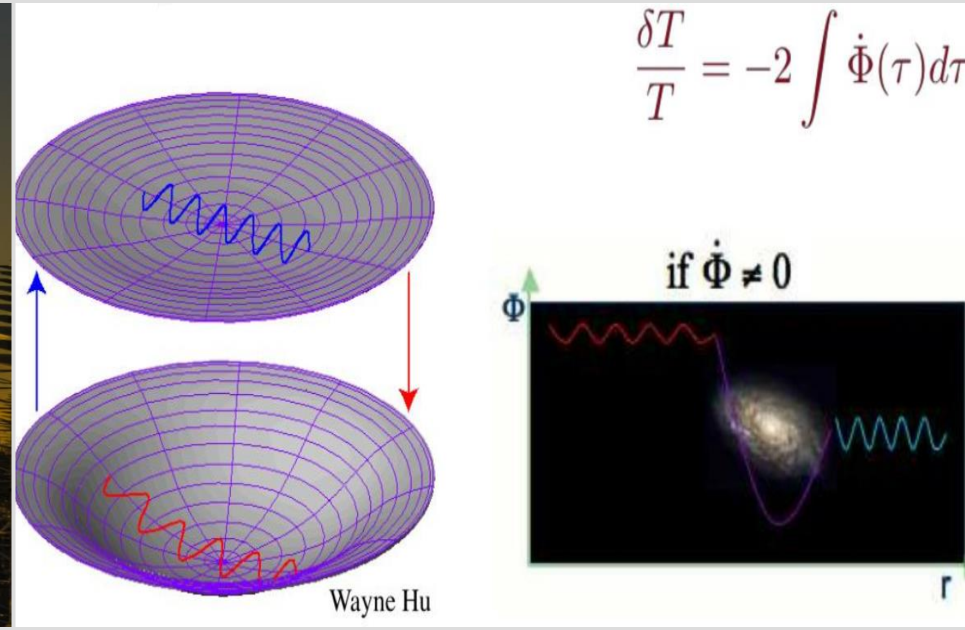
# 21-cm integrated Sachs-Wolfe effect as a probe of the global 21-cm background





Kyungjin Ahn (Chosun University)

with Minji Oh (Chosun)


Cosmic Dawn at High Latitudes, Stockholm

June 2024

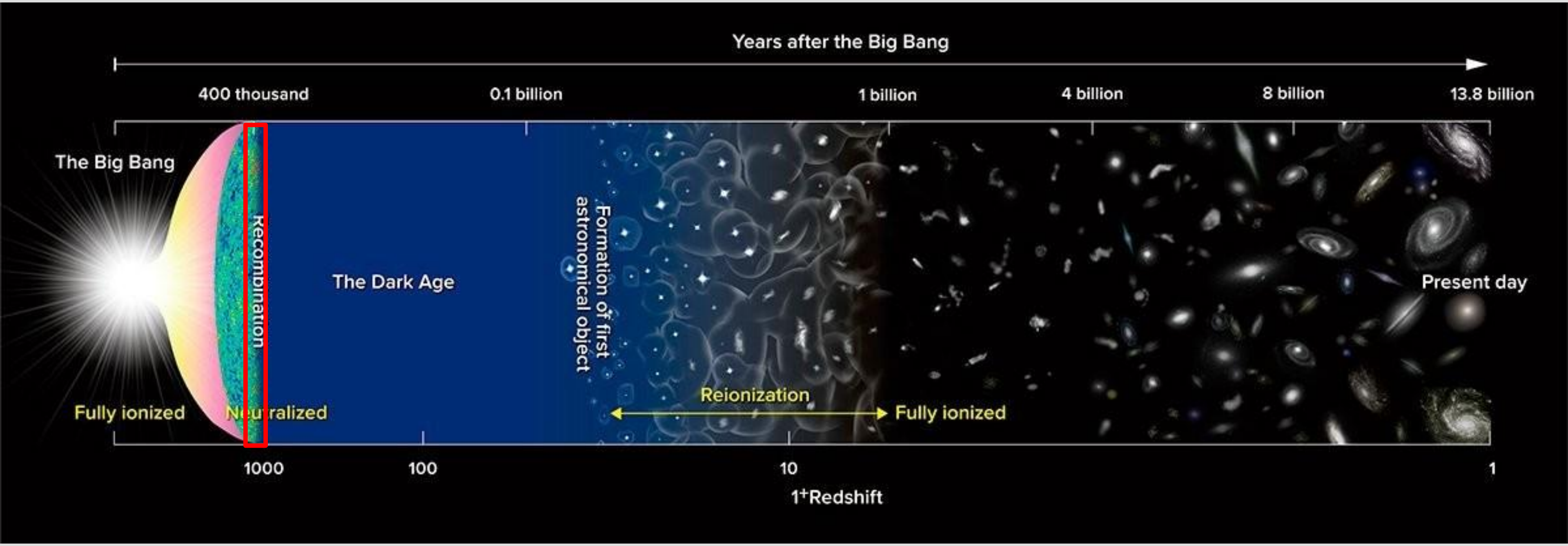
Usual collaboration: C2Ray, CoDa, Renaissance

P. Shapiro, I. Iliev, P. Ocvirk, H. Park, J. Lewis, J. Sorce, M. Bianco, J. Lee, G. Mellema, S. Majumdar, H. Xu, M. Norman, J. Wise

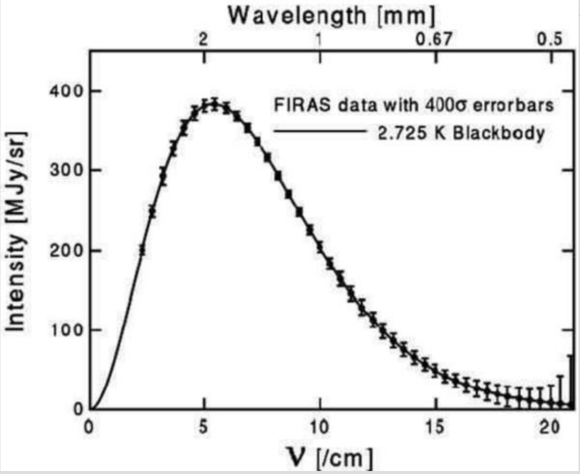
# CMB vs 21B (21-cm background)

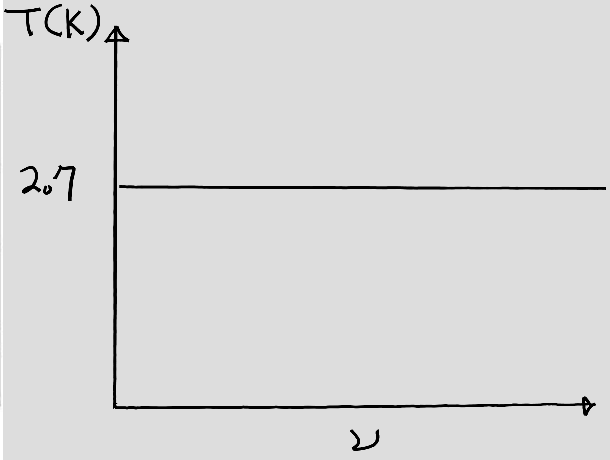
# CMB: from when?

From z =~ 1100, recombination epoch




Monopole=
Blackbody
continuum,
const. brightness
temperature

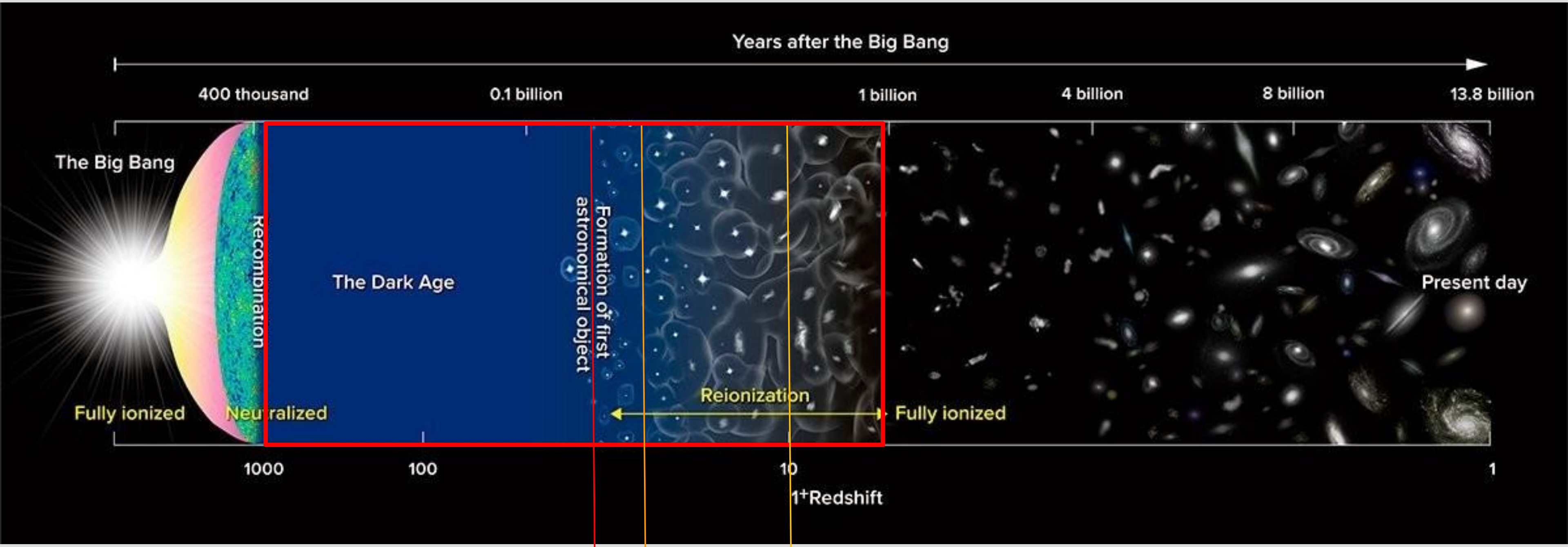


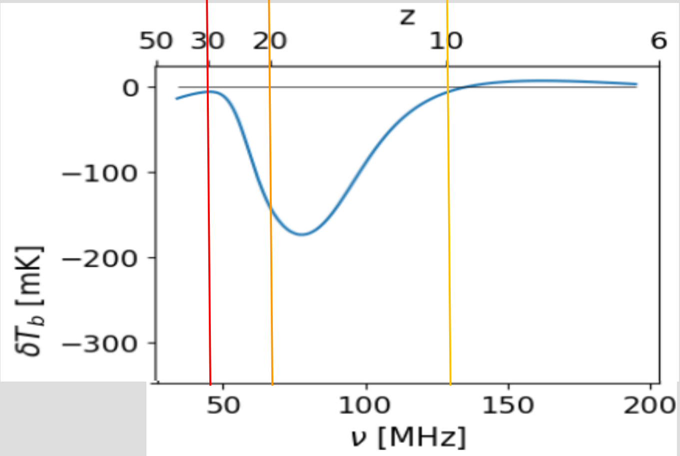
# 21B: from when?

From z =~ 1100 to 6, dark ages + epoch of reionization

post-reionization (z<6): only from galaxies (IGM ionized)




21cm monopole: lines redshifted → "brightness temperature spectrum"

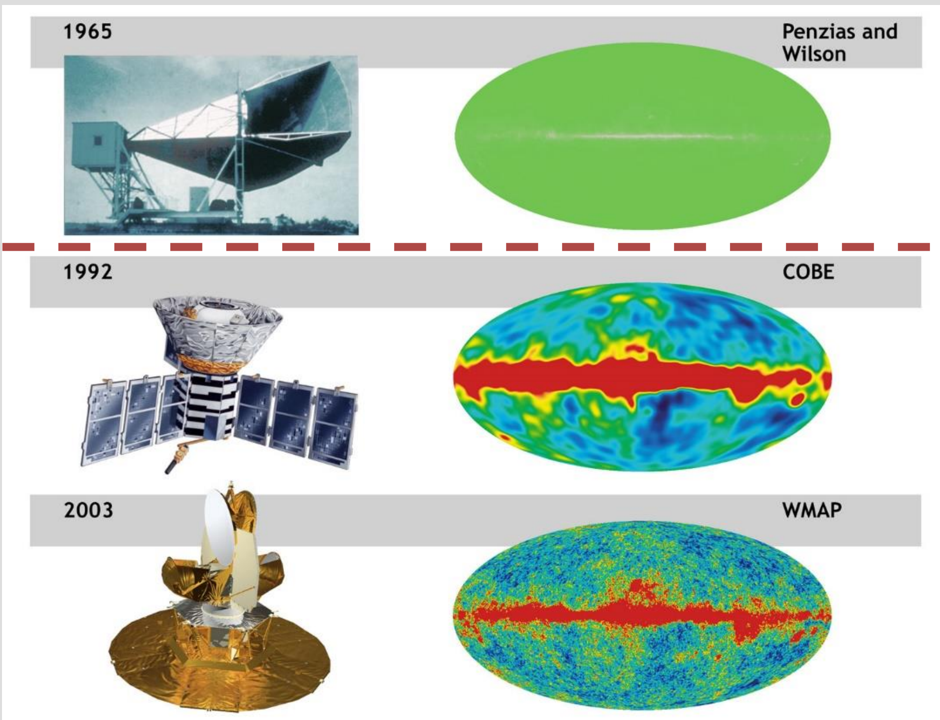



$\delta T_b(\nu) = T_b(\nu) - 2.7K$

$\nu = 1.4/(1+z)$ GHz

# 21B: isotropy to anisotropy

isotropy (monopole)

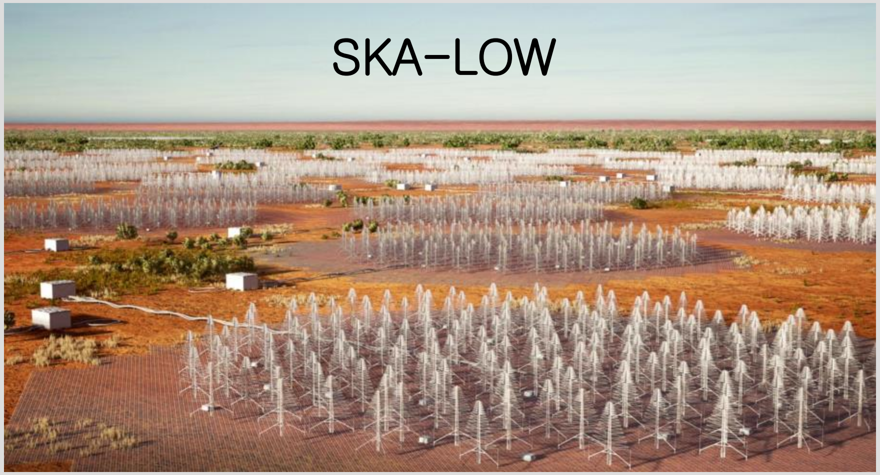



anisotropy (multipole): large H II bubbles

EDGES

SARAS

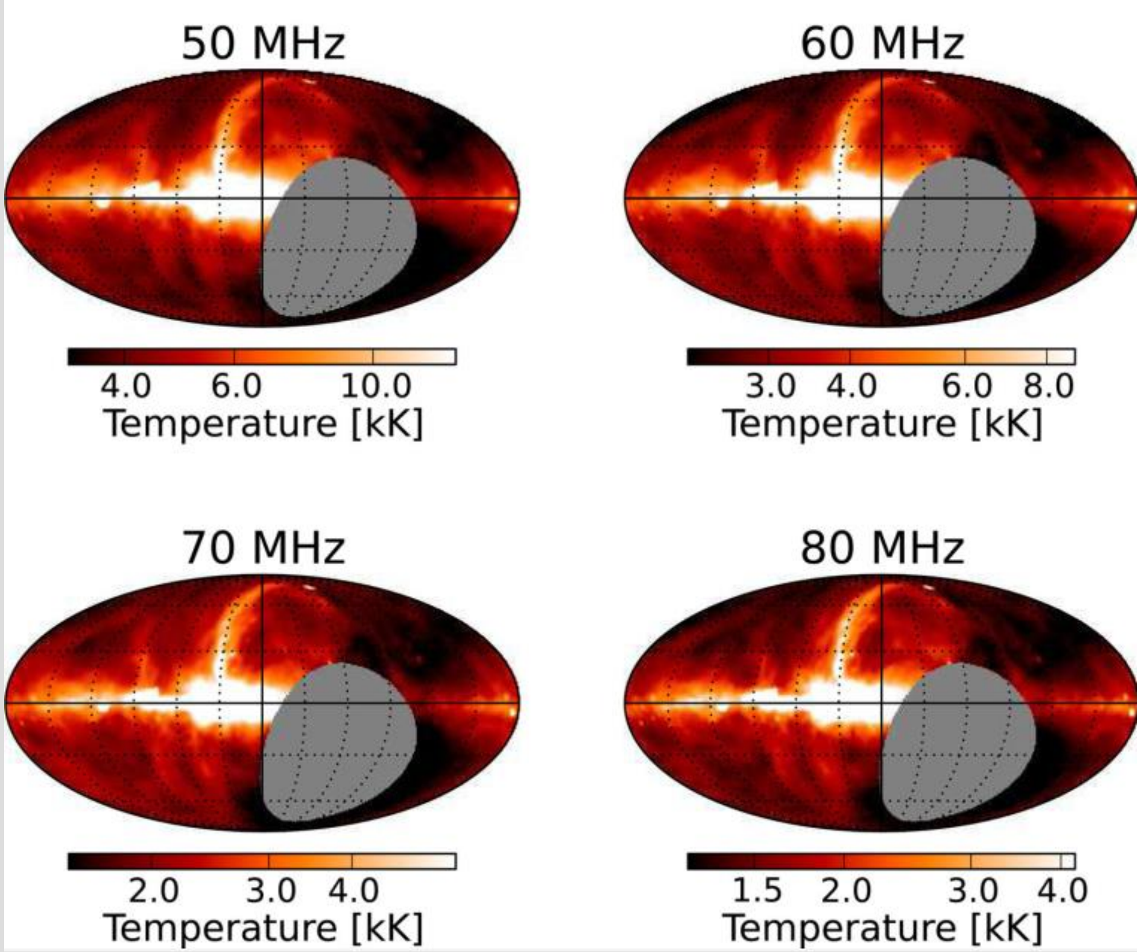
LUsee-Night



Why has 21B measurement been delayed by the human?

# Answer: mostly Milky Way

- 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)

# Foreground removal needed

# 21B monopole conflict:

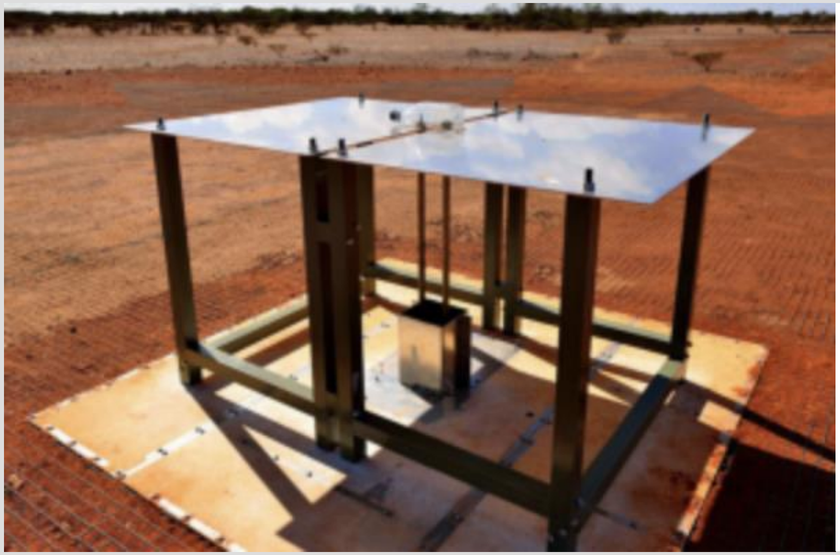
# EDGES vs SARAS

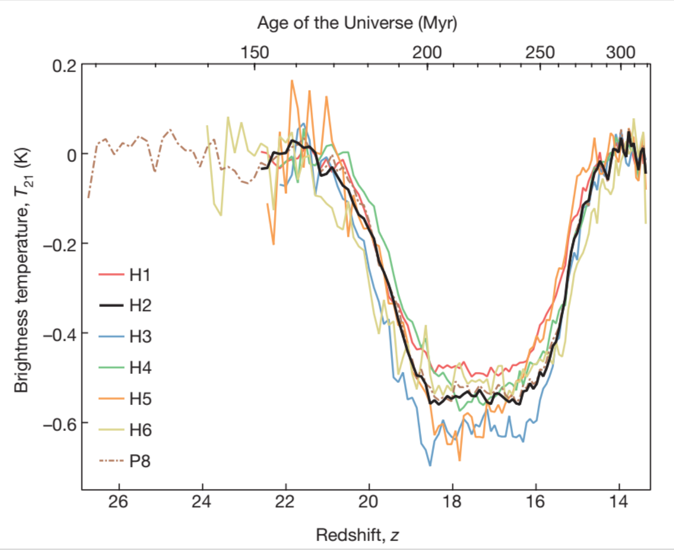
# (where are we humans in 21B measurement)

# 21B: Strong absorption vs ~Null signal

Bowman+2018

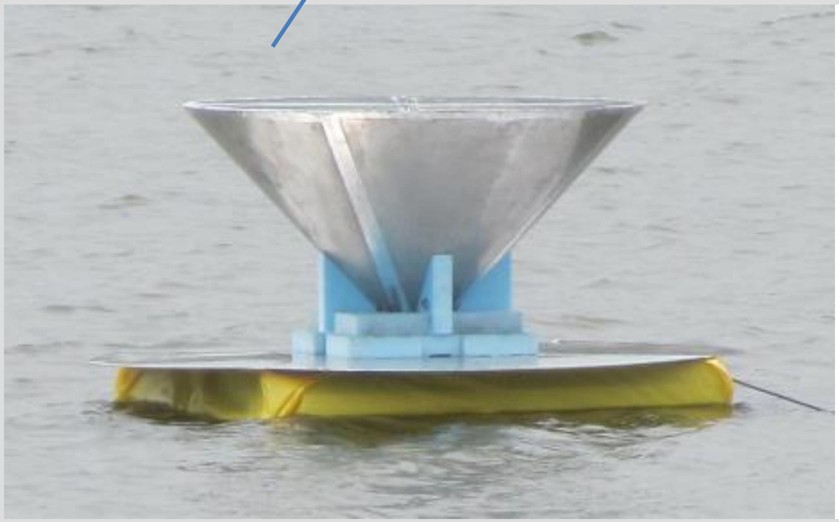
EDGES

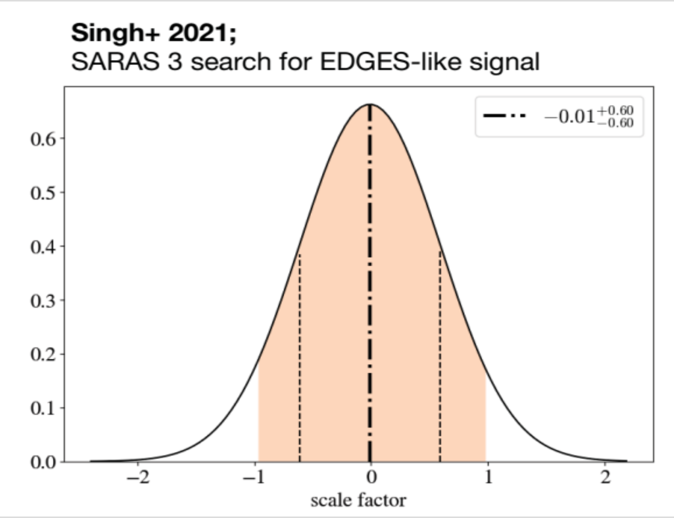





water – high dielectricity

SARAS





# EDGES

- 500 mK dip (Barkana 2018)
  - coller-than-standard $T_{gas}$
  - extra background: Draine & Miralda-Escude 2018, Fialkov & Barkana 2019, Ewall-Wice+2020; Sikder+2024

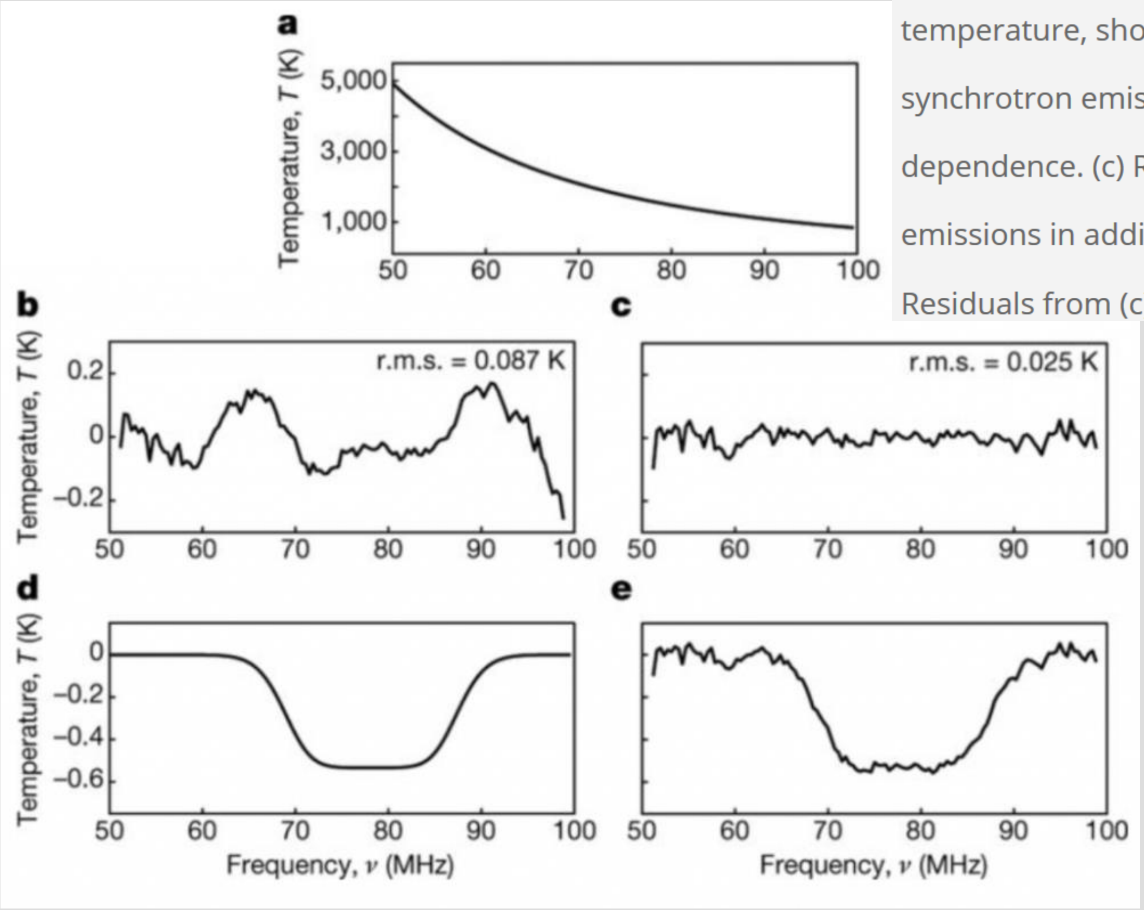



**Figure 3:** (a) The EDGES sky measurement in units of brightness temperature, showing the strong power-law spectrum due to galactic synchrotron emission. (b) Residuals after removing the power-law dependence. (c) Residuals after removing the power-law synchrotron emissions in addition to a model (d)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

# EDGES

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  - ambiguity

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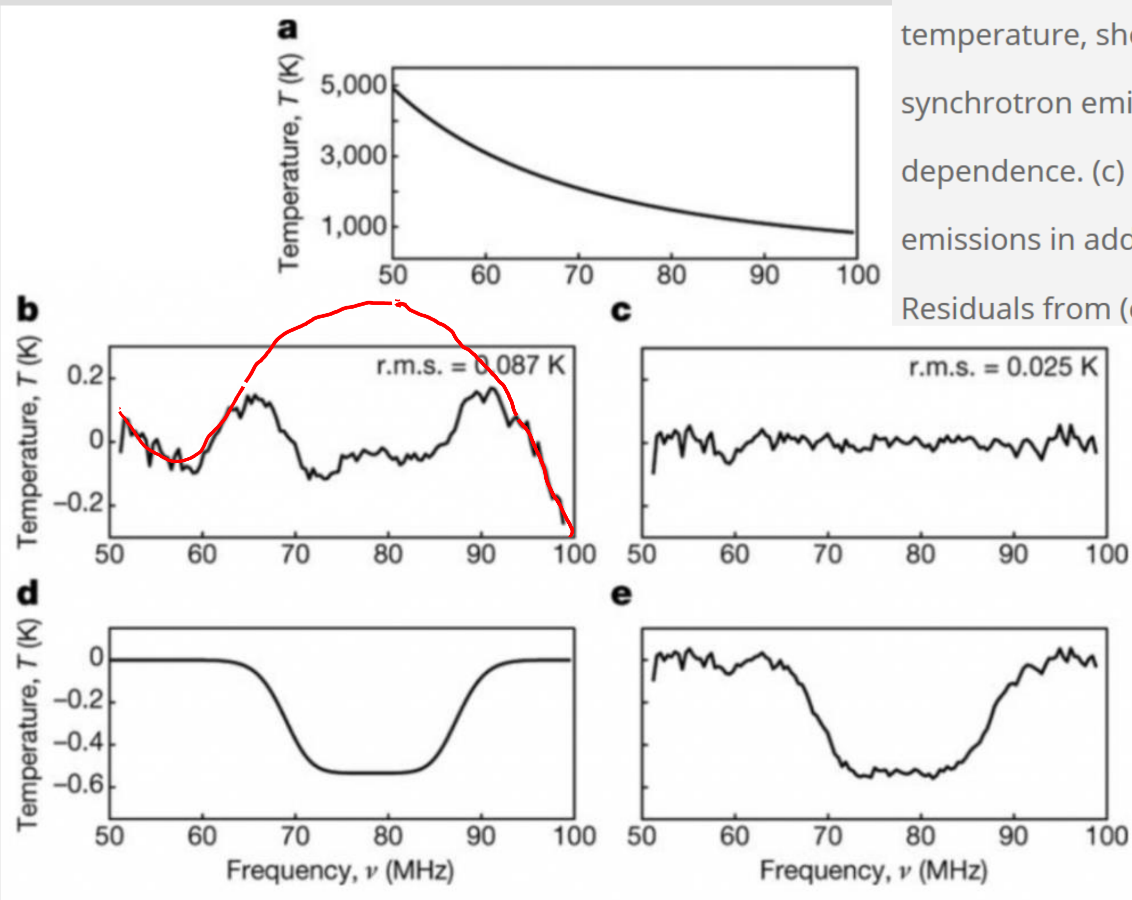
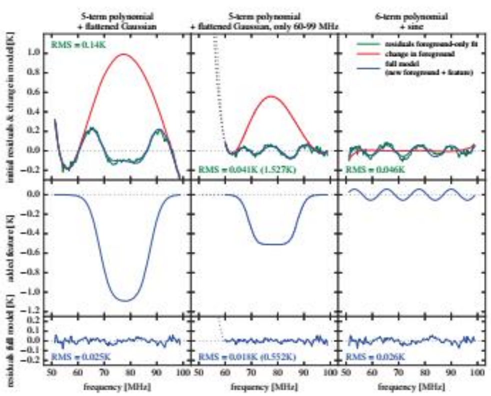


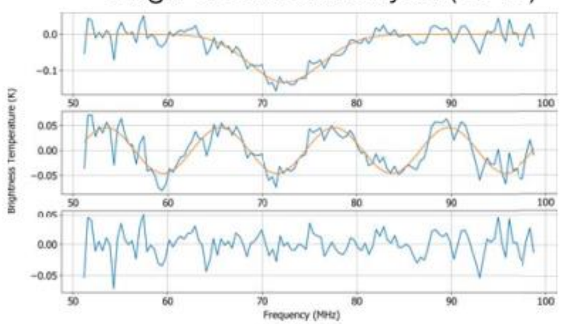
# Single-dish experiment: ambiguous

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

Hills, Kulkarni et al.

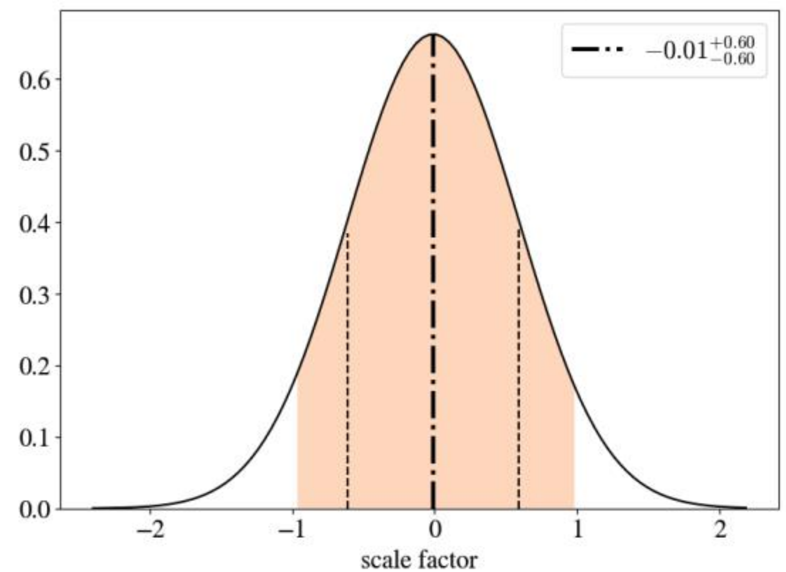



Singh & Subrahmanyan (2019)



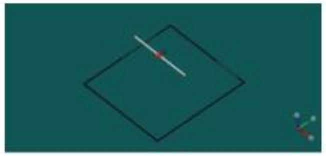

Singh+ 2021;

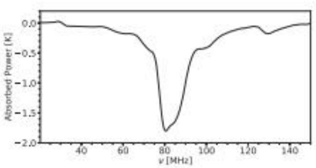
SARAS 3 search for EDGES-like signal




Complexity in foreground?

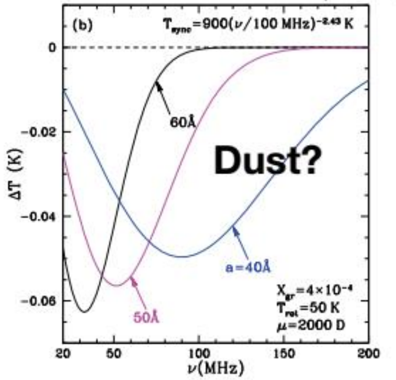
Instrument?






Bradley, Tauscher et al.

Draine & Miralda-Escudé (2018)




(slide excerpted from Jordan Mirocha's talk)

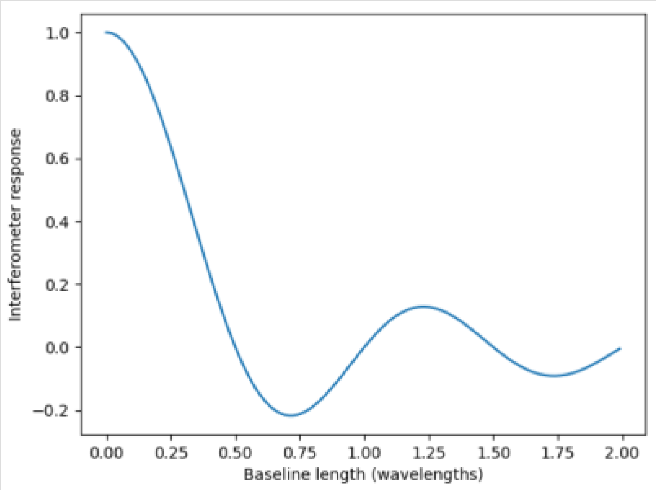
# 21B anisotropy for monopole:

# independent measure, different systematics

# Non-zero response of interferometer to monopole

- Presley+2015
  - short baseslines are reponsive to monopole

- Singh+2015
  - dipole antennas can do this

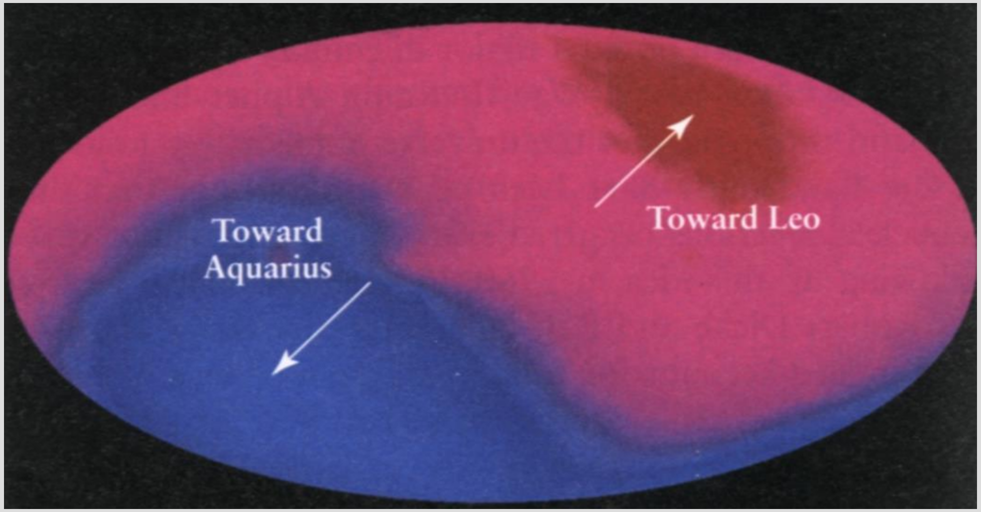


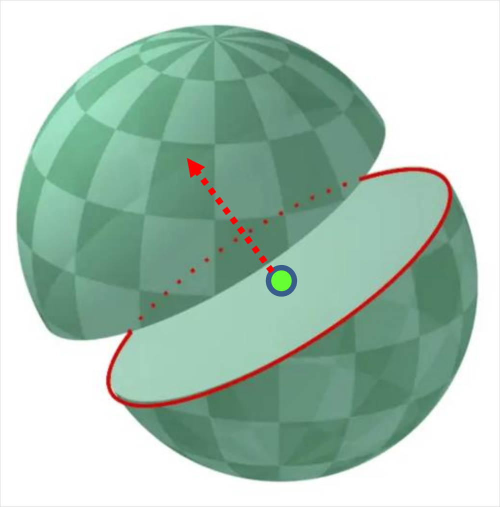
# Punching a hole on the sky

- McKinley,Bernardi,Trott+2020
  - lunar occultation of sky -> anisotropy

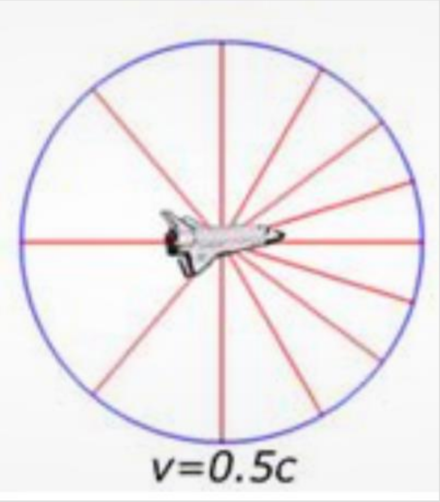
# Induced dipole, quadrupole, …

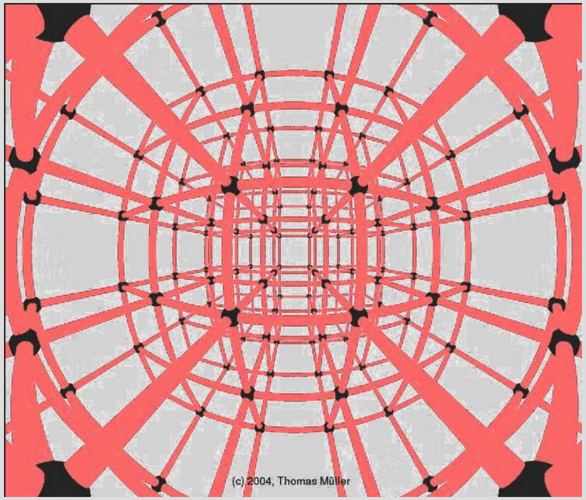
Doppler effect

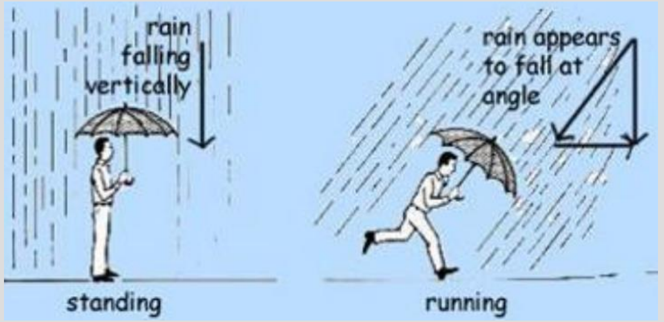


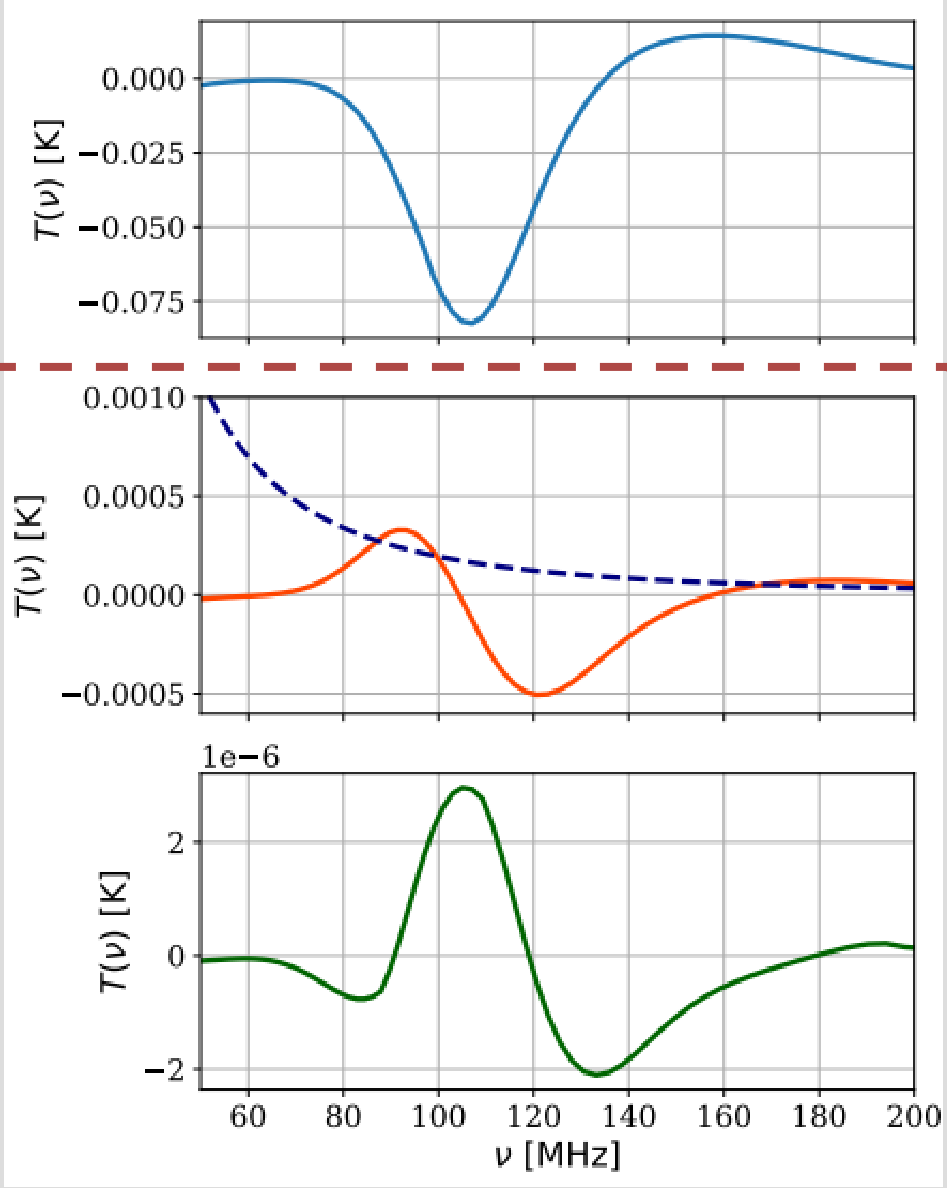
aberration



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




--- monopole (M)

anisotropic measure

--- dipole (~ T(ν) − dT(ν)/dlnν )

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

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

- due to aberration + Doppler
- $Y_{20}$

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

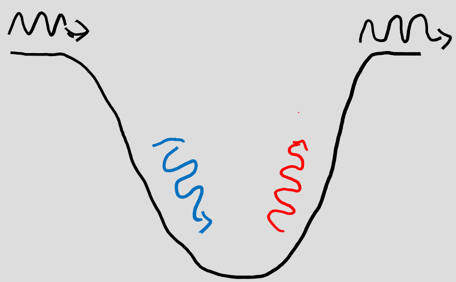
# 21B anisotropy for monopole: 21cm ISW

(KA & Oh, PRD 109, 043539)

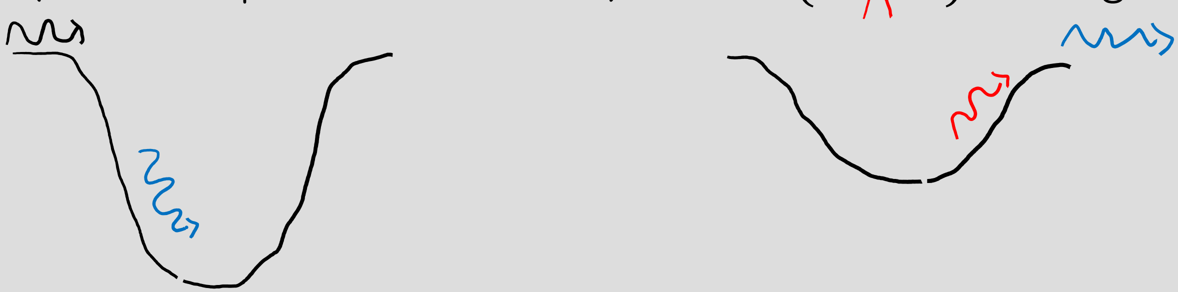
# Integrated Sachs-Wolfe effect (ISW; Sachs & Wolfe 1967)

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

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

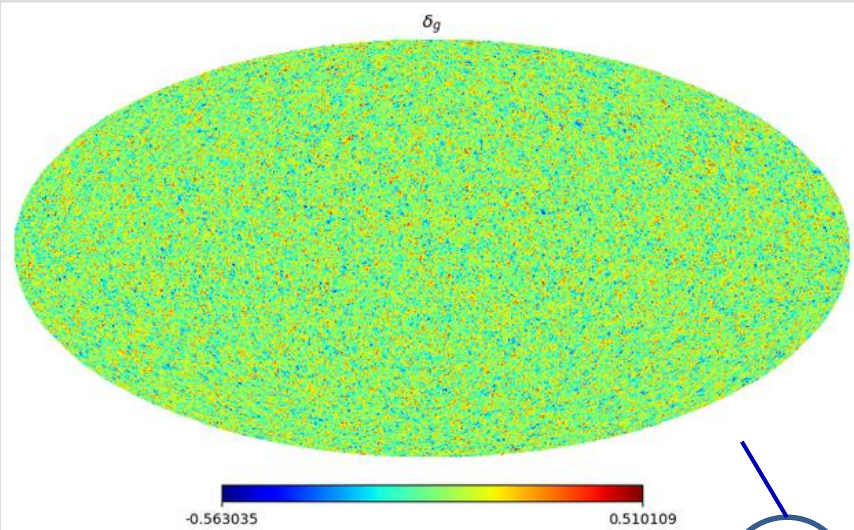


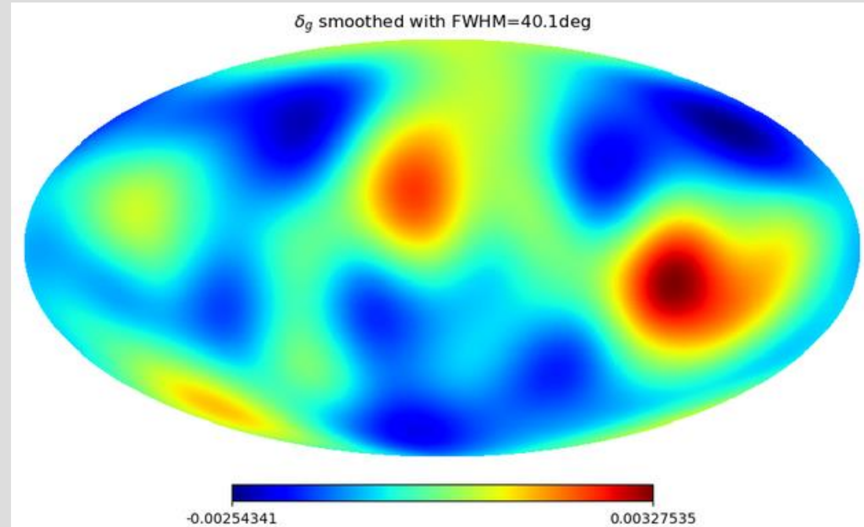
otherwise (LCDM; open universe; ⋯): $\dot{\Phi} \neq 0$ ($M \not\propto a$) @ large scales



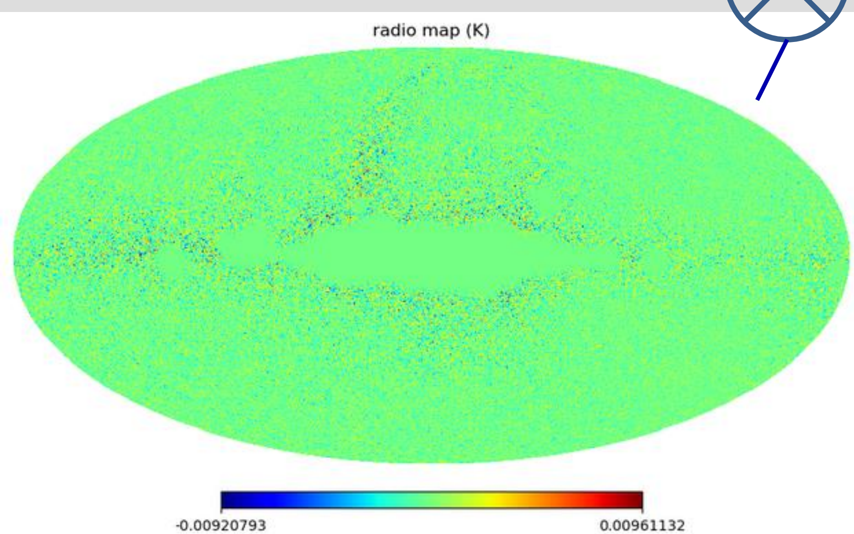
# 21B ISW map in cross-correlation map

galaxy map

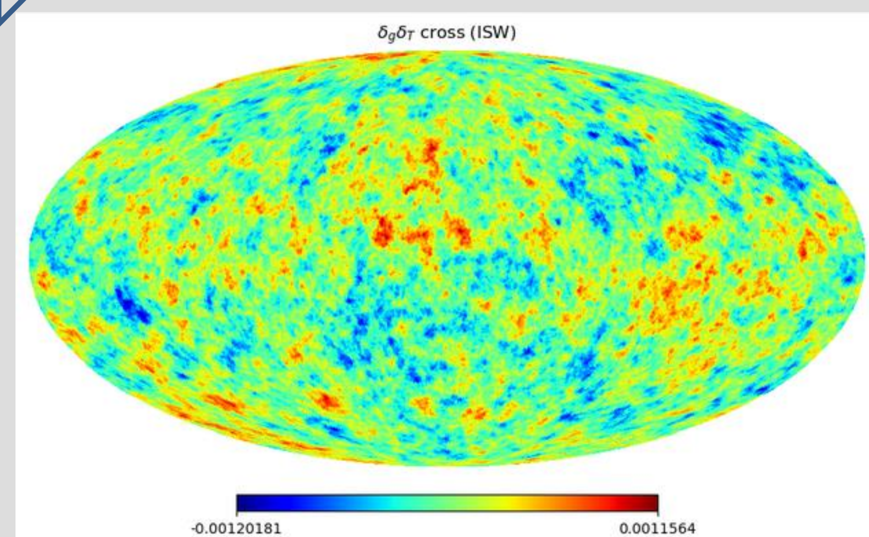



temperature map




galaxy−temperature cross map



# galaxy - δT correlation: 21B ISW measurement

frequency dependence:

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

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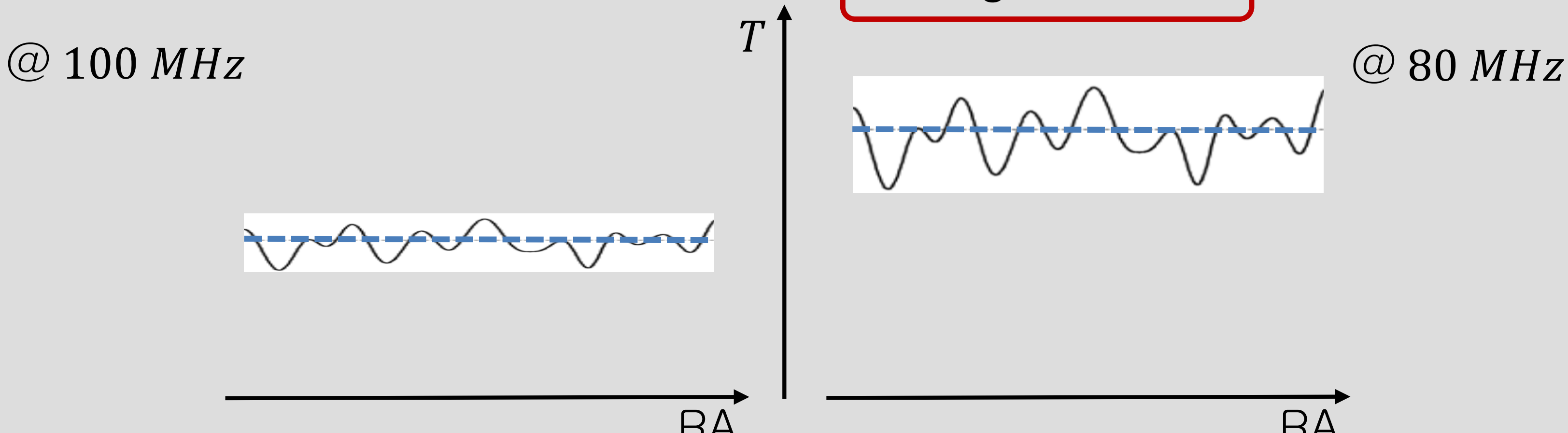
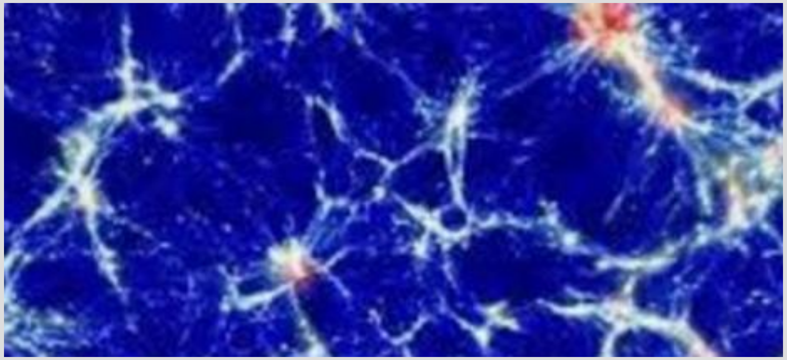
average 21B @ $\nu$




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

→ same fluctuation pattern on sky, but different contrast



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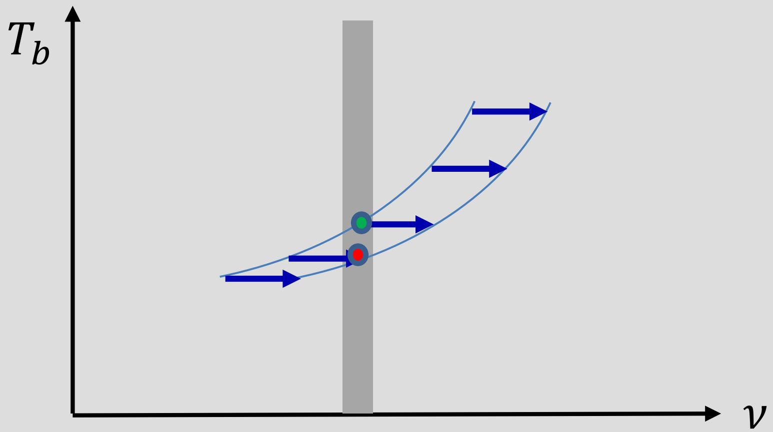


blueshifted by overdensity

→ 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 ⊗ ~ 2 − 5

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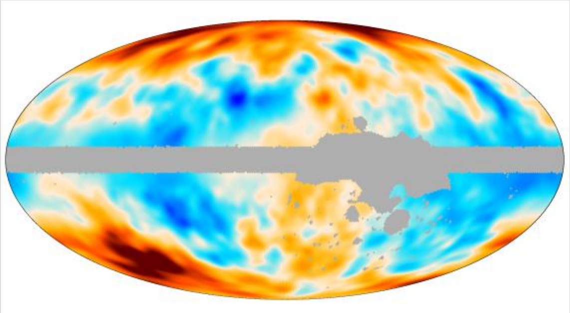
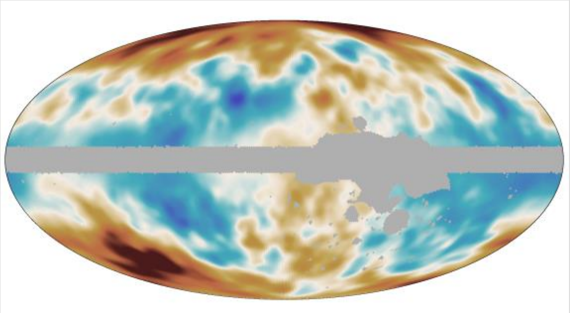
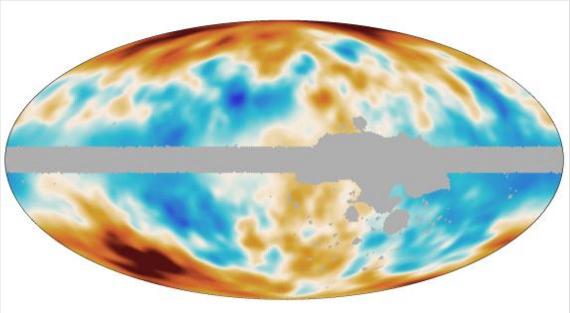
$$C_\ell^{gT_{21}}(\nu) \propto T_{21}(\nu) = \langle T_b(\nu)\rangle - \frac{\partial\langle T_b(\nu)\rangle}{\partial \ln \nu}$$

ν = 80 MHz | 100 MHz | 120 MHz

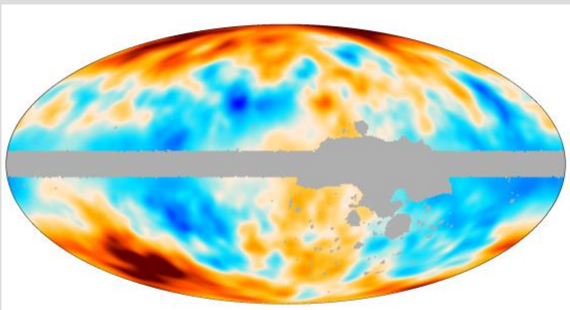


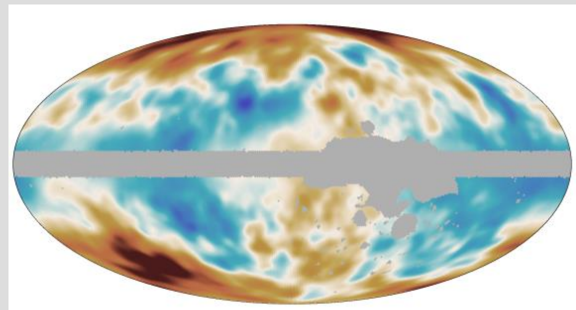


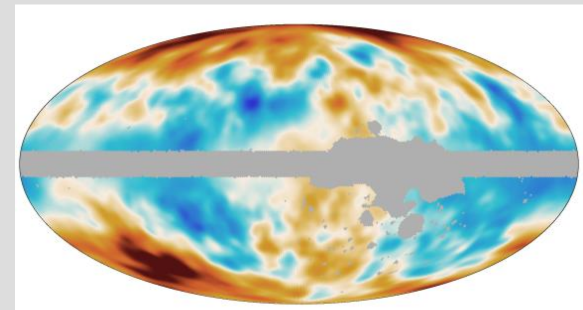


# galaxy - δT correlation: (21B ISW) / (CMB ISW)

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







ν = 80 MHz 100 MHz 120 MHz

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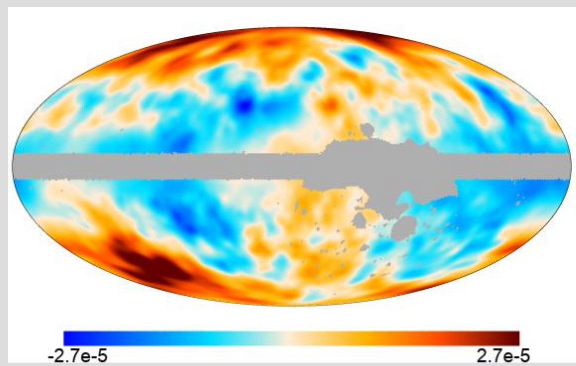


CMB

× 2.7K − 2.7K

galaxy auto (SPHEREX)

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

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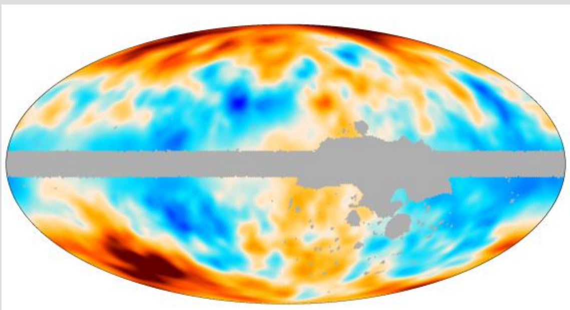
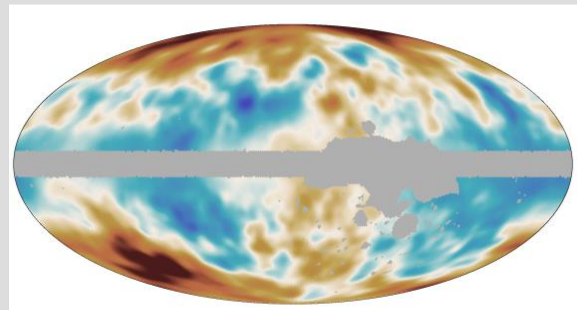
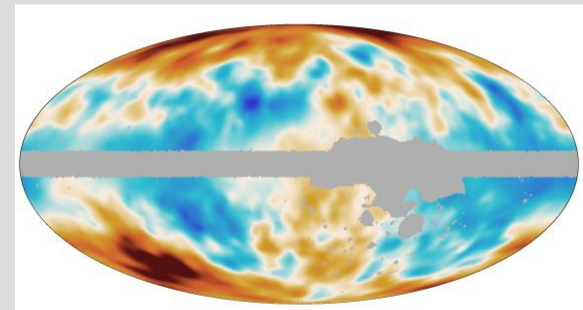
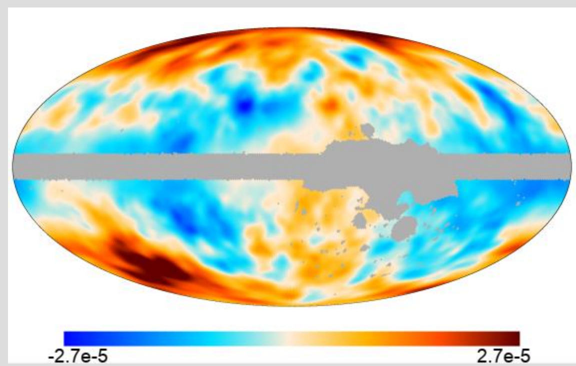






ν = 80 MHz 100 MHz 120 MHz




CMB

2.7K – 2.7K

21cm temperature auto

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

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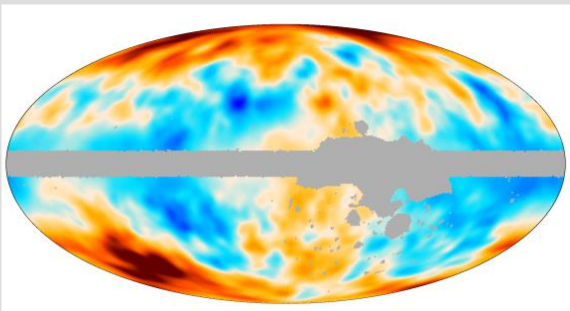
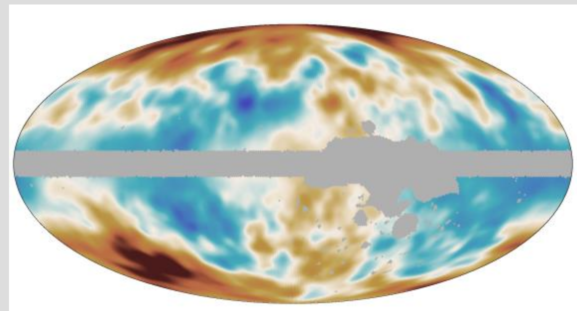
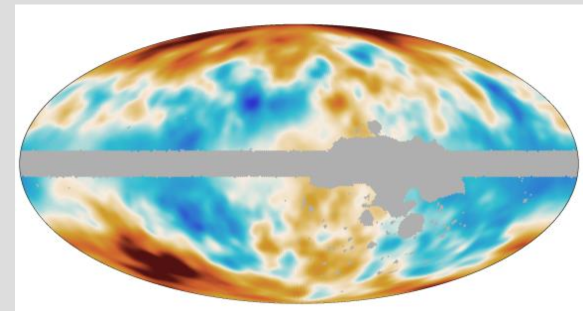
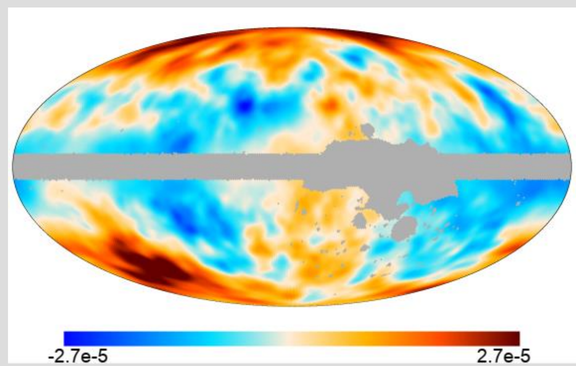




ν =    80 MHz    100 MHz    120 MHz




2.7K – 2.7K

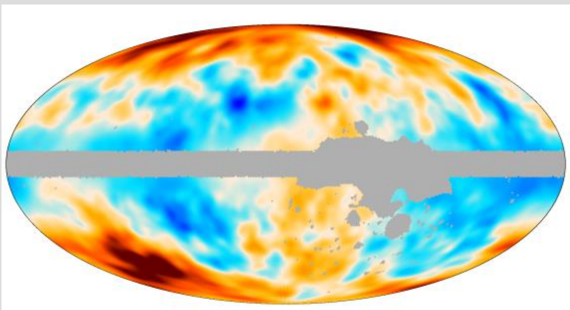
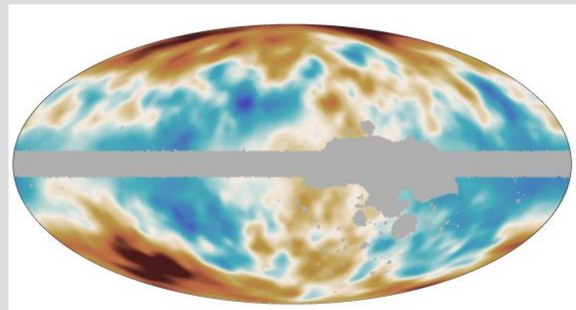
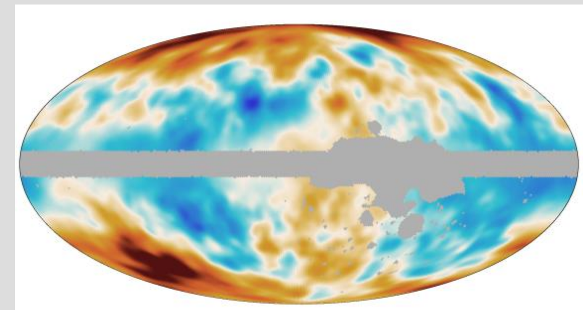
CMB

sky brightness

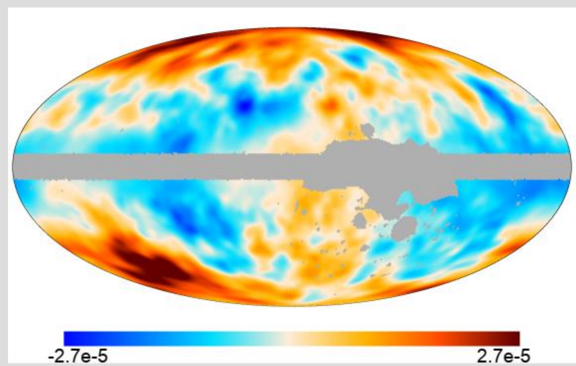
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0}\rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[ \frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta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

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

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

ν = 80 MHz 100 MHz 120 MHz




CMB

2.7K – 2.7K

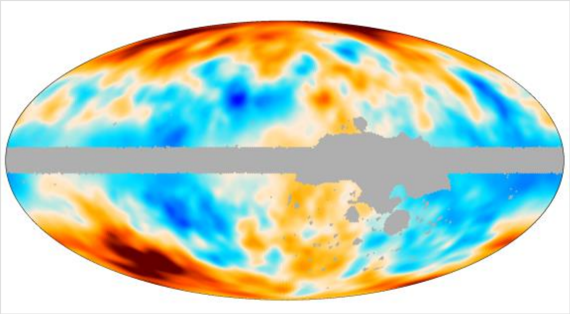
CMB temperautre auto

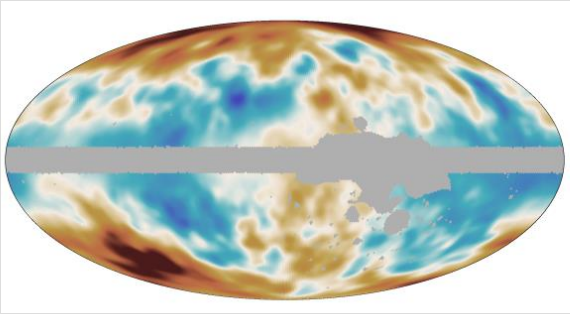
(Planck)

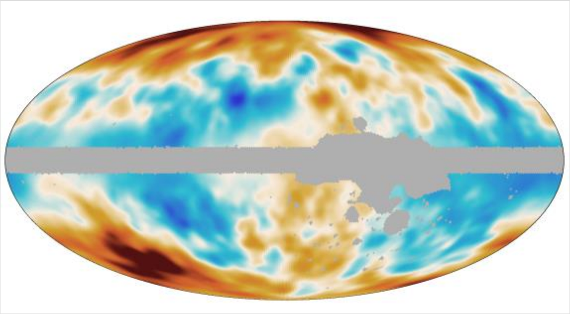
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0}\rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[ \frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left( \frac{\delta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

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

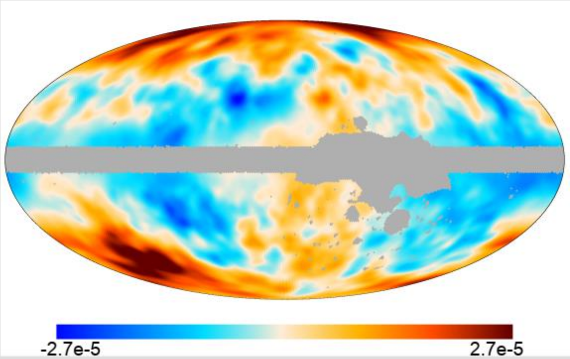
observable: $T_{21}(\nu) \equiv \left( \frac{C_\ell^{gT_{21}}(\nu)}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$







ν = 80 MHz 100 MHz 120 MHz




CMB

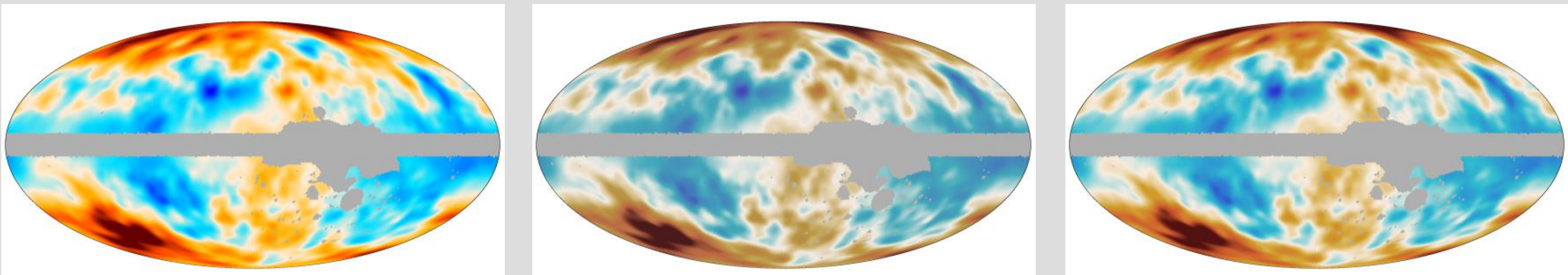
2.7K – 2.7K

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

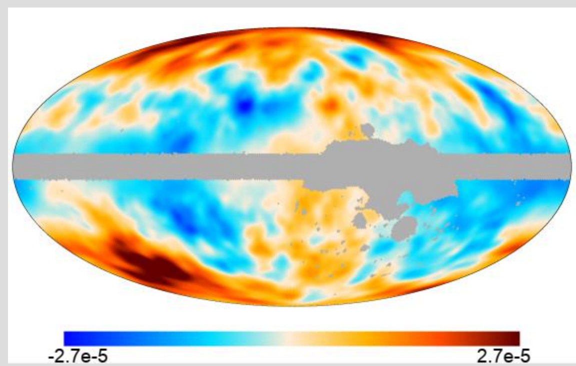
↑ CMB ISW (Planck)

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

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



ν = 80 MHz 100 MHz 120 MHz



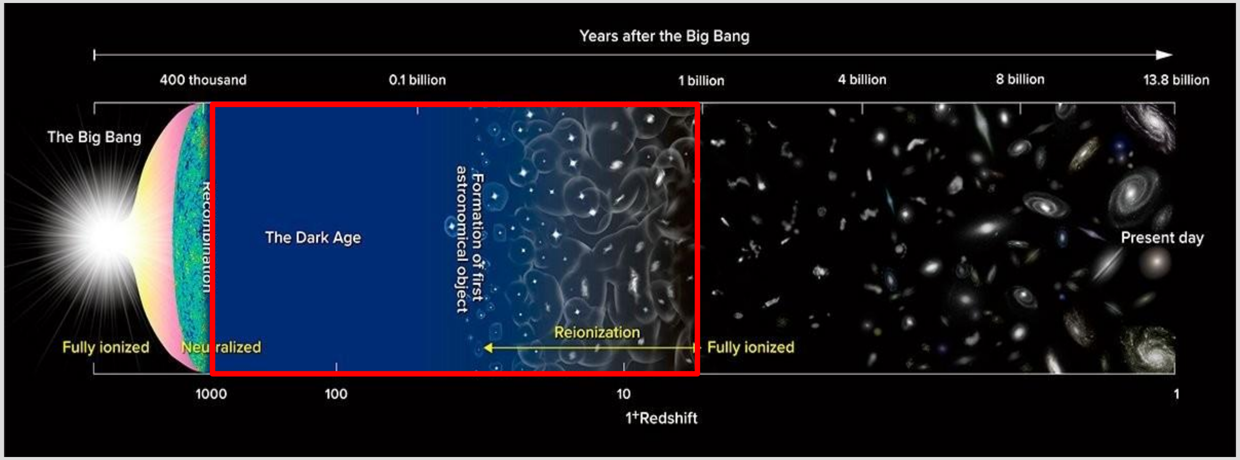

CMB

2.7K − 2.7K

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

# galaxy - δT correlation: 21B ISW measurement

- Merit: Milky Way signal irrelevant!!!
  - c.f. single-dish (EDGES, SARAS, …) signal swamped by MW

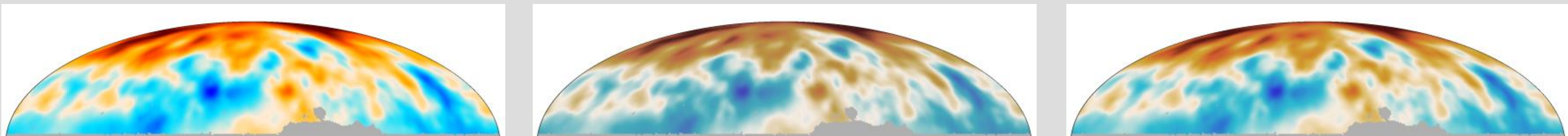


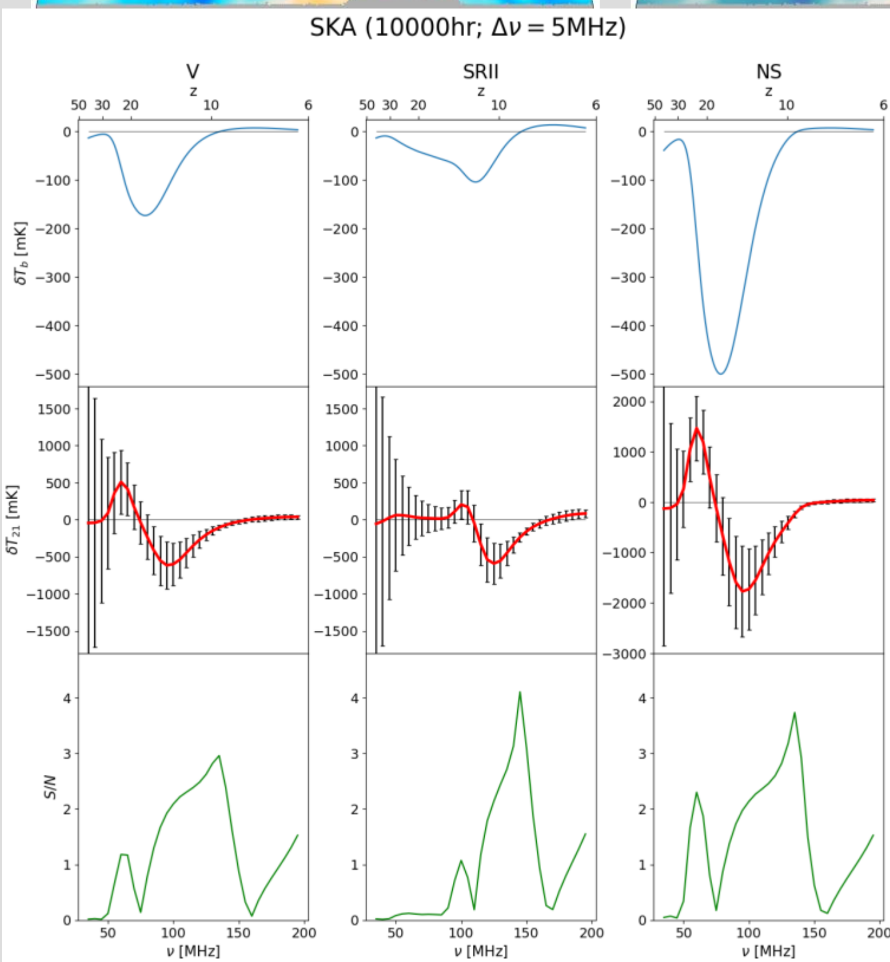

- Noise estimate basis
  - SKA1-Low ~500 stations, small UV ($2 \leq \ell < 20$) gets fair observation time, sky coverage ~70%
  - Large # of survey galaxies: SPHEREX-like $\frac{dN}{d\Omega} \geq \left(\frac{b}{2}\right)^{-2} 2 \times 10^7 \mathrm{sr}^{-1}$

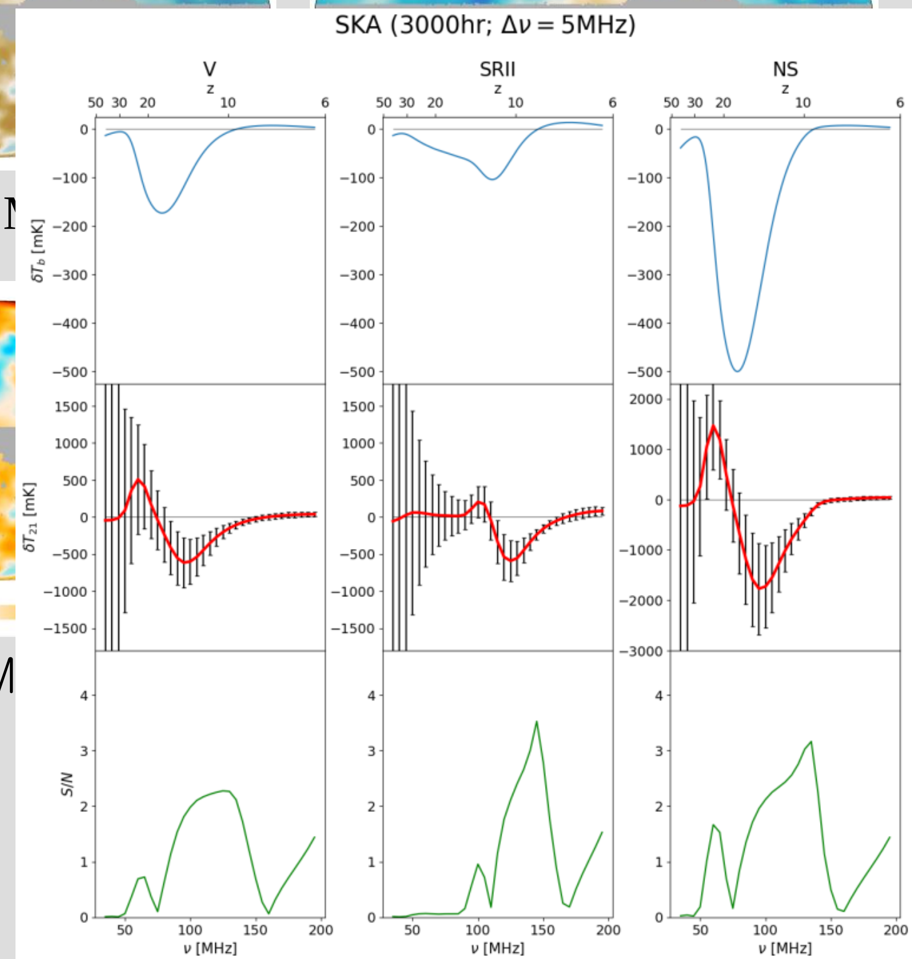
- High-z (z>~2) exgal background still to affect 21B ISW
  - for future study

# galaxy - δT correlation: 21B ISW measurement

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

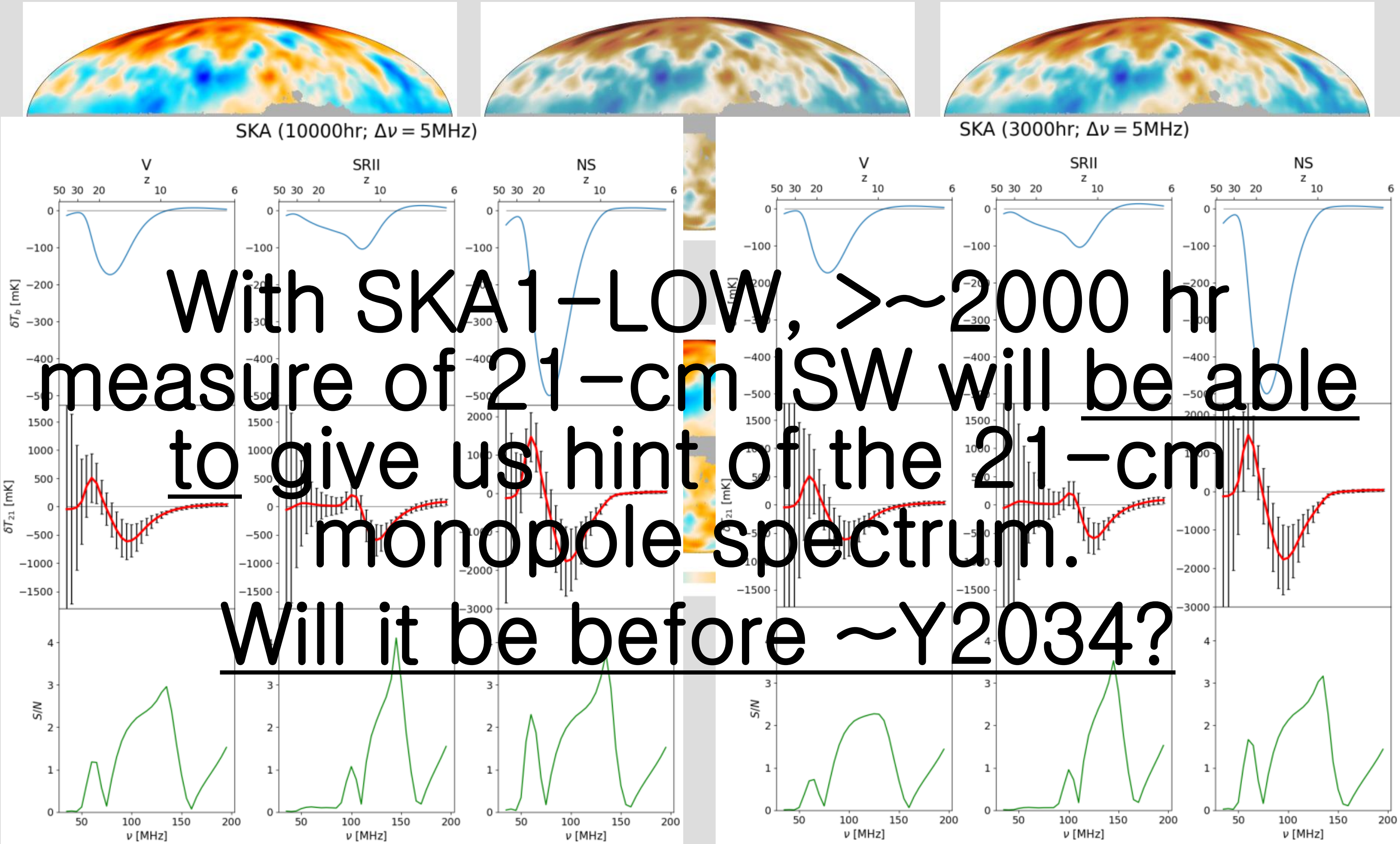




# galaxy - δT correlation: 21B ISW measurement

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

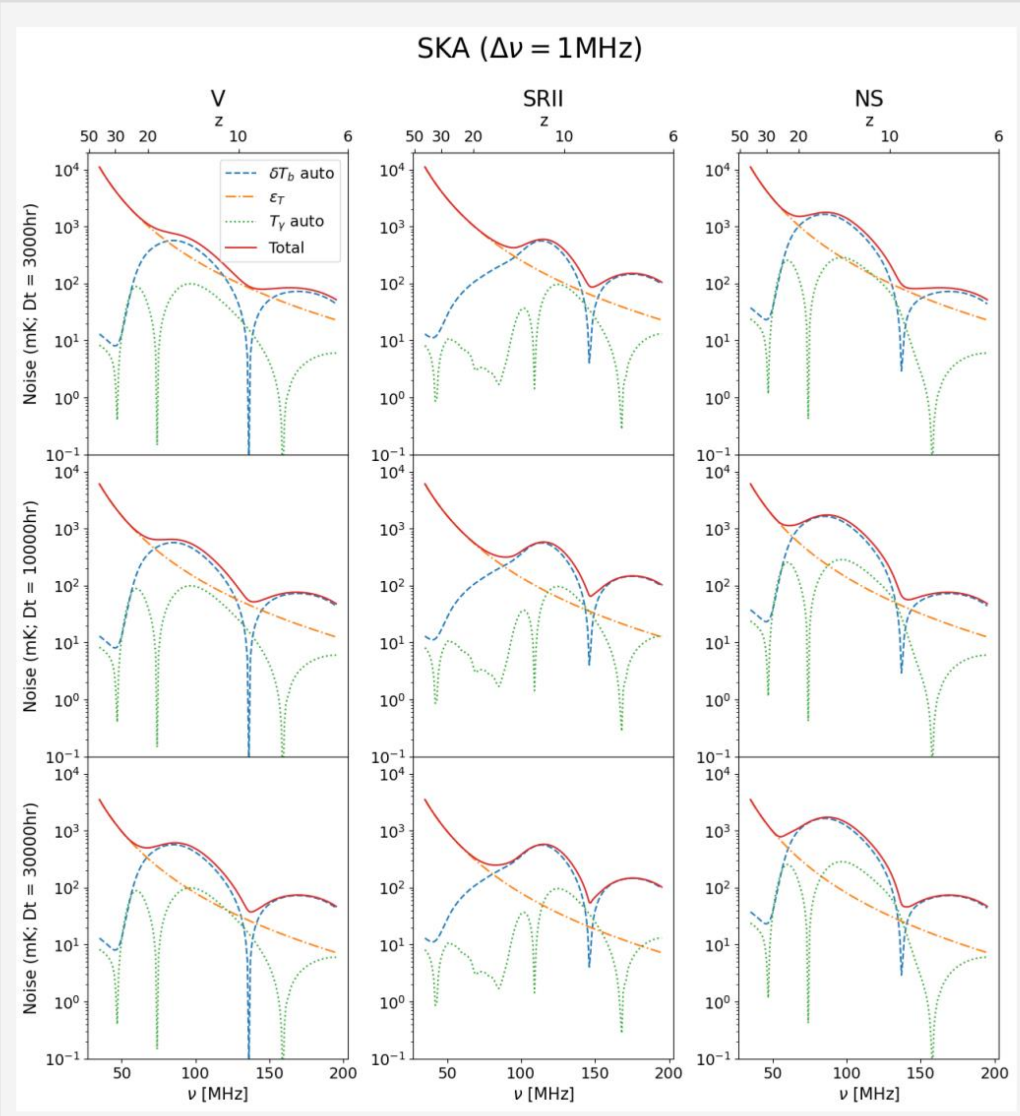


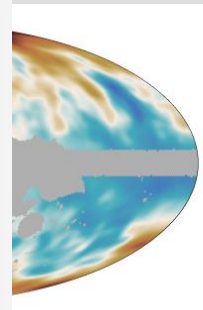

With SKA1−LOW, >~2000 hr measure of 21−cm ISW will <u>be able to</u> give us hint of the 21−cm monopole spectrum.

<u>Will it be before ~Y2034?</u>

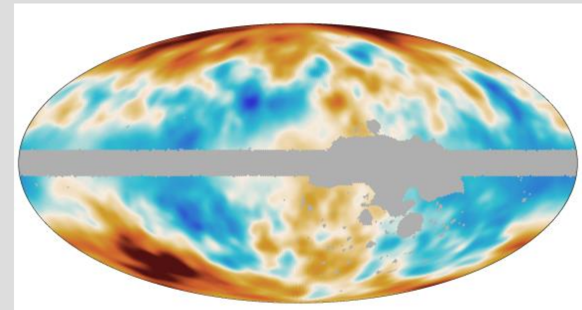
# galaxy - δT correlation: 21B ISW measurement

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

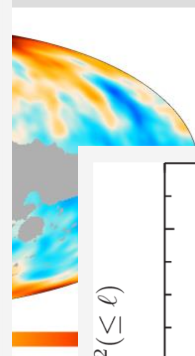


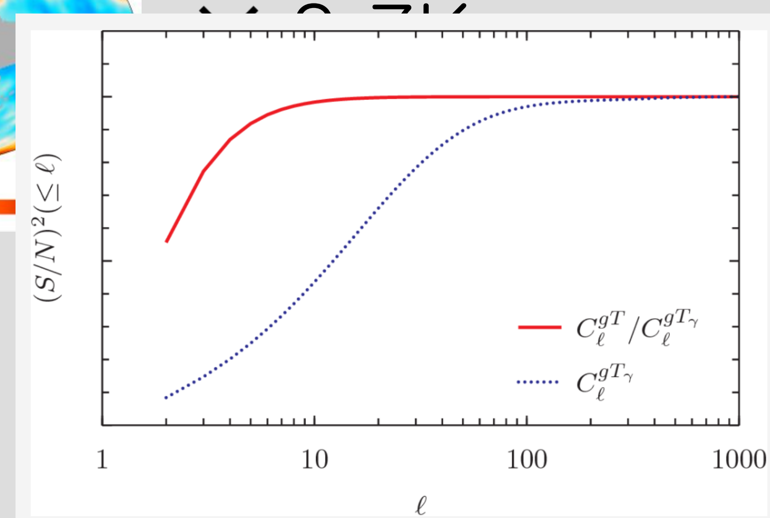



z



120 MHz





# 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

- multi-frequency 21cm ISW
  - “same pattern” with CMB ISW
  - moduleated by 21cm monopole spectrum → varying “constrast” over frequency

| | Dipole+Quadrupole | ISW |
|---|---|---|
| pros | dipole signal is strong | MW foreground removed |
| cons | MW foreground dominated | expensive: ISW signal is weak |

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