

21 cm Cosmology and the PopIII IMF

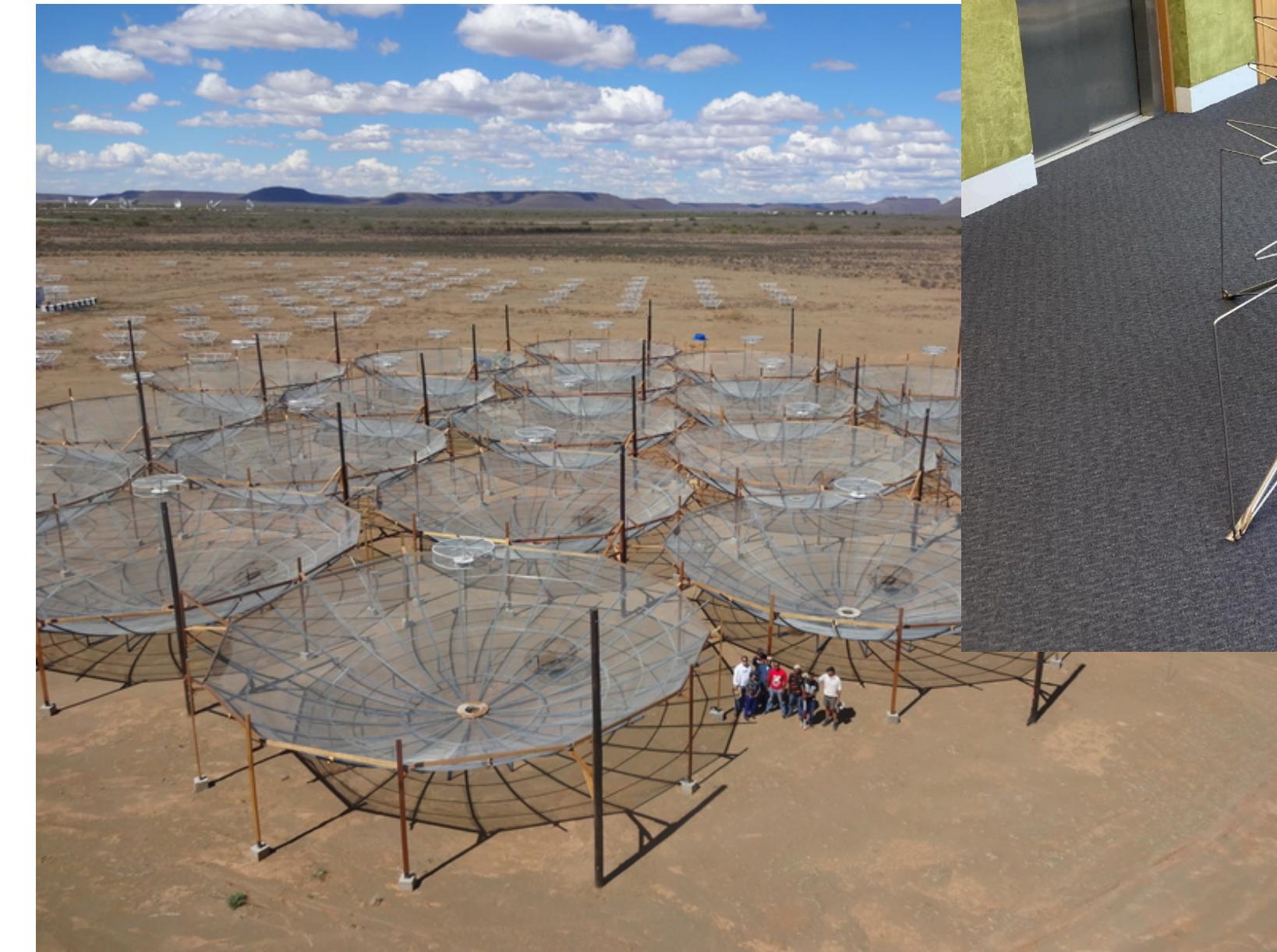
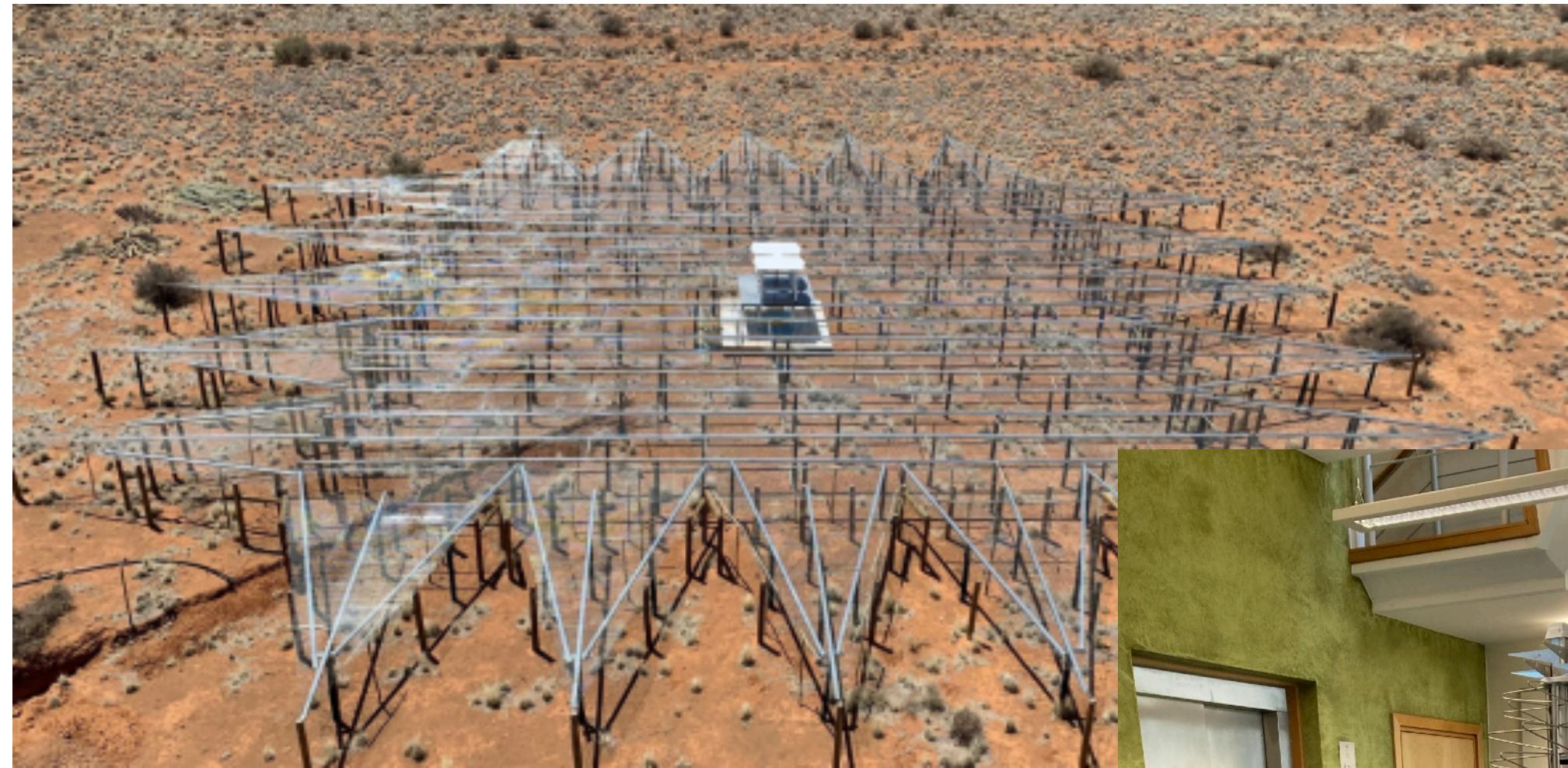
H. Bevins

arXiv:2502.18098

**T. Gessey-Jones, N. Sartorio, A. Fialkov, W. J. Handley, E. de Lera Acedo,
G. M. Mirouh, R. G. Izzard, R. Barkana**

Contents

- Review of 21cm Cosmology
- Observing the 21cm signal
- Simulating the 21cm signal
- PopIII IMF with REACH and the SKA

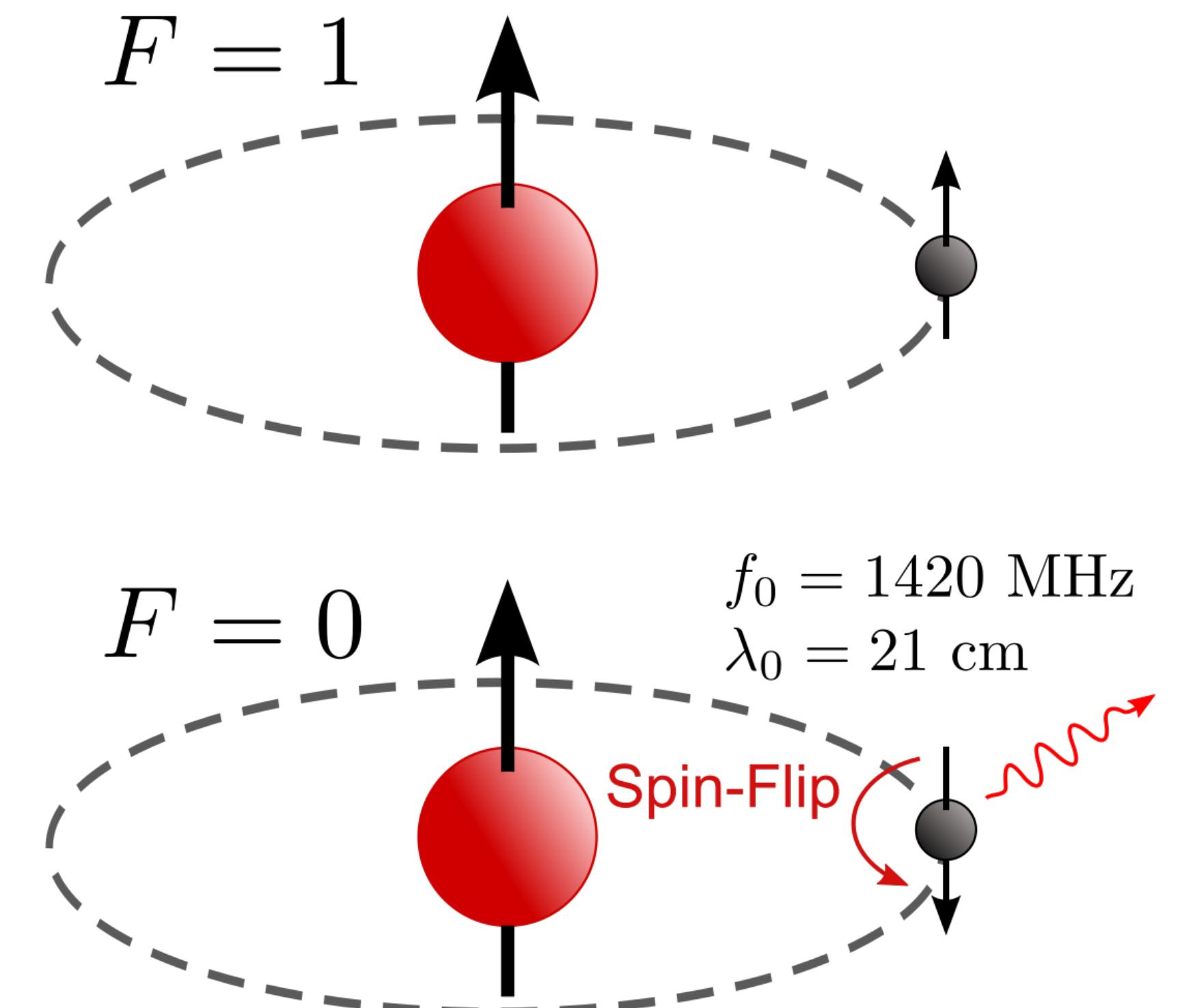


21cm Cosmology

21cm Spin Temperature

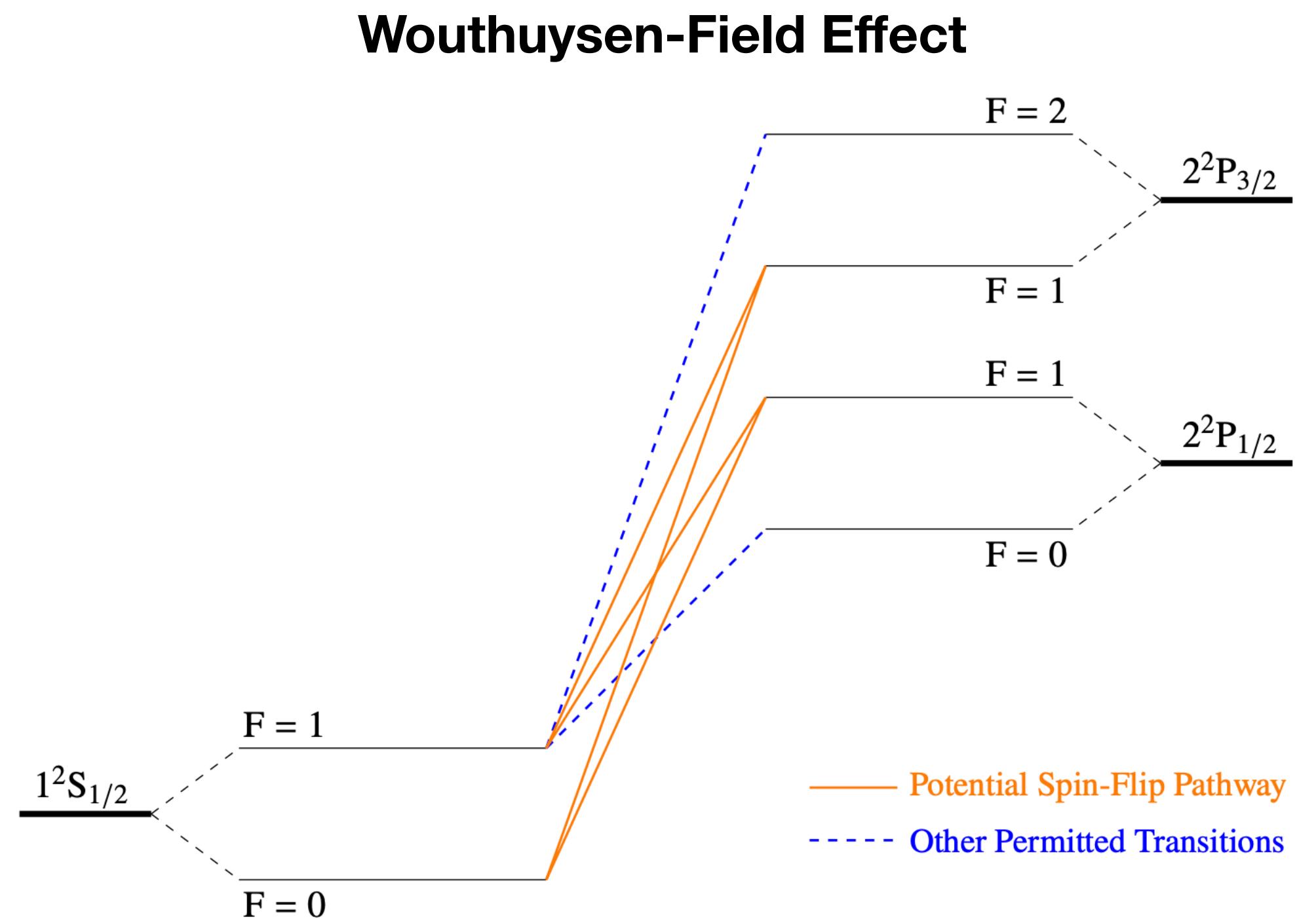
- Forbidden spin flip transition in neutral hydrogen
- So much hydrogen in early universe that this is happening a lot despite being forbidden
- Define a statistical temperature T_s

$$\frac{n_1}{n_0} = 3 \exp\left(-\frac{T_*}{T_s}\right)$$



21cm Spin Temperature

- The transition from one spin state to the other in the early universe is governed by interactions with different radiative fields and collisions
- In particular interactions with the CMB, light from the first stars and various sources of gas heating
- Track how this signal varies over time you can learn about the first stars and cosmology

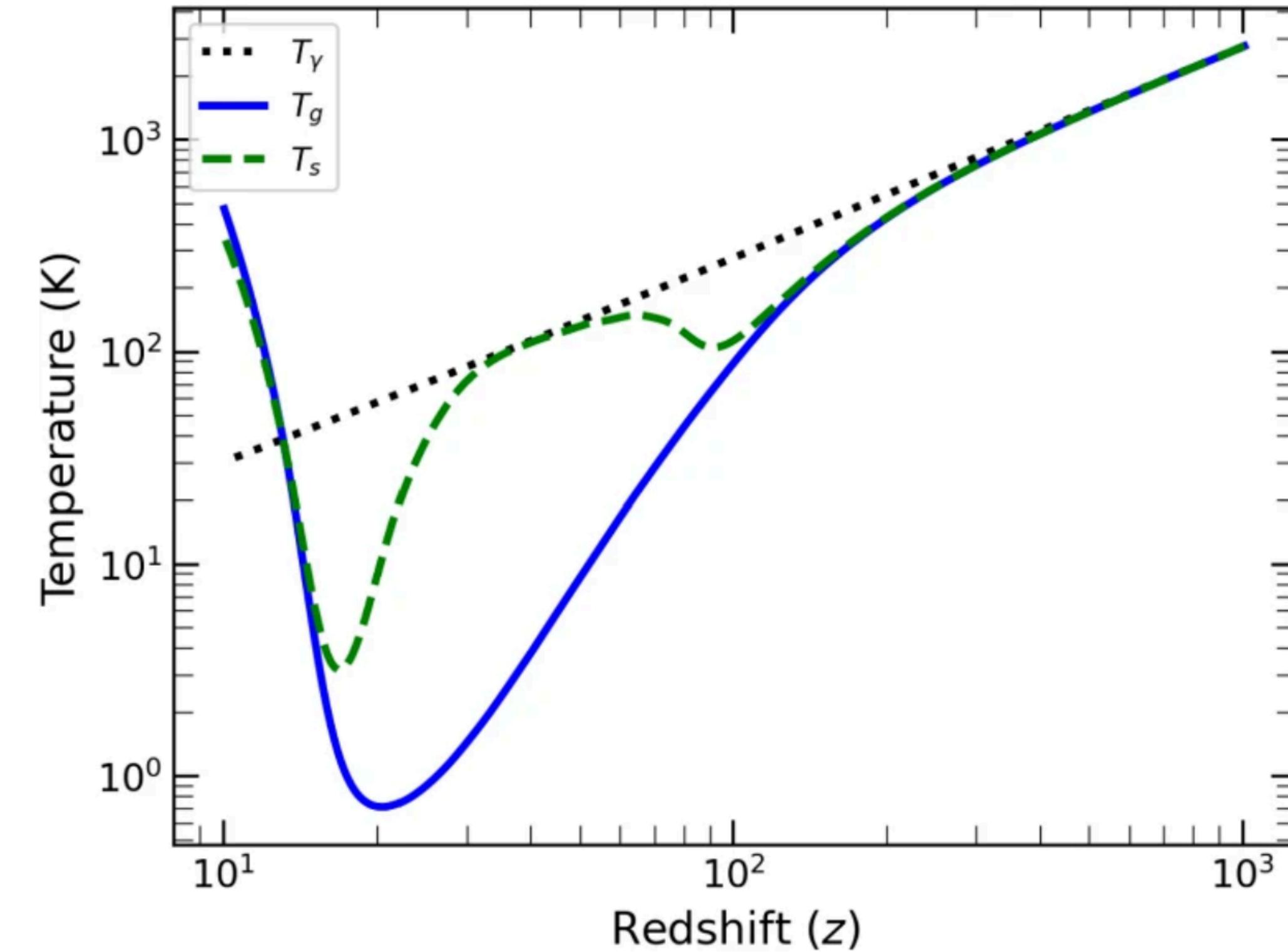


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21cm Signal

- As the processes driving the number of hydrogen atoms with aligned and anti-aligned spins changes over time T_s couples to different fields

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

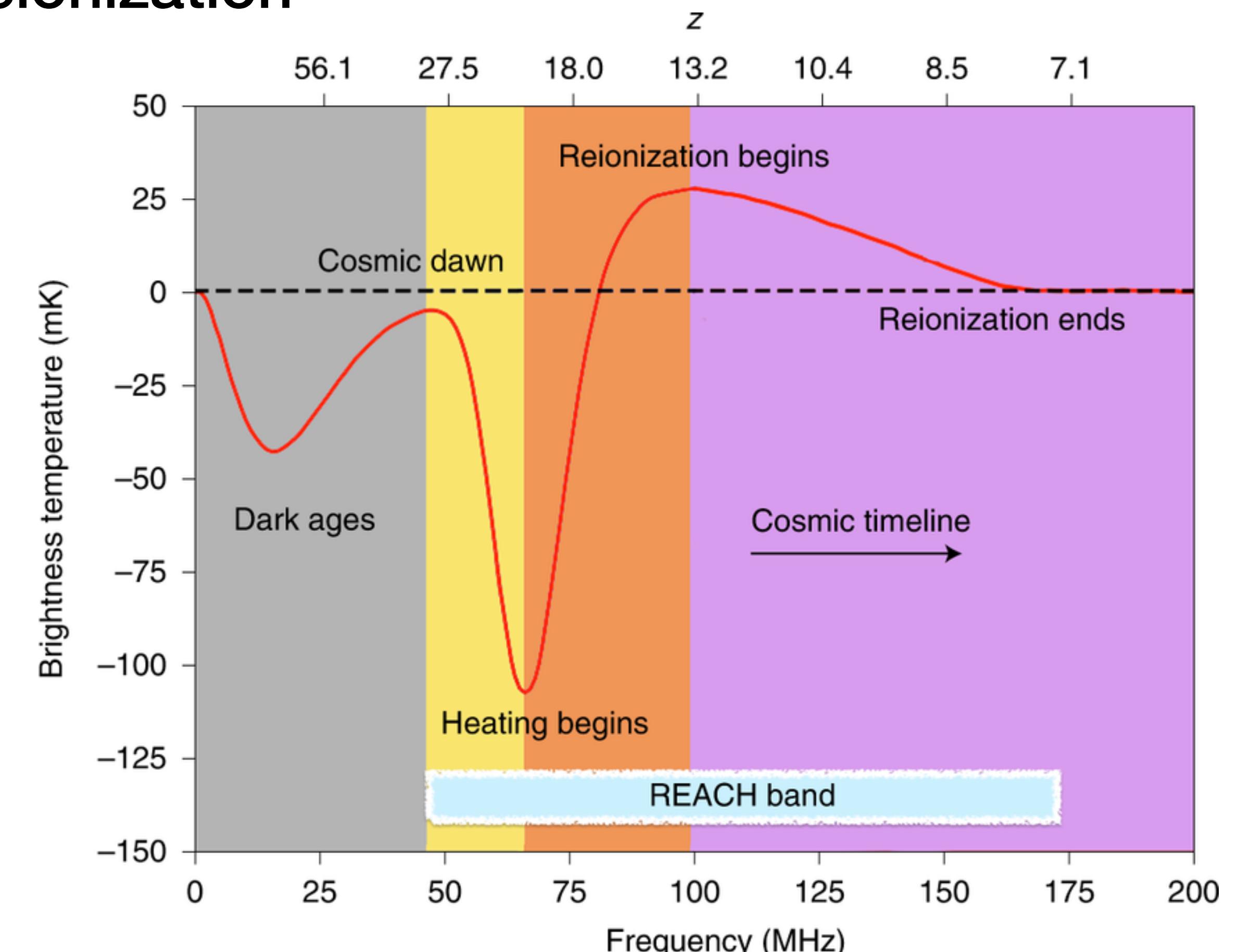


21cm Signal

- Measure the signal relative to the radio background
- Eventually it disappears because of reionization

$$\delta T_b = \frac{T_s - T_\gamma}{1 + z} (1 - \exp(-\tau_{21}))$$

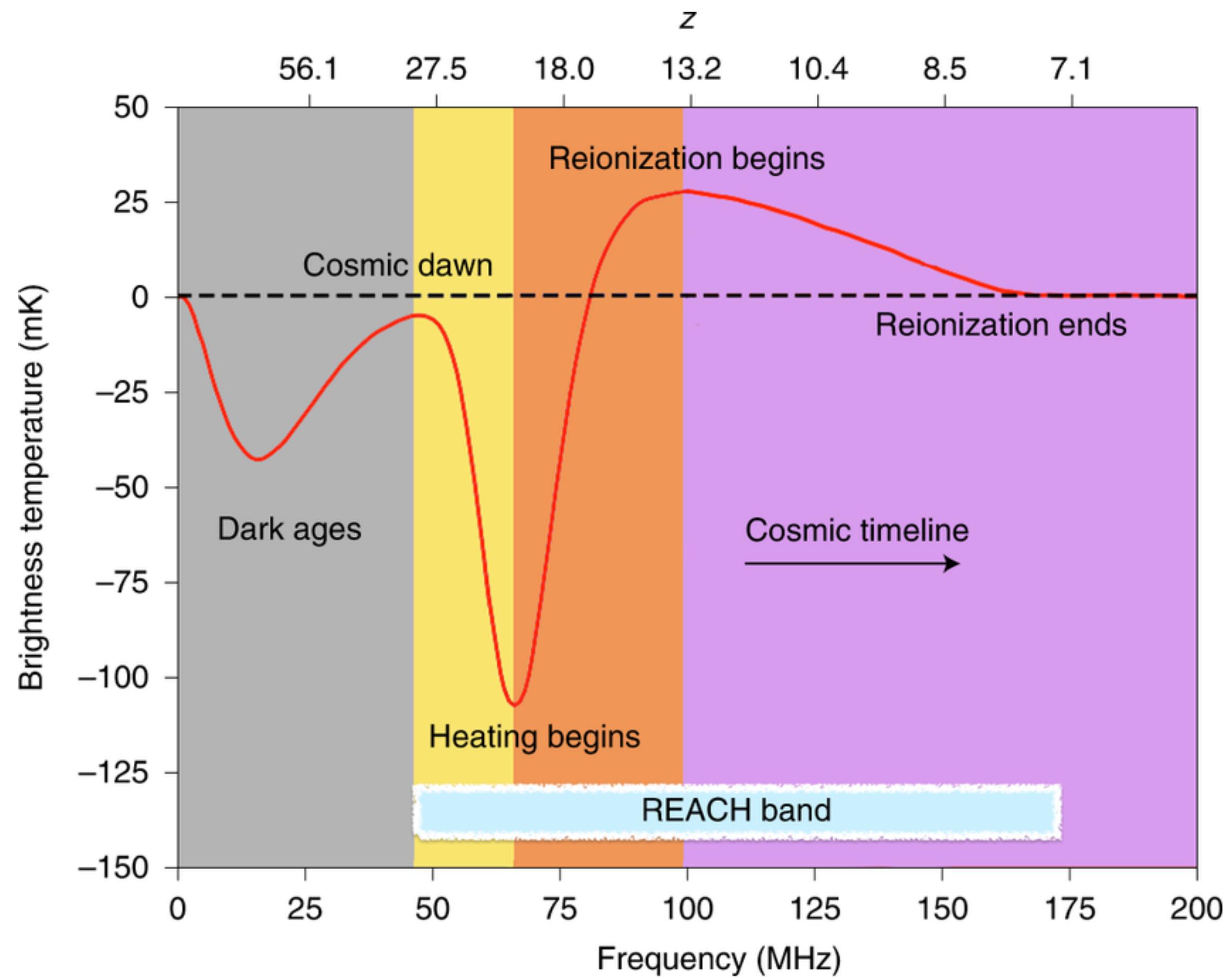
- Signal is redshifted into the low frequency radio band



Observational challenges

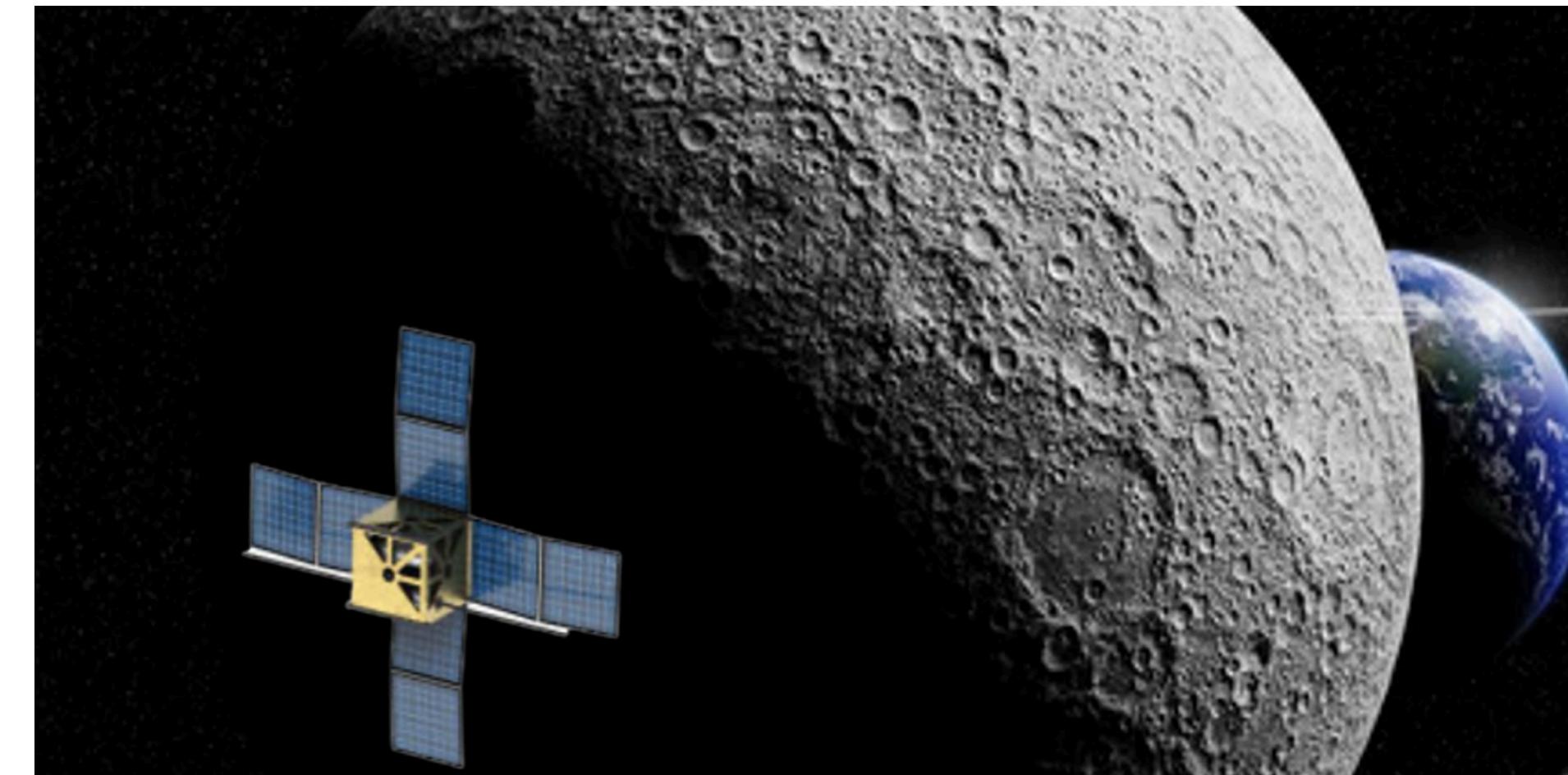
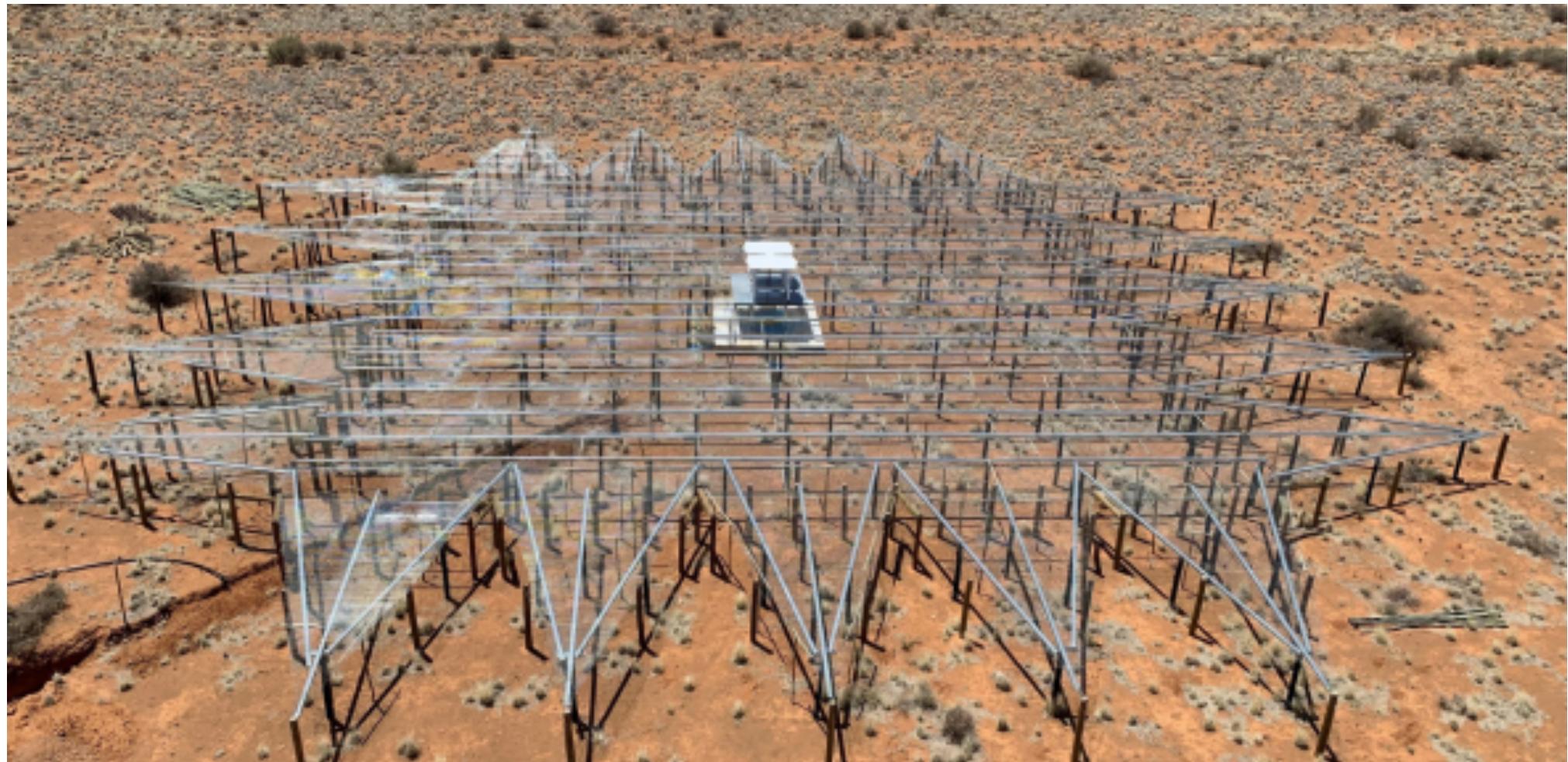
The sky-averaged signal

- The signal can be observed in a few different ways
- This is the global or sky-averaged 21cm signal
- Sensitive to changes in galaxy populations but no spatial information



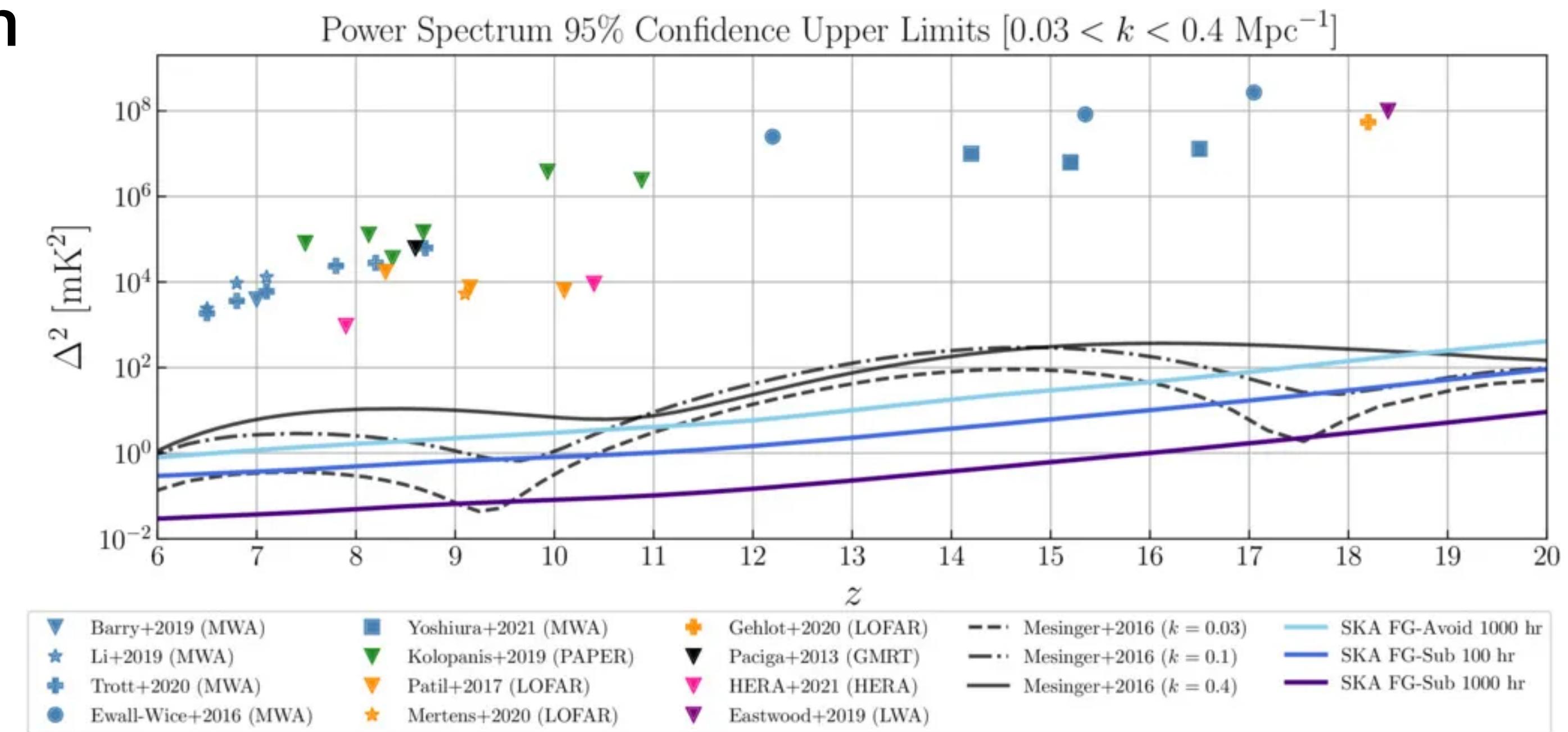
The sky-averaged signal

- Ground based missions target 50-200 MHz
- Cosmic Dawn and Epoch of Reionization
- Looking for first stars
- e.g. REACH
- Spaced based missions will target 5-50 MHz
- Dark Ages before first stars
- Purely Cosmology
- e.g. CosmoCube



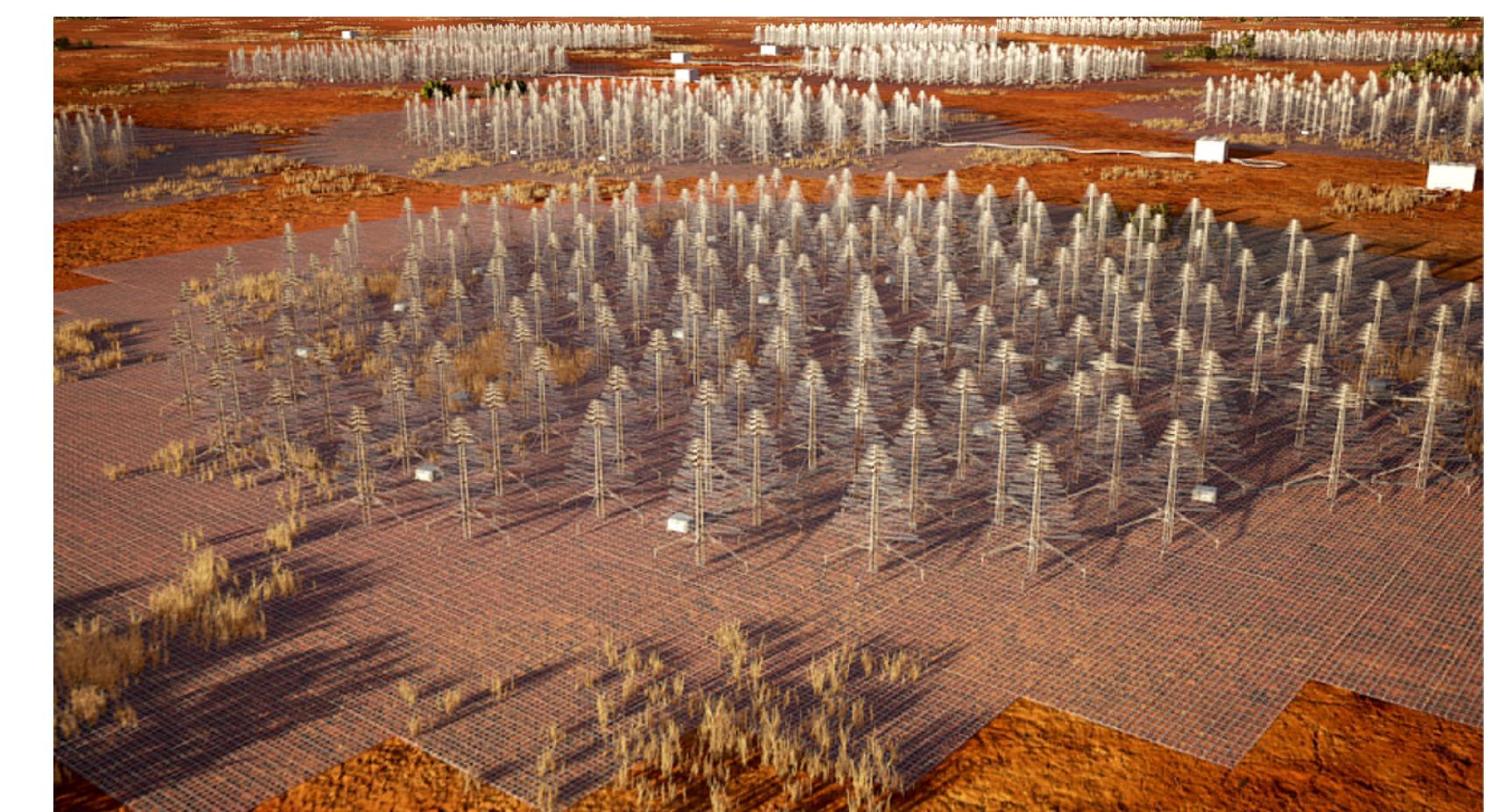
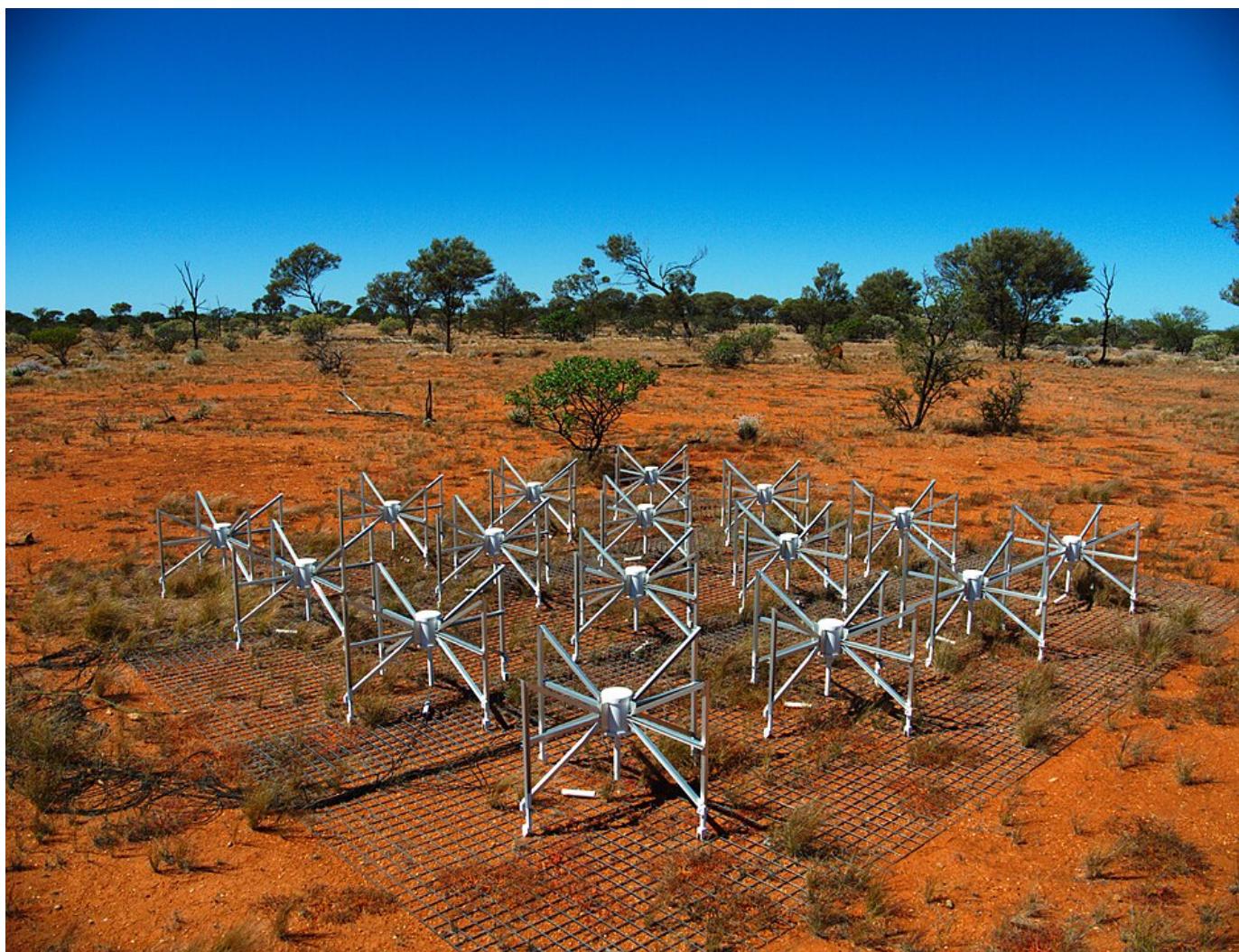
Fluctuations

- Look at fluctuations in the 21cm signal across the sky and time with a power spectrum
- Typically we look at spherically averaged 1D power spectrum at fixed redshift
- But also the 2D power spectrum $P(k_{\parallel}, k_{\perp})$



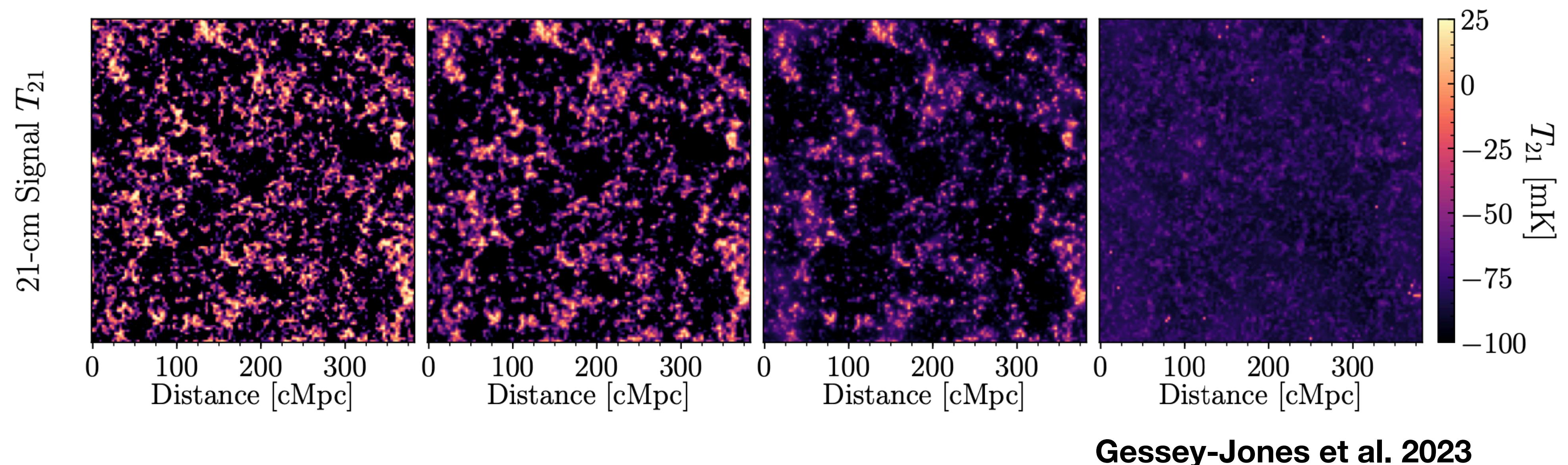
Fluctuations

- Observe with interferometers like HERA, LOFAR, MWA and eventually SKA Low



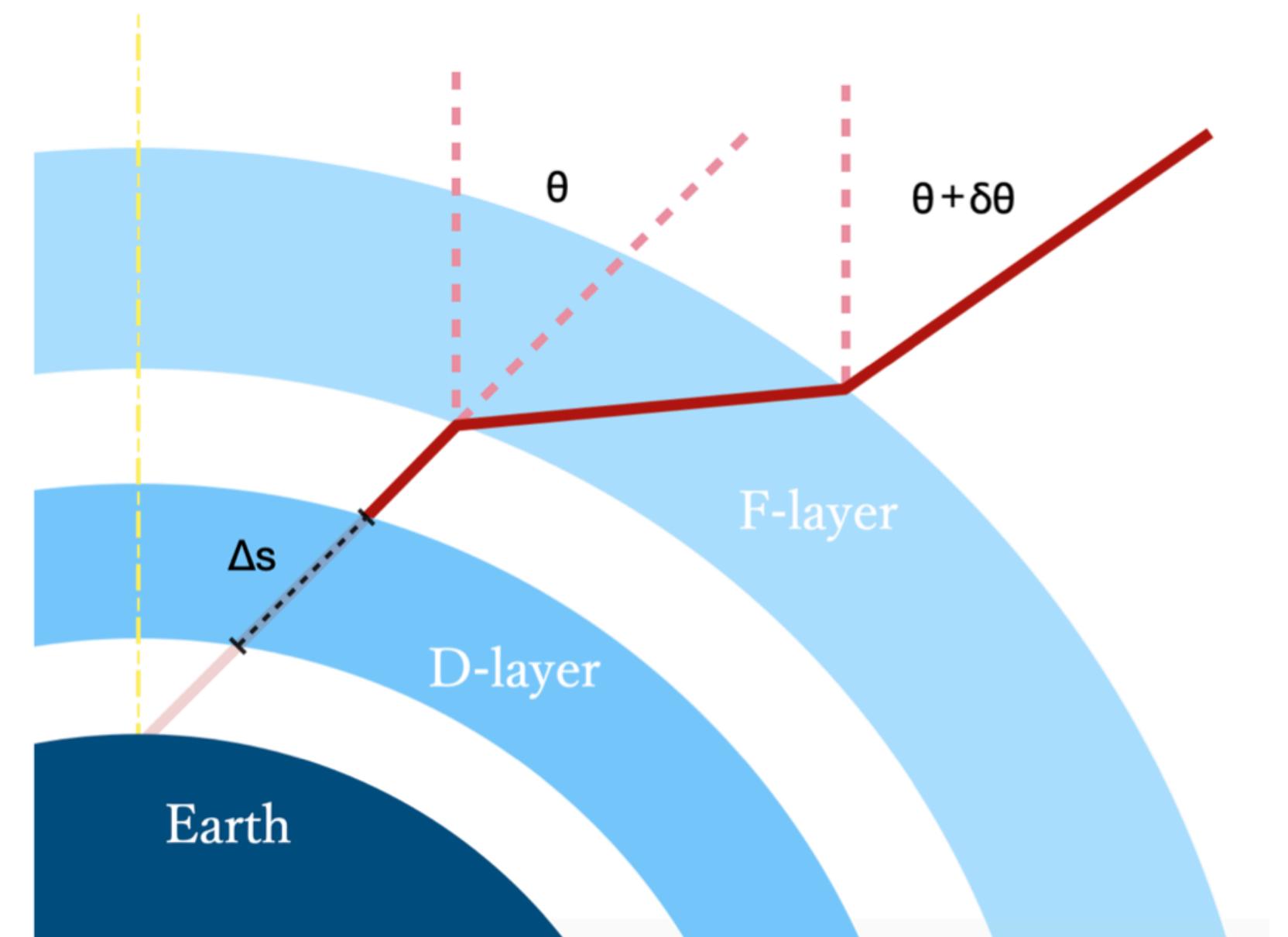
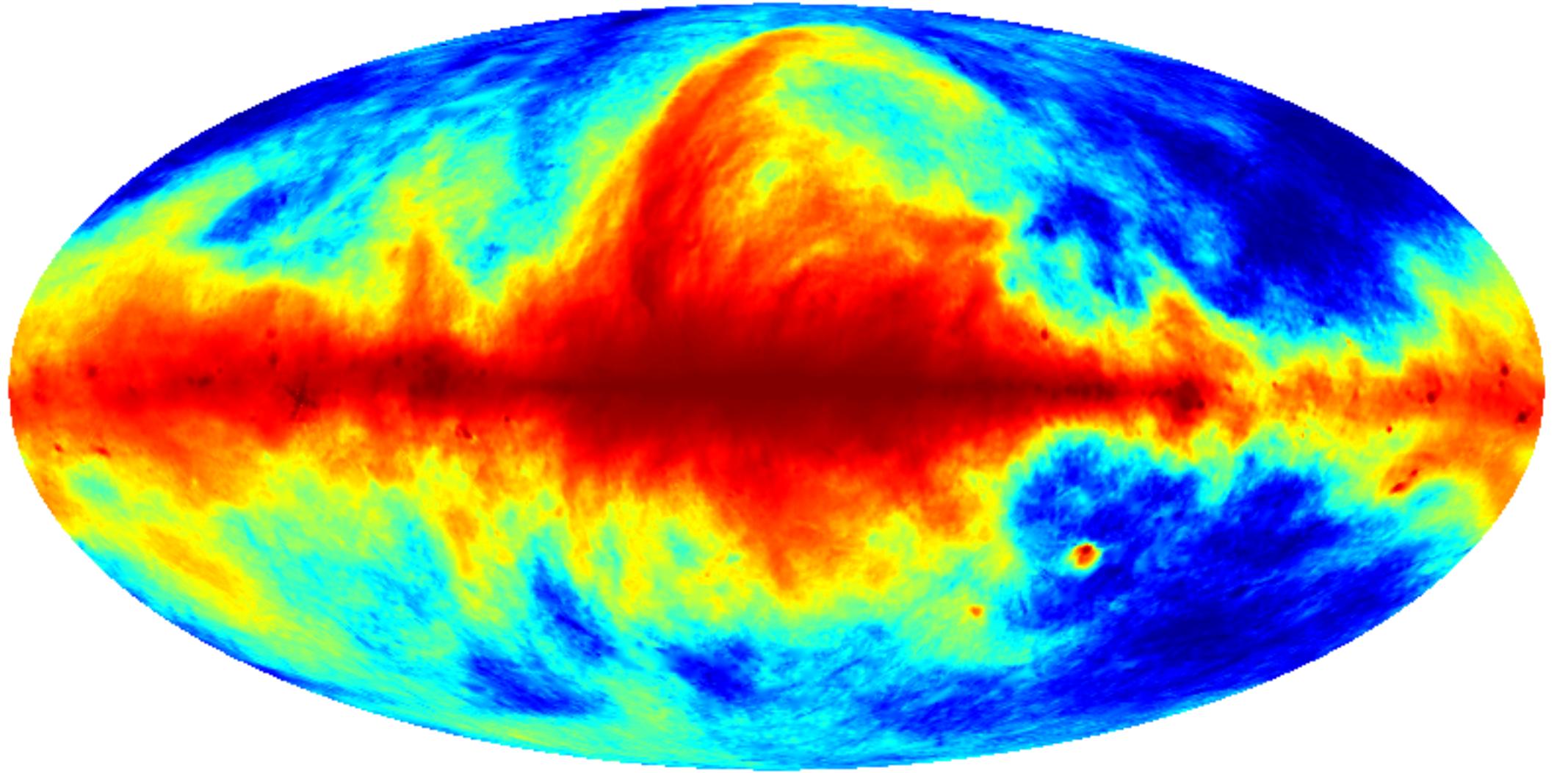
Tomography

- SKA Low will also take images of the 21cm fluctuations
- Likely that the analysis will be done on the power spectrum
- However advances in simulation based inference mean that we could do “field level” inference as well



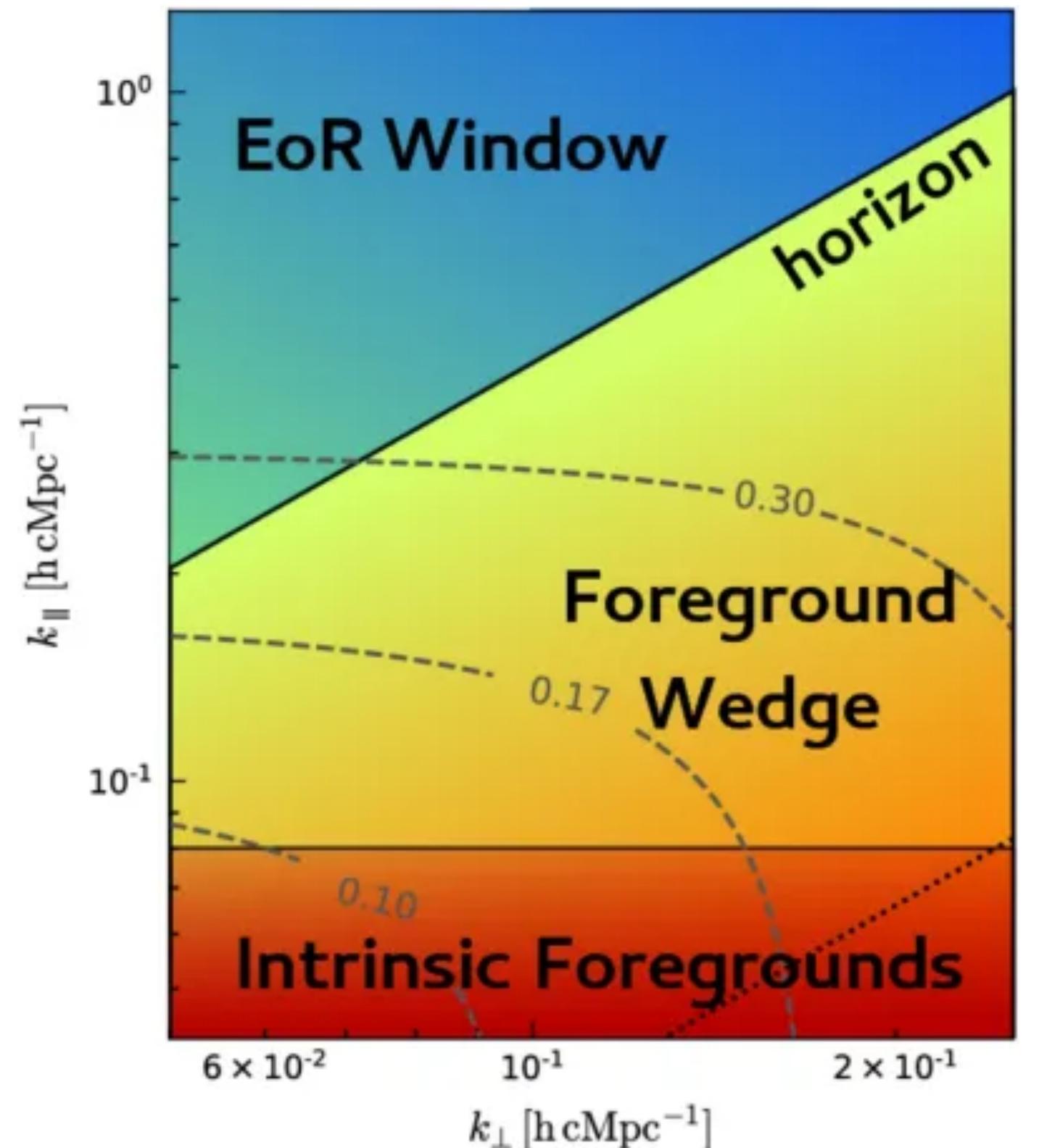
Challenges

- Telescopes are sensitive to the signal but also emission from our own galaxy and others known as foregrounds
- Effected by ionosphere
- Pick up radio stations, walkie-talkies, satellites, reflections of planes...
- Radiation from horizon and soil
- Instrumental effects



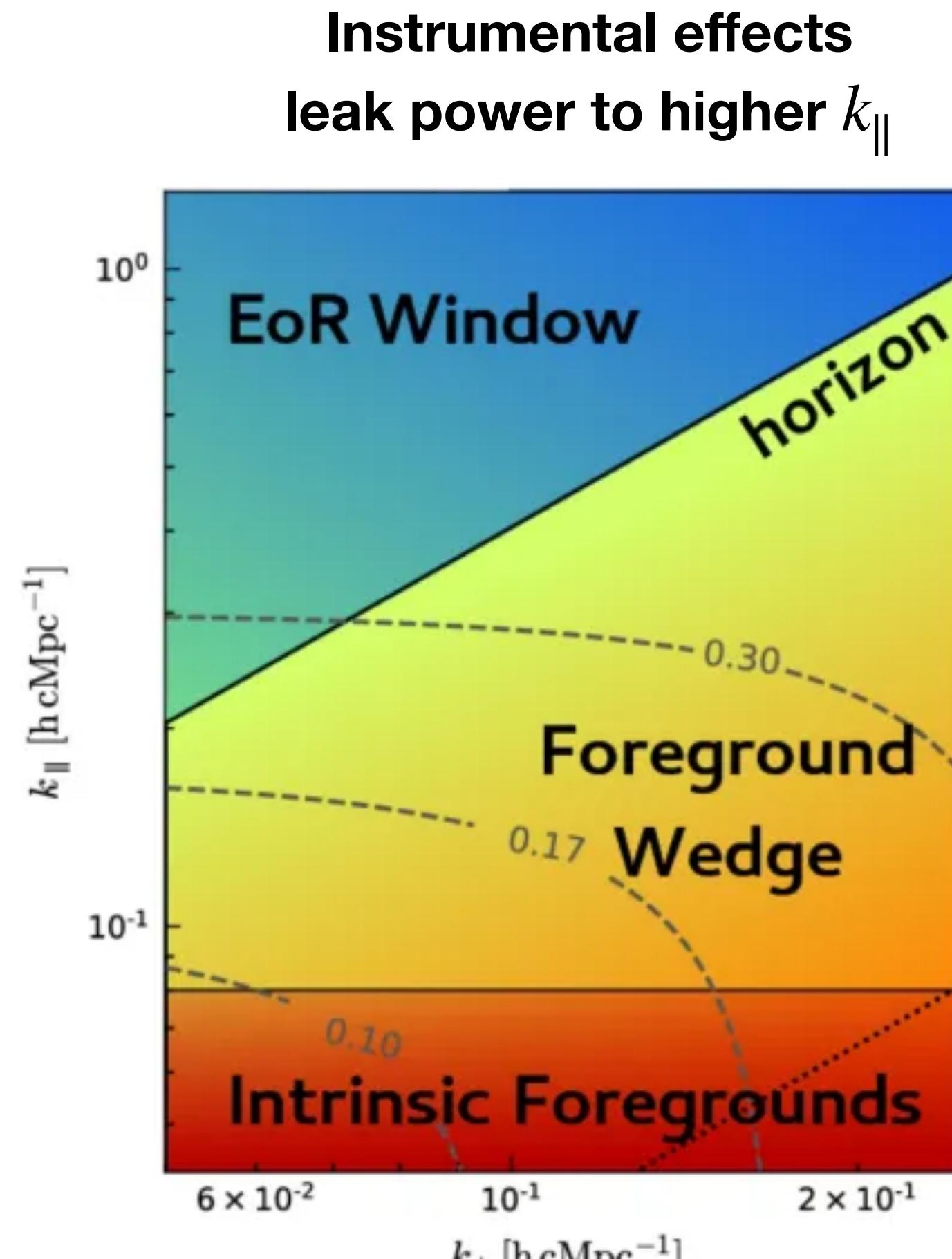
Observing the signal

Instrumental effects
leak power to higher k_{\parallel}

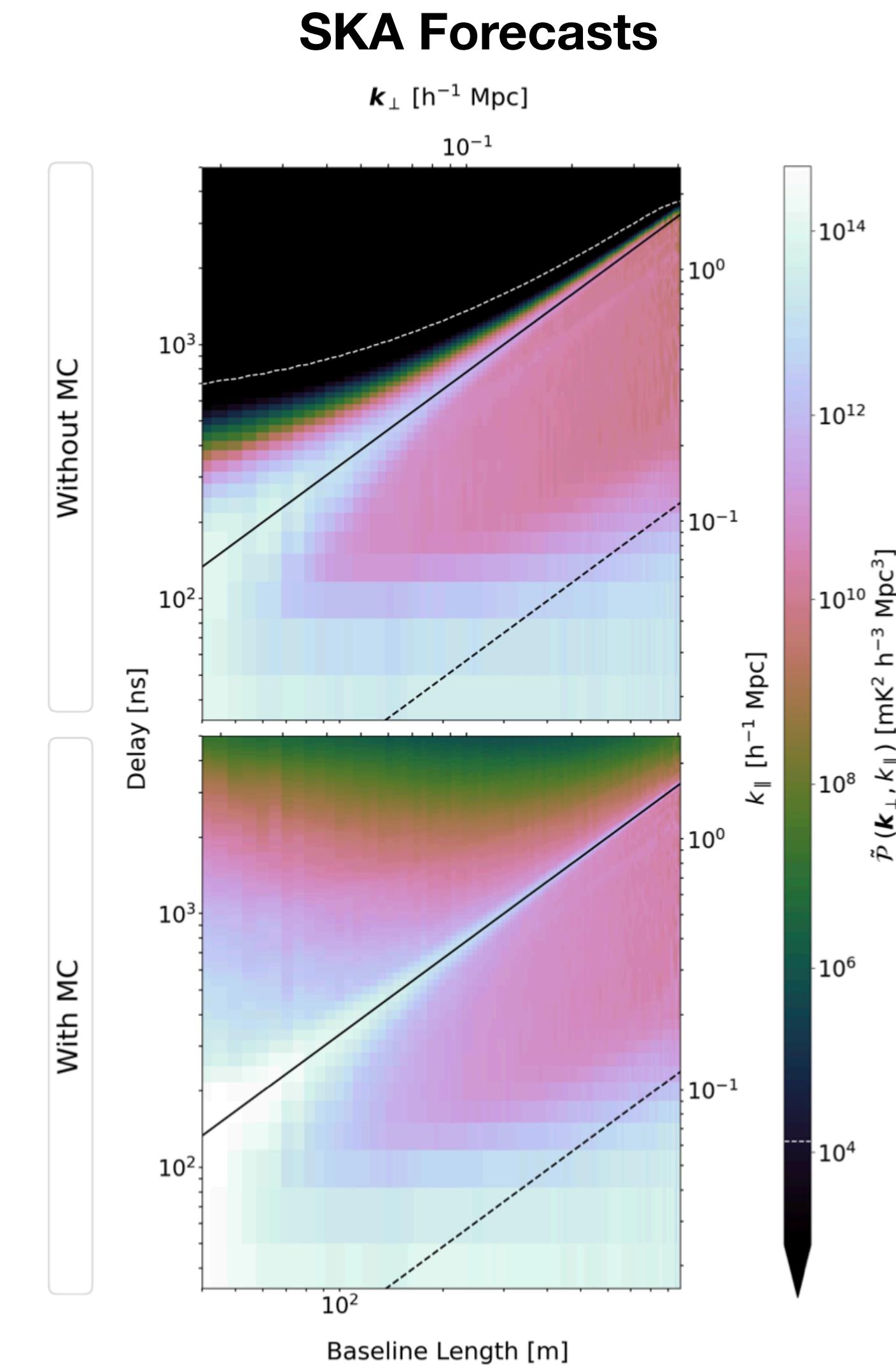


Foregrounds are smooth
so live at low k_{\parallel}

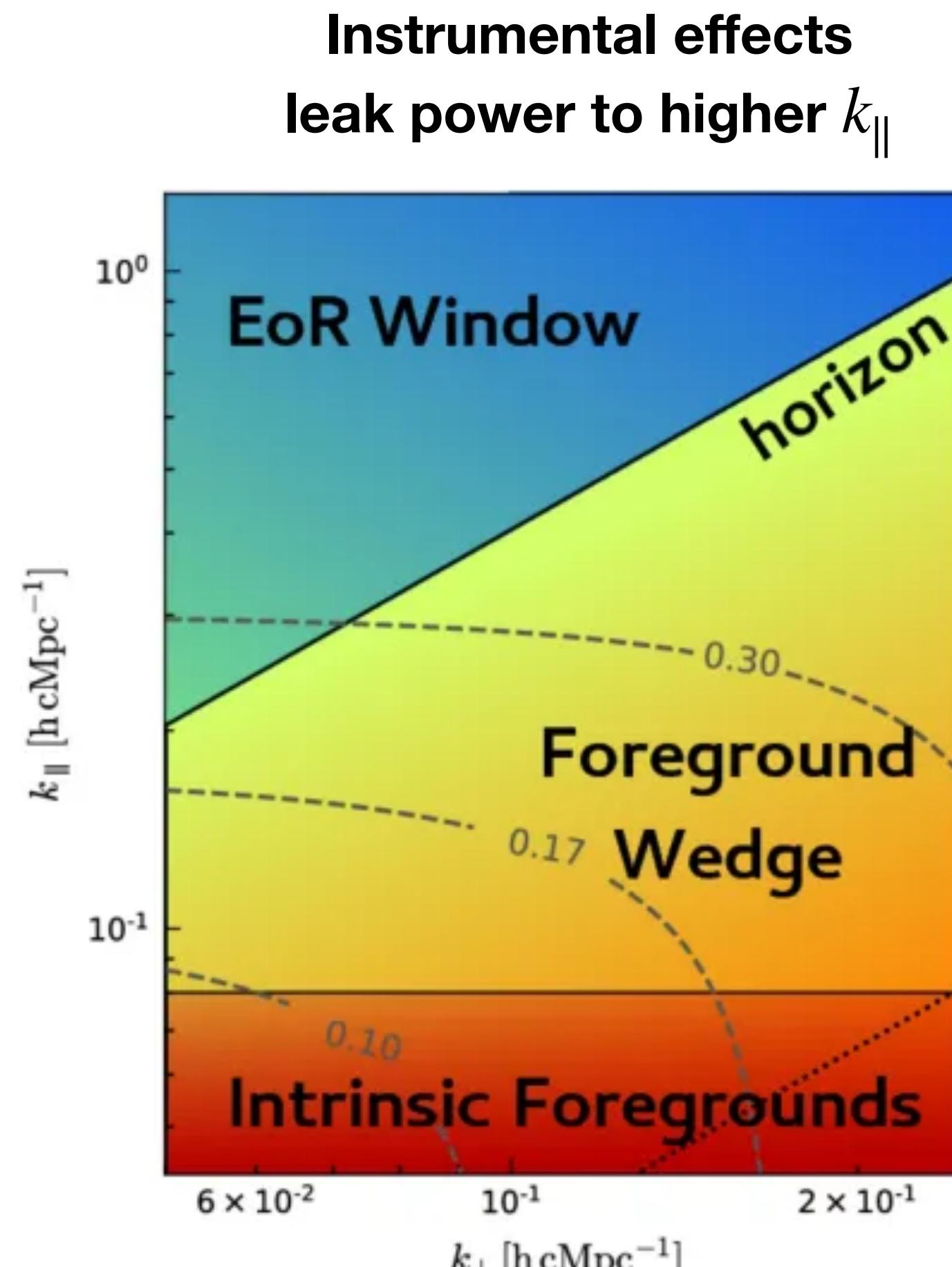
Observing the signal



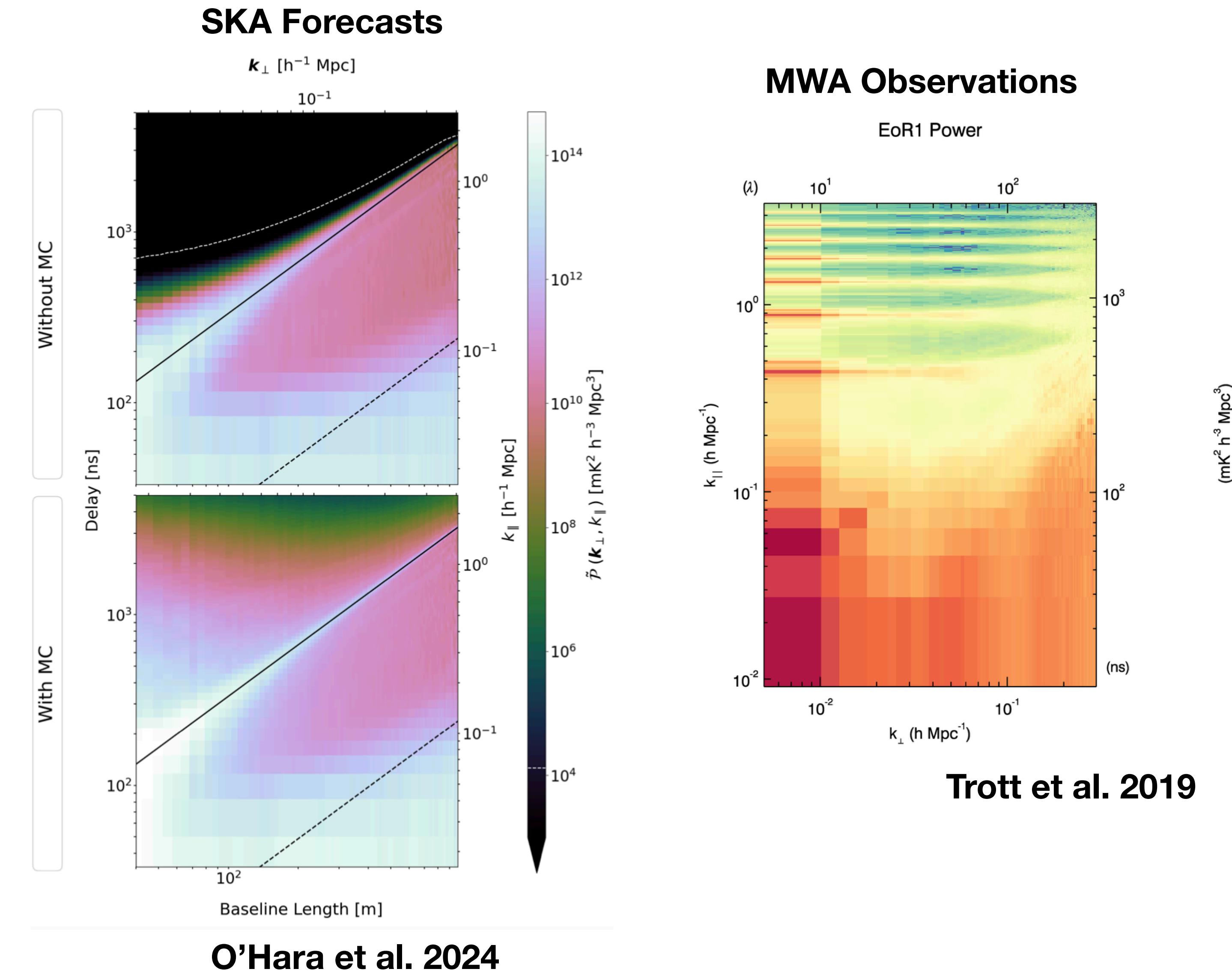
Foregrounds are smooth
so live at low k_{\parallel}



Observing the signal



Foregrounds are smooth
so live at low k_{\parallel}



Simulations

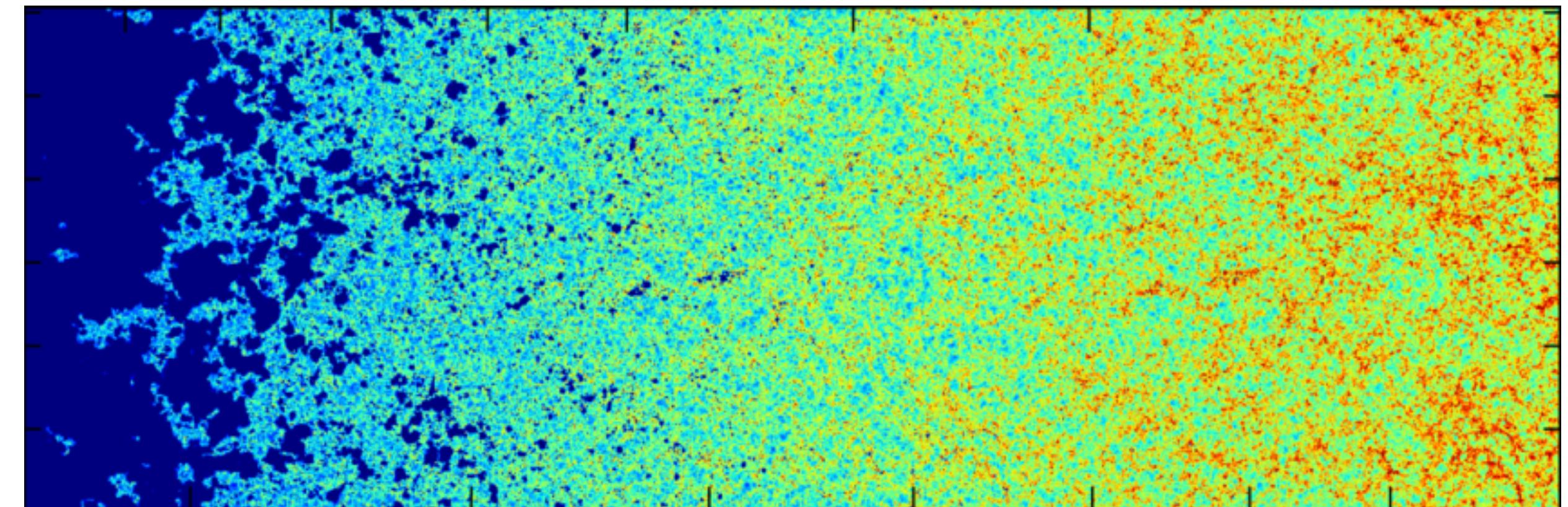
Types of simulations

- Hydro simulations like C2-Ray
- Semi-numerical simulations like 21cmFAST and 21cmSPACE
- 1D radiative transfer codes like ZEUS21, ECHO21 and ARES
- We use 21cmSPACE which was developed by Fialkov et al.
- Very high level summary!



21cmSPACE

- Start with some initial matter power spectrum, gas temperature, cmb temperature and neutral fraction and evolve this over cosmological time
- Have a pixelated cube of some fixed size
- Assign values for the matter density etc to each pixel based on the matter power spectrum
- Coupled differential equations



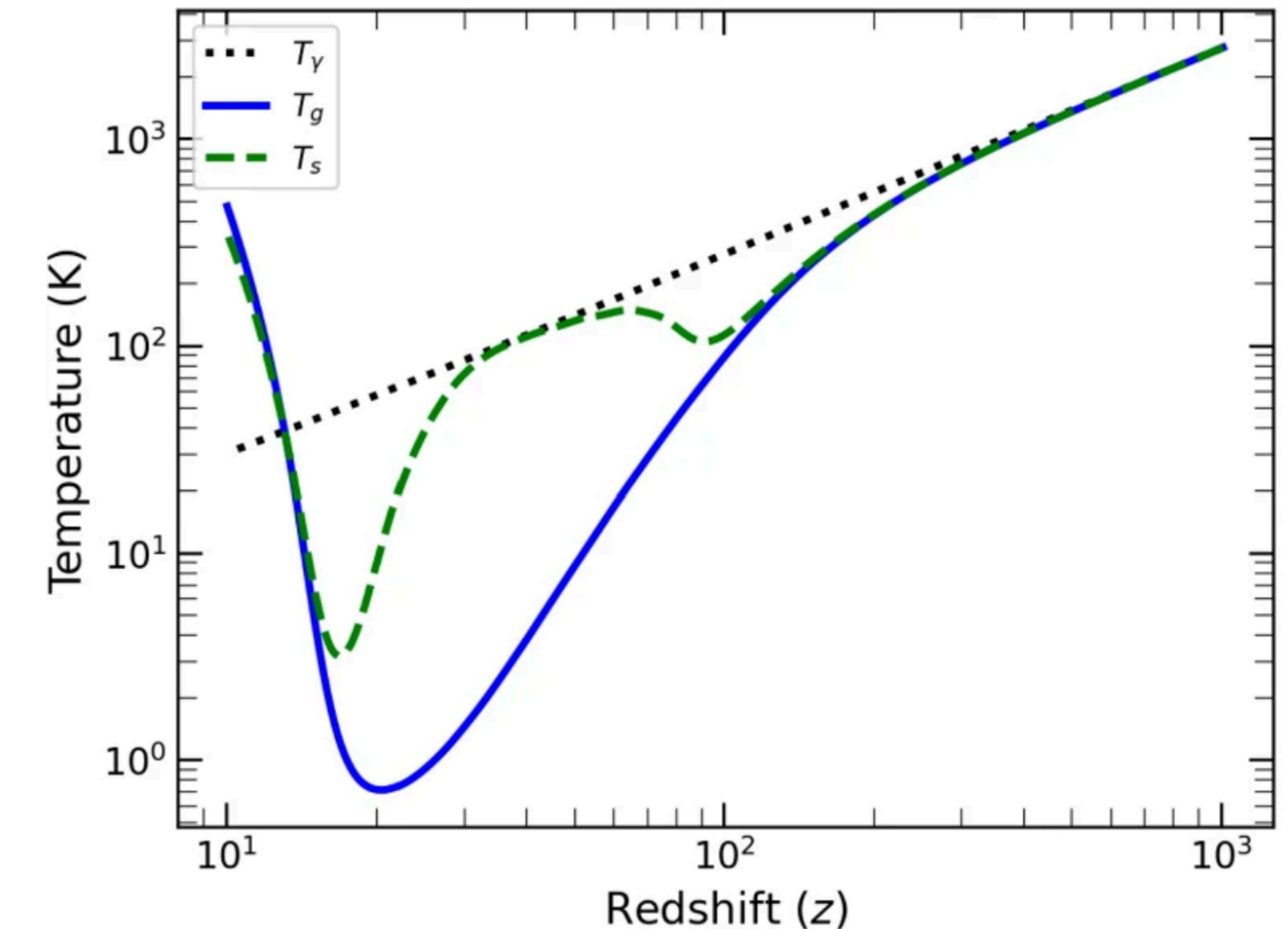
21cmSPACE

- Populate the pixels with halos based on some halo mass function
- Dependent on some minimum viral temperature for star formation
- Populate the halos with stars according to an initial mass function
- Assume some star formation rate and scale PopII and PopIII SEDs for halos over time



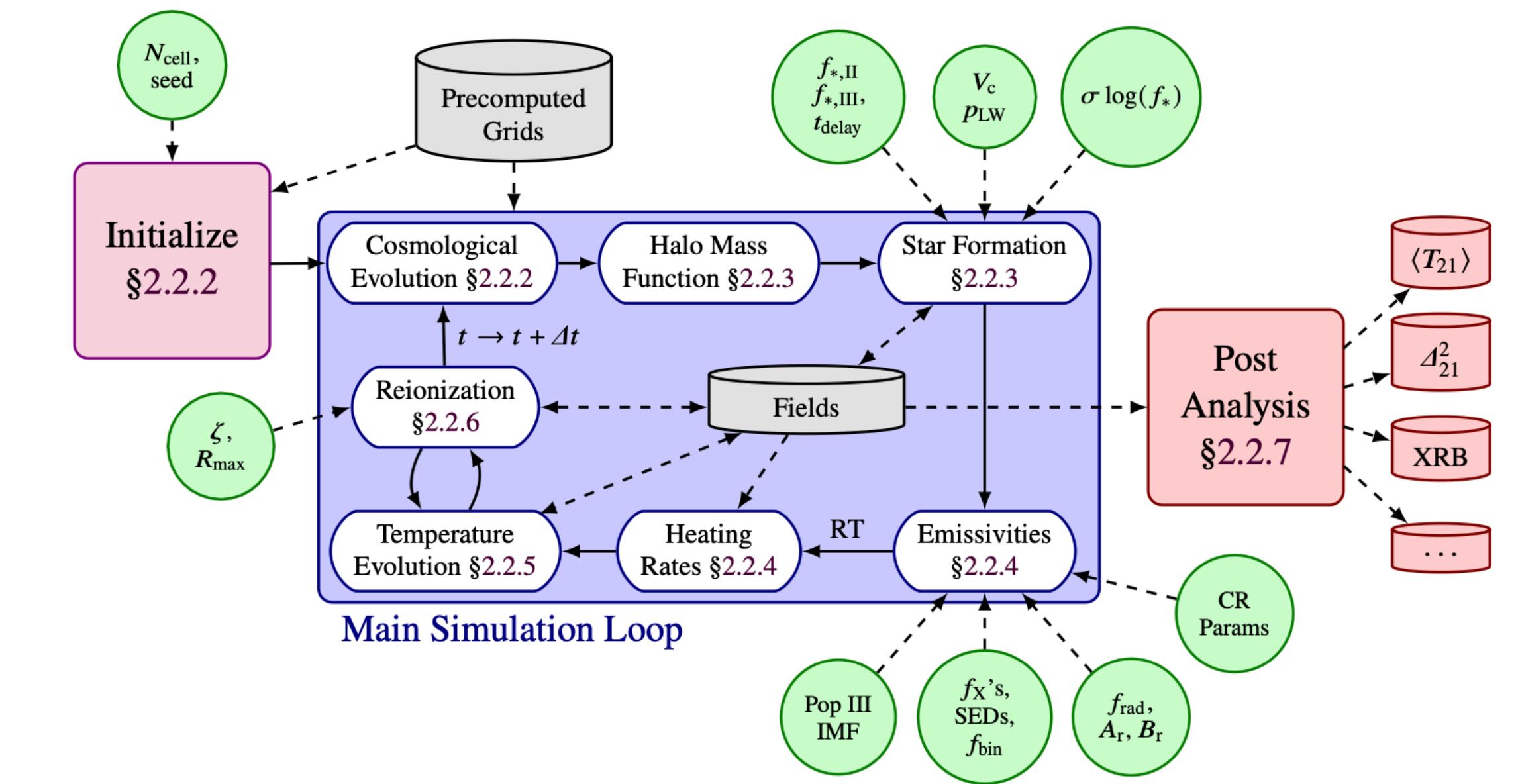
21cmSPACE

- Calculate emissivities of different fields using scaled SEDs
- Propagate radiation into the IGM as you evolve the density field
- Keep track of different temperatures like gas temperature and radio background
- Calculate 21cm as you go
- Construct power spectrum or sky-average from the cubes



21cmSPACE

- 21cm signal is sensitive to lots of processes
- Need to model UV emission, X-ray emission, cosmic rays, star formation rates, cosmology, IMF and HMF...
- So there are many parameters that can be varied and fit for in inference loops
- <https://www.cosmicdawnlab.com/>
21cmSPACE

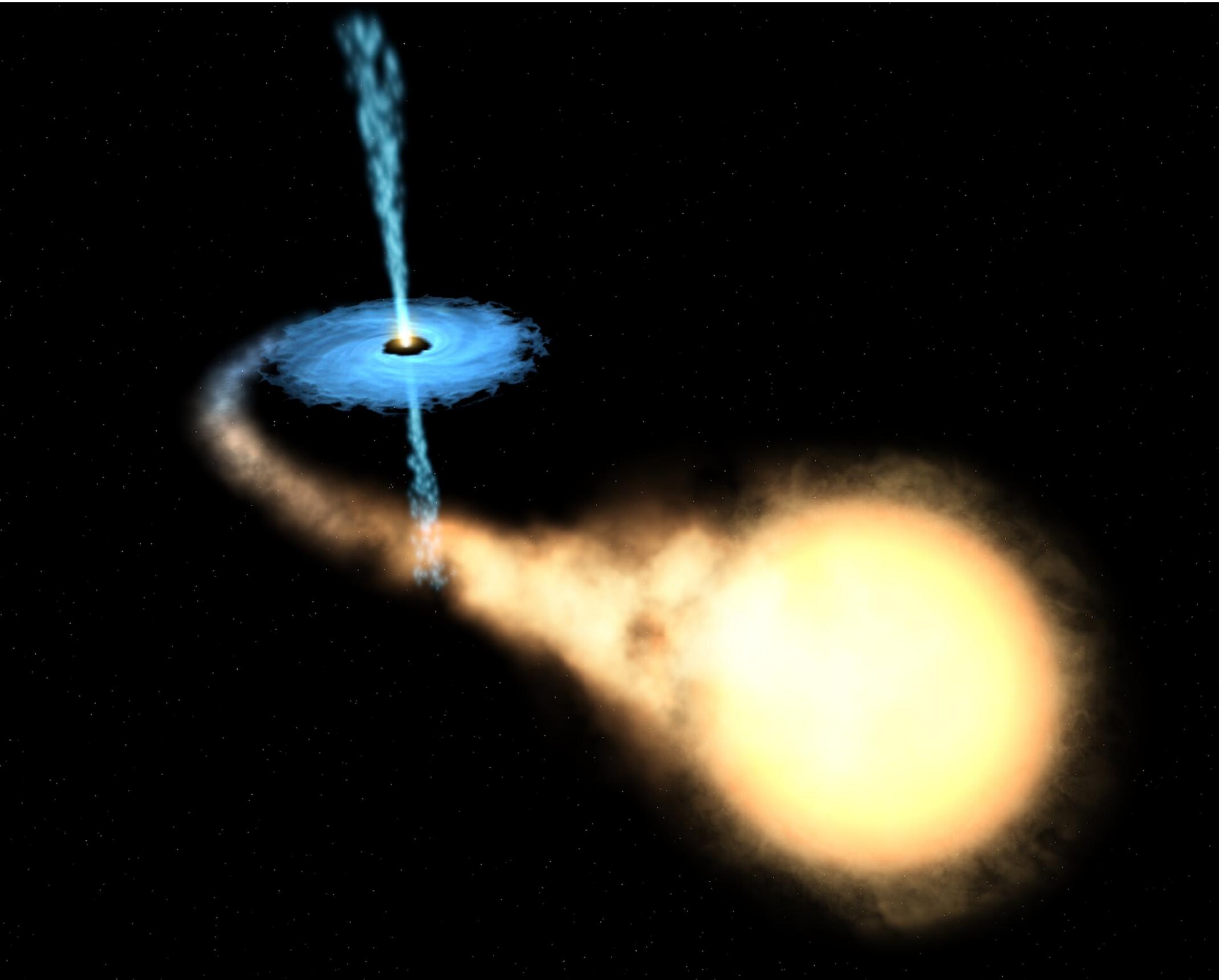


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IMF, REACH and the SKA

PopIII Initial Mass Function

- Mass distribution of first stars when they reach main sequence
- Recent paper from Gessey-Jones et al. 2502.18098
- Following on from earlier work in 2202.02099 that introduce PopIII Lyman-photon mediated effects
- First time included heating from PopIII X-ray binaries (black hole or neutron star with partner star)



PopIII Initial Mass Function

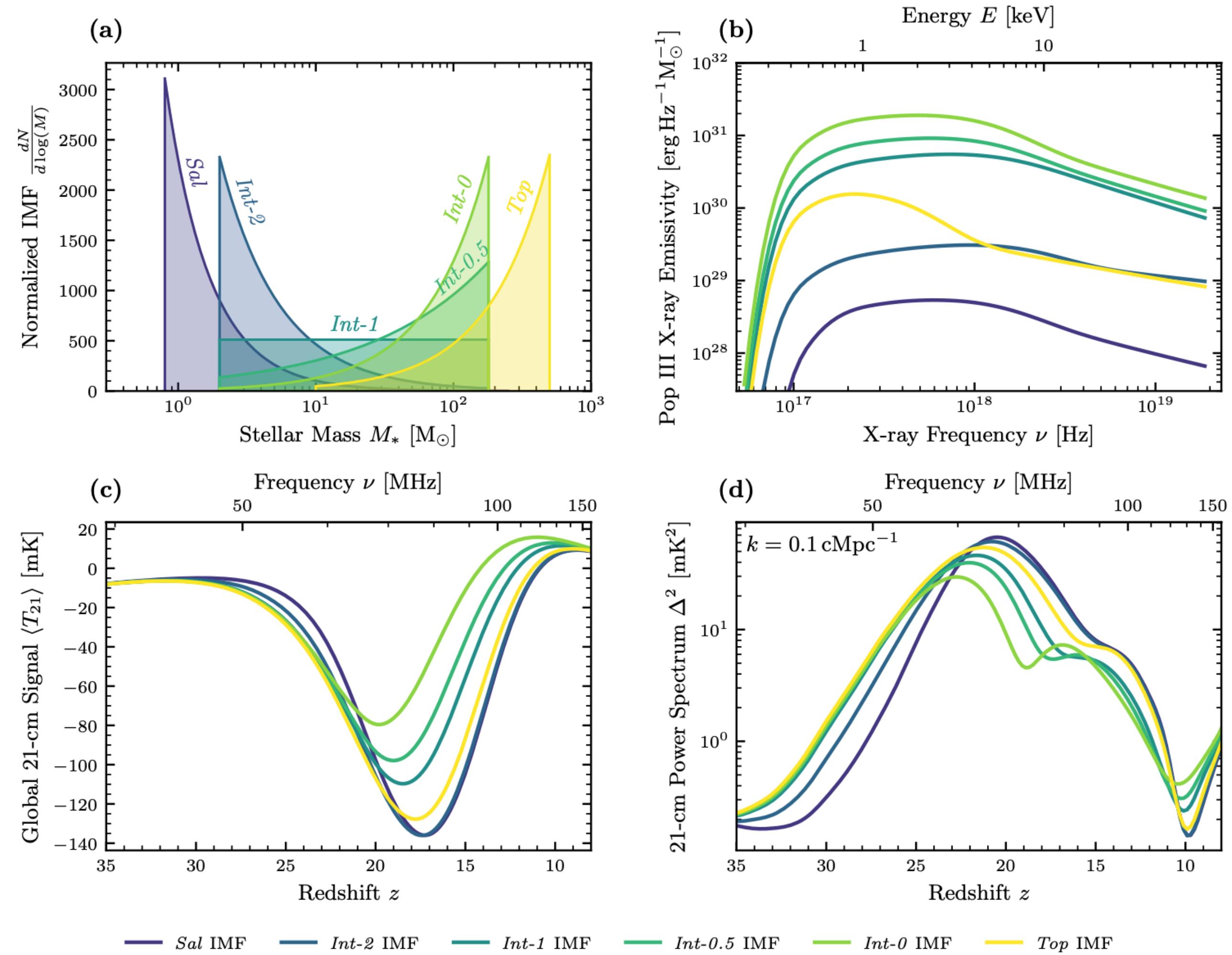
- PopIII IMF will have a significant impact on the number of X-ray binaries that form and the mass of the stars within them

$$\frac{dN}{dM} \propto M^{-\alpha_{III}}, M \in [M_{min}, M_{max}]$$

IMF Name	Color code	IMF exponent α_{III}	Minimum stellar mass $M_{min} (M_\odot)$	Maximum stellar mass $M_{max} (M_\odot)$
<i>Sal</i> (i.e., Salpeter [43])		2.35	0.8	250.0
<i>Int-2</i>		2.00	2.0	180.0
<i>Int-1</i>		1.00	2.0	180.0
<i>Int-0.5</i>		0.50	2.0	180.0
<i>Int-0</i>		0.00	2.0	180.0
<i>Top</i>		0.00	10.0	500.0

Impact of the IMF

- In theory α_{III} , M_{\min} and M_{\max} could be free parameters of the model but its expensive
- Have to estimate the population of X-ray binaries that form and calculate their emissivity using `binary_c`
- Would need to emulate `binary_c` for this to work



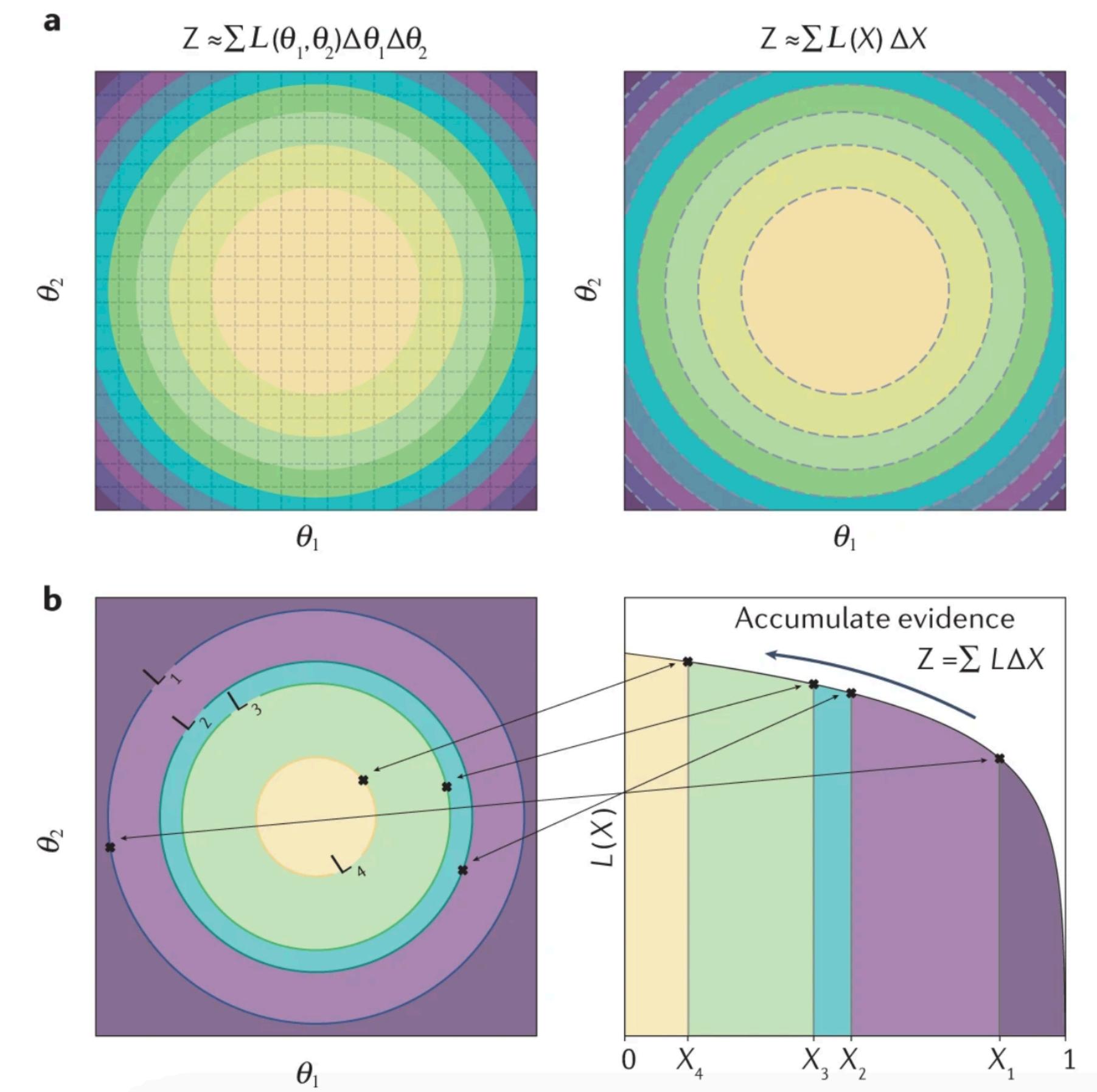
Statistical Methods

- We tend to use Bayesian inference in 21cm Cosmology

- Primarily for model comparison

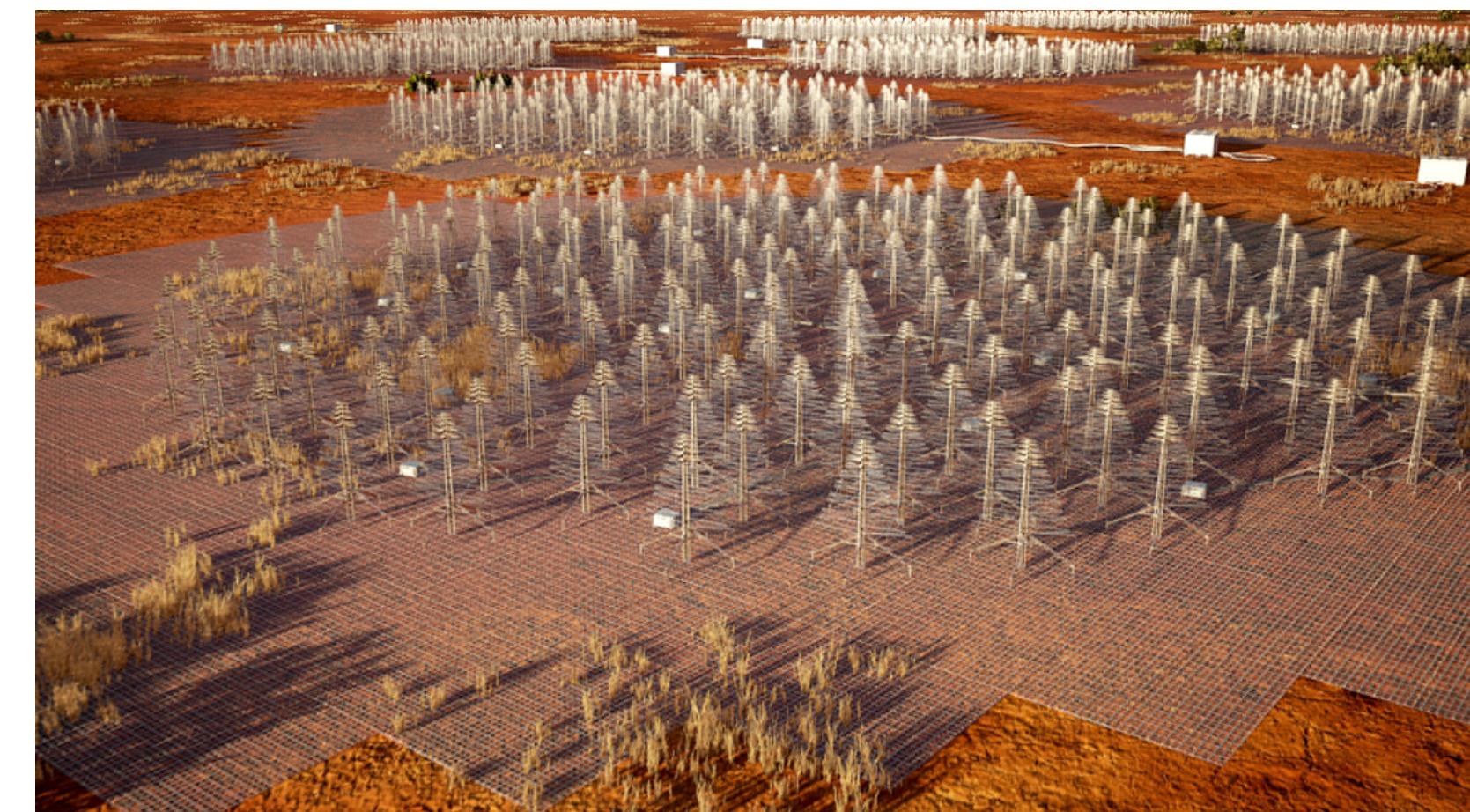
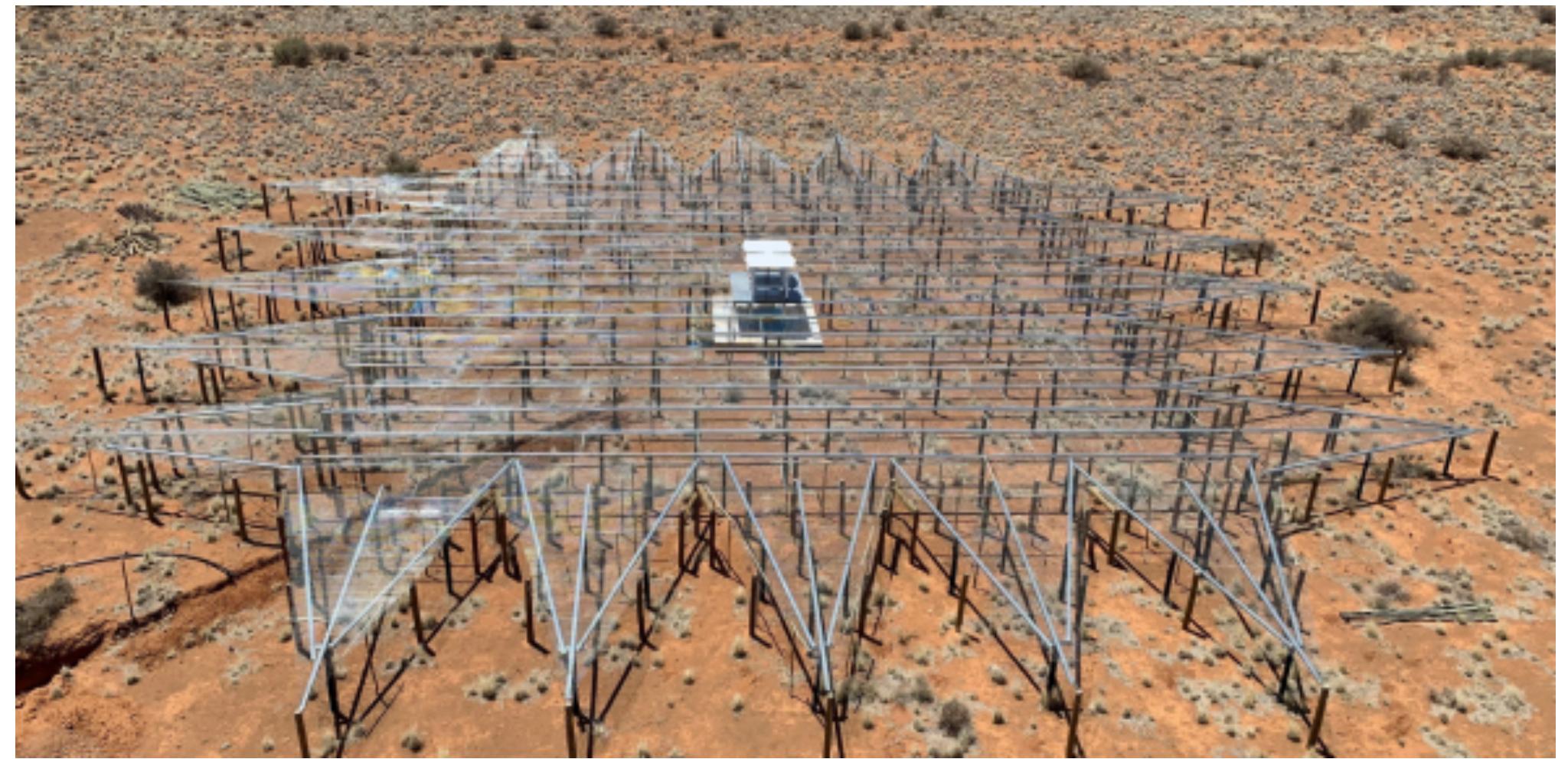
$$P(D | M_2) > P(D | M_1)$$

- So if I am looking for the 21cm signal and $M_2 = M_{fg} + M_{21}$ and $M_1 = M_{fg}$ then I will have found statistical evidence for it
- But could also have $M_1 \rightarrow \text{IMF}_1$ and $M_2 \rightarrow \text{IMF}_2$



Statistical Methods

- In this paper ran several simulations for each IMF under investigation
- Trained neural network emulators
- Can then fit synthetic observations from REACH and the SKA
- Not worrying about foregrounds or contaminating signals here just noise
- Can fit with varying IMFs and use the Bayesian evidence to determine what we can learn about PopIII stars

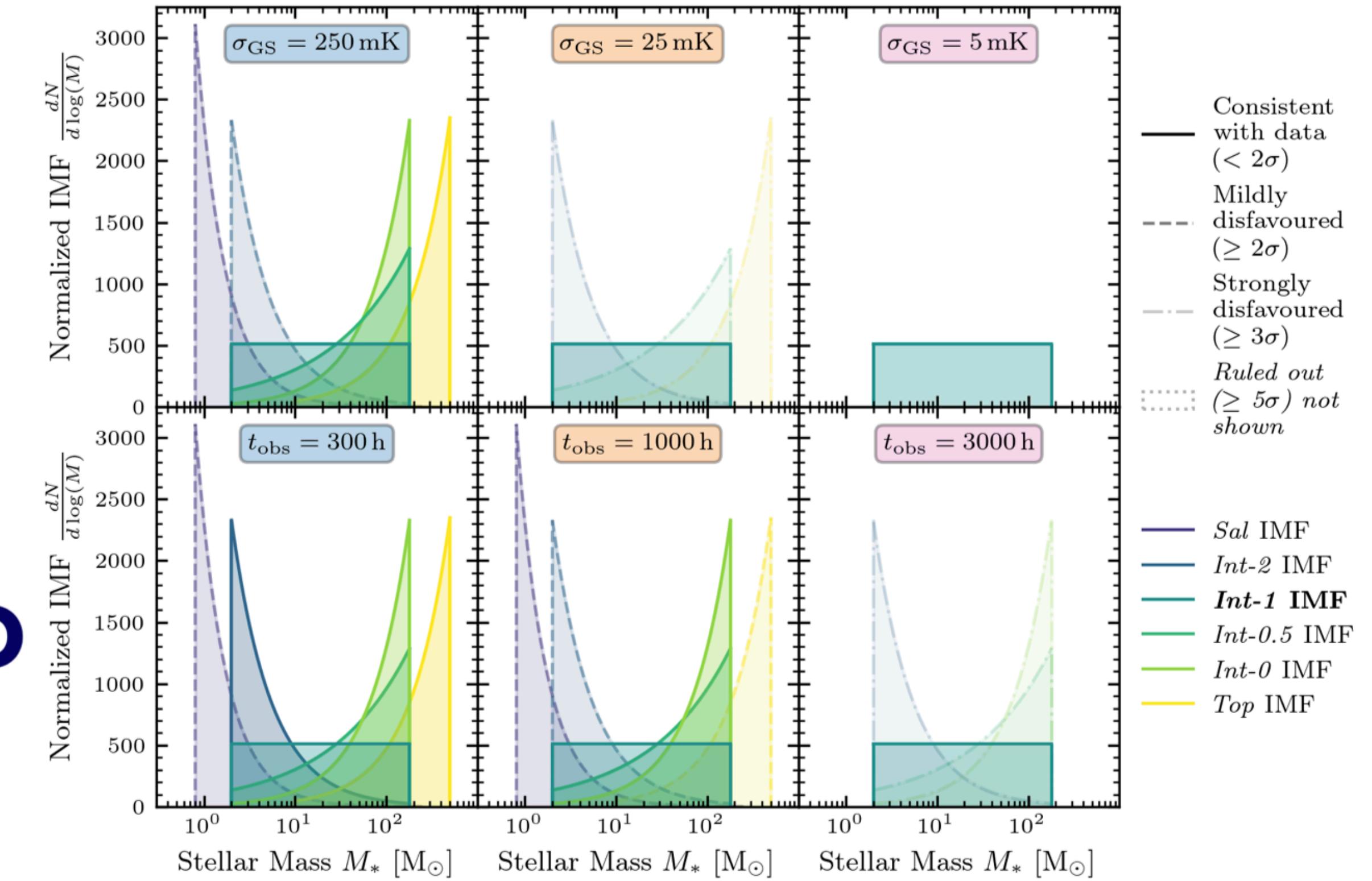


Results

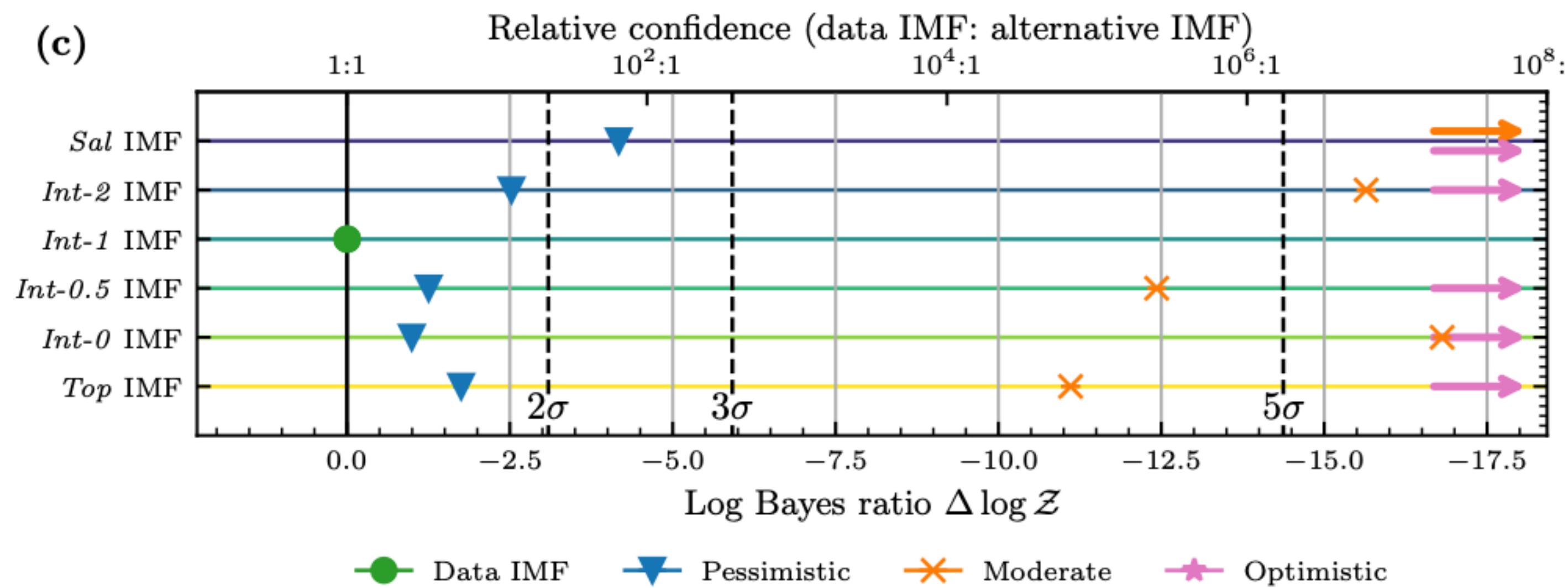
- Generated data with IMF Int-1 and model with the other 5 IMFs
- Determine posterior probability on IMFs via

$$P(\text{IMF} | D) = \frac{Z_{\text{IMF}}}{\sum_i^{\text{IMFs}} Z_i}$$

- Successfully identify the IMF with SKA and REACH data



Results



Conclusions

- 21cm is a powerful probe of the early universe
- Dependent on cosmology and the properties of the first stars
- Can observe several different summary statistics e.g. sky-averaged signal and power spectrum
- We showed that the IMF can have a significant impact on the structure of the 21cm signal
- Showed that we can determine the structure of the IMF with REACH and SKA observations