Searching for Dark Matter at Cosmic Dawn

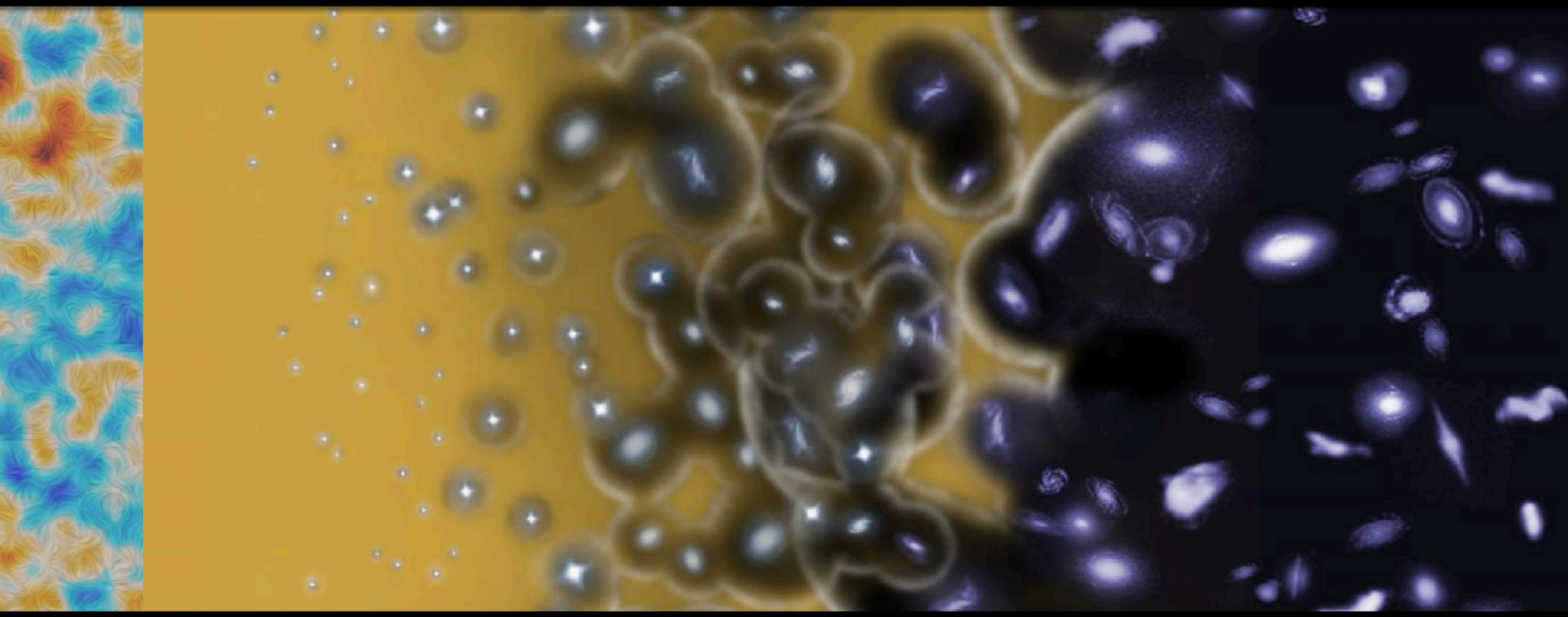
Julian B. Muñoz

Based on
arXiv:1509.00029
arXiv:1802.10094
arXiv:1804.01092
arXiv:1910.XXXXX

with
Yacine Ali-Haimoud
Francis-Yan Cyr-Racine
Cora Dvorkin
Avi Loeb
Ely Kovetz

Brief history of Hydrogen

CMB



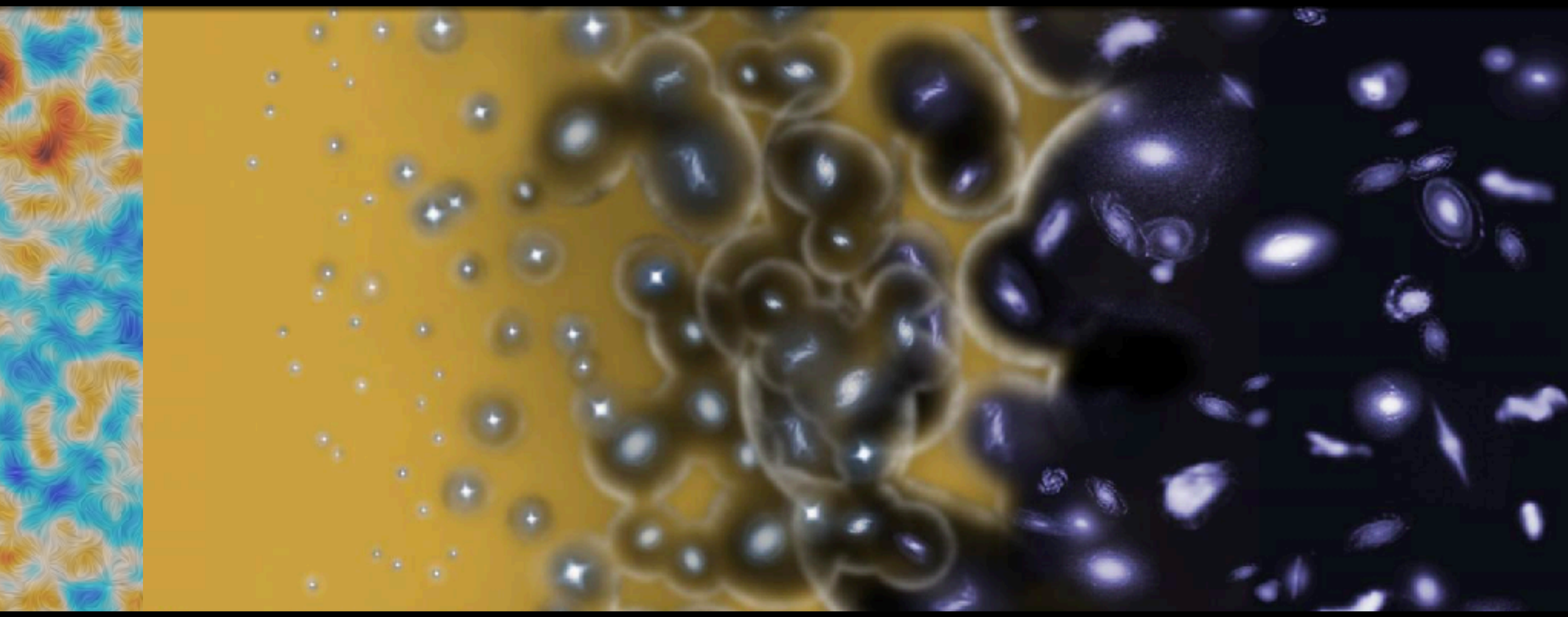
$z{=}1100$

Image: ESA

Brief history of Hydrogen

CMB

Cosmic Dawn



$z{=}1100$ $z{=}20$

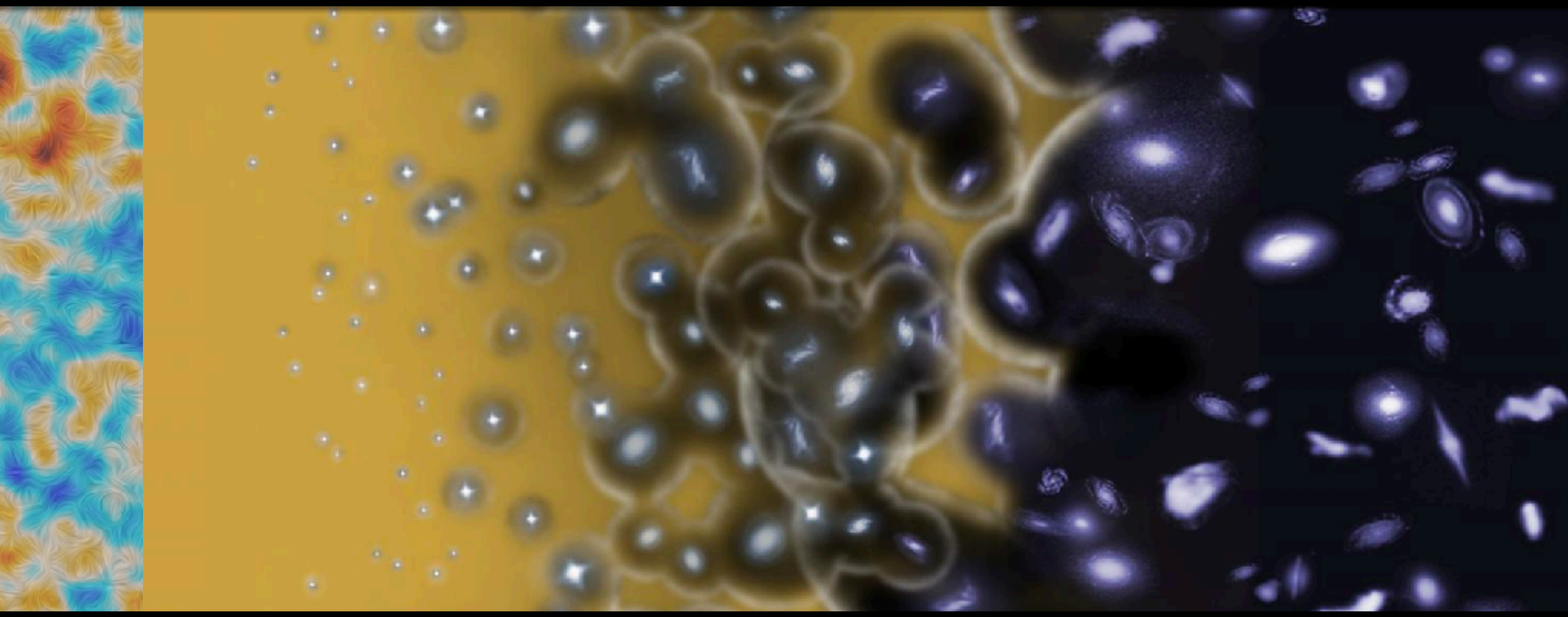
Image: ESA

Brief history of Hydrogen

CMB

Cosmic Dawn

Reionization



z=1100

z=20

z=6

Image: ESA

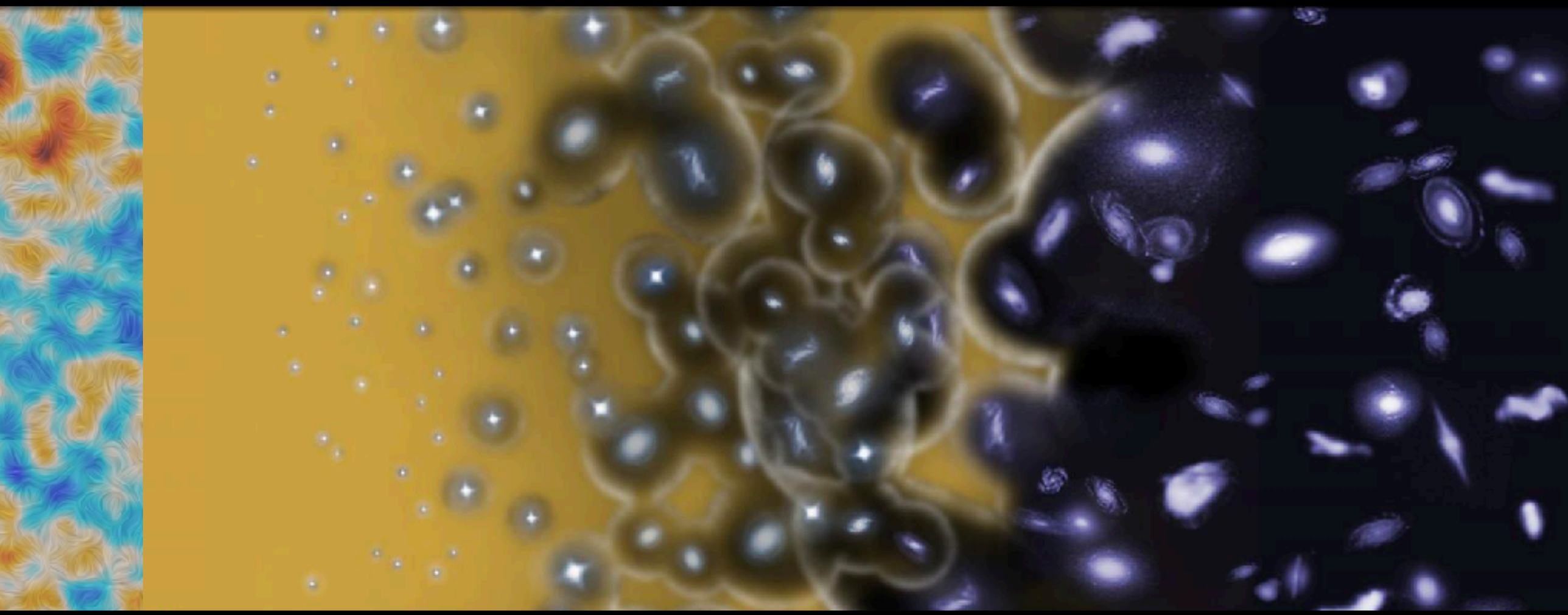
Brief history of Hydrogen

CMB

Cosmic Dawn

Reionization

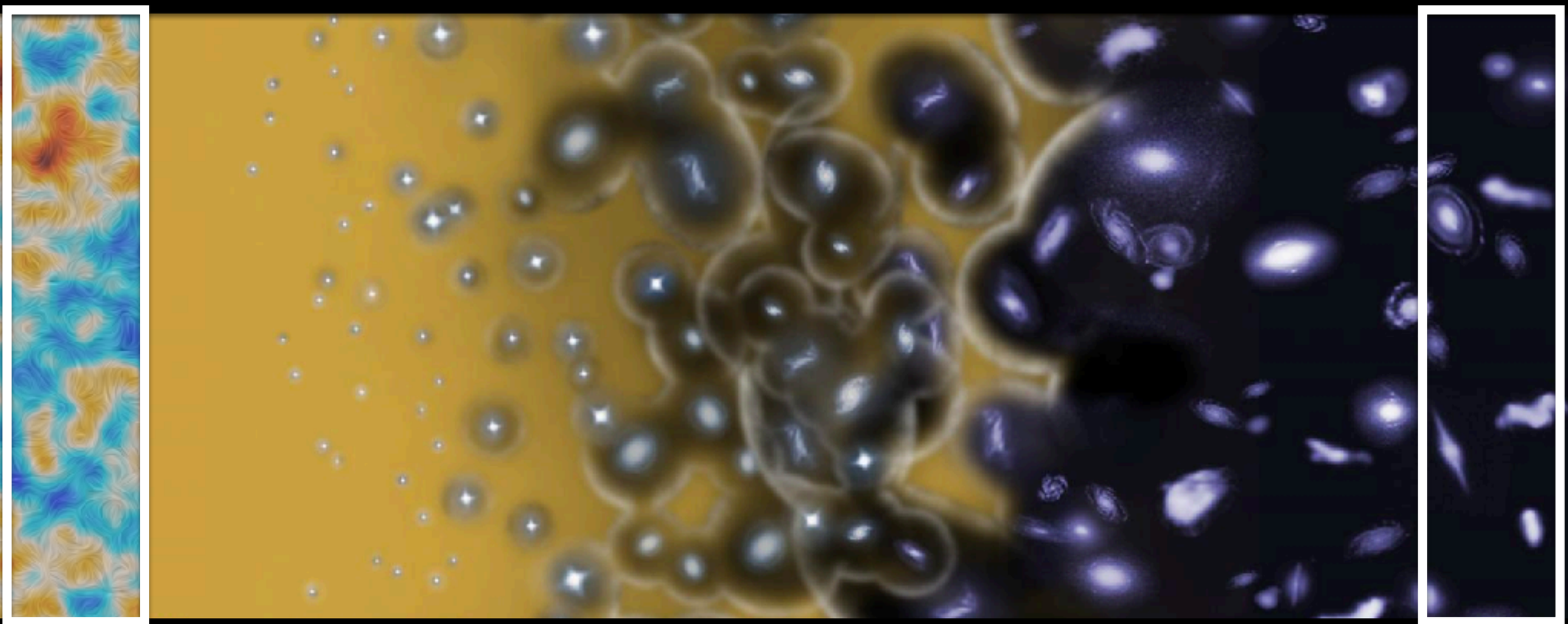
Earth and Telescopes



$z{=}1100$ $z{=}20$ $z{=}6$ $z{=}0$

Image: ESA

DM is cold and collisionless

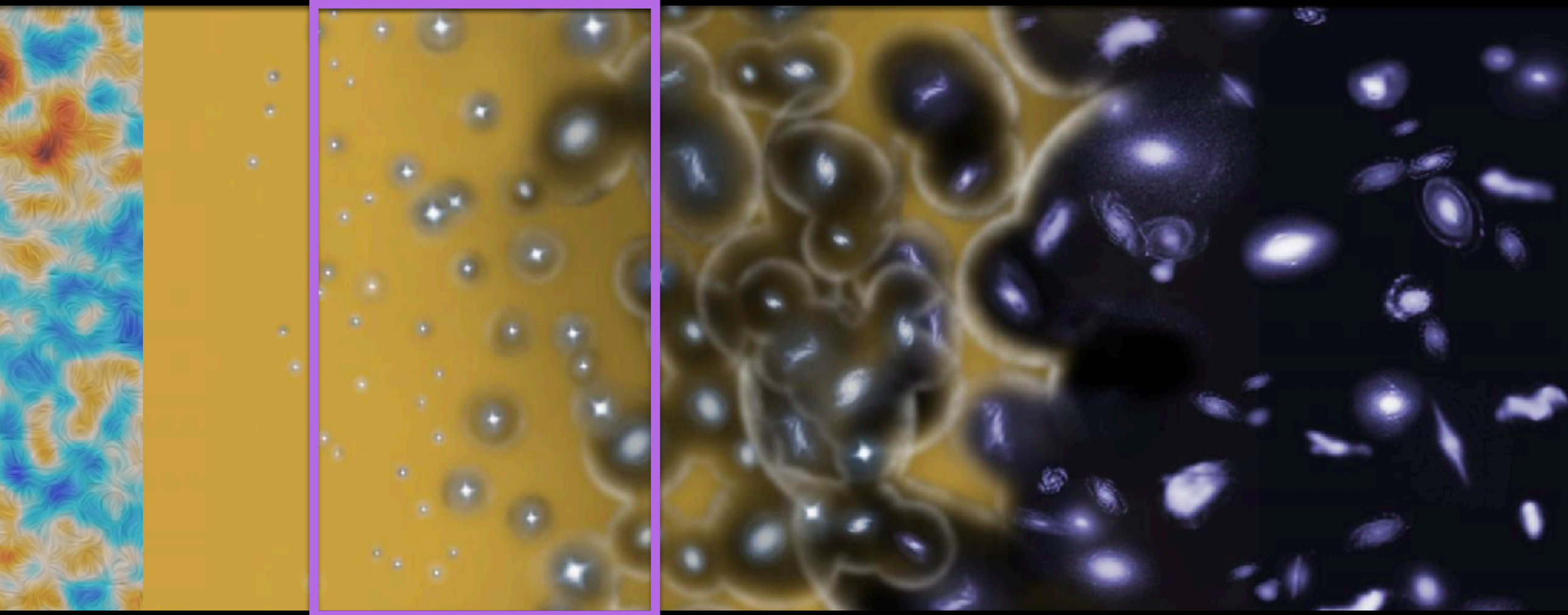


$z{=}1100$ $z{=}20$ $z{=}6$ $z{=}0$

Image: ESA

What can we learn?

Cosmic Dawn



$z{=}1100$ $z{=}20$ $z{=}6$ $z{=}0$

Image: ESA

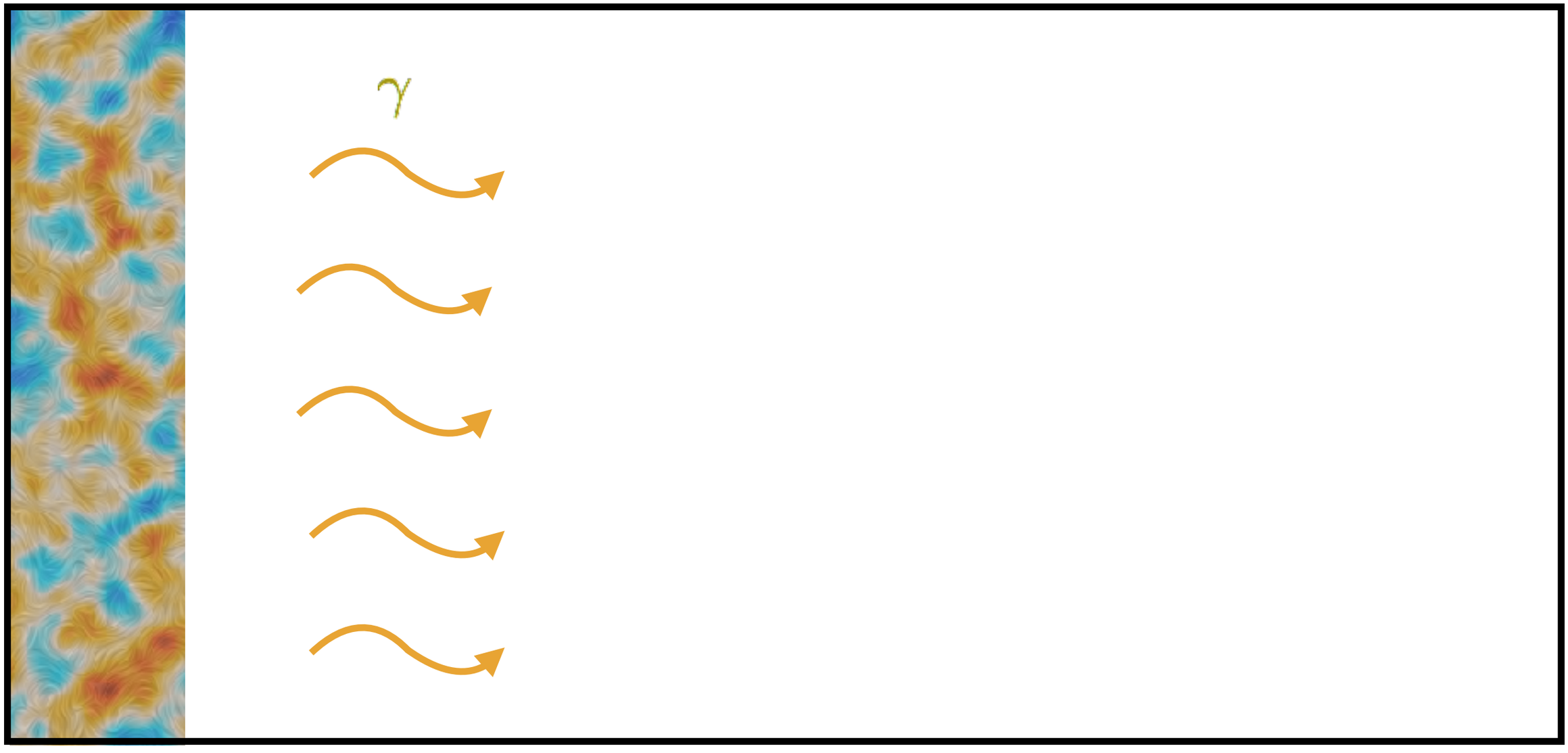
Outline

- Introduction to 21-cm cosmology

- Non-collisionless DM

- Non-cold DM

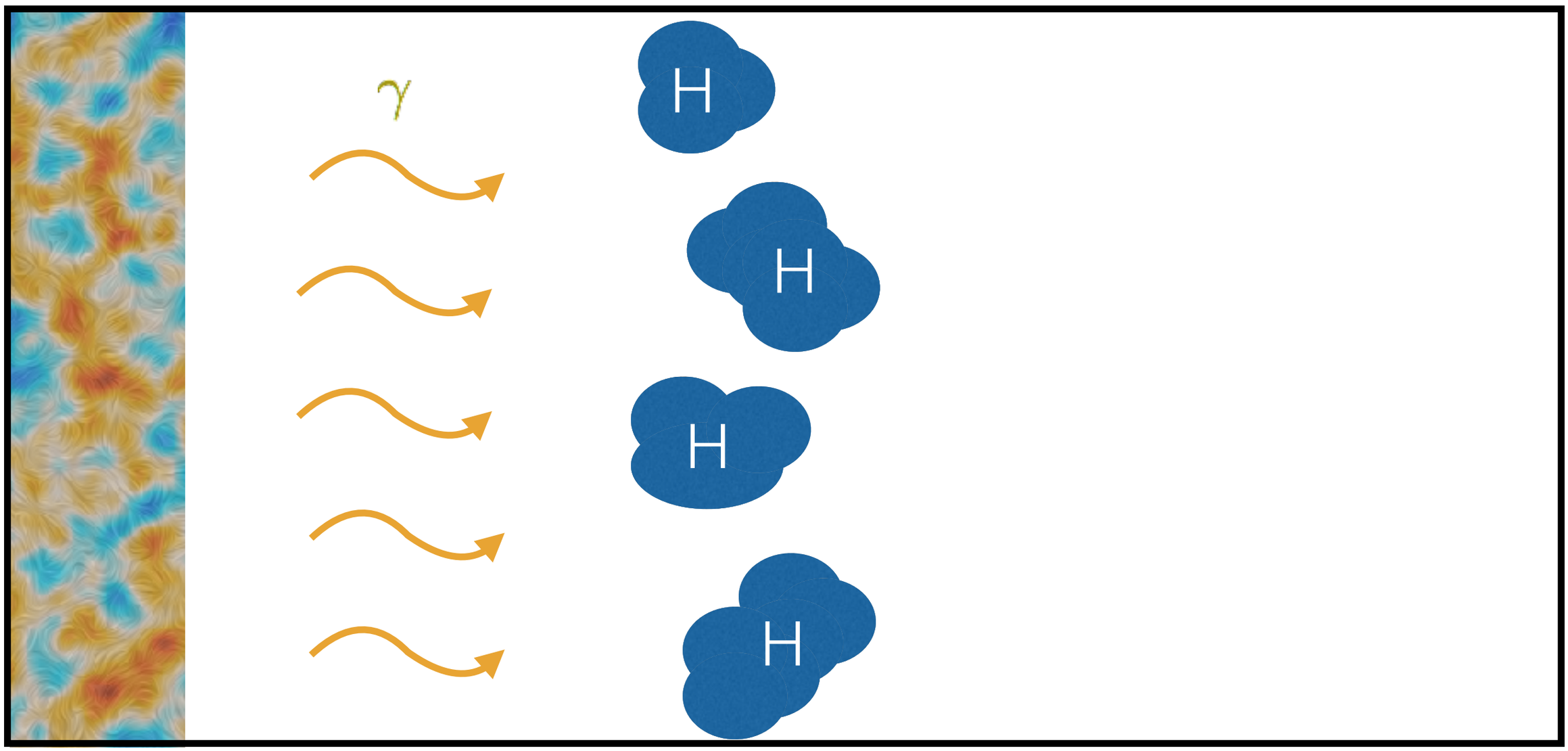
$z = 1100$



$I_\nu \propto T_{\rm CMB}\nu^2$

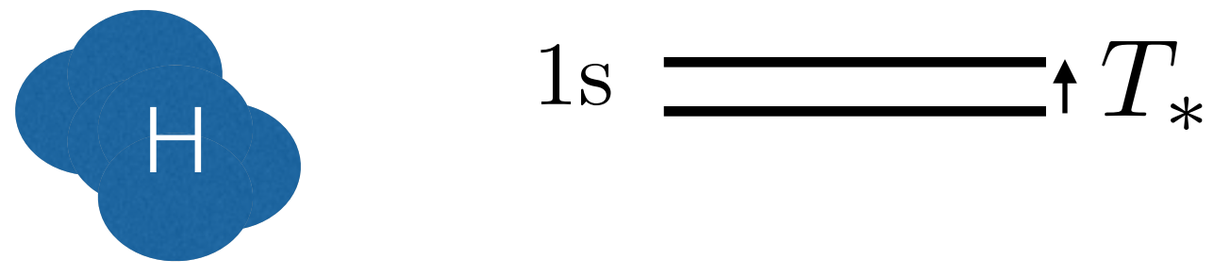
(@ 21 cm)

$z = 1100$ $z \approx 20$



$$I_\nu \propto T_{\rm CMB} \nu^2$$

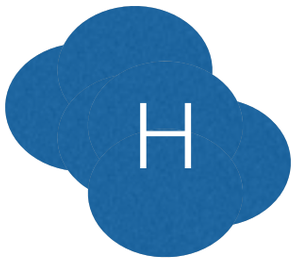
(@ 21 cm)



Triplet

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s}$$

Singlet



$1\mathrm{s}$ ⟹ T_*

Triplet

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s}$$

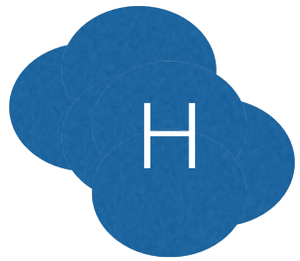
$6\ \mu\mathrm{eV}$

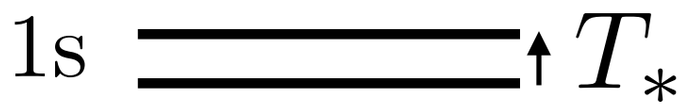
Singlet

3

$T_S < T_{\rm cmb}$ Absorption

$T_S > T_{\rm cmb}$ Emission





Triplet

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s}$$

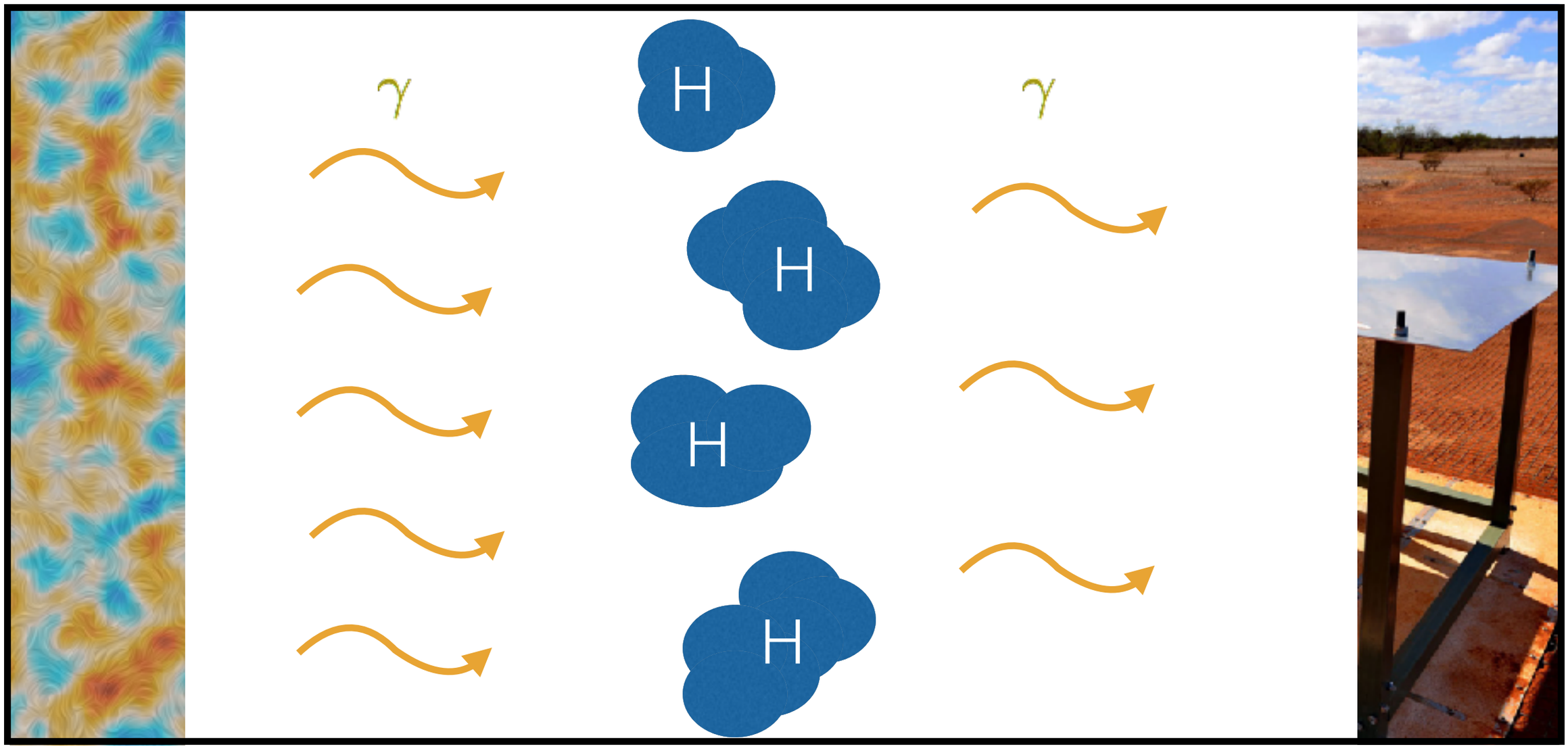
$6\,\mu\mathrm{eV}$

Singlet

3

$T_S < T_{\rm cmb}$ Absorption

$z = 1100$ $z \approx 20$ Earth



$I_\nu \propto T_{\rm CMB}\nu^2$ $\Delta I_\nu \propto T_{21}\nu^2$

Thermal
Decoupling (from CMB)

T_γ

T_H

T(K)

1000
500
100
50
10
5
1

10
50
100
500
1000

1+z

Cosmic
Dawn

Thermal
Decoupling (from CMB)

T_γ

T_H

1000
500
100
50
10
5
1

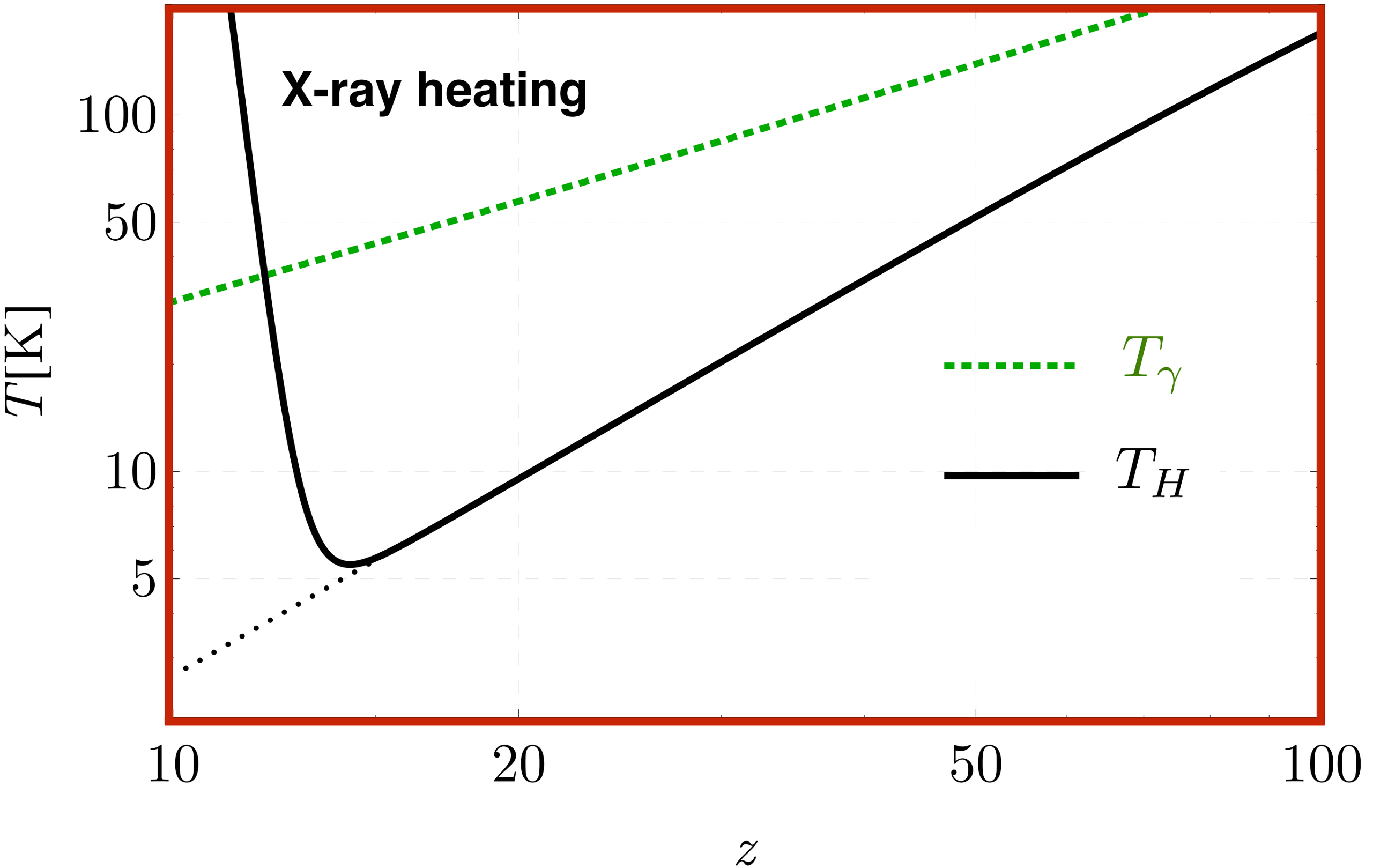
T(K)

10
50
100
500
1000

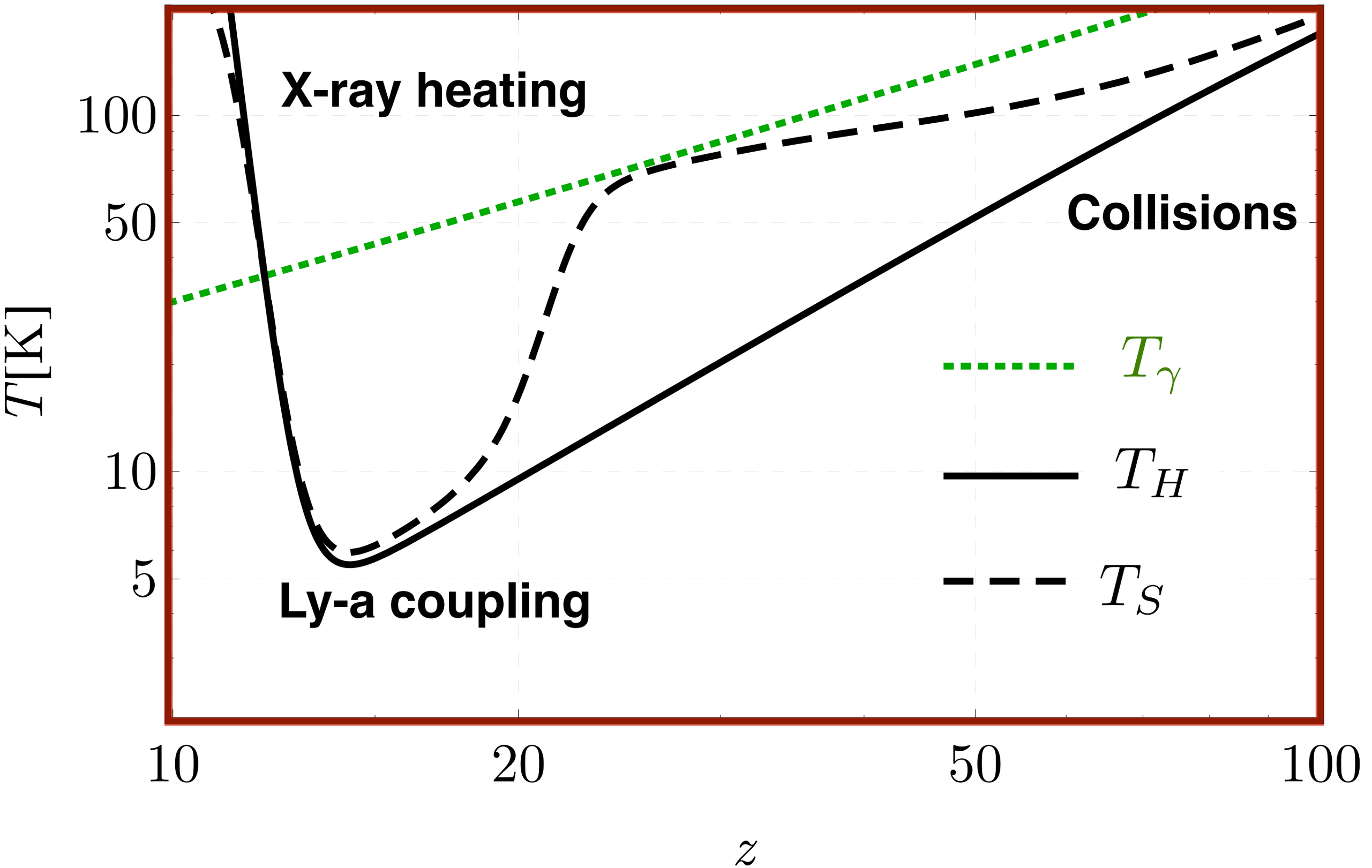
1+z

Cosmic
Dawn

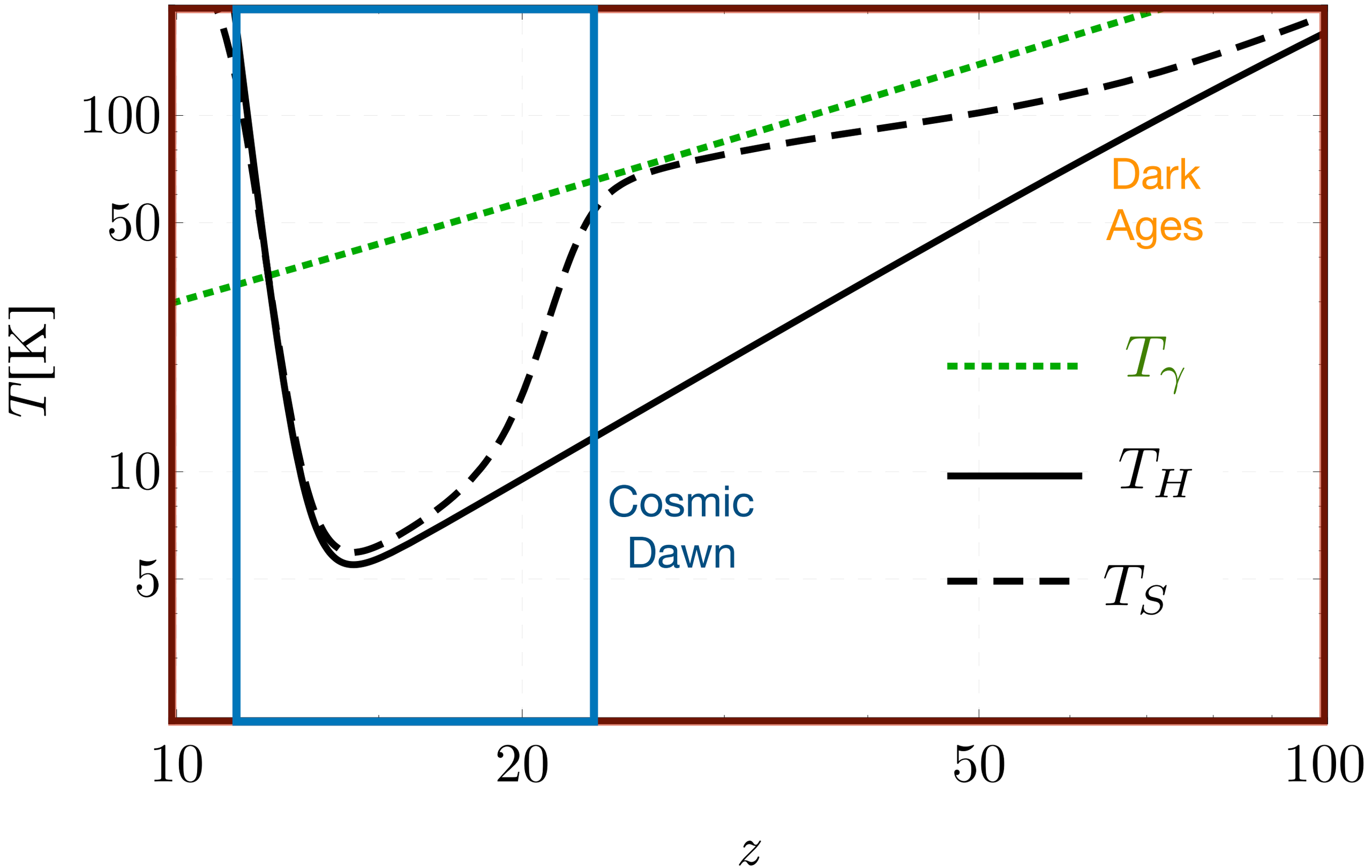
A cartoon of the evolution of T_S



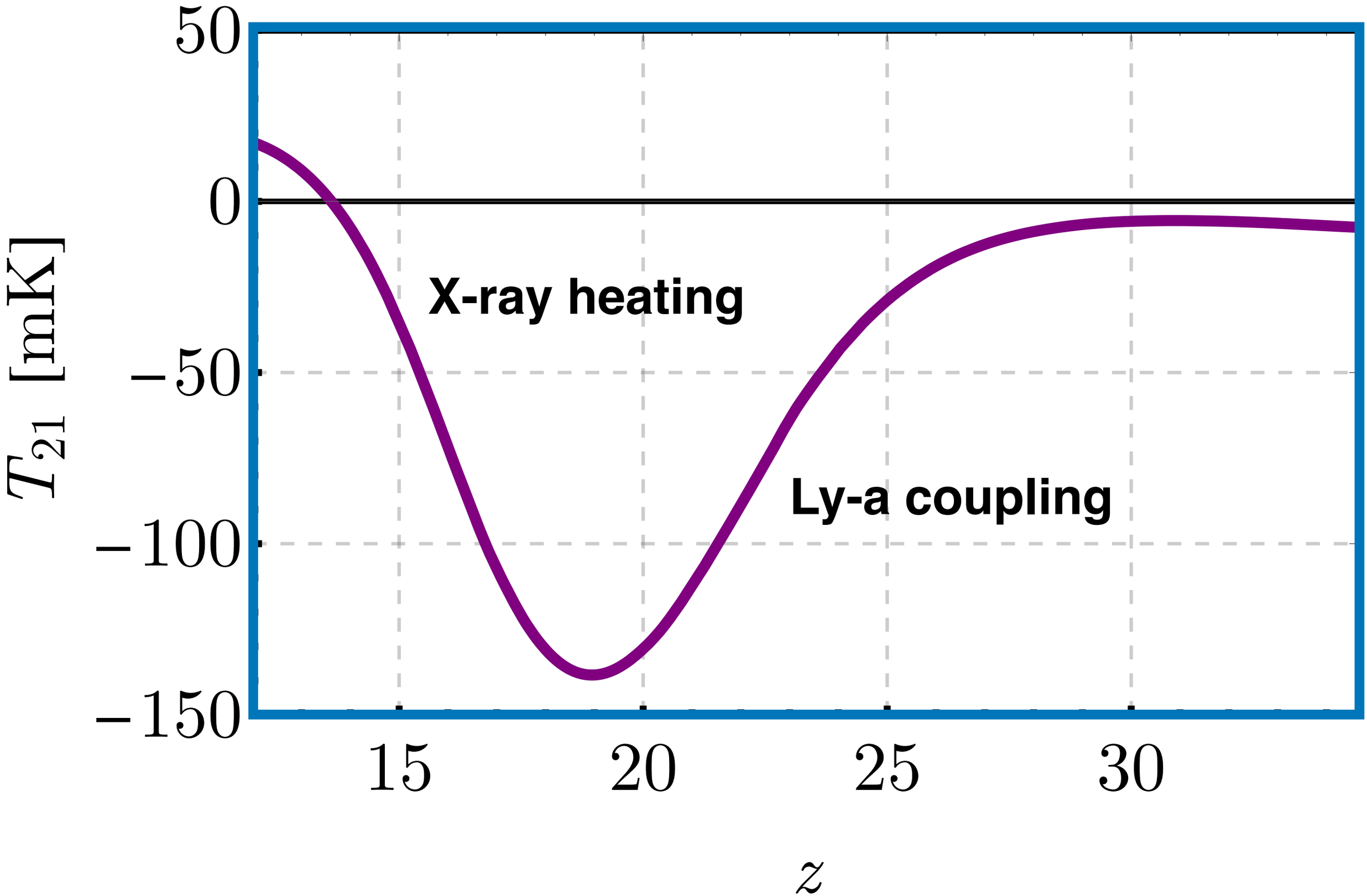
A cartoon of the evolution of T_S



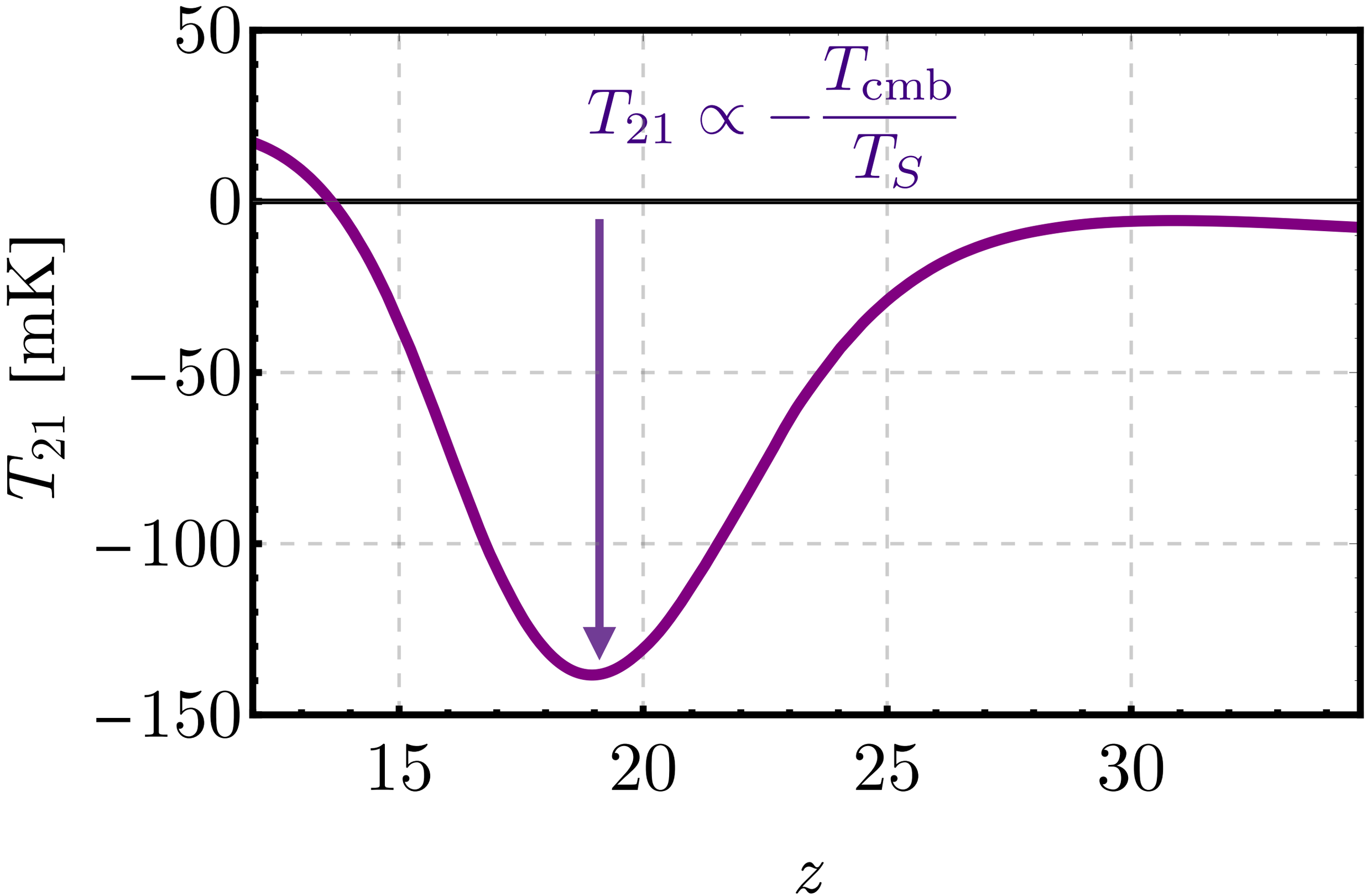
A cartoon of the evolution of T_S



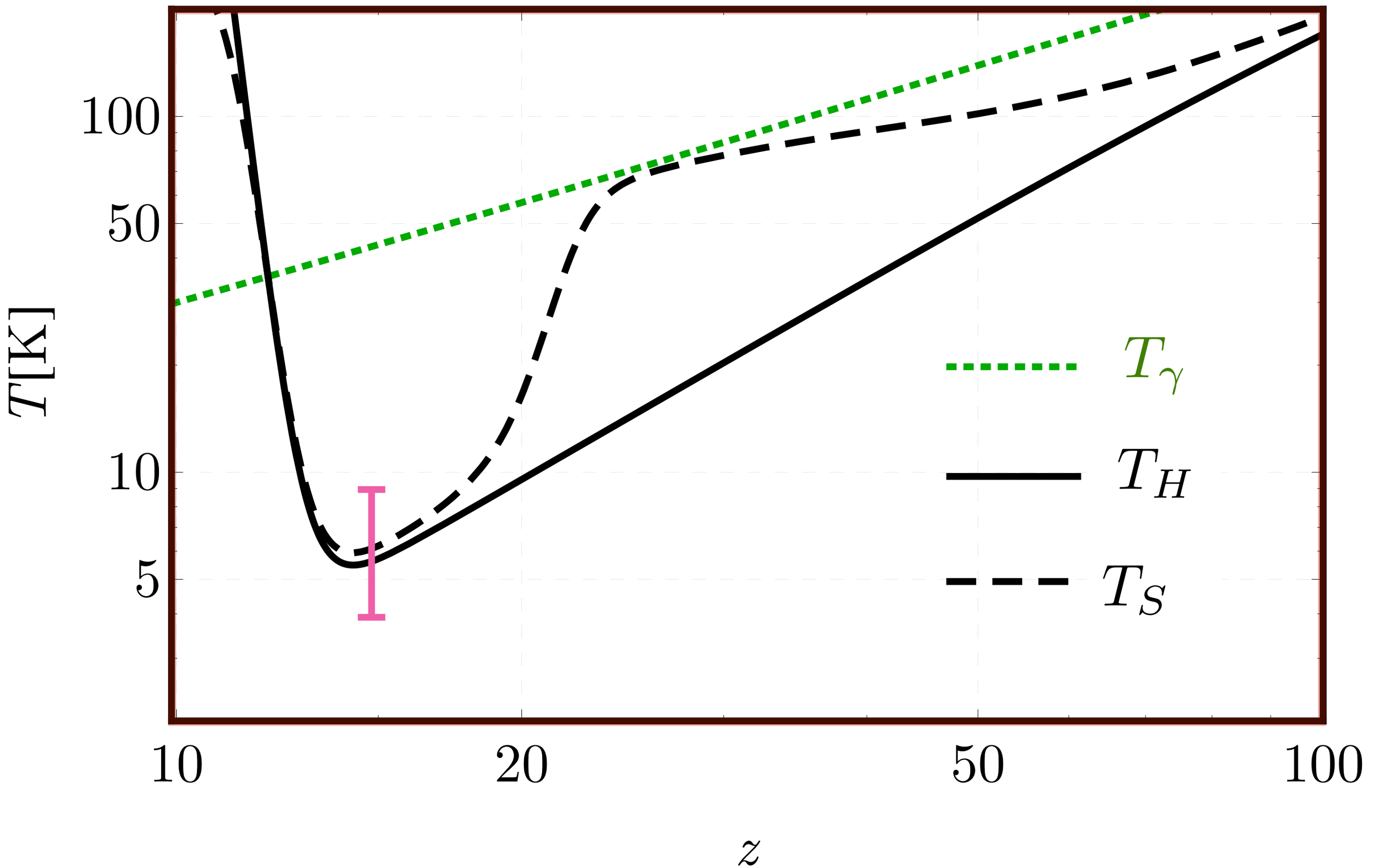
A typical 21-cm profile



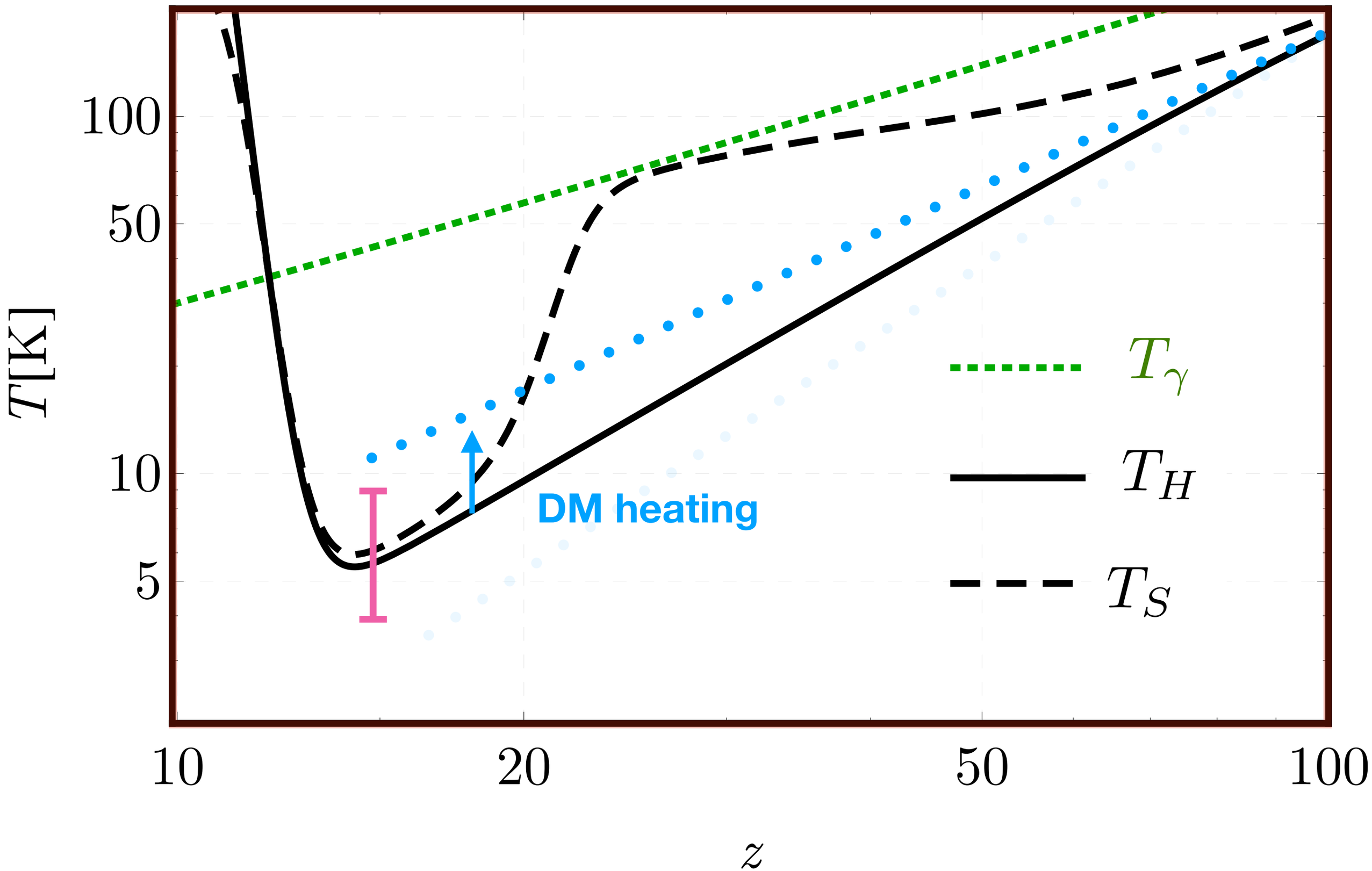
Learning about DM: Depth



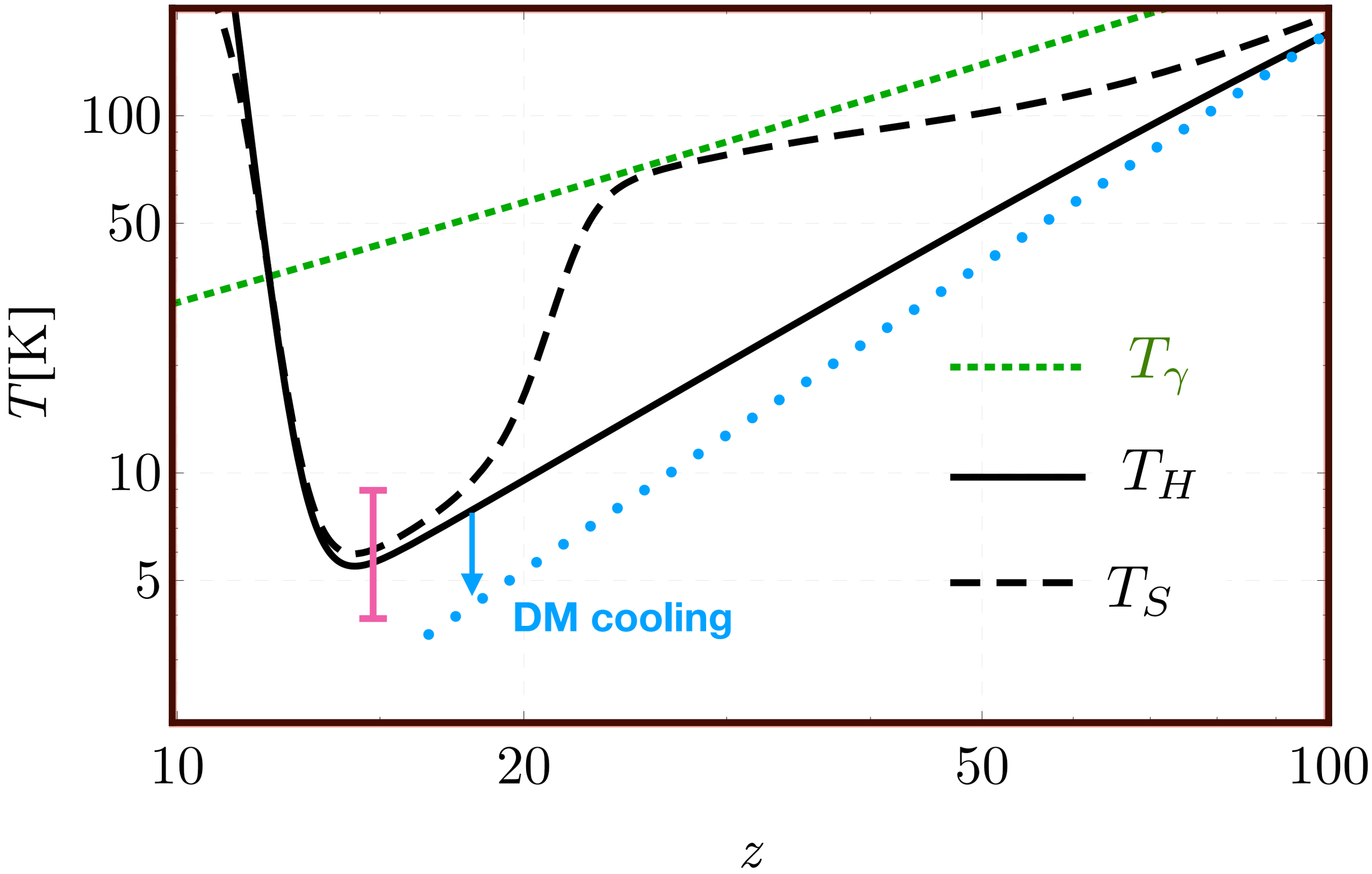
A thermostat at cosmic dawn



A thermostat at cosmic dawn



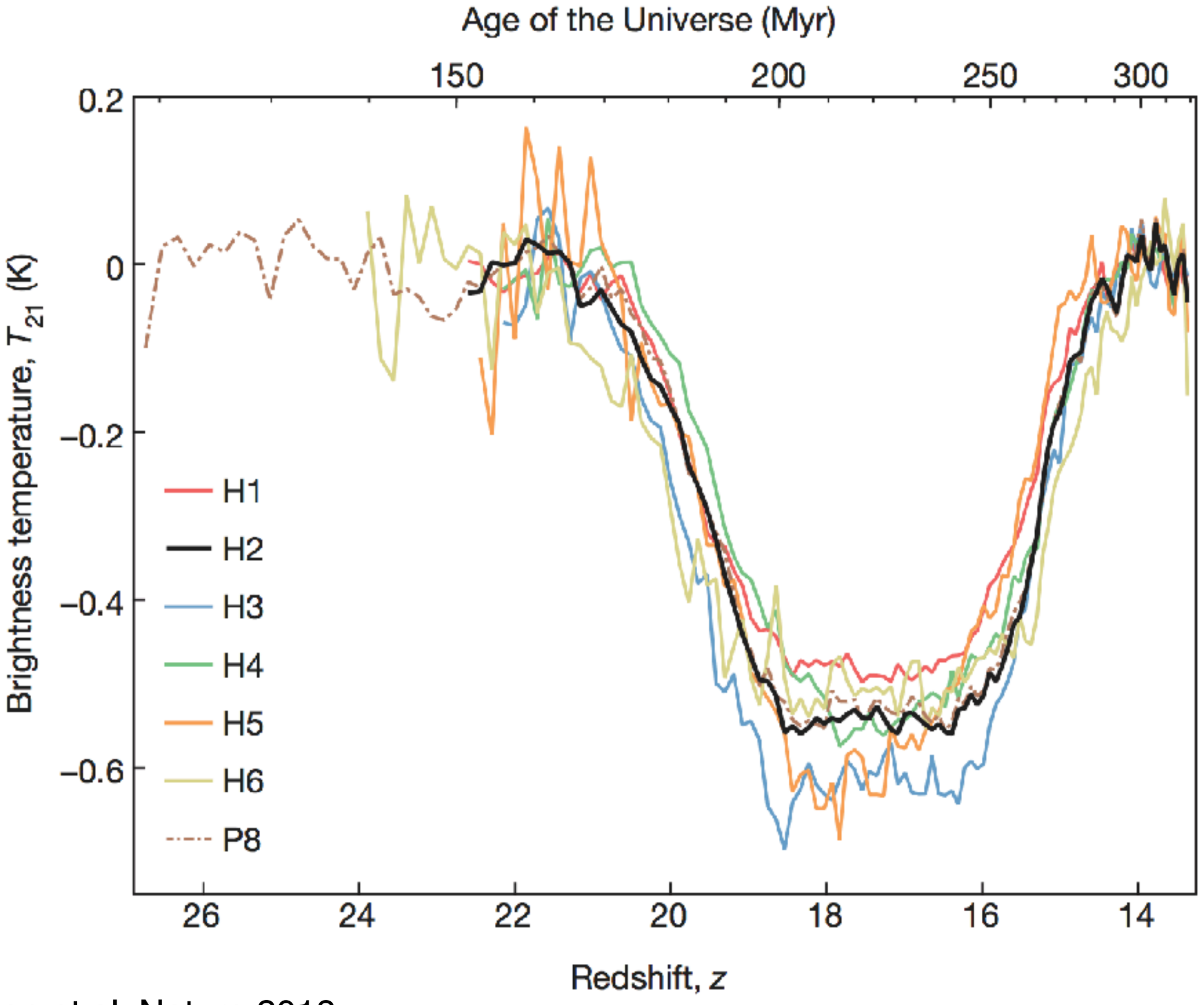
A thermostat at cosmic dawn



EDGES

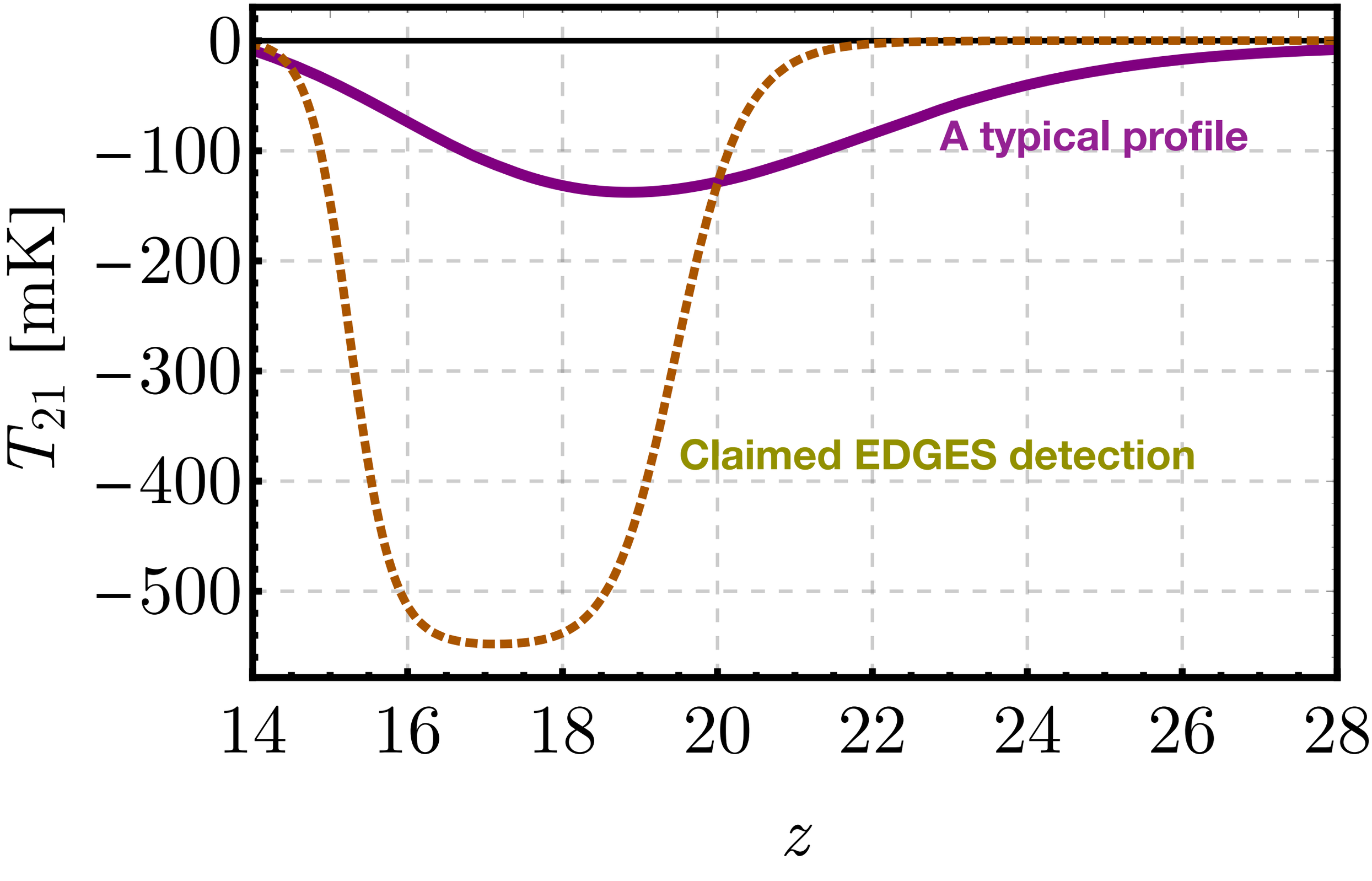
Experiment to Detect the Global EoR Signature

Credit: ASU

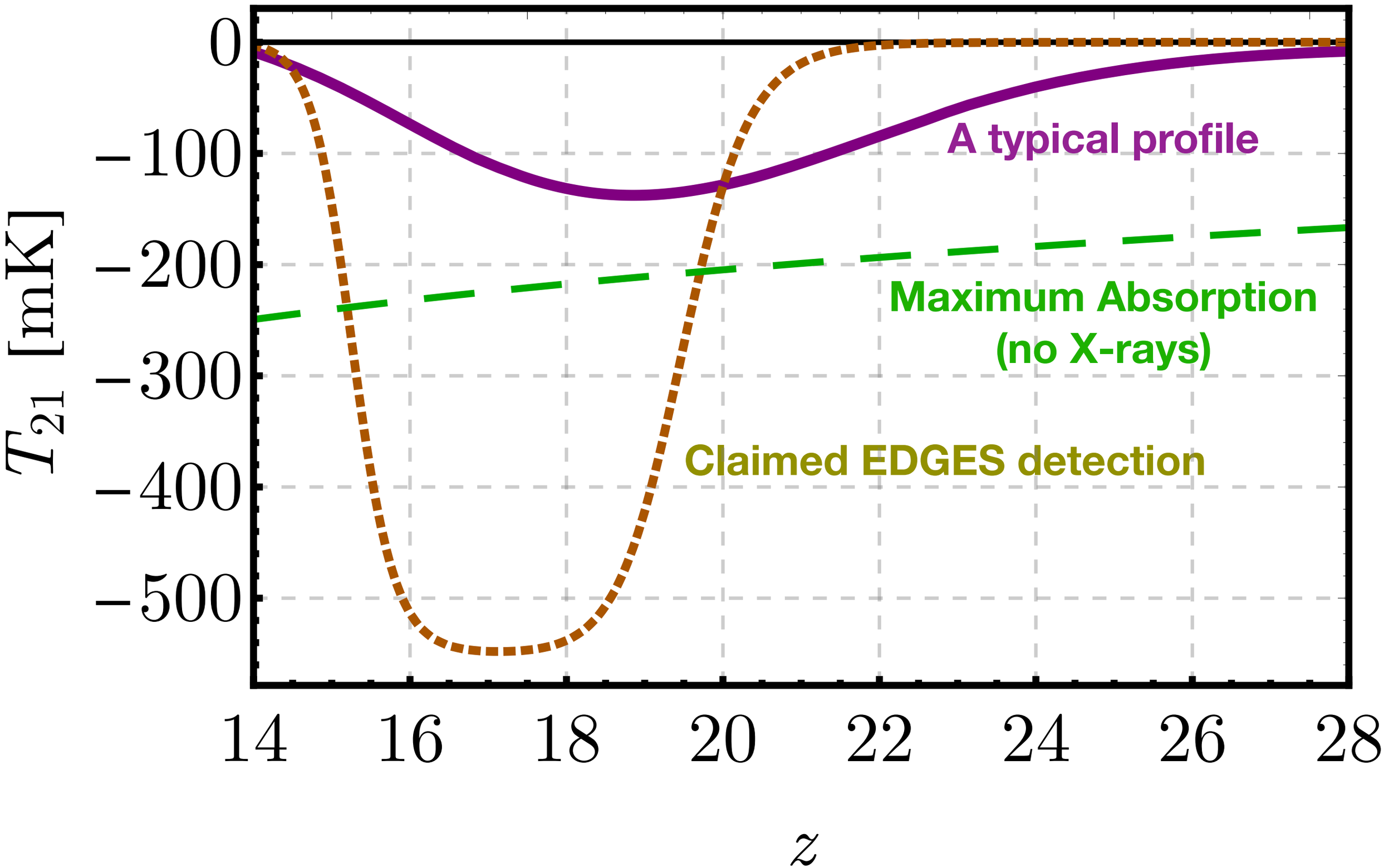


Bowman et al. Nature 2018

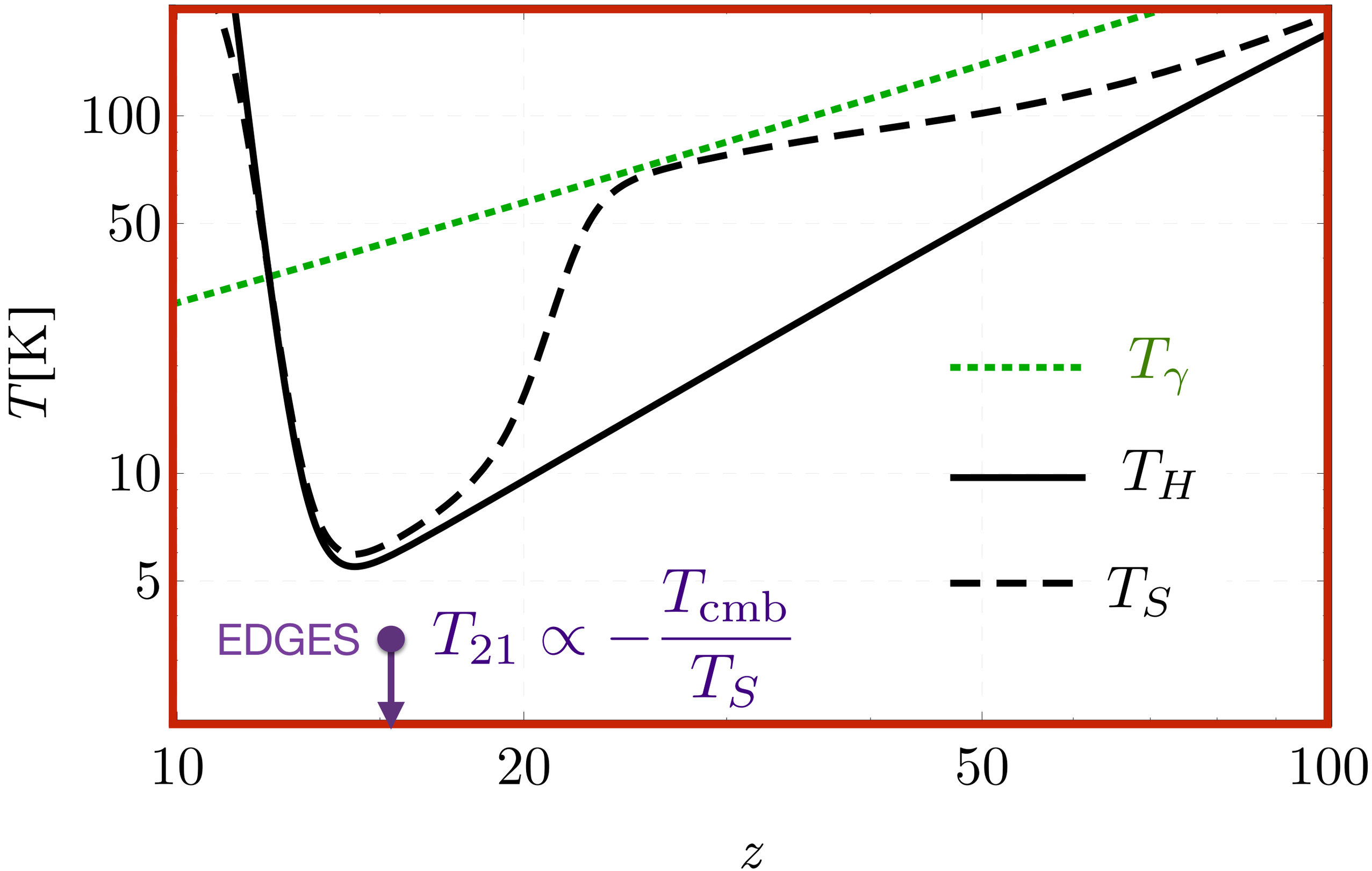
Learning about DM: Depth



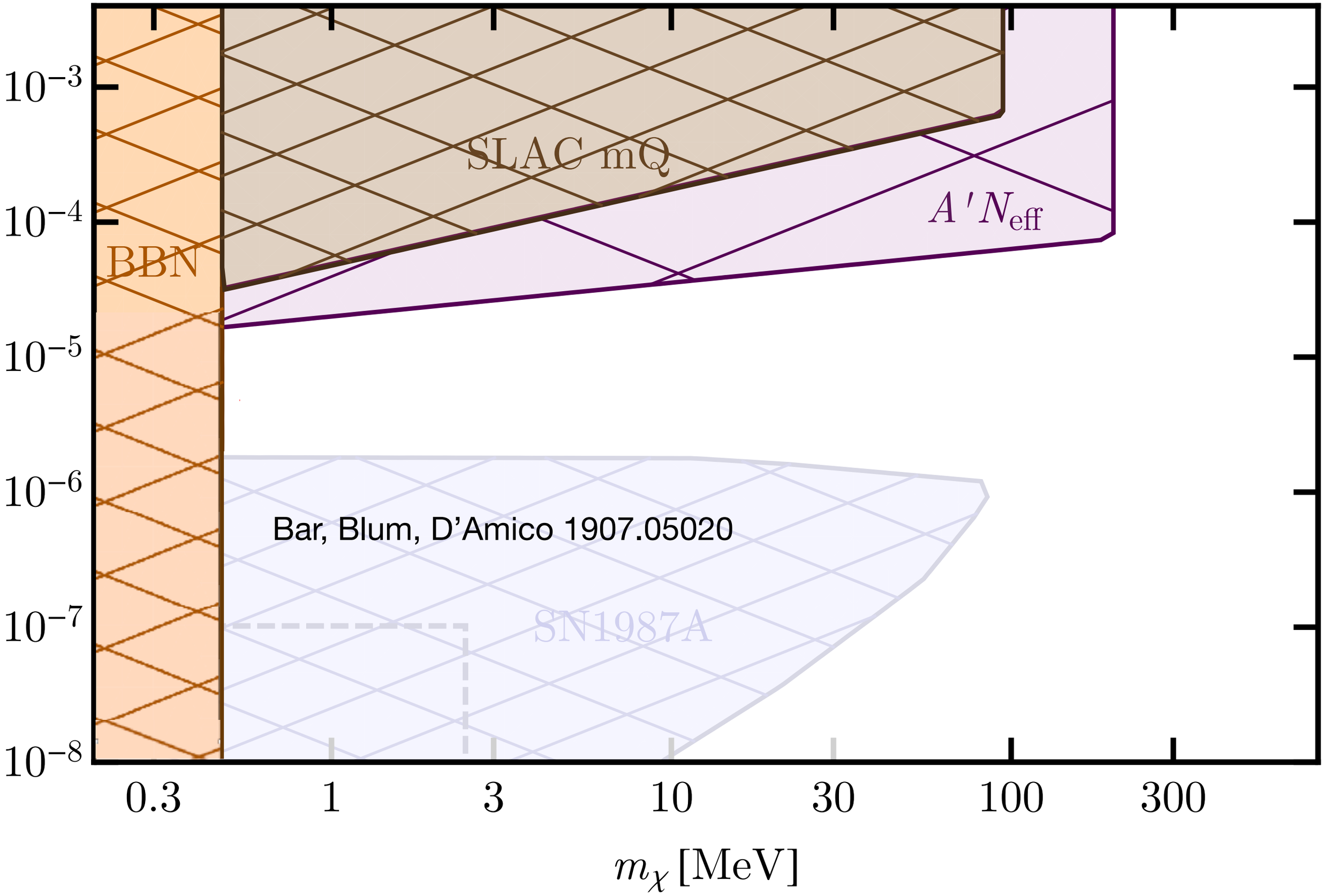
Learning about DM: Depth



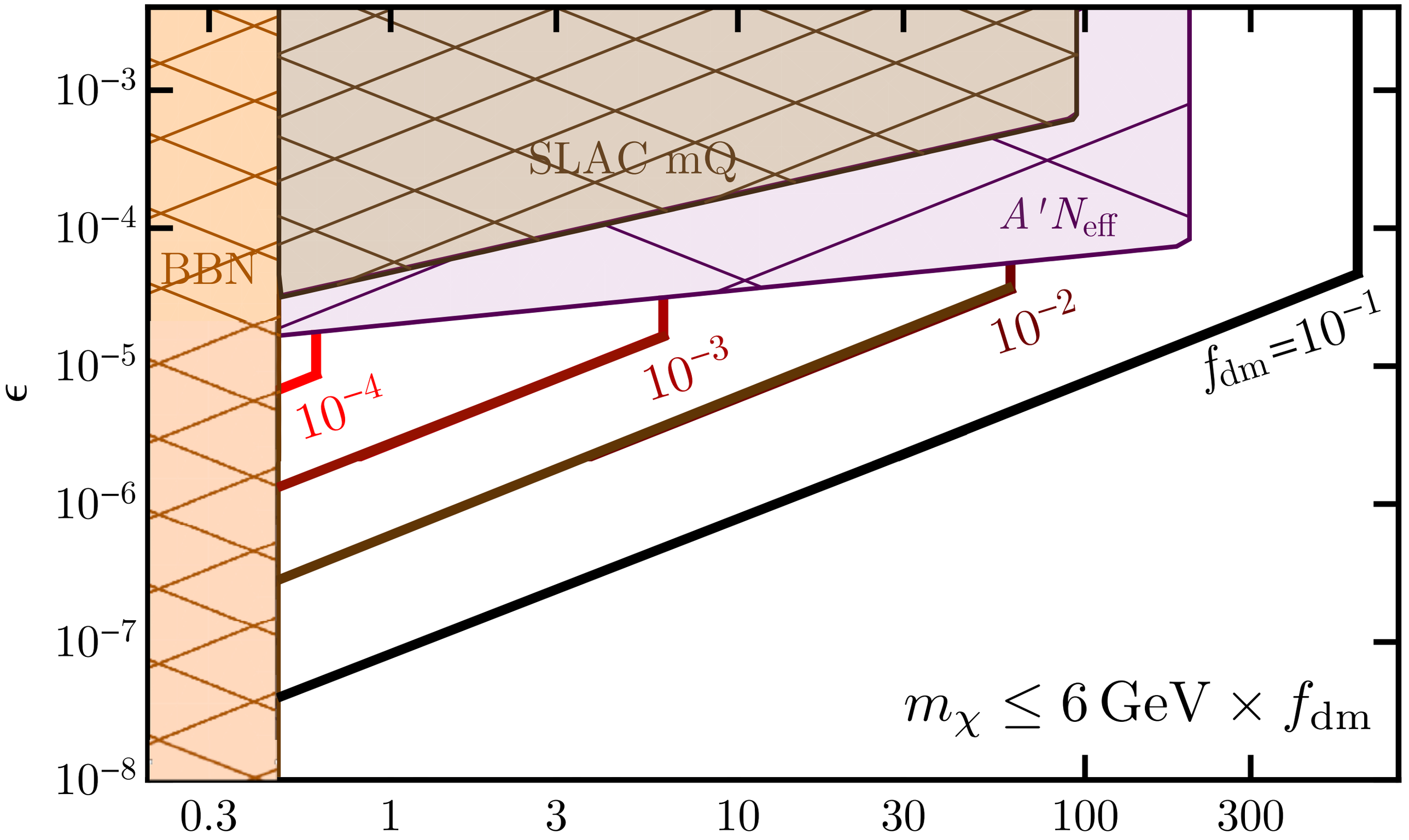
What does the thermostat say?



Learning about DM: Millicharges

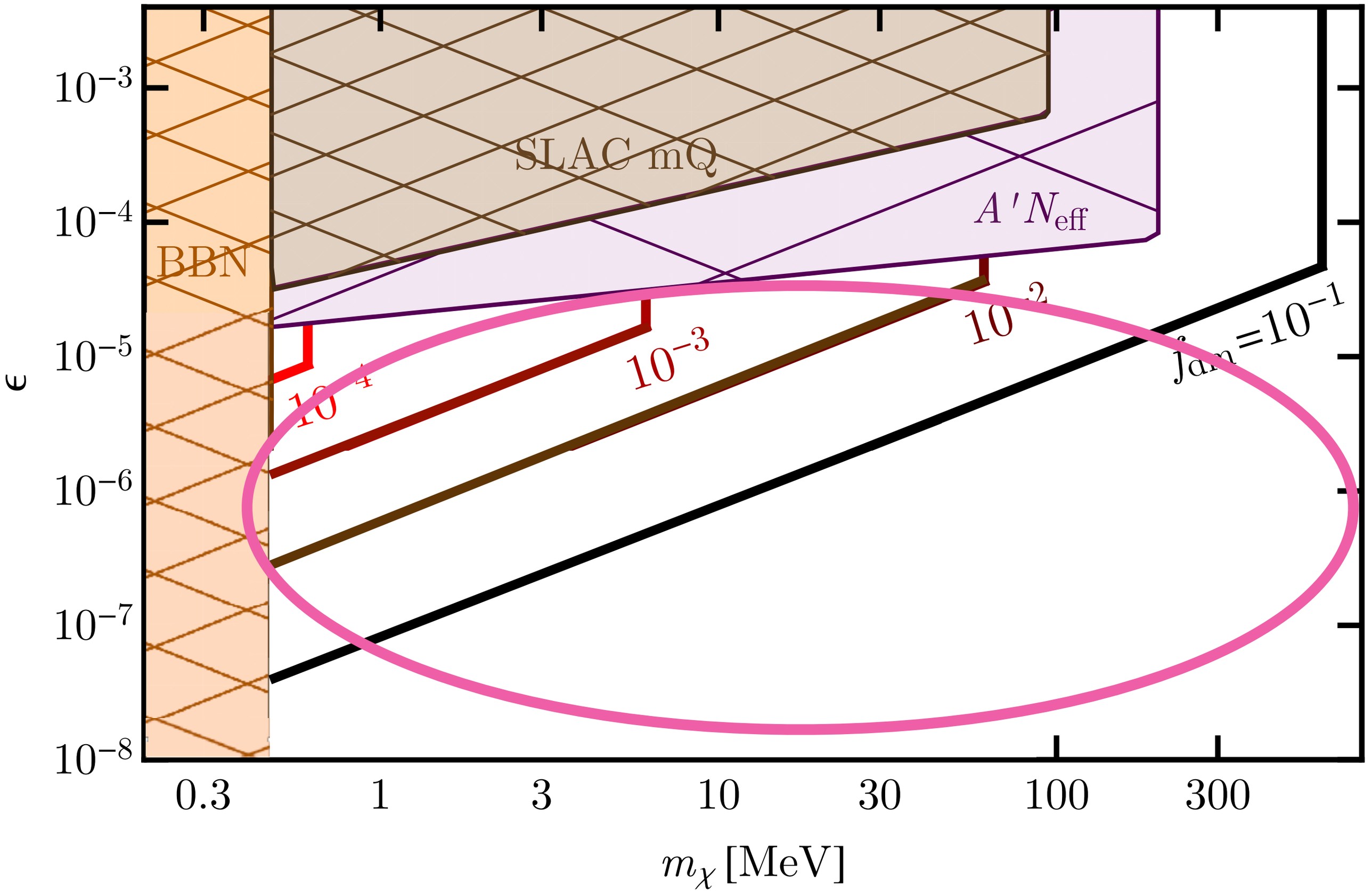


Learning about DM: Millicharges



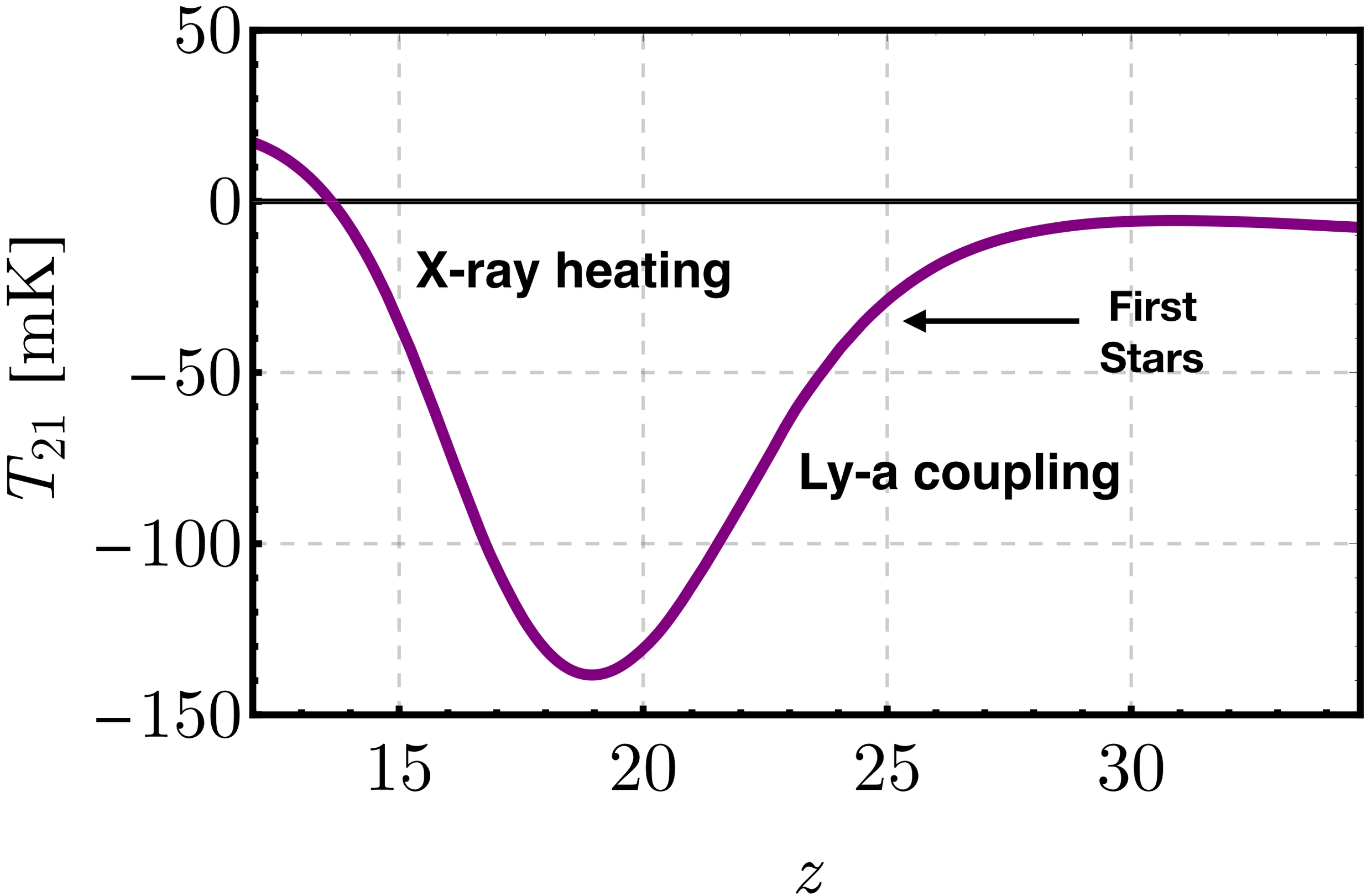
JBM and Loeb 1802.10094

also:
Berlin+ 1803.02804
Liu+ 1908.06986

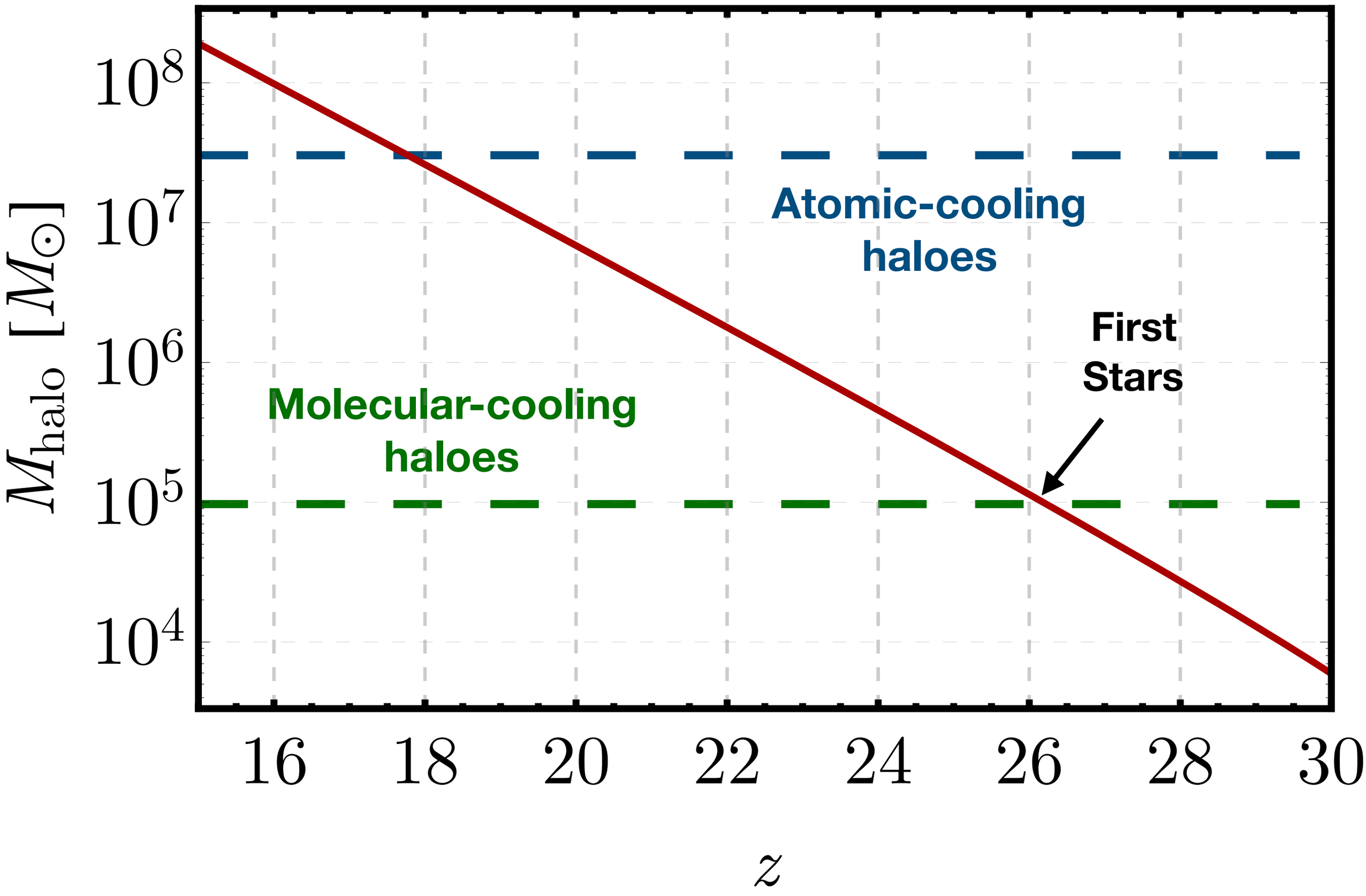


JBM and Loeb 1802.10094

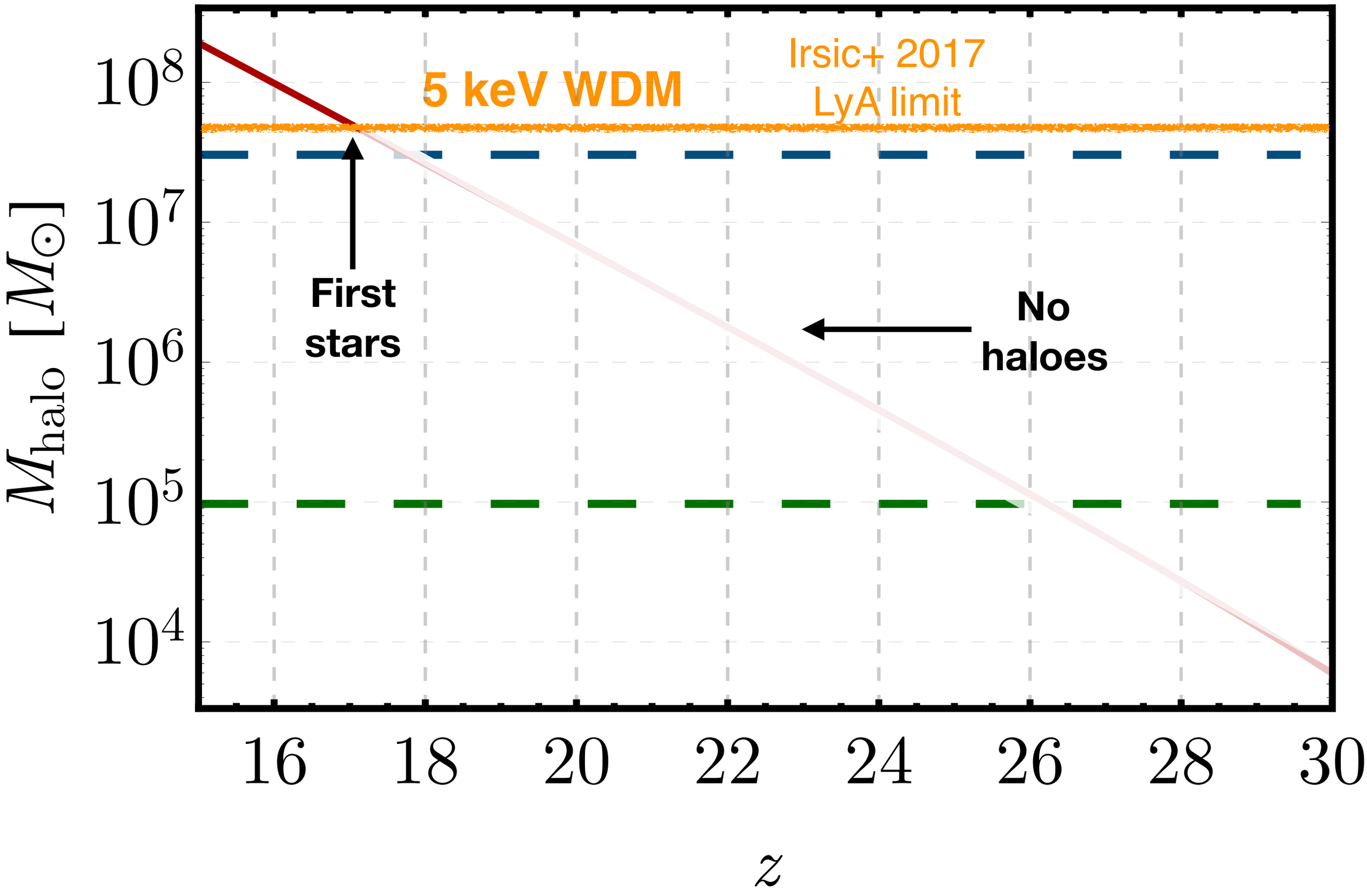
Learning about DM: Timing



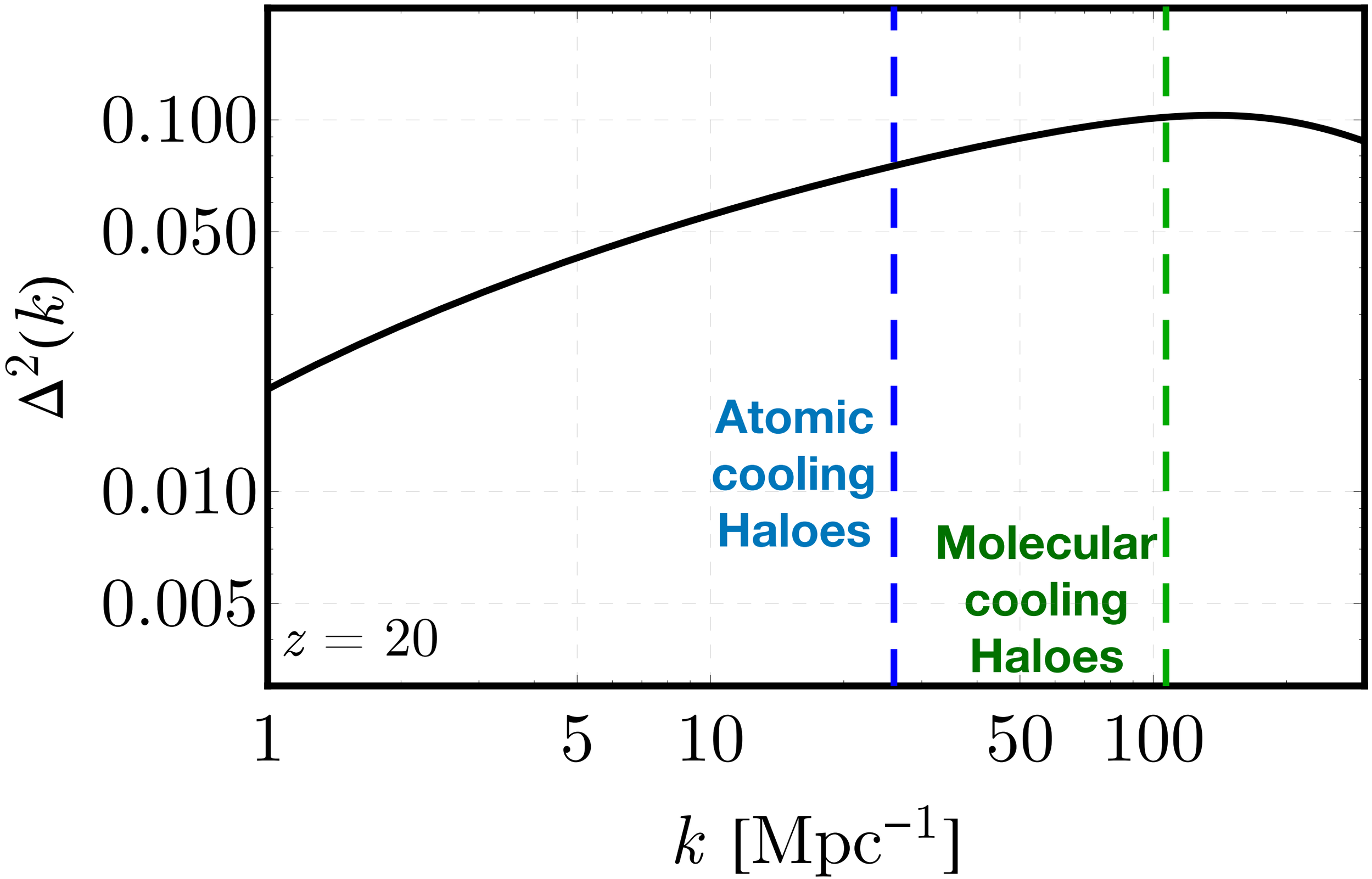
Learning about DM: Timing



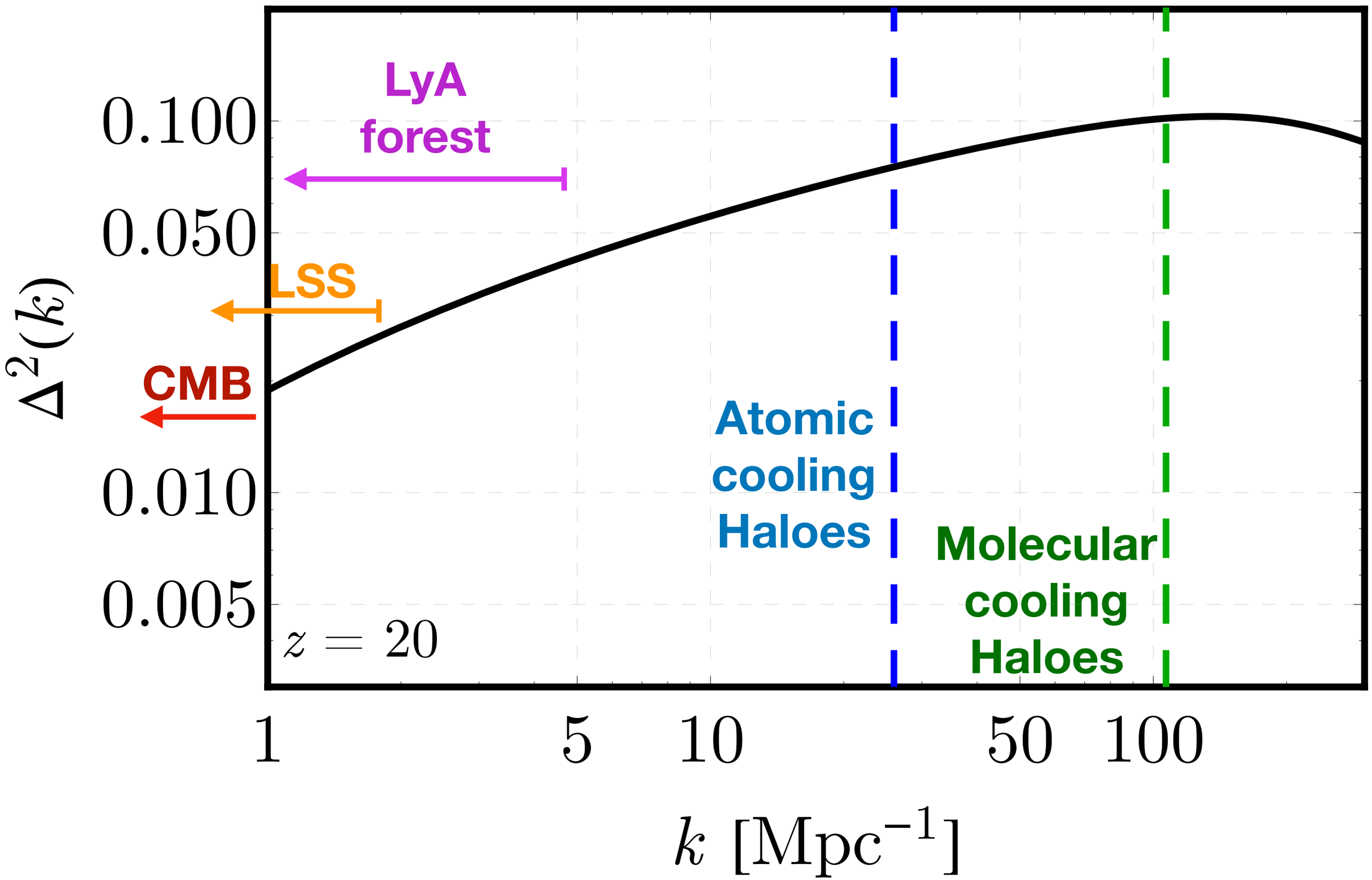
With non-CDM:


5 keV WDM
Irsic+ 2017
LyA limit
First
stars
No
haloes
$M_{\rm halo}\ [M_\odot]$
10^8
10^7
10^6
10^5
10^4
16
18
20
22
24
26
28
30
z

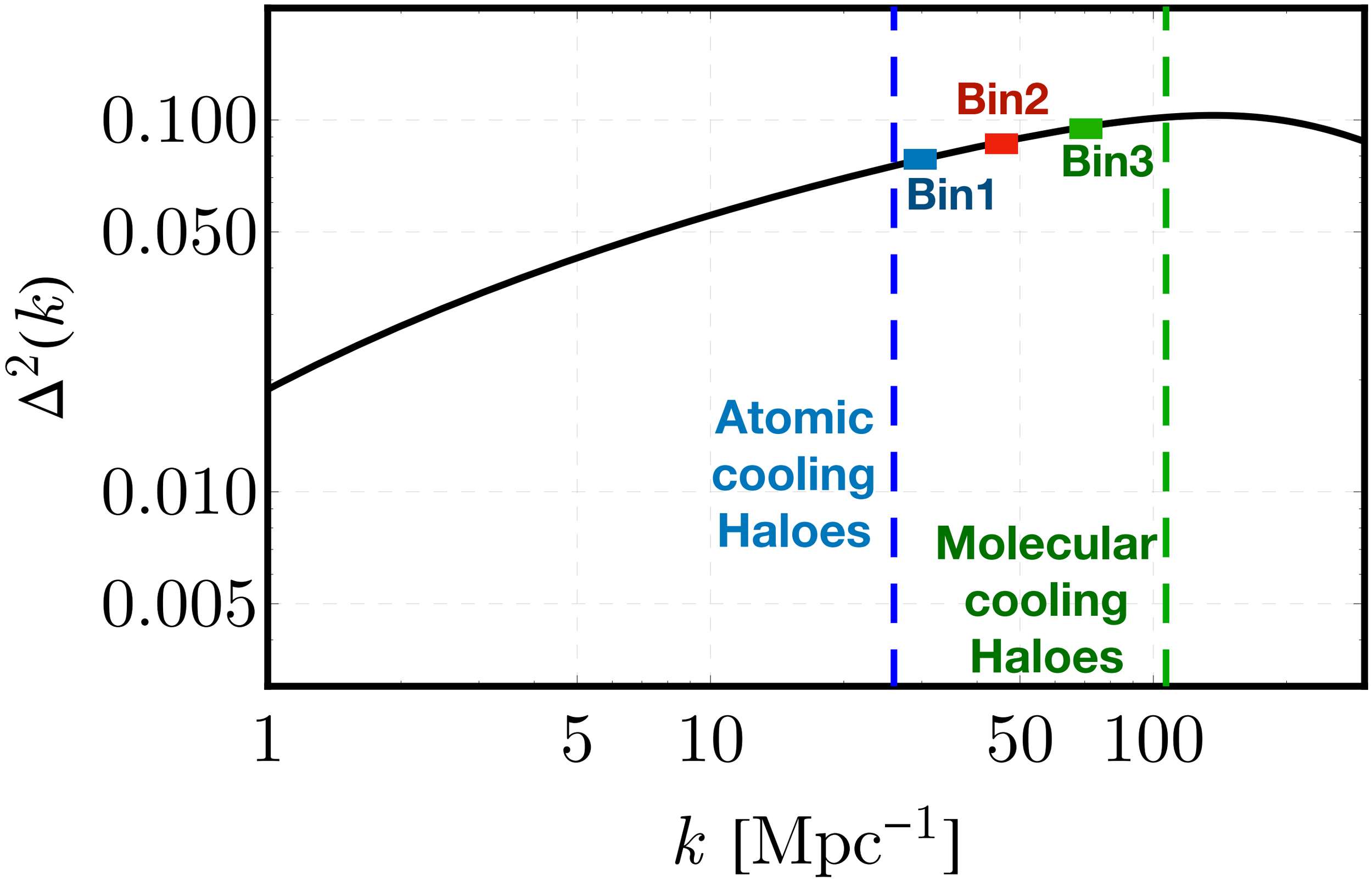
The small-scale matter power spectrum



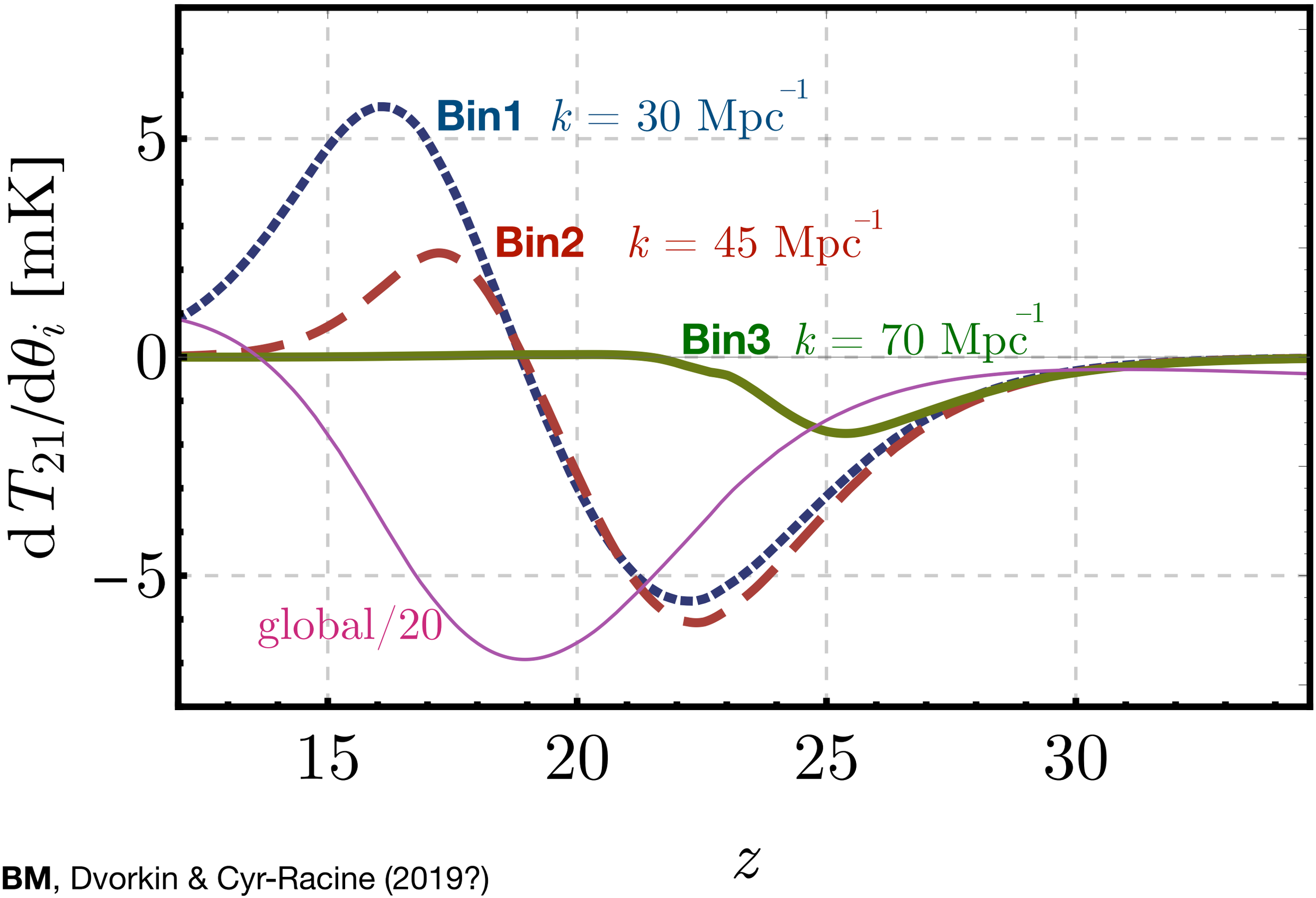
LCDM small-scale power spectrum



LCDM small-scale power spectrum

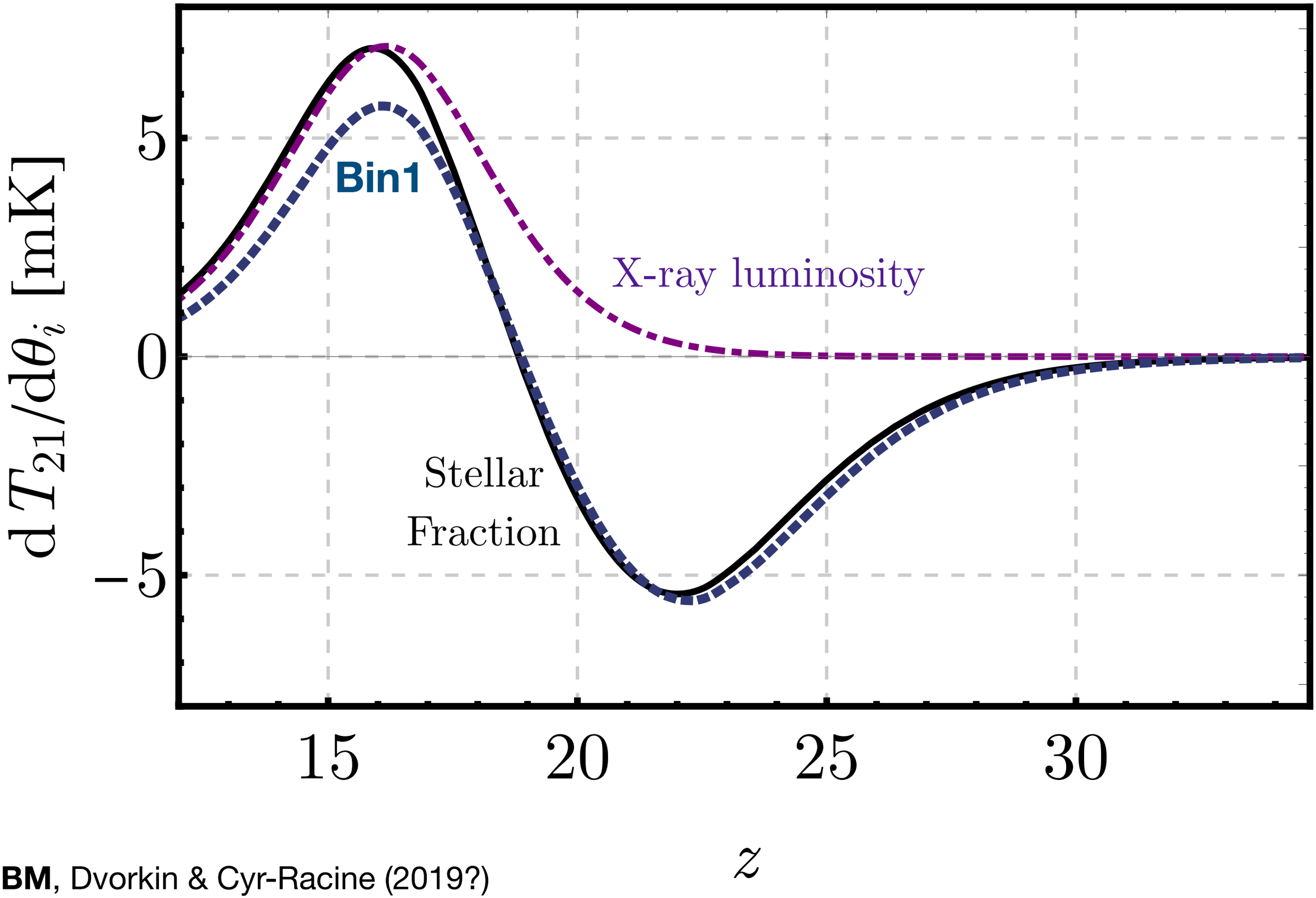


The impact on the 21-cm signal



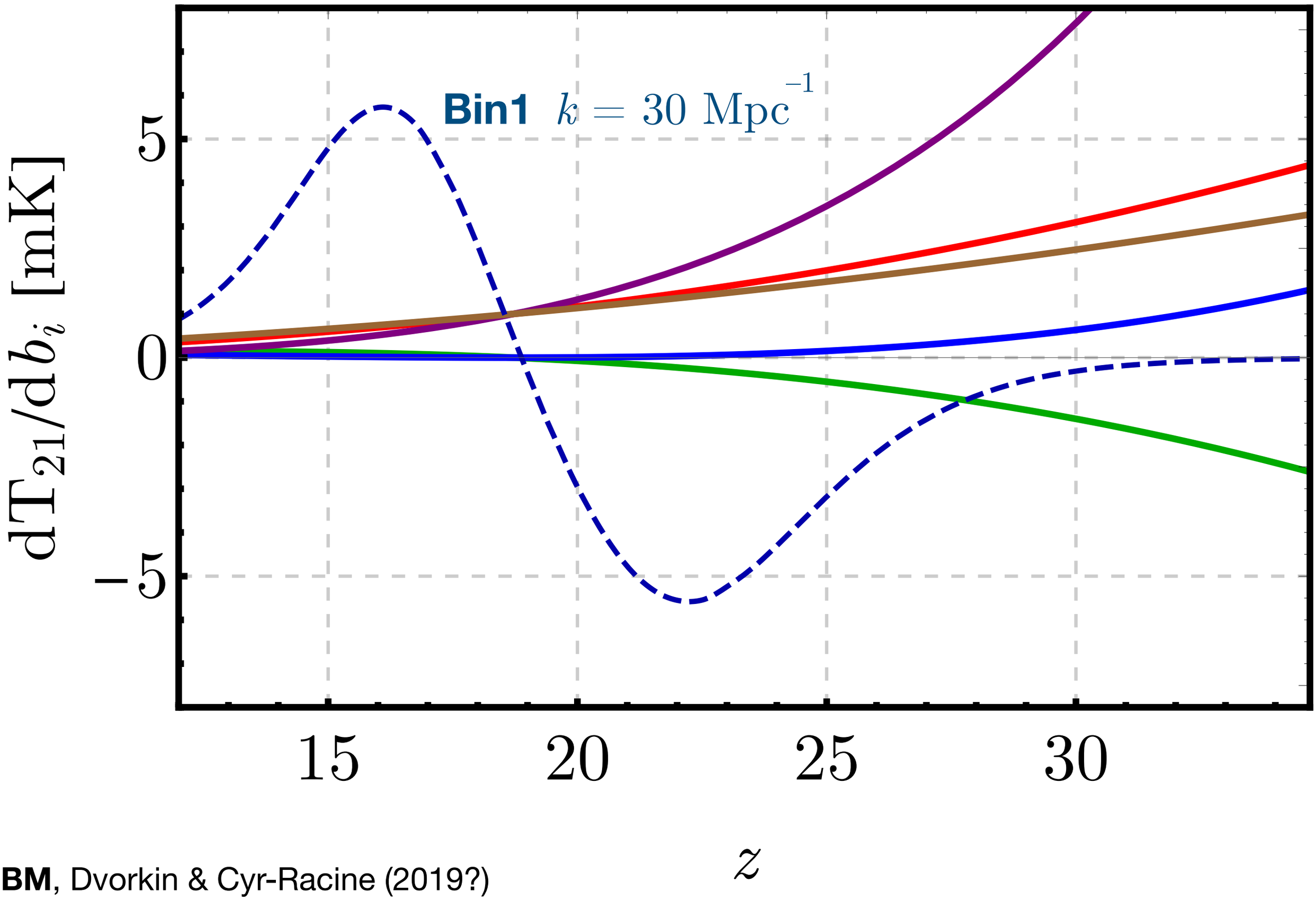
JBM, Dvorkin & Cyr-Racine (2019?)

But astrophysics, though…



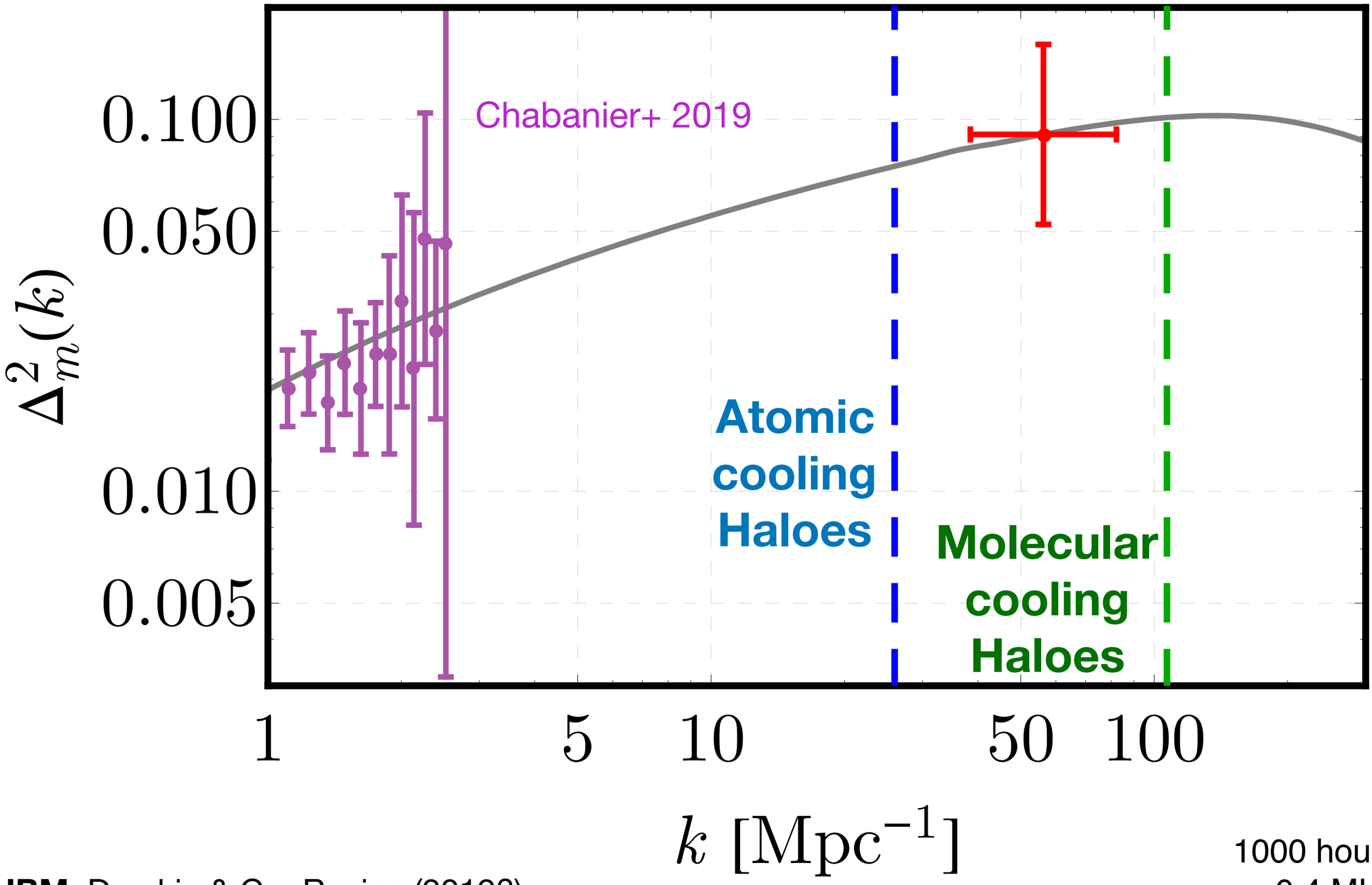
JBM, Dvorkin & Cyr-Racine (2019?)

And foregrounds…



JBM, Dvorkin & Cyr-Racine (2019?)

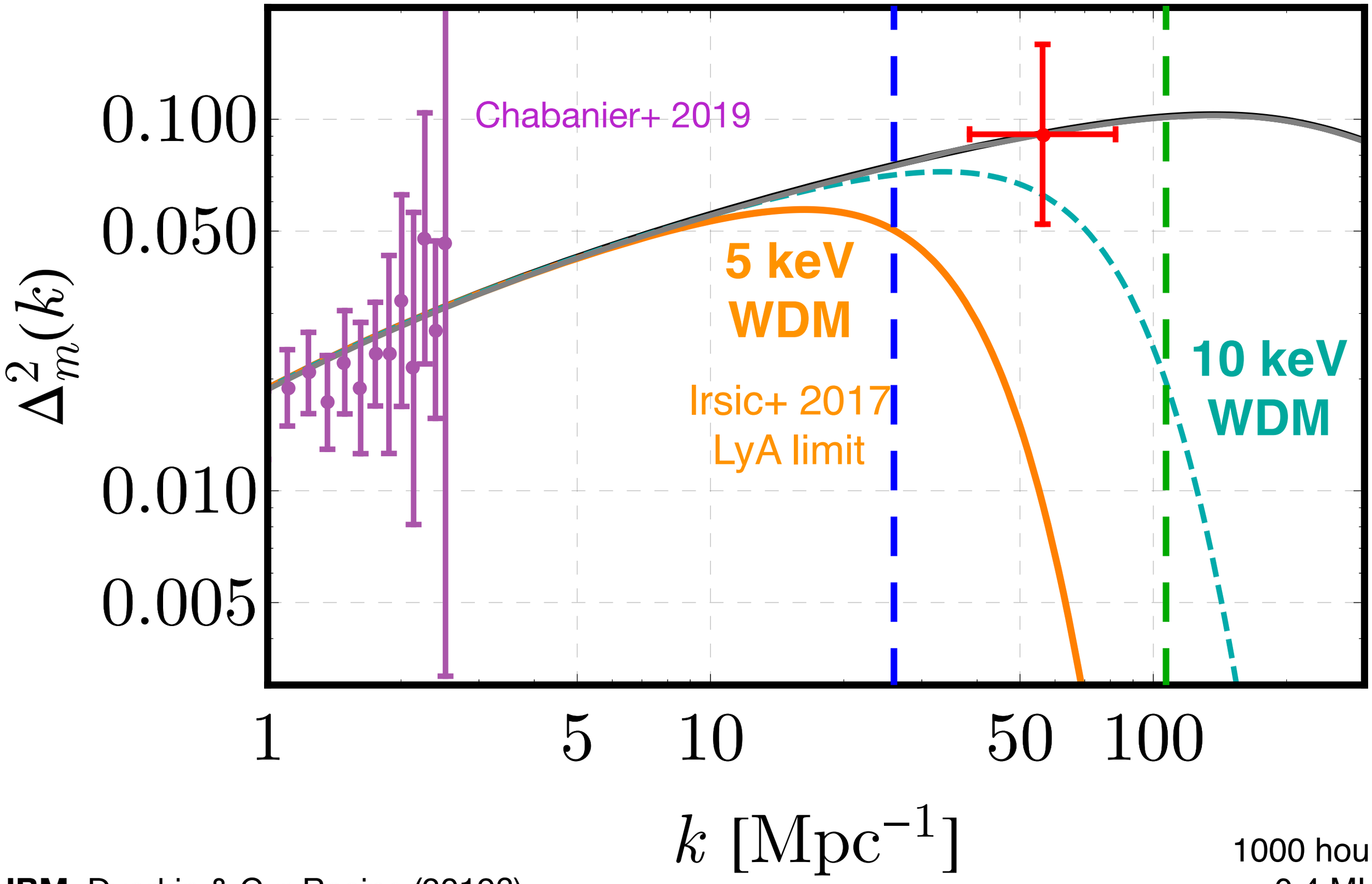
Forecasted errors in matter power



JBM, Dvorkin & Cyr-Racine (2019?)

1000 hours
0.4 MHz

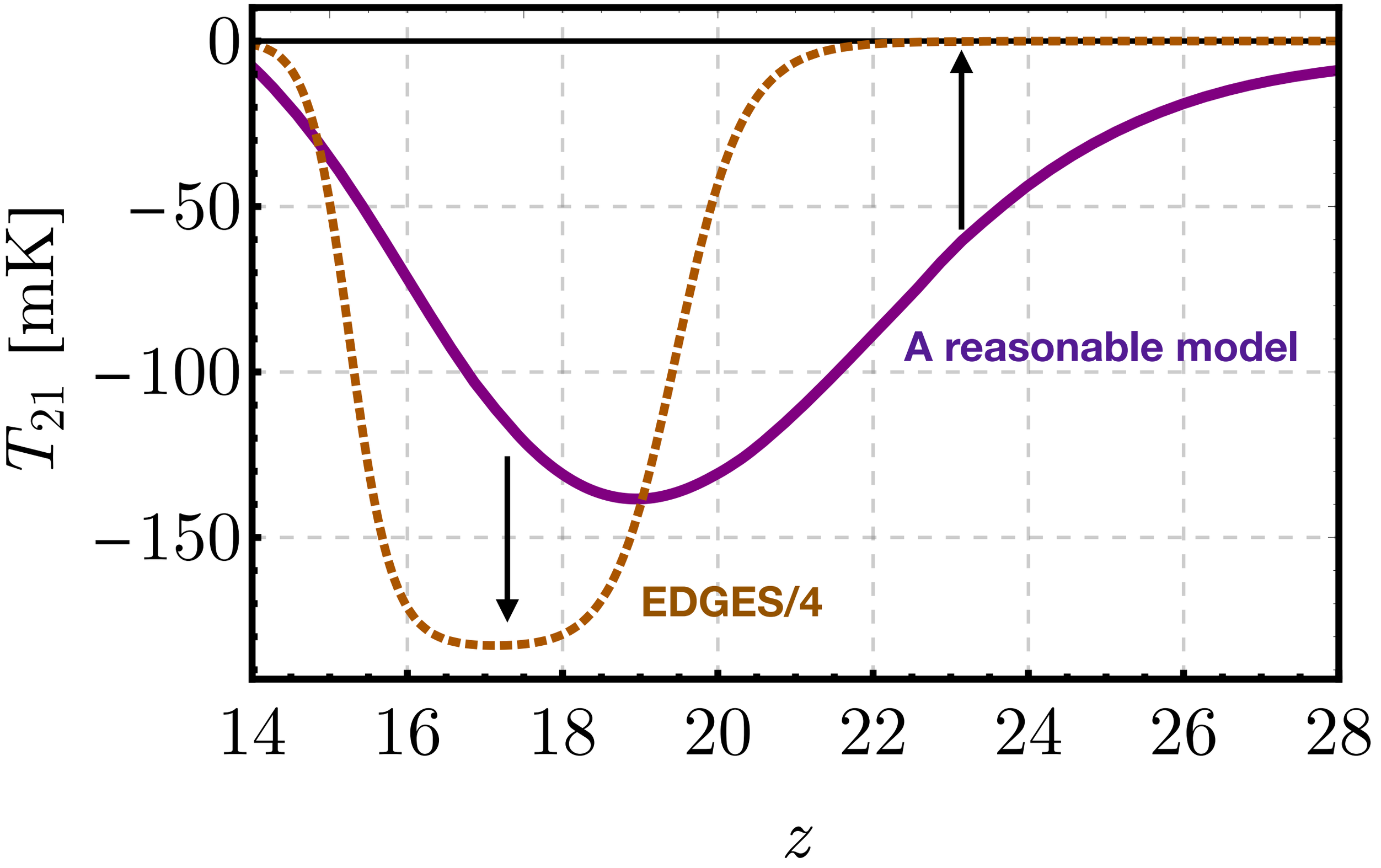
An example of non-CDM constraint



JBM, Dvorkin & Cyr-Racine (2019?)

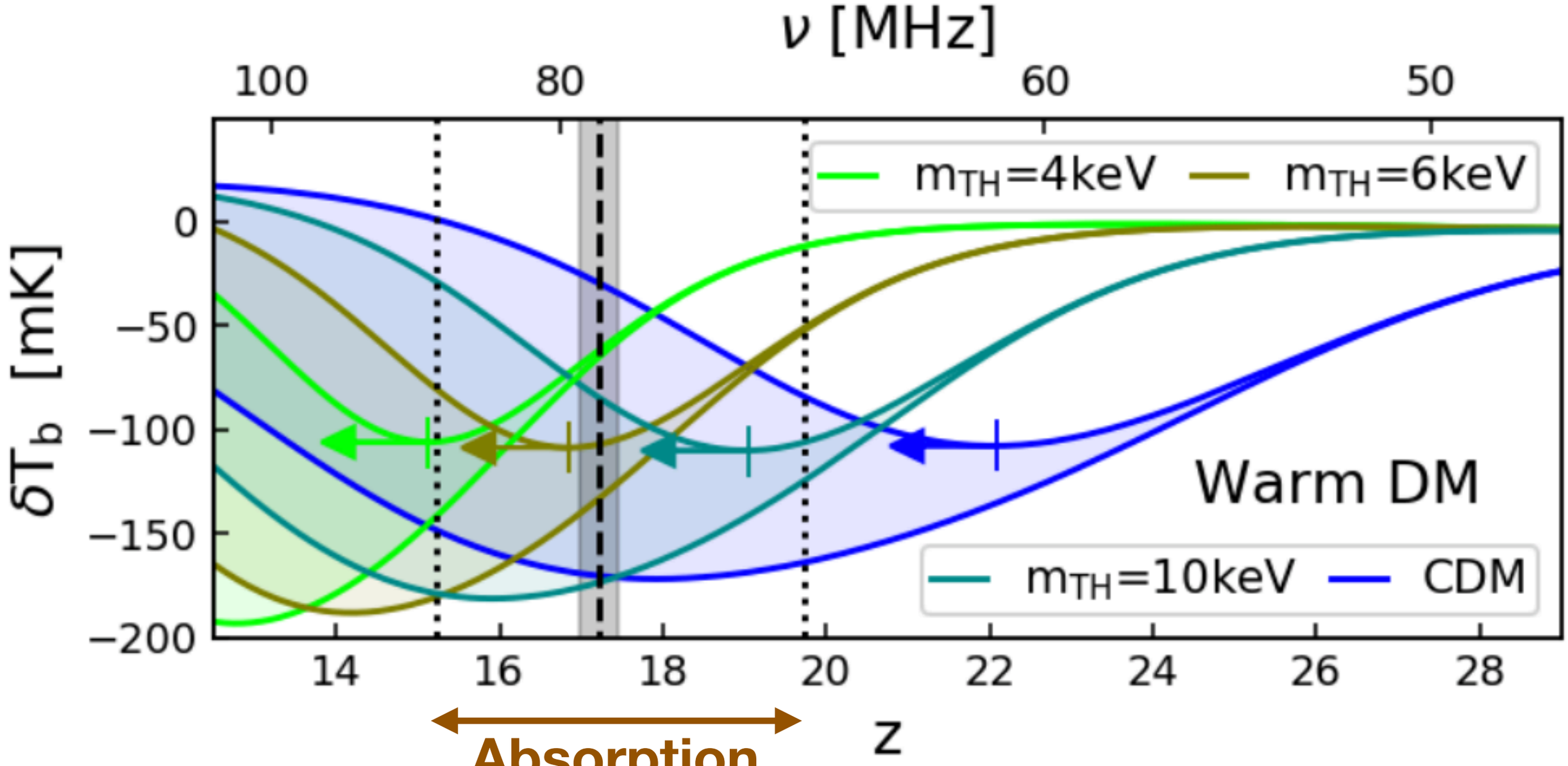
1000 hours
0.4 MHz

But what about EDGES?



Kaurov+ 2018

If you just focus on the centroid:



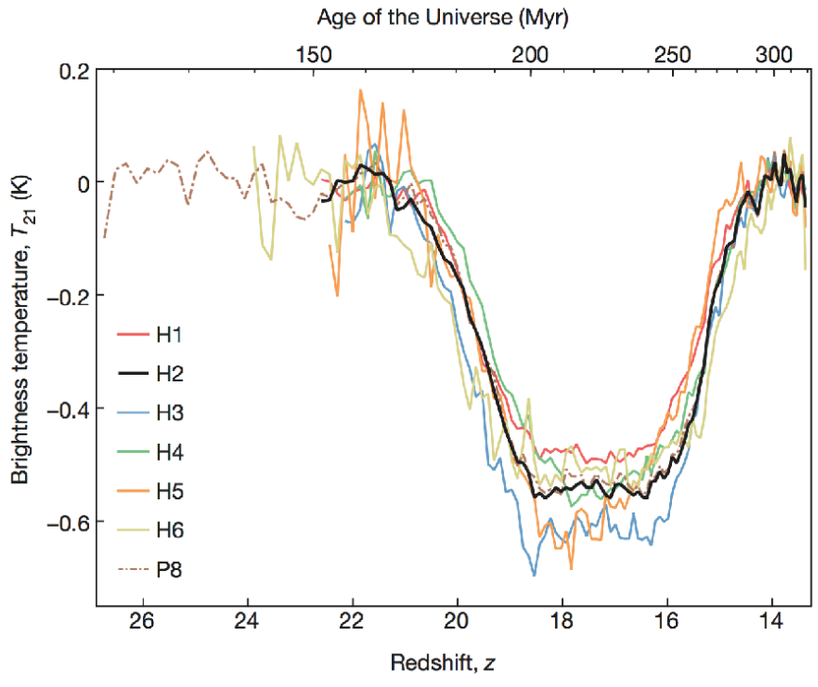
$m_{WDM} > 6$ keV

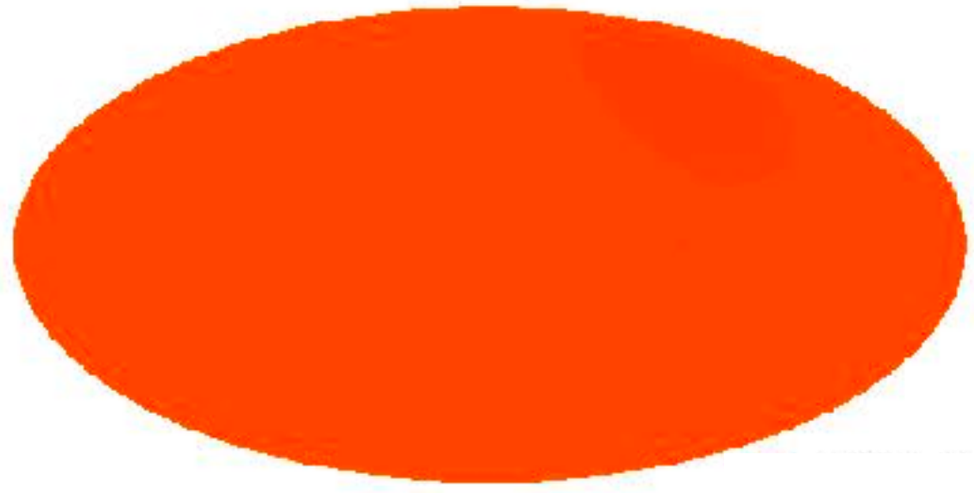
Credit: Schneider 2018

<u>also:</u>
Safarzadeh+ 2018
Lidz & Hui 2018
Boyarsky+ 2018
Yoshiura+ 2018

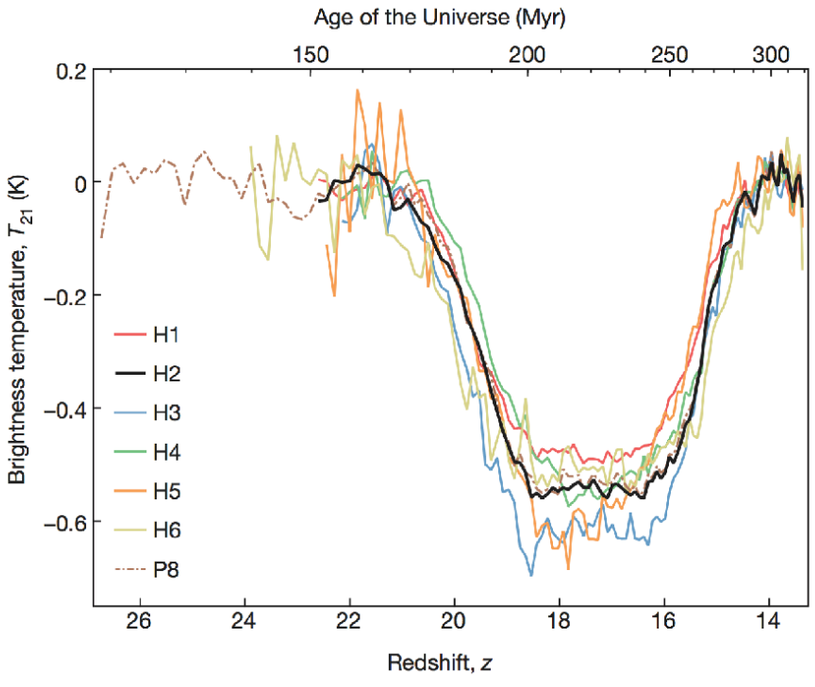
The 21-cm fluctuations

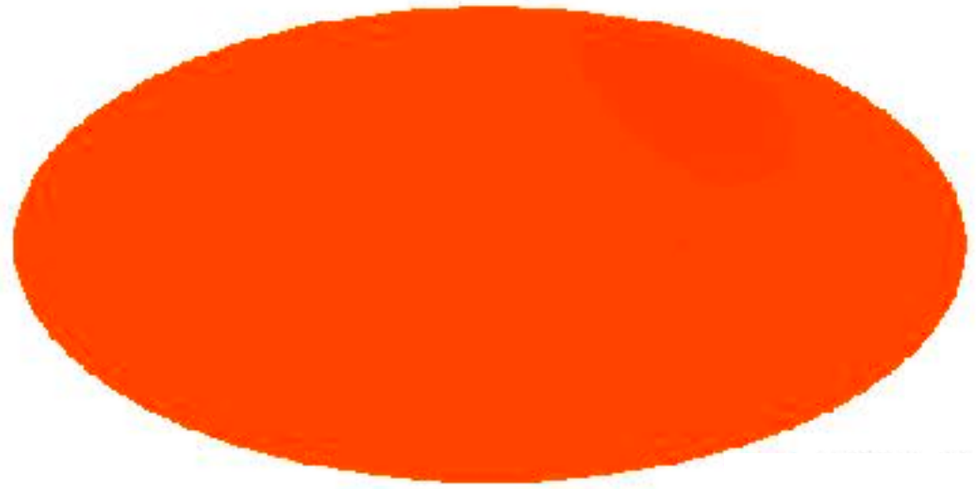
21-cm Global Signal = CMB Monopole



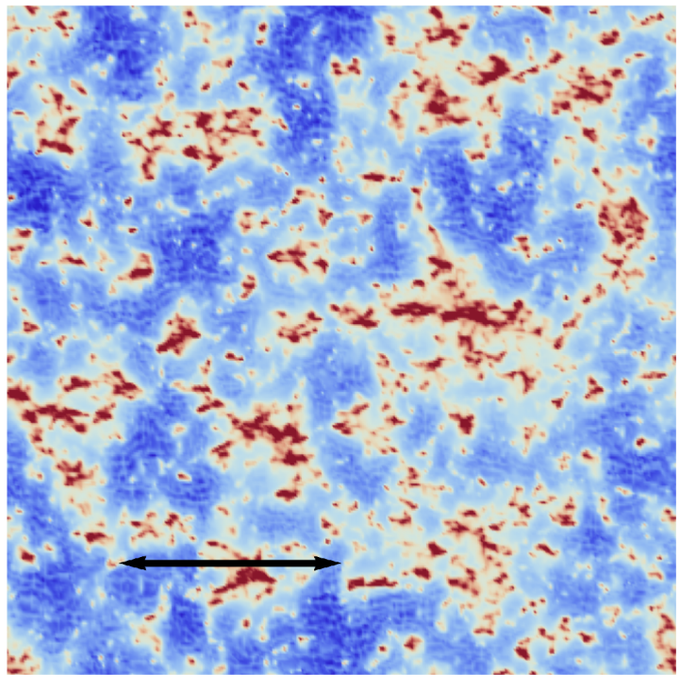


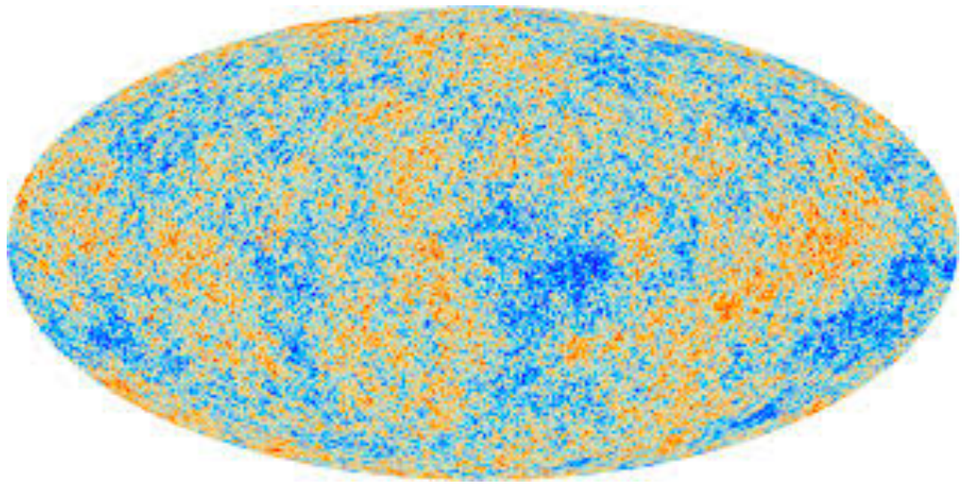
21-cm Global Signal = CMB Monopole



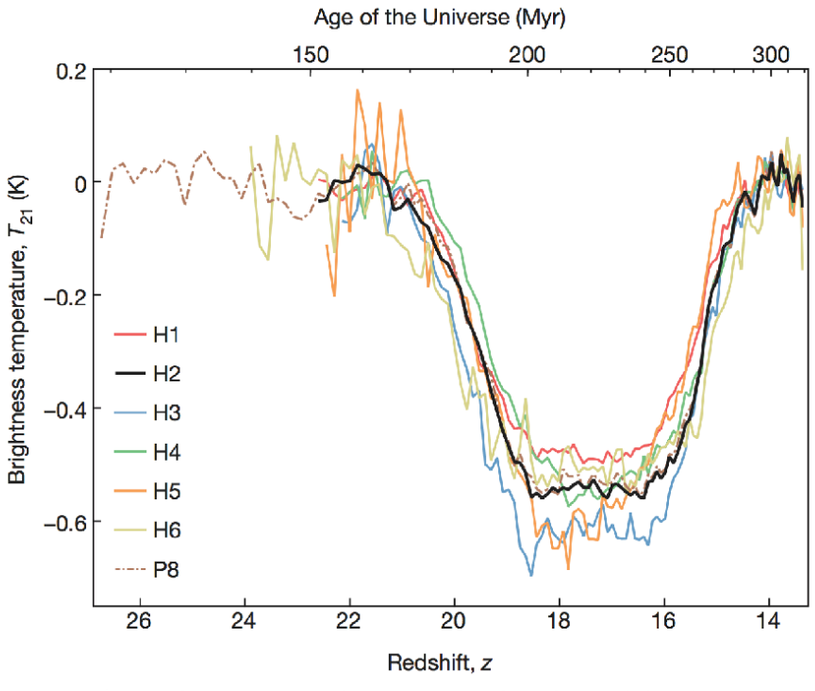


21-cm Fluctuations = CMB Anisotropies

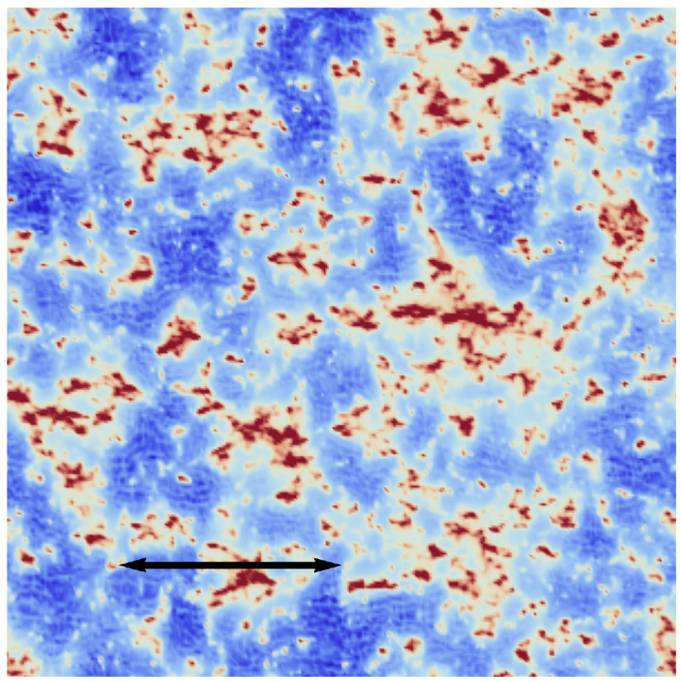




Is this observable?



1 antenna
~100 hours



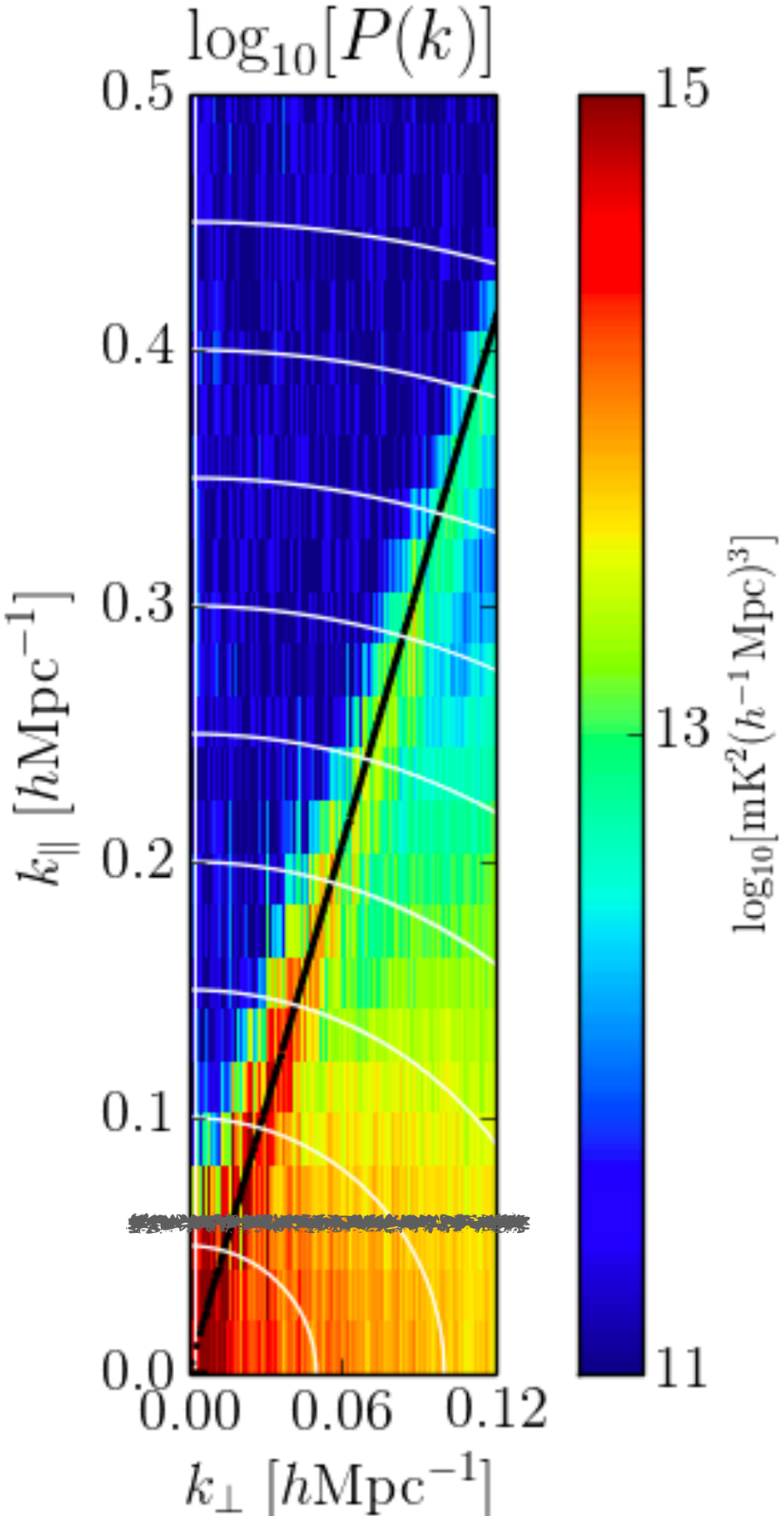
~100 antennae
~1000 hours

Is this observable?

HERA (Hydrogen Epoch of Reionization Array):
350 antennas, 14-m in diameter

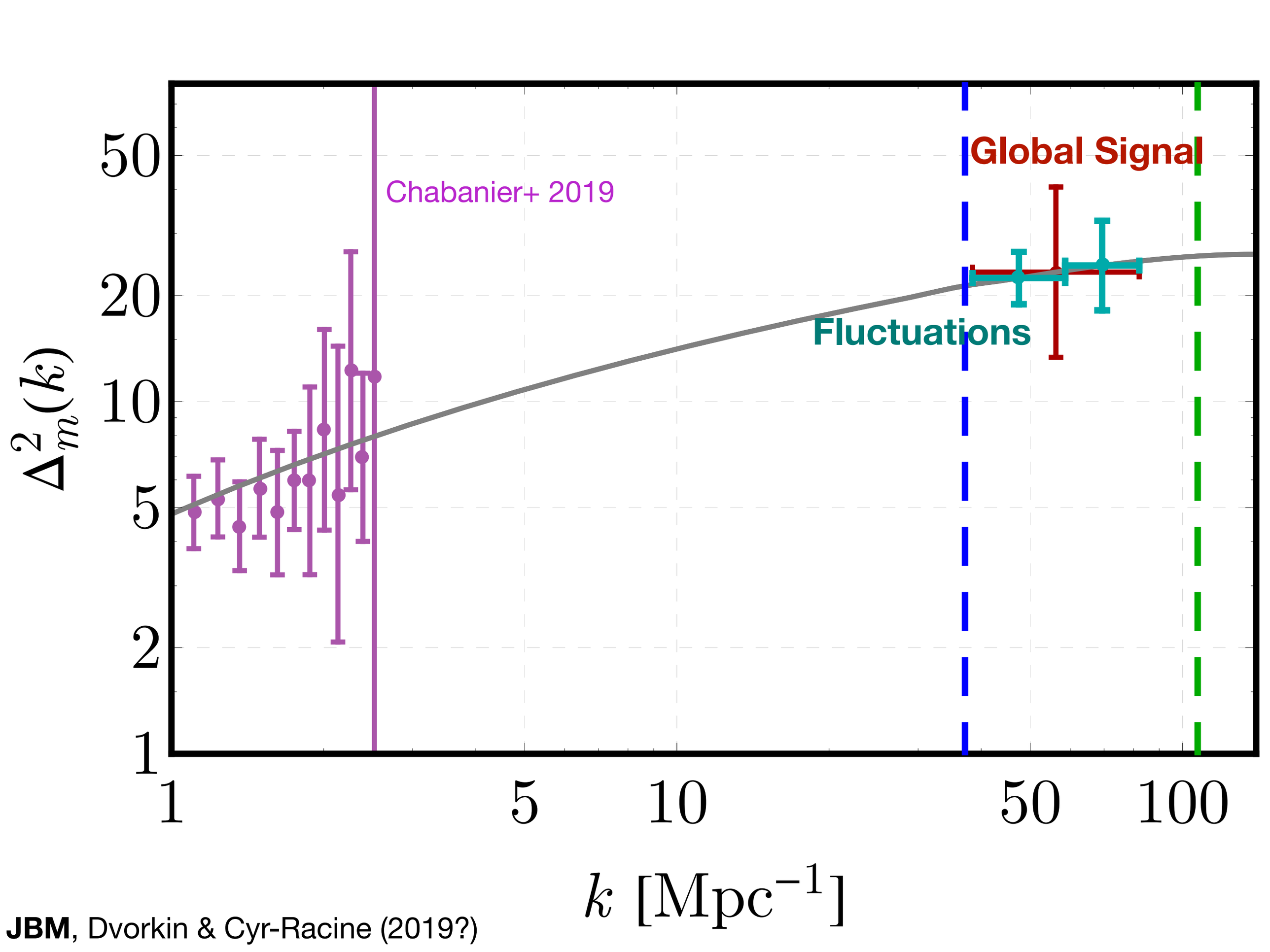
DeBoer+ 2016

Foreground “wedge”



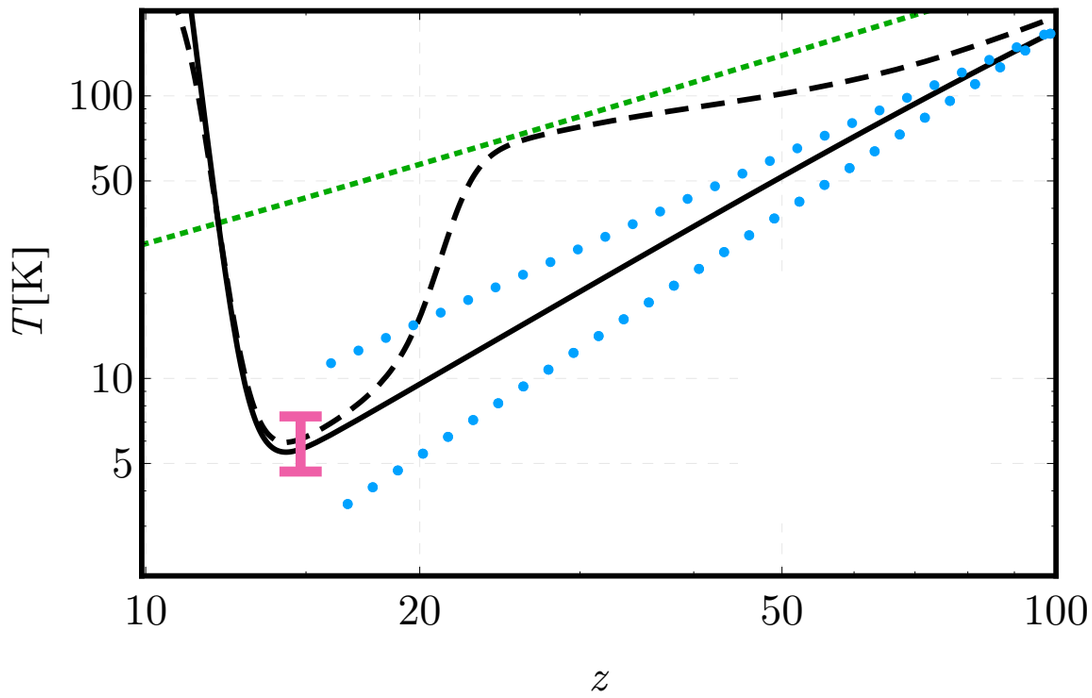
Foregrounds swamp the signal.
Avoid the “wedge”

Pober 2014, PAPER Coll.
Parsons+ 2011

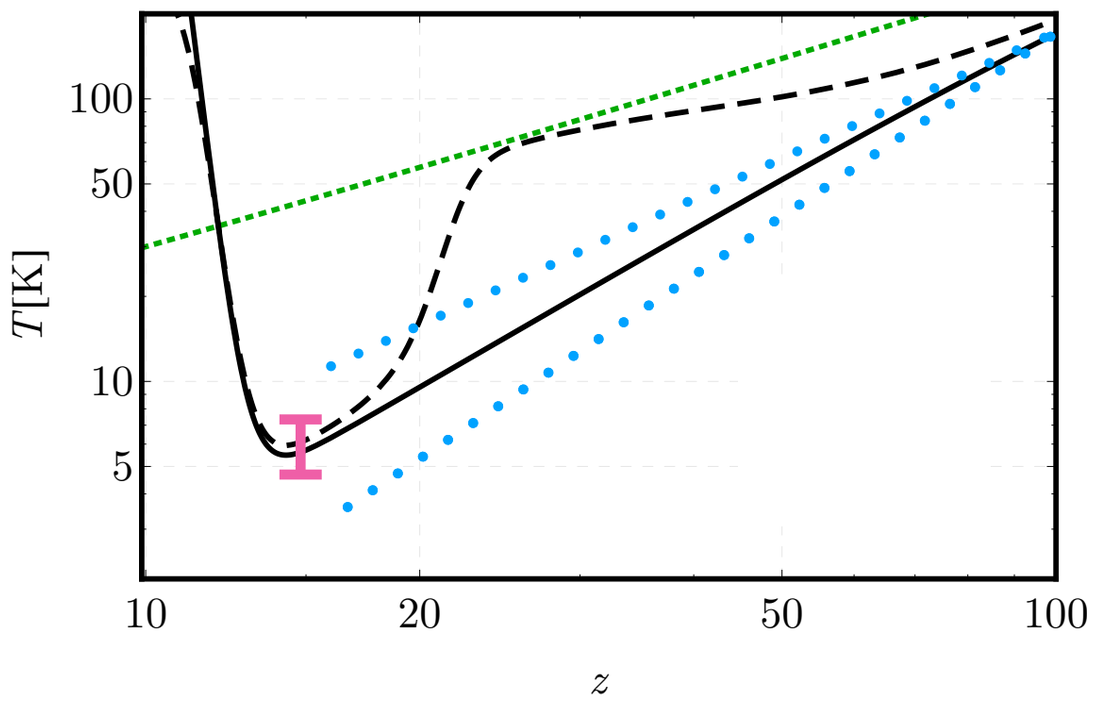


JBM, Dvorkin & Cyr-Racine (2019?)

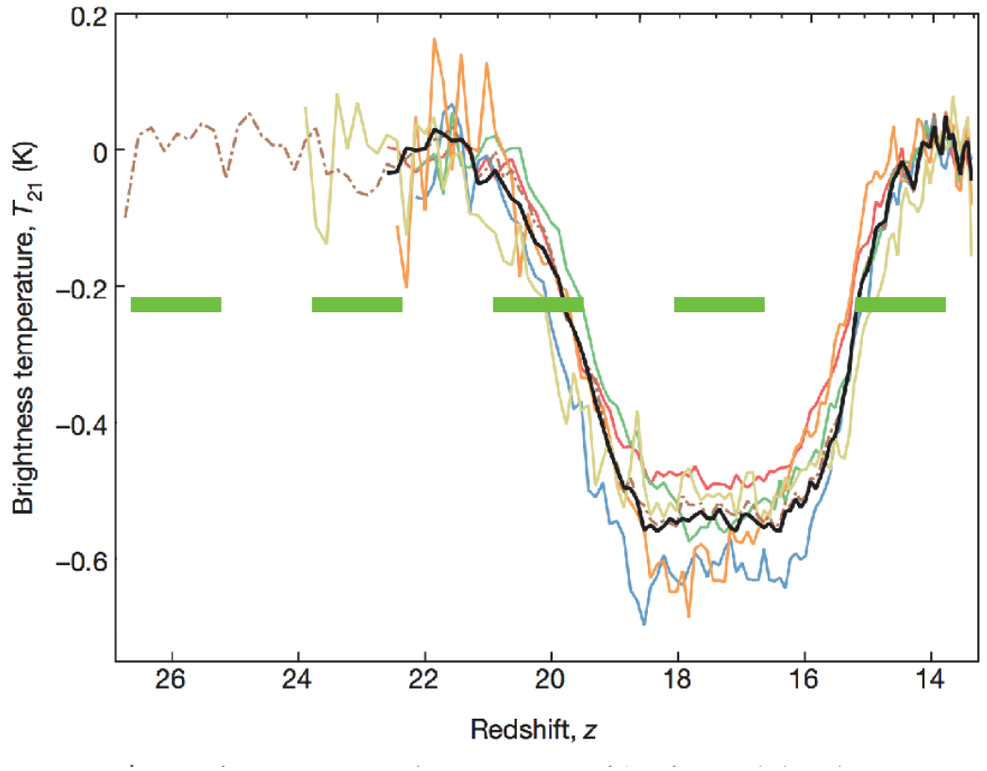
Summary



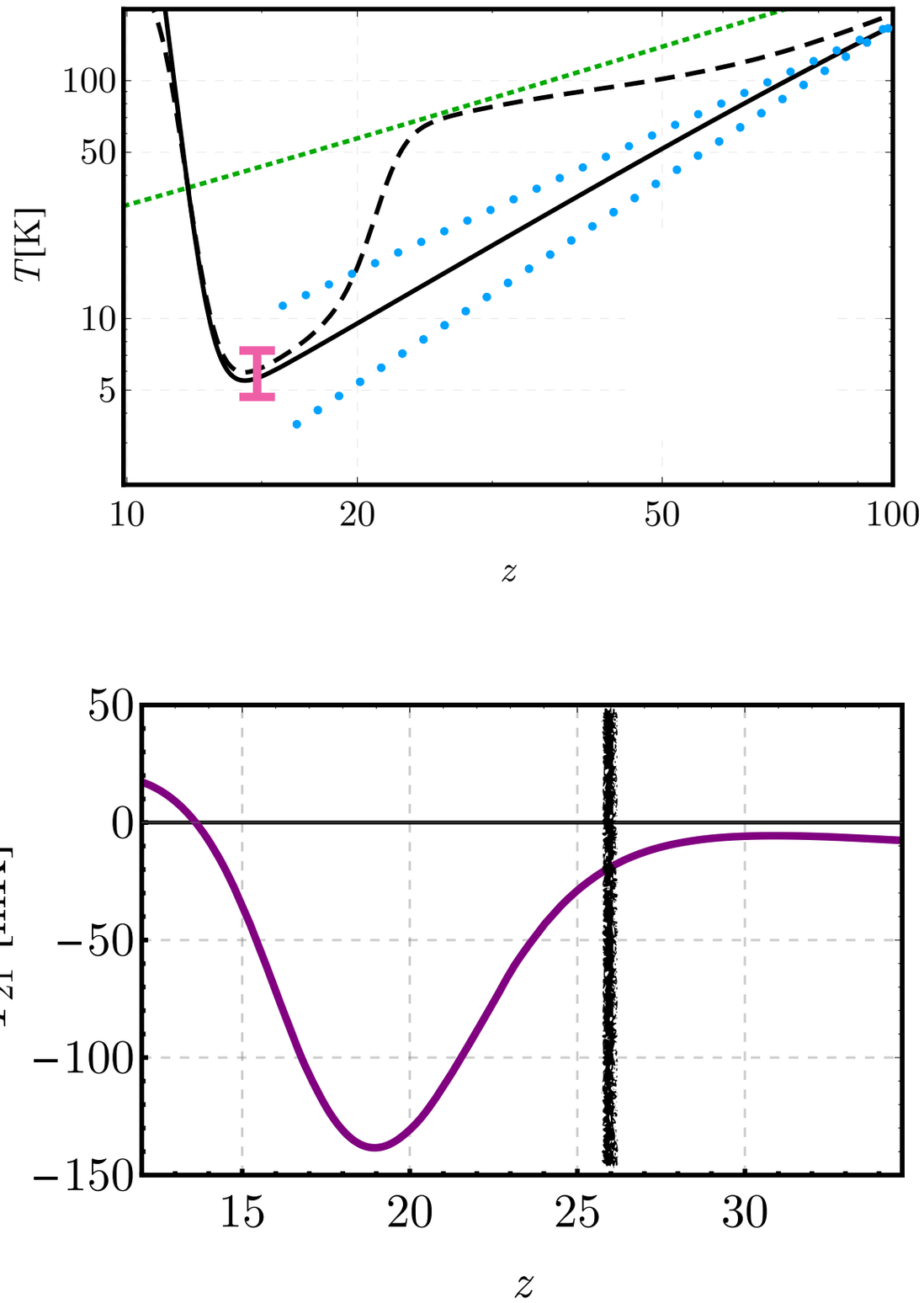
Summary



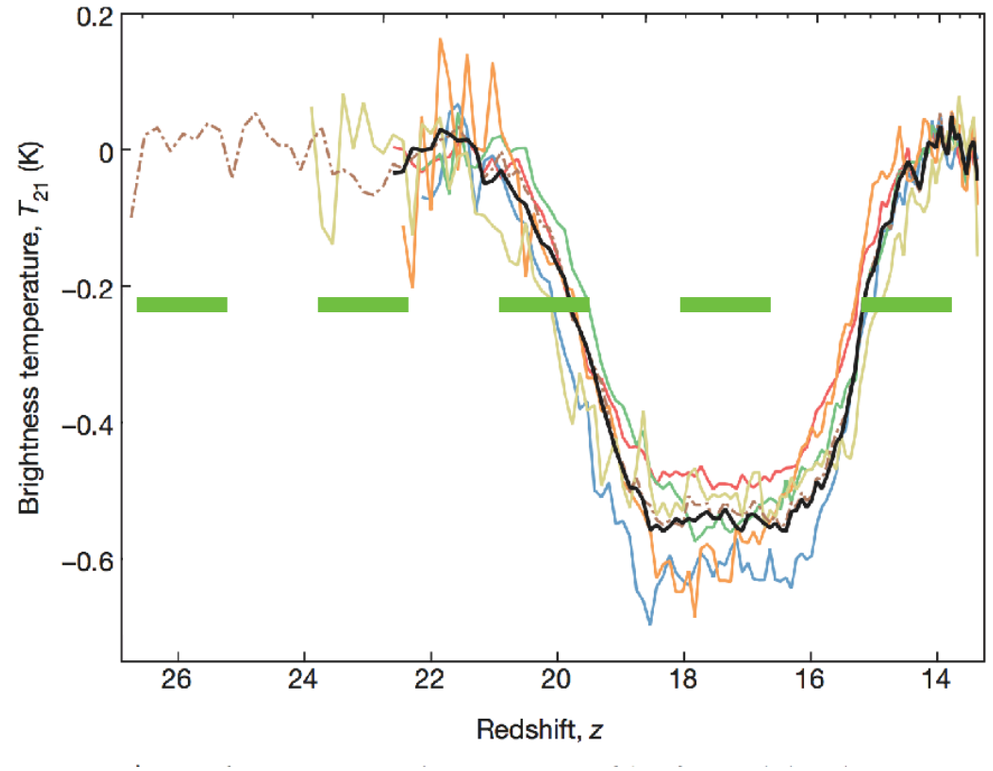
EDGES*



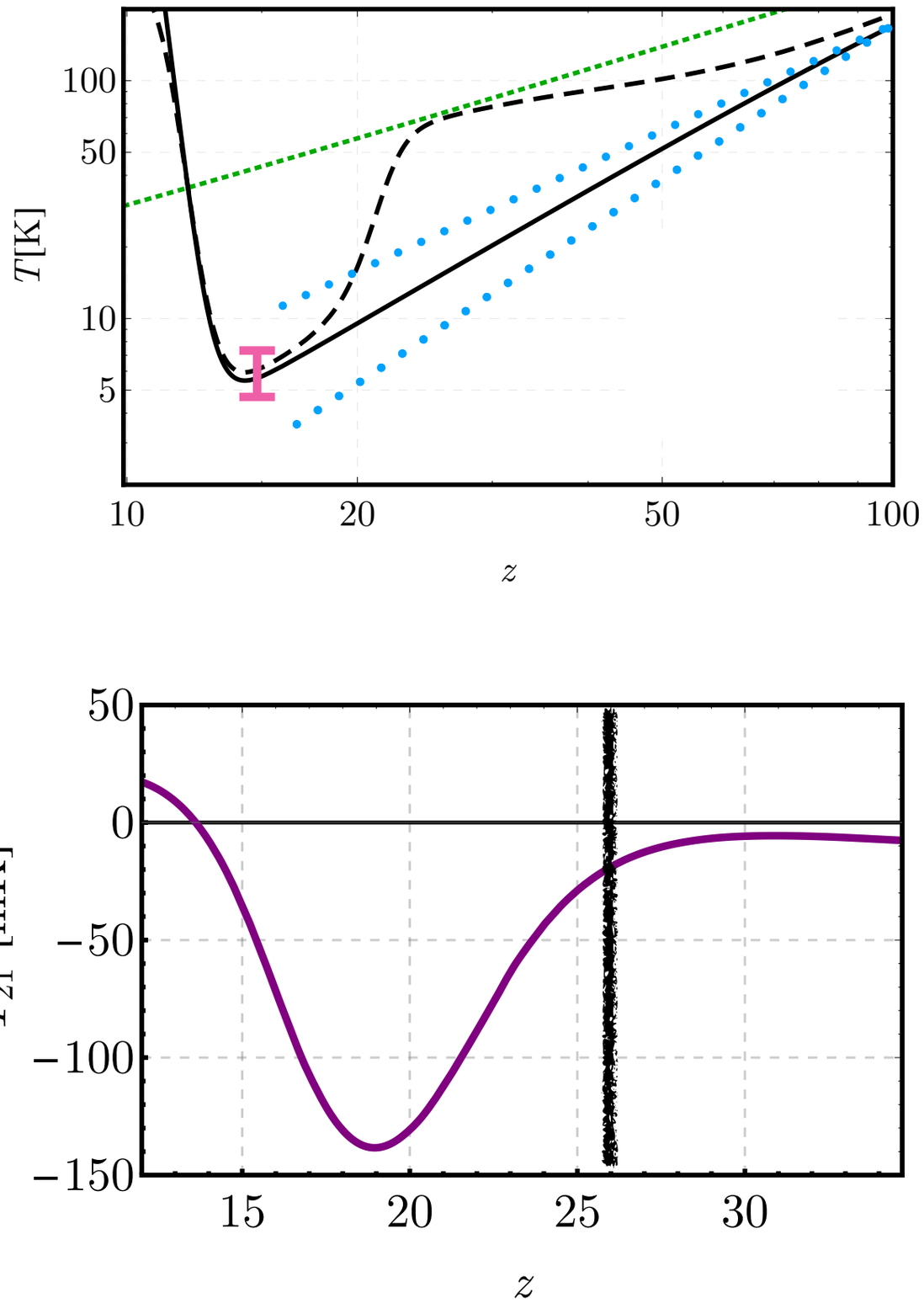
Summary



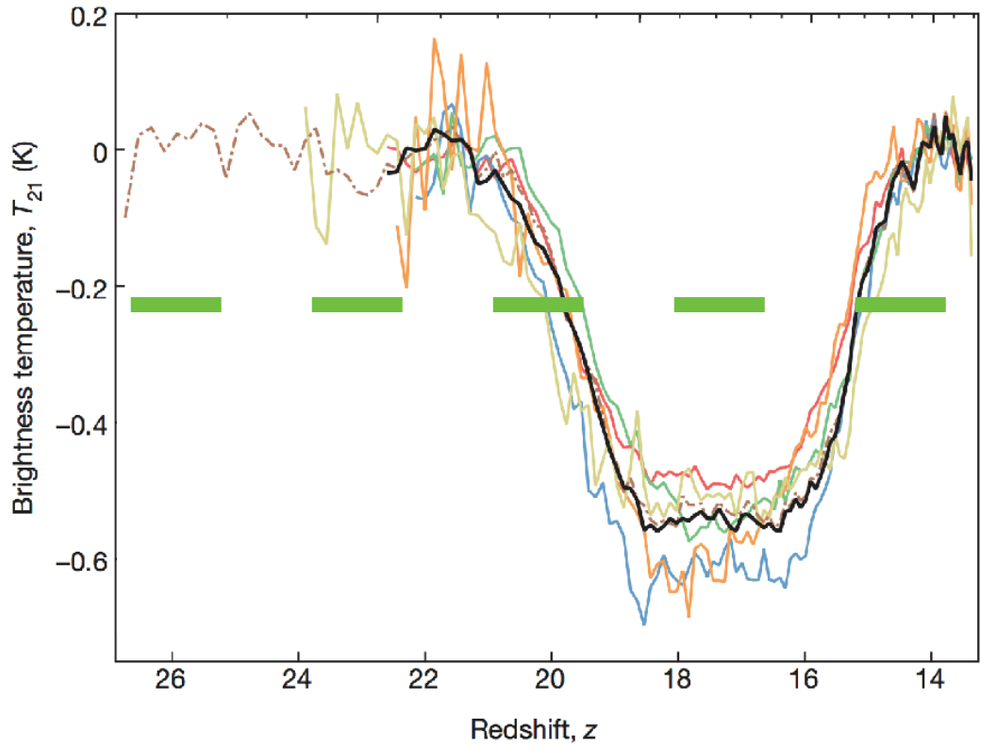
EDGES*

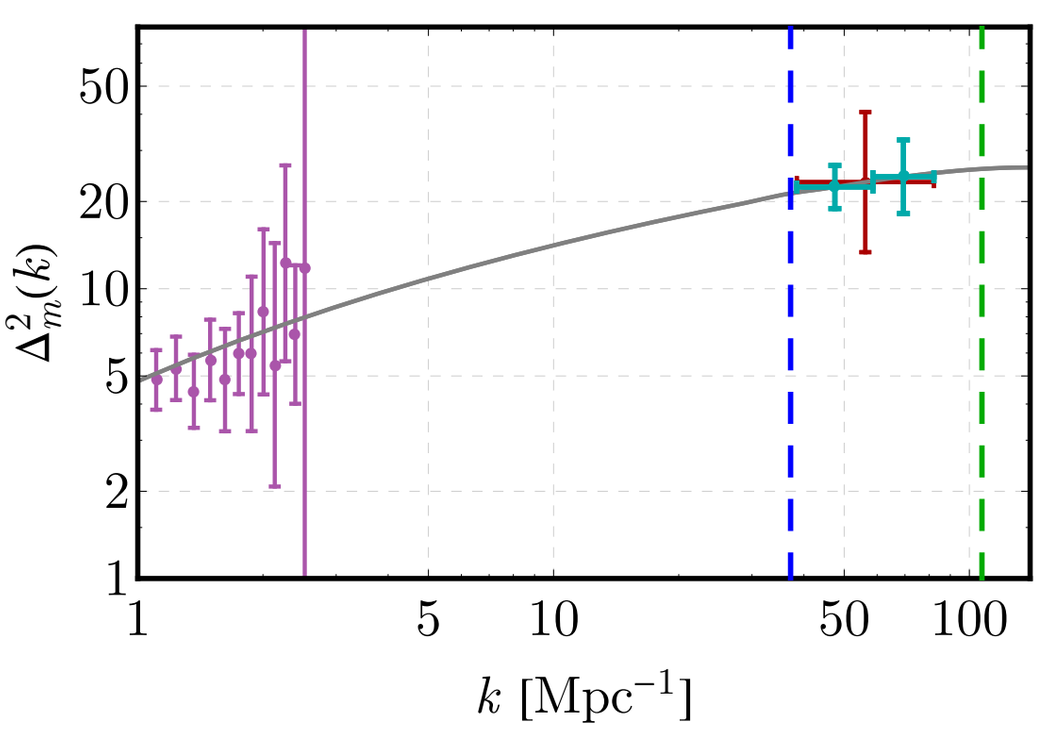


Summary



EDGES*



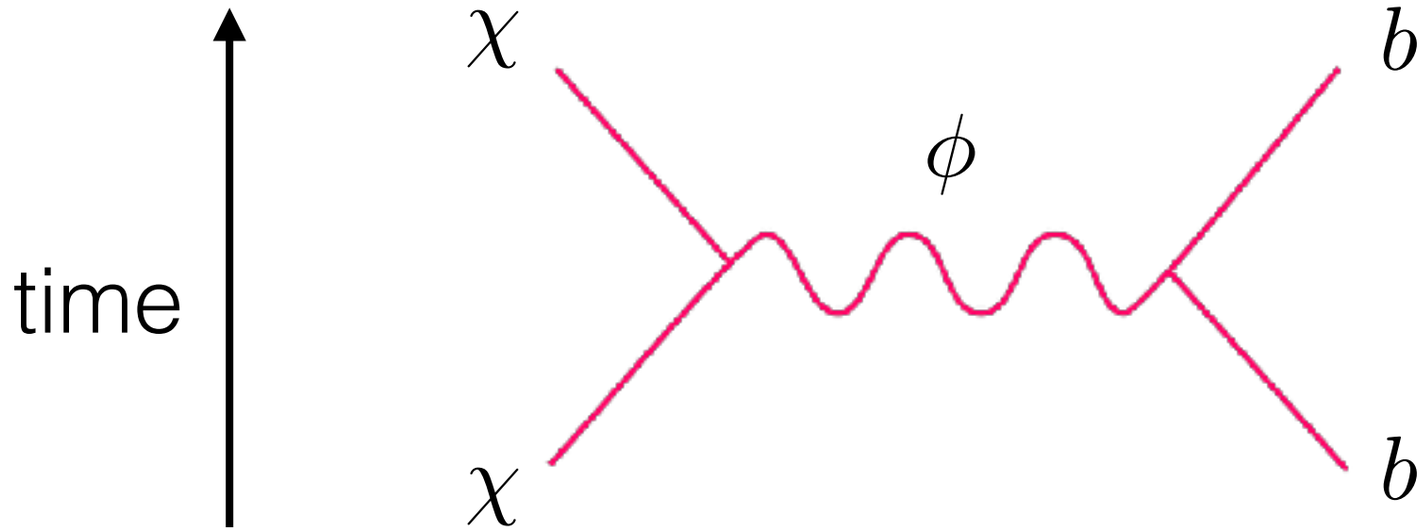


Fifth-force

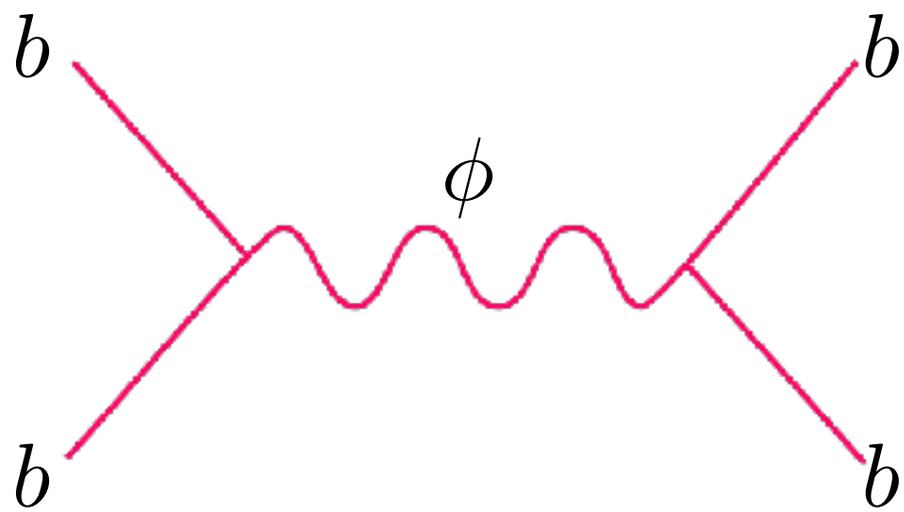
Barkana Nature 2018

$$\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4} = \sigma_1 \left(\frac{v}{1\ \mathrm{km/s}}\right)^{-4}$$

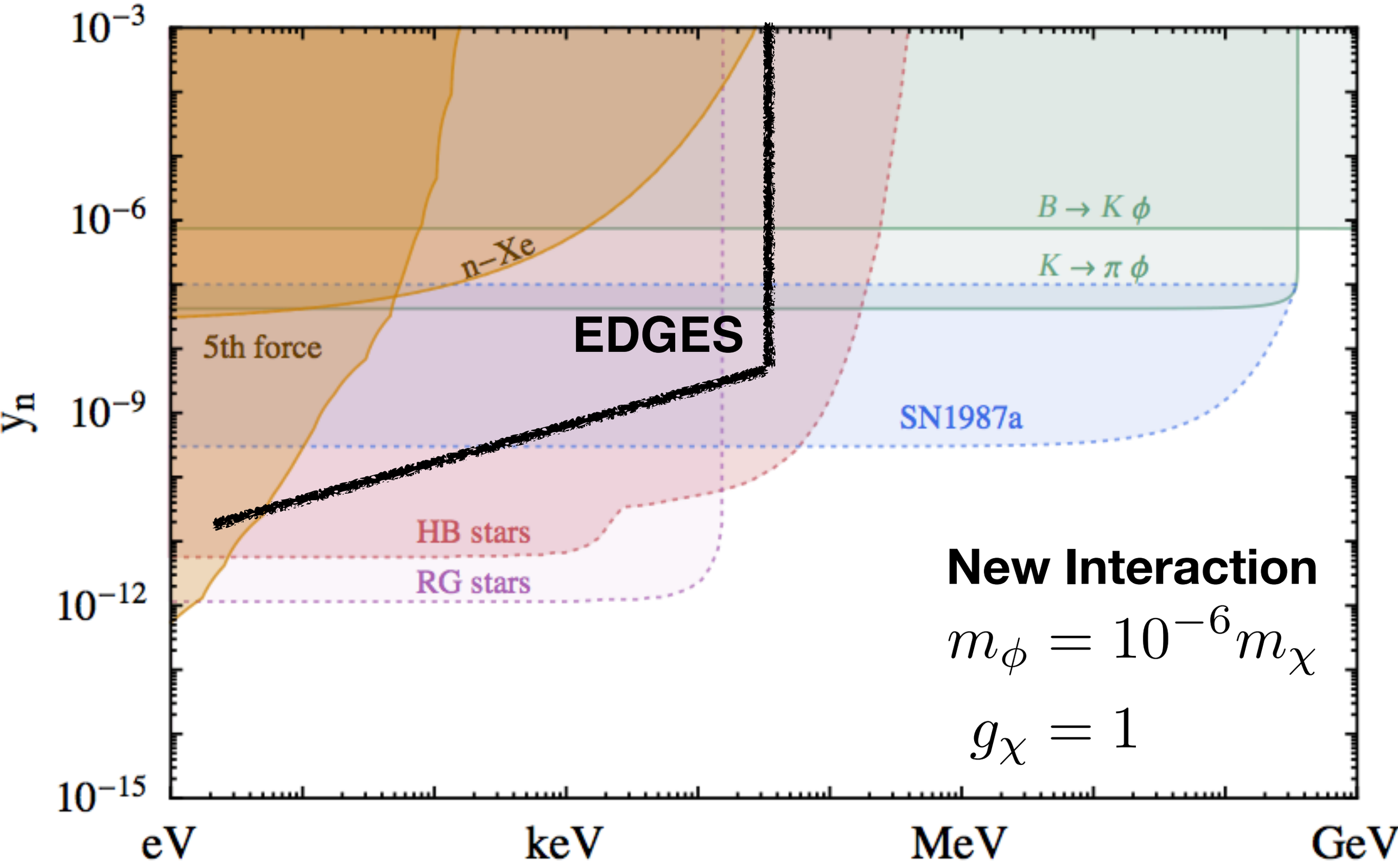
However, this:



Also implies this:

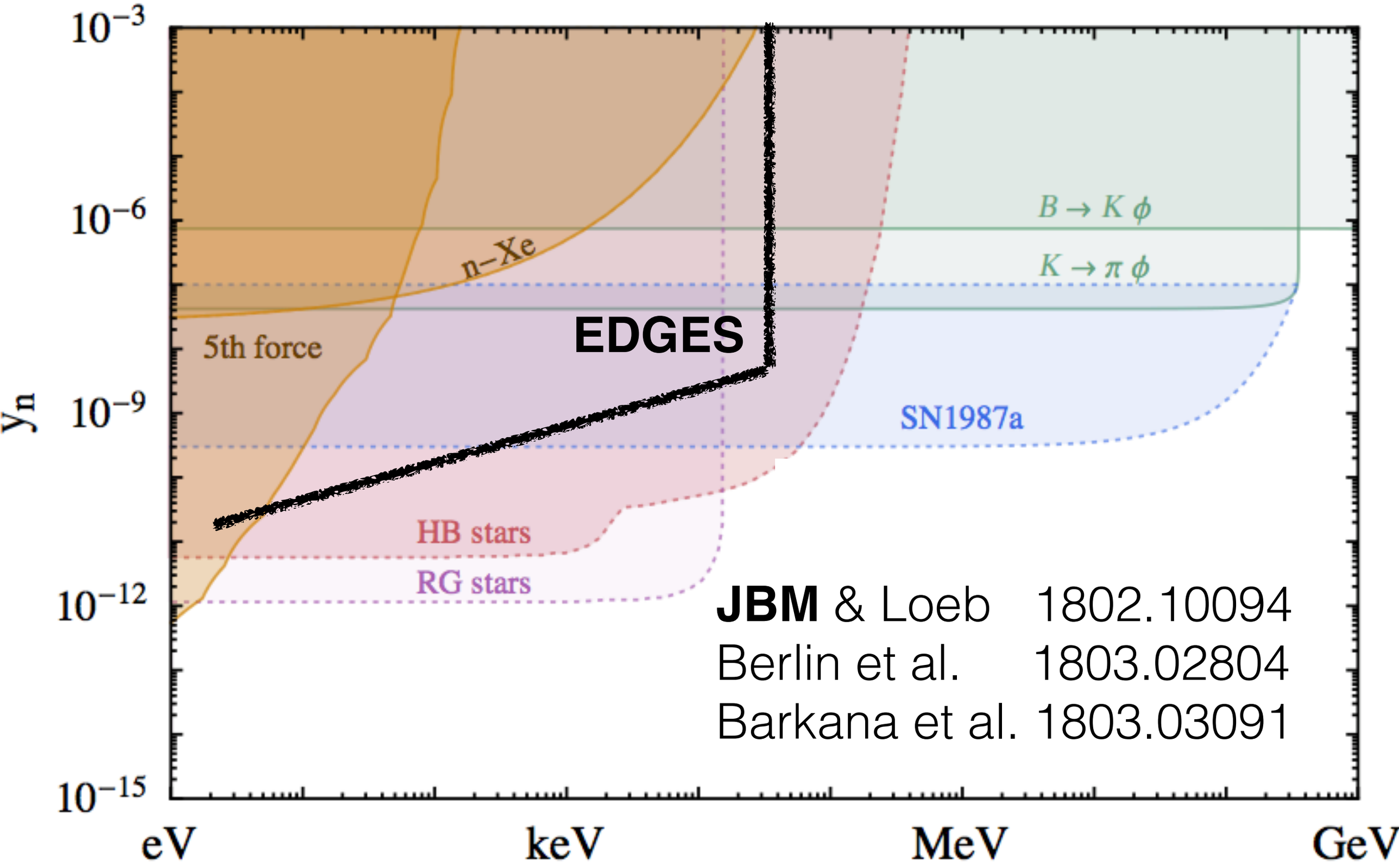


Fifth-force constraints



Knapen, Lin, Zurek 2017

Fifth-force constraints

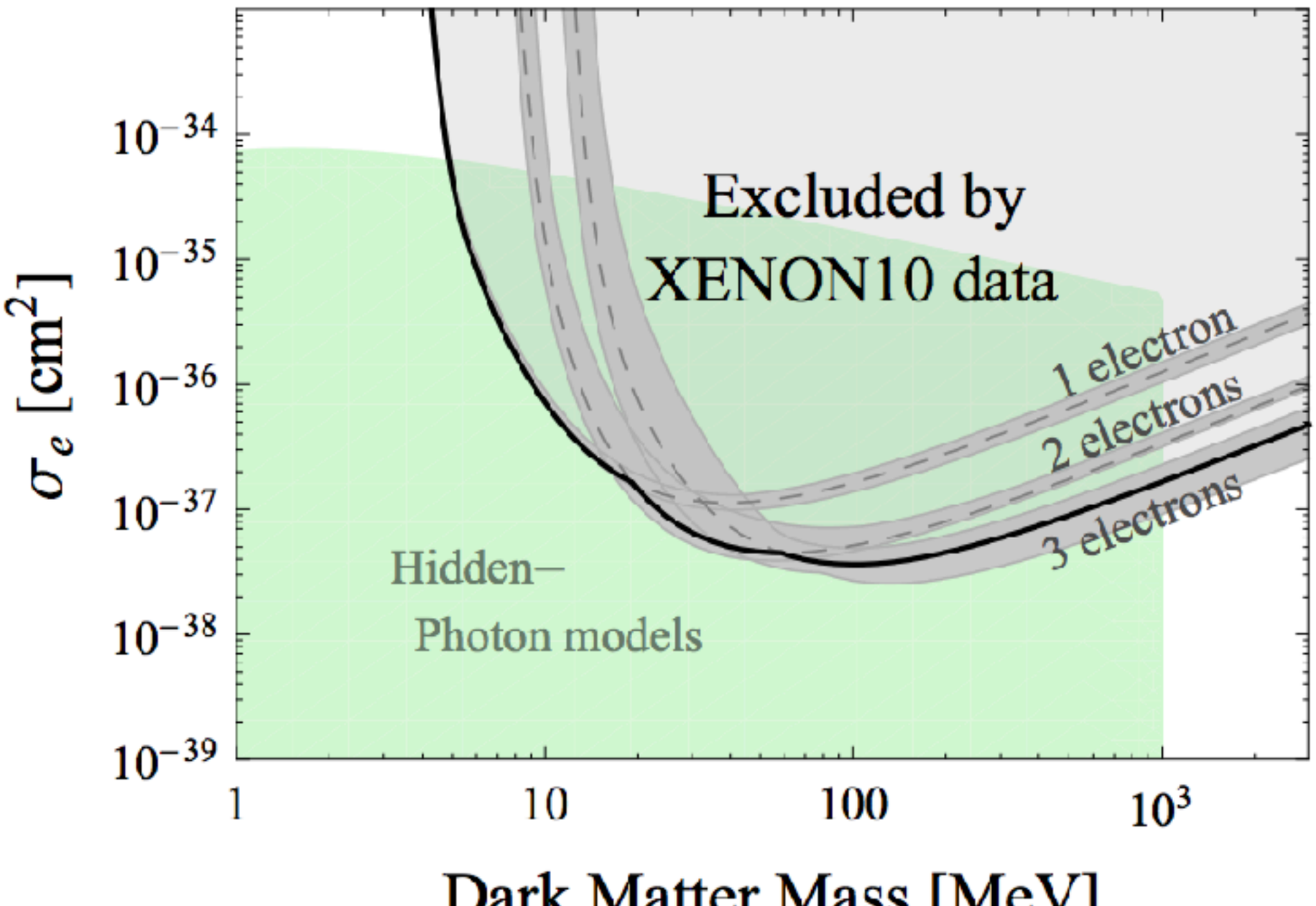


Knapen, Lin, Zurek 2017

Can you test this?

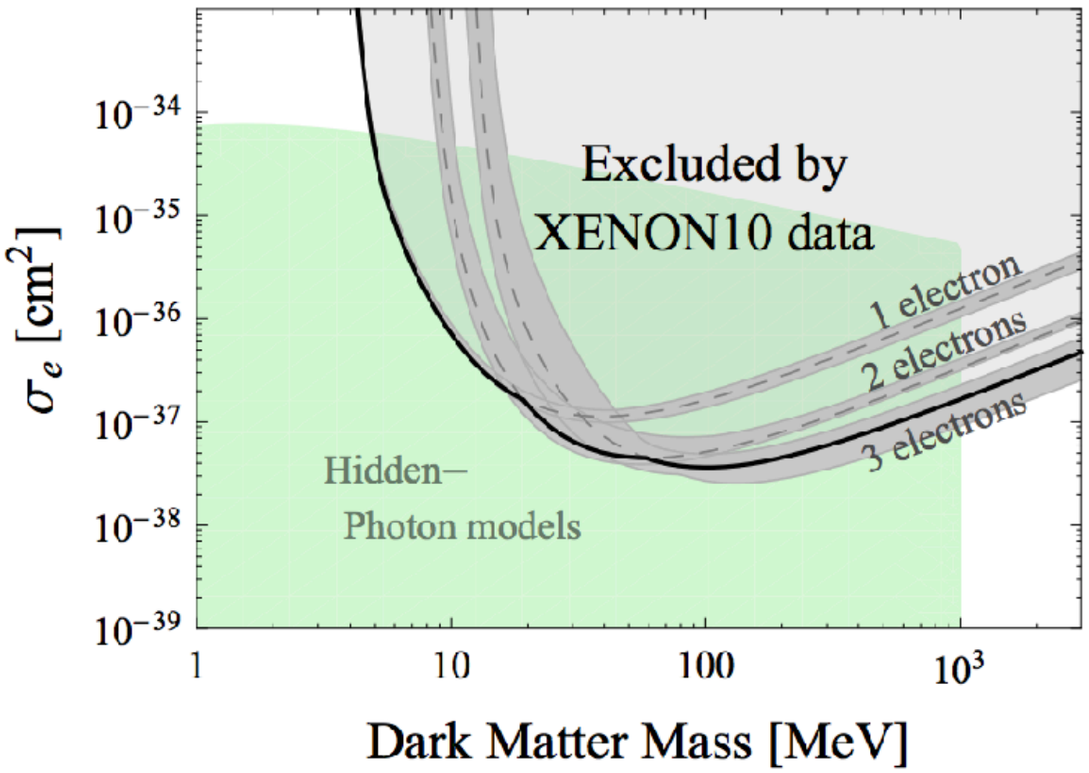
Essig et al. 2012

$$\sigma_{DD} \sim 10^{-27}\,\mathrm{cm}^2$$



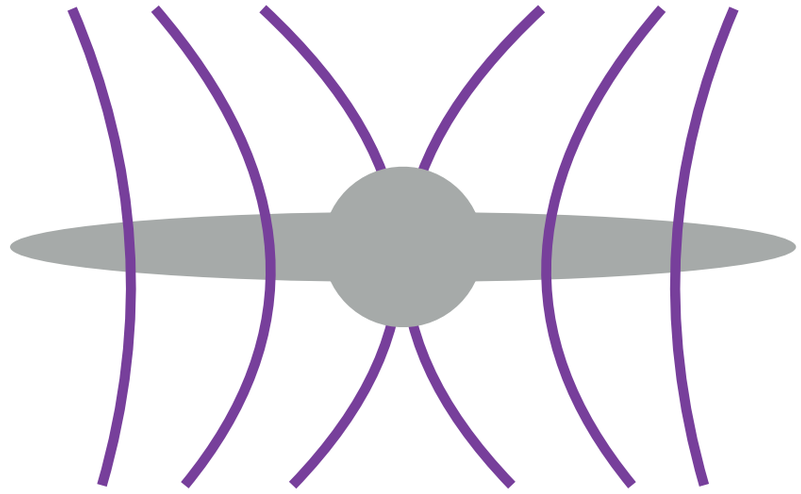
Can you test this?

Essig et al. 2012



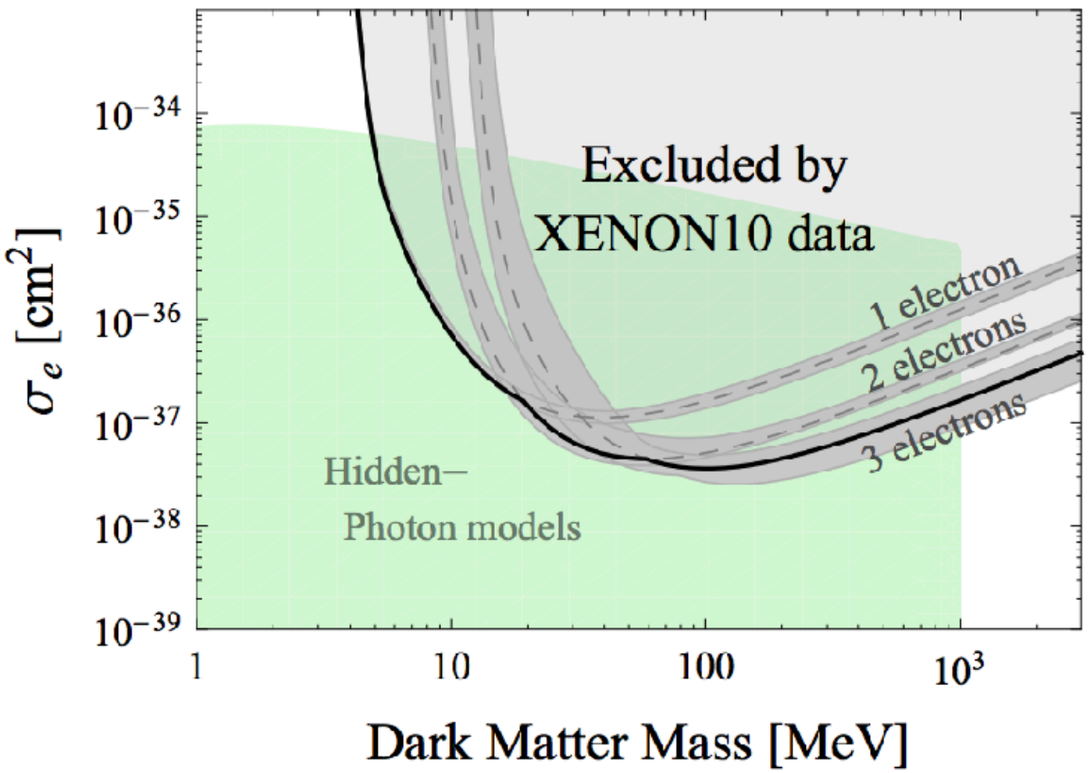
Although:

$$\sigma_{DD} \sim 10^{-27}\,\mathrm{cm}^2 > \sigma_{\mathrm{m.f.p.}}$$



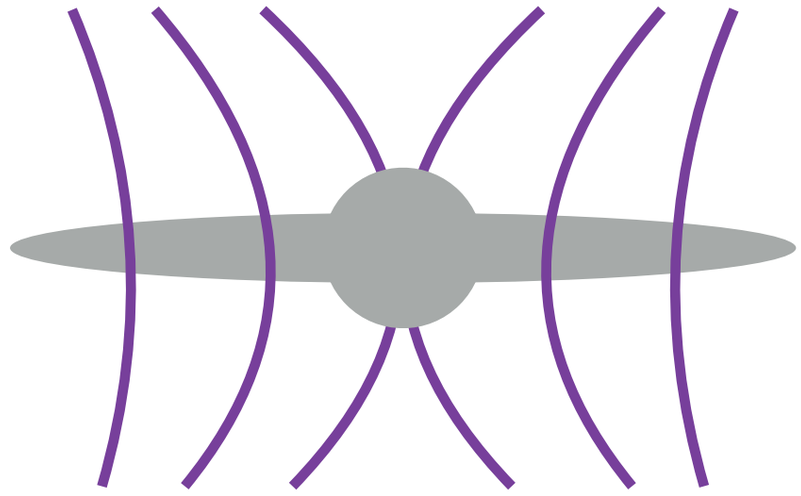
Can you test this?

Essig et al. 2012



Although:

$$\sigma_{DD} \sim 10^{-27}\,\mathrm{cm}^2 > \sigma_{\mathrm{m.f.p.}}$$

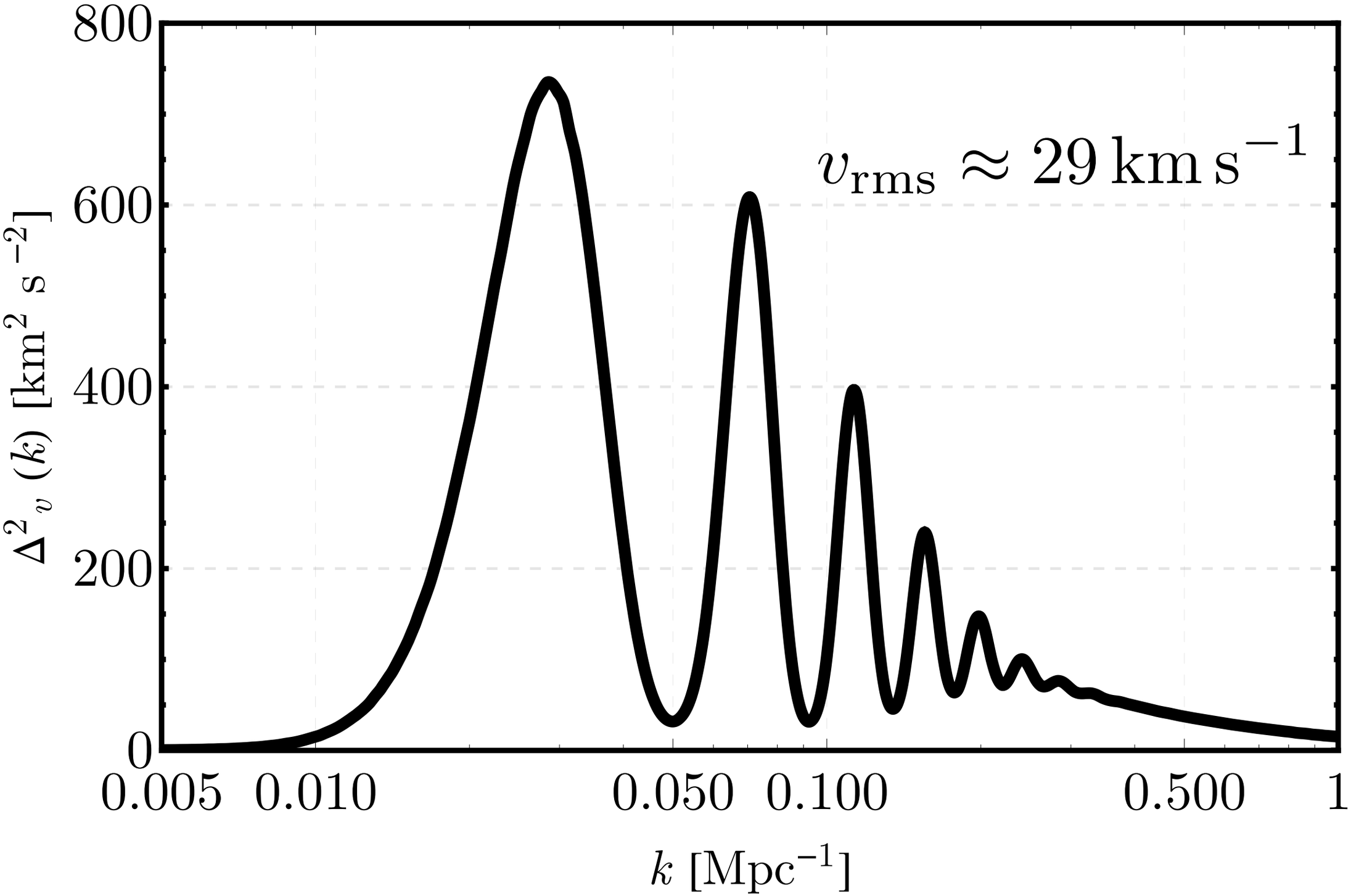


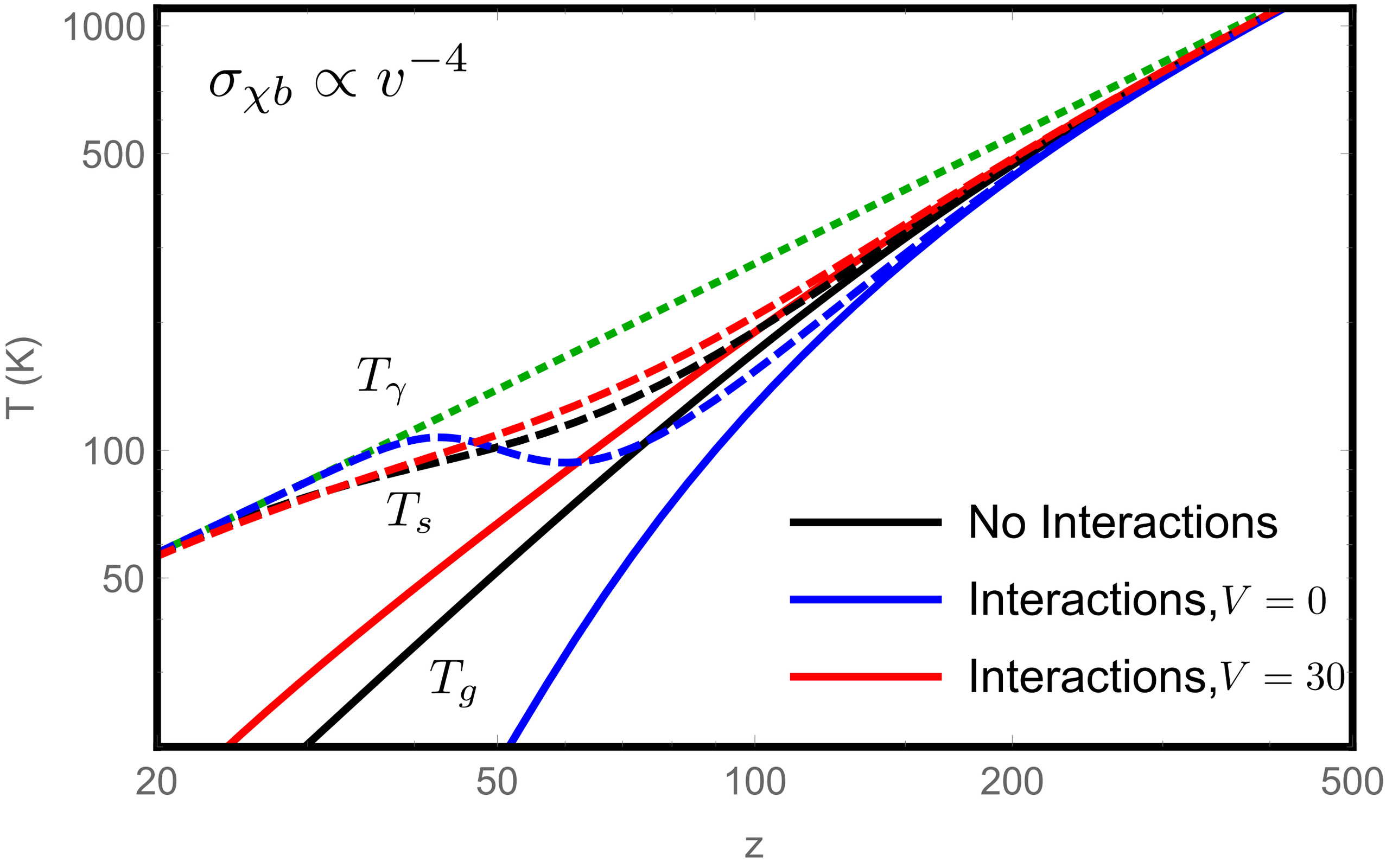
SHiP @ CERN + others

$$\epsilon > 10^{-3}$$

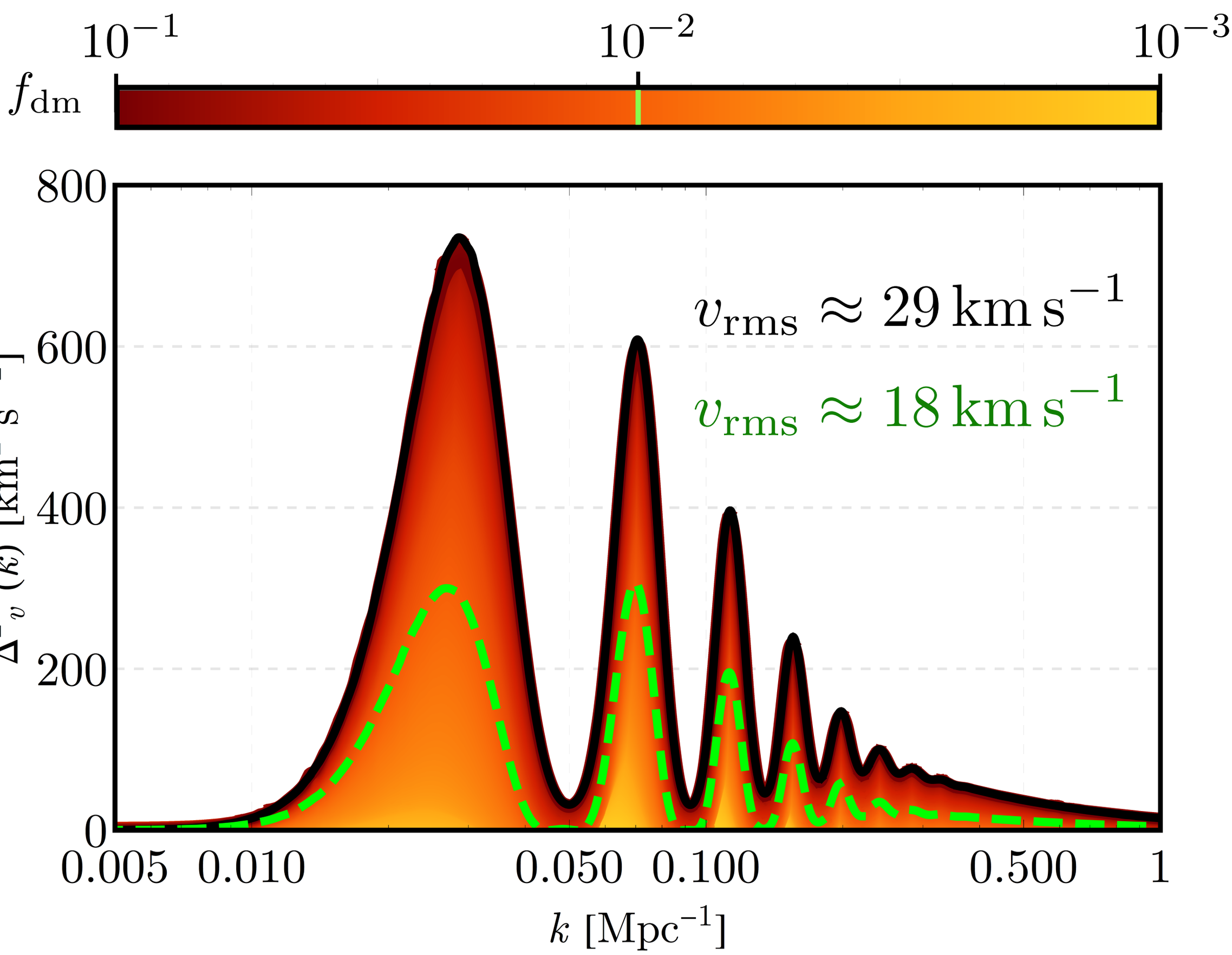
LDMX ~ SLAC mQ/10

Tseliakhovich and Hirata PRD 2010





JBM, Kovetz, Ali-Haimoud PRD 2015

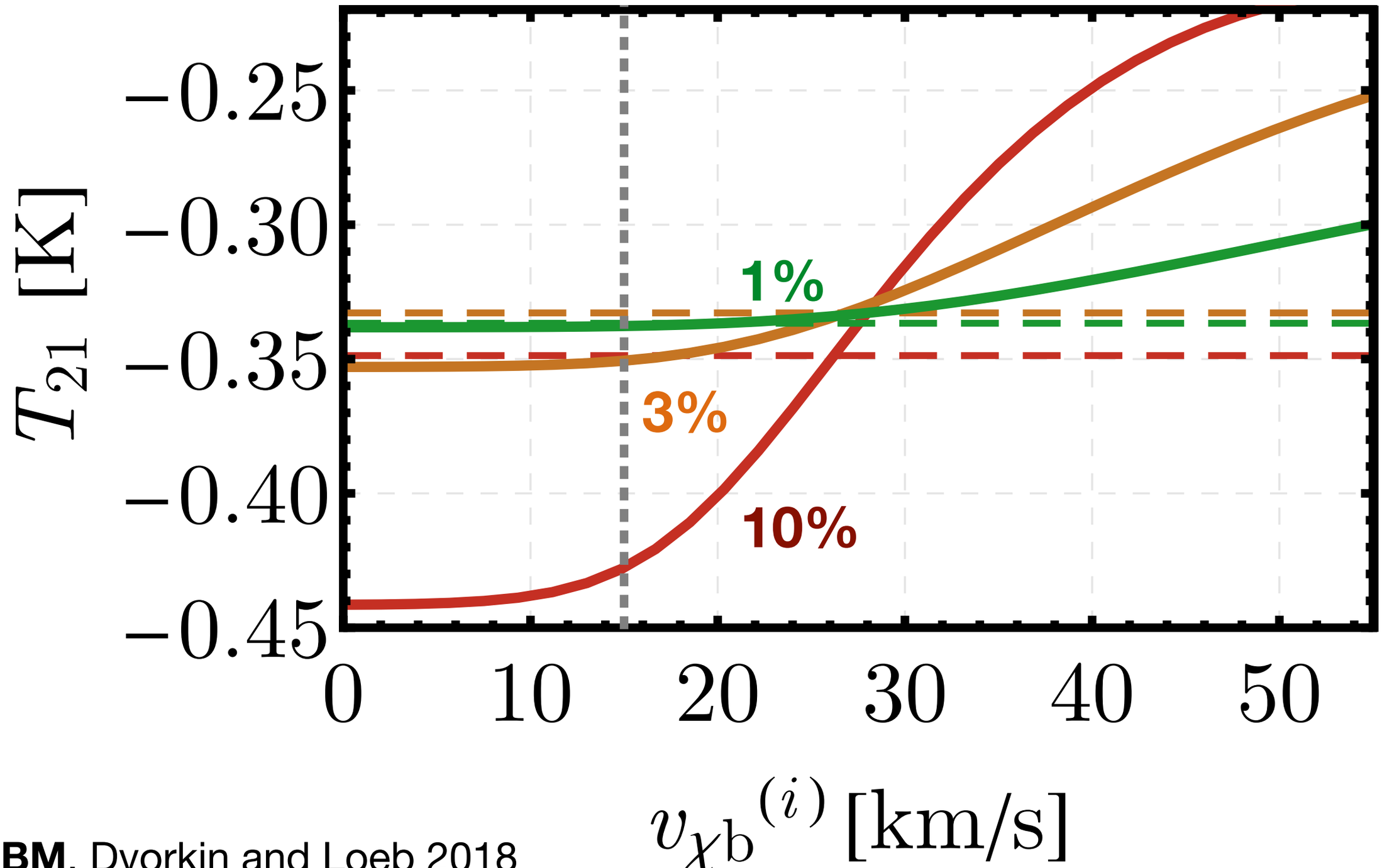


JBM, Dvorkin and Loeb 2018

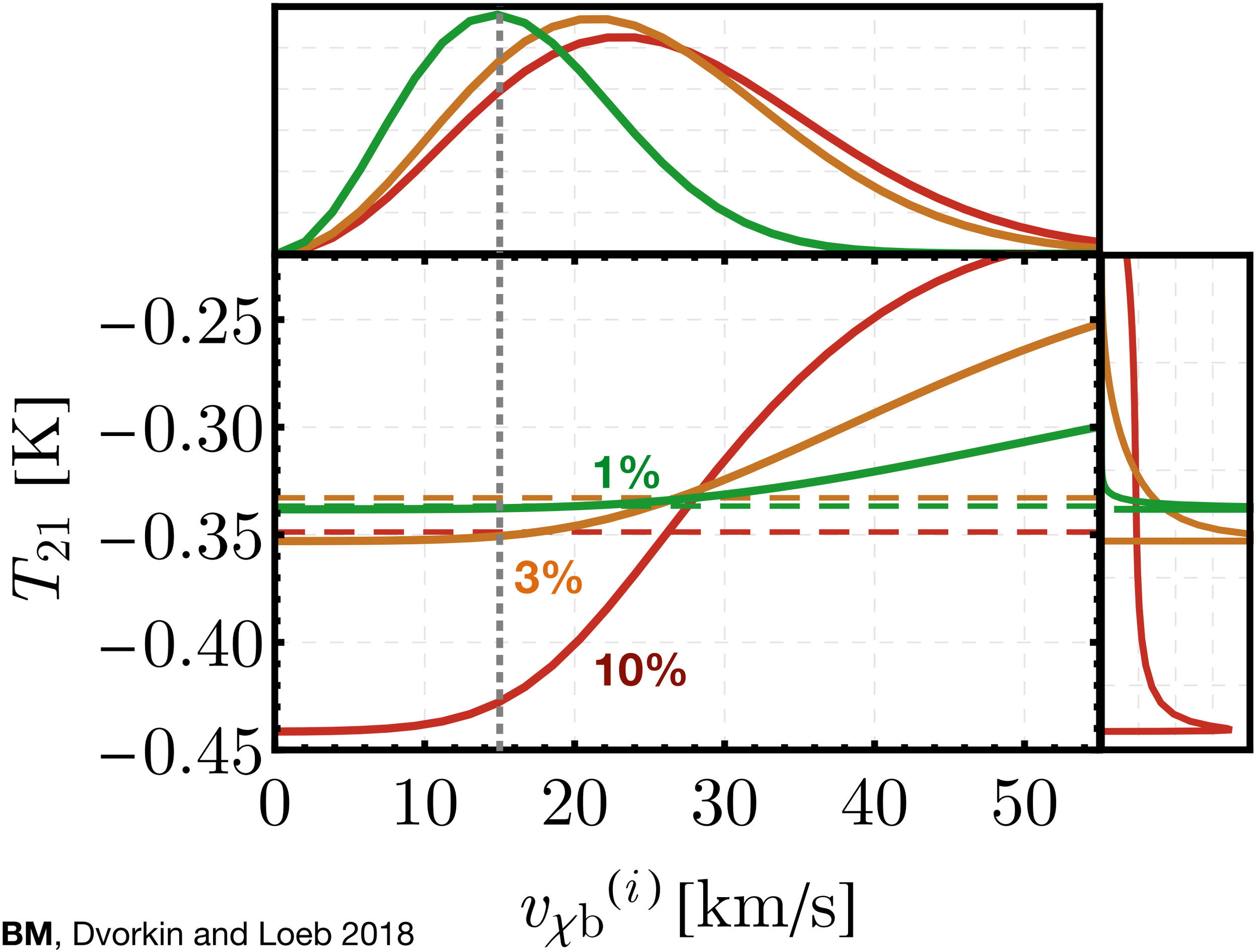
$$T^{(21)} = \tau \frac{T_s - T_{\rm cmb}}{1+z} (v_{\chi,b}^{(i)})$$

Relative velocity at decoupling

$$\sigma_{\chi b} \propto v^{-4}$$

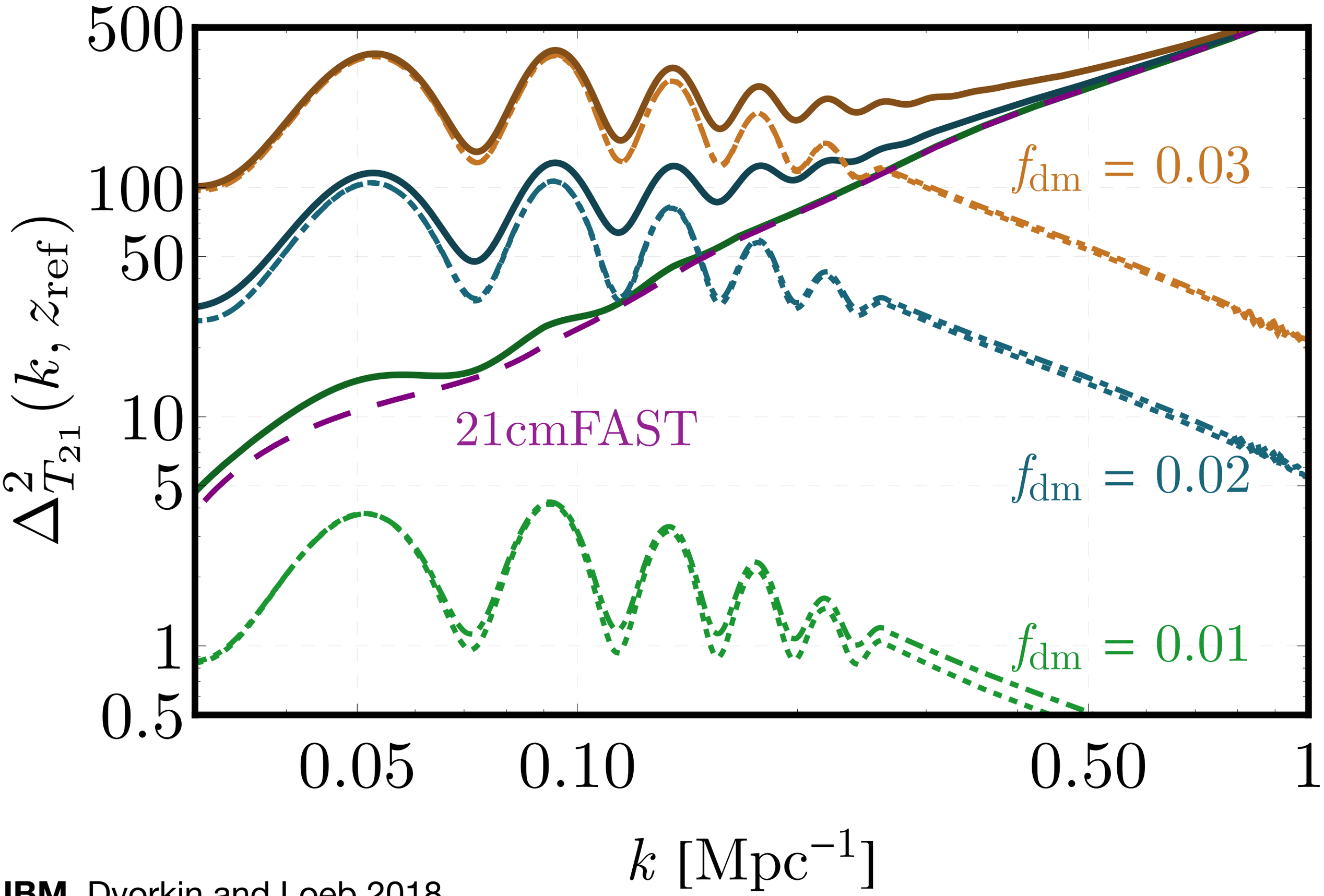


JBM, Dvorkin and Loeb 2018



JBM, Dvorkin and Loeb 2018

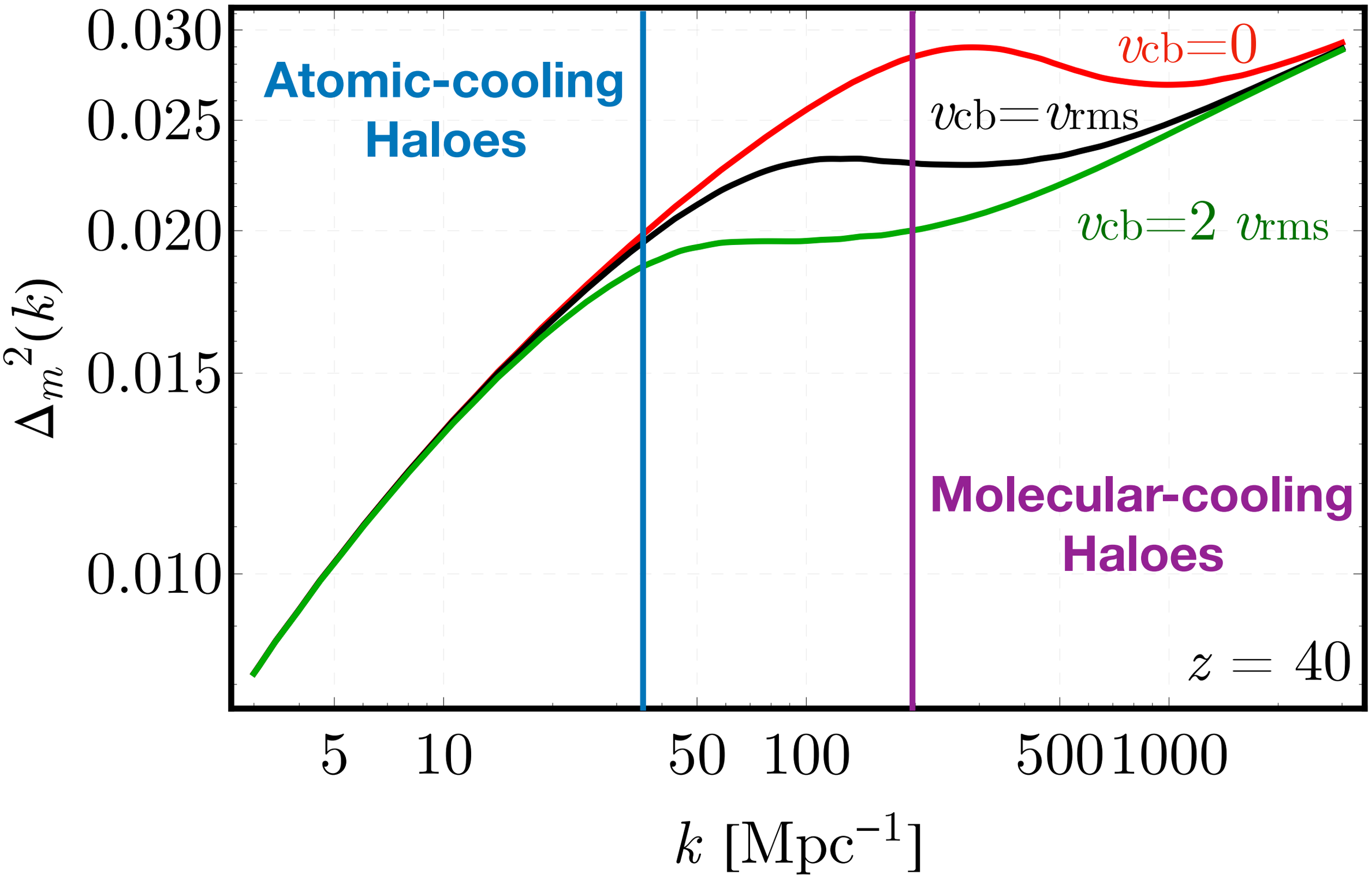
21-cm fluctuations



JBM, Dvorkin and Loeb 2018

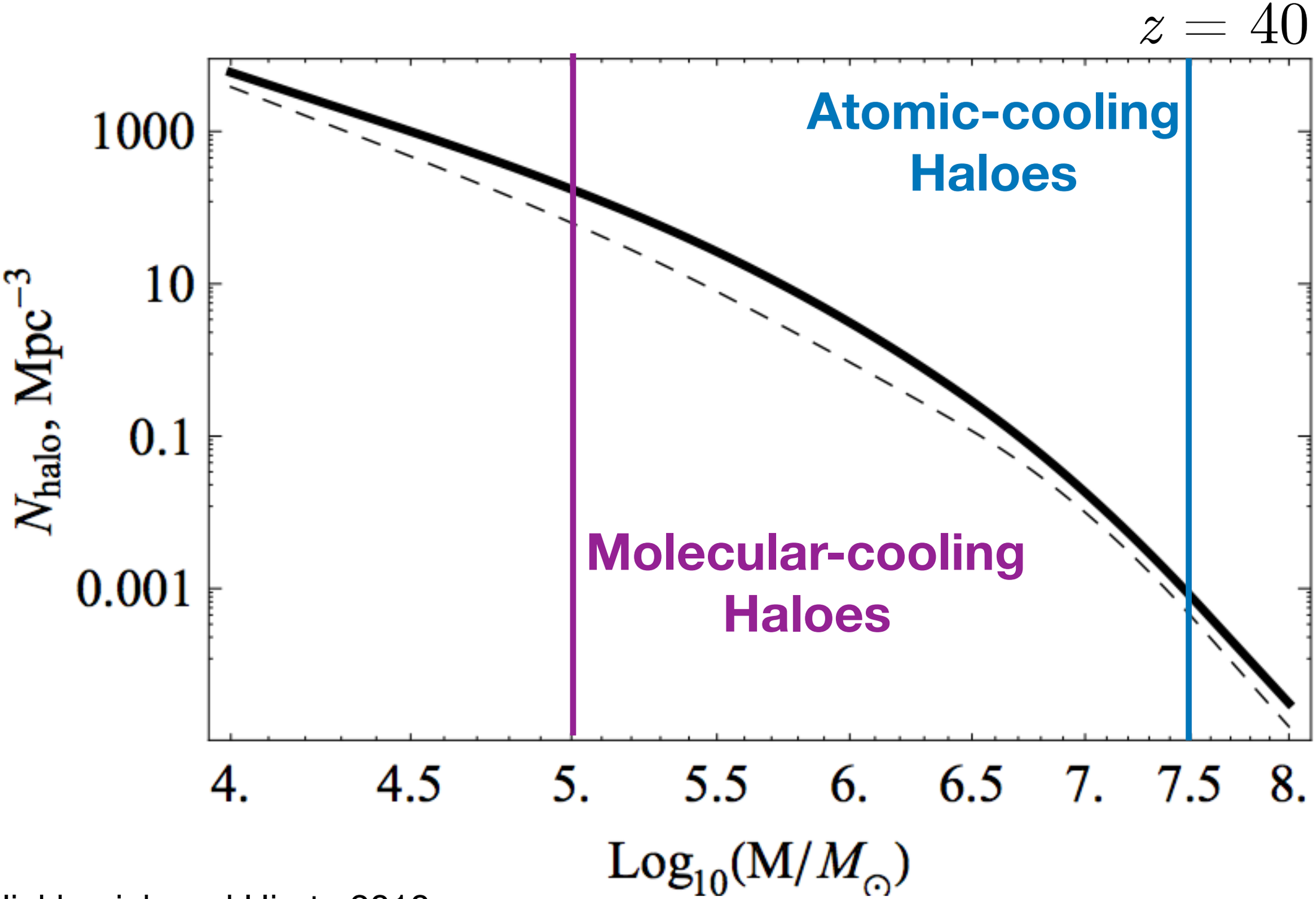
Relative velocities: effects

1- Power Spectrum



Relative velocities: effects

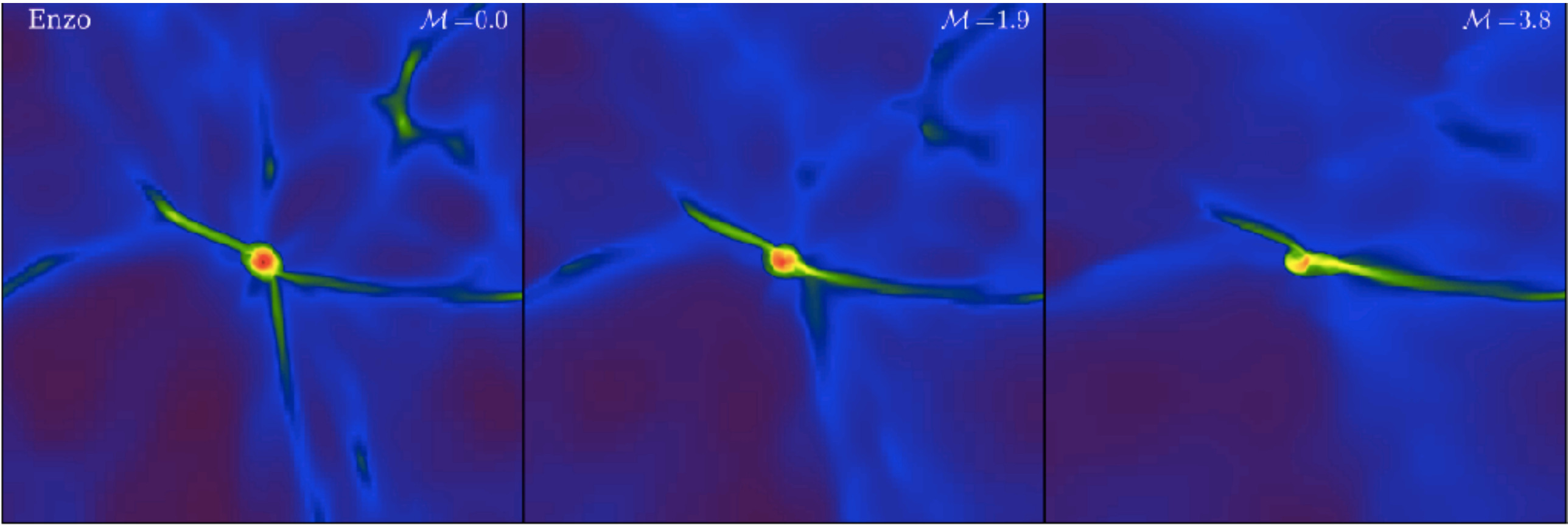
1- Power Spectrum -> Number of haloes



Tseliakhovich and Hirata 2010

Relative velocities: effects

2- Threshold for stellar cooling (molecular only)

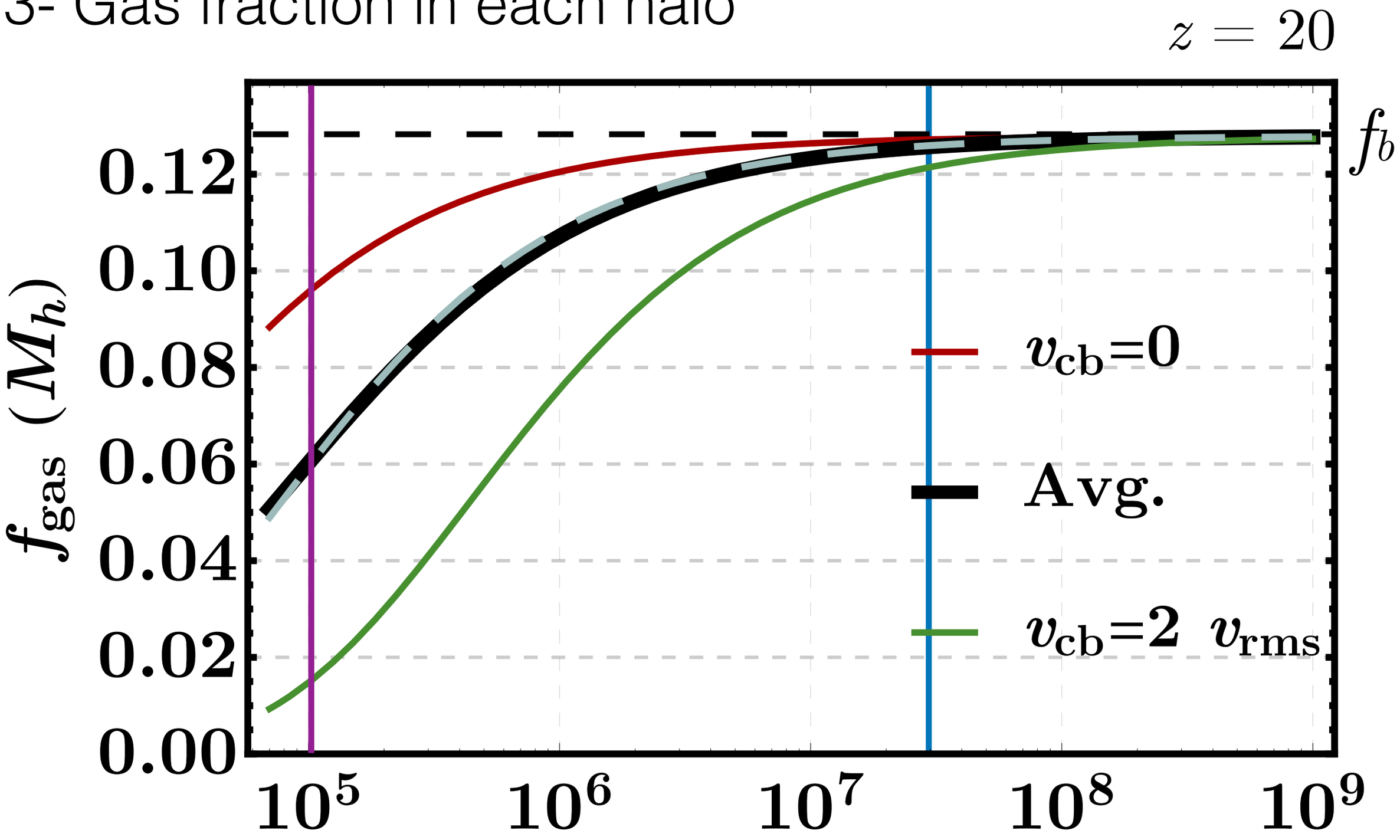


No velocity **Average velocity** **High velocity**

Oleary & McQuinn 2010

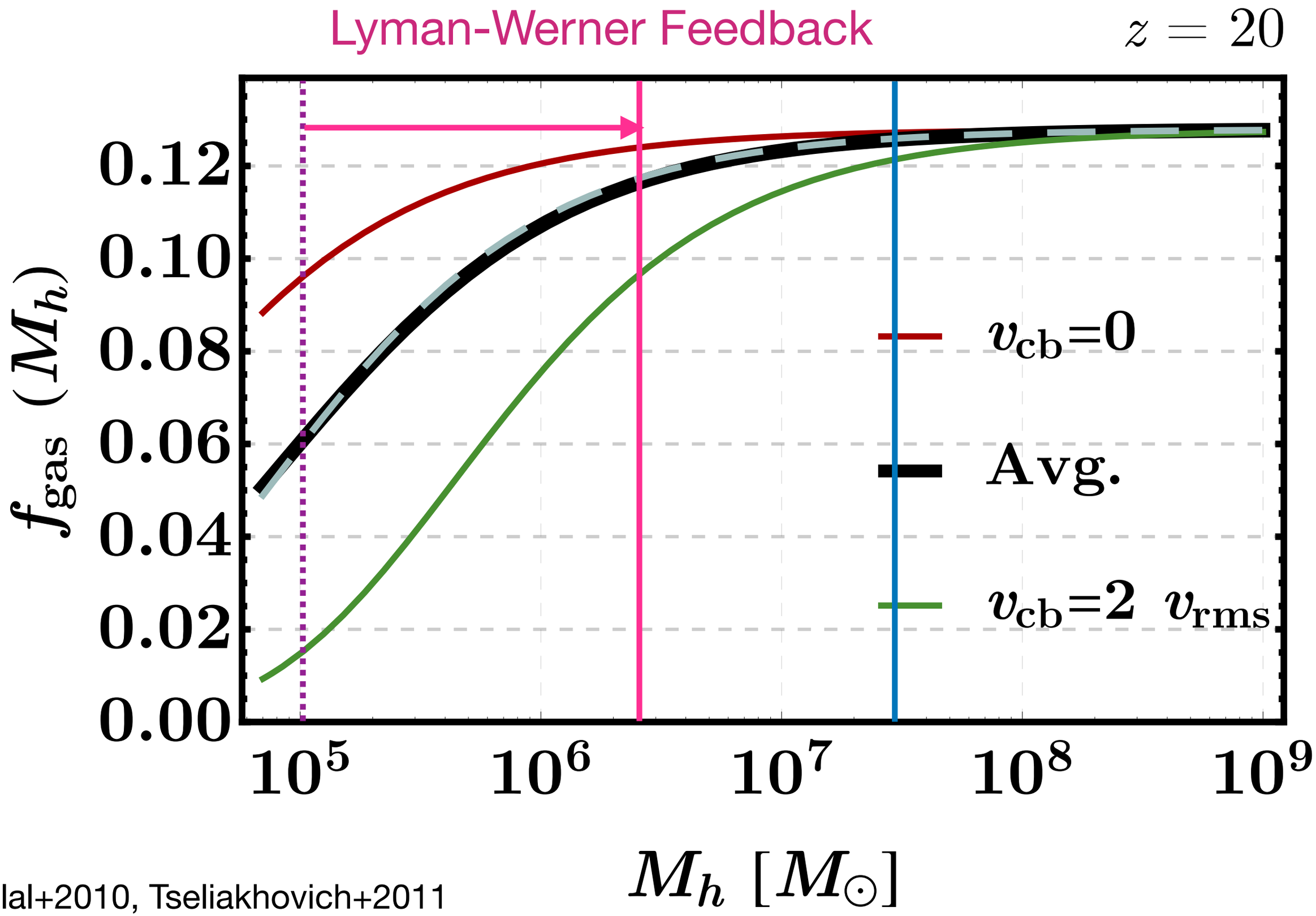
Relative velocities: effects

3- Gas fraction in each halo



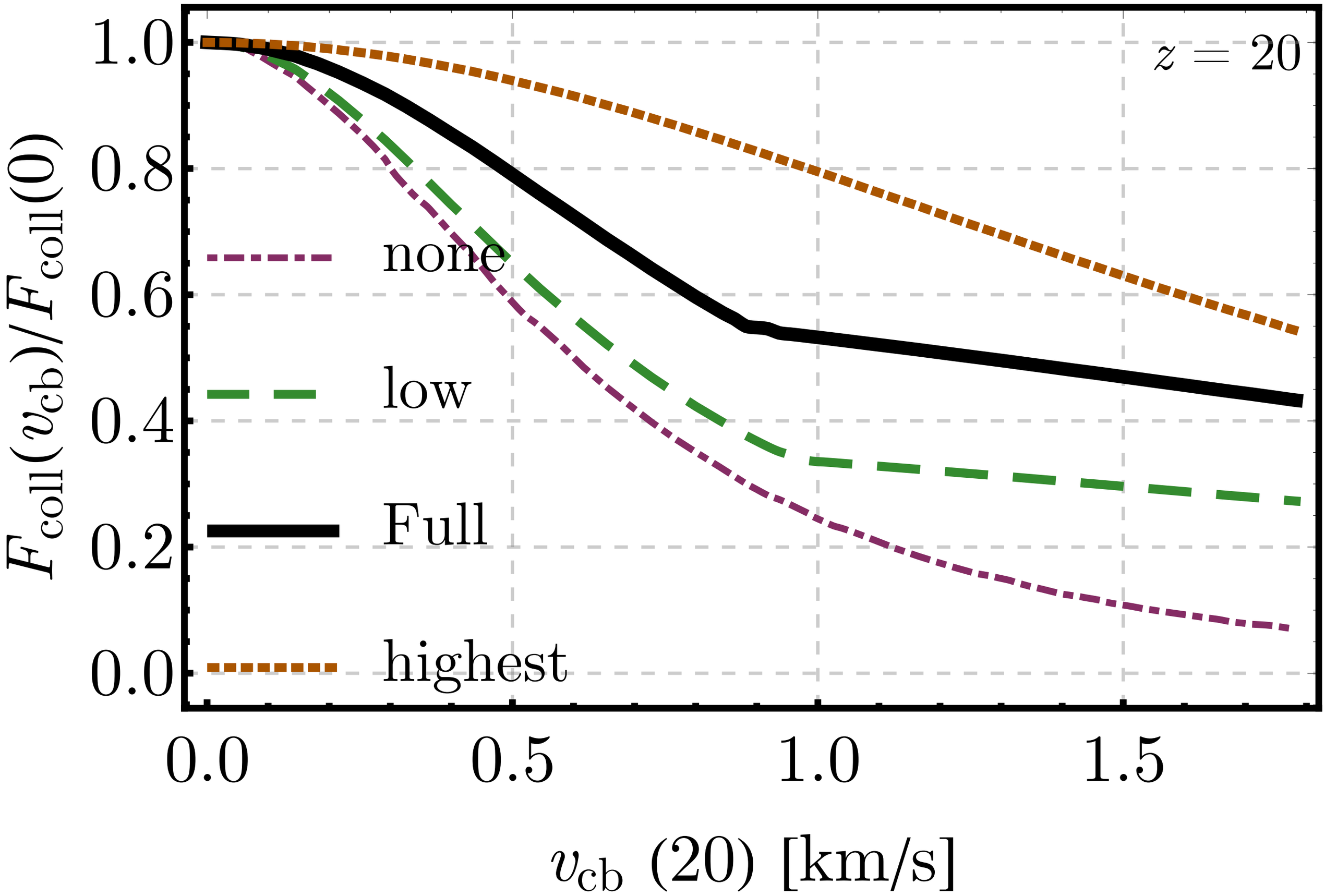
Dalal+2010, Tseliakhovich+2011

Relative velocities: effects



Dalal+2010, Tseliakhovich+2011

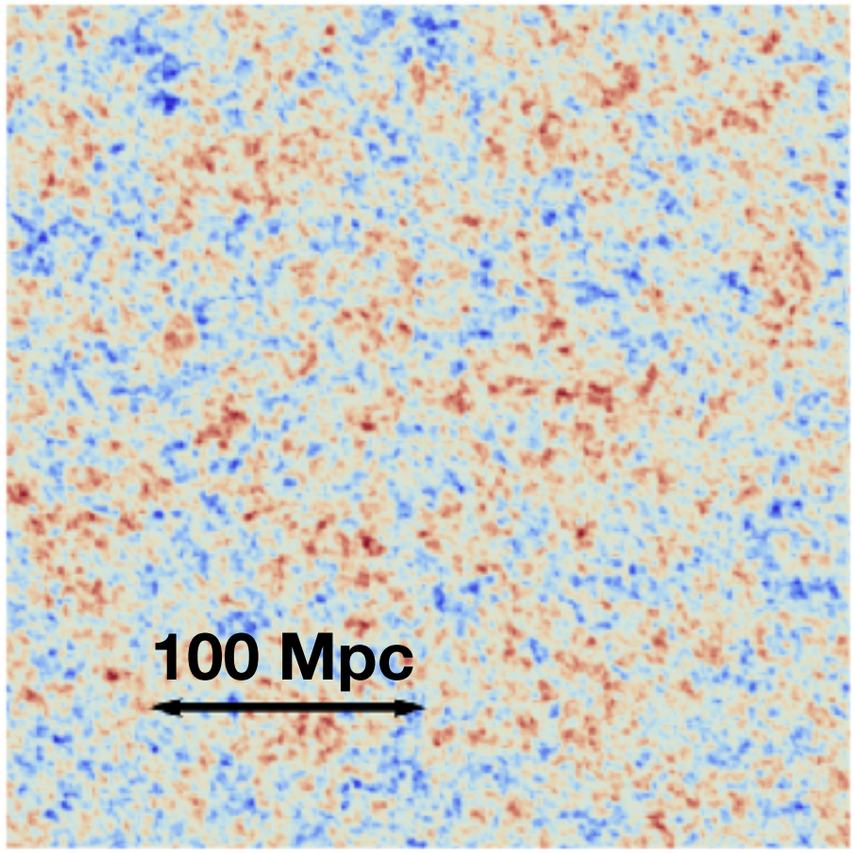
Relative velocities: effects

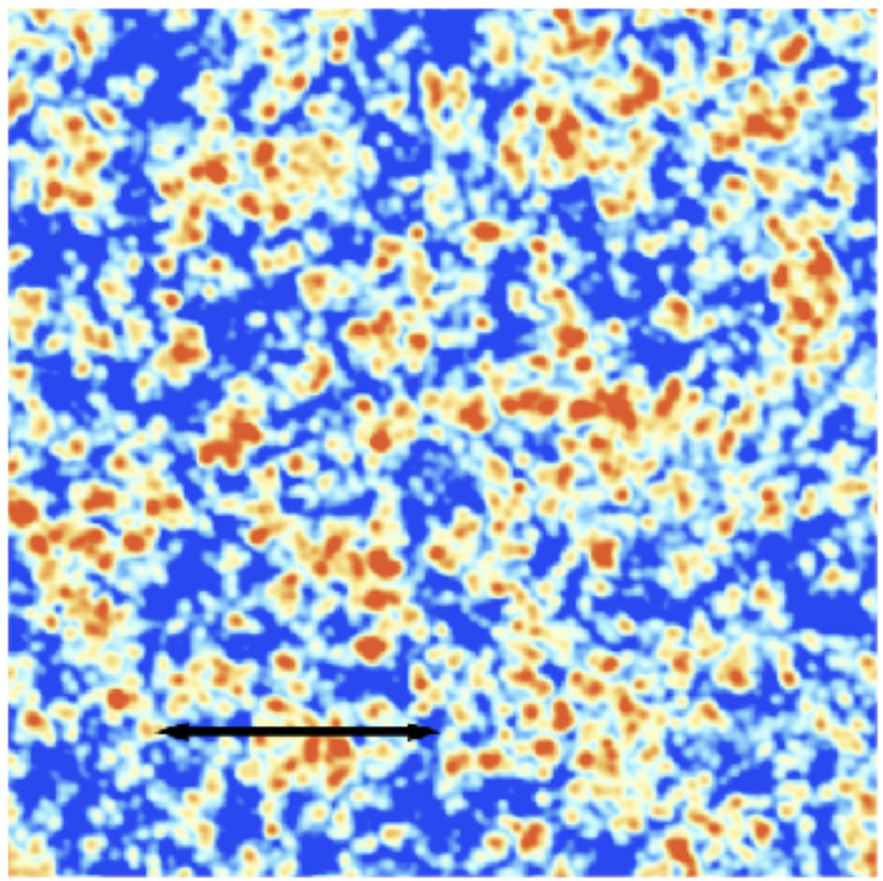


Densities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6





$z{=}20$

$\log_{10}(F_{\rm coll})$

−3.75
−4.00
−4.25
−4.50
−4.75
−5.00

Densities

Velocities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

100 Mpc

100 Mpc

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

$\log_{10}(F_{\rm coll})$

−3.75
−4.00
−4.25
−4.50
−4.75
−5.00

$z{=}20$

Densities

Velocities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

100 Mpc

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

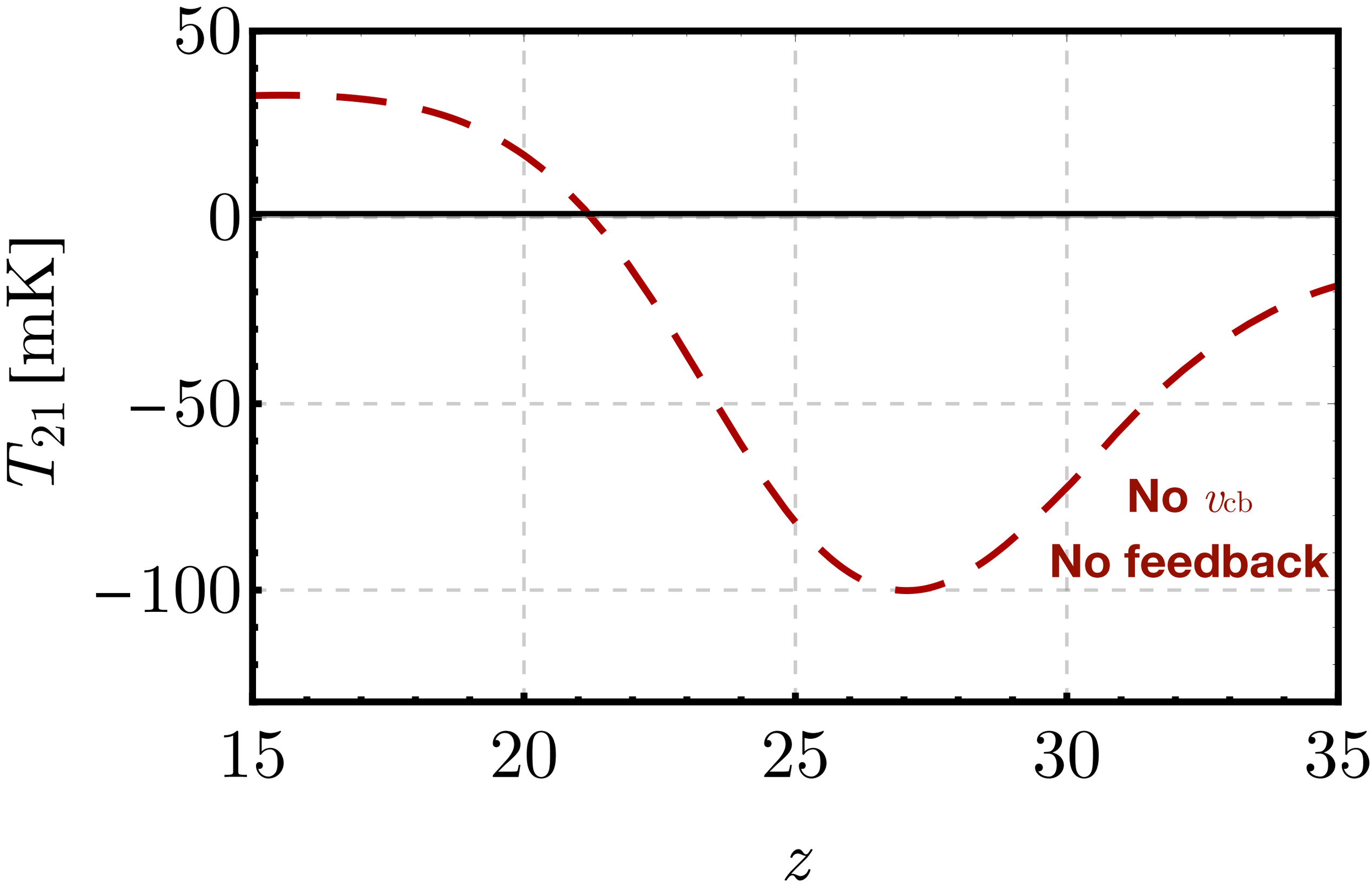
100 Mpc

$\log_{10}(F_{\rm coll})$

−3.75
−4.00
−4.25
−4.50
−4.75
−5.00

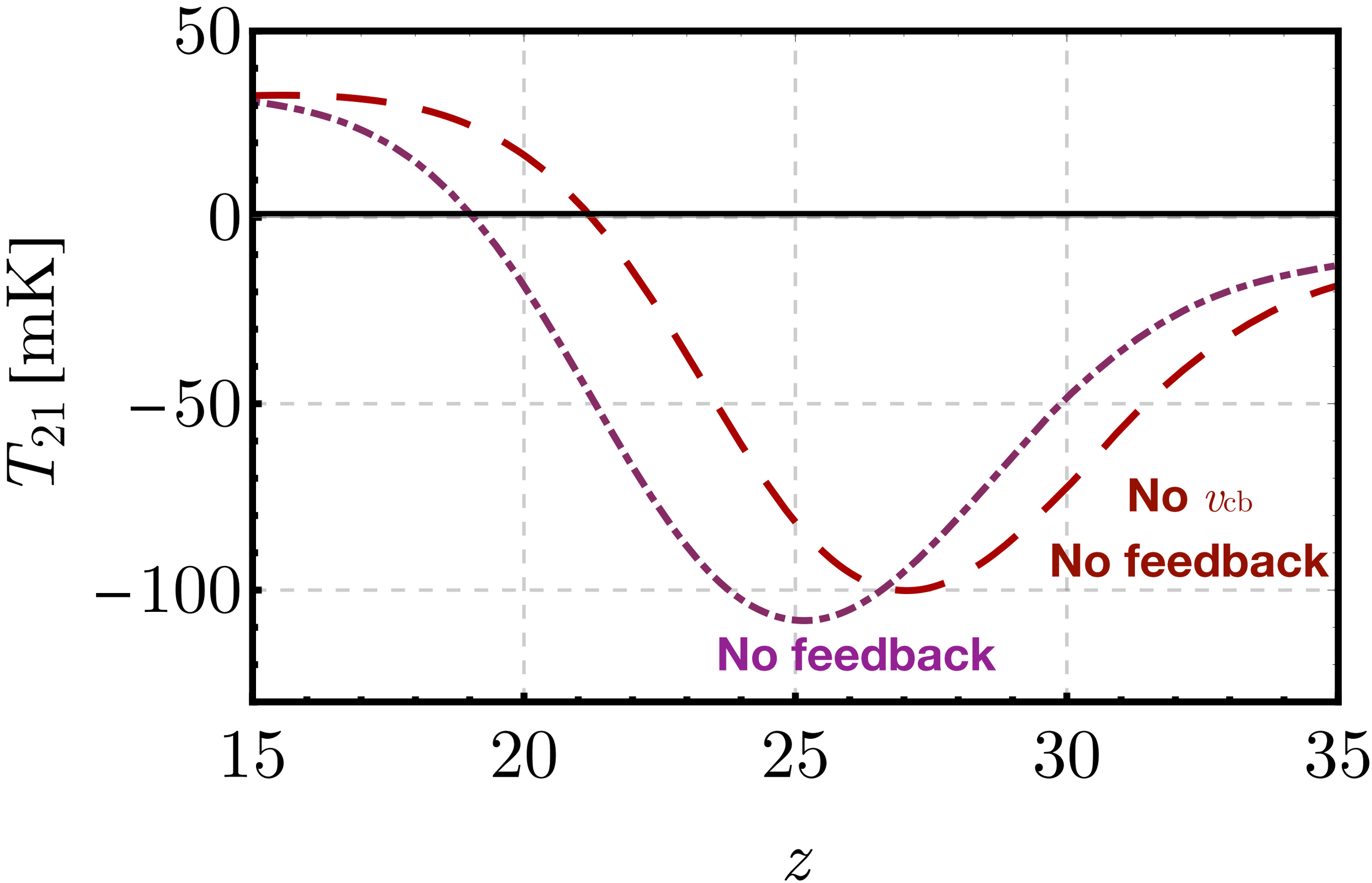
$z{=}20$

Evolution of T_{21}



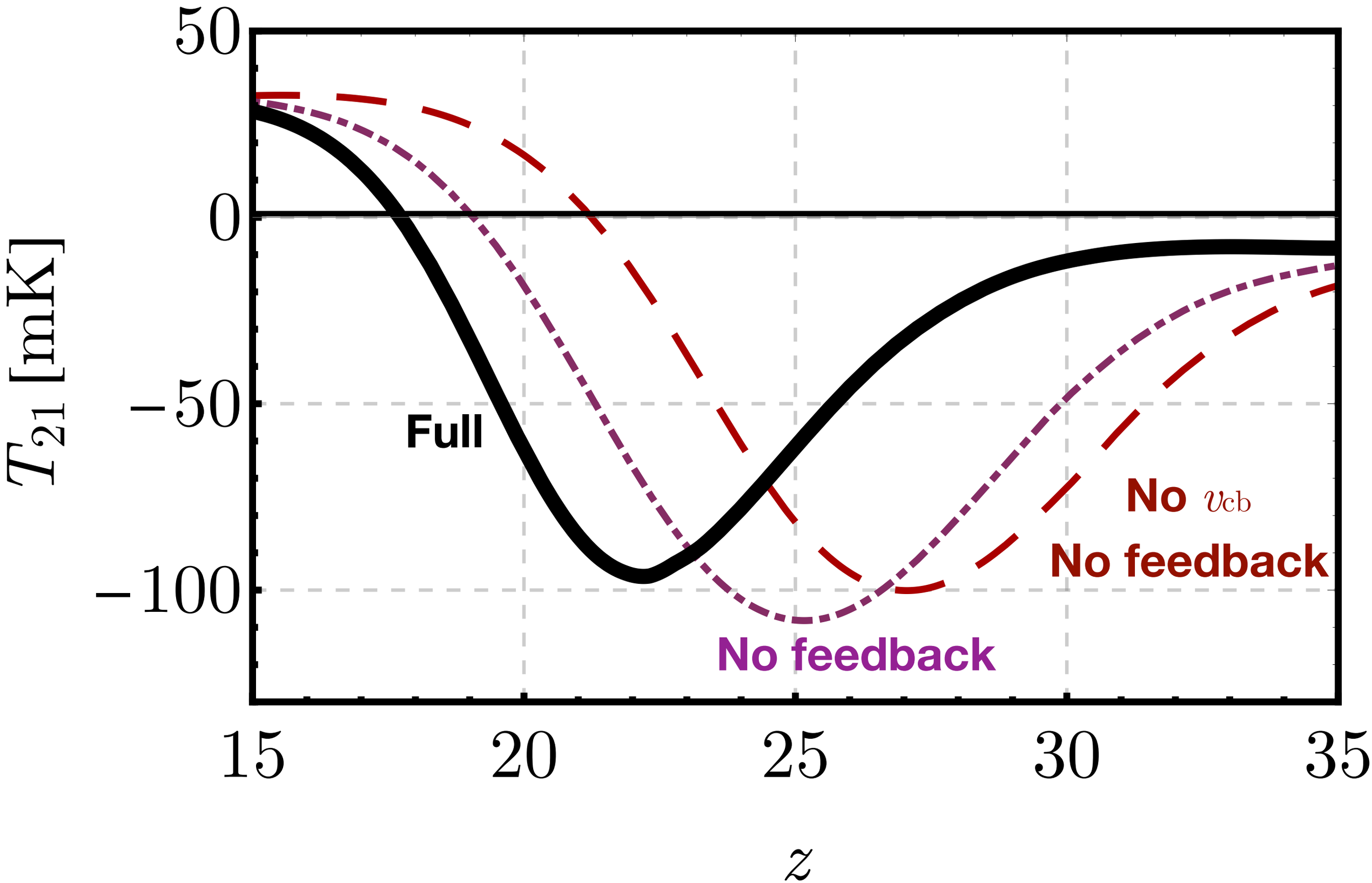
Modifying 21cmFAST (Mesinger+ 2010)

Evolution of T_{21}



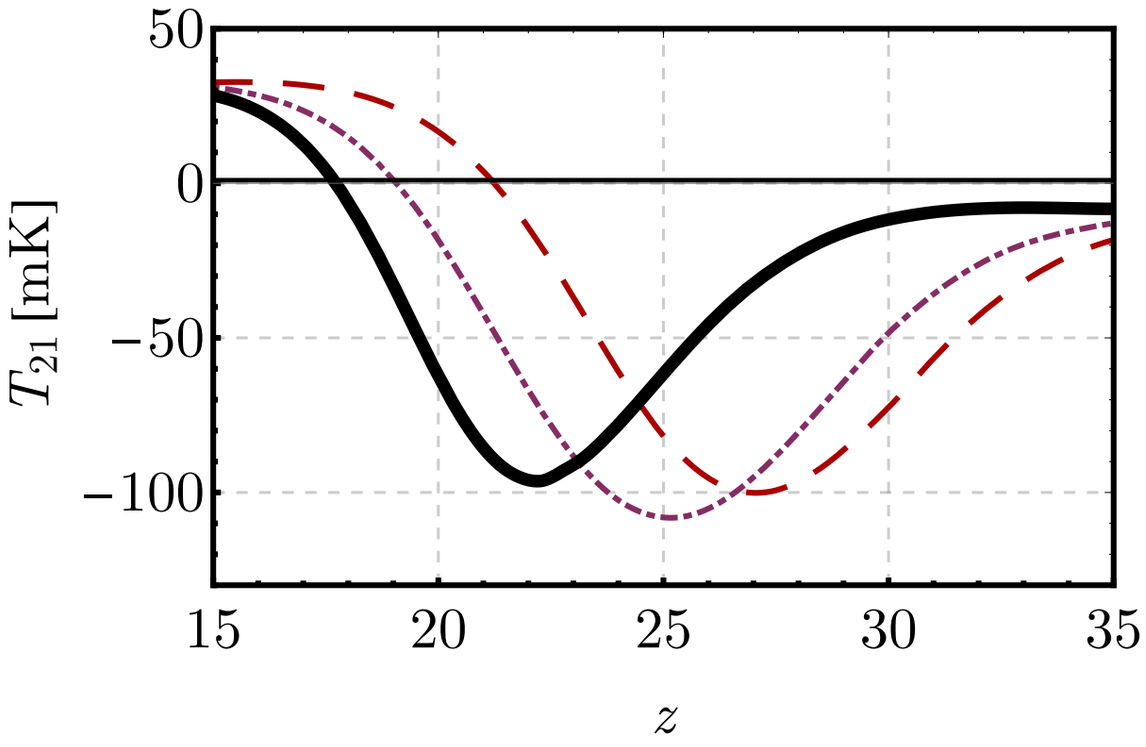
Modifying 21cmFAST (Mesinger+ 2010)

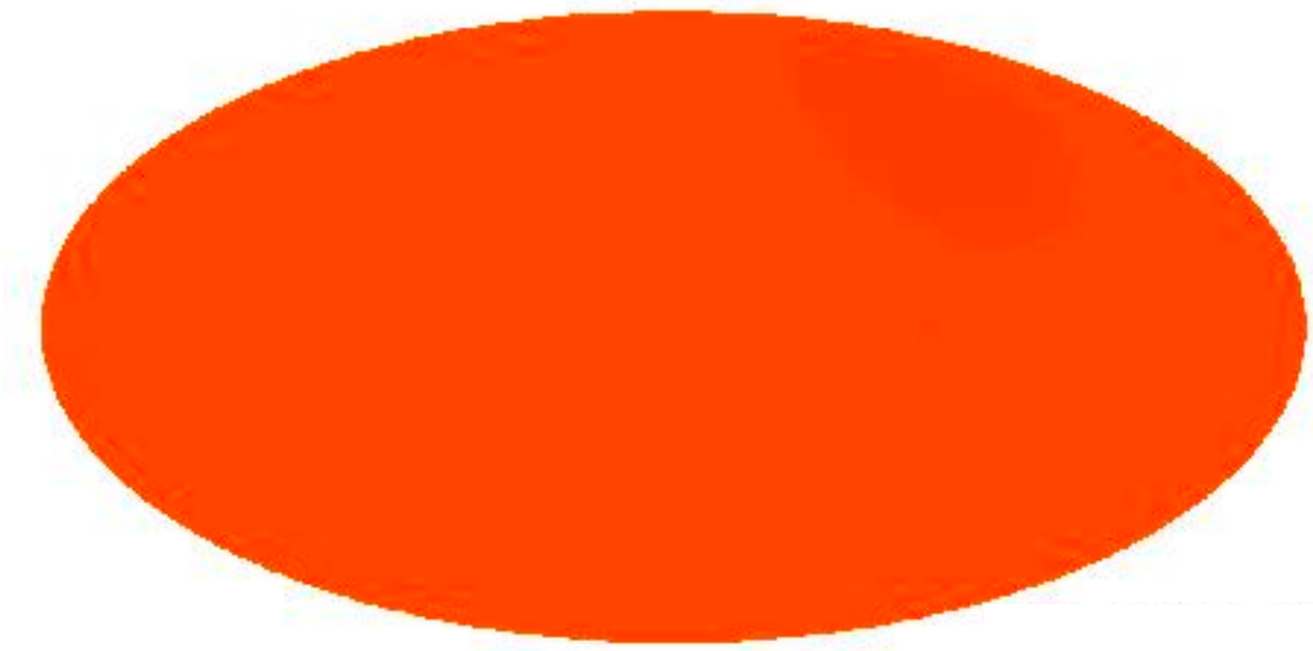
Evolution of T_{21}



Modifying 21cmFAST (Mesinger+ 2010)

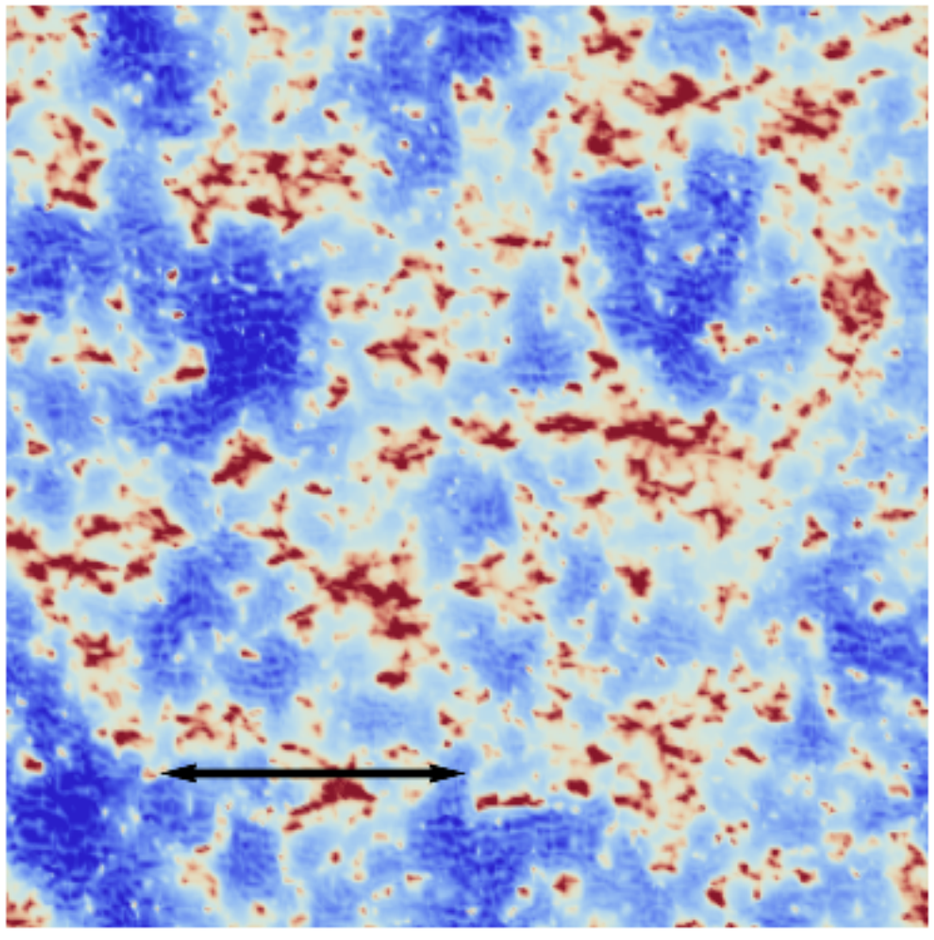
Fluctuations on T_{21}

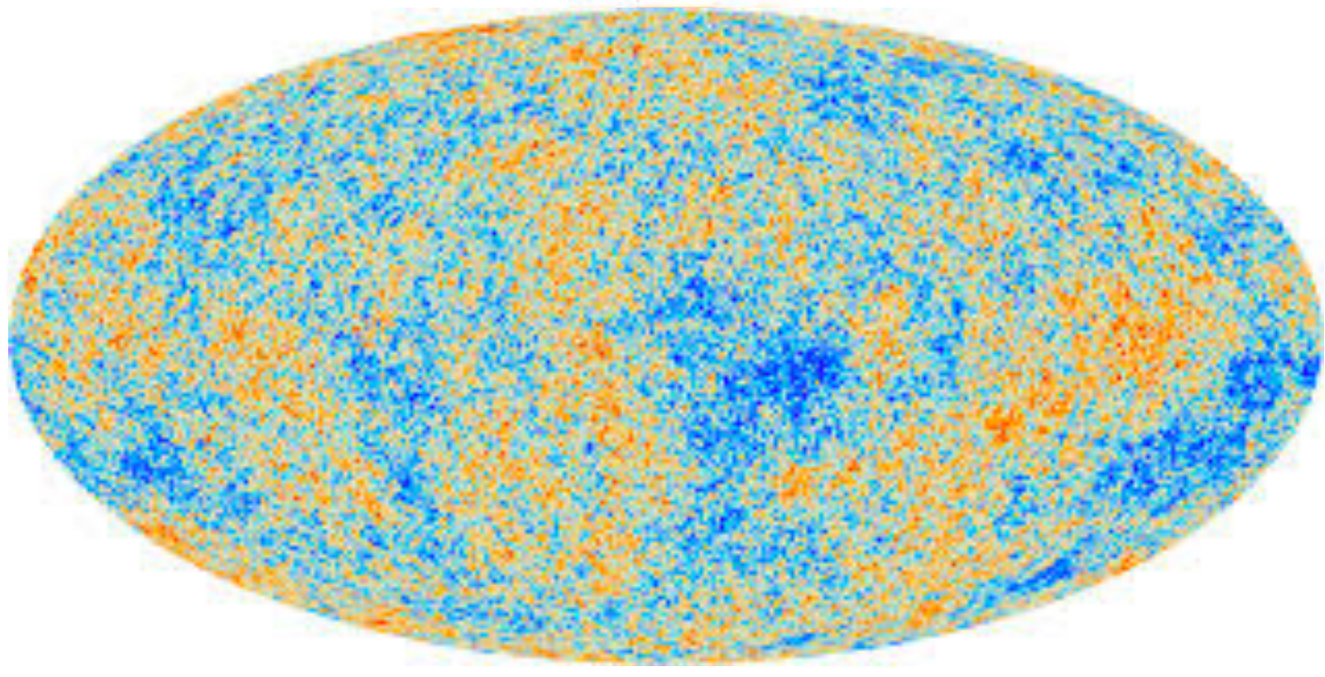




21-cm Global Signal = CMB Monopole

Fluctuations on T_{21}

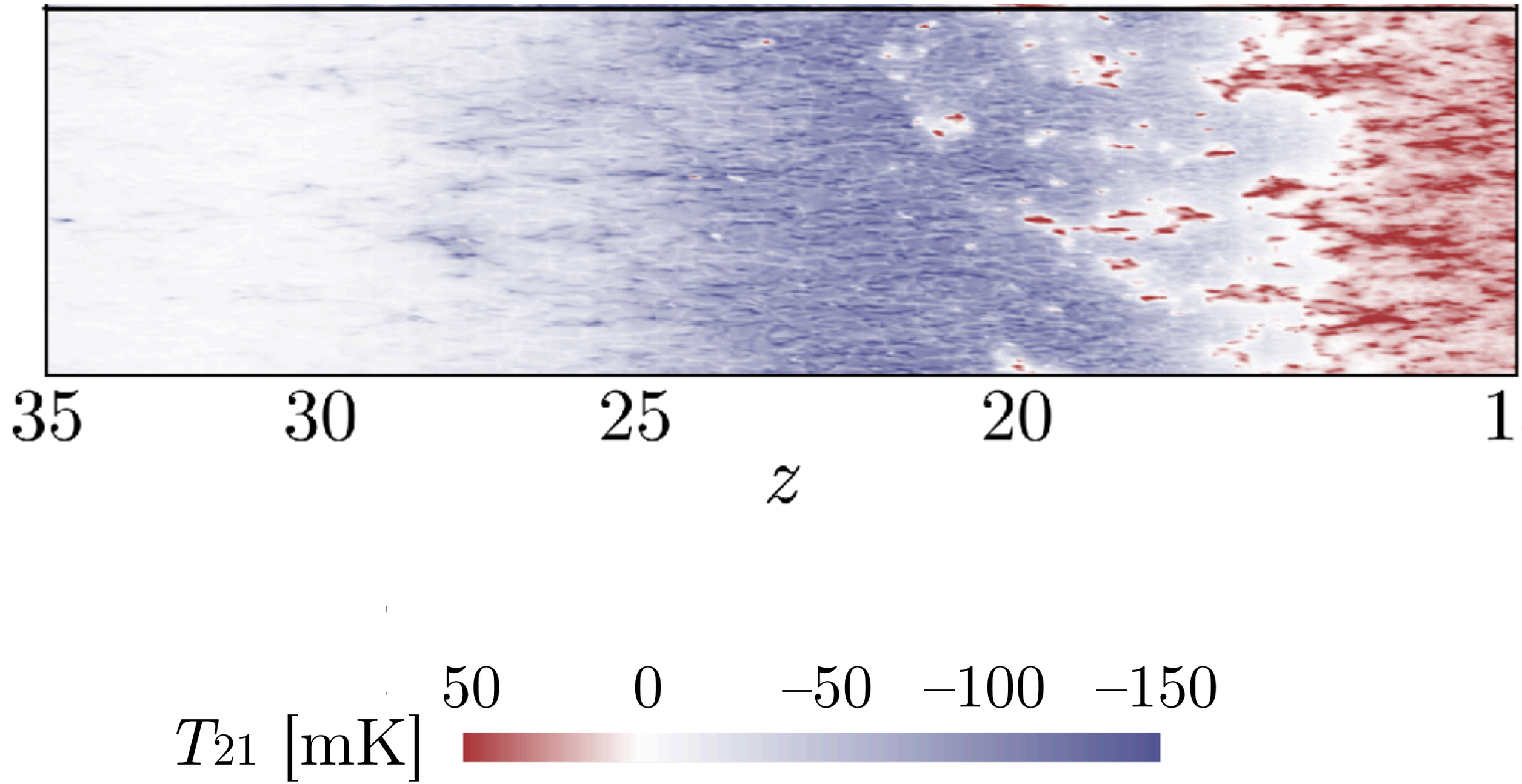




21-cm Fluctuations = CMB Anisotropies

Fluctuations on T_{21}

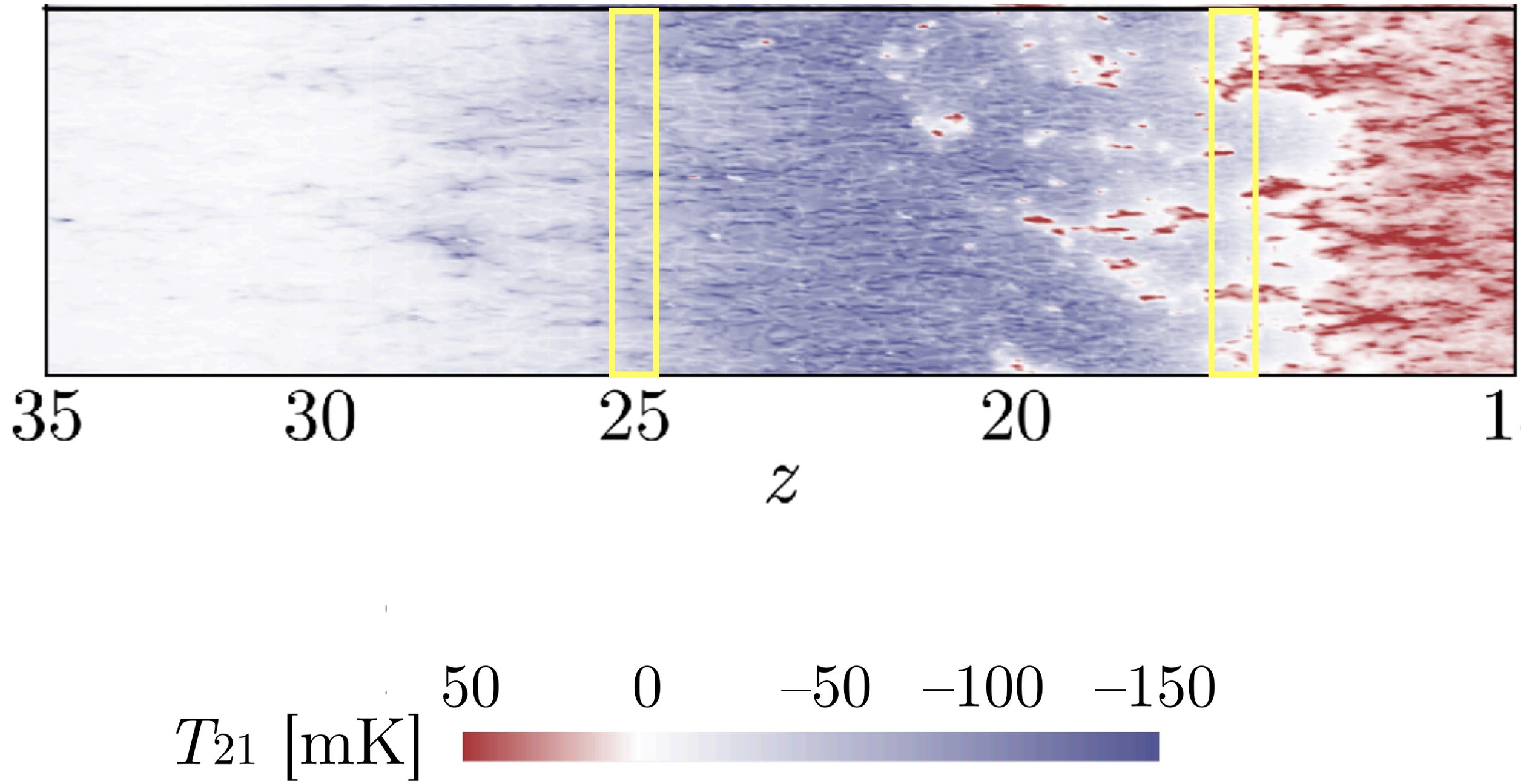
(Full)



Modifying 21cmFAST (Mesinger+ 2010)

Fluctuations on T_{21}

(Full)



Modifying 21cmFAST (Mesinger+ 2010)

Densities

Velocities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

$z = 25$

δT_{21} [mK]

20
10
0
−10
−20
−30
−40

Densities

Velocities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

δT_{21} [mK]

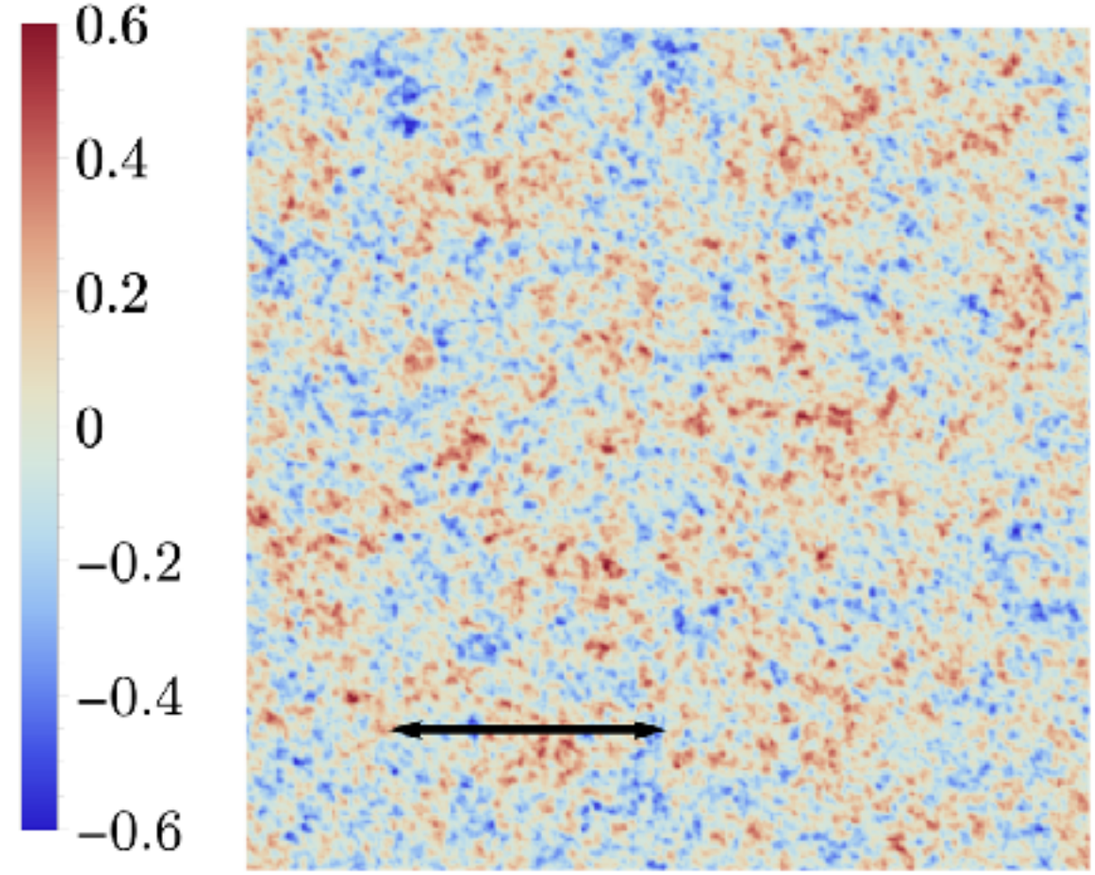
20
10
0
−10
−20
−30
−40

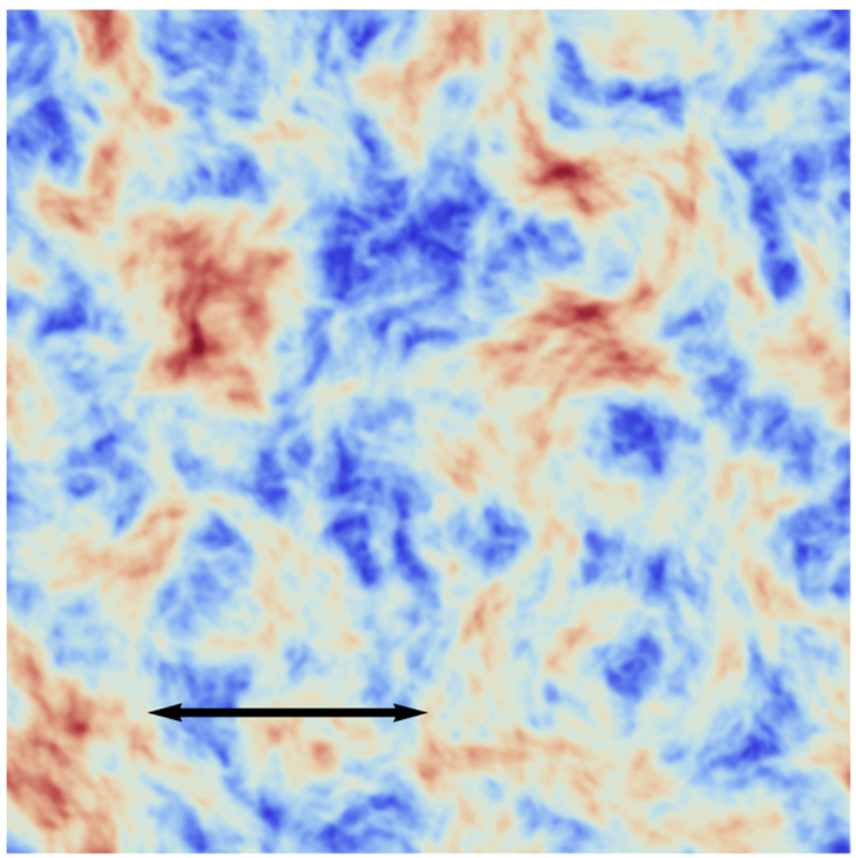
$z = 25$

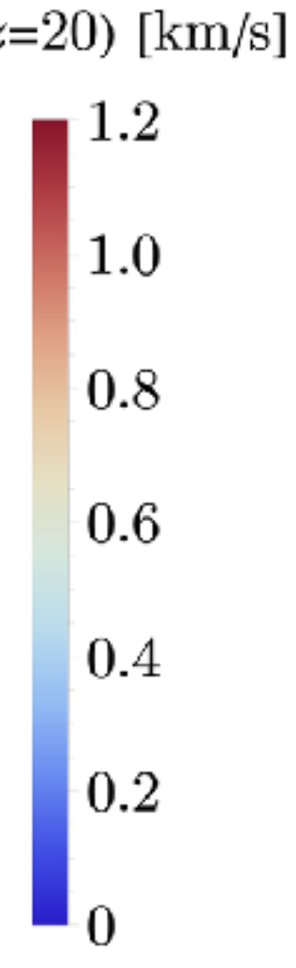
$z = 25$

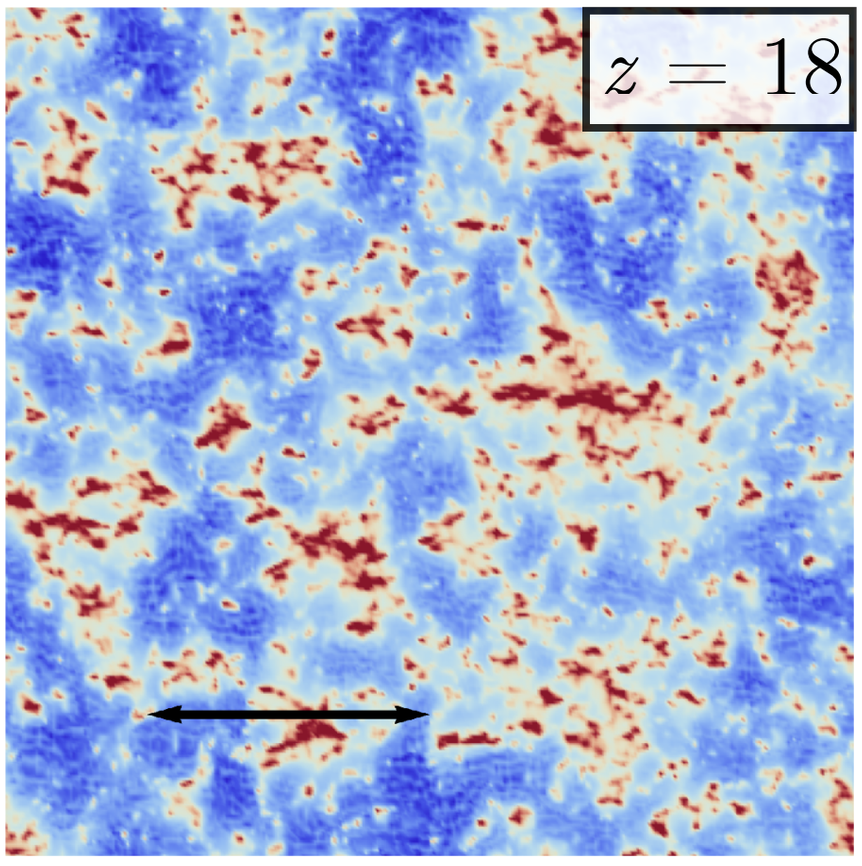
Densities

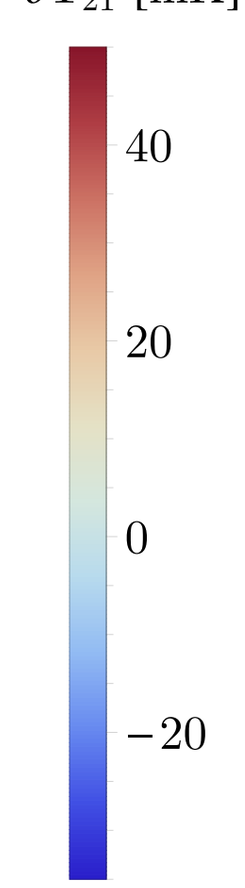
Velocities











Densities

Velocities

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

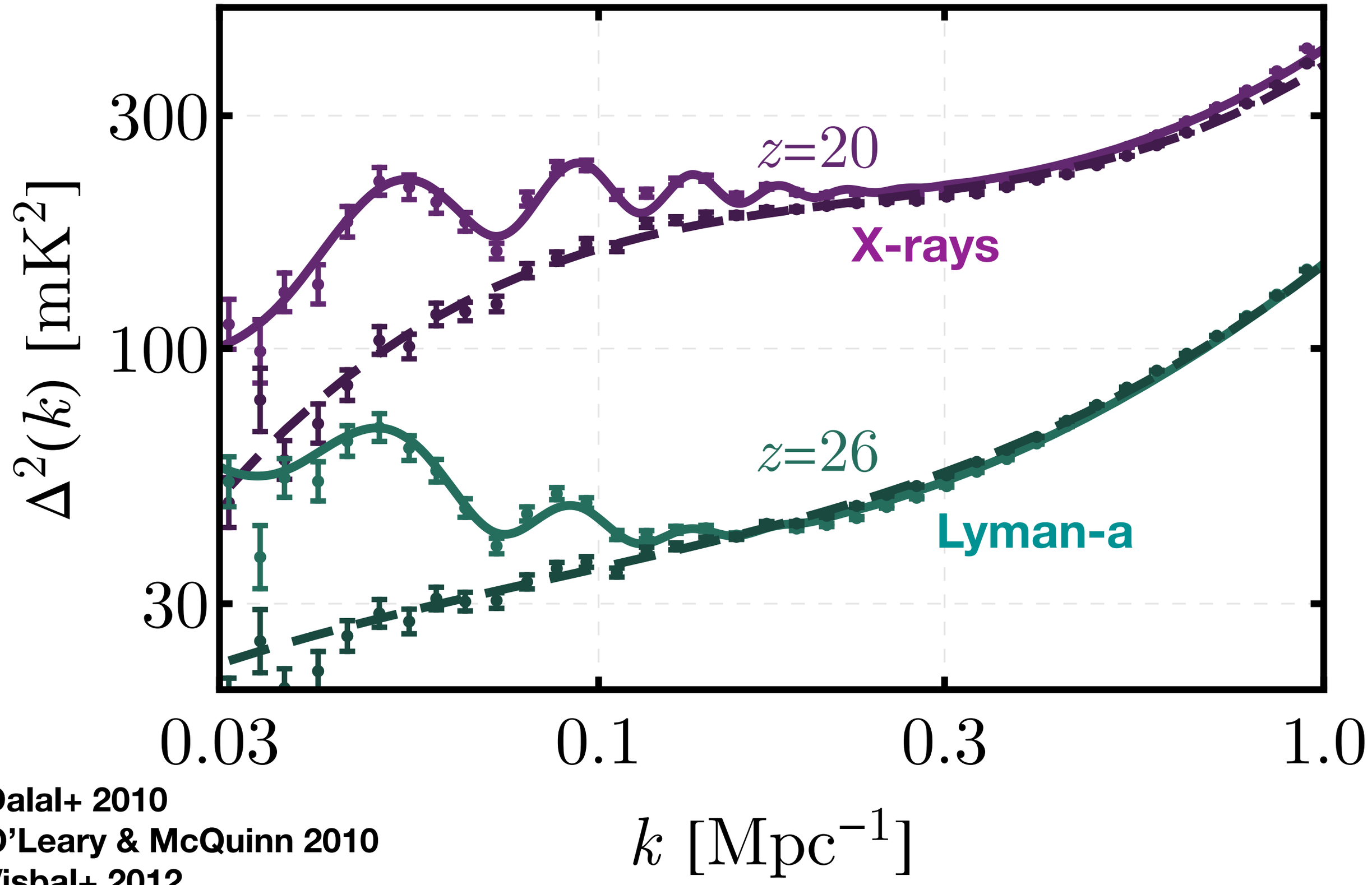
δT_{21} [mK]

40
20
0
−20

$z = 18$

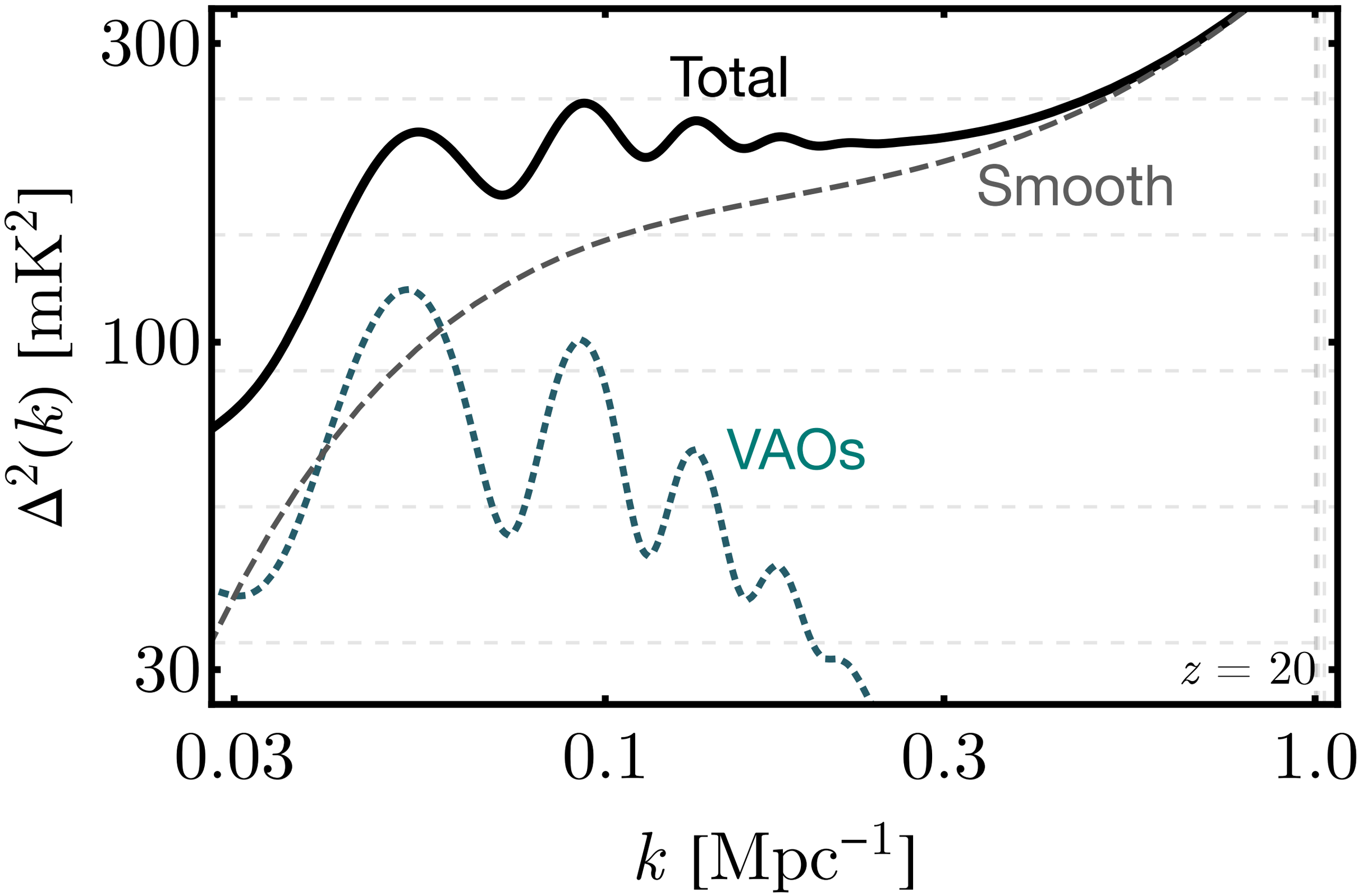
$z = 18$

Acoustic oscillations on T_{21} !

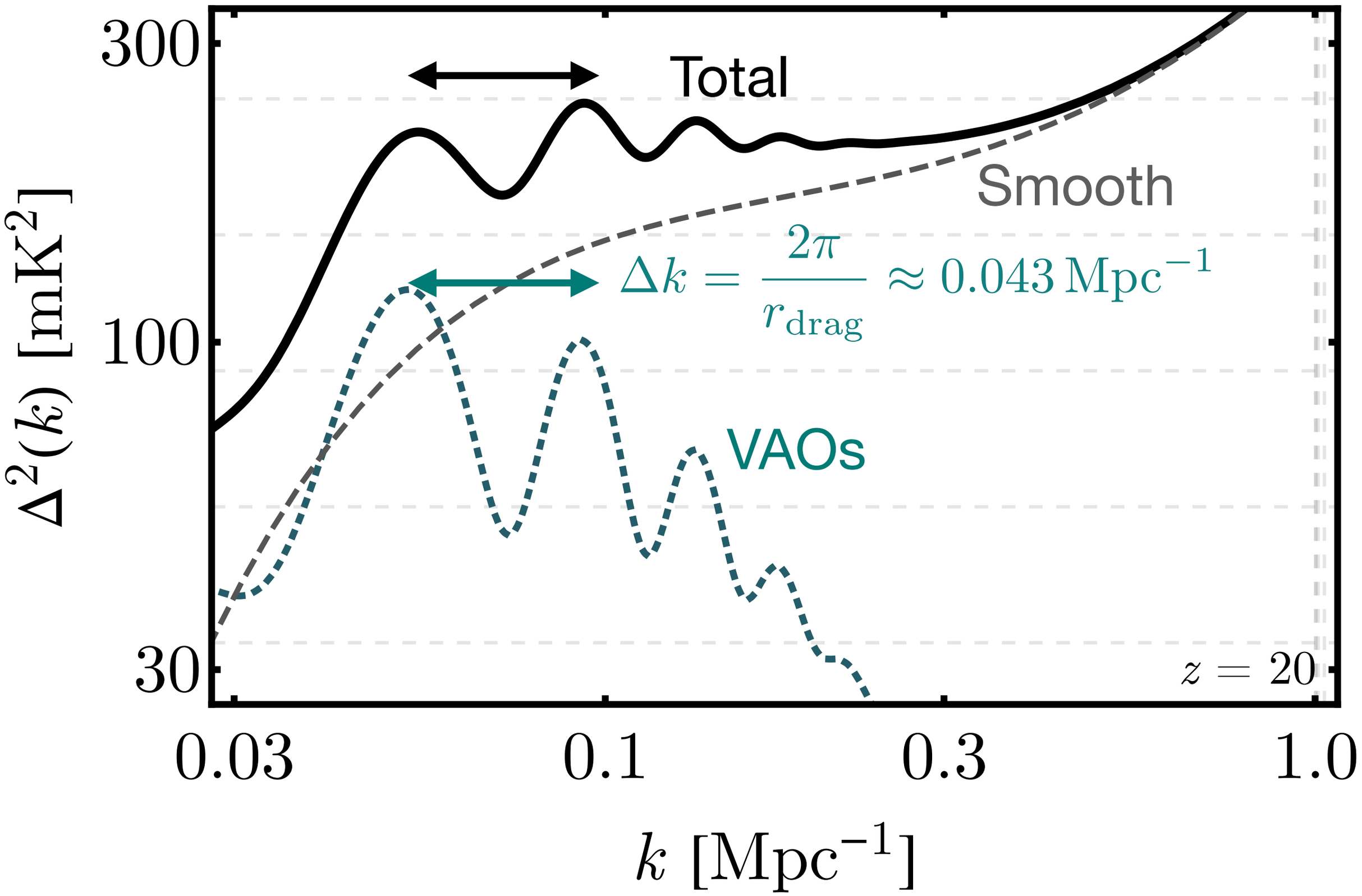


Dalal+ 2010
O'Leary & McQuinn 2010
Visbal+ 2012
Fialkov+2014

Acoustic oscillations on T_{21} !

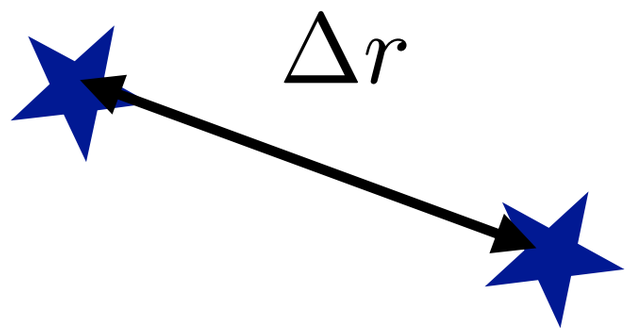


Acoustic oscillations on T_{21} !

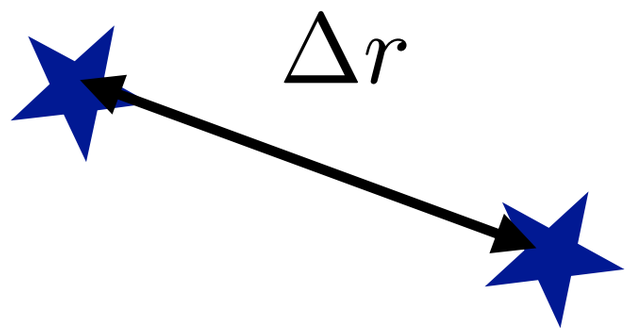


How to use a standard ruler

How to use a standard ruler



How to use a standard ruler

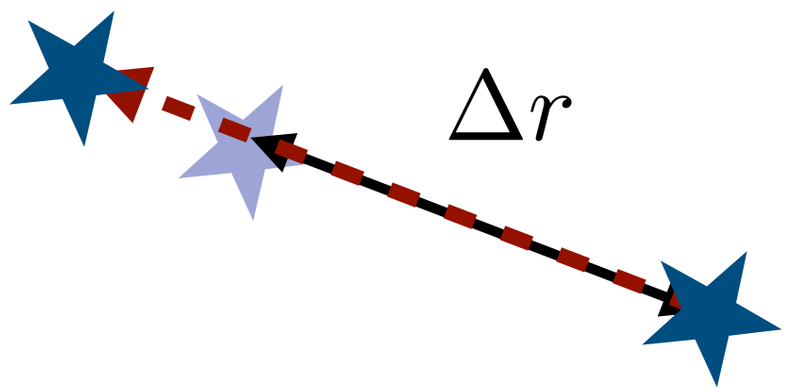


$$\Delta\theta = \frac{\Delta r}{D_A(z)}$$

$$\Delta z = H(z)\Delta r$$

Alcock and Paczynski 1979

How to use a standard ruler

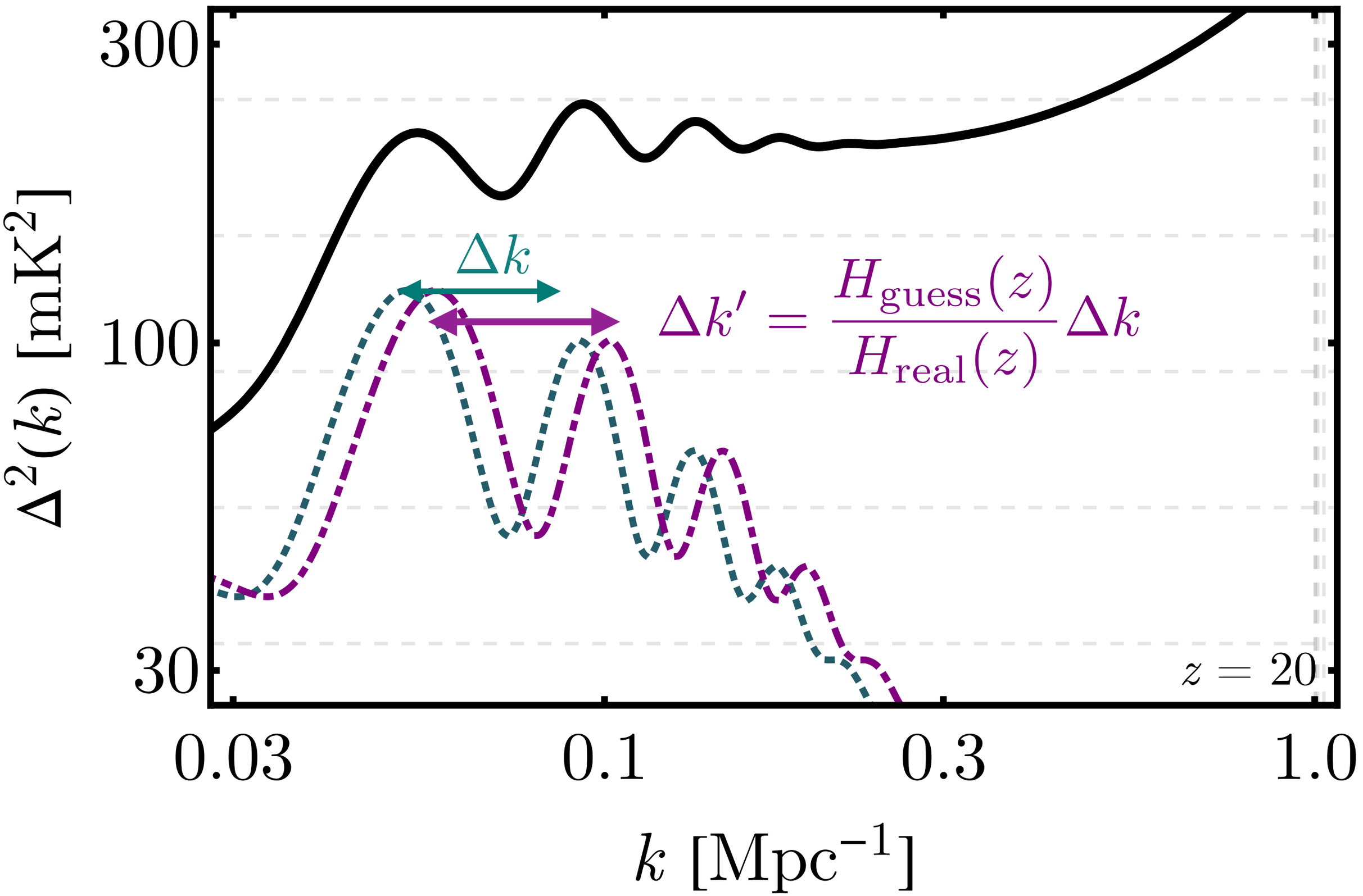


$$\Delta z = H(z)\Delta r$$

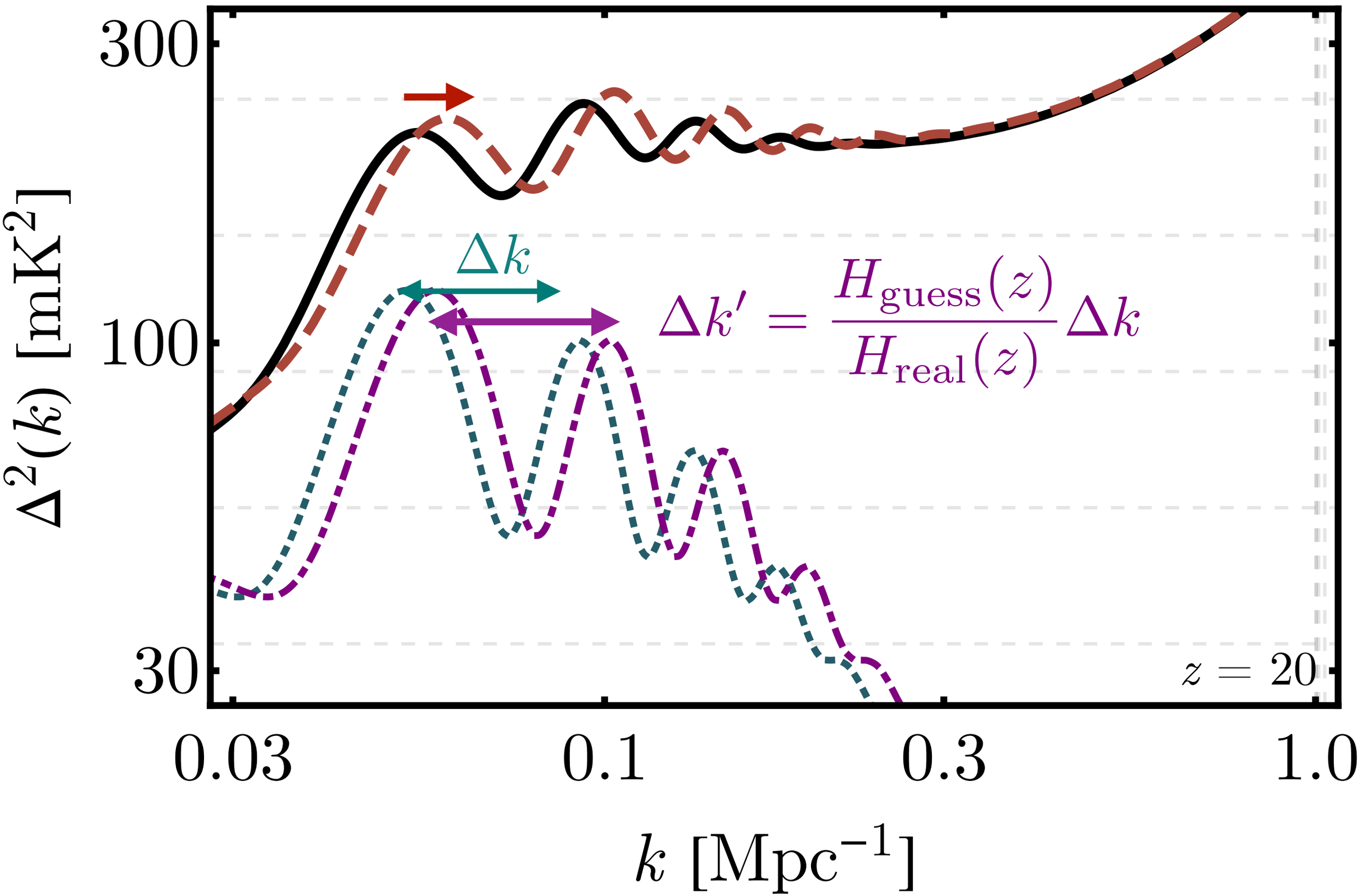
$$\Delta r_{\rm guess} = \frac{H_{\rm real}(z)}{H_{\rm guess}(z)}\Delta r_{\rm real}$$

Alcock and Paczynski 1979

VAOs as a standard ruler



VAOs as a standard ruler

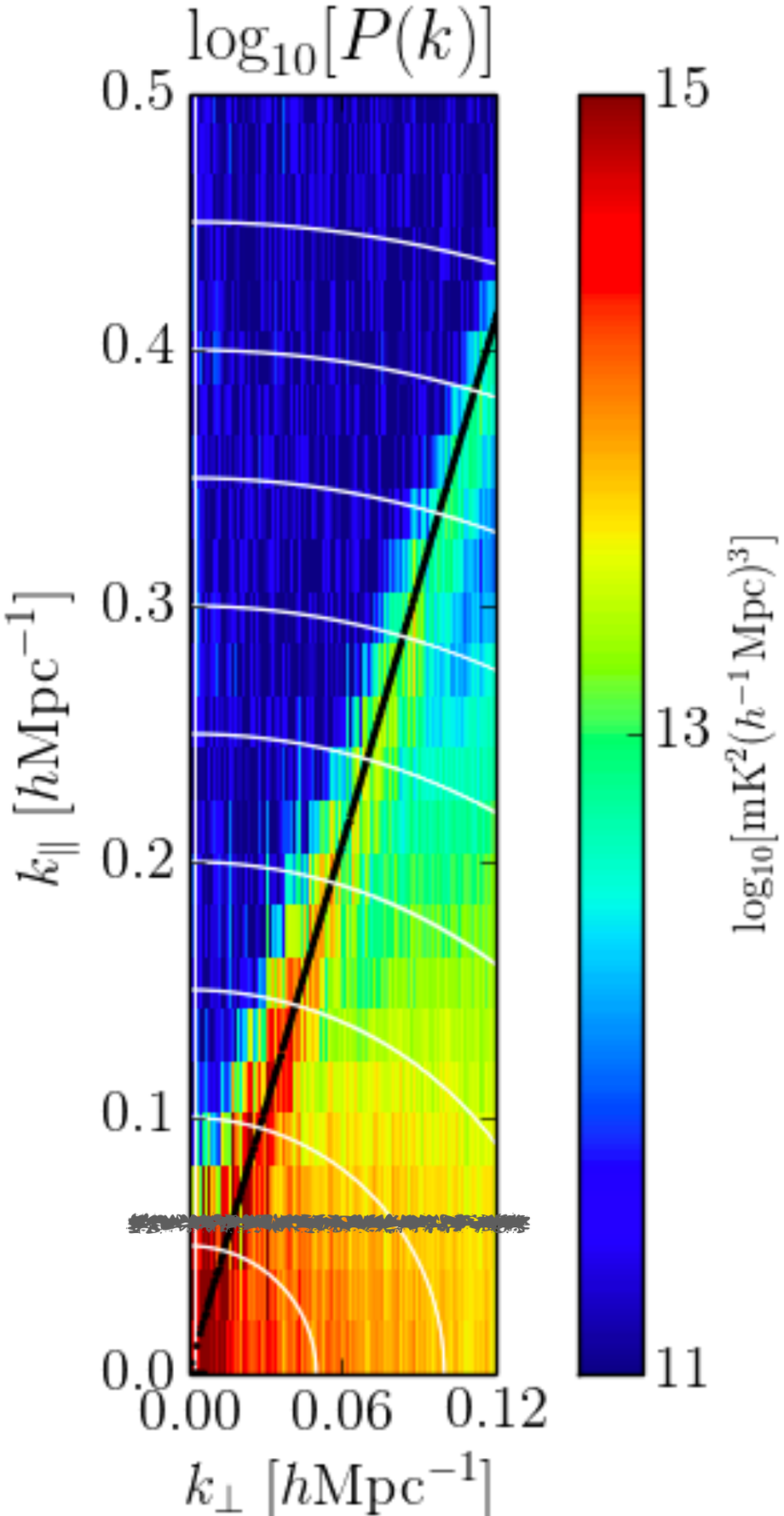


Is this observable?

HERA (Hydrogen Epoch of Reionization Array):
350 antennae, 14-m in diameter

DeBoer+ 2016

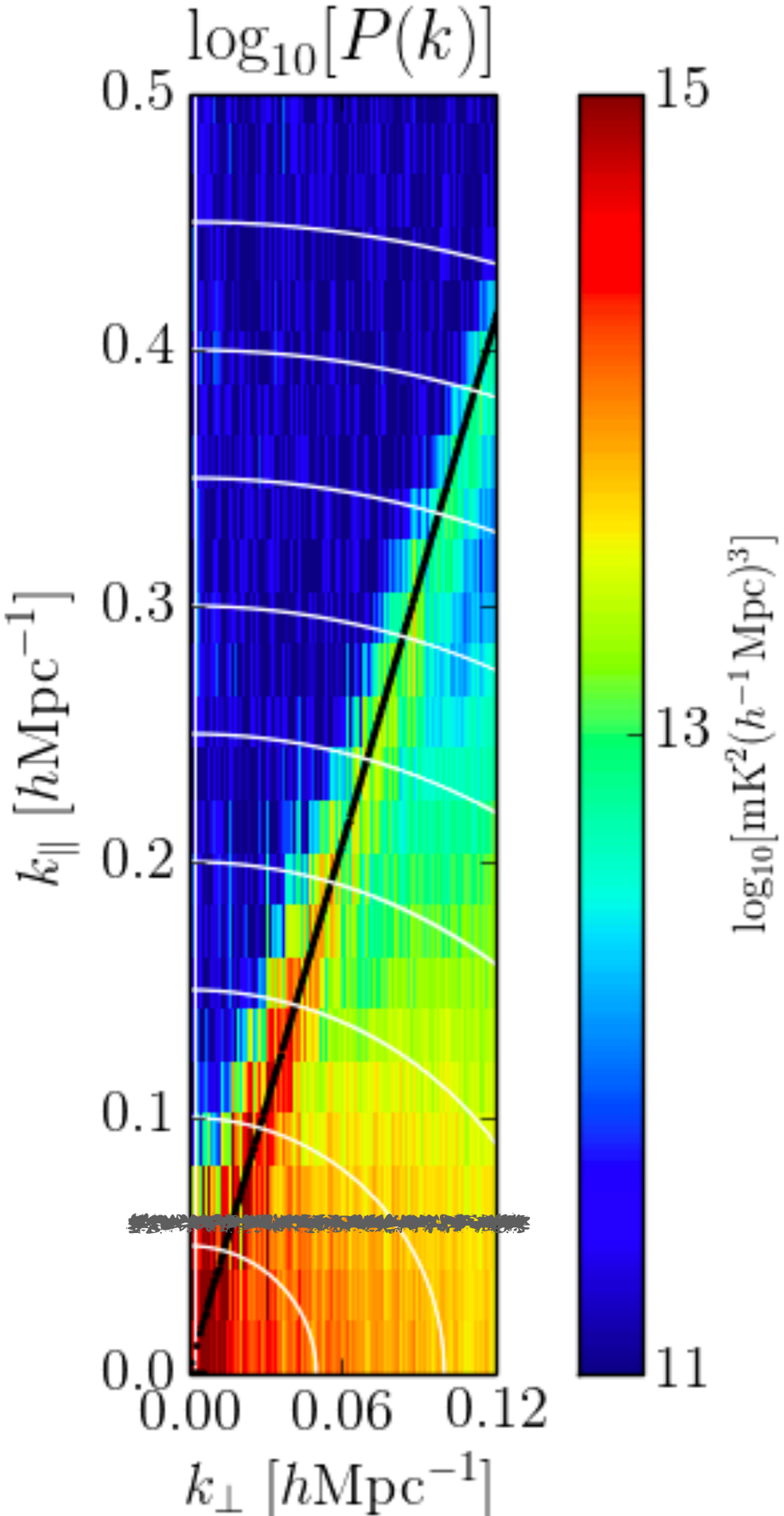
Foreground “wedge”



Foregrounds swamp the signal.
Avoid the “wedge”

Pober 2014, PAPER Coll.
Parsons+ 2011

Foreground "wedge"



Foregrounds swamp the signal.
Avoid the "wedge"

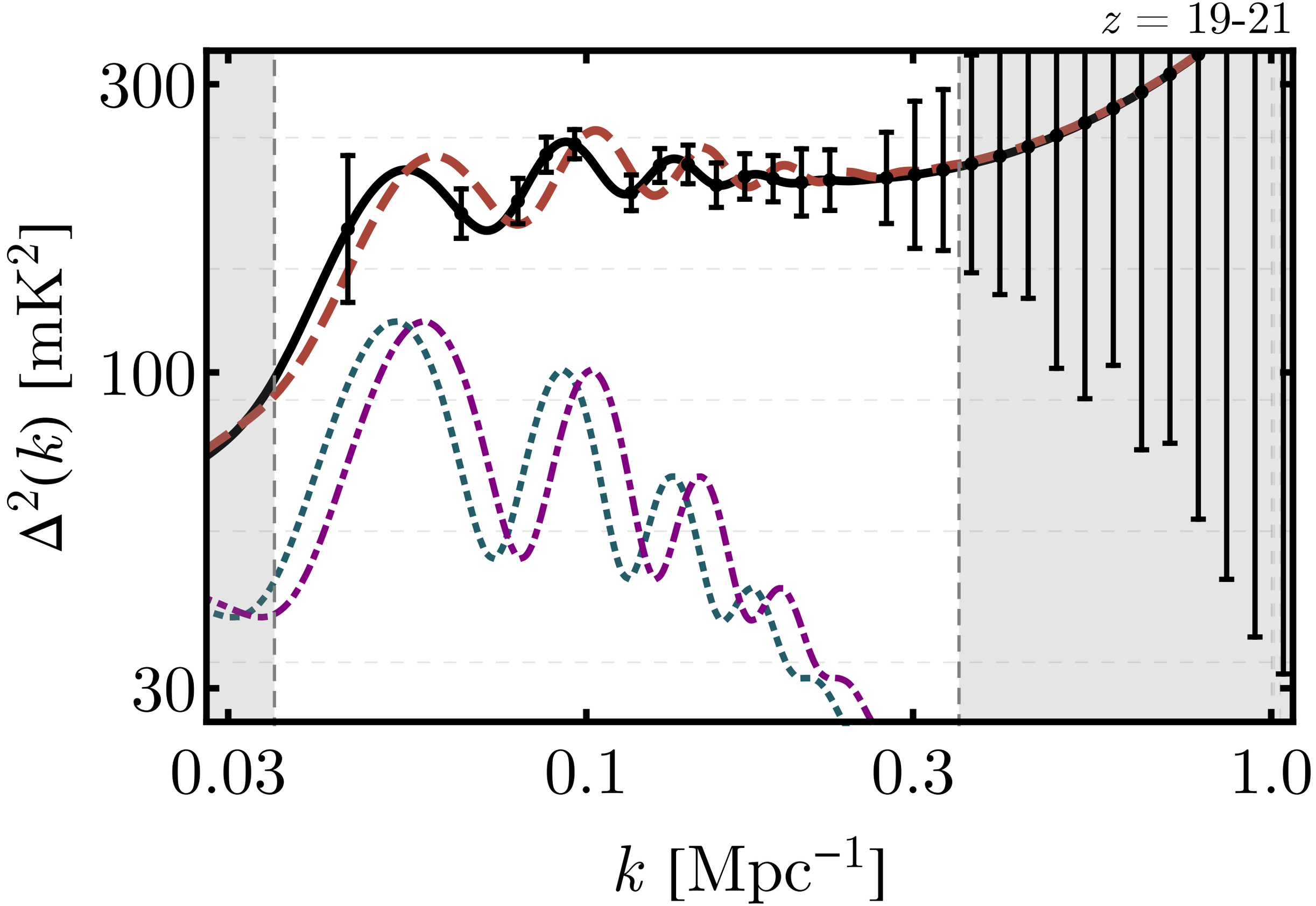
$$k_{||}^{\min} = a + bk_\perp$$

a: $0.05\ h/\mathrm{Mpc}$ — b: 6

But the foreground gods might not be kind to us…

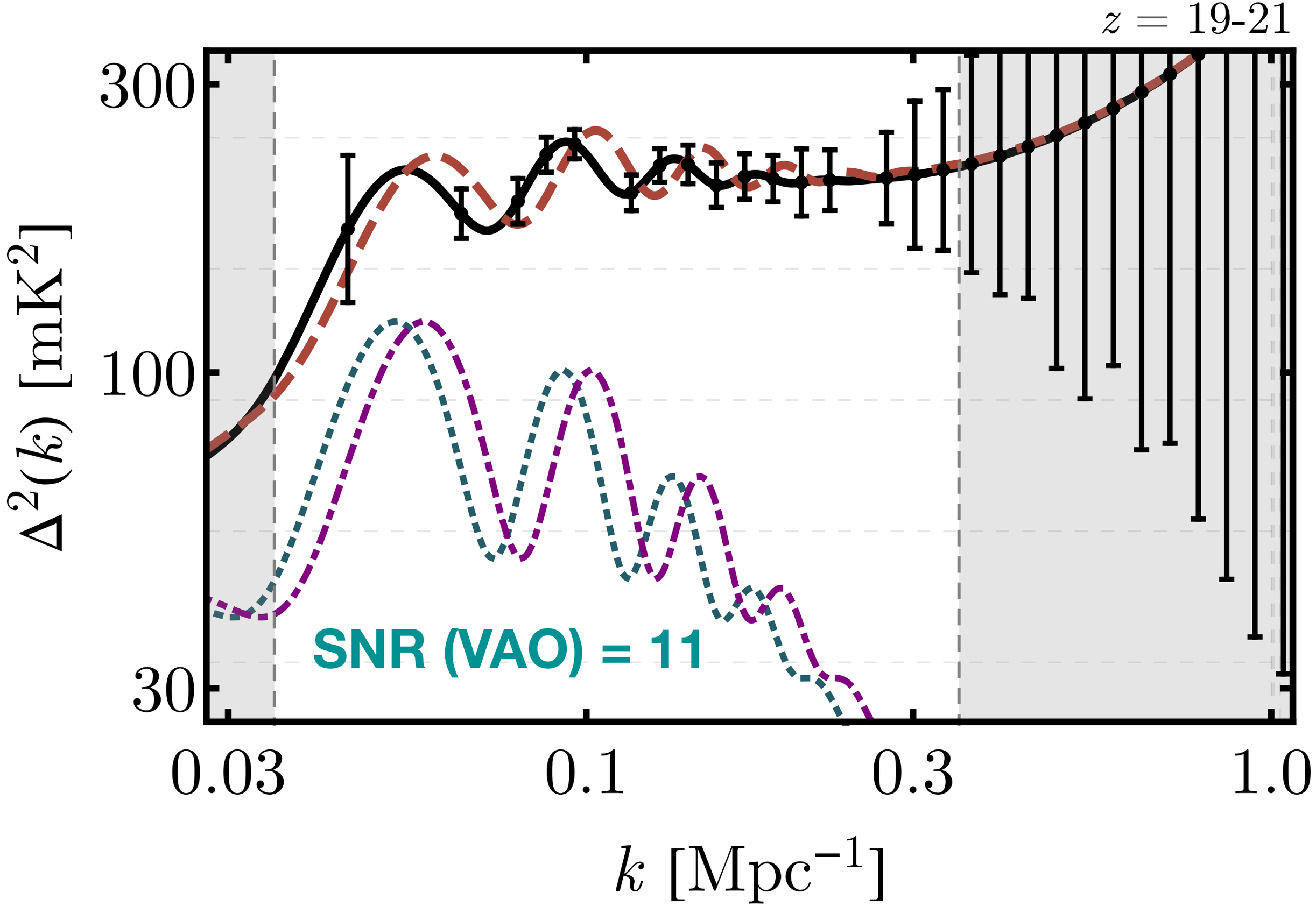
Pober 2014, PAPER Coll.
Parsons+ 2011

VAOs as a standard ruler



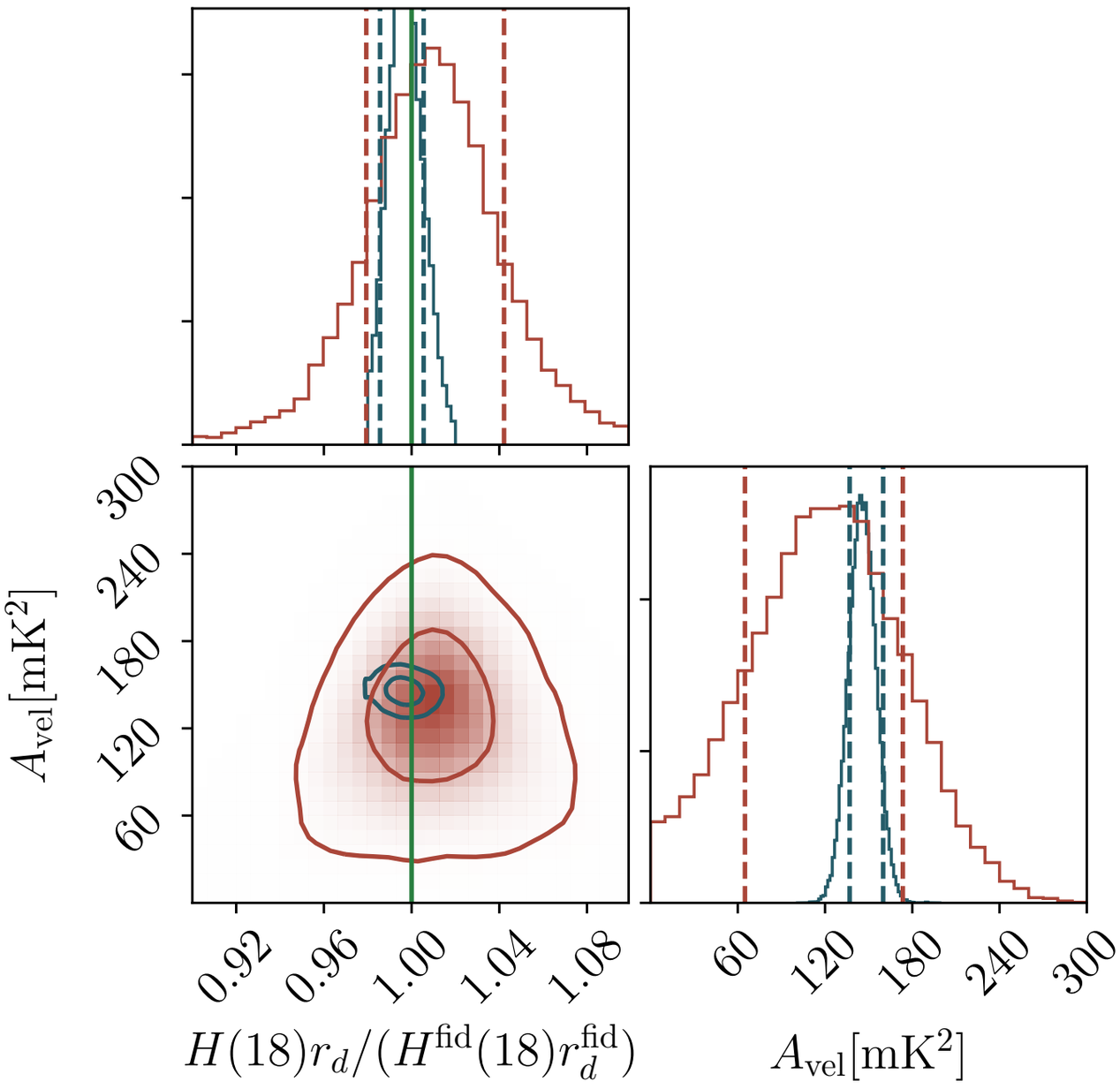
Using 21cmSense (Pober+ 2014)

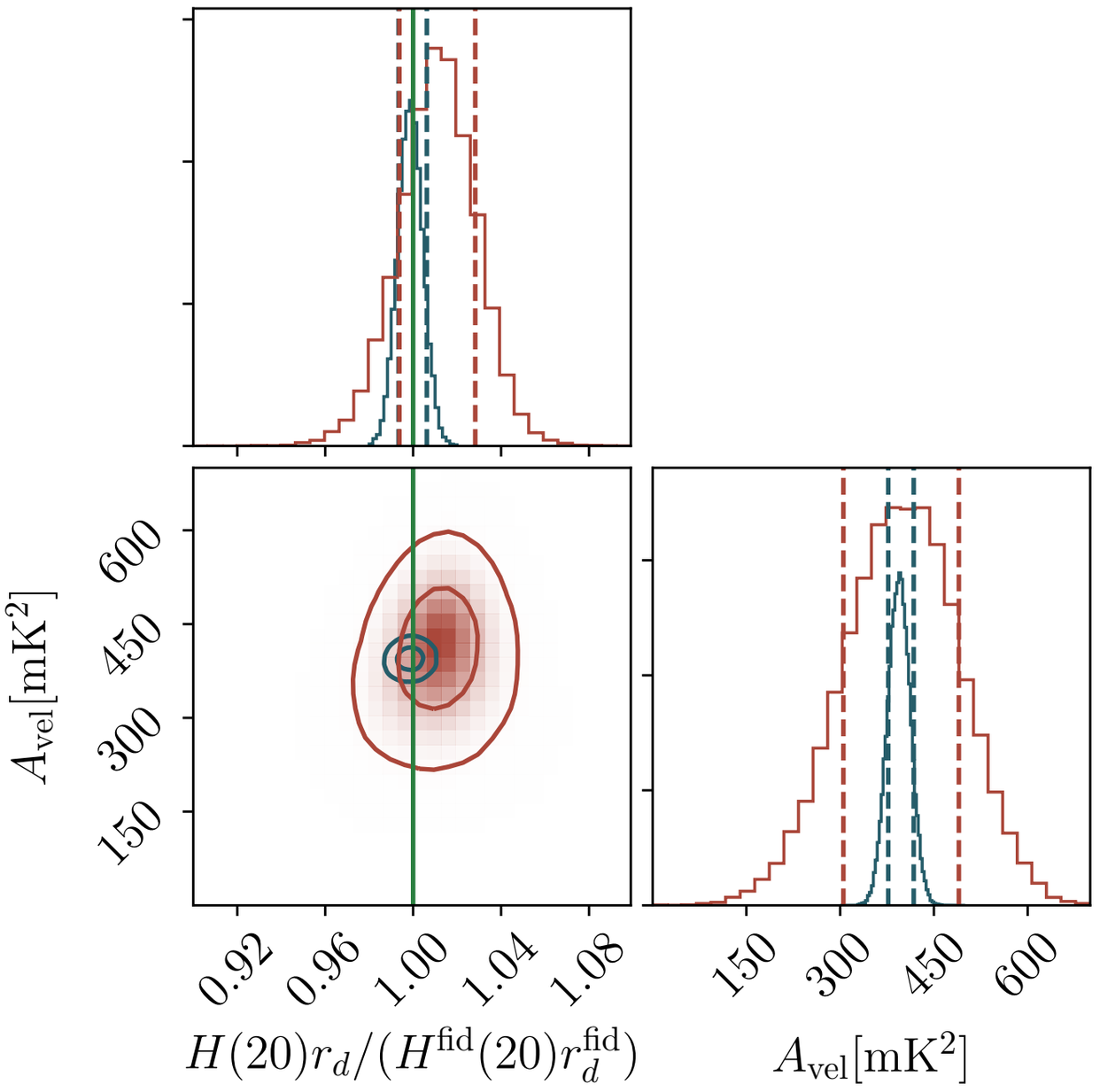
VAOs as a standard ruler



Using 21cmSense (Pober+ 2014)

Measuring $H(z)$





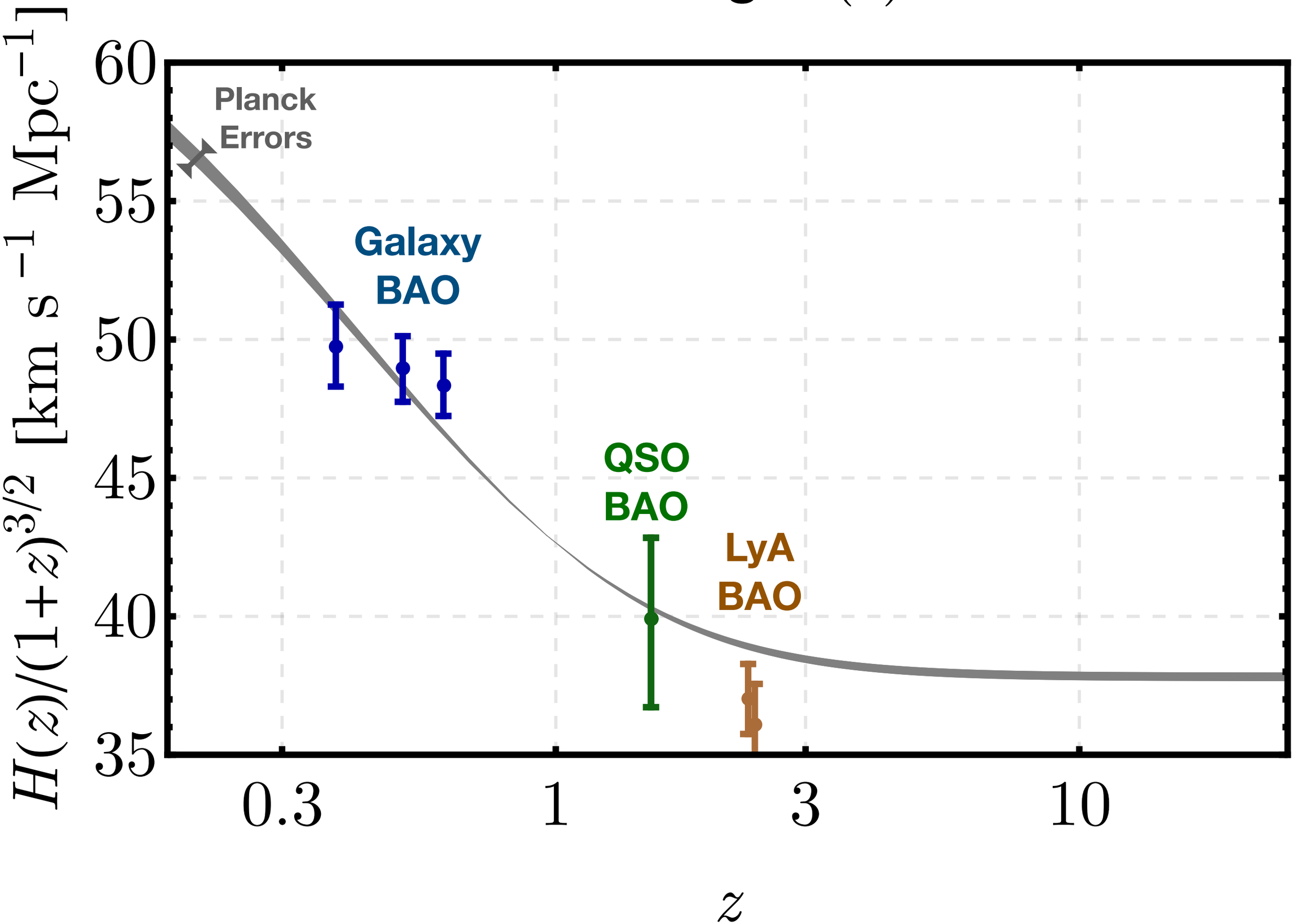
$z = 17$–19

$\sigma(H)/H = 3\%$

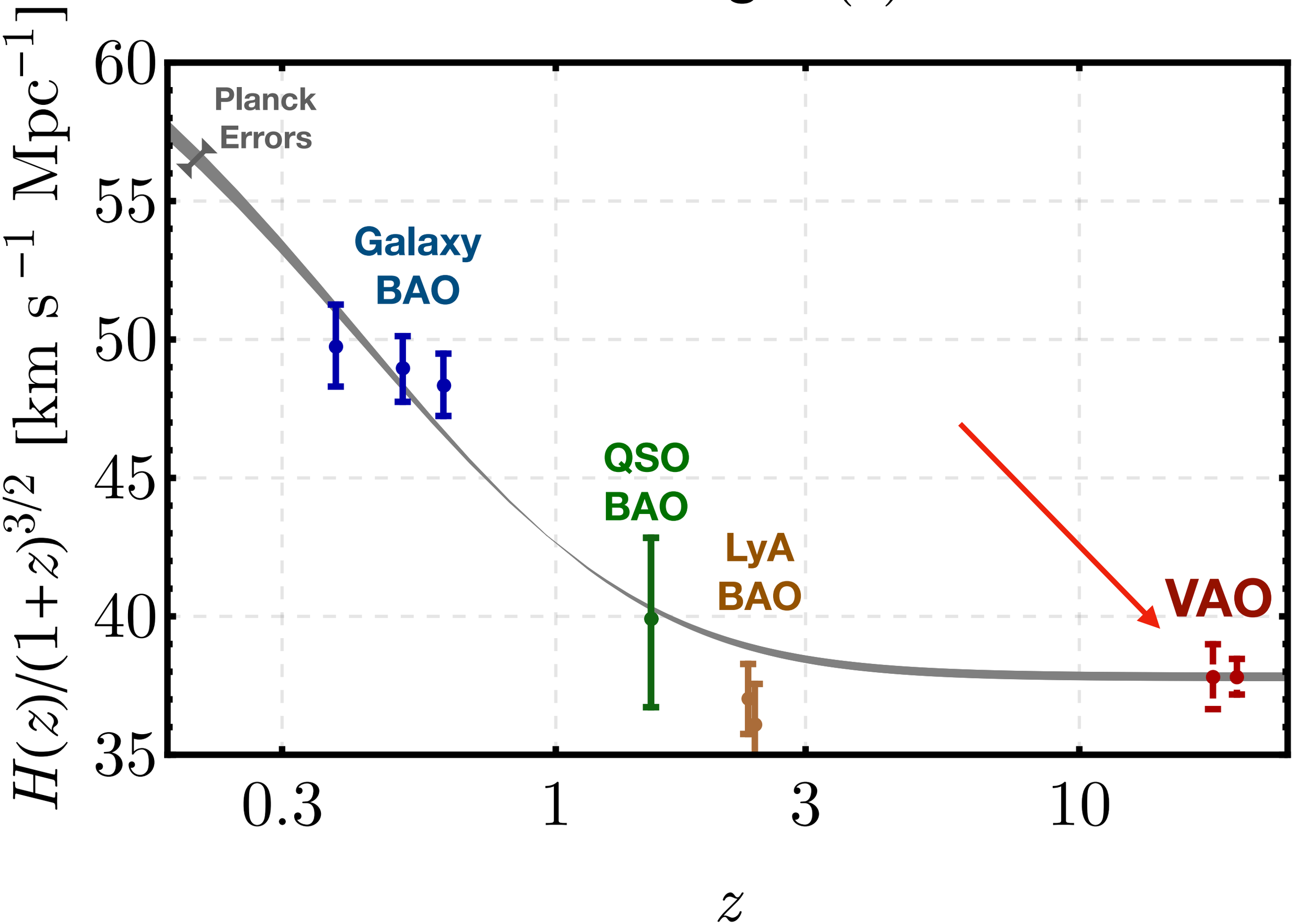
$z = 19$-21

$\sigma(H)/H = 2\%$

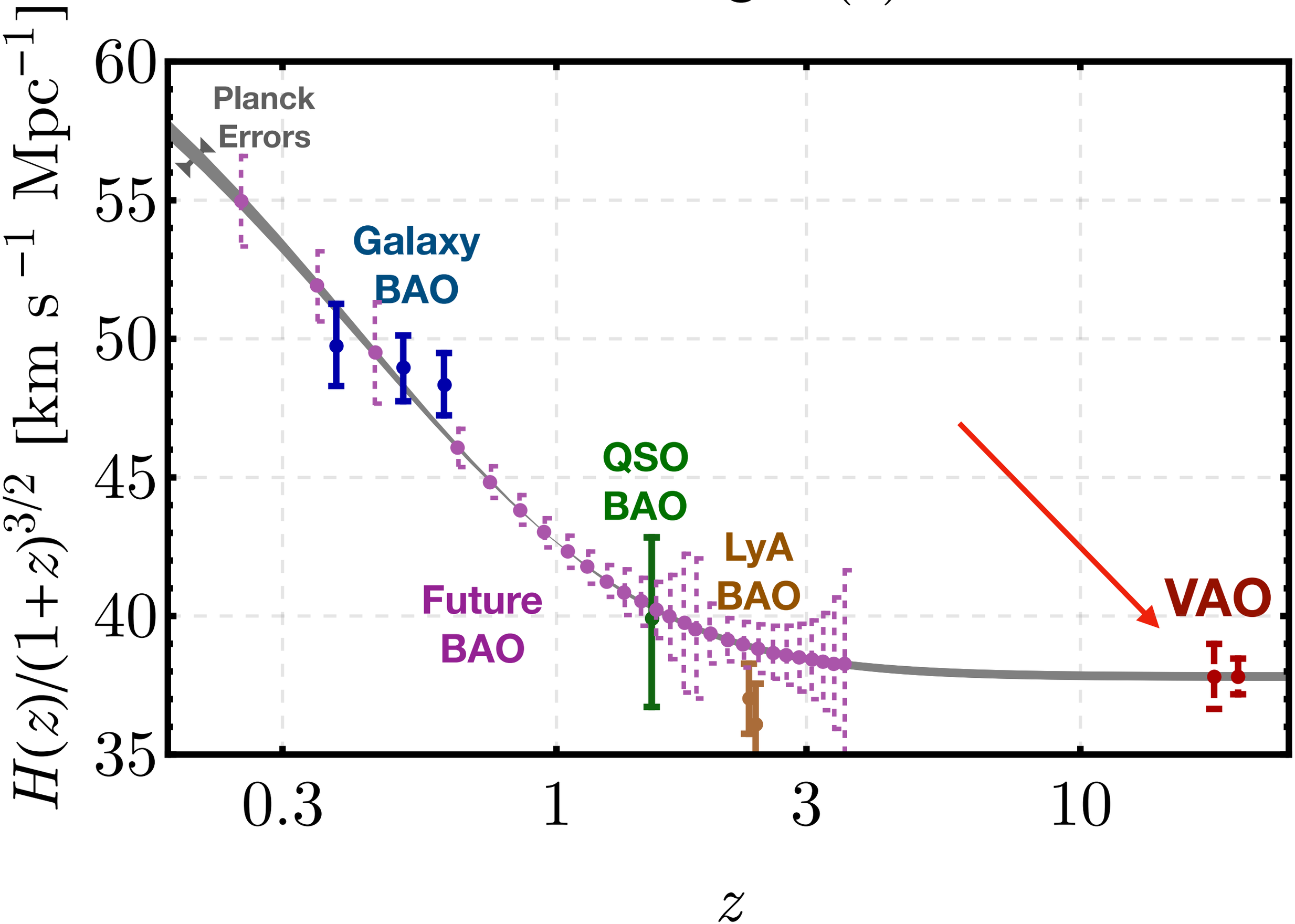
Measuring $H(z)$



Measuring $H(z)$



Measuring $H(z)$



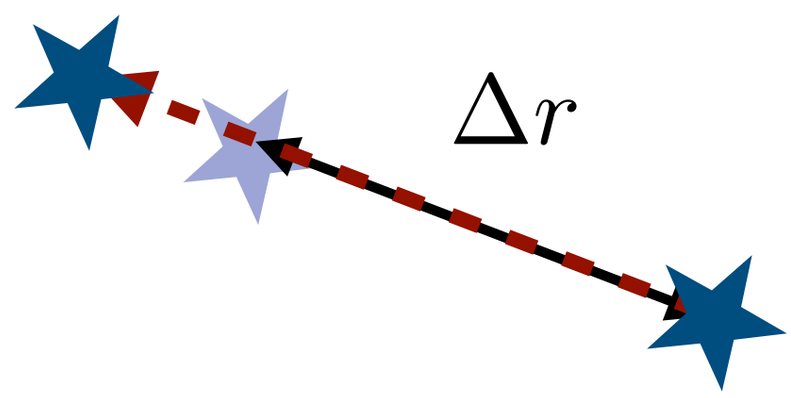
Applications

- H_0 tension (although in LCDM we measure $H_0\sqrt{\Omega_M}$)

- BSM cosmology (e.g., decaying DM, Mnu…)

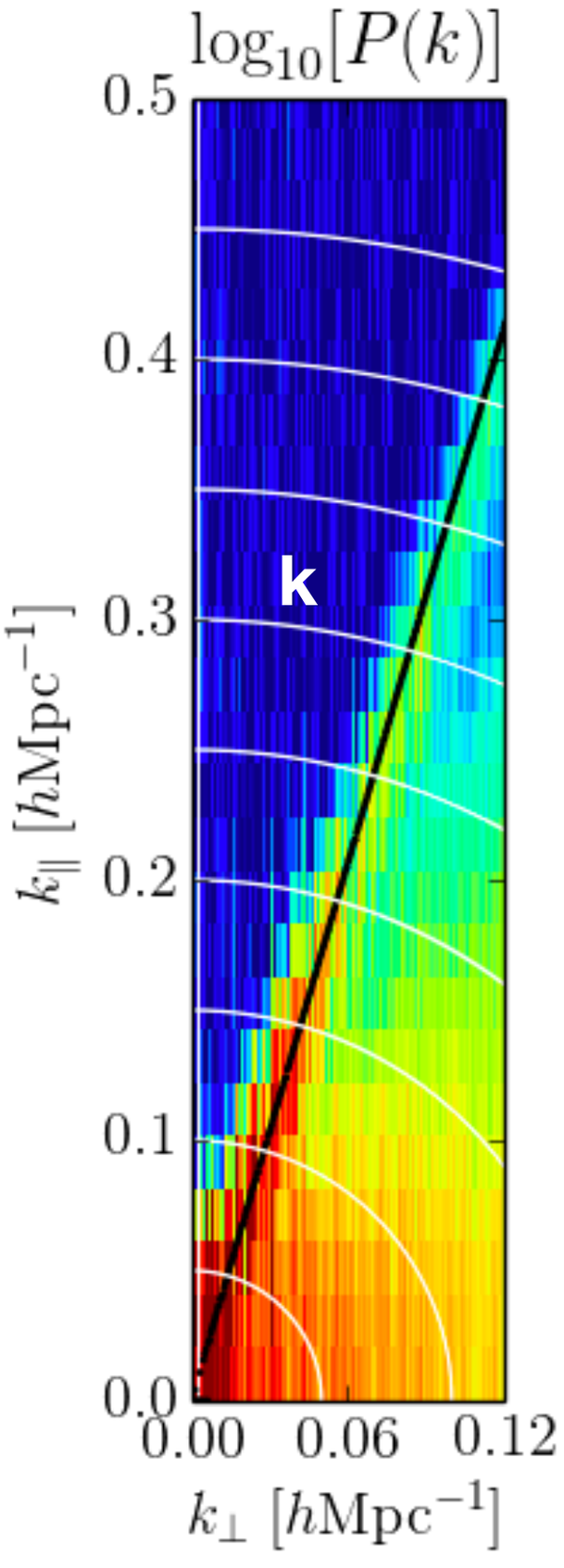
- It’s unexplored territory!

What about D_A?



$$\Delta r_{\rm guess} = \frac{D_A^{\rm guess}(z)}{D_A^{\rm real}(z)} \Delta r_{\rm real}$$

What about D_A?



Foregrounds are not isotropic:

$$k_{||}^{\min} = a + bk_\perp \approx 10 \times k_\perp$$

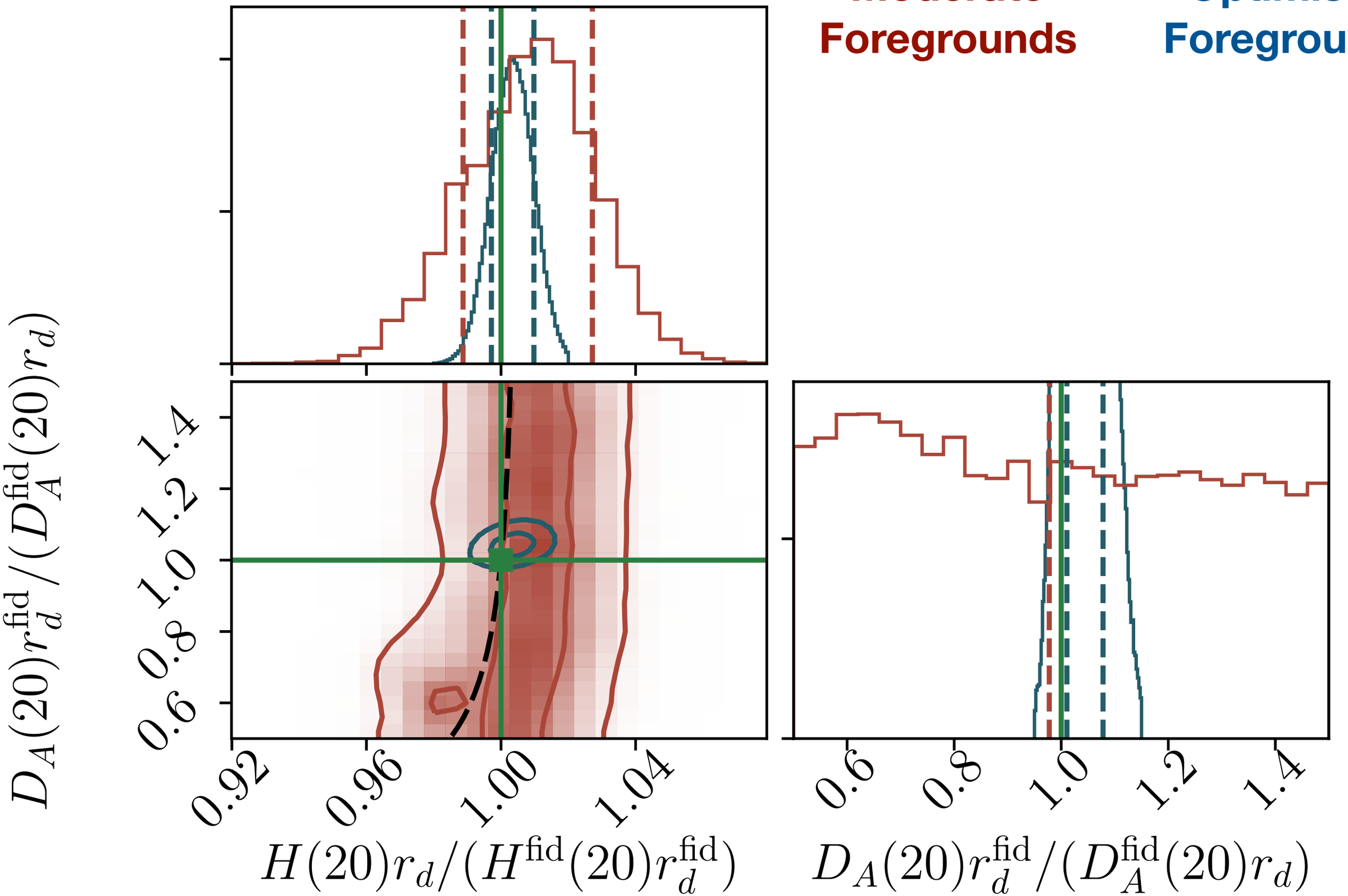
So we mostly observe parallel modes:

$$\frac{\sigma(D_A)}{D_A} \gtrsim 10 \times \frac{\sigma(H)}{H}$$

What about D_A?

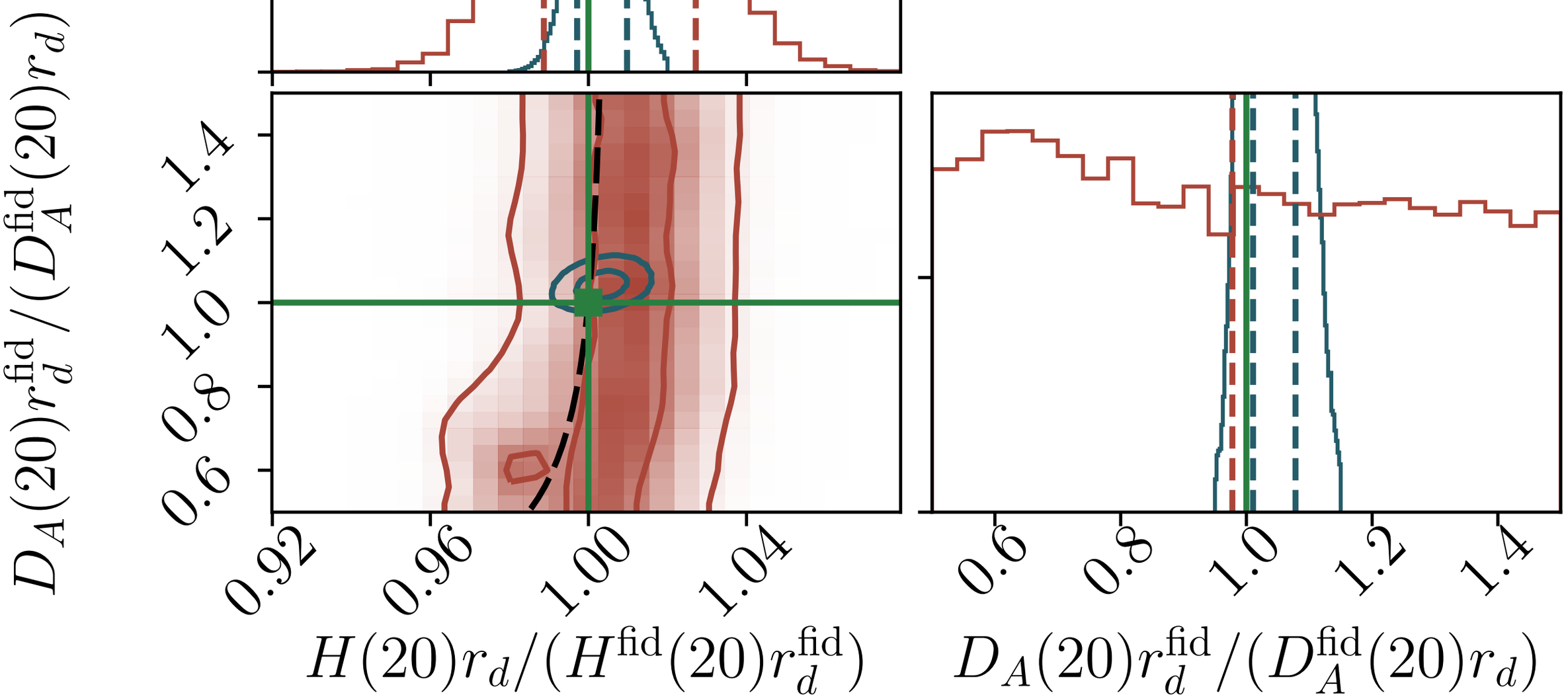
Moderate Foregrounds

Optimistic Foregrounds



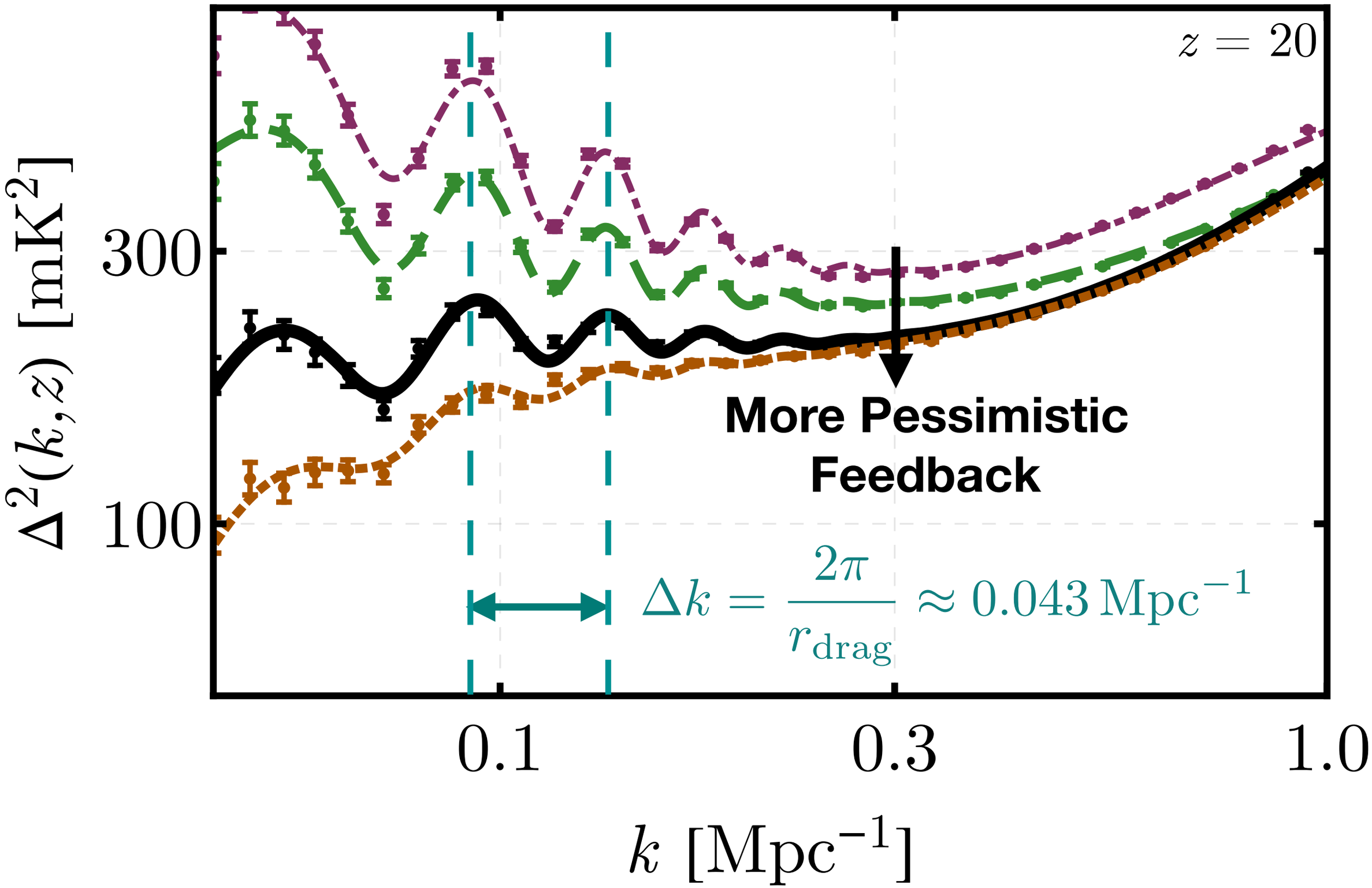
What about D_A?

	Moderate Foregrounds	**Optimistic Foregrounds**
$\sigma(H)/H =$	2%	0.6%
$\sigma(D_A)/D_A =$	150%	3%



Terms and Conditions

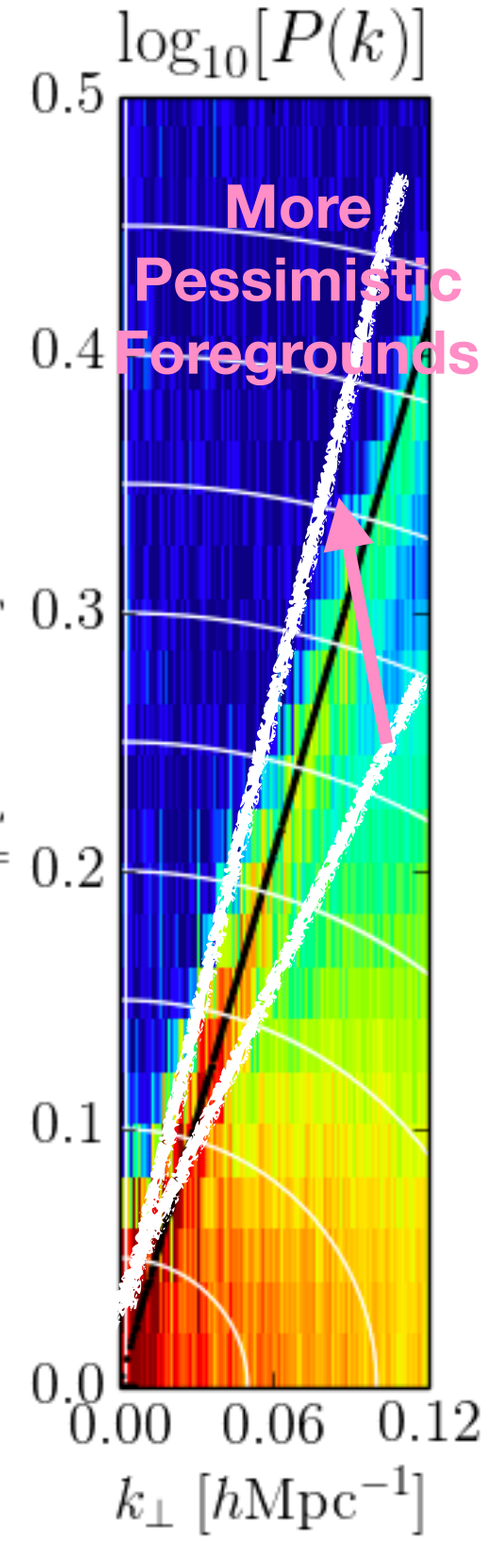
-Size of LW feedback unknown (plus other processes?)



Terms and Conditions

-Size of LW feedback unknown (plus other processes?)

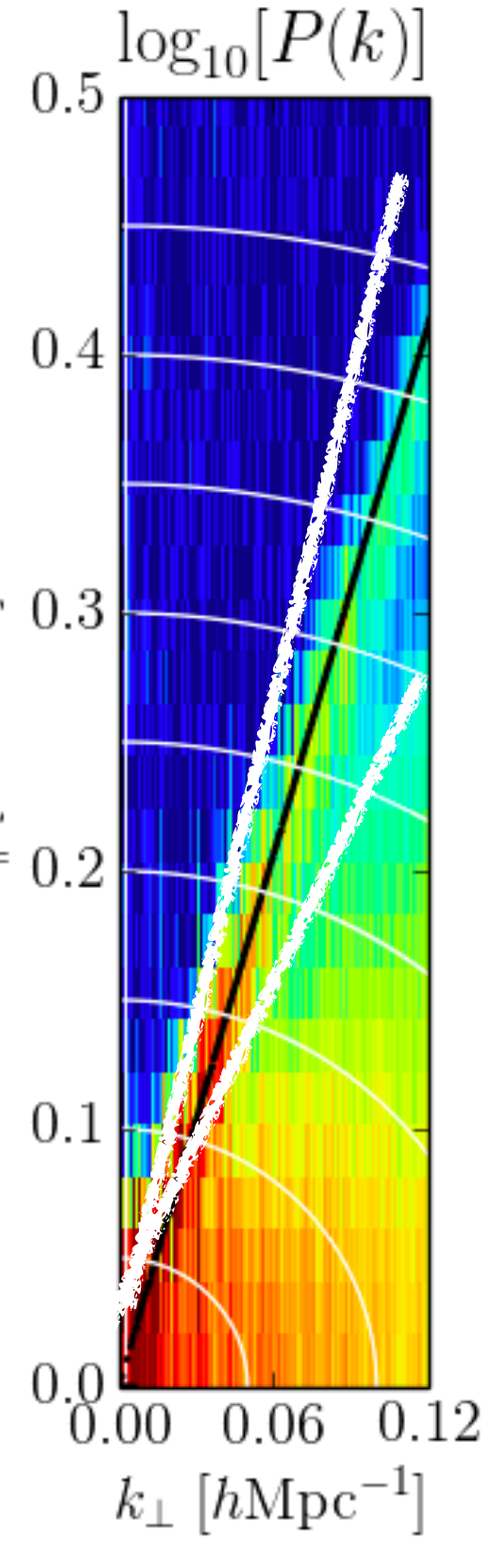
-Severity of foregrounds also unknown



Terms and Conditions

-Size of LW feedback unknown (plus other processes?)

-Severity of foregrounds also unknown



Foregrounds

Feedback strength	Pessimistic	Moderate	Optimistic
High	–	11%	3.2%
Regular	5.6%	1.7%	0.7%
Low	1.7%	0.9%	0.3%

$$\sigma[H(20)]/H(20)$$

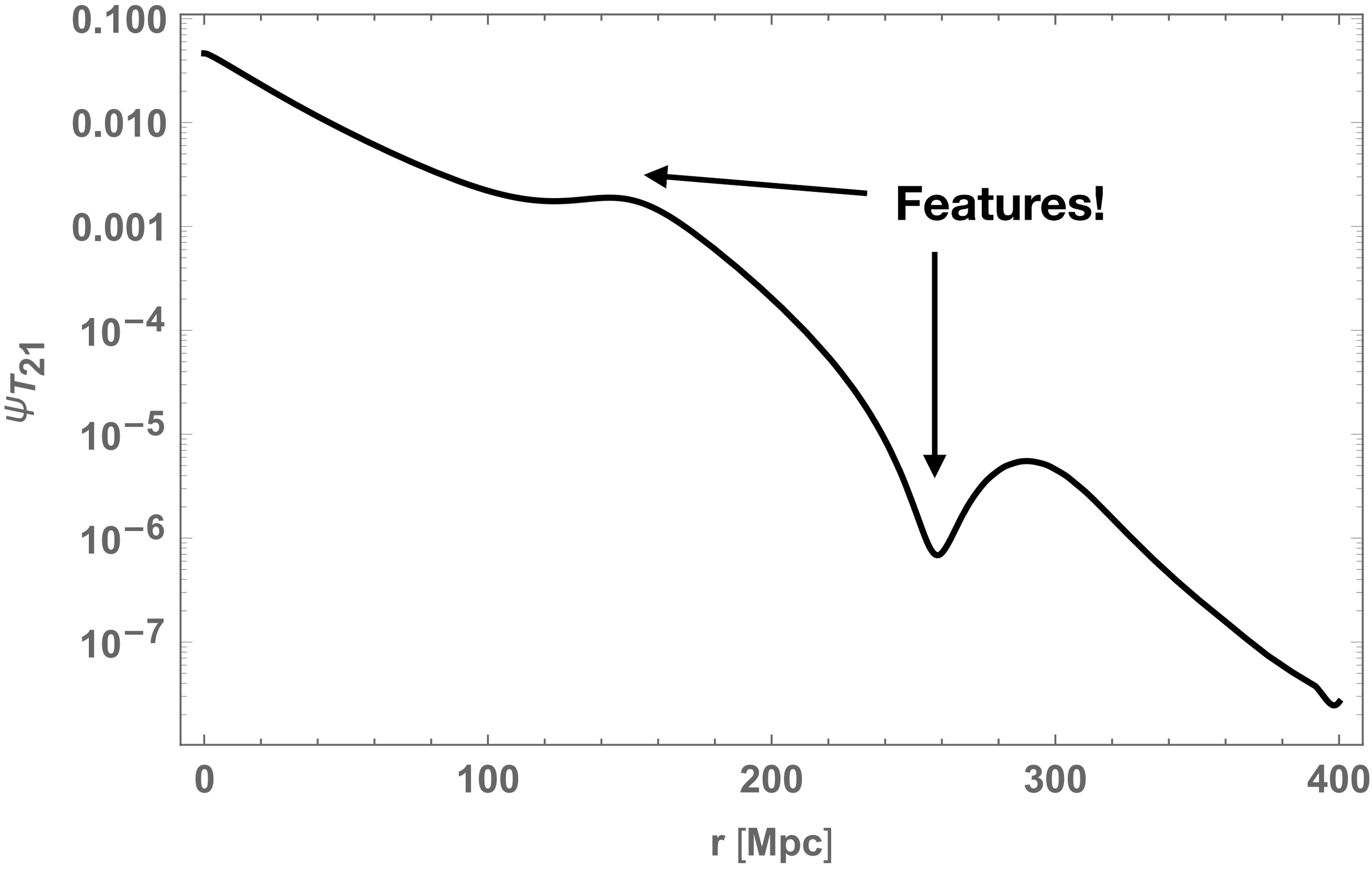
Summary

- Relative velocities between DM and baryons affect the formation of the first structures by O(1).

- They produce VAOs, with the same origin as BAOs but a different effect (large at z = 20, irrelevant today).

- Using VAOs as a standard ruler, we *should* be able to measure $H(z{=}20)$ with 21-cm data from HERA.

Backup


0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ψT_{21}
Features!
0
100
200
300
400
r [Mpc]

$\langle v^n v^m \rangle$

n,m={1,2,3,4}

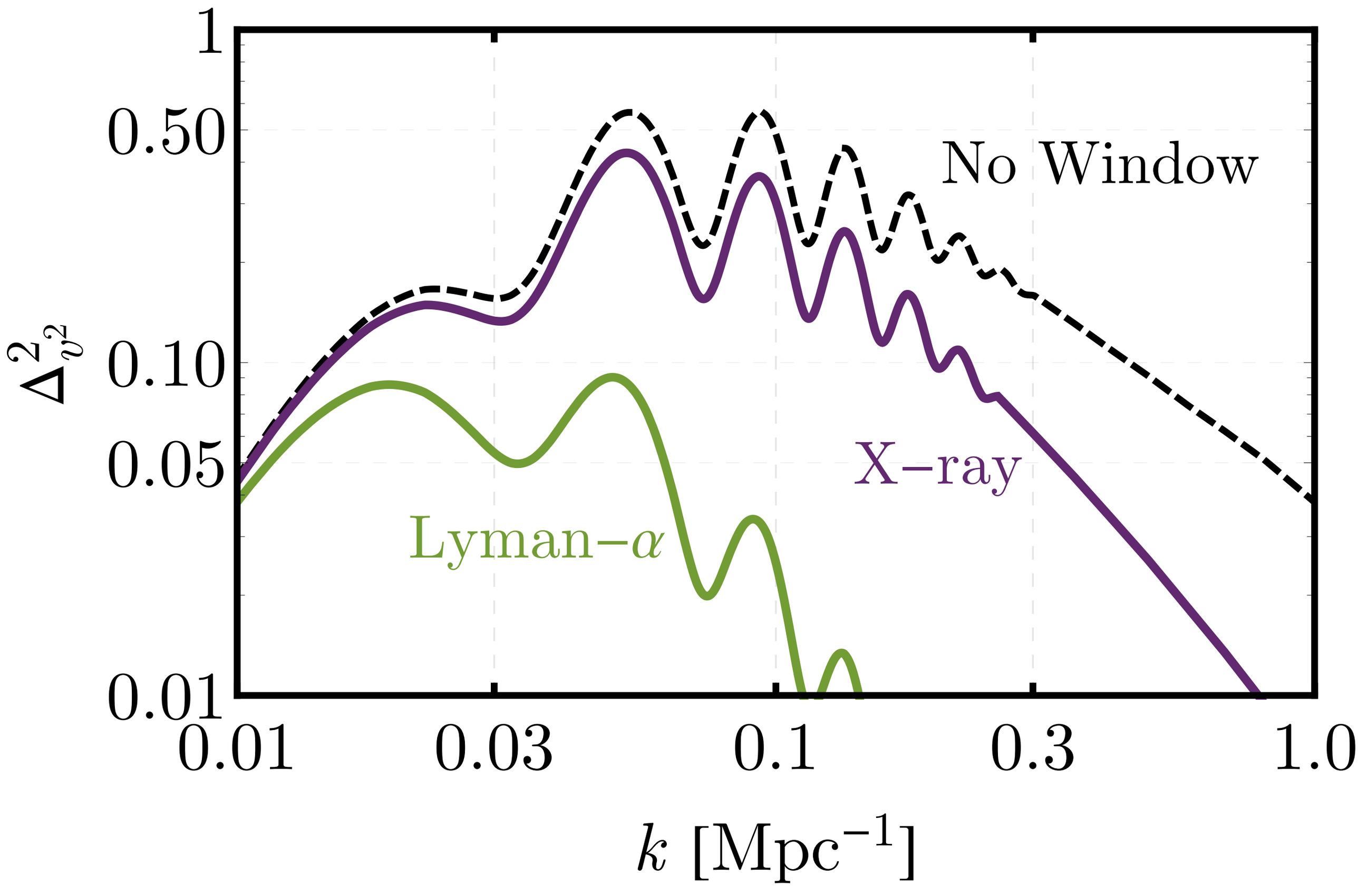
$\Delta^2_{n,m}(k)$

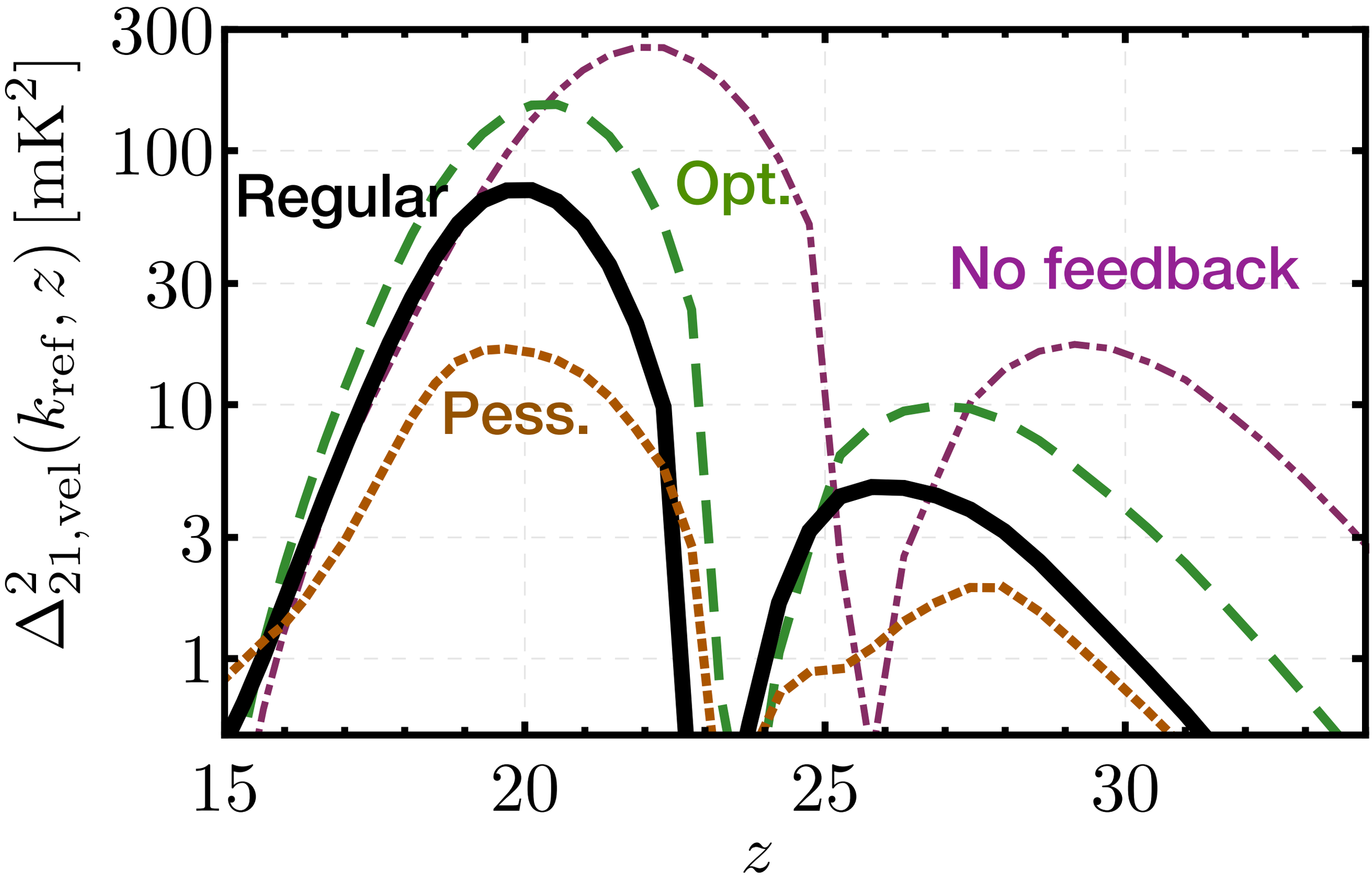
1.2
1.0
0.8
0.6
0.4
0.2
0.0

0.01 0.02 0.05 0.10 0.20

k [Mpc^{-1}]

Effect of Photon Propagation




300
100
30
10
3
1
$\Delta^2_{21,\mathrm{vel}}(k_{\mathrm{ref}}, z)\ [\mathrm{mK}^2]$
Regular
Opt.
No feedback
Pess.
15
20
25
30
z

Harder X-ray Spectrum

$\delta(z{=}20)$

0.6
0.4
0.2
0
−0.2
−0.4
−0.6

100 Mpc

$v_{\rm cb}(z{=}20)$ [km/s]

1.2
1.0
0.8
0.6
0.4
0.2
0

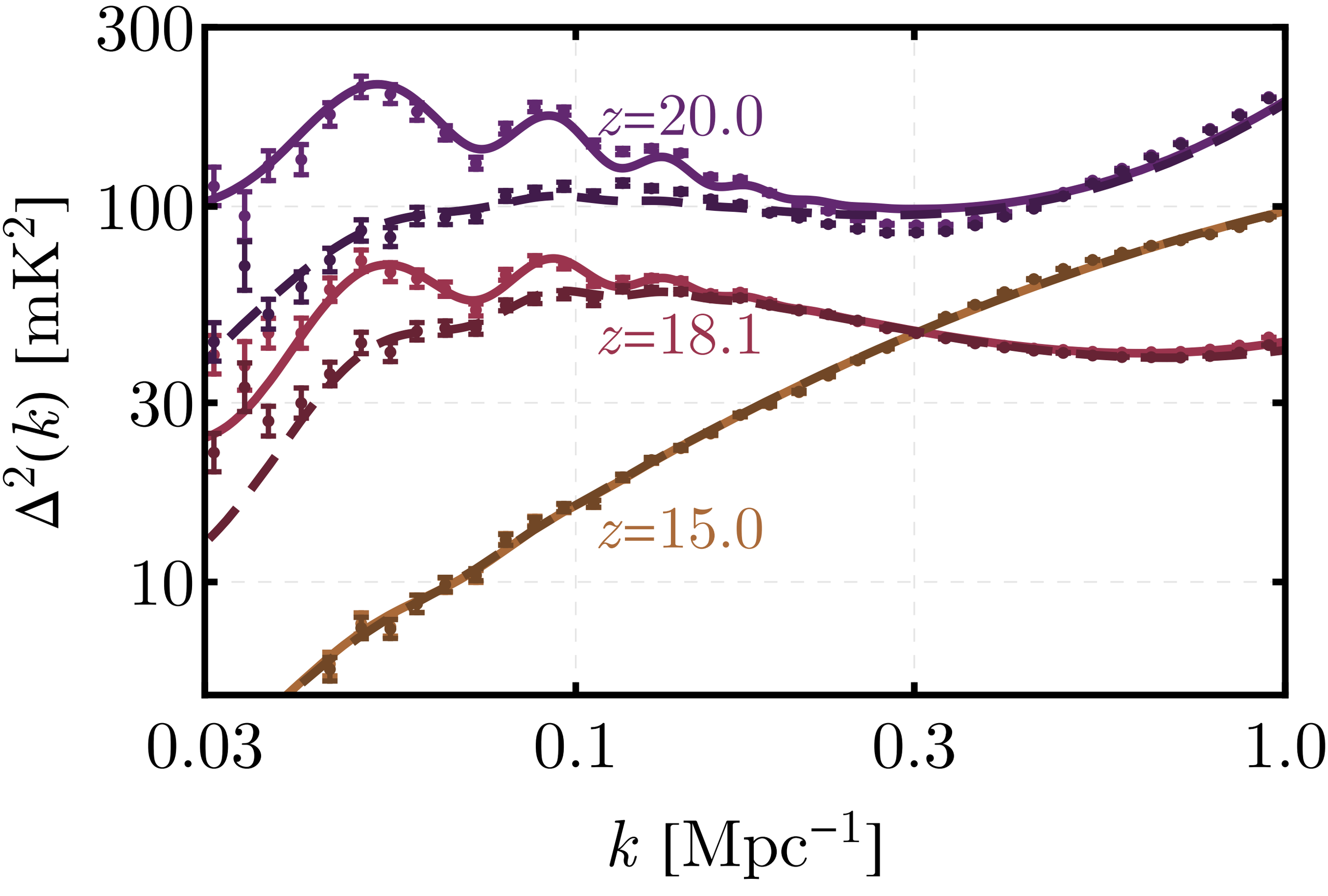
100 Mpc

$\log_{10}(F_{\rm coll})$

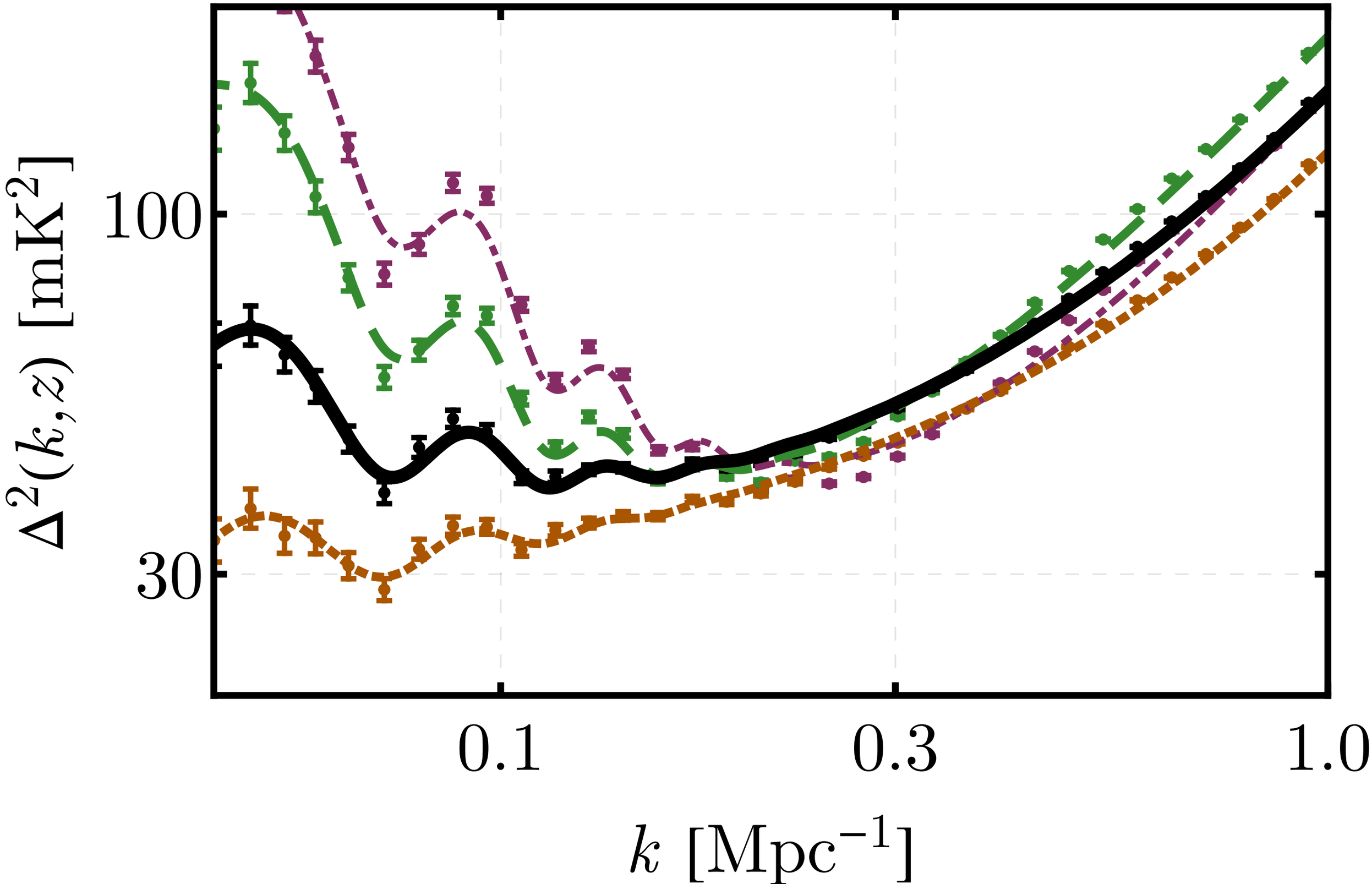
−3.75
−4.00
−4.25
−4.50
−4.75
−5.00

$z{=}20$

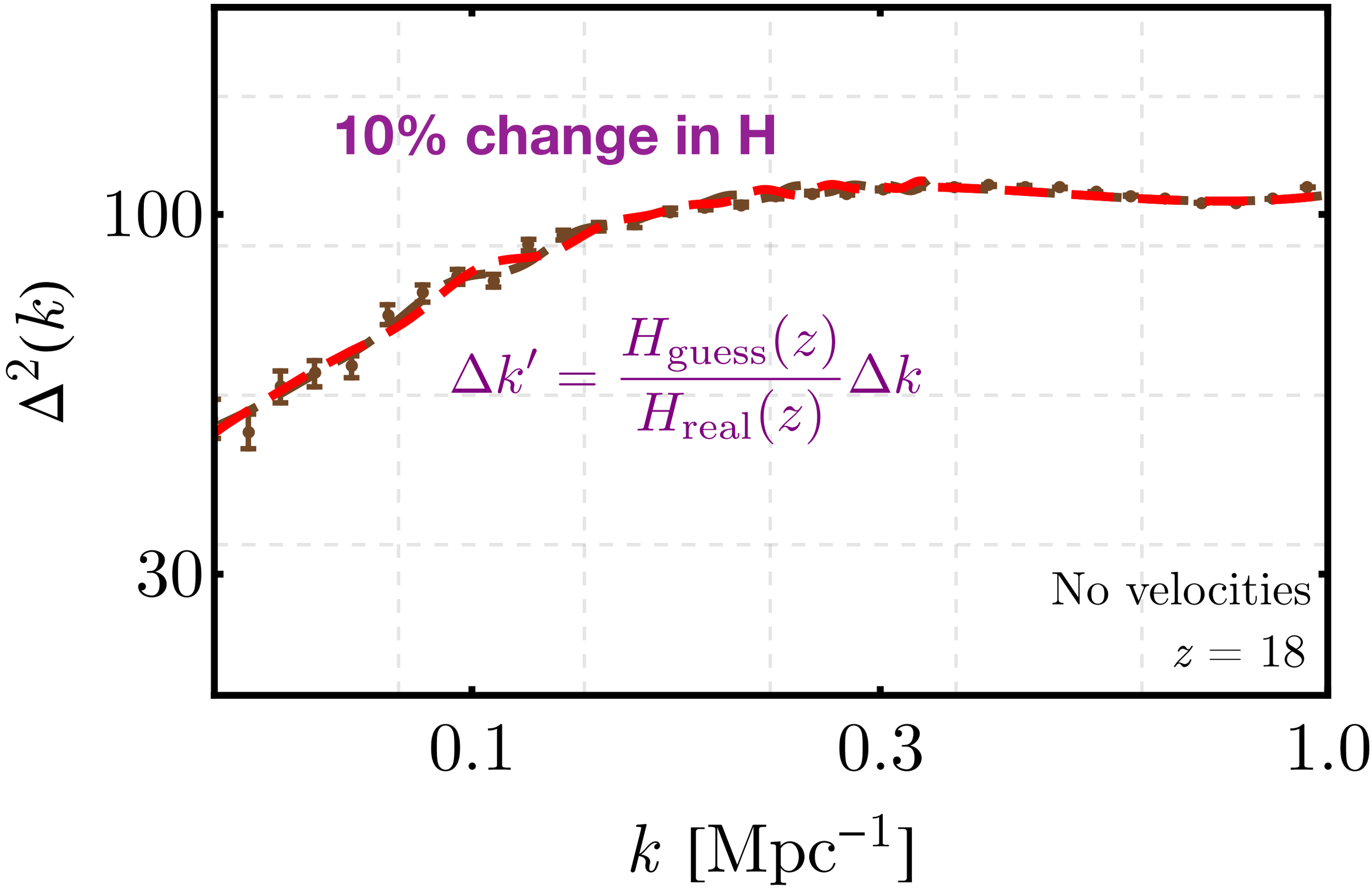
Harder X-ray Spectrum



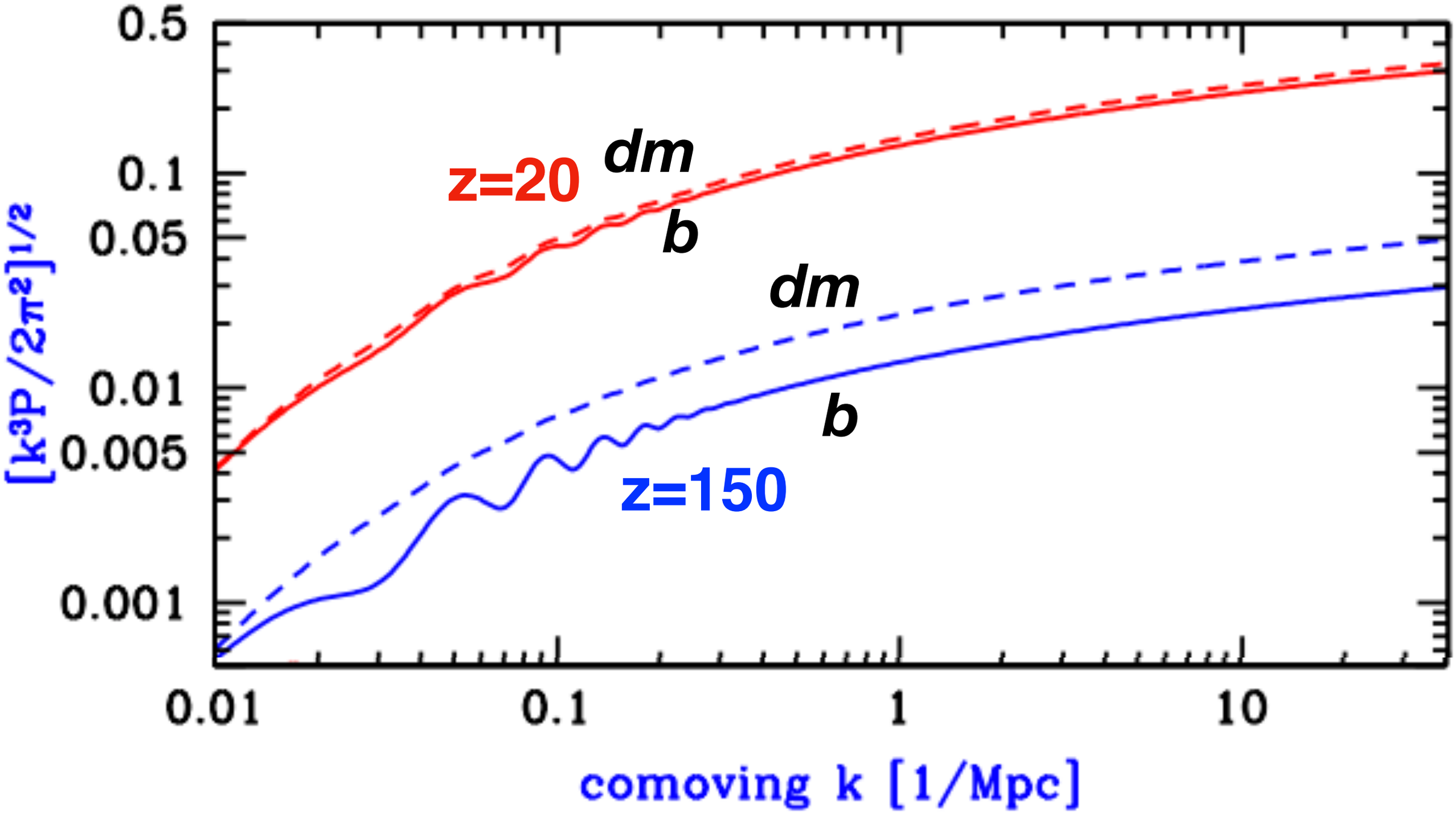
During Lyman-Alpha era



AP with “traditional” density BAO



AP with “traditional” density BAO

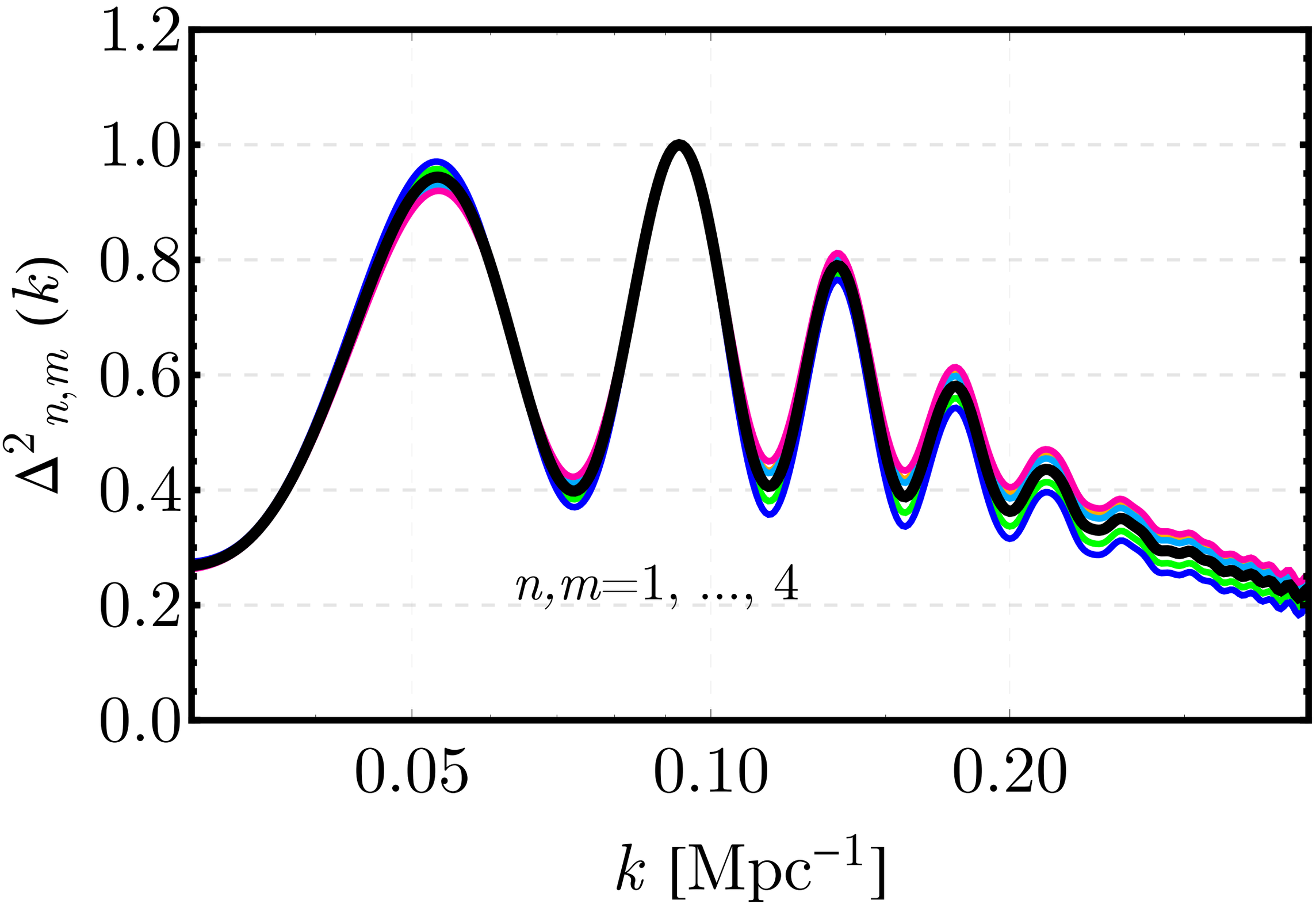


In agreement with **Barkana and Loeb 2005**

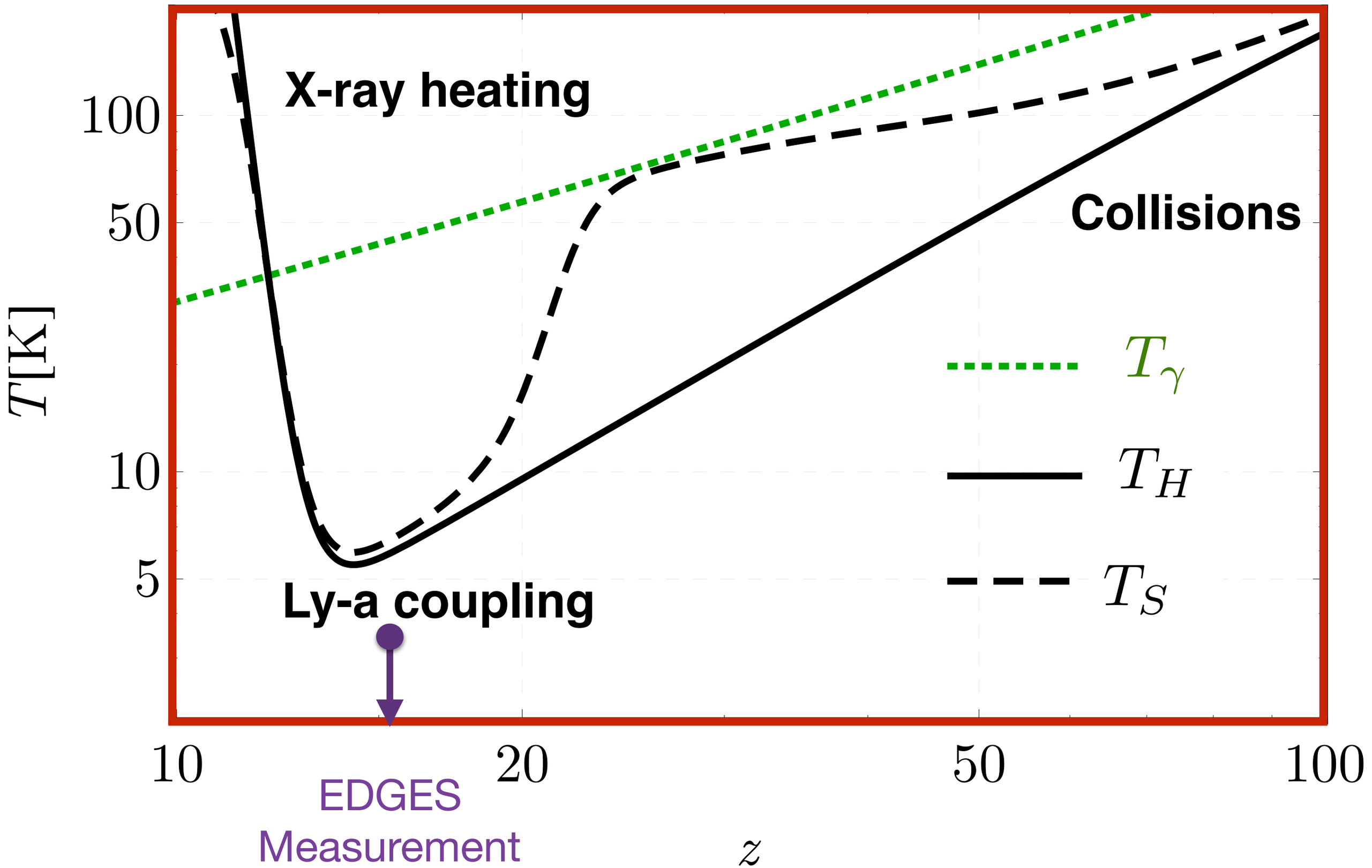
HERA on April 2018 (reionization.org)

$$\delta T_{21}(v) = \sum_n a_n \left(\frac{v^n}{\langle v^n \rangle} - 1 \right)$$

$$\delta T_{21}(v) = \sum_n a_n \left(\frac{v^n}{\langle v^n \rangle} - 1 \right)$$



A cartoon of the evolution of T_S



$z = 27$

$z = 11$

T_{21}

$$T_{21} \propto -\frac{T_{\rm cmb}}{T_S}$$

$T_{\rm CMB}$ [K]

2.70

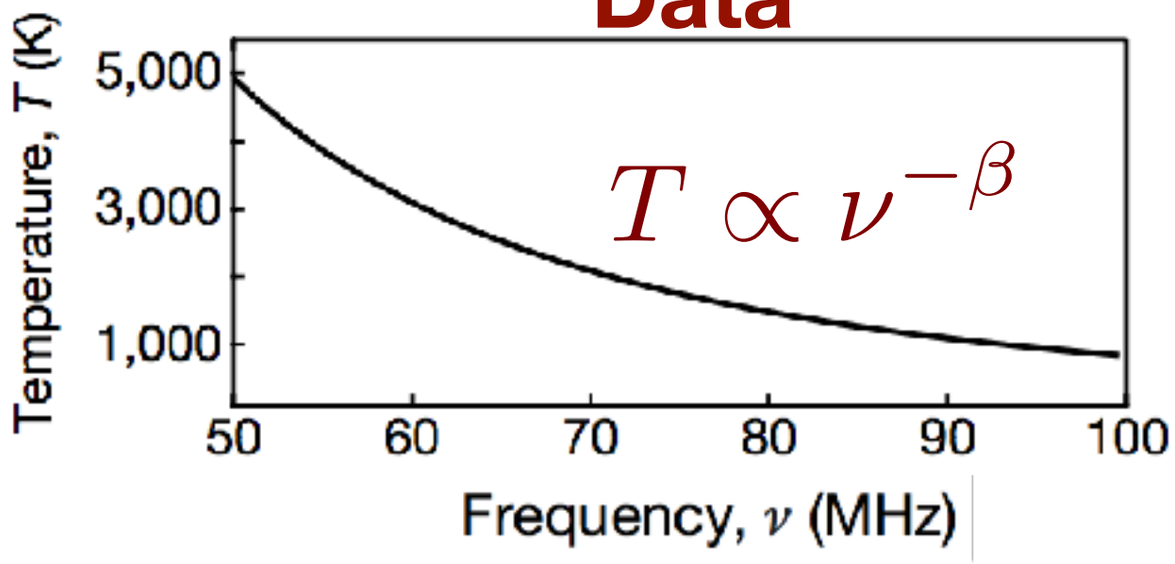
2.65

2.60

50 60 70 80 90 100 110 120

ν [MHz]

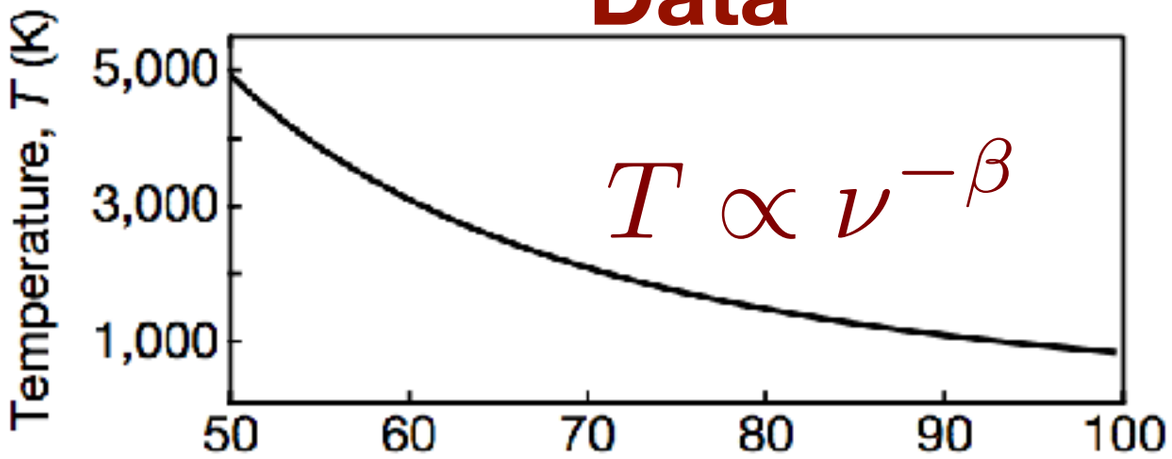
Data



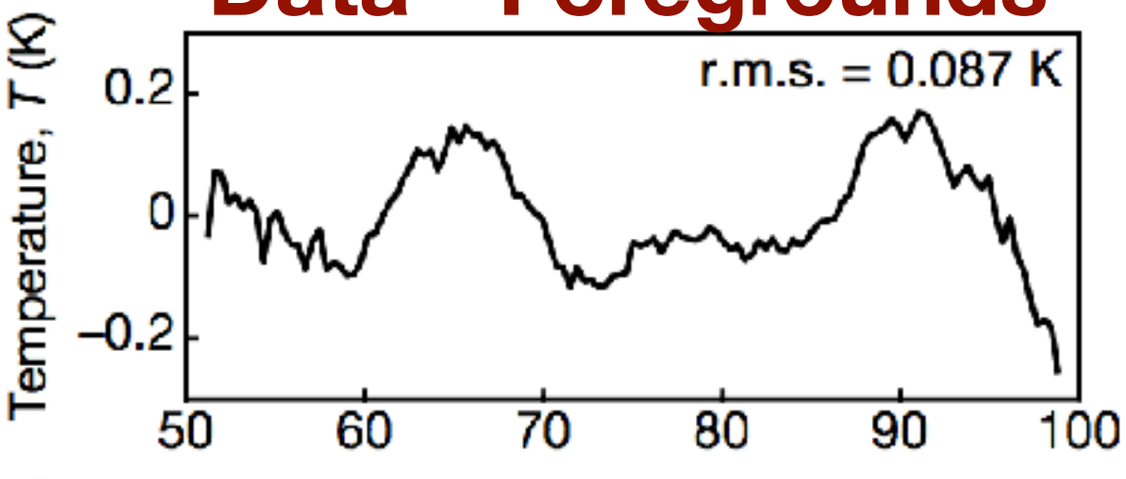
Bowman et al. Nature 2018

EDGES (Experiment to Detect the Global EoR Signature)

Data



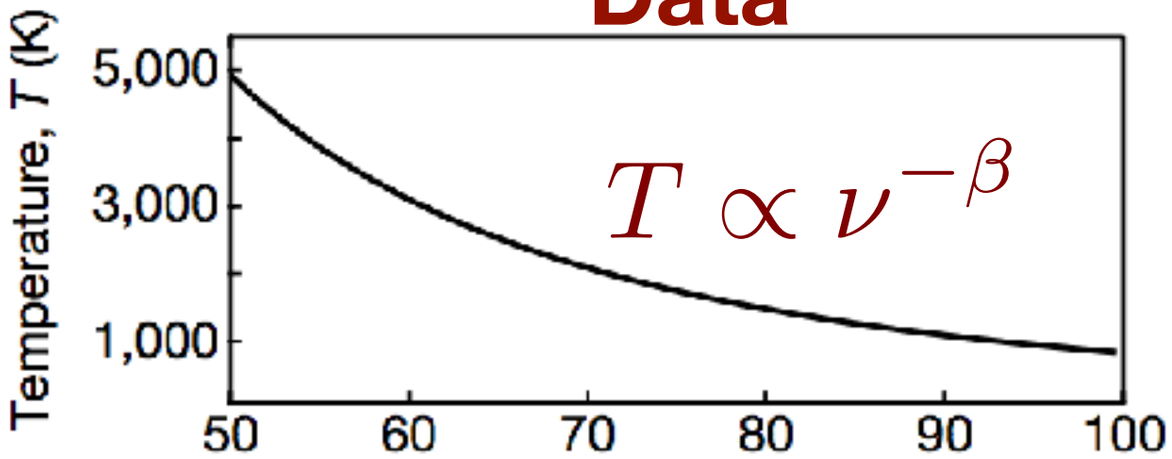
Data - Foregrounds



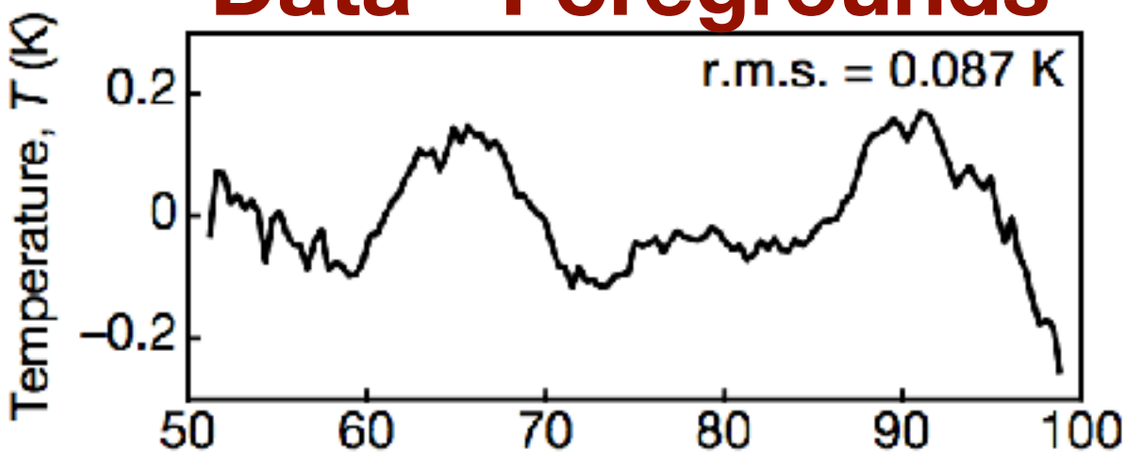
Bowman et al. Nature 2018

EDGES (Experiment to Detect the Global EoR Signature)

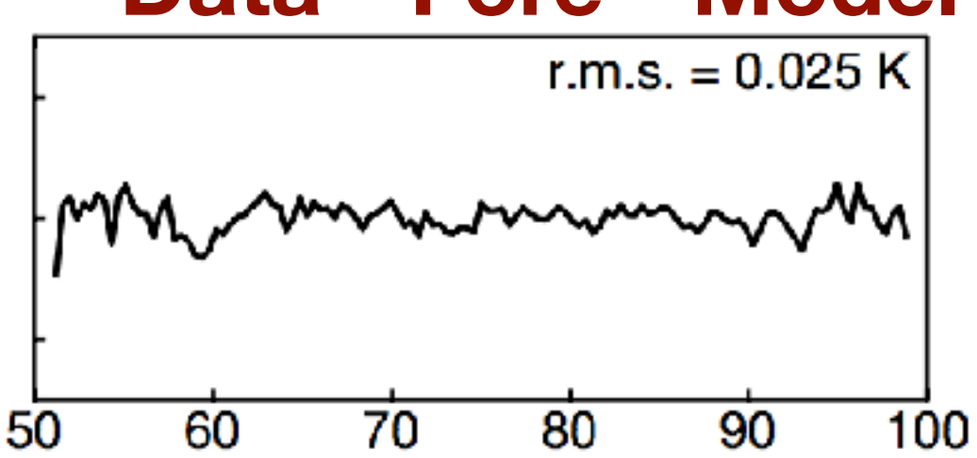
Data



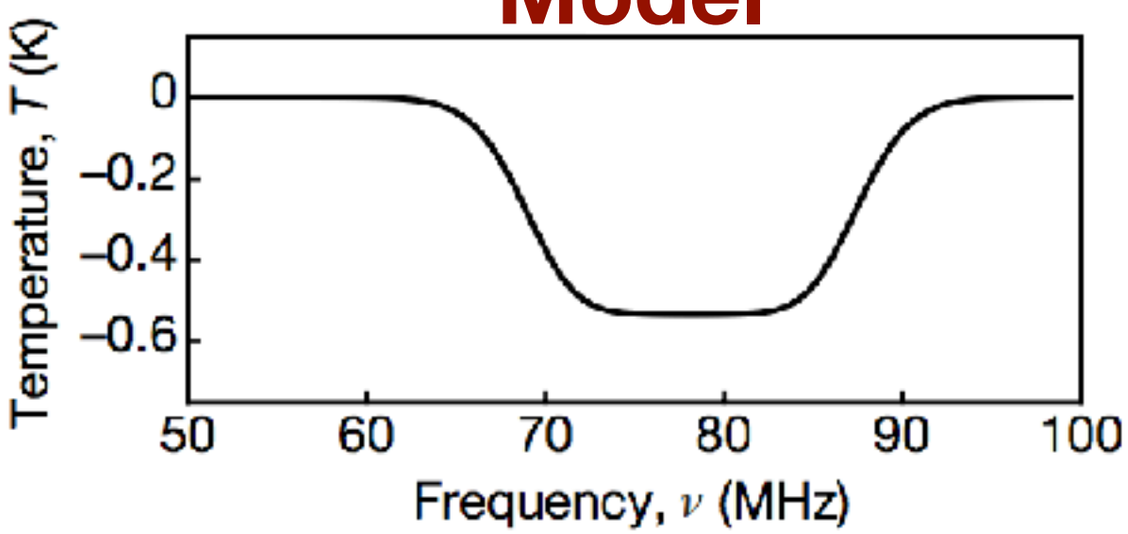
Data - Foregrounds



Data - Fore - Model

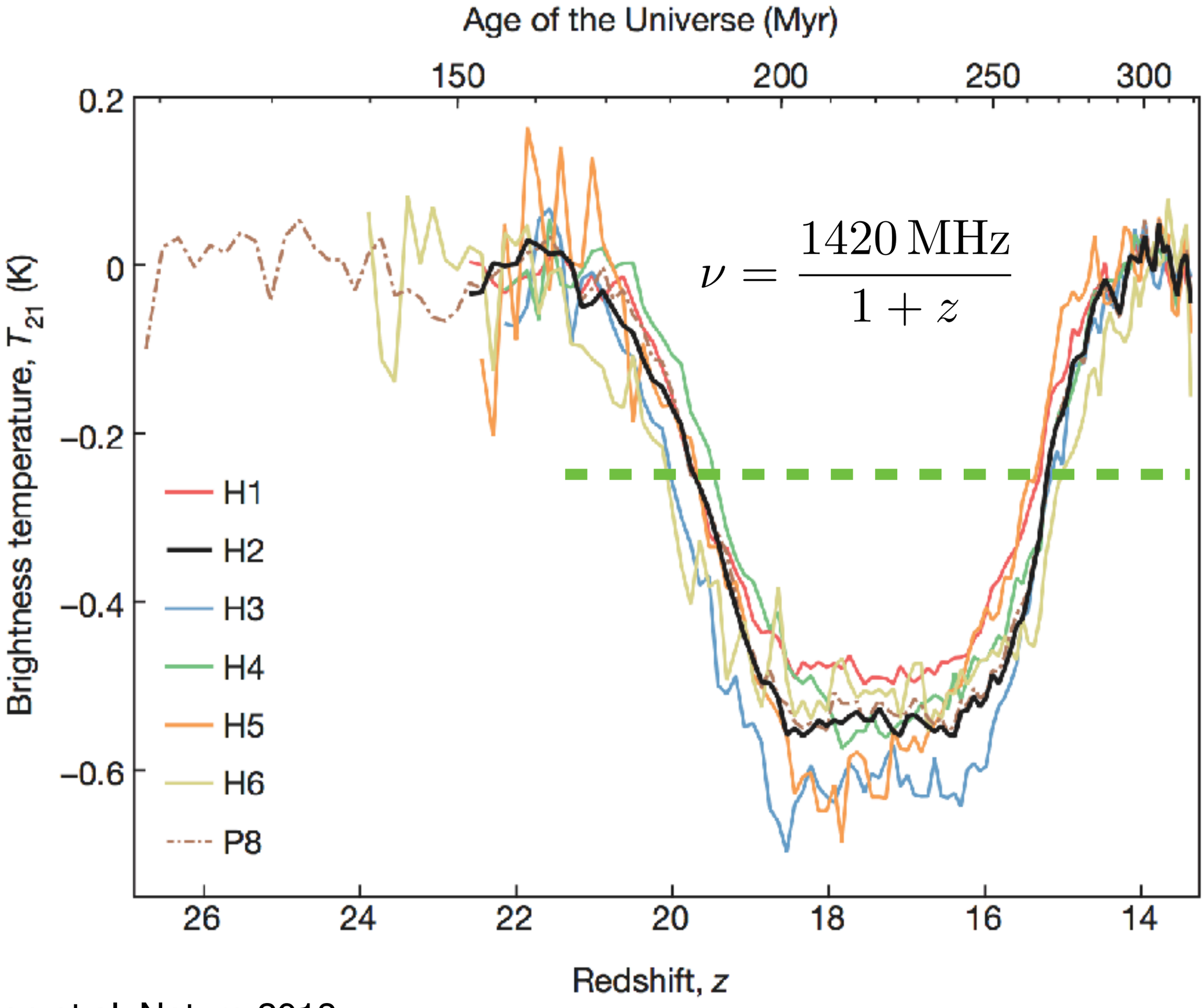


Model



Bowman et al. Nature 2018

EDGES (Experiment to Detect the Global EoR Signature)



Bowman et al. Nature 2018

Thermal
Decoupling (from CMB)

T_γ

T_H

T(K)

1000
500
100
50
10
5
1

10
50
100
500
1000

1+z

EDGES
Measurement

JBM, Kovetz, Ali-Haimoud PRD 2015

Thermal Coupling (to DM)

Thermal Decoupling (from CMB)

$\sigma_{\chi b} \propto v^{-4}$

T_γ

T_H

T_H with interactions

T_χ with interactions

T(K)

1000
500
100
50
10
5
1

10
50
100
500
1000

1+z

EDGES Measurement

JBM, Kovetz, Ali-Haimoud PRD 2015

Can DM explain EDGES?

Requirements

$$n_\chi \geq n_b \quad \rightarrow \quad m_\chi \leq 6\,\mathrm{GeV}$$

$m_\chi = 1\,\mathrm{GeV}$

$n_\chi \approx 6\, n_b$

T_γ

T_b

T_b with interactions

T_χ with interactions

T(K)

1000
500
100
50
10
5
1

10
50
100
500
1000

1+z

JBM, Kovetz, Ali-Haimoud PRD 2015

Can DM explain EDGES?

Requirements

$$n_\chi \geq n_b \quad \rightarrow \quad m_\chi \leq 6\,\mathrm{GeV}$$

$$\sigma_{\chi b} \propto v^{-4}$$

Can DM explain EDGES?

Requirements

$$n_\chi \geq n_b \quad \rightarrow \quad m_\chi \leq 6\,\mathrm{GeV}$$

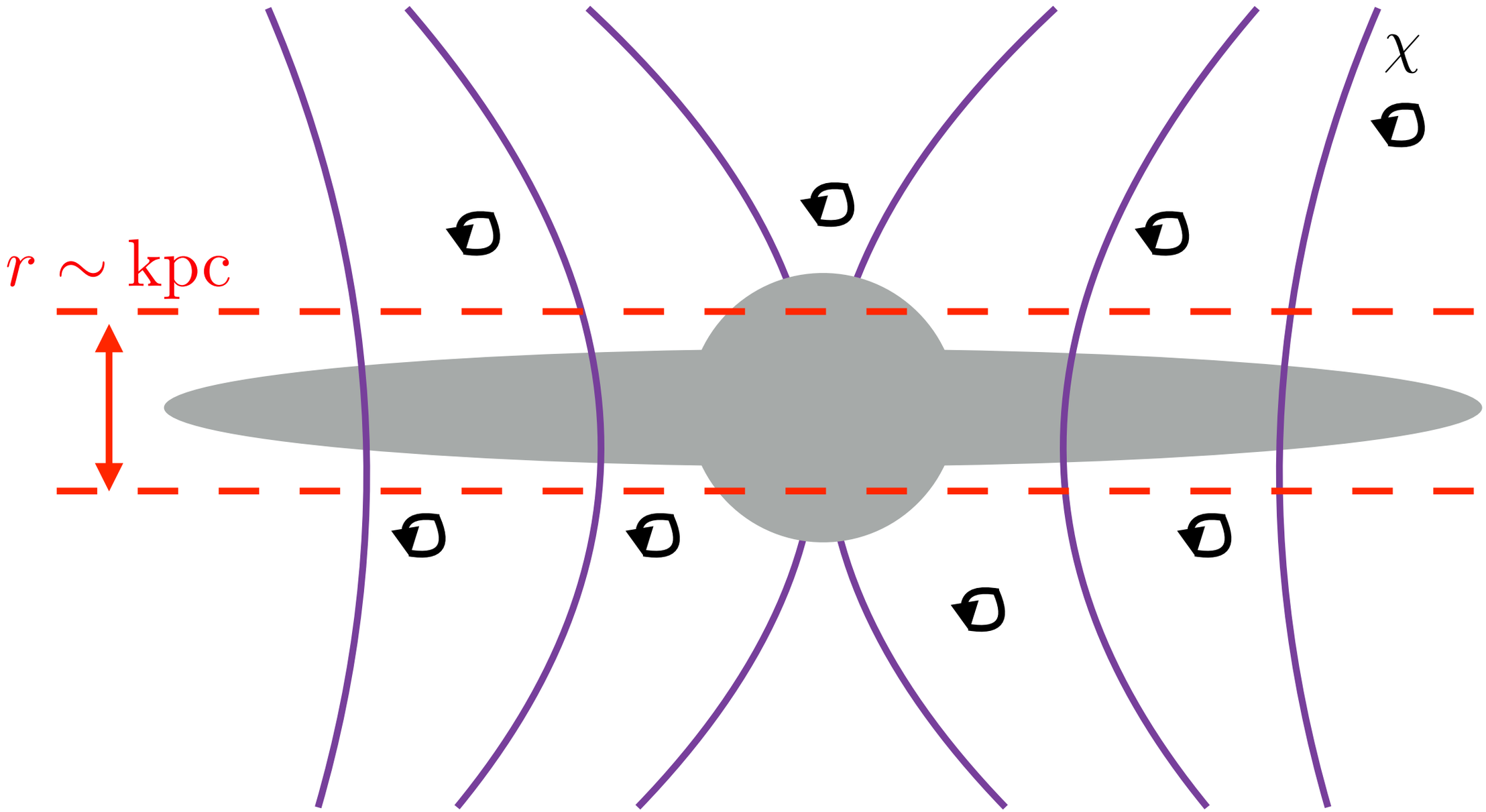
$$\sigma_{\chi b} \propto v^{-4}$$

Fifth Force — **JBM**+ 2015; Barkana 2018 ($m_\phi < 10\,\mathrm{keV}$)

Millicharged DM — **JBM** and Loeb 2018

Chuzhoy and Kolb (2009)

$$r_g \propto \frac{m_\chi}{\epsilon} \gtrsim 100\,\mathrm{kpc}$$

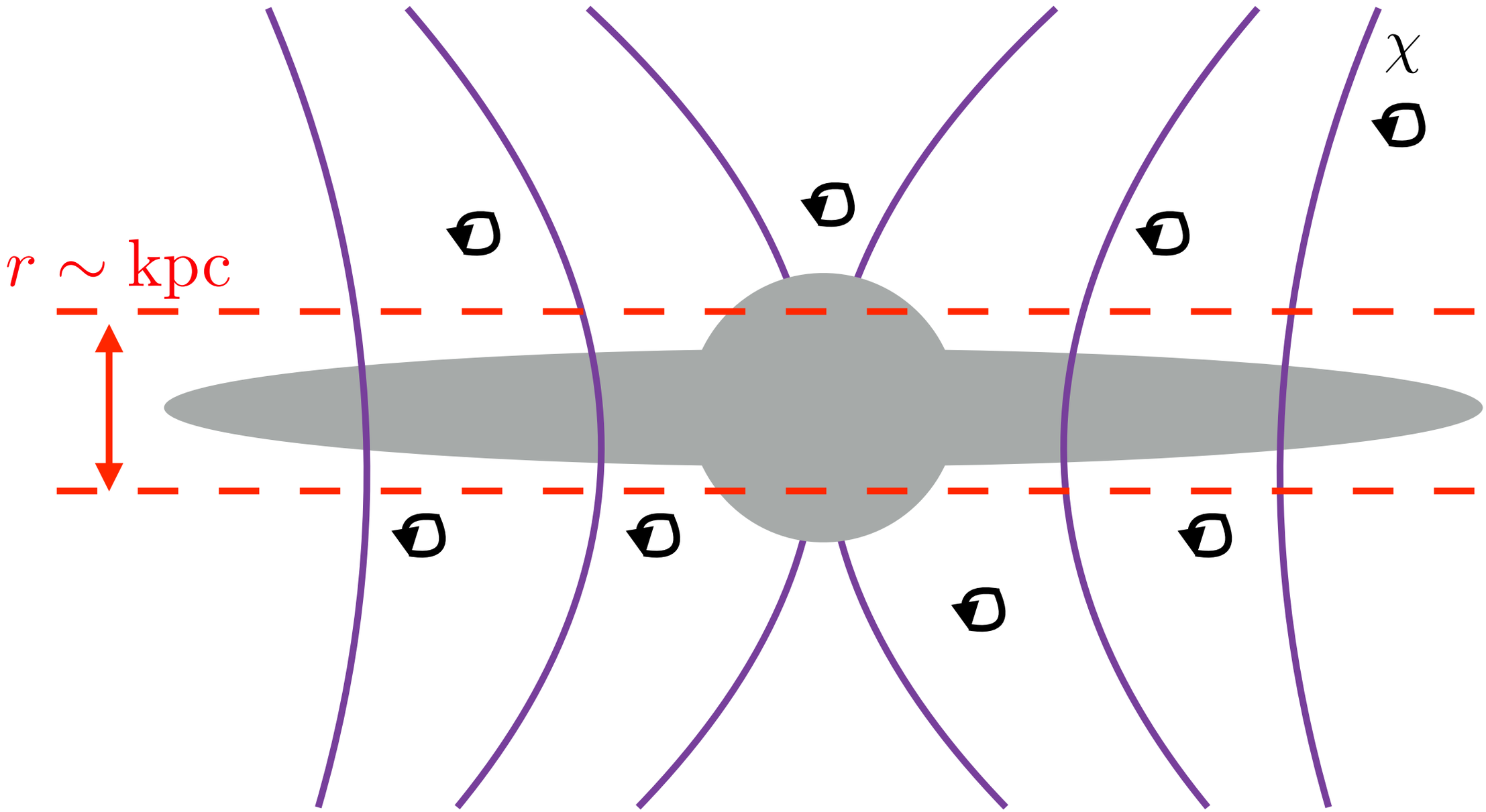


$$\rho_{\mathrm{DM}} = 0.3 \pm 0.1\,\mathrm{GeV\,cm^{-3}}$$

Bovy and Tremaine (2012)

Chuzhoy and Kolb (2009)

$$r_g \propto \frac{m_\chi}{\epsilon} \gtrsim 100\,\mathrm{kpc}$$



$$\rho_{\mathrm{DM}} = 0.3 \pm 0.1\,\mathrm{GeV\,cm^{-3}}$$

Bovy and Tremaine (2012)

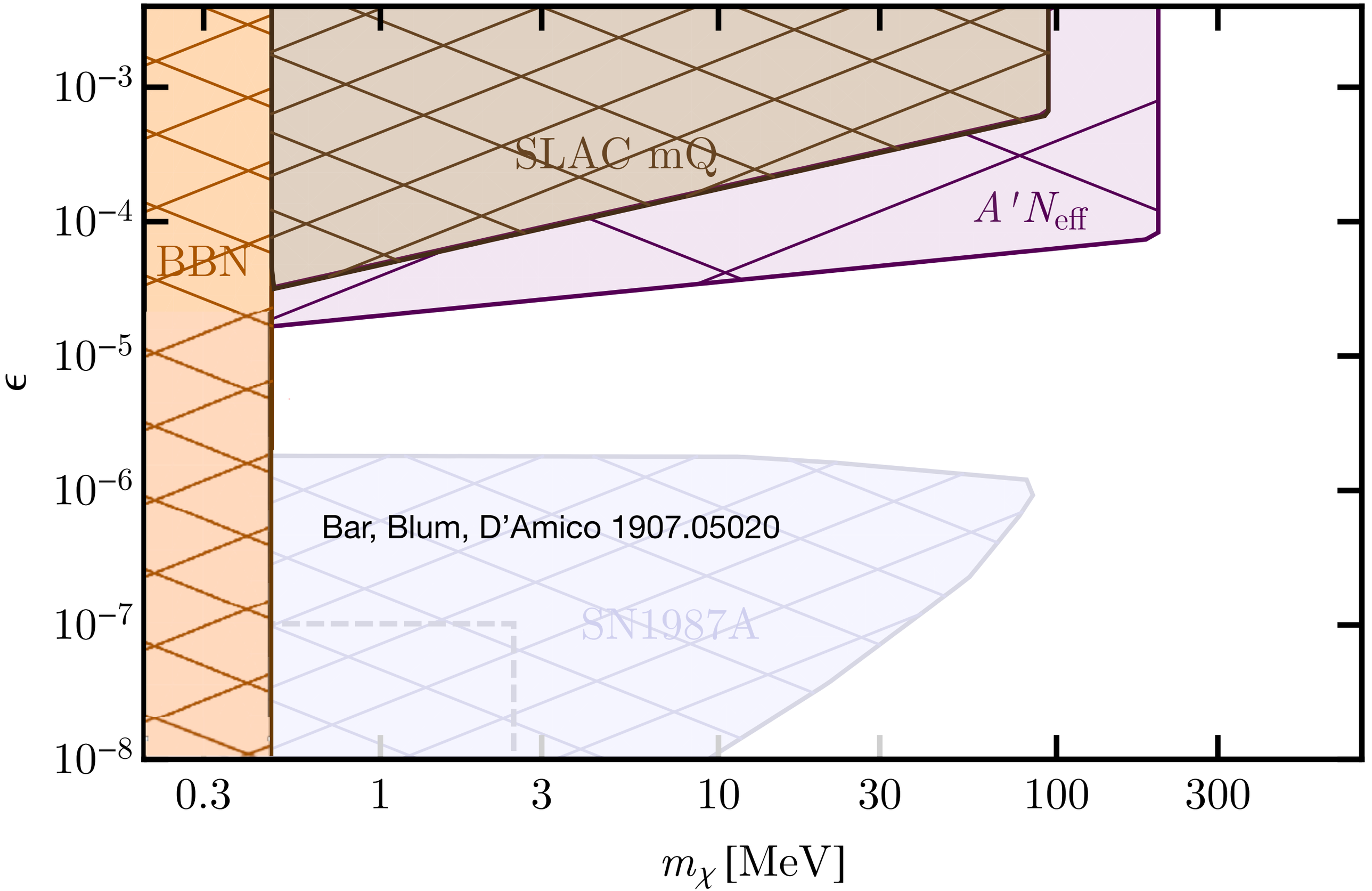
However:

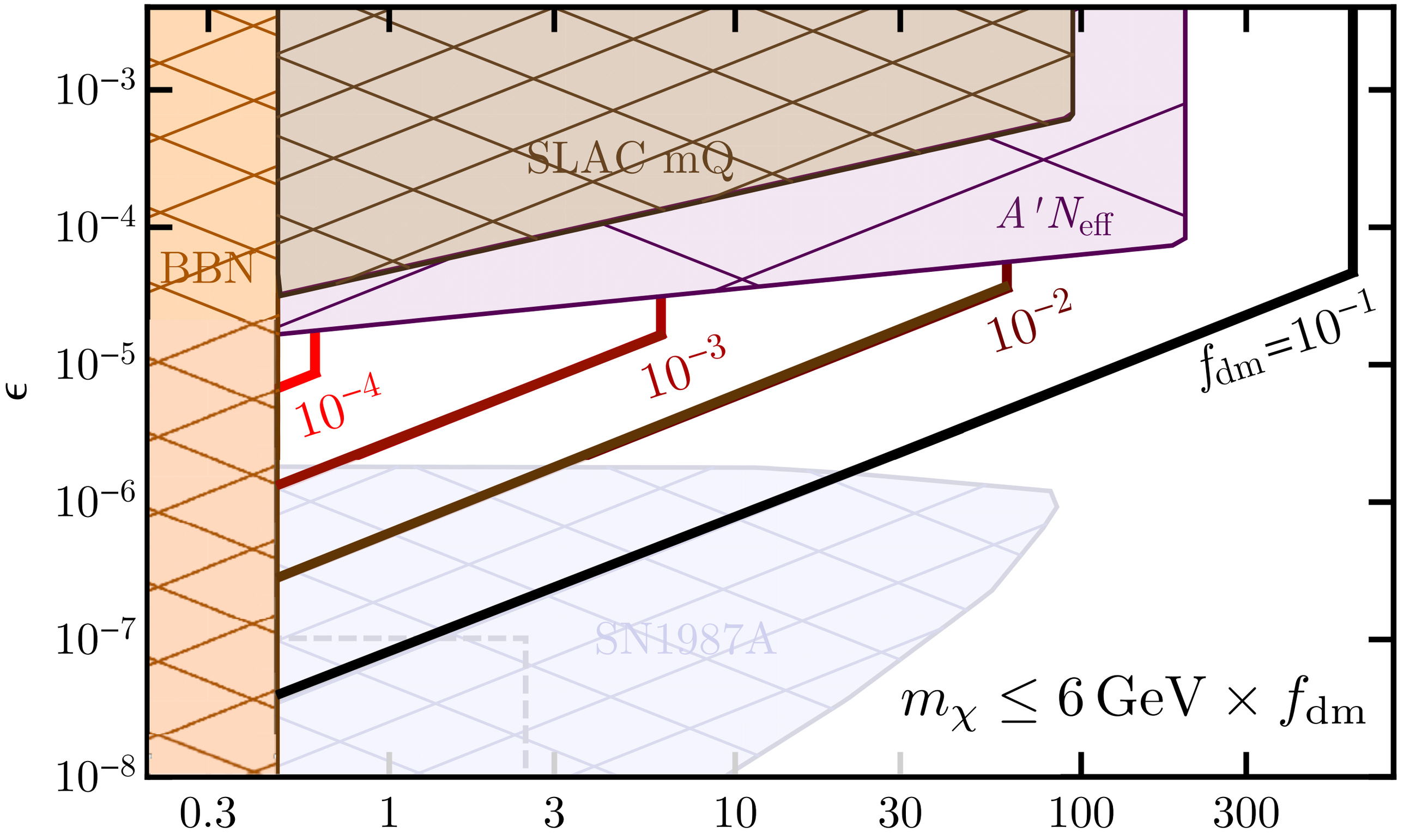
Dunsky, Hall, Harigaya (2018)

$$r_g \propto \frac{m_\chi}{\epsilon} \gtrsim 100\,\mathrm{kpc}$$

Image: NASA/CXC/CfA/STScI ESO/WFI

Limits on millicharged particles

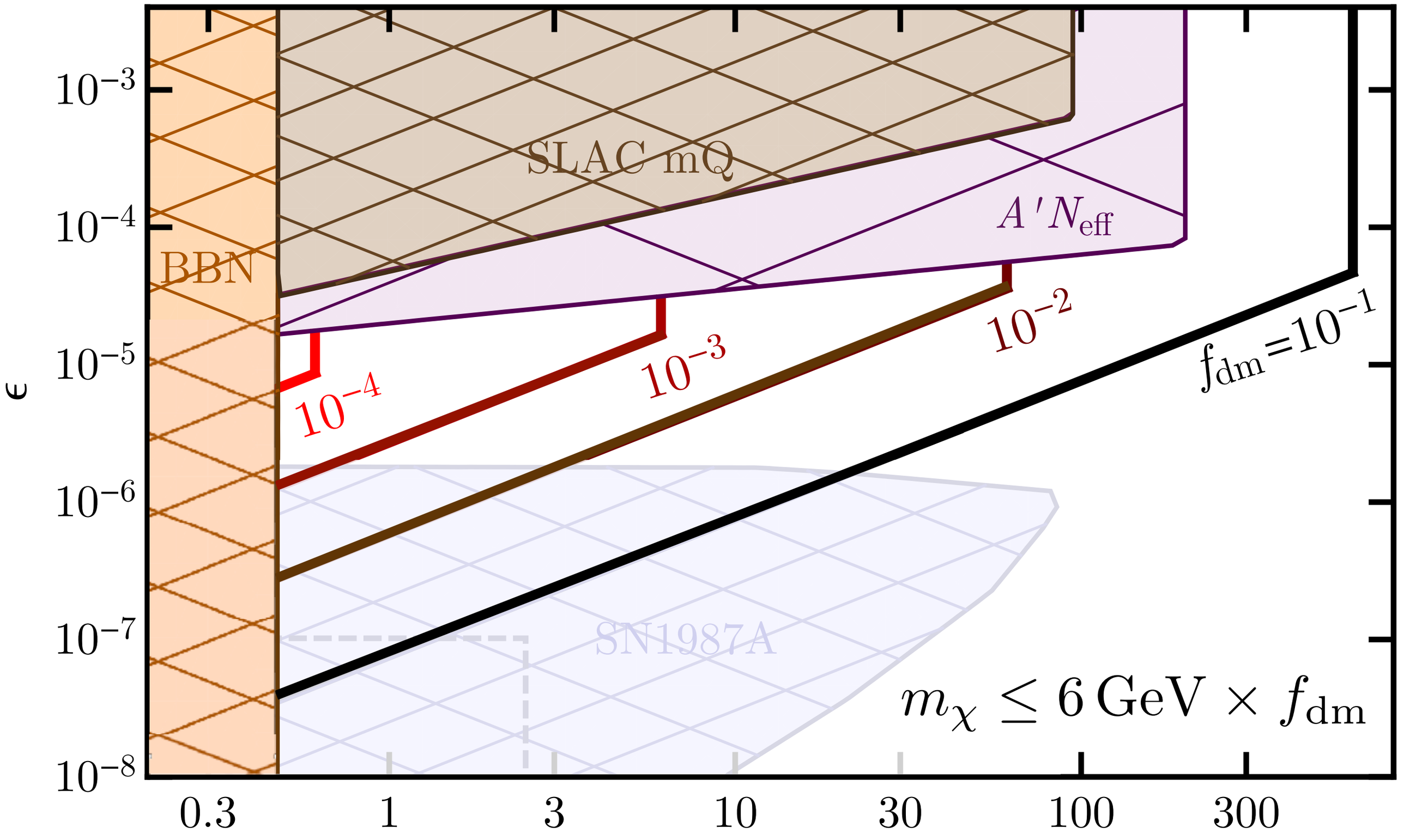




JBM and Loeb 1802.10094

See also:

Berlin+	1803.02804
Barkana+	1803.03091

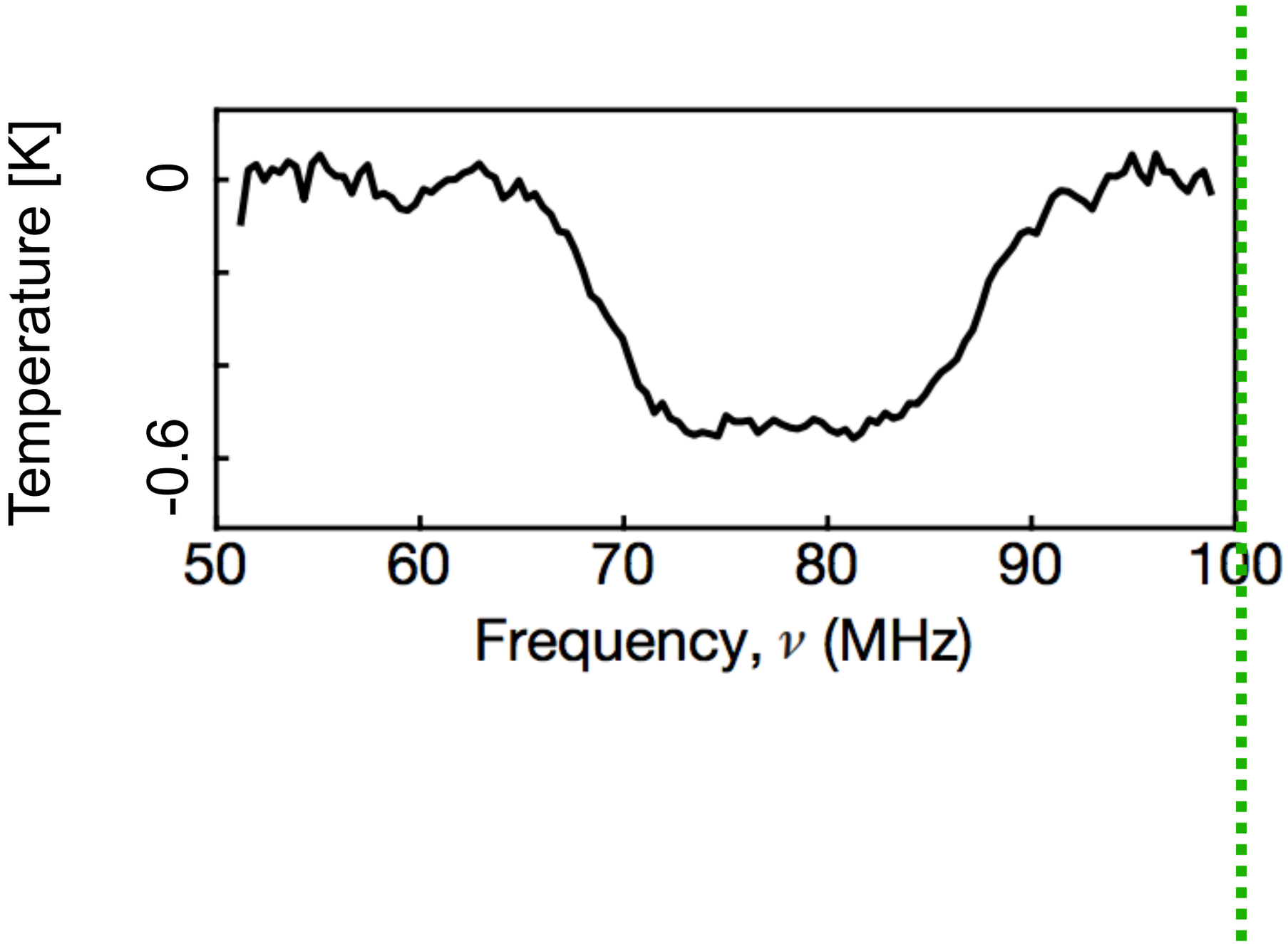


JBM and Loeb 1802.10094

See also:

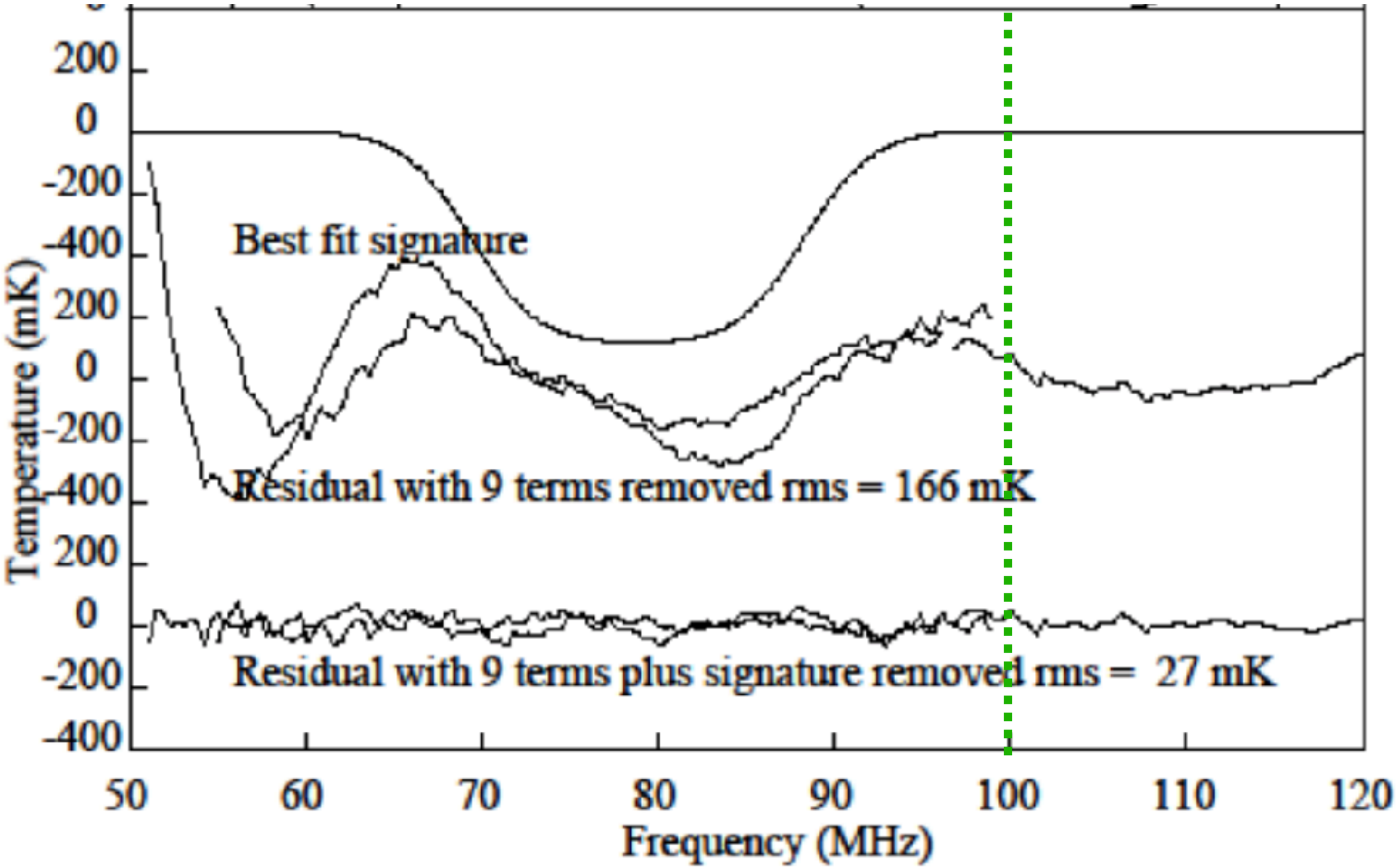
Berlin+	1803.02804
Barkana+	1803.03091

Low-Band EDGES

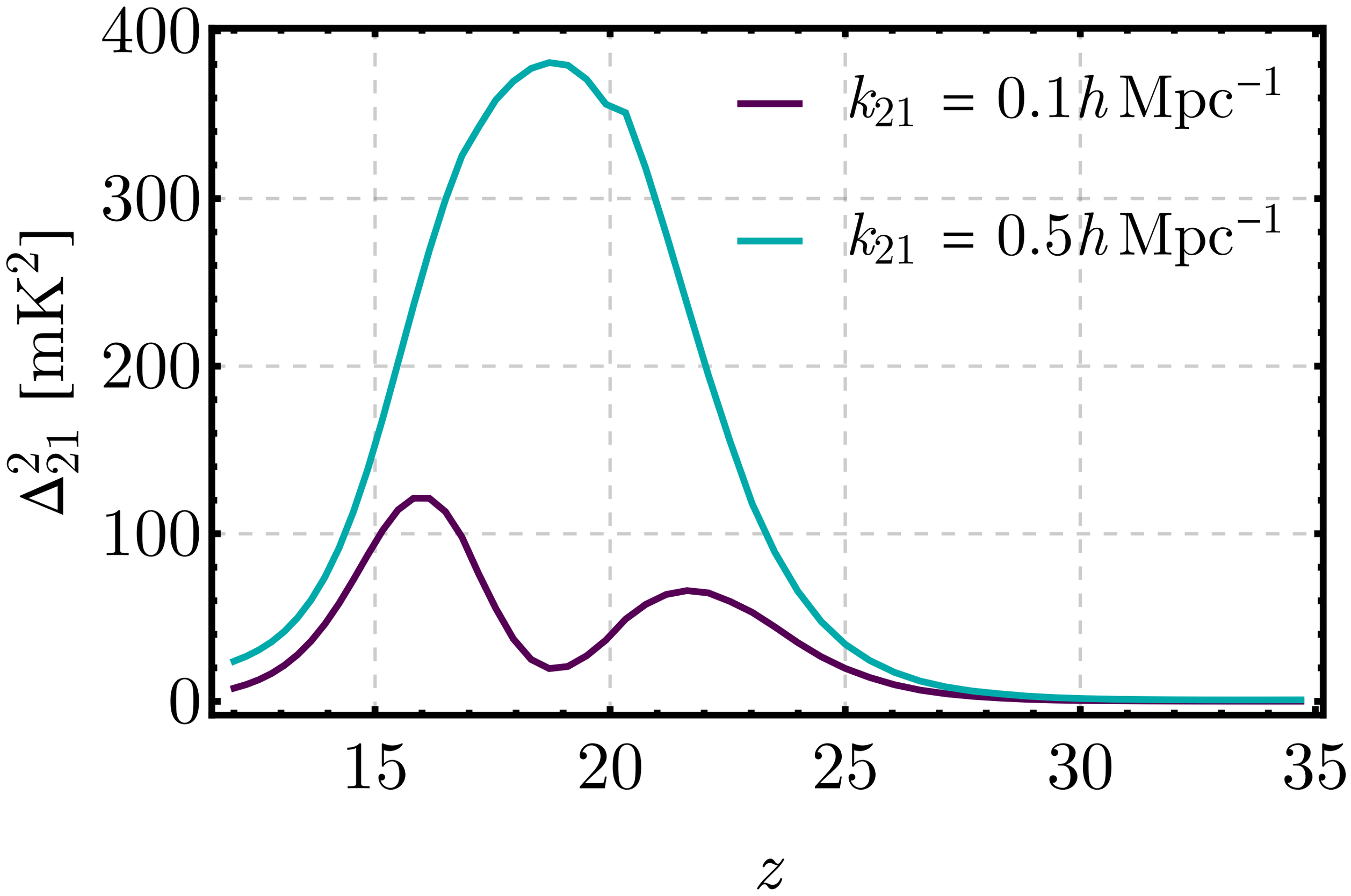


Bowman et al. Nature 2018

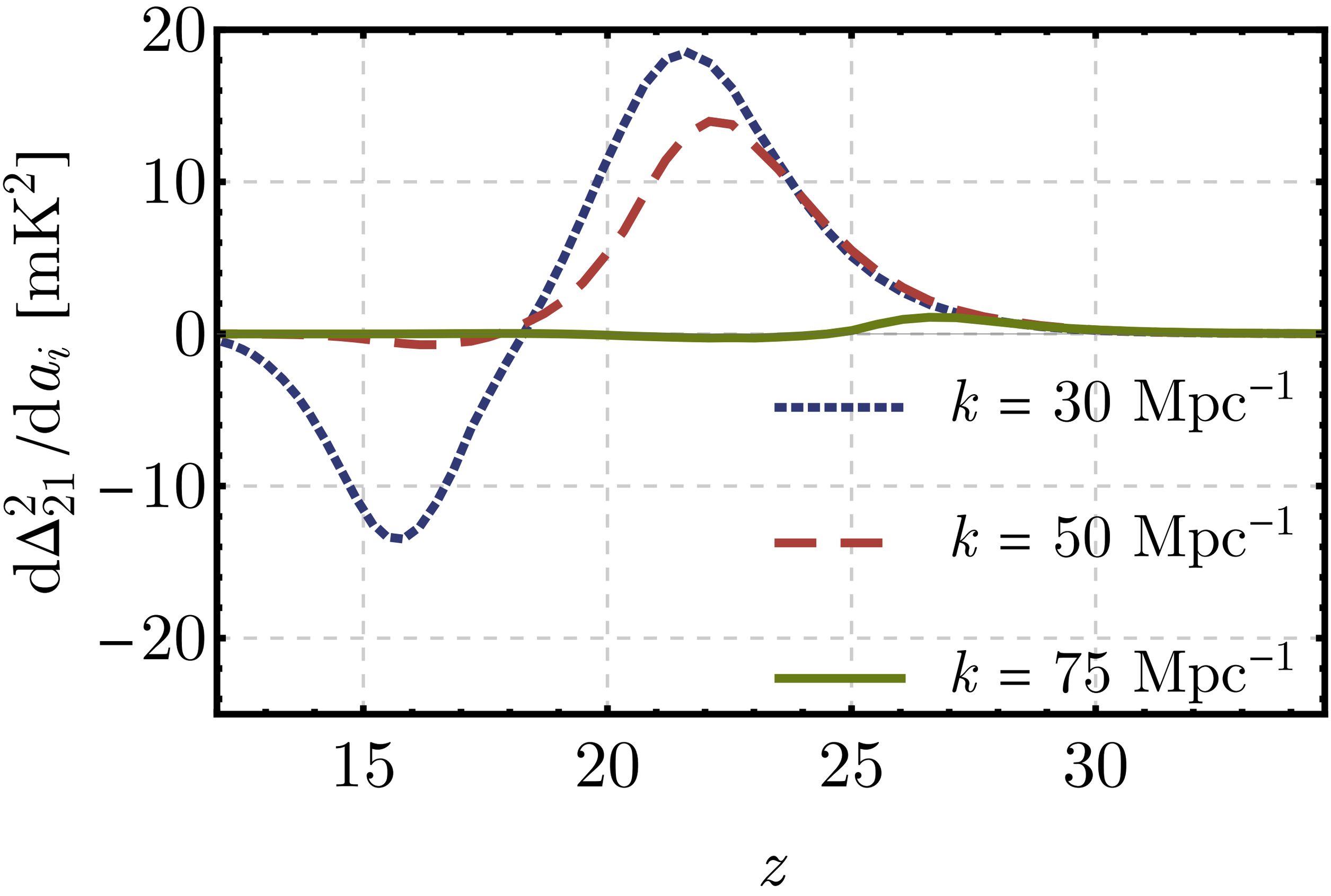
Low + Mid-Band EDGES



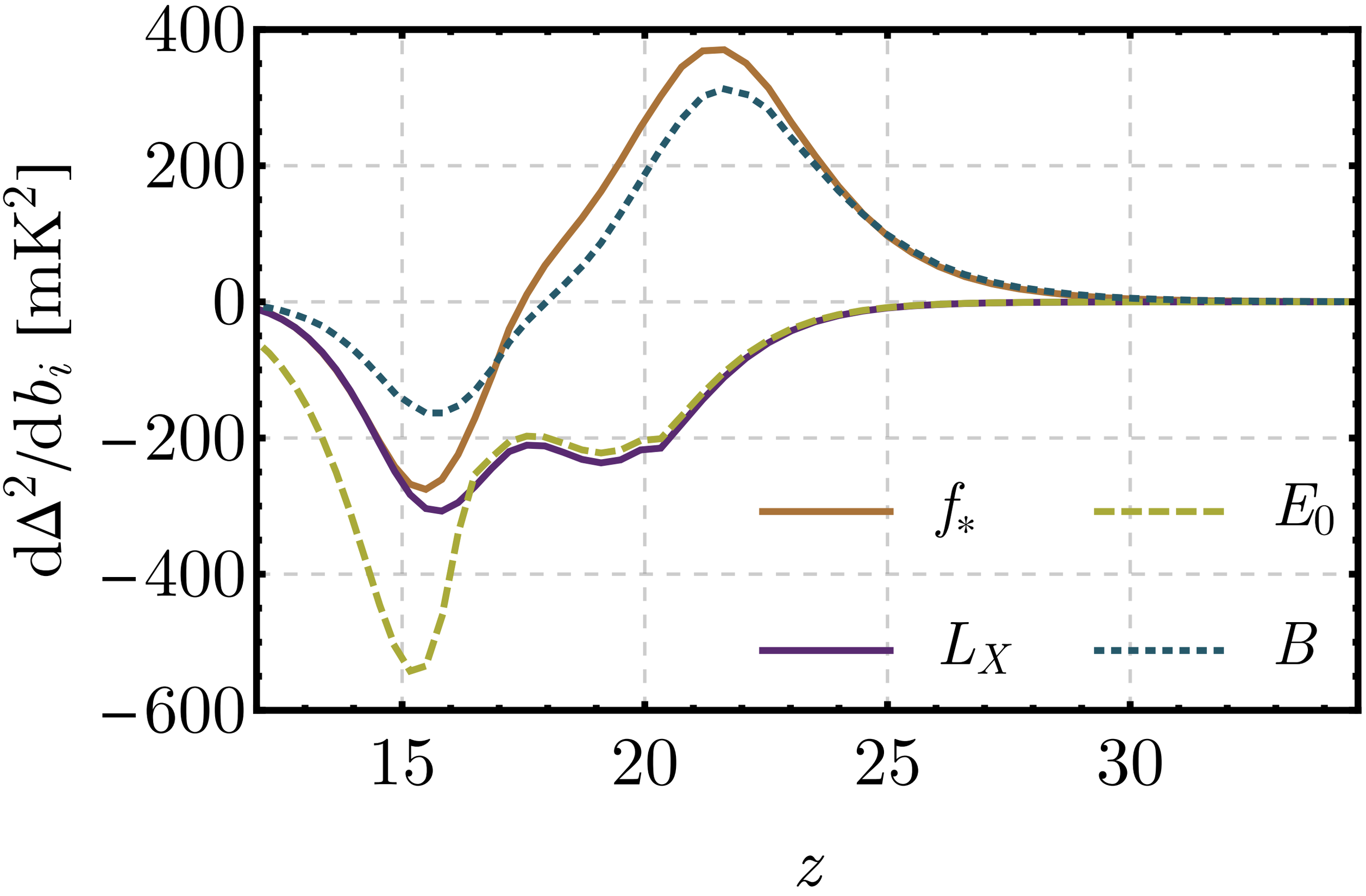
EDGES memo 286


400
300
200
100
0
Δ^2_{21} [mK^2]
15
20
25
30
35
z
$k_{21} = 0.1h\,\mathrm{Mpc}^{-1}$
$k_{21} = 0.5h\,\mathrm{Mpc}^{-1}$

Large k21


20
10
0
−10
−20
15
20
25
30
z
$\mathrm{d}\Delta^2_{21}/\mathrm{d}\,a_i$ [mK^2]
$k = 30$ Mpc^{-1}
$k = 50$ Mpc^{-1}
$k = 75$ Mpc^{-1}

Large k21


400
200
0
−200
−400
−600
15
20
25
30
z
$\mathrm{d}\Delta^2/\mathrm{d}\ln b_i\ [\mathrm{mK}^2]$
f_*
E_0
L_X
B

Small k21