The Status of 21cm Measurements

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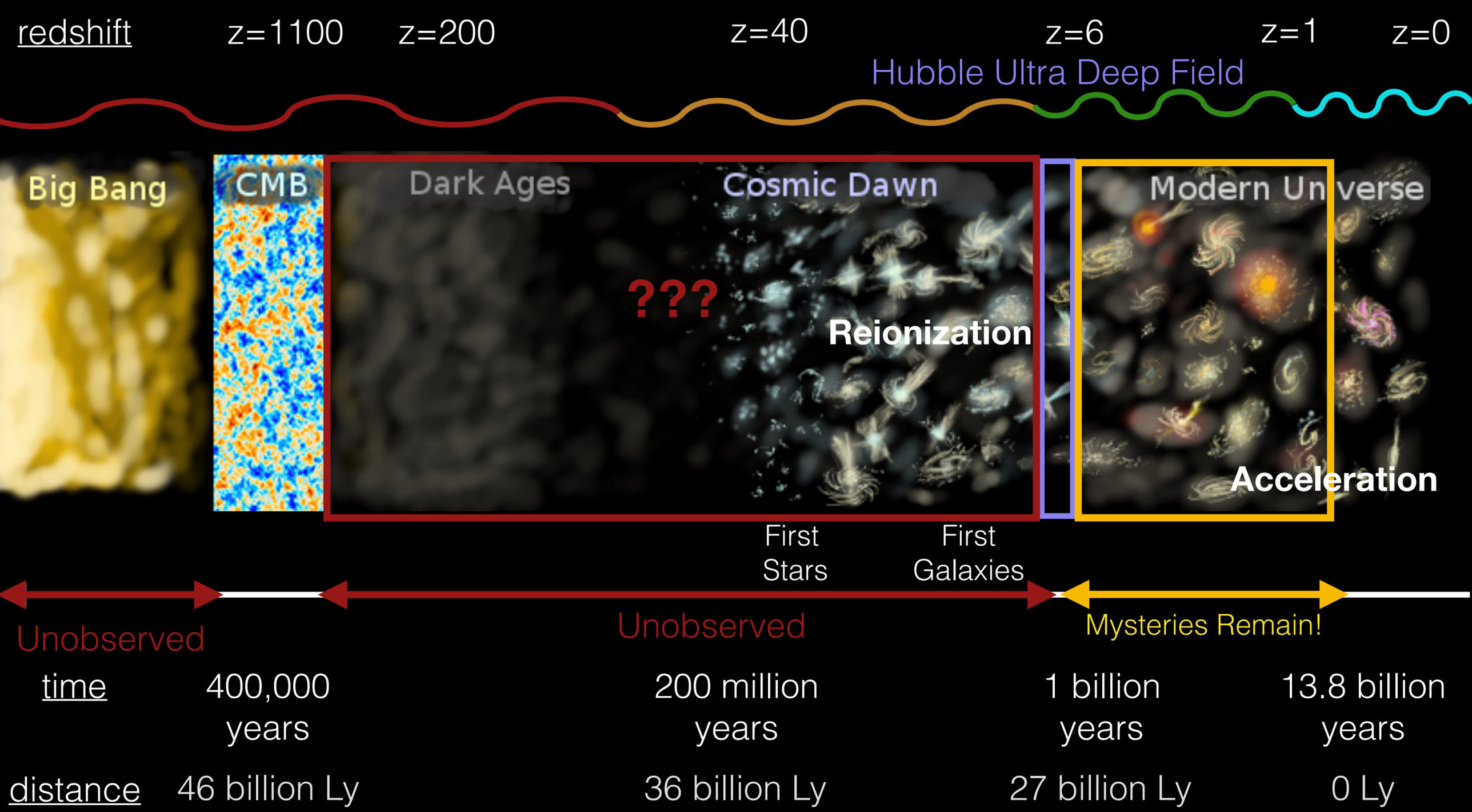
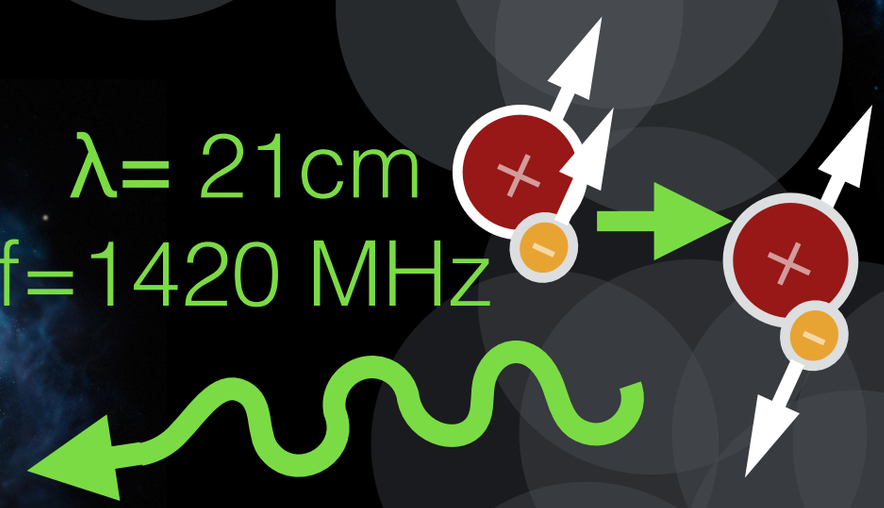
Outline

- What we want to do (Cosmology / Cosmic Dawn).
- What we are doing (mitigating systematics).
- EDGES
- Everybody else.
- Looking Forward.

We want to use 21cm to fill in our Cosmic History

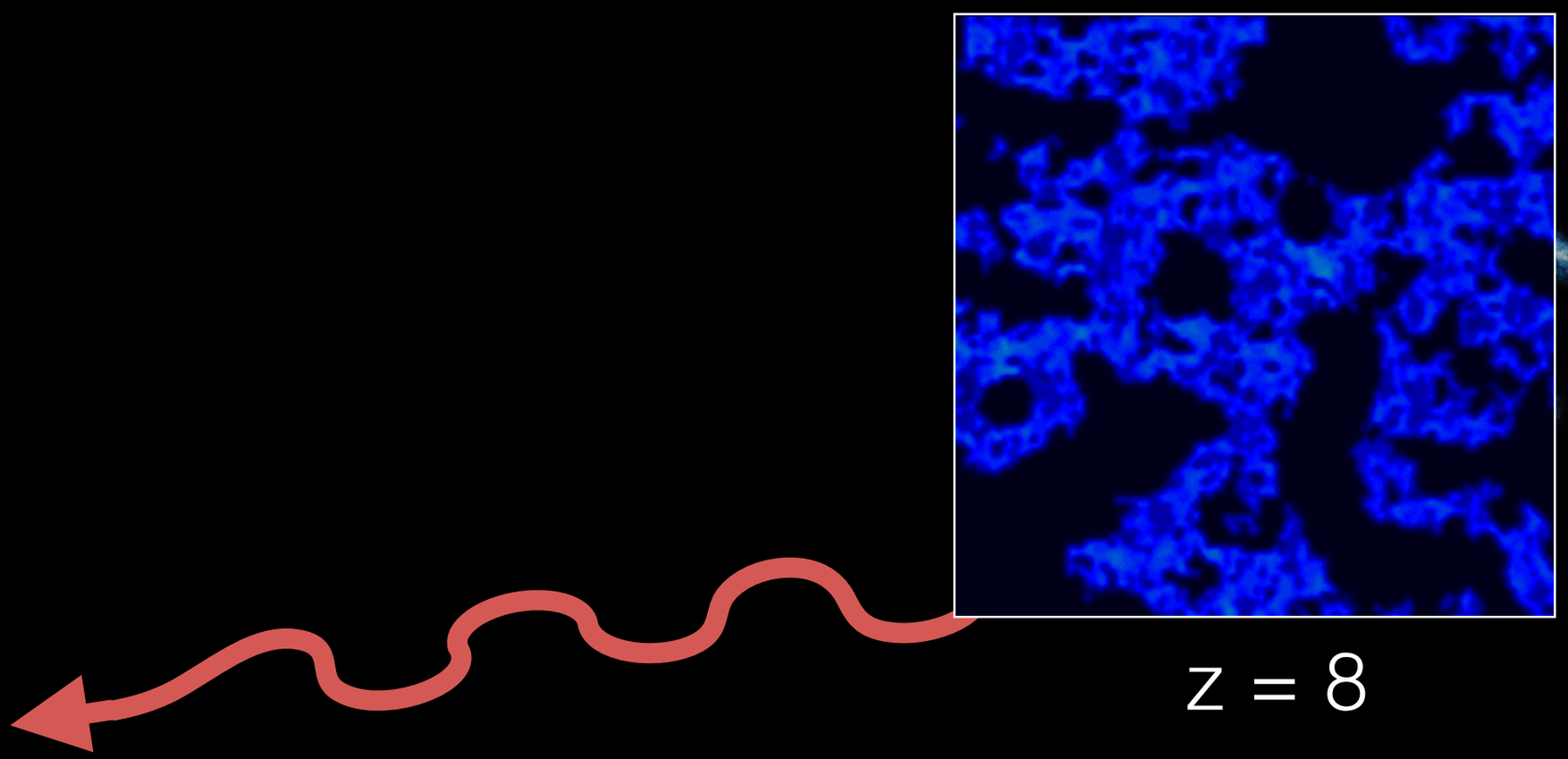


21cm Tomography
Lets us Observe the Impact of the first Galaxies on Intergalactic Gas



21cm Tomography

λ= 1.68m
f=158 MHz



z = 8

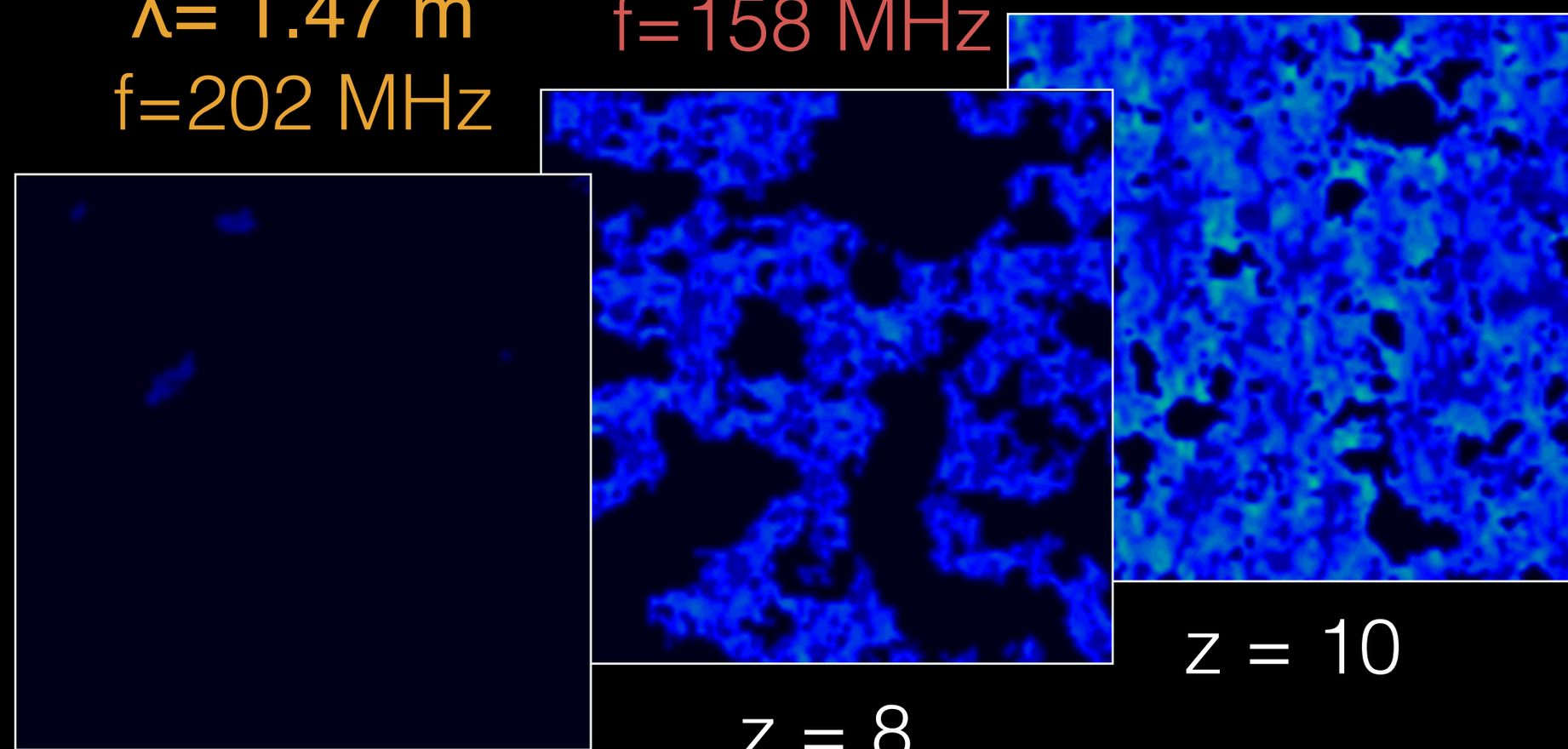
Mesinger 2011

21cm Tomography

λ= 2.1m
f=130 MHz

λ= 1.68m
f=158 MHz

λ= 1.47 m
f=202 MHz



z = 6

z = 8

z = 10

Mesinger 2011

How Astrophysics Affects 21cm Emission

δT_b =Differential Brightness Temperature

= Brightness temperature of 21cm

- Brightness temperature of CMB

How Astrophysics Affects 21cm Emission

δT_b =Differential Brightness Temperature
= Brightness temperature of 21cm
- Brightness temperature of CMB

Temperature of cosmic microwave background

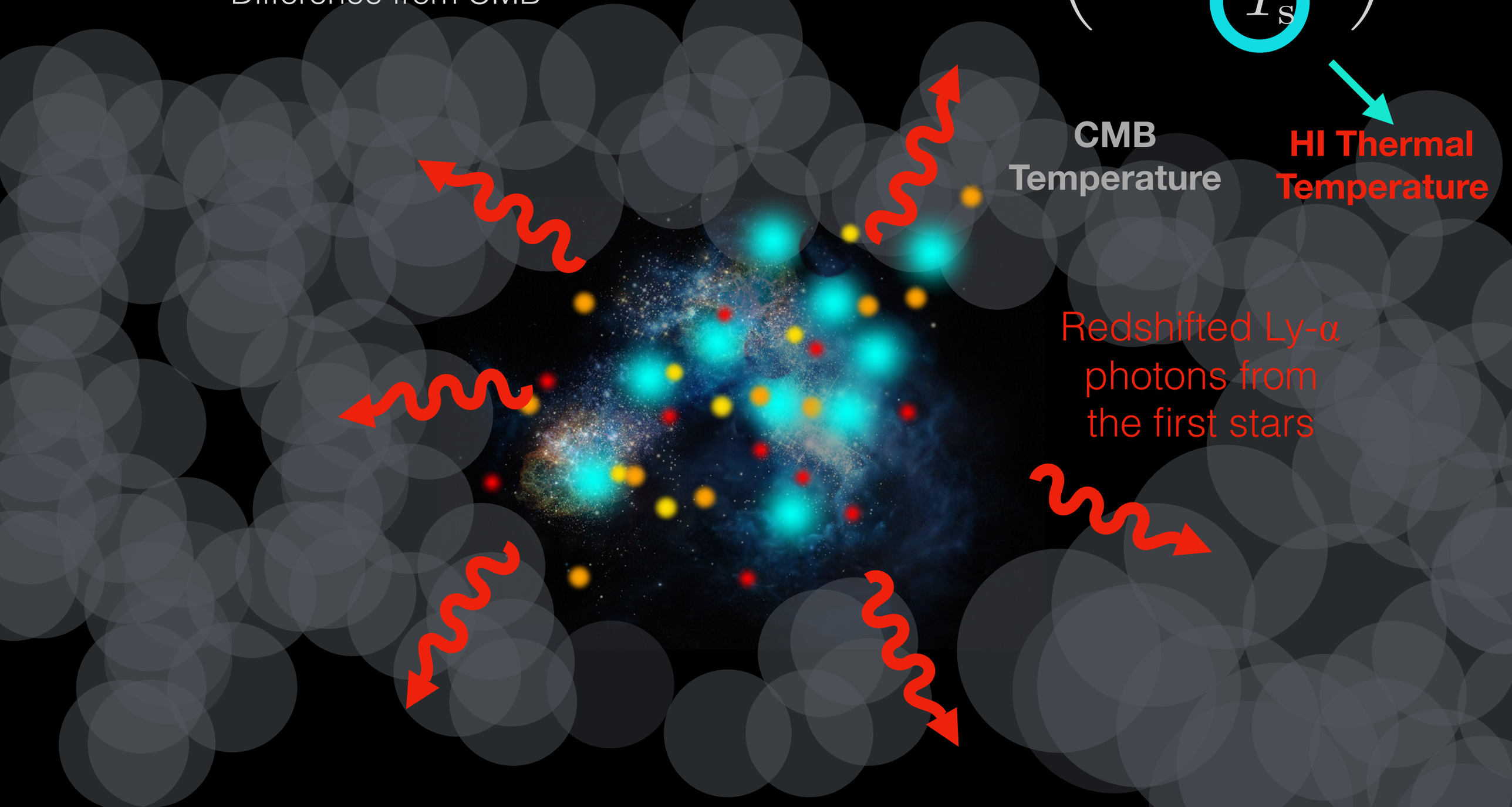
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{s}}}\right)$$

- x_{HI}: The Neutral Fraction -> ionizations?
- T_s: Spin Temperature -> Temperature of Hyperfine Transition
- ρ: Density

Lyman-α Pumping: Couple Spin to Thermal Temperature

δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

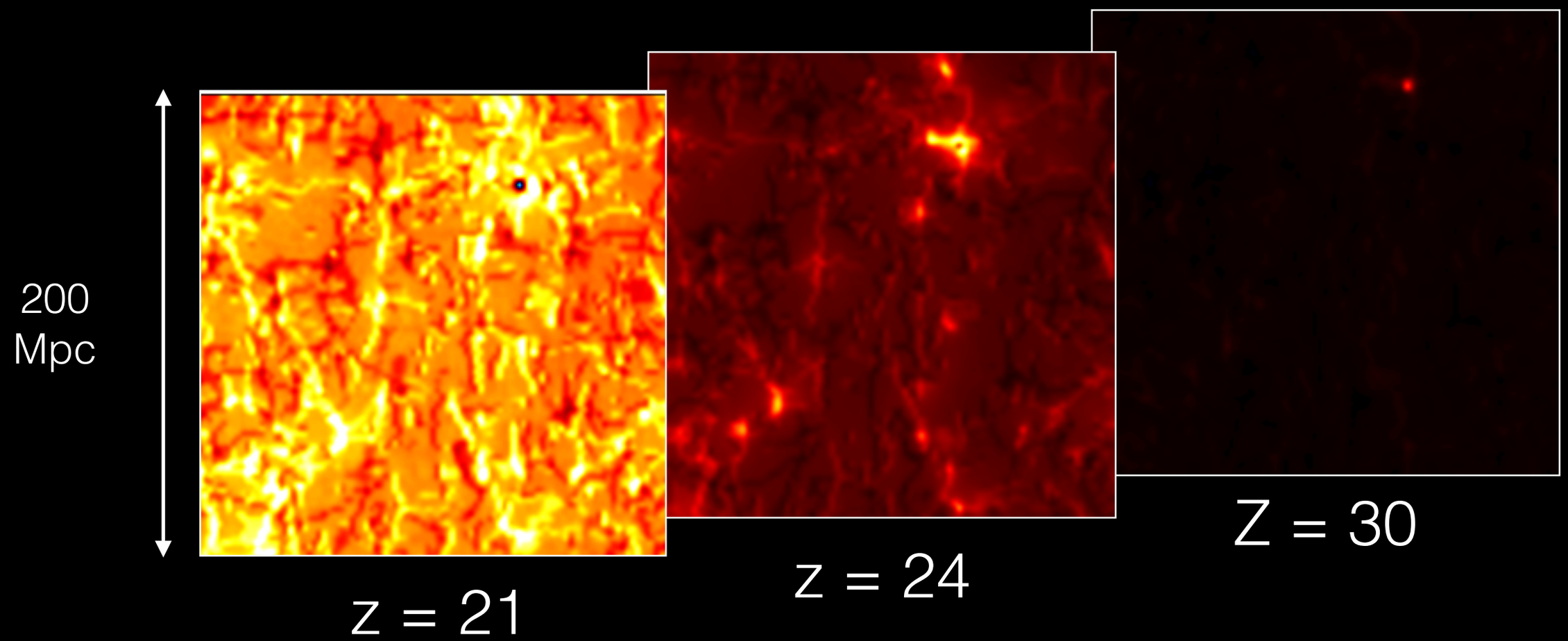
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$

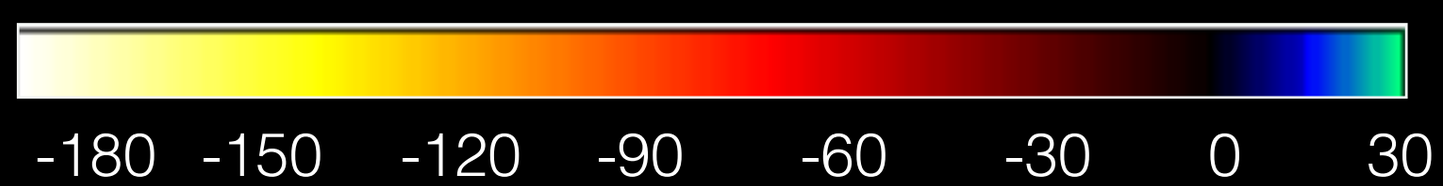


Simulations from 21cmFAST (Mesinger+ 2011)

Lyman-α Pumping

Blue = Emission against CMB
Yellow/Red=Absorption against CMB
Black=Same brightness as CMB with Ts=Tcmb or xHI=0





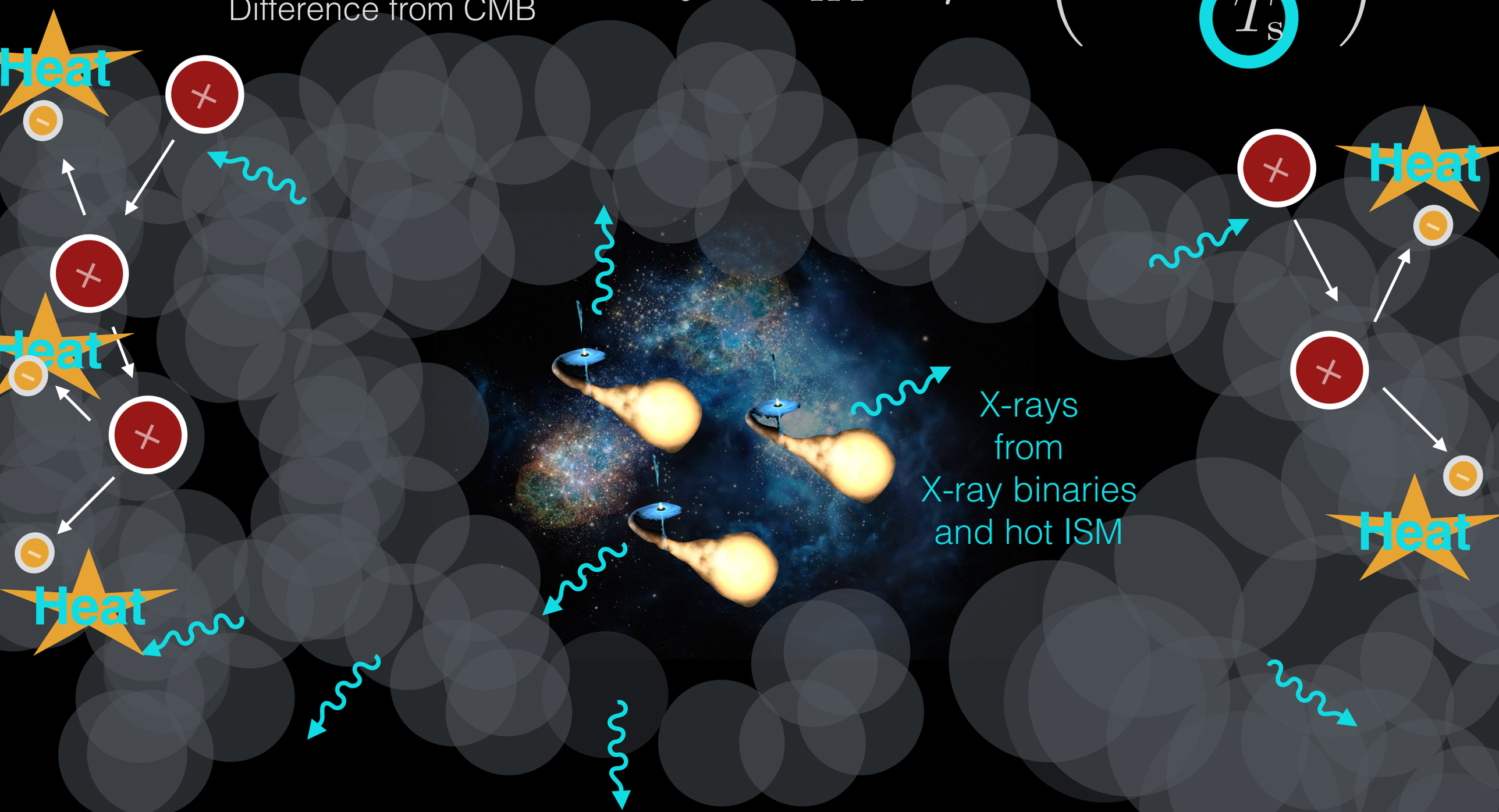
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right) \quad \text{(mK)}$$

T_s -> T_k

X-rays: Raise Thermal Temperature

δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

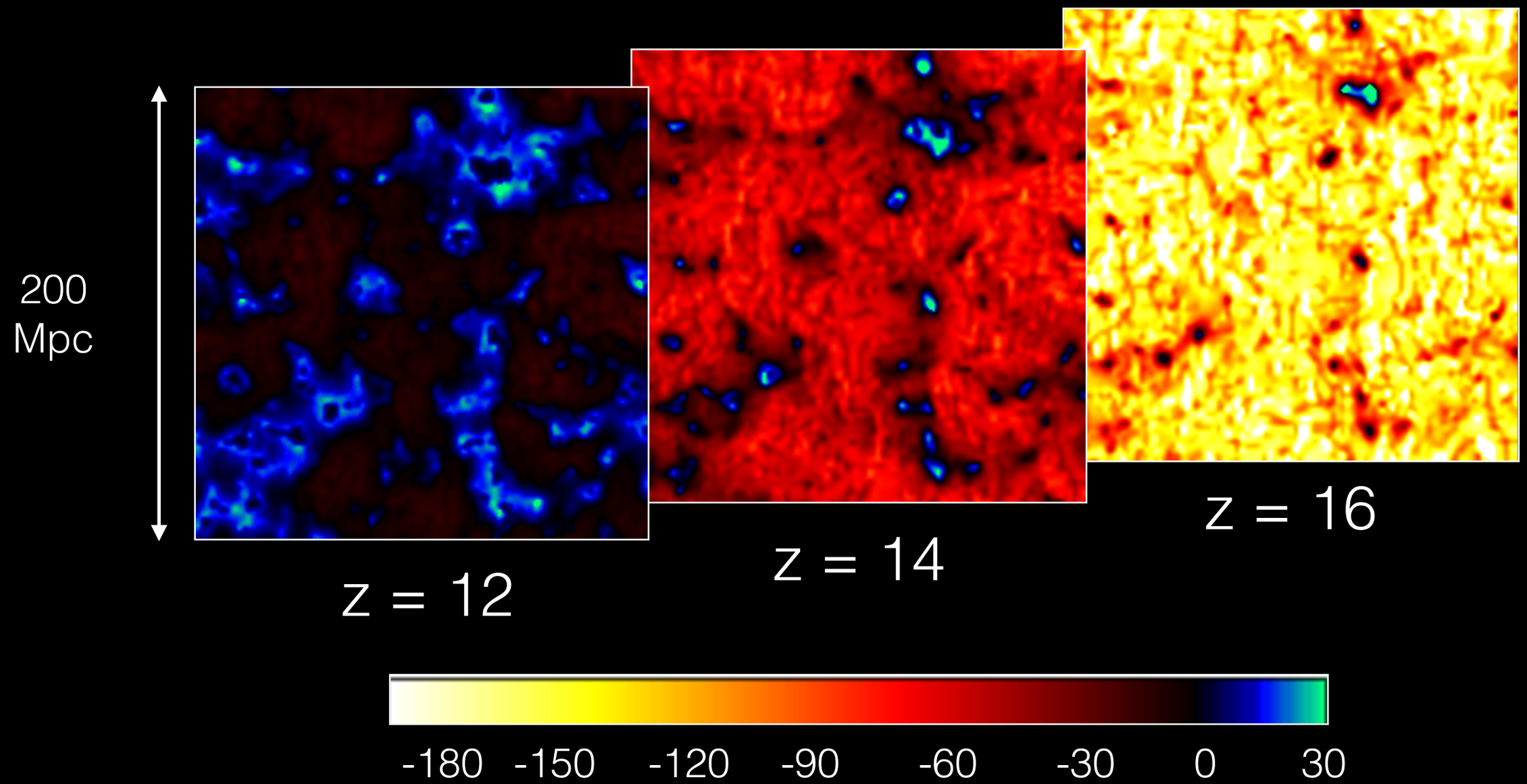
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$



Simulations from 21cmFAST (Mesinger+ 2011)

Heating

Blue = Emission against CMB
Yellow/Red=Absorption against CMB
Black=Same brightness as CMB with Ts=Tcmb or xHI=0

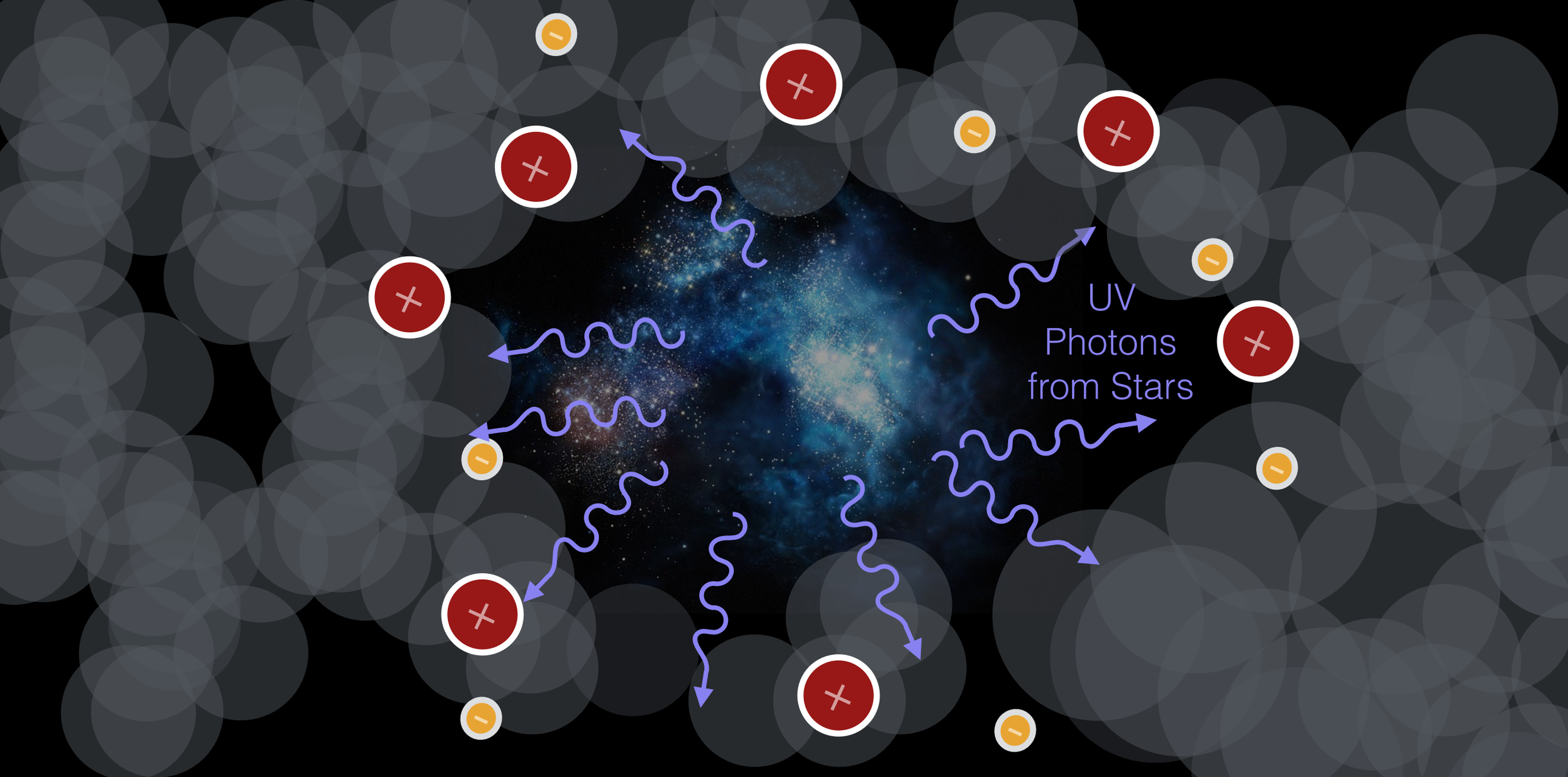


$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right) \quad \text{(mK)}$$

Lyman Continuum Photons: Ionize the IGM

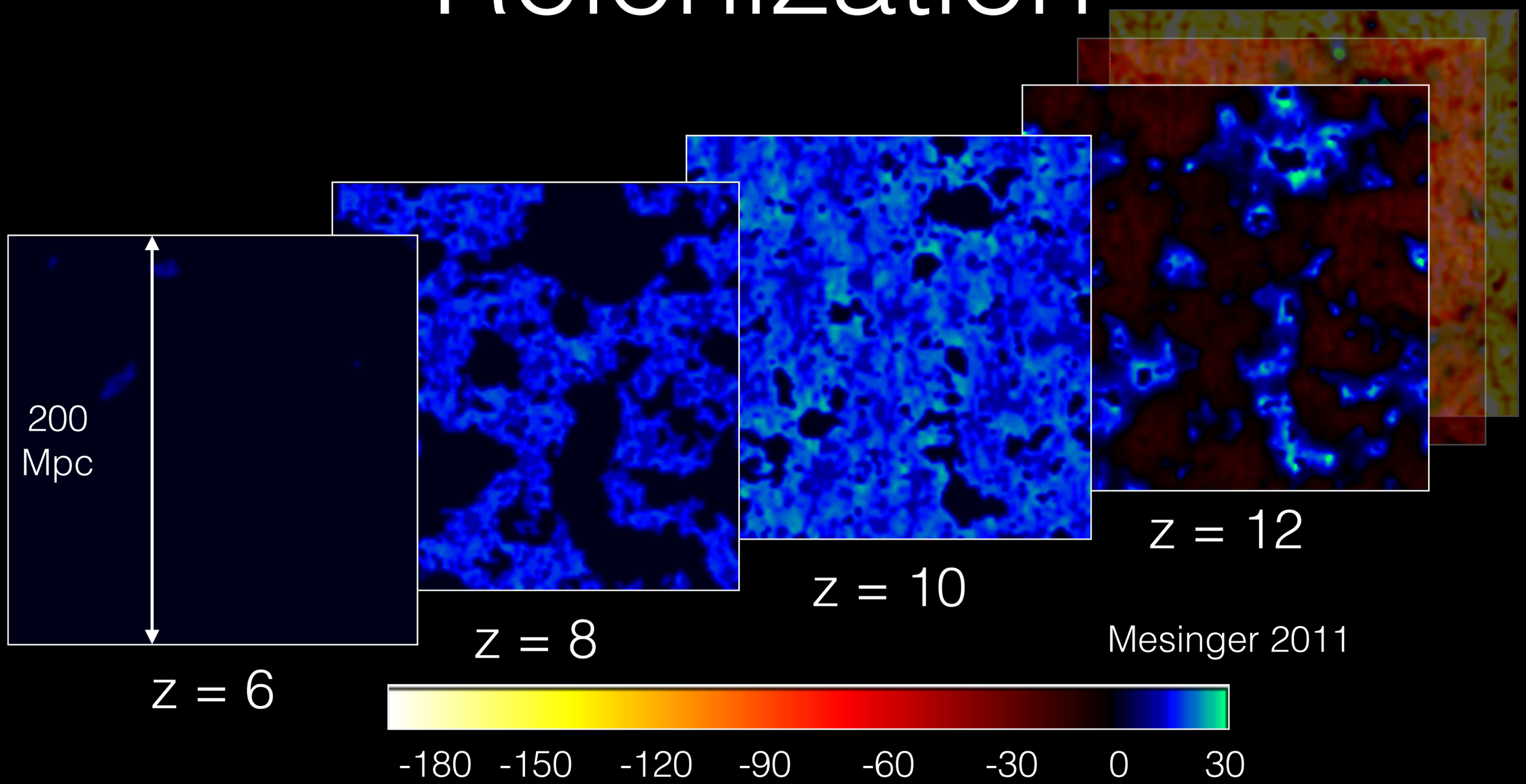
δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$



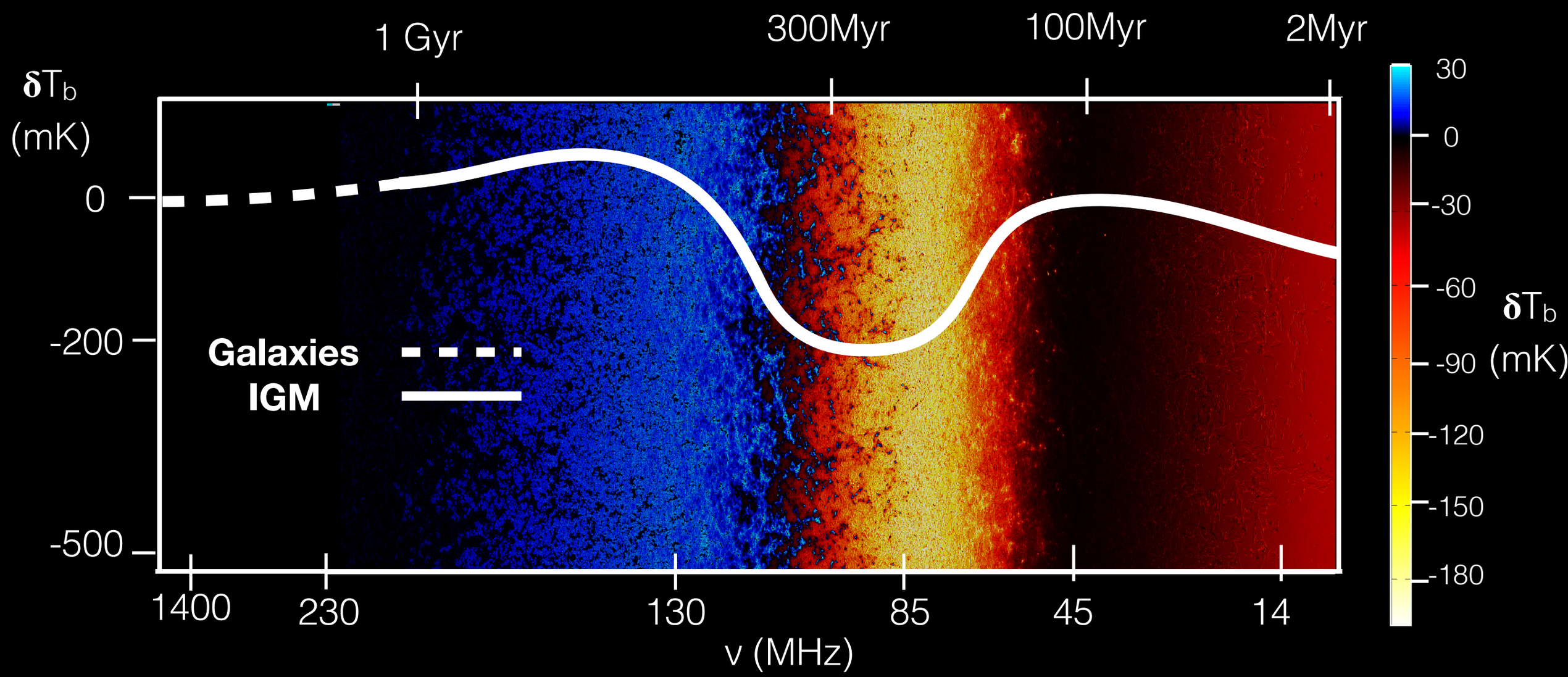
Simulations from 21cmFAST (Mesinger+ 2011)

Reionization



$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right) \quad \text{(mK)}$$

The Global Signal



Cosmology

HI in galaxies
Trace density

Probably Mostly Astrophysics

H Reionization
Stars
Quasars?

X-ray heating
From stellar
Remnants

Lyman-Alpha
Pumping from
the first Stars

Cosmology

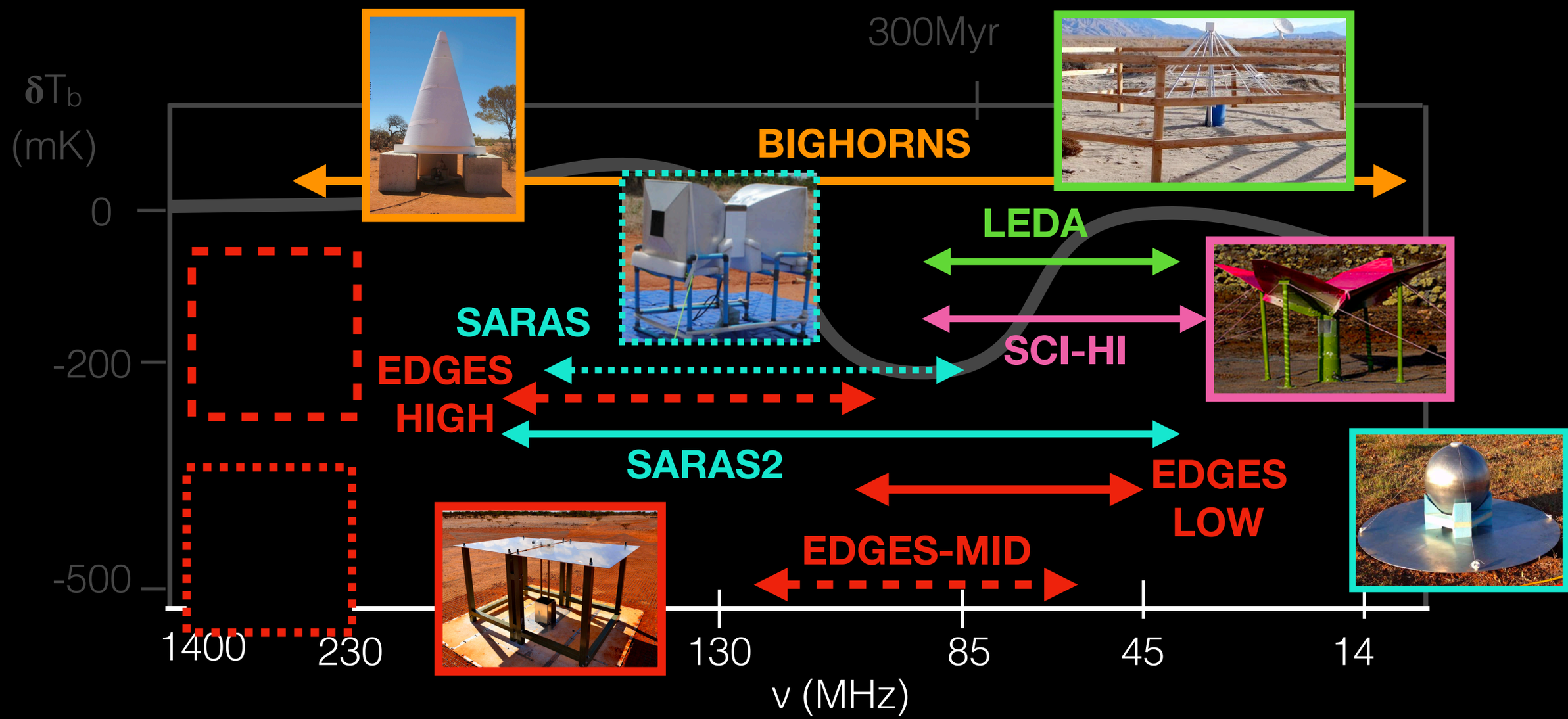
IGM HI traces
Density field
Compton vs H

$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$

width=1600Mpc

Eos Simulation: Mesinger et al. 2016

Global Signal Experiments — Basically Cosmic Dawn



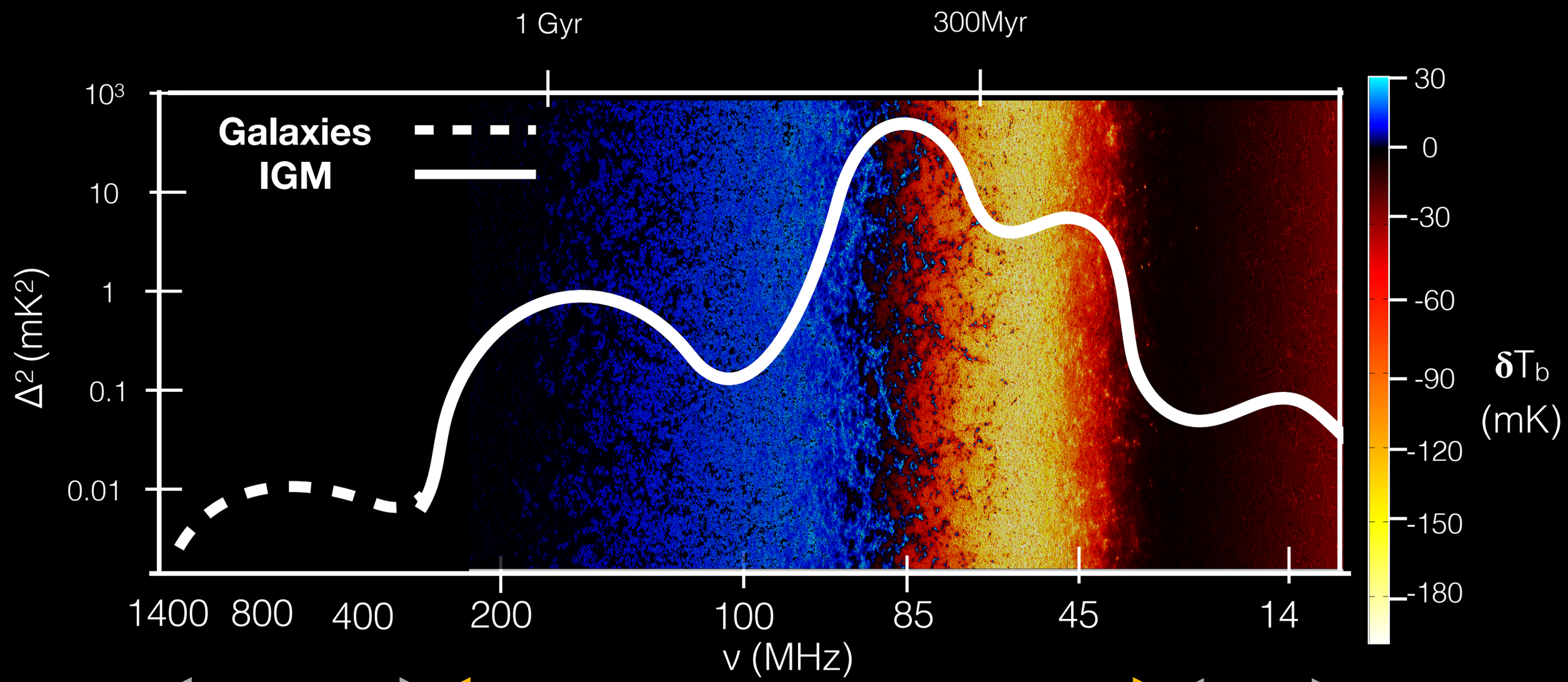
Dark Ages — Need to leave ionosphere

Low Redshift — Too Smooth

width=1600Mpc

Eos Simulation: Mesinger et al. 2016

The Fluctuations



Cosmology

Probably Mostly Astrophysics

Cosmology

HI in galaxies
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Stars
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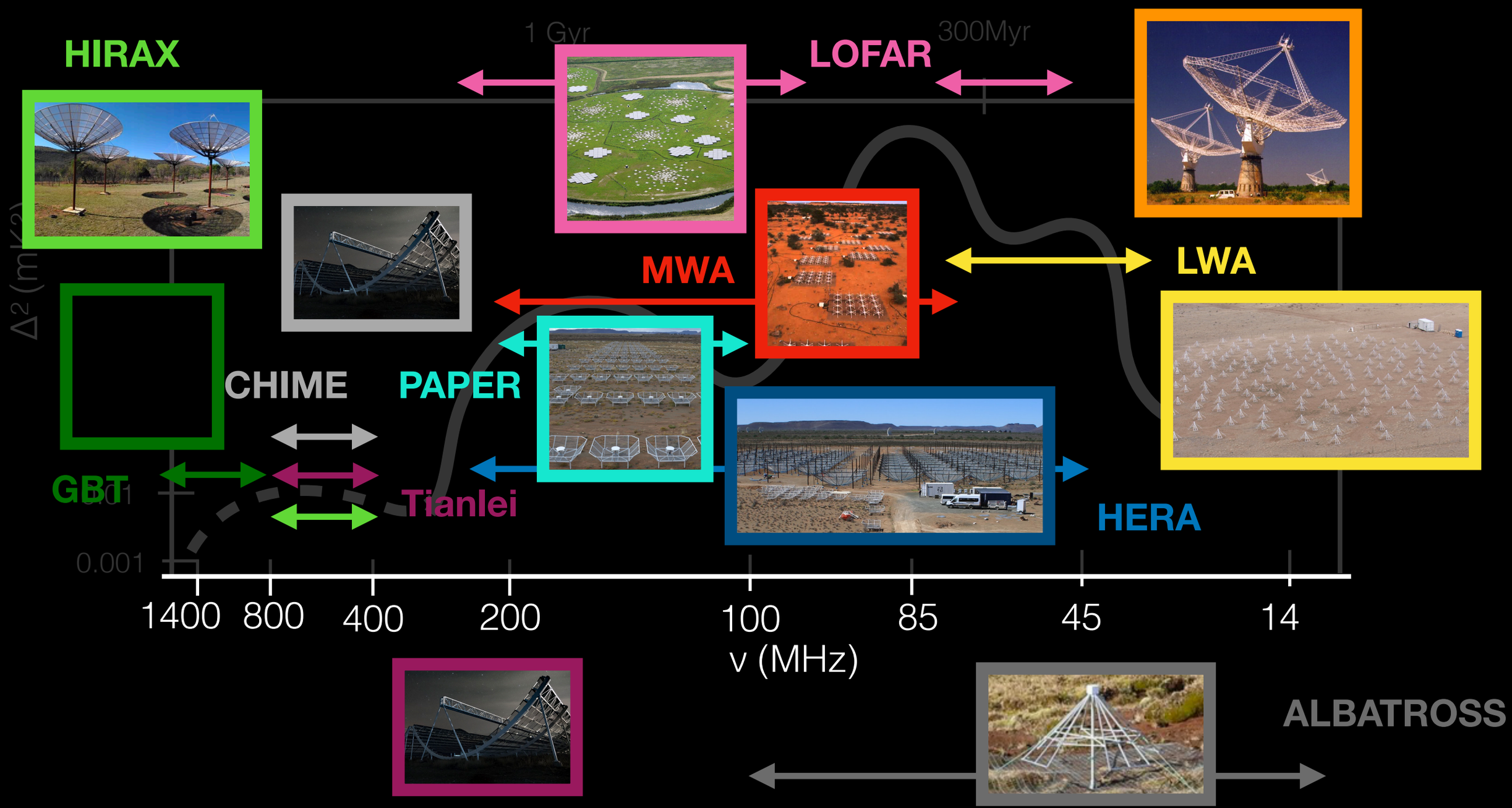
width=1600Mpc

Eos Simulation: Mesinger et al. 2016

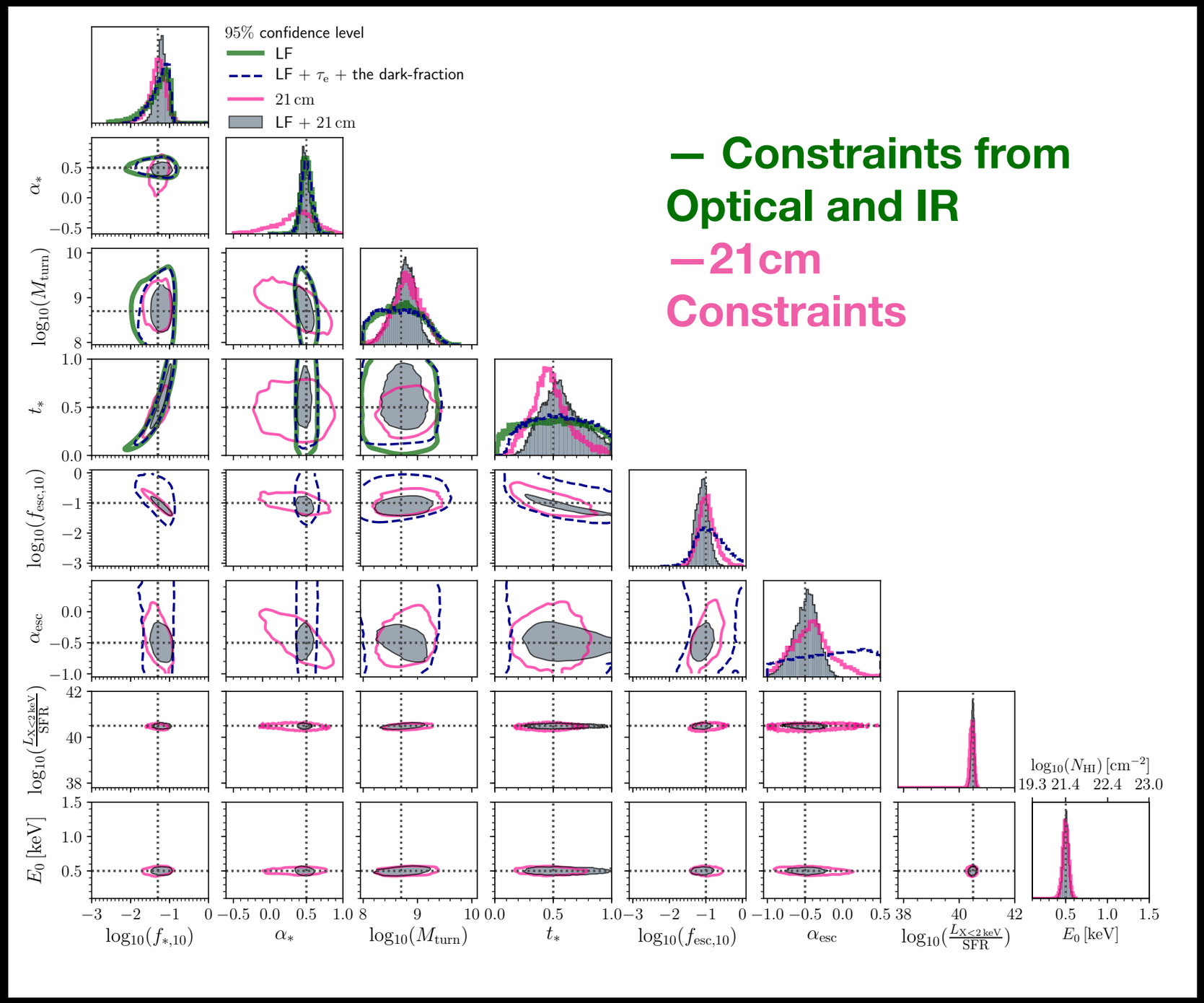


Fluctuation Experiments — Cosmic Dawn and Acceleration

width=1600Mpc

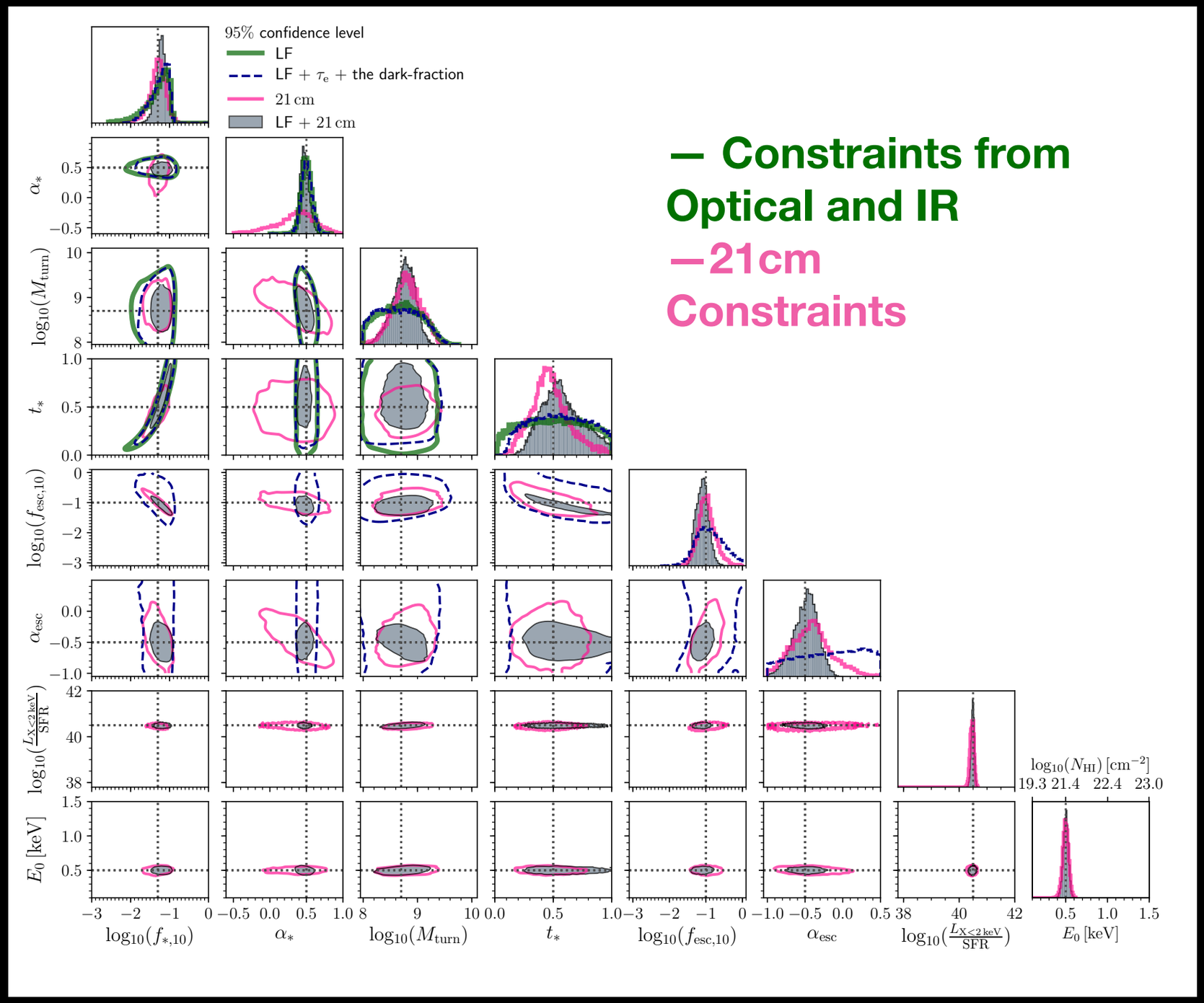
Eos Simulation: Mesinger et al. 2016

During the Cosmic Dawn we hope to obtain statistical constraints on the Properties of the early Sources



Park+2018

And at low redshift, Cosmology



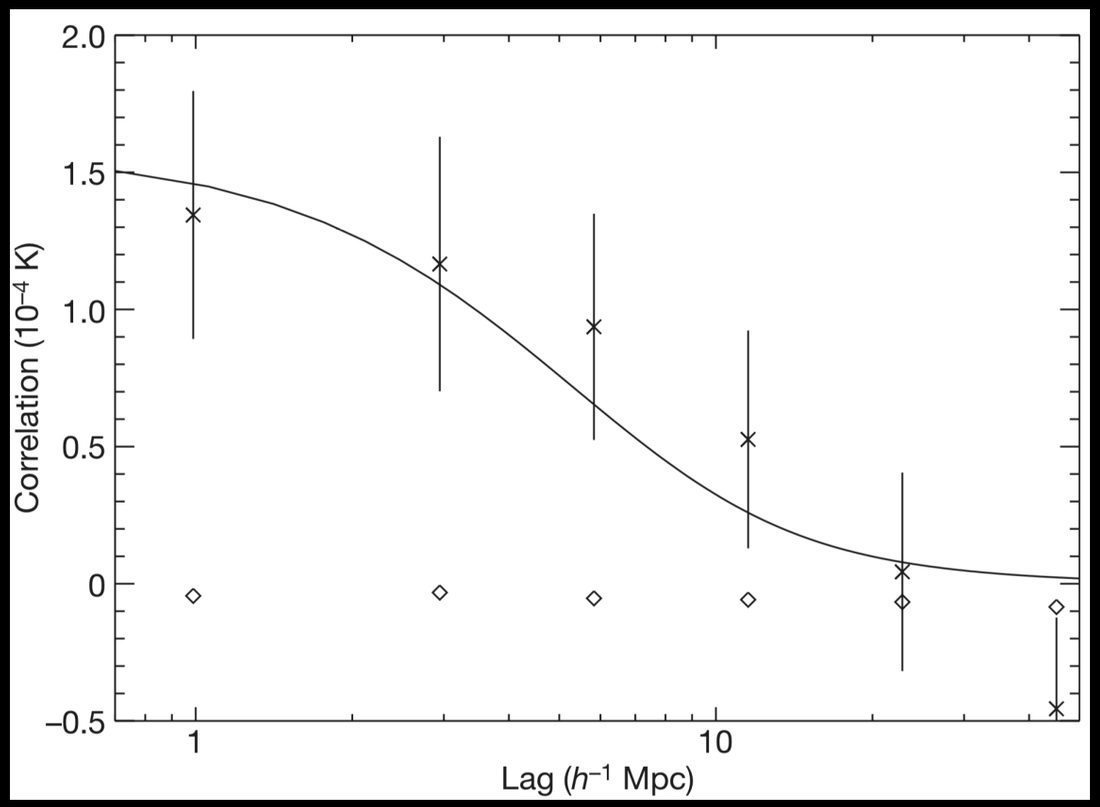
— Constraints from Optical and IR

—21cm Constraints

Park+2018

Low Redshift Detections: GBT

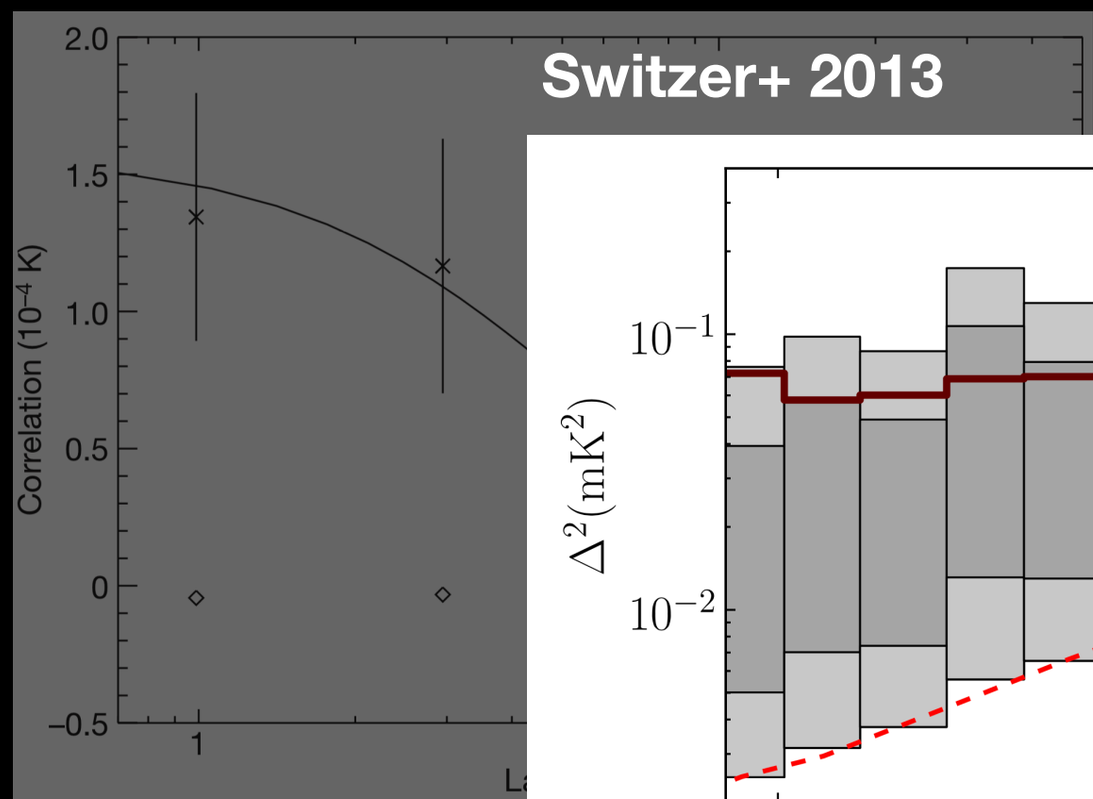
Chang+ 2010



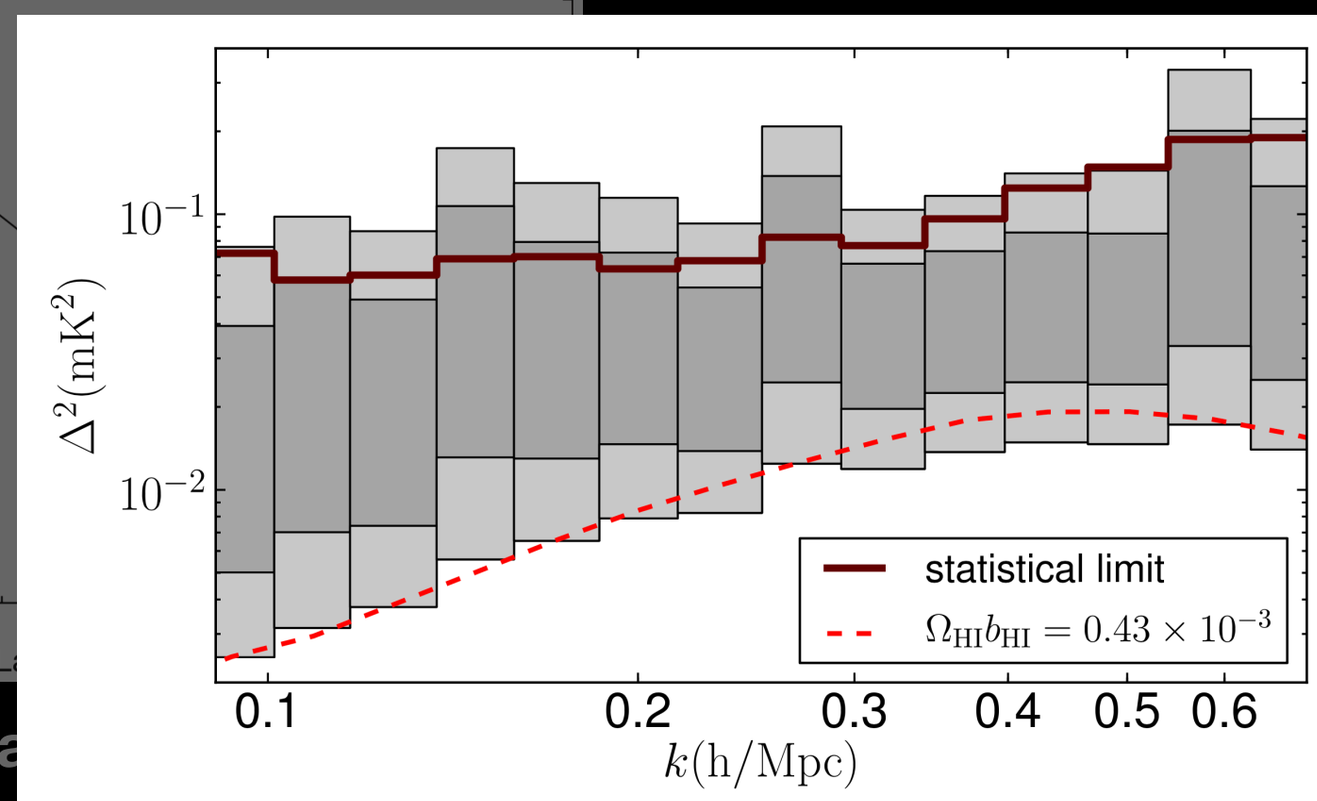
HI x Galaxies **z=0.8**

Low Redshift Detections: GBT

Switzer+ 2013



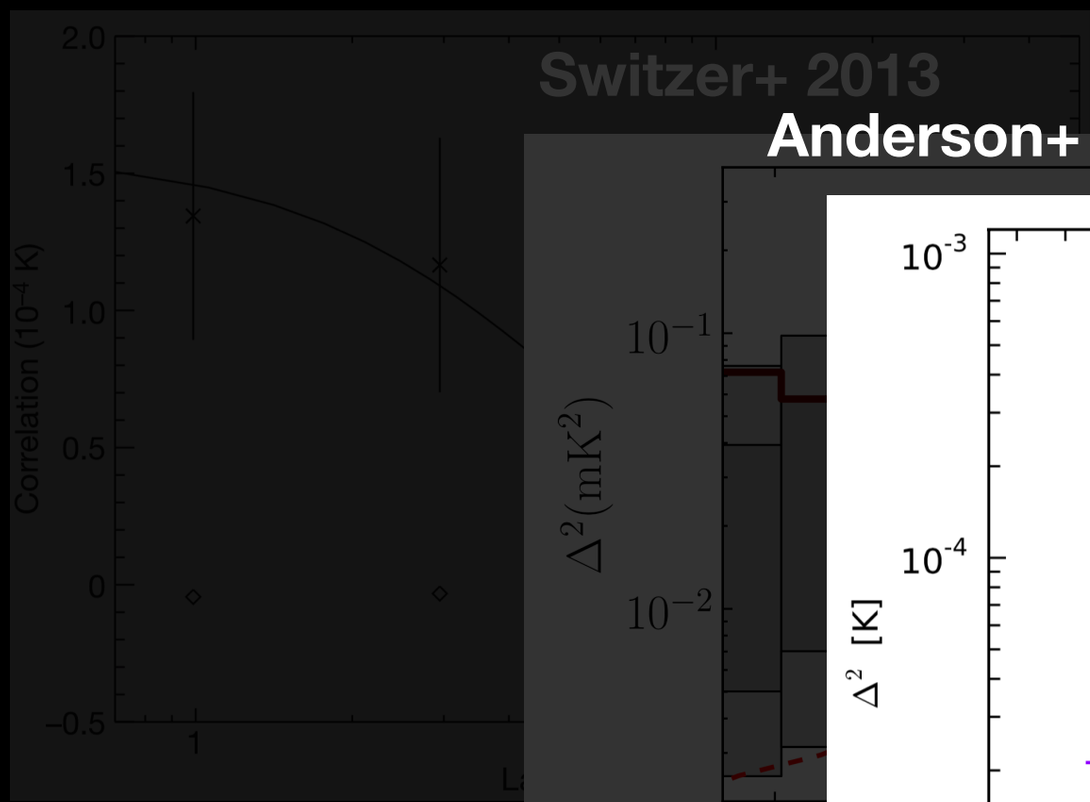
GBT x optical gala



HI x HI **0.6 < z < 1**

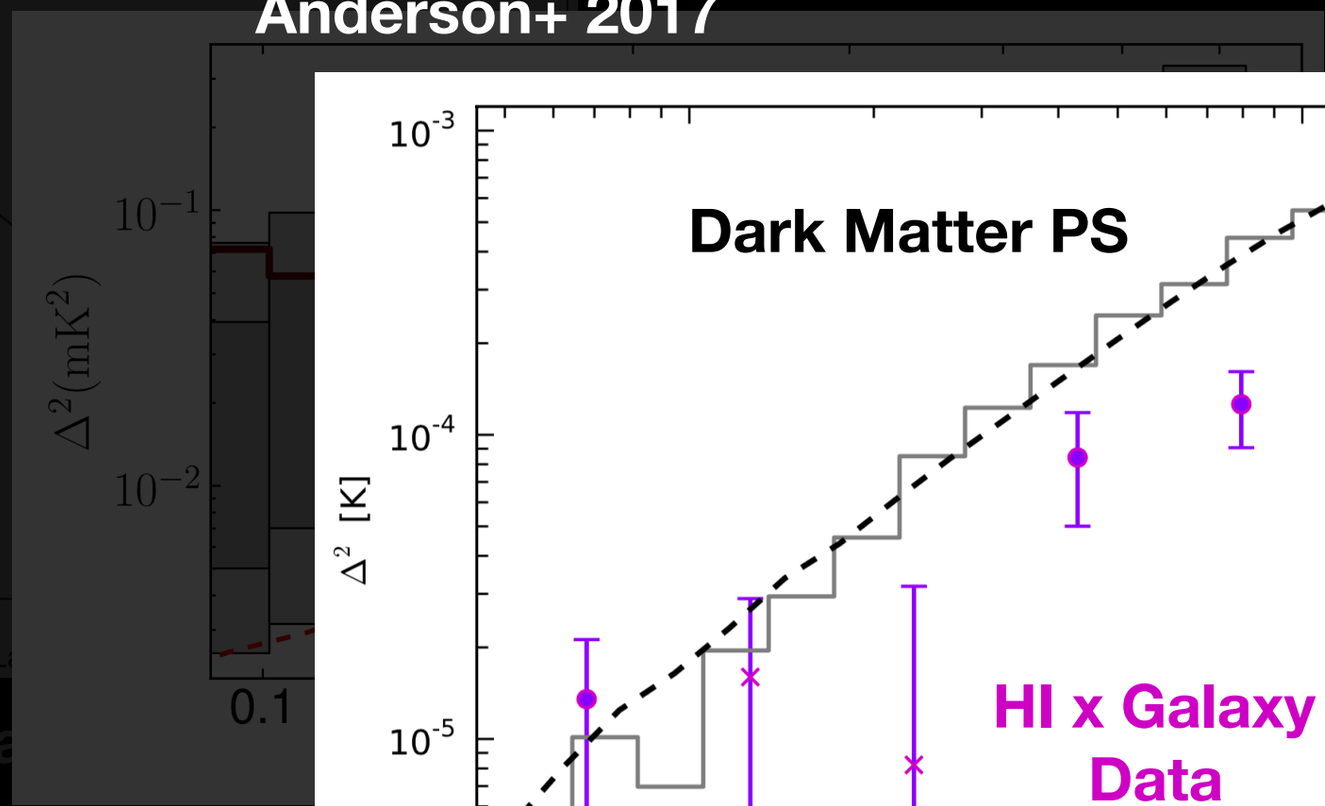
Low Redshift Detections: GBT

Switzer+ 2013



GBT x optical gala

Switzer+ 2013



GBT auto

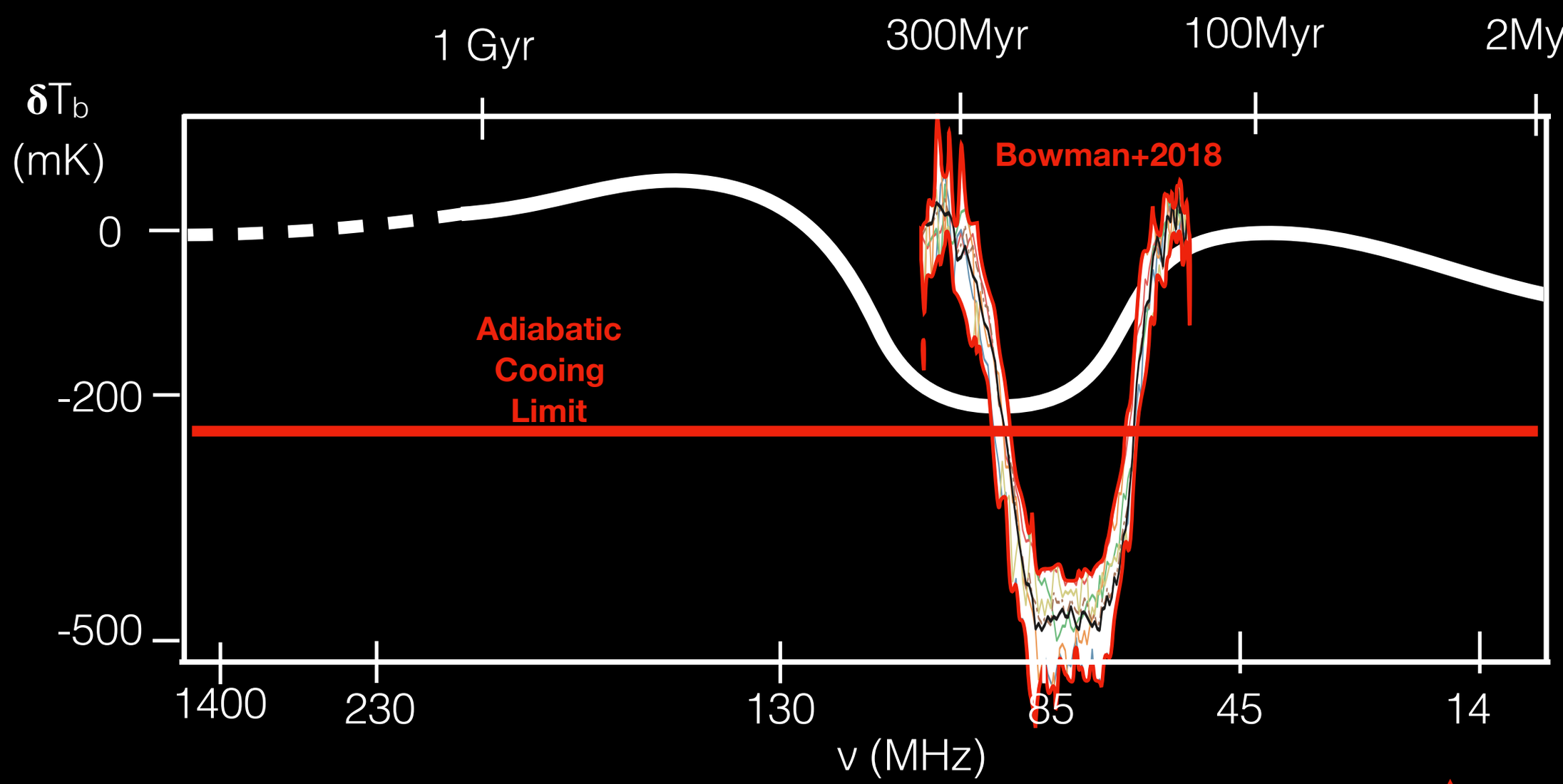
Anderson+ 2017

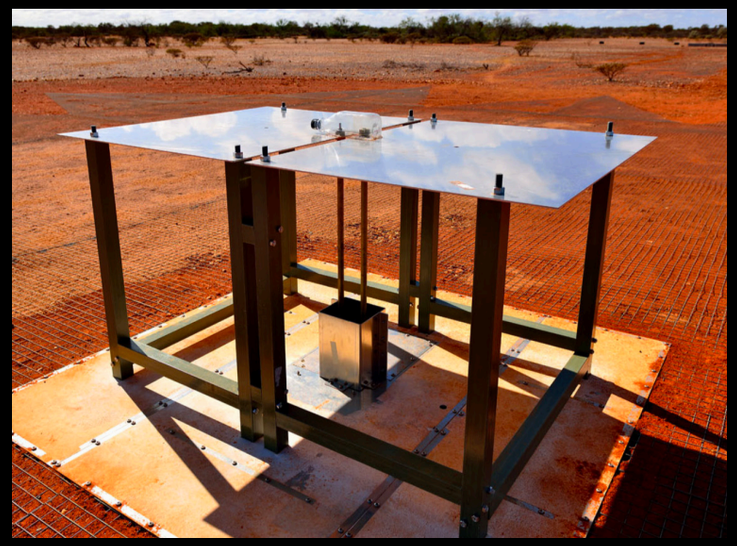
Clustering Deficit On Small Scales!

HI x Galaxies **.057 < z < .085**

What about z>1?

Only Claimed "Detection": EDGES-LOW



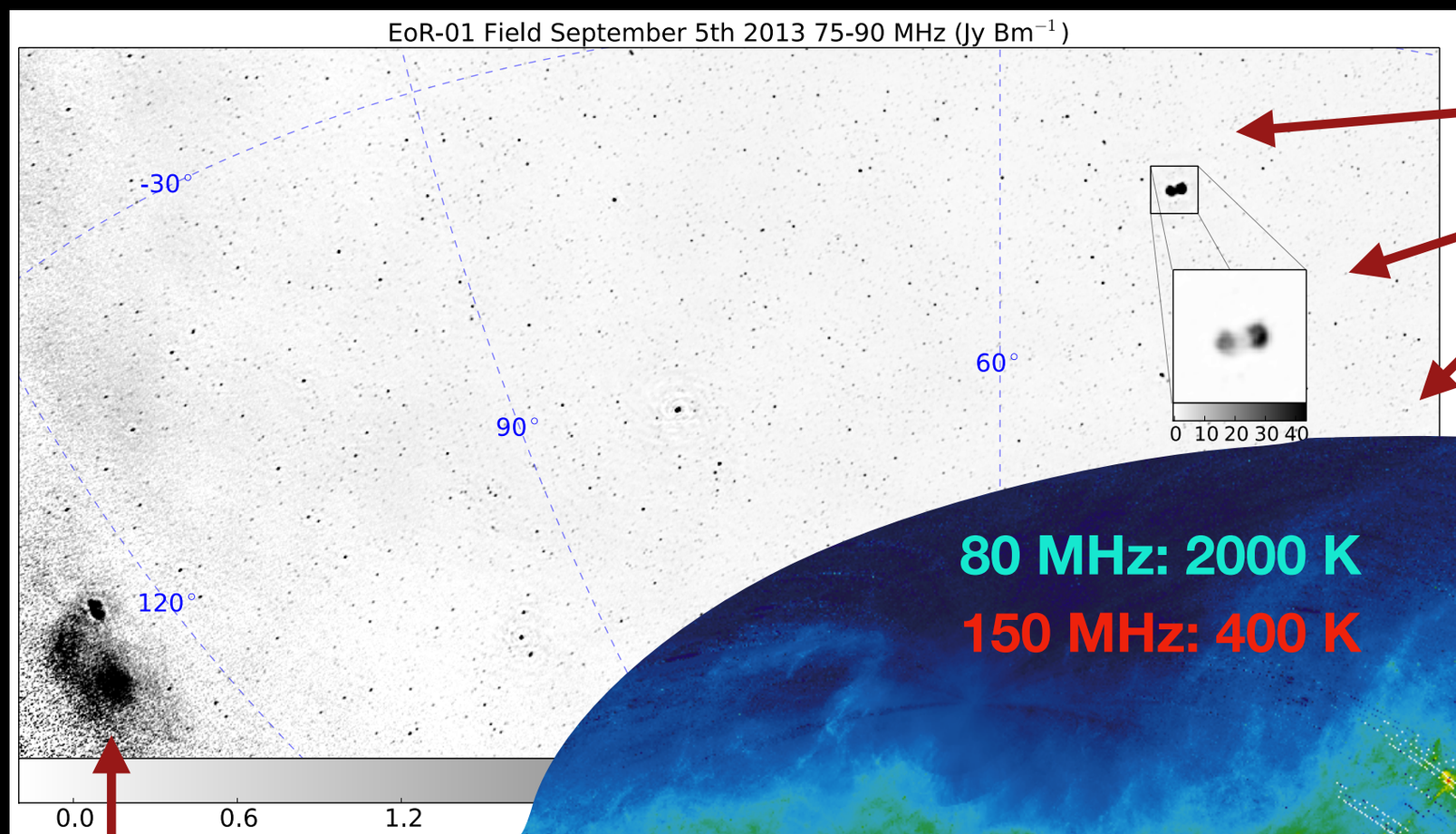


$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$

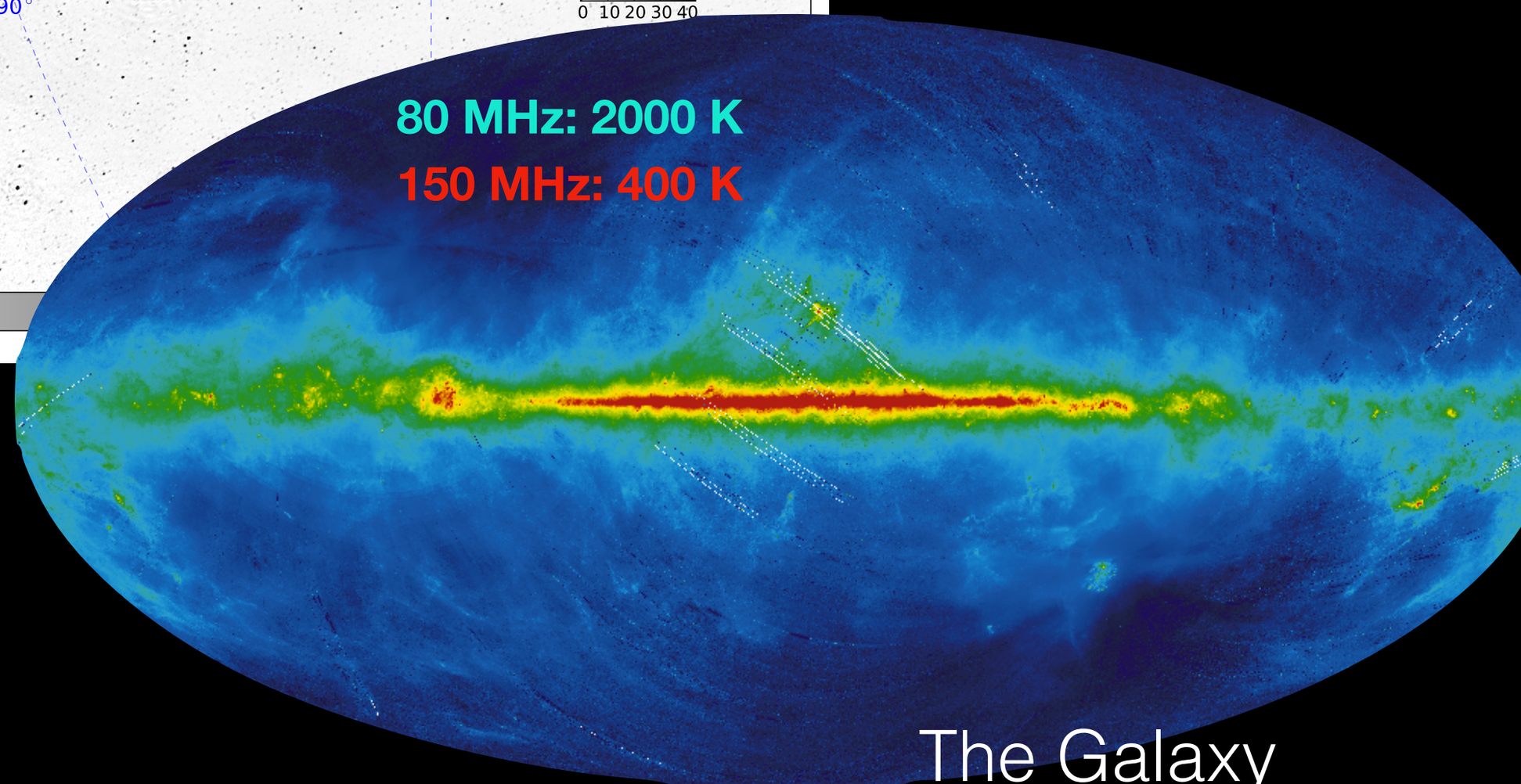
Raise T_{CRB}: Black Holes, Star forming galaxies, axion decay

Lower T_s: Dark matter -Baryon interactions

Radio Foregrounds: ~**10^4x** the signal level!



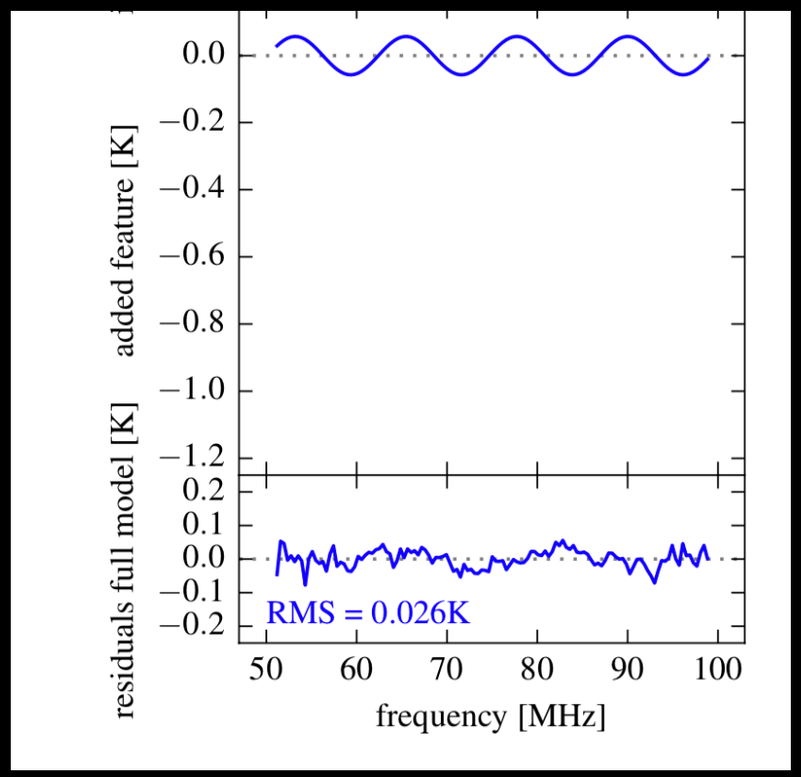
Active Galactic Nuclei



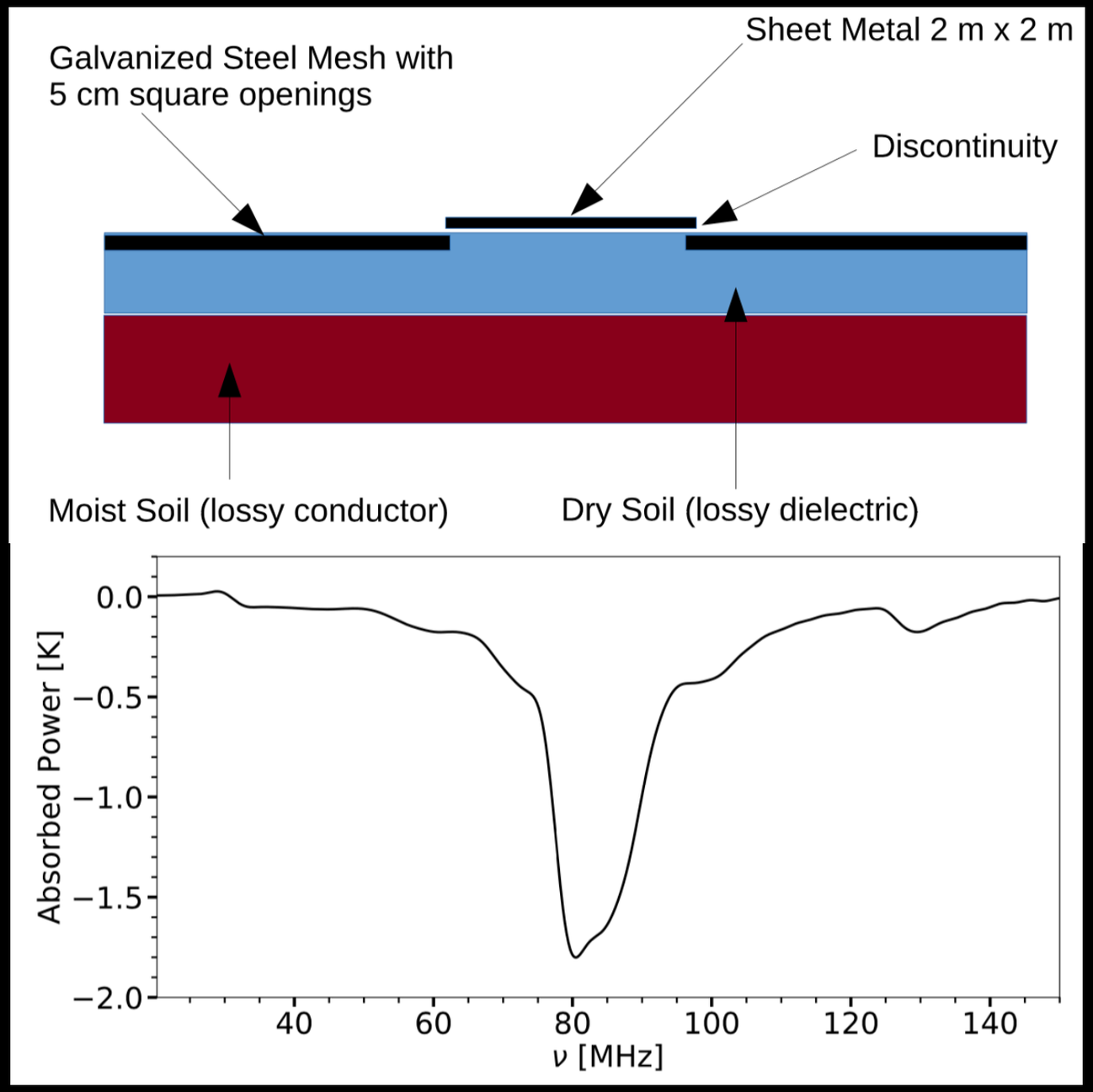
Supernova Remnant

The Galaxy

Foreground Instrument Interactions



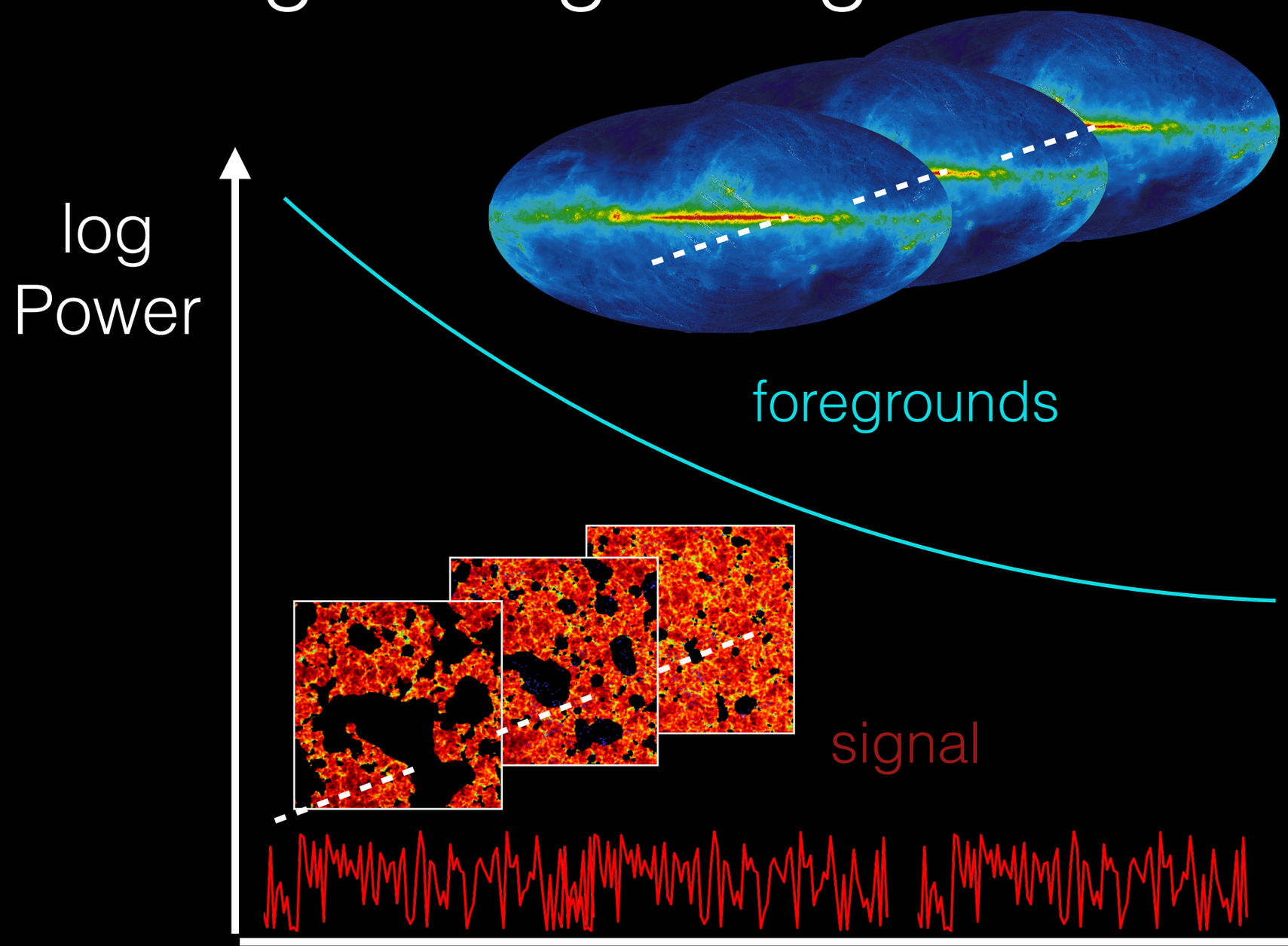
Hills+ 2018:
Fit data just as well
With a sinusoid
(Also Sing+2018)



Bradley+2018:
Demonstrates possible production by resonance between soil layers and ground plane.

Fluctuation Measurements Offer a Potential Check

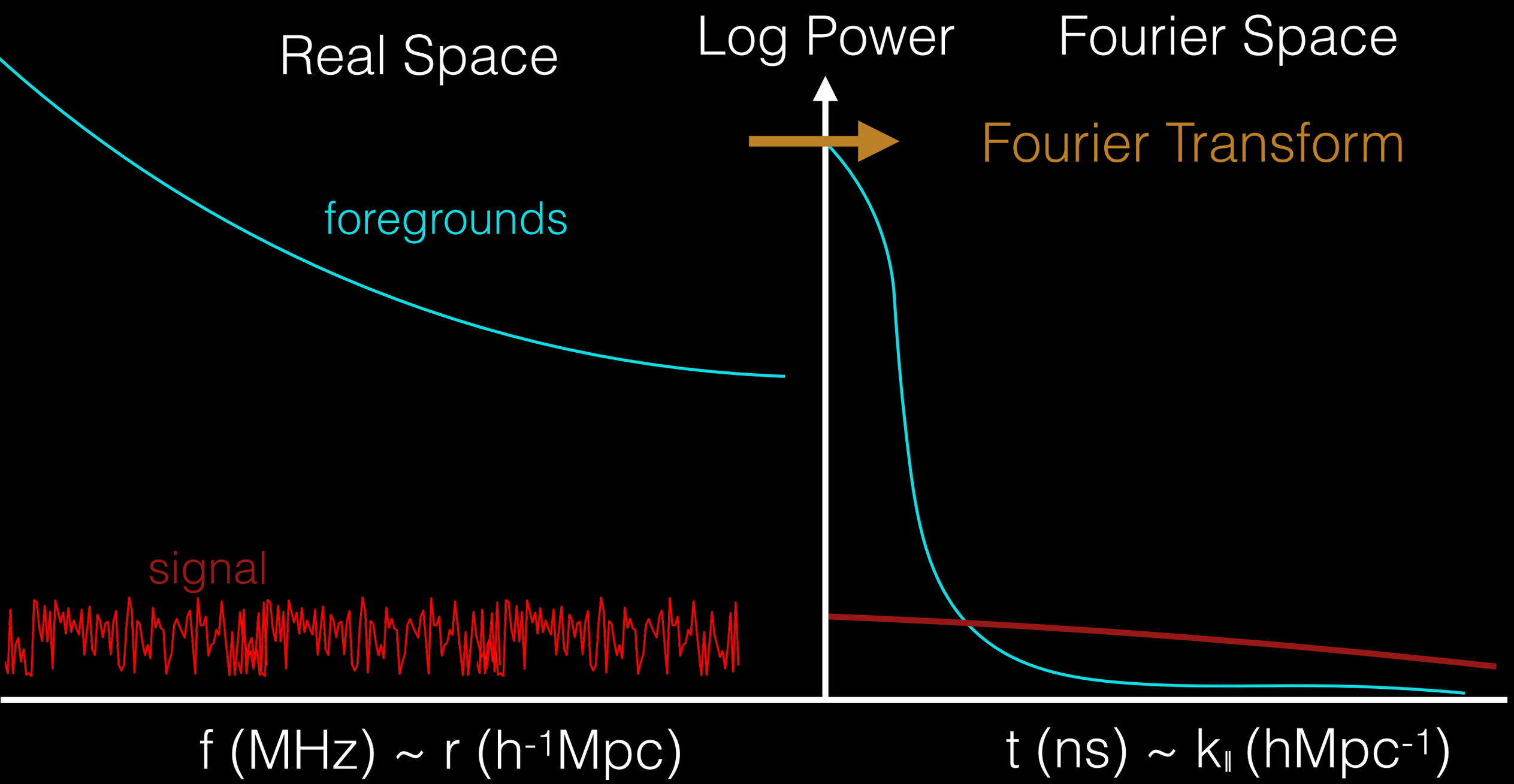
Distinguishing Foregrounds from Signal

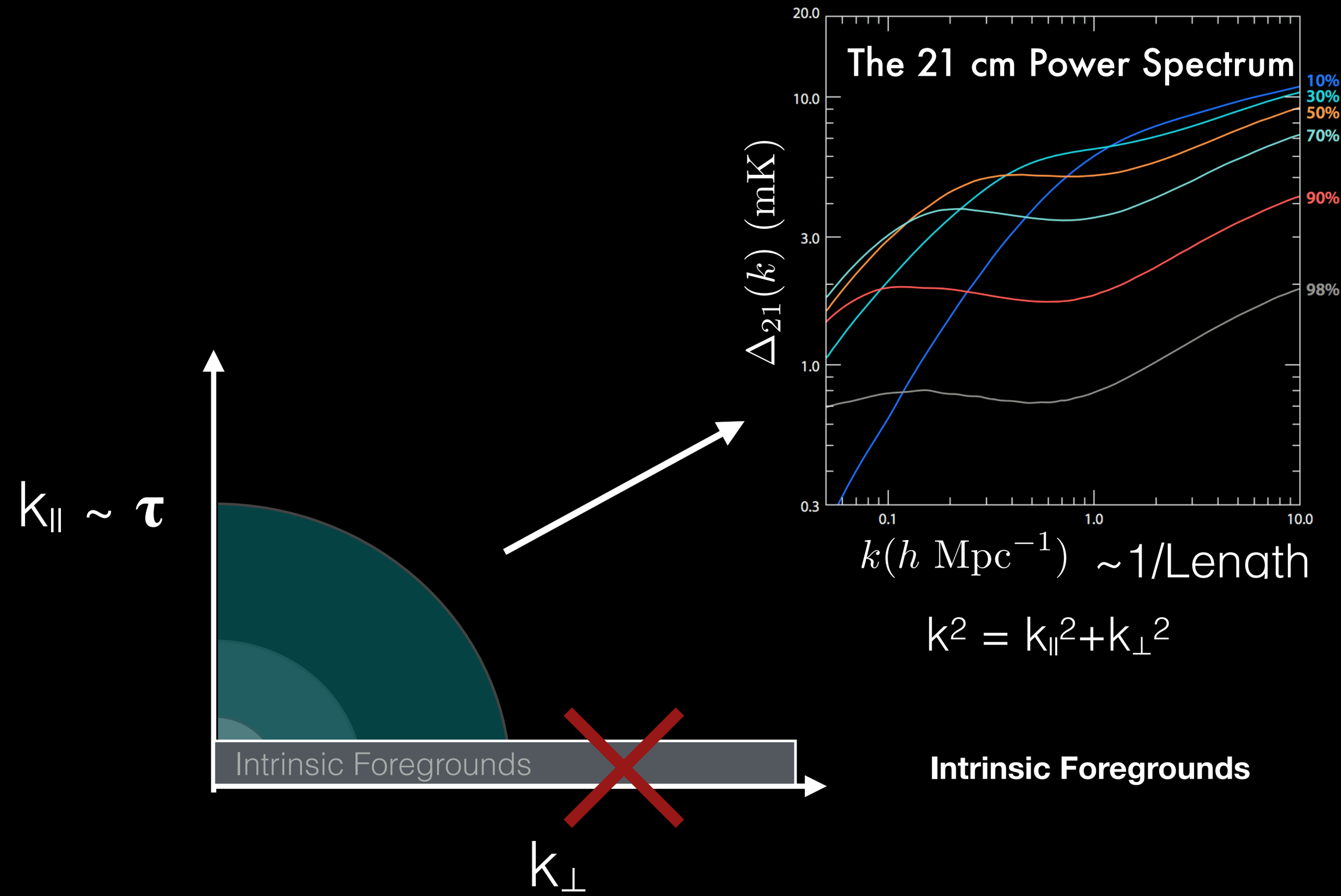


frequency ~ distance

f (MHz) ~ r (h^{-1}Mpc)

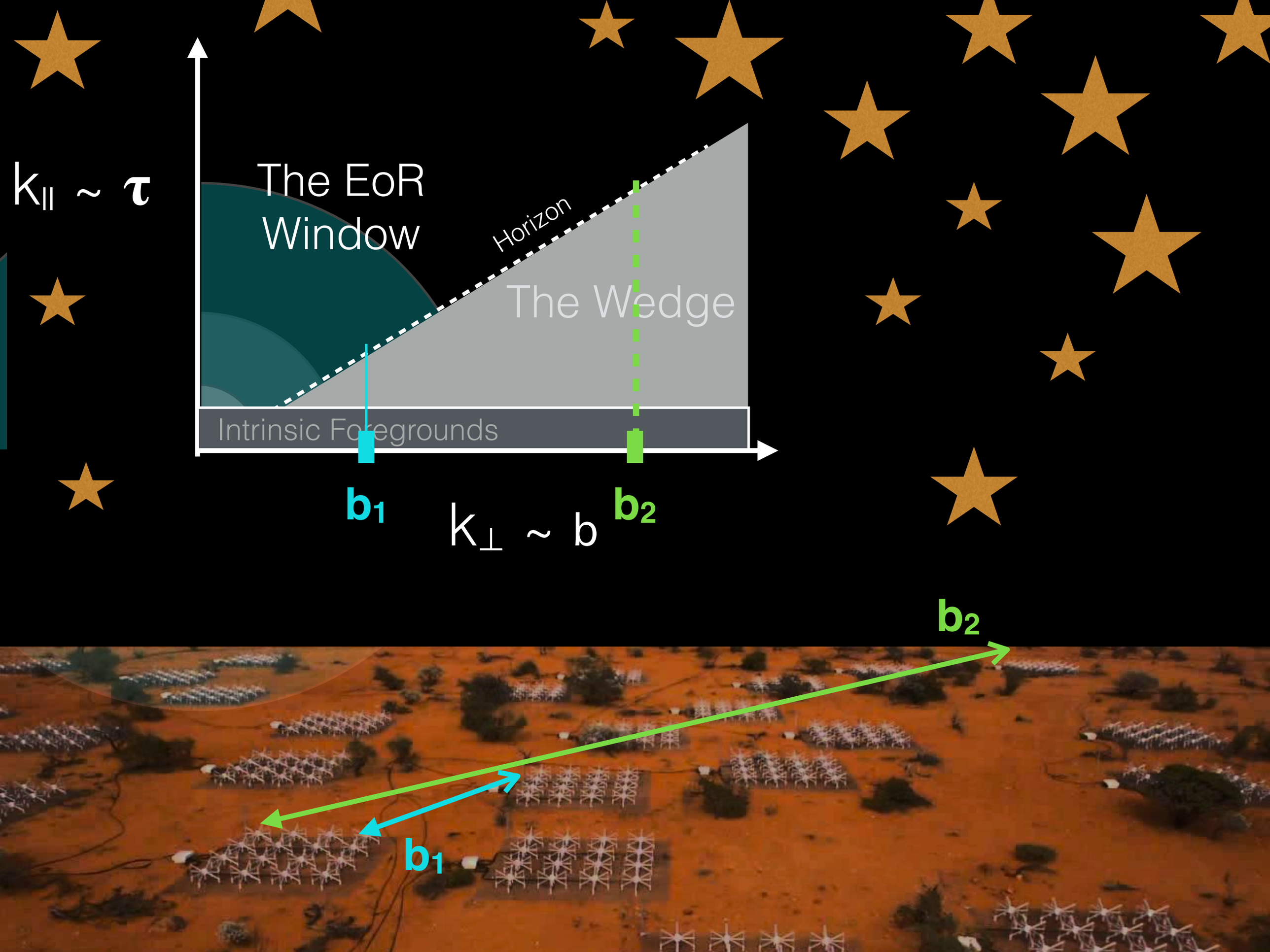
Isolating Foregrounds Using the Fourier Transform

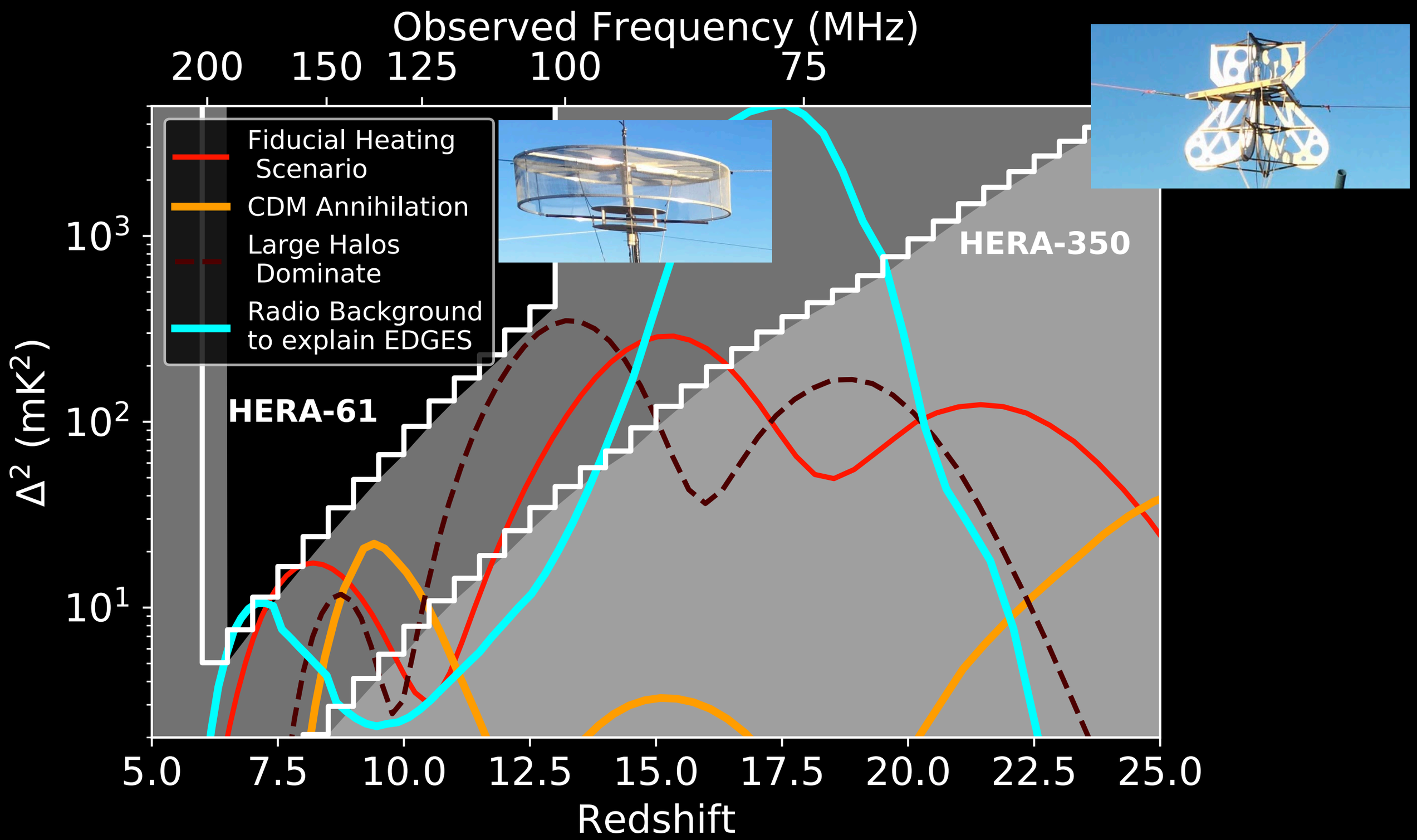




$k^2 = k_{\parallel}^2 + k_{\perp}^2$

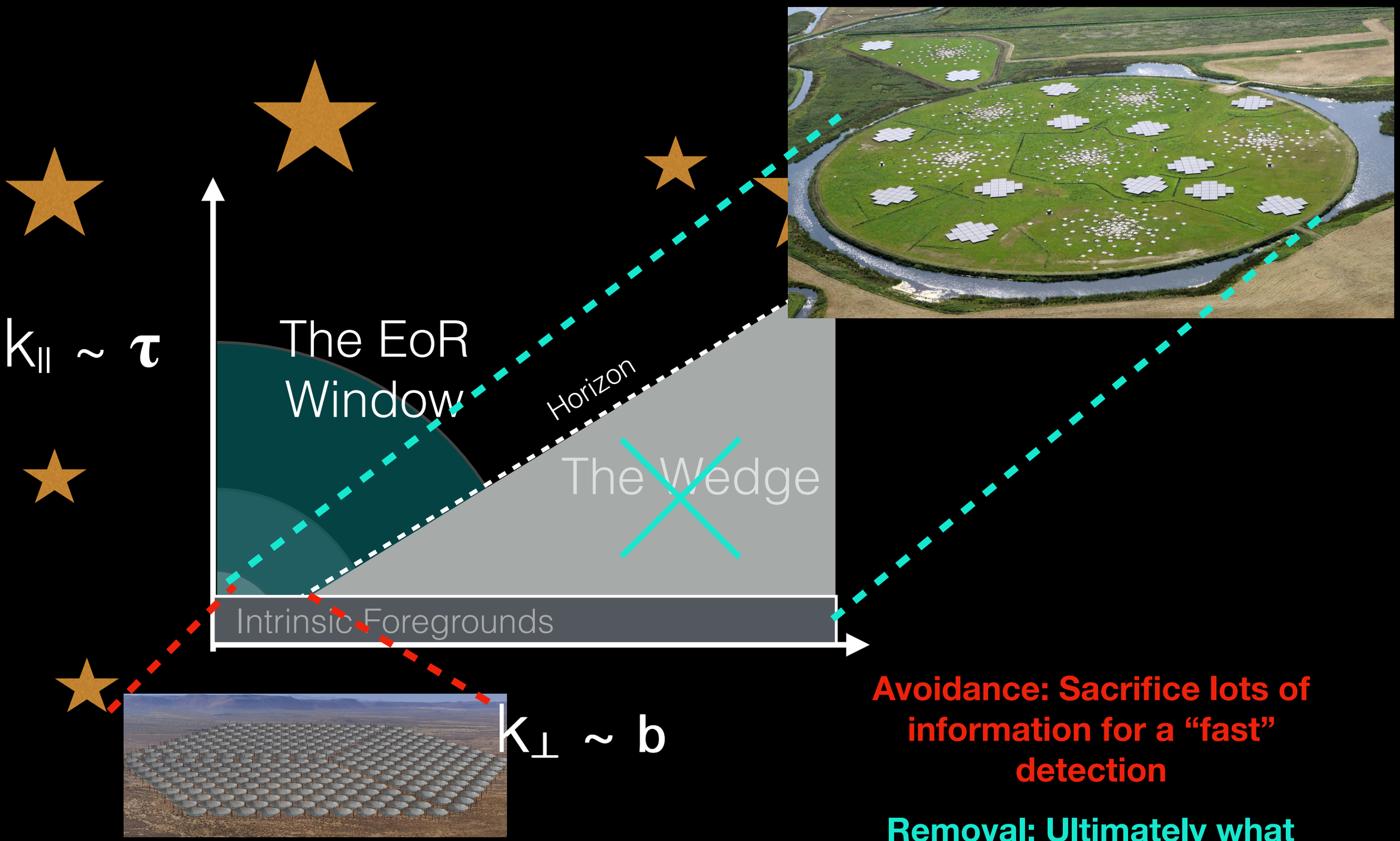
Intrinsic Foregrounds


$k_{\parallel} \sim \tau$
The EoR Window
Horizon
The Wedge
Intrinsic Foregrounds
b_1
b_2
$k_{\perp} \sim b$
b_2
b_1


Observed Frequency (MHz)
200
150
125
100
75
Fiducial Heating Scenario
CDM Annihilation
Large Halos Dominate
Radio Background to explain EDGES
HERA-61
HERA-350
10^3
10^2
10^1
Δ^2 (mK^2)
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
Redshift

The Wedge motivates two strategies

1: Remove



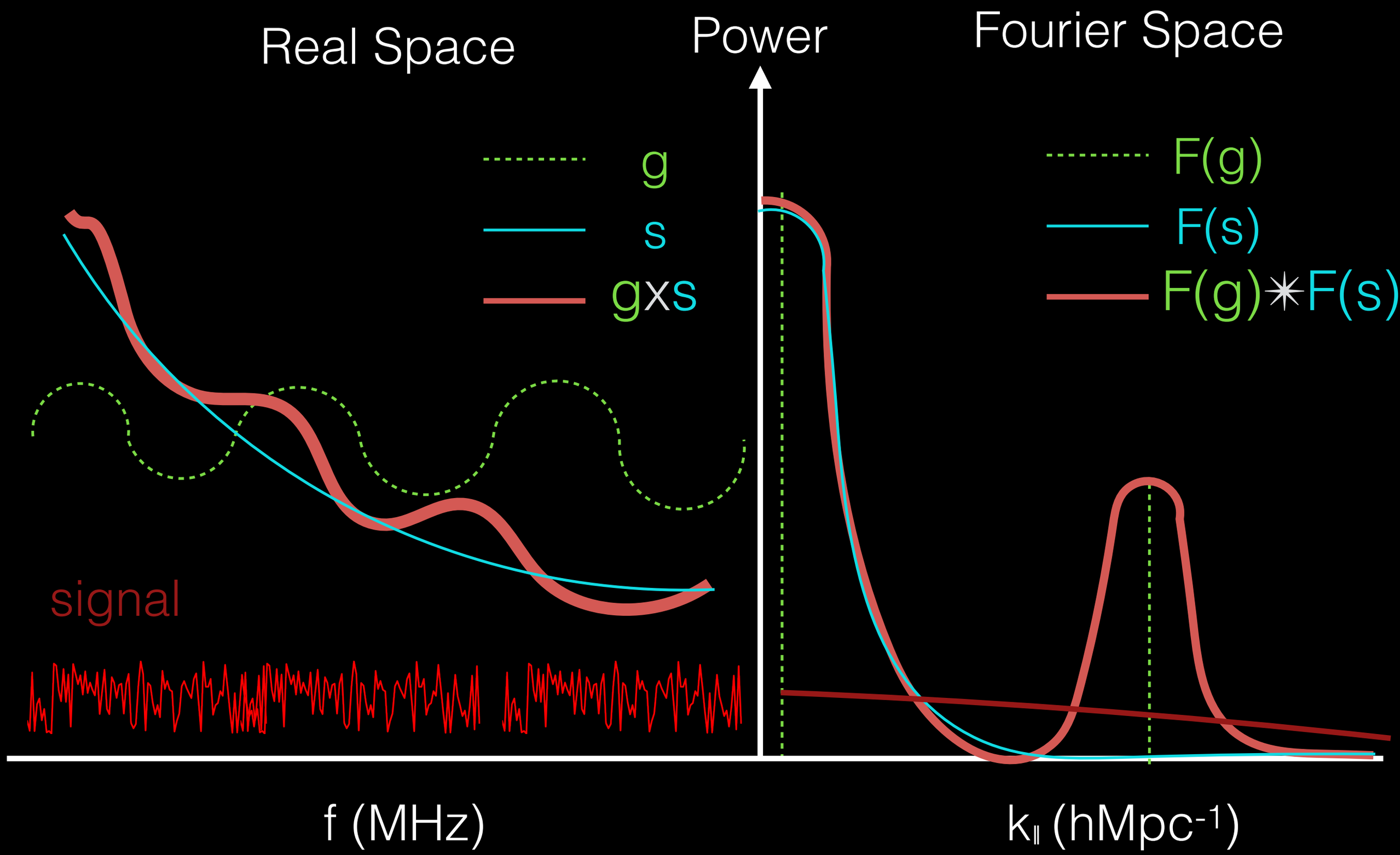
2: Avoid

Avoidance: Sacrifice lots of information for a "fast" detection

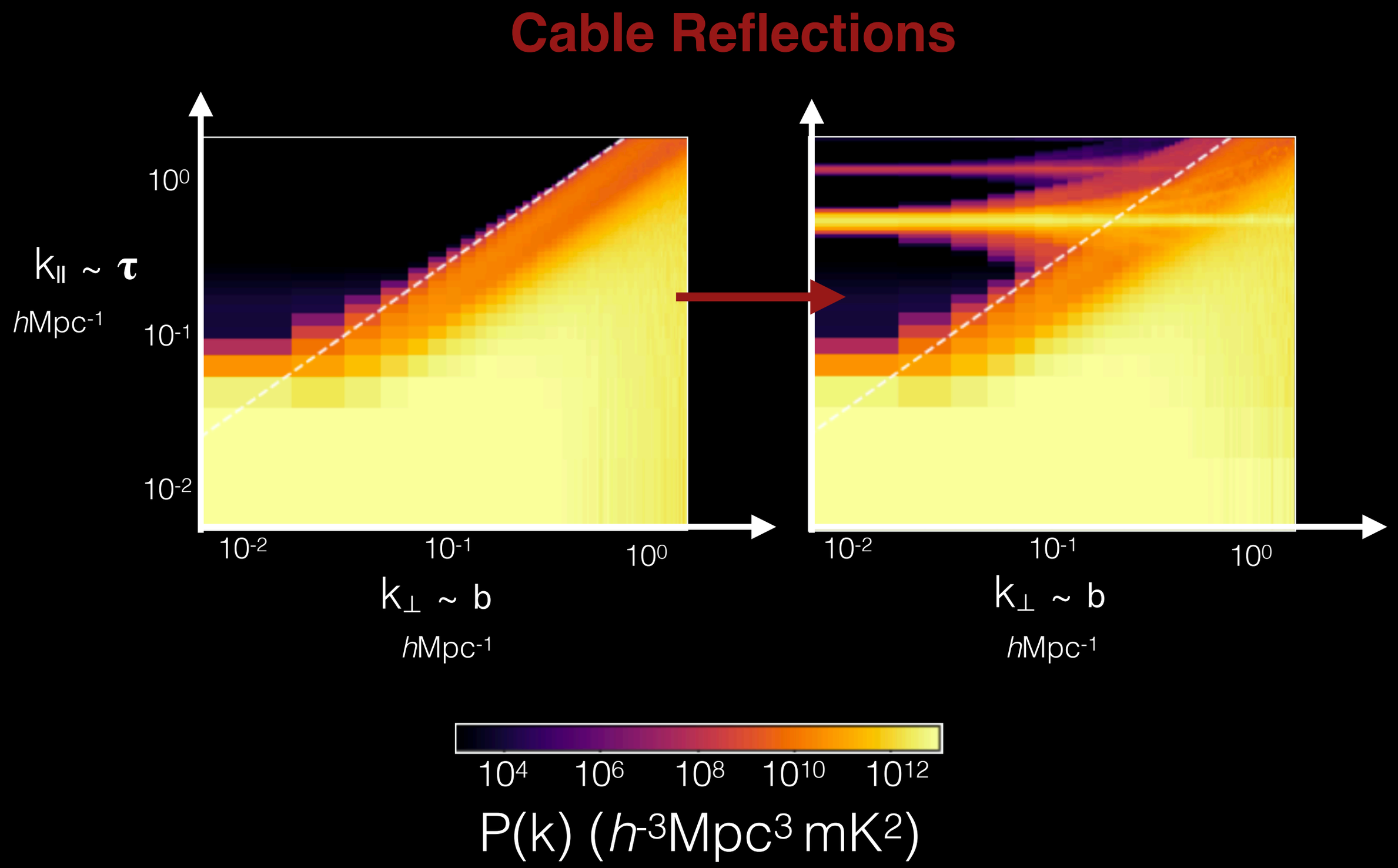
Removal: Ultimately what everyone would like to do.

If we have **Instrumental Spectral Structure**

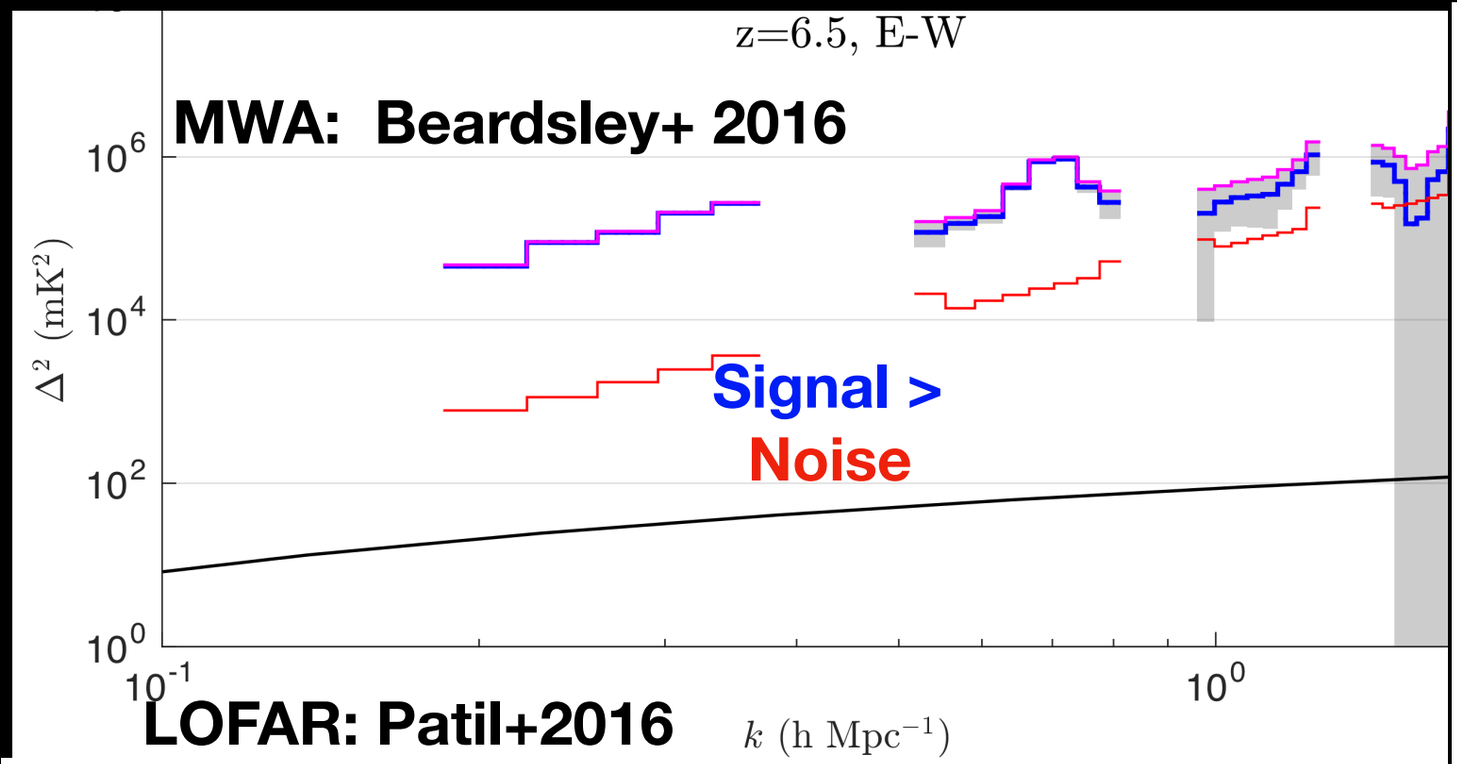
Things fall apart!

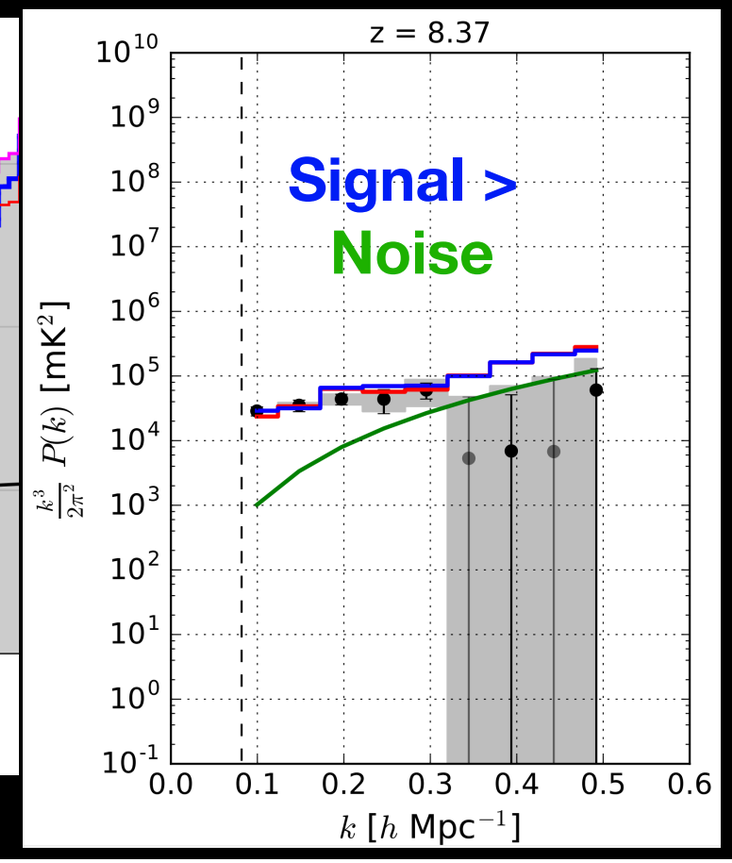


The Effect of uncalibrated Cable Reflections

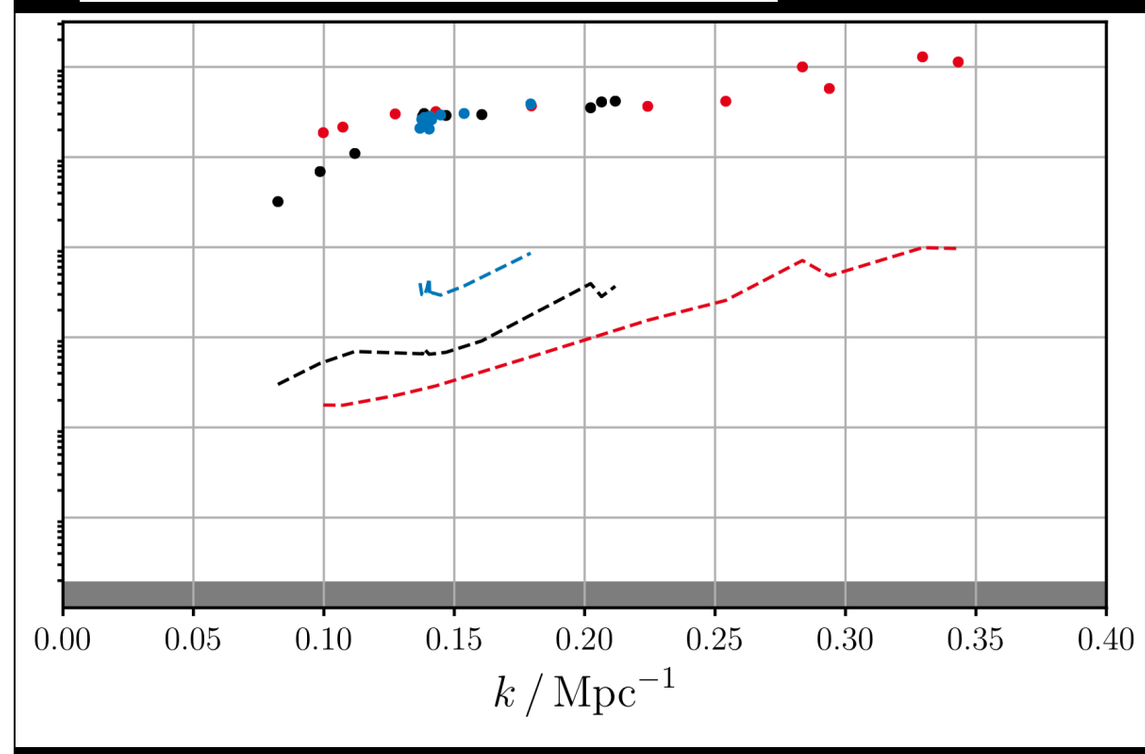


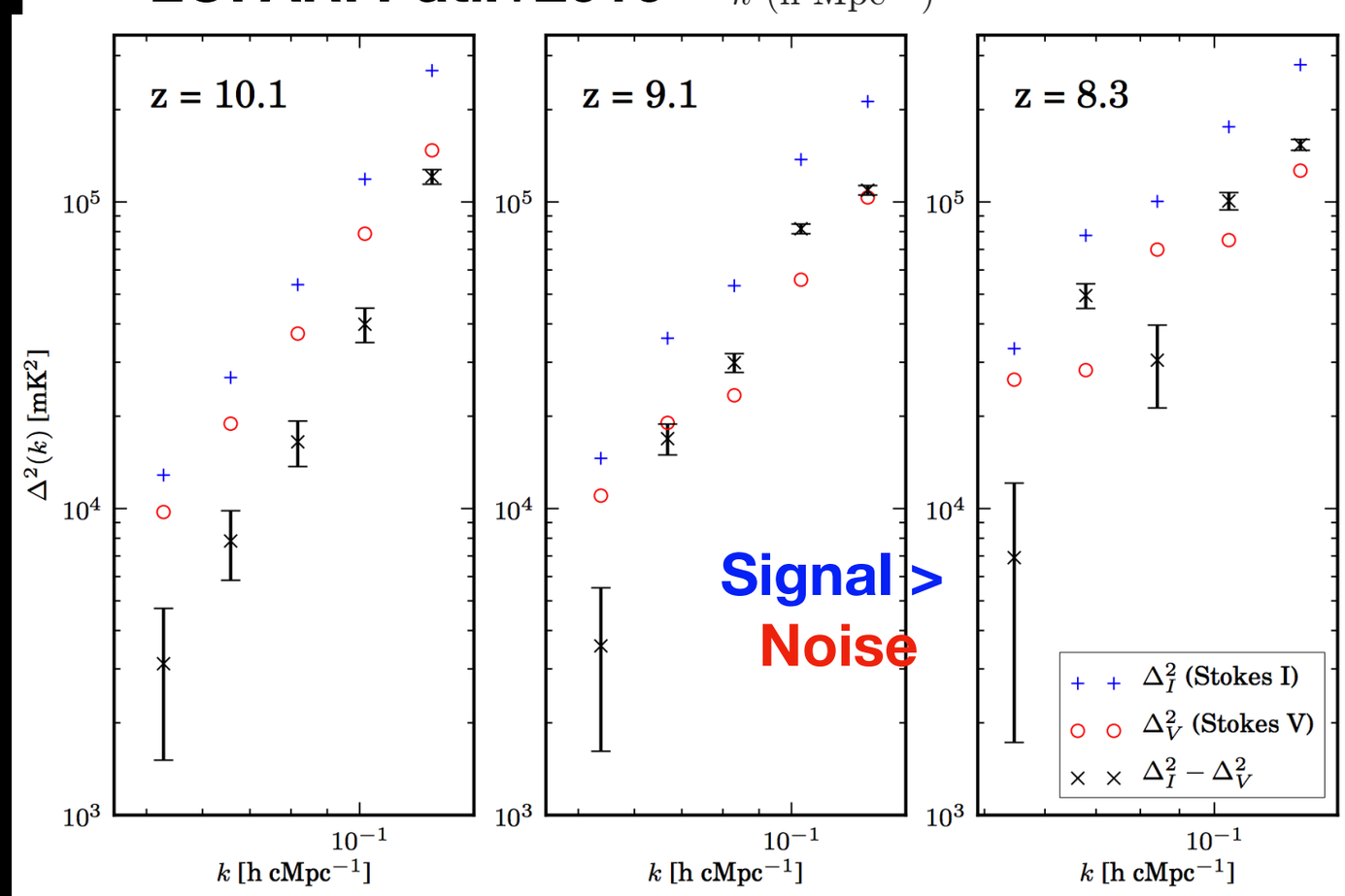
Existing Cosmic Dawn Limits are set by Systematics





PAPER:
Cheng+2018





CHIME: “But FRBs!”

Observations of Fast Radio Bursts at Frequencies Down to 400 MHz

They likely face similar problems.

Spectrally Smooth*

"All you need is ^ paperclips and a supercomputer"

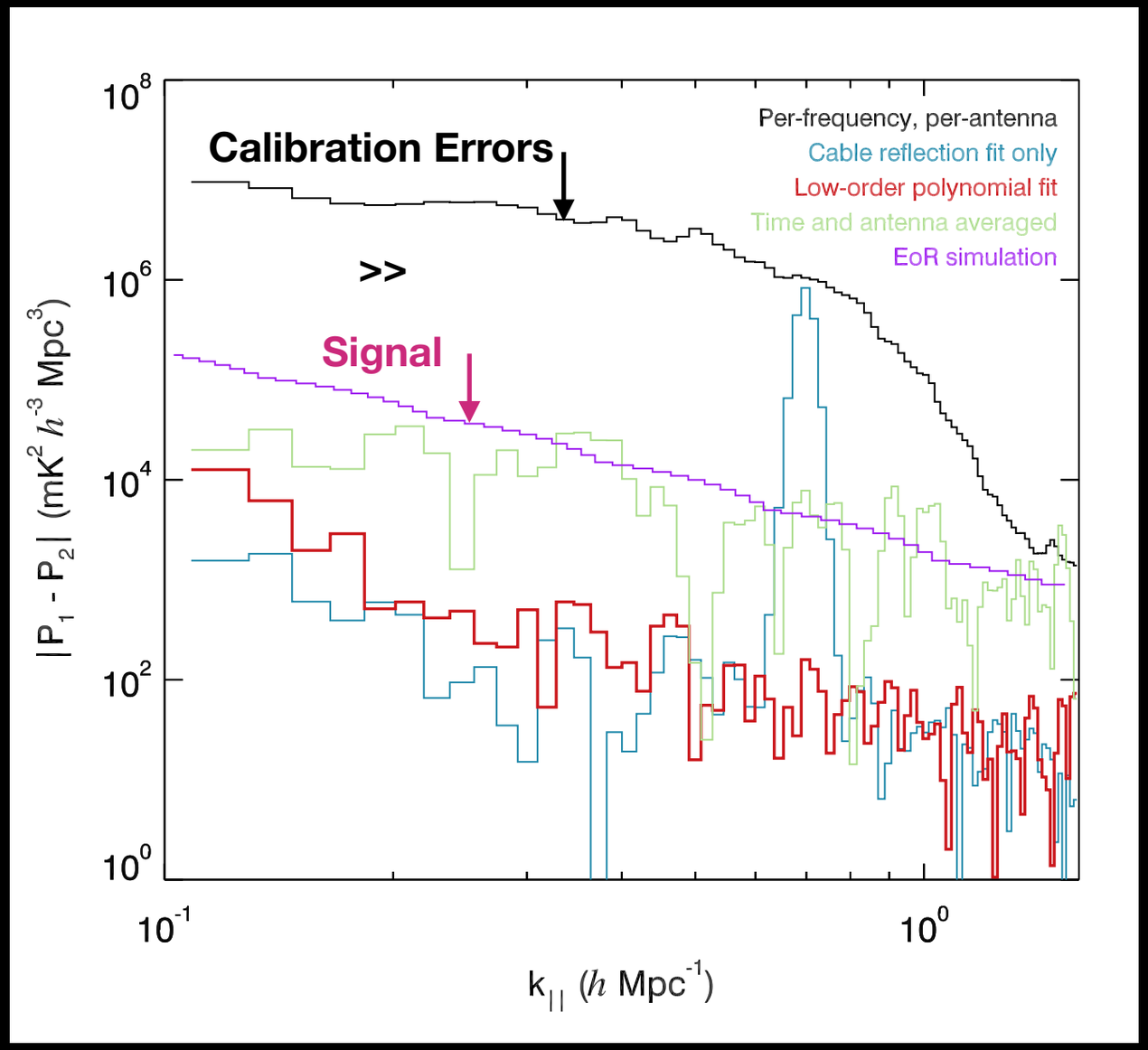
-Don Backer

***up to one part in ~10^{-5}**

Calibration <u>should</u> remove spectral structure

Sky-based calibration errors
Exceed the power-spectrum level

MWA Simulation



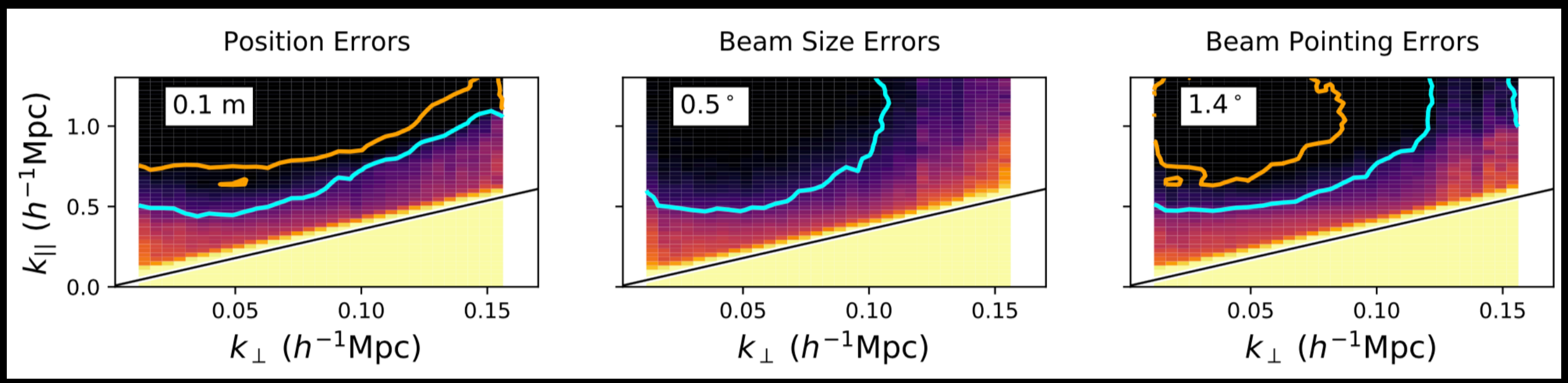
Barry+ 2017

Will also limit nominal SKA-low designs.

also AEW+ 2017, Patil+ 2017, Trott+2017

Redundant Calibration Faces Similar Issues

Non-redundancies introduce calibration errors that also fill in the “window”.

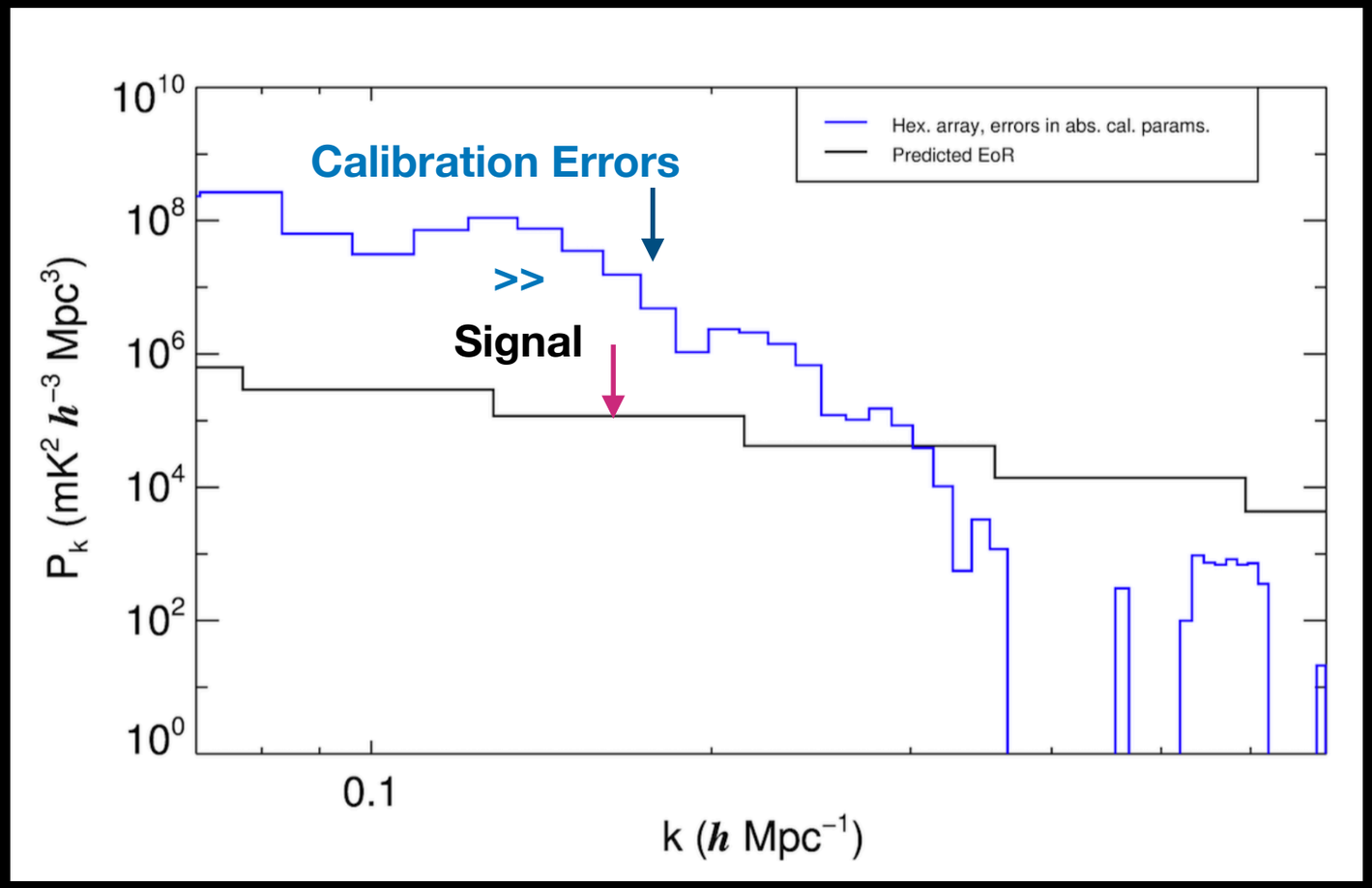


Orosz+2018

See Josh’s Talk

Sky model errors a problem, even for perfectly redundant instruments

An Imperfect sky-model leads to “abs-cal” errors



Byrne+2018

See Josh’s Talk

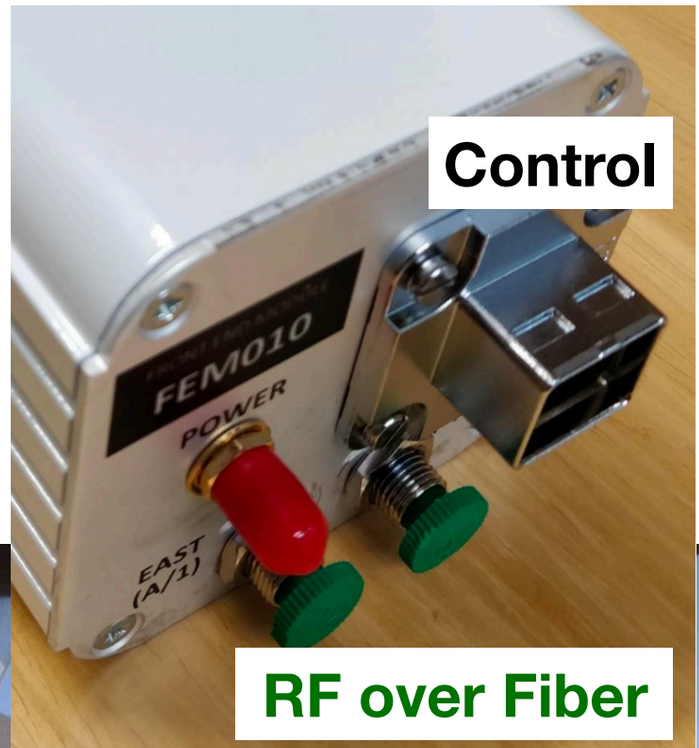
Strategies for dealing with spectral structure

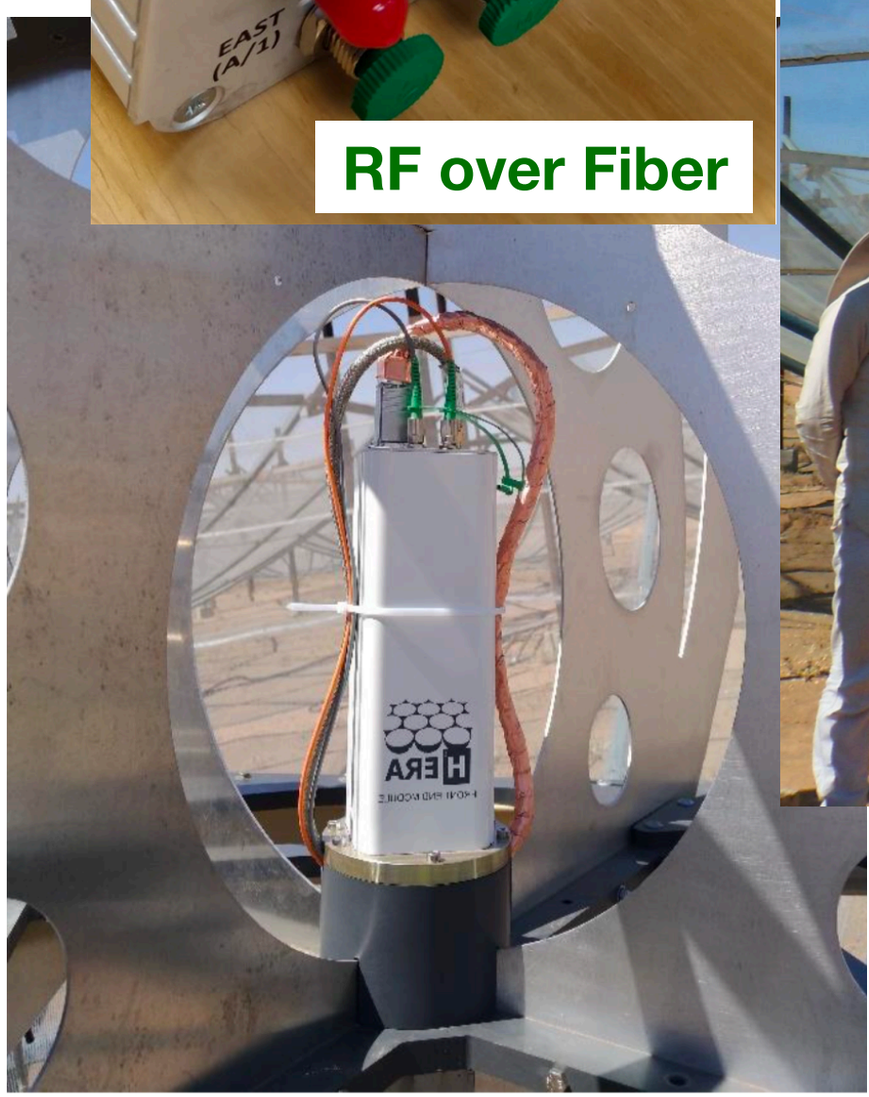
1. **Make sure your signal path is “spectrally smooth”.**

2. **Figure out ways to robustify redundant calibration against non-redundancy and sky-model incompleteness.**

Many experiments are switching to RF over fiber to reduce reflections

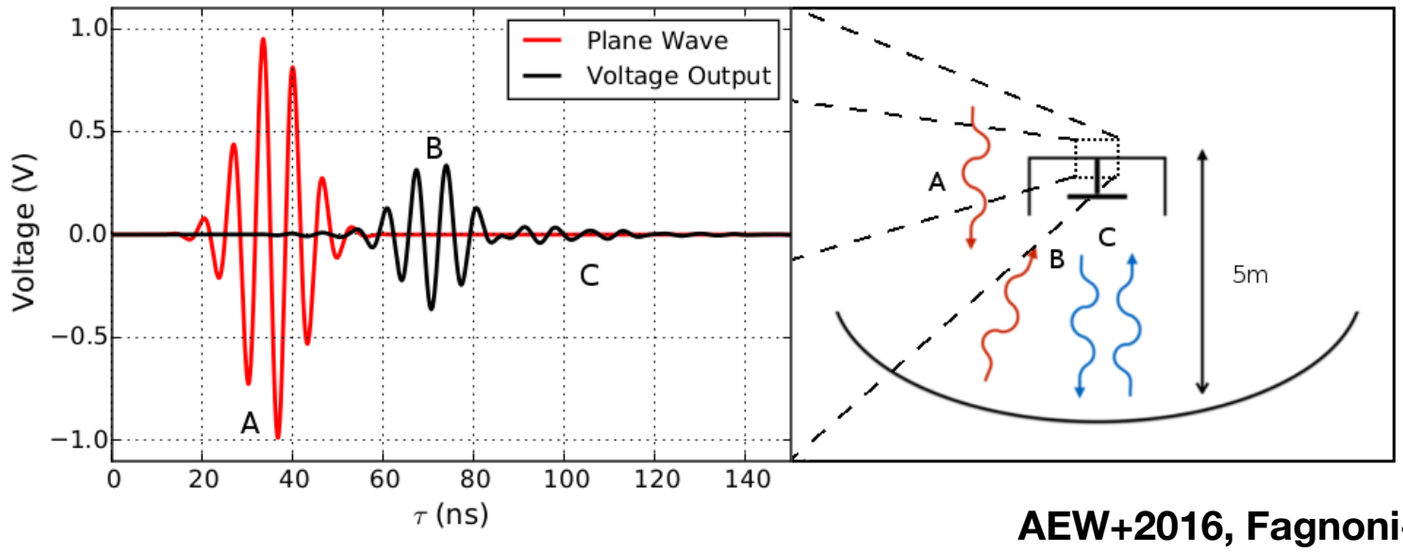
HERA, HIRAX, MWA

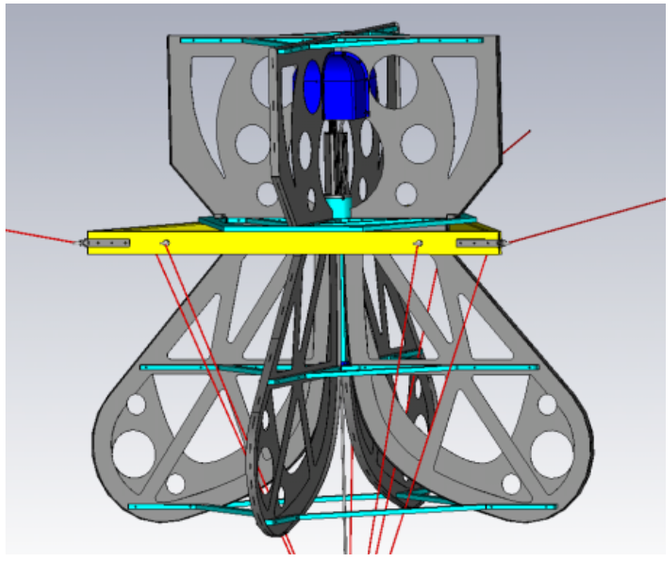




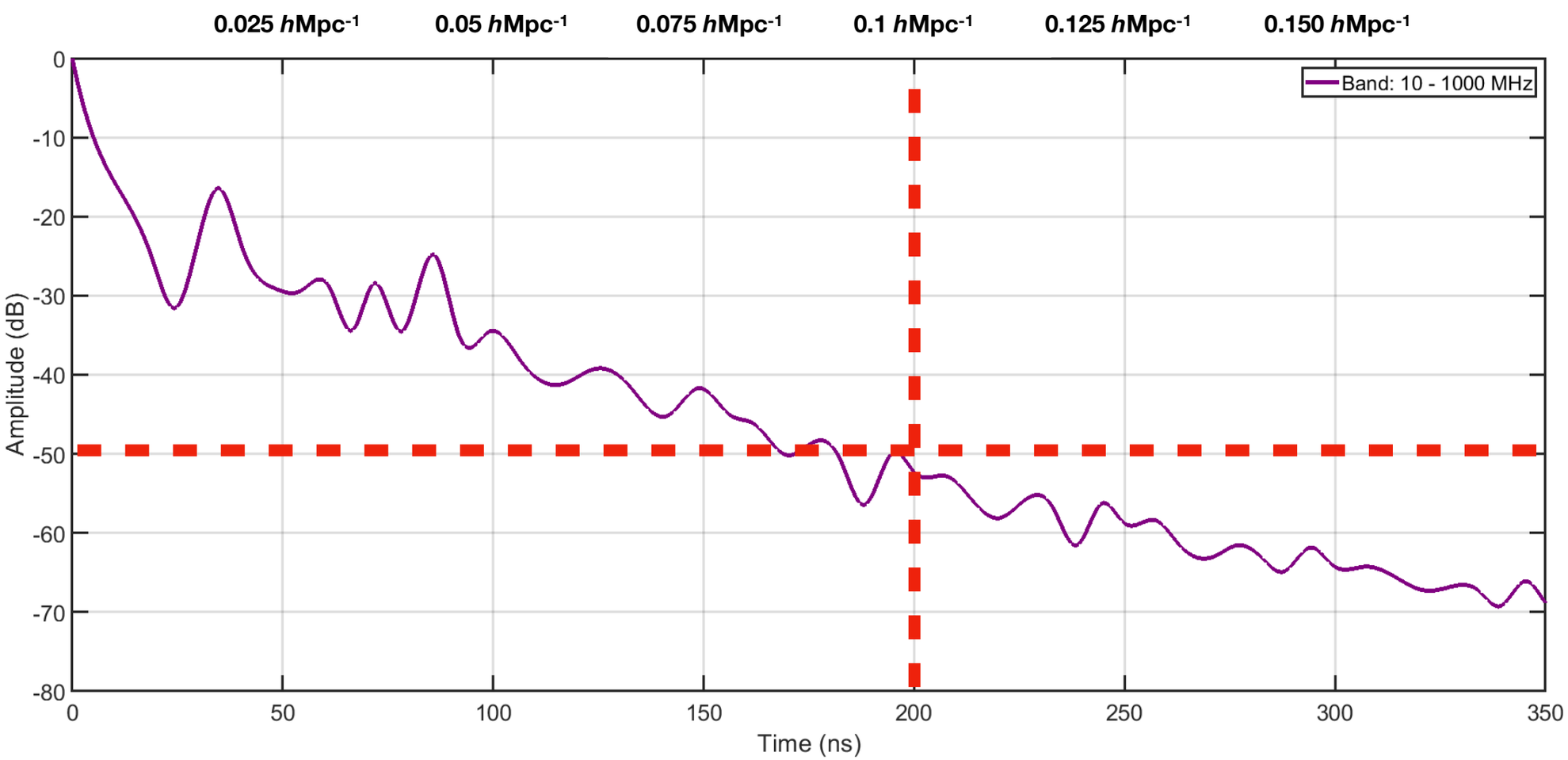
HERA site trip deploying RFoF chains and new feeds

We use Electromagnetic Simulations to optimize the spectral performance of the feed and RF front-end





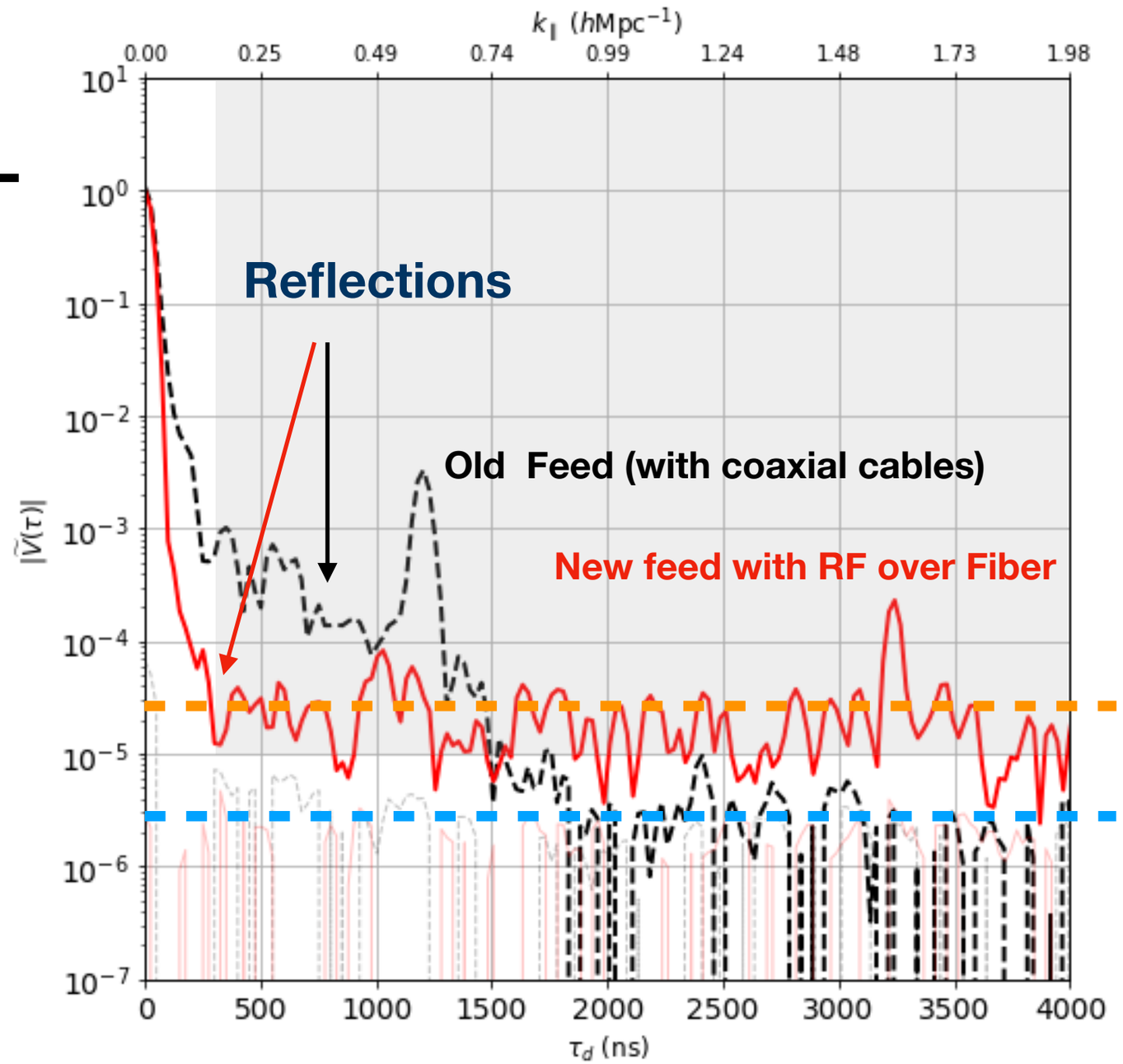
AEW+2016, Fagnoni+ 2016



Fagnoni+ in prep.

How do we verify that our signal chain is spectrally smooth?

Solution: Look at Autocorrelations!



Bias may be additive Internal RFI. Does not appear in Cross Correlations

Noise Level

Kern+ 2019

AEW in prep.

When subtracting internal RFI bias, spectral leakage falls fast enough to allow 21cm Detection. <u>Necessary</u> but <u>not sufficient</u>

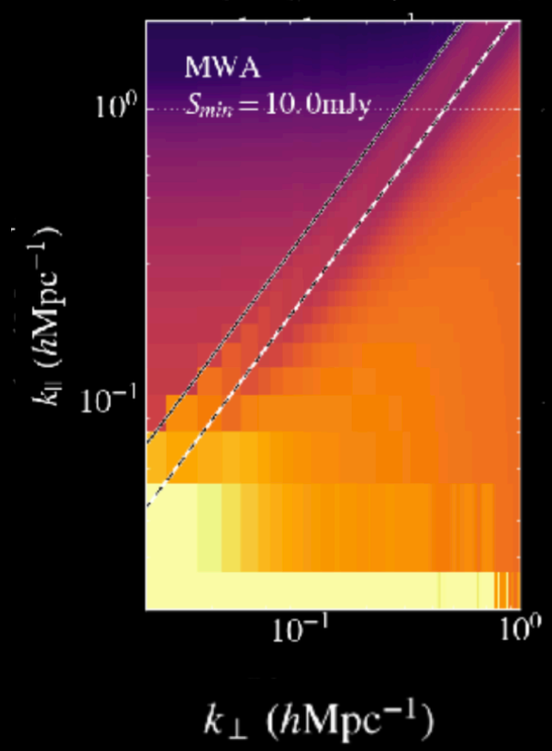
Strategies for dealing with spectral structure

1. Make sure your signal path is “spectrally smooth”.

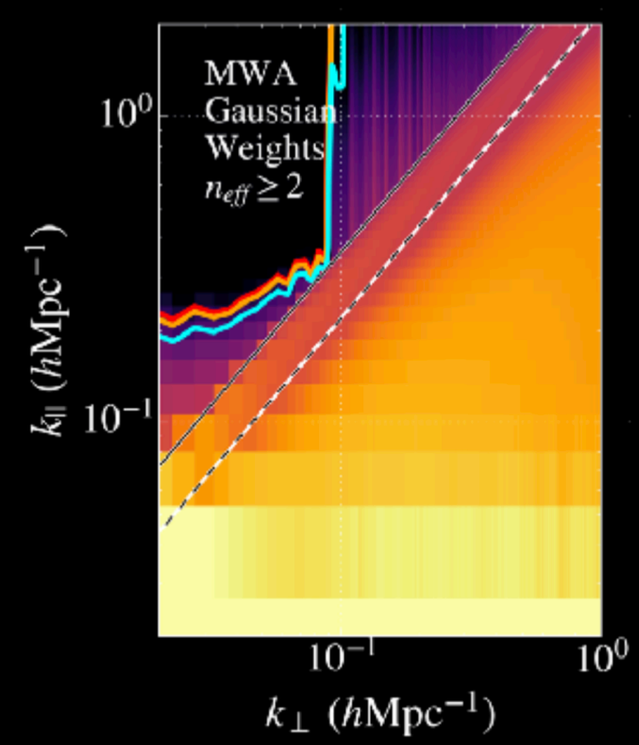
2. Figure out ways to robustify redundant calibration against non-redundancy and sky-model incompleteness.

Calibrating with Short Baselines: Can help with all calibration strategies!

All baselines



Short baselines

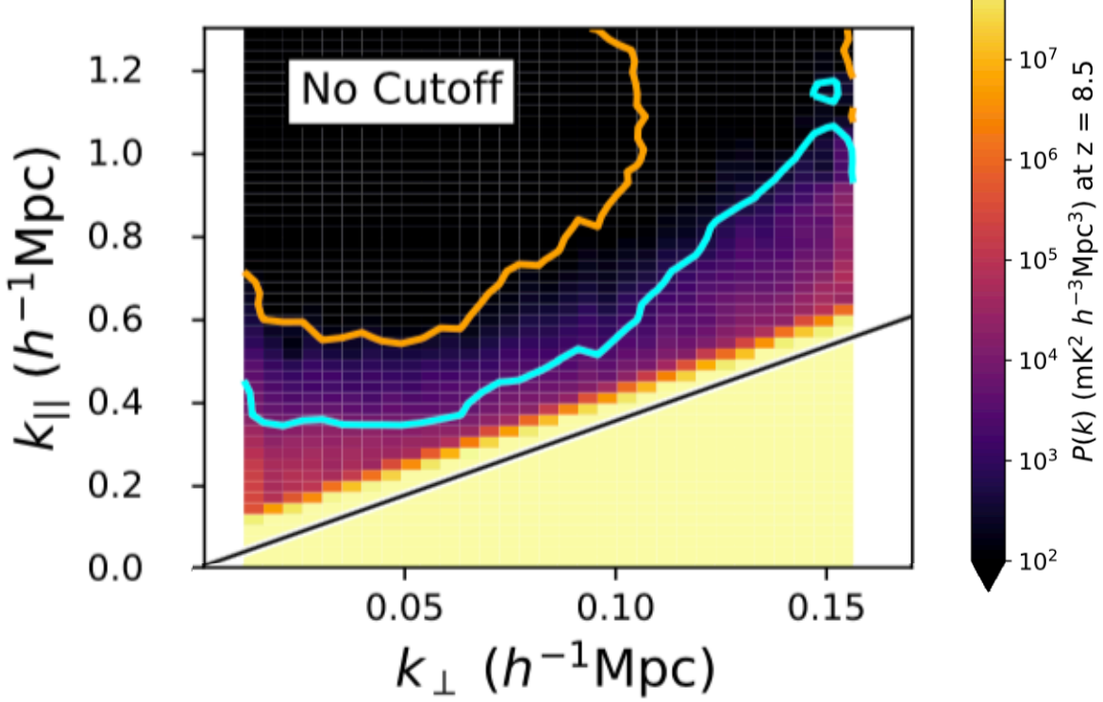


AEW+ 2018

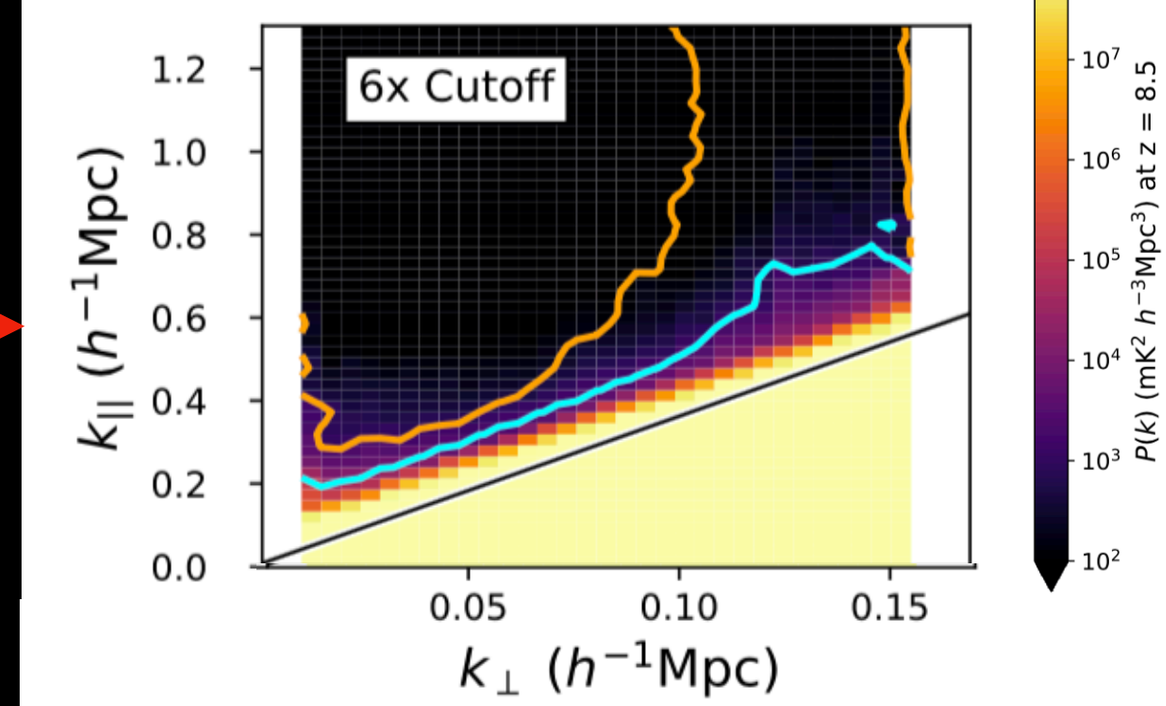
You'll Need
A
"Good enough"
Diffuse Sky Model!

Orosz+ 2018

All baselines



Short baselines



Take Aways

1. Global 21cm experiment, EDGES -> Exotic physics or new radio sources? Needs validating.

2. 21cm Fluctuation measurements
   I. Offer a way to validate EDGEs.
   II. Better foreground separation but instruments much more complicated/difficult to characterize.
   III. Can be used to probe cosmic dawn and epoch of acceleration!

3. **All existing fluctuation experiments are systematics limited.**
   I. Primary hurdle is **instrumental spectral structure**.
   II. Progress is being made in **Calibration** and **Instrument design.**