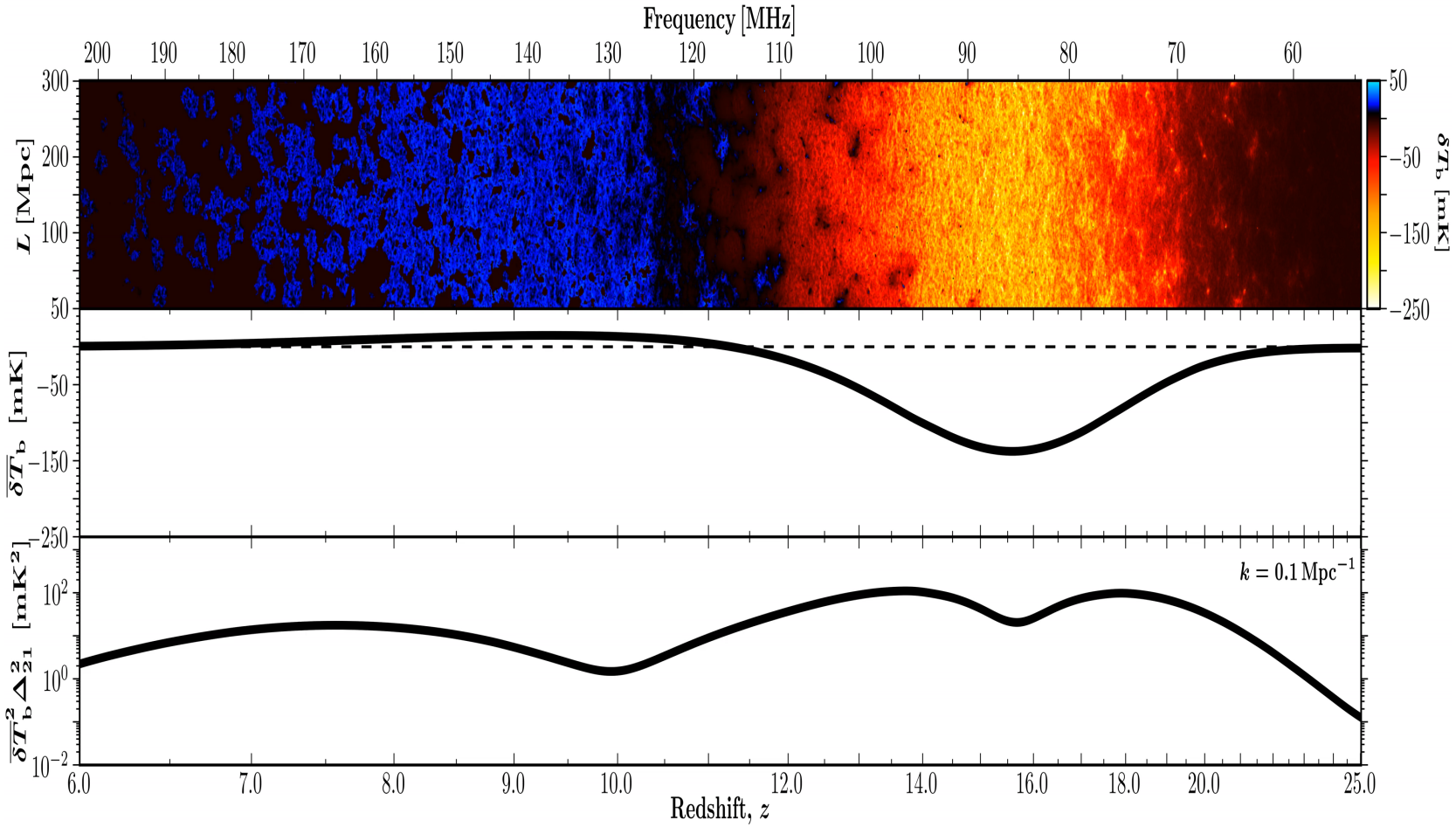
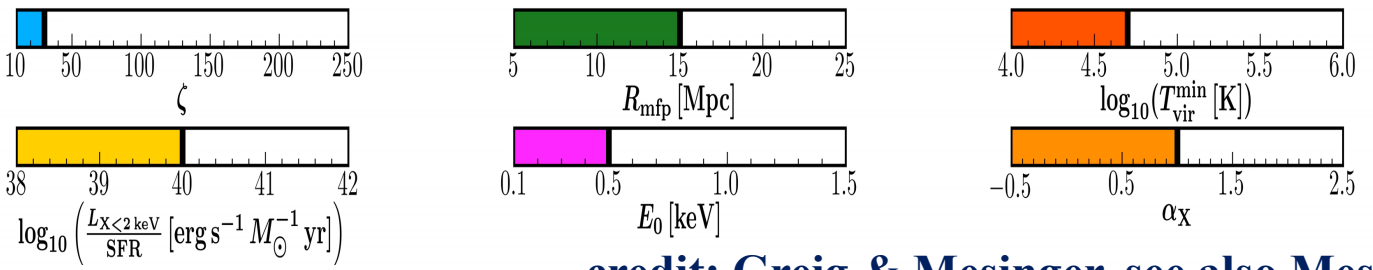
# Observing the Cosmic Dawn and Epoch of Reionization with the 21-cm line

**Gianni Bernardi**

**Special kudos: C. Carilli, H. Garsden, A. Ghosh, L. Greenhill, A. Mesinger, C. Nunhokee, M. Spinelli, N. Thyagarajan + HERA collaboration**

# What physics?




**credit: Greig & Mesinger, see also Mesinger's talk**

# 21-cm cosmology observational requirements/challenges

1) **Low frequency (< 200 MHz) interferometers with large collecting area → high brightness sensitivity, a lot of collecting area within a few km. SKA-low is tailored to measure the CD/EoR signal;**

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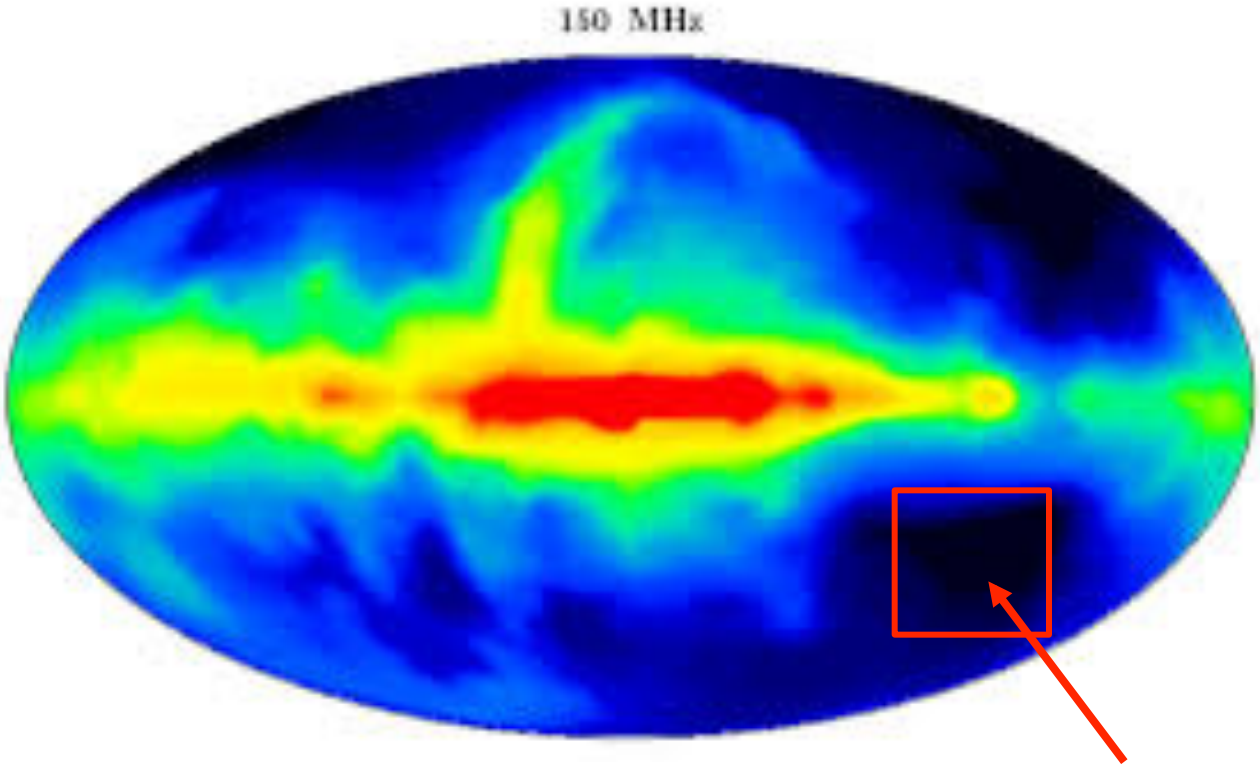
1) Low frequency (< 200 MHz) interferometers with large collecting area → high brightness sensitivity, a lot of collecting area within a few km. SKA-low is tailored to measure the CD/EoR signal;

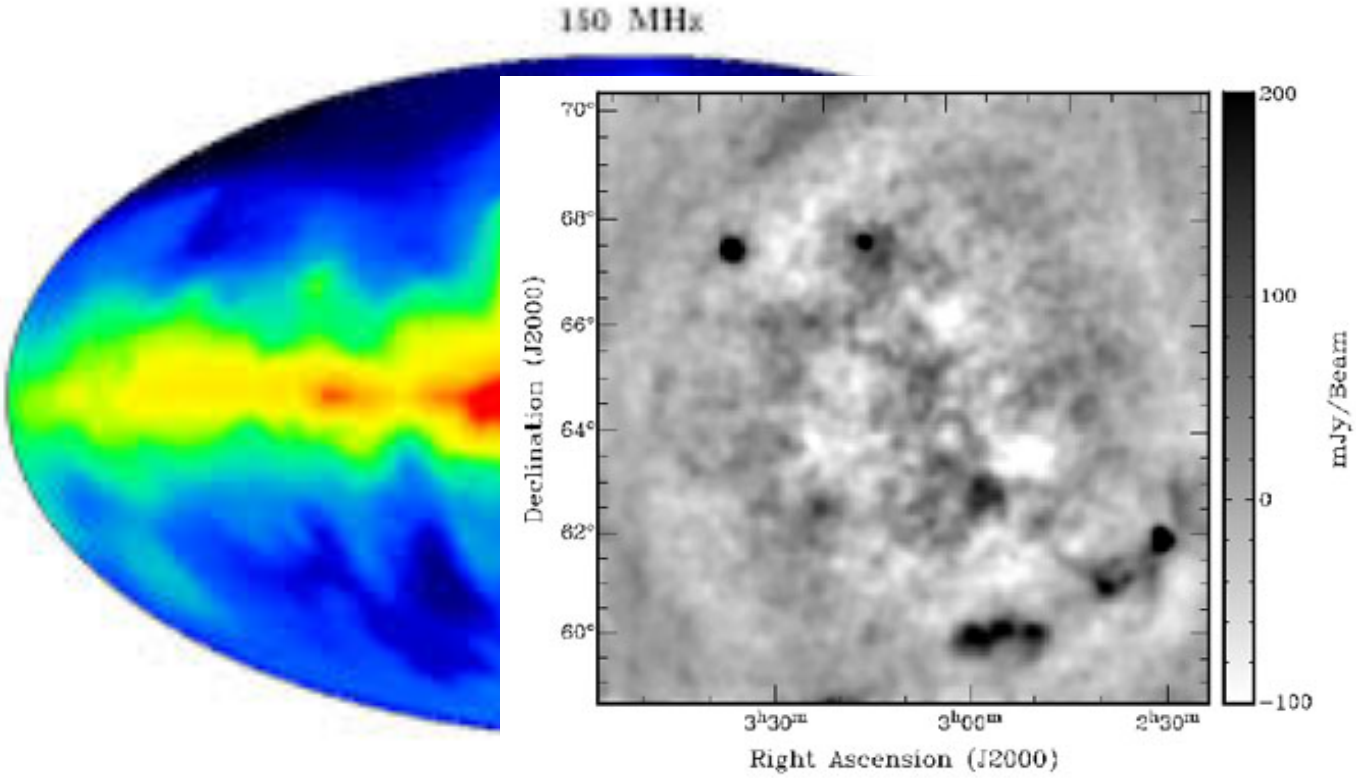
2) Foreground separation/isolation;

# Foreground separation/isolation




coldest regions are ~100-200 K

# Foreground separation/isolation




GB et al. (2009)

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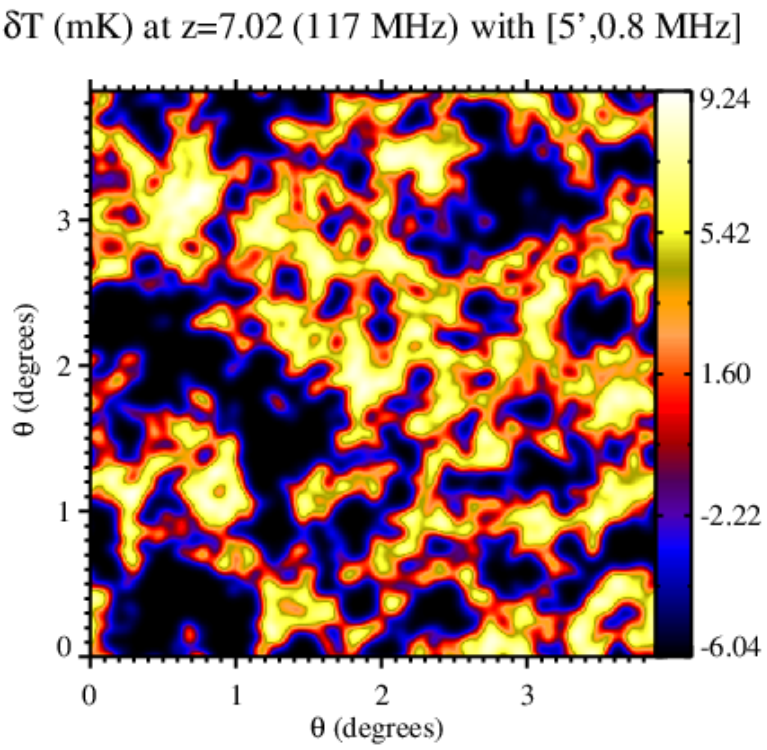
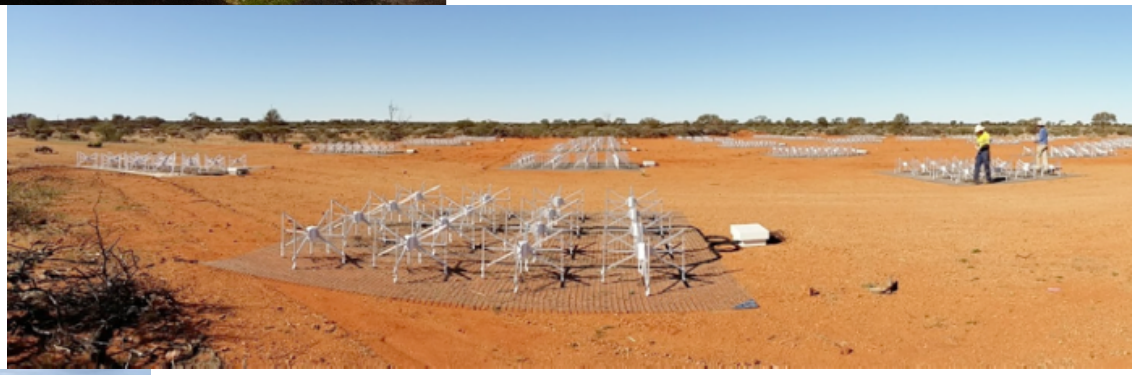



Mellema et al. (2015)

# A tale of 20 years…

LOFAR

MWA



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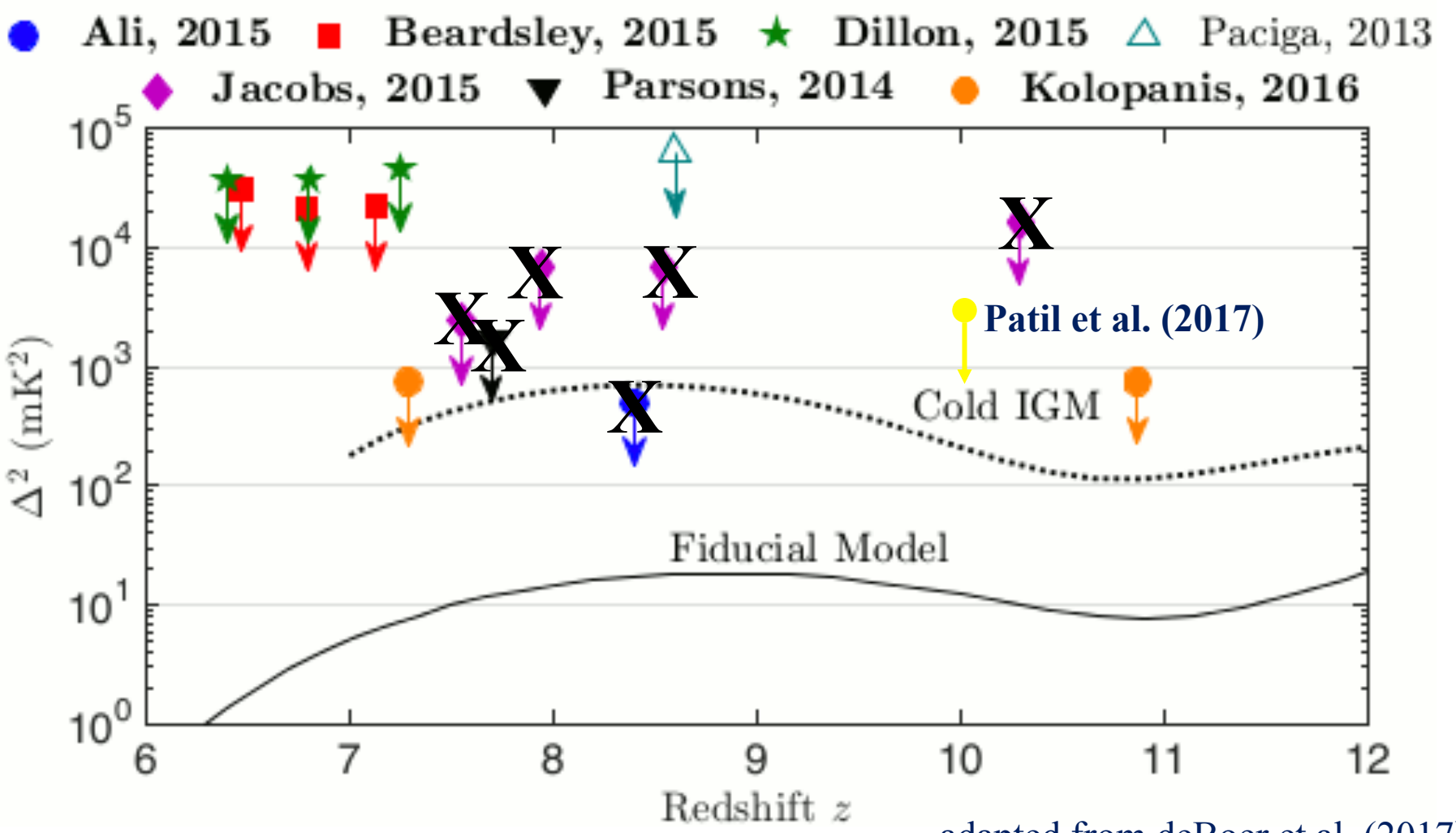
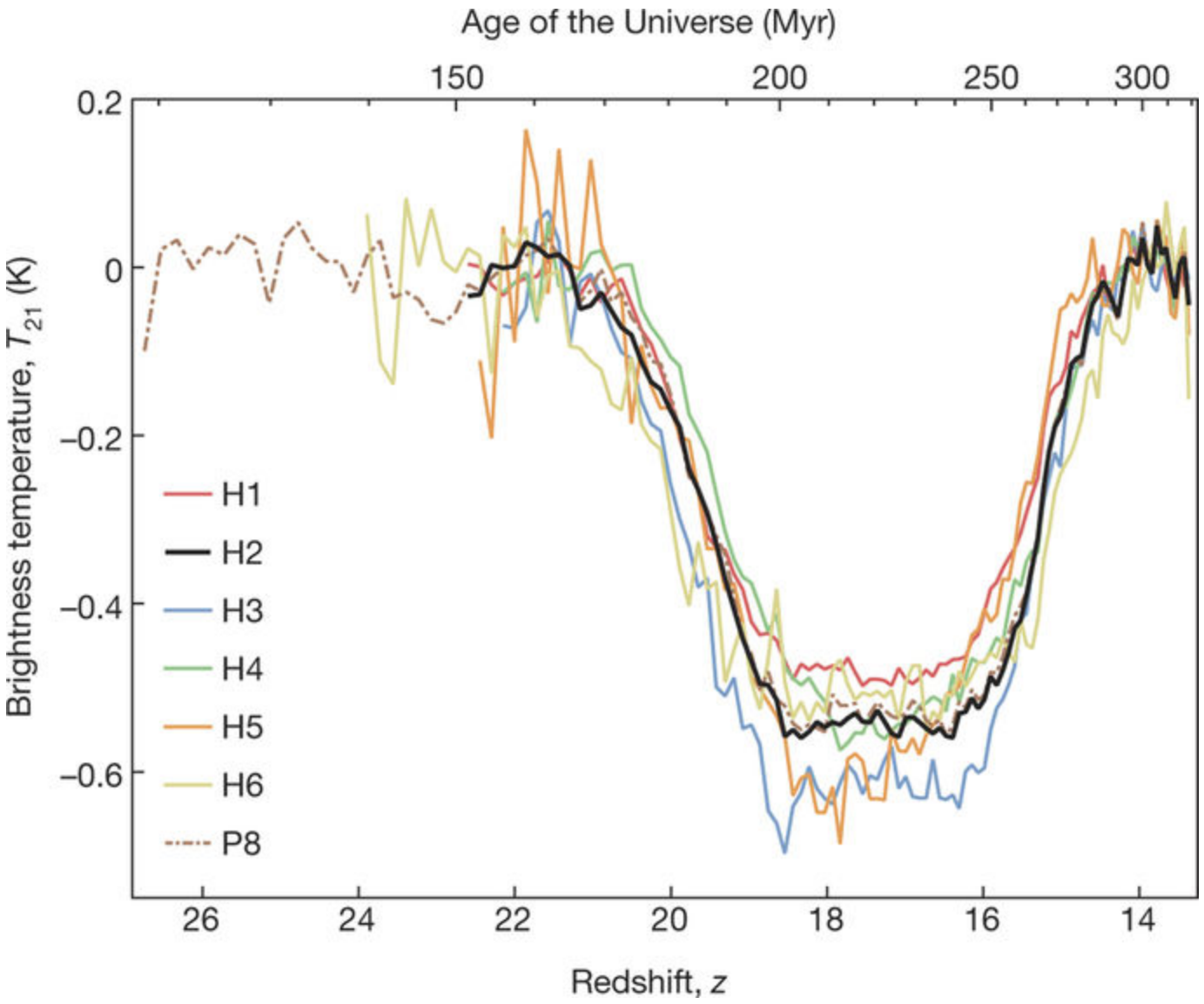
# So far only upper limits… still some ground to cover…




adapted from deBoer et al. (2017)

# … but with a recent, unexpected upturn!




Bowman et al. (2018), see also Braun's talk

# … but with a recent, unexpected upturn!




if the origin is cosmological (also see Spinelli's talk) it needs a complete re-thinking of current models

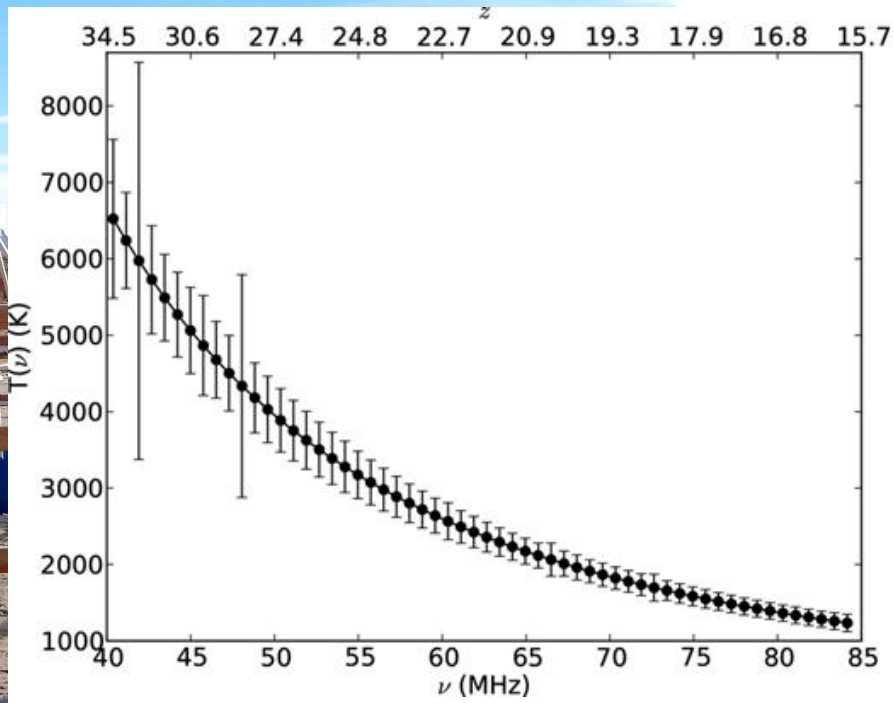
Bowman et al. (2018)

# Large-aperture Experiment to detect the Dark Ages (LEDA) or chasing the sky-averaged 21-cm signal from the Cosmic Dawn

- four V-inverted dipoles sensitive to the 21-cm emission in the $15 < z < 35$ range;
- custom built front-end for calibration;
- site: Owens Valley (CA);

GB, Greenhill & McQuinn (2015);
Price, Greenhill, Fialkov, GB et al. (2018)

# LEDA early results




GB et al. (2016)

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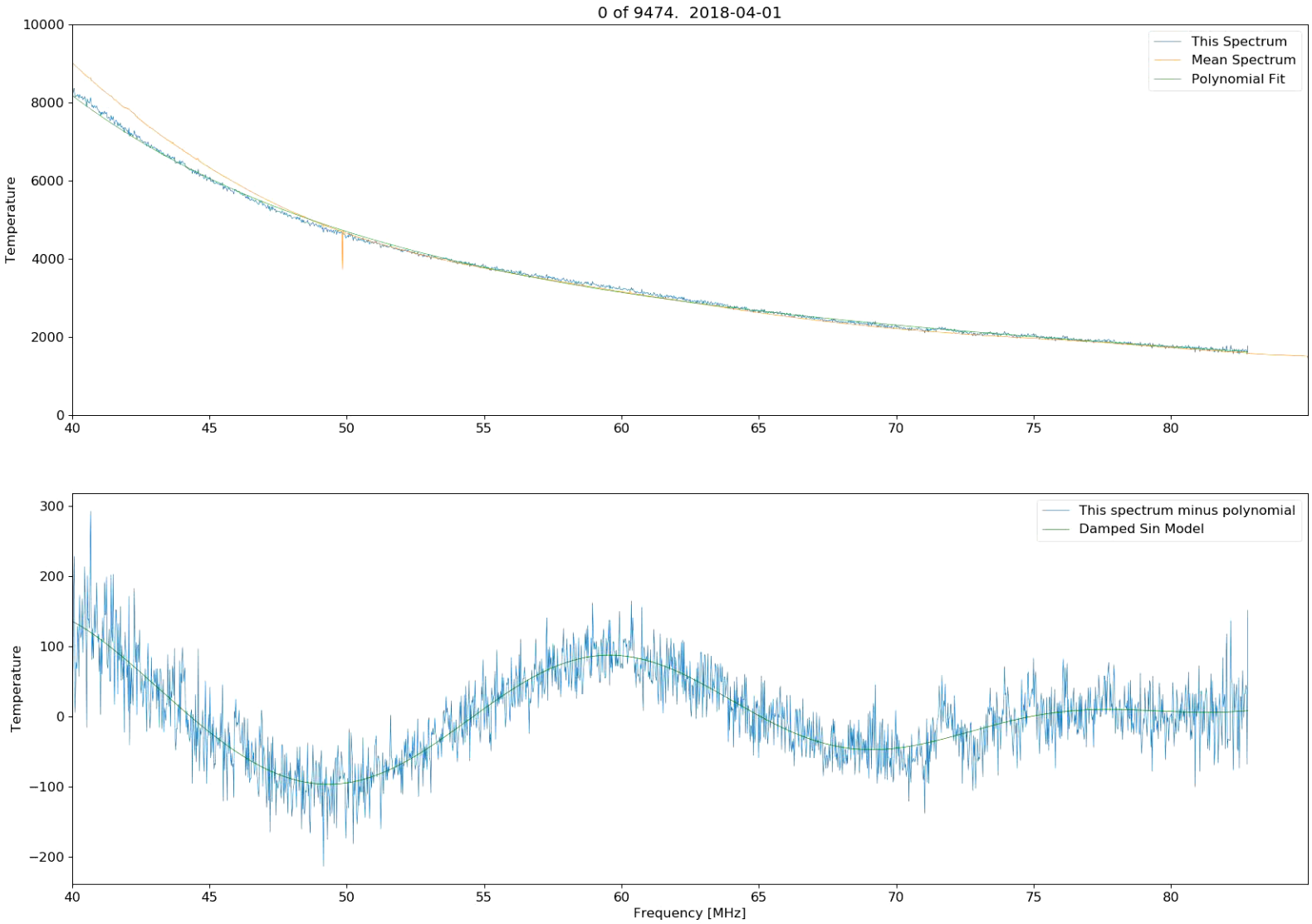
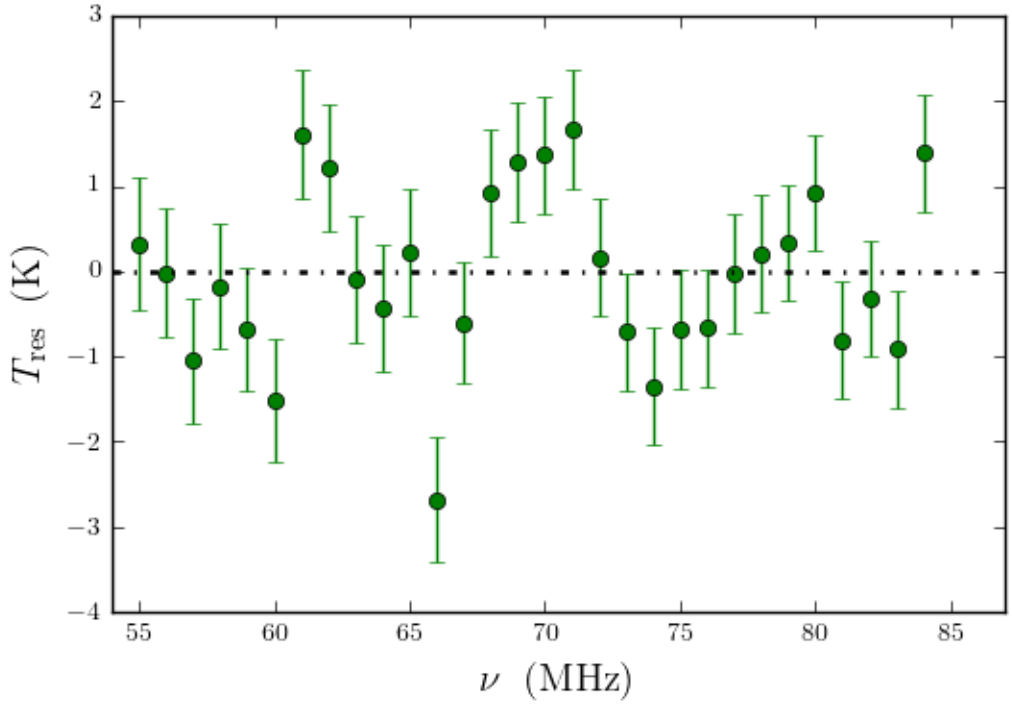
# LEDA current status



# LEDA current status

$$T(\nu) = 10^{\sum_{n=0}^{3} c_n \log\left(\frac{\nu}{\nu_0}\right)^n} + \cos(c_4\nu^2 + c_5)\, e^{c_6\nu}$$




12-day averaged spectrum (11 h < LST < 12 h, effectively 4 hours on the sky):
~1.1 K residual rms

Room for improvement: add 10 more days (with broader LST range), improve the RFI rejection, + …

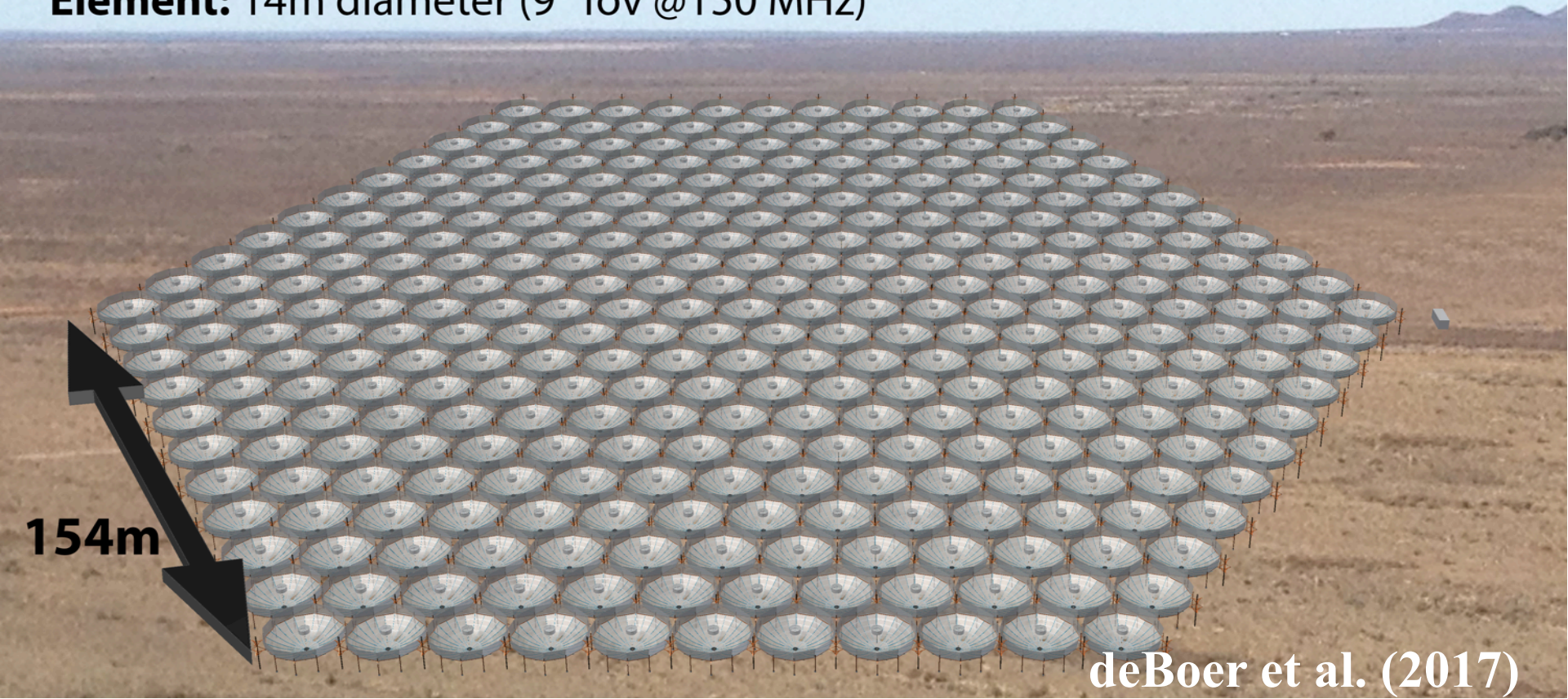
# The Hydrogen Epoch of Reionization Array (HERA) or the next 21-cm cosmology interferometer

**Location:** S30° 34′, E21° 25′ E (South Africa)
**Configuration:** 331 hex-pack, 21 outriggers
- **Min baseline:** 14.6m (7.8° scale)
- **Max baseline:** 1066m (9′ beam)

**Array core:** 310m diameter
**Element:** 14m diameter (9° fov @150 MHz)

**Frequency**
- **Digitized:** 50 - 250 MHz
- **EOR band:** 100 - 200 MHz
- **Channel:** 97.7 kHz

$T_{sys} = 100 + T_{sky}$




deBoer et al. (2017)

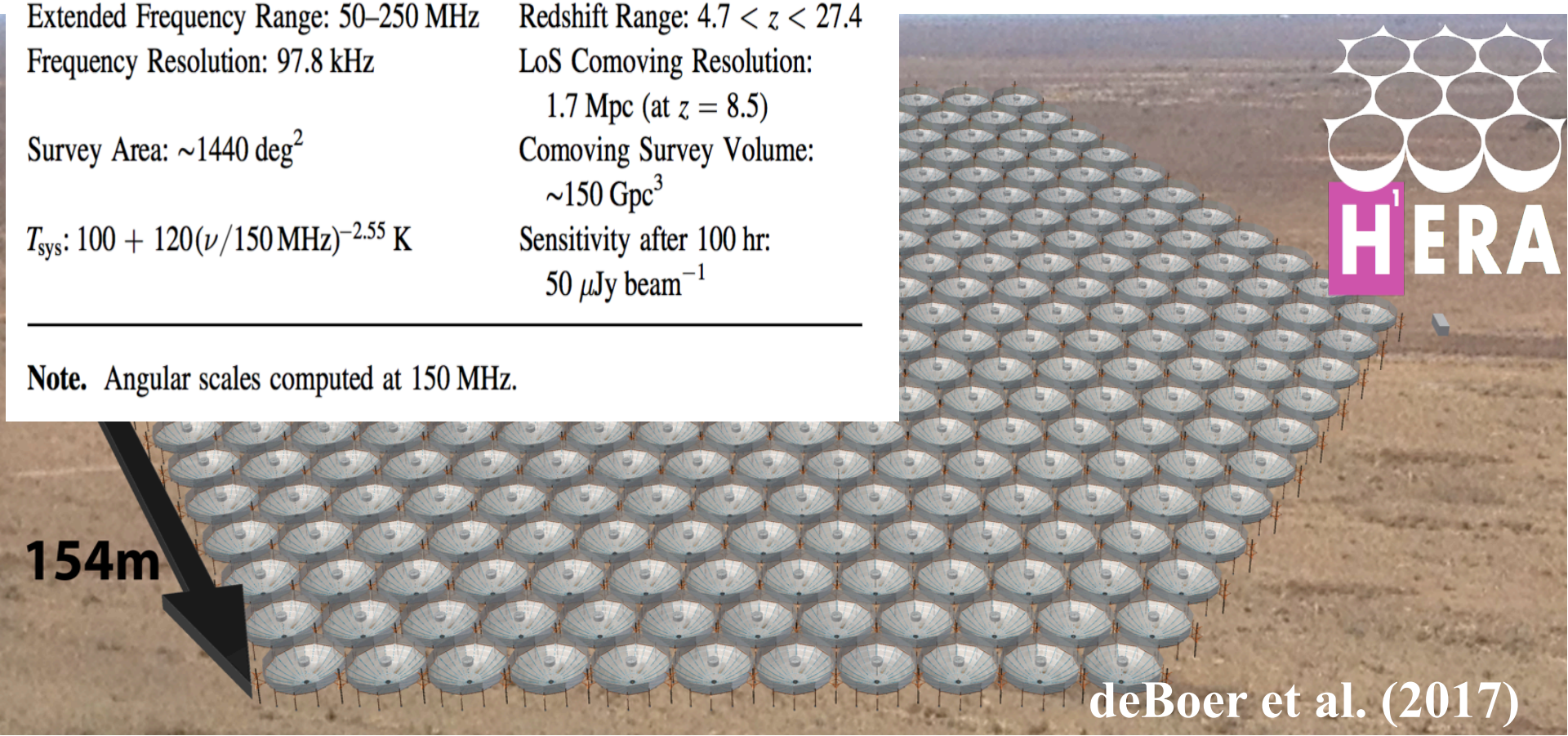
# HERA collaboration

Aaron Parsons (PI)
Zuhra Abdurashidova
James Aguirre
Gianni Bernardi
Judd Bowman
Rich Bradley
Phil Bull
Chris Carilli
Cherie Day
Dave DeBoer
Eloy de Lera Acedo
Steve Furlanetto
Brian Glendenning
Bryna Hazelton
Jacqueline Hewitt
Jack Hickish
Danny Jacobs
Adrian Liu
Dave MacMahon
Andrei Mesinger
Miguel Morales
Jonathan Pober
Nima Razavi-Ghods
Daniel Riley
Kathryn Rosie
Alexander Rudolph
Mario Santos
Jon Sievers
Ian Sullivan
Max Tegmark
Dan Werthimer
Peter Williams
Adam Beardsley
Josh Dillon
Bradley Greig
Zaki Ali
Saul Kohn
Abraham Neben
Matt Kolopanis
Paul La Plante
Juan Mena Parra
Jordan Mirocha
Steven Murray
Ridhima Nunhokee
Nipanjana Patra
Nithyanandan Thyagarajan
Nichole Barry
Jacob Burba
Ruby Byrne
Carina Cheng
Nic Fagnoni
Deepthi Gorthi
Nick Kern
Josh Kerrigan
Adam Lanman
Victor Li
Wenyang Li
Zak Martinot
Honggeun Kim

# HERA specs

| Instrument Design Specification | Observational Performance |
|---|---|
| Element Diameter: 14 m | Field of View: 9° |
| Minimium Baseline: 14.6 m | Largest Scale: 7.°8 |
| Maximum Core Baseline: 292 m | Core Synthesized Beam: 25′ |
| Maximum Outrigger Baseline: 876 m | Outrigger Synthesized Beam: 11′ |
| EOR Frequency Band: 100–200 MHz | Redshift Range: $6.1 < z < 13.2$ |
| Extended Frequency Range: 50–250 MHz | Redshift Range: $4.7 < z < 27.4$ |
| Frequency Resolution: 97.8 kHz | LoS Comoving Resolution: 1.7 Mpc (at $z = 8.5$) |
| Survey Area: ~1440 $\deg^2$ | Comoving Survey Volume: ~150 $\mathrm{Gpc}^3$ |
| $T_{\mathrm{sys}}$: $100 + 120(\nu/150\,\mathrm{MHz})^{-2.55}$ K | Sensitivity after 100 hr: 50 $\mu$Jy $\mathrm{beam}^{-1}$ |

**Note.** Angular scales computed at 150 MHz.




deBoer et al. (2017)

# HERA at the SKA SA site

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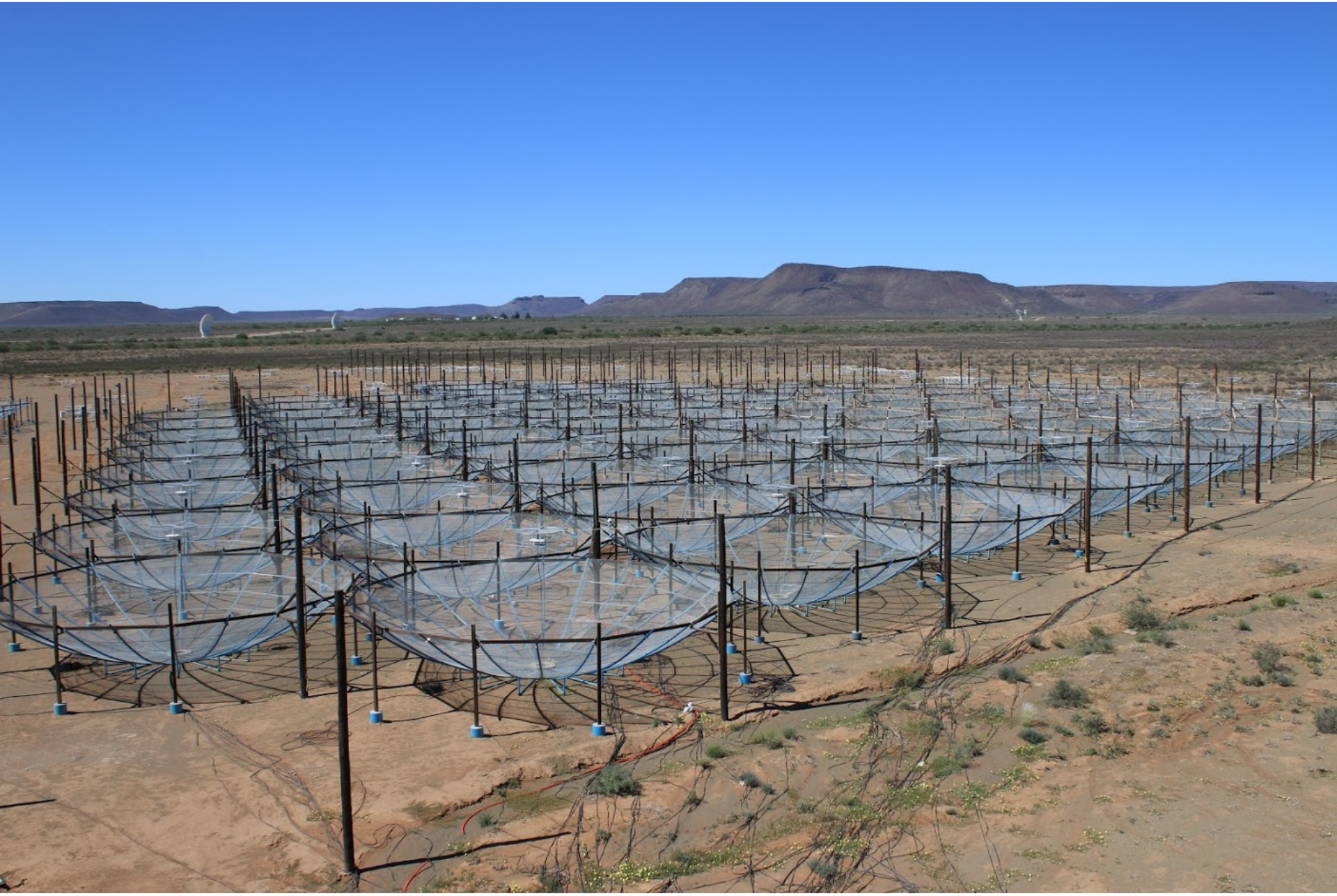
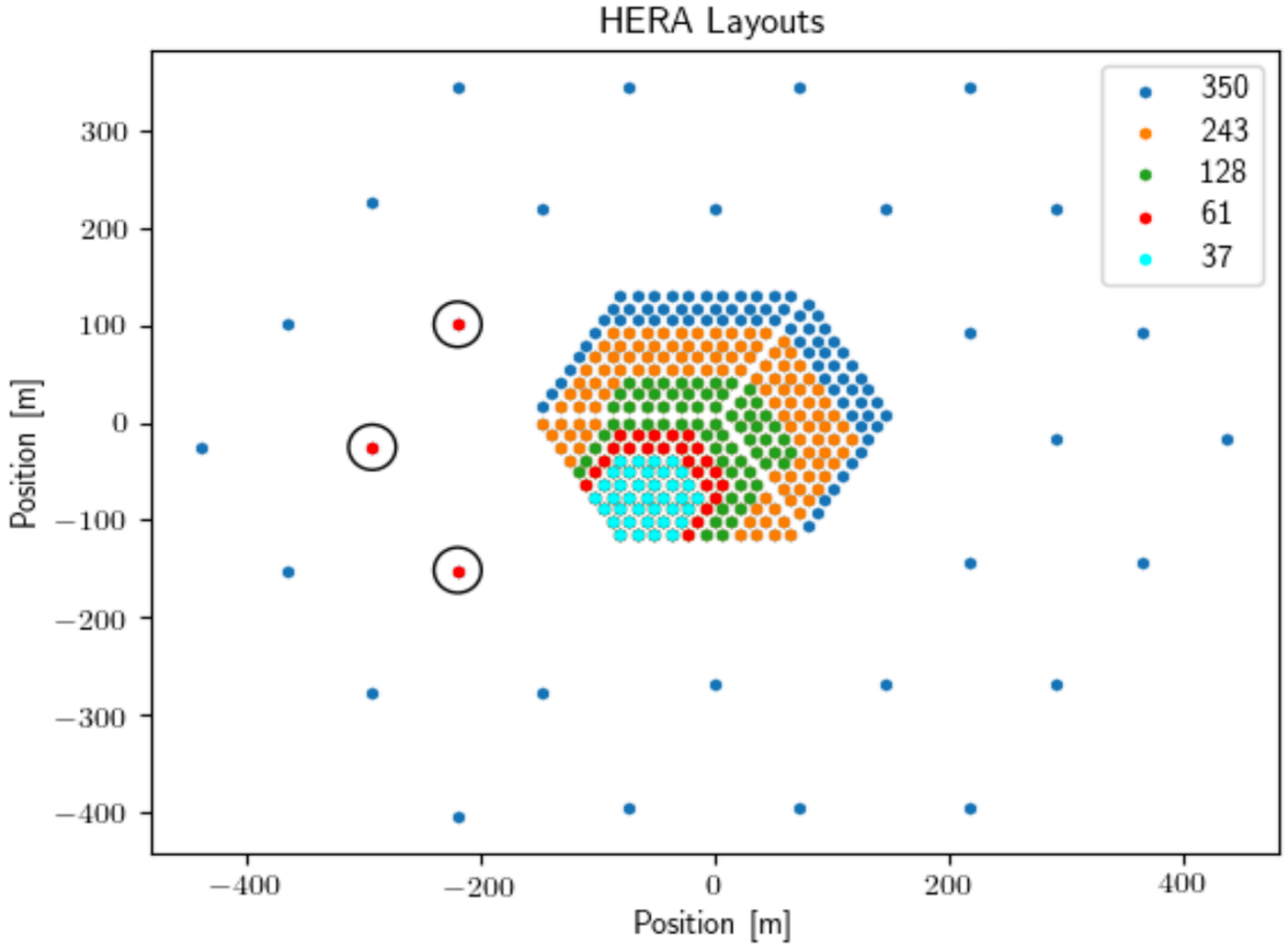
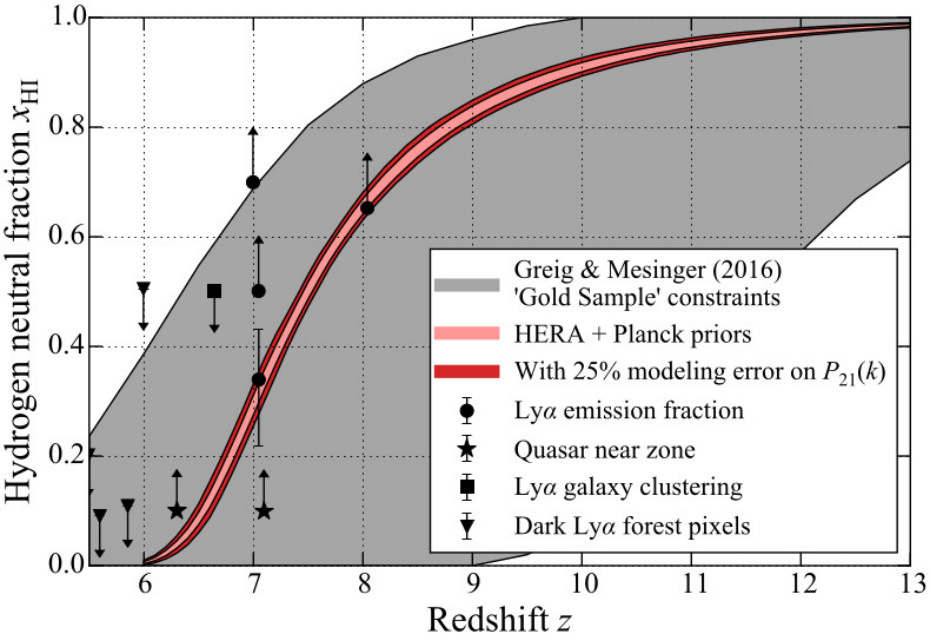
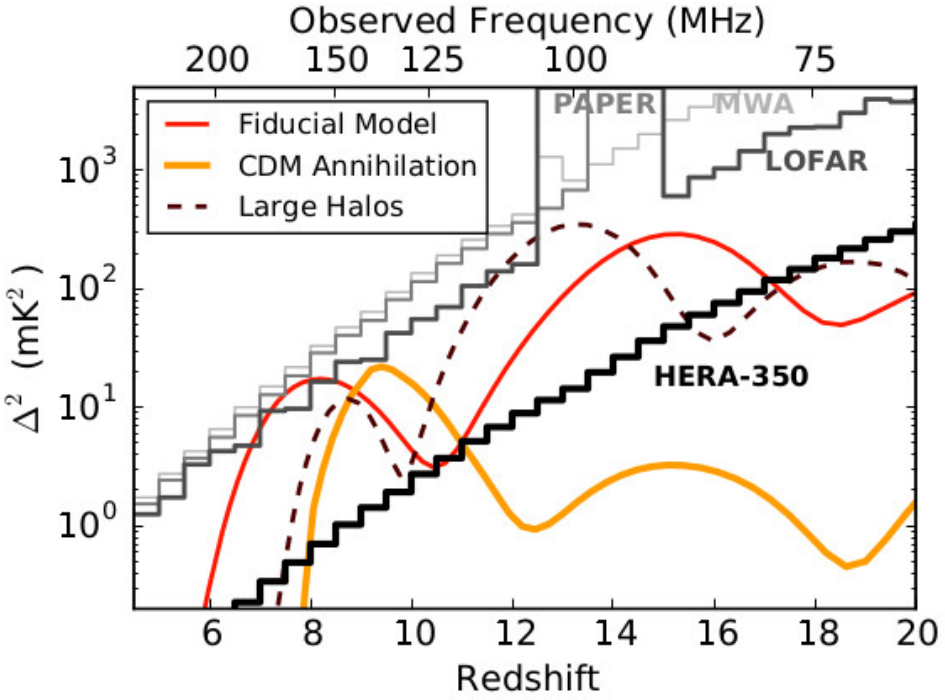





**Highly redundant configuration to boost sensitivity on selected 21-cm modes,**
**A number of outriggers to aid foreground modelling and calibration**

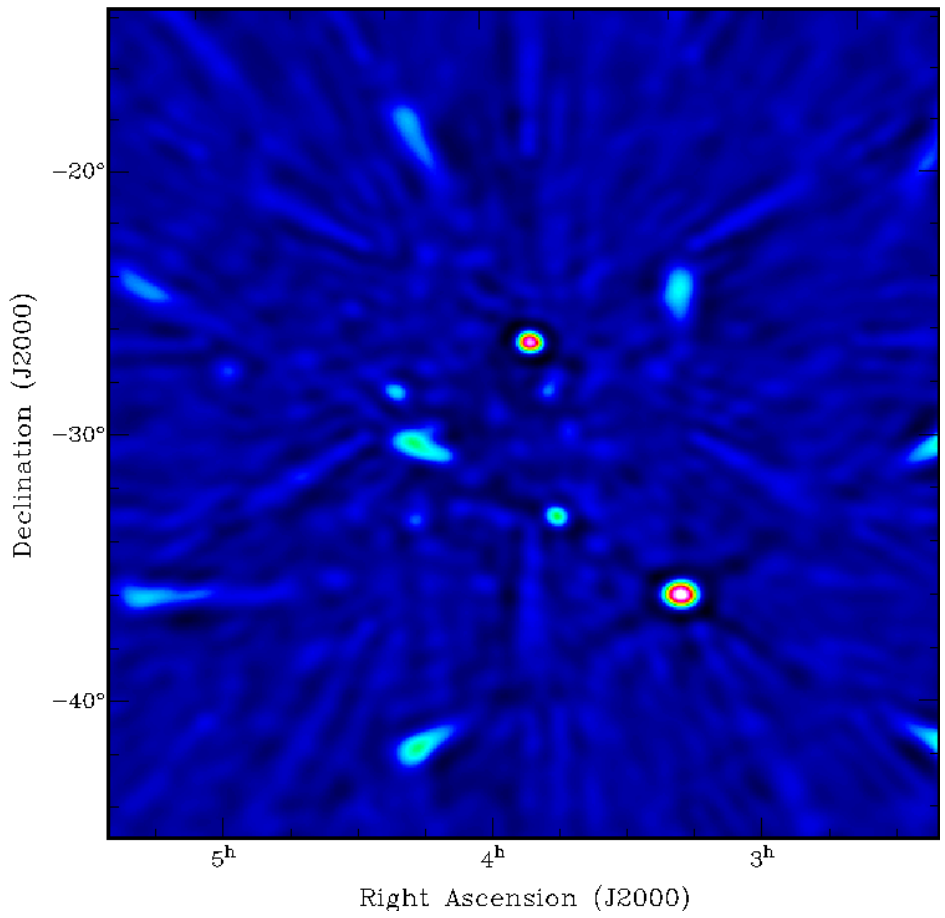
# HERA constraints on CD/EoR

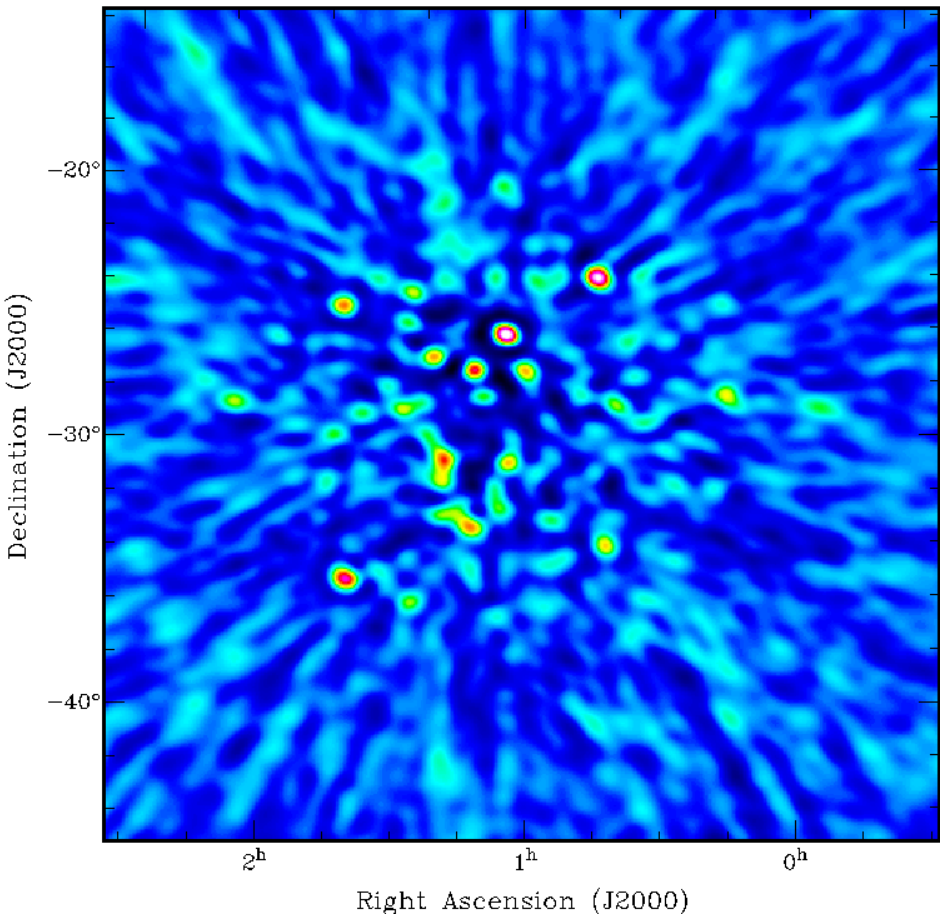


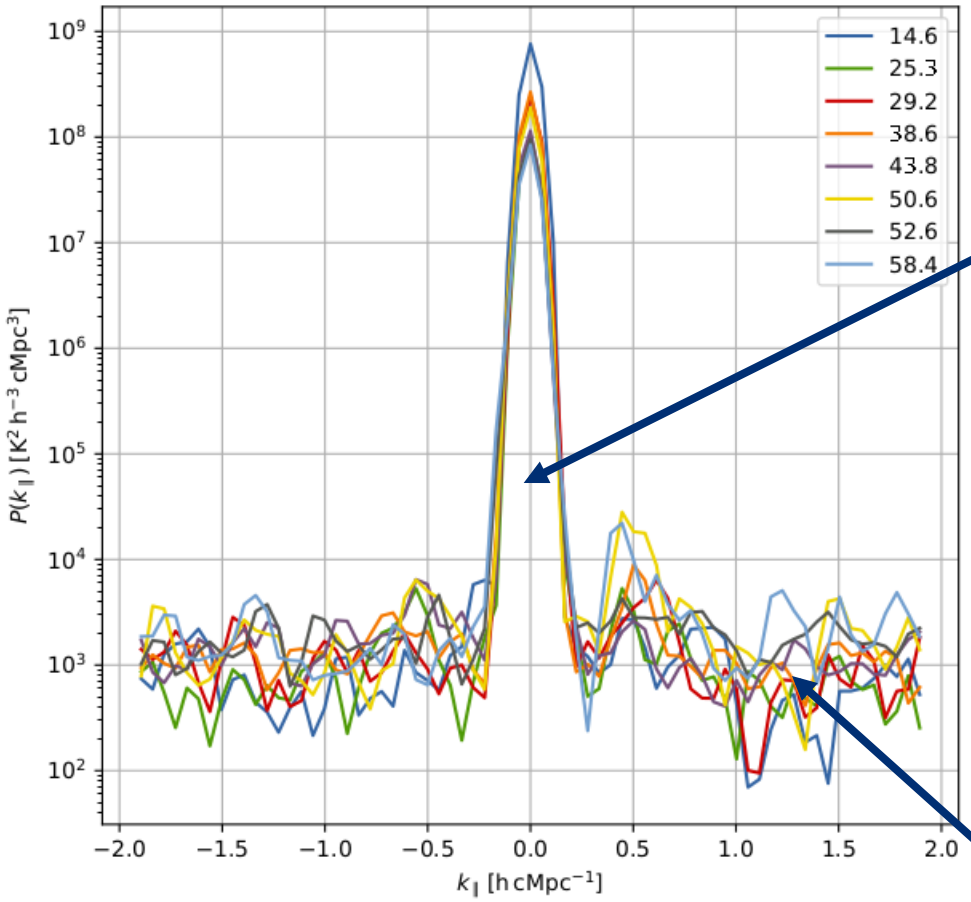

deBoer et al. (2017)

# Early science has started…



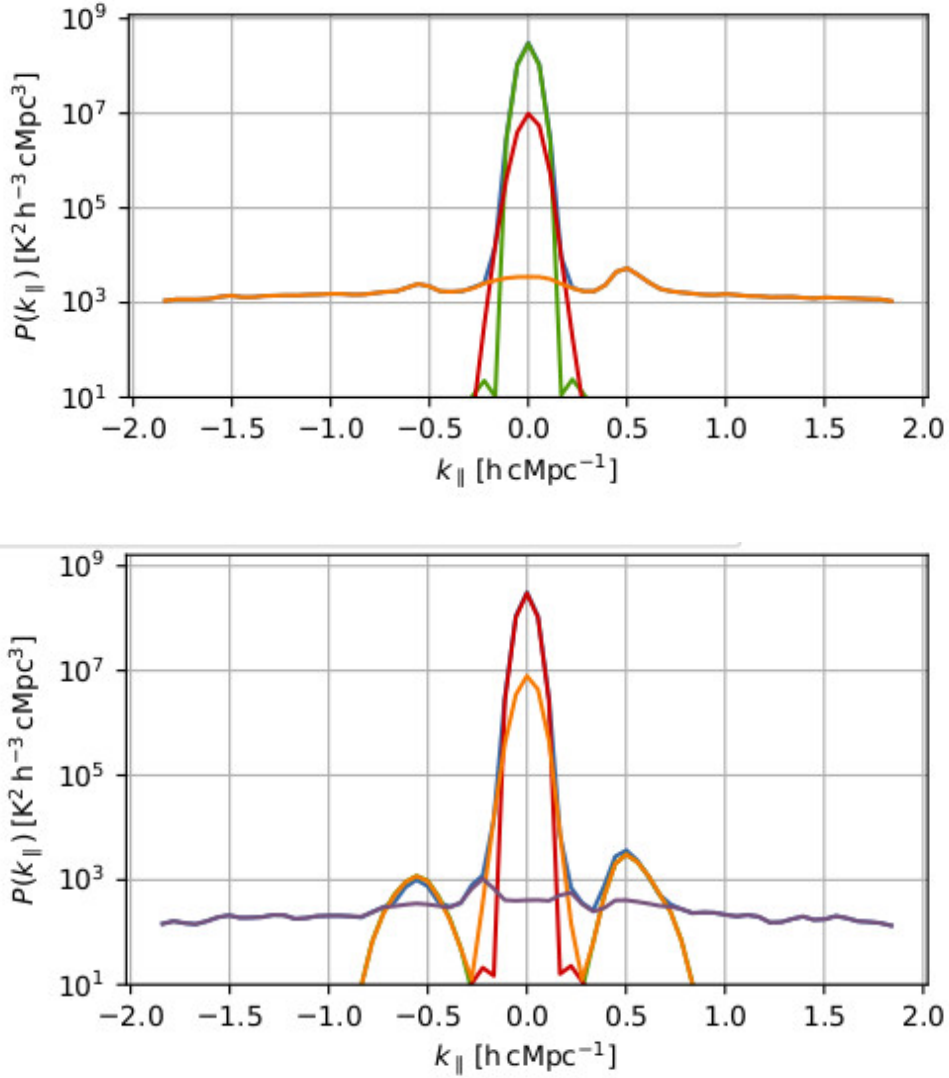
# … including foreground separation/isolation




**Foreground dominated modes (coherent emission on tens of MHz scales → small k modes along the line of sight)**

**"Foreground free" (EoR) region**

# and modelling systematic effects




Ghosh, Mertens, GB et al., in prep

# Conclusions

1) We are actively pursuing a confirmation (or lack) of the anomalous global 21-cm signal claimed by EDGES: hopefully an answer in the next few months;

2) HERA (the most sensitive 21-cm SKA precursor) is coming online: upper limits appearing in 2019 (?);

3) The Italian CD/EoR community is still small but very active;

4) The measurement of the 21-cm signal from the CD/EoR is where SKA-low will really be transformational, probing a redshift range inaccessible to any other probe;