Title: Searching for new physics with the 21-cm line

Speakers: Julian MuÃ±oz Bermejo

Series: Particle Physics

Date: November 22, 2019 - 1:00 PM

URL: http://pirsa.org/19110046

Abstract: I will describe how current and upcoming 21-cm measurements during cosmic dawn can probe a plethora of dark-matter and dark-energy models. This era saw the formation of the first stars, which coupled the spin temperature of hydrogen to its kinetic temperature---producing 21-cm absorption. The depth of this absorption acts as a thermostat, allowing us to constrain exotic cooling or heating due to dark matter. Additionally, the timing of the 21-cm signal strongly depends on the abundance of the small minihalos that hosted the first stars, allowing us to tightly constrain dark-matter models with suppressed power, such as warm or fuzzy dark matter. Finally, I will describe how in LCDM the acoustic physics of recombination are imprinted onto the 21-cm power spectrum during cosmic dawn, resulting in robust velocity-induced acoustic oscillations (VAOs). These act as a new standard ruler at z~20, opening up searches for early dark energy and perhaps resolving the H0 tension.

What can we learn from 21-cm measurements?

Julian B. Muñoz

Based on

PRD 92 083528 (2015) w/ Kovetz and Ali-Haïmoud
Nature 557 7707 (2018) w/ Loeb
PRD 100 063538 (2019)
PRL 123 131301 (2019)
In progress (2019?) w/ Dvorkin and Cyr-Racine

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What can we learn?

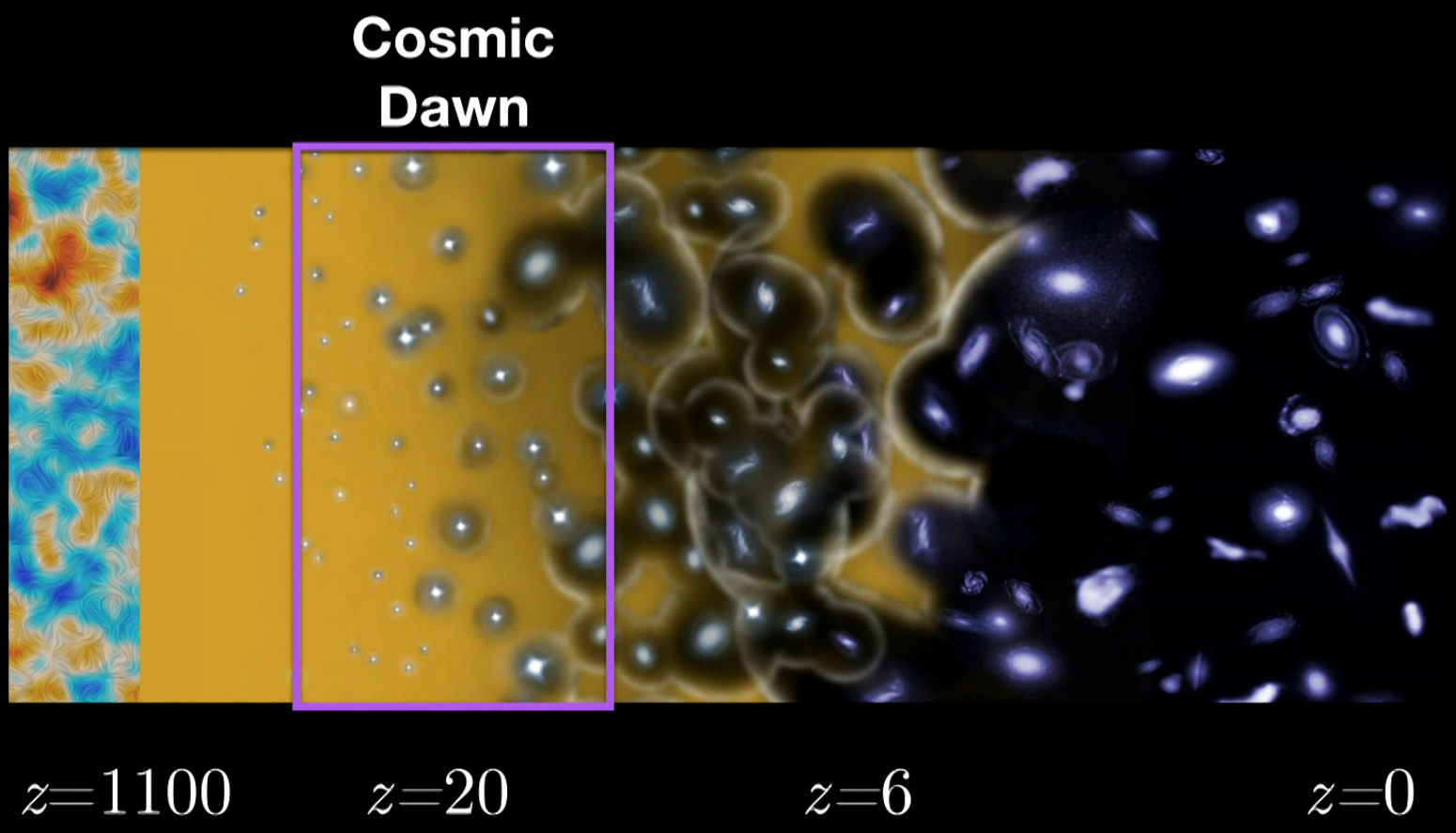
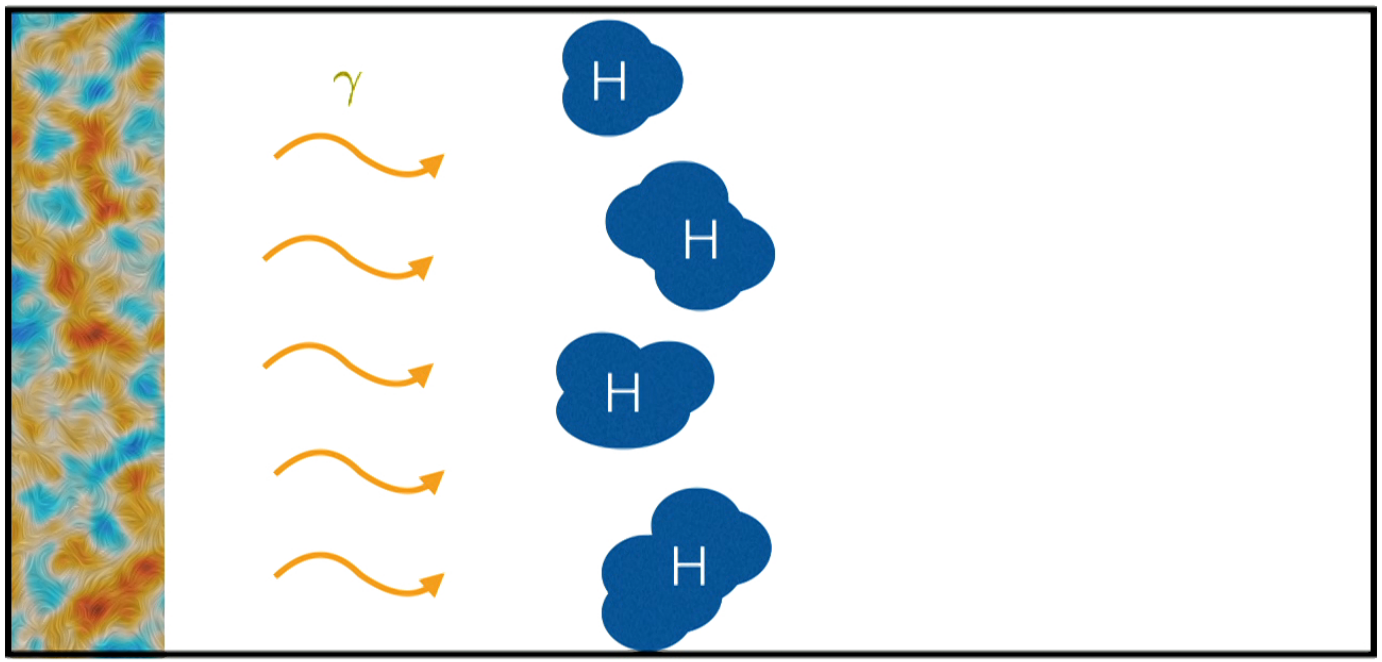


Image: ESA

Outline

- Introduction to 21-cm cosmology
- Searching for DM
- A standard ruler at $z = 20$

$z = 1100$ $z \approx 20$

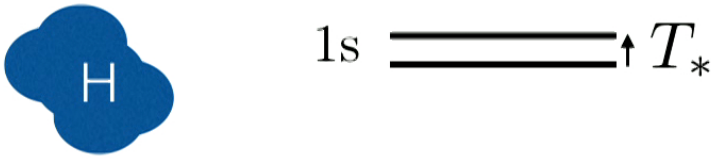


$I_\nu \propto T_{\rm CMB}\nu^2$

(@ 21 cm)

$T_S < T_{\rm cmb}$ Absorption

$T_S > T_{\rm cmb}$ Emission



Triplet

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

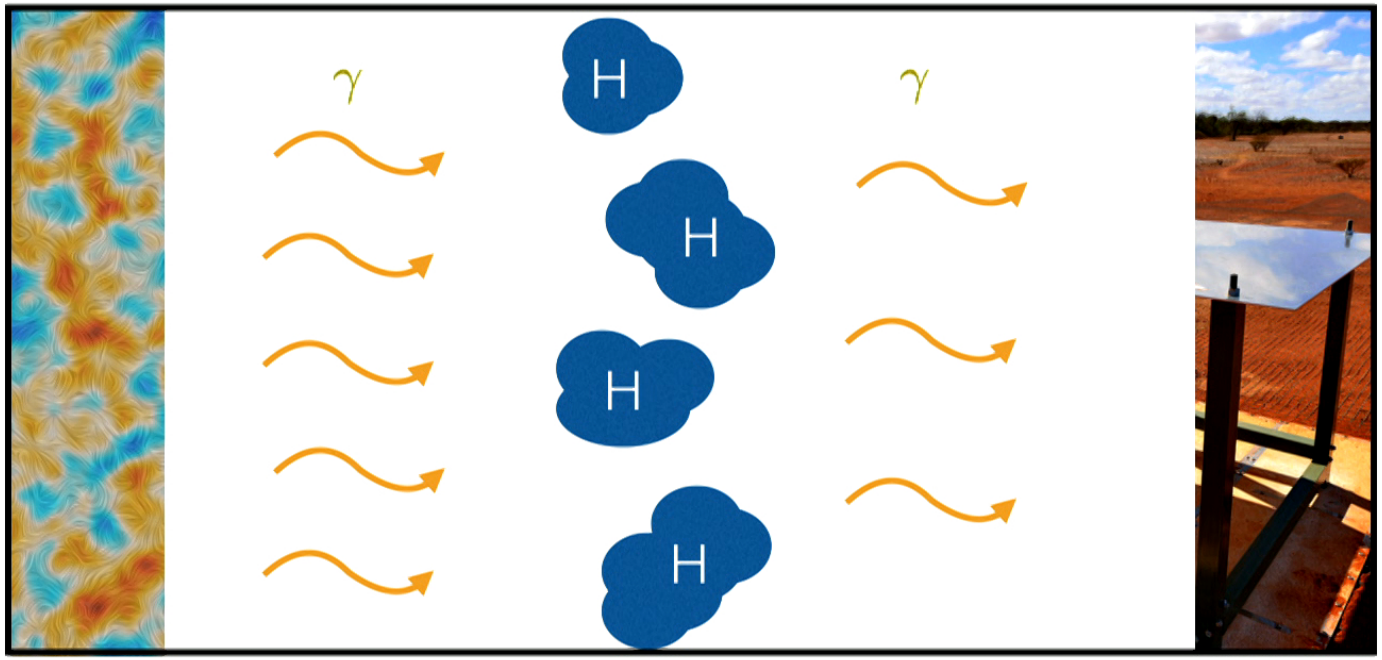
$6\,\mu\mathrm{eV}$

Singlet

3

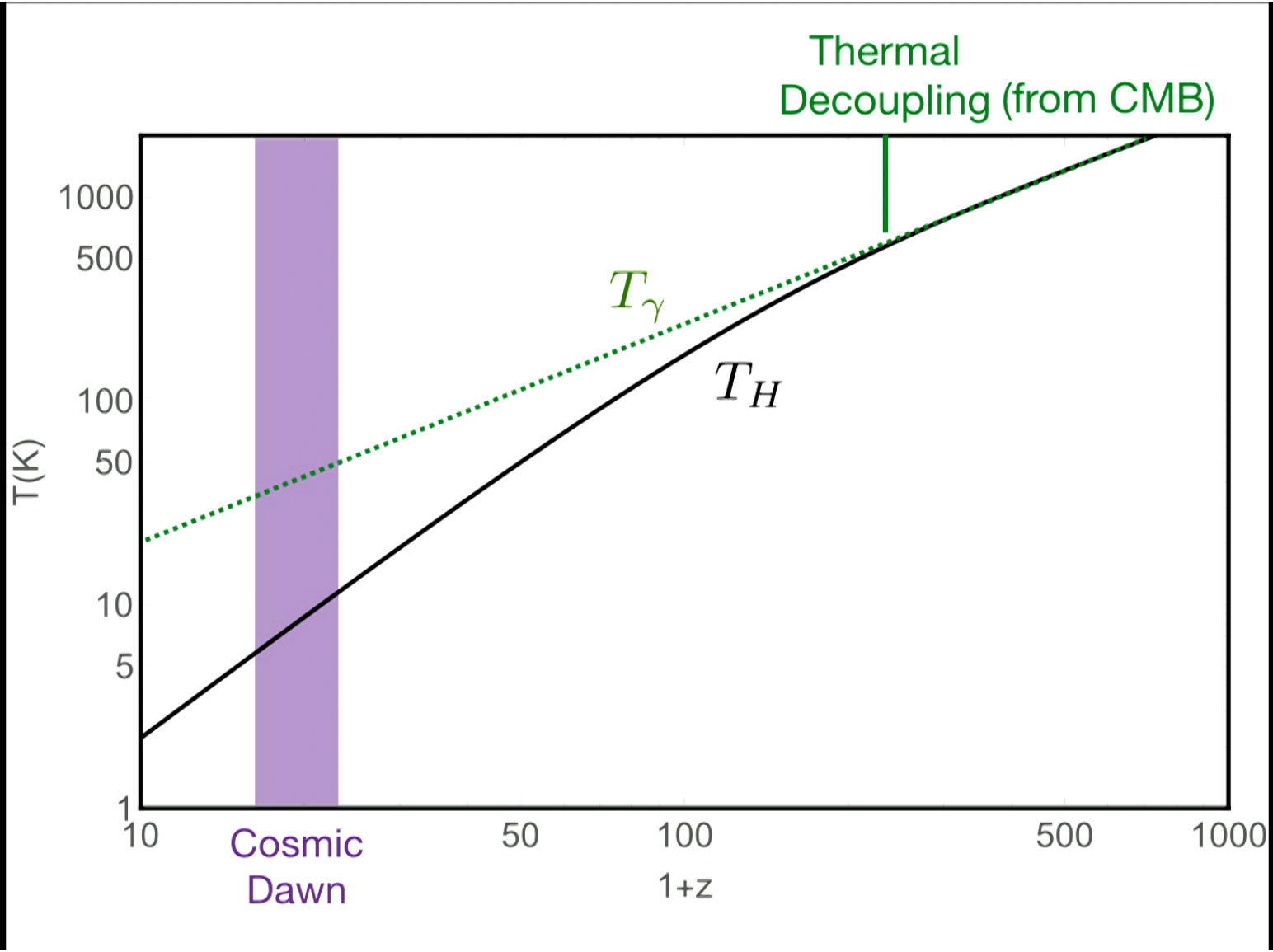
$T_S < T_{\rm cmb}$ Absorption

$z = 1100$ $\quad$ $z \approx 20$ $\quad$ Australia

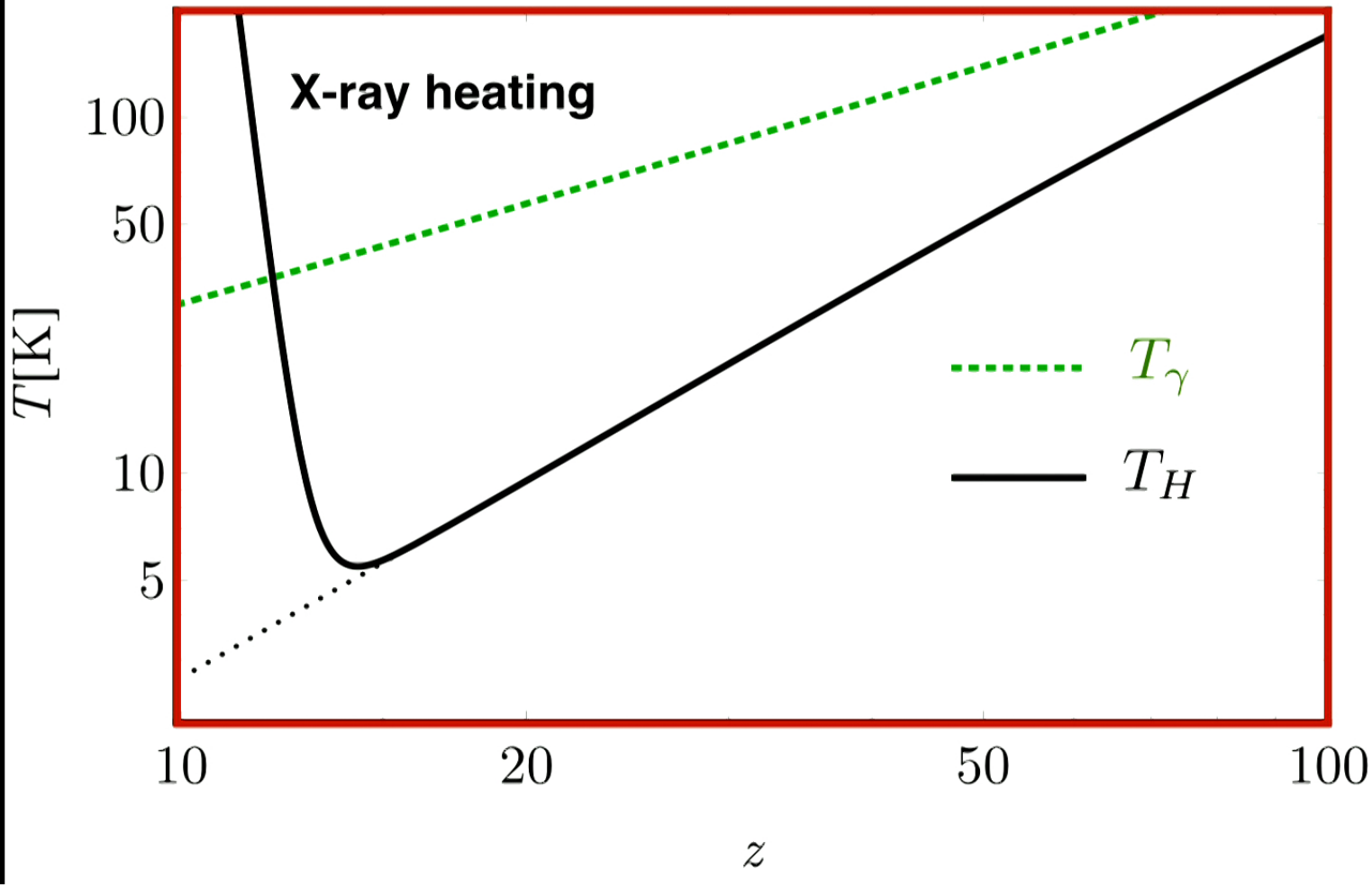


EDGES

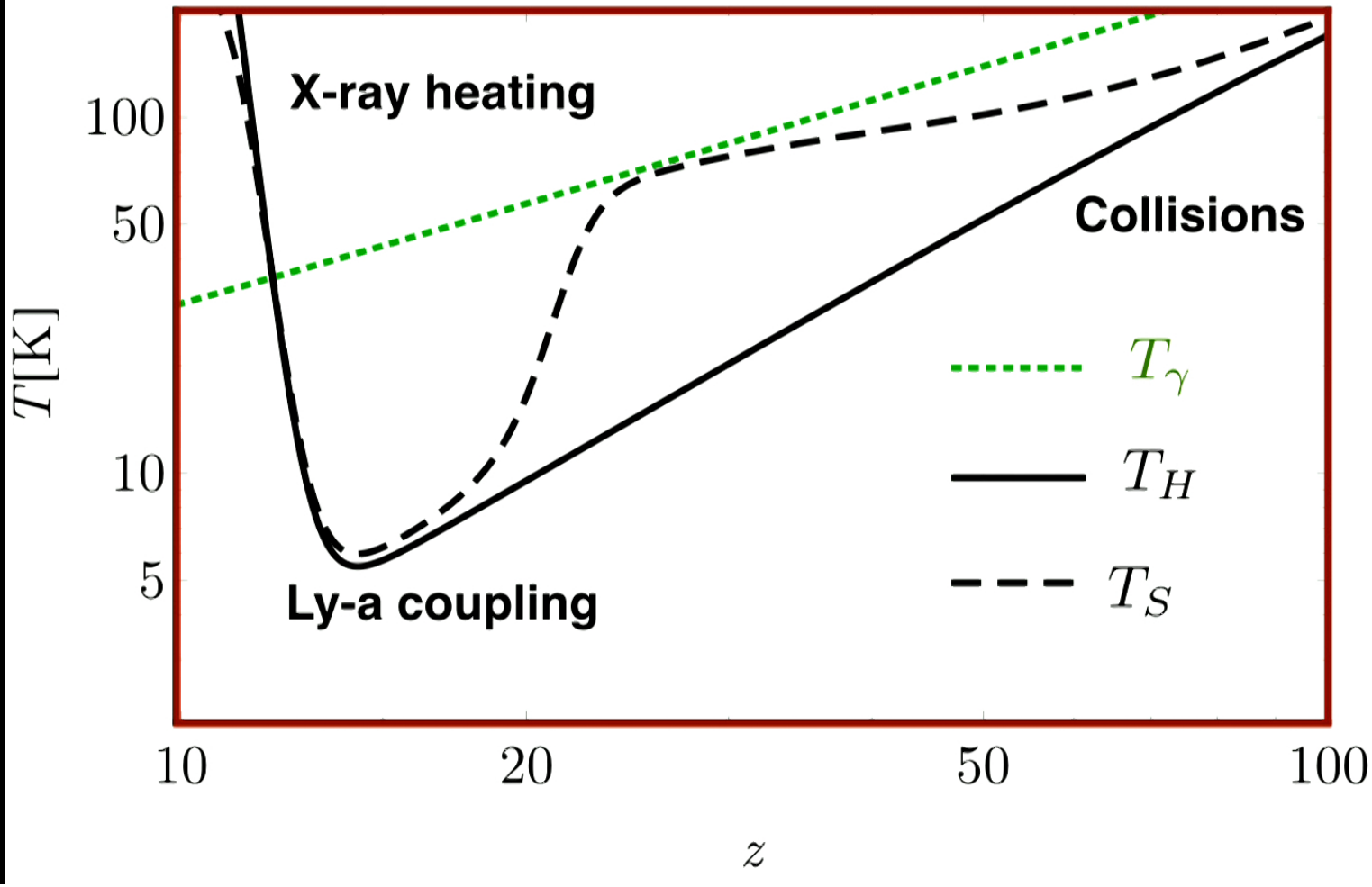
$I_\nu \propto T_{\rm CMB}\nu^2$ $\quad$ $\Delta I_\nu \propto T_{21}\nu^2$


Thermal
Decoupling (from CMB)
1000
500
100
50
10
5
1
T(K)
T_γ
T_H
10
50
100
500
1000
1+z
Cosmic
Dawn

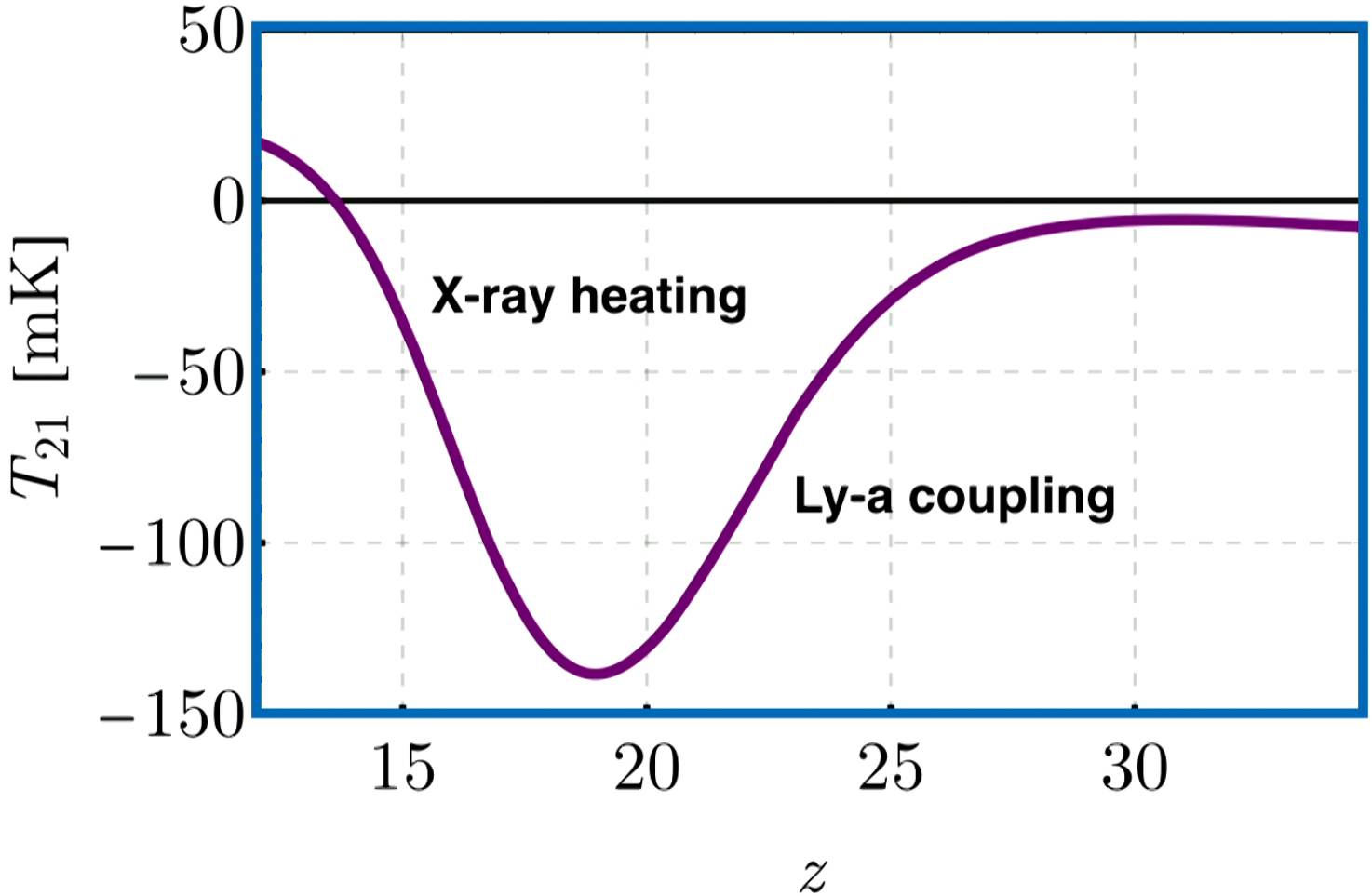
A cartoon of the evolution of Ts



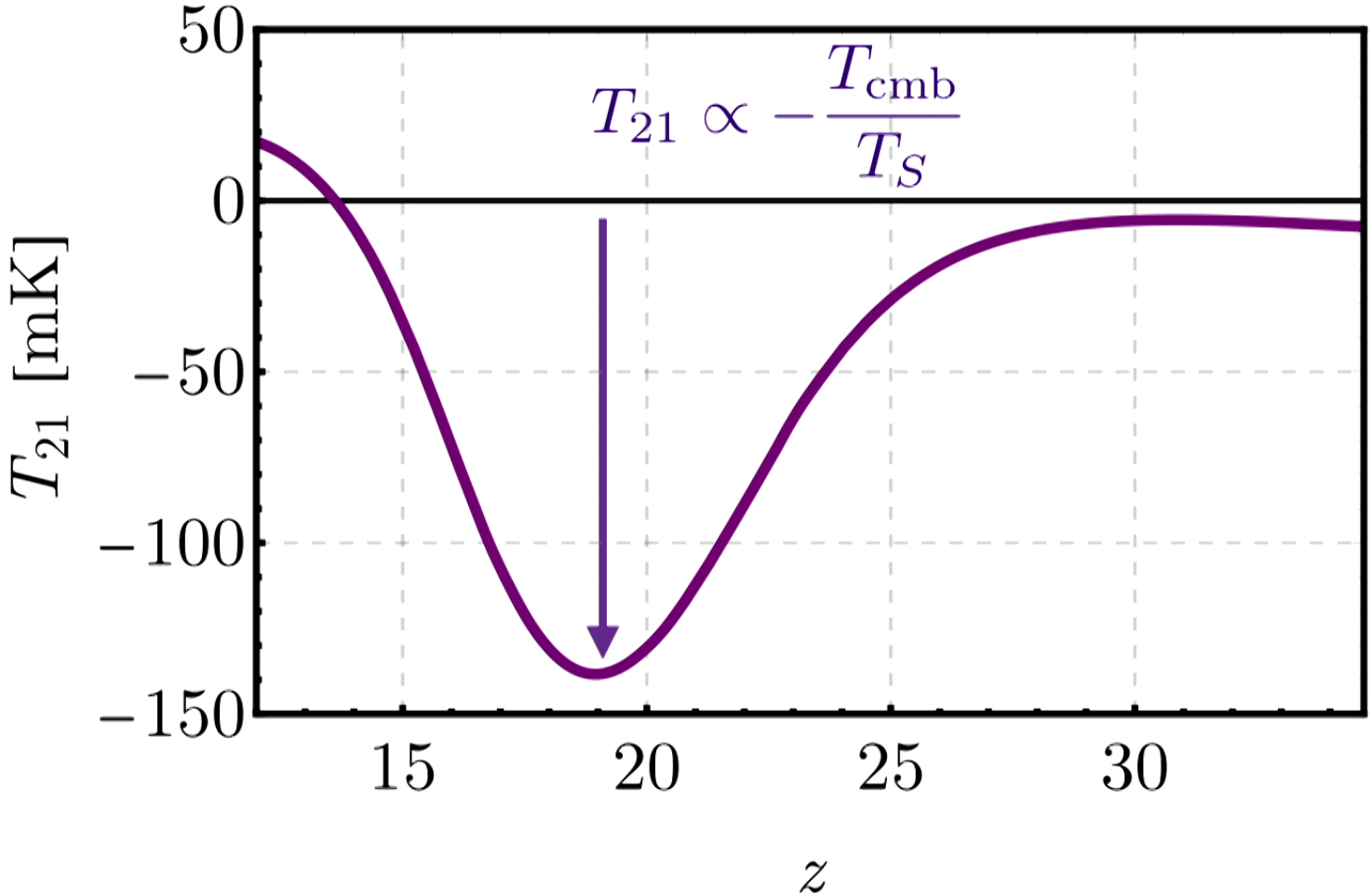
A cartoon of the evolution of Ts



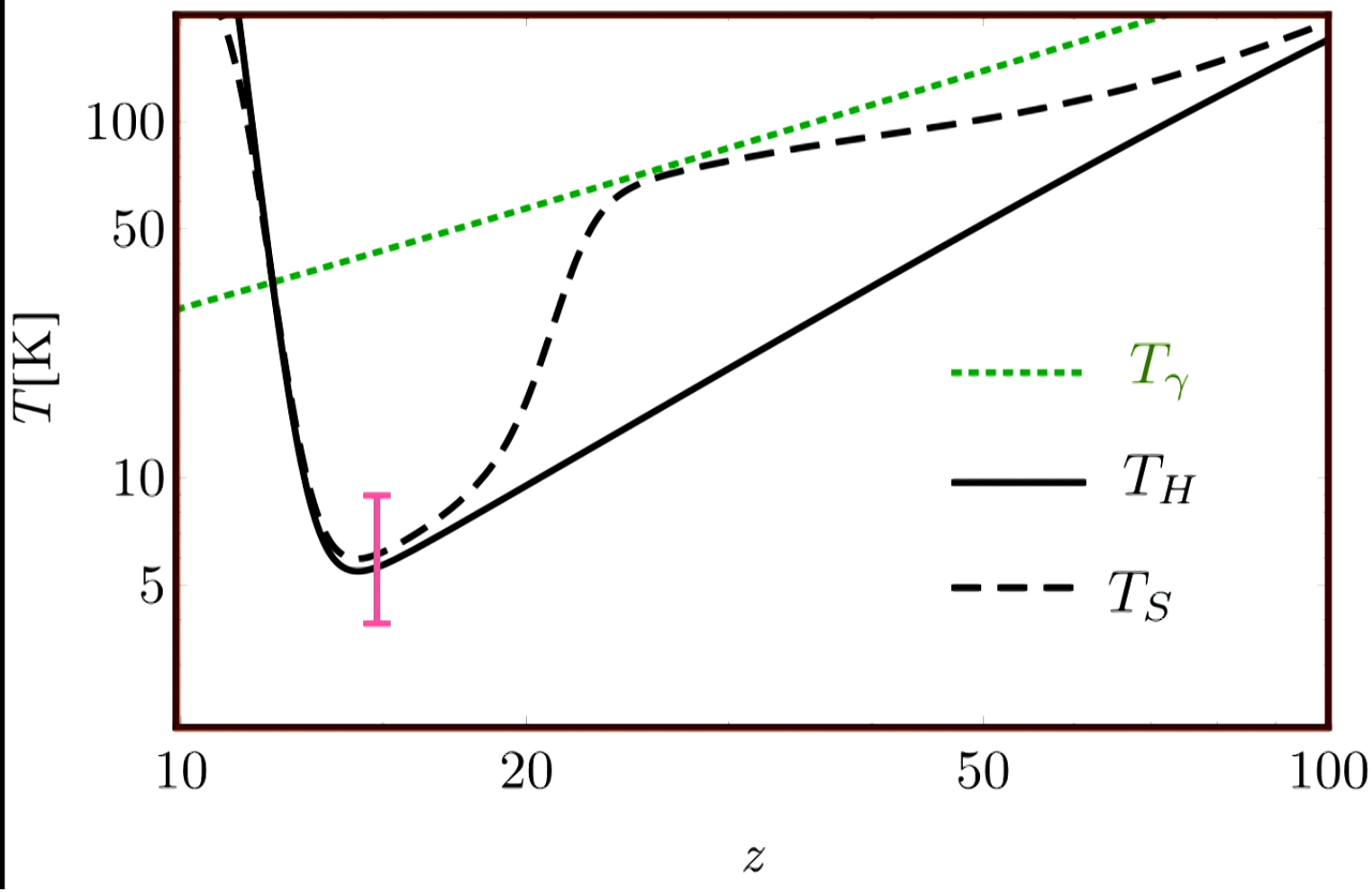
A typical 21-cm profile



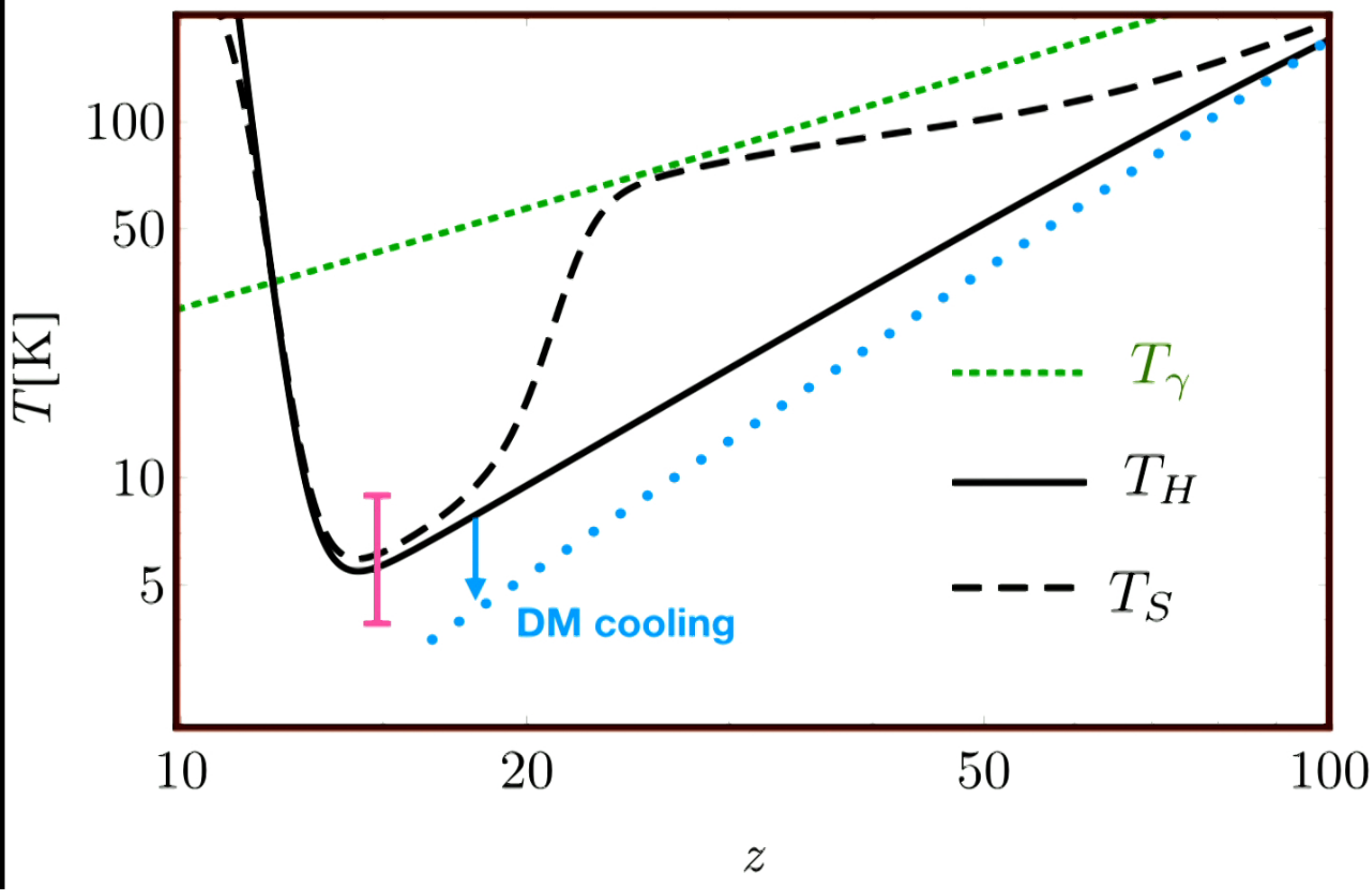
Learning about DM: Depth

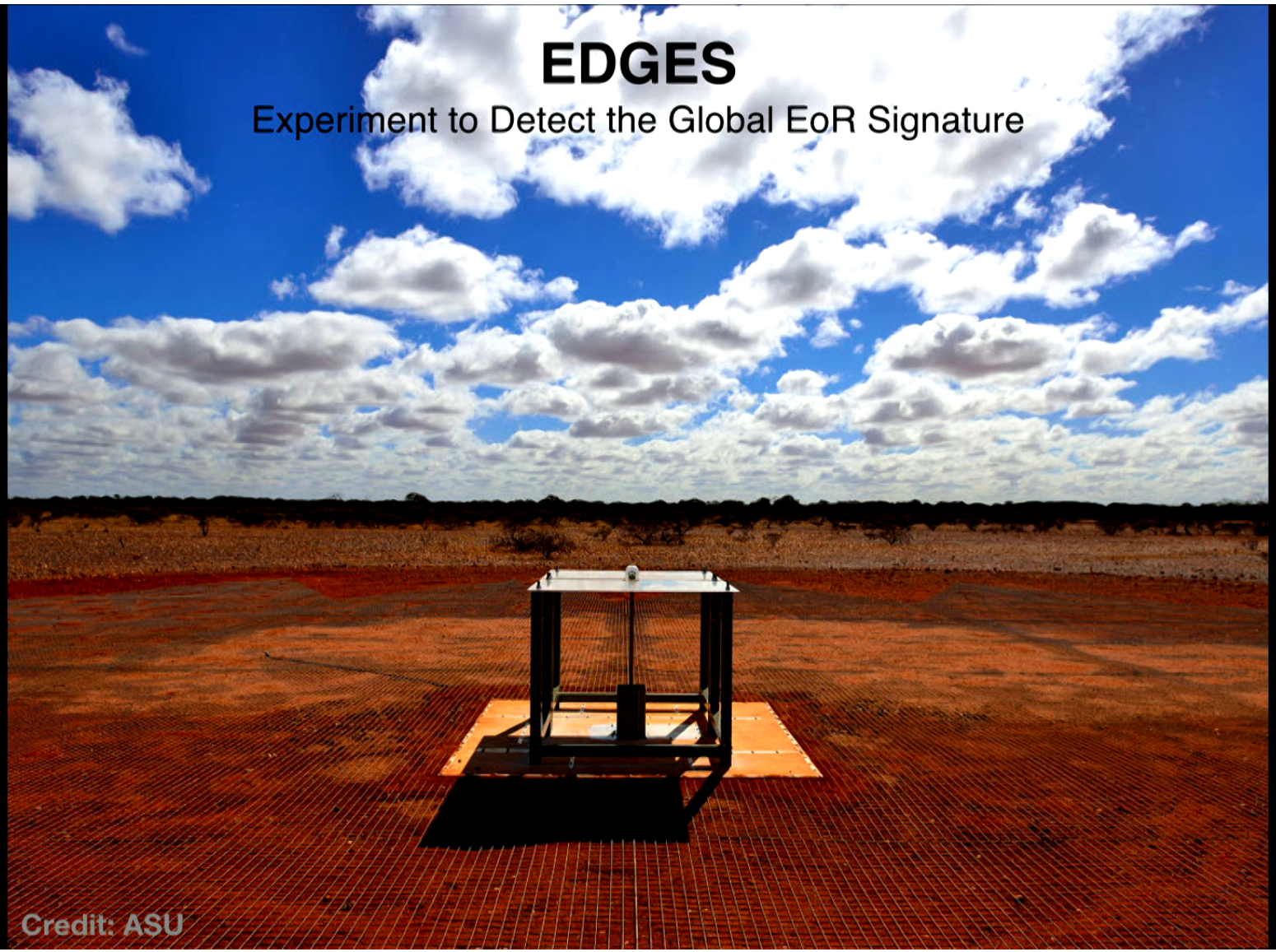


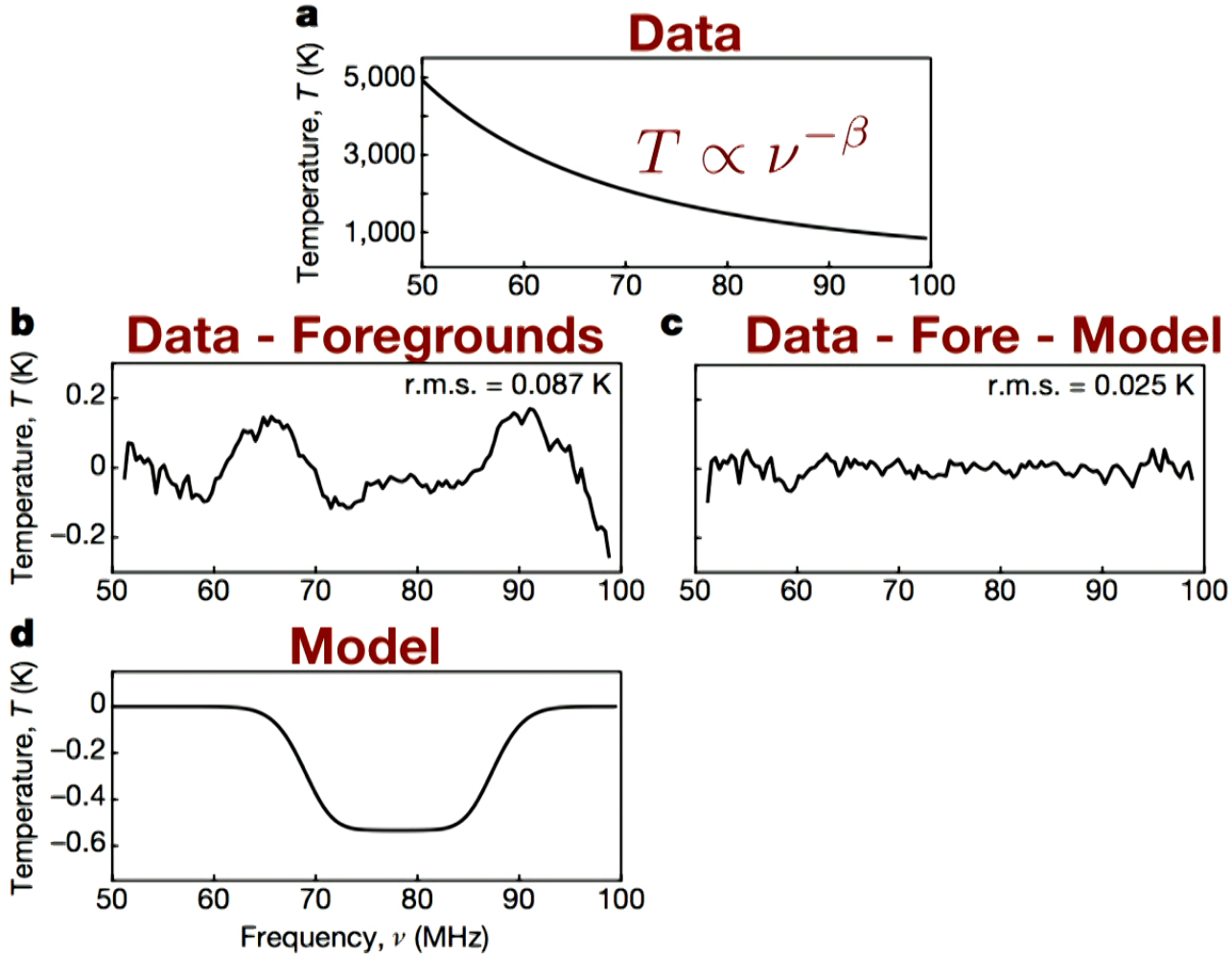
A thermostat at cosmic dawn



A thermostat at cosmic dawn



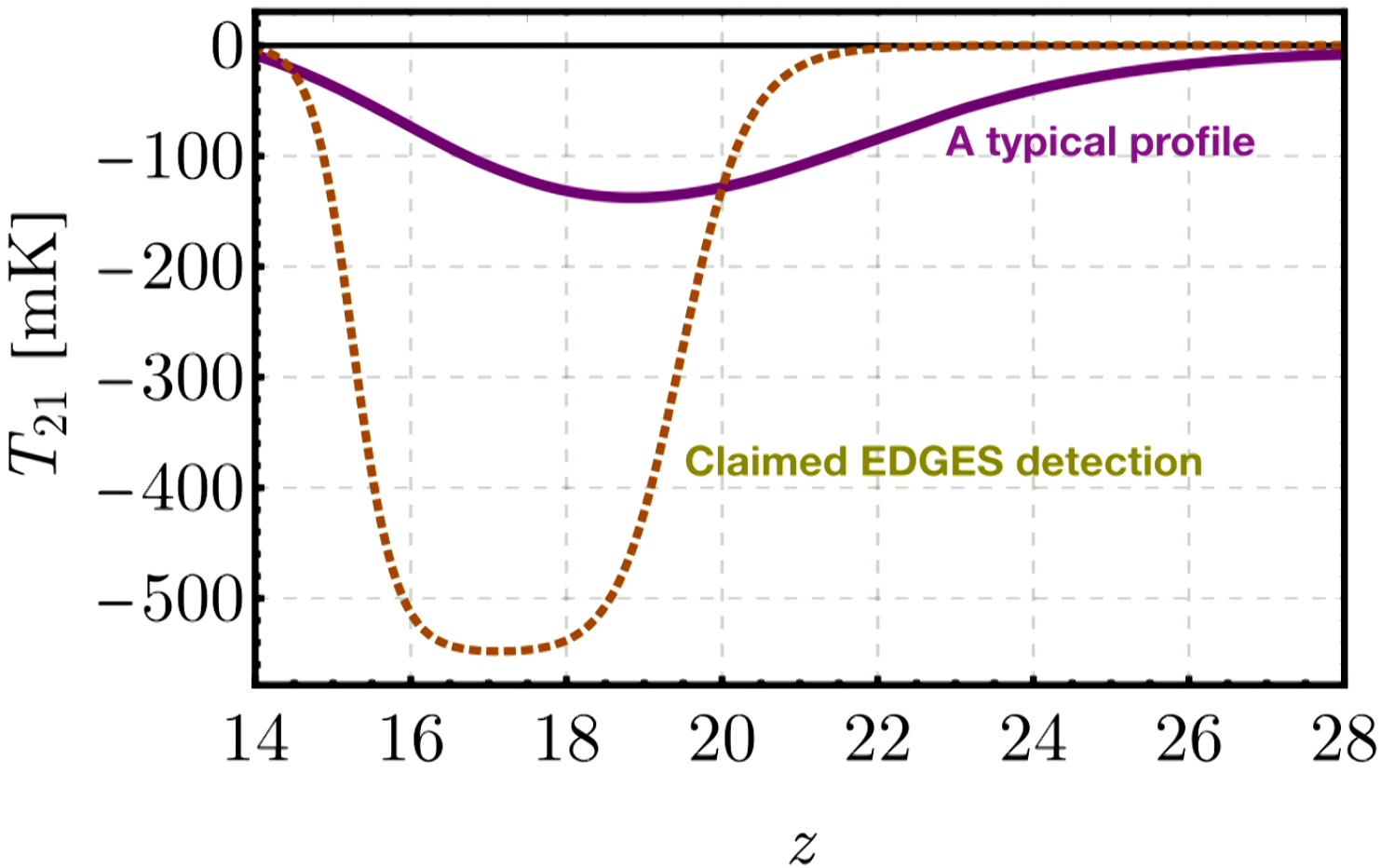

EDGES
Experiment to Detect the Global EoR Signature
Credit: ASU

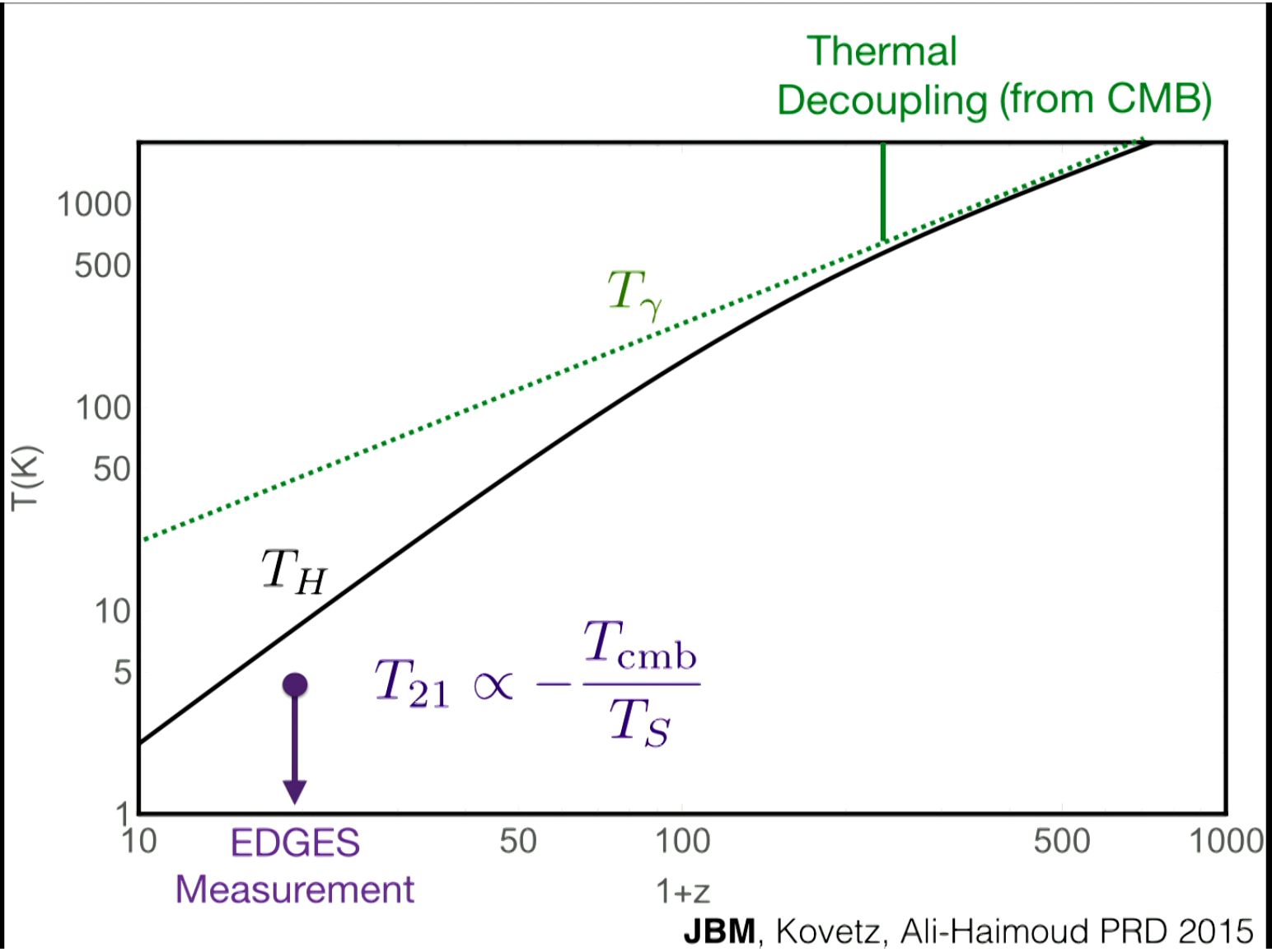


Bowman et al. Nature 2018

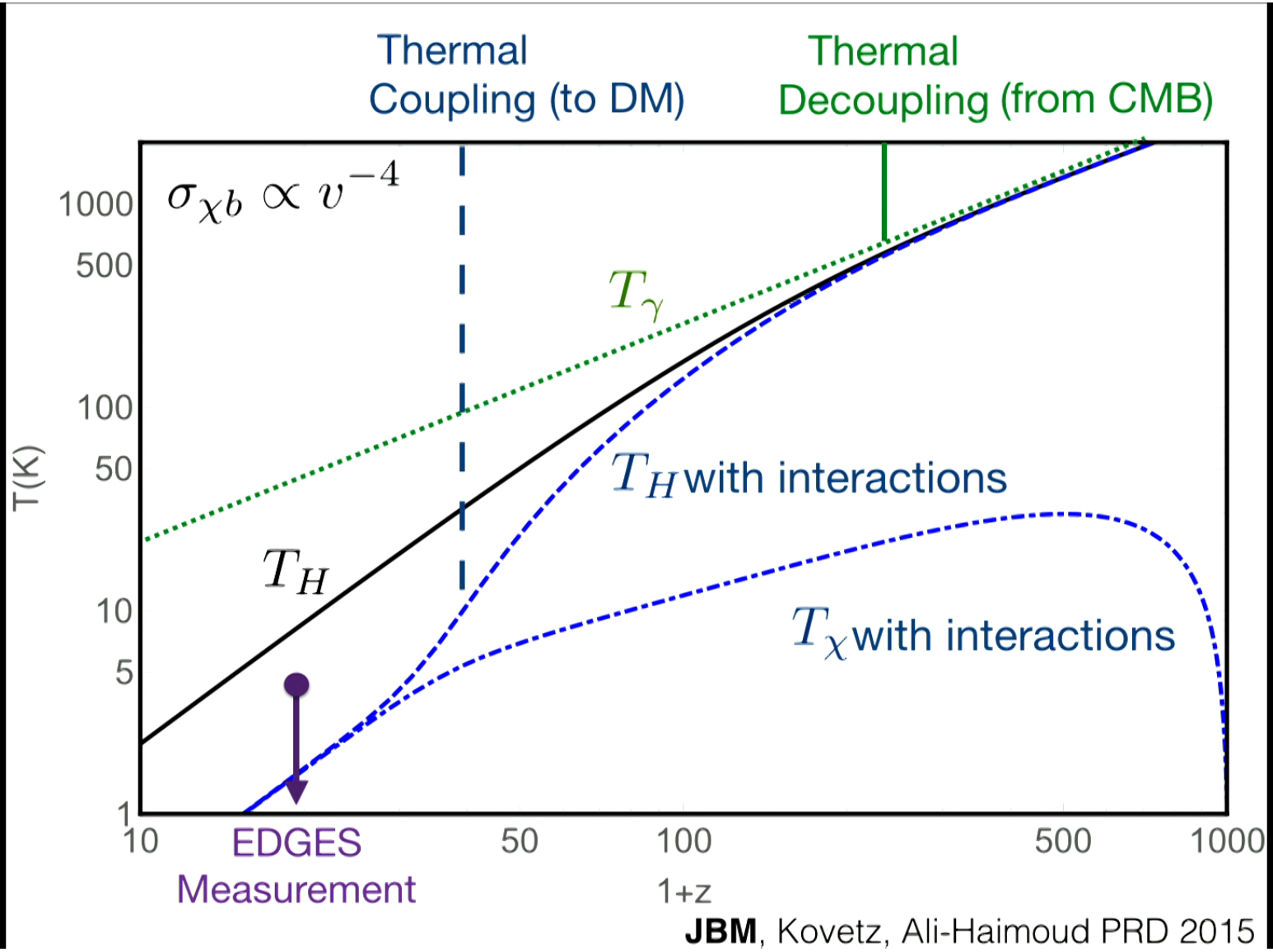
EDGES (Experiment to Detect the Global EoR Signature)

Learning about DM: Depth





JBM, Kovetz, Ali-Haimoud PRD 2015



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

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

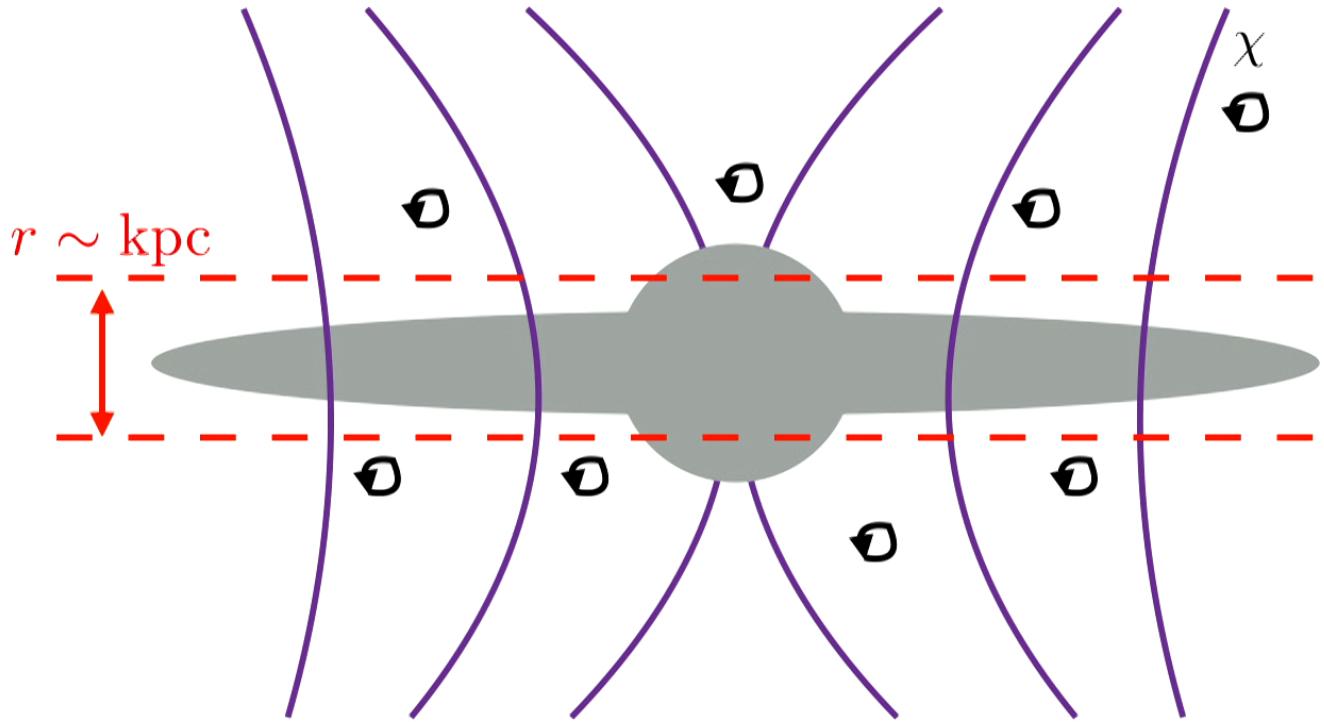
~~Fifth Force~~ $m_\phi < 10\,\mathrm{keV}$

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

Millicharged DM

Chuzhoy and Kolb (2009)

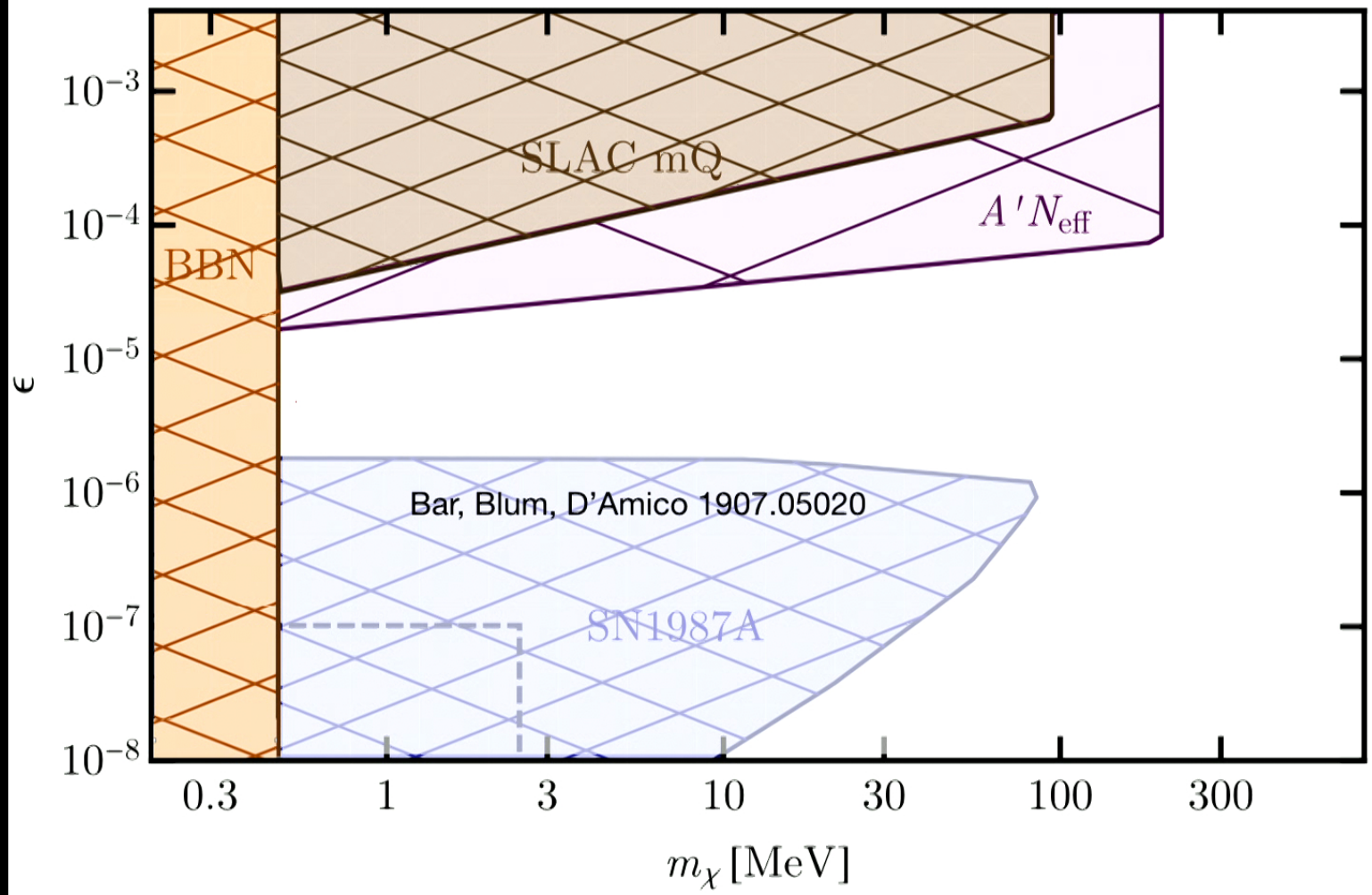
$$r_g \propto \frac{m_\chi}{\epsilon} \gtrsim 100\,\mathrm{kpc}$$



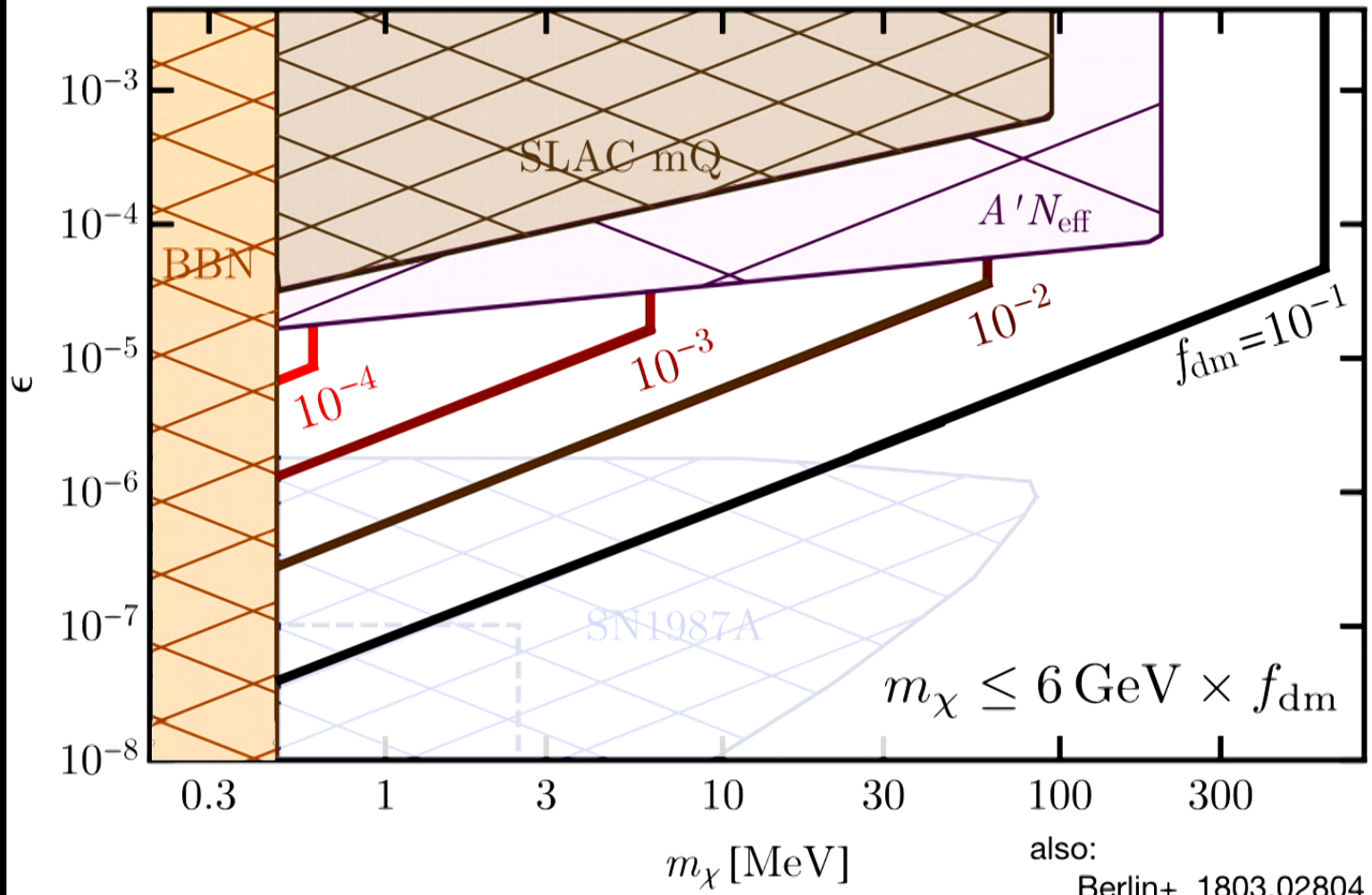
$$\rho_{\mathrm{DM}} = 0.3 \pm 0.1\,\mathrm{GeV\,cm^{-3}}$$

Bovy and Tremaine (2012)

Learning about DM: Millicharges

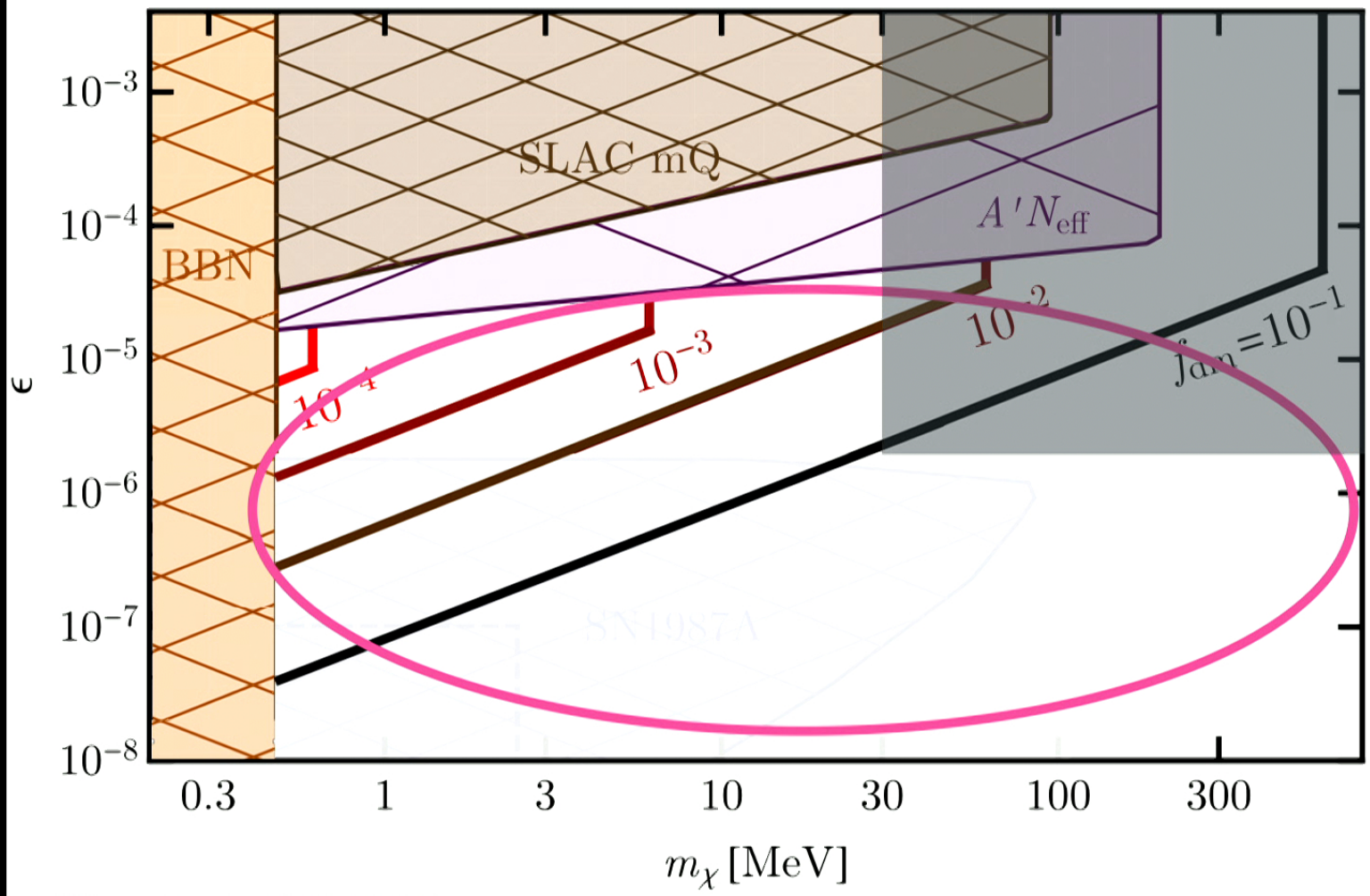


Learning about DM: Millicharges



JBM and Loeb 1802.10094

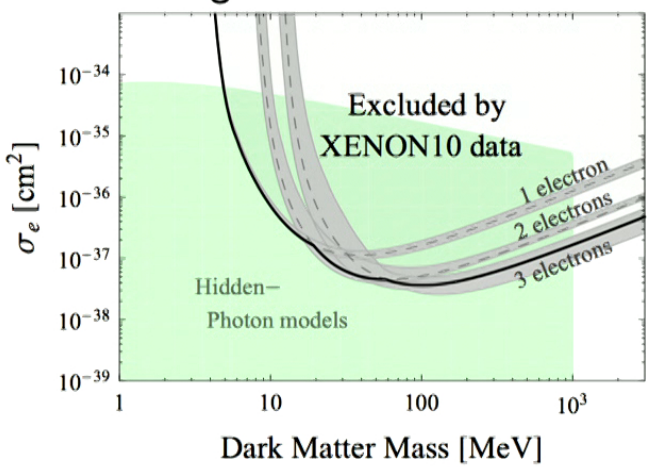
also:
Berlin+ 1803.02804
Barkana+ 1803.03091



JBM and Loeb 1802.10094

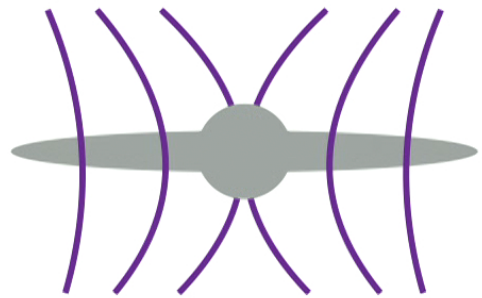
Accelerators?

Essig et al. 2012



Although:

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



SHiP/MilliQan @ CERN $\epsilon > 10^{-3}$

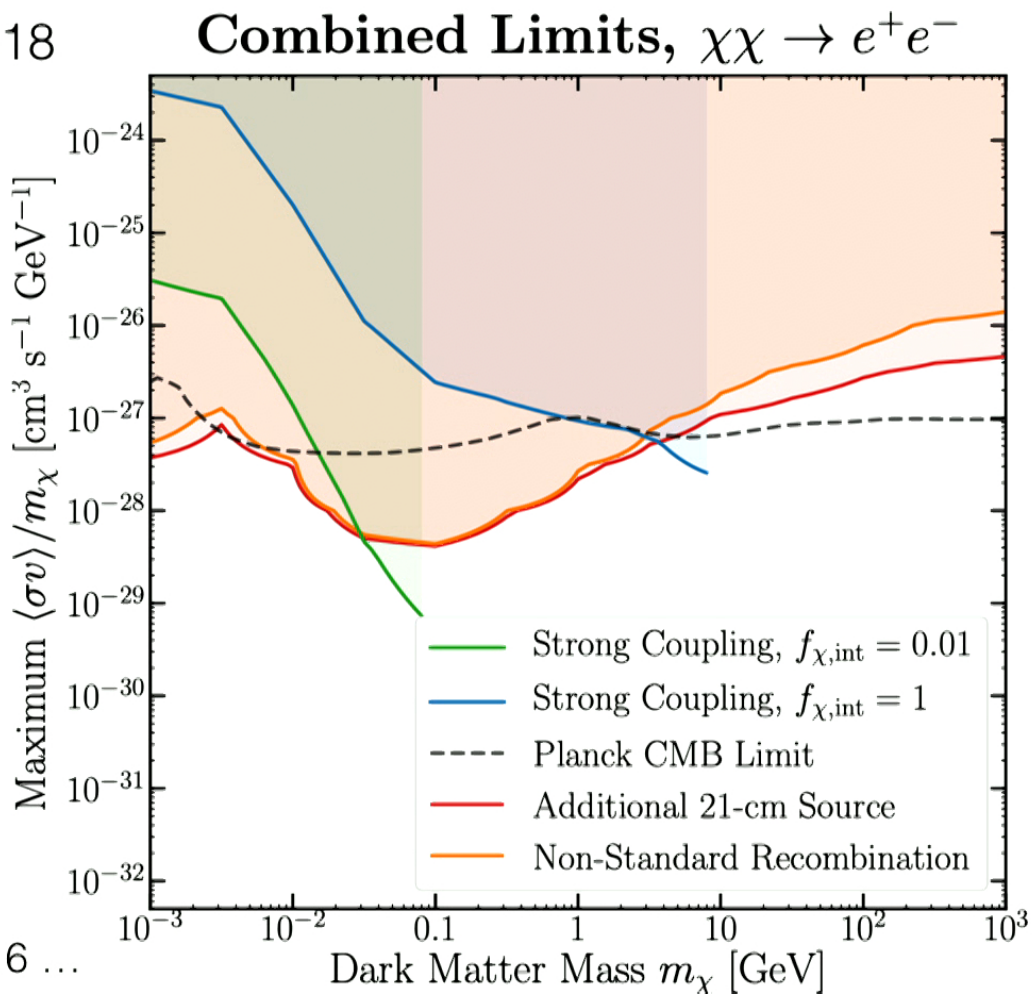
LDMX @ SLAC/Jlab/CERN $\epsilon \approx 10^{-1} \times \mathrm{SLAC\,mQ}$

LSND/Dune $\epsilon \approx 0.5 \times \mathrm{SLAC\,mQ}$

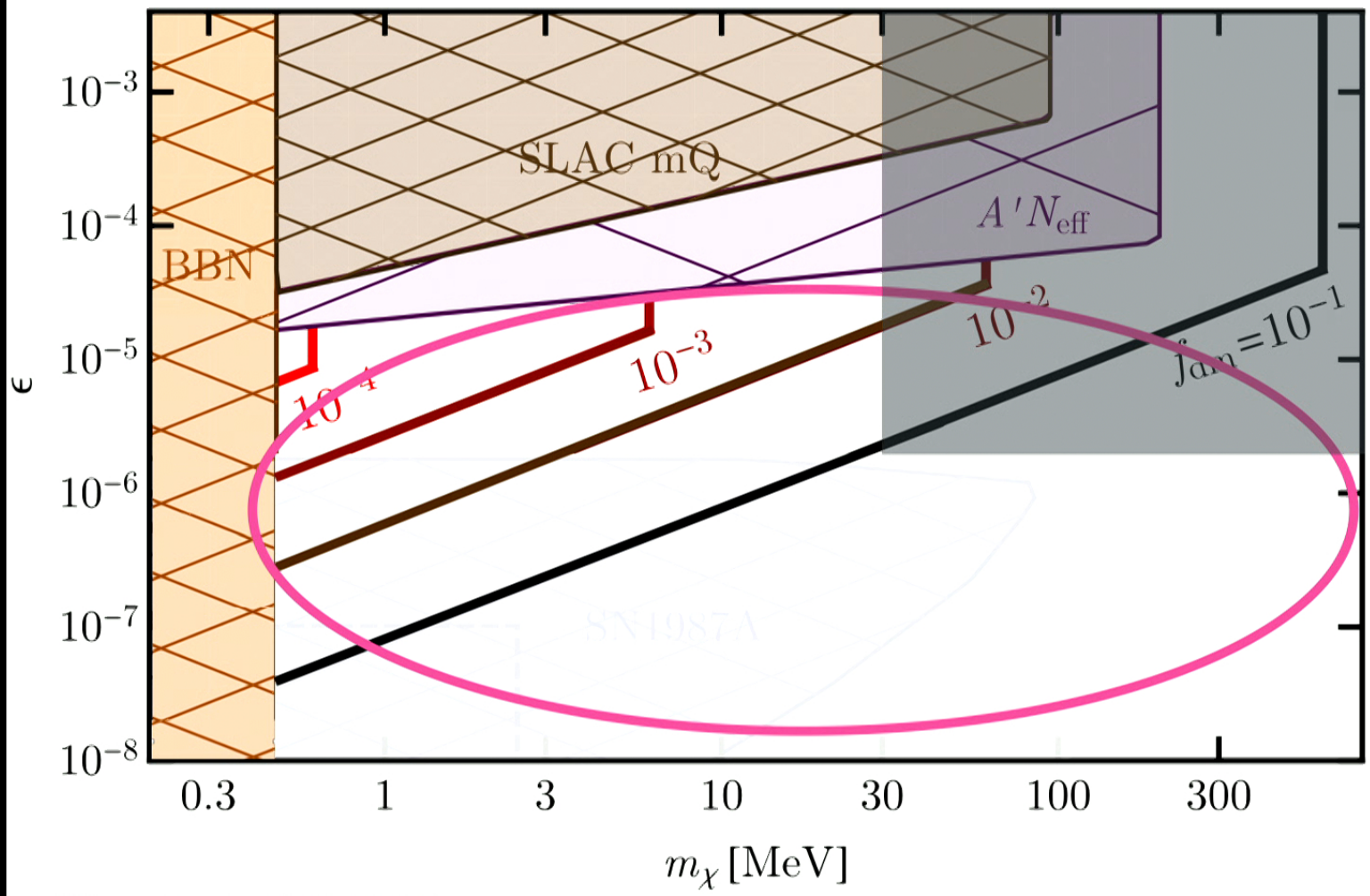
Magill+ 1806.03310

Searching for WIMPs

Liu & Slatyer, 2018

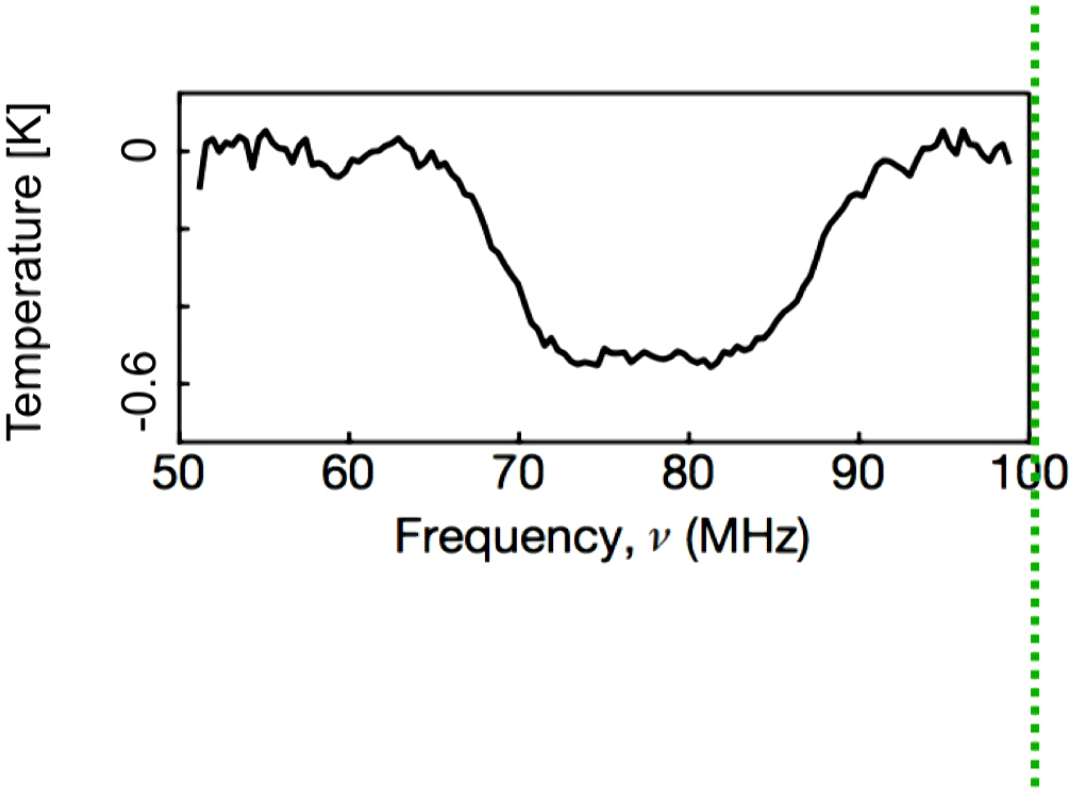


also:
D'Amico+ 2018
Lopez-Honorez+ 2016 …



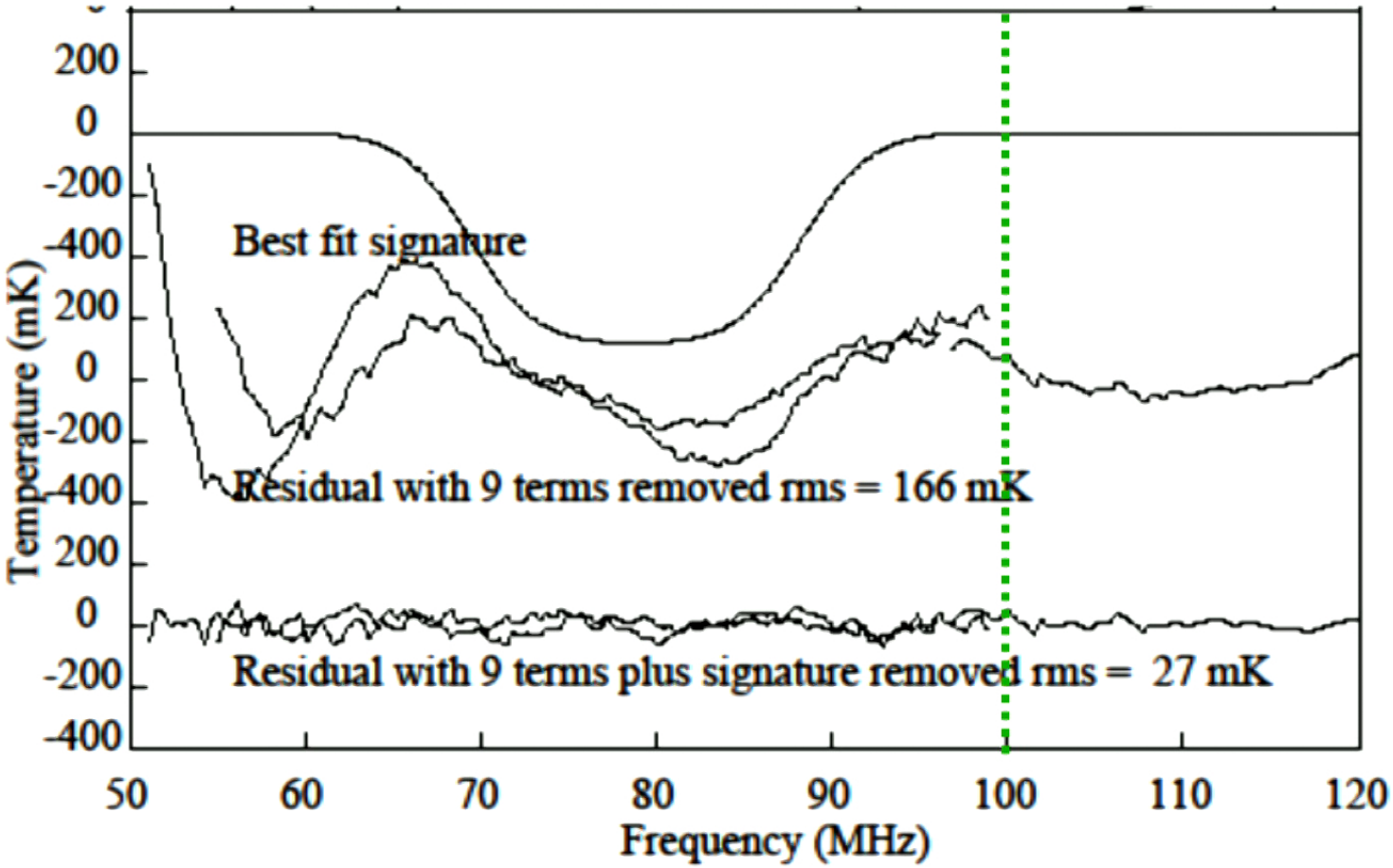
JBM and Loeb 1802.10094

Low-Band EDGES



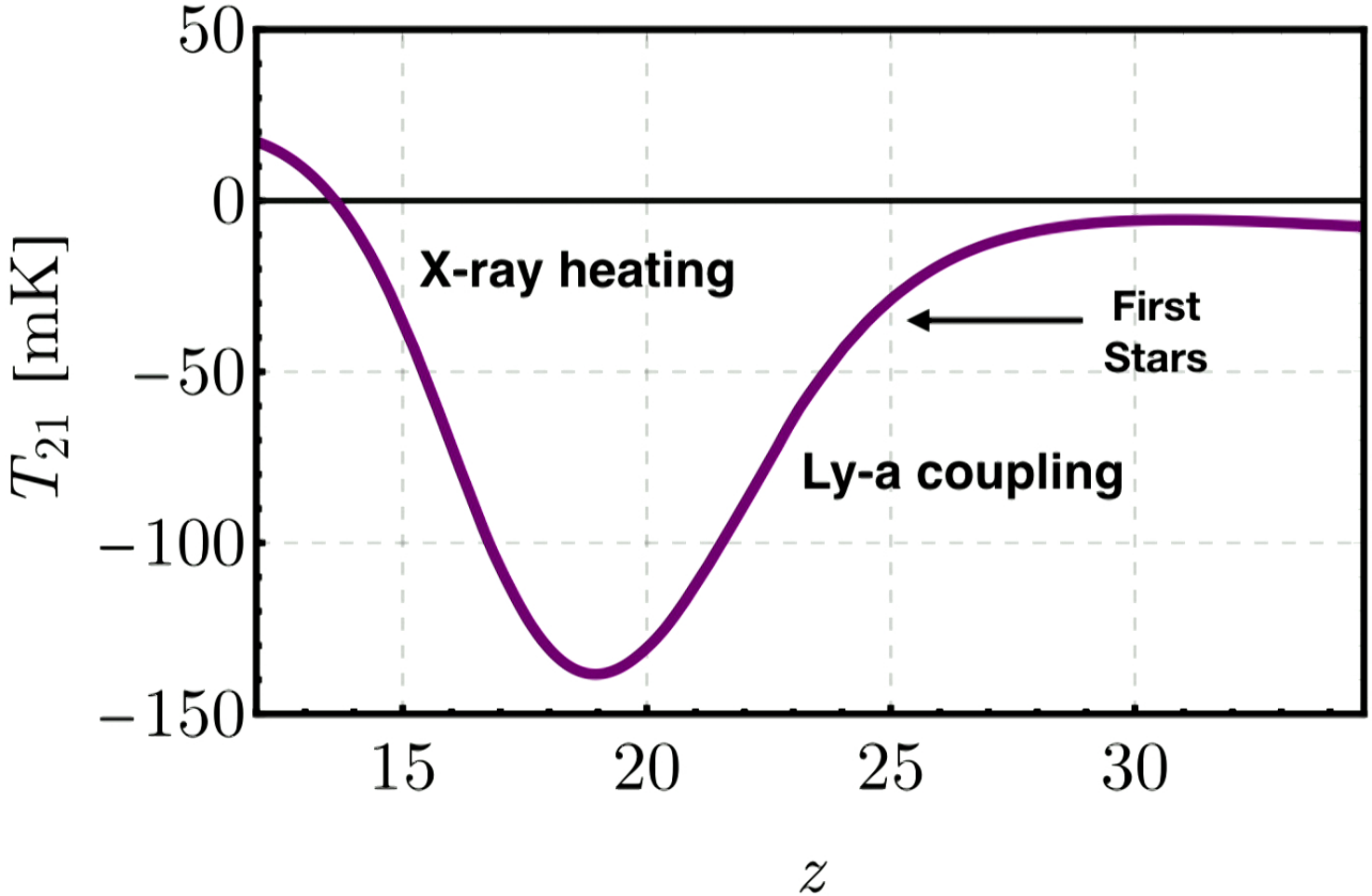
Bowman et al. Nature 2018

Low + Mid-Band EDGES

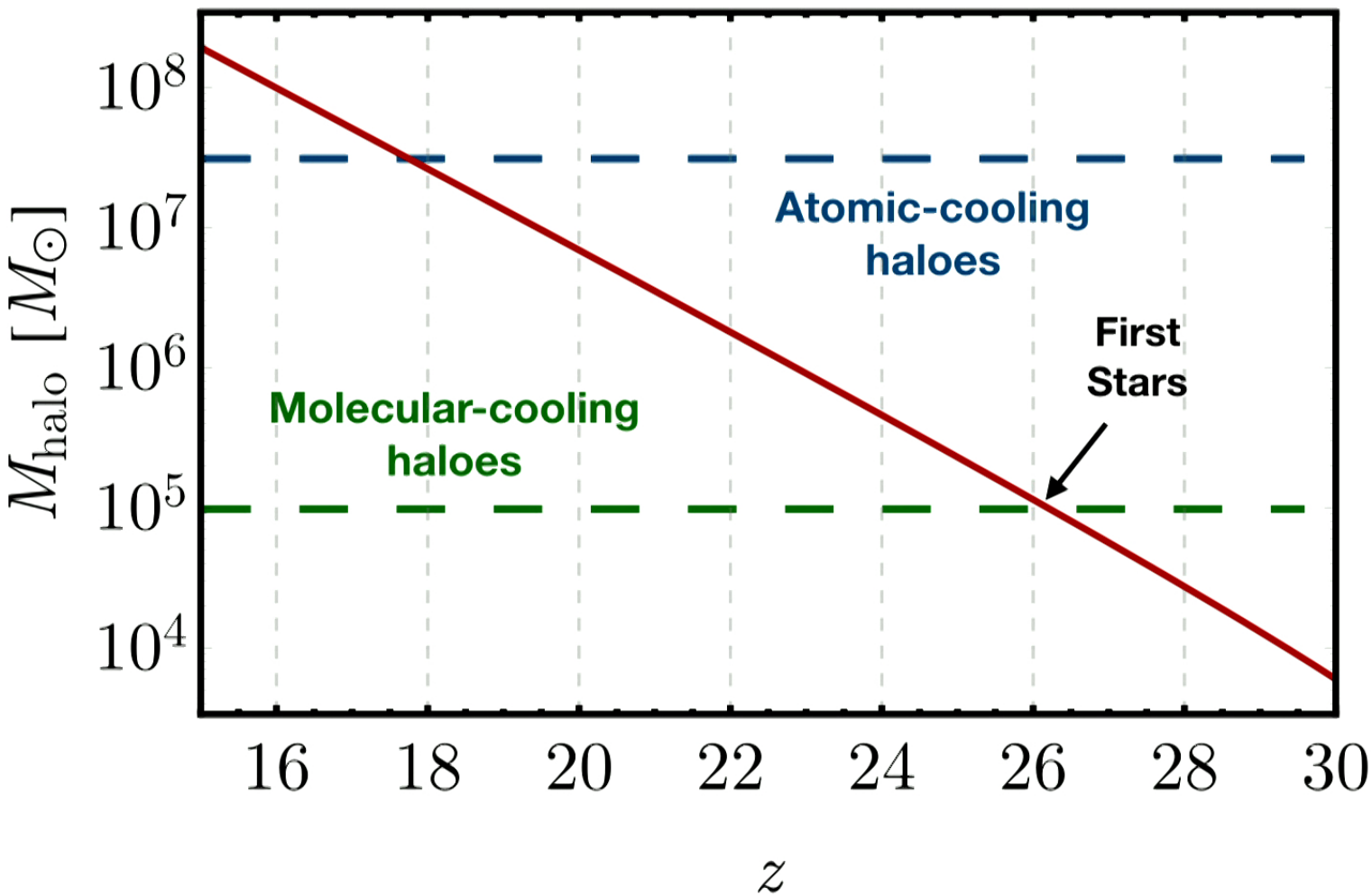


EDGES memo 286

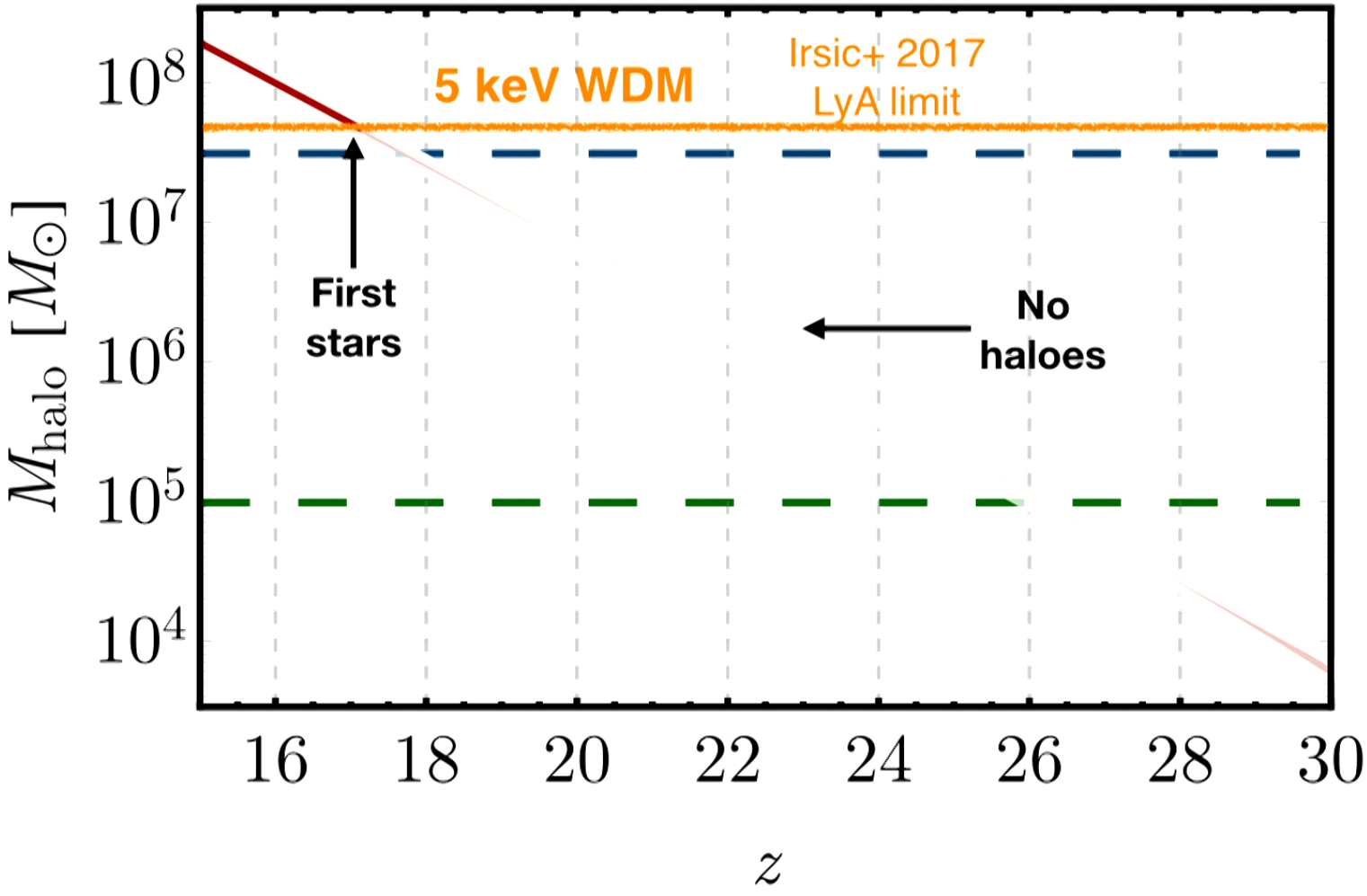
Learning about DM: Timing



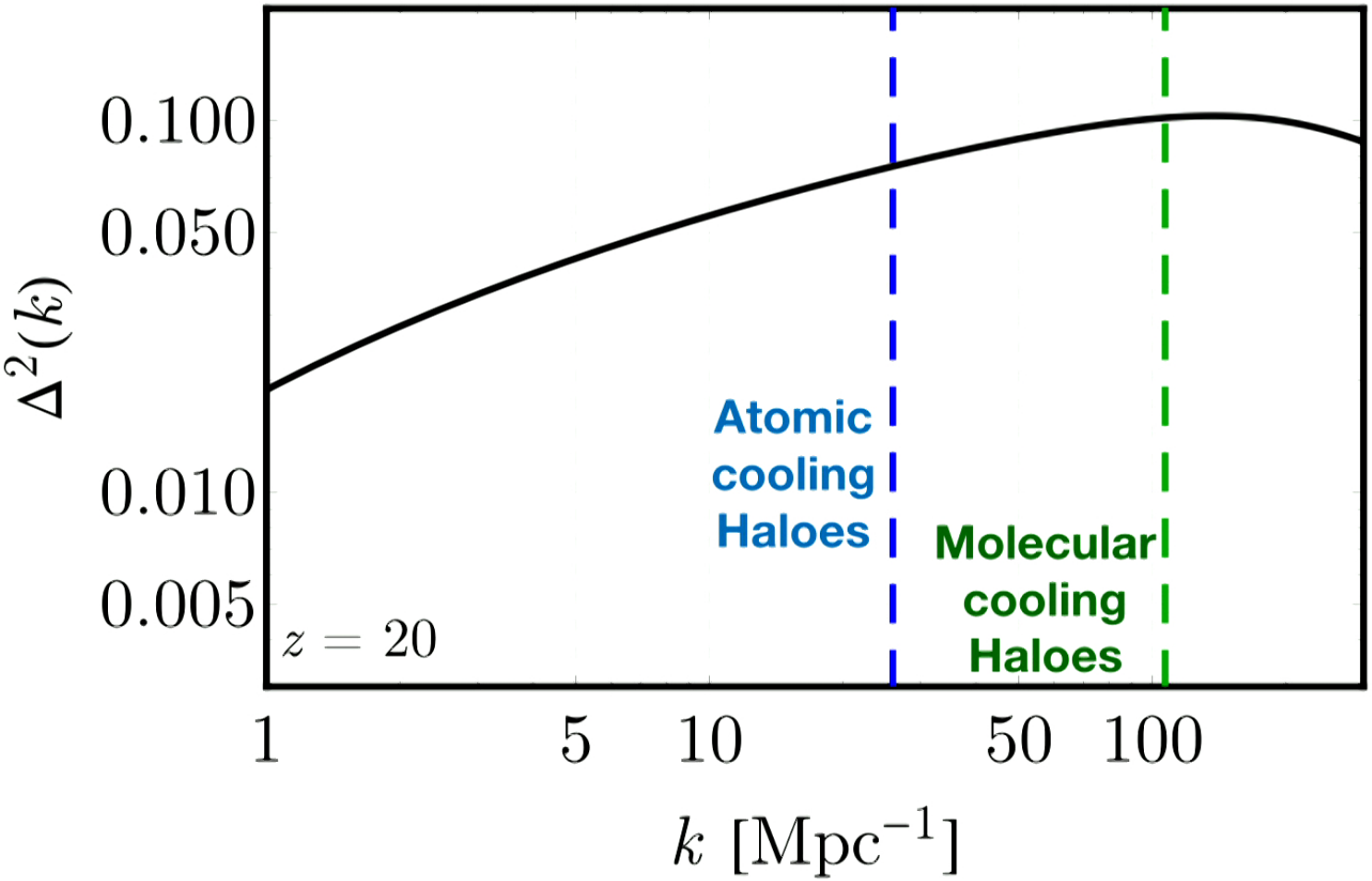
Learning about DM: Timing



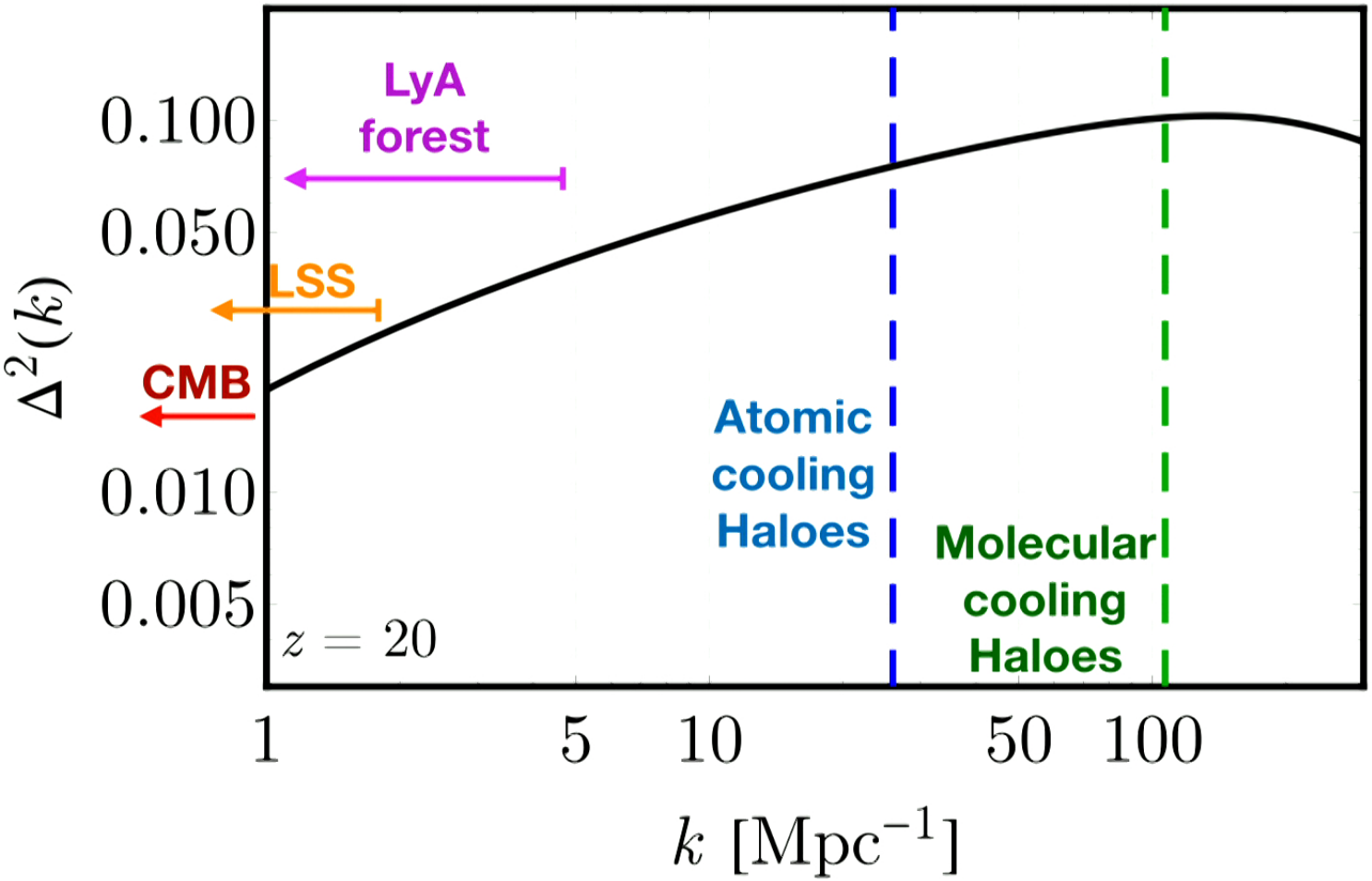
With non-CDM:


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

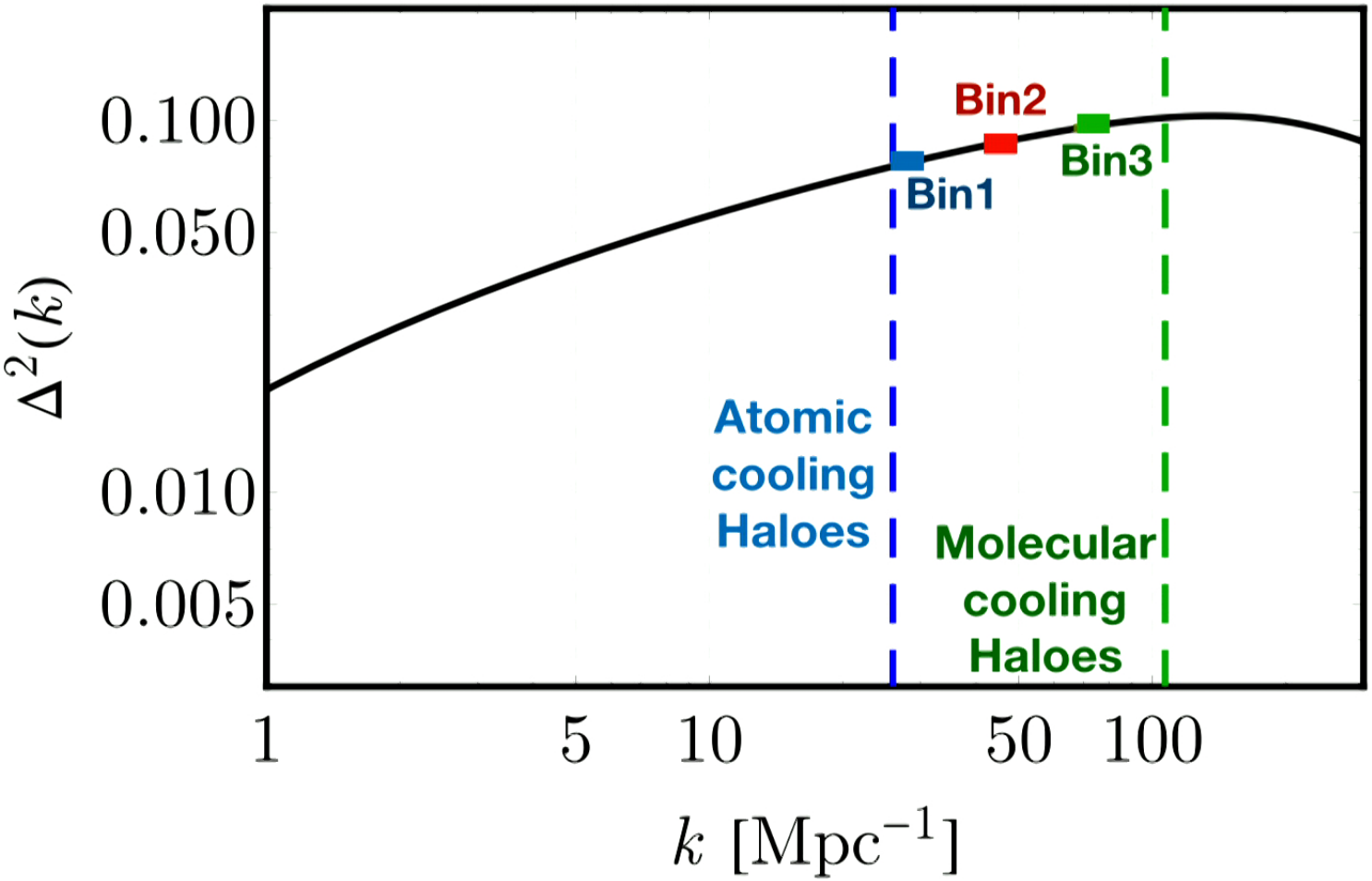
LCDM small-scale power spectrum



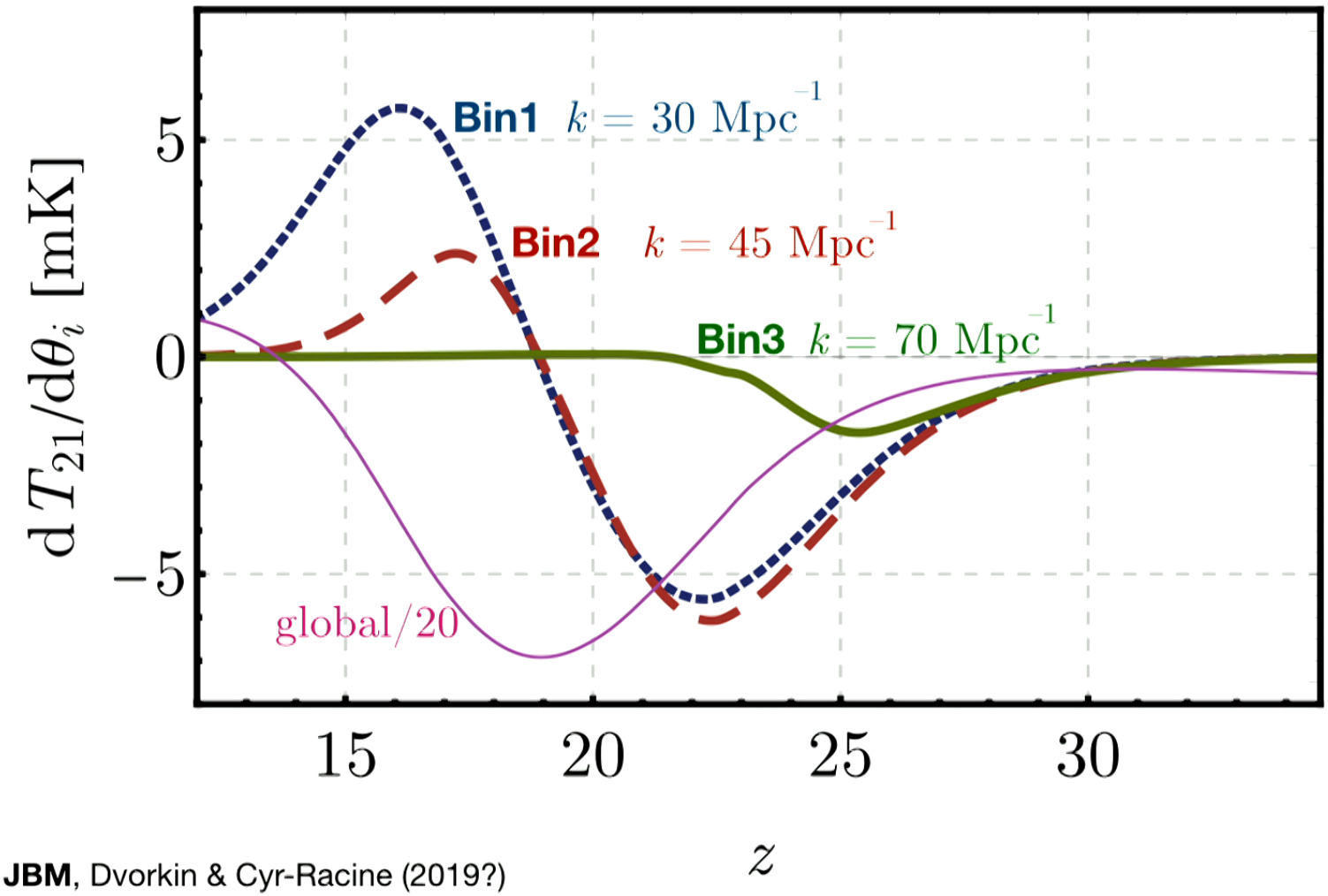
LCDM small-scale power spectrum



LCDM small-scale power spectrum

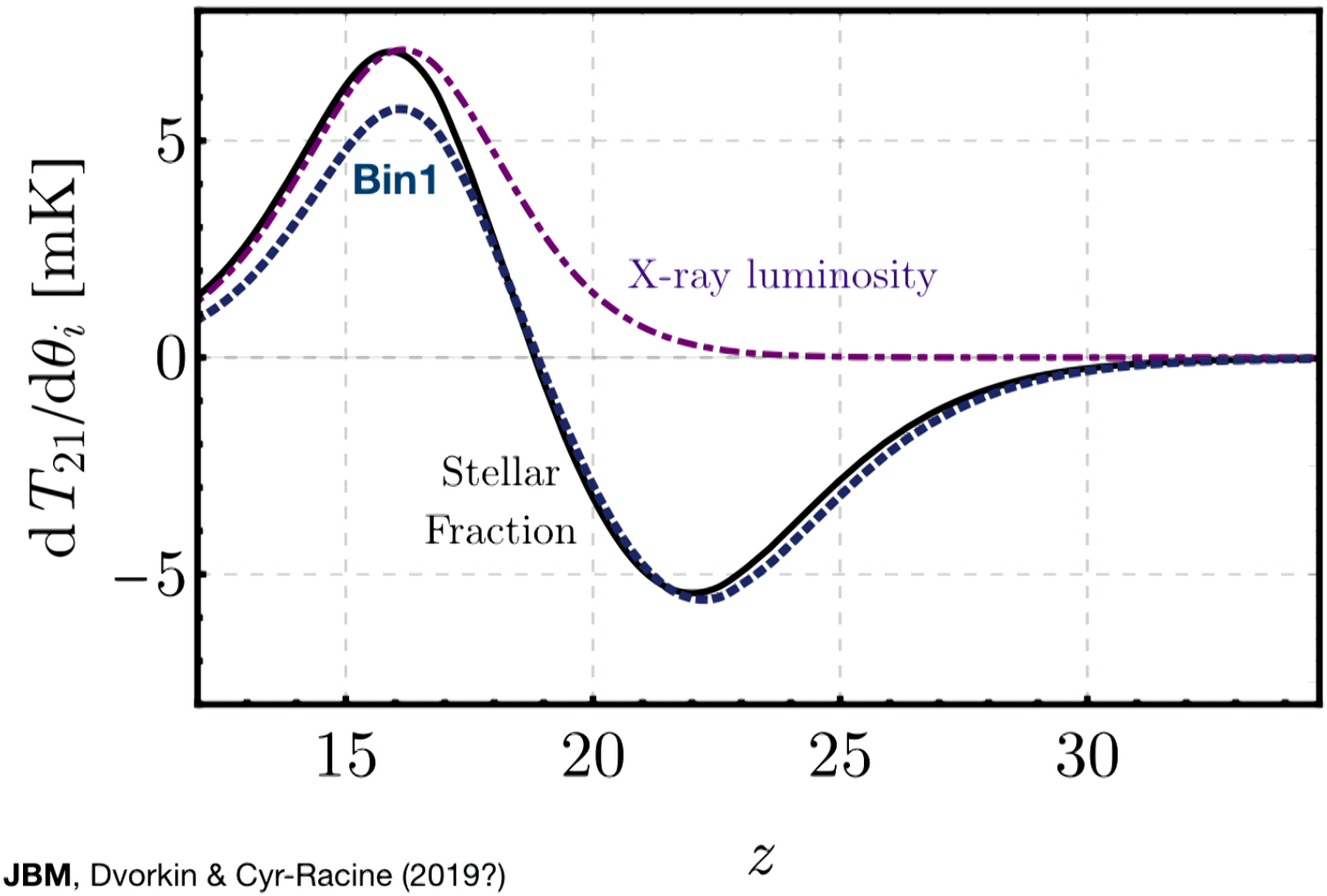


The impact on the 21-cm signal



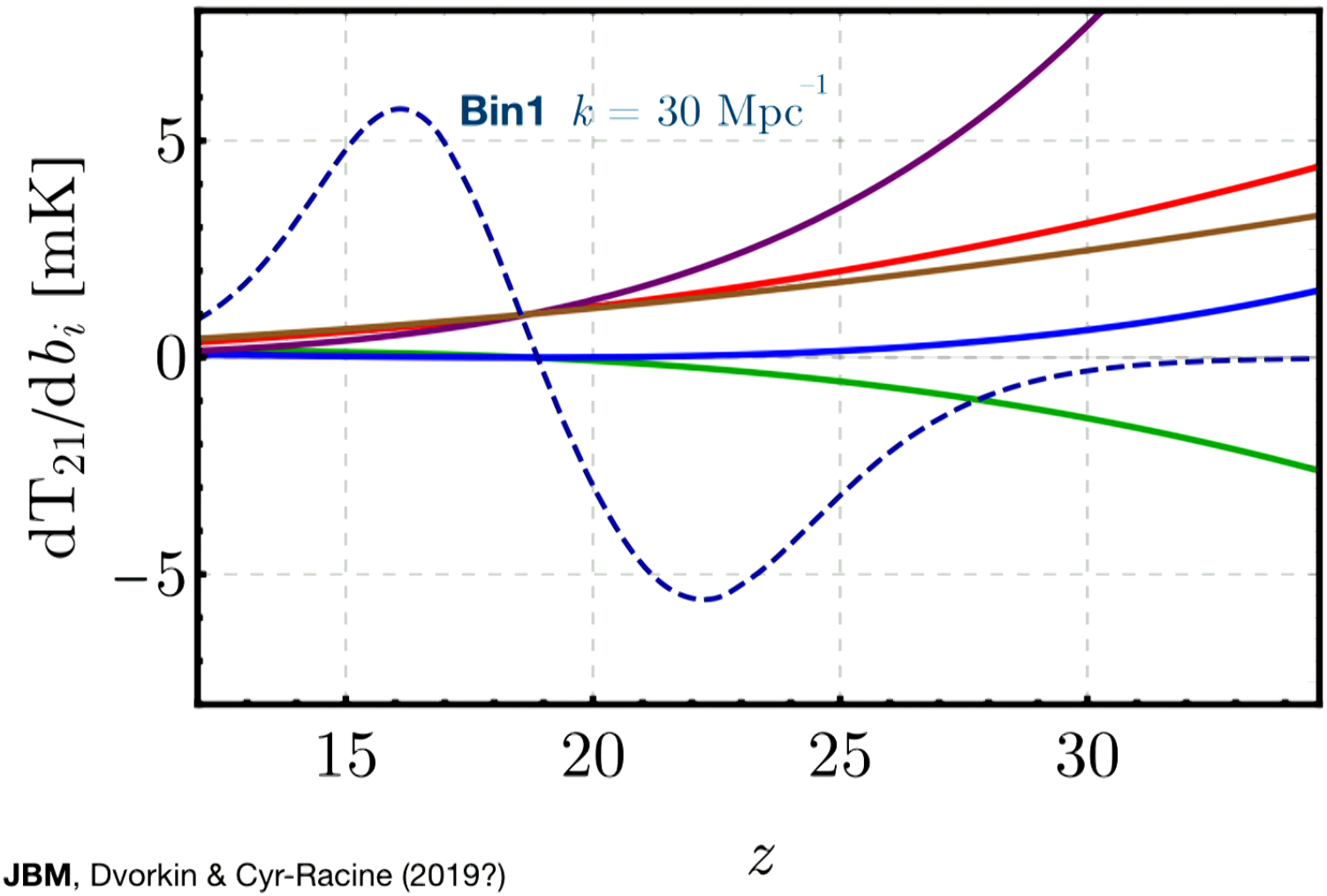
JBM, Dvorkin & Cyr-Racine (2019?)

But astrophysics, though…



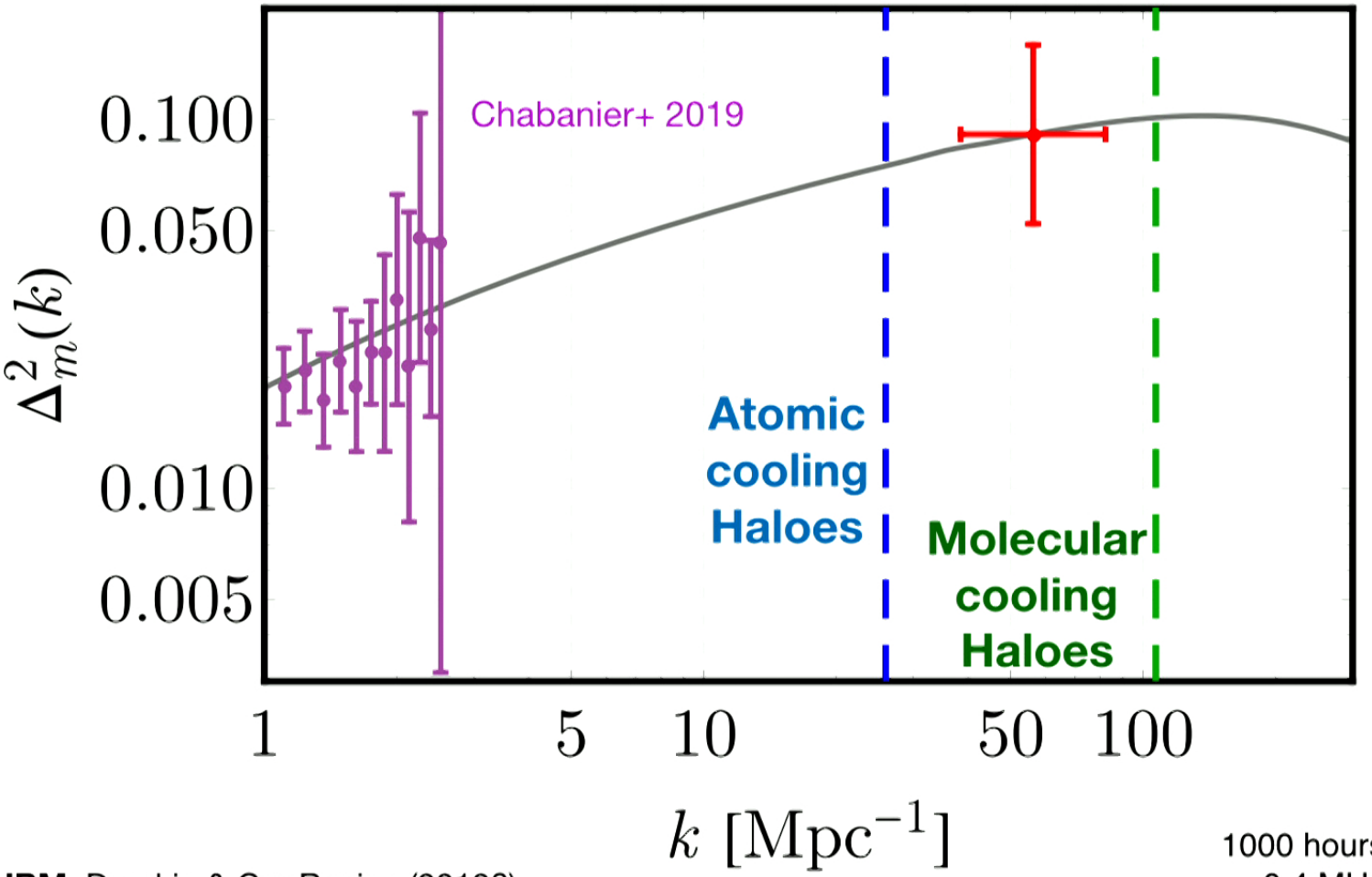
JBM, Dvorkin & Cyr-Racine (2019?)

And foregrounds…



JBM, Dvorkin & Cyr-Racine (2019?)

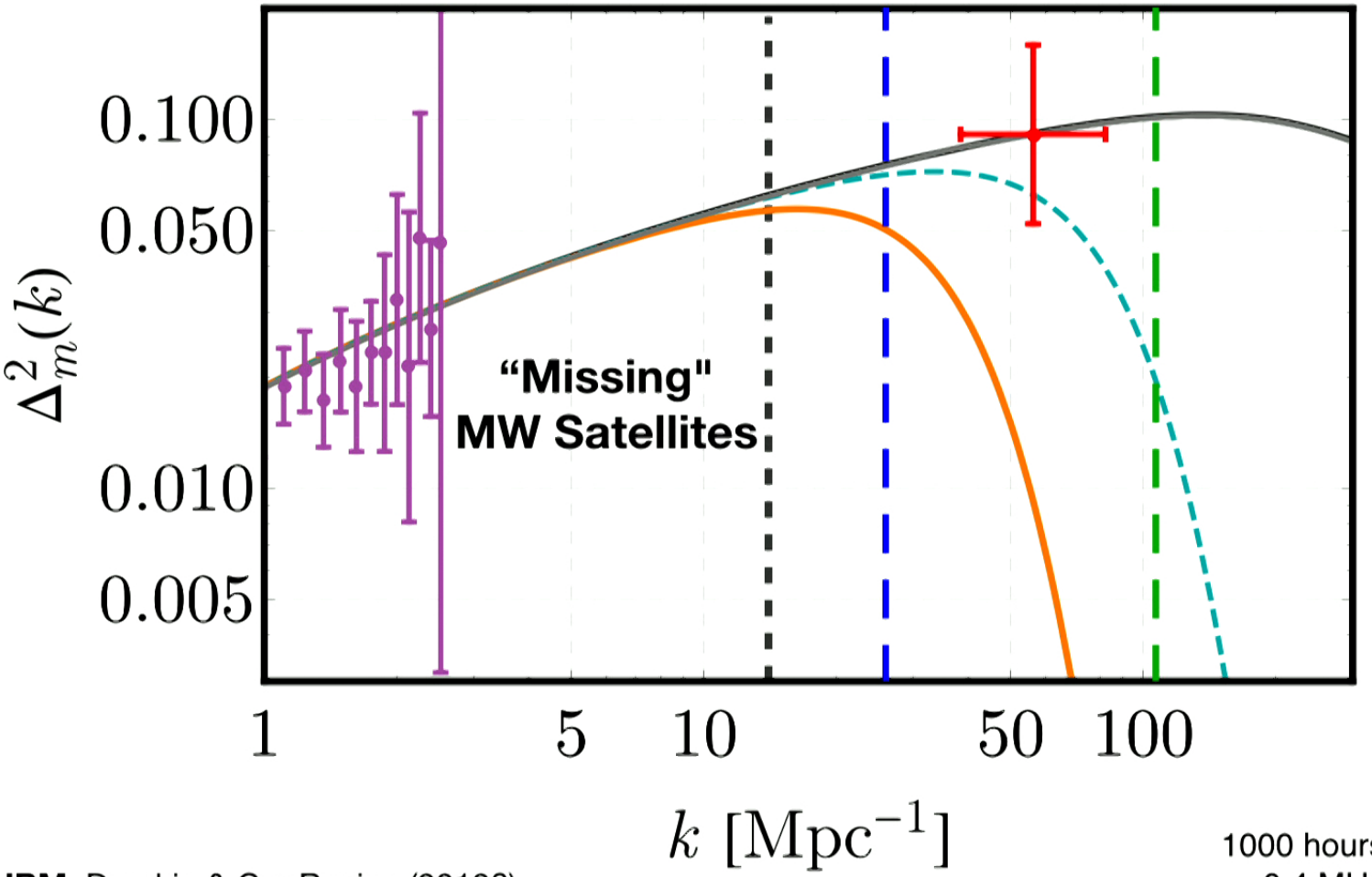
Forecasted errors in matter power



JBM, Dvorkin & Cyr-Racine (2019?)

1000 hours
0.4 MHz

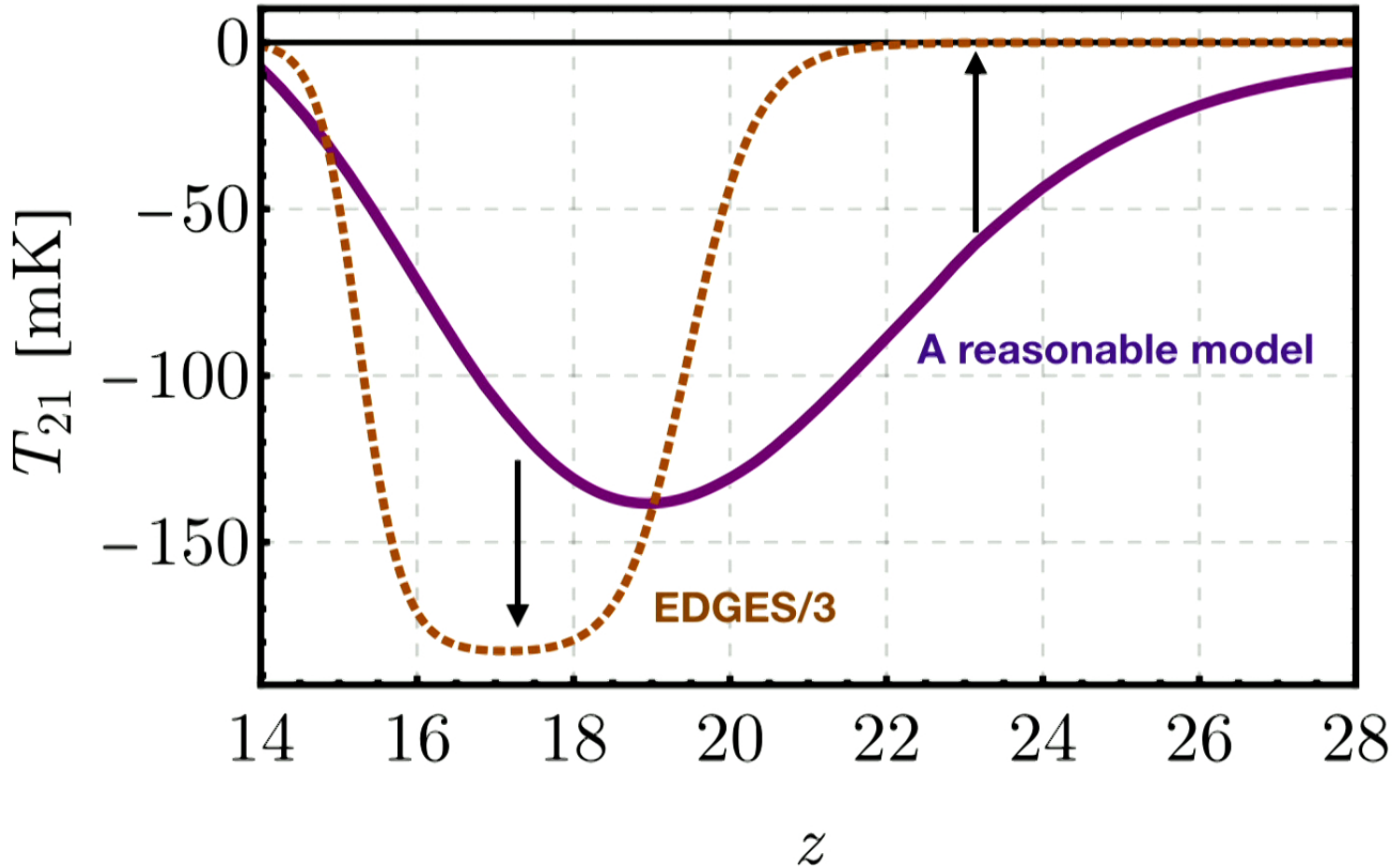
Find out any small-scale problem



JBM, Dvorkin & Cyr-Racine (2019?)

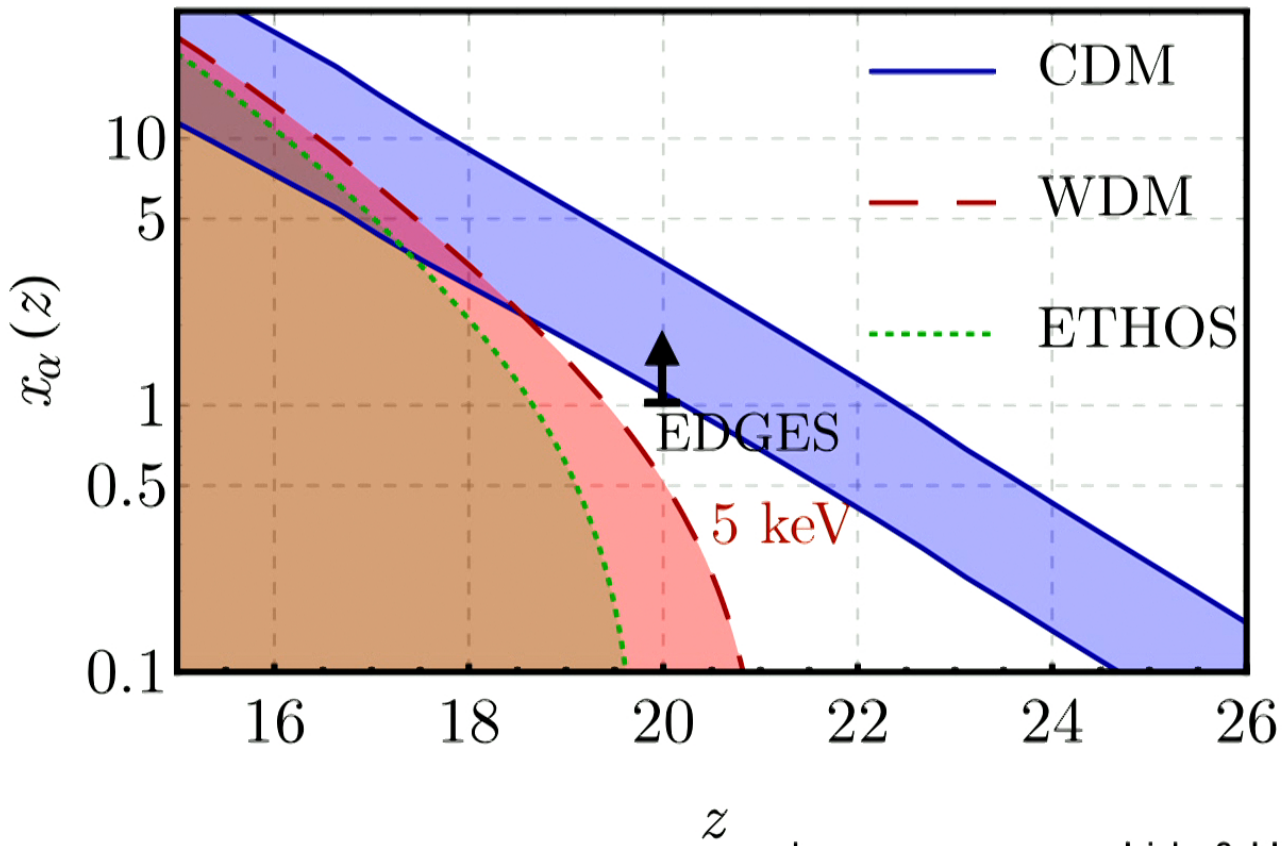
1000 hours
0.4 MHz

But what about EDGES?



Kaurov+ 2018

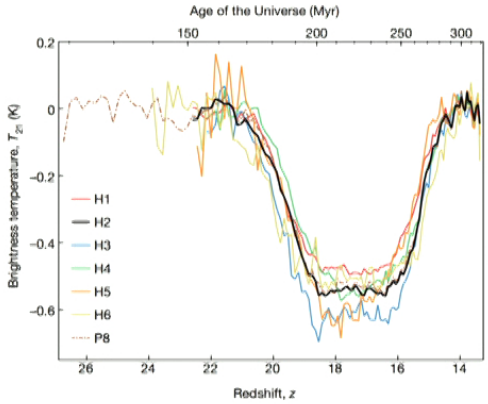
If you just focus on the Ly-A coupling:

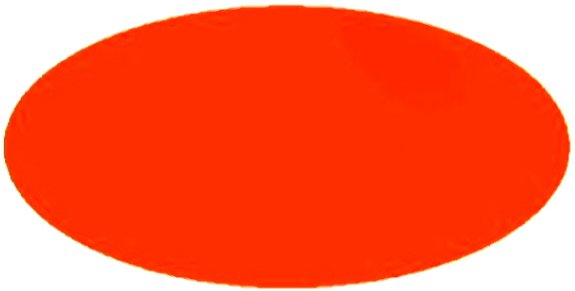


JBM, Dvorkin & Cyr-Racine (2019?)

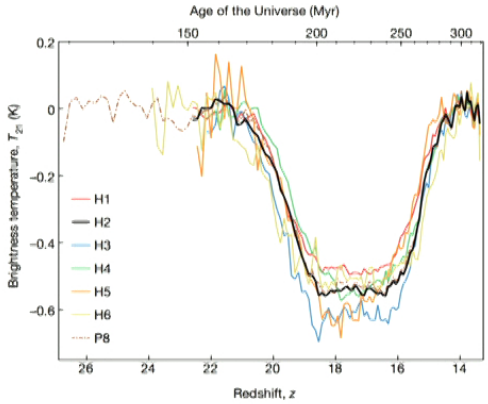
also:
Schneider 2018
Safarzadeh+ 2018
Lidz & Hui 2018
Boyarsky+ 2018
Yoshiura+ 2018

21-cm Global Signal = CMB Monopole

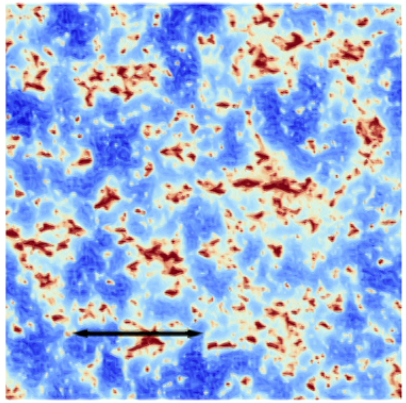




Is this observable?



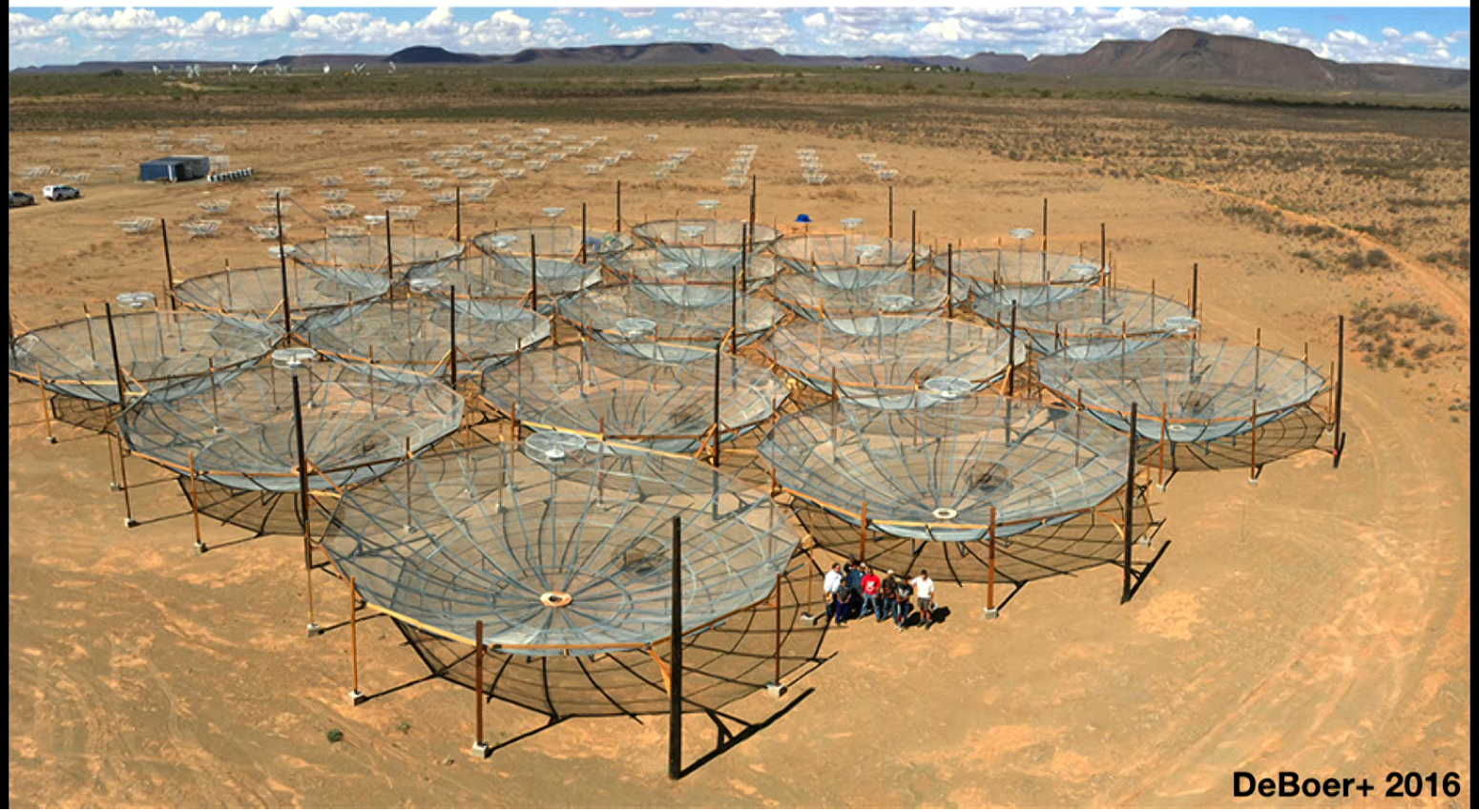
1 antenna
~100 hours



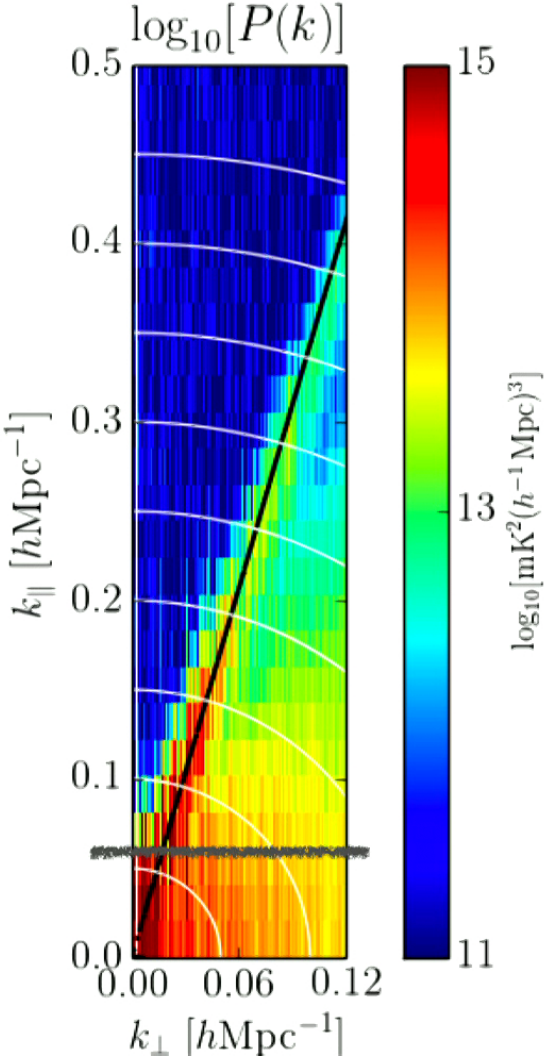
~100 antennae
~1000 hours

Is this observable?

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



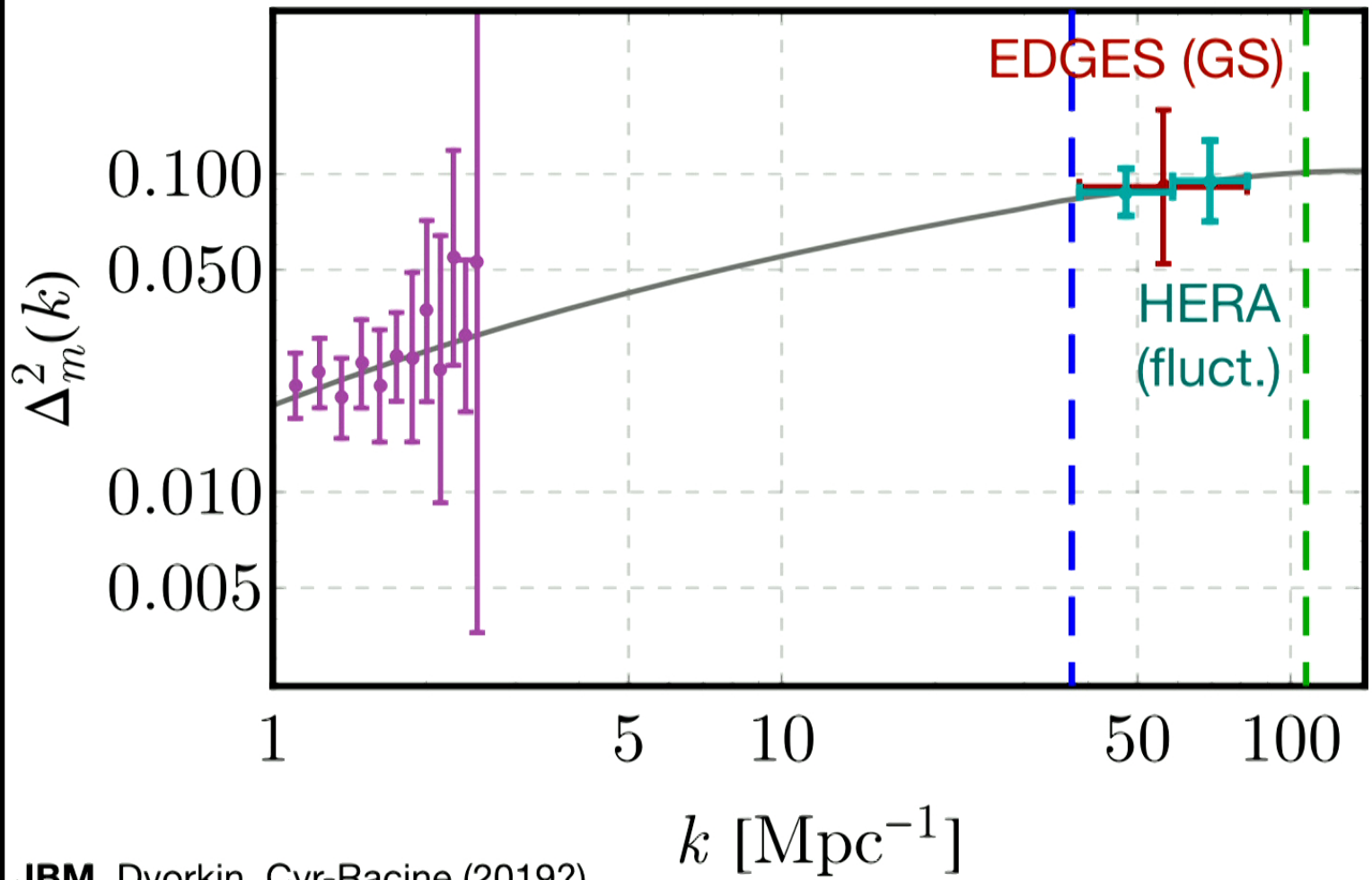
Foreground “wedge”



Foregrounds swamp the signal.
Avoid the “wedge”

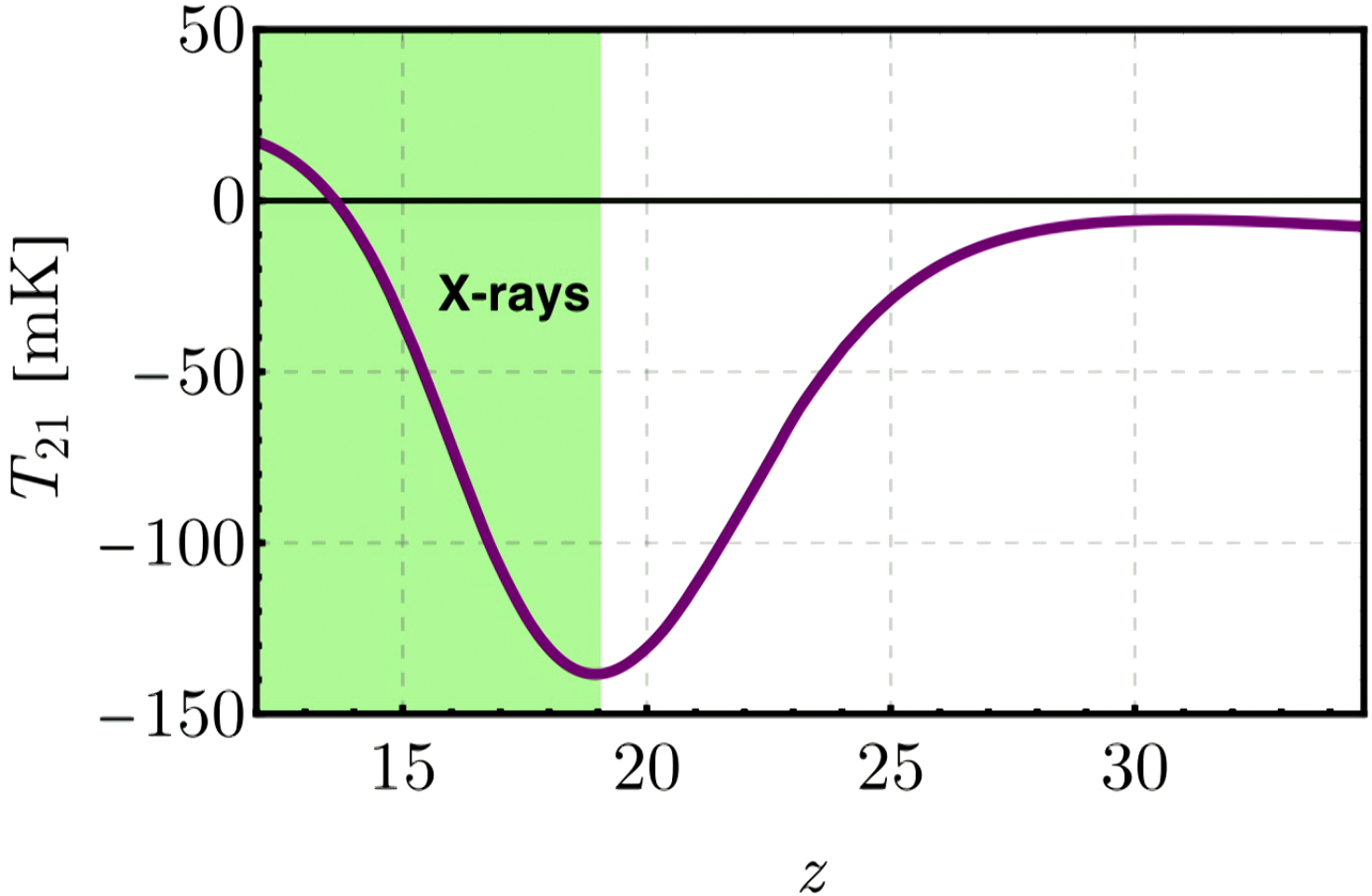
Pober 2014, PAPER Coll.
Parsons+ 2011

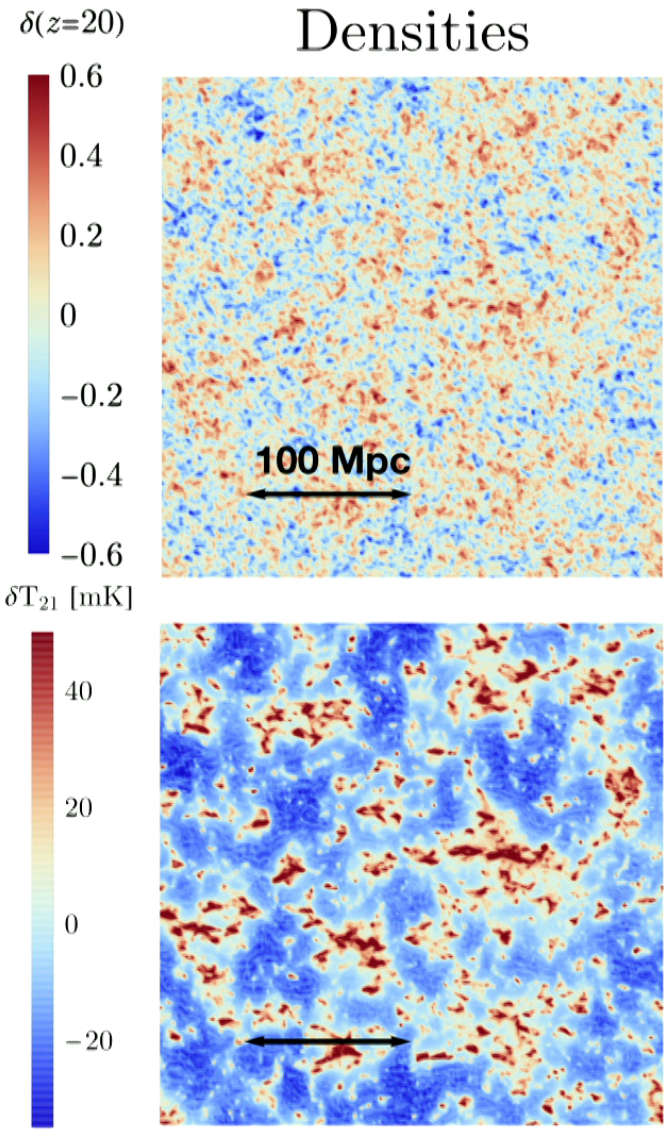
Forecasted errors in matter power



JBM, Dvorkin, Cyr-Racine (2019?)

Where do the fluctuations come from?





With 21cmFAST (Mesinger+ 2010)

Relative velocities: origin

$$\theta_i = \nabla \cdot \mathbf{v}_i$$

$$\dot{\theta}_c = -\mathcal{H}\theta_c + k^2\psi$$

$$\dot{\theta}_b = -\mathcal{H}\theta_b + k^2\psi + c_s^2 k^2 \delta_b + \boxed{\Gamma_c(\theta_\gamma - \theta_b)}$$

Sound speed

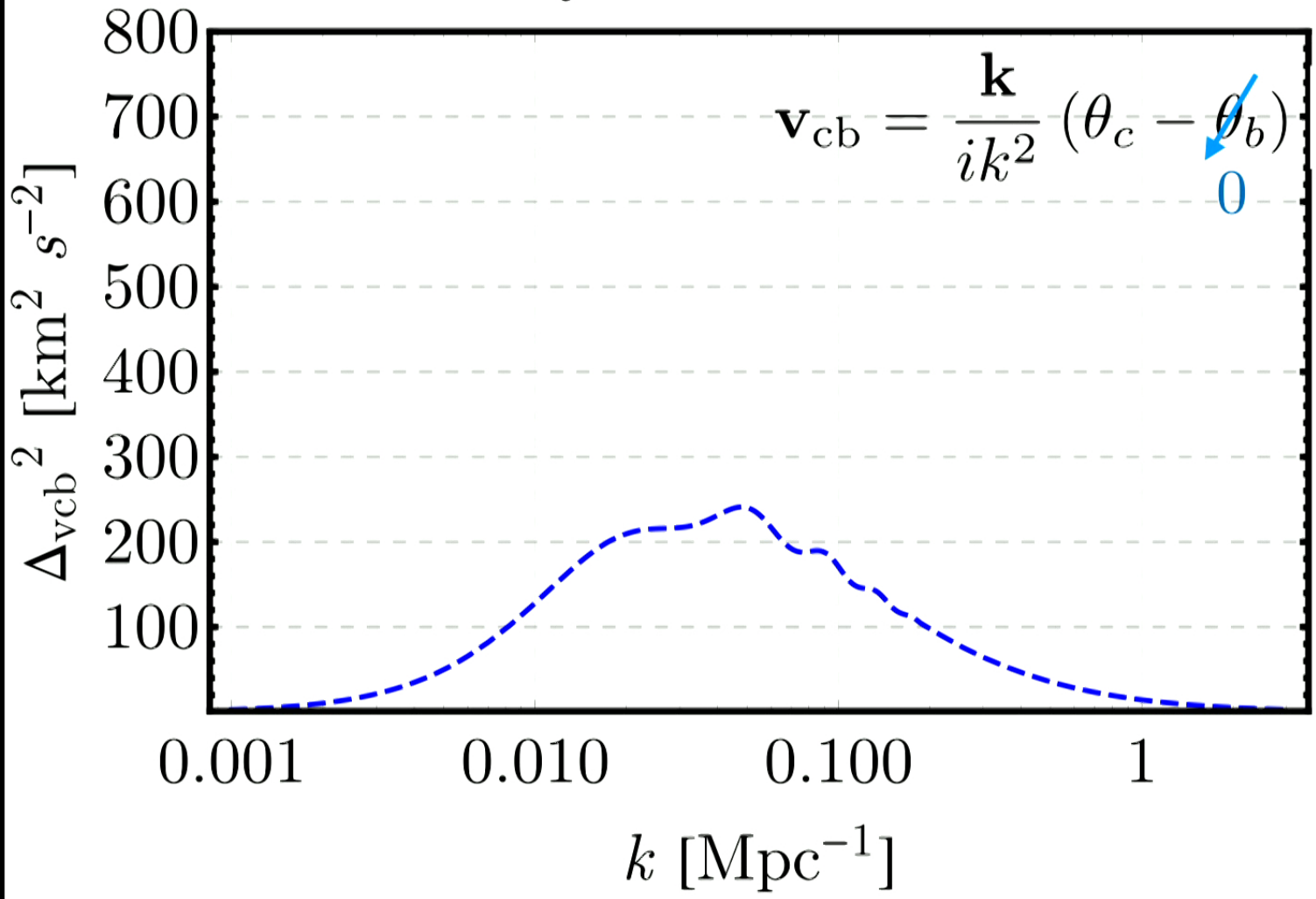
Coupling to photons

Ma and Bertschinger 1995

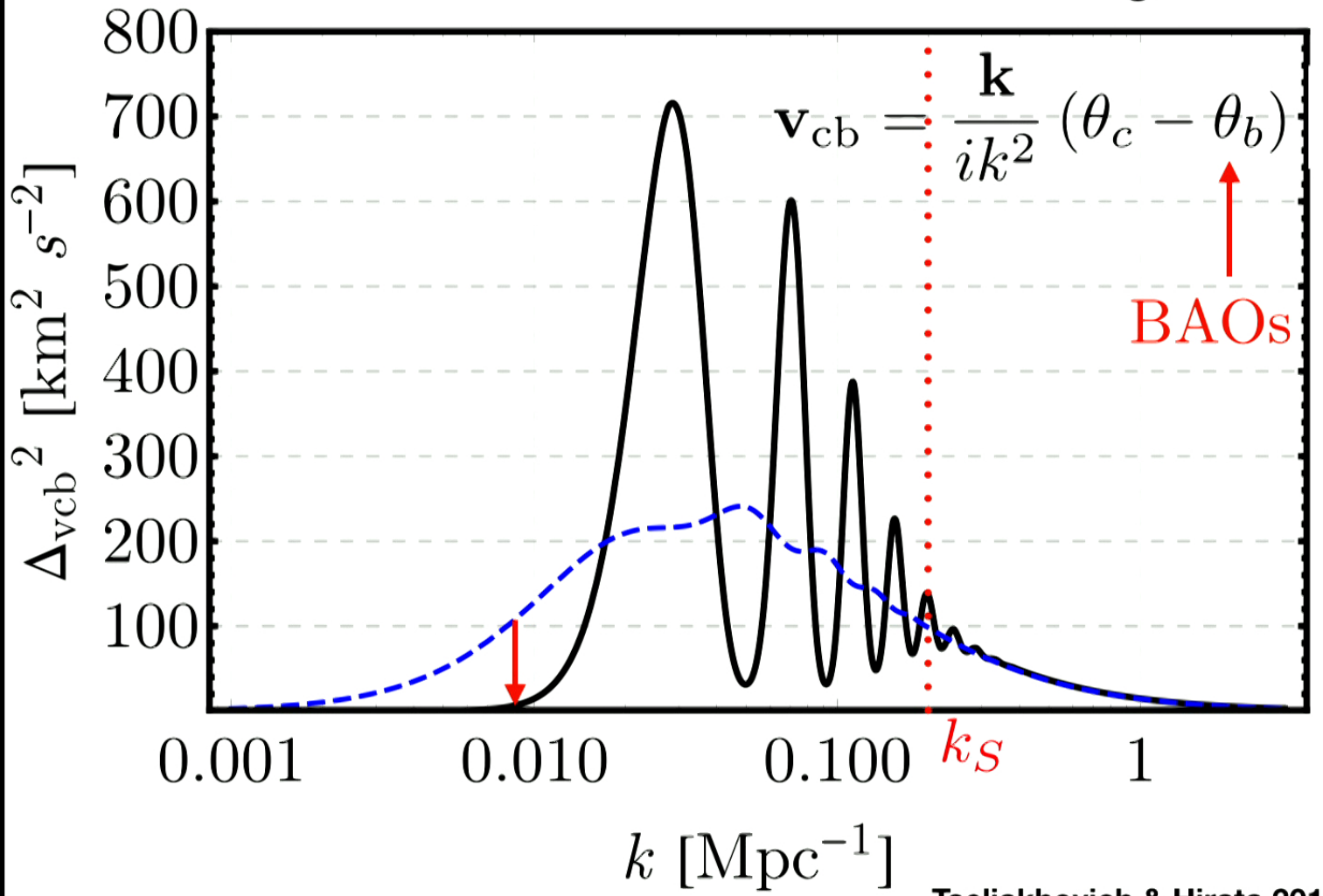
We can define a **relative** velocity

$$\mathbf{v}_{\mathrm{cb}} = \frac{\mathbf{k}}{ik^2}\left(\theta_c - \theta_b\right)$$

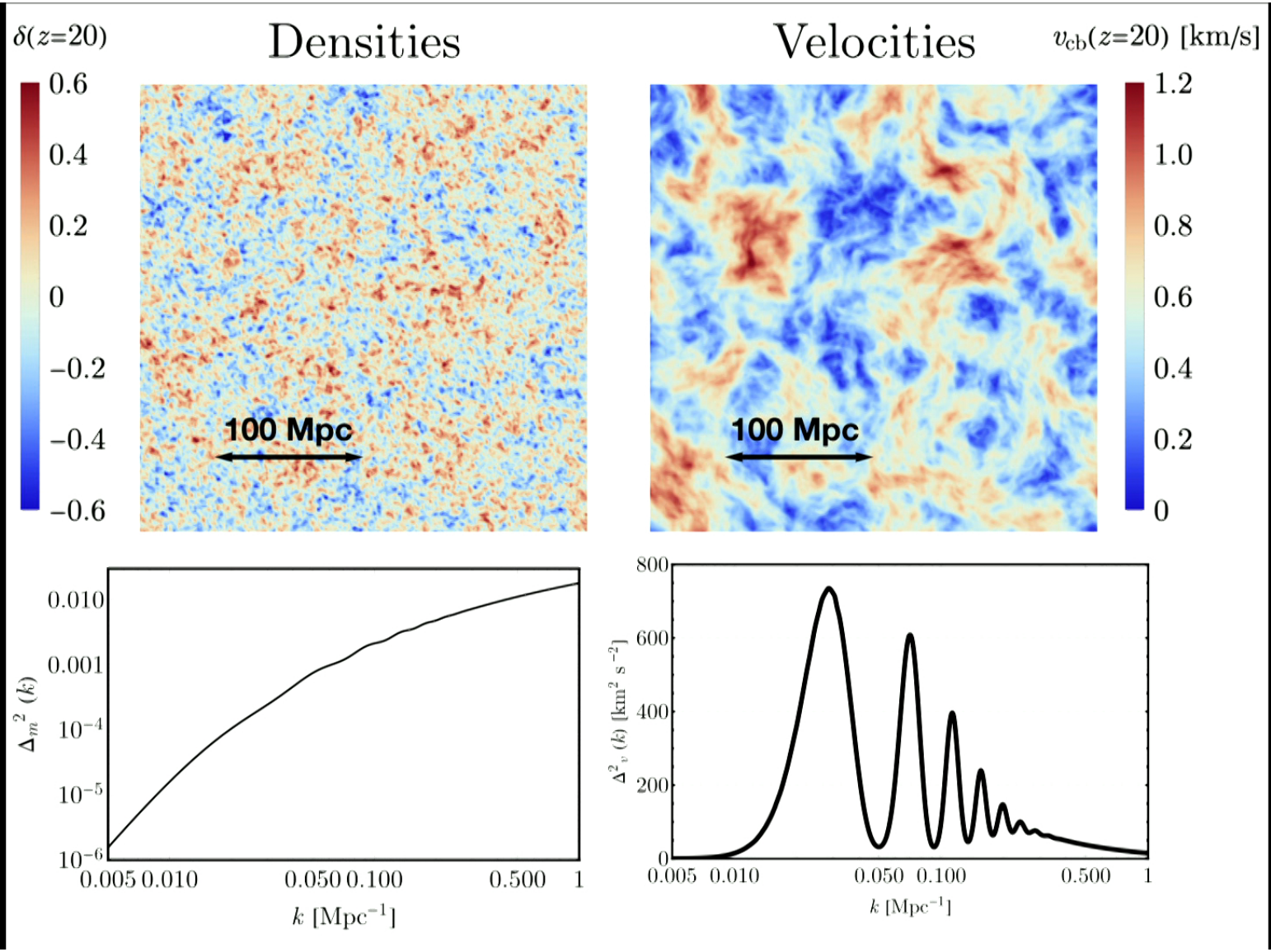
What if baryons did not fluctuate



Relative velocities: acoustic origin



Tseliakhovich & Hirata 2010


Densities
Velocities
$\delta(z{=}20)$
$v_{\rm cb}(z{=}20)$ [km/s]
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
1.2
1.0
0.8
0.6
0.4
0.2
0
100 Mpc
100 Mpc
$\Delta_m^2(k)$
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0.005 0.010 0.050 0.100 0.500 1
k [Mpc^{-1}]
$\Delta^2_v(k)$ [km^2 s^{-2}]
800
600
400
200
0
0.005 0.010 0.050 0.100 0.500 1
k [Mpc^{-1}]

Supersonic nature of v_{cb}

$$\dot{\theta}_c = -\mathcal{H}\theta_c + k^2\psi$$

$$\dot{\theta}_b = -\mathcal{H}\theta_b + k^2\psi + \boxed{c_s^2 k^2 \delta_b} + \Gamma_c(\theta_\gamma - \theta_b)$$

$$c_s = \sqrt{\frac{T_b}{m_b}} \approx 6\,\mathrm{km/s}$$

Whereas the **relative** velocity:

$$v_{\mathrm{cb}} \approx 30\,\mathrm{km/s}$$

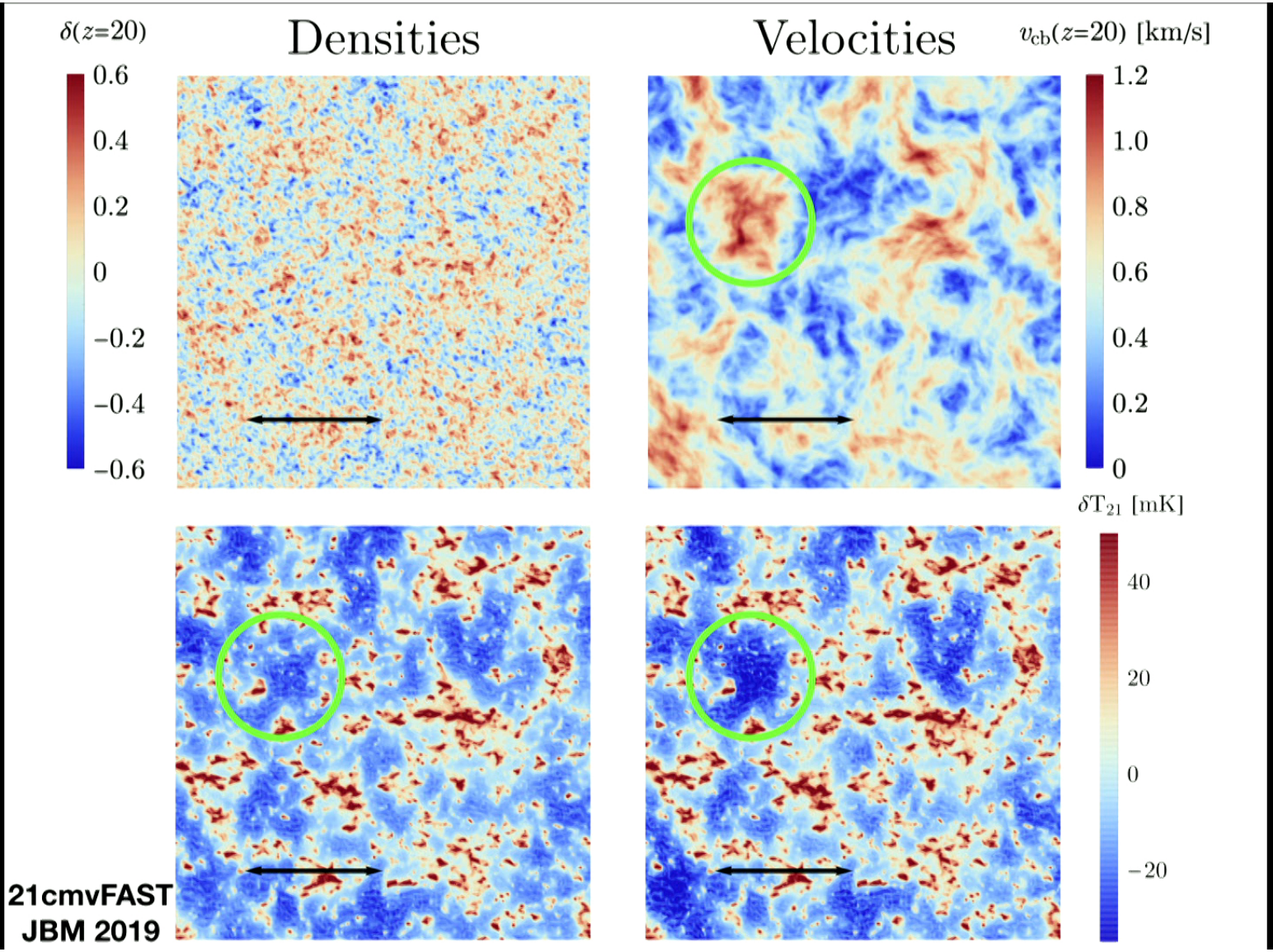
Supersonic nature of v_{cb}

Sound Speed $\longrightarrow$ **Jeans Scale**

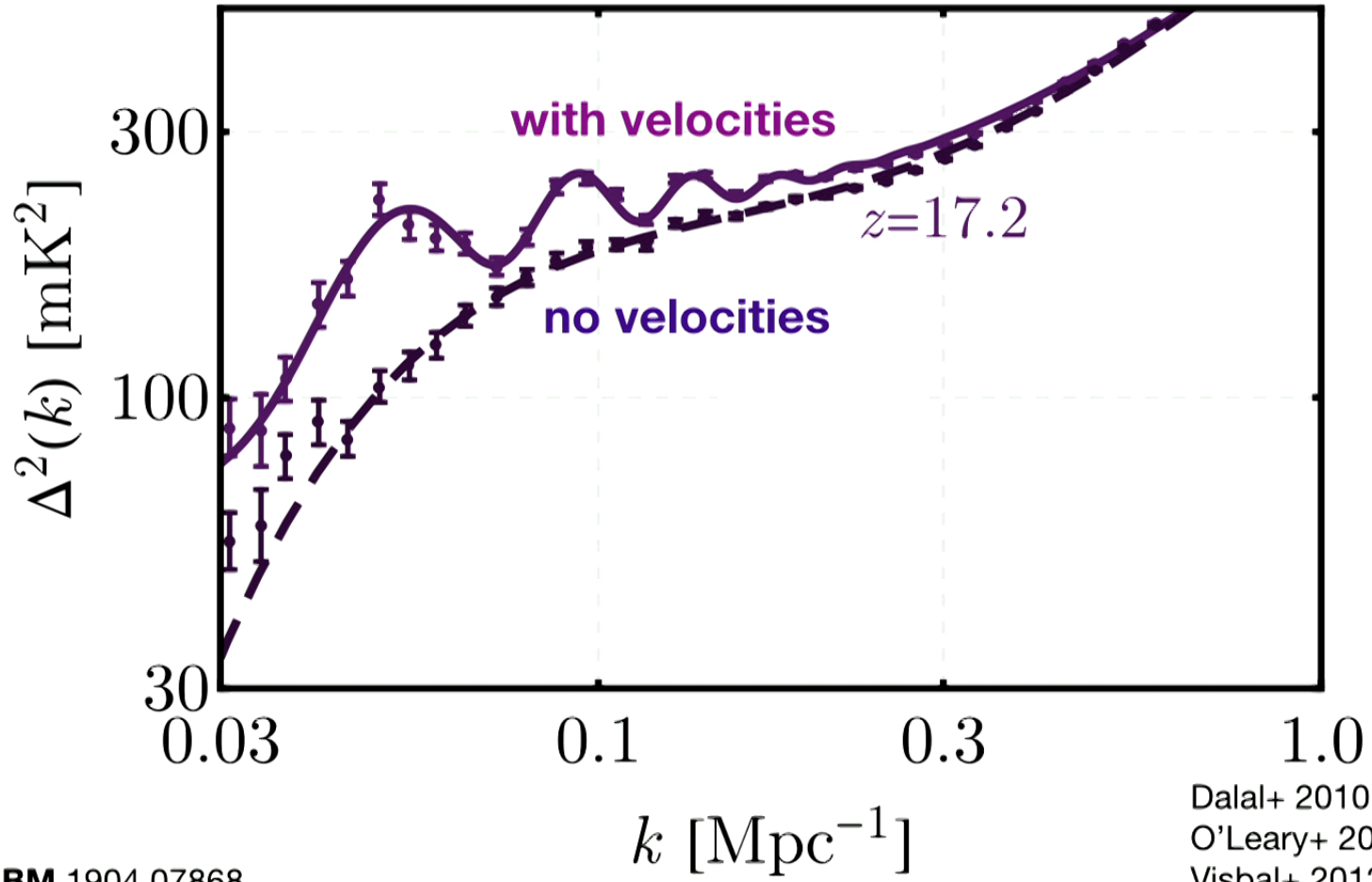
$$c_s = \sqrt{\frac{T_b}{m_b}} \approx 6\,\mathrm{km/s} \longrightarrow k_J \sim 500\,\mathrm{Mpc}^{-1}$$

Whereas the **relative** velocity:

$$v_{\mathrm{cb}} \approx 30\,\mathrm{km/s} \longrightarrow k_{\mathrm{cb}} \sim 100\,\mathrm{Mpc}^{-1}$$


δ(z=20)
Densities
Velocities
v_cb(z=20) [km/s]
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
1.2
1.0
0.8
0.6
0.4
0.2
0
δT_21 [mK]
40
20
0
−20
21cmvFAST
JBM 2019

Velocity-induced Acoustic Oscillations

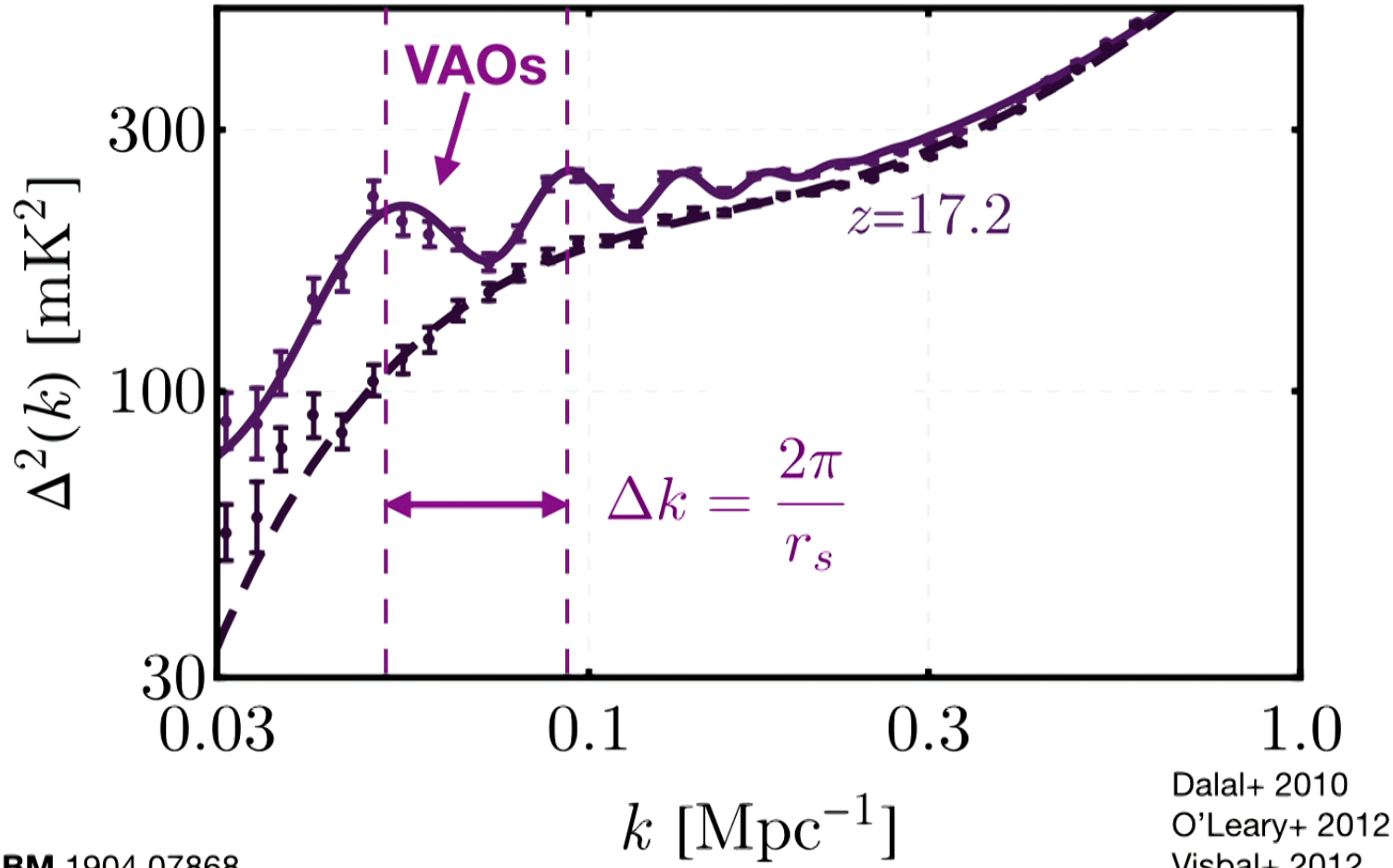


JBM 1904.07868
1904.07881

Code available at: https://github.com/JulianBMunoz/21cmvFAST

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

Velocity-induced Acoustic Oscillations



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JBM 1904.07868
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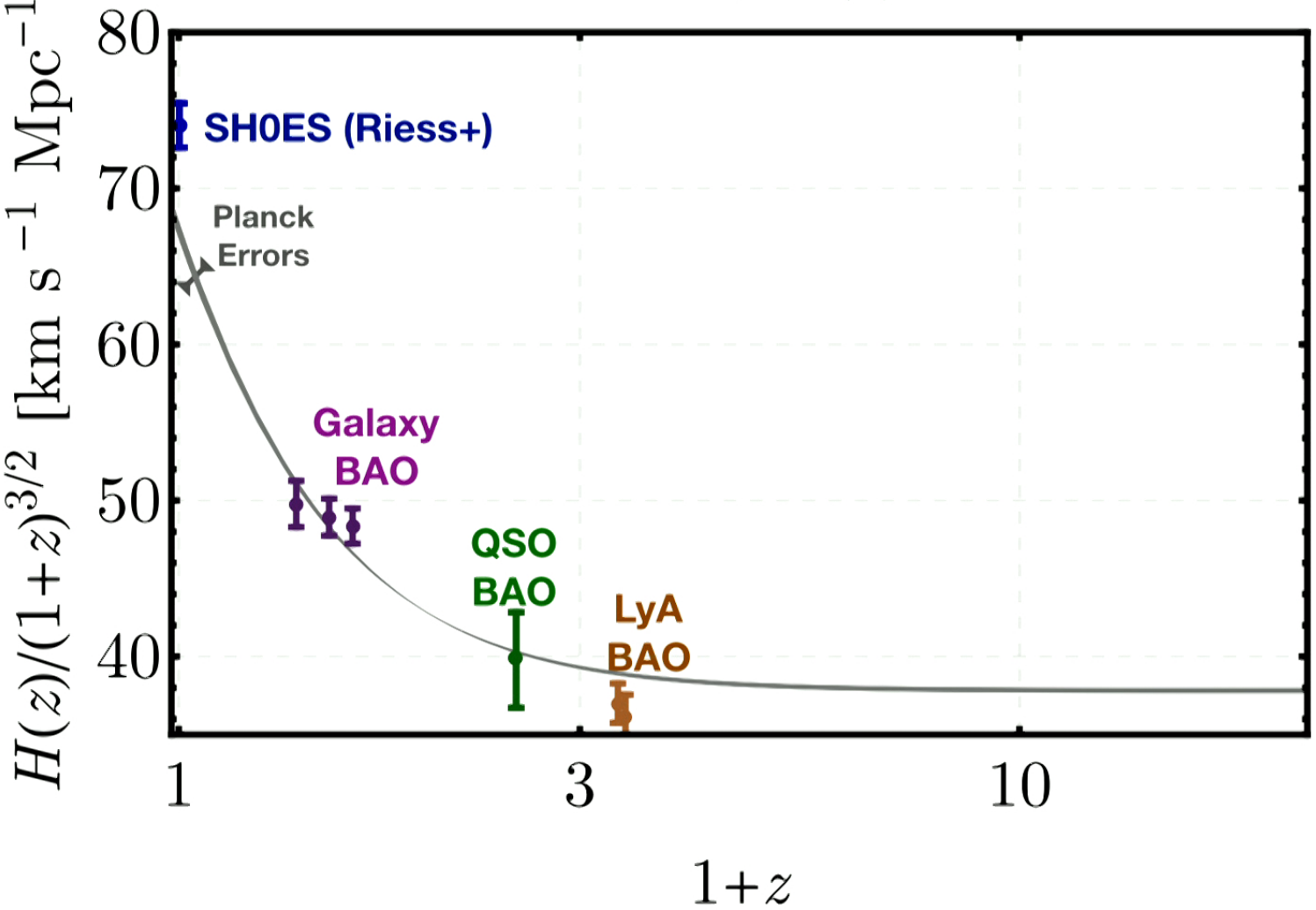
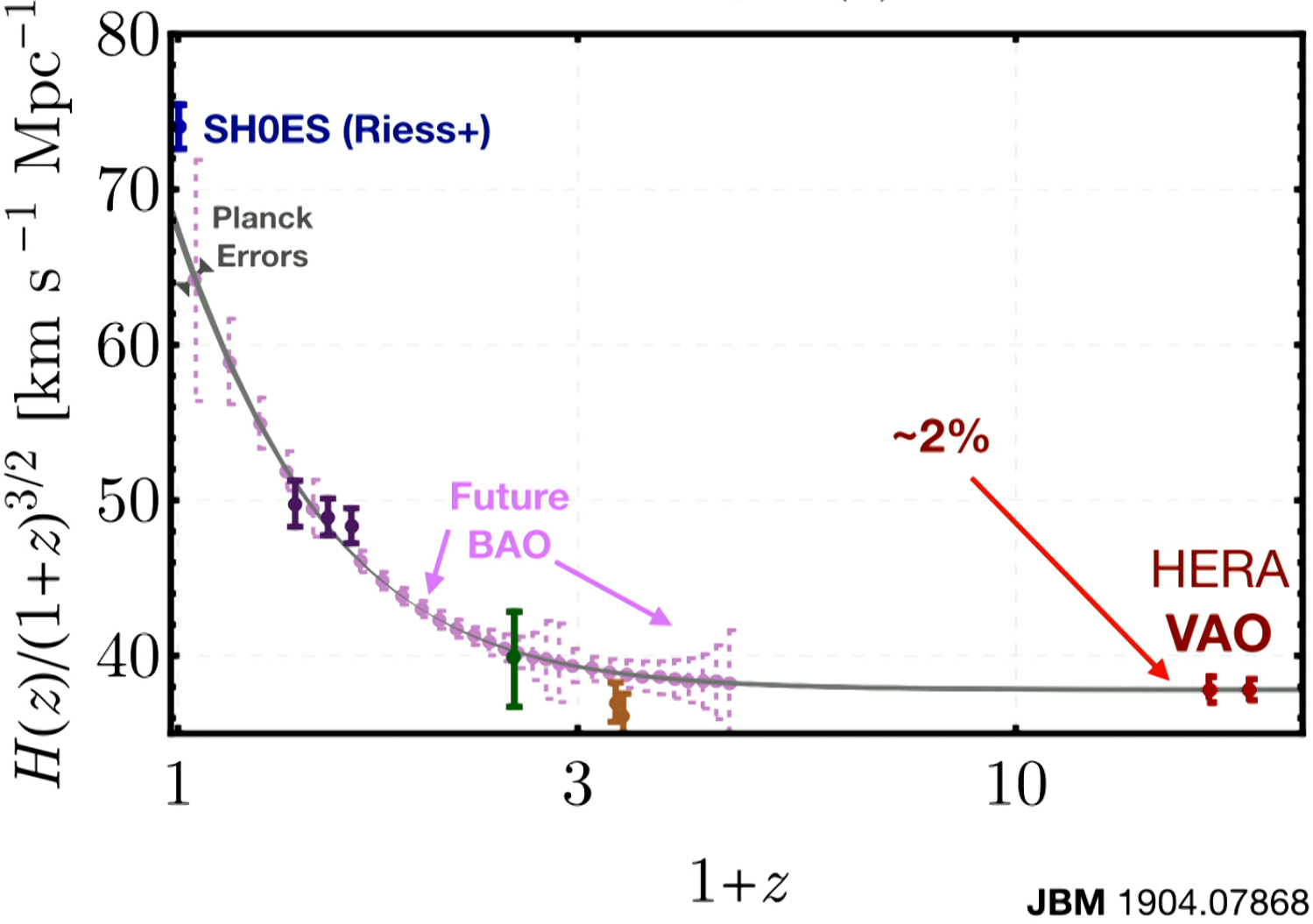
Measuring $H(z)$



Measuring $H(z)$

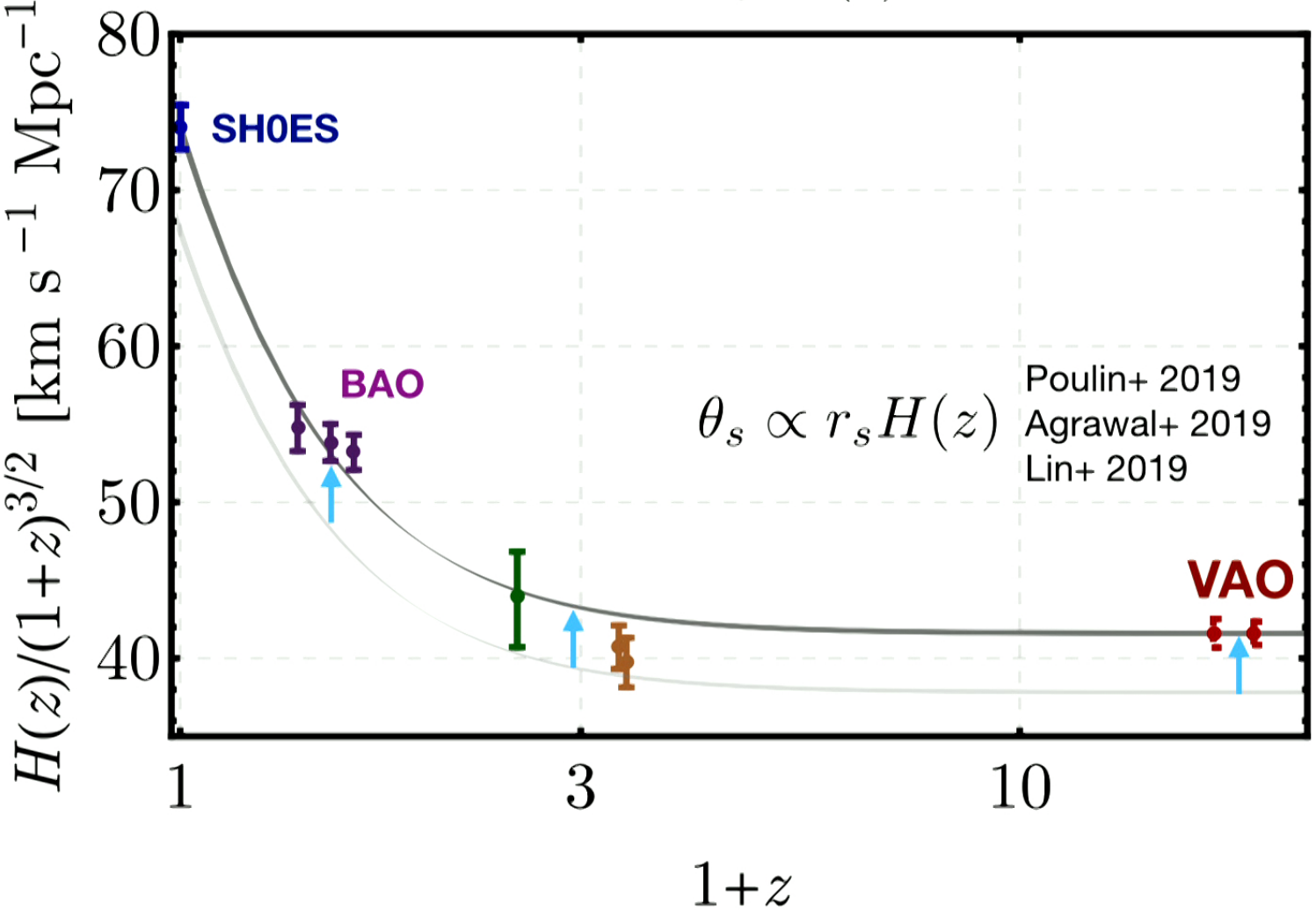


JBM 1904.07868

Applications

- BSM cosmology (e.g., EDE, decaying DM…)
- It's unexplored territory!
- H_0 tension

Measuring $H(z)$



Applications

- BSM cosmology (e.g., EDE, decaying DM, Mnu…)
- It's unexplored territory!
- H_0 tension

Caveats

- Astrophysics is hard…
- However, **no astrophysics can mimic the VAOs**

Summary

EDGES*