Cosmology from Reionization and Cosmic Dawn:

Theory and Data

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Clay Fellow

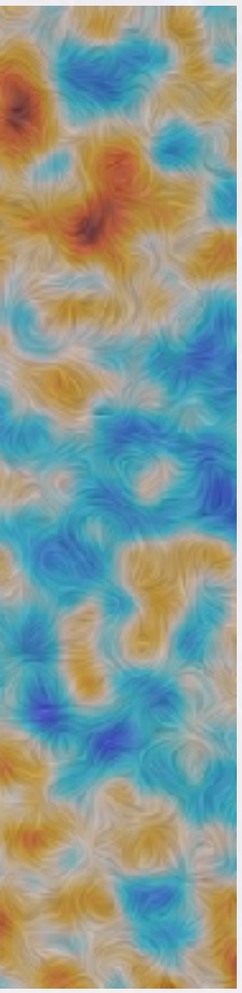
CENTER FOR ASTROPHYSICS

HARVARD & SMITHSONIAN

Image: Fuller/NSF

An abridged history of the cosmos

CMB



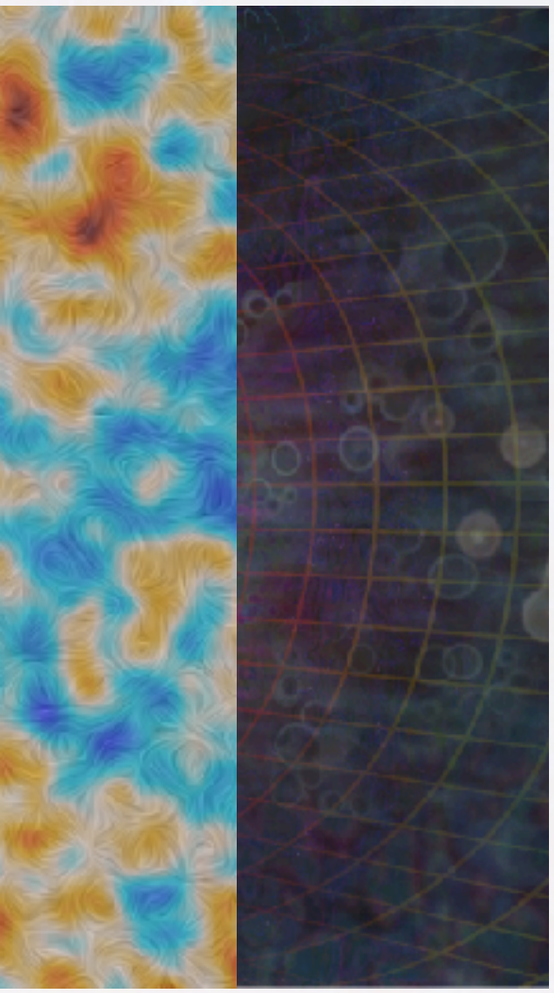
$z \approx 10^3$

Image: ESA

cosmic time

An abridged history of the cosmos

CMB



$z \approx 10^3$

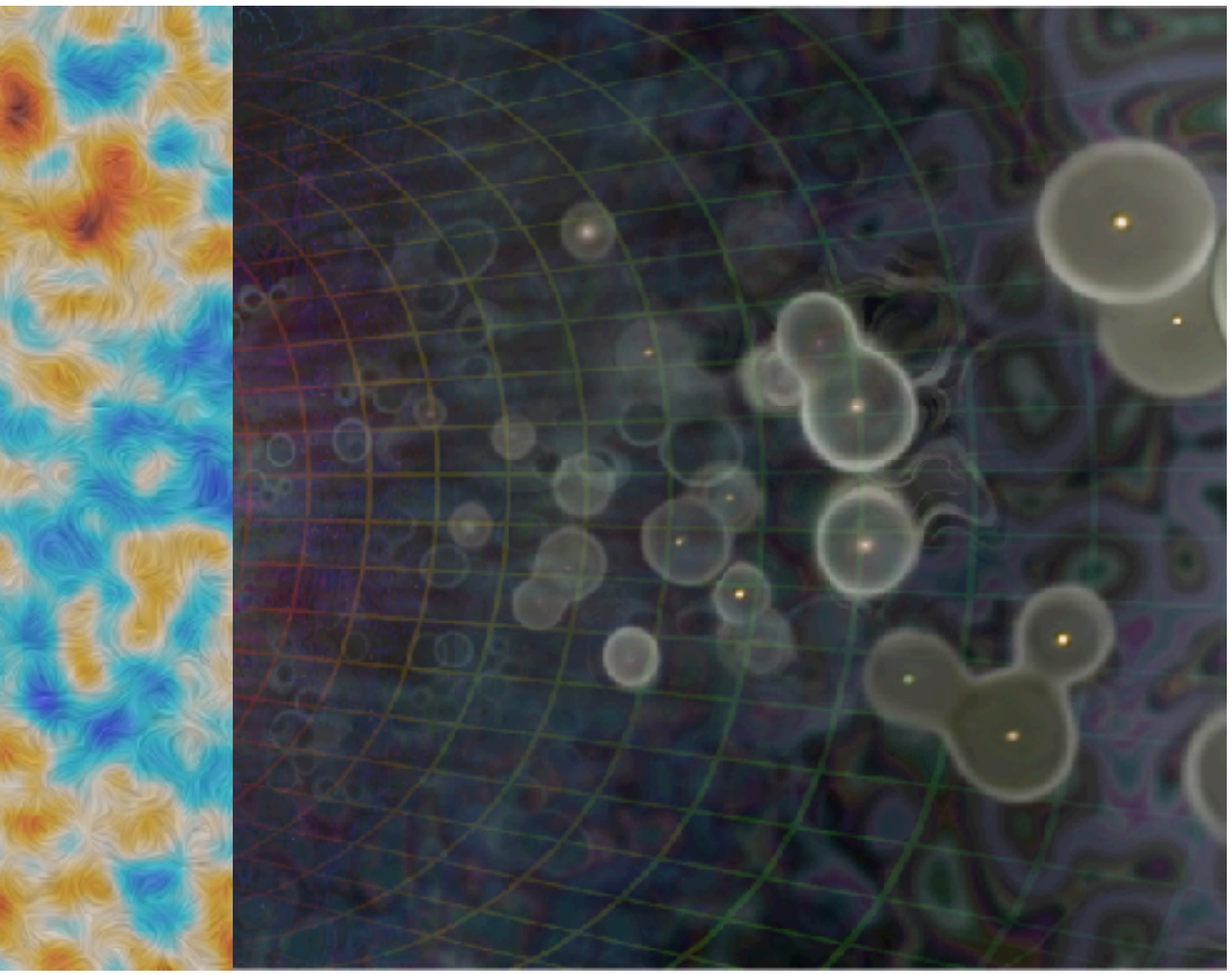
Image: NASA/CXC/M.WEISS

cosmic time →

An abridged history of the cosmos

CMB

Cosmic Dawn



$z \approx 10^3$

$z \approx 30$

Image: NASA/CXC/M.WEISS

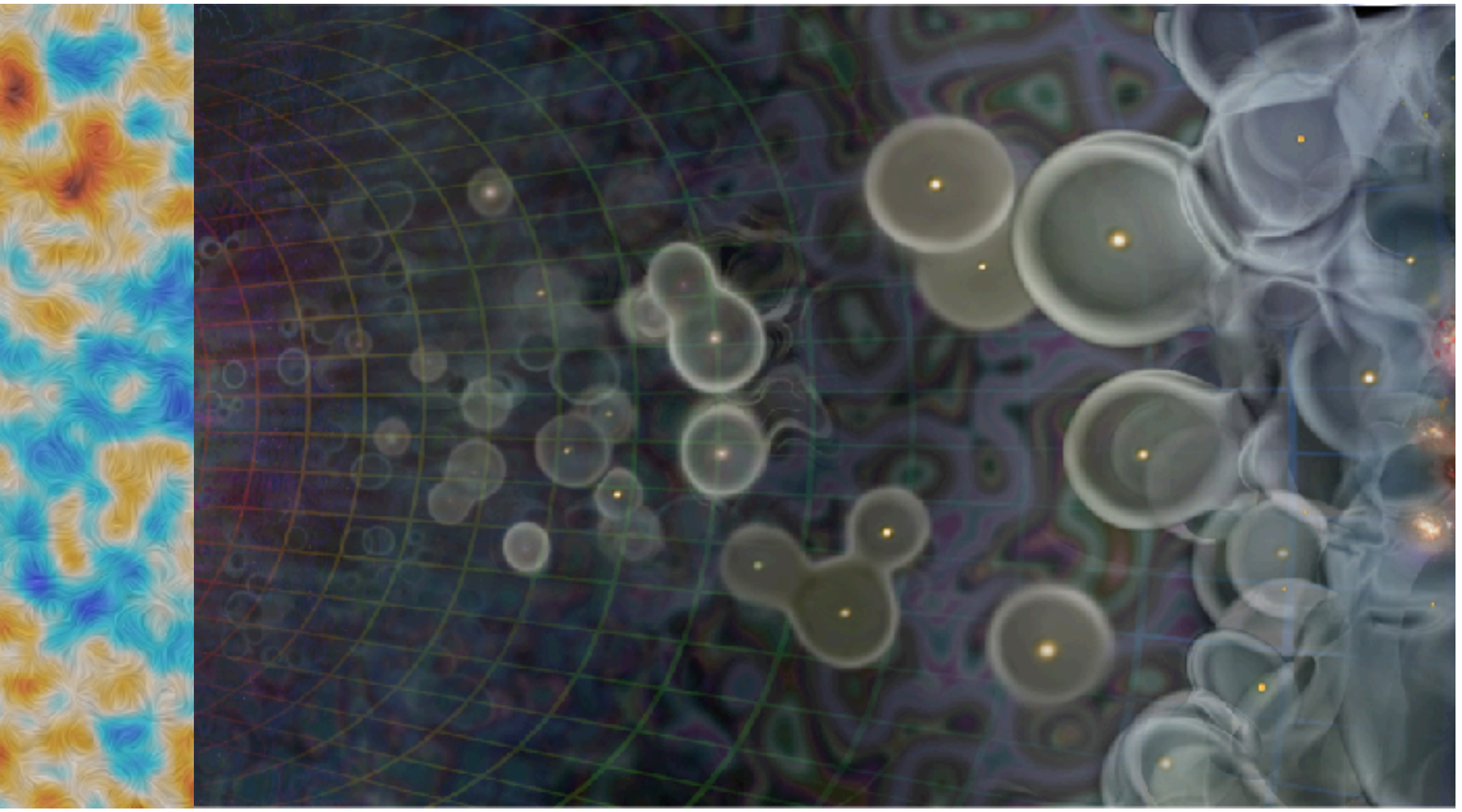
cosmic time →

An abridged history of the cosmos

CMB

Cosmic Dawn

Reionization



Nash's talk

$z \approx 10^3$

$z \approx 30$

$z \approx 6$

cosmic time →

Image: NASA/CXC/M.WEISS

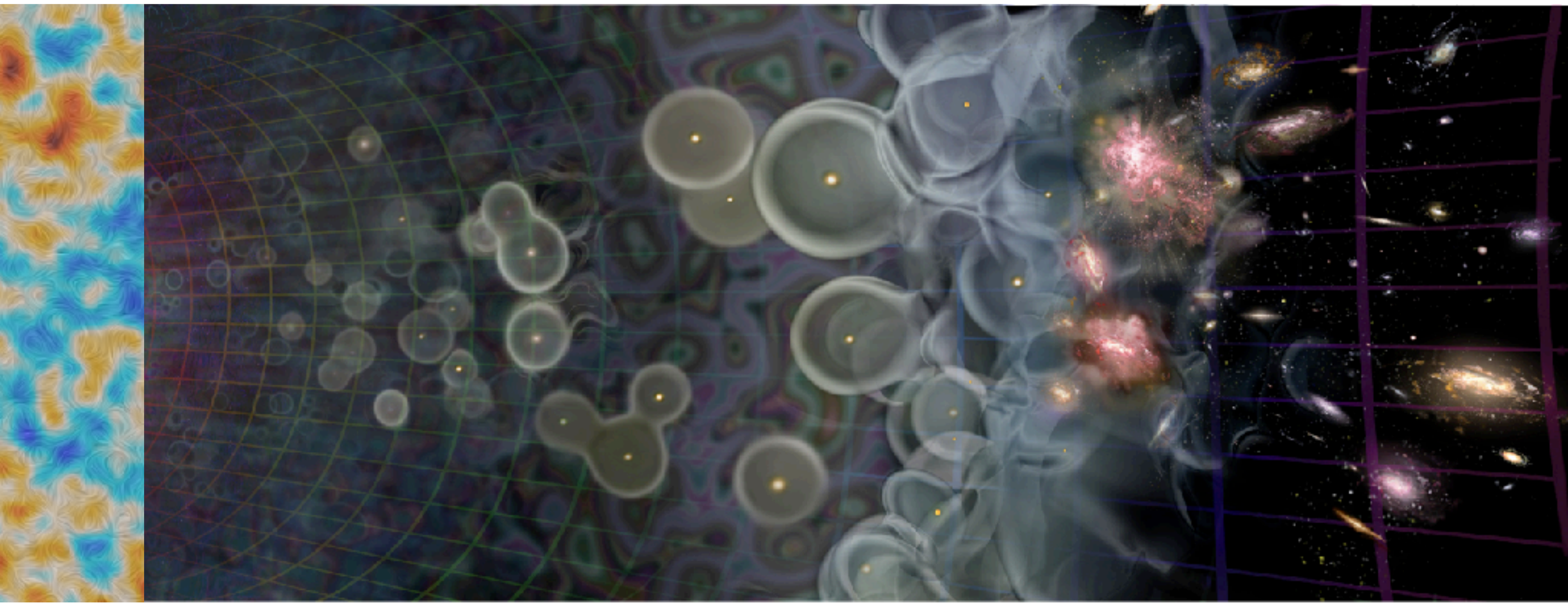
An abridged history of the cosmos

CMB

Cosmic Dawn

Reionization

Local Universe



$z \approx 10^3$

$z \approx 30$

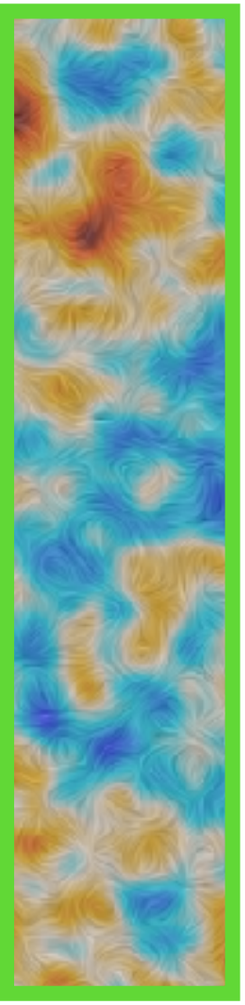
$z \approx 6$

$z = 0$

cosmic time →

Image: NASA/CXC/M.WEISS

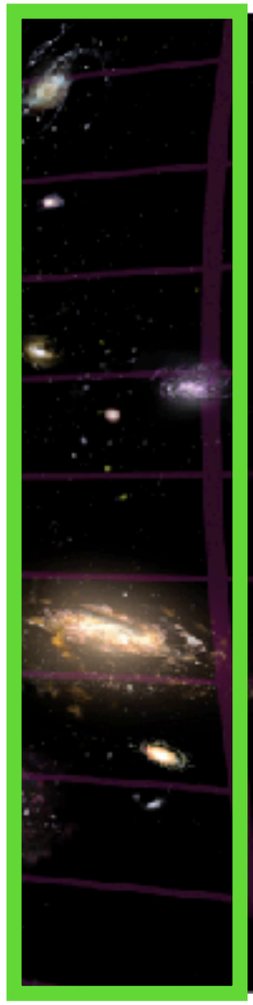
CMB



Vivien’s talk

$z \approx 10^3$

Local Universe



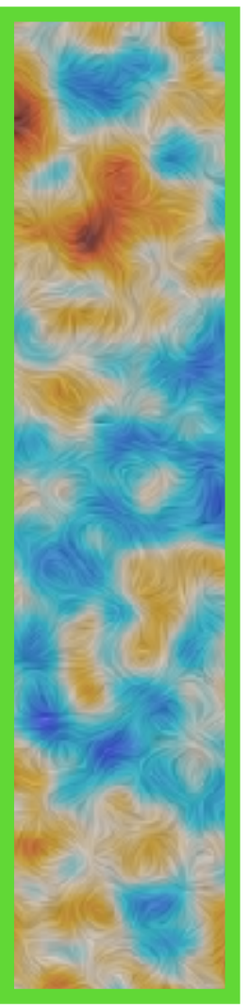
Héctor’s and Zvonimir's talks

$z = 0$

Image: NASA/CXC/M.WEISS

The pillars of cosmology

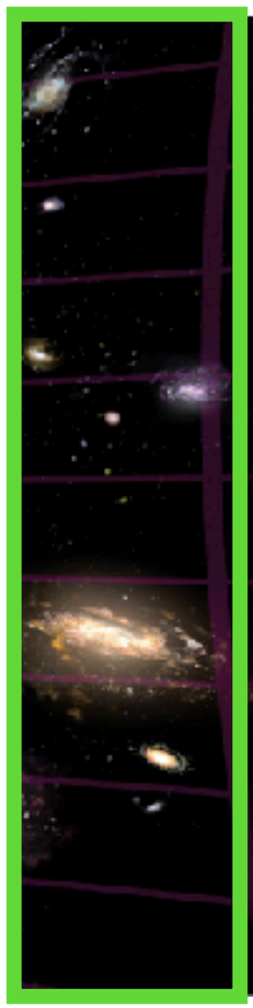
CMB



$z \approx 10^3$

There is Dark Matter

Local Universe

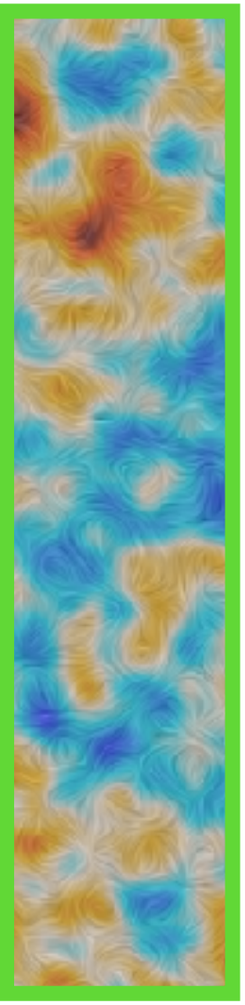


$z = 0$

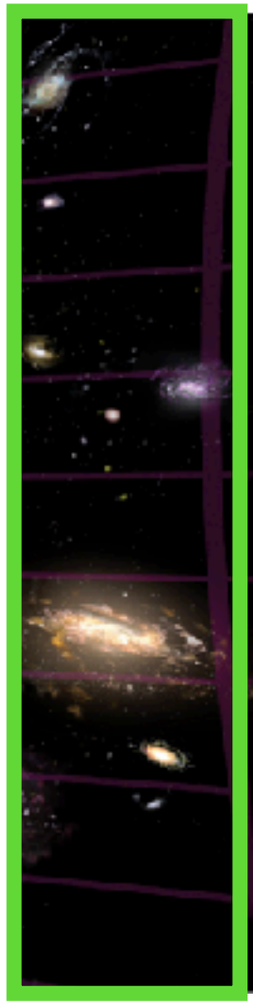
Image: NASA/CXC/M.WEISS

The pillars of cosmology

CMB



Local Universe



There is Dark Matter

This DM is cold and collisionless

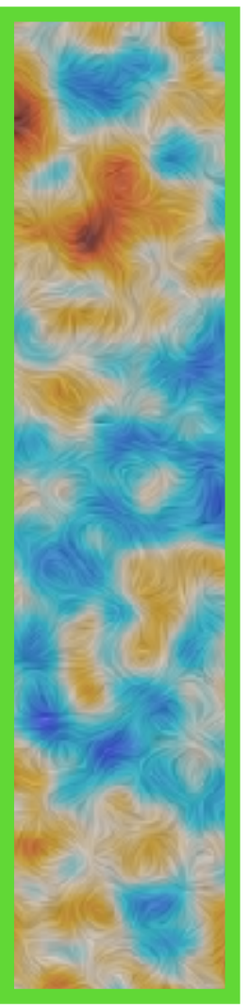
$z \approx 10^3$

$z = 0$

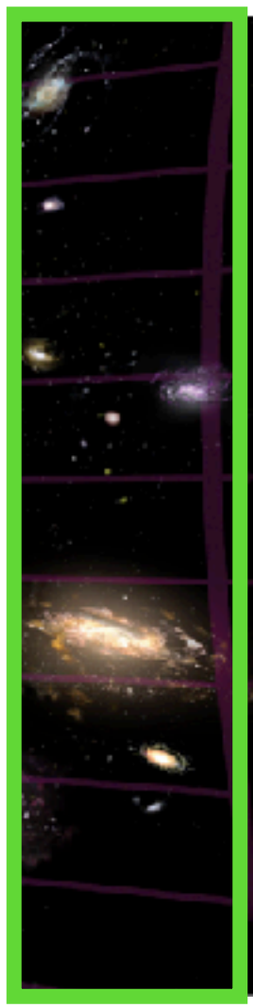
Image: NASA/CXC/M.WEISS

The pillars of cosmology

CMB



Local Universe



There is Dark Matter

This DM is cold and collisionless

There is Dark Energy

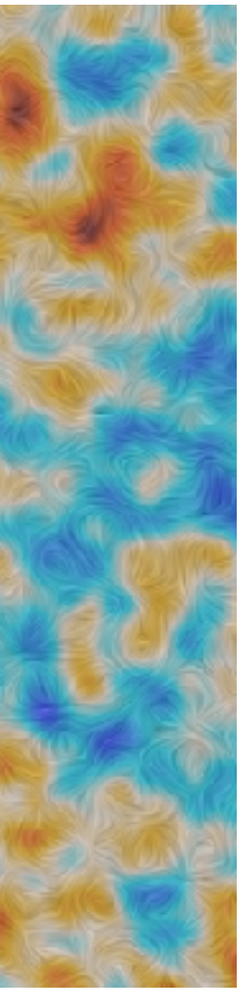
$z \approx 10^3$

$z = 0$

Image: NASA/CXC/M.WEISS

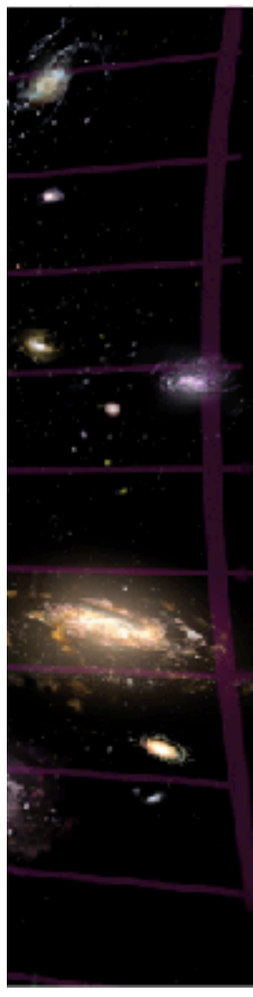
We've learned a lot, but…

CMB



$z \approx 10^3$

Local Universe

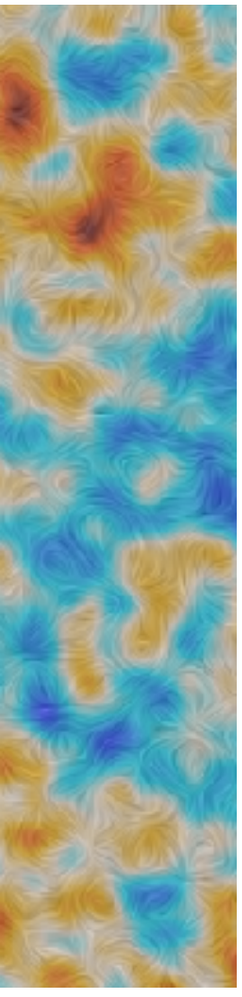


$z = 0$

-We don't know what DM or DE are

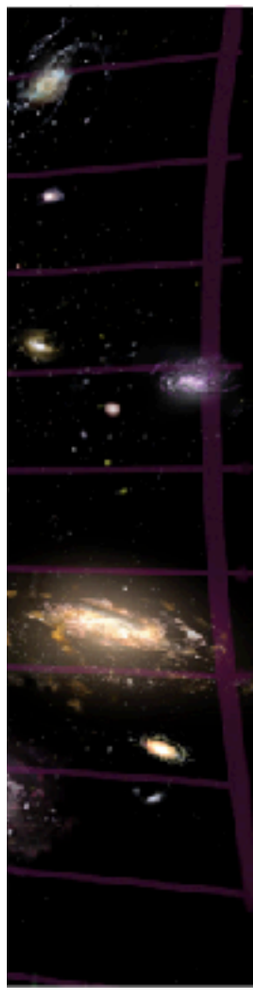
We've learned a lot, but…

CMB



$z \approx 10^3$

Local Universe



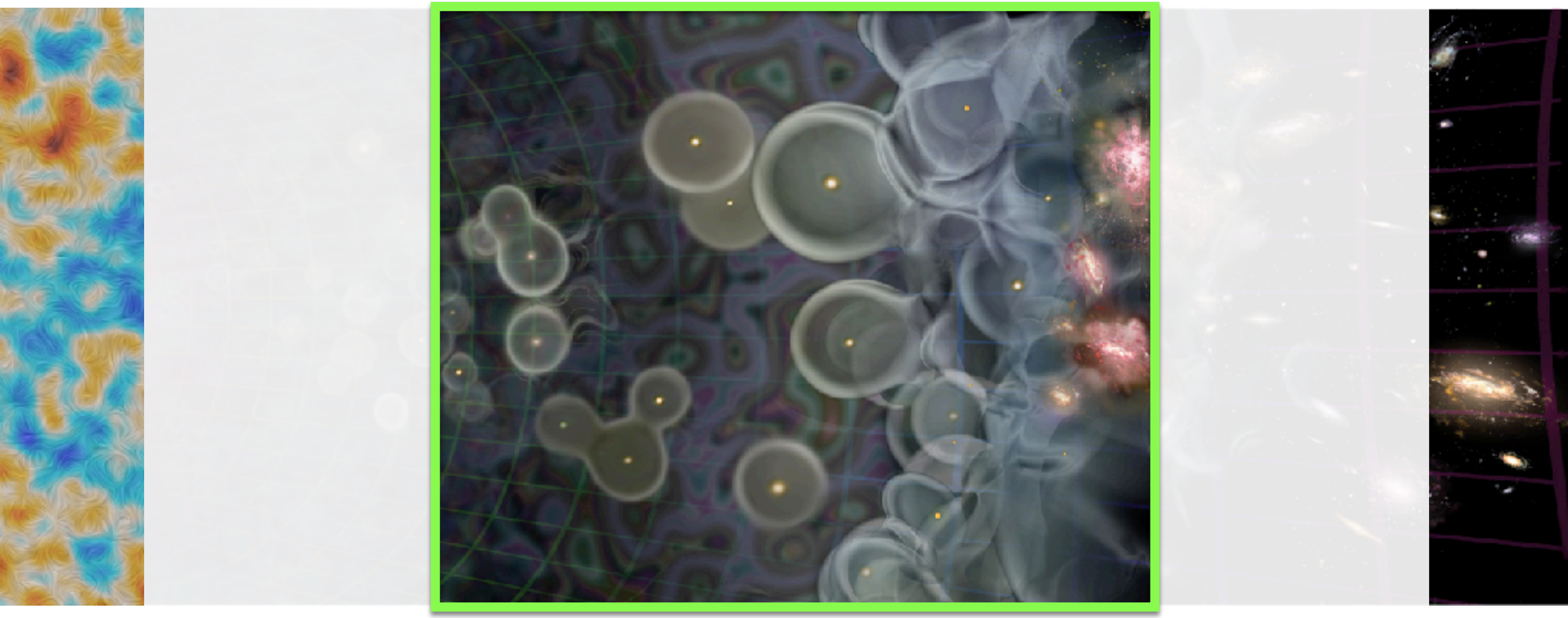
$z = 0$

-We don't know what DM or DE are

-Cosmic tensions (e.g., H_0).

A third pillar

Cosmic Dawn and EoR

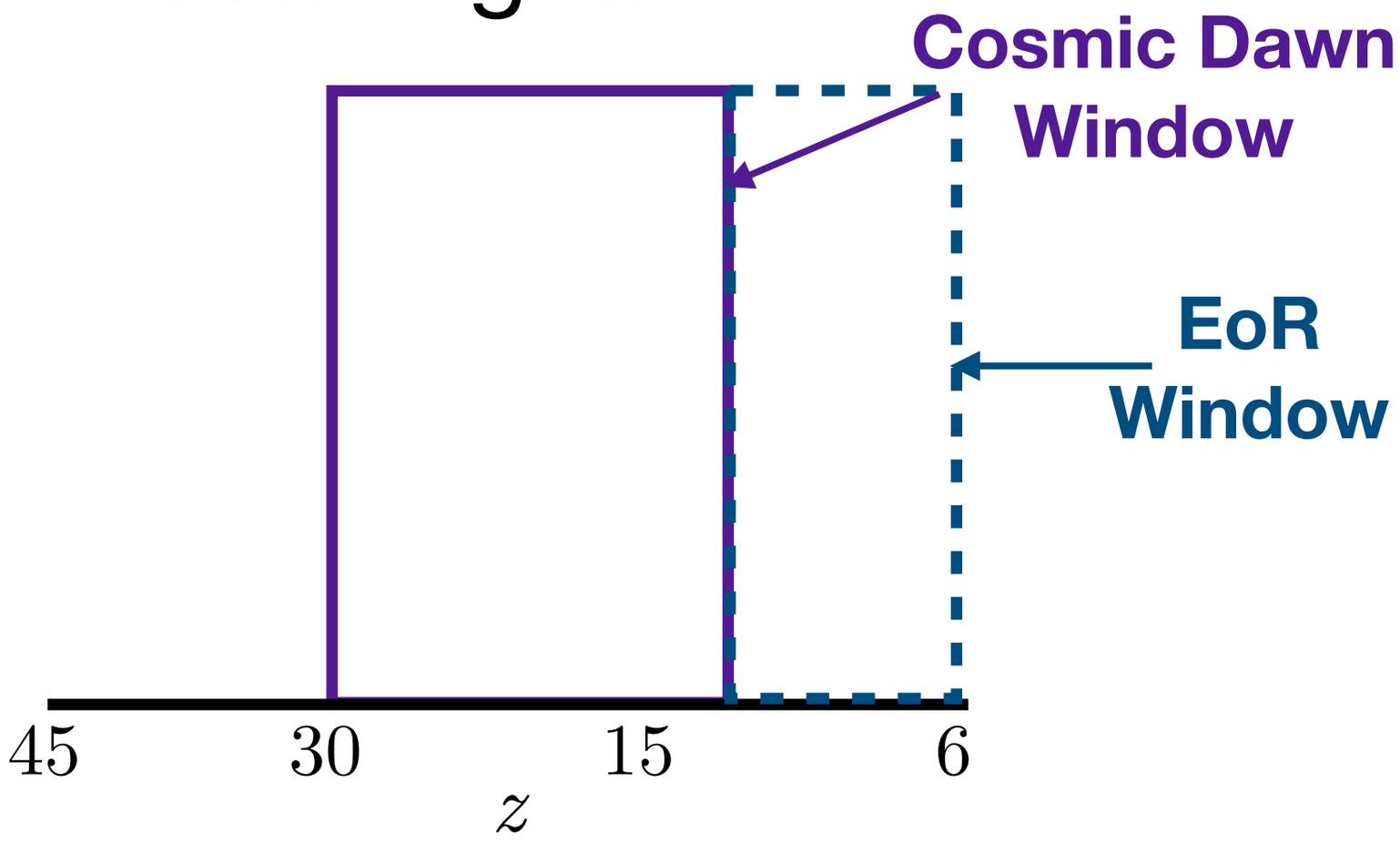


$z \approx 30$ $z \approx 6$

cosmic time →

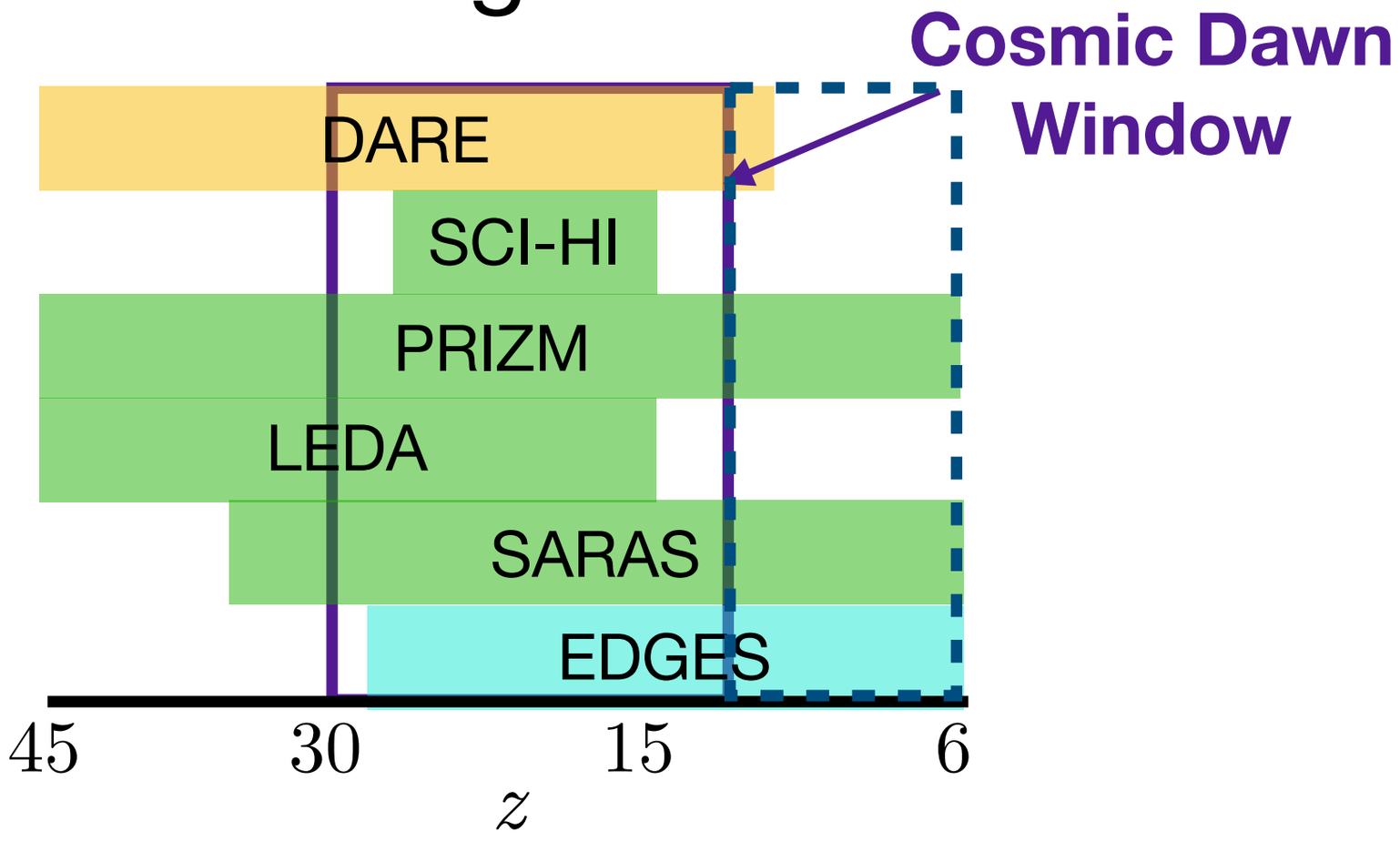
The 21-cm experimental landscape

Global Signal



The 21-cm experimental landscape

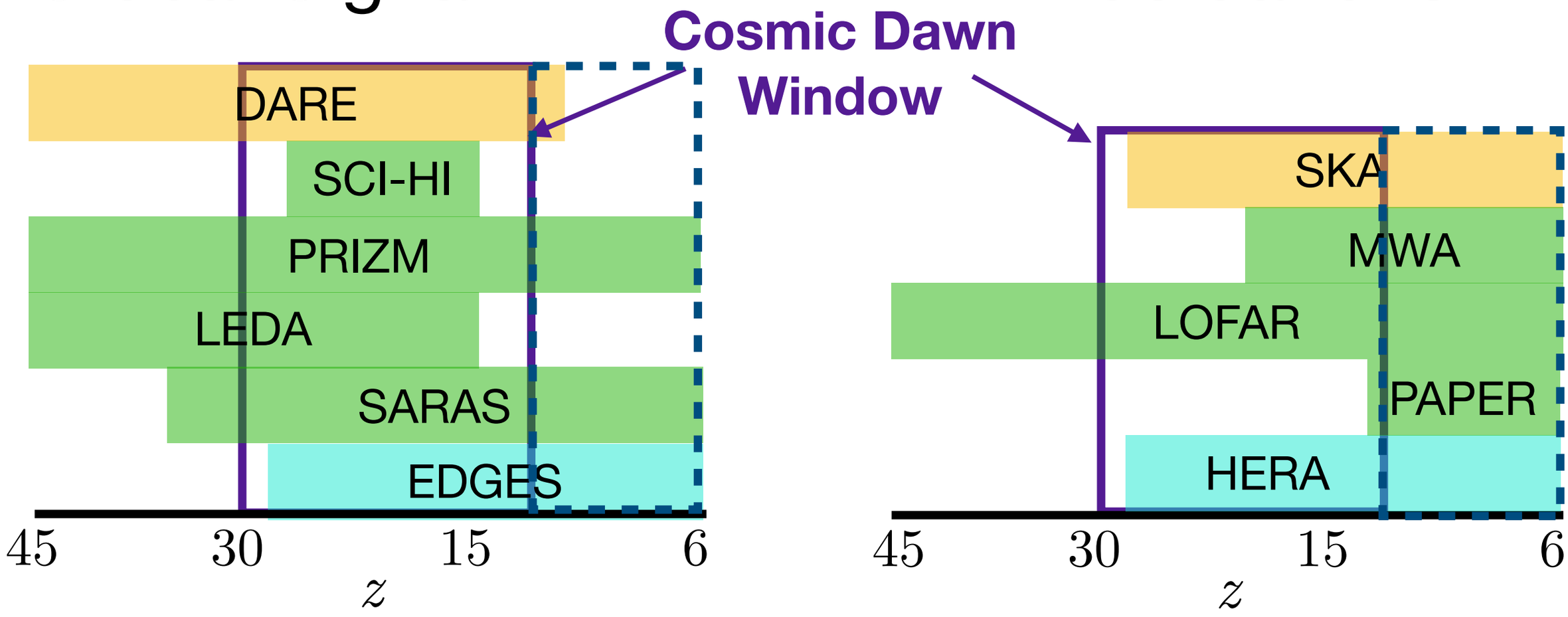
Global Signal



The 21-cm experimental landscape

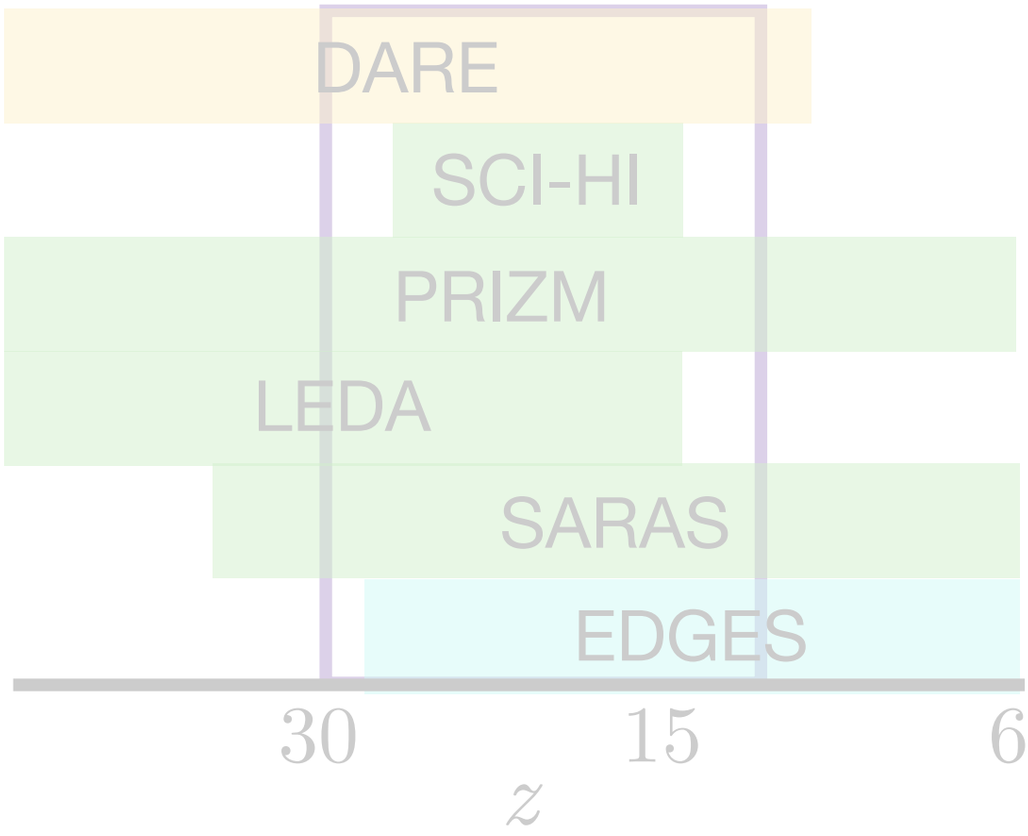
Global Signal

Fluctuations

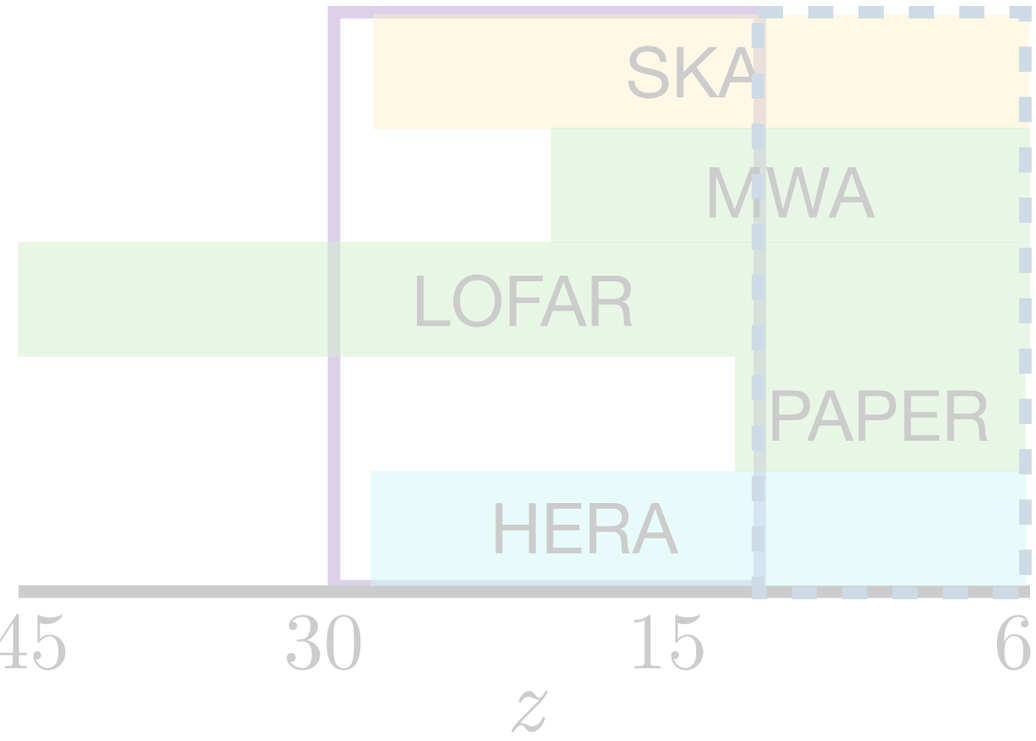


What can we learn?

Global Signal



Fluctuations



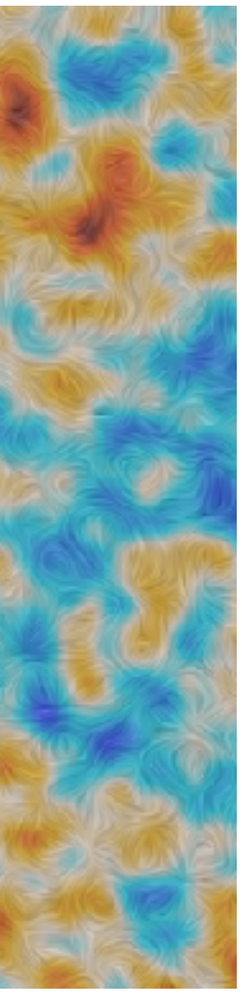
Does DM interact with us?

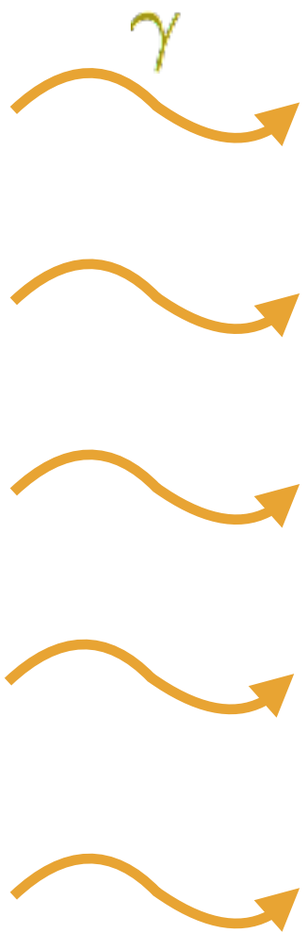
Is DM warm, fuzzy, or self-interacting?

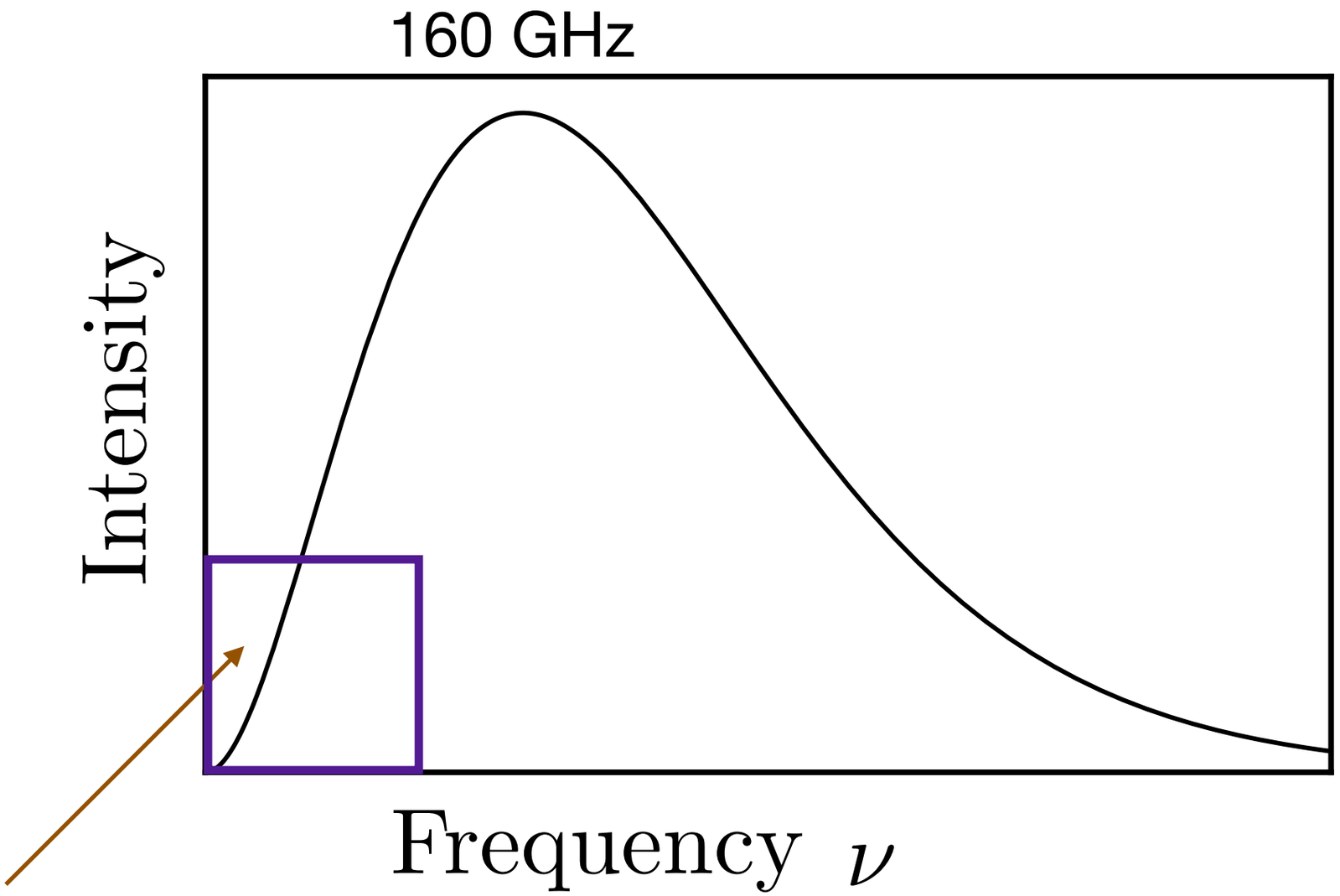
What is the expansion rate $H(z{=}10\text{-}20)$?

The basics of 21-cm

CMB



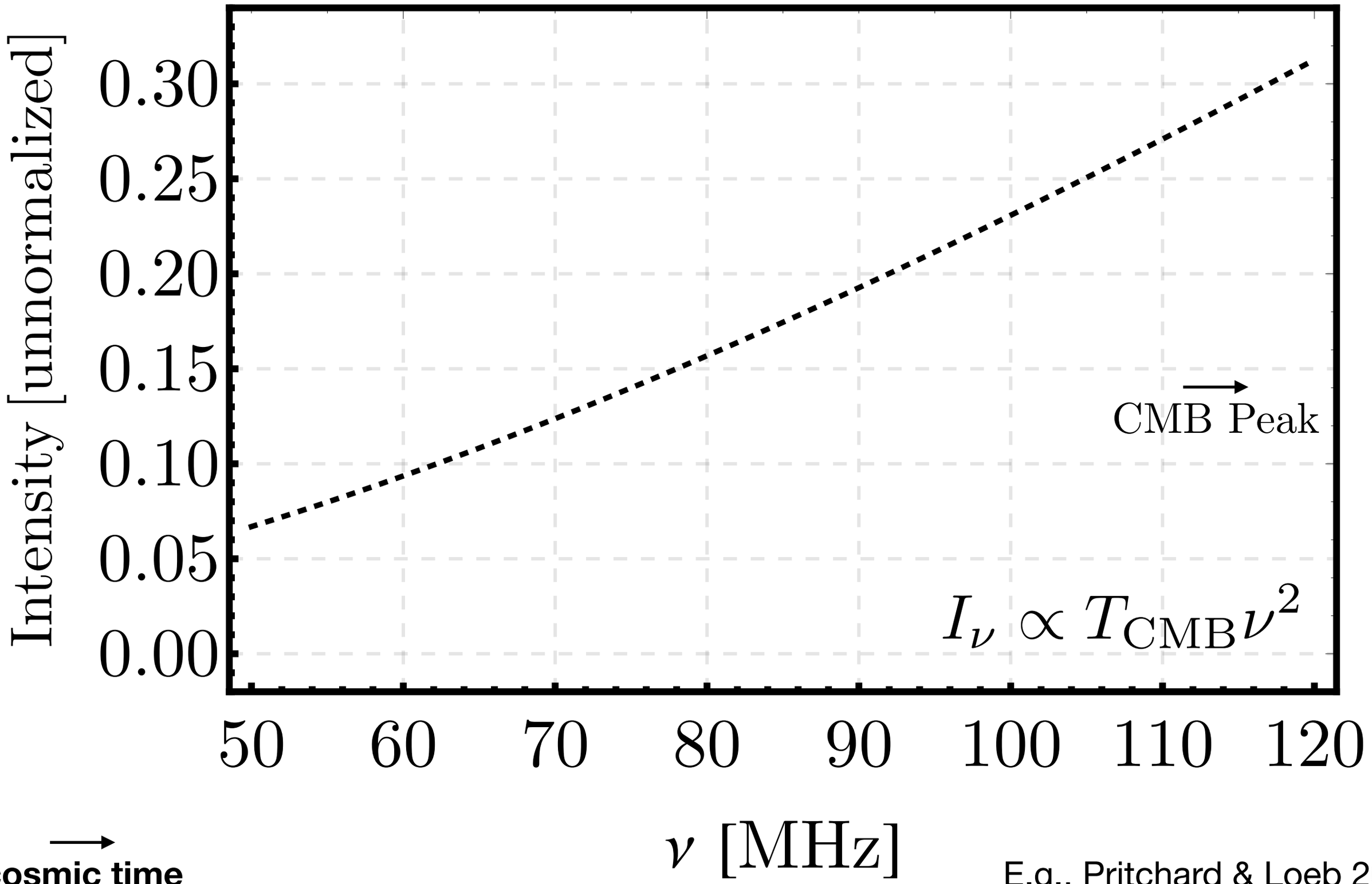




$z \approx 10^3$

21-cm wavelength: 1.4 GHz

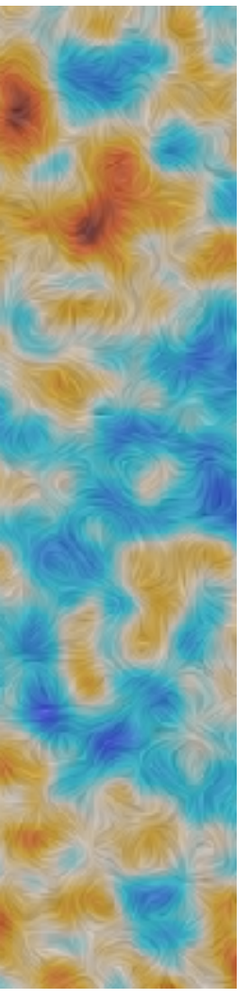
The basics of 21-cm: The low-ν tail



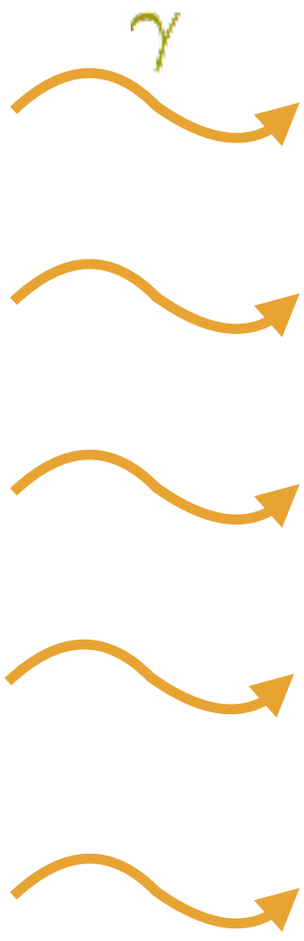
E.g., Pritchard & Loeb 2012

The basics of 21-cm: Absorption

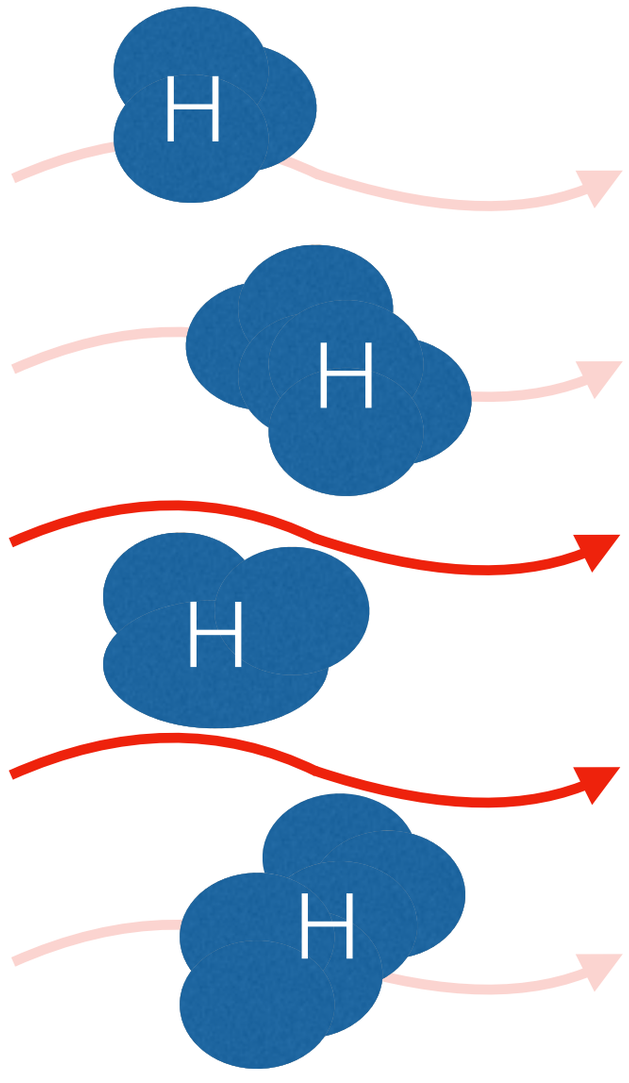
CMB



$z \approx 10^3$



$\lambda = 21\,\mathrm{cm}$



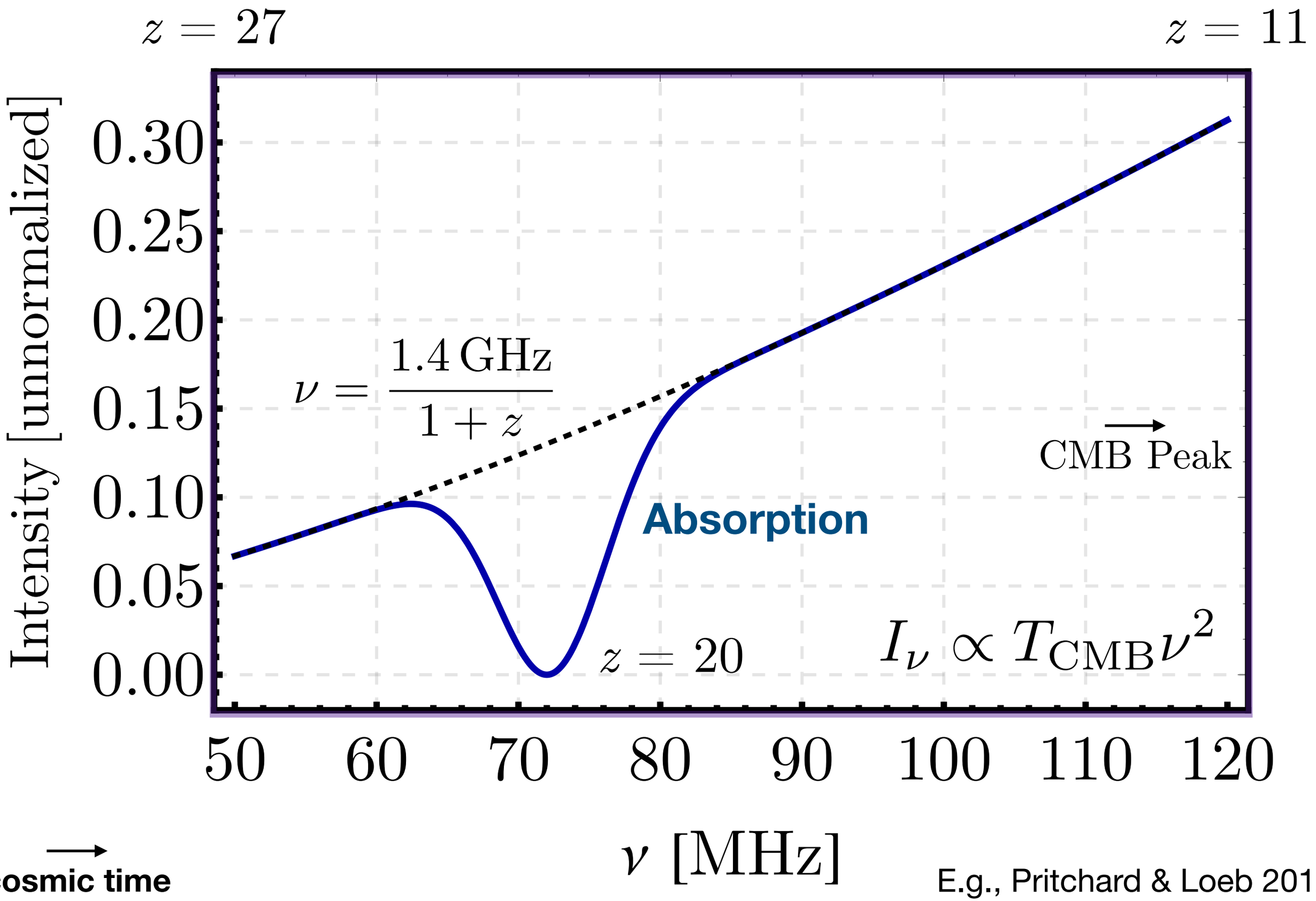
$z = 20$

Earth

$z = 0$

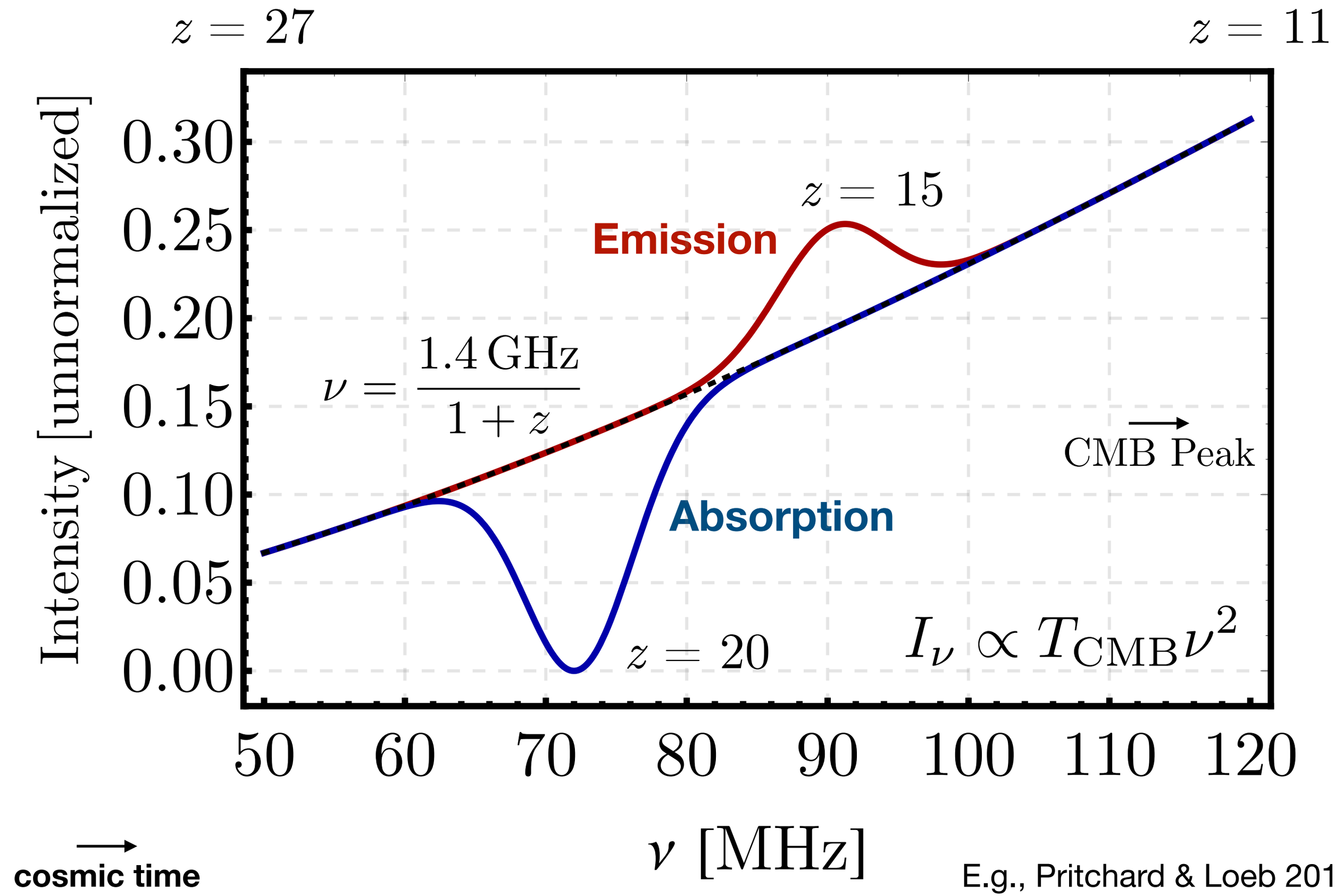
cosmic time

The basics of 21-cm: Absorption



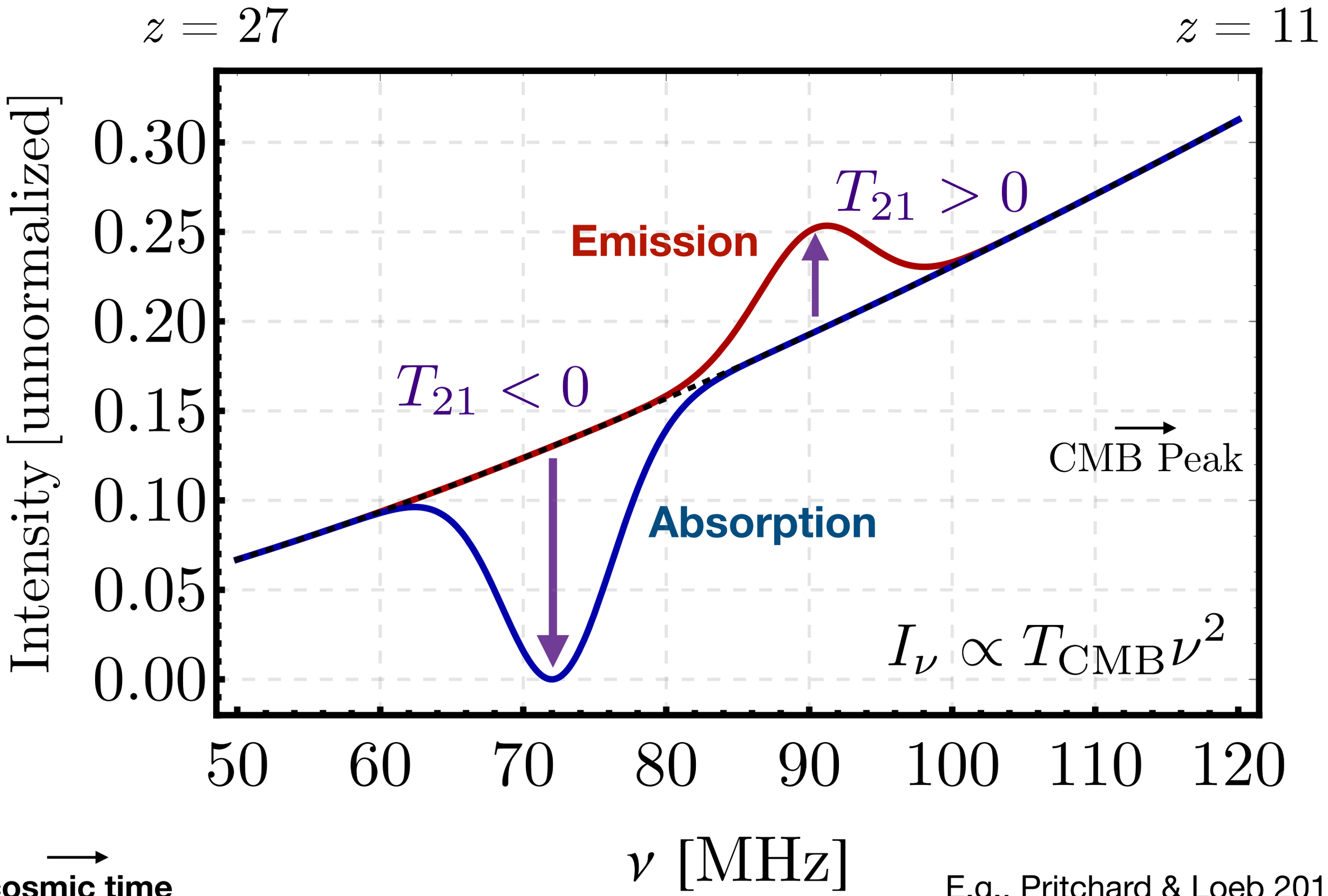
E.g., Pritchard & Loeb 2012

The basics of 21-cm: Emission



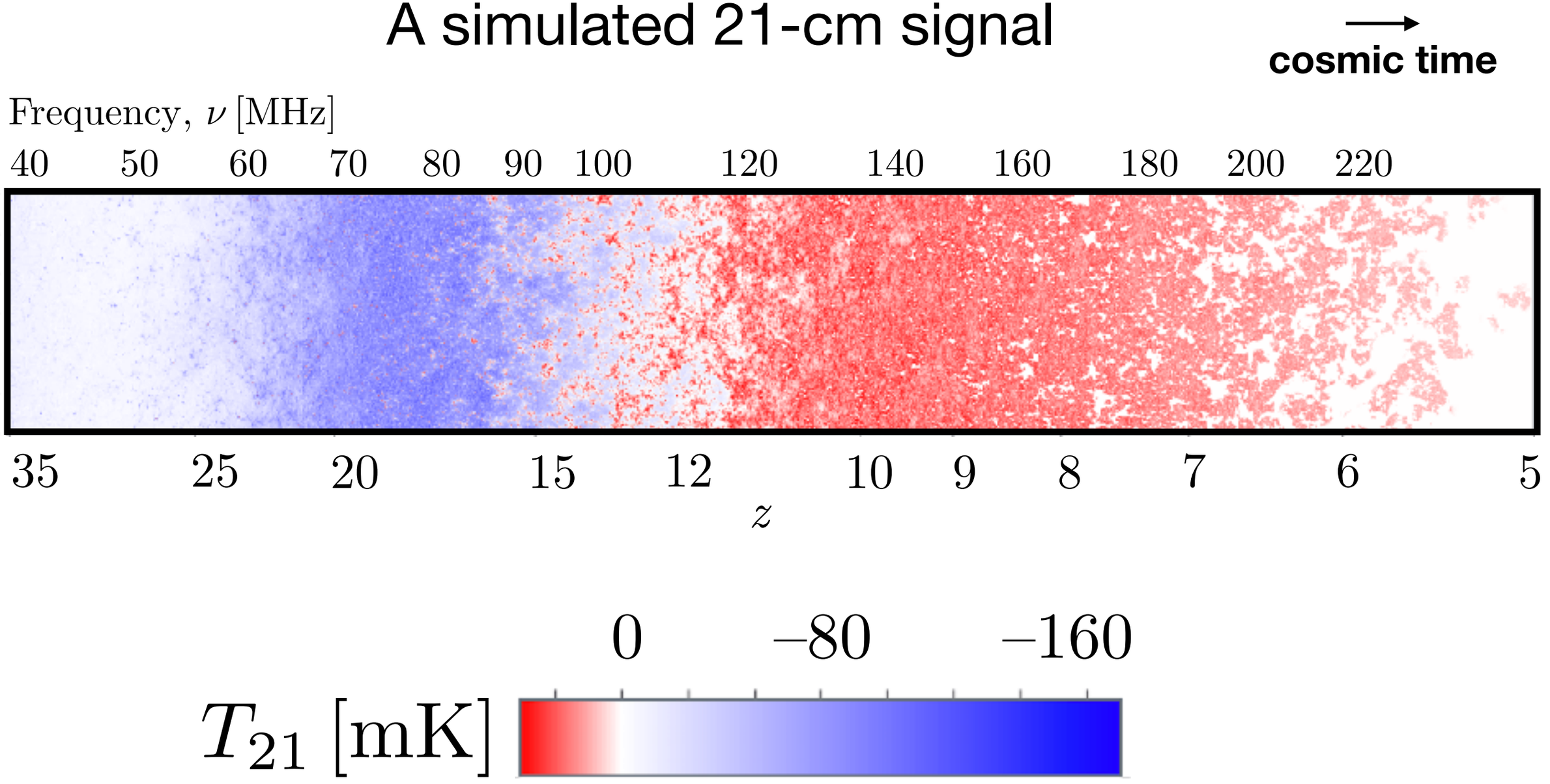
E.g., Pritchard & Loeb 2012

What would we see?



E.g., Pritchard & Loeb 2012

A simulated 21-cm signal

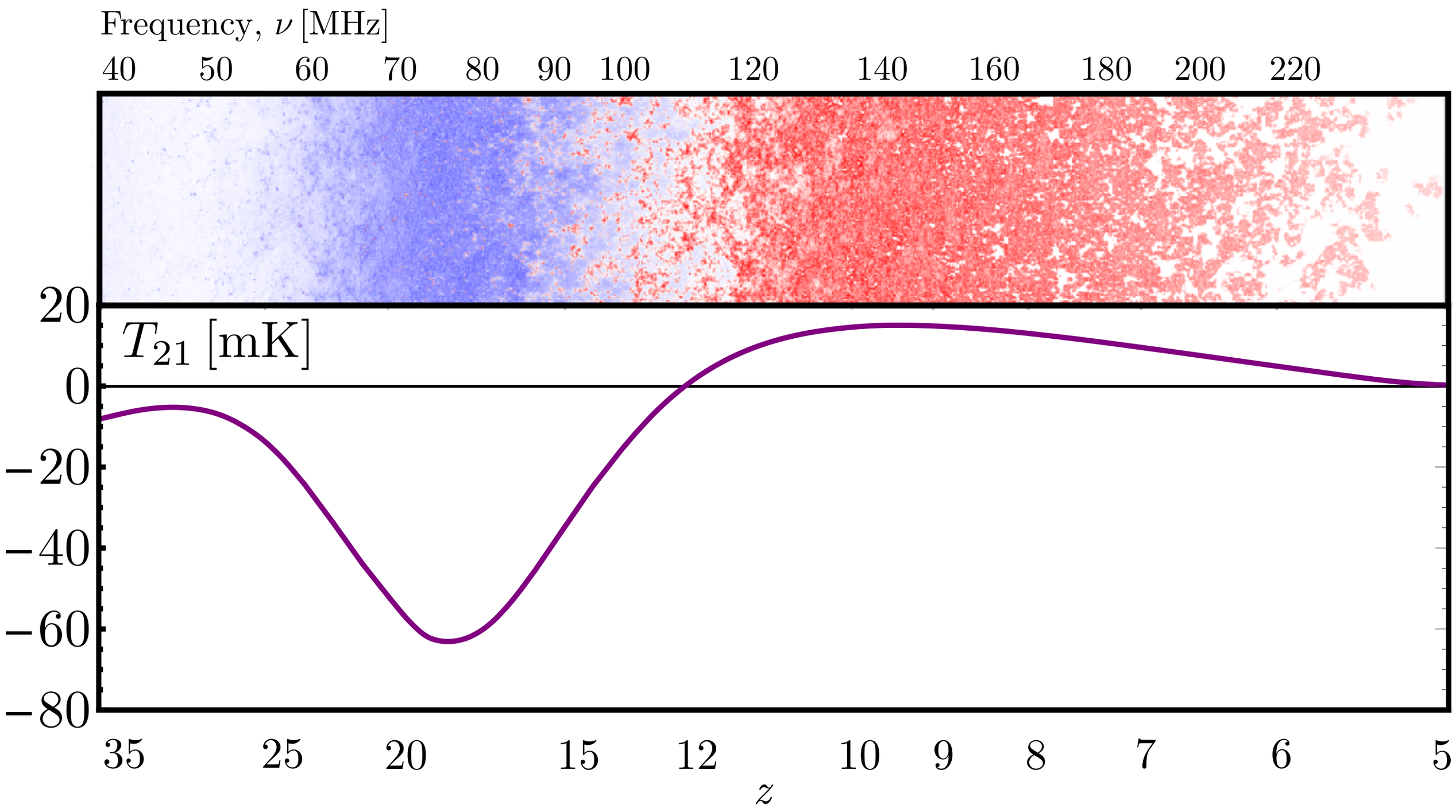


JBM 2019 https://github.com/JulianBMunoz/21cmvFAST

JBM, Qin, Murray, Greig, Mesinger+ (In prep. 2021?) https://github.com/21cmfast/21cmFAST

A simulated 21-cm **global** signal

cosmic time →



JBM 2019 https://github.com/JulianBMunoz/21cmvFAST

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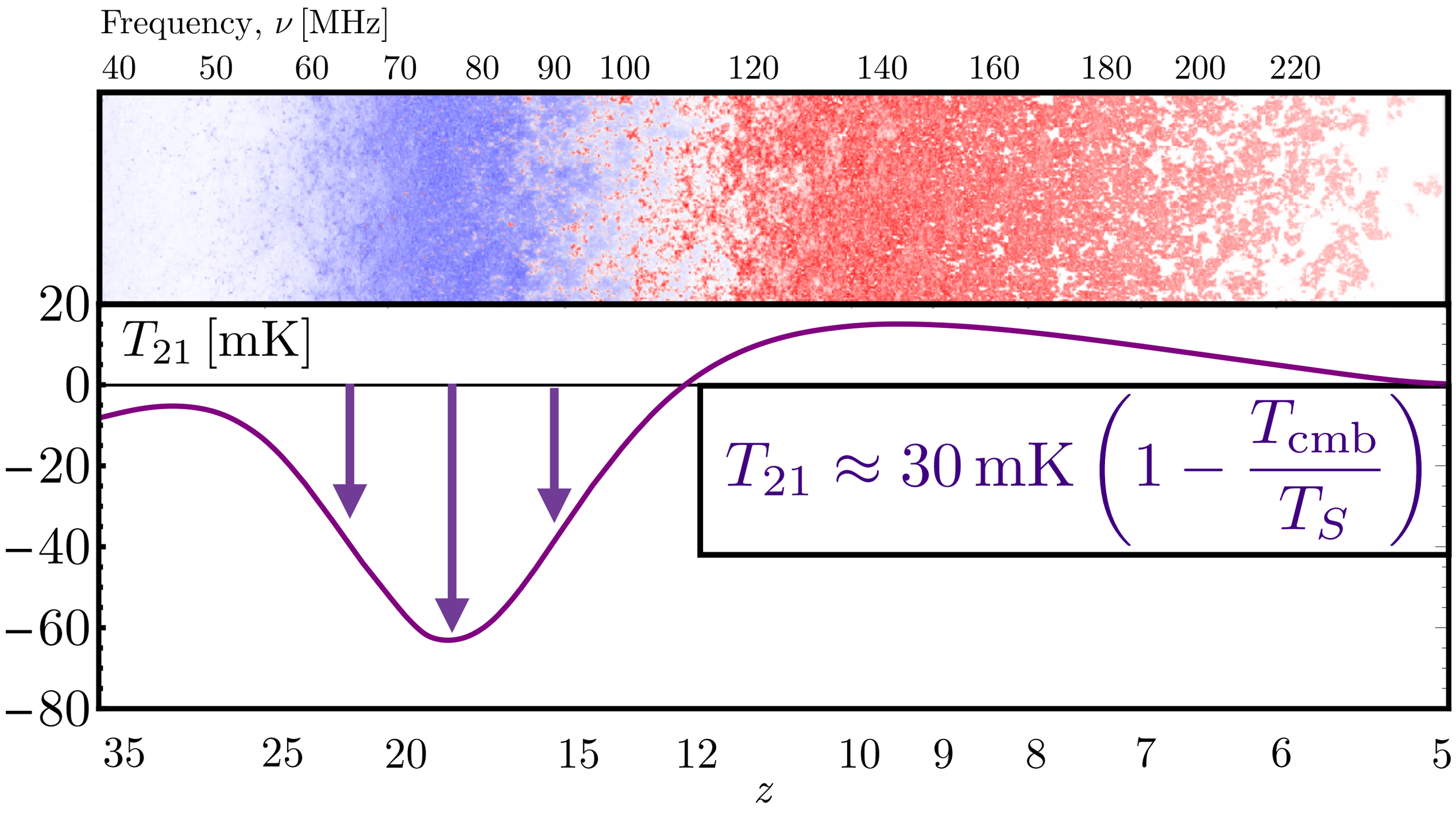
21-cm as a **thermometer** at high z

cosmic time →



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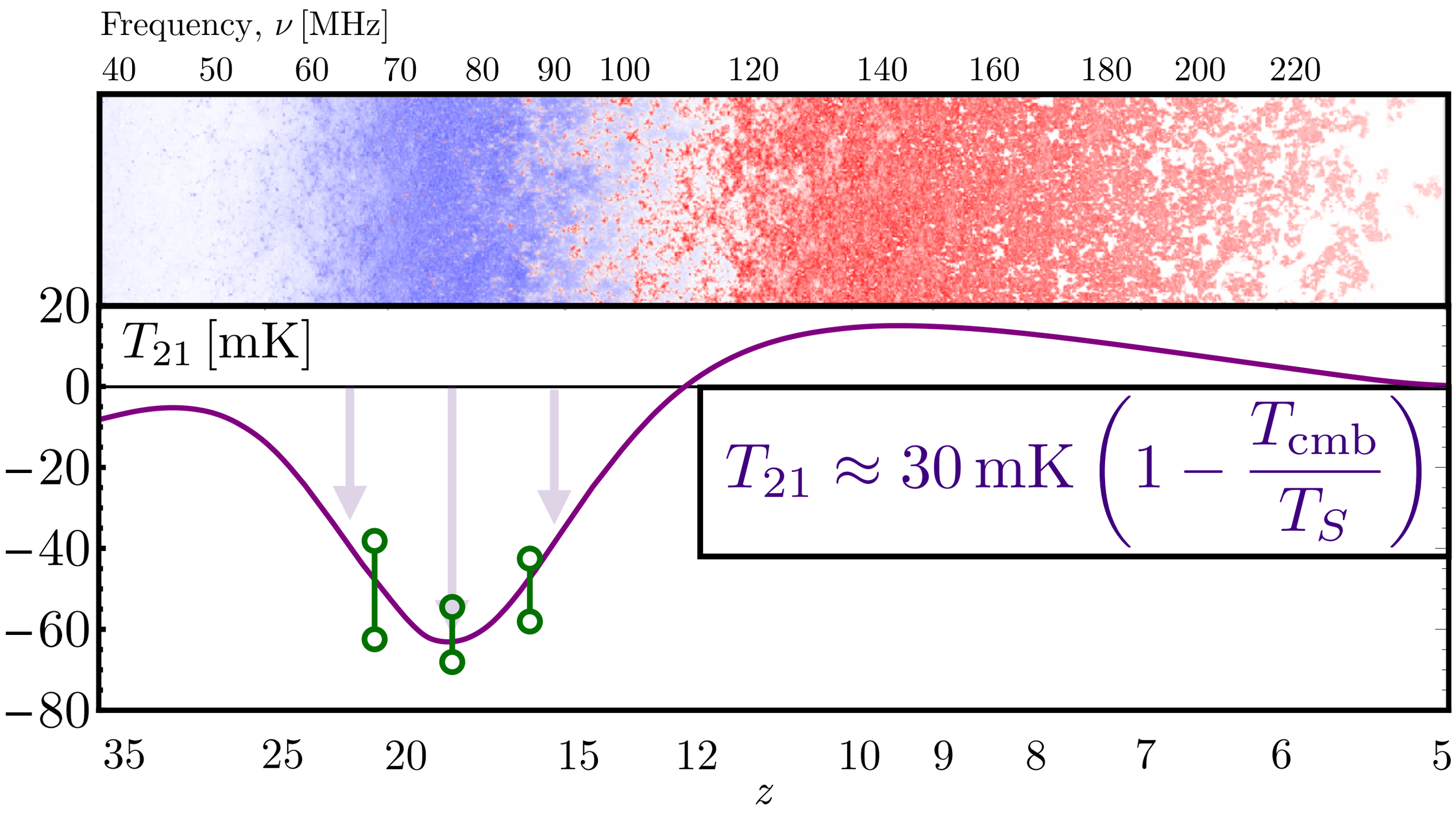
21-cm as a **thermometer** at high z

cosmic time →

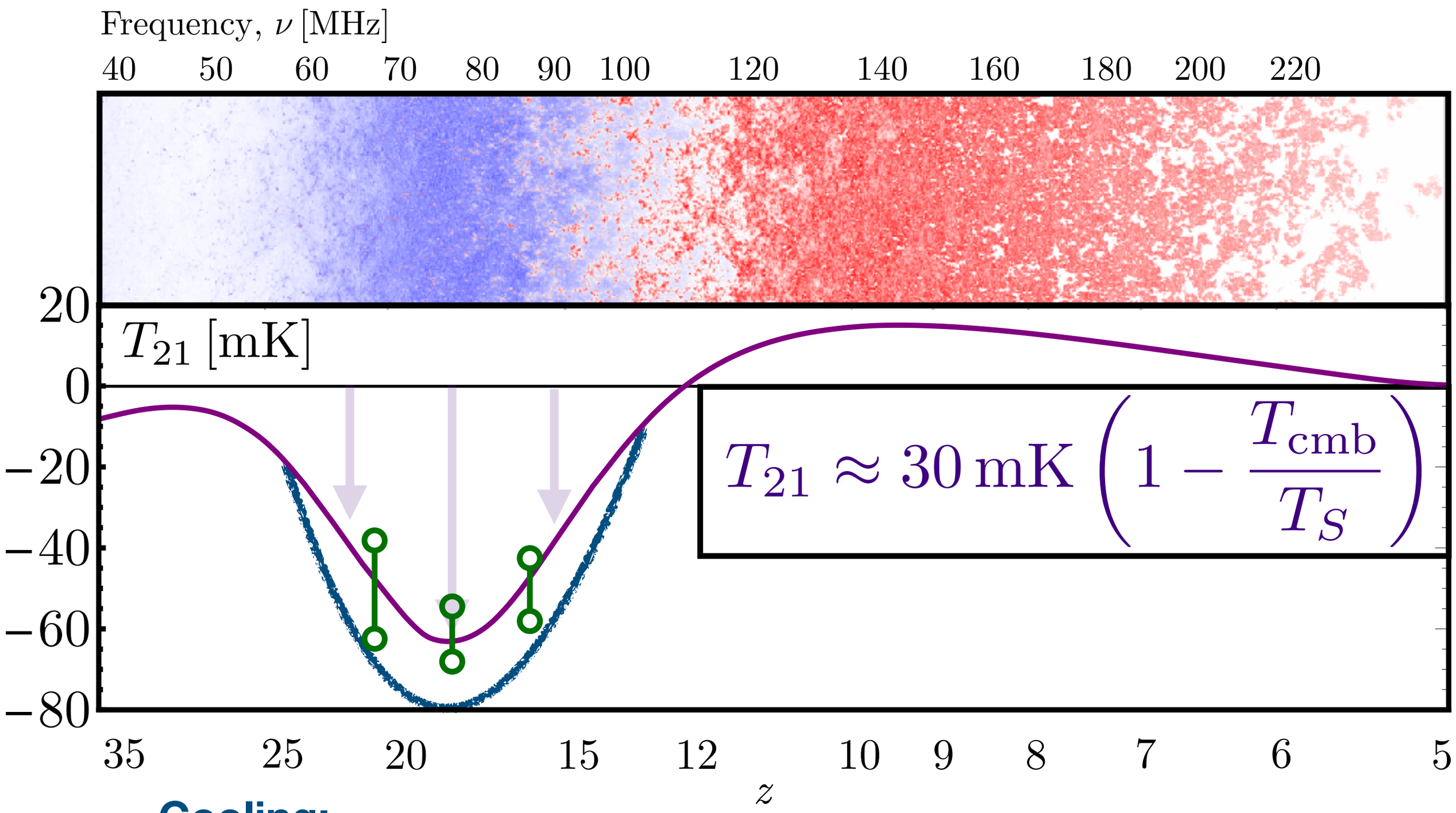


Learn about first galaxies:

Pritchard+ 11
Fialkov+ 14
Park+ 19

21-cm as a **thermometer** at high z

cosmic time →



Cooling:

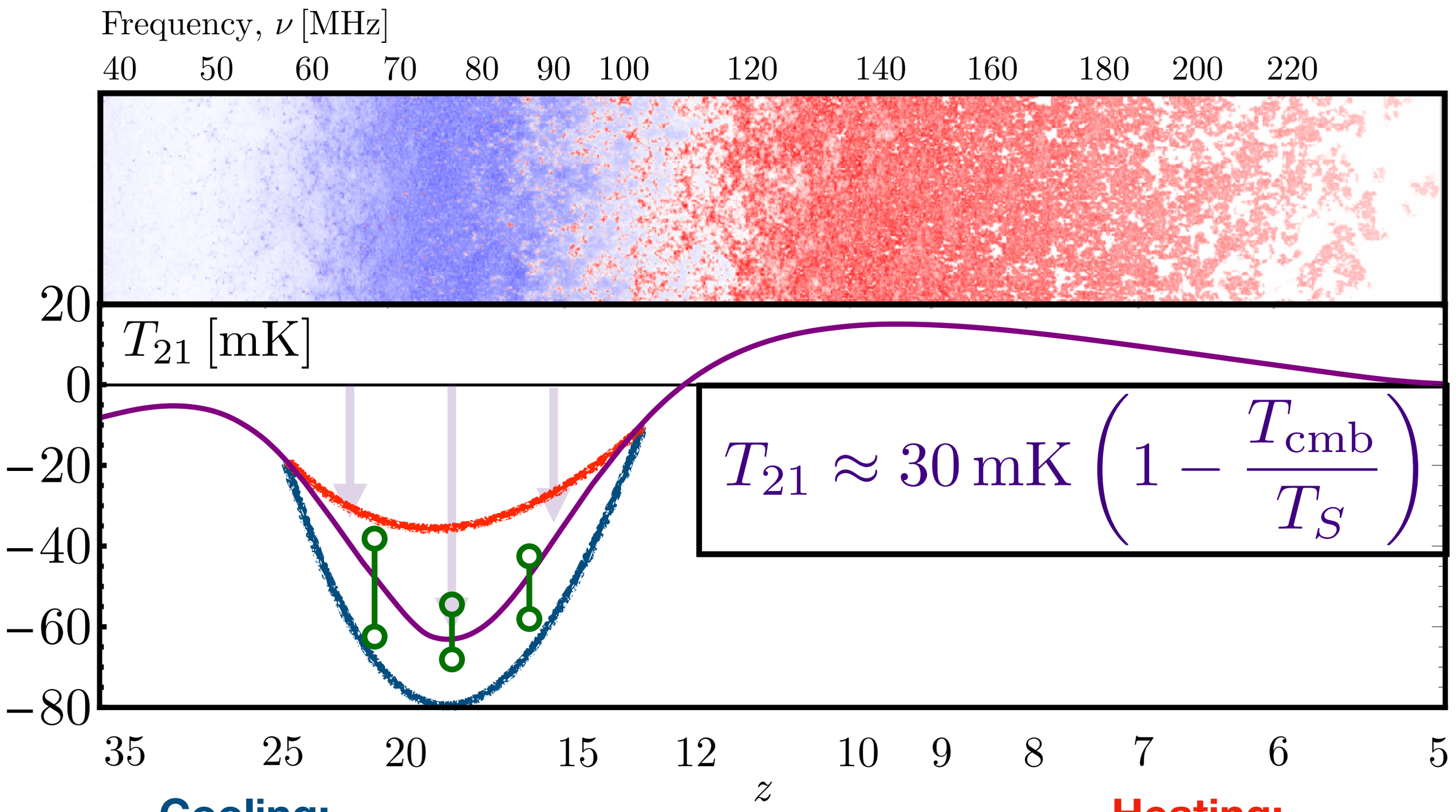
5th force: Tashiro+, **JBM**, Ali-Haïmoud & Kovetz 2015

mQ: **JBM** & Loeb, Barkana+, Berlin+ 2018…

Radio: Fraser+, Pospelov+ 18,

21-cm as a **thermometer** at high z

cosmic time →



Cooling:

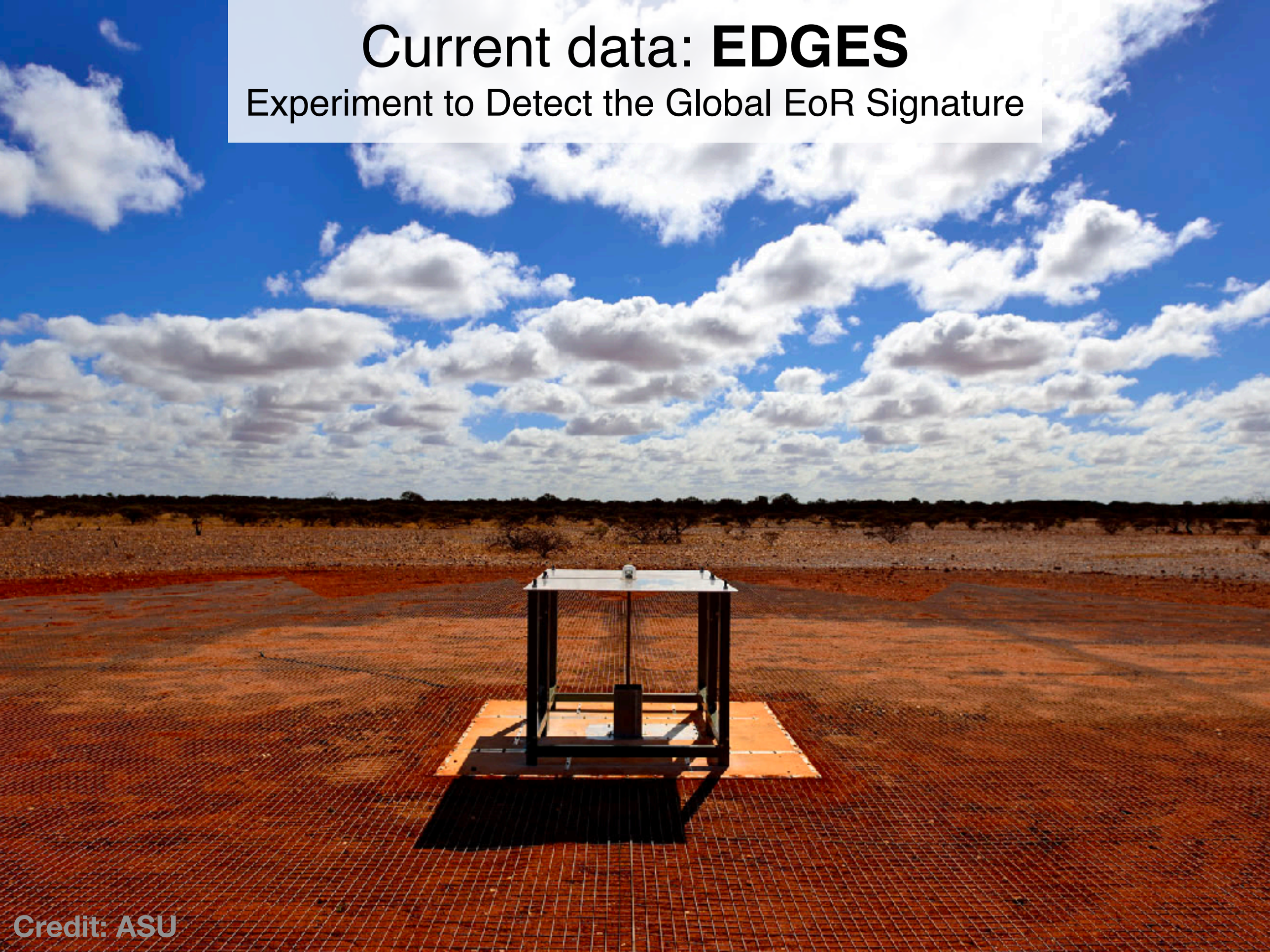
5th force: Tashiro+, **JBM**, Ali-Haïmoud & Kovetz 2015
mQ: **JBM** & Loeb, Barkana+, Berlin+ 2018…
Radio: Fraser+, Pospelov+ 18,

Heating:

WIMP: Lopez-Honorez+ 2016
Liu & Slatyer, D'Amico+ 2018
PBHs: Clark+ 2018,
A' DM: Kovetz, Cholis, Kaplan 2018

Current data: **EDGES**

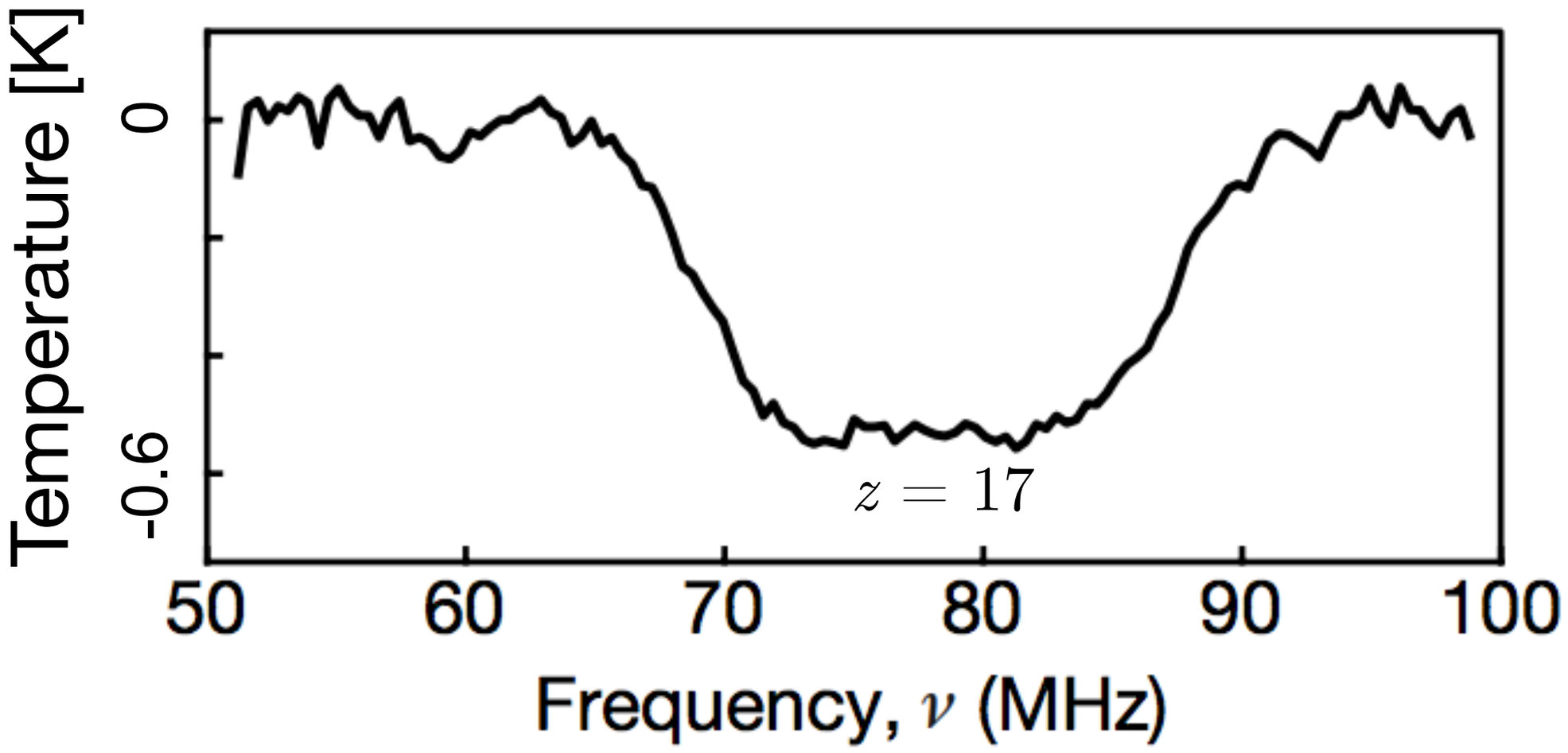
Experiment to Detect the Global EoR Signature



Credit: ASU

Current data: **EDGES** (Low-Band)

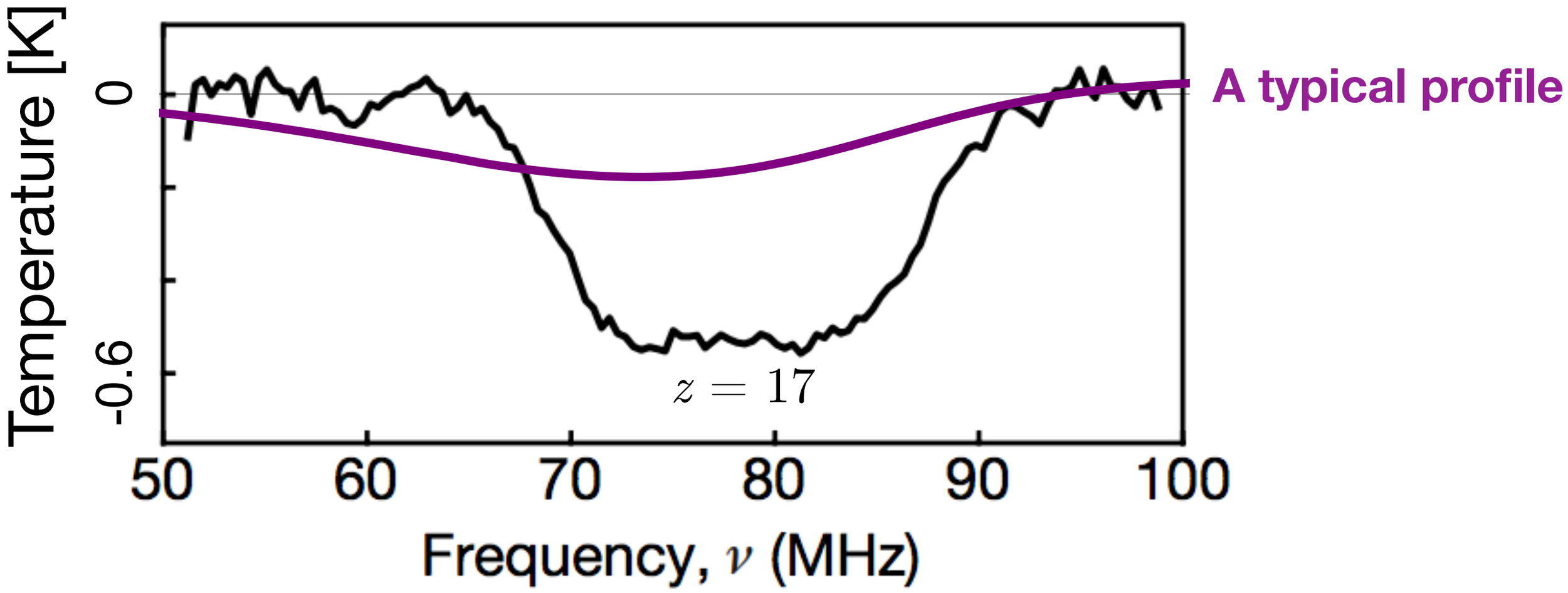
(+foregrounds subtracted!)



Bowman et al. Nature 2018

Current data: **EDGES** (Low-Band)

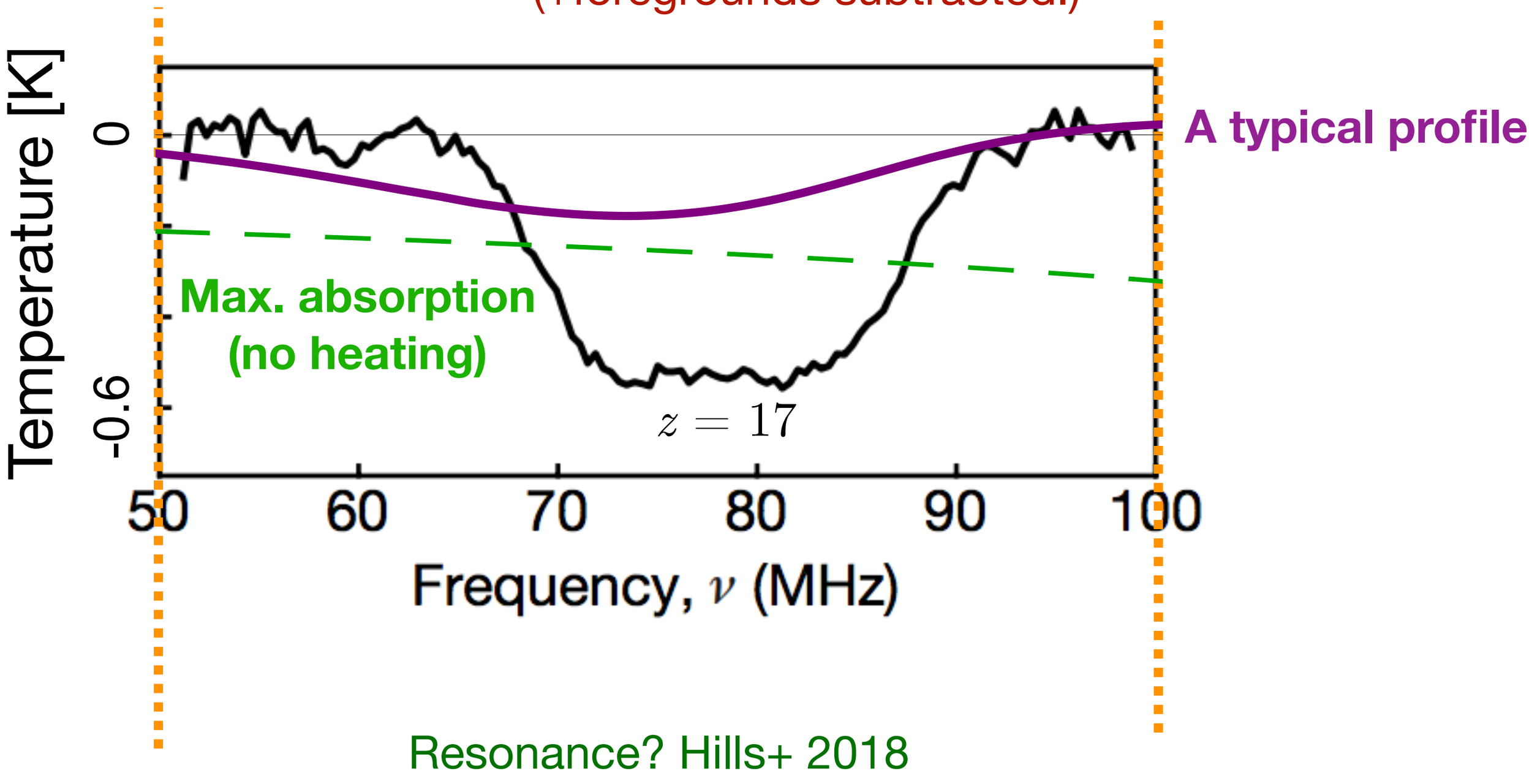
(+foregrounds subtracted!)



Bowman et al. Nature 2018

Current data: **EDGES** (Low-Band)

(+foregrounds subtracted!)

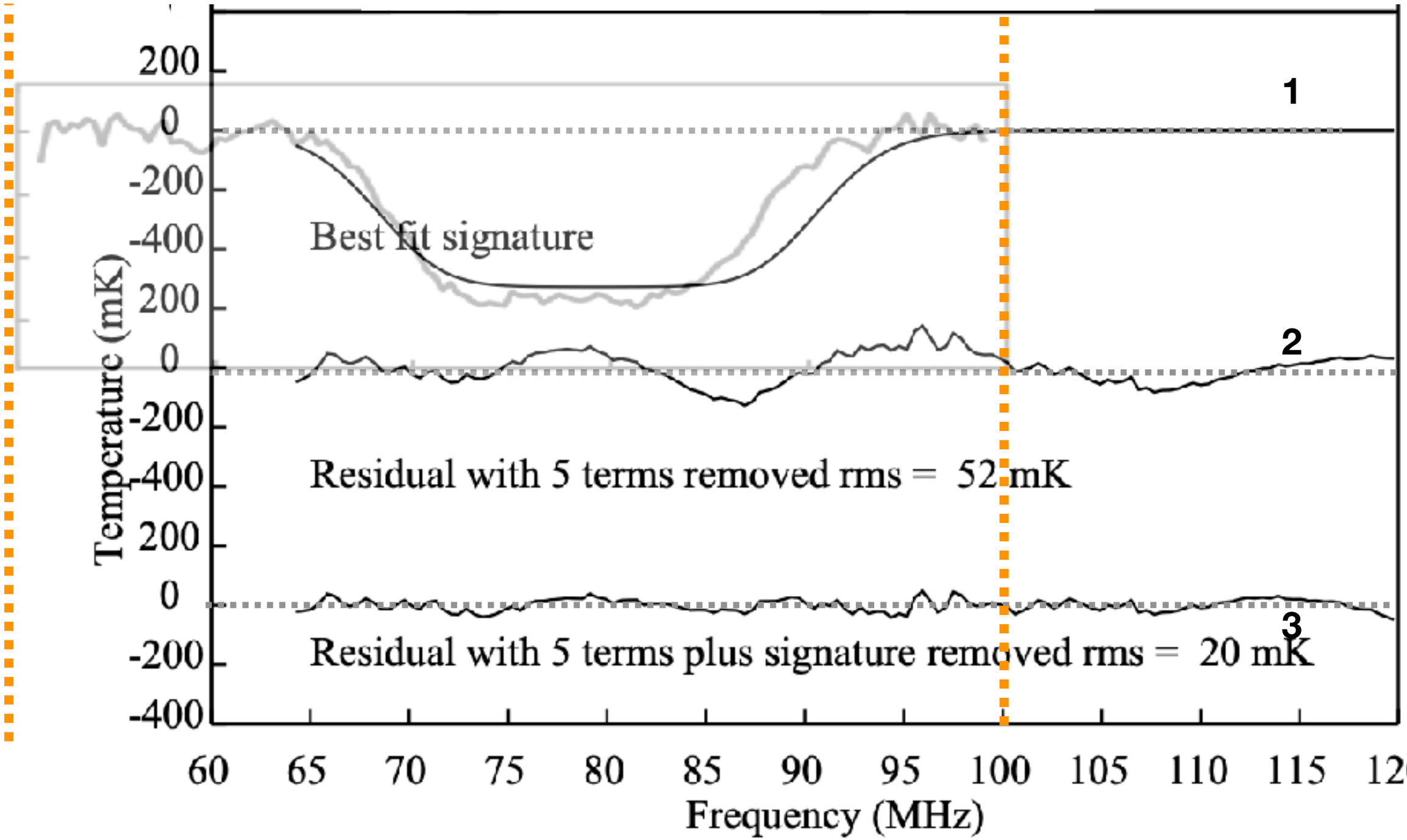


Resonance? Hills+ 2018

Bowman et al. Nature 2018

Mid-Band EDGES

(+foregrounds subtracted!)

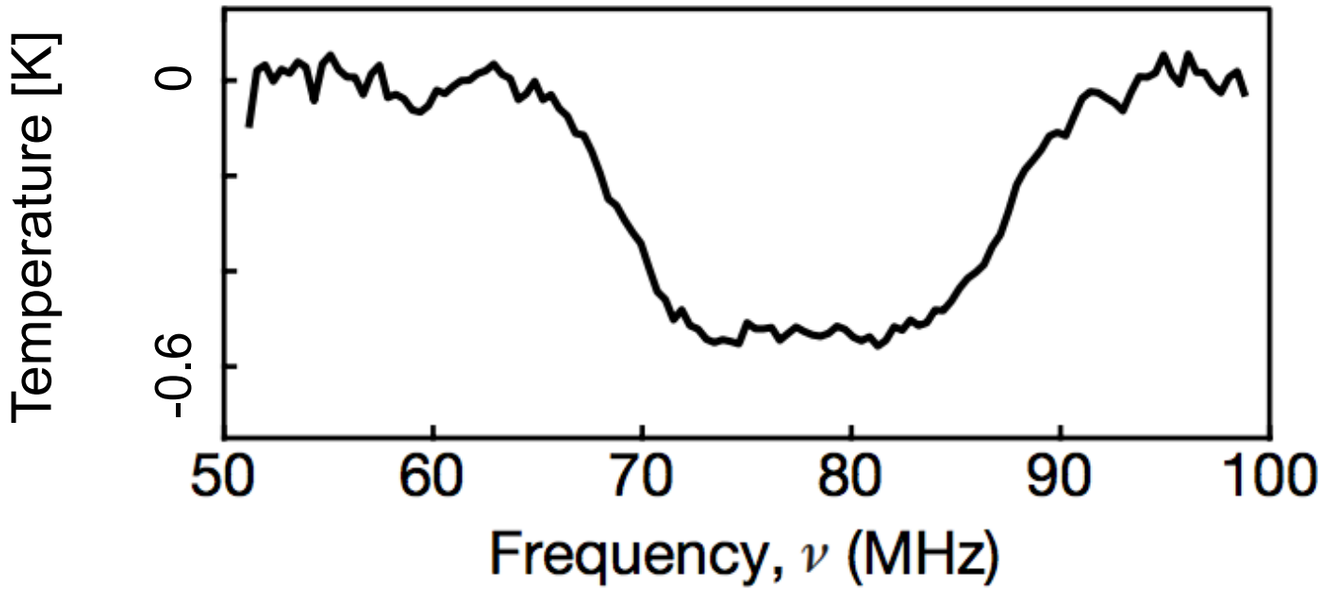


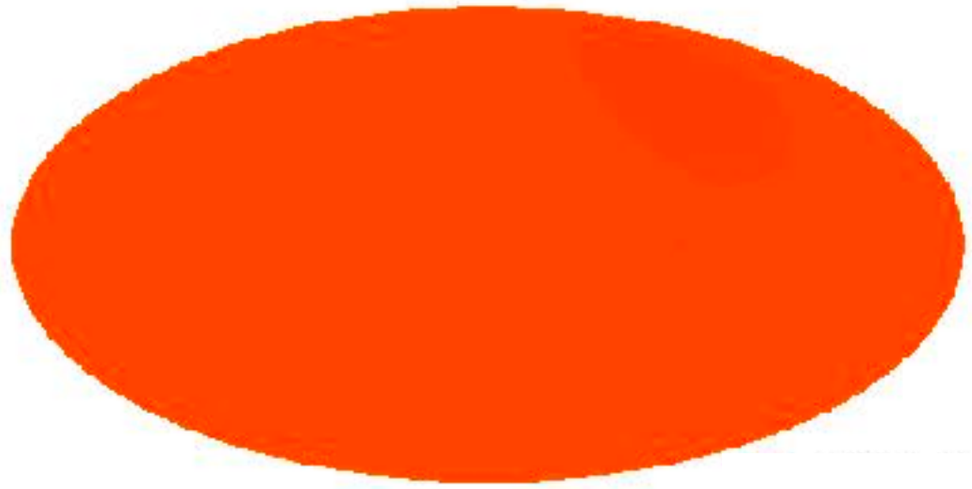
-Awaiting second result: **LEDA, SARAS, SciHi,…**

EDGES memo 354

21-cm Global Signal = CMB Monopole

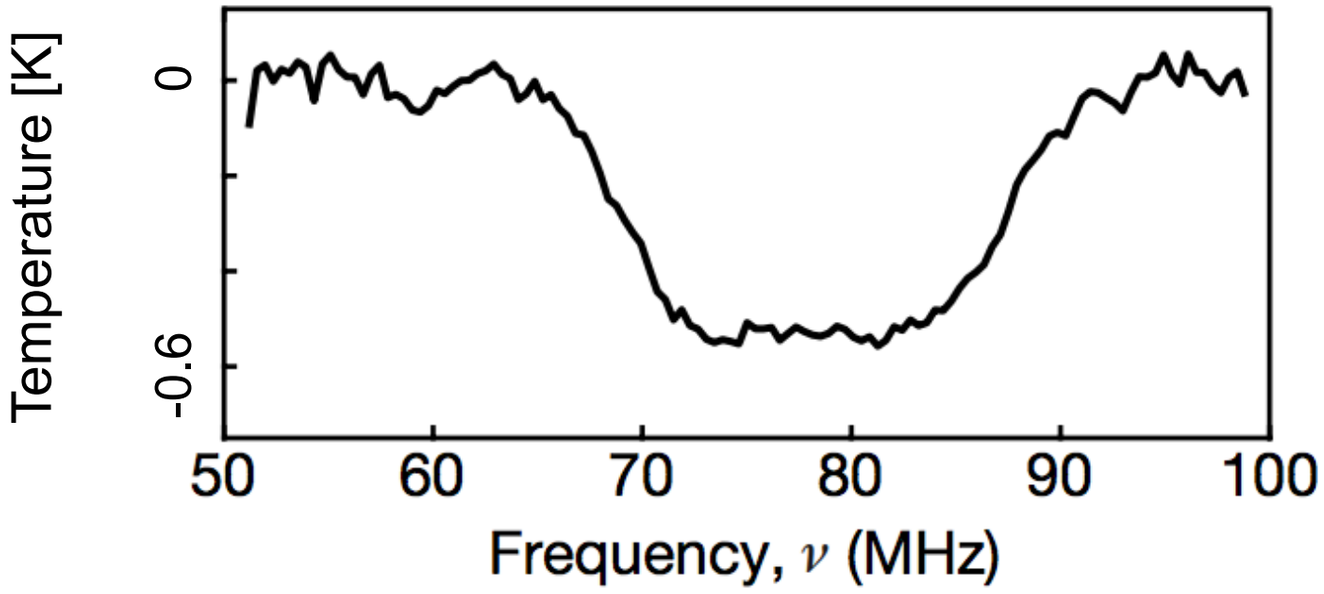
(**EDGES**, LEDA, SARAS, Sci-HI,…)

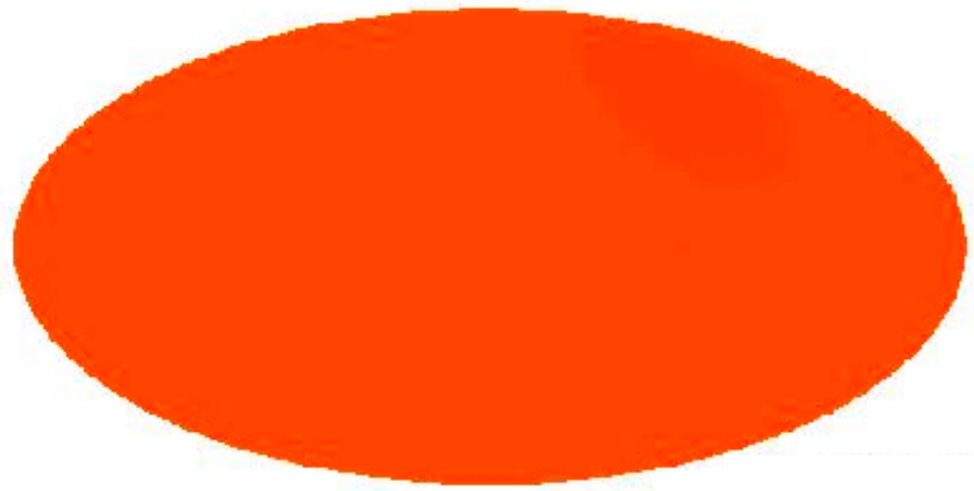




21-cm Global Signal = CMB Monopole

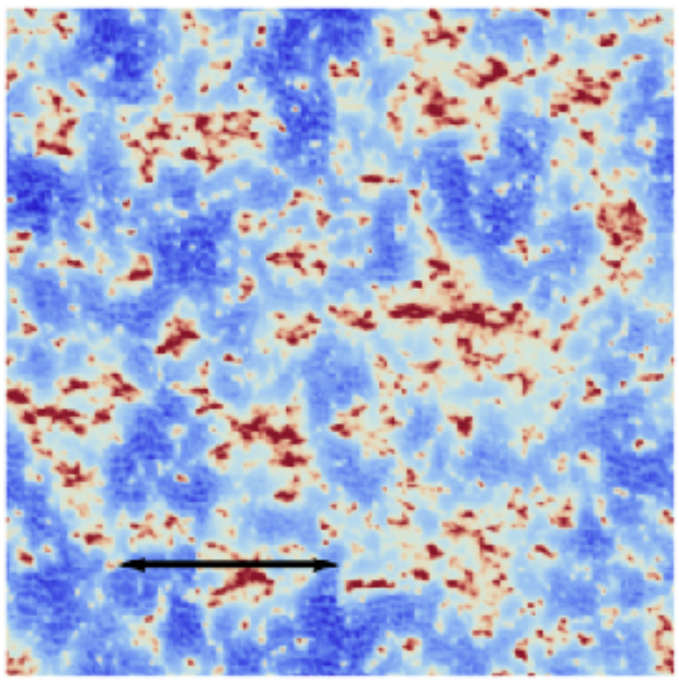
(**EDGES**, LEDA, SARAS, Sci-HI,…)

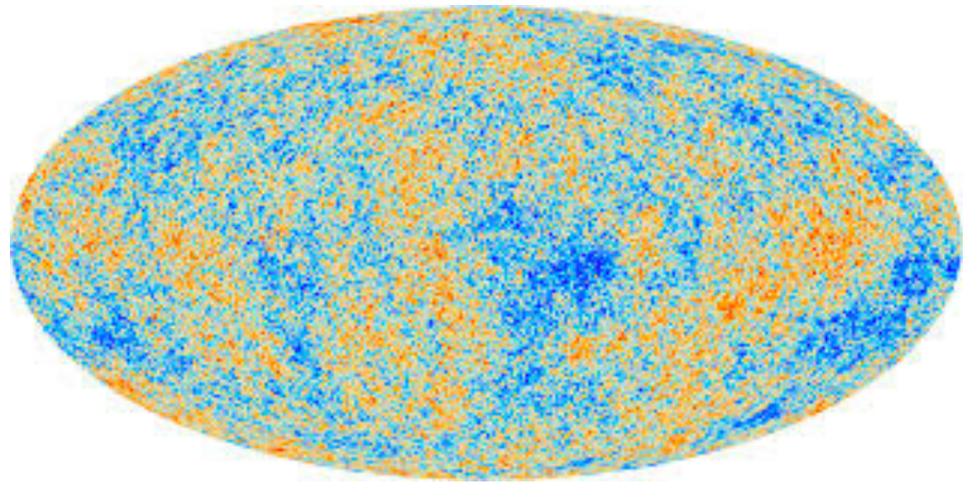


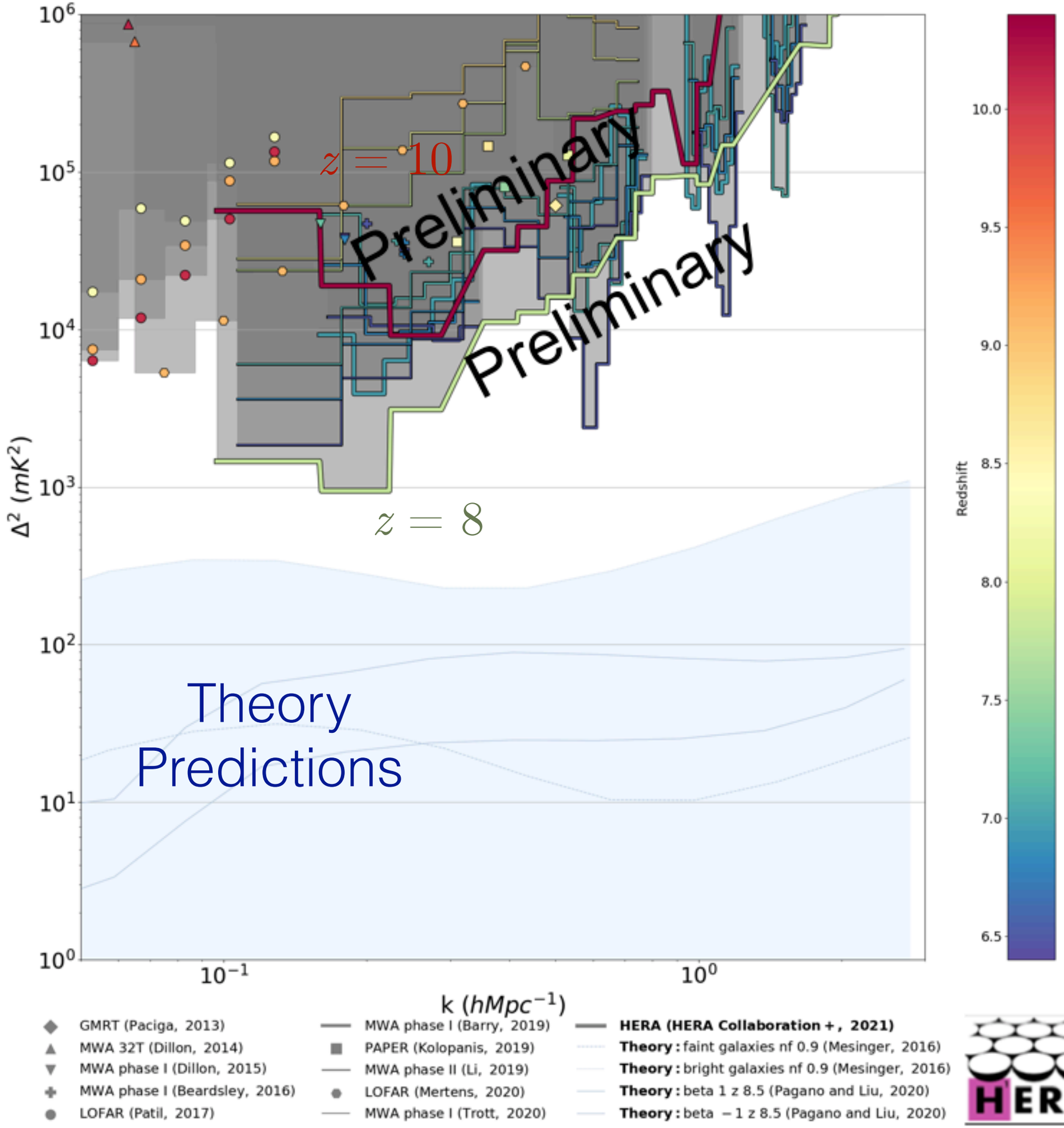


21-cm Fluctuations = CMB Anisotropies

(**HERA**, MWA, LWA, PAPER, SKA,…)



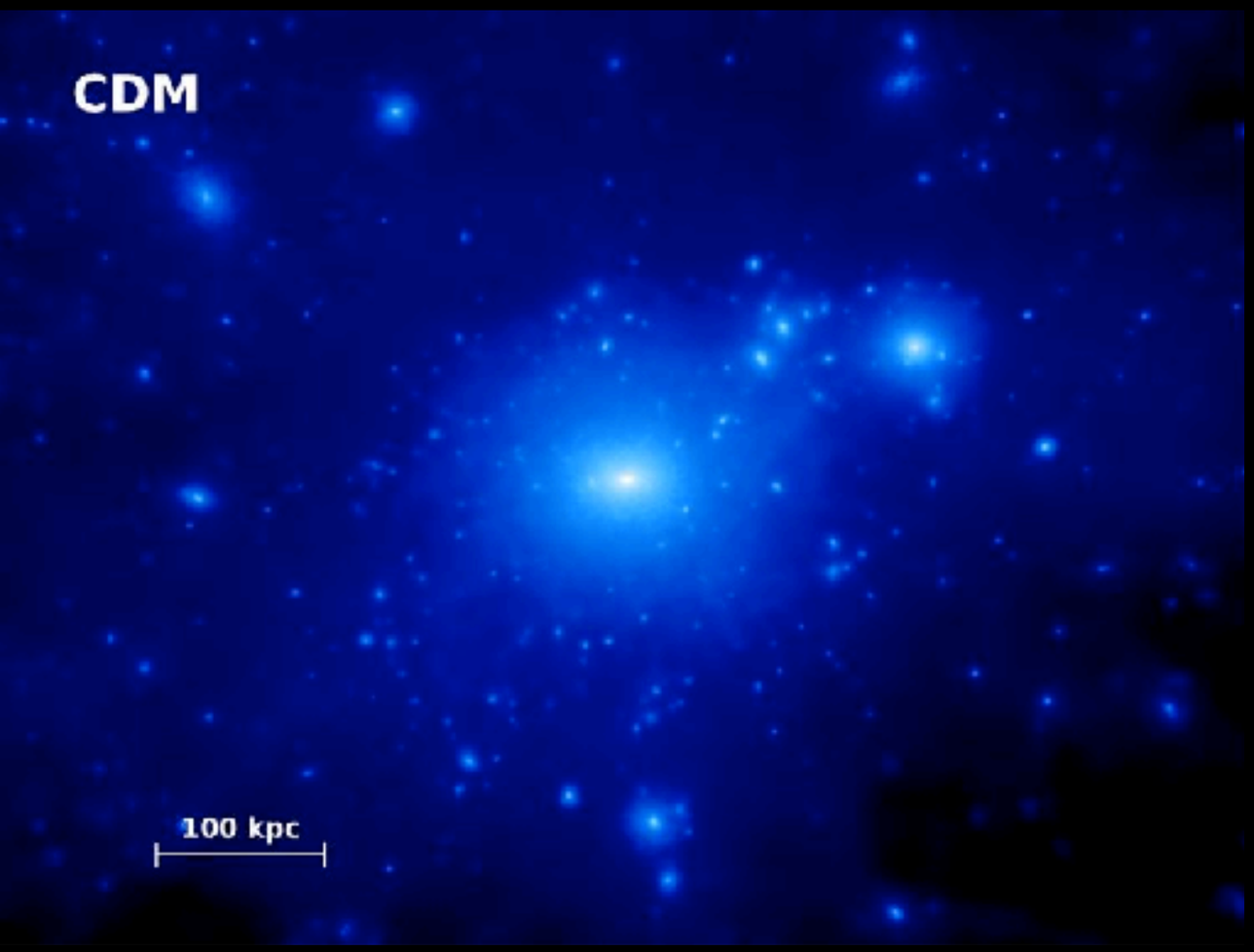




HERA coll. ++
(in prep.)

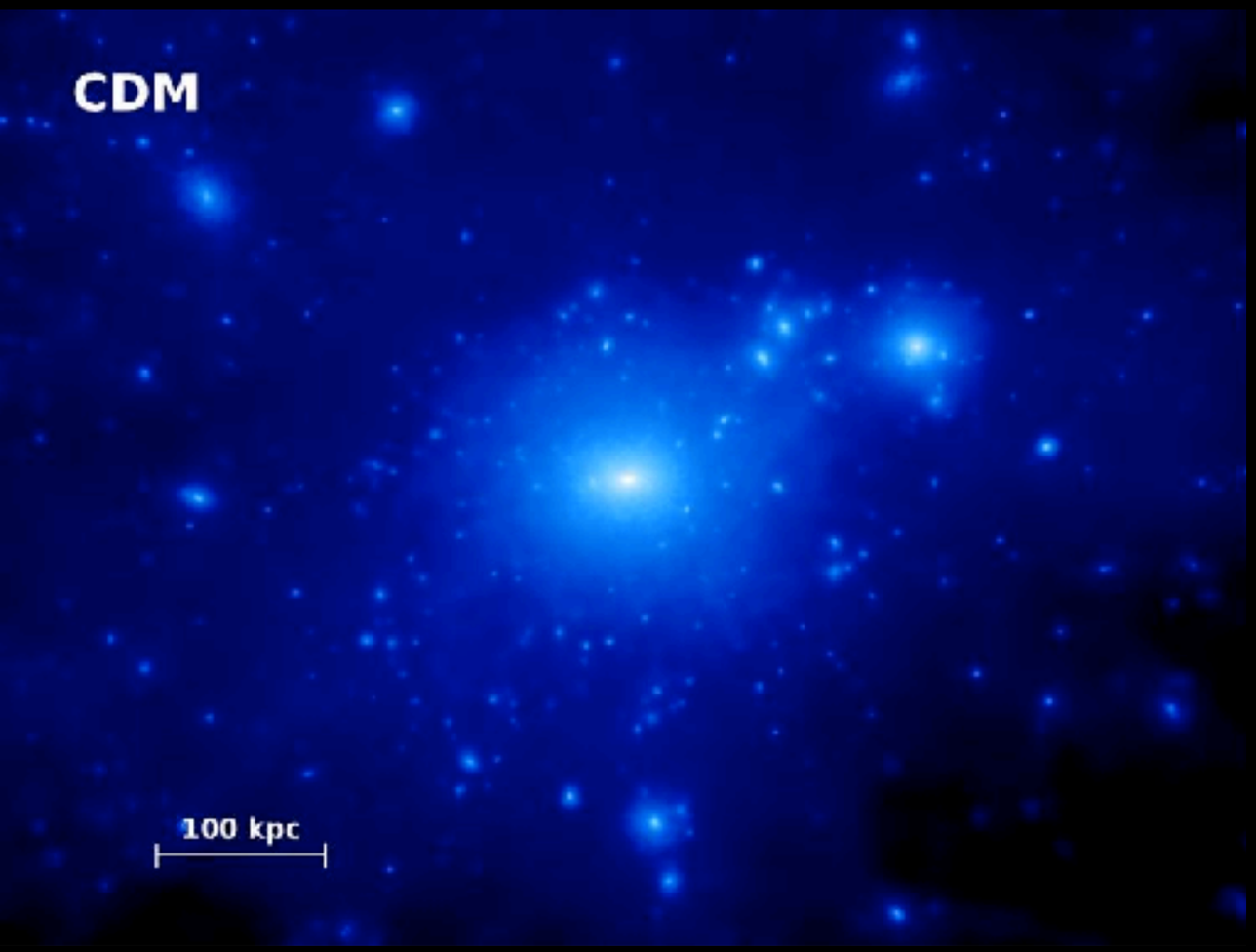
~20 nights
~50 antennas

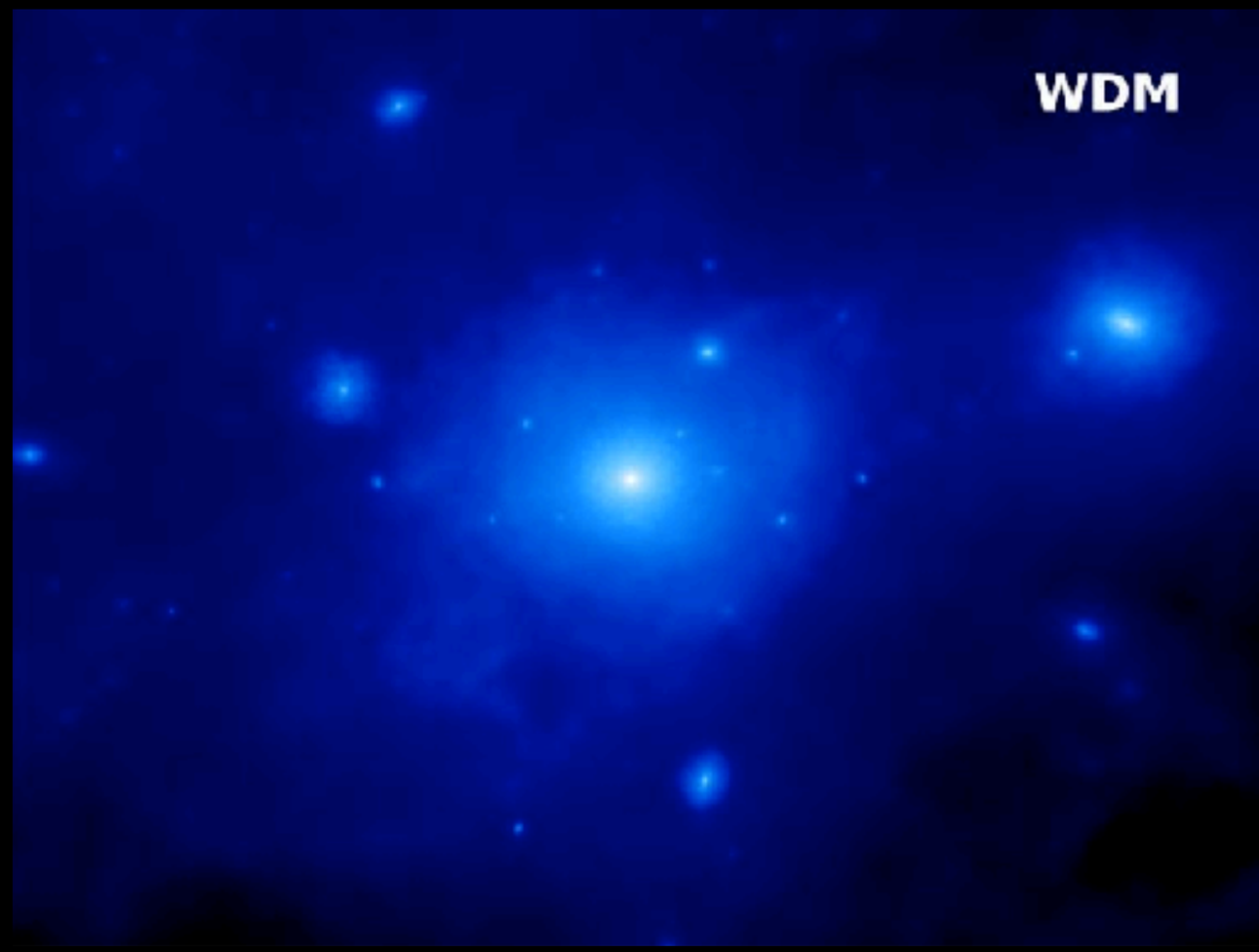
Is DM cold?



Credit: Boehm (IPP Durham)

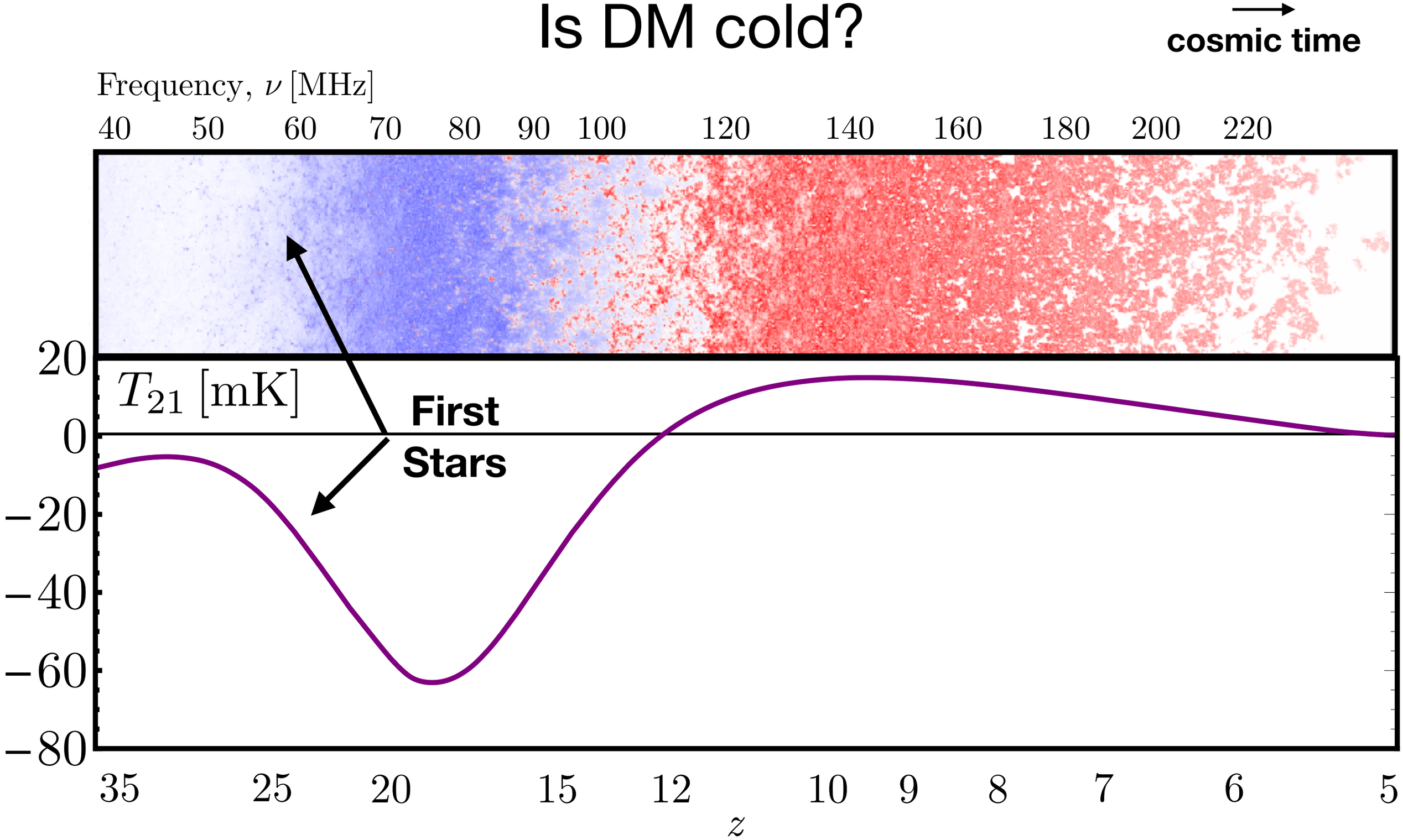
Is DM cold?



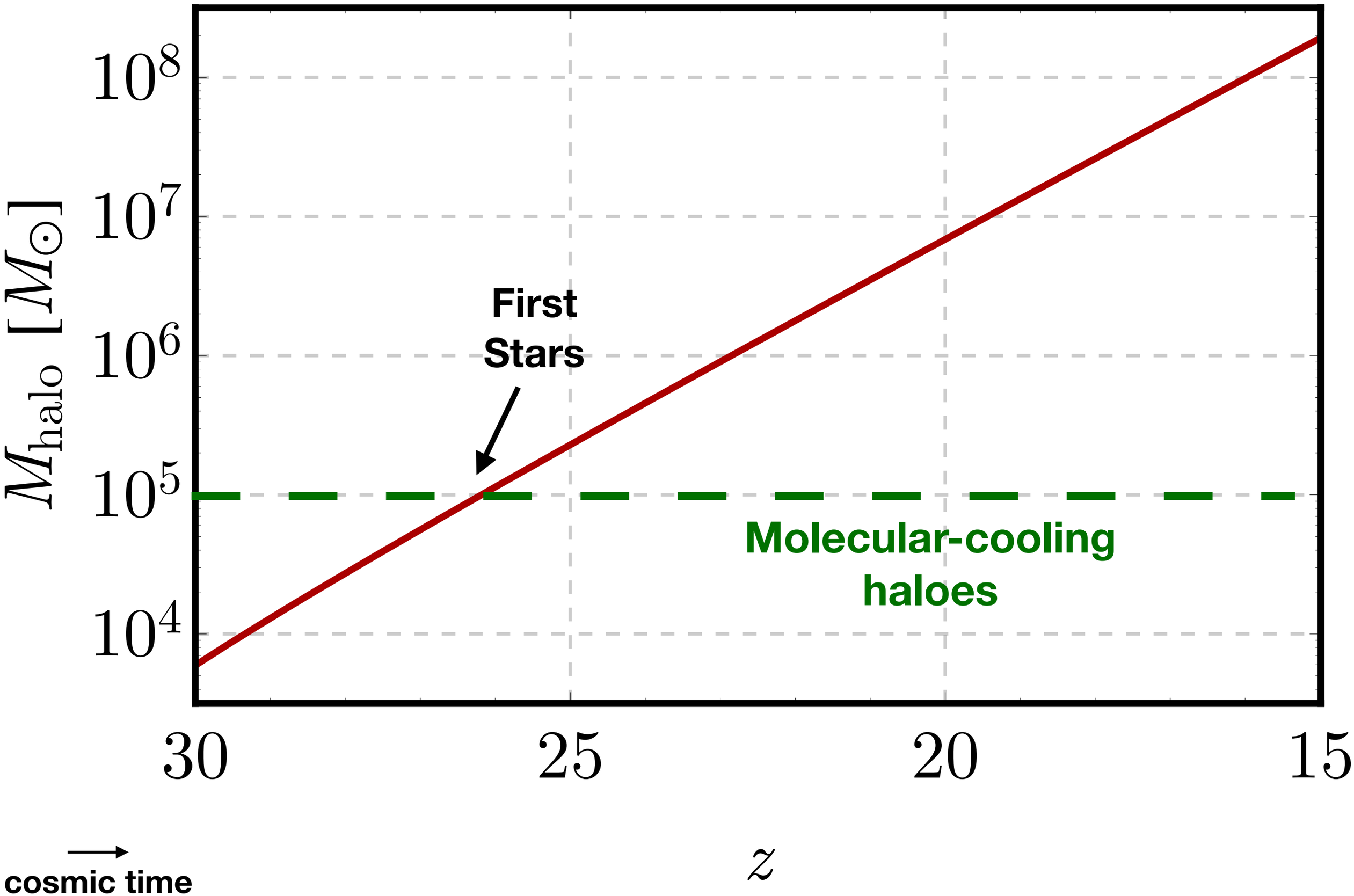


Credit: Boehm (IPP Durham)

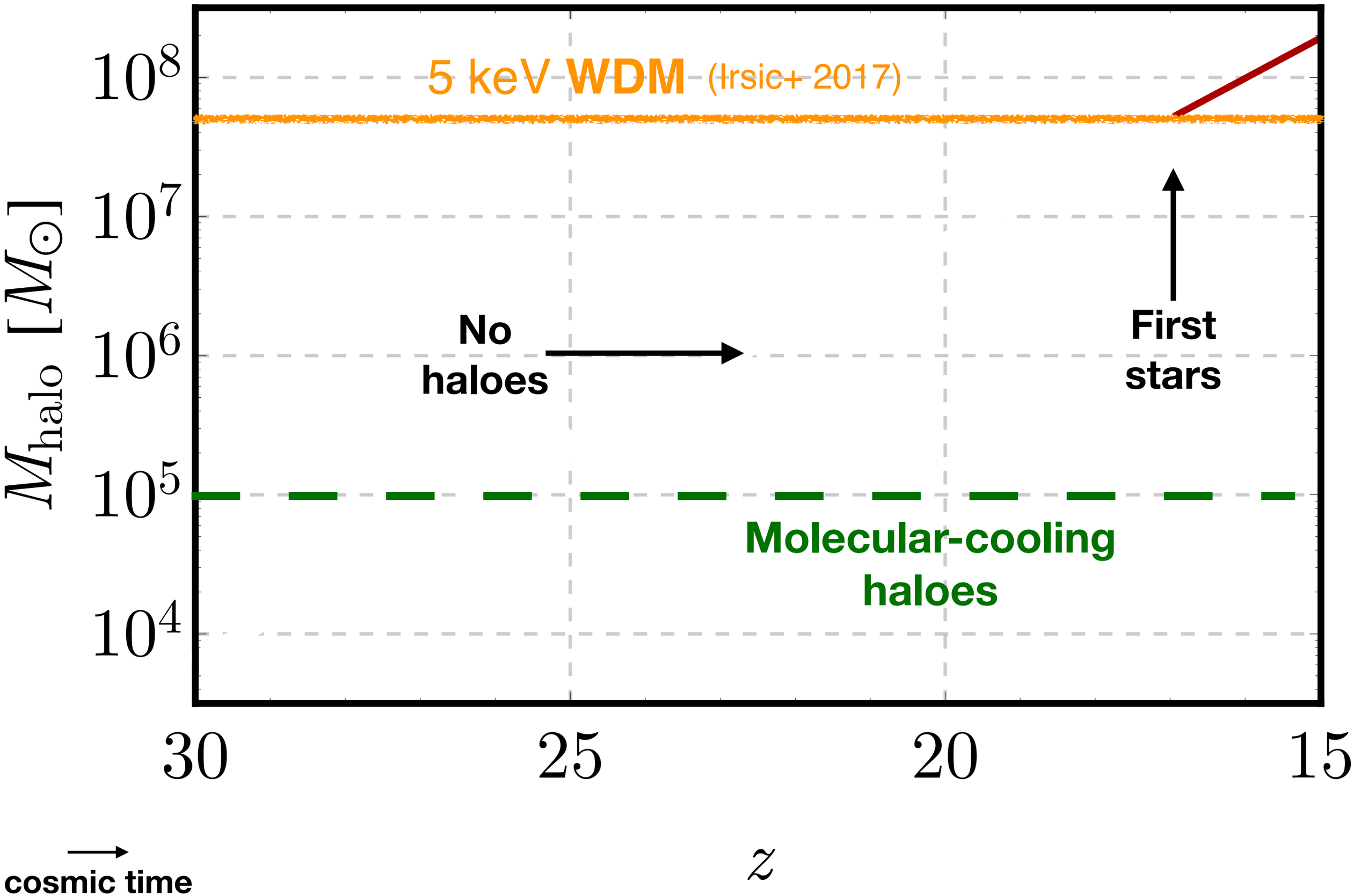
Is DM cold?


cosmic time
Frequency, ν [MHz]
40
50
60
70
80
90
100
120
140
160
180
200
220
20
0
−20
−40
−60
−80
T_{21} [mK]
First
Stars
35
25
20
15
12
10
9
8
7
6
5
z

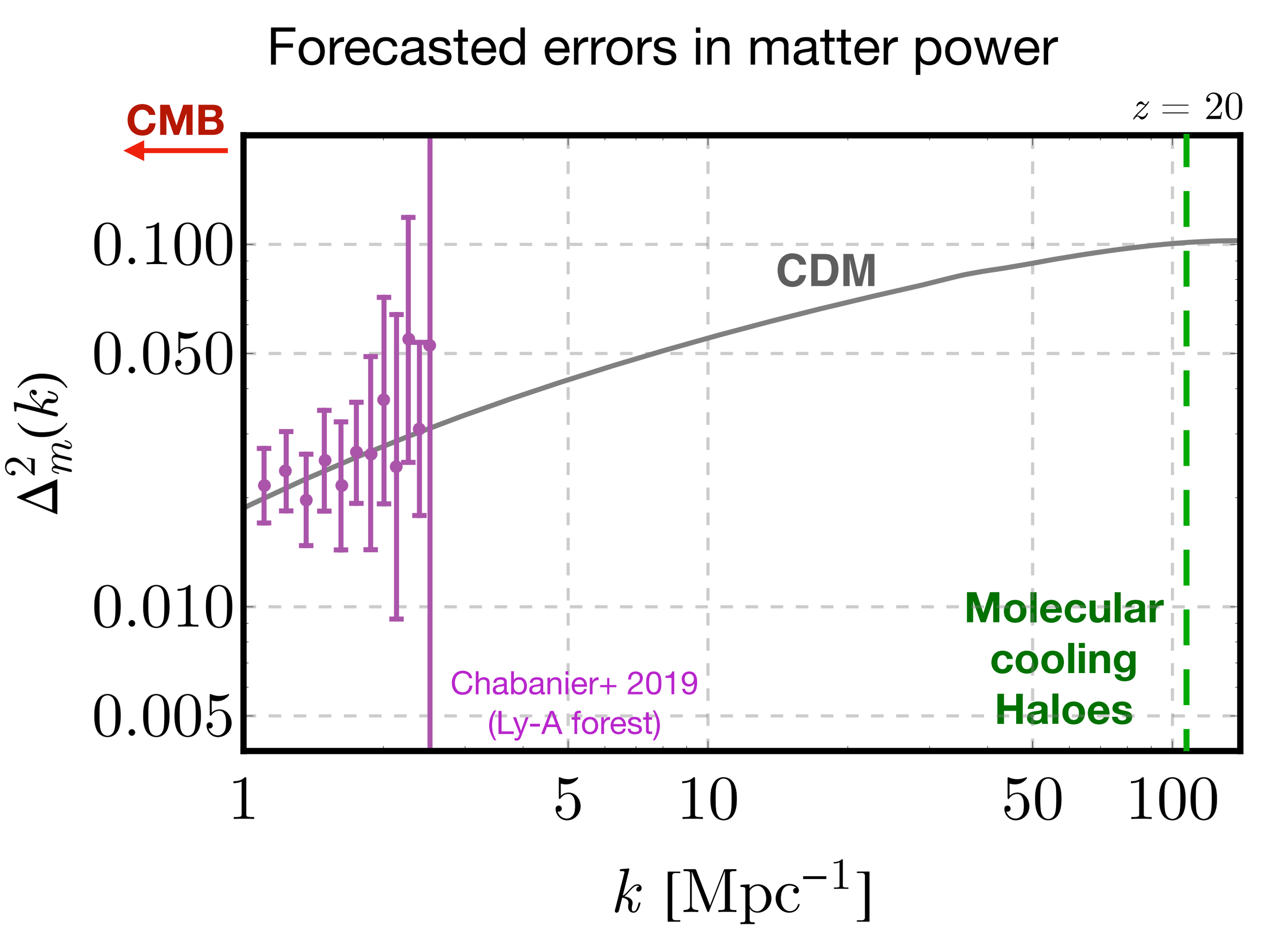
Is DM cold?


10^8
10^7
10^6
10^5
10^4
$M_{\rm halo}$ [$M_\odot$]
First Stars
Molecular-cooling haloes
30
25
20
15
z
cosmic time

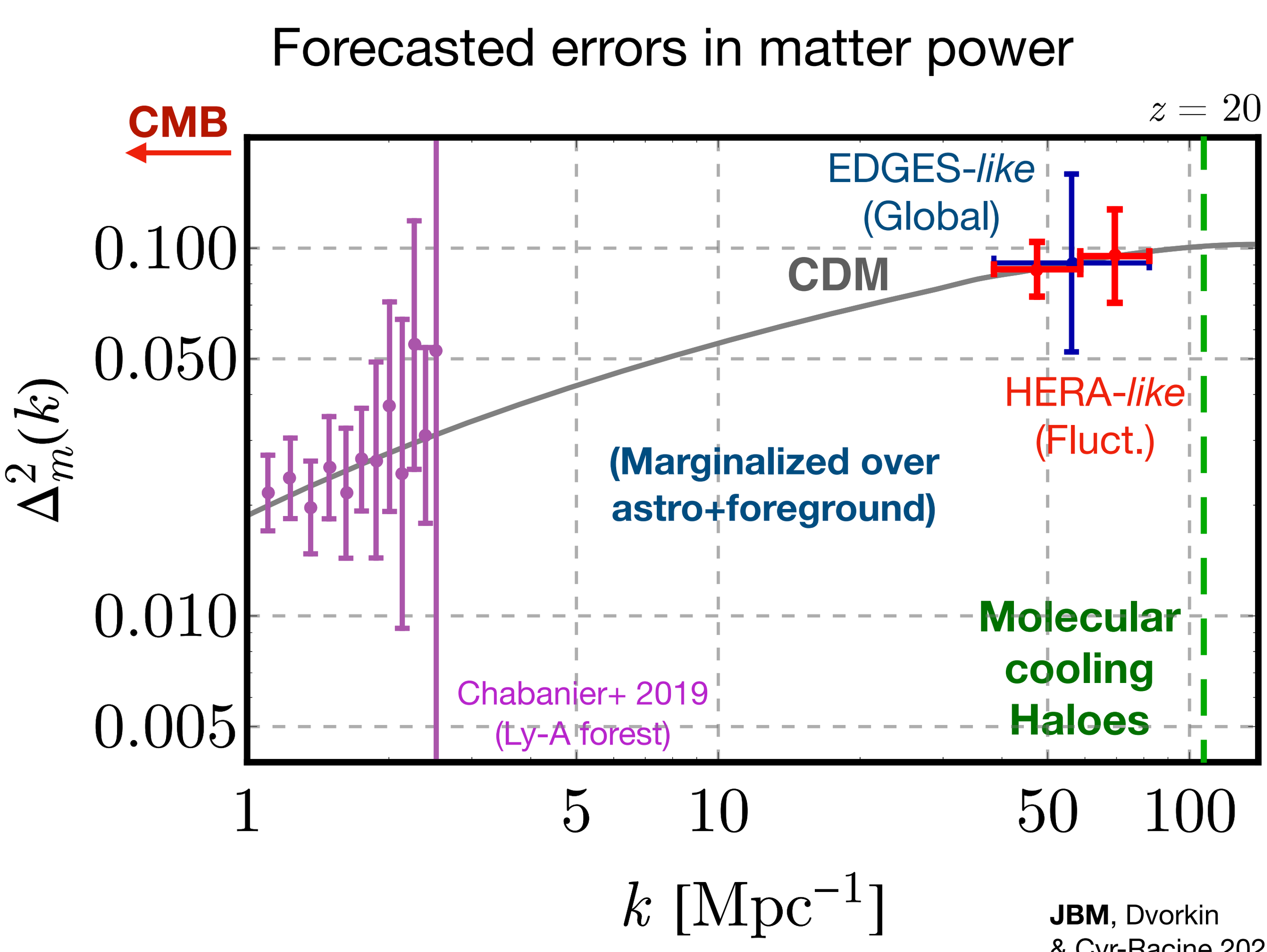
Is DM cold?


5 keV WDM (Irsic+ 2017)
No haloes
First stars
Molecular-cooling haloes
$M_{\rm halo}$ $[M_\odot]$
10^8
10^7
10^6
10^5
10^4
30
25
20
15
z
cosmic time

Forecasted errors in matter power

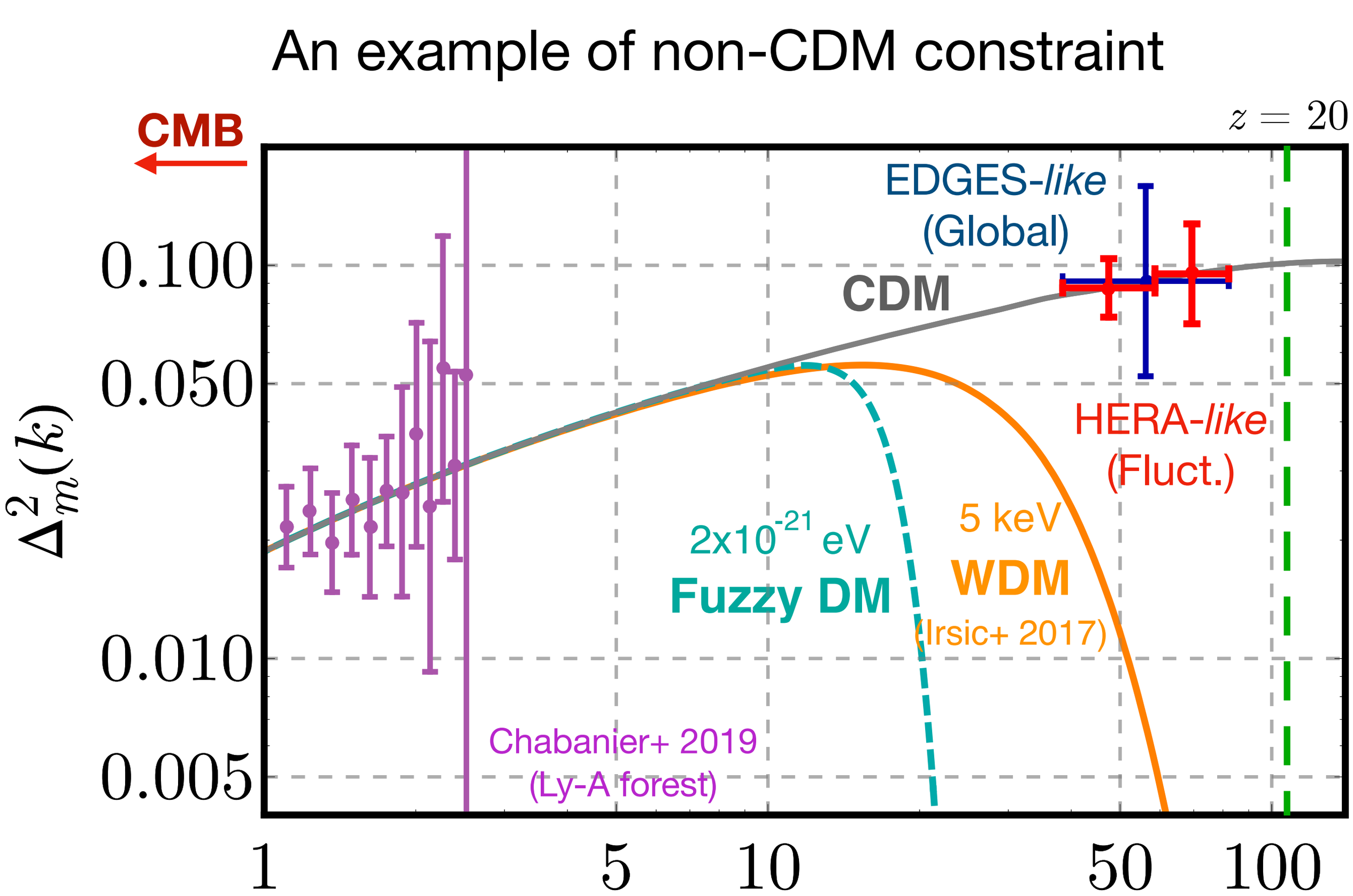


Forecasted errors in matter power



JBM, Dvorkin & Cyr-Racine 2020

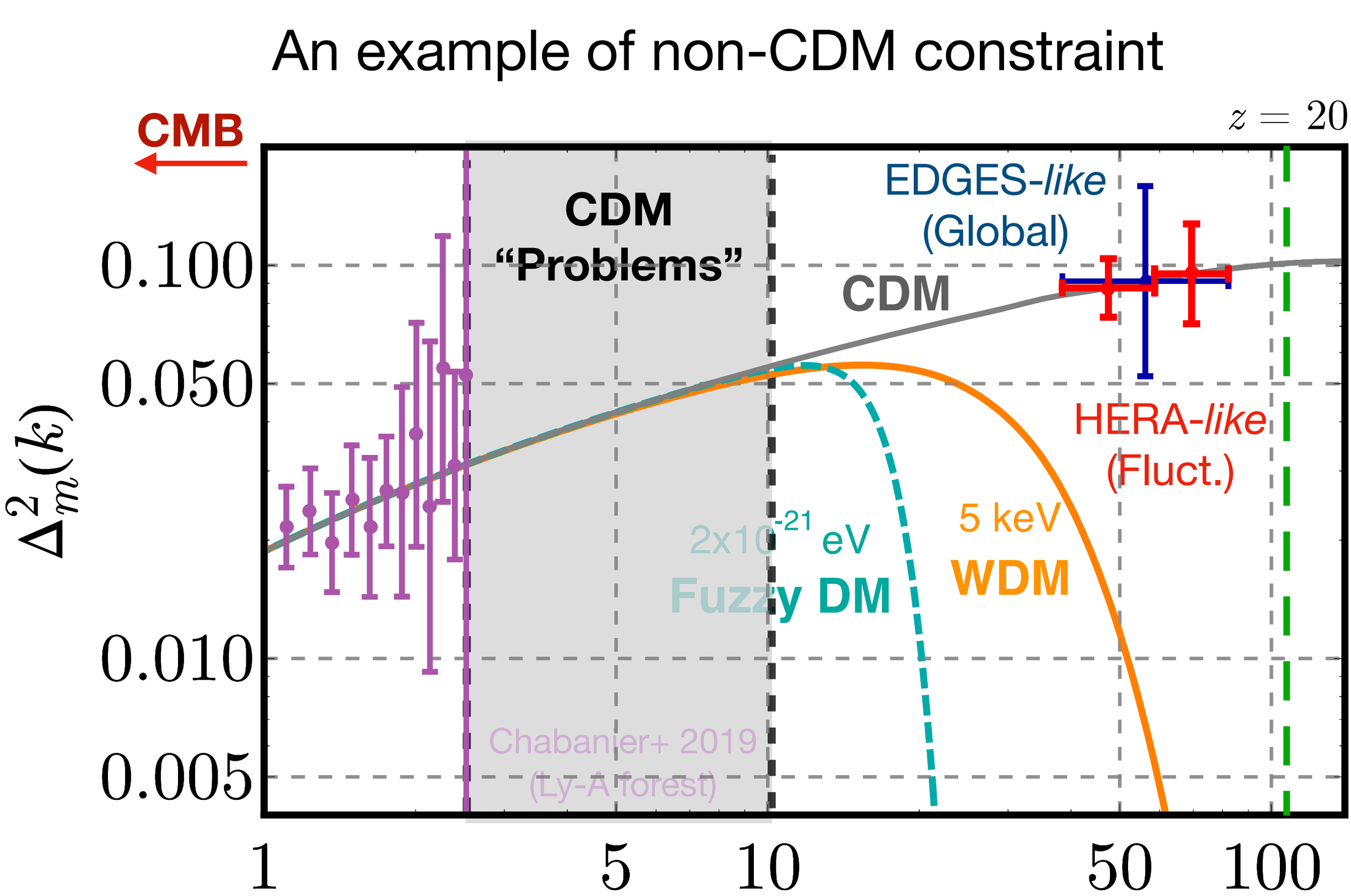
An example of non-CDM constraint



Also:
Schneider 2018
Safarzadeh+2018
Lidz & Hui 2018
Boyarsky+ 2018
Yoshiura+ 2018

JBM, Dvorkin & Cyr-Racine 2020

An example of non-CDM constraint



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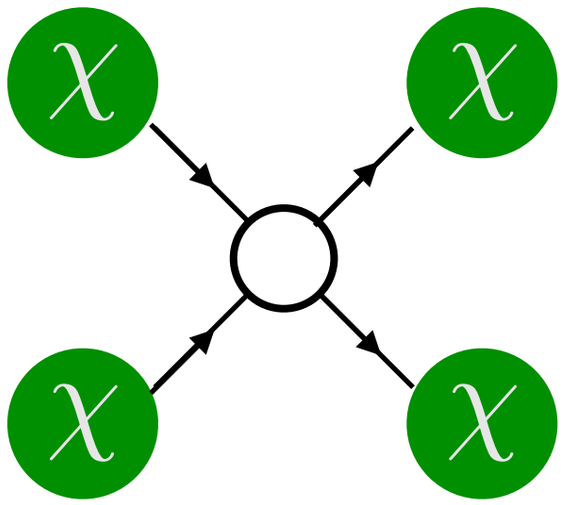
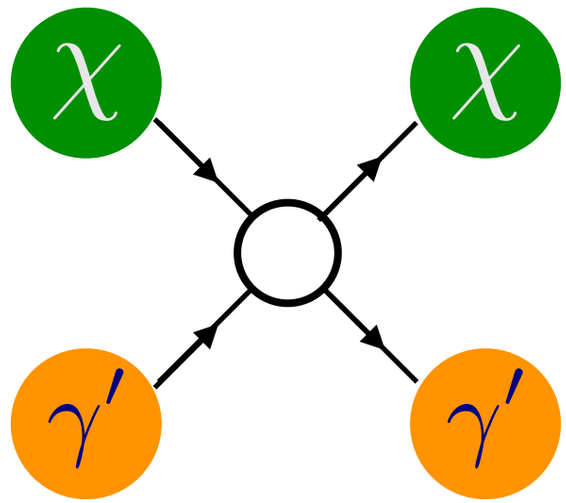
JBM, Dvorkin & Cyr-Racine 2020

Beyond a cutoff: Self Interactions

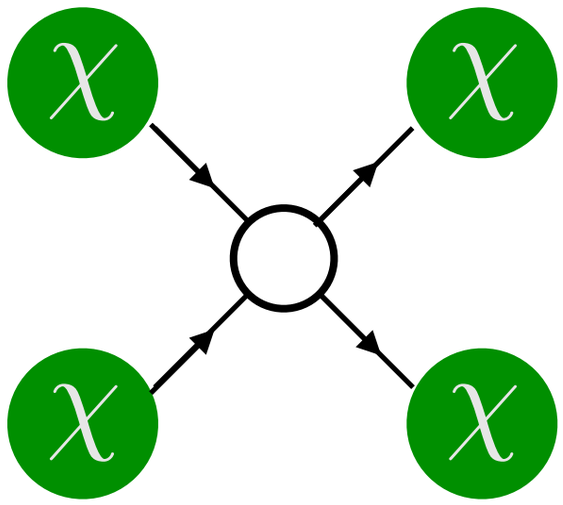


DM-DM:
Halo profiles, etc.

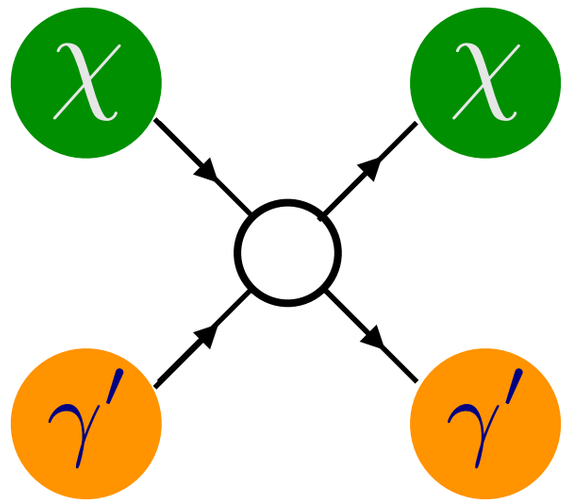


DM-DR:
Power Spectrum

Beyond a cutoff: Self Interactions



DM-DM:
Halo profiles, etc.

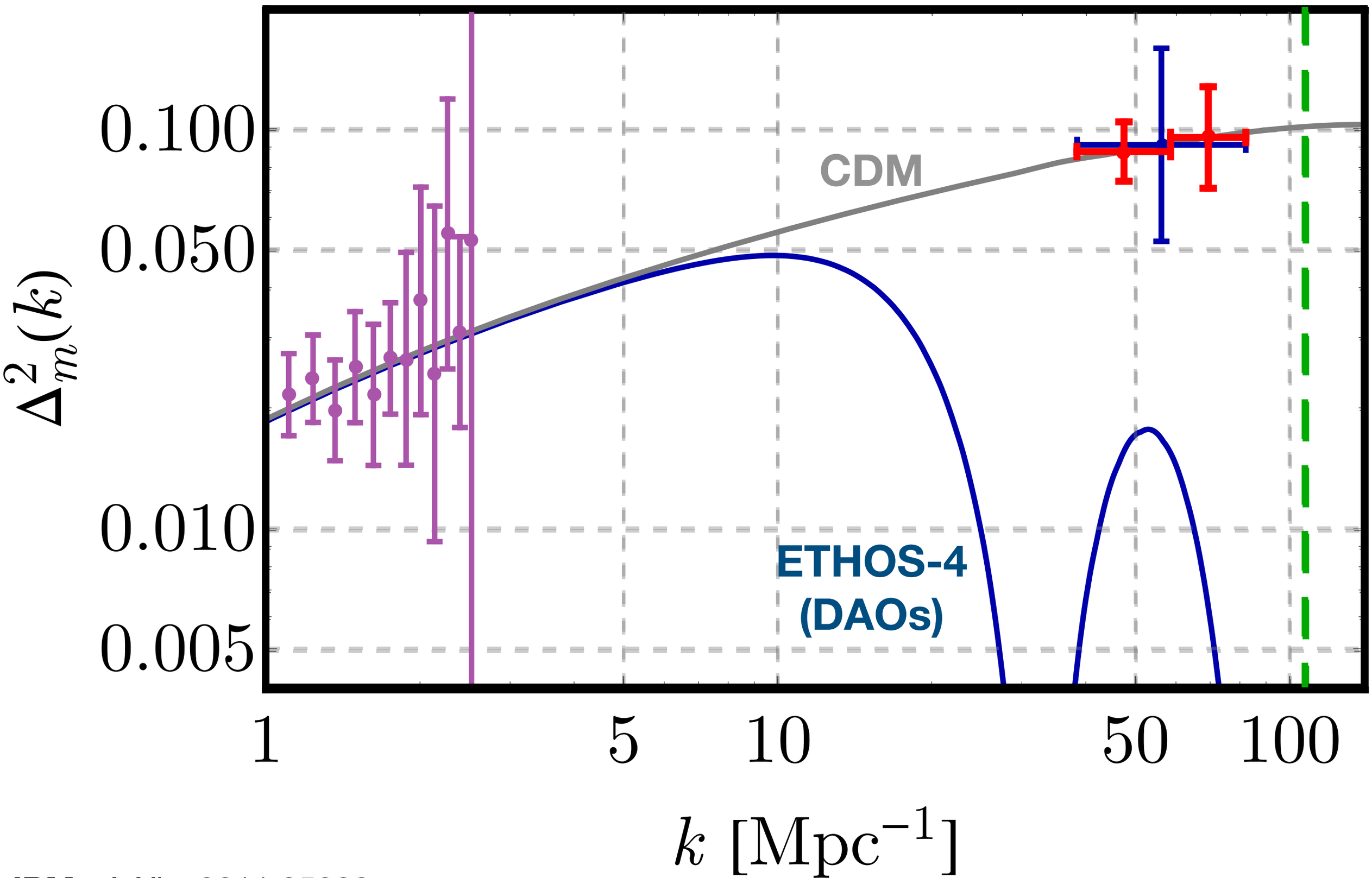


DM-DR:
Power Spectrum

Effective Theory of Structure Formation: **ETHOS**

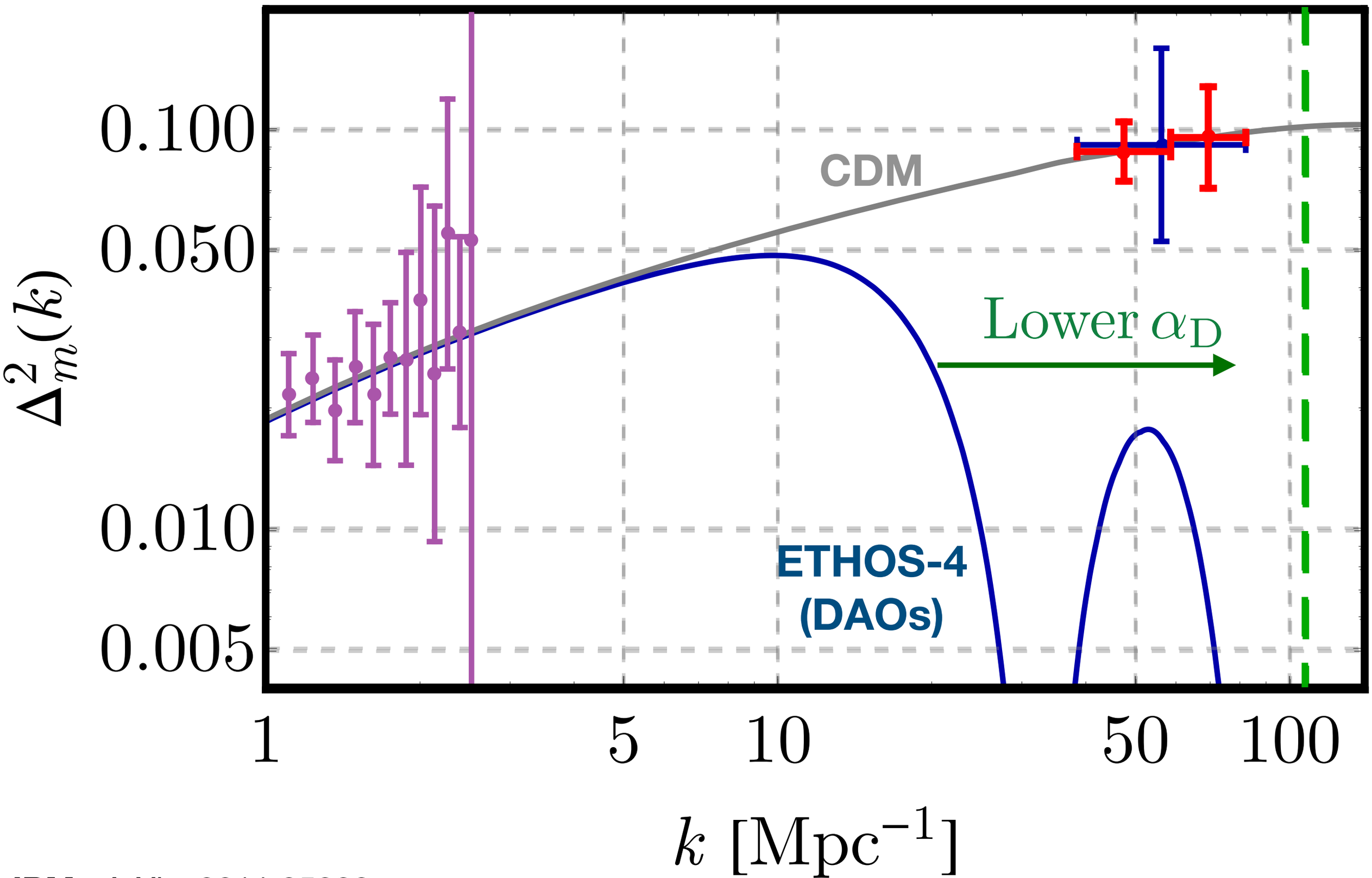
Vogelsberger+ 2016
Cyr-Racine+2016

Beyond a cutoff: 21-cm ETHOS



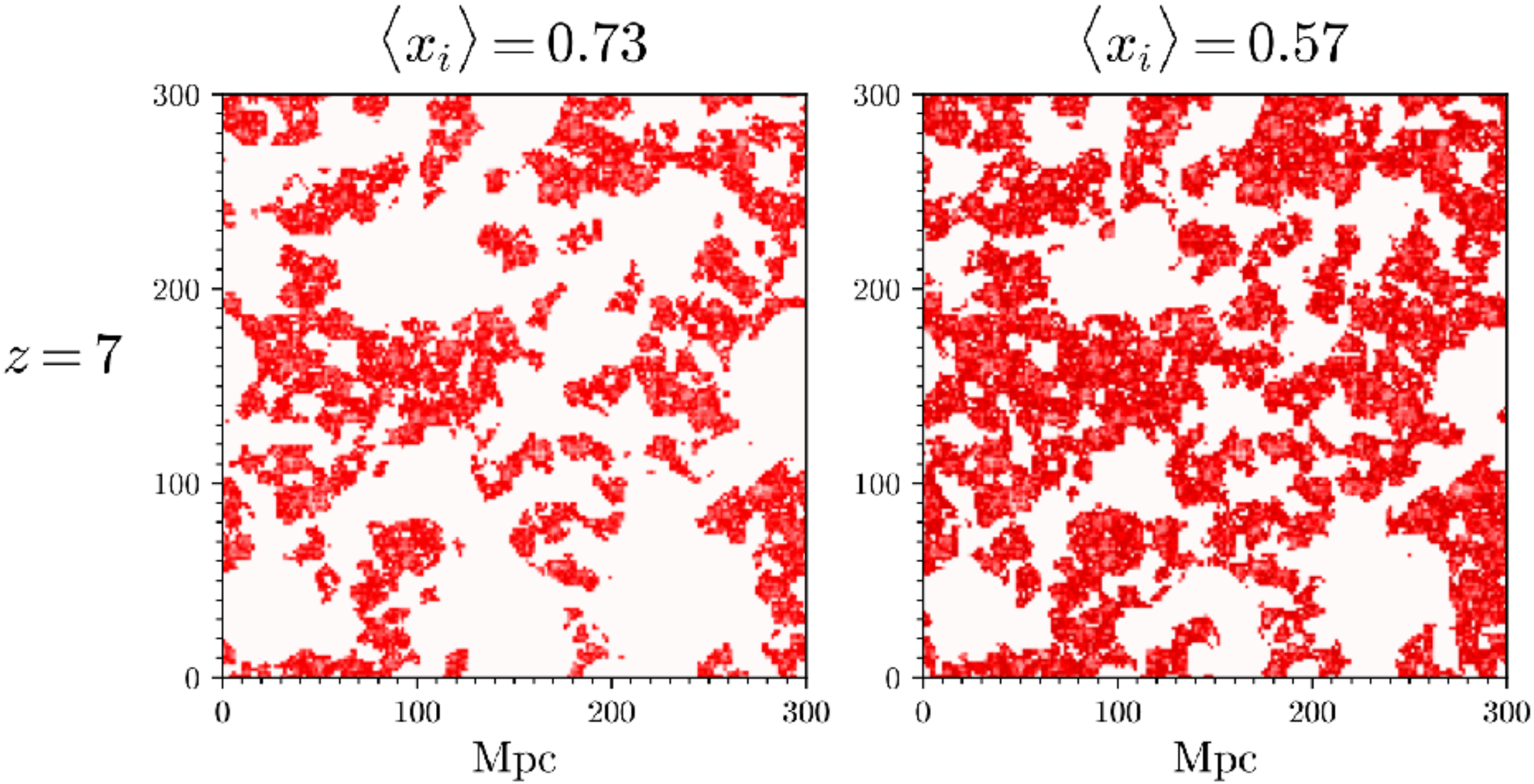
JBM+ ArXiv: 2011.05333

Beyond a cutoff: 21-cm ETHOS



JBM+ ArXiv: 2011.05333

Also during the EoR!



Jones+ 2021

10^{-21} eV

The expansion rate $H(z)$

$H(z)/(1+z)^{3/2}$ [km s^{-1} Mpc^{-1}]

80
70
60
50
40

20
9
2
0

Redshift, z

SH0ES

(Late = standard candles)

CMB

(Early = acoustic standard ruler)

Galaxy BAO

QSO BAO

LyA BAO

cosmic time

The expansion rate $H(z)$

$H(z)/(1+z)^{3/2}$ [km s^{-1} Mpc^{-1}]

80
70
60
50
40

20
9
2
0

Redshift, z

Cosmic Dawn and EoR

?
?
?

(Early = acoustic standard ruler)

SH0ES

(Late = standard candles)

CMB

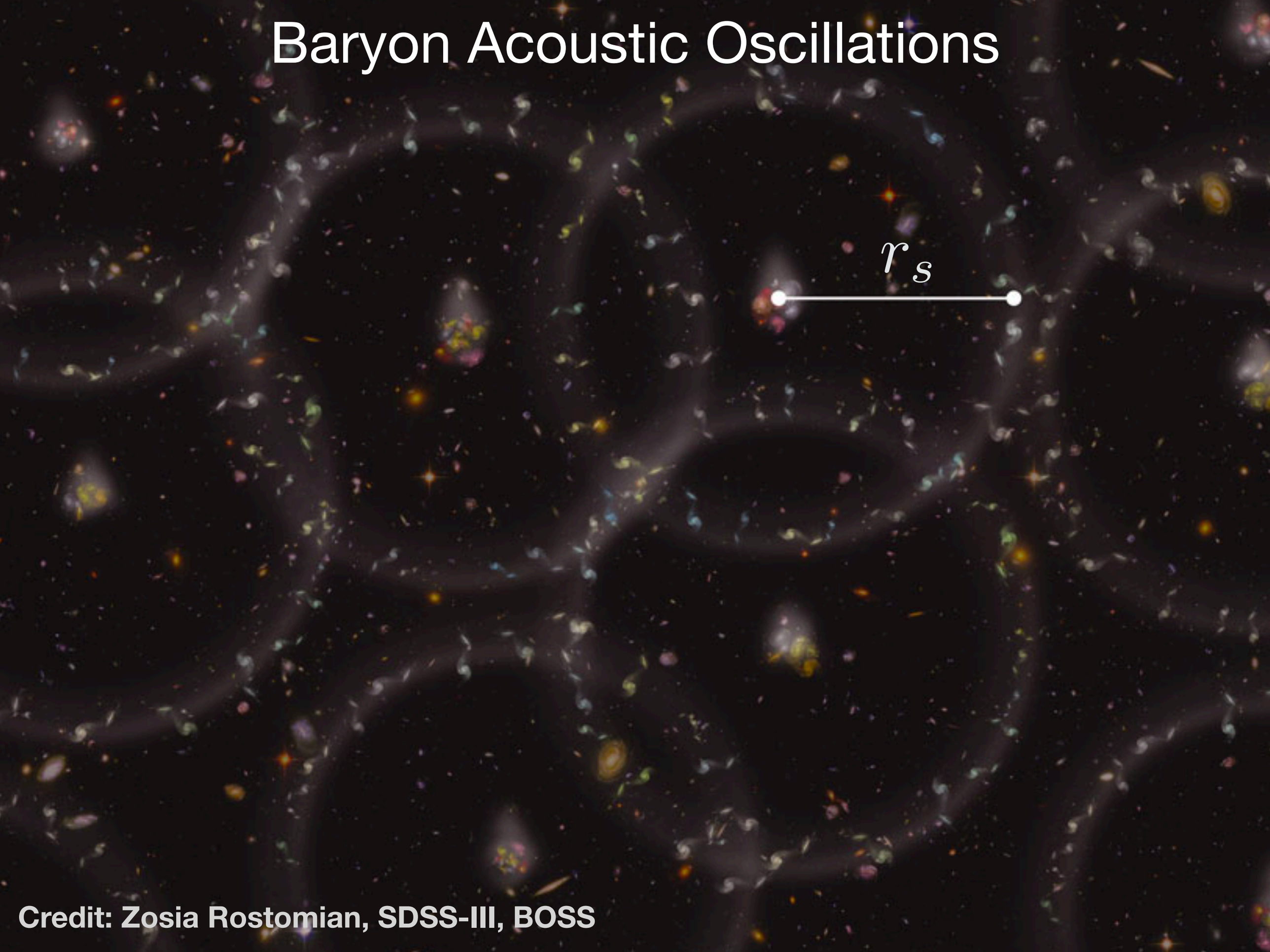
Galaxy BAO

QSO BAO

LyA BAO

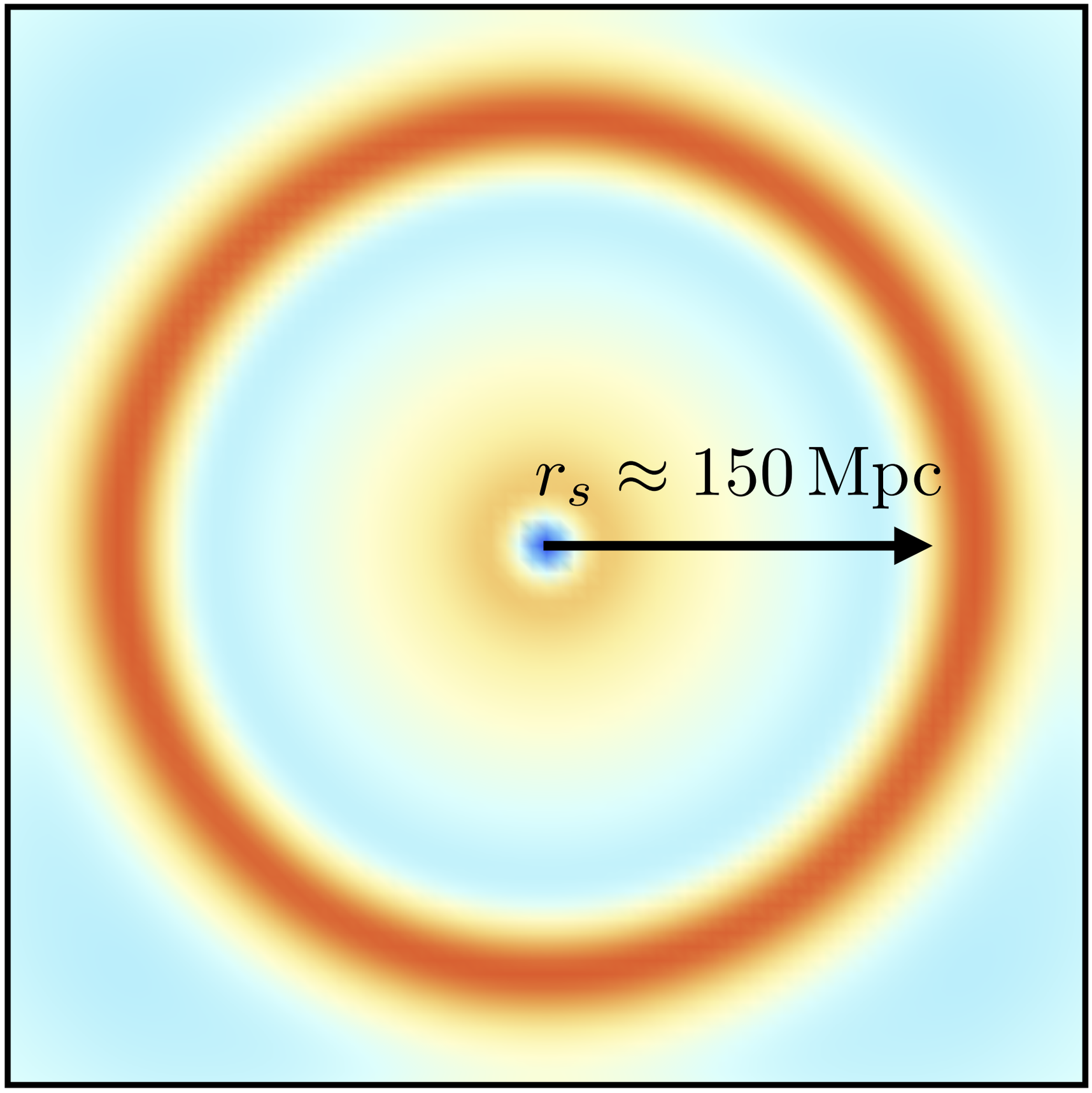
cosmic time

Baryon Acoustic Oscillations



Credit: Zosia Rostomian, SDSS-III, BOSS

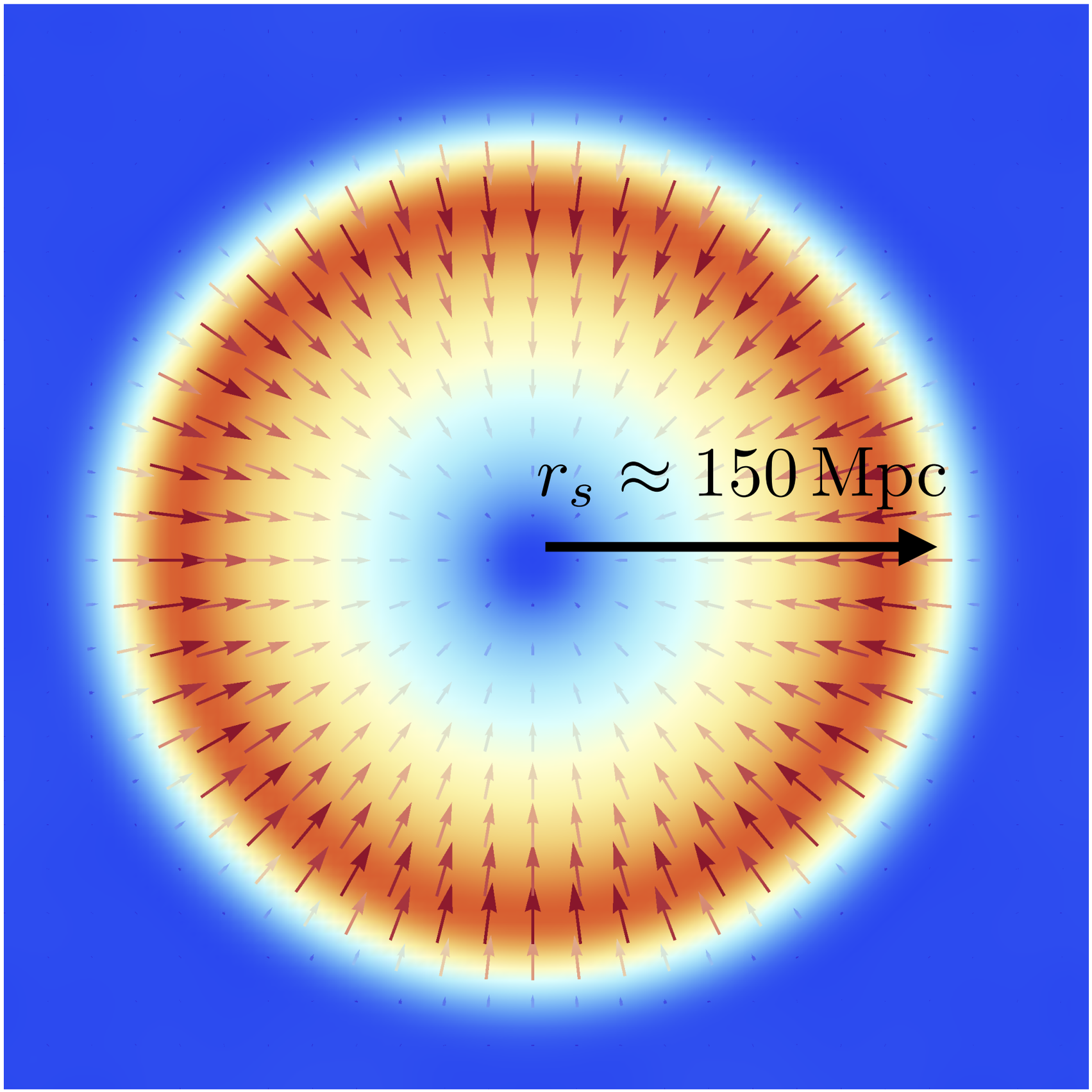
A preferred distance scale



Density

Tseliakhovich & Hirata 2010

$$\vec{v}_{b\chi} = \vec{v}_b - \vec{v}_\chi$$



Velocity

Tseliakhovich & Hirata 2010

r_s

δ

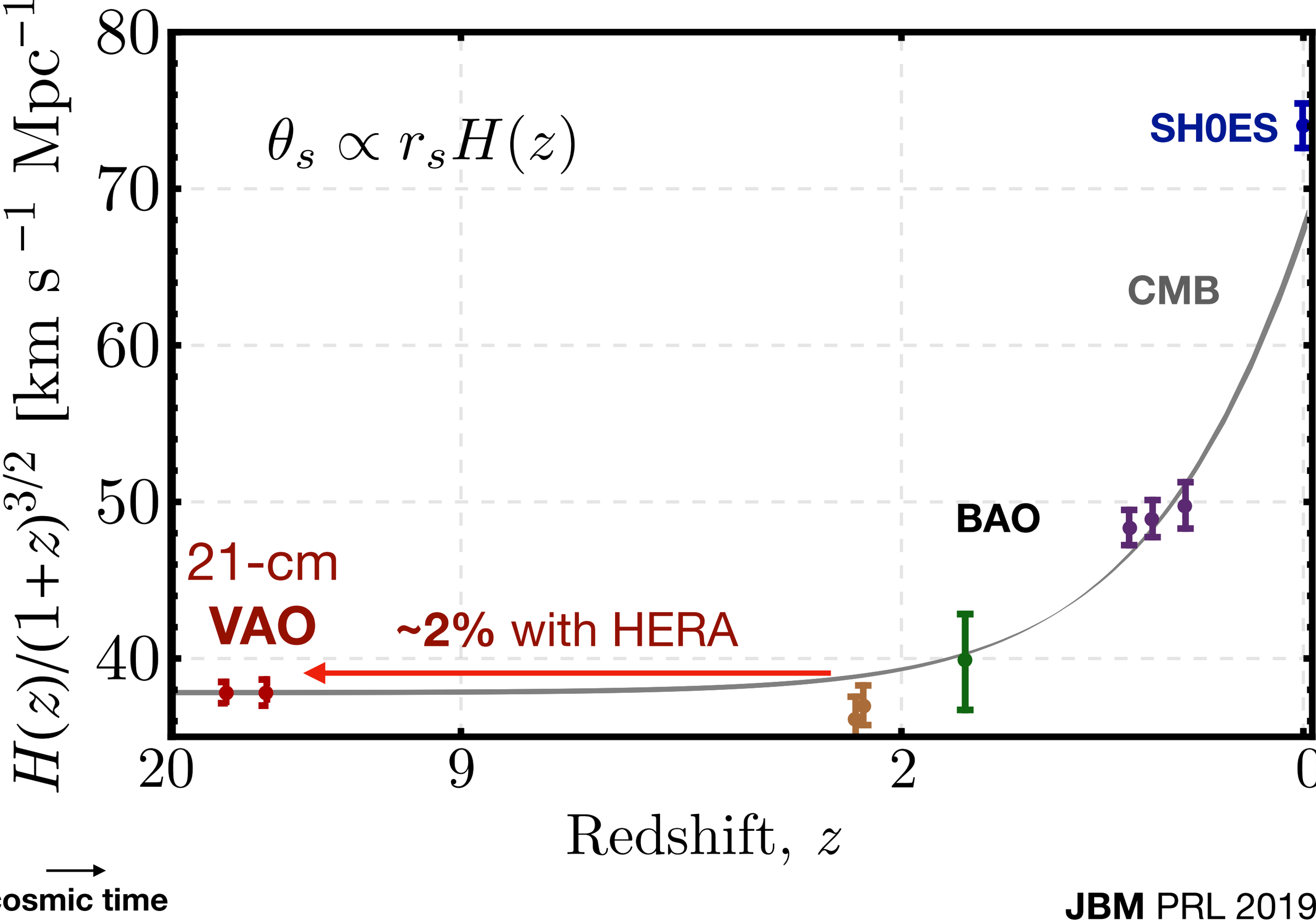
v_{bx}

VAOs: A new standard ruler

JBM PRL 2019

Image: Zosia Rostomian, SDSS-III, BOSS

The expansion rate $H(z)$



JBM PRL 2019

The expansion rate $H(z)$

$\theta_s \propto r_s H(z)$

SH0ES

CMB

BAO

21-cm

VAO

$H(z)/(1+z)^{3/2}$ [km s^{-1} Mpc^{-1}]

80
70
60
50
40

20
9
2
0

z

cosmic time

JBM PRL 2019

Measuring r_s

$\theta_s \propto r_s H(z)$

Standard-ruler length

SH0ES

CMB

BAO

21-cm

VAO

$H(z)/(1+z)^{3/2}$ [km s^{-1} Mpc^{-1}]

80
70
60
50
40

20
9
2
0

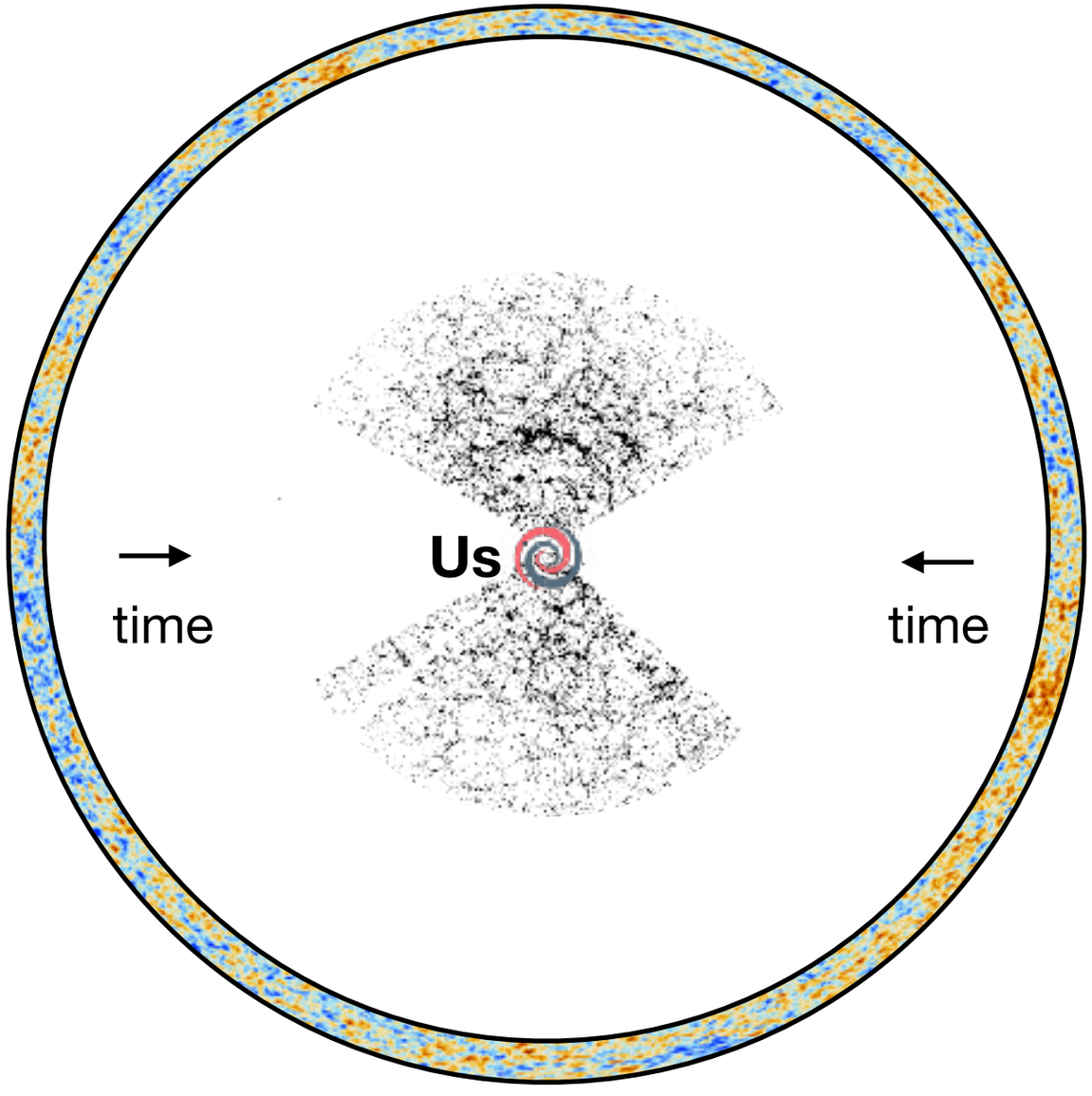
z

cosmic time

JBM PRL 2019

Summary

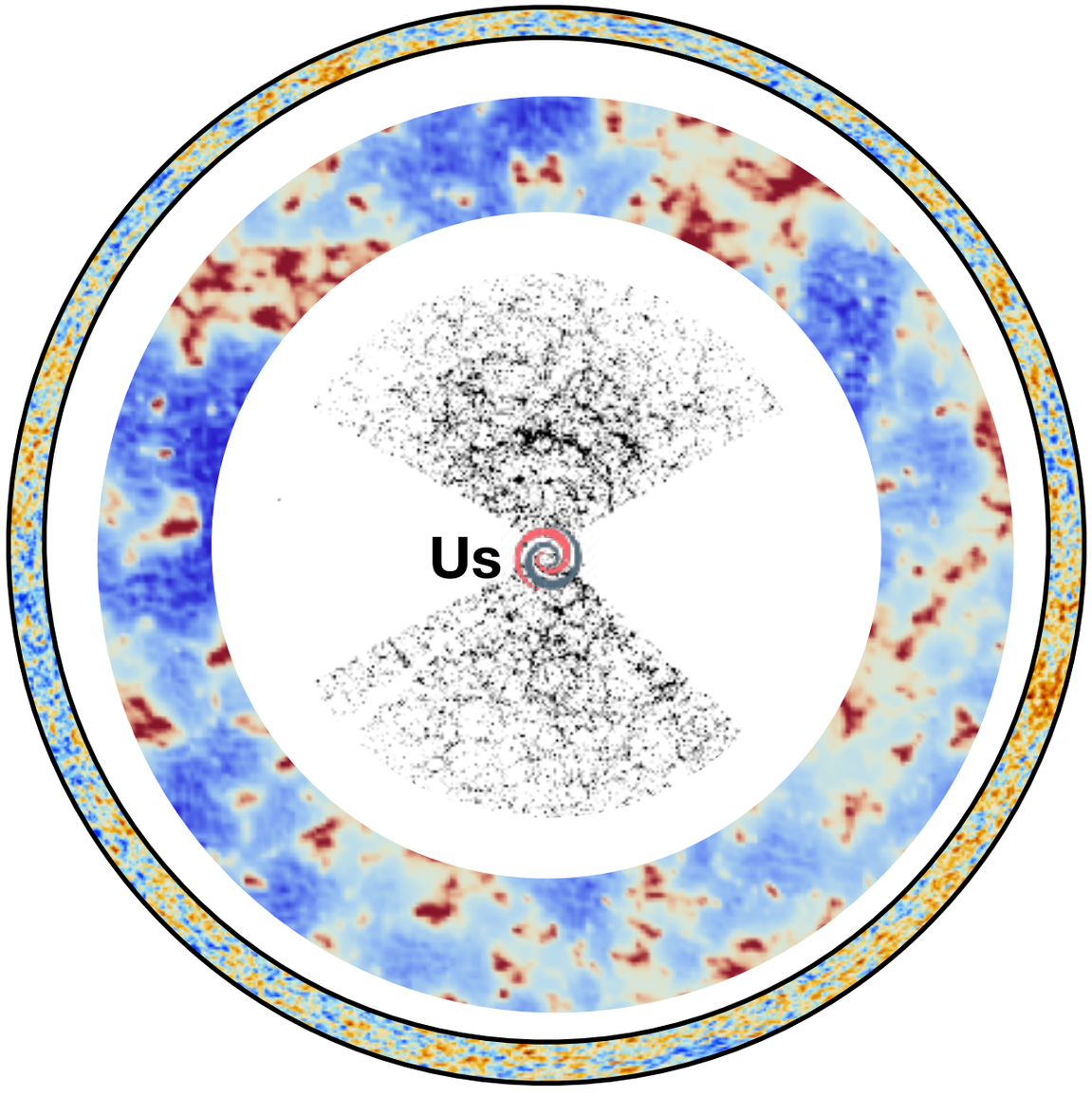
Data: SDSS/Planck



-We have not observed most of the Universe (yet)

Summary

Data: SDSS/Planck

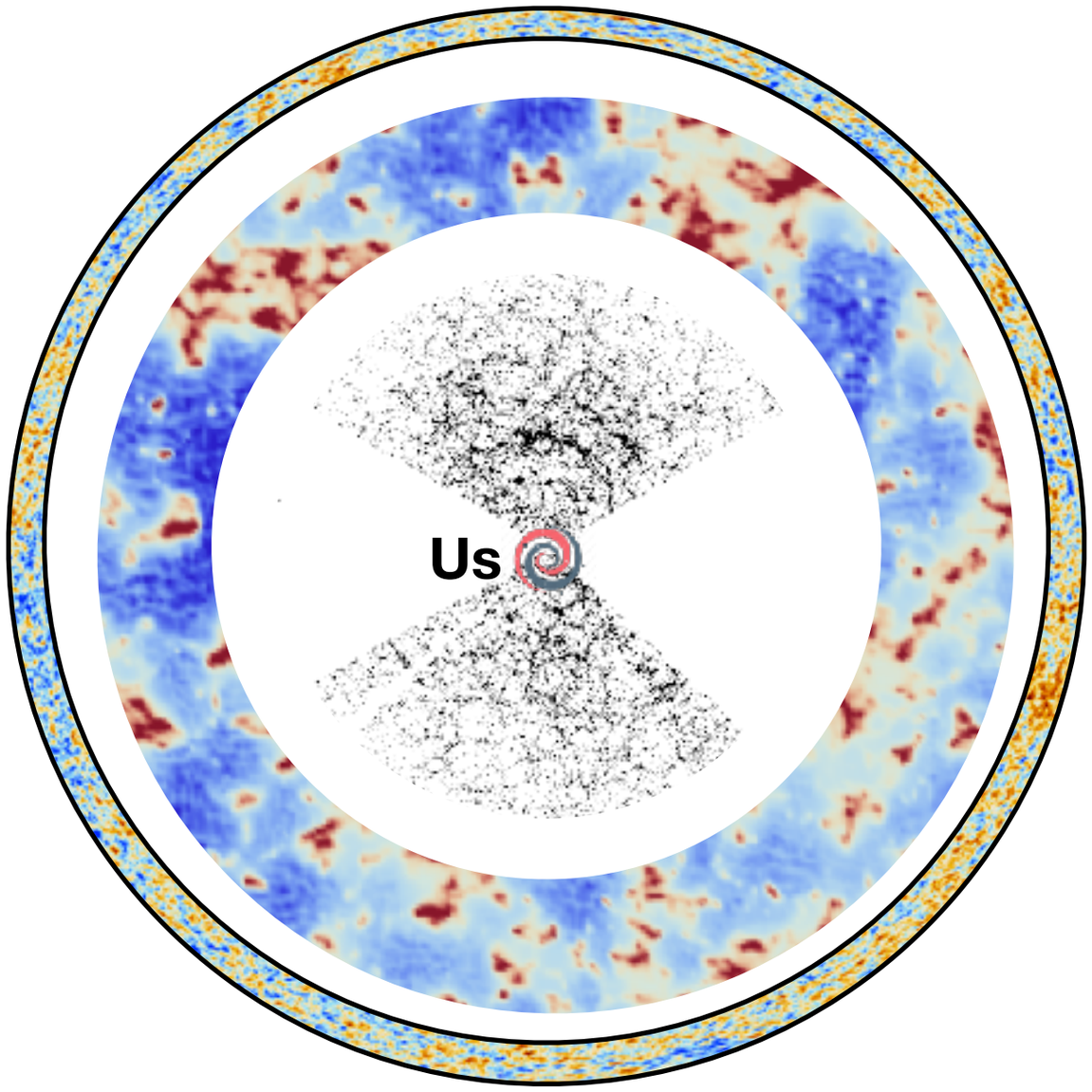


-We have not observed most of the Universe (yet)

-The 21-cm line will allow us to map the cosmos during unexplored eras.

Summary

Data: SDSS/Planck



-We have not observed most of the Universe (yet)

-The 21-cm line will allow us to map the cosmos during unexplored eras.

-Use it to answer questions:

Does DM interact with us?

JBM, Ali-Haïmoud, Kovetz 2015
JBM & Loeb Nature 2018

Is DM warm, fuzzy, or self-interacting?

JBM, Dvorkin & Cyr-Racine PRD 2020
JBM, Bohr++ PRD 2021

What is the expansion rate $H(z{=}10\text{-}20)$?

JBM PRL, PRD 2019
JBM++ (in prep.)