The Diffuse Galactic and Extragalactic Radio Emission

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Radio Synchrotron Background Workshop
University of Richmond, 20 July 2017

The isotropic radio background revisited

NF, Lineros, Regis, Taoso

JCAP 04 (2014) 008

Assessment of the size of the ARCADE excess

Reanalysis to include detailed galactic foreground modeling and treatment of point-like and extended sources

Galactic synchrotron emission from WIMPs at radio frequencies

NF, Lineros, Regis, Taoso

JCAP 01 (2012) 005

Bounds on particle DM from diffuse galactic radio emission

Total brightness of extra galactic sky

Collect all radio emission arriving from the sky

- Requires subtraction of galactic foregound

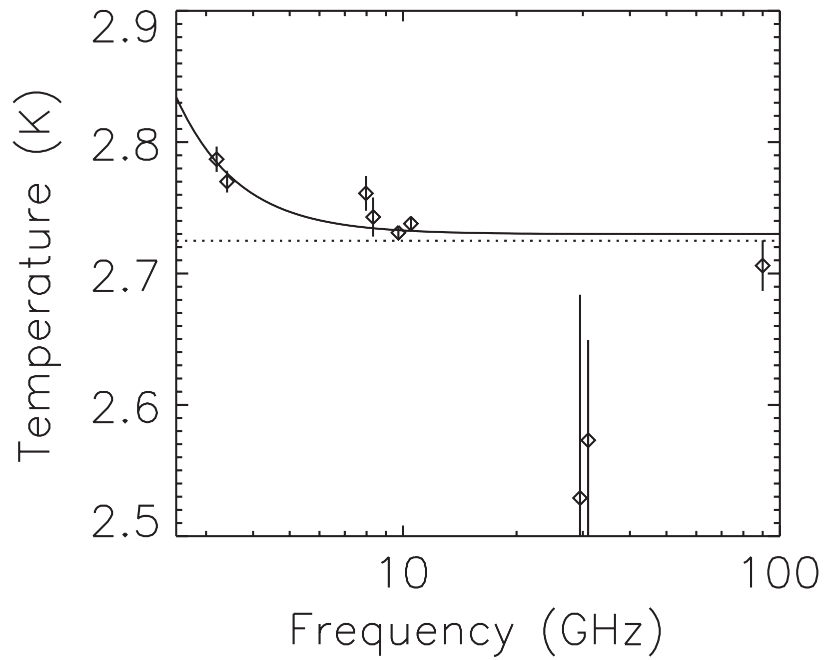
Add up single contributions from all EG sources

- Individually resolved sources
- Statistical determination from fluctuations below detection threhold

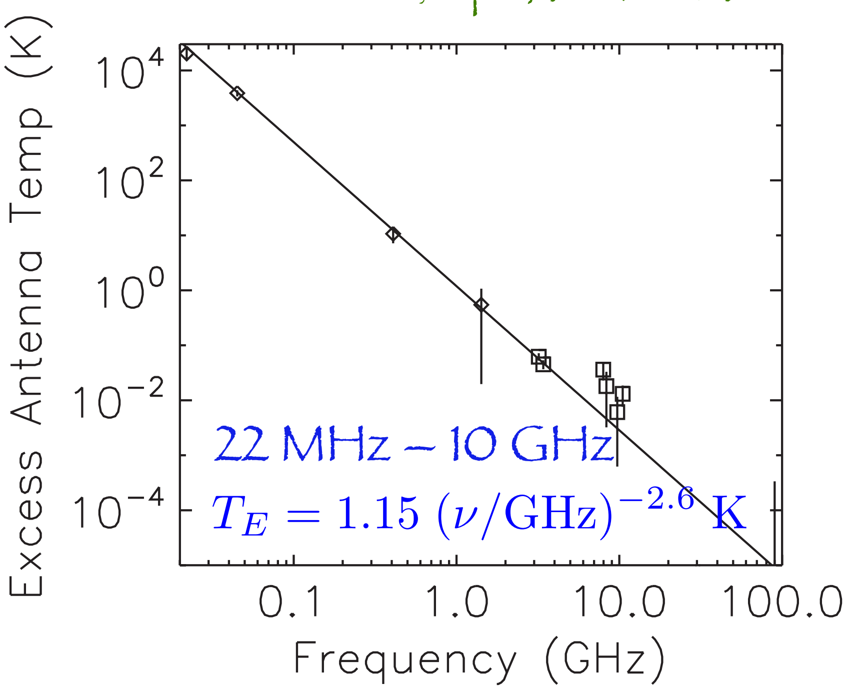
The two do not match

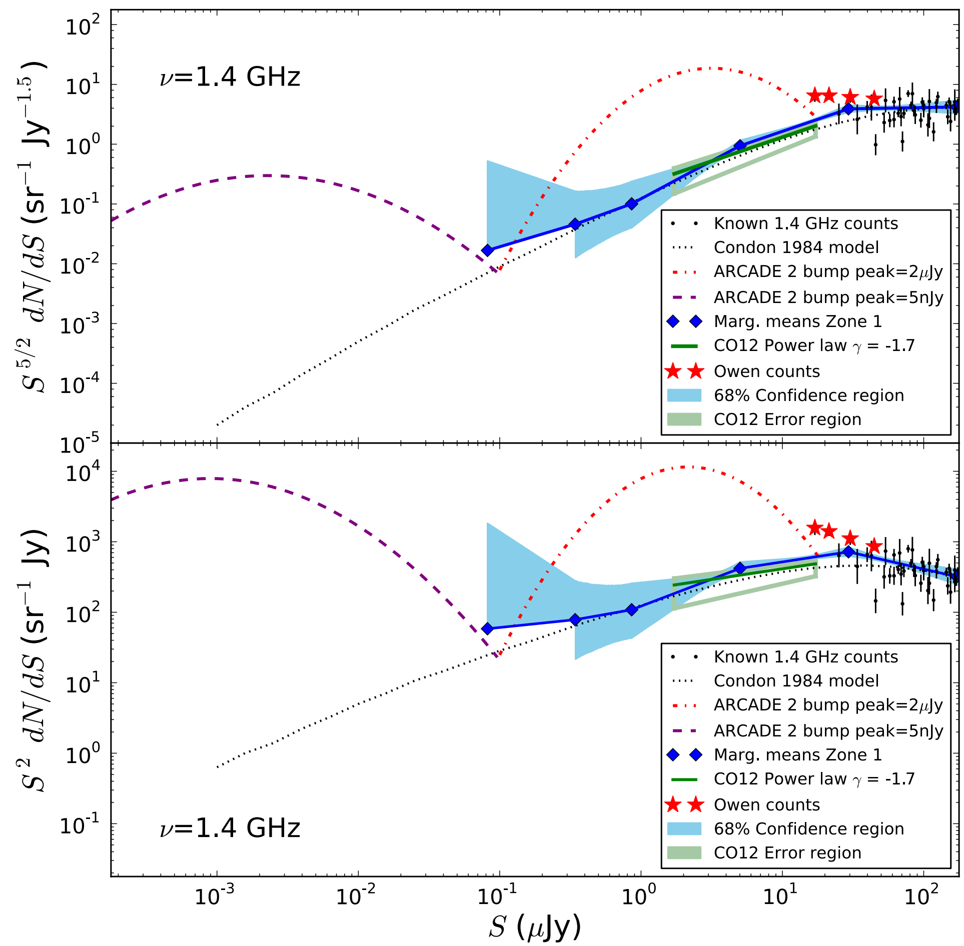
Faint emitters are required

- New population(s) of astrophysicsl sources
- Dark matter



Fixsen et al, ApJ 734 (2011) 5





Vernstrom et al, MNRAS 440 (2014) 2791

Radio Surveys

Requirements

Good coverage of high latitudes

necessary to determine the EG emission

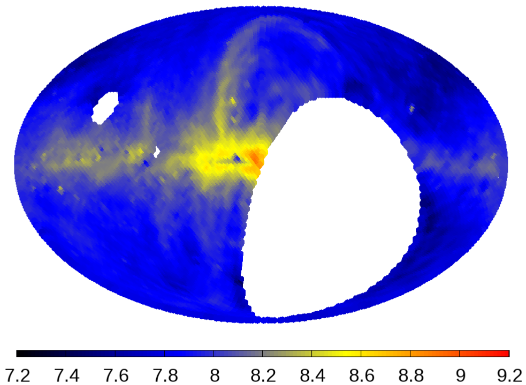
Large fraction of the sky observed

useful to anchor galactic foreground models

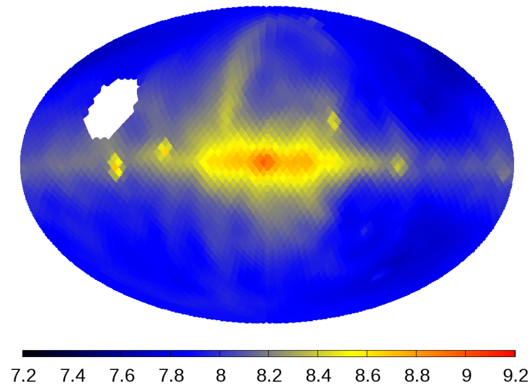
Frequency [MHz]	Angular resolution	rms Noise [K]	Calibration error	Zero-level [K]	Fraction of Sky	Survey reference
22	$1.1° \times 1.7° / \cos Z$	3000	5%	5000	73%	Roger et al.
45	5°	2300/300	10%	544	96%	Guzman et al.
408	0.85°	1.2	10%	3	100%	Haslam et al.
820	1.2°	0.5	6%	0.6	51%	Berkhuijsen
1420	0.6°	0.017	5%	0.2 (0.5)	100%	Reich et al.
2326	0.33°	0.03	5%	0.08	67%	Jonas et al.

Maps

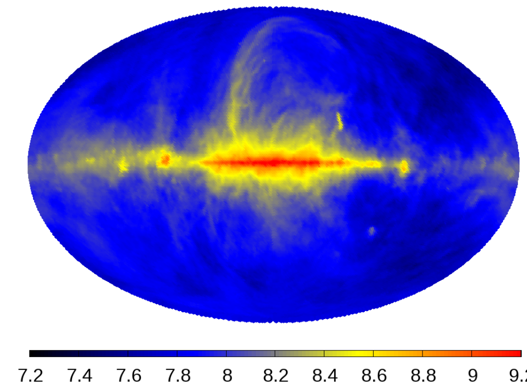
22 MHz

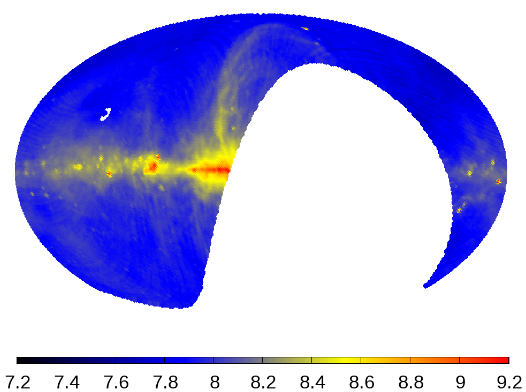


45 MHz

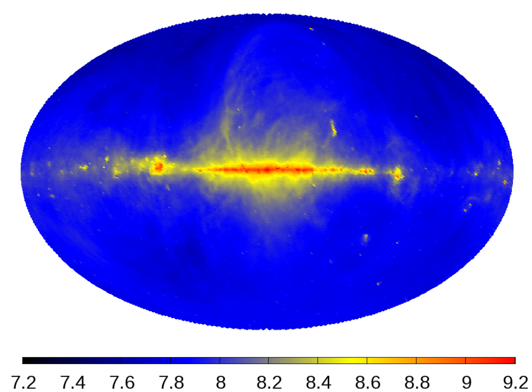


408 MHz

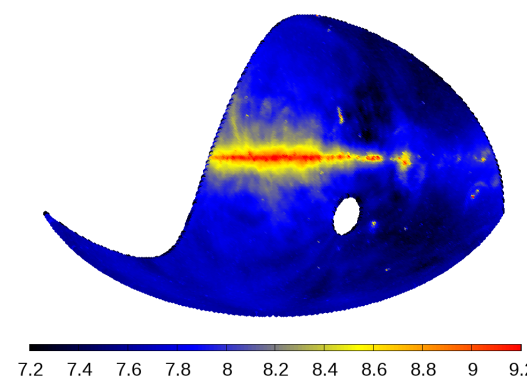




820 MHz



1420 MHz



2326 MHz

Models

$$T(l,b) = T_E + T_S(l,b) + T_G(l,b)$$

Isotropic EG emission (constant)

Discrete sources (mask or templated)

Galactic diffuse emission (model)

Galactic diffuse emission

Free-free

Finkbeiner et al, ApJS 146 (2003) 407

Traced through Hα line template with free norm

Not that crucial, since we mask the galactic plane

Synchrotron

Primary electrons

Secondary electrons and positrons

Most relevant energy range (1 - 30) GeV

Synchrotron source term

Primary electrons

Radial profile from SNR distribution [a,b]

Vertical profile: $\exp(-z/z_s)$ with z_s ≈ 0.2 Kpc

Secondary electrons and positrons

Interactions of primary p and He on ISM

Sources injection spectra: broken power laws

Spectral indeces $\beta_{\rm inj,nuc}$ and $\beta_{\rm inj,e}$

Breaks at 9 GeV/4 GeV for nuclei/electrons

[a] Strong et al, ApJ 772 (2010) L58

[b] Lorimer et al, MNRAS 372 (2006) 777

Propagation setup

GALPROP v. 54.1.984

Cylindrical box:

Radial size: 20 Kpc

Vertical half-height: L = 1÷40 Kpc

Pure diffusion (no reacceleration)

Reacceleration: increases secondary $e^{\pm}$ at low energies as compared to pure diffusion: some tension with low frequency radio data

Energy losses

Magnetic fields

ApJ 761 (2012) L11
ApJ 757 (2012) 14

Reference model: Jansson & Farrar

- Large-scale regular field
  - disk component
  - toroidal halo
  - out-of-plane component
- Small-scale random field
- Striated random field

Constrained on extragalactic Faraday rotation measures and on 22-GHz WMAP7 polarized and total intensity

Magnetic fields

To allow flexibility in the mid-high latitude emission (relevant for the determination of the extragalactic background), we let the random component to be more general:

$$B(R,z) = B_0 \exp[-(R-R_T)/R_B] \exp(-|z|/z_B)$$

R_T = 8.5 kpc
R_B = 30 Kpc
B_0: determined by the fit

Model a: z_B = L
Model b: z_B = 2 kpc < L (only for L = 4, 8, 16 kpc)

The z-scaling represents the main source of uncertainty related to the magnetic field modeling

Benchmark propagation models

code name	L [kpc]	D_0 $[10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}]$	$\beta_{\mathrm{inj,nuc}}$	$\beta_{\mathrm{inj},e}$	B_0 $[\mu\mathrm{G}]$	color coding
L1	1	0.75	1.80/2.3	1.20/2.3	12	red
L2	2	1.7	1.80/2.3	1.20/2.35	8.0	blue
L4	4	3.4	1.80/2.3	1.20/2.35	6.0/7.0	green
L8	8	5.8	1.80/2.3	1.20/2.35	4.6/4.7	orange
L16	16	8.0	1.80/2.3	0.5/2.35	4.0/4.7	cyan
L25	25	8.1	1.80/2.3	0.5/2.35	3.9	maroon
L40	40	8.3	1.80/2.3	0.5/2.35	3.8	brown
		[1]	[2]	[3]	[4]	

[1] $D(\rho) = D_0\,(\rho/4\,\mathrm{GV})^{0.5}$

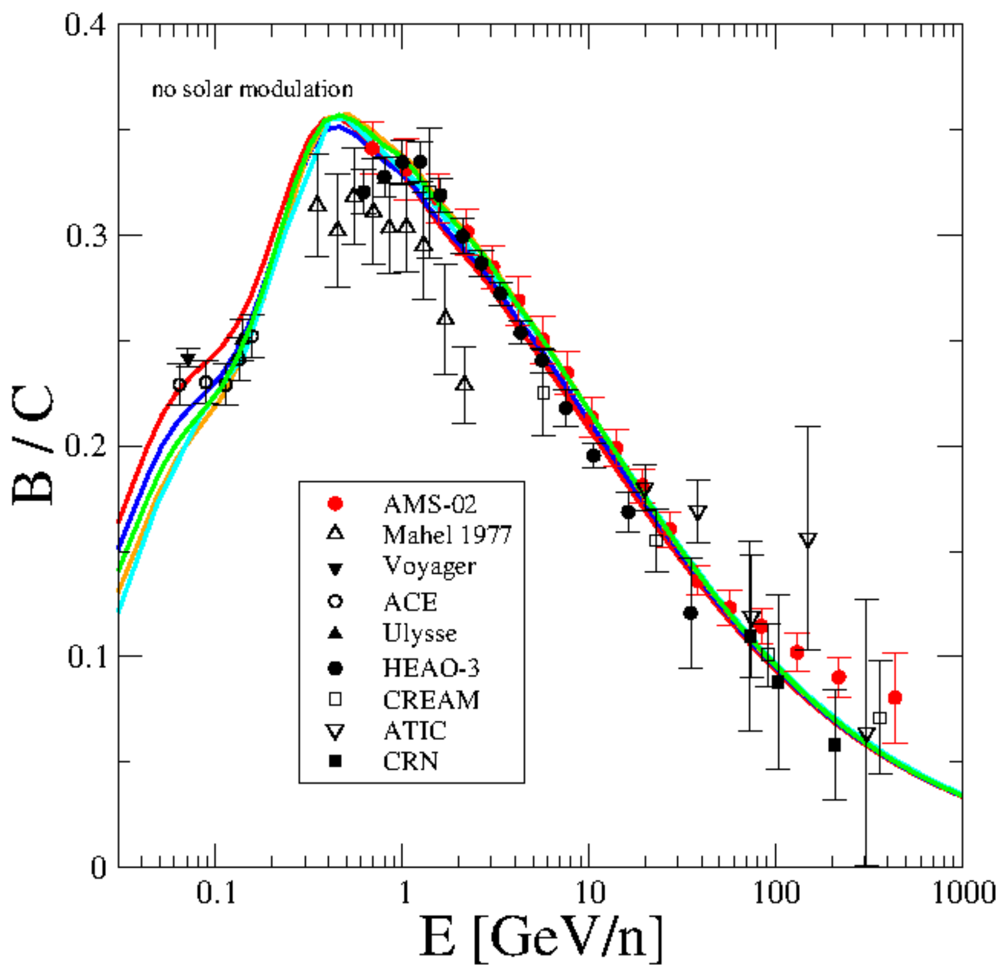
[2] Index below/above break at 9 GeV

[3] Index below/above break at 4 GeV

[4] Model a or Model a/Model b

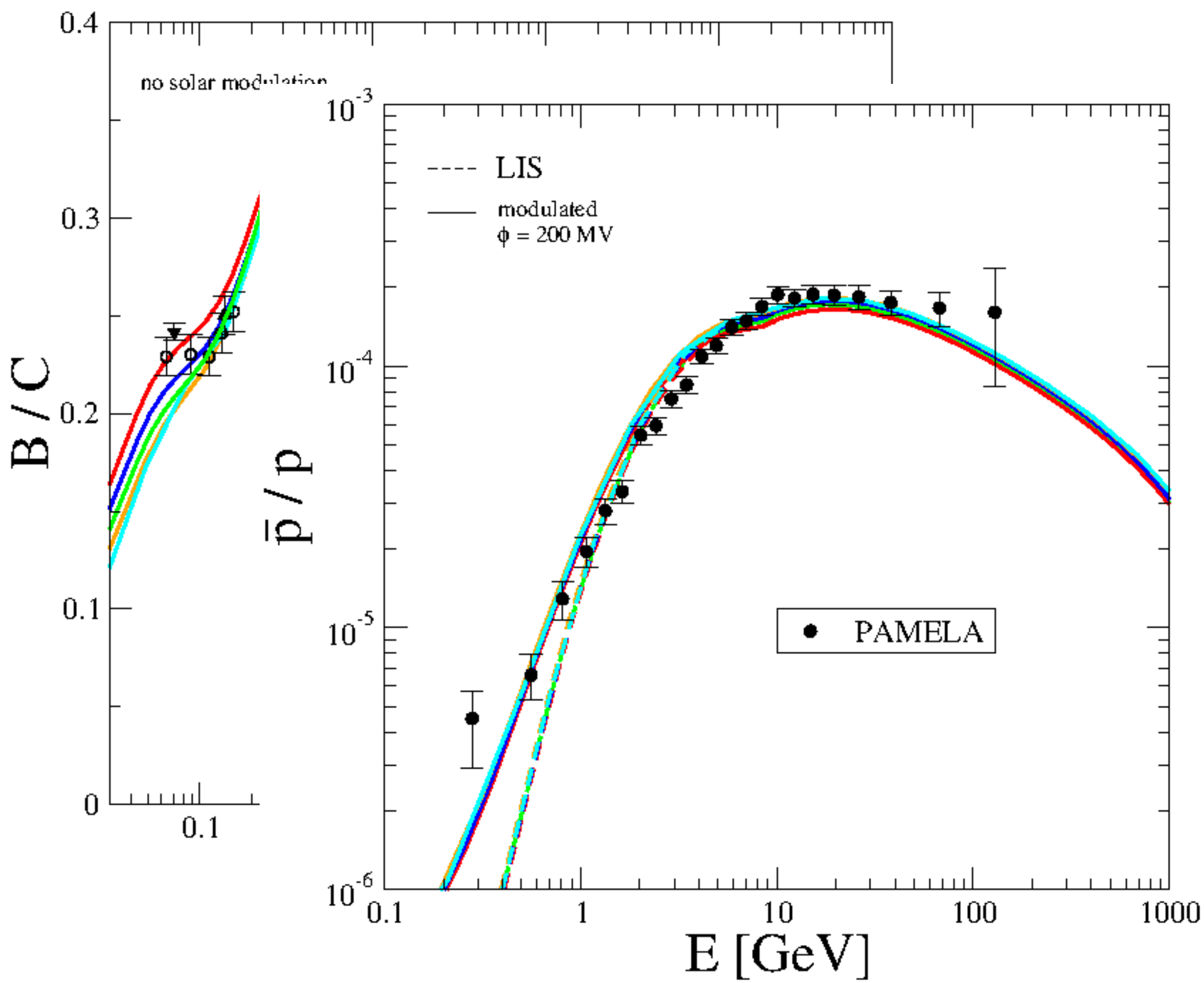
Tuned on CR data

Comparison with CR data



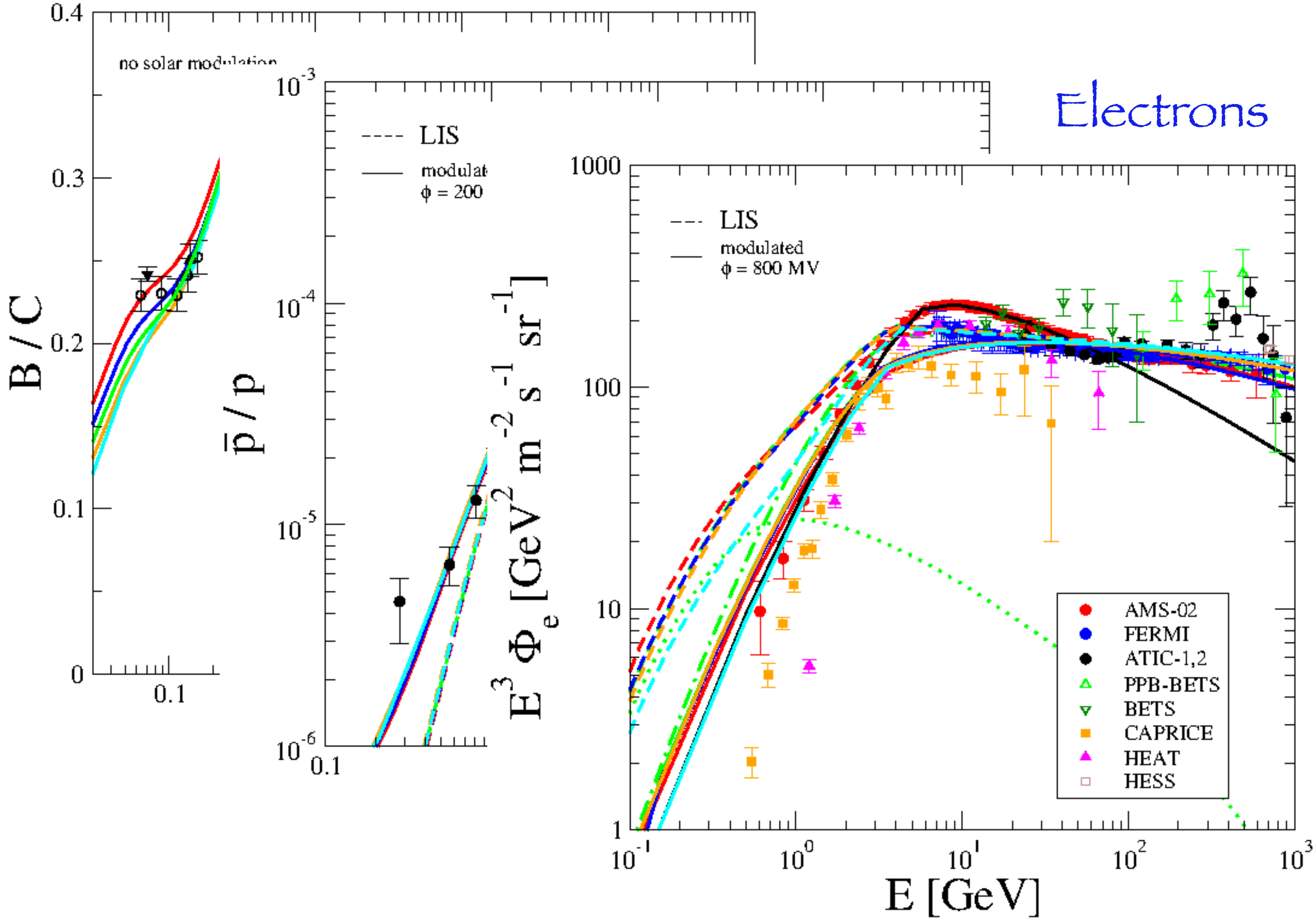
Boron/Carbon

Comparison with CR data



Antiprotons

Comparison with CR data



Fitting procedure of radio maps

CMB monopole is subtracted: $T = (2.72548 \pm 0.00057)$ K

Radio maps averaged over 15 deg scale ($N_{side} = 4$)

The GMF components have 2 different scales

Regular: O(kpc)

Random: O(100 pc)

Stocasticity due to the random component introduces variance on the scale of its coherence length

Better to compare emission averaged on this scale

Best angular scale not obvious, due to LOS effect

15 deg as a conservative assumption

Fitting procedure of radio maps

$$\chi^2 = \sum_{i=\text{pixels}} \frac{(T_i^{\text{data}} - T_i^{\text{model}})^2}{\sigma_i^2}$$

$$\boxed{T_i^{\text{model}} = T_E + c_{\text{gal}} T_i^{\text{gal,synch}} + c_{\text{brem}} T_i^{\text{gal,brem}}}$$

$$\sigma_i^2 = (\sigma_i^B)^2 + (\sigma_i^{\text{exp}})^2$$

σ_i^B: Variance induced by turbulence (data variance in pixel i)

σ_i^{exp}: Experimental uncertainty

Extended sources

Galactic disk mask: |b| < 10 deg

Intercepts galactic points sources and low lat sources

Extended local sources (like radio loops)

High-lat sources

Masks

Modeling

Masks – Take 1

Iterative method:

1. Fit of the map (out of the |b|<10 deg mask) with model

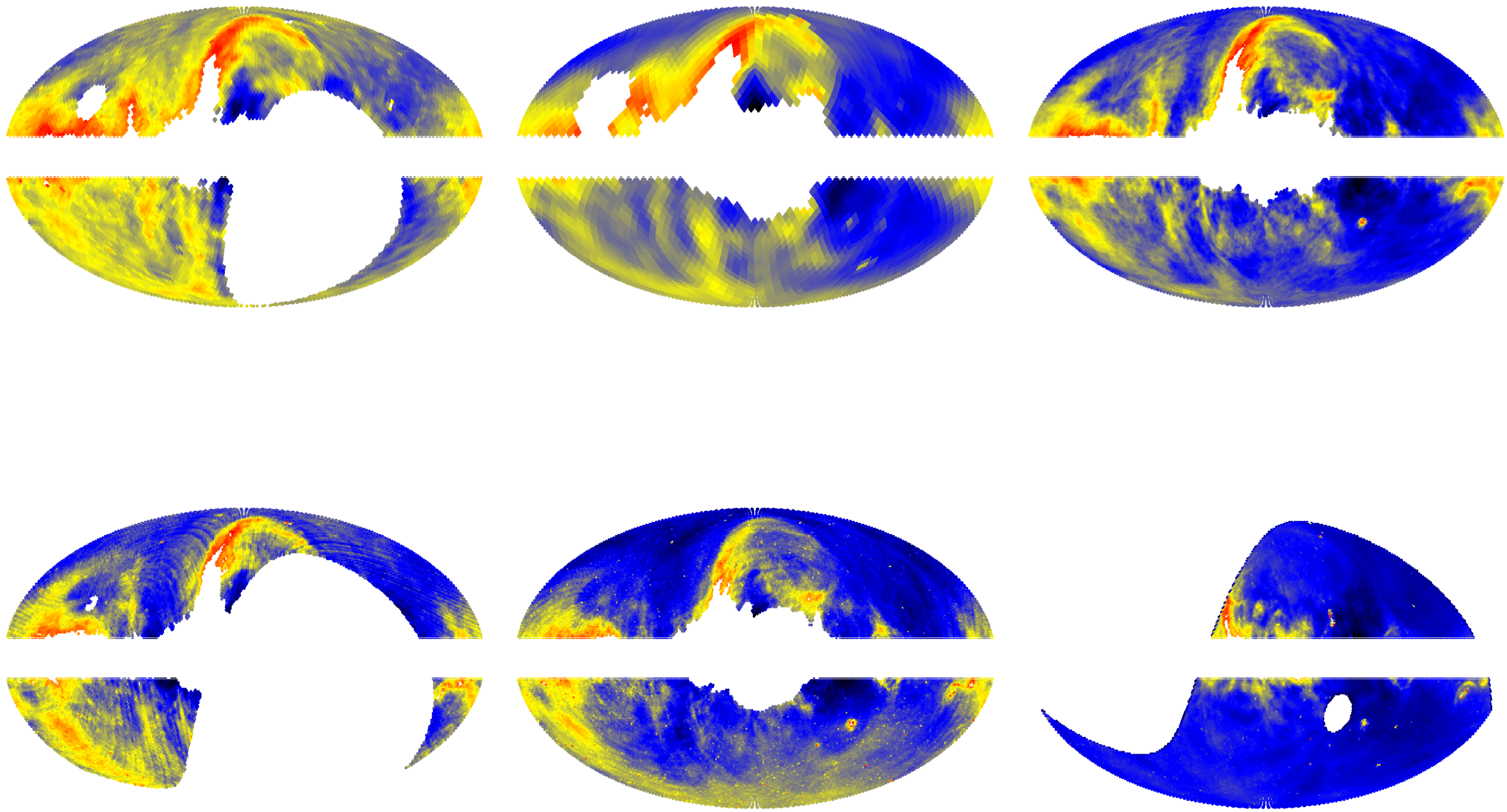
$$T_i^{\mathrm{model}} = T_E + c_{\mathrm{gal}} T_i^{\mathrm{gal,synch}} + c_{\mathrm{brem}} T_i^{\mathrm{gal,brem}}$$

2. Compute residuals $R_i - T_i^{\mathrm{data}} - T_i^{\mathrm{BFmodel}}$
3. Compute mean $T_{R,i}$ and $\sigma_{R,i}$ in 50 deg regions around the pixel i
4. Mask defined as $R_i > T_{R,i} + 5\sigma_{R,i}$
5. Repeat, with masked pixel excluded

Iteration stops when masks stabilises

The model fit is then performed on $N_{side} = 4$ downgraded maps

Iterative masks



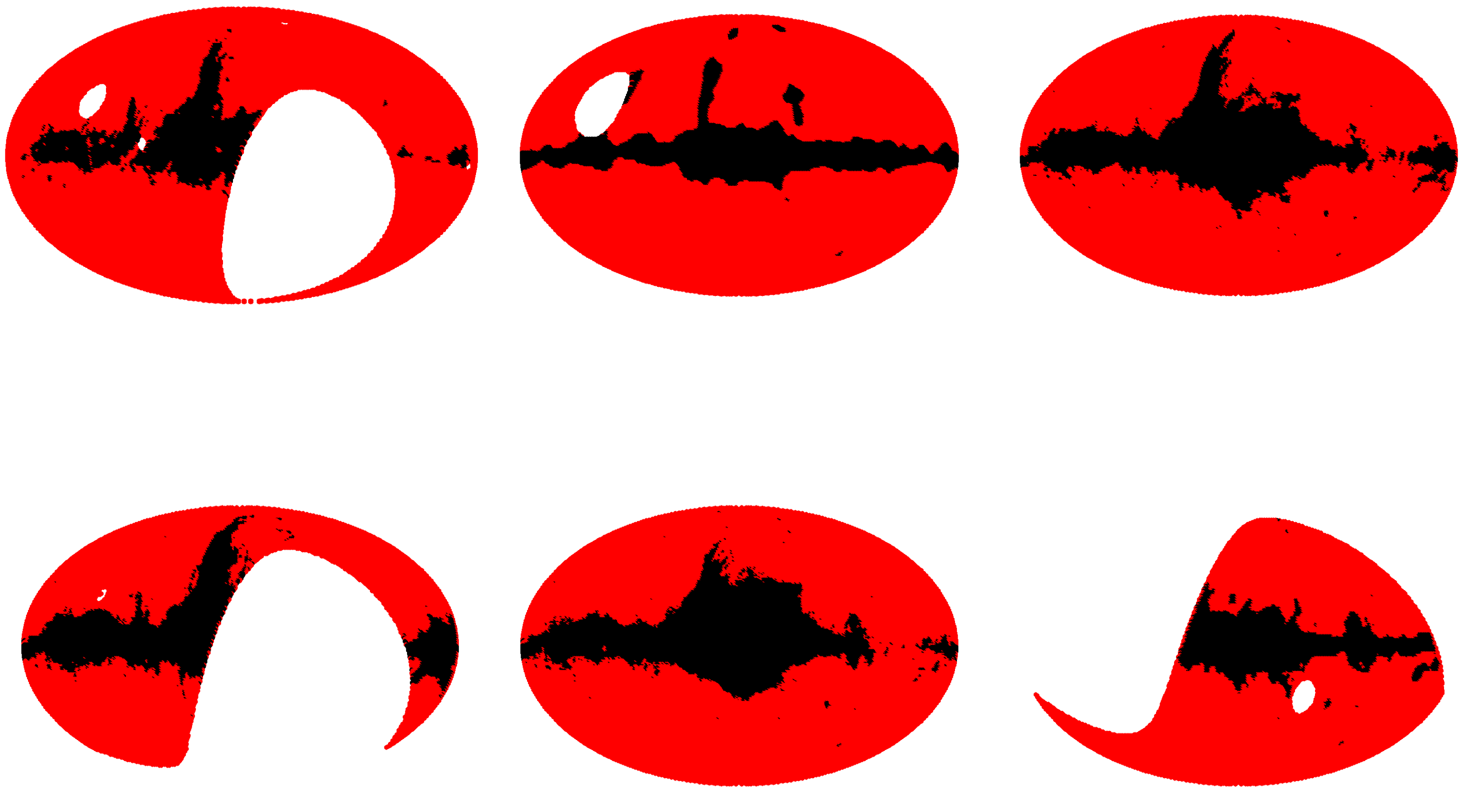
Masks – Take 2 and 3

In order to cross-check and/or improve the impact of masks, we perform two additional trials:

- WMAP mask at 22 GHz
- SExtractor to determine masks at different frequencies
  - Analyze original maps on 50 deg scale: mean, std deviation, detection threshold at 5σ
  - Similar to the iterative method: difference stays in flat local backgroud, while with iterative method galactic foregroud variations are taken into account
  - Slightely larger masks

Wmap mask

SExtractor masks

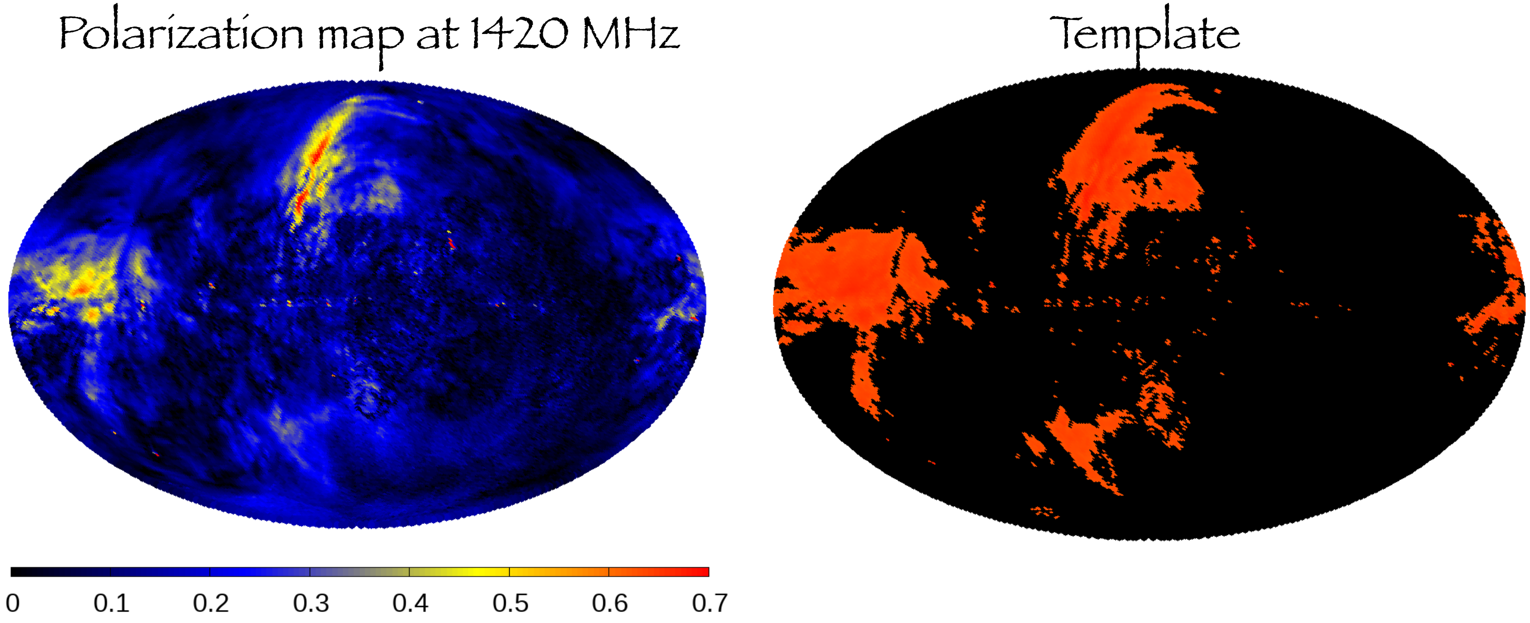


Templates

Polarization template to intercept the most intense synchro sources

Template: DRAO + Villa Elisa T > 5σ σ = 45 mK

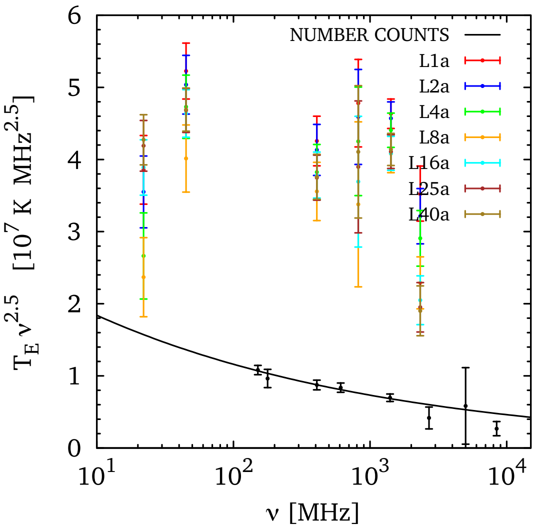
(noise: 15mK
zero level accuracy: 30mK(

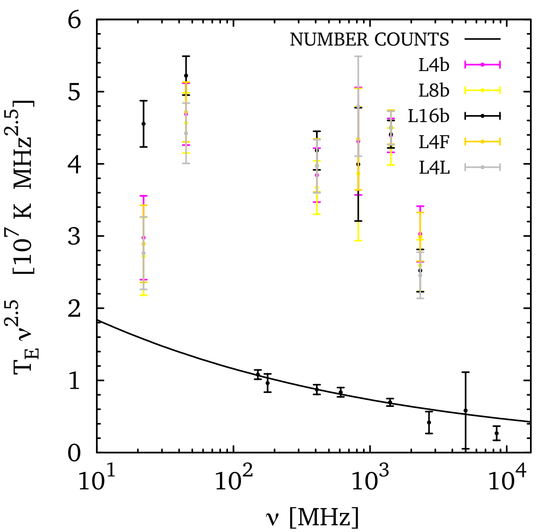


$$T_i^{\rm model} = T_E + c_{\rm gal} T_i^{\rm gal,synch} + c_{\rm brem} T_i^{\rm gal,brem} + c_{\rm pol} T_i^{\rm gal,pol}$$

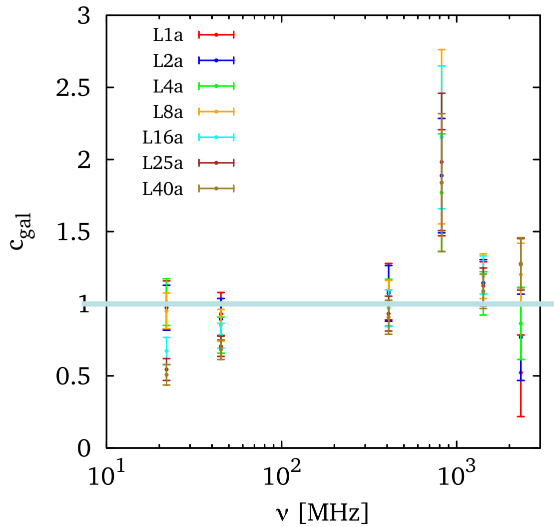
Results

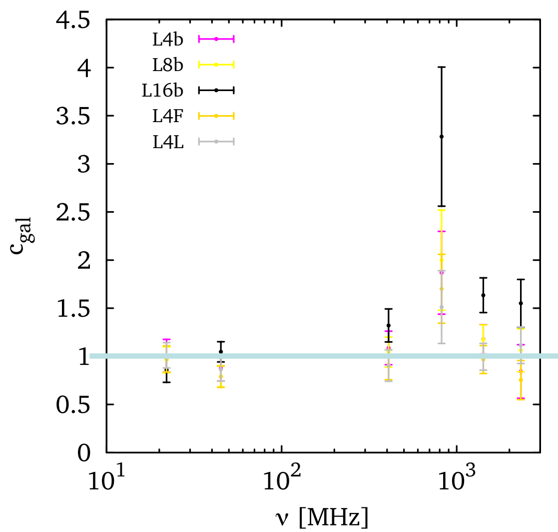
Temperature



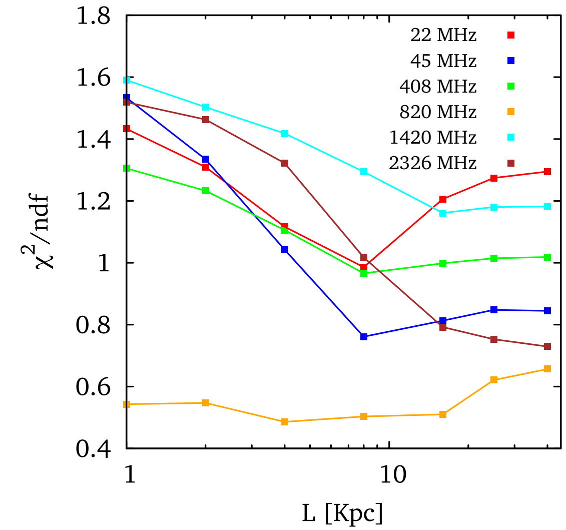


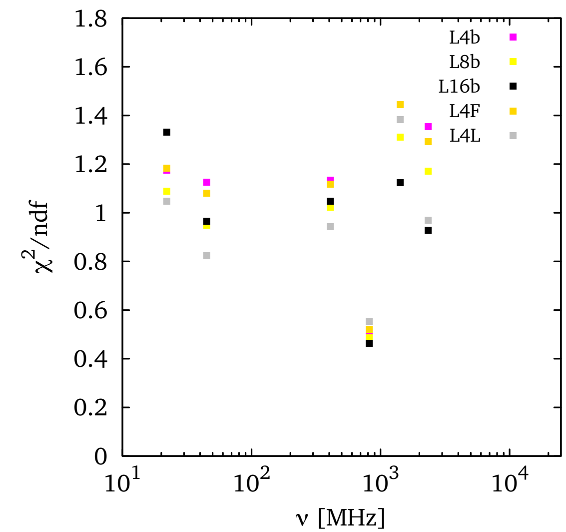
Norm coefficients



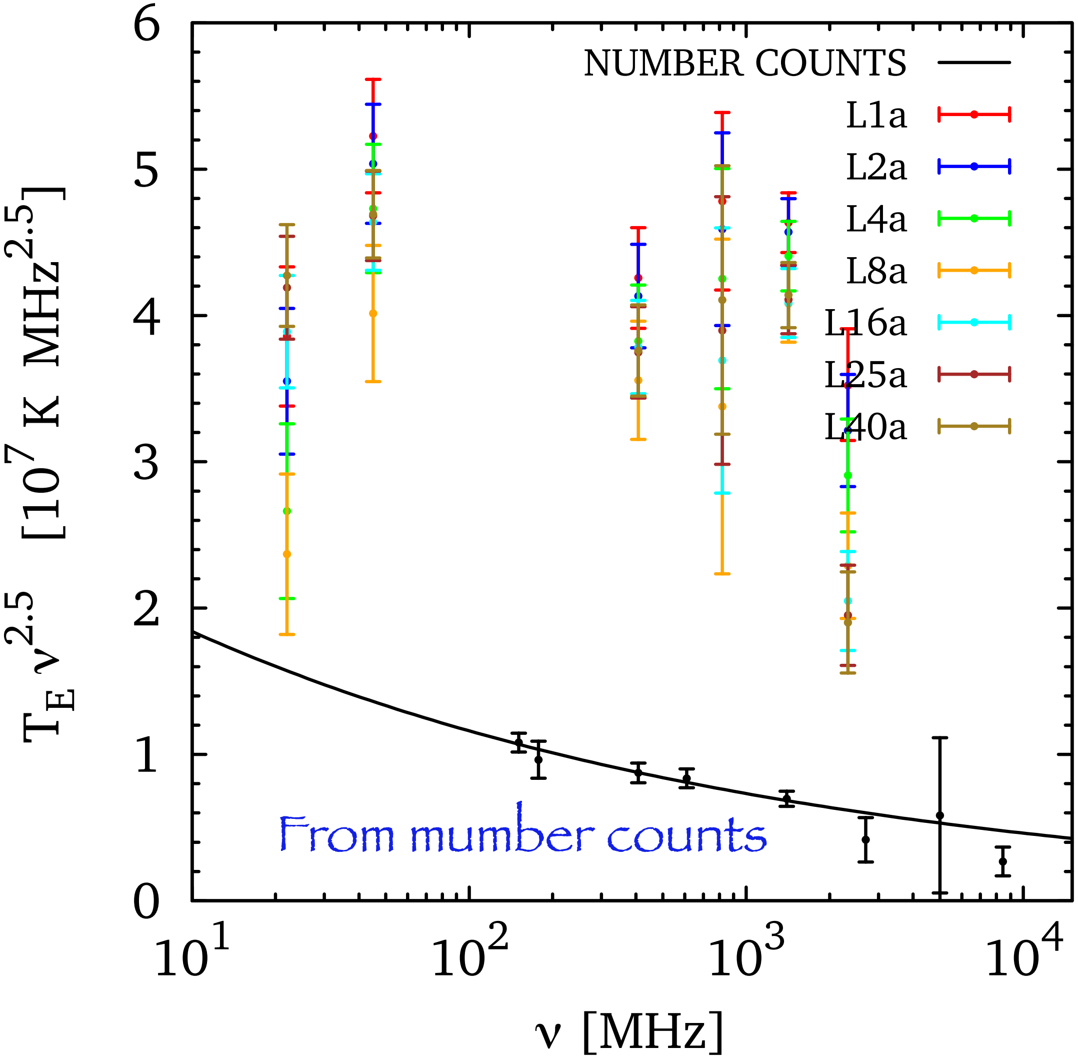


Chi squared



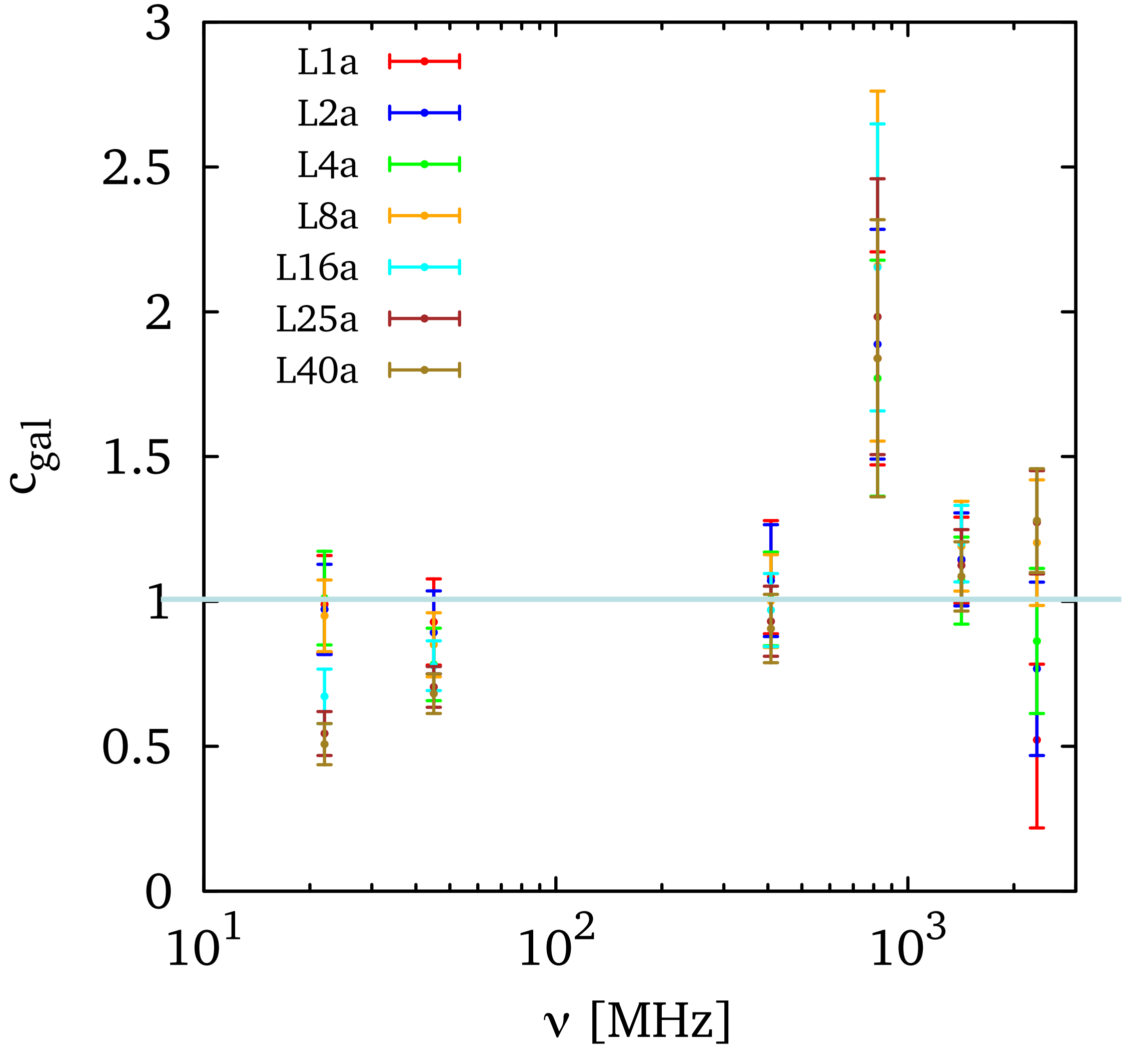


Results



NUMBER COUNTS
L1a
L2a
L4a
L8a
L16a
L25a
L40a
From mumber counts
$T_E \nu^{2.5}$ [10^7 K MHz$^{2.5}$]
ν [MHz]
0
1
2
3
4
5
6
10^1
10^2
10^3
10^4

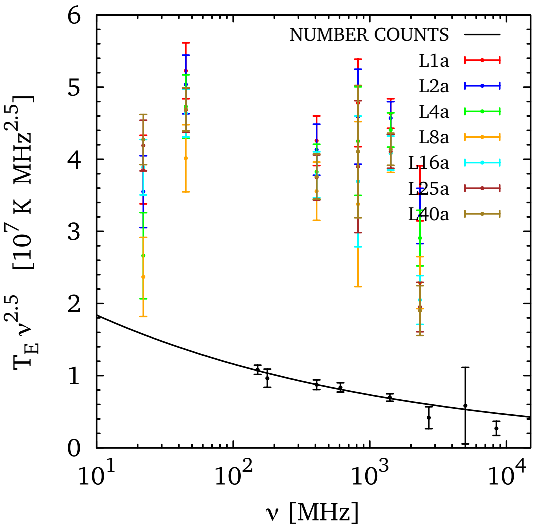
Results



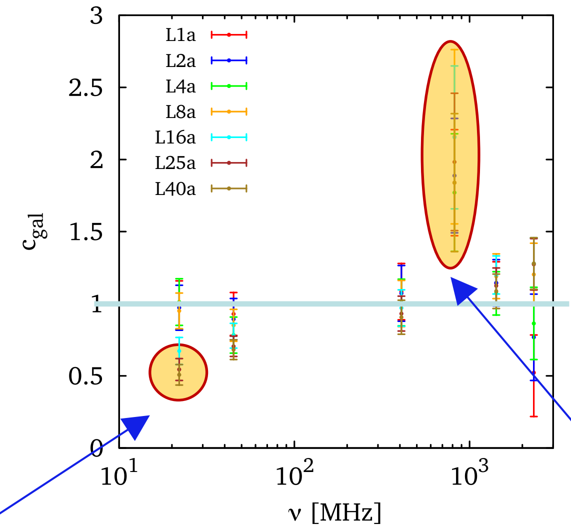
L1a
L2a
L4a
L8a
L16a
L25a
L40a
c_{gal}
3
2.5
2
1.5
1
0.5
0
10^1
10^2
10^3
ν [MHz]

Results

Temperature



Norm coefficients



Models with large L

$e^{\pm}$ softer: larger radio at low ν

No large impact on T

820 MHz

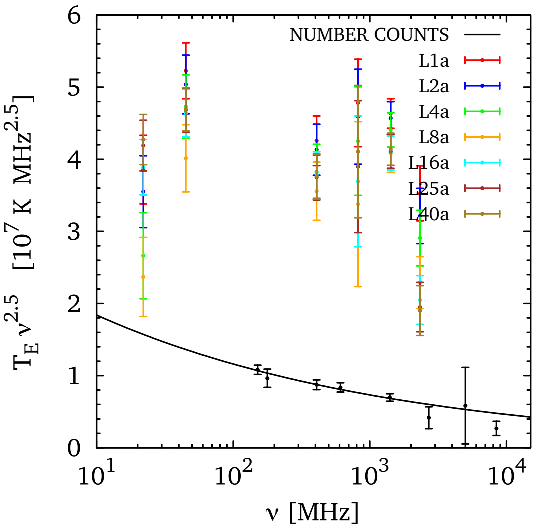
Calibration issues?

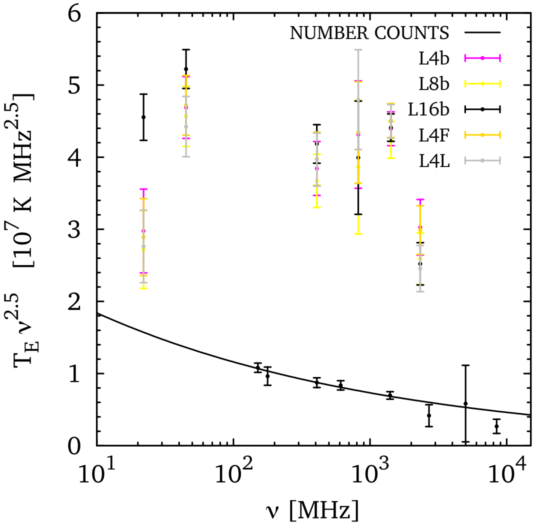
Limited fraction of the sky?

(smaller map: gal and EG more degenerate)

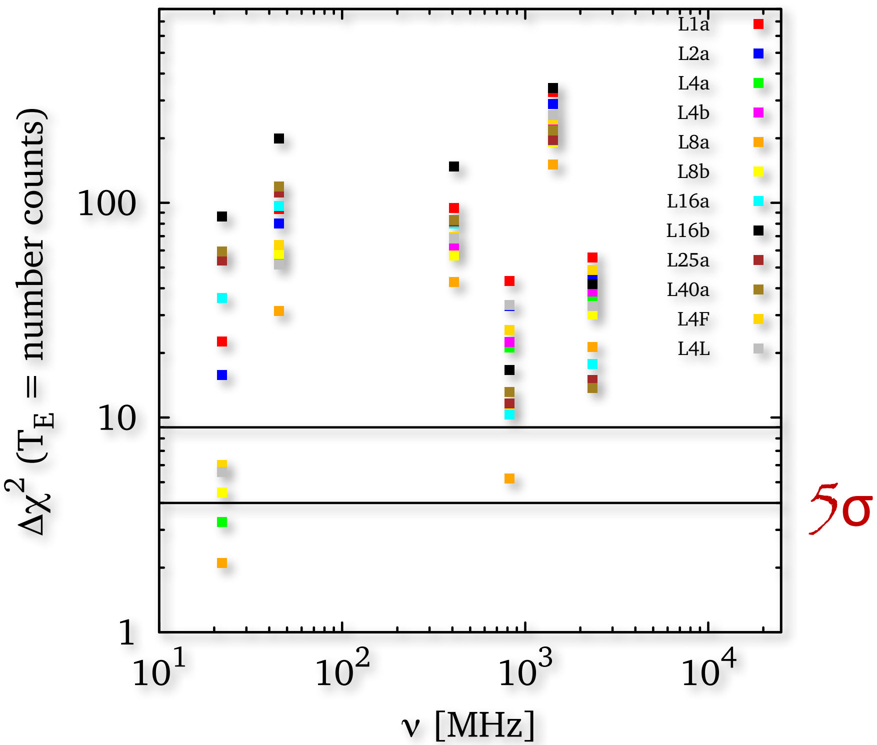
Results

Temperature





Some dependence on the galactic model
Not large (within a factor of 2)
Smaller scatter for large-coverage maps



Increase in chi2 assuming T_E from number counts

Results

Isotropic emission systematically in excess of what inferred from number counts

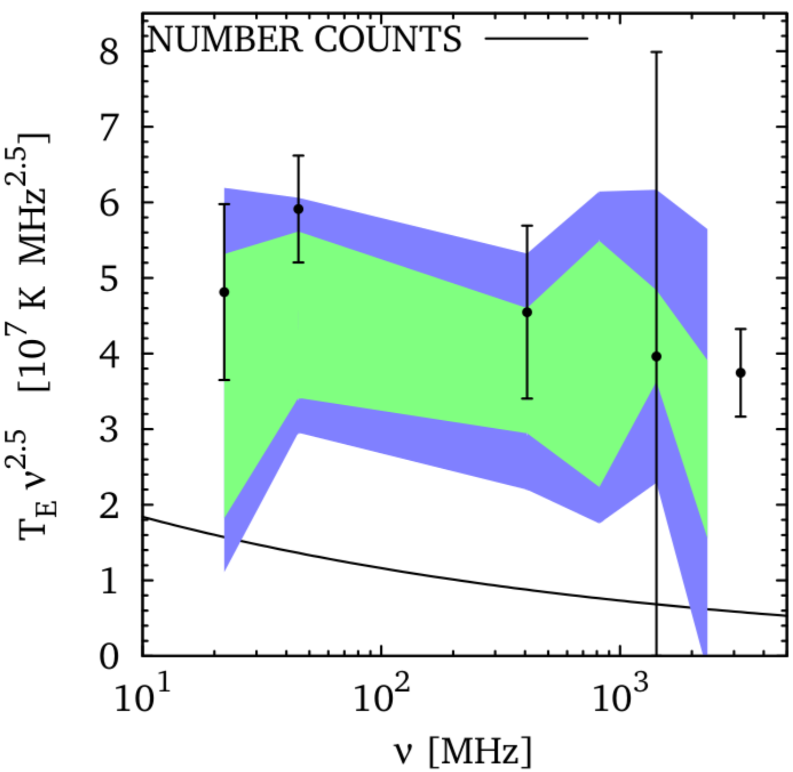
Results appear stable against:

- Galactic halo modeling
- Galactic magnetic fields
- Spatial distribution of cosmic rays sources
- Different resolution of maps

Results From number counts

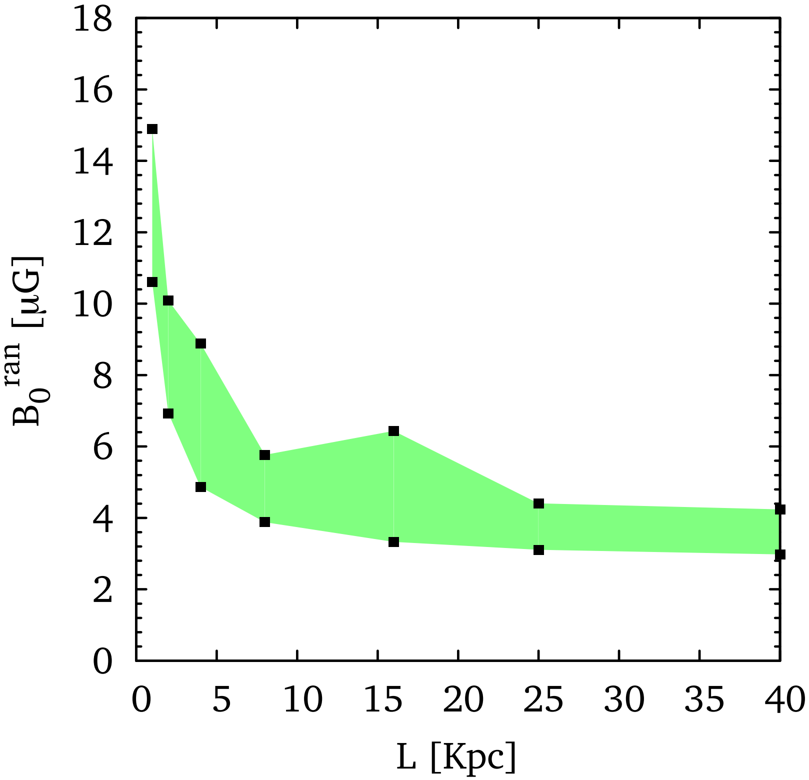
Frequency [MHz]	T_E [K]	T_{NC} [K]	zero-level [K]	$T_{\rm cold\,spot}$ [K]
22	$(1.04 \pm 0.24) \times 10^4$	6.92×10^3	5000	1.80×10^4
45	$(2.95 \pm 0.34) \times 10^3$	1.0×10^3	544	3.84×10^3
408	11.8 ± 1.1	2.61	3	12.14
820	2.21 ± 0.39	0.39	0.6	2.91
1420	0.580 ± 0.025	0.09	0.2	0.589
2326	0.073 ± 0.013	0.024	0.08	0.098

Summary



Conservative uncertainty band on T_E

(points: ARCADE 2)



Random component of magnetic field

Overall significance of the excess: 4.5σ

Galactic synchrotron emission from WIMPs at radio frequencies

Electron number density

Source term

$$q(\mathbf{x}, E) = \frac{1}{2}(\sigma v)\left(\frac{\rho(\mathbf{x})}{M_{\rm DM}}\right)^2 \frac{dn}{dE}(E)$$

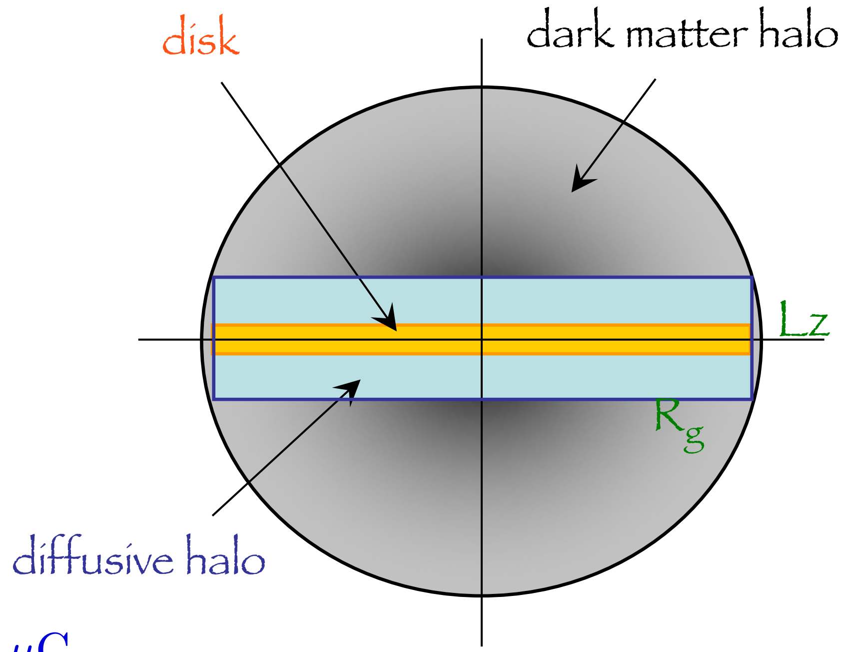
Electron/positron propagation

- Diffusion
- Energy losses
- Synchrotron emission

$$B(r,z) = B_0 \exp\left(-\frac{r - r_\odot}{R_m} - \frac{|z|}{L_m}\right)$$

GMF Model	Parameters	
	L_m [kpc]	R_m [kpc]
I	δL_z	δR_g
II	L_z	R_g
III	1	R_g
IV	constant	

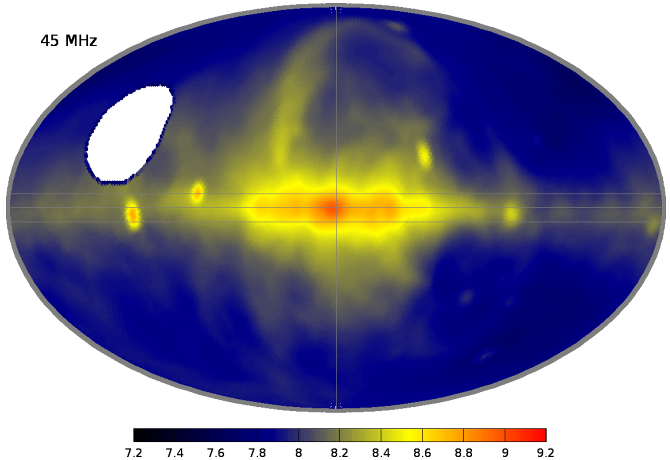
$B_0 = 6\ \mu$G



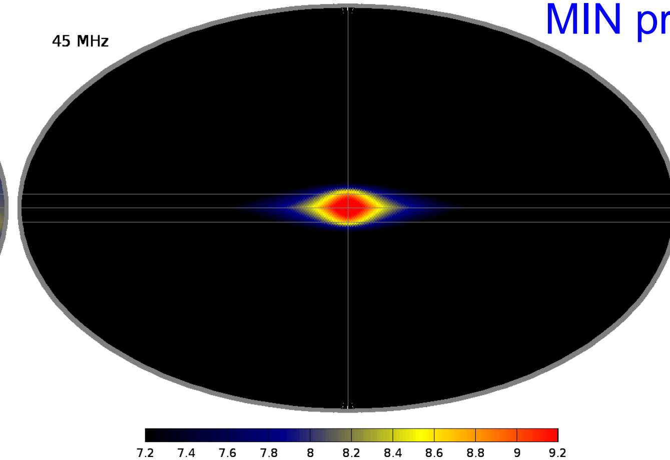
$$\chi\chi \longrightarrow (\bar{l}l, \bar{q}q, ZZ, W^+W^-, GG, HH)^{\rm had}_{\rm dec} \longrightarrow \gamma\,,\,\nu\,,\,e^\pm\,,\,\bar{p}, \bar{D}$$

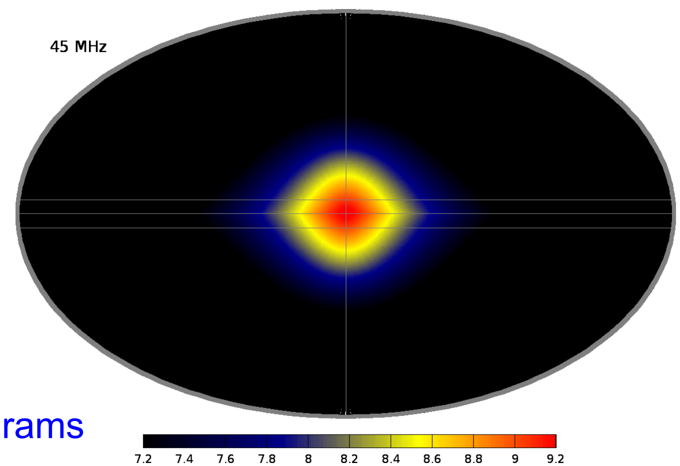
Morphology of radio sky at 45 MHz

observed

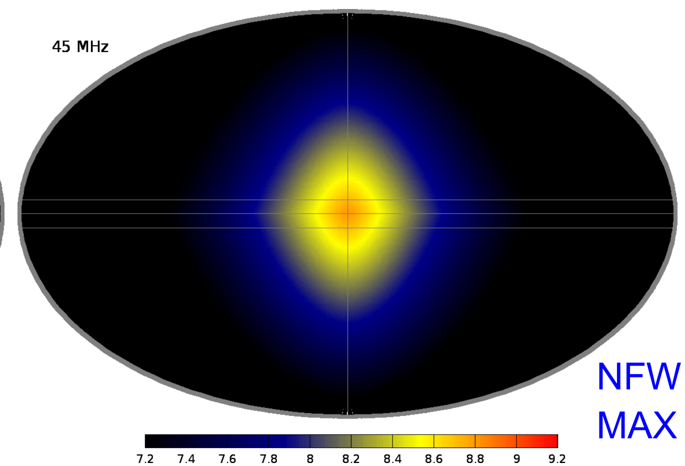


NFW
MIN propag params





NFW
MED propag params



NFW
MAX propag params

10 GeV DM
Annihilation into muon with thermal cross section
Exp decaying B(r,z) with B_{TOT} = 6 microG (GMF I)

NFW tuned to Via Lactea II
No substructures included

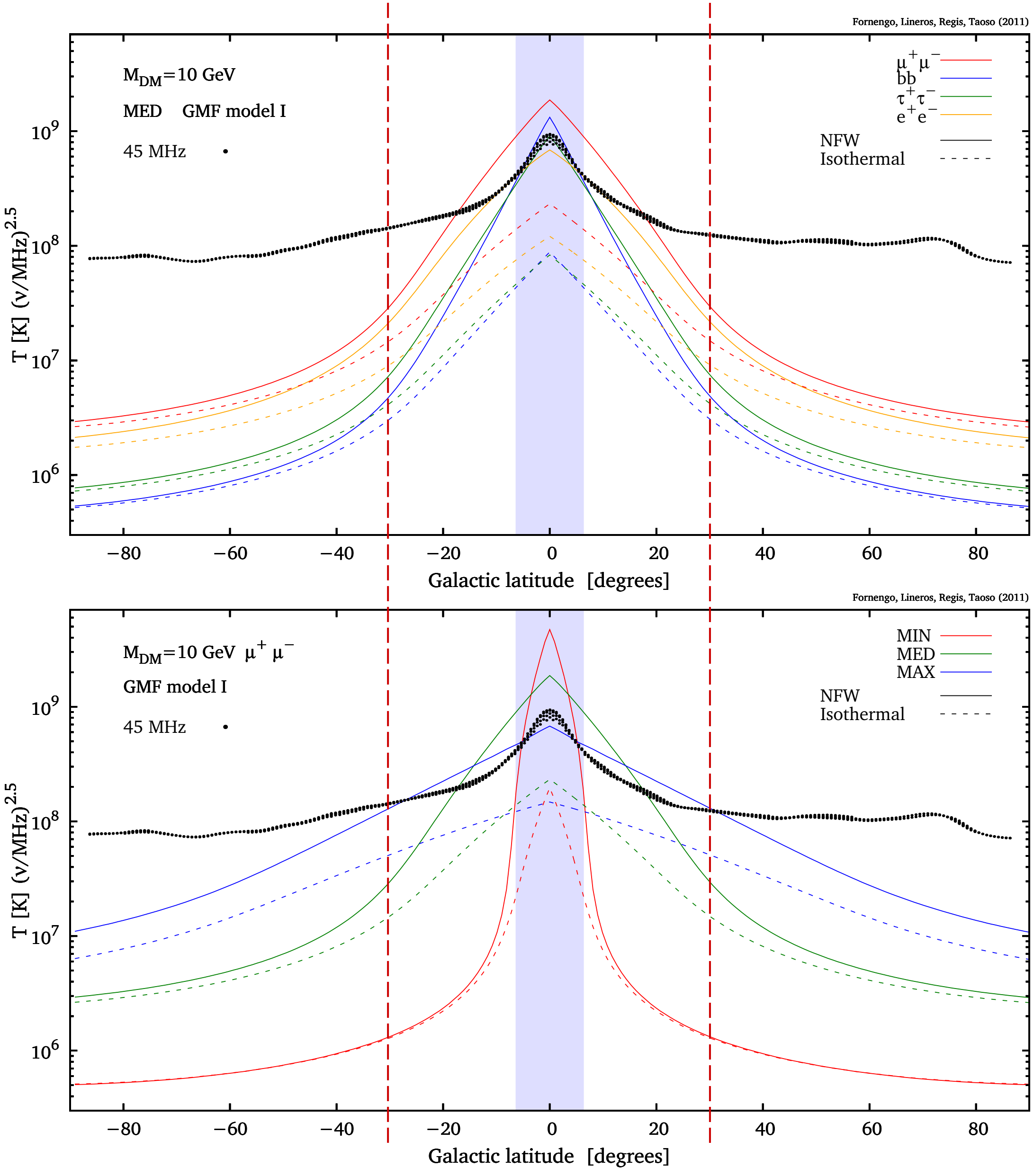
Galactic radio signal

45 MHz

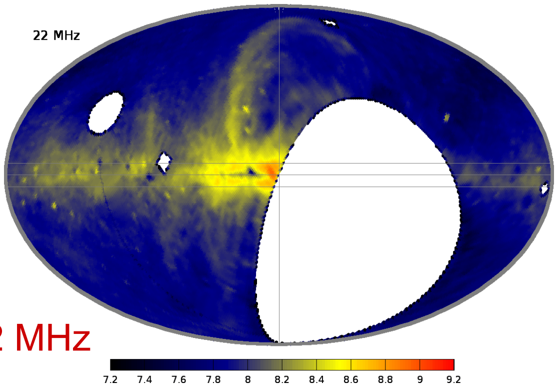
Data: |l| < 3°
DM models: l = 0°

DM could substantially contribute to the radio flux

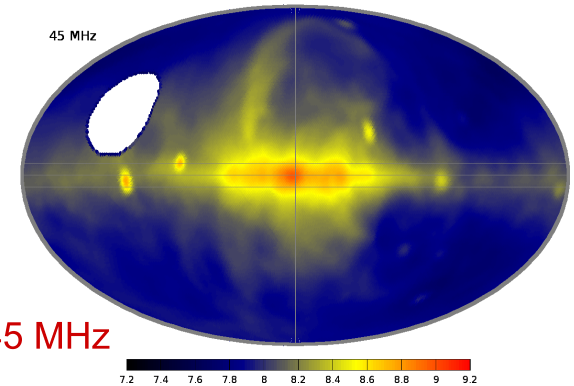
MED, MAX: allow to search for DM outside the GC region (while form MIN is too concentrated)



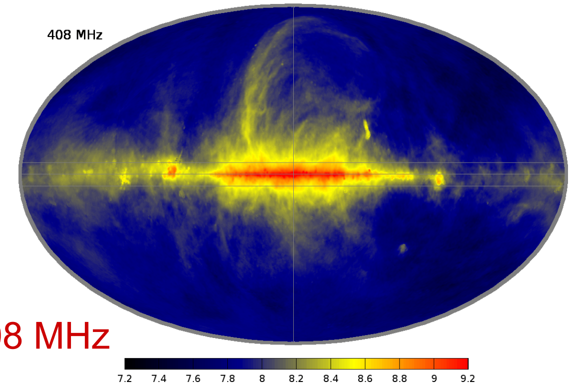
Skymaps



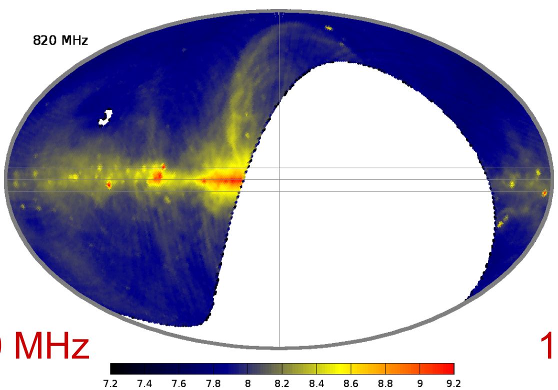
22 MHz



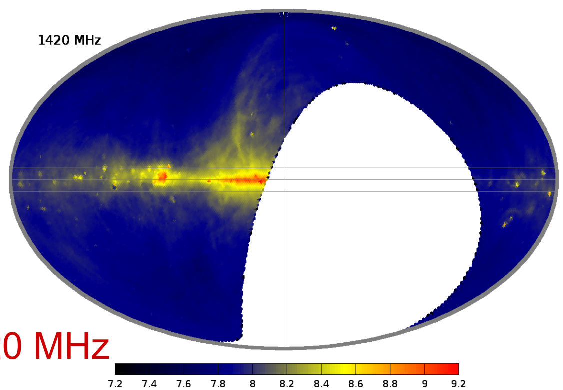
45 MHz



408 MHz



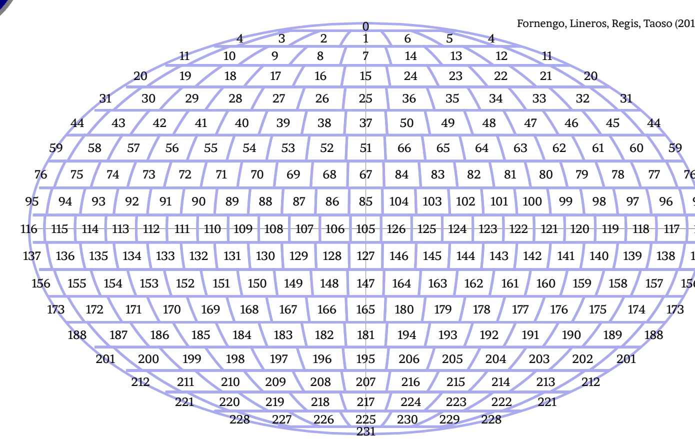
820 MHz



1420 MHz

$(T_{\rm obs})^i$ $\quad$ $i = \text{patches}$

(232)



Galactic radio signal: bounds

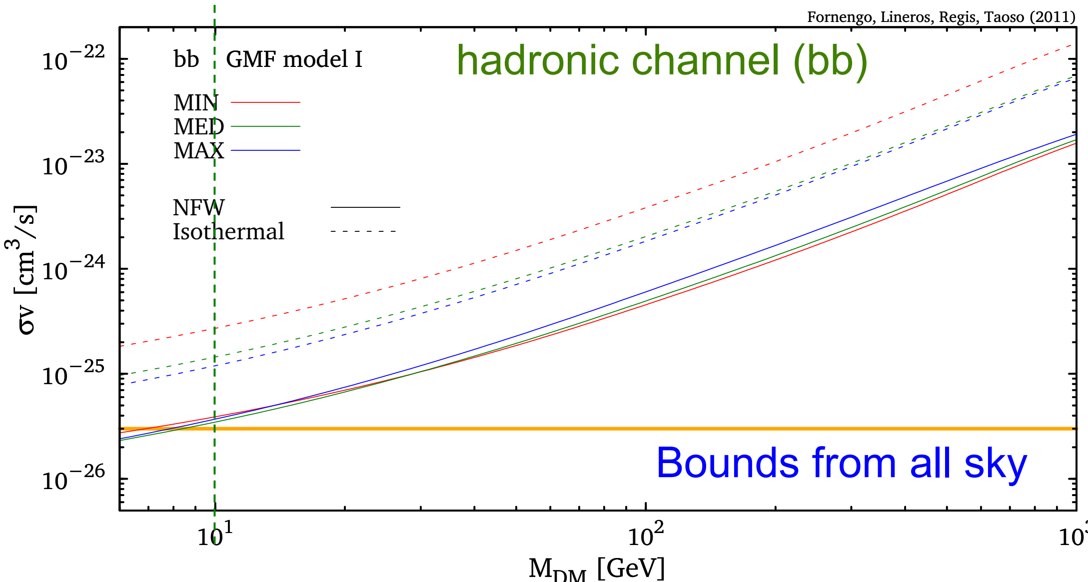
Bounds from combination of all frequency-skymaps

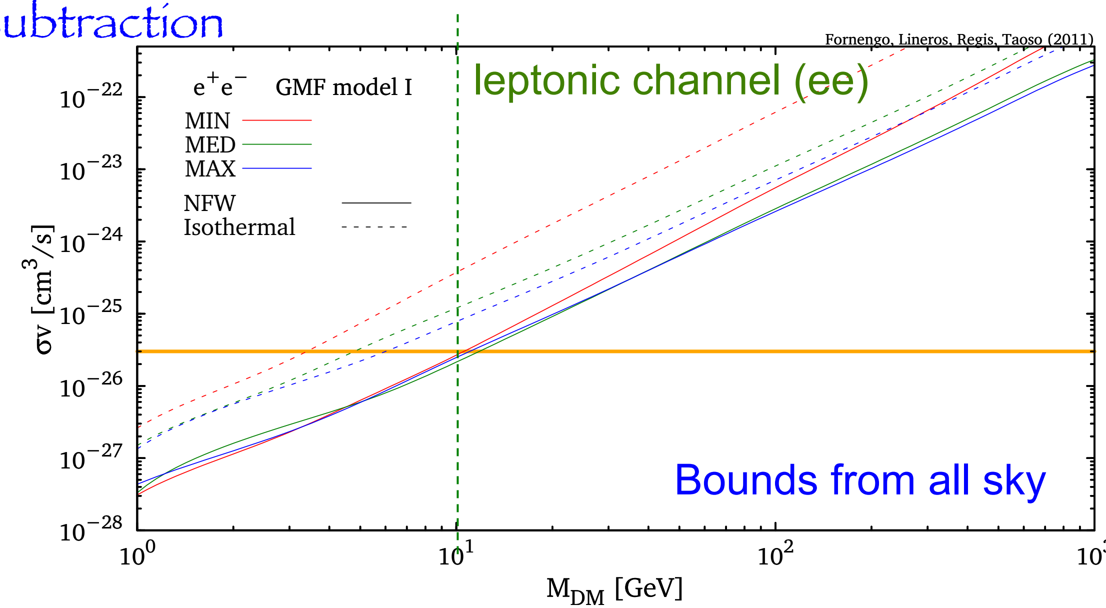
$$(T_{\rm DM})^i \le (T_{\rm obs})^i + 3\sigma$$

$$[\langle \sigma v \rangle, M_{\rm DM}] \longleftrightarrow \min_i \{(T_{\rm DM})^i\}$$

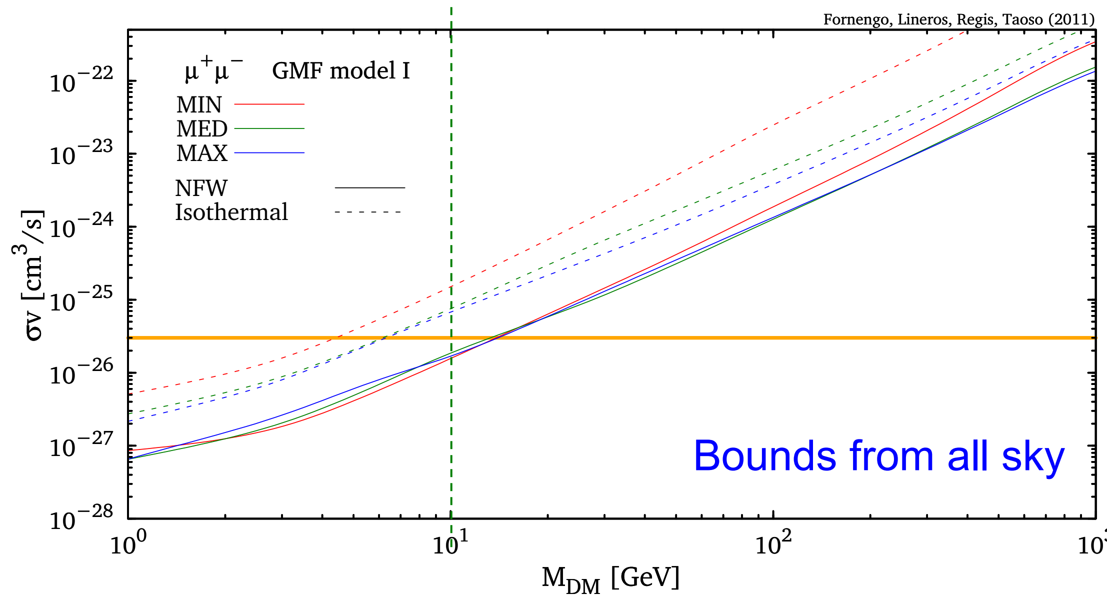
Conservative bounds:

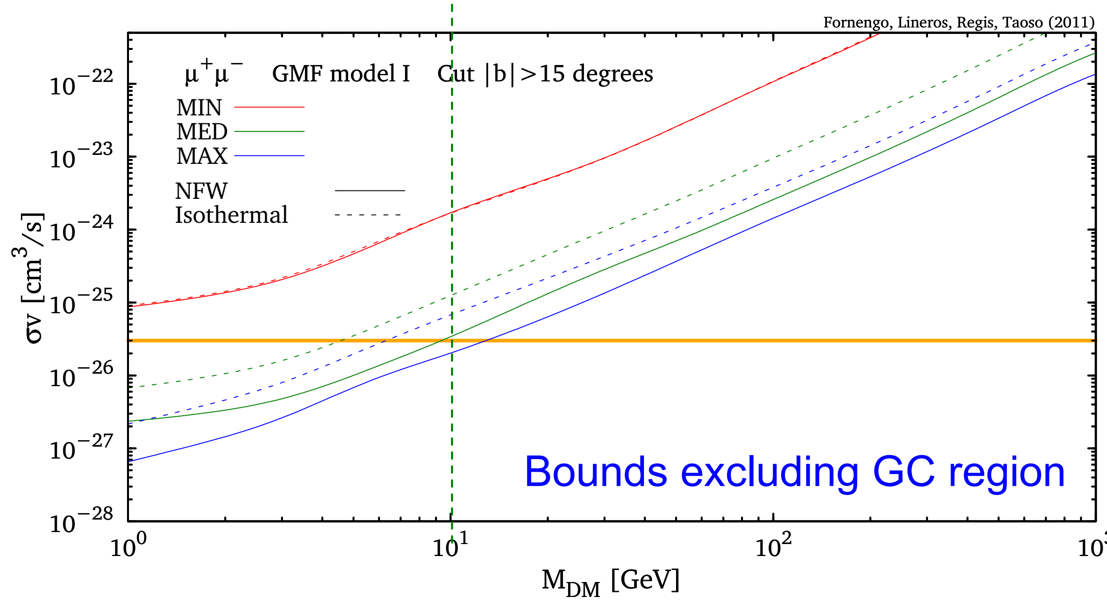
- No astrophysical background subtraction
- No DM substructures included





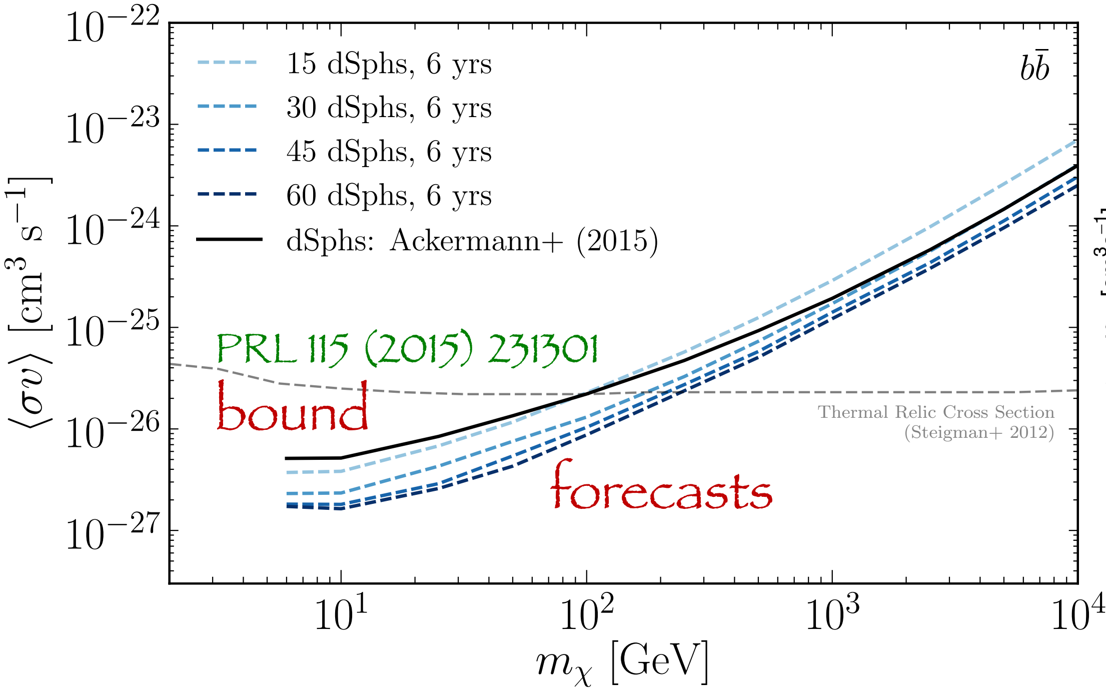
Galactic radio signal: bounds



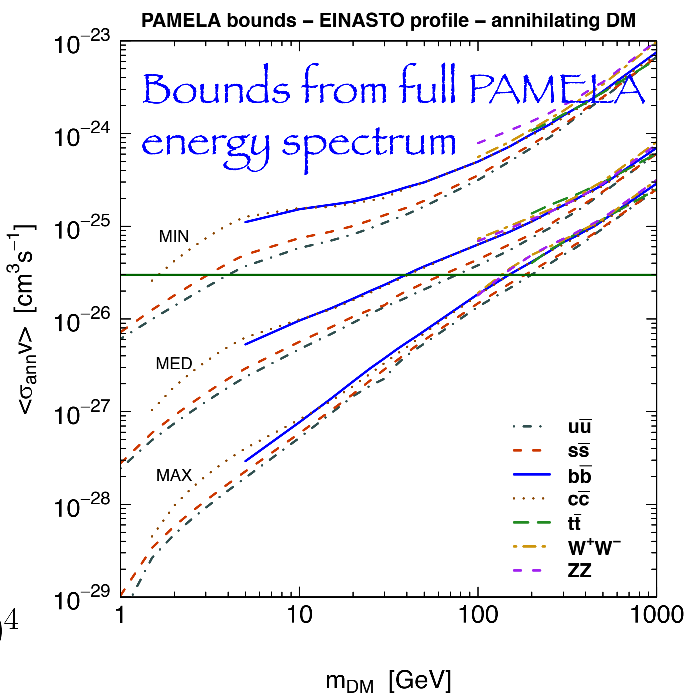


Not strong dependence of bound on magnetic field because the most constraining patches are those at low latitude, where the various B(r,z) do not sizeably differ

Bounds from other techniqus

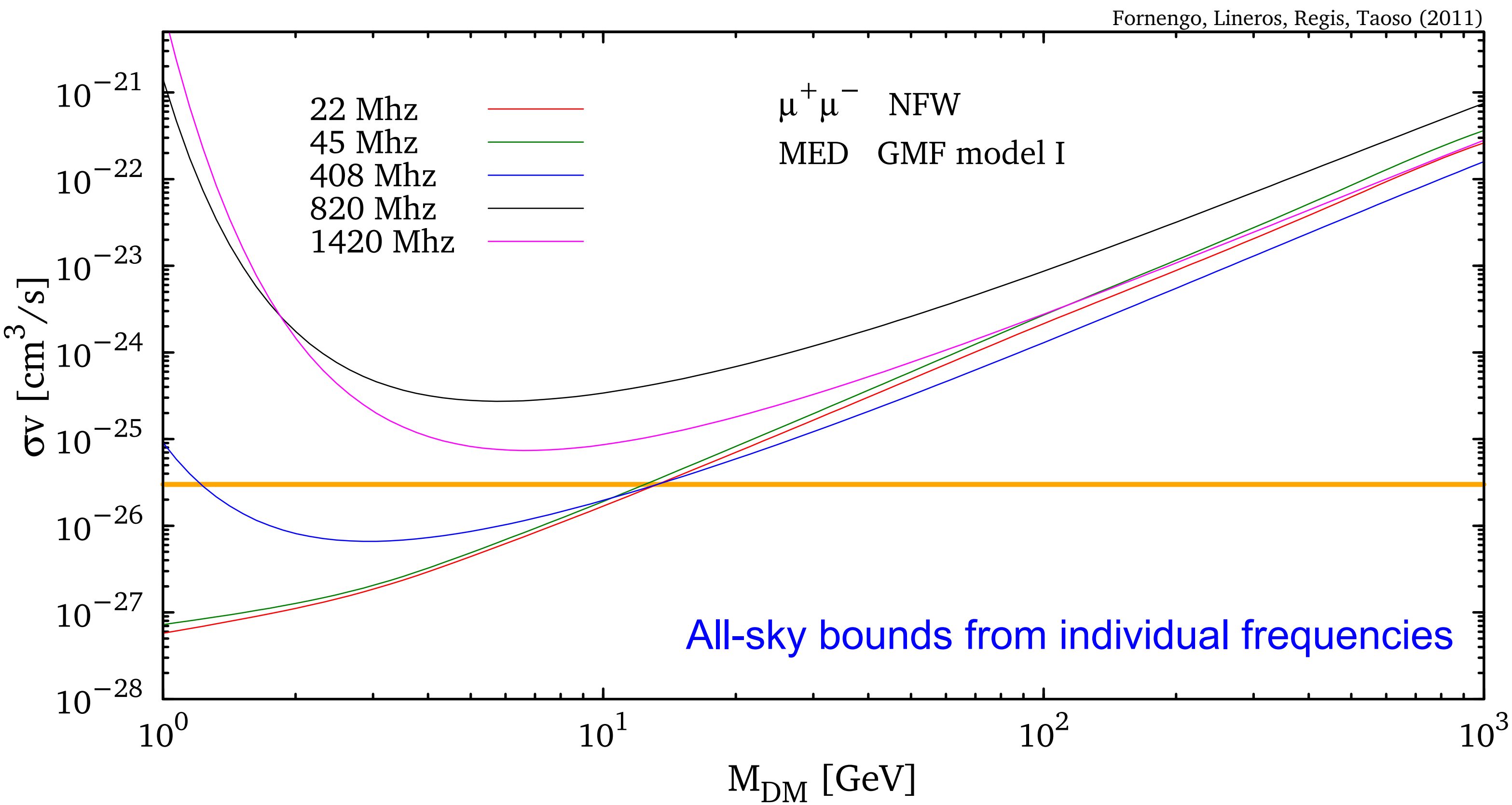


Charles et al (Fermi Collab) Phys Rep 636 (2016) 1



NF, Maccione, Vittino, JCAP 09 (2013) 031

Galactic radio signal: bounds



Lower frequencies better for lighter DM

Constraining power also depends on sky-coverage and sensitivity of the survey

Conclusions

Isotropic radio emission systematically in excess of what inferred from number counts: about a factor of $3 \div 6$

Results appear stable against:

- Galactic halo modeling (mild dependence on the resulting T)
- Galactic magnetic fields
- Spatial distribution of cosmic rays sources
- Different resolution of maps

Radio bounds on dark matter from our own galaxy provide relevant bounds, comparable to what obtained from other indirect detection signals