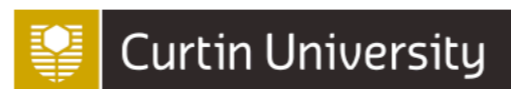




International  
Centre for  
Radio  
Astronomy  
Research

# Cosmic Dawn/EoR SWG

Cathryn Trott



THE UNIVERSITY OF  
WESTERN AUSTRALIA



# EoR and Cosmic Dawn

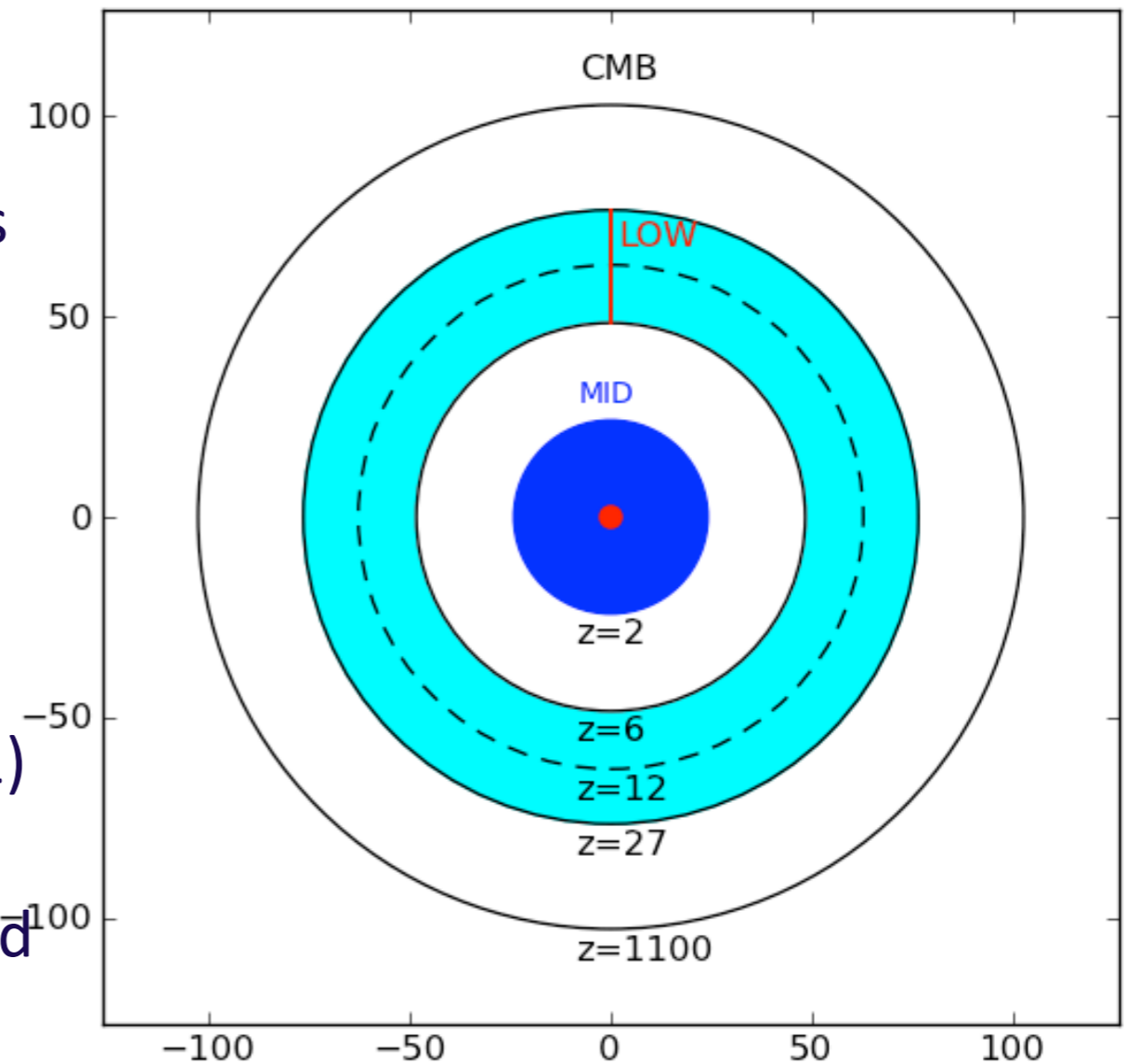
## Cosmic Dawn

$z \sim 12 \rightarrow 28$

Growth of structure; high sky temp. (1000s K); completely uncharted territory  
Epoch of Heating

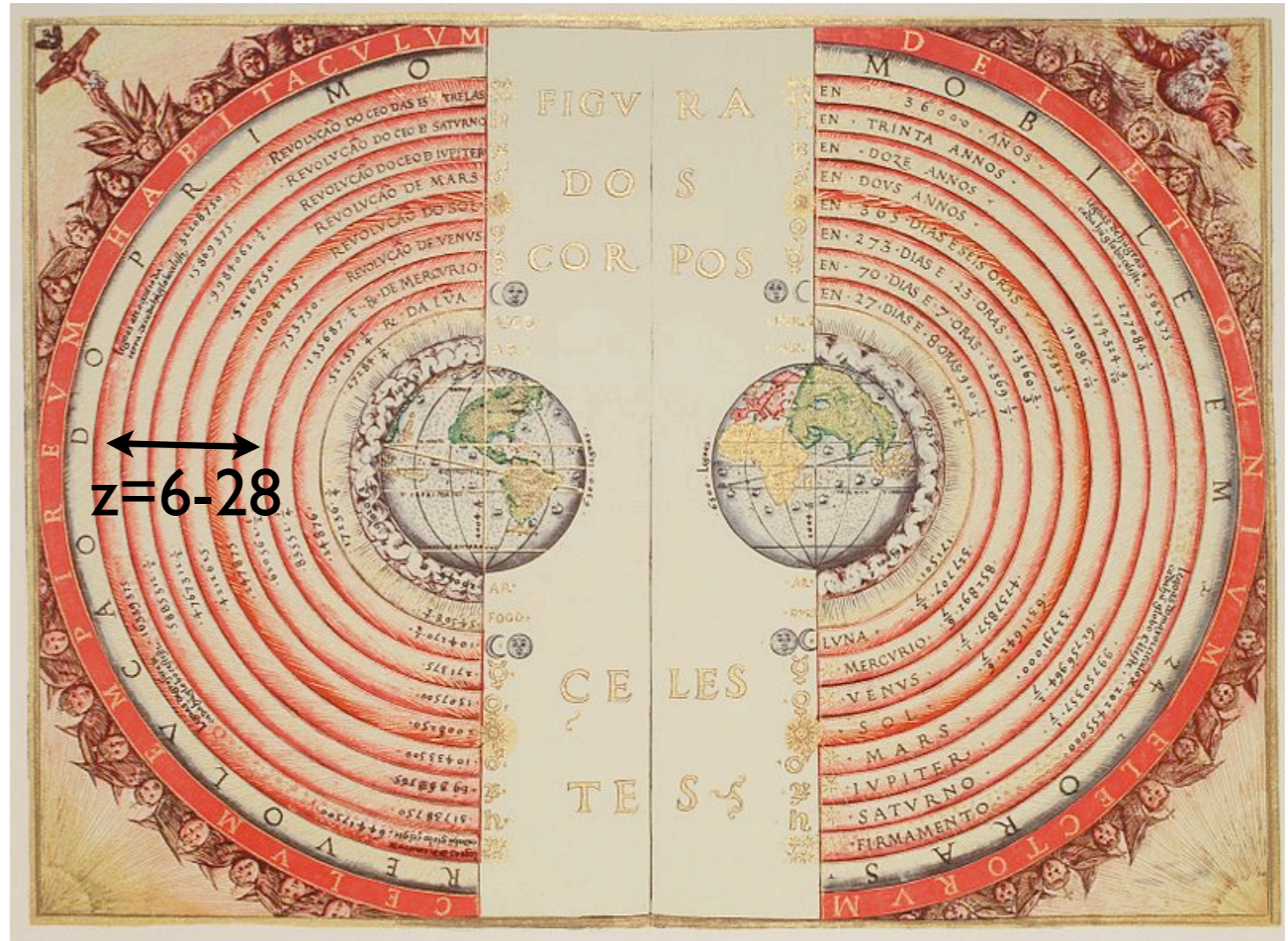
## Epoch of Reionisation

Framed by CMB Thompson scattering ( $z=11$ ) and  $z=6$  quasar spectra; lower sky temp. (100s K); chartered but relatively unexplored (MWA, LOFAR, PAPER...)



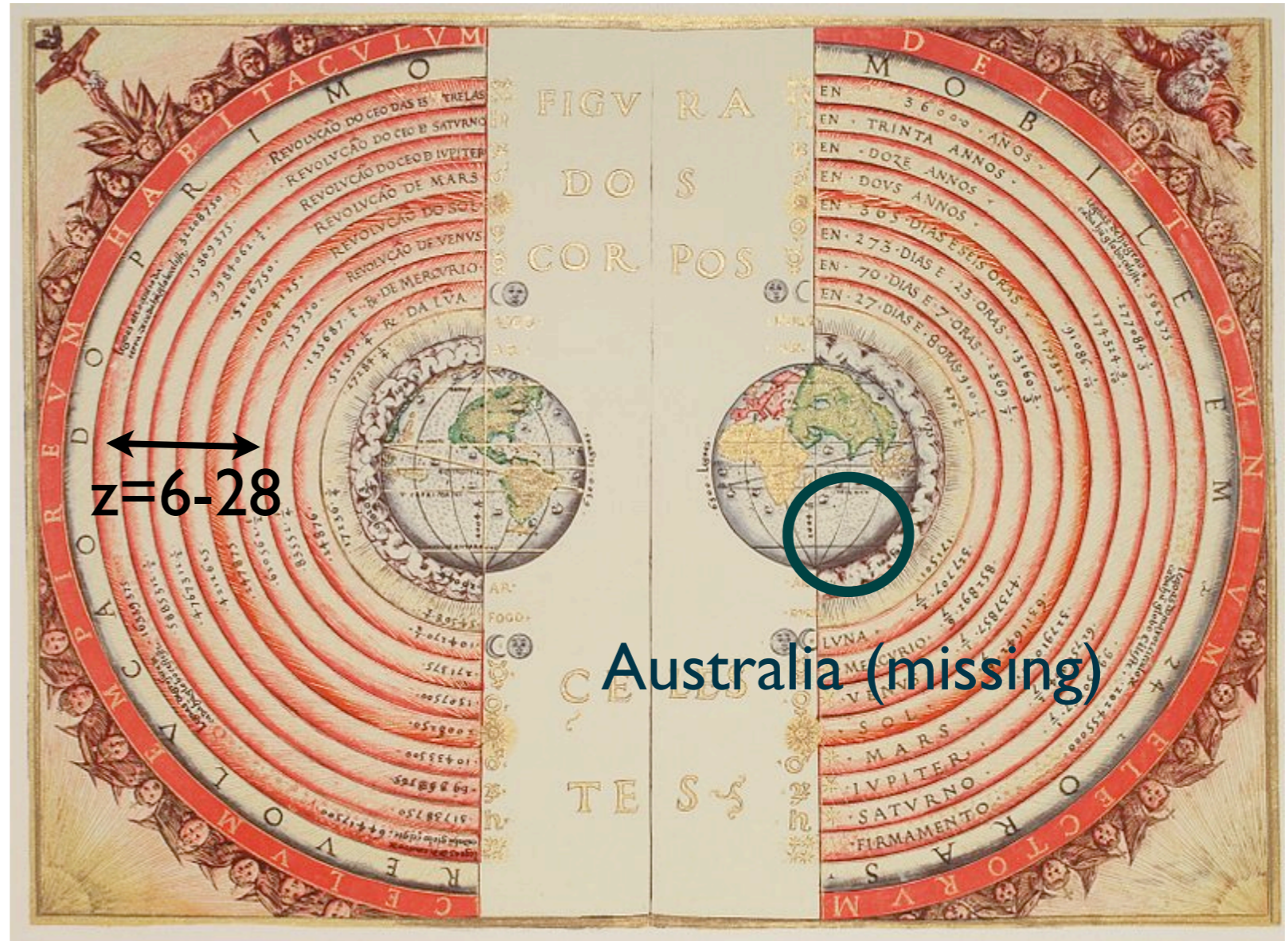
Pritchard+CD/EoR SWG (2015)

Terra (Western)  
Australis Incognita



Bartolomeu Velho, 1568

Terra (Western)  
Australis Incognita



Australia (missing)

Bartolomeu Velho, 1568



# Mission statement

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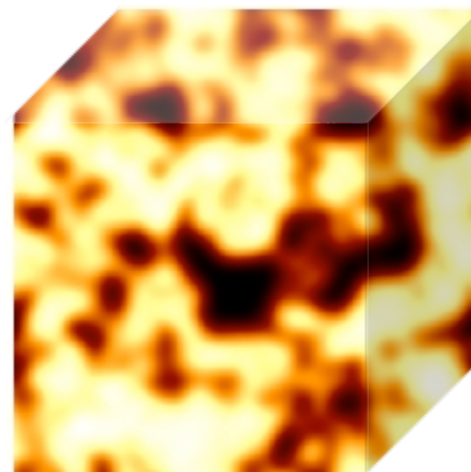
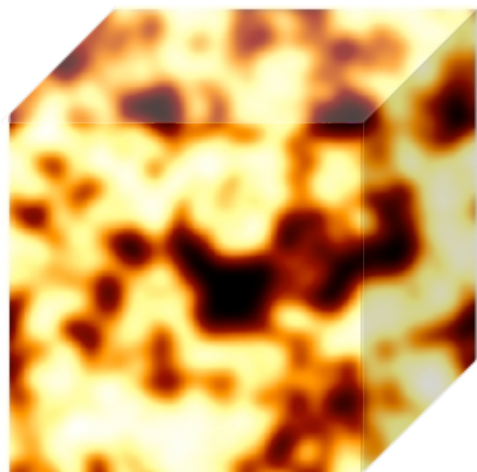
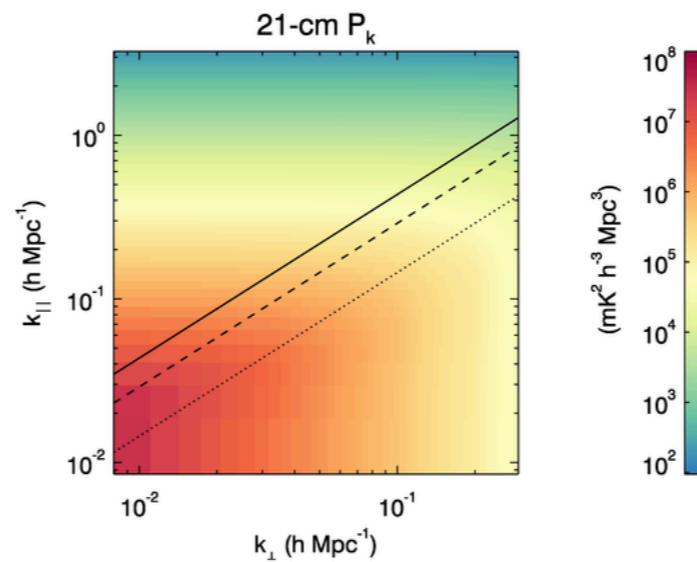
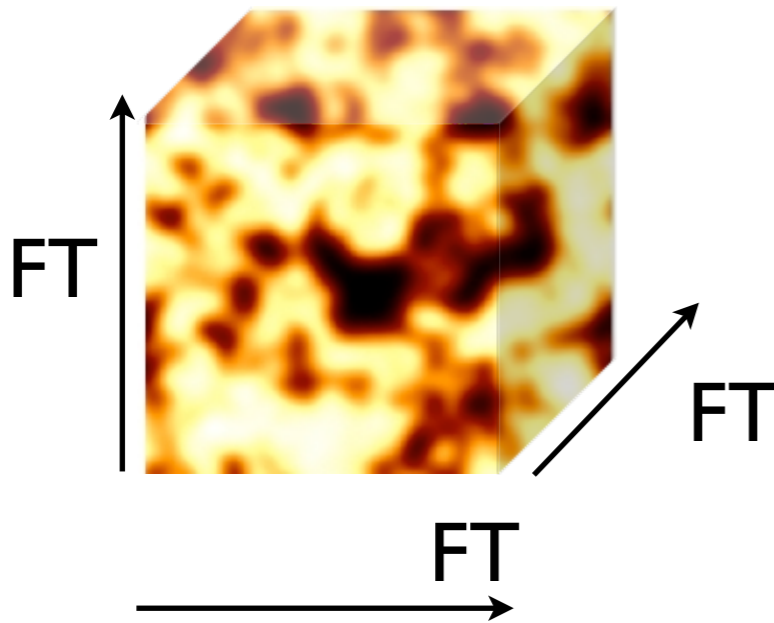
A SKA CD/EoR KSP should:

- Quantify observationally and understand, via theory and simulations, the formation and evolution of the first stars, galaxies, black holes, stellar remnants, IGM/ISM (HI and metals) and the underlying DM distribution, including feedback processes and physical mechanisms, covering the Dark Ages, Cosmic Dawn and Epoch of Reionization. Carry this program out in the context of the  $\Lambda$ CDM model (or alternatives or modifications thereof) in the redshift regime of  $z > 5$ , and connect this to observations and understanding of the Universe at  $z < 5$  and that beyond the Dark Ages and Recombination.



# SKA EoR experiments

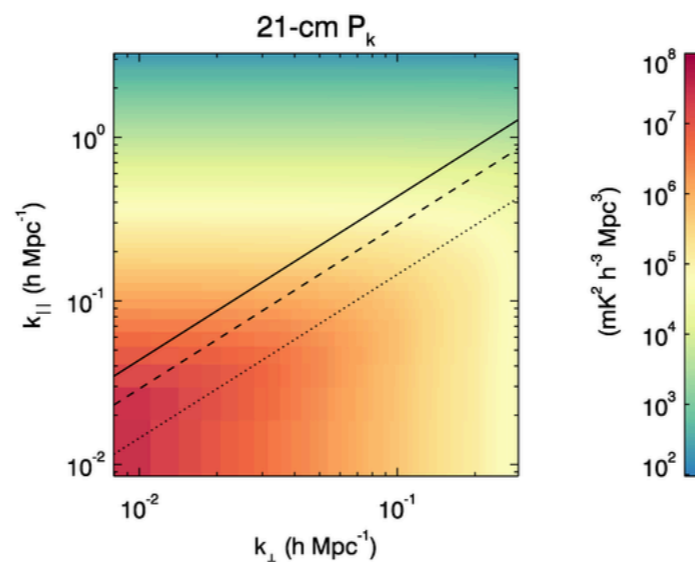
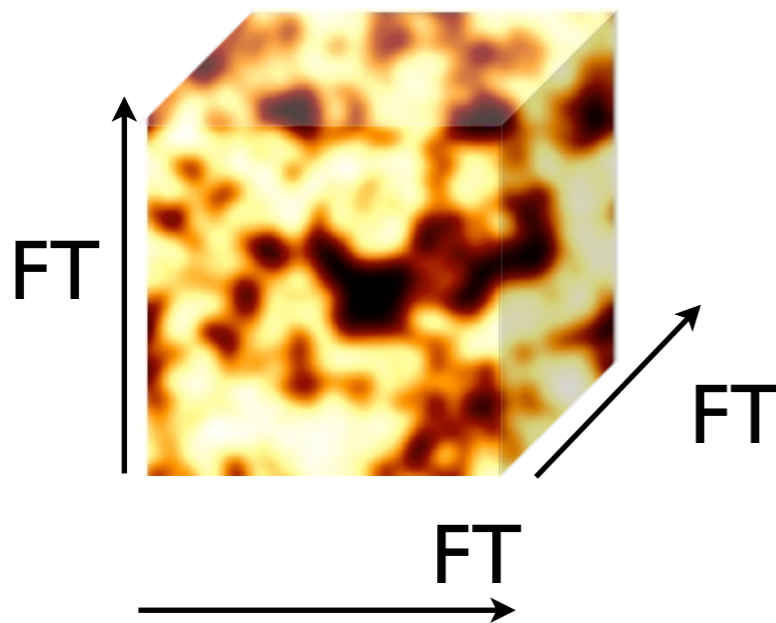
Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3





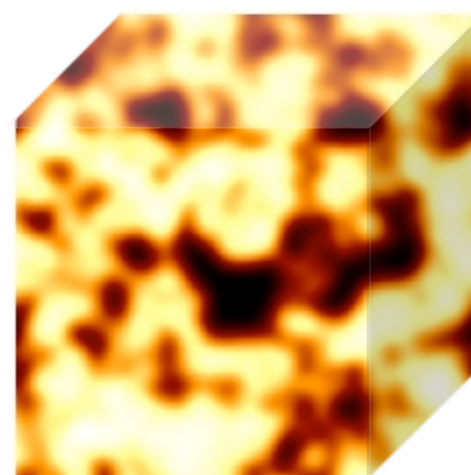
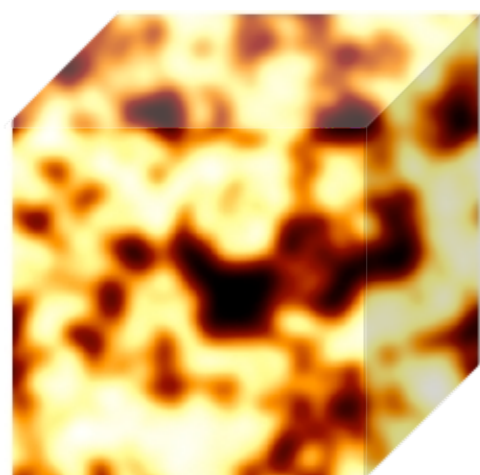
# SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3



## Power spectrum

- integrates signal for each spatial scale
- lower signal-to-noise ratio
- retains scale information
- yields “cosmic-scale” information



## HI tomography (imaging)

- direct imaging of brightness temperature fluctuations
- provides “local” structural information
- **weak signal requiring SKA-scale sensitivity**



# SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
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3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3

	Science	Details
Imaging/tomography	Direct imaging of HI structures; $z=5-28$	100 sq. deg.; 5000/Nbeams hours; 200MHz BW; $z=5-28$ ; $\Delta\nu=0.1$ MHz
Power Spectrum	2D and 1D power spectra of $T_B$ fluctuations	Medium: 1,000 sq. deg. (100h per field) Shallow: 10,000 sq deg. (10h per field)
HI Absorption	Narrow HI systems along LOS to $z\sim 6$ radio sources	1,000h integrations toward select $z=6$ radio sources. Study small scale HI distribution.





# SKA EoR experiments

Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
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## Chapters

## Challenges

Imaging/tomography

Mellema et al.; Wyithe et al.

Instrument calibration; surface brightness sensitivity; good lines-of-sight; beam models

Power Spectrum

Koopmans et al.; Pritchard et al.; Mesinger et al.; Subrahmanyan et al.

Foregrounds; sample variance; polarization leakage

HI Absorption

Ciardi et al.

Identifying high-z sources ( $z=10$ ); S/N for broad systems; contamination by spatially-coincident T fluctuations



# KSP Key Design: working model

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## Single KSP covering CD/EoR experiments

Rationale: Manage data processing and analysis (common refined dataset to provide many scientific goals)

- Redundancy
- Focus Groups
- Membership rights and responsibilities
- Publication rights and responsibilities

### Data processing:

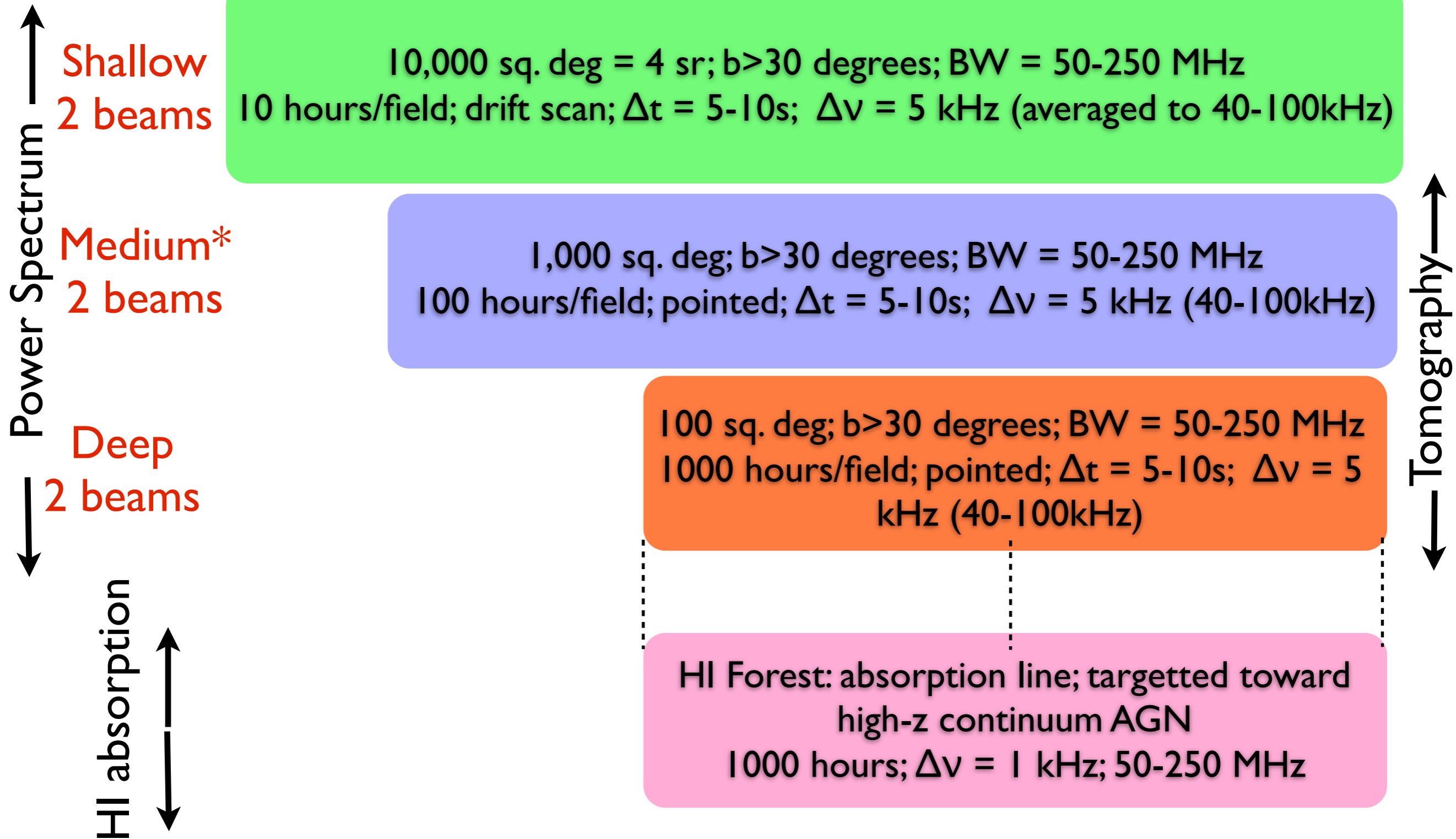
- direction-dependent calibration
- foreground subtraction
- curvature terms
- calibrated visibilities (5 kHz/5-10s)

### Signal extraction and interpretation

- Error analysis
- Modelling
- Synergies with other facilities
- Simulations



# Observational parameters and strategies





# Observational parameters and strategies

Power Spectrum ↑  
↓

Shallow  
2 beams

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

Medium\*  
Single beam  
**Cosmology**  
**Continuum**  
**HI ExtraG**

1,000 sq. deg;  $b > 20$  degrees; **BW = 50-350 MHz**  
100 hours/field; pointed;  $\Delta t = 5-10s$ ;  $\Delta \nu = 5$  kHz (40-100kHz)  
**5,000 hours\*\***

Deep

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

HI absorption ↑  
↓

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

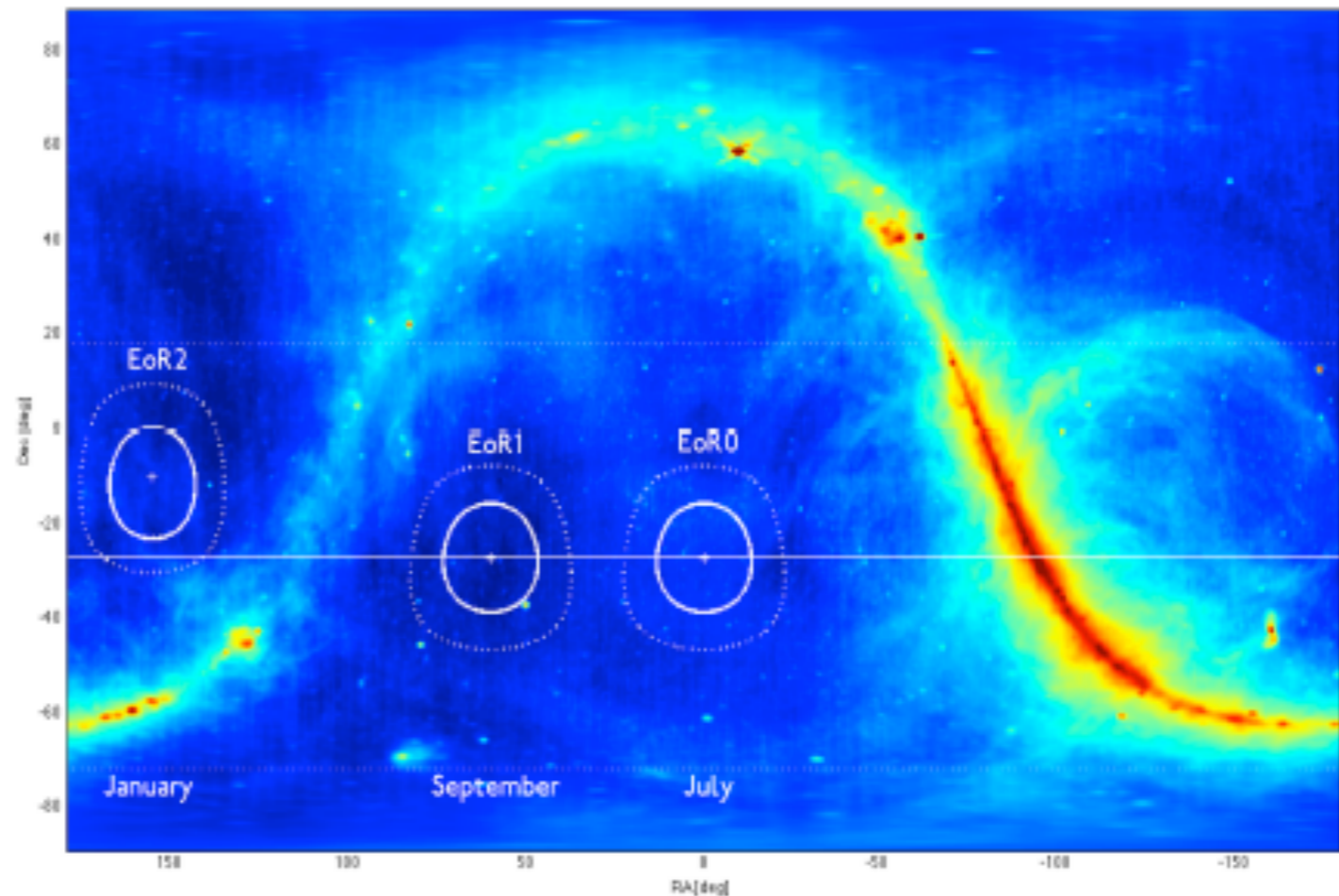
Tomography ↑  
↓



# Sky coverage

- Avoid Galactic Plane
- Higher frequencies: ionosphere, smaller FOV --> closer to GP?
- All of southern sky,  $b > 20$ -30 degrees, within 2 hours of zenith (dipole response)

## MWA EoR fields



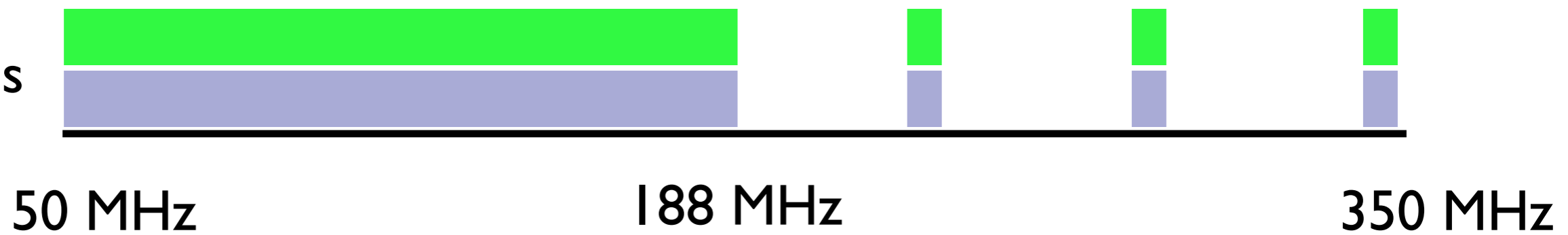


# Frequency coverage: *indicative* coverage with 1, 2 beams

Single  
w Cosmology,  
Continuum,  
HI Extragalactic



Two beams



Two beams





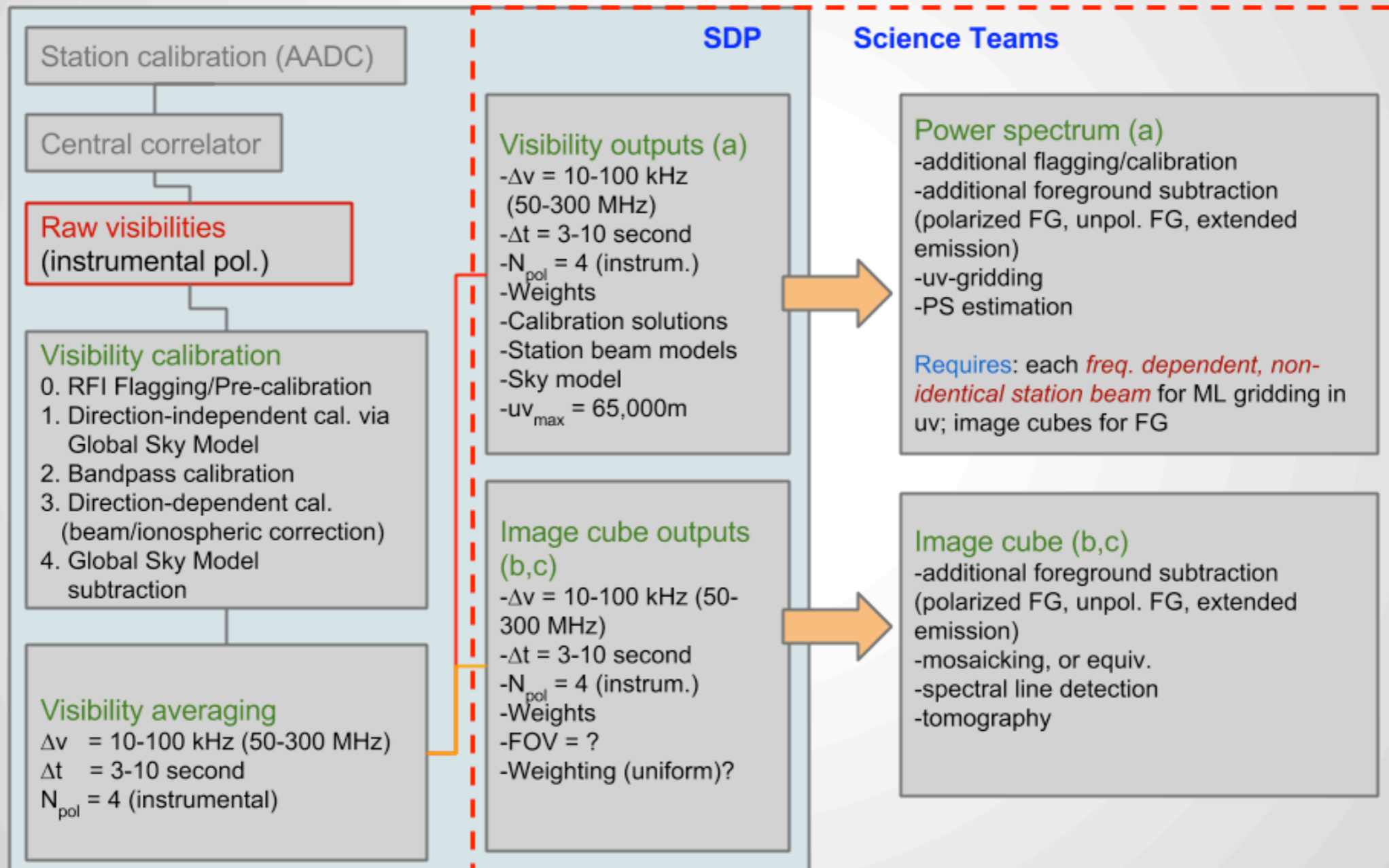
## Low-Level Data Products:

1. Flagged/Calibrated full-Stokes visibility data from 50-250 (350) MHz ( $z=27.4-4.7$  (3.0)) for all baselines with 5-10 sec and 5 kHz resolution over a (mostly) contiguous 150 MHz BW and various other compressed (in time/freq/spatial scale) data-sets.
2. Directionally-dependent complex gain solutions (instrument and ionosphere) as function of time and frequency.
3. Visibilities for absorption 21-cm line spectra in selected directions with kHz spectral resolution with lower temporal resolution.



# Data products and processing model

## Outputs from SDP: *integration of KSP/SWG with SDP for EoR pipeline*

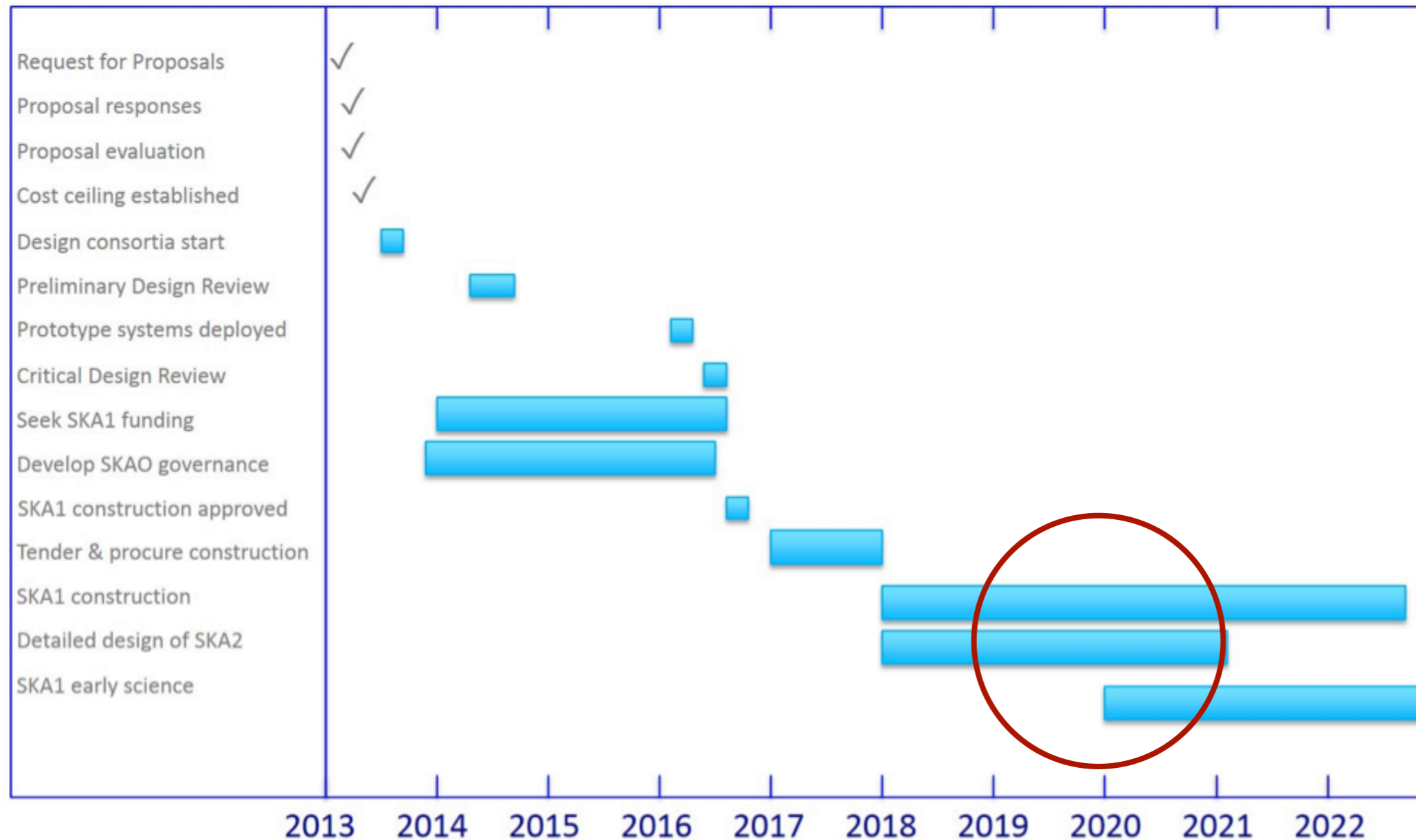






# Early science/commissioning period

- Further development of foreground model
- Testing of pipelines and initial interrogation of data
- “Super-shallow” commissioning survey





## Foregrounds: “removal is not separation”

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Foreground contamination is a major impediment for EoR/CD detection and estimation (along with instrumental systematics)

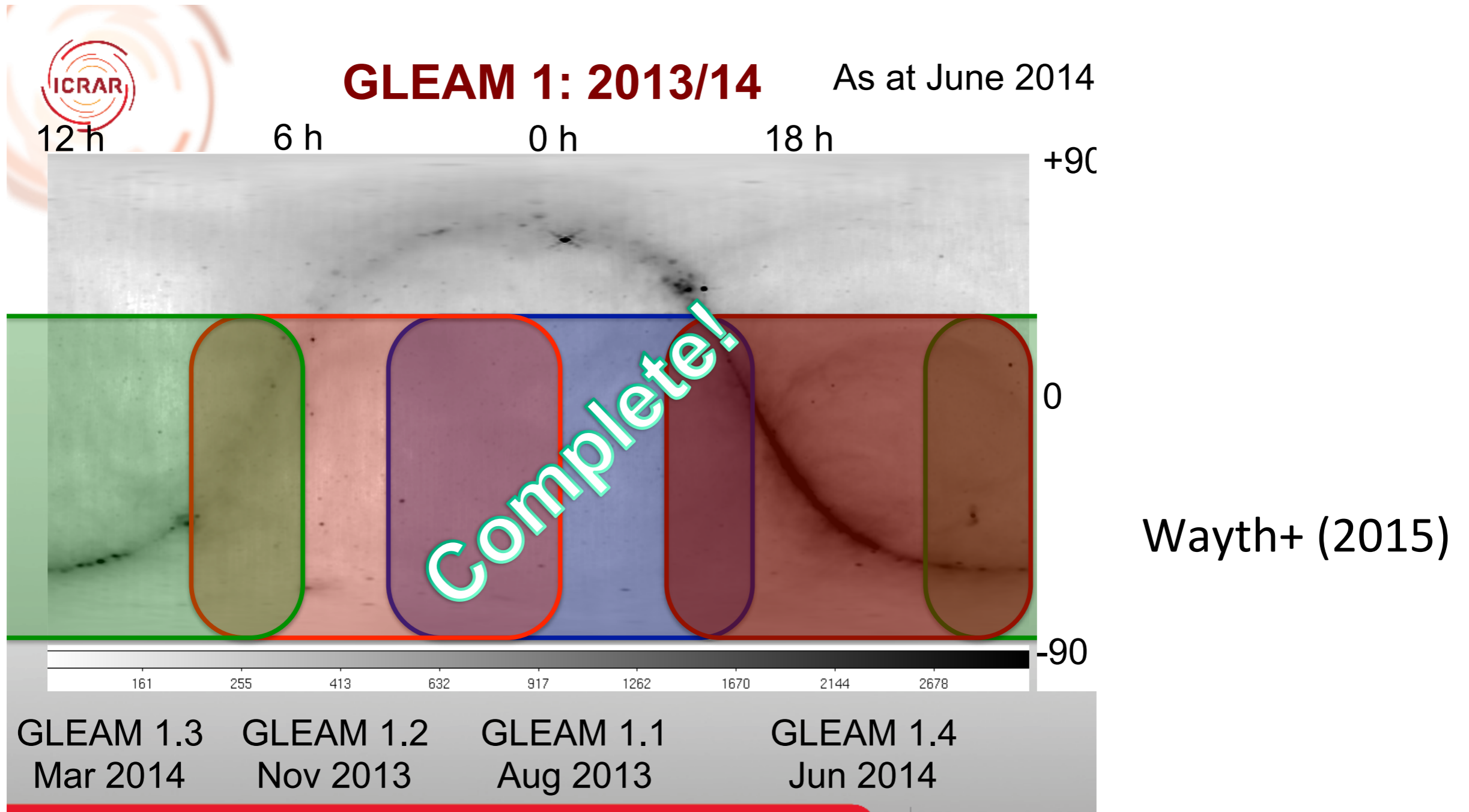
A major component of EoR/CD data processing is foreground “treatment”

Subtract (peel from visibilities) measured point sources, diffuse emission model, polarised structures  
--> “treat” remaining foregrounds with statistical models/parametric models/non-parametric models



Foregrounds: input polarised/total intensity catalogue

# MWA GLEAM survey has surveyed whole southern sky between 73-230MHz to 50mJy Survey released end of 2015

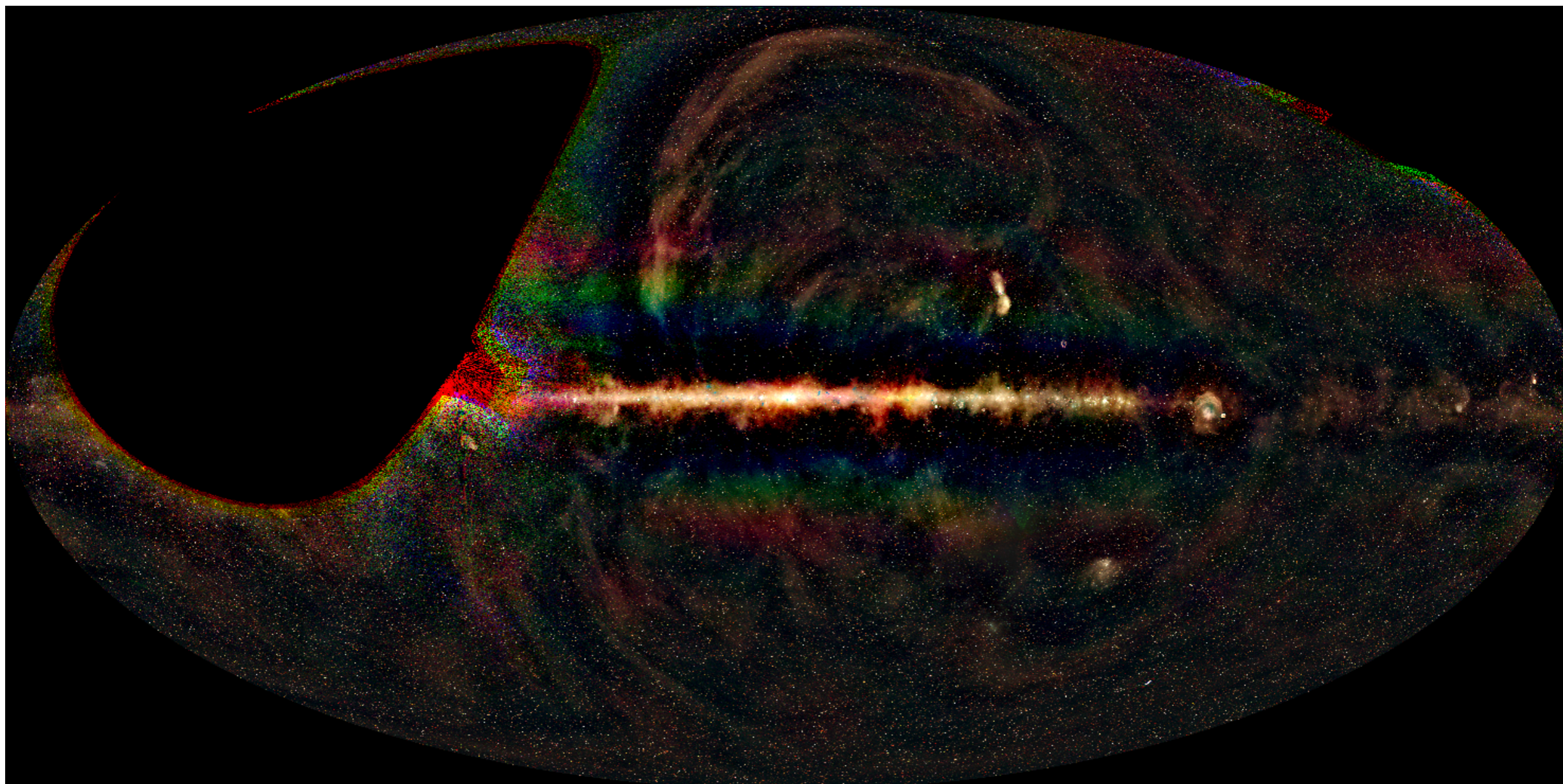




## Foregrounds: GLEAM all-sky survey

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**MWA GLEAM survey has surveyed whole southern sky between  
73-230MHz to 50mJy  
Survey released end of 2015**



N. Hurley-Walker + GLEAM team



# Commensality and key relationships

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- Transients
- Continuum
- Cosmology
- Cradle of Life
  
- HI extragalactic science
  
- Others!

Commensality, shared techniques,  
shared tools, shared resources

Total time: 10,000 hours over 5 years  
(including experiments of other WG)



# Commensality and key relationships

---

- Transients
- Continuum
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- Others!

**Commensal incoherent transients dataset from all EoR data. Siphon off data early in process and analyse.**

**Potential for Transients to provide archive/database of variable sources in EoR fields for our foreground modelling.**



# Commensality and key relationships

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- Transients
- Continuum
- Cosmology
- Cradle of Life
  
- HI extragalactic science
  
- Others!

Continuum 31,000 sq. degrees survey. Confusion-limited at 8" resolution.

Commensal with SHALLOW survey (50-250MHz) and MEDIUM survey (50-350MHz) away from Galactic Plane.



# Commensality and key relationships

---

- Transients
- Continuum
- Cosmology
- Cradle of Life
- HI extragalactic science
- Others!

**$z = 3-6$  intensity mapping with LOW in interferometric mode.**

**Commensal with MEDIUM survey (50-350MHz) away from Galactic Plane.**





# Commensality and key relationships

---

- Transients
- Continuum
- Cosmology
- Cradle of Life
- HI extragalactic science
- Others!

Exoplanet cyclotron emission. Cross-correlation of known exoplanets with Stokes V circular polarisation.

Commensal with all surveys away from Galactic Plane. Can target many exoplanets within 100 pc. Stokes V not confusion-limited. Multi-epoch observations useful.

Siphon data early in process and perform simple calibration.



# Commensality and key relationships

- Transients
- Continuum
- Cosmology
- Cradle of Life
- HI extragalactic science
- Others!

Exoplanet cyclotron emission. Cross-correlation of known exoplanets with Stokes V circular polarisation.

Commensal v from Galactic Plane. Can target many exoplanets within 100 pc. Stokes V not confusion-limited. Multi-epoch observations useful.

Siphon data early in process and perform simple calibration.

*+ Our Galaxy*



# Commensality and key relationships

---

- Transients
- Continuum
- Cosmology
- Cradle of Life
- HI extragalactic science
- Others!

LOW absorption survey over 1000 sq. deg. with ~5 kHz spectral resolution.

Commensal with MEDIUM survey (50-350MHz) away from Galactic Plane.



# Commensality and key relationships

---

- Transients
- Continuum
- Cosmology
- Cradle of Life
- HI extragalactic science
- Others!

**List not exhaustive!**



# Resourcing and planning

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- SWG currently in discussions with SDP to inform/contribute to development of EoR data pipeline
- Lessons from pathfinder instruments (LOFAR, MWA, PAPER etc.)
- Lessons from EoR/GLEAM projects at MRO (ionosphere, fields, observing strategies)
- Science Use Case/ECPs to ensure commensal data products available to all shared programs
- Science Use Case/ECPs to ensure performance of instrument for desired science
- Science Use Case/ECPs to use real-time (LOW) data to assess ionospheric conditions and dynamically-schedule telescope (TM).