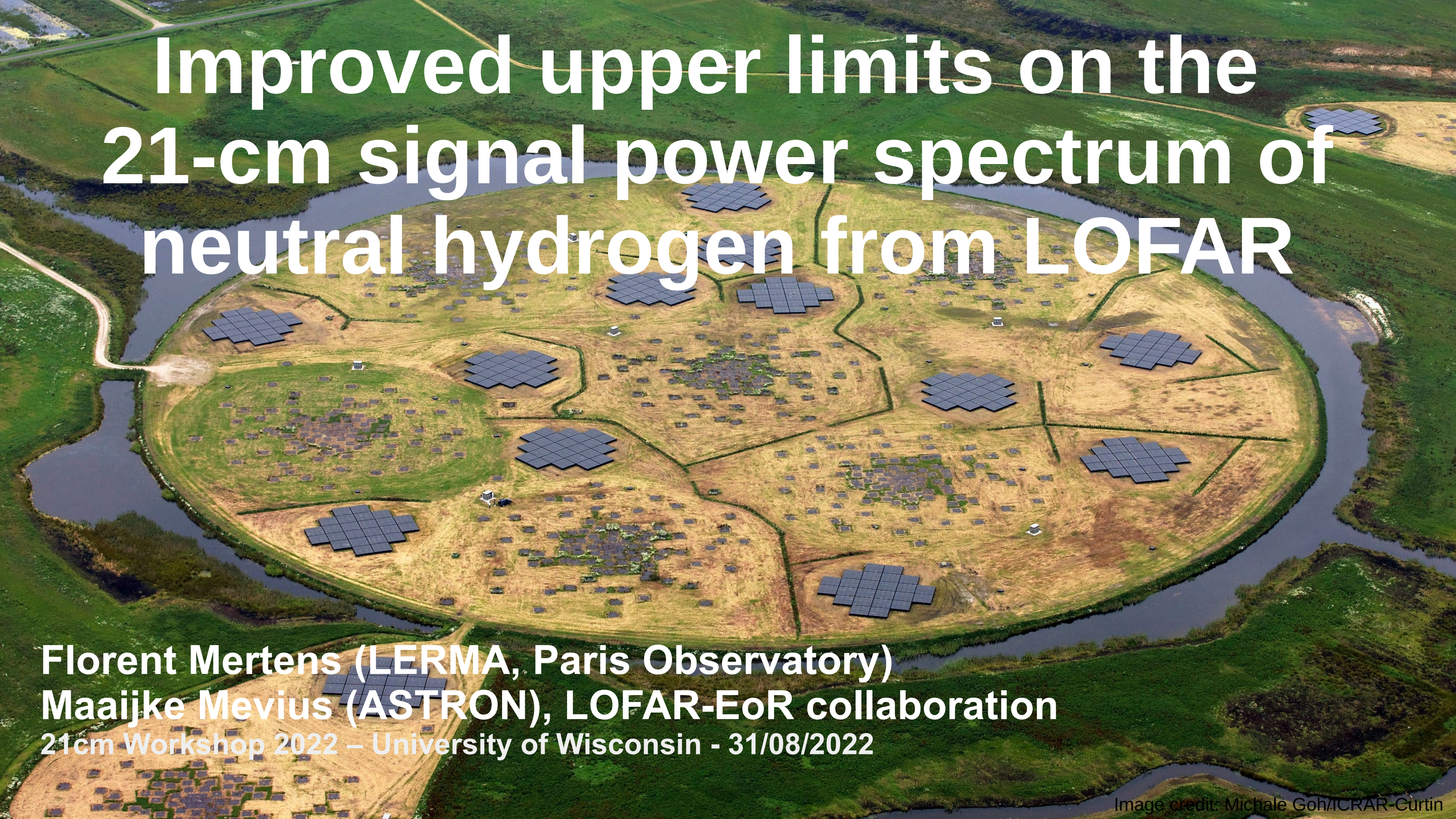
Improved upper limits on the 21-cm signal power spectrum of neutral hydrogen from LOFAR



Florent Mertens (LERMA, Paris Observatory)
Maaijke Mevius (ASTRON), LOFAR-EoR collaboration
21cm Workshop 2022 – University of Wisconsin - 31/08/2022

Image credit: Michale Goh/ICRAR-Curtin

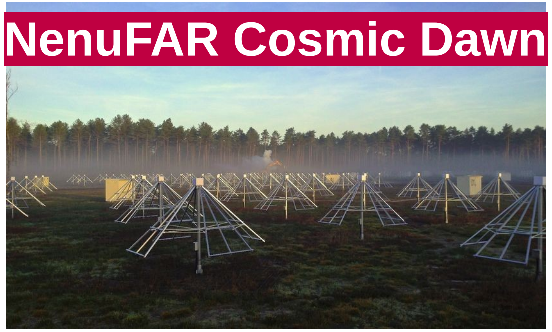
The LOFAR-EoR team

LOFAR-EoR plenary 2019 - Groningen

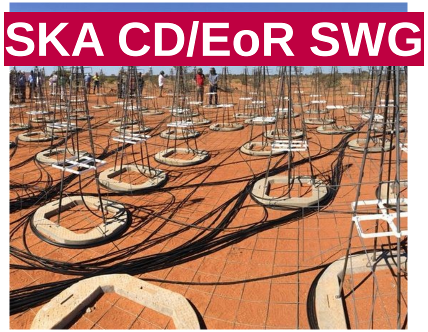
LOFAR-EoR plenary 2022 - Paris

21-cm experiments

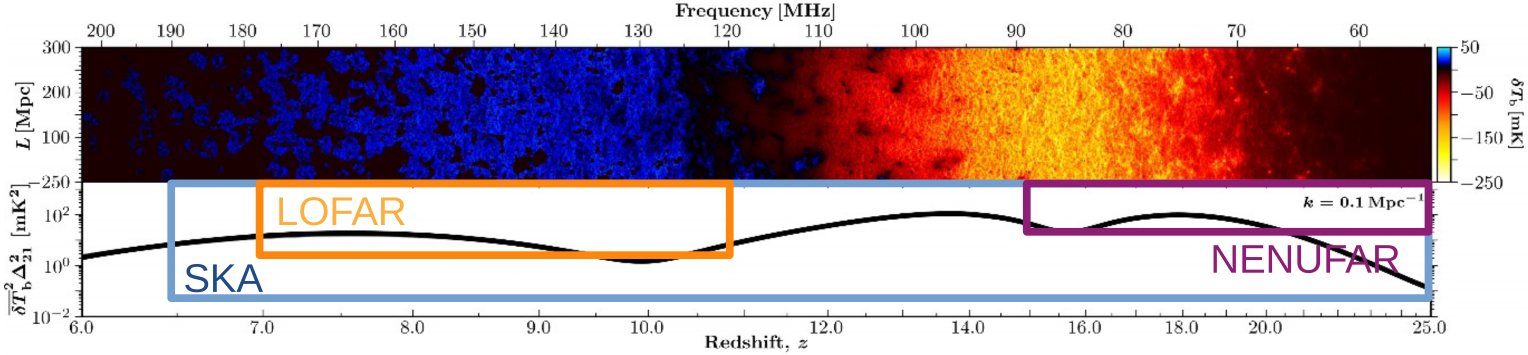
LOFAR-HBA
The Netherlands
z ~ 7 – 11
+ 2000 h observed
Patil et al. 2017
Mertens et al. 2020



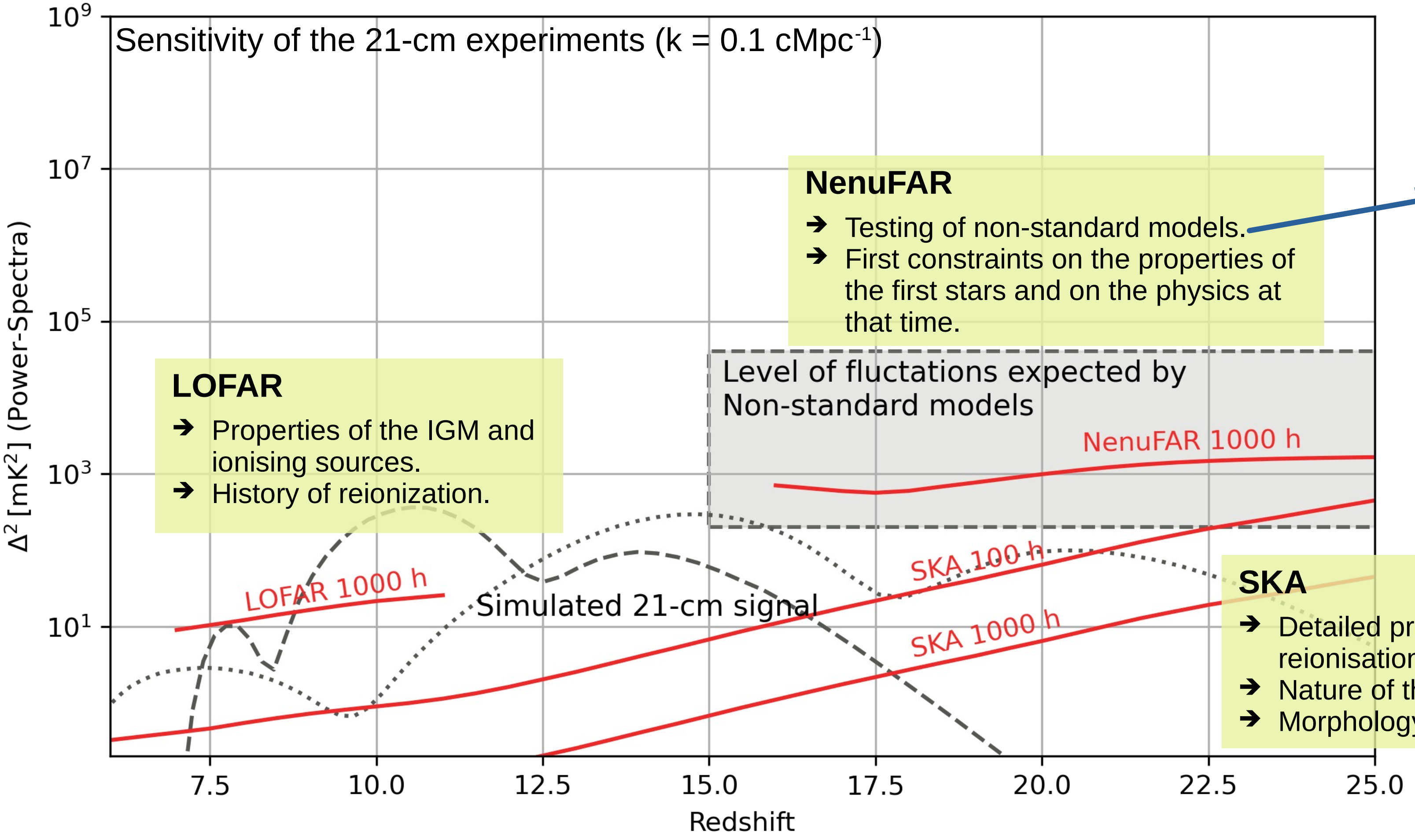
NENUFAR
France
z ~ 16 – 30
Target: ~ 1000 h
Mertens et al. in prep.
Munshi et al. in prep.

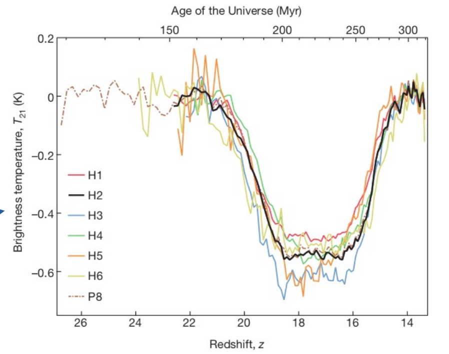


SKA-LOW
Western Australia
z ~ 6 – 25



The Science of the EoR and Cosmic Dawn

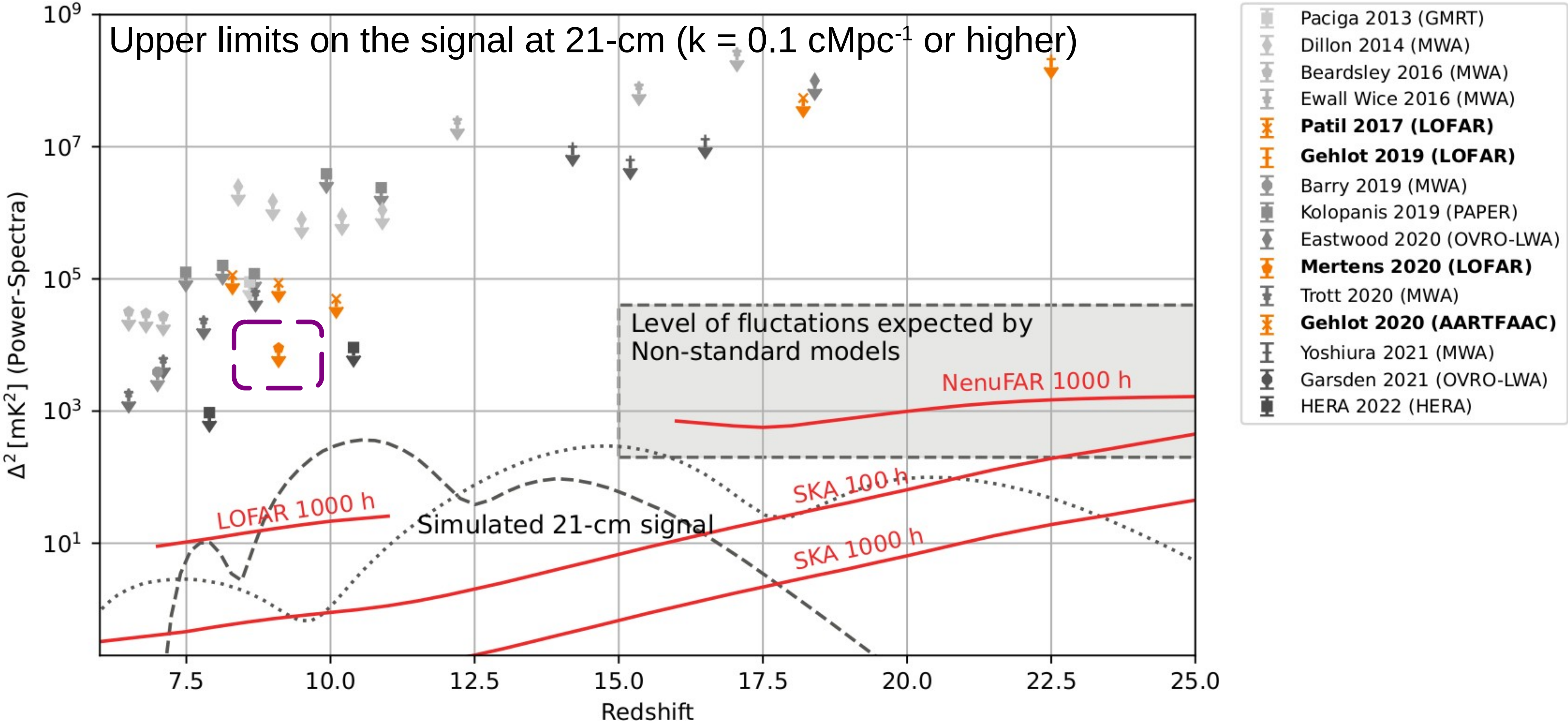




21-cm absorption profile observed by EDGES (Bowman et al., Nature 2018

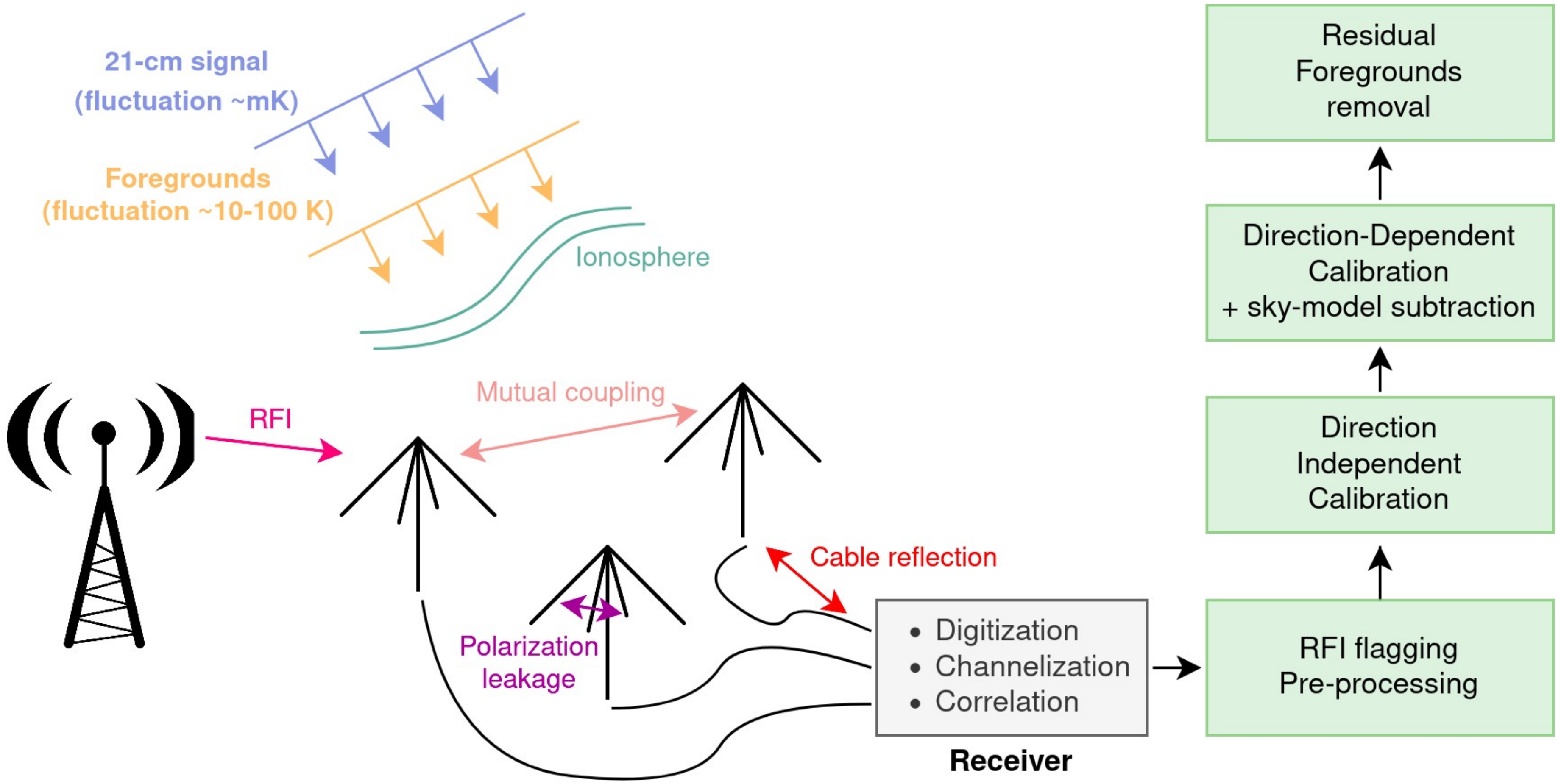
Grey dotted lines: expected signal fluctuations at 21 cm according to simulations.

Progress towards a signal detection



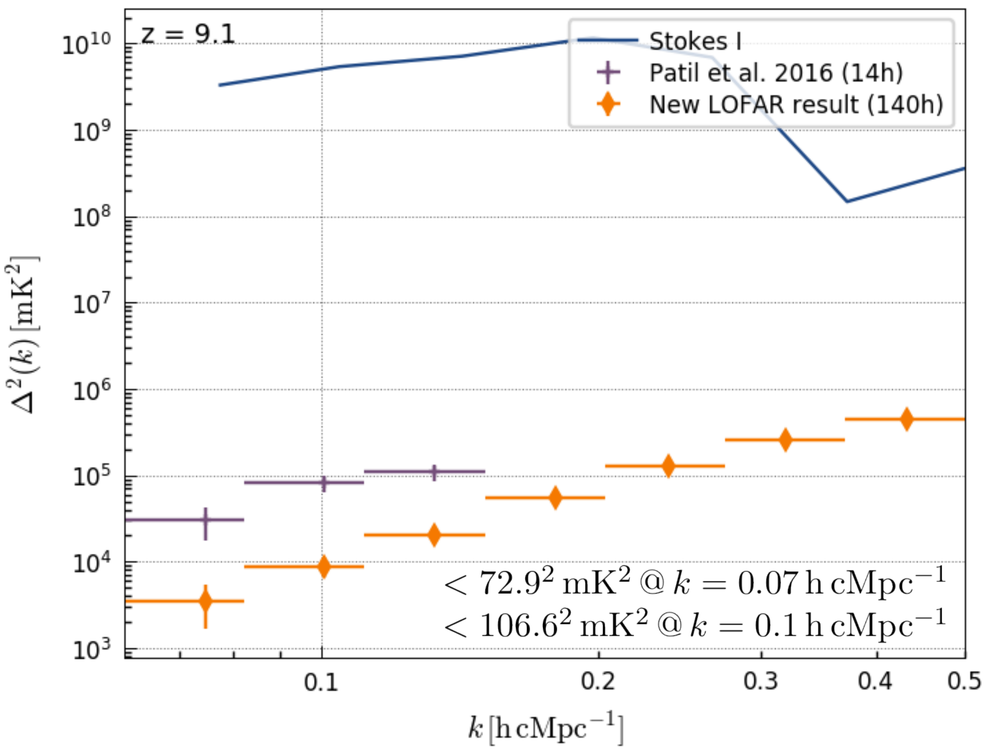
Orange marks: LOFAR & AARTFAAC upper limits

A challenging experiment

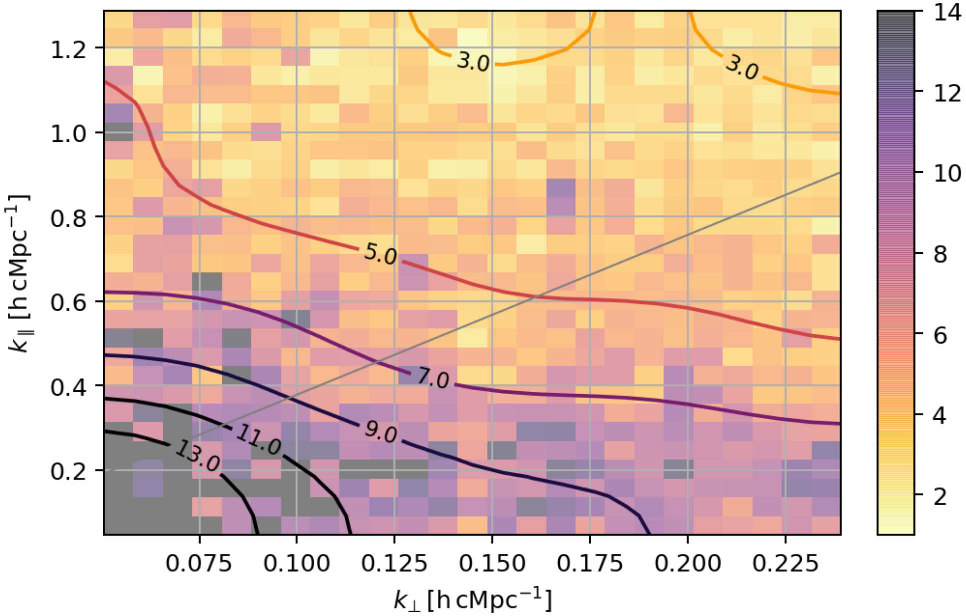


Current LOFAR upper limit at z~9

NCP field, 140 hours, 134-146 MHz, z ~ 9.1



PS ratio Stokes I residual / thermal noise



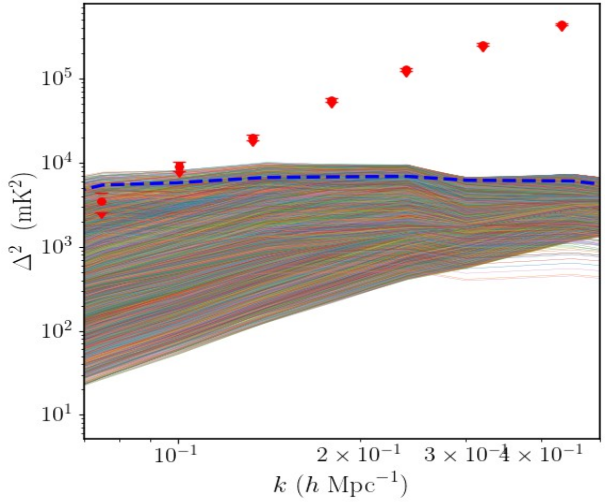
A reduction by a factor ~ 10 compared to our previous upper limit, the deepest at z ~ 9 ...

... but still affected by large excess power.

(Mertens et al. 2020)

Astrophysical interpretations of the upper limit

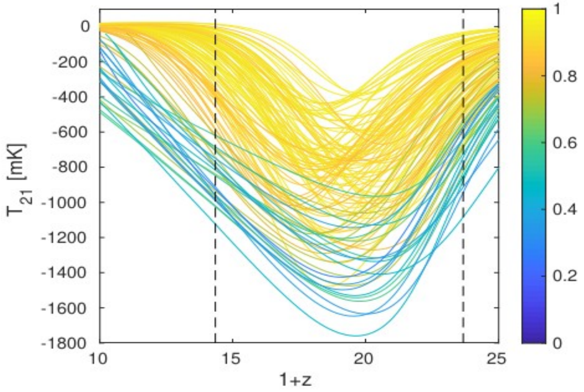
Constraining the IGM during the EoR (Ghara et al. 2020)



Discard several scenarii with **cold** IGM models (large emission regions, high UV photon emission rate).

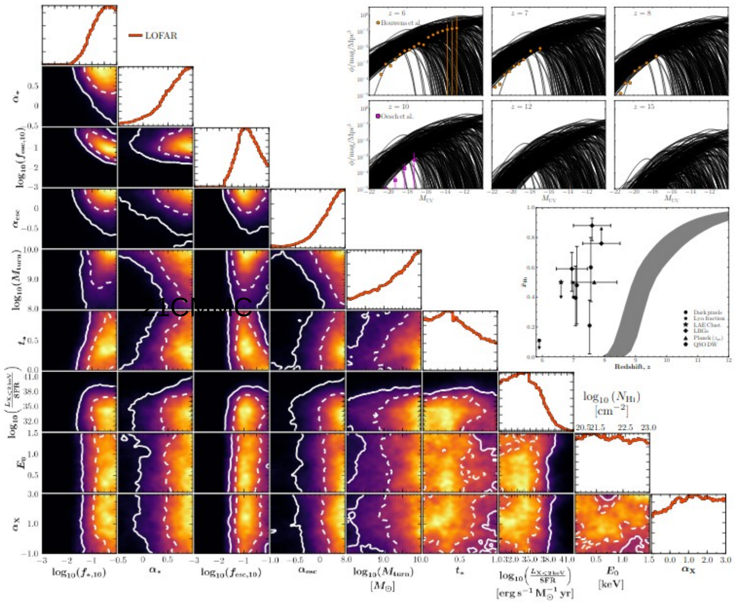
Constraint on the excess radio background (Mondal et al. 2020)

Global signal models.
Yellow to blue: likely to less likely model.



Discard excess radio background < 9.6 % CMB at 1.42 GHz but excess level could still explain the EDGES detection

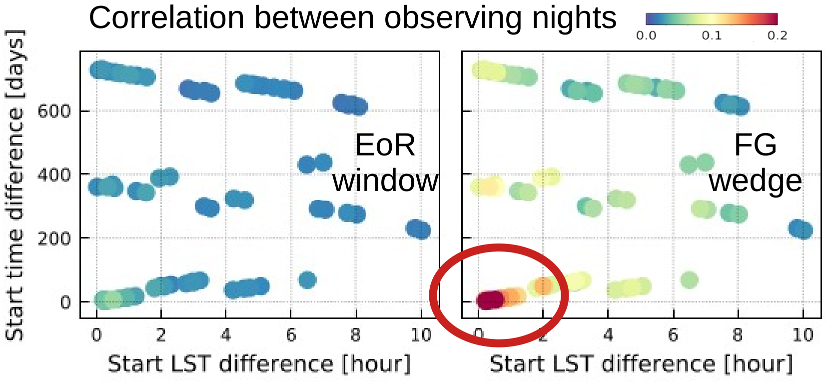
Constraint on the properties of the high-z galaxies (Greig et al. 2021)



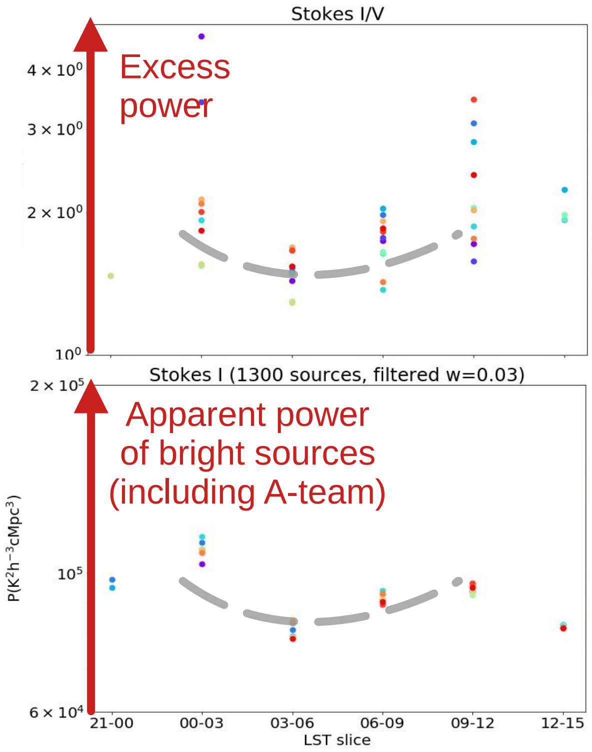
Use 21CMMC framework

Origin of the excess power

Excess power is correlated between nights

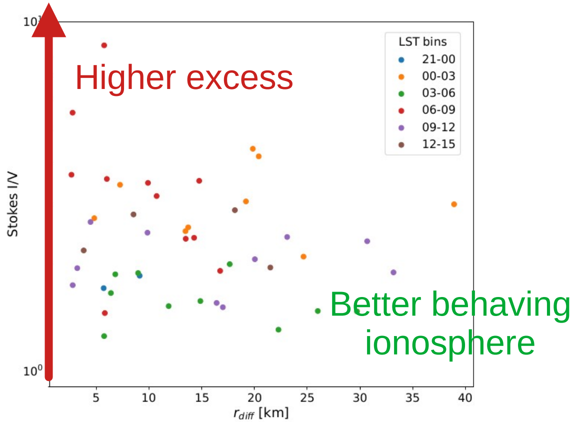


… but excess is stronger when apparent flux from bright (distant) sources is stronger



No strong correlation between excess power and ionosphere ...

Higher diffractive scale does not translate to smaller excess



(H. Gan et al. 2022)

… and we also know it is not related to visibility gridding or flagged data (Offringa et al. 2019a,b)

LOFAR-EoR processing pipeline

2019 – 2020

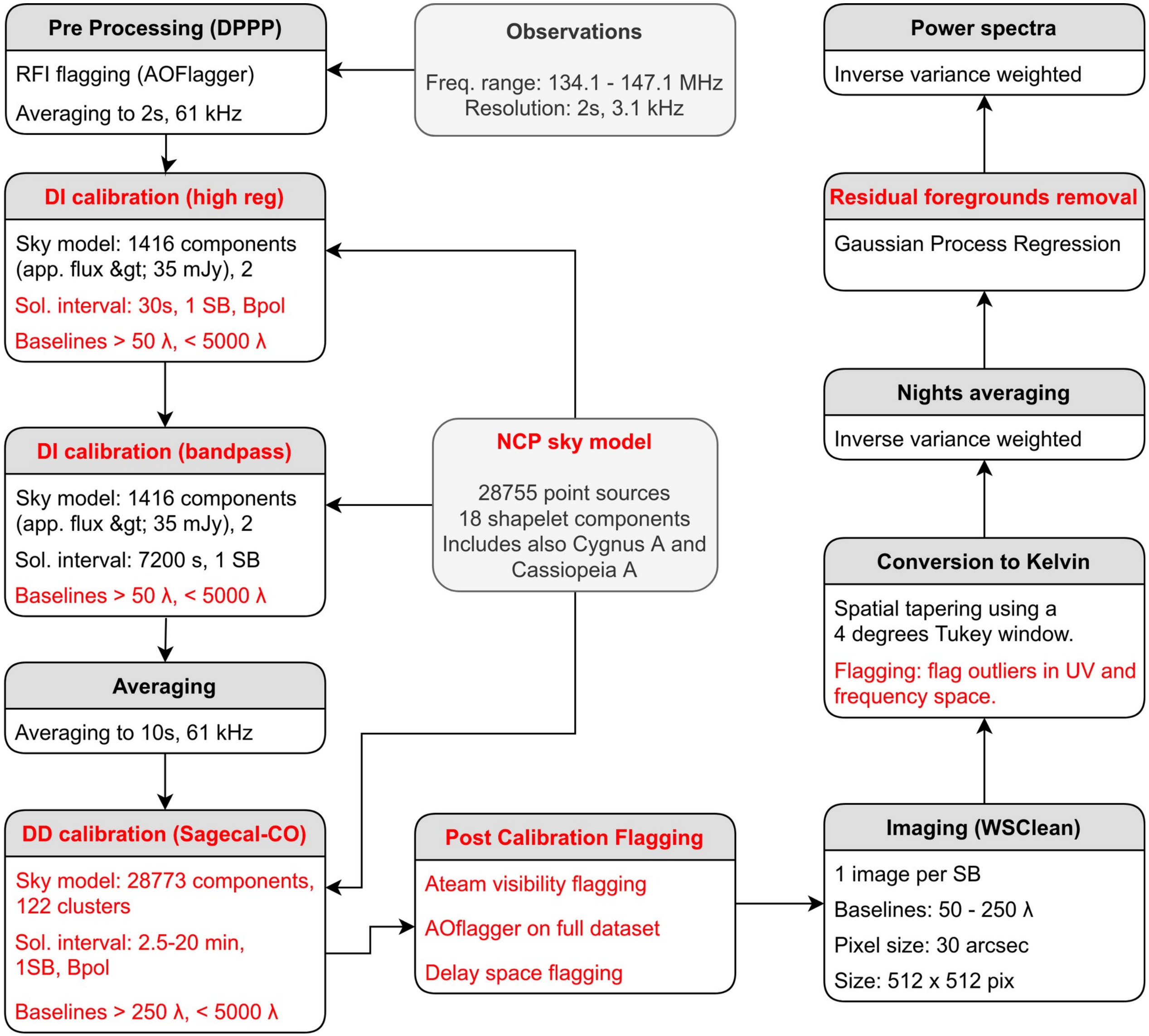
Improvements in DI calibration
- Separate Band-pass calibration
- Enforce smooth gain solutions

Improvements in RFI flagging
- Post calibration flagging
- Baseline flagging affected by local source of RFI

New improvements

Improvements in DD calibration
- Enforce smooth gain solutions
- Discard outer clusters
- Improved Ateam model

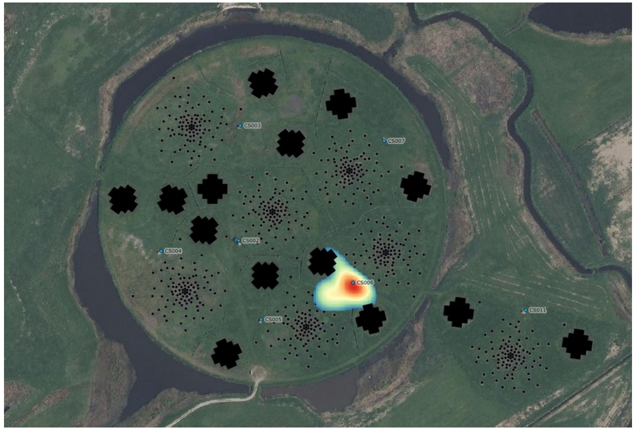
New ML-GPR
- Covariance from simulations
- Covariance depend on baseline
- Improved PS uncertainities



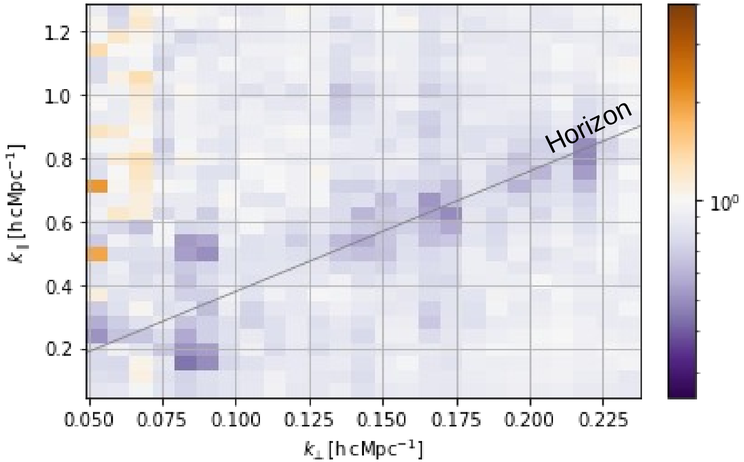
Mitigating the excess: improved RFI flagging

Aim: Better filter faint broadband RFI.

➔ Post-calibration broad-band RFI flagging.
➔ Better flagging of baselines affected by local sources of RFI.



Near-field images of the LOFAR super-terp:
Local source of RFI can be identified and mitigated



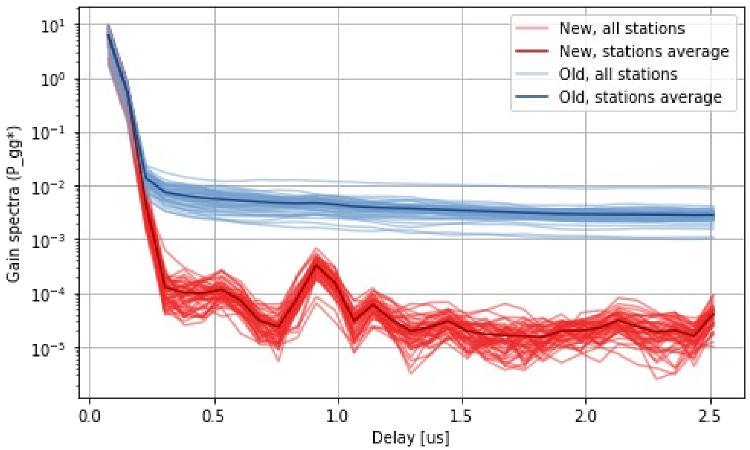
2D Power-spectra ratio after / before:
Significant improvement along the horizon line and at low k_per

Mitigating the excess: improved DI calibration

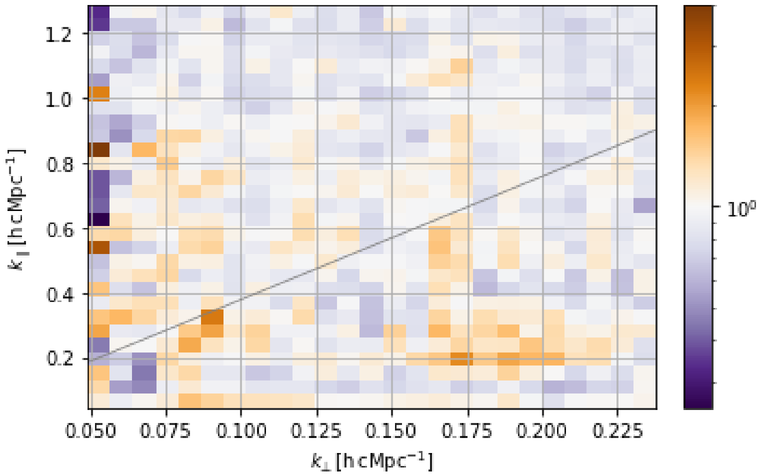
Aim: Reduce DI calibration errors.

➔ Fully enforce spectrally-smooth gain solutions.

➔ Separate Band-pass calibration with long time interval solution to capture the fast frequency varying band-pass response of the instrument.



DI calibration gain spectra:
gain noise considerably reduced.

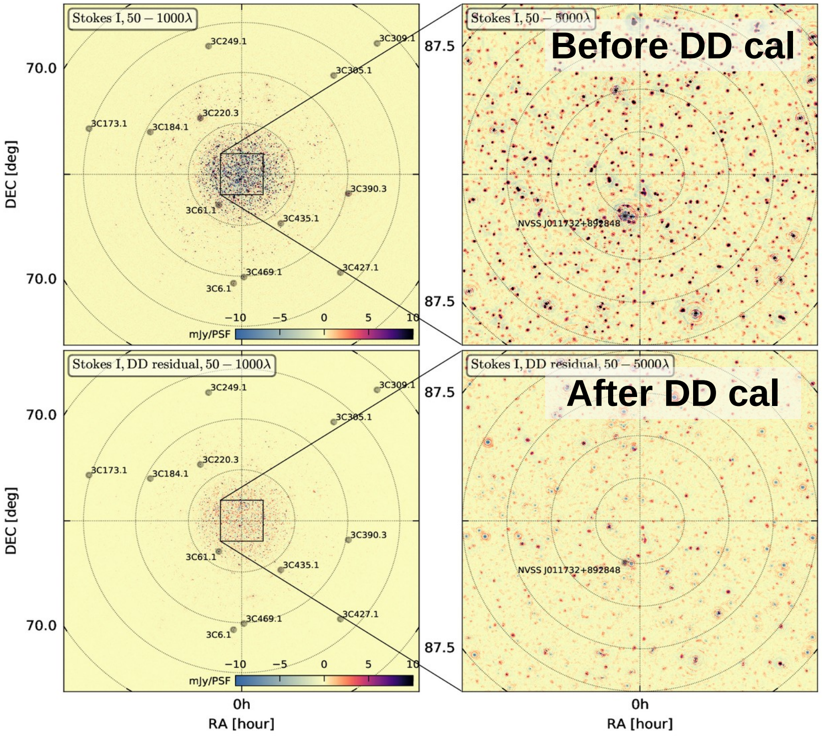


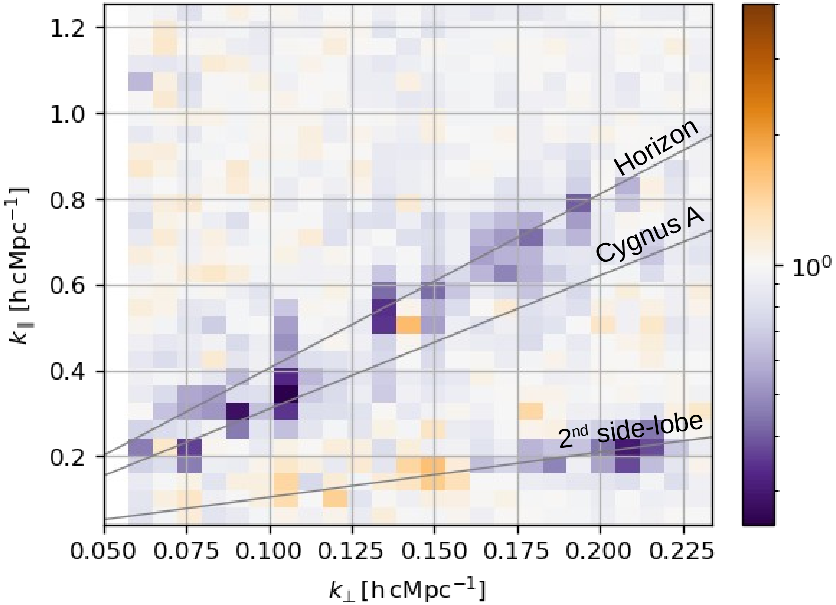
2D Power-spectra ratio after / before:
No significant changes but much more resilient to signal loss.

Mitigating the excess: improved DD calibration

Aim: Reduce DD calibration errors from sources/clusters outside the FoV.

➔ Fully enforce spectrally-smooth gain solutions (see Mevius et al. 2022).
➔ Revised sky-model.

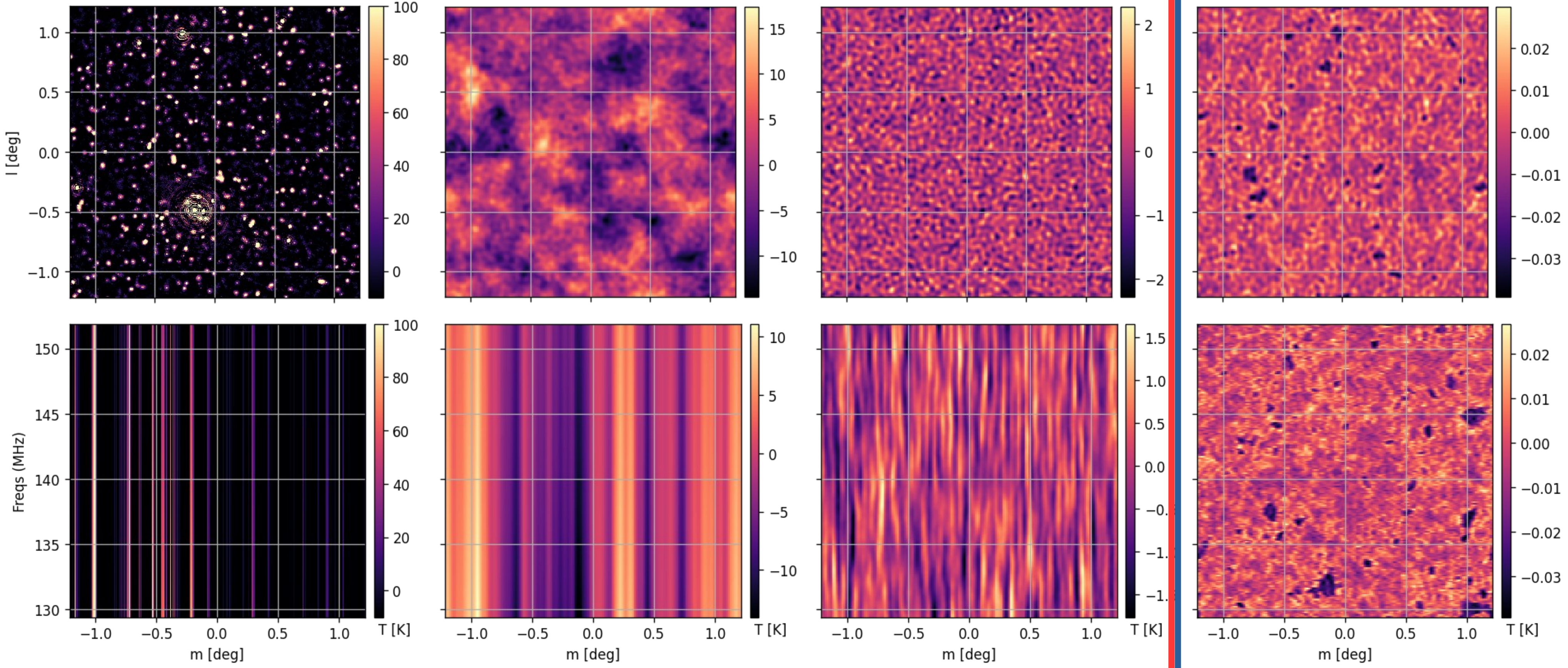




2D Power-spectra ratio after / before:
Significant improvement along the Cygnus A (~50°) and 2nd LOFAR beam side-lobe (~15°)

The challenge of the foregrounds

Foregrounds | **21-cm signal**

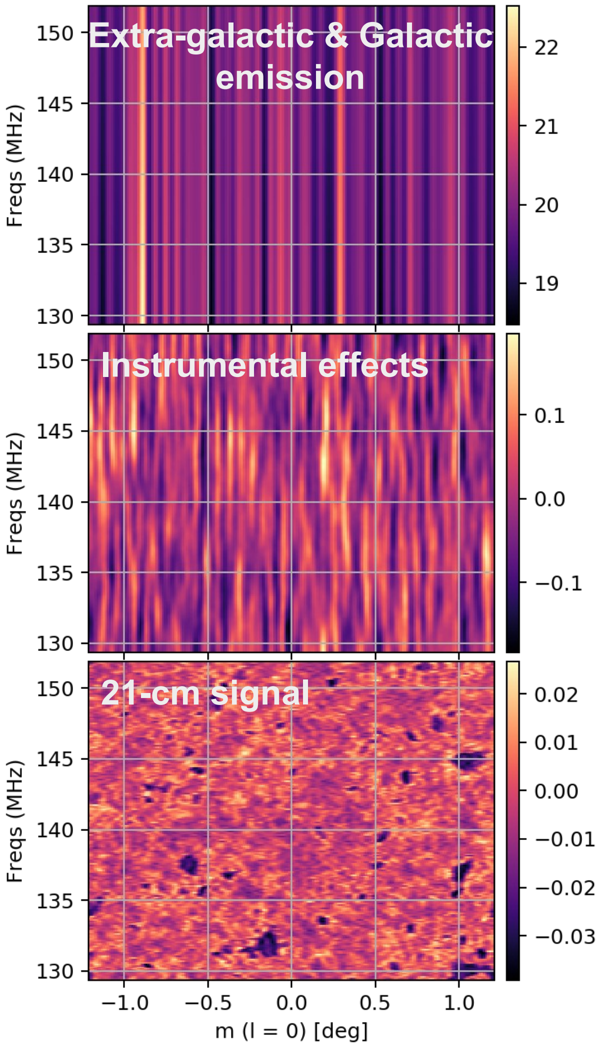


Extragalactic point sources

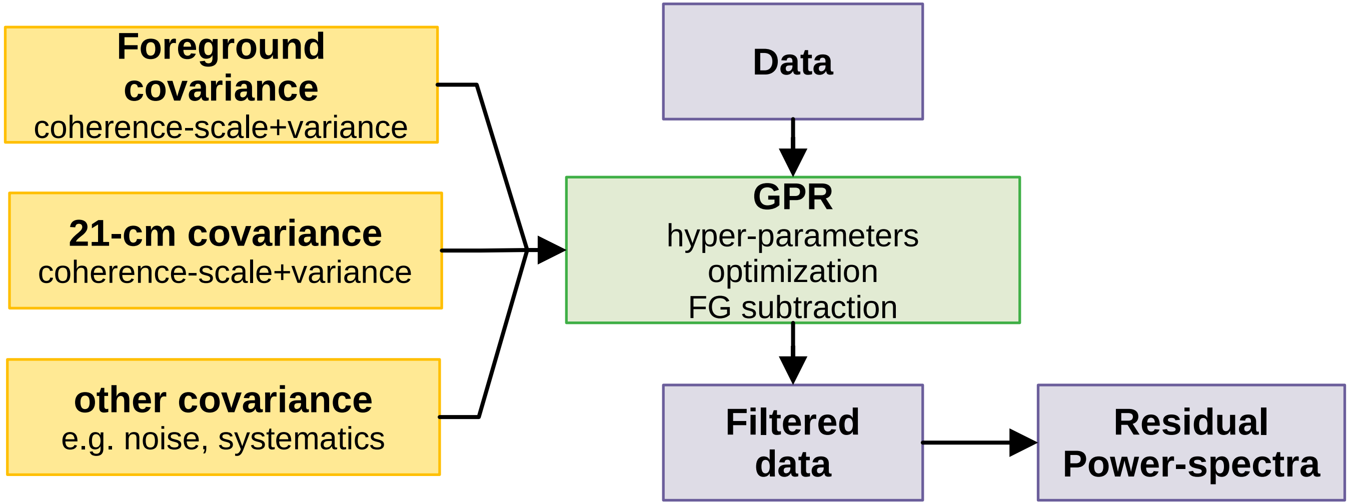
Galactic diffuse emission

Instrumental effects

The GPR foreground removal method



No functional forms but very different spectral characteristic
→ Statistical model prior made of Gaussian Process (GP).
→ In standard GPR, the covariance function are analytically defined. We use typically the Matern class covariance function.

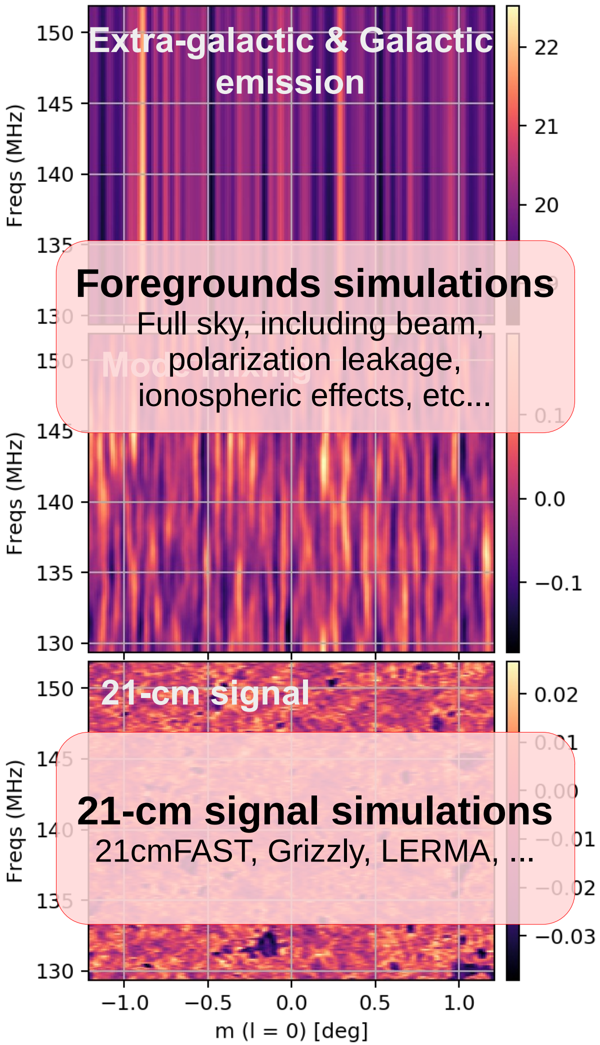


$$E(\mathbf{f}_{\mathrm{fg}}) = K_{\mathrm{fg}} \left[K_{\mathrm{fg}} + K_{21} + \sigma_n^2 I \right]^{-1} \mathbf{d}$$

$$\mathrm{cov}(\mathbf{f}_{\mathrm{fg}}) = K_{\mathrm{fg}} - K_{\mathrm{fg}} \left[K_{\mathrm{fg}} + K_{21} + \sigma_n^2 I \right]^{-1} K_{\mathrm{fg}}$$

(Mertens et al. 2018)

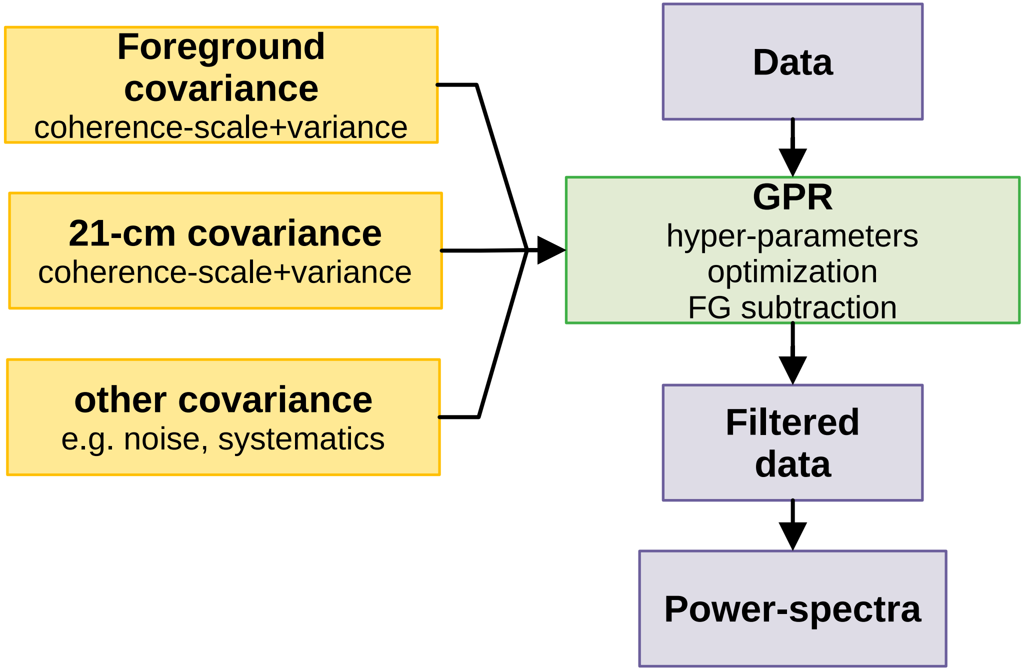
GPR: how to improve the prior covariance ?



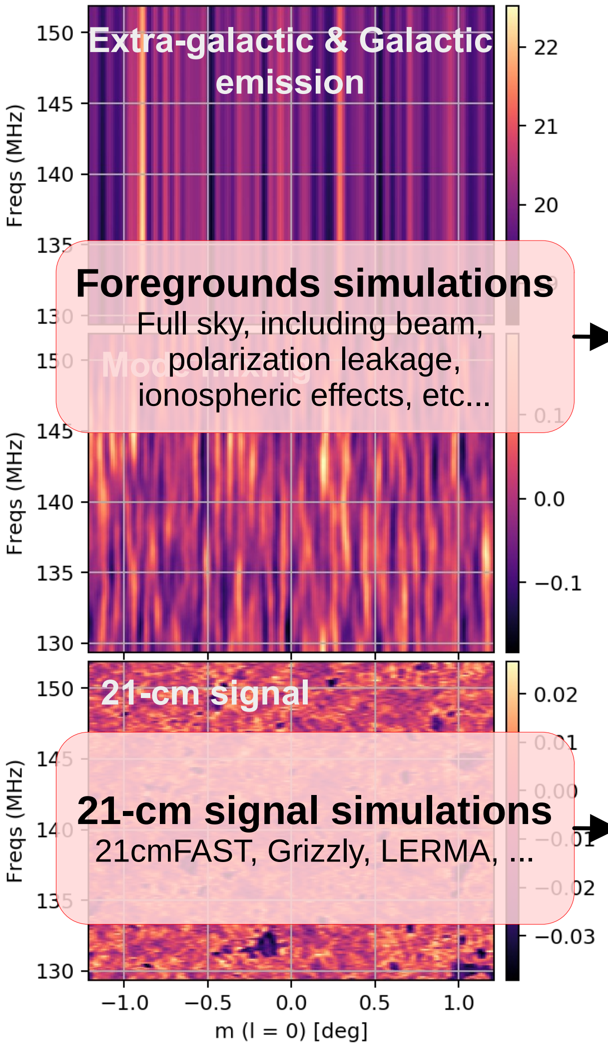
Strong mismatch between prior covariance and true covariance can lead to biases.

→ Need for more physically motivated covariance prior.

→ Simulations encompass the full complexity of the FG and 21-cm signal.



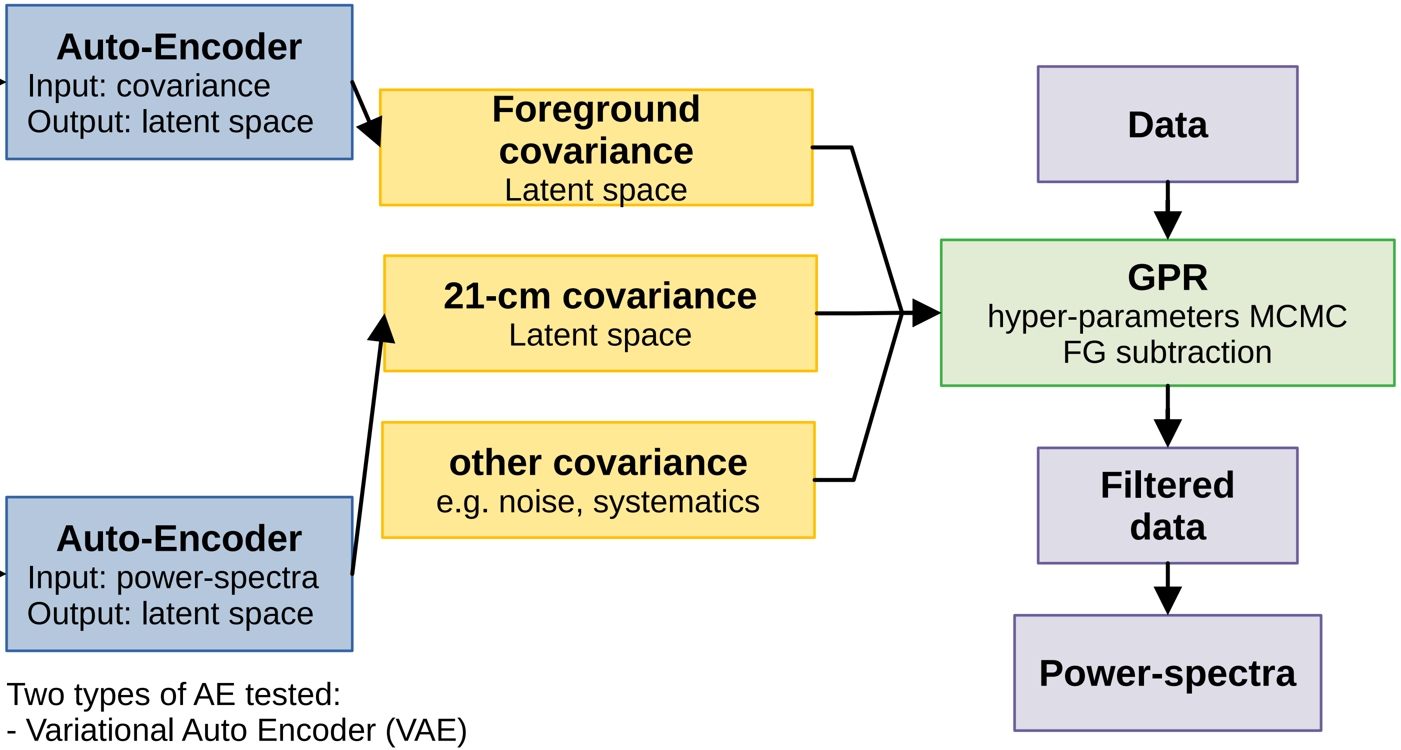
GPR: how to improve the prior covariance ?



Strong mismatch between prior covariance and true covariance can lead to biases.

→ Need for more physically motivated covariance prior.

→ Simulations encompass the full complexity of the FG and 21-cm signal.



Two types of AE tested:
- Variational Auto Encoder (VAE)
- interpolatory Auto Encoder (IAE) (Bobin et al. 2021)

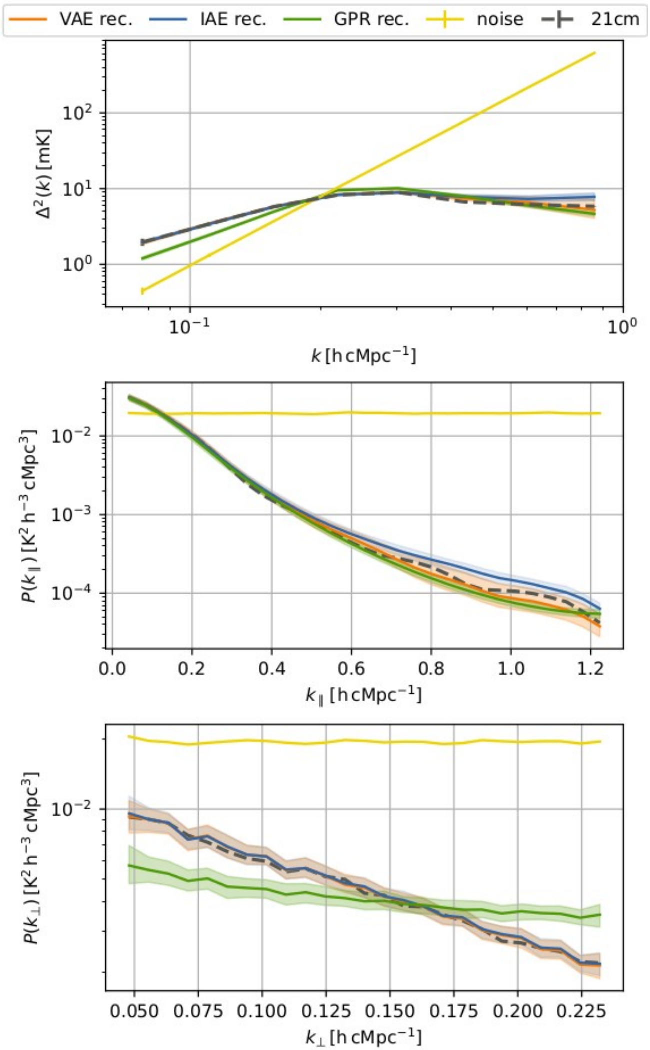
(Mertens, Bobin, Carucci, in prep.)

ML-GPR simulations

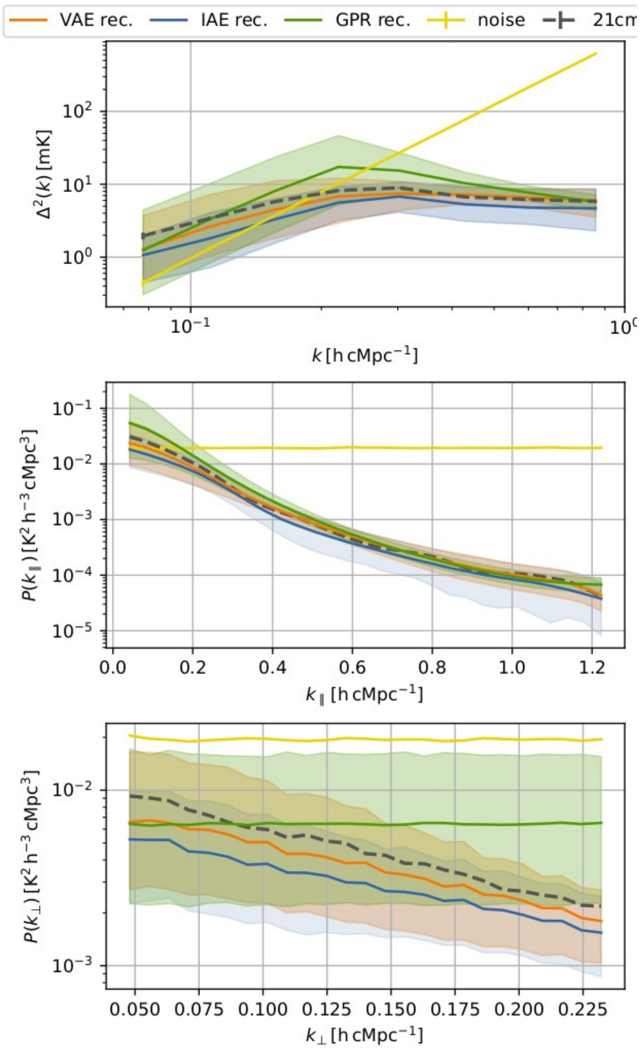
Setup:

- ➔ 21-cm AE trained using 21cmFAST simulations. Reference signal to recover not part of training set.
- ➔ Simulated noise with $\sigma^2_{21} = 0.2\ \sigma^2_{noise}$
- ➔ Foregrounds simulated using standard covariance functions.

Simulation without foregrounds component



Simulation with foregrounds component



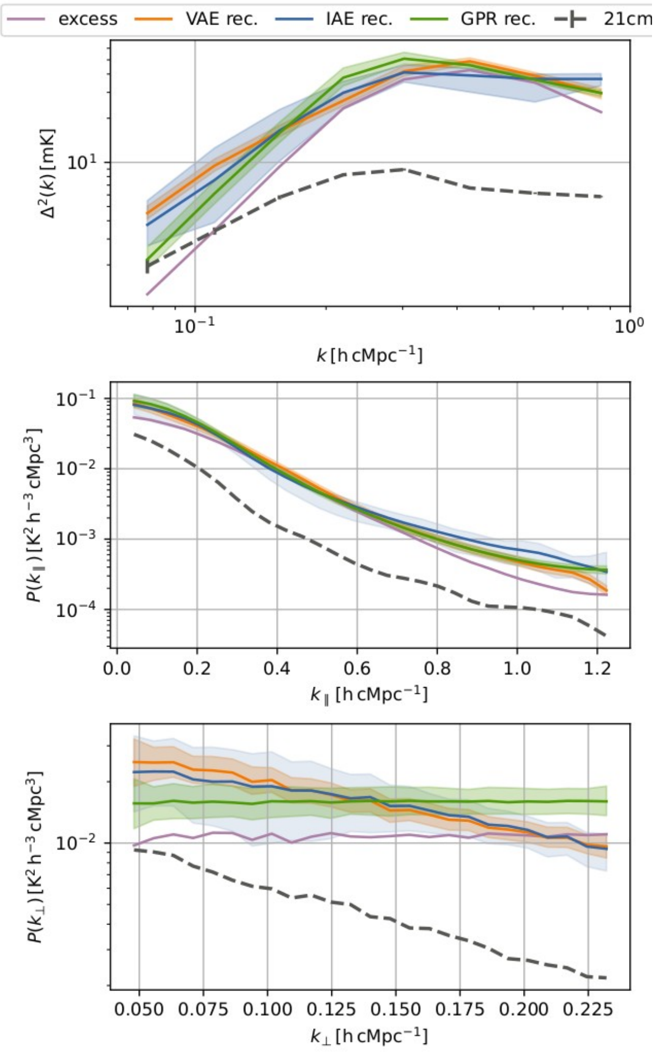
- ➔ Excellent reconstruction of the 21-cm signal
- ➔ Adding foregrounds increased uncertainties but do not biases
- ➔ IAE and VAE performs similarly.

ML-GPR simulations

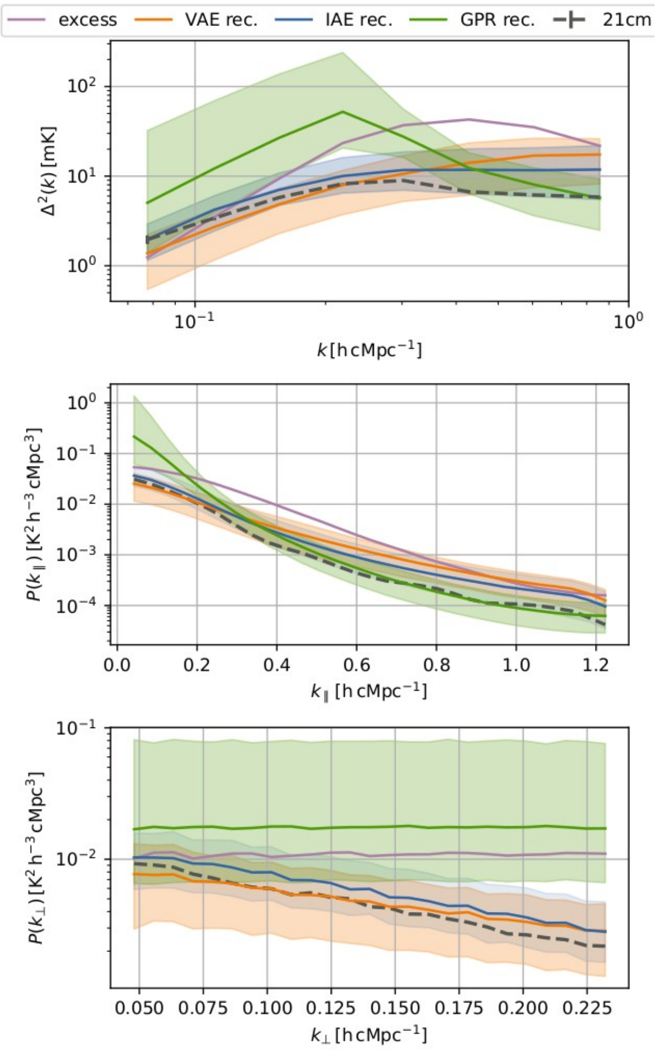
Setup:

- ➔ 21-cm AE trained using 21cmFAST simulations. Reference signal to recover not part of training set.
- ➔ Simulated noise with $\sigma^2_{21} = 0.2\ \sigma^2_{noise}$
- ➔ Foregrounds and excess simulated using standard covariance functions.

Simulation with excess component



Simulation with excess accounted for



- ➔ Unaccounted systematics (excess) does not lead to over-fitting
- ➔ When the excess can be charachterized, the 21-cm signal can be recovered again (with increased uncertainties).

New LOFAR results on the 21-cm signal from the EoR

Reprocessing the 2020 dataset

Preliminary results

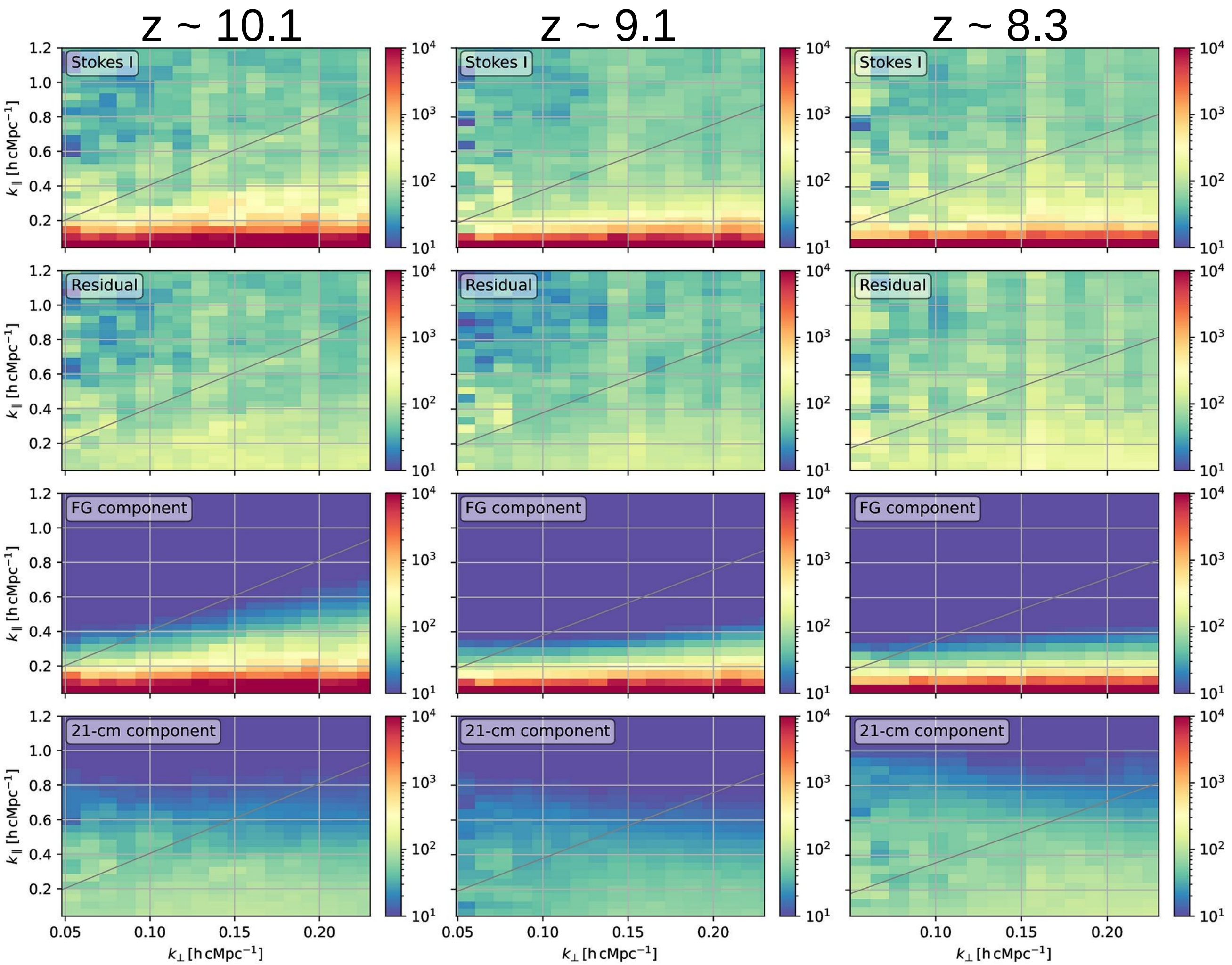
New LOFAR 140h – GPR decomposition

Observed data

Residual after Foregrounds removed

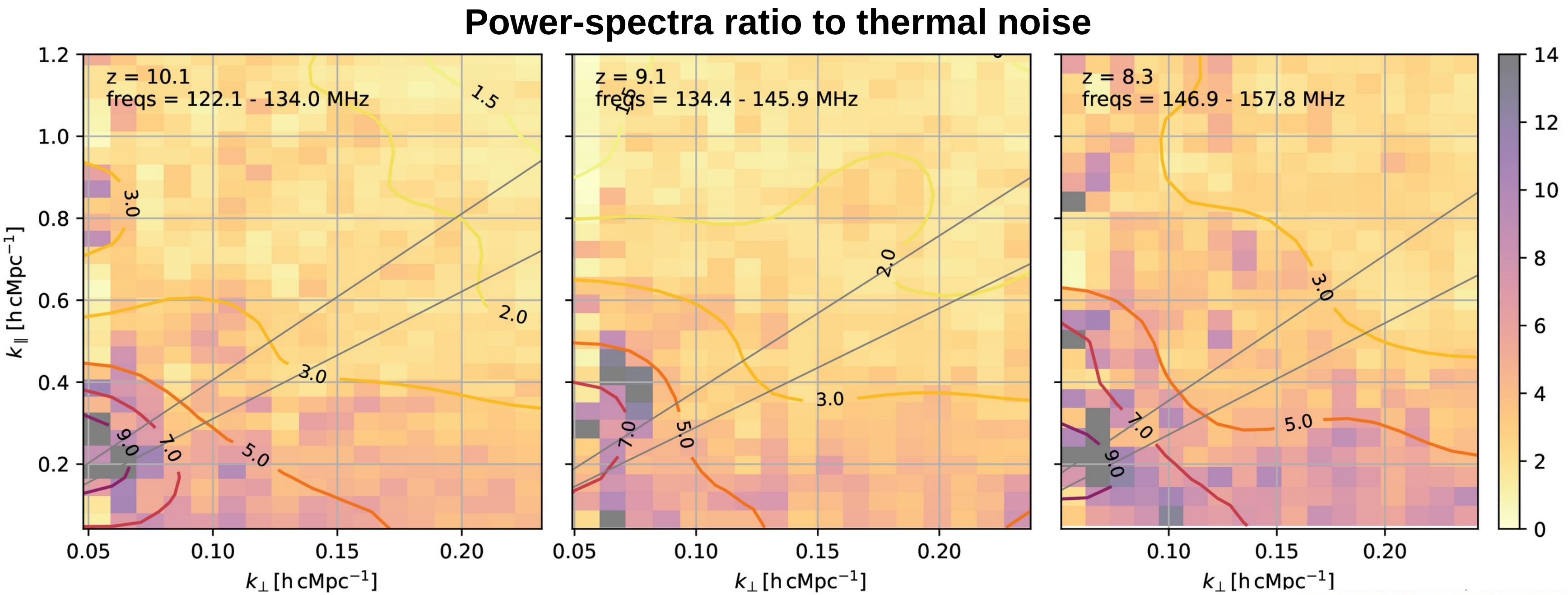
Foregrounds component

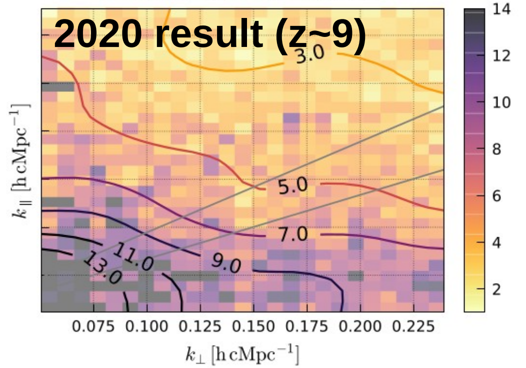
21-cm (VAE) component



Preliminary results

New LOFAR 140h – Ratio to thermal noise





- Much improved residual compared to 2020 results.
- Improvement in all part of the 2D Power-spectra: EoR window, FG wedge, small baselines.

Preliminary results

Summary

- ➔ The 21-cm signal from the Cosmic Dawn and Epoch of Reionization promises a new and unique probe of the first billion year of the Universe, **but very challenging experiment.**
- ➔ **Current upper limit of the LOFAR-EoR project:**
  - The LOFAR-EoR project reported in 2020 its **deepest upper limit** at **z~9:**
    $\Delta^2 < (100\ \mathrm{mK})^2$ @ $k=0.1\ \mathrm{cMpc}^{-1}$, $z \sim 9$ (based on ~5% of data)
  - It allows to start discarding (extreme) models (e.g. Ghara et al. 2020) !
- ➔ **On going work on mitigating the excess power:**
  - Investigation of the excess power: more likely related to distant bright sky sources and RFI, less likely related to ionospheric disturbance (Gan et al. 2022).
  - With recent improvements in **calibration, RFI excision**, and **residual foreground removal** we are able to **reduce this excess by a factor 2 to 3.**
  - More improvements expected from further refinement of the sky model and ML-GPR covariance kernels.