Extracting Global 21-cm Signal from Low-Resolution Full-Sky Survey: Dipole Anisotropy and the Integrated Sachs-Wolfe Effect in the 21-cm Background

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Hongo 21cm workshop, Tokyo

Oct. 2024

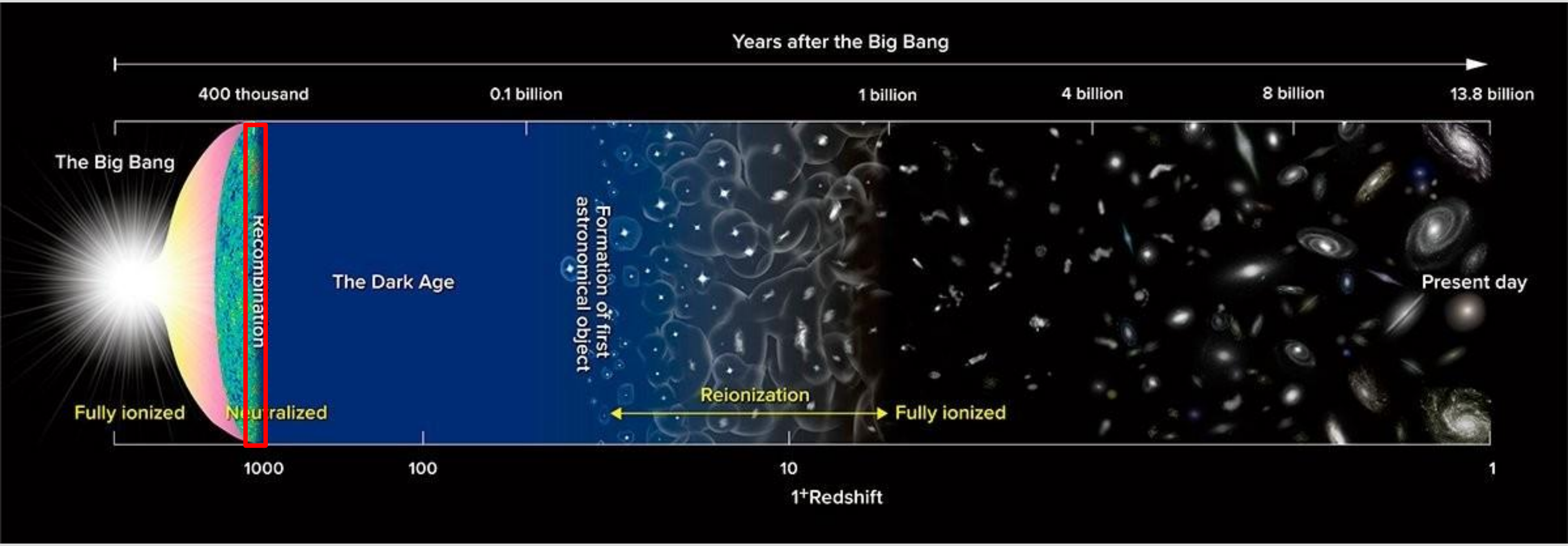
Curiosity:

How 21-cm radiation works as a background radiation?

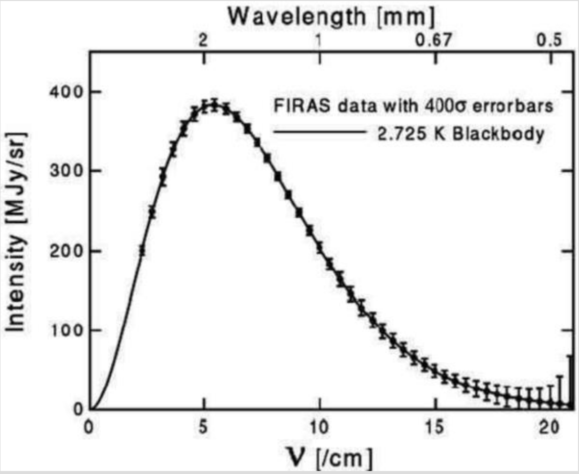
CMB vs 21B (21-cm background)

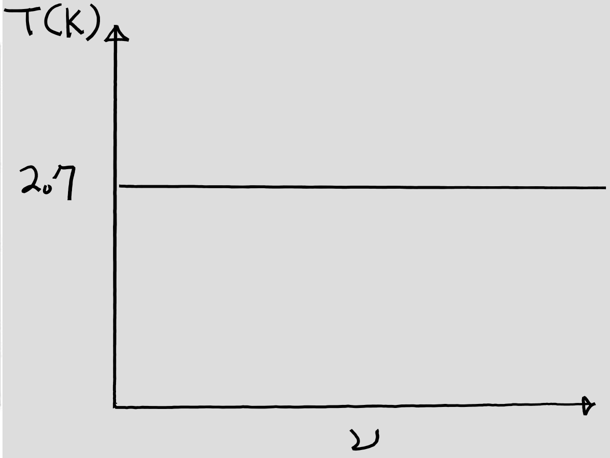
CMB: from when?

From single epoch (recombination epoch)



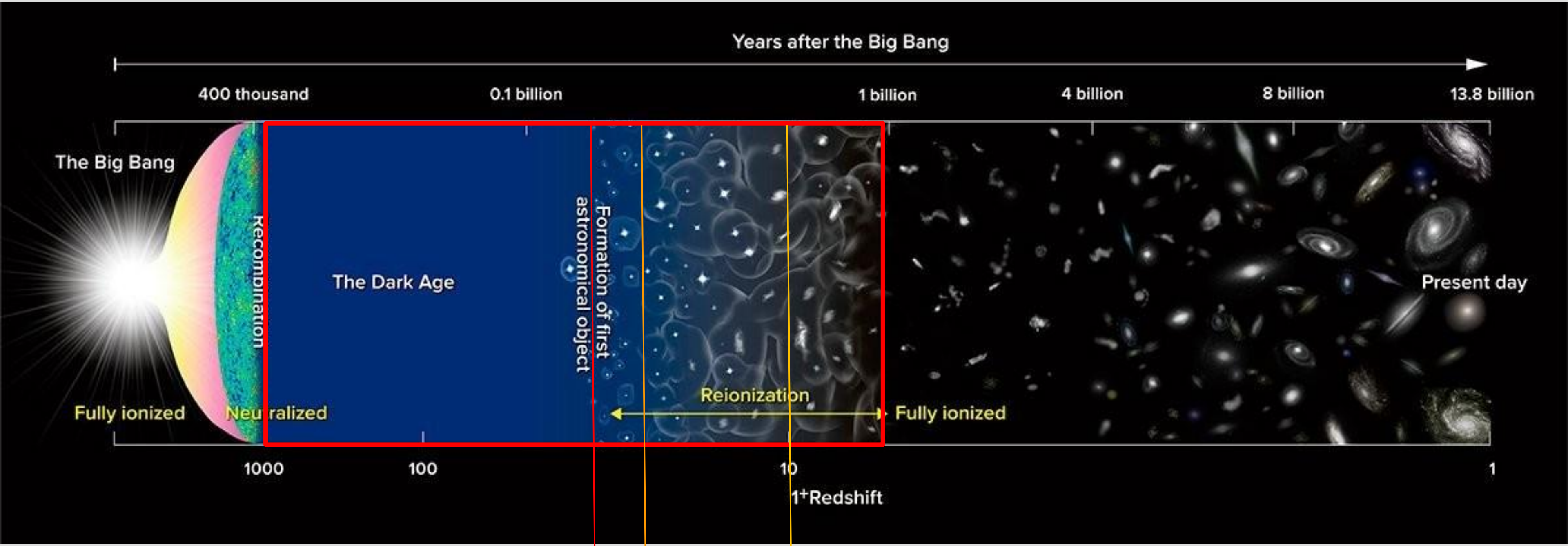
Monopole=
Blackbody
continuum,
const. brightness
temperature



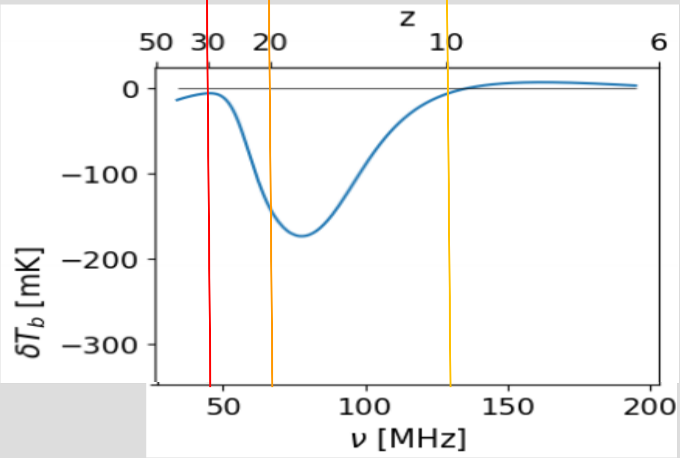


21B: from when?

From multiple redshifts, dark ages + epoch of reionization + post-reionization galaxies (ignored here)



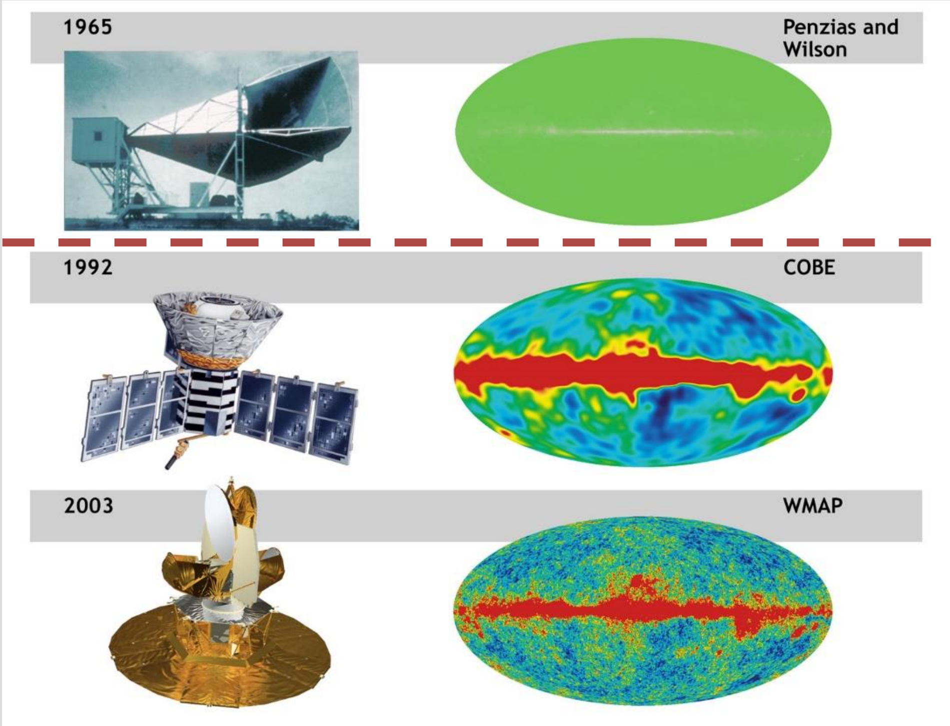
21cm monopole: lines redshifted → "brightness temperature spectrum"



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

21B: isotropy to anisotropy

isotropy (monopole)

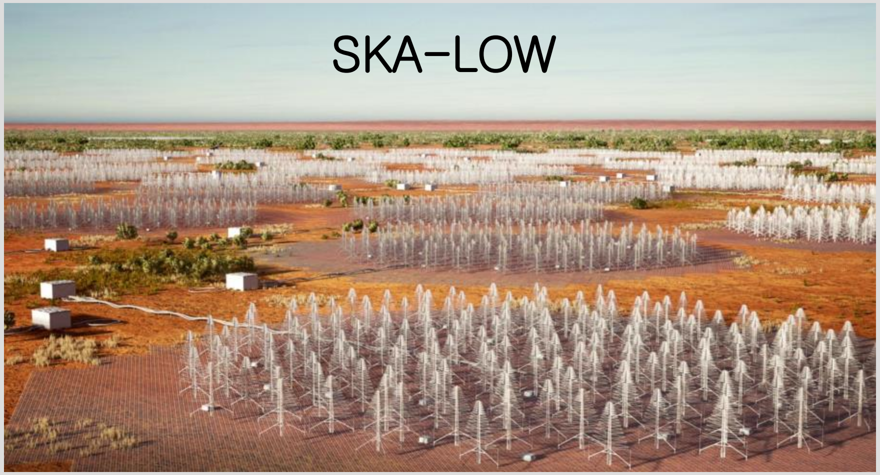


anisotropy (multipole): large H II bubbles

(2018)
EDGES

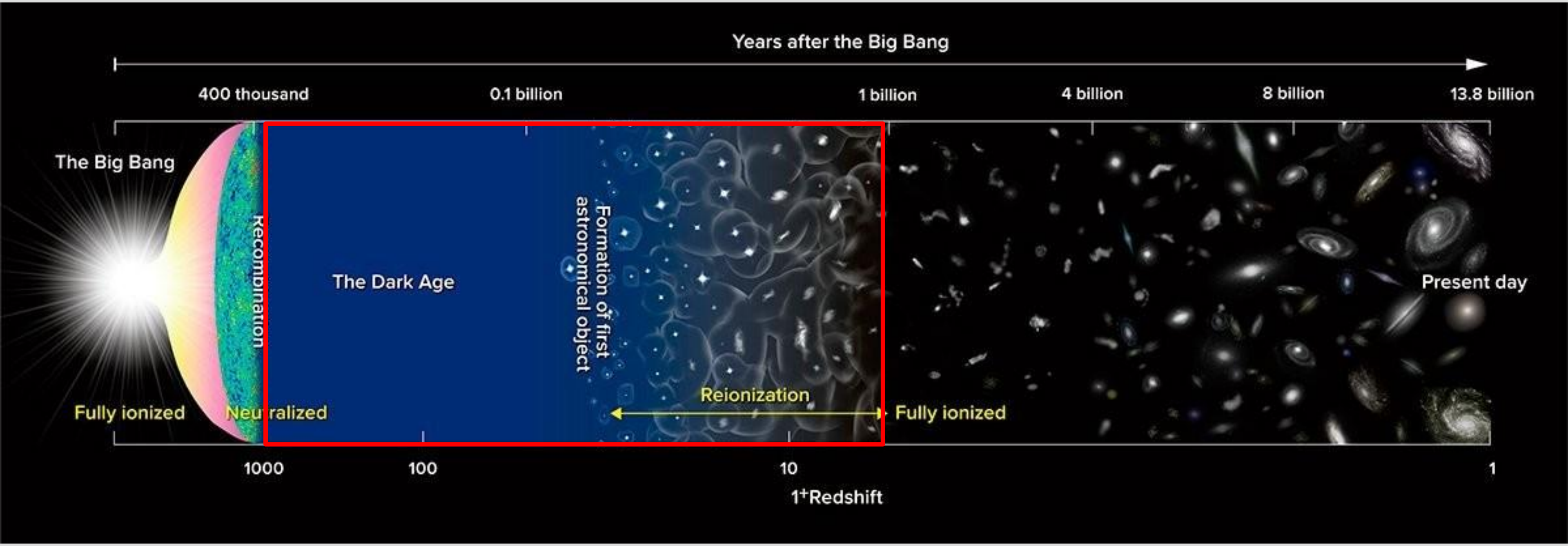
(2021)
SARAS

LUsee-Night, DSL, TREED, TSUKUYOMI



21B merit

- 21cm background
  - 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)



21B monopole conflict:

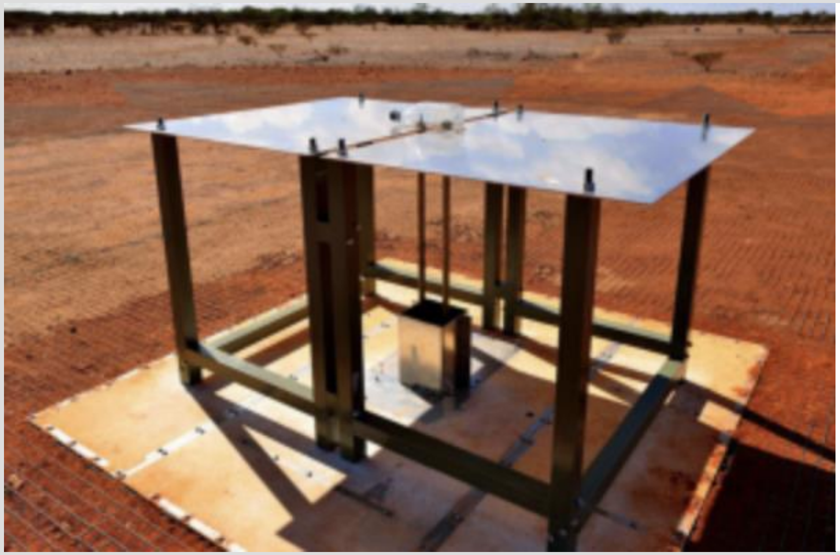
EDGES vs SARAS

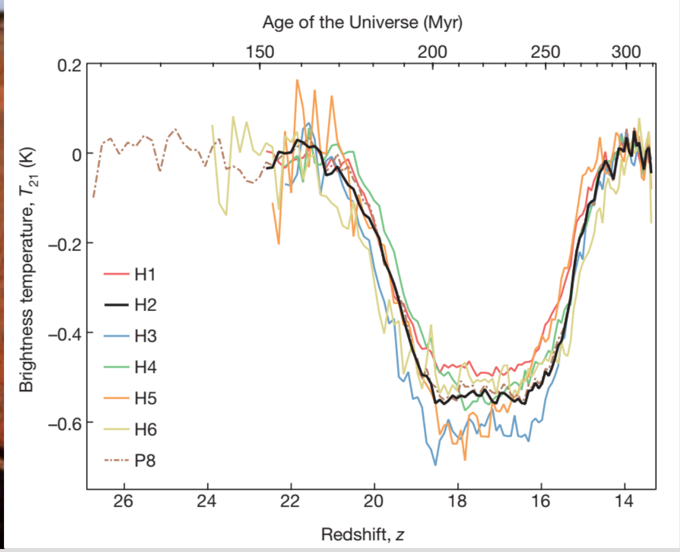
(where are we humans in 21B measurement)

21B: Strong absorption vs ~Null signal

Bowman+2018

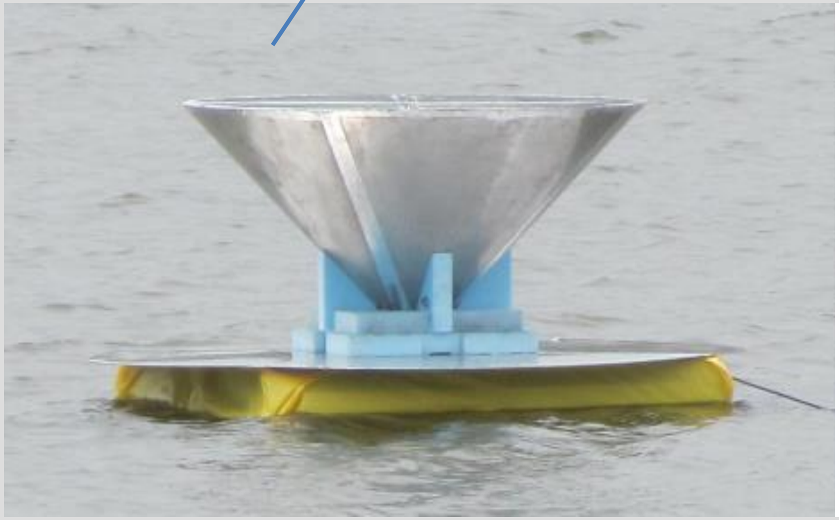
EDGES



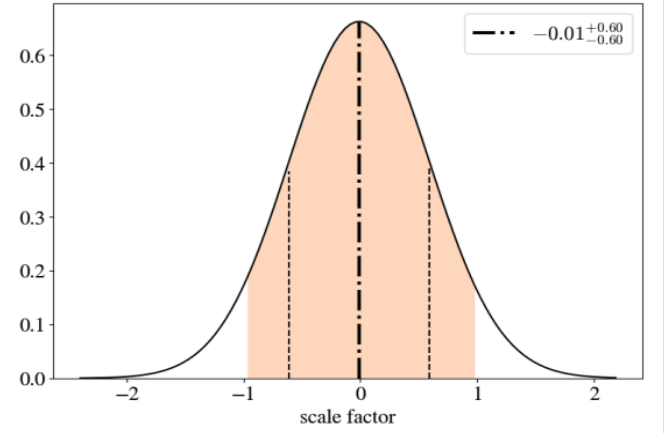


water – high dielectricity

SARAS



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



EDGES

- 500 mK dip (Barkana 2018)
  - cooler-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

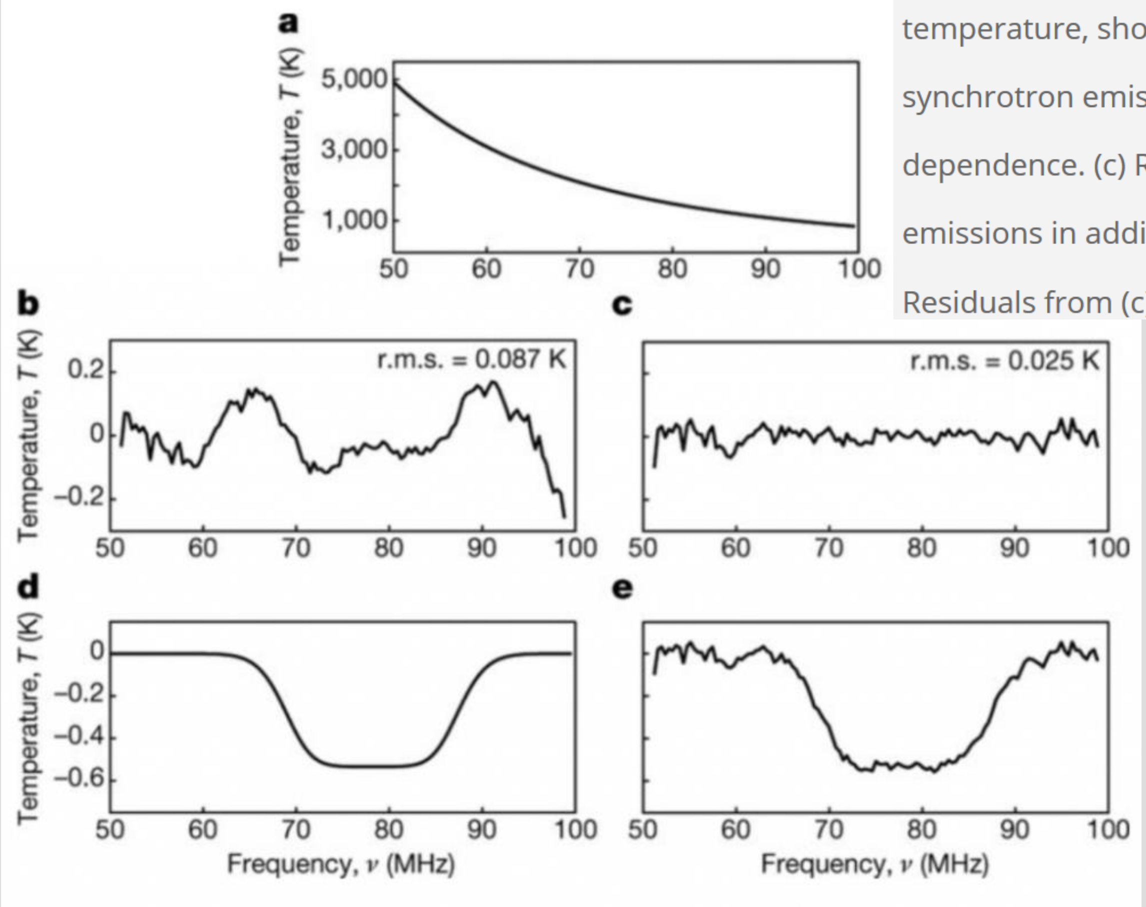


Figure 3: (a) The EDGES sky measurement in units of brightness temperature, showing the strong power-law spectrum due to galactic synchrotron emission. (b) Residuals after removing the power-law dependence. (c) Residuals after removing the power-law synchrotron emissions in addition to a model (d) of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

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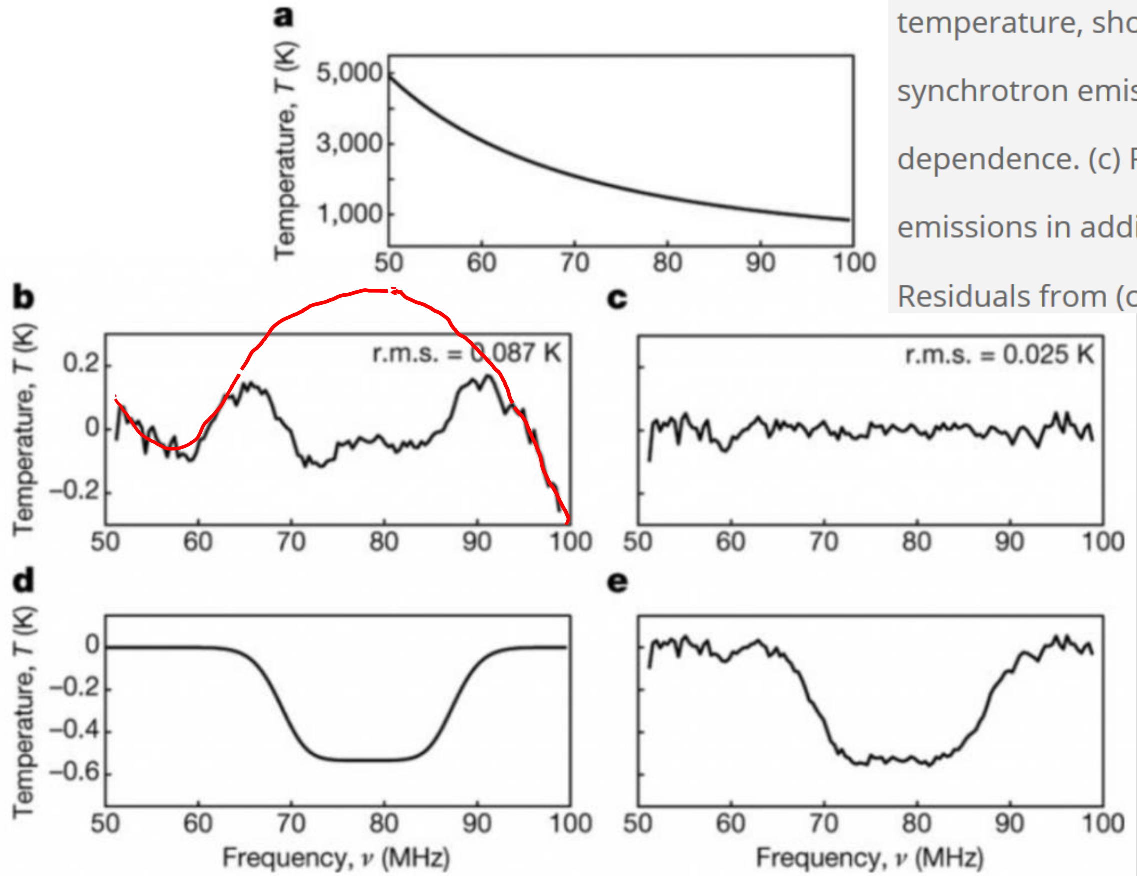
  - ambiguity



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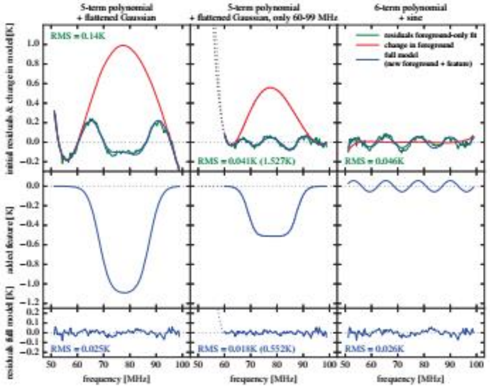
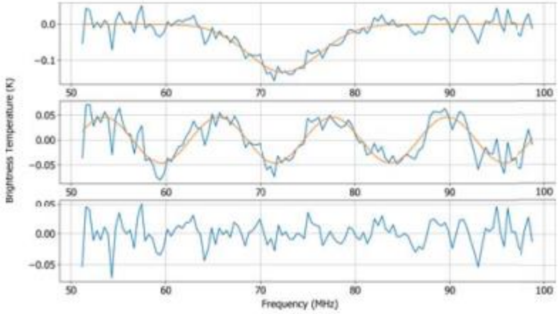
Single-dish experiment: ambiguous

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

Hills, Kulkarni et al.



Singh & Subrahmanyan (2019)



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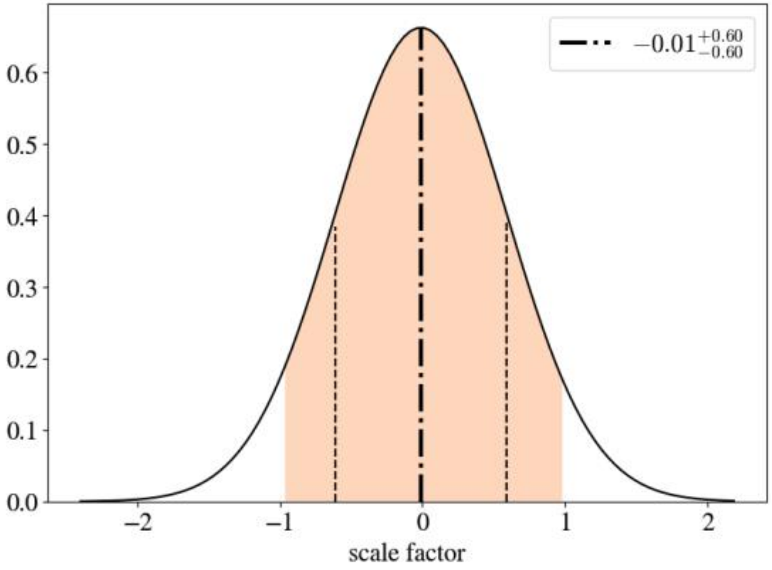
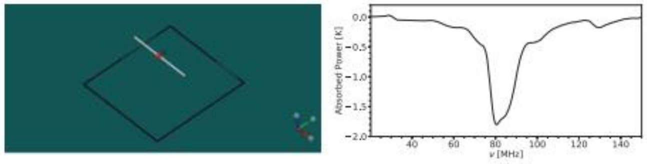
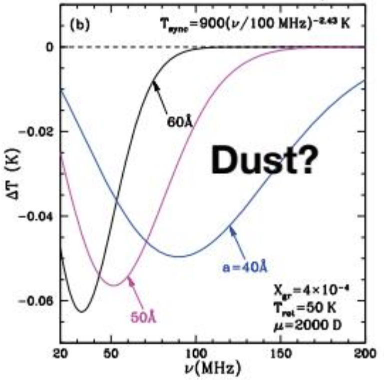


Complexity in foreground?
Instrument?



Bradley, Tauscher et al.

Draine & Miralda-Escudé (2018)



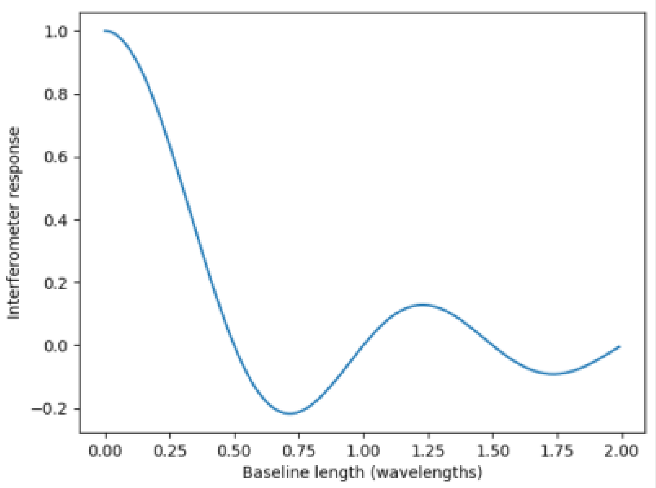
(slide excerpted from Jordan Mirocha's talk)

21B anisotropy for monopole:
independent measure, different systematics,
mitigating ambiguity

Non-zero response of interferometer to monopole

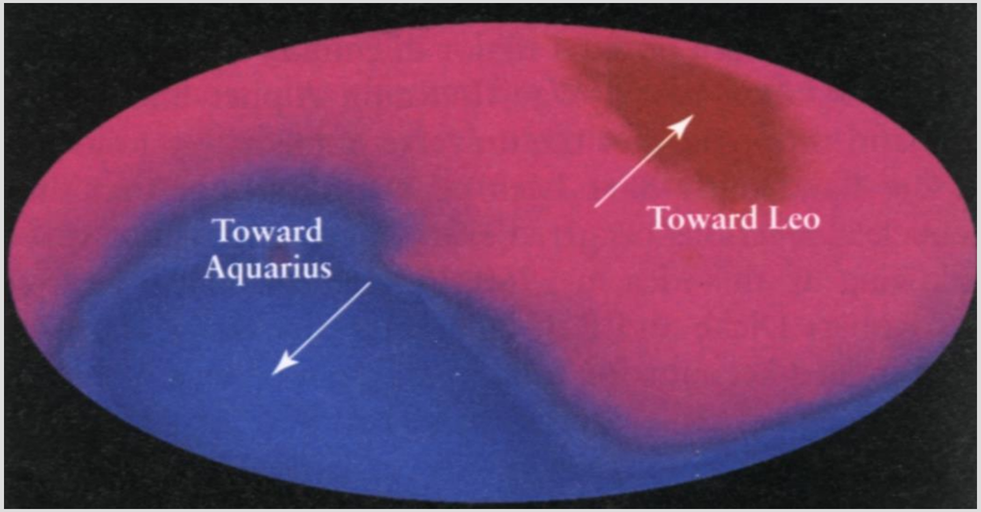
- Presley+2015
  - short baseslines are reponsive to monopole

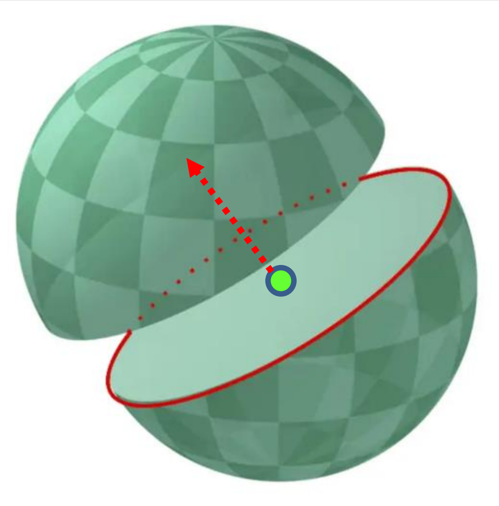
- Singh+2015
  - dipole antennas can do this



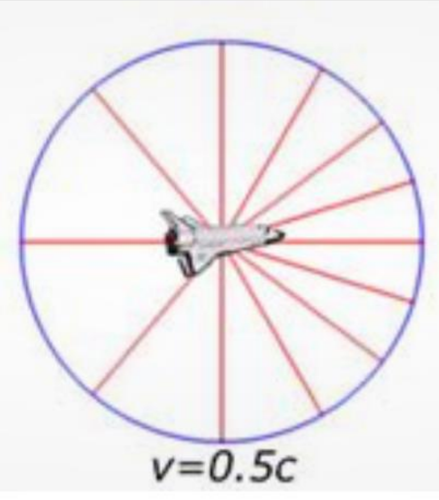
Induced dipole, quadrupole, …

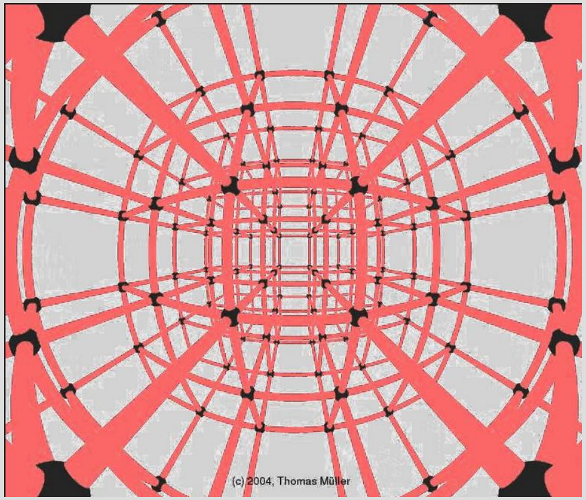
Doppler effect

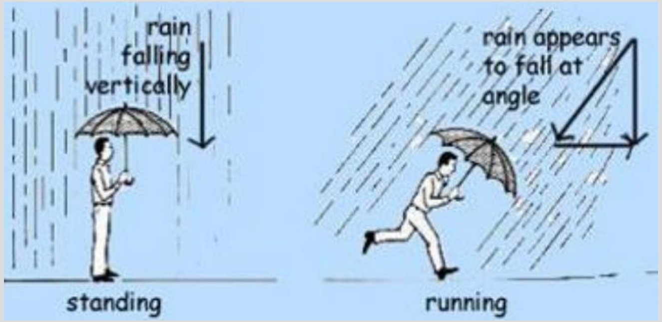




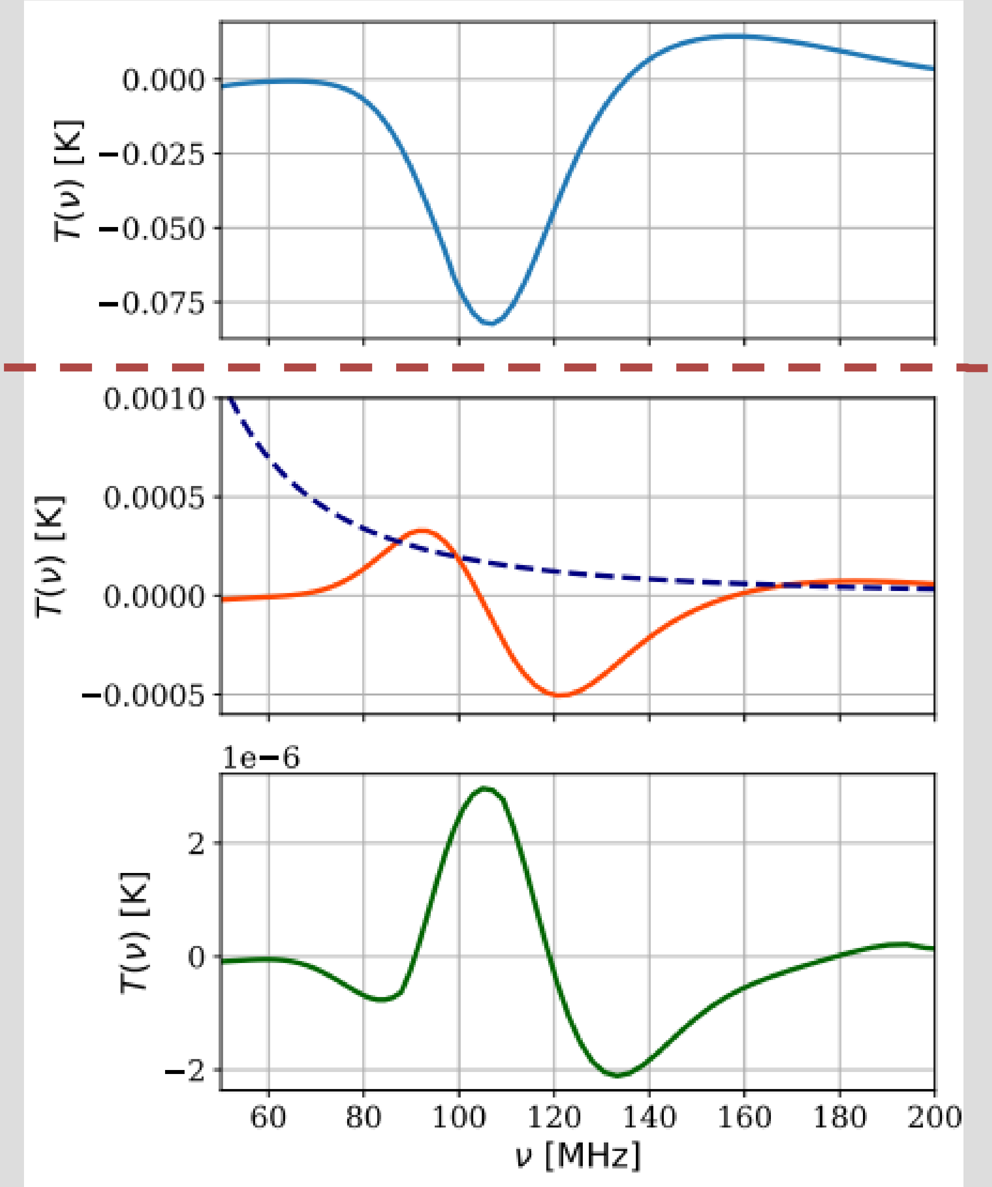
aberration







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



−−− monopole (M)

anisotropic measure

−−− dipole = $\left(\delta T_b(\nu) - \frac{d\delta T_b}{d\ln\nu}\right)\beta$

- Slosar 2017; Deshpande 2018
- feasibility study by Ignatov+2023; Mirocha+2024
- due to Doppler effect
- Y_{10}

−−− quadrupole $\sim -\nu^2 \frac{d^2\delta T_b}{d\nu^2}\beta^2$

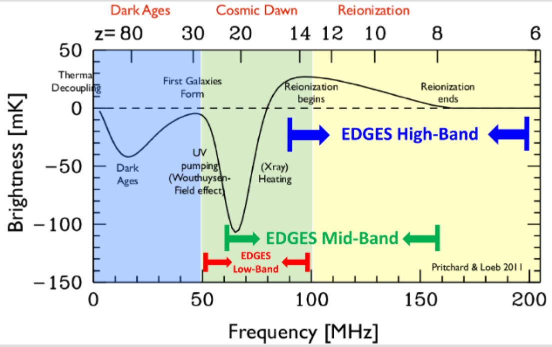
- due to aberration + Doppler
- Y_{20}

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

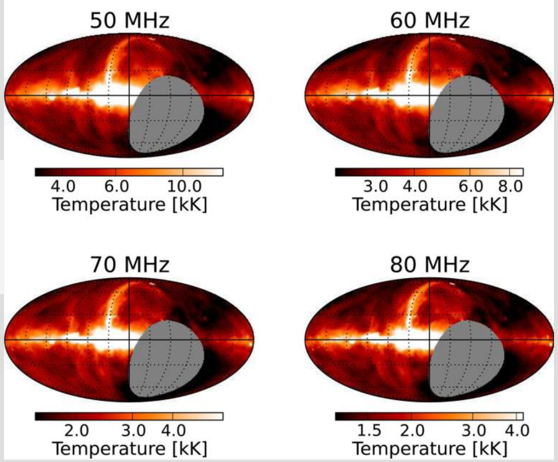
$f_{*,10}$
L_X
α_{esc}
α_*
t_*



  - on foreground

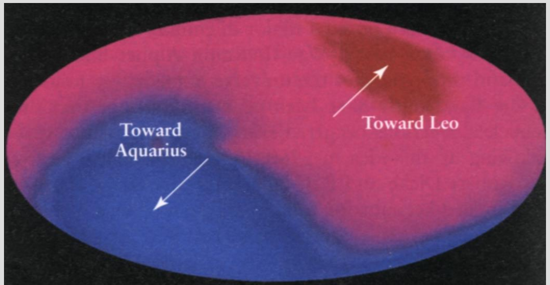
$$T^{(\mathrm{FG})}(\nu,\hat{n}) = \sum_{\ell,m} a_{\ell m}^{(\mathrm{FG})}(\nu) Y_\ell^m(\hat{n})$$

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



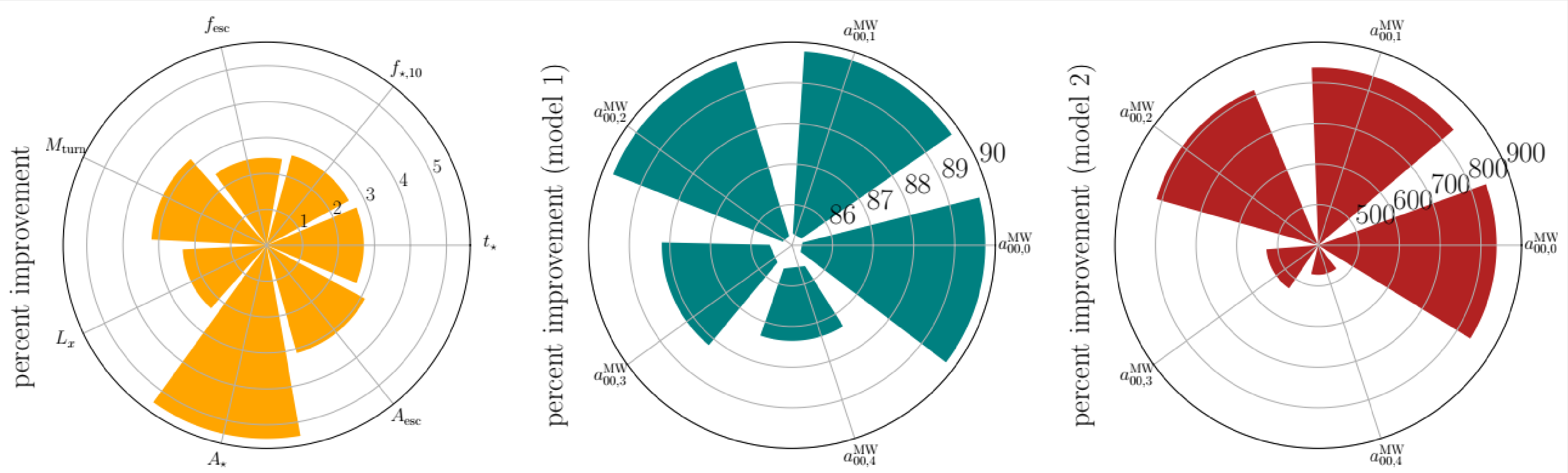
  - on solar velocities (against MW & CMB)

$V_{\odot,\mathrm{MW}}$ $V_{\odot,\mathrm{CMB}}$



Error estimation (Fisher analysis)

- dipole measurement helps parameter estimation
- quadrupole measurement helps it a little more, but much more difficult to measure



- consistency check with direct monopole probe!!!

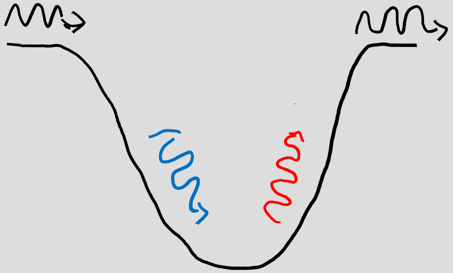
21B anisotropy for monopole: 21cm ISW

(KA & Oh, PRD 109, 043539)

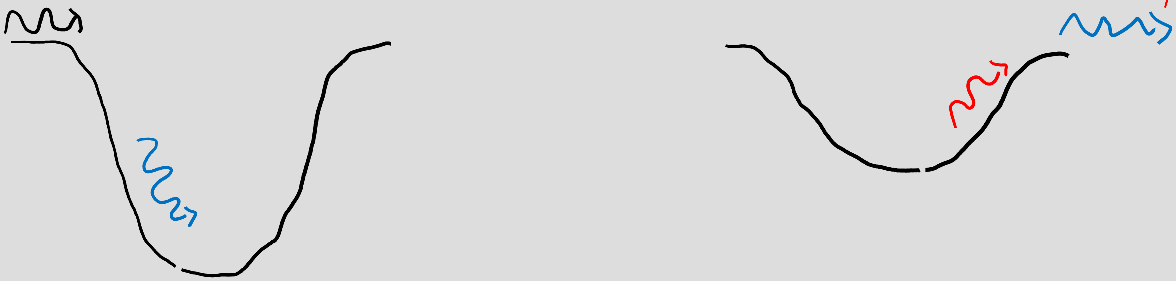
Integrated Sachs-Wolfe effect (ISW; Sachs & Wolfe 1967)

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

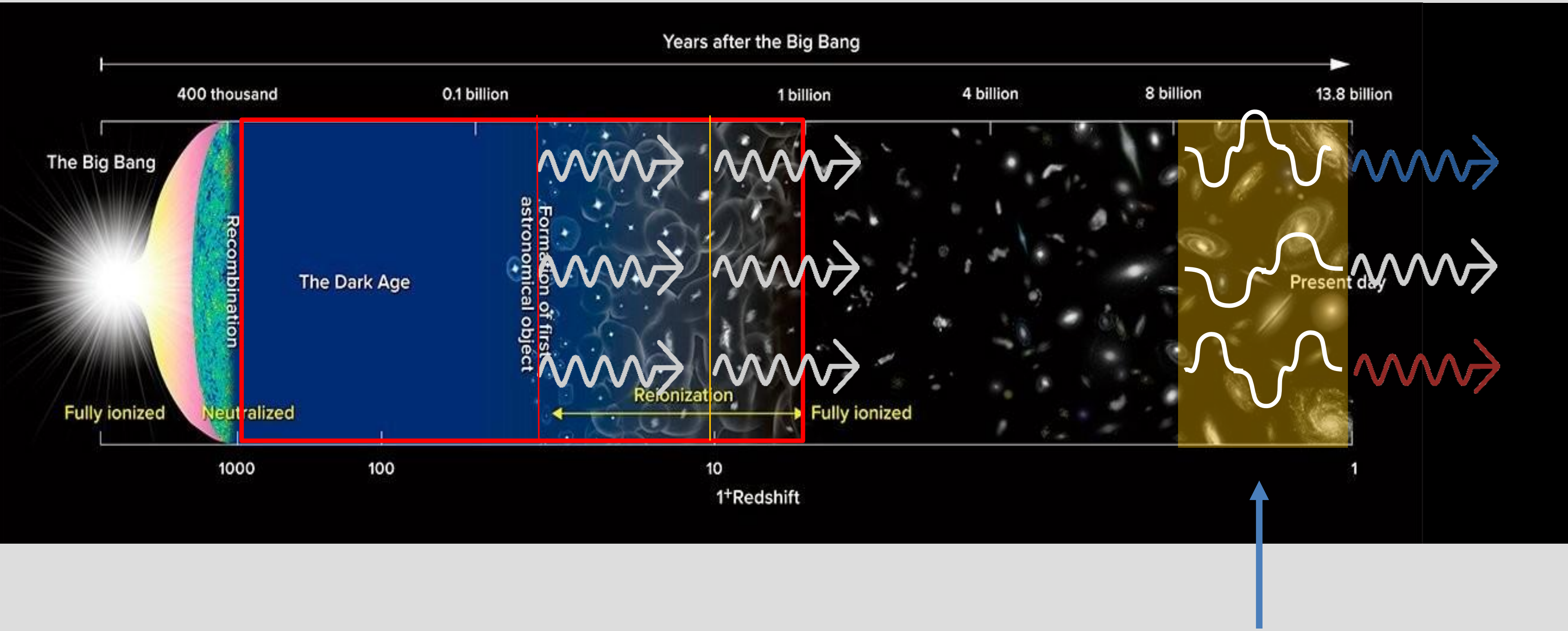
Flat, matter−dominated universe: $\dot{\Phi} = 0$ $(\Phi \sim \frac{M}{R} \sim \frac{a}{a} = const.)$ @ large scales



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



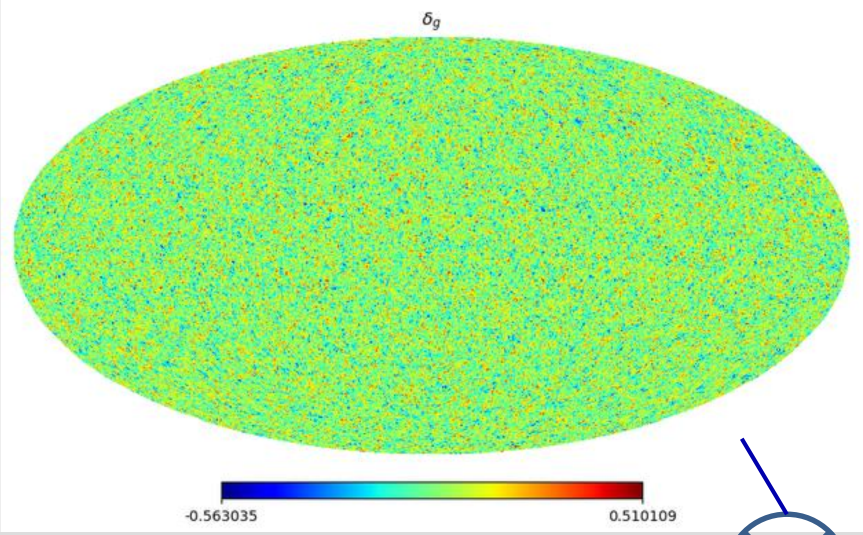
(late-time) ISW zone of influence: z<~2

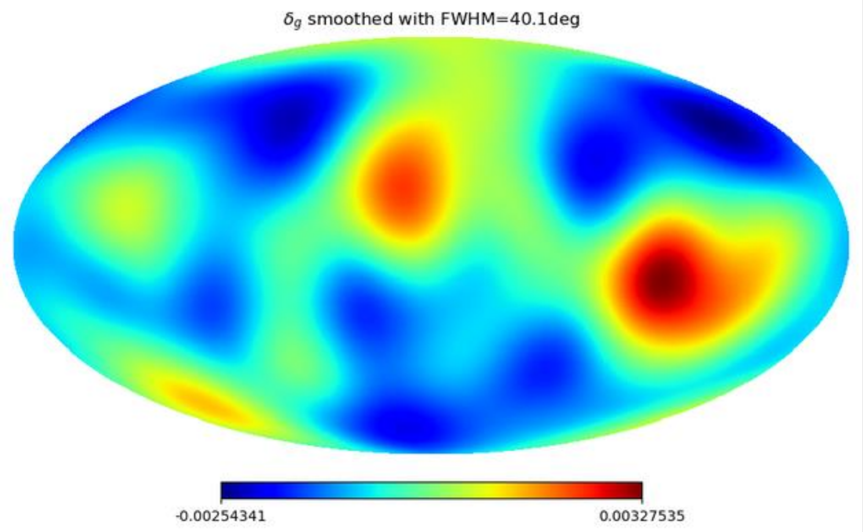


traced by galaxies

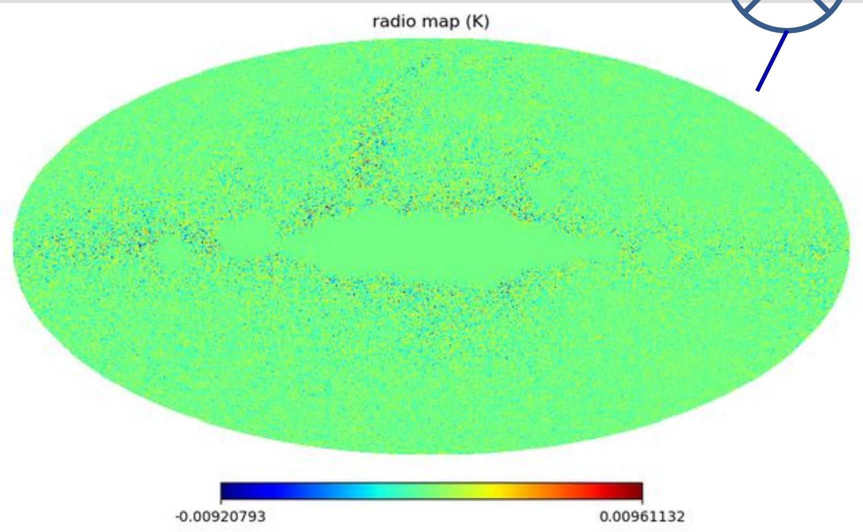
21B ISW map in cross-correlation map

galaxy map

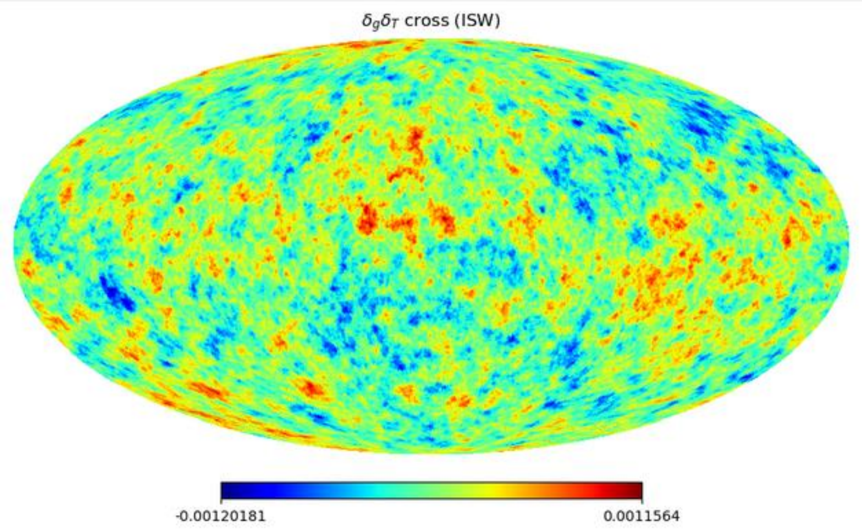




temperature map

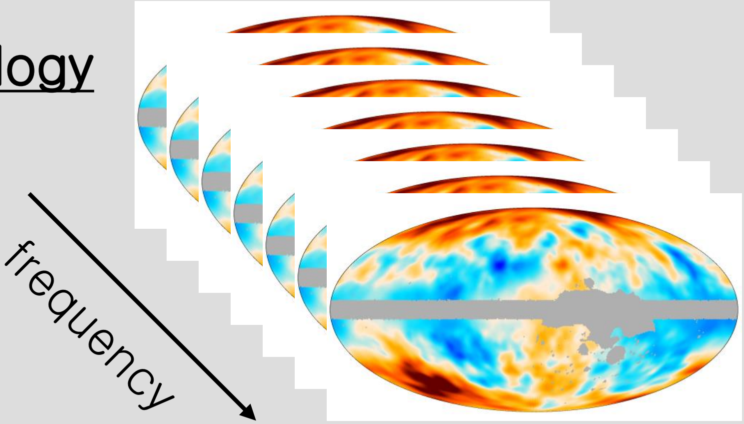


galaxy−temperature cross map



galaxy - δT correlation: 21B ISW measurement

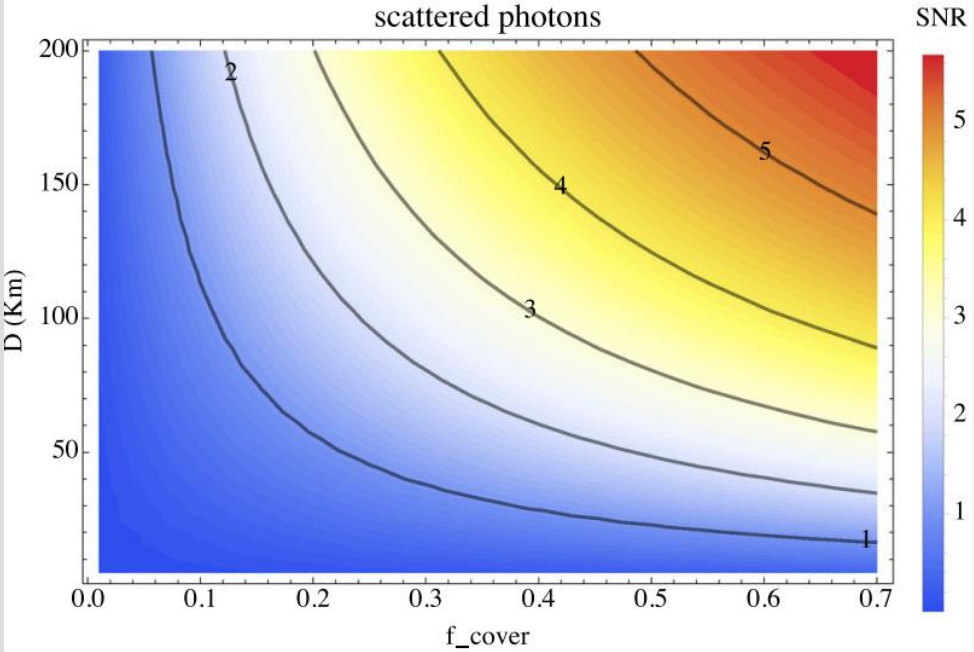
[Raccanelli+2016]: 21B ISW first suggested



- target: <u>**redundancy for cosmology**</u>
- $C_\ell^{gT_{21}}(\nu)$
- estimated sensitivity: **impractical**!

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

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



- us: “Not so fast!”

galaxy - δT correlation: 21B ISW measurement

Low frequency:

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

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

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

CMB (with subscript γ):

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

then,

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

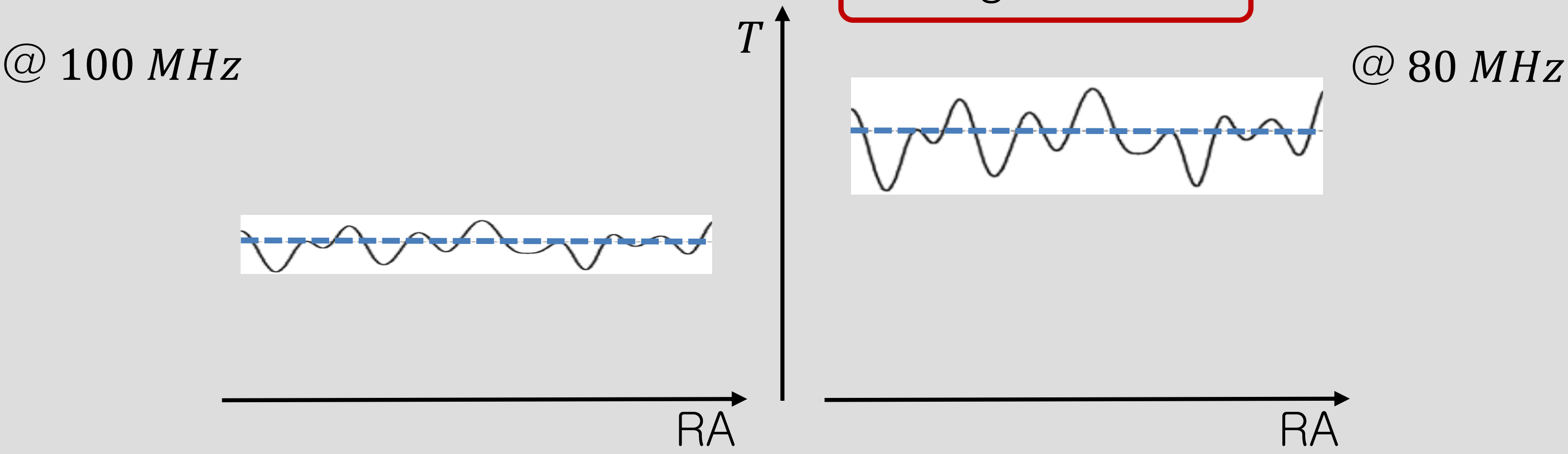
$$\frac{C_\ell^{gT}(\nu)}{C_\ell^{gT_\gamma}} - 1 = \frac{\delta T_{21}(\nu)}{T_\gamma}$$

galaxy - δT correlation: 21B ISW measurement

frequency dependence:

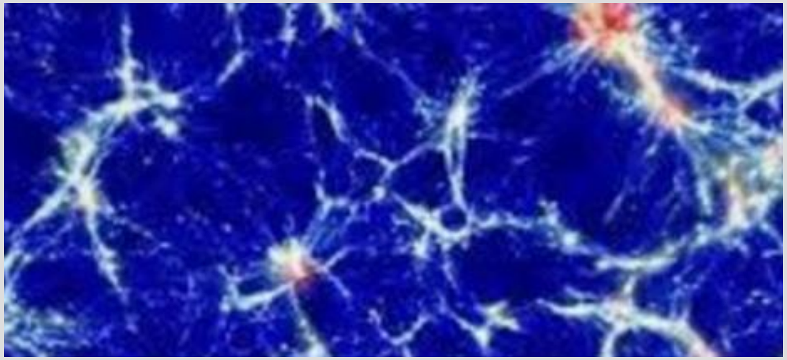
$$C_\ell^{gT}(\nu) \propto T_{21}(\nu) = \boxed{\langle T_b(\nu)\rangle} - \frac{\partial \langle T_b(\nu)\rangle}{\partial \ln \nu}$$

average 21B @ ν



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

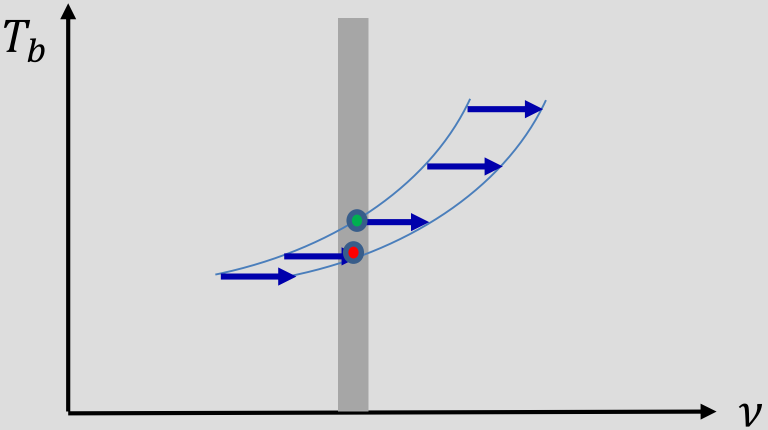
→ same fluctuation pattern on sky, but different contrast



galaxy - δT correlation: 21B ISW measurement

frequency dependence:

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



blueshifted by overdensity
→ observing frequency band probes shorter−wavelength $\langle T_b(\nu)\rangle$

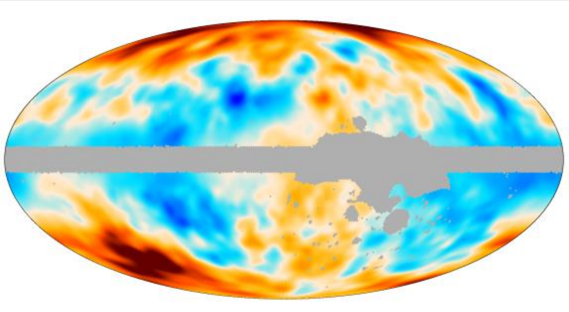
** max($T_{21}(\nu)$) gets boosted from max($\langle T_b(\nu)\rangle$) by ⊗ ~ 2 − 5

galaxy - δT correlation: 21B ISW measurement

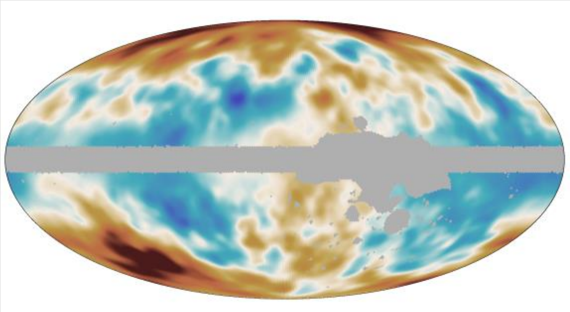
frequency dependence:

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

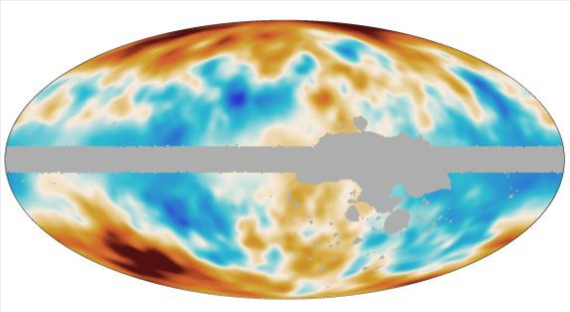
$\nu =$



80 MHz



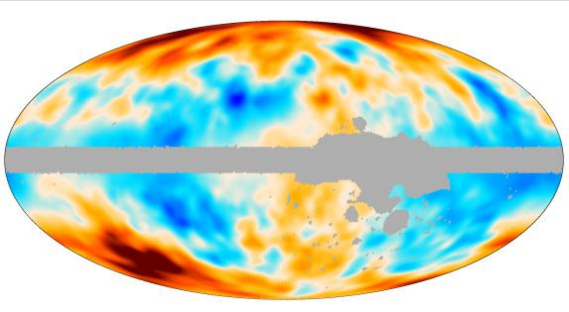
100 MHz

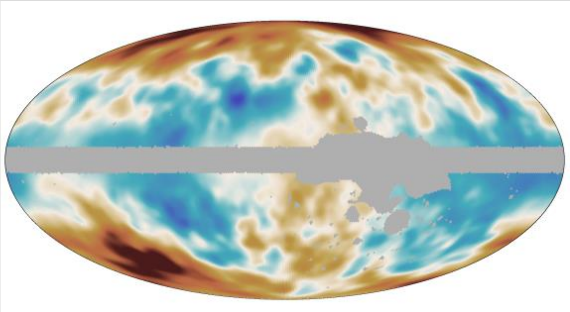


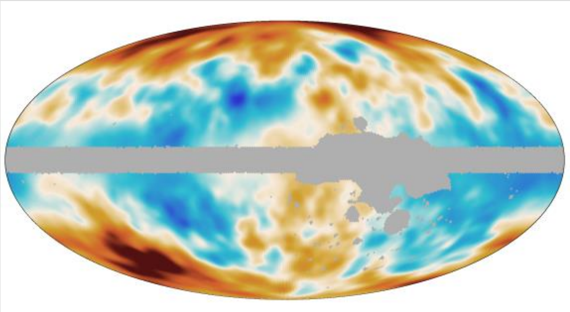
120 MHz

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

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

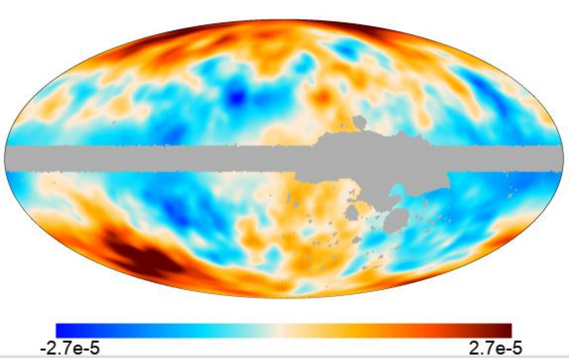






ν = 80 MHz 100 MHz 120 MHz

÷



× 2.7K − 2.7K

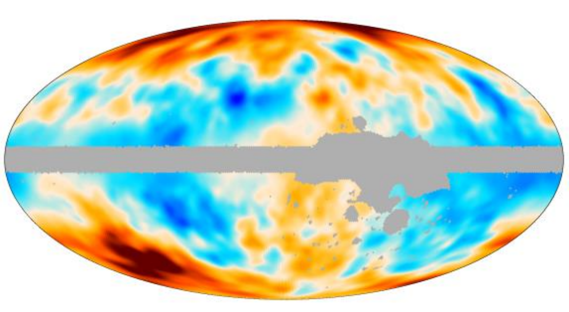
CMB

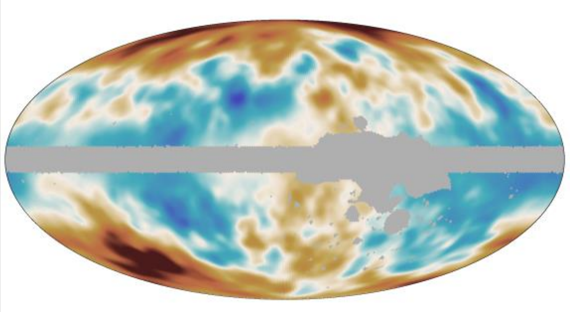
galaxy auto
(SPHEREX)

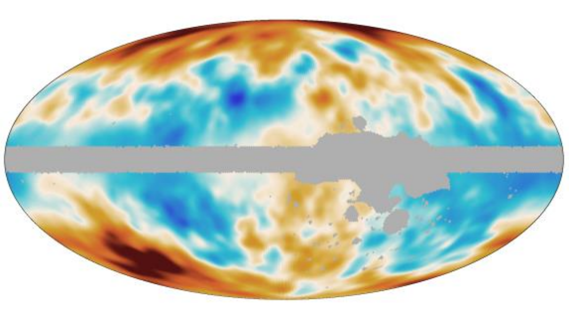
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar\nu) = \frac{\delta T_{21}^2(\bar\nu)}{\langle T_{\gamma,0}\rangle^2}\sum_{\ell=\ell_{\min}}^{\ell_{\max}}\left[\frac{(C_\ell^{gg}+\bar n_g^{-1})\left\{C_\ell^{\delta T_b\delta T_b}(\bar\nu)+\epsilon_{\ell,T}(\bar\nu)+\left(\frac{\delta T_{21}(\bar\nu)}{\langle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

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

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







ν = 80 MHz 100 MHz 120 MHz

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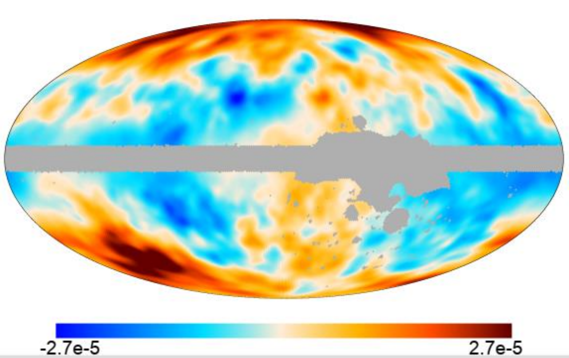


× 2.7K − 2.7K

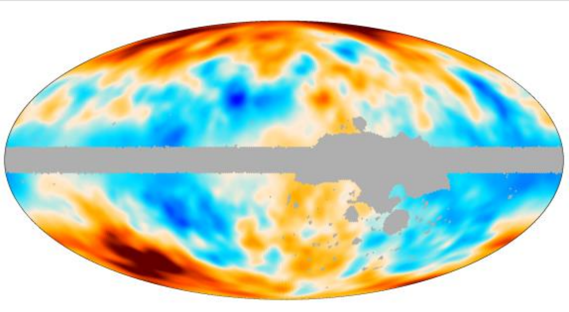
CMB

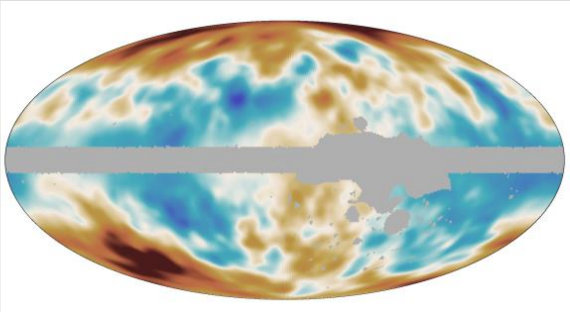
21cm temperature auto

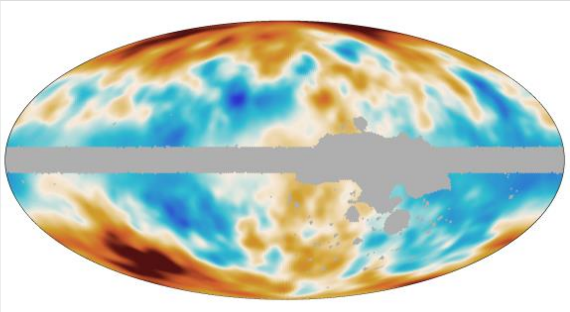
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0}\rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{\left(C_\ell^{gg} + \bar{n}_g^{-1}\right) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta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

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

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







ν = 80 MHz 100 MHz 120 MHz

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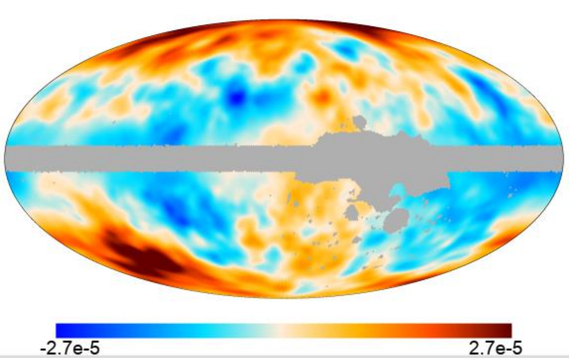


× 2.7K − 2.7K

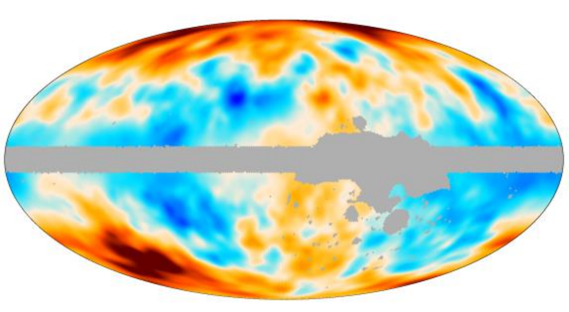
CMB

sky brightness

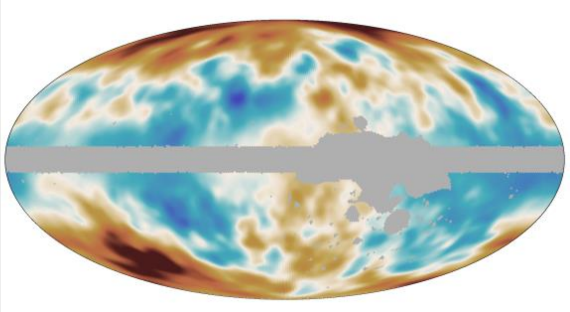
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0}\rangle^2} \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \left[\frac{(C_\ell^{gg} + \bar{n}_g^{-1}) \left\{ C_\ell^{\delta T_b \delta T_b}(\bar{\nu}) + \epsilon_{\ell,T}(\bar{\nu}) + \left(\frac{\delta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

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

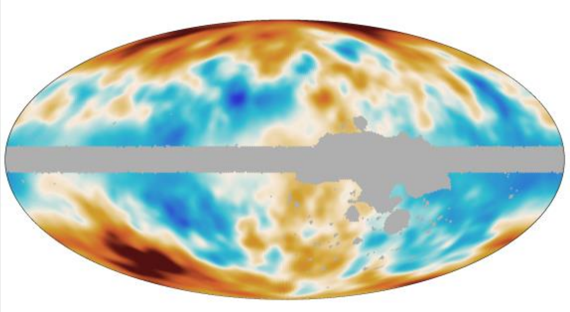
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}}(\nu)}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$



ν = 80 MHz



100 MHz



120 MHz

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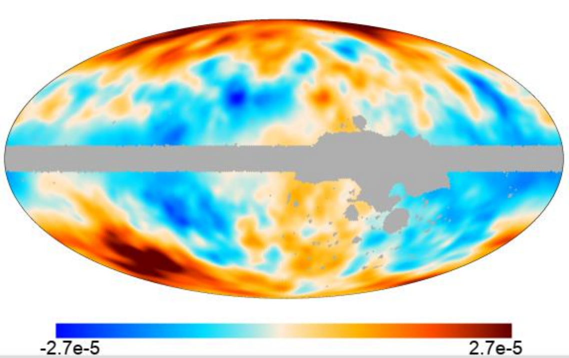


CMB

× 2.7K − 2.7K

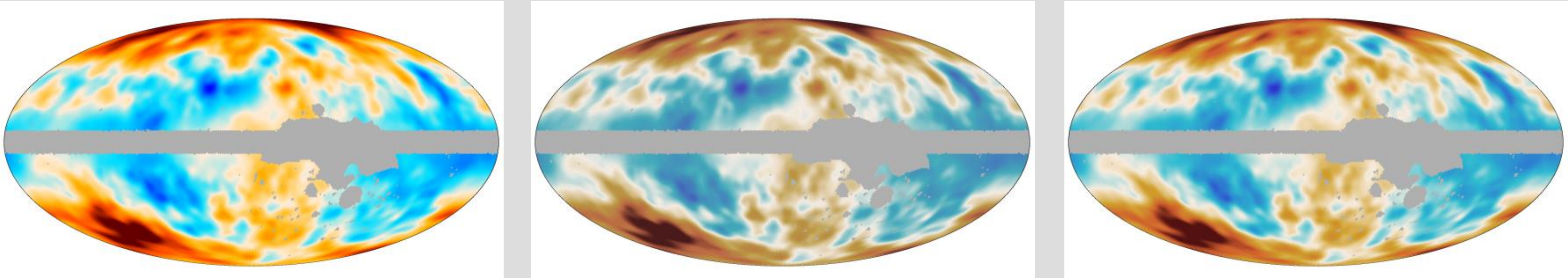
CMB temperautre auto

(Planck)

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

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

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



ν = 80 MHz 100 MHz 120 MHz

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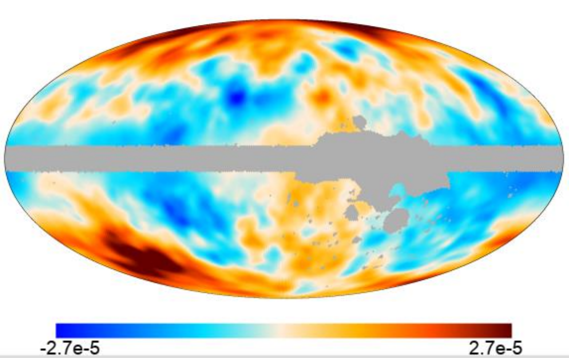


× 2.7K − 2.7K

CMB

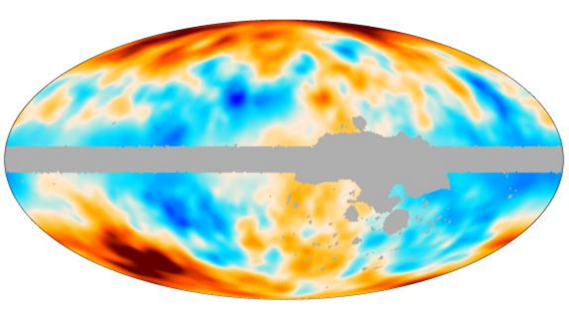
$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2(\bar{\nu}) = \frac{\delta T_{21}^2(\bar{\nu})}{\langle T_{\gamma,0}\rangle^2}\sum_{\ell=\ell_{\min}}^{\ell_{\max}}\left[\frac{(C_\ell^{gg}+\bar{n}_g^{-1})\left\{C_\ell^{\delta T_b\delta T_b}(\bar{\nu})+\epsilon_{\ell,T}(\bar{\nu})+\left(\frac{\delta T_{21}(\bar{\nu})}{\langle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

CMB ISW (Planck)

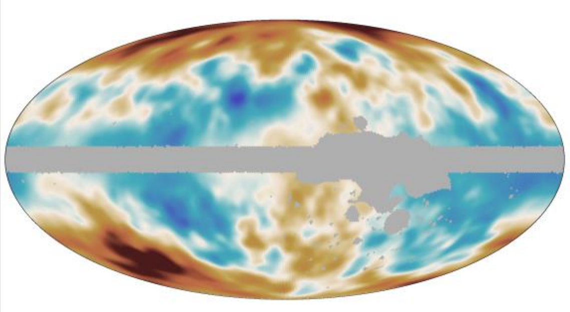
galaxy - δT correlation: (21B ISW) / (CMB ISW)

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

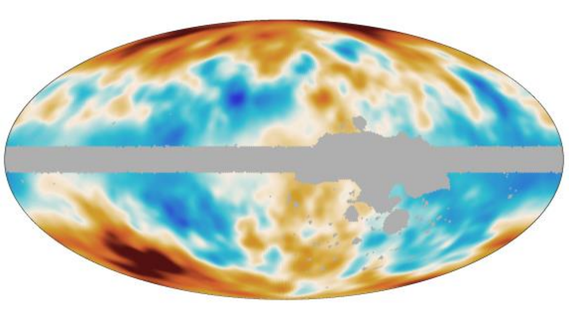
ν =



80 MHz



100 MHz



120 MHz

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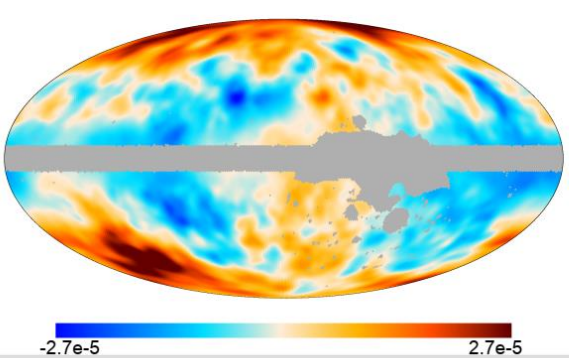


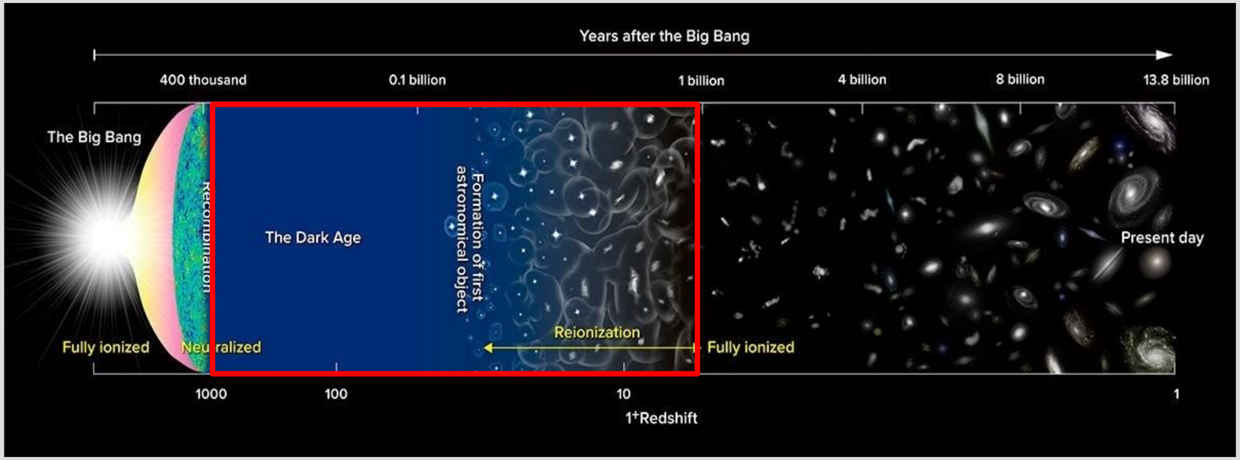
CMB

× 2.7K − 2.7K

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

galaxy - δT correlation: 21B ISW measurement

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

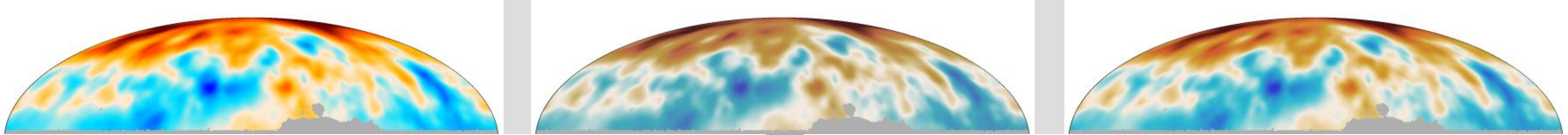


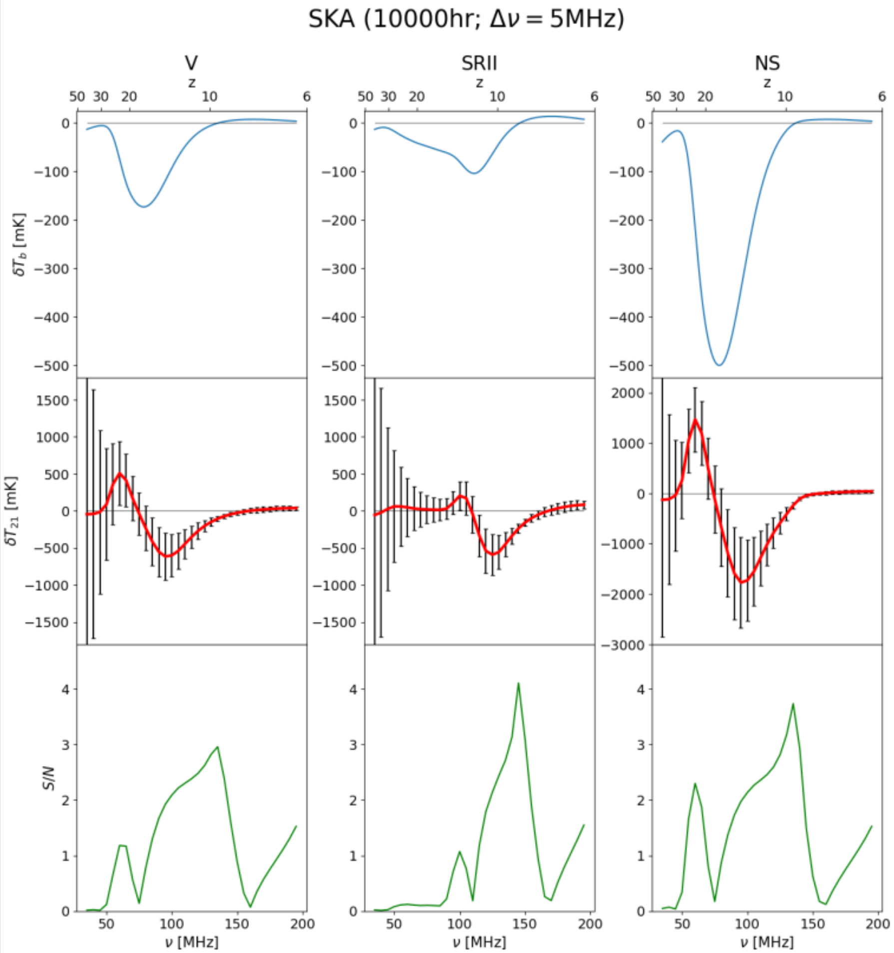
- Noise estimate basis
  - SKA1-Low ~500 stations, small UV ($2 \le \ell < 20$) gets fair observation time, sky coverage ~70%
  - Large # of survey galaxies: SPHEREX-like $\frac{dN}{d\Omega} \ge \left(\frac{b}{2}\right)^{-2} 2 \times 10^{7}\mathrm{sr}^{-1}$

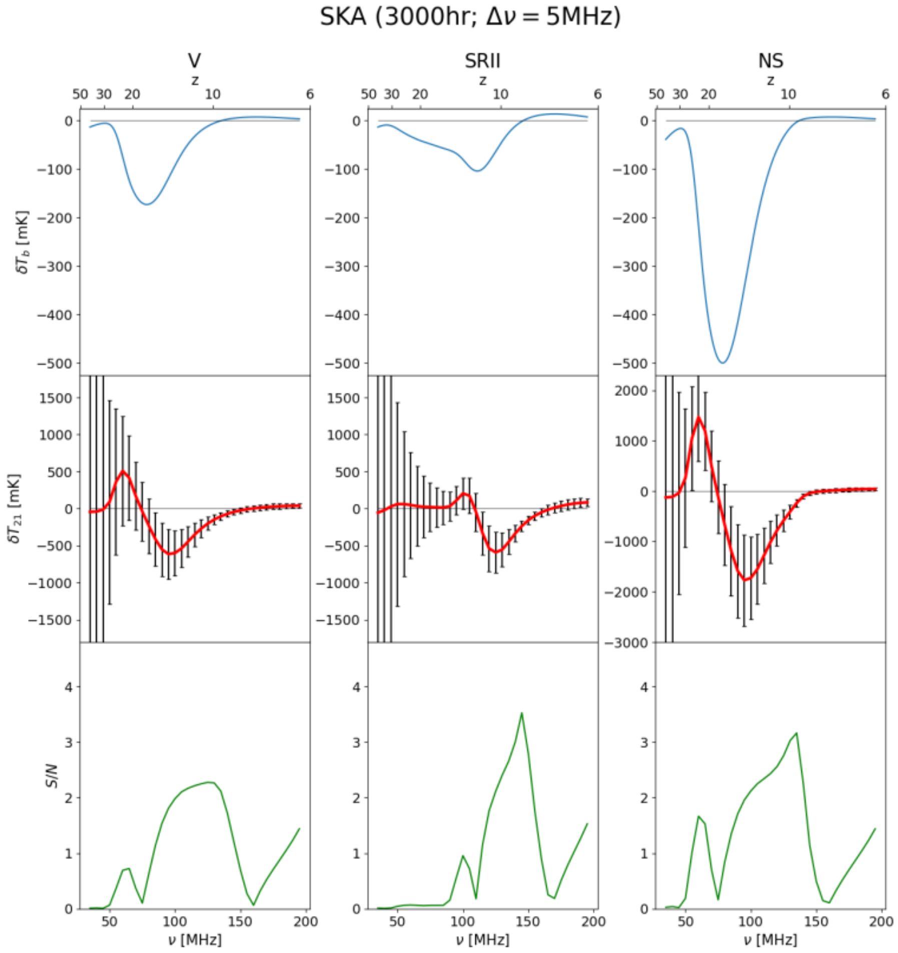
- High-z (z>~2) exgal background still to affect 21B ISW
  - for future study

galaxy - δT correlation: 21B ISW measurement

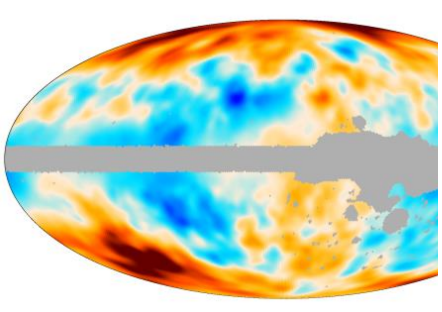
observable: $\delta T_{21}(\nu) \equiv \left(\frac{C_\ell^{gT_{21}}(\nu)}{C_\ell^{gT_\gamma}} - 1 \right) T_\gamma$ ← galaxy survey + CMB + 21cm

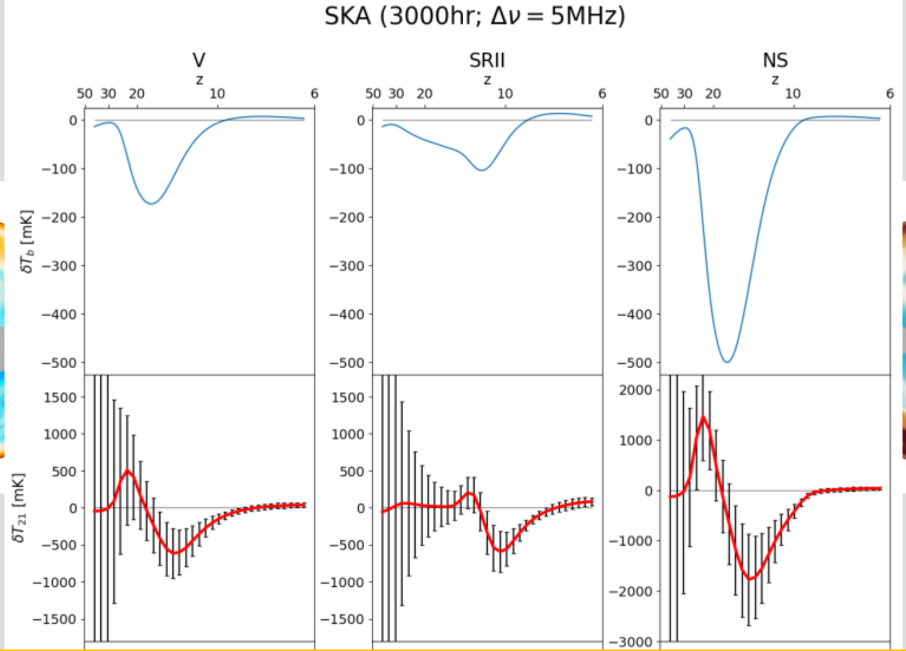


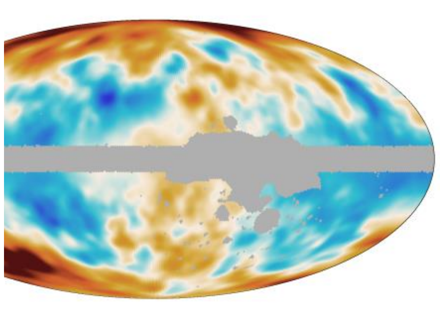




galaxy - δT correlation: 21B ISW measurement







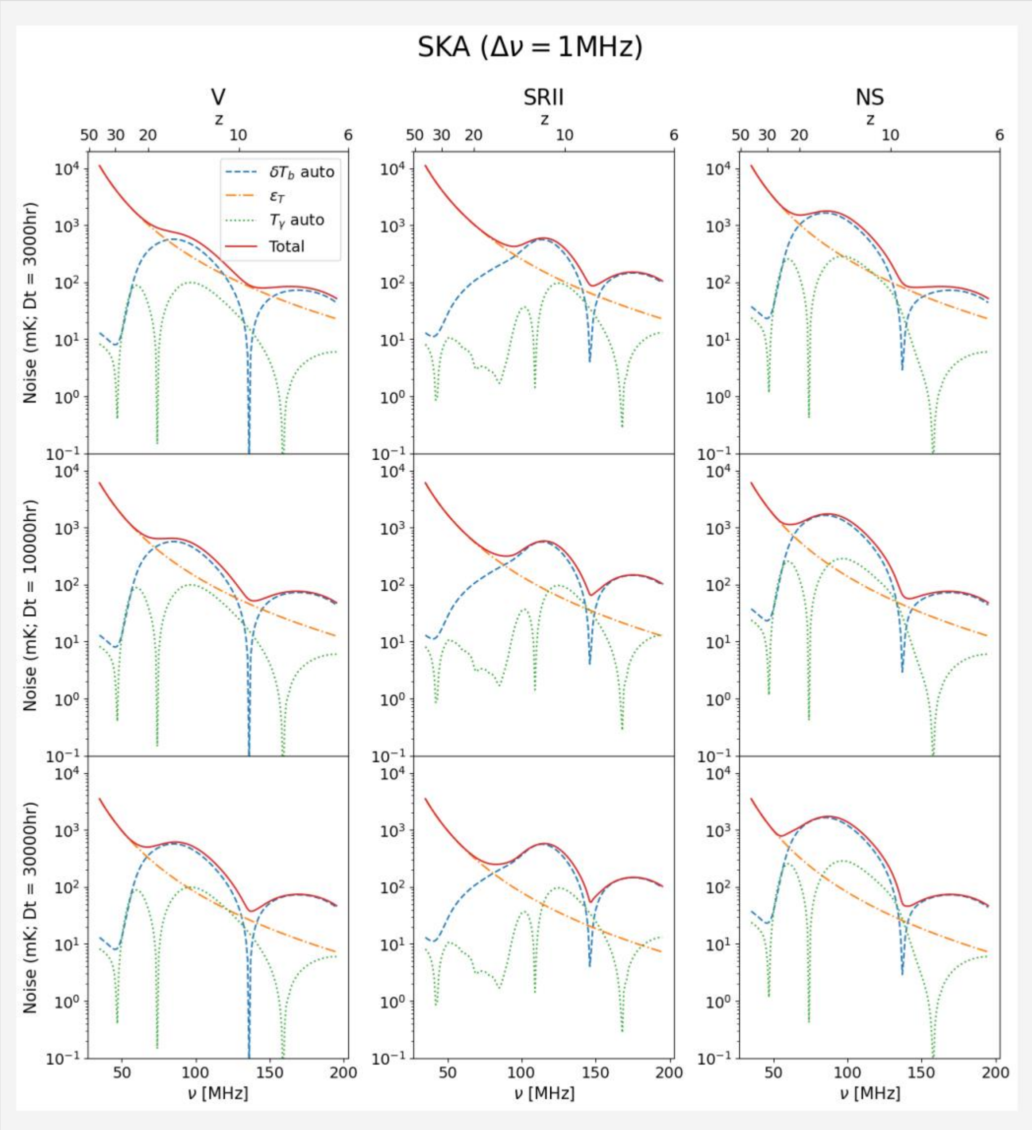
With SKA1-LOW,

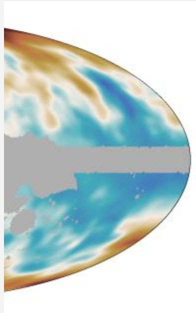
(1) >~2000 hr measure of 21-cm ISW will be able to probe 21-cm monopole spectrum.

(2) <~400 hr measure of 21-cm ISW may test (rule out) EDGES signal

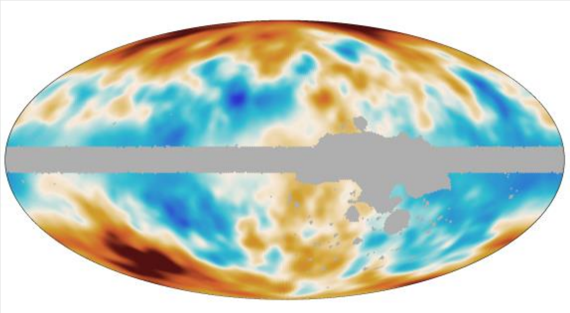
galaxy - δT correlation: 21B ISW measurement

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

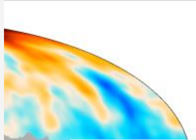


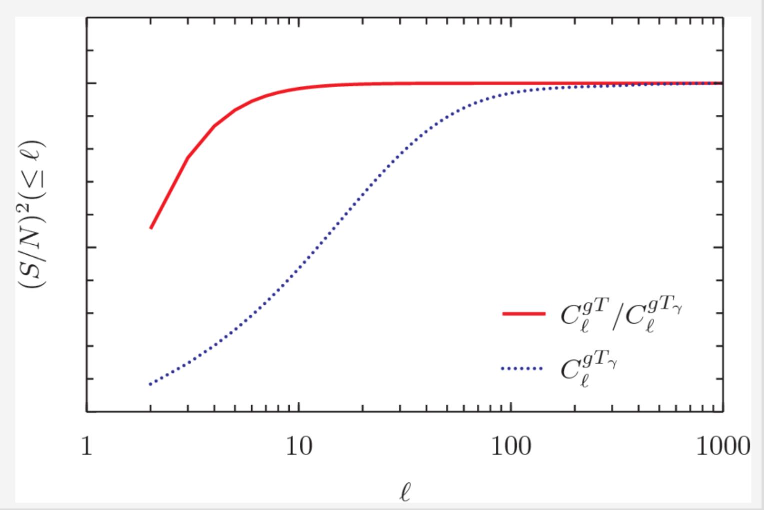


z



120 MHz



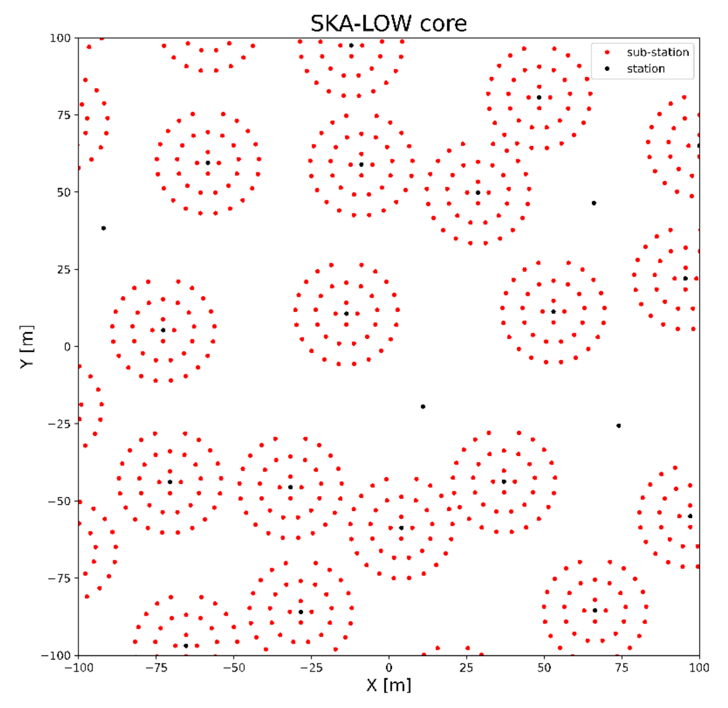


21B ISW with SKA

with

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

substationing for low-ℓ sensitivity boost



Summary / Ad

- 21cm monopole extraction using interferometers
  - 21cm dipole = $\left(\langle\delta T_b(\nu)\rangle - \frac{\partial\langle\delta T_b(\nu)\rangle}{\partial \ln \nu}\right)\beta$ with $\beta \sim 10^{-3}$
  - 21cm ISW = $\left(\langle\delta T_b(\nu)\rangle - \frac{\partial\langle\delta T_b(\nu)\rangle}{\partial \ln \nu}\right)\int \dot{\Phi} d\eta$ with $\int \dot{\Phi} d\eta \sim 10^{-5}$

- multi-frequency 21cm ISW for 21cm monopole extraction
  - galaxy survey (SPHEREX) + CMB (Planck) + 21cm (SKA)

- Which is better

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

- SKA fit for these largest-angle survey?
  - proposed a SKA science book chapter on this, with: A. Deshpande, S. Hotinli, J. Mirocha, J. Pritchard, A. Slosar, C. Trott

- postdoc or grad student position: kjahn@chosun.ac.kr