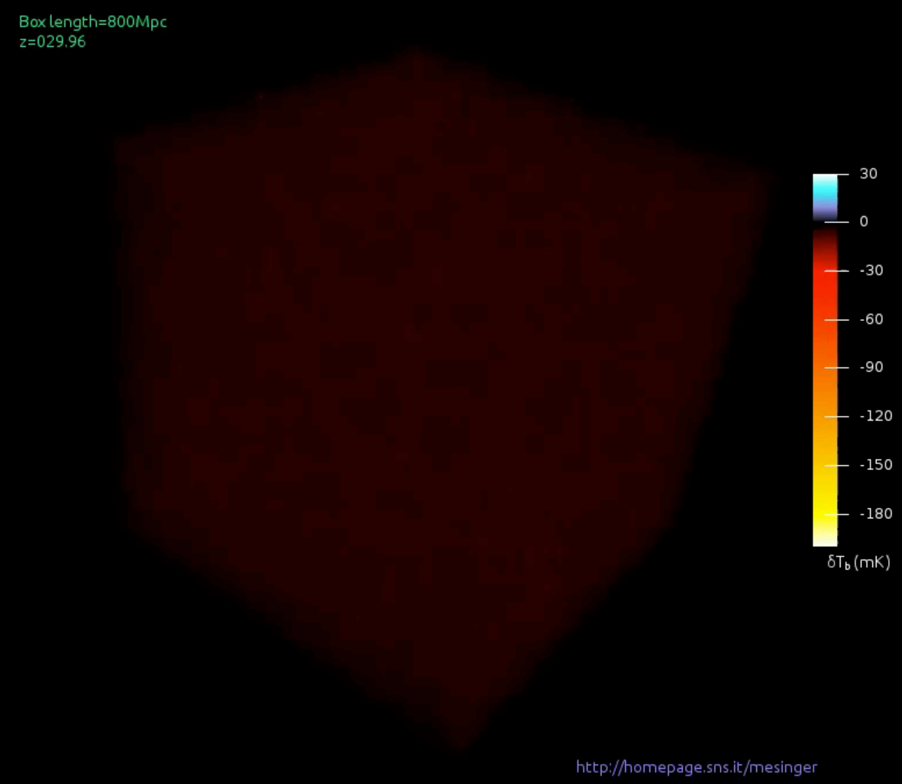
Status of 21-cm cosmology

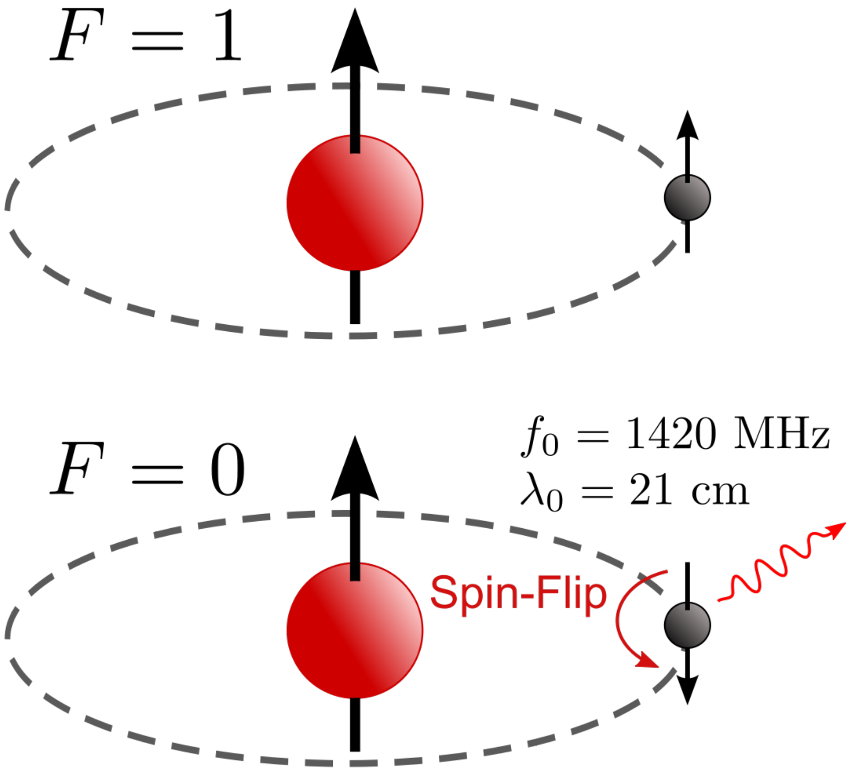


Andrei Mesinger

SCUOLA
NORMALE
SUPERIORE

erc
European Research Council
Established by the European Commission

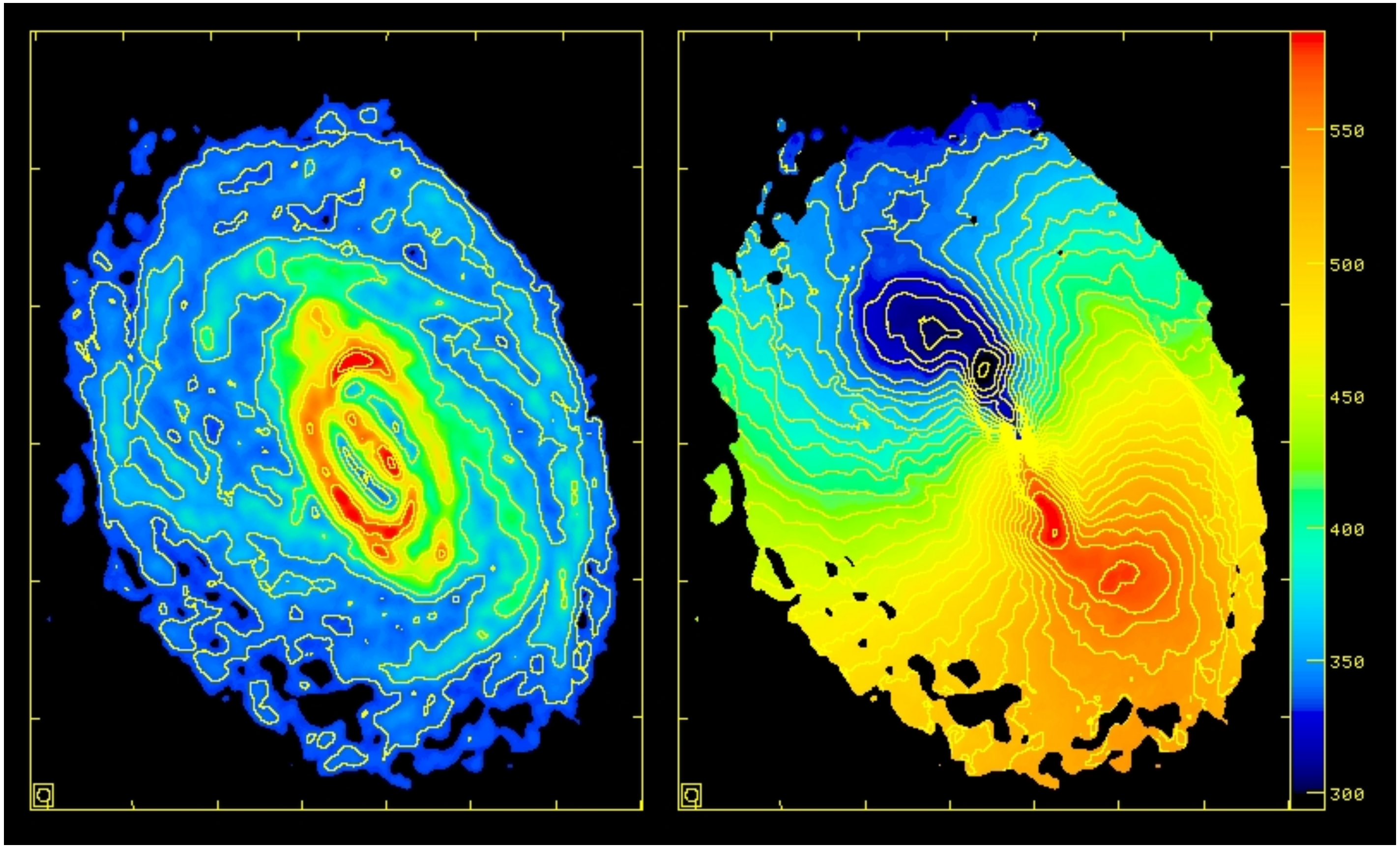
21 cm line from neutral hydrogen



First theoretically predicted by van de Hulst in 1942.

Detected by Ewen and Purcell in 1951.

Widely used to map the HI content of our galaxy and nearby galaxies



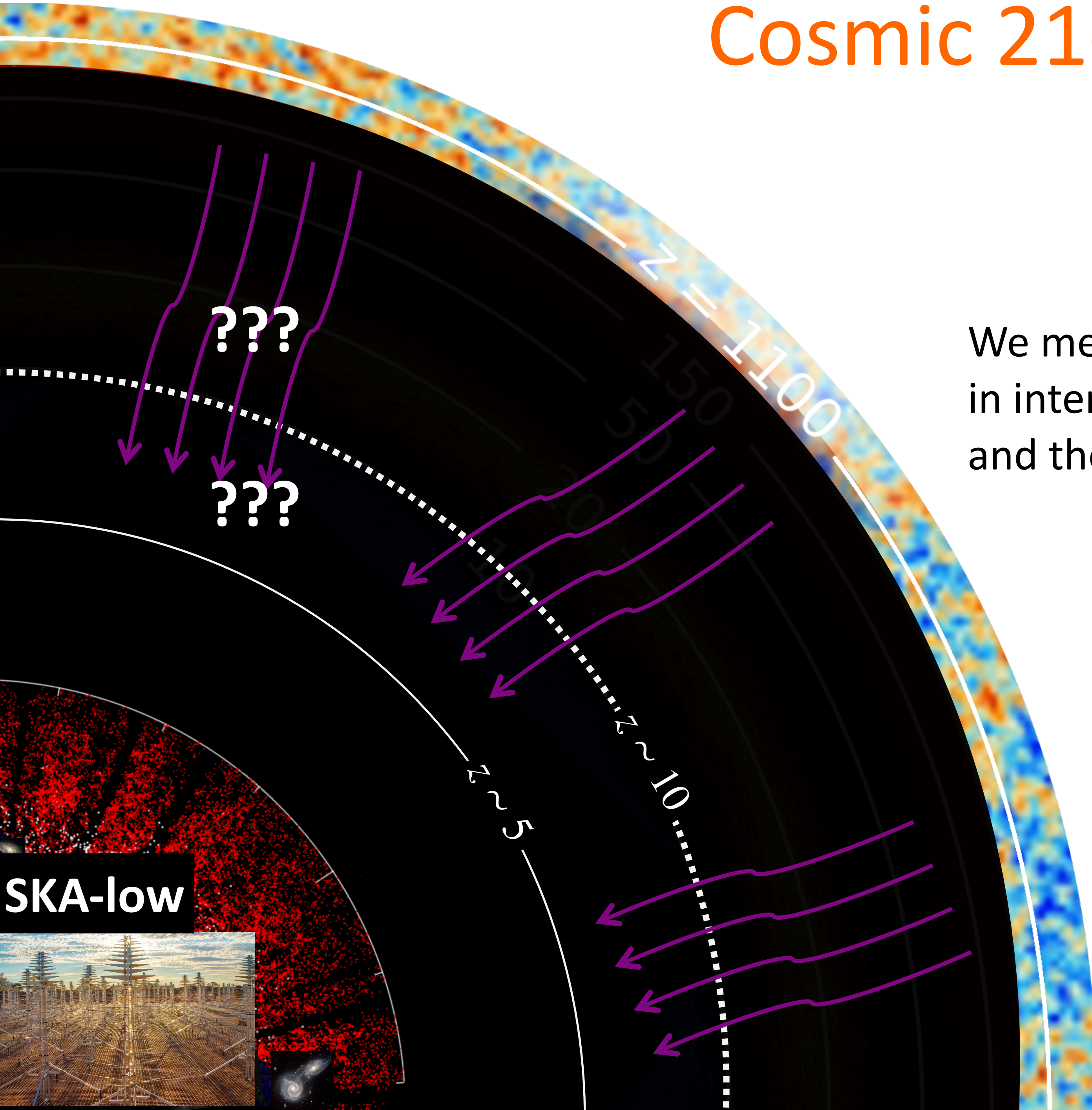
Circinus Galaxy

ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

But the potential of the 21-cm line as a cosmic probe is revolutionary

adapted from C. Chiang

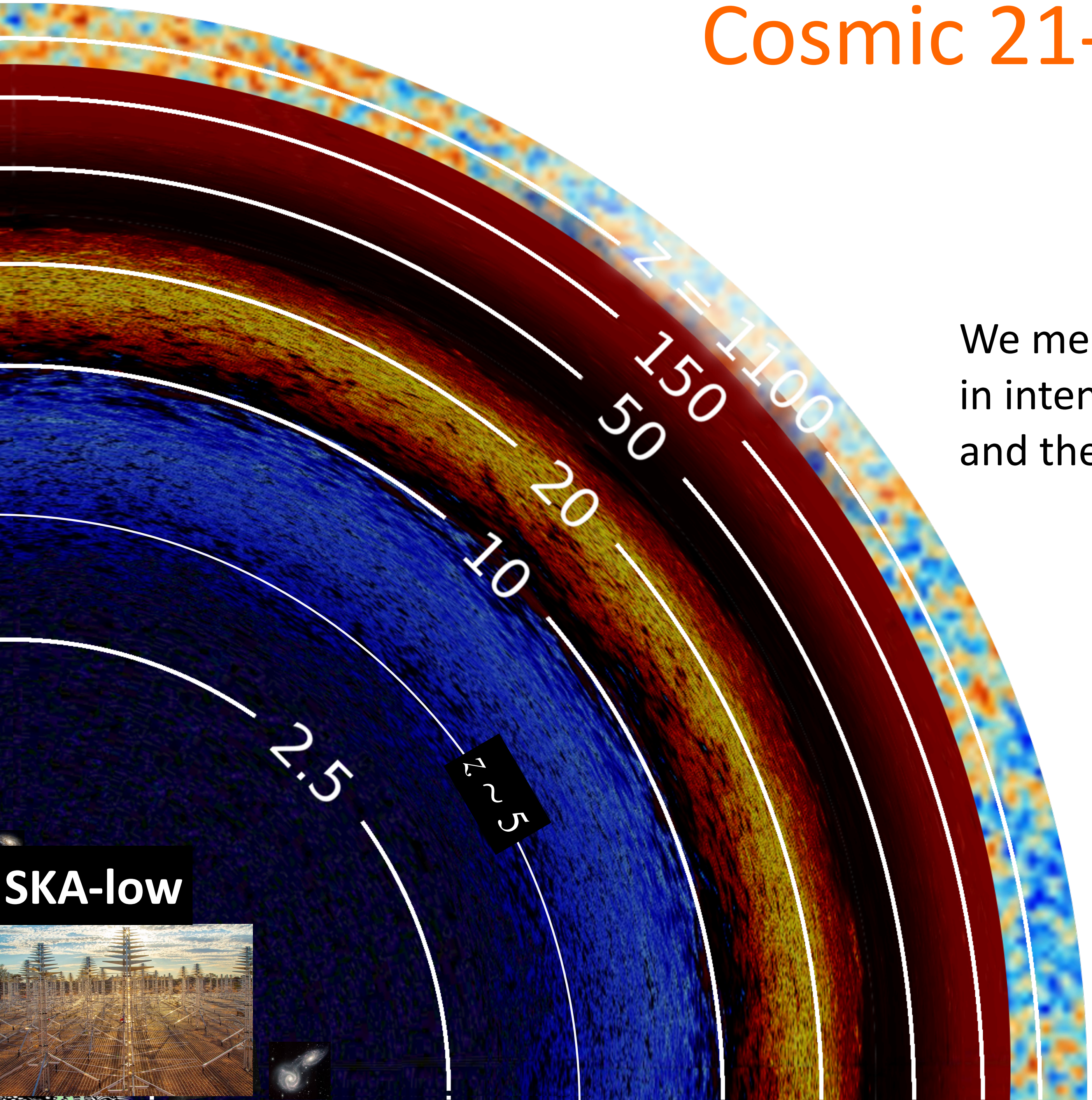
Cosmic 21-cm



We measure the difference in intensities of the CMB and the cosmic HI.

adapted from C. Chiang

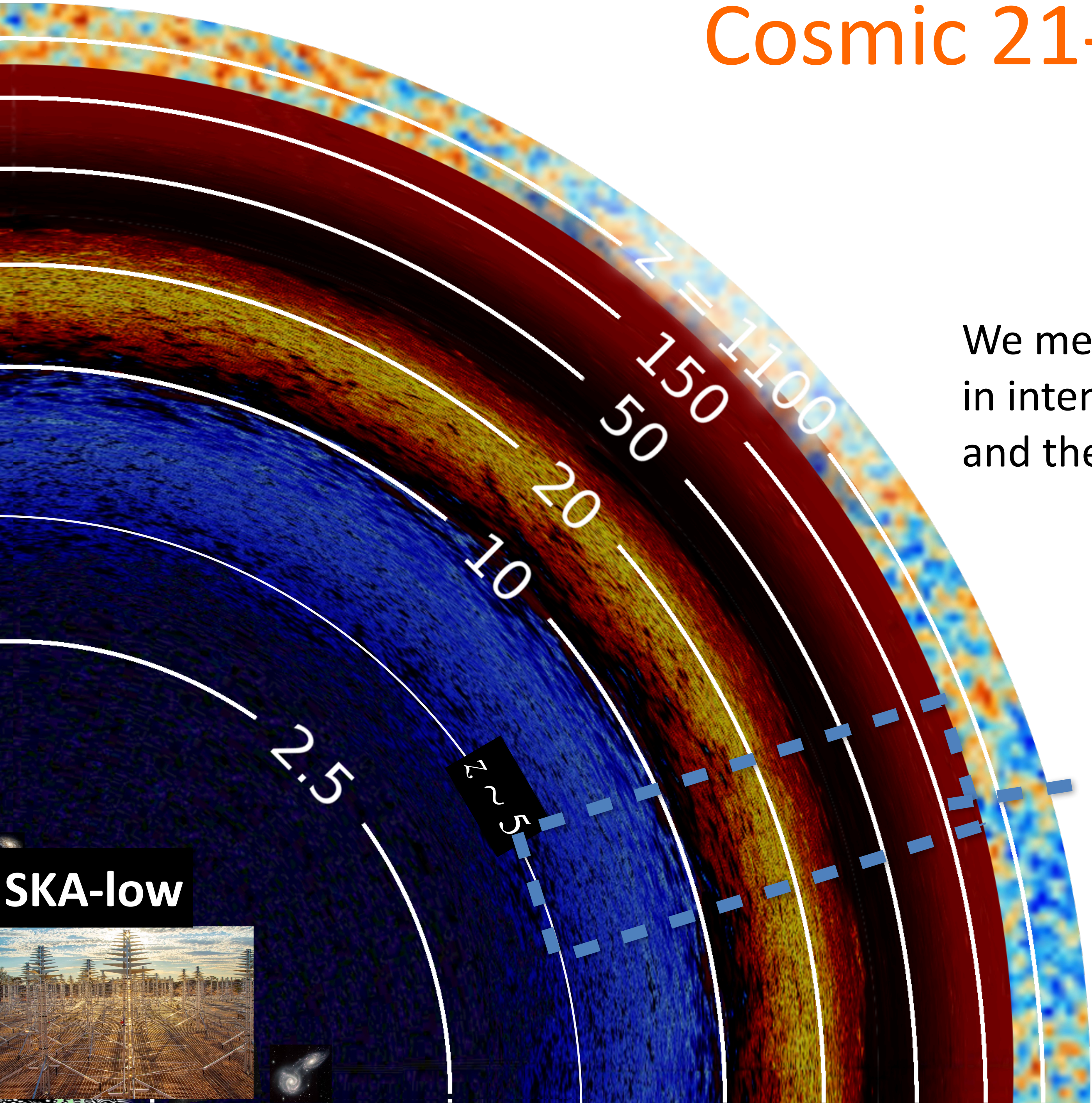
Cosmic 21-cm



We measure the difference in intensities of the CMB and the cosmic HI.

adapted from C. Chiang

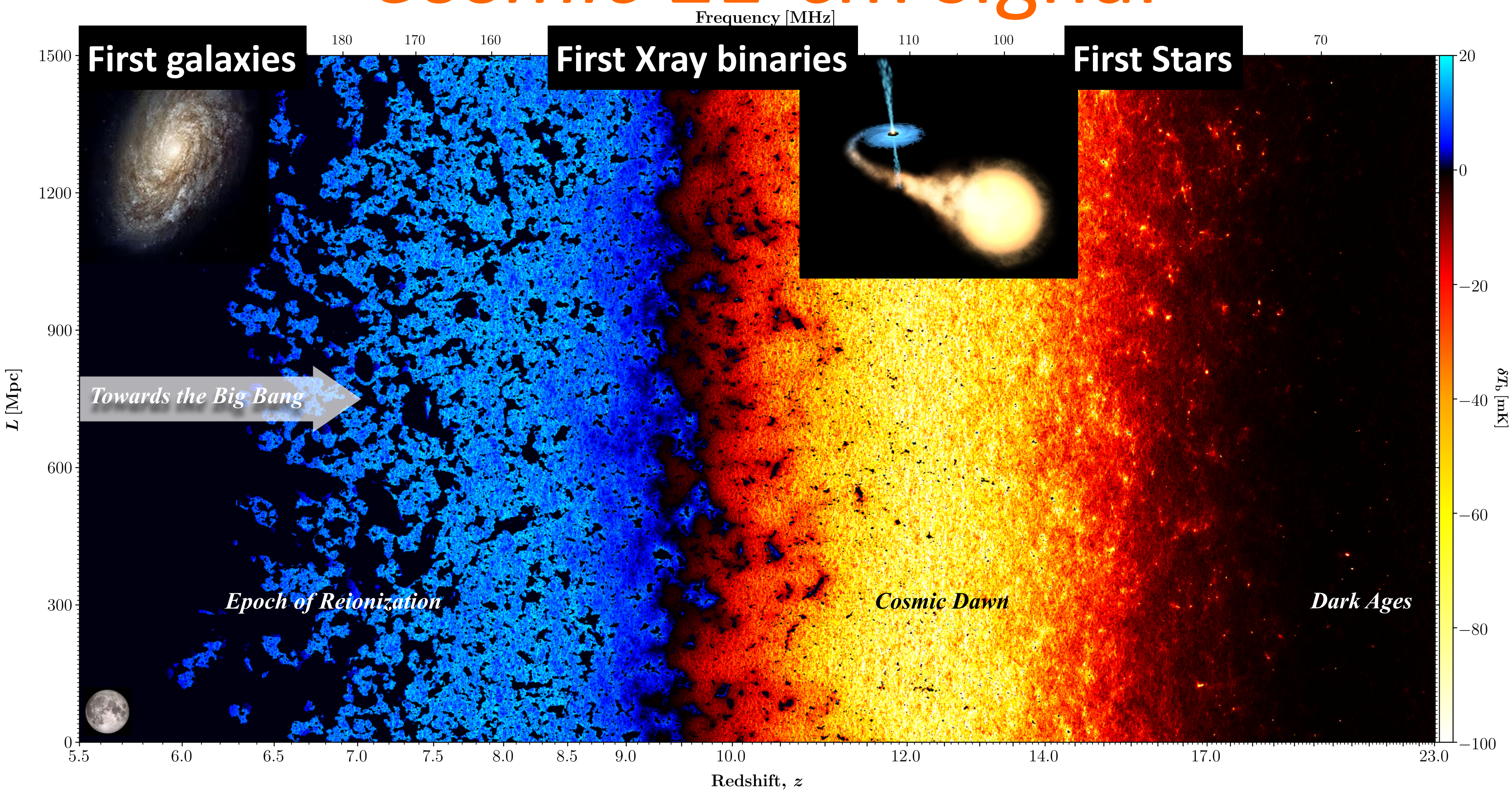
Cosmic 21-cm



We measure the difference in intensities of the CMB and the cosmic HI.

adapted from C. Chiang

Cosmic 21-cm signal

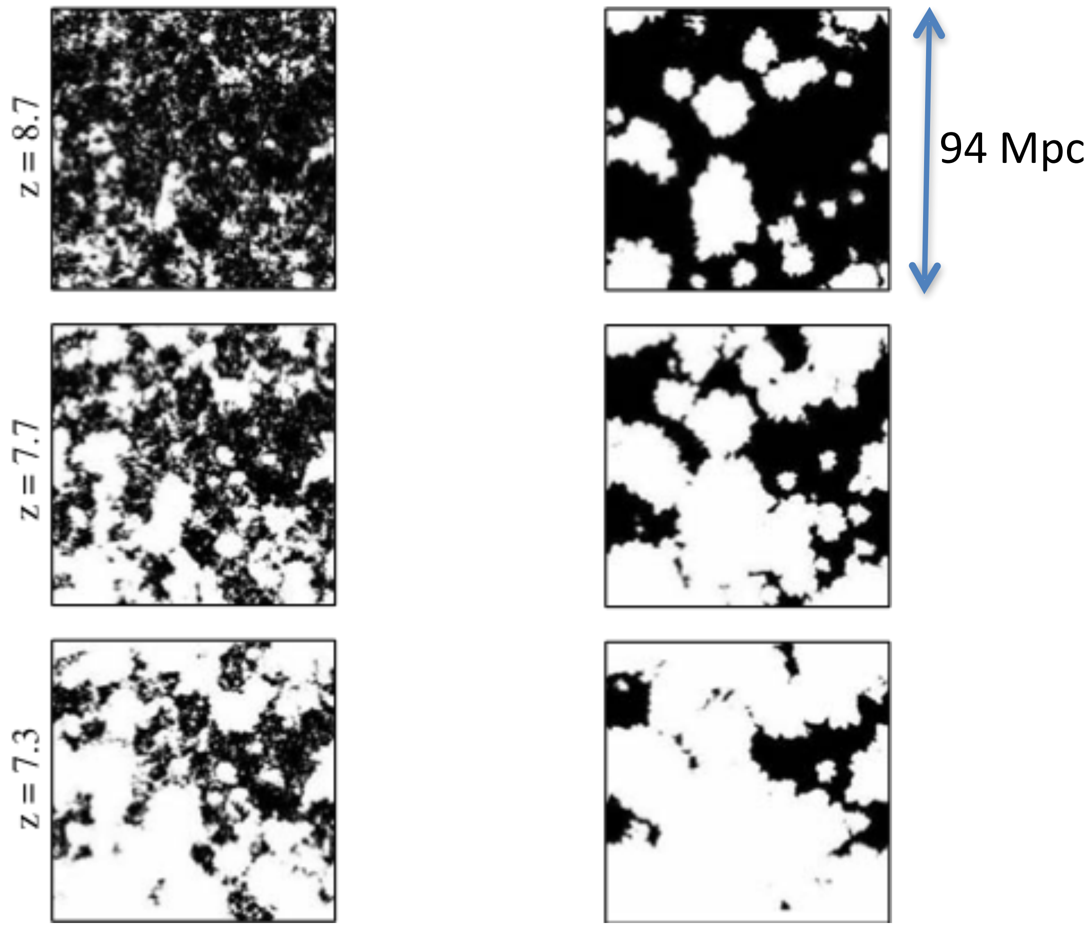


$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

What can we learn?

Timing of reionization and the properties of the (unseen) galaxies that drive it

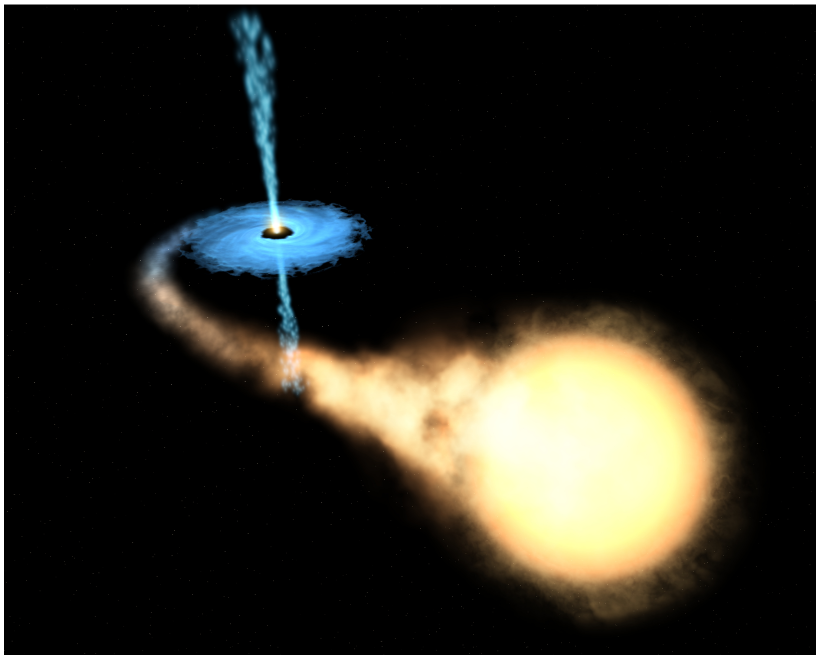
- Galaxy clustering + stellar properties → *evolution of large-scale EoR/CD structures*



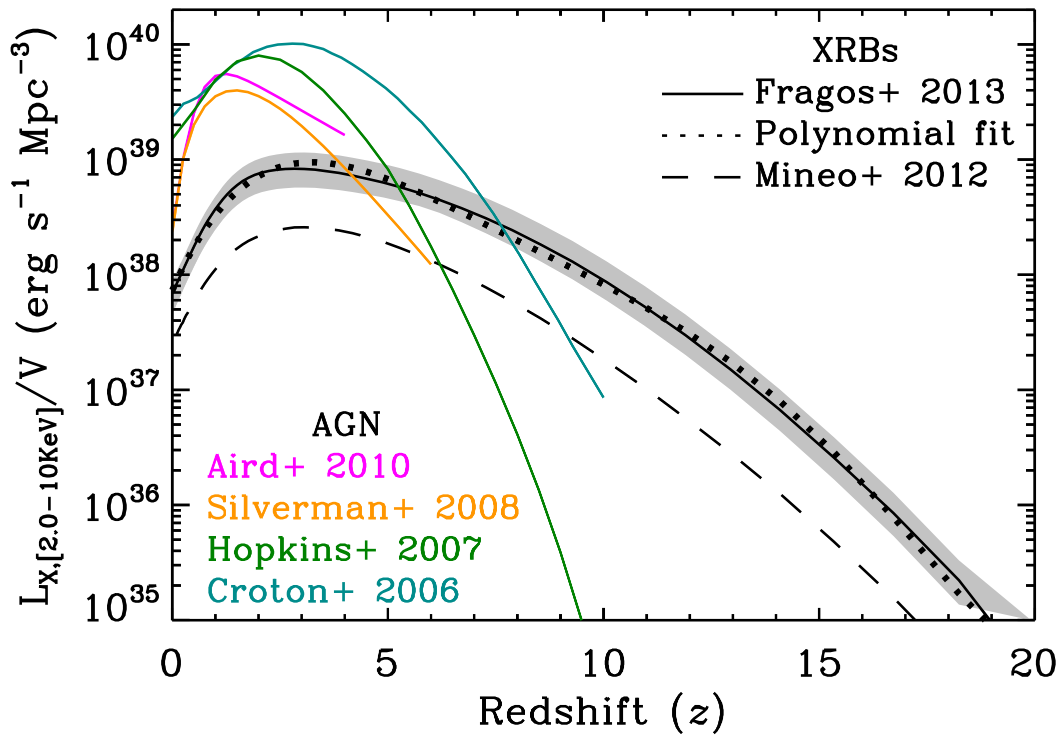
Abundant, faint galaxies vs **Rare, bright galaxies**

McQuinn+ 2007

Properties of sources that heat the IGM

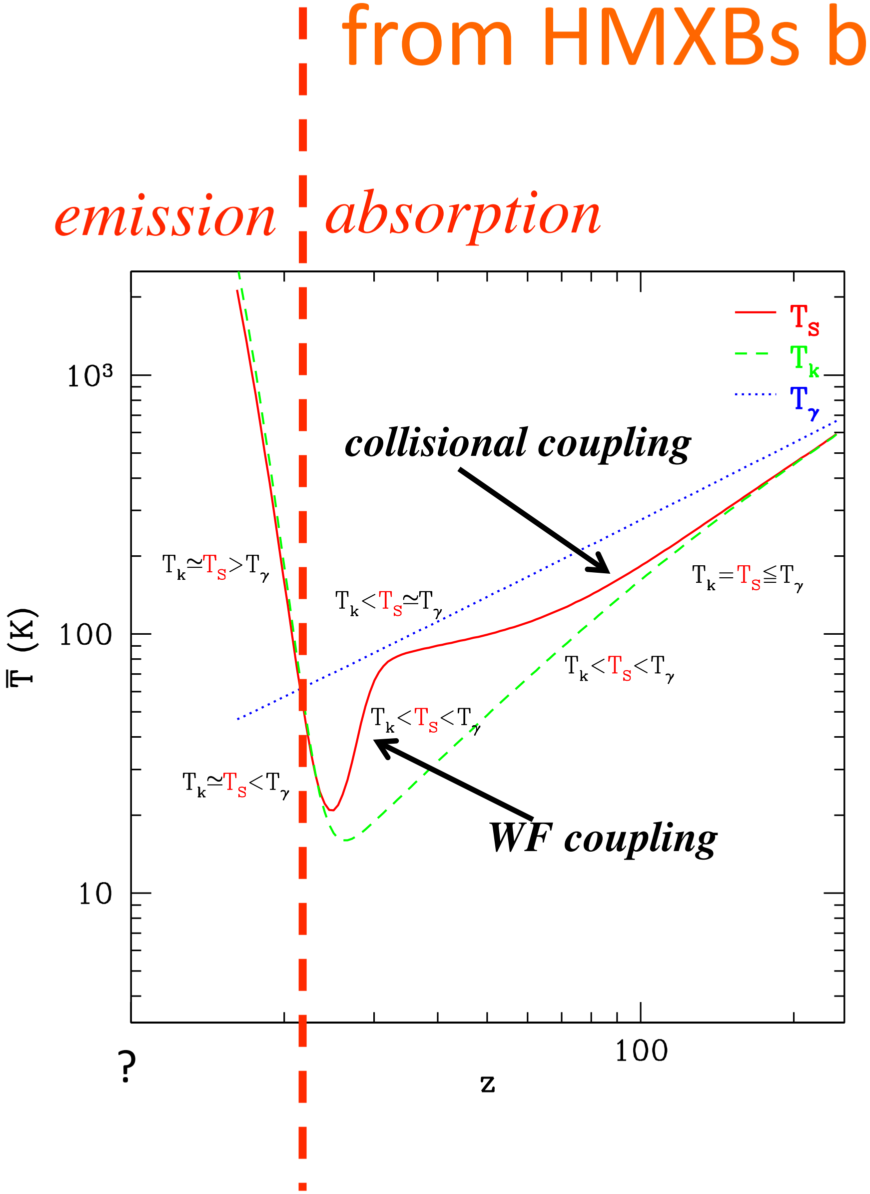


High Mass X-ray Binaries are expected to dominate the X-ray background beyond z >~ 5



Fragos+ 2013

"*Fiducial*" scenario: the IGM is heated by X-rays from HMXBs before reionization



SFR required to reionize the Universe:

$$[\dot{\rho}_{\rm SFR}]_{\rm ion} = 4.4 \times 10^{-1}\, \bar{x}_i\, Z_{20}^{3/2} \left(\frac{t_{\rm SFR}}{0.1\, t_H}\right)^{-1} \times \left(\frac{f_{\rm esc}}{0.1} \frac{N_{\rm ion}}{4000}\right)^{-1} \; {\rm M_\odot\ yr^{-1}\ Mpc^{-3}}, \quad (11)$$

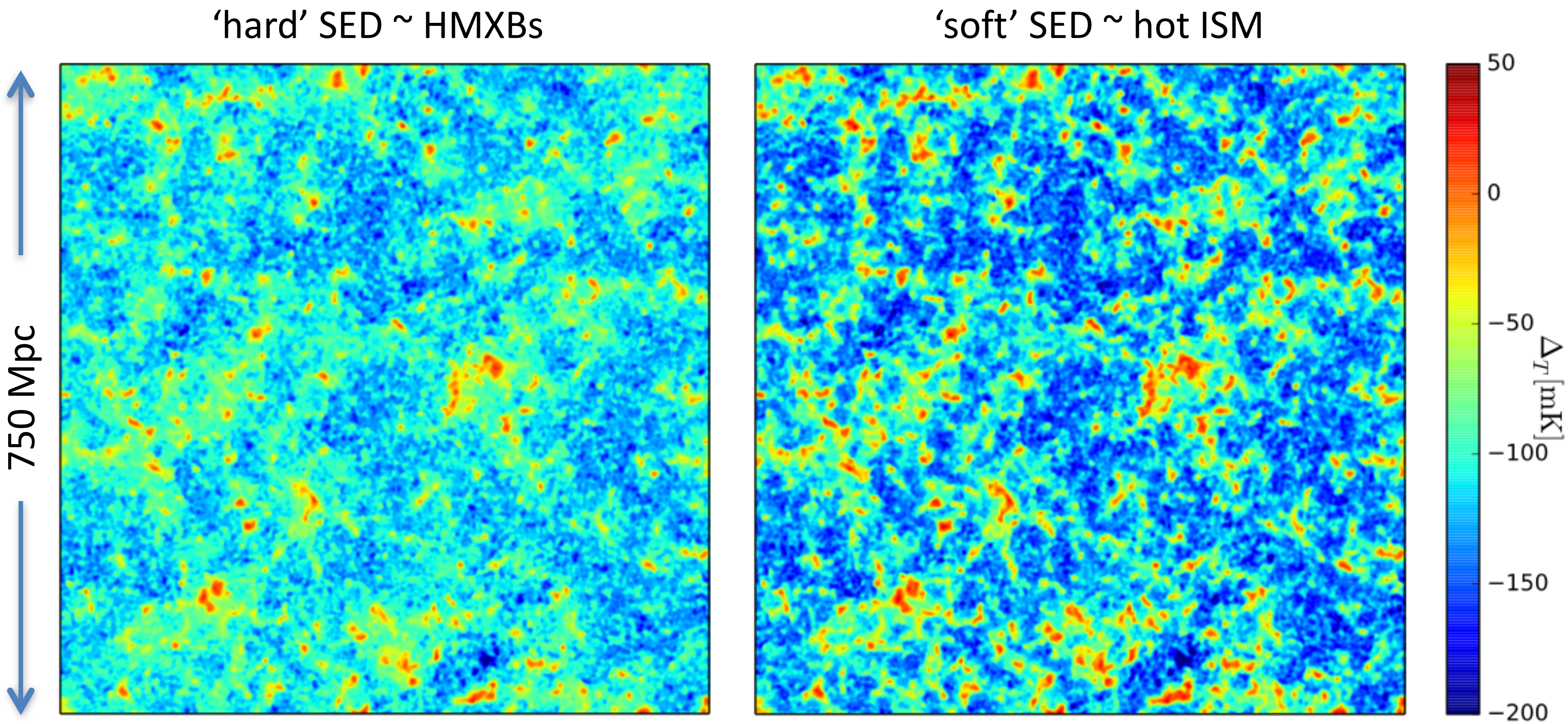
is larger than the SFR needed to heat it to above CMB with HMXBs:

$$[\dot{\rho}_{\rm SFR}]_{\rm X} = 4.0 \times 10^{-2}\, Z_{20}^{5/2} \left(\frac{t_{\rm SFR}}{0.1\, t_H}\right)^{-1} \left(\frac{f_X}{0.2}\right)^{-1} \times \left(\frac{L_X/{\rm SFR}}{10^{40}\ {\rm erg\ s^{-1}\ M_\odot{}^{-1}\ yr}}\right)^{-1} \; {\rm M_\odot\ yr^{-1}\ Mpc^{-3}}, \quad (10)$$

McQuinn & O'Leary (2012)

Patterns in the Epoch of Heating

High-energy processes in the first galaxies are also encoded in the cosmic 21-cm signal

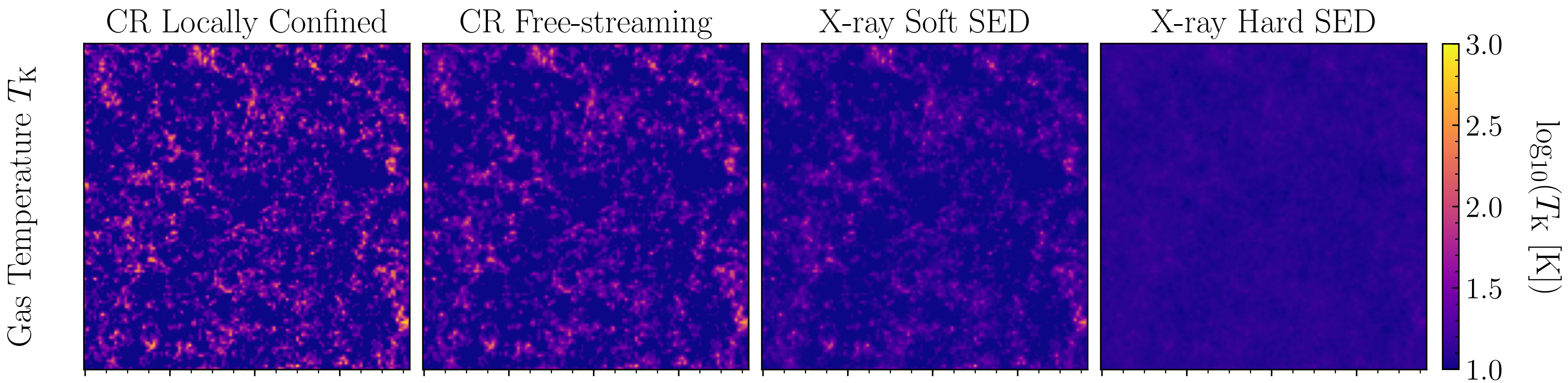


differences are easily detectable with HERA and the SKA

Pacucci, AM + 2014

More exotic sources of early IGM heating?

- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)



Gessey-Jones+2023

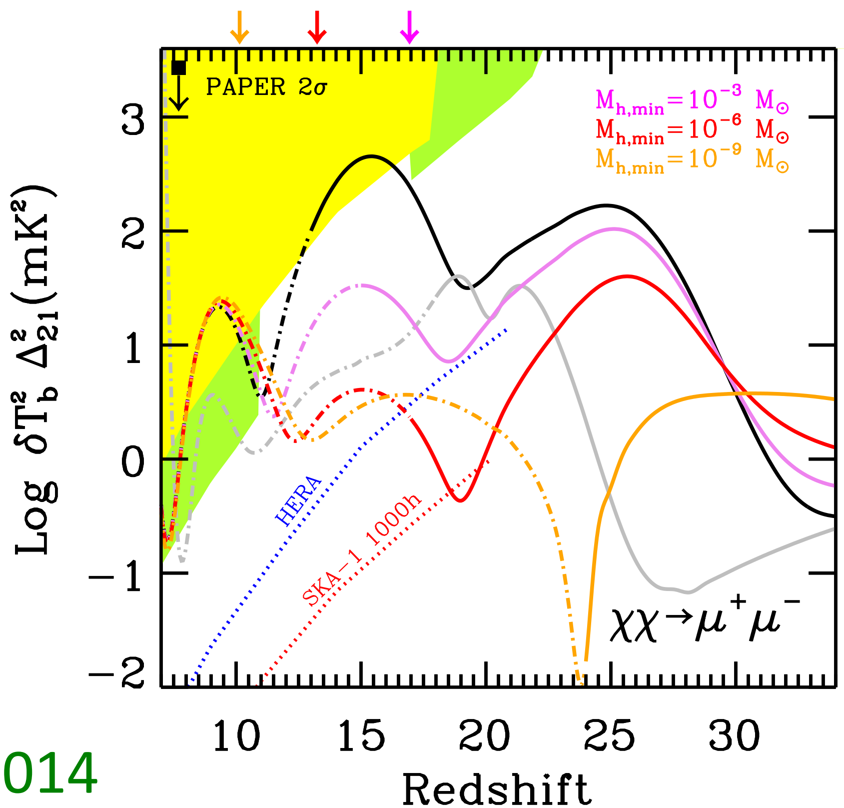
Different mean free paths —> patchiness of heating

More exotic sources of early IGM heating?

- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)

- Dark matter annihilations? (e.g. Evoli+2014; Lopez-Honorez+2016)

heating is more uniform —>
not degenerate with galaxy heating



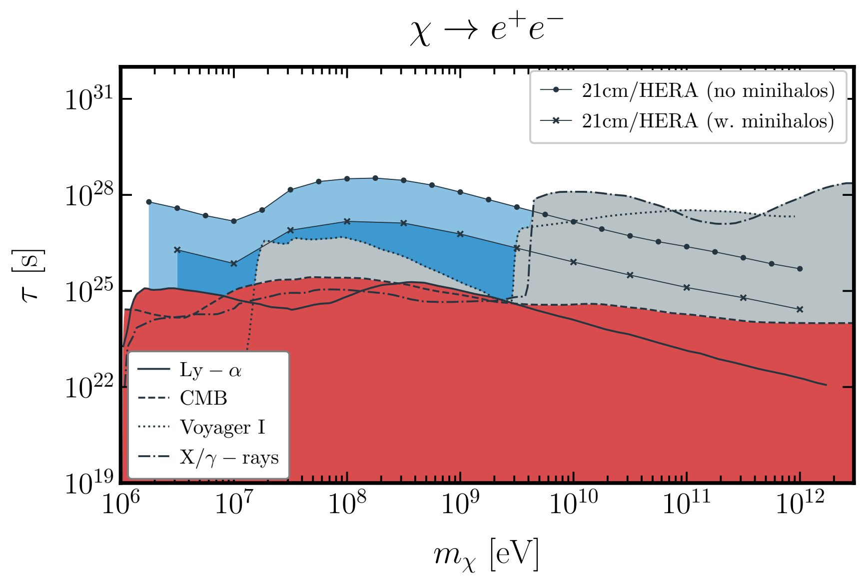
Evoli, AM+2014

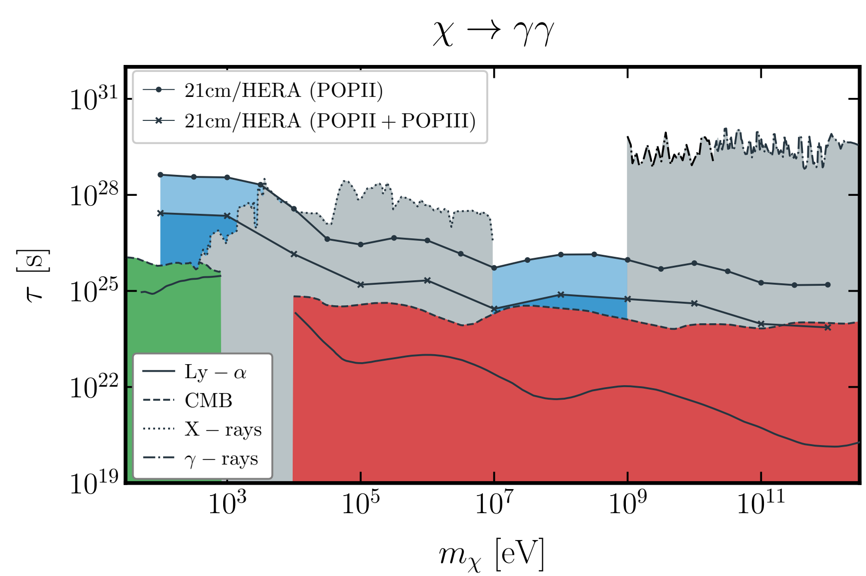
More exotic sources of early IGM heating?

- Cosmic Rays? (e.g. Leite+2017; Jana and Nath 2018; Gessey-Jones+2023)
- Dark matter annihilations? (e.g. Evoli+2014; Lopez-Honorez+2016)

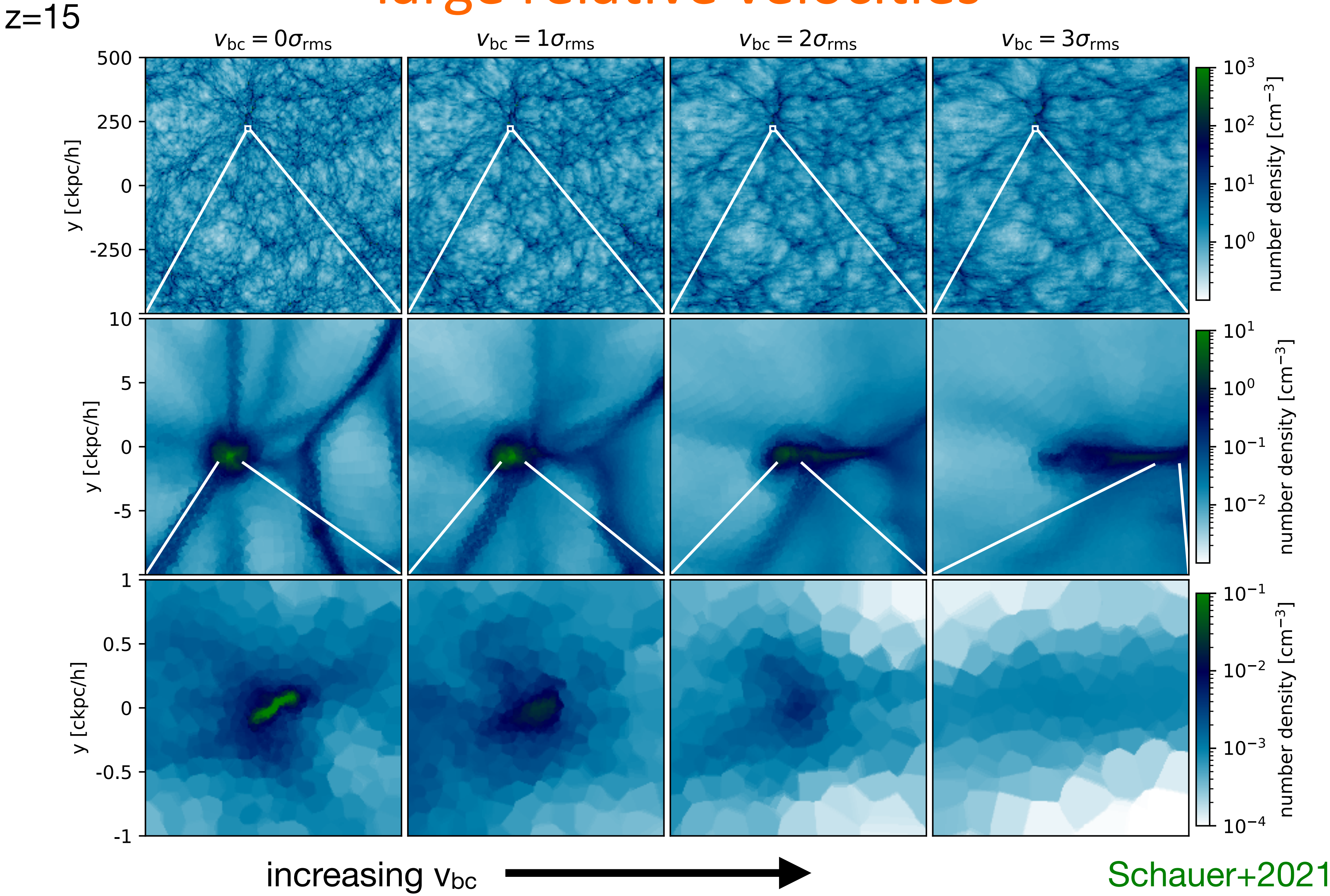
- Dark matter decay? (e.g. Facchinetti+ 2023)

see Gaetan's talk!

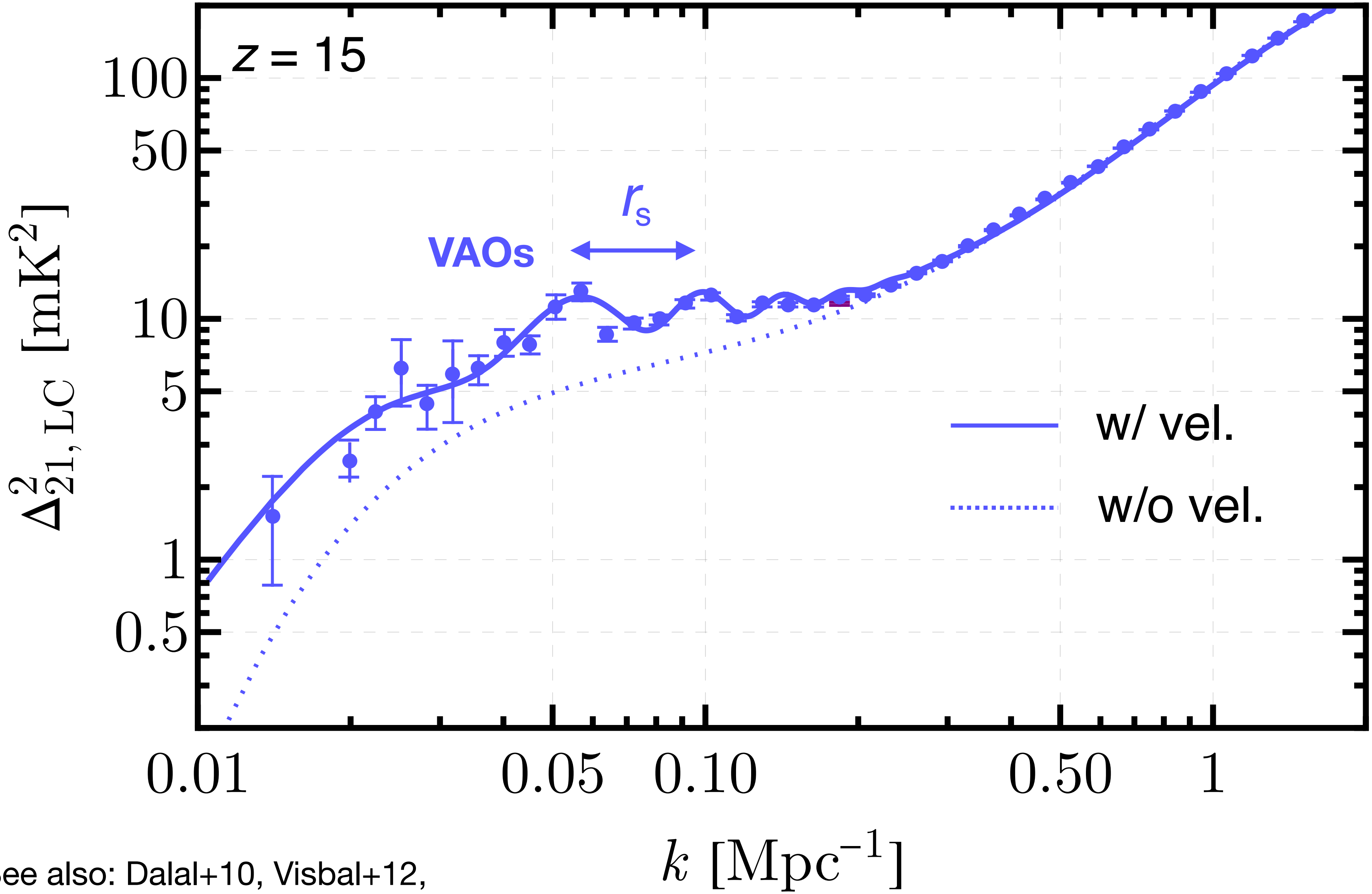




Star formation is suppressed in regions with large relative velocities



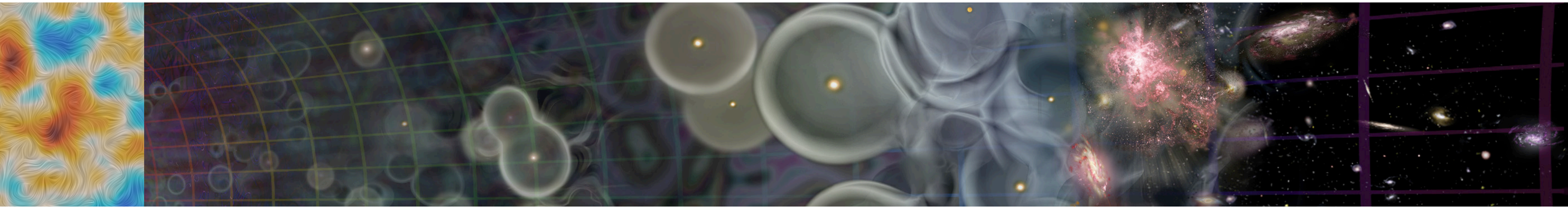
Standard ruler

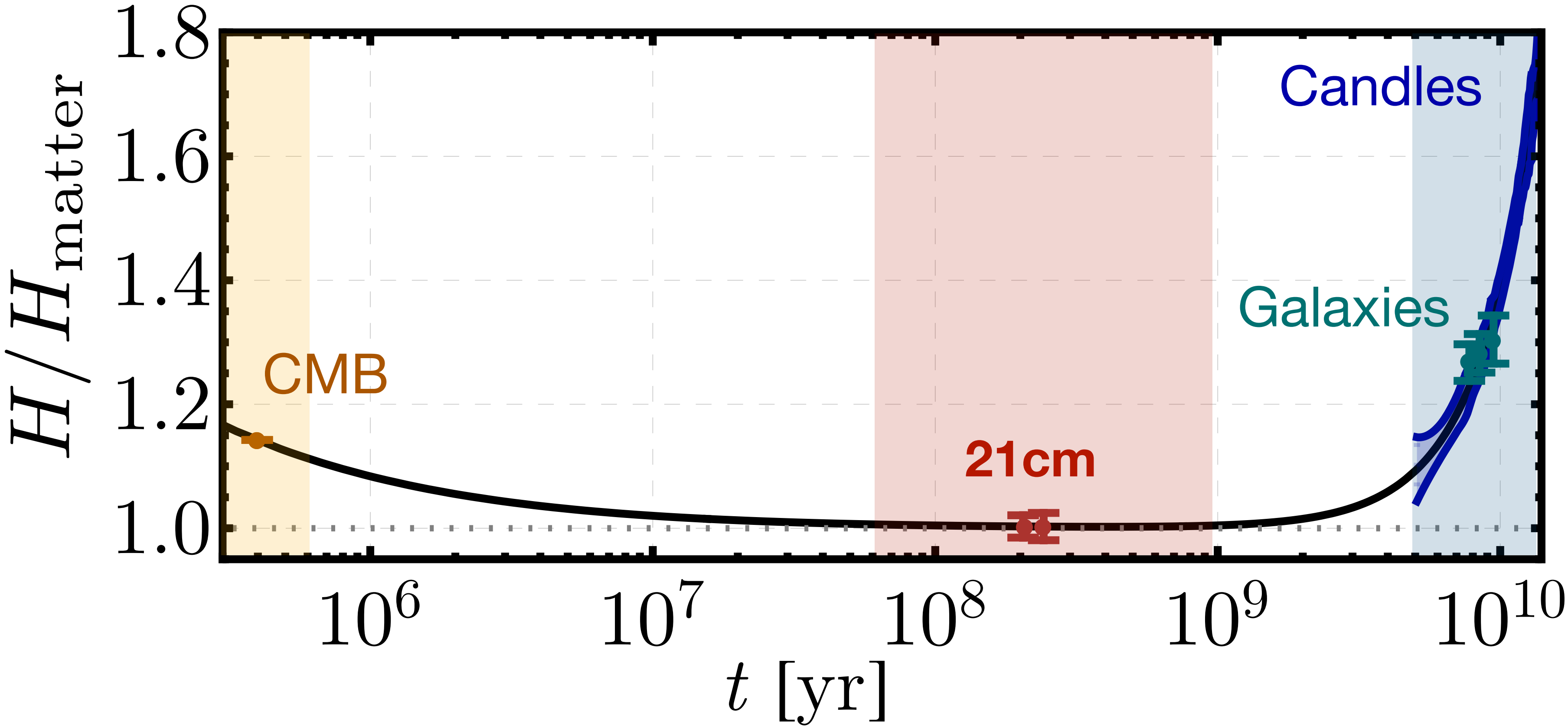


See also: Dalal+10, Visbal+12,
Fialkov+12, McQuinn+12
Munoz 19, Park+19, Cain+20

Munoz, Qin, AM+ 2022

Measuring the expansion history



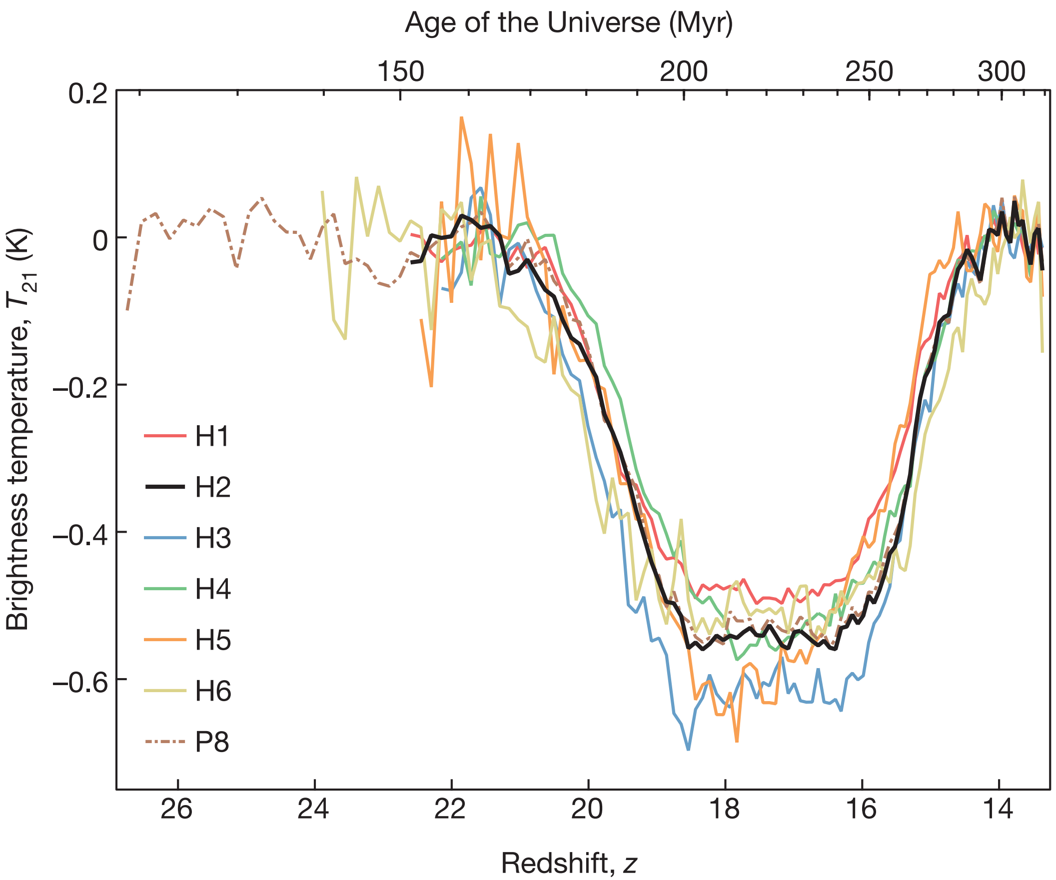


Munoz+ 2019

That sounds great, but where are we now?

Current status
global experiments

Claim of a detection by EDGES



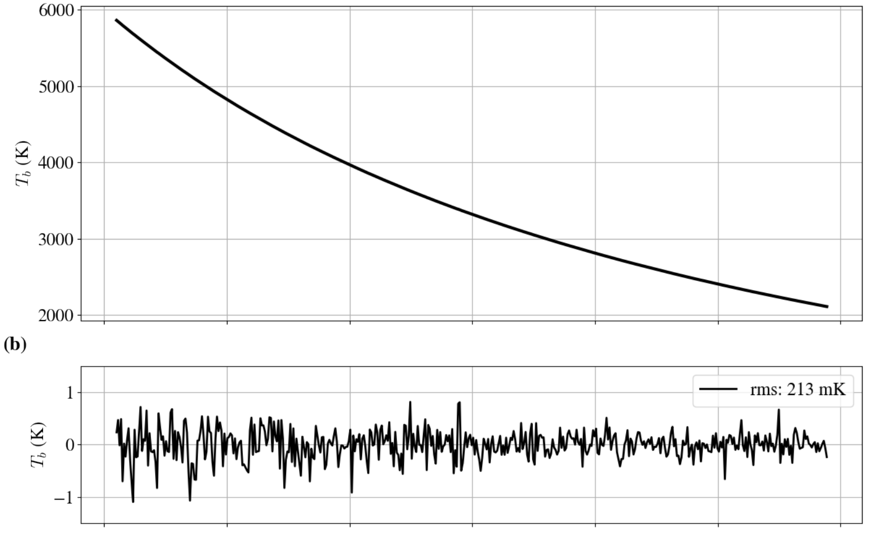
Bowman et al. 2018

Current status
global experiments

Claim of a detection by EDGES

BUT

No evidence of the signal in SARAS3



Singh+ 2021

6th order polynomial + NO cosmic signal

Current status
global experiments

Claim of a detection by EDGES

BUT

No evidence of the signal in SARAS3

Upcoming results from REACH, MIST, RHINO, etc.
updates from EDGES, SARAS (see more during global section)

First generation 21-cm interferometers

MWA

LOFAR

GMRT

PAPER

HERA

It is HARD!

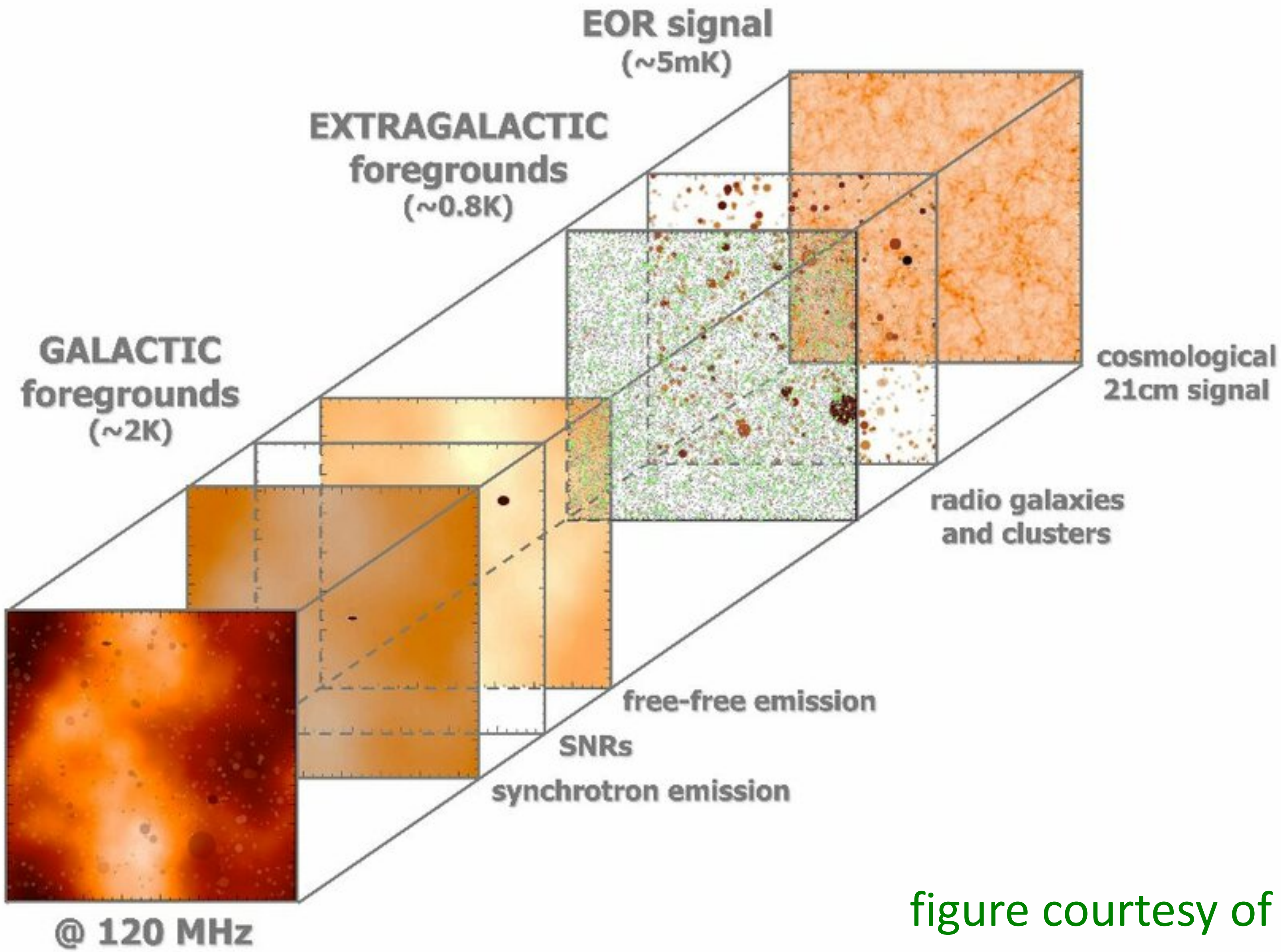


figure courtesy of V. Jelić

Hope is to measure PS in the "EoR window"

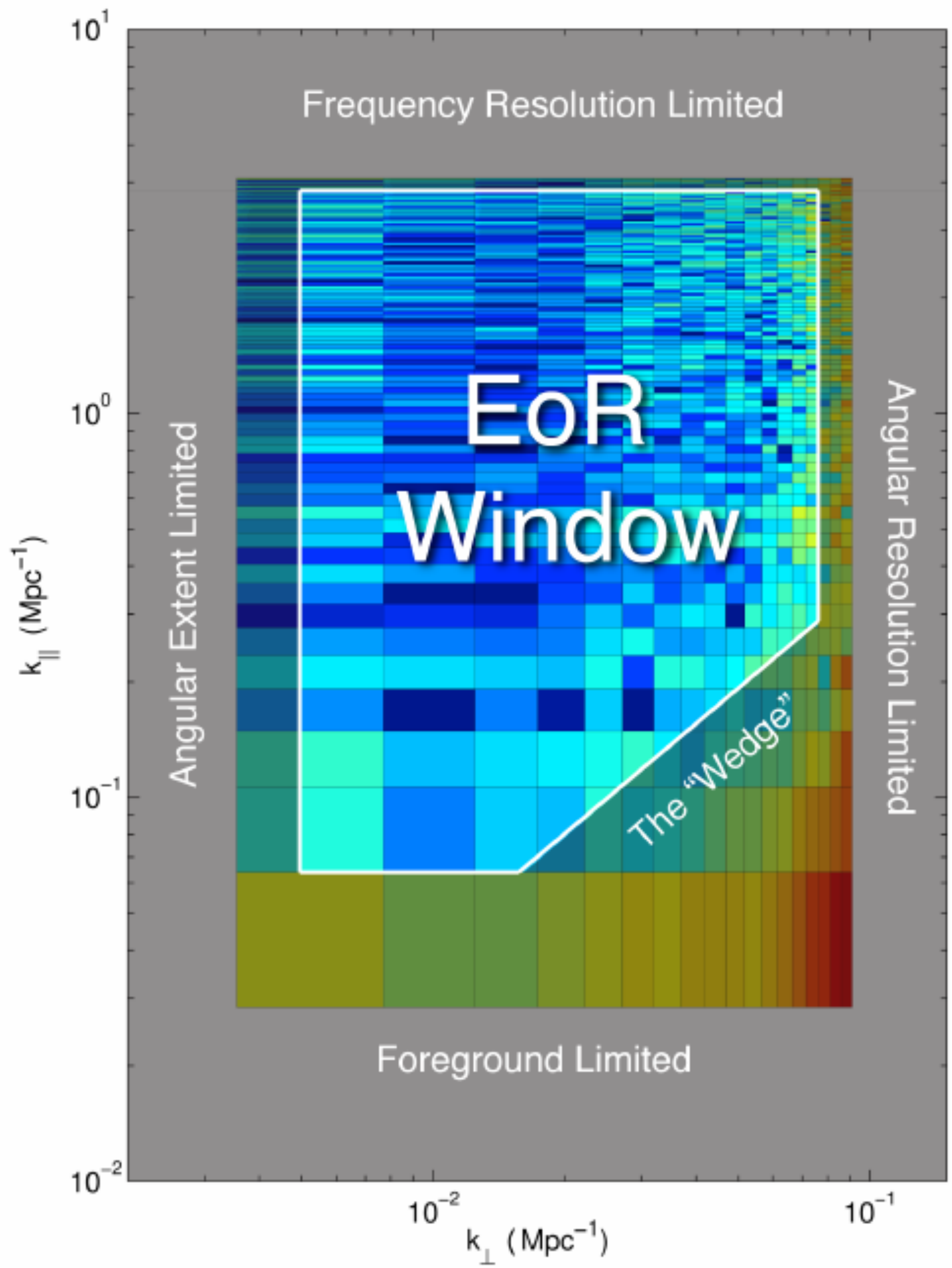
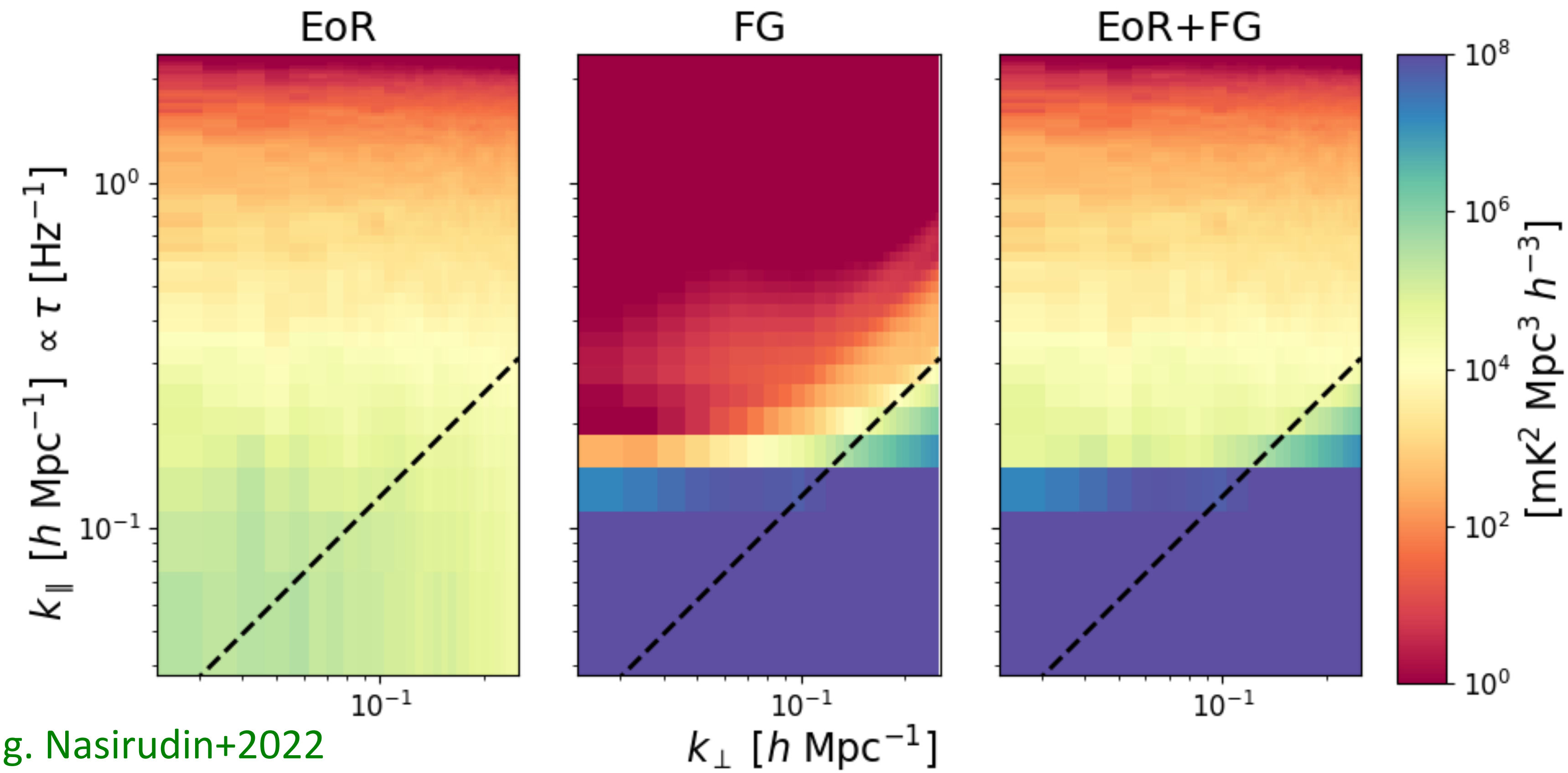


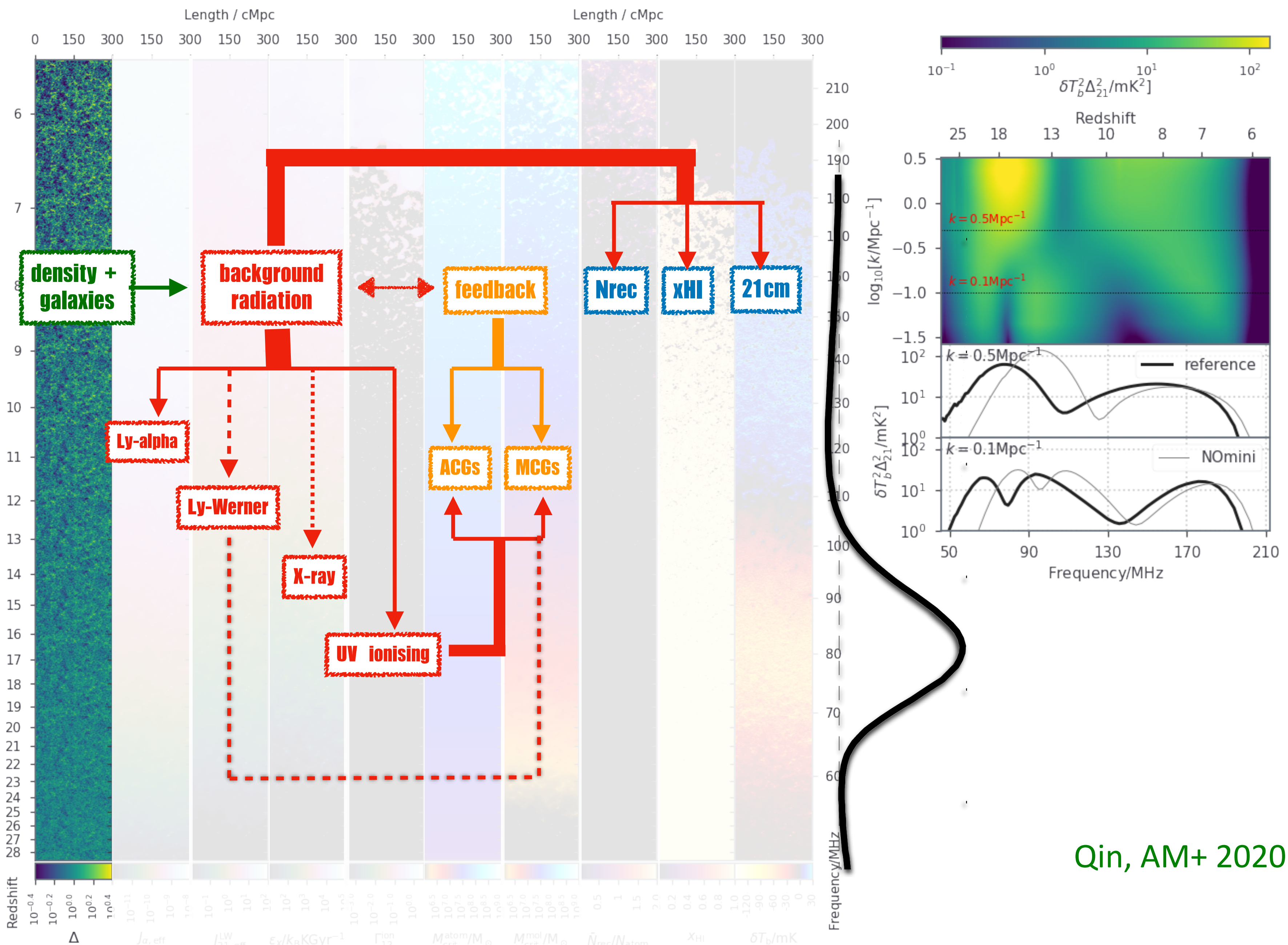
figure courtesy of J. Dillon

Hope is to measure PS in the "EoR window"



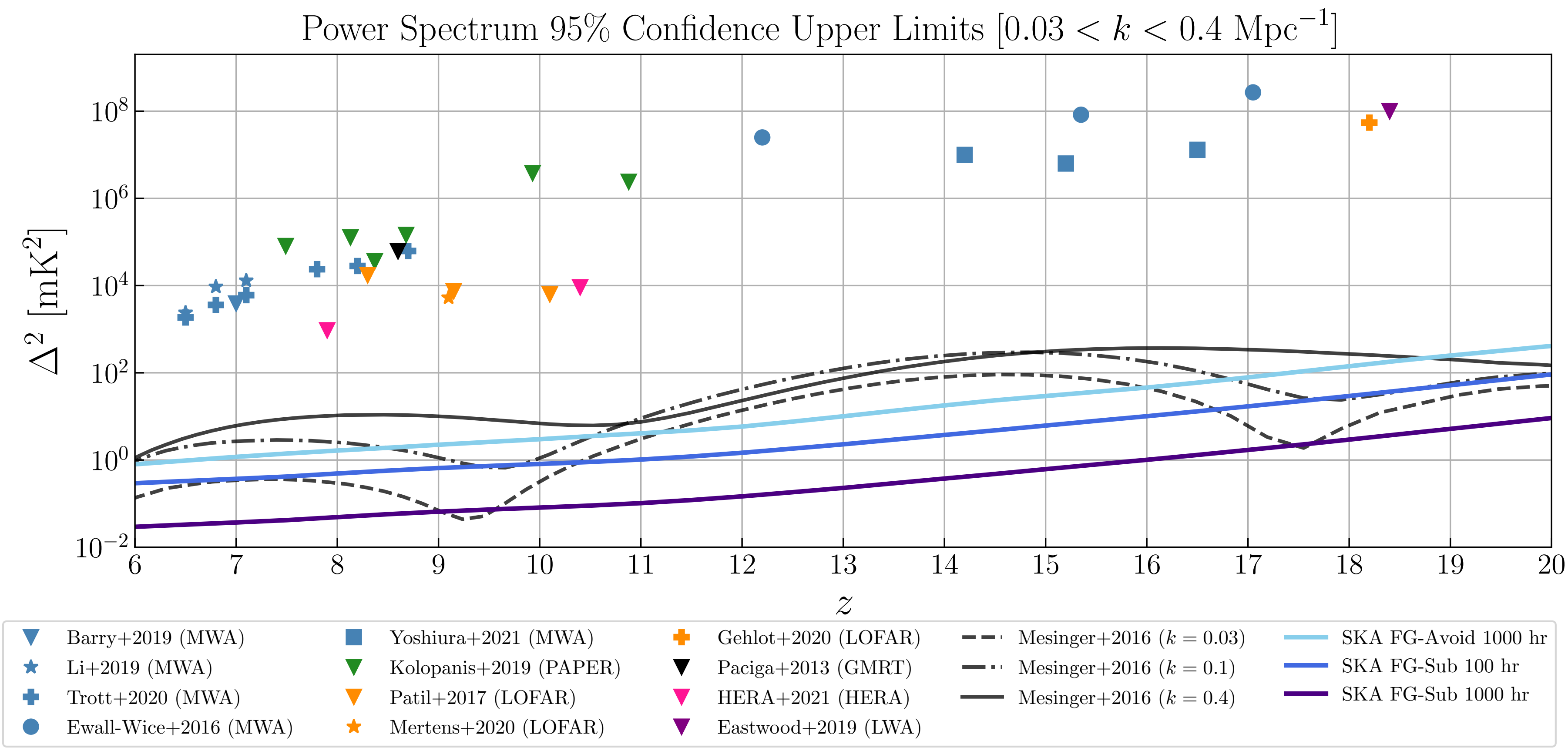
e.g. Nasirudin+2022

Theoretical modeling is also hard...



Qin, AM+ 2020

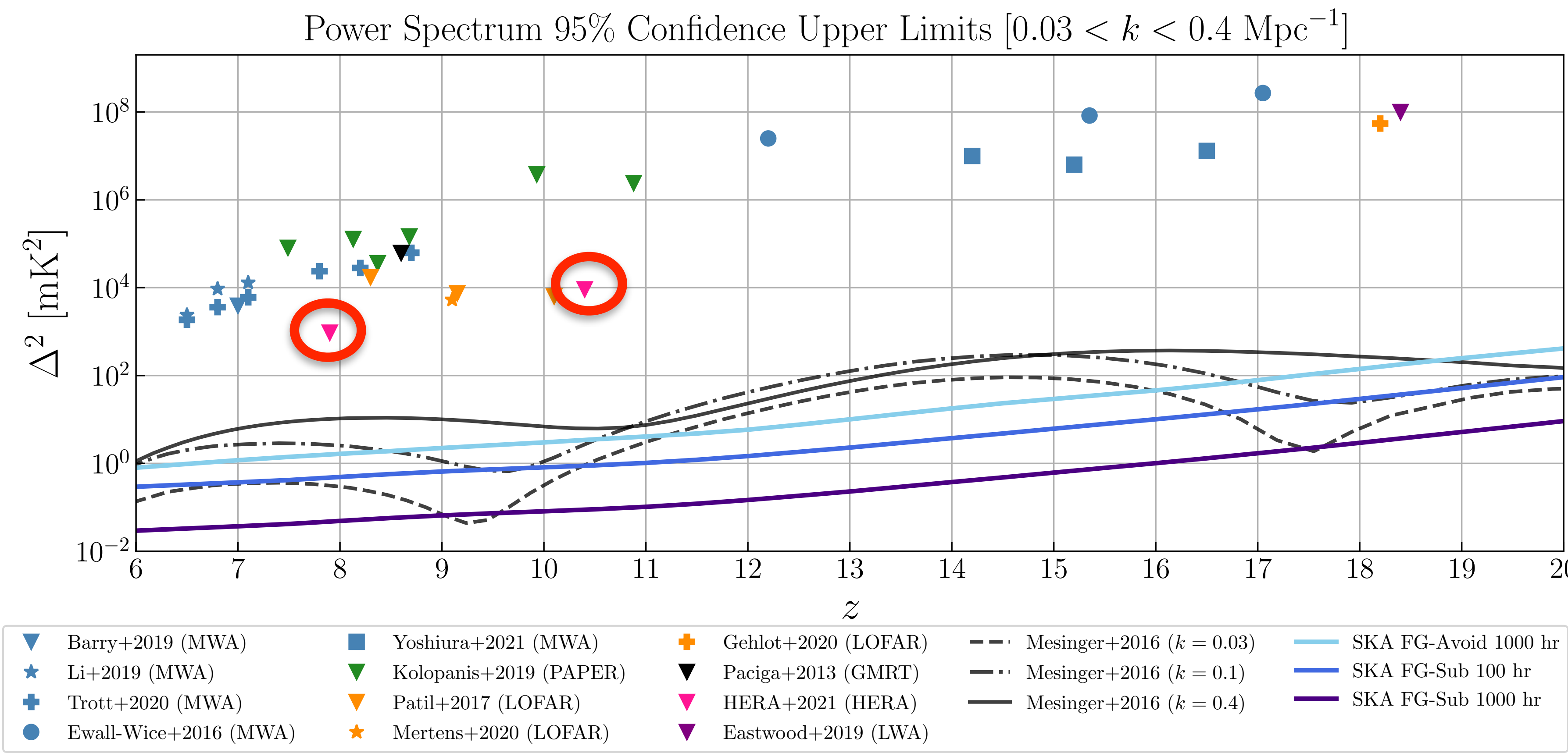
Measurements are improving, but currently only upper limits on the PS



Barry+ 2022

Can we learn something from upper limits that are still x10-100 above the expected signal?

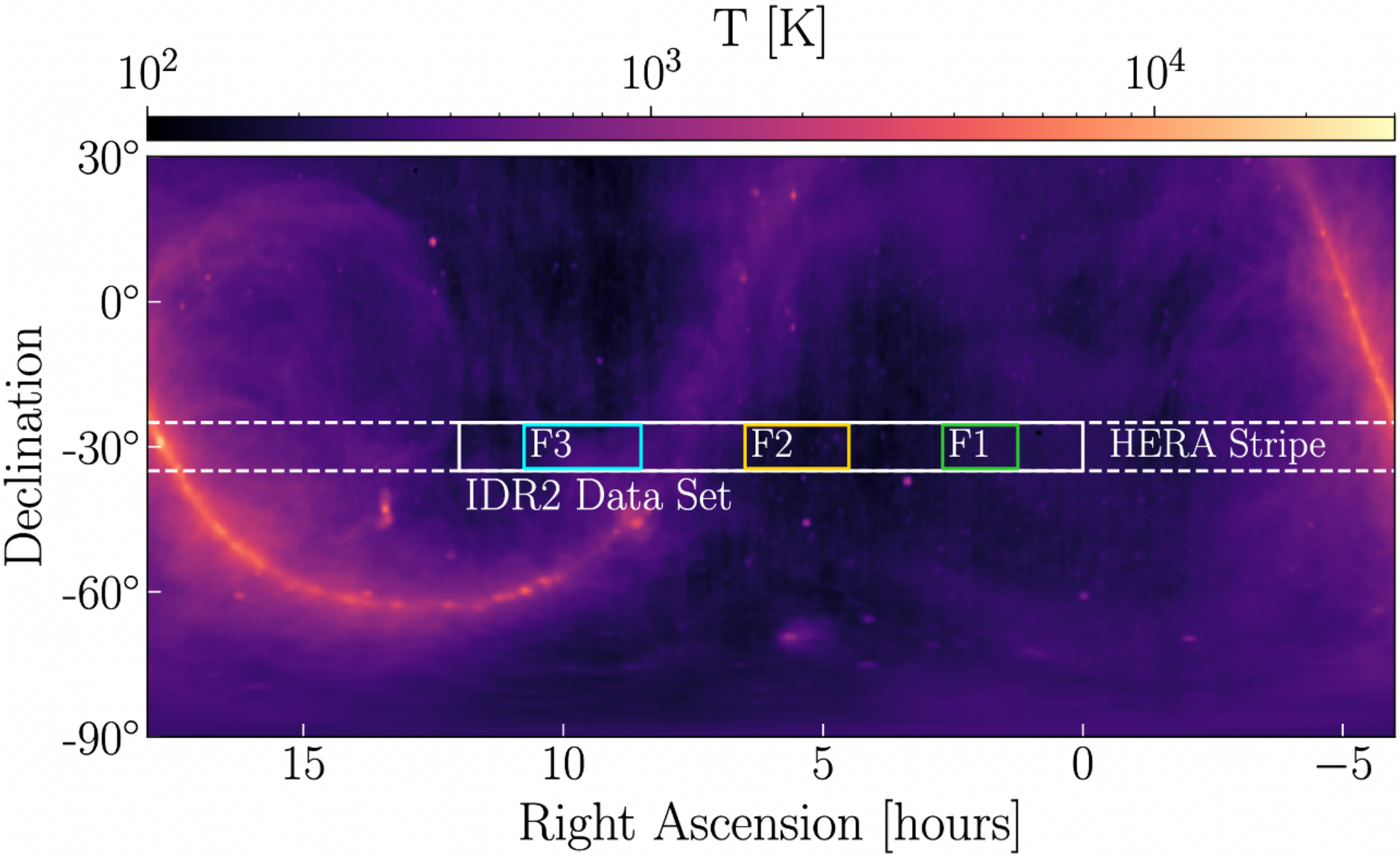
Currently only upper limits on the PS



Application to **HERA** (HERA collaboration 2022ab).
For similar studies on **LOFAR** and **MWA** data see (Ghara+2020; Mondal+2020; Greig+2020, Greig+2021)

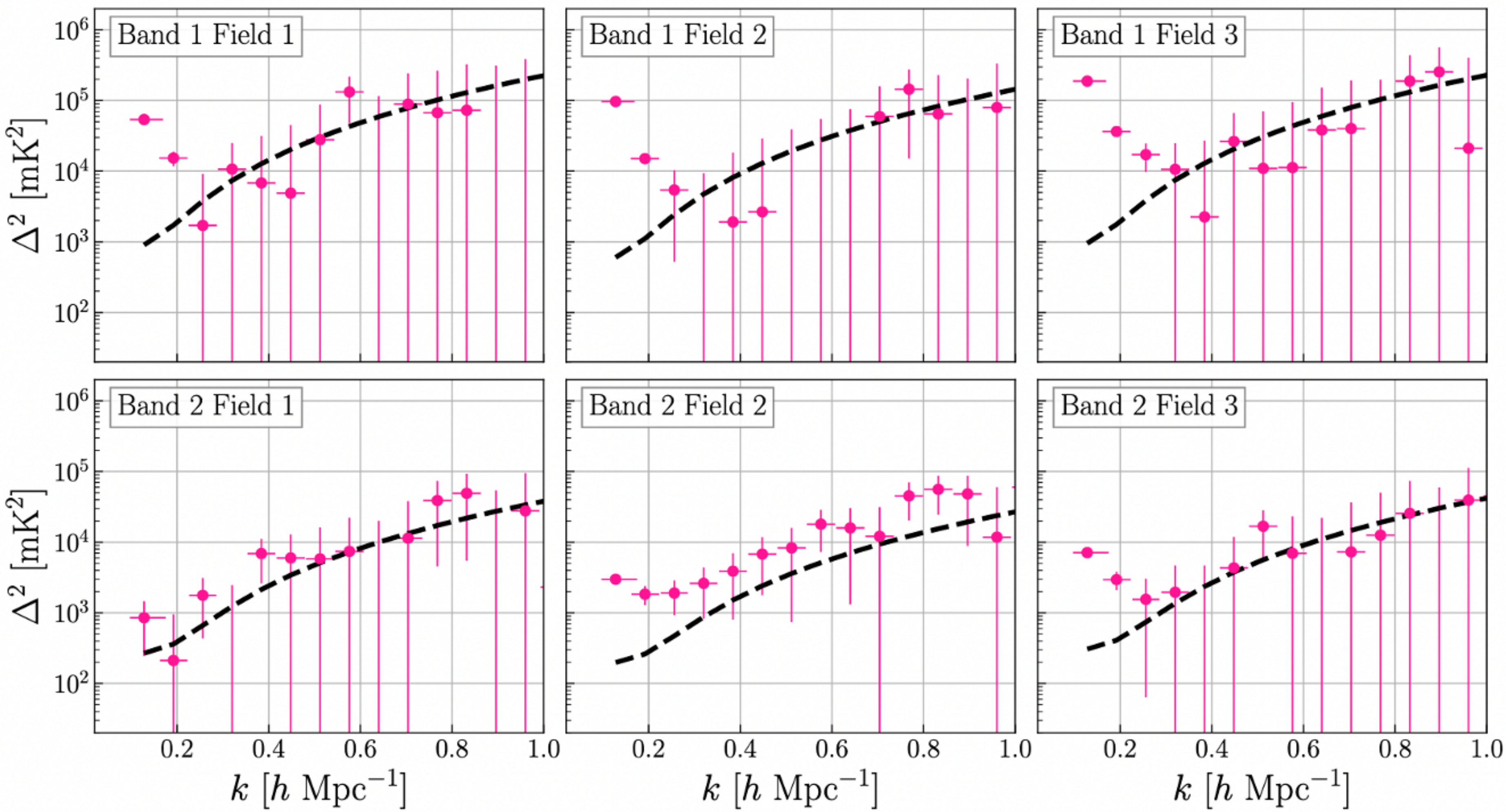
Recent results from HERA

An initial observing campaign in 2017-18, with just 39/~350 antennas and 18 nights (2108.02263).



HERA collaboration (2022a)

Interpreting recent results from HERA



These are consistent with thermal noise, and are still ~1-2 orders of magnitude above the expected signal

HERA collaboration (2022a; *led by Nick Kern)*

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \text{mK}$$

~ 0 — 1

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) \text{mK}$$

~ 0.1 — 1

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

~ **-10(!)** — 1

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

+

Spatial fluctuations *in either:*

- *ionization fraction (patchy EoR)*

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

+

Spatial fluctuations *in either:*

- *ionization fraction (patchy EoR)*
- *matter density*

What kind of models are the easiest to rule out (i.e. have the largest power)?

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

Models that are ruled out must have:

COLD IGM: $T_S \ll T_\gamma$

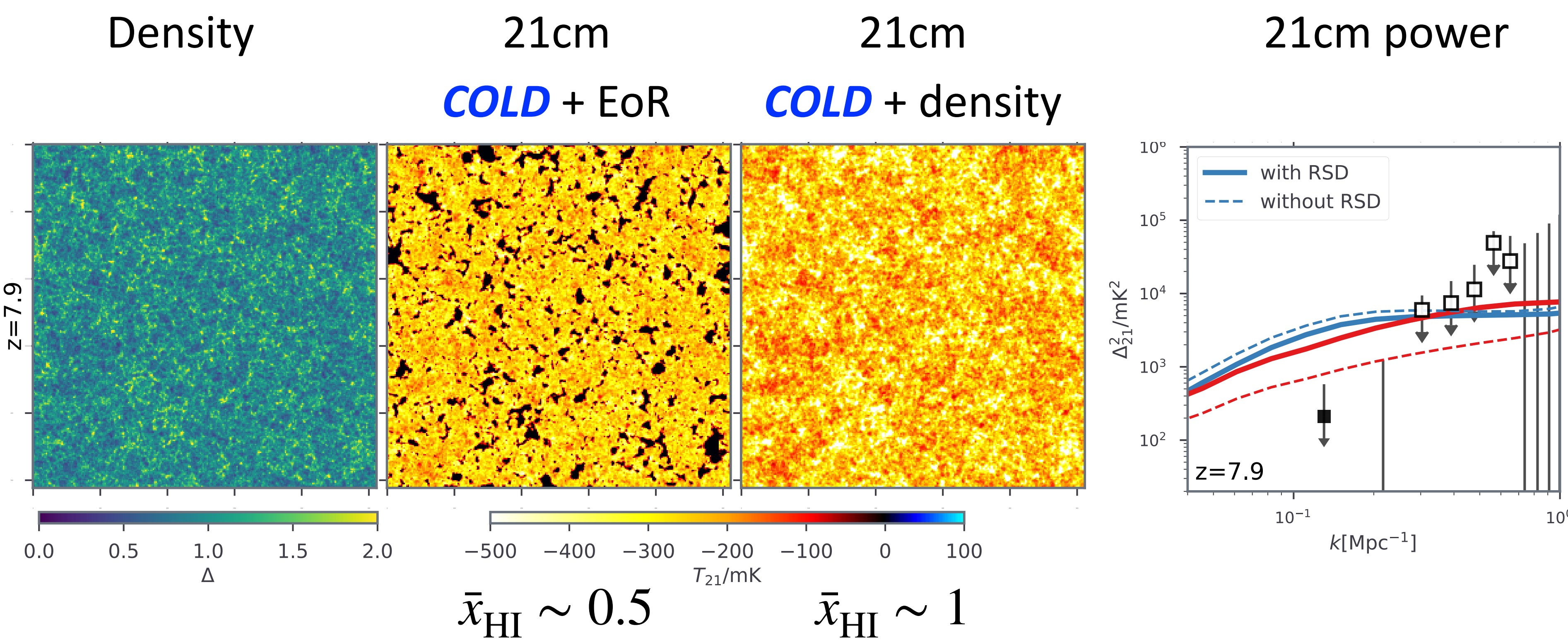
+

Spatial fluctuations *in either:*

- ***ionization fraction (patchy EoR)***
- ***matter density***
- *temperature (requires extremely soft SEDs)*

see also e.g. Ewall-Wice+2013; Ghara+2020; Greig+2020; Mondal+2020; Reis+2020; Greig+2021

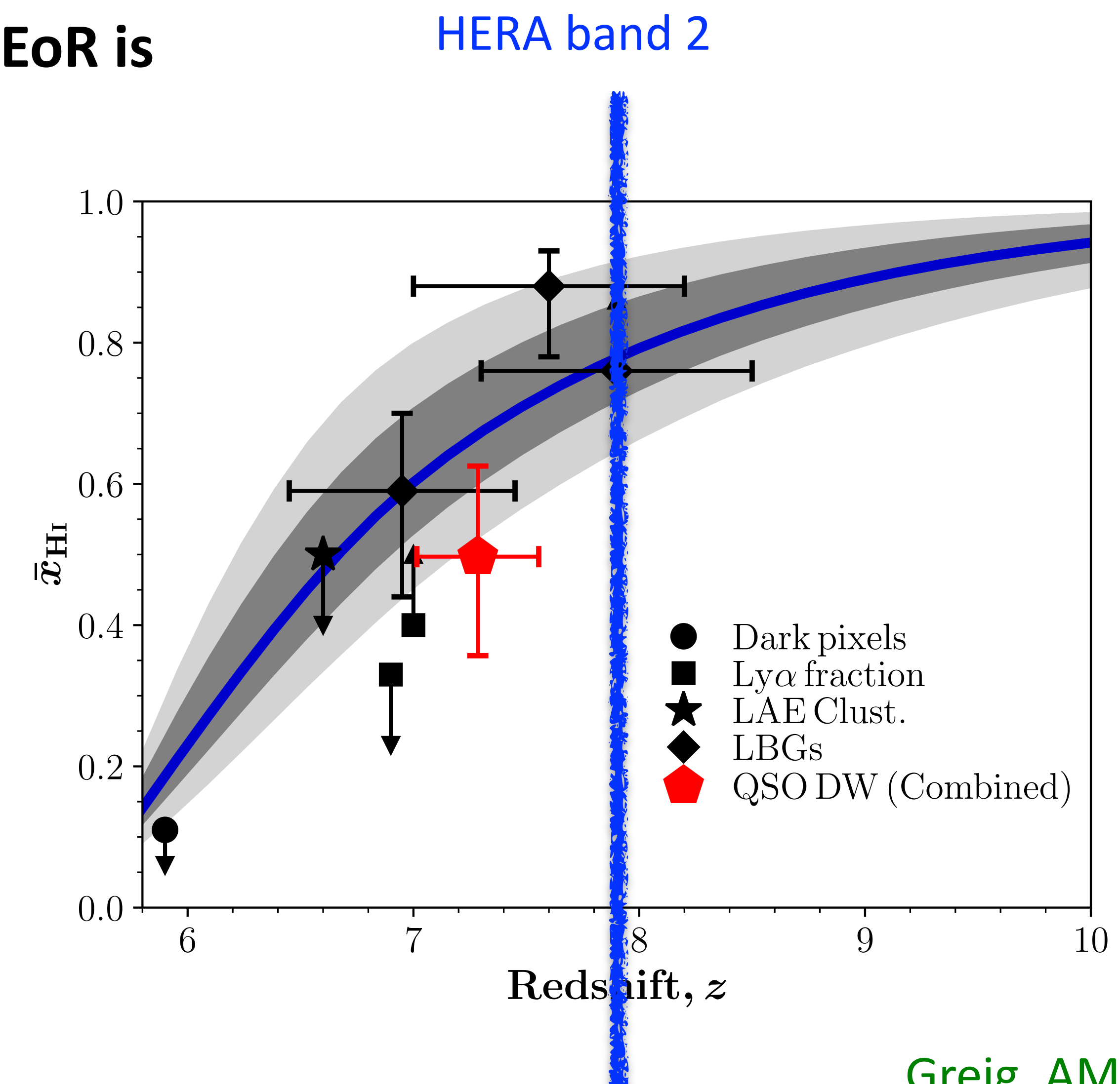
Examples



HERA collaboration (2021)

Current constraints on EoR history

BUT we know the EoR is underway at z~8!

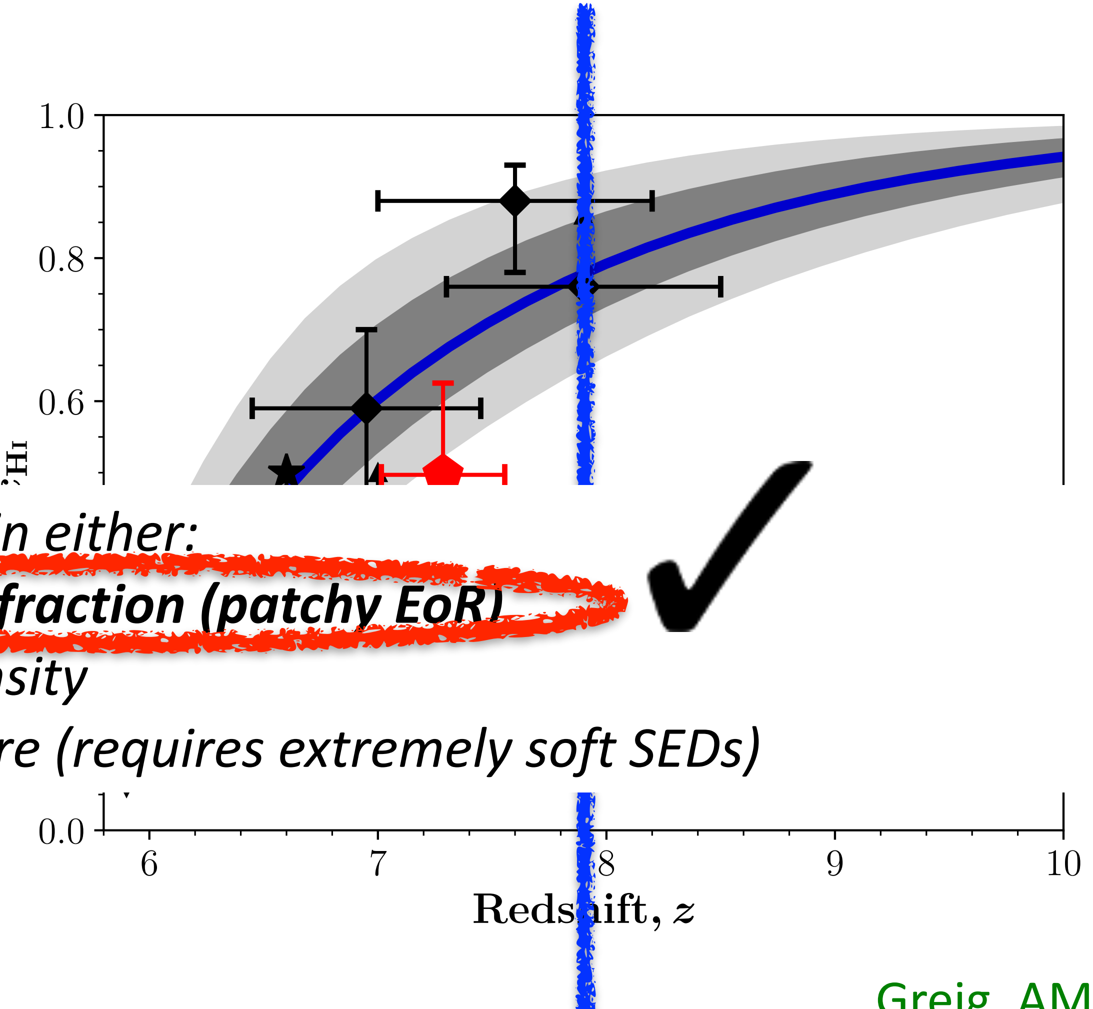


Greig, AM+2021

Current constraints on EoR history

BUT we know the EoR is underway at z~8!

HERA band 2



COLD IGM: $T_S \ll T_\gamma$

+

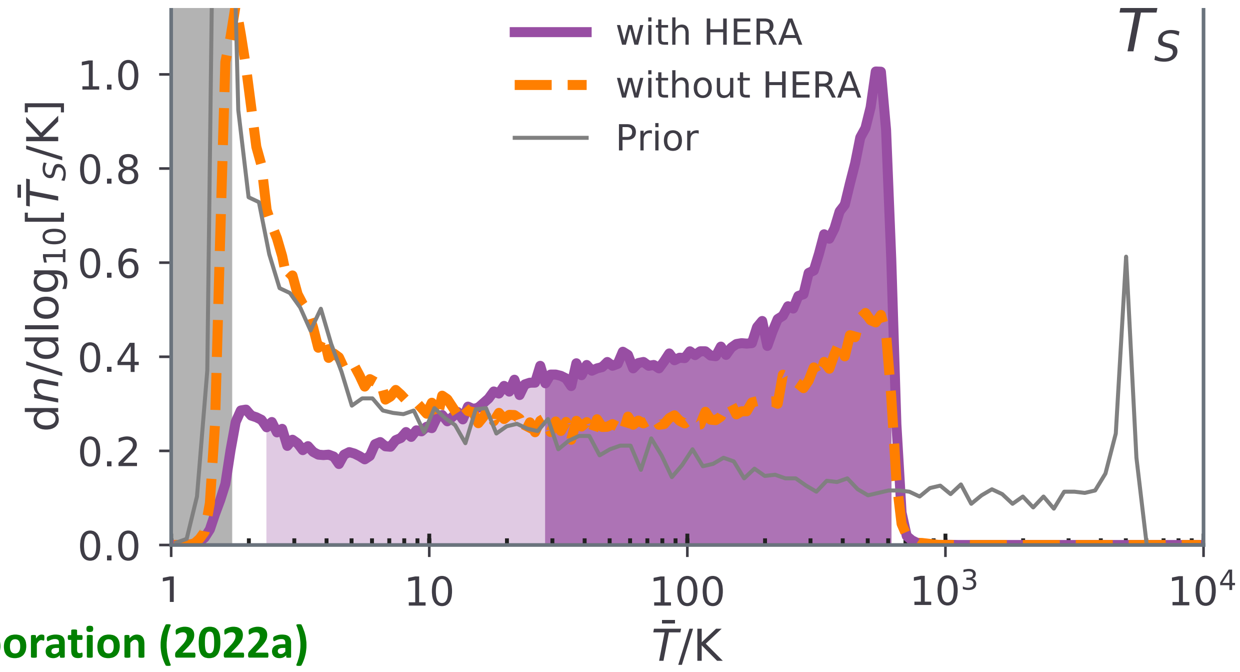
Spatial fluctuations *in either:*

- ***ionization fraction (patchy EoR)*** ✓
- *matter density*
- *temperature (requires extremely soft SEDs)*

Greig, AM+2021

Constraints on IGM properties

Cold IGM disfavored by HERA



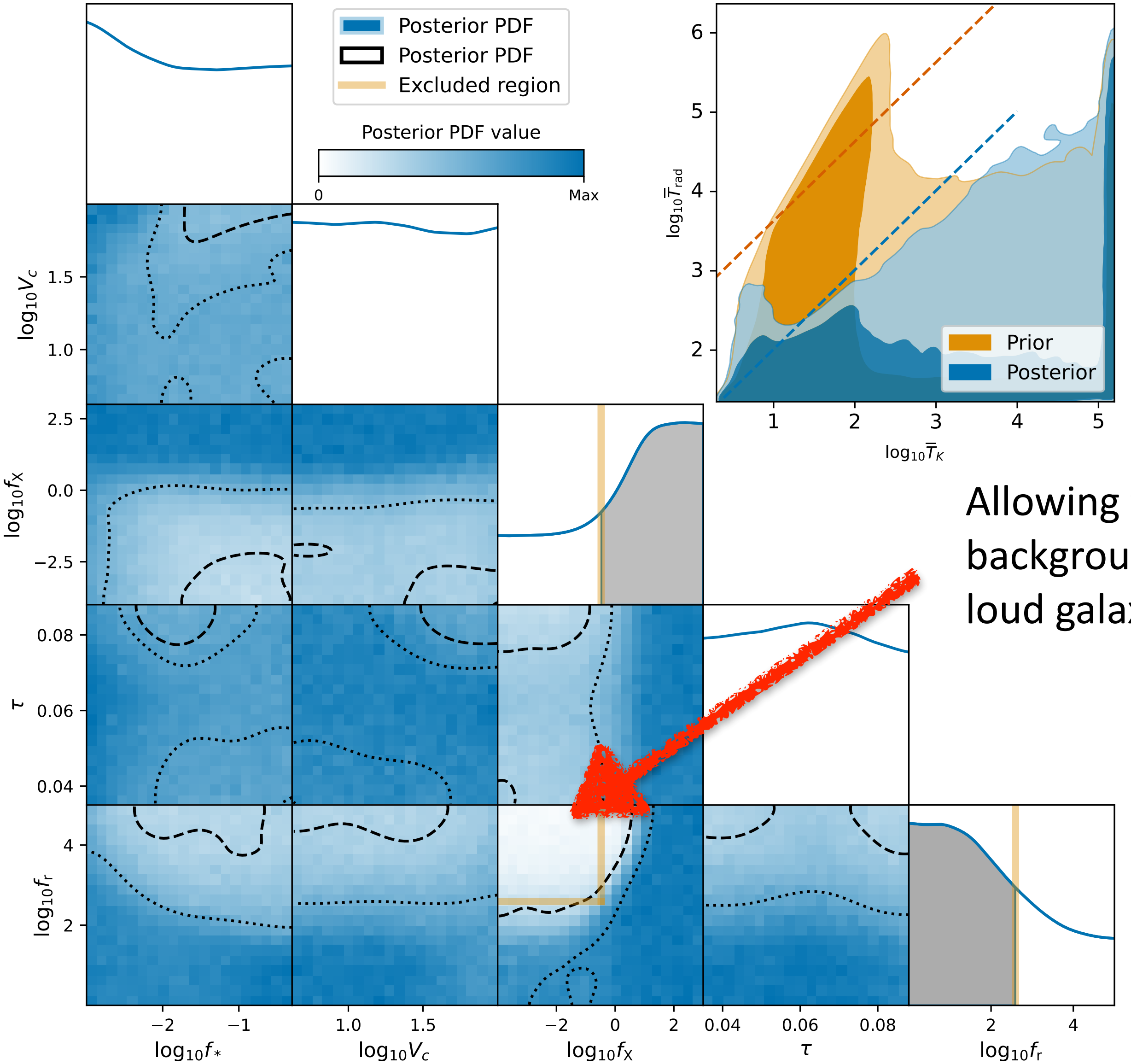
The HERA collaboration (2022a)

Extra-radio background

$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

If there is a radio background in excess of the CMB, signal can be larger!

Extra-radio background

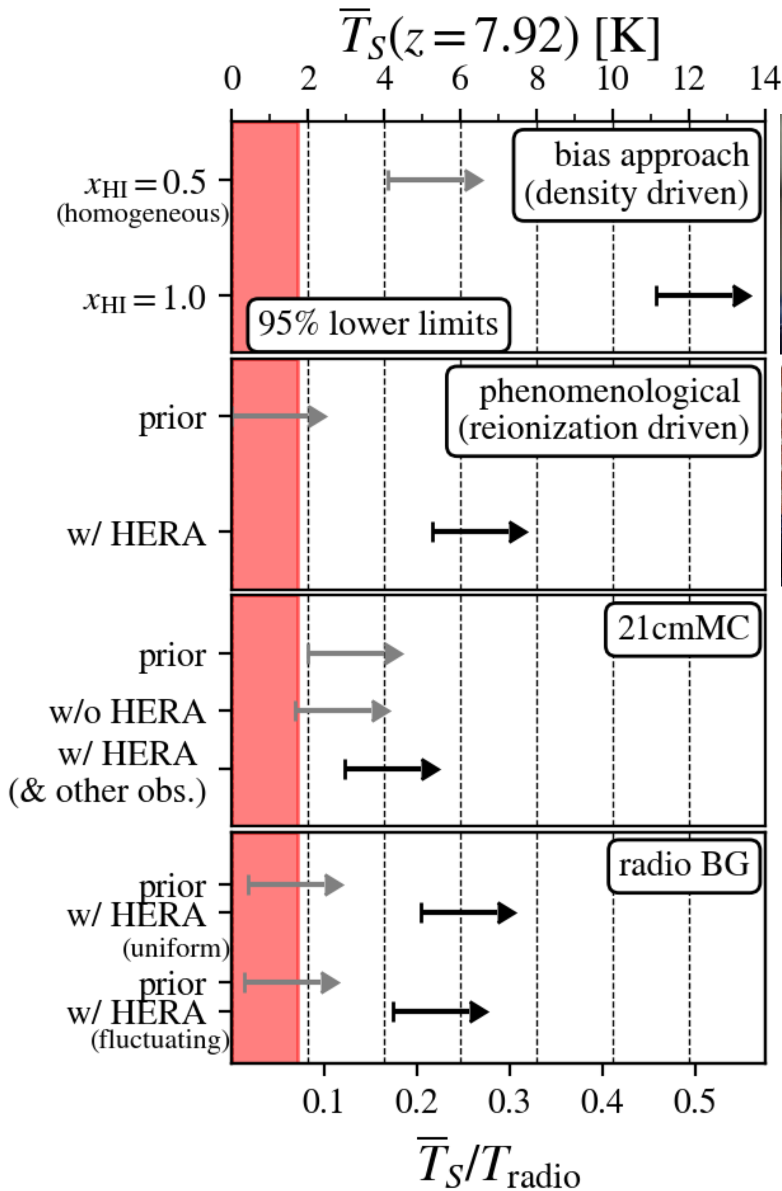


Allowing for a fluctuating extra radio background rules out Xray faint + radio loud galaxies

led by S. Heimersheim

The HERA collaboration (2022a)

Four independent analysis roughly agree on temperature constraints



led by Julian Munoz

led by Jordan Mirocha

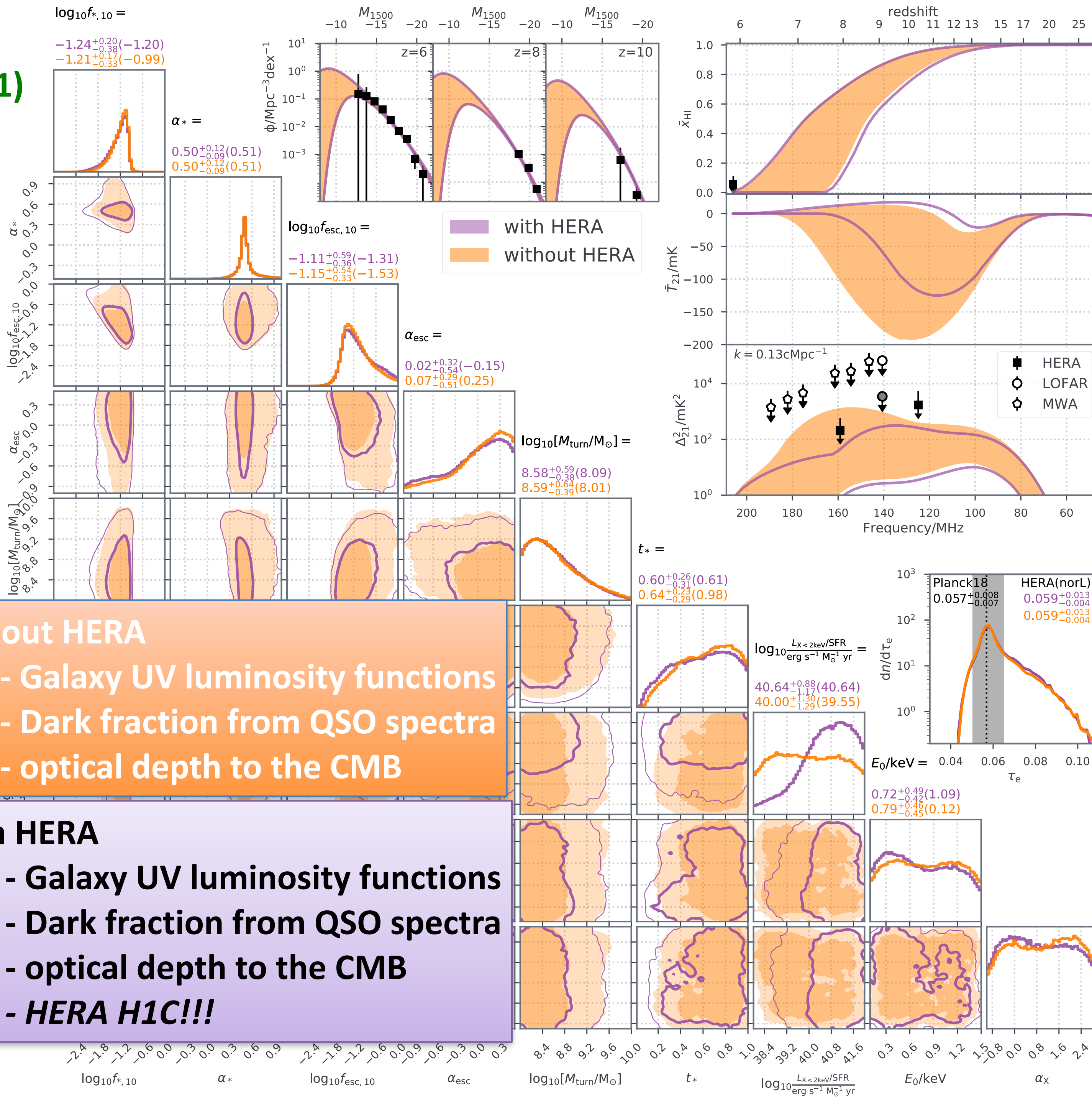
led by Yuxiang Qin

led by Stefan Heimersheim

pure adiabatic cooling is ruled out!!

What about galaxy properties?

HERA (2021)



Without HERA

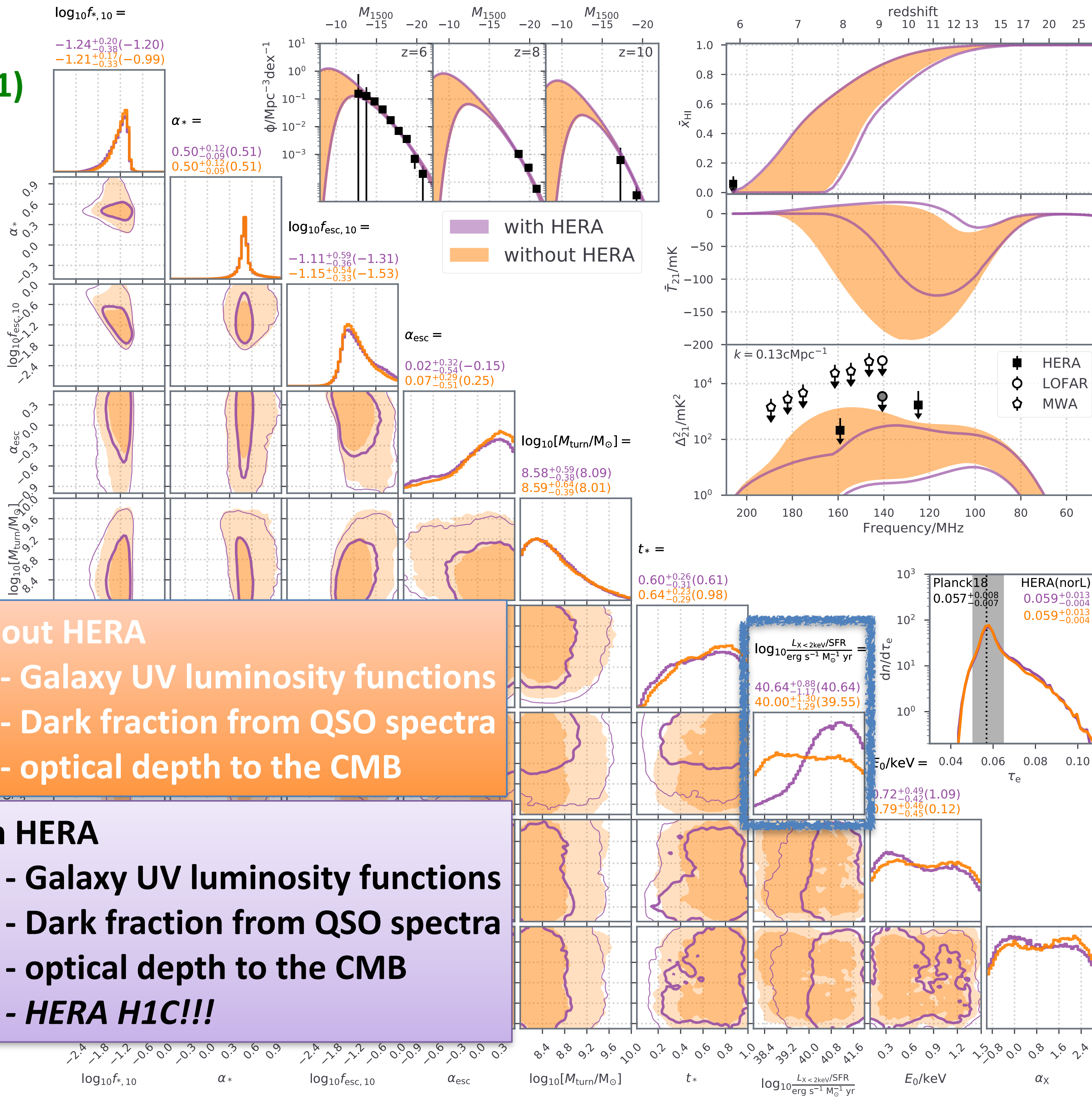
- Galaxy UV luminosity functions
- Dark fraction from QSO spectra
- optical depth to the CMB

With HERA

- Galaxy UV luminosity functions
- Dark fraction from QSO spectra
- optical depth to the CMB
- ***HERA H1C!!!***

led by Y. Qin

HERA (2021)

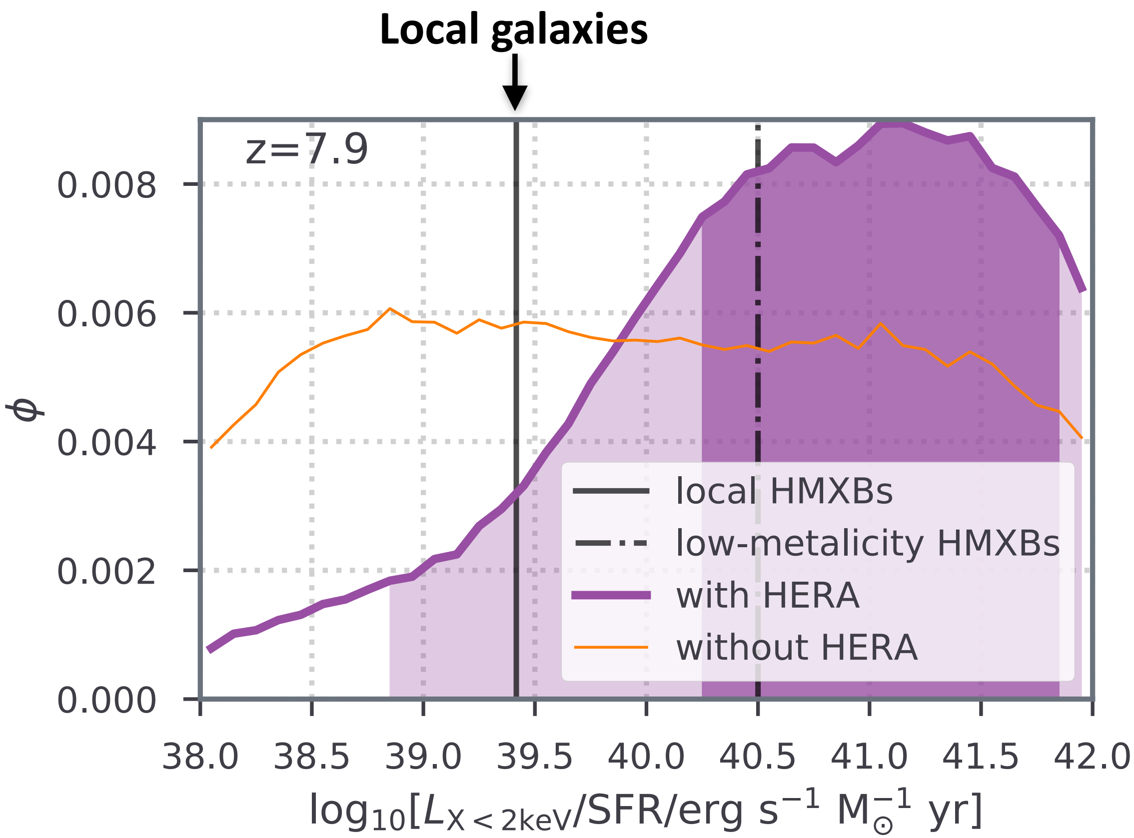


Without HERA
- Galaxy UV luminosity functions
- Dark fraction from QSO spectra
- optical depth to the CMB

With HERA
- Galaxy UV luminosity functions
- Dark fraction from QSO spectra
- optical depth to the CMB
- ***HERA H1C!!!***

led by Y. Qin

X-ray luminosity per unit SFR

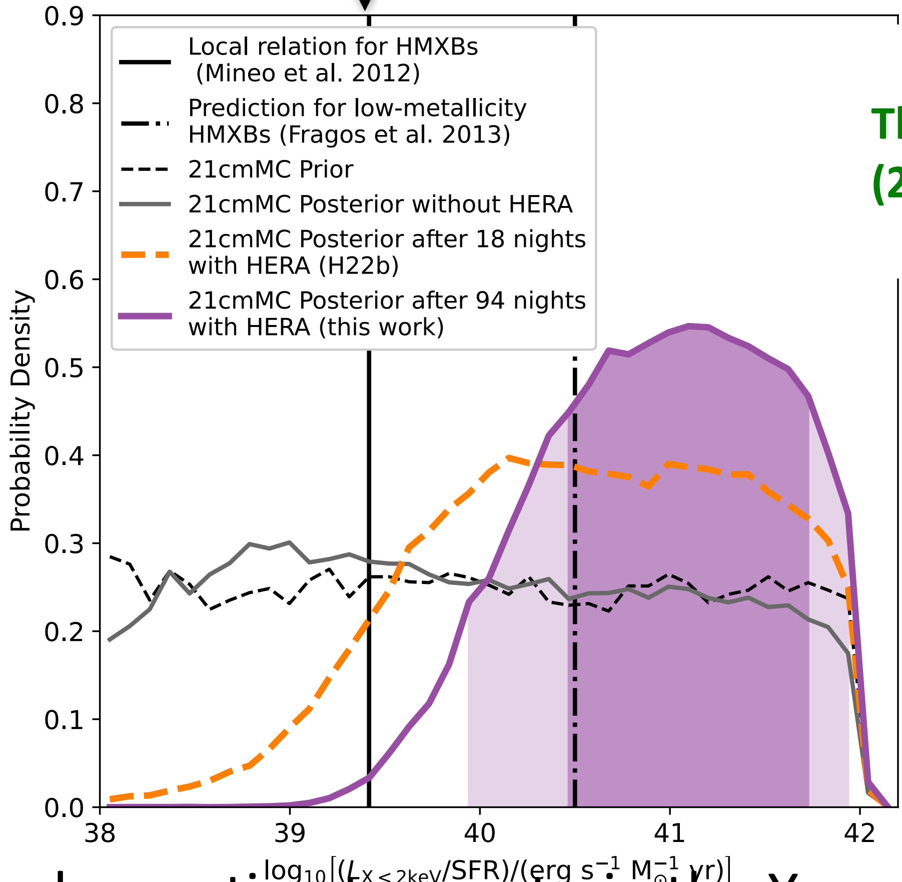


HERA is the first observation to constrain the X-ray luminosities of Cosmic Dawn galaxies (e.g., Fragos+13), *disfavoring the values seen in local, metal-enriched galaxies*

The HERA collaboration (2022a; led by N. Kern)

X-ray luminosity per unit SFR

Local galaxies



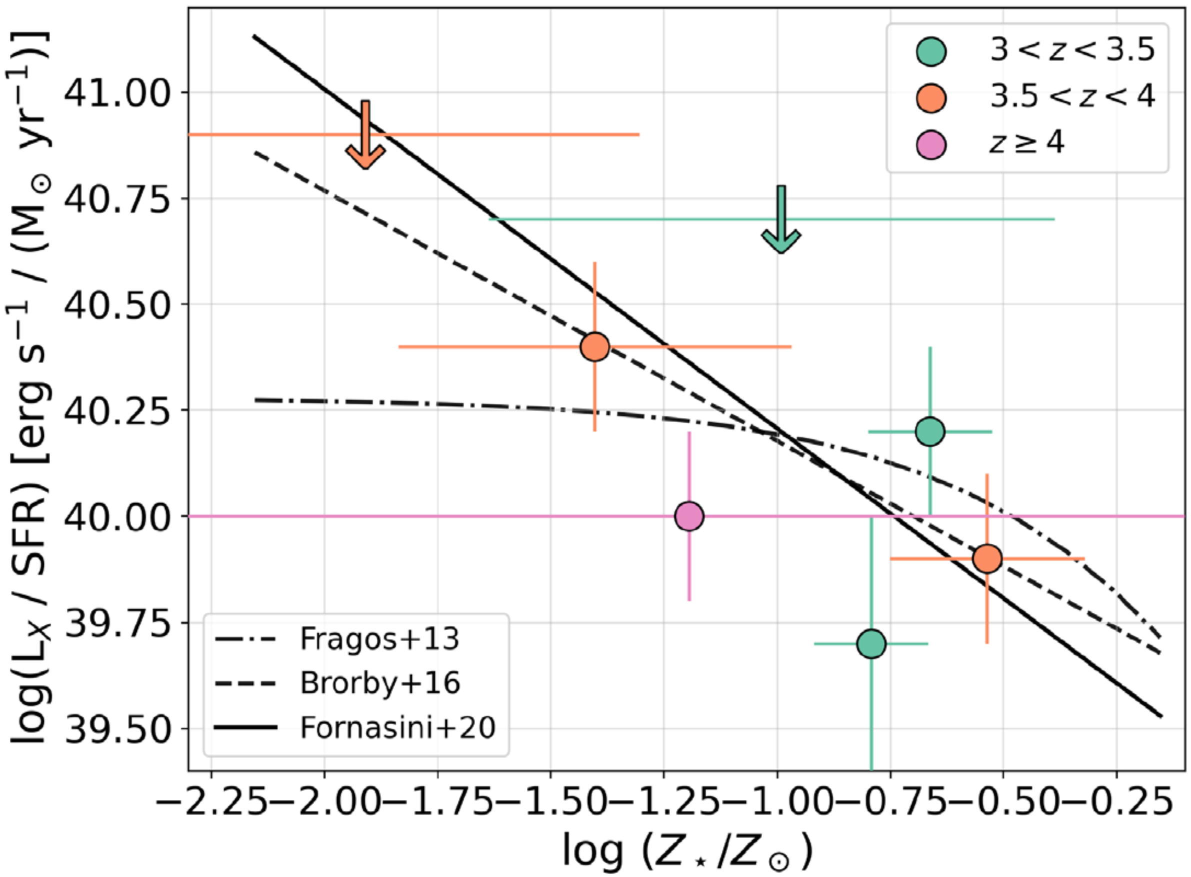
The HERA collaboration (2022b) - 94 nights of data

HERA is the first observation to constrain the X-ray luminosities of Cosmic Dawn galaxies (e.g., Fragos+13), *disfavoring the values seen in local, metal-enriched galaxies*

The HERA collaboration (2022b, *led by J. Dillon*)

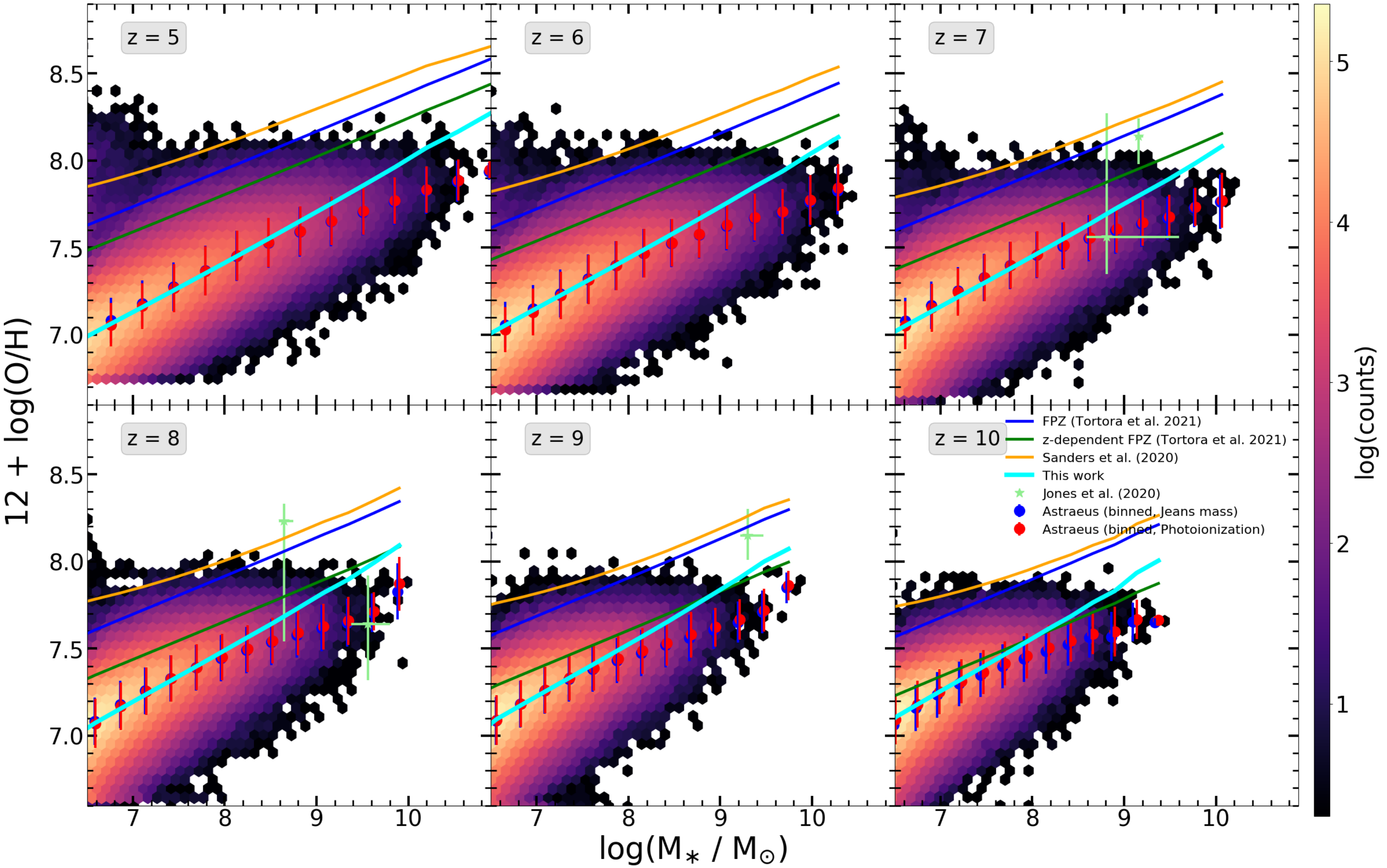
Is this surprising?

The Lx-SFR scaling of HMXBs depends on metalicity



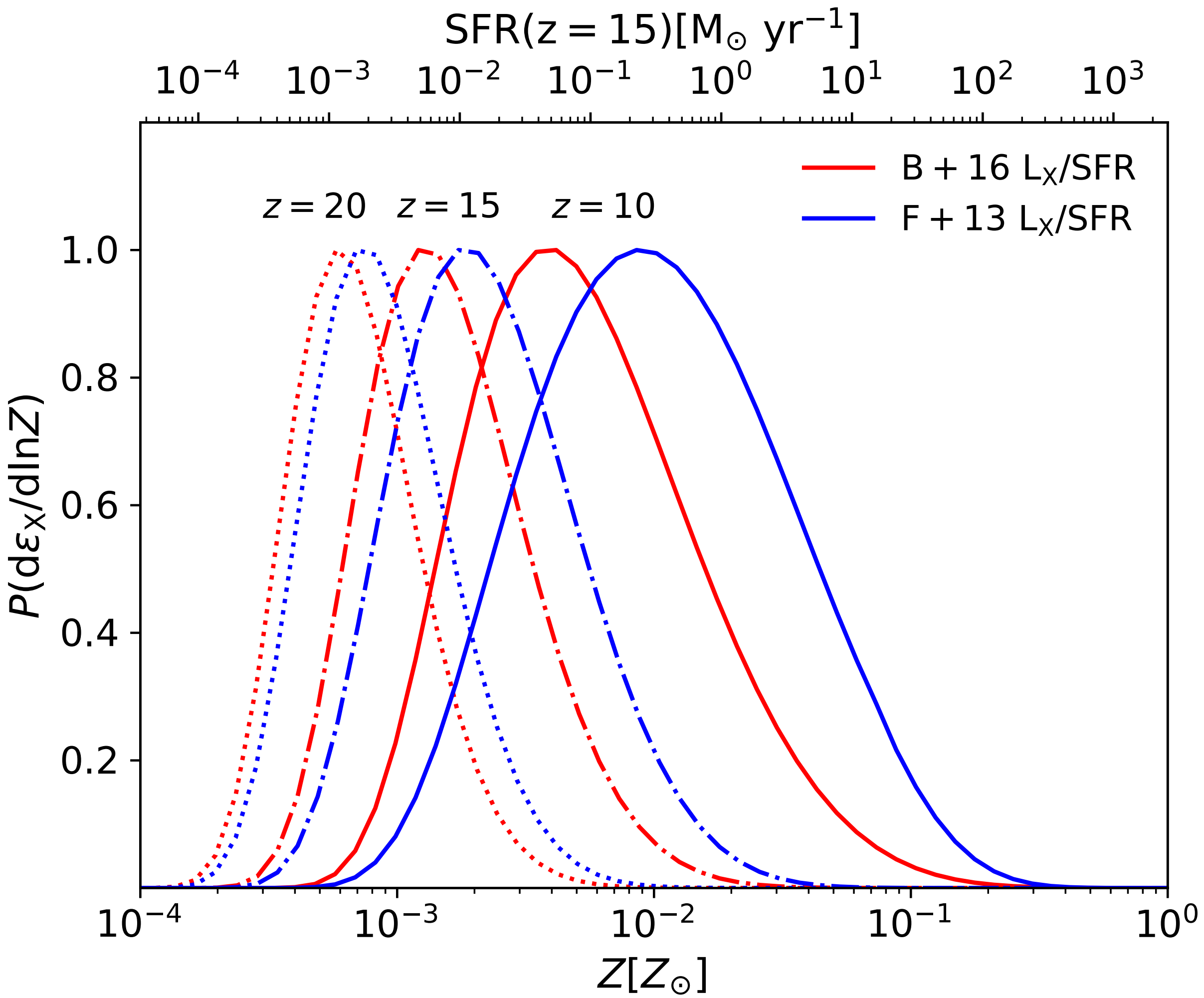
Saxoni+ (2022)

Metallicity evolves with galaxy mass



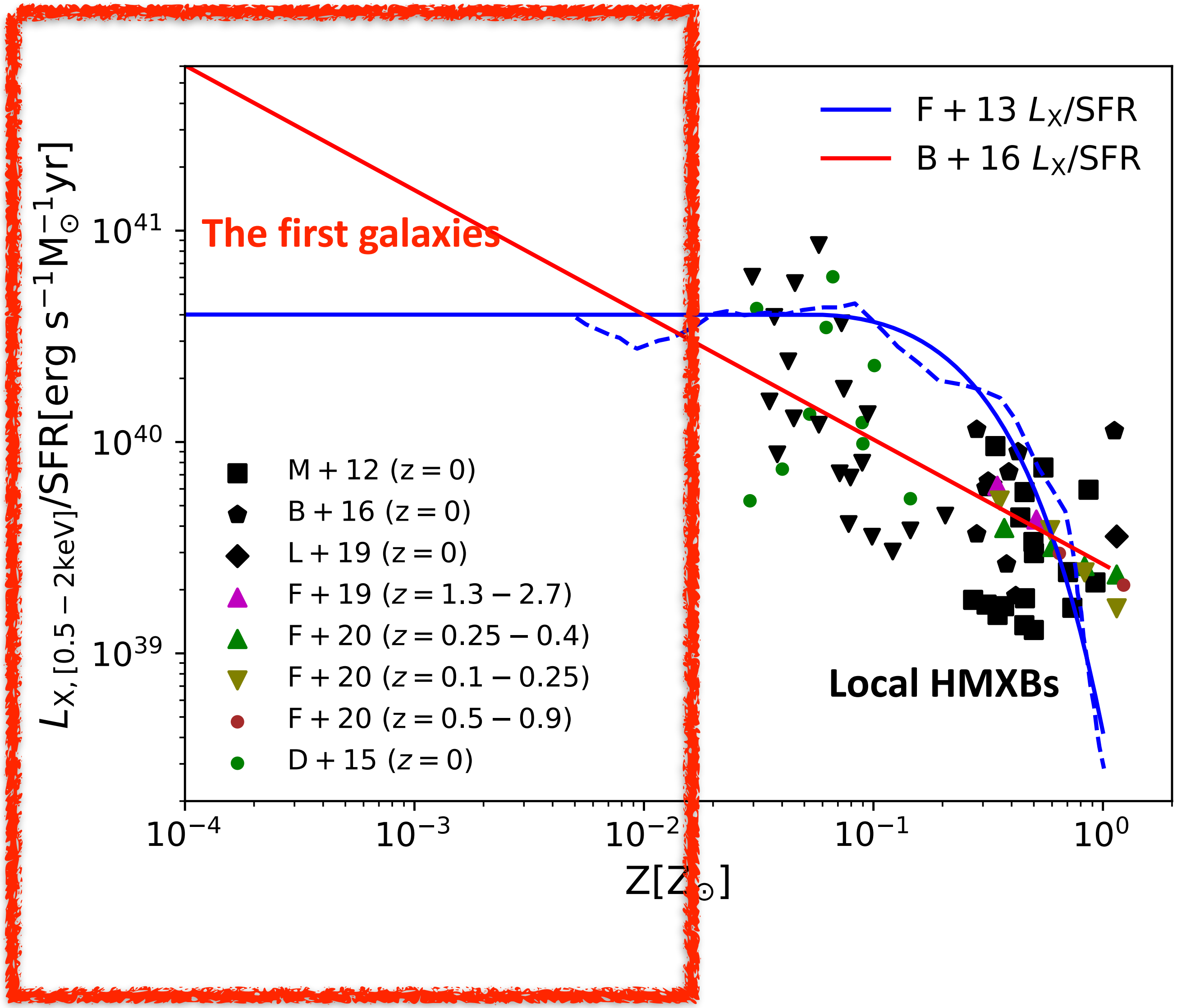
Ucci+ (2021)

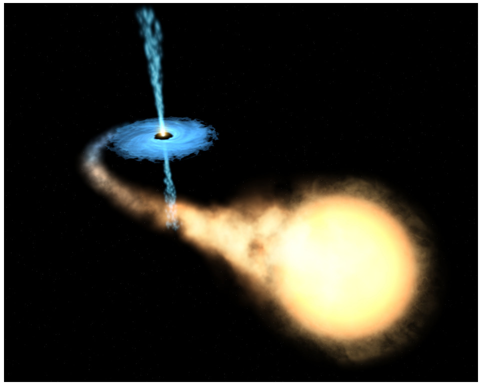
The 21-cm signal probes a new regime for HMXBs - ultra low mass, low metalicity



Kaur, Qin, AM+ (2022)

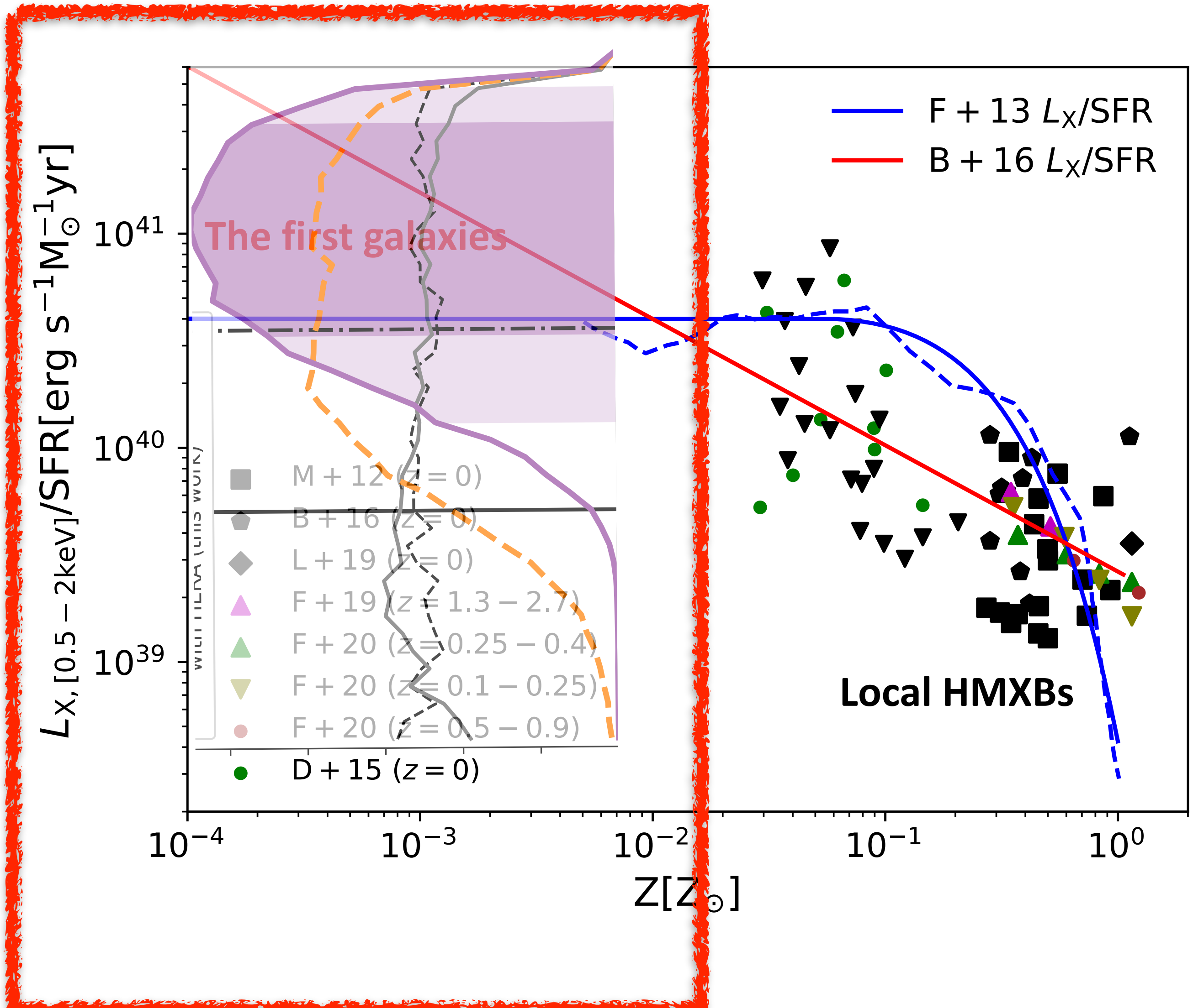
The 21-cm signal probes a new regime for HMXBs: *low mass galaxies + low metalicity*

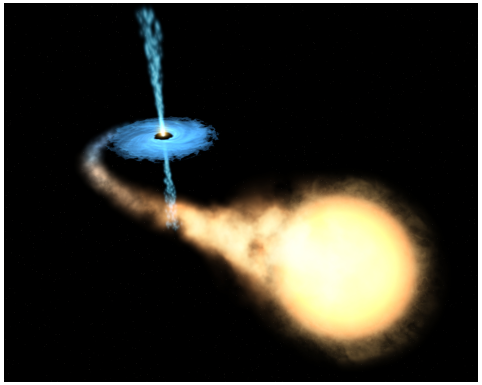




Kaur, Qin, AM+ (2022)

The 21-cm signal probes a new regime for HMXBs: *low mass galaxies + low metalicity*





Kaur, Qin, AM+ (2022)

Milestones

aka “The path to the 21-cm revolution”

Where we are now

Upper limits on the 21-cm power spectrum

Where we are now

Upper limits on the 21-cm power spectrum

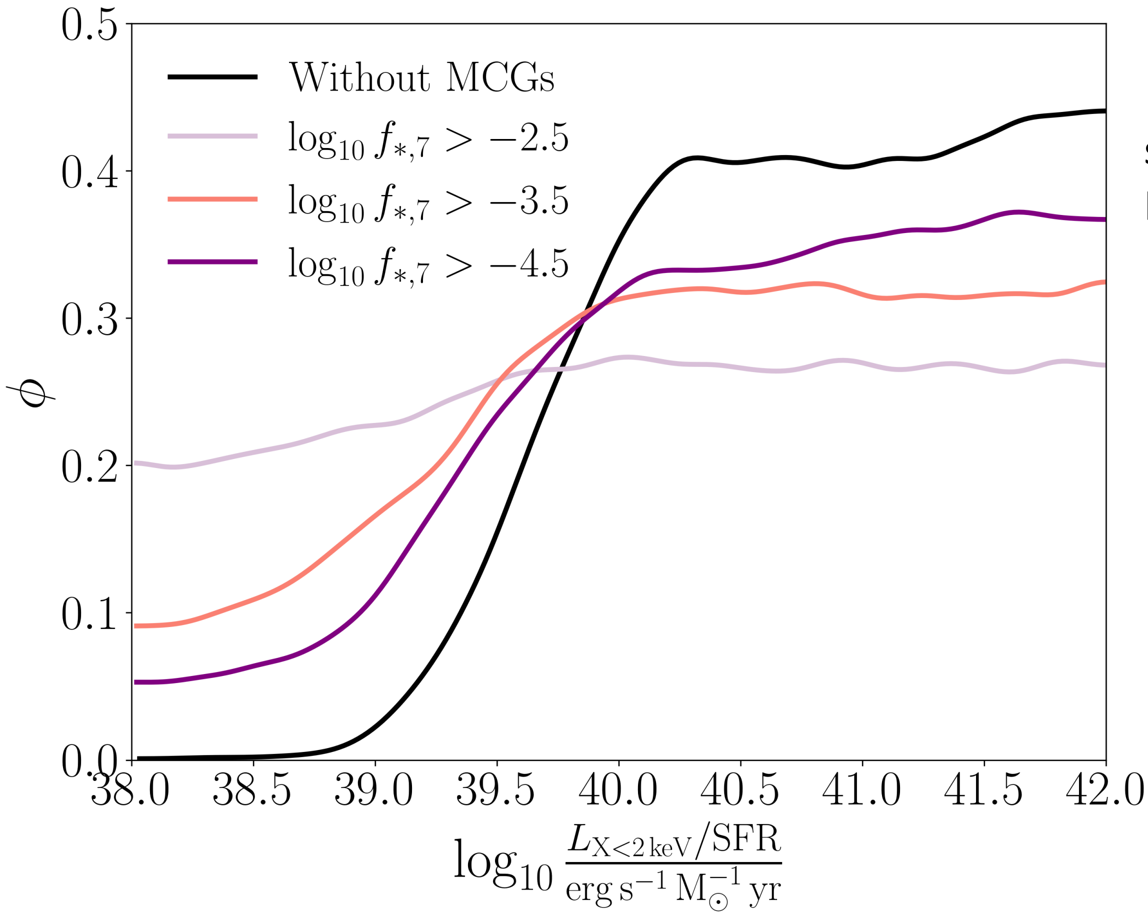
- *understand **systematics**! can we parametrize / sample our uncertainties?*

Where we are now

Upper limits on the 21-cm power spectrum

- *understand* ***systematics****! can we parametrize / sample our uncertainties?*
- *do we have all of the* ***physics*** *we need, especially regarding heating sources?*

Including a contribution from even earlier, molecularly-cooled galaxies (MCGs)?



Lazare+(2023)
see also Qin, AM+2021;
HERA 2022a

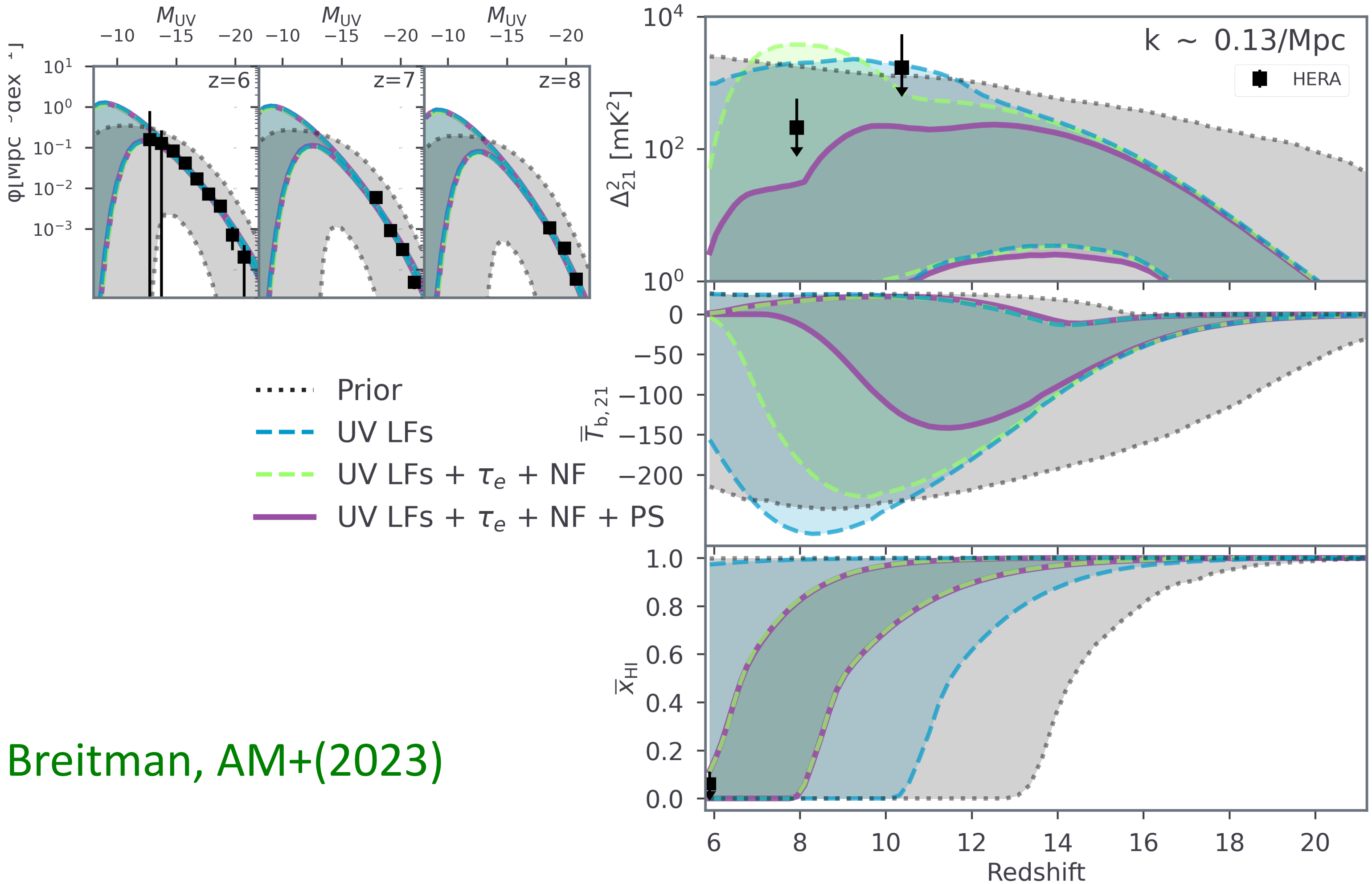
Constraints from HERA can weaken, though results depend strongly on priors

Where we are now

Upper limits on the 21-cm power spectrum

- *understand* ***systematics****! can we parametrize / sample our uncertainties?*
- *do we have all of the* ***physics*** *we need, especially regarding heating sources?*
- *posteriors will be* ***prior-dominated*** *UNLESS we have "realistic" galaxy models that can be constrained by other observations*

Contribution of different data



Breitman, AM+(2023)

Where we are now

Upper limits on the 21-cm power spectrum

- *understand **systematics**! can we parametrize / sample our uncertainties?*
- *do we have all of the **physics** we need, especially regarding heating sources?*
- *posteriors will be **prior-dominated** UNLESS we have "realistic" galaxy models that can be constrained by other observations*
- ***emulators** are useful! error is currently sub-dominant*

  (e.g. Kern+2017; Schmit & Pritchard 2017; Shimabukuro & Semelin 2017; Jennings+2019; Ghara+2020; Mondal+2022; Bye+2022a; Lazare+2023; Breitman+2023)

see talk by D. Breitman!

Where we will be soon

Low S/N detection of the 21-cm PS

Where we will be soon

Low S/N detection of the 21-cm PS

- *understand **systematics**! can we parametrize / sample our uncertainties?*

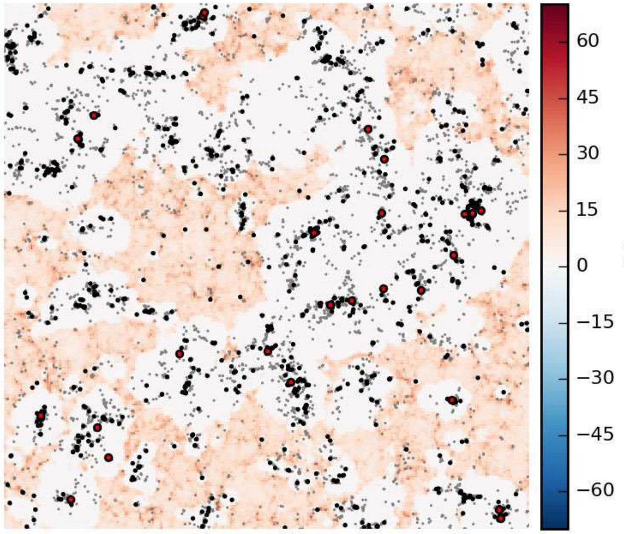
Where we will be soon

Low S/N detection of the 21-cm PS

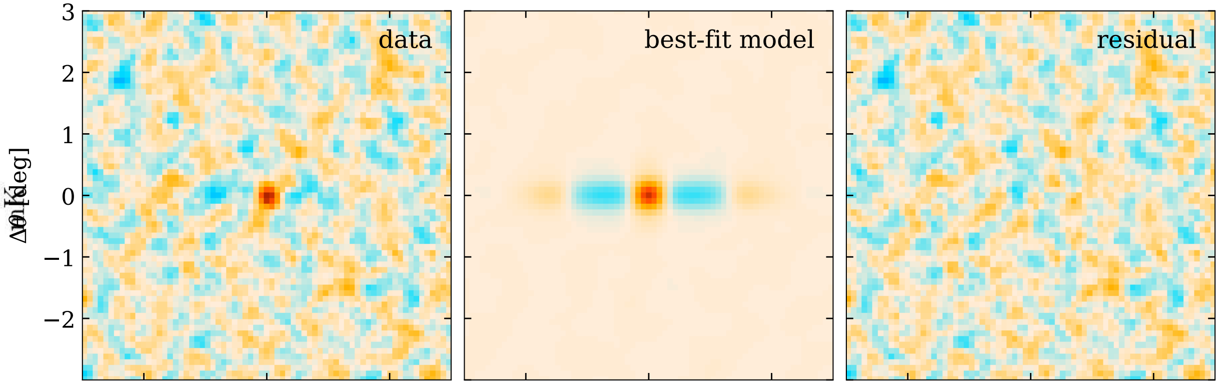
- *understand **systematics**! can we parametrize / sample our uncertainties?*
- *how can we convince ourselves and everyone else that the detection is **REAL —> cross-correlation with signal of known cosmic origin***

The importance of cross-correlations

- It is an important sanity check to verify claims of detection/analysis pipeline
- improves S/N for preliminary detections (systematics and noise are uncorrelated in cross)
- with images, it lets us study individual HII (or heated) regions, comparing them to their host galaxy properties



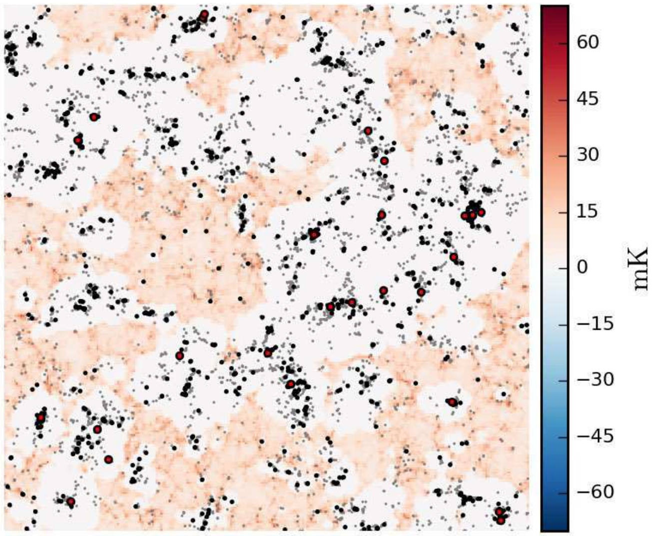
Moriwaki+2019



The CHIME collaboration 2022

The importance of cross-correlations

- It is an important sanity check to verify claims of detection/analysis pipeline
- improves S/N for preliminary detections (systematics and noise are uncorrelated in cross)
- with images, it lets us study individual HII (or heated) regions, comparing them to their host galaxy properties



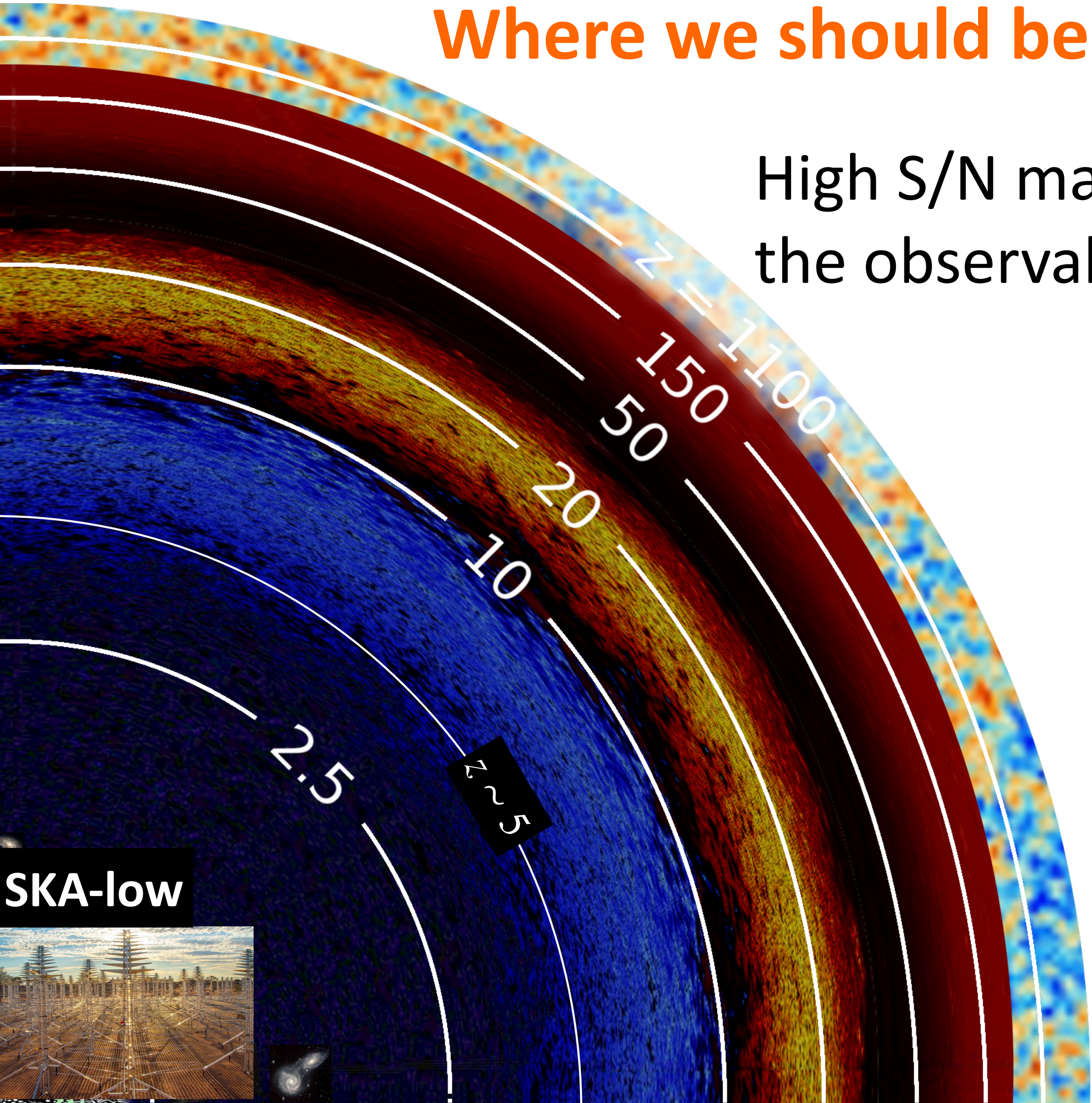
Moriwaki+2019

see talk by S. Gagnon-Hartman

Signals to cross with 21cm during EoR/CD

1. **Cosmic Backgrounds** (difficult to get good S/N because signal integrates over redshift)
   - (i) CMB (e.g. kSZ with SPT/ACT/SO; e.g. Ma+2018; LaPlante+2022)
   - (ii) NIR (e.g. CIBERII Mao 2014)
   - (iii) XRB (Athena) e.g. Ma+2018
2. Resolved **Galaxies** (need wide and deep, and redshifts to better than percent precision-> grism or multi-object spectroscopy)
   - (i) ROMAN grism (e.g. Vrbanec+2020; LaPlante+2023)
   - (ii) SUBARU narrow-band (e.g. Sobacchi+ 2016; Vrbanec+2020; Hutter+2017; Kubota+ 2020; Heneka & Mesinger 2020);
   - (iii) SUBARU spectroscopy with PFS
   - (iv) ELT spectroscopy
3. **Intensity mapping** (best footprint overlap; signal is generally faint at z>6)
   - (i) Lya - SPHEREx (e.g. Heneka & Cooray 2021) CDIM (Cooray+2016)
   - (ii) OIII - SPHEREx (Kana+ 2019; Moriwaki+2019; Schengqi+2021)
   - (iii) CII - CONCERTO (Lagache+2017), TIME-Pilot (Crites+2014), CCAT-prime (Parshley+2018)

Where we should be >2030-2040



High S/N map of ~50% of the observable Universe

adapted from C. Chiang

The Square Kilometer Array is coming

Timing of major science milestones

Milestone event (earliest)		SKA-Mid (end date)	SKA-Low (end date)
AA0.5	4 dishes 6 stations	2024 Dec	2024 Aug
AA1	8 dishes 18 stations	2025 Nov	2025 Oct
AA2	64 dishes 64 stations	2026 Oct	2026 Sep
AA*	144 dishes 307 stations	2027 Aug	2028 Jan
Operations Readiness Review		2027 Nov	2028 Apr
End of staged delivery programme		2028 Jul	2028 Jul
AA4	197 dishes 512 stations	TBD	TBD

Pre science Verification
- SRCs not needed to support commissioning
- Opportunity for testing (data, transfer, access, pipelines)!

Science Verification
- Data immediately public
- Full dress rehearsal!
- Some SRCNet resources for analysis would be an advantage
- Observed as trickle but also in dedicated blocks

Cycle 0
- "Proper" shared risk projects
- Teams, proprietary periods, visualisation, ADP creation etc

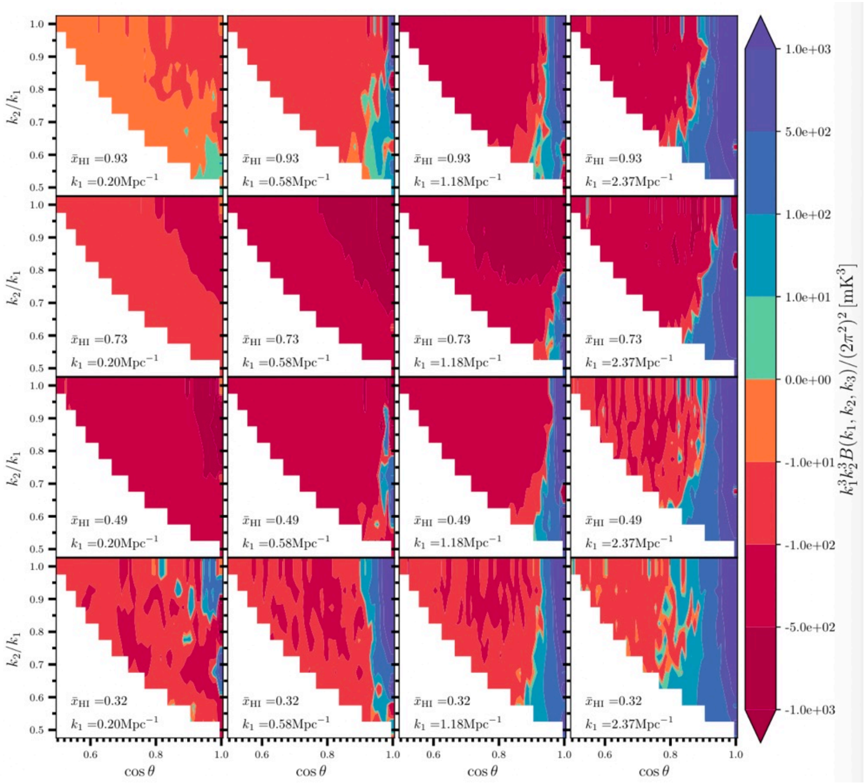
*Data product rollout is somewhat predictable in the earlier periods (follows a rollout plan) - could become useful for planning.

slide courtesy R. Braun

Where we should be >2030-2040

High S/N map with the SKA

- *optimal compression of **non-Gaussian** signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*



e.g. Watkinson+2017 (see also, e.g. Majumdan+2020; Chen+2019; Giri&Mellema2021; Kamran+2023..)

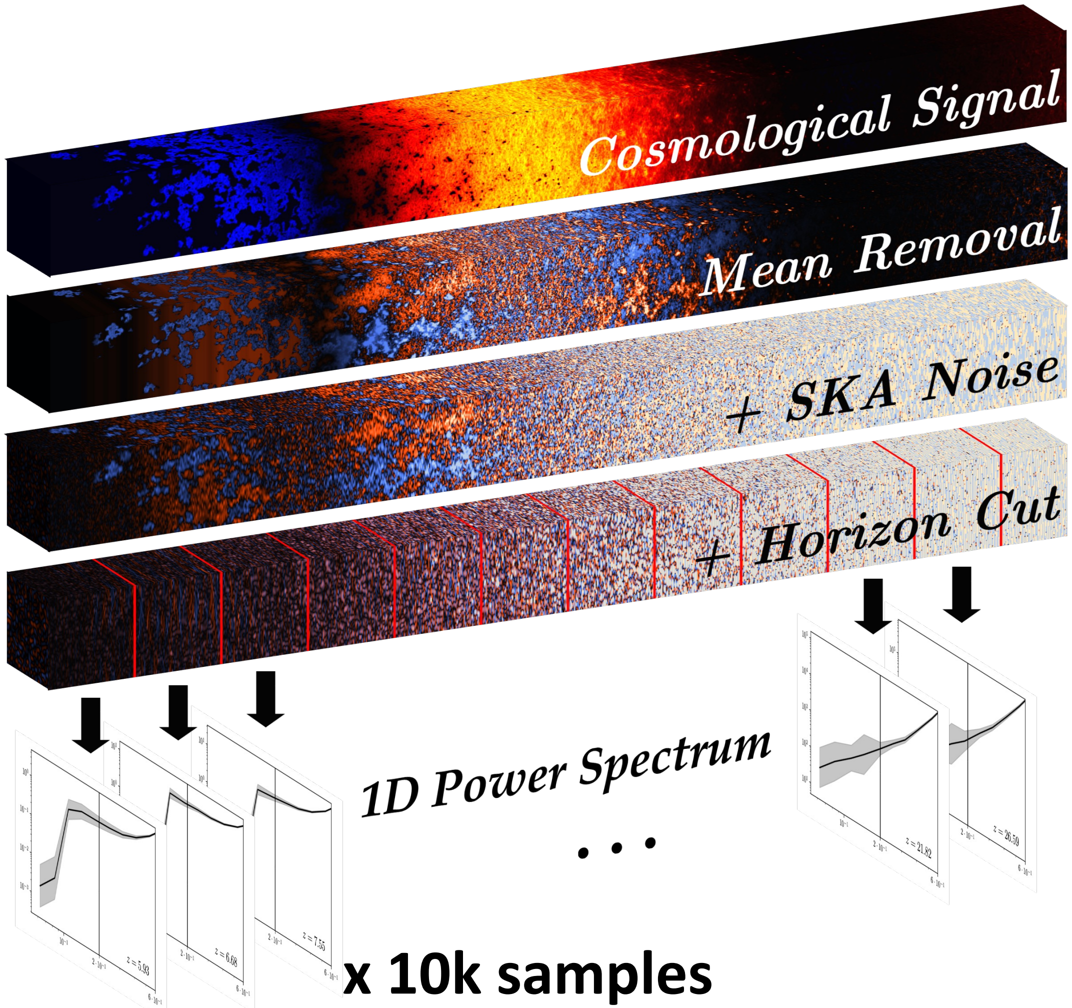
Where we should be >2030-2040

High S/N map with the SKA

- *optimal compression of **non-Gaussian** signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*
- *do we actually know the likelihood analytically? —> **Simulation Based Inference (SBI)***

Simulation Based Inference (SBI)

Precompute database **of forward models (varying cosmic ICs, noise, etc.) and** ***train density estimators*** **to fit the likelihood.**



x 10k samples

Prelogović & AM (2023)

see also
Zhao+2022ab, Saxena+2023

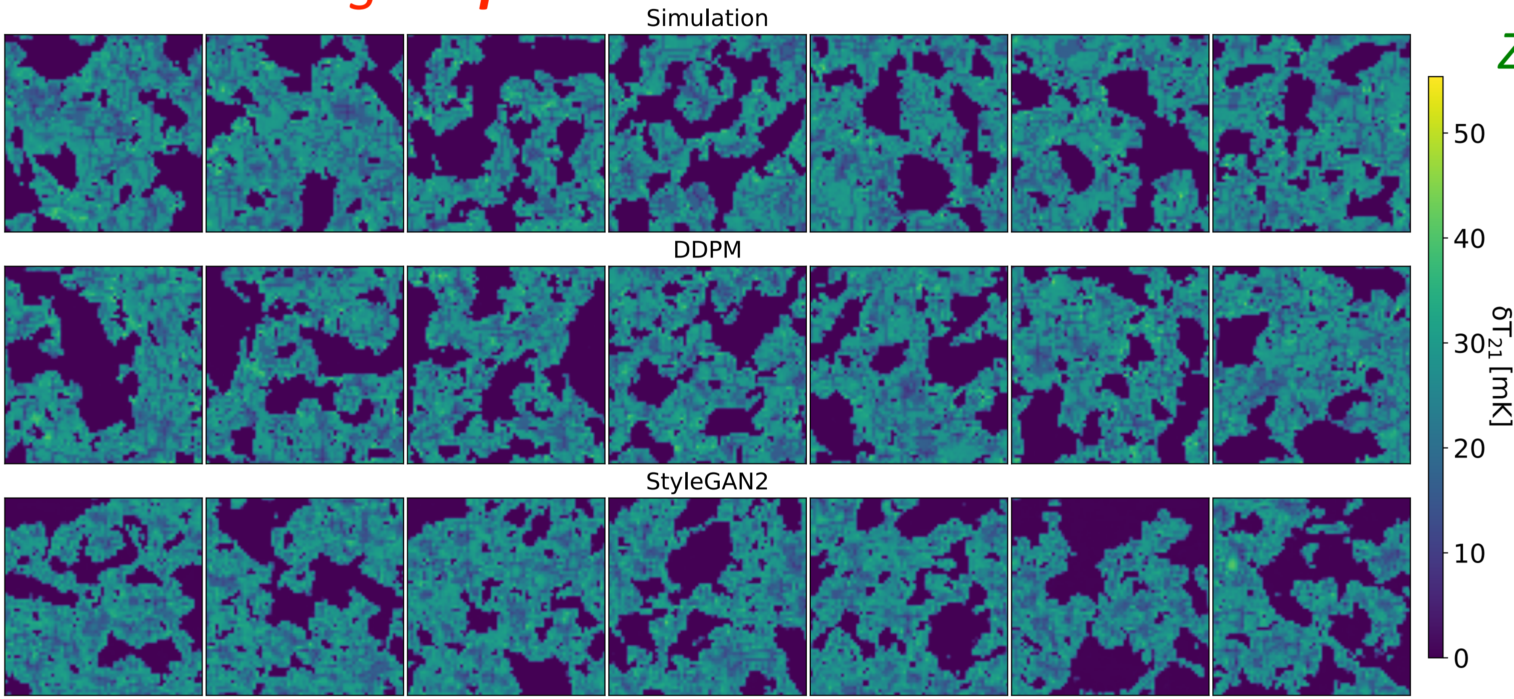
see talks by D. Prelogović and A. Saxena

Where we should be >2030-2040

High S/N map with the SKA

- *optimal compression of **non-Gaussian** signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*
- *do we actually know the likelihood analytically? —> **Simulation Based Inference (SBI)***
- *emulating **maps***

Zhao+ (2023)

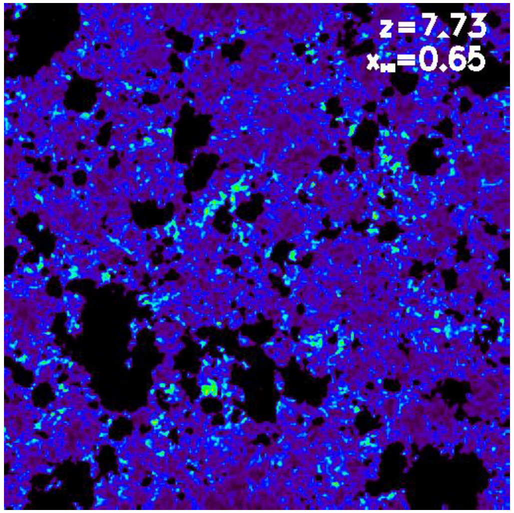


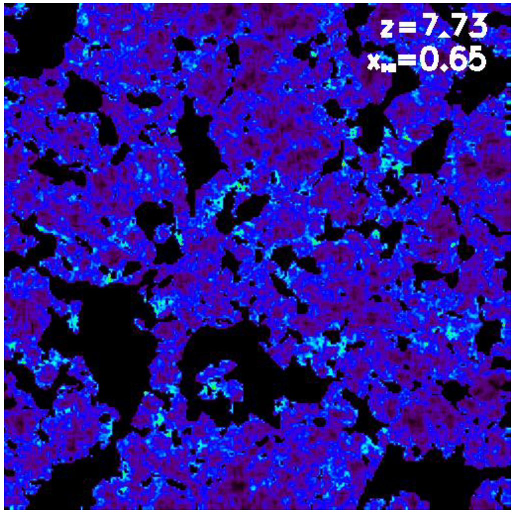
Where we should be >2030-2040

High S/N map with the SKA

- *optimal compression of **non-Gaussian** signal (e.g. bispectrum, Minkowski functionals, wavelets, data-driven compression…)*
- *do we actually know the likelihood analytically? —>* ***Simulation Based Inference (SBI)***
- *emulating **maps***
- *how well do we trust our **simulators** (analytic, semi-numeric, moment-based RT, ray tracing, hydro…)**??***

AM+ (2011)





Conclusions

- The cosmic 21cm signal will allow us to learn the **average UV and Xray properties of the first galaxies** as well **physical cosmology.**
- There are current claims of a detection/non-detection of the **global signal**.
- **Upper limits** on the 21-cm power spectrum by LOFAR, MWA and HERA imply some **heating of the IGM by z>10**.
- If heating is provided by high mass X-ray binary stars, they are likely **more luminous** then local ones, likely due to their **low-metallicities**.
- Future detections will need **cross-correlations** with signals of known origin in order to be believed.
- **High S/N maps** of half of our observable Universe should be enabled by the **SKA** over the next couple of decades, ushering in a Big Data revolution