Constraining the frequency spectrum of cosmic radio background signals with dipole analyses on sky areas observed by SKA

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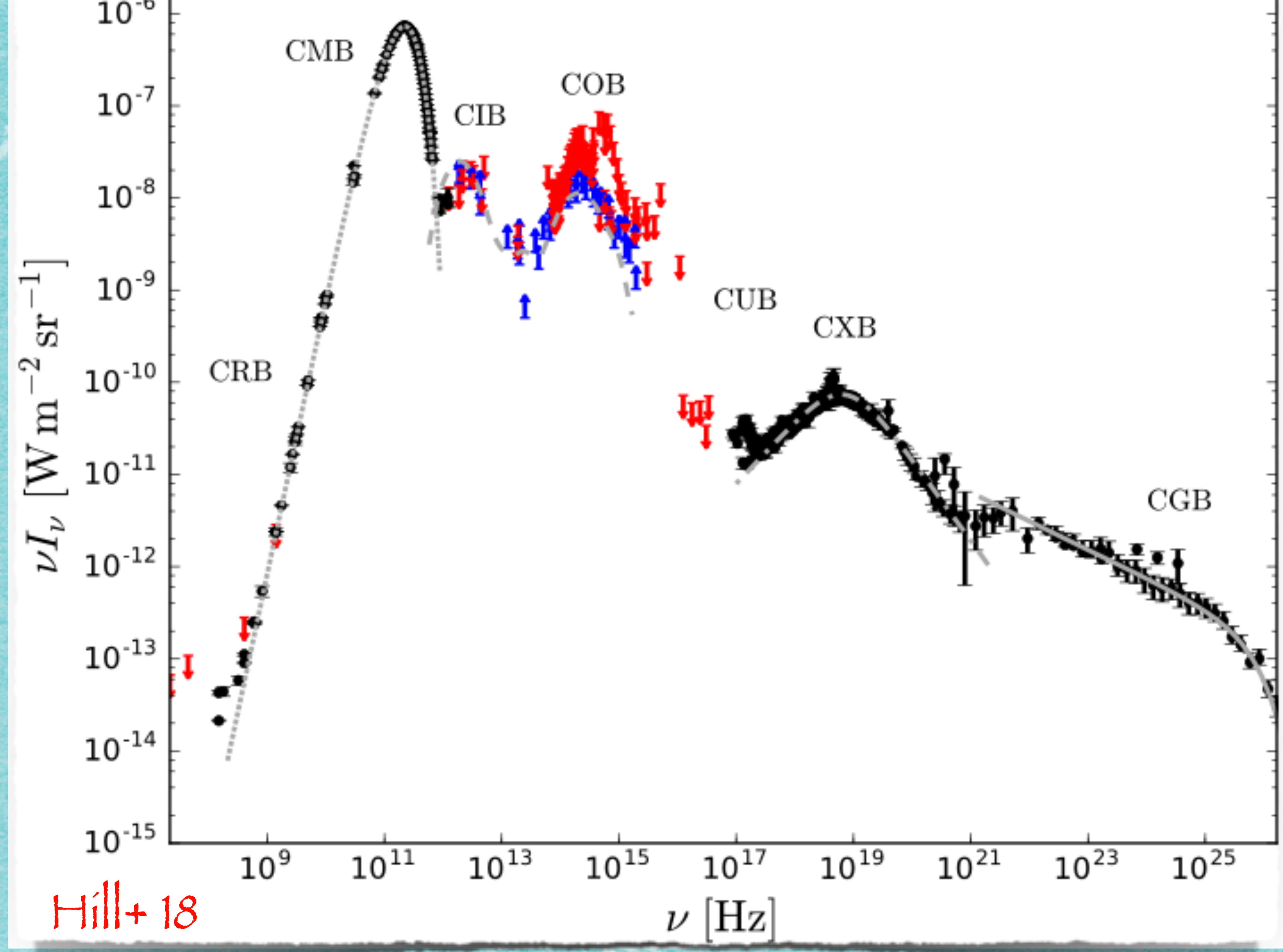
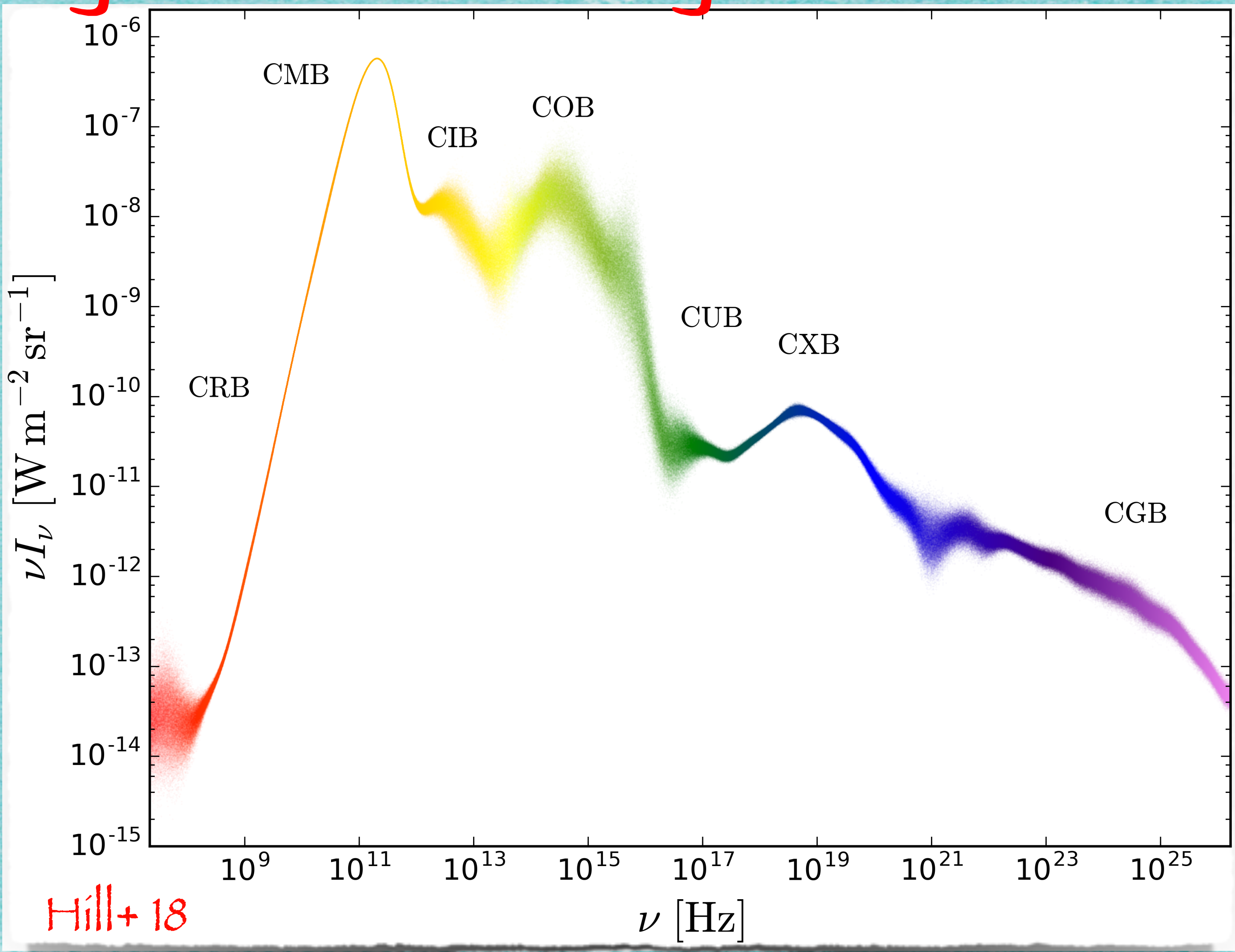
Best way to study the CB monopole frequency spectrum is to observe & map the whole sky with:

- ☑ precise absolute, relative and inter-frequency calibrations
- ☑ extreme sensitivity
- ☑ good resolution to identify & subtract discrete sources
- ☑ improve data analysis with a spectral resolution set according to expected spectral variations of the signal



Various experiments and observational projects dedicated to global radio signal BUT...

ABSOLUTE CALIBRATION is difficult... on-going & future microwave & far-IR projects (LiteBIRD) are inherently differential as well as radio interferometers ➡ best sensitivities & resolutions (LOFAR, SKA)



Why not take advantage of the possibility of measuring the CB spectrum by exploiting these intrinsically differential designs relying only on relative and interfrequency calibration?

Peculiar motion of the observer naturally offers this possibility

The peculiar motion of an observer relative to an ideal reference frame at rest wrt the CB in a given frequency band produces boosting effects in the anisotropy patterns at low multipoles with frequency spectral behaviour related to the spectrum of the isotropic monopole emission

The largest effect is on the dipole ($\ell = 1$) mainly attributed to the solar system barycentre motion

The peculiar velocity effect can be evaluated on the whole sky using the complete description of the Compton-Getting effect (based on Lorentz invariance of photon distribution function $\eta(\nu)$)

The effect is given in terms of equivalent thermodynamic temperature, $T_{th}(\nu)$, defined as the temperature of the BB having the same $\eta(\nu)$ @ ν

$$T_{\rm th}(\nu) = \frac{h\nu}{k} \frac{1}{\ln(1 + 1/\eta(\nu))}.$$

where $\eta(\nu, \hat{n}, \boldsymbol{\beta}) = \eta(\nu')$ with $\nu' = \nu(1 - \hat{n} \cdot \boldsymbol{\beta})/(1 - \beta^2)^{1/2}$

$\hat{n}$ ↛ sky direction unit vector associated to polar coordinates (colat) & (long) ➛dipole vector: $\vec{\beta} = \vec{v}/c$

Planck Collaboration 2020

$\beta \simeq 1.2336 \times 10^{-3} \simeq A_{dip} / T_0$

CMB dipole direction in Galactic coord

$l = 264.021°$, $b = 48.253°$

$v = (369.82 \pm 0.11)$ km/s

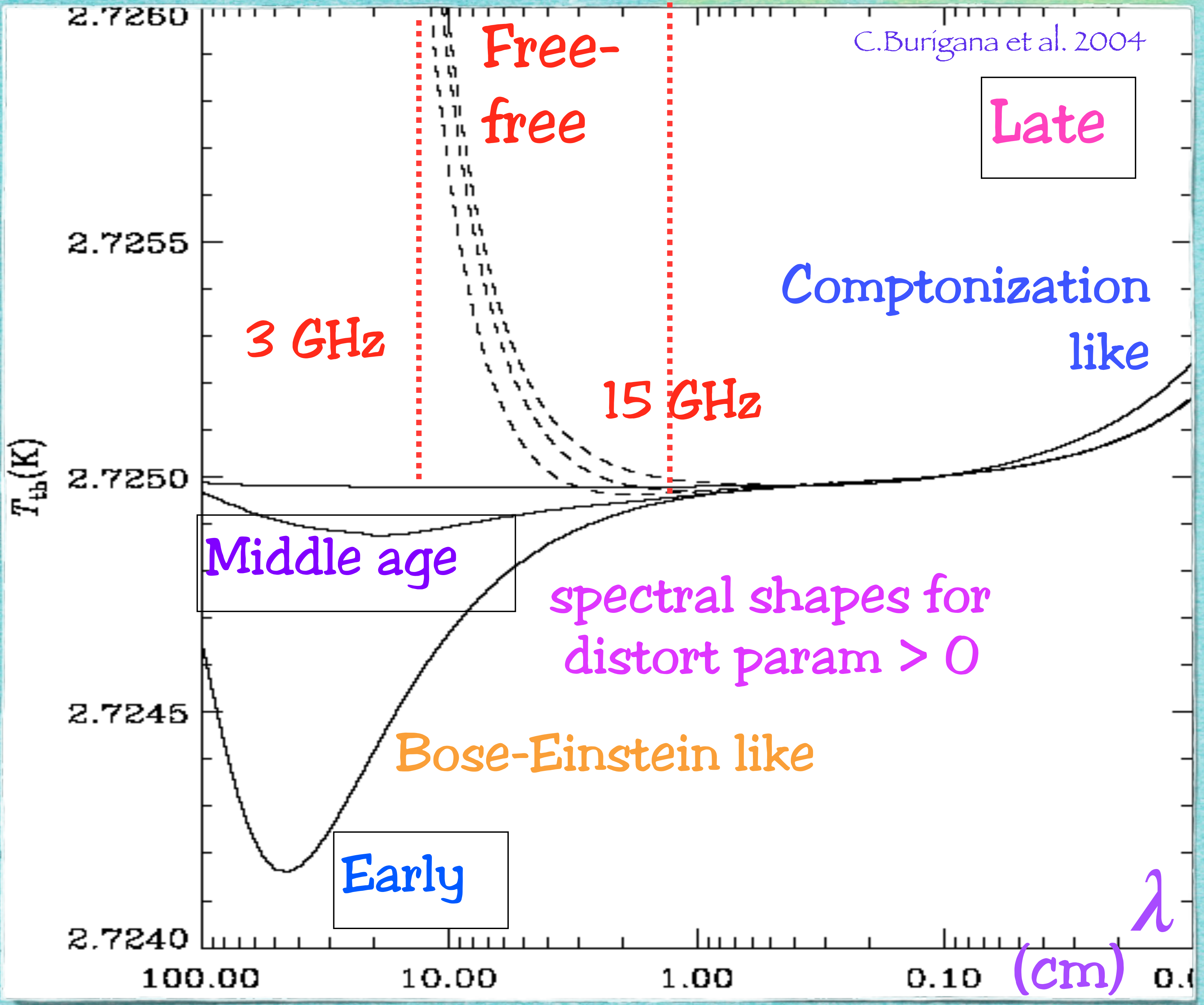
velocity of the Solar System barycentre wrt the CMB

CMB distortions @ different cosmic times

Zeldovich & Sunyaev 1969; Illarionov & Sunyaev 1974; Danese & de Zotti 1977; Burigana et al. 1991; Hu & Silk 1993

Blackbody Photoshpere

BIG BANG



Intermediate distortions

today

$z_{thermalization}$ — z_{BE} — z — $z_{recombination}$ — z

Primordial distortions

Late distortions

Related (mainly) to the reionization history of the universe

... accounting for BE-like & FF + Comptonization distortions...

$$\eta^{FF+C} \simeq \eta_i + u \frac{x/\phi_i \, e^{x/\phi_i}}{(e^{x/\phi_i} - 1)^2} \left(\frac{x/\phi_i}{\tanh[x/(2\phi_i)]} - 4 \right) + \frac{y_B(x)}{x^3}$$

$$y_B(t,x) = \int_{t_h}^{t} (\phi - \phi_i)\phi^{-3/2} g_B(x,\phi) K_{0B} \, dt = \int_{z}^{z_h} (\phi - \phi_i)\phi^{-3/2} g_B(x,\phi) K_{0B} t_{exp} \frac{dz}{1+z}$$

$$K_{0B}(z) = K_B(z)/\phi^{-7/2}$$

$$K_B(z) = \frac{8\pi}{3} \frac{e^6 h^2 n_e (n_H + 4n_{He})}{m(6\pi m k T_e)^{1/2} (kT_e)^3} \sim 2.6 \times 10^{-25} \phi^{-7/2} (T_0/2.7\,K)^{-7/2} (1+z)^{5/2} \hat{\Omega}_b^2 \chi_e^2 \sec^{-1}$$

z_{BE} up to $\sim 10^5$

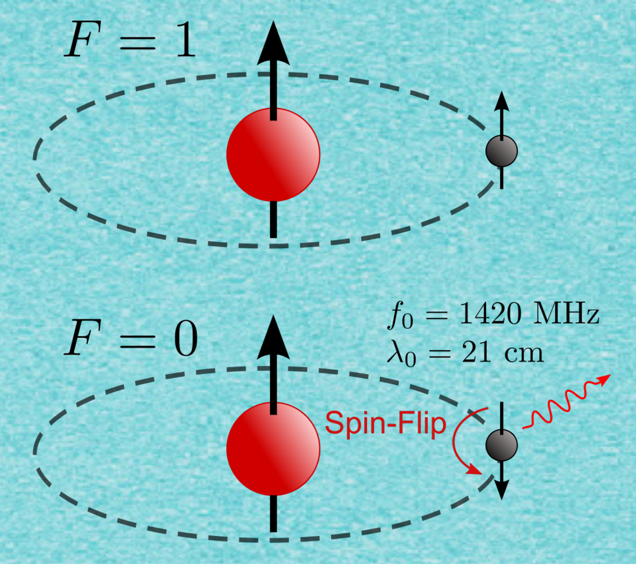
$$\eta_{BE} = \frac{1}{e^{x_e + \mu} - 1}$$

Quantify the fractional E exchanged in the plasma during the interaction

with μ function of x

$$\mu(x) \simeq \mu_0 e^{(-x_C/x)} \qquad \mu_0 \sim 1.4 \Delta\varepsilon / \varepsilon_i \qquad u \simeq (1/4)\Delta\varepsilon / \varepsilon_i$$

The 21 cm line corresponds to the spin-flip transition in the ground state of neutral hydrogen



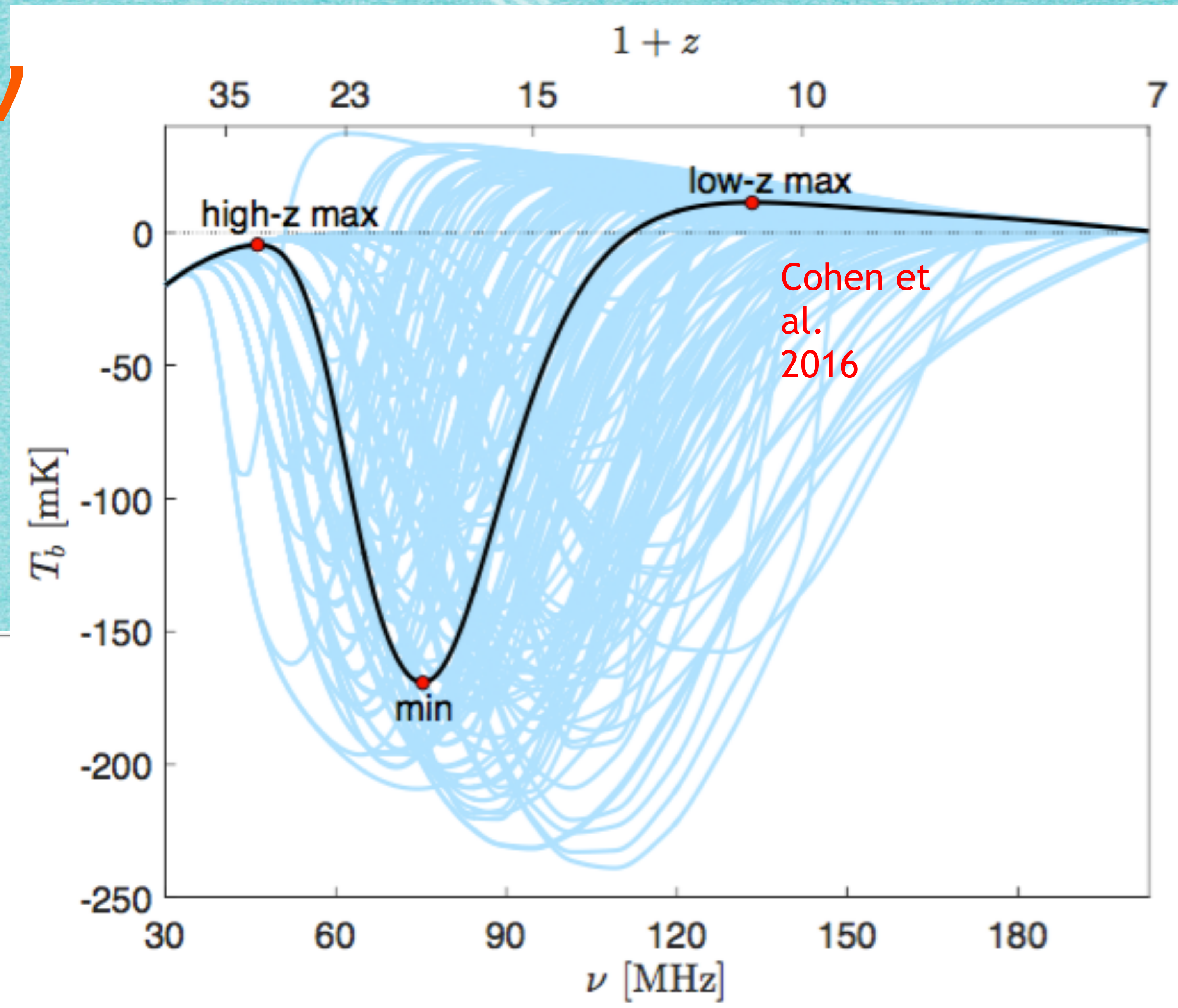
In cosmology, this signal (usually in T_{ant}) is described as the offset of the 21 cm T_{bright} from T_{CMB} along the observed line of sight at ν

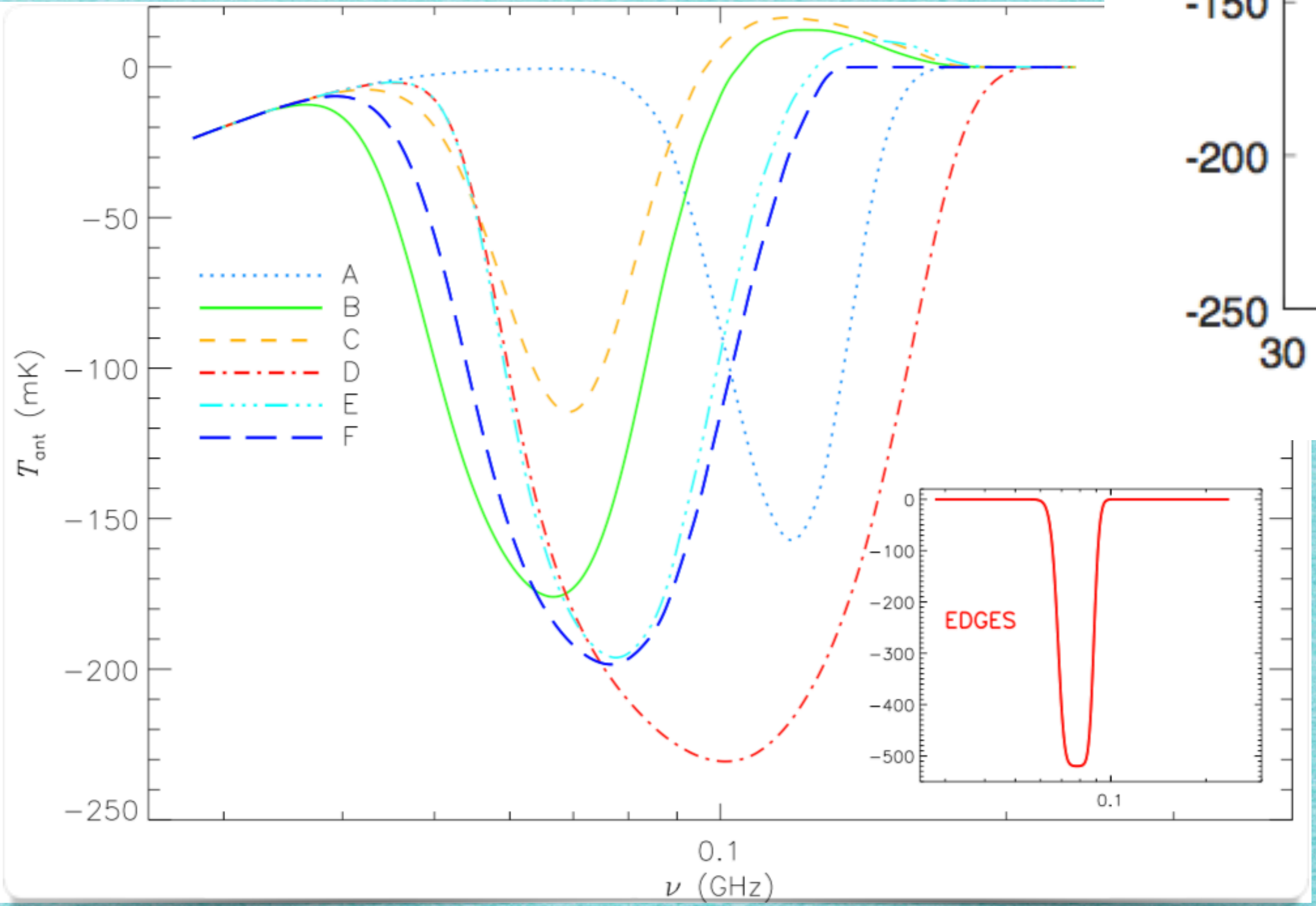
$$T_{\rm ant}^{21\,{\rm cm}}(\nu) = \frac{T_{\rm S} - T_{\rm CMB}}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$
$$\simeq 27 x_{\rm HI}\left(1 - \frac{T_{\rm CMB}}{T_{\rm S}}\right)(1+\delta_{nl})\left(\frac{H(z)}{{\rm d}v_r/{\rm d}r + H(z)}\right)$$
$$\sqrt{\frac{1+z}{10}\frac{0.15}{\Omega_{\rm m}h_{100}^2}}\left(\frac{\Omega_{\rm b}h_{100}^2}{0.023}\right){\rm mk},$$

Furlanetto et al. 2006, Phys. Rep.

$\delta_{nl}(\vec{x}, z) \equiv \rho/\bar{\rho} - 1$ evolved (Eulerian) density contrast

dv_r/dr comoving gradient of the line of sight component of the comoving velocity





Assuming CMB assumed as a backlight

➢ if $T_S < T_{CMB}$ the gas seen in absorption

➢ if $T_S > T_{CMB}$ the gas seen in emission

Note: in principle T_{CMB} can be replaced by any possible background radiation

peaking in a wide range of ν: ~50 and 150 MHz ➝ z ~ 30 to 10

Wide envelope of possible predictions

✓negative signals up to ~ 250mK

✓positive signals up to ~ 50mK

Important extragalactic (EG) background signal expected from the integrated contribution of discrete sources

Large fraction resolved through galactic surveys but a residual background (observationally diffuse) comes from faint sources below detection limits & depends on their number counts (very high compared to the fine reionization signatures)

Careful analysis by Gervasi+08 and prediction of the EG source radio background between 0.151 and 8.44 GHz, including different detection thresholds

Consider their best-fit single power-law model multiplied by 1.3 to account for a larger contribution likely ascribed to emerging SFG and radio-quiet AGN at fainter flux densities

LOFAR Boötes image support a flattening of differential number counts N′(ν) @ 1.4 GHz below ≃100μJy (Prandoni+ 18) & @ 0.15 GHz below ≃1mJy (Retana-Montenegro+ 18)

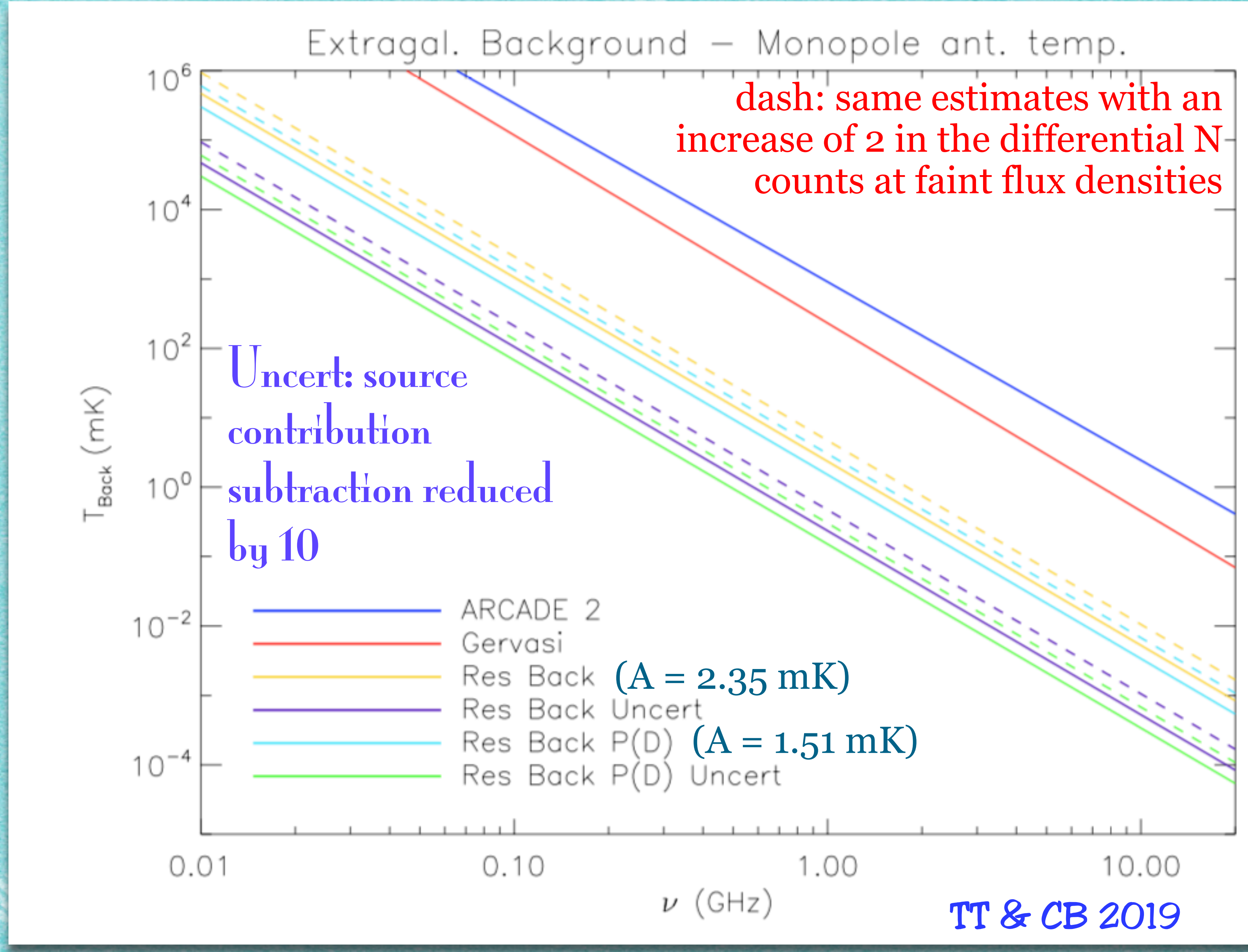
Suggest an increase in N′(ν) of a factor of ~ 2 at the faint flux densities and a ~30 % increase in the EG radio background

- S_{max} = 50 nJy (typical limits of ultra deep ref SKA continuum surveys planned)
- S_{max} = 15 nJy (number counts down to flux densities fainter than the threshold can be investigated through P(D) methods)

$$T_{\rm ant}^{\rm Back}(\nu) \simeq A\,(\nu/{\rm GHz})^{-2.65}$$

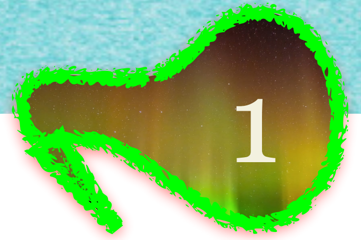
$$\int_{S_{\rm min}}^{S_{\rm max}} S\,N'(\nu)\,{\rm d}S$$

P(D) confusion probability distribution



FORMALISM

observed signal map



$$T_{\rm th}^{\rm BB/dist}(\nu,\hat{n},\boldsymbol{\beta}) = \frac{xT_0}{\ln(1+1/(\eta(\nu,\hat{n},\boldsymbol{\beta}))^{\rm BB/dist})} = \sum_{\ell=0}^{\ell_{\rm max}} \sum_{m=-\ell}^{\ell} a_{\ell,m}(\nu,\beta)Y_{\ell,m}(\theta,\phi),$$

$$T_r = T_0(1+z)$$

CMB redshift dependent effective temperature

$x = h\nu/(kT_r)$ redshift invariant dimensionless frequency

Expand the function $T_{th}^{BB/dist}(\nu,\hat{n},\beta) = T_{th}^{BB/dist}(\nu,\theta,\phi,\beta)$ in spherical harmonics & adopt a reference system with the z axis parallel to the observer velocity

$Y_{\ell,m}(\theta,\phi)$ are the spherical harmonics related to the associated Legendre polynomials $P_m^{\ell}(cos\theta)$ & $a_{\ell,m}(\nu,\beta)$ contain information on the background spectrum and the observer velocity

the isotropy of the background monopole implies that when $\vec{z} \parallel \beta$ ➠ $T_{th}^{BB/dist}$ depends only on colat. θ but not on long. ϕ ⇝ only the $a_{\ell,m}$ terms with m=0 do not vanish

Thus $Y_{\ell,m}(\theta,\phi) = \tilde{P}_{\ell}^{m}(cos\theta)$ ➠ renormalized associated Legendre polynomials

$$\tilde{P}_{\ell}^{m}(\cos\theta) = \sqrt{\frac{2\ell+1}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}P_{\ell}^{m}(\cos\theta).$$

Method:
choose 7 directions, 7 linear equations from $\ell = 0$ up to $\ell = 6$

$$
\begin{aligned}
T_{\rm th}^{\rm BB/dist} = & \, a_{0,0}\sqrt{\frac{1}{4\pi}} \\
& + a_{1,0}\sqrt{\frac{3}{4\pi}}\cos\theta \\
& + a_{2,0}\sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) \\
& + a_{3,0}\sqrt{\frac{7}{4\pi}}\left(\frac{5}{2}\cos^3\theta - \frac{3}{2}\cos\theta\right) \\
& + a_{4,0}\sqrt{\frac{9}{4\pi}}\left(\frac{35}{8}\cos^4\theta - \frac{15}{4}\cos^2\theta + \frac{3}{8}\right) \\
& + a_{5,0}\sqrt{\frac{11}{4\pi}}\left(\frac{63}{8}\cos^5\theta - \frac{35}{4}\cos^3\theta + \frac{15}{8}\cos\theta\right) \\
& + a_{6,0}\sqrt{\frac{13}{4\pi}}\left(\frac{231}{16}\cos^6\theta - \frac{315}{16}\cos^4\theta + \frac{105}{16}\cos^2\theta - \frac{5}{16}\right),
\end{aligned}
$$

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& expanding $T_{th}^{BB/dist}$ in spherical harmonics

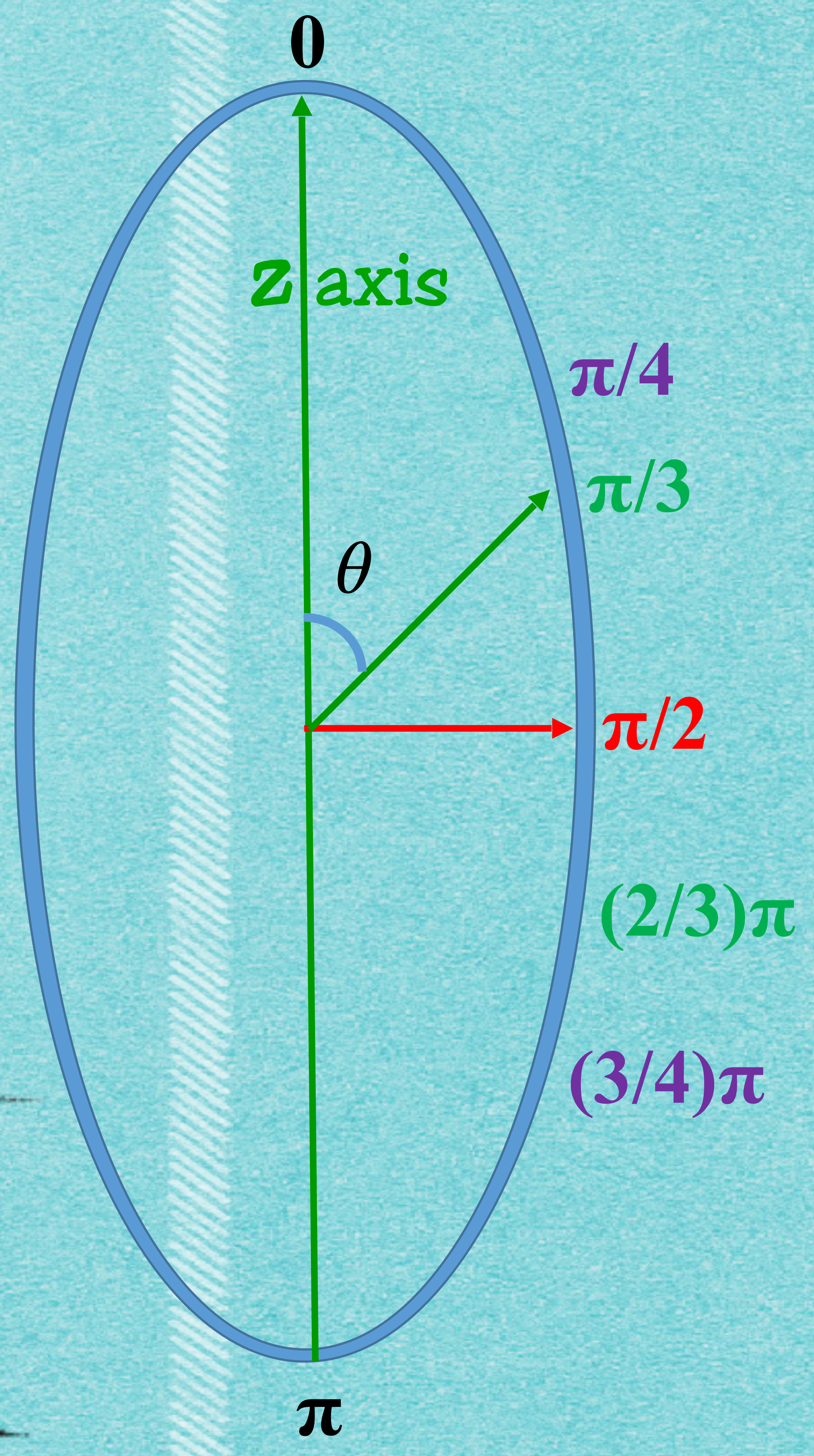
directions $\rightarrow$ N = $\ell_{max} + 1$

Directions choice:
(anti)symmetric wrt π/2...
also to simplify algebra

$\nu = \nu_{obs}$

$\nu' = \nu_{CMB}^{rest,frame}$

* $Y_{0,0} = \sqrt{1/(4\pi)}$
* for $\ell = 0$ & even ℓ the Legendre $P_0^\ell(cos\theta)$ are symmetric wrt $\theta = \pi/2$
* for odd ℓ they vanish at $\theta = \pi/2$ and are antisymmetric wrt $\theta = \pi/2$



$$
\frac{1-\beta}{(1-\beta^2)^{1/2}} \le \frac{\nu'}{\nu} \le \frac{1+\beta}{(1-\beta^2)^{1/2}};
$$

Symmetry of directions implies separation in 2 systems

- ➢ for 0 and even multipoles
- ➢ for odd multipoles

Among the possible choices satisfying these symmetry properties select a set of colatitudes θ_i such that the values of $cos(\theta_i)$ are rational numbers or just involve $\sqrt{2}$ to simplify the algebra

➡ $\theta_i = 0, \pi/4, \pi/3, \pi/2, (2/3)\pi, (3/4)\pi, \pi$

$$T_{\rm th}^{\rm BB/dist}(\theta = 0) = \sqrt{\frac{1}{4\pi}} a_{0,0} + \sqrt{\frac{3}{4\pi}} a_{1,0} + \sqrt{\frac{5}{4\pi}} a_{2,0} + \sqrt{\frac{7}{4\pi}} a_{3,0} + \sqrt{\frac{9}{4\pi}} a_{4,0} + \sqrt{\frac{11}{4\pi}} a_{5,0} + \sqrt{\frac{13}{4\pi}} a_{6,0},$$

$$T_{\rm th}^{\rm BB/dist}(\theta = \pi/4) = \sqrt{\frac{1}{4\pi}} a_{0,0} + \frac{\sqrt{2}}{2} \sqrt{\frac{3}{4\pi}} a_{1,0} + \frac{1}{4} \sqrt{\frac{5}{4\pi}} a_{2,0} - \frac{\sqrt{2}}{8} \sqrt{\frac{7}{4\pi}} a_{3,0} - \frac{13}{32} \sqrt{\frac{9}{4\pi}} a_{4,0} - \frac{17\sqrt{2}}{64} \sqrt{\frac{11}{4\pi}} a_{5,0} - \frac{19}{128} \sqrt{\frac{13}{4\pi}} a_{6,0},$$

$$T_{\rm th}^{\rm BB/dist}(\theta = \pi/3) = \sqrt{\frac{1}{4\pi}} a_{0,0} + \frac{1}{2} \sqrt{\frac{3}{4\pi}} a_{1,0} - \frac{1}{8} \sqrt{\frac{5}{4\pi}} a_{2,0} - \frac{7}{16} \sqrt{\frac{7}{4\pi}} a_{3,0} - \frac{37}{128} \sqrt{\frac{9}{4\pi}} a_{4,0} + \frac{23}{256} \sqrt{\frac{11}{4\pi}} a_{5,0} + \frac{331}{1024} \sqrt{\frac{13}{4\pi}} a_{6,0},$$

$$T_{\rm th}^{\rm BB/dist}(\theta = \pi/2) = \sqrt{\frac{1}{4\pi}} a_{0,0} + 0 \cdot a_{1,0} - \frac{1}{2} \sqrt{\frac{5}{4\pi}} a_{2,0} + 0 \cdot a_{3,0} + \frac{3}{8} \sqrt{\frac{9}{4\pi}} a_{4,0}, + 0 \cdot a_{5,0} - \frac{5}{16} \sqrt{\frac{13}{4\pi}} a_{6,0}$$

Linear system to be solved using the methods of elimination and substitution

$$T_{\rm th}^{\rm BB/dist}(\theta = (2/3)\pi) = \sqrt{\frac{1}{4\pi}} a_{0,0} - \frac{1}{2} \sqrt{\frac{3}{4\pi}} a_{1,0} - \frac{1}{8} \sqrt{\frac{5}{4\pi}} a_{2,0} + \frac{7}{16} \sqrt{\frac{7}{4\pi}} a_{3,0} - \frac{37}{128} \sqrt{\frac{9}{4\pi}} a_{4,0} - \frac{23}{256} \sqrt{\frac{11}{4\pi}} a_{5,0} + \frac{331}{1024} \sqrt{\frac{13}{4\pi}} a_{6,0}$$

$$T_{\rm th}^{\rm BB/dist}(\theta = (3/4)\pi) = \sqrt{\frac{1}{4\pi}} a_{0,0} - \frac{\sqrt{2}}{2} \sqrt{\frac{3}{4\pi}} a_{1,0} + \frac{1}{4} \sqrt{\frac{5}{4\pi}} a_{2,0} + \frac{\sqrt{2}}{8} \sqrt{\frac{7}{4\pi}} a_{3,0} - \frac{13}{32} \sqrt{\frac{9}{4\pi}} a_{4,0} + \frac{17\sqrt{2}}{64} \sqrt{\frac{11}{4\pi}} a_{5,0} - \frac{19}{128} \sqrt{\frac{13}{4\pi}} a_{6,0},$$

$$T_{\rm th}^{\rm BB/dist}(\theta = \pi) = \sqrt{\frac{1}{4\pi}} a_{0,0} - \sqrt{\frac{3}{4\pi}} a_{1,0} + \sqrt{\frac{5}{4\pi}} a_{2,0} - \sqrt{\frac{7}{4\pi}} a_{3,0} + \sqrt{\frac{9}{4\pi}} a_{4,0} - \sqrt{\frac{11}{4\pi}} a_{5,0} + \sqrt{\frac{13}{4\pi}} a_{6,0}.$$

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$w_i = \cos\theta_i = 1, \sqrt{2}/2, 1/2, 0, -1/2, -\sqrt{2}/2, -1$

For $\ell = 0$ and even multipoles

$\mapsto$ sums of signals

$$a_{\ell,0} = A_\ell \sqrt{\frac{4\pi}{2\ell+1}} \Big[d_{\ell,1} \left(T_{\rm th}^{\rm BB/dist}(w=1) + T_{\rm th}^{\rm BB/dist}(w=-1)\right) + d_{\ell,2} \left(T_{\rm th}^{\rm BB/dist}(w=\sqrt{2}/2) + T_{\rm th}^{\rm BB/dist}(w=-\sqrt{2}/2)\right) + d_{\ell,3} \left(T_{\rm th}^{\rm BB/dist}(w=1/2) + T_{\rm th}^{\rm BB/dist}(w=-1/2)\right) + d_{\ell,4} T_{\rm th}^{\rm BB/dist}(w=0) \Big]$$

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neglects contributions only from ℓ = 8, 10...

An expansion up to ℓ_{max} leads to neglect the contributions from $\ell > \ell_{max}$

For odd multipoles ➨ differences of signals

$$a_{\ell,0} = A_\ell \sqrt{\frac{4\pi}{2\ell+1}} \Big[d_{\ell,1} \left(T_{\rm th}^{\rm BB/dist}(w=1) - T_{\rm th}^{\rm BB/dist}(w=-1)\right) + d_{\ell,2} \left(T_{\rm th}^{\rm BB/dist}(w=\sqrt{2}/2) - T_{\rm th}^{\rm BB/dist}(w=-\sqrt{2}/2)\right) + d_{\ell,3} \left(T_{\rm th}^{\rm BB/dist}(w=1/2) - T_{\rm th}^{\rm BB/dist}(w=-1/2)\right) \Big]$$

neglects contributions only from ℓ = 7, 9...

Simple & fast solution accurate up to $\ell = 6$

Fully Explicit Solution (FES)

ℓ	A_ℓ	$d_{\ell,1}$	$d_{\ell,2}$	$d_{\ell,3}$	$d_{\ell,4}$
0	1/630	29	120	64	204
1	1/210	29	$60\sqrt{2}$	32	–
2	1/693	121	396	−352	−330
3	2/135	13	$15\sqrt{2}$	−56	–
4	8/385	9	−10	−16	34
5	32/189	1	$-3\sqrt{2}$	4	–
6	64/693	1	−6	8	−6

Assuming that contributions scale as $\beta^{\ell \cdot p}$ with $p \sim 1$ & $\beta \simeq 10^{-3}$ then neglected contributions are negligible for current & future applications

Dipole sensitivity on patches

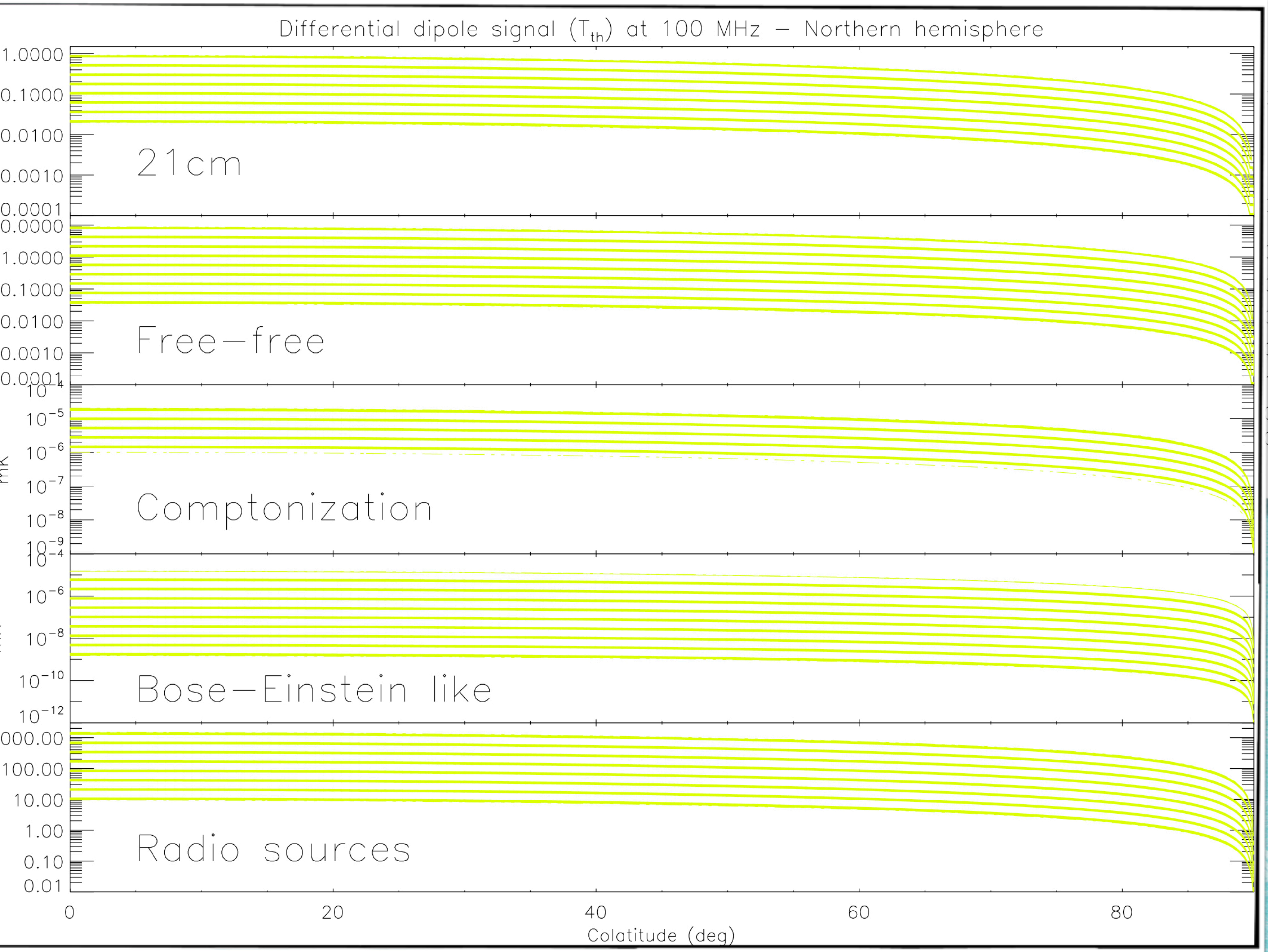
Sensitivity @ 100 kHz band

Rescaled in 10 MHz (21cm) & 40 MHz bandwidth

24h of integration on 1° or 3° patch

Rescaled on a 2 arcmin pixel size

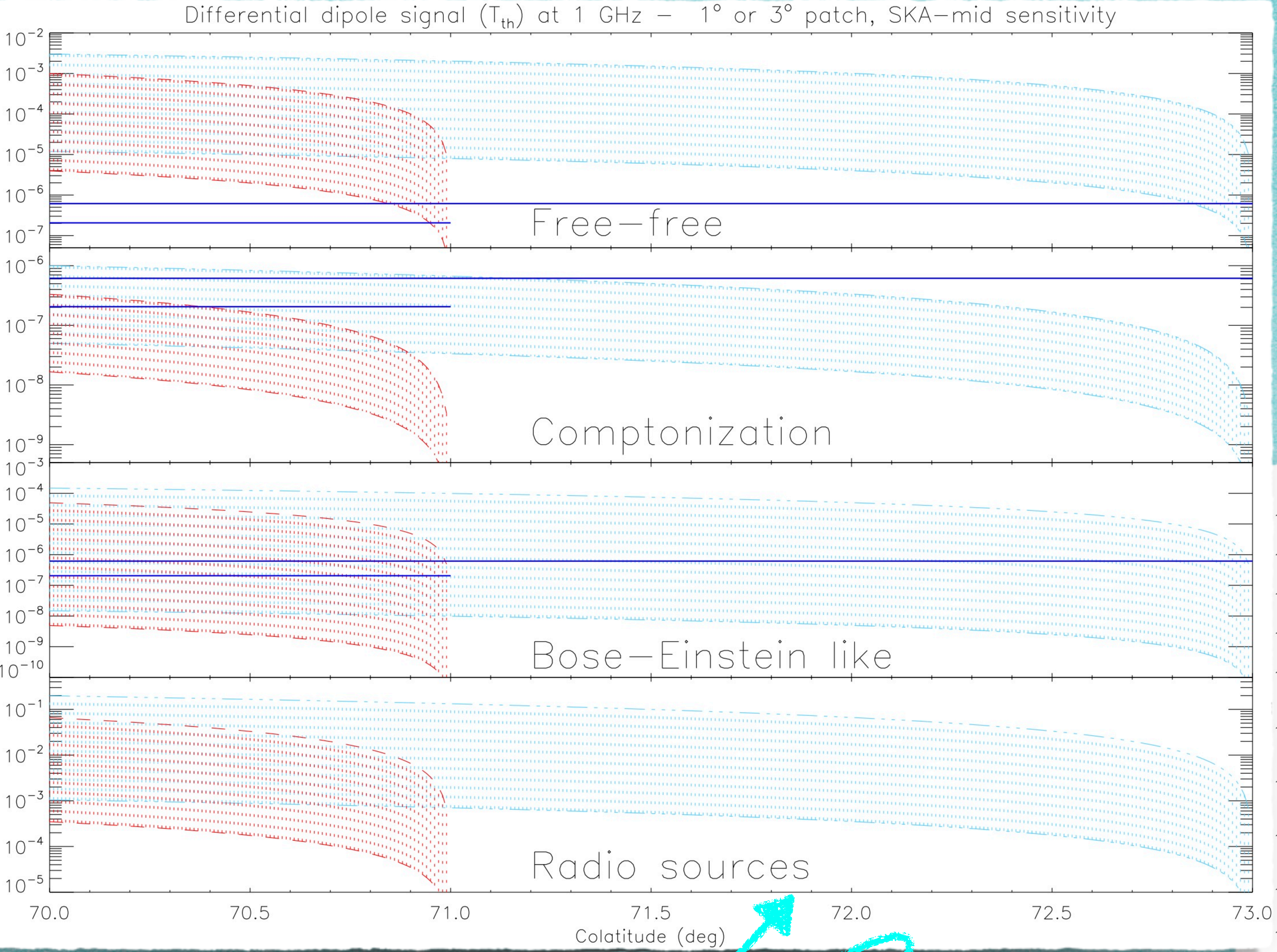
Sensitivity levels: Dewdney+ 16 SKA1 System Baseline Design, SKA Org



Frequency Range SKA-low (MHz): 50 - 350

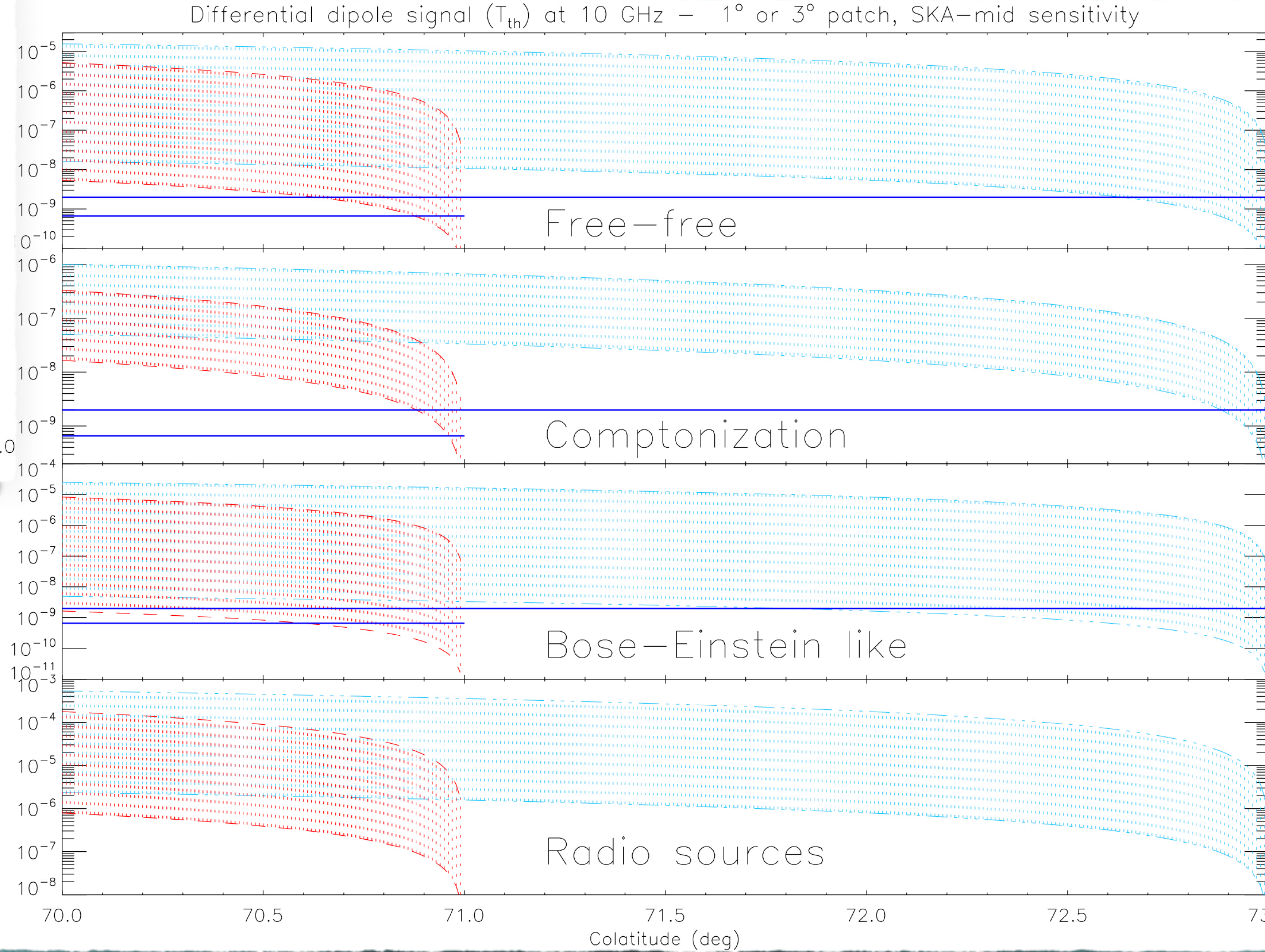
LOFAR (MHz): 30 - 220

Simple estimate: along a meridian with z-axis // to dipole direction signal variation @ colat θ from a dipole with amp ΔT in sky patch of linear size $\Delta\theta$ has amp $|\Delta T_{\Delta\theta}| \simeq \Delta T \cdot (\Delta\theta/90°) sin\theta$, $sin\theta \simeq 1$ @ angles large from poles



Frequency Range SKA-mid (GHz): 0.35 - 14

Sensitivity @ 100 kHz band
Rescaled to 400 MHz (@ 1GHz)
& 4 GHz (@ 10GHz) bandwidth



ALWAYS

several tens of mK could
identify EG background
from few μK to ~mK could
study the reionization imprints

TT, SKA Cosmology SWG Meeting 2024, 4-6 Nov, Nice, France

CONCLUSIONS

- CB monopole ν spectrum → key understand many physical, cosmological & astrophysical processes @ different cosmic epochs
- Absolute measurements of the spectrum is standard & most accurate way
- BUT precise absolute calibration is needed
- Differential methods on precise inter-ν calibration are promising: by using low ℓ pattern (mainly dipole) could significantly improve current limits w/o precise absolute calibration measurements
- Observations @ extreme sensitivity/resolution, differential method can be extended to sky patches → interferometric observations → SKA
- SKA ν coverage jointly offered by low- & mid- is particularly suitable for 21cm redshifted line, radio background, FF signals & (depending on models) of the FF2Compton dominance transition
- SKA resolution and sensitivity allow to detect point sources and to probe their number counts to very faint flux densities → enable substantial subtractions of their contribution to radio background

CONCLUSIONS II

Subtracting sources with different detection thresholds would help to clarify to what extent the radio EG background could be ascribed to EG sources or if is of intrinsic cosmological or diffuse origin

Contribute to answer about level & origin of the radio EG background, still controversial
Collecting many patches would improve the statistical information & Galactic foreground subtraction

Despite an intense theoretical and experimental effort over the past decade EG radio background obs @ multiple ν < 10 GHz are not understood in terms of known radiosources and may represent a sign of new physics (Caputo+ 23)