

A Science Case for the Full-sky Probe of the 21-cm Background: Dipole and Integrated Sachs-Wolfe Effect as a Global 21-cm Measurement

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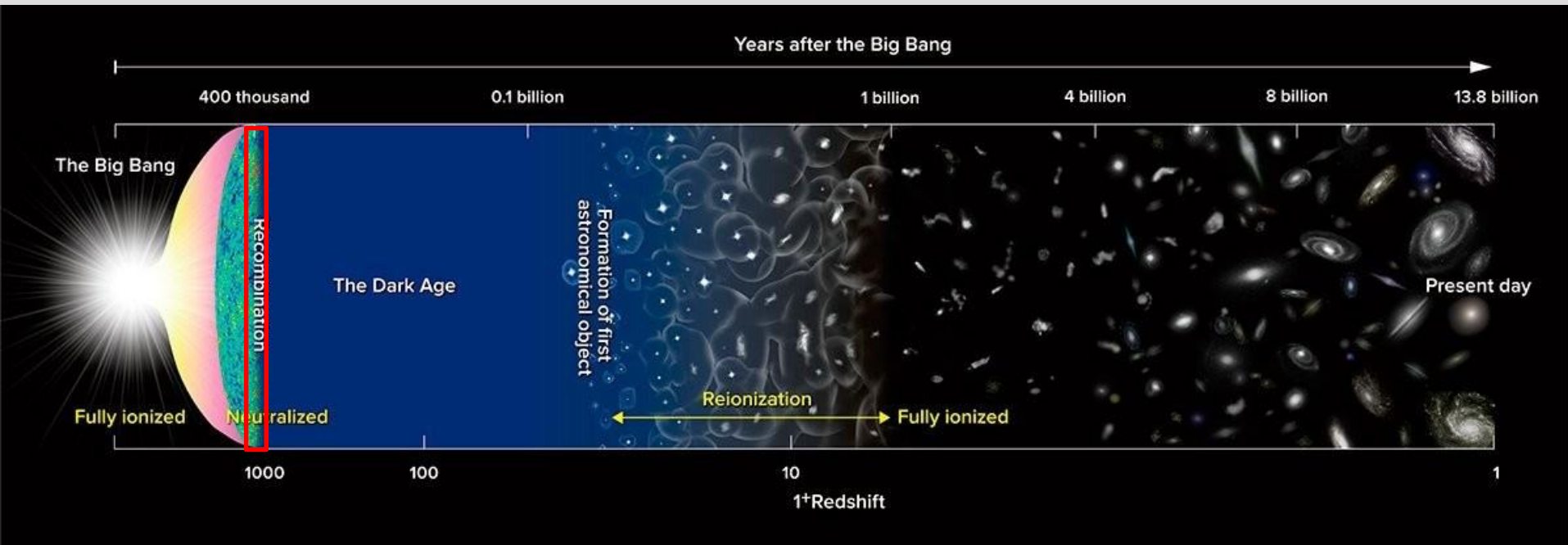
Motivation:

Cosmic reionization scientist →
hydrogen as a tracer of high- z universe →
21-cm background

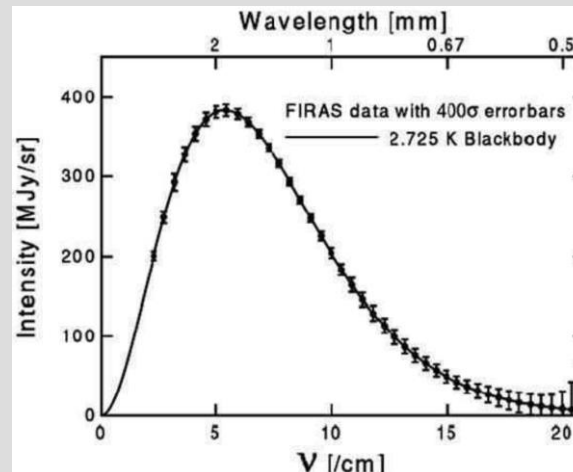
CMB vs 21B (21-cm background)

CMB: from when?

From $z \approx 1100$, recombination epoch

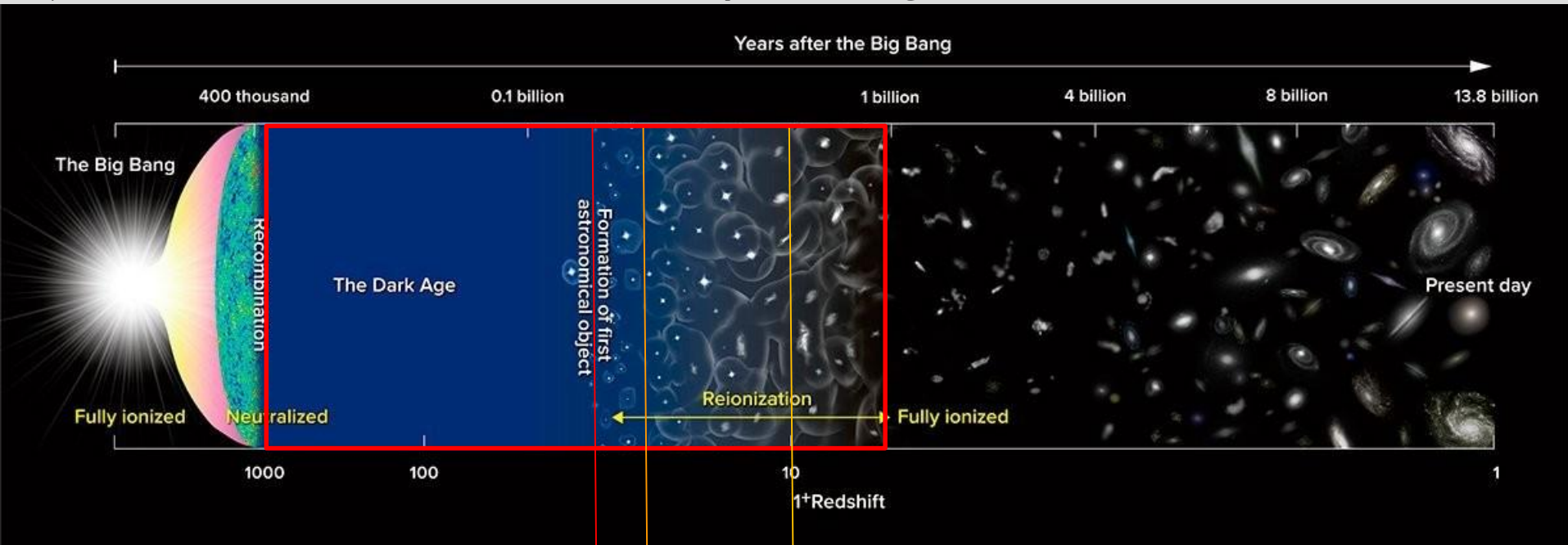


Monopole=
Blackbody
continuum,
const. brightness
temperature

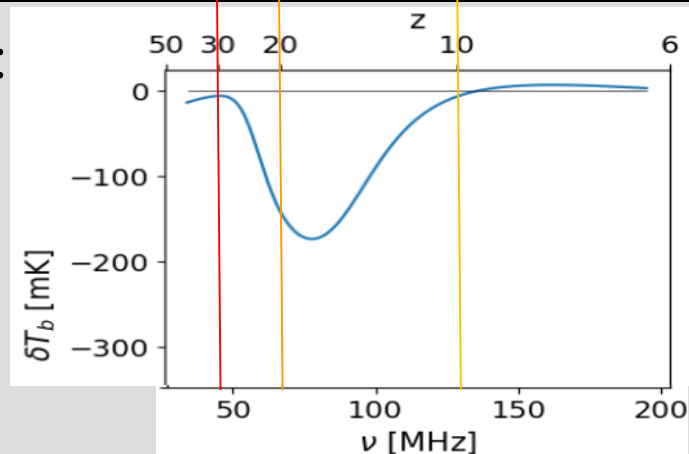


21B: from when?

From $z \approx 1100$ to 6, dark ages + epoch of reionization
post-reionization ($z < 6$): only from galaxies (IGM ionized)



21cm monopole:
lines
redshifted
→ “brightness
temperature
spectrum”

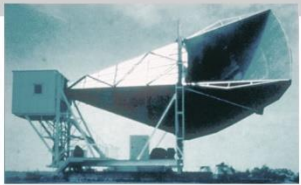


$$\delta T_b(\nu) = T_b(\nu) - 2.7K$$
$$\nu = 1.4/(1+z) \text{ GHz}$$

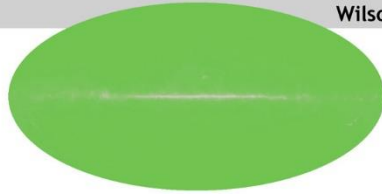
21B: isotropy to anisotropy

isotropy (monopole)

1965



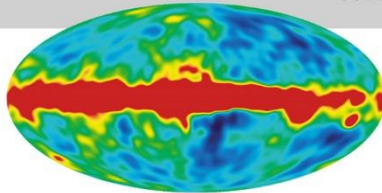
Penzias and
Wilson



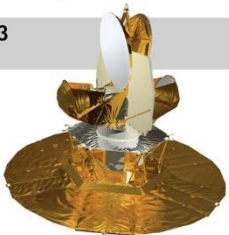
1992



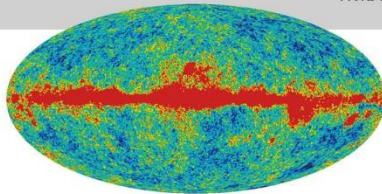
COBE



2003

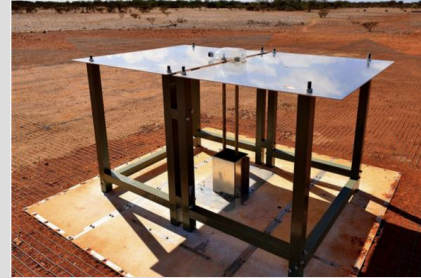


WMAP



anisotropy (multipole): large H II bubbles

(2018)
EDGES



(2021)
SARAS



LUsee-Night

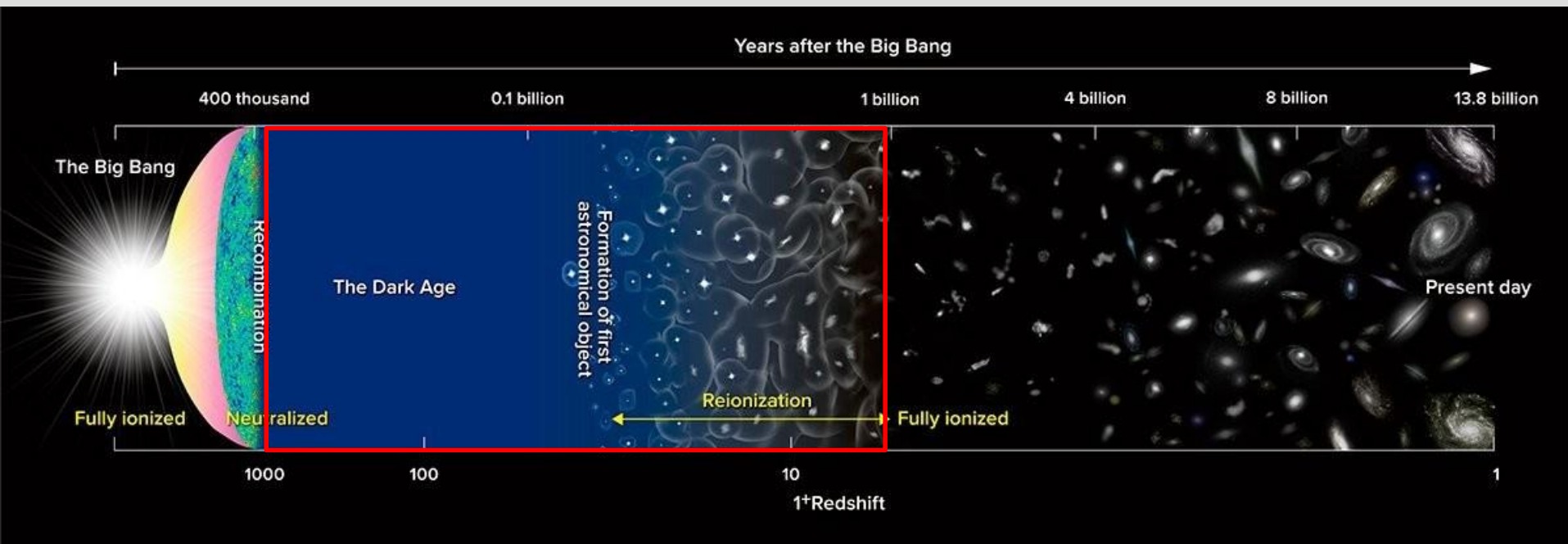


SKA-LOW



21B merit

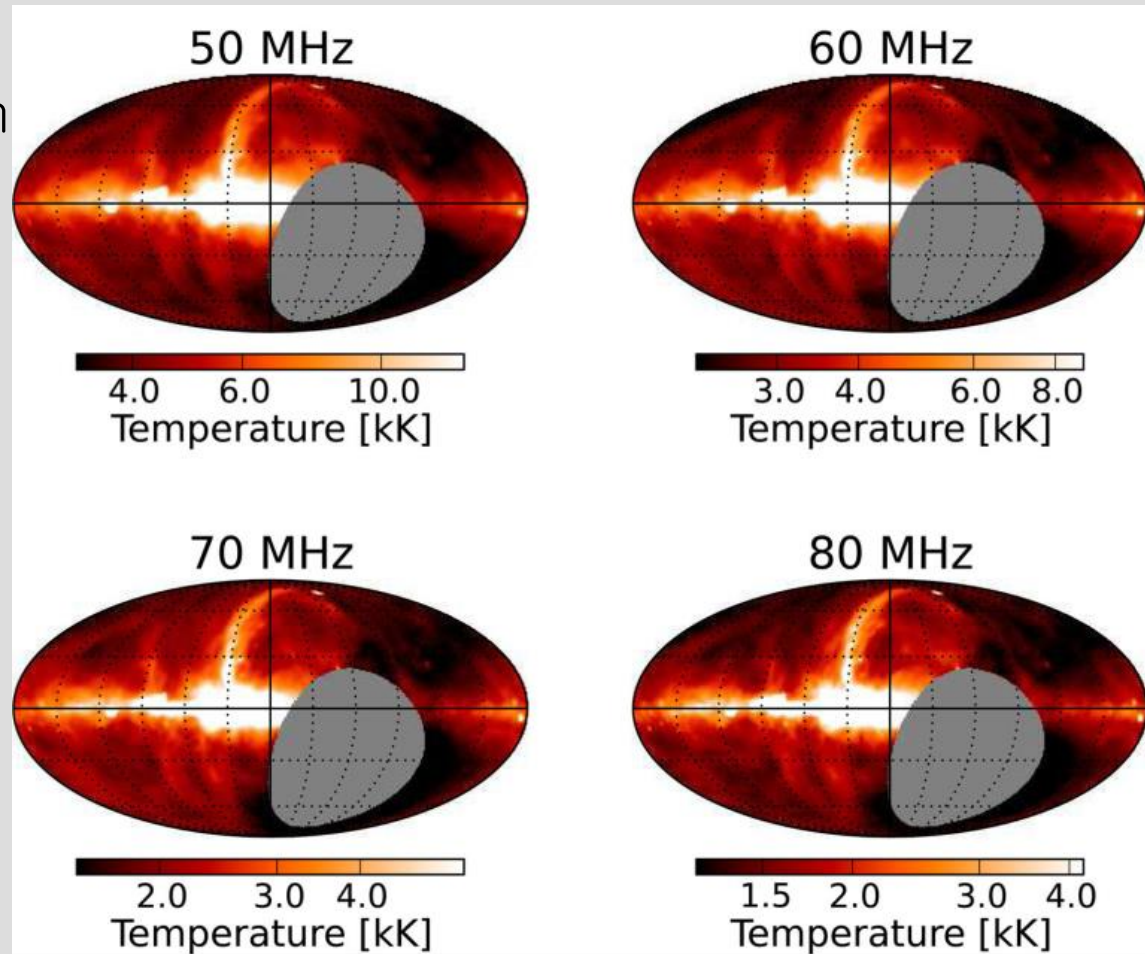
- Redundancy
 - pros
 - Another primordial background
 - Comes from many redshift slices → redundancy in information
 - cons
 - too weak
 - foreground (Milky Way mostly) removal or avoidance necessary (CMB sky is much cleaner)



Low-frequency sky

- Foreground
 - Milky Way synchrotron
 - Milky Way free-free
 - Milky Way dust
 - Exgal radio

- 21B is dim
 - 10~100 mK



- Prerequisite: removal of foreground
 - 3~4 orders of magnitude larger than 21B
 - spectral smoothness of foreground (otherwise we are doomed)

21B monopole conflict:

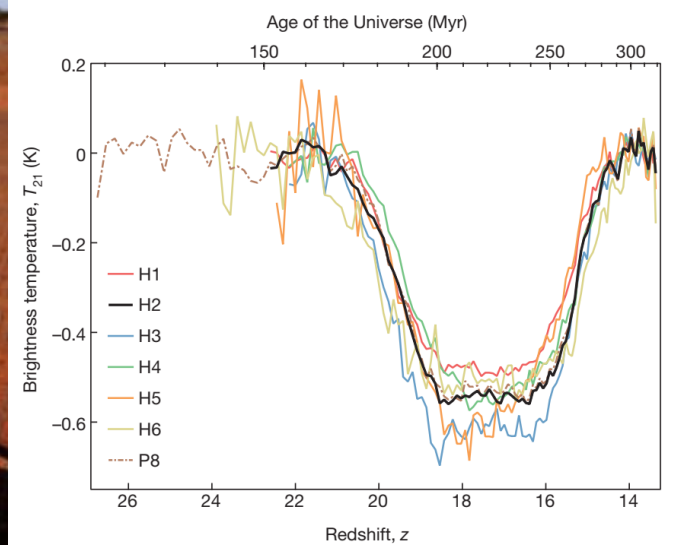
EDGES vs SARAS

(where are we humans in 21B measurement)

21B: Strong absorption vs ~Null signal

Bowman+2018

EDGES

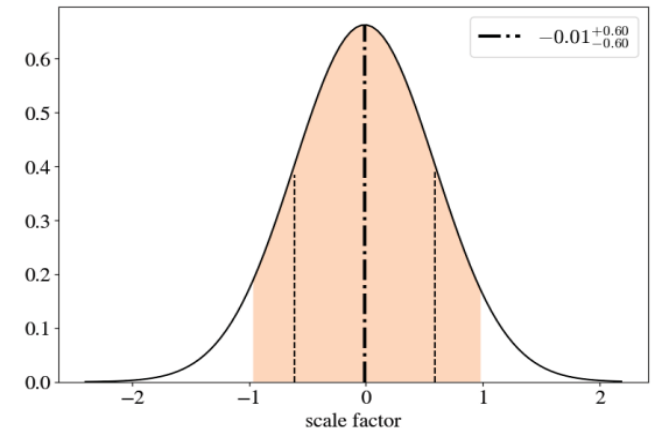


water – high dielectricity

SARAS



Singh+ 2021;
SARAS 3 search for EDGES-like signal



EDGES

- 500 mK dip (Barkana 2018)
 - colder-than-standard T_{gas} : strong DM–baryon scattering (Tashiro+2014; Barkana 2018); faster expansion (Hill & Baxter 2018)
 - extra background: Draine & Miralda-Escude 2018, Fialkov & Barkana 2019, Ewall-Wice+2020; Sikder+2024

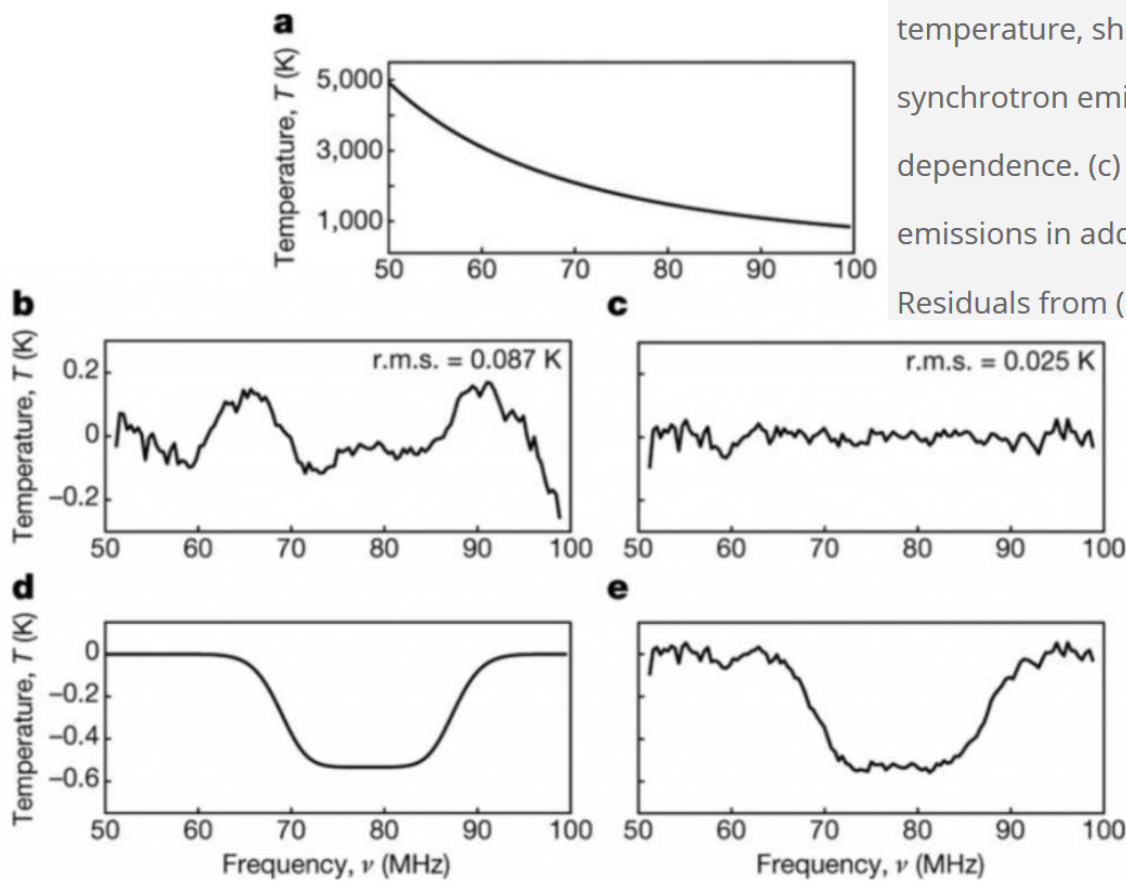


Figure 3: (a) The EDGES sky measurement in units of brightness temperature, showing the strong power-law spectrum due to galactic synchrotron emission. (b) Residuals after removing the power-law dependence. (c) Residuals after removing the power-law synchrotron emissions in addition to a model (d) of the 21 cm absorption signal. (e) Residuals from (c) added to model in (d).

EDGES

- 500 mK dip (Barkana 2018)
 - colder-than-standard T_{gas} : strong DM–baryon scattering (Tashiro+2014; Barkana 2018); faster expansion (Hill & Baxter 2018)
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 - ambiguity

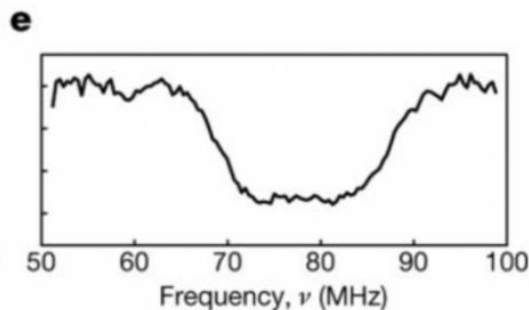
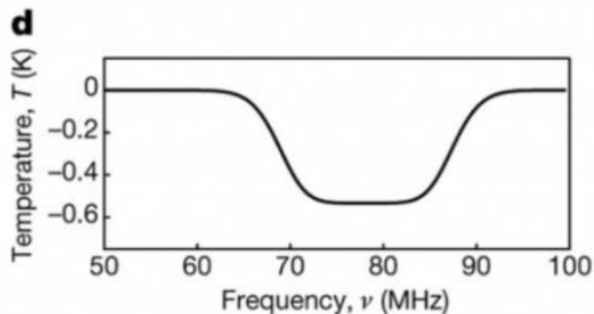
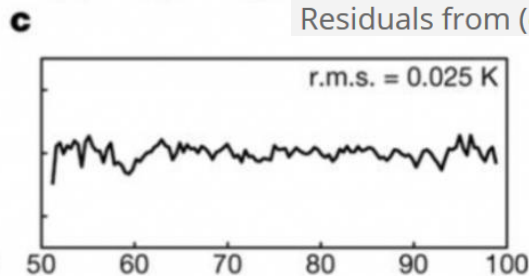
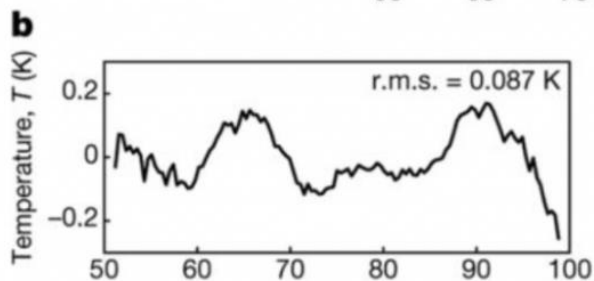
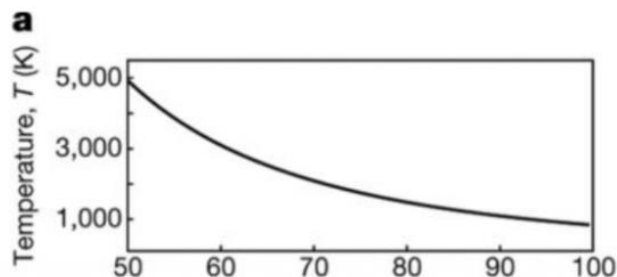
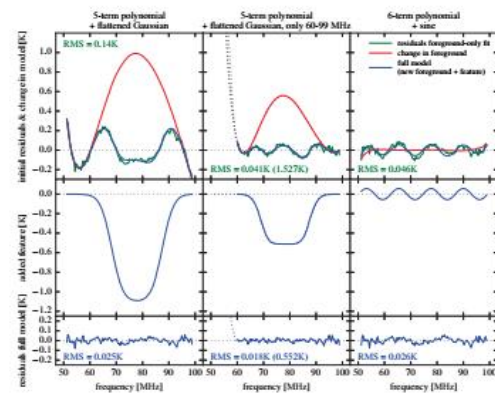


Figure 3: (a) The EDGES sky measurement in units of brightness temperature, showing the strong power-law spectrum due to galactic synchrotron emission. (b) Residuals after removing the power-law dependence. (c) Residuals after removing the power-law synchrotron emissions in addition to a model (d) of the 21 cm absorption signal. (e) Residuals from (c) added to model in (d).

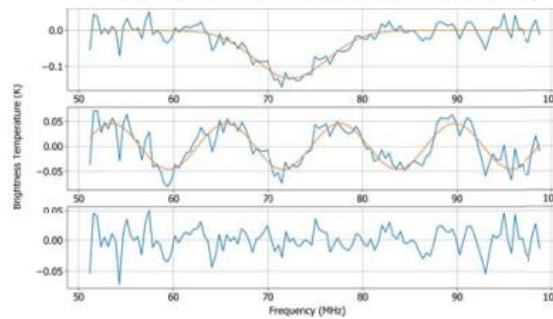
Single-dish experiment: ambiguous

- EDGES analysis is ambiguous – Hills+2018; Singh & Subrahmanyan 2019
- SARAS is NOT free from ambiguity

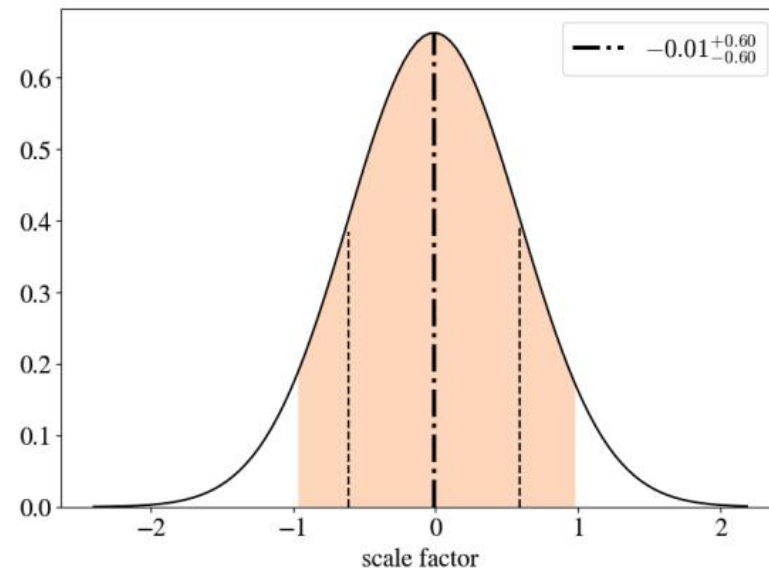
Hills, Kulkarni et al.



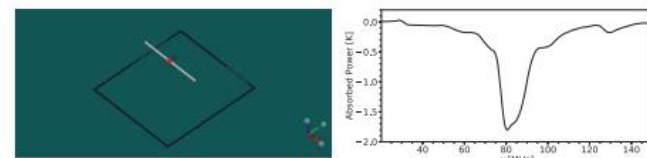
Singh & Subrahmanyan (2019)



Singh+ 2021;
SARAS 3 search for EDGES-like signal

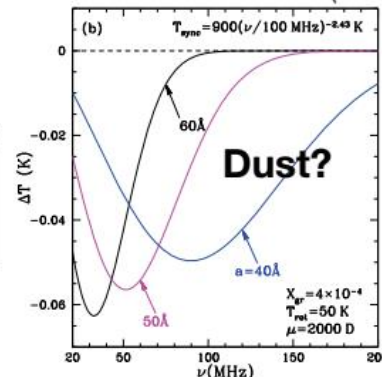


**Complexity in foreground?
Instrument?**



Bradley, Tauscher et al.

Draine & Miralda-Escudé (2018)

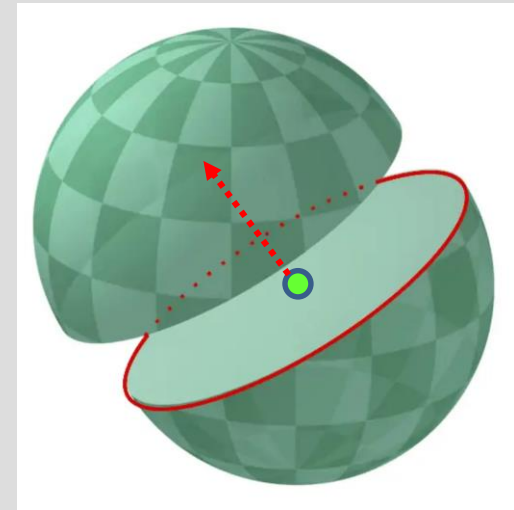
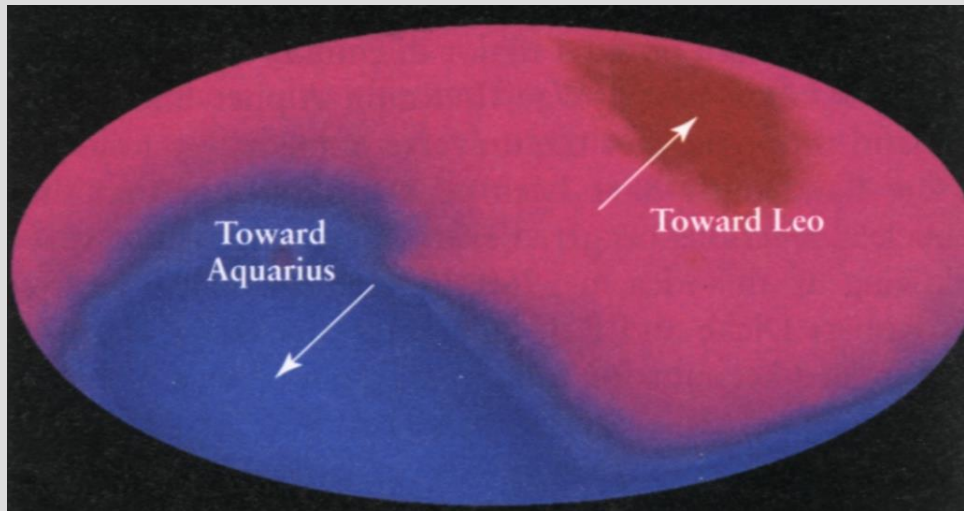


(slide excerpted from Jordan Mirocha's talk)

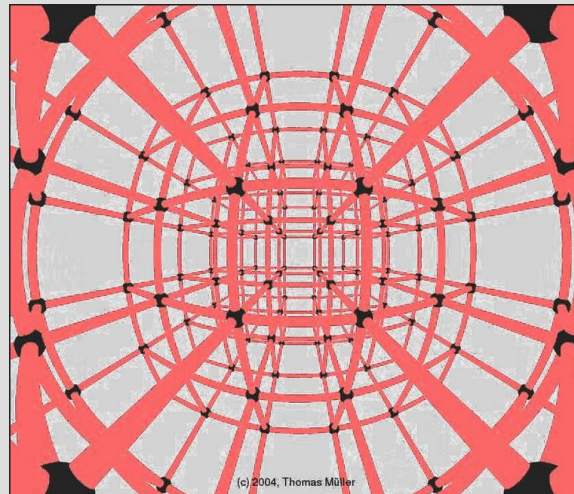
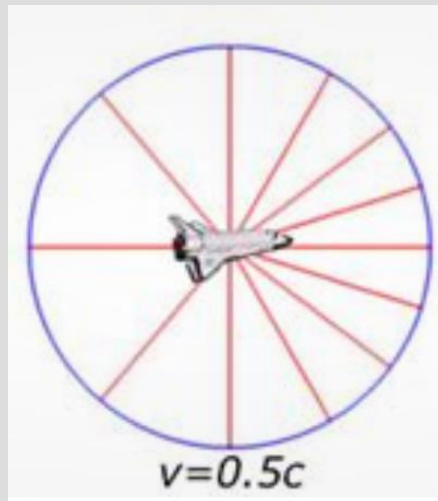
21B anisotropy for monopole:
independent measure, different systematics

Induced dipole, quadrupole, ...

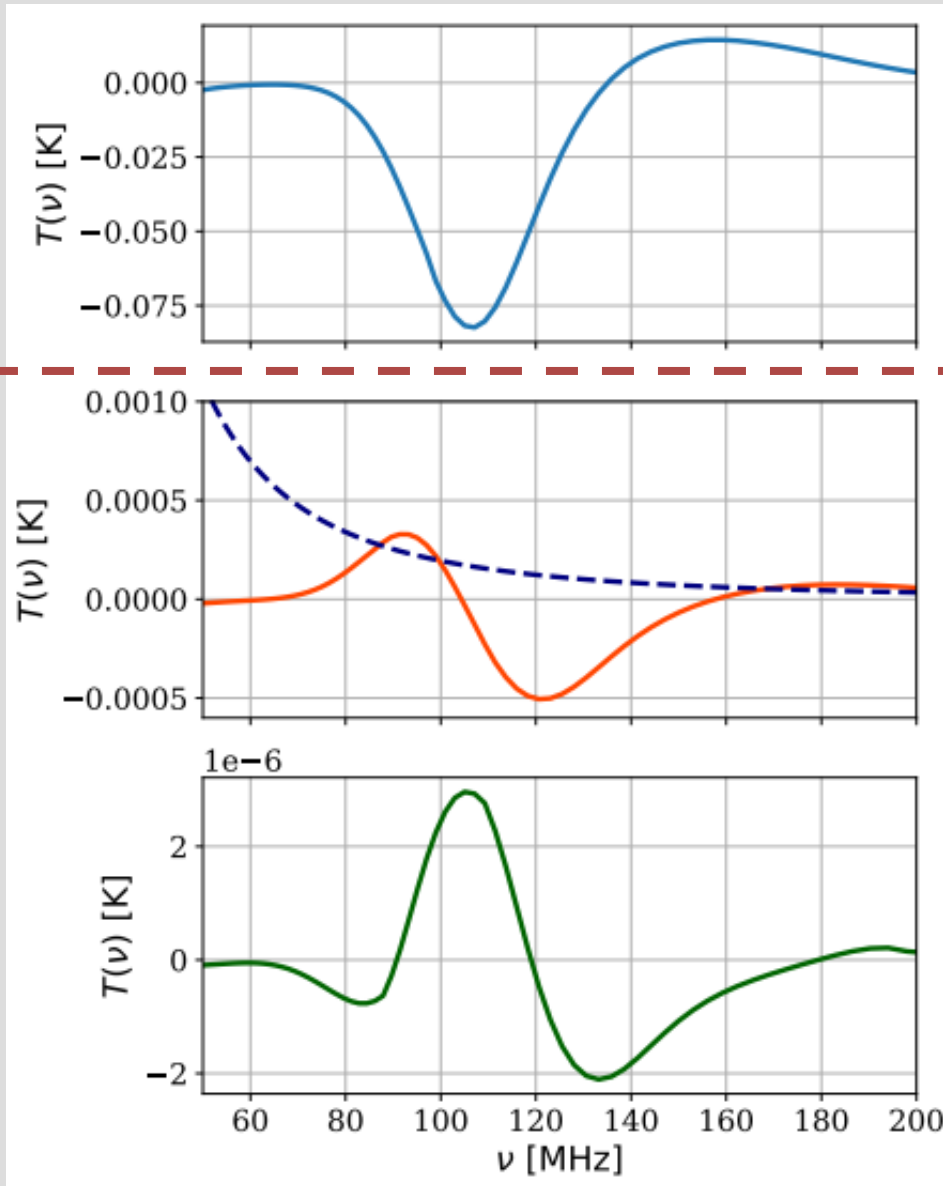
Doppler effect



aberration



Dipole+Quadrupole spectrum (Hotinli & KA 2024, ApJ 964, 21)



--- monopole (M)

anisotropic measure

--- dipole ($\sim T(\nu) - dT(\nu)/d\ln\nu$)

- Slosar 2017; Deshpande 2018
- feasibility study by Ignatov+2023
- due to Doppler
- Y_{10}

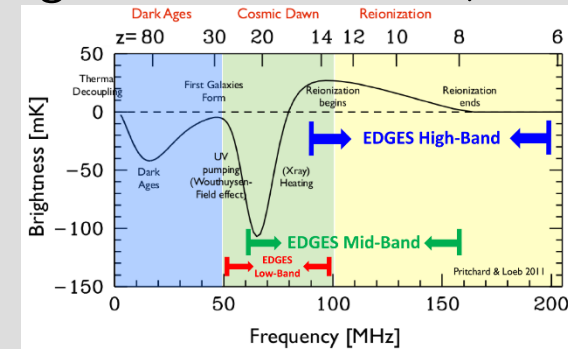
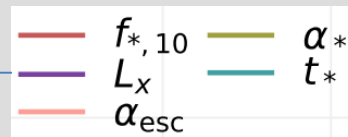
--- quadrupole ($\sim d^2T(\nu)/d\nu^2$)

- due to aberration + Doppler
- Y_{20}

The purple dashed line on the middle left panel corresponds to $T_{\text{noise}}(\nu_0) = 0.44$ mK measurement noise at $\nu_0 = 76$ MHz, representative of the EDGES survey.

Error estimation (Fisher analysis)

- with foreground (MW synch. + free-free + exgal + ...)
 - on EoR-relevant astrophysical parameters (e.g. for 21CMFAST)



- on foreground

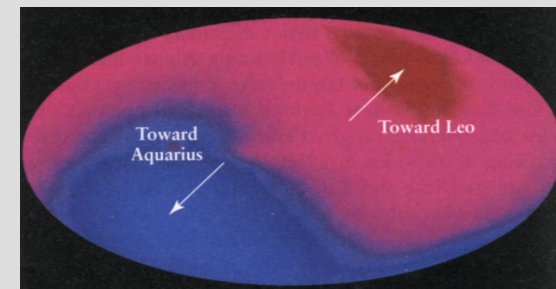
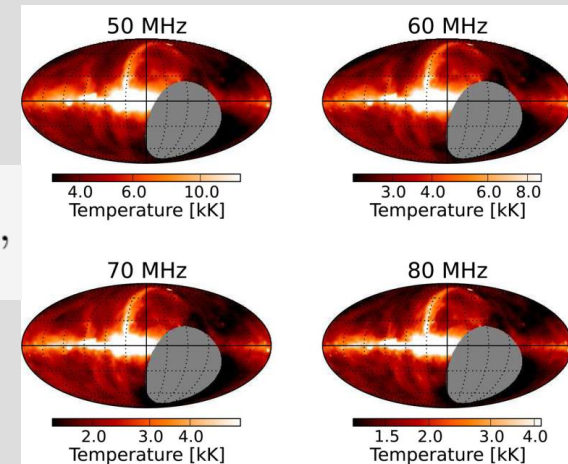
$$T^{(\text{FG})}(\nu, \hat{n}) = \sum_{\ell, m} a_{\ell m}^{(\text{FG})}(\nu) Y_{\ell}^m(\hat{n})$$

$$a'_{\ell m}(\nu') = \sum_{l'} \int \frac{d\hat{n}}{\gamma(1 + \beta\mu)} a_{\ell' m}(\nu) Y_{\ell' m}(\hat{n}) Y_{\ell m}^*(\hat{n}') = \sum_{l'} \mathcal{K}_{\ell}^{\ell'} a_{\ell' m}(\nu'),$$

- on solar velocities (against MW & CMB)

$$V_{\odot, \text{MW}}$$

$$V_{\odot, \text{CMB}}$$



21B anisotropy for monopole: 21cm ISW

(KA & Oh, PRD 109, 043539)

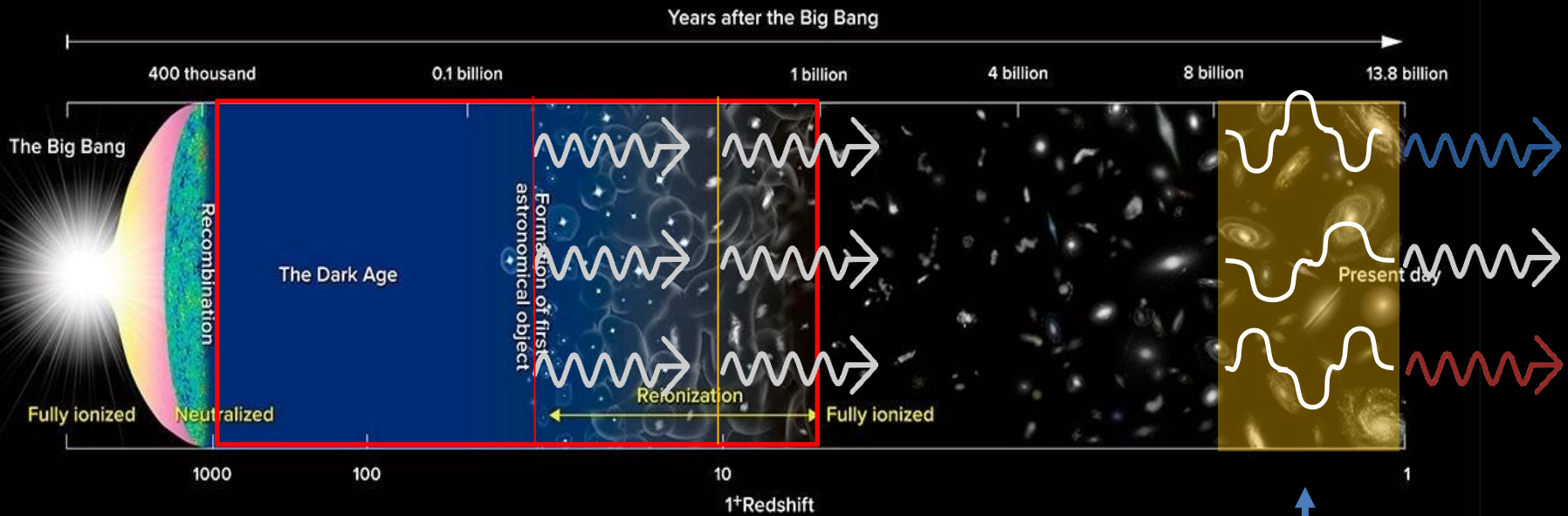
Integrated Sachs-Wolfe effect (ISW; Sachs & Wolfe 1967)

$$\delta T = -2\langle T \rangle \int \dot{\Phi} d\tau$$

Flat, matter-dominated universe: $\dot{\Phi} = 0$ ($\Phi \sim \frac{M}{R} \sim \frac{a}{a} = \text{const.}$) @ large scales

otherwise (LCDM; open universe; rad dominance): $\dot{\Phi} \neq 0$ ($M \propto a$) @ large scales

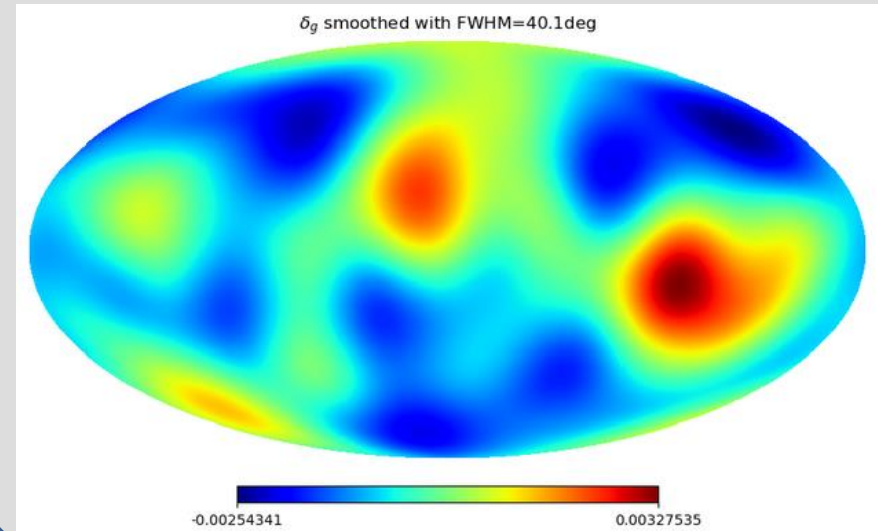
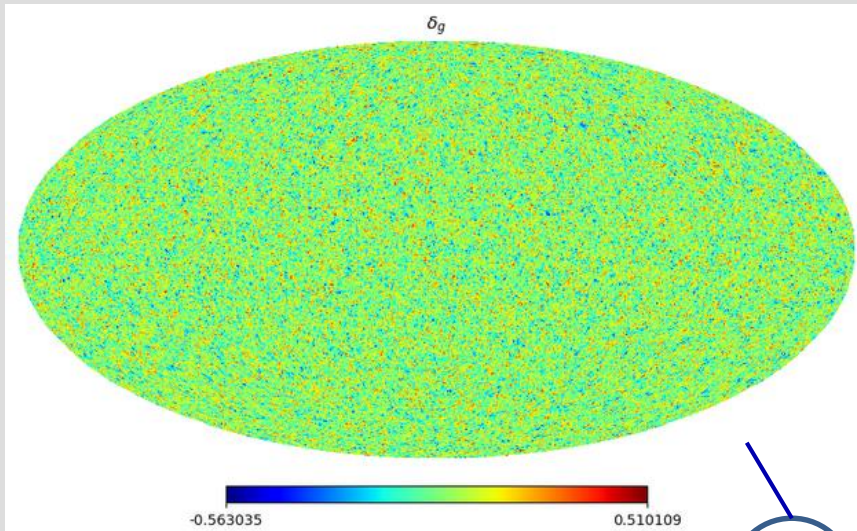
(late-time) ISW zone of influence: $z < \sim 2$



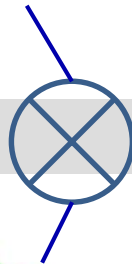
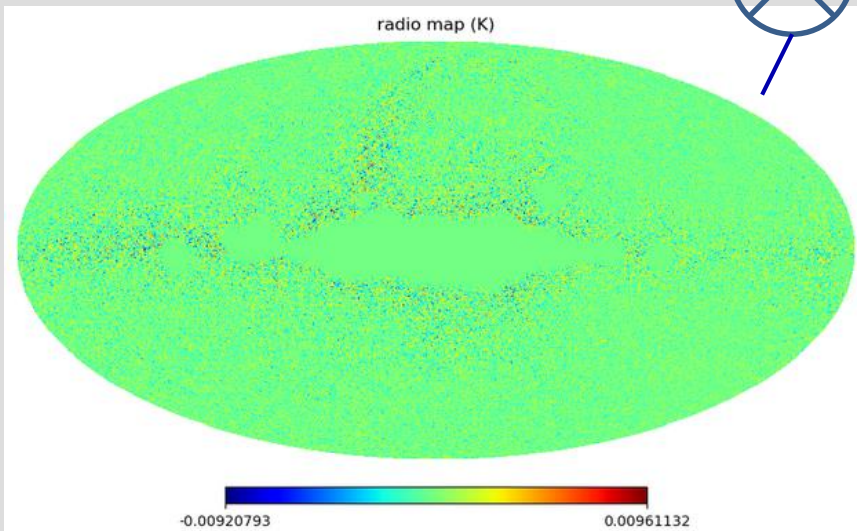
traced by galaxies

21B ISW map in cross-correlation map

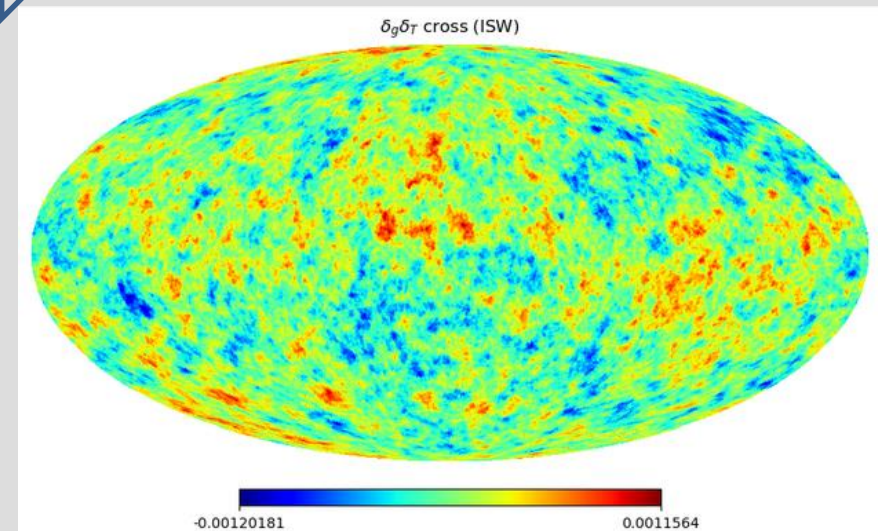
galaxy map



temperature map



galaxy-temperature cross map

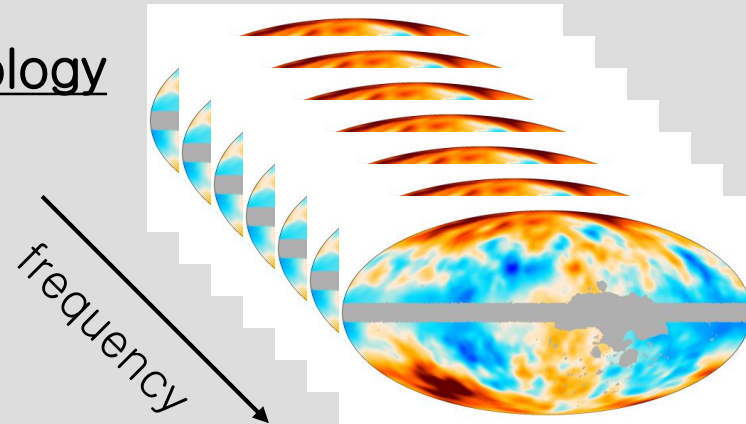


galaxy - δT correlation: 21B ISW measurement

[Raccanelli+2016]: 21B ISW first suggested

- target: redundancy for cosmology

- $C_{\ell}^{gT_{21}}(\nu)$

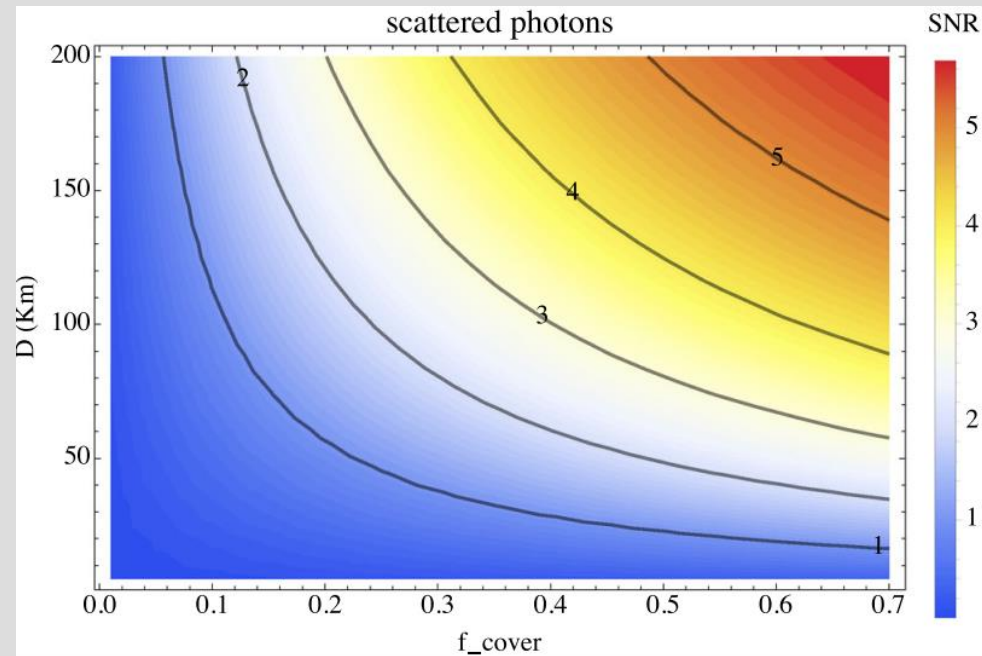


- estimated sensitivity: **impractical!**

$$\sigma_{C_{\ell}^{gT}} = \sqrt{\frac{(C_{\ell}^{gT})^2 + [(C_{\ell}^{gg} + \bar{n}_g^{-1})(C_{\ell}^{TT} + \epsilon)]}{(2\ell + 1)f_{\text{sky}}}}$$

$$\epsilon_{\ell,T} = \frac{2\pi\lambda^2(\bar{\nu}) \left\{ 180 (\bar{\nu}/180 \text{ MHz})^{-2.6} \text{ K} \right\}^2}{f_{\text{cov}}^2 D^2 \Delta t \Delta \nu}$$

- us: “Not so fast!”



galaxy - δT correlation: 21B ISW measurement

Low frequency:

$$C_{\ell}^{gT}(\nu) = -2T_{21}(\nu) \int \dot{\Phi} d\tau$$

$$T_{21}(\nu) = \langle T_b(\nu) \rangle - \frac{\partial \langle T_b(\nu) \rangle}{\partial \ln \nu}$$

CMB:

$$C_{\ell}^{gT_{\gamma}} = -2T_{\gamma} \int \dot{\Phi} d\tau$$

then,

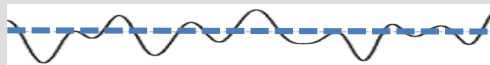
$$\frac{C_{\ell}^{gT}(\nu)}{C_{\ell}^{gT_{\gamma}}} = \frac{T_{21}(\nu)}{T_{\gamma}}$$

galaxy - δT correlation: 21B ISW measurement

frequency dependence:

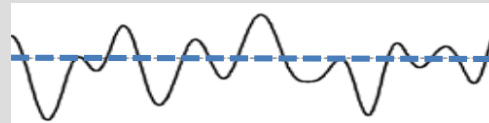
$$C_{\ell}^{gT_{21}}(\nu) \propto T_{21}(\nu) = \underbrace{\langle T_b(\nu) \rangle}_{\text{average 21B @ } \nu} - \frac{\partial \langle T_b(\nu) \rangle}{\partial \ln \nu}$$

@ 100 MHz



T

@ 80 MHz

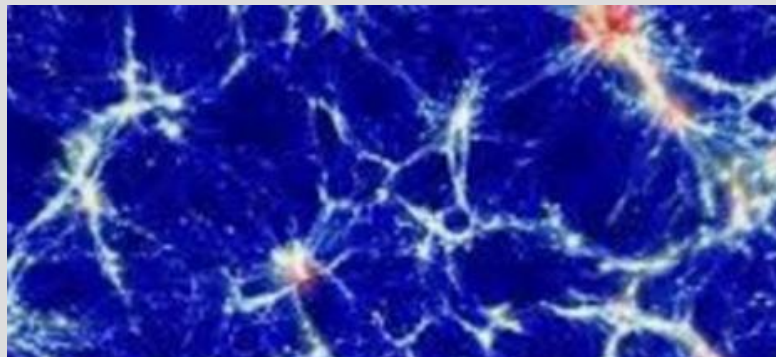


RA

RA

same clusters+voids, but different $\langle T_b(\nu) \rangle$'s at different ν 's

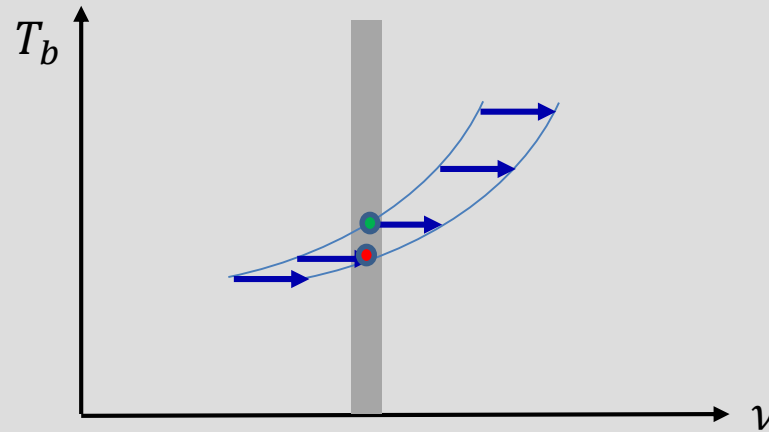
→ same fluctuation pattern on sky, but different contrast



galaxy - δT correlation: 21B ISW measurement

frequency dependence:

$$C_{\ell}^{gT_{21}}(\nu) \propto T_{21}(\nu) = \langle T_b(\nu) \rangle - \frac{\partial \langle T_b(\nu) \rangle}{\partial \ln \nu}$$



blueshifted by overdensity

→ observing frequency band probes shorter-wavelength $\langle T_b(\nu) \rangle$

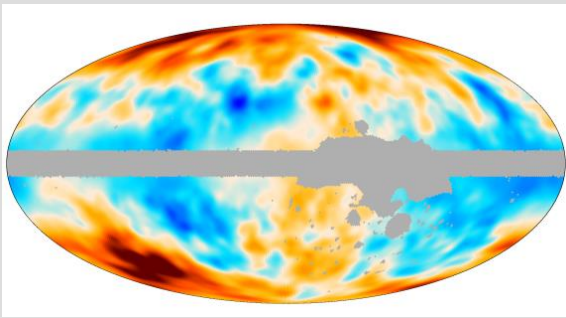
** $\max(T_{21}(\nu))$ gets boosted from $\max(\langle T_b(\nu) \rangle)$ by $\otimes \sim 2 - 5$

galaxy - δT correlation: 21B ISW measurement

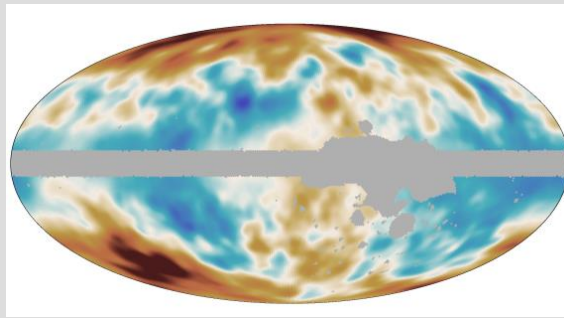
frequency dependence:

$$C_{\ell}^{gT_{21}}(\nu) \propto T_{21}(\nu) = \langle T_b(\nu) \rangle - \frac{\partial \langle T_b(\nu) \rangle}{\partial \ln \nu}$$

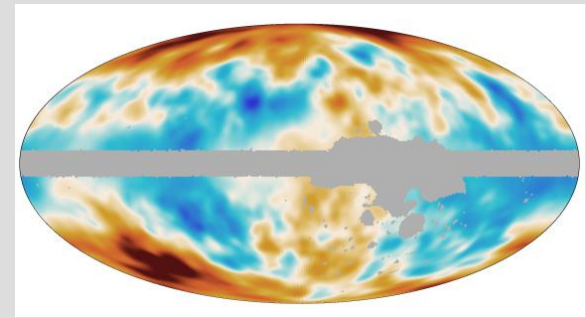
$\nu =$ 80 MHz



100 MHz

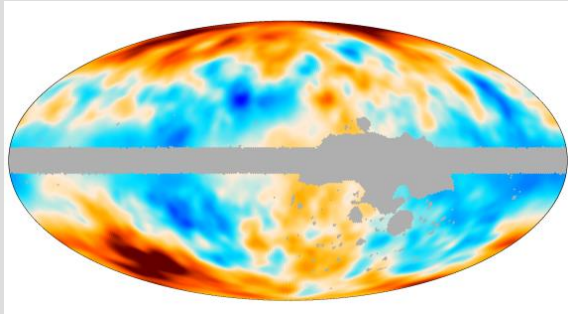


120 MHz

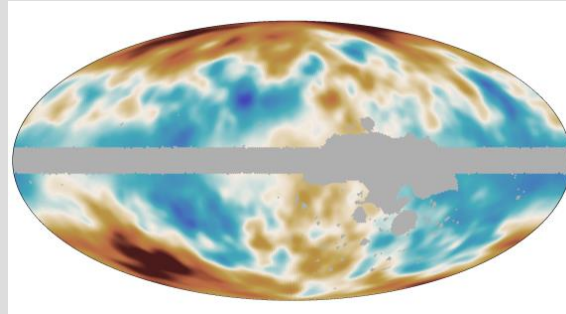


galaxy - δT correlation: (21B ISW) / (CMB ISW)

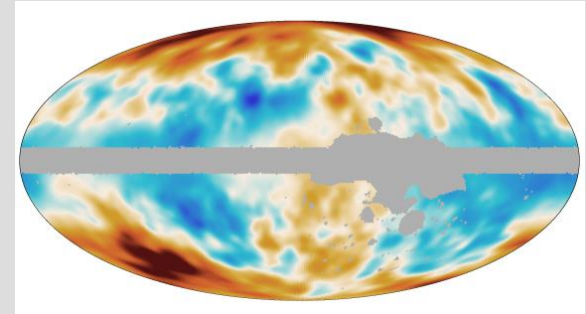
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma \cdots$ blind to ℓ



$\nu =$ 80 MHz

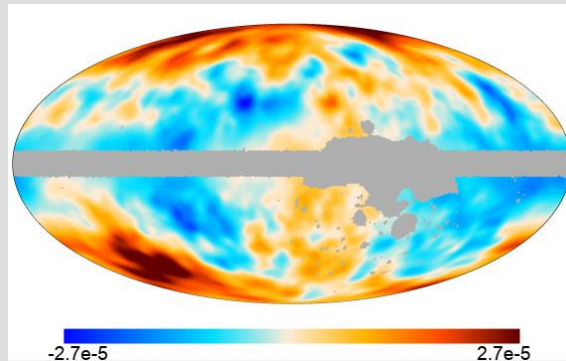


100 MHz



120 MHz

$\div$



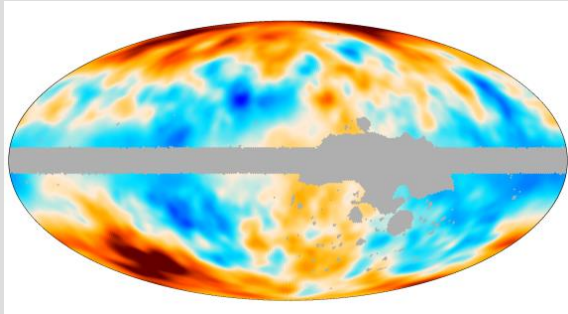
CMB

$\times 2.7\text{K} - 2.7\text{K}$

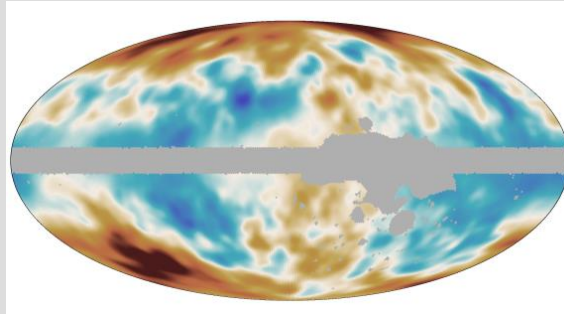
$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: (21B ISW) / (CMB ISW)

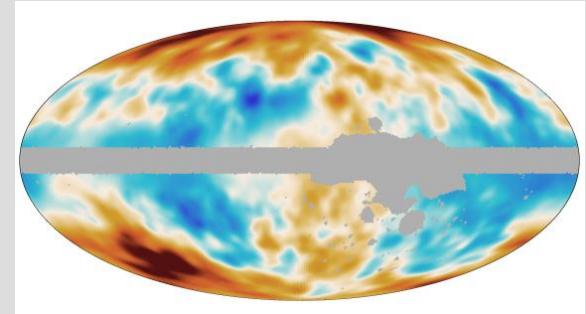
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



$\nu =$ 80 MHz

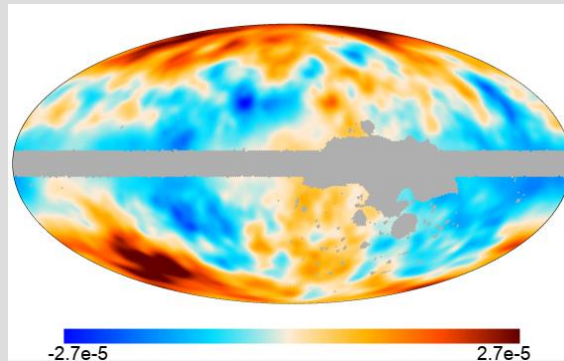


100 MHz



120 MHz

$\div$



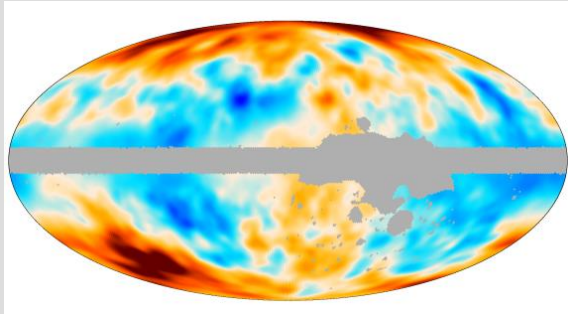
CMB

$\times 2.7K - 2.7K$

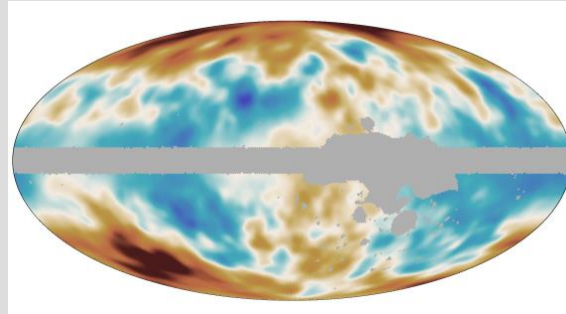
$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: (21B ISW) / (CMB ISW)

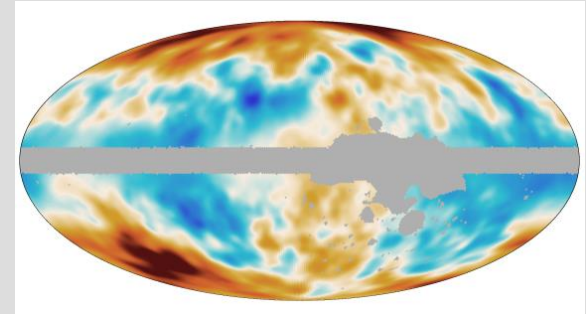
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



$\nu =$ 80 MHz

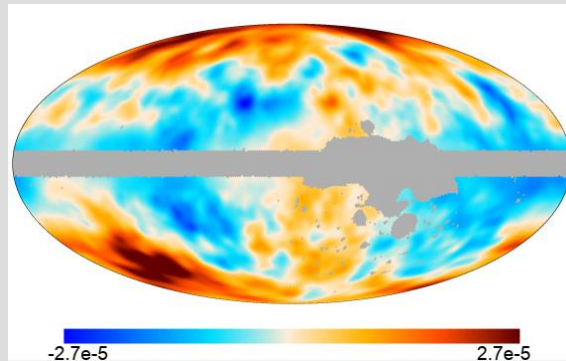


100 MHz



120 MHz

$\div$



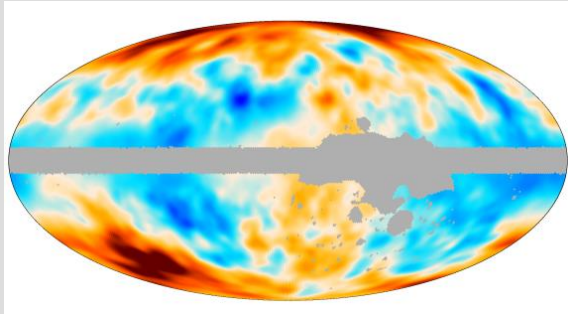
CMB

$\times 2.7K - 2.7K$

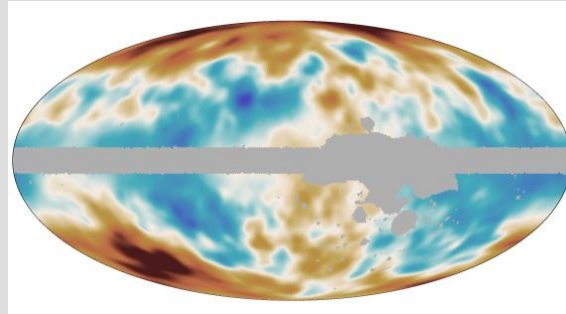
$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: (21B ISW) / (CMB ISW)

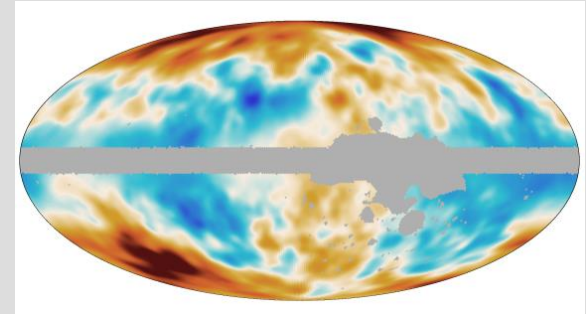
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



$\nu =$ 80 MHz

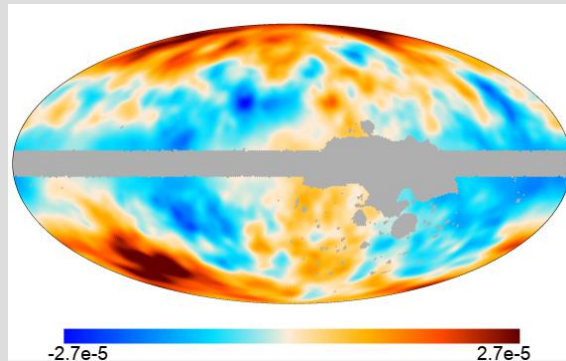


100 MHz



120 MHz

$\div$



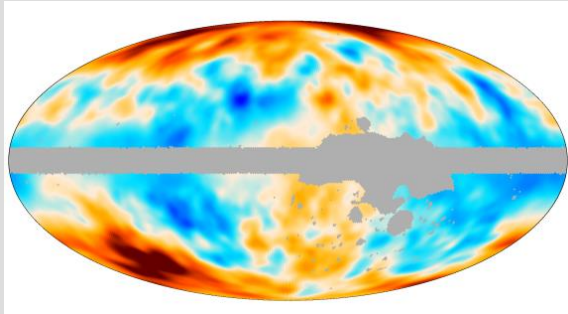
CMB

$\times 2.7K - 2.7K$

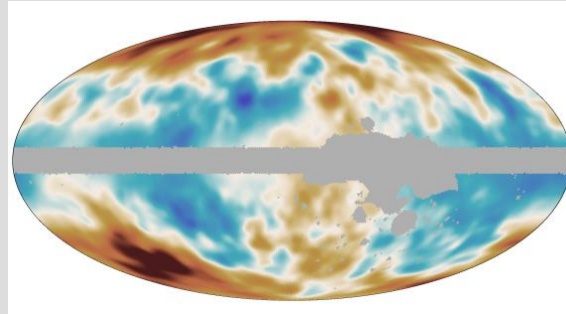
$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: (21B ISW) / (CMB ISW)

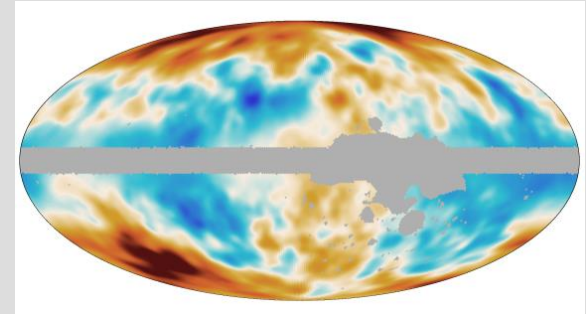
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



$\nu =$ 80 MHz

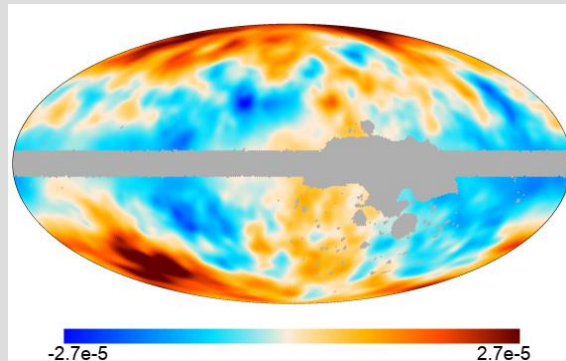


100 MHz



120 MHz

$\div$



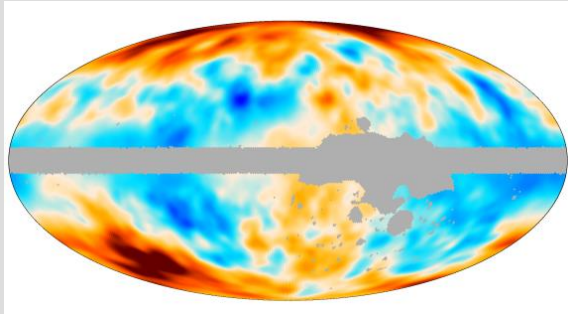
CMB

$\times 2.7K - 2.7K$

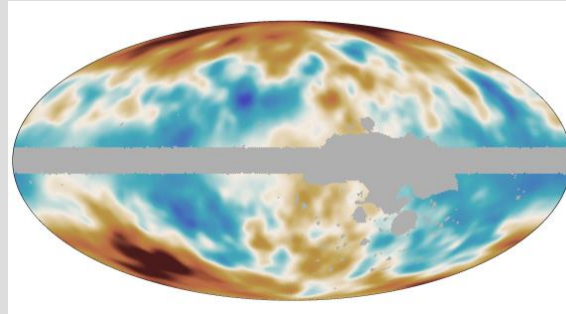
$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: (21B ISW) / (CMB ISW)

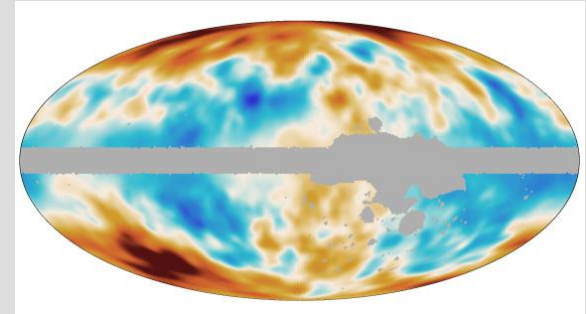
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



$\nu =$ 80 MHz

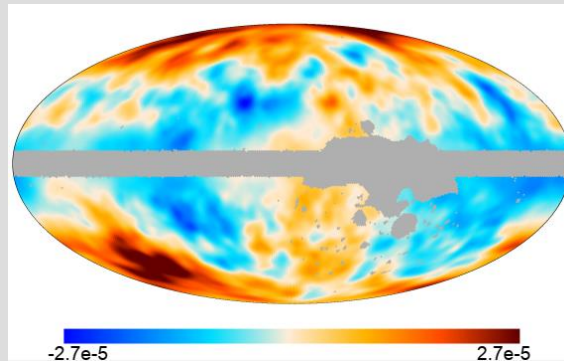


100 MHz



120 MHz

$\div$



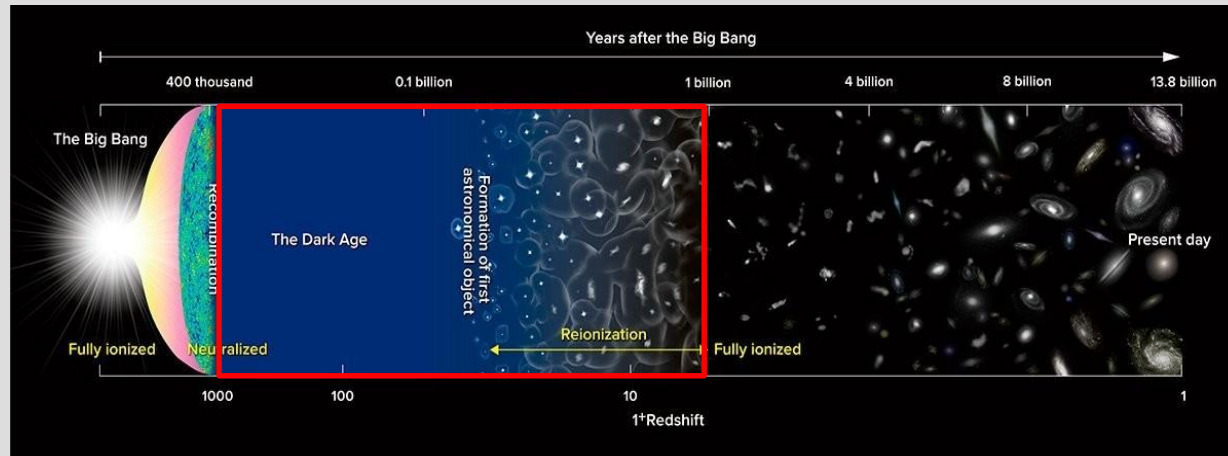
CMB

$\times 2.7K - 2.7K$

$$\left(\frac{S}{N} \right)^2 (\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0} \rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta T_{21}(\bar{\nu})}{\langle T_{\gamma,0} \rangle} \right)^2 C_\ell^{T_\gamma T_\gamma} \right\}}{(C_\ell^{gT_\gamma})^2 f_{\text{sky}} (2\ell + 1)} \right]^{-1}$$

galaxy - δT correlation: 21B ISW measurement

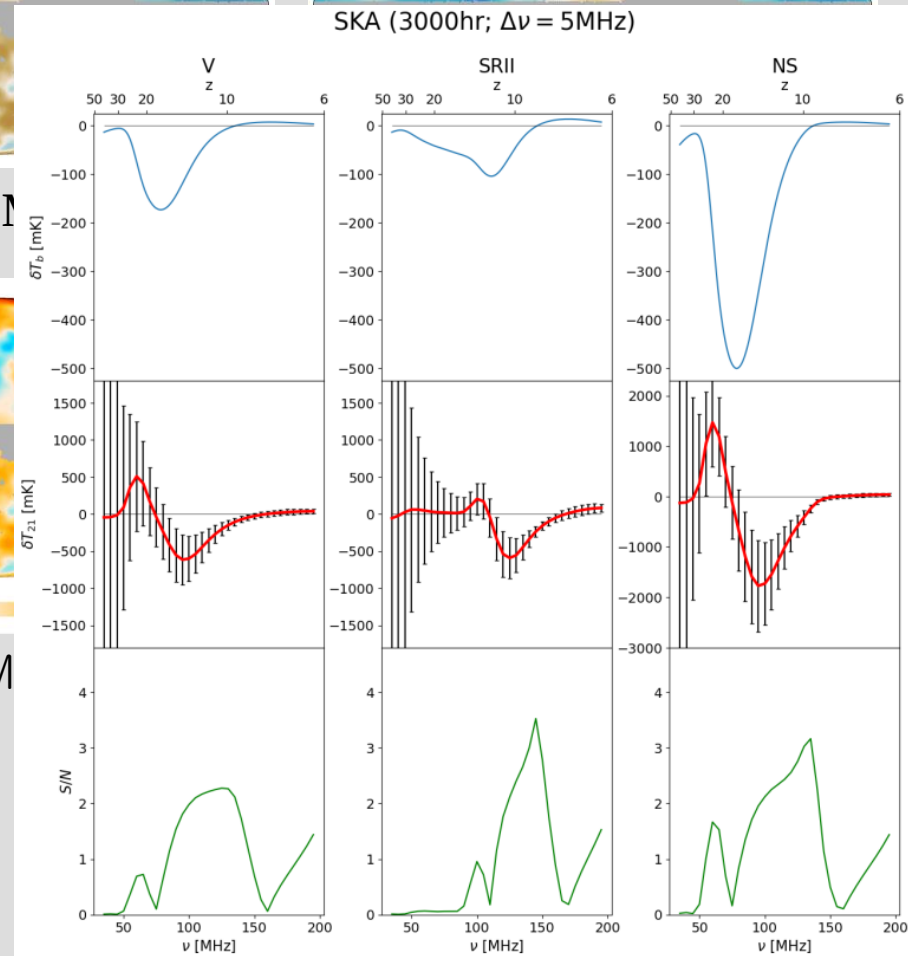
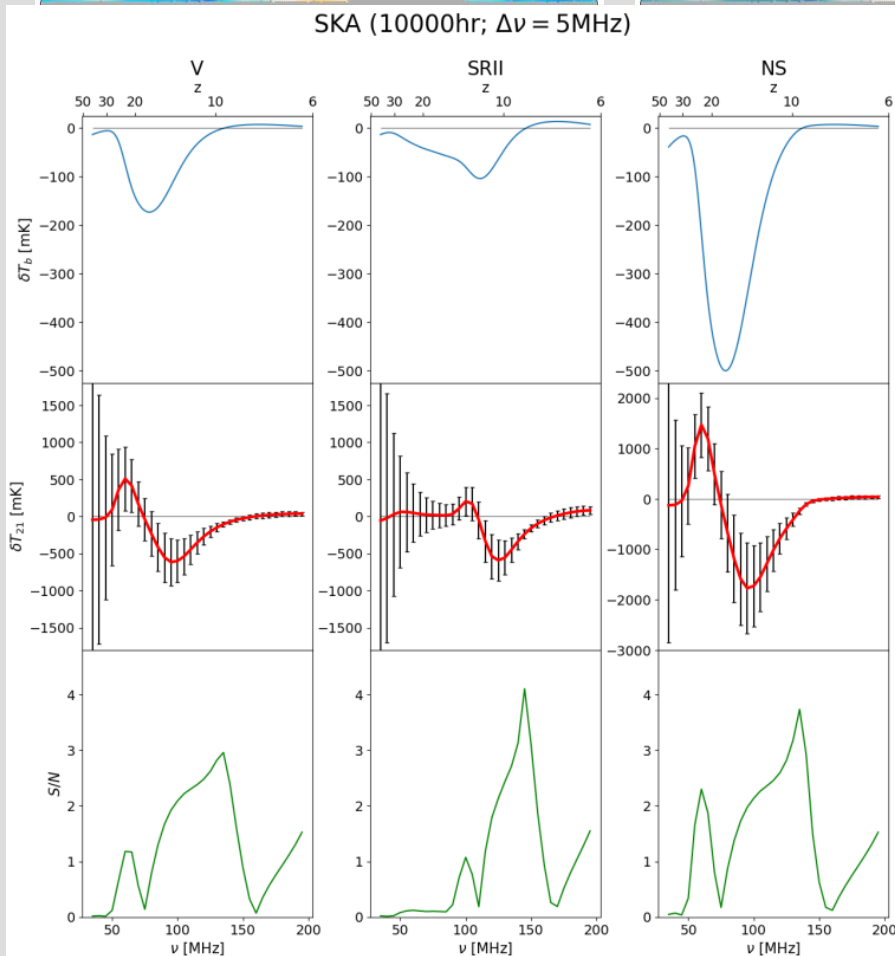
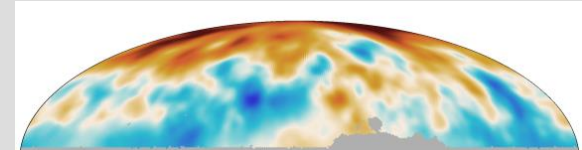
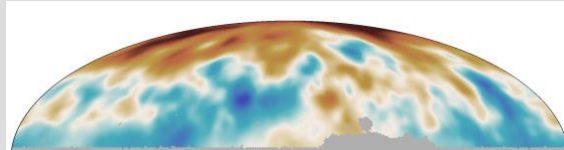
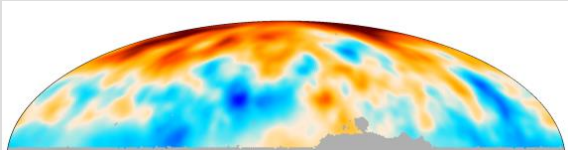
- Merit: Milky Way signal irrelevant $\leftarrow$ galaxy~MW uncorrelated
 - c.f. single-dish (EDGES, SARAS, ...) signal is ambiguous



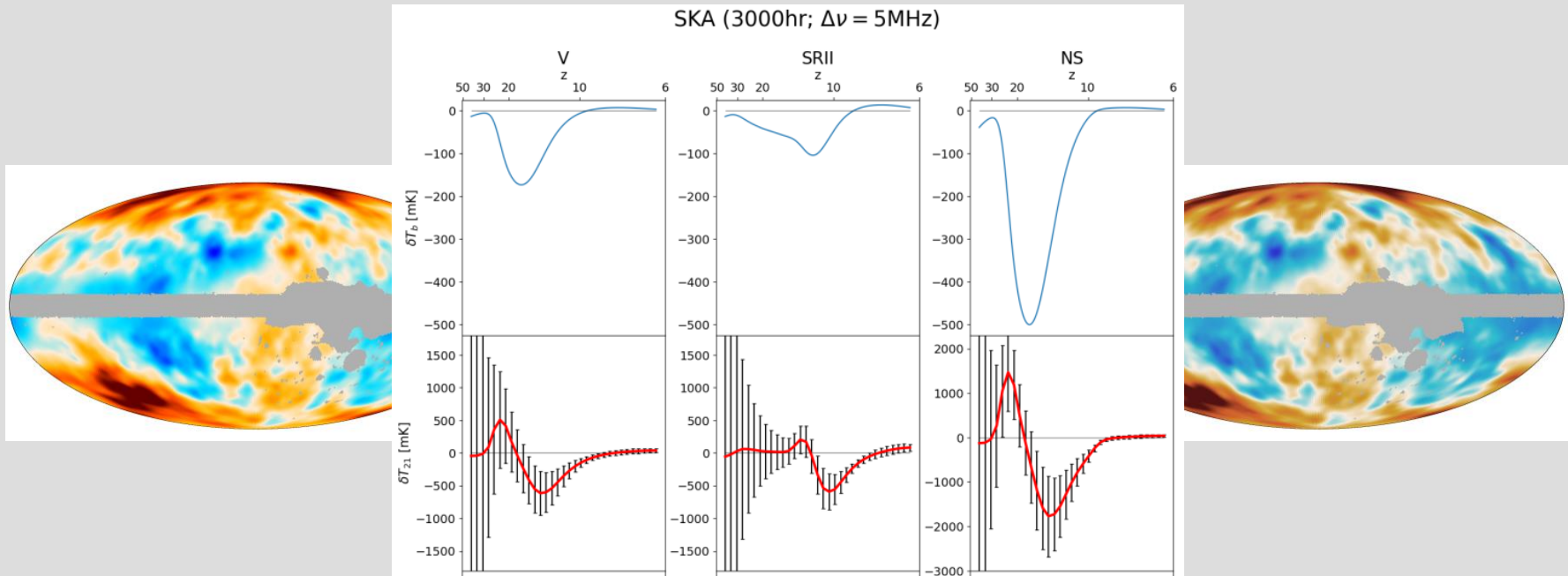
- Noise estimate basis
 - SKA1-Low ~ 500 stations, small UV ($2 \leq \ell < 20$) gets fair observation time, sky coverage $\sim 70\%$
 - Large # of survey galaxies: SPHEREX-like $\frac{dN}{d\Omega} \geq \left(\frac{b}{2}\right)^{-2} 2 \times 10^7 \text{ sr}^{-1}$
- High- z ($z > \sim 2$) exgal background still to affect 21B ISW
 - for future study

galaxy - δT correlation: 21B ISW measurement

observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



galaxy - δT correlation: 21B ISW measurement

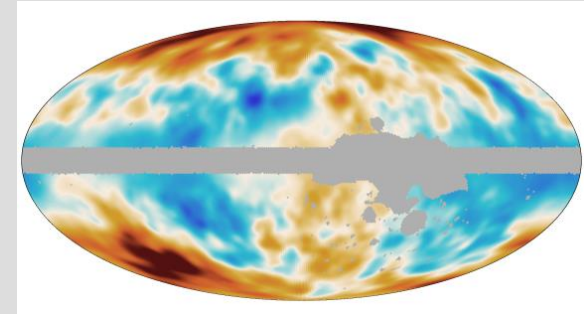
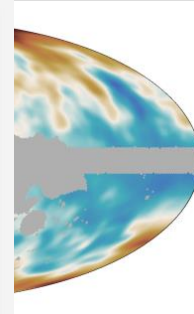
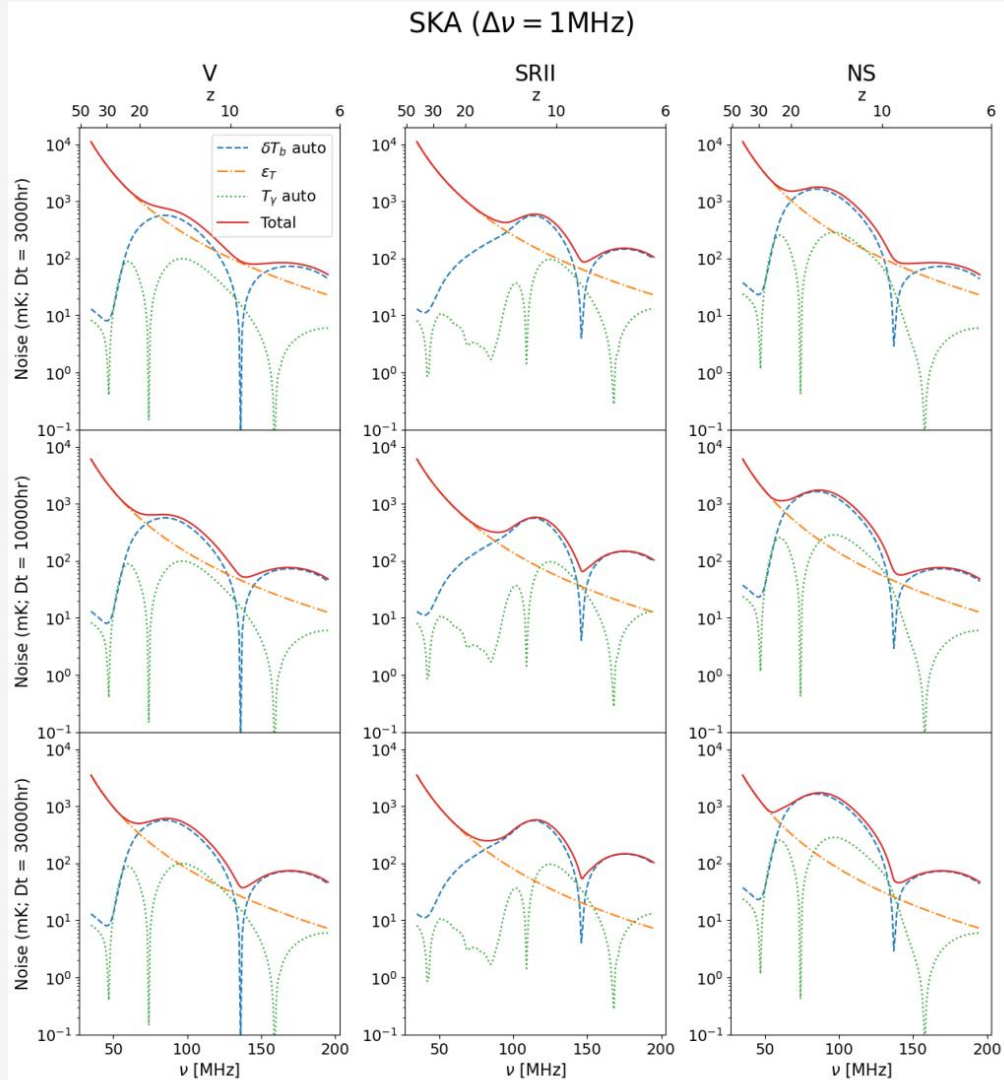


With SKA1-LOW,

- (1) $>\sim 2000$ hr measure of 21-cm ISW will be able to probe 21-cm monopole spectrum.
- (2) ~ 400 hr measure of 21-cm ISW may test (rule out) EDGES signal

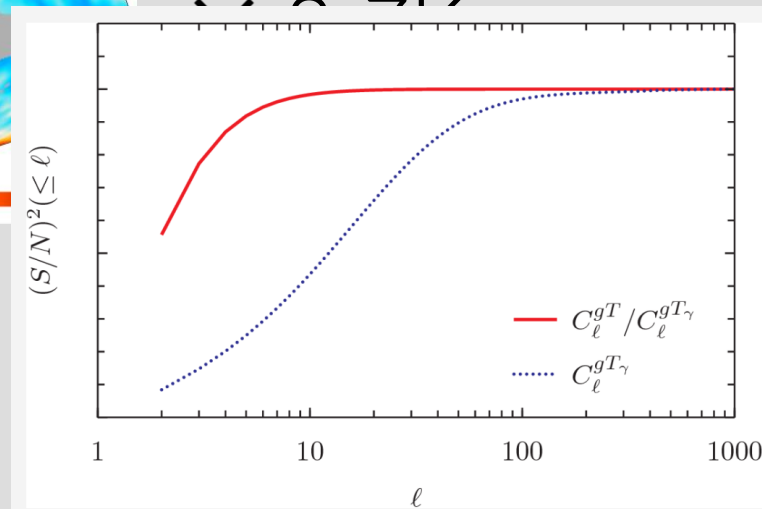
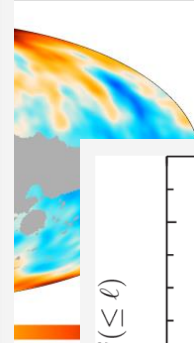
galaxy - δT correlation: 21B ISW measurement

observable: $\frac{C_\ell^{gT_{21}(\nu)}}{C_\ell^{gT_\gamma}} T_\gamma = T_{21}(\nu)$



120 MHz

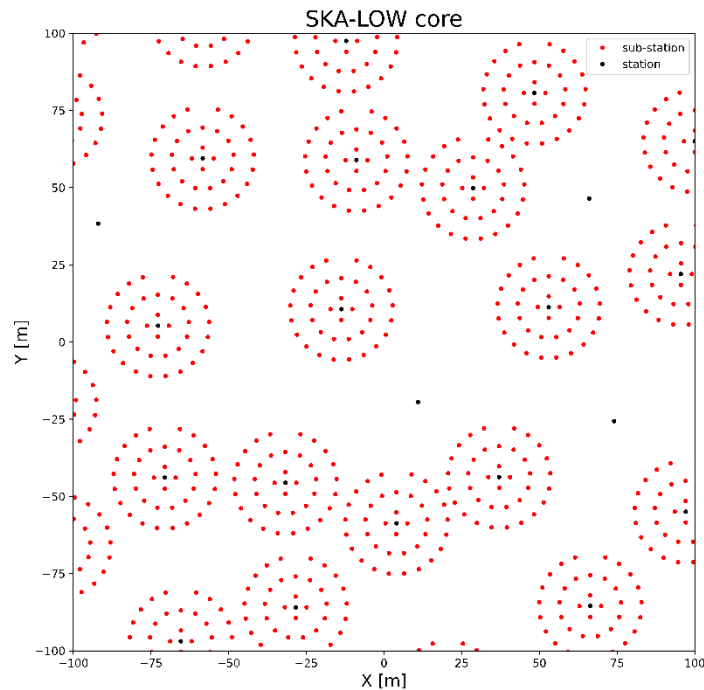
z



21B ISW with SKA

with

M. Oh (Chosun), D. Parkinson (KASI), C. Trott (Curtin), M. Hurley-Walker (Curtin),
B. Bahr-Kalus (Lyon), J. Asorey (Madrid)



Summary / Ad

- Using interferometers for global 21cm detection is beneficial
 - Can SKA1-LOW spare ~ 400 hrs for full-sky observation?
- multi-frequency 21cm ISW
 - “same pattern” with CMB ISW
 - modulated by 21cm monopole spectrum $\rightarrow$ varying “contrast” over frequency

	Dipole	ISW
pros	not too demanding	MW foreground removed
cons	foreground removal required	expensive: ISW signal is weak

- Postdoc / grad student opportunity
 - Talk to me
 - email to kjahn@chosun.ac.kr