Constraining Cosmic Reionization with 21cm & Fast Radio Bursts

Stefan Heimersheim

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21cm cosmology *constraints, based on paper with the HERA Collaboration & Theory team (especially Julian B. Muñoz, Jordan Mirocha, and Yuxiang Qin):*

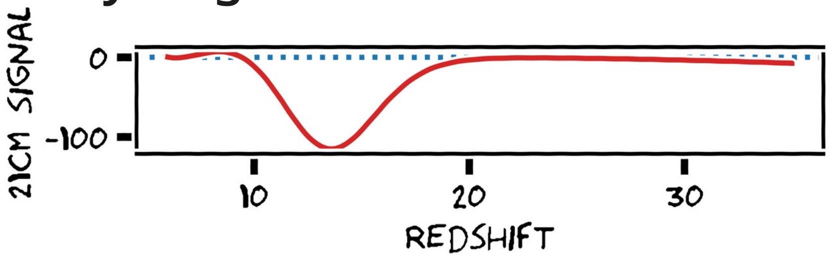
HERA Phase I Limits on the Cosmic 21-cm Signal: Constraints on Astrophysics and Cosmology During the Epoch of Reionization
[ApJ 924 51, arXiv 2108.07282]

Fast Radio Burst *forecast, based on paper with Nina Sartorio, Anastasia Fialkov & Duncan Lorimer*

What it takes to Measure Reionization with Fast Radio Bursts
[arXiv 2107.14242]

Two ways to probe the era of reionization

21cm – probing neutral hydrogen in the Universe



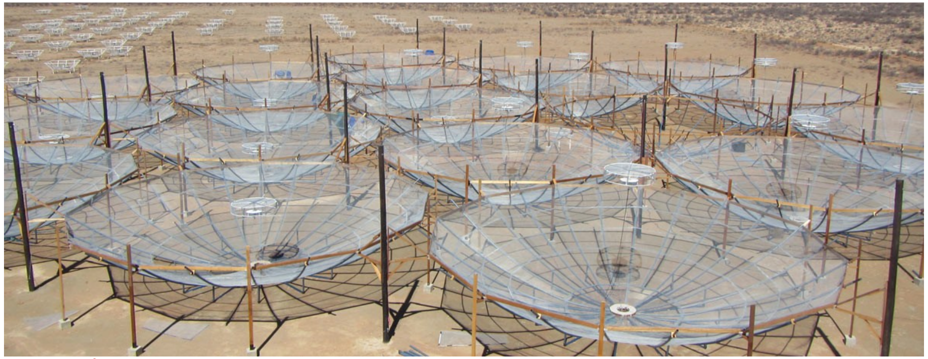


Foto credit: HERA

FRBs – radio bursts that probe the ionized medium

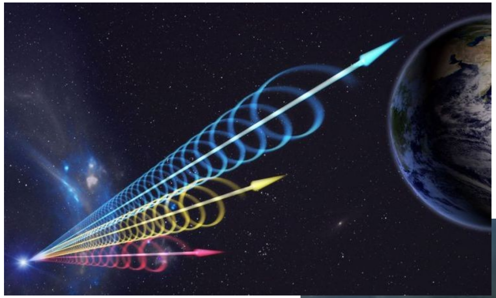


Image credit: Jingchuan Yu, Beijing Planetarium

Foto credit: Absolute Cosmos

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Reionization – the missing piece in the cosmological puzzle

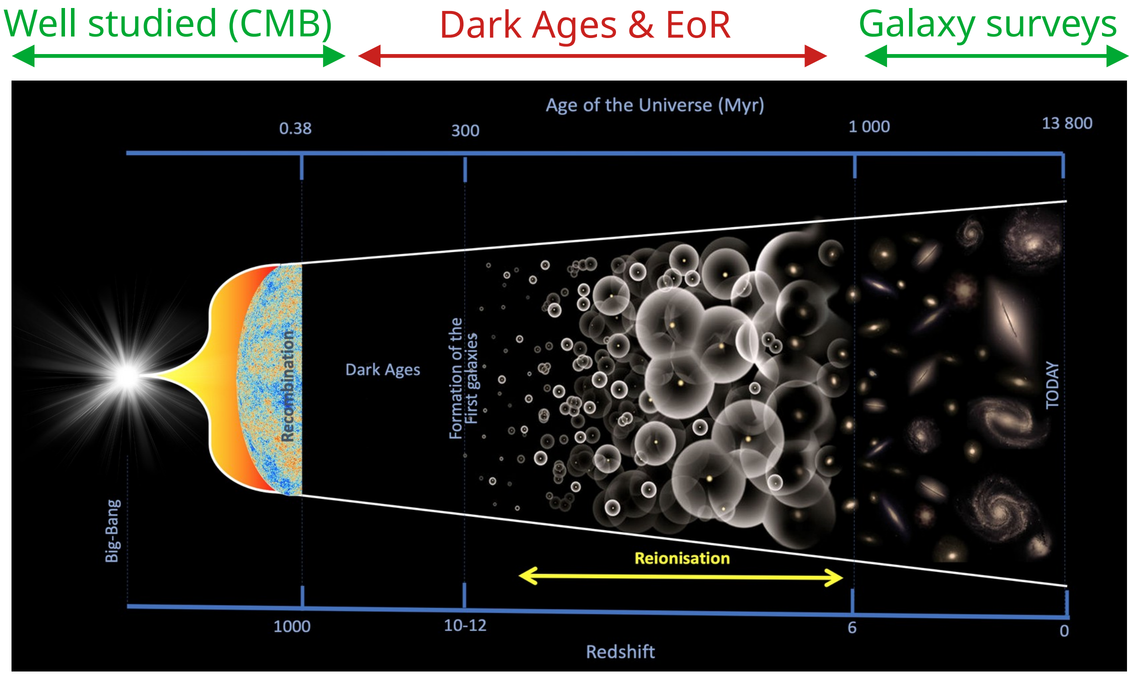

Image credit: Nicolas Laporte

Cosmological standard model
(Planck analysis incl. BAO):

$$\ln A_s \pm 0.5\%$$
$$n_s \pm 0.4\%$$
$$\Omega_m h^2 \pm 0.6\%$$
$$\Omega_b h^2 \pm 0.6\%$$
$$H_0 \pm 0.6\%^*$$
$$\tau \pm 12\%$$

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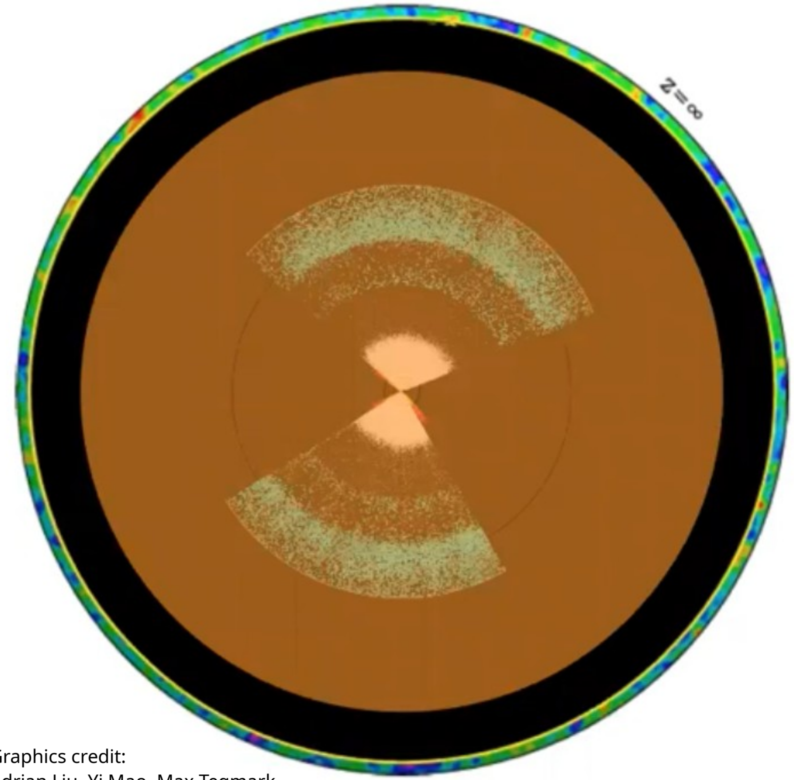
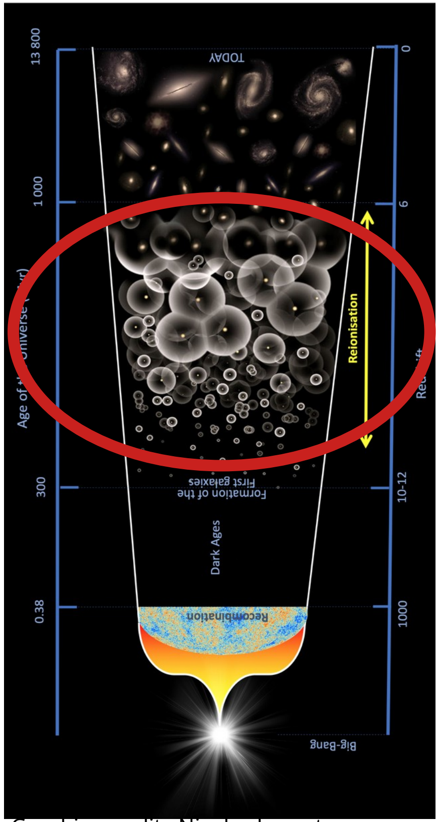
21-cm Cosmology



Graphics credit:
Adrian Liu, Yi Mao, Max Tegmark



Graphics credit: Nicolas Laporte

Observe all the Hydrogen in the Universe, from redshift z=6 to ~100 (in principle)

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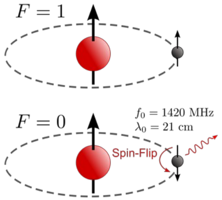
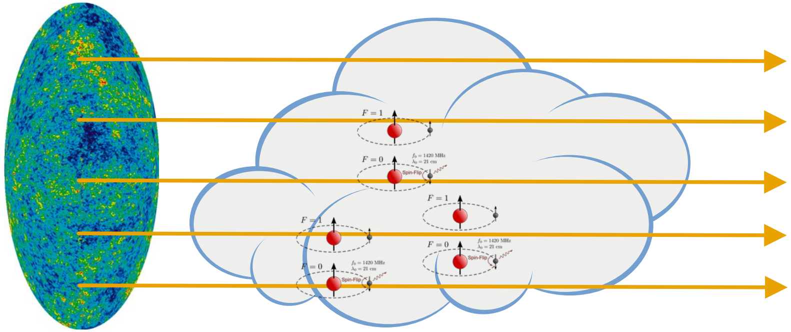
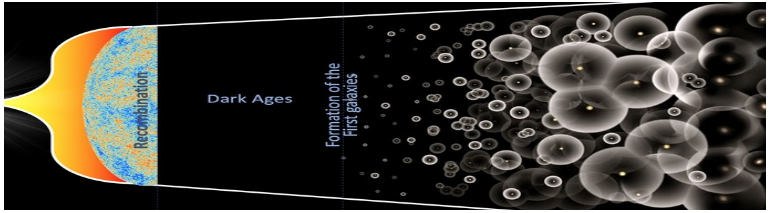
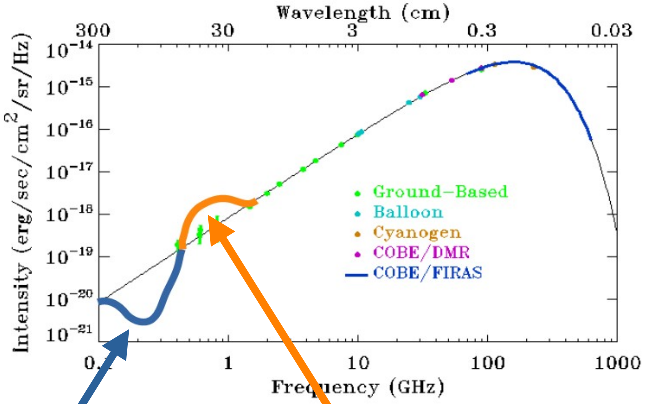
The 21cm signal

Neutral hydrogen distorts CMB black-body spectrum









Graphic adopted from ARCADE, NASA

Cold hydrogen gas absorbs some of the CMB radiation

Emission from hot hydrogen gas at z~7

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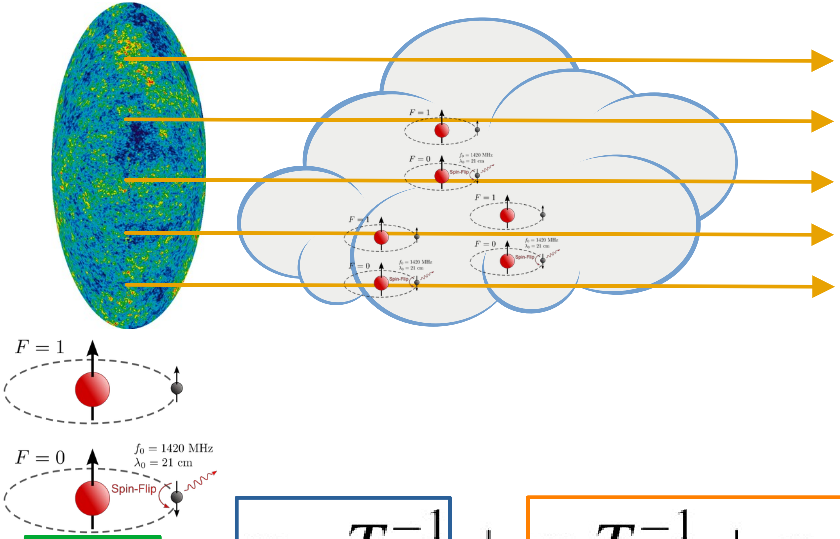
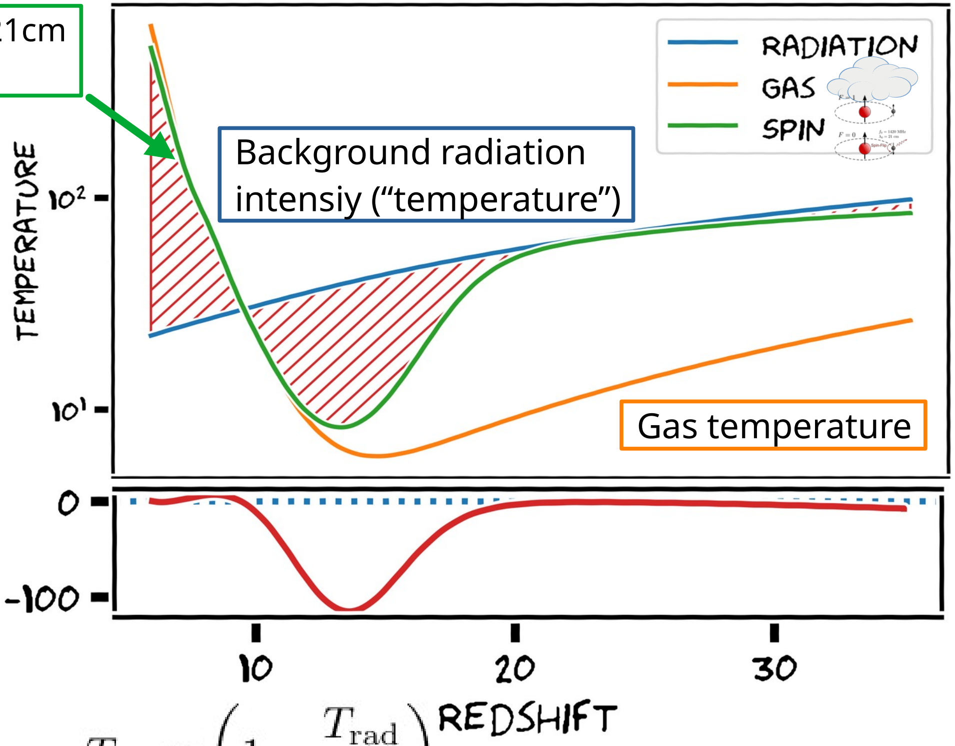
The spin temperature

Spin distribution ("temperature") of neutral hydrogen determines 21cm absorption/emission. Coupled to gas temperature and radiation.



$$T_S^{-1} = \frac{x_{\rm rad} T_{\rm rad}^{-1} + x_c T_K^{-1} + x_\alpha T_K^{-1}}{x_{\rm rad} + x_c + x_\alpha}$$



$$T_{21} \propto \left(1 - \frac{T_{\rm rad}}{T_S}\right)$$

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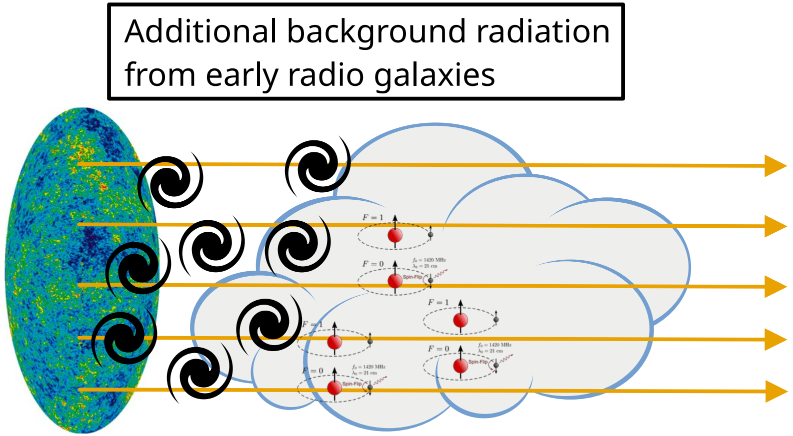
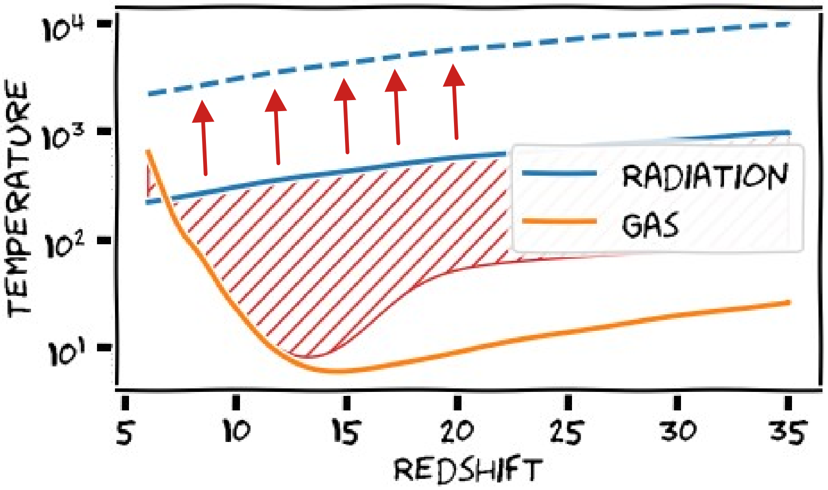
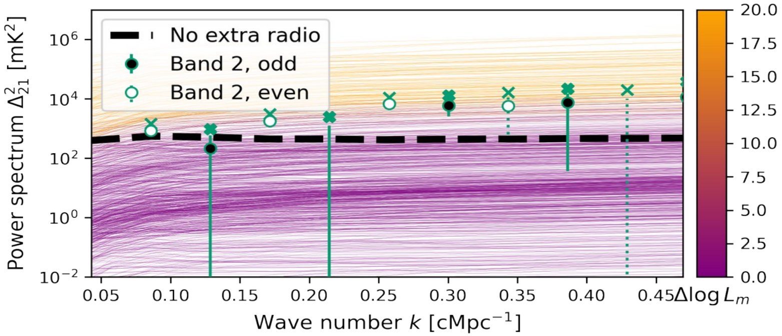
Radio backgrounds





Extra radio background from

- Early galaxies ~ SFR
- Exotic sources ~ Synchrotron



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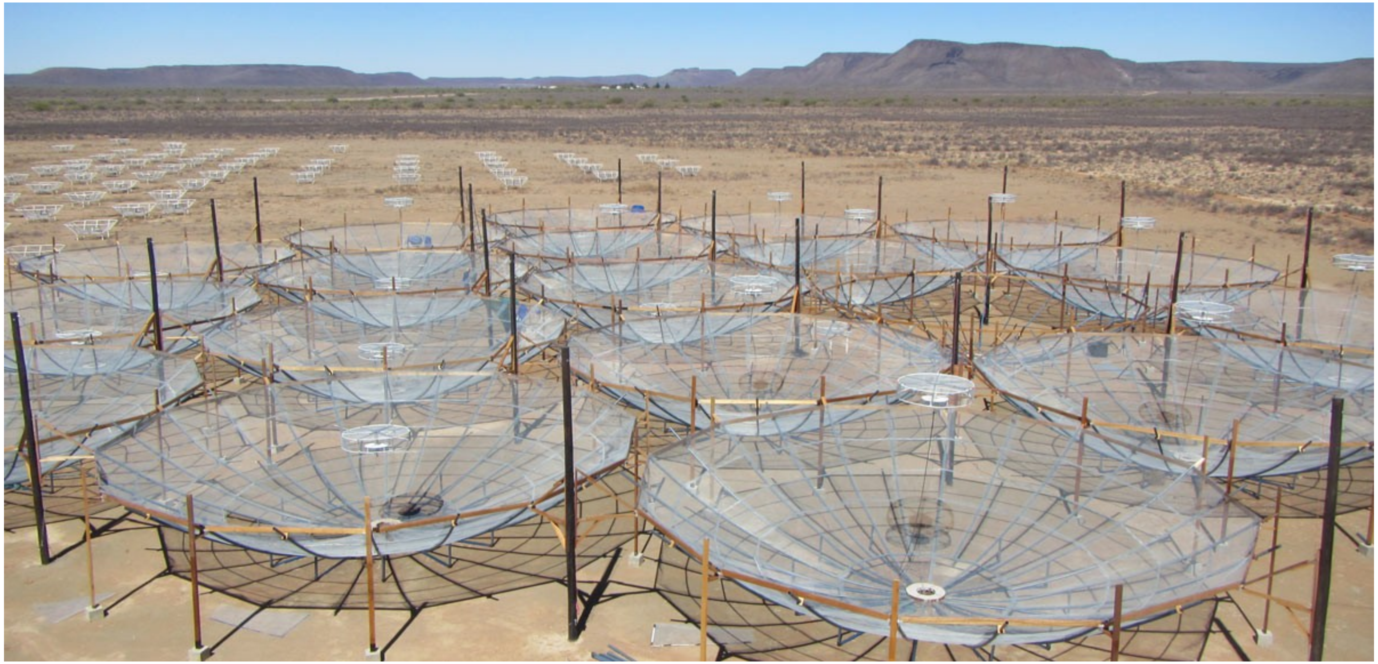
The HERA radio interferometer



Hydrogen **E**poch of **R**eionization **A**rray, Karoo desert, South Africa
This data: 39 science-quality antennas operational
Foto credit: HERA

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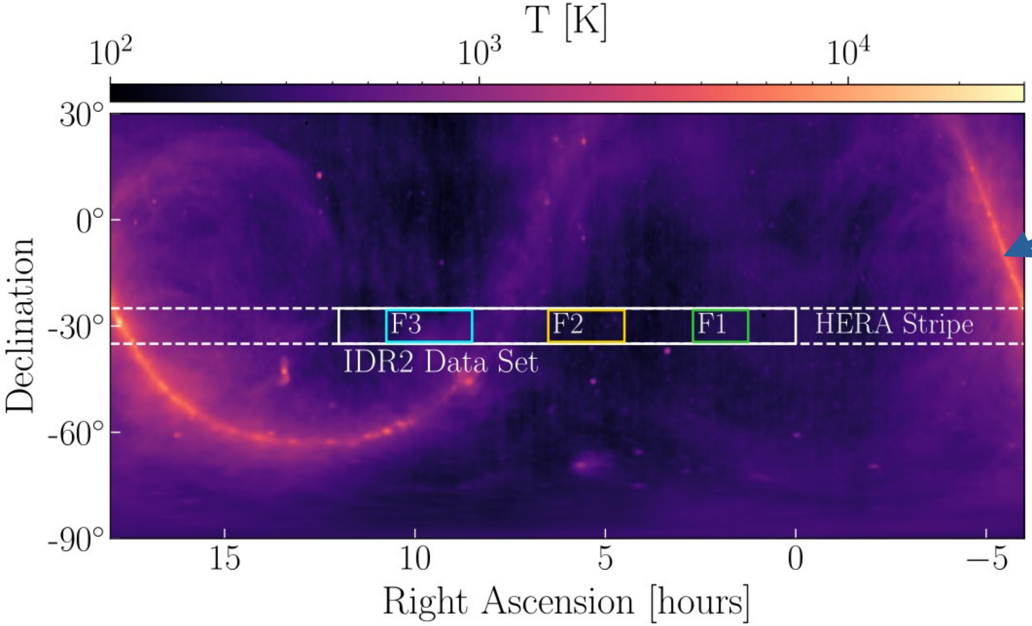
21cm signal & foregrounds



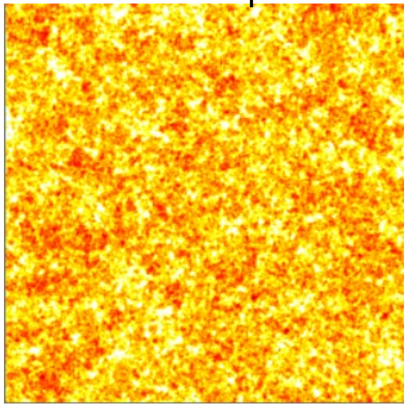
Driftscan observations of sky, 18 nights

(Figure: HERA Collaboration 2021a)

Foregrounds: Much brighter than cosmological signal (<1K), but spectrally smooth

21cm signal not smooth in redshift

Simulation snapshot:



(Figure: HERA Collaboration 2021b)

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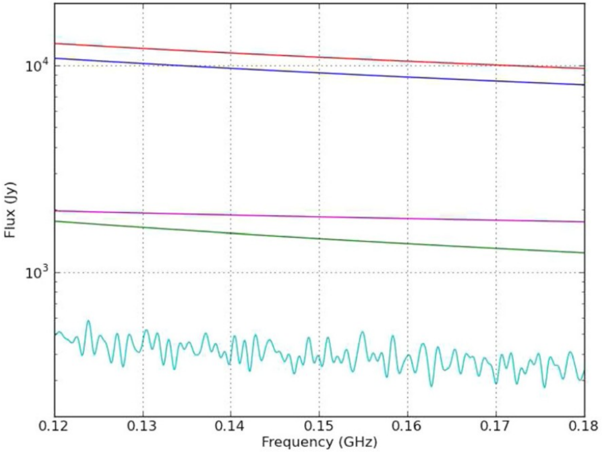
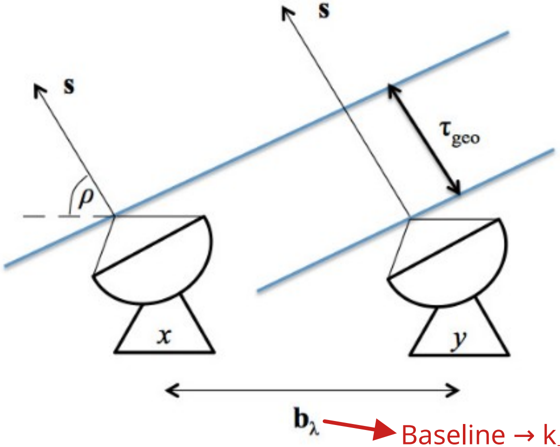
What do we measure? Baselines & delays

Figure credit: Parsons et al. 2012



Frequency → $k_\parallel$



Baseline → $k_\perp$

Interferometer

- Baseline ~ $k_\perp$
- Frequency ~ $k_\parallel$

⇒ Cylindrical power spectrum $P(k_\perp, k_\parallel)$

Graphics credit: Avison & George, arXiv 1211.0228

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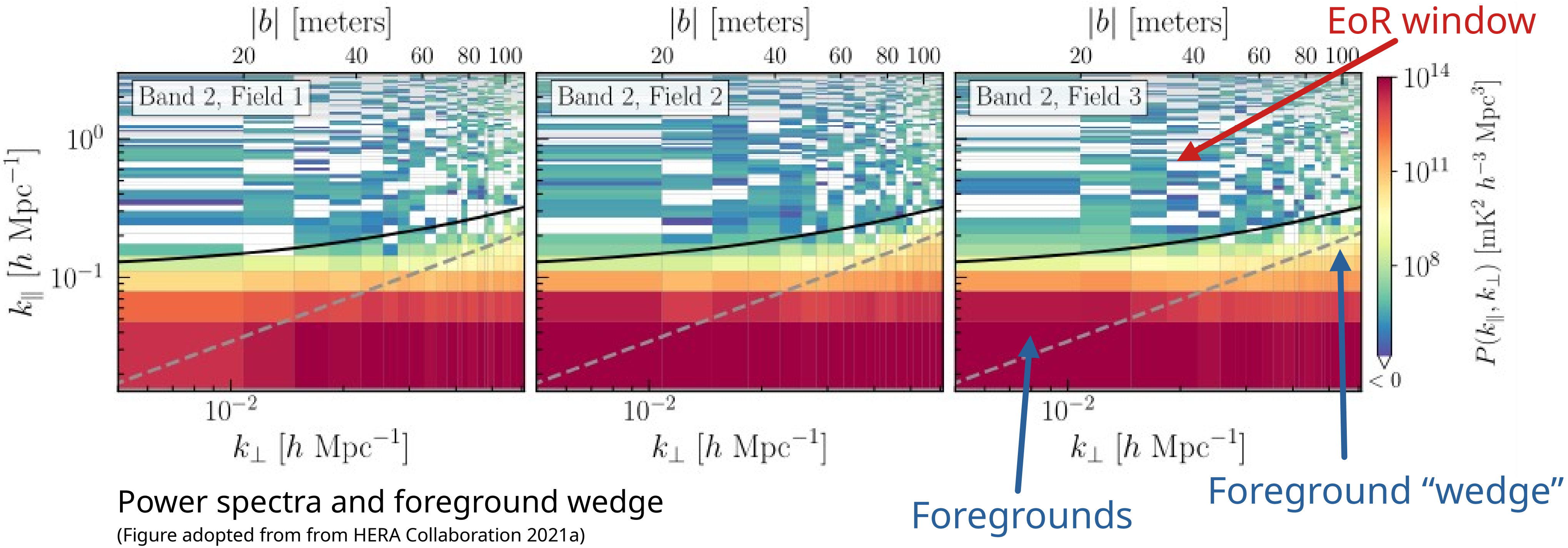
The 21cm signal EoR window



Power spectra and foreground wedge

(Figure adopted from from HERA Collaboration 2021a)

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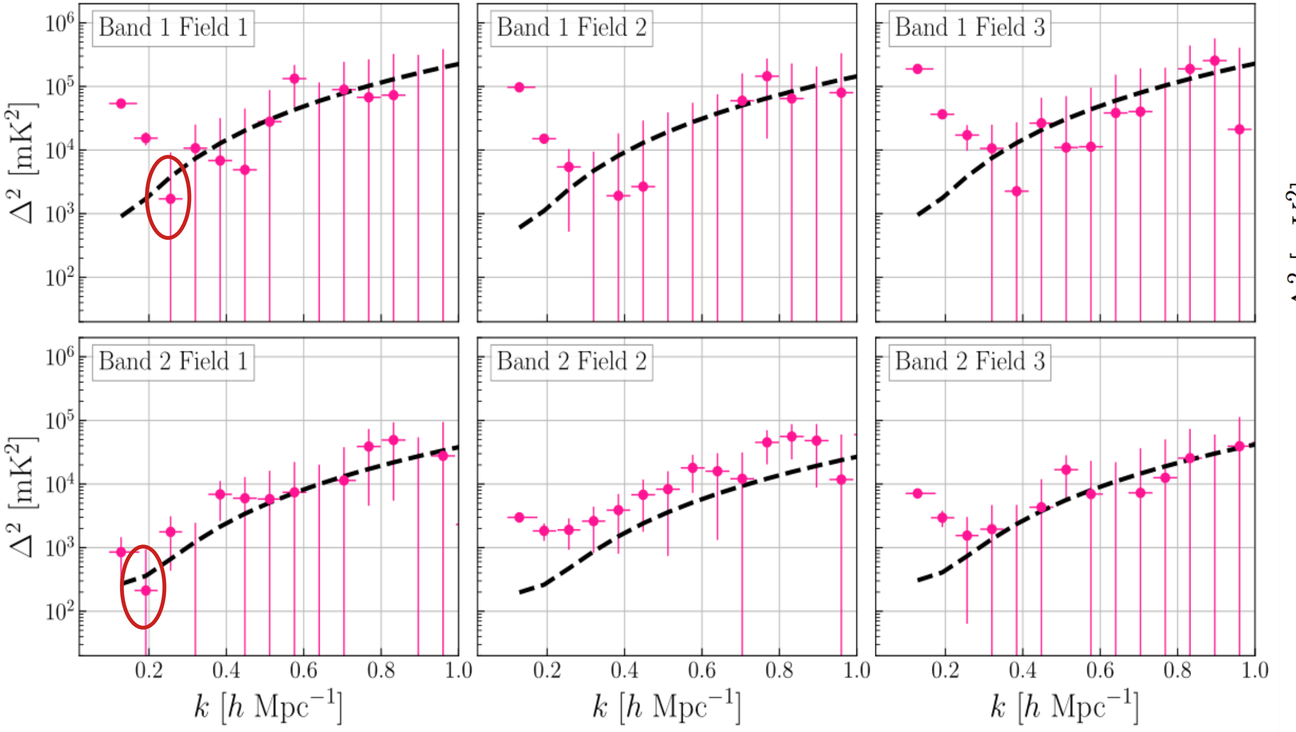
21cm power spectrum

z=10

z=8



(Figure: HERA Collaboration 2021a)

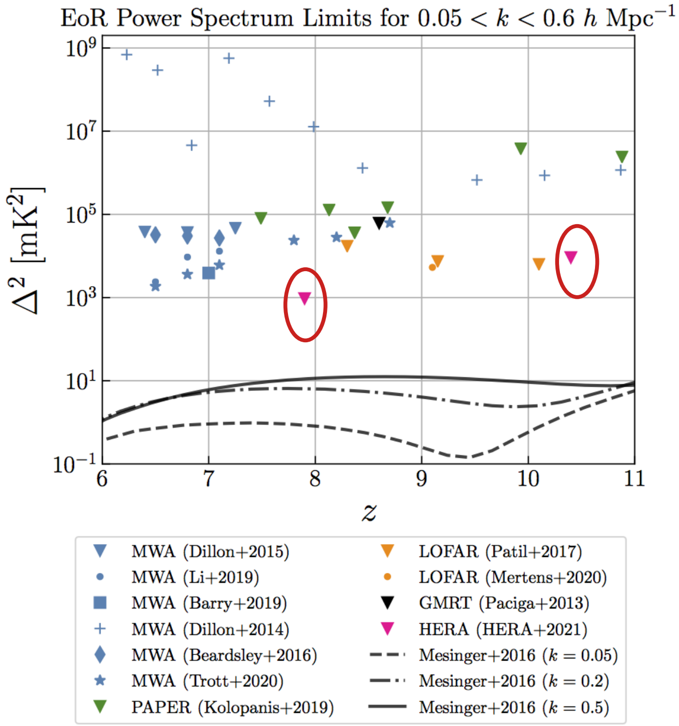


Figure: HERA (http://reionization.org/science/public-data-release-1/)

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

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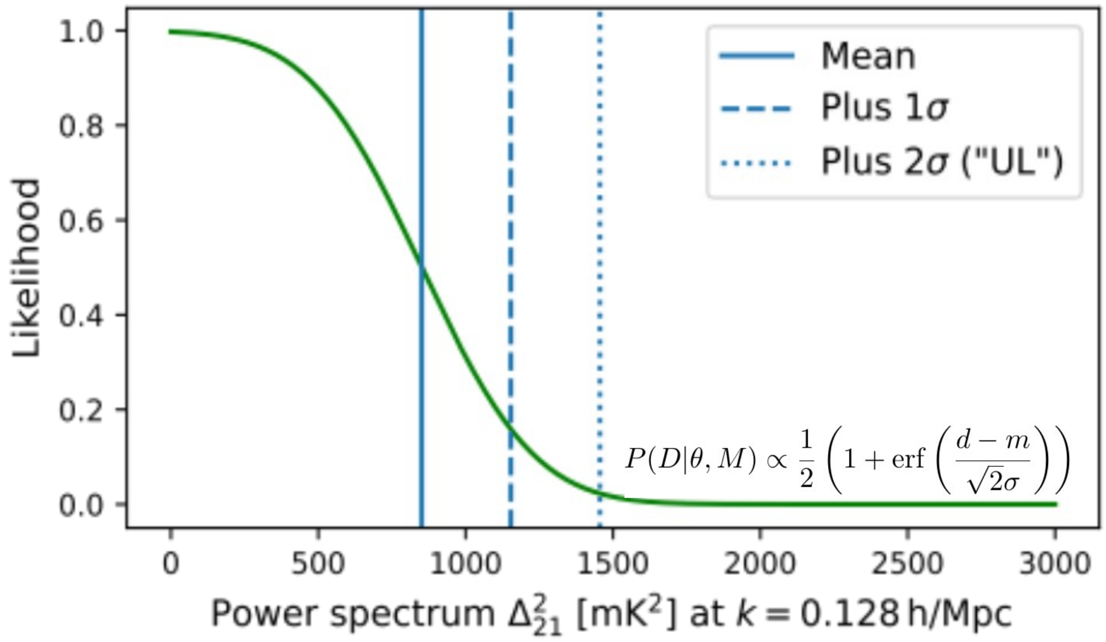
What do we mean by an “upper limit”?

k $h\ \mathrm{Mpc}^{-1}$	Δ^2 $(\mathrm{mK})^2$	1σ $(\mathrm{mK})^2$	Δ^2_{UL} $(\mathrm{mK})^2$
0.128	$(29.17)^2$	$(17.39)^2$	$(38.16)^2$
0.192	$(14.55)^2$	$(19.17)^2$	$(30.76)^2$

Measurement ($14^2 \pm 19^2$ mK^2) = Cosmological + Systematics

→ Cosmological signal anywhere between 0 and measurement

Δ^2 $(\mathrm{mK})^2$	1σ $(\mathrm{mK})^2$	Δ^2_{UL} $(\mathrm{mK})^2$
$(29.17)^2$	$(17.39)^2$	$(38.16)^2$
$(14.55)^2$	$(19.17)^2$	$(30.76)^2$



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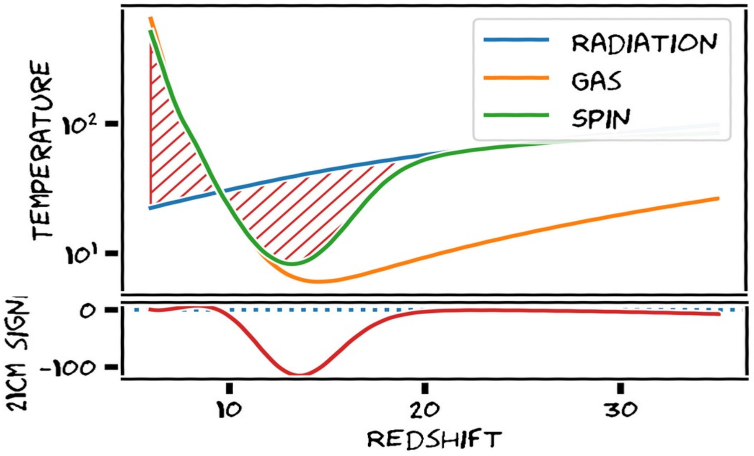
Intuitive interpretation of HERA limits

(lead by Julian B. Muñoz)

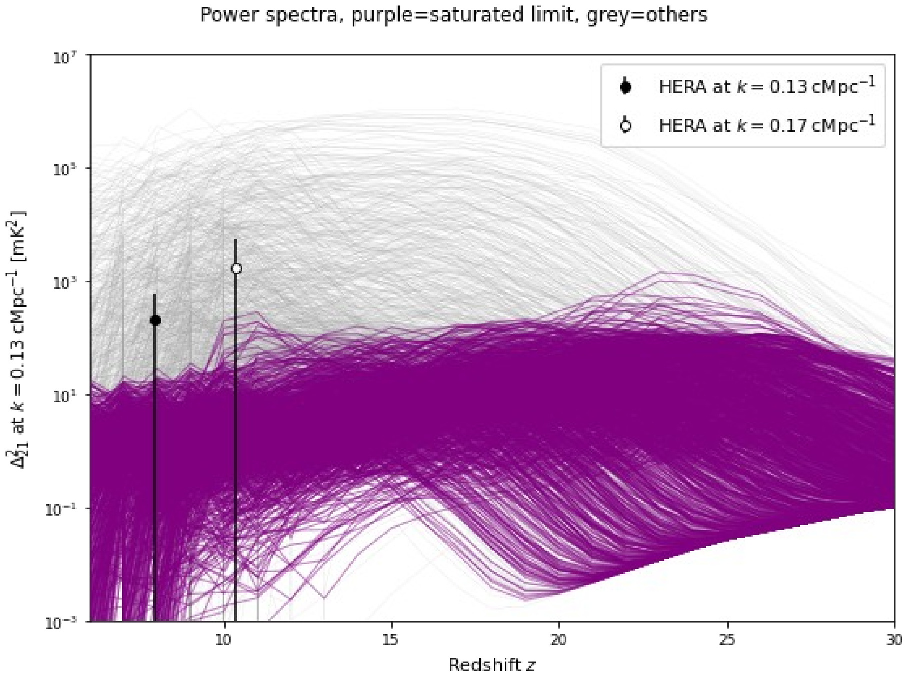
$$T_{21} \propto \left(1 - \frac{T_{\rm rad}}{T_S}\right)$$

Positive: Emission, saturated at ~30 mK

Negative: Absorption, up to 100% in principle



Emission not yet detectable:



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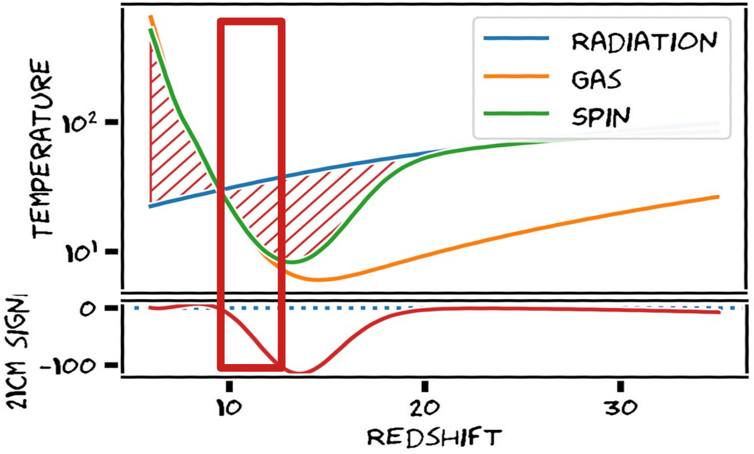
Intuitive interpretation of HERA limits

(lead by Julian B. Muñoz)

If 21cm PS traces matter power spectrum ("bias approach")

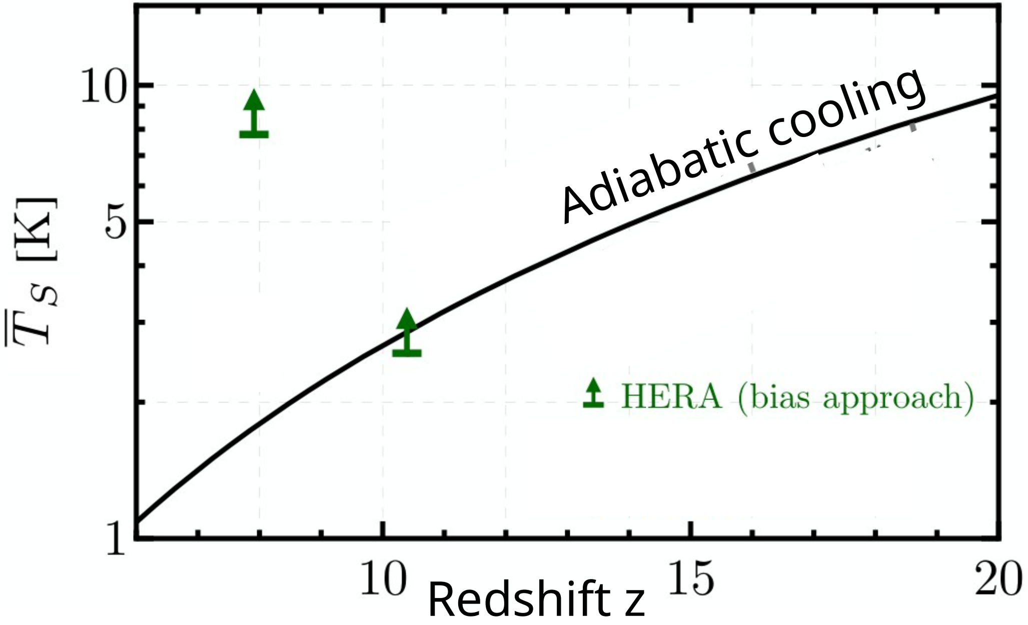
$$\Delta^2_{21}(k,z) = b^2_m(z)\Delta^2_m(k,z)$$

$$b_m = T_0 x_{\rm HI}\left\{(1+\mu) - \frac{T_{\rm rad}}{\overline{T}_{\rm S}}[(1+\mu) - C_T]\right\}$$



Absorption:

Upper limit on $|T_{21}|$ → Lower limit on T_S/T_{rad}



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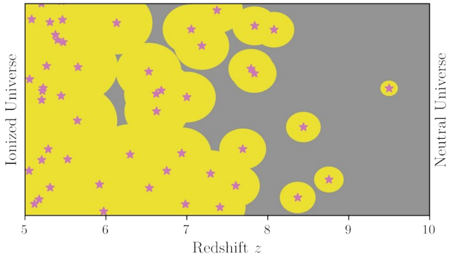
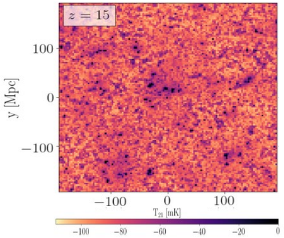
Seminumerical codes (Mesinger et al. & Fialkov et al.)

Numerical simulations: (384 cMpc)^3 size, 3 cMpc cells

- Evolve density field & identify star-forming halos
    (parameterized by M_{min} or V_c)



- Model emission of UV, X-Ray, Radio, LyA etc.
    - (parameterized by τ, f_X, f_r, f_*)



- Compute 21cm brightnes temperature fields and derive power spectra

Image adopted from Reis et al. 2021

Parameters (V_c τ f_* f_X f_r) → **Few hours** → Power spectrum **$\Delta^2_{21cm}(k,z)$**

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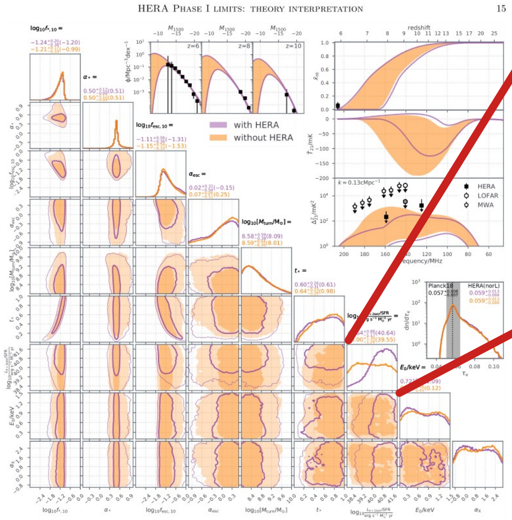
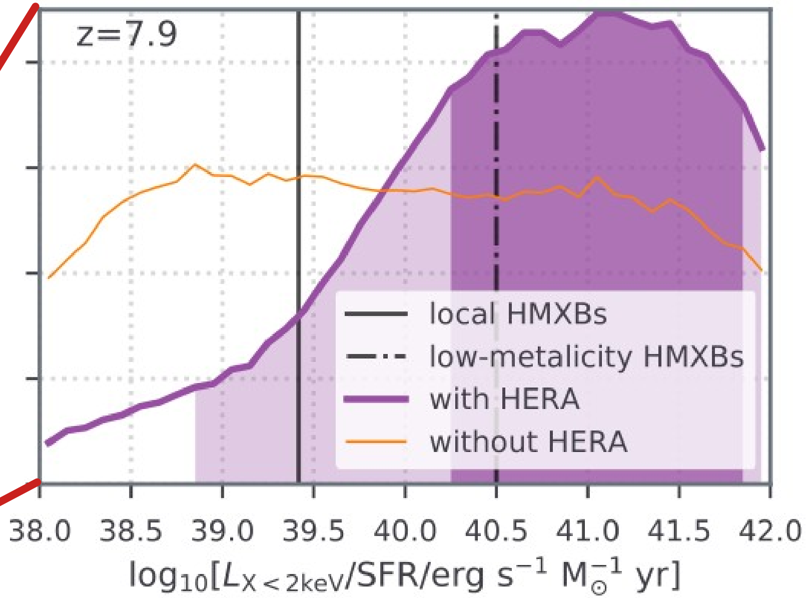
HERA improving complementary constraints

(lead by Yuxiang Qin, with Bradley Greig and Andrei Mesinger)

HERA
+ CMB optical depth
+ QSO Dark Fraction
+ Galaxy UV LF





- **Constraints on galaxies X-ray luminosity**
  - Slightly disfavour X-ray faint galaxies

(CMB-only radio background)

Note: This uses a different numerical code (21cmFAST) → Slightly different parameterization

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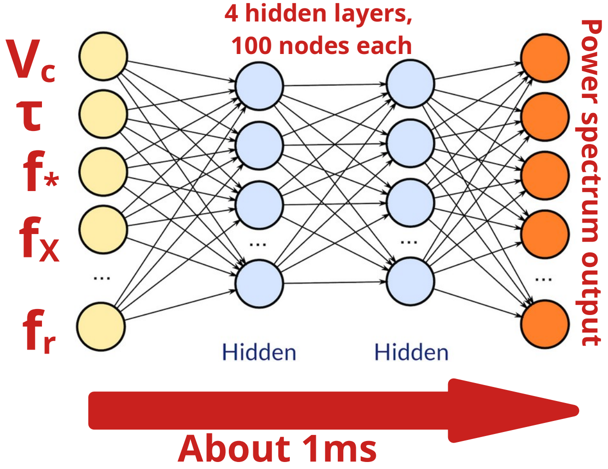
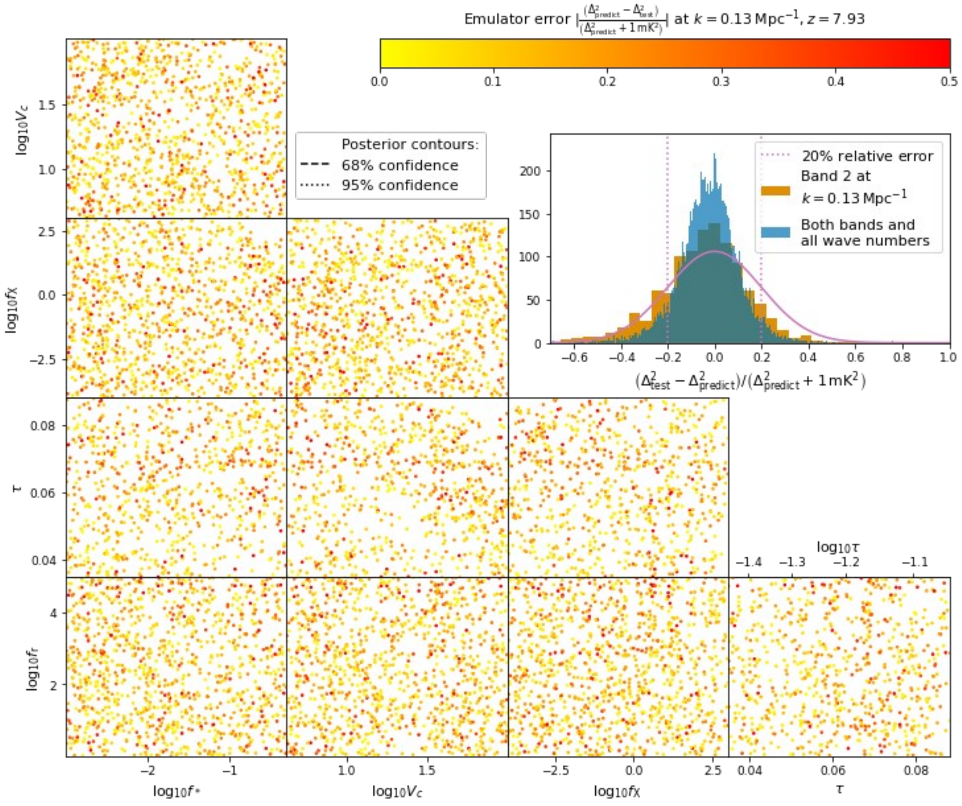
Emulator for Fialkov et al.'s simulations
(lead by S.H., with Anastasia Fialkov)

Neural network

- Use to "emulate" simulation. i.e. effectively interpolate between existing simulations
- 10,000 simulations in 5D parameter space
- Uncertainty ca. 20% of power spectrum





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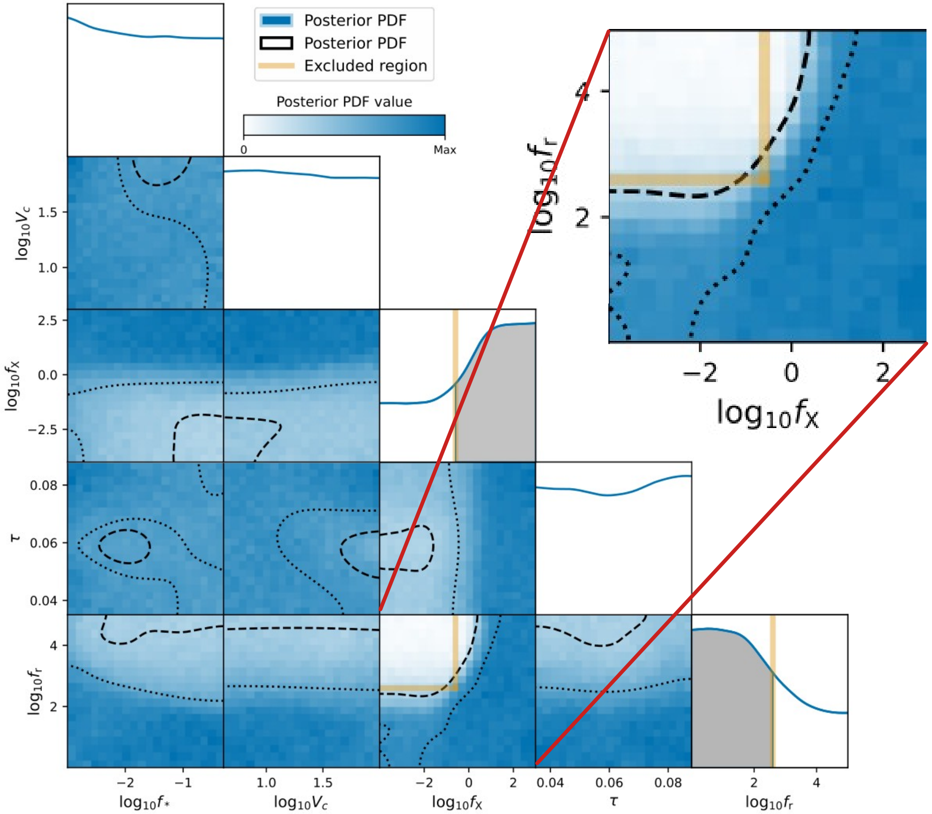
Constraints from HERA limits (alone) on models

(lead by S.H., with Anastasia Fialkov)



Rule out cold IGM together with strong radio background

- Preference for high f_X and low f_r, models with both, ***low f_X and high f_r*** are ***excluded*** (f_X<25% today's X-ray efficiency, f_r>400 times today's radio emissivity)
- Similar constraints: Low f_X with ***synchrotron radio background*** > 5×CMB (large, but lower than ARCADE 2 limits, 50×CMB, Fixsen et al. 2011) ruled out

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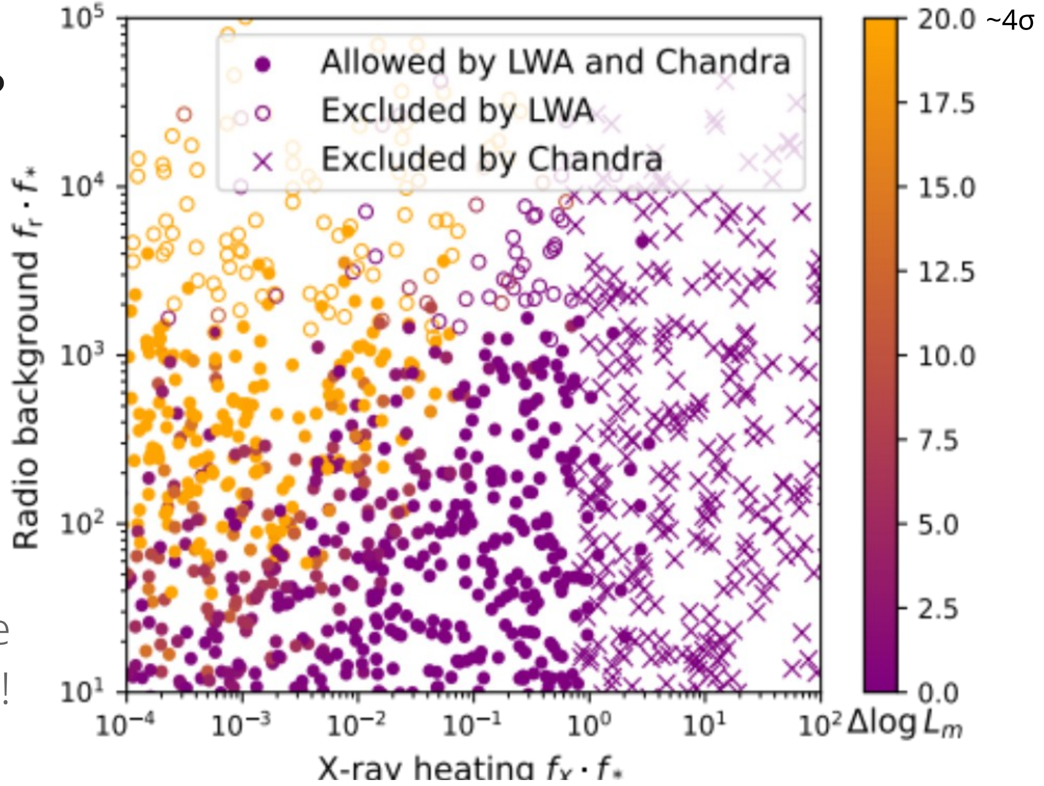
Reality check: Compatible at all with X-ray / radio today?

(lead by S.H., with Anastasia Fialkov)

Are these models consistent with observed radio- and X-ray background?

- **LWA**: Models with $f_r\, f_* > 10^3$ (approx) would produce too much radio background by z=8
- **Chandra**: Unresolved X-ray background allows for (approx) $f_X\, f_* < 1$

HERA clearly reduces the allowed parameter space!



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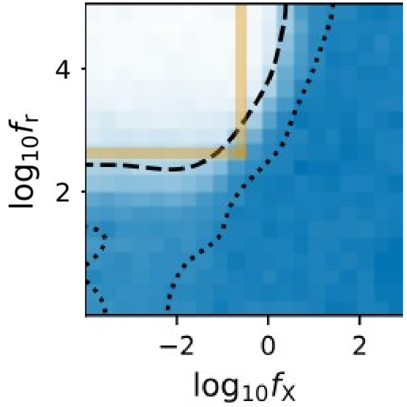
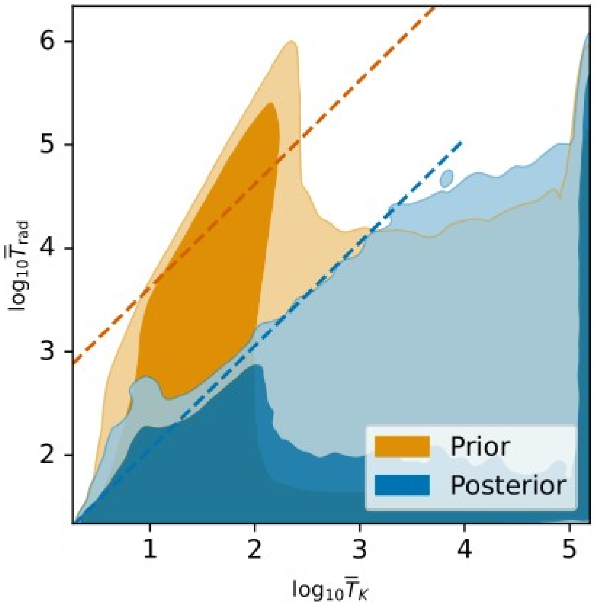
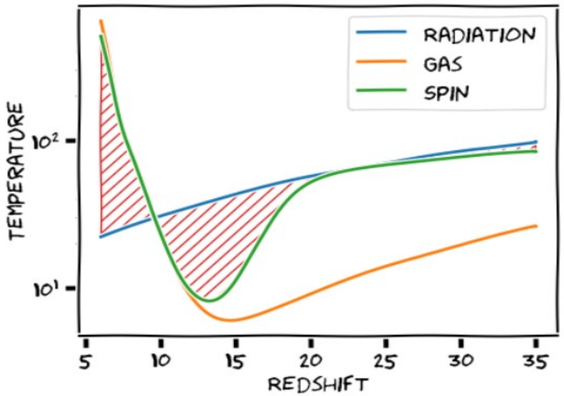
More useful quantities: IGM temperatures

(lead by S.H., with Anastasia Fialkov)







High contrast corresponds to large signal:

$$T_{21} \propto \left(1 - \frac{T_{\rm rad}}{T_S}\right)$$

Excluded models correspond to those with high radio background and relativey low gas temperature (T_{rad} / T_K > 10 excluded)

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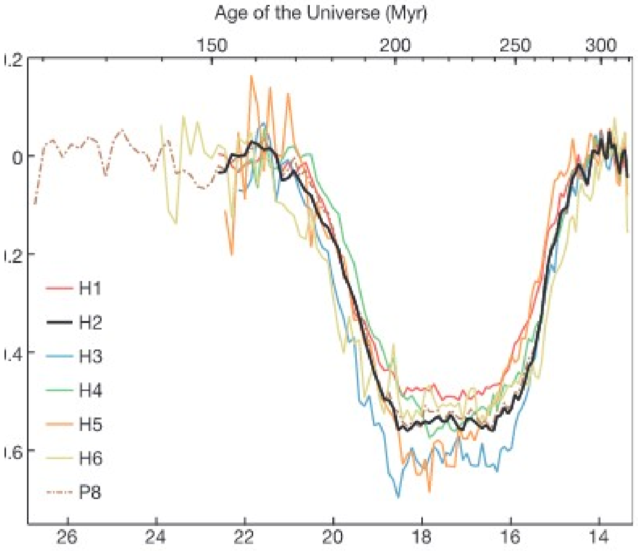
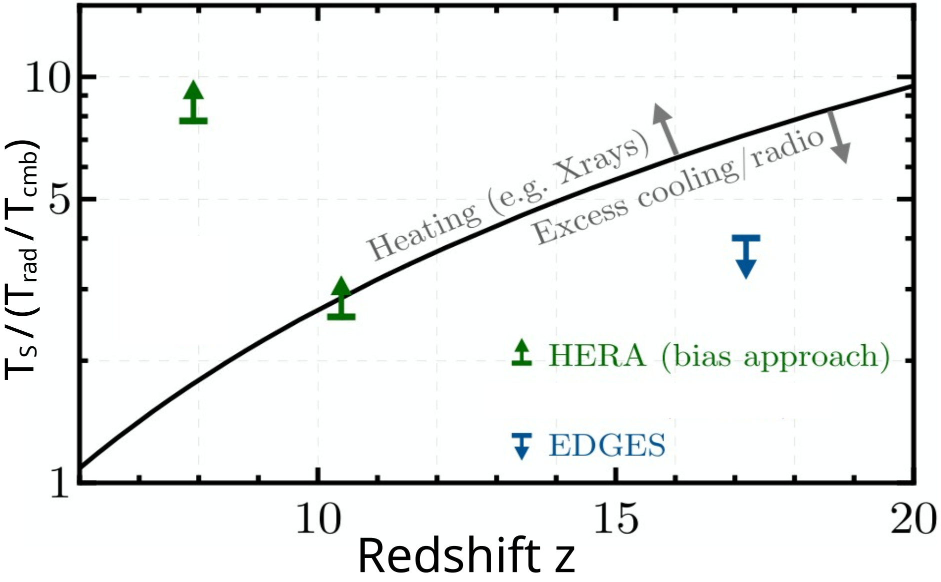
Comparison to EDGES claimed detection and models

HERA → Lower limit on T_S/T_{rad}

EDGES → Upper limit on T_S/T_{rad}



Bowman et al. 2018



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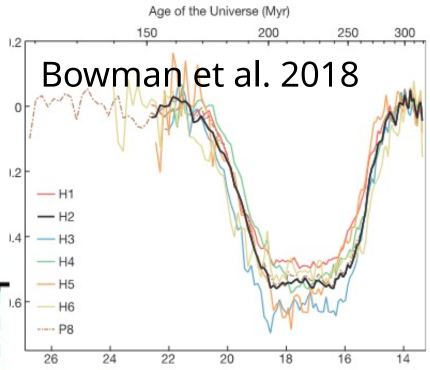
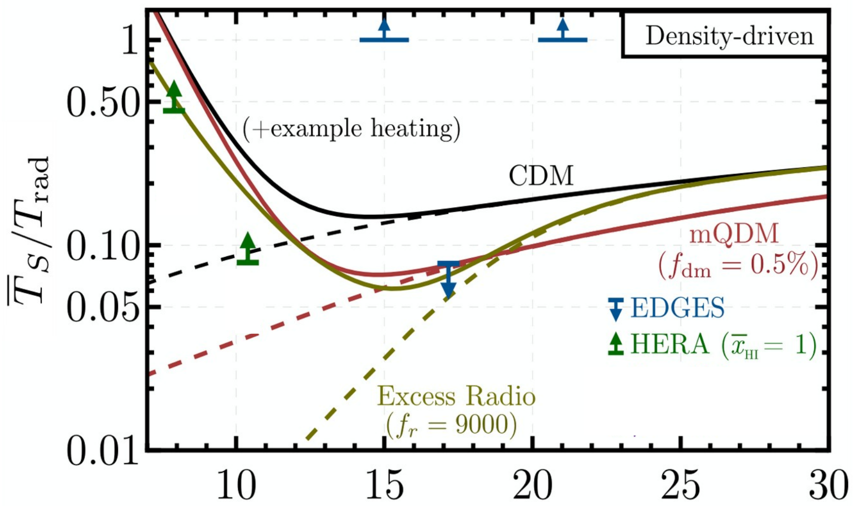
Millicharged Dark Matter constraints

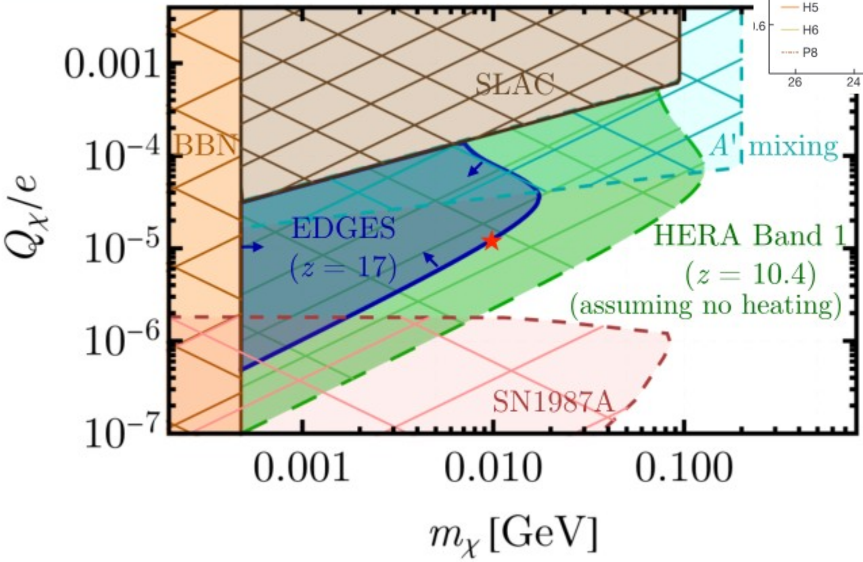
(lead by Julian B. Muñoz)

DM interacting with baryons (e.g. millicharge) cools gas
→ Explains claimed EDGES detection → Ruled out by HERA *(unless heated again)*



Bowman et al. 2018





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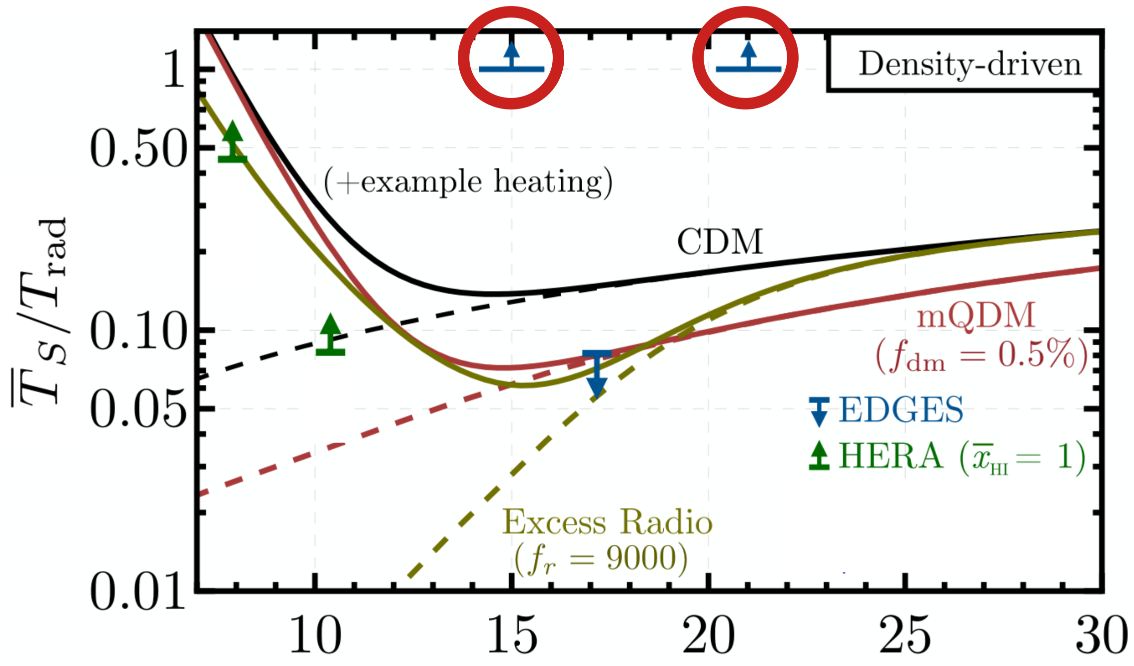
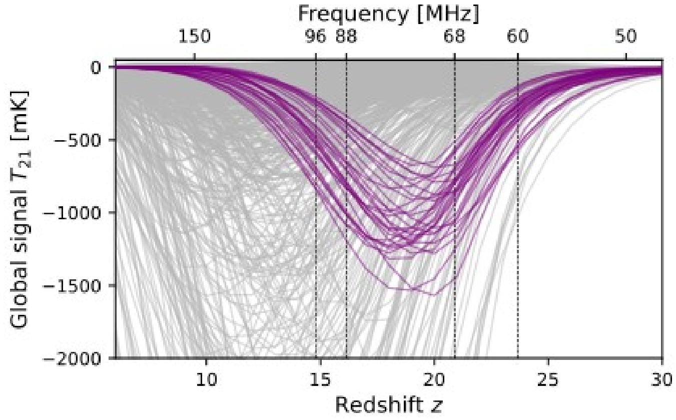
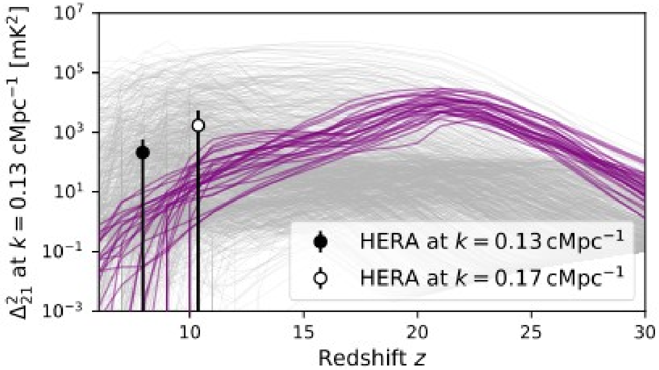
Comparison to full claimed EDGES trough







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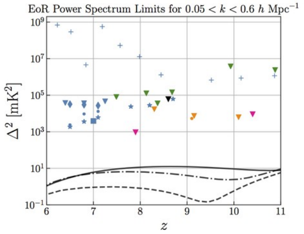
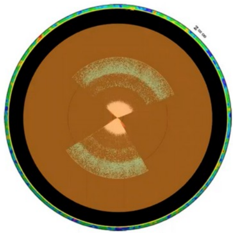
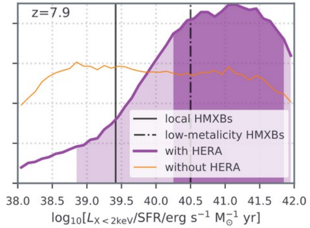
Intermediate summary – HERA 21cm constraints

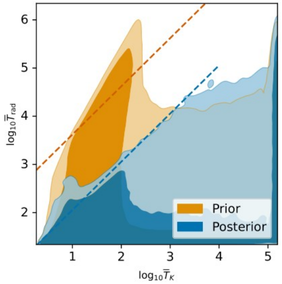
- **21cm cosmology will probe a large part of the observable Universe**
  - Current most stringent power spectrum limits from HERA, $(14.55\text{mK})^2$ +/- $(19.17\text{mK})^2$ at z=7.93, k=0.2 h/Mpc



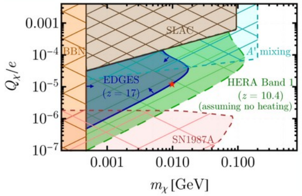


- **Constrain IGM & radiation temperature**
  - Require heating of IGM by redshift 8
  - Ratio $T_{rad}/T_{gas} < 10$





- **Constrain astrophysical models**
  - Rule out some parts of astrophysical parameter space (those leading to high radio / less heating)



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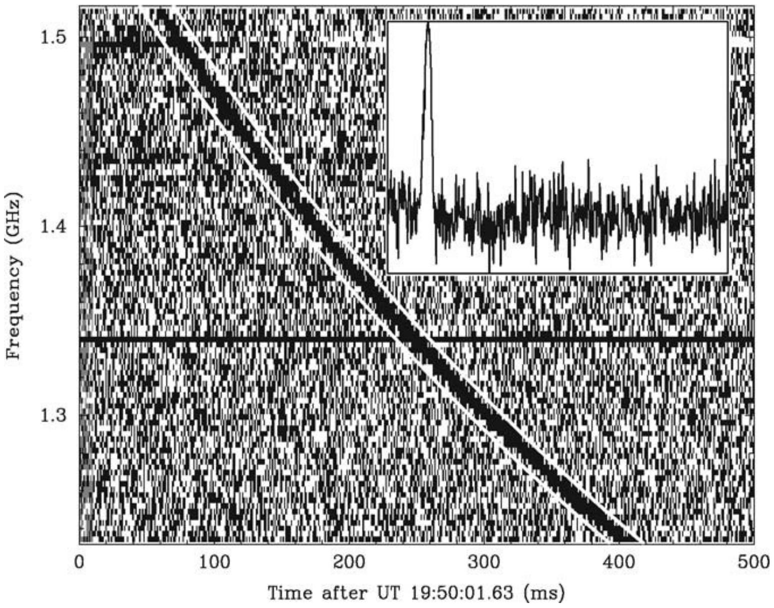
Fast Radio Bursts – the next probe of reionization!

- Short, bright, radio signals
- Extra-galactic (up to z~3)



- Velocity frequency-dependent
  → Arrival times shifted $\propto 1/\nu^2$

$$\mathrm{DM} = \int \frac{n_e}{1+z} \mathrm{d}l$$

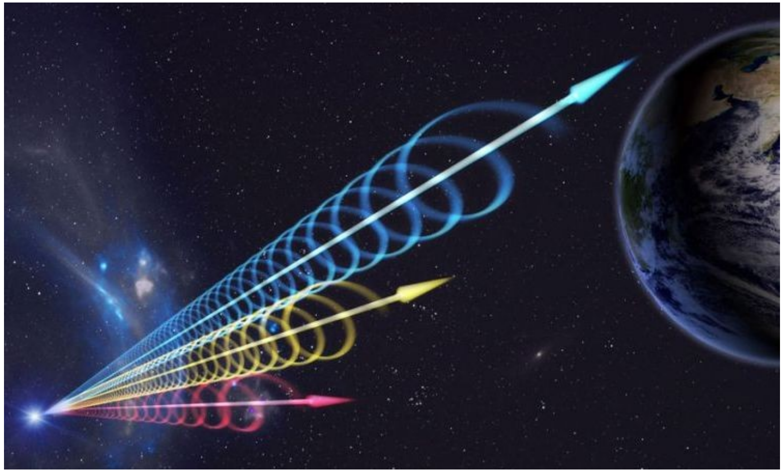
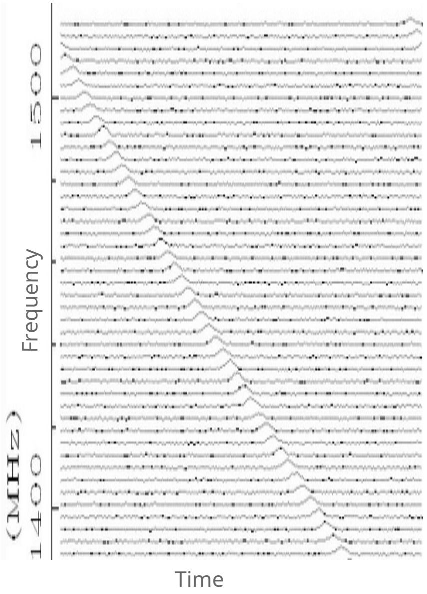


Image credit: Jingchuan Yu, Beijing Planetarium

Plot from Lorimer 2008

- Well know effect in pulsars:



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Fast Radio Bursts – the next great probe of reionization?

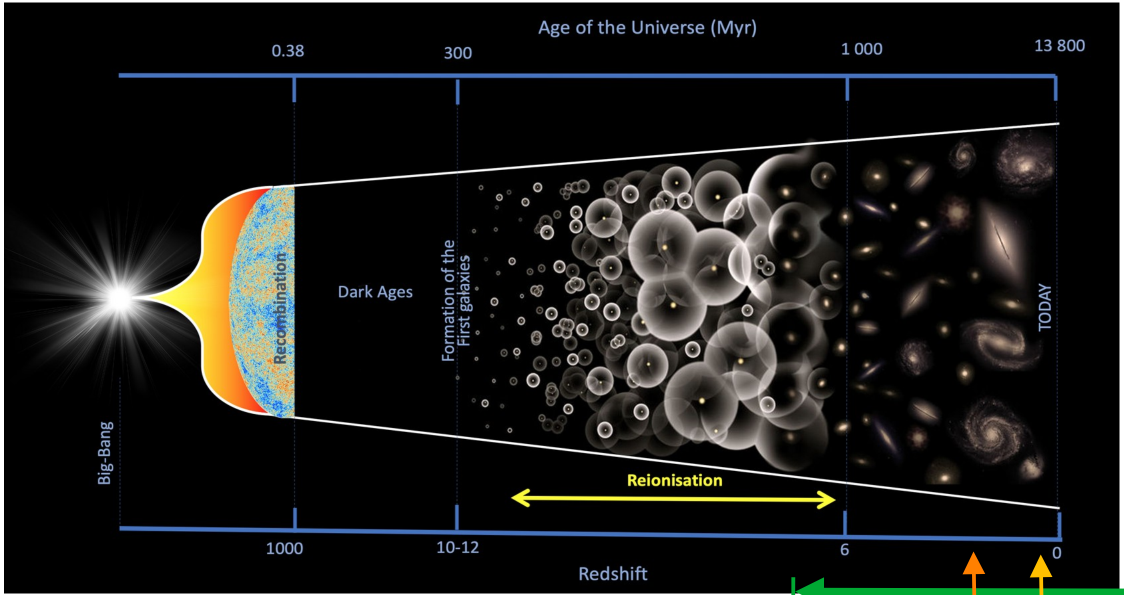
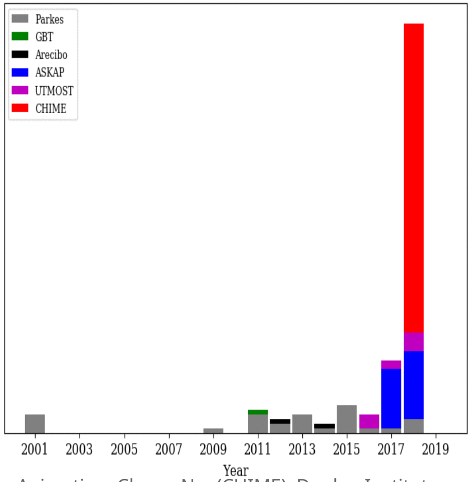


Image credit: Nicolas Laporte



Animation: Cherry Ng, (CHIME), Dunlap Institute
github.com/cherryng

Localized FRBs

Farthest FRBs today

Possible range of FRB sources

Current constraints:

- Quasars z<7.7
- Galaxies z<8

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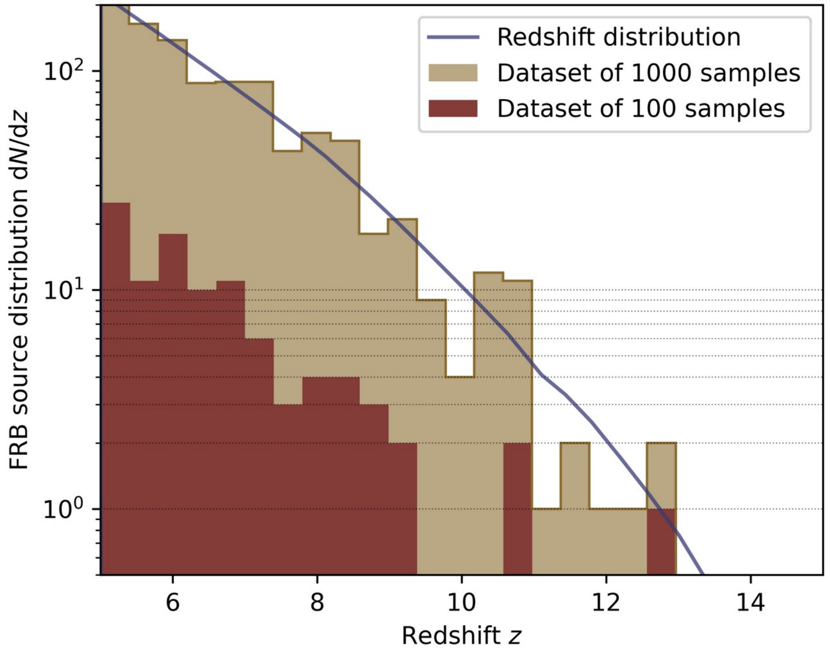
Where do FRBs come from

- **Origin of FRBs unknown – progenitor candidates:**
  - Magnetars
    - FRB200428 was a magnetar but much weaker than extragalactic FRBs
  - Mergers of compact objects
    - White dwarfs / neutron stars / black holes
  - And about 50 further theories at *frbtheorycat.org*
    - From Alien light sails to Axion mini clusters

- **Many mechanisms approximately follow Star Formation Rate**
  - Forecasts for SKA predict up to *100 FRBs/sky/day at z>6* (Hashimoto et al. 2020 [2008.00007])



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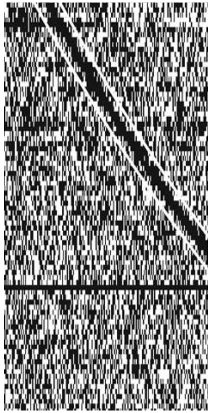
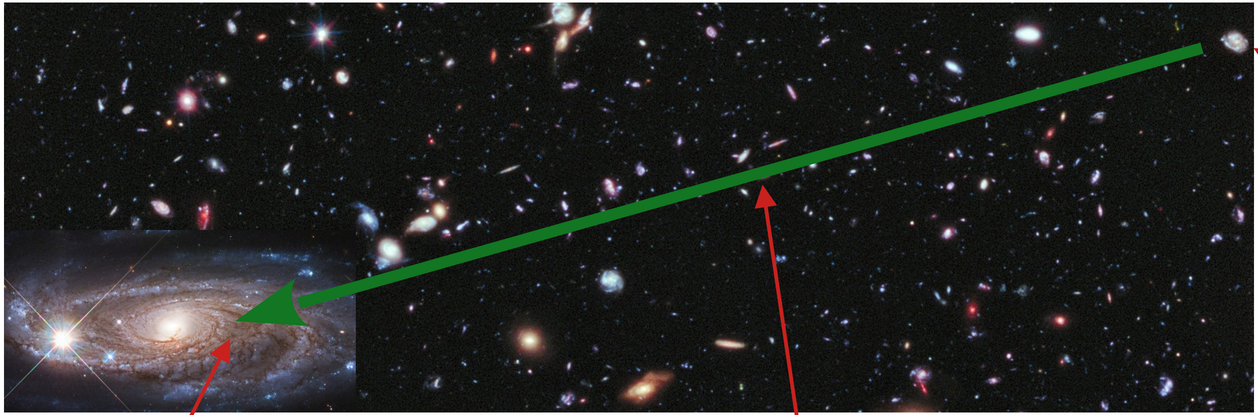
Free electrons between Earth and the FRB source





Host galaxy – **unknown properties** ~ 200 +/- 100 pc/cm^3

Milky Way – from 10 to 500 pc/cm^3 but **known** from MW model

Intergalactic medium – depending on the **distance**, and **ionization** of the IGM along the line of sight

$$DM(z)^{\mathrm{IGM}} = \int_{\mathrm{earth}}^{\mathrm{source}} \frac{n_e^{\mathrm{IGM}}(z)}{(1+z)} \mathrm{d}l$$

~ 4000 - 6000 pc/cm^3 ± 5-9%

(for z=5 to 15)

Image credits: NASA; ESA; B. Holwerda; Illingworth, Oesch, Bouwens and the HUDF09 Team

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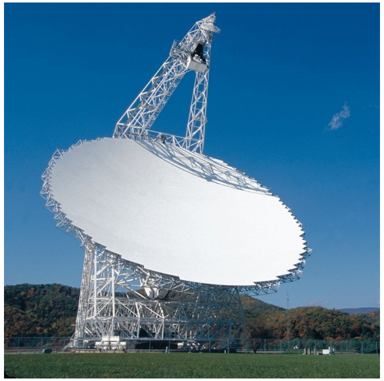
Observational prospects



CHIME: Thousands of low-z FRBs

GBT: Search for high-z high-DM FRBs

FAST: Forecast FRBs up to z=10

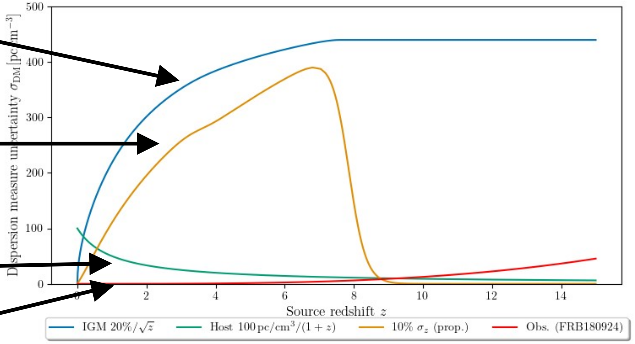
Image credits: CHIME; Absolute Cosmos; NRAO/AUI/NSF

Main uncertainty: IGM inhomogeneity

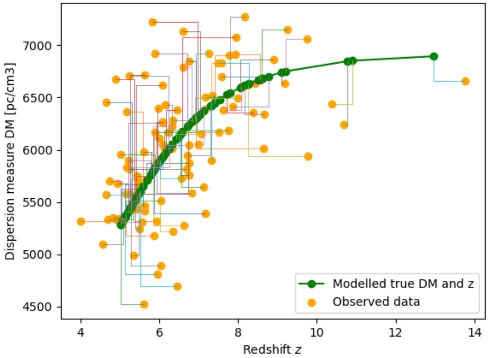
Redshift error (DM-equivalent)

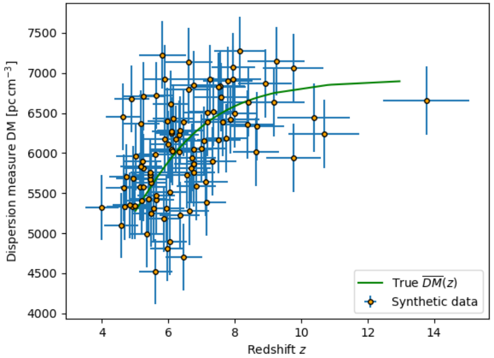
Unknown host contribution

Observational error



Simulated synthetic observations:





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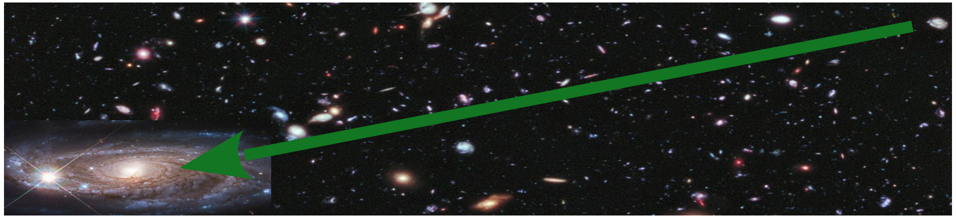
How Reio affects FRBs



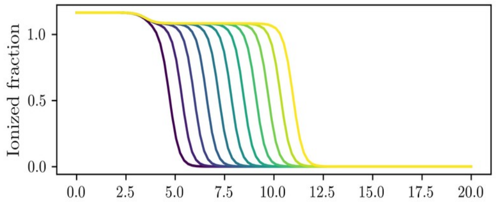
$$\overline{\mathrm{DM}}^{\mathrm{IGM}}(z) = \int_0^z c \underbrace{\frac{\Omega_b}{H(z)}}_{\text{Cosmology}} \underbrace{\frac{\bar{n}_e(z')/\Omega_b}{(1+z')^2}}_{\text{Ionization}} \mathrm{d}z'$$

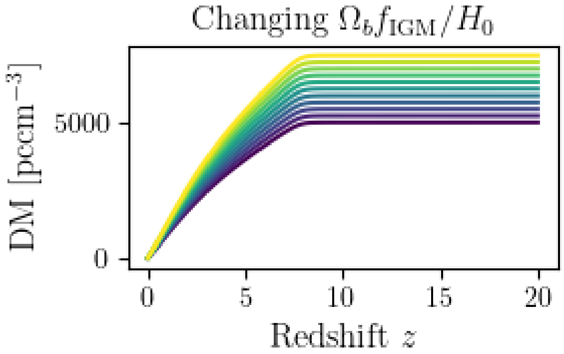
$$H_0, \Omega_b, \Omega_m, w(z)$$

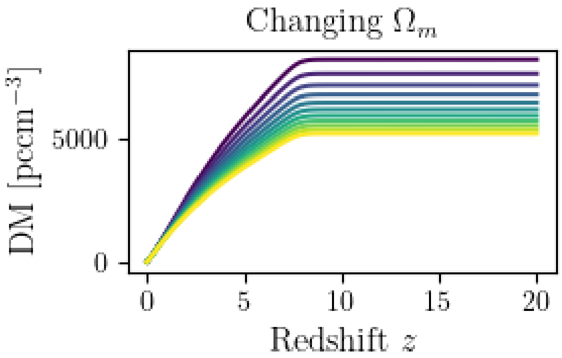
Hagstotz et al. 2021,
Qiu et al. 2021

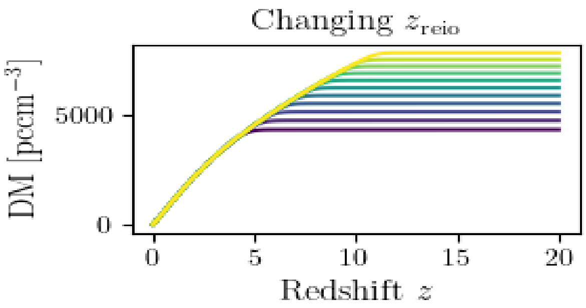
Macquart et al. 2020

E.g. Zhou et al. 2014 (forecast)









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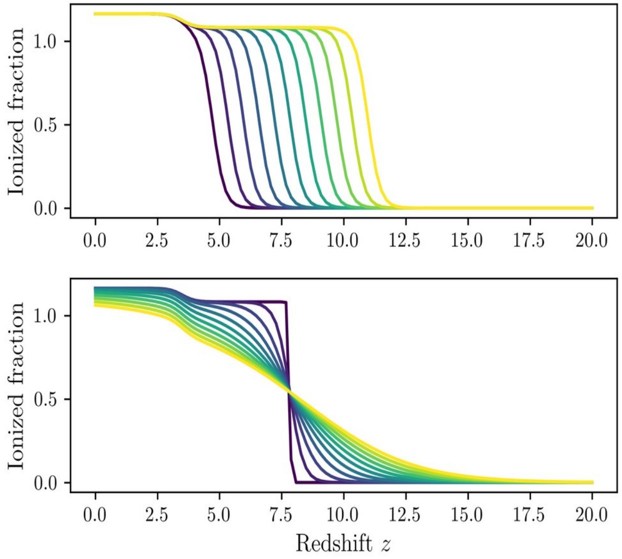
Parameterizing reionization history function

Common *tanh* parameterization:



***Planck* 2018 results**

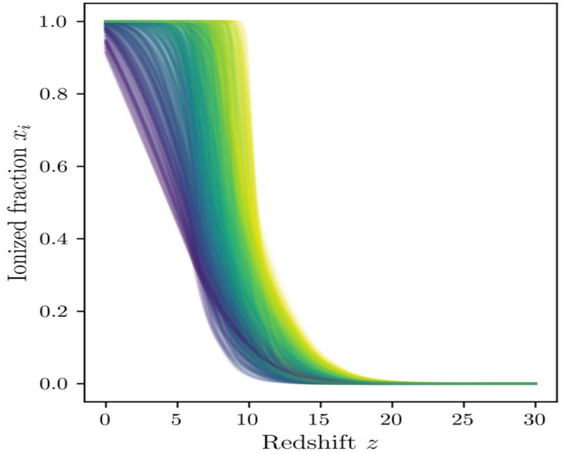
VI. Cosmological parameters

SEVEN-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*[*]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

Results from EDGES High-band. I. Constraints on Phenomenological Models for the Global 21 cm Signal

Reconstruction of Reionization History through Dispersion Measure of Fast Radio Bursts

Reionization simulations (Fialkov et al.):



Problem: Assuming a model → Wrong result if model ≠ reality

E.g. the standard *tanh* step function reionization underestimates τ by 10%

$$\tau_{\text{tanh}} = 0.052 \pm 0.002 \text{ for } \tau_{\text{true}} = 0.057 \text{ (1,000 FRBs)}$$

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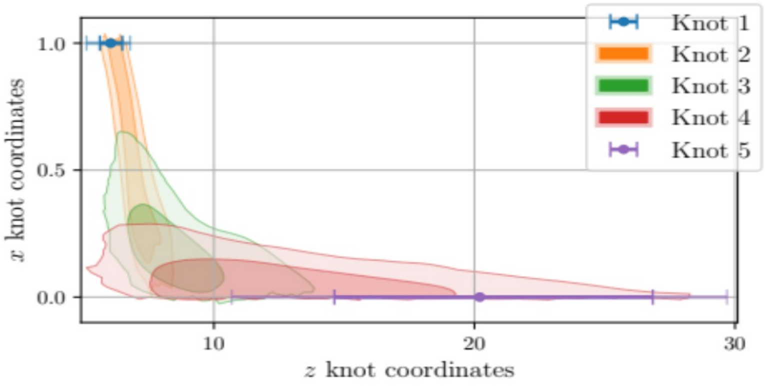
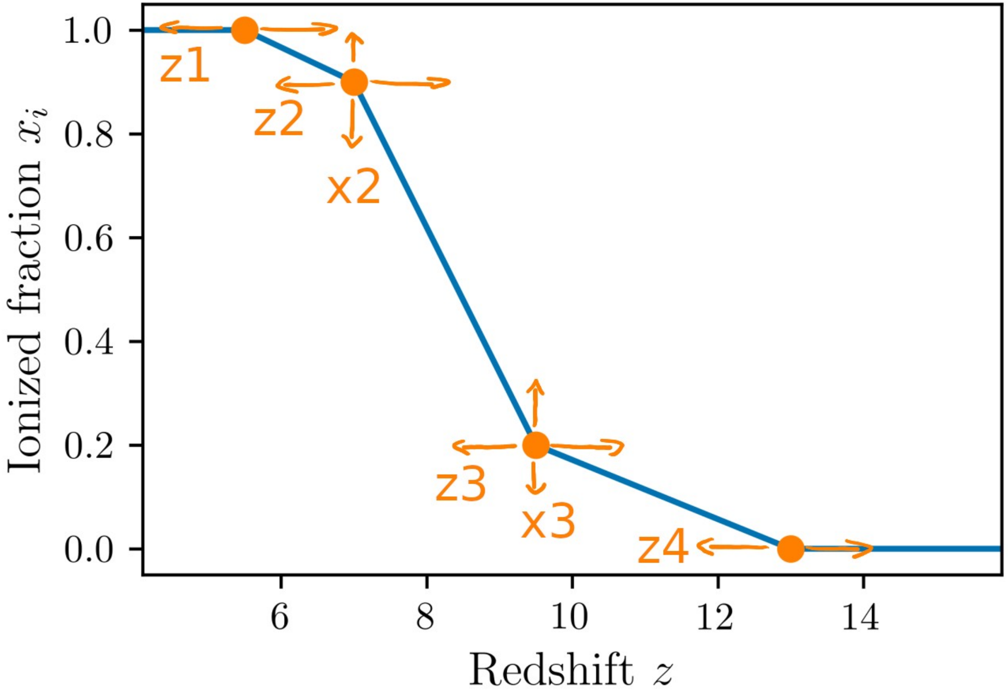
Model-independent parameterization FlexKnot

- **“Free-form” parameterization, interpolate between “knots”**
  - Use coordinates of knots as parameters
  - Interpolate function between knots
  - Obtain constraints on parameters





FlexKnot method CMB: Millea & Bouchet 2018, arXiv 1804.08476

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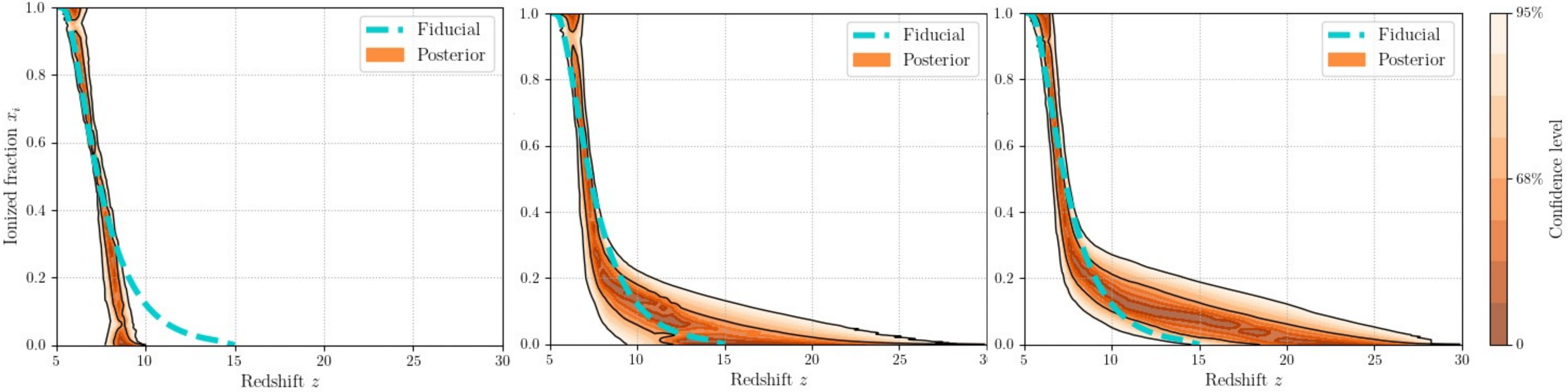
FlexKnot: How many knots?



Only start + end knot:

too simple?

Add +2 more knots:

fits well?

Add +9 additional knots:

too many params?

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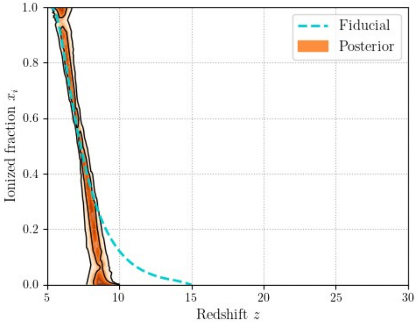
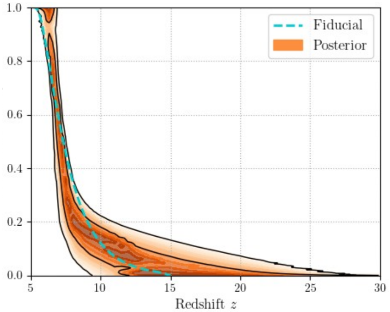
FlexKnot: How many knots?

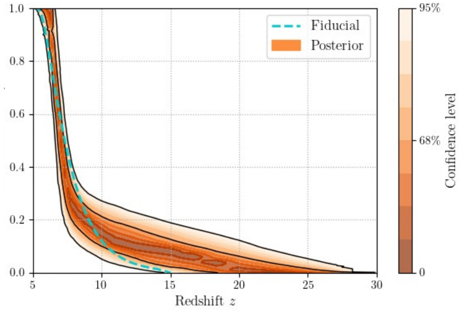
Marginalize over number of knots (→ Evidence)



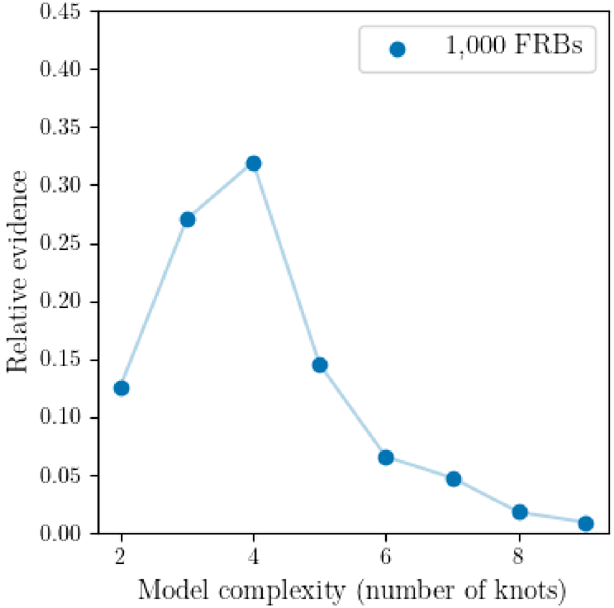
Only start + end knot:
too simple
Evidence Z = 0.4



Add +2 more knots:
fits well
Evidence Z = 1



Add +9 additional knots:
too many params
Evidence Z = 0.01



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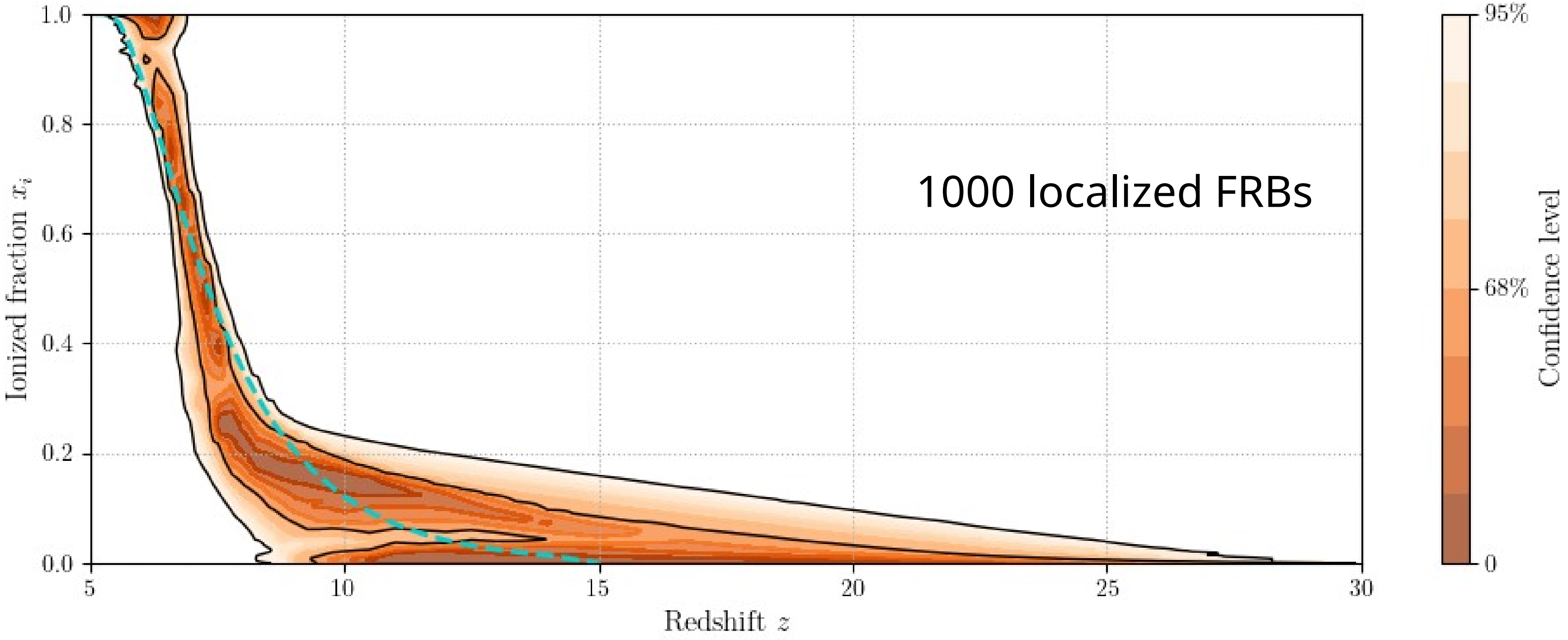
Reionization history constraints: FRBs only



1000 localized FRBs

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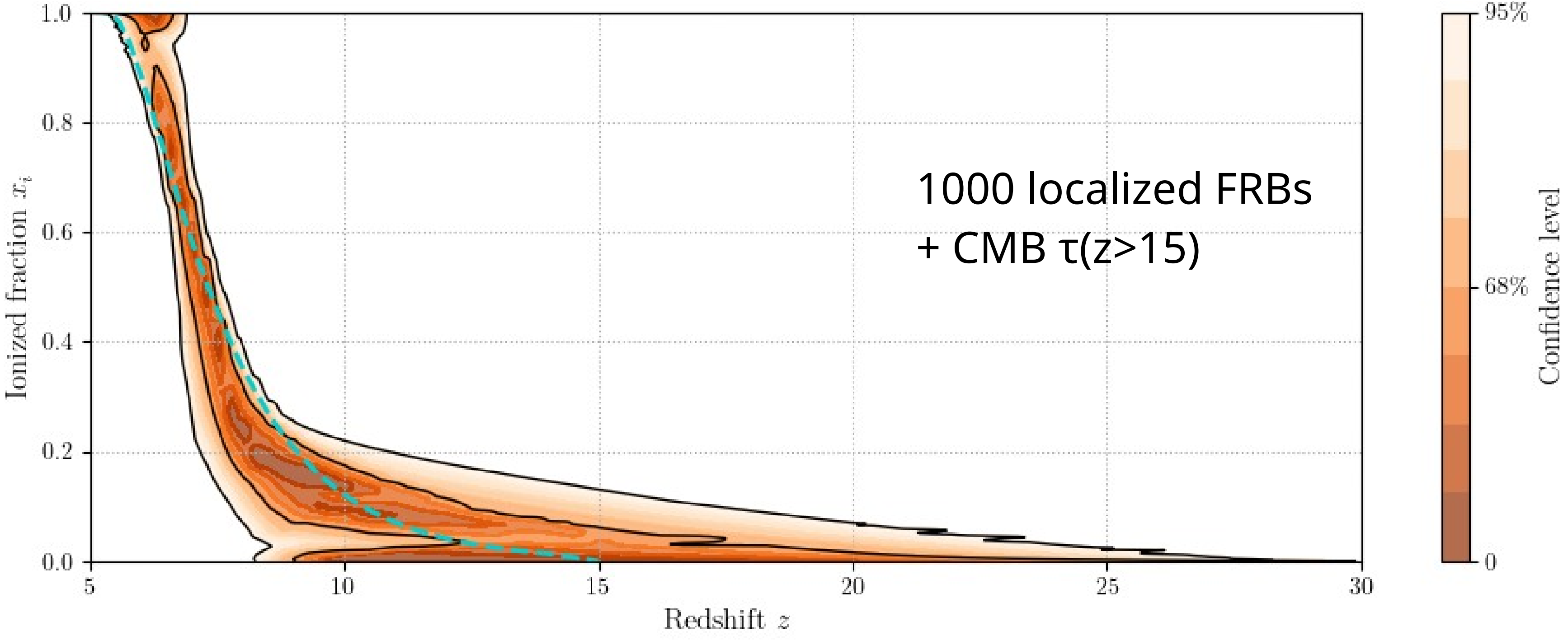
Reionization history constraints: Add τ(15,30)

Advantages of having *function* $x_i(z)$: 1) Combine with integral constraint τ(15,30)



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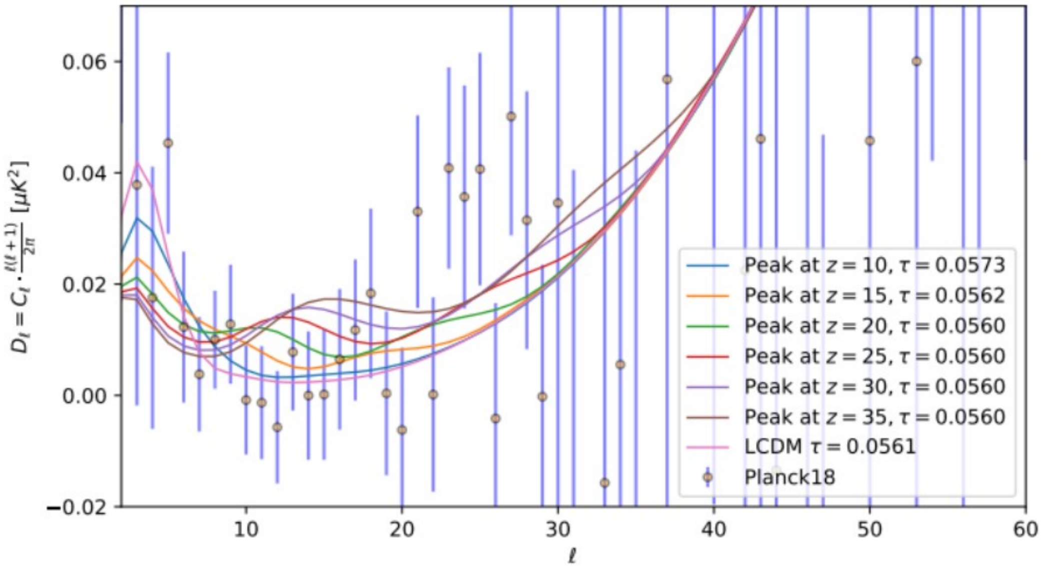
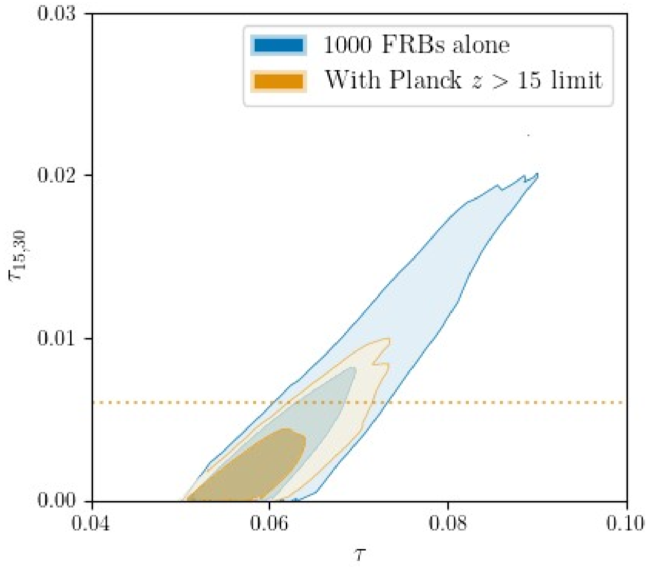
Synergy with Cosmic Microwave Background

CMB poralization power spectra observations limit early reionization, *Planck* **FlexKnot:** τ(15,30) < 0.006



FRBs provide weak constraints for z>15



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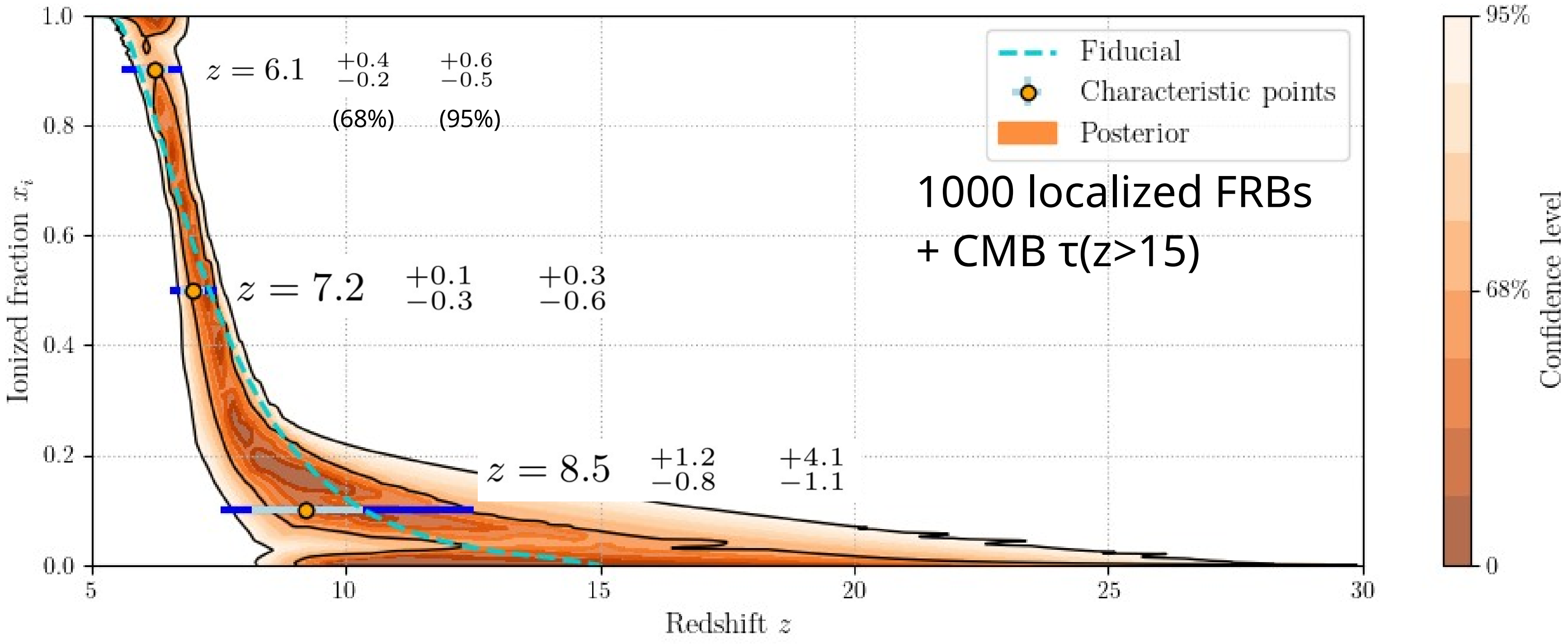
Reionization history constraints: Redshifts

Advantages of having *function* $x_i(z)$: 2) Derive additional constraints (e.g. midpoint)



1000 localized FRBs
+ CMB τ(z>15)

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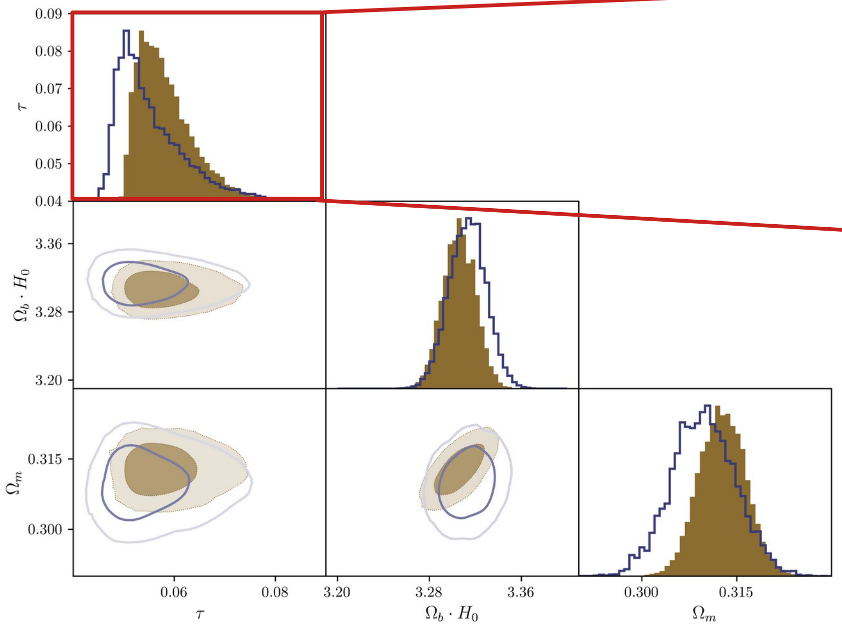
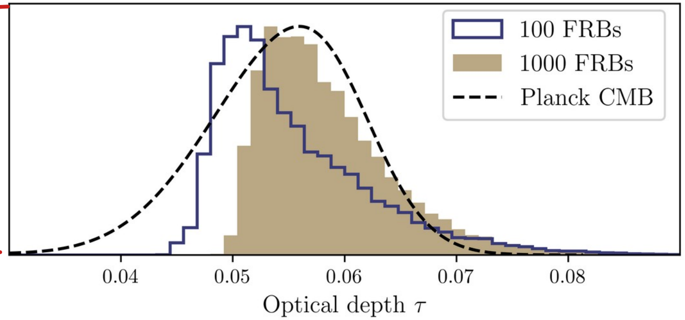
Cosmology constraints

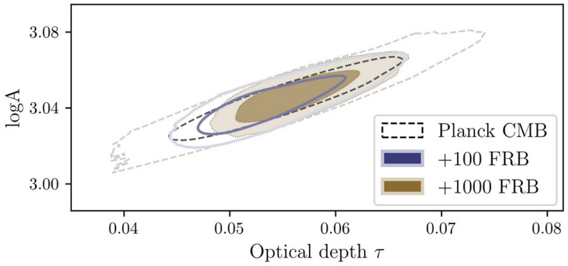
Key point: Reionization model-*marginalized* (“independent”), i.e. averaged over all reionization models.





Improvements on other parameters

- Improve primordial PS (A_s and n_s) constraints
- Better neutrino mass constraints (especially with future LSS surveys)



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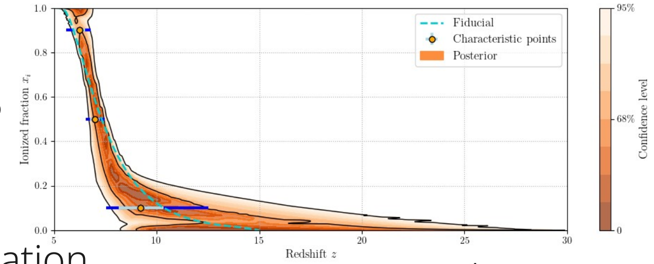
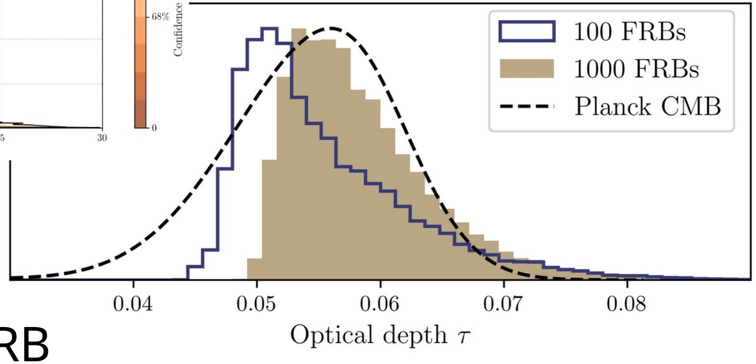
Summary

- **FRBs can probe Era of Reionization**
  - Competetive constraints with 100 FRBs @z>5
- **Need to avoid biases in our methods**
  - Model-independent reionization parameterization
  - Applicable to all kinds of function constraints



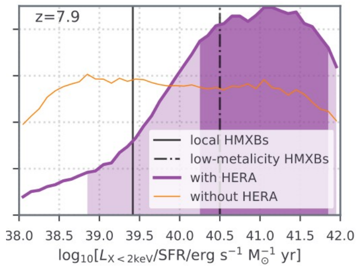


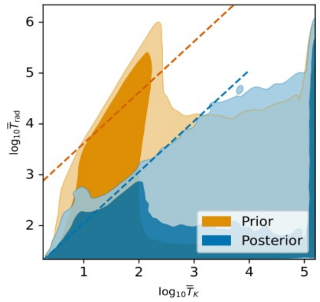
arXiv: 2107.14242

Source code: github.com/Stefan-Heimersheim/FlexKnotFRB

- **HERA 21cm power spectrum rules out first astrophysical models**

  → Constrain X-ray heating & radio background / temperatures





arXiv: 2108.07282

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