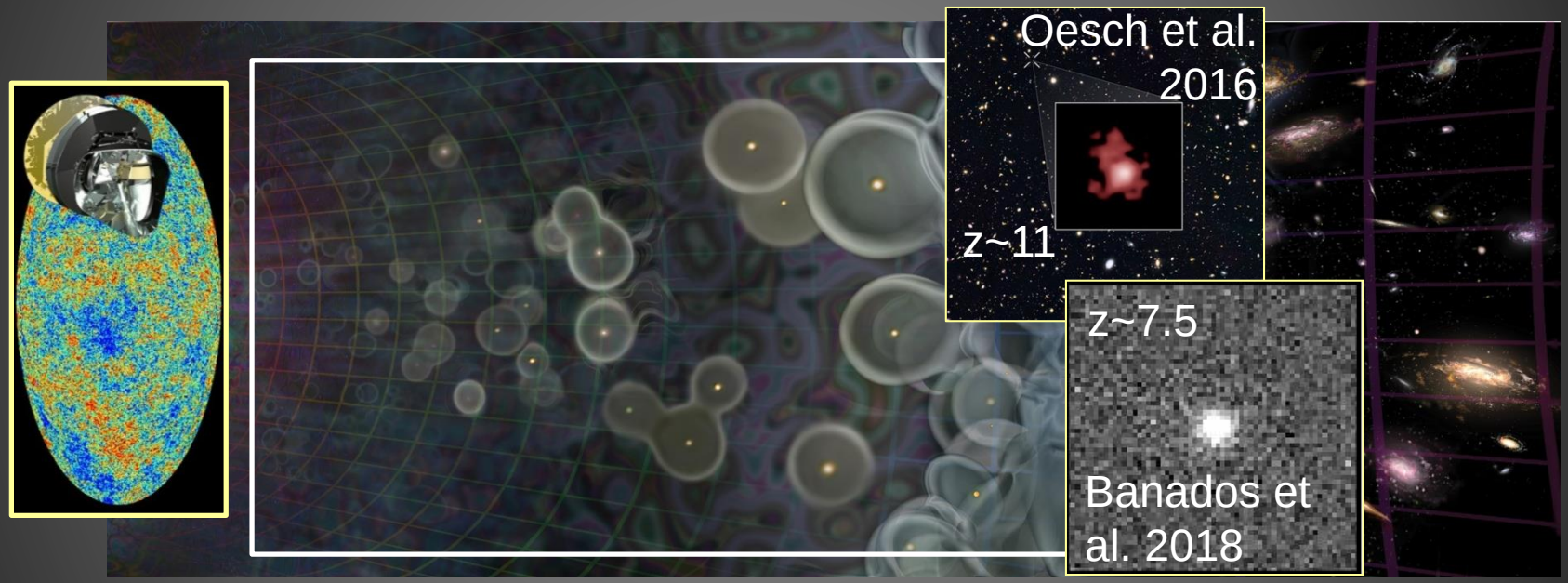
Unveiling Cosmic Dawn

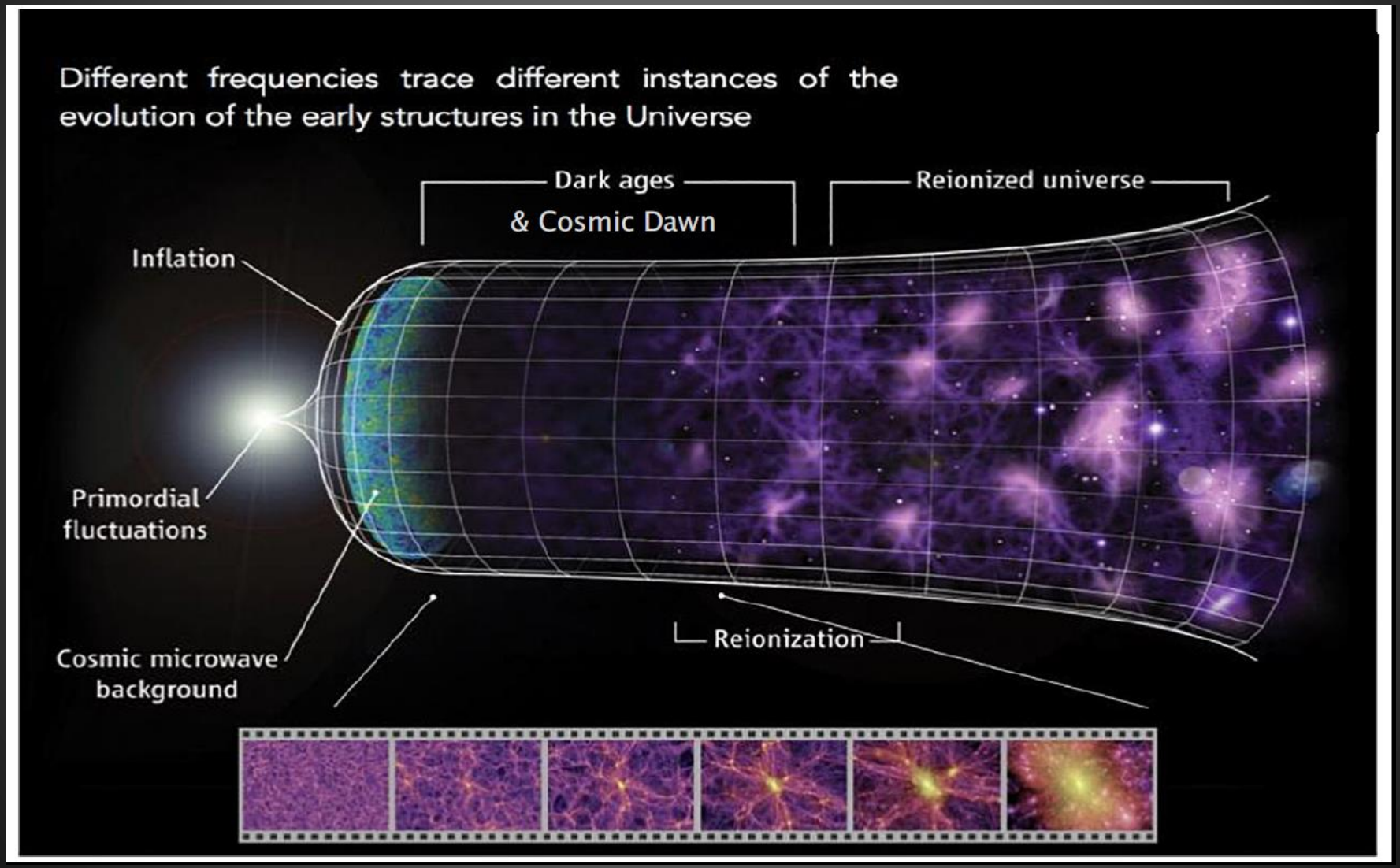


Anastasia Fialkov (IoA, Cambridge)

11.12.2021

Synergies @ Prague

History of the Universe in a Nutshell

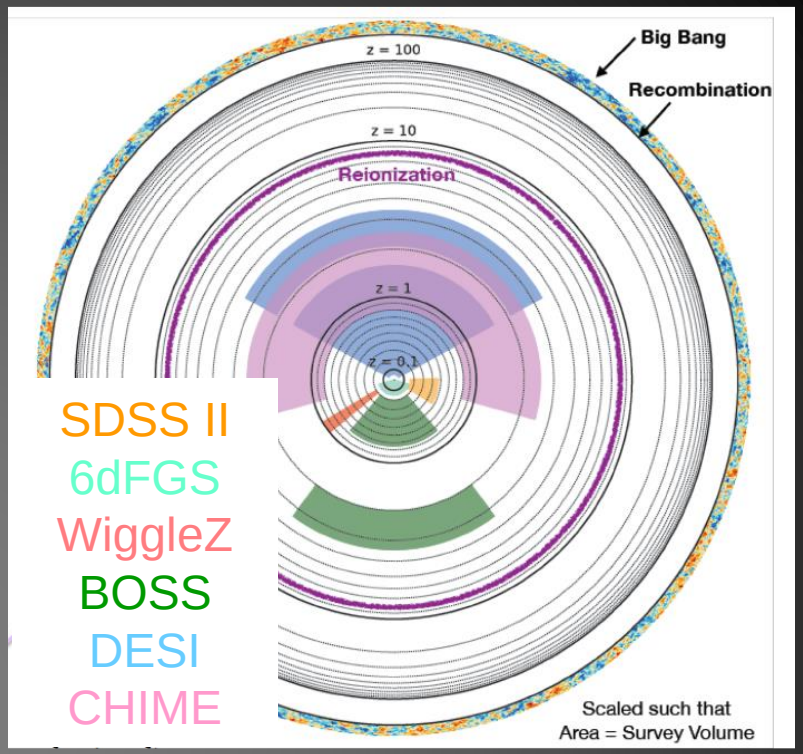


Koopmans et al. 2021

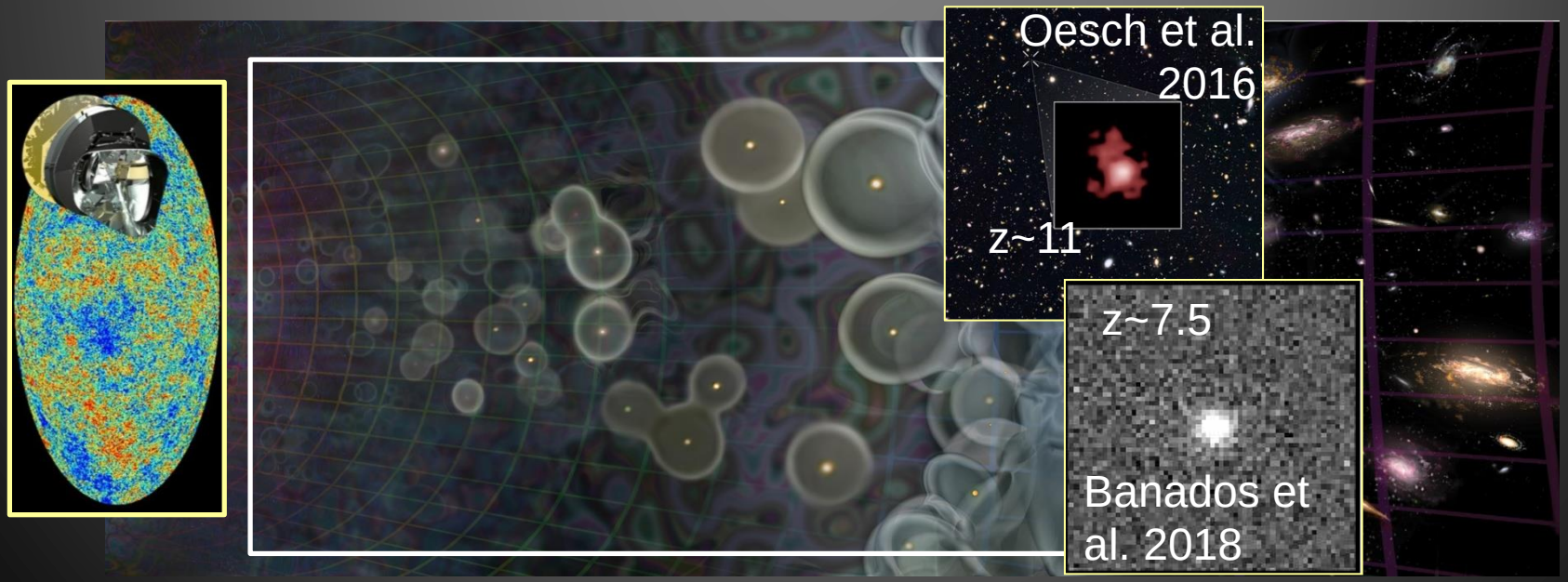
The Unobserved Universe

Existing surveys:
Last scattering surface CMB
Local Universe (out to z ~ 3)

Bright galaxies out to z ~ 11
Bright quasars out to z ~ 7.5



Credit: Seth Siegel



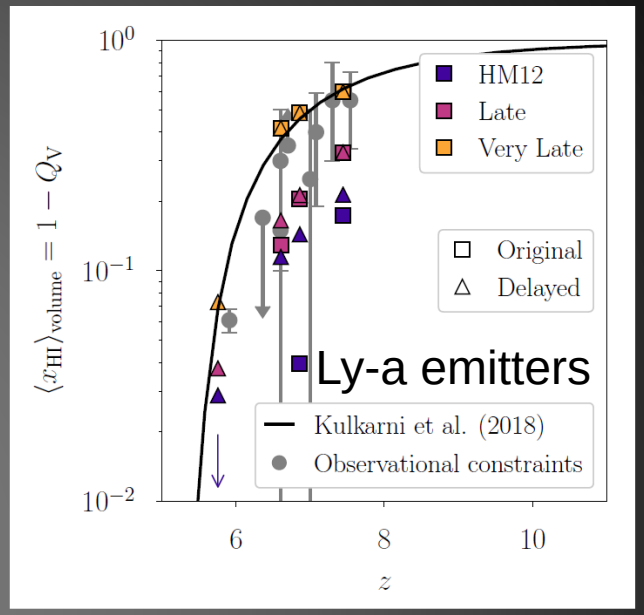
Emerging Picture of the High-z Universe

Late reionization (z < 6)

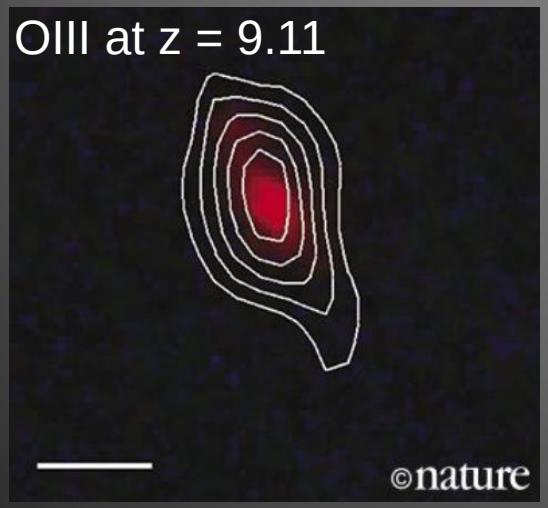
- High-z quasars
- Ly-a emitters

Early onset of star formation (z >15):

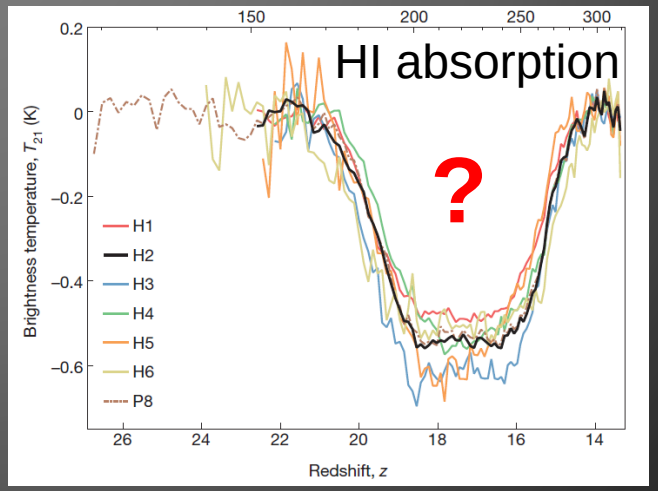
- ALMA OIII: onset of star formations at z ~ 15
- Luminous galaxies at z ~ 11
- EDGES 21-cm (TBC): Ly-a coupling at z ~ 21



Weinberger et al. 2019



Hashimoto et al. (2018)

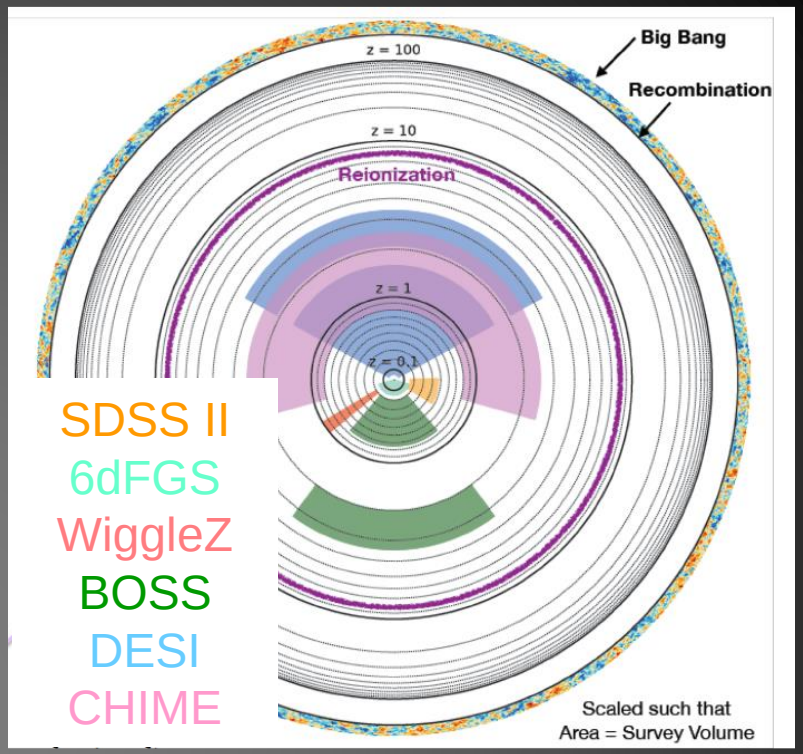


Bowman, et al. (2018)

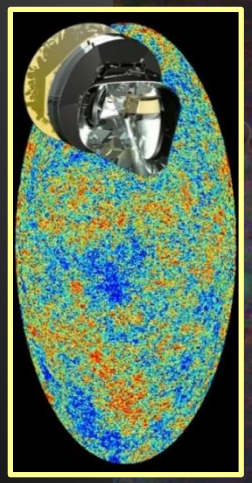
21-cm Observations will Fill the Gap

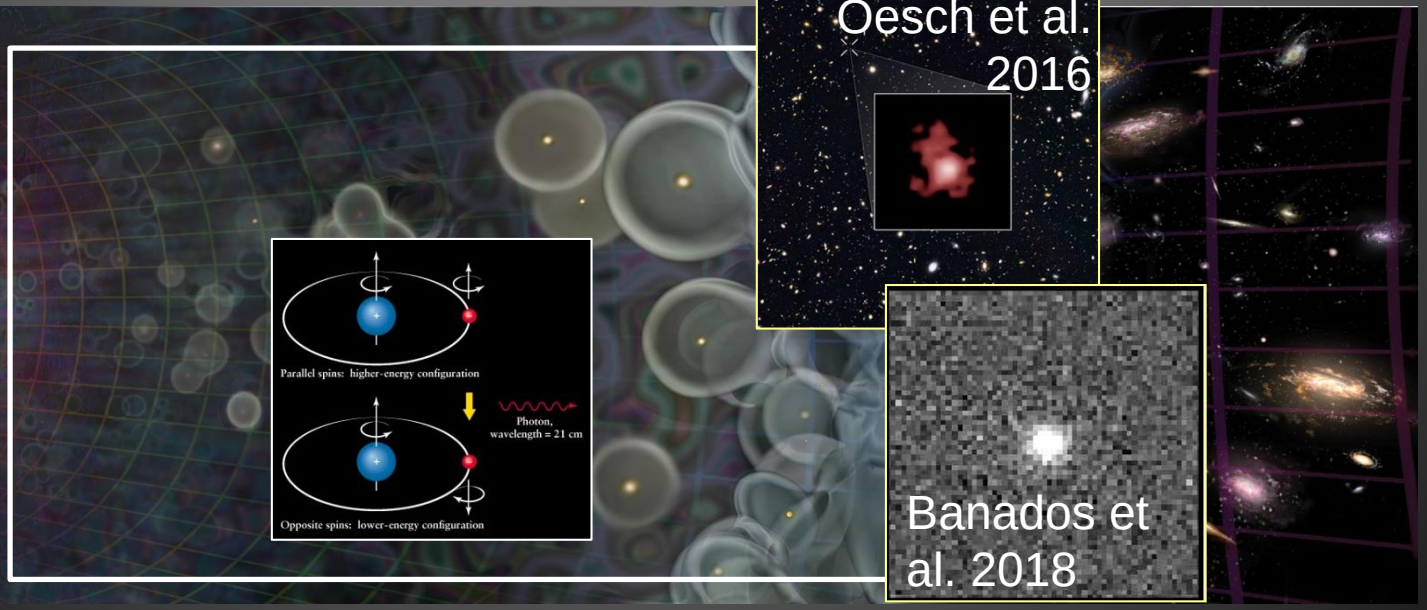
Existing surveys:
Last scattering surface CMB
Local Universe (out to z ~ 3)

Bright galaxies out to z ~ 11
Bright quasars out to z ~ 7.5



Credit: Seth Siegel



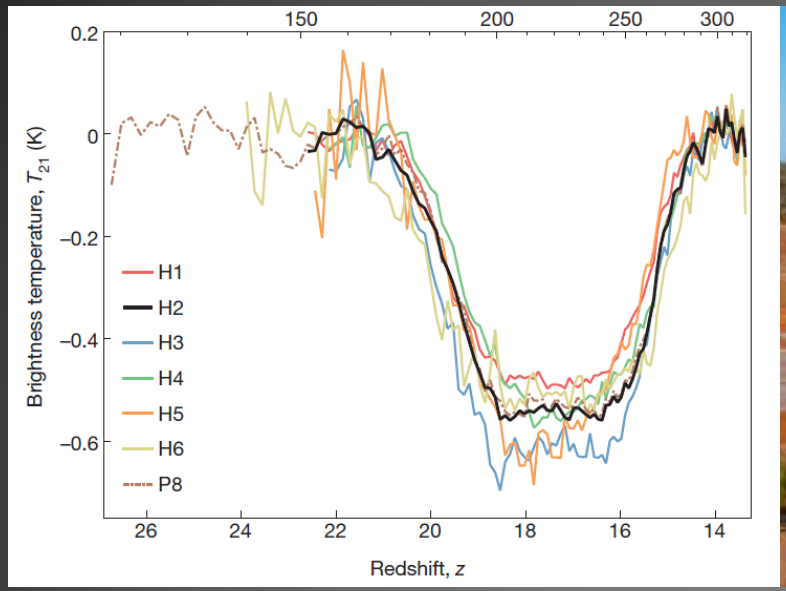


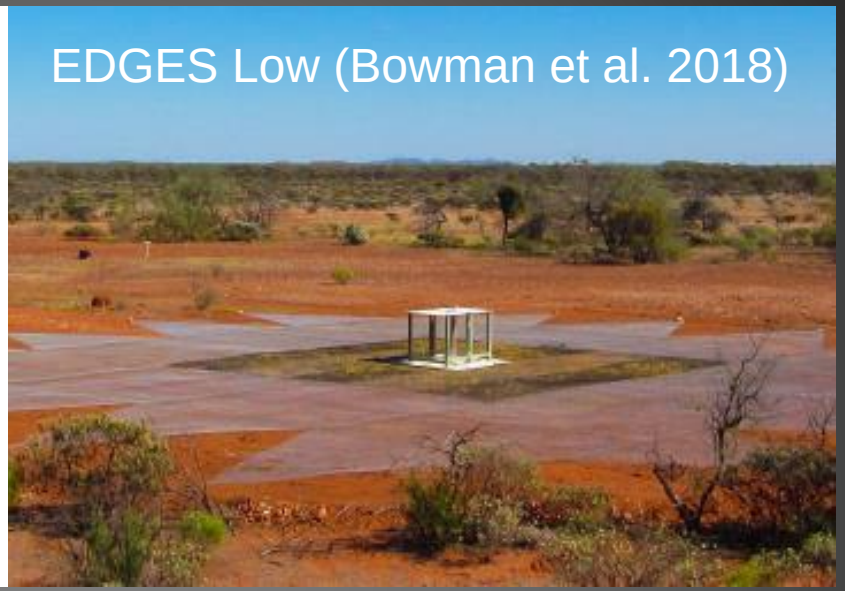
Ongoing Observational Effort

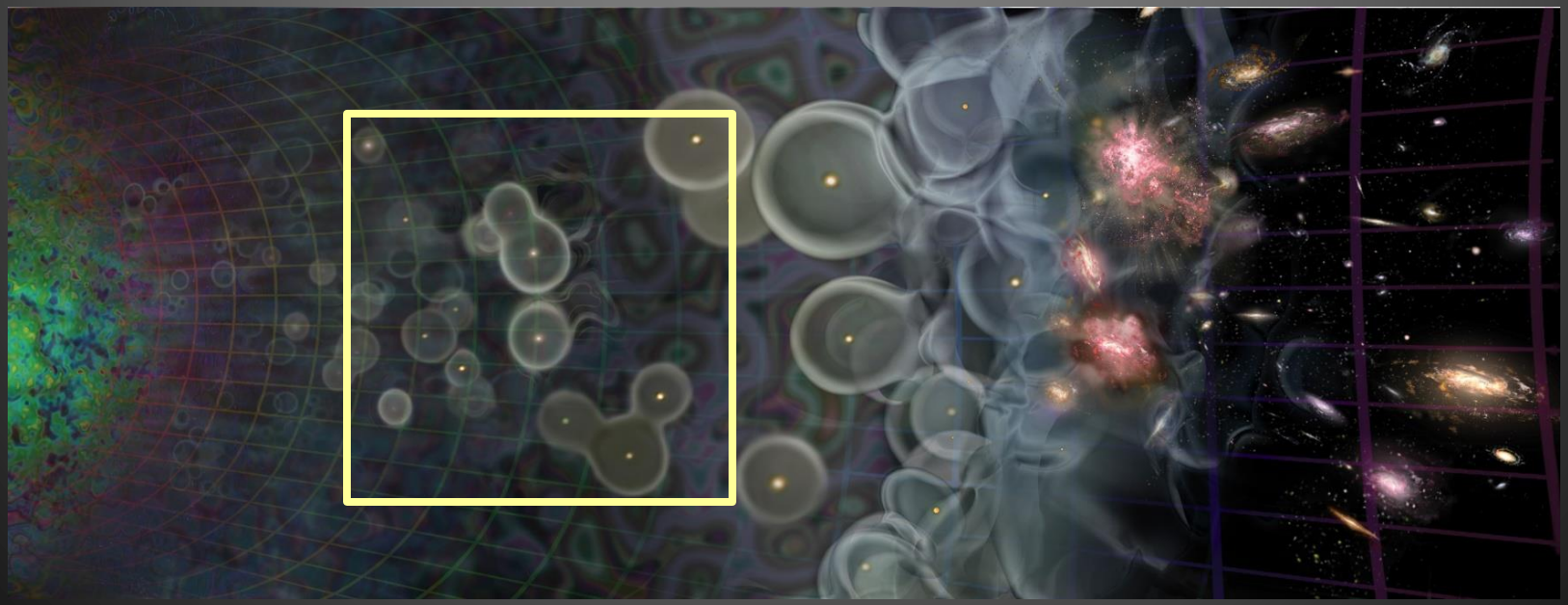
Global signal
and
power spectra
experiments

Koopmans et al. 2021

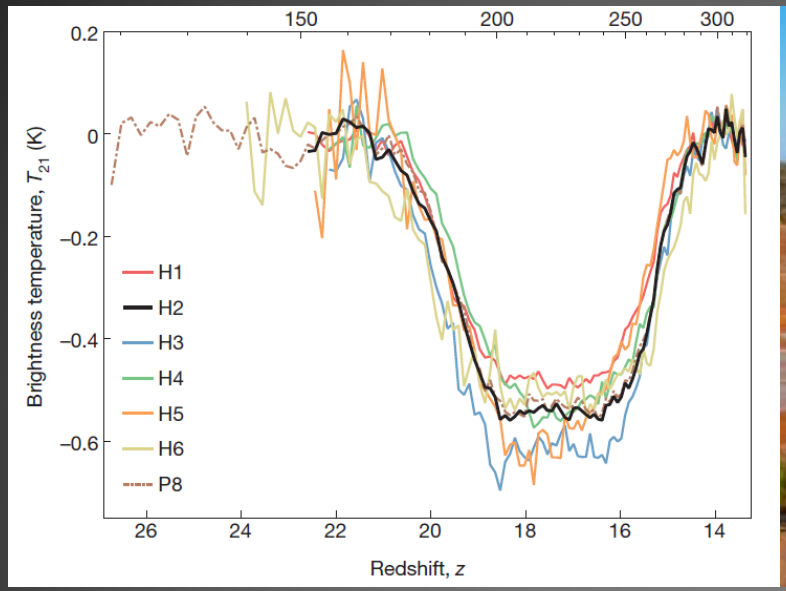
First Claimed Detection of the 21-cm from Cosmic Dawn

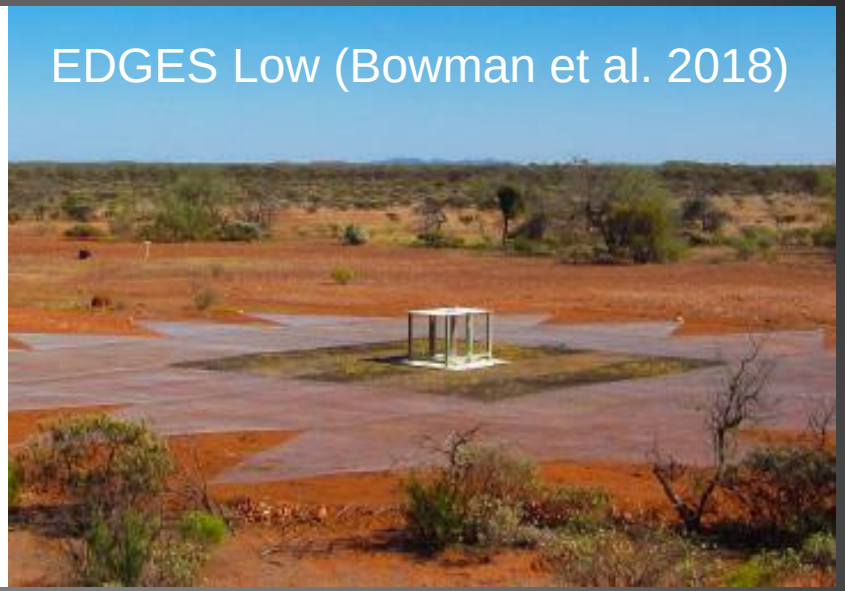


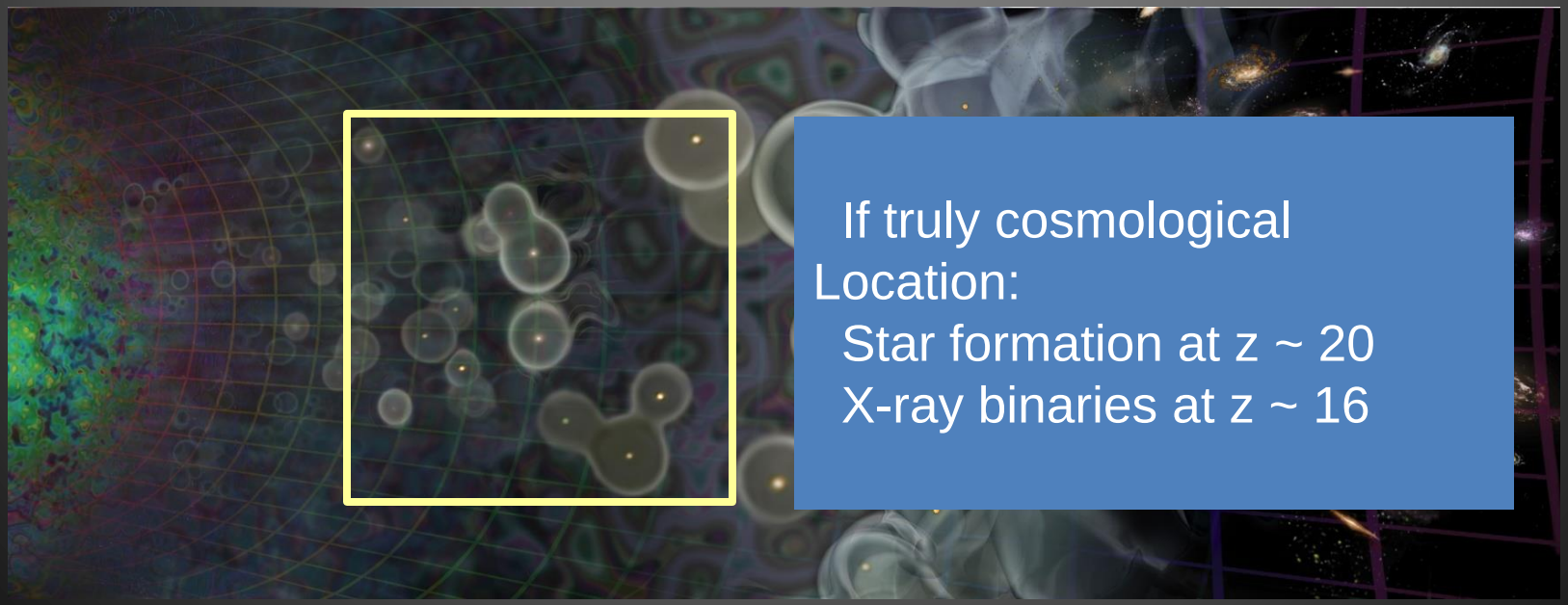




First Claimed Detection of the 21-cm from Cosmic Dawn

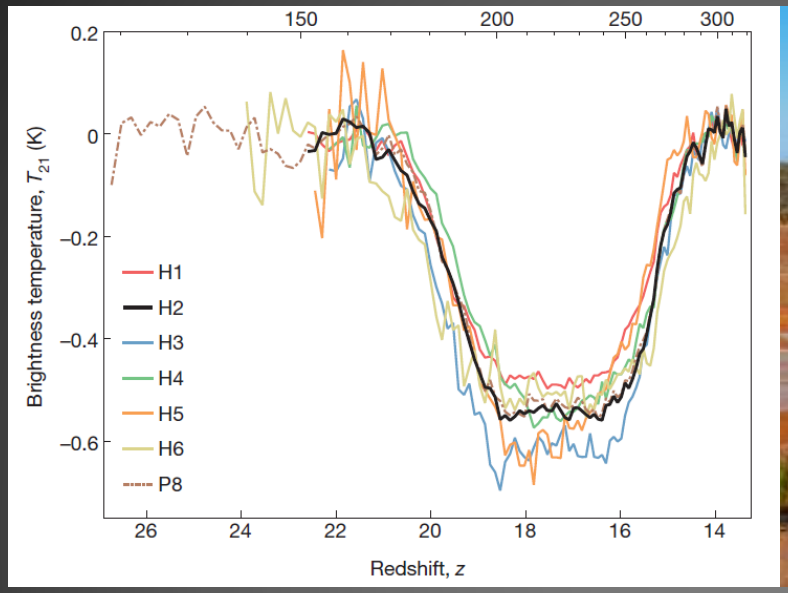


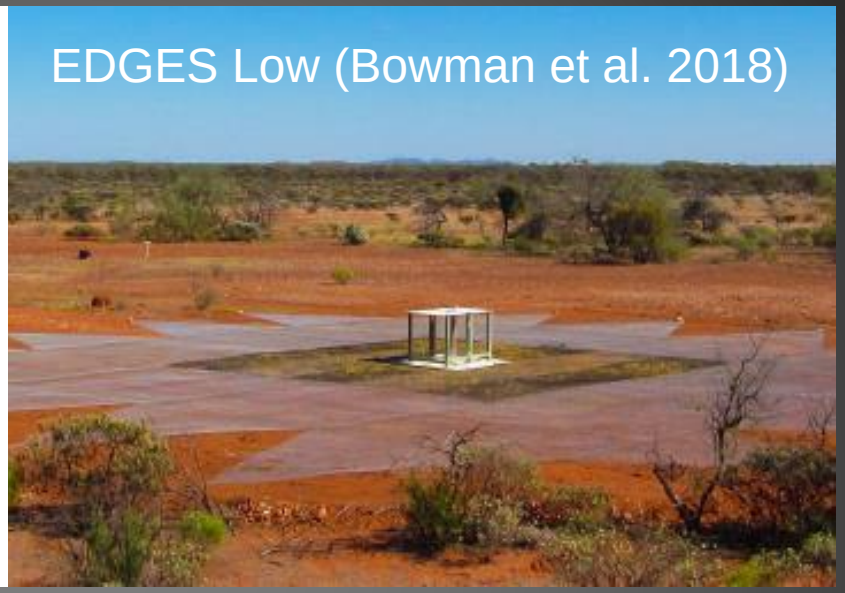


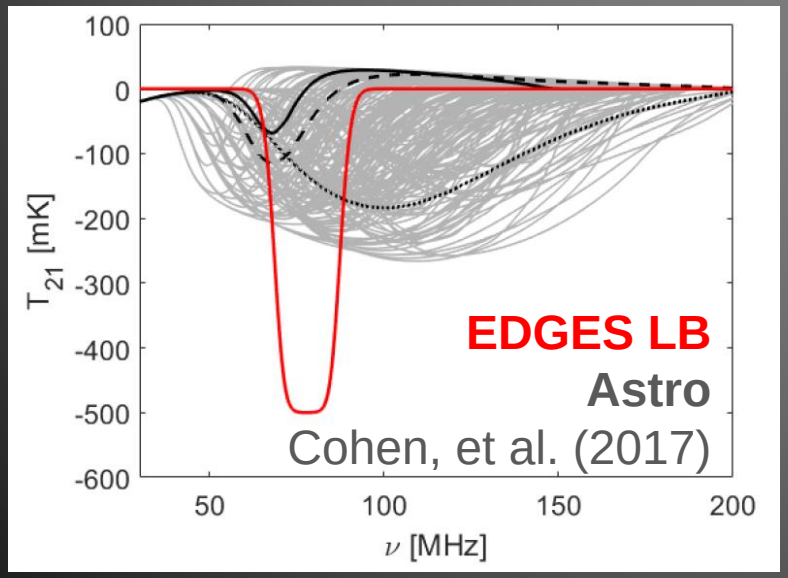


If truly cosmological
Location:
Star formation at z ~ 20
X-ray binaries at z ~ 16

First Claimed Detection of the 21-cm from Cosmic Dawn





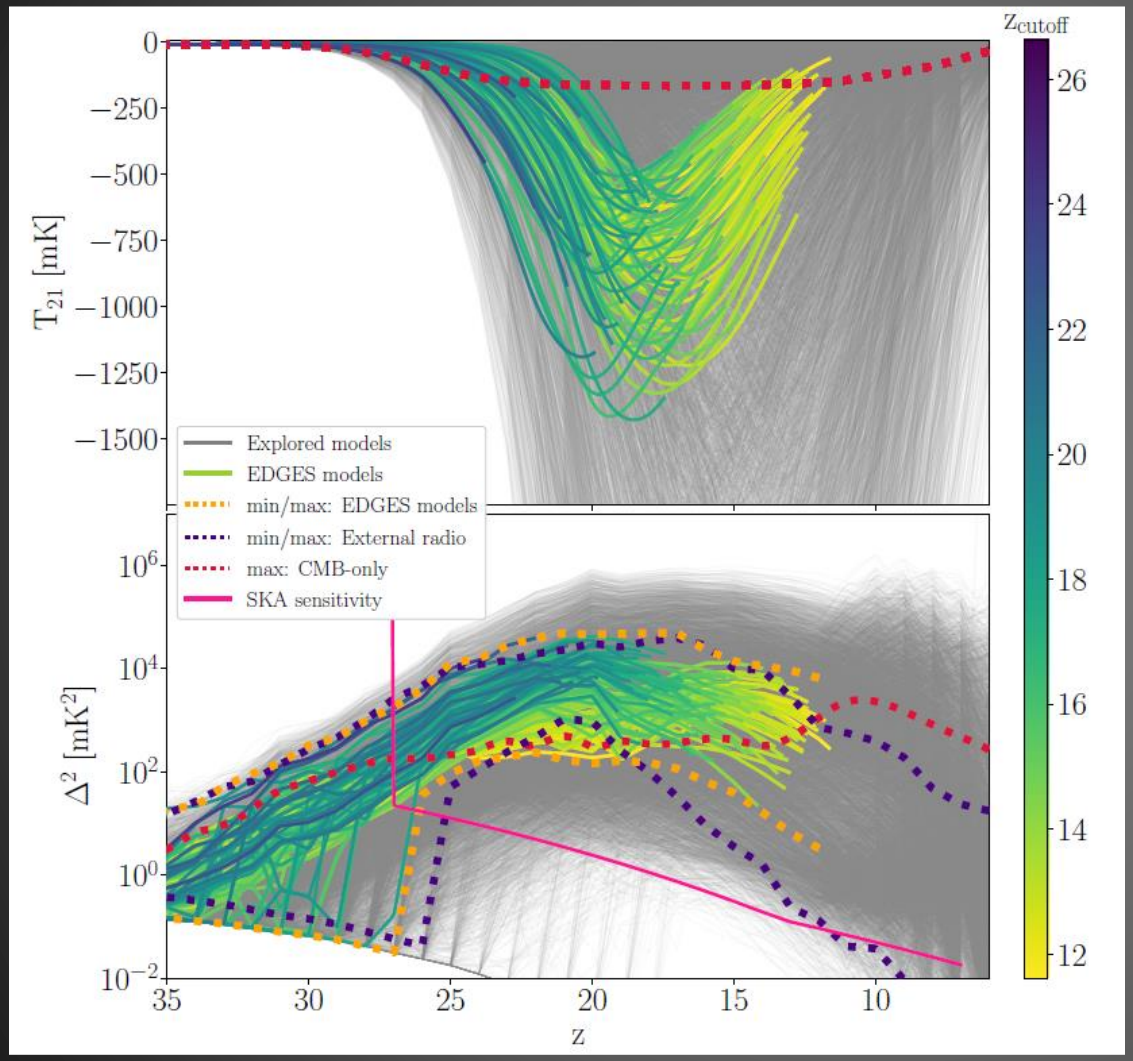


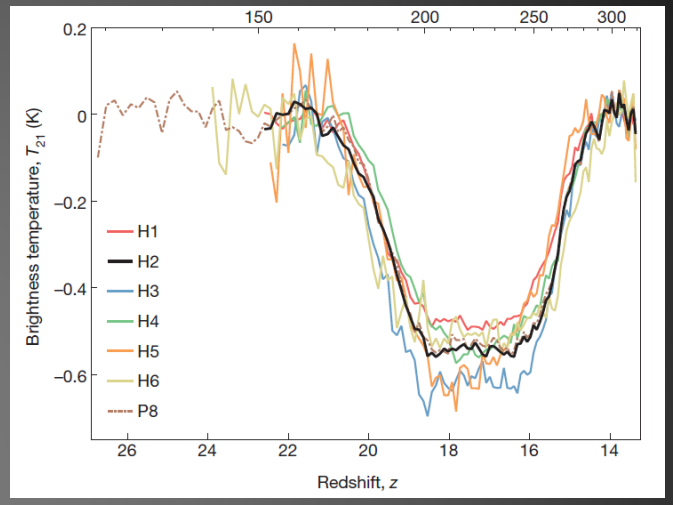
Inconsistent with standard astro

Proposed solutions:

- dark matter interactions (fine-tuned)
- extra-radio background (extreme)

New Tests of EDGES-Motivated Models: High-z Power Spectra





Bowman, et al. (2018)

Enhanced PS
High-z population (z cutoff)

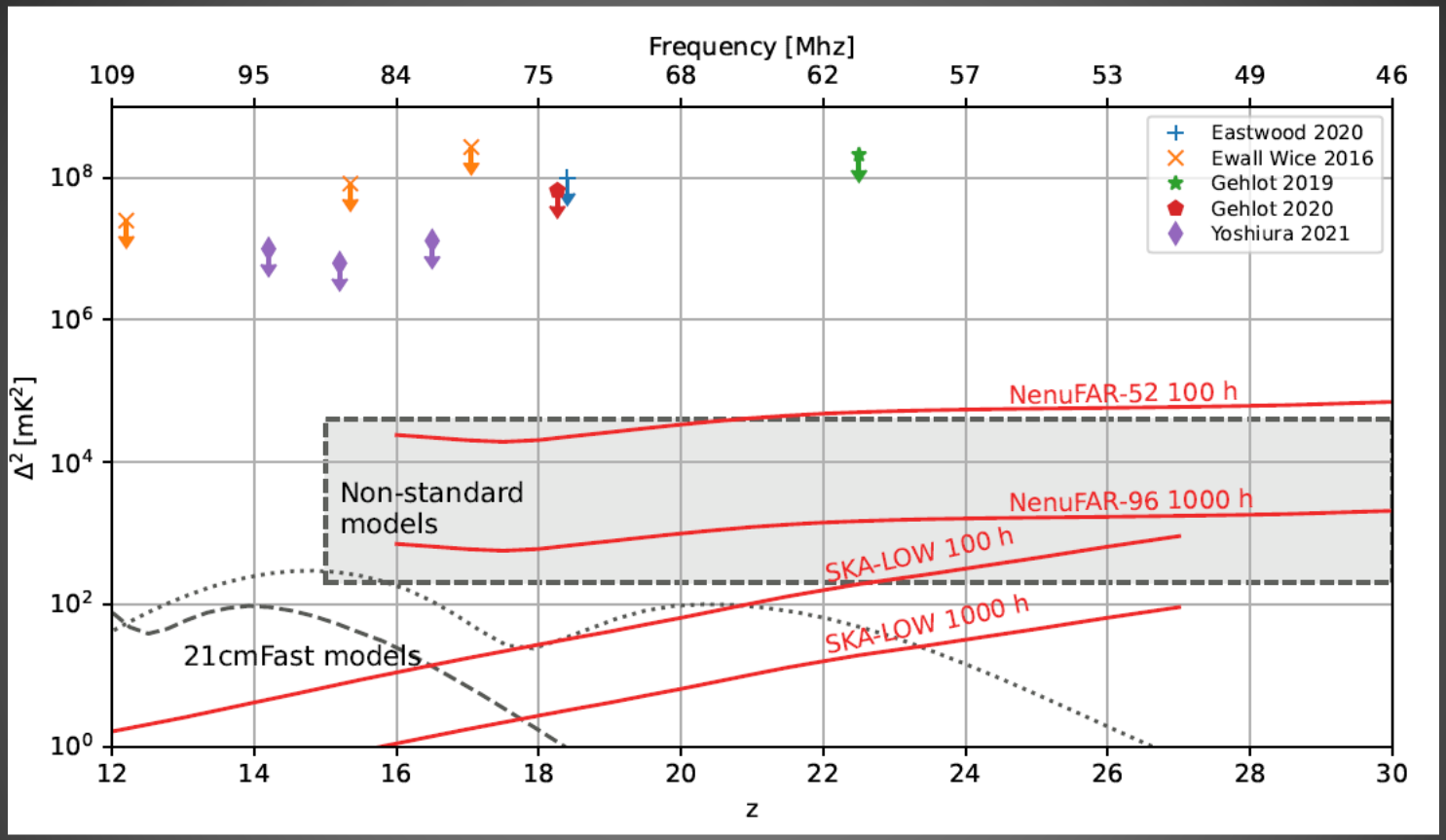
Reis, **Fialkov**, Barkana (2020)

Verification Attempts

Global signal
and
power spectra
experiments

Credit: Udaya Shankar (RRI)

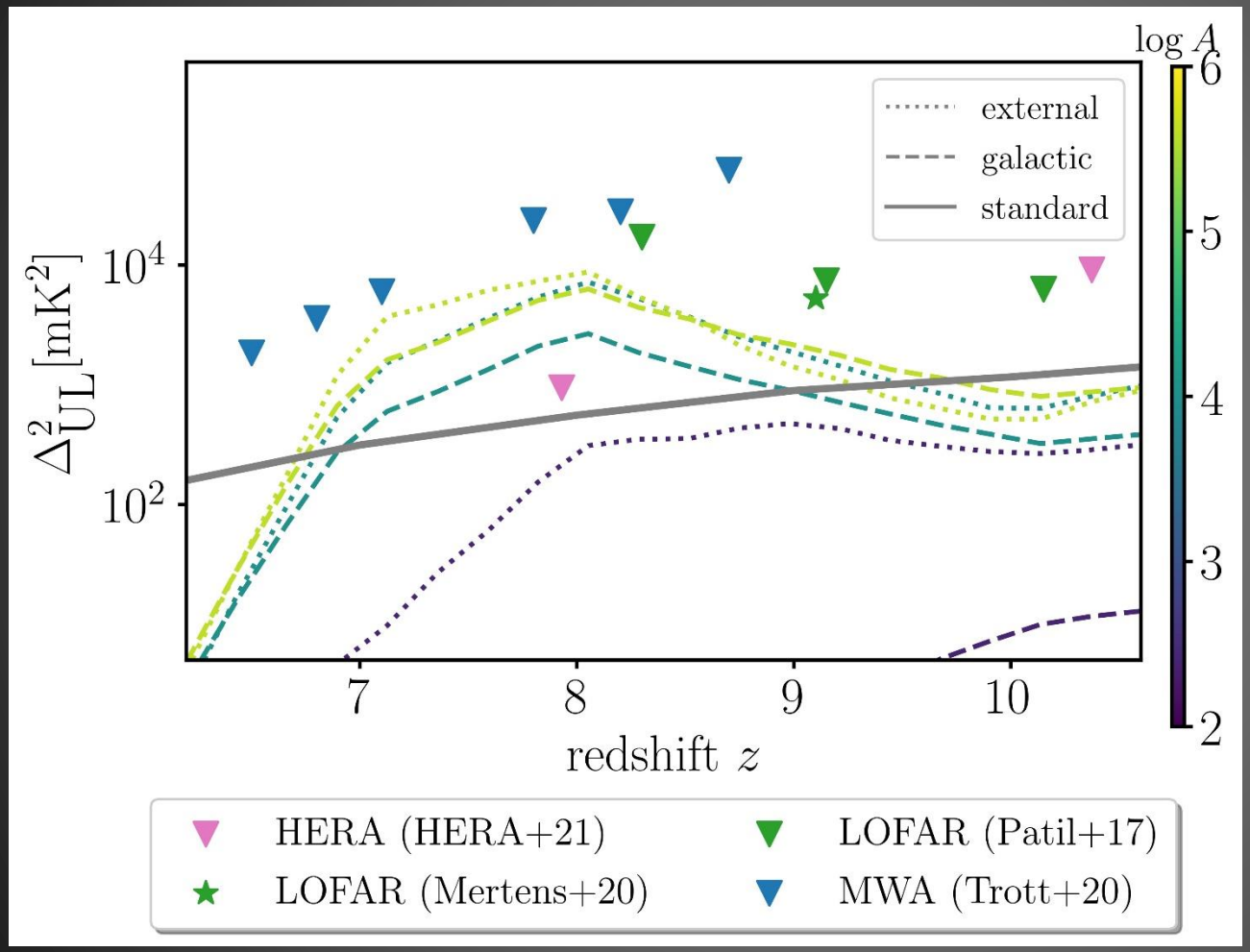
Observational Status at Cosmic Dawn



Upper limits on the 21 cm power spectrum at 95% confidence from various experiments at z = 12-30

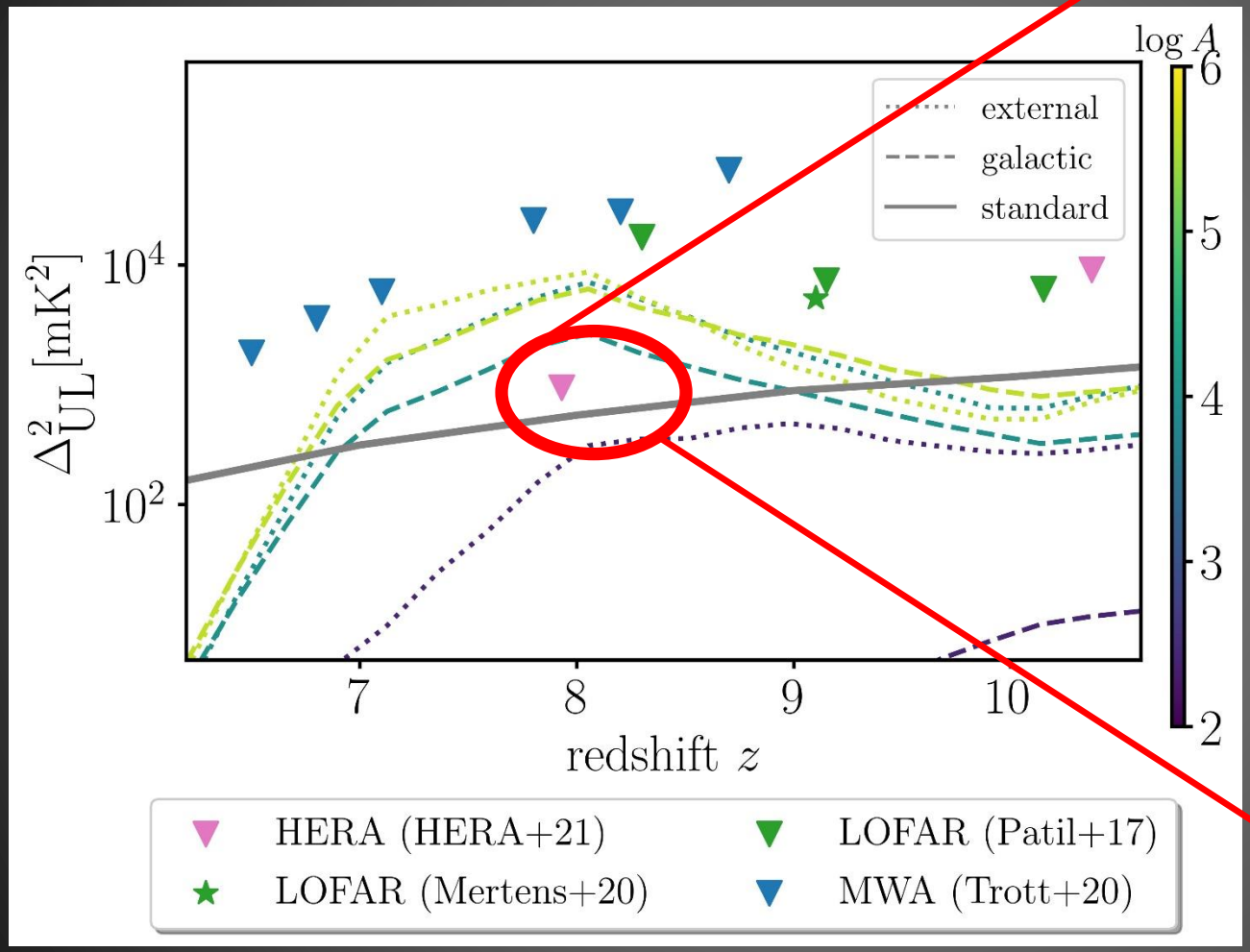
Mertens et al. 2021

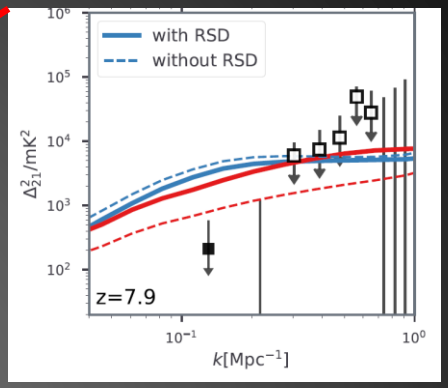
Observational Status at the EoR

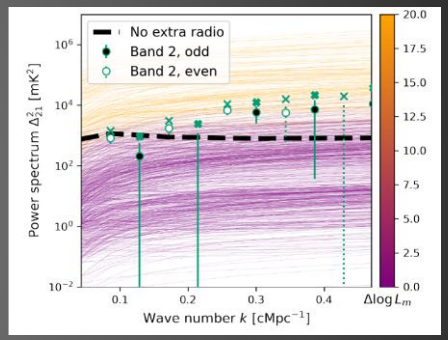


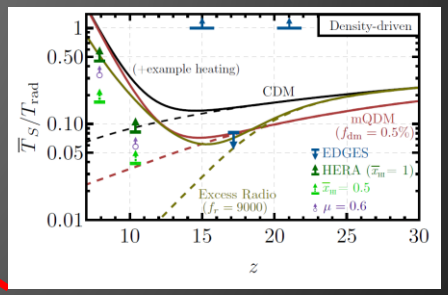
By I. Abril Cabezas & S. Heimersheim

HERA – Best Limits so Far









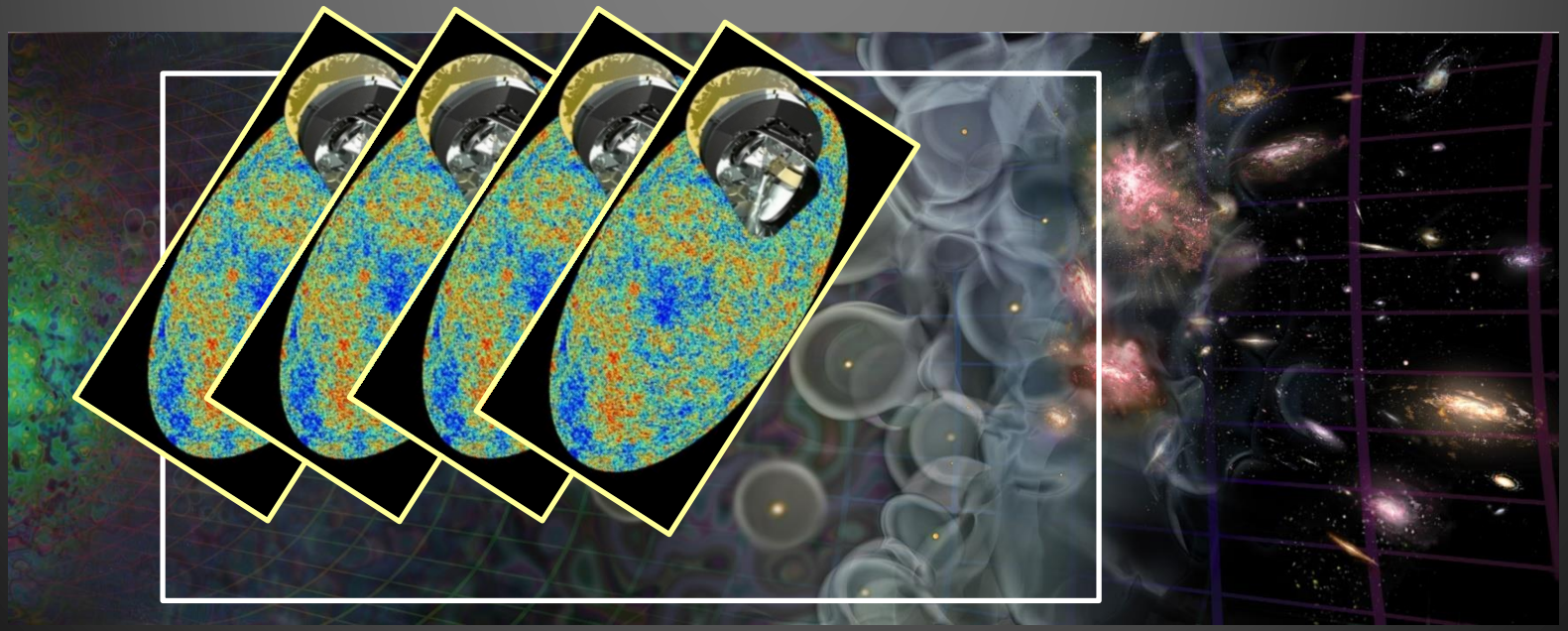
By I. Abril Cabezas & S. Heimersheim

The HERA collaboration

Future: Tomographic Scan of the Neutral Universe

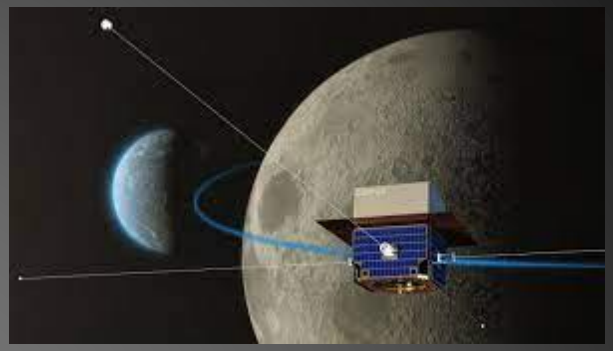
With 21-cm signal: Information from every redshift

- Timing of cosmic events
- Astrophysical properties of high-redshift sources
- Cosmology in the new redshift regime
- Baryonic matter distribution
- Probe of dark matter physics
- Thermal and ionization histories



Dark Ages from Space!

DAPPER



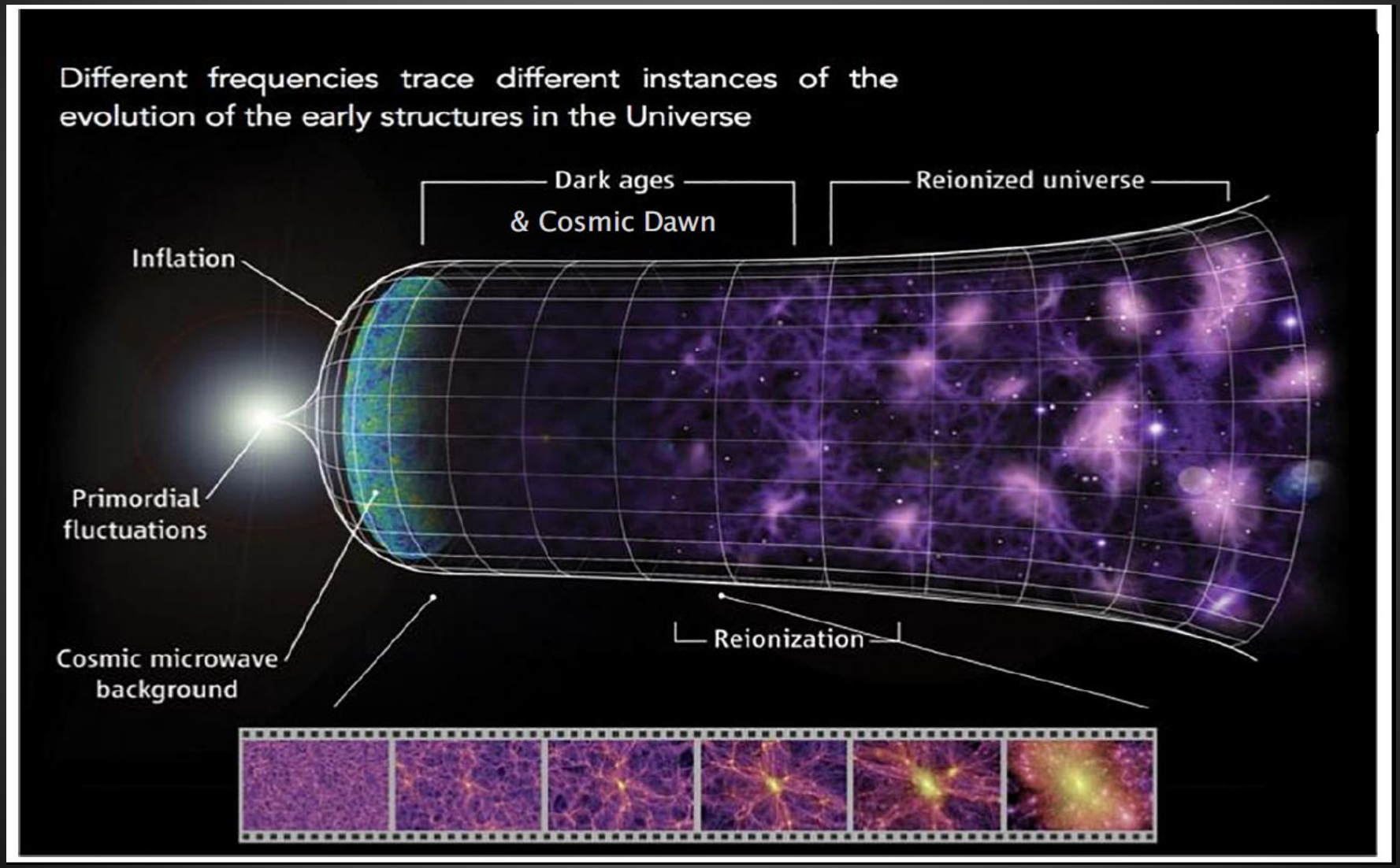
- Avoid Ionosphere
- Avoid RFI
- Unique way to probe the dark ages

NCLE

FARSIDE

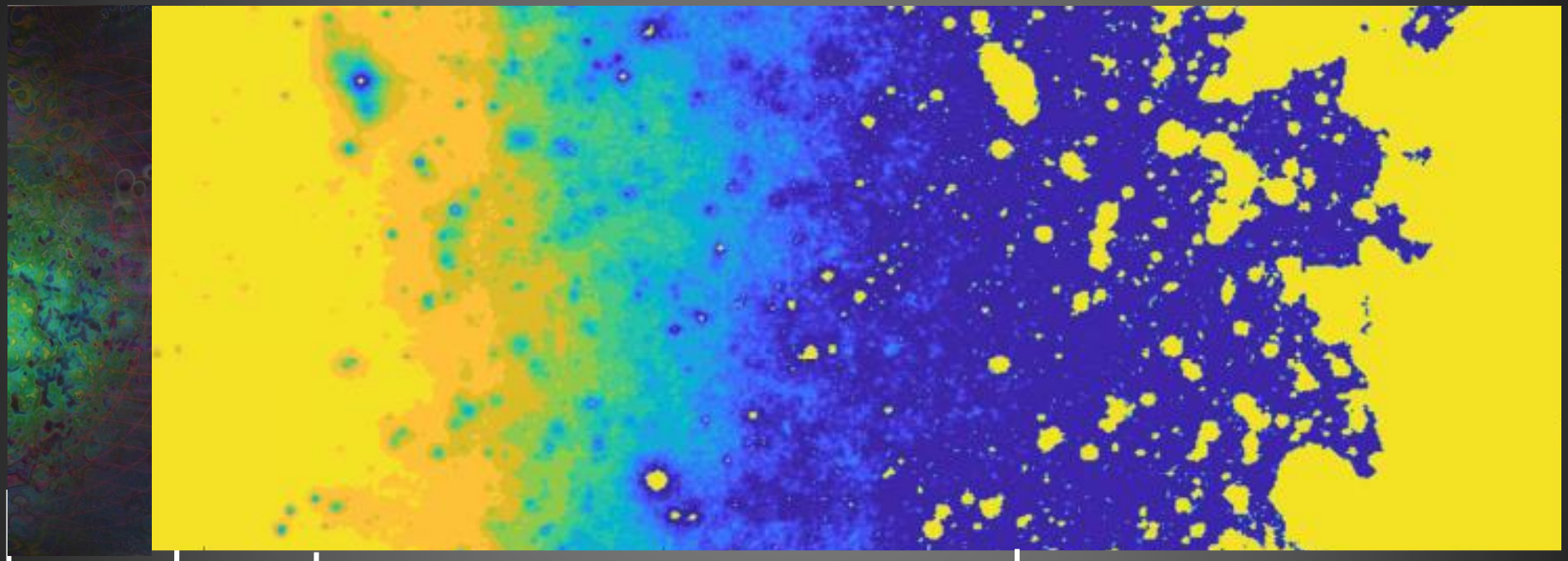
DSL

History of the Universe in a Nutshell



Koopmans et al. 2021

21-cm is Rich in Astrophysics and Cosmology



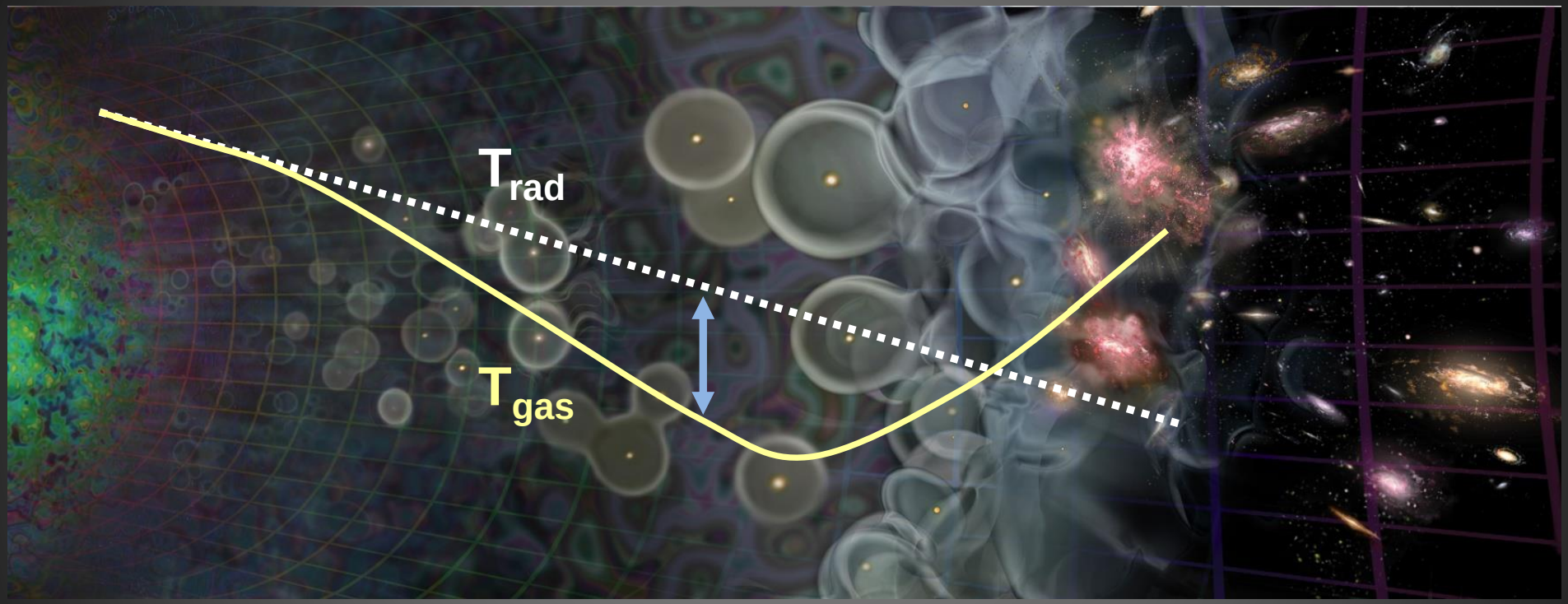
Epoch of Reionization

Cosmic Dawn: First Stars and Galaxies

Dark Ages

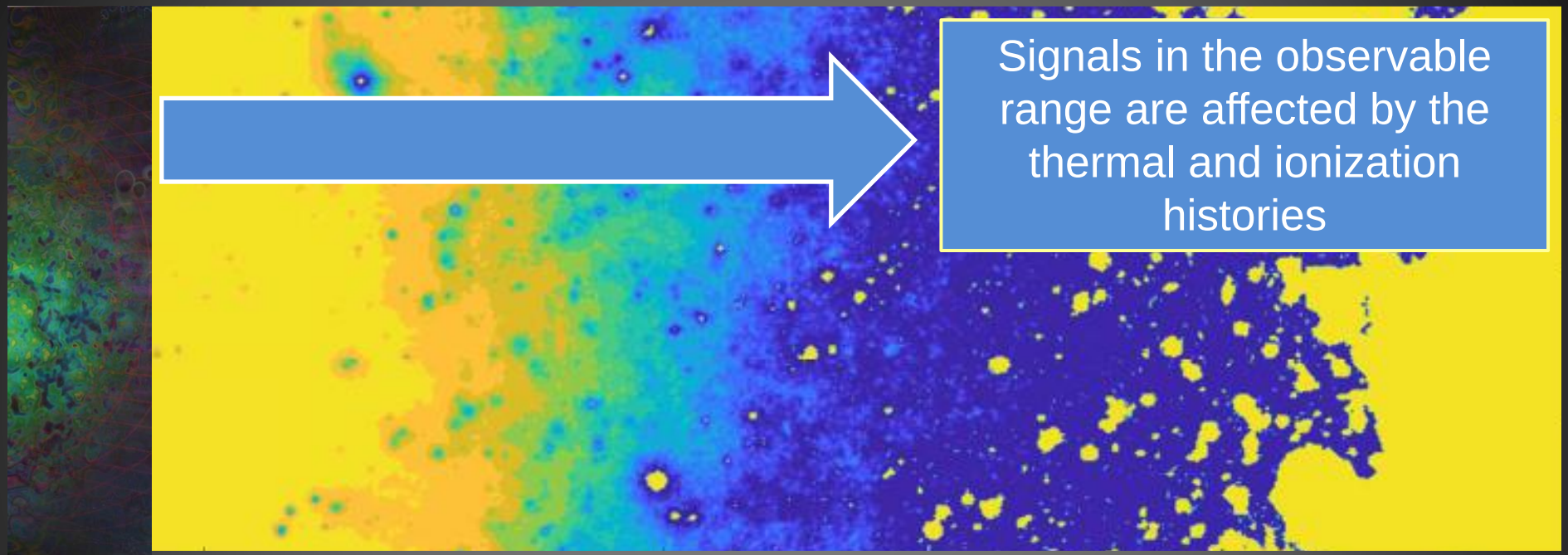
Cosmic Microwave Background

Main Players:



- Ly-a (WF) coupling of $T_S \rightarrow T_{gas}$
- Contrast between T_{gas} and T_{rad}
- Ionization History
- DM physics

21-cm is Rich in Astrophysics and Cosmology



Epoch of Reionization

Ionization: Massive galaxies and quasars

Gas temperature: Integrated history

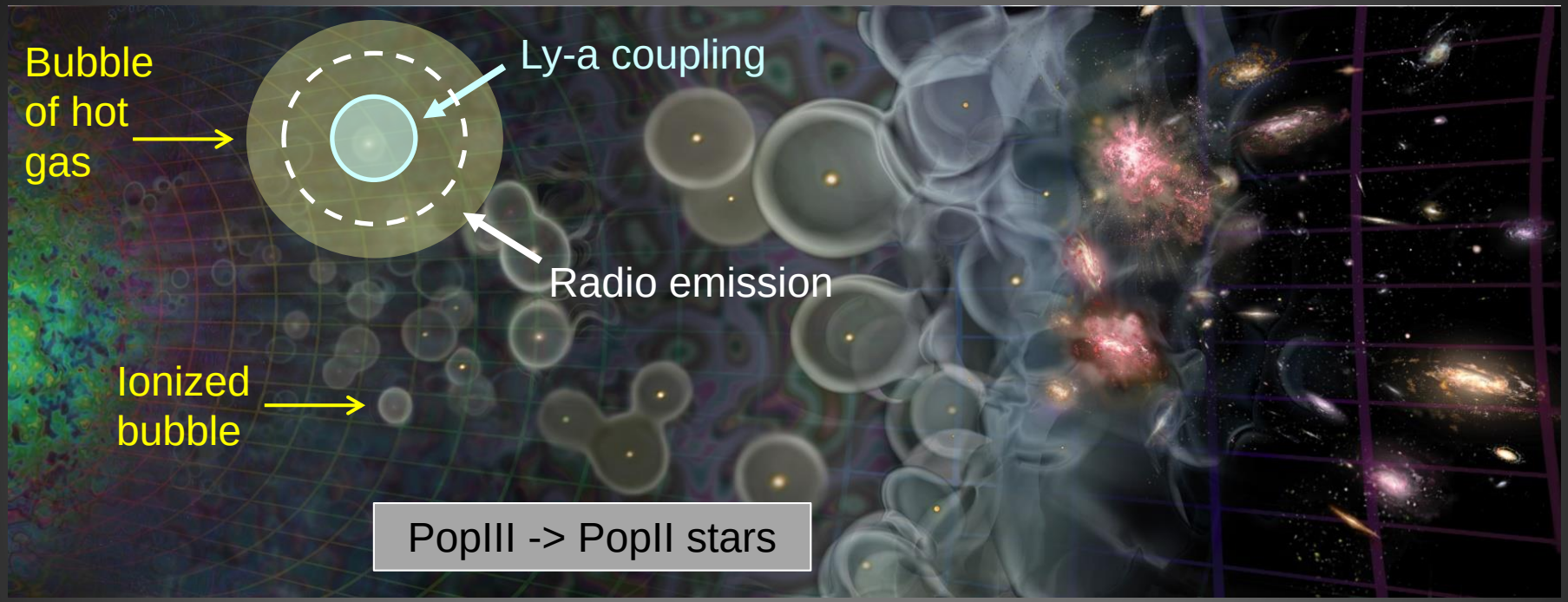
Cosmic Dawn

First stars and black holes

Dark Ages

Dark matter and cosmology

Rich structure in Fluctuations
Subtle Processes that Have Long-Lasting Effects



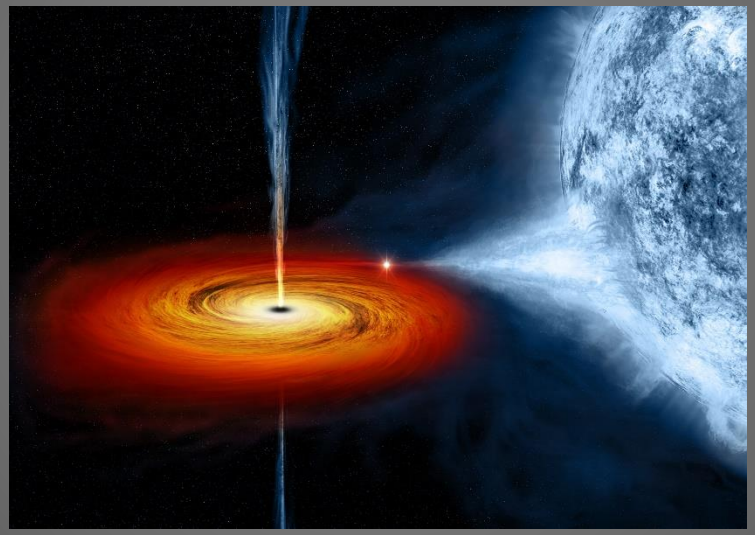
Fluctuations:

- Density and velocity
- Ly-a, heating, radio, ionization
- Structure formation
- Evolution of populations

Example of subtle processes:

- Ly-a scattering
- Ly-a heating
- Evolution of populations
- DM effects

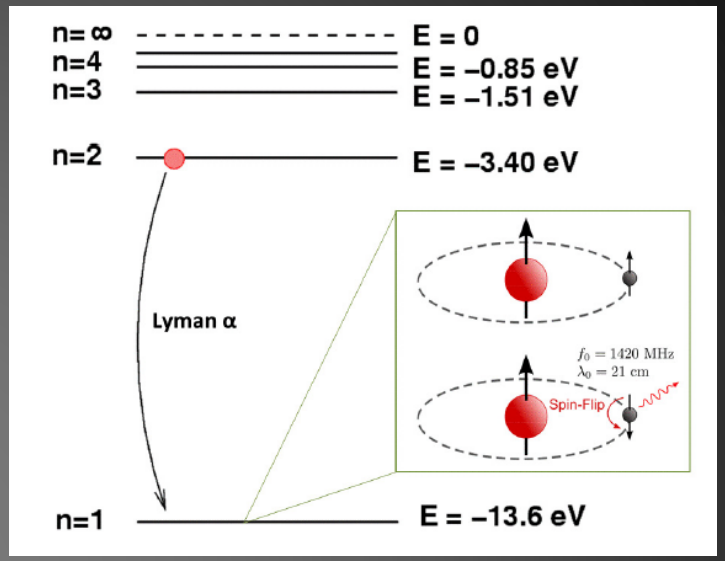
Learning about Astrophysics from the 21-cm Signal

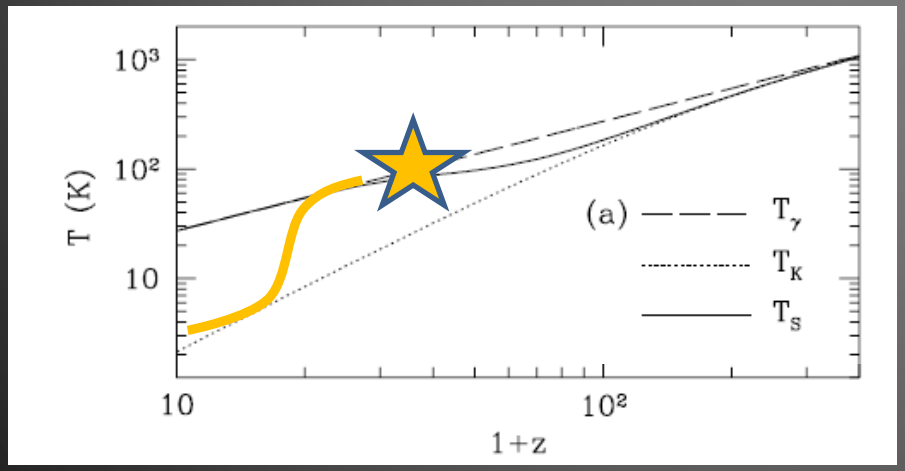


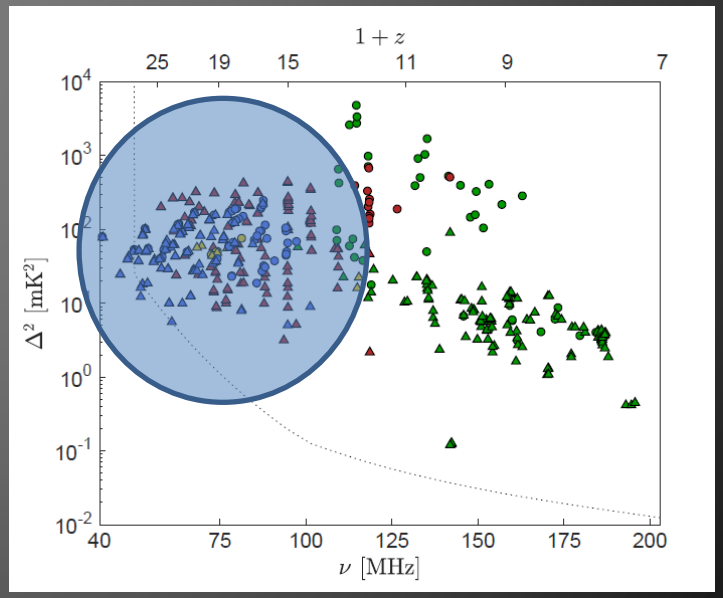
Ly-a Physics

- Fundamental, enables 21-cm line observations
- Radiation produced by first stars couples between the 21-cm levels and the cold gas temperature

- Can happen late (if massive galaxies dominate)!

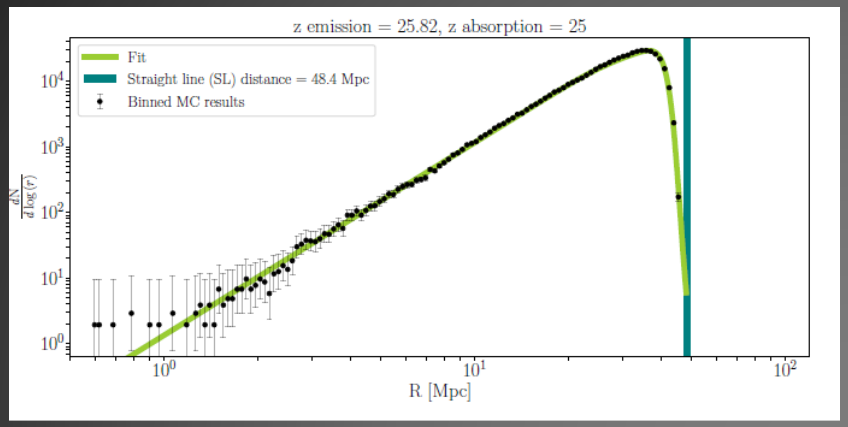






Cohen, Fialkov, Barkana 2017

Detecting the First Star Light: Lyman-a Coupled Bubbles

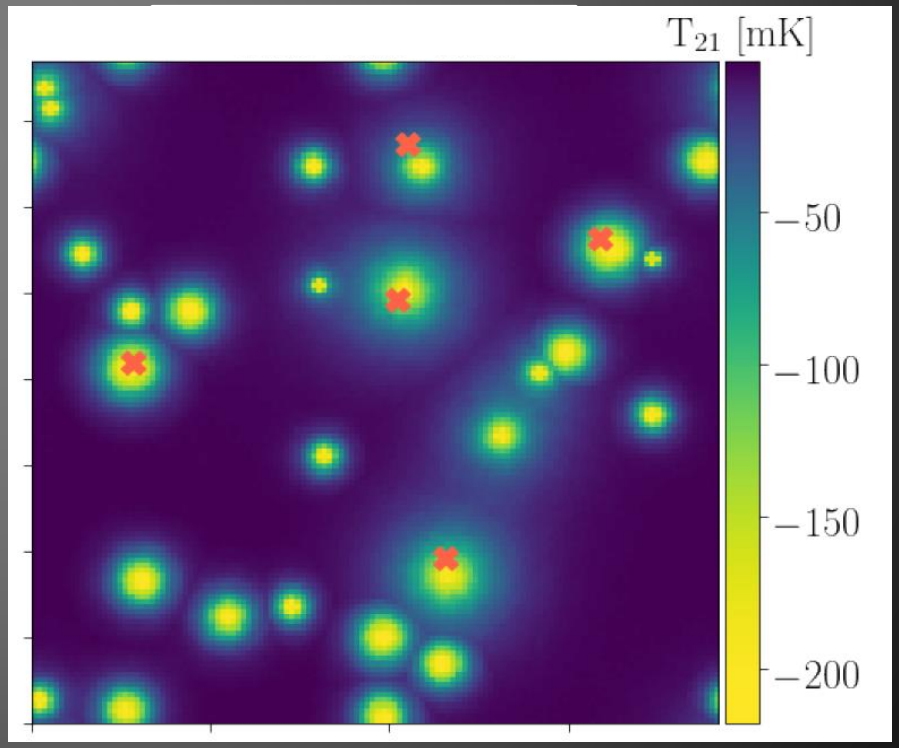


- Scattering
- Ly-a window function
- Effective horizon of Ly-a radiation

Ly-a coupled bubbles (3D)

Strong observable 21cm signal, seen in absorption against the background.

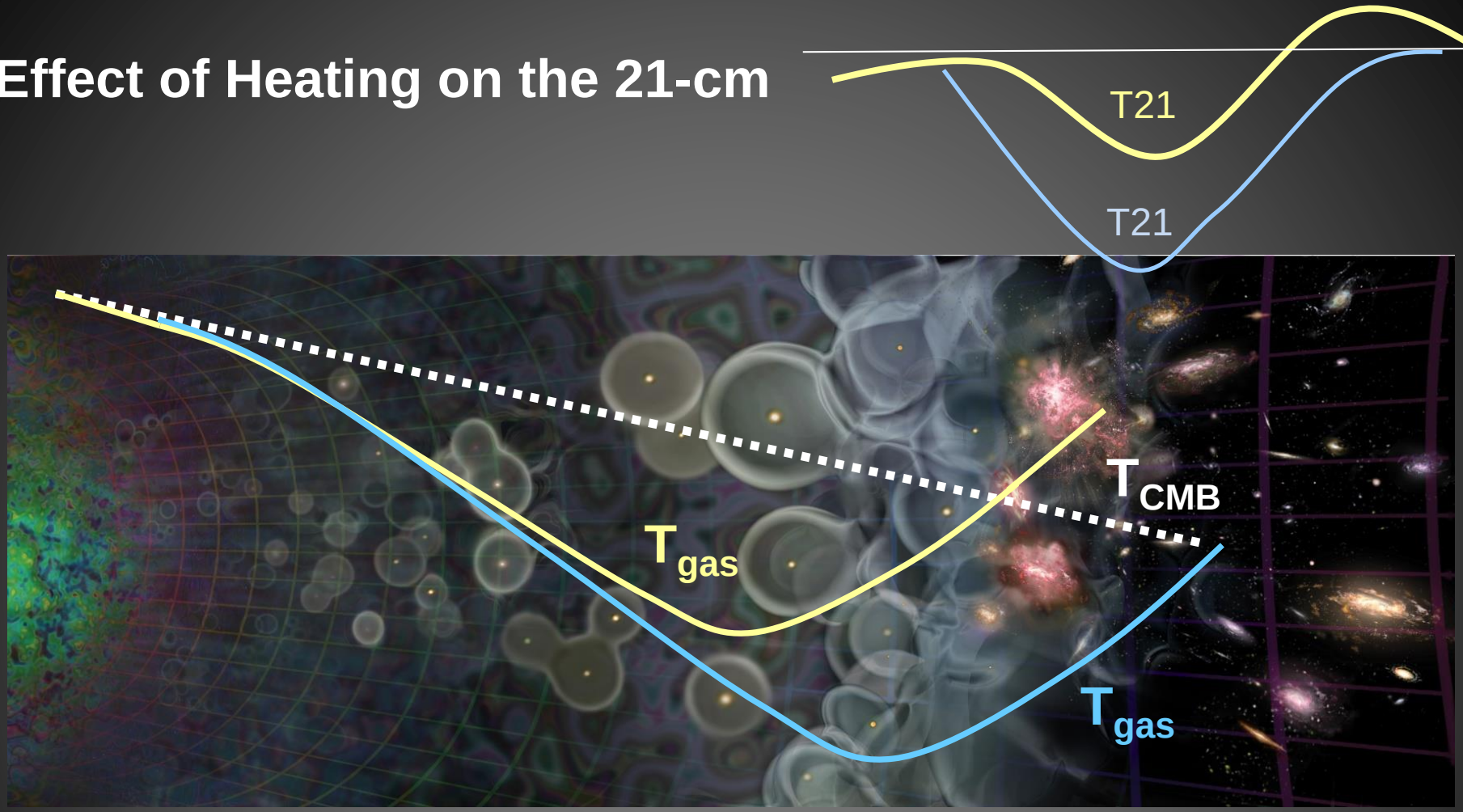
- Mass of star forming halos
- Feedback
- Star formation efficiency



~ 400 Mpc

Reis, Barkana, **Fialkov** (2021)

Effect of Heating on the 21-cm



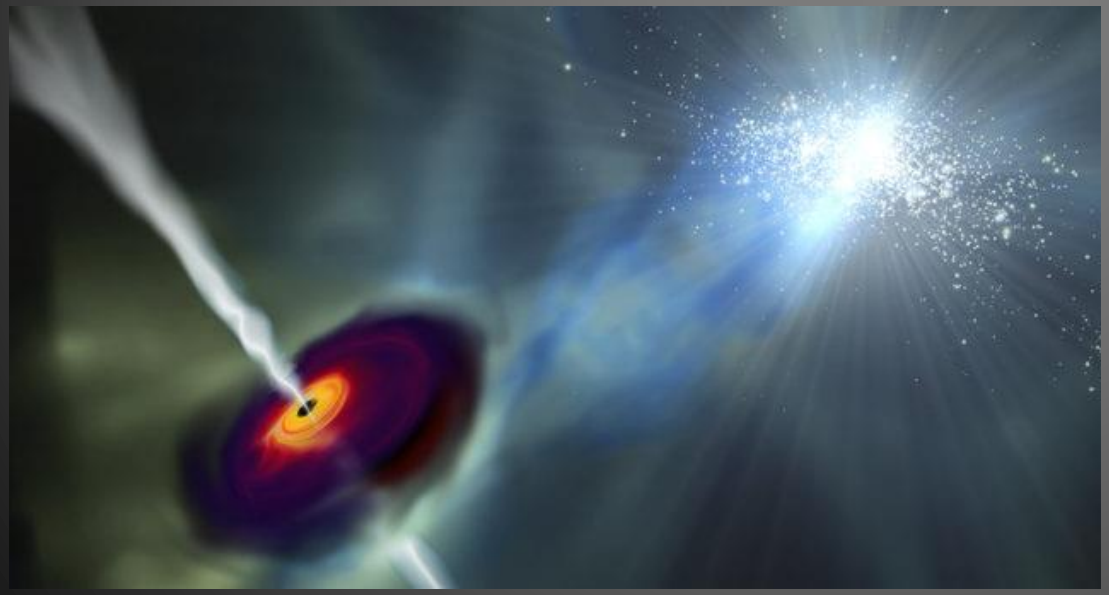
- Details of heating affect the observable signal
- Cumulative effect – the whole history matters!
- Gas can be hotter or colder than the background in the EoR range.
- Stronger heating leads to weaker contrast between the gas temperature and the background, weaker 21-cm PS.

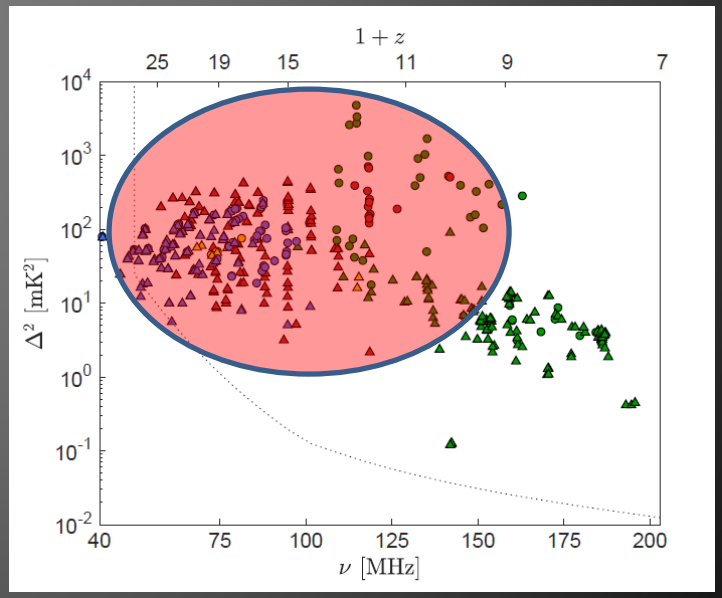
X-ray Heating

Heating by X-ray binaries likely dominates

Depends on intensity of sources and their SED (spectral energy distribution)

- Wide possible redshift range of models
- Strong impact on PS in a broad range





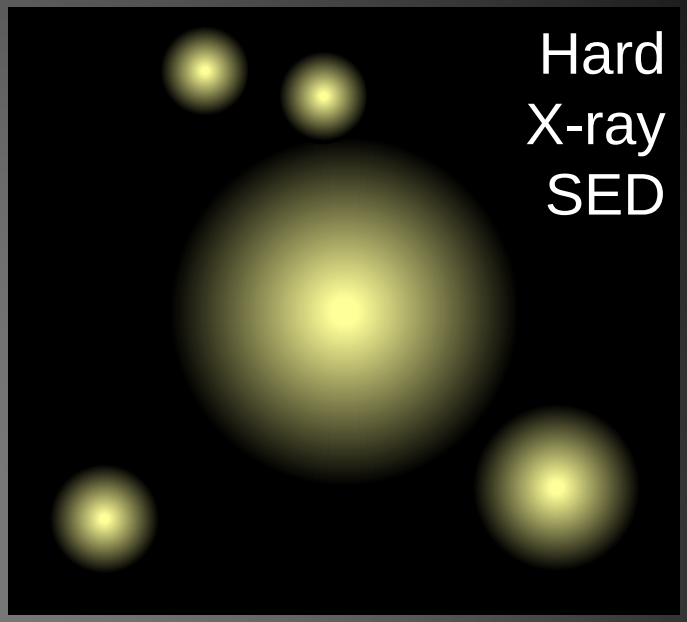
Cohen, Fialkov, Barkana 2017

Heated Bubbles

With Ly-a coupling: 21-cm signal is seen in absorption in cold gas, emission in hot.

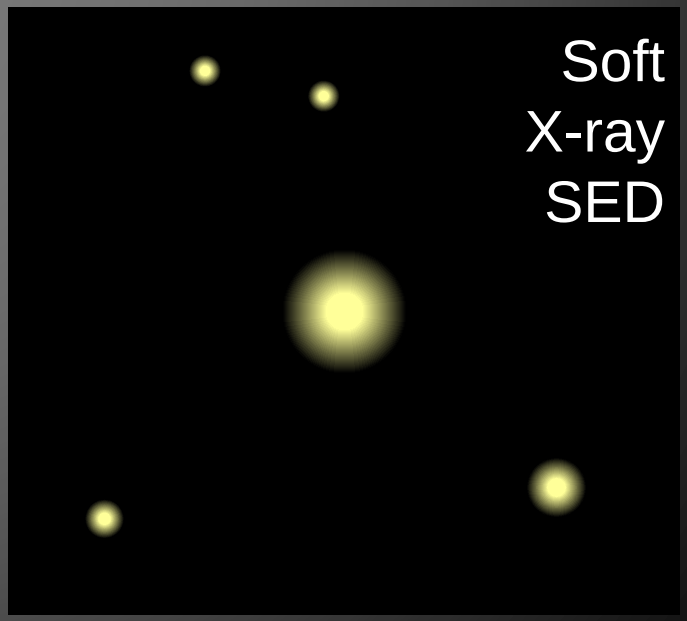
Non-uniform heating -> heated bubbles

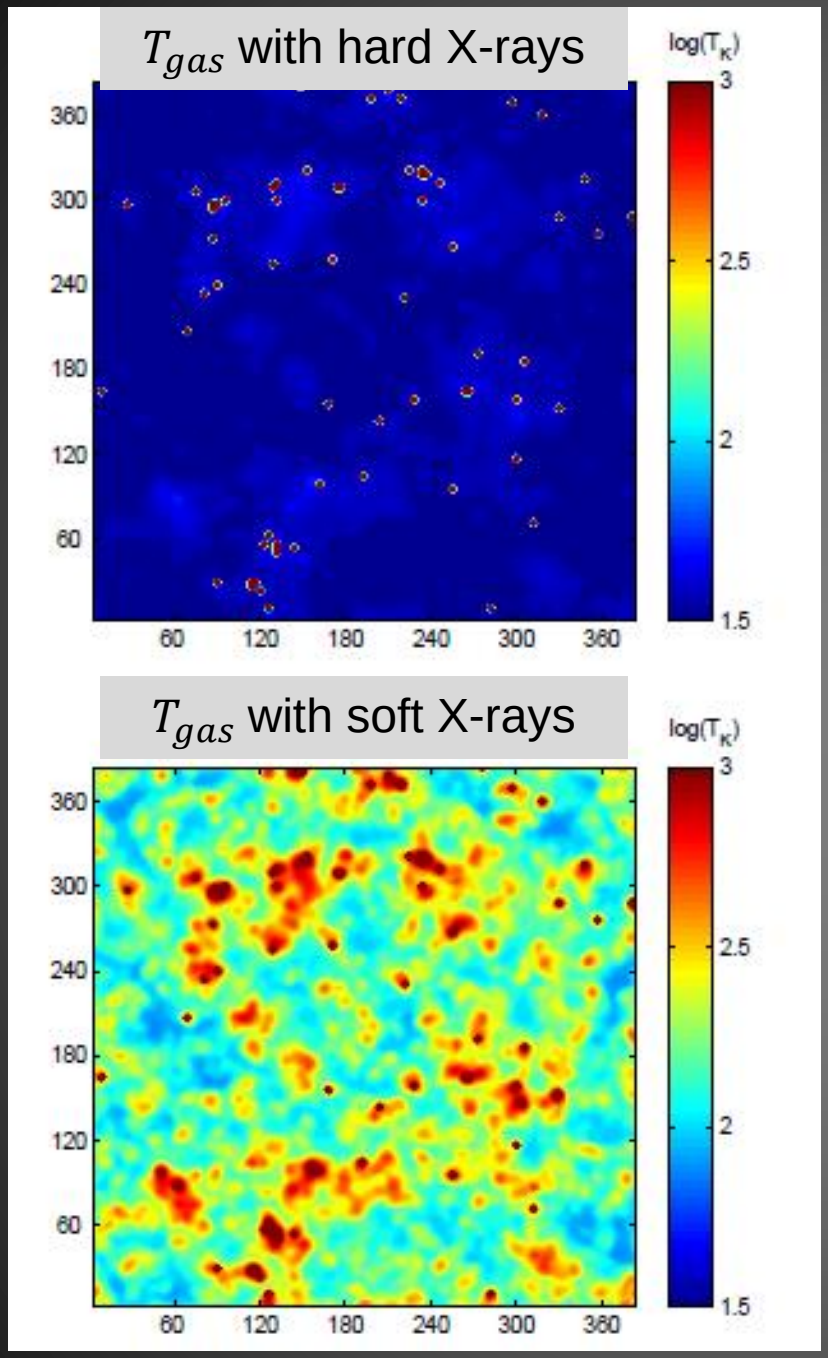
Fluctuations in the 21cm.

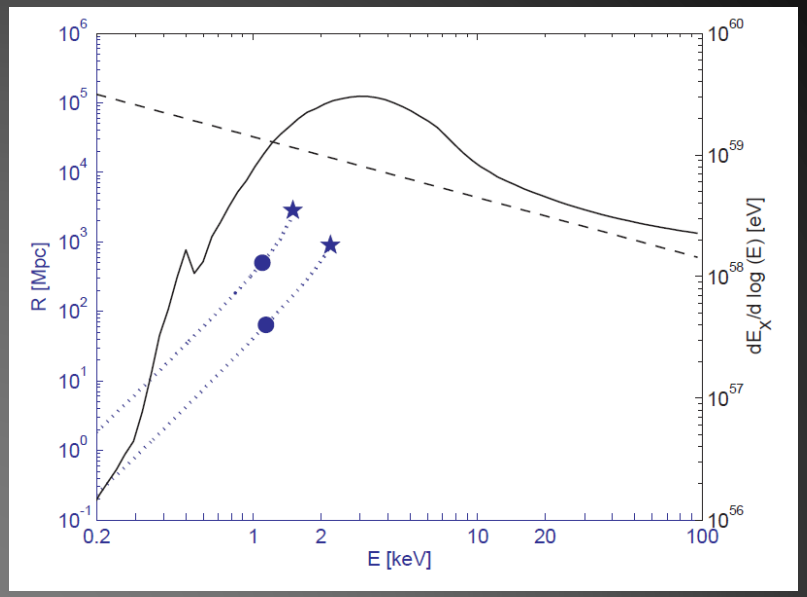


X-ray SED matters!
Hard X-rays are more diffused than soft X-rays, carry energy further from the source

- Heating of gas is on larger scales
- Heating is less efficient
- X-ray SED is imprinted in the 21cm PS





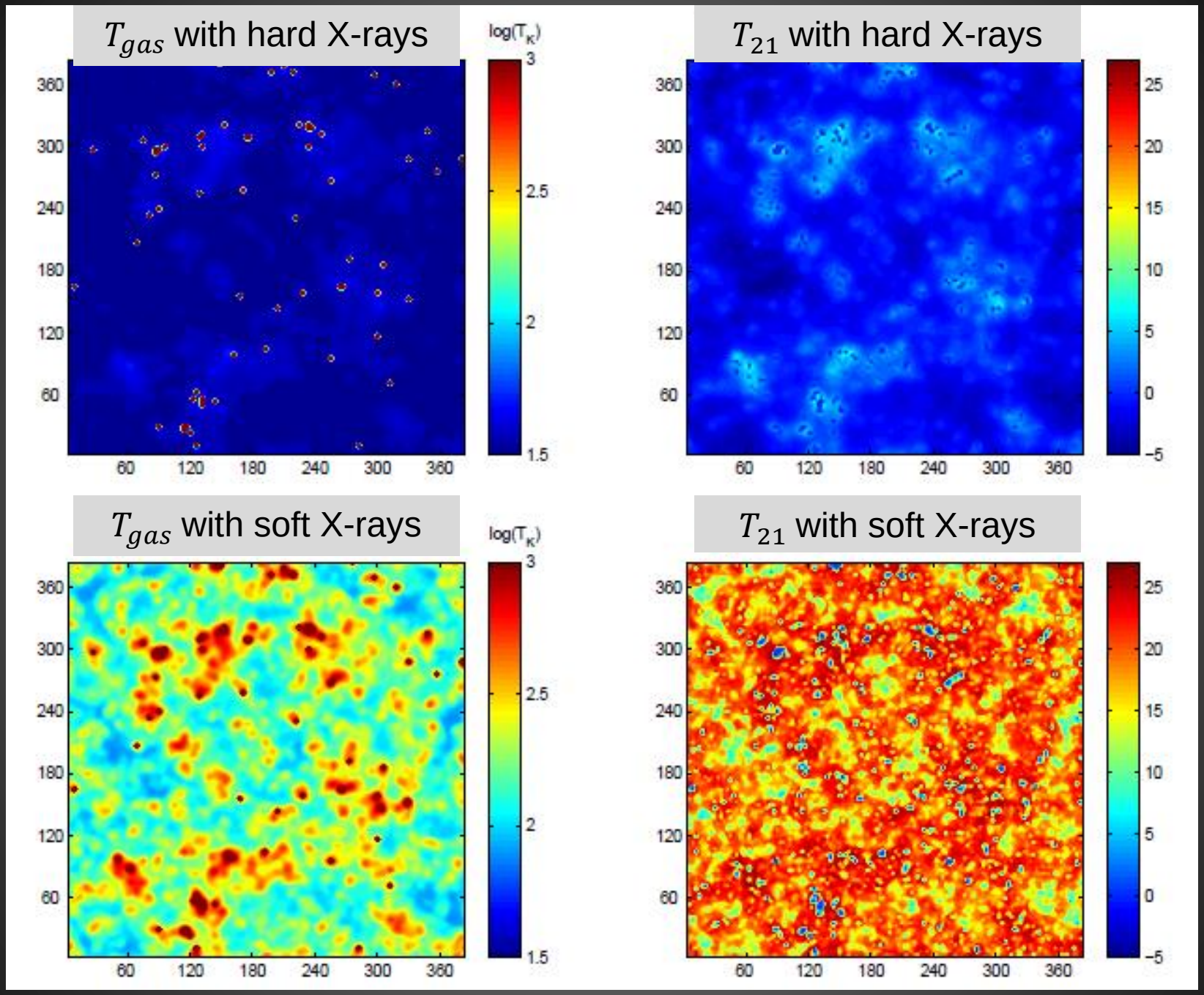


Fialkov et al. 2014

Hard vs soft X-ray SEDs.
Same total energy output.

Heating maps from realistic 21-cm simulations shown at the same redshift.

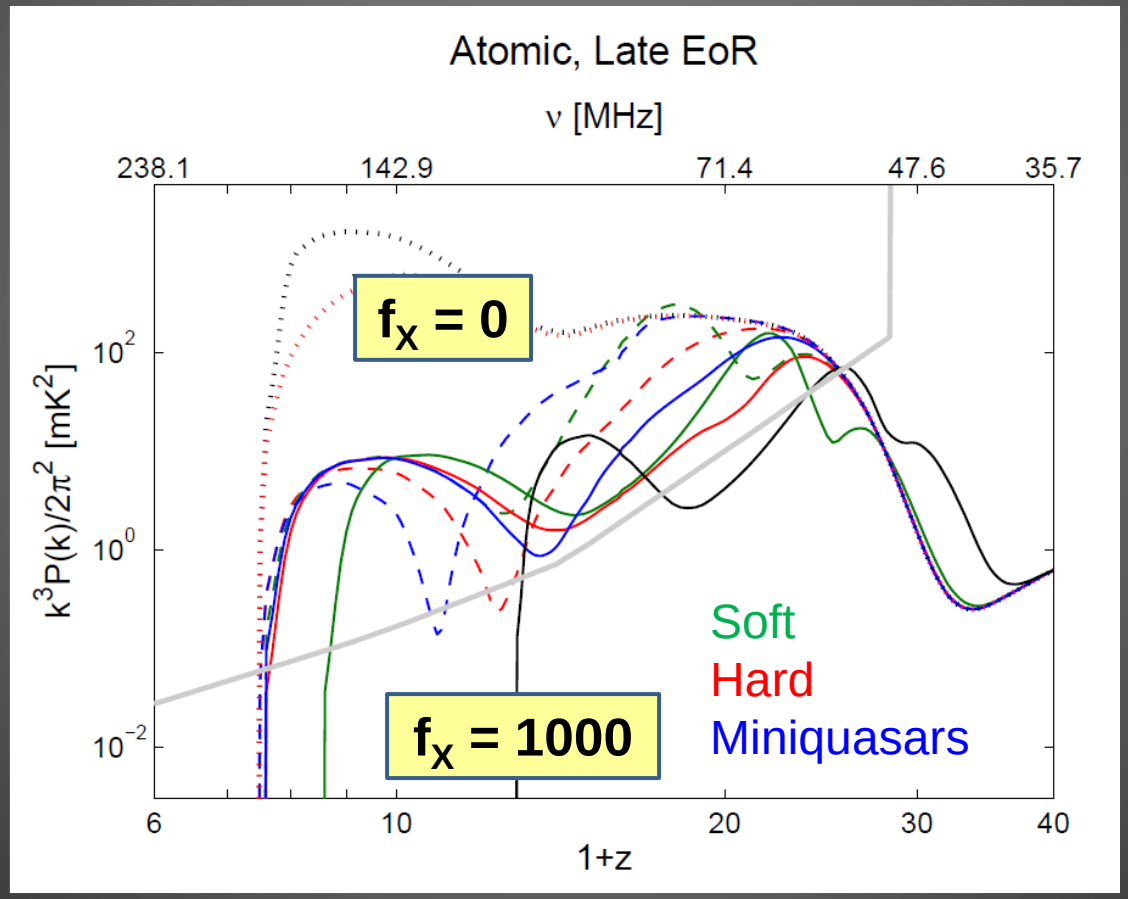
Fialkov & Barkana (2014)



Fialkov & Barkana (2014)

Diversity of X-ray Heating Models

Hot or cold IGM during the EoR: emission or absorption signal?
Hard or soft SED? Peak in the 21-cm power spectrum



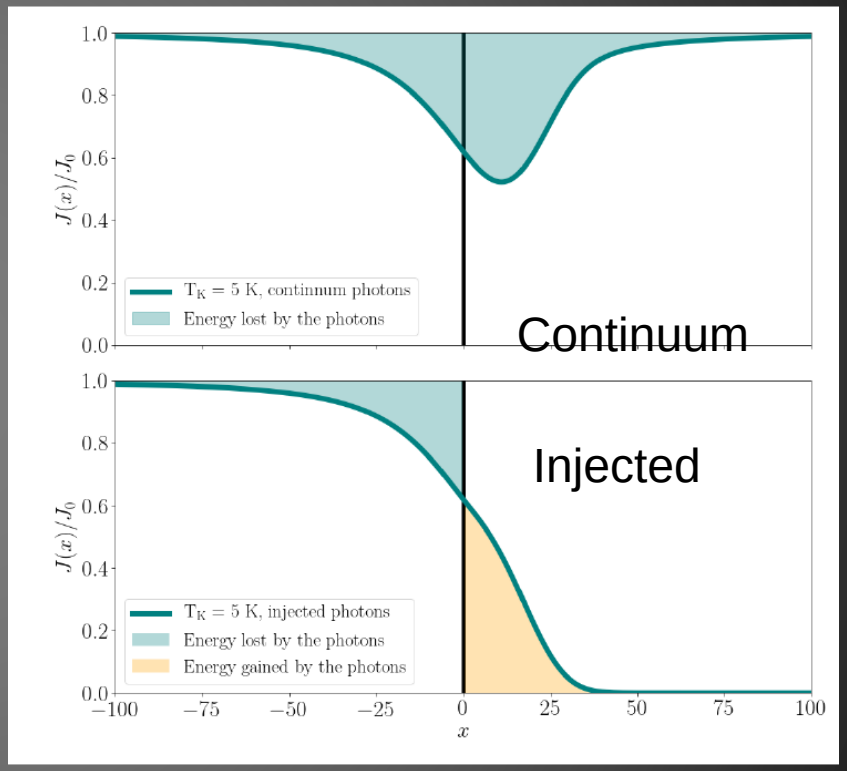
Fialkov et al. (2017)

Subtle Effect - Ly-a Heating
Important for upper limits at low z!

Heating/cooling due to recoil of atoms as a result of Ly-a scattering
e.g. Chen & Miralda-Escude 2004, Chuzhoy & Shapiro 2006, 2007, Furlanetto & Pritchard 2006

- Continuum photons (between Ly-b and Ly-a) redshift into Ly-a. Heat the gas.
- Injected photons (cascade from higher levels). Cool the gas.
- Net heating by ~100 K!

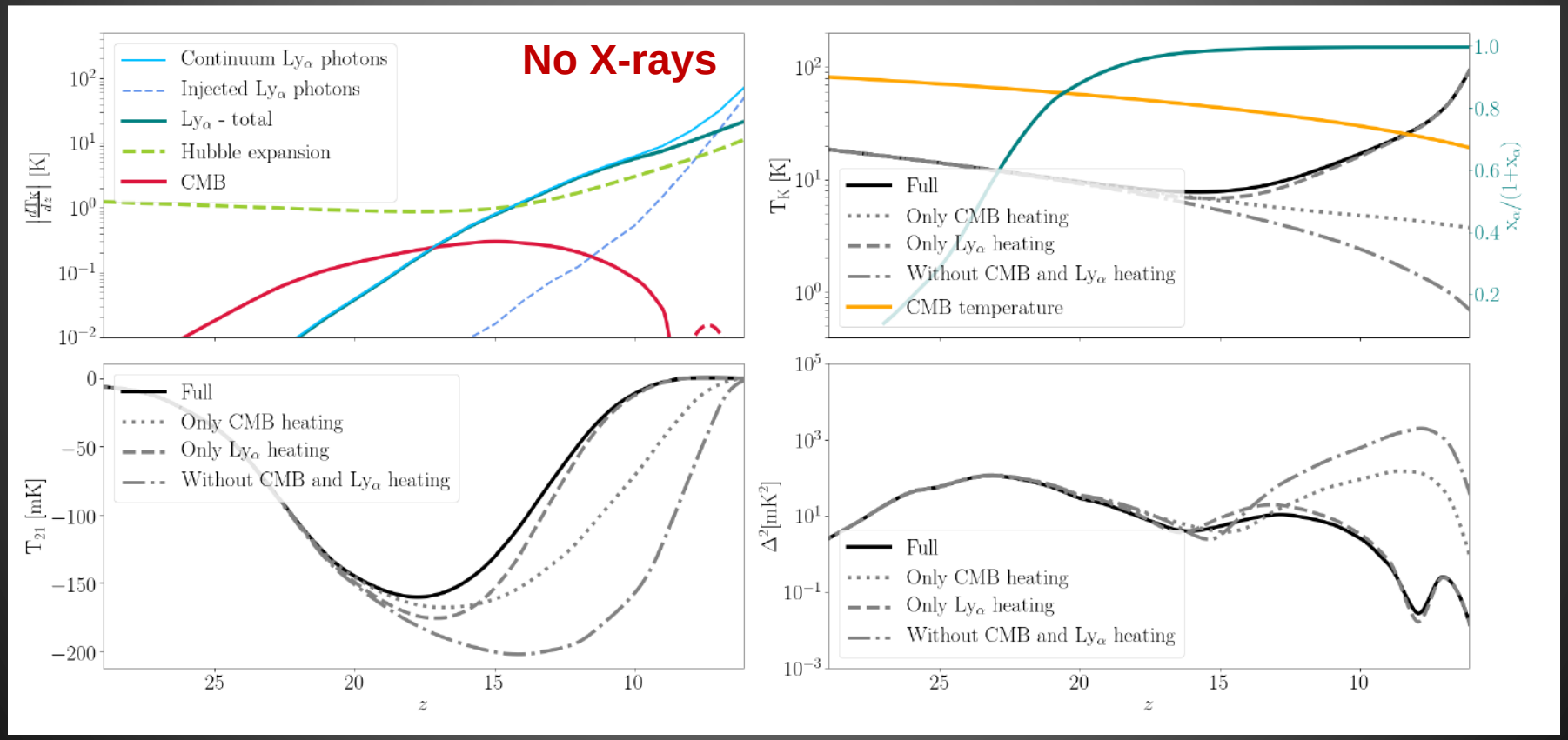
Spectral shape around Ly-a line



Reis, Fialkov, Barkana (2021)

Ly-a Heating & CMB Heating

- Require high Ly-a intensity
- Dominates at low redshifts (z<15)
- Ly-a heating of ~100 K; CMB heating ~ a few degrees
- Effect on signals for no/weak X-ray heating in the observable range

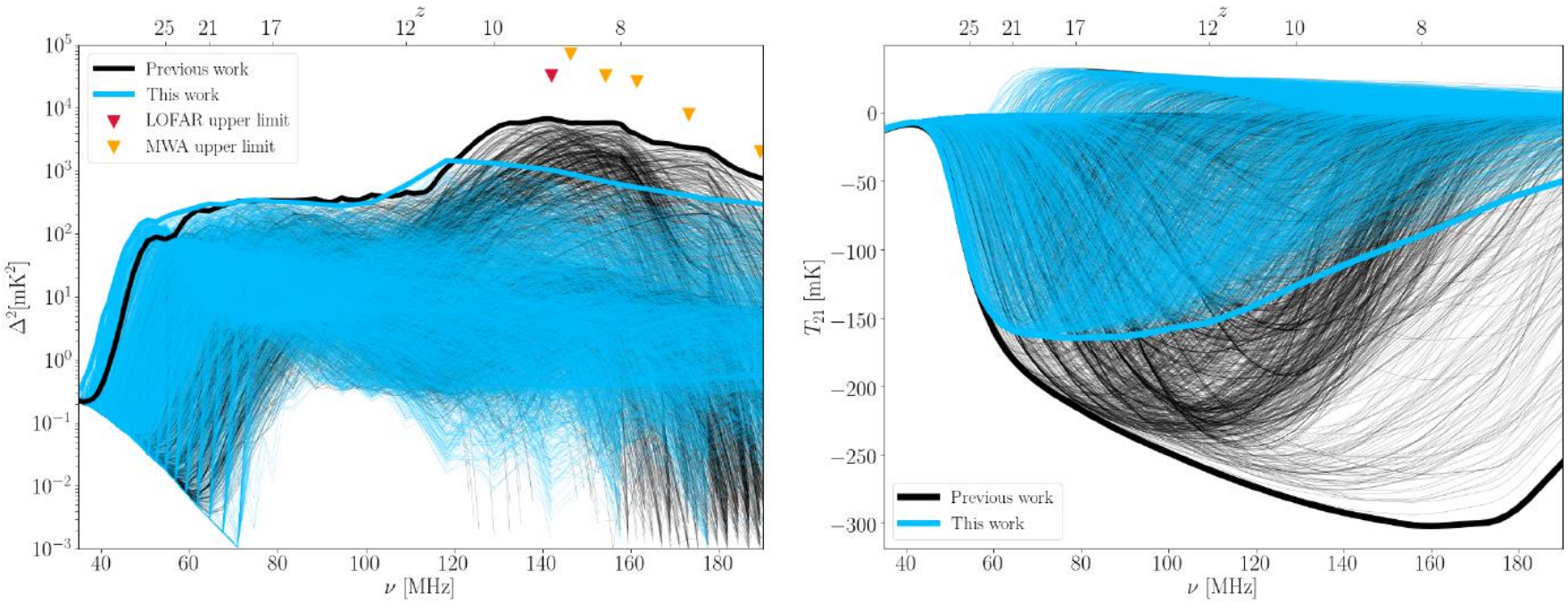


Reis, Fialkov, Barkana (2021)

Effect of Ly-a & CMB Heating on the Space of Plausible 21-cm Signals

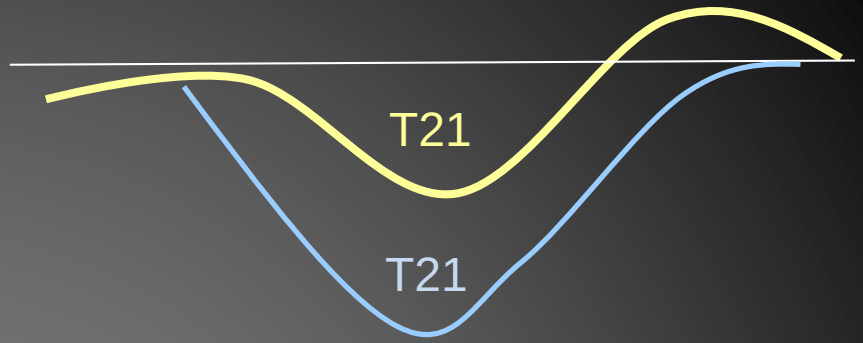
Large parameter study to explore ranges of possible signals in the observable scale/frequency range.

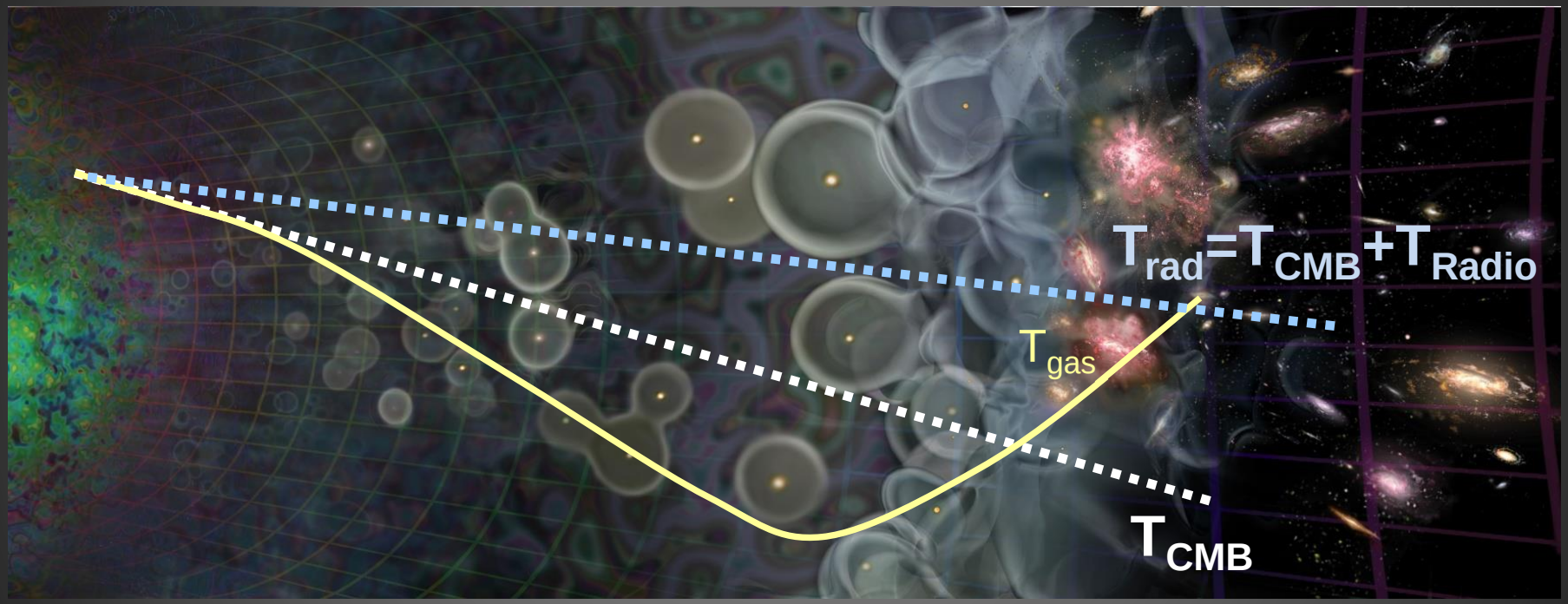
Impact on the deepest signals that are the easiest to rule out



Reis, Fialkov, Barkana (2021)

Enhanced Radio Background
CMB + Extra Contribution





Radio background (RB) could be created by galaxies or exotic sources.

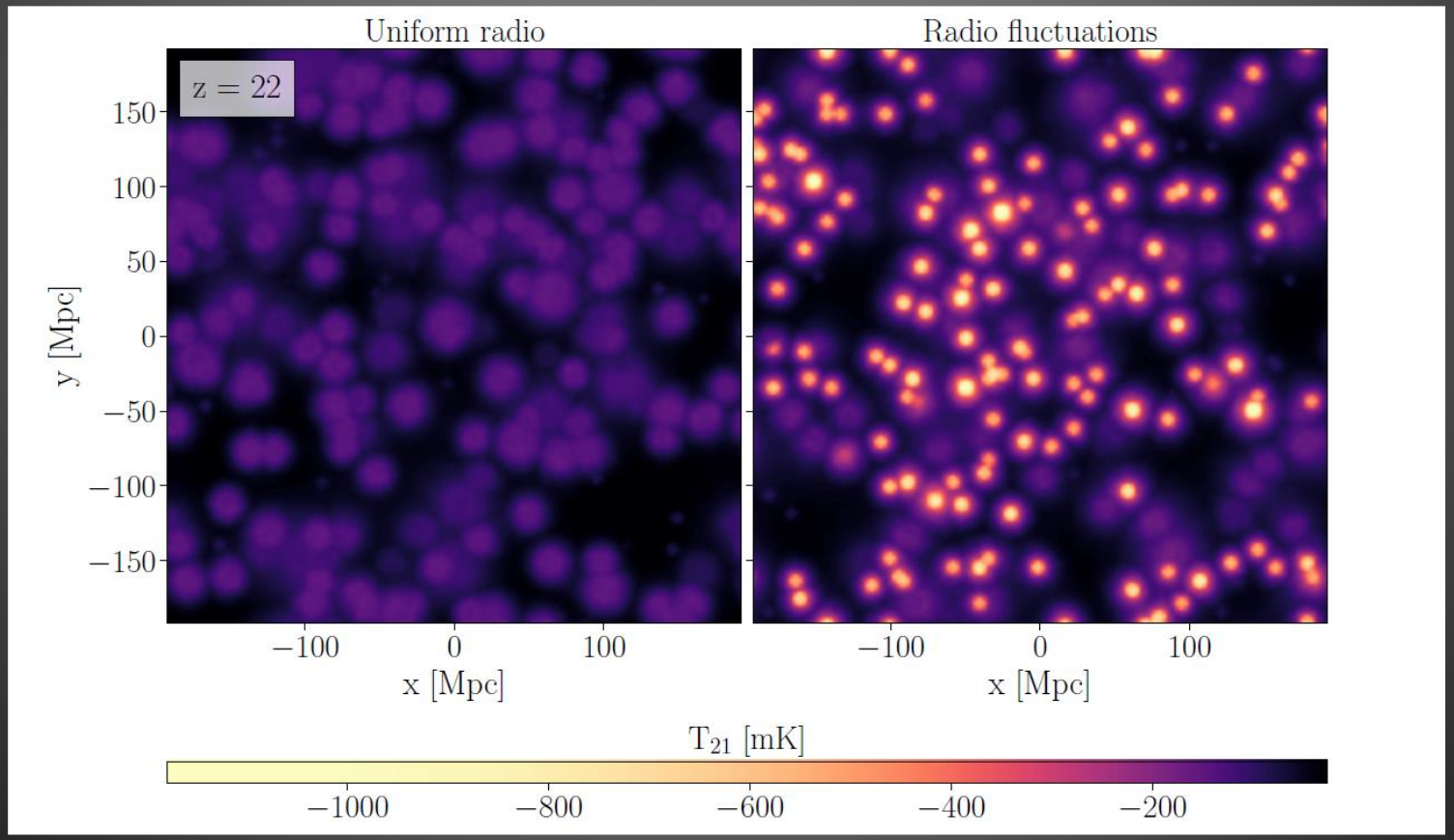
With RB above the CMB: larger contrast between the gas temperature and the background, stronger 21-cm signal.

EDGES can be explained by strong RB, stronger signals in the EoR range

Radio Galaxies at High Redshifts

Increased contrast and modified structure of Ly-a coupled bubbles
Additional source of fluctuations

Uniform excess radio, $< T_{Radio} >$ Fluctuating excess radio, T_{Radio}

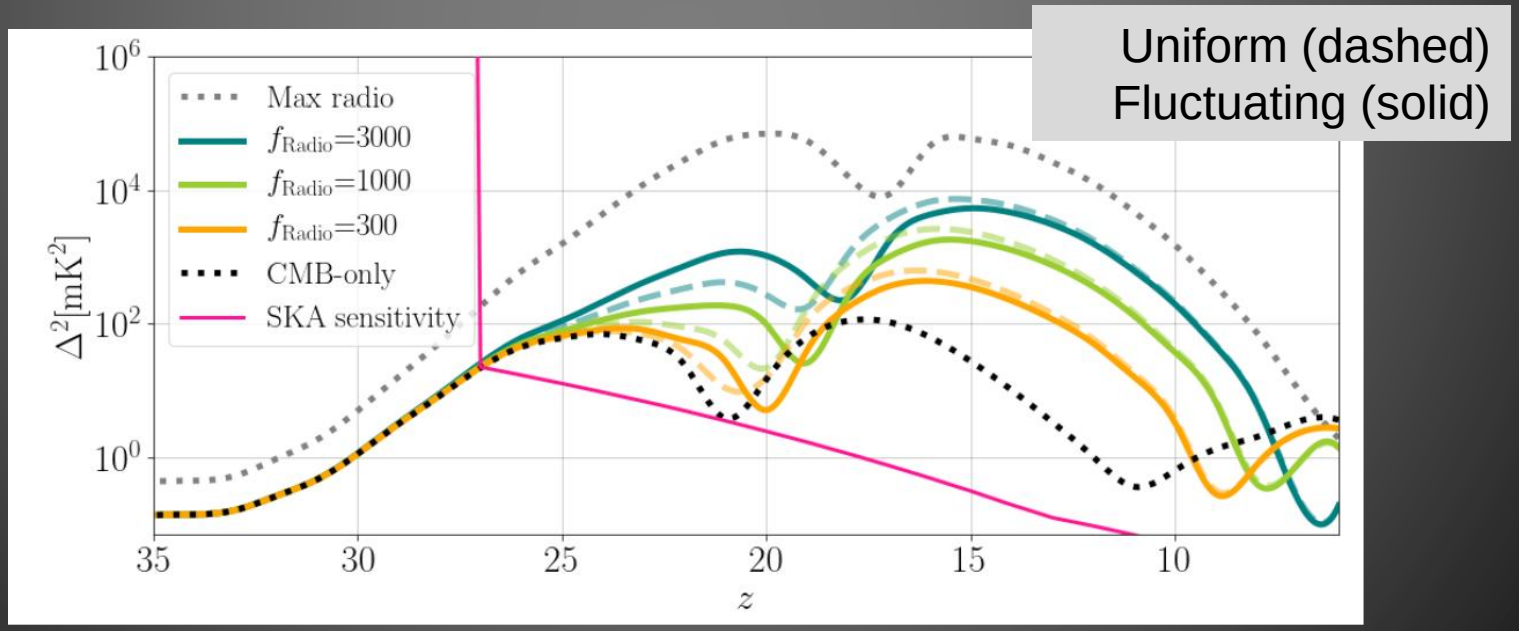


Reis, **Fialkov**, Barkana (2020)

Signatures of Fluctuating Radio Background

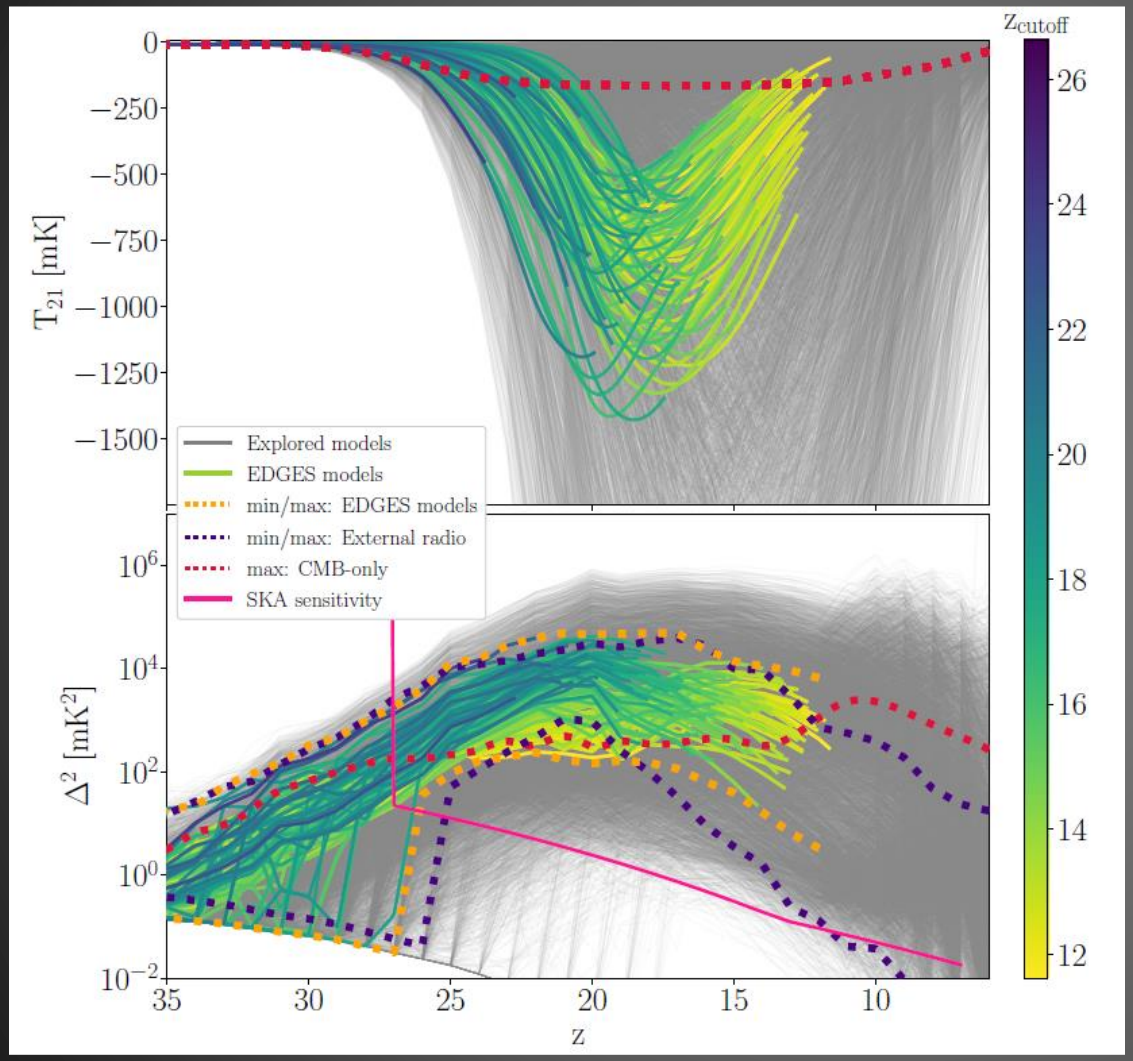
- Sizable (model-dependent) effect even for modest values of f_{Radio}
- Boost in the power spectrum
- Radio fluctuations are correlate with Ly-a and density & anti-correlate with heating
- Effect depends on model parameters (e.g., X-ray SED, stellar mass)

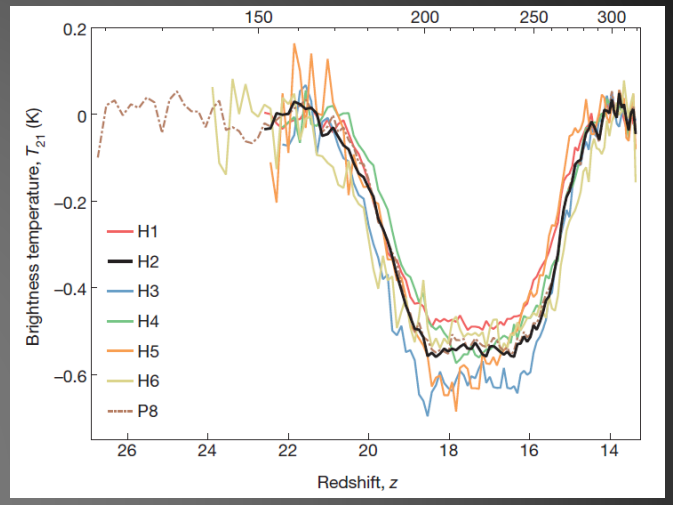
Case study: 21-cm with soft X-ray SED and large f_{Radio}



Reis, **Fialkov**, Barkana (2020)

New Tests of EDGES-Motivated Models: High-z Power Spectra



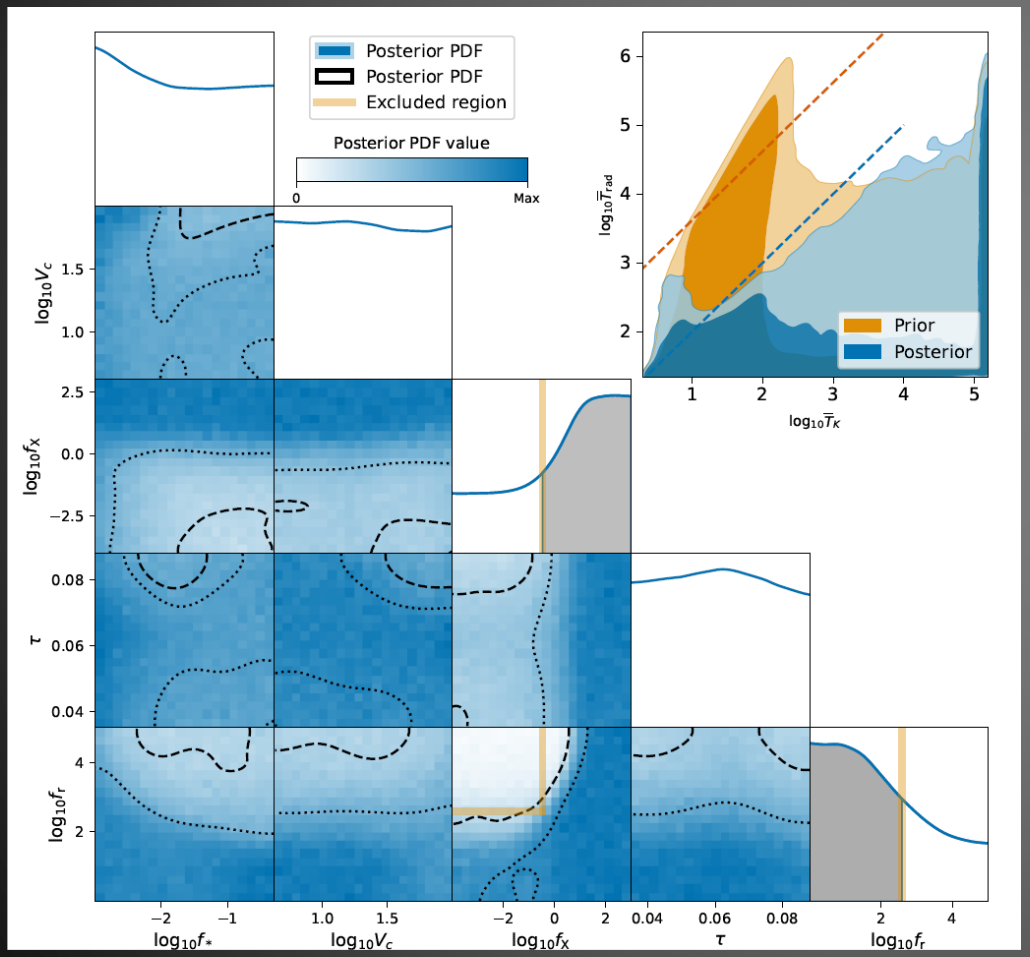


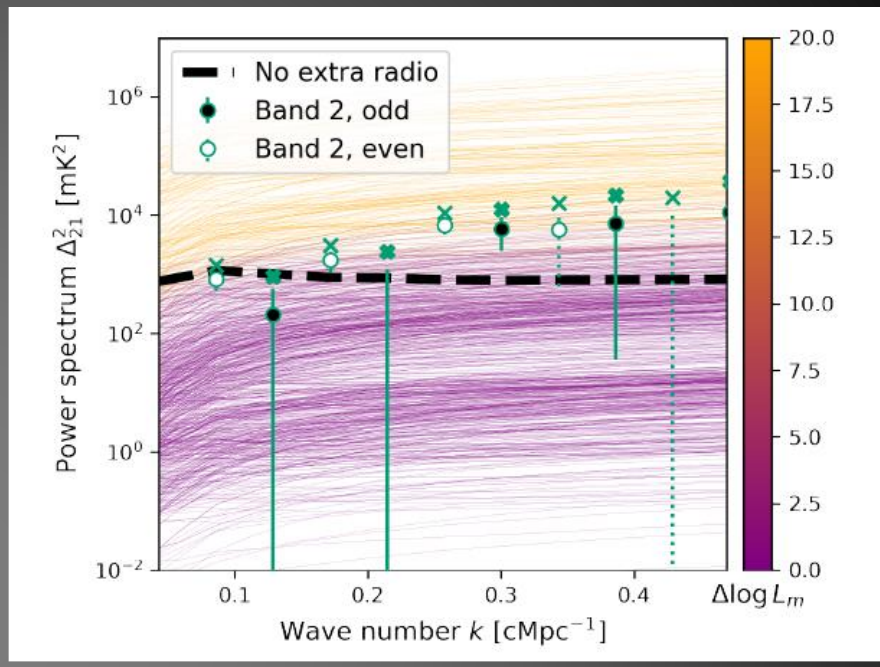
Bowman, et al. (2018)

Enhanced PS
High-z population (z cutoff)

Reis, **Fialkov**, Barkana (2020)

HERA Constraints on Excess Radio Background Models





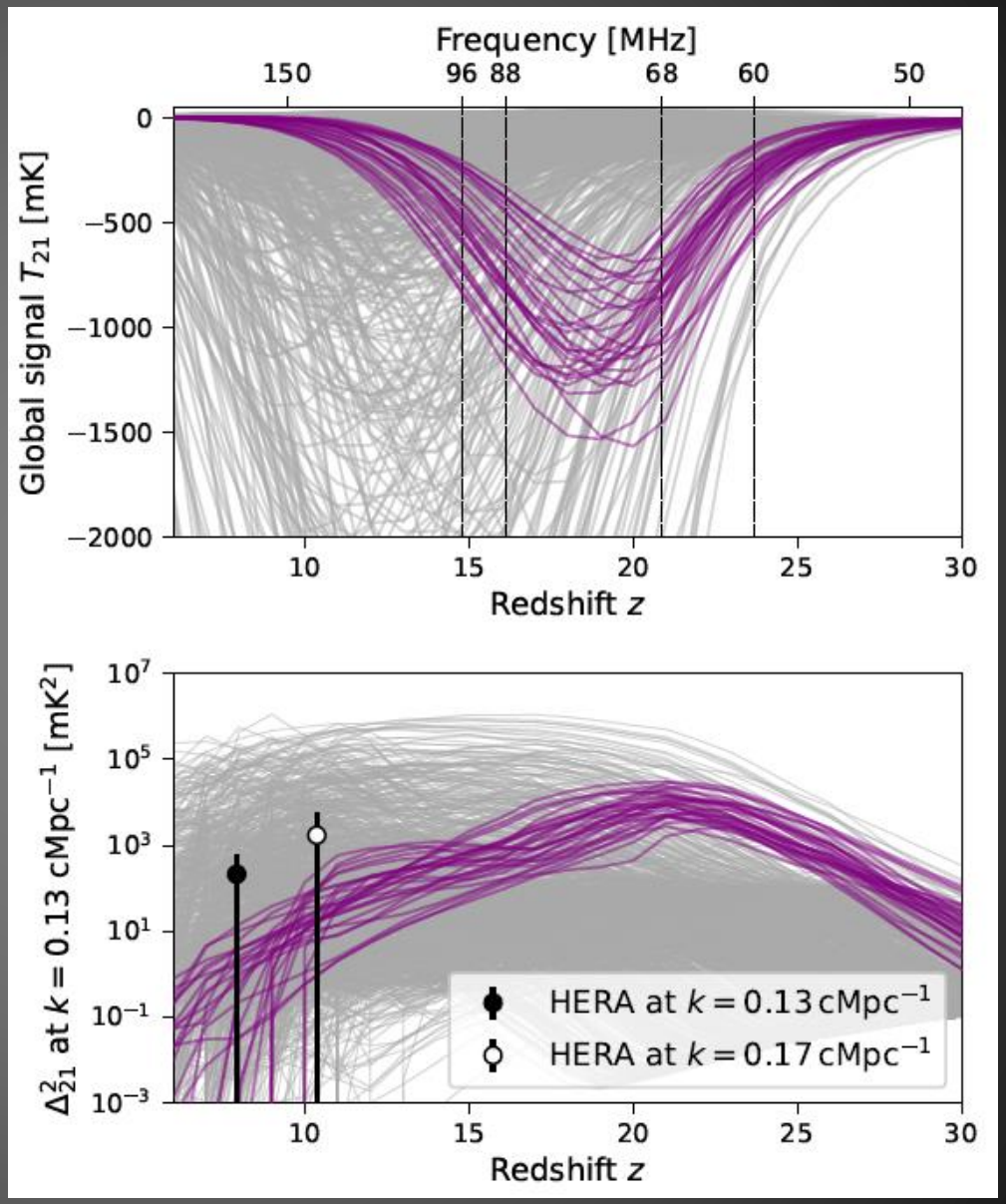
- Radio galaxies models are constrained by the HERA data
- Main effects from heating and radio background

The HERA Collaboration 2021

No Clarity on EDGES

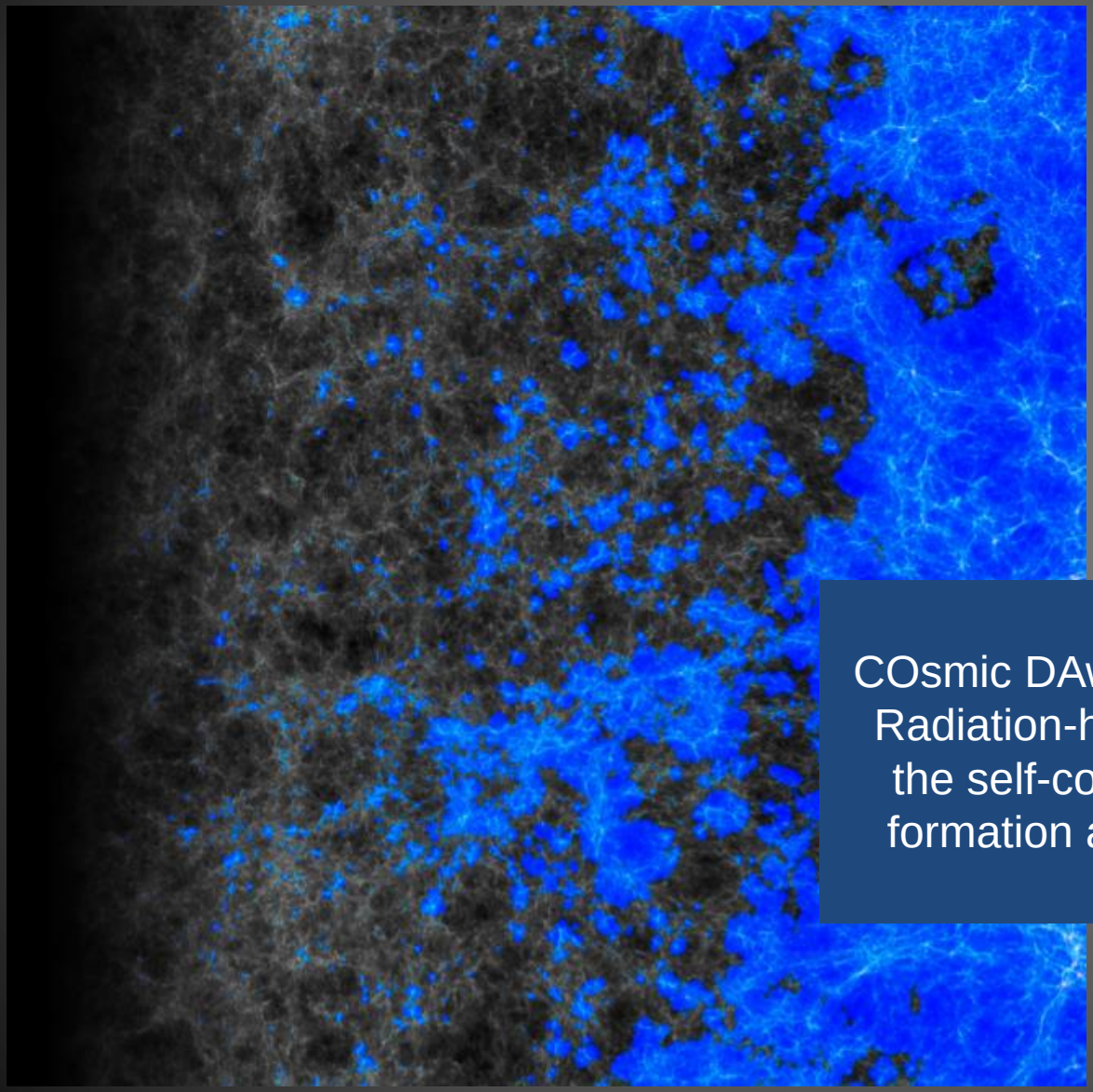
HERA and EDGES observe different redshifts.

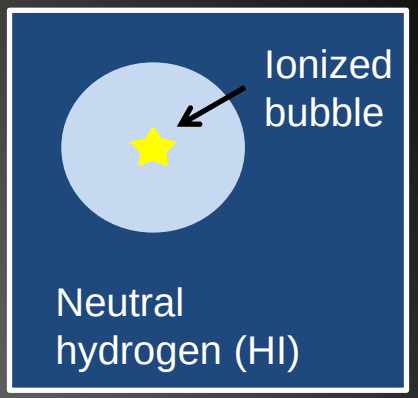
Models that are bright in EDGES will be below limit of HERA



The HERA Collaboration 2021

Reionization!



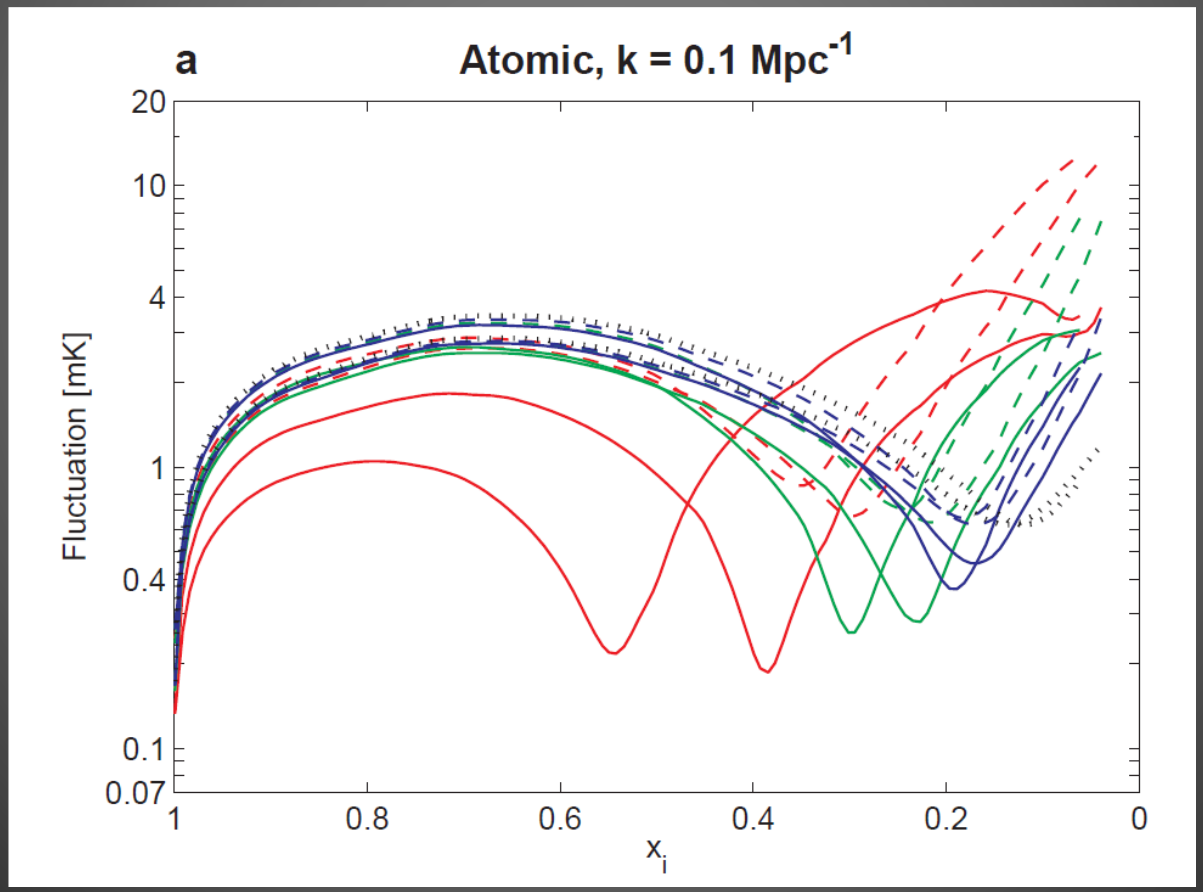


COsmic DAwn simulation: a masterpiece
Radiation-hydrodynamics simulation of the self-consistent coupling of galaxy formation and reionization (~100Mpc)

Ocvirk et al. 2016

HERA : Probe of the EoR 21-cm PS

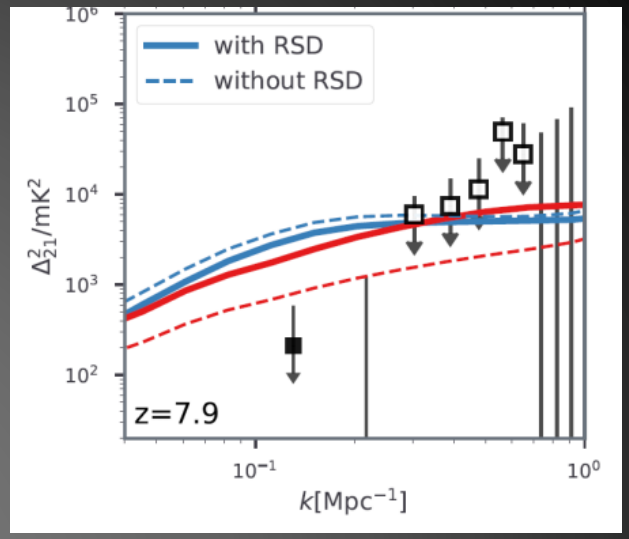
- Driven by massive galaxies
- Strongest signals: cold IGM and close to mid-point reionization

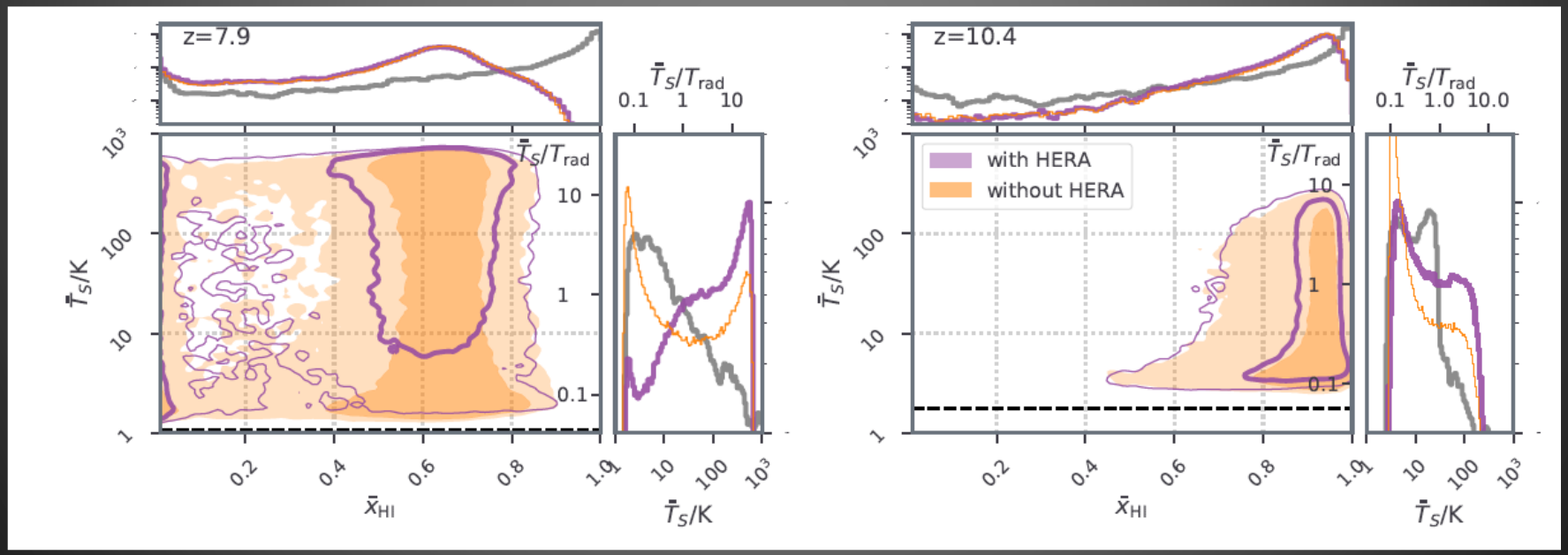


Fialkov et al. 2014

HERA : Probe of the EoR 21-cm PS

Mild constraints on standard astrophysical models (with CMB background)

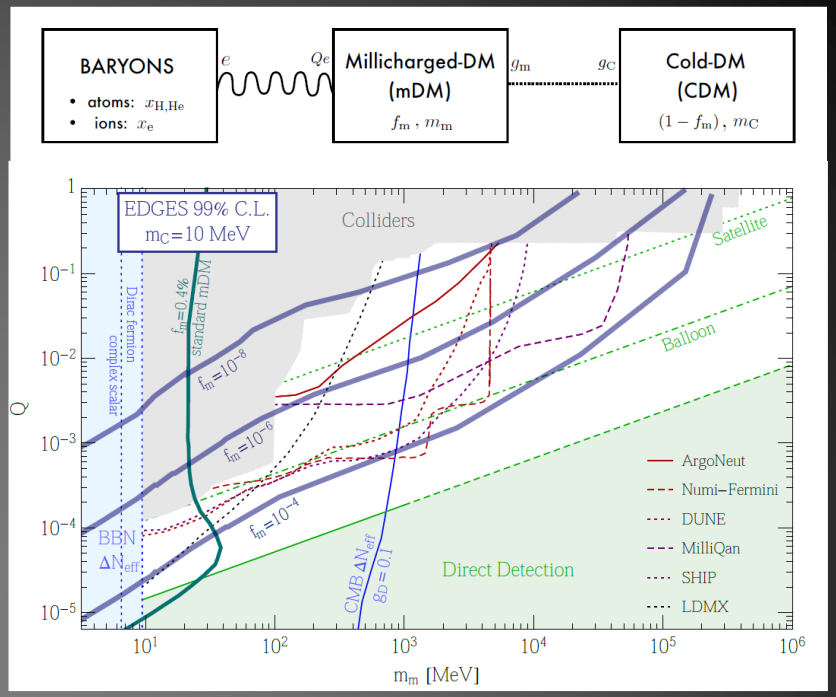




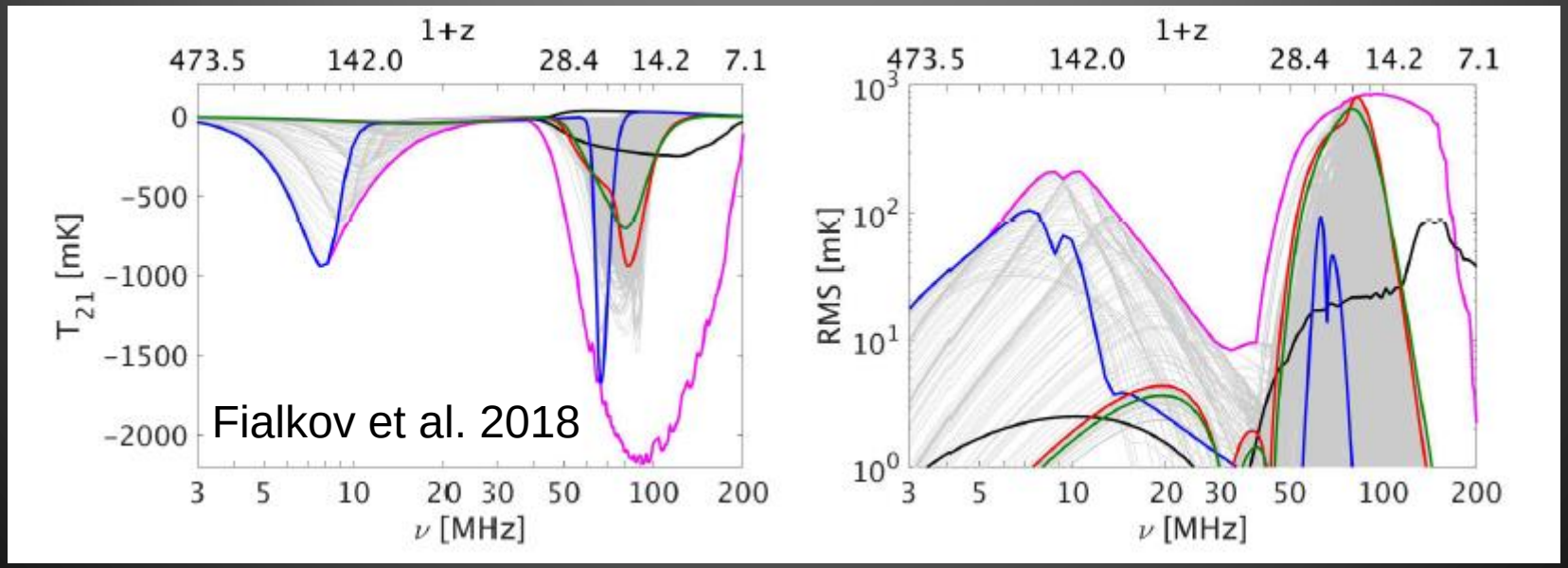
The HERA Collaboration theory paper

Dark Matter Physics

- Example: Energy exchange via Rutherford scattering with velocity-dependent cross-section (Tashiro et al. 2014, Munoz et al. 2015, Barkana 2018)
- Millicharged DM
- Very constrained
- Strong fluctuations at high redshifts



Liu et al. 2019



Fialkov et al. 2018

Summary:

- 21-cm signal is rich in information
- Current HERA limits are the best available at the EoR
- Subtle effects need to be included for precision modelling
- No clarity on EDGES
- Weak limits on standard models, stronger constraints on models with excess radio background
- Looking forward to next data releases!

Thank you!