The SKA Epoch of Reionisation and Cosmic Dawn Experiment

EoR/Cosmic Dawn Science Team

Cathryn Trott

ICRAR
International Centre for Radio Astronomy Research

ASTRO 3D

CAASTRO
ALL-SKY ASTROPHYSICS

Curtin University

The University of Western Australia

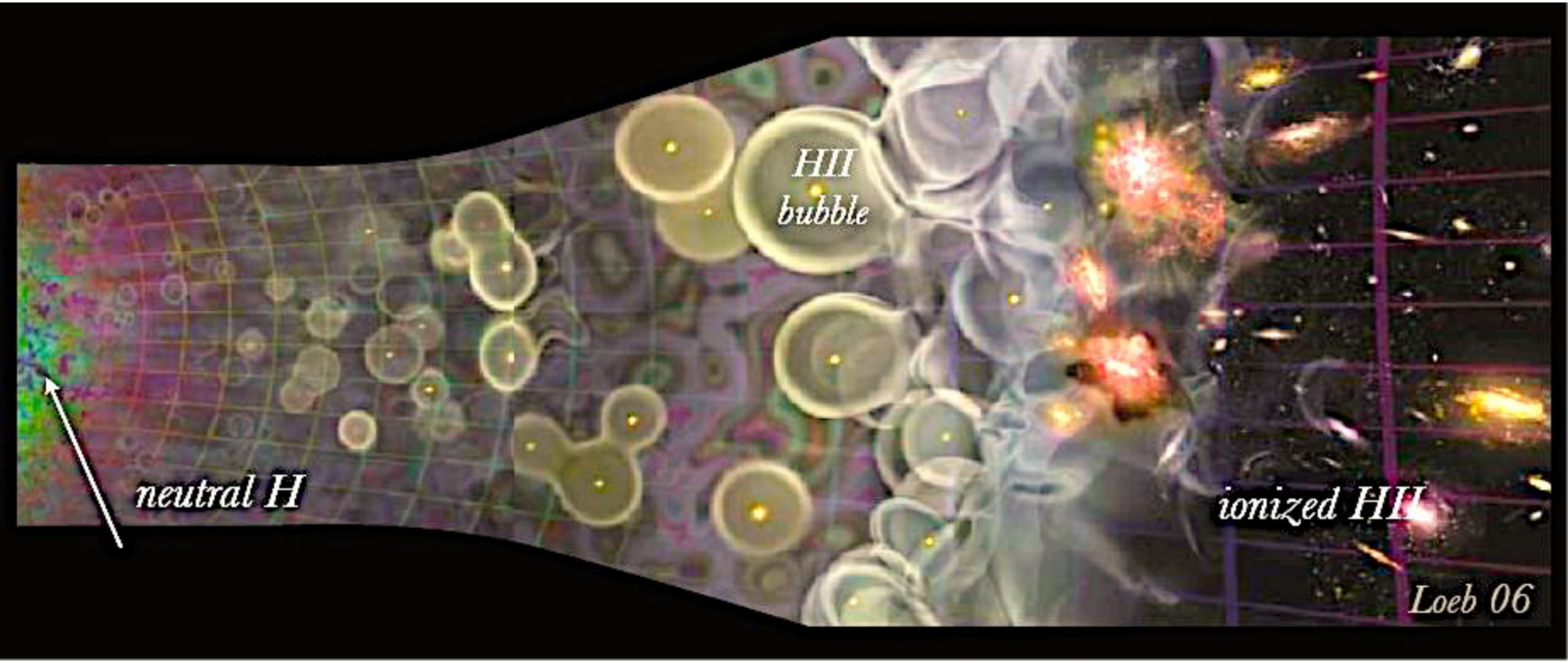
Toward SKA: pioneers

Giovanni Bignami
INAF
SKA Board Chair

Ger de Bruyn
ASTRON
LOFAR, SKA

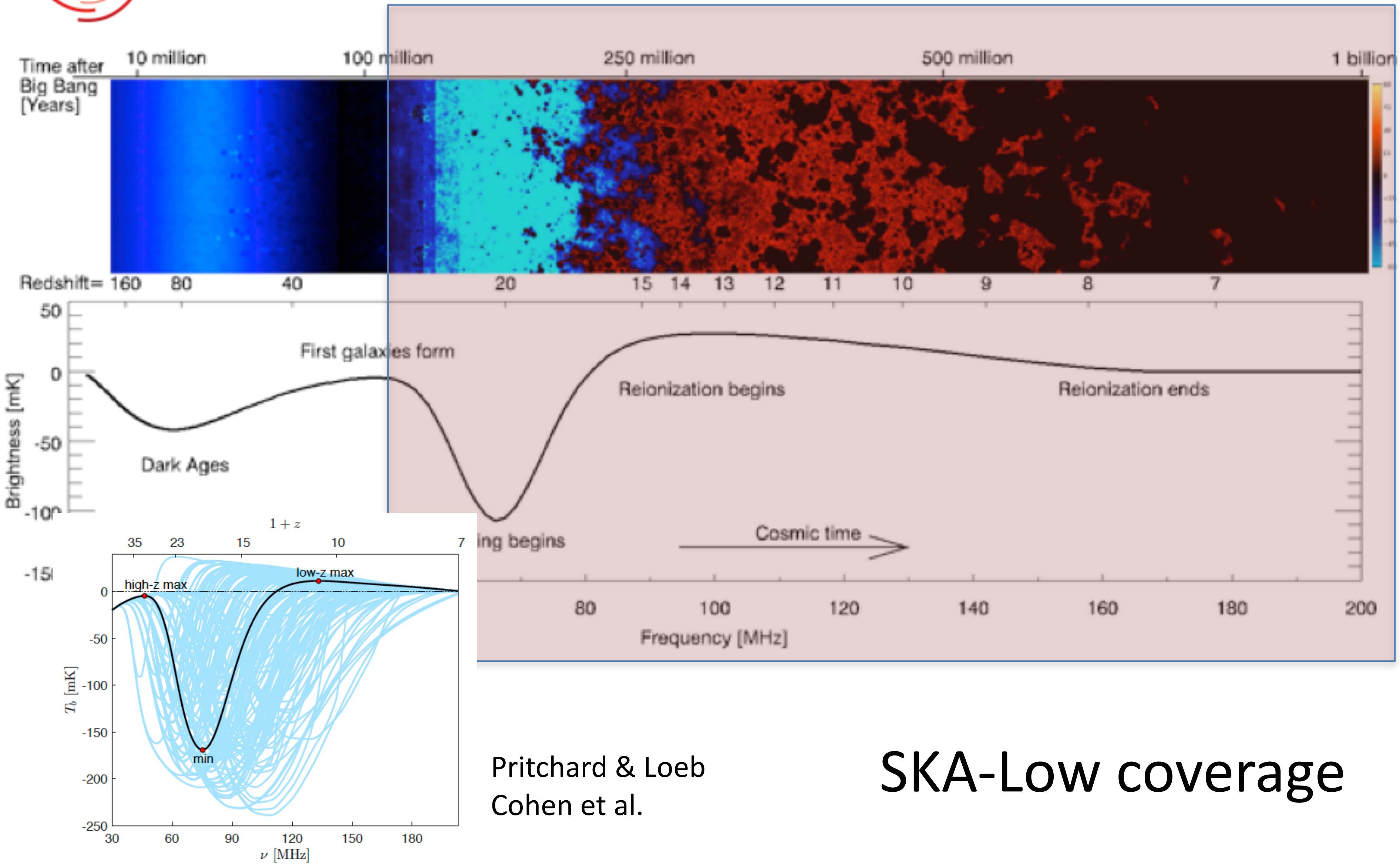
Nan Rendong
NAOC
Founder, FAST

EoR/CD: z=5.5-27 HI temperature fluctuations



Mapping the distribution of neutral hydrogen in the first billion years of the Universe

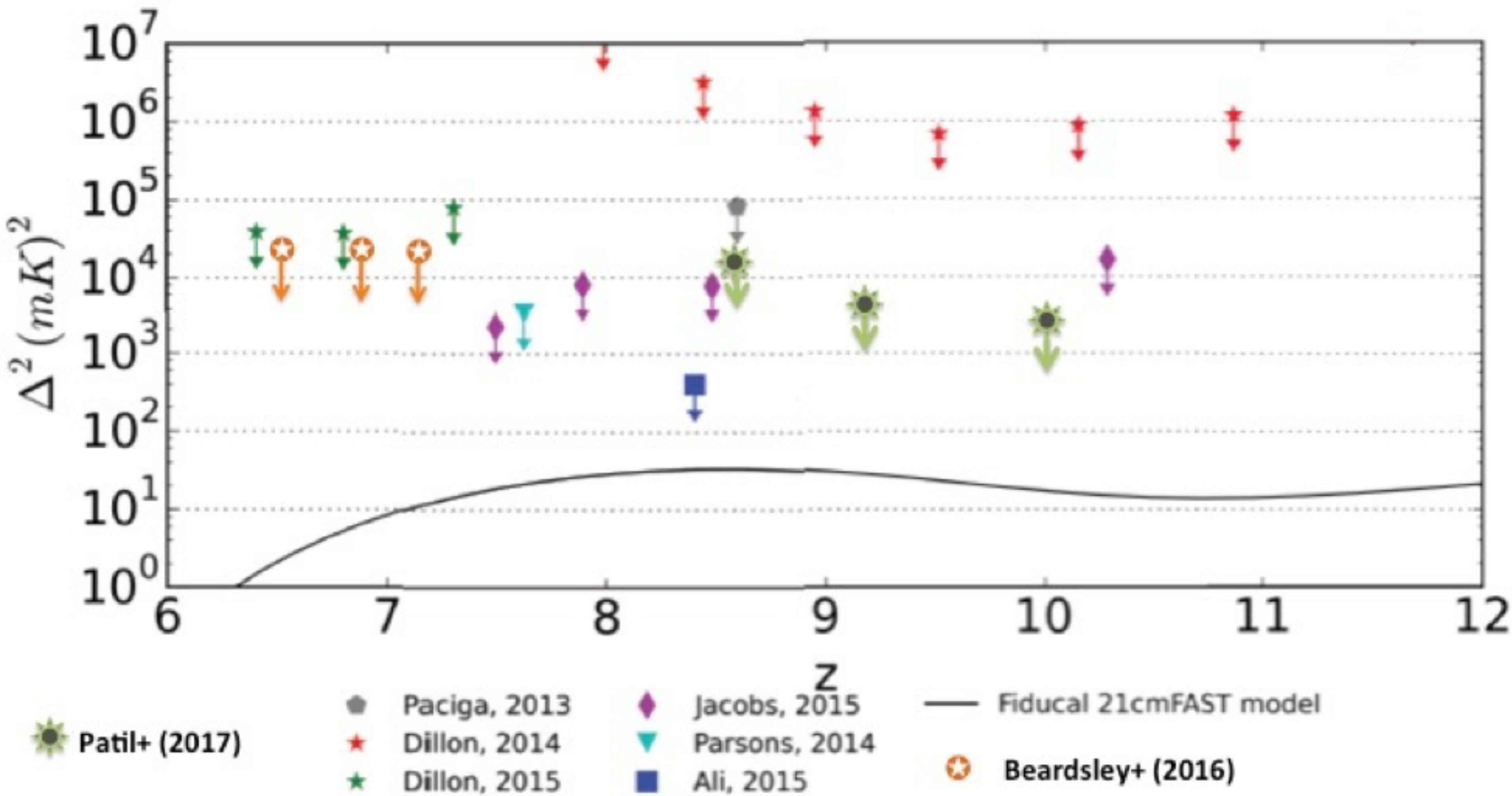
EoR/CD: z=5.5-27 HI temperature fluctuations



Pritchard & Loeb
Cohen et al.

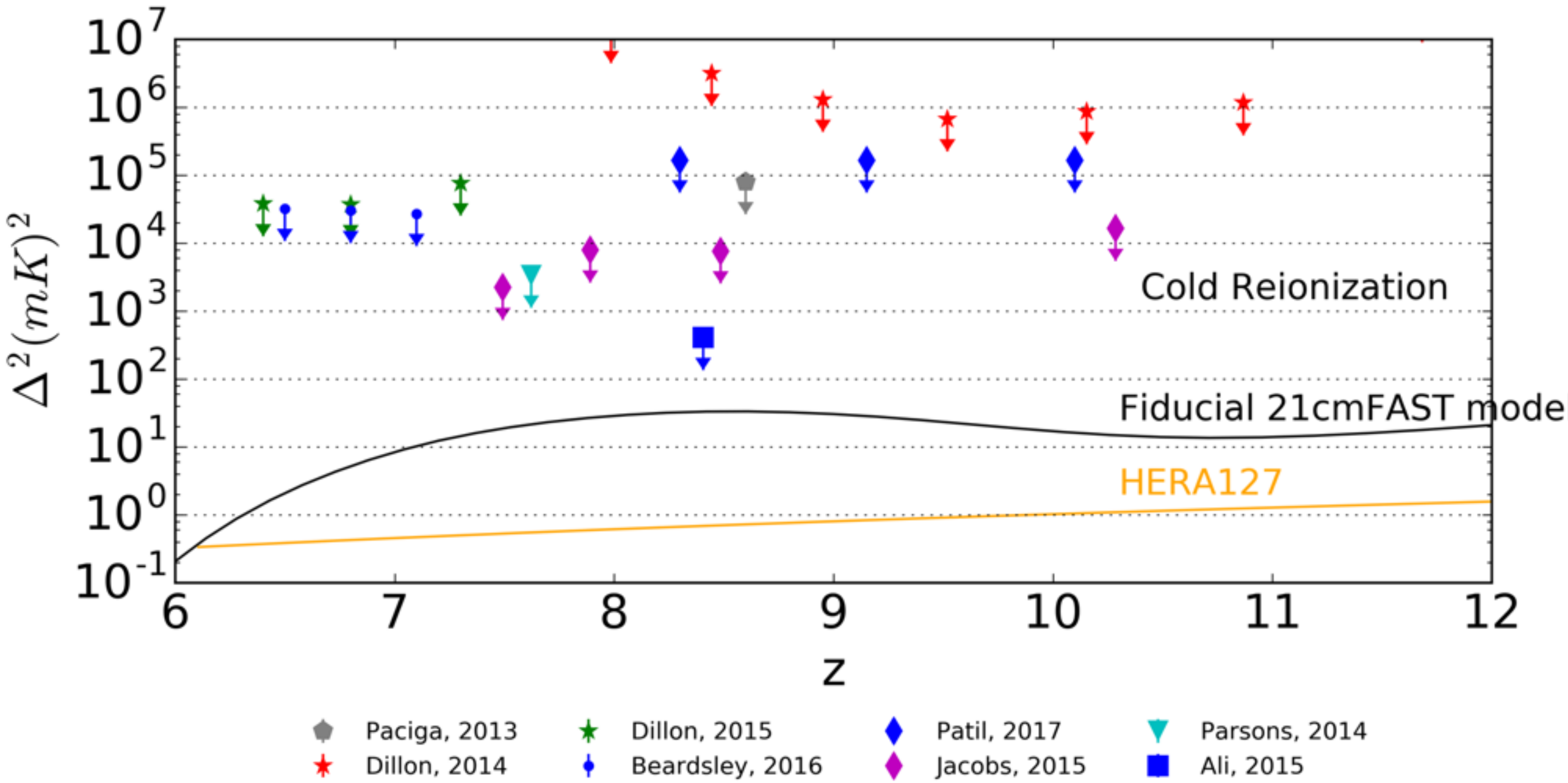
SKA-Low coverage

Current state of the field (any spatial wavemode)



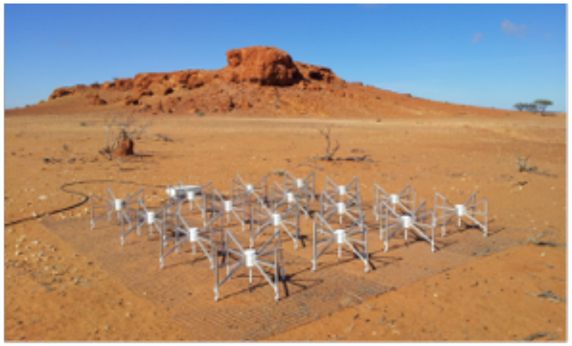
Adapted from de Boer+ (2016)

Current state of the field (k=0.1 Mpc^{-1})



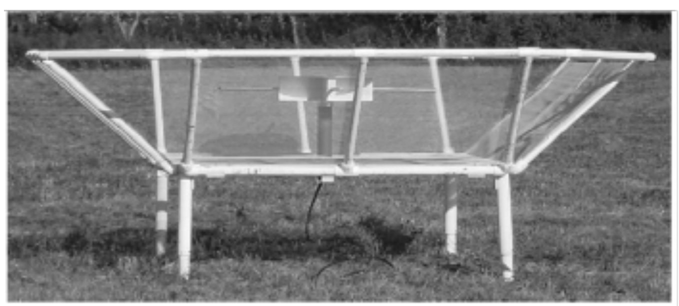
Courtesy Danny Jacobs

Pathfinder instruments: LOFAR, MWA, PAPER, GMRT, LWA



- Murchison Widefield Array (MWA; Australia)
- z = 6-10
- Resolution: 2 arcmin
- Array diameter ~3km
- Effective collecting area: 3,500 m^2

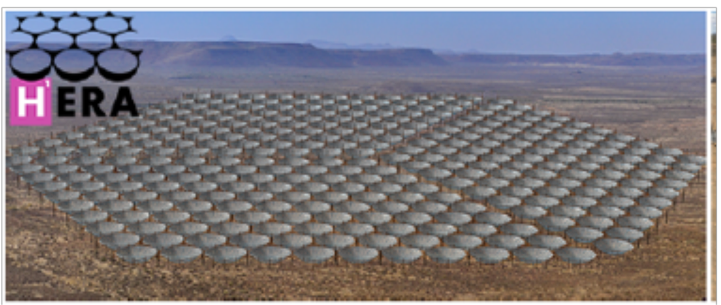
- Low-Frequency Array (LOFAR; Netherlands)
- z = 8-10.6
- Resolution: 4 arcsec
- Array diameter ~70km
- Effective collecting area: 18,000 m^2



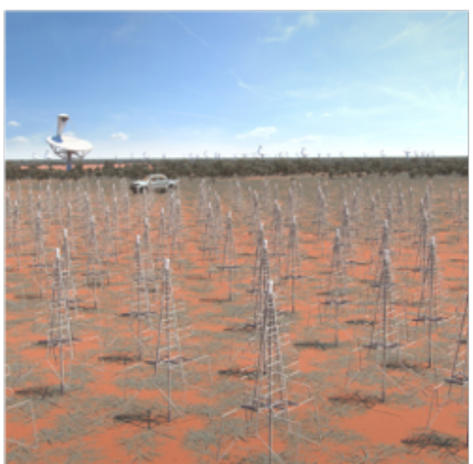
- Precision Array for Probing the Epoch of Reionisation (PAPER; USA, South Africa)
- z = 8-10.6
- Resolution: 30 arcmin
- Array diameter 200m
- Effective collecting area: 1,100 m^2

Future instruments: SKA, MWA++, HERA, LEDA

- Murchison Widefield Array Phase 2->3 (MWA; Australia)
- z = 6-11
- Resolution: 1 arcmin
- Array diameter ~5km
- Effective collecting area: 7,000 m^2

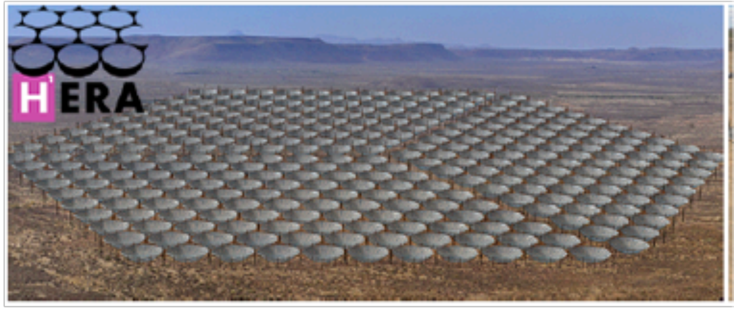


- Hydrogen Epoch of Reionisation Array (HERA; USA/South Africa)
- z = 6-13
- Resolution: 15 arcmin
- Array diameter 400m
- Effective collecting area: 53,000 m^2



- Square Kilometre Array (SKA; Australia, international)
- z = 4-27
- Resolution: 3 arcsec
- Array diameter 50km
- Effective collecting area: 400,000 m^2

How to design an EoR experiment

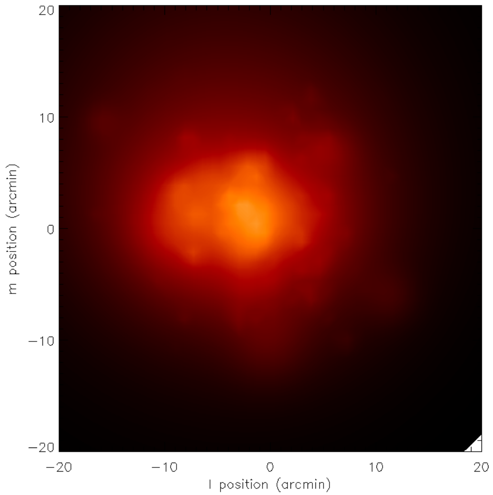


How does one design a 21cm EoR experiment?

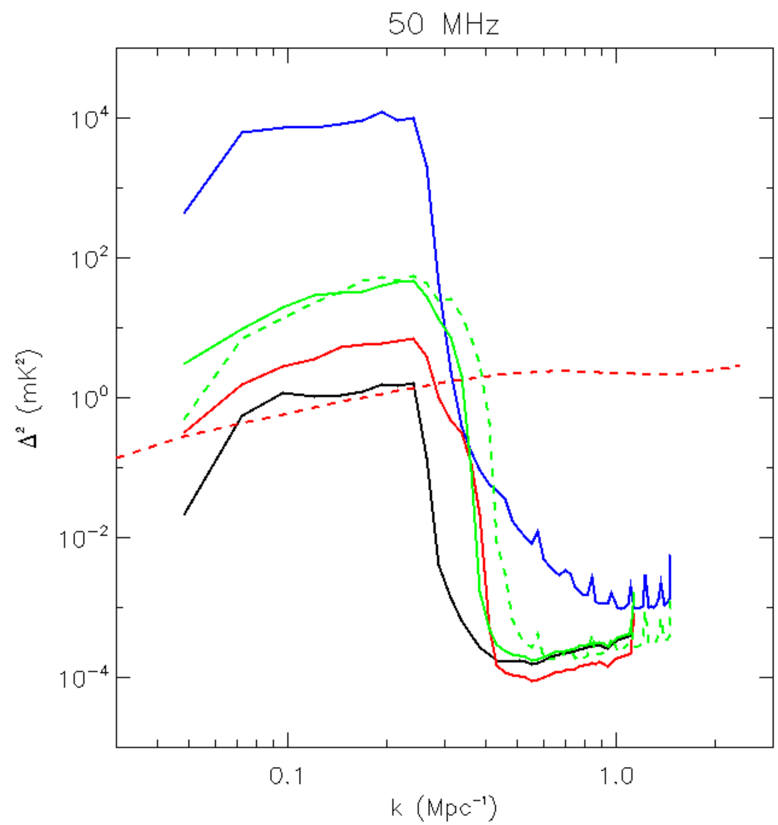
Steps	Mode	Resolution	Array size
Instrument calibration	Redundant baselines	10s arcmin —> degrees	100s metres (EoR scales)
Instrument calibration	Fit for sky model	arcseconds	1000s metres (or longer)
Sky model subtraction	Internal instrument model	arcseconds	1000s metres (or longer)
Sky model subtraction	External instrument model	arcseconds	1000s metres (or longer)
Power spectrum		10s arcmin —> degrees	100s metres (EoR scales)

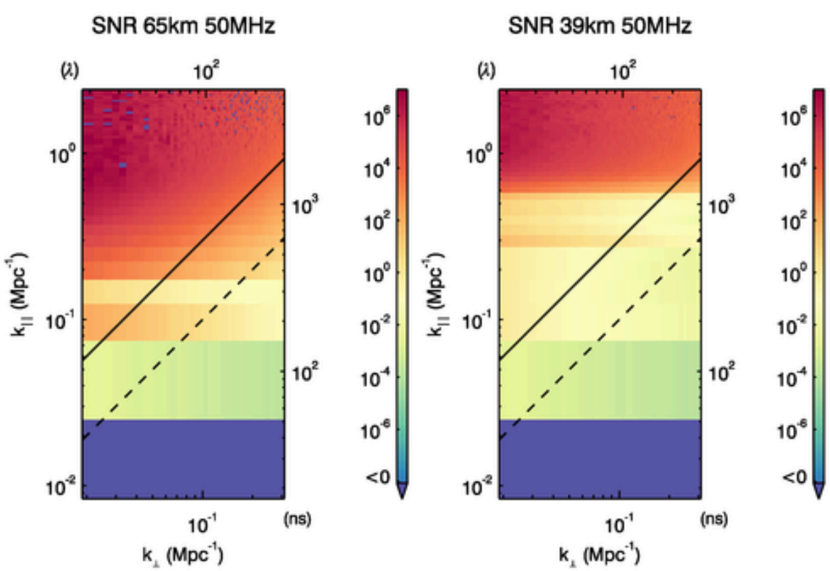
Challenges of calibration: building the sky model

-- SKA will build its own sky model
-- Important to understand impact of calibrating on models built from the same instrument.

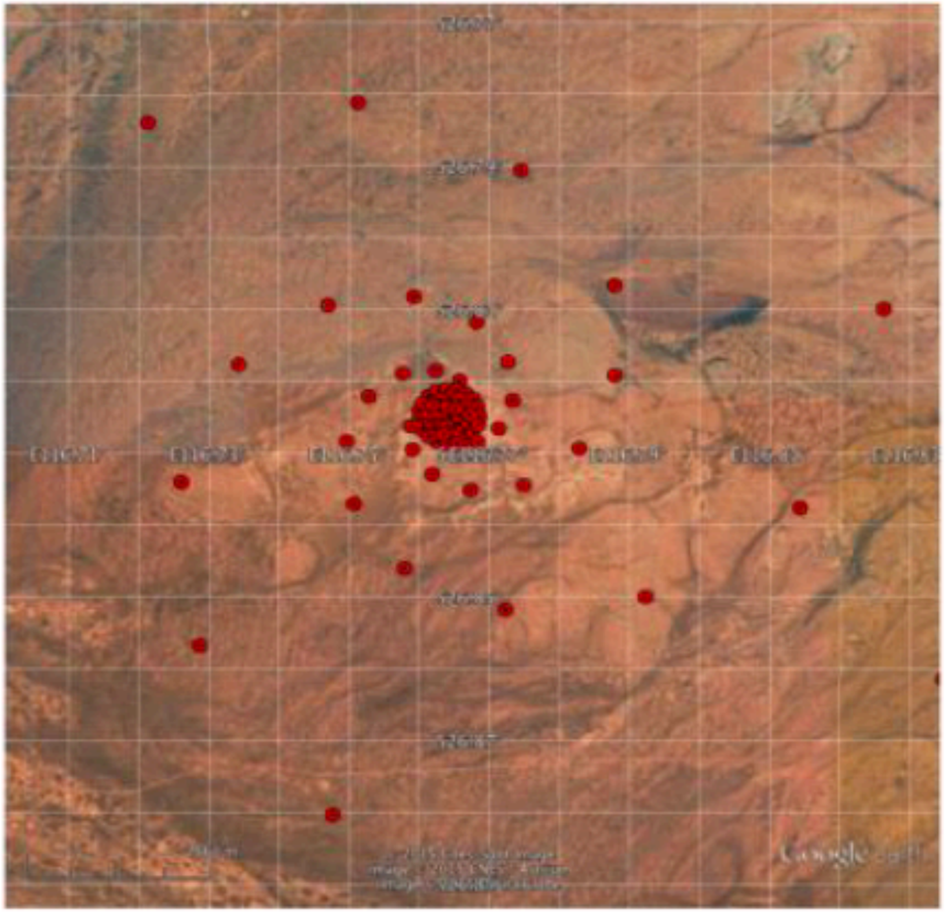


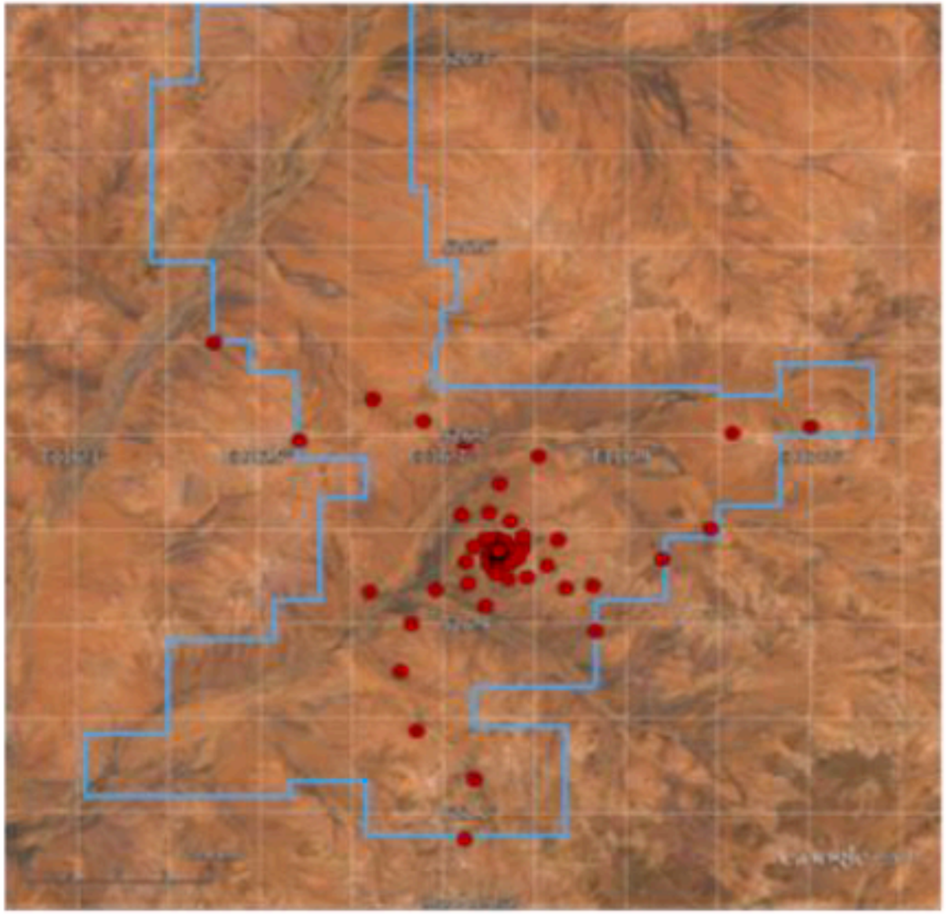
1D PS in Cosmic Dawn with calibration errors of extended sources





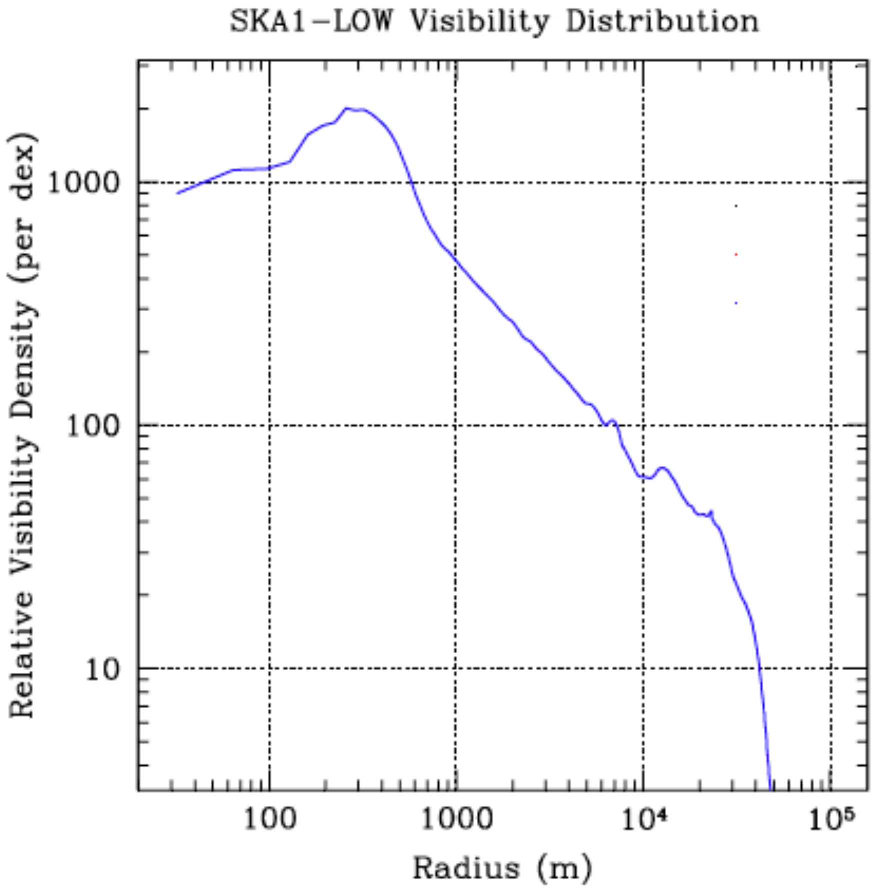
SKA-Low core and extended configuration

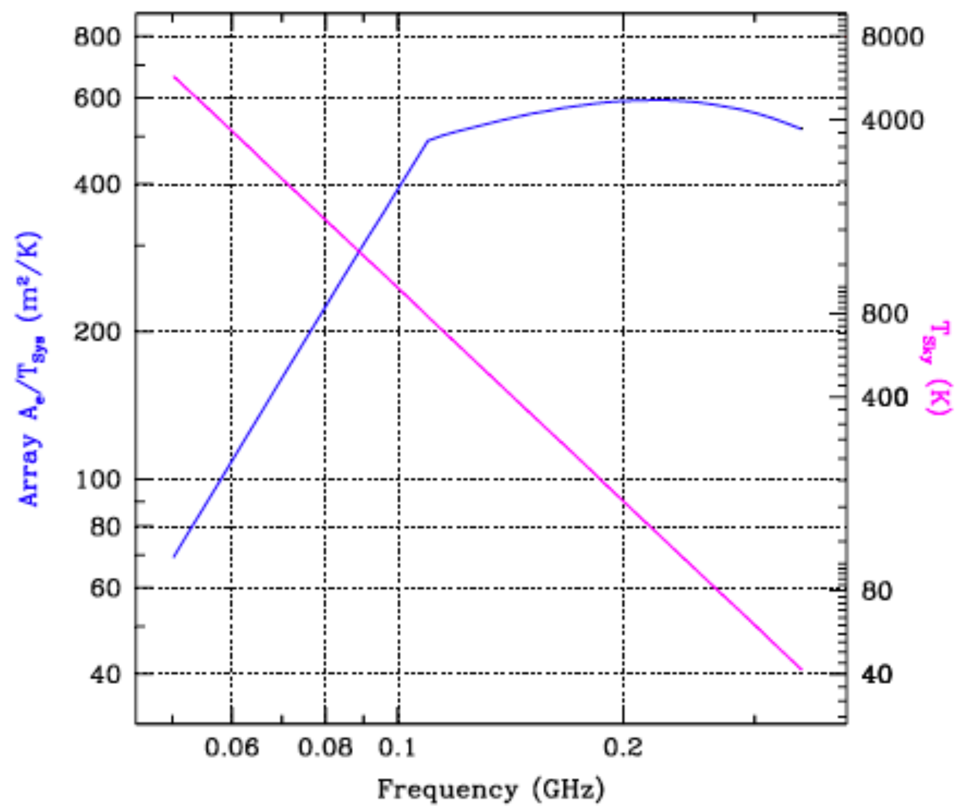




Murchison Radioastronomy Observatory site: shared with MWA, ASKAP, Bighorns, EDGES

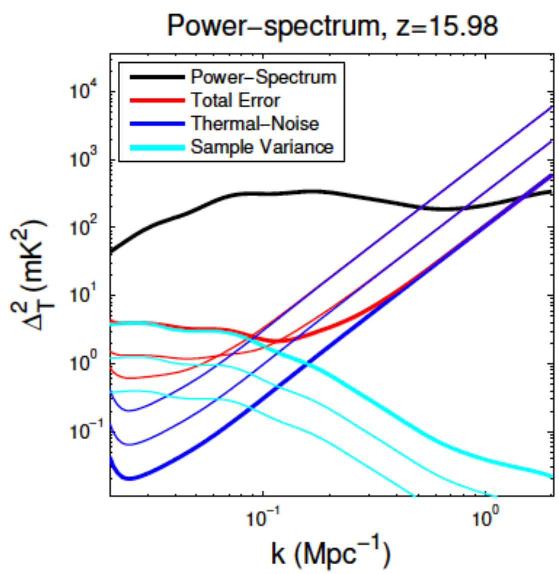
The SKA-Low telescope – compact core

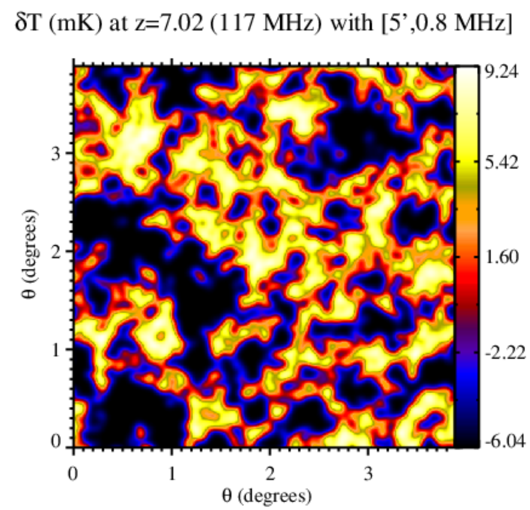


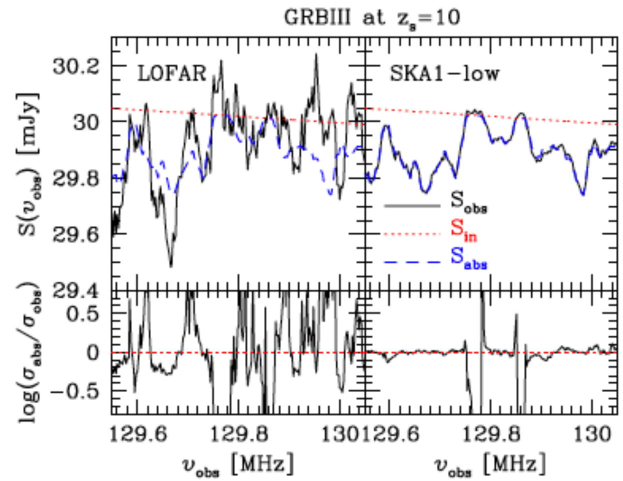


Filling factor within inner 1 km is ~1

Three experiments: statistical, imaging, spectral line







Power spectrum; skewness; wavelet spectrum; PDF

Imaging in matched spectral bands, T_B

HI 21cm Forest: absorption against high-z sources (QSOs, GRBs)

EoR/CD suite of experiments – tiered surveys

Power Spectrum

Tomography

HI absorption

Shallow
2 beams

10,000 sq. deg = 4 sr; b>30 degrees; BW = 50-250 MHz
10 hours/field; drift scan; Δt = 5-10s; Δν = 5 kHz (averaged to 40-100kHz)
2,500 hours

Medium
2 beams

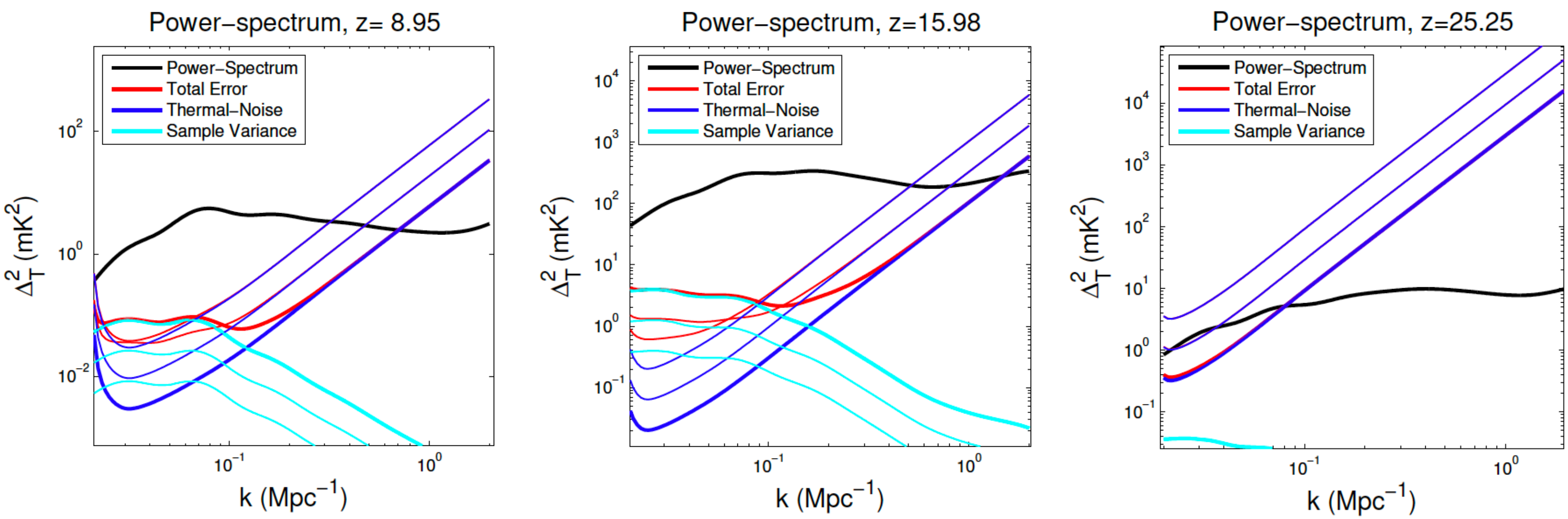
1,000 sq. deg; **b>20** degrees; **BW = 50-350 MHz**
100 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz)
2,500 hours

Deep

100 sq. deg; b>30 degrees; BW = 50-250 MHz
1000 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz) **2,500 hours**

HI Forest: absorption line; targetted toward high-z continuum AGN
1000 hours**; Δν = 1 kHz; **50-350 MHz**

Motivation for tiered surveys: balance sample variance and thermal noise



$T_{sys} \propto \lambda$ → thermal noise-limited at high redshift
FOV $\propto \lambda^2$ → sample variance-limited at low redshift

Shallow-wide survey guides deep survey fields
Shallow-medium-deep optimise different k → different physical insight
Smaller stations improve thermal noise

Power spectrum – noise considerations

- Sample variance determined by number of measurements of a given mode in the observation volume: bigger FOV = less sample variance
- Sample variance scales as: $\Delta^2 \propto D$

- Thermal noise scales as:

$$\Delta^2 \propto D$$

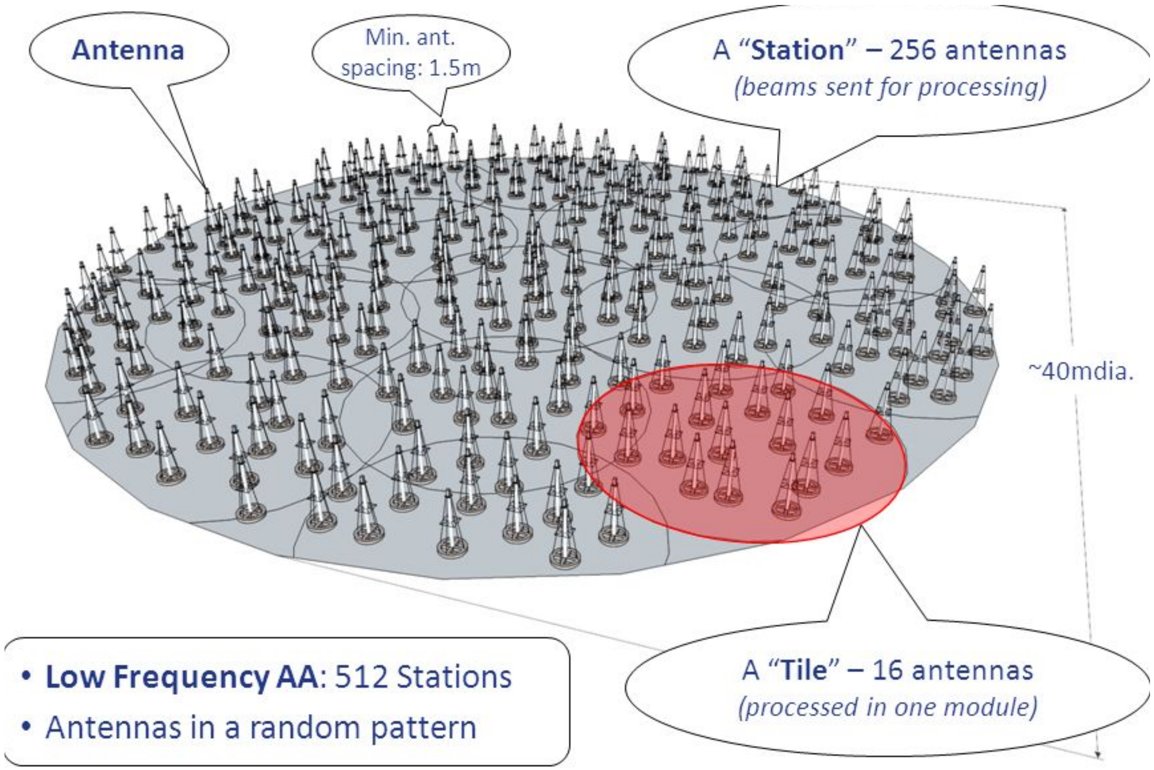
  - Therefore, for *constant collecting area* and core size

$$\Delta^2 \propto \sqrt{A_{eff}}$$

  - ***Smaller stations are better for sample variance and thermal noise, assuming no loss in sensitivity***

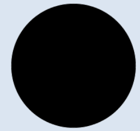
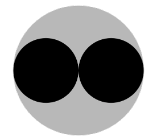
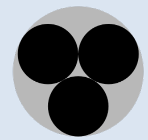
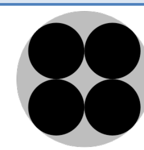
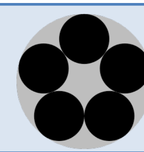
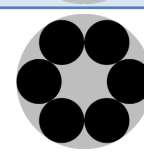
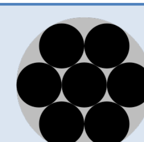
Power spectrum – sub-arrays

- Form sub-arrays of smaller stations for CD → larger FOV + shorter baselines

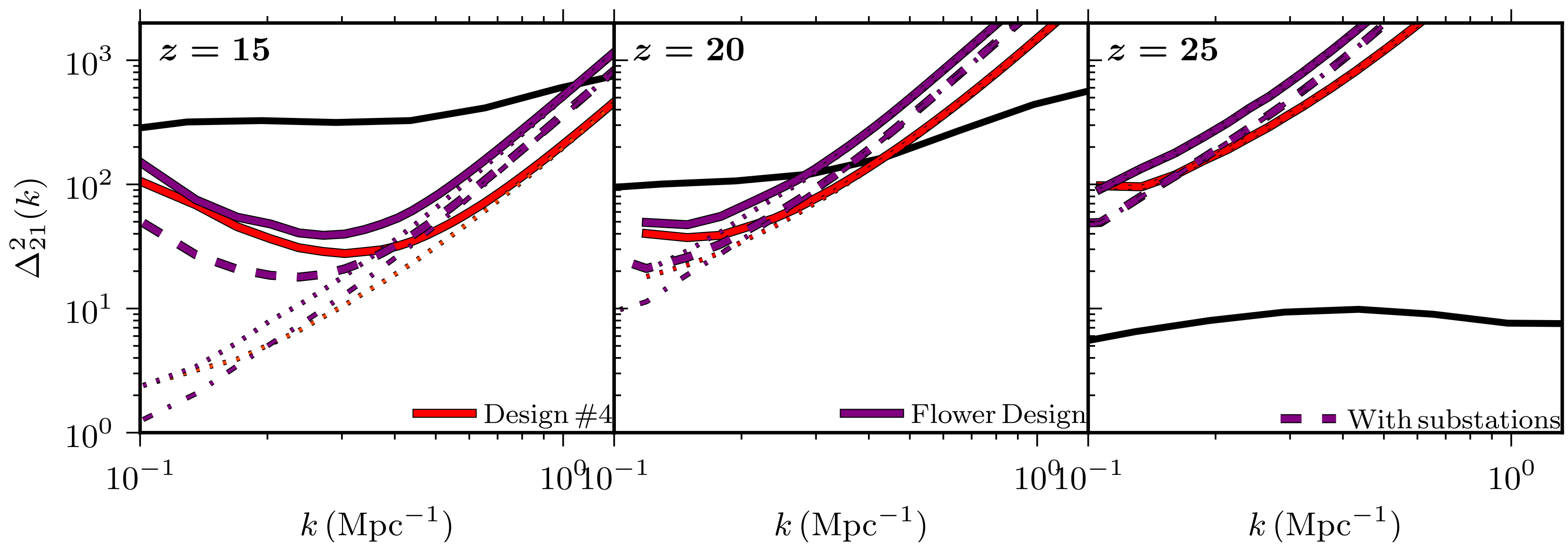


Courtesy: Andy Faulkner

Power spectrum – packing problem

# circles	Radius (cf unity)	Density	Optimal configuration	Δ^2 (V4A)	Δ^2 (V4D)
1	1	1		1	1
2	0.5	0.5		0.5	2
3	0.46	0.65		0.46	1.11
4	0.41	0.69		0.41	0.88
5	0.37	0.69		0.37	0.79
6	0.33	0.67		0.33	0.55
7	0.33	0.78		0.33	0.56

Power spectrum – sensitivity – “high” z



Brad Greig and Andrei Mesinger

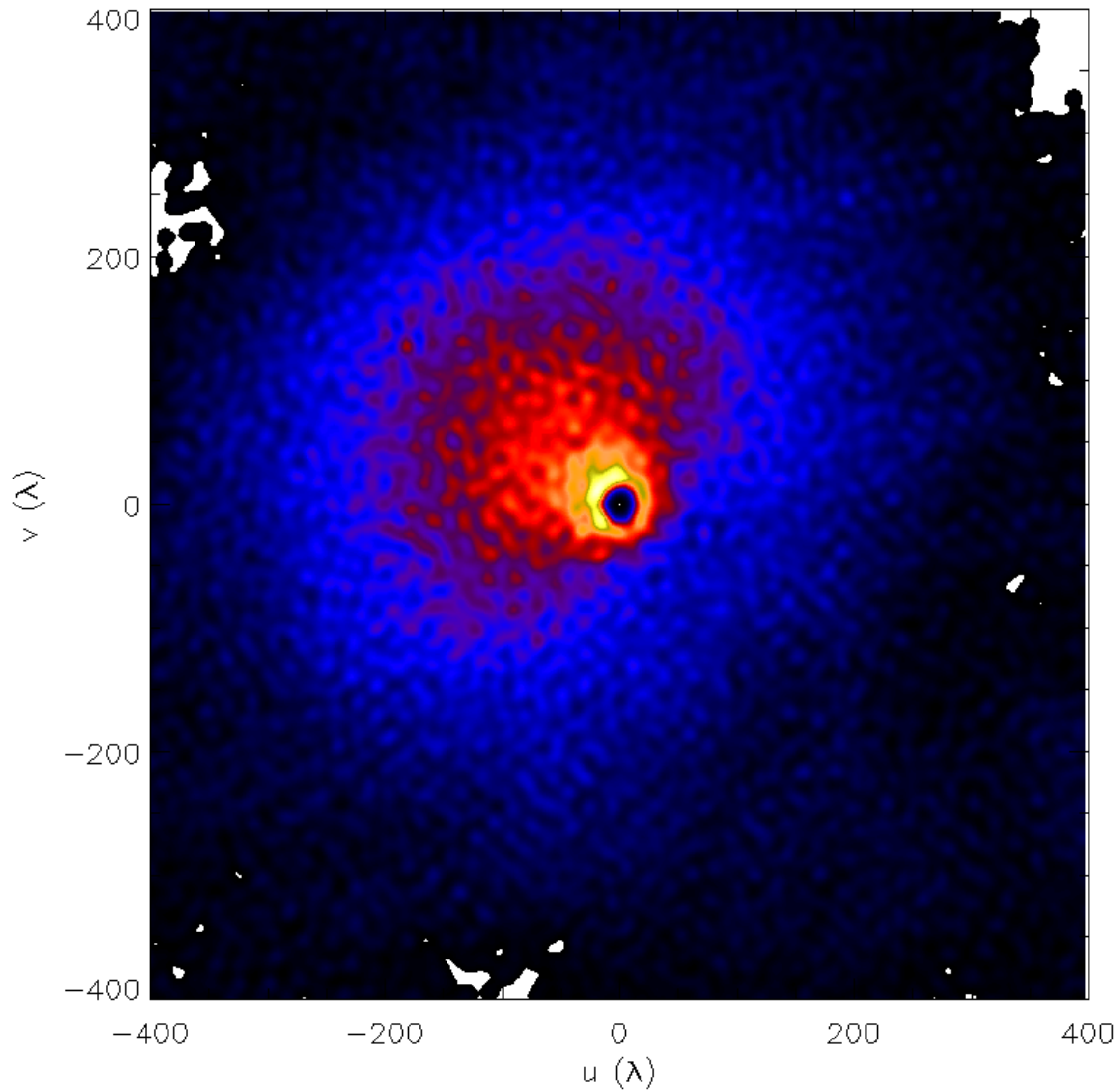
Sample variance reduced for substations for z < 20

Thermal noise slightly reduced (when full sensitivity retained)

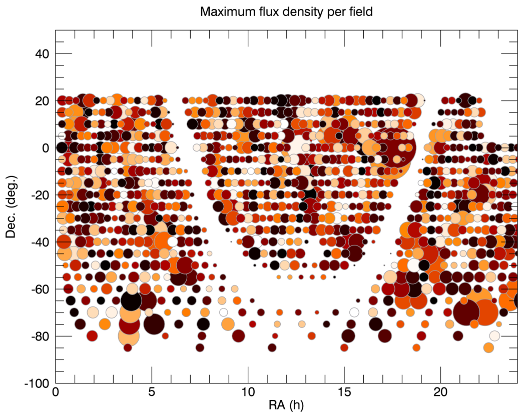
Motivation for tiered surveys: quasi-redundancy in a dense core leads to substantial correlation

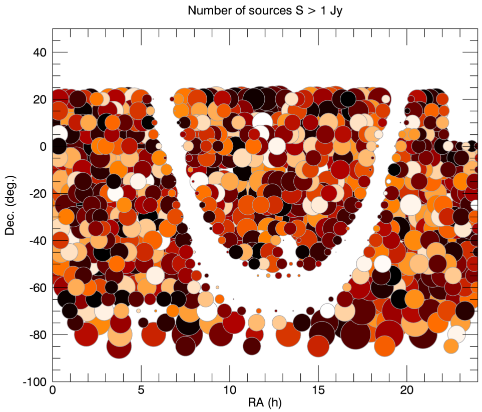
Density of gridded baselines in uv plane.

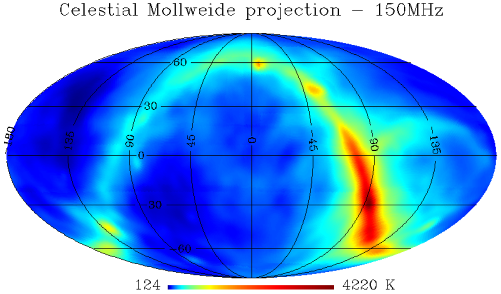
Mode-mixing is reduced and algorithms can be optimised to account for coherence of baselines

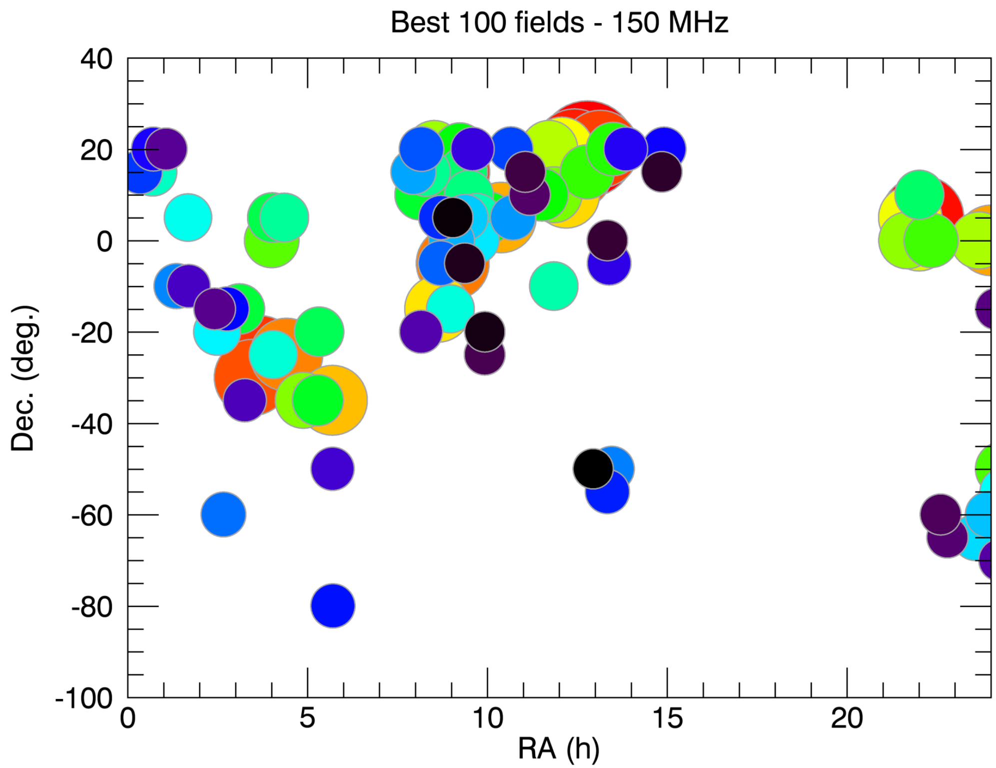


Observing fields for tiered surveys (Observational Strategies FG)





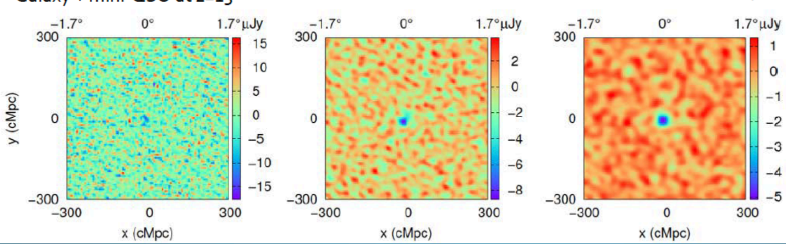




Synergy with other wavelengths/experiments (Zackrisson, Ferrara, Dayal)

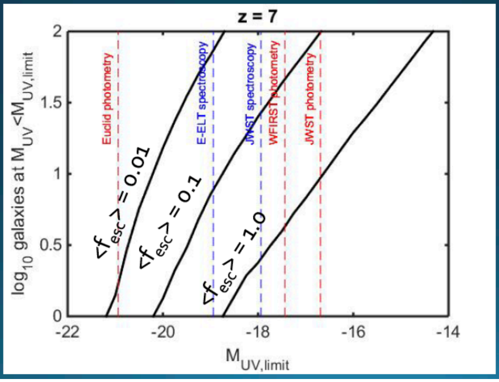
Recent updates I: Quasars

- Quasar project: 21 cm signatures of individual objects (quasars, galaxies) up to z=15
  - Datta, K. et al. 2016, arXiv1610.08177
  - Ghara, R. et al. 2017, MNRAS 464, 2234
  - Ghara, R. et al. 2016, MNRAS 460, 827



Recent updates II: Deep surveys of individual bubbles

- Preliminary results distributed within team, paper in prep.
- ≈30 spectroscopically detectable galaxies expected in IGM bubbles that SKA-1 can resolve at z ≈ 7-10



Recent updates III: Large-field surveys for LAEs –Subaru/HSC

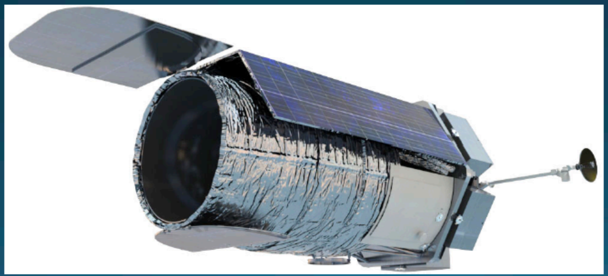
- Northern hemisphere telescope, but survey at dec ~ -30 deg is in principle possible
- Lyα in Δz≈0.1 slices at z≈ 6.6 and 7.3
- Forecasts in Hutter et al. (2017, ApJ, 836, 176)
- Coordinated HSC+ SKA survey possible, but not until 2022+

Hyper Suprime-cam (HSC), 1.8 deg² FoV

This meeting: LBGs & LAEs with WFIRST

WFIRST deep field(s):

~20 deg² multiband imaging @ 0.8-2 μm to ~ 28 AB mag and R~600 grism spectroscopy to ~ 10^{17} erg/s/cm²

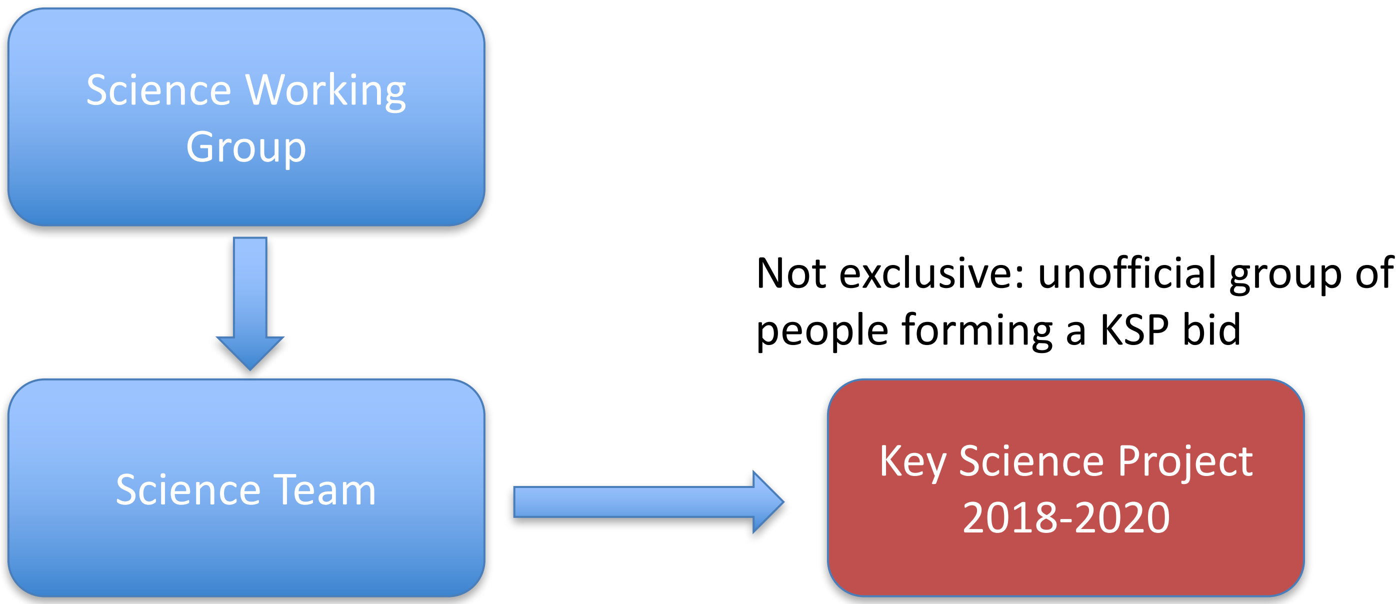


WFIRST, 2.4m, 0.28 deg² FoV, launch around 2025

Science Working Group

Chairs: Jonathan Pritchard (Imperial College London)
Garrelt Mellema (SW Representative)

Board: Leon Koopmans (NL Representative)
Gianni Bernardi (SA Representative)
Cath Trott (AU Representative)
Abhirup Datta (IN Representative)
Andrei Mesinger (IT Representative)
Xuelei Chen (CN Representative)



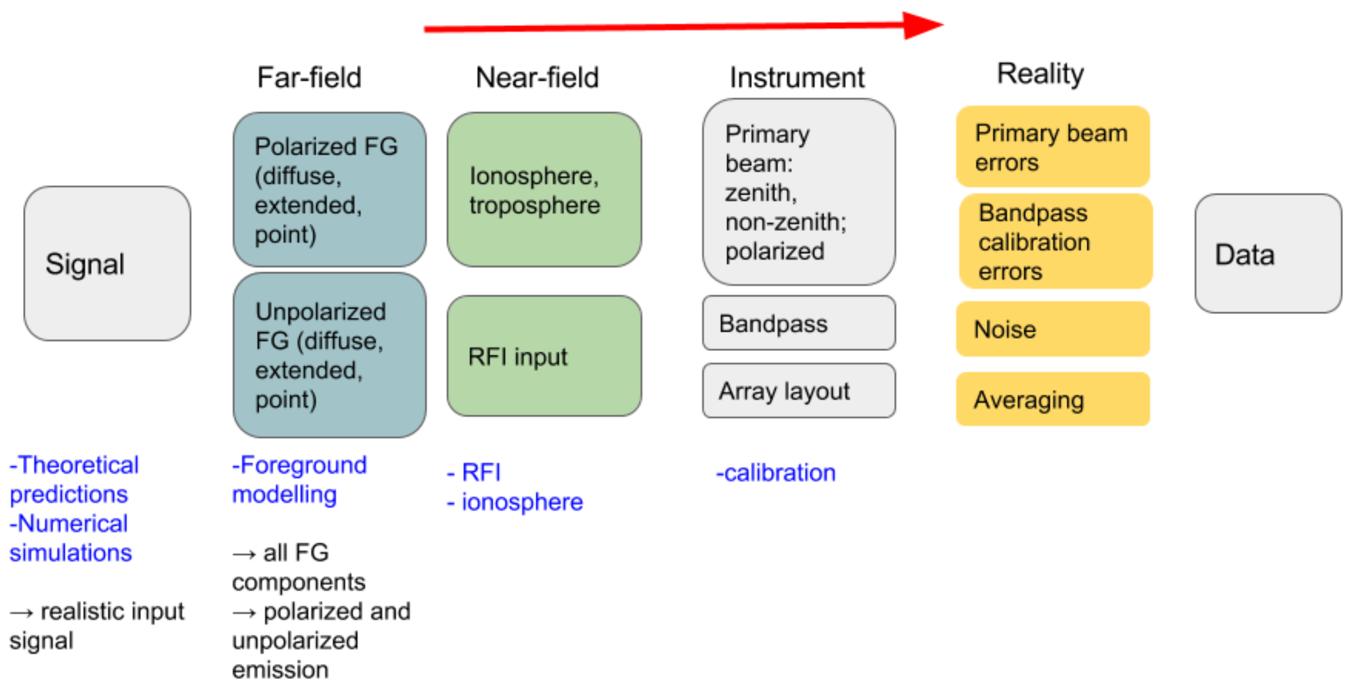
Science Team → KSP → E2E Simulations

Lead: Leon Koopmans (Kapteyn Institute)

Science Working Group

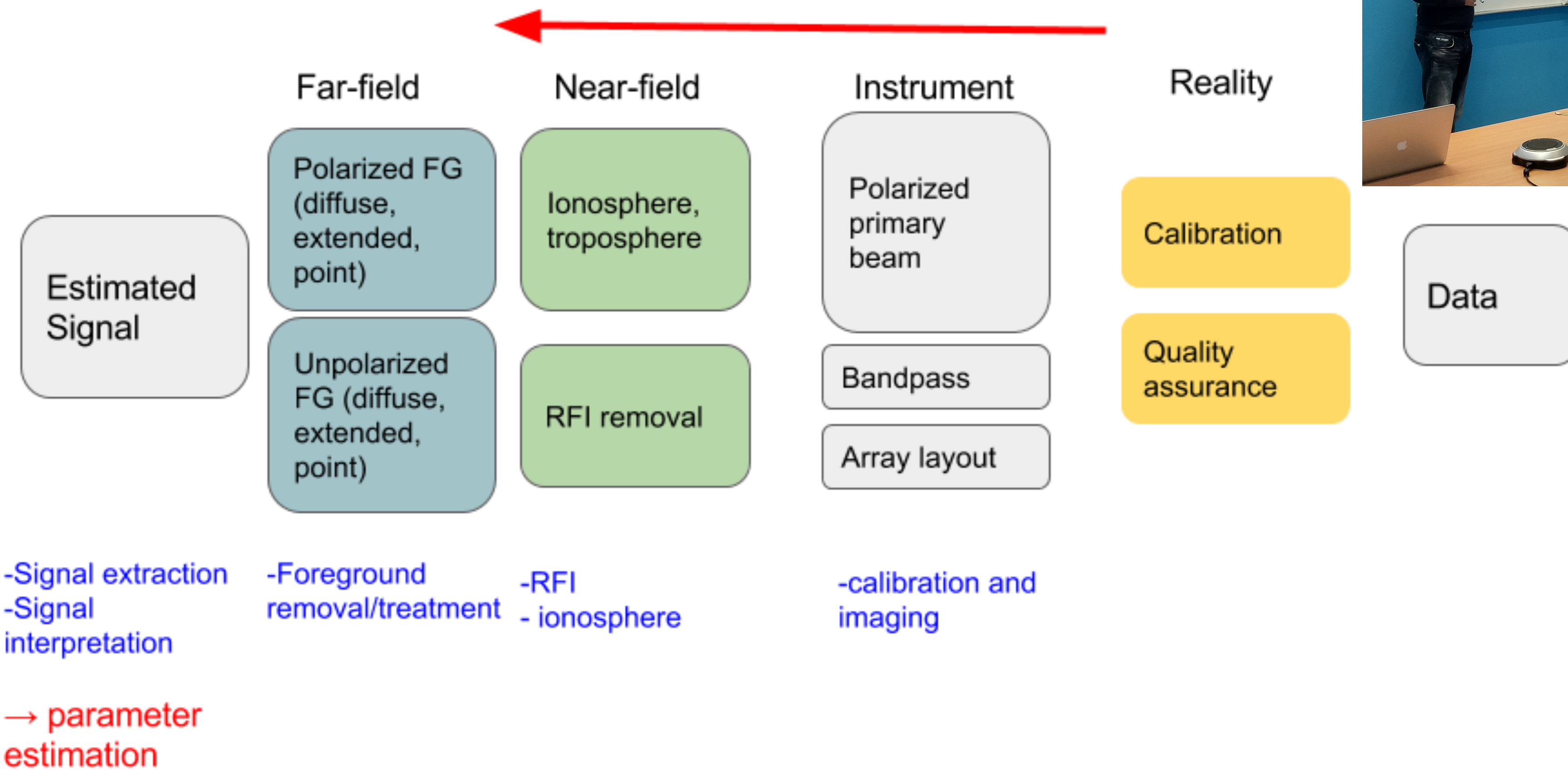
>50 members across ~15 countries

Input Components



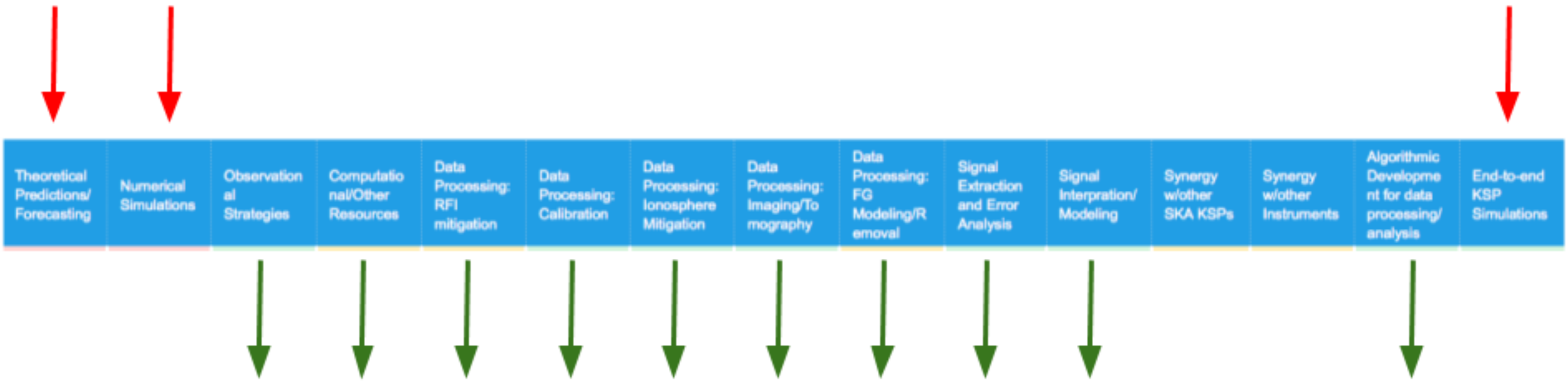
Science Team → KSP → E2E Simulations

Extraction Components



Science Team → KSP → Focus Groups

Umbrella task - Input + Extraction



2017-2018: Development of blind data challenge for power spectrum estimation. Open to the community

KSP Focus Groups

A) Theory/Numerical Simulations

A1: Theory/Physics for understanding model space/subgrid physics

A2: Full numerical simulations for calibration

A3: Fast simulations for analysis

A4: Foreground Studies and simulations

B) Observational Strategies

B1: Interferometric

B2: Global Signal

B3: 21cm Forest

C) Data Processing

C1: RFI Excision

C2: Calibration/Ionosphere

C3: Imaging/Sky-model building

C4: Foreground Fitting/Removal

C5: New Algorithmic Development/Computational and Other Resources

D) Signal Extraction and Error Analysis

E) Signal Analysis and Interpretation

F) Synergy (SKA + Other instruments)

G) End-to-End (Data) Simulations

Science Team meetings

Stockholm, SW – August 2015

Groningen, NL – October 2015

Goa, IN – November 2016

Pisa, IT – March 2017

Zagreb, CR – October 2017

Summary

The EoR/CD Science Working Group is very active, collaborative and productive

The Science Team are developing a proposal for the five-year EoR/CD experiments

Blind data challenge (open to community) in development for 2017-2018

Development of the KSP has led to improved and productive collaboration between existing EoR instrument teams (in particular LOFAR and MWA).