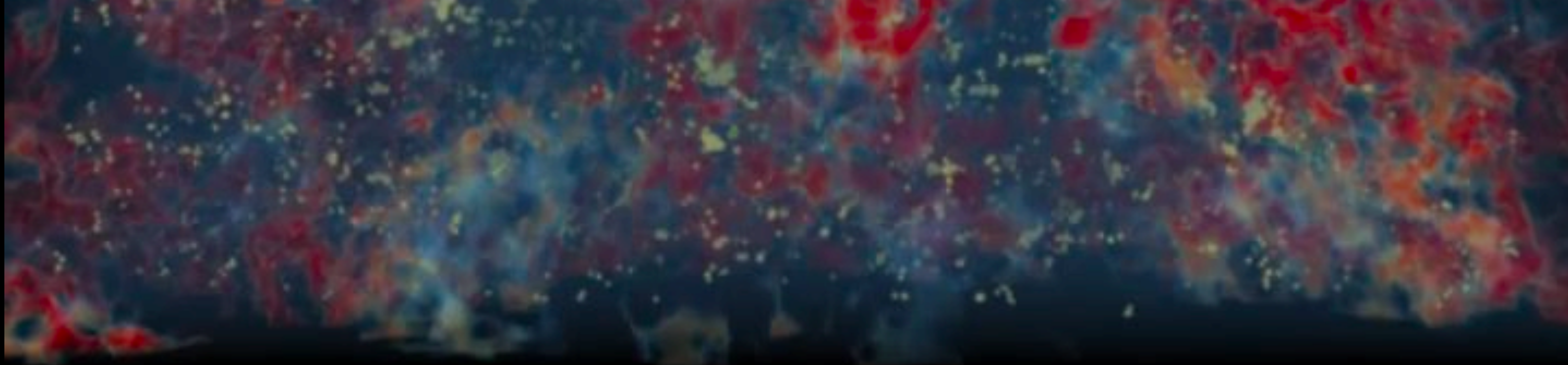


Chasing The Demons of the Cosmic Dawn with 21cm

Aaron Ewall-Wice

Berkeley Astronomy Department and Center for Cosmological Physics.

We want to use 21cm to fill in our cosmic timeline

redshift z=1100 z=200 z=40 z=6 z=1 z=0

Hubble Ultra Deep Field

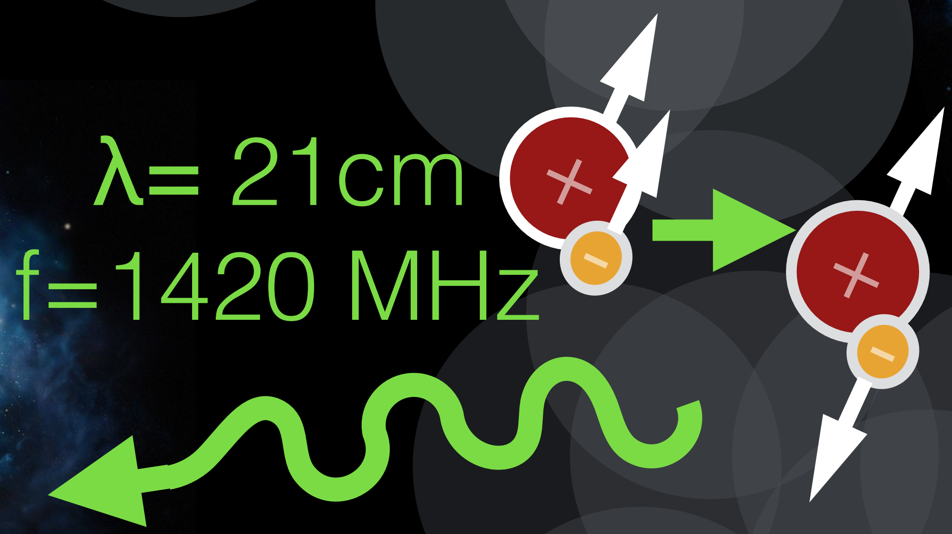
First Stars

First Galaxies

The first luminous structures

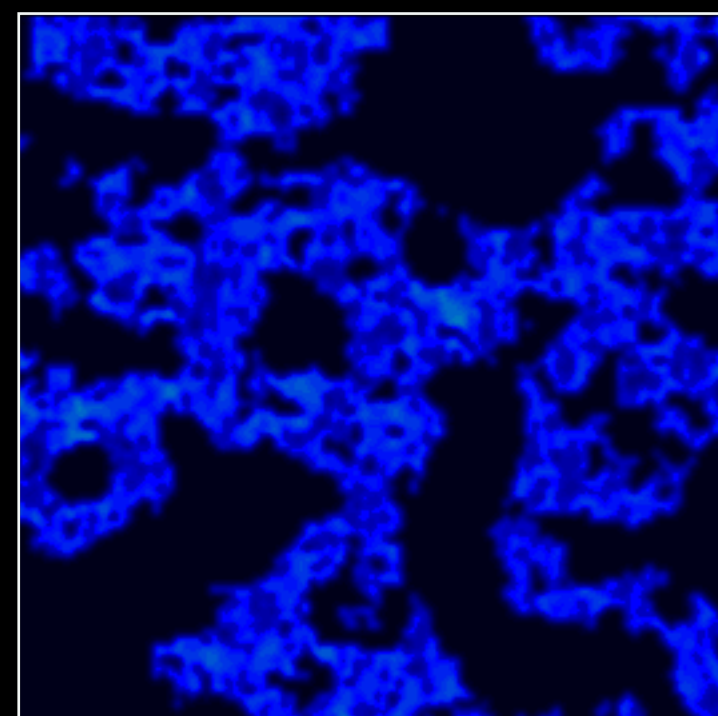
time 400,000 years 200 million years 1 billion years 13.8 billion years

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



21cm Tomography

λ= 1.68m
f=158 MHz

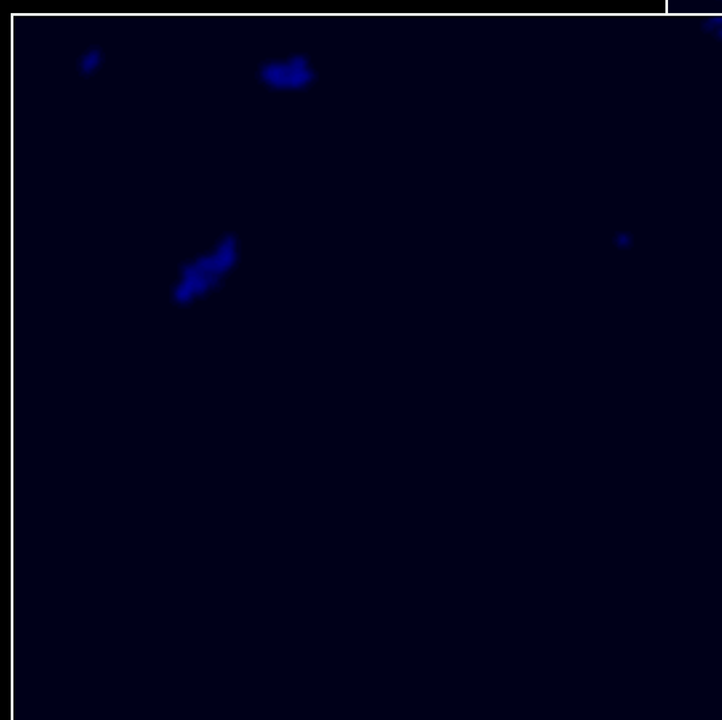


z = 8

Mesinger 2011

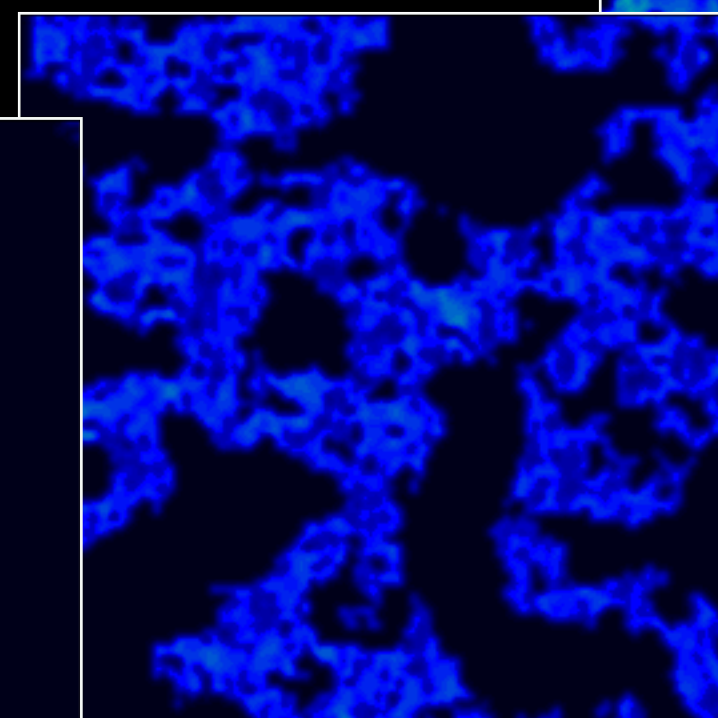
21cm Tomography

λ= 1.47 m
f=202 MHz



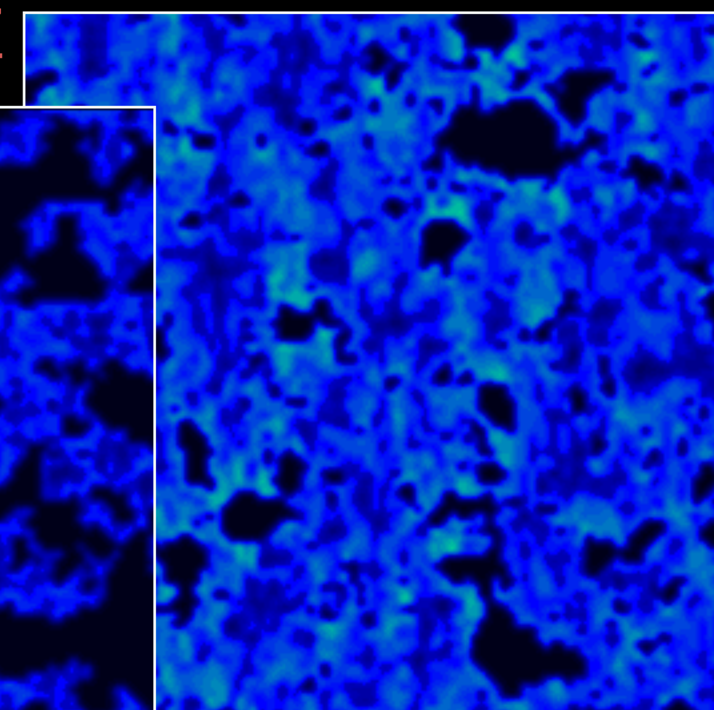
z = 6

λ= 1.68m
f=158 MHz



z = 8

λ= 2.1m
f=130 MHz



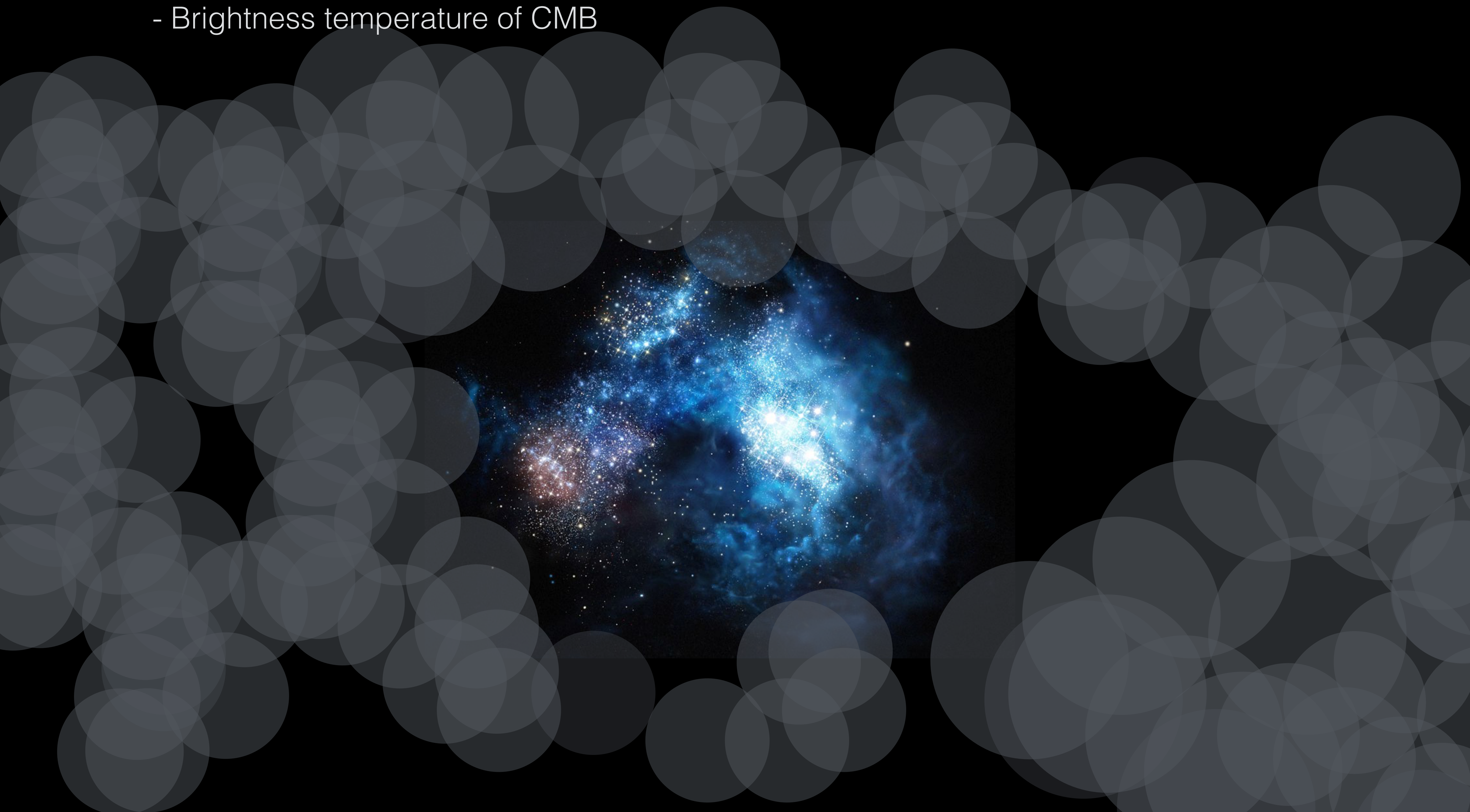
z = 10

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

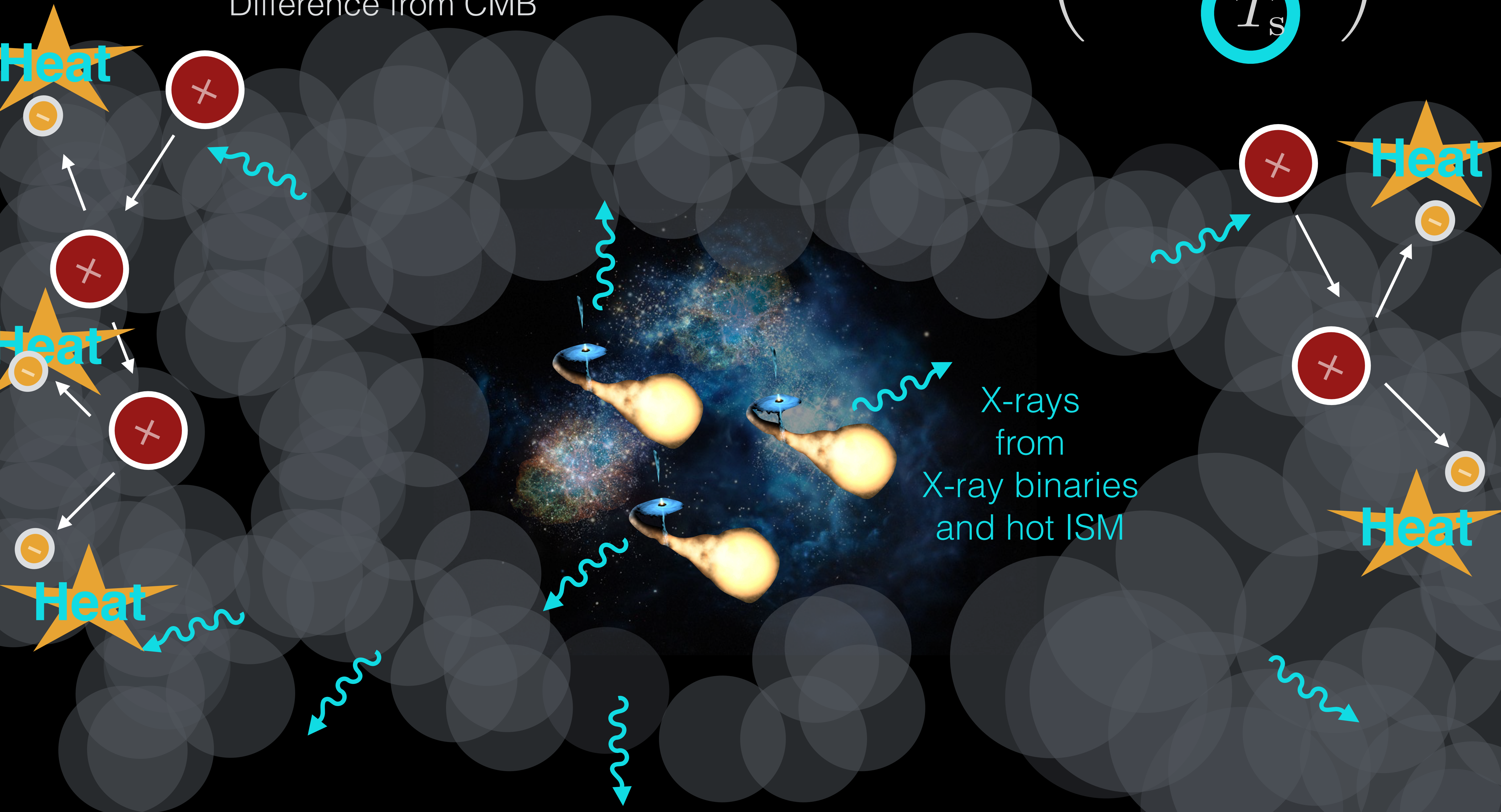
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_{\rm s}}\right)$$

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

X-rays: Raise Thermal Temperature

δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

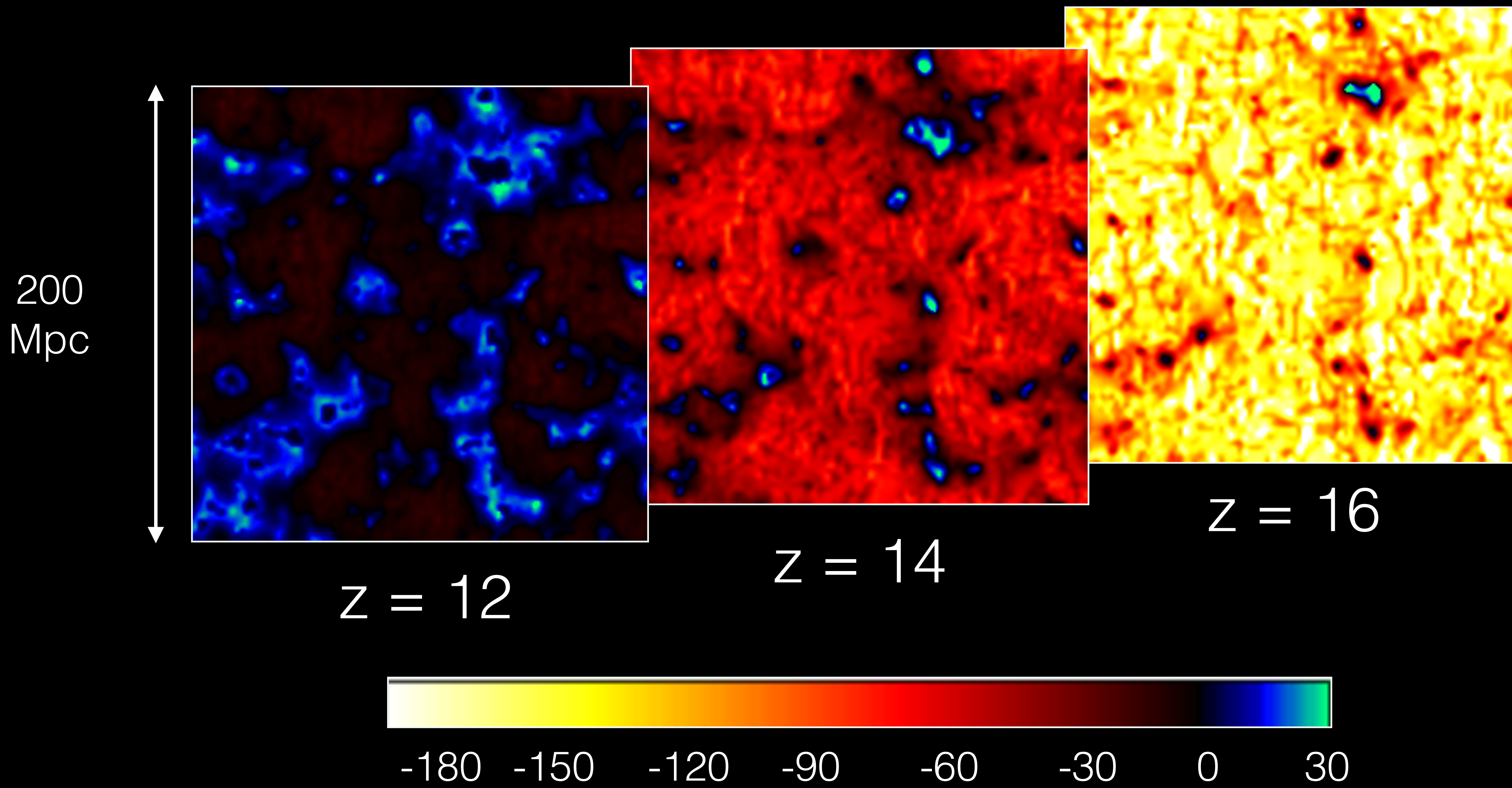
$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{s}}}\right)$$



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

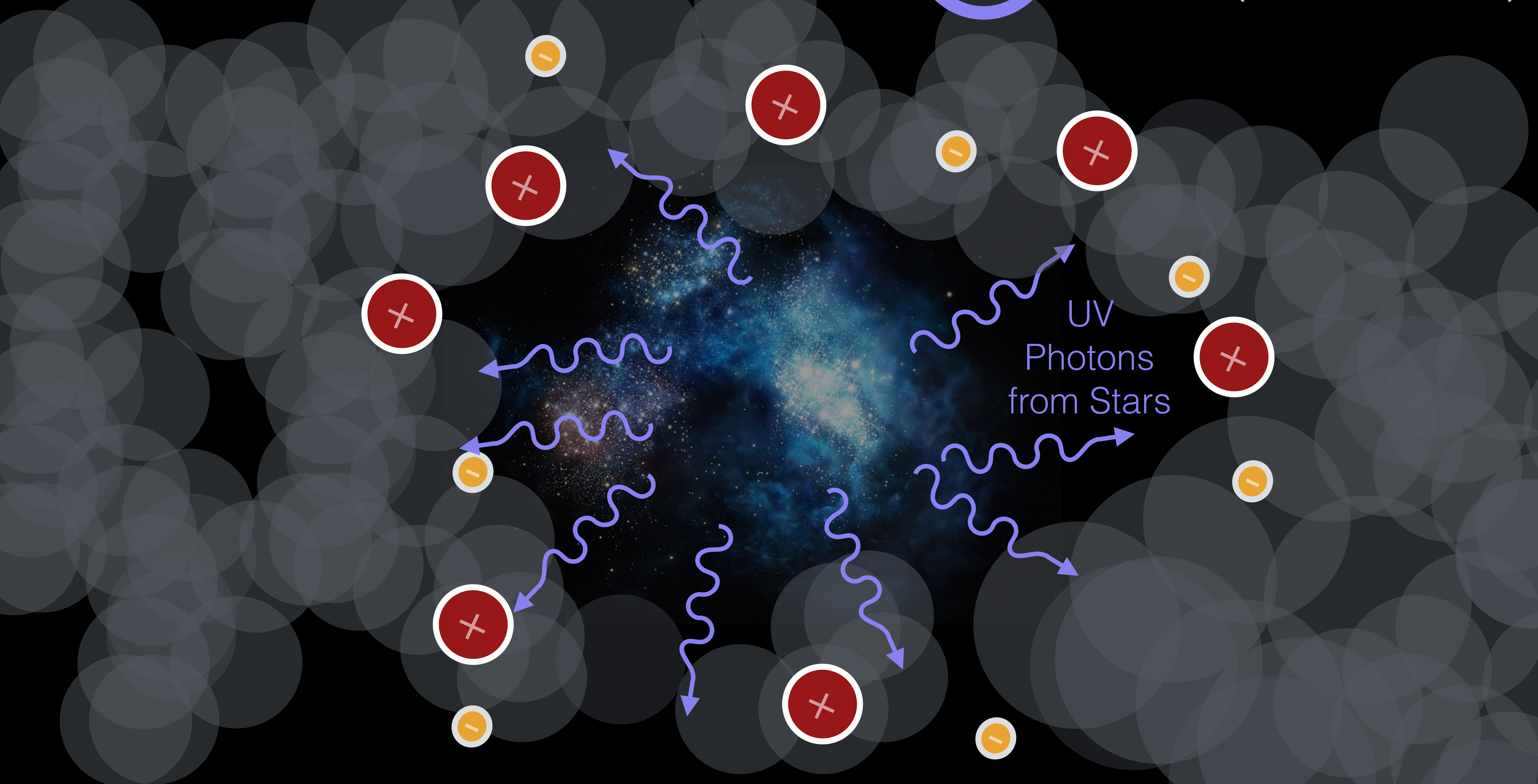


$$\delta T_b \propto x_{HI} \times \rho \times \left(1 - \frac{T_{\rm CMB}}{T_s}\right) \quad \text{(mK)}$$

Lyman Continuum Photons: Ionize the IGM

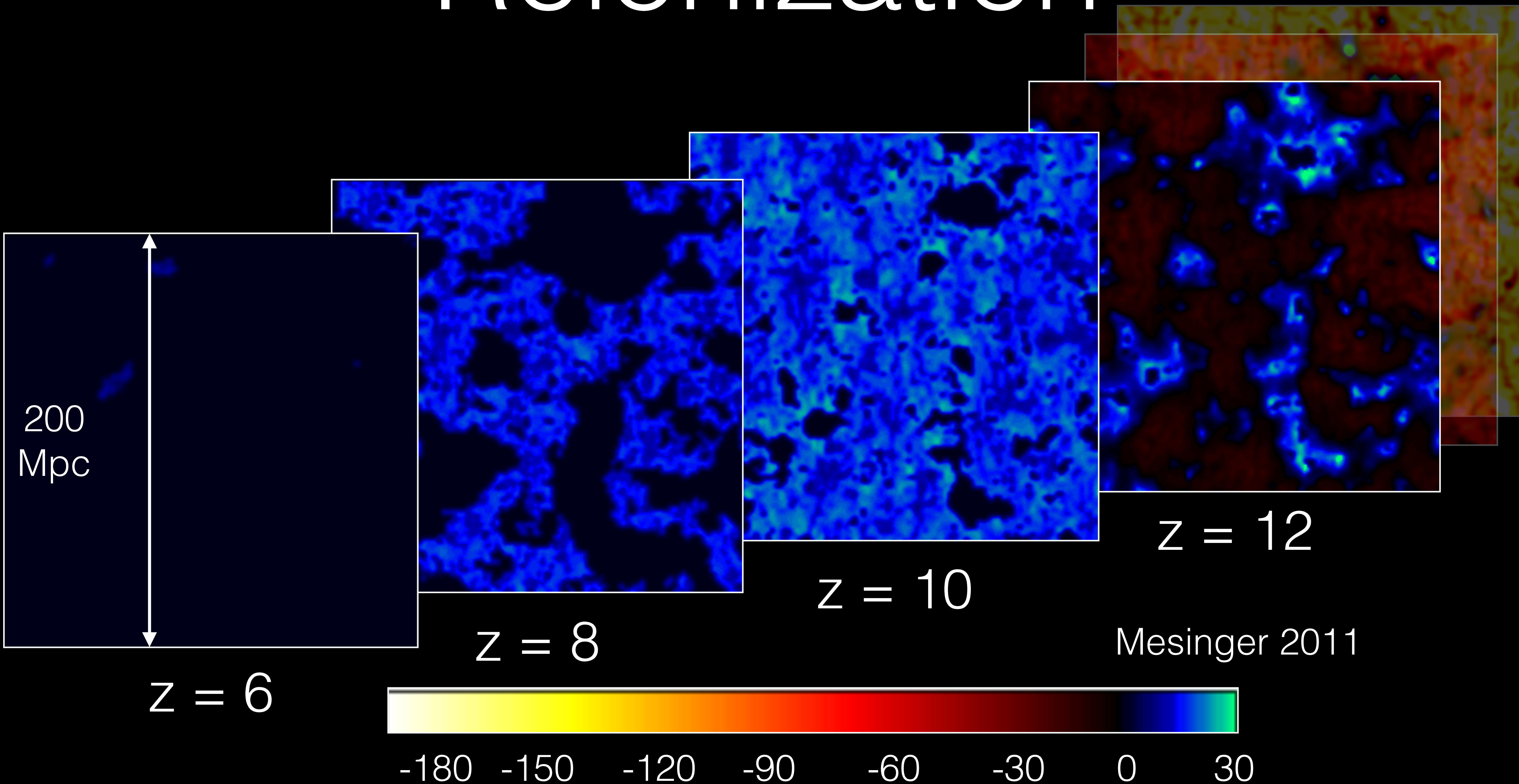
δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

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



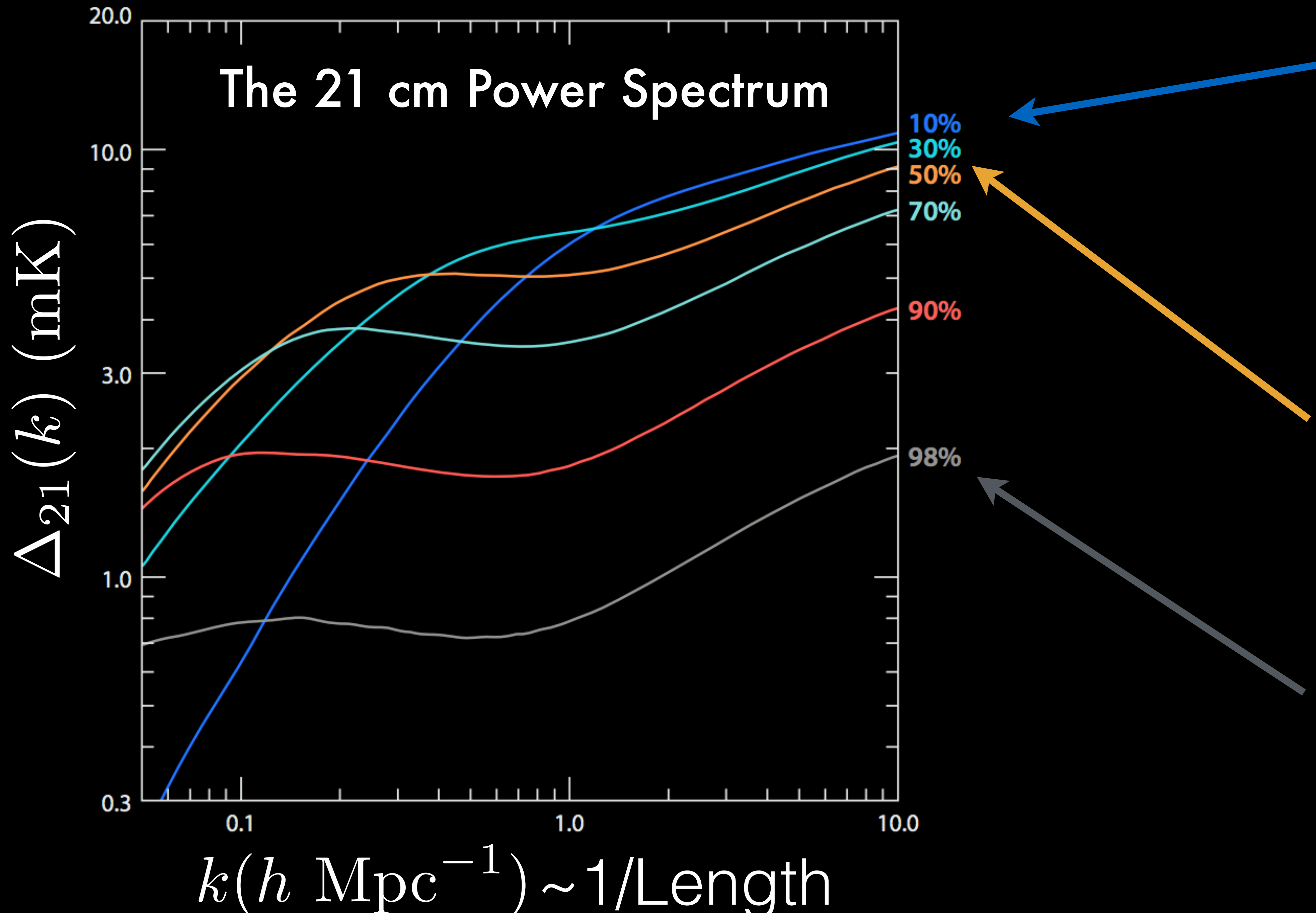
Simulations from 21cmFAST (Mesinger+ 2011)

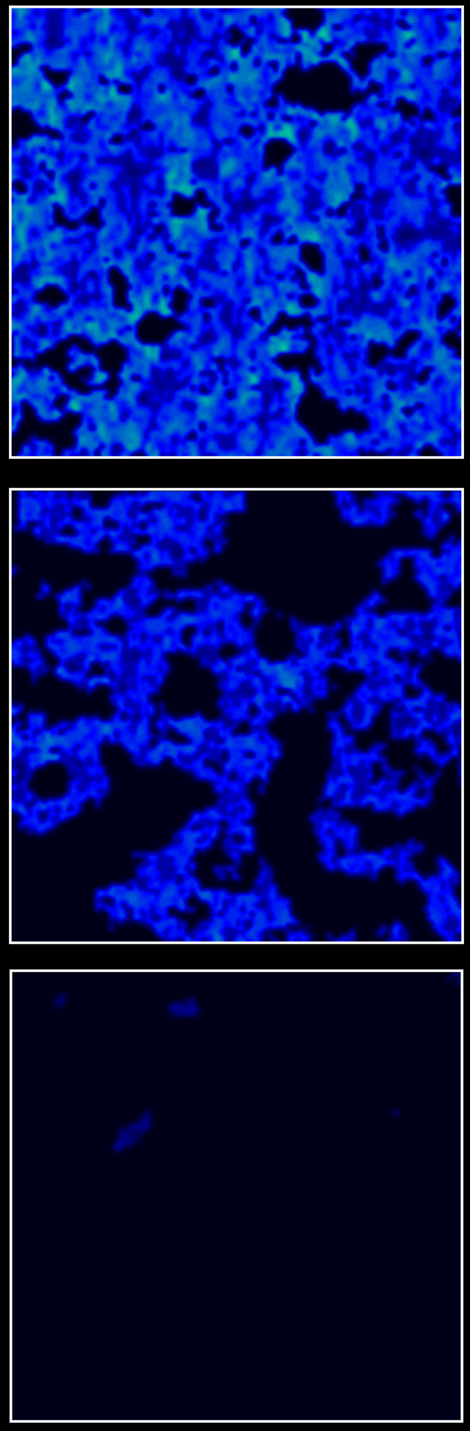
Reionization



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

Early Detections of 21cm will be Statistical





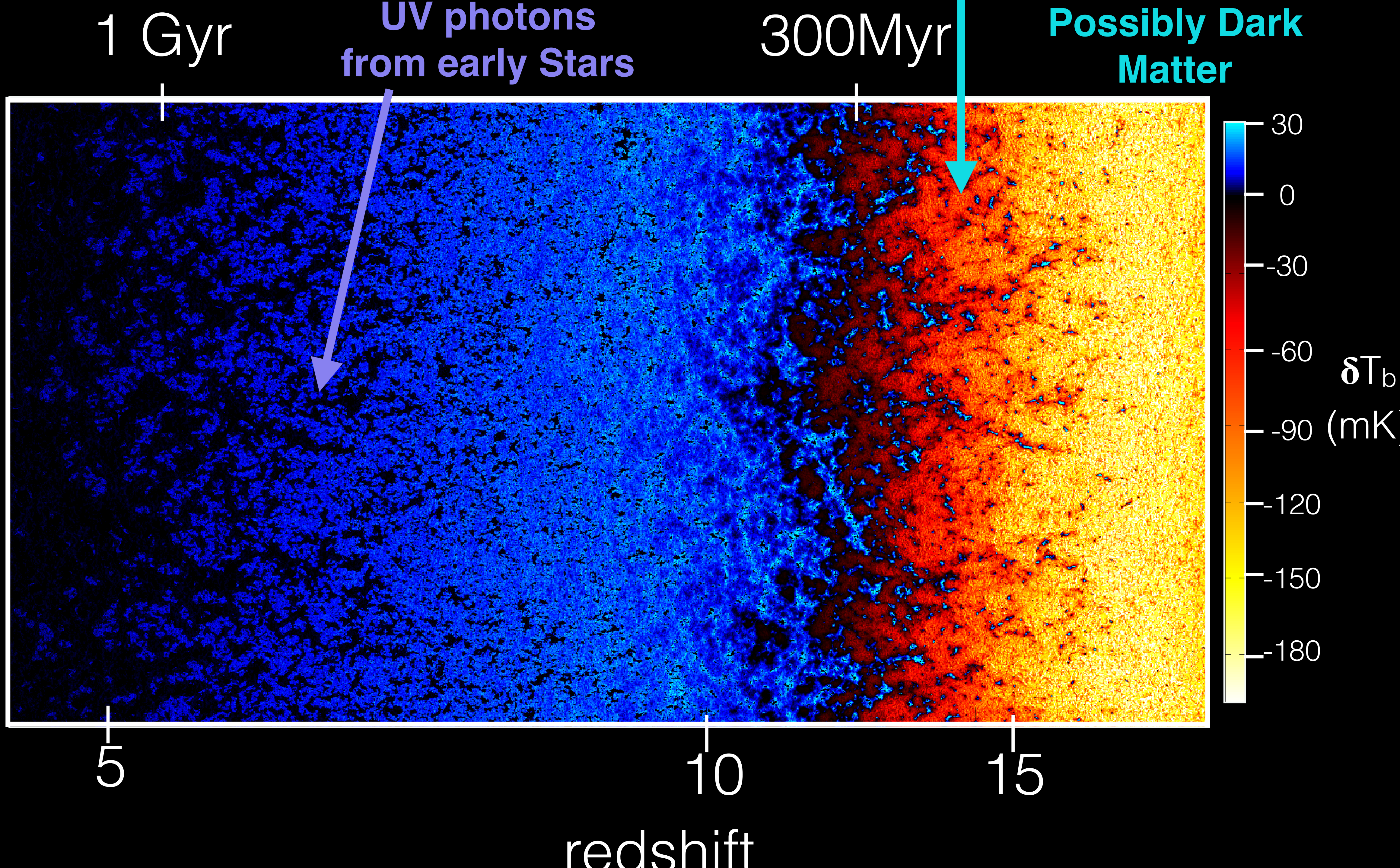
Slide adopted from Josh Dillon

Barkana (2009), Morales & Wyithe (2010)

$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$

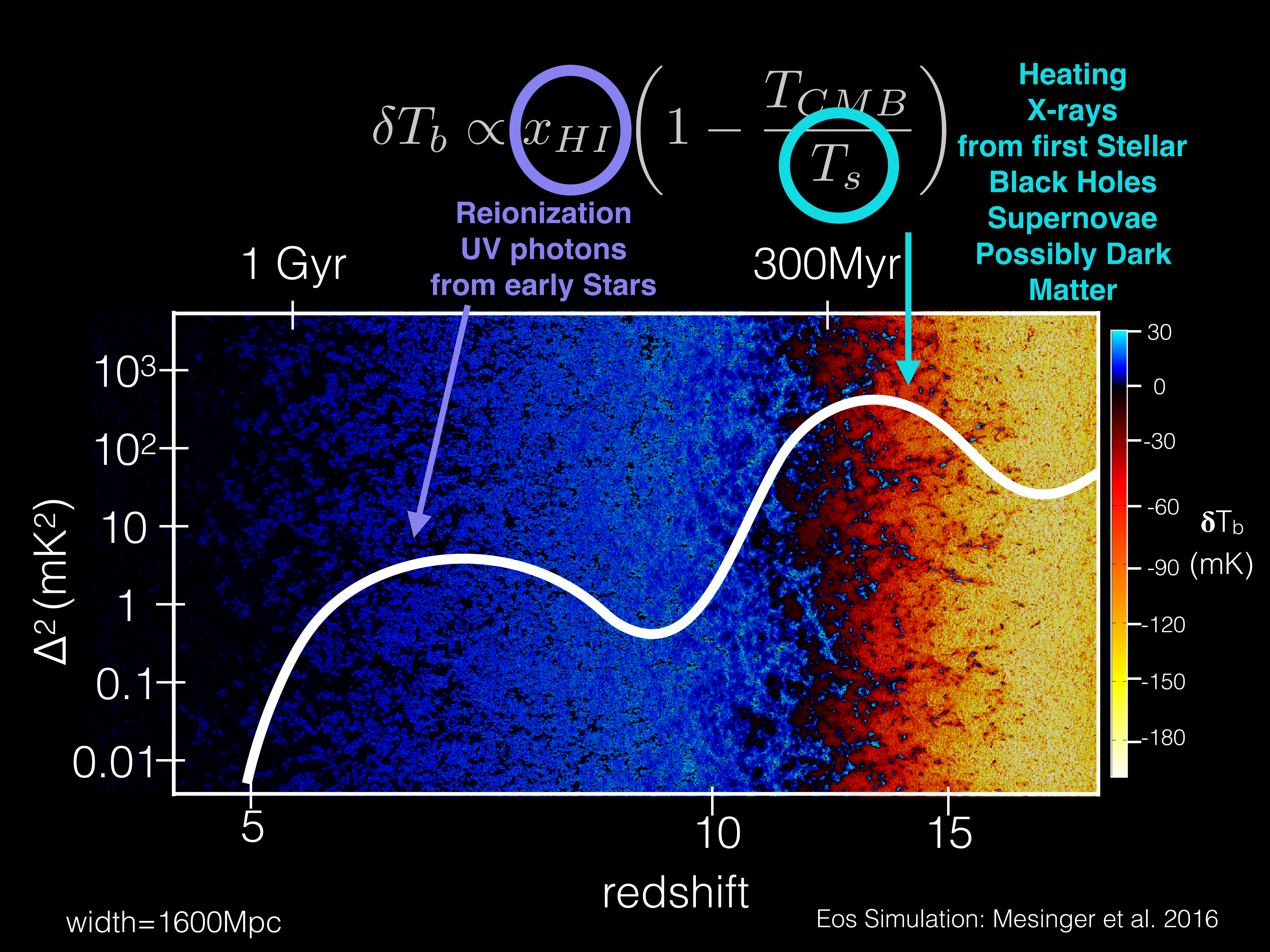
Reionization
UV photons
from early Stars

Heating
X-rays
from first Stellar
Black Holes
Supernovae
Possibly Dark
Matter



width=1600Mpc

Eos Simulation: Mesinger et al. 2016



$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$
Reionization
UV photons
from early Stars
Heating
X-rays
from first Stellar
Black Holes
Supernovae
Possibly Dark
Matter
1 Gyr
300Myr
10^3
10^2
10
1
0.1
0.01
Δ^2 (mK^2)
5
10
15
redshift
30
0
-30
-60
-90
-120
-150
-180
δT_b (mK)
width=1600Mpc
Eos Simulation: Mesinger et al. 2016

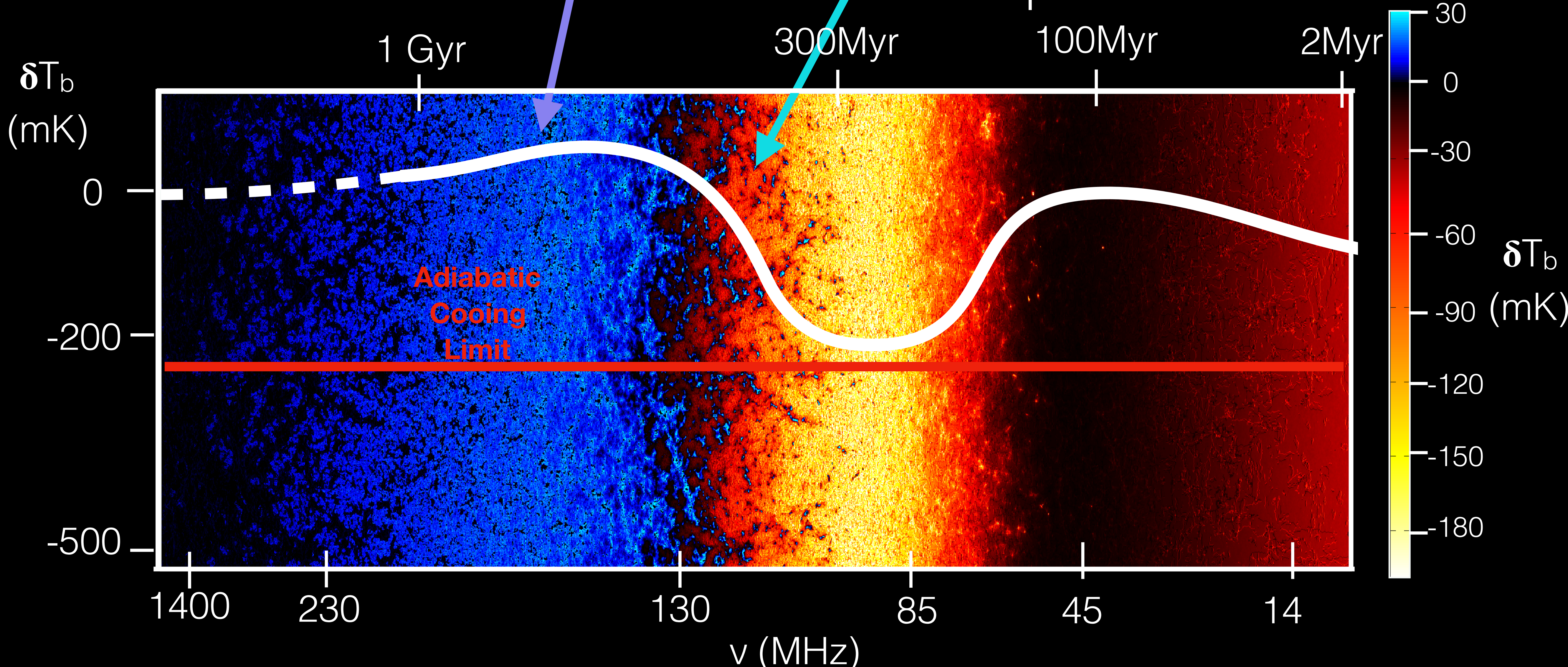
$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$

Reionization
UV photons
from early Stars

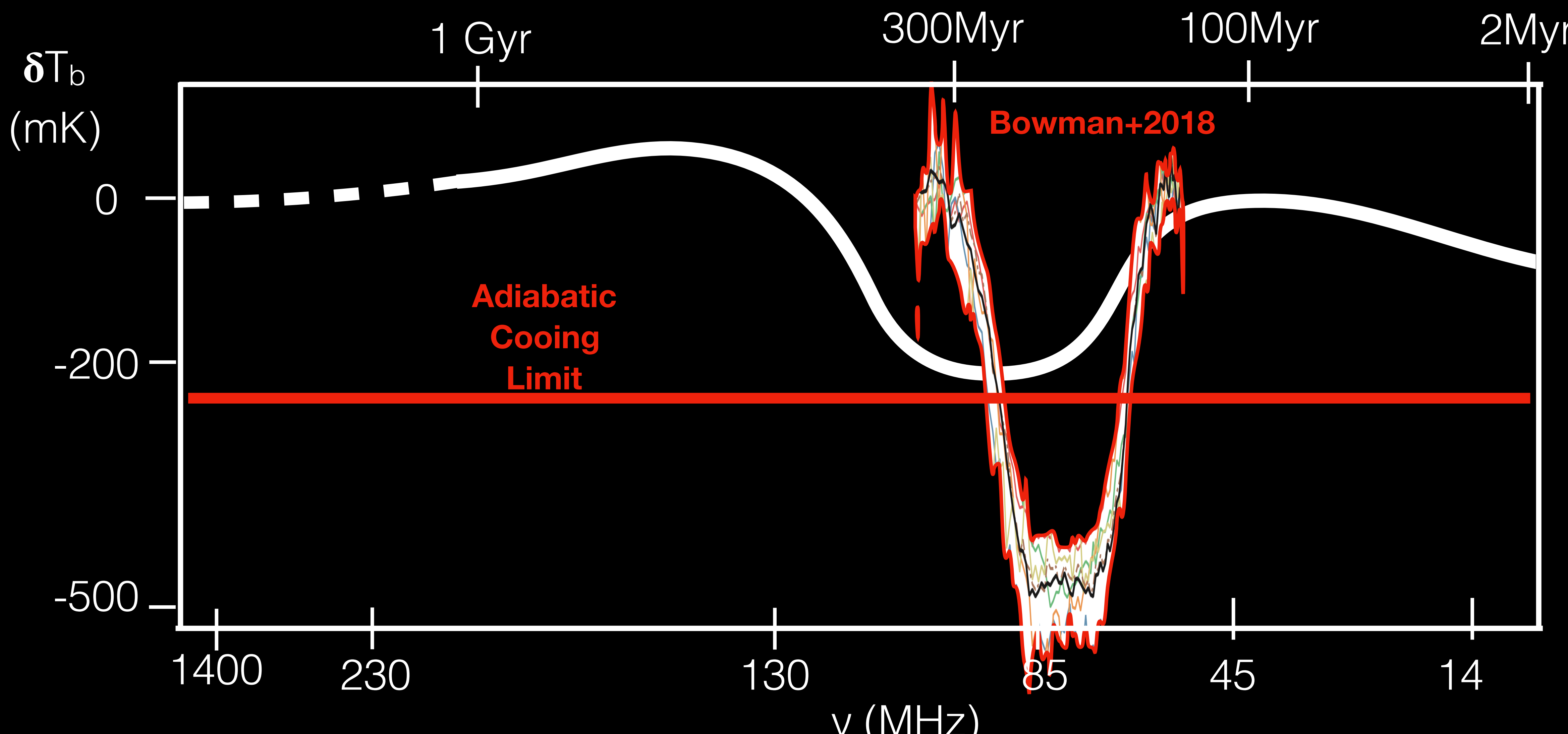
Heating
X-rays
from first Stellar
Black Holes
Supernovae
Possibly Dark
Matter

1 Gyr

300Myr

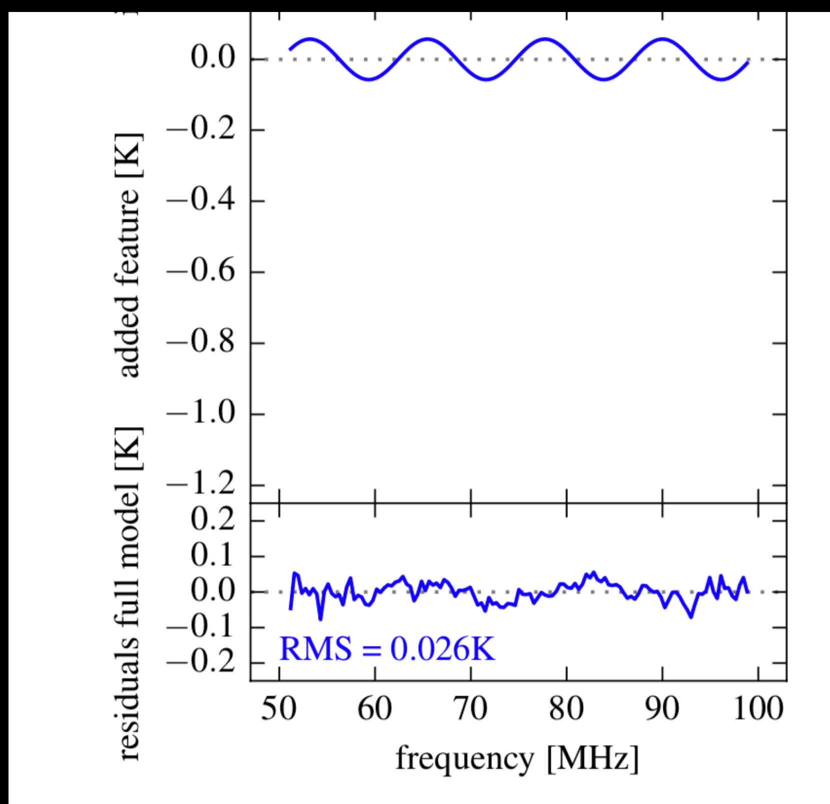


Eos Simulation: Mesinger et al. 2016



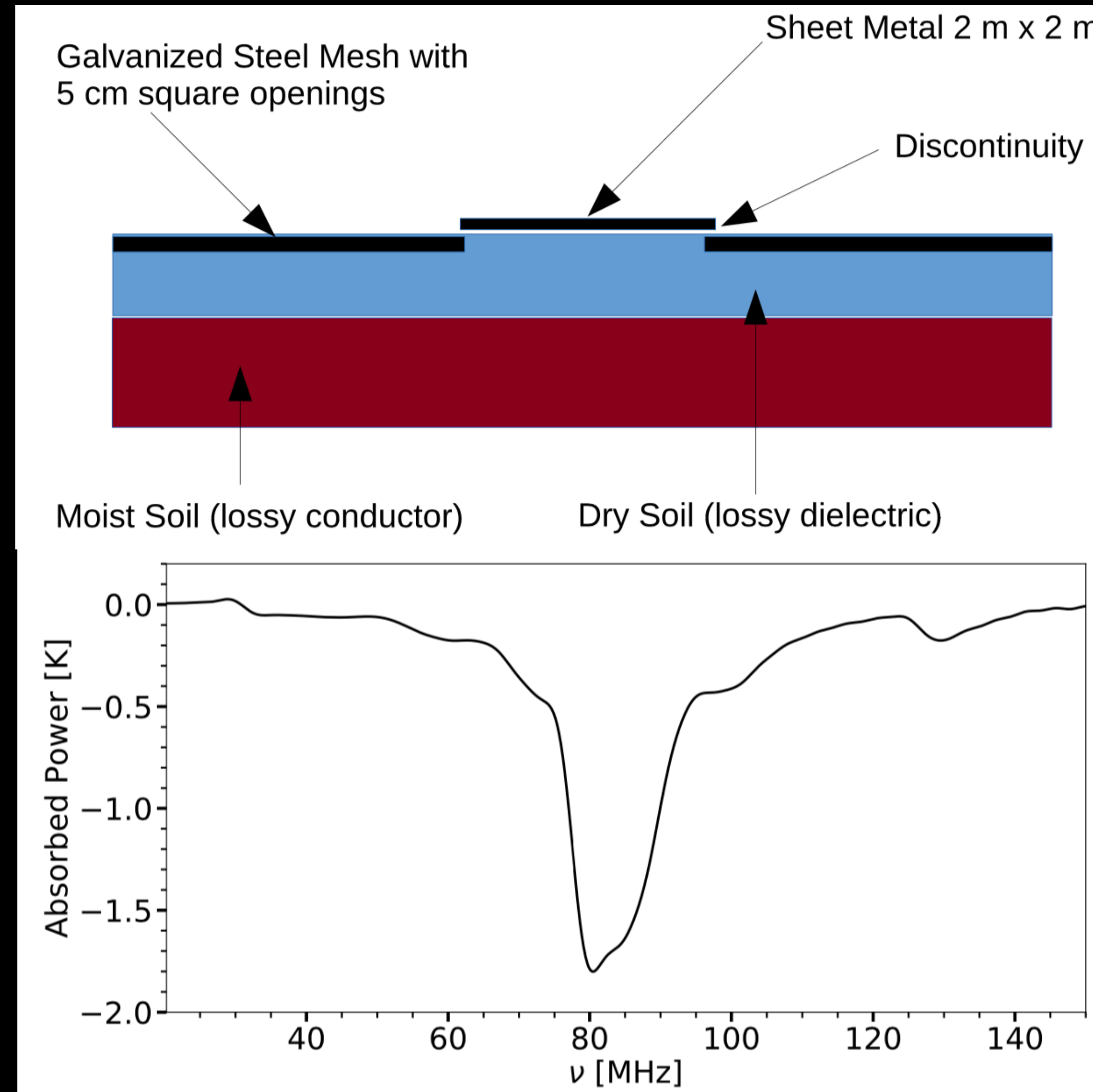
2018: The first claimed "Detection": EDGES
k=0 h/Mpc

Could be systematics



Residual Reflection/beam ripple

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



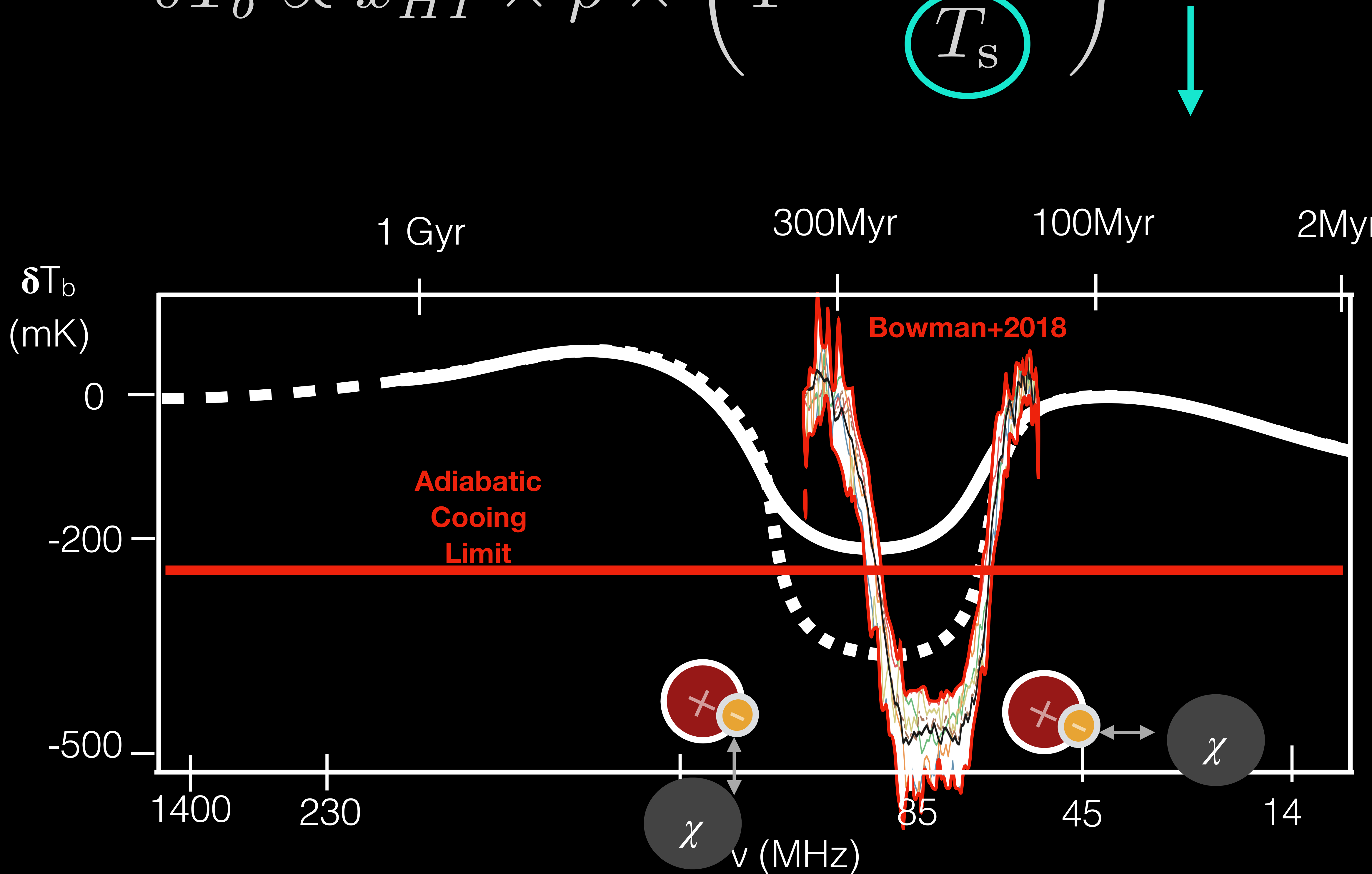
Resonance between ground plane and Moist Soil

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

If EDGEs is taken at face value…

Option 1: Cool T_s below the adiabatic limit!

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

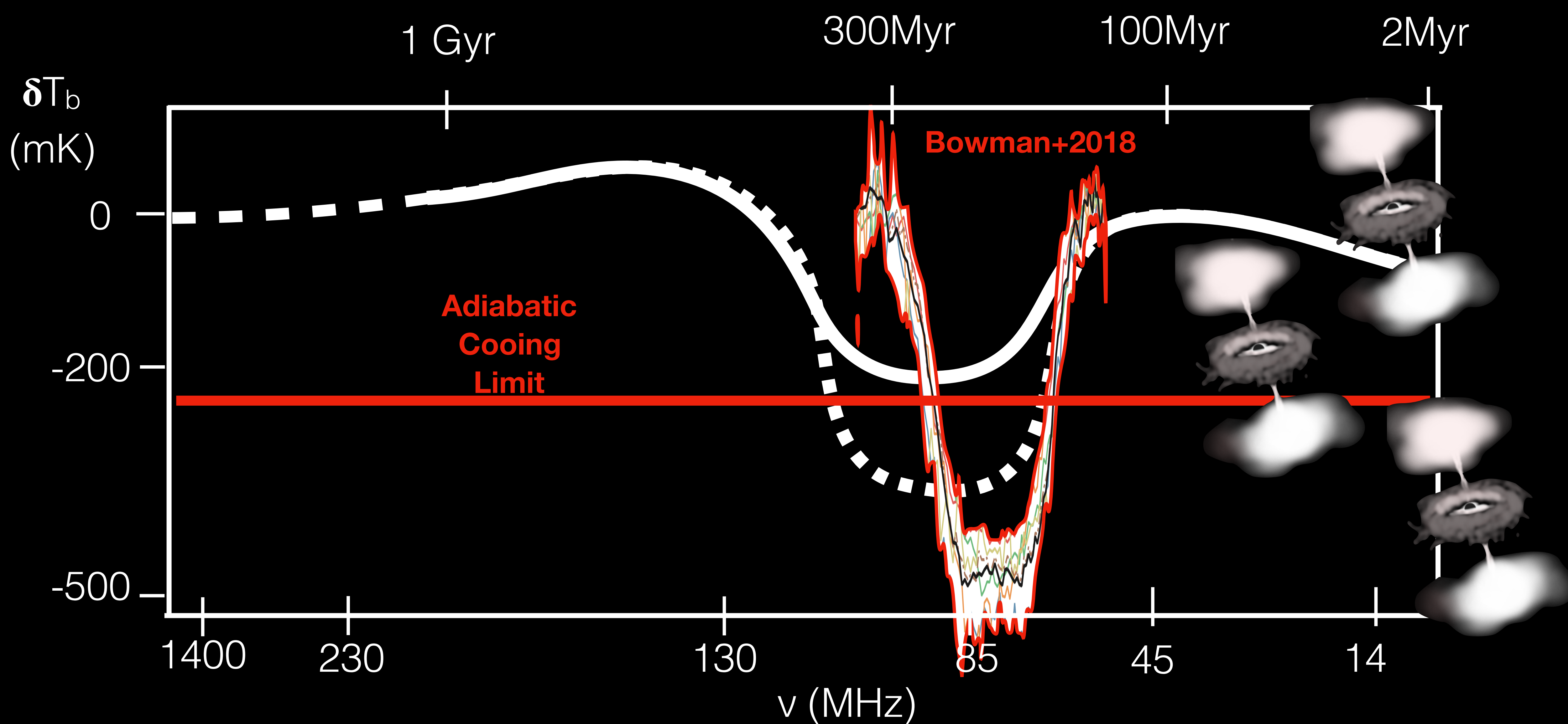


Dark Matter is one substance cold enough to do this!

Barkana+2018
Flalkov+2018
Munoz+2018

Option 2: Raise T_{CMB}!

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

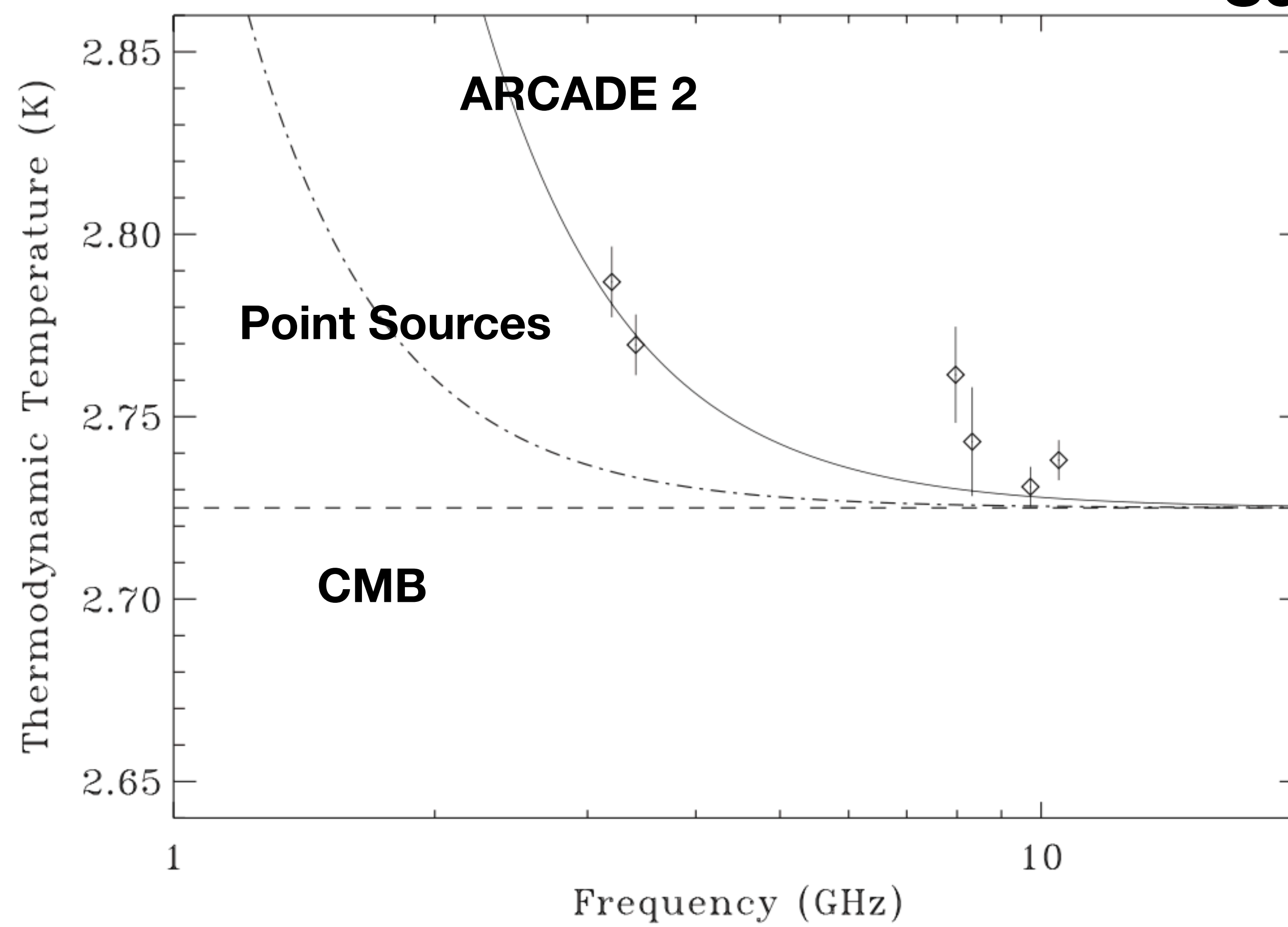


Requires new radio sources at high redshift!

(Feng+2018, AEW+2018/2019, Mirabel+2018, Fraser+2018,Fialkov+2019)

Some Evidence for new radio sources already existed.

Seiffert 2011



Excess radio background claimed by ARCADE-2

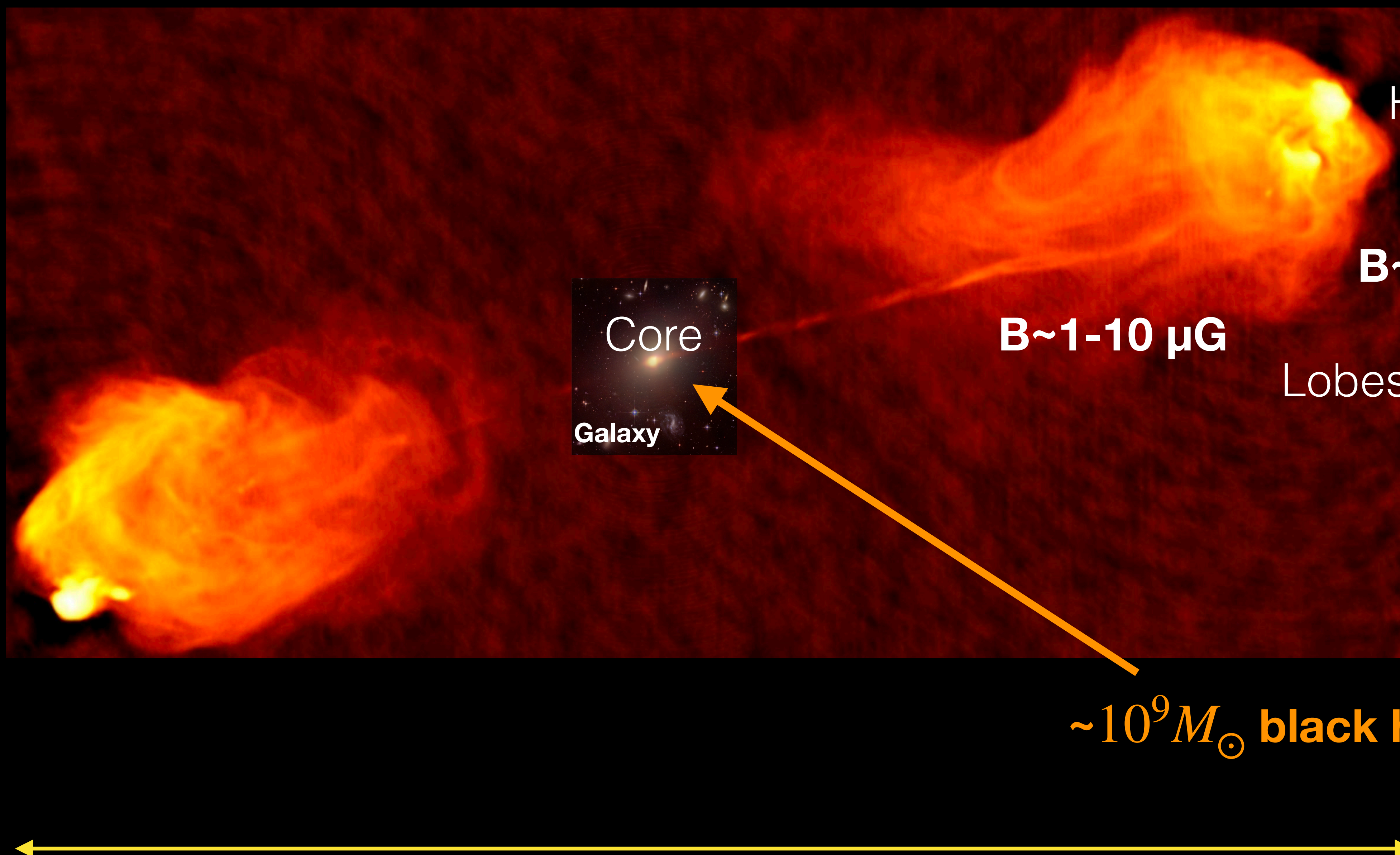
Some Potential Sources of Radio Emission at z>17.

- Star forming galaxies. **(Mirocha+2018)**
- Annihilation of a μeV dark matter particle. **(Fraser+2018)**
- Active Galactic Nuclei: Black Holes.

(AEW+ 2018 / 2019)

At z~1 radio galaxies produce ~10% of the CMB at ~GHz

Cygnus A



Differences

1. Any Black holes at $z \sim 17$ would have to be far less massive.

2. Such black holes would have to be heavily obscured

   A. To prevent heating from erasing feature.

   B. To prevent Early Reionization ($z \sim 16$).

3. Magnetic Fields must be substantially larger then low-z AGN.

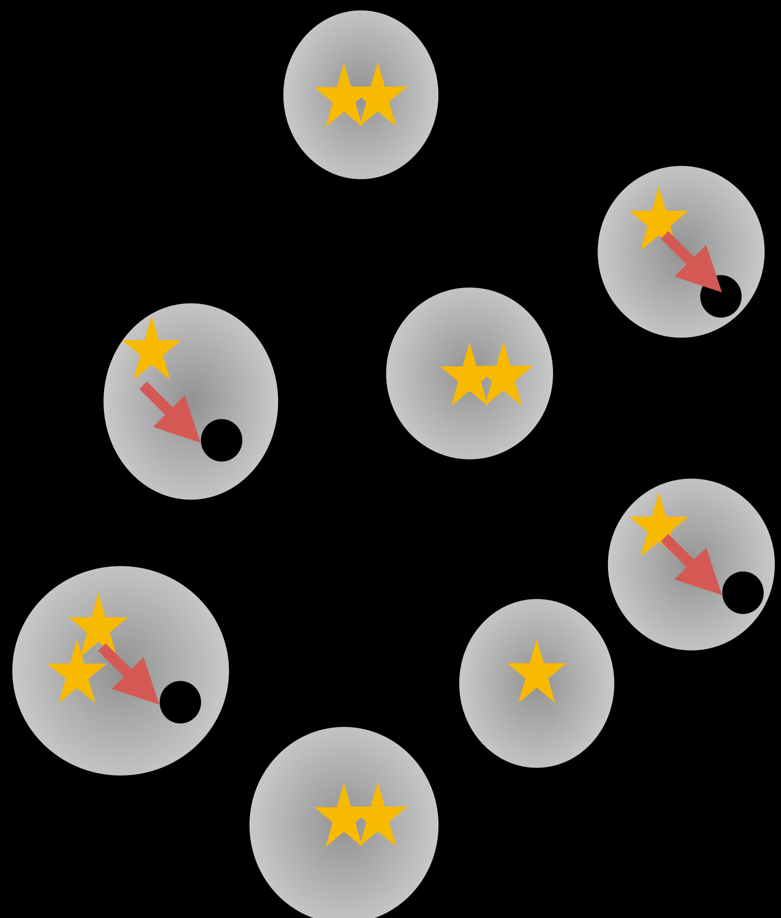
We consider several scenarios explain the ~billon solar mass quasars at z~7

Artist impression of ULAS J1120+0641

ESO/Kornmesser

How did super-massive black holes (observed at z=7) form?

Three Potential Scenarios:



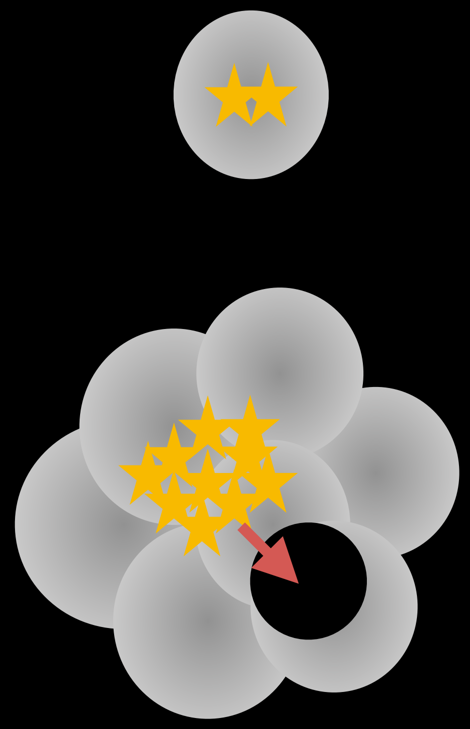
1. Remnants of Population III Stars

(A) Form in ~10^5-10^7 $M_\odot$ halos

(B) Seed mass of ~10-1000 $M_\odot$

How did super-massive black holes (observed at z=7) form?

Three Potential Scenarios:



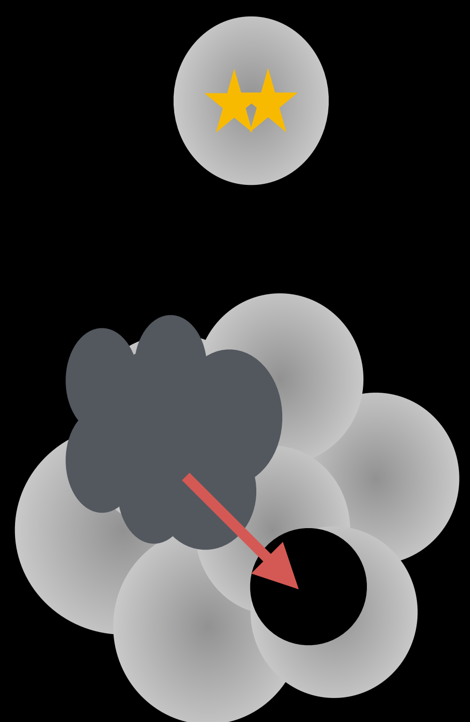
1. Remnants of Population III Stars
2. Cluster Collapse

(A) Form in $\sim 10^8 \, M_\odot$ halos

(B) Seed mass of $\sim 1000 \, M_\odot$

How did super-massive black holes (observed at z=7) form?

Three Potential Scenarios:



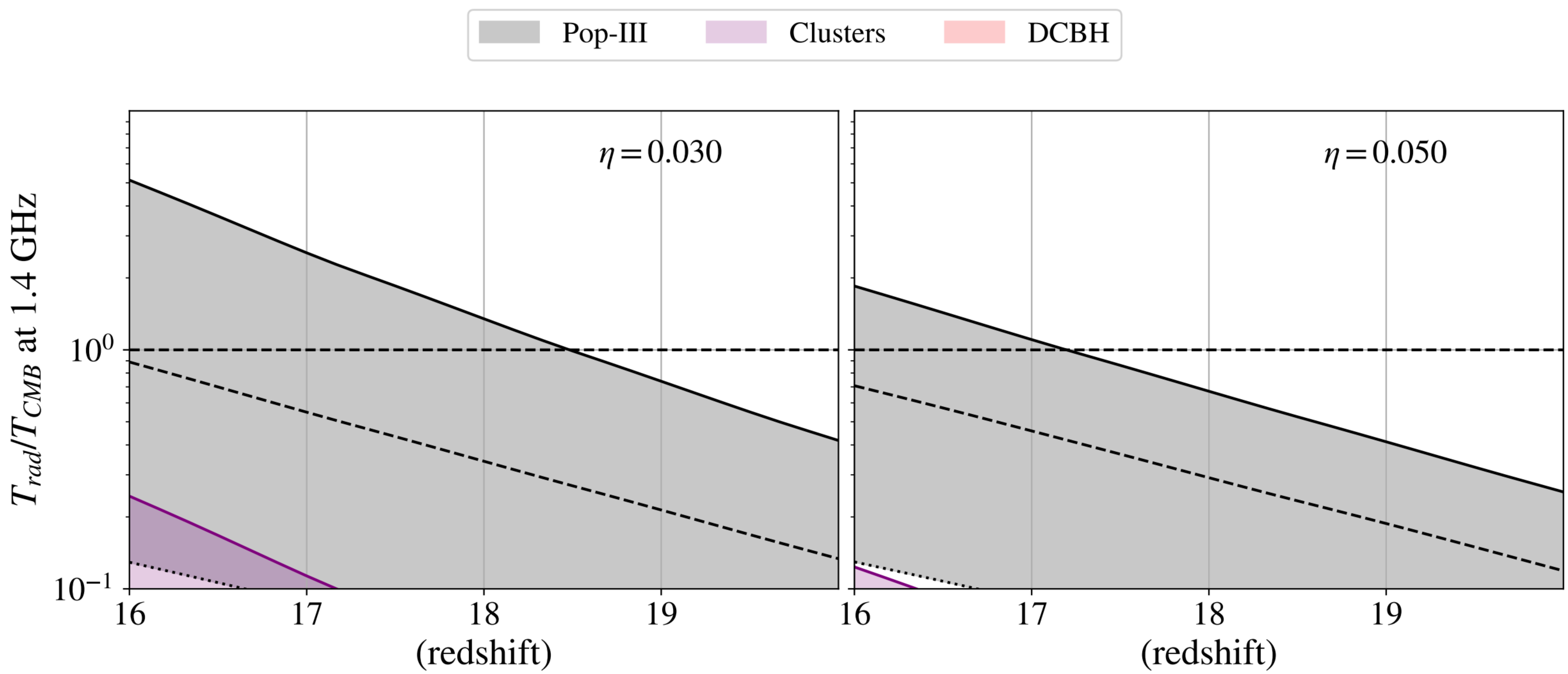
1. Remnants of Population III Stars
2. Cluster Collapse
3. Direct Collapse Black Hole

(A) Form in $\sim 10^8$ $M_\odot$ halos

(B) Seed mass of $\sim 10^5$ $M_\odot$

(C) Most models require pristine "massive" halos with UV background

Can we get enough radio emission?
Yes!



10% radio loud

Radio loudness of ~1000

AEW+ 2018

Differences

1. Any Black holes at $z \sim 17$ would have to be far less massive.

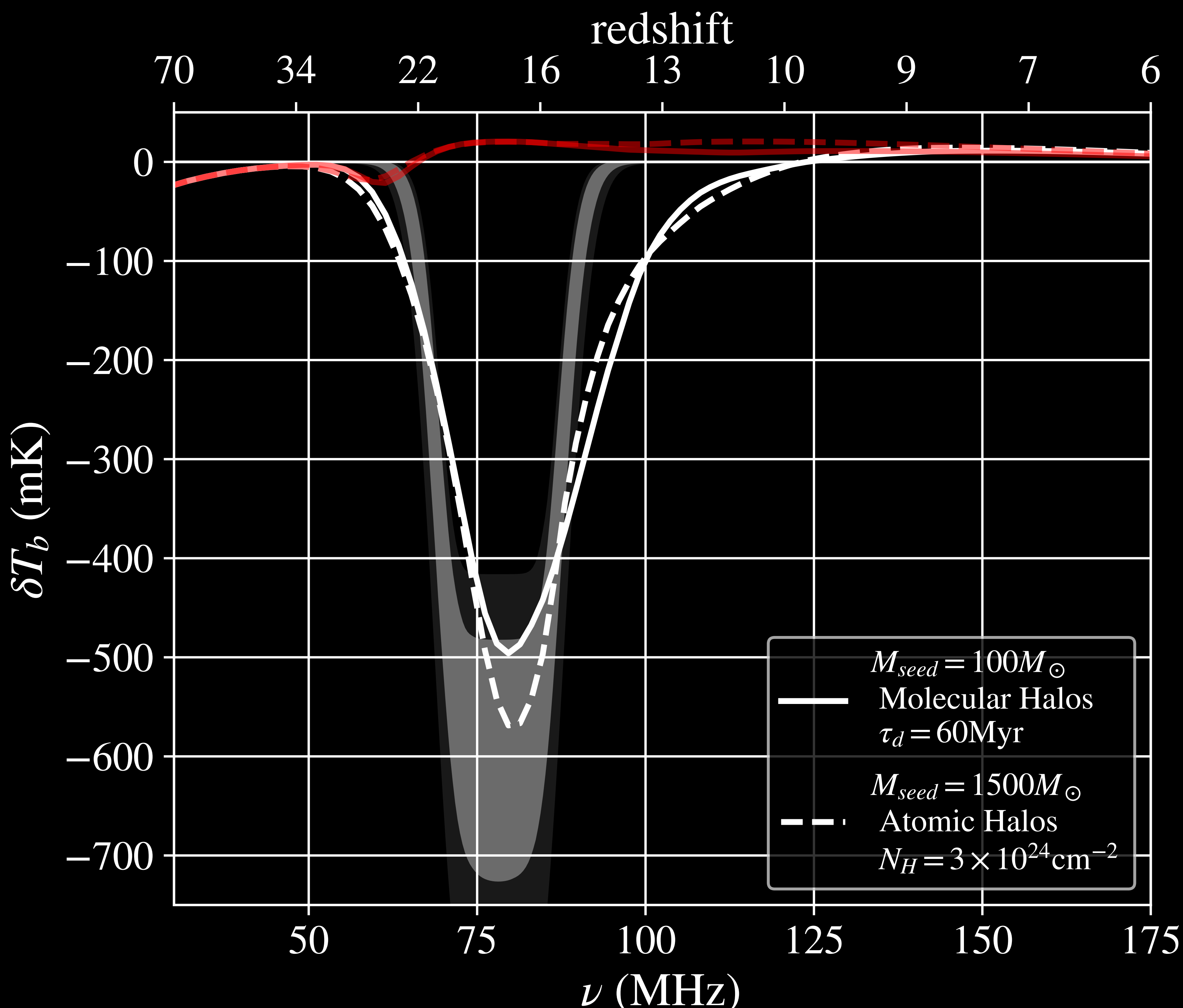
2. Such black holes would have to be heavily obscured (Compton Thick)

   A. To prevent heating from erasing feature.

   B. To prevent Early Reionization ($z \sim 16$).

3. Magnetic Fields must be substantially larger then low-z AGN.

Self Consistent Obscured Models Reproduce EDGEs.



Unobscured.

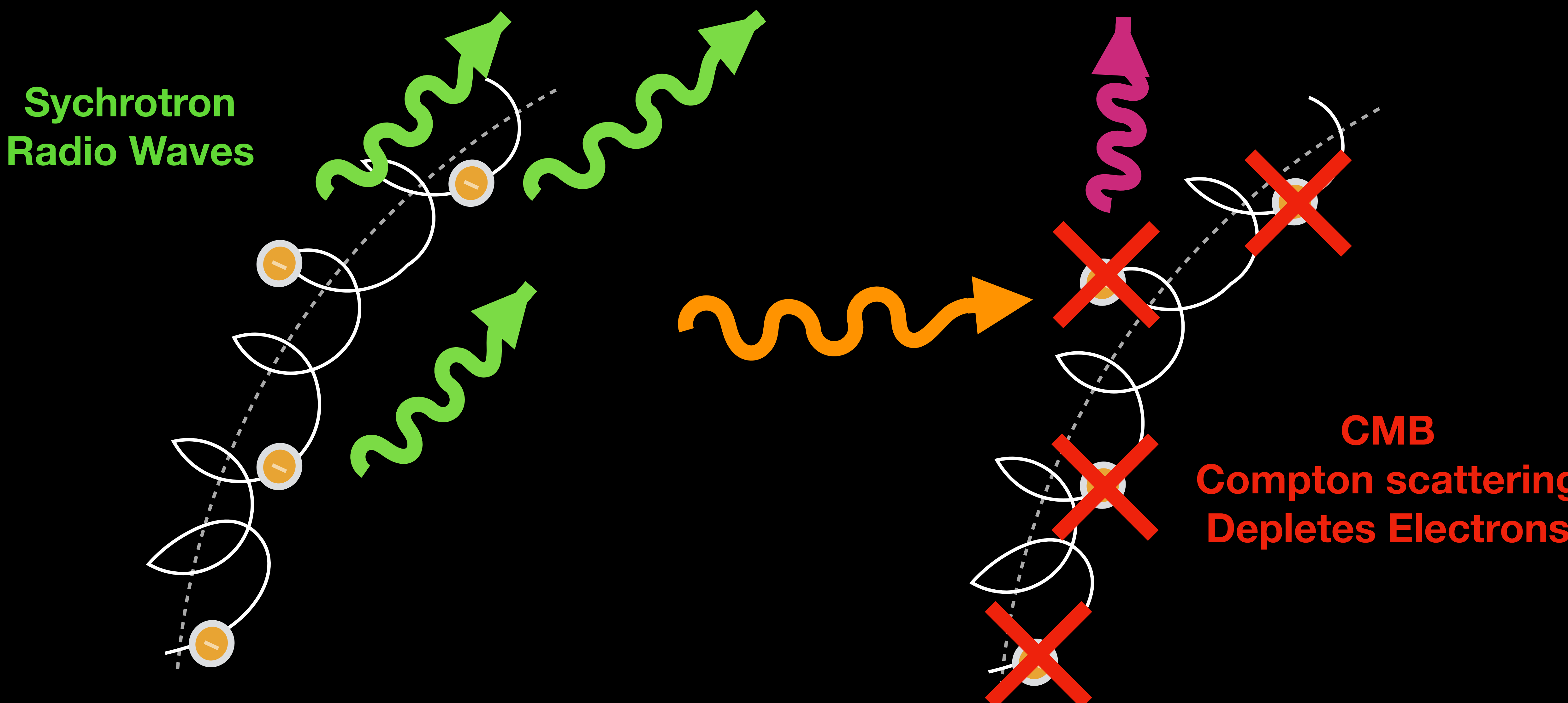
EDGES typically Requires 10 Myr Salpeter Times

AEW+2019

Differences

1. Any Black holes at $z \sim 17$ would have to be far less massive.
2. Such black holes would have to be heavily obscured
   - A. To prevent heating from erasing feature.
   - B. To prevent Early Reionization ($z \sim 16$).
3. Magnetic Fields must be substantially larger then low-z AGN.

Large B-fields (> mG) required To prevent Inverse Compton Losses.

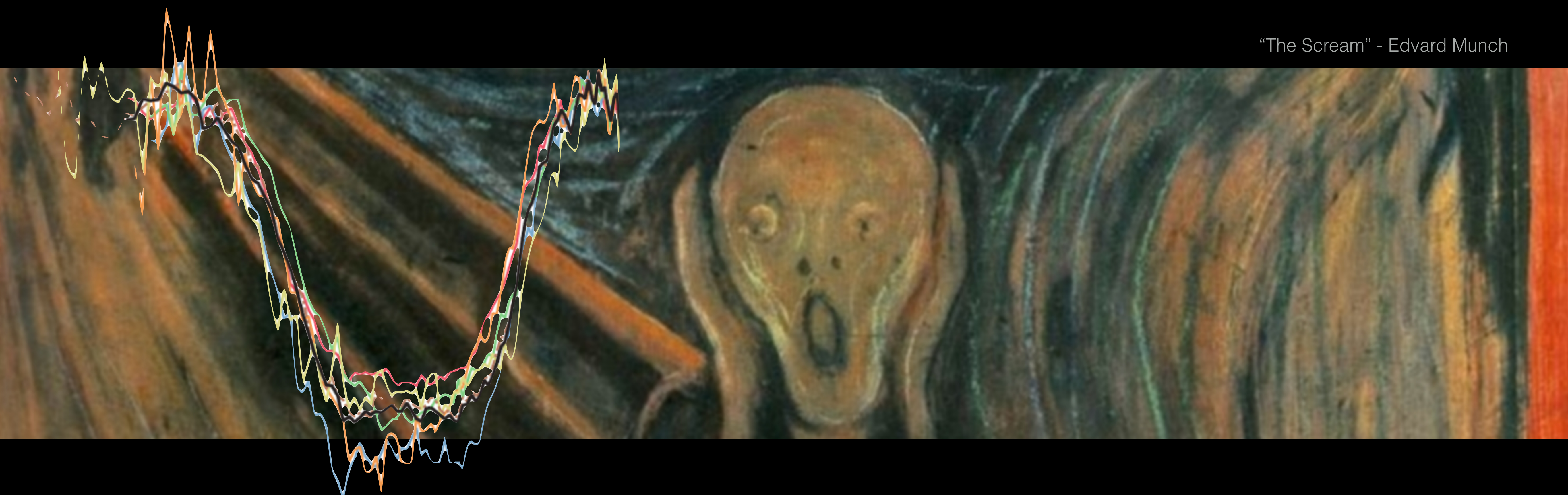


B-field energy density
> CMB

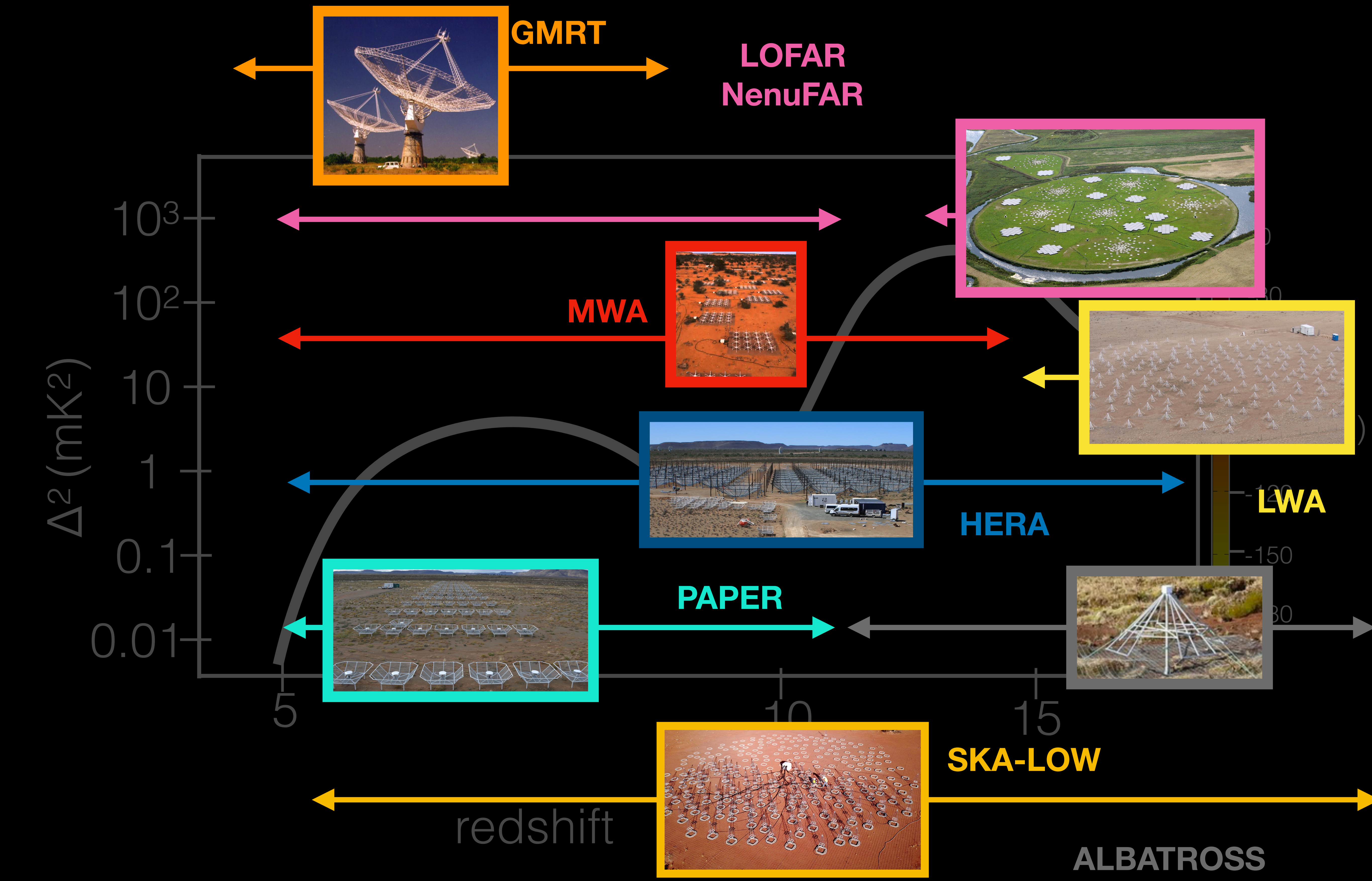
B-field energy density
< CMB

Sharma+
2018

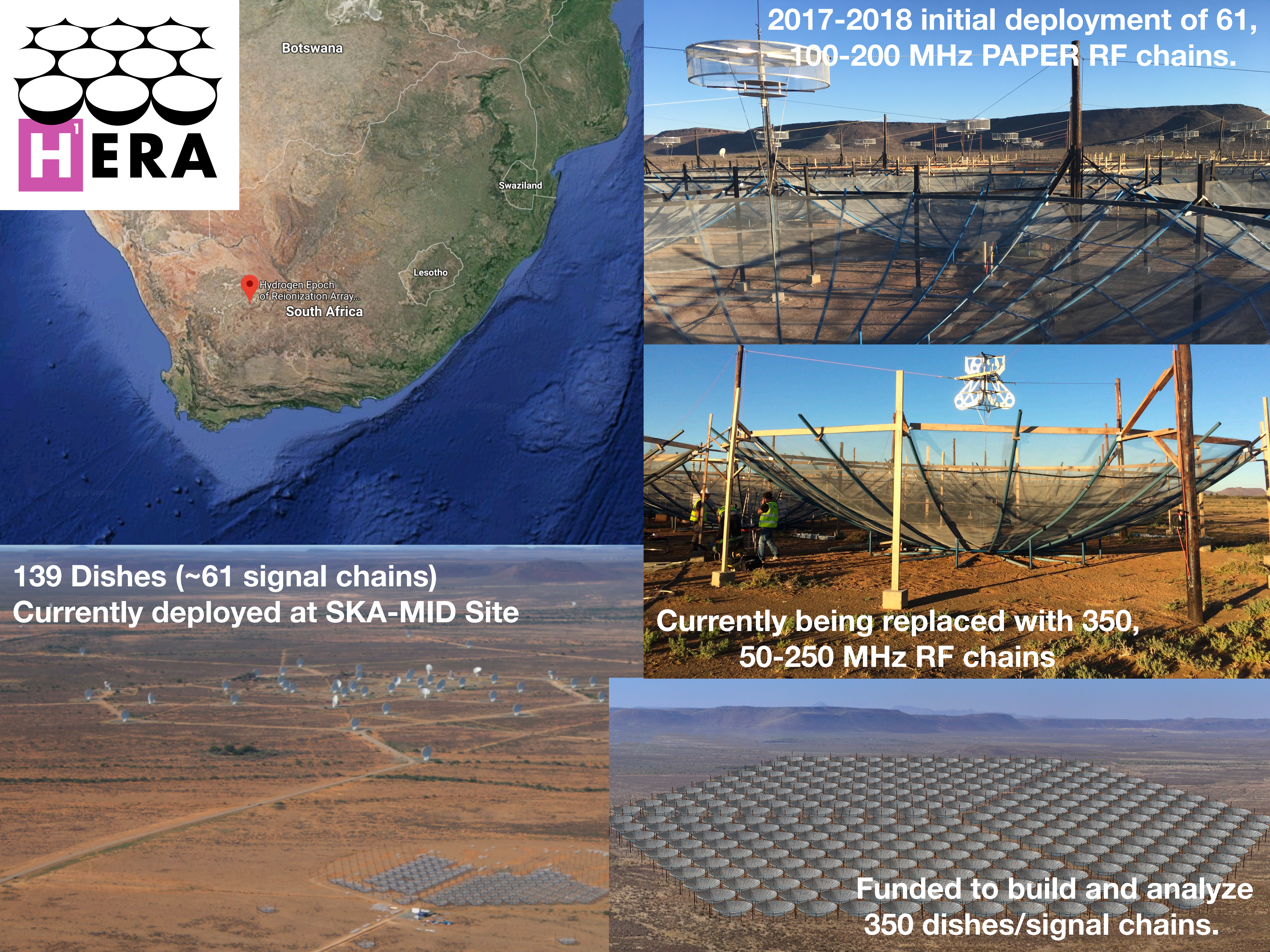
Black holes may be a ~plausible explanation of EDGEs

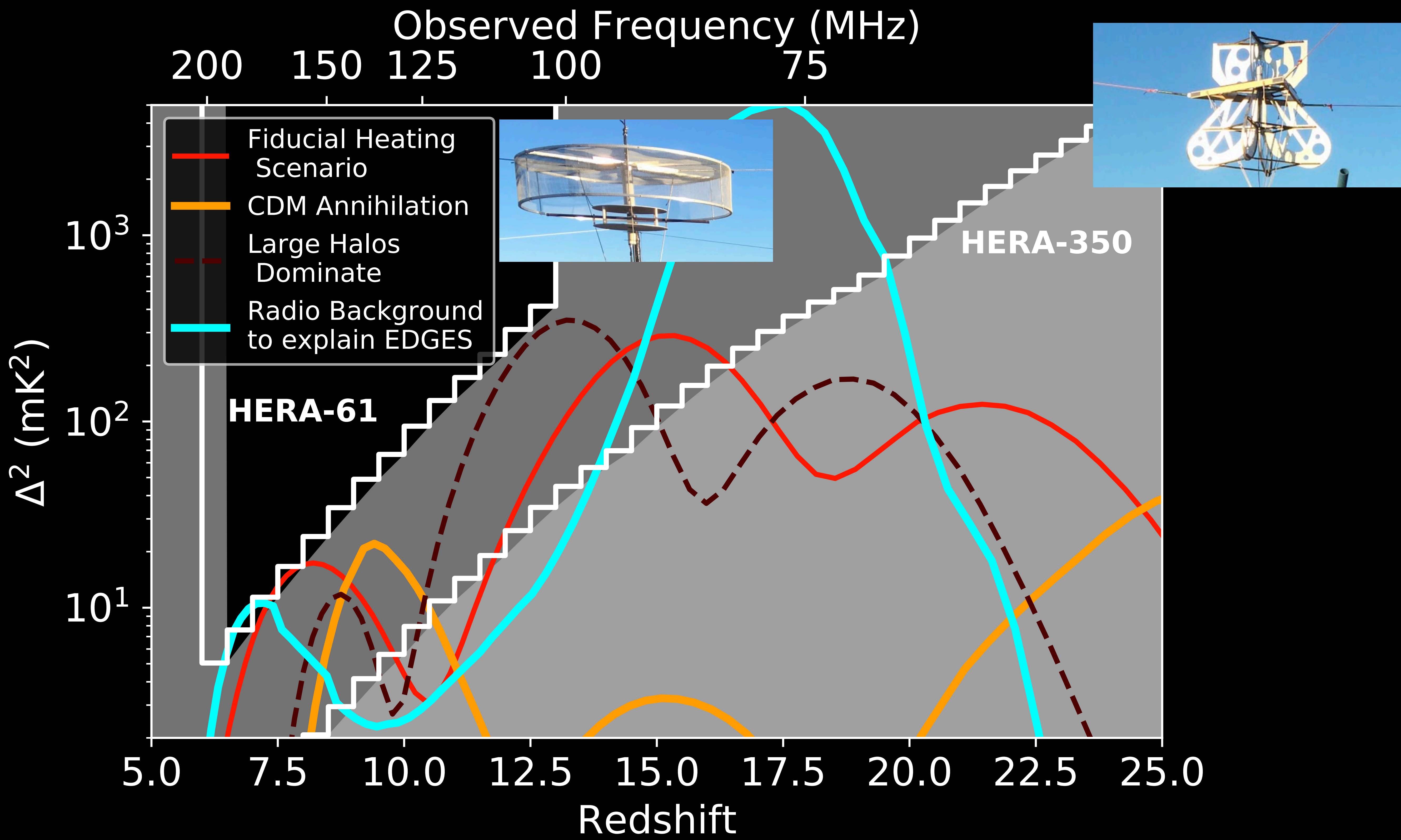


But eliminating the systematics explanation requires validation with independent measurements

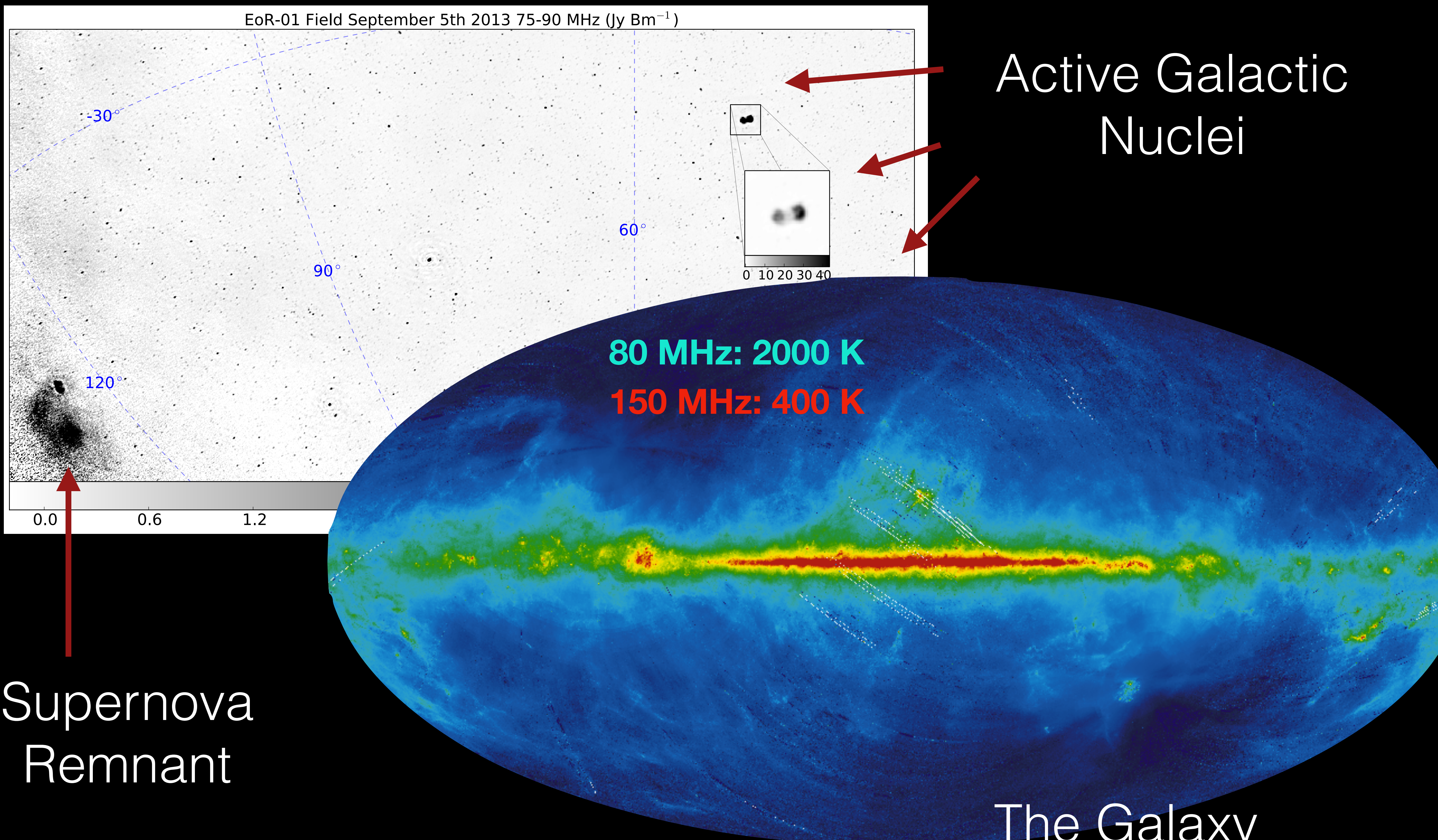


Fluctuation Experiments — Targeting the Cosmic Dawn


HERA
Botswana
Swaziland
Lesotho
Hydrogen Epoch of Reionization Array...
South Africa
2017-2018 initial deployment of 61, 100-200 MHz PAPER RF chains.
Currently being replaced with 350, 50-250 MHz RF chains
139 Dishes (~61 signal chains) Currently deployed at SKA-MID Site
Funded to build and analyze 350 dishes/signal chains.


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

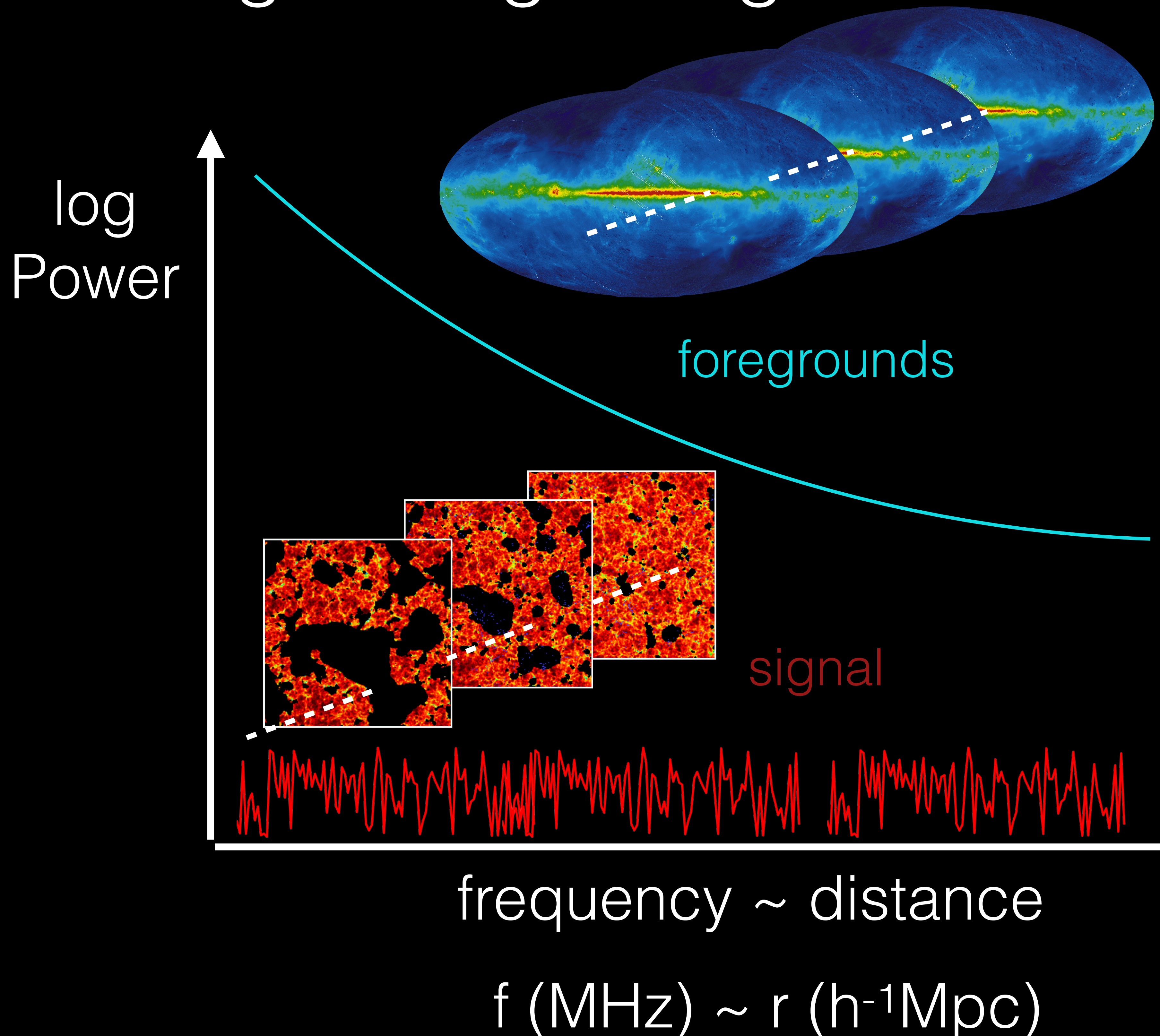
Radio Foregrounds: ~**10⁴x** the signal level!



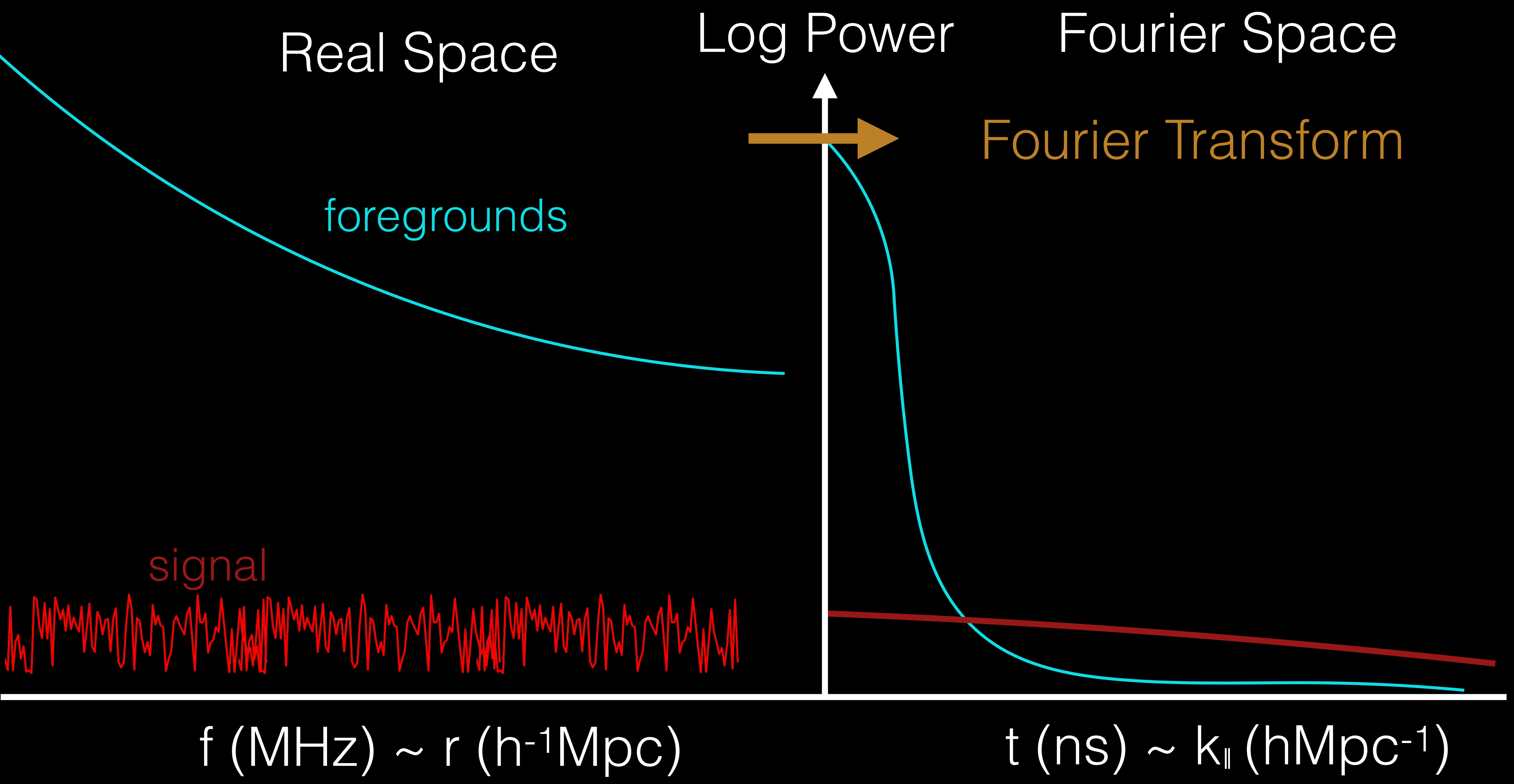
Active Galactic Nuclei

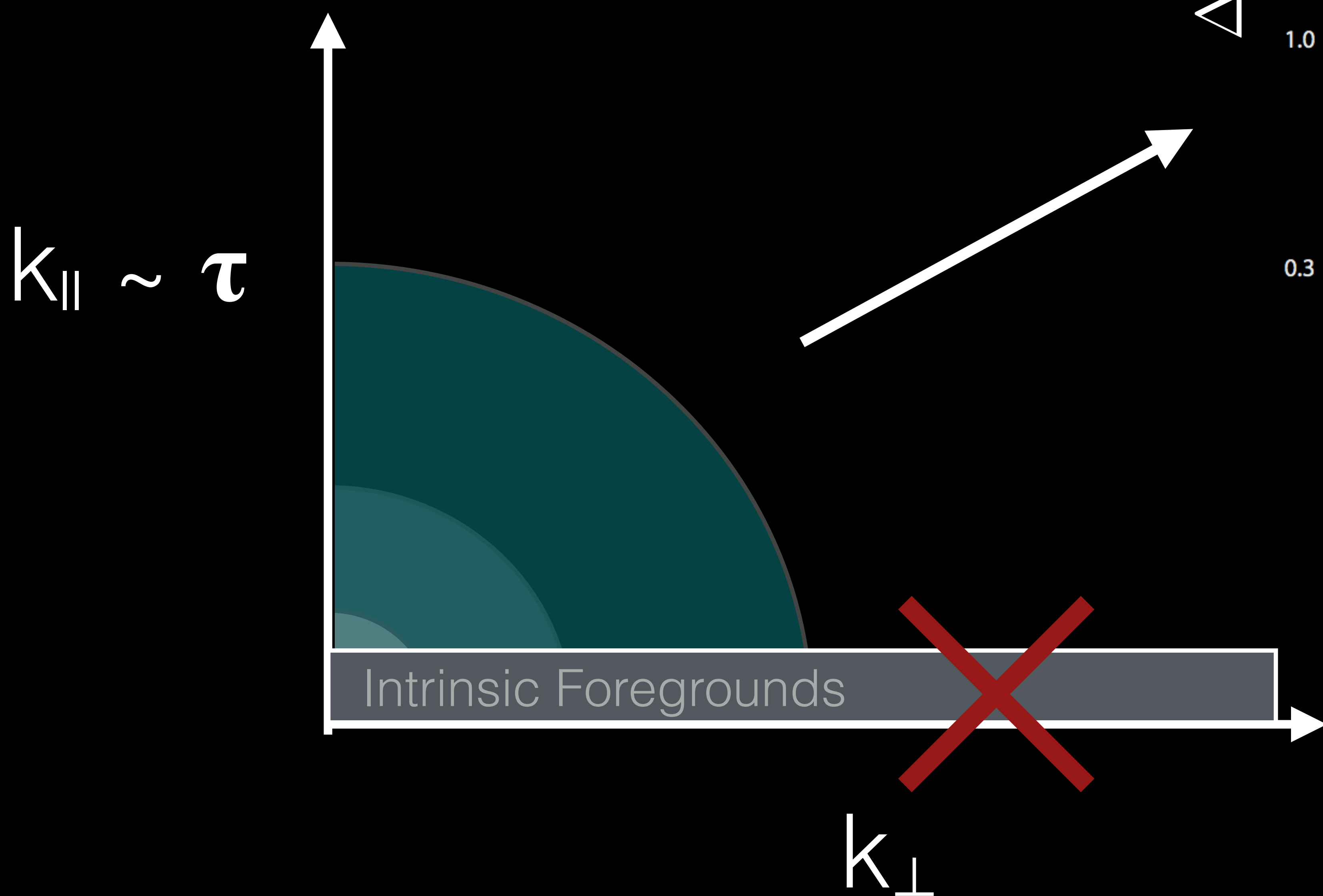
Supernova Remnant

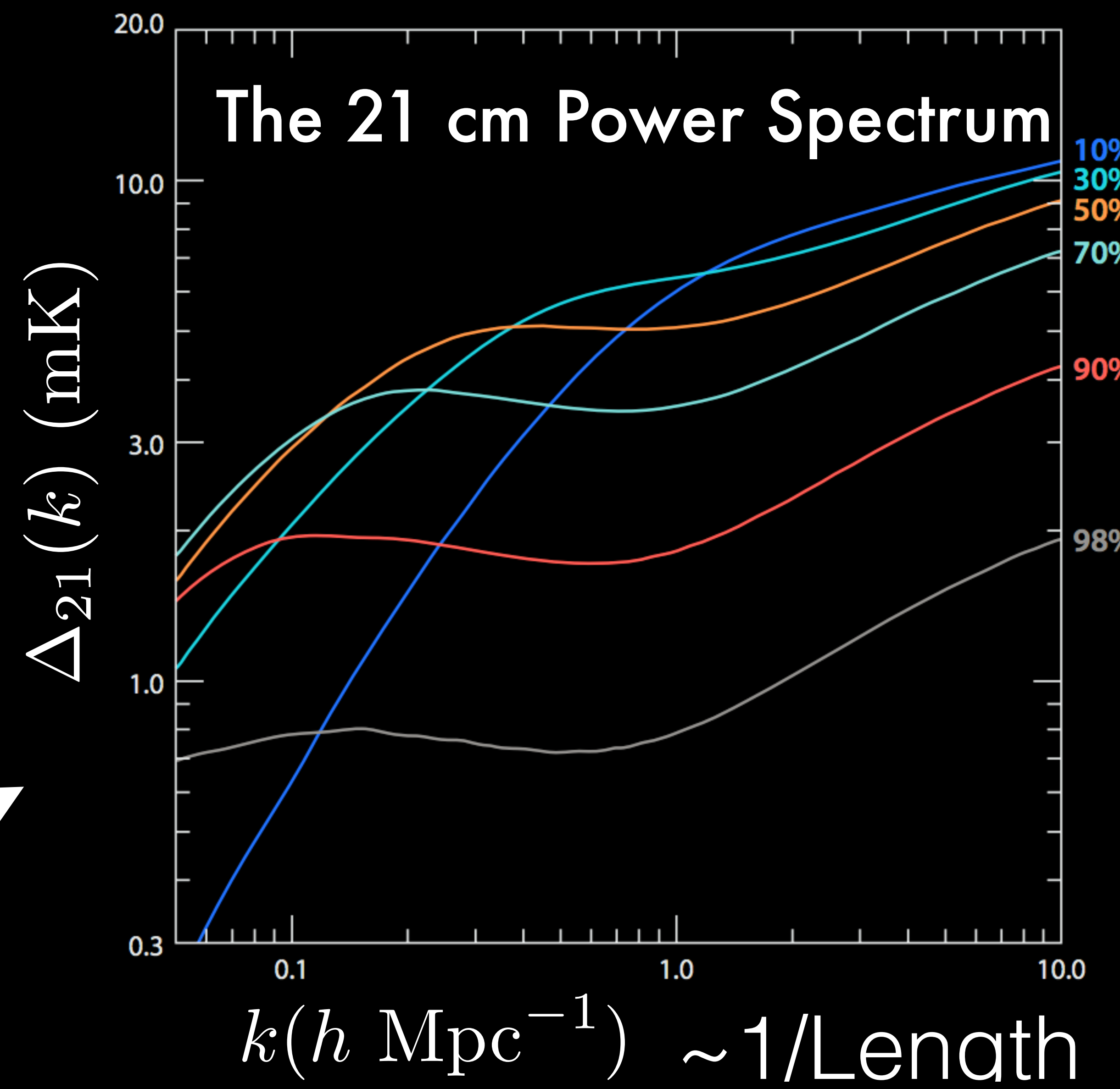
Distinguishing Foregrounds from Signal



Fluctuations can be isolated using the Fourier transform.

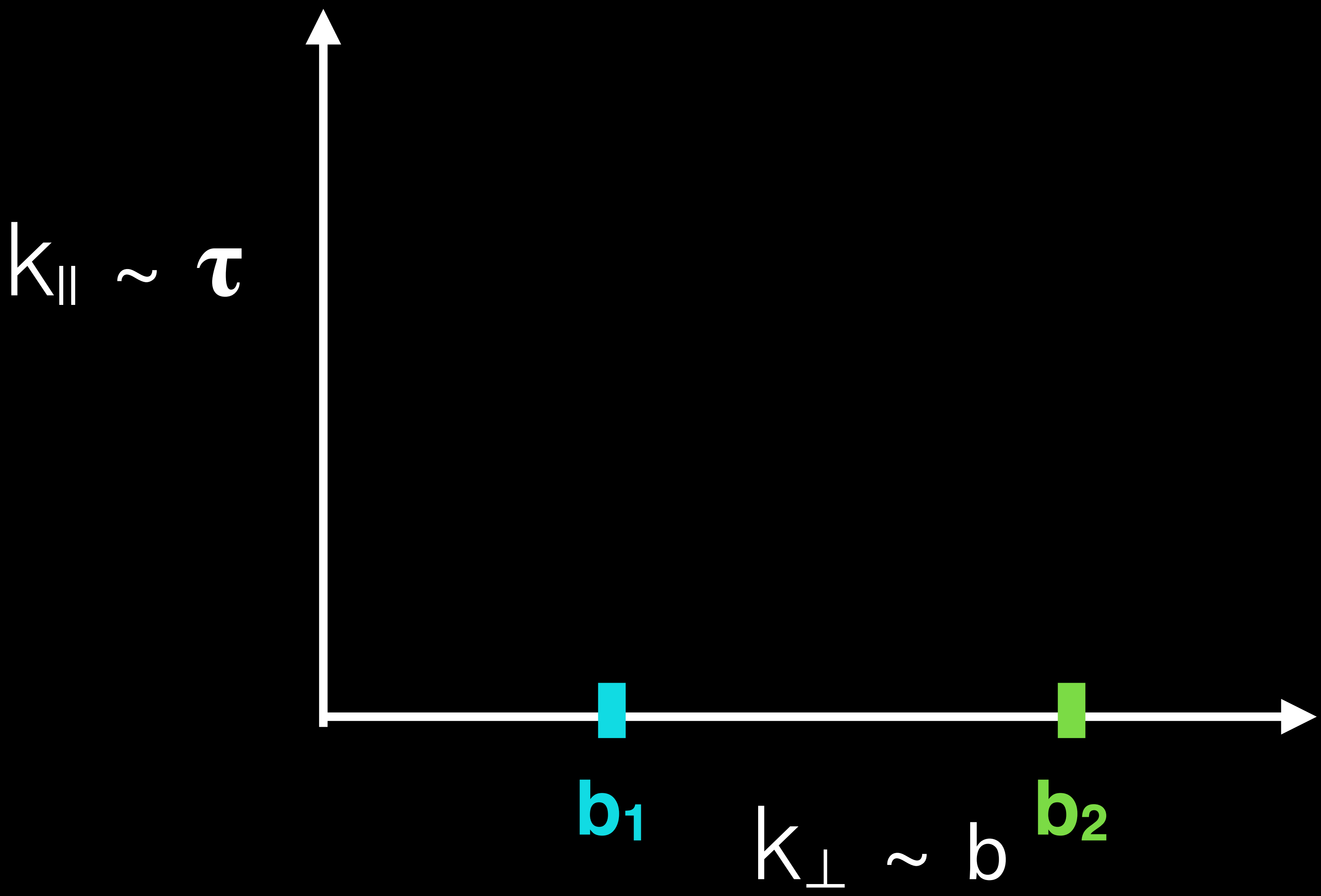


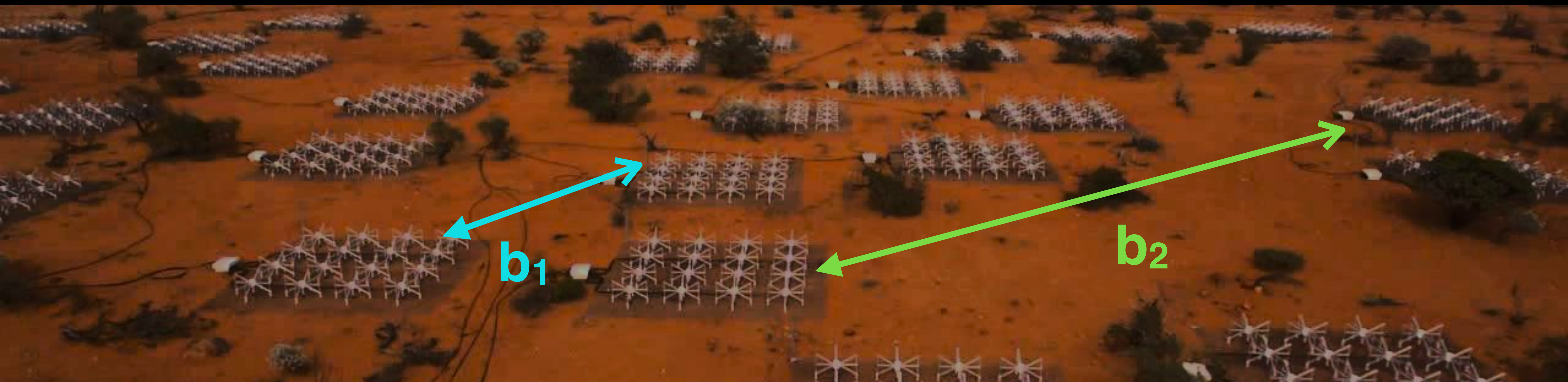


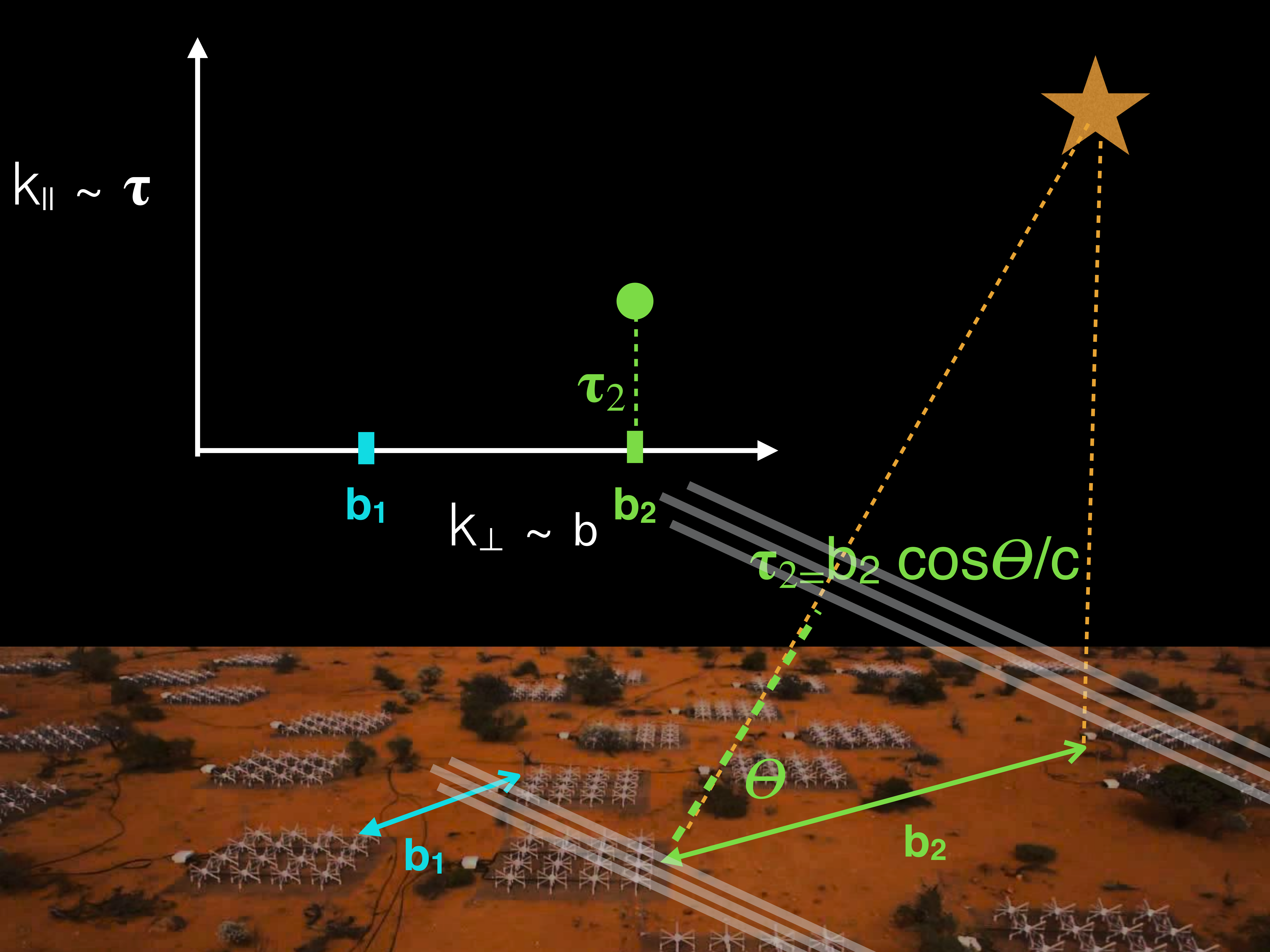


$$k^2 = k_{\parallel}^2 + k_{\perp}^2$$

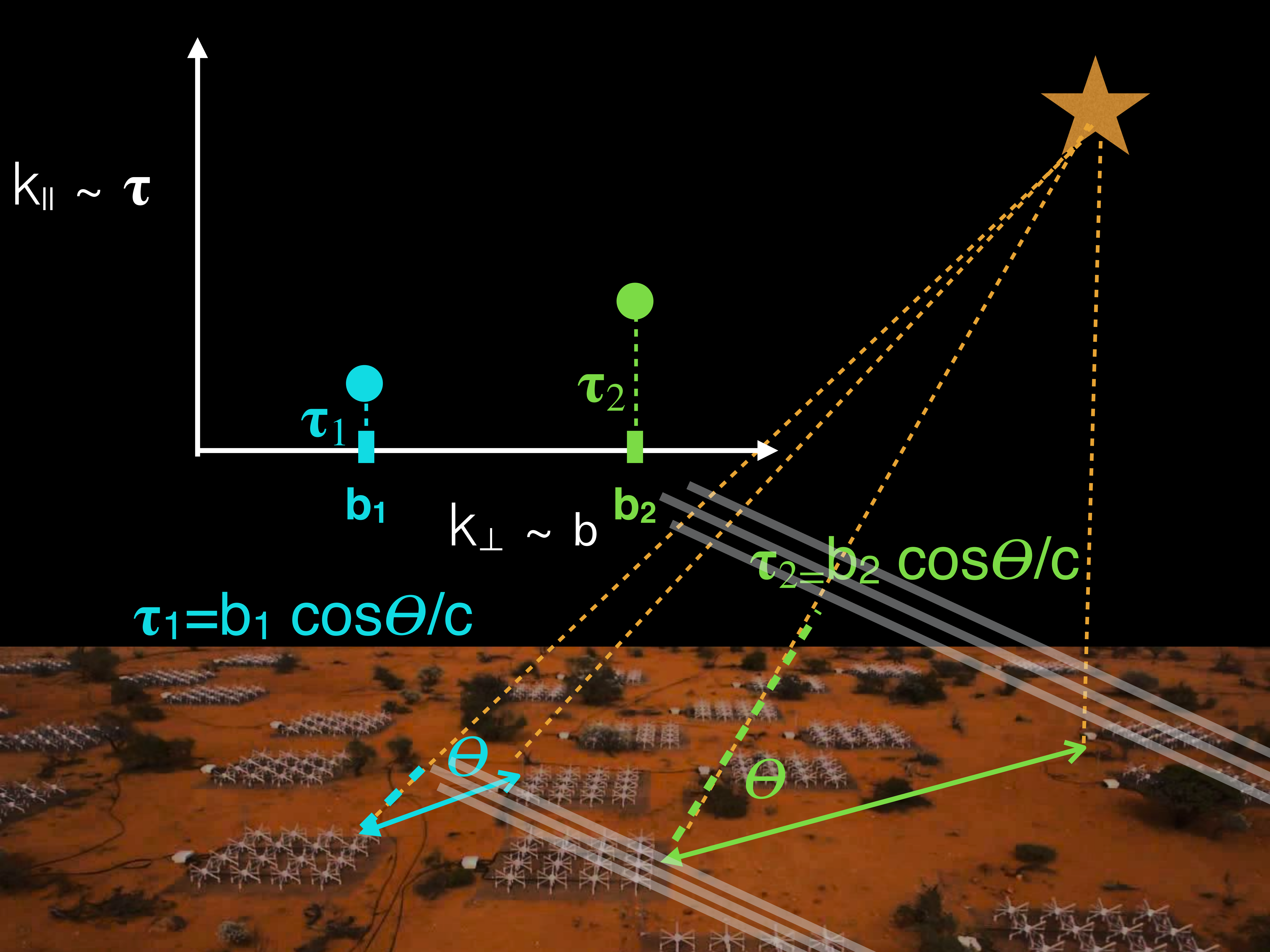
Intrinsic Foregrounds

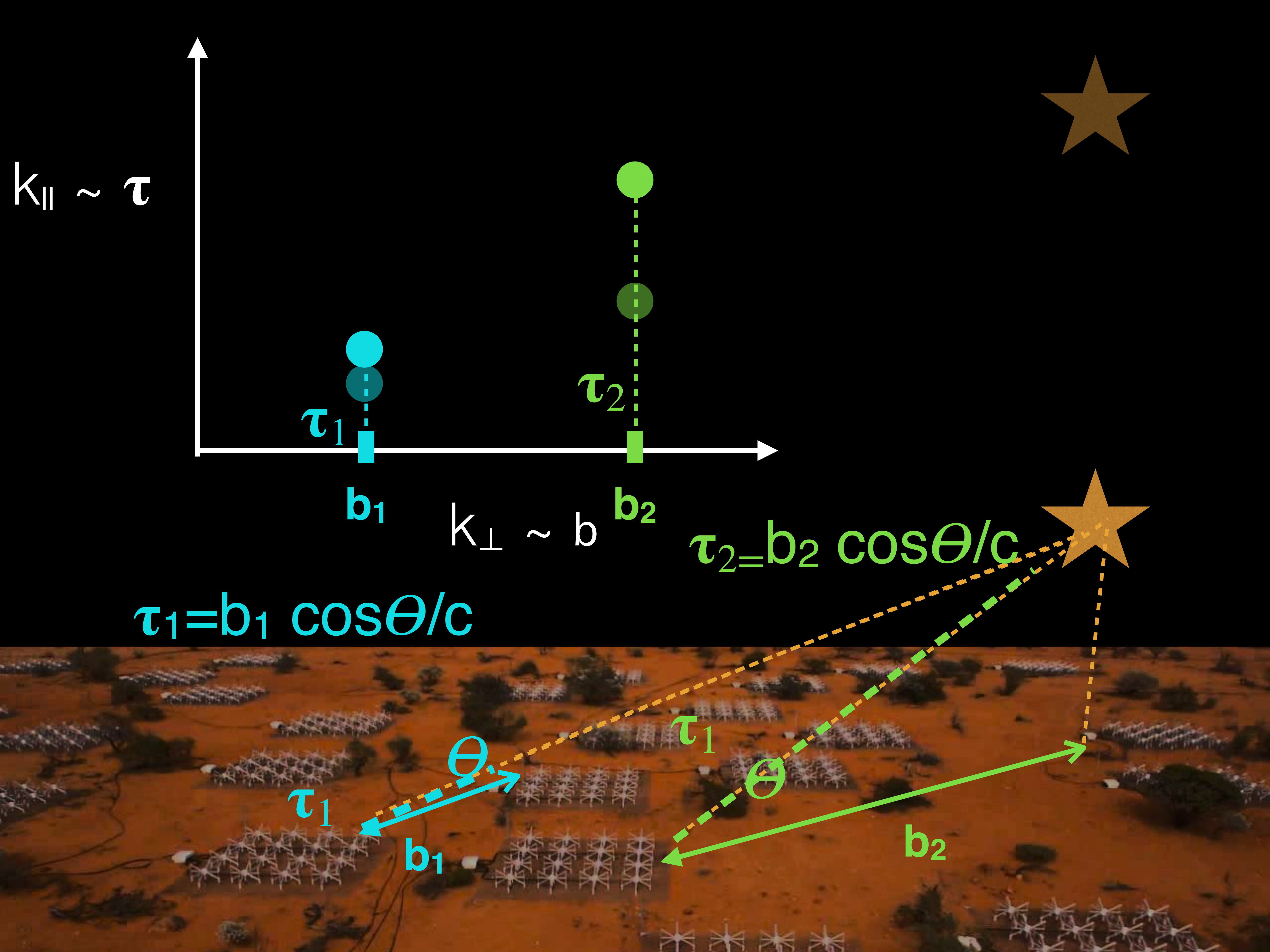

k|| ~ τ
b1
k⊥ ~ b
b2

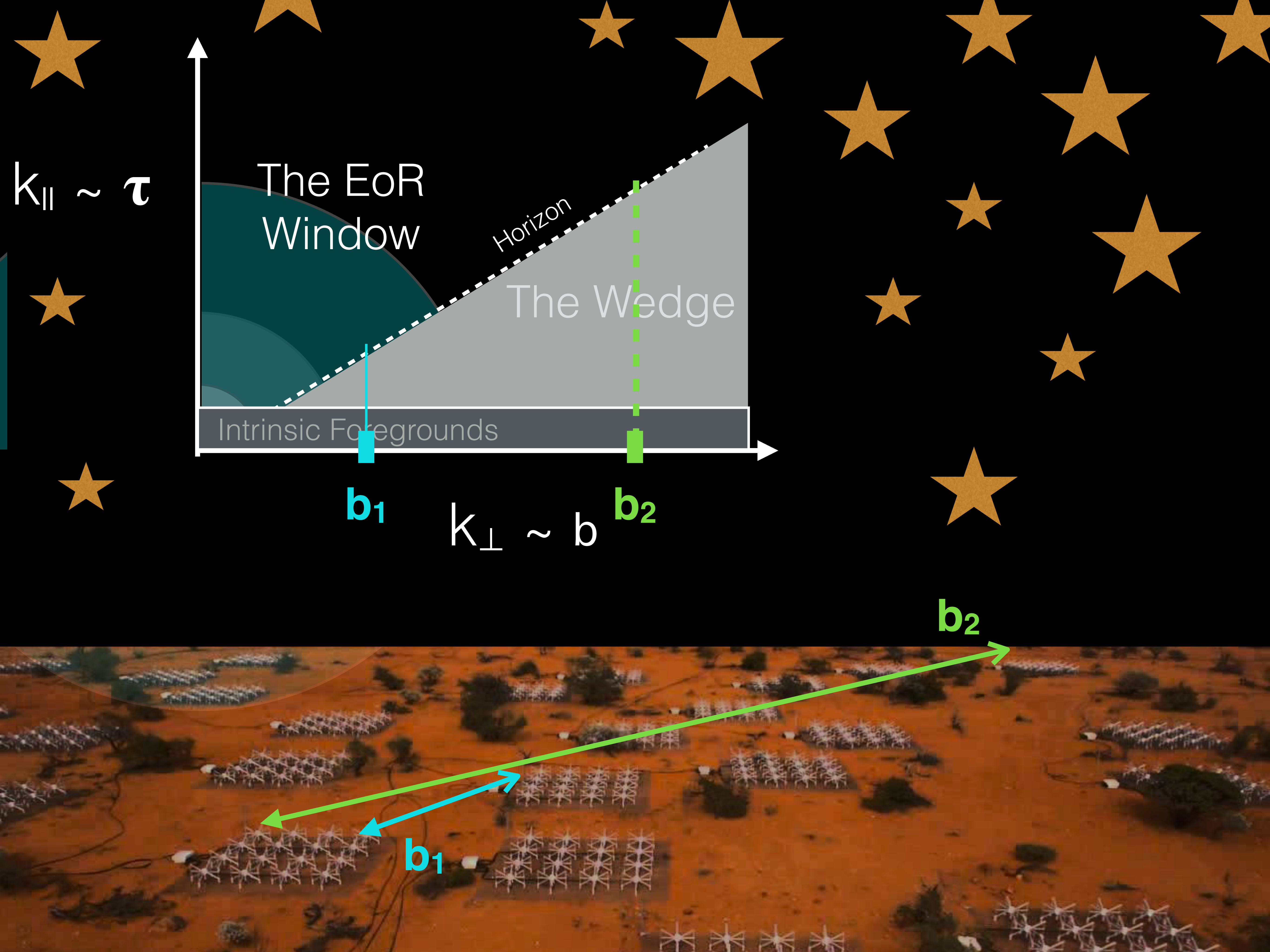

b1
b2



k|| ~ τ
τ2
b1
k⊥ ~ b
b2
τ2=b2 cosθ/c
θ
b1
b2


$k_{\parallel} \sim \tau$
τ_1
τ_2
b_1
b_2
$k_{\perp} \sim b$
$\tau_2 = b_2 \cos\theta / c$
$\tau_1 = b_1 \cos\theta / c$
θ
θ

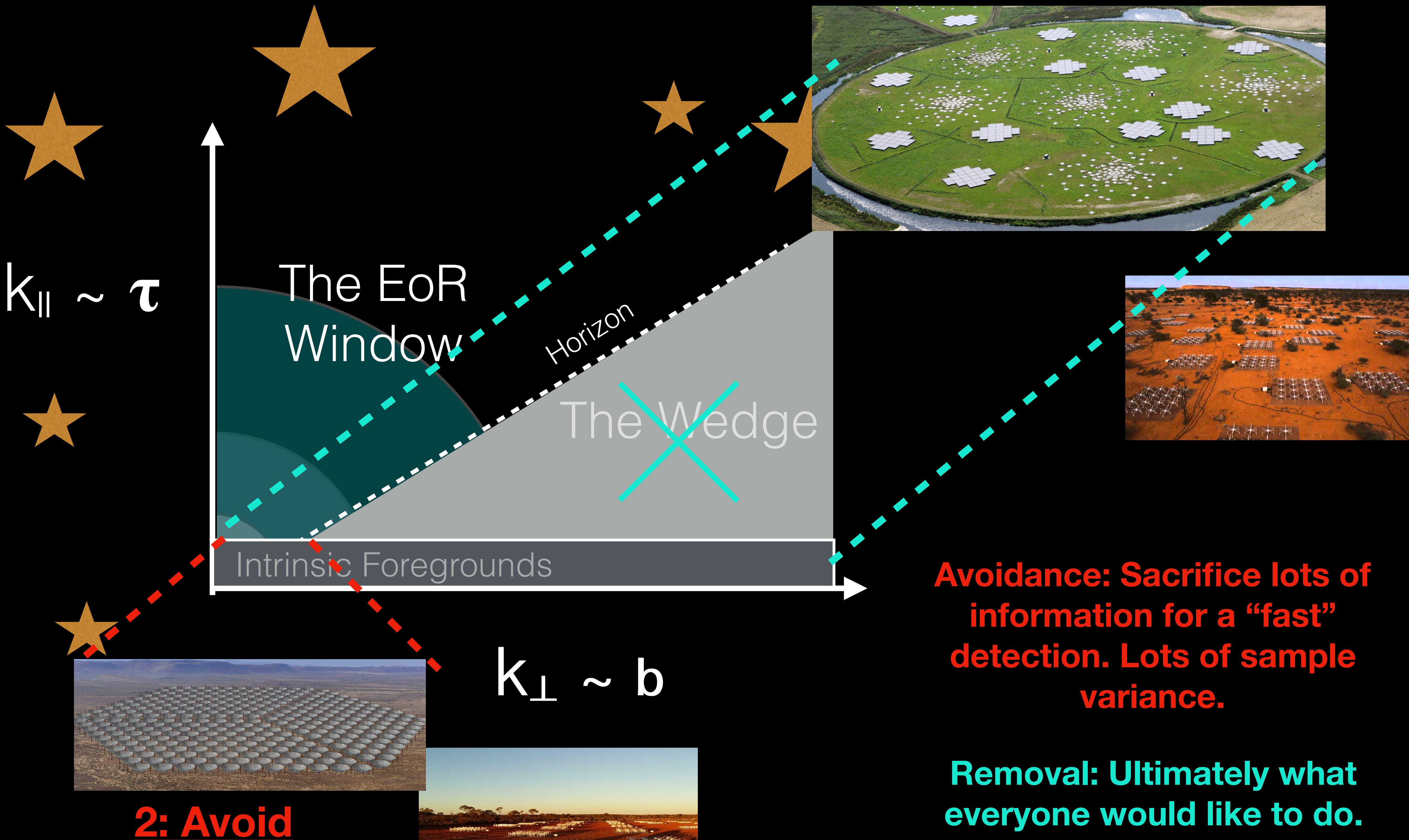

k∥ ~ τ
τ1
τ2
b1
k⊥ ~ b
b2
τ2=b2 cosθ/c
τ1=b1 cosθ/c
τ1
θ
θ
τ1
b1
b2



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

The Wedge motivates two strategies

1: Remove

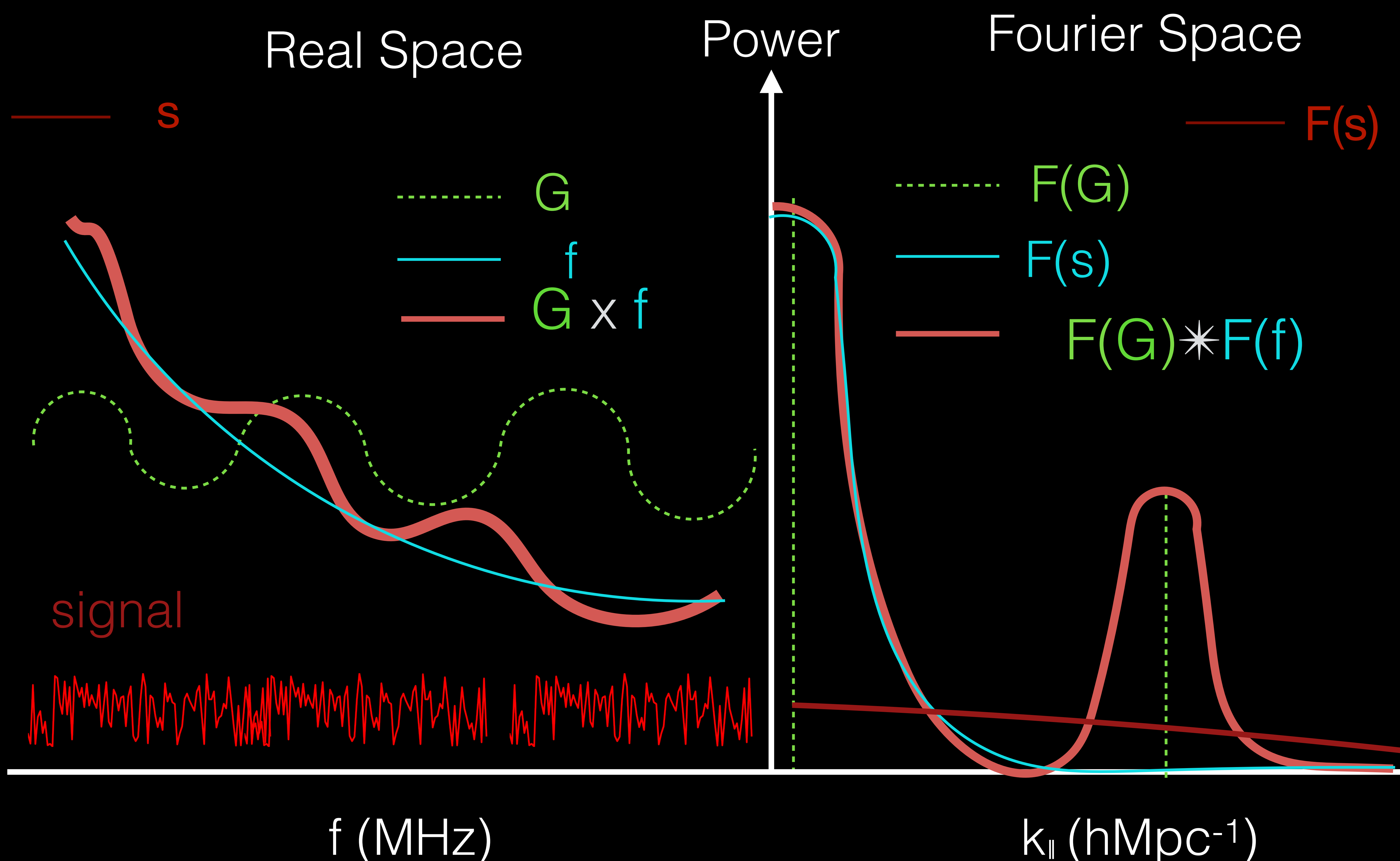


2: Avoid

Avoidance: Sacrifice lots of information for a "fast" detection. Lots of sample variance.

Removal: Ultimately what everyone would like to do.

Foregrounds stay in the wedge only when each antenna has No spectral structure.


Real Space
Power
Fourier Space
s
F(s)
G
F(G)
f
F(s)
G x f
F(G)✳F(f)
signal
f (MHz)
k∥ (hMpc-1)

Spectrally Smooth*

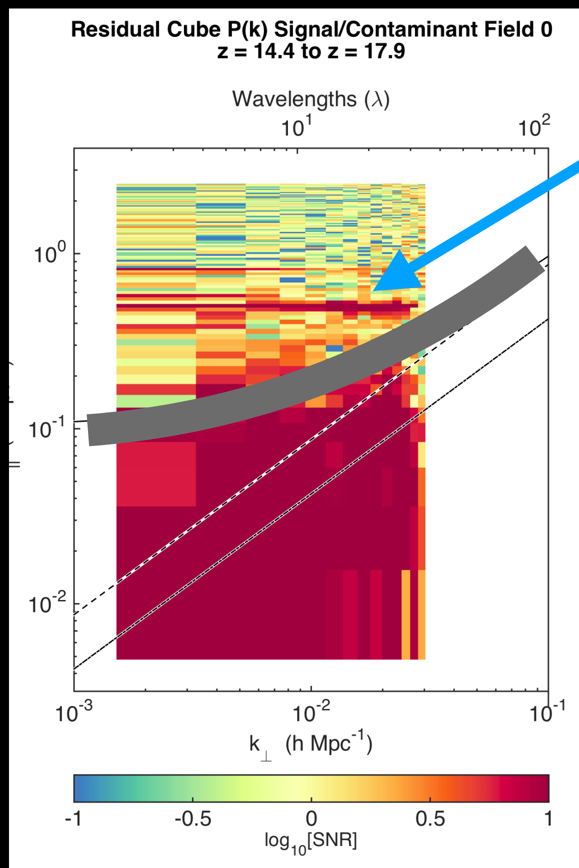
^

“All you need is paperclips and a supercomputer”

-Don Backer

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

Example: Coaxial Cables

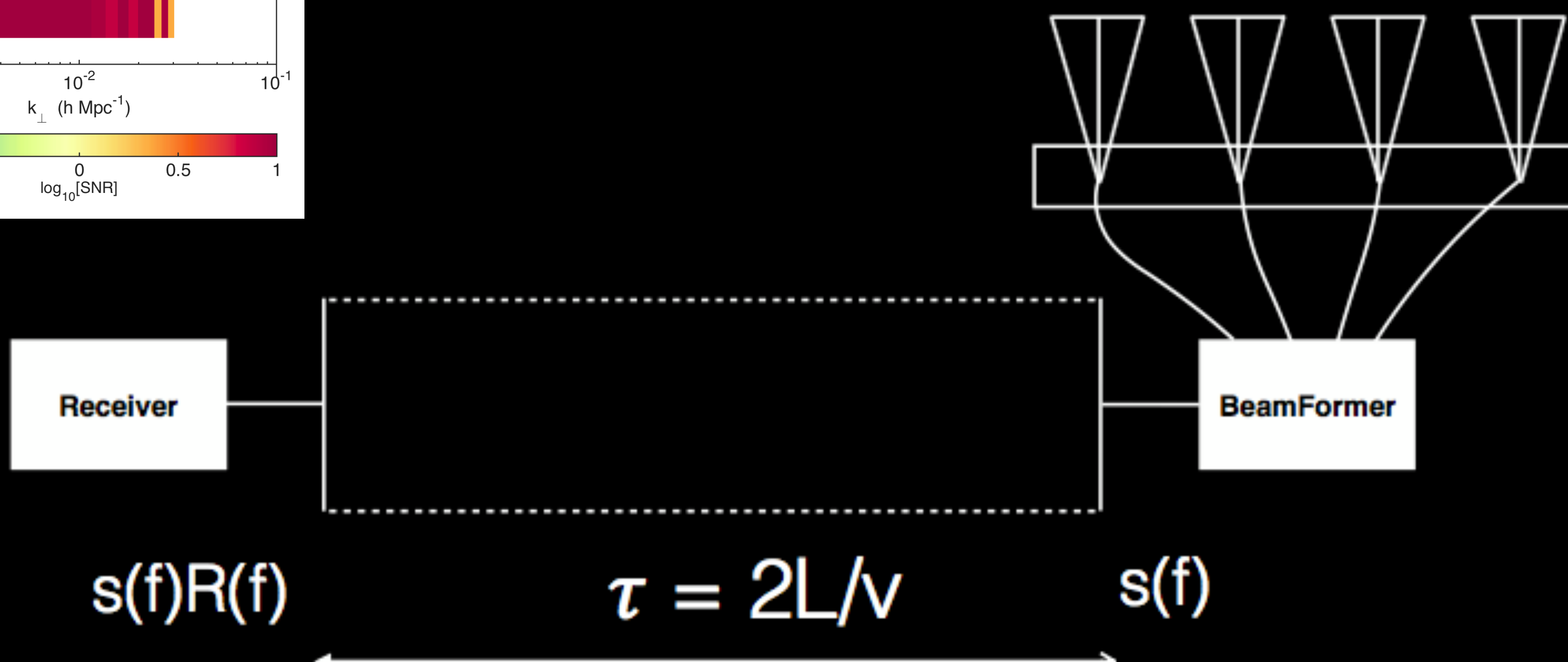


Stripe

At the $\tau = 2L/v$

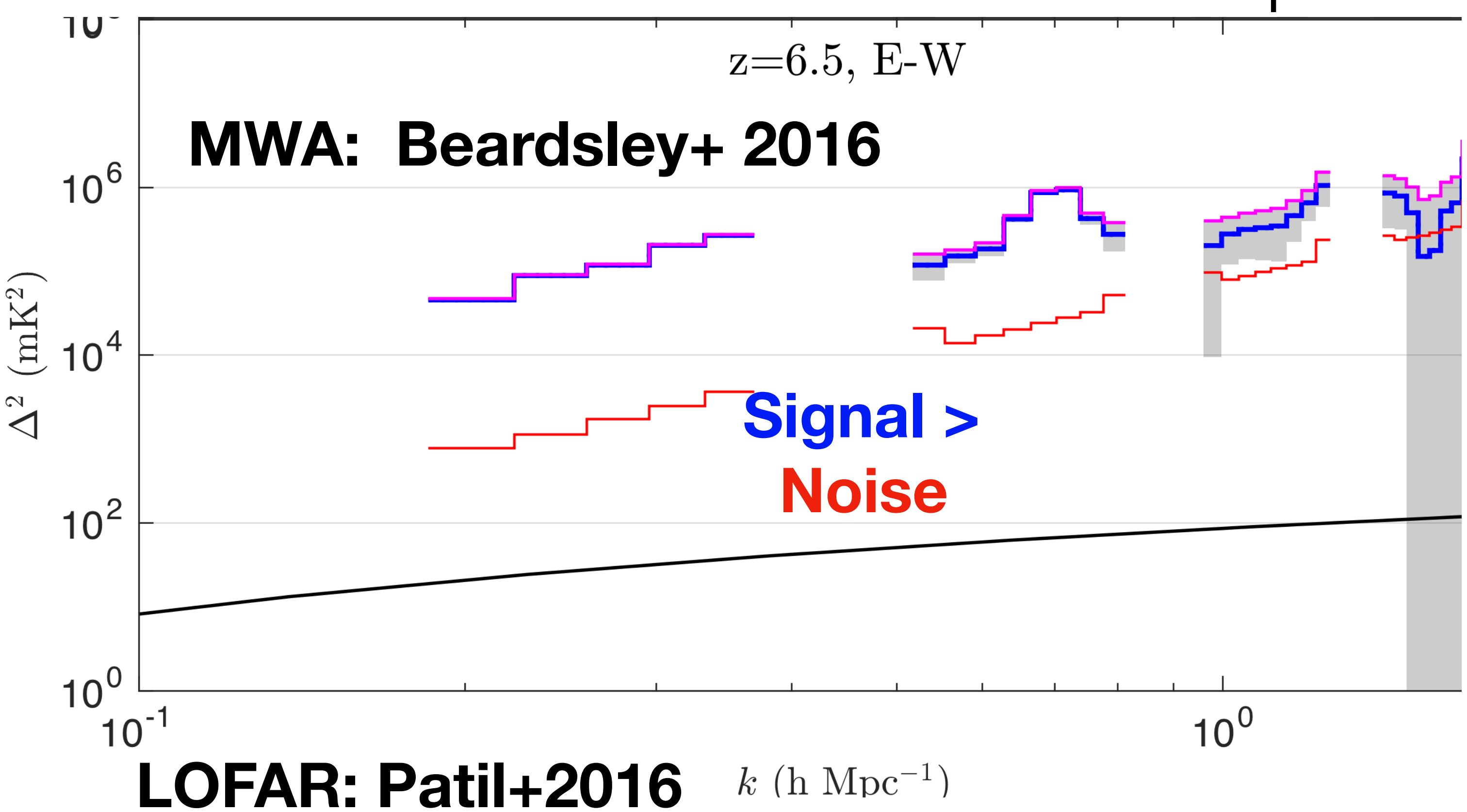
L = 150 meters

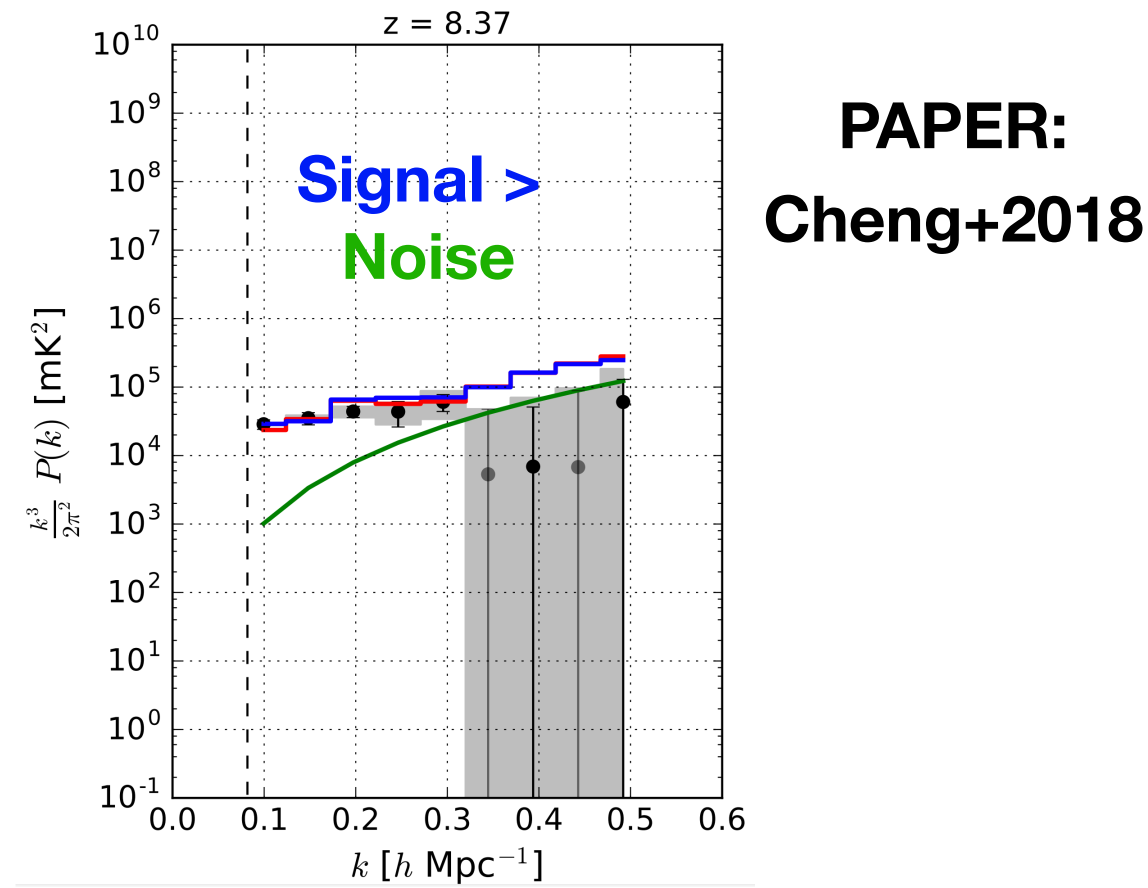
-> coaxial cables!

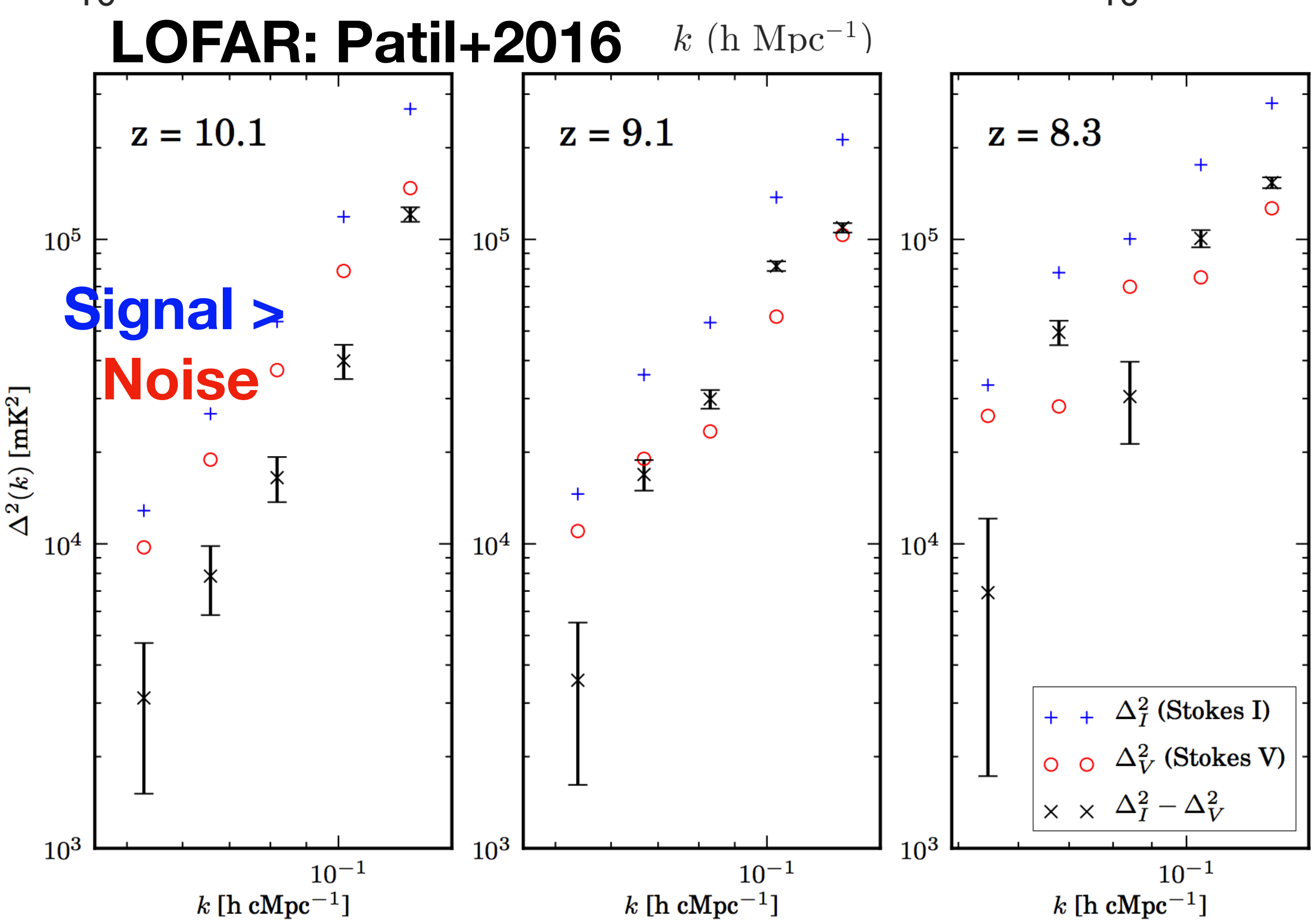


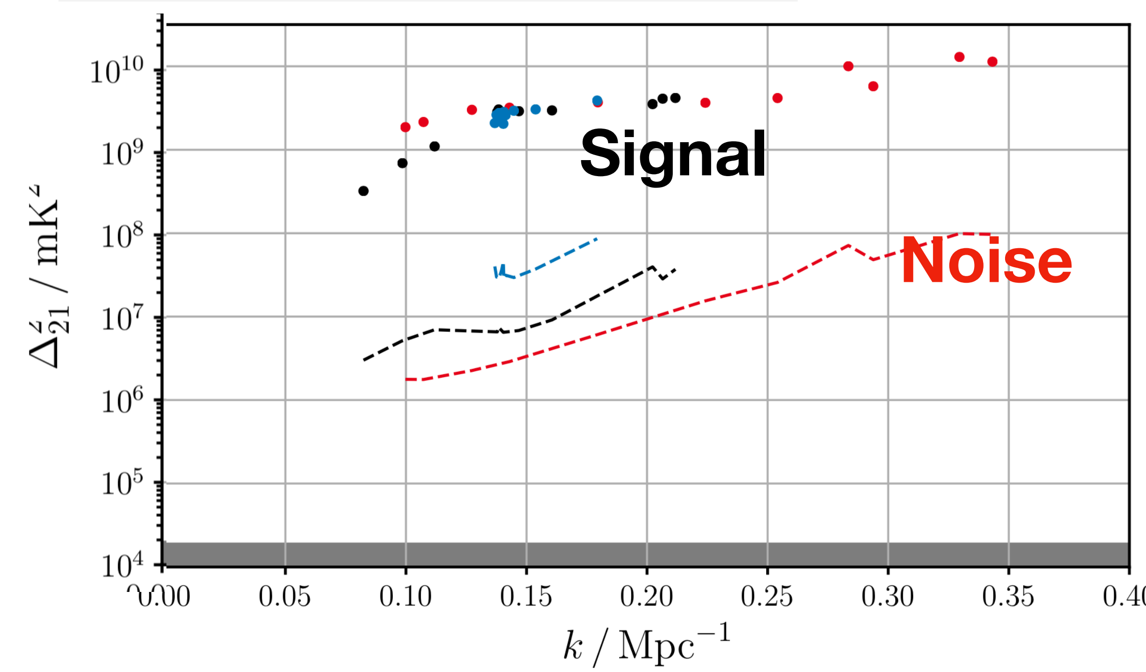
AEW+2016

All of the fluctuation measurements are limited by instrumental spectral structure.









Eastwood+2019 LWA

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

Calibration by the numbers

Measurements

- N(N-1)/2 Measured Visibilities

Unknowns

- N Complex Gains
- N(N-1)/2 True Visibilities

Two Kinds of Calibration

Sky-Based

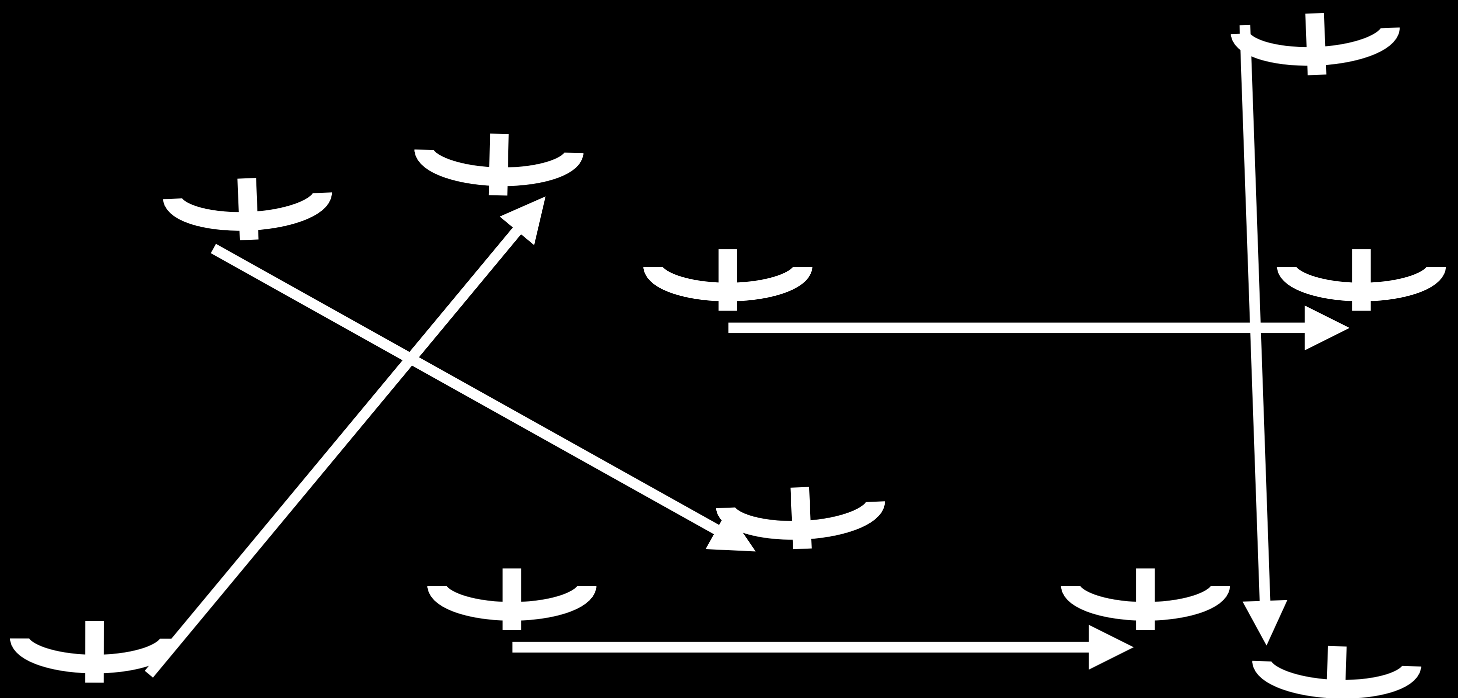
Redundant

Measurements

- N(N-1)/2 Measured Visibilities

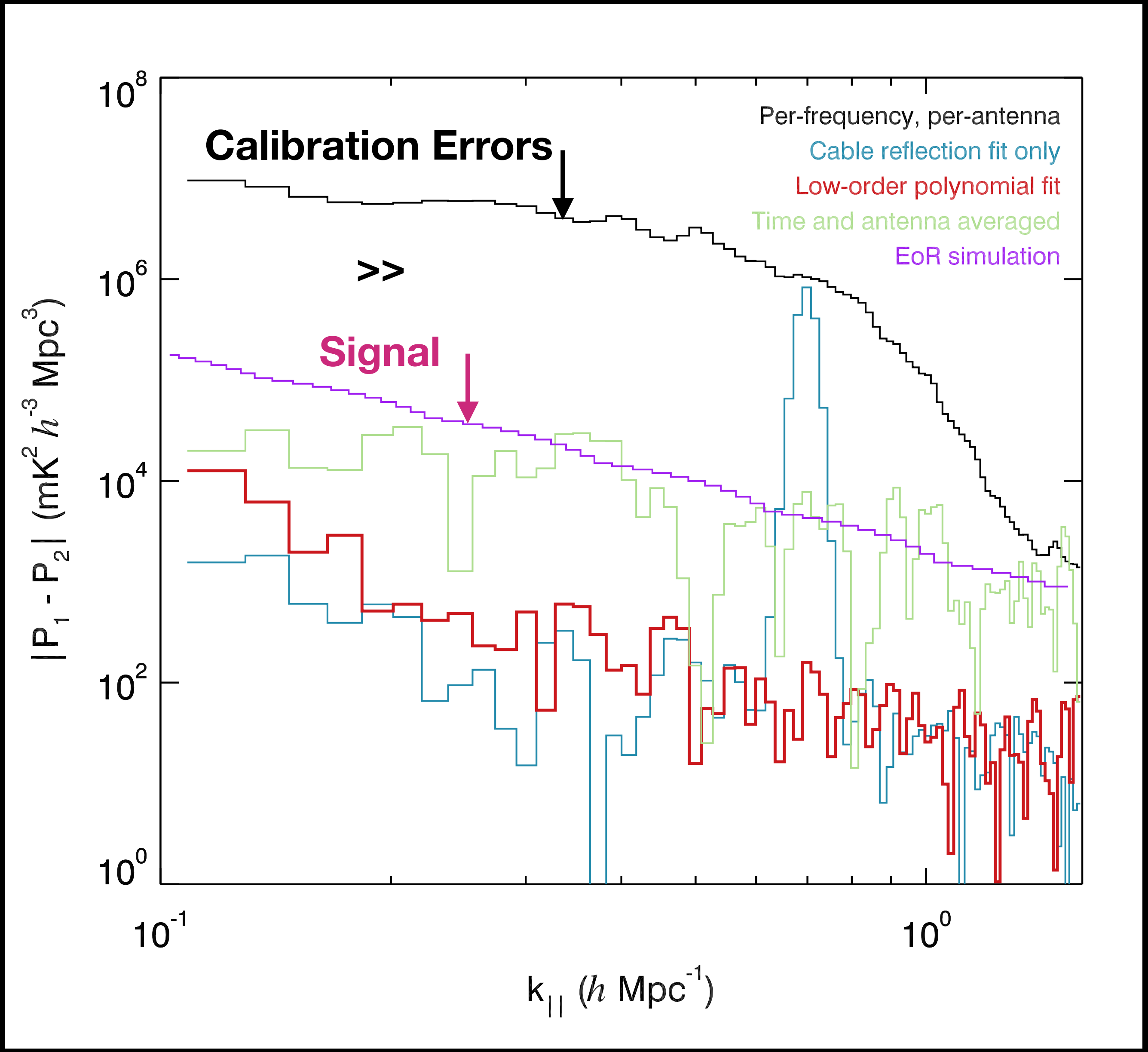
Unknowns

- N Gains
- **<u>N(N-1)/2 True Visibilities assumed to be known</u>**



Sky-based calibration errors
Exceed the power-spectrum level

MWA Simulation



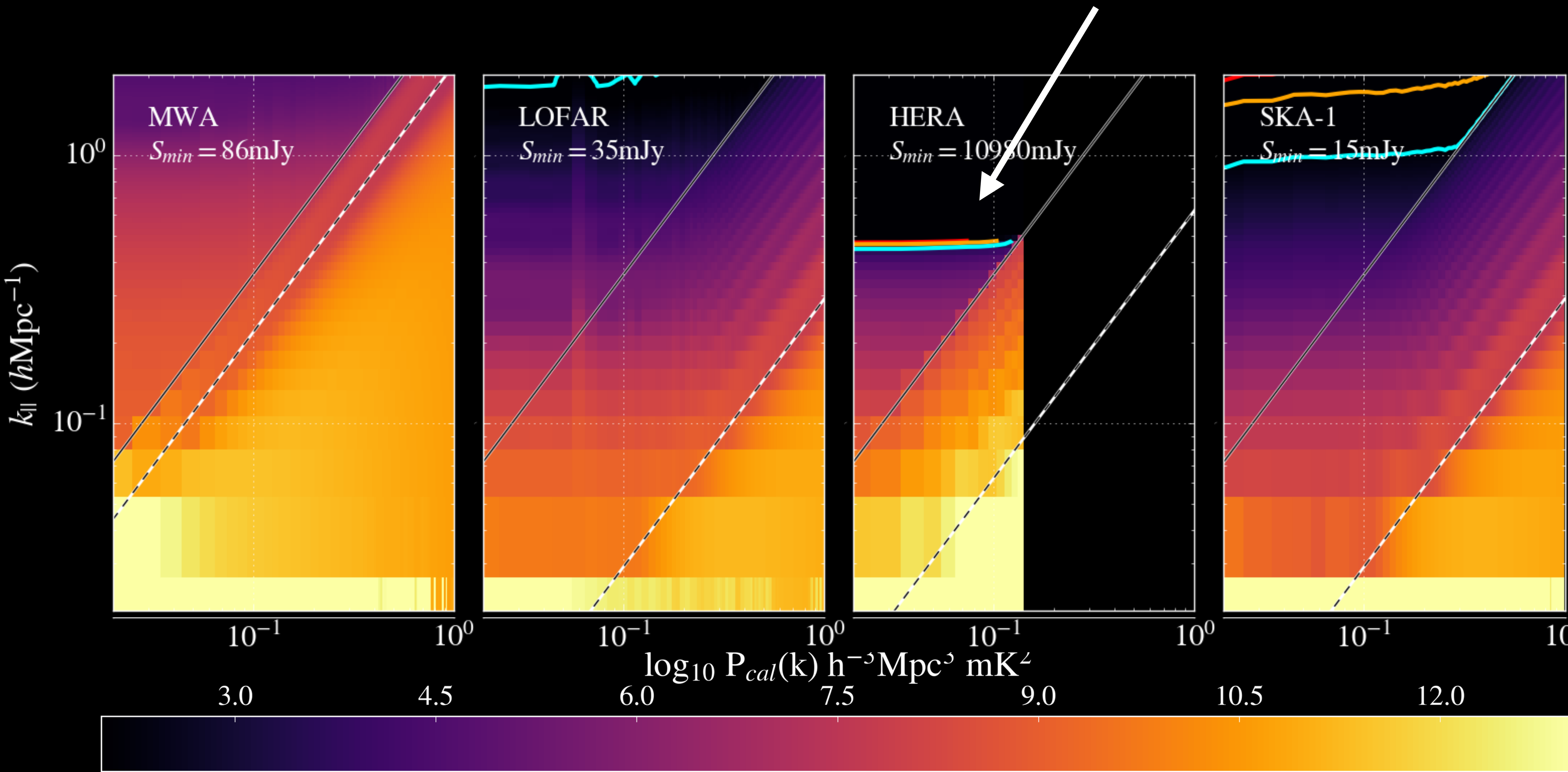
Barry+ 2017

Will also limit nominal SKA-low designs.

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

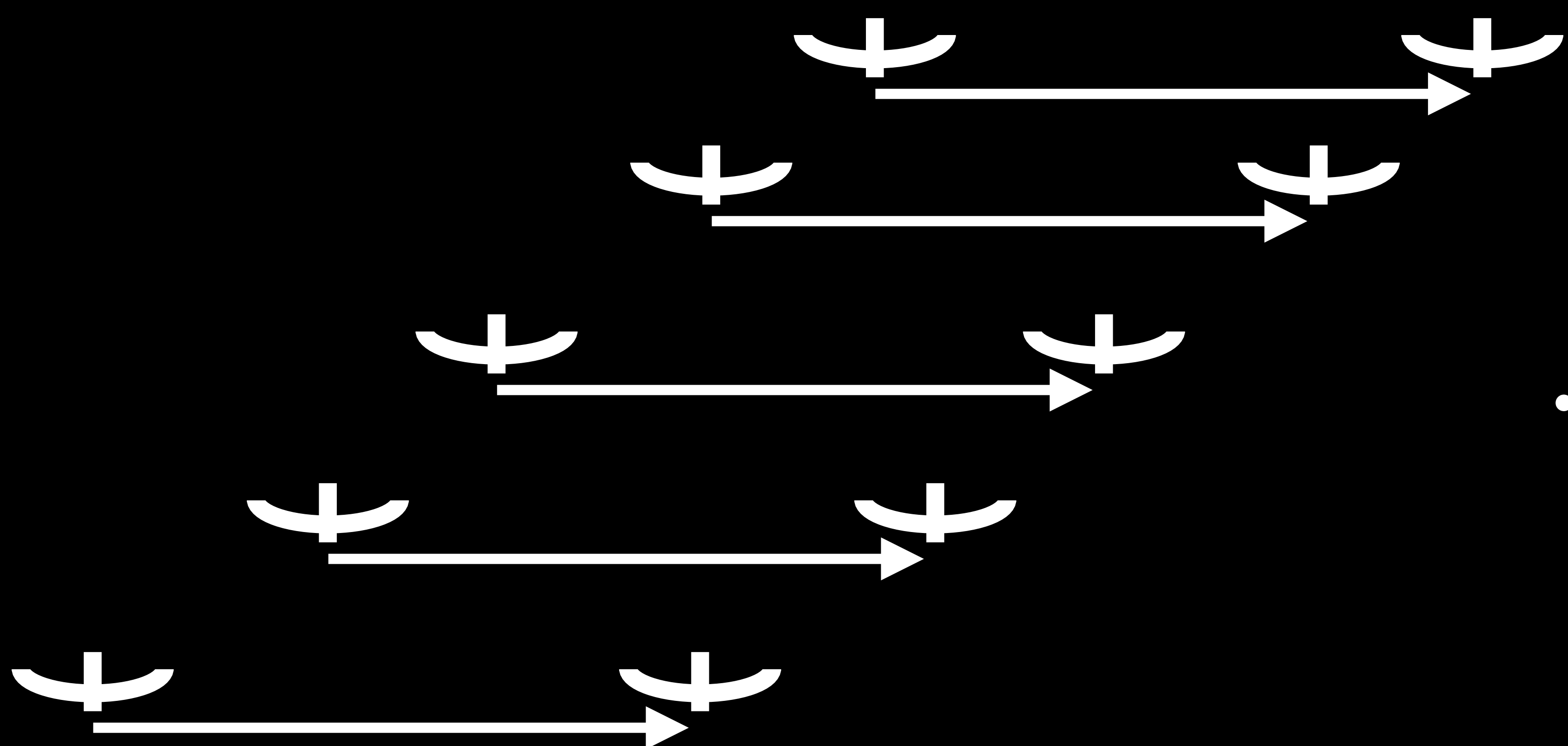
Sky modeling errors are prohibitive for all experiments

Bias = {1,5,10} x 21 cm Signal



AEW+2016

Two Kinds of Calibration



Sky-Based

Redundant

Measurements

- N(N-1)/2 Measured Visibilities

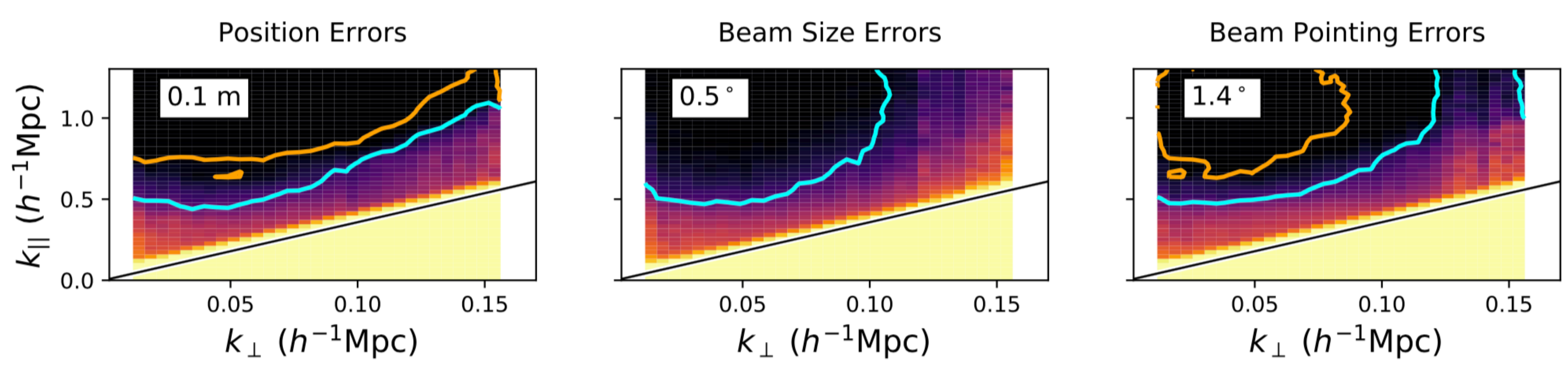
Unknowns

- N Gains
- **<<N(N-1)/2 True Visibilities**

Wieringa 1992, Liu+ 2010, Zheng+ 2014

Redundant Calibration Faces Similar Issues

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



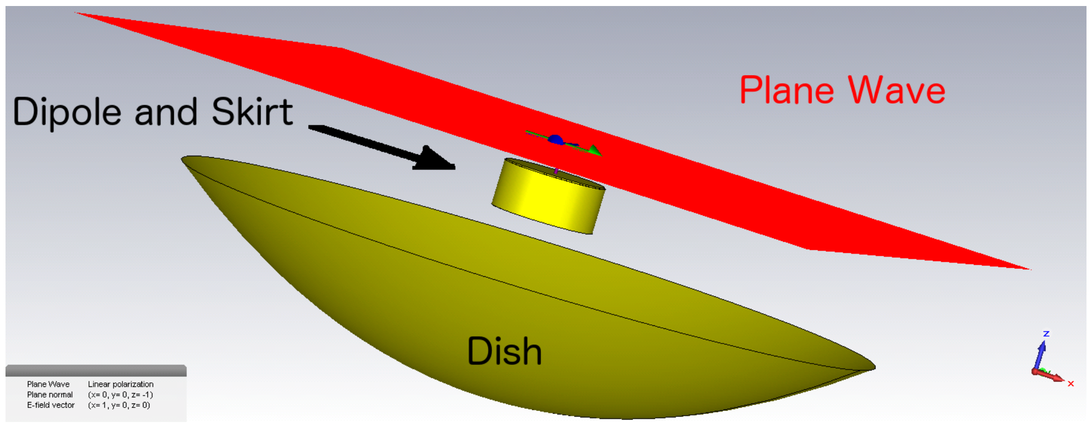
Orosz+2018

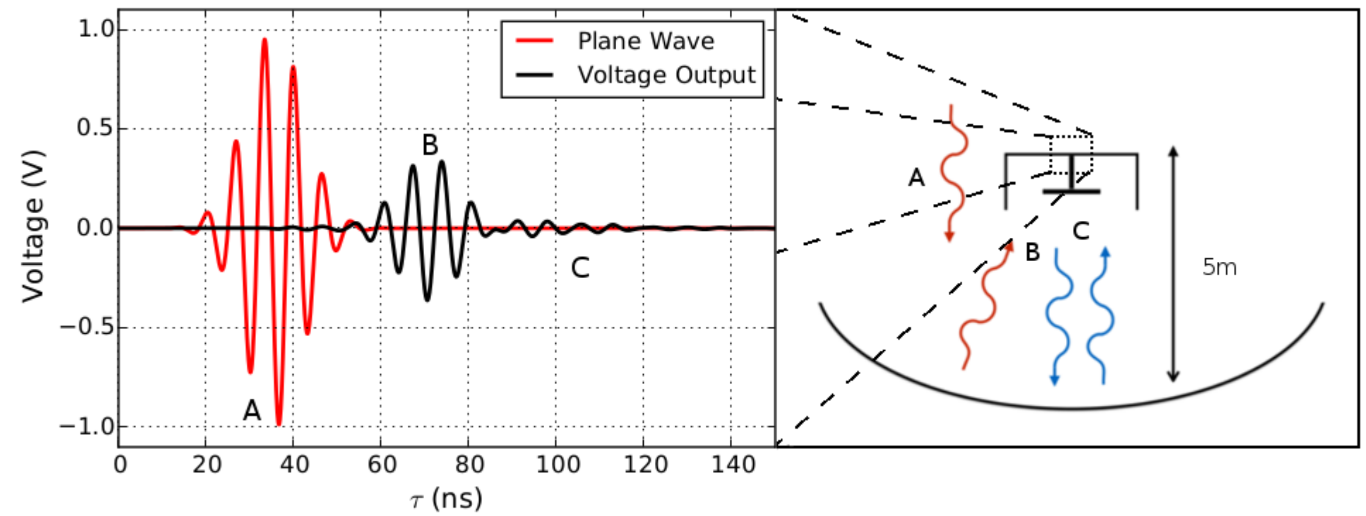
How do we move foreward?

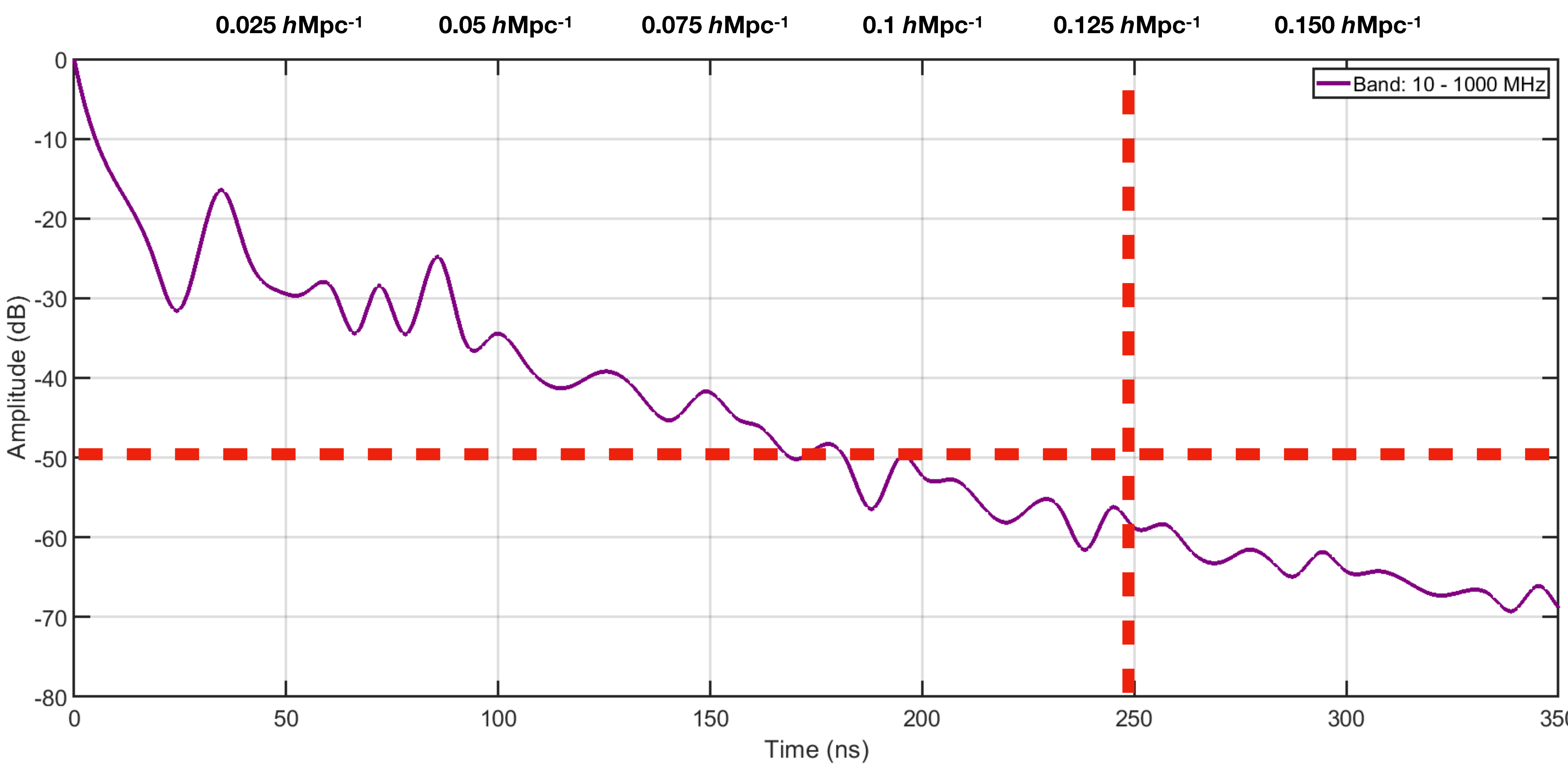
1. **Make sure our signal path is “spectrally smooth”.**

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

We use Electromagnetic Simulations to optimize the spectral performance of HERA's feed and RF chain







Delay Kernel from RF Simulation

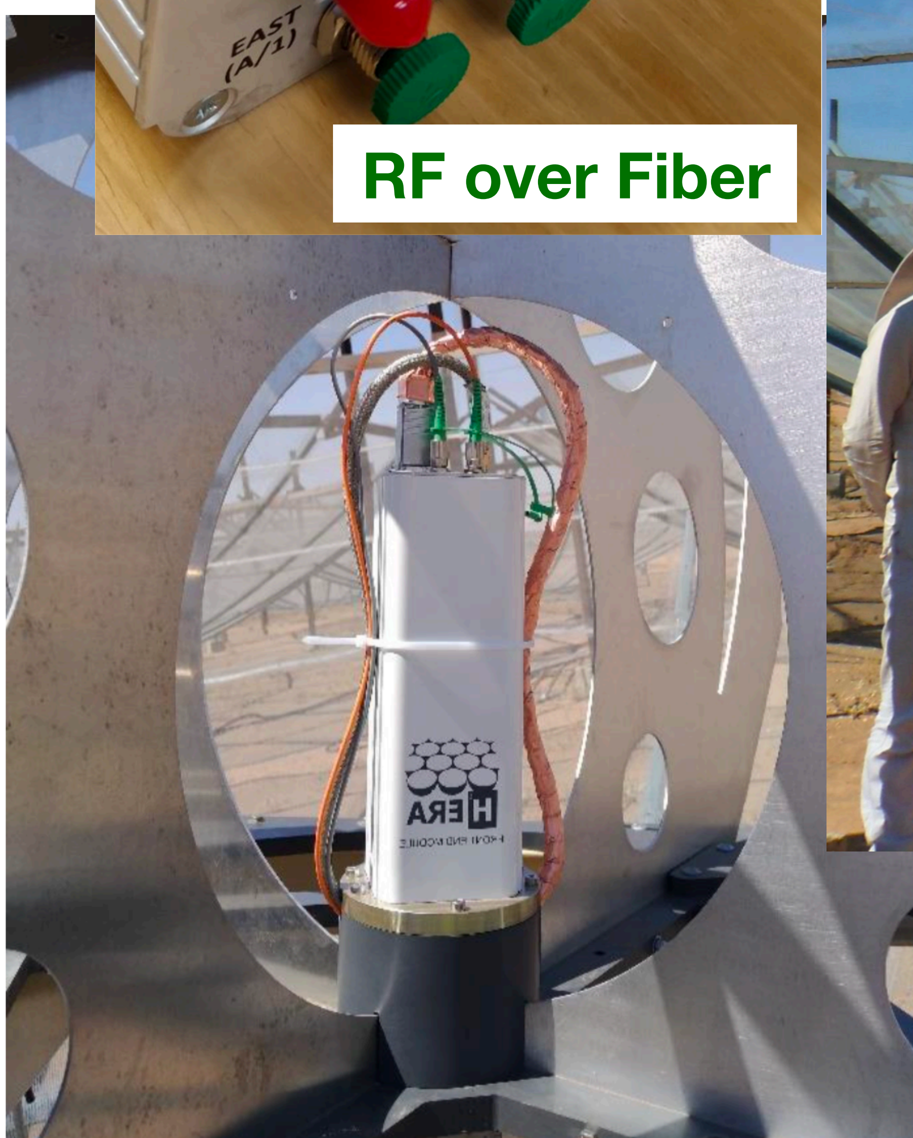
AEW+2016,
Thyagarajan+ 2016
Fagnoni+ 2016

Fagnoni+ in prep.

Many experiments are switching to RF over fiber to reduce reflections.

Modulate an optical laser in a fiber by the RF signal.

HERA, HIRAX, MWA



HERA site trip deploying RFoF chains and new feeds

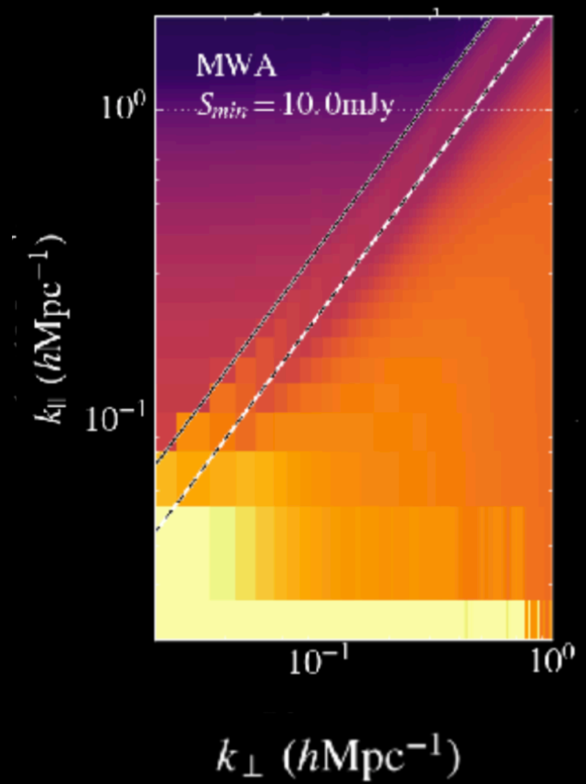
How do we move foreward?

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

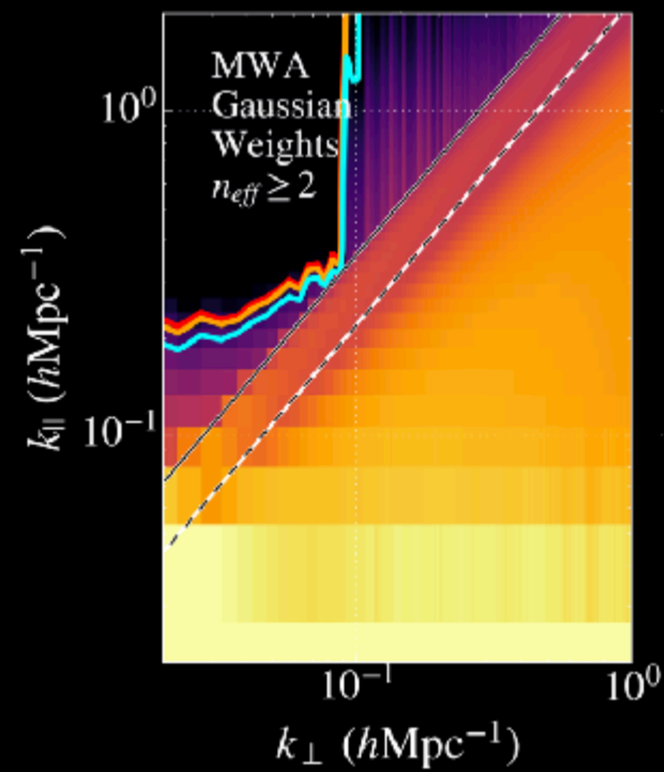
2. Figure out ways to robustify calibration against non-redundancy and sky-model incompleteness.

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

All baselines



Short baselines

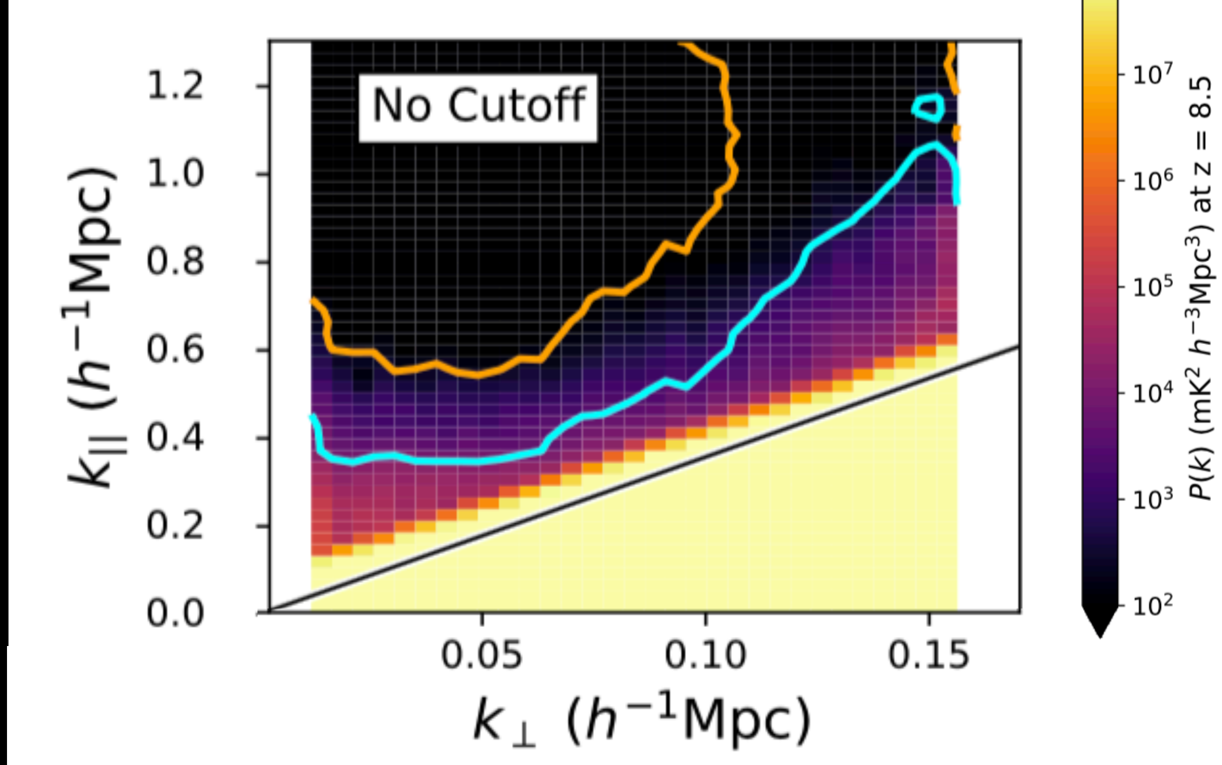


AEW+ 2016

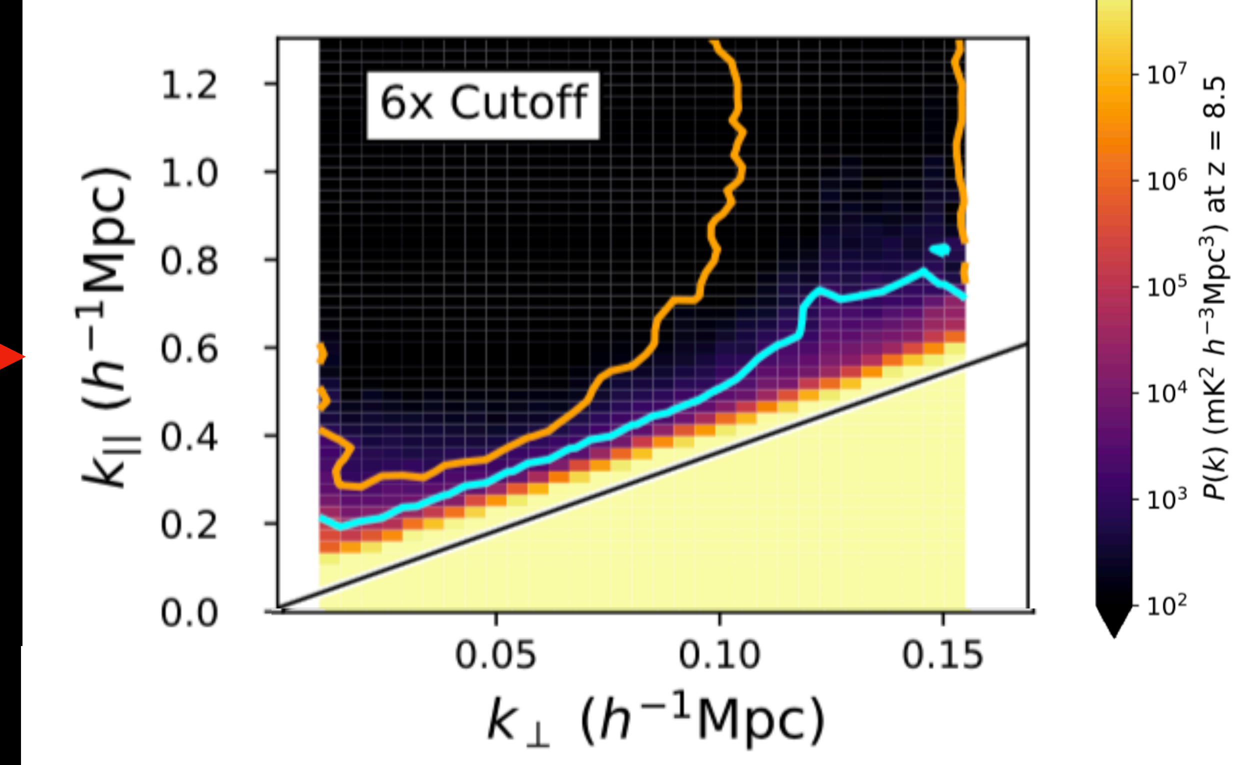
You'll Need
A
<u>"Good enough"</u>
<u>Diffuse Sky Model!</u>

Orosz+ 2018

All baselines



Short baselines



Take Aways

1. Claimed “Detections” are already here. EDGES -> Exotic physics or new radio sources? We showed that Black holes are a plausible explanation.

2. 21cm Fluctuation measurements

I. Can characterize the first stars and galaxies.
II. Offer a way to validate EDGEs.
III. Better foreground separation but instruments much more complicated/difficult to characterize.

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.**