Small-scale structure at cosmic dawn

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

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Based on

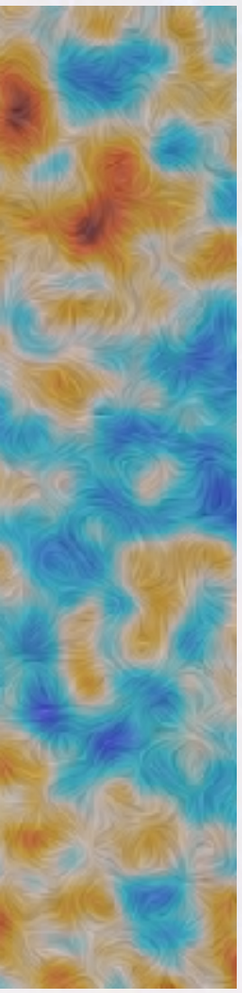
PRD 101 063526 (2020) w/ Dvorkin and Cyr-Racine

In progress w/ Cyr-Racine, Bohr, Zavala, and Vogelsberger

Image: Fuller/NSF

A brief history of hydrogen

CMB



$z \approx 10^3$

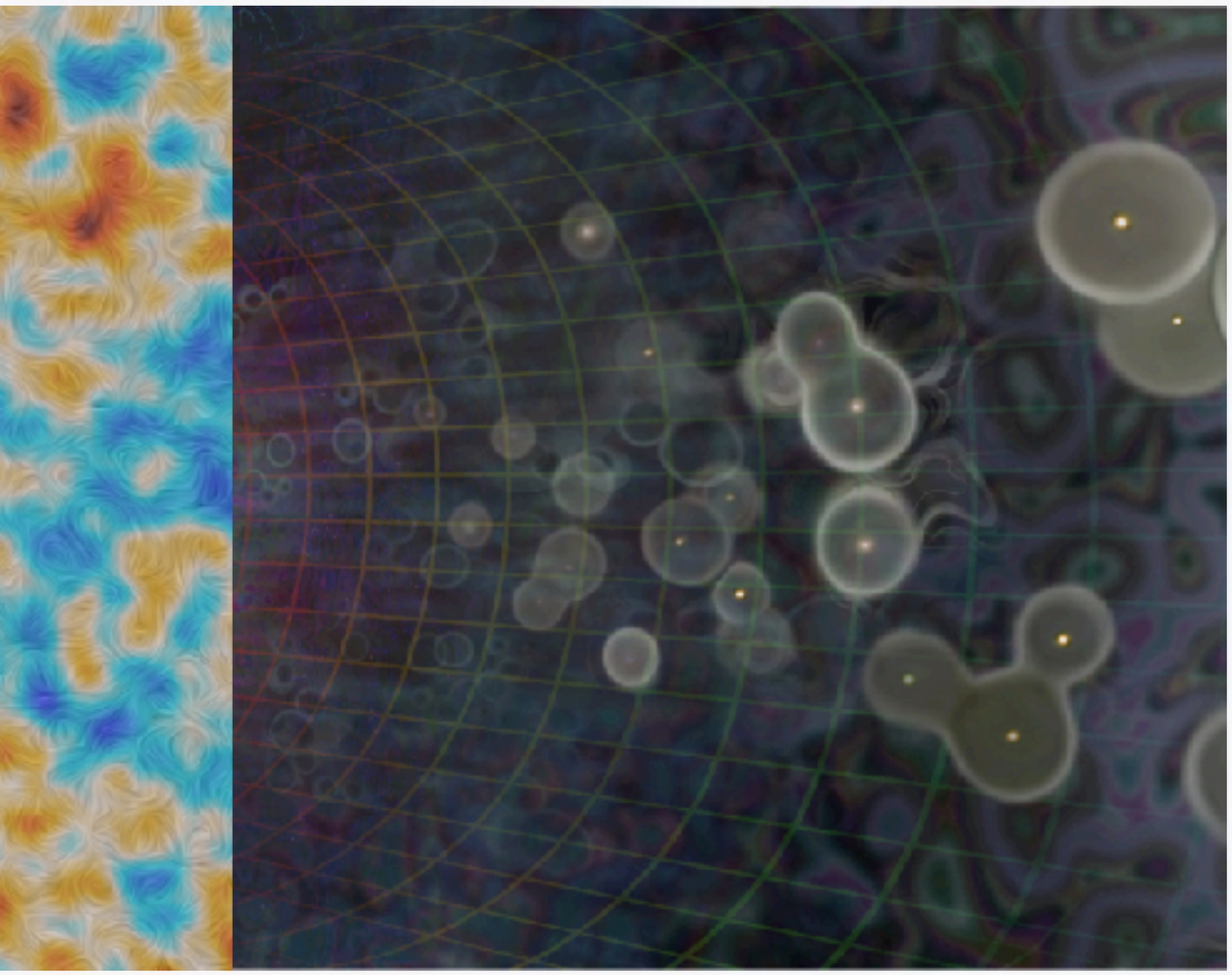
Image: ESA

cosmic time

A brief history of hydrogen

CMB

Cosmic Dawn



$z \approx 10^3$

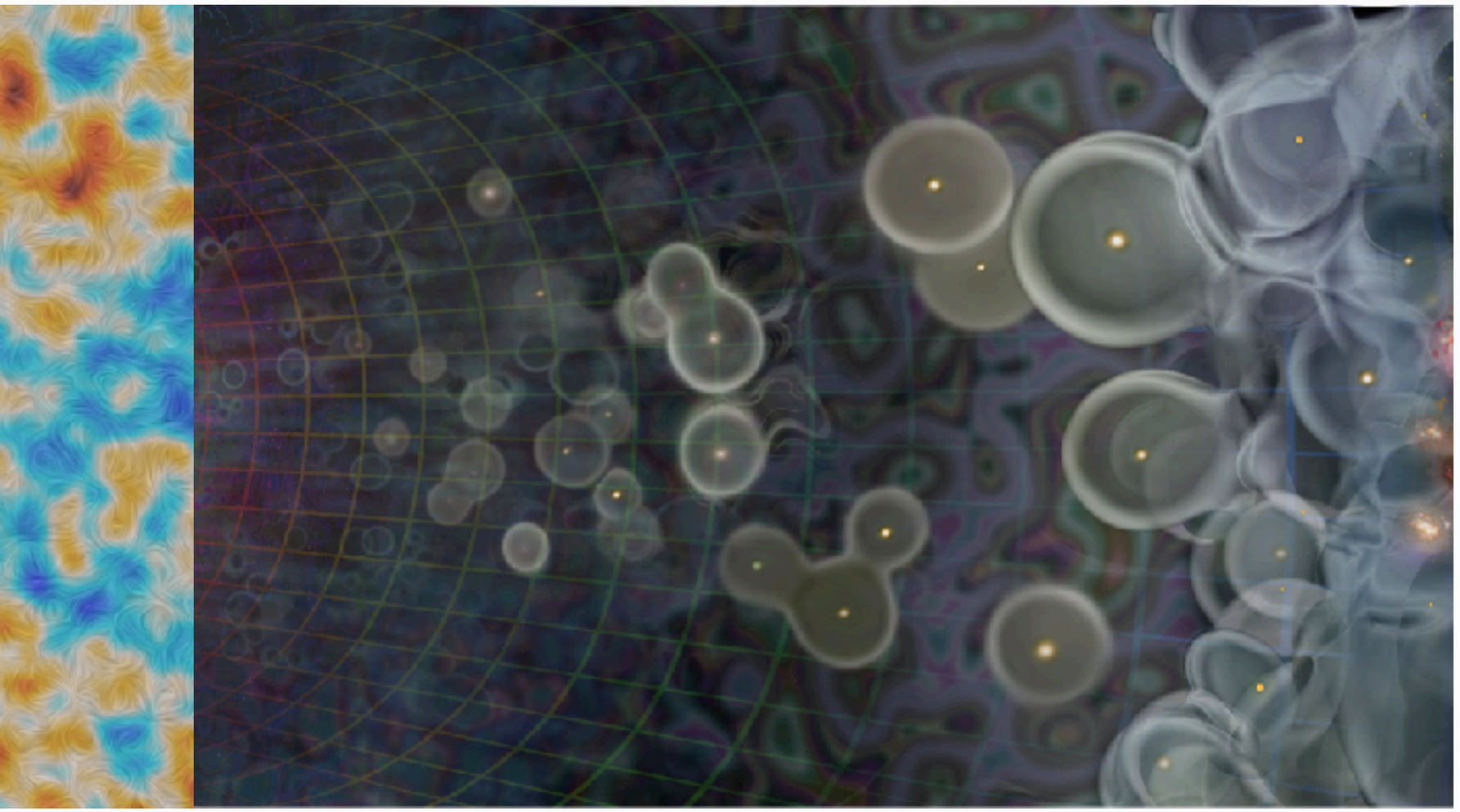
$z \approx 20$

cosmic time →

Image: NASA/CXC/M.WEISS

A brief history of hydrogen

CMB Cosmic Dawn **Reionization**



$z \approx 10^3$ $z \approx 20$ $z \approx 6$

cosmic time →

Image: NASA/CXC/M.WEISS

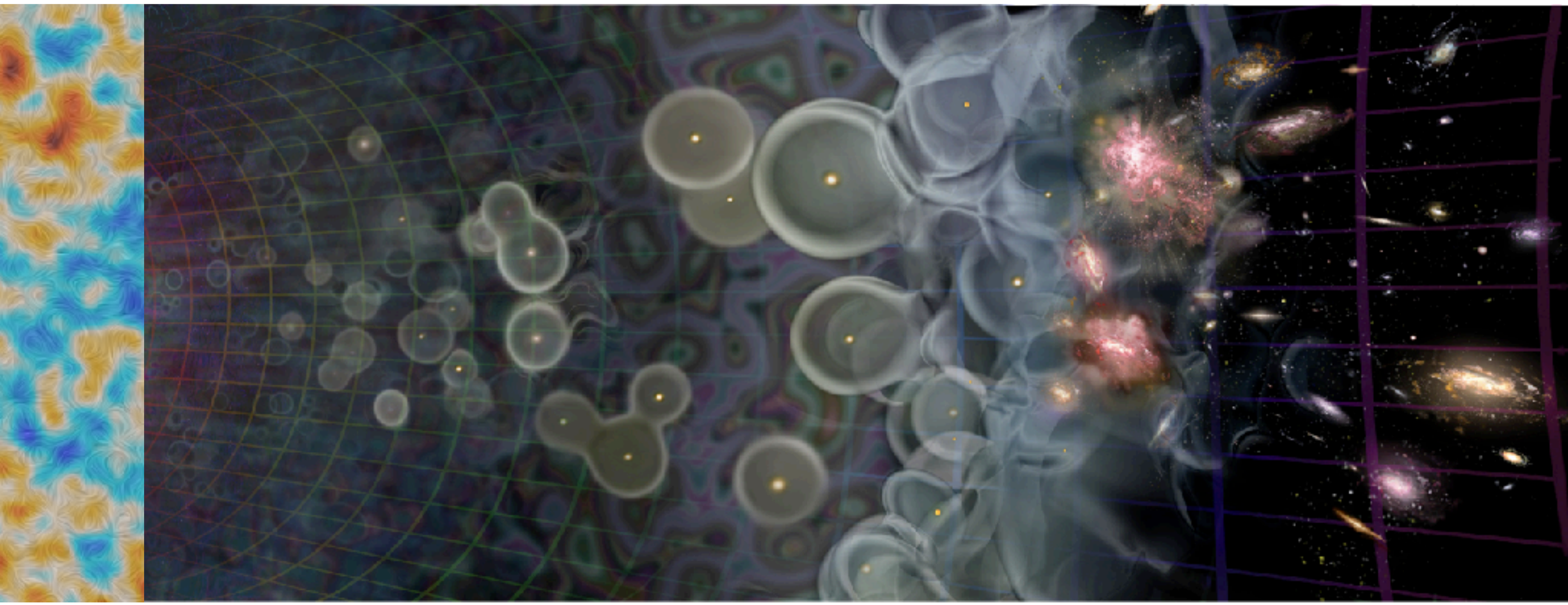
A brief history of hydrogen

CMB

Cosmic Dawn

Reionization

Local Universe



$z \approx 10^3$

$z \approx 20$

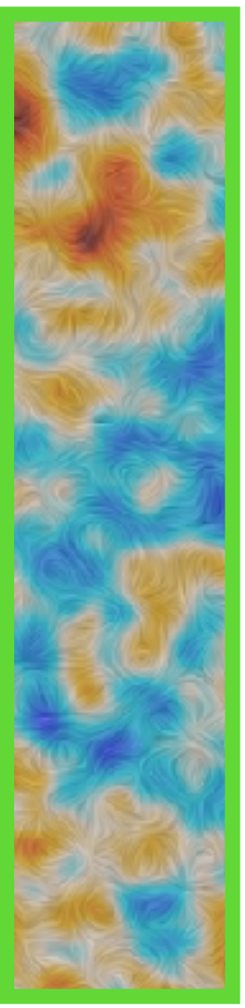
$z \approx 6$

$z = 0$

cosmic time

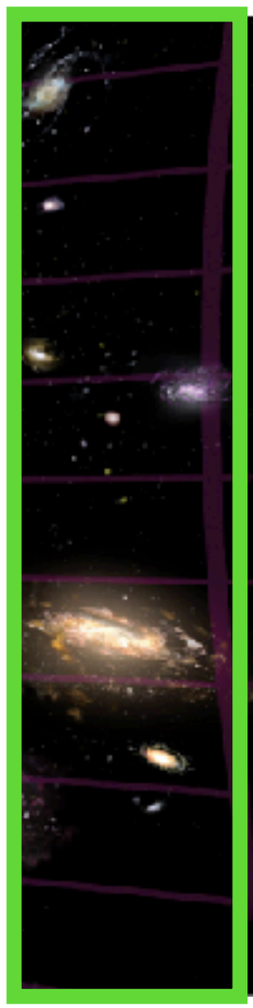
Image: NASA/CXC/M.WEISS

CMB



$z \approx 10^3$

Local Universe

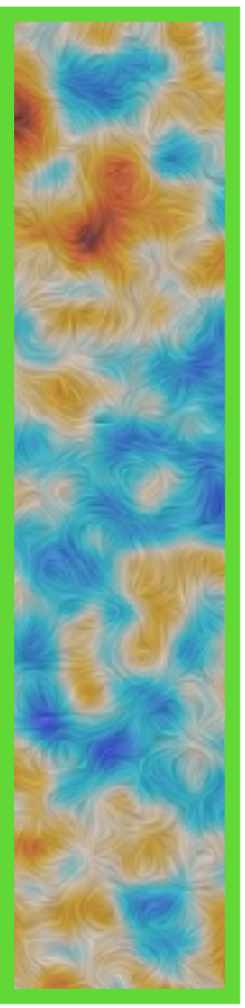


$z = 0$

Image: NASA/CXC/M.WEISS

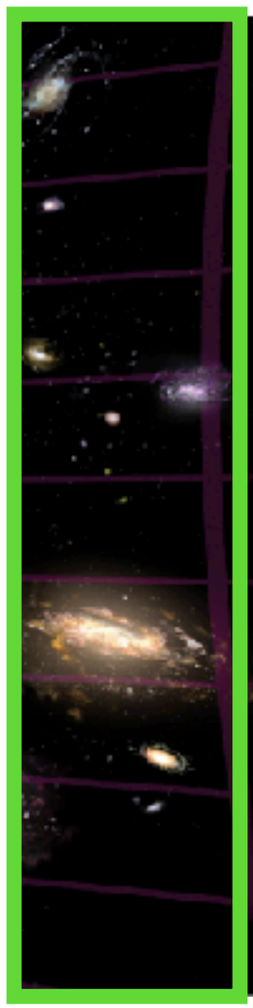
The pillars of cosmology

CMB



$z \approx 10^3$

Local Universe



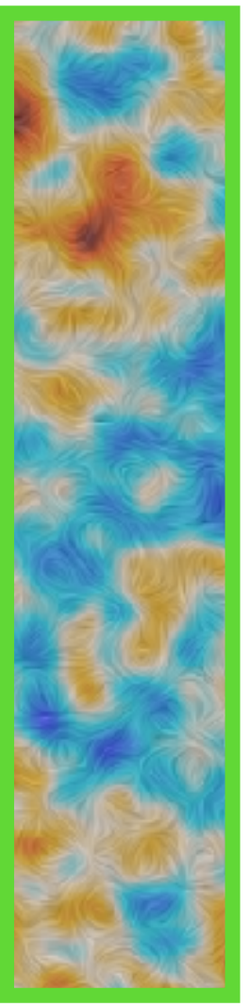
$z = 0$

There is ~5 times more matter than we can directly see (DM)

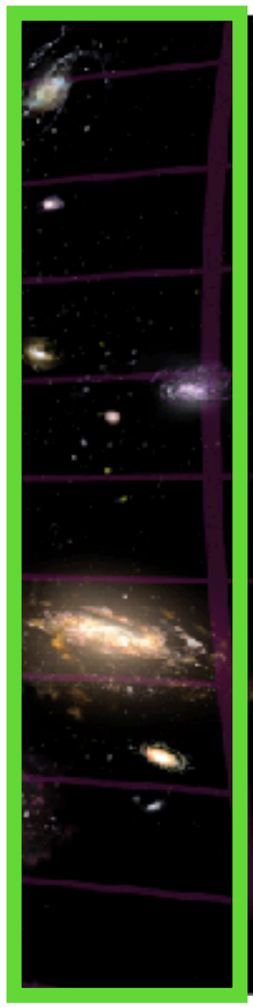
Image: NASA/CXC/M.WEISS

The pillars of cosmology

CMB



Local Universe



There is ~5 times more matter than we can directly see (DM)

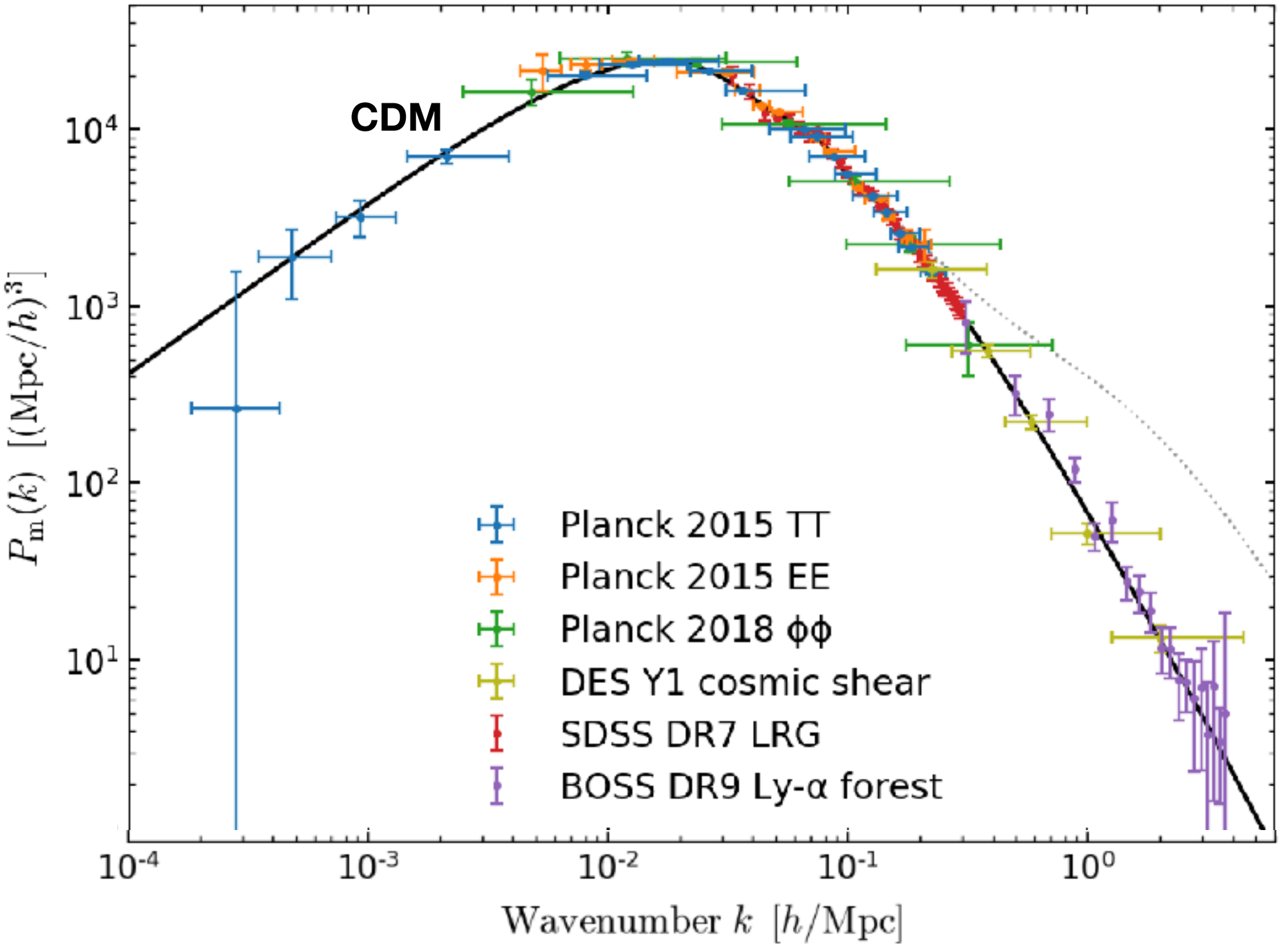
This DM is cold and collisionless

$z \approx 10^3$

$z = 0$

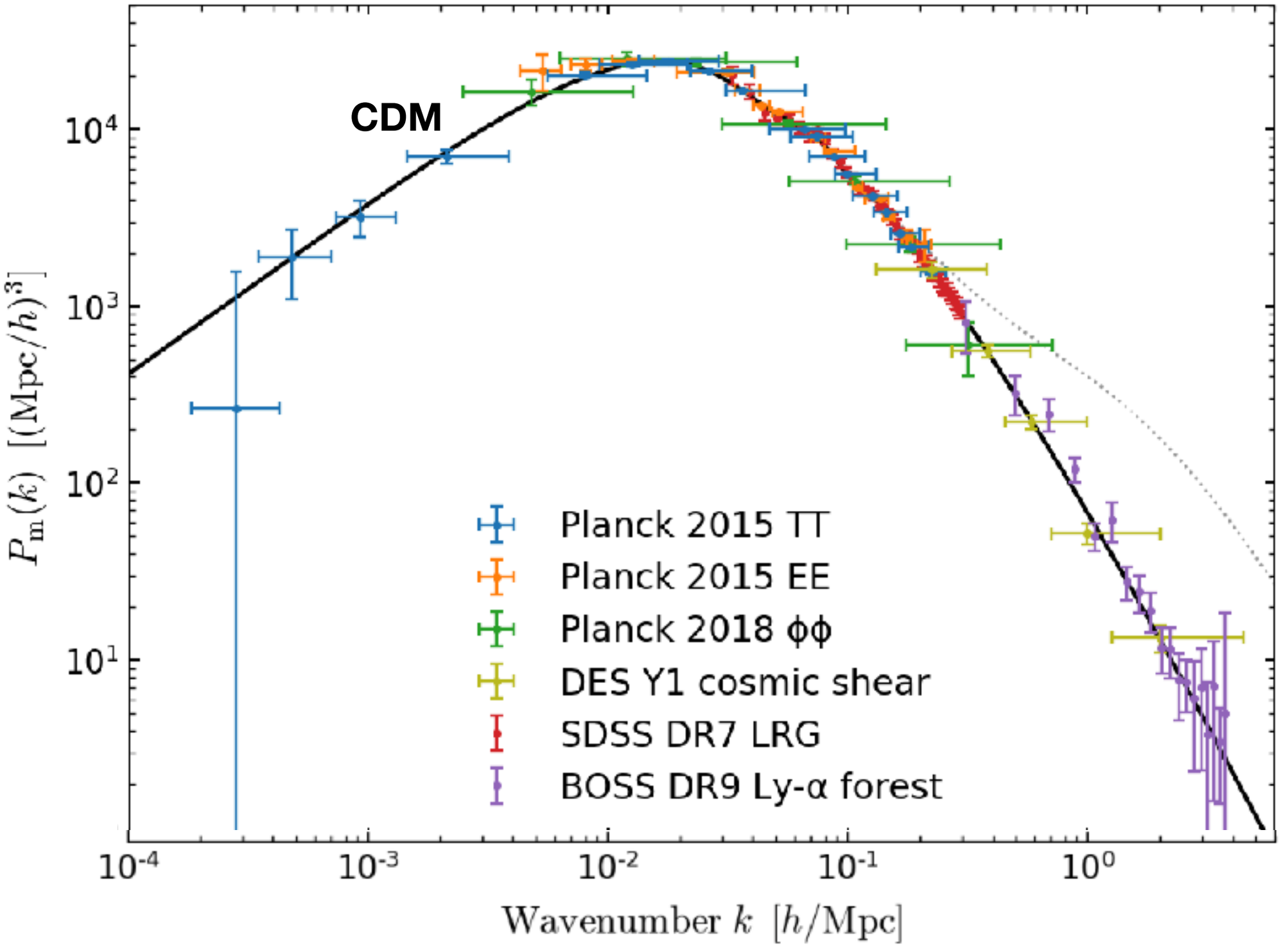
Image: NASA/CXC/M.WEISS

DM is cold and collisionless



Chabanier+ arXiv: 1905.08103

DM is cold and collisionless… or is it?



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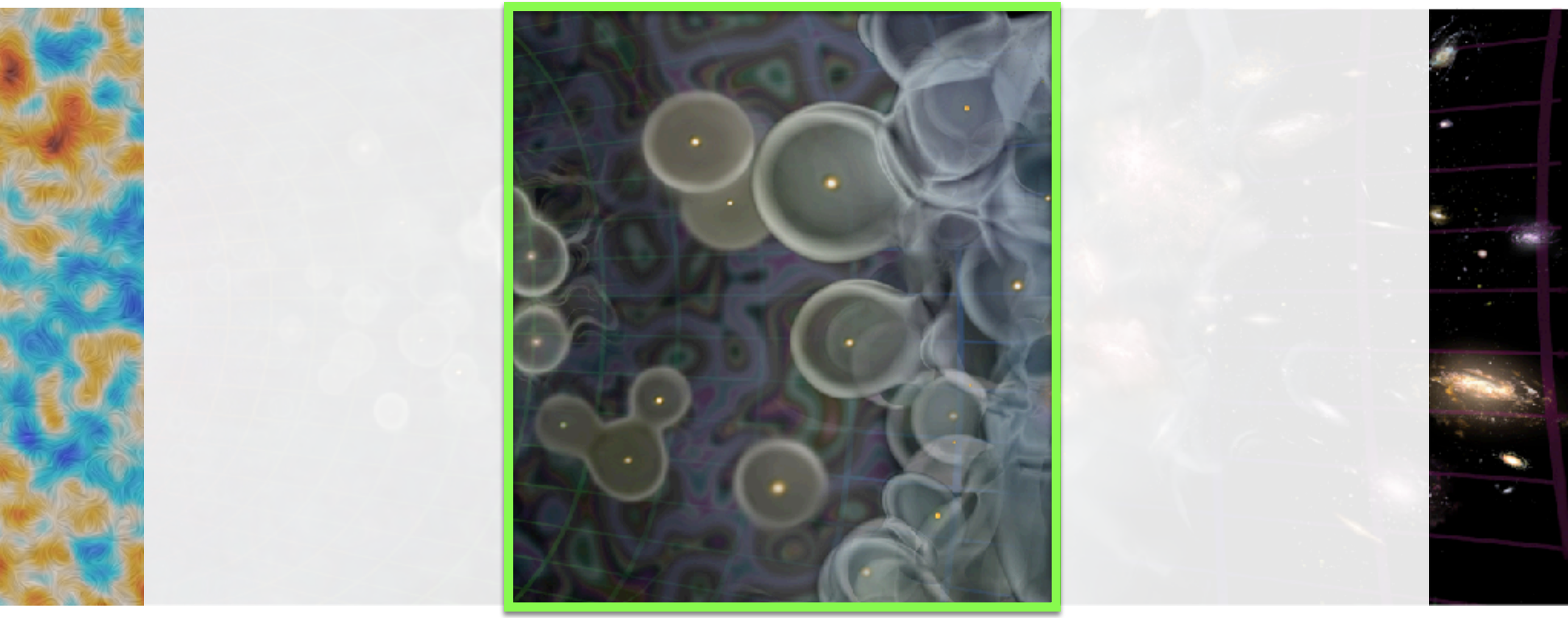
Chabanier+ arXiv: 1905.08103

DM is cold and collisionless… or is it?

Cosmic Dawn

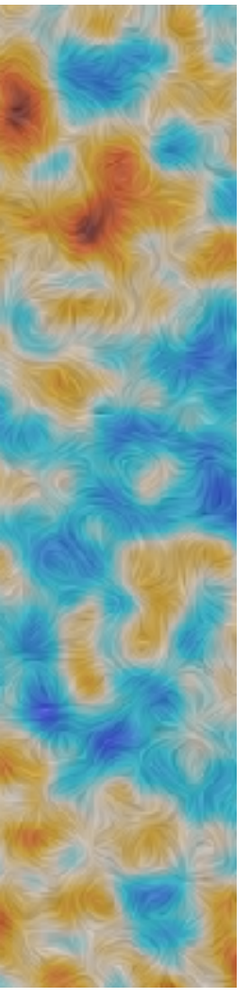


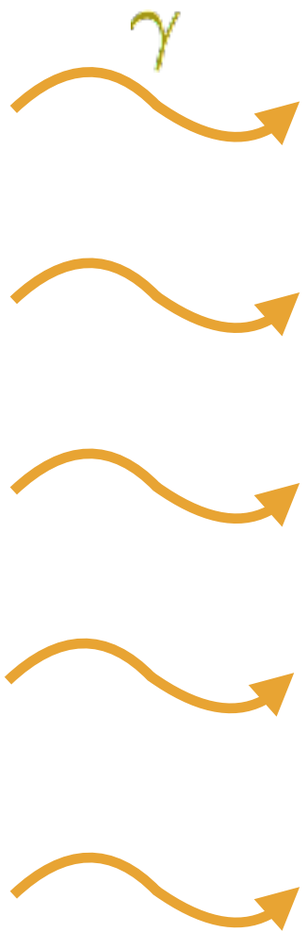
$z \approx 20$

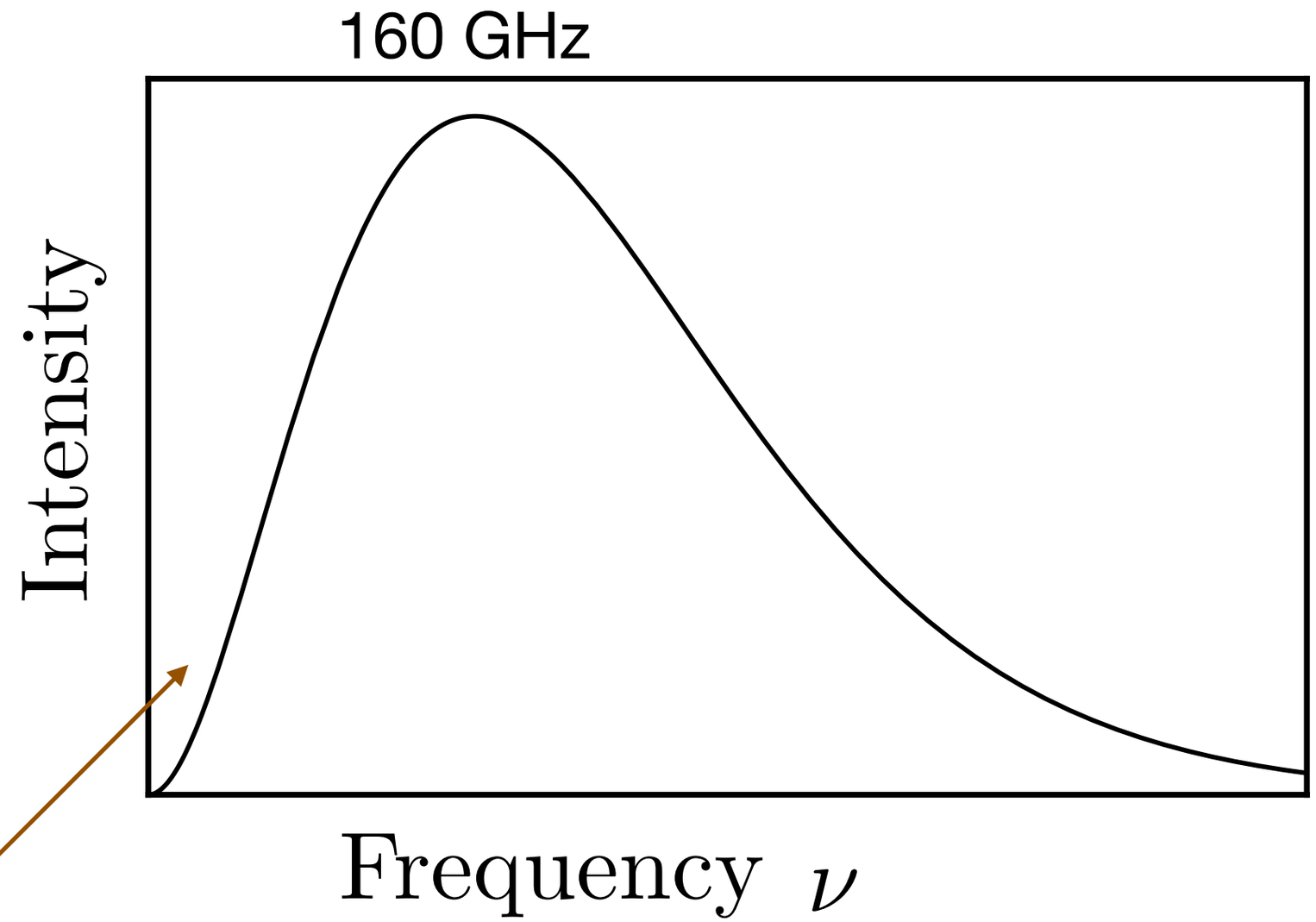
cosmic time →

The basics of 21-cm

CMB





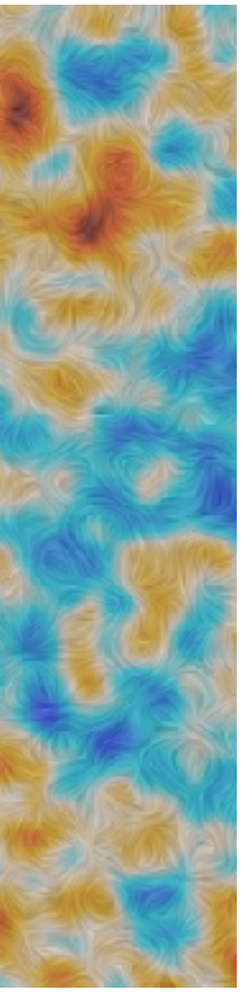


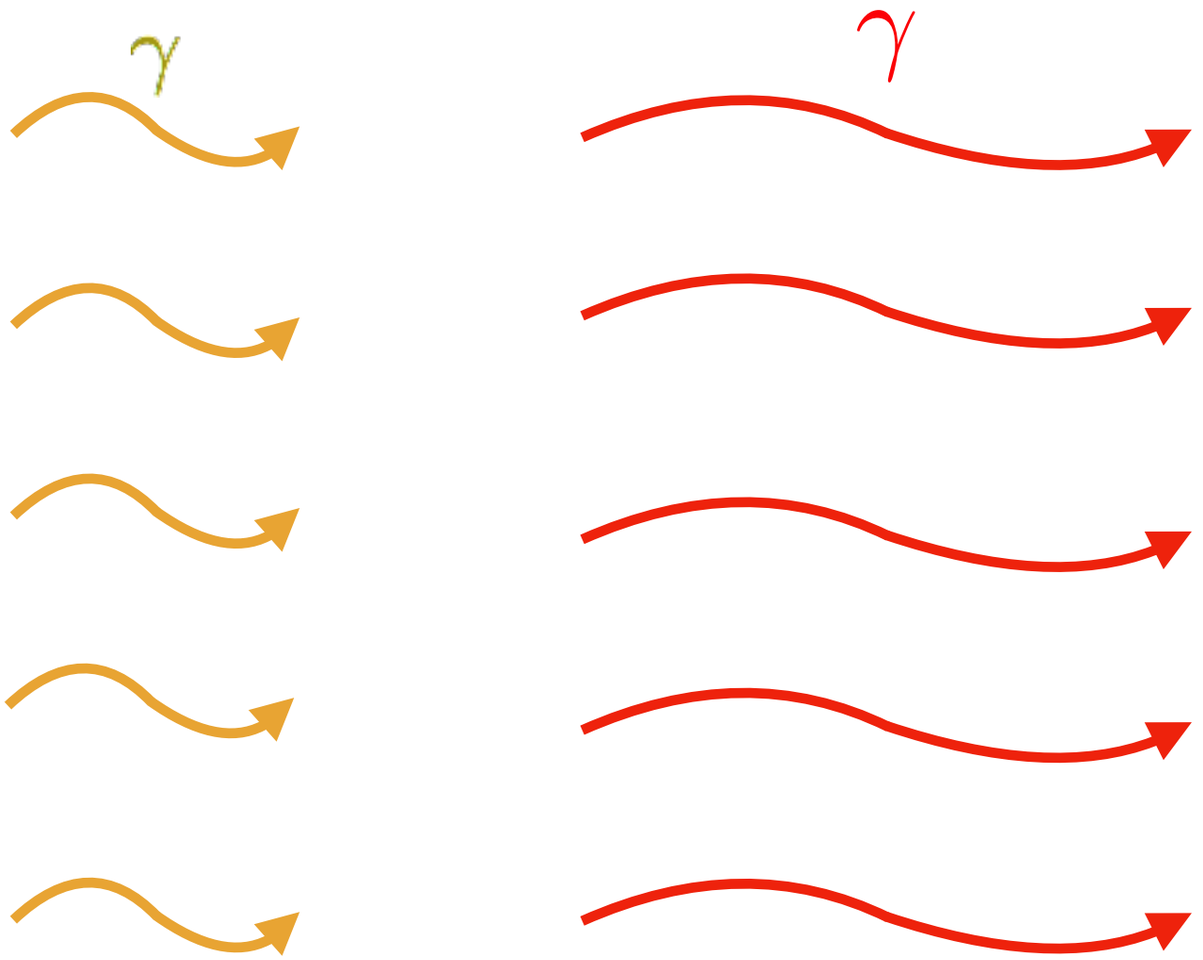
$z \approx 10^3$

21-cm wavelength: 1.4 GHz

The basics of 21-cm

CMB





Earth

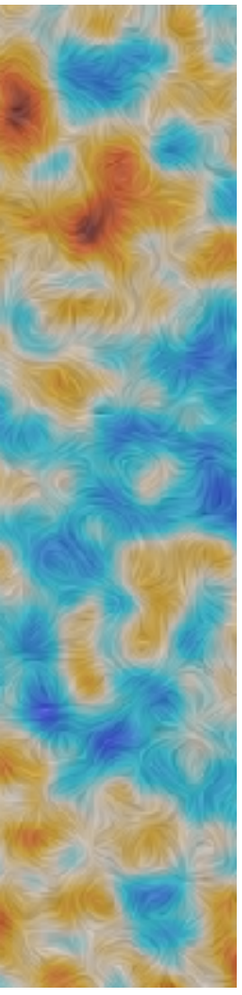
$z \approx 10^3$

$z = 0$

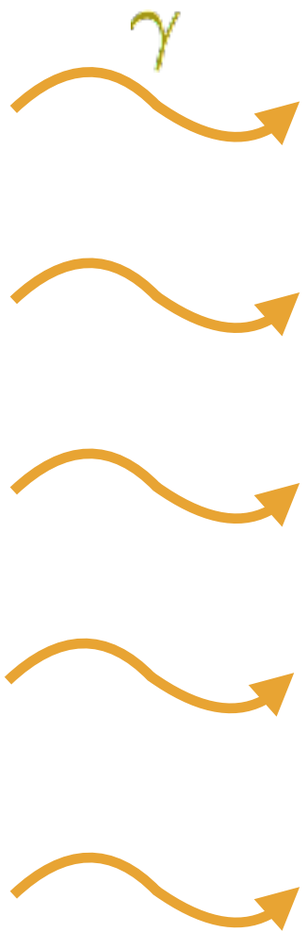
cosmic time

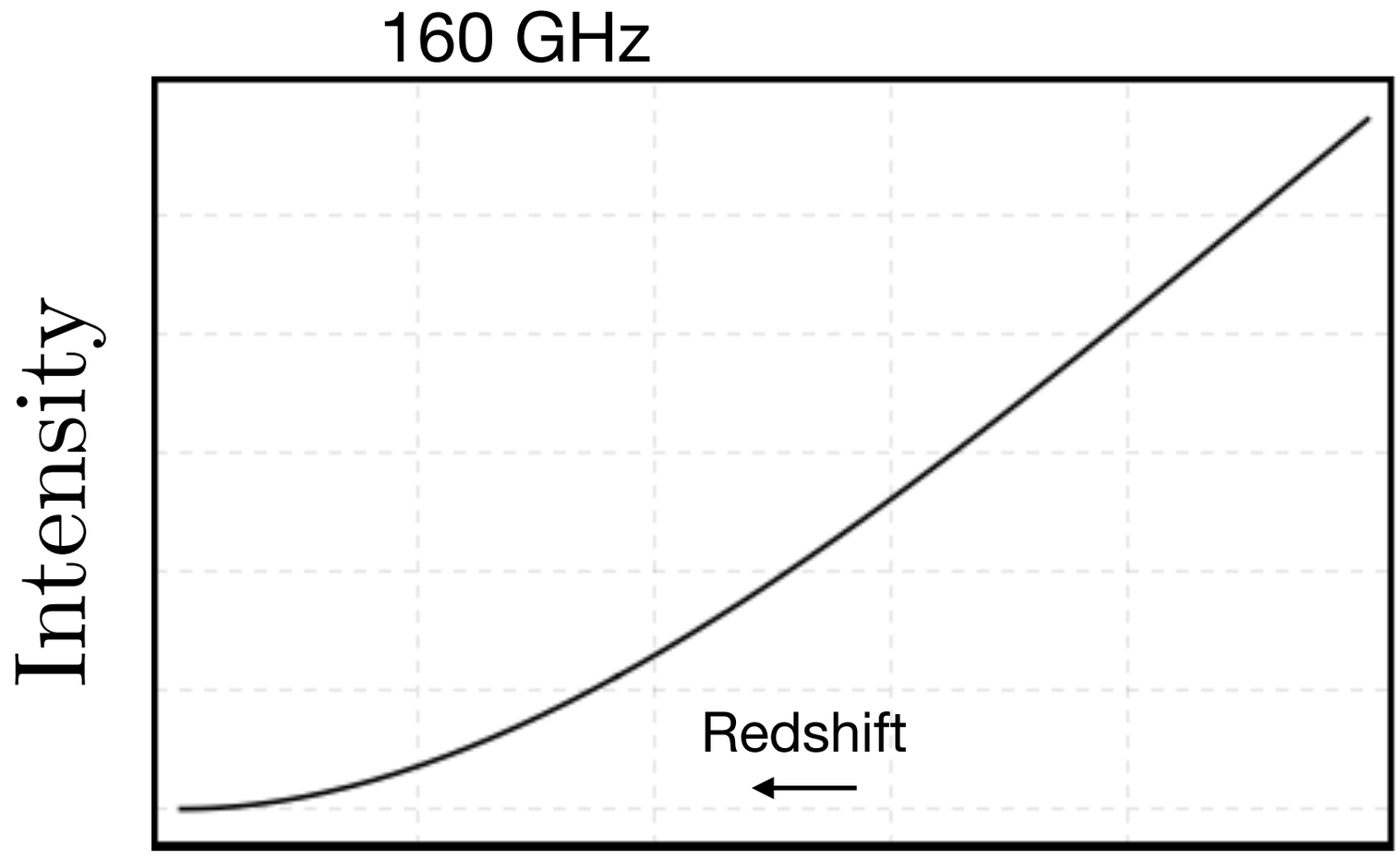
The basics of 21-cm

CMB



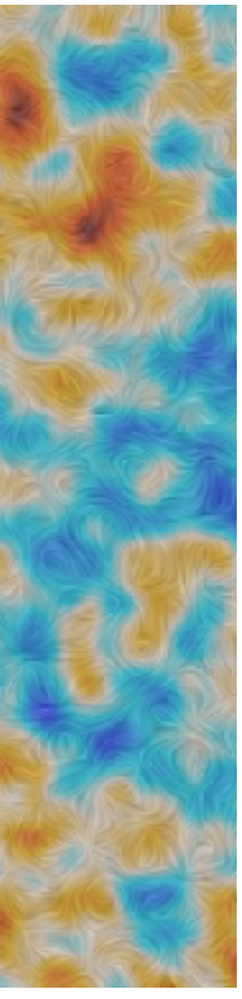
$z \approx 10^3$



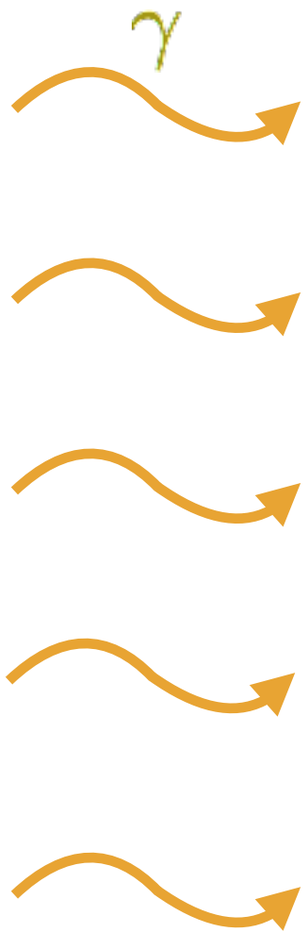


The basics of 21-cm

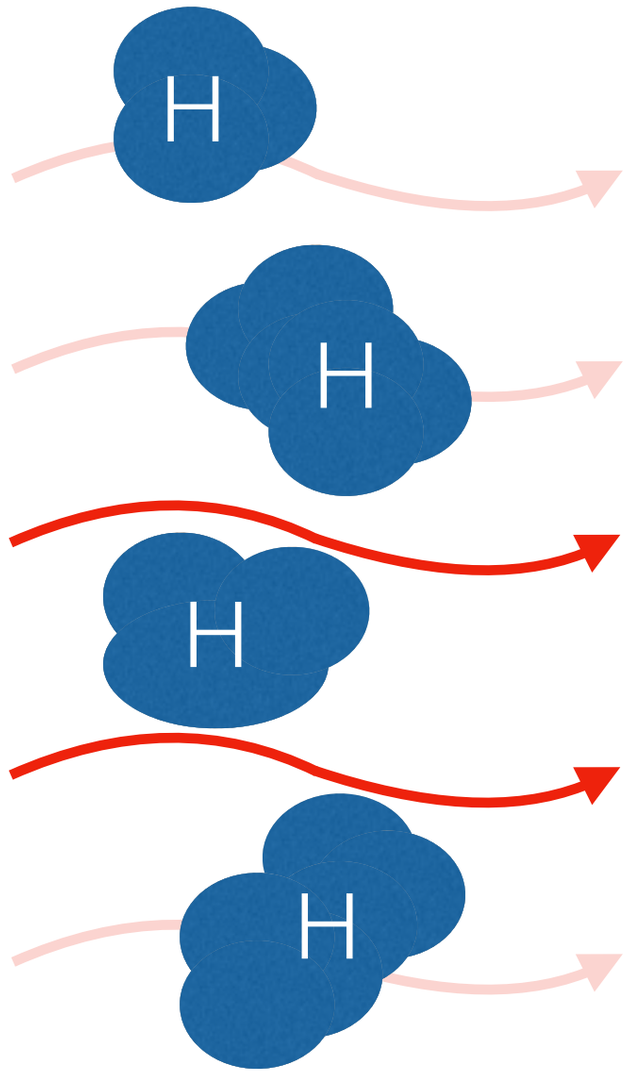
CMB



$z \approx 10^3$



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



$z = 20$

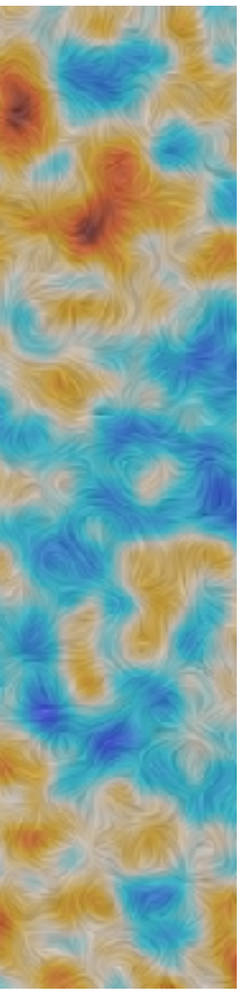
Earth

$z = 0$

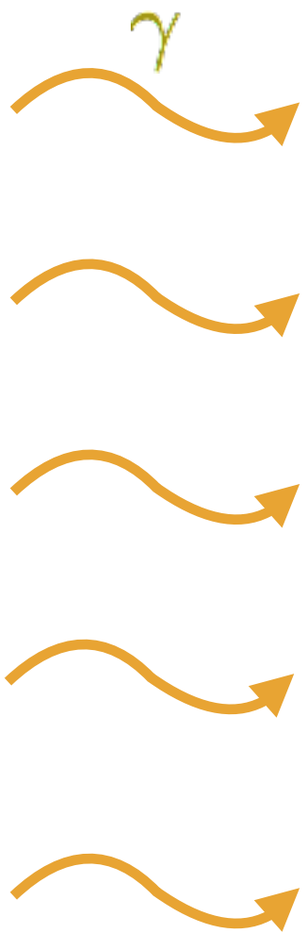
cosmic time

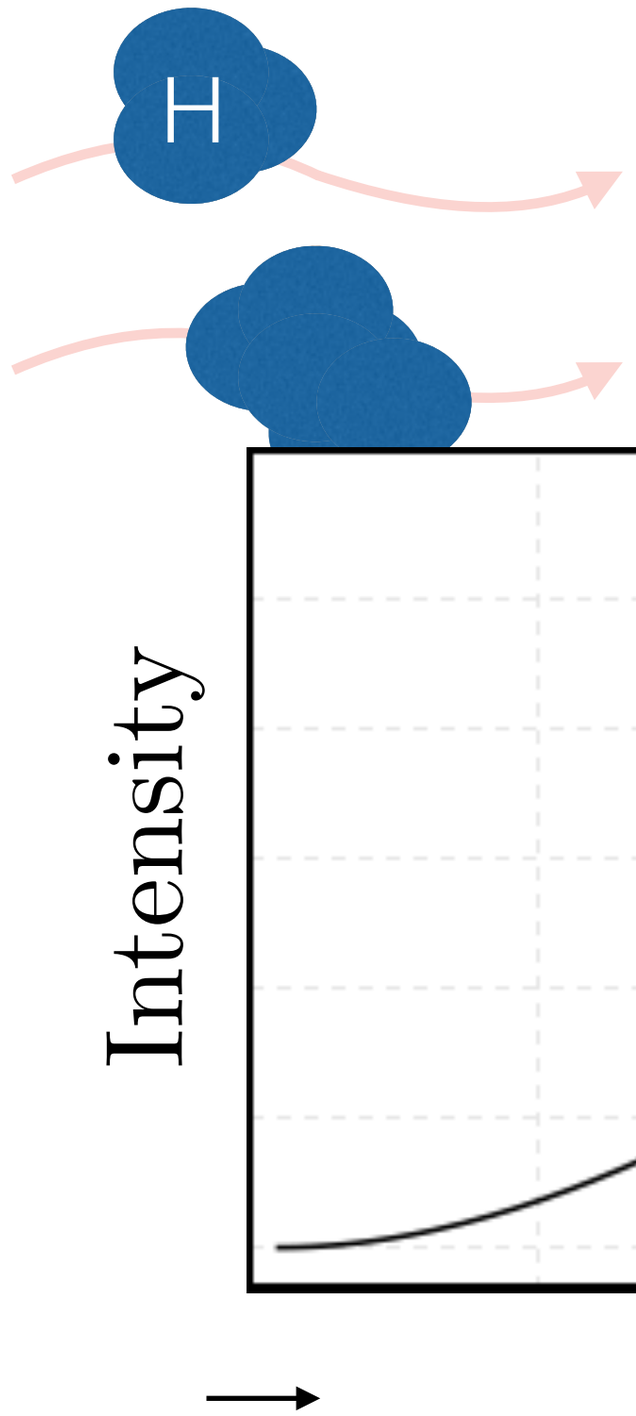
The basics of 21-cm

CMB



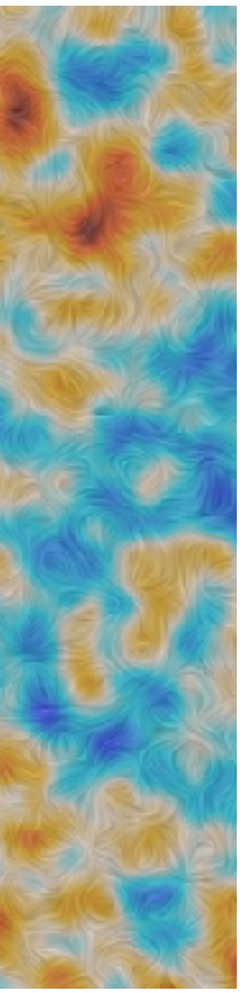
$z \approx 10^3$



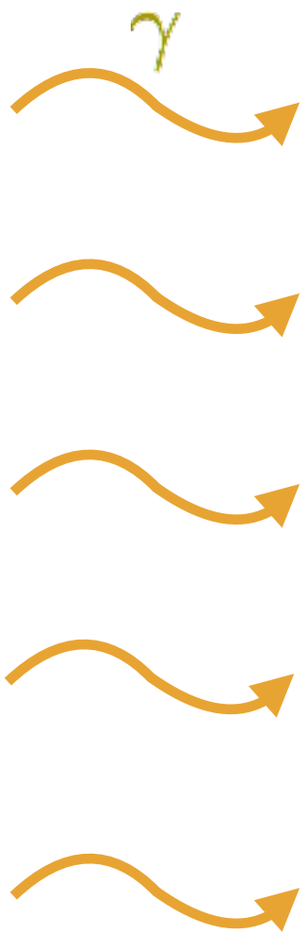


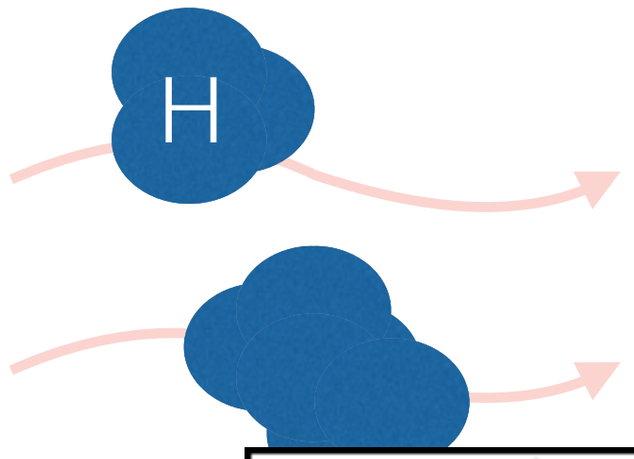
The basics of 21-cm

CMB

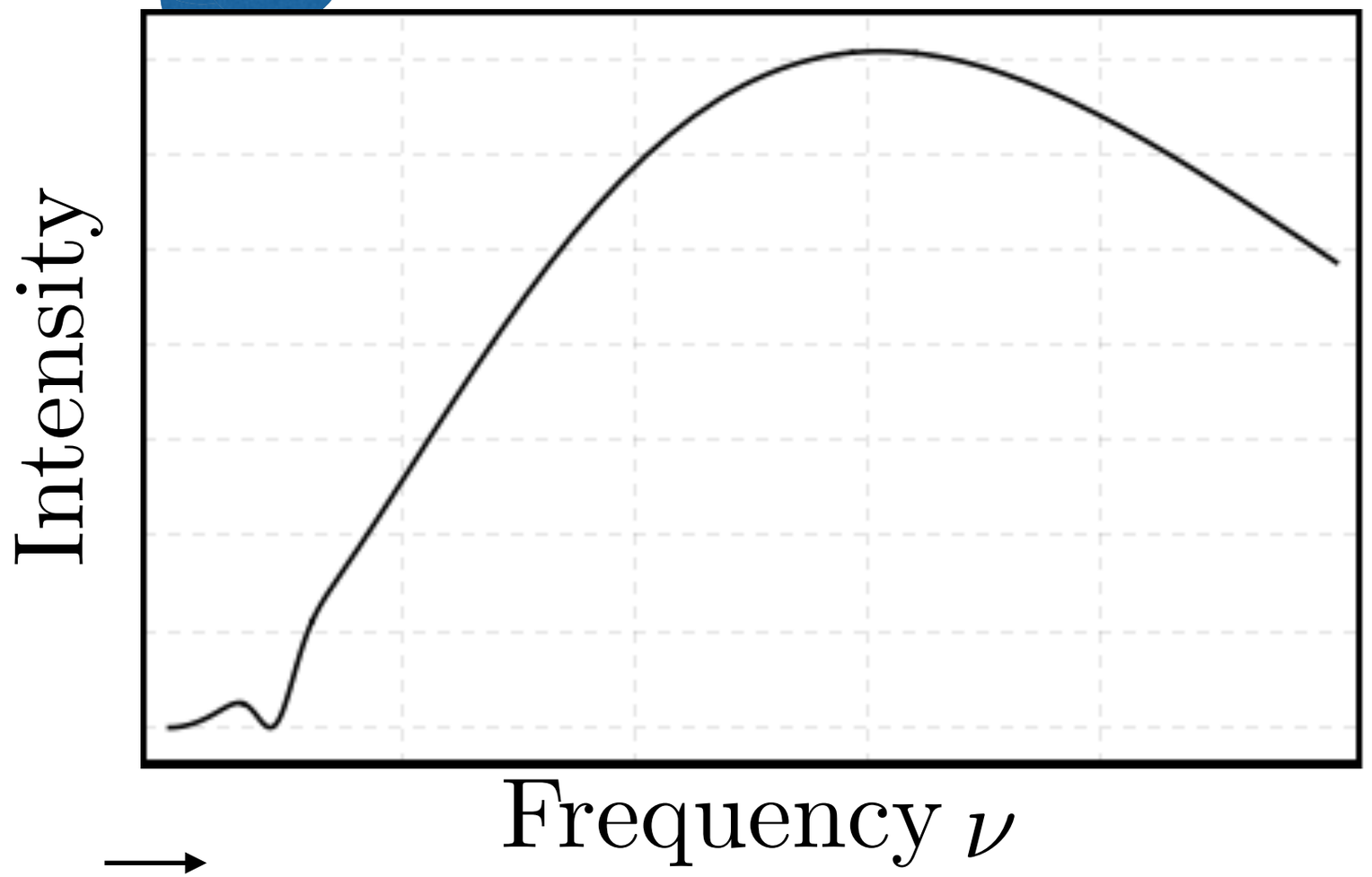


$z \approx 10^3$





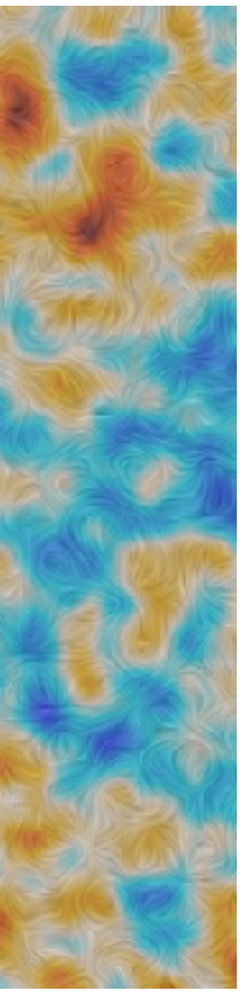
$z \approx 20 \rightarrow 0$



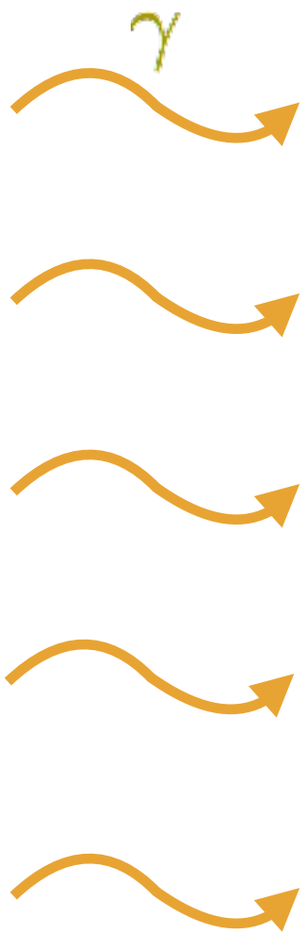
cosmic time

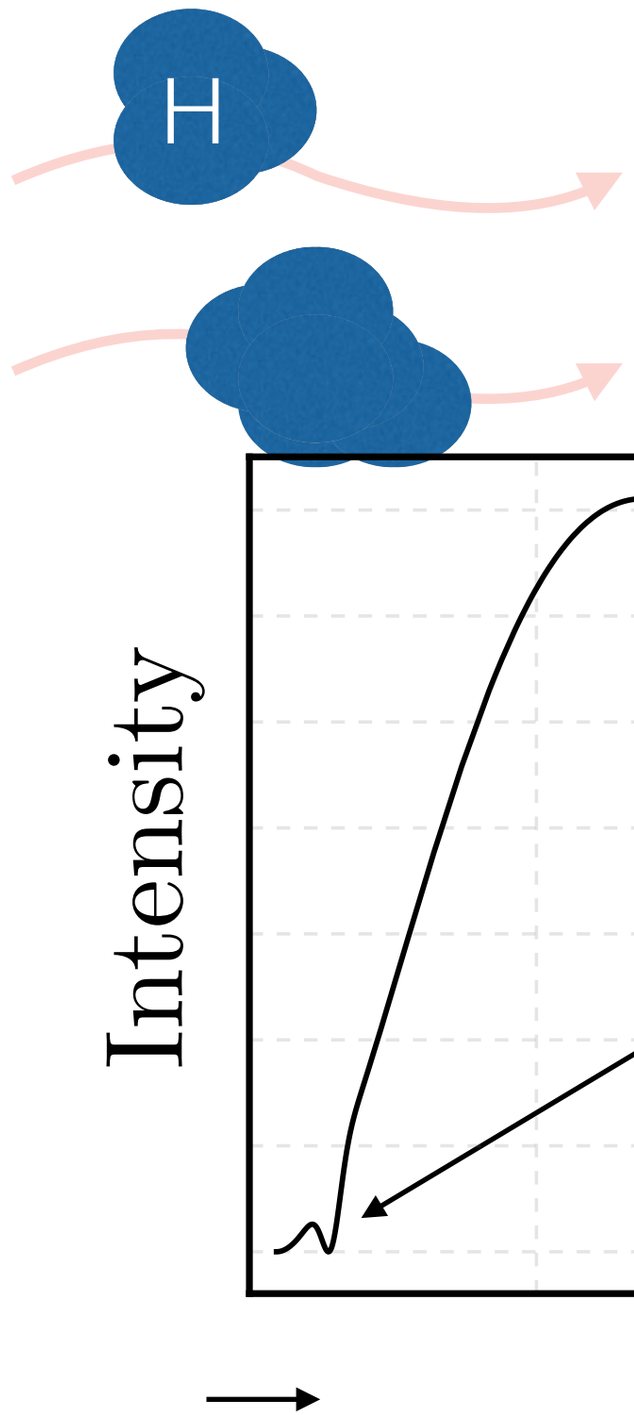
The basics of 21-cm

CMB



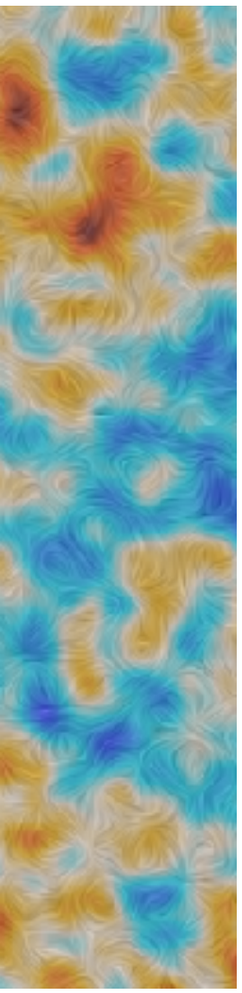
$z \approx 10^3$



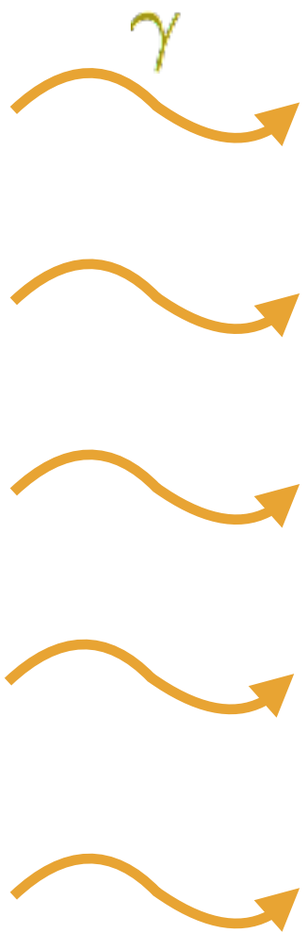


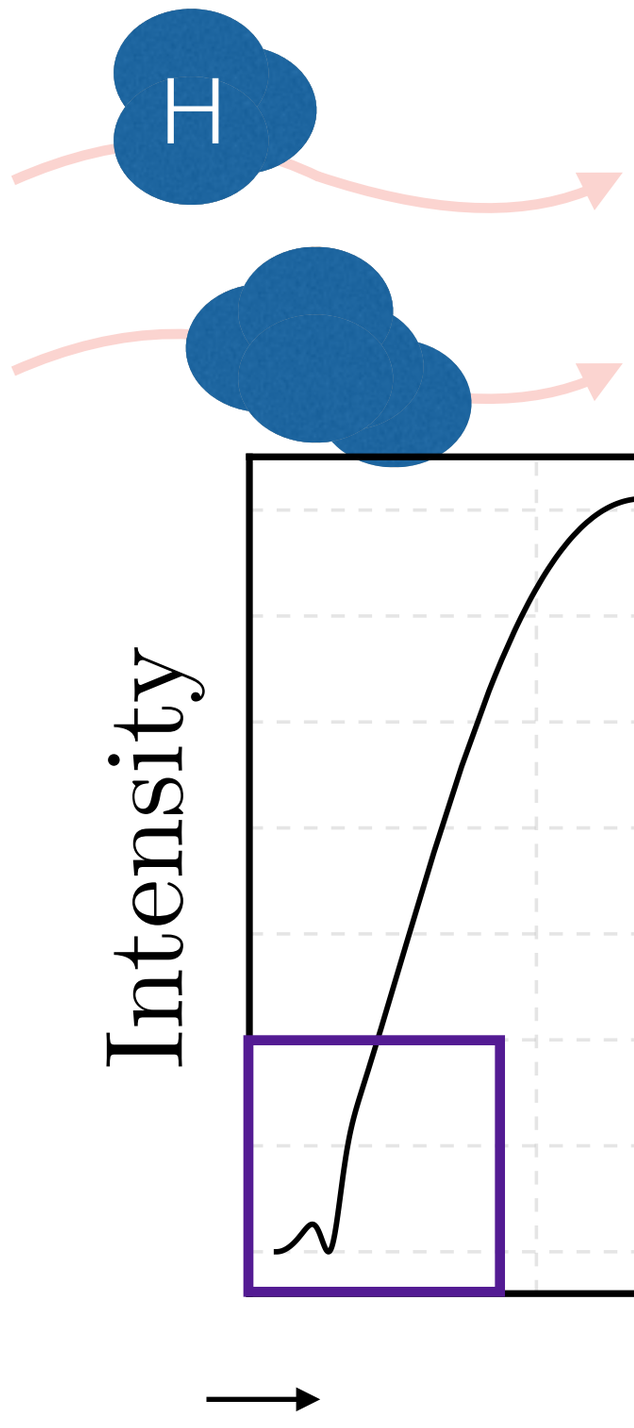
The basics of 21-cm

CMB

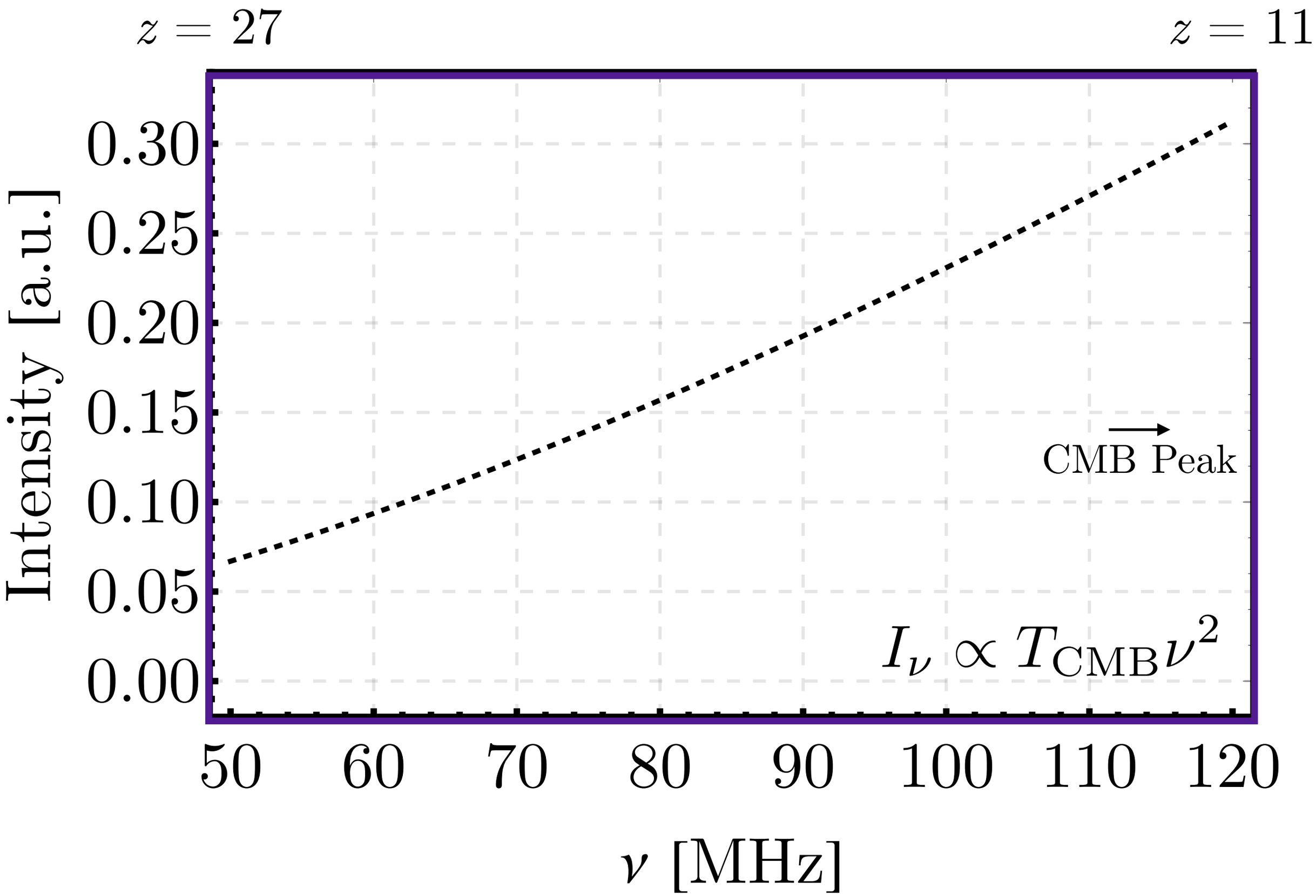


$z \approx 10^3$

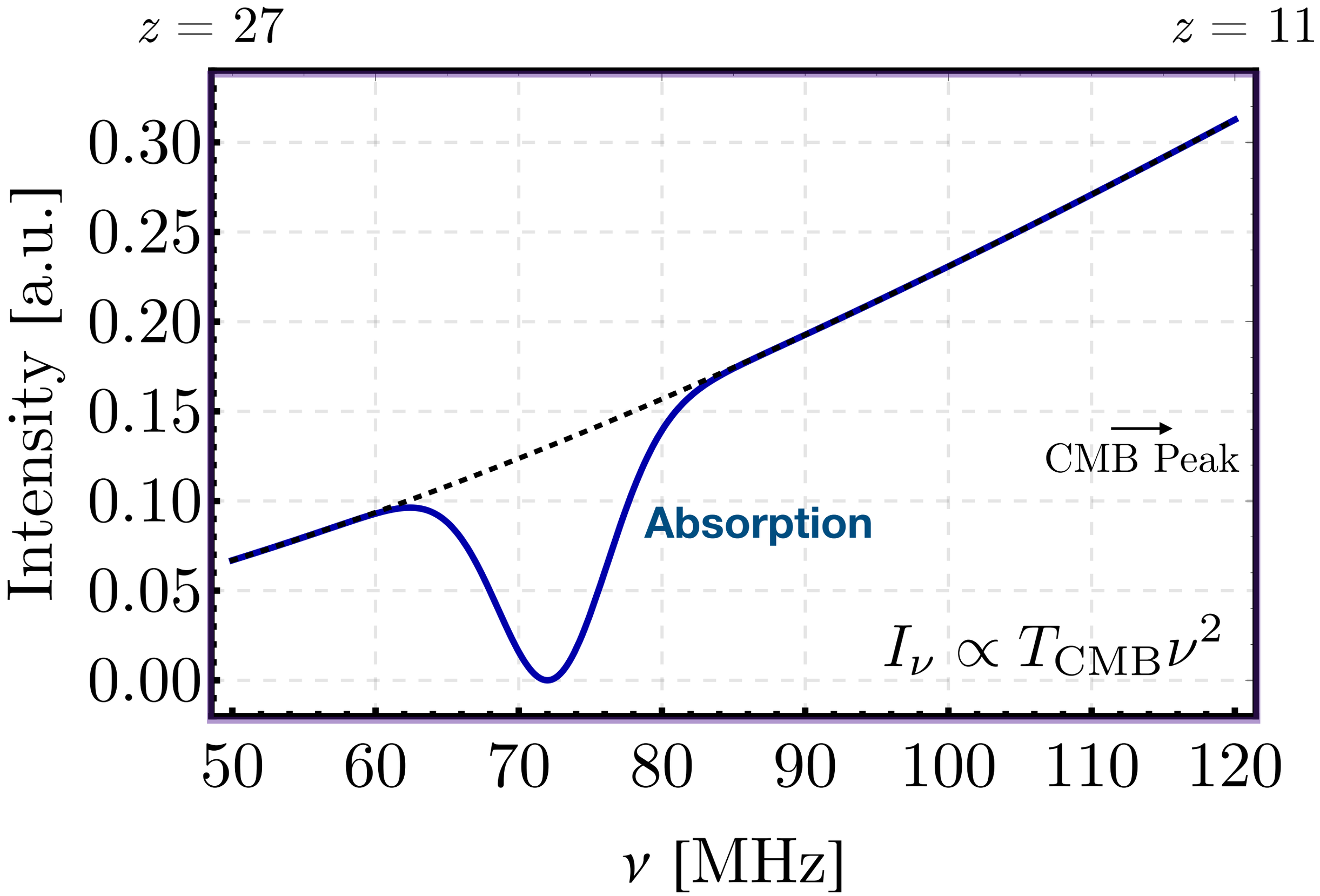




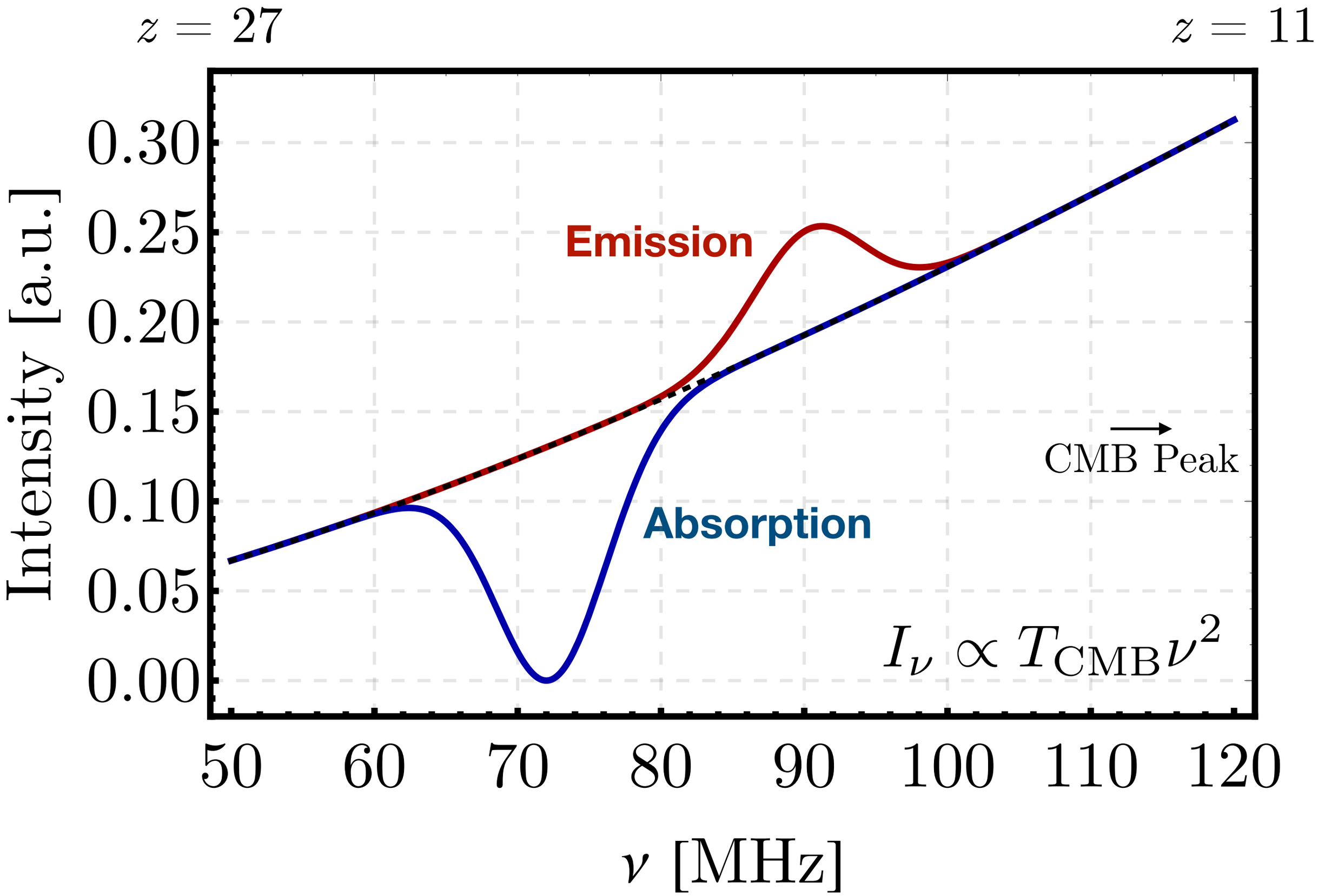
What would we see?



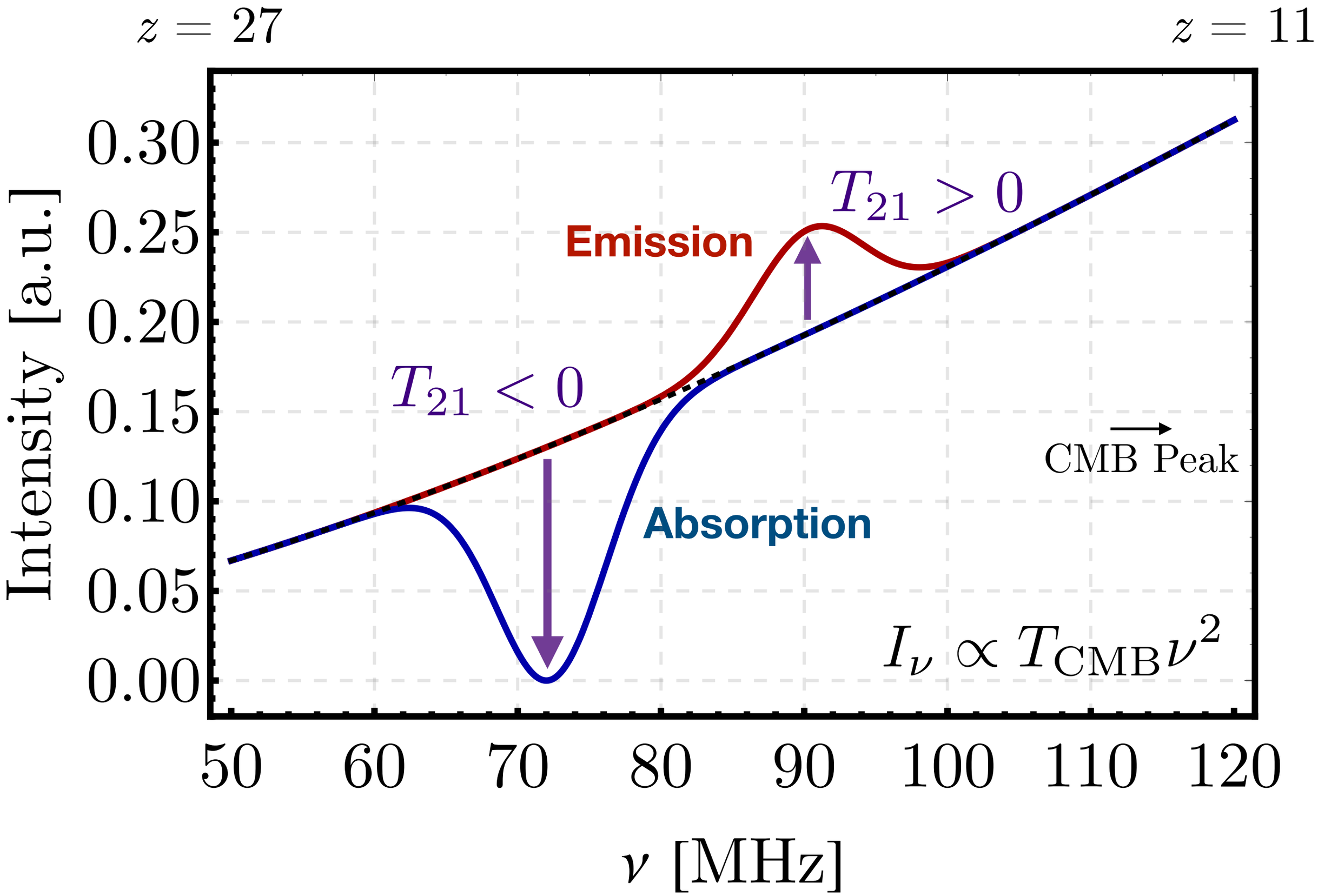
What would we see?



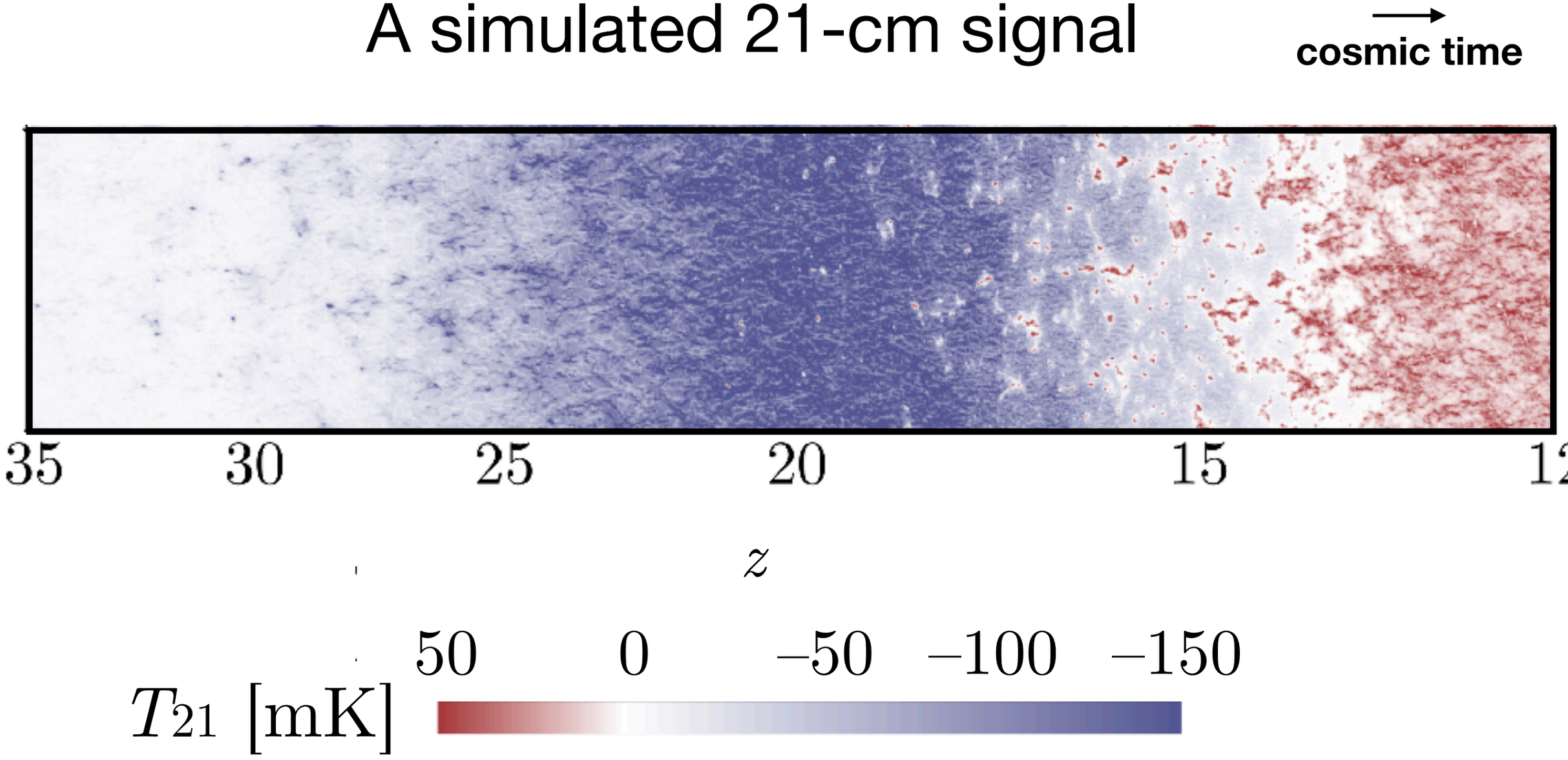
What would we see?



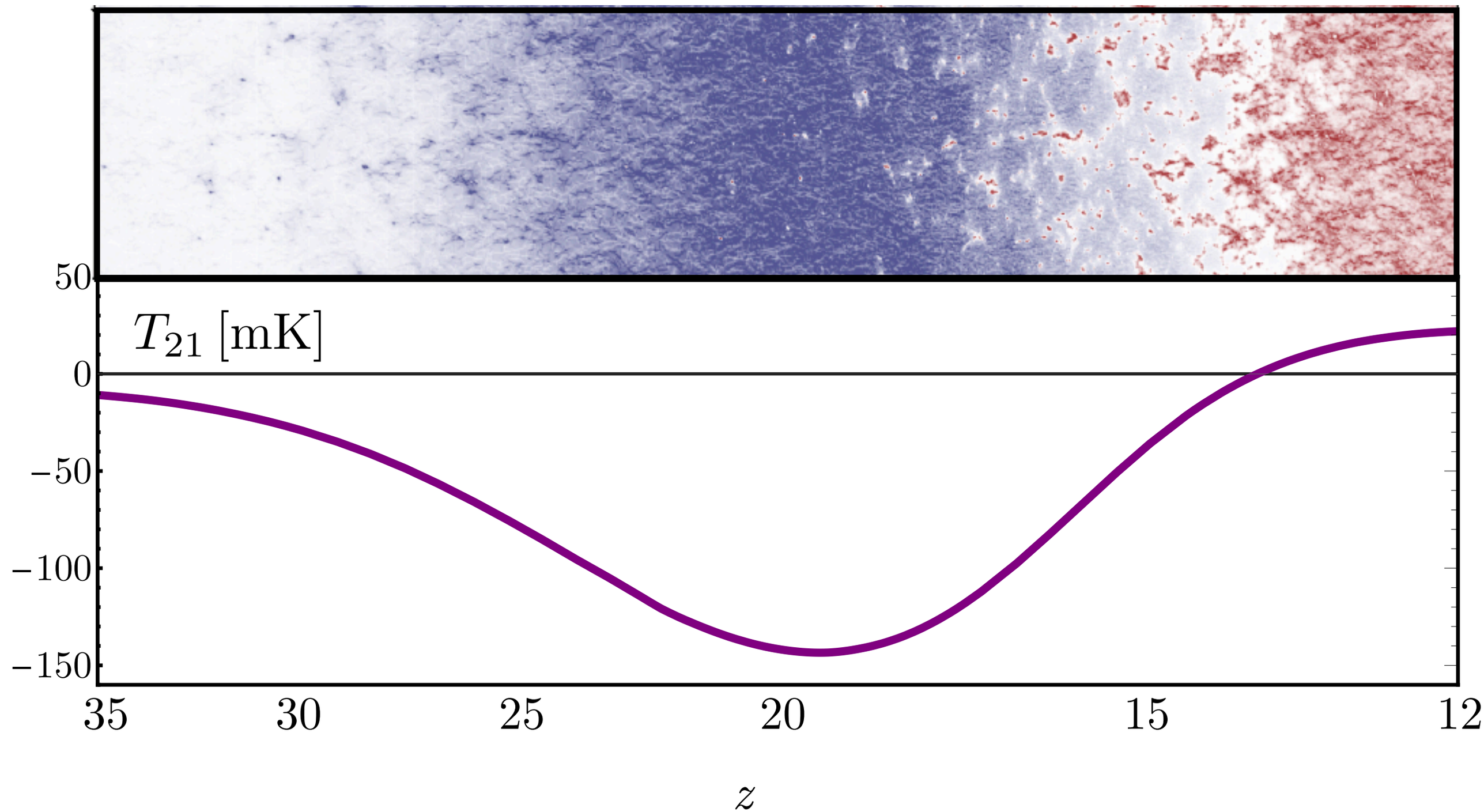
What would we see?



A simulated 21-cm signal

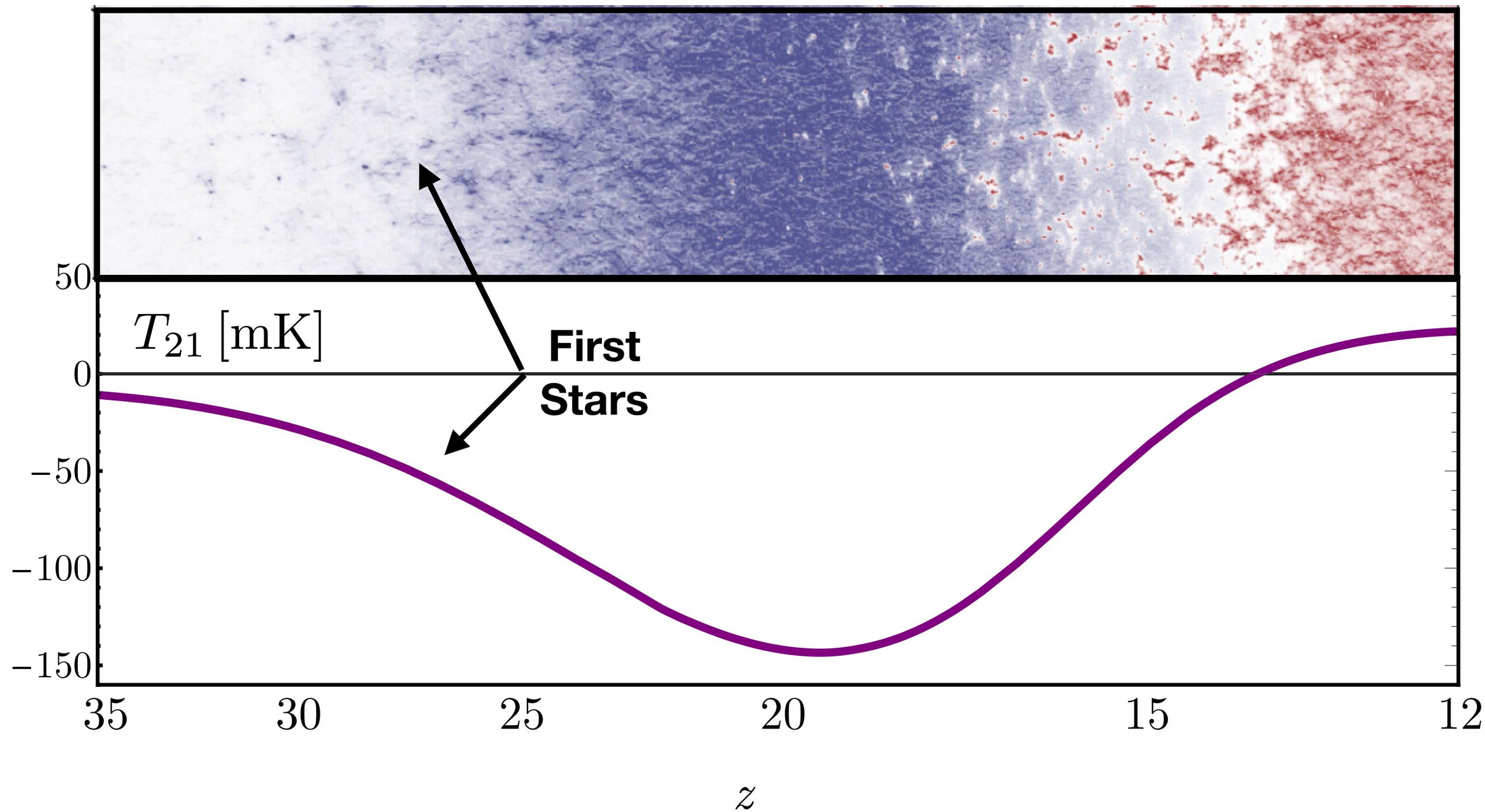


A simulated 21-cm global signal

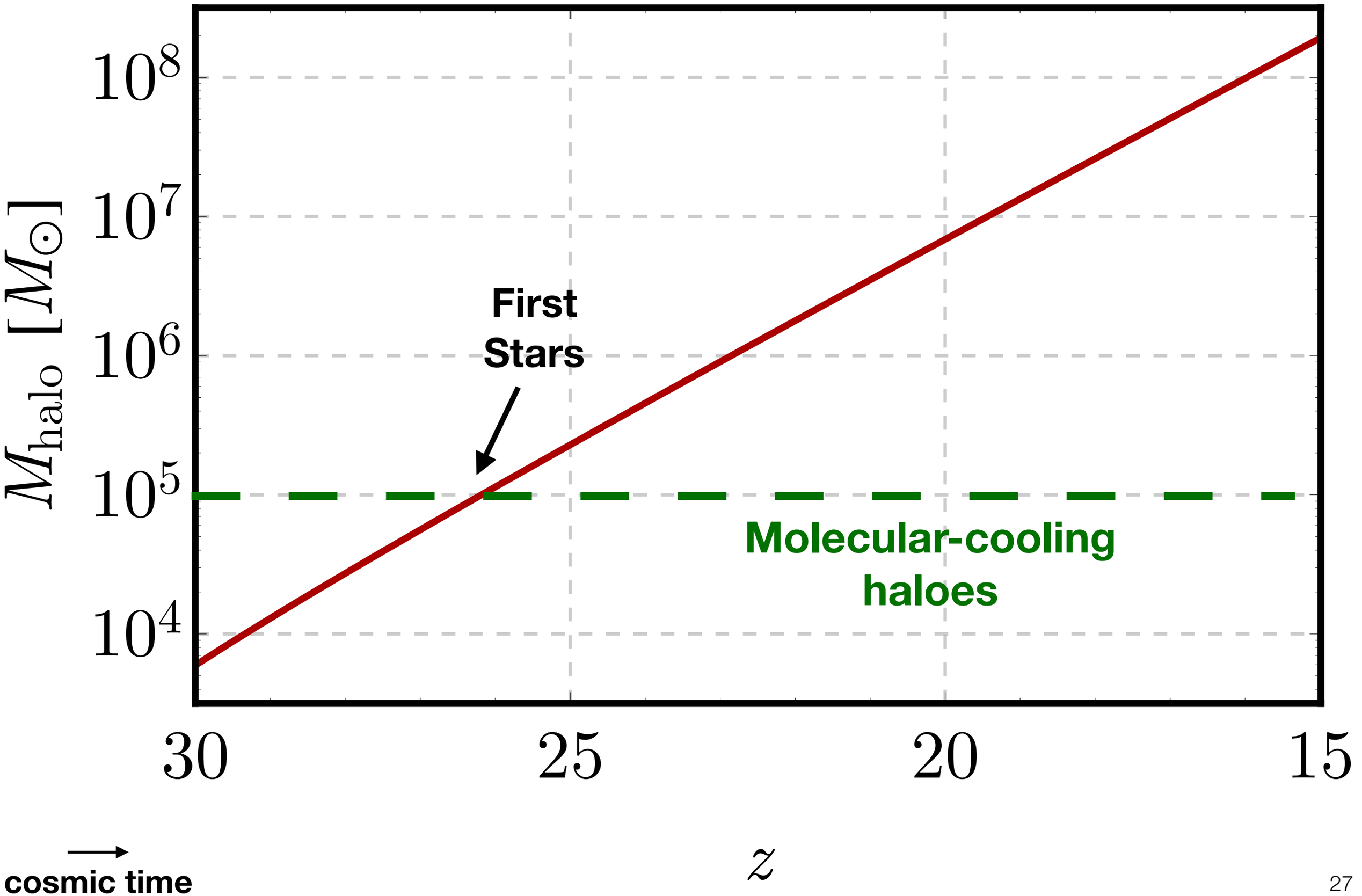


Reionization

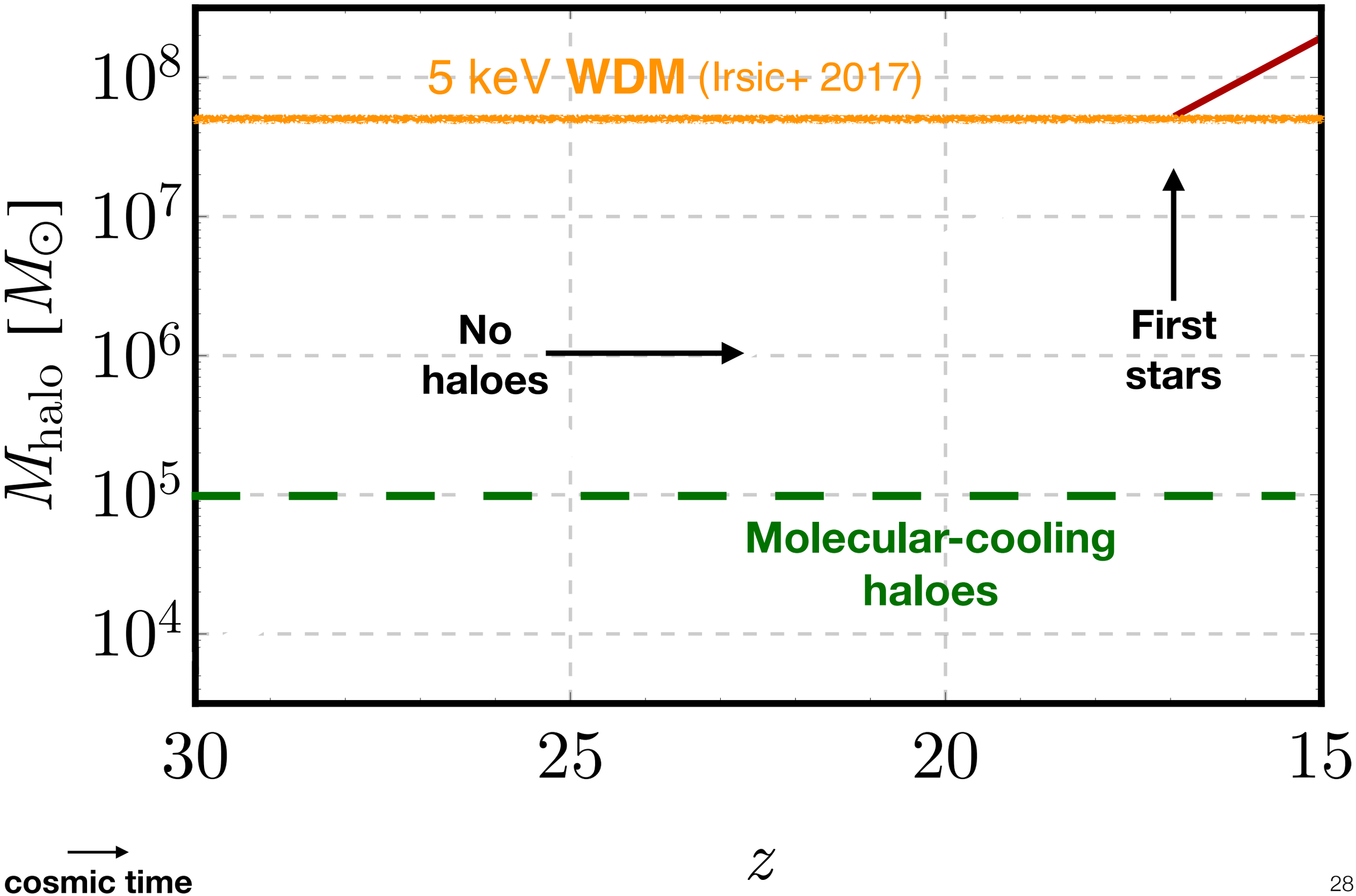
Is DM cold?



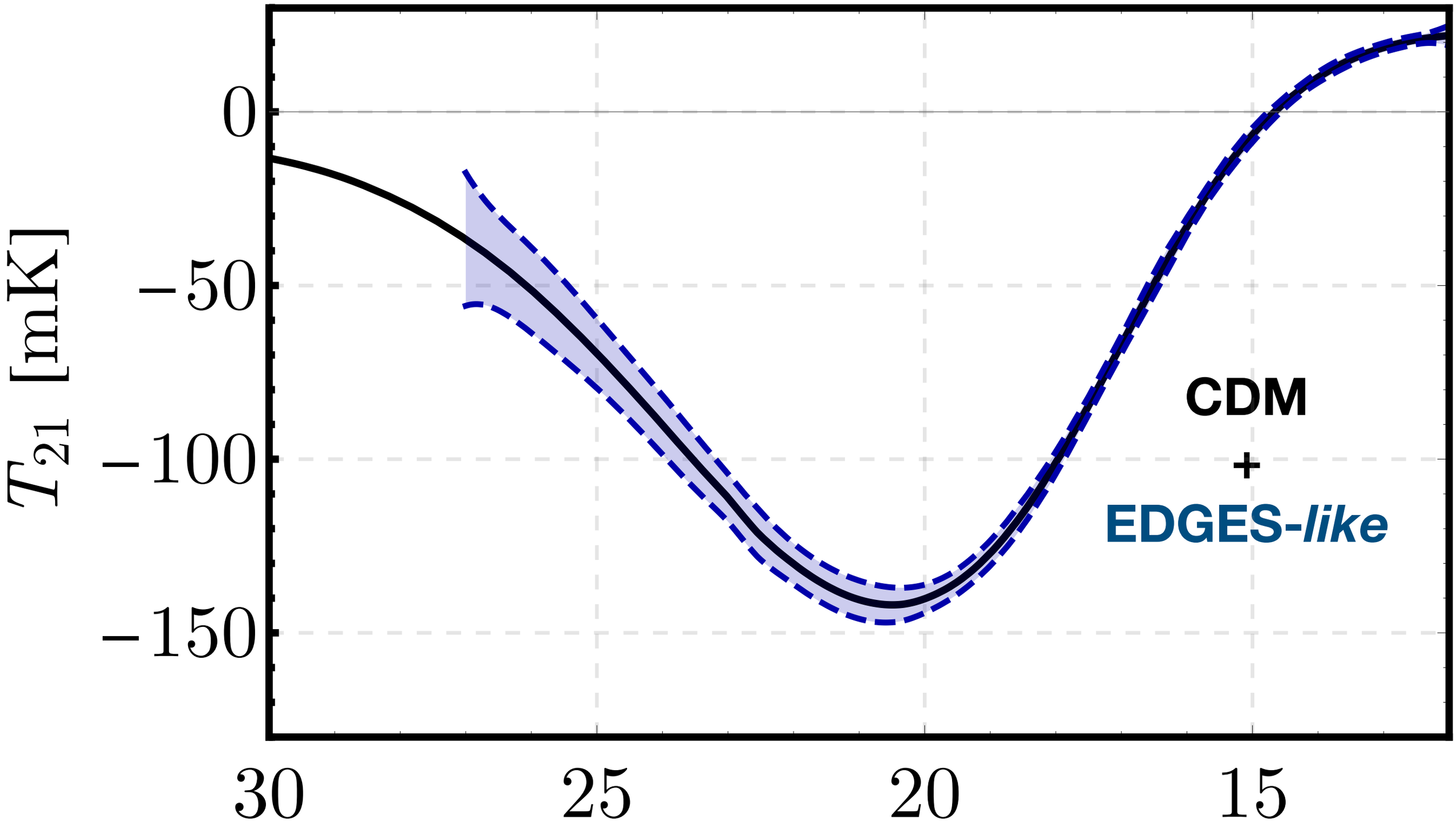
Is DM cold?


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?

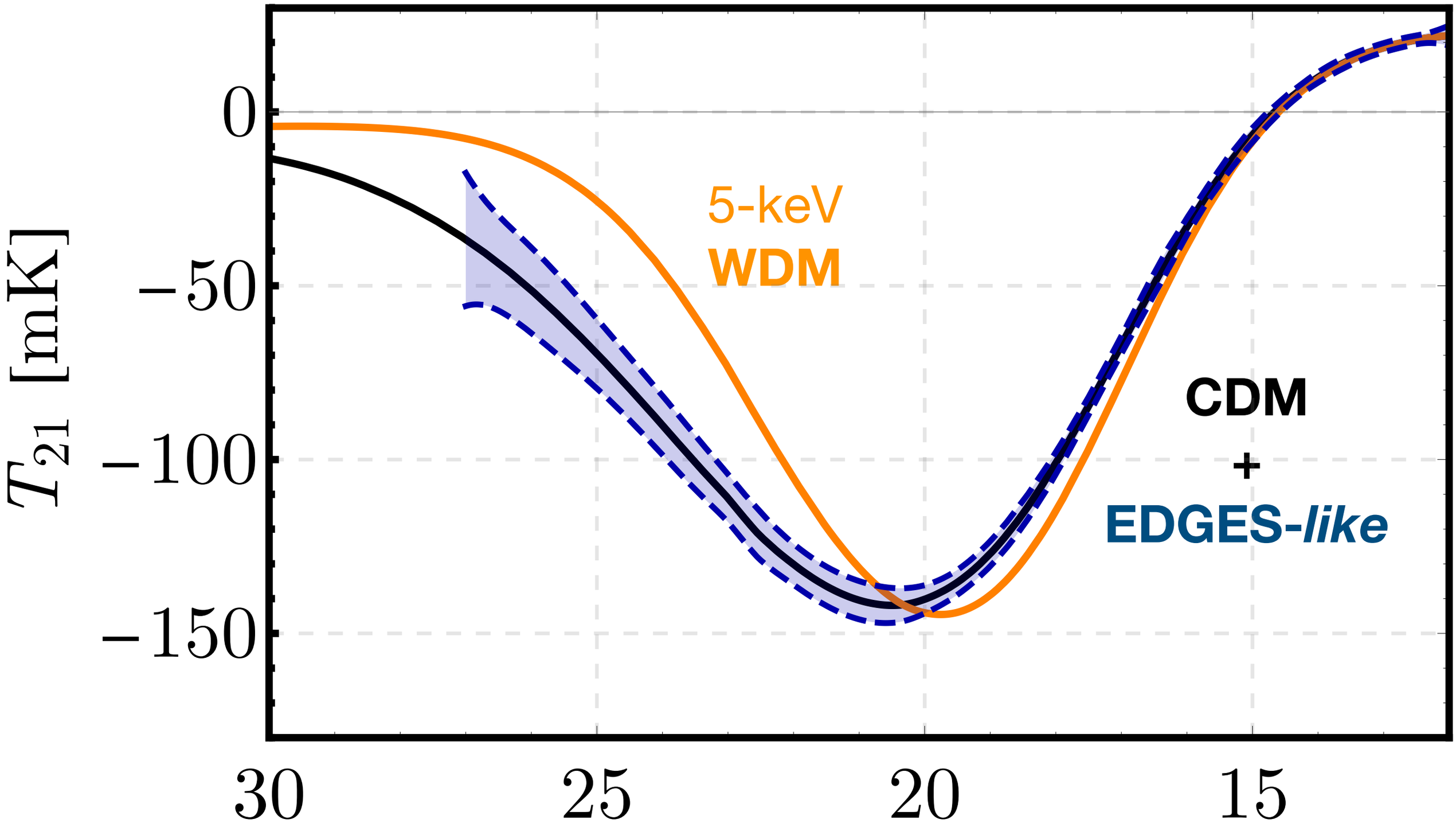

5 keV WDM (Irsic+ 2017)
No haloes
First stars
Molecular-cooling haloes
$M_{\rm halo}$ $[M_\odot]$
10^8
10^7
10^6
10^5
10^4
30
25
20
15
z
cosmic time

Is DM cold?



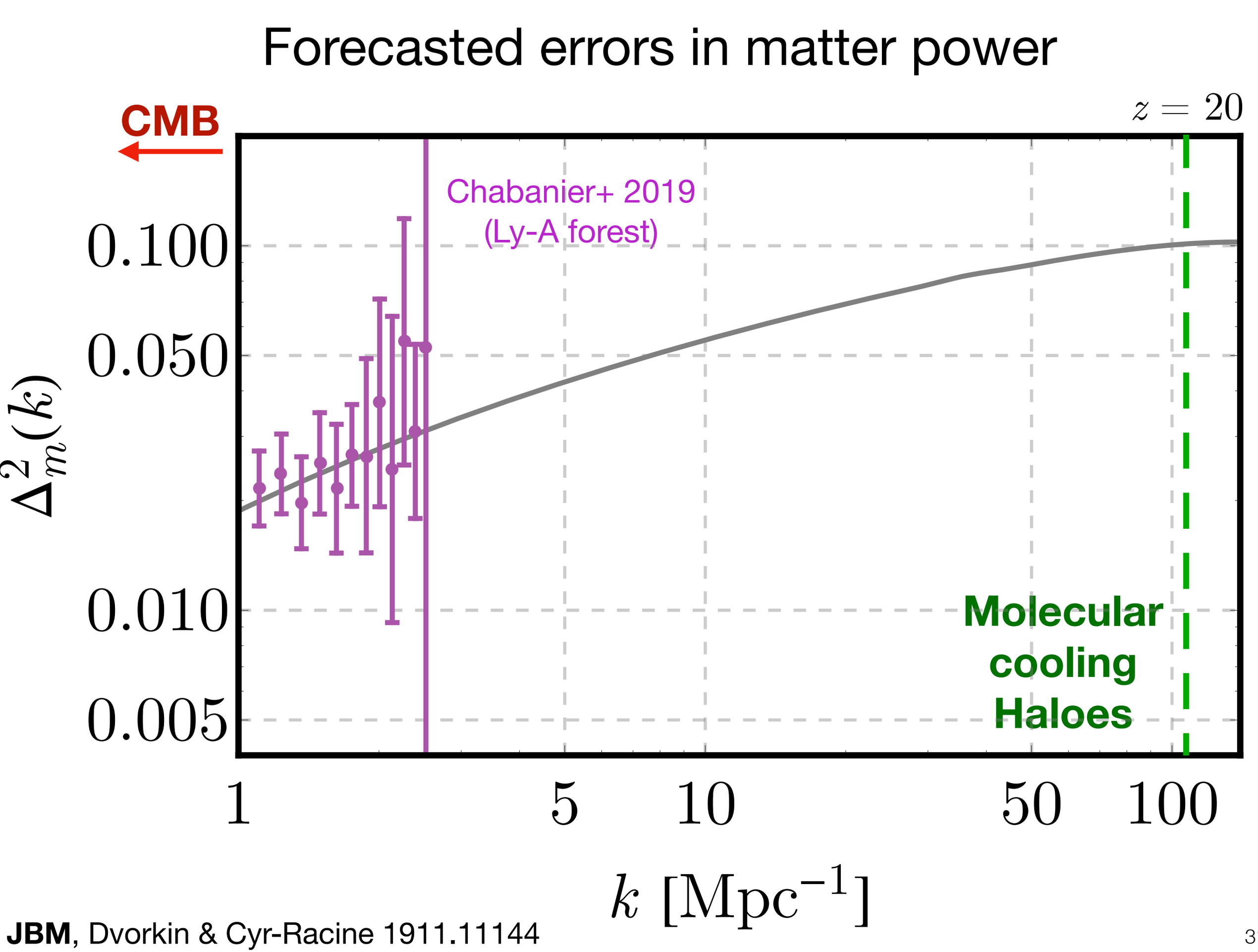
JBM, Dvorkin & Cyr-Racine (1911.11144)

Is DM cold?



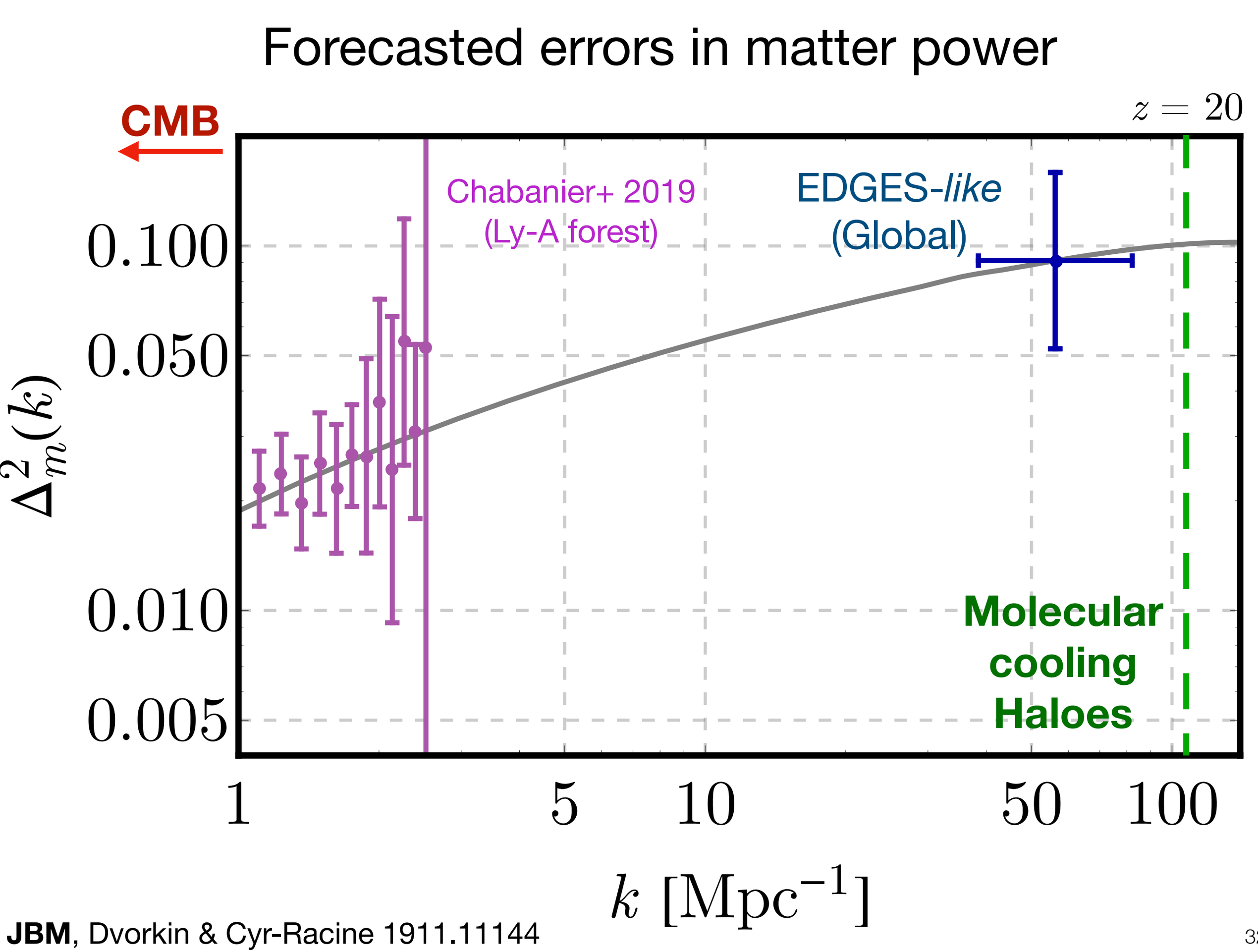
JBM, Dvorkin & Cyr-Racine (1911.11144)

Forecasted errors in matter power



JBM, Dvorkin & Cyr-Racine 1911.11144

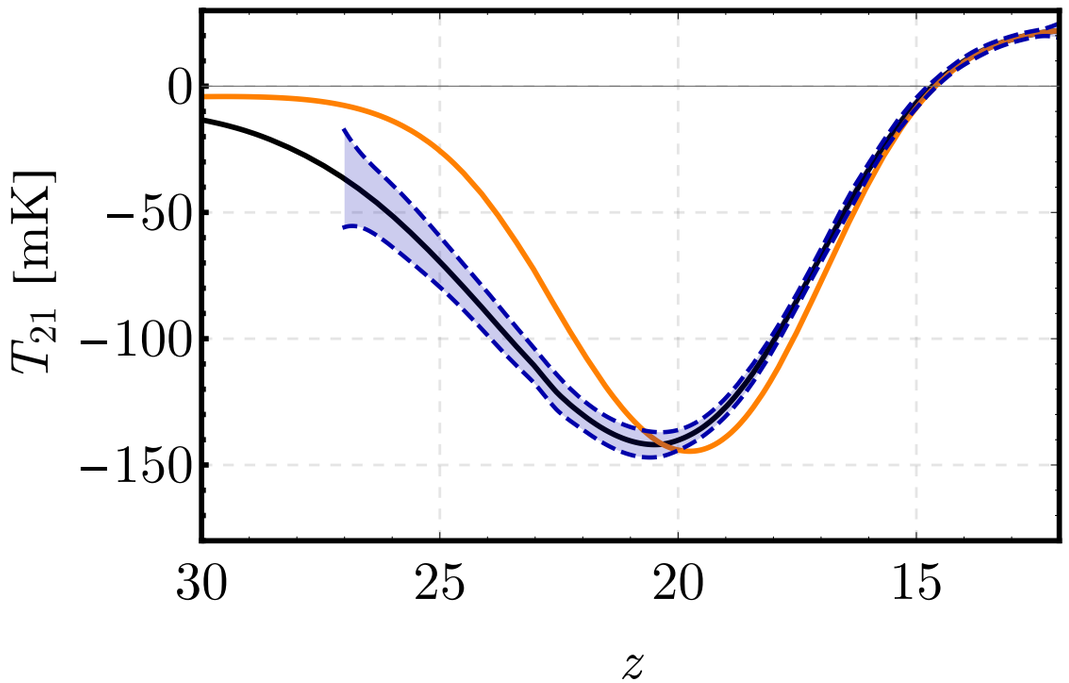
Forecasted errors in matter power

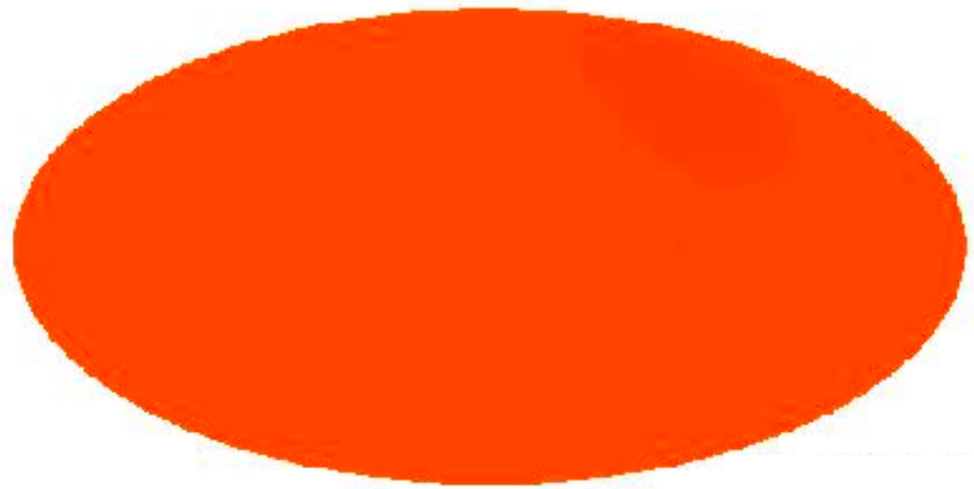


JBM, Dvorkin & Cyr-Racine 1911.11144

21-cm Global Signal = CMB Monopole

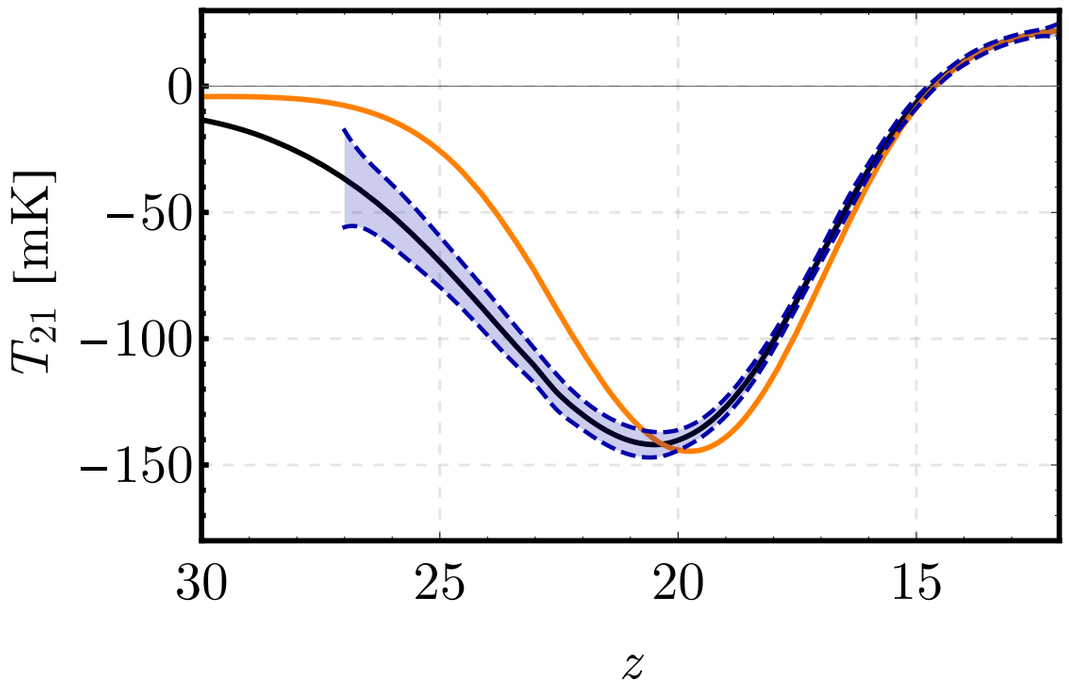
(**EDGES**, LEDA, SARAS, Sci-HI,…)

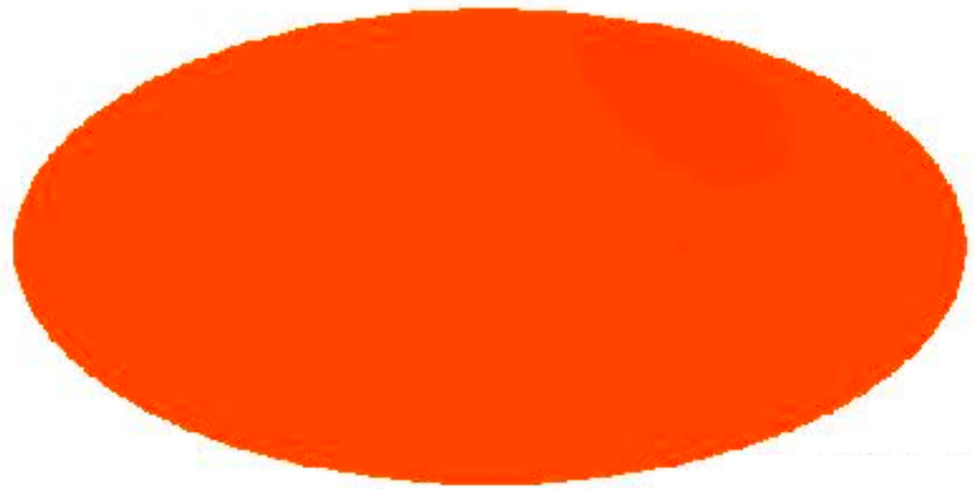




21-cm Global Signal = CMB Monopole

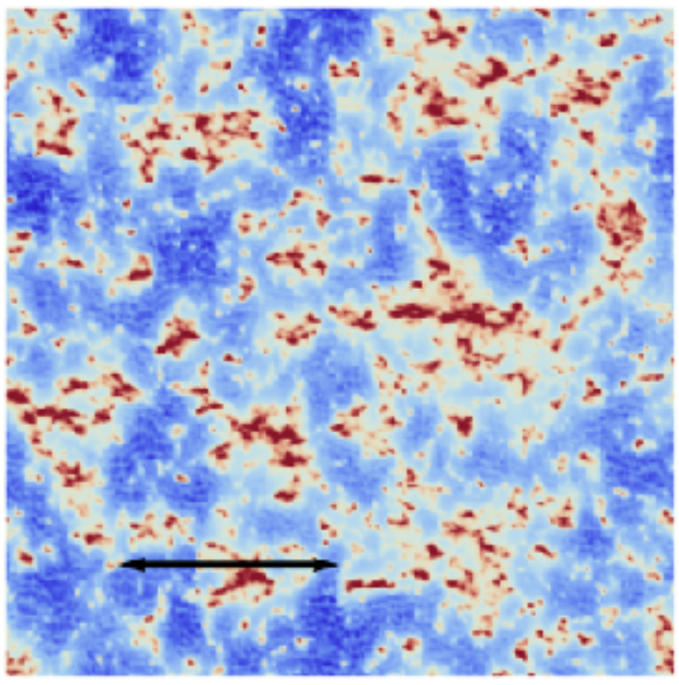
(**EDGES**, LEDA, SARAS, Sci-HI,…)

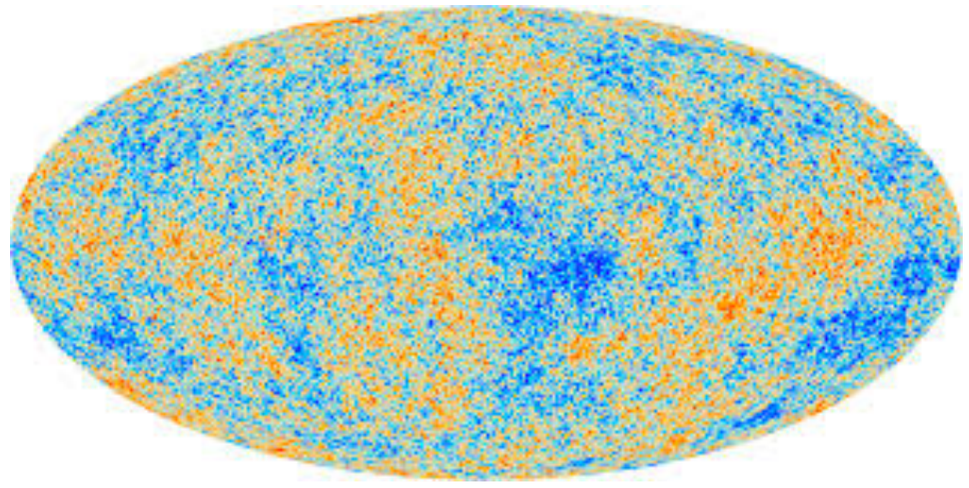




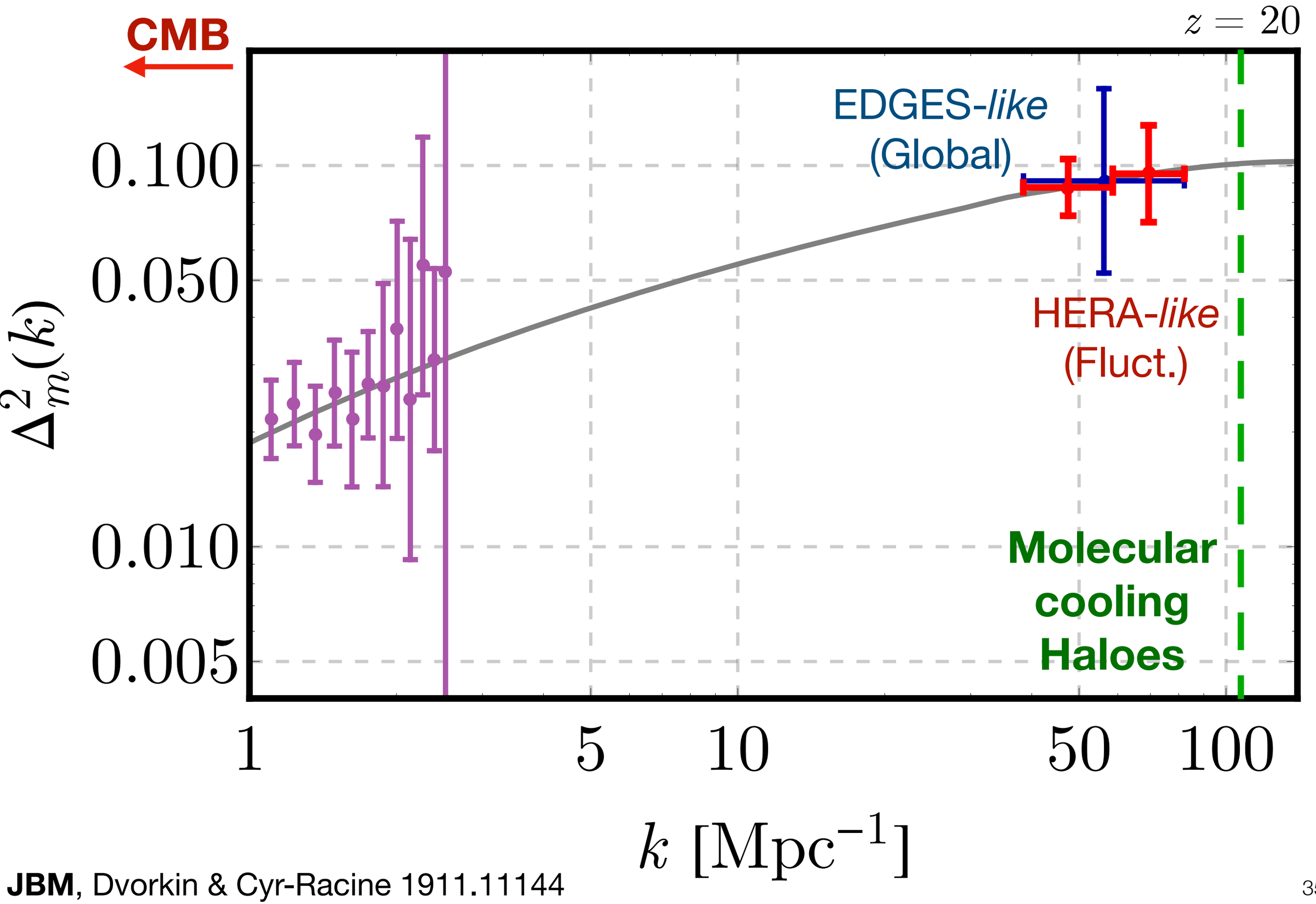
21-cm Fluctuations = CMB Anisotropies

(**HERA**, MWA, LWA, PAPER, SKA,…)



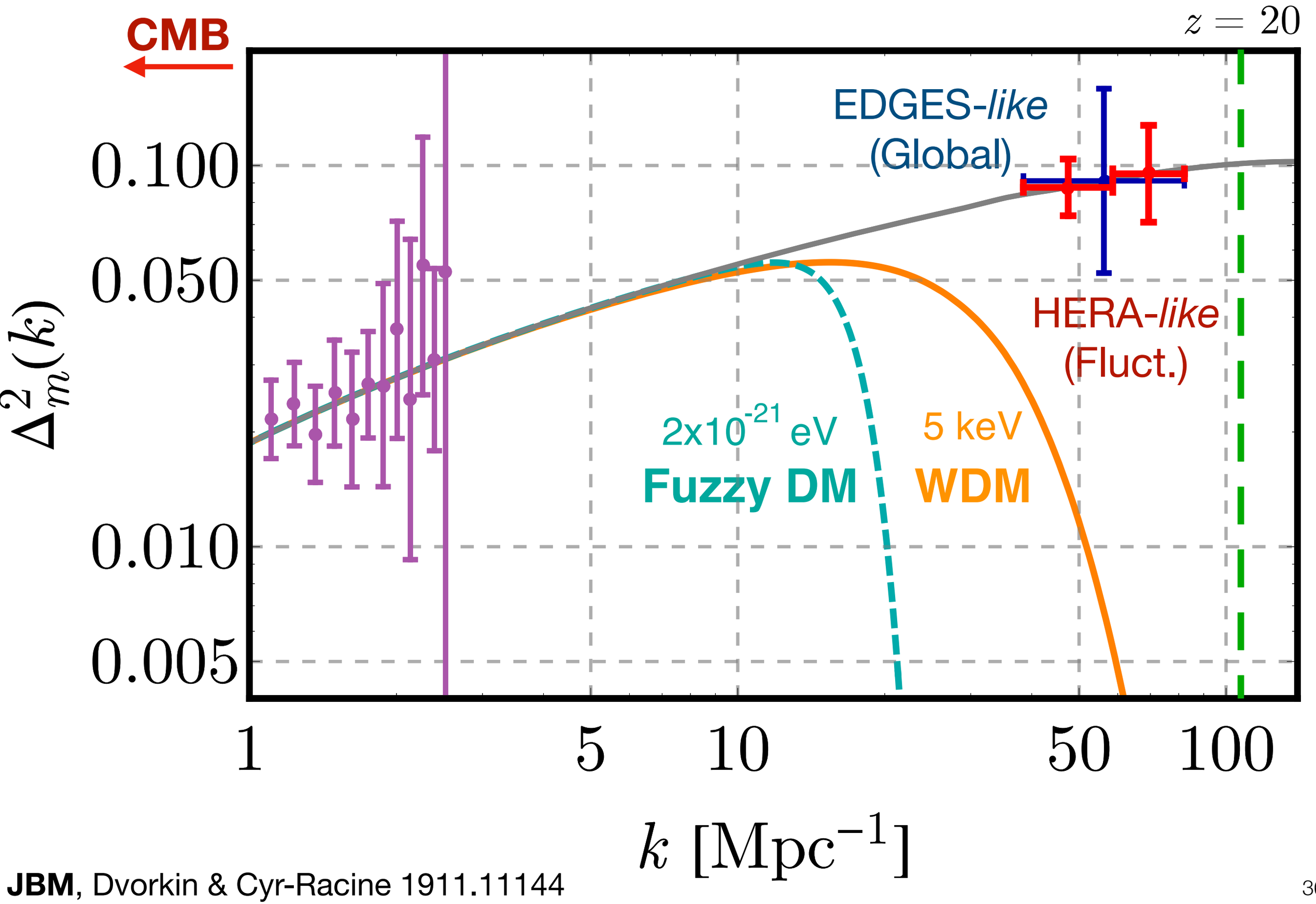


Forecasted errors in matter power



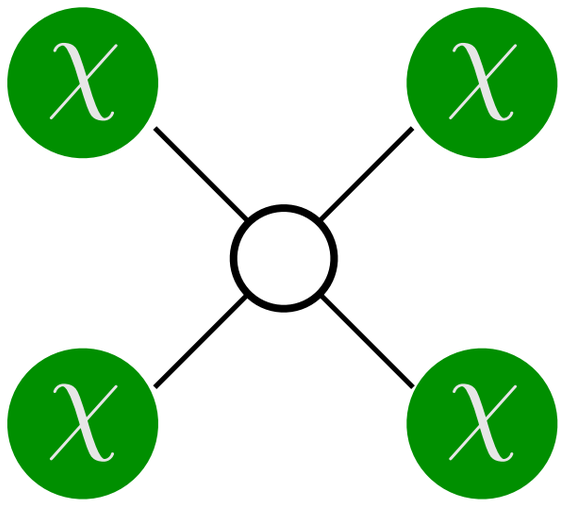
JBM, Dvorkin & Cyr-Racine 1911.11144

An example of non-CDM constraint

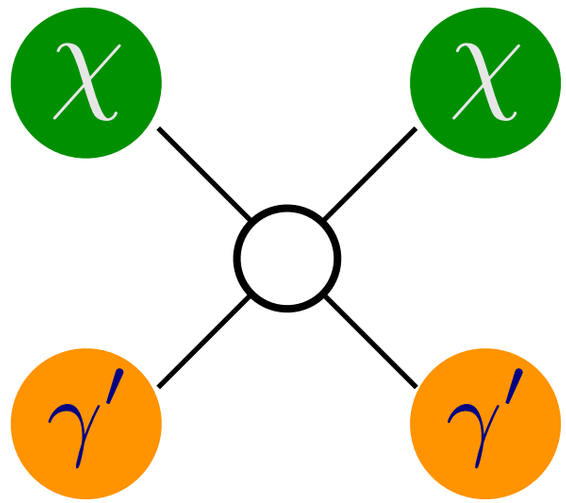


JBM, Dvorkin & Cyr-Racine 1911.11144

Beyond a cutoff: Self Interactions

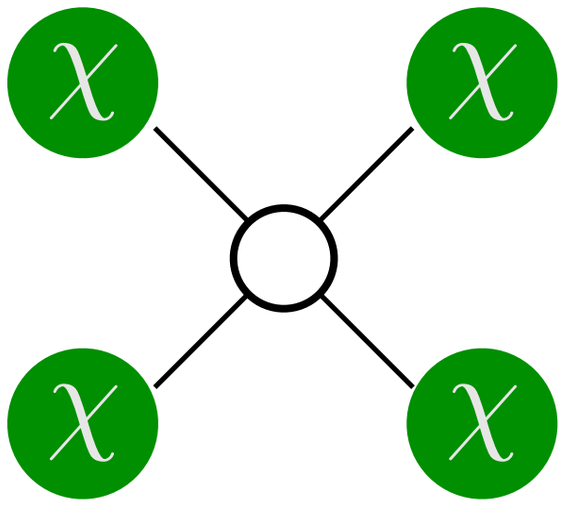


DM-DM:
Halo profiles, etc.

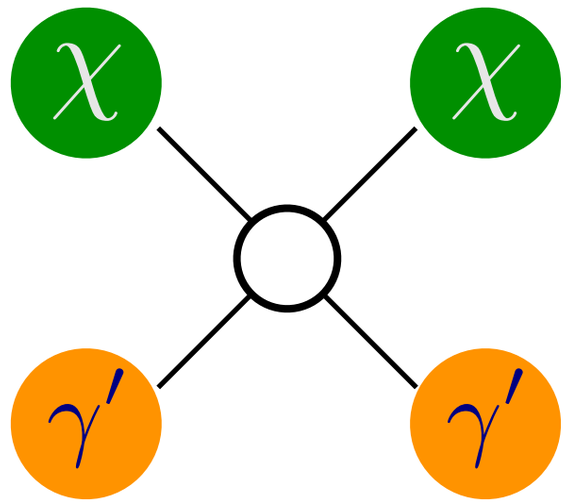


DM-DR:
Power Spectrum

Beyond a cutoff: Self Interactions



DM-DM:
Halo profiles, etc.



DM-DR:
Power Spectrum

Effective Theory of Structure Formation: **ETHOS**

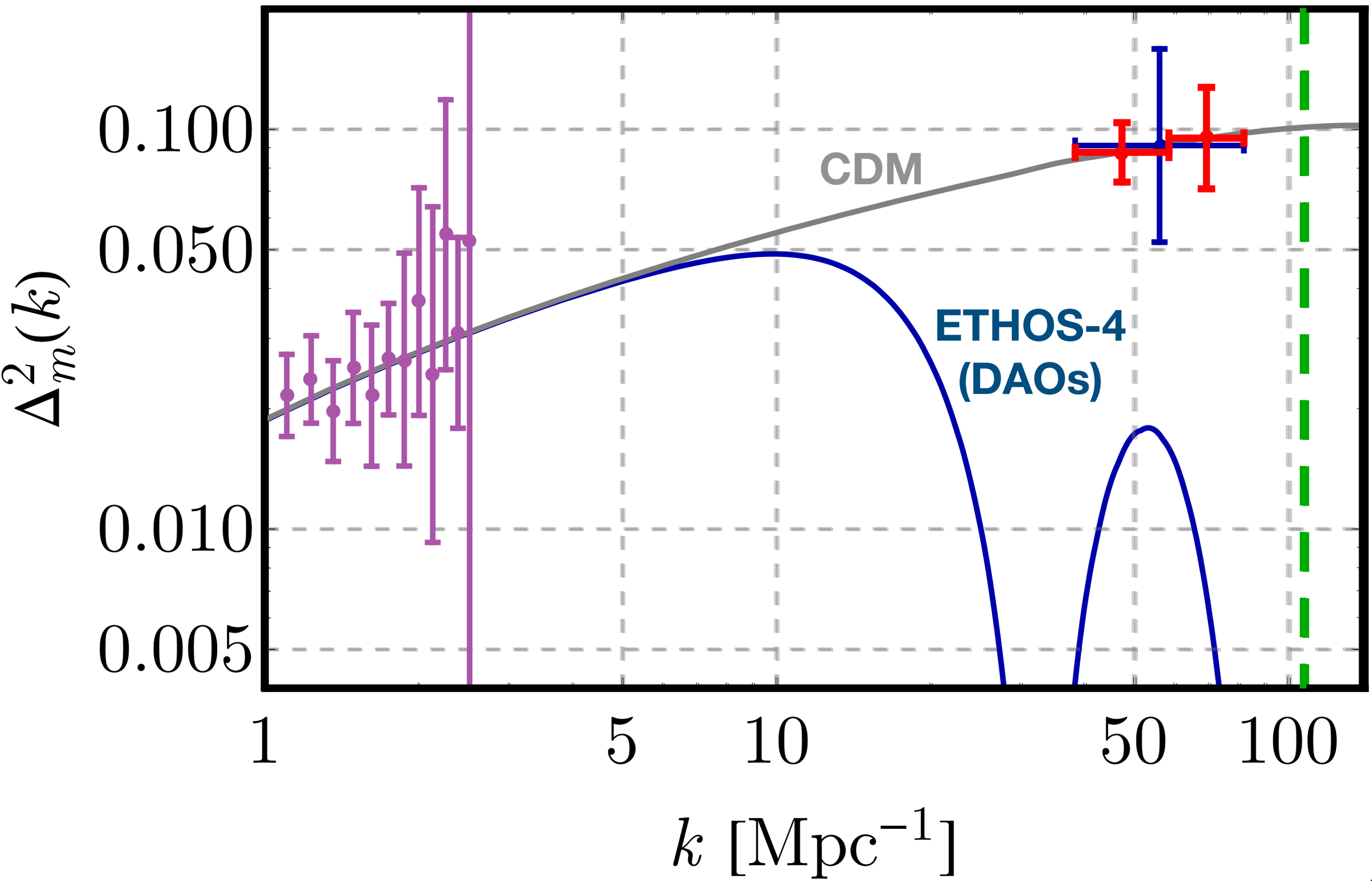
Vogelsberger+ 2016
Cyr-Racine+2016

Beyond a cutoff: ETHOS

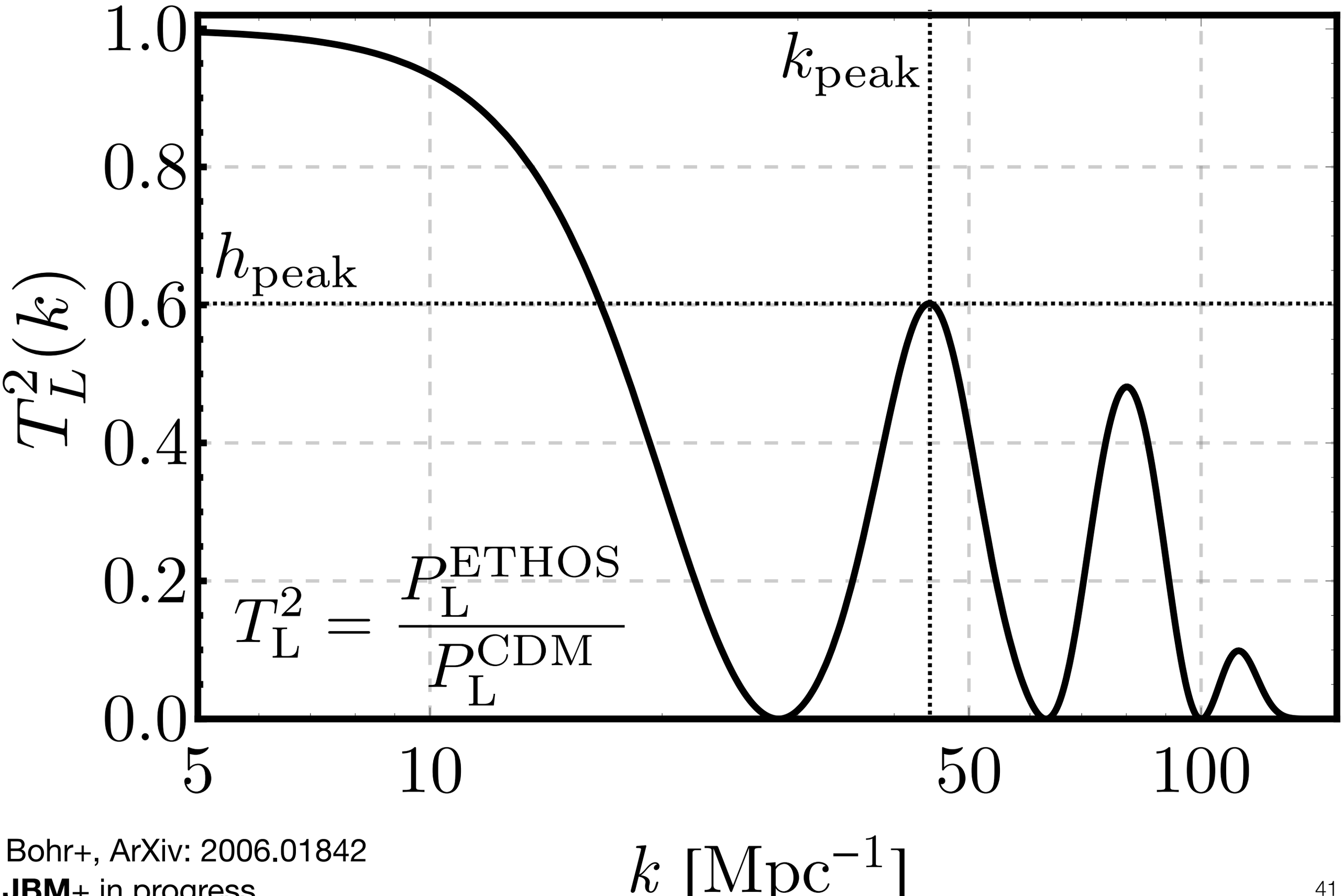
Vogelsberger+ 2016
Cyr-Racine+2016

Credit: Volgesberger/MIT

Beyond a cutoff: ETHOS



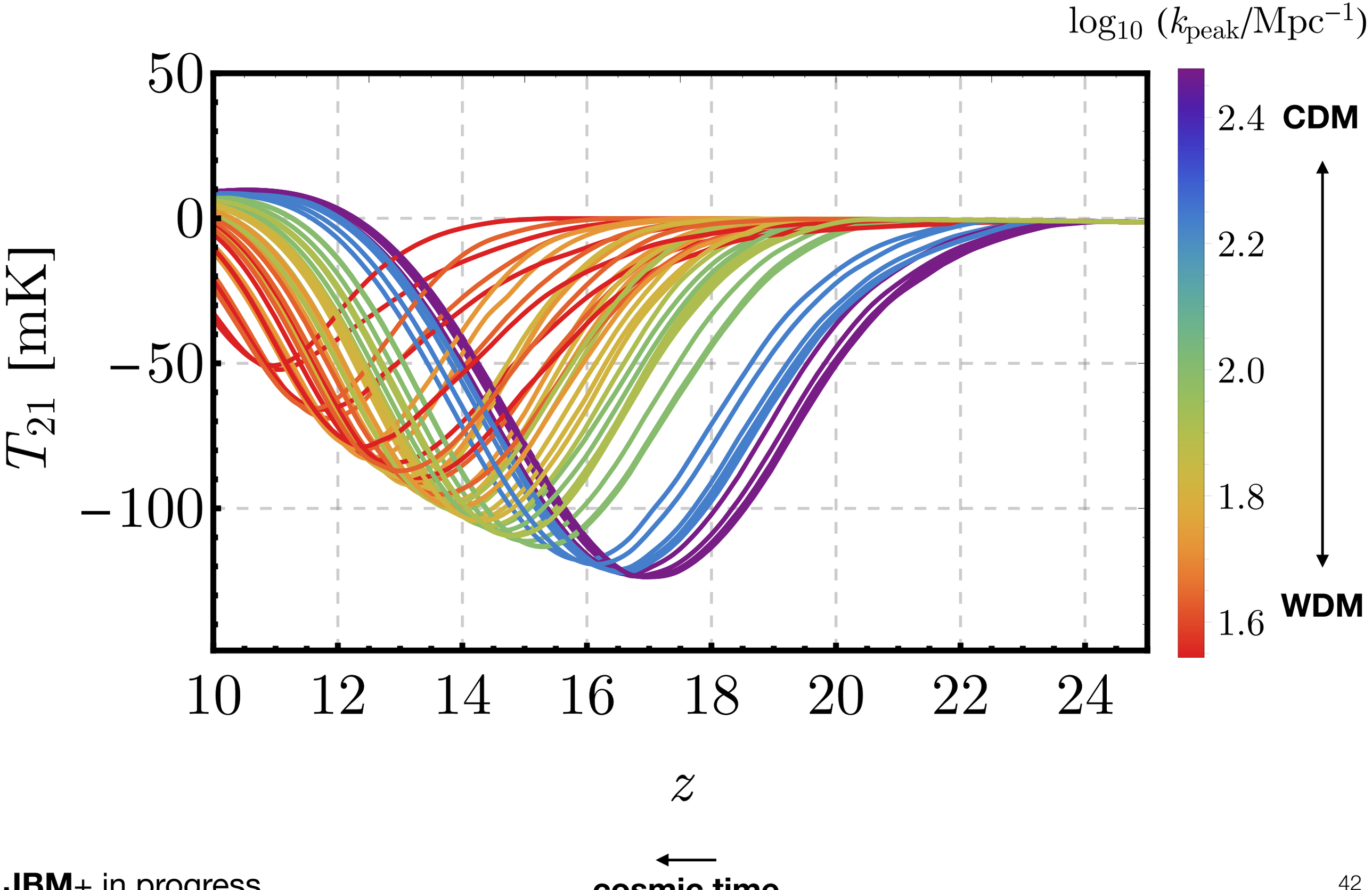
A two-parameter model



Bohr+, ArXiv: 2006.01842

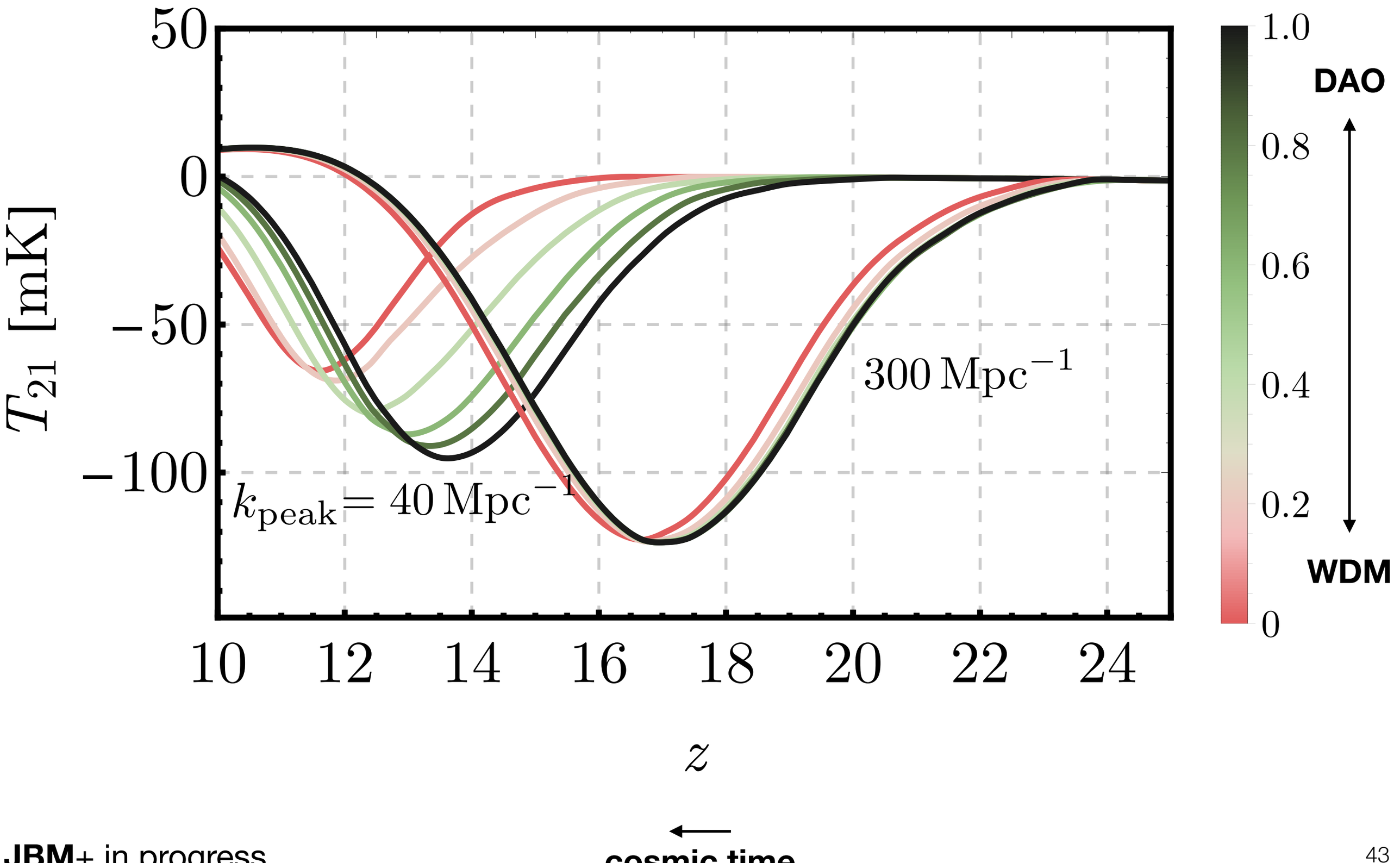
JBM+ in progress

The 21-cm global signal in ETHOS



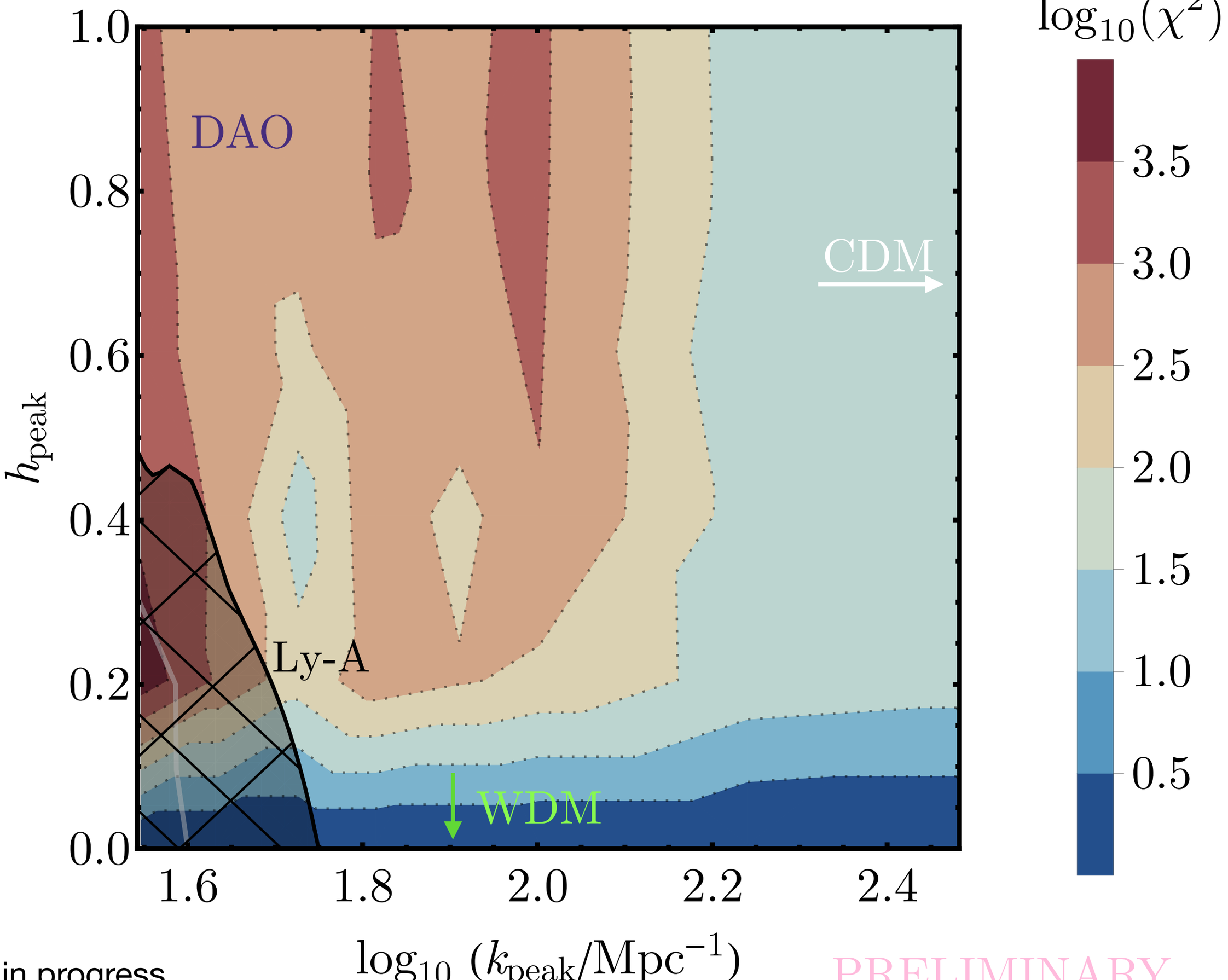
JBM+ in progress

The 21-cm global signal in ETHOS



JBM+ in progress

HERA can distinguish ETHOS from WDM!

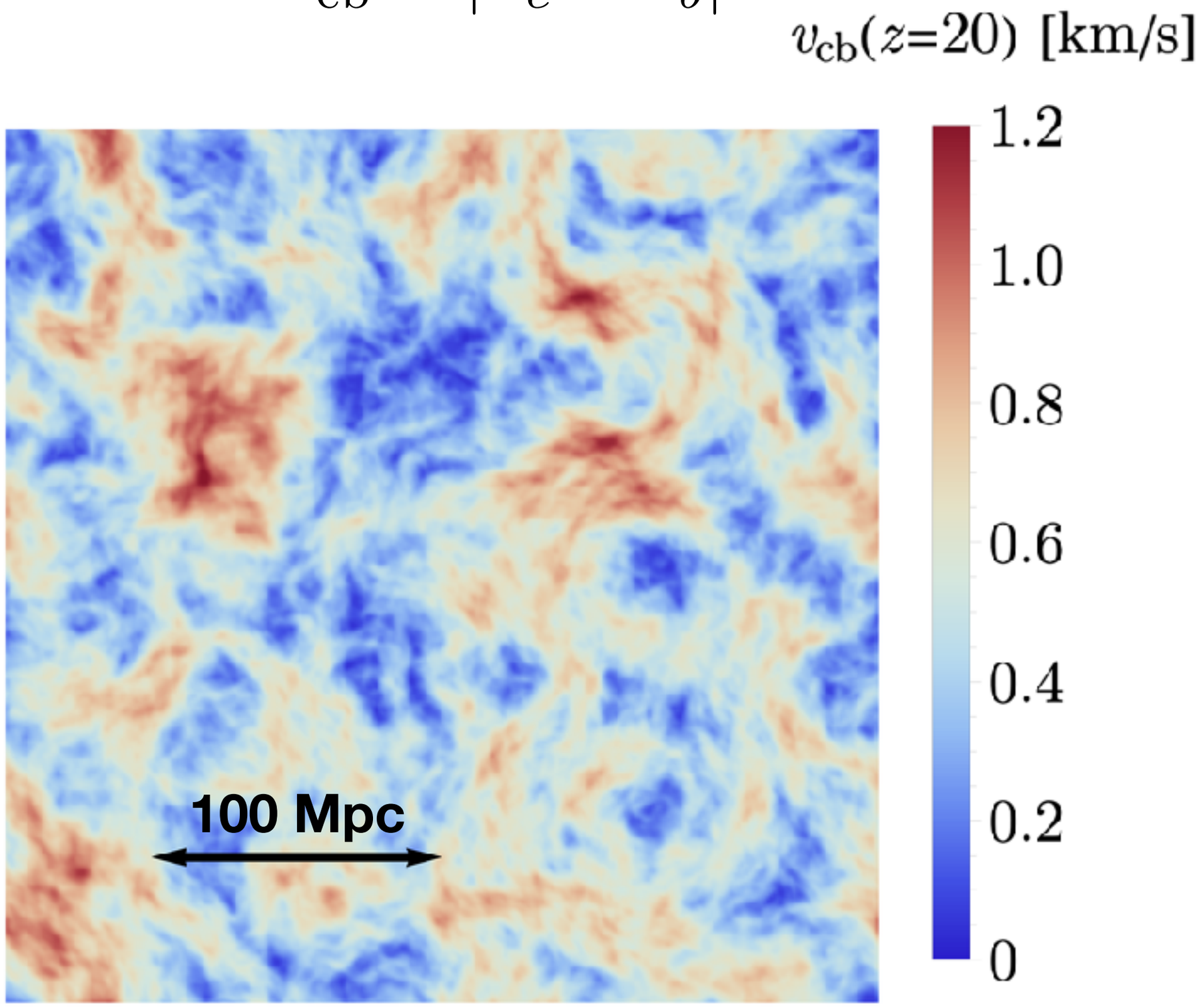


JBM+ in progress

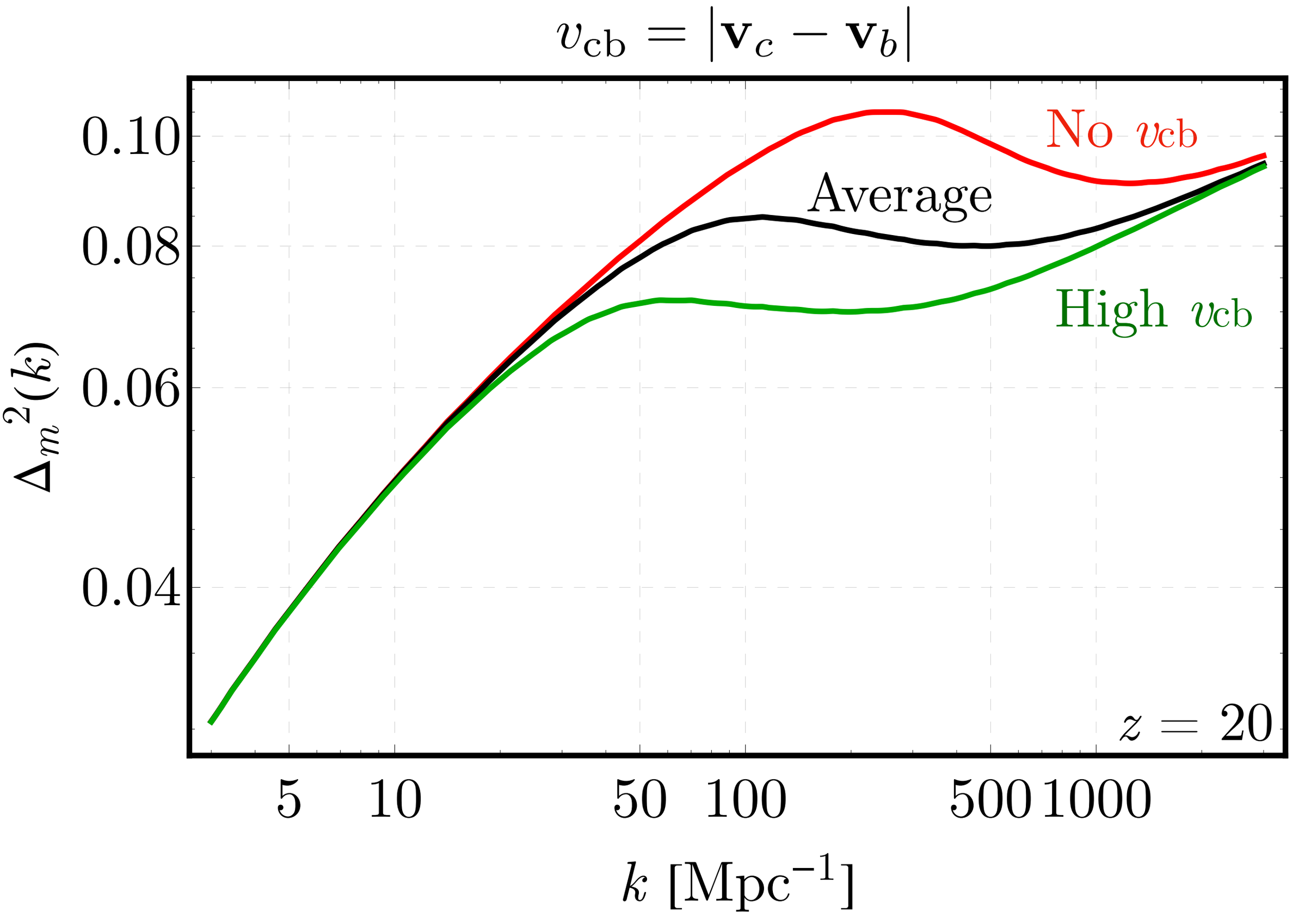
PRELIMINARY

Even LCDM has surprises!

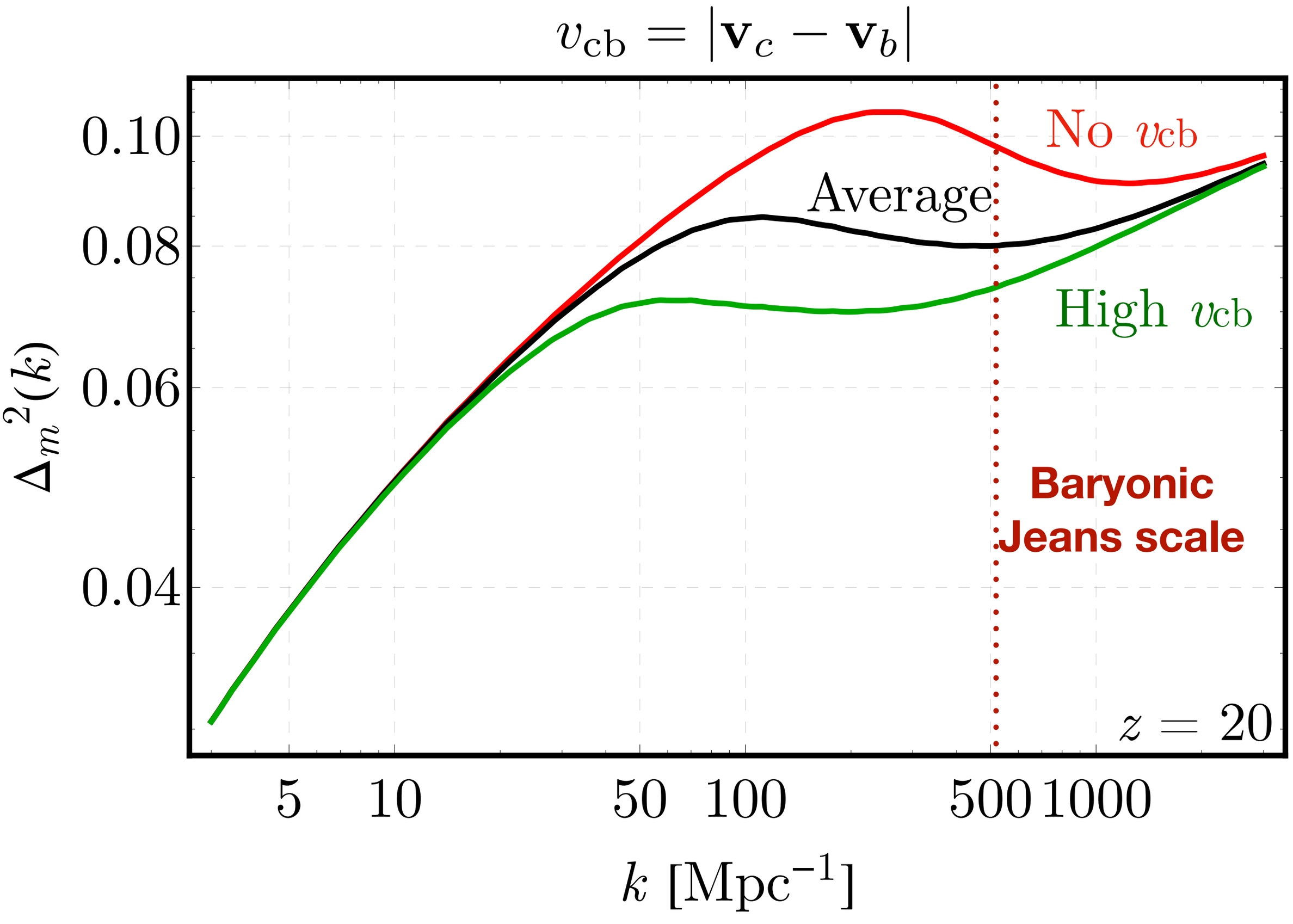
$$v_{\rm cb} = |\mathbf{v}_c - \mathbf{v}_b|$$



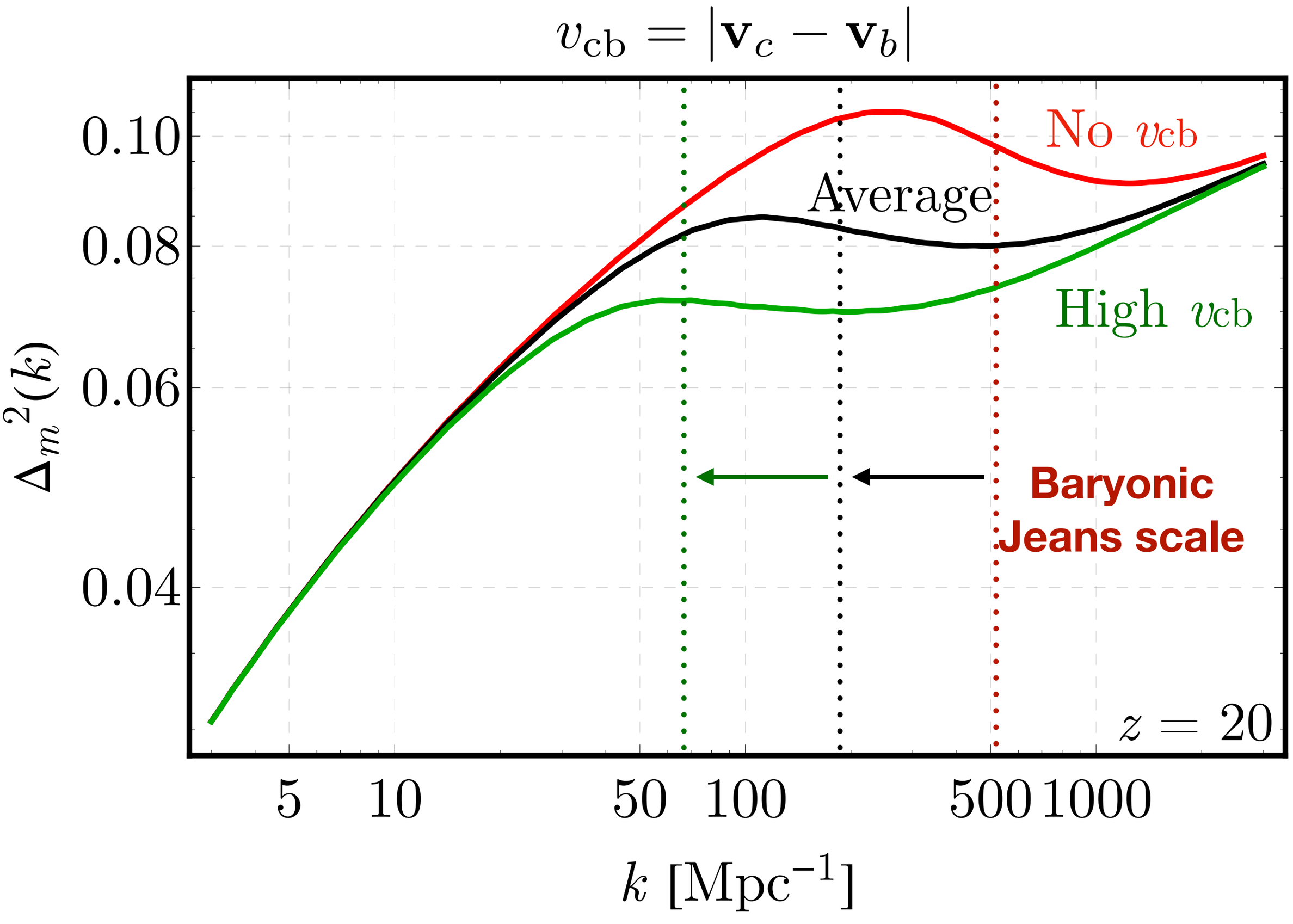
Even LCDM has surprises!



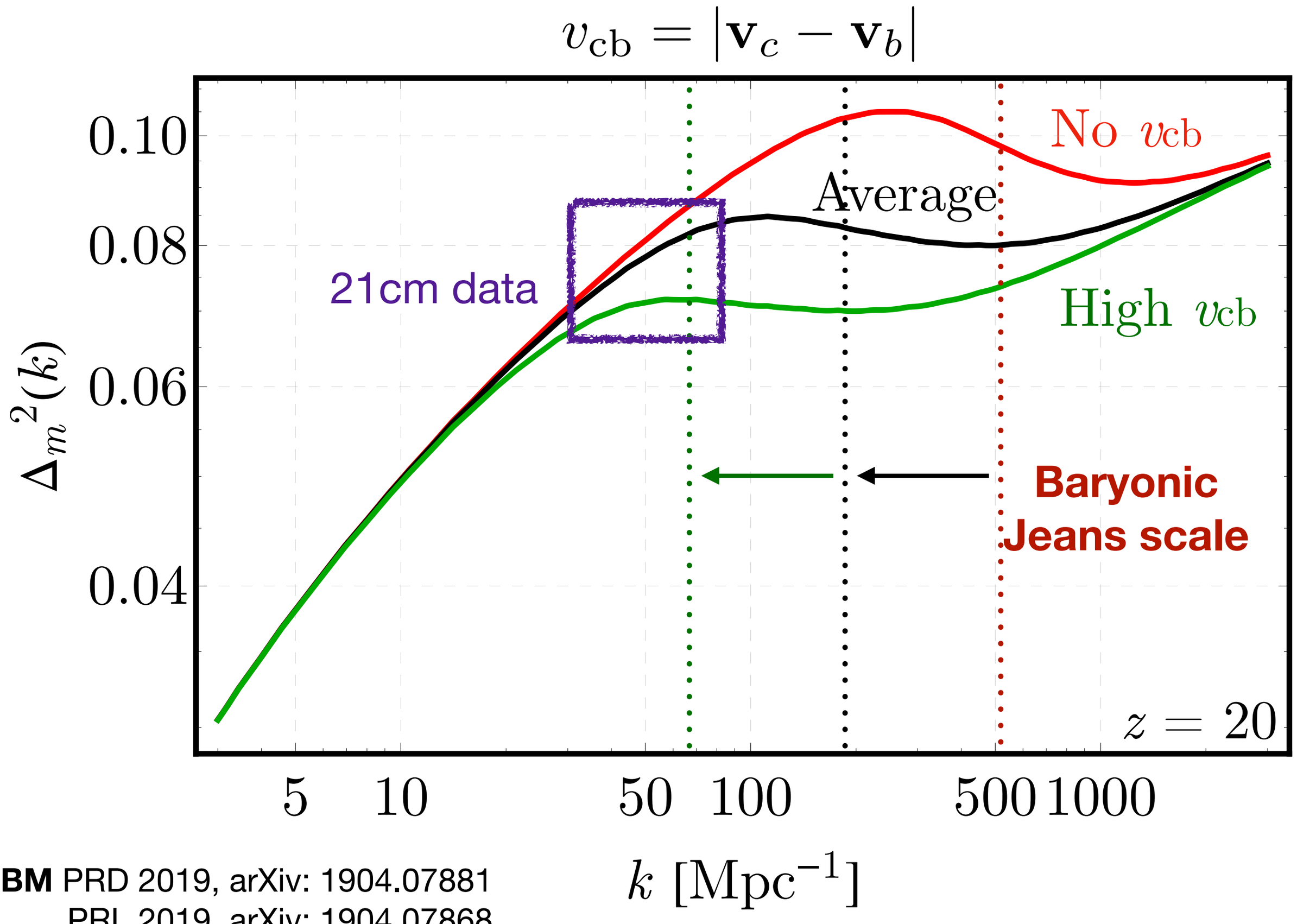
Even LCDM has surprises!



Even LCDM has surprises!

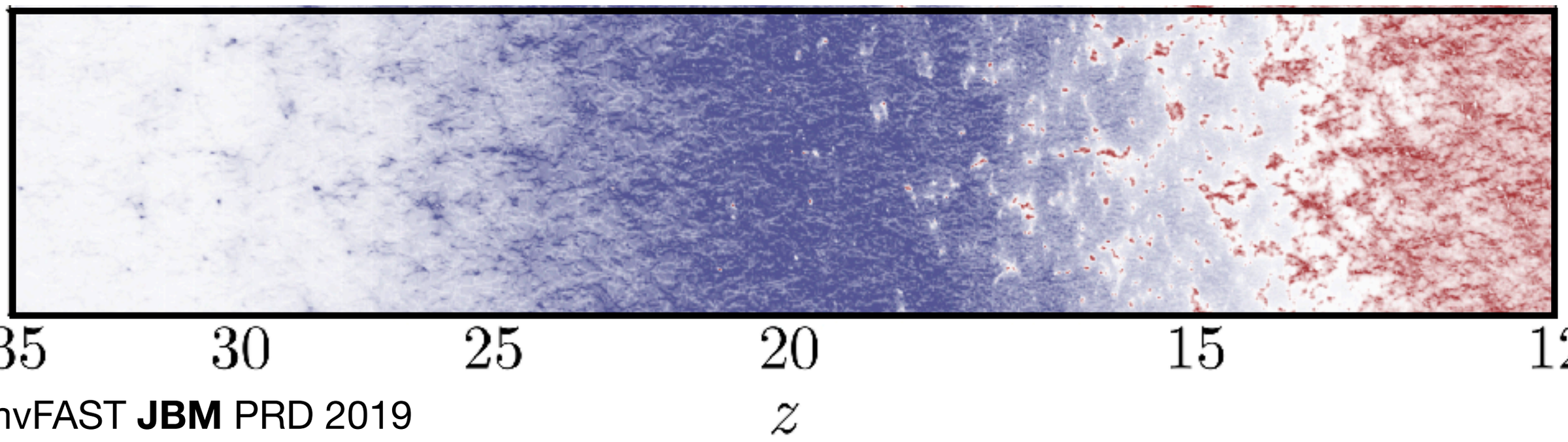


Even LCDM has surprises!



JBM PRD 2019, arXiv: 1904.07881
PRL 2019, arXiv: 1904.07868

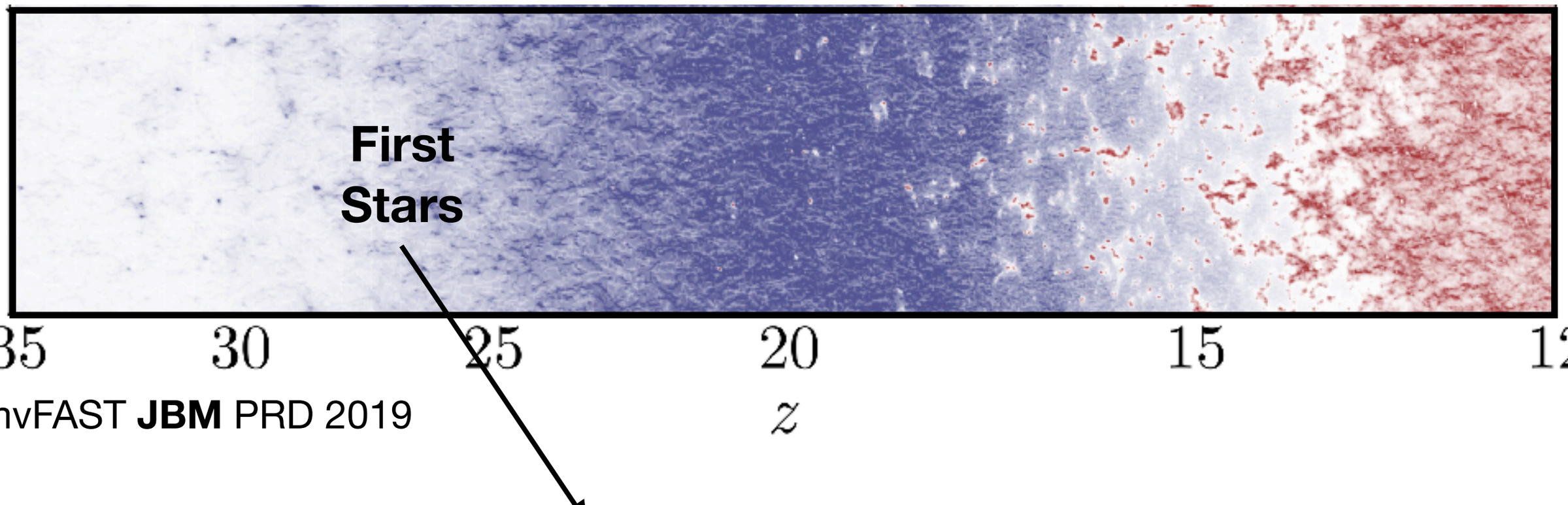
Summary



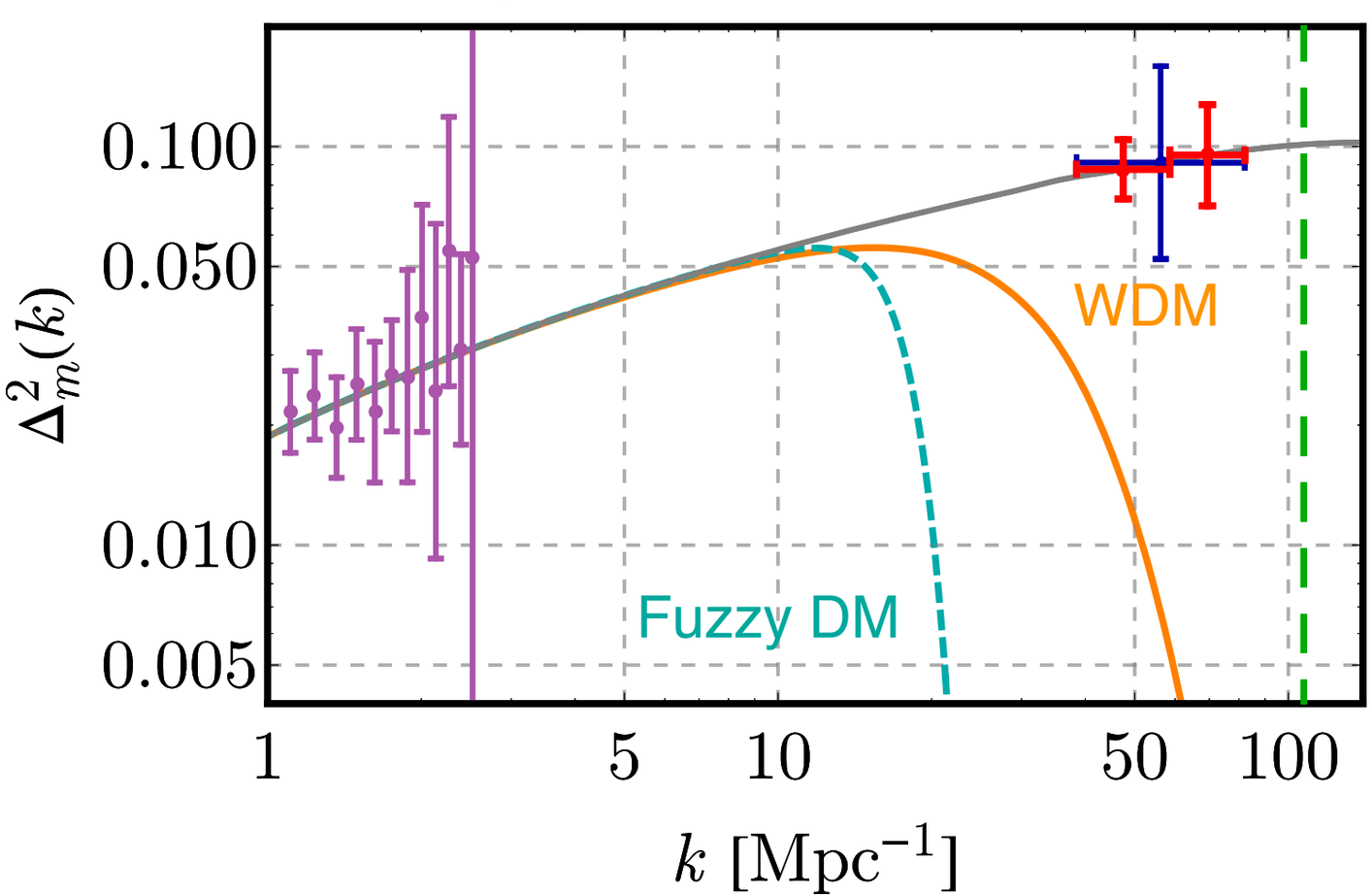
21cmvFAST **JBM** PRD 2019

Summary

cosmic time

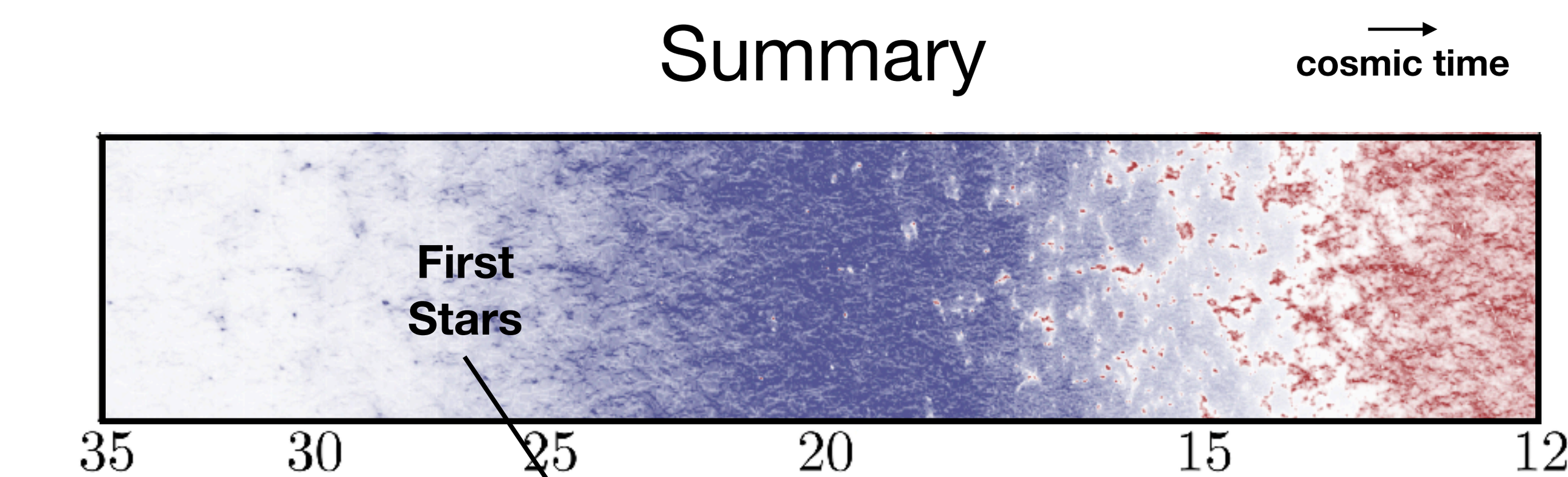


21cmvFAST **JBM** PRD 2019

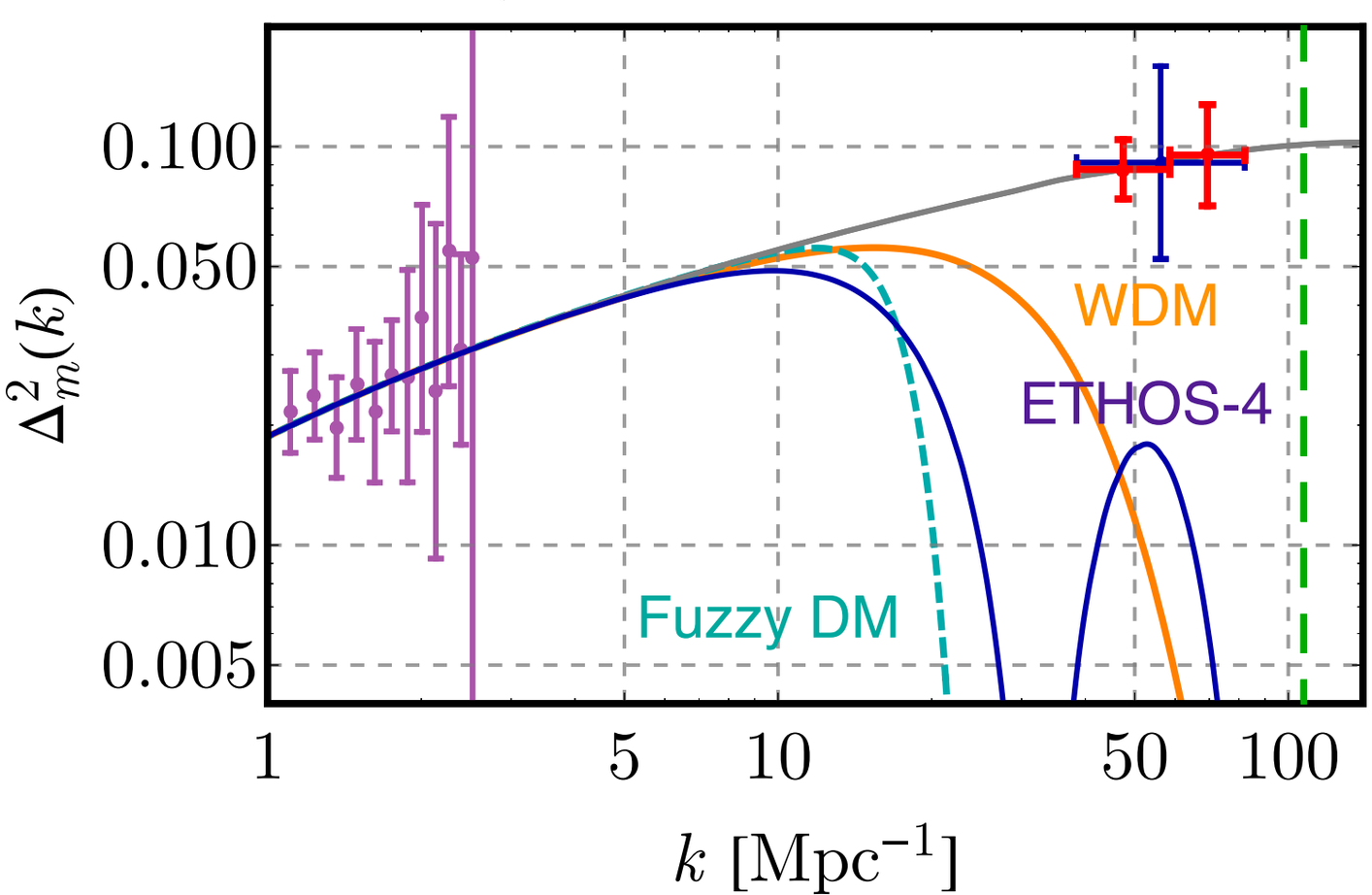


JBM, Dvorkin, and Cyr-Racine 2020

Summary



21cmvFAST **JBM** PRD 2019



JBM, Dvorkin, and Cyr-Racine 2020

JBM, Cyr-Racine, Bohr, Zavala, Vogelsberger 2020(?)