Learning Cosmology from the First Stars

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Julian B. Muñoz

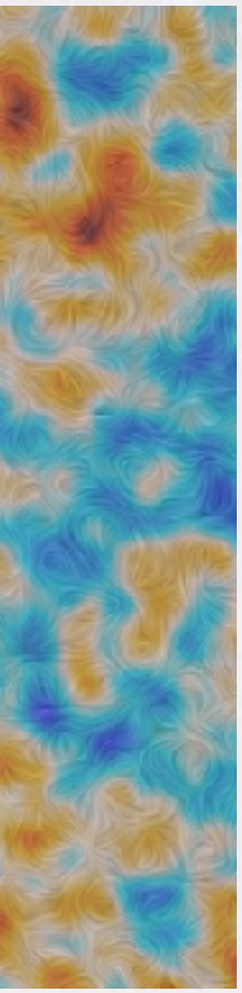
Based on

PRD 100 063538 (2019)
PRL 123 131301 (2019)
PRD 101 063526 (2020) w/ Dvorkin and Cyr-Racine
JCAP 01 (2021) w/ **Sabti** and Blas
PRD (2021) w/ **Bohr**, Cyr-Racine, Zavala & Vogelsberger

Image: Fuller/NSF

An abridged history of the cosmos

CMB



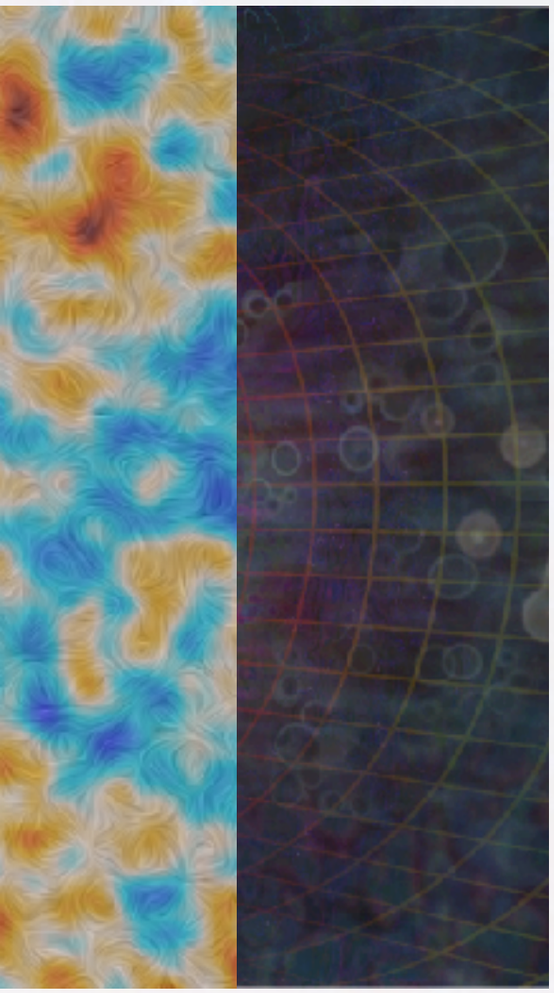
$z \approx 10^3$

Image: ESA

cosmic time

An abridged history of the cosmos

CMB



$z \approx 10^3$

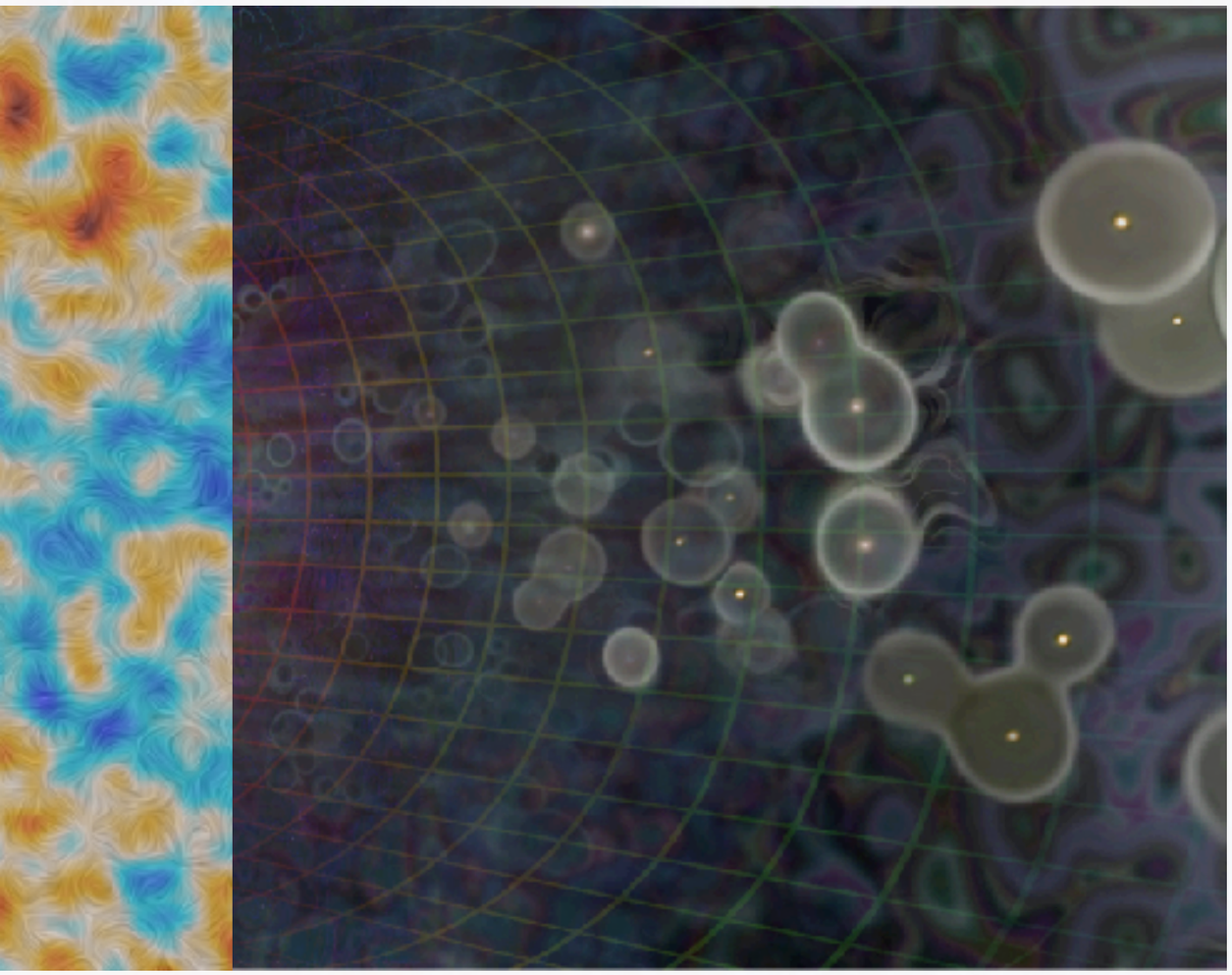
Image: NASA/CXC/M.WEISS

cosmic time →

An abridged history of the cosmos

CMB

Cosmic Dawn



$z \approx 10^3$

$z \approx 20$

Image: NASA/CXC/M.WEISS

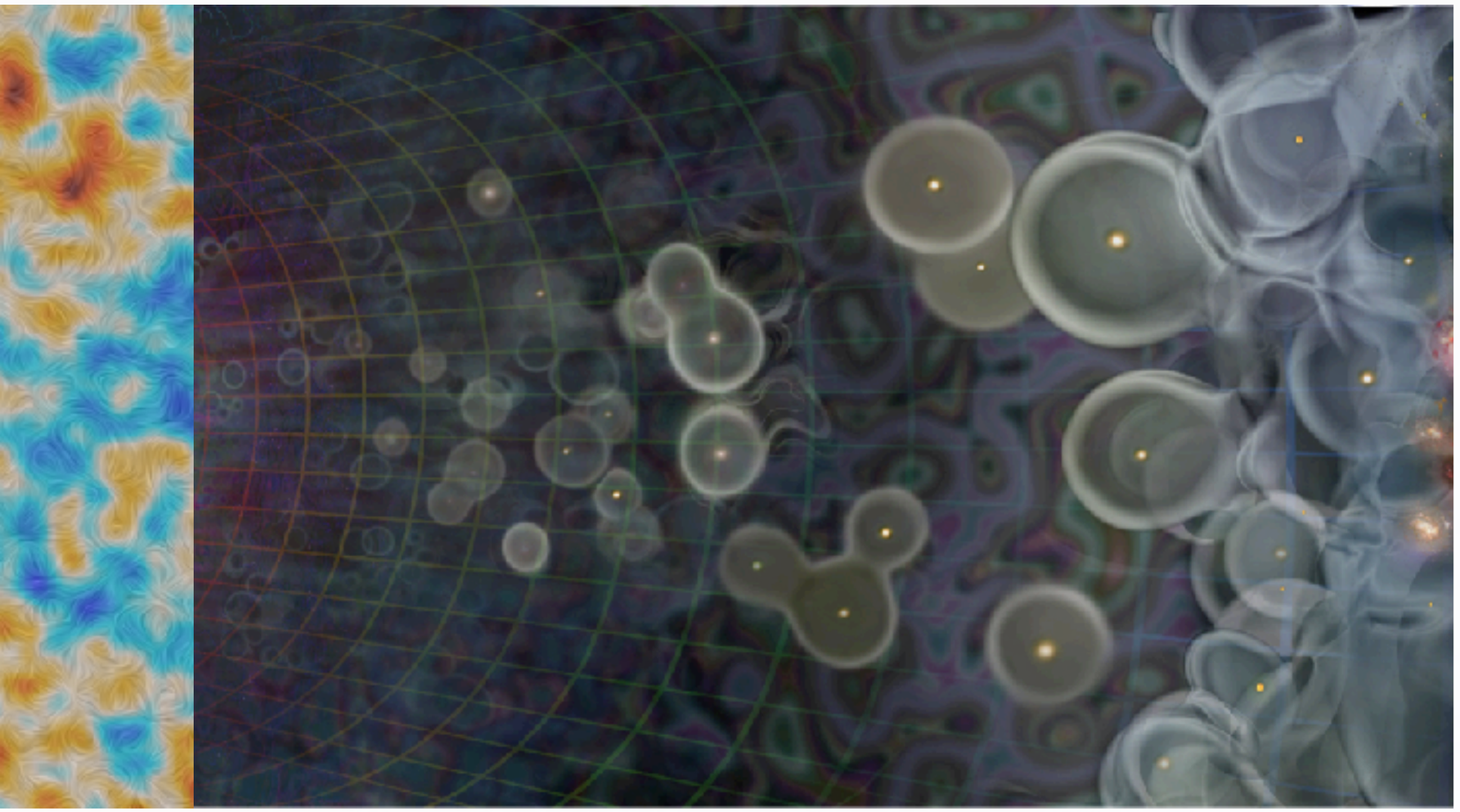
cosmic time →

An abridged history of the cosmos

CMB

Cosmic Dawn

Reionization



$z \approx 10^3$

$z \approx 20$

$z \approx 6$

cosmic time →

Image: NASA/CXC/M.WEISS

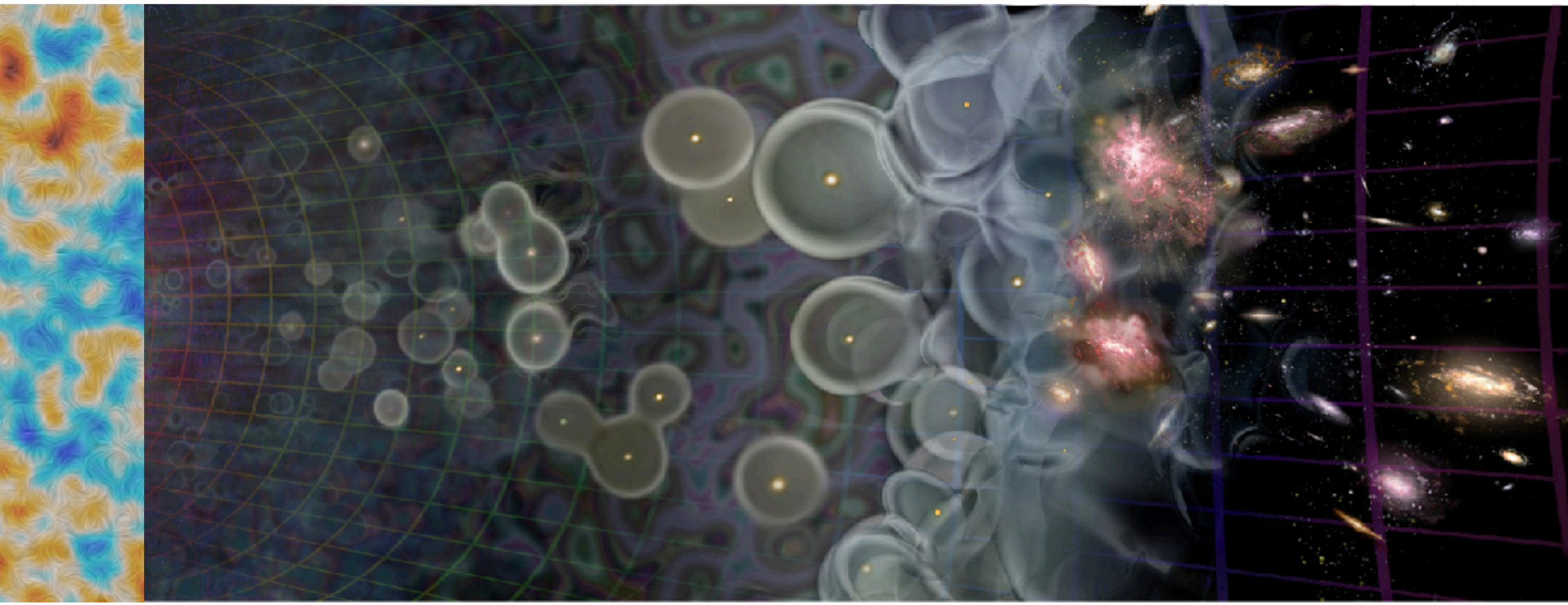
An abridged history of the cosmos

CMB

Cosmic Dawn

Reionization

Local Universe



$z \approx 10^3$

$z \approx 20$

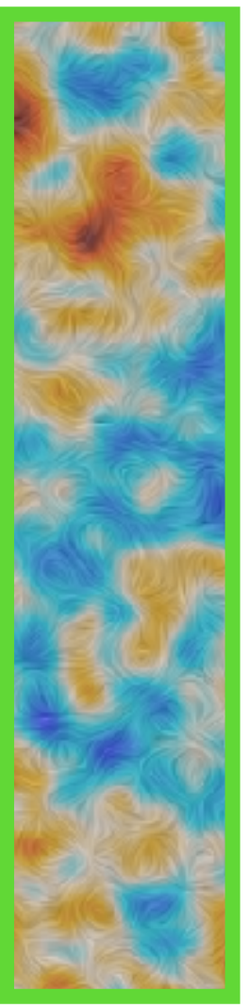
$z \approx 6$

$z = 0$

cosmic time →

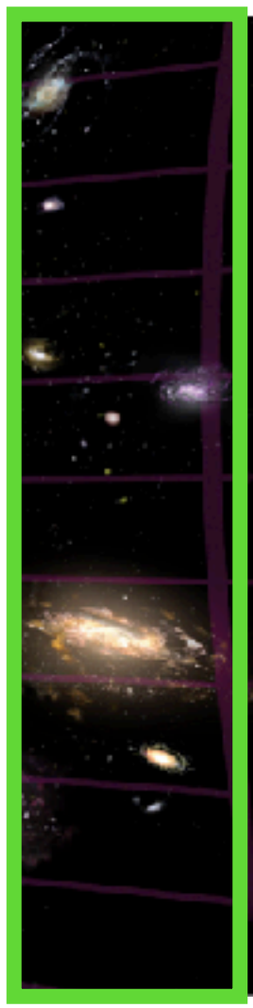
Image: NASA/CXC/M.WEISS

CMB



$z \approx 10^3$

Local Universe

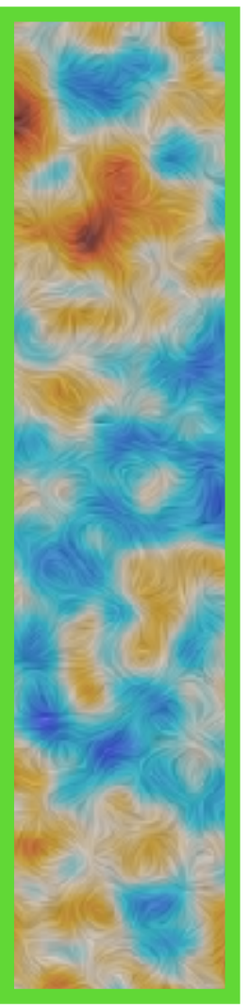


$z = 0$

Image: NASA/CXC/M.WEISS

The pillars of cosmology

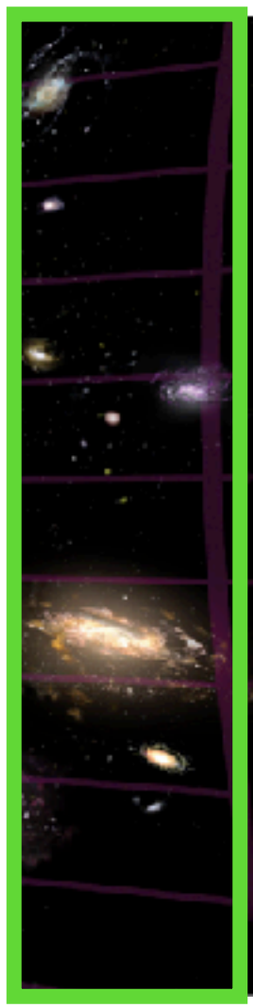
CMB



$z \approx 10^3$

There is Dark Matter

Local Universe

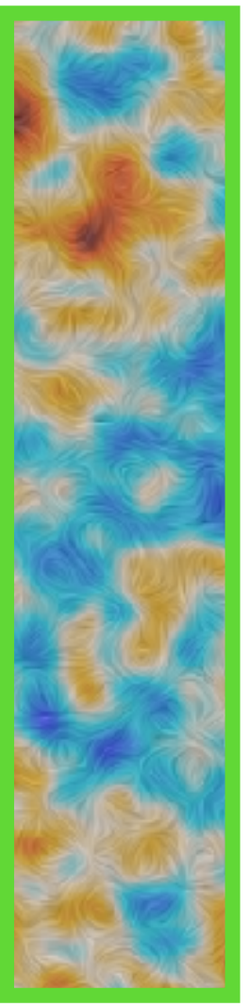


$z = 0$

Image: NASA/CXC/M.WEISS

The pillars of cosmology

CMB



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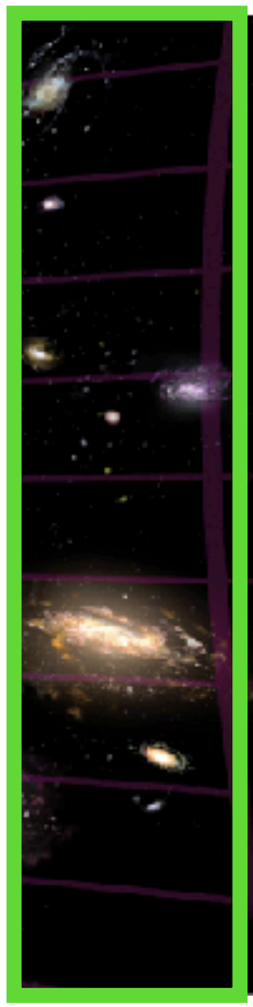


There is Dark Matter

This DM is cold and collisionless

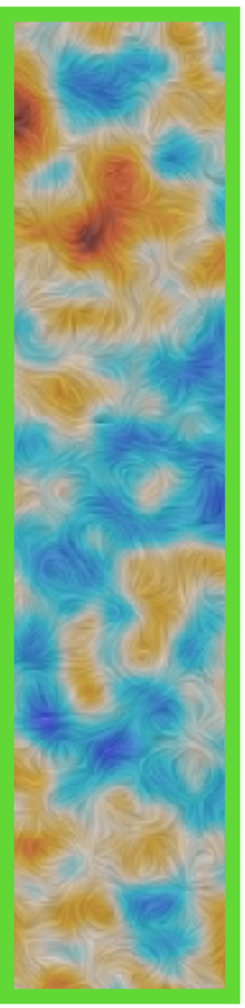
$z \approx 10^3$

$z = 0$

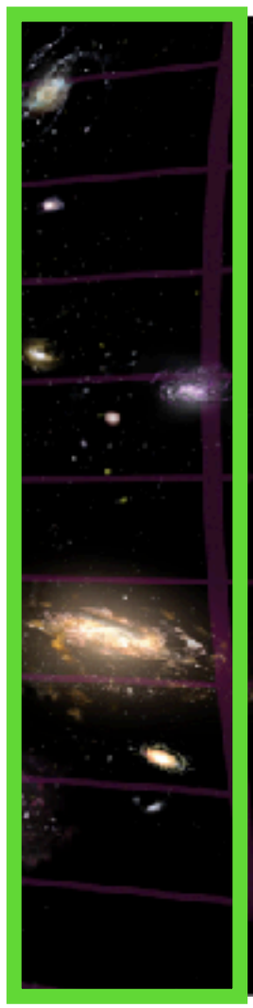
Image: NASA/CXC/M.WEISS

The pillars of cosmology

CMB



Local Universe



There is Dark Matter

This DM is cold and collisionless

There is Dark Energy

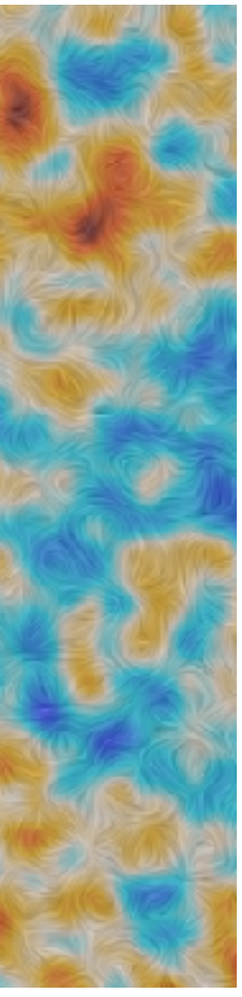
$z \approx 10^3$

$z = 0$

Image: NASA/CXC/M.WEISS

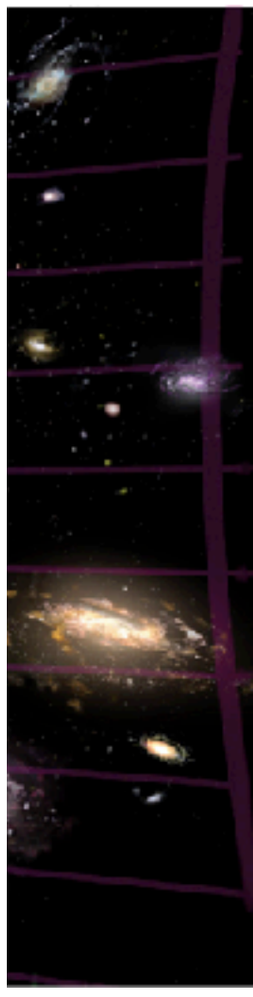
We've learned a lot, but…

CMB



$z \approx 10^3$

Local Universe



$z = 0$

-We don't know what DM or DE are

We've learned a lot, but…

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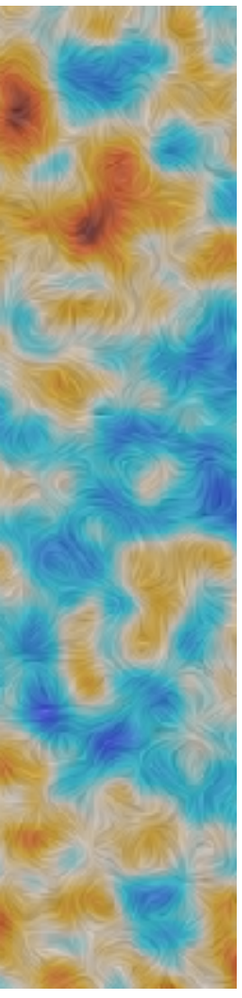
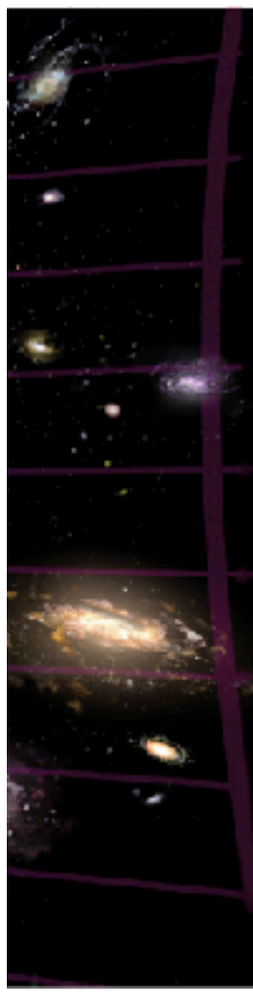


$z \approx 10^3$

Local Universe



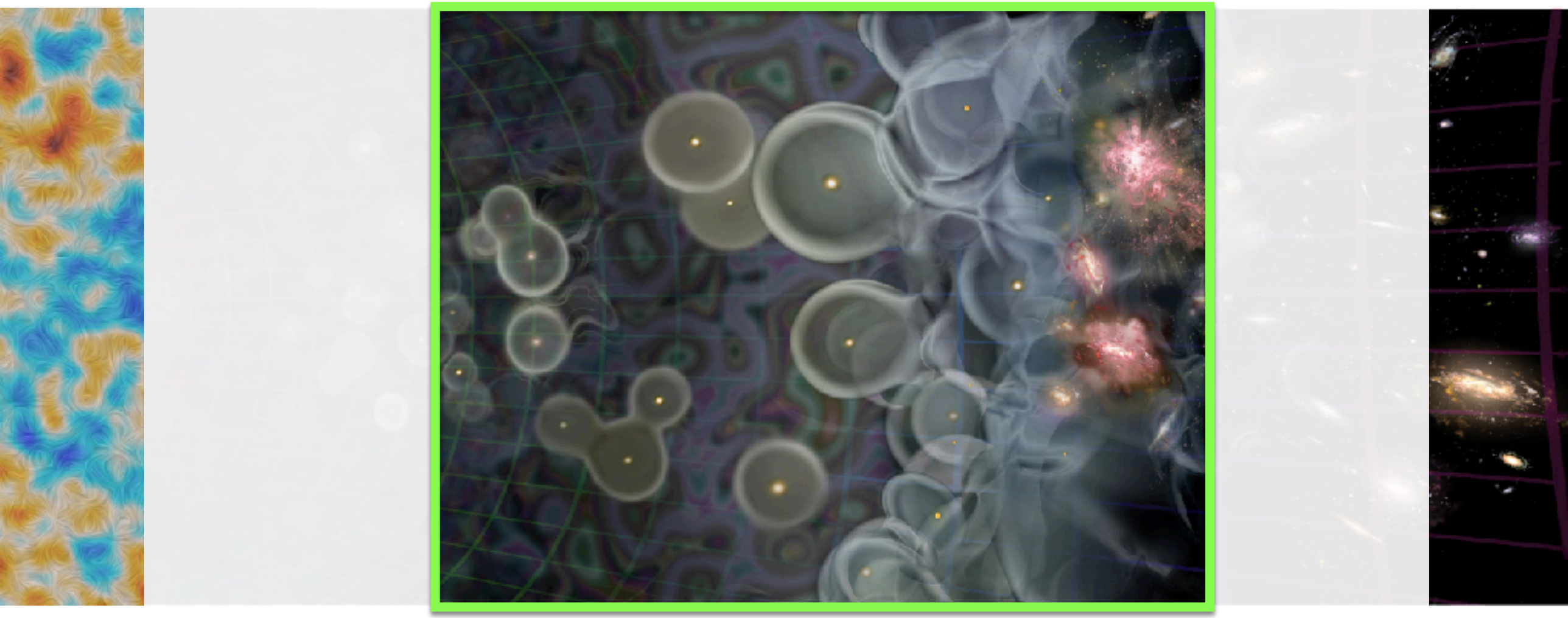
$z = 0$

-We don't know what DM or DE are

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

What can we learn?

Cosmic Dawn and Reionization

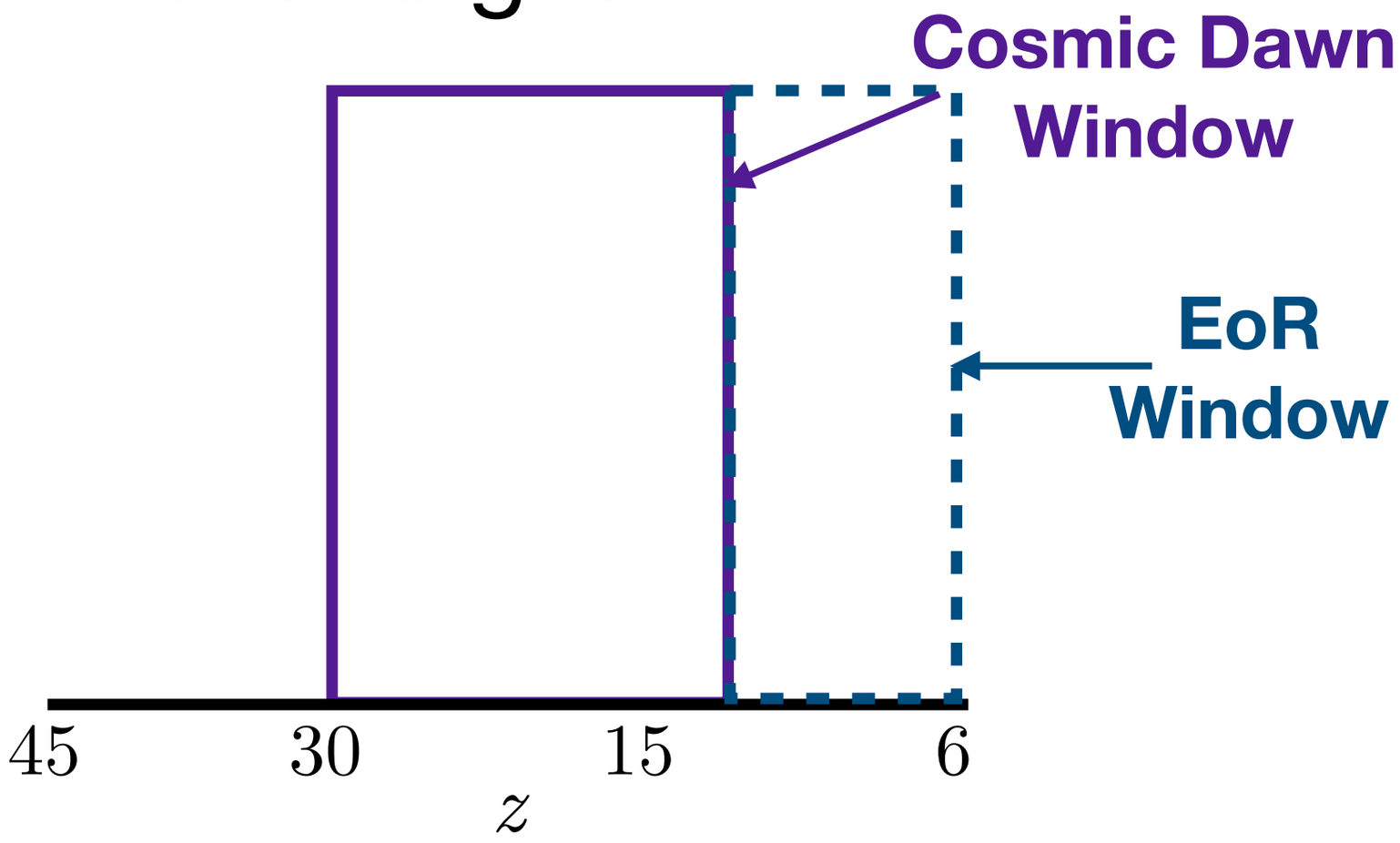


$z \approx 20$ $z \approx 6$

cosmic time

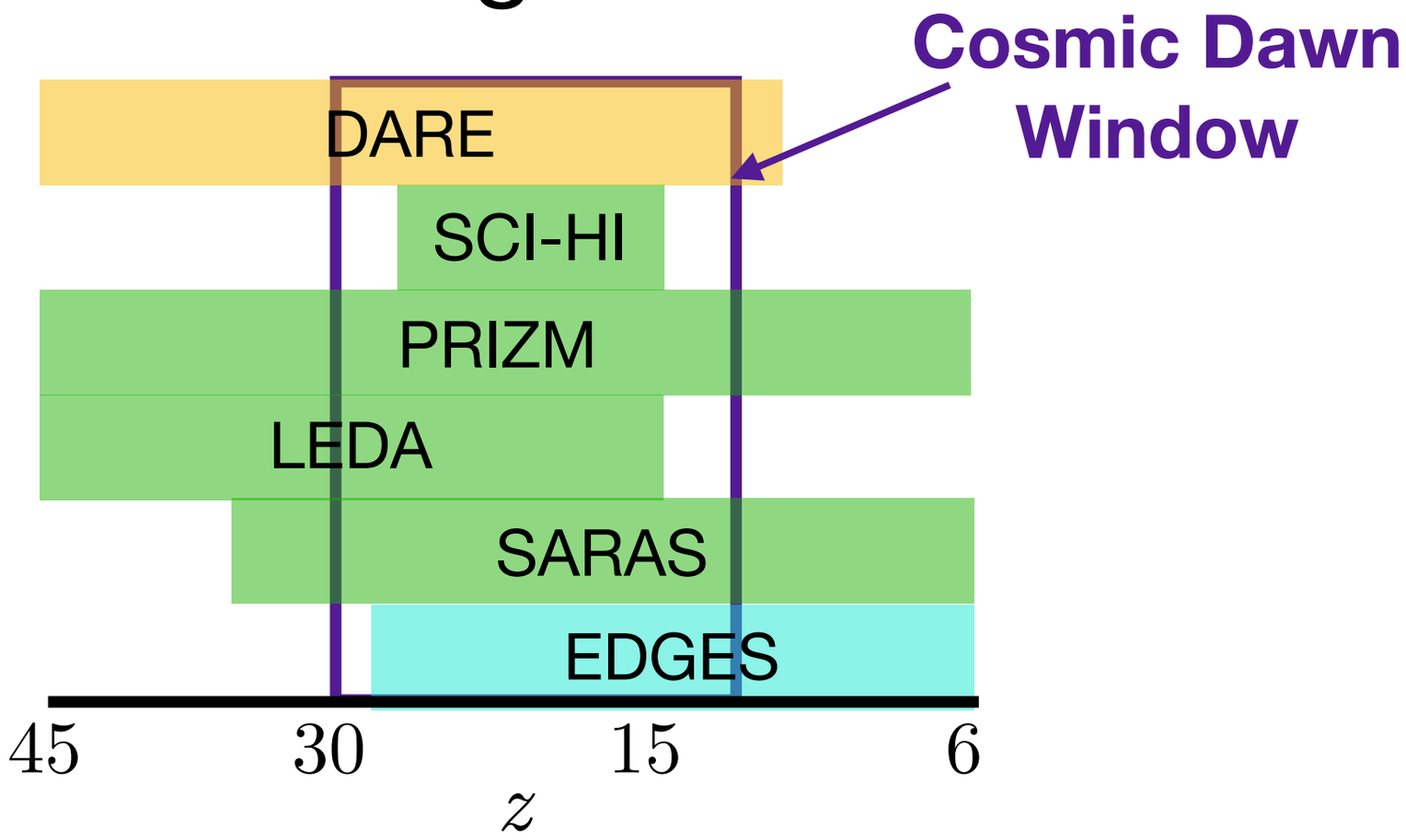
The 21-cm experimental landscape

Global Signal



The 21-cm experimental landscape

Global Signal

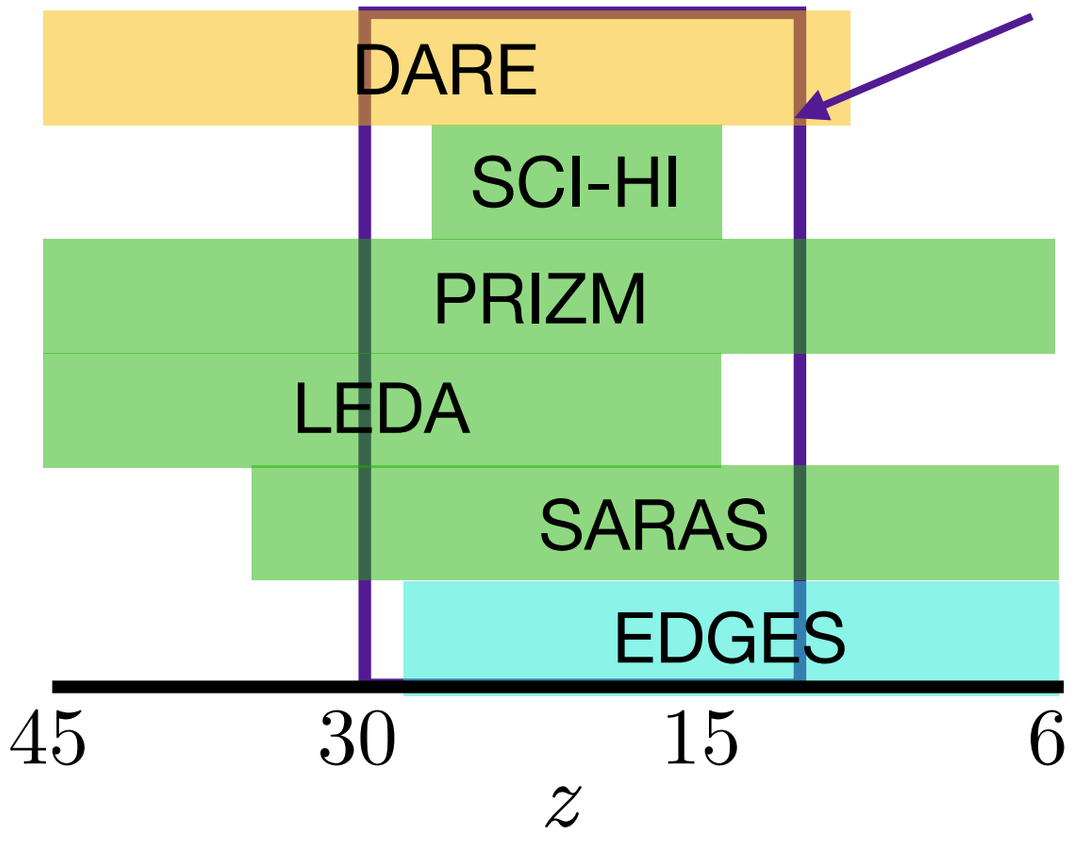


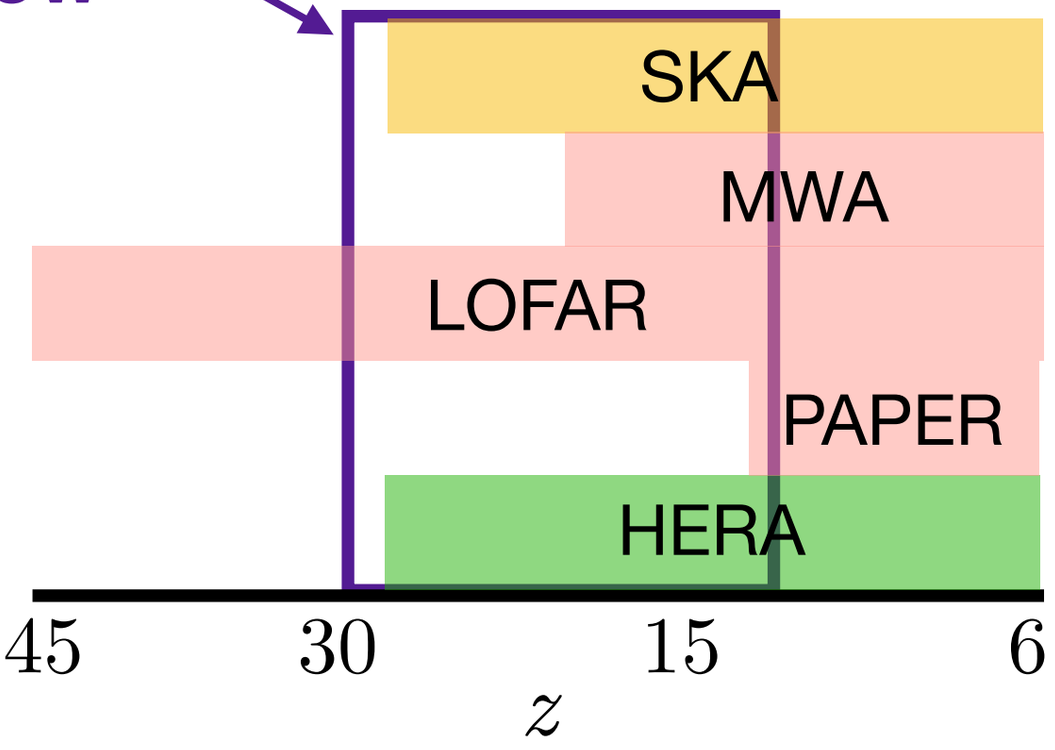
The 21-cm experimental landscape

Global Signal

Fluctuations

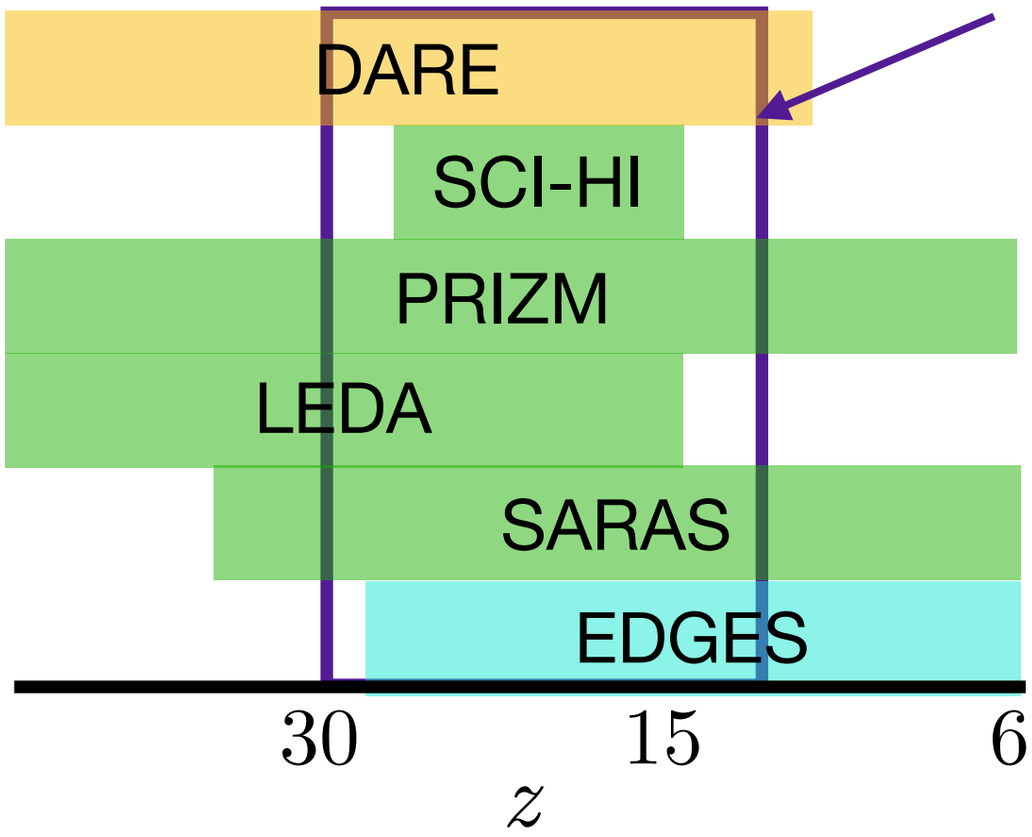
Cosmic Dawn Window



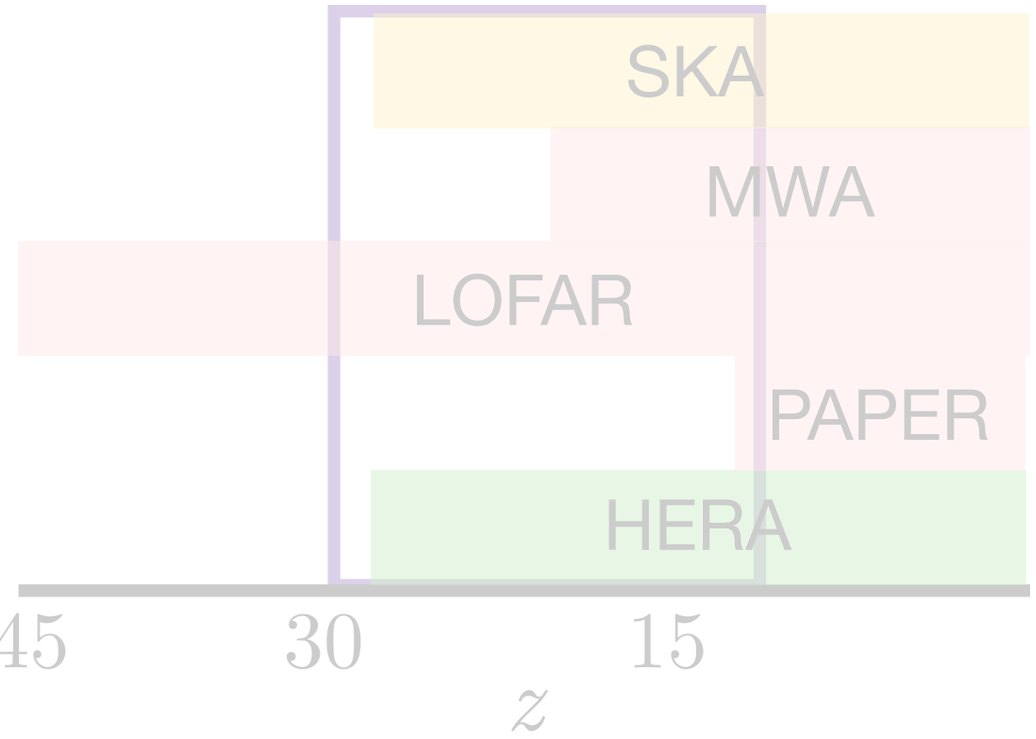


What can we learn?

Global Signal



Fluctuations

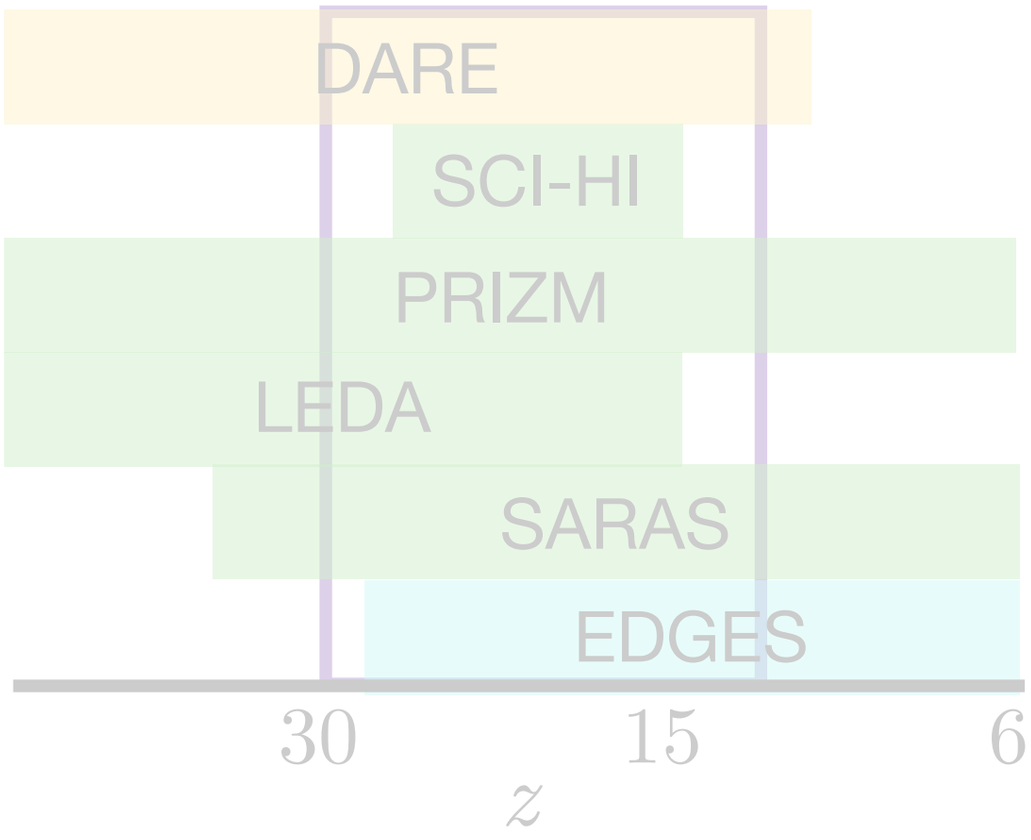


-Is DM collisionless?

-Is DM cold?

What can we learn?

Global Signal



-Is DM collisionless?

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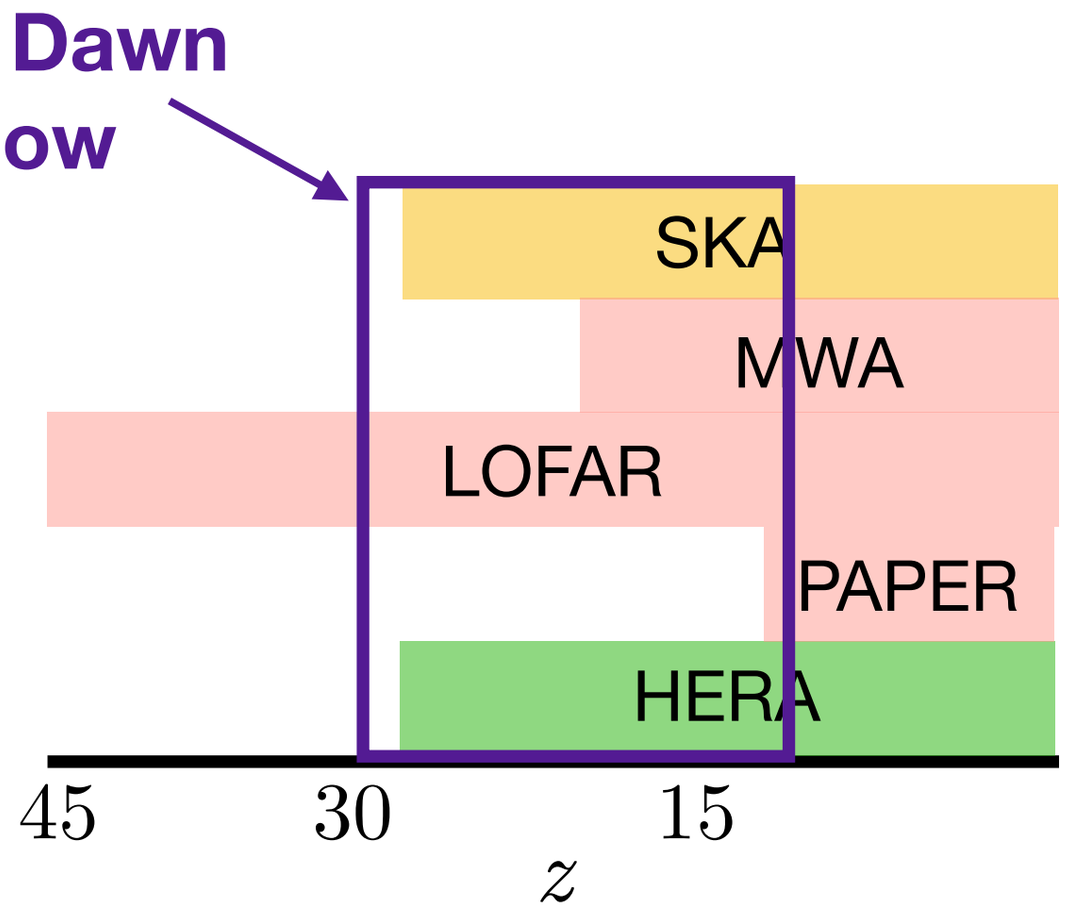
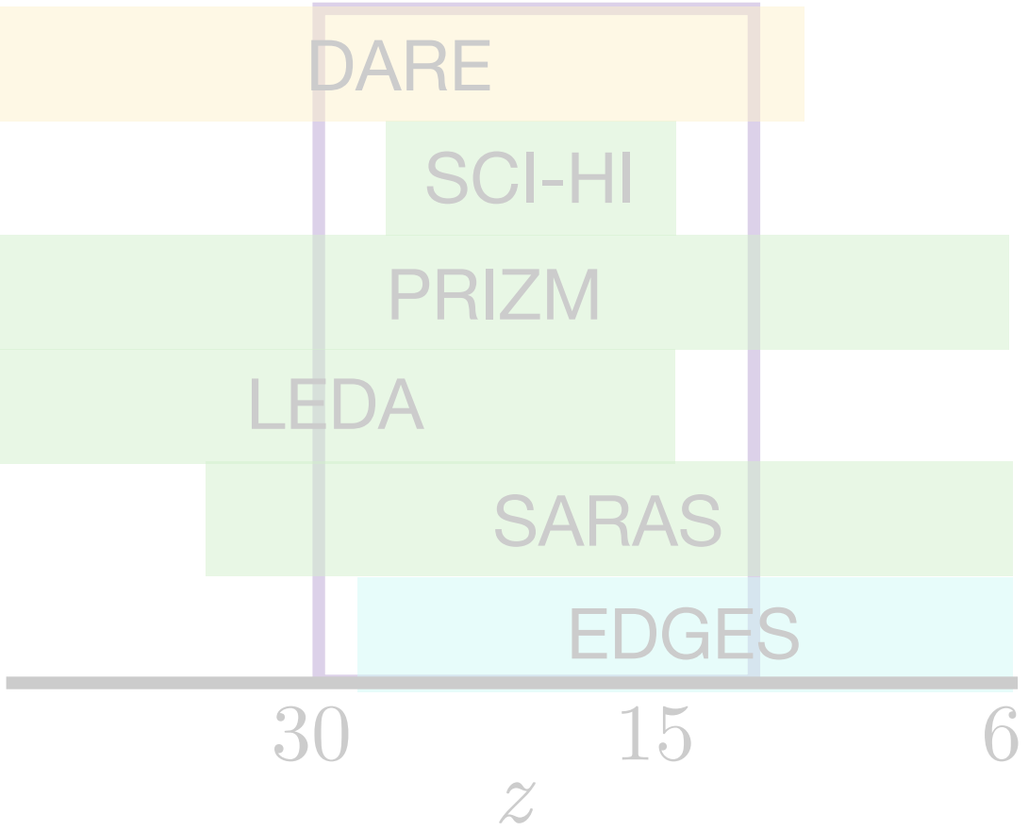
Fluctuations



-What is the expansion rate of the Universe? H_0?

What can we learn?

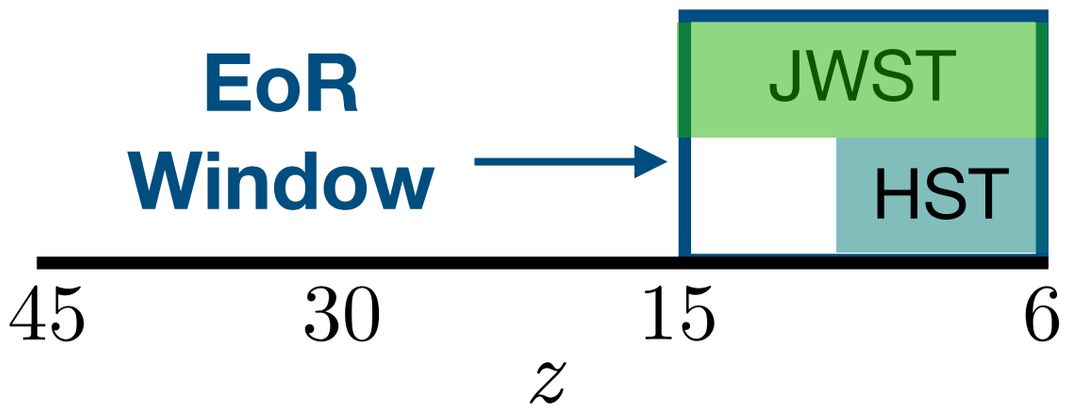
Global Signal



Fluctuations

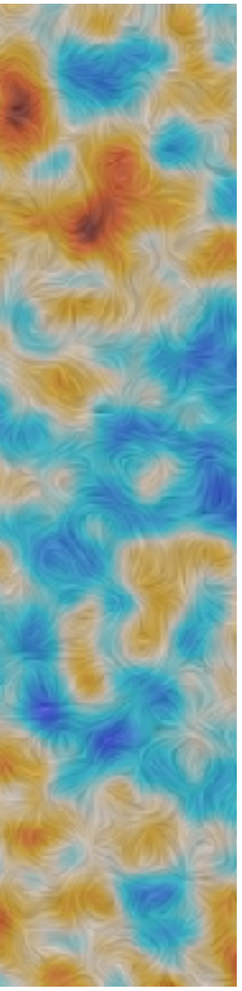
-What happened during inflation?

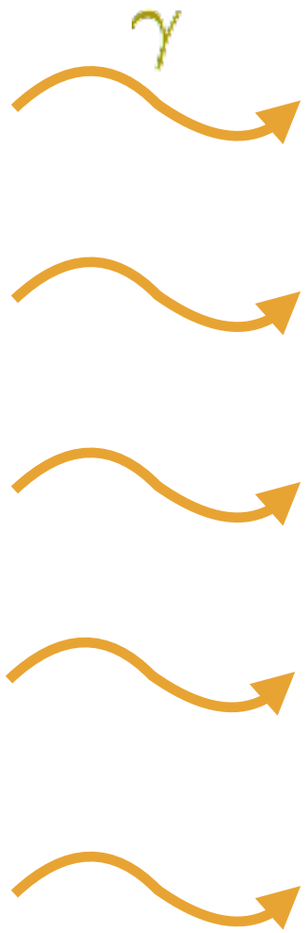
UV Luminosity Functions



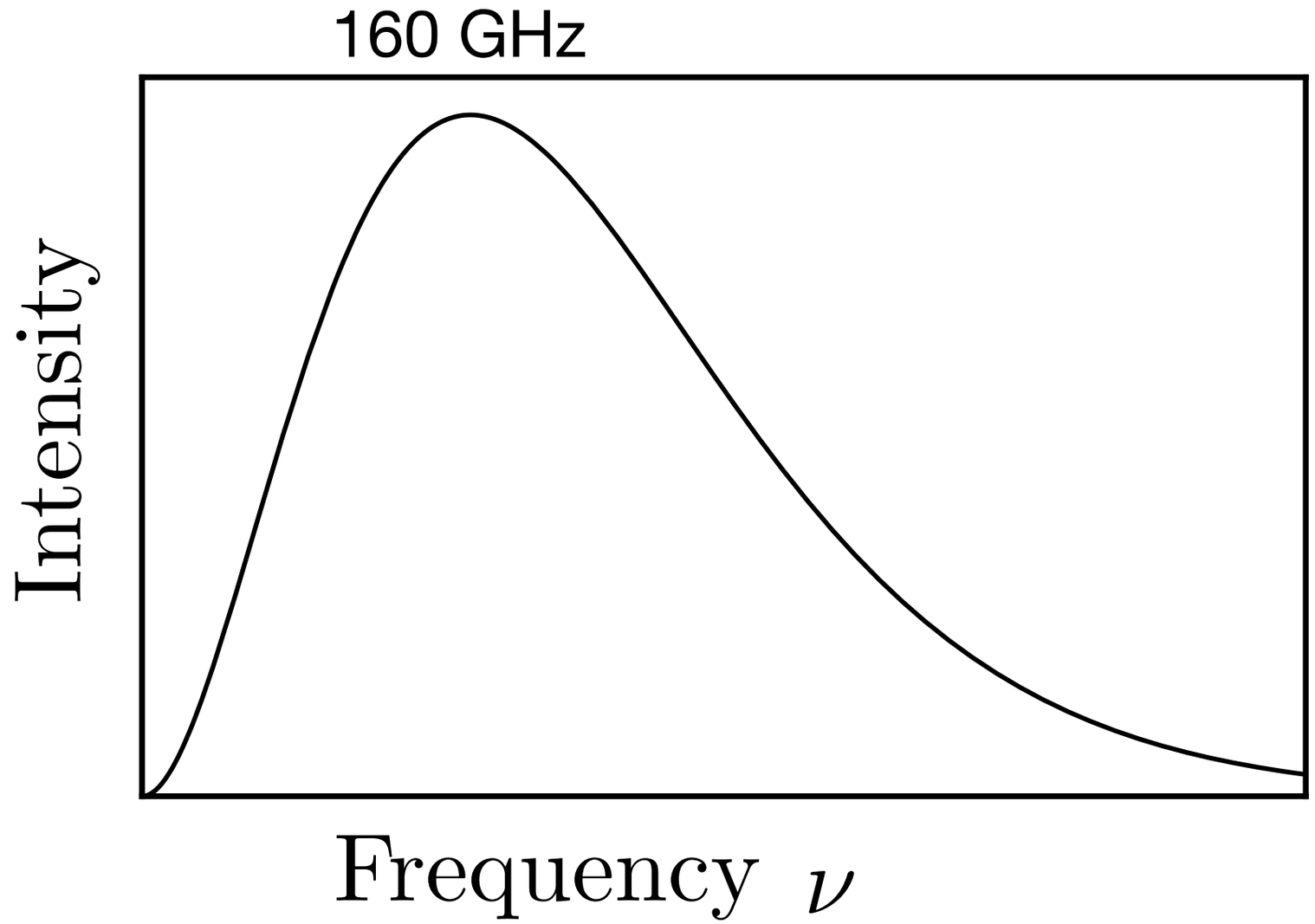
The basics of 21-cm

CMB



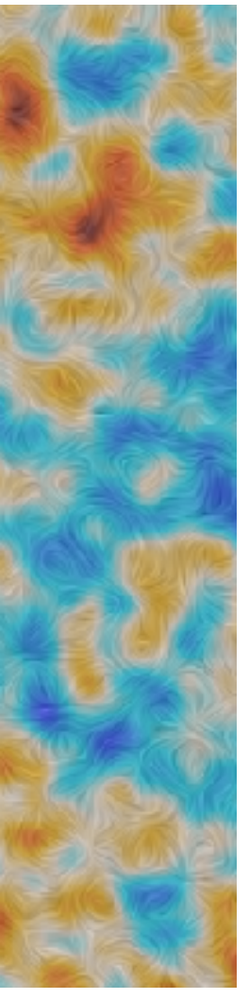


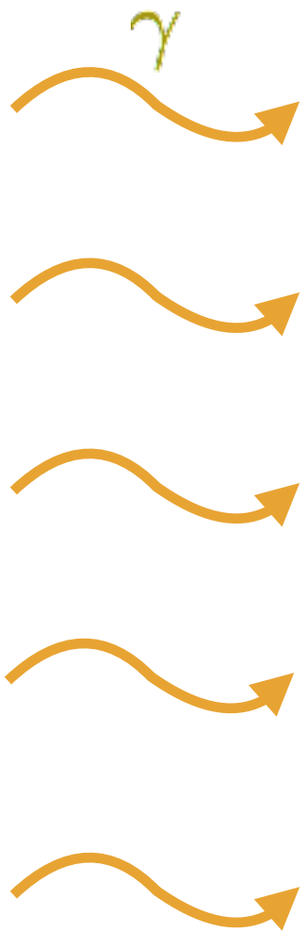
$z \approx 10^3$

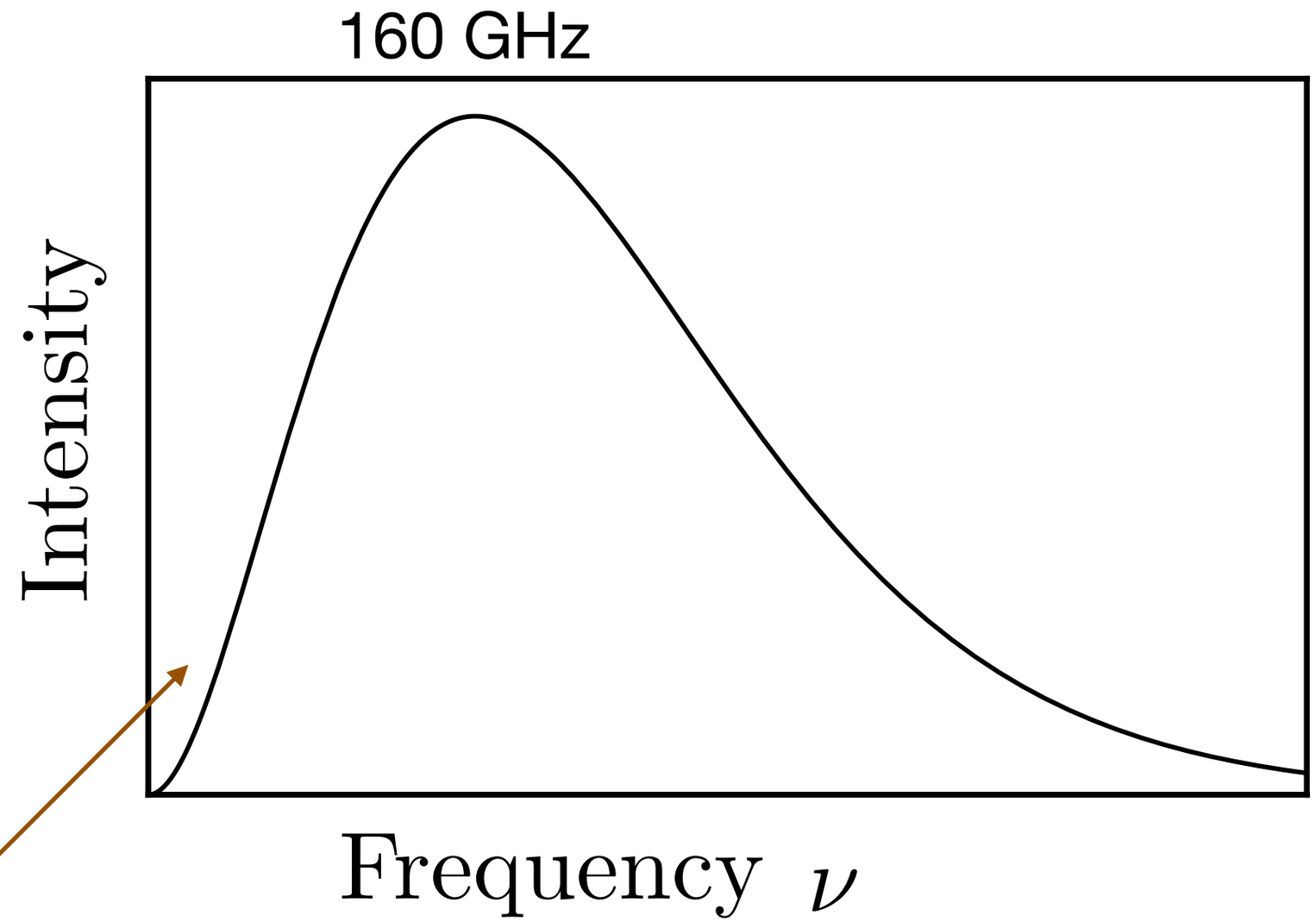


The basics of 21-cm

CMB





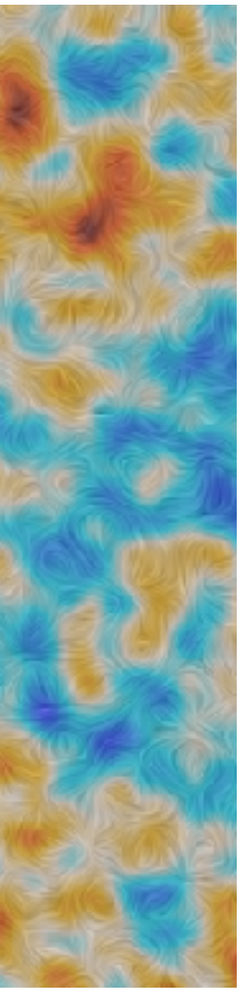


$z \approx 10^3$

21-cm wavelength: 1.4 GHz

The basics of 21-cm

CMB



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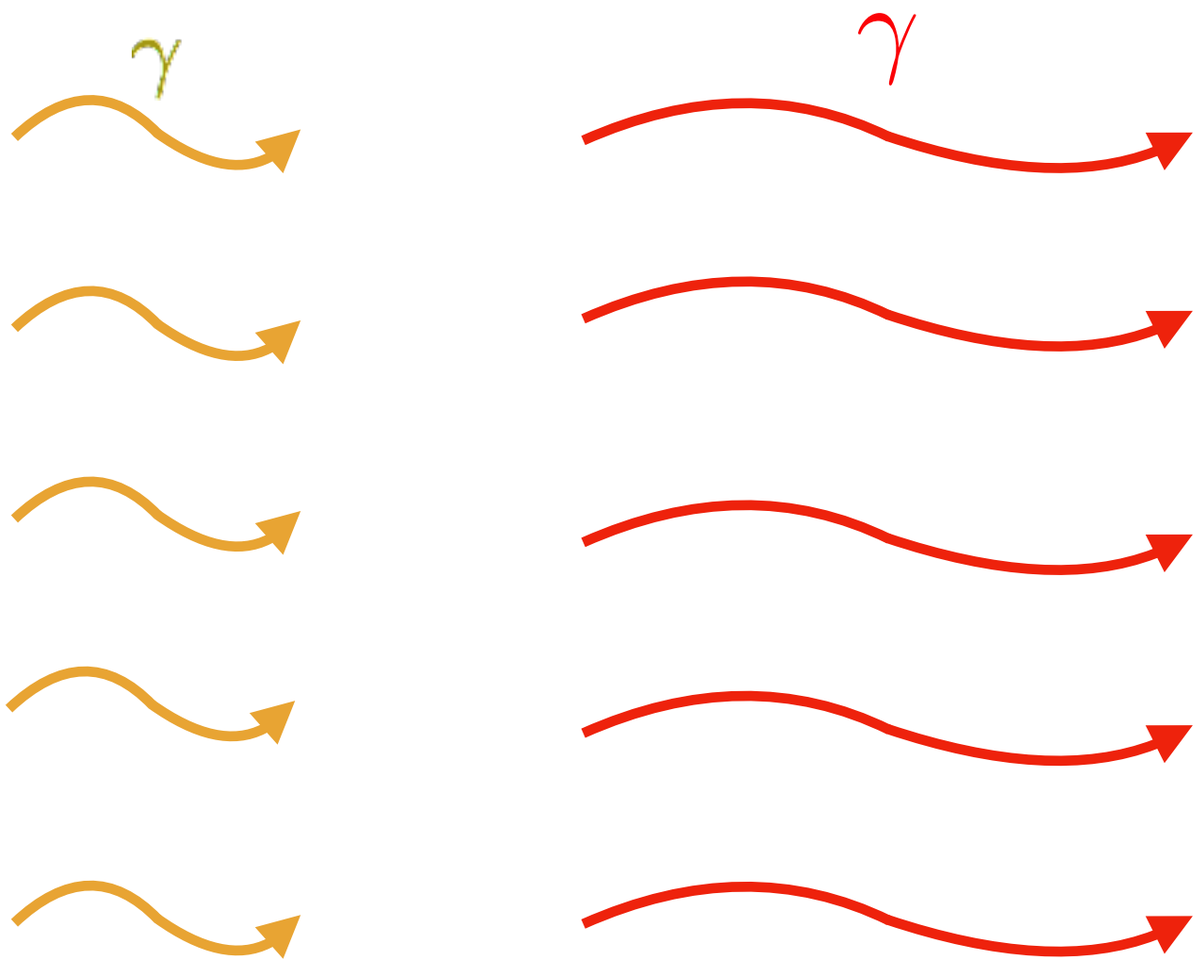


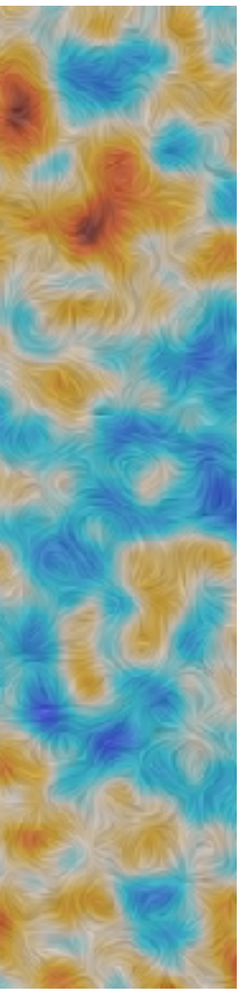
Earth

$z = 0$

cosmic time

The basics of 21-cm

CMB



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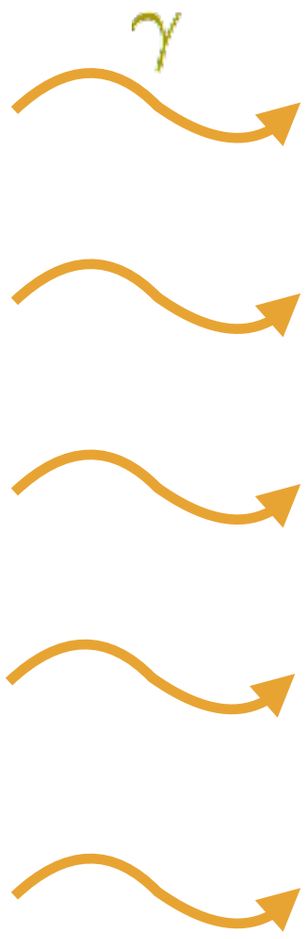

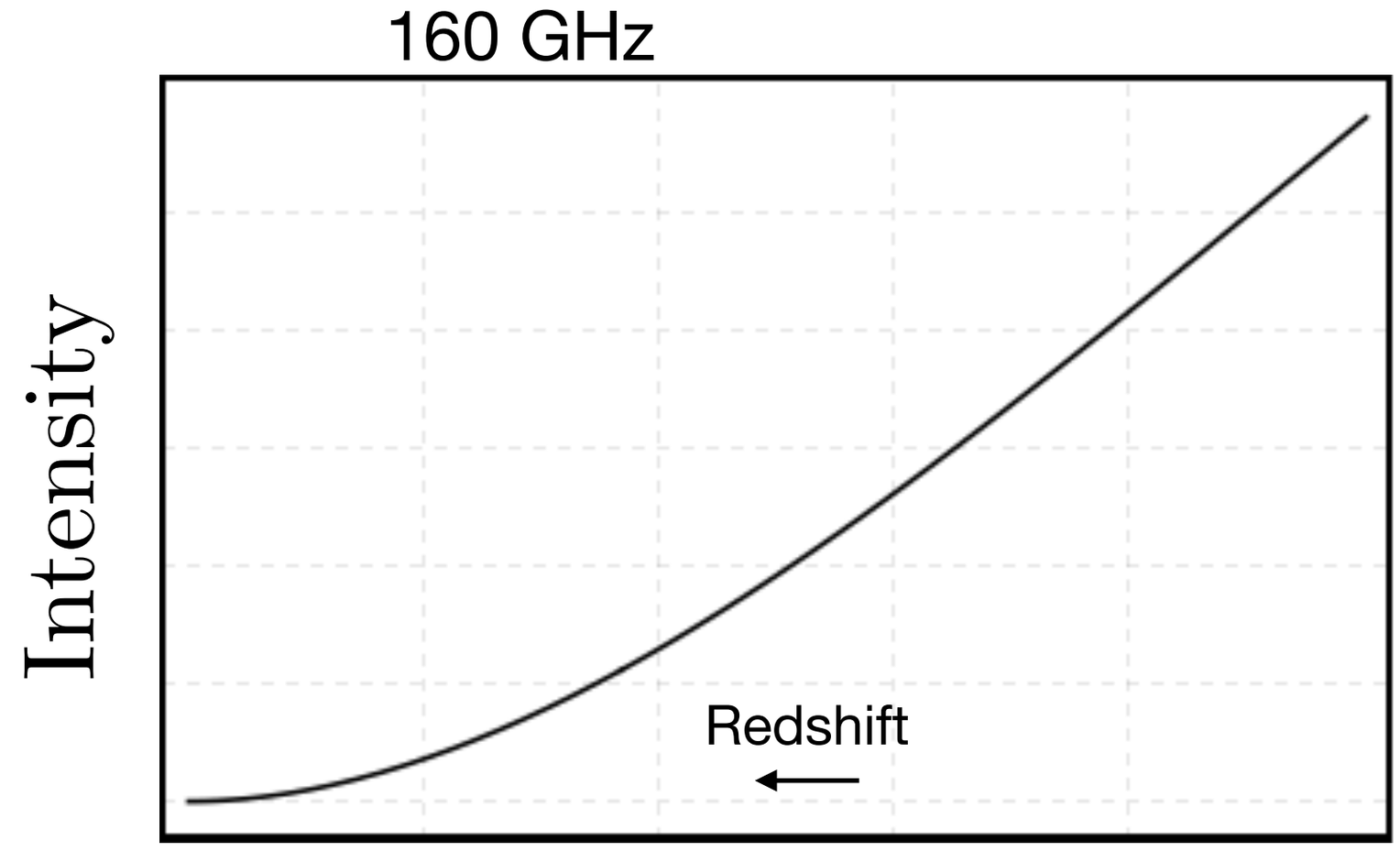

The basics of 21-cm

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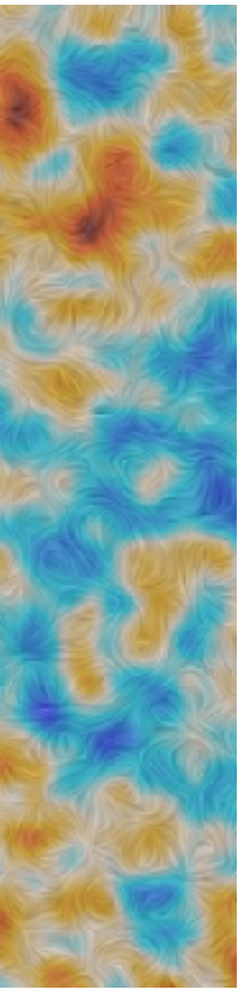

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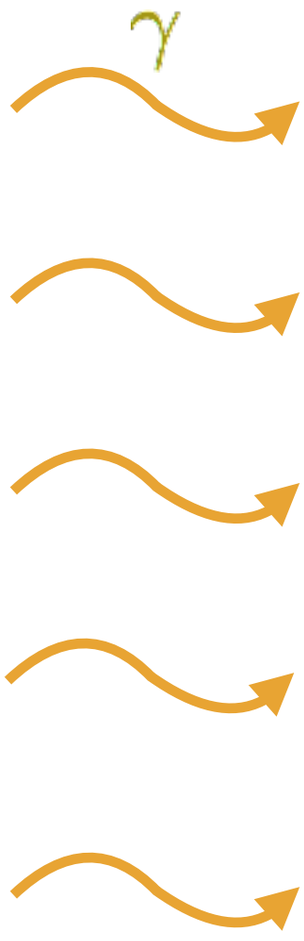
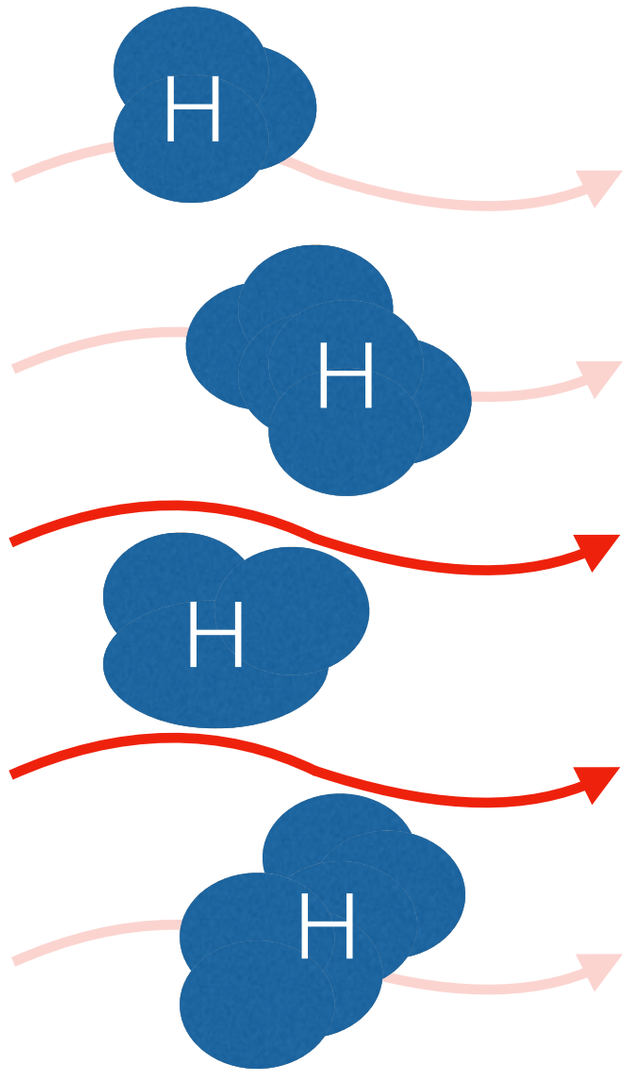


$\lambda = 21\,\mathrm{cm}$



$z = 20$

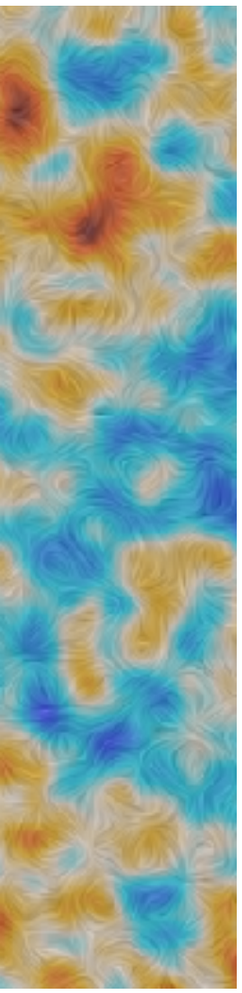
Earth

$z = 0$

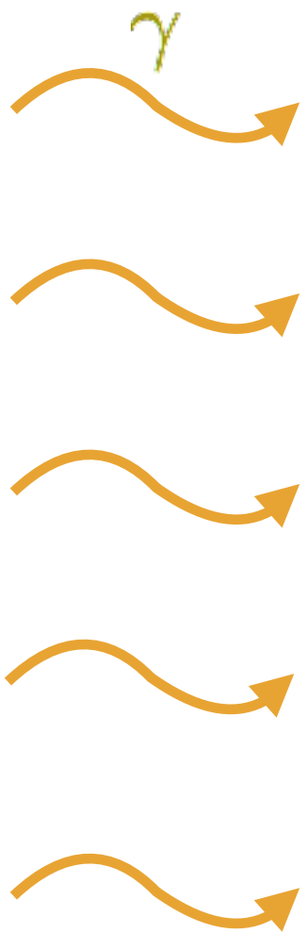
cosmic time

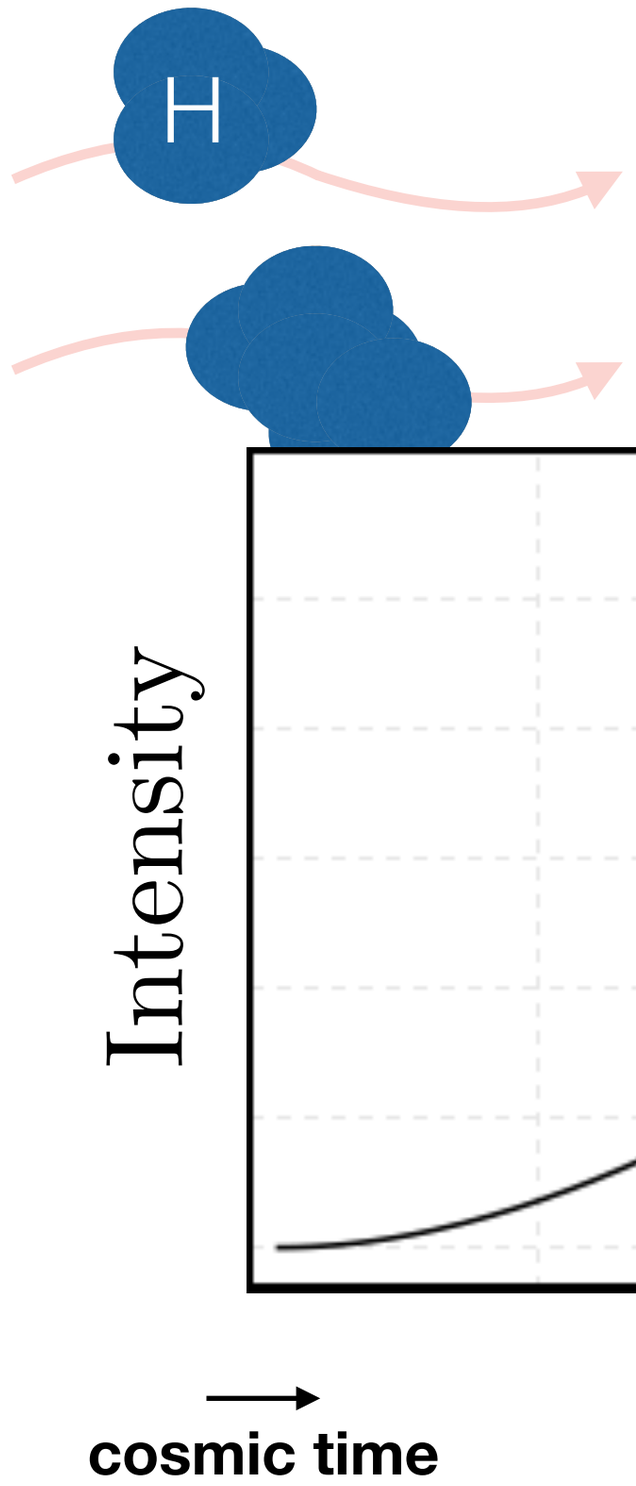
The basics of 21-cm

CMB



$z \approx 10^3$





The basics of 21-cm

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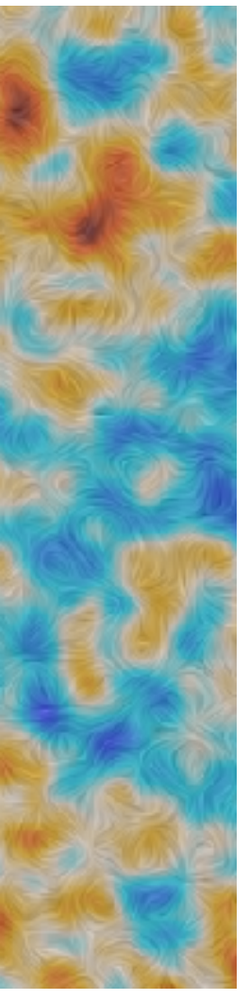

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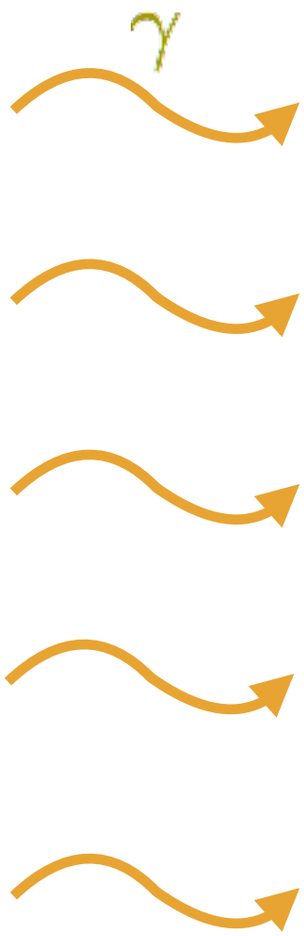
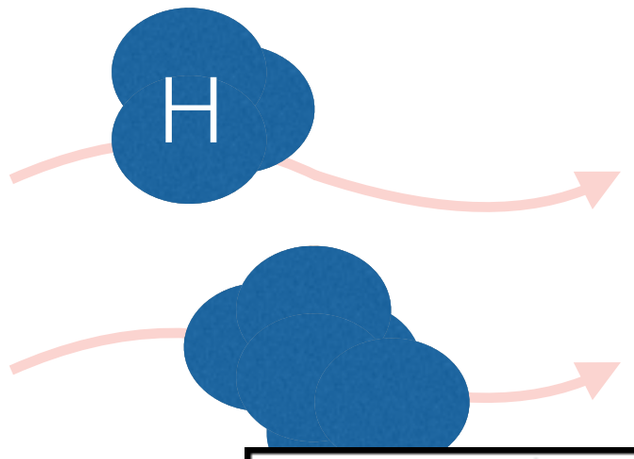
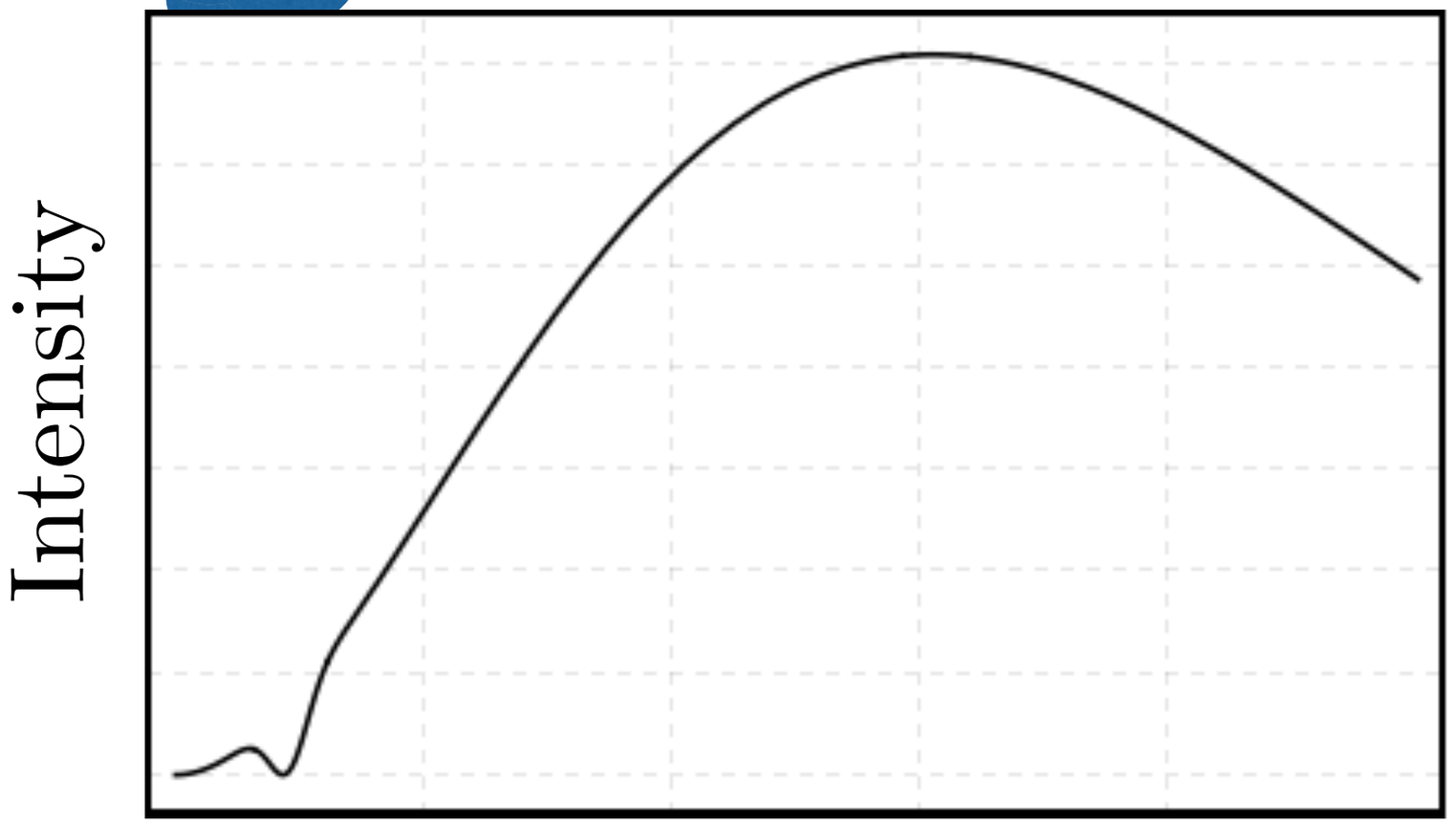




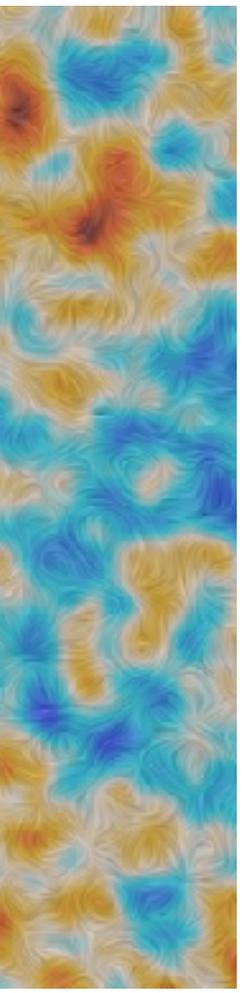
$z \approx 20 \rightarrow 0$



cosmic time

The basics of 21-cm

CMB



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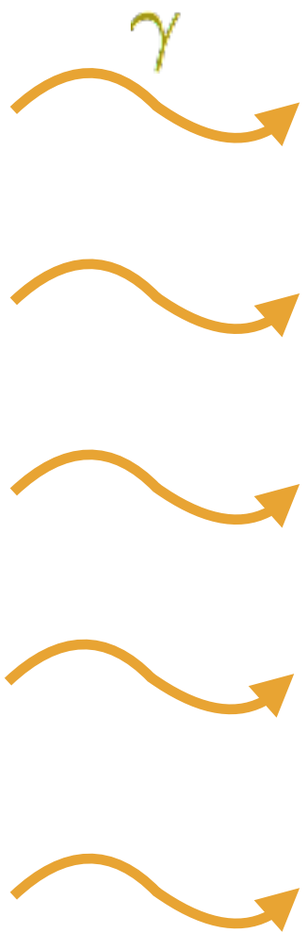

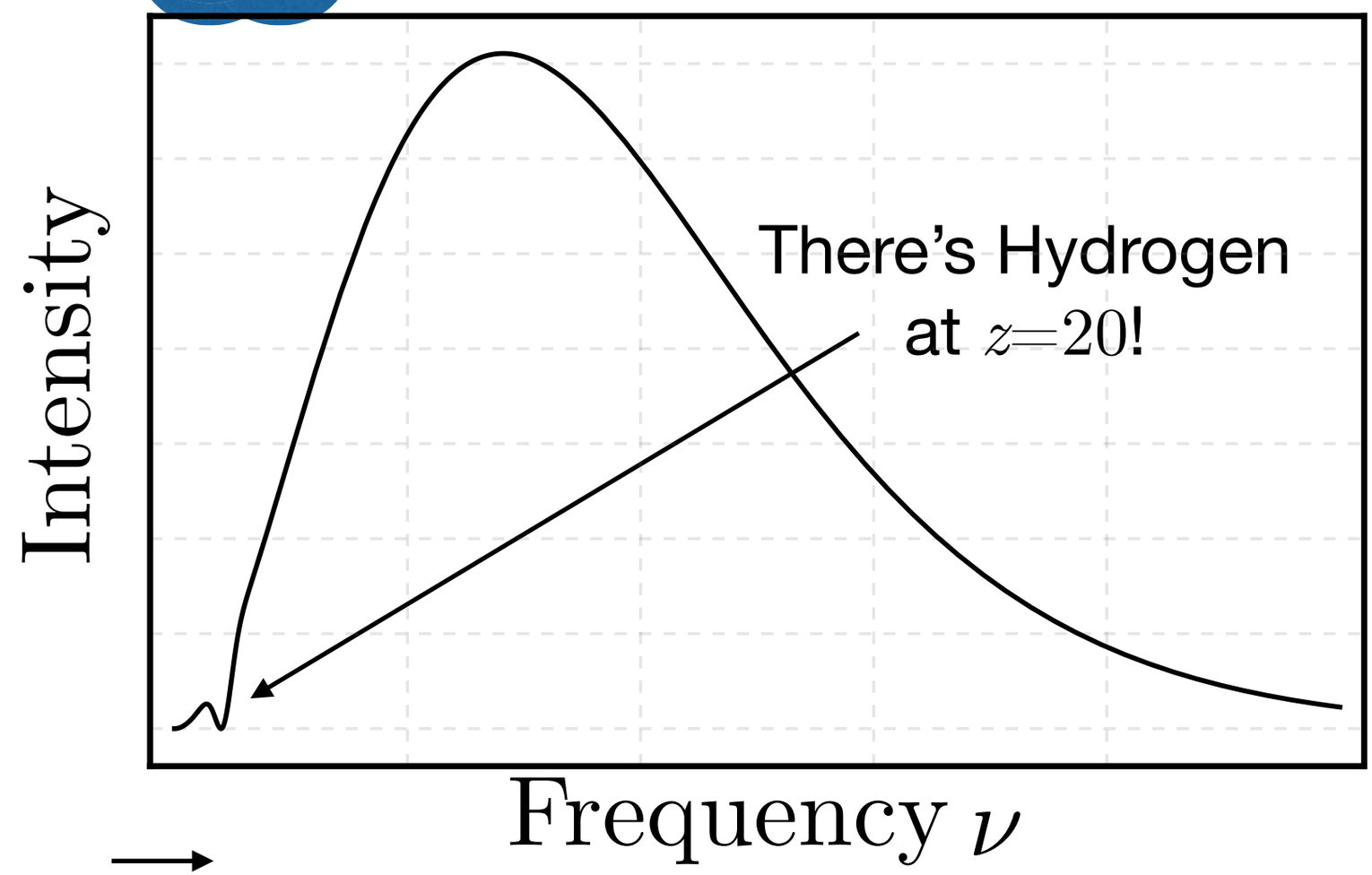

cosmic time →

The basics of 21-cm

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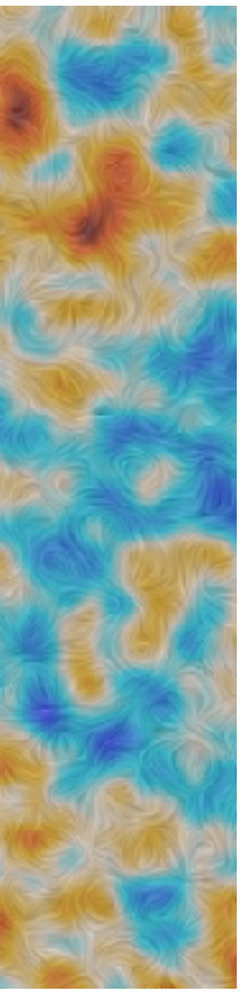
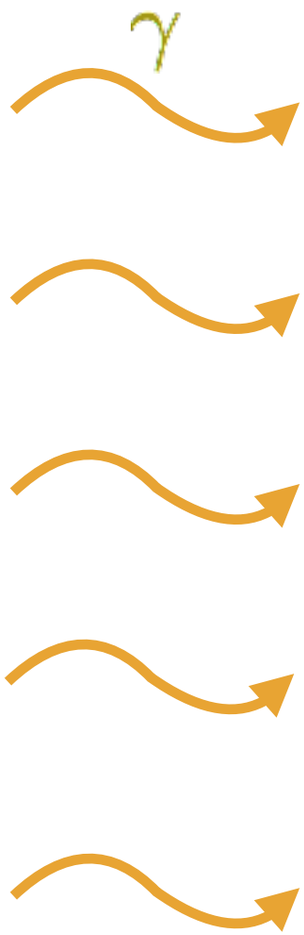
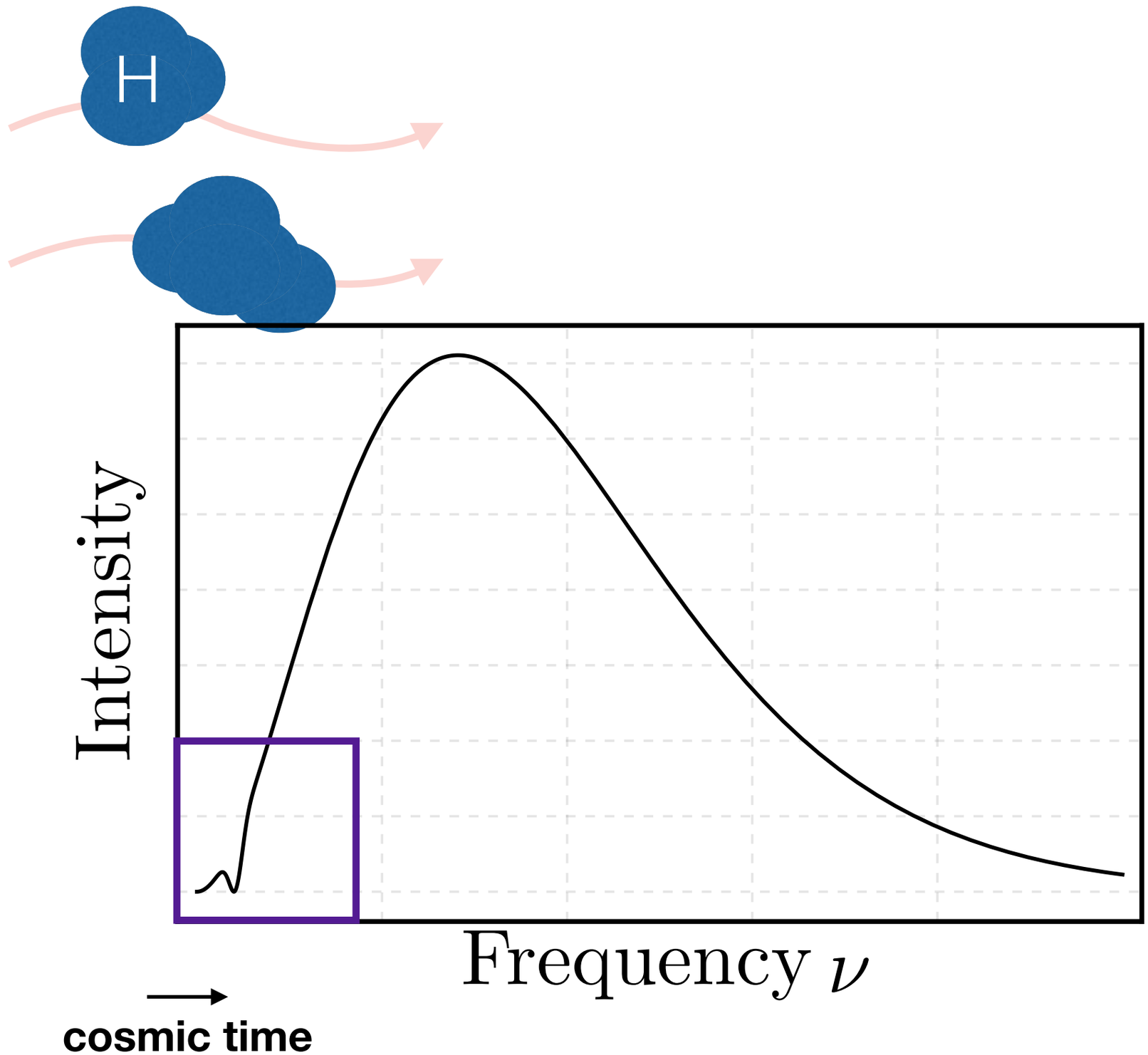
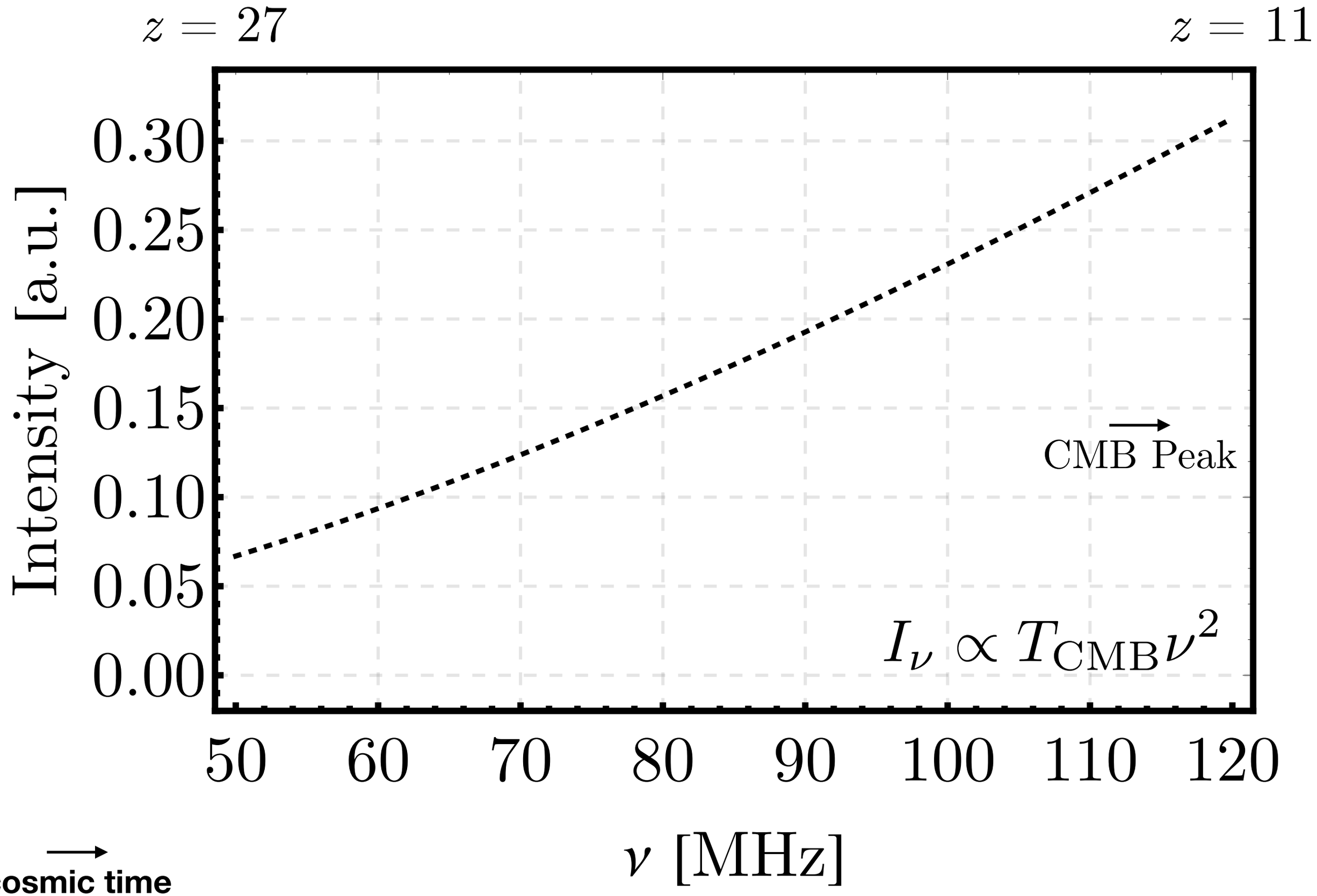


$z \approx 10^3$

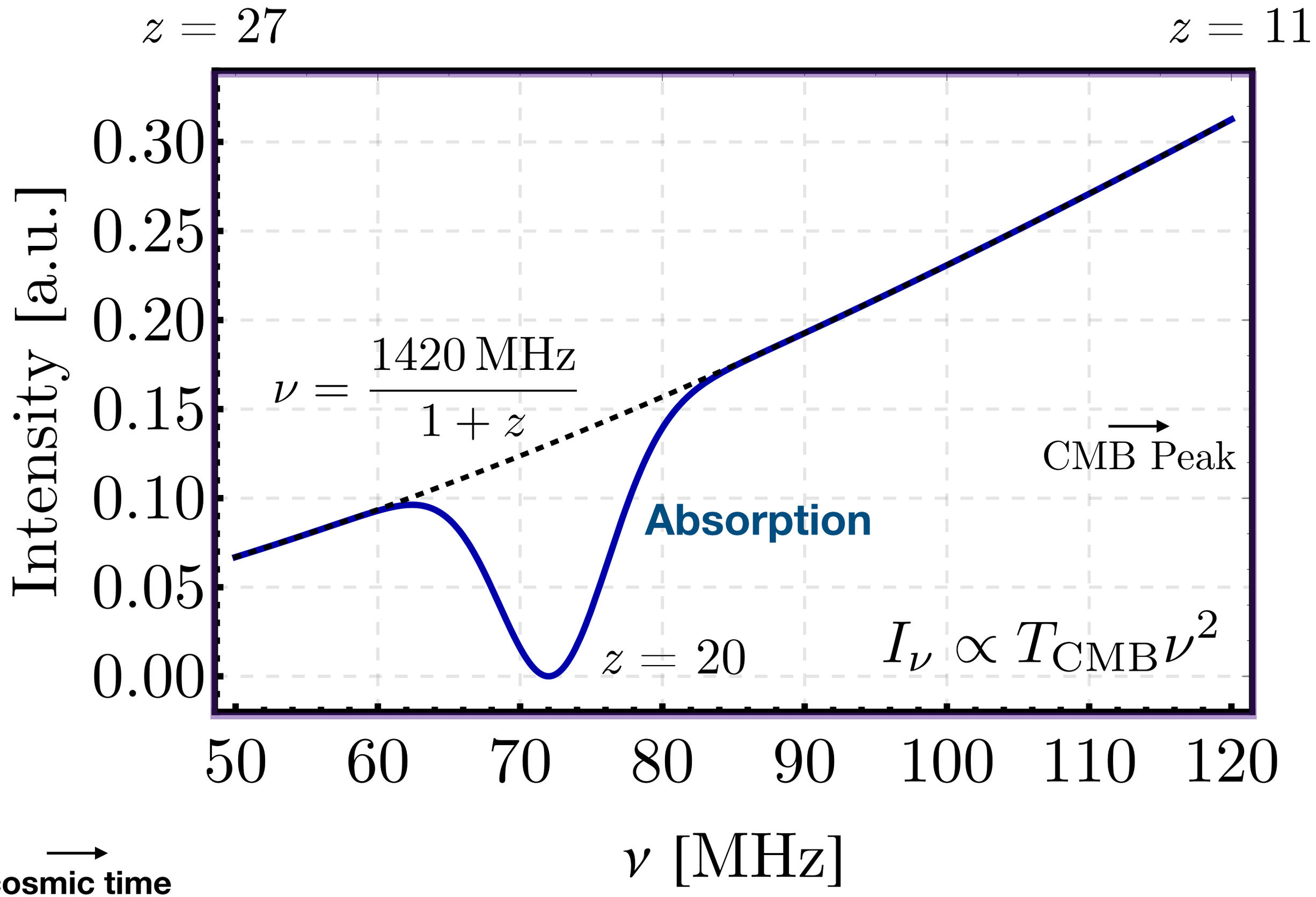




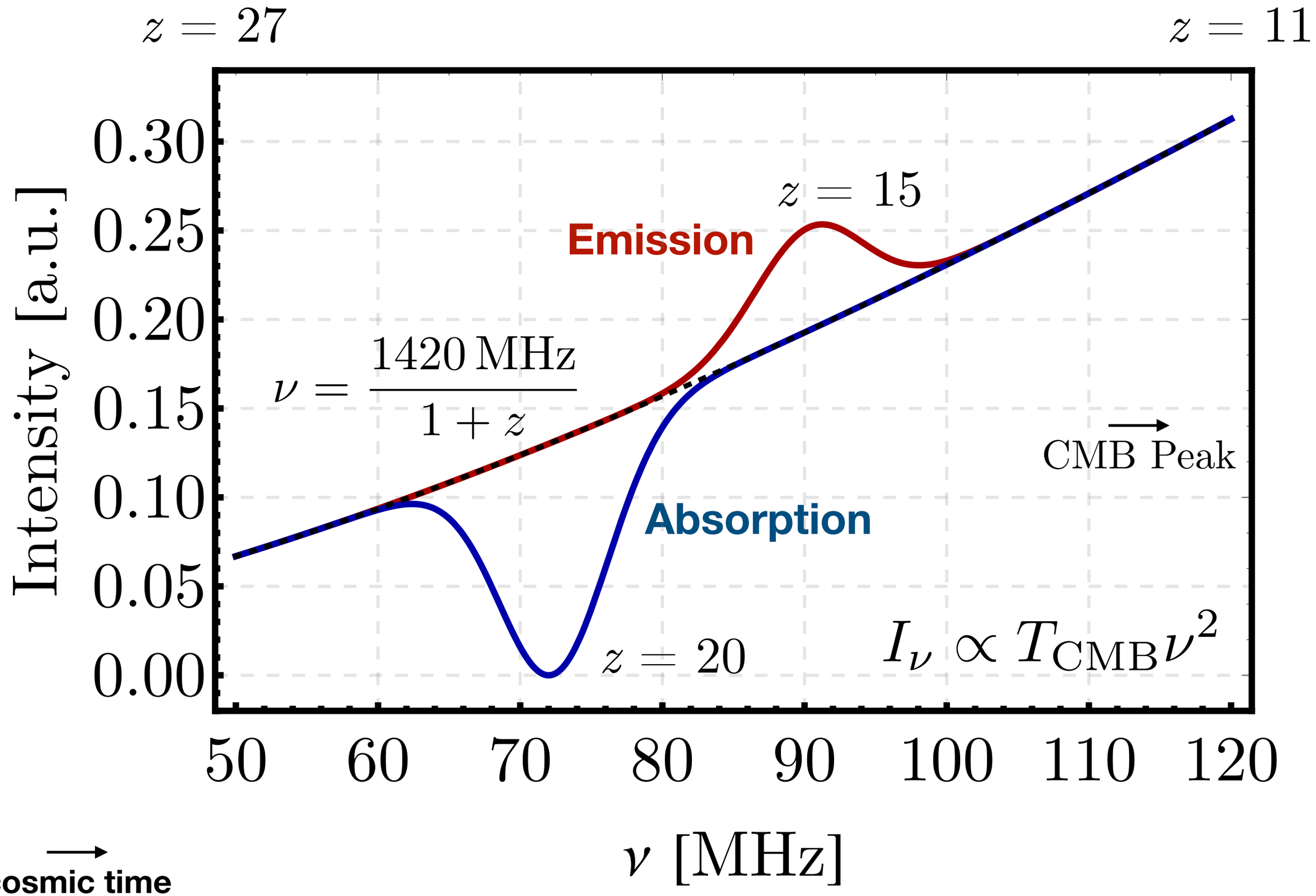
What would we see?



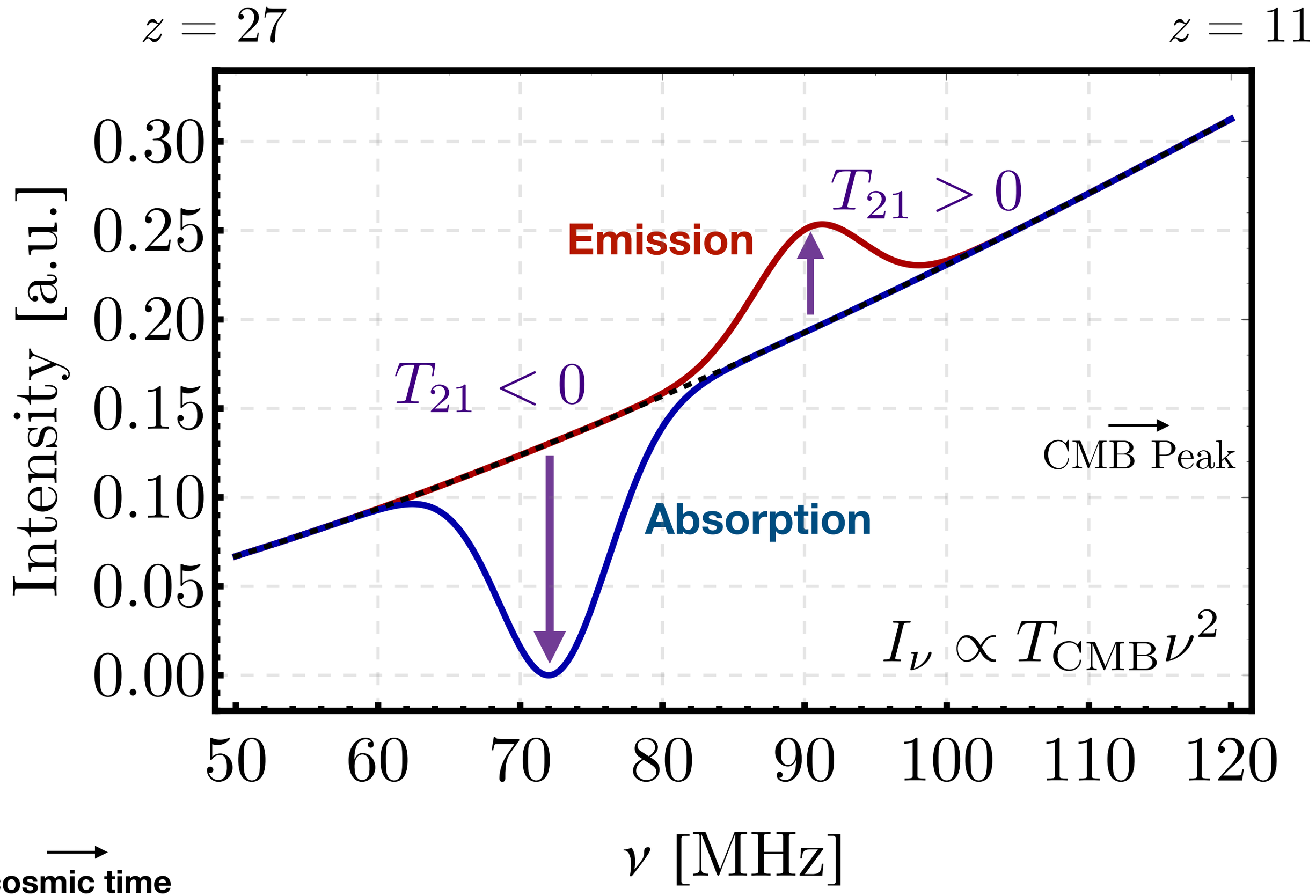
What would we see?



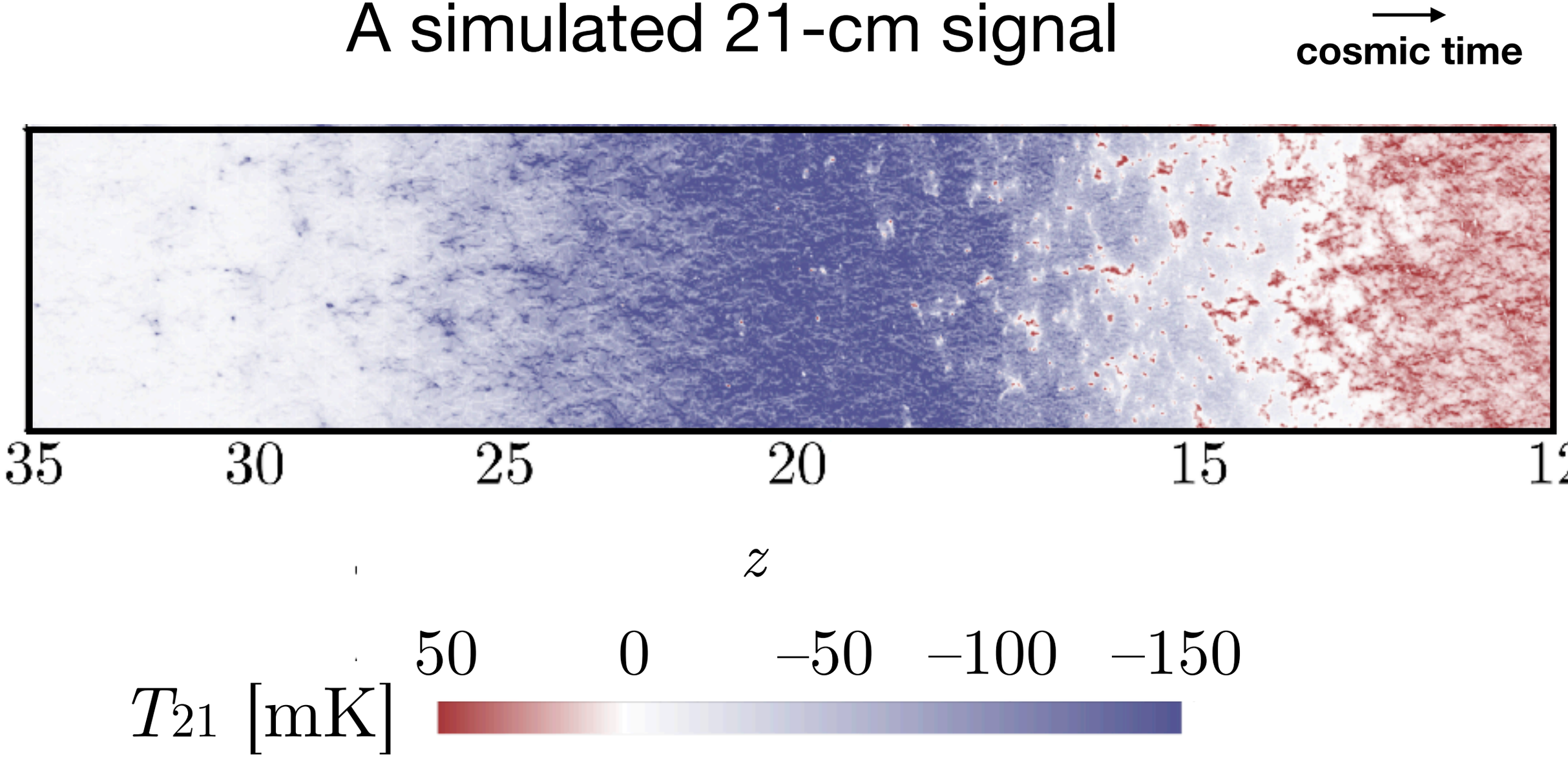
What would we see?



What would we see?

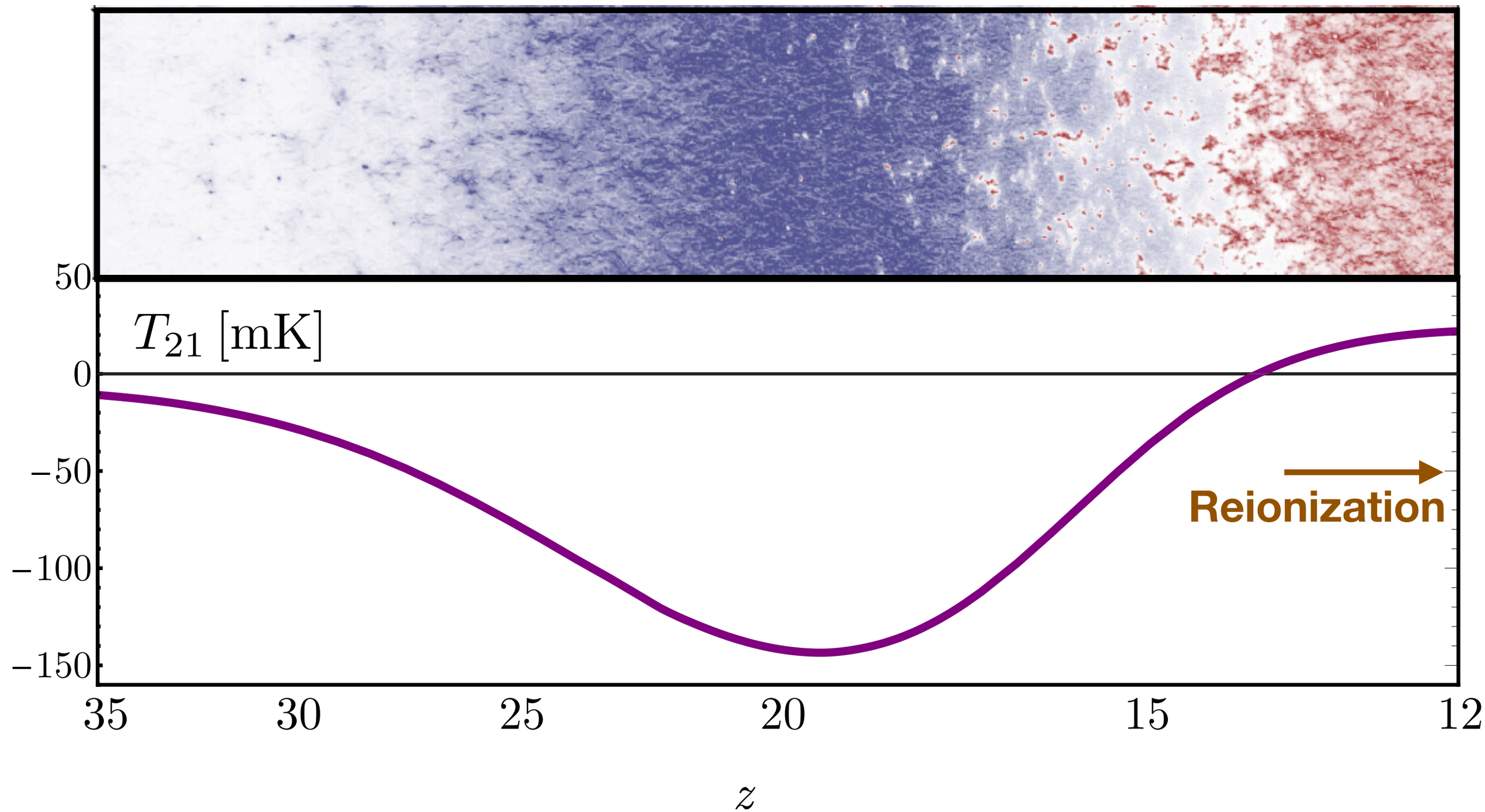


A simulated 21-cm signal



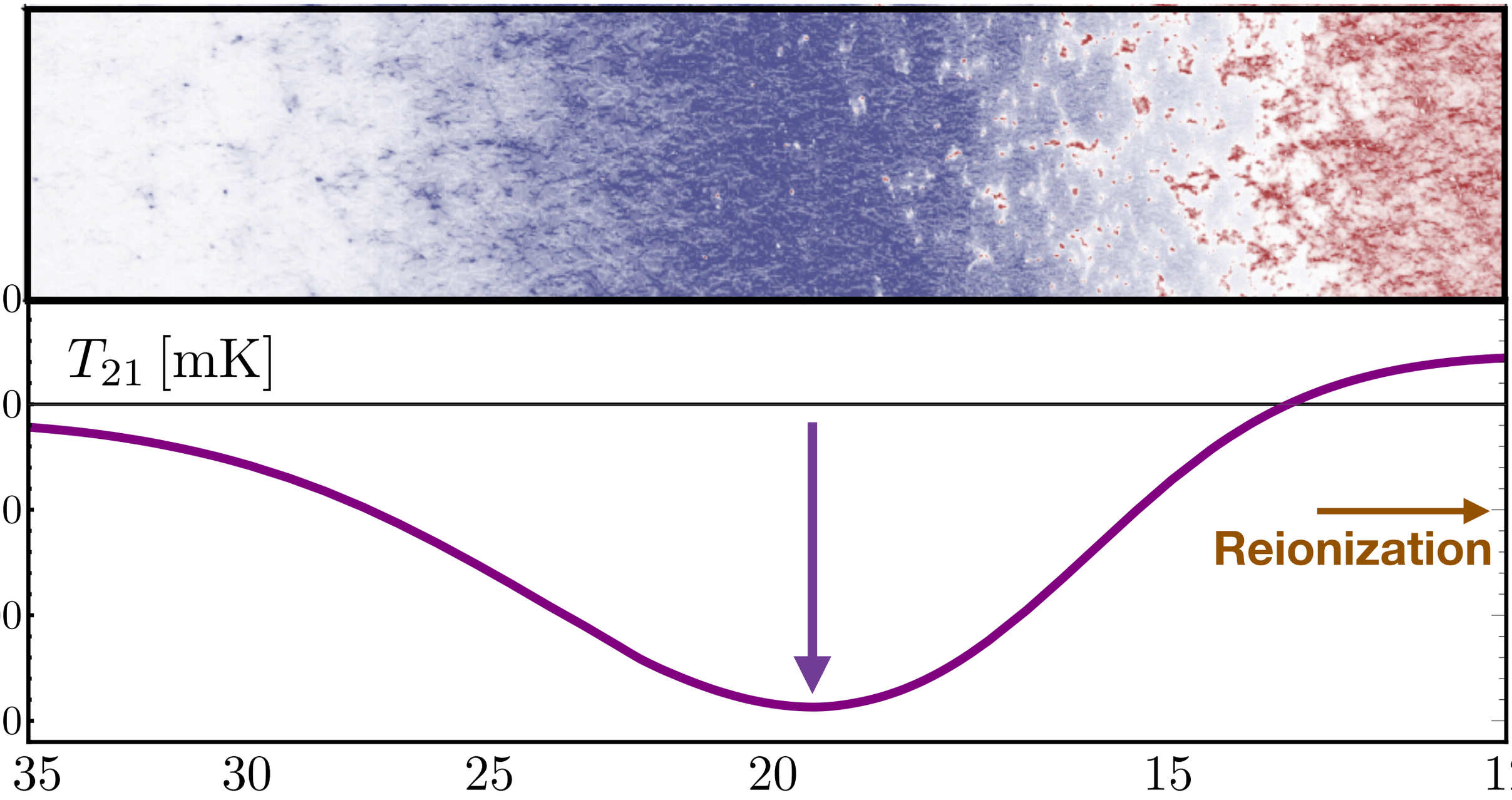
21cmvFAST **JBM** PRD 2019

A simulated 21-cm global signal



21cmvFAST **JBM** PRD 2019

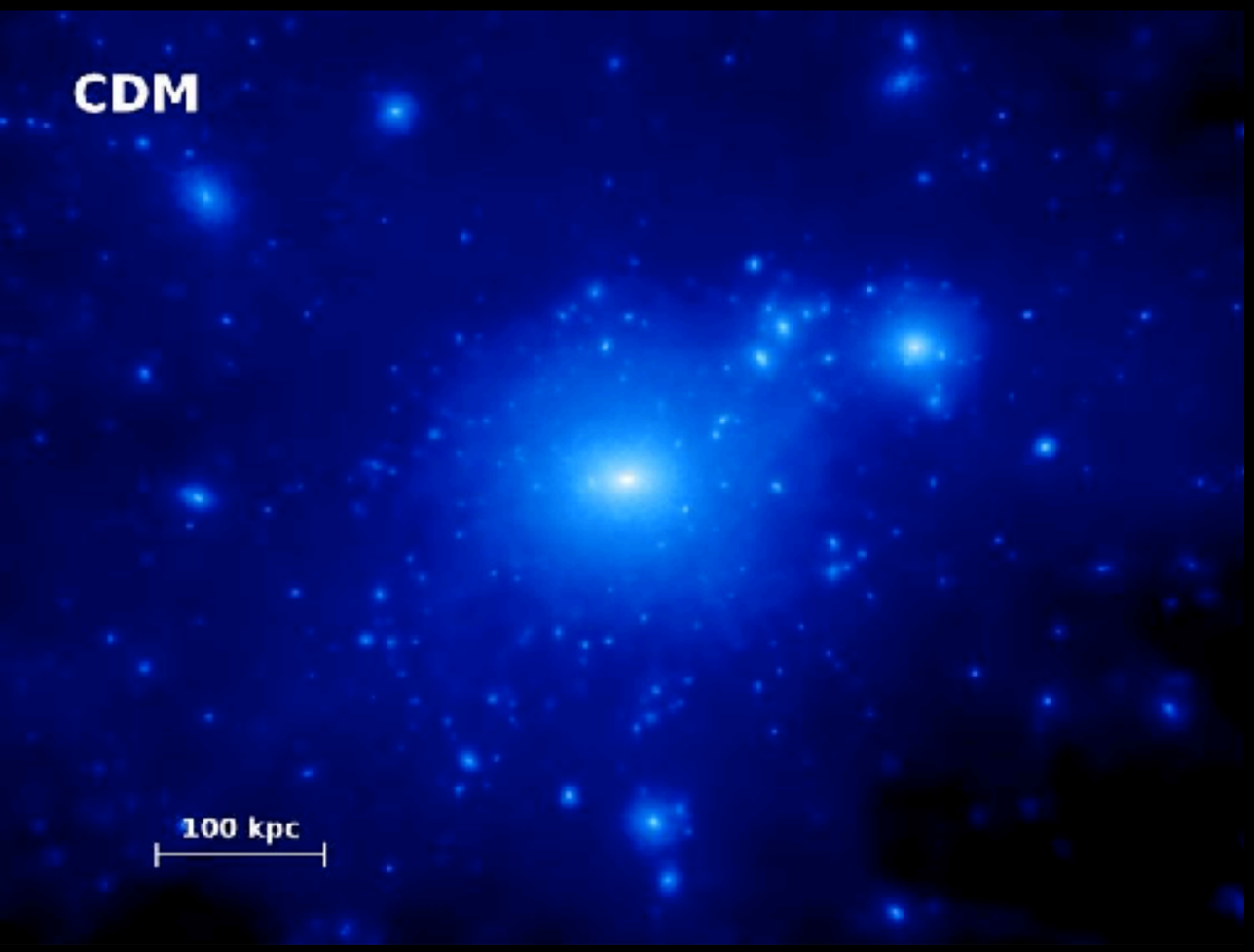
21-cm as a thermometer at cosmic dawn



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

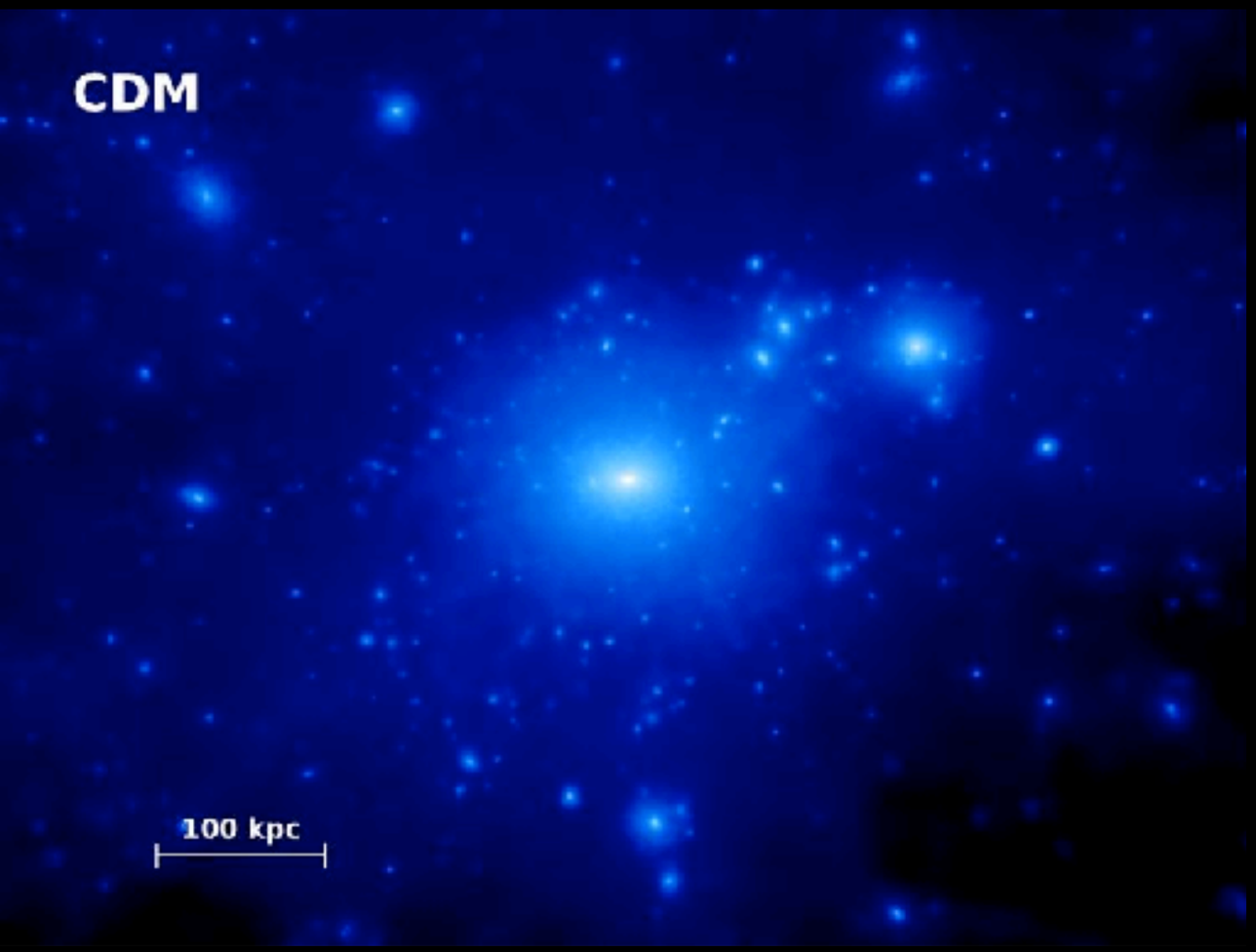
$$T_{21} \approx 30\,\mathrm{mK}\left(1-\frac{T_\gamma}{T_S}\right)$$

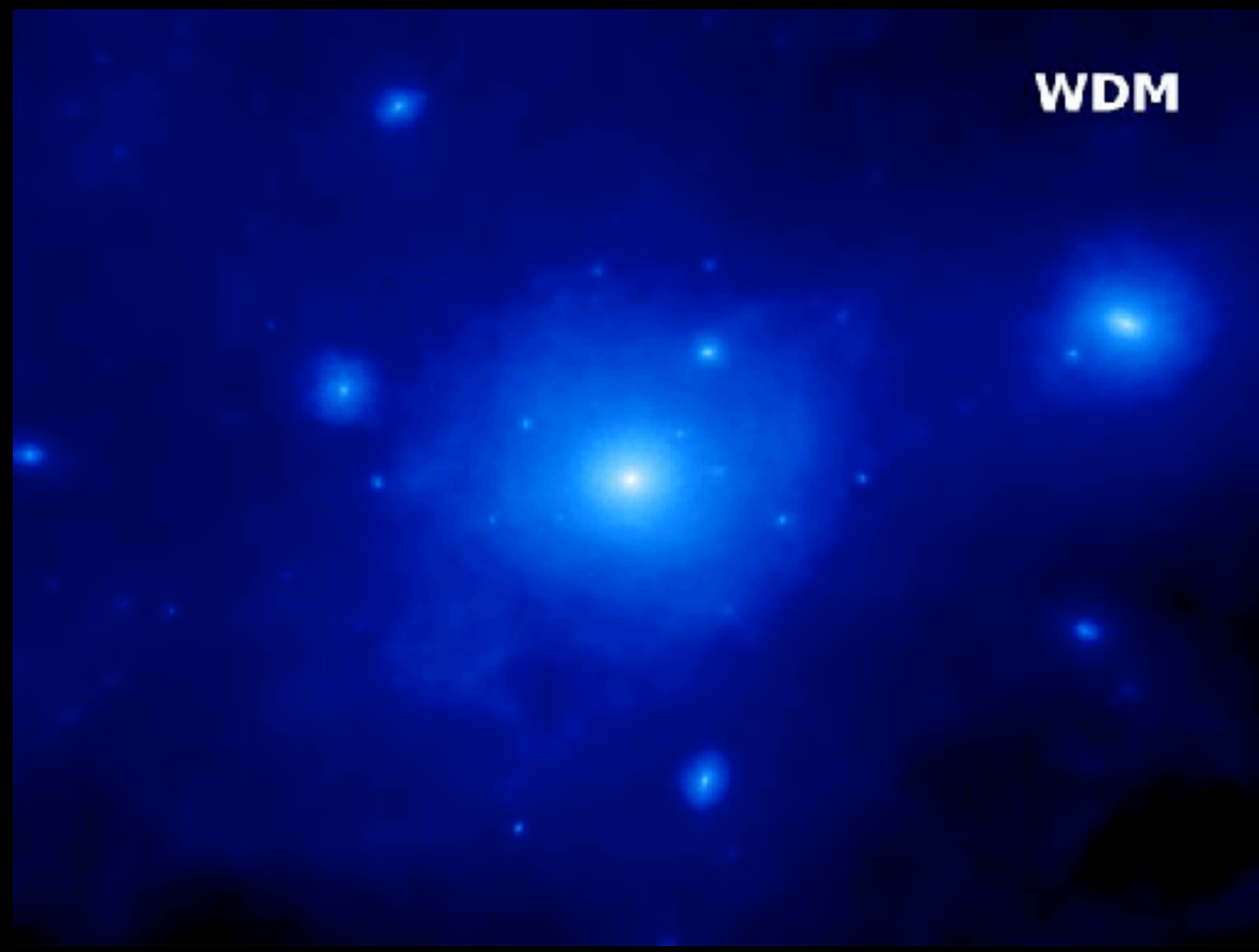
Is DM cold?



Credit: Boehm (IPP Durham)

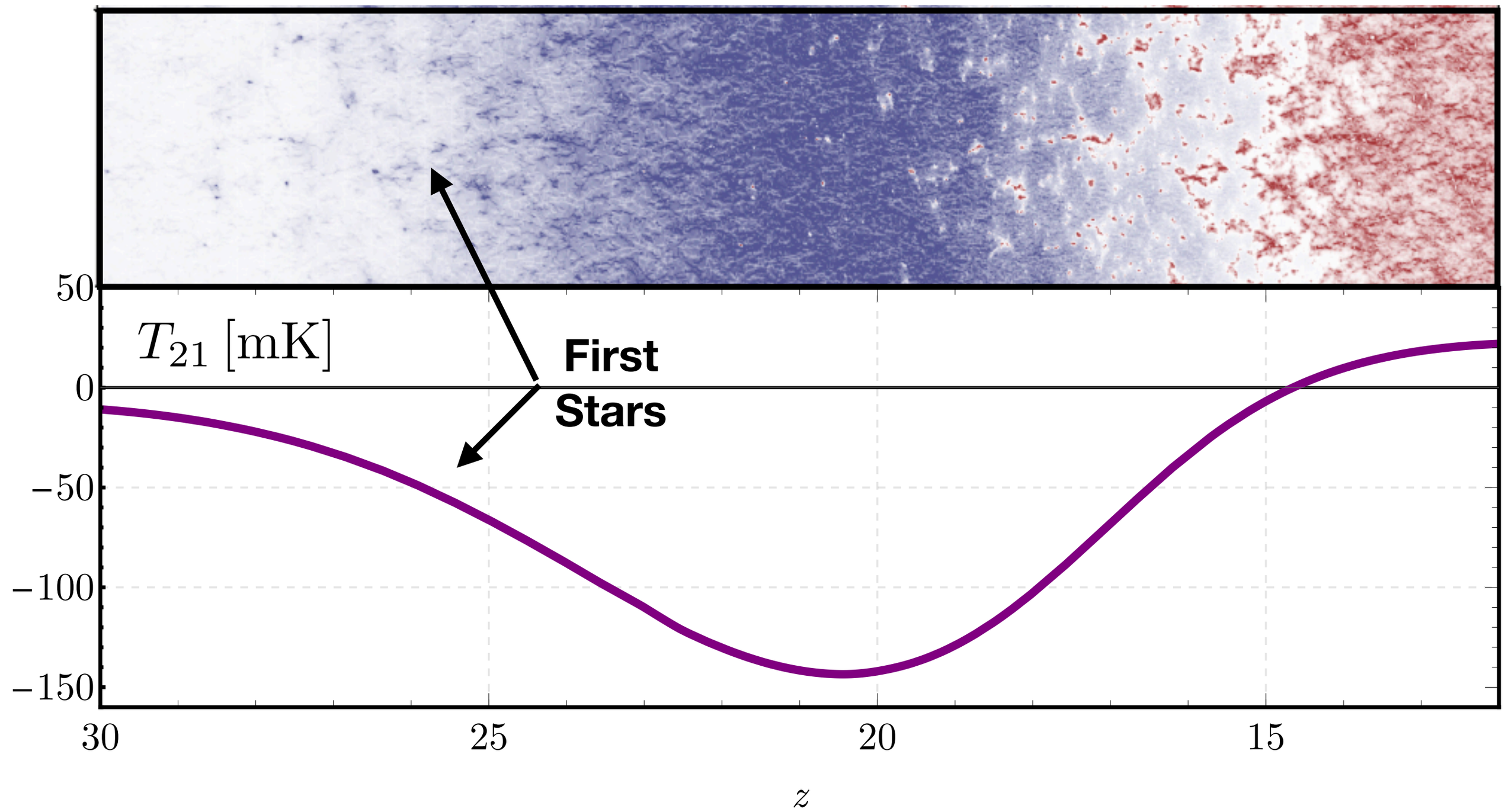
Is DM cold?



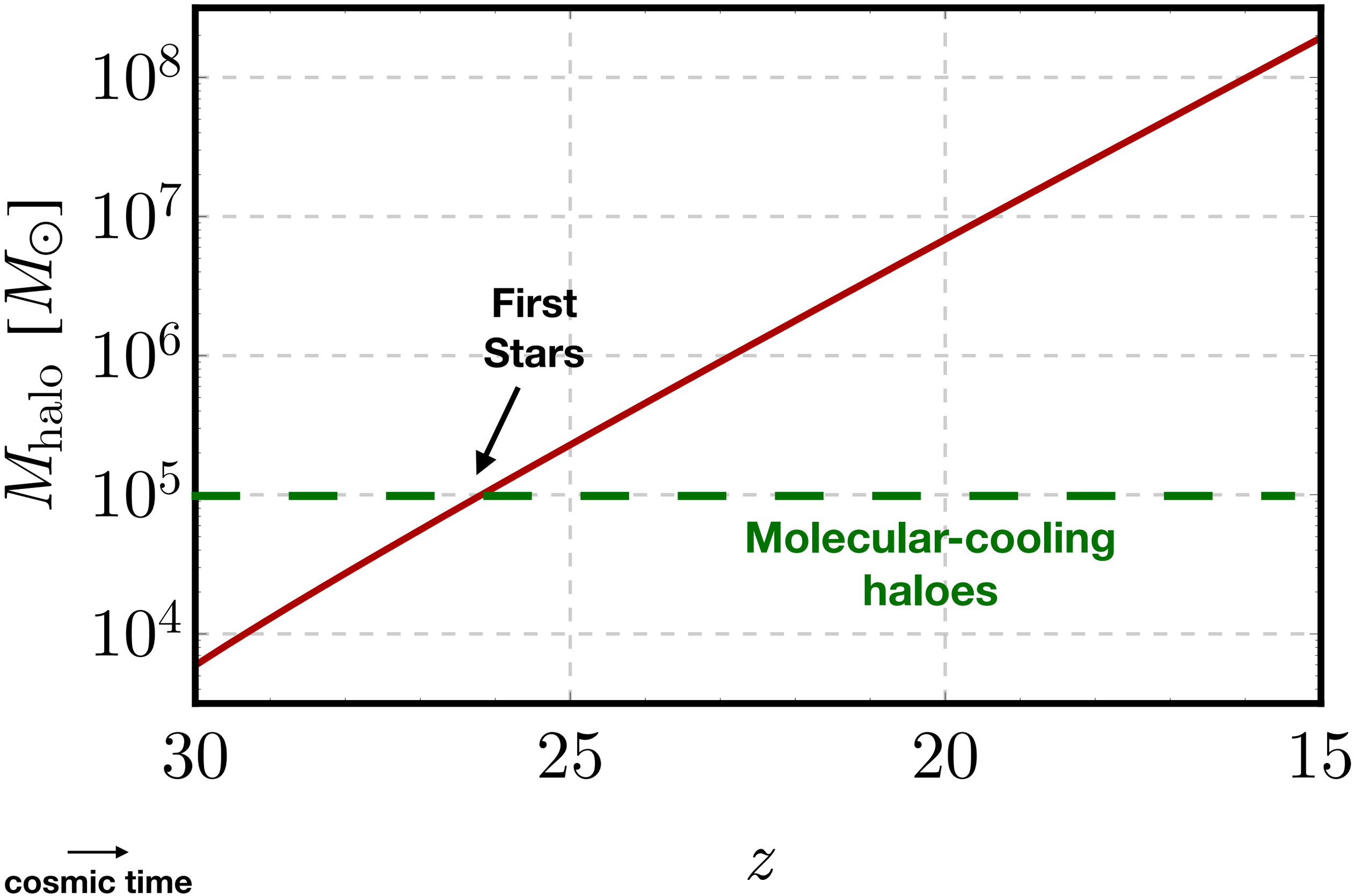


Credit: Boehm (IPP Durham)

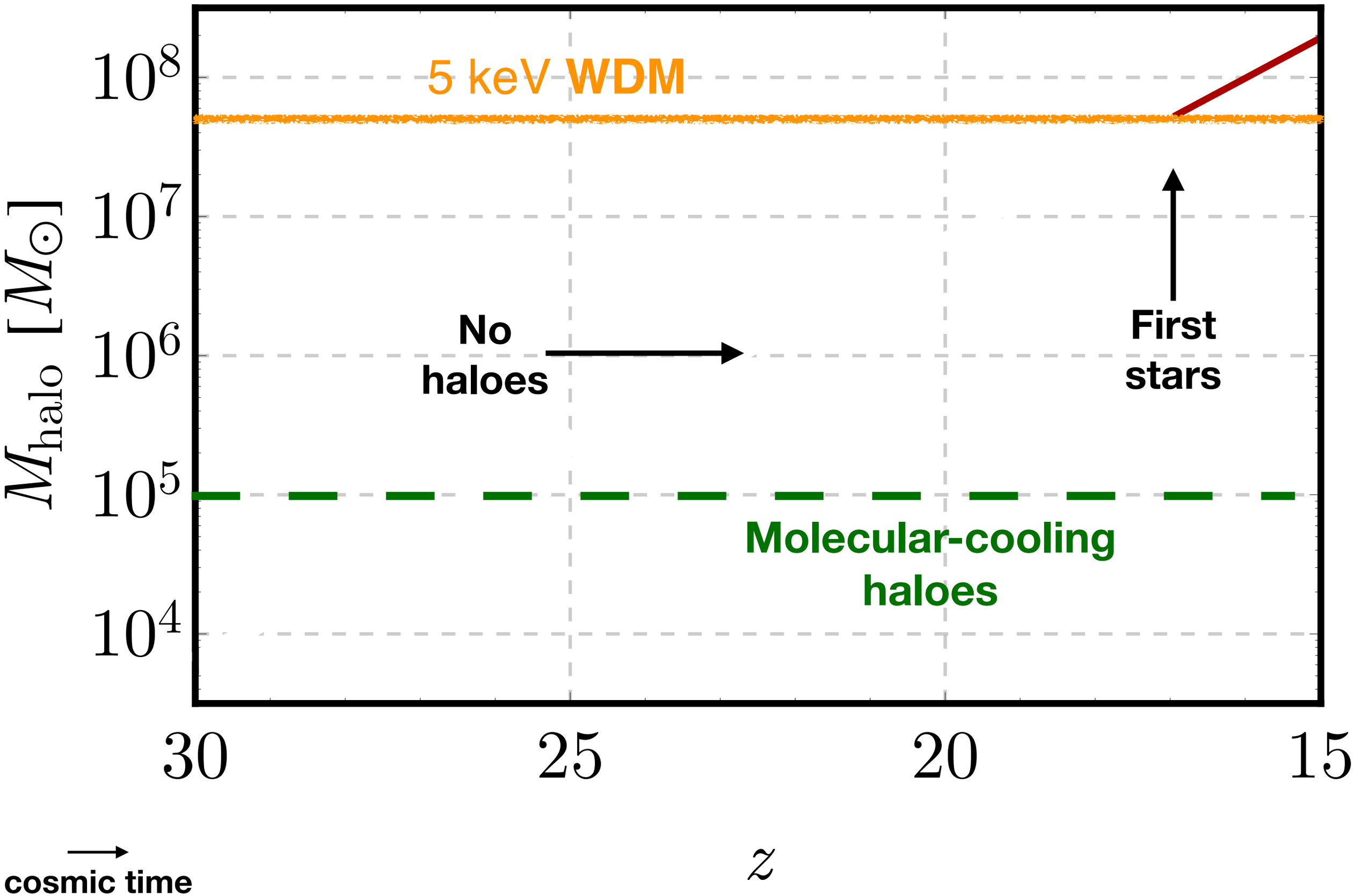
Is DM cold?



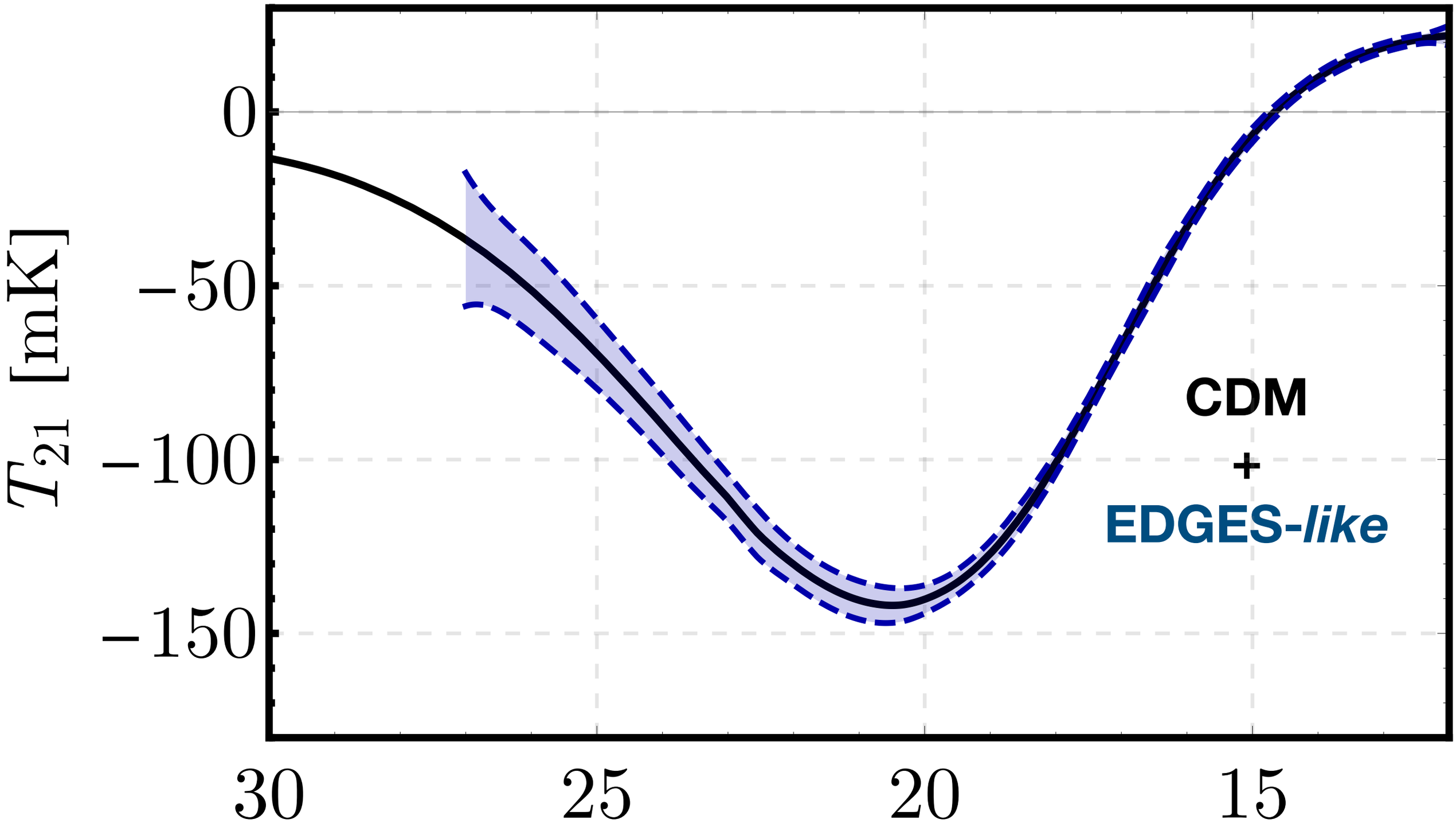
Is DM cold?


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?

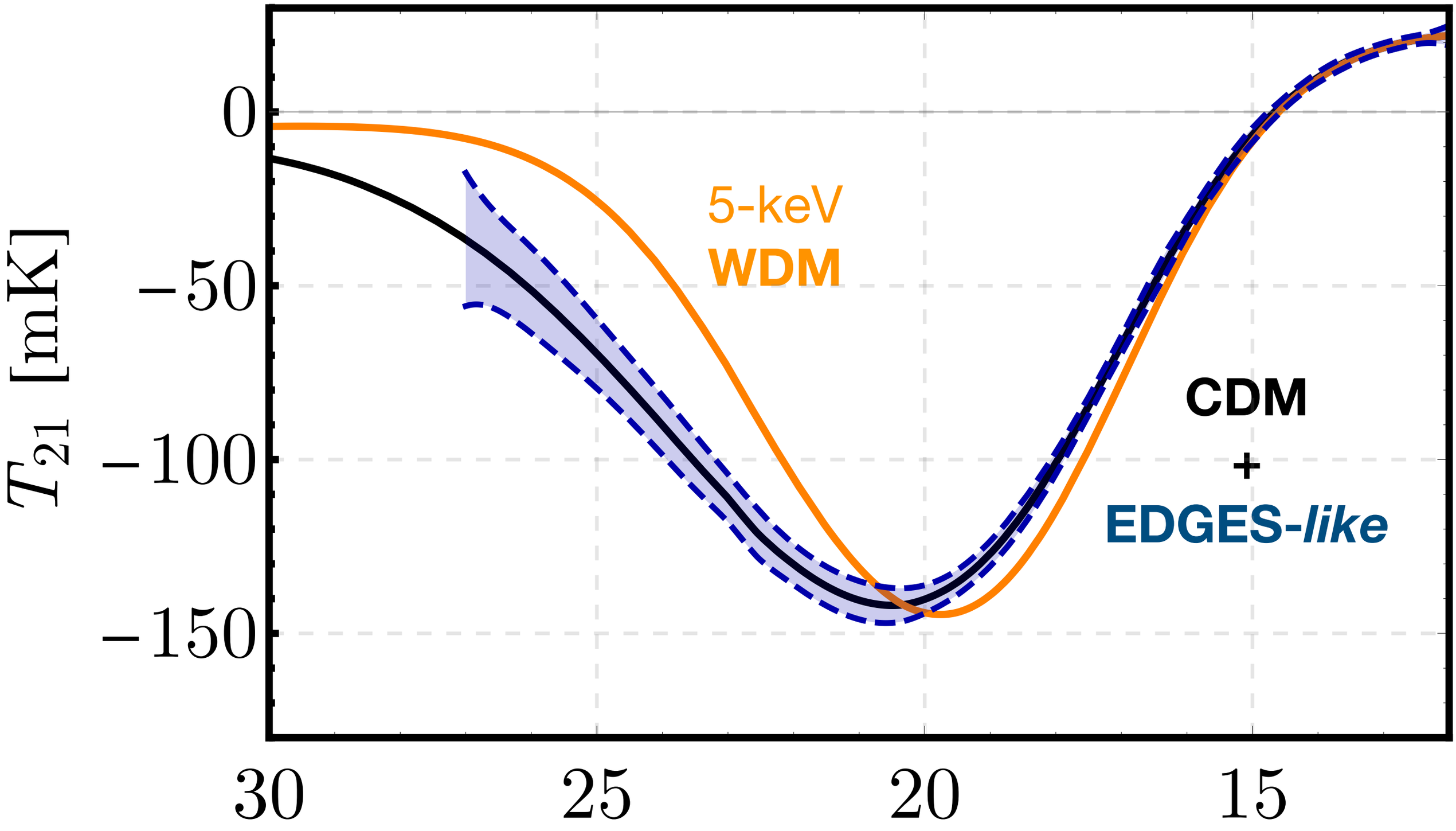

5 keV WDM
No haloes
First stars
Molecular-cooling haloes
$M_{\rm halo}$ [$M_\odot$]
10^8
10^7
10^6
10^5
10^4
30
25
20
15
z
cosmic time

Is DM cold?



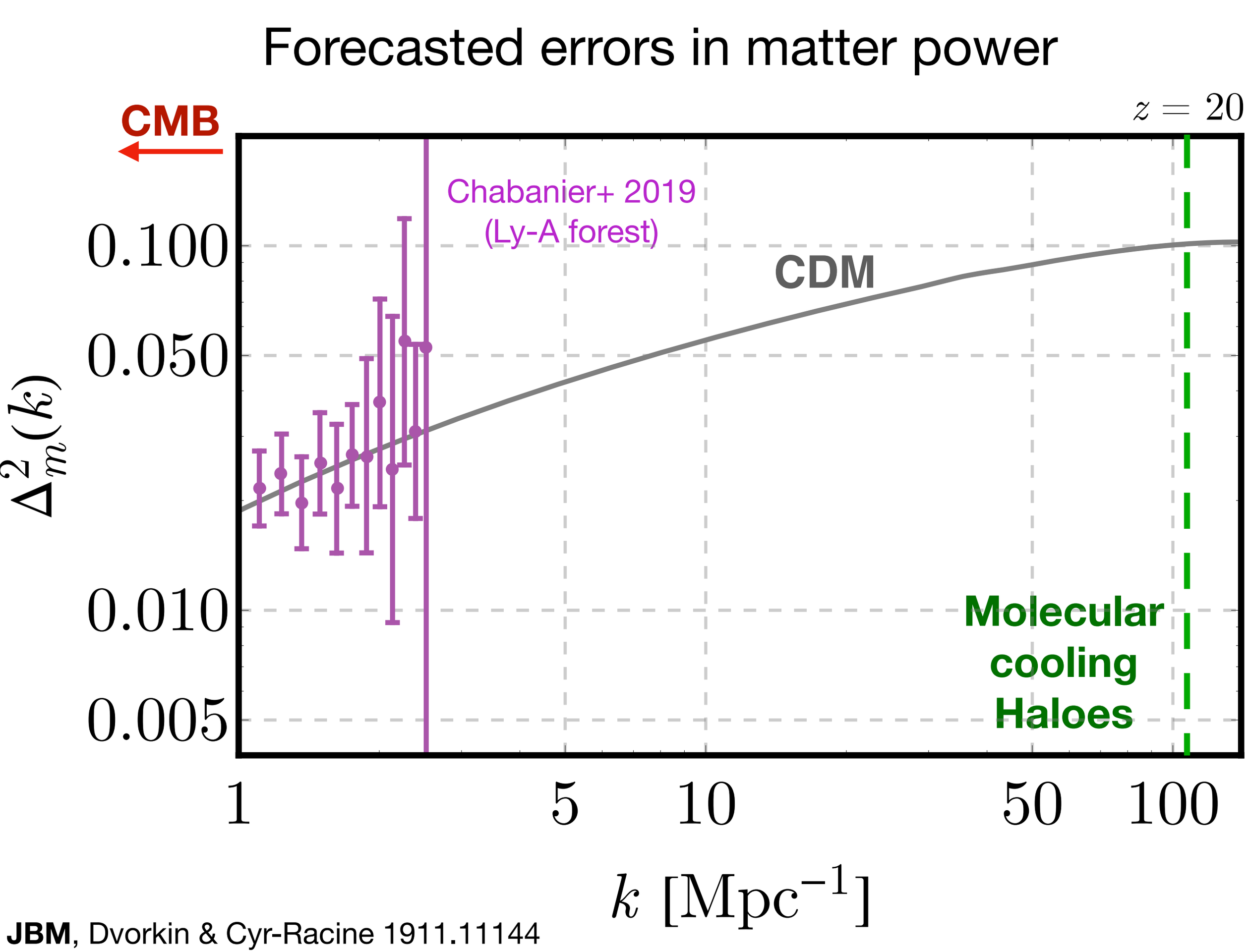
JBM, Dvorkin & Cyr-Racine 1911.11144

Is DM cold?



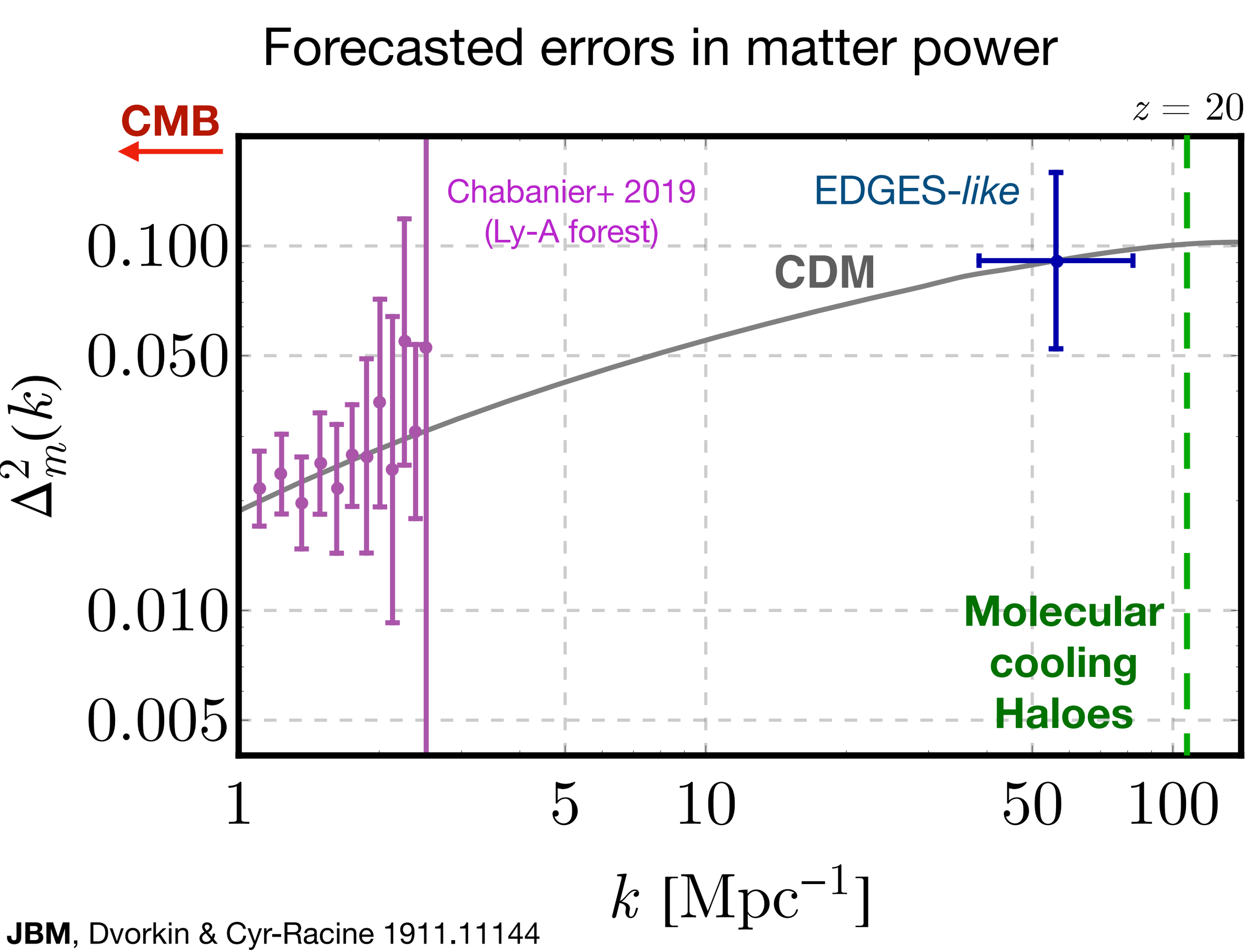
JBM, Dvorkin & Cyr-Racine 1911.11144

Forecasted errors in matter power



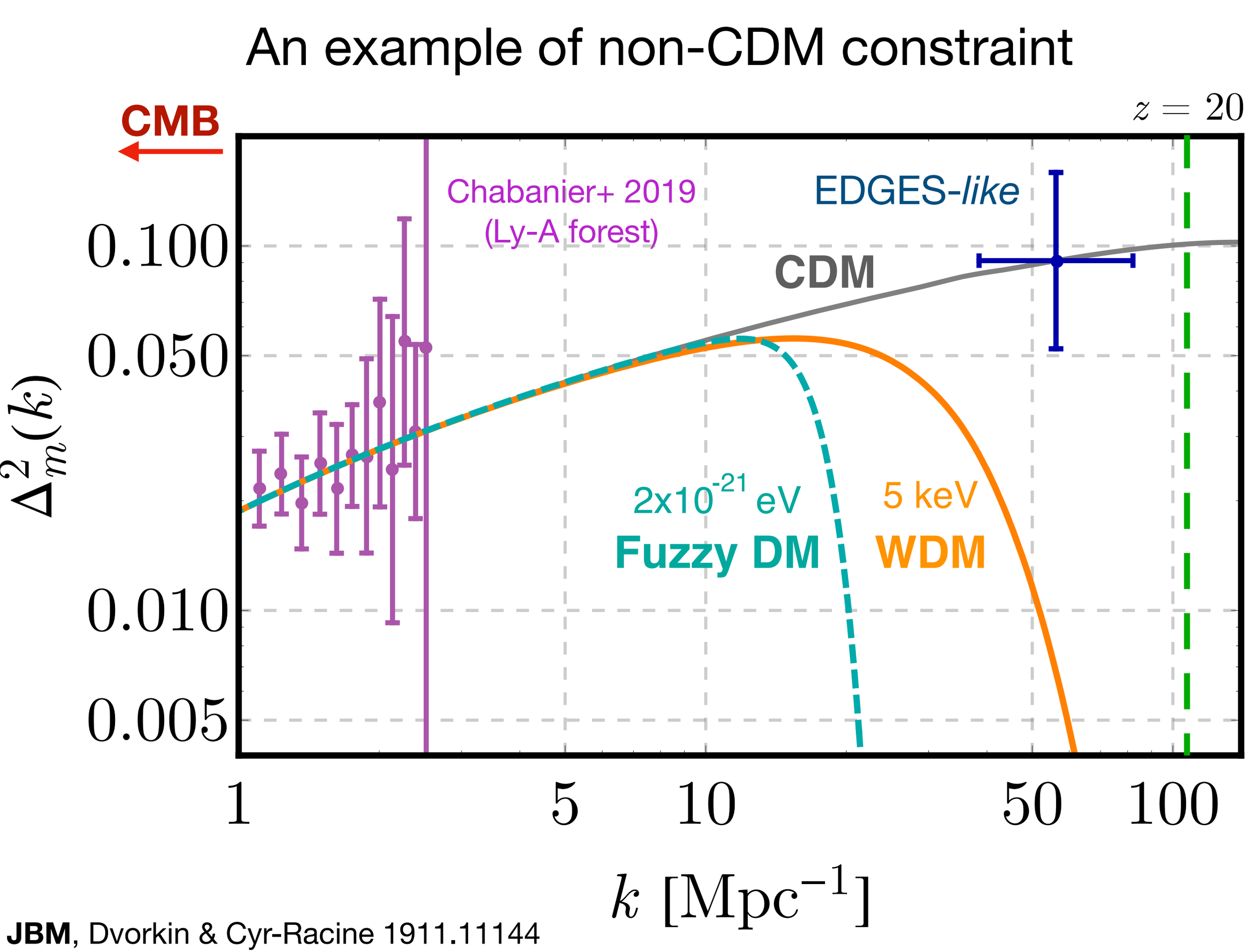
JBM, Dvorkin & Cyr-Racine 1911.11144

Forecasted errors in matter power



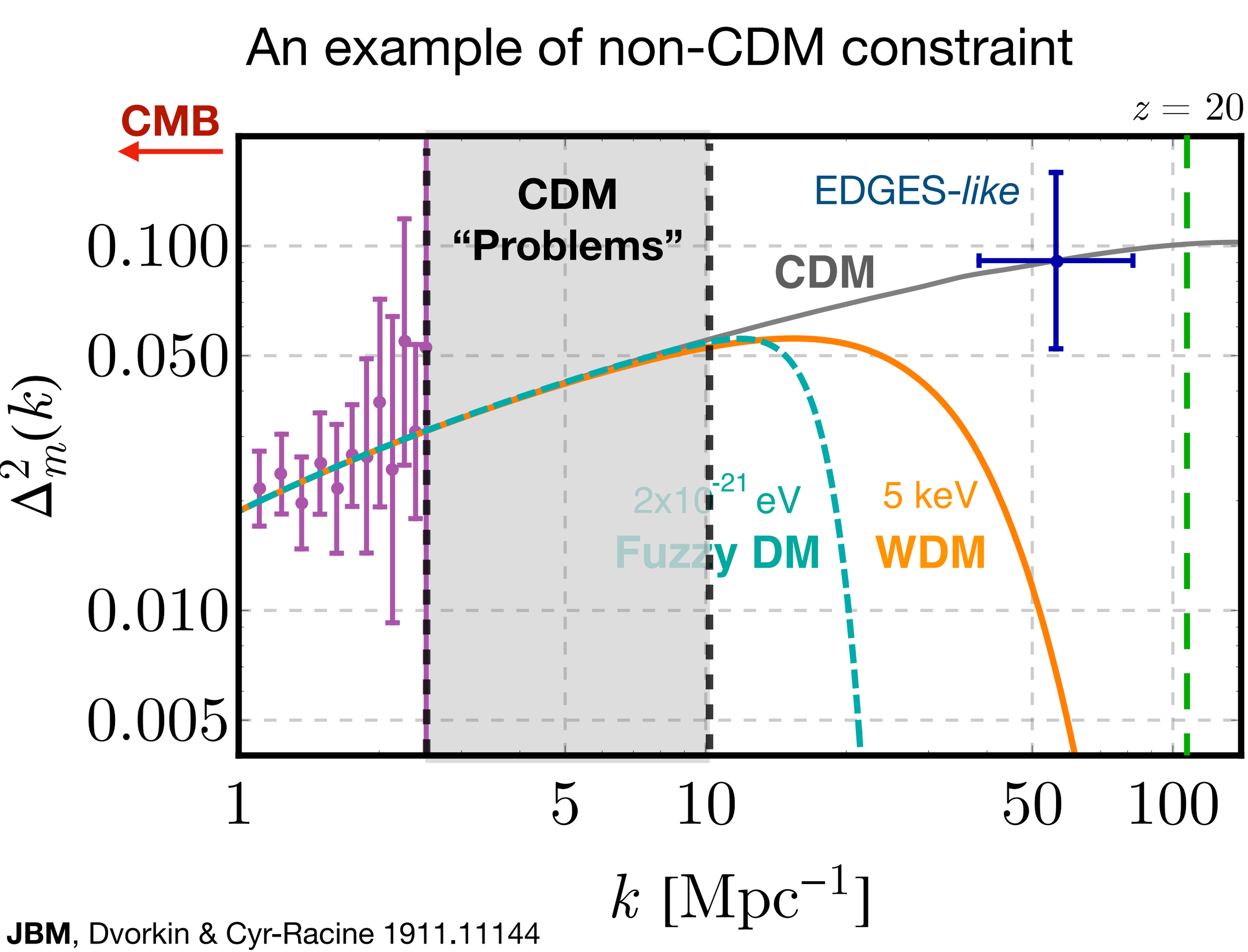
JBM, Dvorkin & Cyr-Racine 1911.11144

An example of non-CDM constraint



JBM, Dvorkin & Cyr-Racine 1911.11144

An example of non-CDM constraint

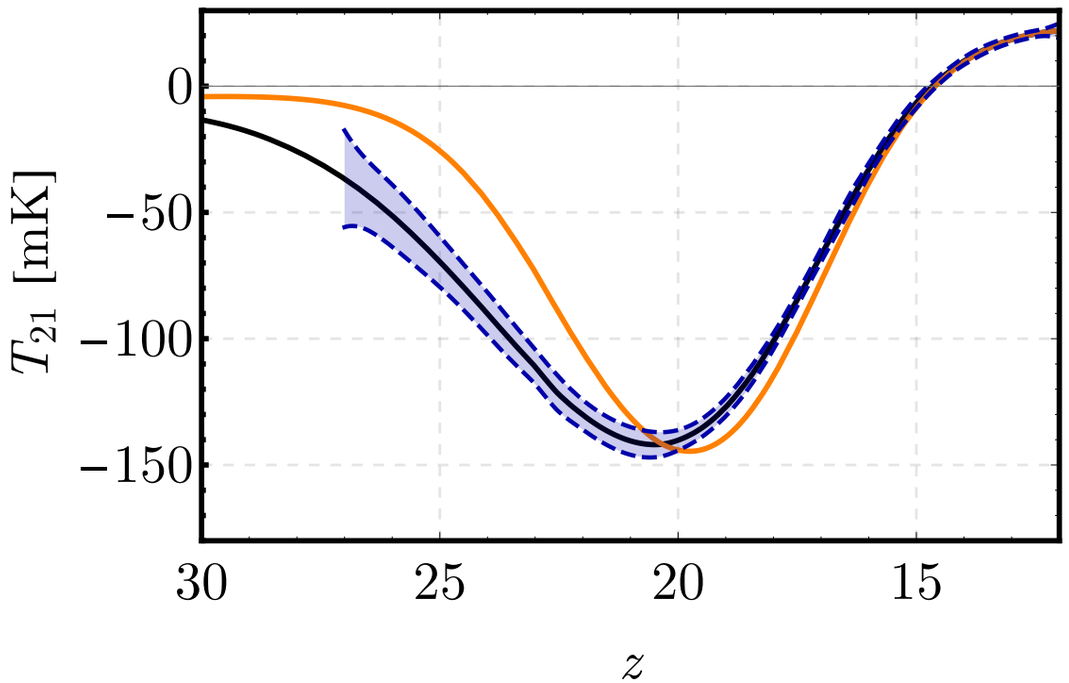


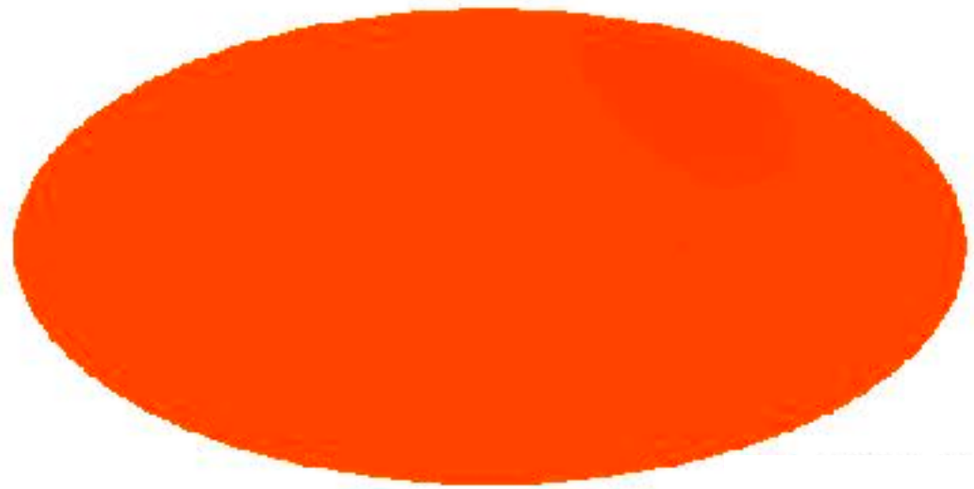
JBM, Dvorkin & Cyr-Racine 1911.11144

The 21-cm fluctuations

21-cm Global Signal = CMB Monopole

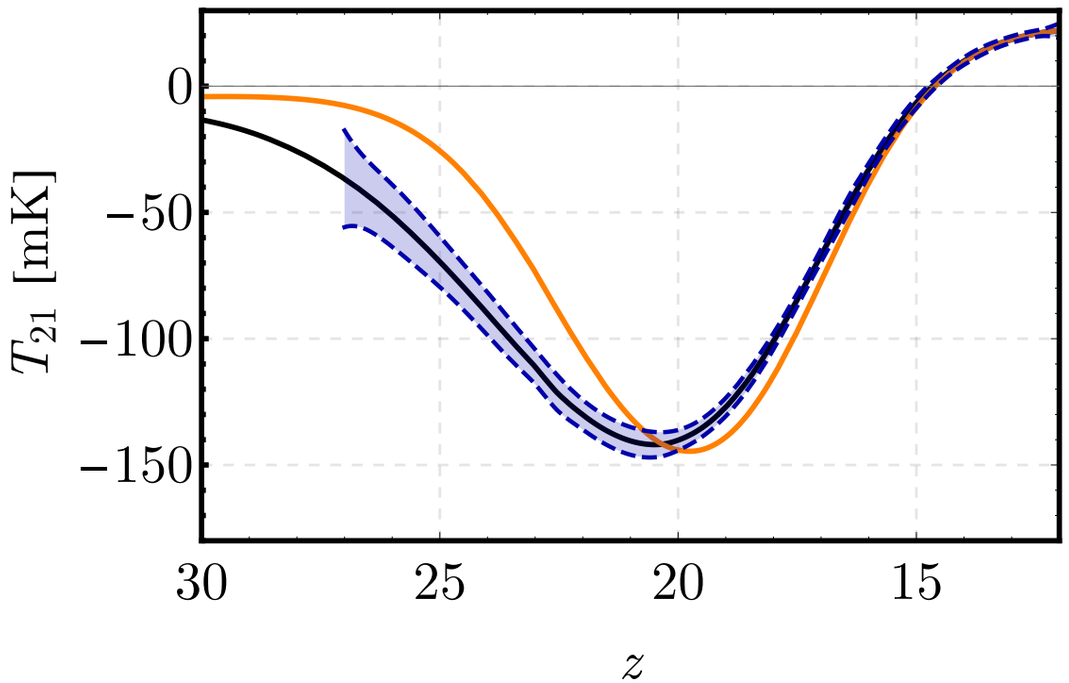
(**EDGES**, LEDA, SARAS, Sci-HI,…)

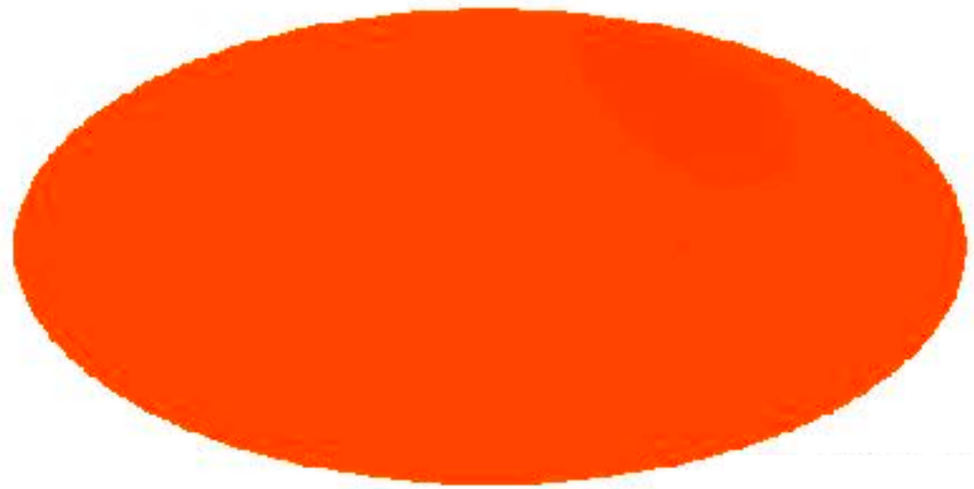




21-cm Global Signal = CMB Monopole

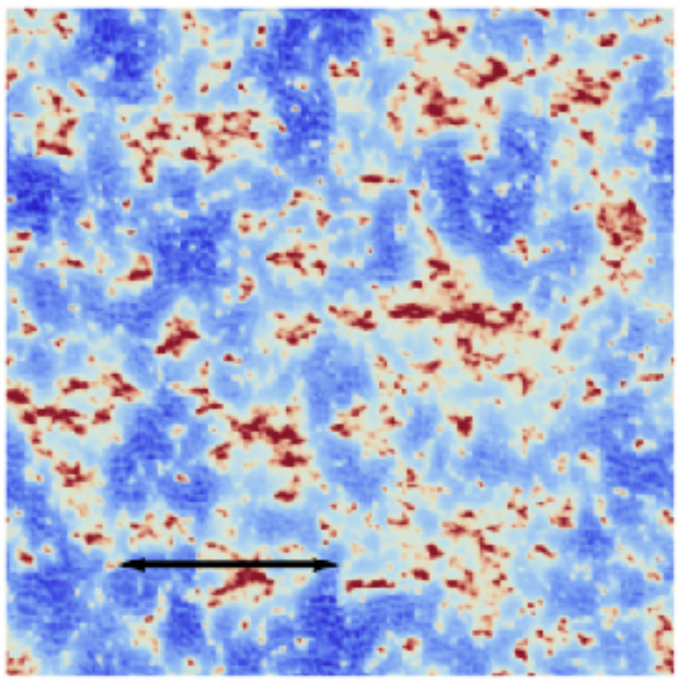
(**EDGES**, LEDA, SARAS, Sci-HI,…)

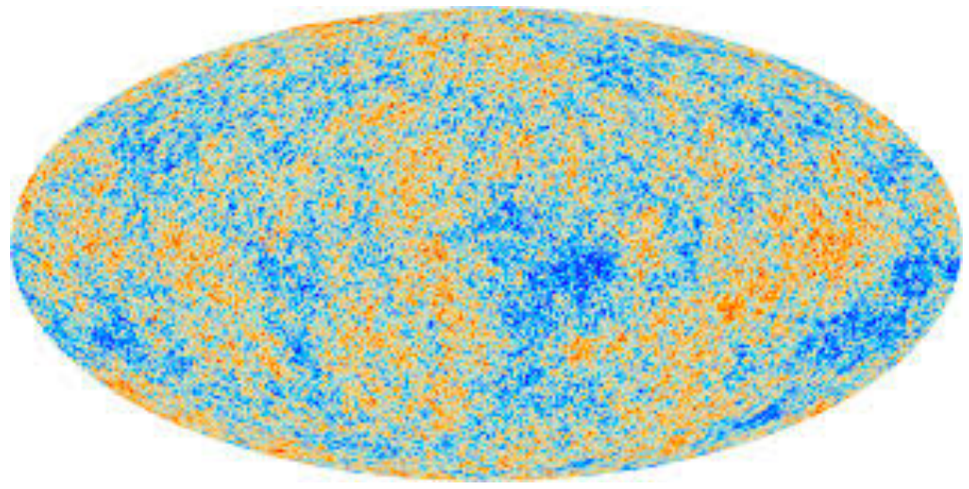




21-cm Fluctuations = CMB Anisotropies

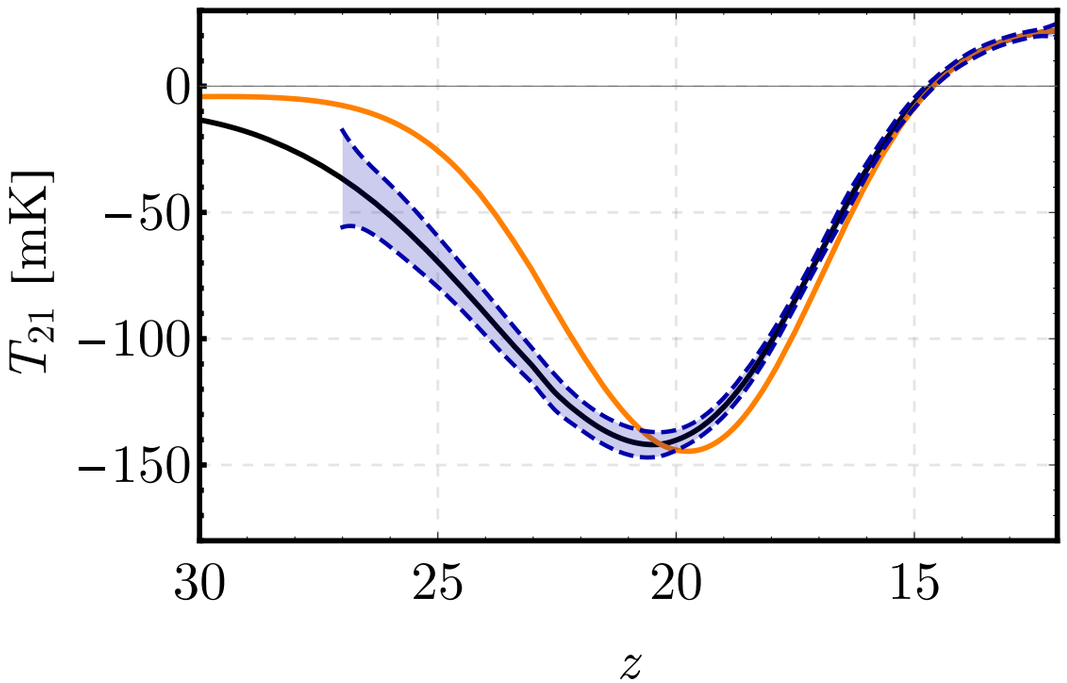
(**HERA**, MWA, LWA, PAPER, SKA,…)





21-cm Global Signal

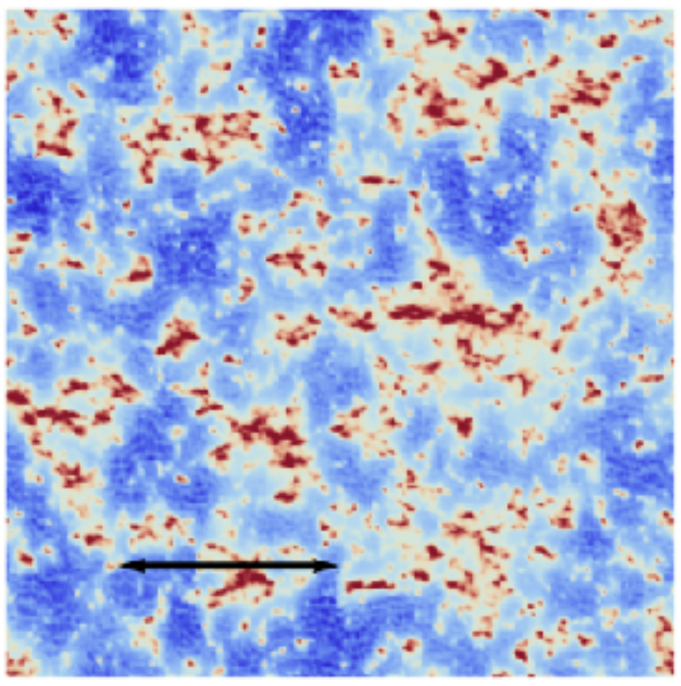
(**EDGES**, LEDA, SARAS, Sci-HI,…)



1 antenna
~100 hours

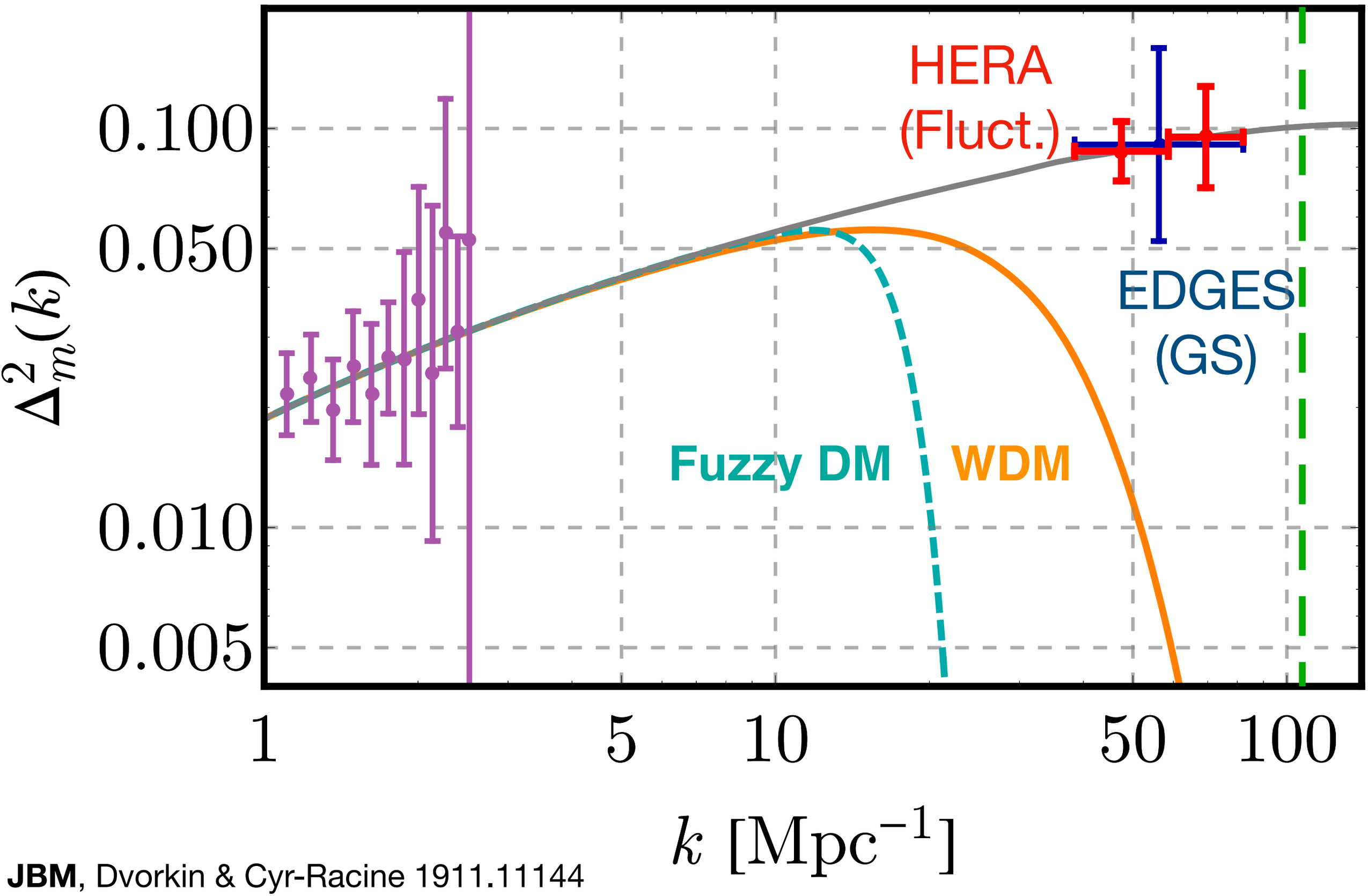
21-cm Fluctuations

(**HERA**, MWA, LWA, PAPER, SKA,…)



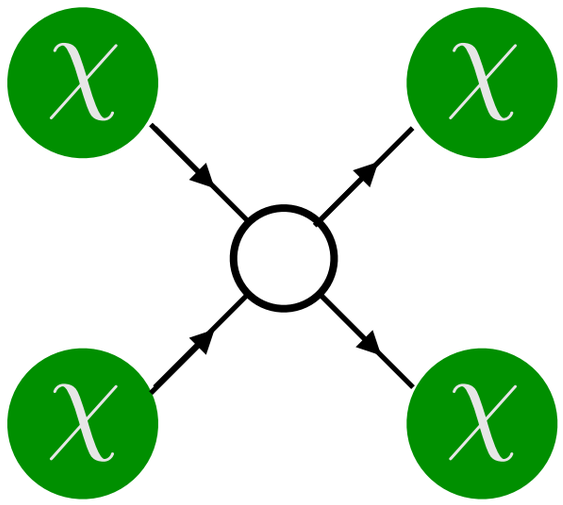
~100 antennae
~1000 hours

Fluctuations do better than global signal

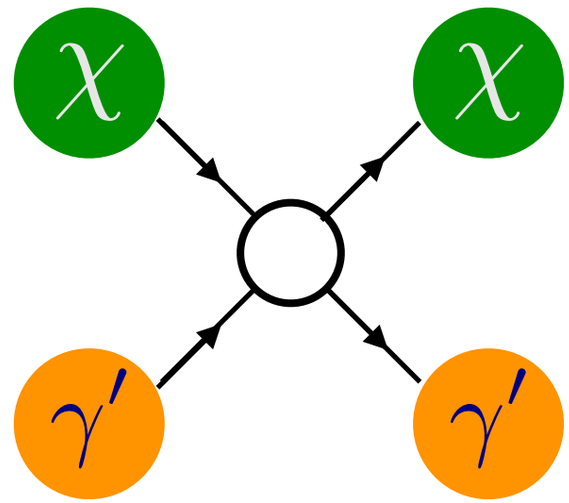


JBM, Dvorkin & Cyr-Racine 1911.11144

Beyond a cutoff: Self Interactions

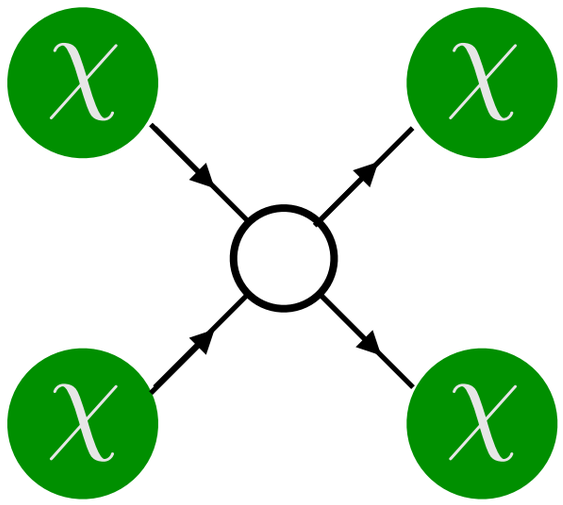


DM-DM:
Halo profiles, etc.

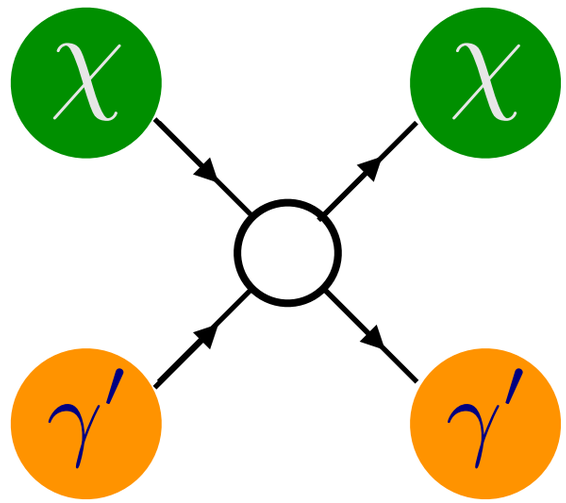


DM-DR:
Power Spectrum

Beyond a cutoff: Self Interactions



DM-DM:
Halo profiles, etc.



DM-DR:
Power Spectrum

Effective Theory of Structure Formation: **ETHOS**

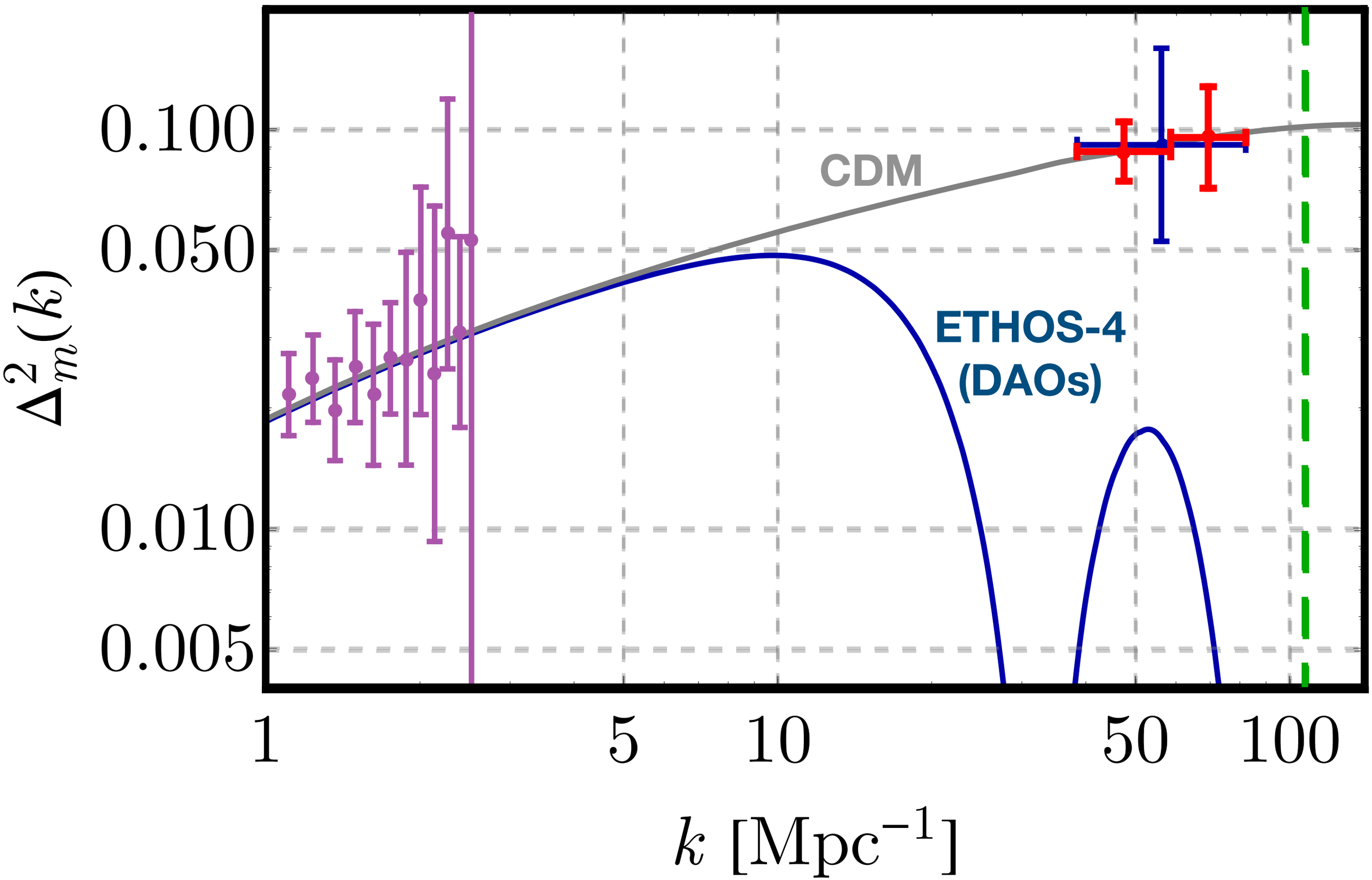
Vogelsberger+ 2016
Cyr-Racine+2016

Beyond a cutoff: ETHOS

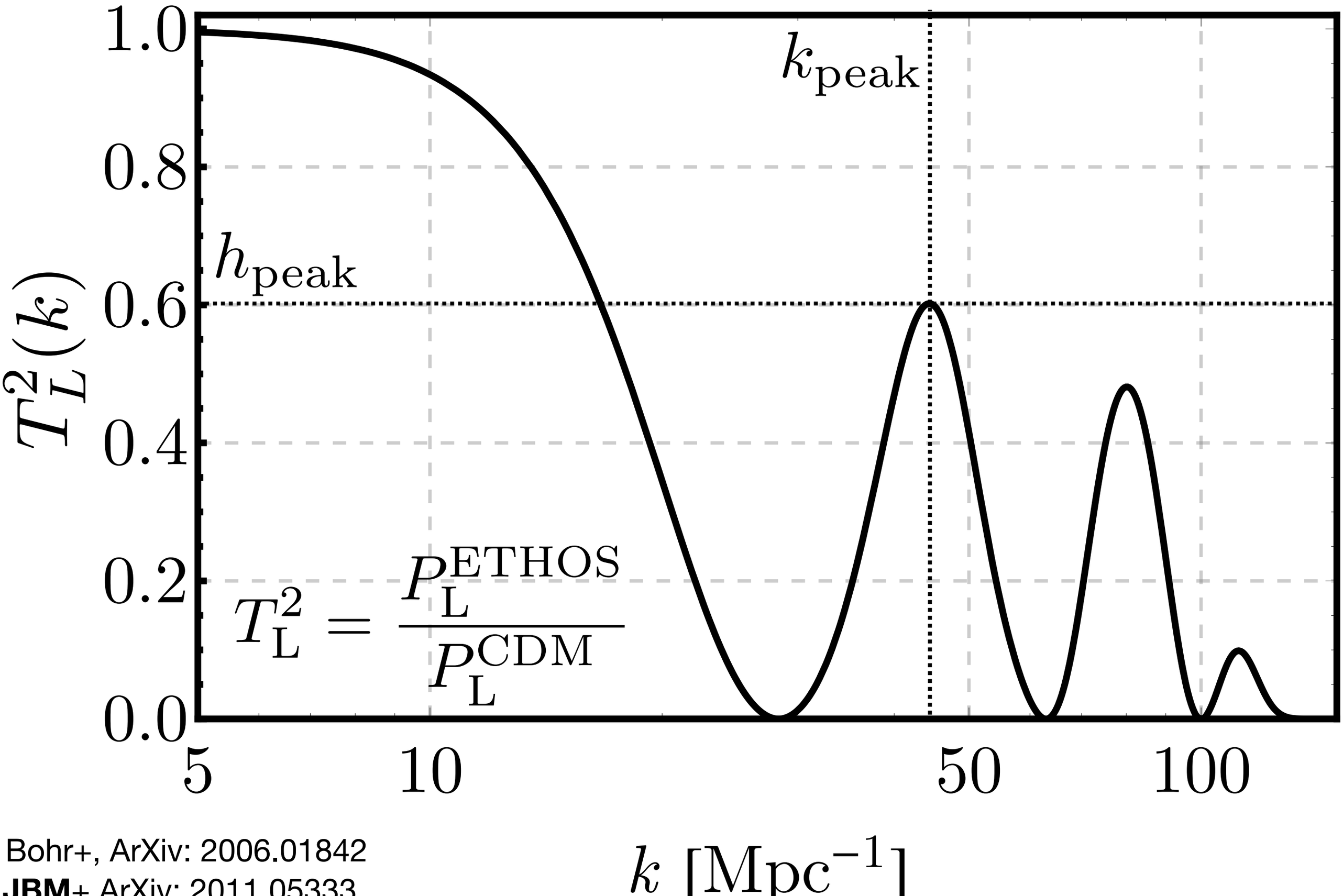
Vogelsberger+ 2016
Cyr-Racine+2016

Credit: Volgesberger/MIT

Beyond a cutoff: ETHOS



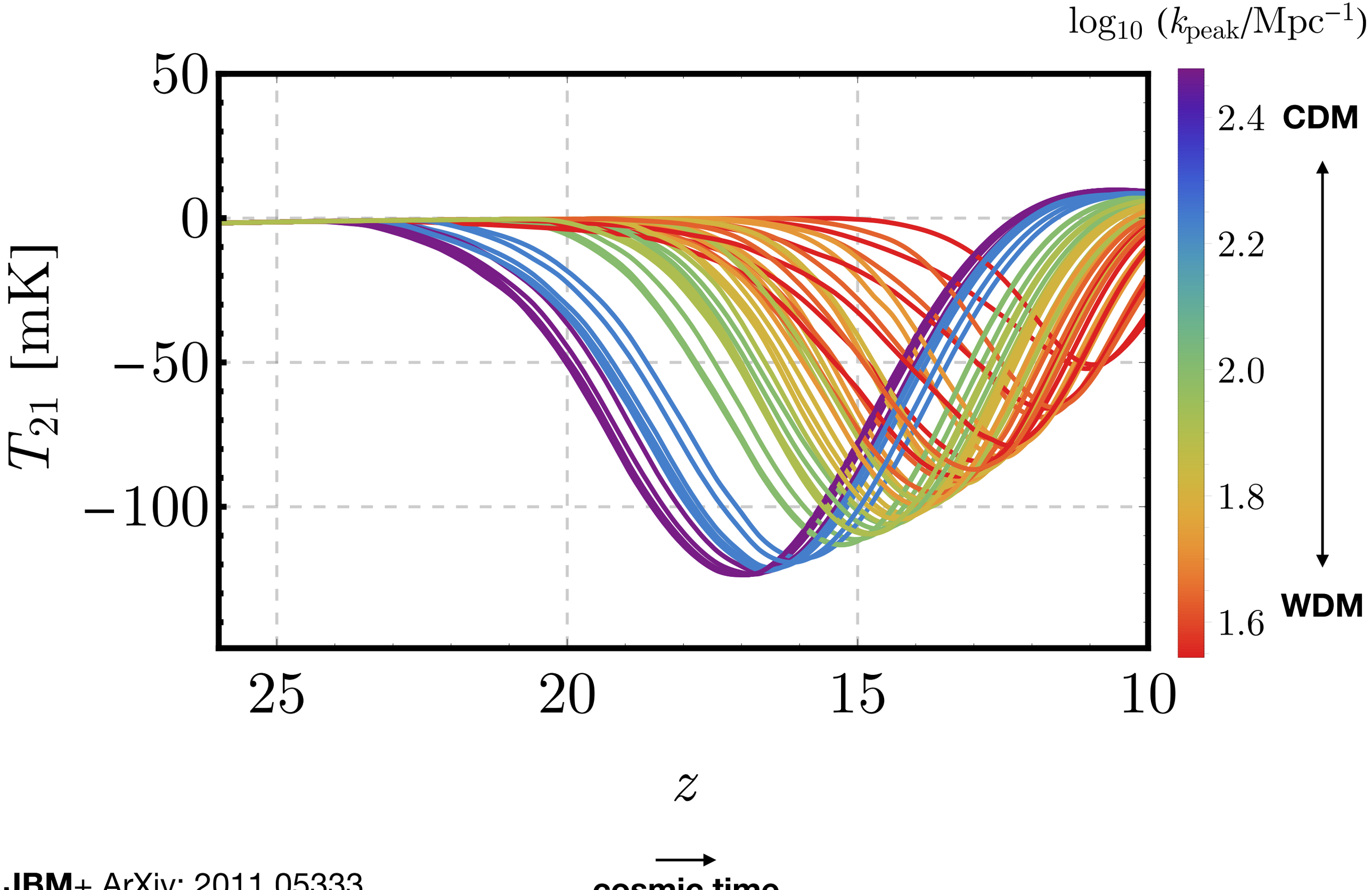
A two-parameter model



Bohr+, ArXiv: 2006.01842

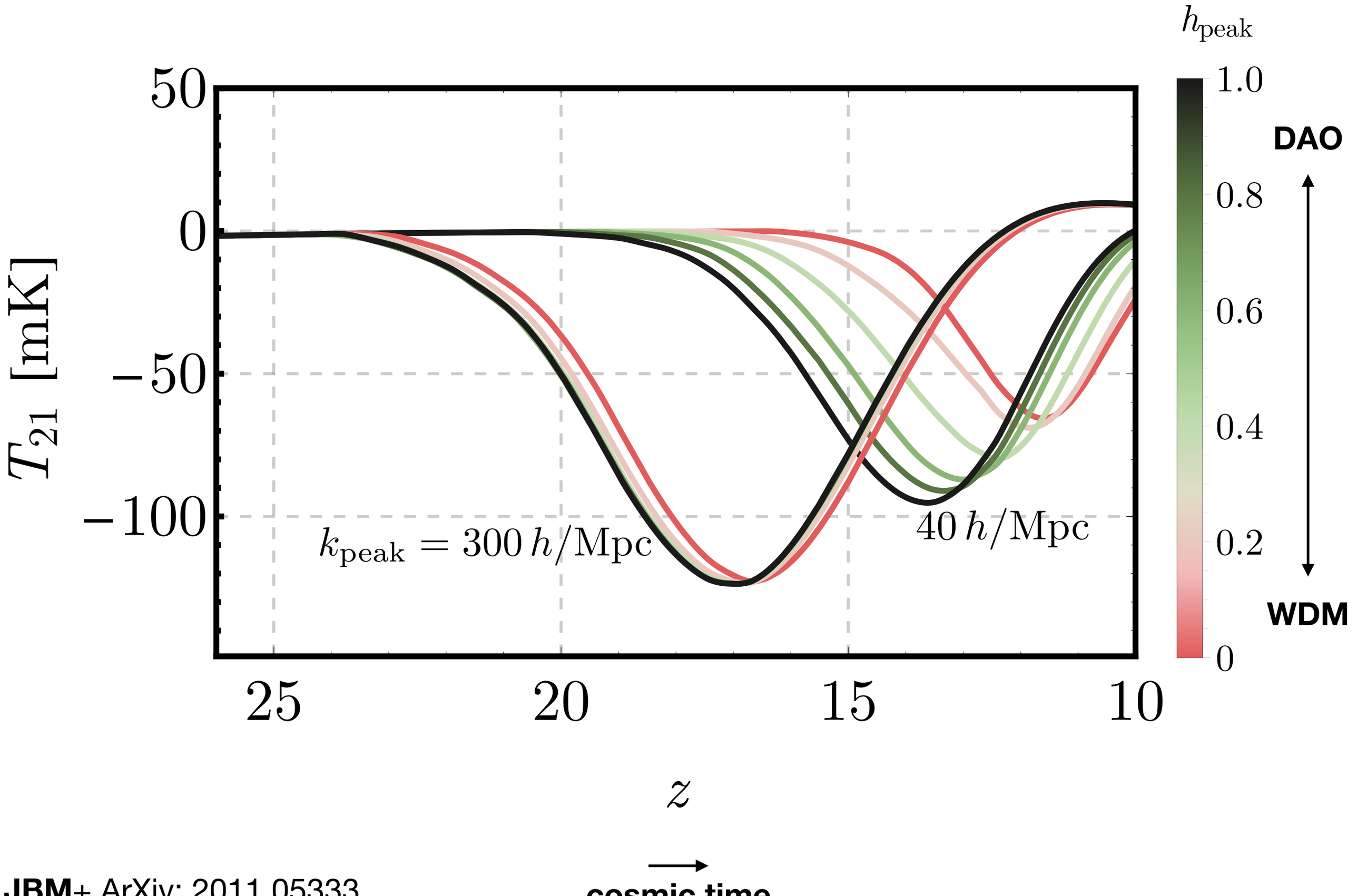
JBM+ ArXiv: 2011.05333

The 21-cm global signal in ETHOS



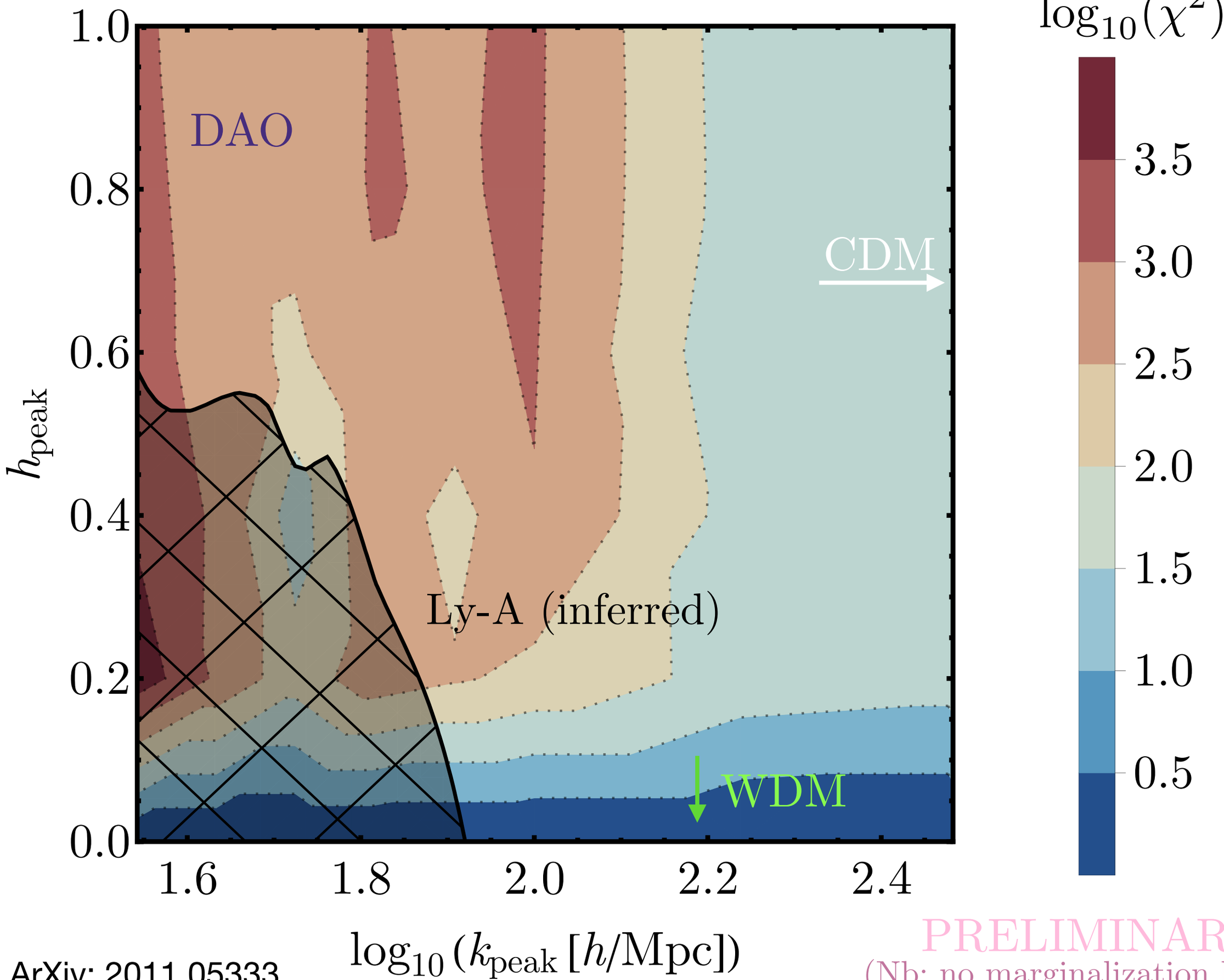
JBM+ ArXiv: 2011.05333

The 21-cm global signal in ETHOS



JBM+ ArXiv: 2011.05333

HERA can distinguish ETHOS from WDM!



JBM+, ArXiv: 2011.05333

PRELIMINARY
(Nb: no marginalization here)

The expansion rate $H(z)$

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

80
70
60
50
40

Supernovae

CMB

Cosmic Dawn
Window

Galaxy
BAO

QSO
BAO

LyA
BAO

?

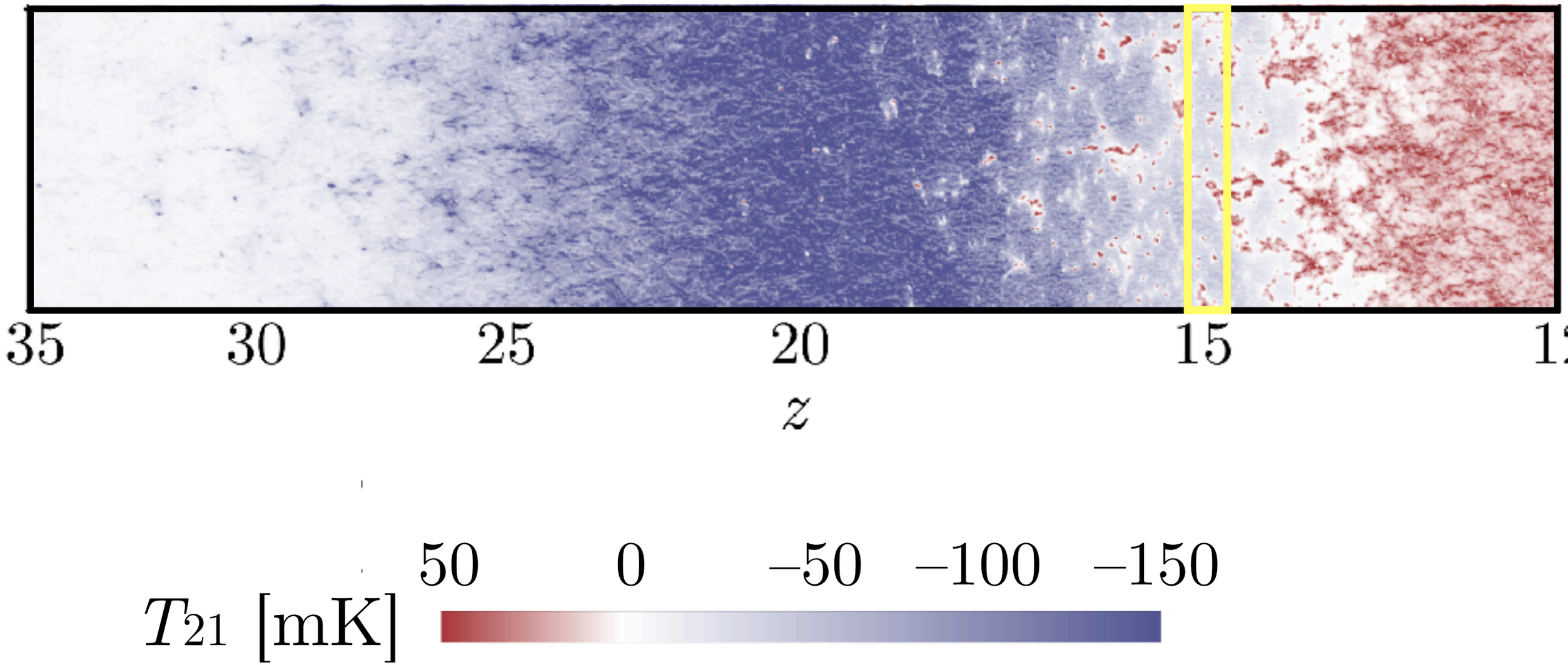
?

20
9
2
0

Redshift, z

cosmic time

A standard ruler during cosmic dawn

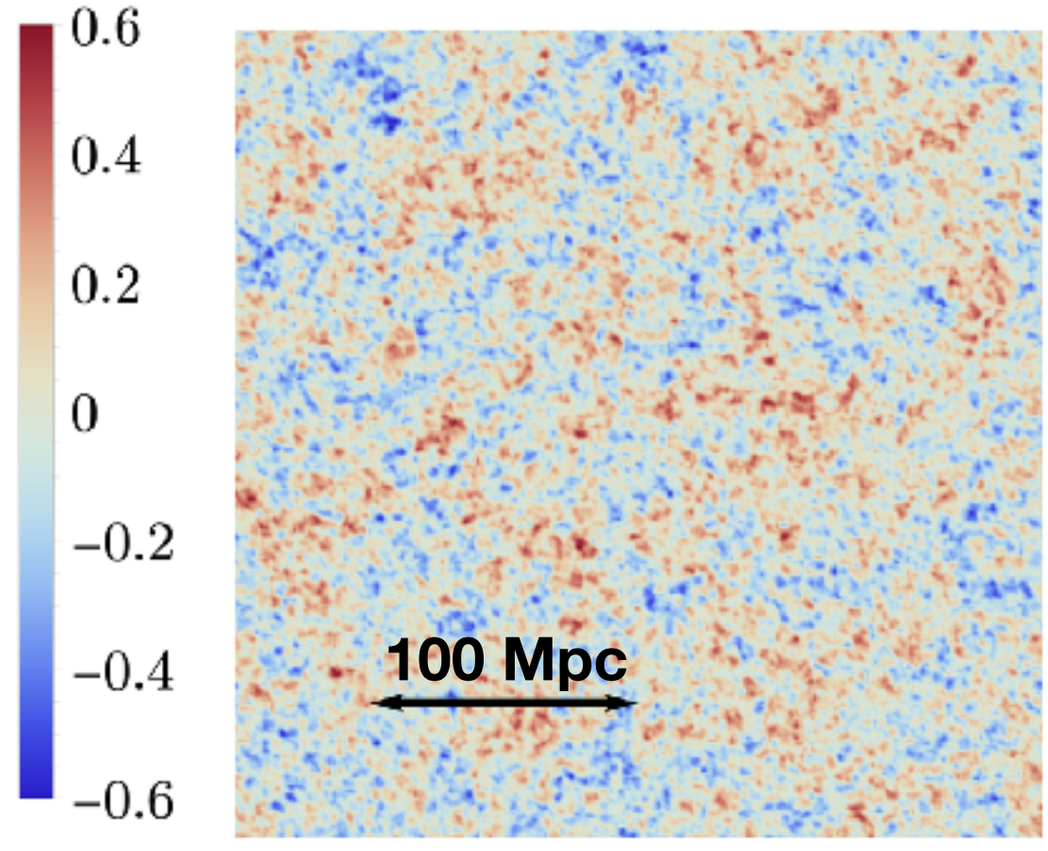


21cmvFAST **JBM** PRD 2019 + PRL 2019

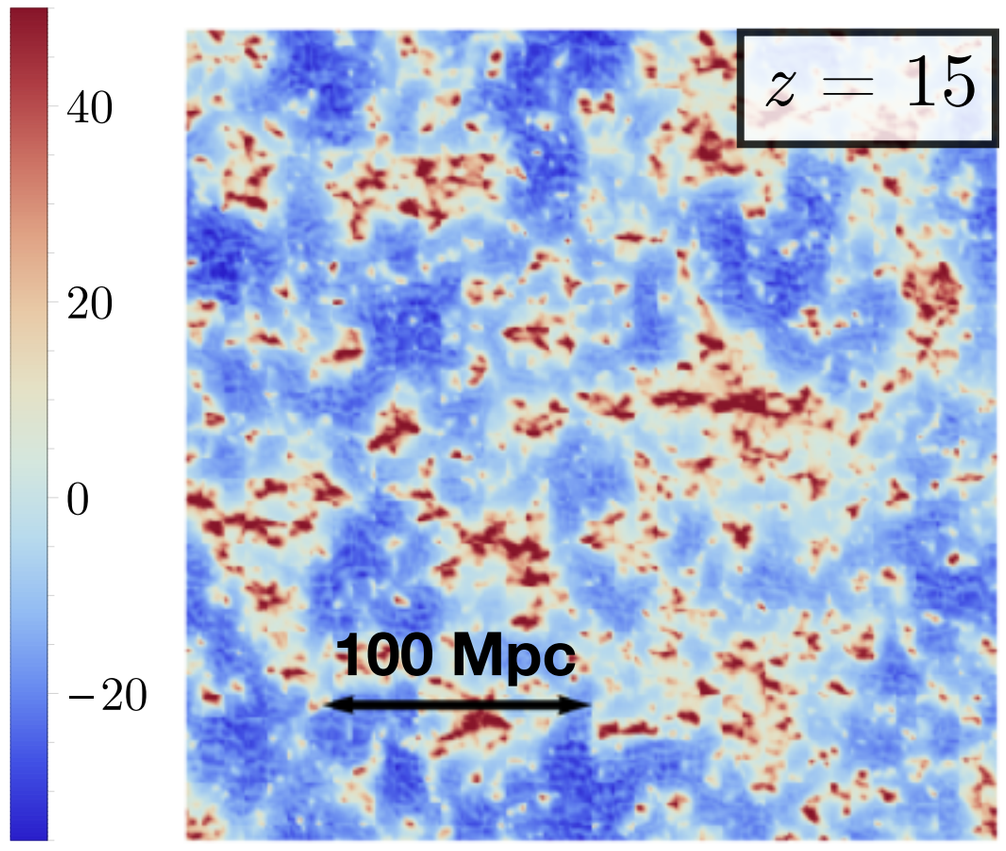
cosmic time →

A cross section of T_{21}

Density, δ



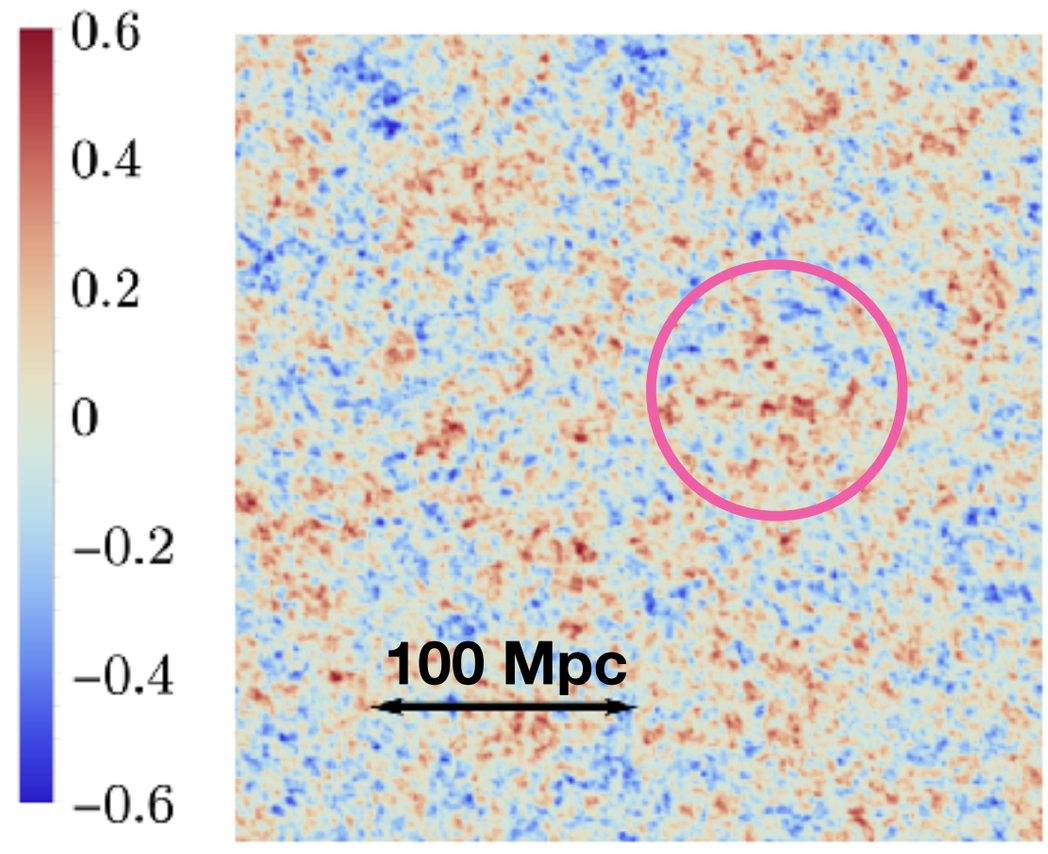
Signal, T_{21}



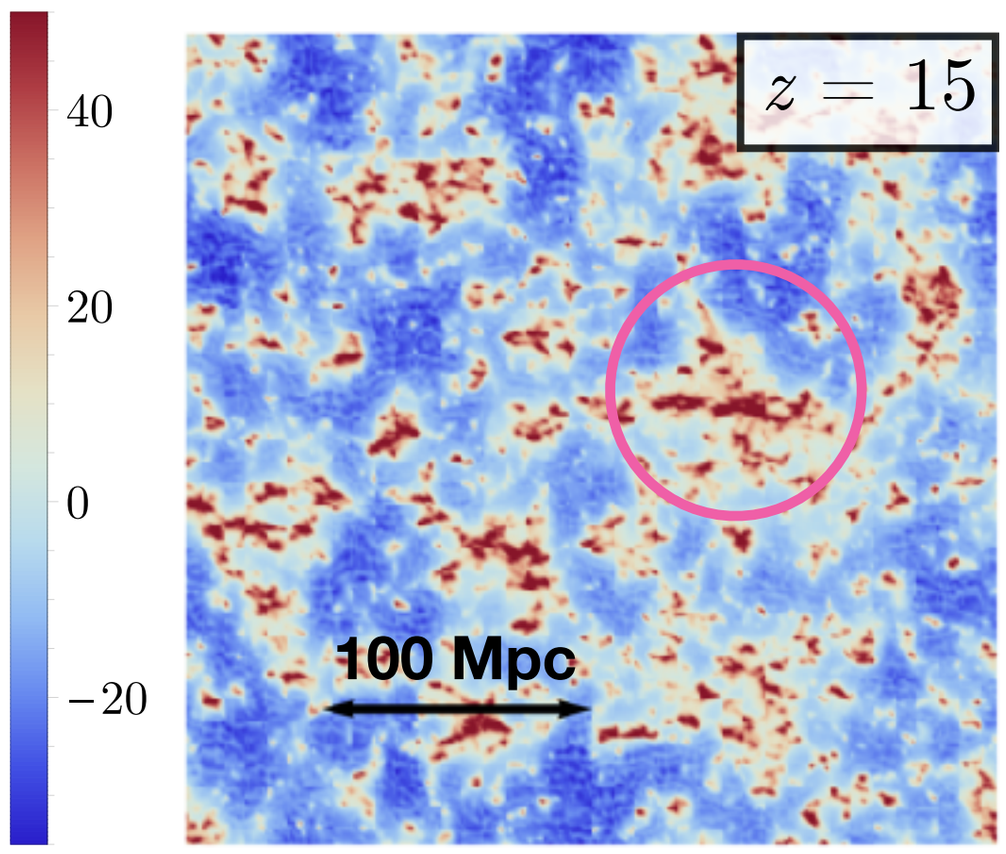
21cmvFAST **JBM 2019**

A cross section of T_{21}

Density, δ



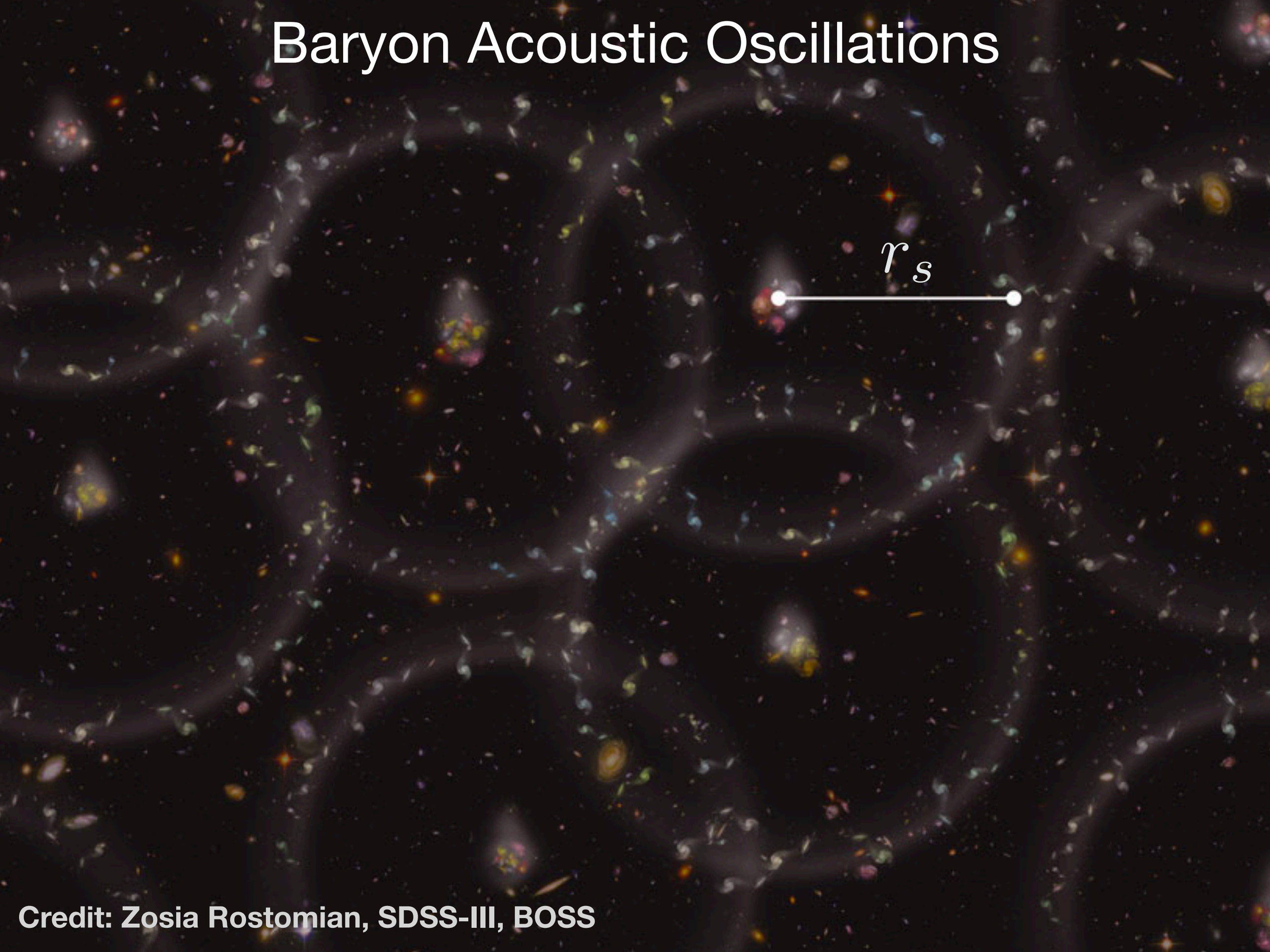
Signal, T_{21}



Not quite like the CMB!

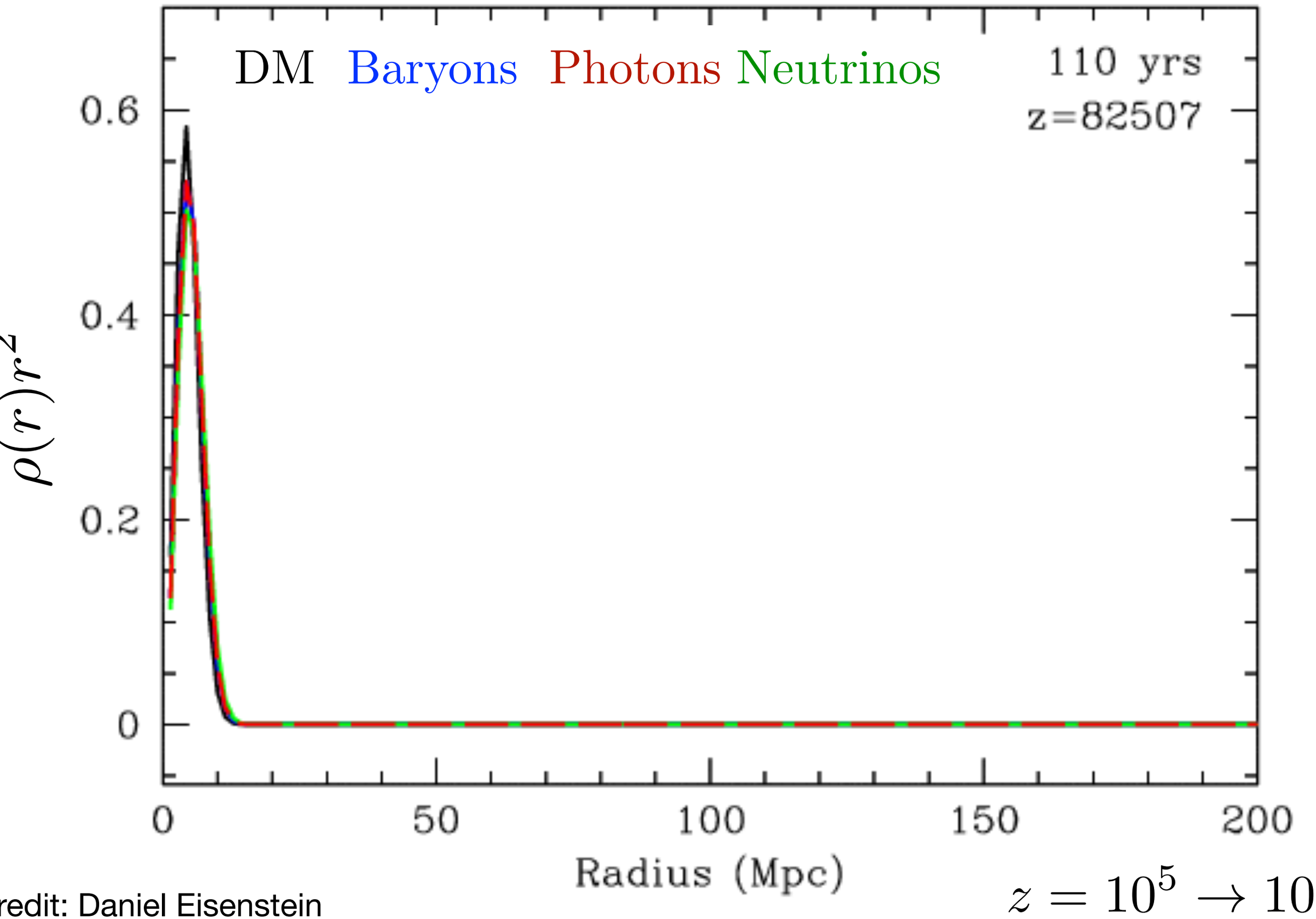
21cmvFAST **JBM 2019**

Baryon Acoustic Oscillations



Credit: Zosia Rostomian, SDSS-III, BOSS

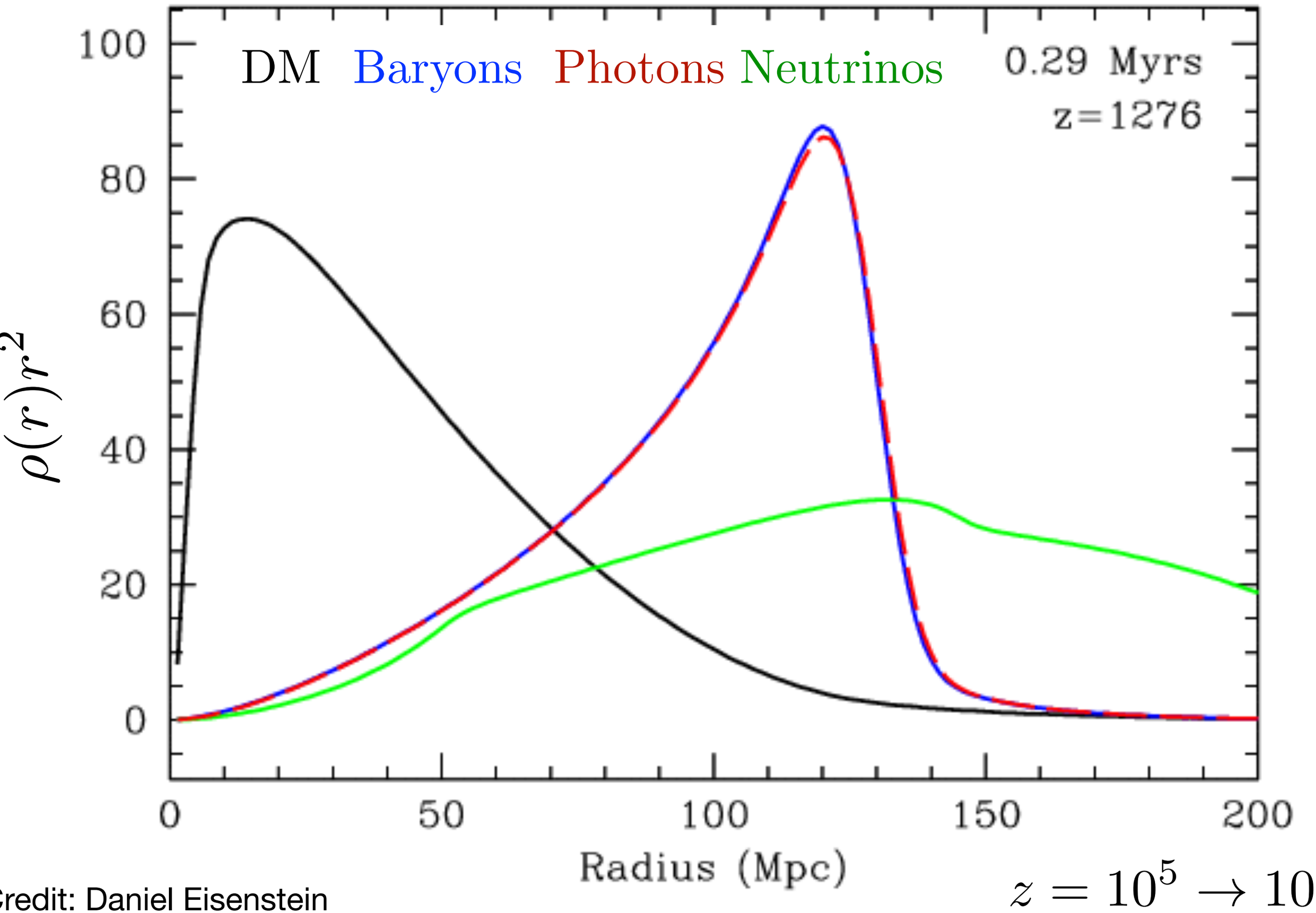
Baryon Acoustic Oscillations



Credit: Daniel Eisenstein

$z = 10^5 \rightarrow 10^3$

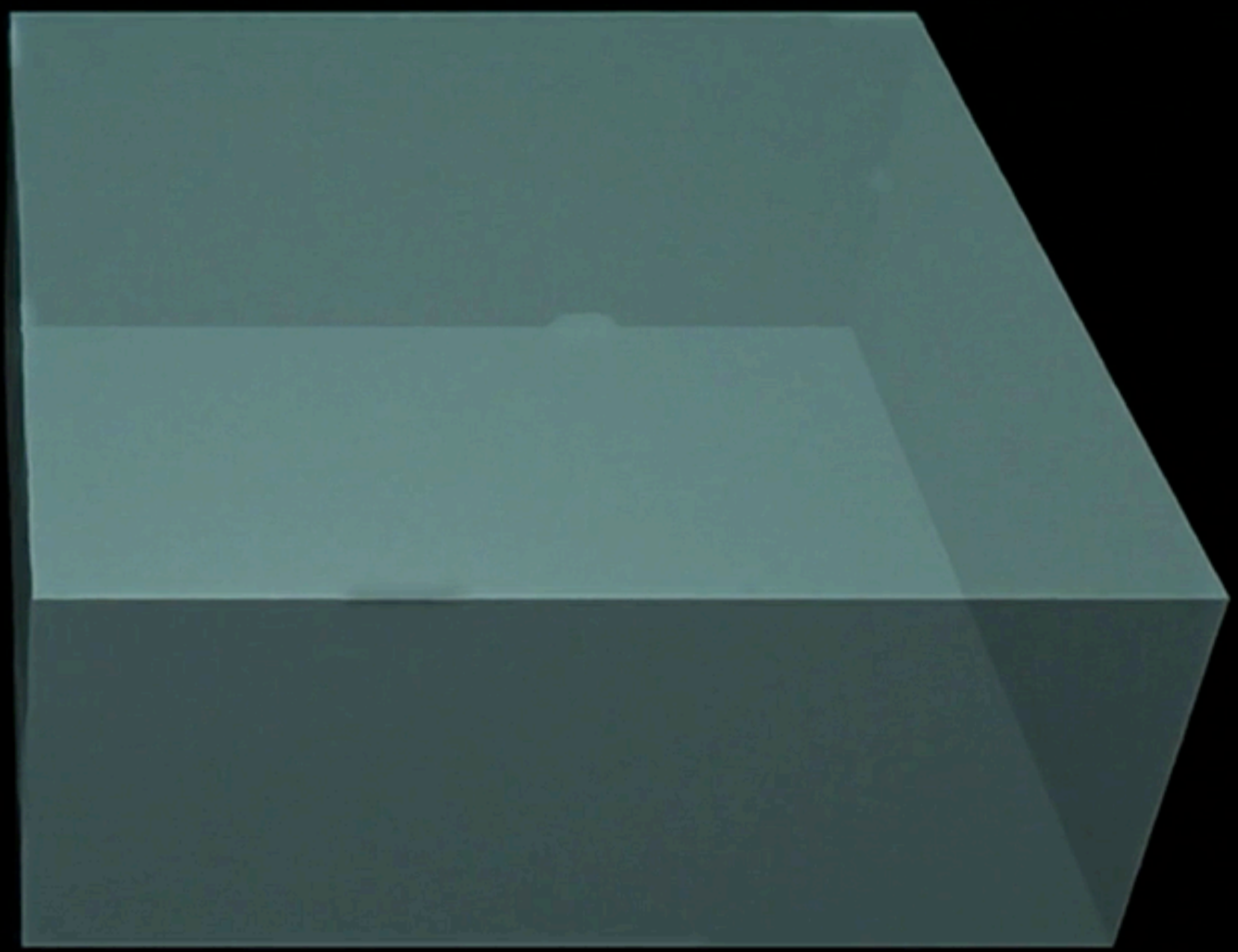
Baryon Acoustic Oscillations



Credit: Daniel Eisenstein

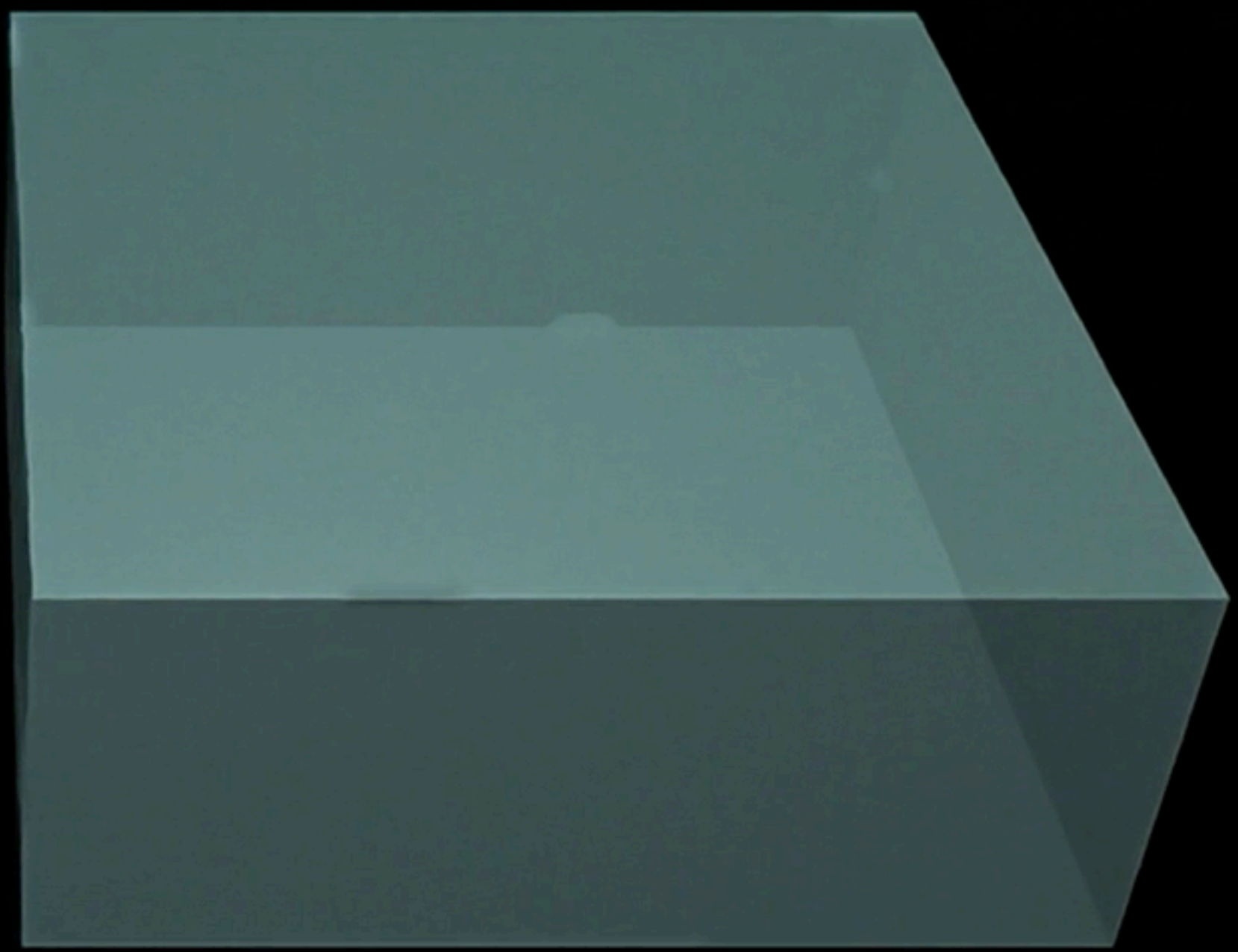
$z = 10^5 \rightarrow 10^3$

It’s just waves!



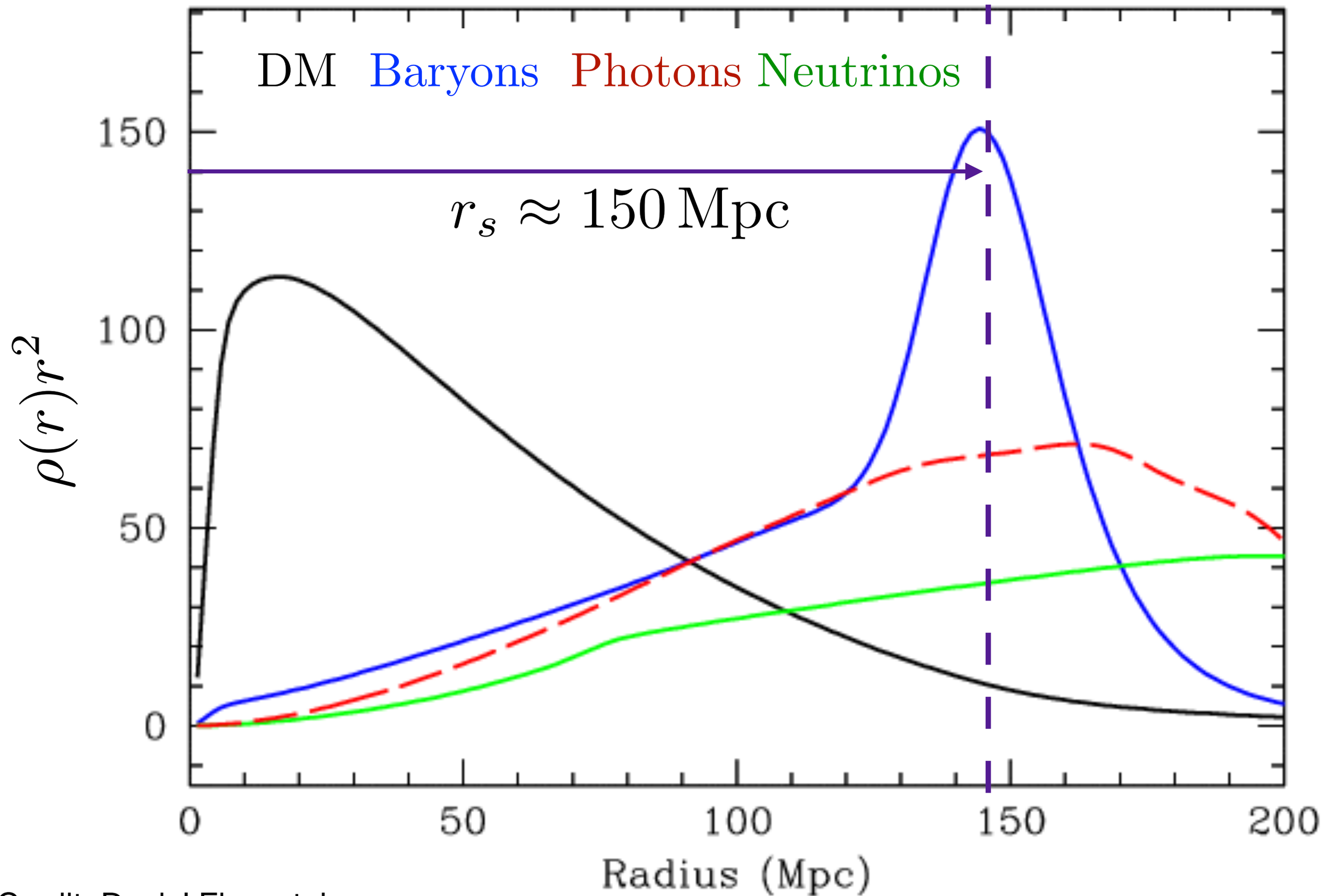
Credit: NASA/WMAP

It’s just waves!



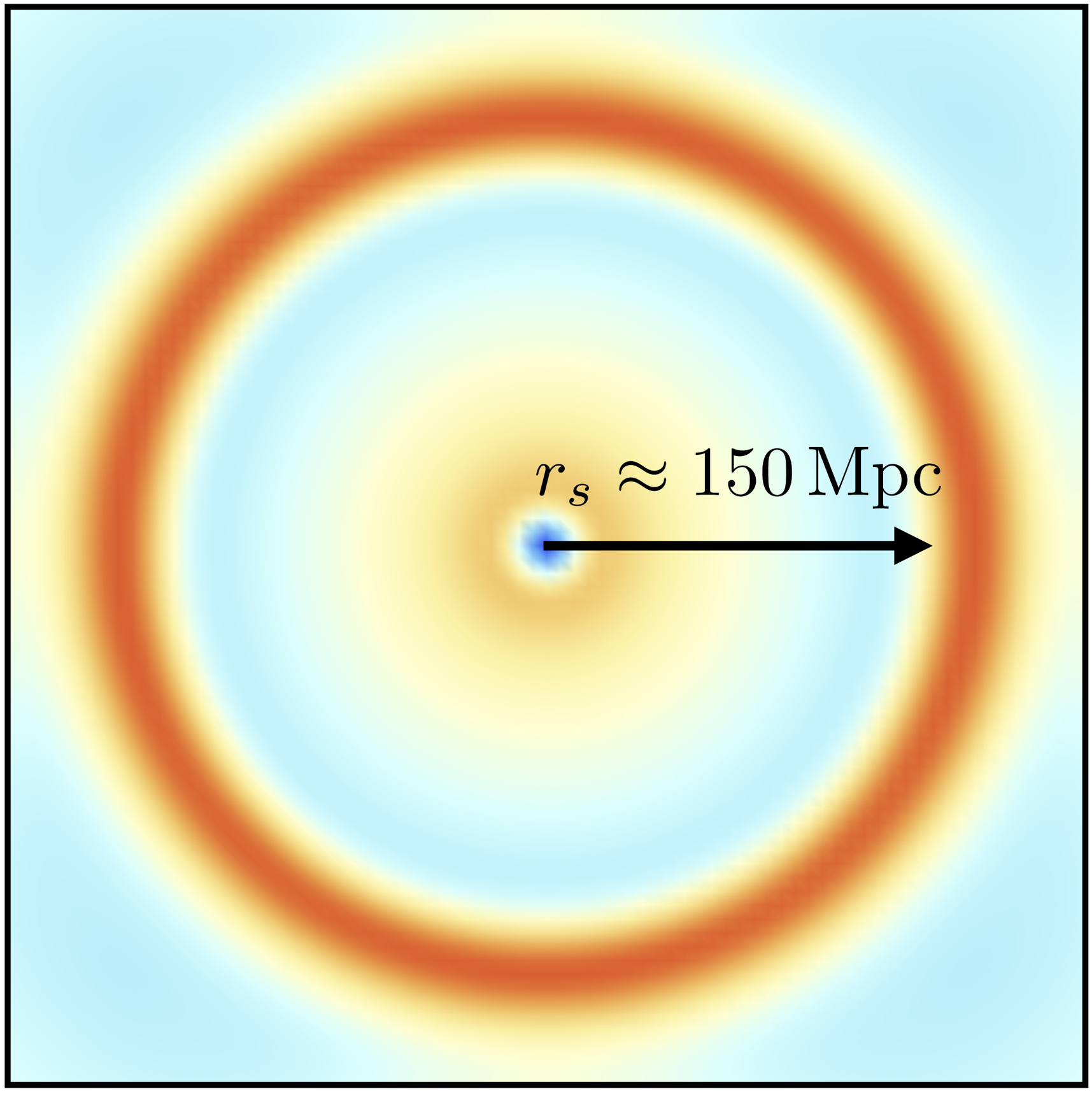
Credit: NASA/WMAP

Baryon Acoustic Oscillations

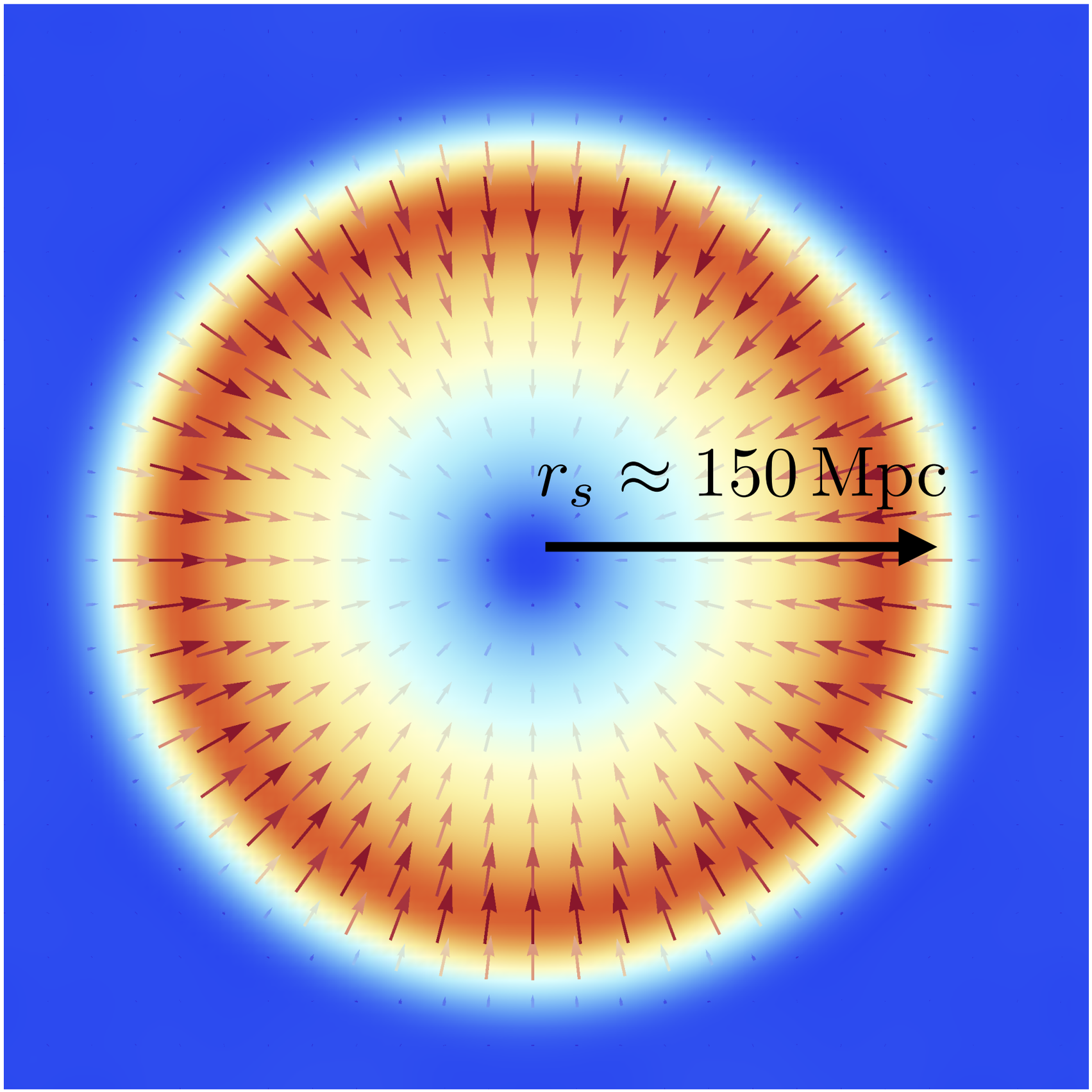


Credit: Daniel Eisenstein

A preferred distance scale



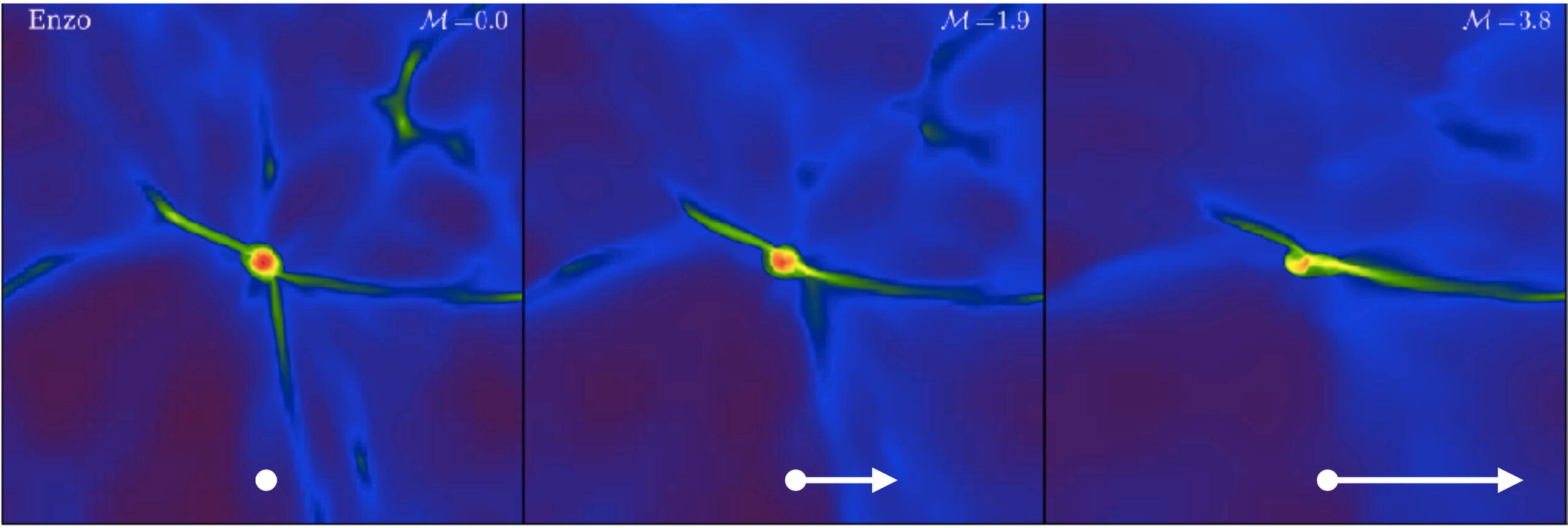
$$\vec{v}_{b\chi} = \vec{v}_b - \vec{v}_\chi$$



Velocity

Tseliakhovich & Hirata 2010

Important for the first galaxies



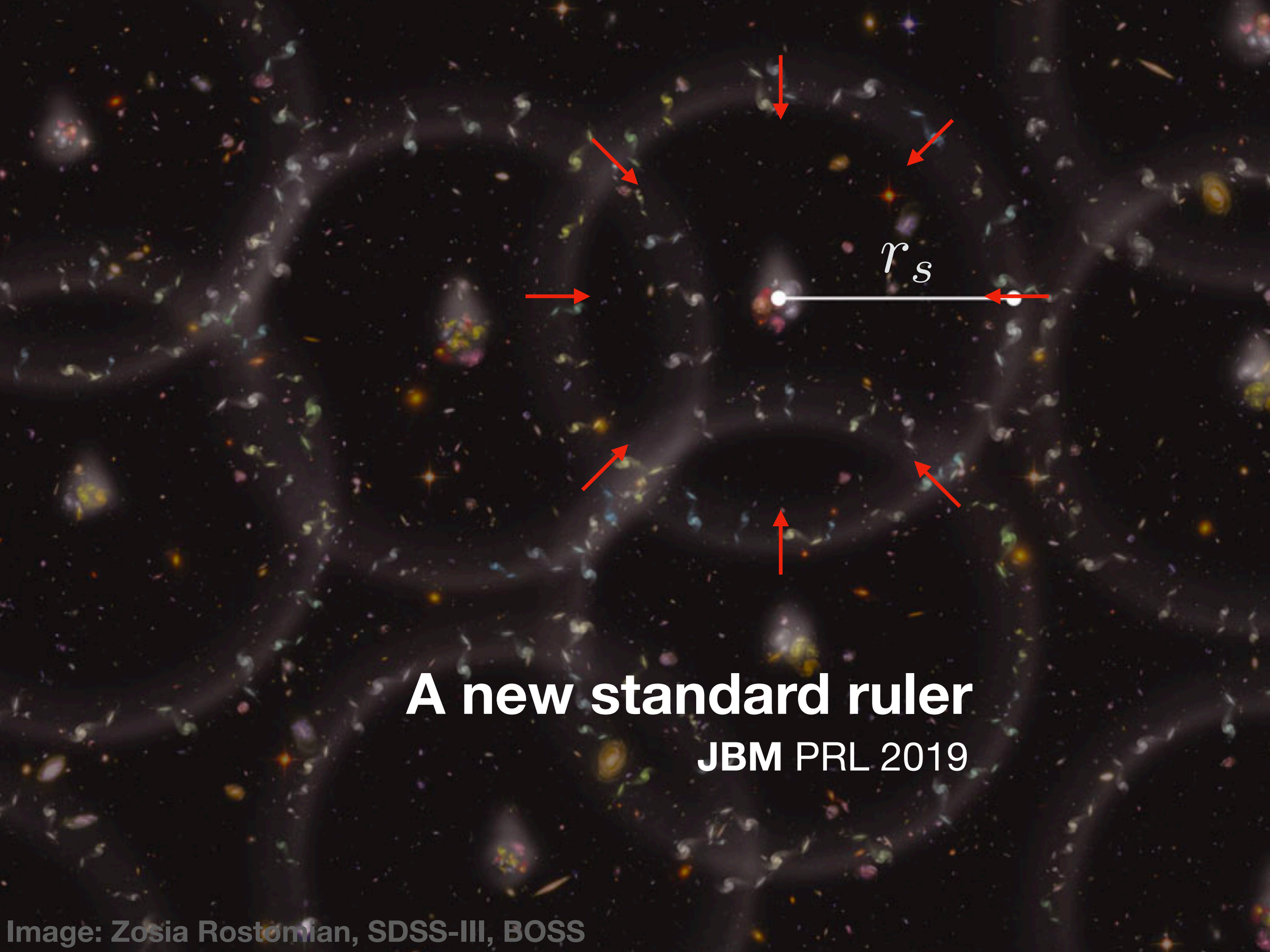
No relative velocity

Average relative velocity

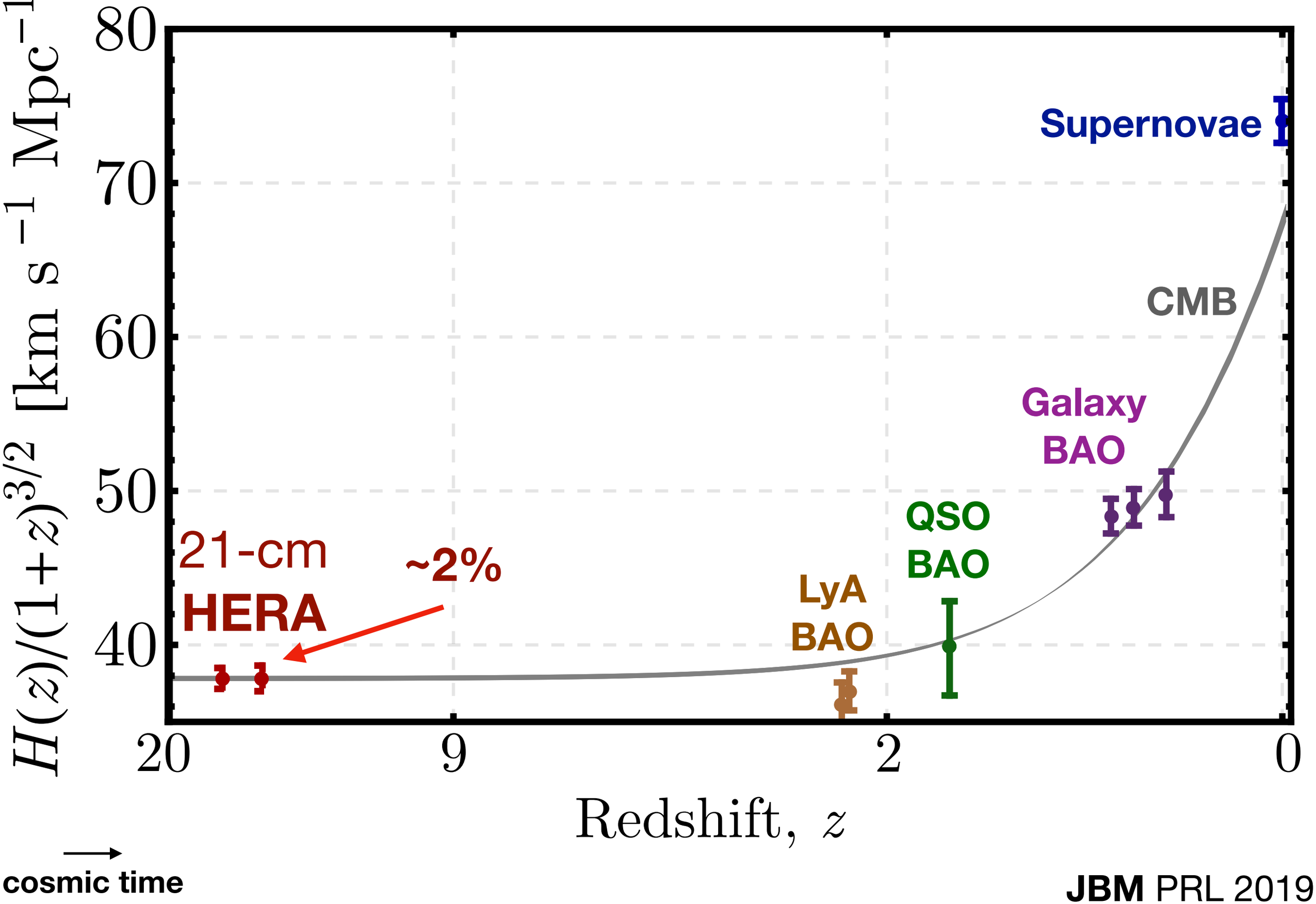
High relative velocity

Oleary & McQuinn 2010

Tseliakhovich & Hirata 2010


r_s
A new standard ruler
JBM PRL 2019
Image: Zosia Rostomian, SDSS-III, BOSS

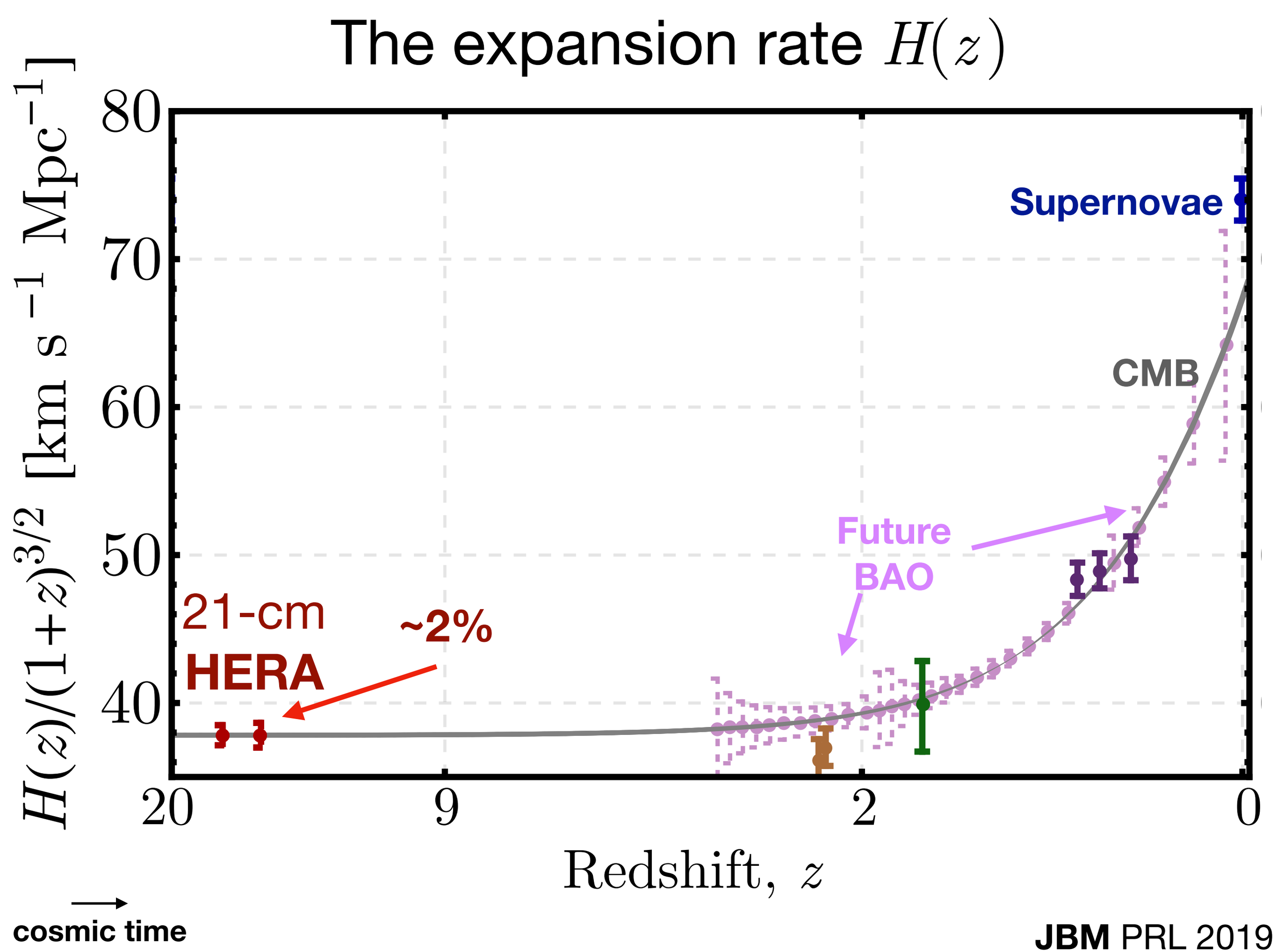
The expansion rate $H(z)$



cosmic time →

JBM PRL 2019

The expansion rate $H(z)$



JBM PRL 2019

Applications

- Important to characterize the first galaxies

Applications

- Important to characterize the first galaxies

- It’s unexplored territory -> new physics

Applications

- Important to characterize the first galaxies

- It’s unexplored territory -> new physics

- H_0 tension

Measuring r_s

$\theta_s \propto r_s H(z)$

Poulin+ 2019
Agrawal+ 2019
...

SNe

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

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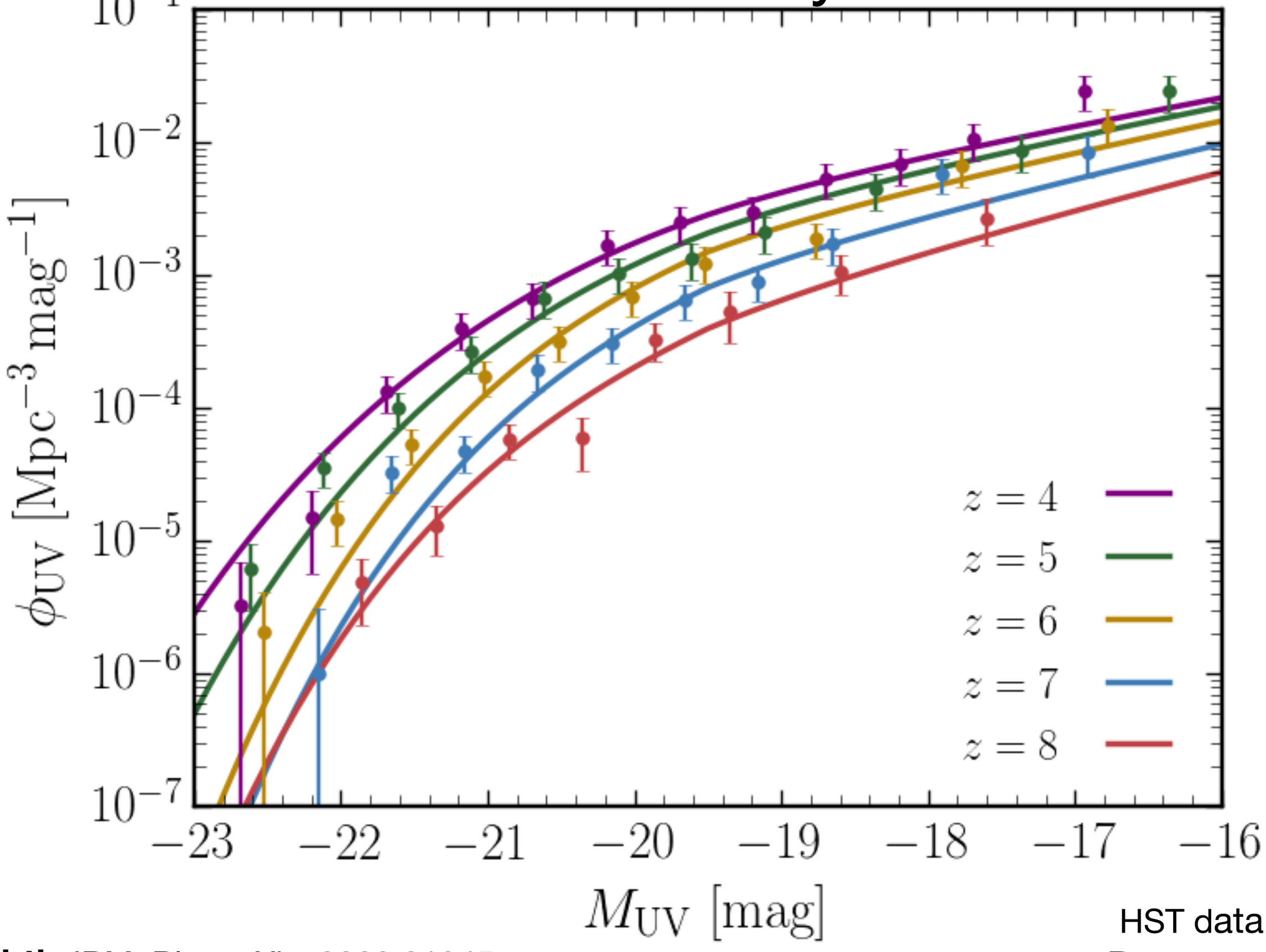
JBM PRL 2019

HST UV Luminosity Functions

Sabti, JBM, Blas arXiv: 2009.01245

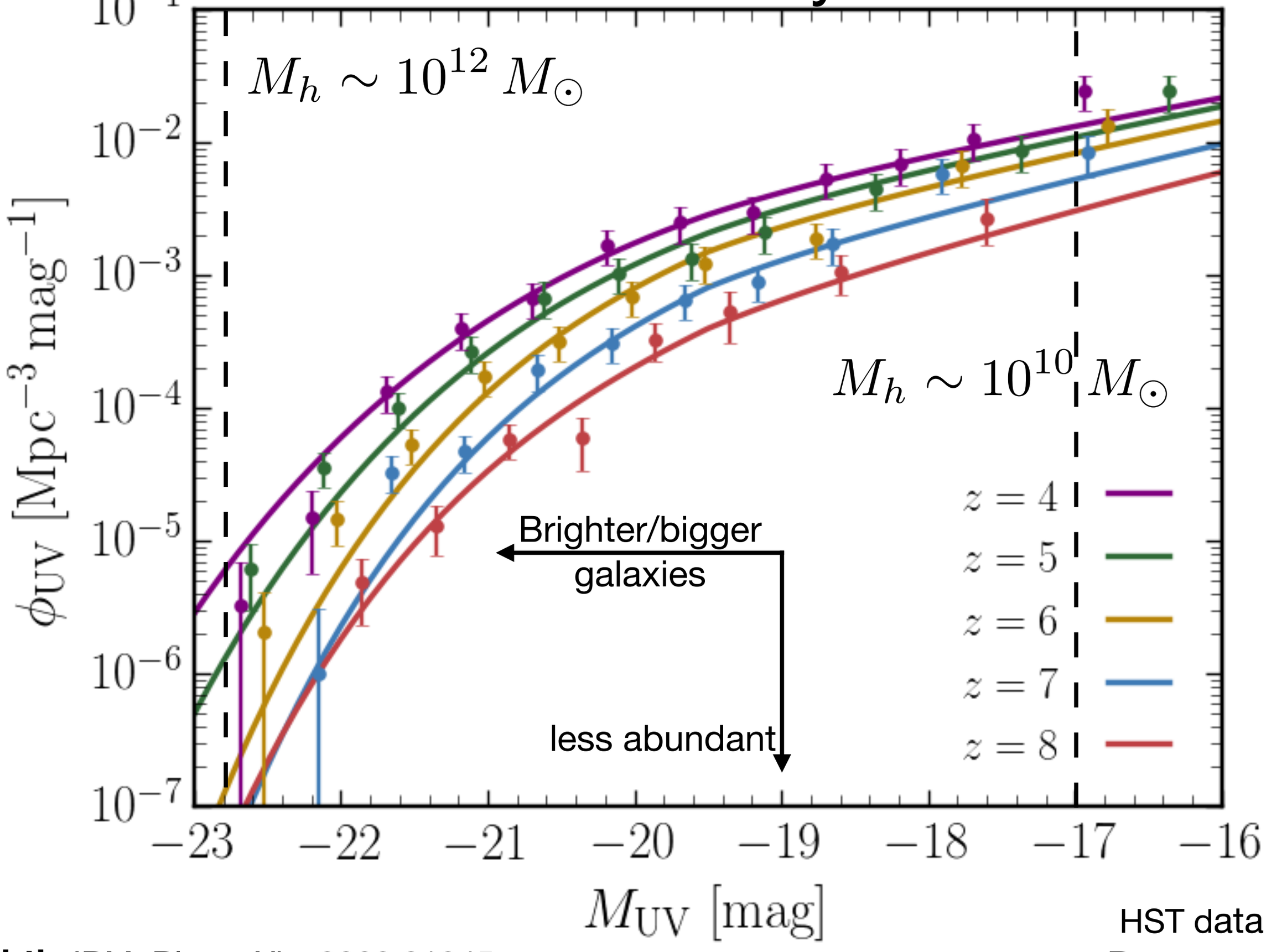
HST UV Luminosity Functions



Sabti, JBM, Blas arXiv: 2009.01245

HST data from:
Bouwens+ 2015

HST UV Luminosity Functions



Sabti, JBM, Blas arXiv: 2009.01245

HST data from: Bouwens+ 2015

HST UV Luminosity Functions
(**Simple** theoretical model)

$$\phi_{\rm UV} = \frac{dn}{dM_{\rm UV}} = \frac{dn}{dM_h} \times \frac{dM_h}{dM_{\rm UV}}$$

UV Luminosity Function

Data

Halo Mass Function

Cosmology

Halo-galaxy connection

Astrophysics

Sabti, JBM, Blas arXiv: 2009.01245

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UV Luminosity Function

Data

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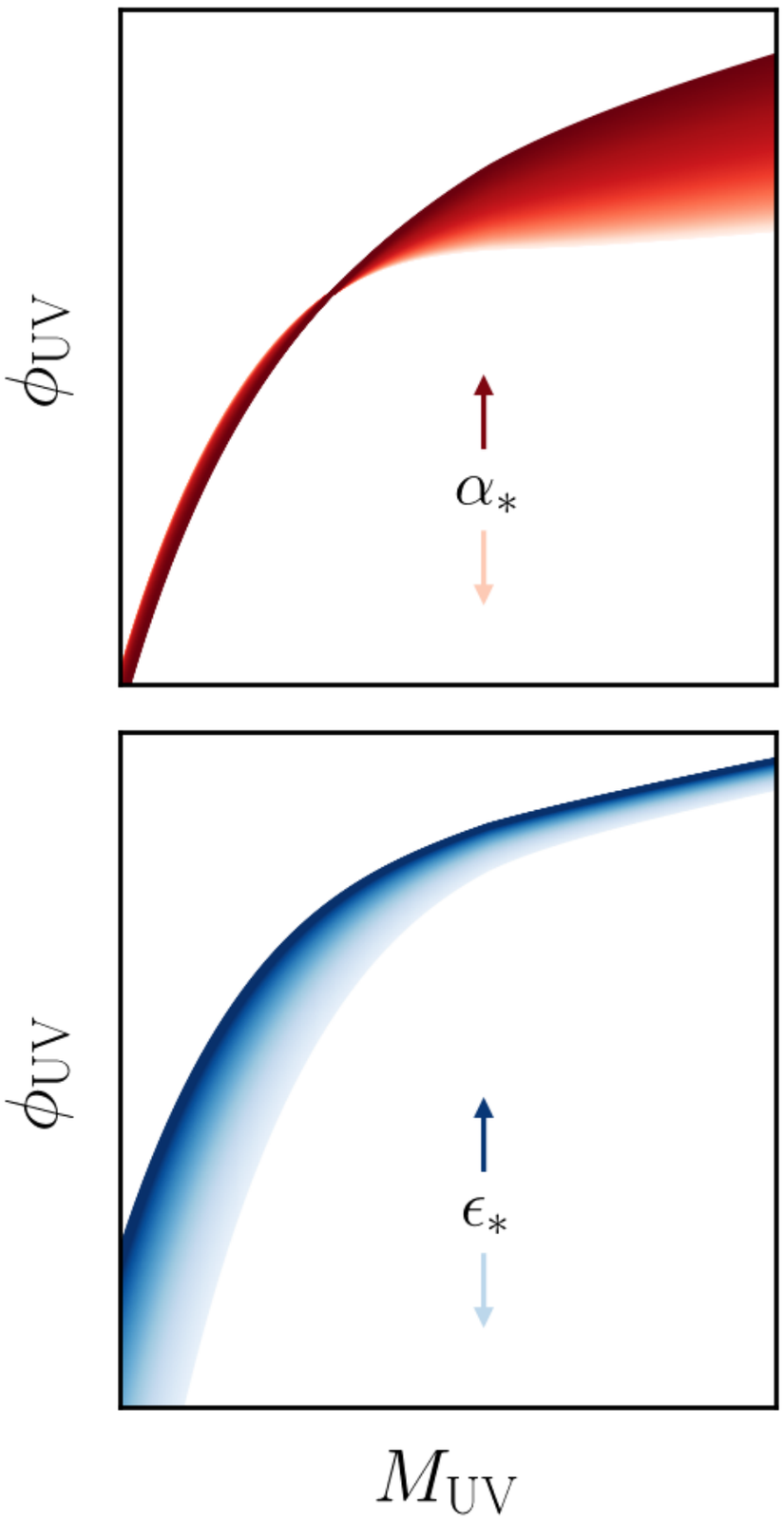
Astrophysics

-Can we separate cosmology from astrophysics?

Sabti, JBM, Blas arXiv: 2009.01245

HST UV Luminosity Functions



Halo-galaxy connection

$$f_*(M_h) = \frac{\epsilon_*}{(M_h/M_c)^{\alpha_*} + (M_h/M_c)^{\beta_*}}$$

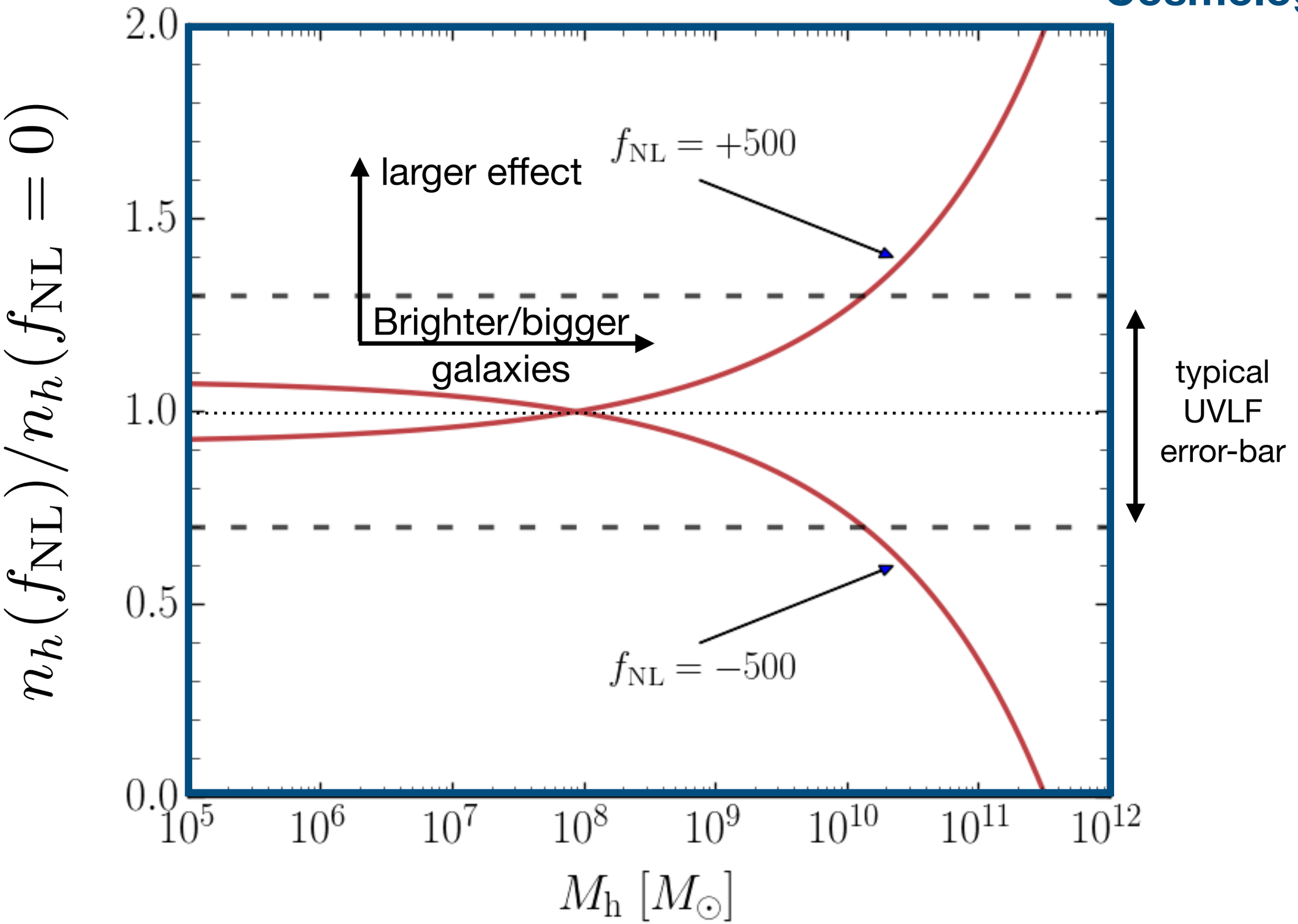
Astrophysics

(plus dust corrections)

Sabti, JBM, Blas arXiv: 2009.01245

Primordial non-Gaussianity

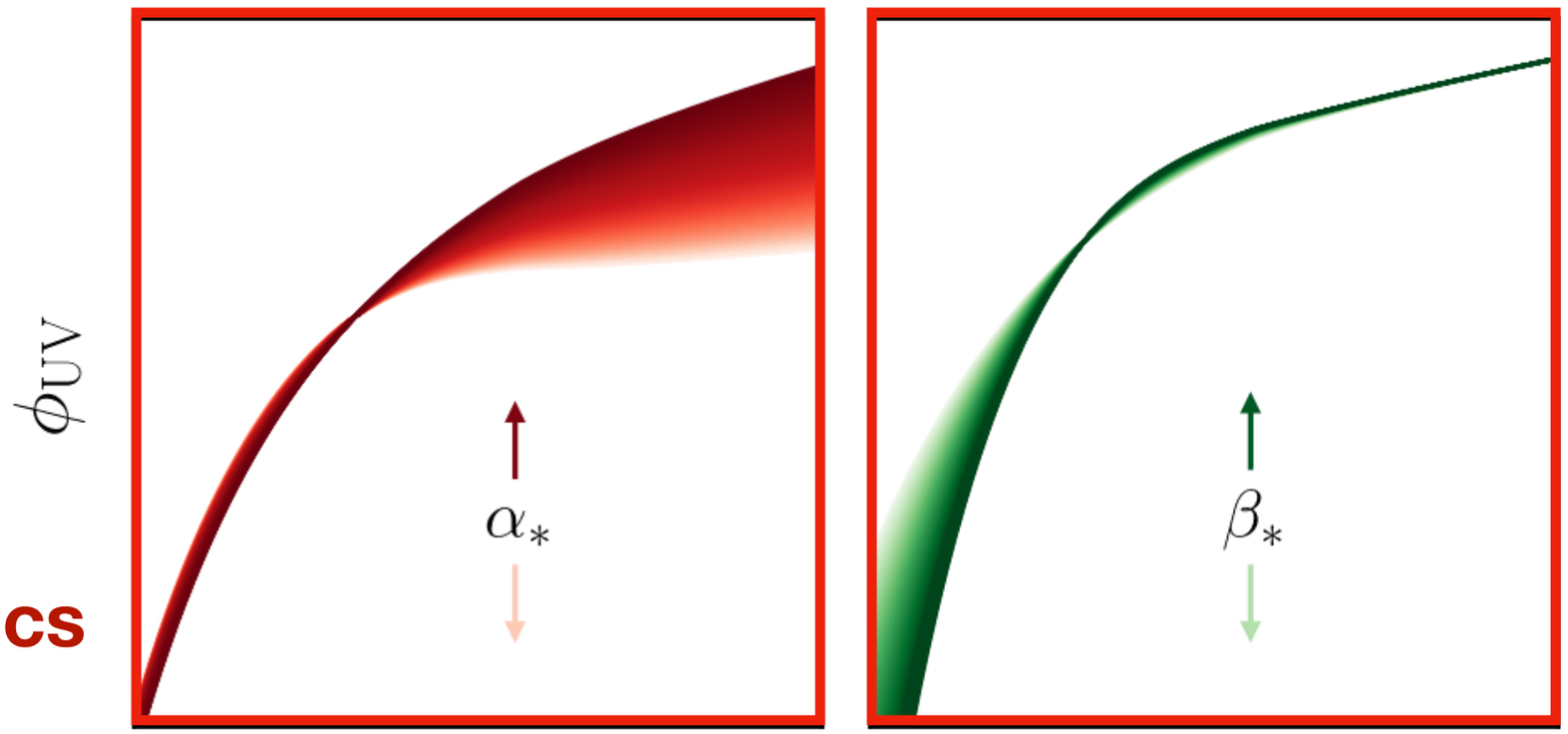
Cosmology



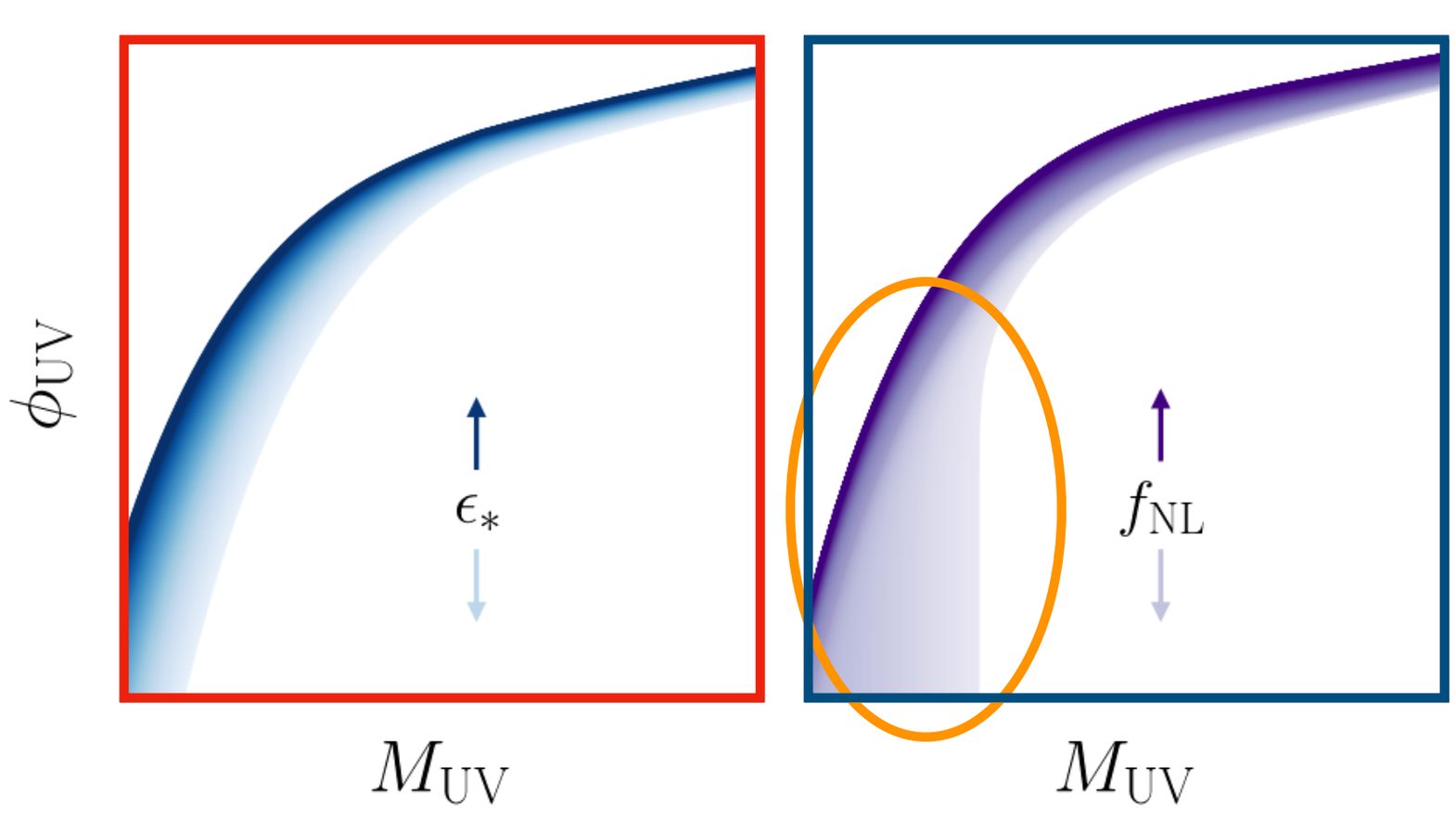
Sabti, JBM, Blas arXiv: 2009.01245

HST UV Luminosity Functions

Astrophysics

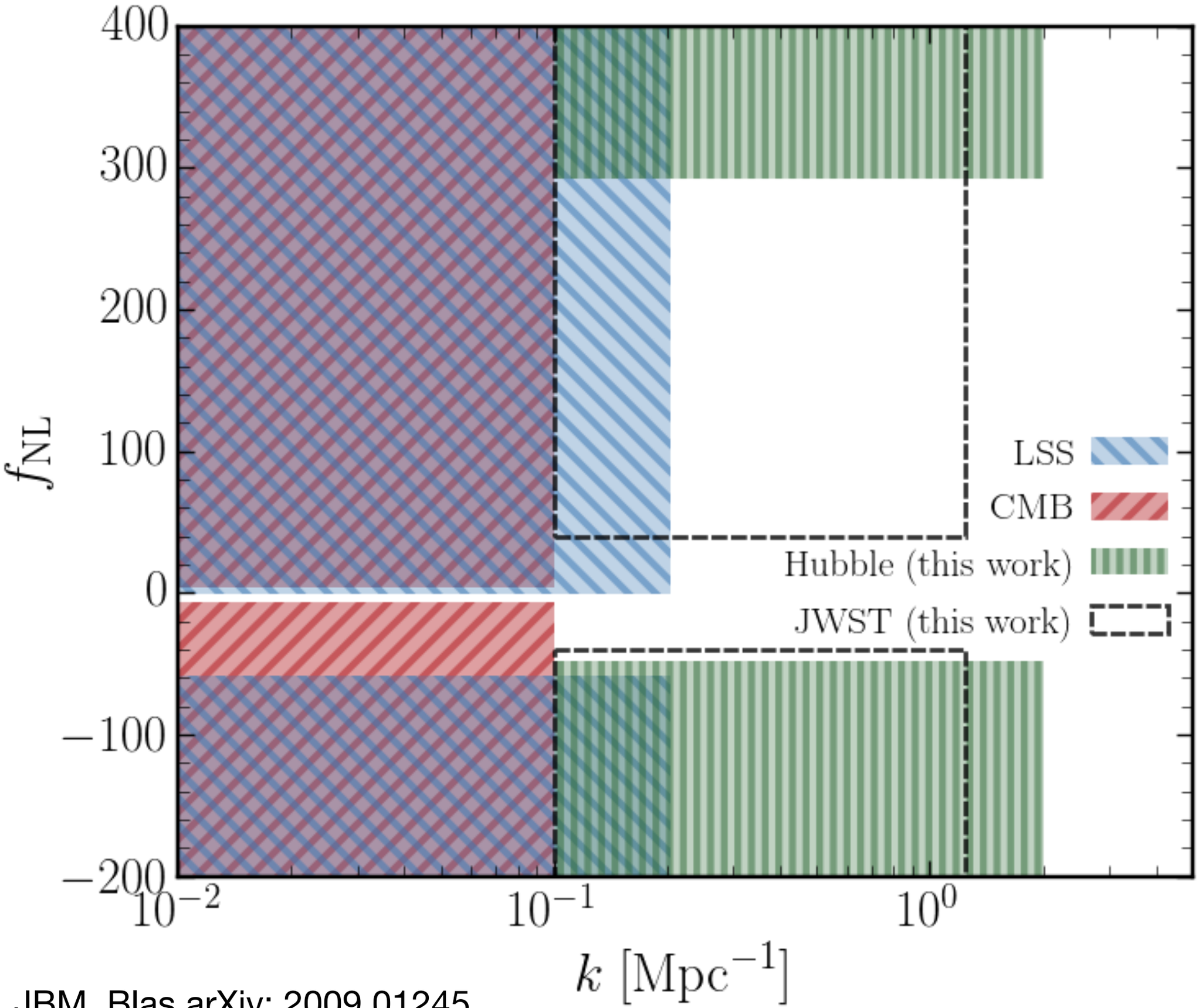


Cosmology



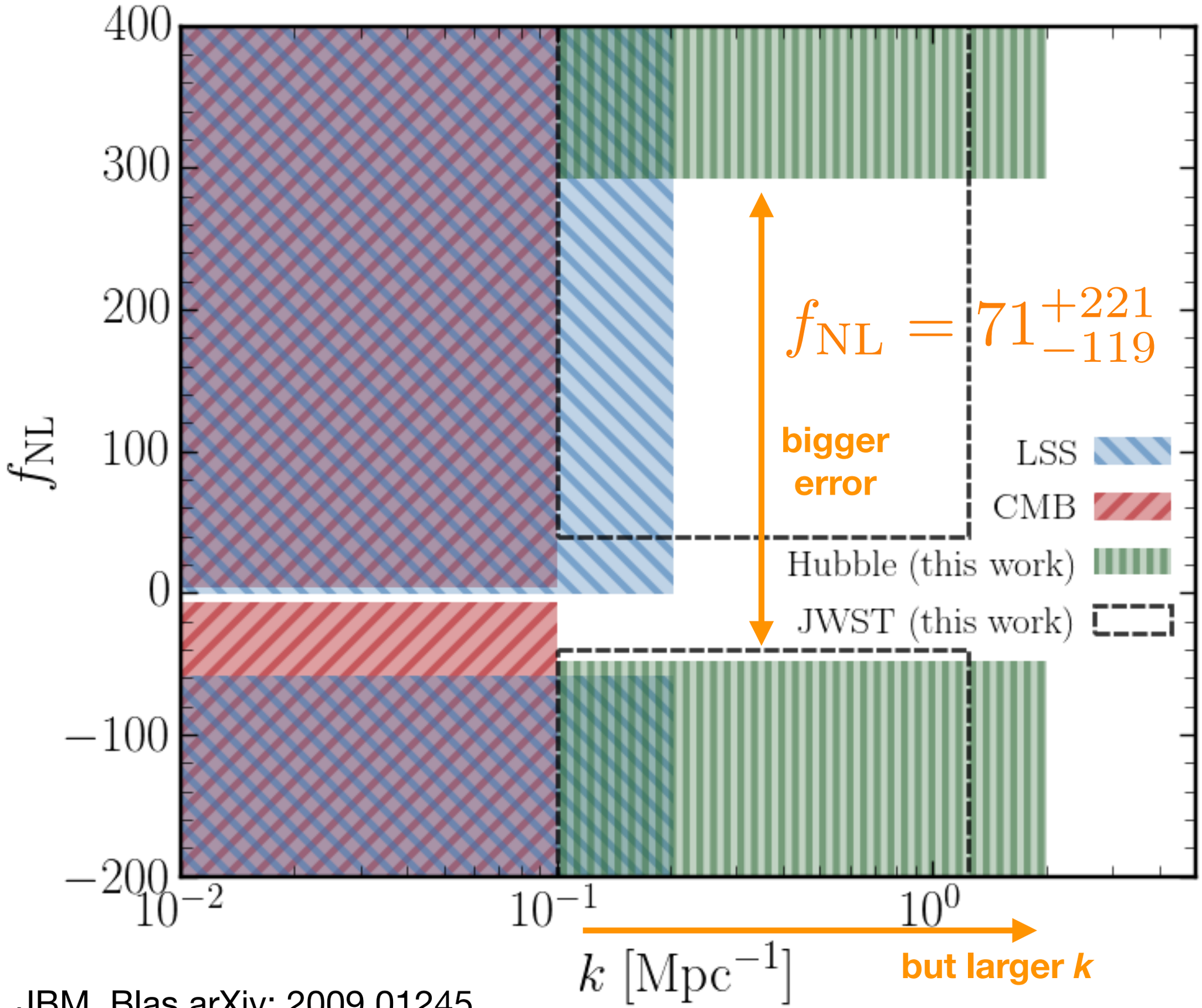
Sabti, JBM, Blas arXiv: 2009.01245

Constraints on PNG at different scales



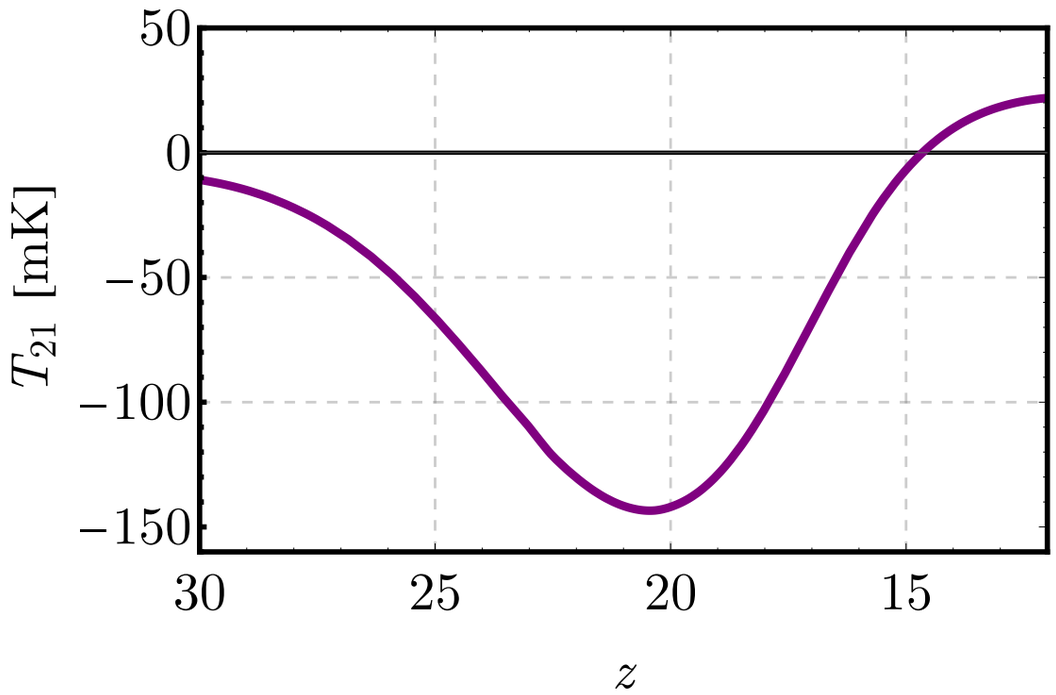
Sabti, JBM, Blas arXiv: 2009.01245

Constraints on PNG at different scales

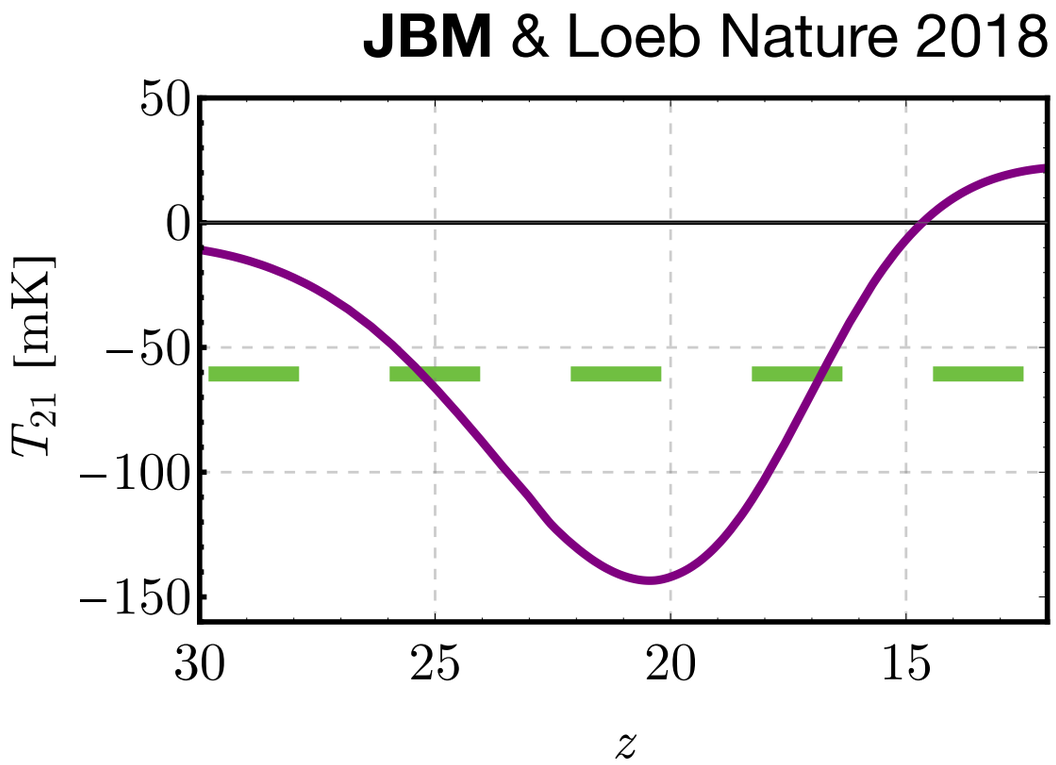


Sabti, JBM, Blas arXiv: 2009.01245

Summary

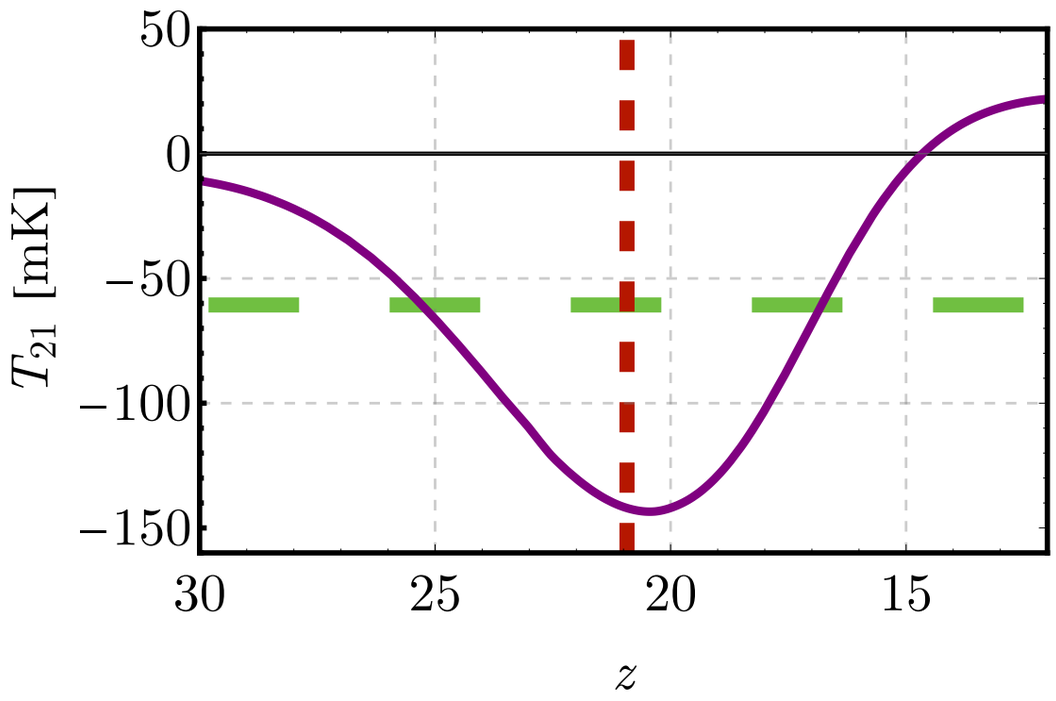


Summary



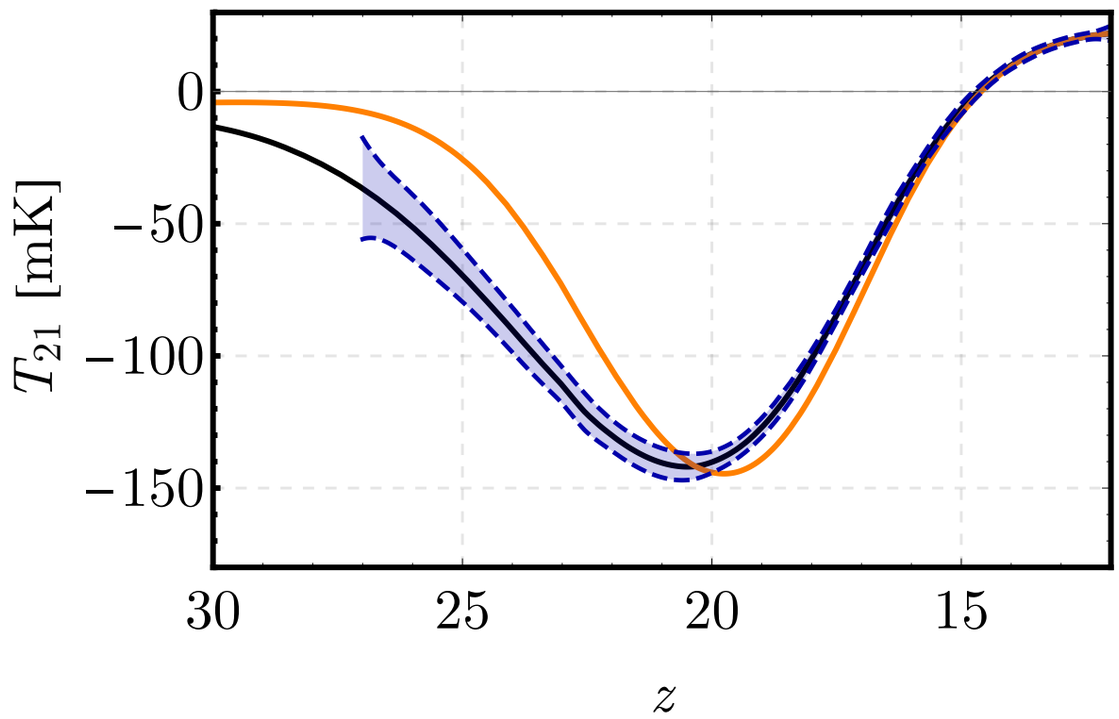
Summary

JBM & Loeb Nature 2018



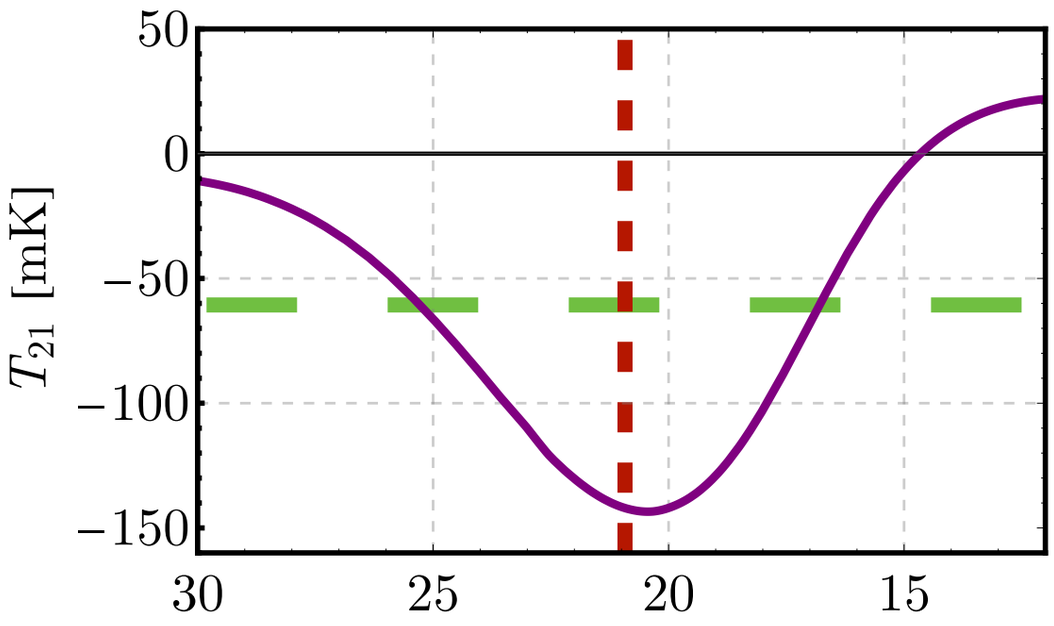
JBM, Dvorkin & Cyr Racine PRD 2020

JBM, Bohr++ 2020

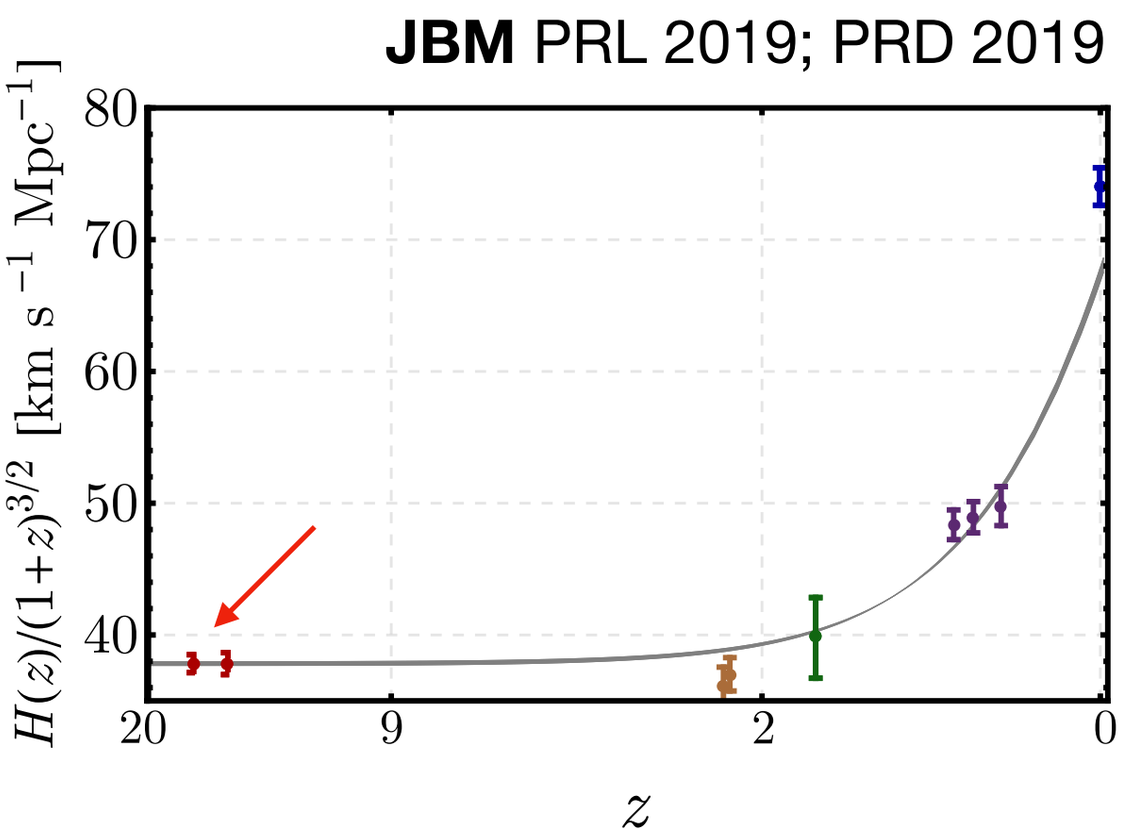


Summary

JBM & Loeb Nature 2018

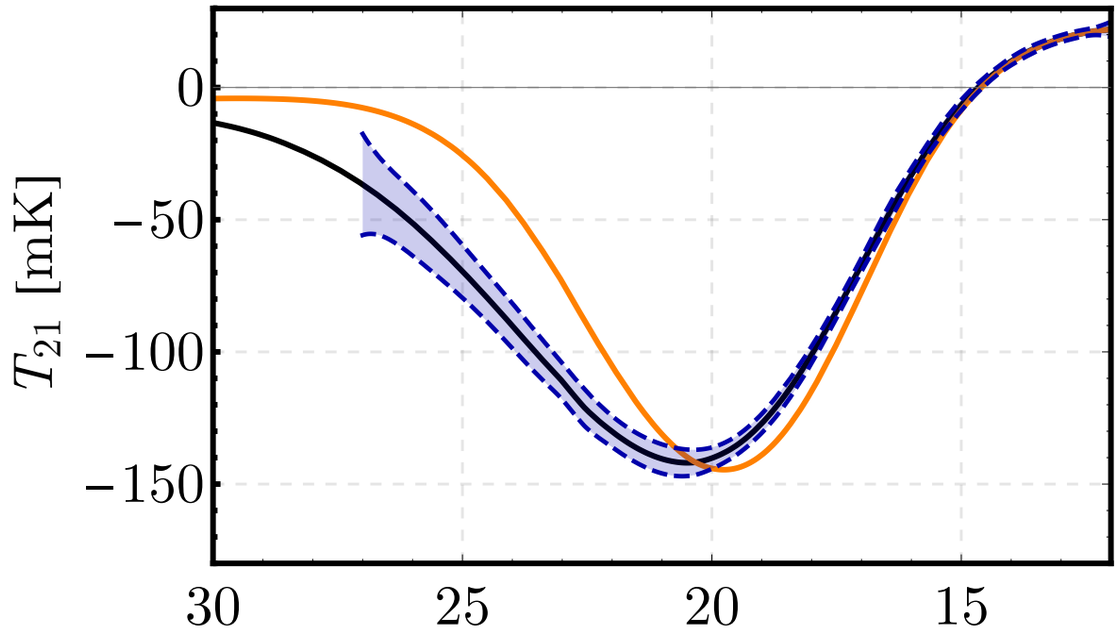


JBM PRL 2019; PRD 2019



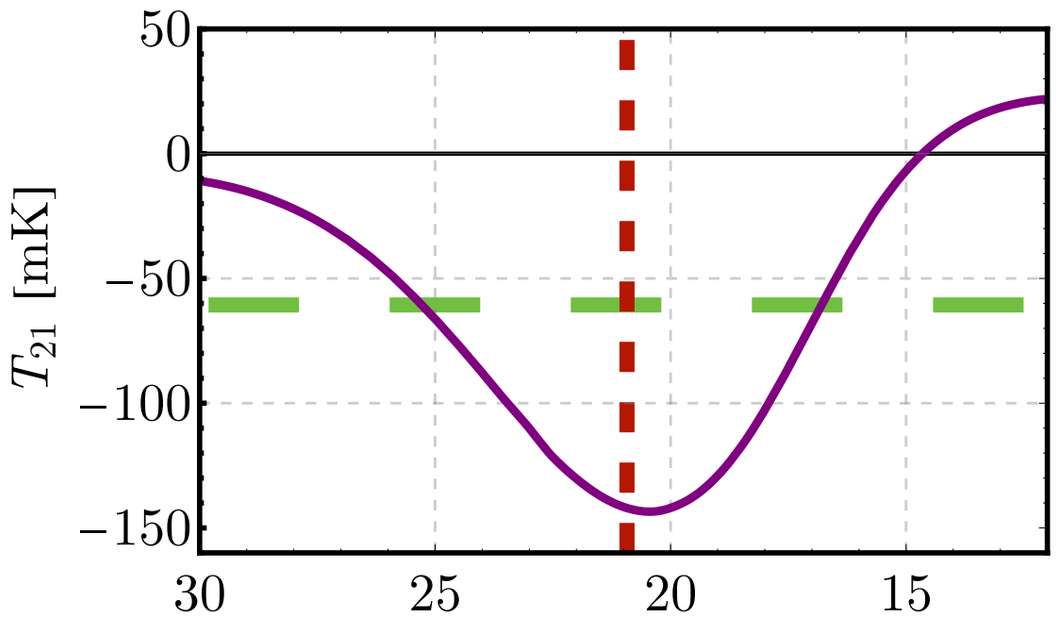
JBM, Dvorkin & Cyr Racine PRD 2020

JBM, Bohr++ 2020

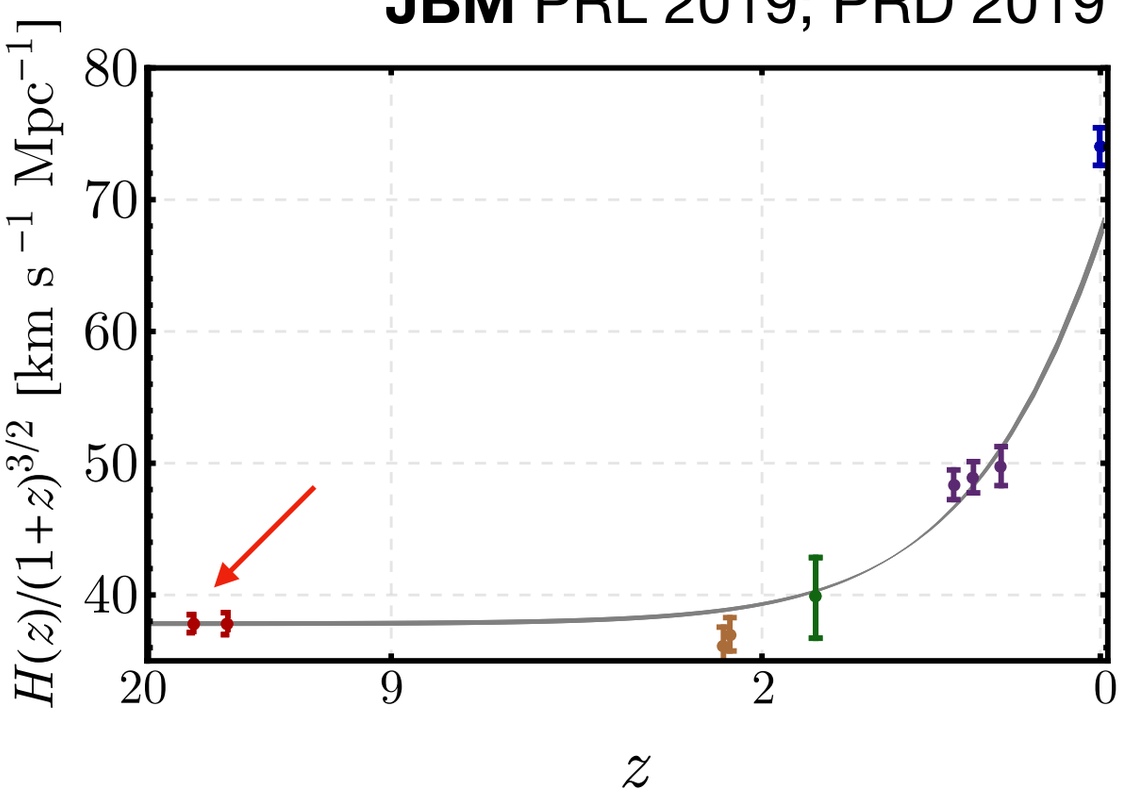


Summary

JBM & Loeb Nature 2018

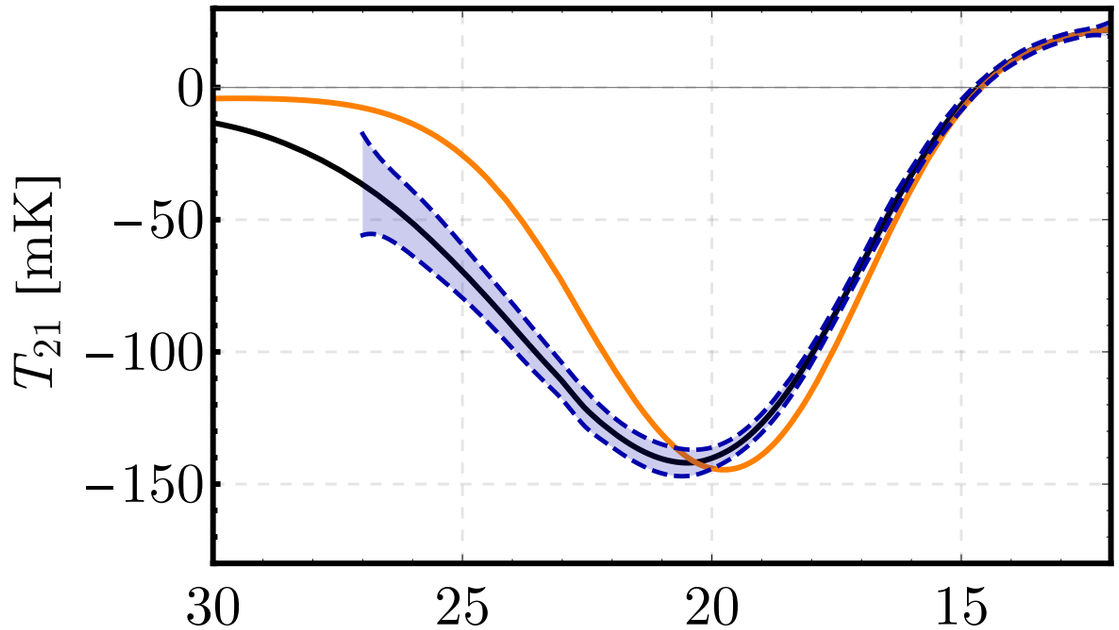


JBM PRL 2019; PRD 2019



JBM, Dvorkin & Cyr Racine PRD 2020

JBM, Bohr++ 2020



Sabti, **JBM,** Blas 2020