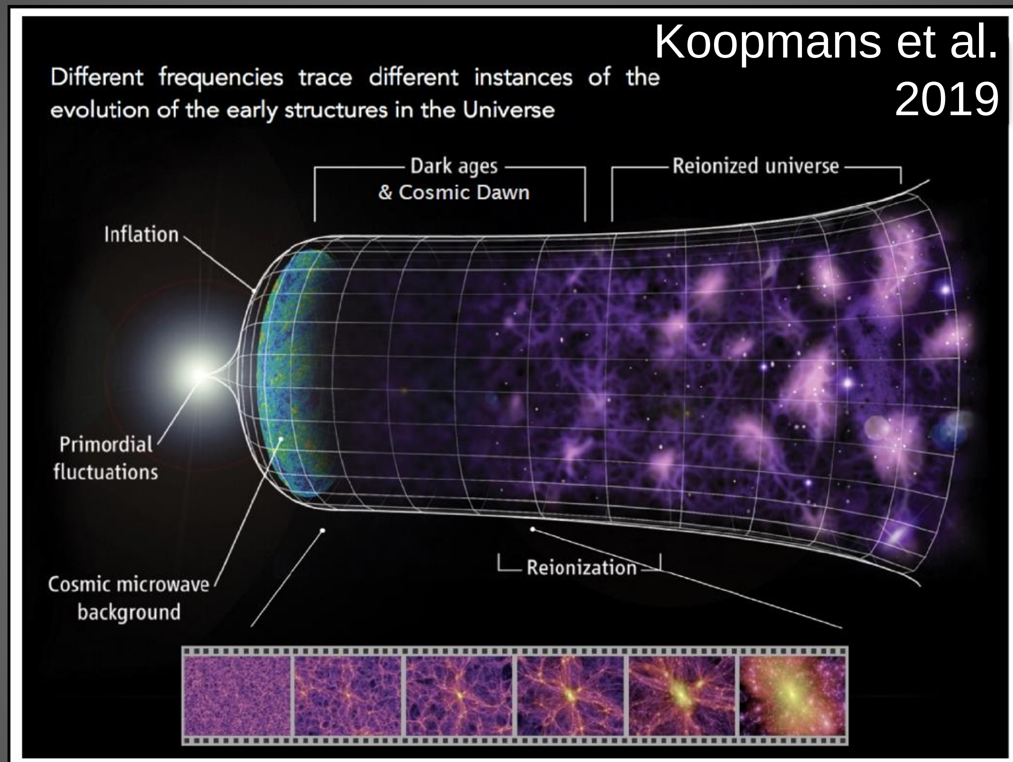
Unveiling Cosmic Dawn



Koopmans et al. 2019

Anastasia Fialkov
Royal Society URF
Sussex University

September 18, 2019

KICC@10

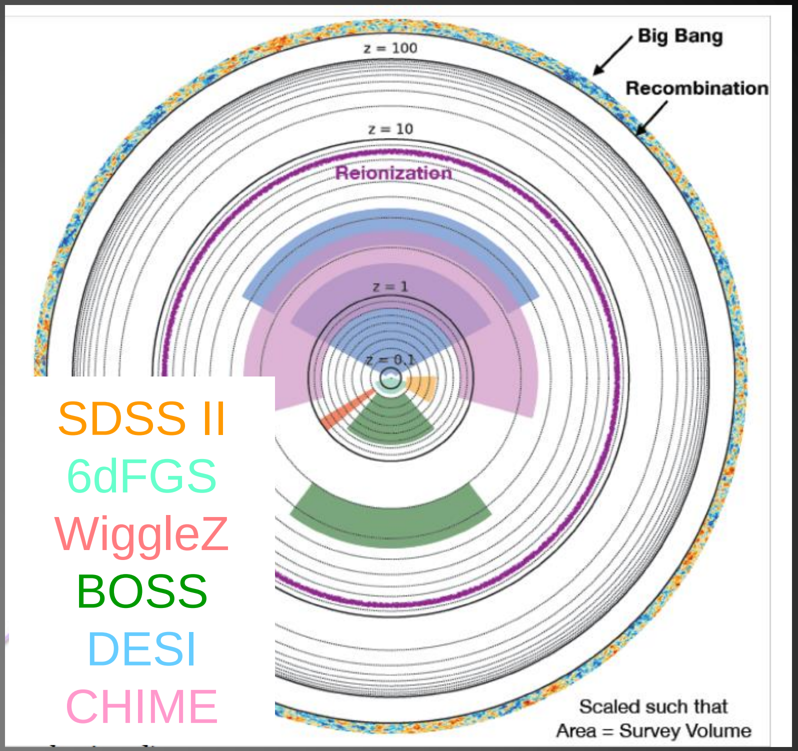
Uncharted Territory

Existing surveys:

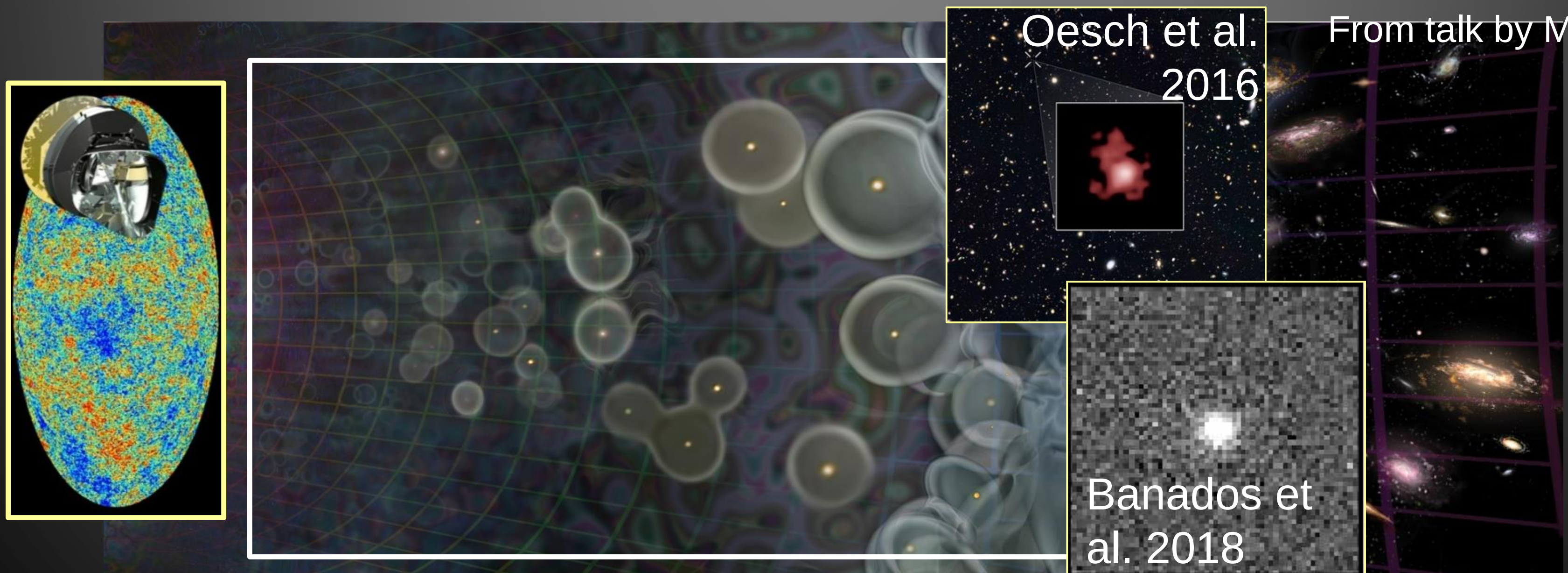
- Last scattering surface CMB
- Local Universe (out to z ~ 3)
- Even future surveys will not go well above z ~ 7

Rare bright sources:

- Galaxies out to z ~ 11
- Quasars out to z ~ 7.5



Credit: Seth Siegel
From talk by M. Dobbs



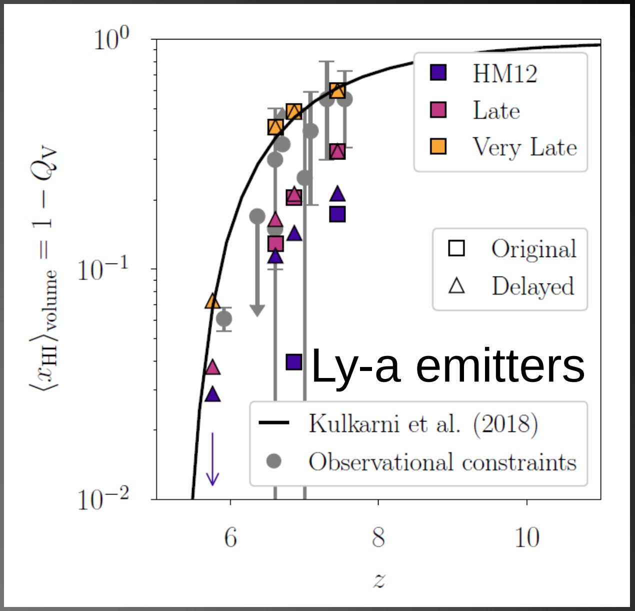
Emerging Picture

Late reionization (z < 6)

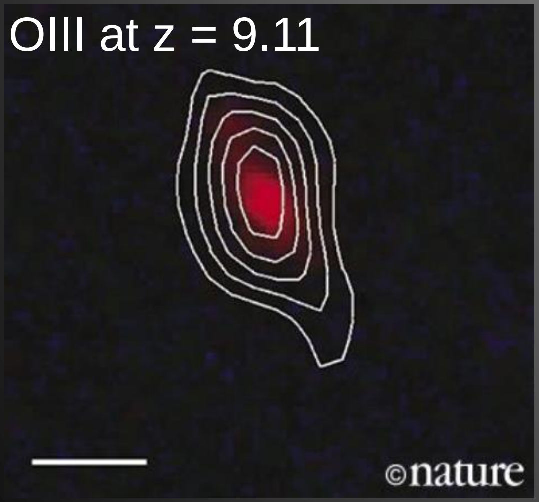
- High-z quasars
- Ly-a emitters
- Low CMB optical depth from Planck

Early onset of star formation (z > 15):

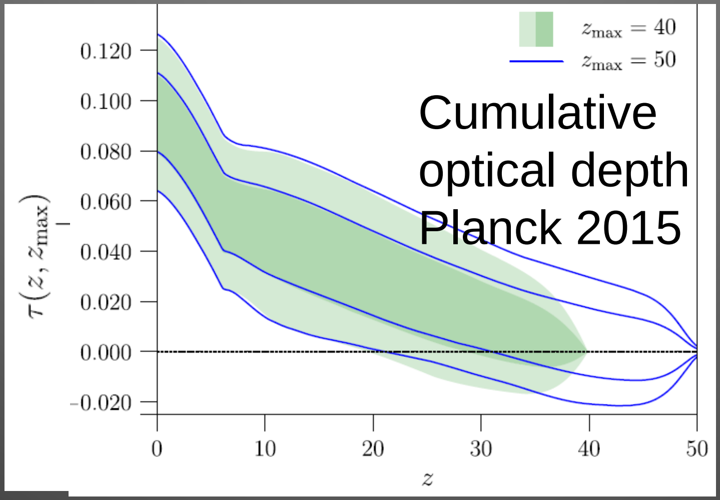
- ALMA OIII: onset of star formations at z ~ 15
- Planck E-modes: ionization z > 15 (>95%CL)
- Existence of supermassive black holes
- EDGES 21-cm of HI (TBC): Ly-a coupling at z ~ 21



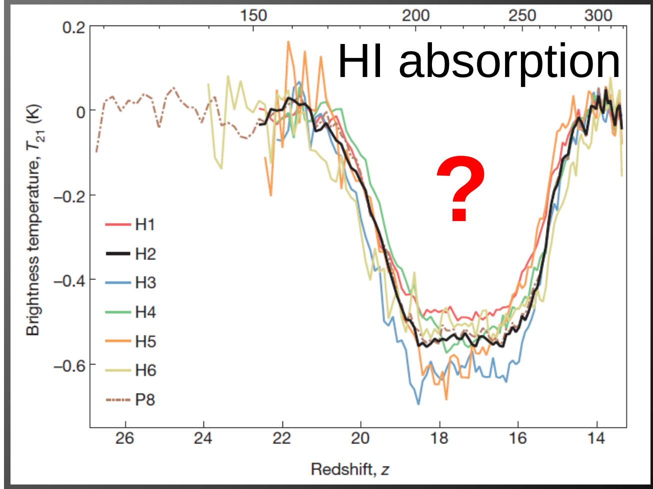
e.g., Weinberger et al. 2019



Hashimoto et al. (2018)



Heinrich & Hu (2018)



Bowman, et al. (2018)

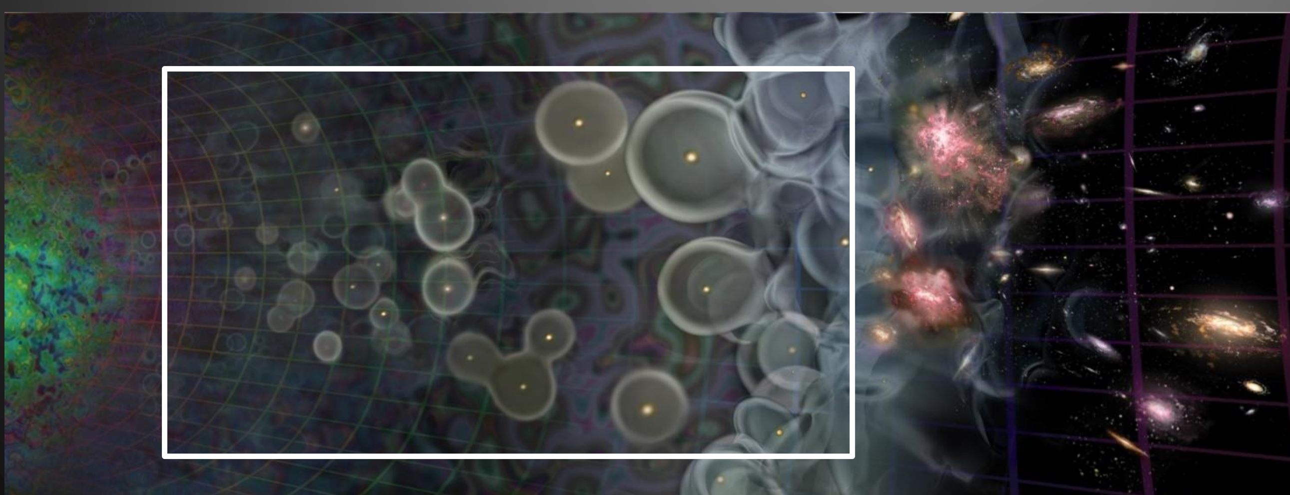
21-cm Signal of Neutral Hydrogen

- 3D scan of the Universe at $5 \leq z \leq 500$
- Line → information from every redshift

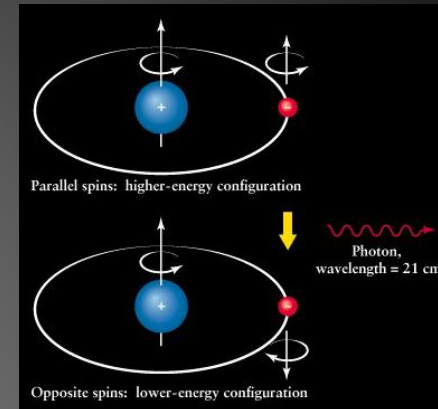
21cm is rich in information:

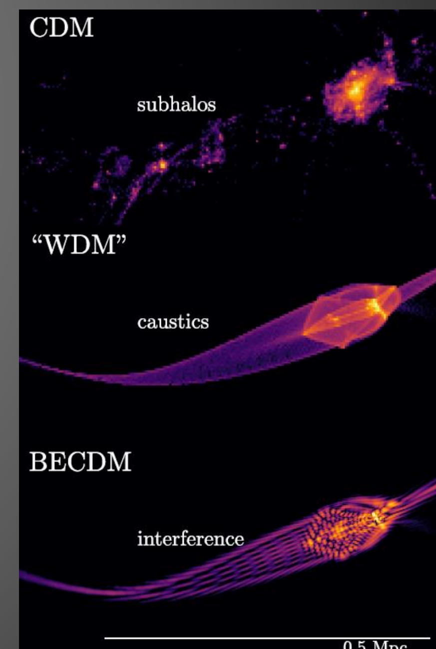
- First stars: Lyα coupling
- First X-ray binaries: IGM heating
- First galaxies: reionization
- Cosmology: τ, H(z), growth of structure, hydrogen abundance, peculiar velocities, NG
- Nature of dark matter (warm/fuzzy/annihilating)

$$\delta T_b \sim x_{HI}\left[1-\frac{T_{rad}}{T_S}\right] \times [\text{Cosmological terms}]$$



21 cm transition of HI





Mocz, Fialkov et al. (2019)

Beginning of the Beginning

21 CENTIMETER TOMOGRAPHY OF THE INTERGALACTIC MEDIUM AT HIGH REDSHIFT

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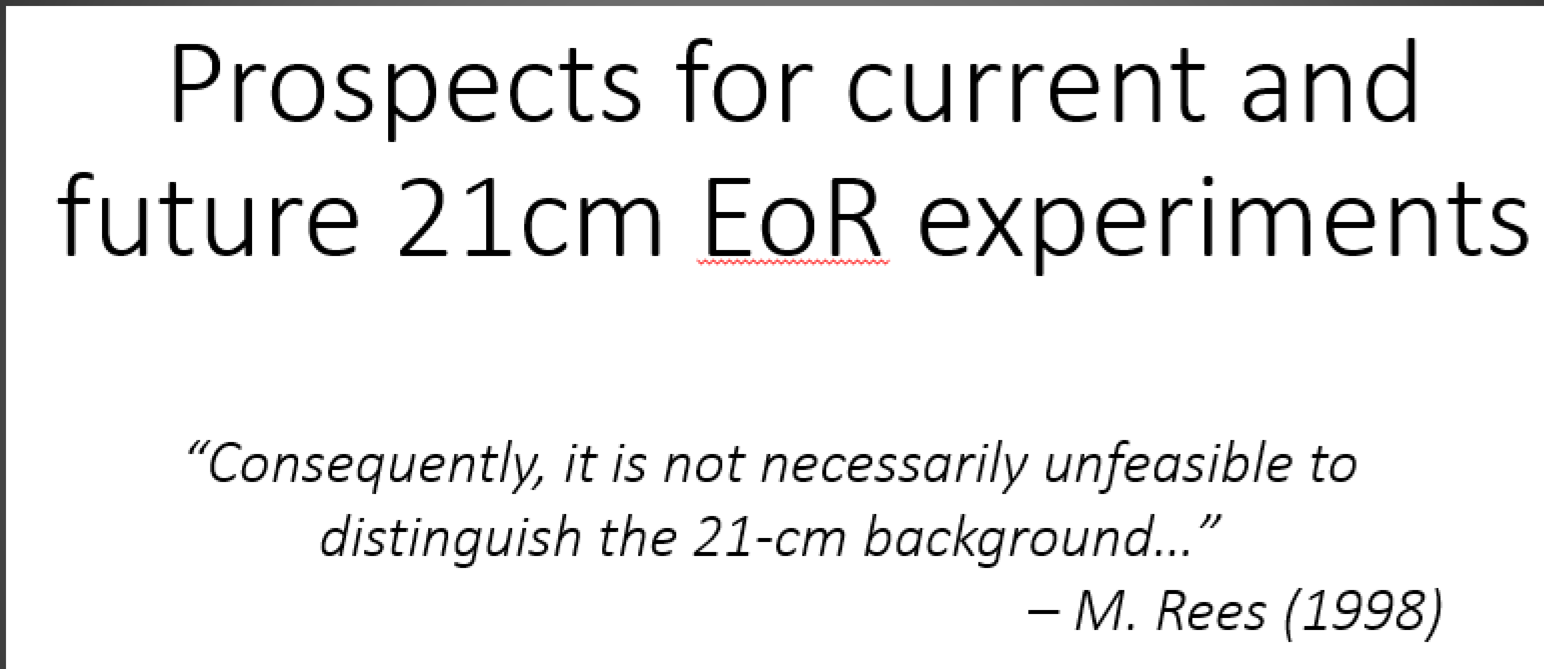
Received 1996 February 9; accepted 1996 August 26

ABSTRACT

We investigate the 21 cm signature that may arise from the intergalactic medium (IGM) prior to the epoch of full reionization ($z > 5$). In scenarios in which the IGM is reionized by discrete sources of photoionizing radiation, the neutral gas that has not yet been engulfed by an H II region may easily be preheated to temperatures well above that of the cosmic background radiation (CBR), rendering the IGM invisible in absorption against the CBR. We identify three possible preheating mechanisms: (1) photoelectric heating by soft X-rays from QSOs, (2) photoelectric heating by soft X-rays from early galactic halos, and (3) resonant scattering of the continuum UV radiation from an early generation of stars. We find that bright quasars with only a small fraction of the observed comoving density at $z \sim 4$ will suffice to preheat the entire universe at $z \gtrsim 6$. We also show that, in a cold dark matter dominated cosmology, the thermal bremsstrahlung radiation associated with collapsing galactic mass halos (10^{10}–$10^{11}\ M_{\odot}$) may warm the IGM to ~ 100 K by $z \sim 7$. Alternatively, the equivalent of $\sim 10\%$ of the star formation rate density in the local universe, whether in isolated pregalactic stars, dwarf, or normal galaxies, would be capable of heating the entire IGM to a temperature above that of the CBR by Lyα scattering in a small fraction of the Hubble time at $z \sim 6$.

Beginning of the Beginning

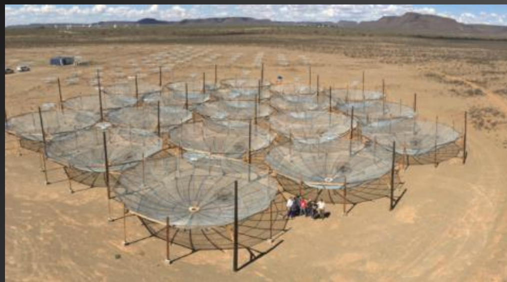
Opening slide of Judd Bowman's talk at Barefoot EoR (July 2019)



Prospects for current and future 21cm EoR experiments

"Consequently, it is not necessarily unfeasible to distinguish the 21-cm background…"

– M. Rees (1998)





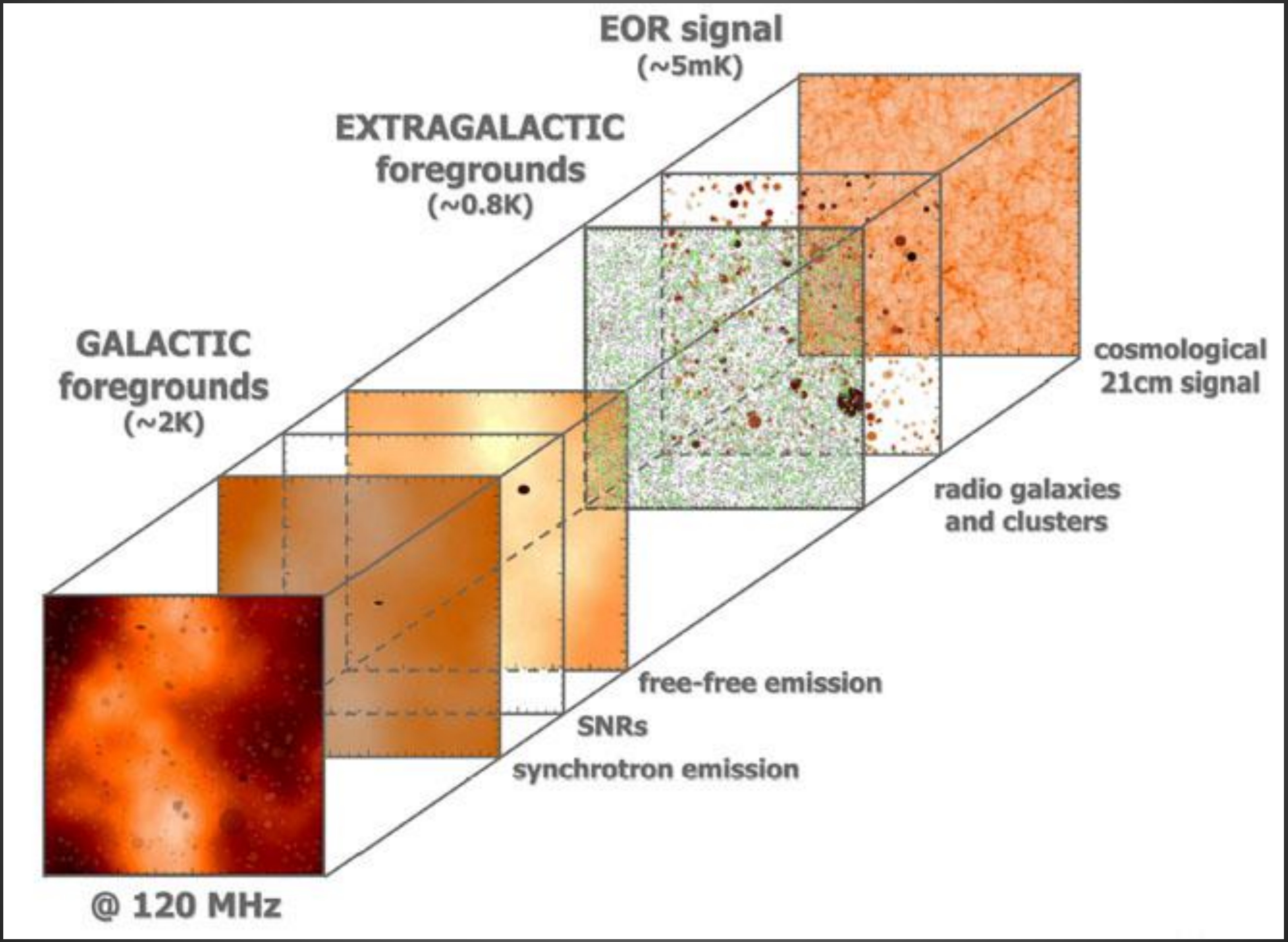


"Consequently, it is not necessarily unfeasible to distinguish the 21-cm background…"

– M. Rees (1998)

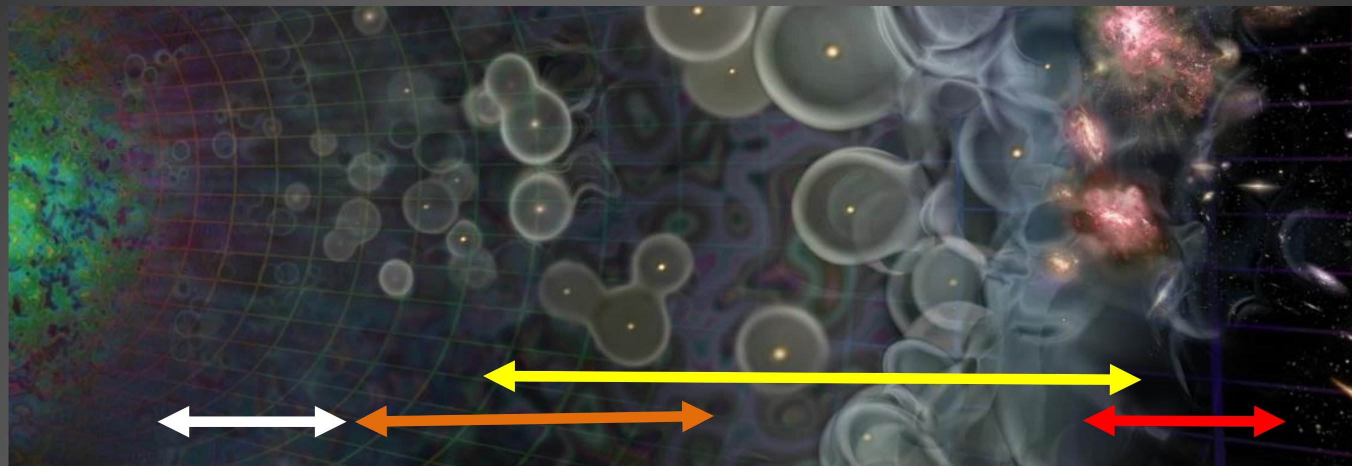


Observations are Very Challenging

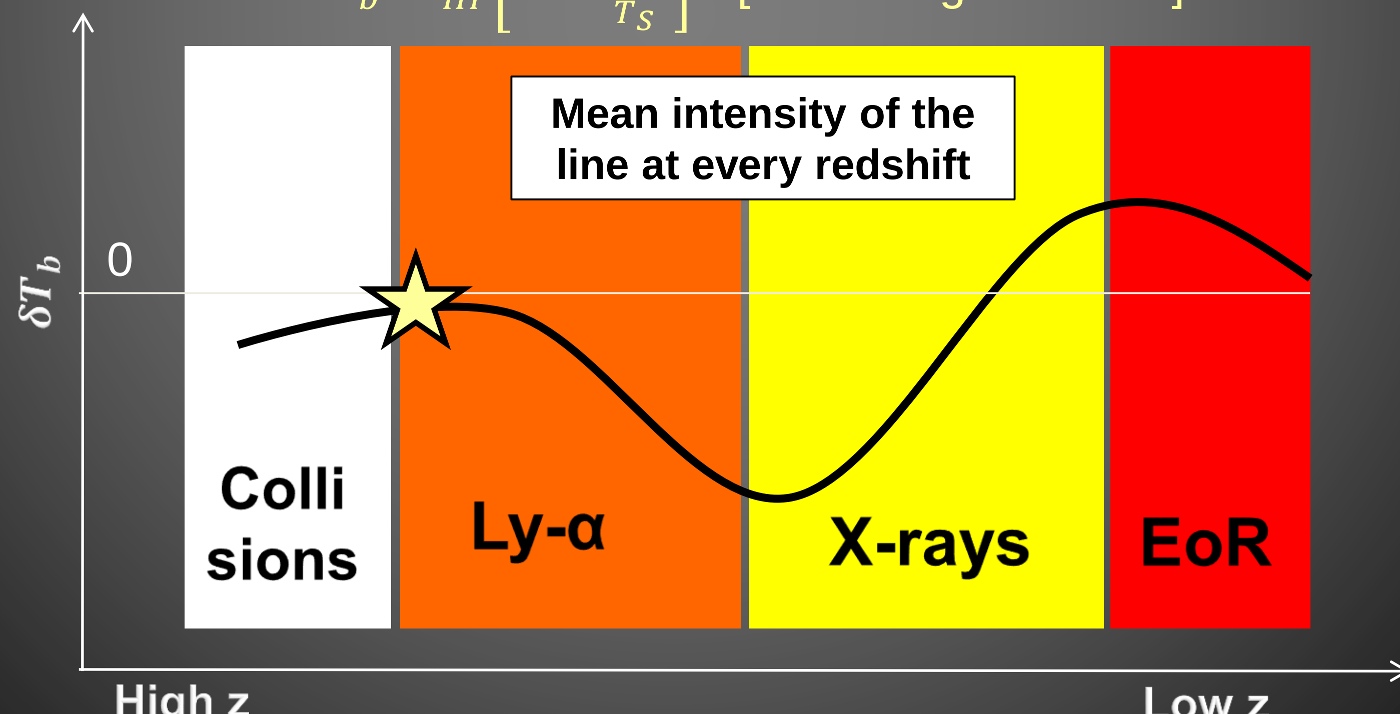


Credit S. Zaroubi

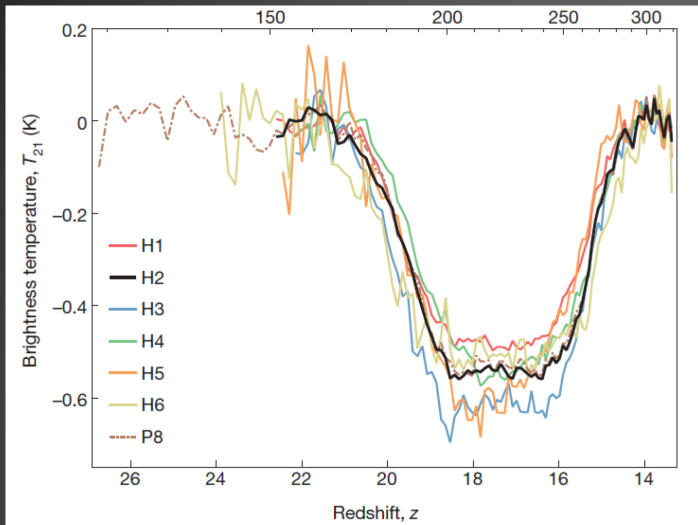
Expected Shape of the Global 21-cm Signals:



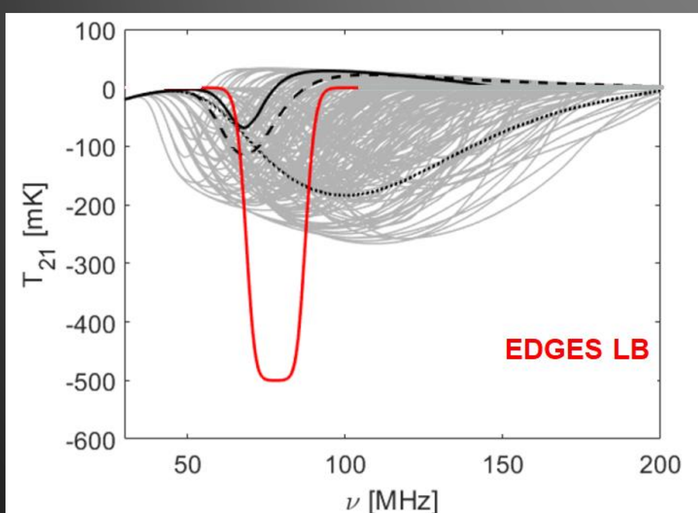
$$\delta T_b \sim x_{HI}\left[1 - \frac{T_{rad}}{T_S}\right] \times [\text{Cosmological terms}]$$



Global 21-cm Signals: First Claimed Detection



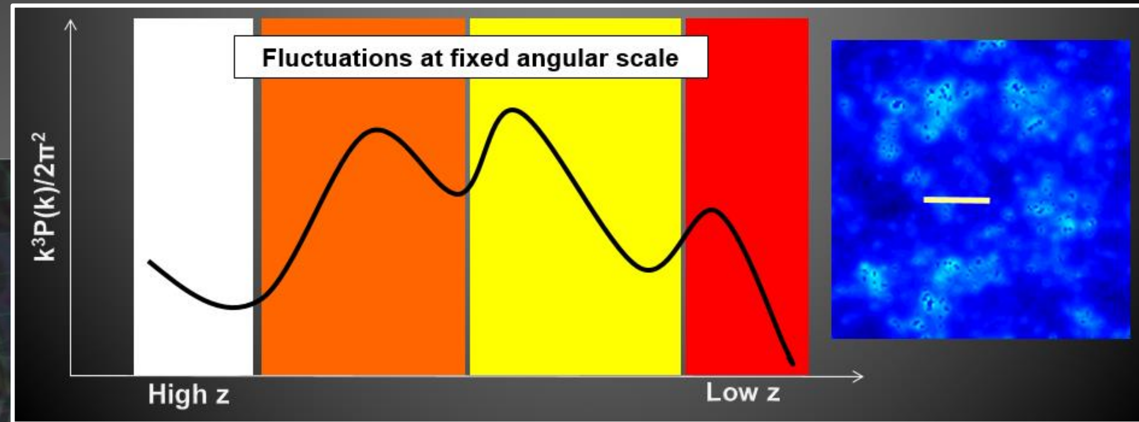
EDGES Low
(Bowman et al. 2018)

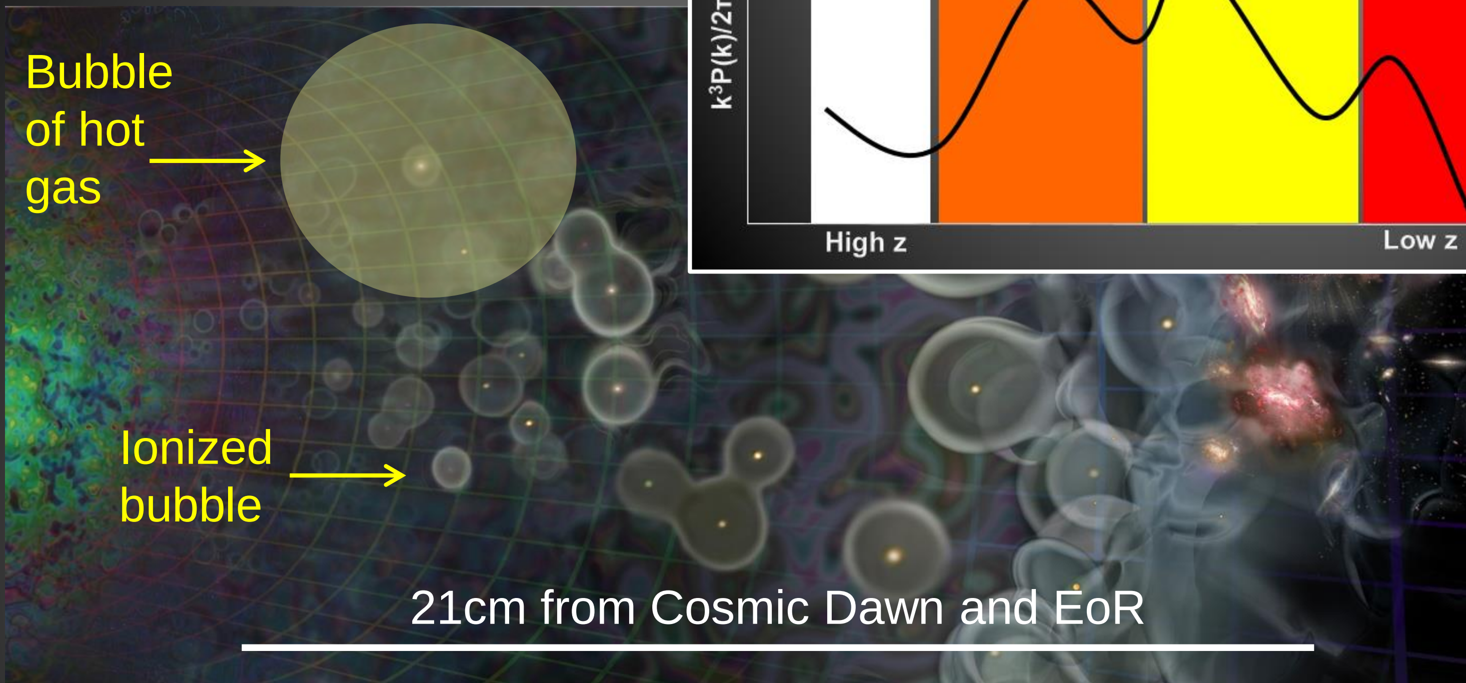


Depth = 500^{+500}_{-200} mK (99% C.L.)

Is the EDGES detection real?

Fluctuations





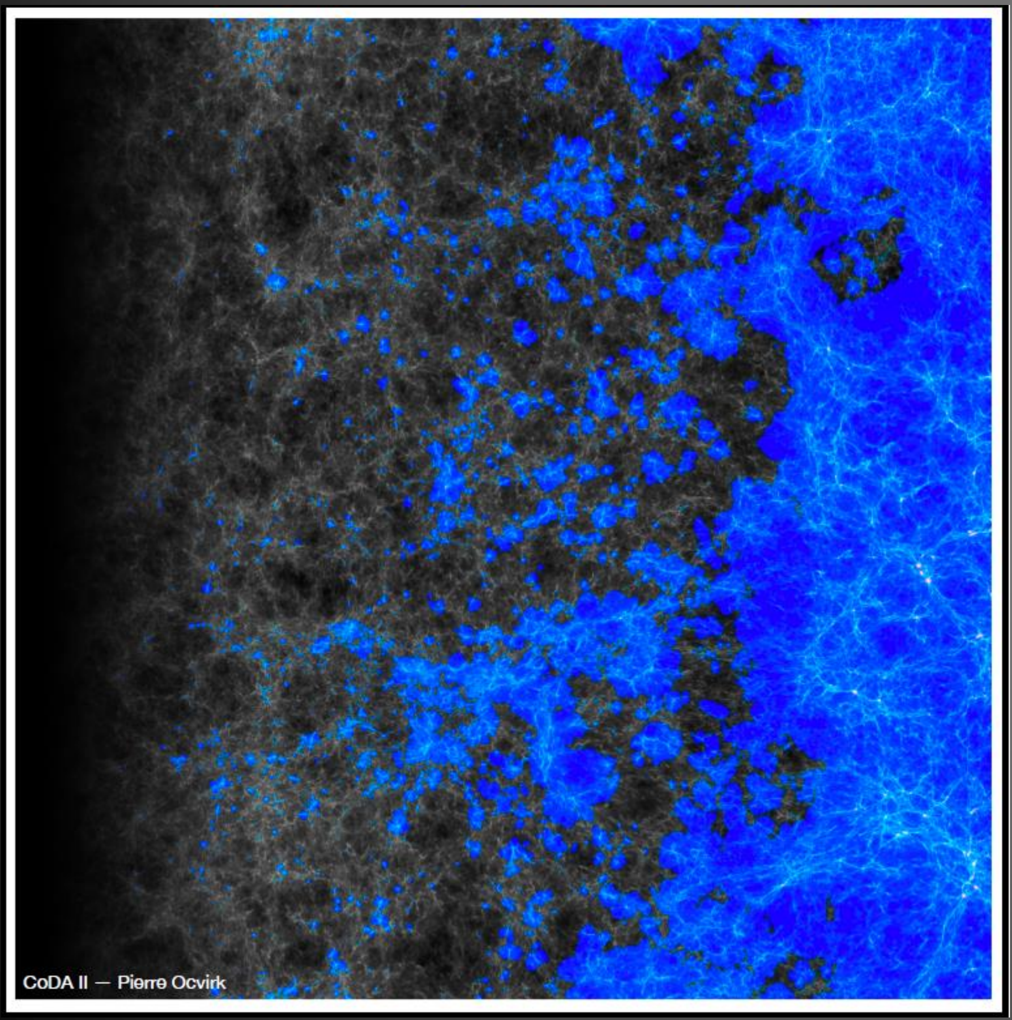
- Highly biased first star forming regions (Lyα and heating)
- Supersonic motion between baryons and gas, BAO
- SED of sources (mean free path of radiation Lyα, LW, X-rays, UV)

$$\delta T_b \sim x_{HI}\left[1-\frac{T_{rad}}{T_S}\right]\ldots$$

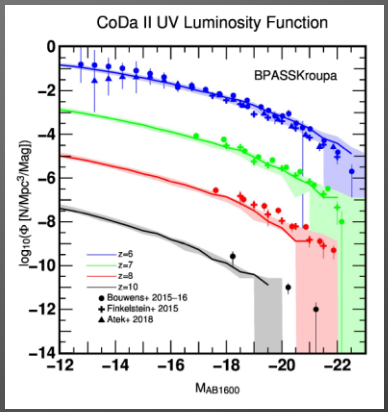
EoR×Heating×Lyα

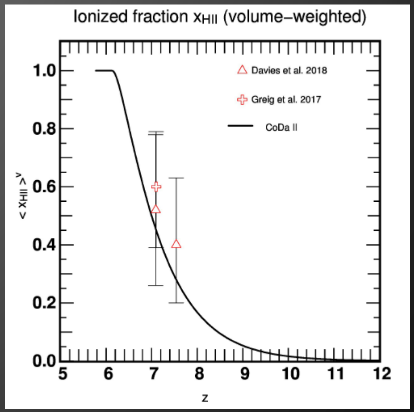
High Resolution Simulations of Reionization

+ Works of art
- Often do not include radiation (X-rays, Ly-a) & velocity flows needed for 21-cm
- Computationally extremely expensive.
- Fixed set of astro parameters.

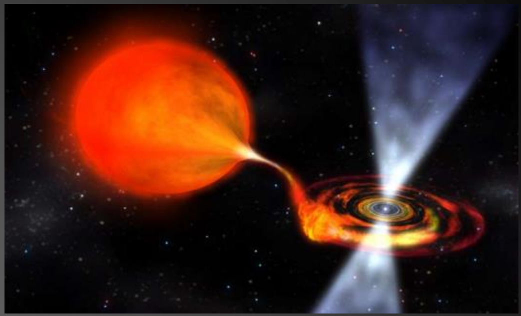


CoDaII by Ocvirk et al. (2018)
Coupled radiation-hydrodynamics galaxy formation code
Specs:
Particles 4096^3
Mass res. $4.07 \times 10^5\ M_\odot$
94 Mpc
$150 < z < 5.8$
16384 GPUs, 65536 CPUs
Run on Titan supercomputer (6 days)



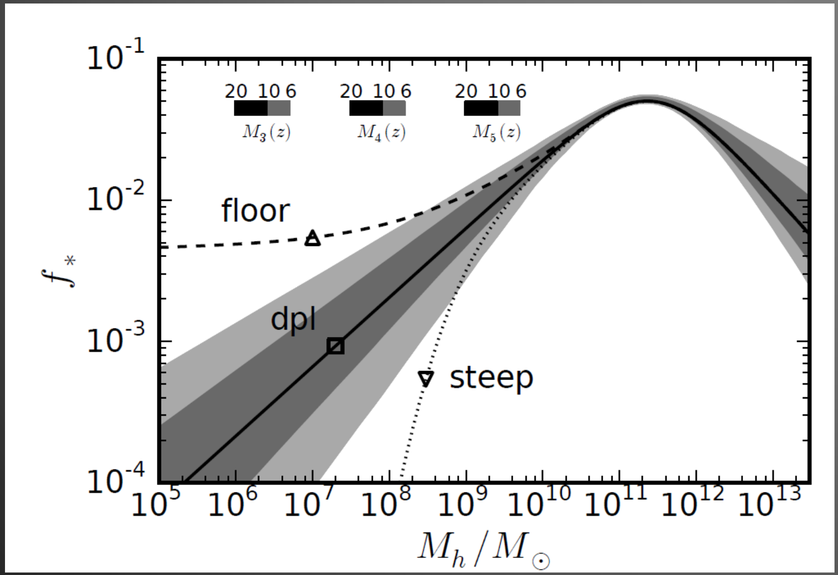


21-cm Signals is Very Model-Dependent

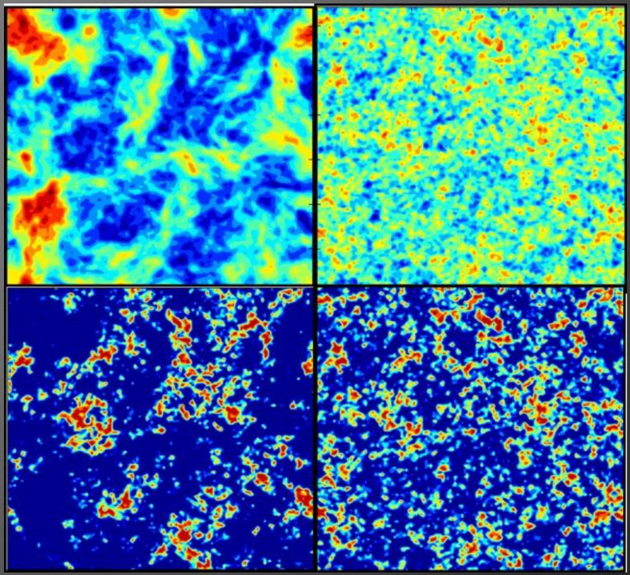


Poorly known high-z astrophysics:

- First stars form in $10^5 - 10^7$ M_{sun} halos
- Feedback mechanisms: Lyman-Werner radiation, large-scale velocity flows, SN feedback, photoheating (from reionization)
- Efficiency of X-ray emitters: X-ray binaries in metal poor regions are brighter
- X-ray SED: nature of X-ray sources, absorption of soft X-rays
- Ionization efficiency: How UV-bright are high-z galaxies?
- Escape fraction: how clumpy is the medium around early sources?
- Nature of dark matter



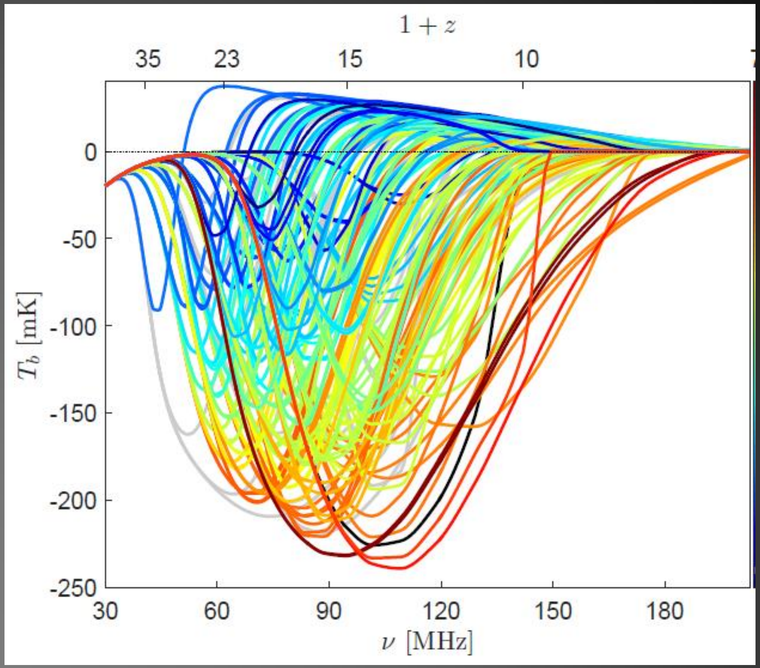
Mirocha et al., 2017



Fialkov et al., 2014

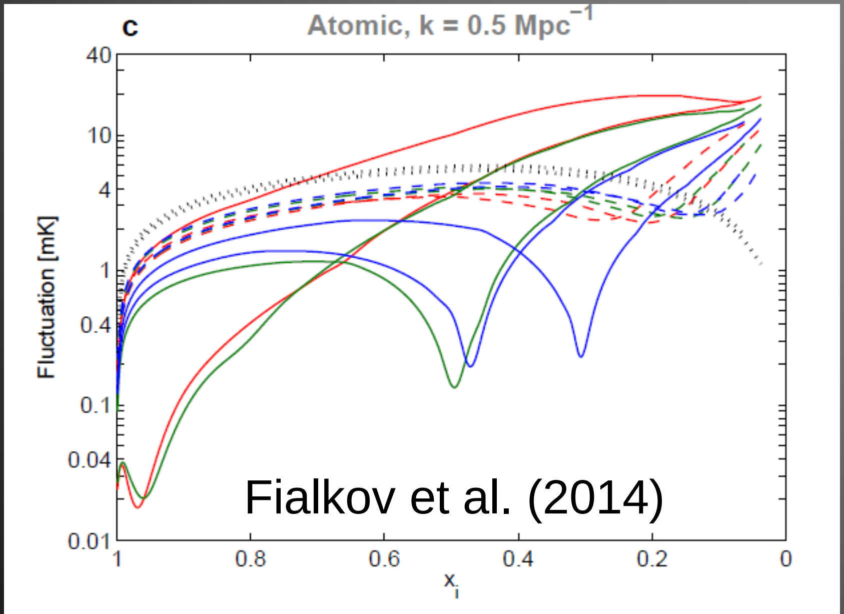
Large Discrepancy in Predicted 21-cm Signals

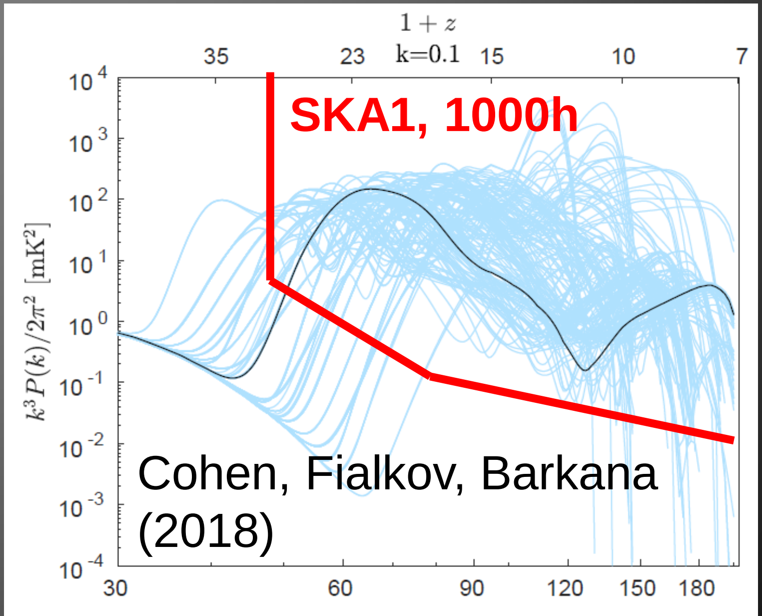
Hybrid simulations
- Star formation efficiency
- Feedback mechanisms
- Efficiency of X-ray emitters
- X-ray SED
- Ionization efficiency
- Escape fraction



Hot or cold EoR?

Variation in 6 astro parameters

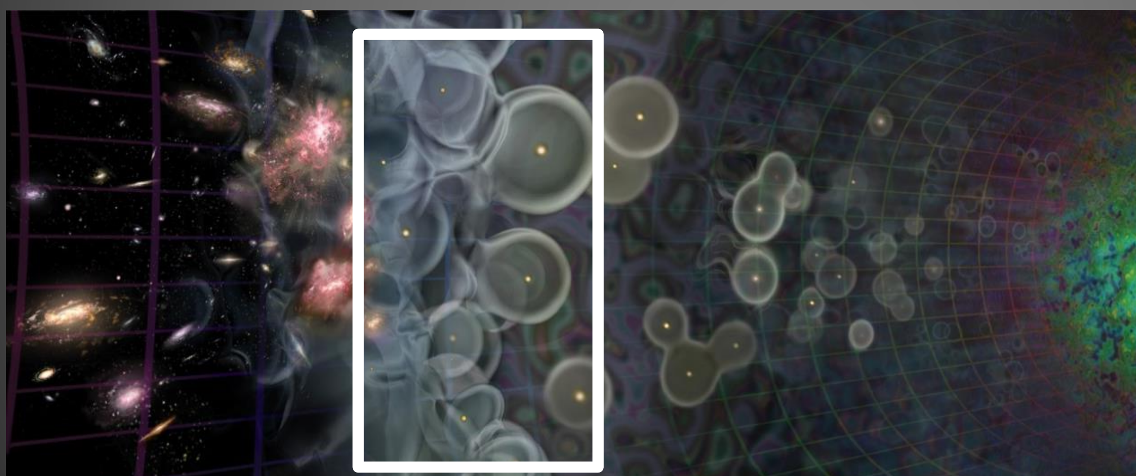




Observational Status
Epoch of Reionization (EoR)

Key question:

Properties of first galaxies ($M_h \sim 10^9\ M_\odot$)
Their impact on the IGM (heating & reionization)



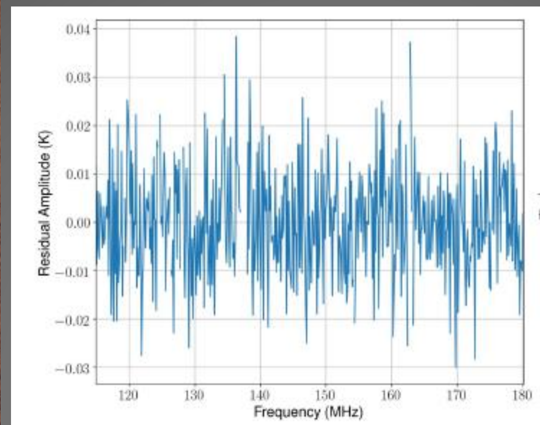
21cm is a combination of heating and ionization

$$\boldsymbol{\delta T_b \sim x_{HI}\left[1 - \frac{T_{rad}}{T_S}\right]\ldots}$$

First Astrophysical Constraints SARAS2

SARAS2: 6<z<12

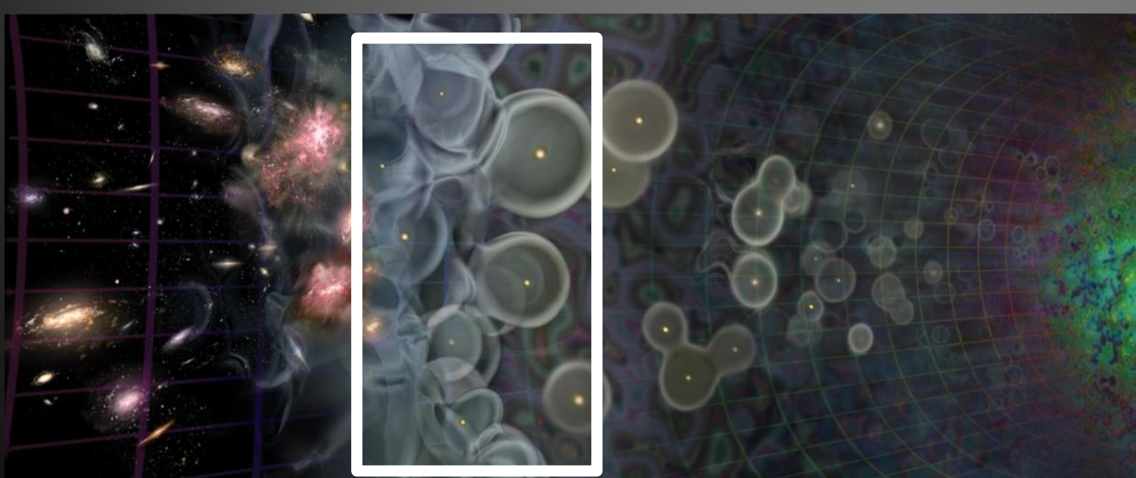
SARAS2 Residuals

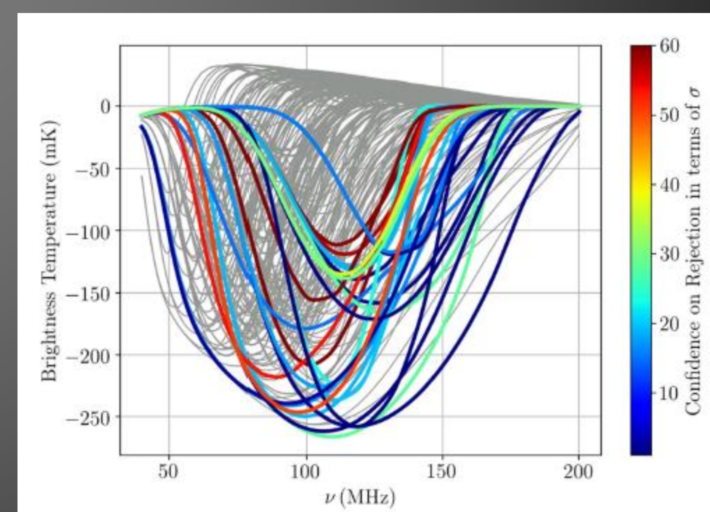


Rule out

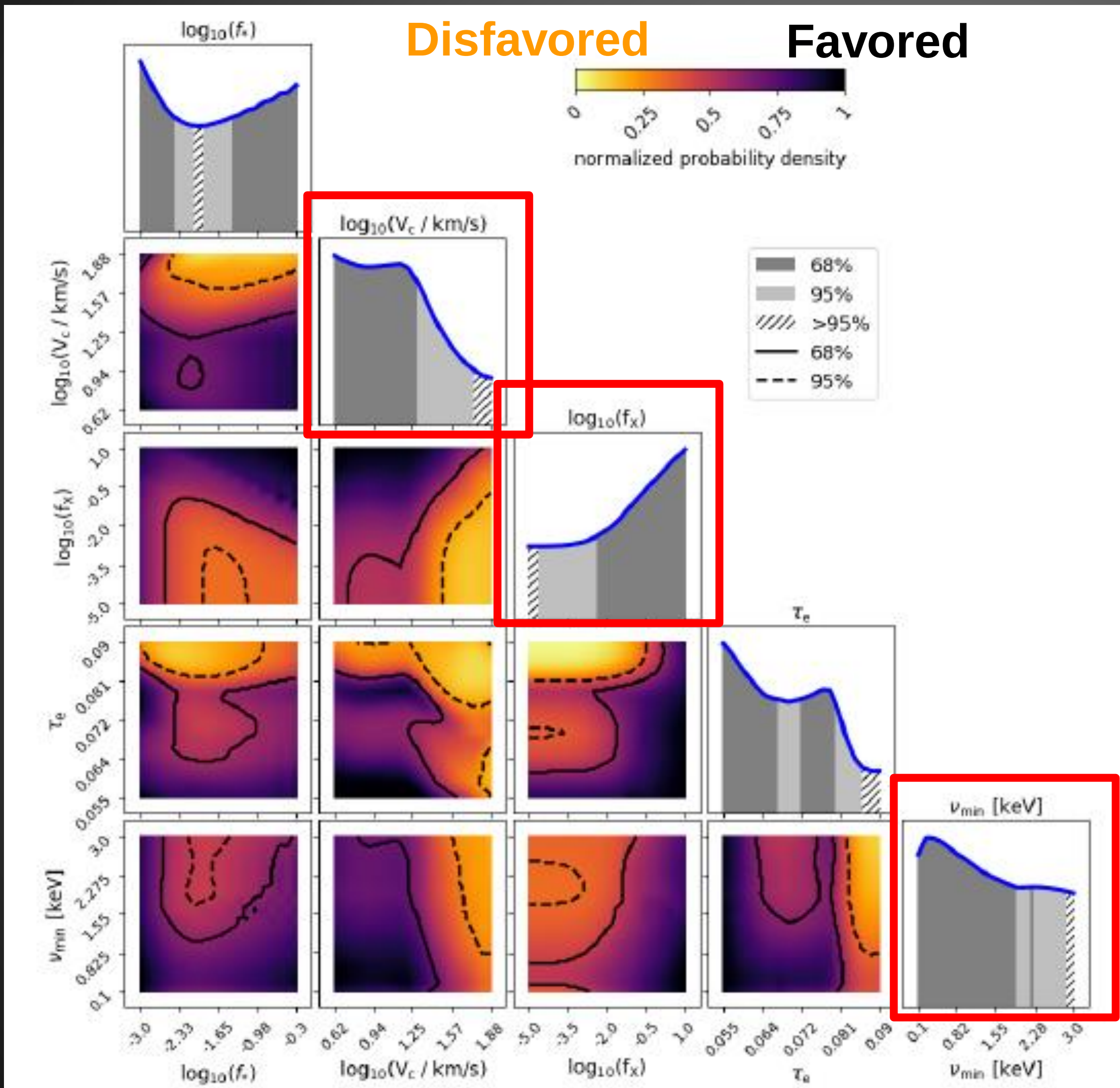
- Inefficient X-ray heating
- Sharp Reionization

Singh et al. 2017, 2018

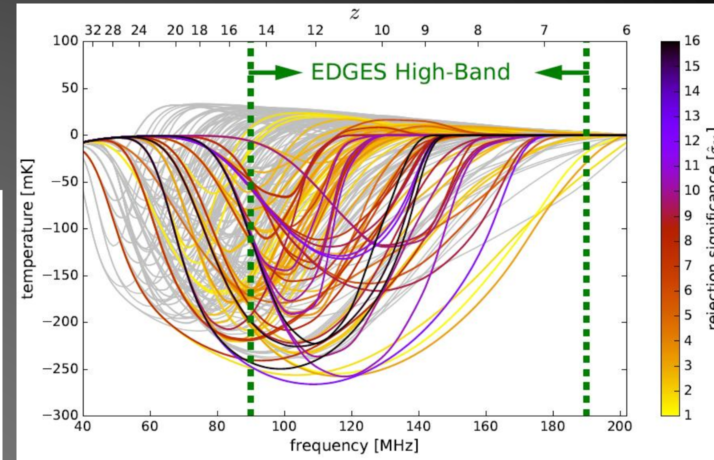




Astrophysical Constraints with EDGES High Band (using ANN)



Monsalve, et al. (2019)



Star formation in small halos

$M_{min} < 1.3 \times 10^8\ M_{\odot}$

Some heating:

$\frac{L_X}{SFR} > 1.2 \times 10^{38}\ \frac{erg}{s}\frac{M}{yr}$

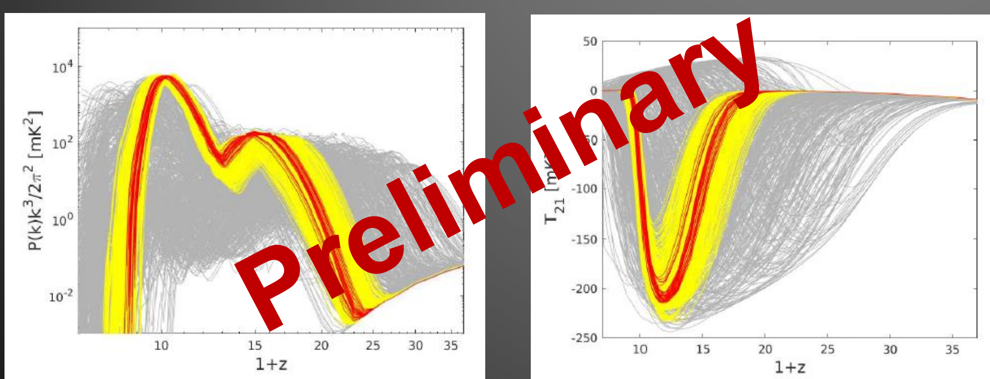
Fluctuations at EoR

MWA

HERA

LOFAR

- HERA: see talk by J. Hewitt
- MWA: $\Delta^2 \leq 3900$ mK² at k = 0.20 h/Mpc and z = 7 using 21 hrs (Barry et al. 2019)
- LOFAR HB: $\Delta^2 \leq 6300$ mK² at k = 0.053 h/Mpc and z = 10.1 using 13 hrs (Patil et al. 2017). Stay tuned for the soon coming LOFAR results from 10 nights of data!!!

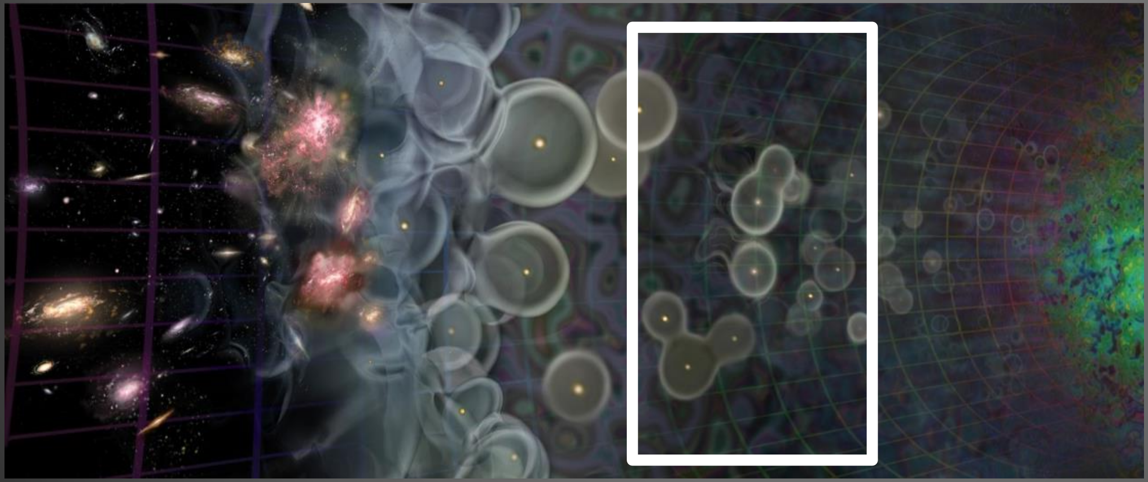


Some heating is required ~2.5K at z = 9, CMB is 27.5K at z = 9)

Observational Status: Cosmic Dawn

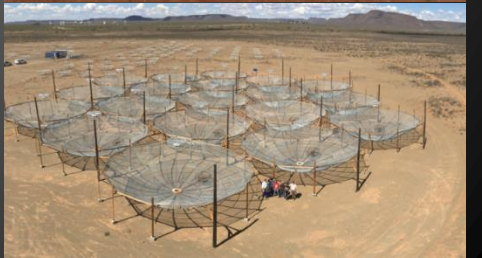
Key Questions:

- How and when first stars and galaxies formed? What were their properties?
- What was the impact of stars on the Universe (heating)?
- Can we constrain dark matter theories using high-z observations?
- Gravity/Cosmology in the completely unexplored regime.



Mostly neutral Universe, primordial star formation, Lya coupling, X-ray heating

$$\delta T_b \sim x_{HI}\left[1-\frac{T_{rad}}{T_S}\right]\ldots$$

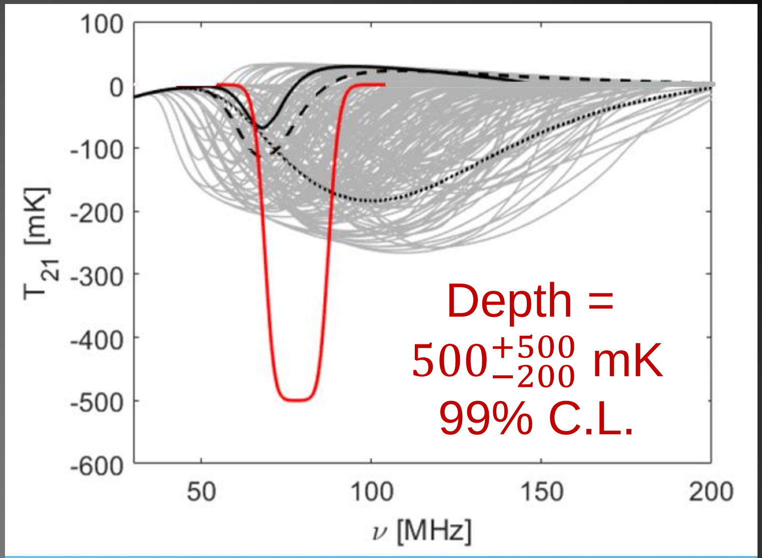


First Claimed Detection: EDGES Low

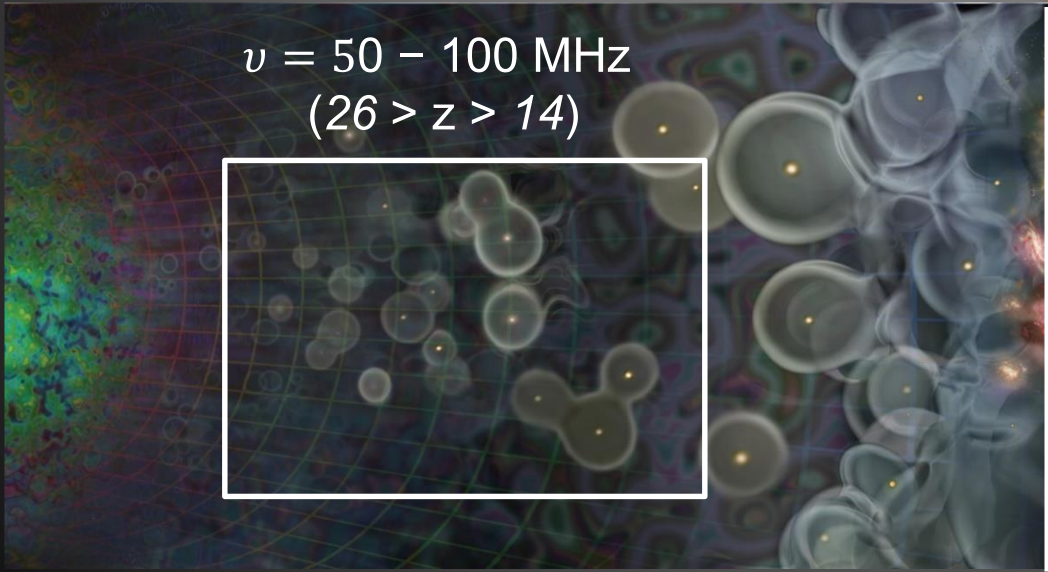
- If true - first signature of first stars! (talks by Ellis, Madau)

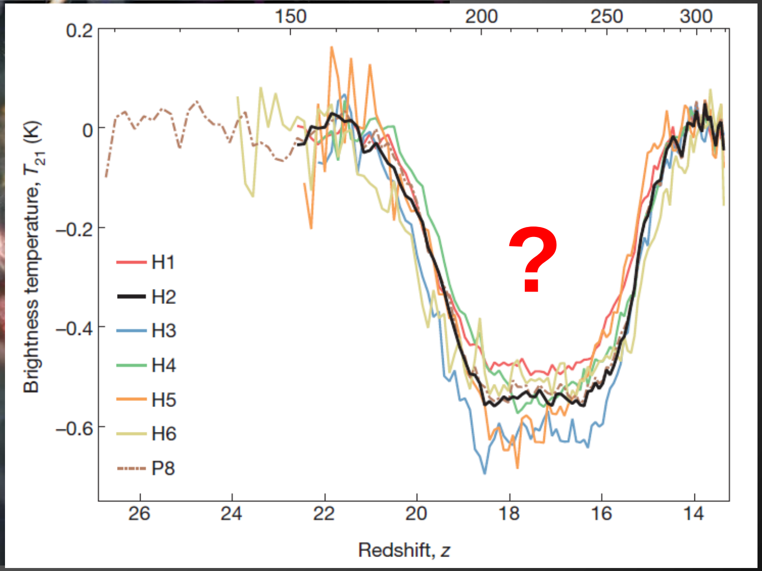
- The feature is too strong
- Are we missing any physics?

- Possible systematic errors (Hills et al. 2018, Singh and Subrahmanyan 2019)



Bowman, et al. (Feb 2018)



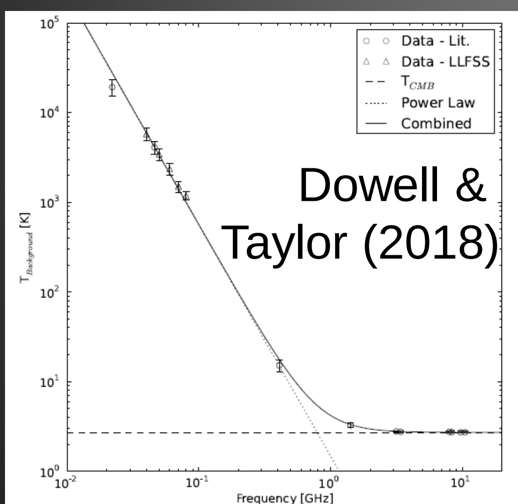


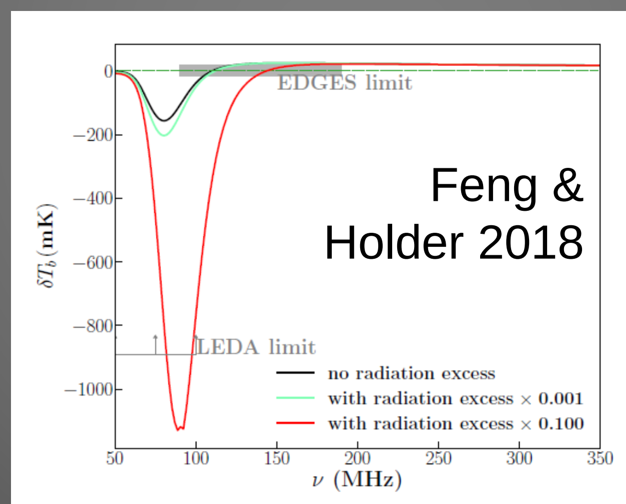
Proposed Physical Solutions are all Exotic:

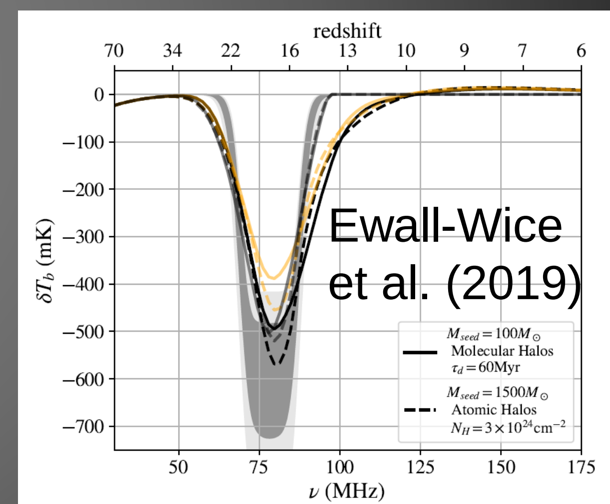
- Extra radio background at intrinsic 1.42 GHz (78 MHz today)
- Extra cooling from baryon - dark matter interactions
- Modification of thermal history

$$\delta T_b \sim x_{HI}\left[1 - \frac{T_{rad}}{T_S}\right]$$

Extra RB LWA1 40-80 MHz	Global 21-cm Signal with +Radio	Obscured Radio Loud Quasars at Cosmic Dawn





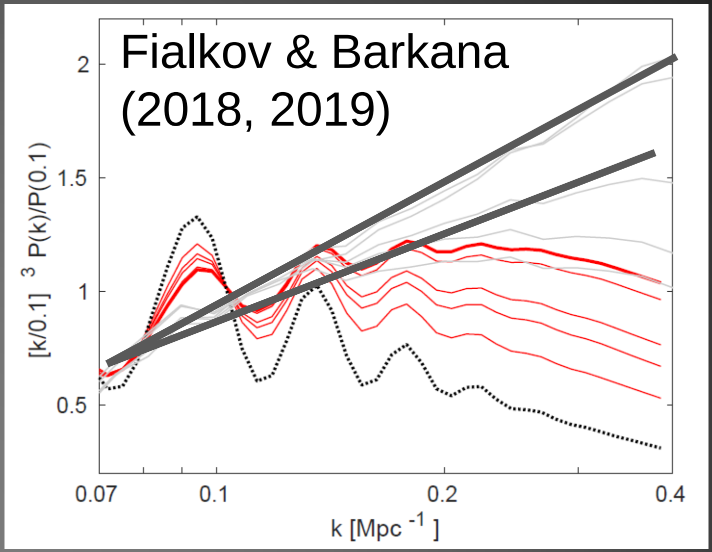


Extra radio background of 0.1-22% above the CMB at 1.42GHz is enough

Data require star formation in small halos $M_{min} < 7.8 \times 10^8\ M_\odot$ at z=17

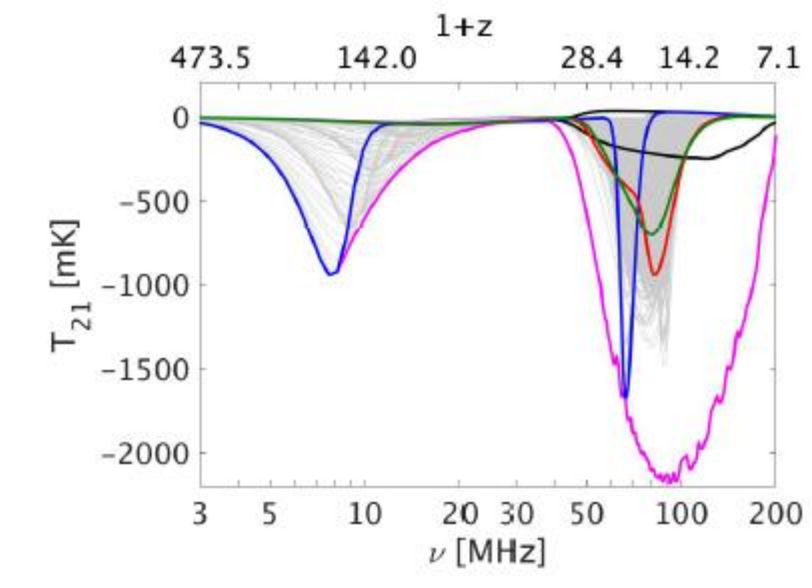
Expected Corresponding Enhancement in Fluctuations:

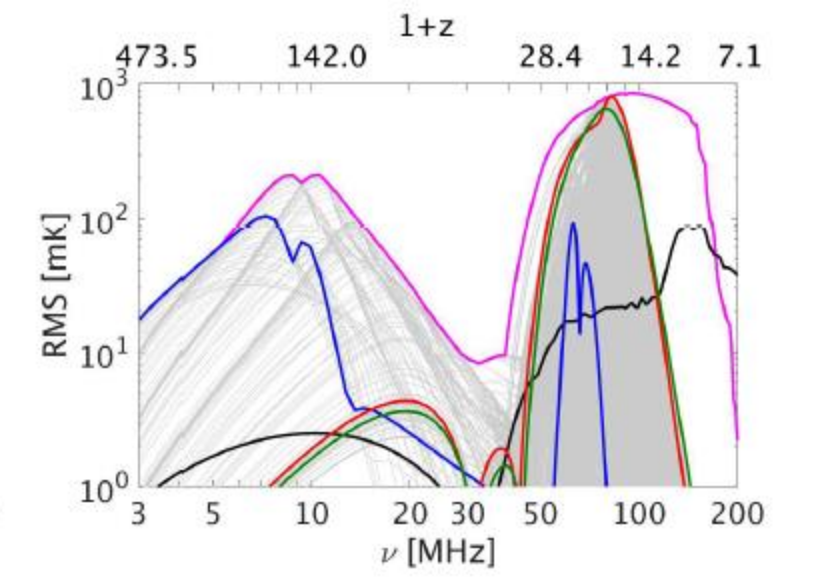
- If EDGES signal is true, fluctuations are also enhanced.
- Shape of the power spectrum is model-dependent and can point out the source of enhancement.



Global

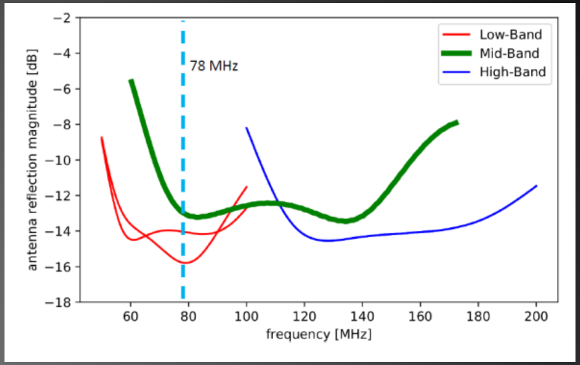
Fluctuations



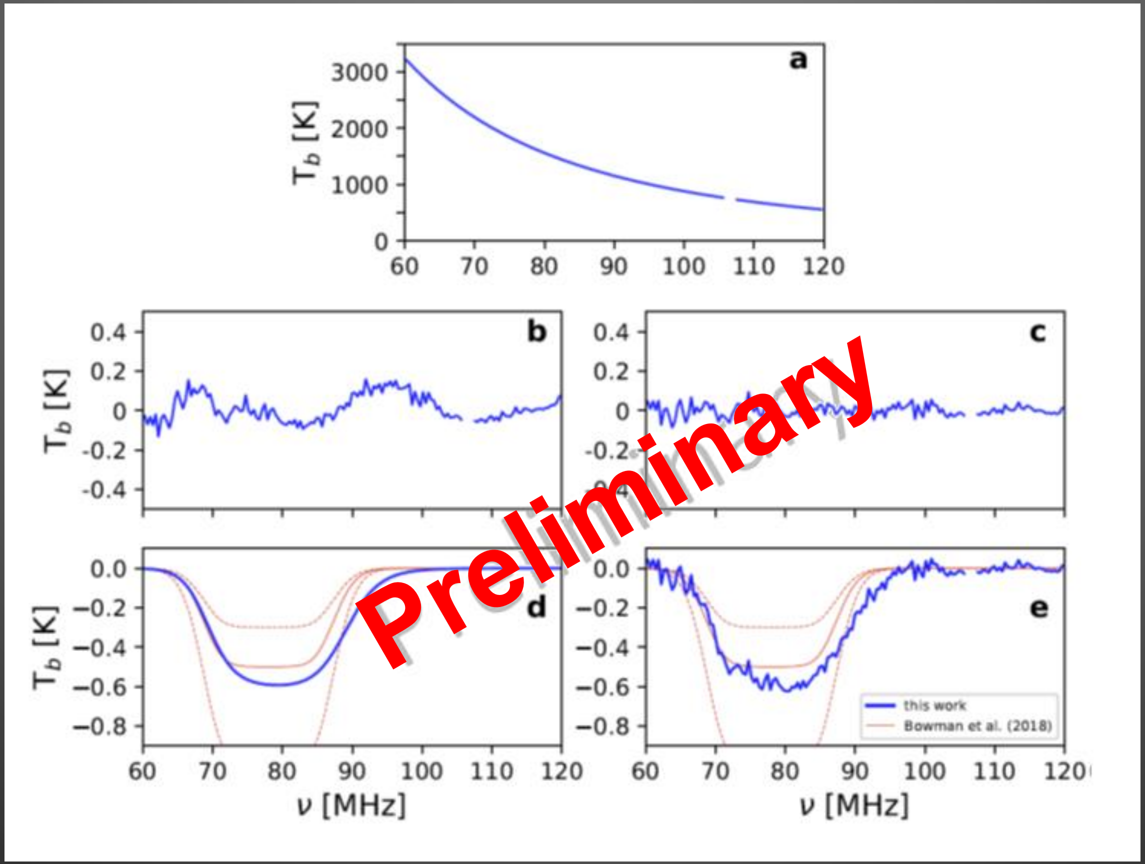


Verification is on the Way: EDGES Mid Band

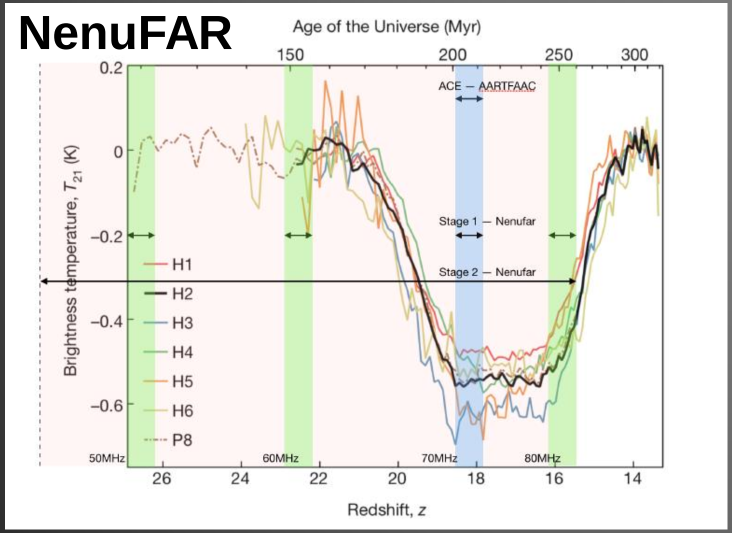
- Mid Band results are in agreement with Low
- Detection is consistent with non-detection by EDGES High, SARAS2, MWA, expected LOFAR upper limits.
- Detection by Mid & Low → Systematics are less likely
- The mystery remains



EDGES collaboration (in prep.)



Follow up: Other Experiments

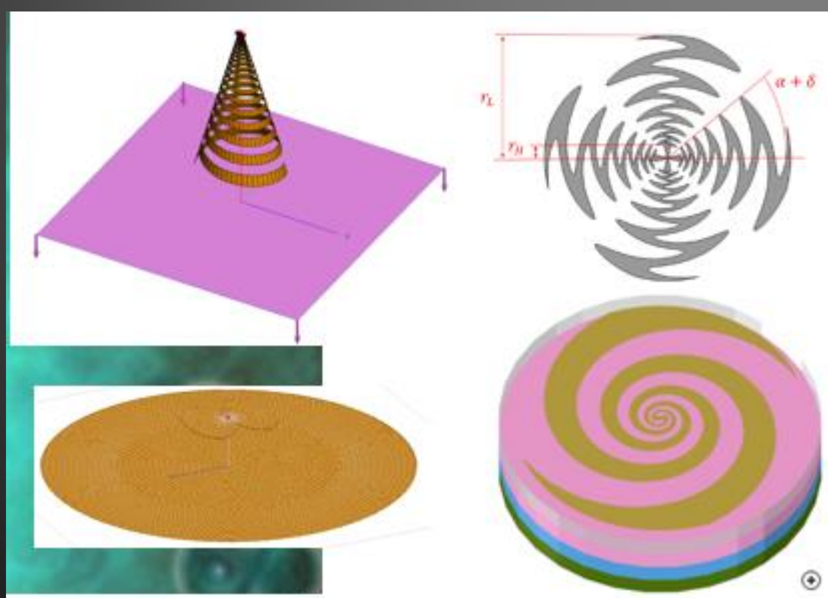


- LOFAR LB: $\Delta^2 \leq 14561^2$ mK, k = 0.038 h/Mpc, z = 19-25, 14 hrs (Gehlot et al. 2019)
- ACE: 1000 h observational programme with LOFAR LB
- NenuFAR: plan to observe ~1000 h at z = 20

Follow up: REACH

PI: Eloy de Lera Acedo (Cambridge)

Global signal
Location: South Africa
Goal to verify the EDGES detection

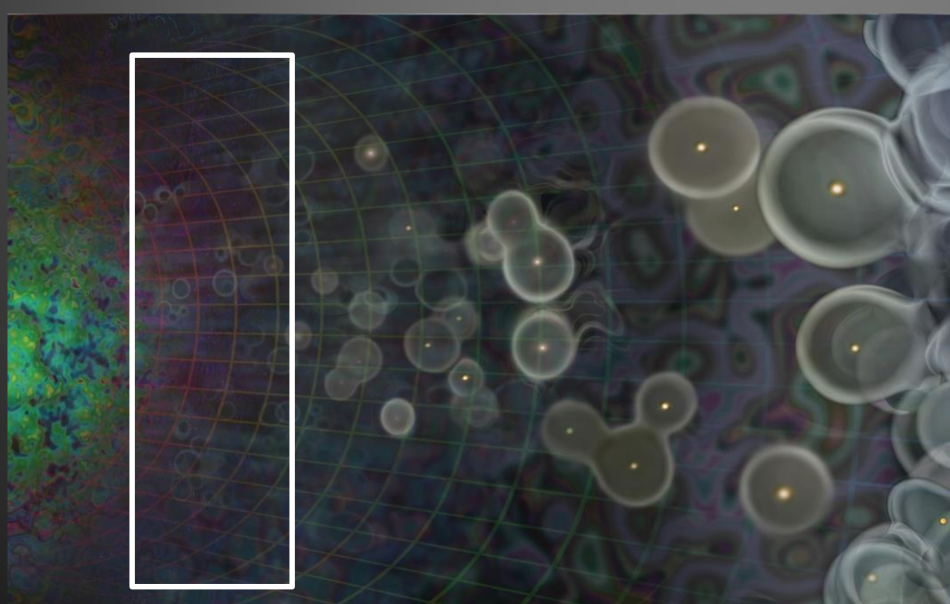


Future Prospects:
Dark Ages from Space

Key questions:
- Dark Matter (clustering/heating/ionization)
- Gravity/Cosmology

Hard to do from the ground: frequencies close to plasma frequency of ionosphere

Missions: DSL, NCLE, DAPPER, FarSide, PRAUSH etc.
Countries: China, USA, India Netherlands



Conclusions:

- **Exciting times for 21-cm cosmology!**
- First claimed detection at z ~ 15-20 (TBC)
- Observational Follow-ups

- All data suggest contribution of small halos $M_{min} < few \times 10^8$ and some heating.
- Constraints on thermal history using SARAS2 and EDGES HB data; soon from LOFAR and MWA