Theory of 21-cm cosmology from the dark ages

Rennan Barkana

רנן ברקנא

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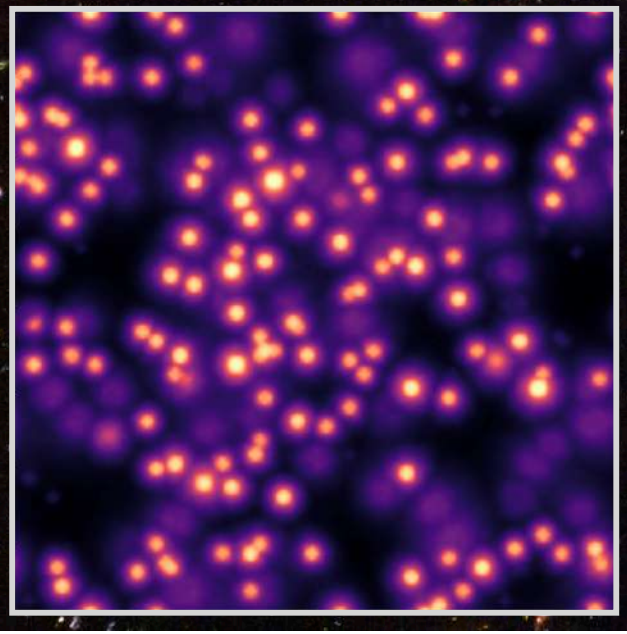
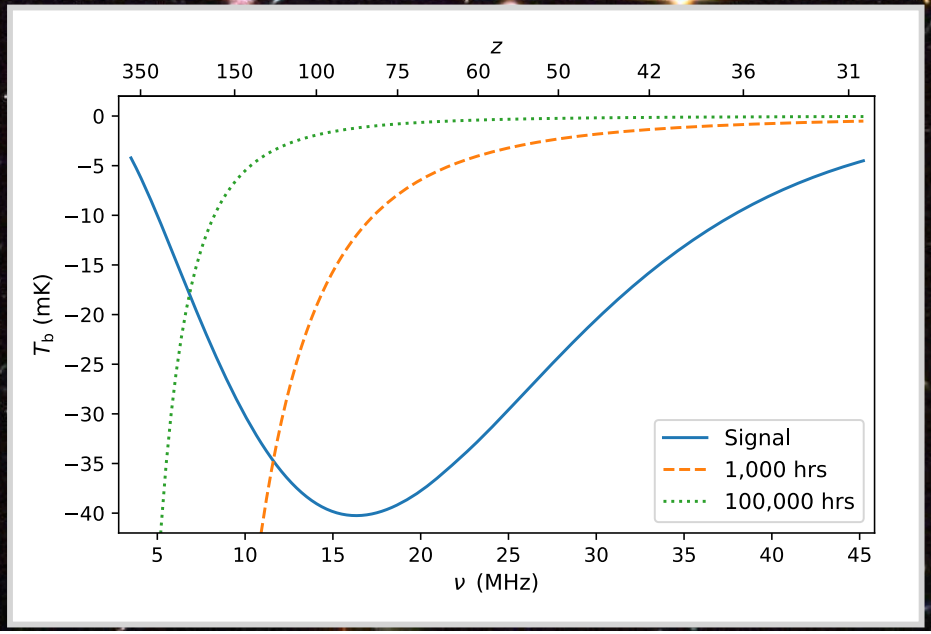
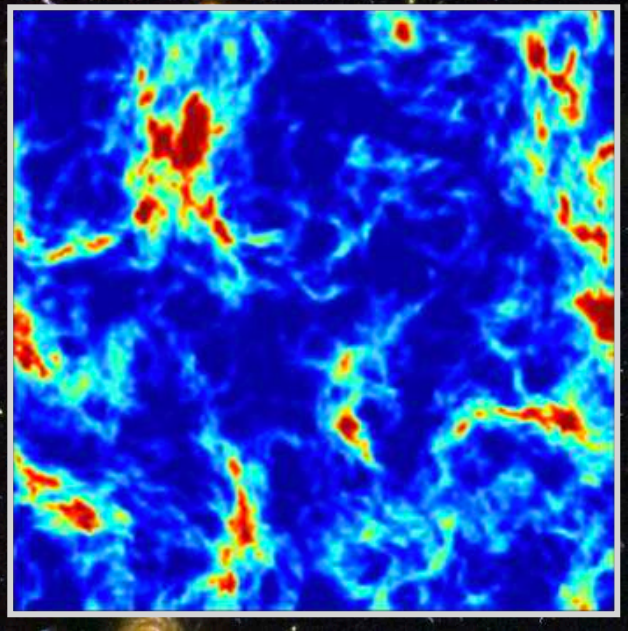
אוניברסיטת תל-אביב







Early History

Reionization:

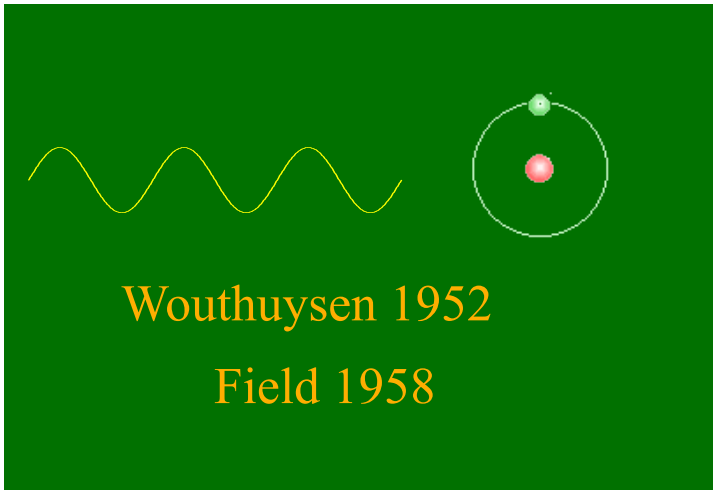
Gunn & Peterson 1965

21-cm Cosmology:

Hogan & Rees 1979: Basic ideas (ρ, T, T_s)
Scott & Rees 1990: CDM + reionization

Madau, Meiksin & Rees 1997: Cosmic Dawn (Ly-α and heating)

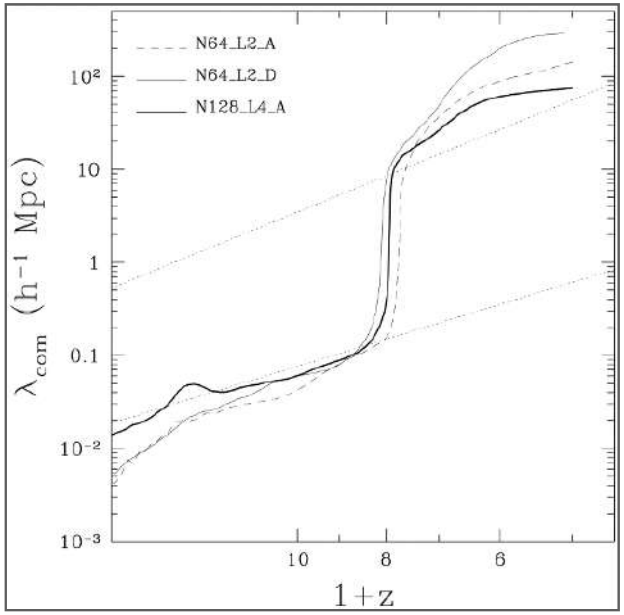
Observational prospects:
Shaver, Windhorst, Madau, de Bruyn 1999
Tozzi, Madau, Meiksin & Rees 2000



Early History

Reionization:

Gnedin 2000
6 Mpc



Santos, Cooray, Haiman, Knox & Ma 2003: CMB & reionization (kSZ): Reionization patch R = 0.1 Mpc

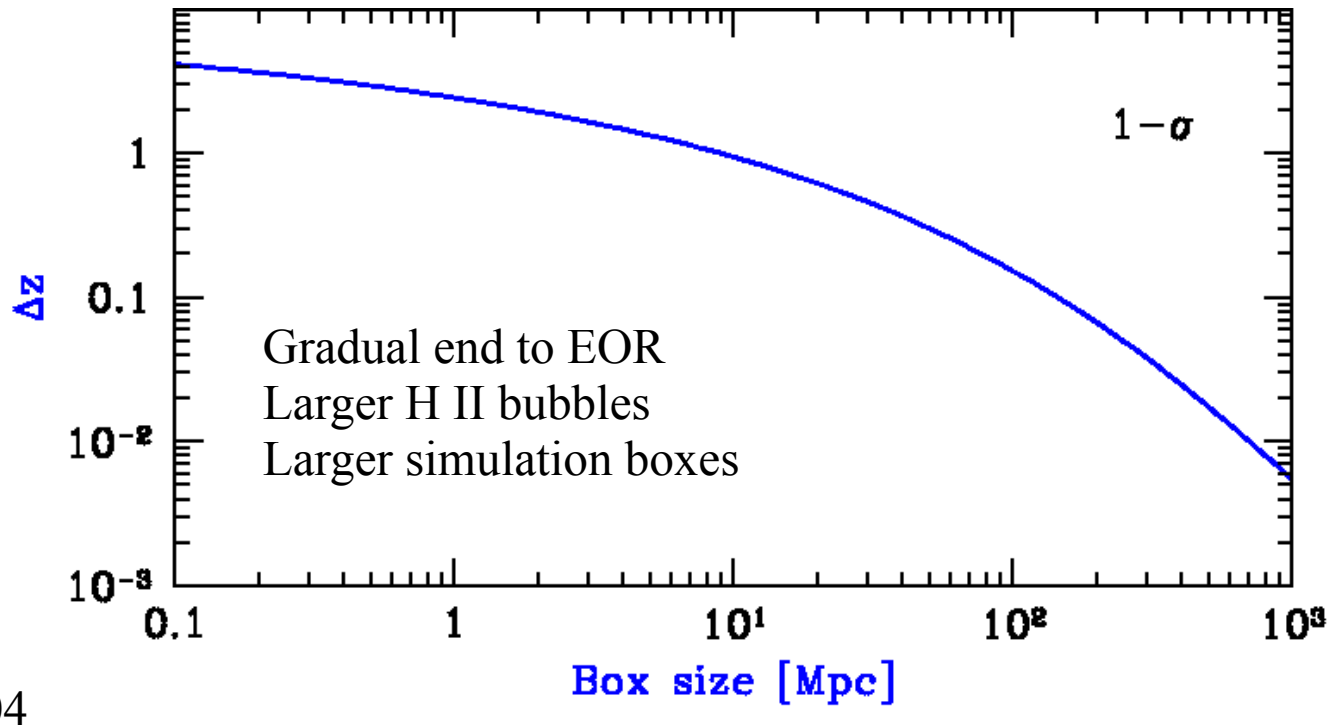
Miralda-Escudé, Haehnelt, & Rees 2000: "In an inhomogeneous universe reionization occurs outside-in, starting in voids and gradually penetrating into overdense regions."

Ciardi, Stoehr, & White 2003: 30 Mpc, field vs. proto-cluster

Early History

Reionization:

Barkana & Loeb 2004: "the recombination rate is higher in overdense regions… these regions still reionize first … since the number of ionizing sources is increased even more strongly"



Furlanetto, Zaldarriaga, Hernquist 2004
Size distribution of H II bubbles

Early History

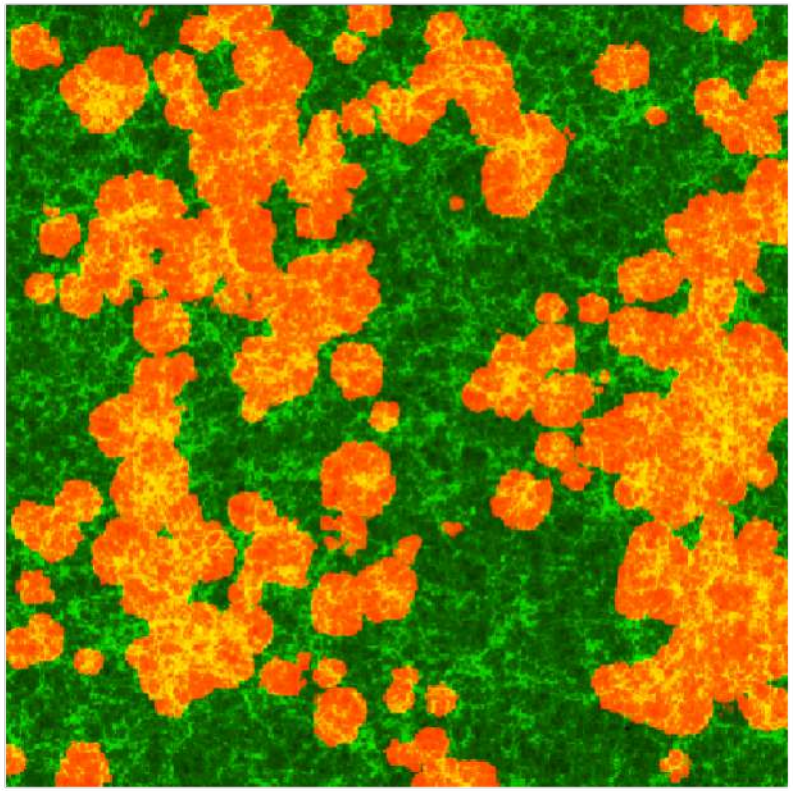
Reionization:

Iliev, Mellema, Pen, Merz, Shapiro, Alvarez 2006

Mellema, Iliev, Pen, Shapiro 2006

Zahn, Lidz, McQuinn, Dutta, Hernquist, Zaldarriaga, Furlanetto 2007

Santos, Amblard, Pritchard, Trac, Cen, Cooray 2008



Early History

Cosmic Dawn?

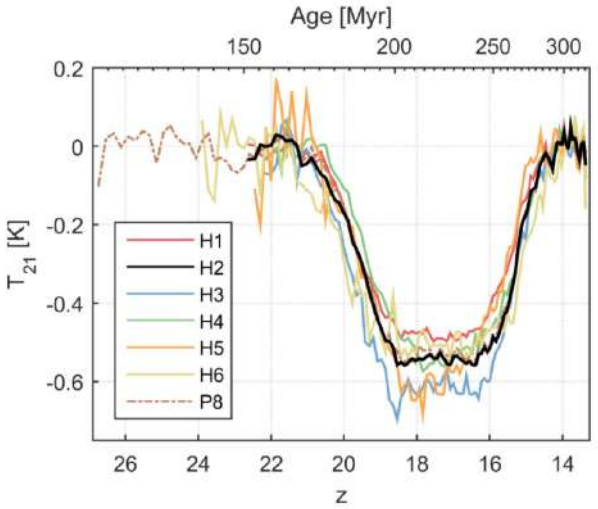
Barkana & Loeb 2005:
Ly-α fluctuations: z~20-30

Semi-Analytical!

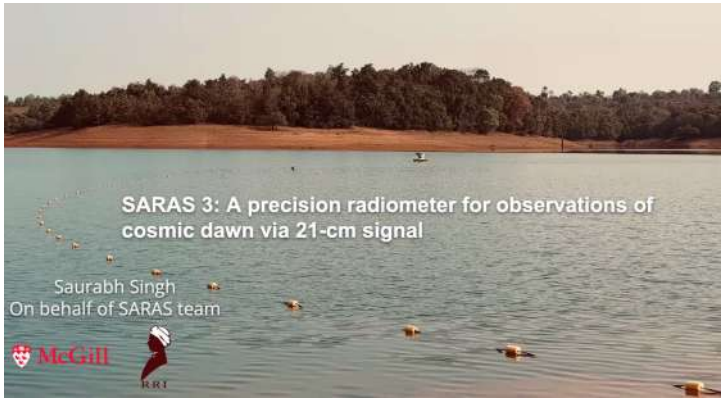
Pritchard & Furlanetto 2007:
Temperature fluctuations
(X-ray heating)

Global 21-cm

EDGES 2018



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018

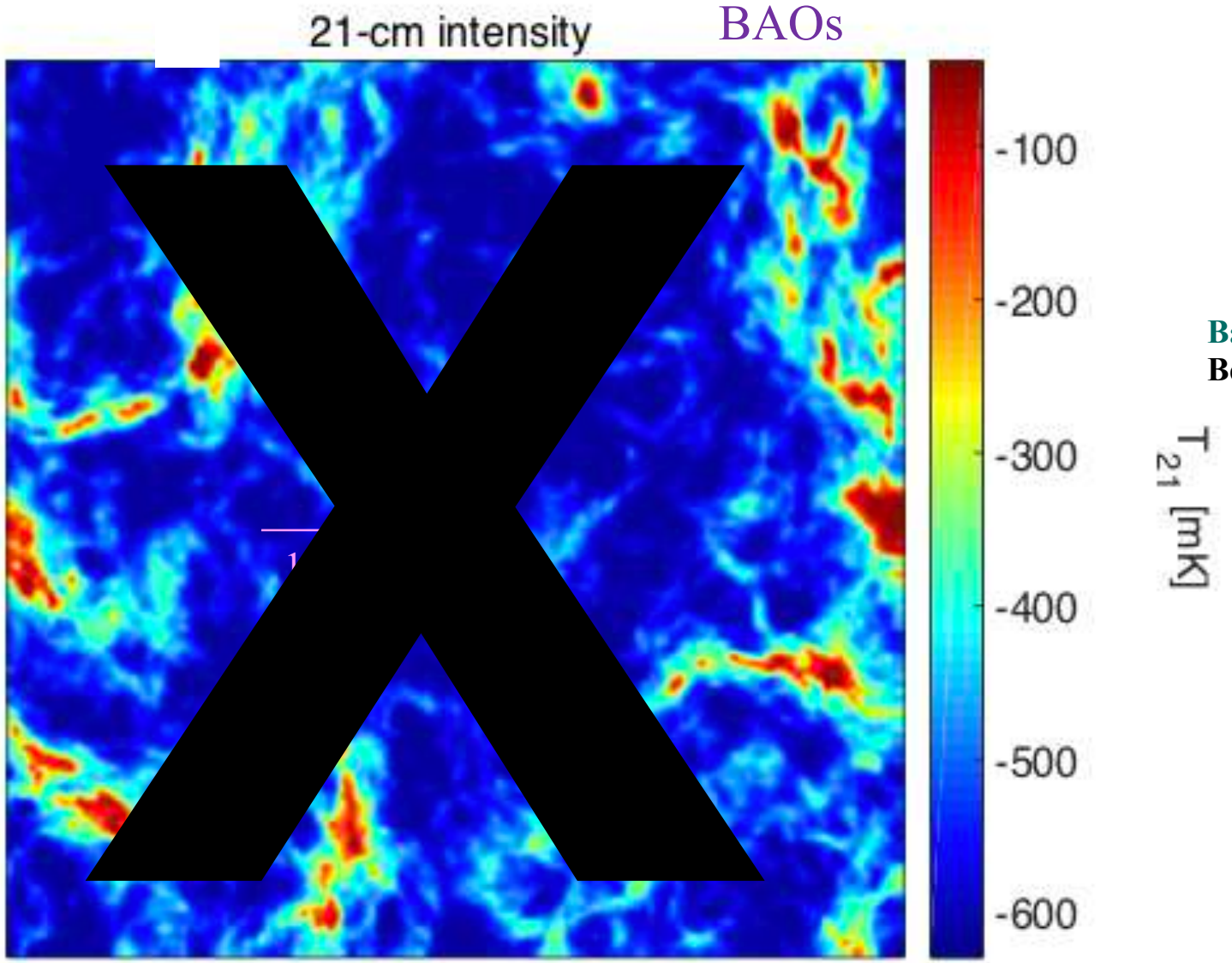


Singh, Nambissan, Subrahmanyan, et al. 2022

$$T_{21} \propto \frac{T_S - T_{\mathrm{CMB}}}{T_S}$$

Lyα coupling +
Cool the gas by scattering with DM

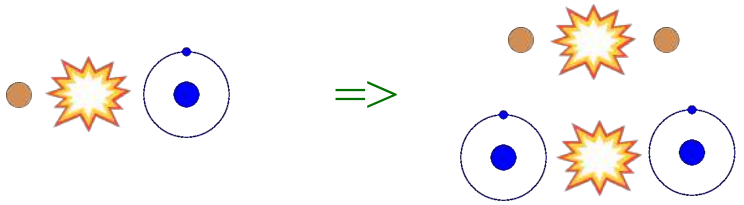
Barkana, Nature 2018



BAOs

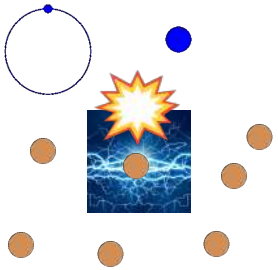
Barkana, Nature 2018

Particle physics models



Barkana, Outmezguine, Redigolo, Volansky 2018
Berlin, Hooper, Krnjaic, McDermott 2018

Millicharged DM

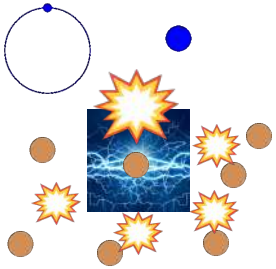


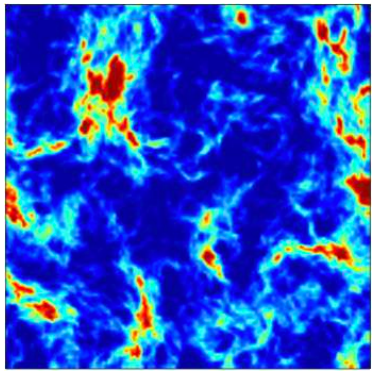
Muñoz & Loeb 2018

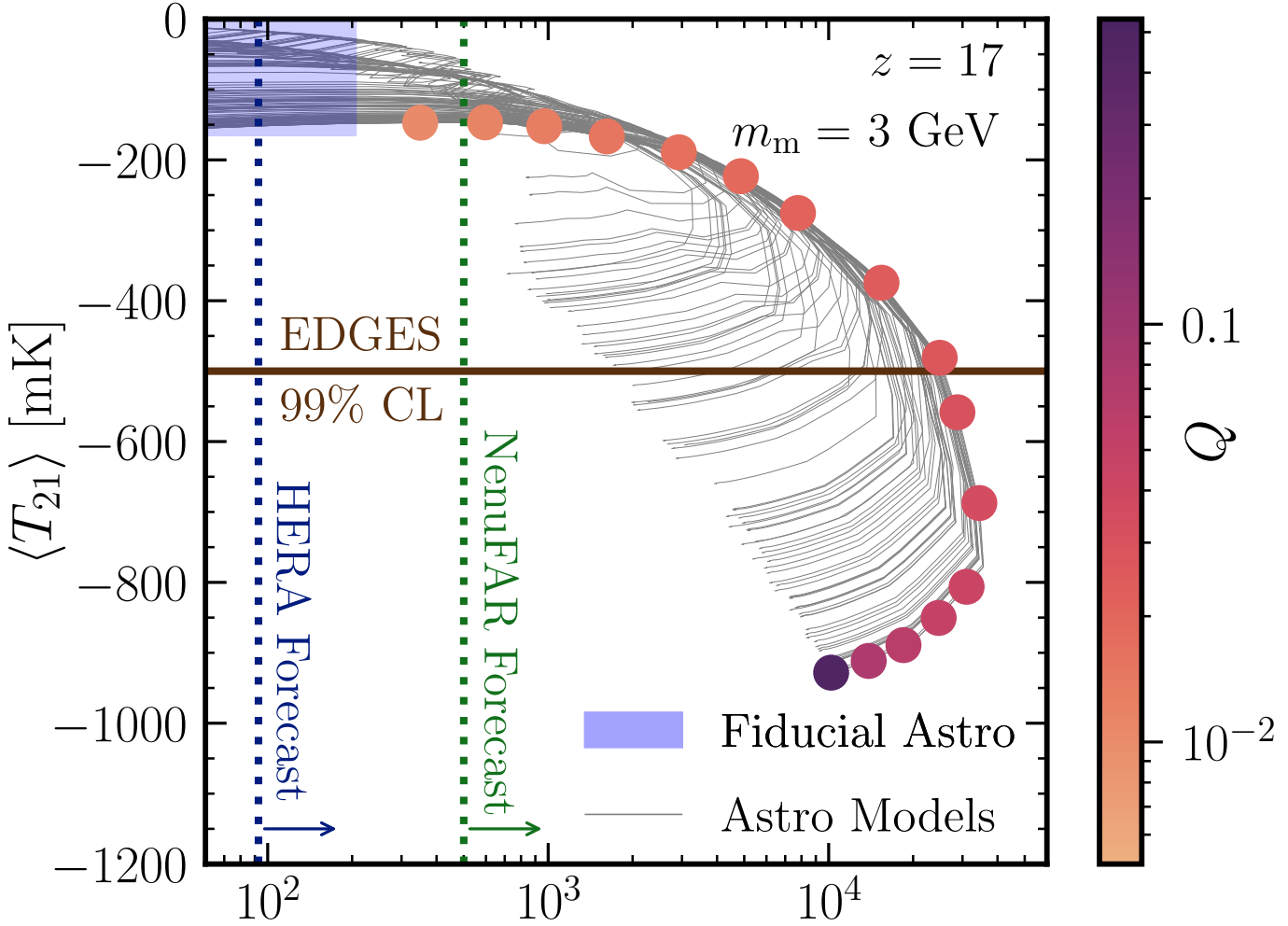
Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski 2018

Interacting Millicharged DM

Liu, Outmezguine, Redigolo, Volansky 2019







Barkana, Fialkov, Liu, Outmezguine 2023

$m_{\rm C} = 100\,\mathrm{MeV}$

$f_{\rm m} = 10^{-4}$

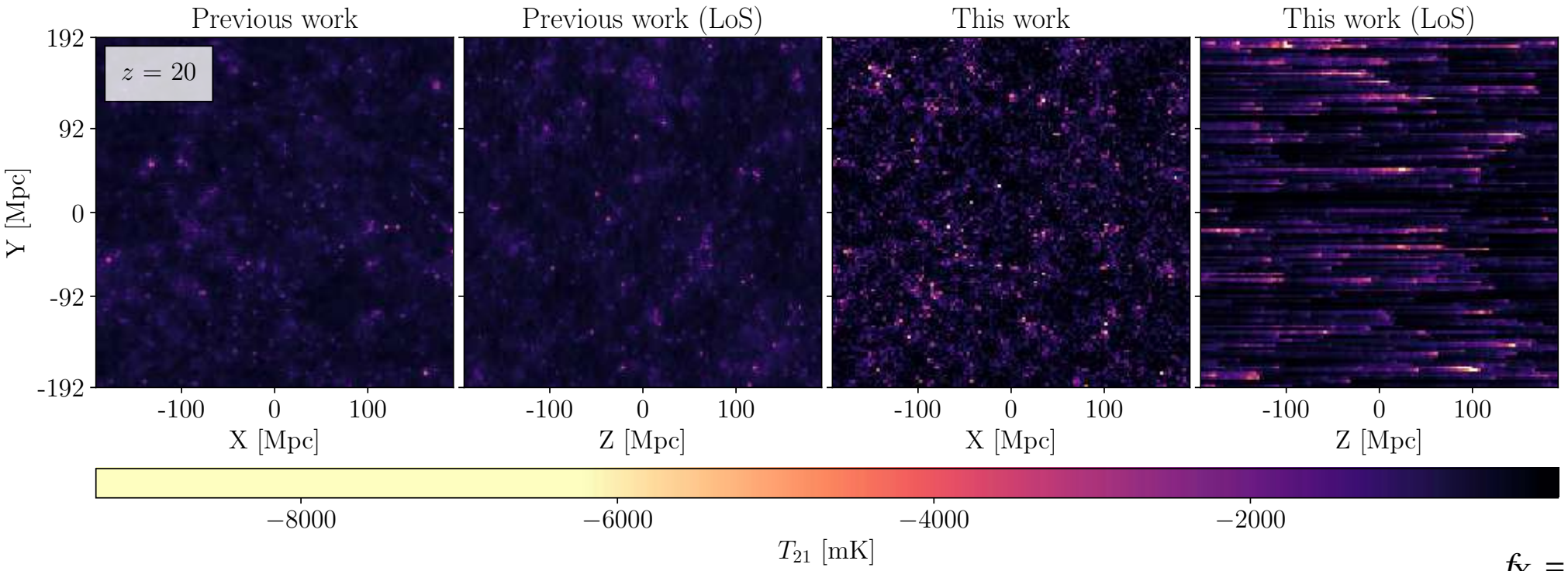
Alternative explanation for EDGES

Early radio background

Bowman et al. 2018
Mirocha & Furlanetto 2018
Feng & Holder 2018
Fialkov & Barkana 2019
Reis, Fialkov & Barkana 2020

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

Early radio background: Line-of-sight effect



Sikder, Reis, Barkana & Fialkov 2023

$f_X = 1$
$V_c = 16.5$ km s^{-1}, $f_* = 0.1$, $f_{\rm Radio} = 3000$

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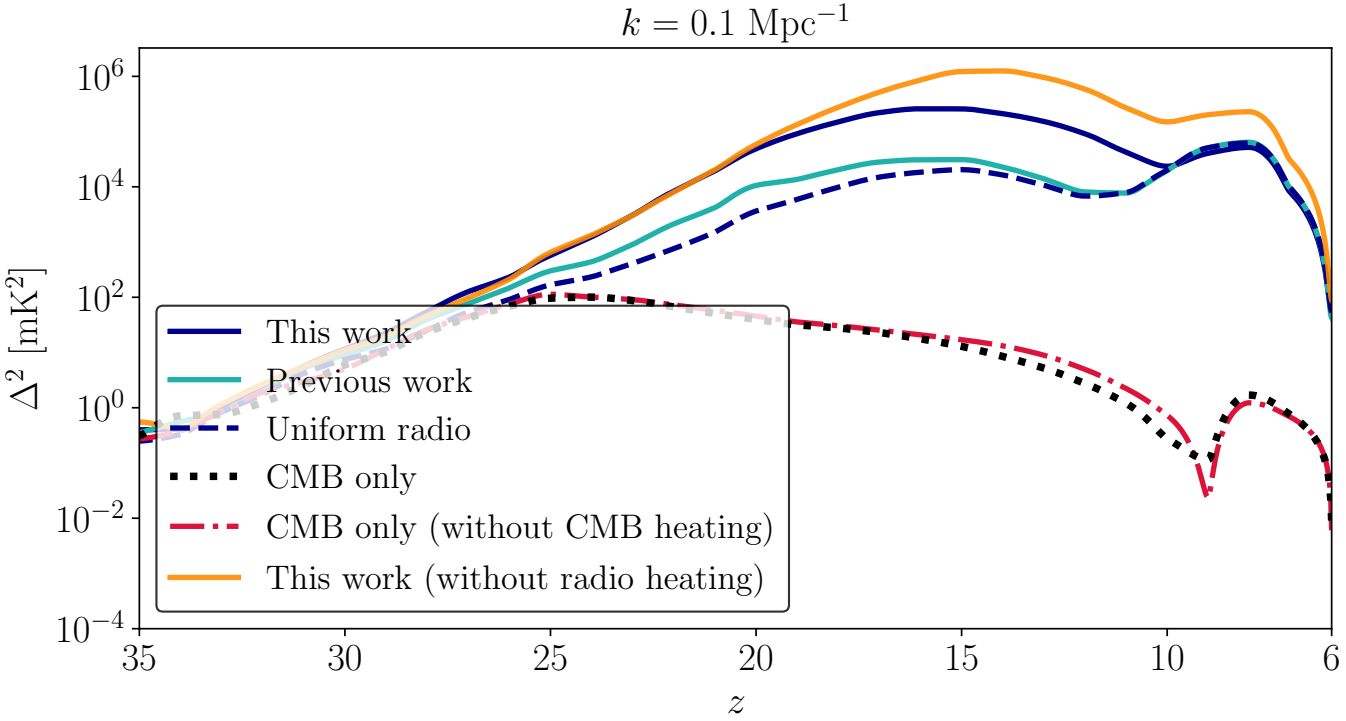


Sikder, Reis, Barkana & Fialkov 2023

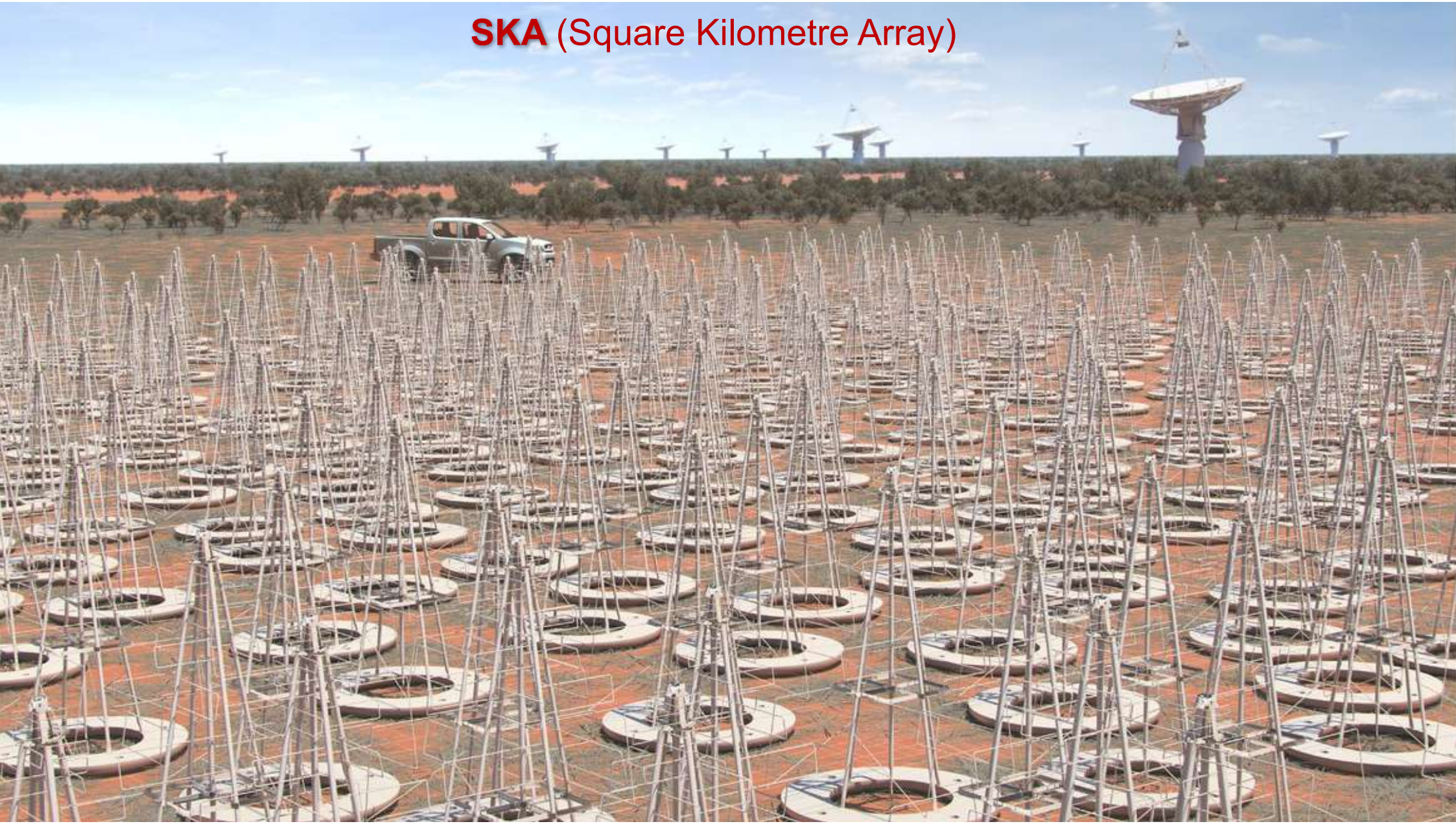
CMB/radio heating:
Venumadhav, Dai, Kaurov & Zaldarriaga 2018

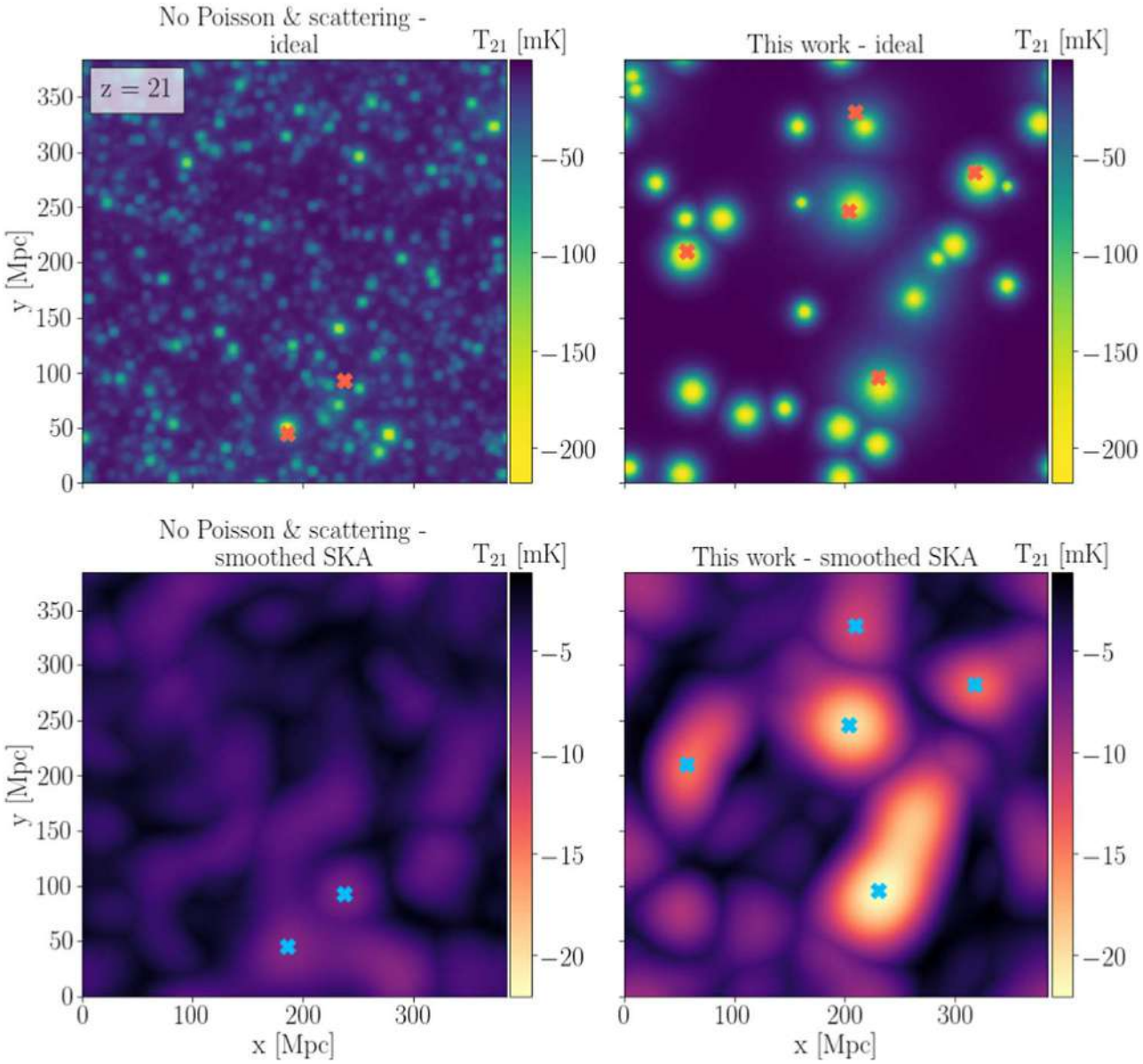
Counter:
Meiksin 2021

Lyα Heating
Madau et al. 1997; Chen & Miralda-Escudé 2004; Chuzhoy & Shapiro 2006/7; Furlanetto & Pritchard 2006

$f_{\rm X} = 0.01$
$V_c = 16.5$ km s^{-1}, $f_* = 0.1$, $f_{\rm Radio} = 3000$

SKA (Square Kilometre Array)





Multiple Lyα scattering + Poisson fluctuations

Mock SKA:
Thermal noise
Angular smoothing
Optimistic foreground avoidance
Analysis:
3-D smoothing
Projection of min value
Model:
$V_c = 50$ km/s ($M_{\rm min} = 8 \times 10^8 M_\odot$), $f_* = 0.1$

+ Scatter in the SF efficiency

Reis, RB, Fialkov 2022

The Moon: The Dark Ages

ROLSES

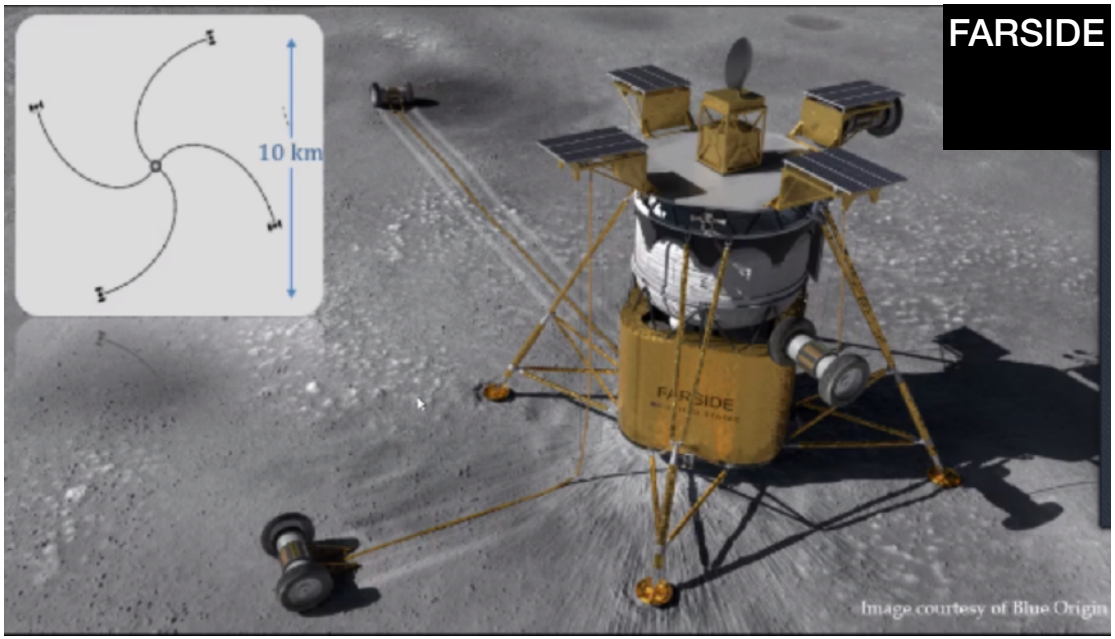
DAPPER, ROLSES, FarView, LuSee Night, FARSIDE (USA)

NCLE (Netherlands-China)

DSL (China)

PRATUSH, SEAMS (India)

ALO (Europe)

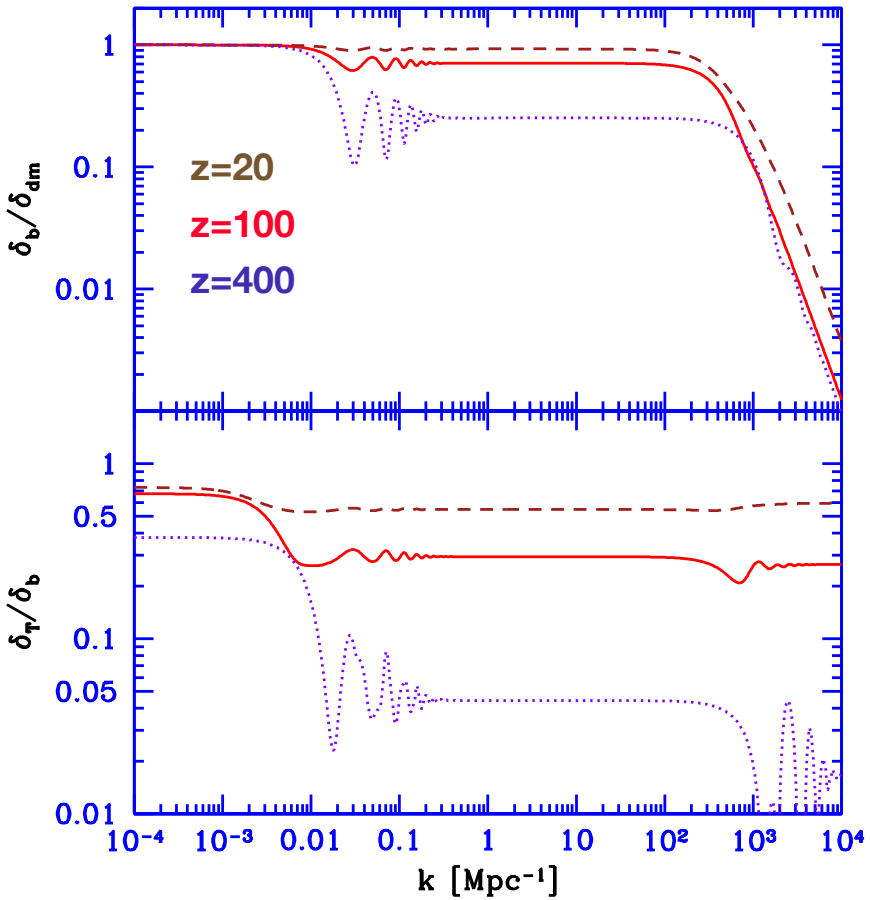


1. No ionosphere
2. No RFI
3. Dry and stable environment

No astrophysics
Linear fluctuations (but small and no galaxy bias)

Standard model: baseline
Exotic models: new window

The Moon: The Dark Ages



Naoz & Barkana 2005

Baryon infall

Loeb & Zaldarriaga 2004

CMBFAST

CAMB Lewis & Challinor 2007

Sensitivity to cosmological parameters

Barkana & Loeb 2005

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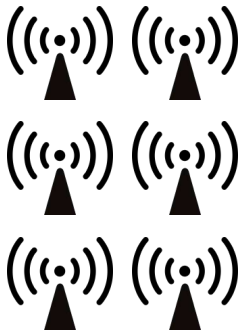
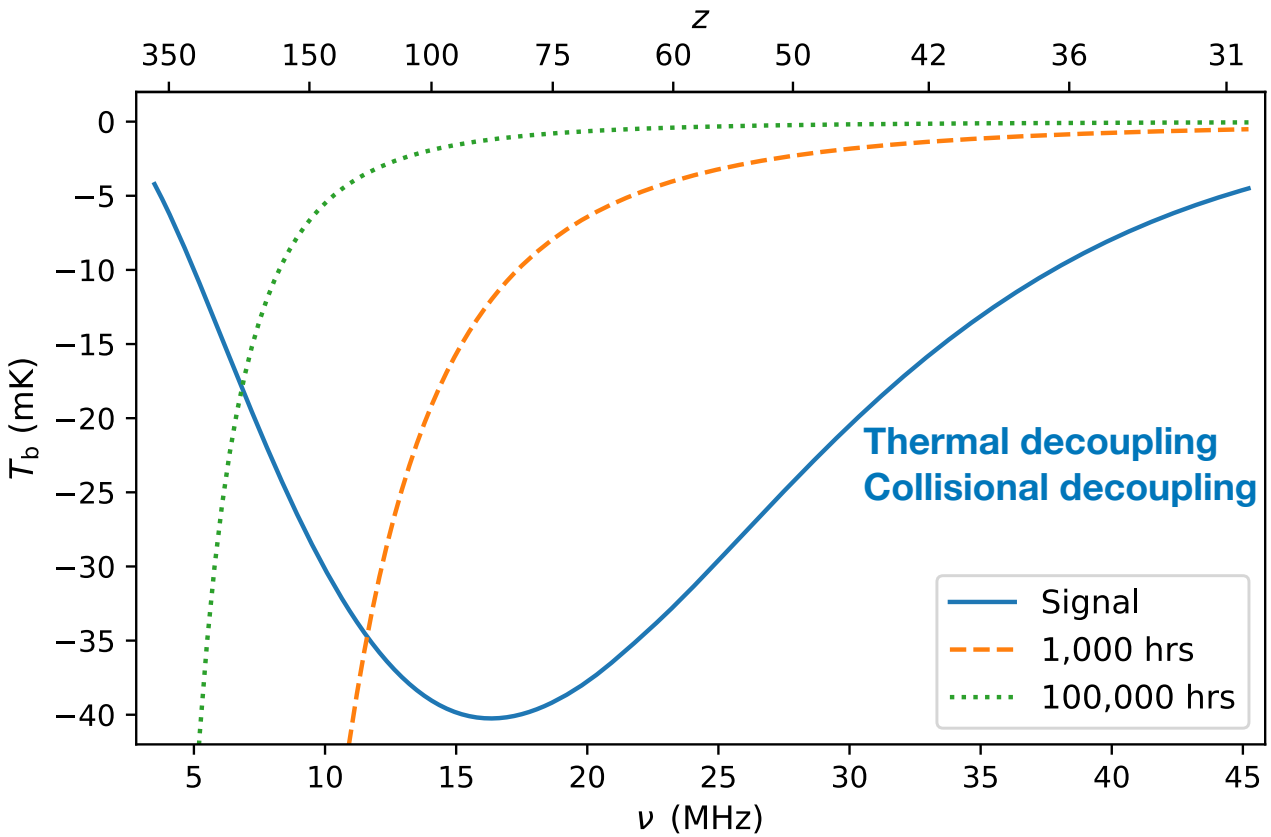
The global 21-cm signal





Thermal noise

Rajesh Mondal
NIT Calicut, India

Model with foreground term

$$\Delta(\ln \nu) = 1$$

Mondal & Barkana 2023

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	Configuration				
	D	C	B	A	G
$A_{\rm coll}$ [km^2]	100	100	10	10	5
$t_{\rm int}$ [hrs]	10,000	1,000	10,000	1,000	1,000

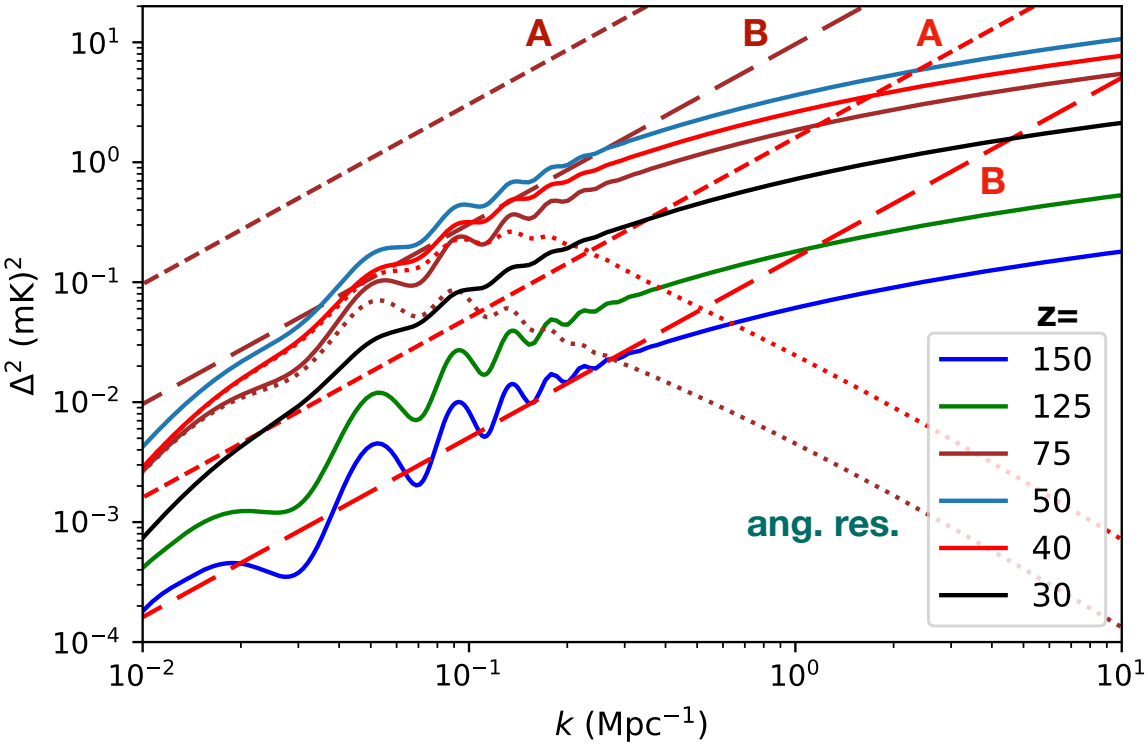
CAMB + :

LOS peculiar velocities
- Kaiser 1987
- Bharadwaj & Ali 2004
- Barkana & Loeb 2005

Alcock-Paczyński effect
- Nusser 2005
- Ali, Bharadwaj & Pandey 2005
- Barkana 2006

Light-cone effect
- Barkana & Loeb 2006

The 21-cm power spectrum



$\Delta(\ln \nu) = 1$ $\Delta(\ln k)=1$

Thermal noise (+ cosmic variance)

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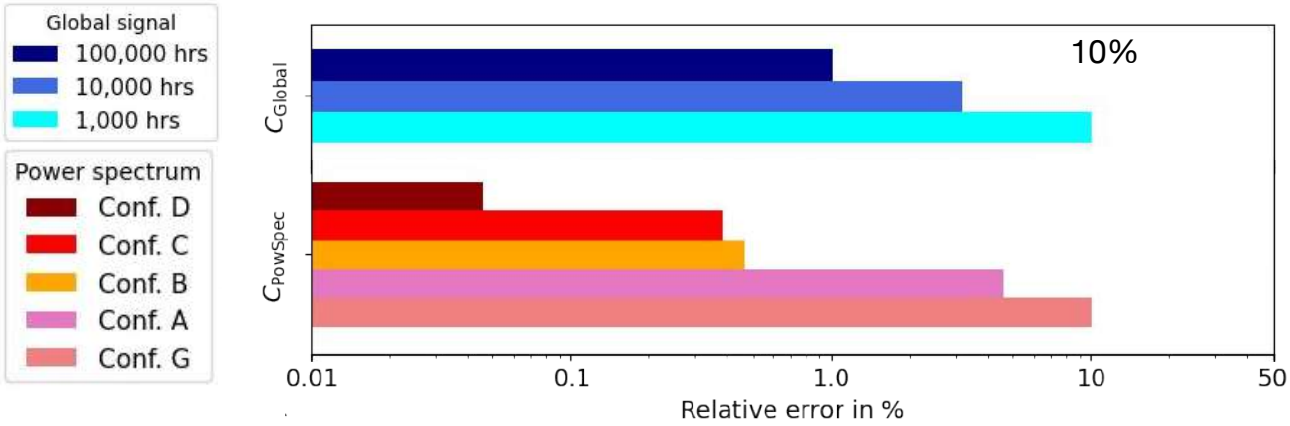
Constraints

Cosmological parameters: degeneracies

$$C_{\rm Global} \equiv \frac{\Omega_{\rm b} h^2}{(\Omega_{\rm m} h^2)^{0.248}}$$

$$C_{\rm PowSpec} \equiv \Omega_{\rm b} h^2 \frac{(A_{\rm s} e^{-2\tau})^{0.307} (0.9950)^{n_{\rm s}}}{(\Omega_{\rm m} h^2)^{0.464} H_0^{0.0753}}$$



1σ errors

	Configuration				
	D	C	B	A	G
$A_{\rm coll}$ [km^2]	100	100	10	10	5
$t_{\rm int}$ [hrs]	10,000	1,000	10,000	1,000	1,000

The significance (# of σ) of the detection

	Integration time		
	1,000 hrs	10,000 hrs	100,000 hrs
Global signal	4.12	13.0	41.2
	Configuration				
	G	A	B	C	D
Power spectrum	3.01	6.71	66.6	81.6	690

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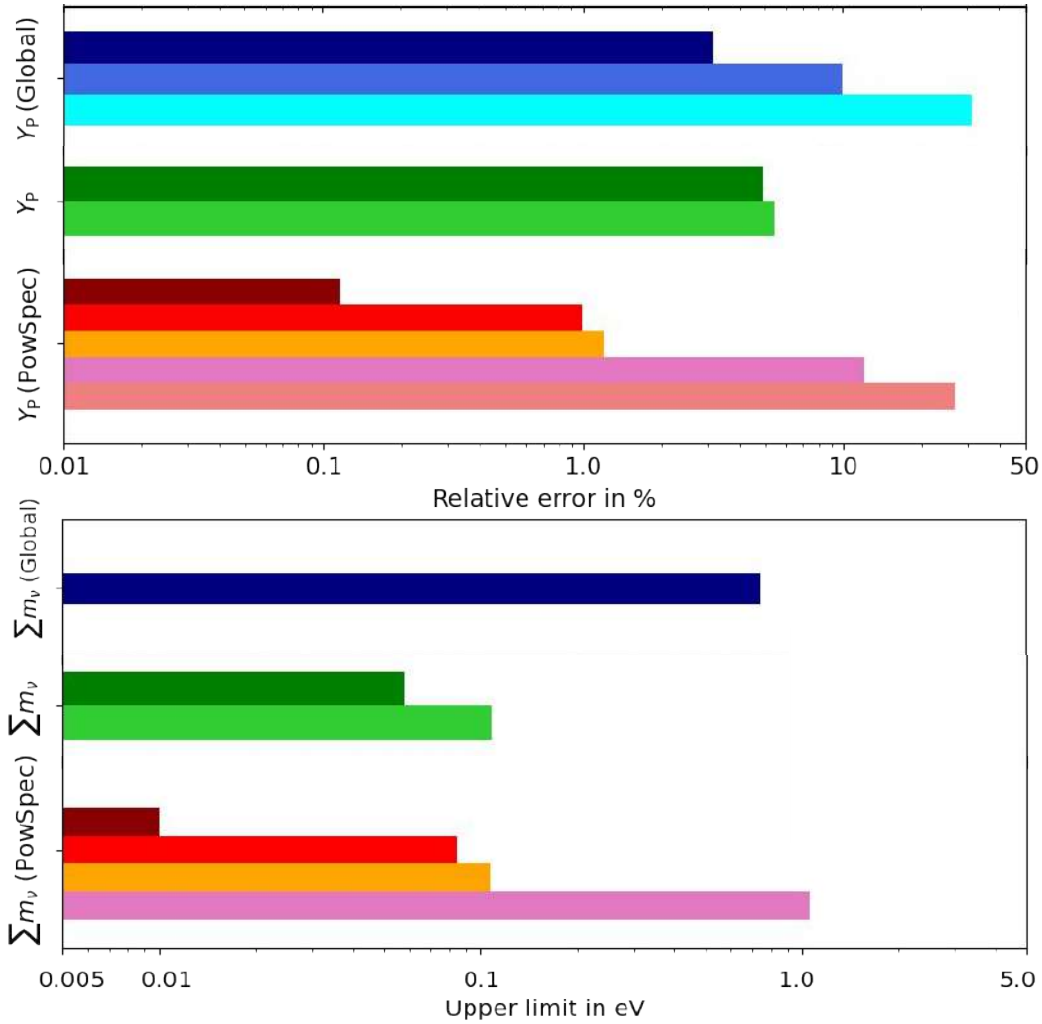
Constraints

As single parameters:

Y_P = Helium mass fraction

Σm_ν = total mass of neutrinos



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All are 1σ

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The Moon: The Dark Ages

Exotic: excess radio background

Fialkov & Barkana 2019

$$T_{\rm R} = T_\gamma \left[1 + A_{\rm r} \left(\frac{\nu_{\rm obs}}{78\ {\rm MHz}}\right)^{\alpha}\right]$$

$$T_\gamma = 2.725\ {\rm K}\ (1+z)$$

$$\nu_{\rm obs} = 1420\,{\rm MHz}/(1+z)$$

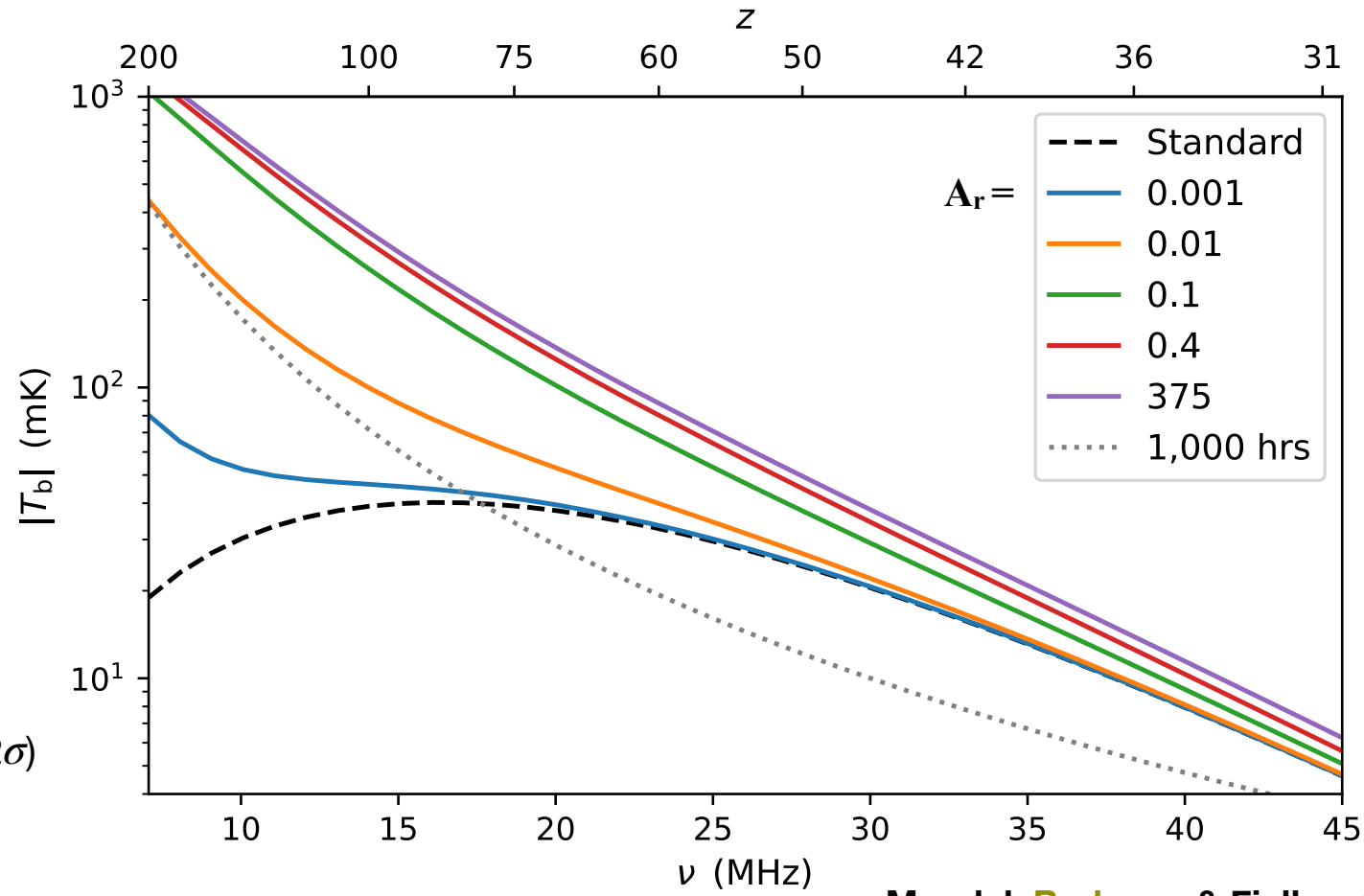
$$\alpha = -2.6$$

ARCADE-2
(Fixsen et al. 2011; Seiffert et al. 2011)

LWA-1
(Dowell & Taylor 2018)

375: extragalactic radio background (2σ)
1.9: min for EDGES
(Fialkov & Barkana 2019)
0.4: 90% saturated

Global 21-cm signal



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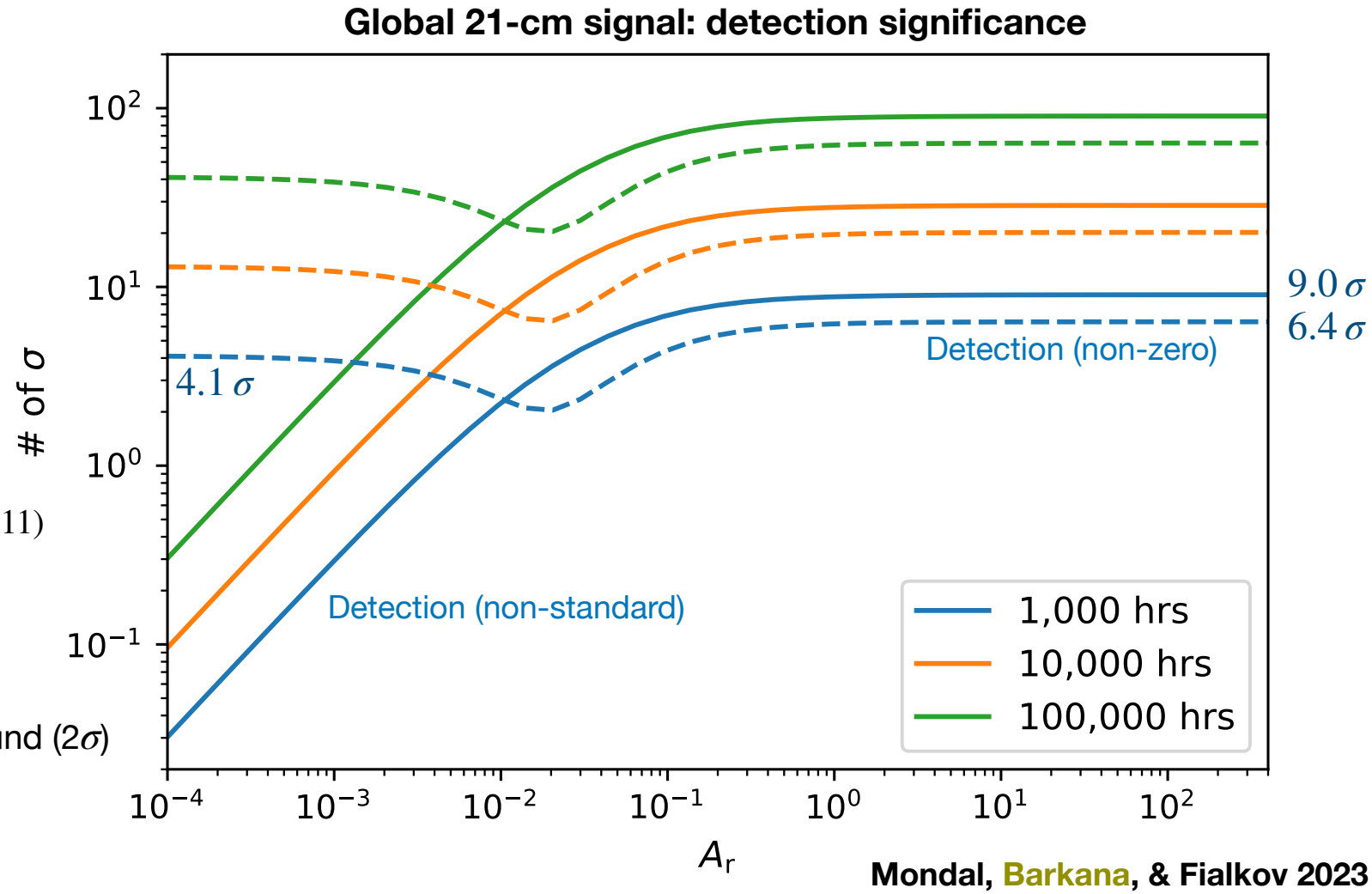

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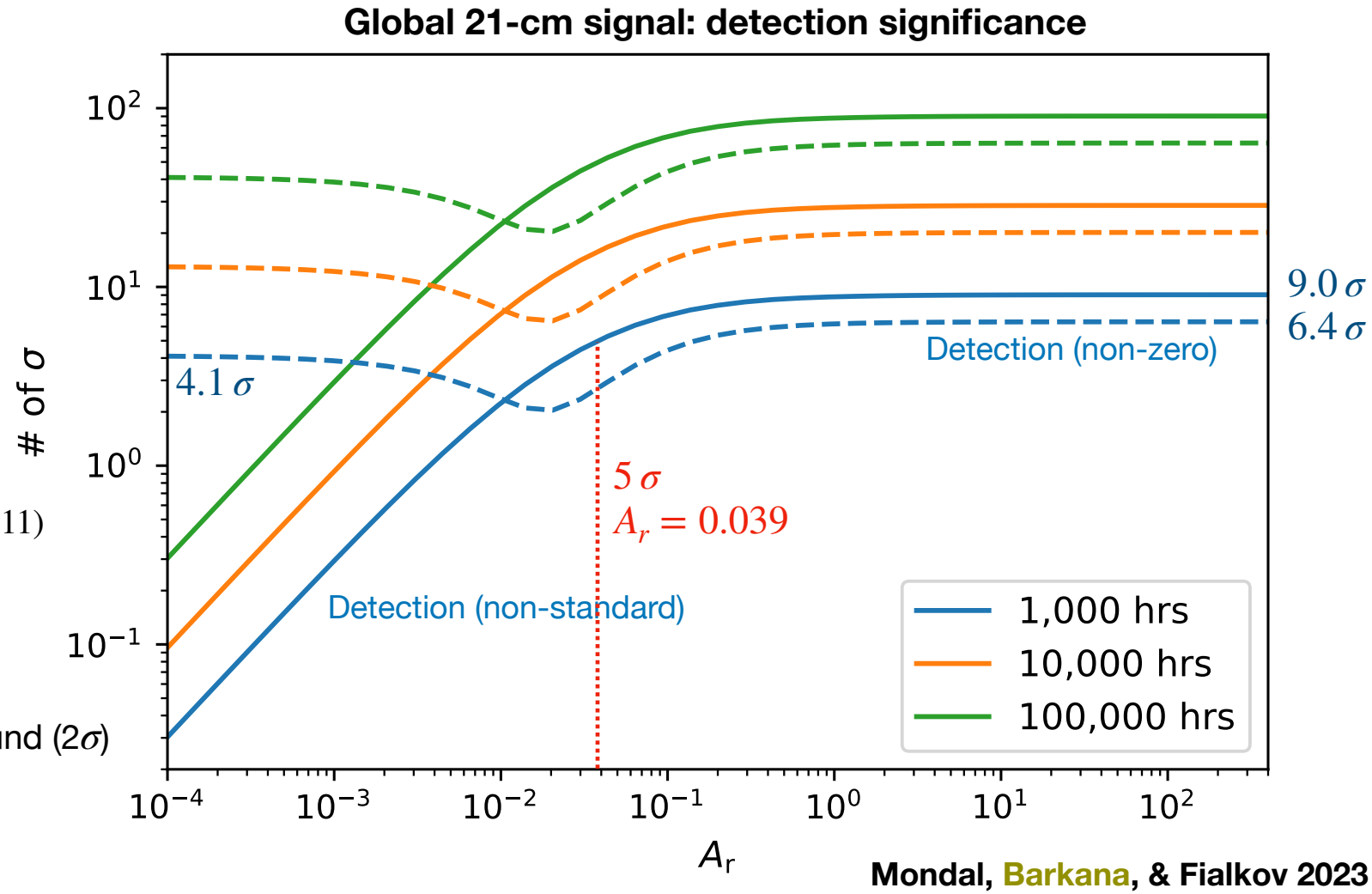

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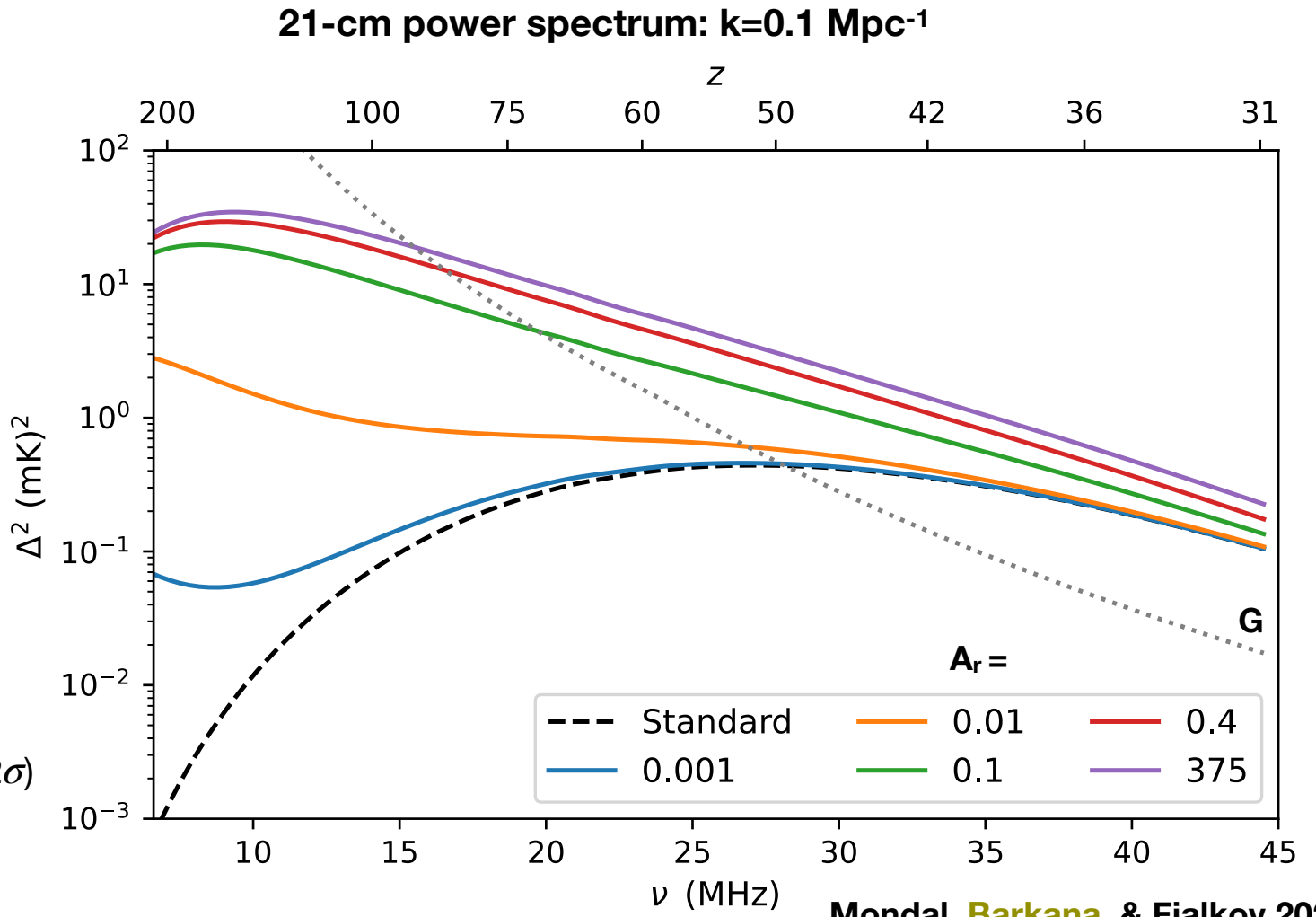

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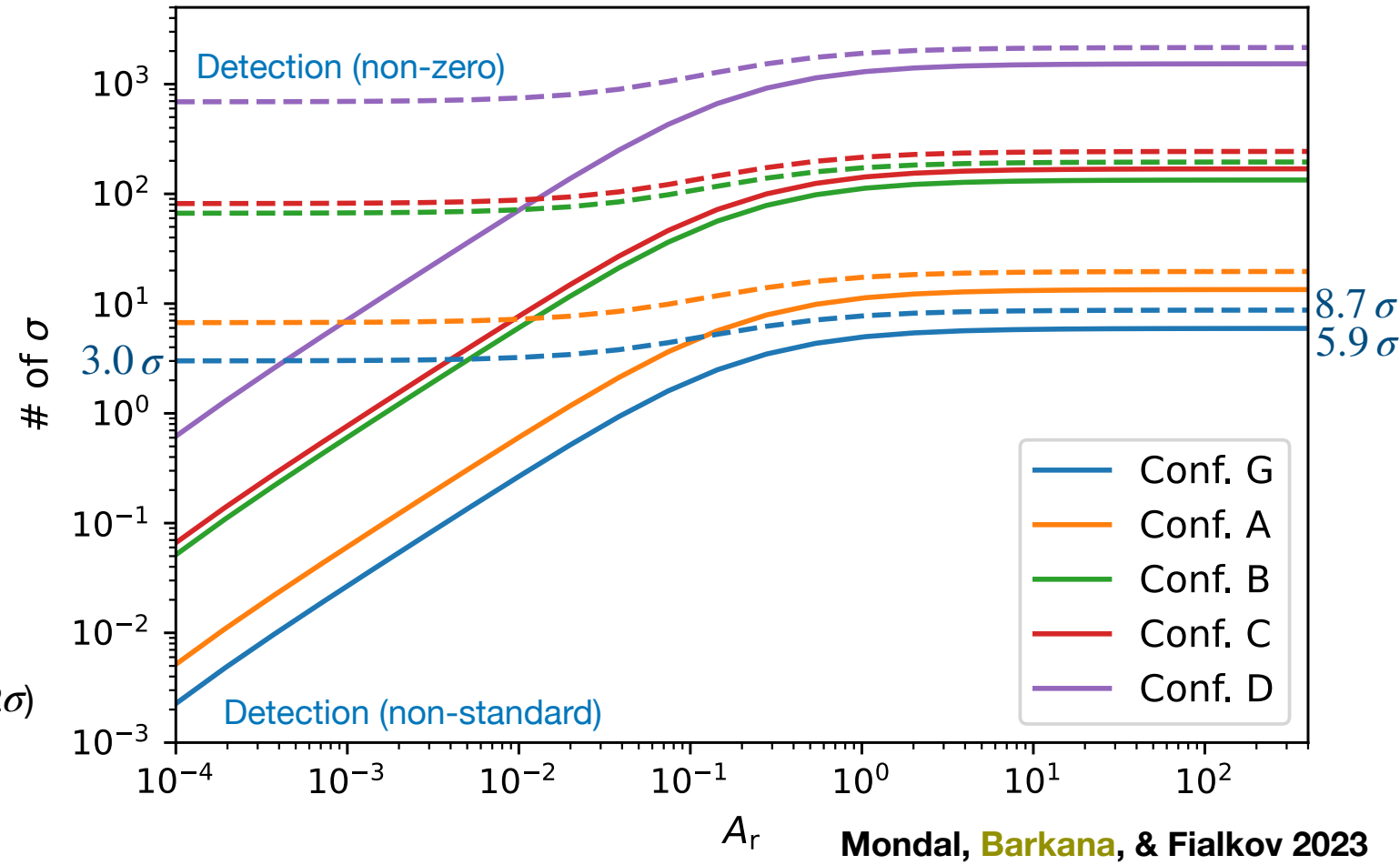
21-cm power spectrum: detection significance



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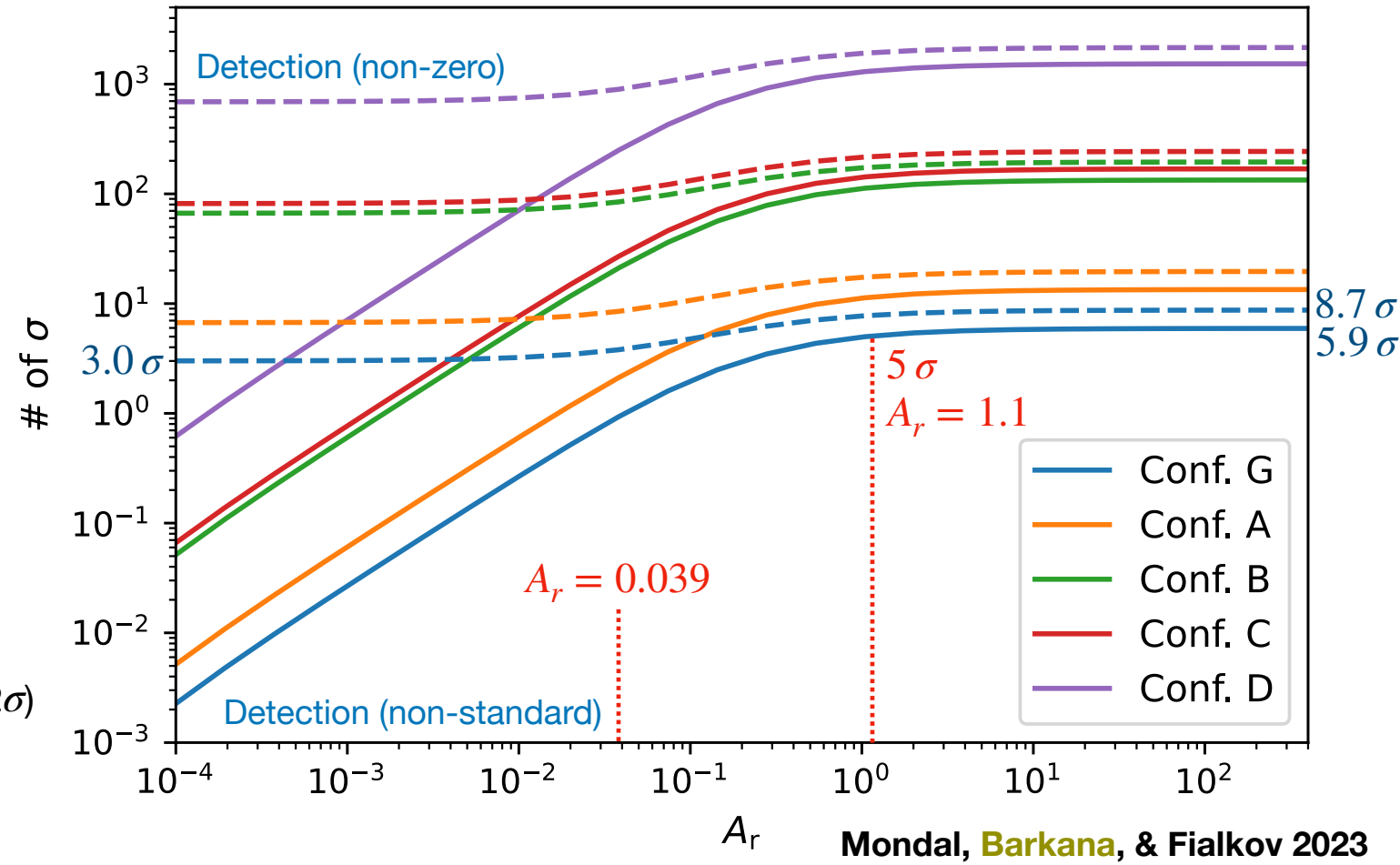

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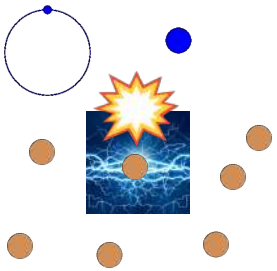
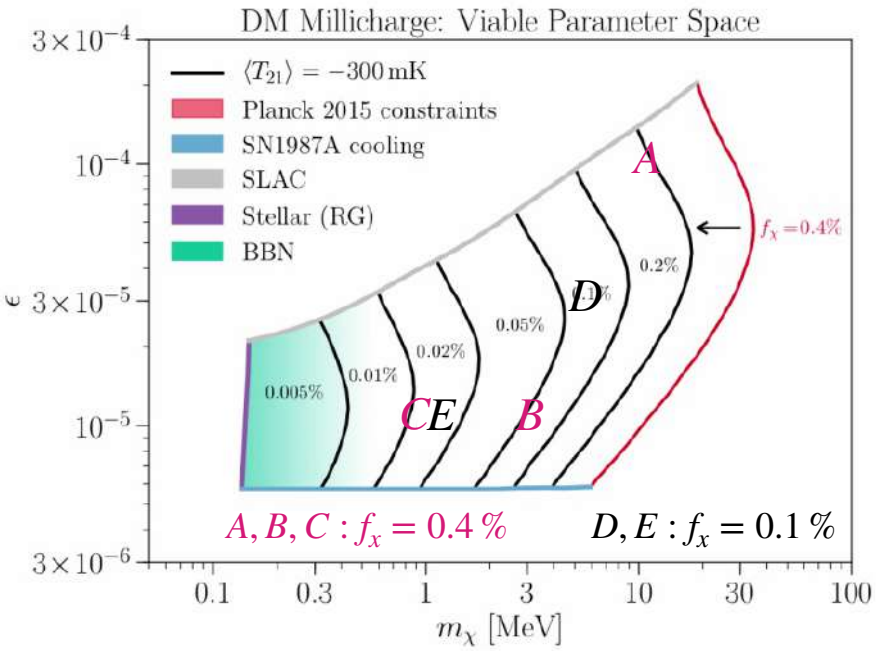
Barkana, Nature 2018



Exotic: millicharged DM

Muñoz & Loeb 2018



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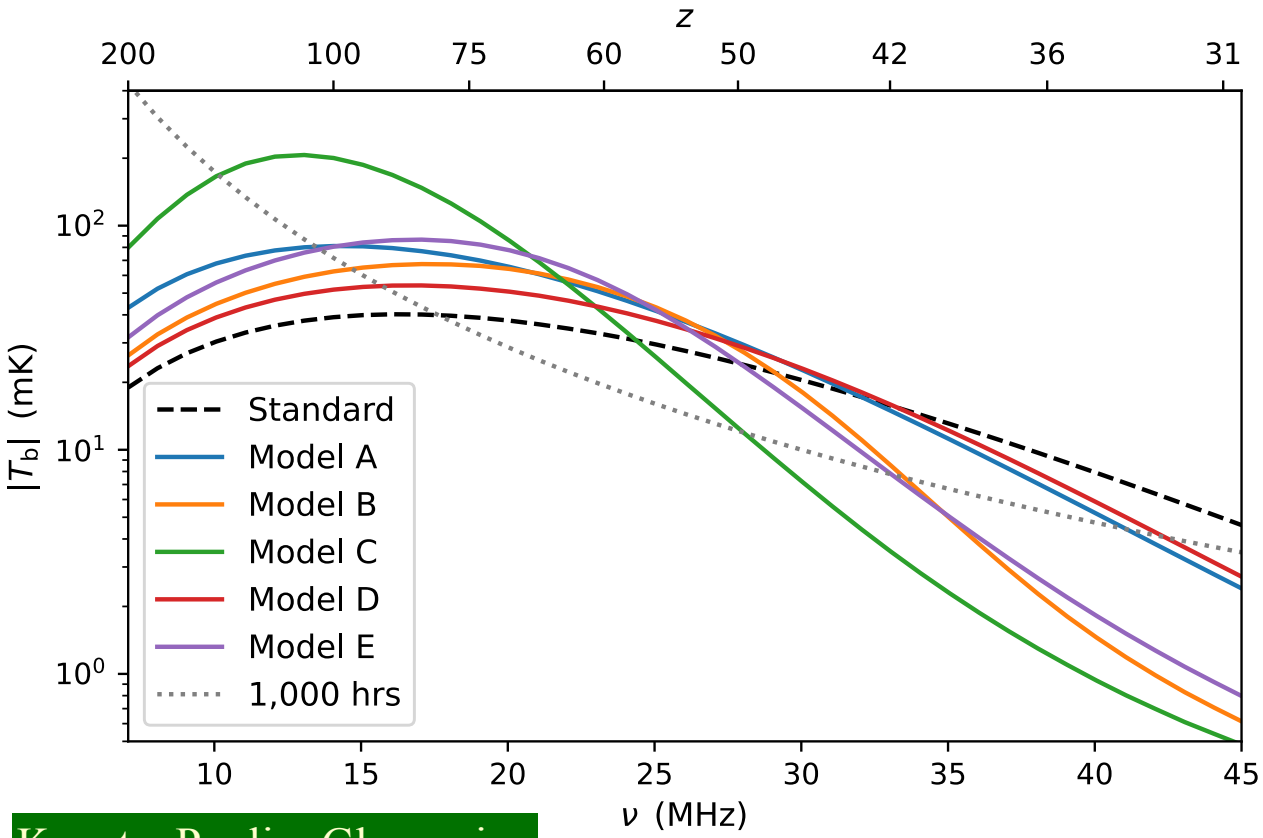


Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski 2018

Mondal, Barkana, & Fialkov 2023

The Moon: The Dark Ages

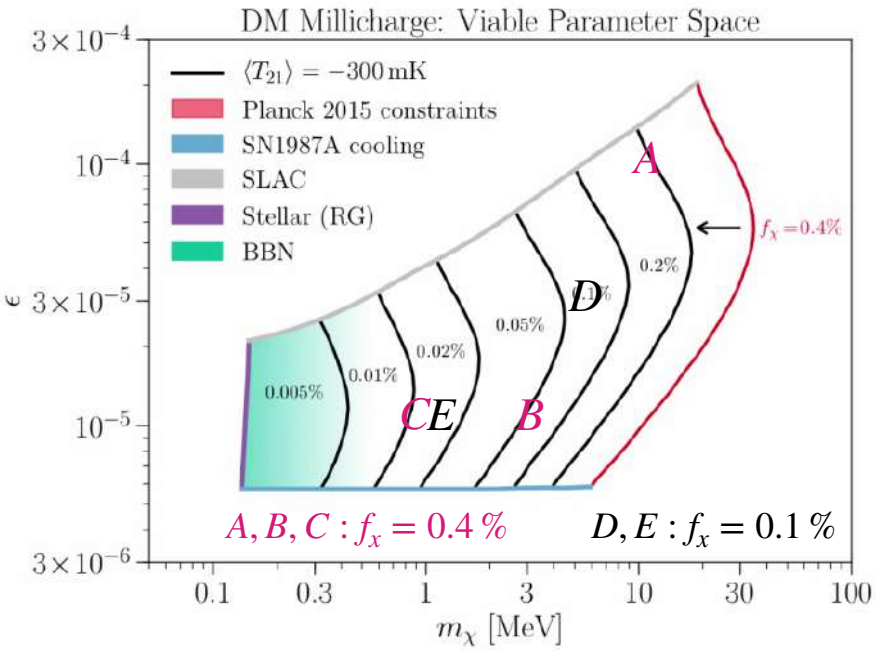
Exotic: millicharged DM

Model	1,000 hrs
A	4.90
B	5.79
C	7.16
D	4.68
E	5.98

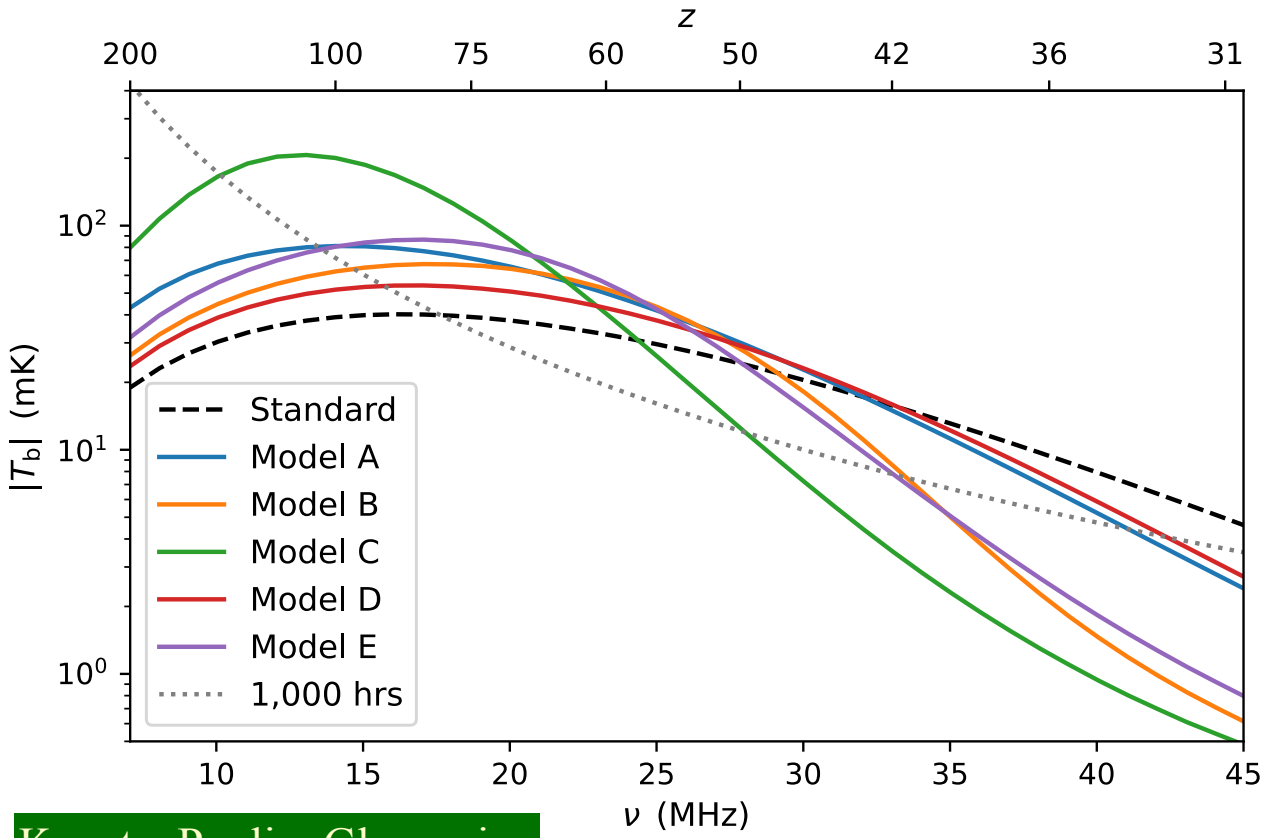
Detection (non-zero)

Model	1,000 hrs
A	3.55
B	5.45
C	9.26
D	2.22
E	6.07

Detection (non-standard)



Global 21-cm signal



Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski 2018

Mondal, Barkana, & Fialkov 2023

Summary

- Early history of 21-cm Cosmology
- Exotic models (inspired by EDGES)
  - (Interacting) millicharged DM
  - Excess radio background
- Imaging cosmic dawn Lyα bubbles
- Dark ages
  - Start with the global 21-cm signal (single, then array)
  - Future: 21-cm power spectrum