21cm Cosmology and the PopIII IMF

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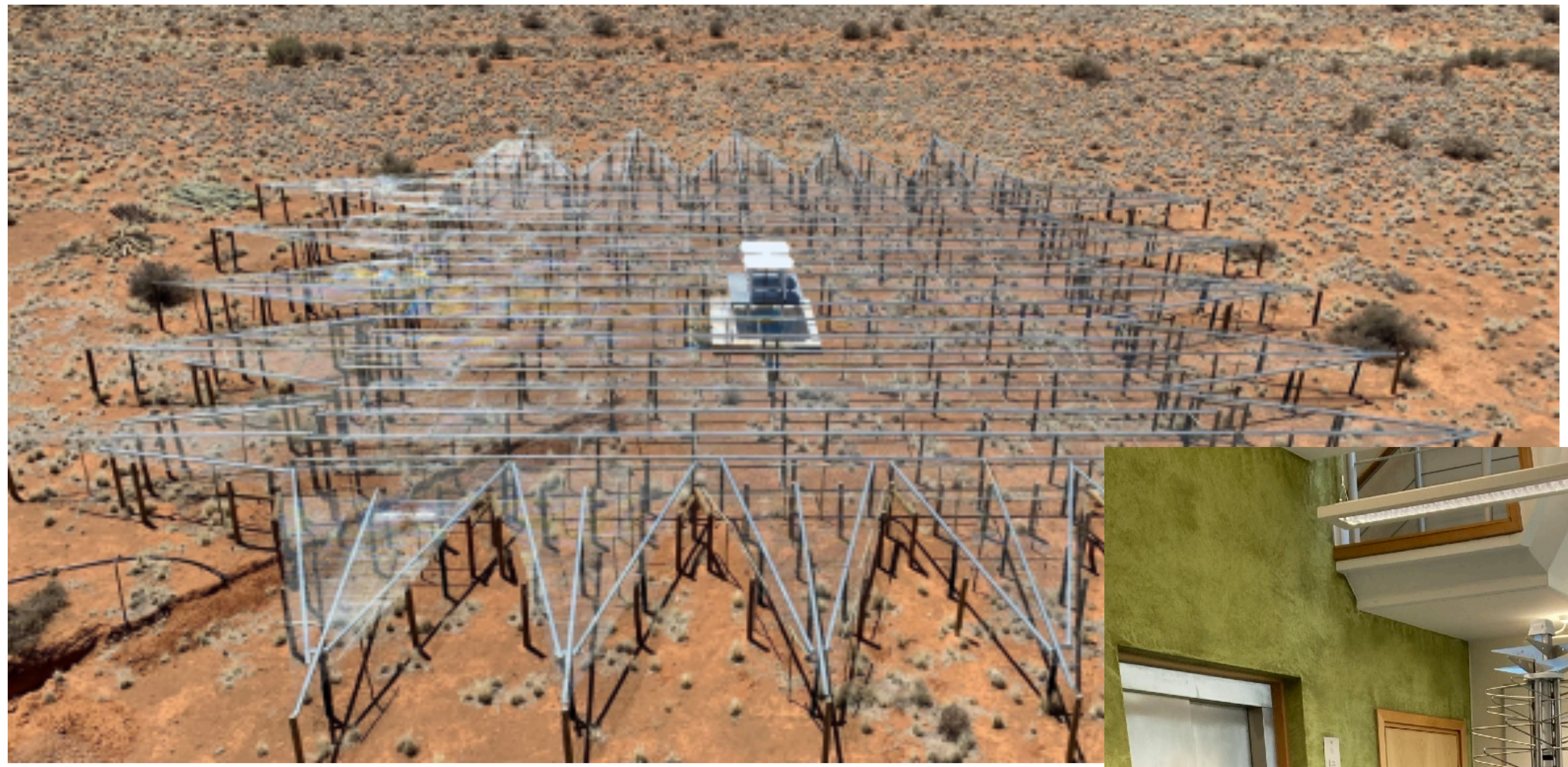


- Review of 21cm Cosmology
- Observing the 21cm signal
- Simulating the 21cm signal
- PopIII IMF with REACH and the SKA

21cm Cosmology

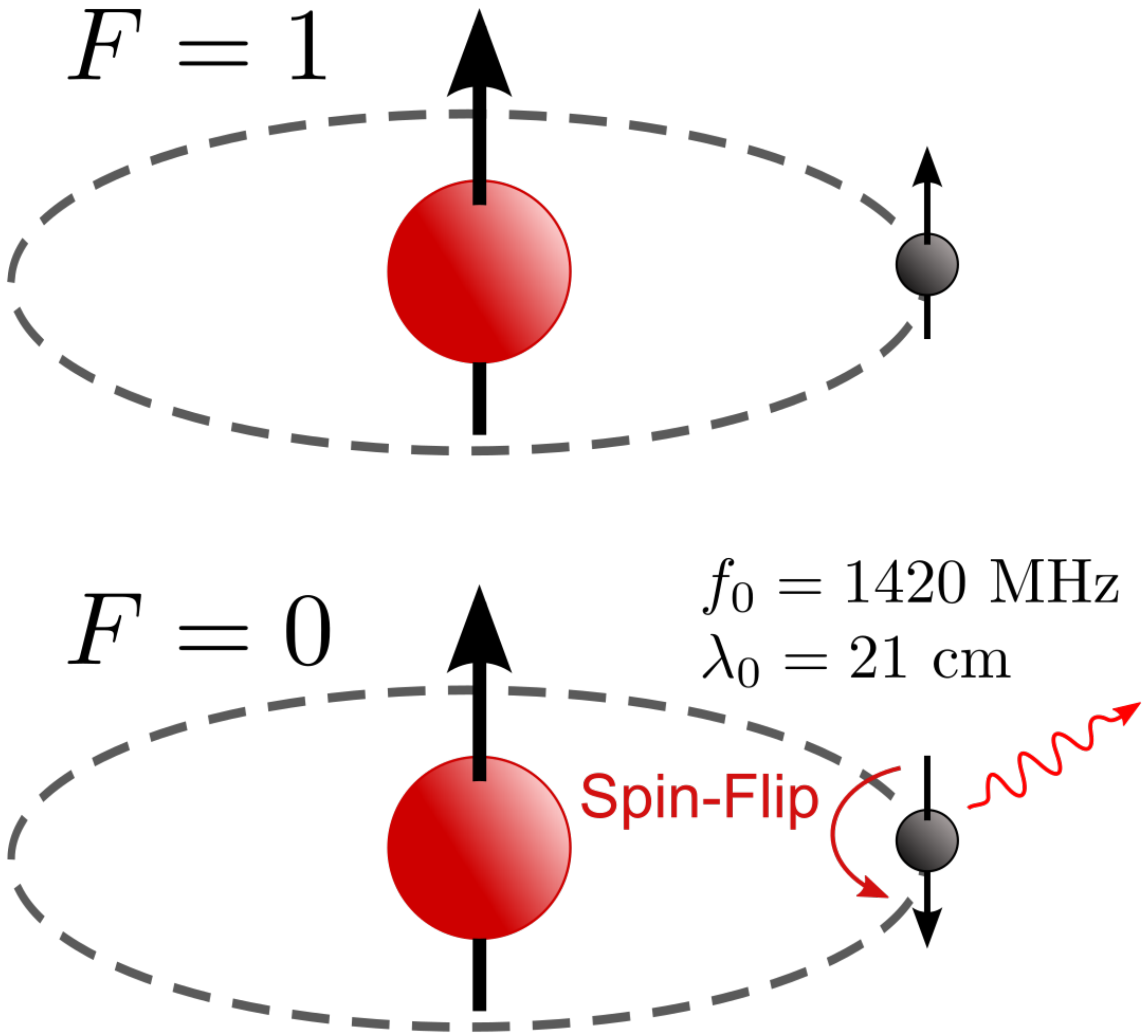
21cm Spin Temperature

- 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

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



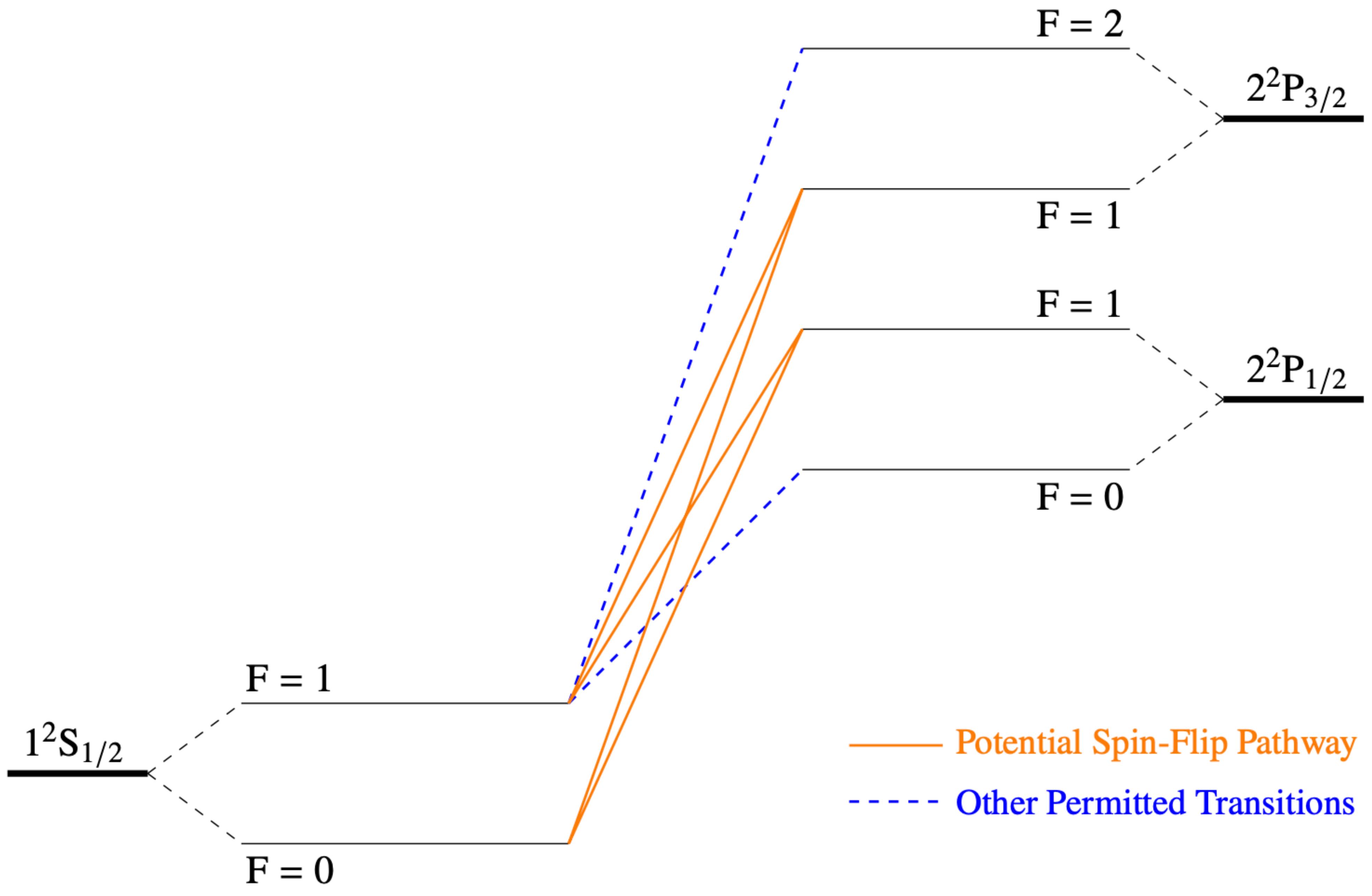
21cm Spin Temperature

- 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

Wouthuysen-Field Effect



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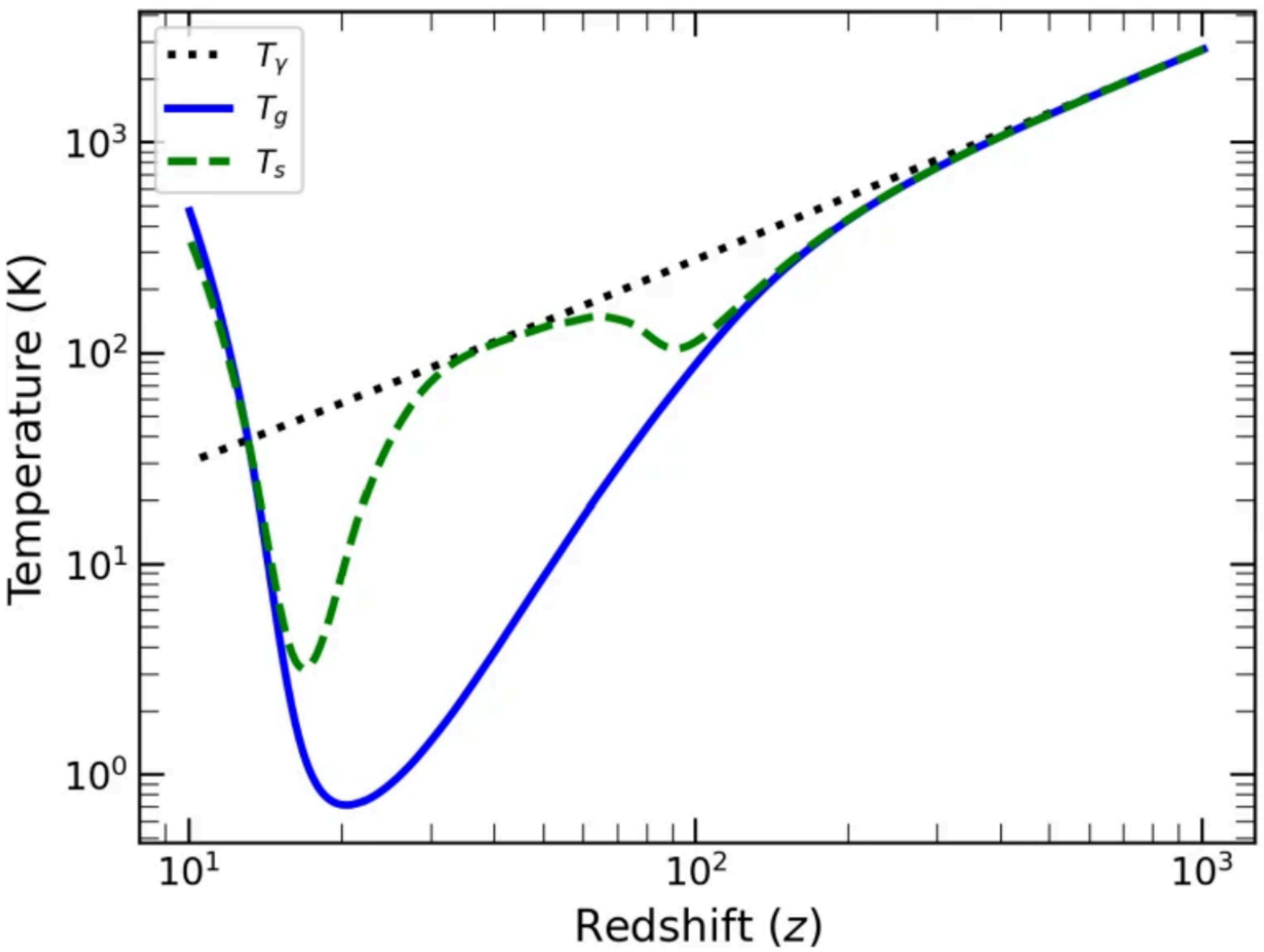
21cm Signal

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

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

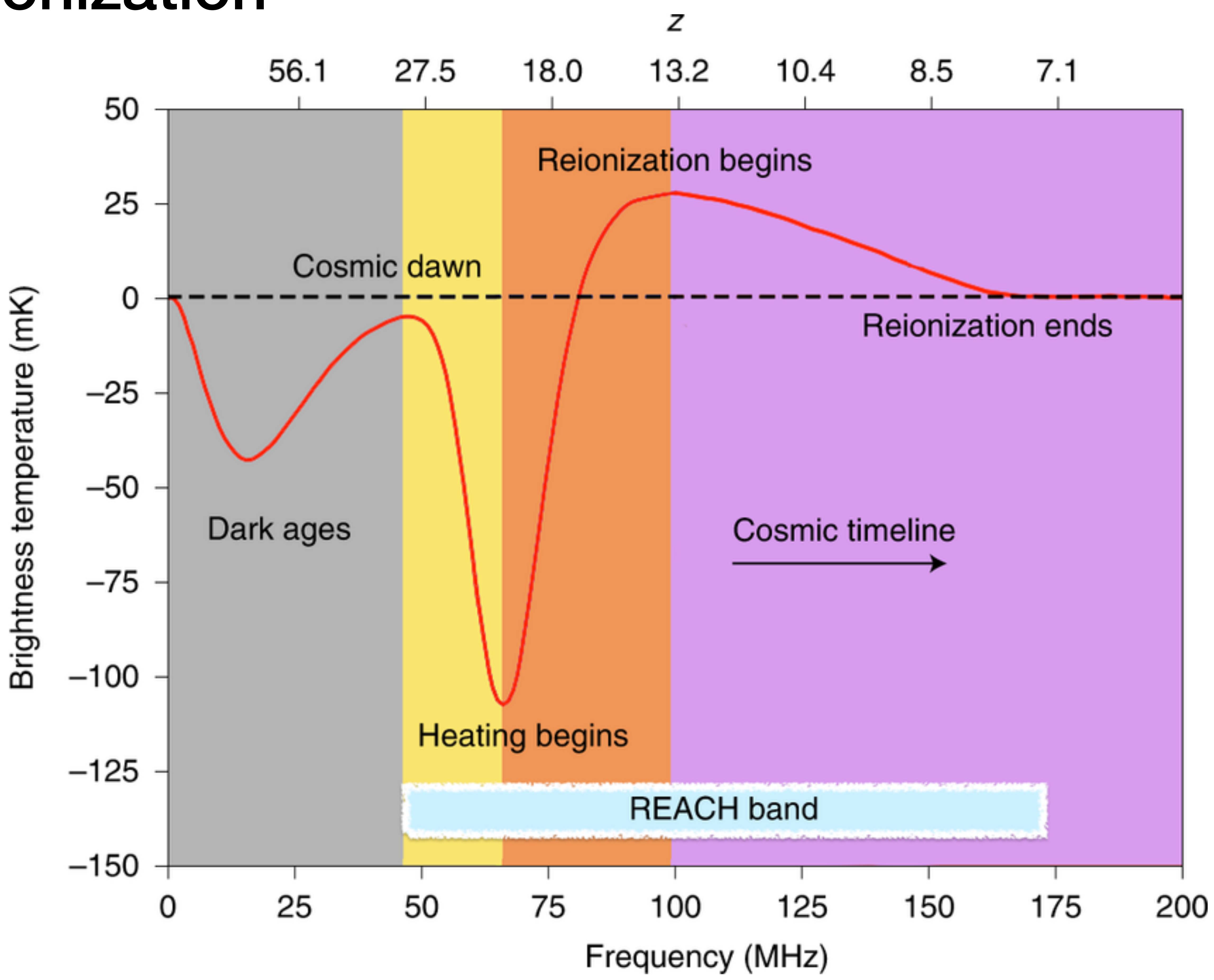


21cm Signal

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

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

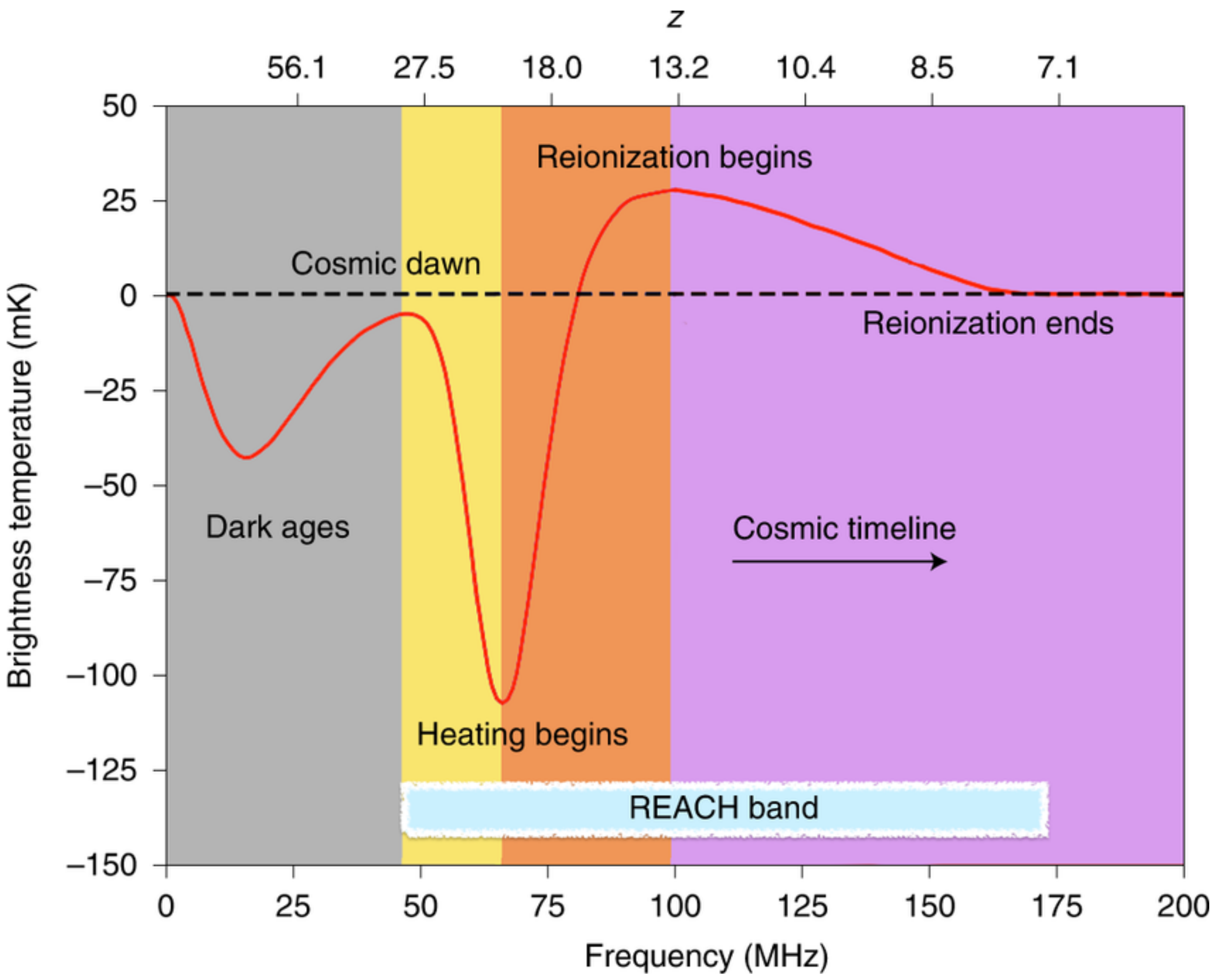
- Signal is redshifted into the low frequency radio band



Observational challenges

The sky-averaged signal

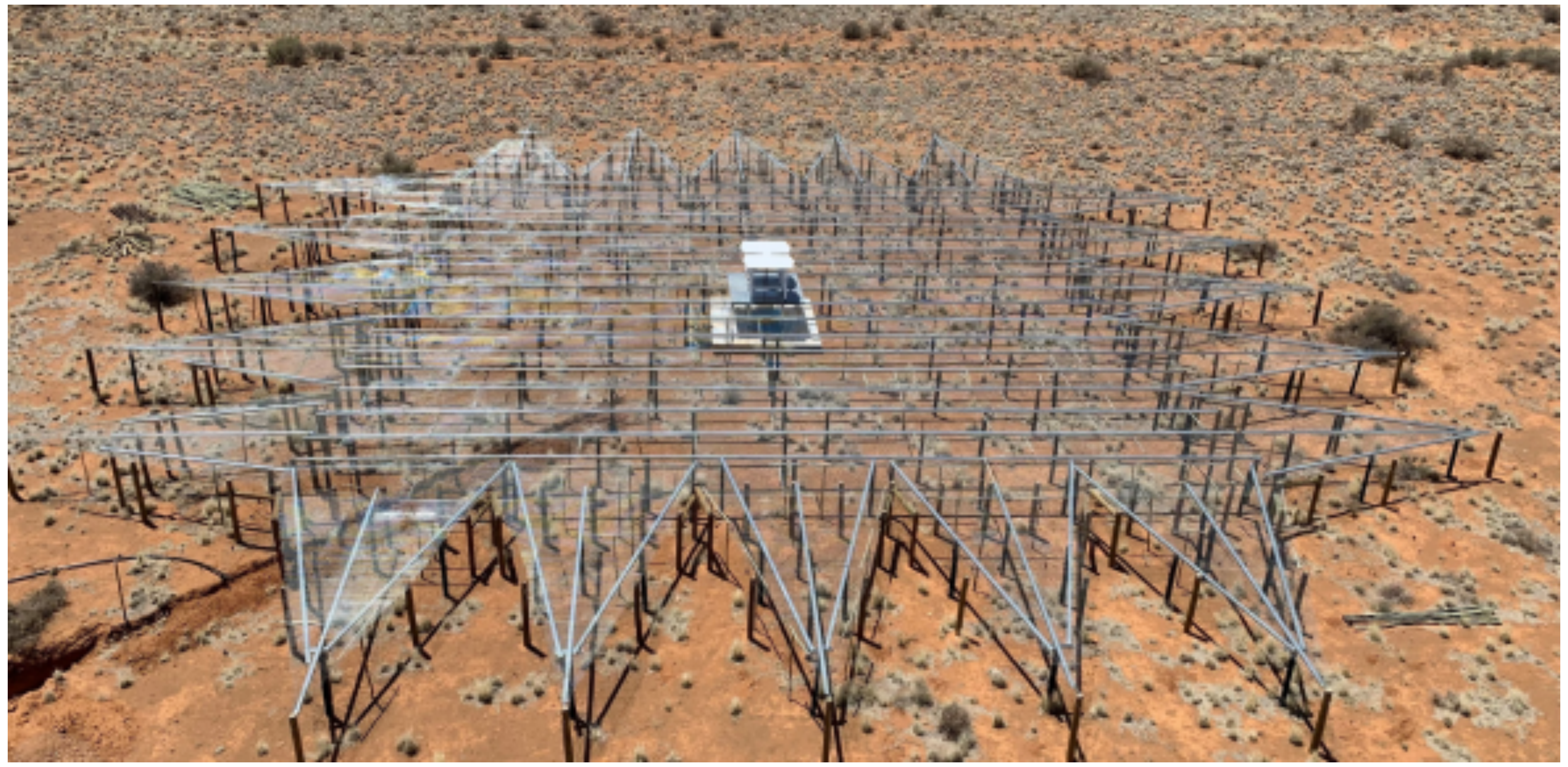
- The signal can be observed in a few different ways
- This is the global or sky-averaged 21cm signal
- Sensitive to changes in galaxy populations but no spatial information

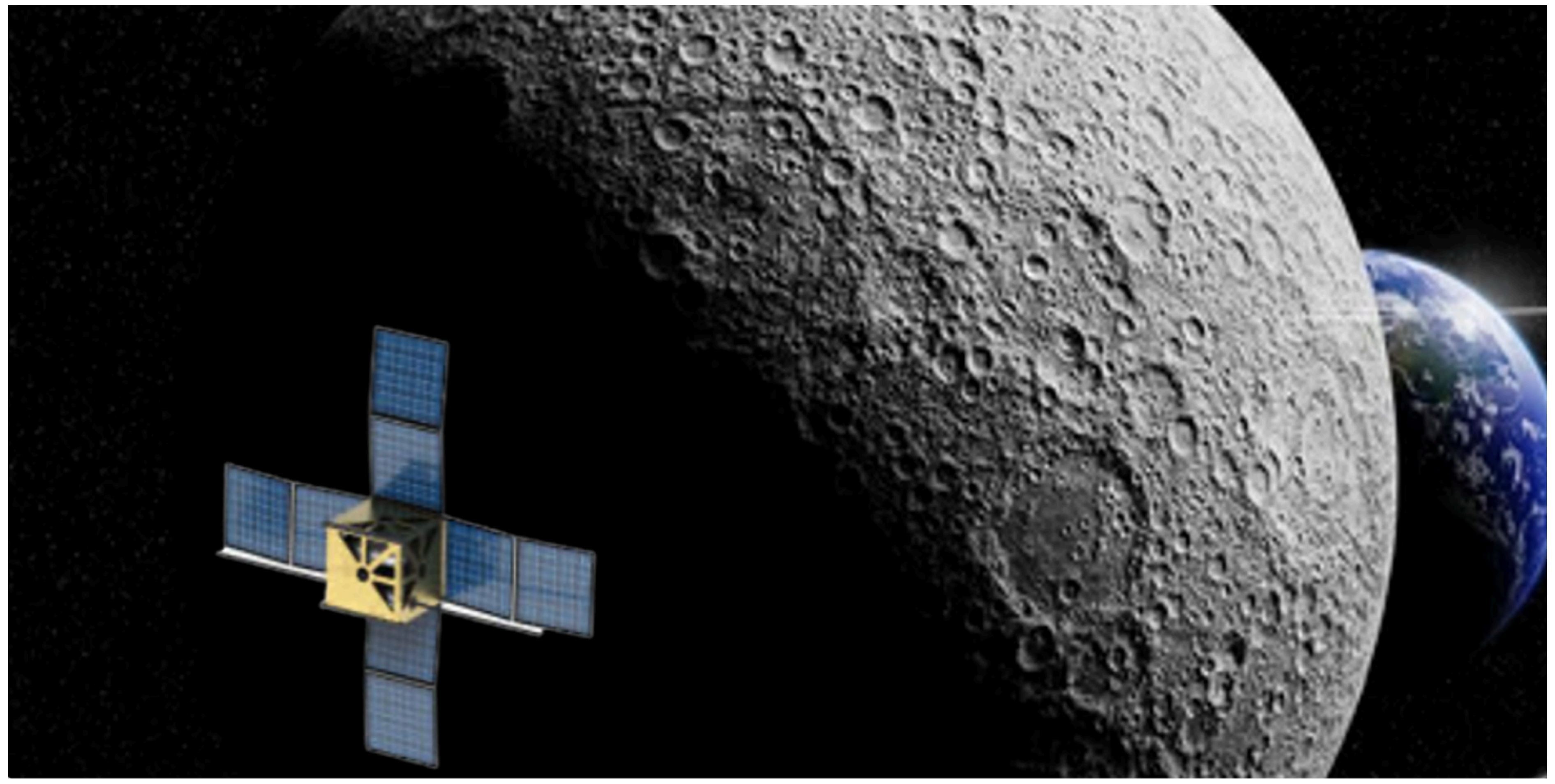


The sky-averaged signal

- Ground based missions target 50-200 MHz
- Cosmic Dawn and Epoch of Reionization
- Looking for first stars

- Spaced based missions will target 5-50 MHz
- Dark Ages before first stars
- Purely Cosmology



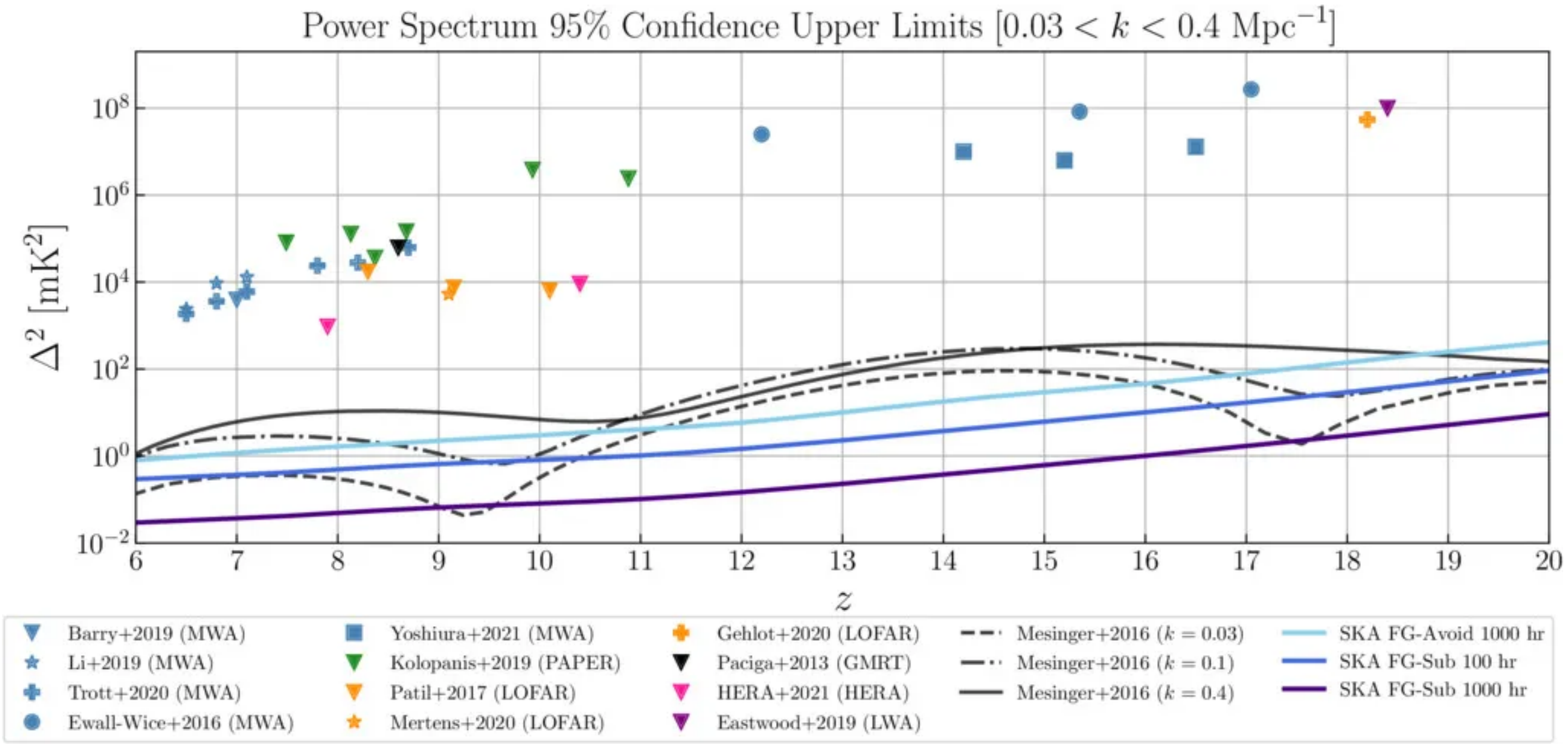


Fluctuations

- Look at fluctuations in the 21cm signal across the sky and time with a power spectrum

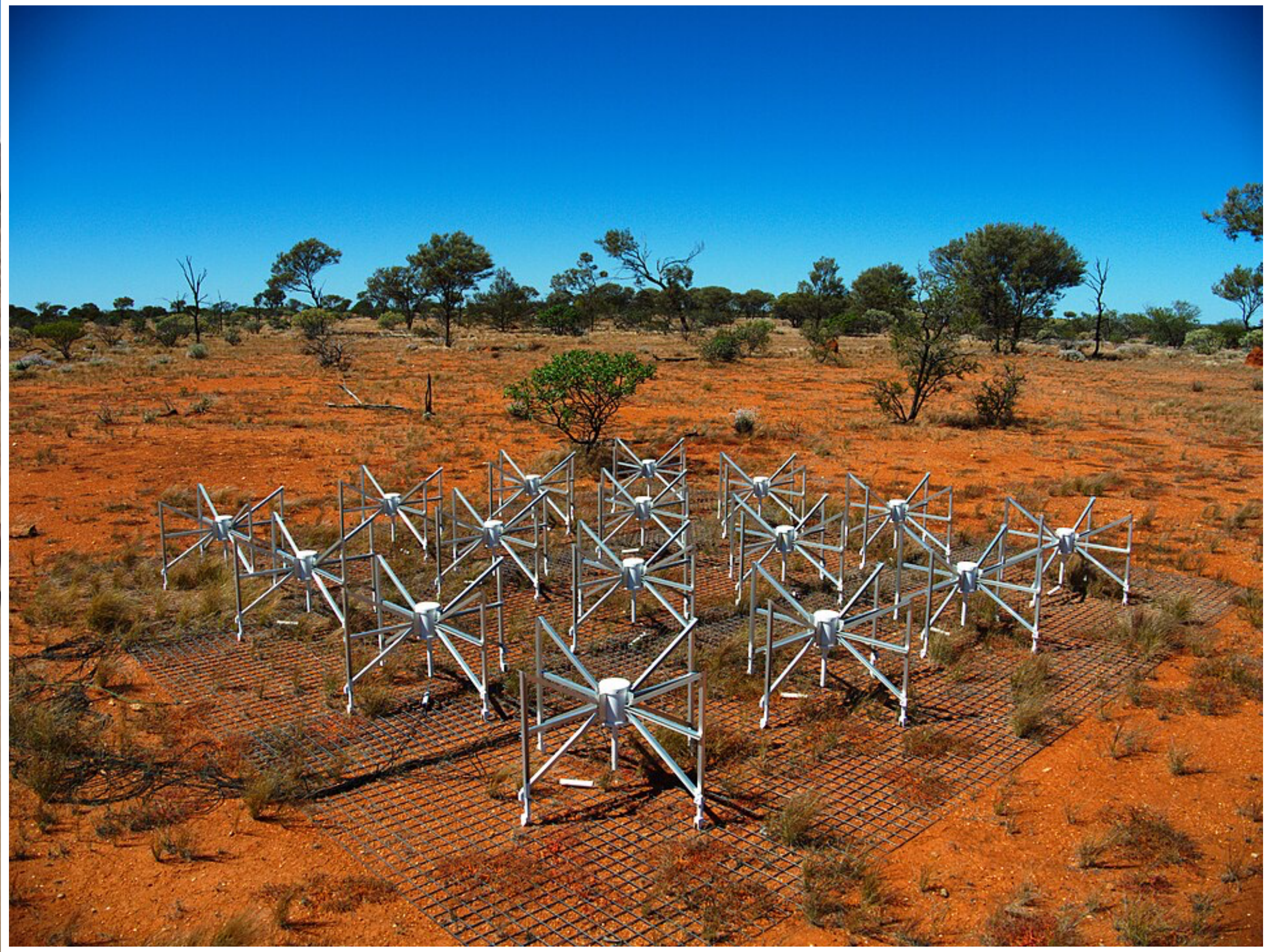
- Typically we look at spherically averaged 1D power spectrum at fixed redshift

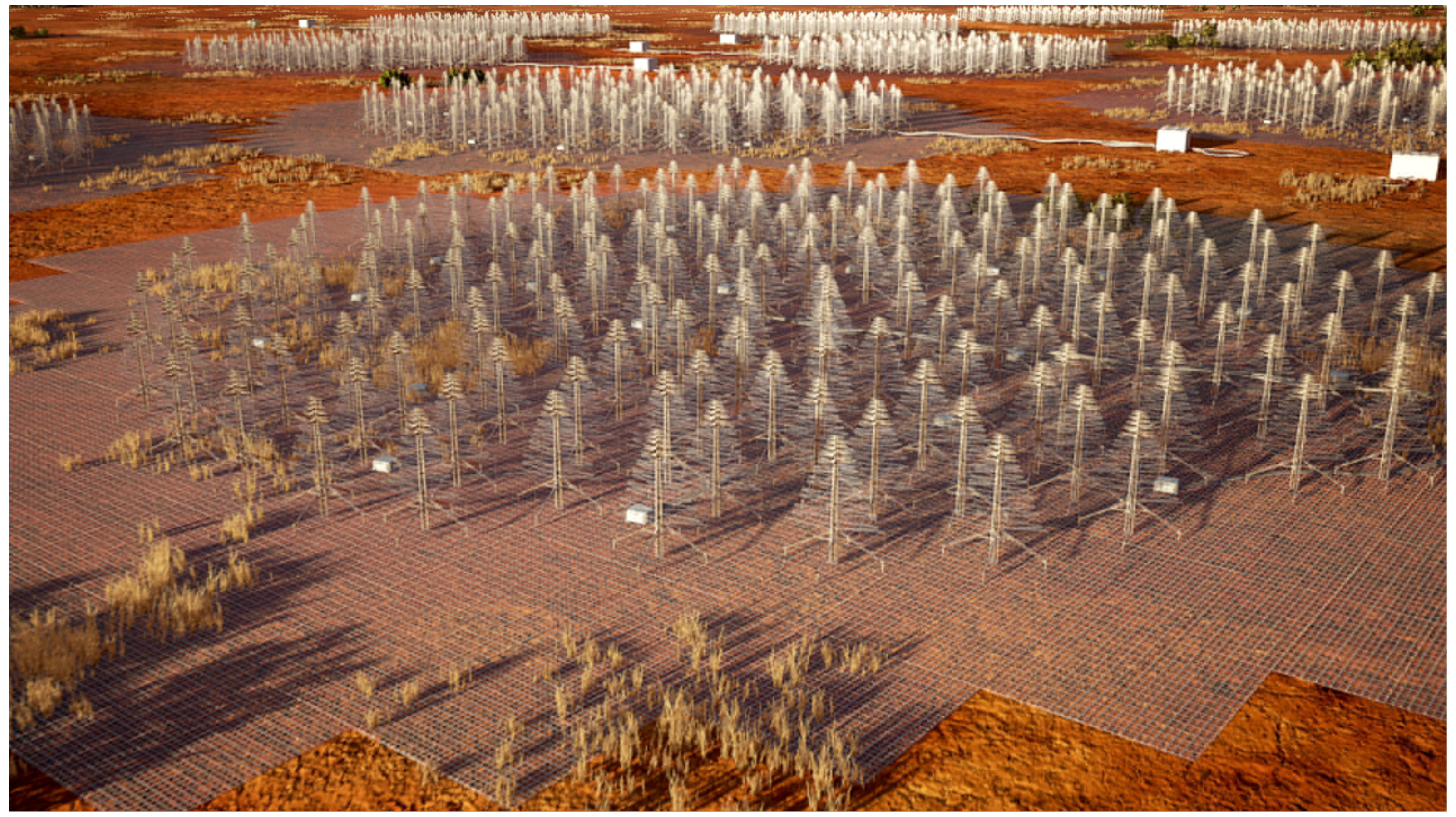
- But also the 2D power spectrum $P(k_{||}, k_{\perp})$



Fluctuations

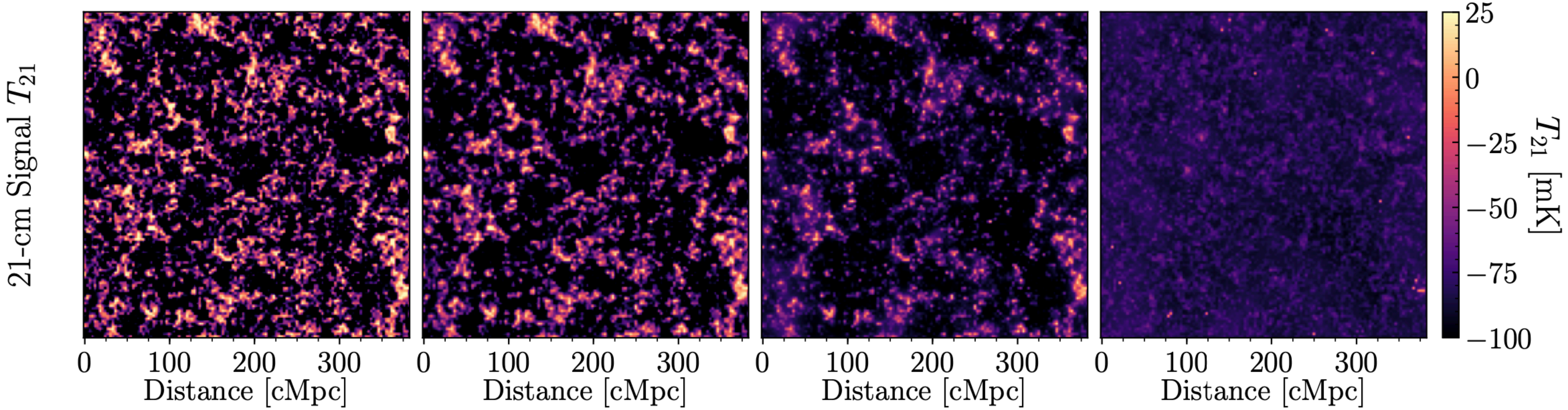
- Observe with interferometers like HERA, LOFAR, MWA and eventually SKA Low





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



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Challenges

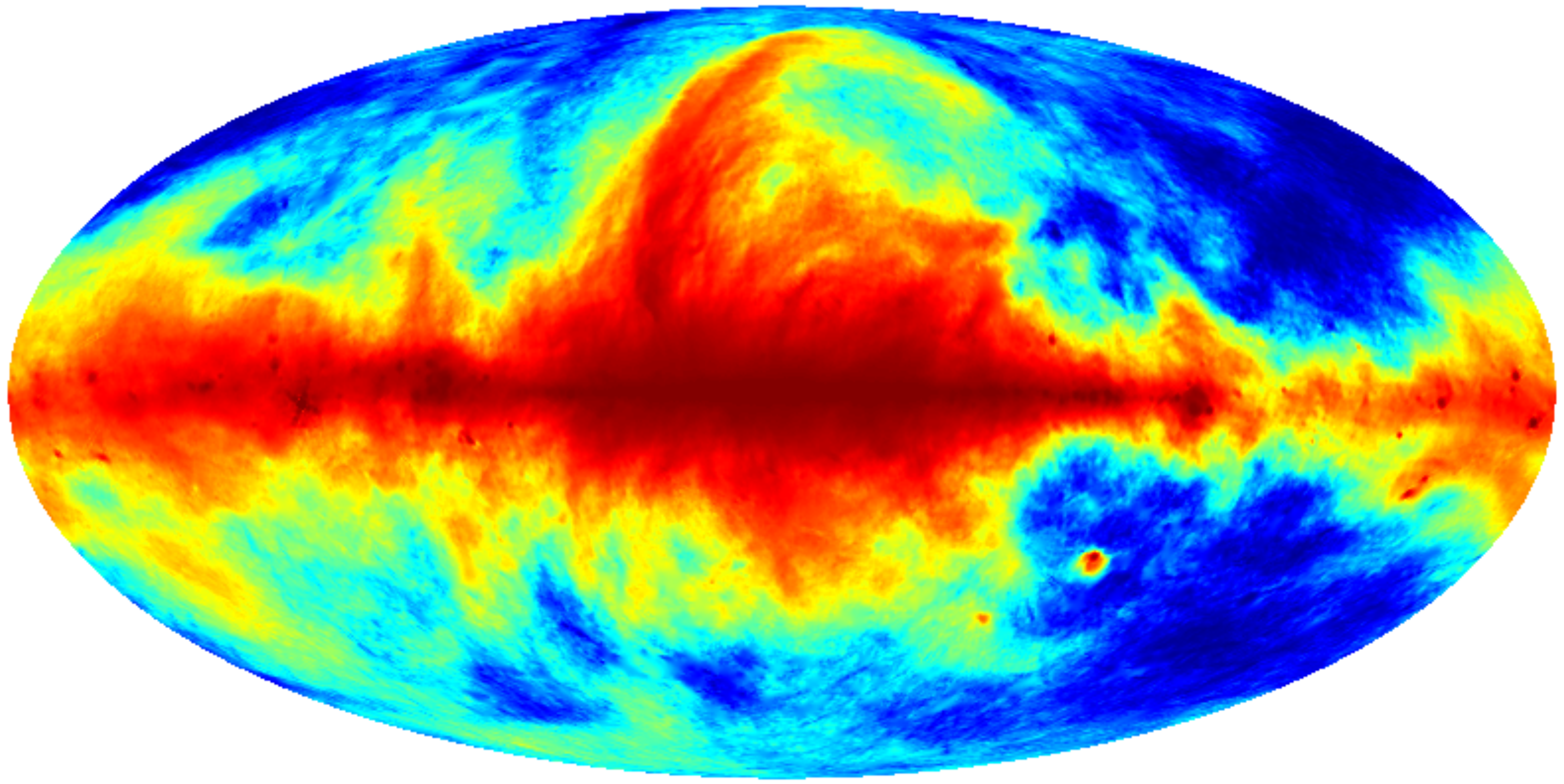
- Telescopes are sensitive to the signal but also emission from our own galaxy and others known as foregrounds

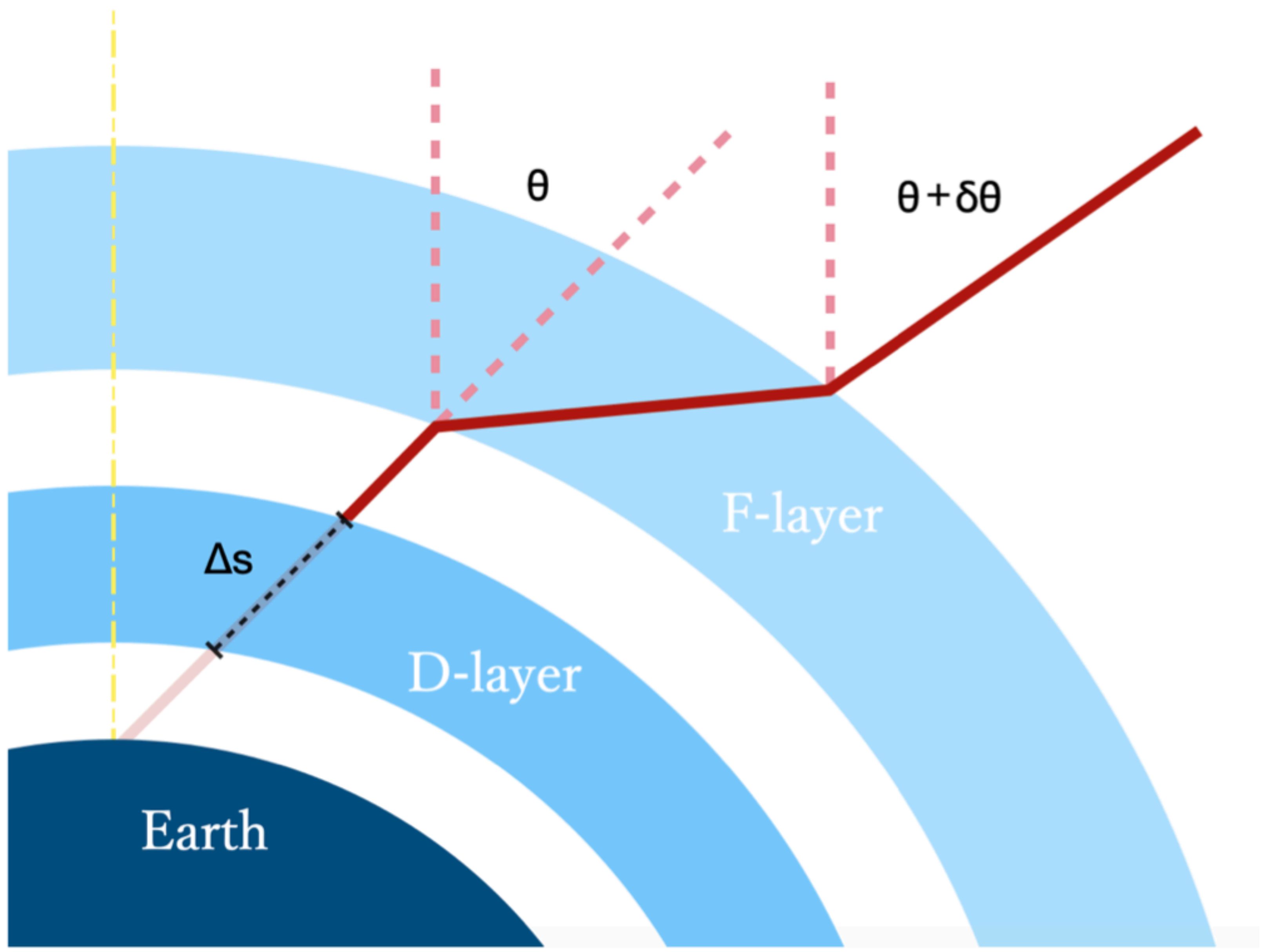
- Effected by ionosphere

- Pick up radio stations, walkie-talkies, satellites, reflections of planes…

- Radiation from horizon and soil

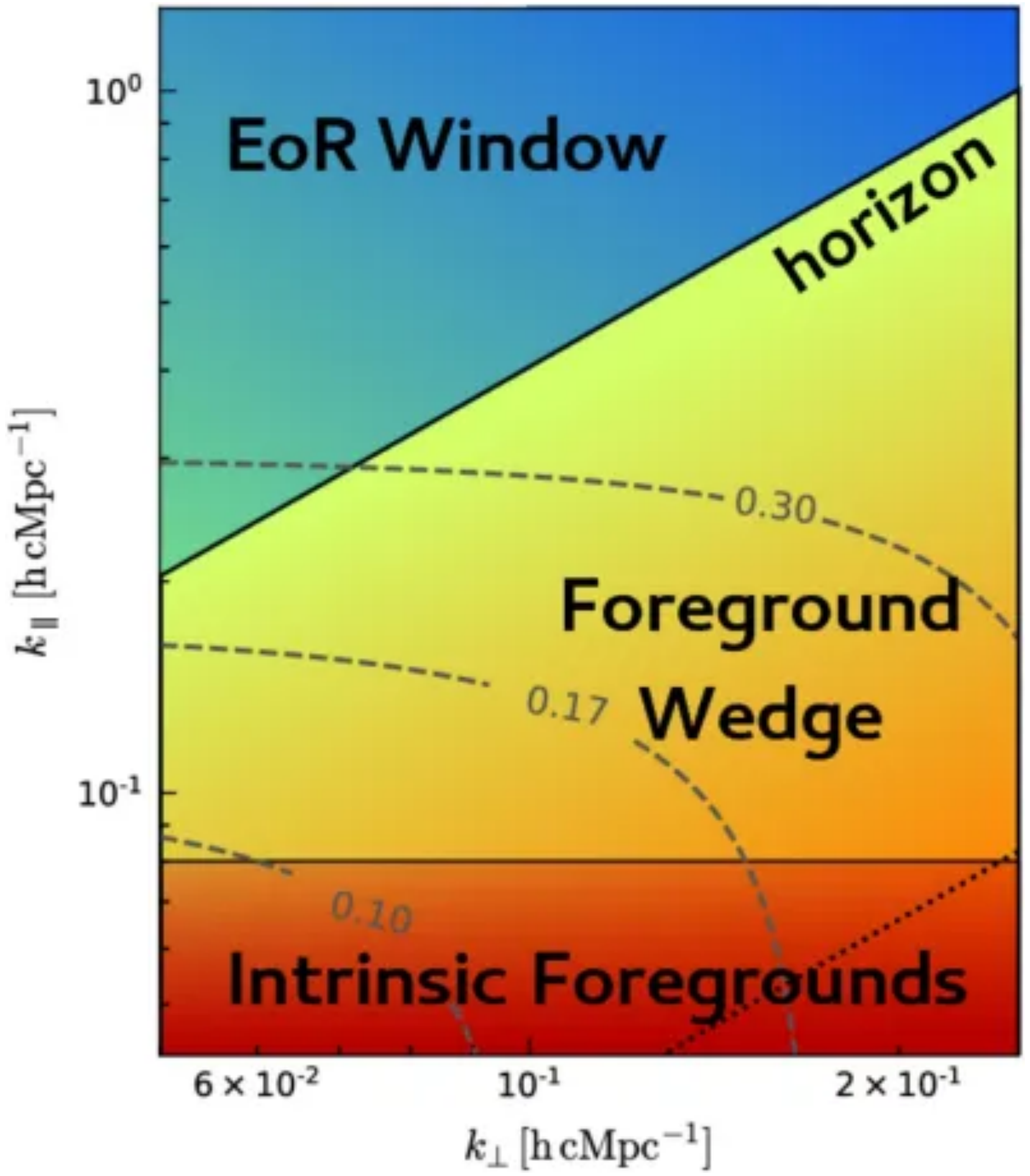
- Instrumental effects





Observing the signal

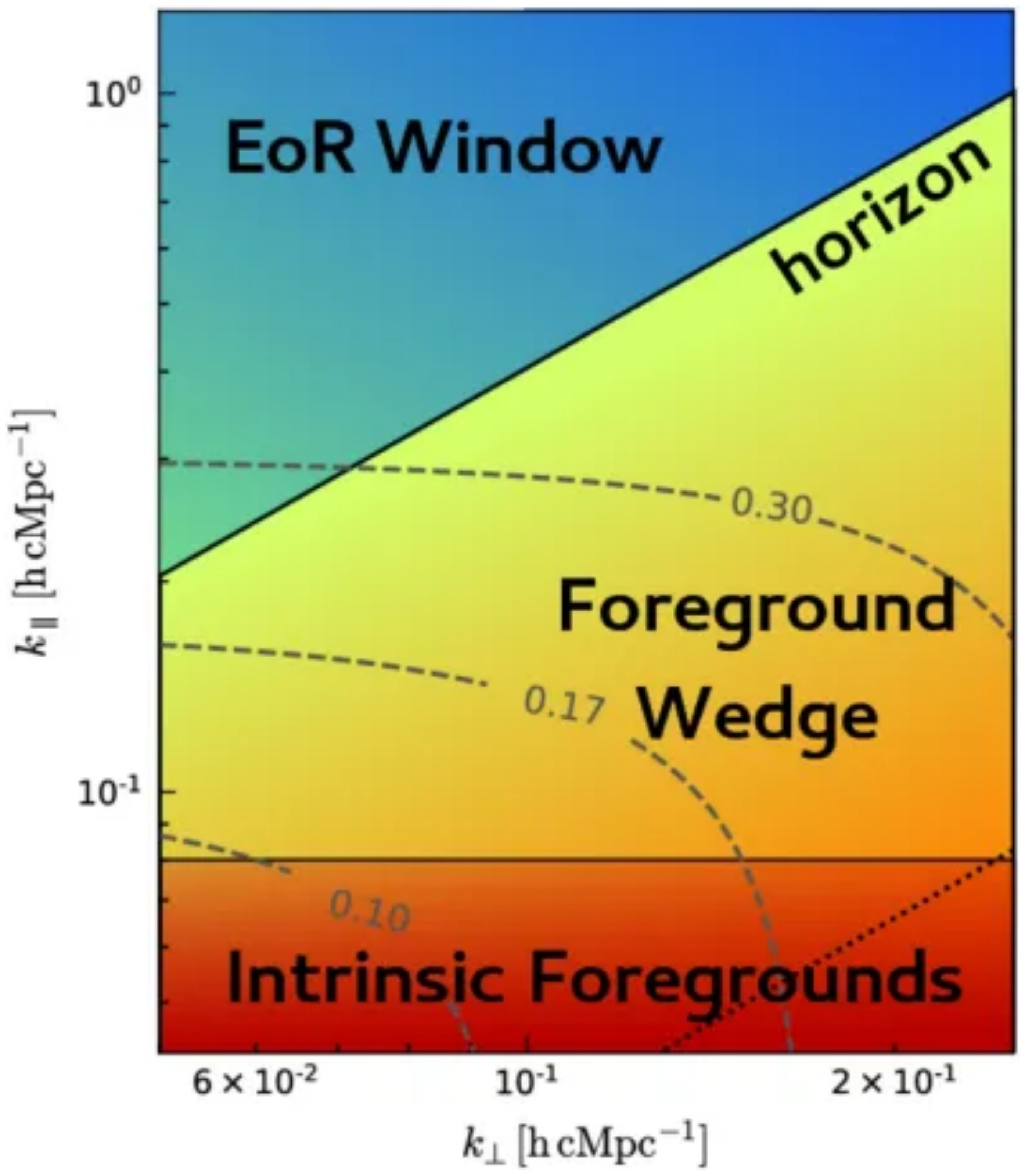
Instrumental effects leak power to higher $k_{||}$



Foregrounds are smooth so live at low $k_{||}$

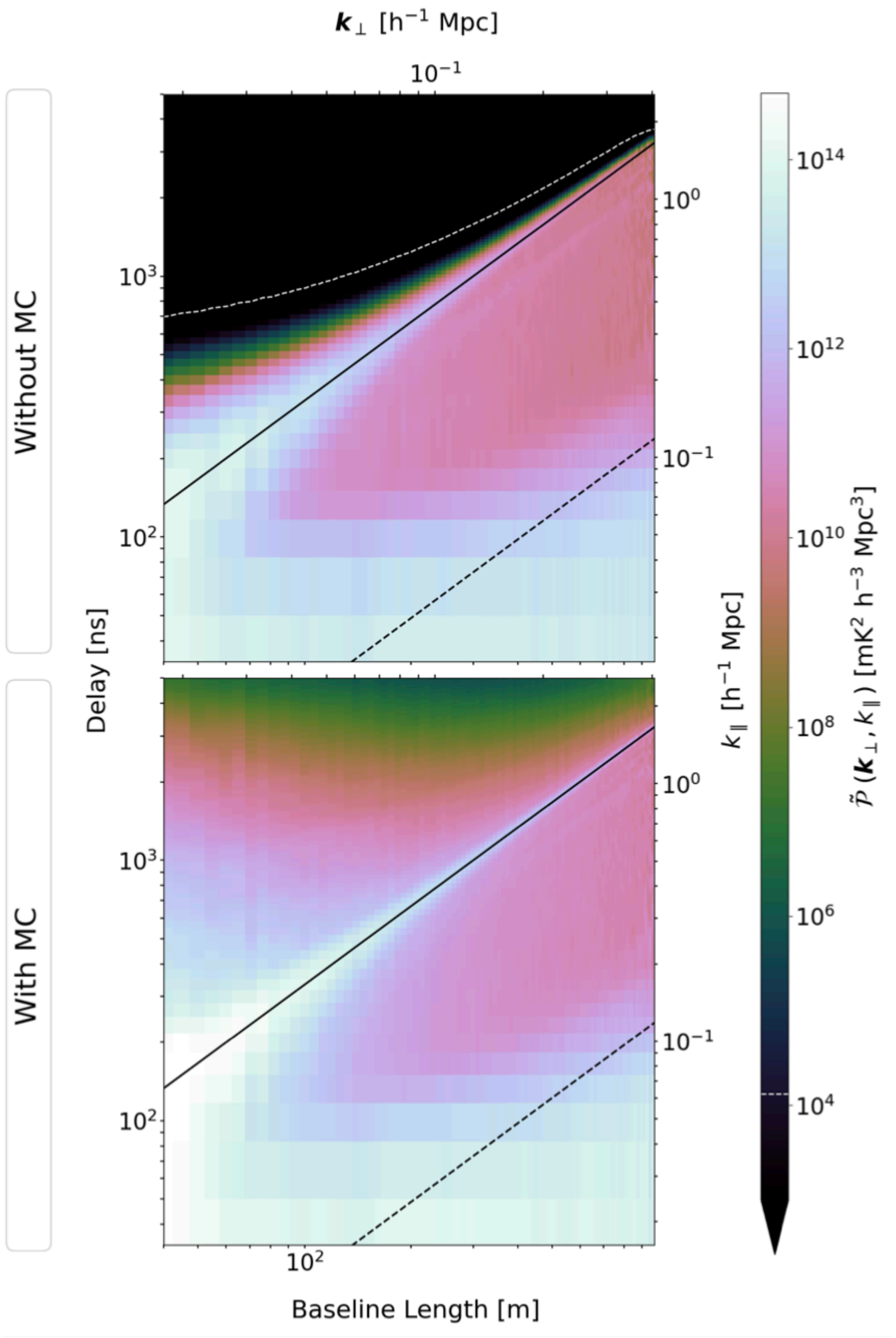
Observing the signal

Instrumental effects leak power to higher $k_{\|}$



Foregrounds are smooth so live at low $k_{\|}$

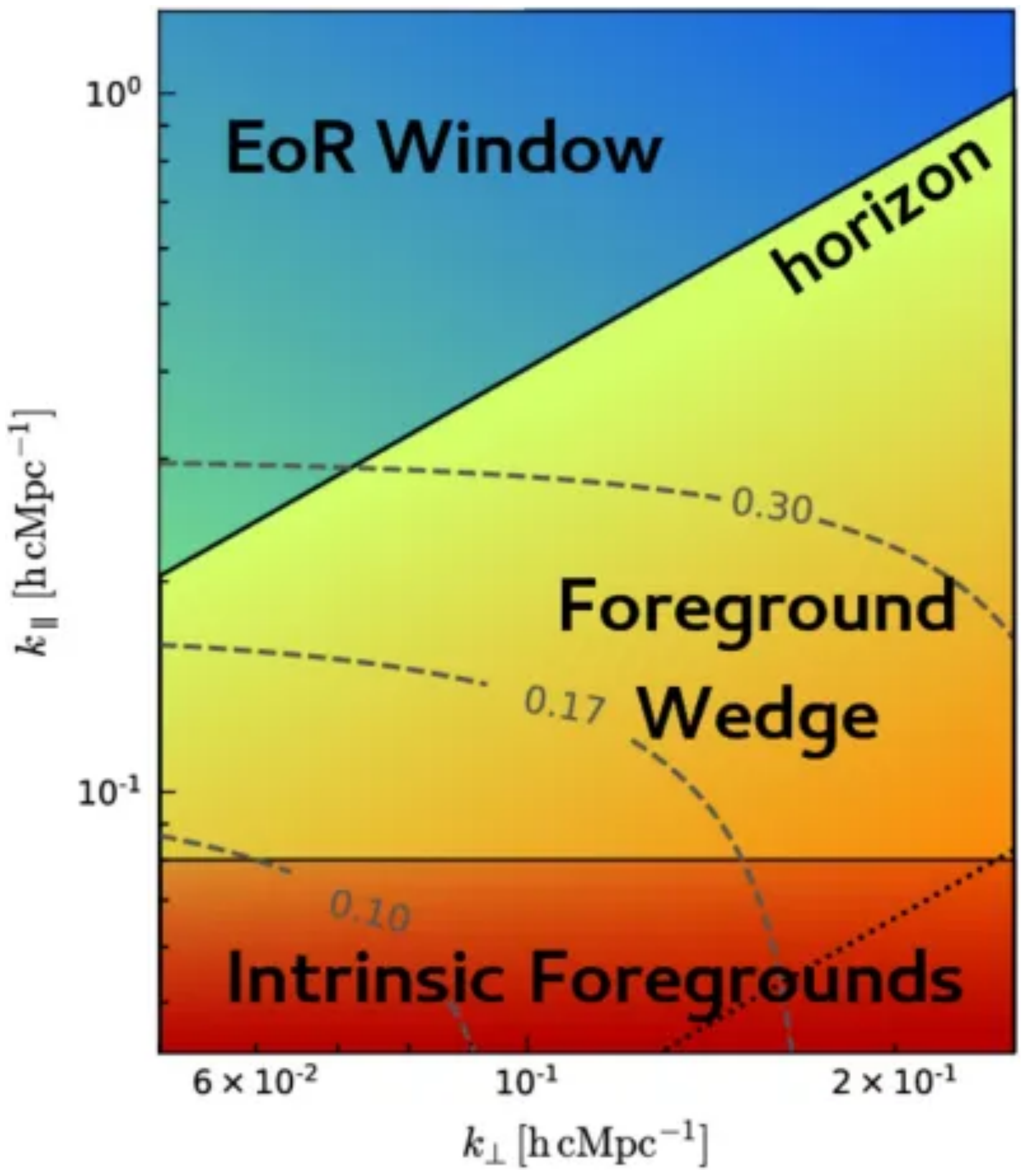
SKA Forecasts



O'Hara et al. 2024

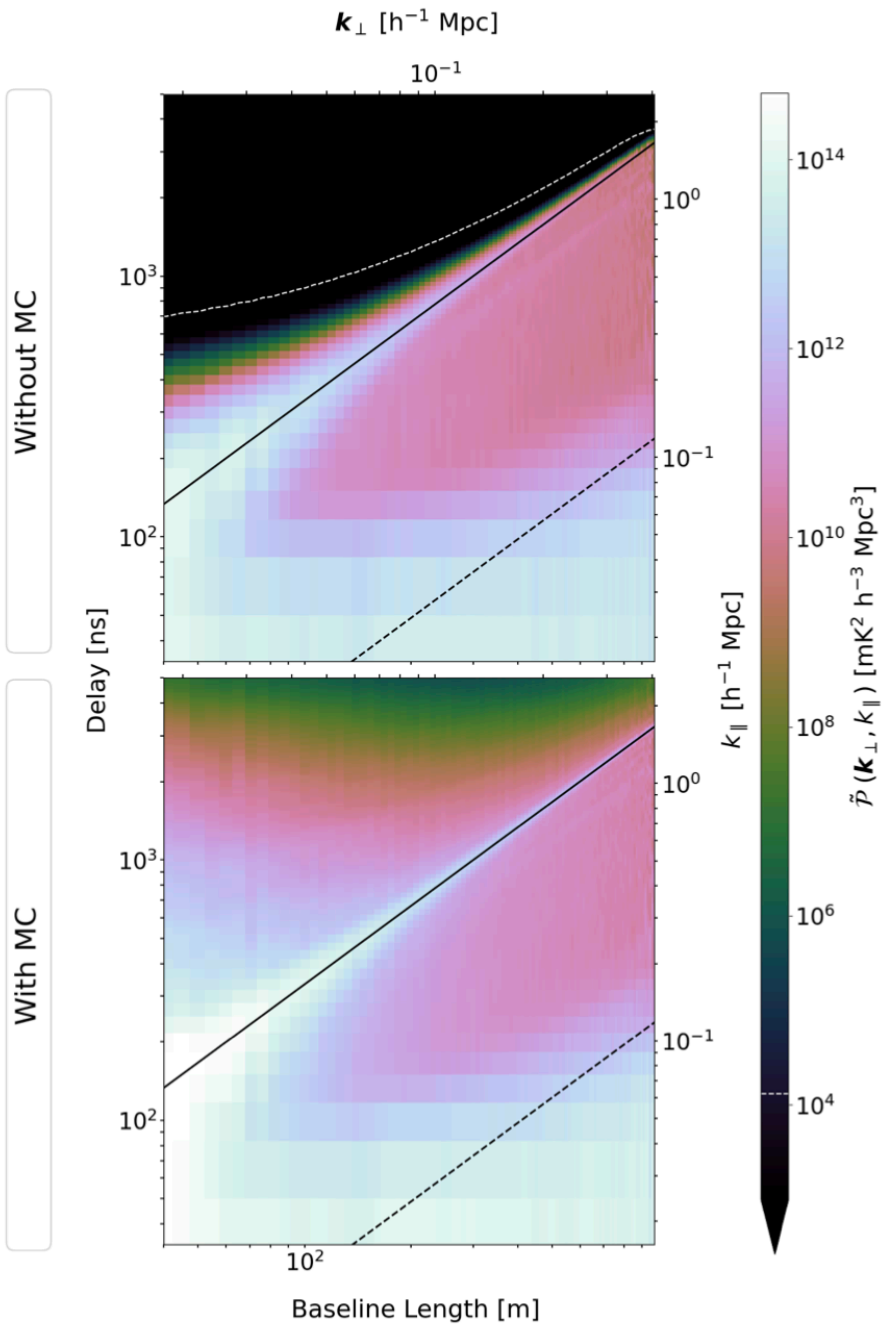
Observing the signal

Instrumental effects leak power to higher $k_{\parallel}$



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

SKA Forecasts



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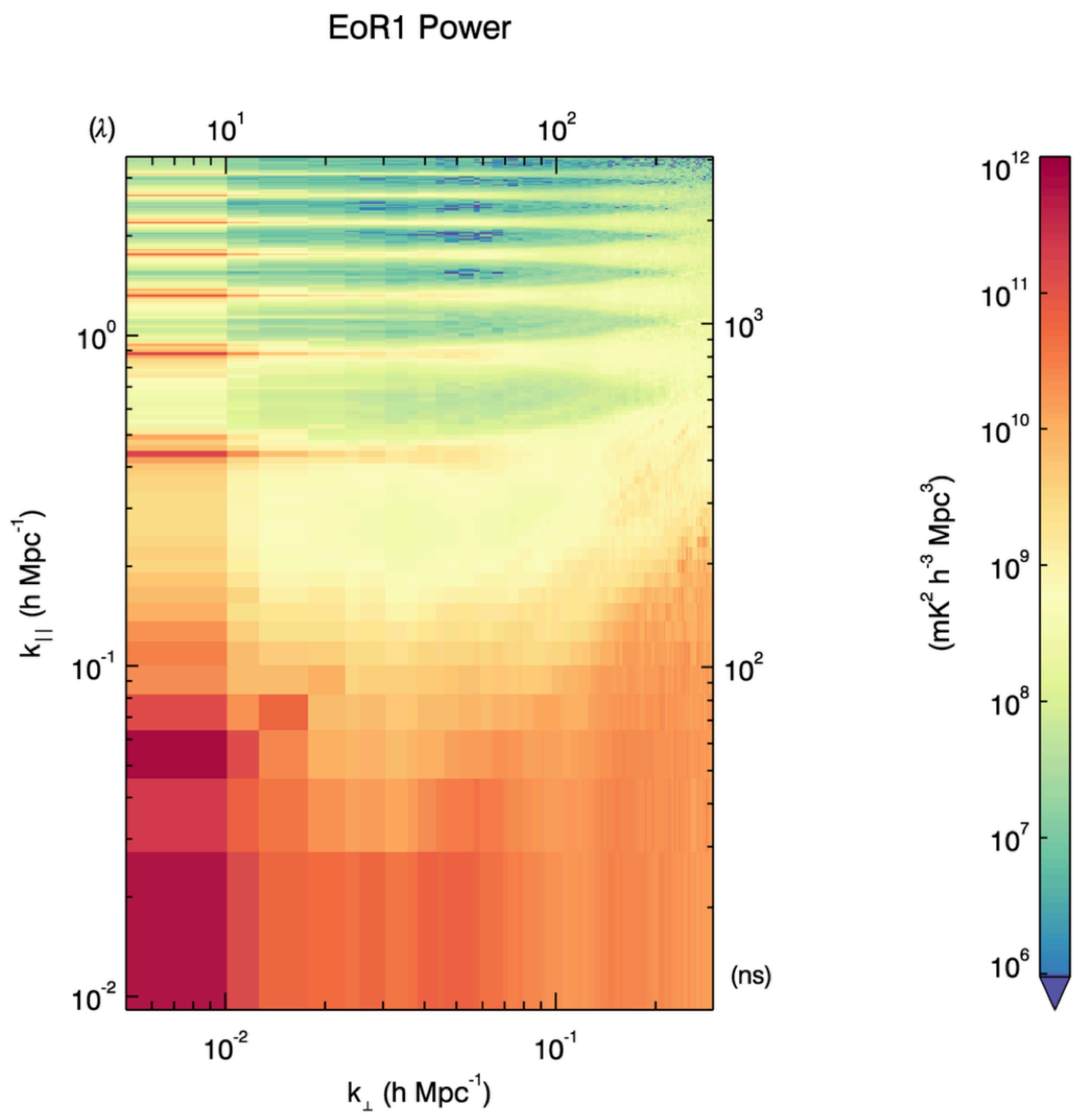
MWA Observations



Trott et al. 2019

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!

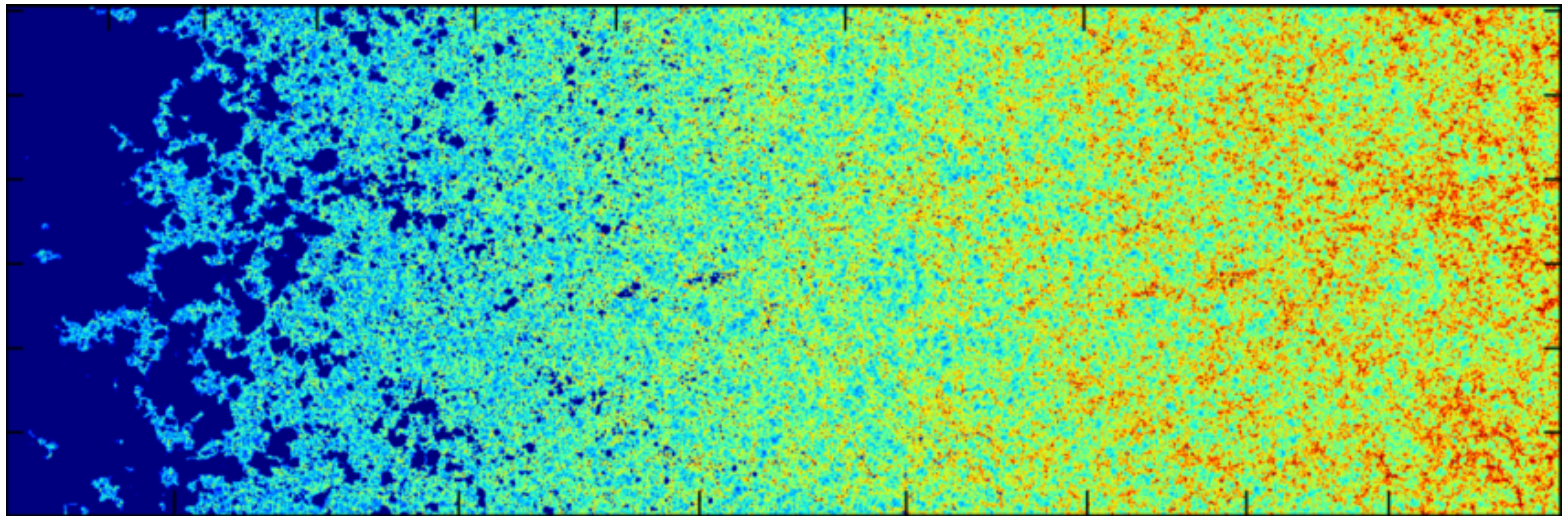
21cmSPACE

- 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

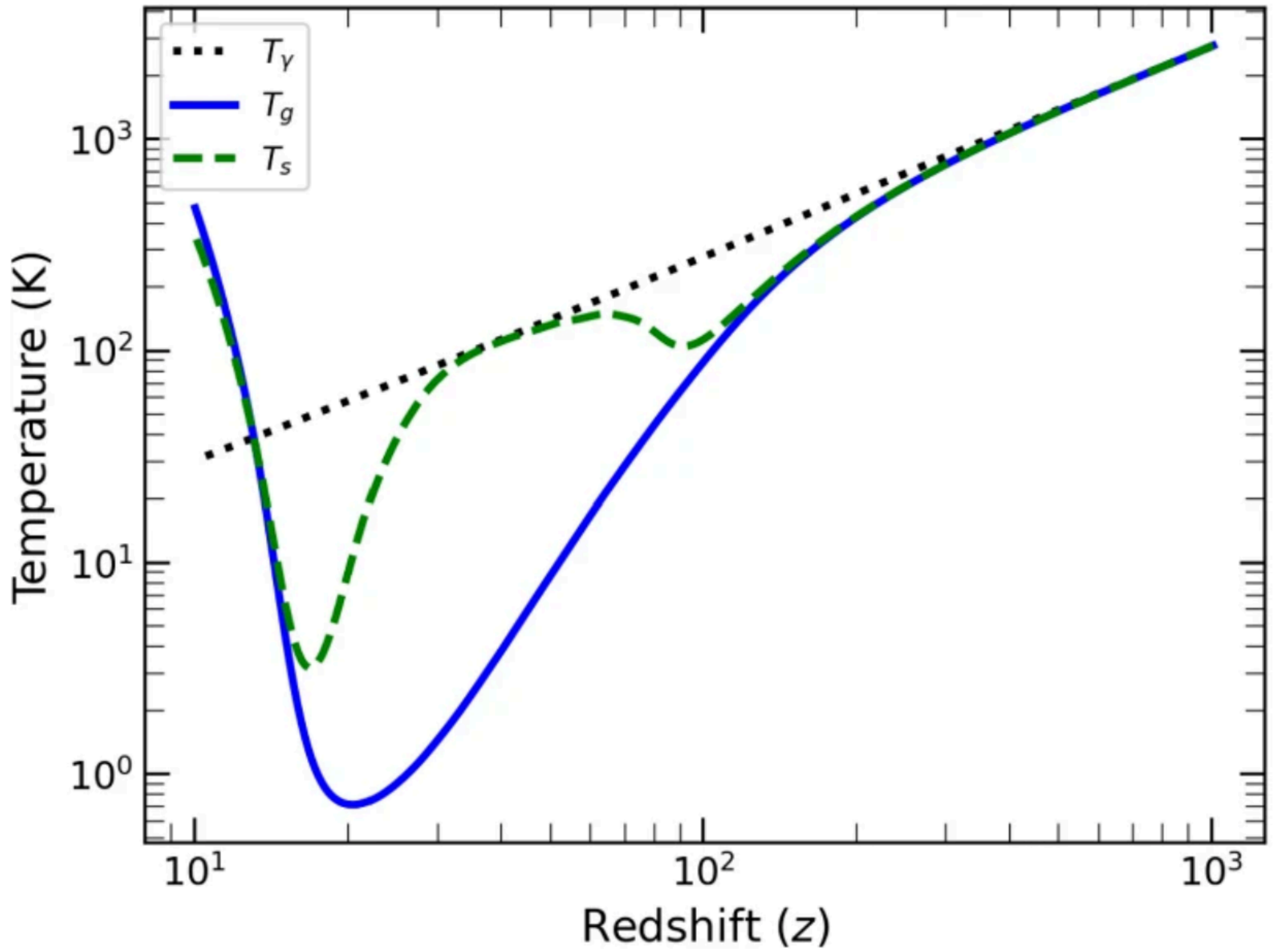


21cmSPACE

- 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

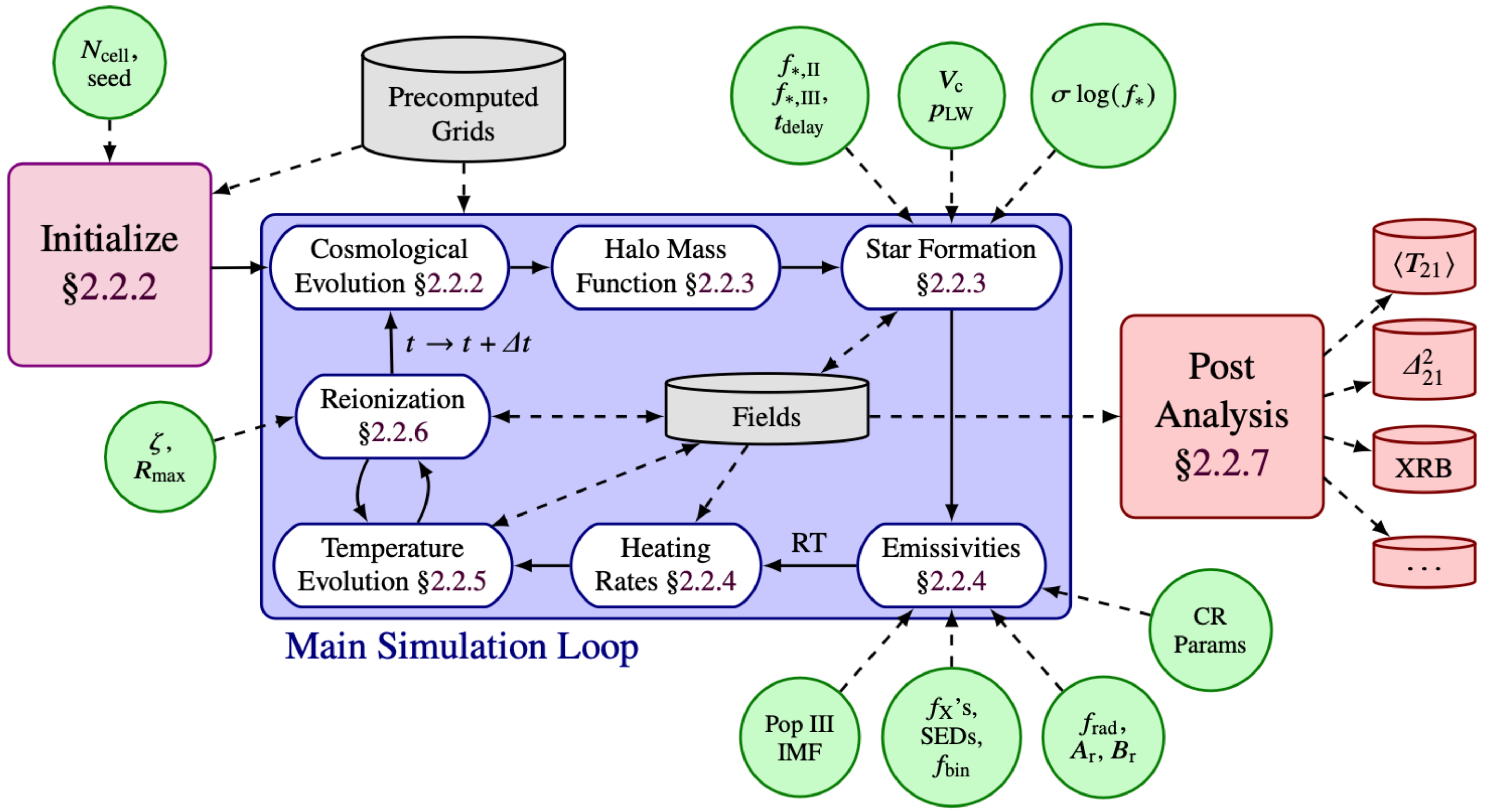
21cmSPACE

- 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



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IMF, REACH and the SKA

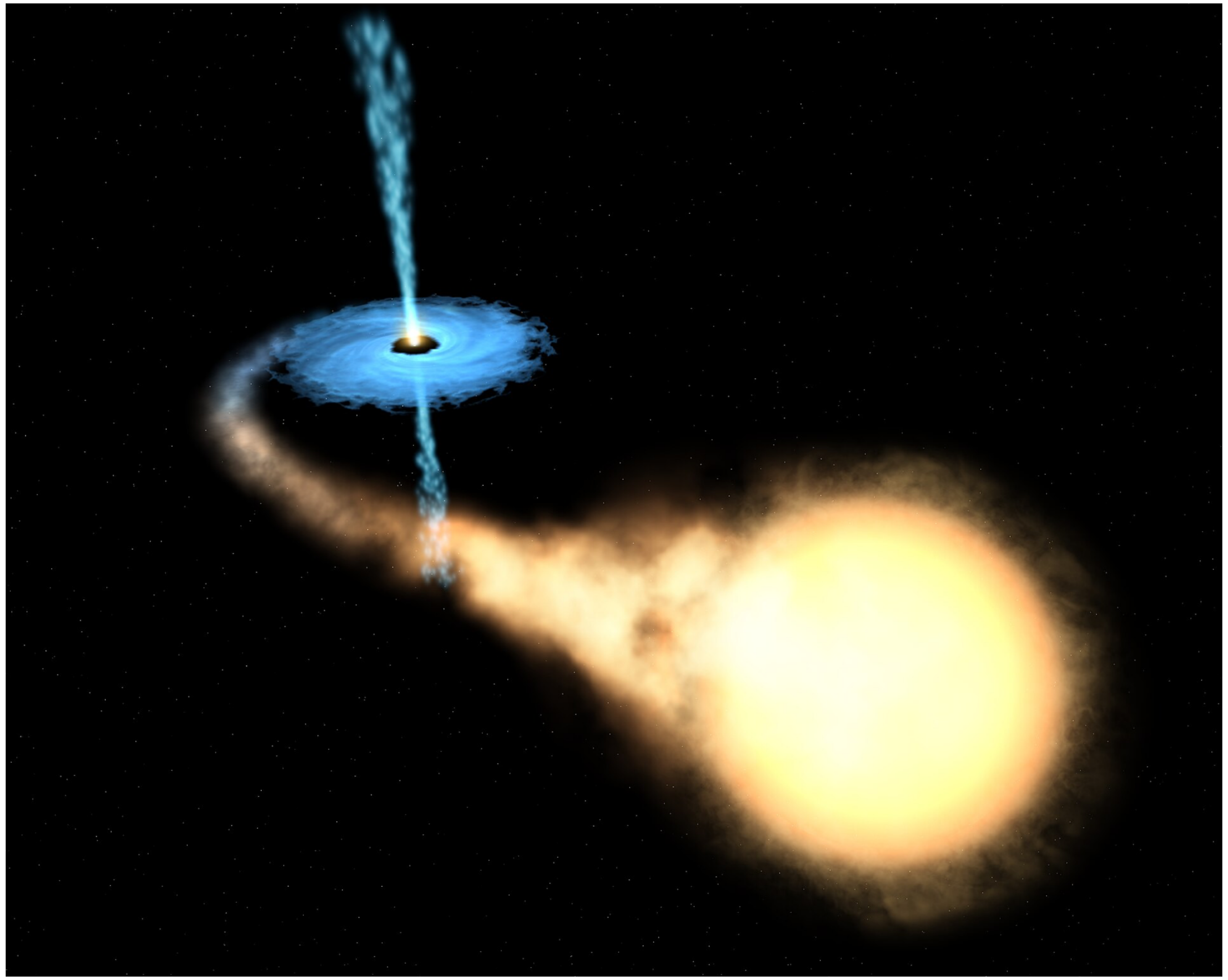
PopIII Initial Mass Function

- 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

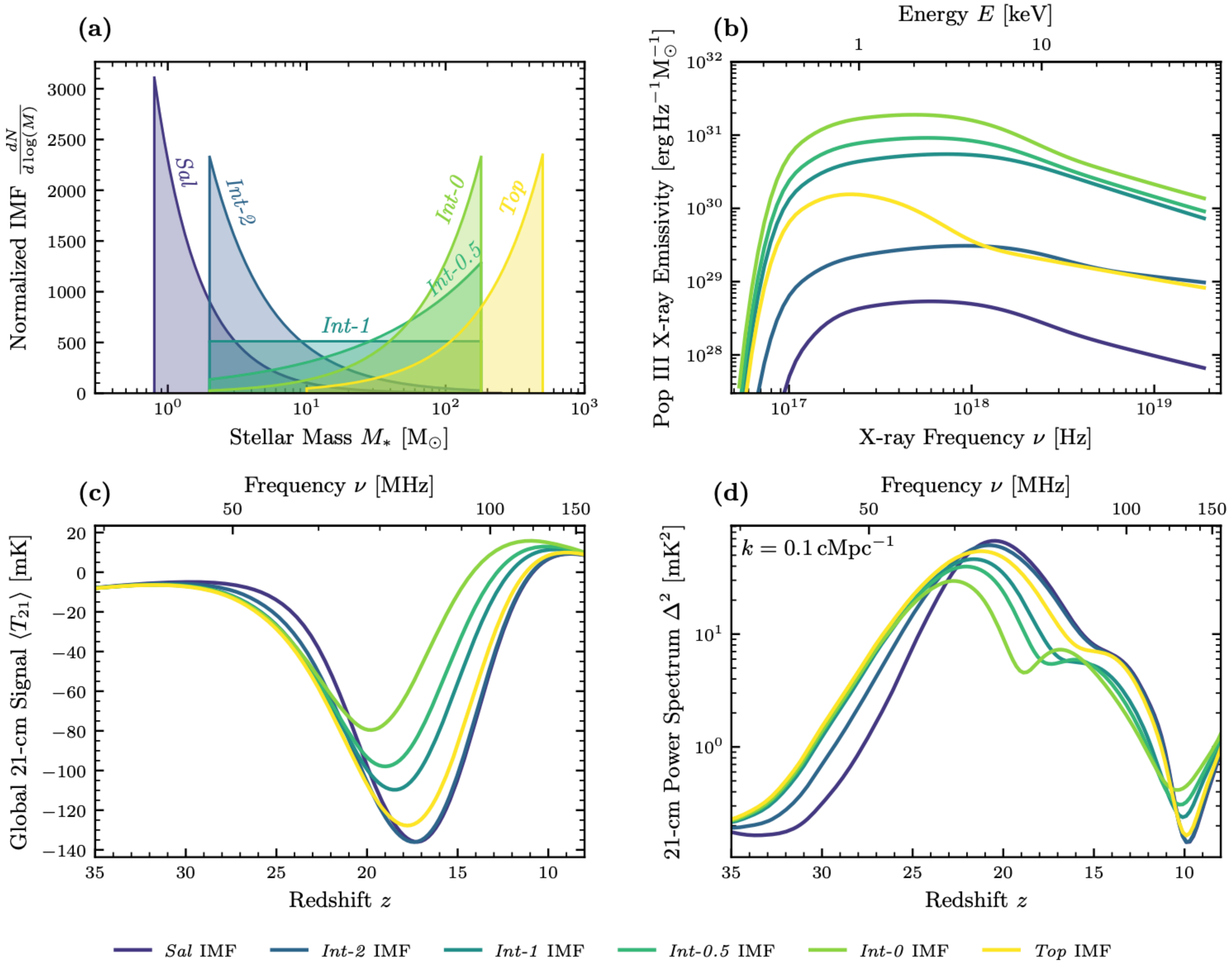
- PopIII IMF will have a significant impact on the number of X-ray binaries that form and the mass of the stars within them

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

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

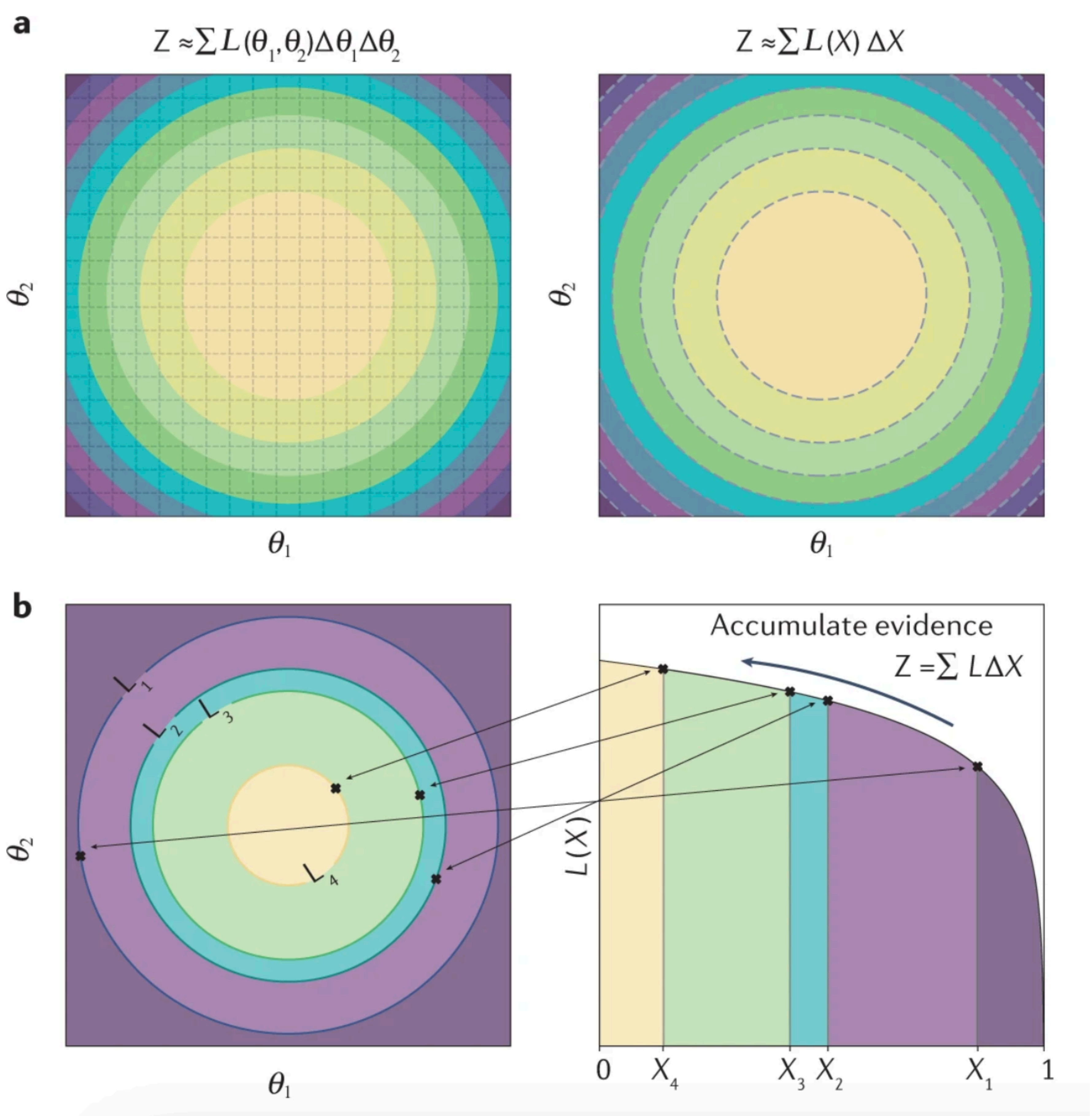
- We tend to use Bayesian inference in 21cm Cosmology

- Primarily for model comparison

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

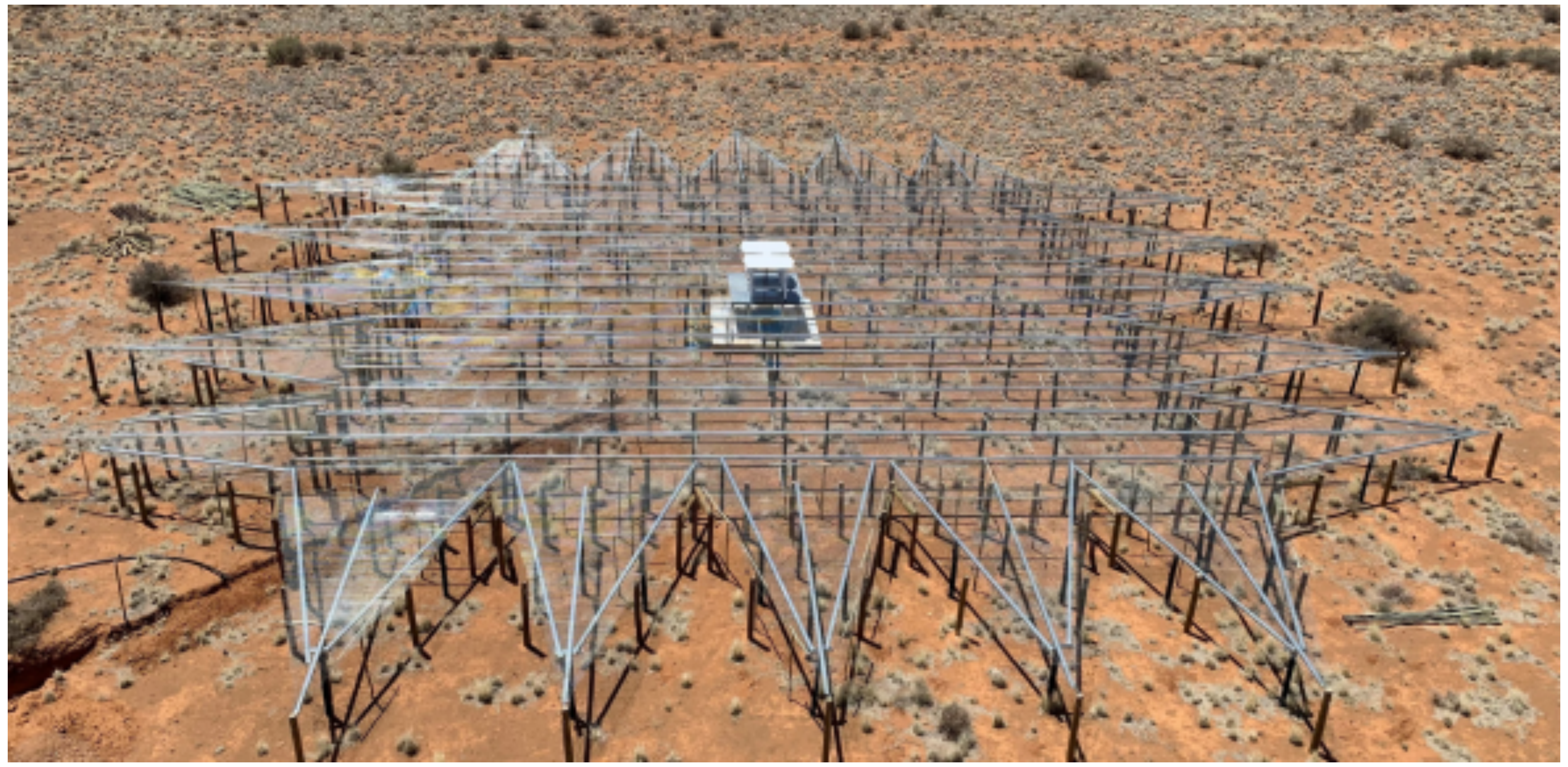
- So if I am looking for the 21cm signal and $M_2 = M_{fg} + M_{21}$ and $M_1 = M_{fg}$ then I will have found statistical evidence for it

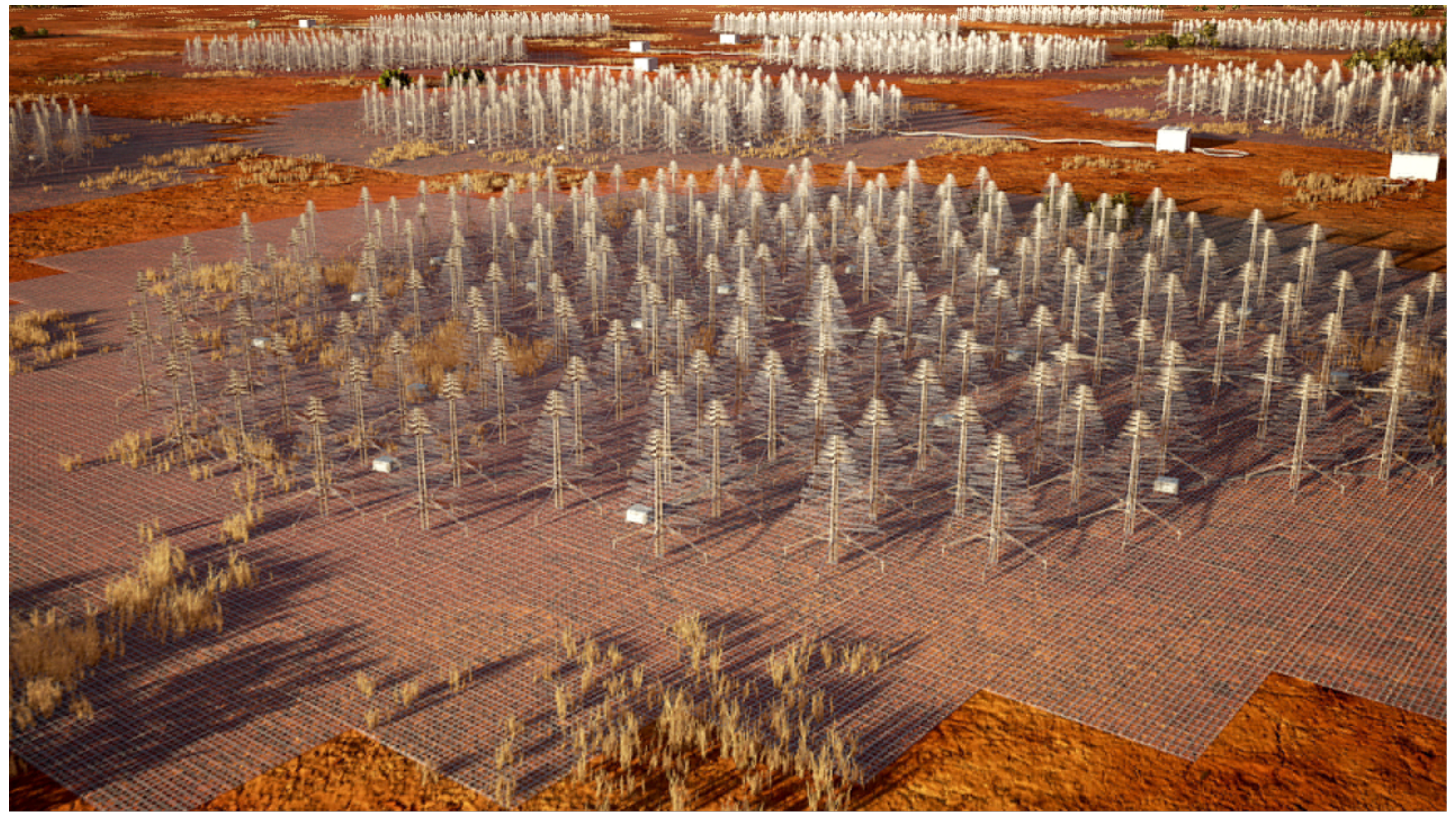
- But could also have $M_1 \rightarrow \mathrm{IMF}_1$ and $M_2 \rightarrow \mathrm{IMF}_2$



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





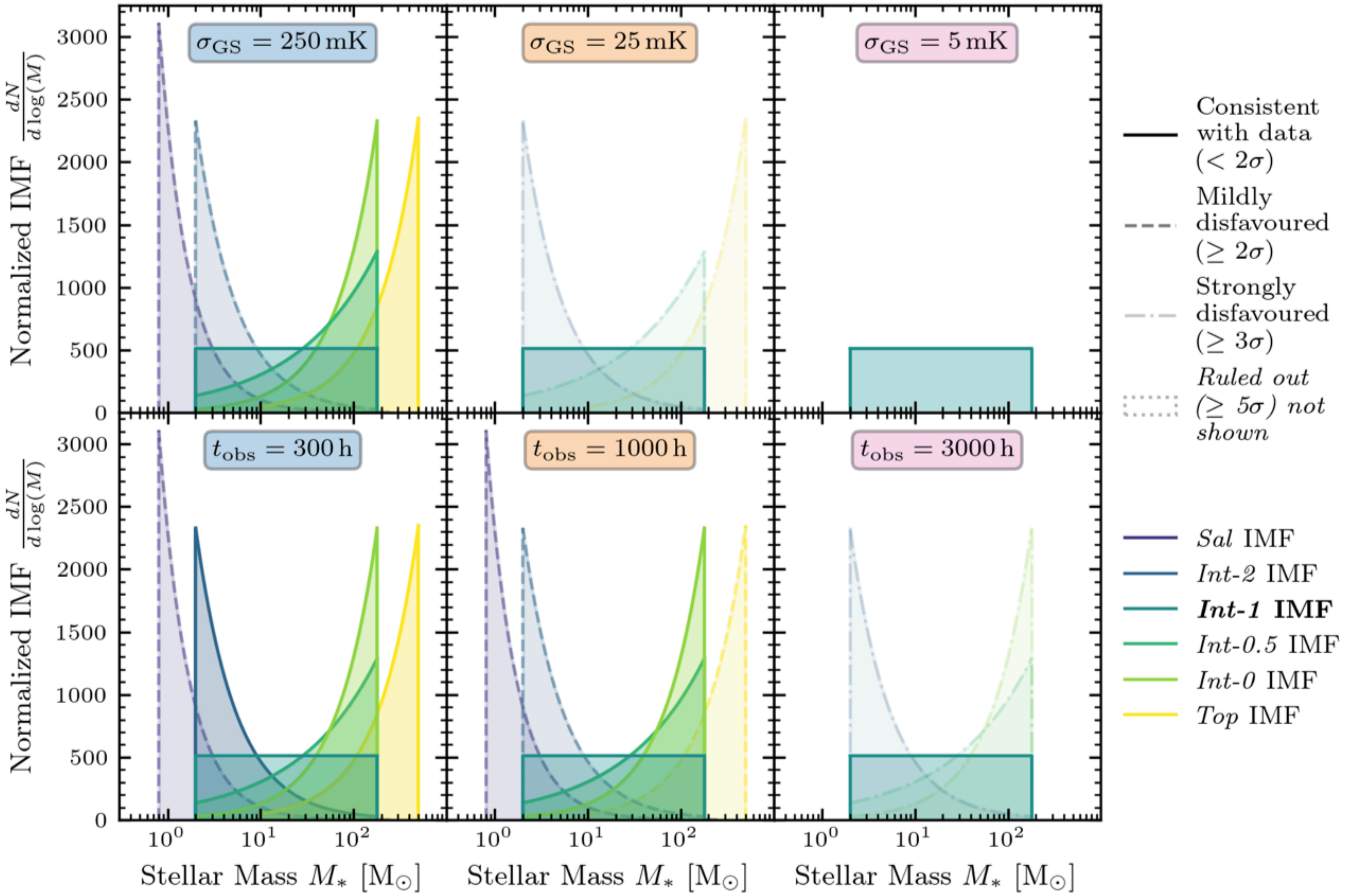
Results

- Generated data with IMF Int-1 and model with the other 5 IMFs

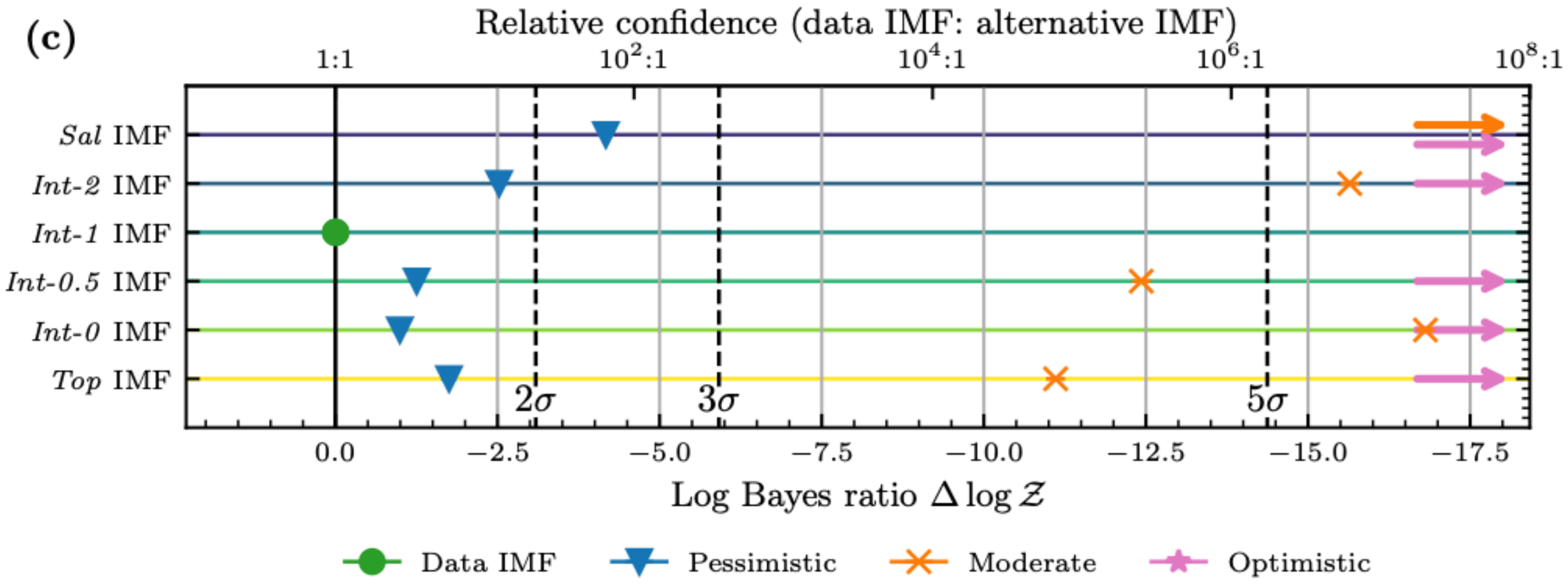
- Determine posterior probability on IMFs via

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

- Successfully identify the IMF with SKA and REACH data



Results


(c)
Relative confidence (data IMF: alternative IMF)
1:1
10^2:1
10^4:1
10^6:1
10^8:1
Sal IMF
Int-2 IMF
Int-1 IMF
Int-0.5 IMF
Int-0 IMF
Top IMF
2σ
3σ
5σ
0.0
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
Log Bayes ratio Δ log Z
Data IMF
Pessimistic
Moderate
Optimistic

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