Reionization constraints from HERA 21cm power spectrum limits

Based on work with the HERA Collaboration & Theory team

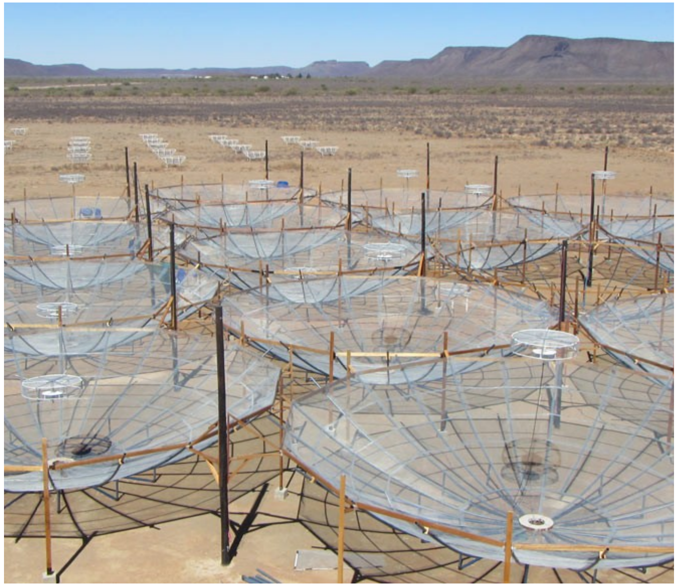
HERA Phase I Limits on the Cosmic 21-cm Signal: Constraints on Astrophysics and Cosmology During the Epoch of Reionization [arXiv 2108.07282]

Stefan Heimersheim

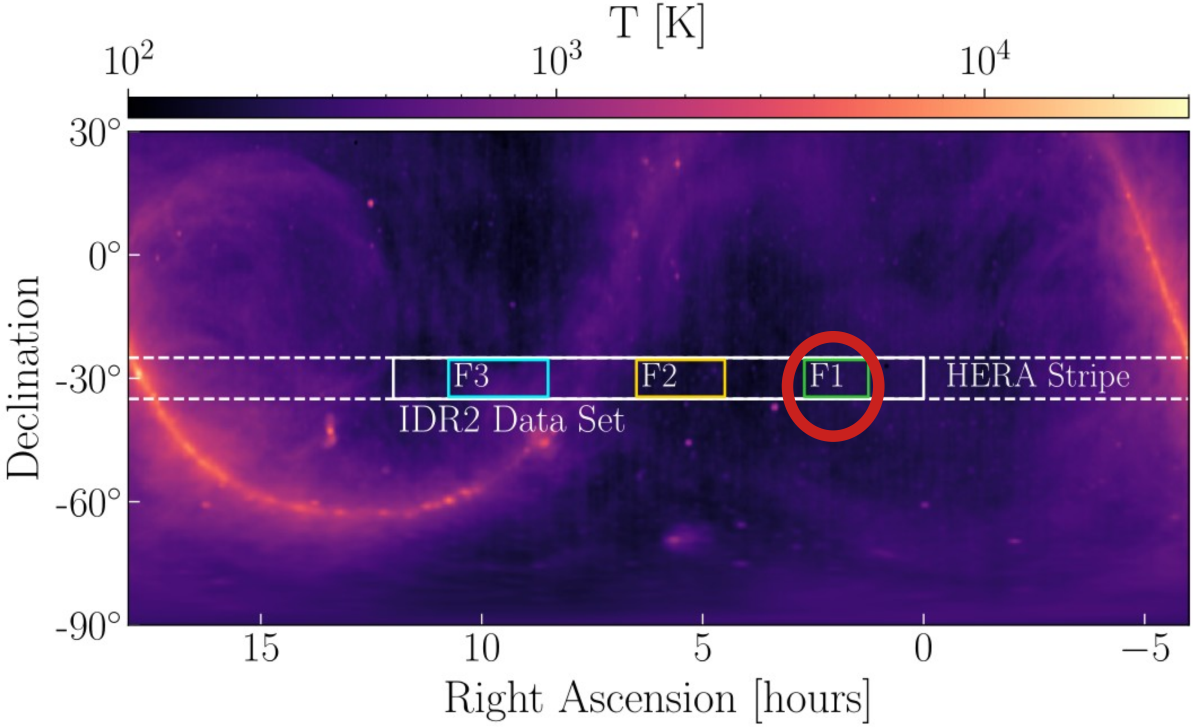
3rd year PhD student with Anastasia Fialkov (IoA)

Other research: Reionization constraints with Fast Radio Bursts

The HERA Telescope



HERA telescope in Karoo desert, South Africa
Image credit: HERA Partnership



39 antennas, 18 nights of observation, separated by LST (fields), drift scan
Figure from HERA papers (arXiv 2108.02263, 2108.07282)

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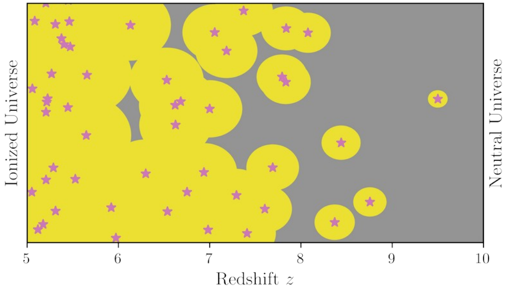
21cm power spectrum



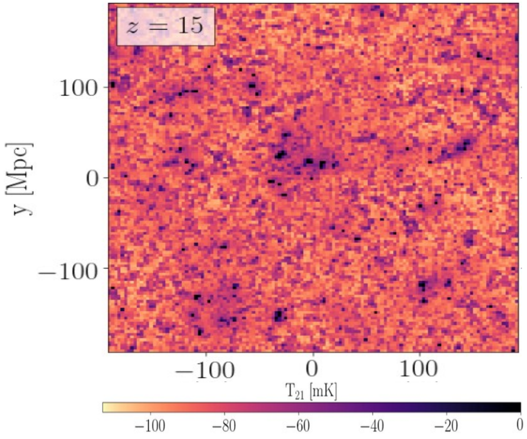
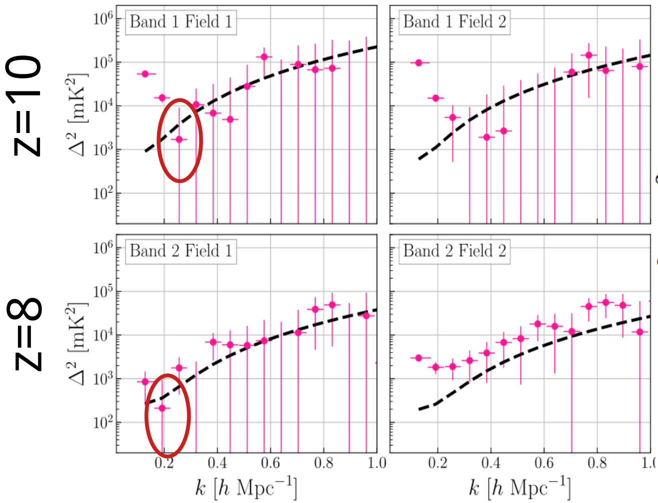


Image adopted from Reis et al. 2021



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

(Figure: HERA Collaboration 2021a)

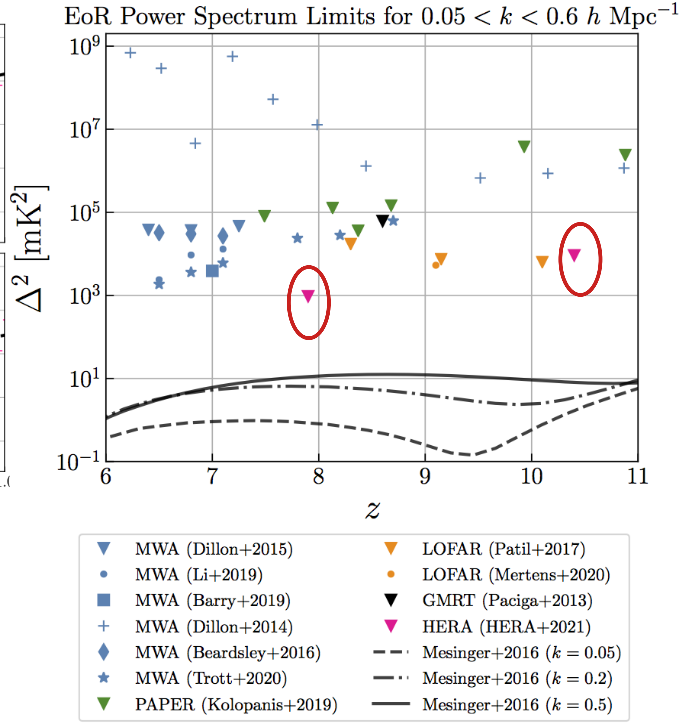


Figure: HERA (http://reionization.org/science/public-data-release-1/)

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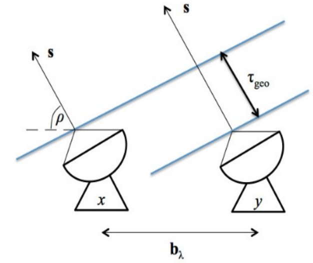
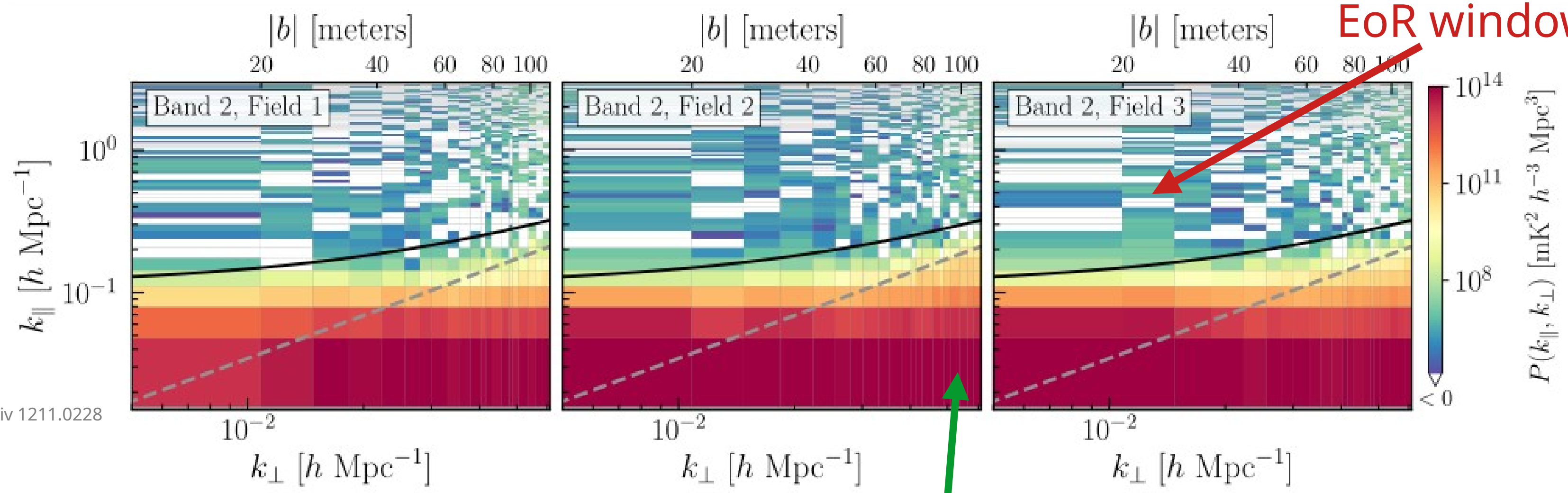
The 21cm signal EoR window



Interferometer
→ Baseline ~ k⊥
→ Frequency ~ k∥

Graphics credit: Avison & George, arXiv 1211.0228

EoR window



Power spectra and foreground wedge
(Figure adopted from from HERA Collaboration 2021a)

Foregrounds

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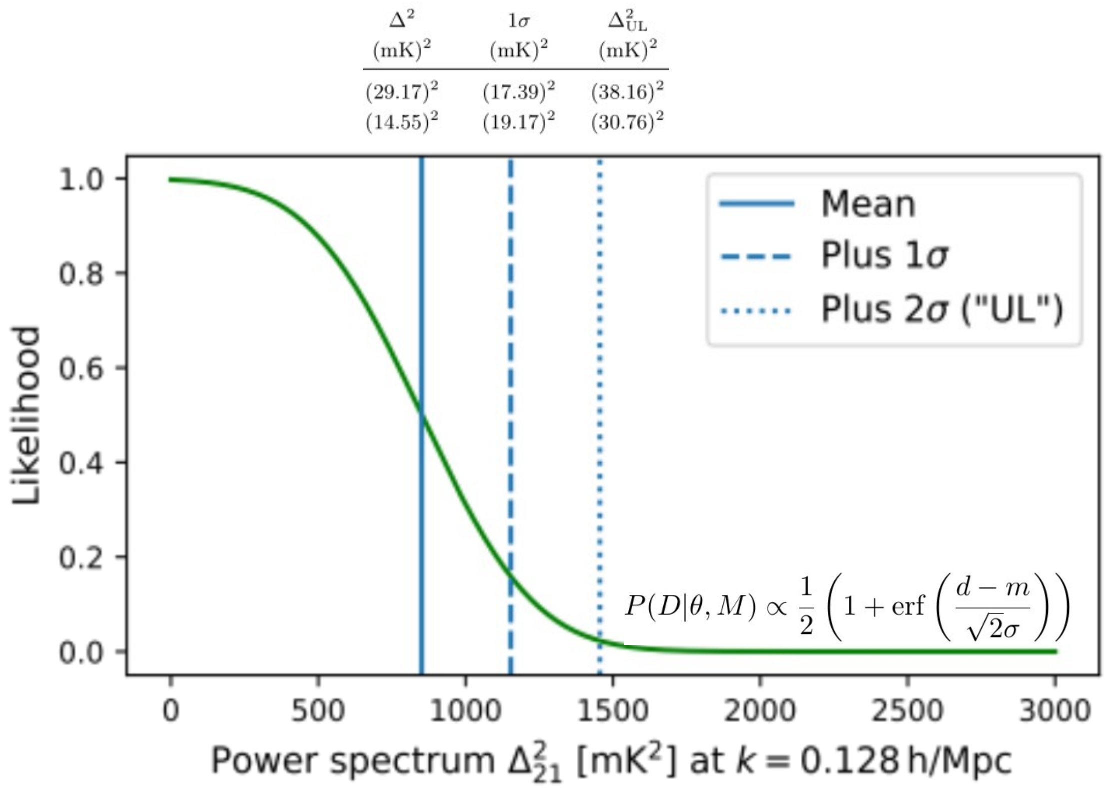
What do we mean by an “upper limit”?

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



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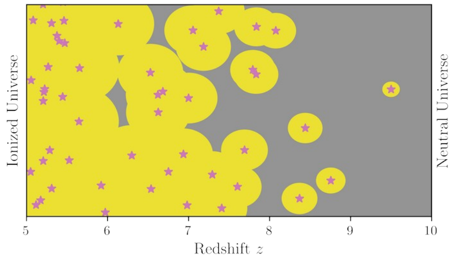
Seminumerical codes (see Thomas' talk)

Numerical simulations (e.g. Fialkov et al.)



- 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

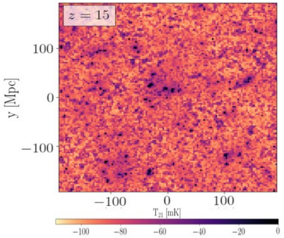


Image adopted from Reis et al. 2021

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

Few hours

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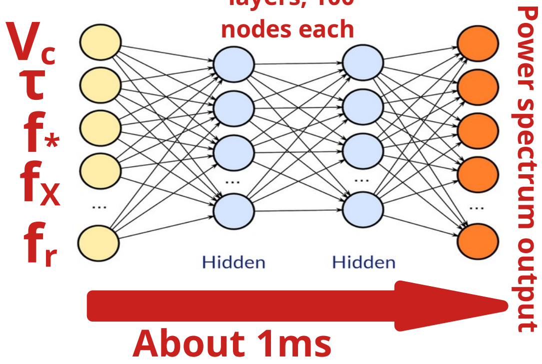
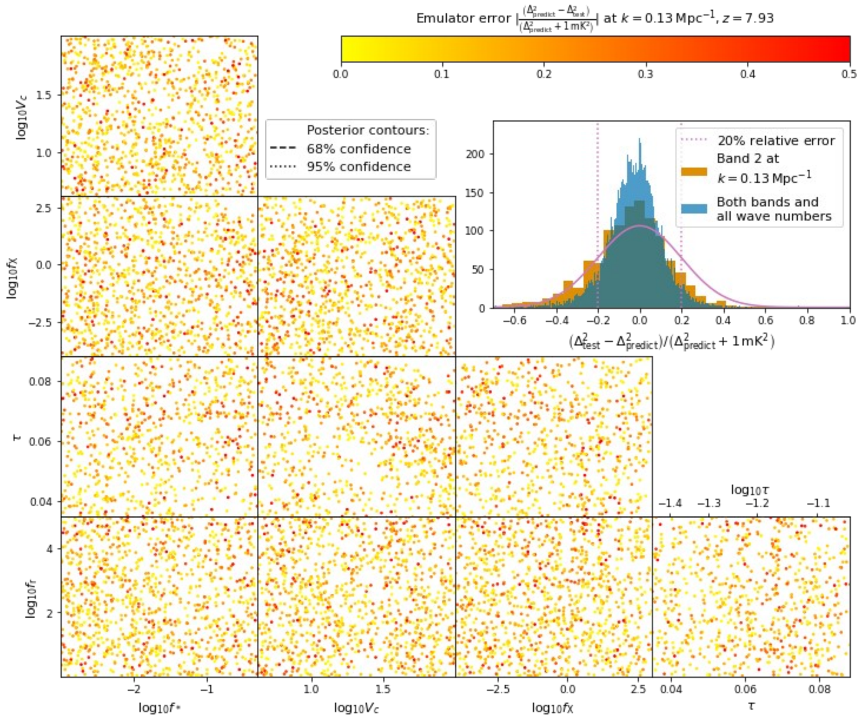
Emulator for semi-numerical simulations

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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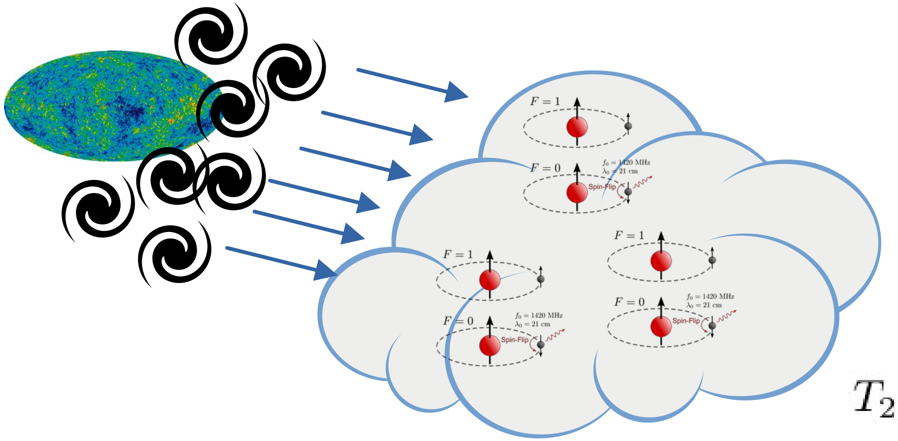
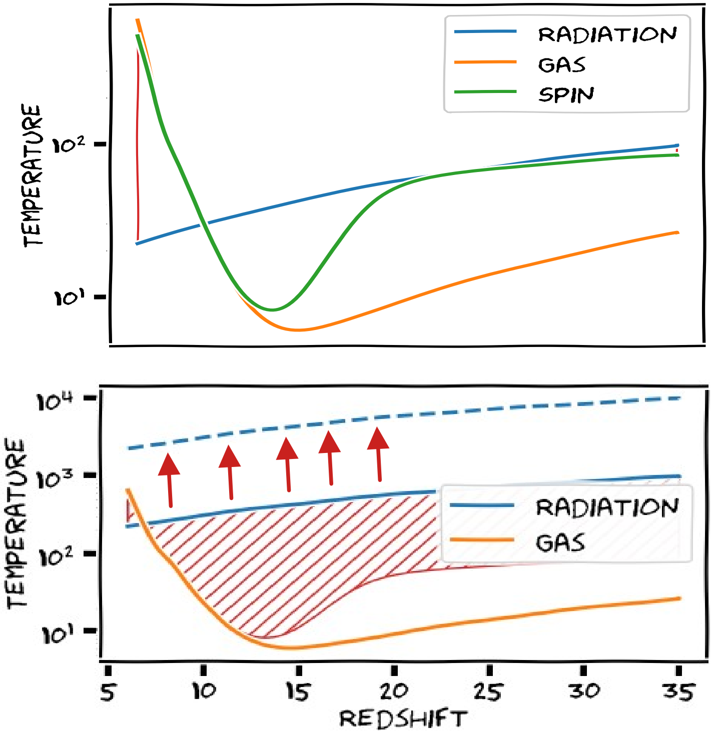
21cm signal & extra radio background



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



- Extra background radiation in addition to CMB:
    - Homogeneous synchrotron background, strong at high z (see also Shikhar's PBH talk)
    - Radio emission from galaxies (inhomogeneous, scaling with SFR)

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Extra Radio Background in 21cm Power Spectra

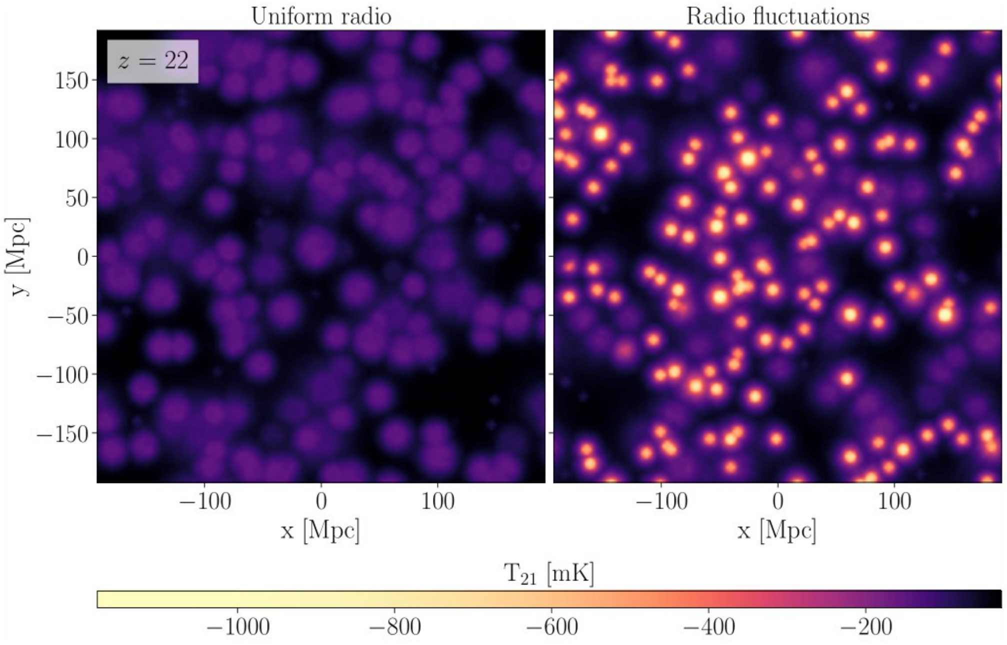
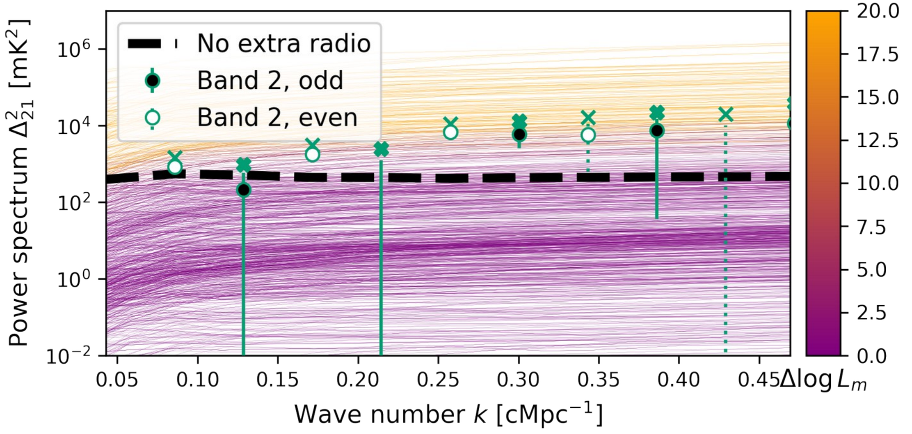


Figure from Reis et al. 2021



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Intuitive interpretation of HERA limits

(lead by Julian B. Muñoz)

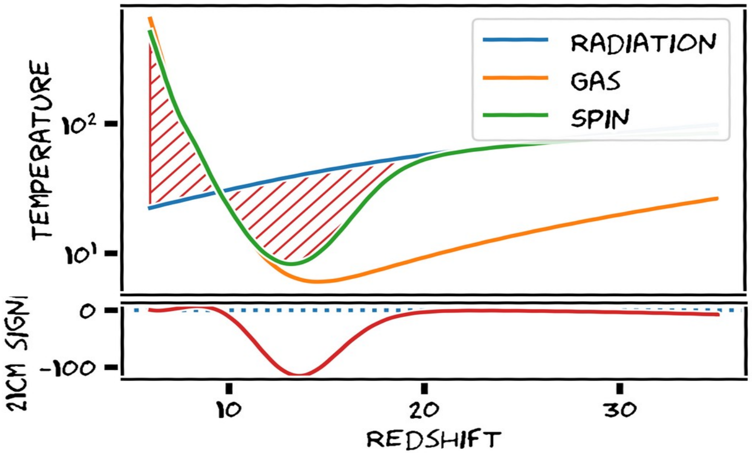
If 21cm PS traces matter power spectrum

$$\Delta_{21}^2(k,z) = b_m^2(z)\Delta_m^2(k,z)$$

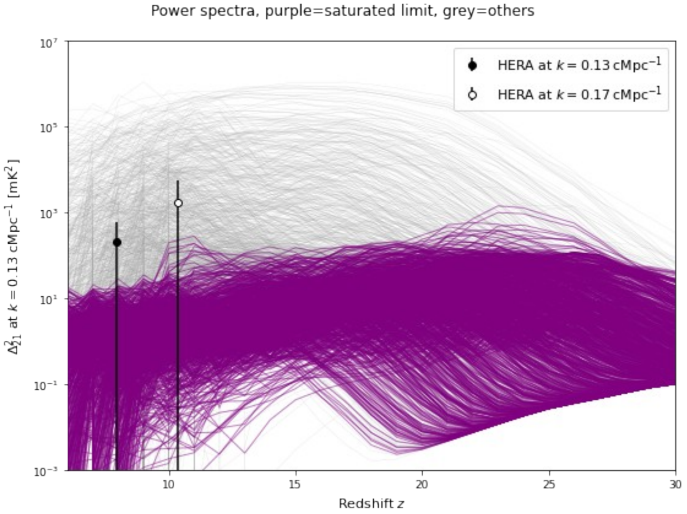
$$b_m = T_0 x_{\rm HI}\left\{\boxed{(1+\mu) - \frac{T_{\rm rad}}{\overline{T}_{\rm S}}}[(1+\mu) - C_T]\right\}$$

Positive: Emission, saturated at ~30 mK

Negative: Absorption, up to 100% in principle



<u>Emission</u> not yet detectable:



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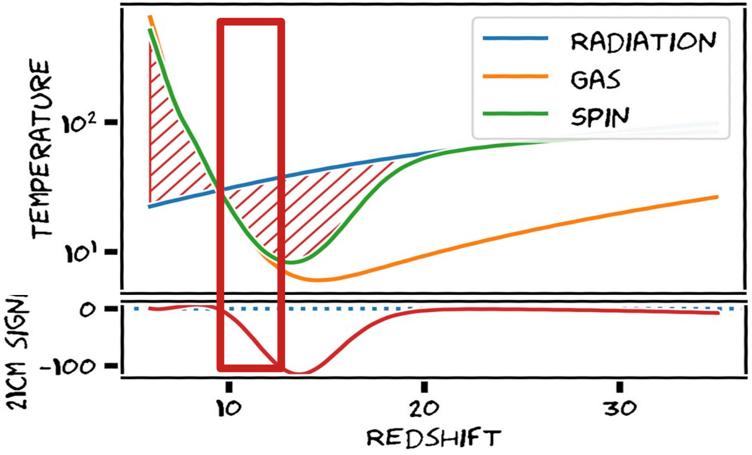
Intuitive interpretation of HERA limits

(lead by Julian B. Muñoz)

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

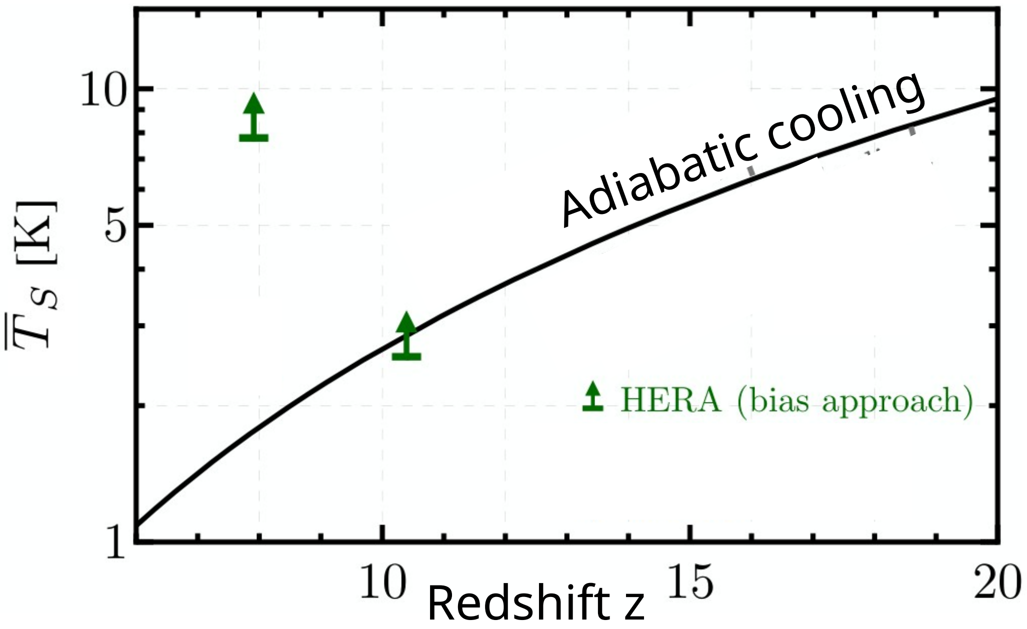
$$\Delta^2_{21}(k,z) = b^2_m(z)\Delta^2_m(k,z)$$

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



Absorption:

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



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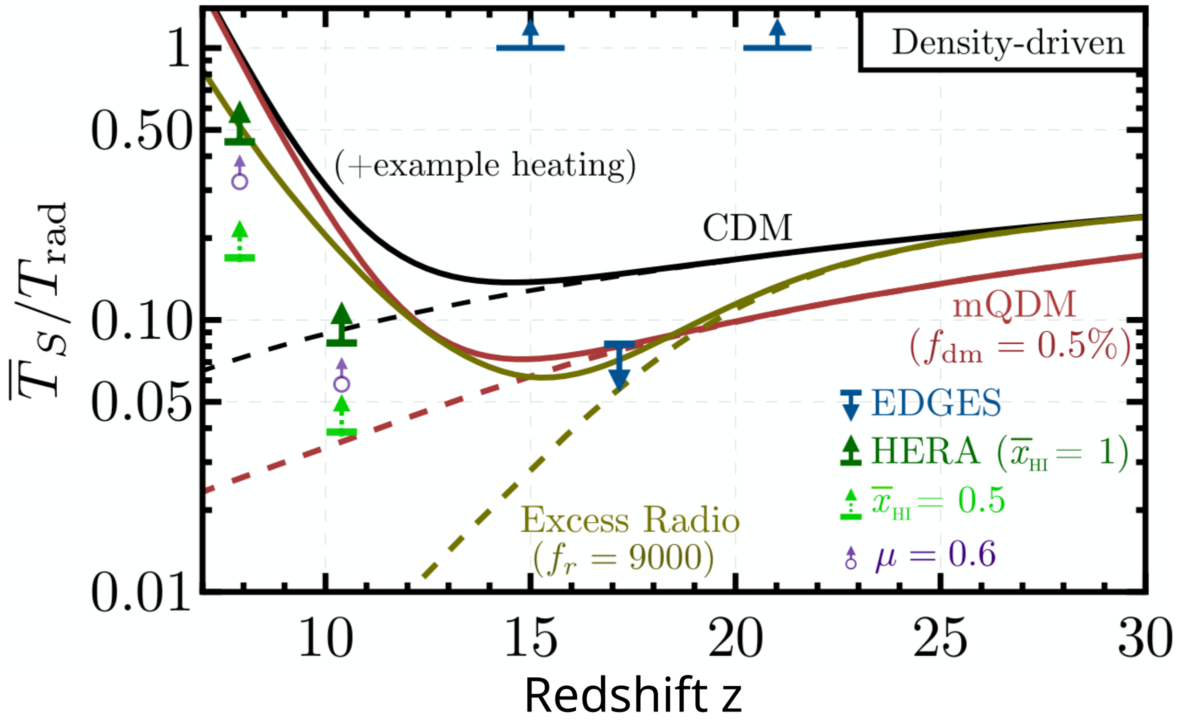
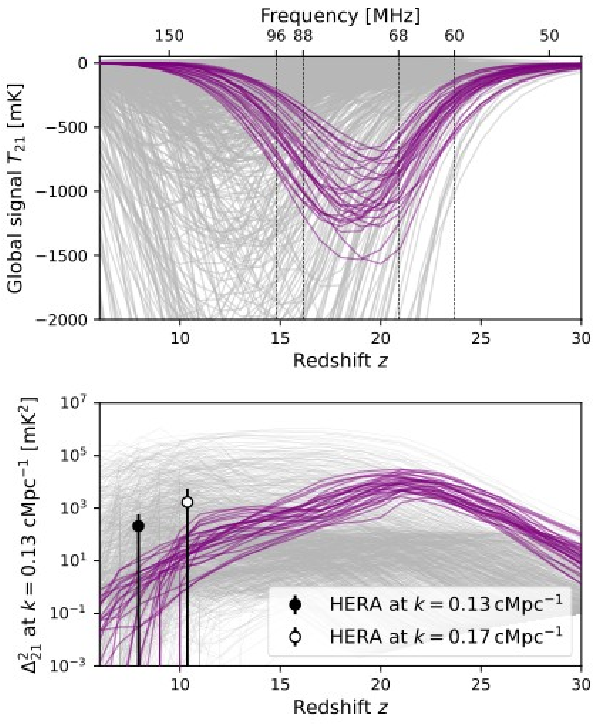
Comparison to claimed EDGES detection





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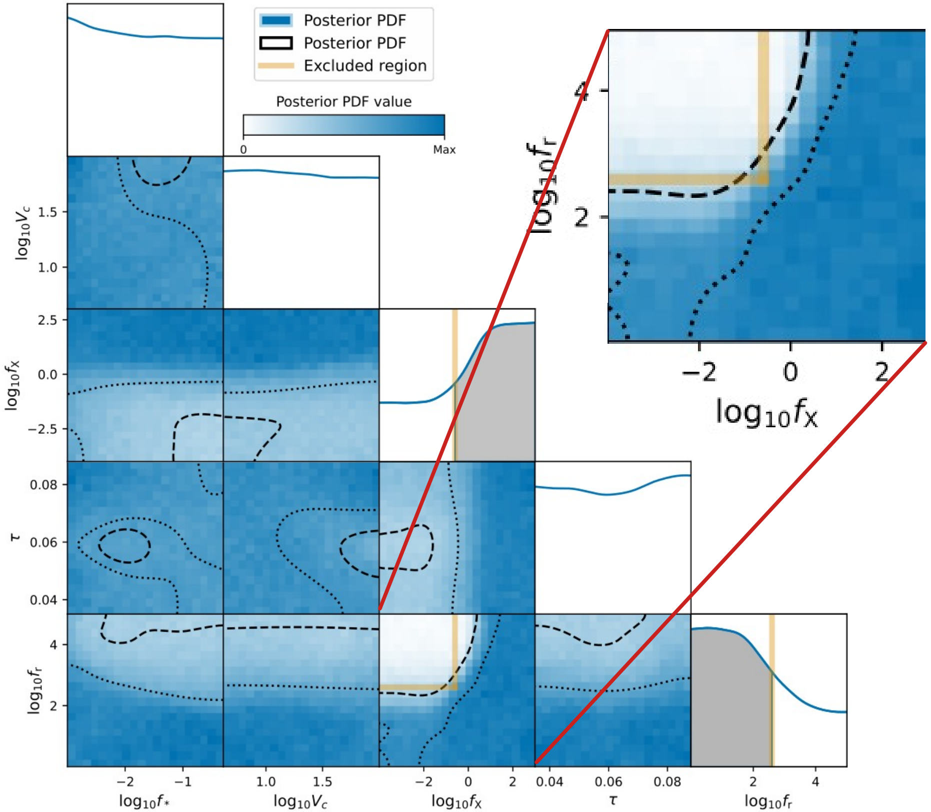
Constraints from HERA limits (alone) on models



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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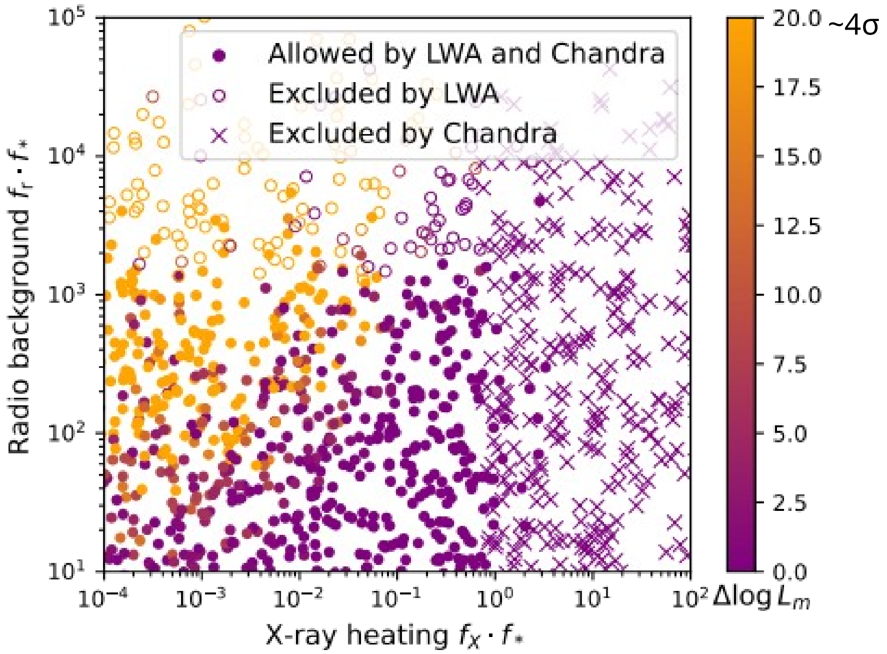
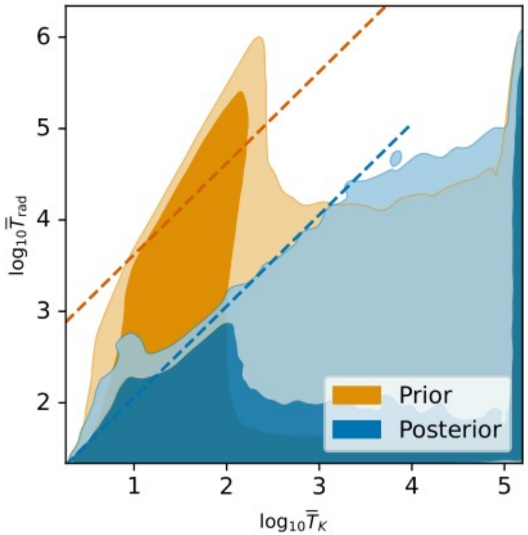
Constraints on Extra Radio Background models



Complementary constraints to LWA/ARCADE2 & Chandra



Excluded models correspond to those with high radio background and relativey low gas temperature

(T_{rad} / T_K > 10 excluded)

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

High contrast

↕

Large Signal

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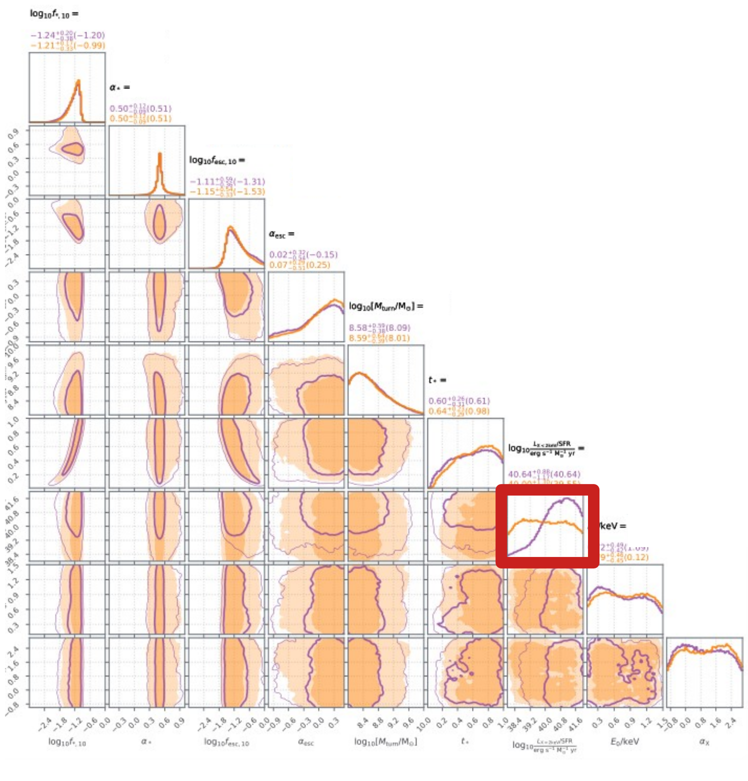
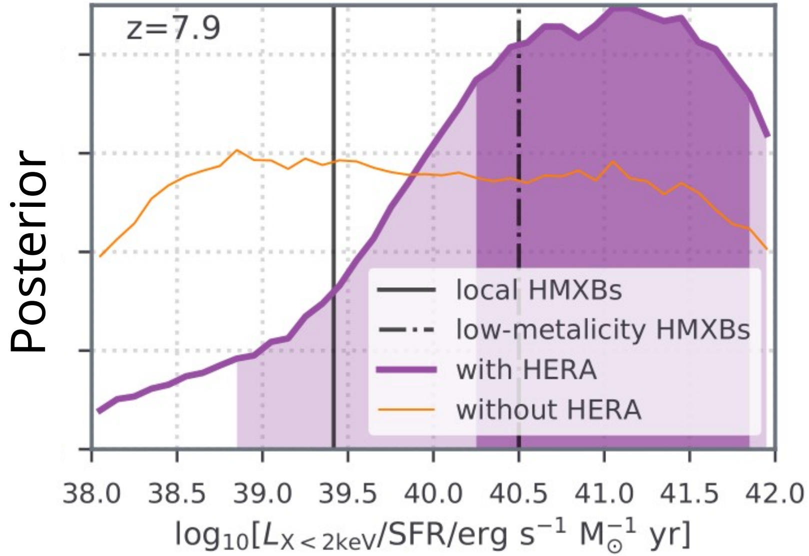
Standard models, no additional radio background

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





- HERA constraints slightly improve constraints over other constraints (UV LVs, QSOs, CMB)
- Especially on the X-ray luminosity (heating)
  → Rule out too-cold IGM

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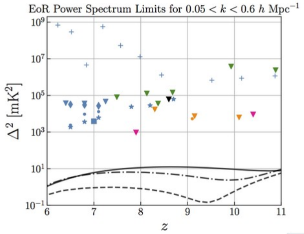
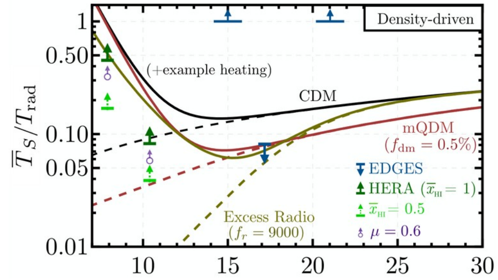
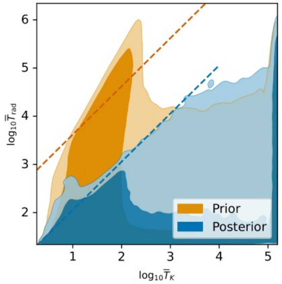
Summary

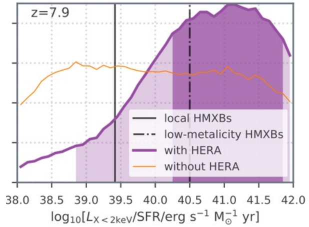
- **21cm cosmology will probe a large part of the observable Universe**
  - Power spectrum measurements by HERA
    $(14.55\text{mK})^2$ +/- $(19.17\text{mK})^2$ at z=7.93, k=0.2 h/Mpc
  - Strongest upper limits on 21cm power spectrum



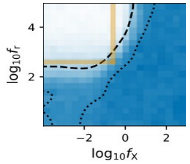


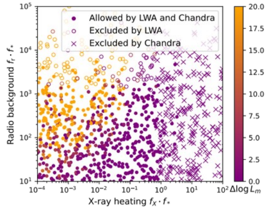
- **Constrain IGM & radiation temperature**
  - Require heating of IGM by redshift 8
  - Ratio $T_{rad}/T_{gas} < 10$





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





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