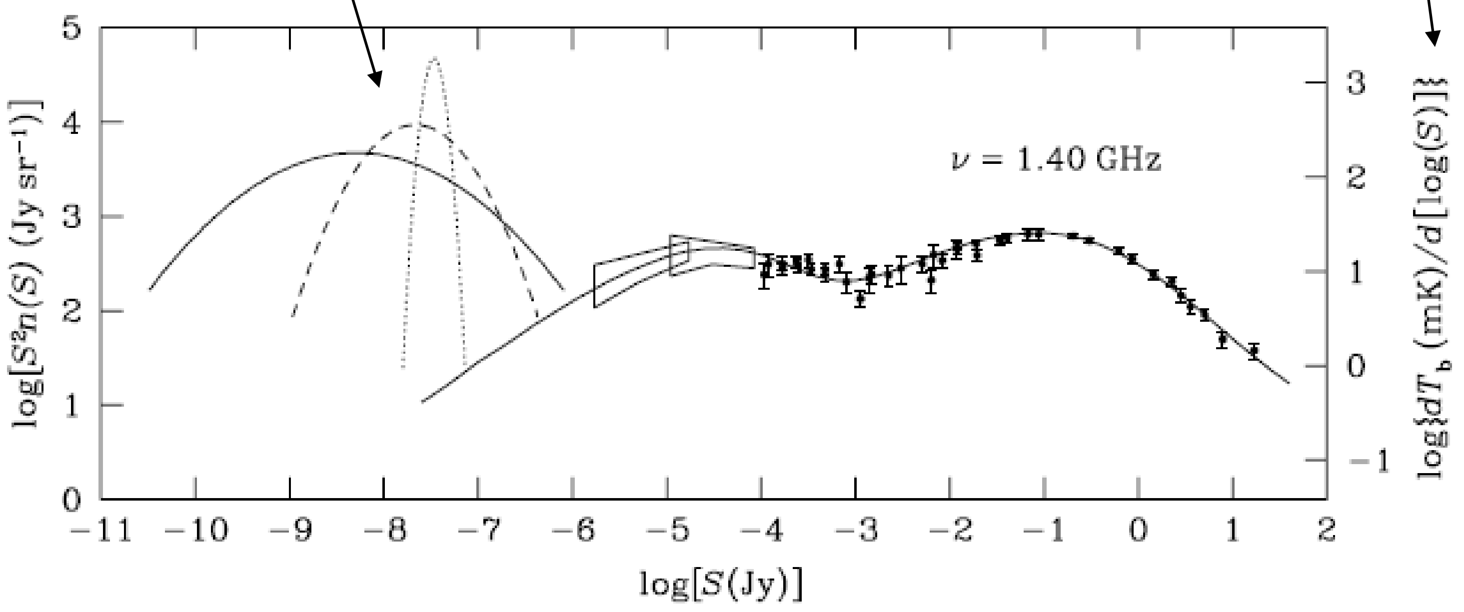
# Extragalactic Radio Source Counts

J. Condon et al., 2012, *ApJ*, 758, 23

Known source classes give only ~1/5 of the claimed radio background level

Integrated contribution to sky surface brightness temperature per log flux bin

Possible source flux distributions that could give background level




**Would need *huge (!)* # of low flux sources**

# Extragalactic Radio Source Counts

J. Condon et al., 2012, *ApJ*, 758, 23

Known source classes give only ~1/5 of the claimed radio background level

**Would need *huge (!)* # of low flux sources**

Consistent conclusions in:

- T. Vernstrom et al., 2014, *MNRAS*, 440, 2971
- A. Draper, S. Northcott, & D. Ballantyne, 2011, *ApJ*, 741, L39

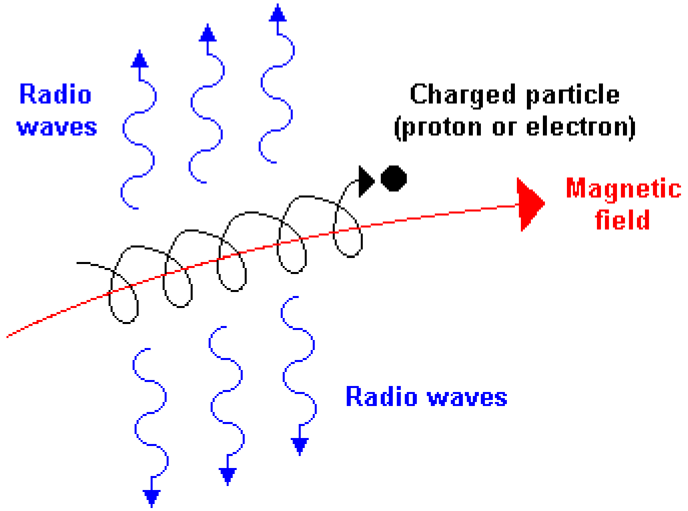
# Inverse-Compton

- J. Singal, L. Stawarz, V. Petrosian, & A. Lawrence (2010, *MNRAS*, 409, 1172)

- Synchrotron emissivity is a combination of electron energy density ($U_{e-}$) and magnetic field energy density ($U_B$)

- For a given observed synchrotron level $\nu_{syn} U_{\nu_{syn}}$ if $U_B \downarrow$ then $U_{e-} \uparrow$

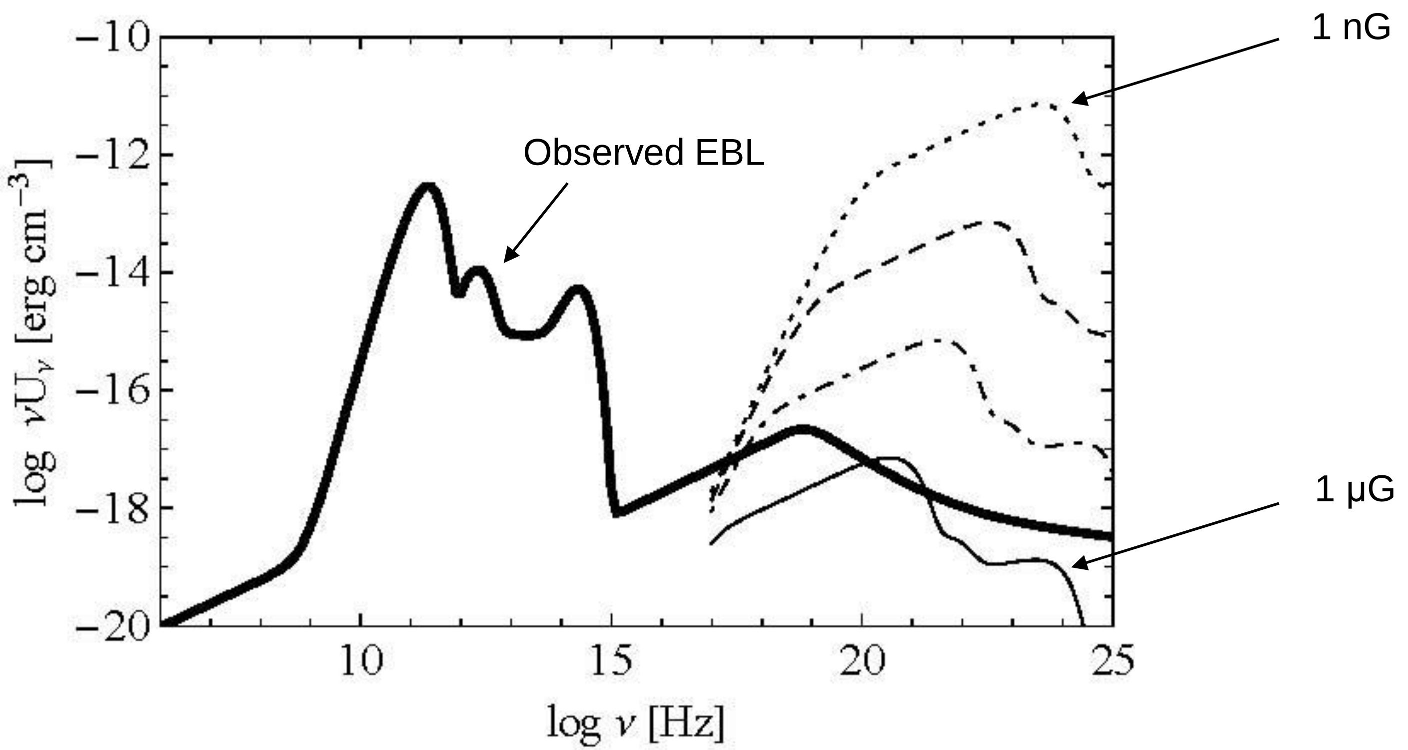
- If $U_{e-} \uparrow$ then inverse-Compton upscattering by these electrons increases



# Inverse-Compton

- Singal et al. (2010, *MNRAS*, 409, 1172)

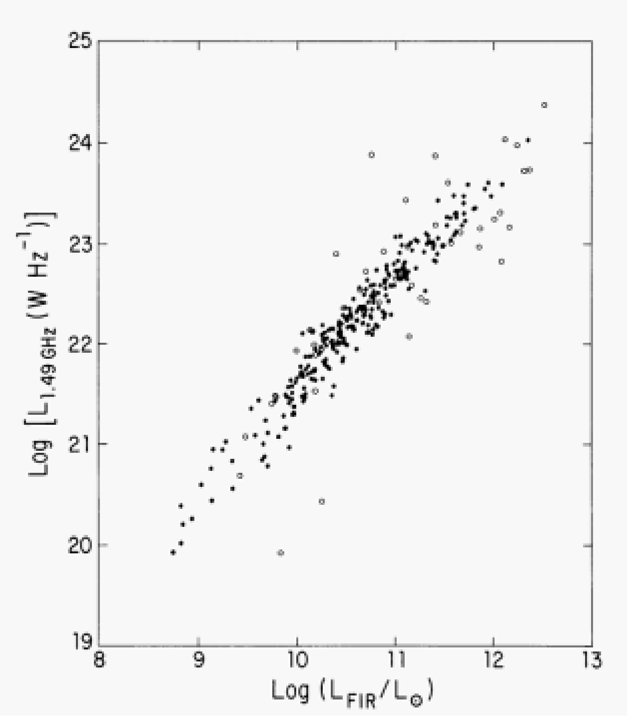
The electrons that produce the radio emission through synchrotron cannot overproduce another background via inverse-Compton – places a lower limit on the magnetic field in the emitting regions



# Radio-FIR Correlatoion

- Singal et al. (2010, *MNRAS*, 409, 1172)

If the source population follows the radio – FIR correlation of the *local* Universe they would overproduce the far-infrared background



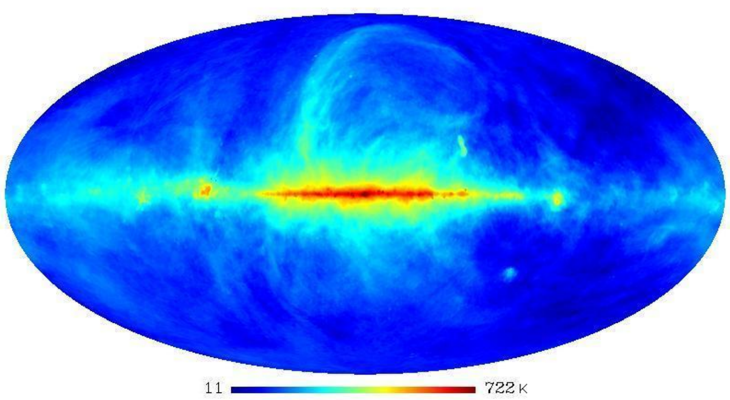

Generally consistent conclusions in:

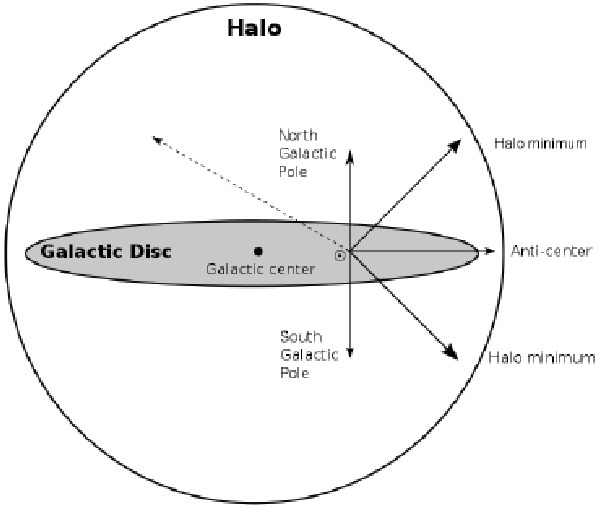
- T. Vernstrom, D. Scott, & J. Wall, 2011, *MNRAS*, 415, 3641
- P. Ponente et al., 2011, *MNRAS*, 419, 691
- N. Ysard & G. Lagache, 2012, *A&A*, 547

# Galactic Halo?

R. Subrahmanyan & R. Cowsik, 2013, *ApJ*, 776, 42 "*Is there an unaccounted excess Extragalactic Cosmic Radio Background?*"

They use a 2-component 5-parameter vs frequency Galactic spatial model for radio emission to get a much higher halo component.



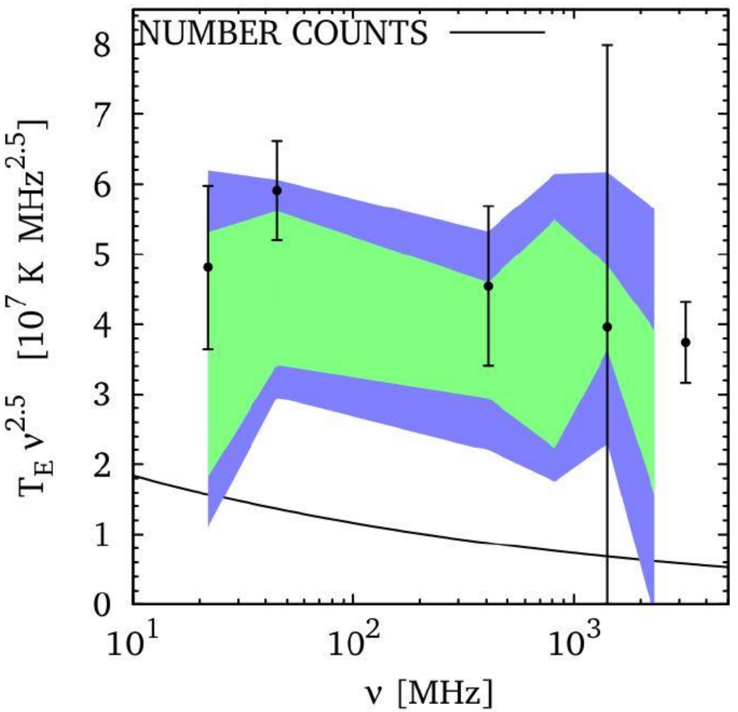

GALPROP sims (e.g. E. Orlando & A. Strong, 2013, *MNRAS*, 436, 2127) can reproduce level of radio background at 408 MHz with a 10 kpc cosmic ray halo.

# Galactic Halo?

• The same X-ray inverse-Compton argument applies to our Galactic halo, where FR measures show the mag field is ~1 μG (Taylor et al, 2009, *ApJ*, 702, 1230) and optical/UV flux is higher

• Large scale Galactic radio emission is well fit by a csc(b) spatial model, and a correlation of radio with C+ emission at 158 μm agrees (Kogut et al, 2011, *ApJ*, 734, 4)

• Fornengo et al. (2014, *JCAP*, 04, 008) with detailed Galactic synchrotron modeling of CR propagation and mag. field structure fit to radio intensity maps

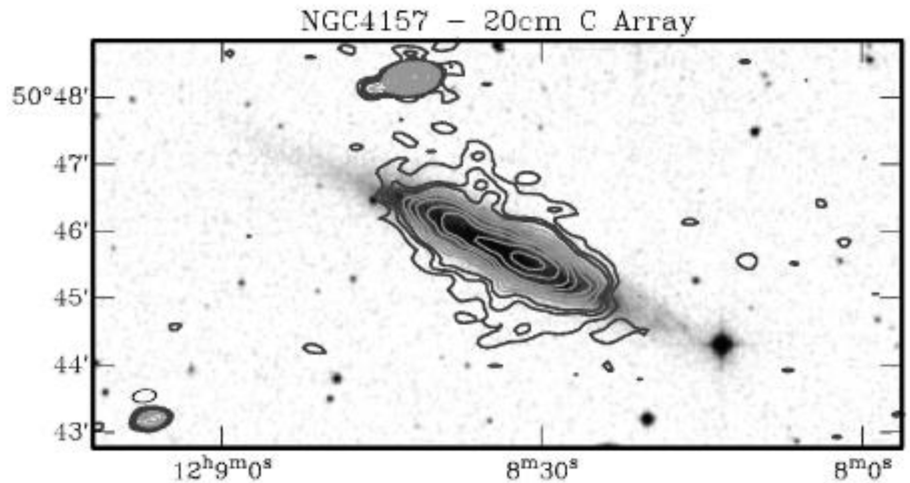


# Galactic Halo?

**We can see whether galaxies similar to ours have a large bright radio halo**

- J. Singal, A. Kogut, E. Jones, & H. Dunlap, 2015, *ApJL*, “Axial Ratio of Edge-On Spiral Galaxies as a Test For Bright Radio Halos.” 799, L10

• There are radio emission contour maps of galaxies nearby enough to be resolved and which are seen edge-on



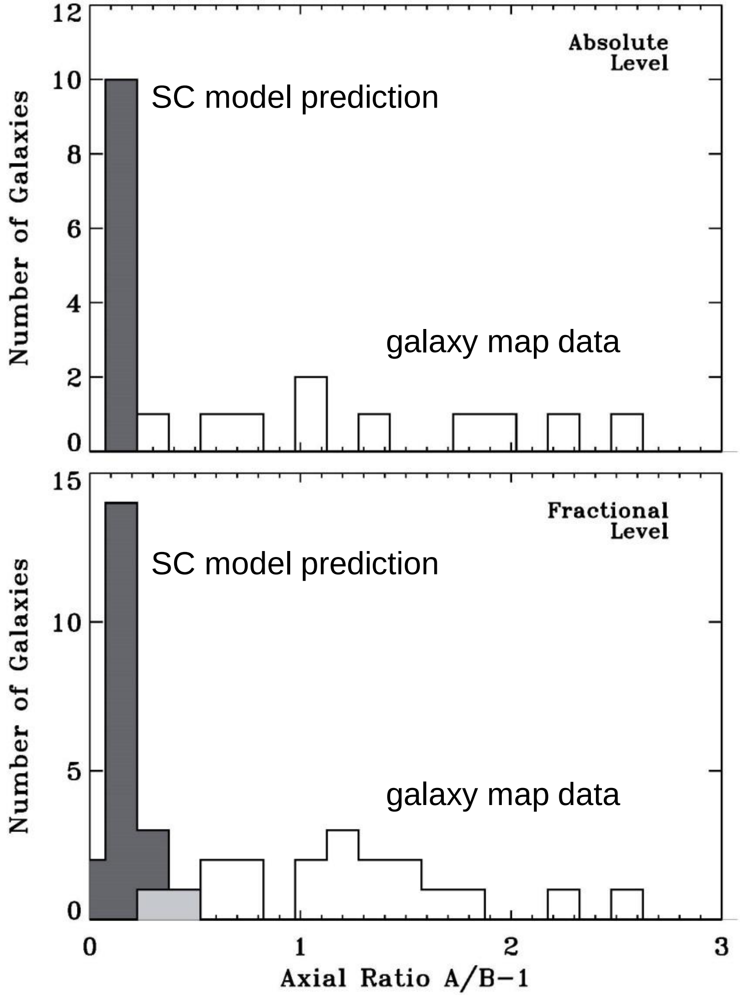

• Do they have a shape structure (round-ish halos bulging above and below the plane of the disk) that would be predicted by the Subrahmanyan & Cowsik model?

# Galactic Halo?

**We can see whether galaxies similar to ours have a large bright radio halo**

- Singal et al., 2015, *ApJL*, “Axial Ratio of Edge-On Spiral Galaxies as a Test For Bright Radio Halos.” 799, L10

**Galaxies similar to the Milky Way are more elliptical than the SC model at contours at relevant temperatures or fractions of the peak brightness, disfavoring this type of large radio halo**

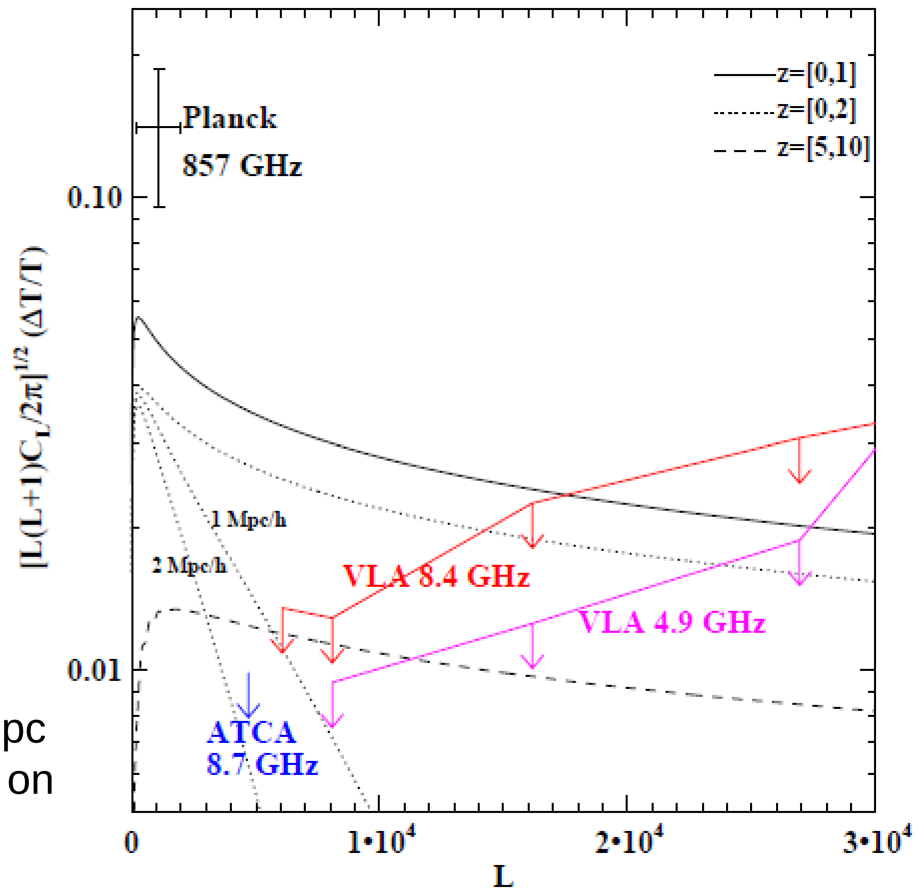


# Anisotropy Limit

- G. Holder (2014, *ApJ*, 780, 112) "*The Unusual Smoothness of the Extragalactic Unresolved Radio Background*"

Sub arcminute-scale fluctuations seen at 4.86 and 8.4 GHz are small enough that Radio Background sources must not be clustered like the observed (optical) structure distribution at low redshifts

However if the sources are >1' scale (~several Mpc at low redshifts) that will suppress the anisotropy on these scales.

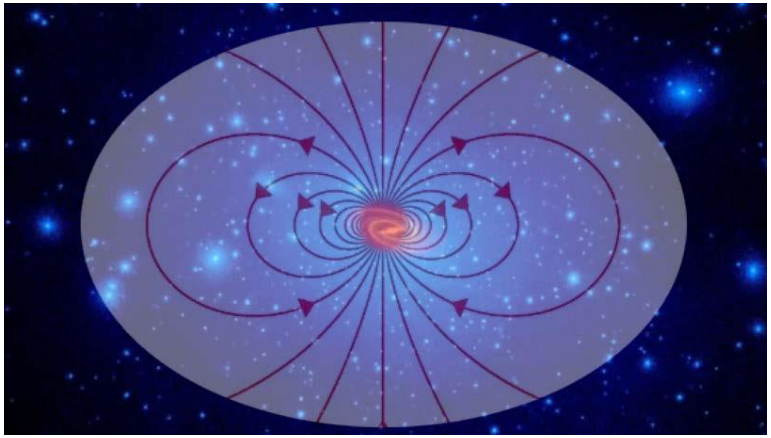


# Interesting Ideas (1)

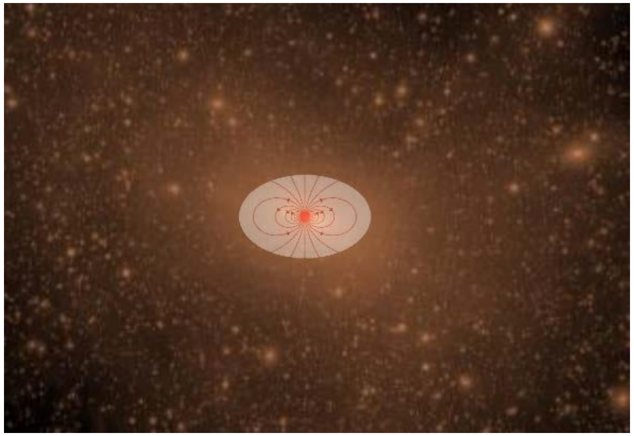
- Regis et al., 2014, *JCAP*, 10, 16;
- Regis et al., 2017, *JCAP*, 7, 25
- Fornengo et al., 2011, *PRL*, 107, 271302
- +

DM decays and annihilations can produce level of RSB if
(a) magnetic fields extending much further than the baryonic matter distribution in galaxies (together with DM profiles having large cores); and/or
(b) significant magnetic fields in dark structures, i.e., in the dark matter structures that do not have significant star formation today. Can potentially be tested with SKA observations of dwarf spheroidals.

a



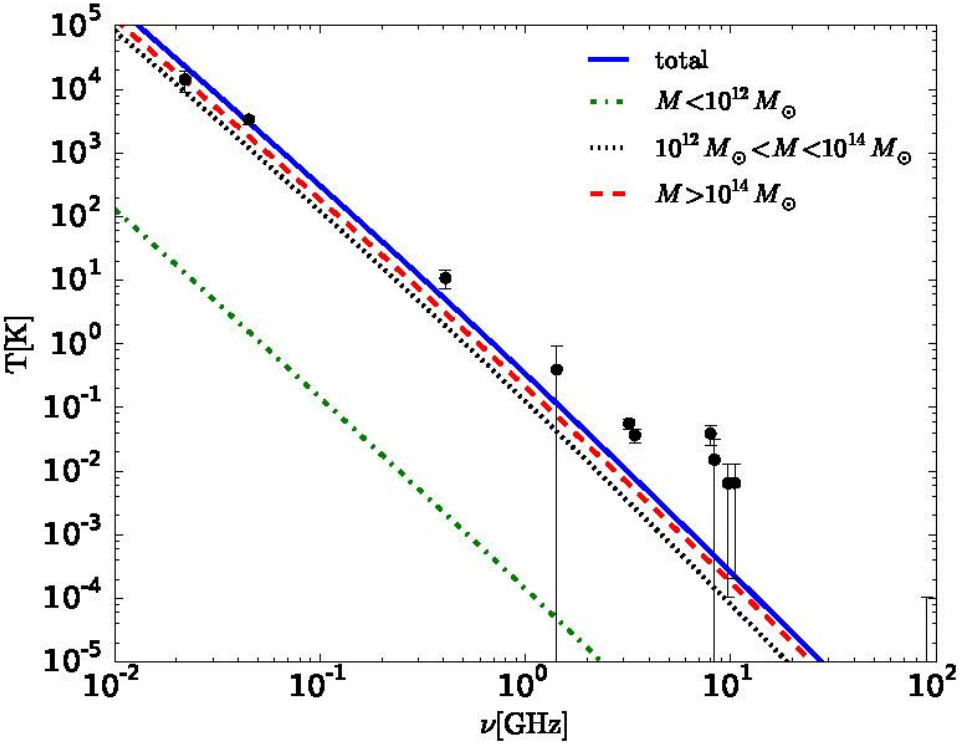
b



# Interesting Ideas (2)

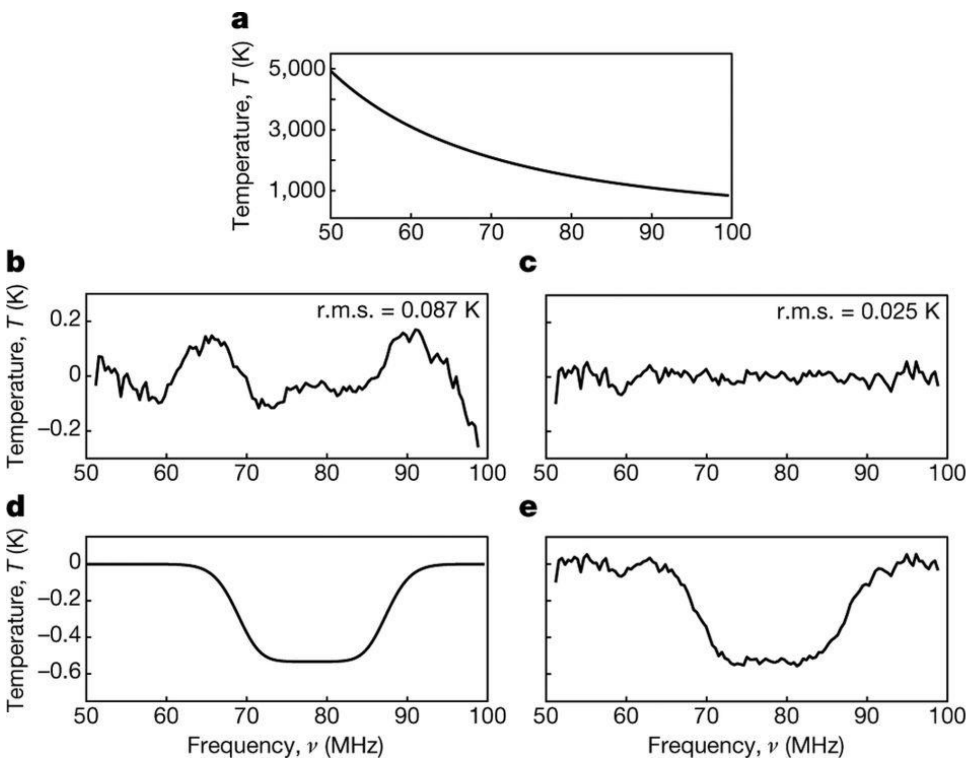
- K. Feng & R. Linden, 2016, *JCAP*, 10, 004

"*Cluster Mergers and the Origin of the ARCADE-2 Excess*"
Cluster mergers produce turbulence which produces Alfen waves which can accelerate electrons and also amplify magnetic fields producing level of RSB. They need at least 4μG magnetic fields at the center of clusters. The sources would be >Mpc scale to get around the smoothness problem.



# 21 cm Issues

Bowman et al., 2018, Nature, 555, 67

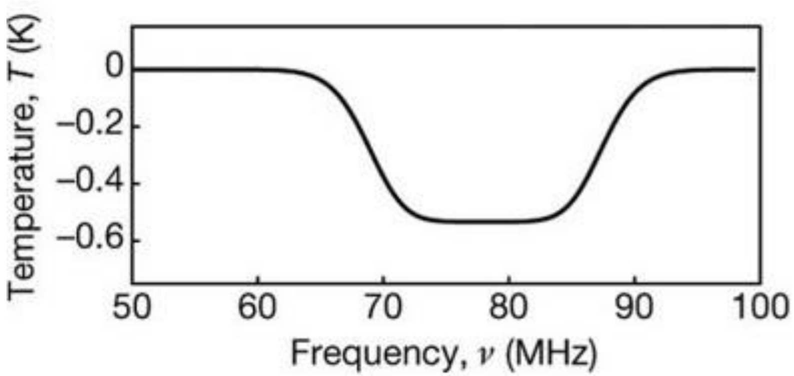



Absorption trough ~2x than expected

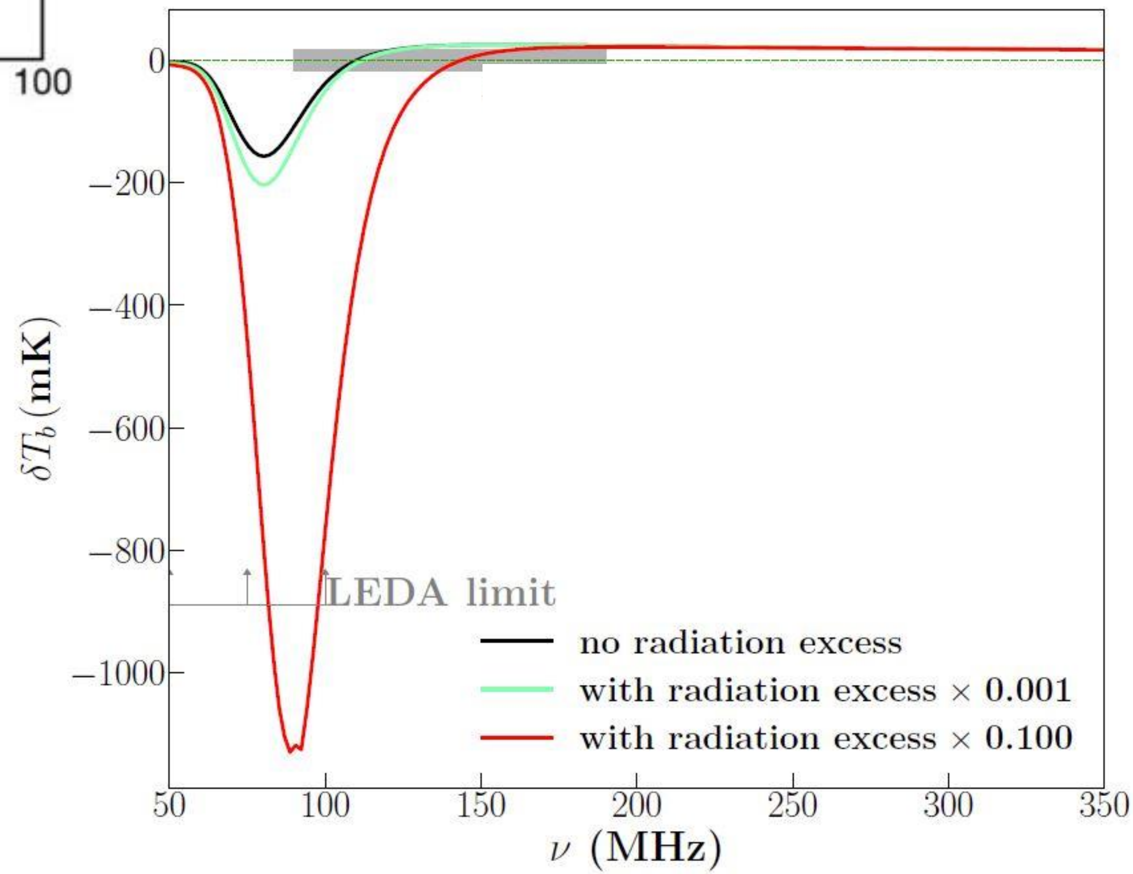
The 21-cm absorption feature results from the lower temperature of the IGM relative to the CMB (at high redshifts).

Any radio synchrotron background at those redshifts increases the effective temperature of the CMB – increasing the depth of the absorption trough.

# 21 cm Issues

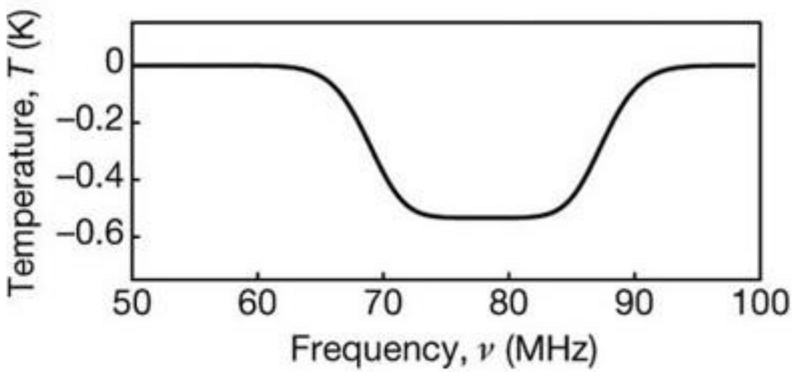



Feng & Holder, 2018 (February), arXiv:1802.07432




Since EDGES measurement is double the previously predicted trough, this would conclude that only <~1% of the z=0 RSB could be present at z~16

# 21 cm Issues



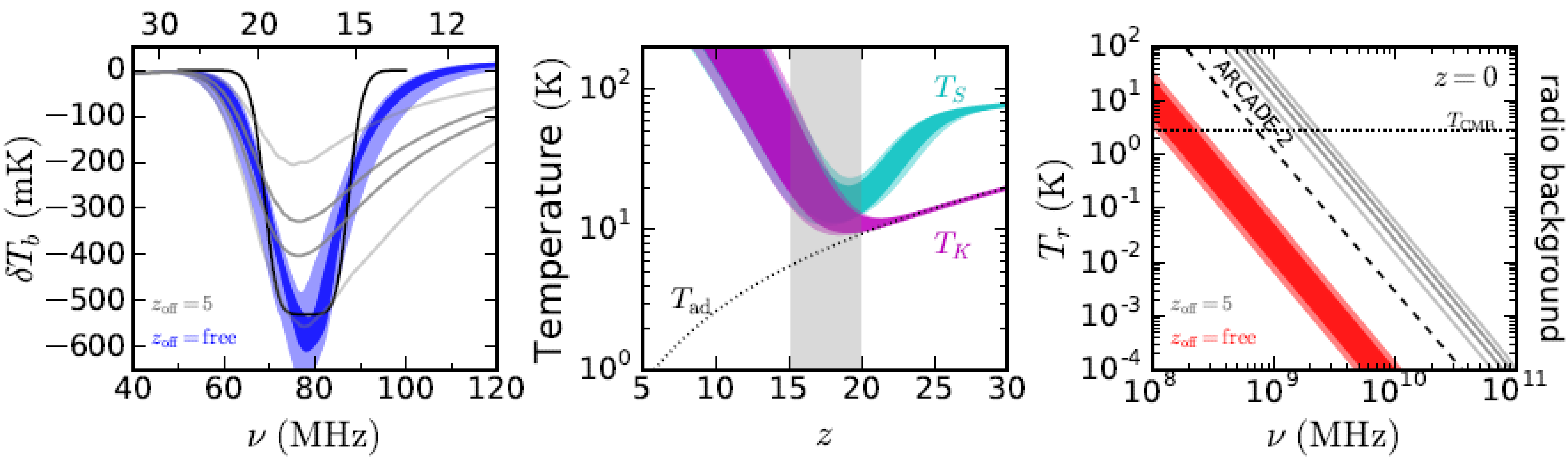

More analytical calculation:

Ewall-Wice et al, 2018 (March),
*ApJ*, submitted (arXiv:1803.01815)

Measured EDGES trough can be explained by RSB which is ~8*$T_{cmb}$ at z~16, which would be about 10% of the current RSB

# 21 cm Issues

Mirocha & Furlanetto, 2018 (March), *MNRAS*, submitted (arXiv:1803.03272)



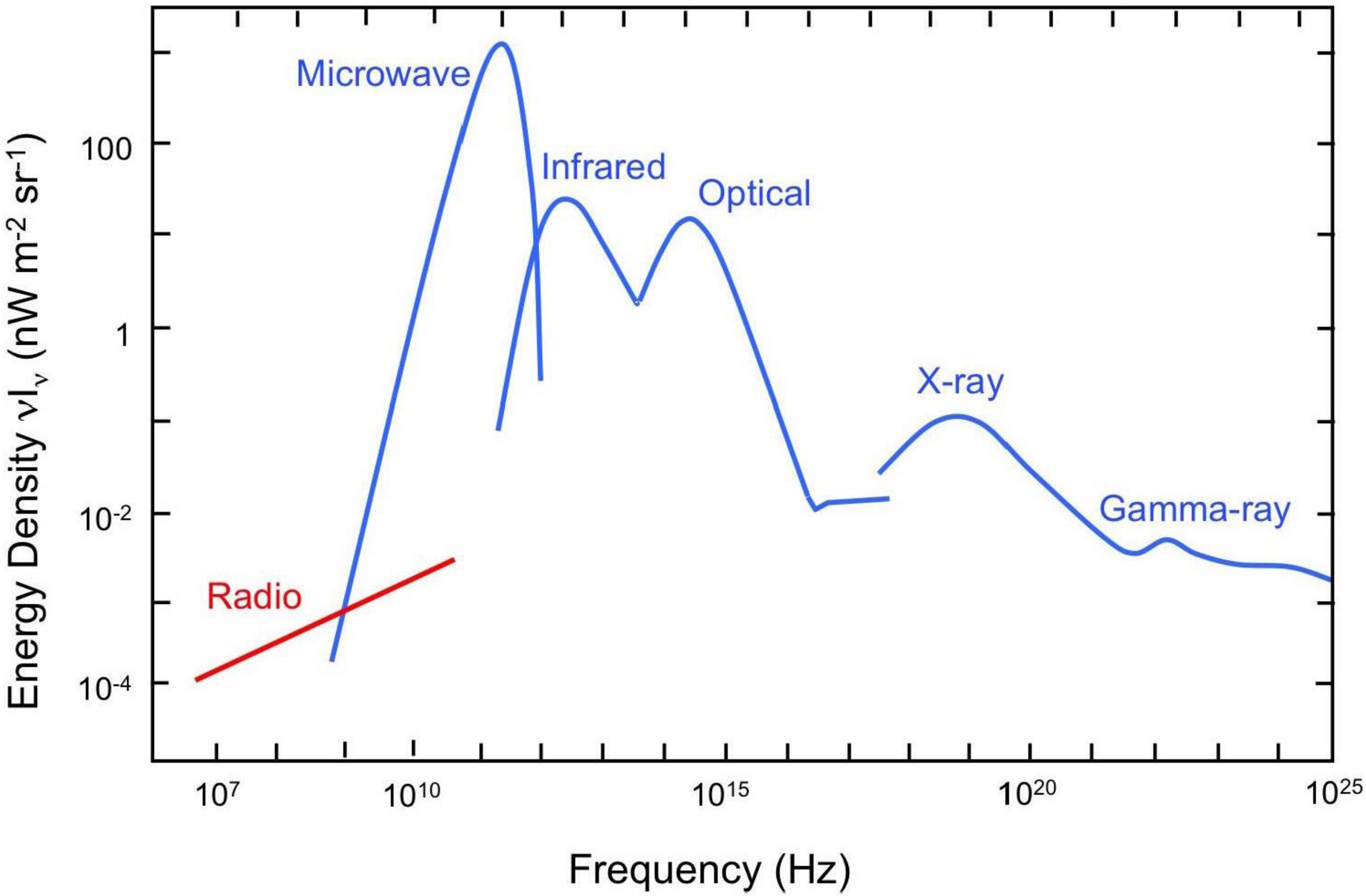

High z RSB emitted by star forming galaxies of the form

$$L_R = 10^{22} f_R \left(\frac{SFR}{M_{\odot} yr^{-1}}\right) W s^{-1} Hz^{-1}$$

Best fits to give EDGES trough but not exceed present day RSB level:

$$f_R = 10^3 \qquad z_{off} = 15$$

# The EM backgrounds



# Conclusions: General

- There is (almost certainly) a significantly brighter radio synchrotron background than can be accounted for by
  - a) Known extragalactic source classes
  - b) Most reasonable models of Galactic diffuse emission

- If extragalactic, the new extragalactic source class(es) would have to be:
  - A) Incredibly numerous
  - B) Not follow the radio/far-infrared correlation
  - C) Have high magnetic fields so as not to overproduce via inverse-Compton
  - D) At least one of
    - i) High (but not too high) redshift
    - ii) Not clustered like typical large scale structure
    - iii) Diffuse

- If Galactic, our Galaxy would be anomalous

- A new absolutely calibrated measurement at around 300 MHz is needed to further understand the diffuse radio sky

- If the EDGES 21-cm trough is real then some (but not too much) RSB may have been present at $z>15$

# Conclusions: Anisotropy

- **The radio synchrotron background is isotropic (*to the level of currently available absolutely calibrated MHz radio maps*) on degree and larger scales**
  - But note this is partially by definition, as all structure on large scales has heretofore been assumed to be Galactic
  - A new, dedicated, ~1 deg resolution absolute map at ~310 MHz (proposed!) will push this limit and clarify
- **It is more isotropic on arcminute scales than the distribution of low-redshift large scale structure in the Universe**
  - ???
- **Sub-degree scale anisotropy has yet to be detected**
  - Such measurements *can't* (?) be made (for the forseeable future) at the MHz frequencies where the radio background dominates
  - Low GHz interferometry?