

# LOFAR, SKA... and beyond!

*... a journey with Ger.*



Leon Koopmans  
Kapteyn Astronomical Institute

Ger's interests are very broad, as we've seen this week but since almost a decade now it has largely been dominated by the search for the **Epoch of Reionization**

This is story of a journey with Ger and how his influence is being felt in the LOFAR-EoR and SKA project, not just scientifically.

# A short story....



Ger's advise to me in some random street in Socorro:

“Don't specialize too early, you can always do that later...”

- In 1994 I followed Ger's course on radio interferometry
- In 1995 I started my PhD on radio-selected *gravitational lenses* under Ger's super-vision.
- In 1996 I was TA for Ger's course.
- In 2004 I joined the LOFAR EoR project
- And in 2014 I will be teaching Ger's course!

I think that only now, nearly two decades later am I slowly starting to understand interferometry, thanks to Ger and the LOFAR EoR project.



Fifteen years back: the EoR was as evasive as SETI

In  
1997/8





# Fifteen years later: we are close to a detection!

In  
2013/14



But this is not a story about lensing, SETI, nor the VLA.

This is a story about LOFAR(-EoR) and SKA and Ger.

*My view on Ger's journey with LOFAR  
toward SKA...*



# How it began *(roughly)*...

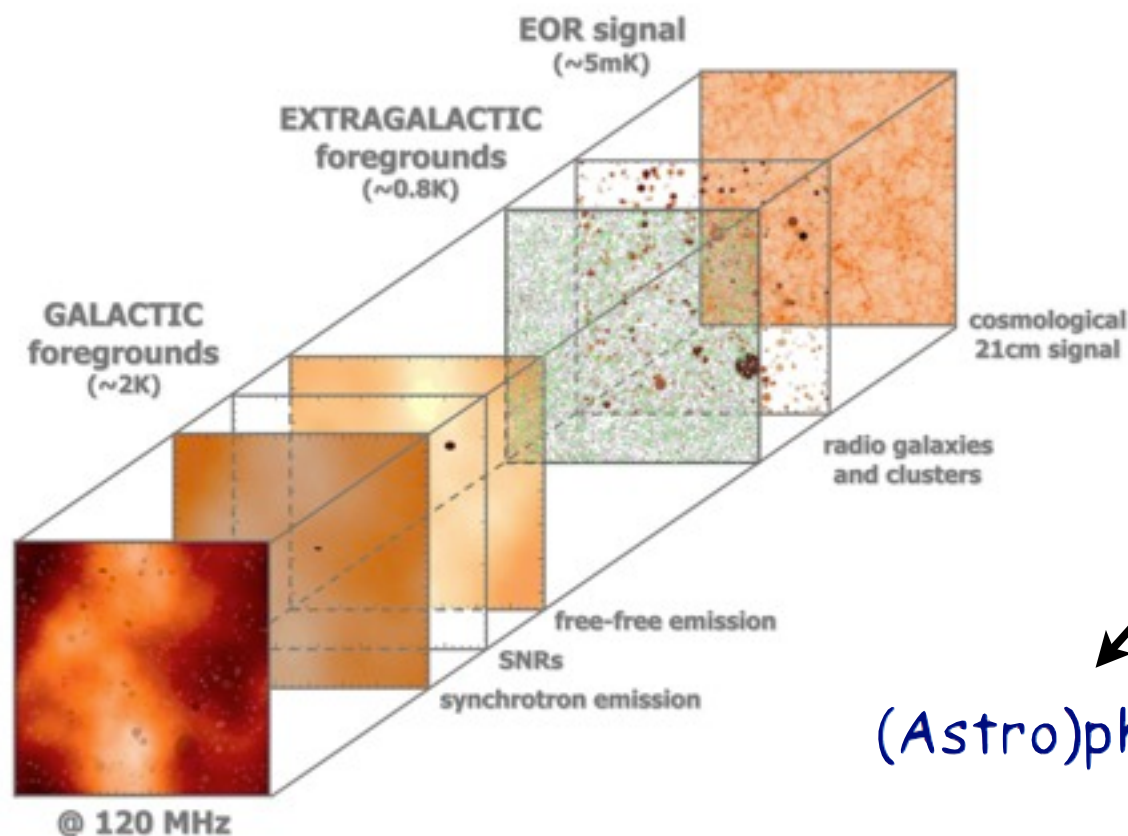
Madau et al. 1997 and the Shaver et al. paper 1999, (partly) inspired both total-power experiments, but also lead to the development of high- $z$  HI arrays (i.e. LOFAR, MWA, 21 CMA PAPER).

(George Miley)

LOFAR came in part from SKA-inspired ideas (initiated in part at ASTRON). But these precursors/pathfinders have also become SKA's inspiration!

Each NL university would lead a LOFAR KSP, with Groningen/ASTRON (i.e. Ger) leading the EoR KSP.

# The LOFAR EoR Project is not easy and requires long-term dedication and a team!



## Many Challenges

### (Astro)physical

- Extragalactic foregrounds
- Galactic foregrounds
- Ionosphere
- Interference
- Polarized emission
- Variability

### Instrumental

- Beam stability
- Sensitivity
- Dynamic Range
- UV Coverage
- Calibratability
- ...

### Computational

- Large data rate
- ~1 Pb raw data
- (Non)-linear optim. of coupled equations
- 10s Tflop\*year
- ...



# How the LOFAR-EoR project began<sup>for me</sup> in 2004..

**From:** Ger de Bruyn  
**Subject:** LOFAR and the EoR: the final HI frontier  
**Date:** April 8, 2004 5:15:47 PM GMT+02:00

Dear All,

I suggest we meet in Groningen on Tuesday the 20th of April (1300-1600?) in room 161 to discuss various aspects of LOFAR observations of the Epoch of Reionization.

Among topics that I would like to see discussed are: observational strategies, preparation (e.g. WSRT-LFFE) in field selection, data-reduction/calibration aspects, data analysis and signal extraction methods, parallel theoretical work. We do not have to discuss all of these in great depth at this moment.

We also have to start thinking about manpower issues and timelines for each of these topics. We could start defining Summer student projects, masters-thesis-projects, PhD projects, postdoc appointments as well as international involvement.

I will send around a more detailed agenda by the middle of next week. Anyone who wishes to contribute to the meeting on one or more of the above topics, or have some other topic he/she wants to see discussed, please let me know and come prepared

I also leave it to each of you to bring or invite students (masters, or PhD) that might want to listen in and/or contribute in the future. Needless to say there is a lot of work to be done.

Hope to see many of you on this day.

Have a nice weekend.

Cheers

Ger

The purpose of Tuesday's meeting, in my view, is to identify the top-level issues for the EoR project as quickly as possible such that at the end of the day it will be clearer what we need to do and how, when we should start and be ready, and identify the interests of the various people that want to play a role.

More specifically I see the following list of fairly urgent discussion points:

- 1) discuss the creation of an 'EoR-project' organizational structure and meeting schedule
- 2) define the interface/liaison to the LOFAR project
- 3) identify the available/required manpower, the required computing resources and the possible ways to acquire financial support
- 4) discuss possible international involvement, i.e. who and how ?

To achieve these goals by the end of the afternoon I suggest the following agenda topics:

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## AGENDA for Tuesday 20-April-2004

- 1) Brief introduction on 'rescoped'-LOFAR and timeline
- 2) The EoR: status of theoretical predictions (signal levels, z-range, etc):  
  
A 'tour de table' of peoples views on what we should and can do, and how they see their role in the project. This possibly might modify the rest of the agenda.
- 3) The LOFAR-EoR product and methods to extract the signals.
- 4) Definition of 'working groups' to define 'workpackages' with timelines
- 5) Liaison to the LOFAR project: important technical milestones in 2004/05
- 6) Preparing in the 115-180 MHz band using the WSRT:
- 7) International 'competition' and (inter)national collaborations
- 8) Meeting schedule
- 9) Upcoming international meetings
- 10) Any other business

Whereas Ger is a team player, I think, leading  
an (international) team in context of building  
LOFAR was not always easy.

BUT it all worked out!

Over the last days we have seen many exciting  
results from a decade of preparation for the  
EoR-project and several years of observations.

Why is it that the LOFAR-EoR team is still  
largely together and remains inspired and driven  
as ever?

This is not only about the science  
itself, but also *how* the science is done!

I would like to focus here on Ger's role.



Whereas Ger is a team player, I think, leading an (international) team in context of building LOFAR was not always easy.

This book might have been useful for all of us in 2004!

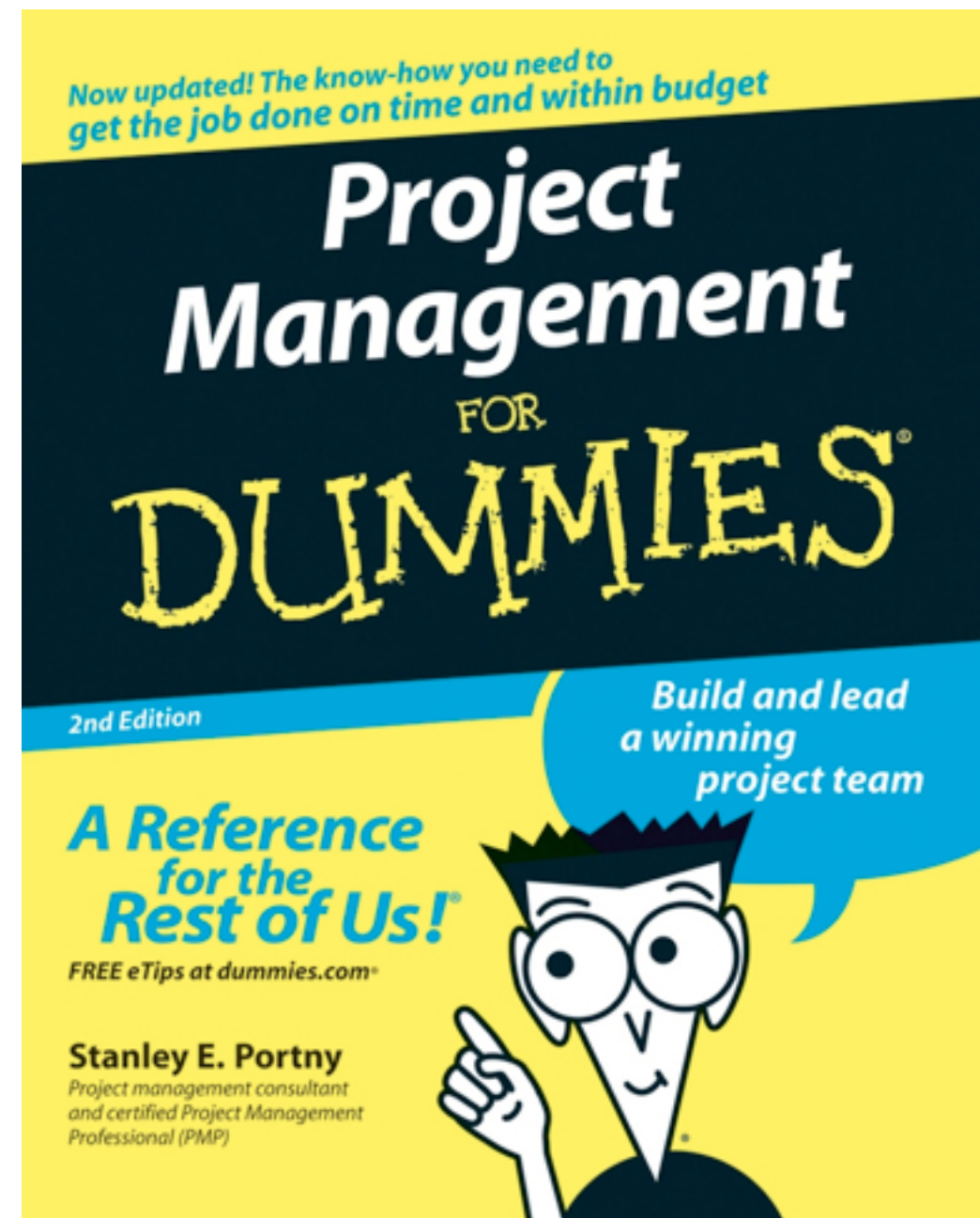
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A pictorial journey:

It's not just about science but  
also team building!



For brainstorming we retreat to the Allersmaborg





# For brainstorming we retreat to the Allersmaborg





# For brainstorming we retreat to the Allersmaborg

## Thinking & talking





# For brainstorming we retreat to the Allersmaborg



Ger instructing the  
younger generation  
on slippery issues...



Thinking & talking



# For brainstorming we retreat to the Allersmaborg



Ger instructing the younger generation on slippery issues...



Ger doing other "research"?



# More brainstorming in the “Kasteel” in Groningen...

*Some EoR members have other ideas...*





But ... once a year we go to a warmer place!

Zadar, Croatia  
2011



LOFAR EoR Team



But ... once a year we go to a warmer place!





But ... once a year we go to a warmer place!





On Crete 2012 we discussed science and found Zeus...





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# Science and Sitges, Spain, May 2013...





# Science and Sitges, Spain, May 2013...



All the good things in life!



... and at the end of the day we stroll home... content...





And then it really started (Dec. 2012)!





Why do I show this?



# Why do I show this?

Science is not just about “the science”  
it is also about **inspiration and building  
a team spirit**. This is needed in such  
complex and long-term projects.

The enthusiasm, the almost “family spirit”  
of the LOFAR-EoR team shows that  
**Ger has managed to do that!**



But Ger's work on LOFAR, LOFAR-EoR  
has also had its impact on SKA.



# Beyond LOFAR: SKA-low



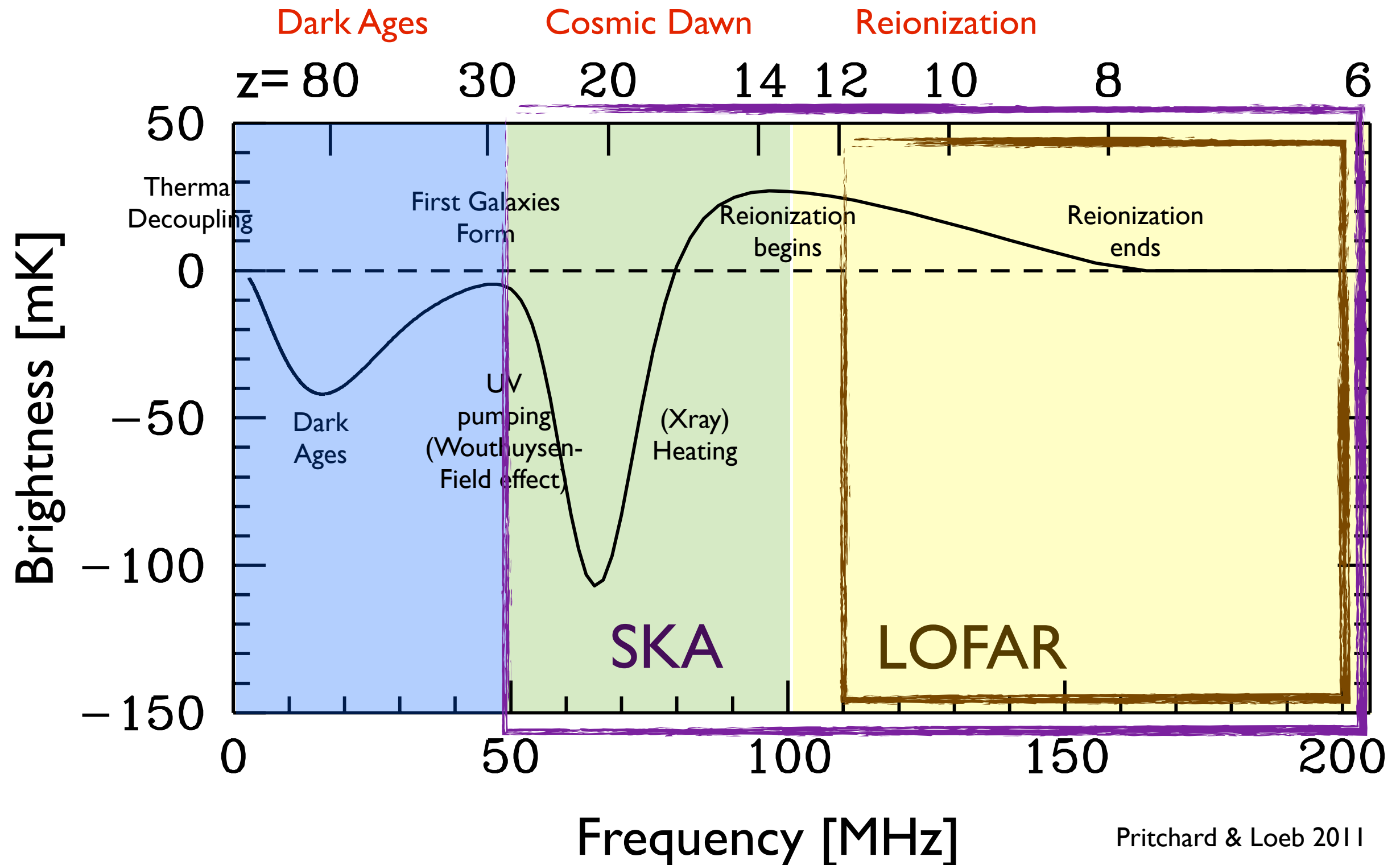
The Square Kilometre Array

Exploring the Universe with the world's largest radio telescope





# Hydrogen Brightness Temperature





# LOFAR, SKA and beyond

## Dark Ages

DM power-spectrum evolution  
DM annihilation physics  
Baryonic Bulk Flows  
Physics of Gravity/GR

## Cosmic Dawn

Appearance of first stars (PopIII?)  
Ly- $\alpha$  radiation field  
Impact of Baryonic Bulk Flows  
First X-ray heating sources

## Reionization

Reionization by stars & mini-quasars  
IGM feedback (e.g. metals)  
PopIII - PopII transition  
Emergence of the visible universe

LOFAR

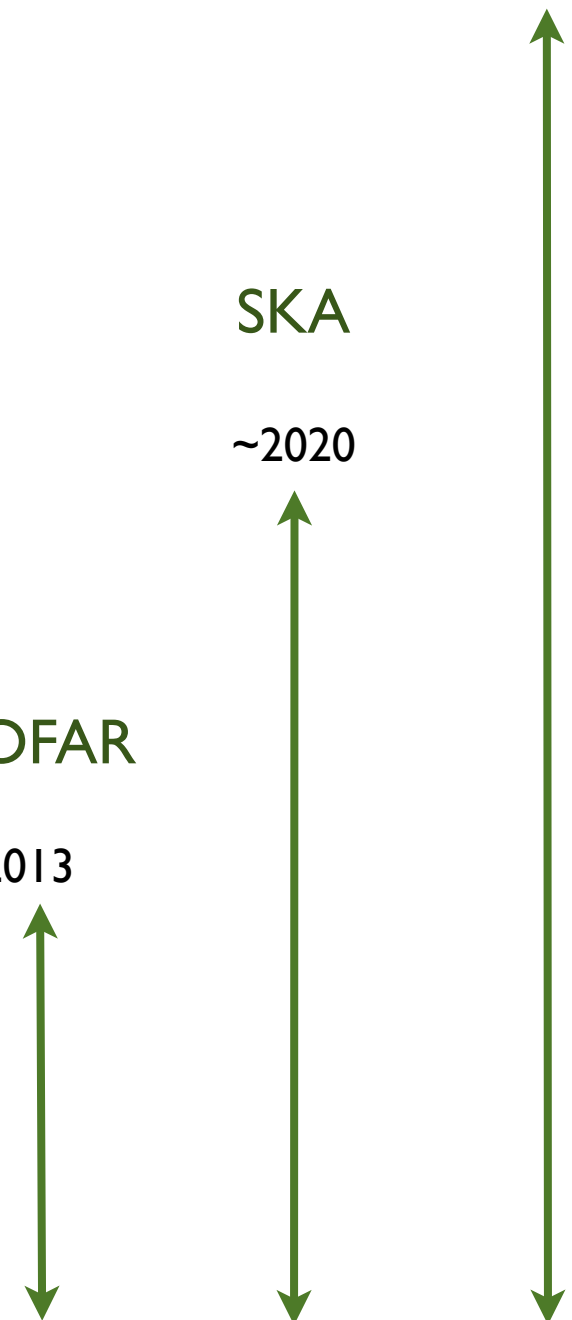
2013

SKA

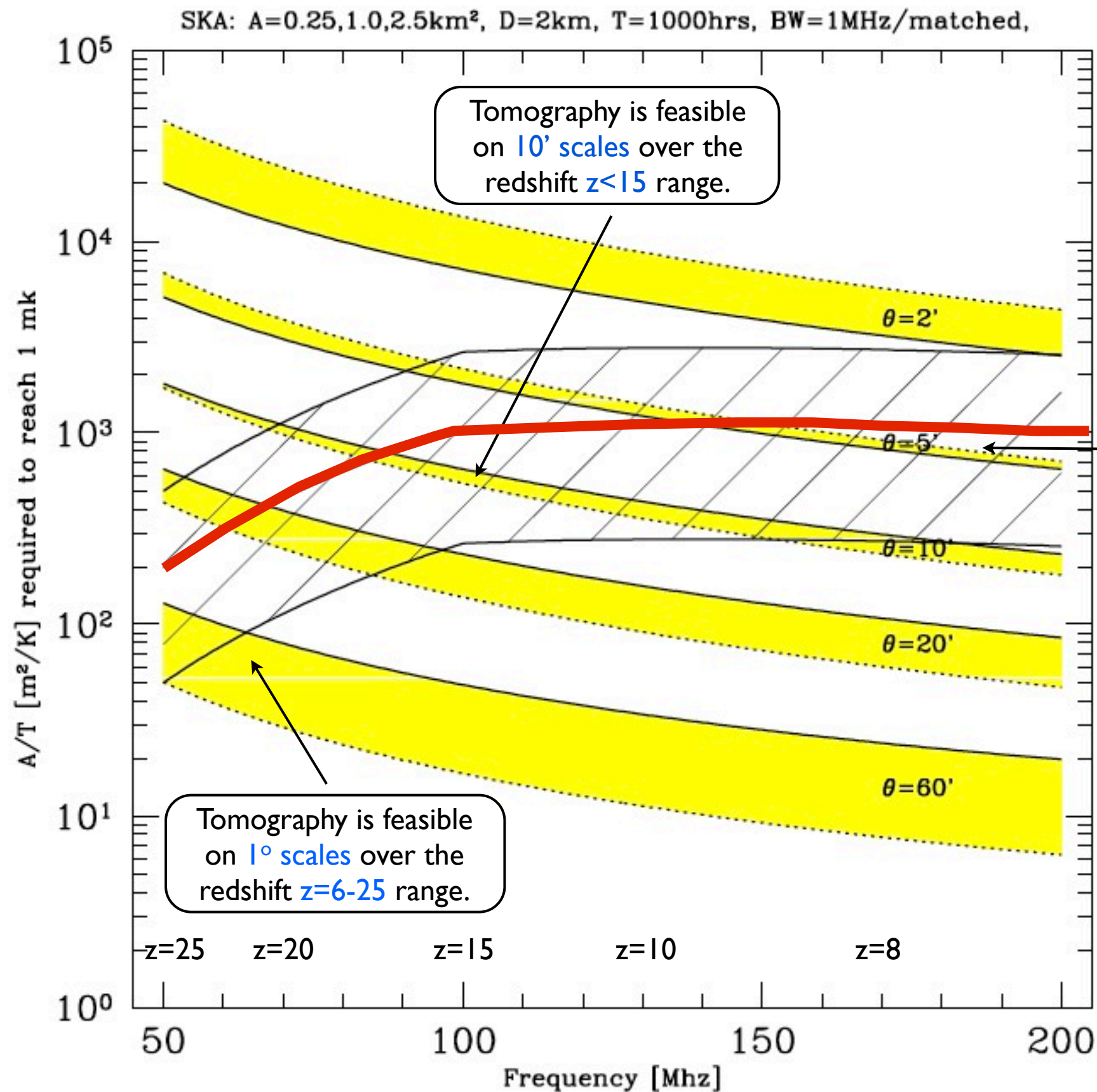
~2020

Space/Moon based  
Interferometers

~2030







# SKA Tomography

**EoR:  $z < 15$**

In 1000hr with a  $BW=1 \text{ MHz}$  or matched to angular scales, one can do tomography to the required level of  $\sim 1 \text{ mK}$  on scale  $> \sim 10'$

**Cosmic Dawn:  $15 < z < 25$**

Idem, on scales  $> \sim 1^\circ$ .



Whereas Ger was involved in the earlier phases of SKA, recently many new developments took place and the LOFAR EoR KSP results have played a major role.

w/o LOFAR EoR, I think, it would be unlikely that SKA1 would have the CD/EoR as one of two main science drivers.



# On the way home from Oxford SKA AAVP meeting Dec 2010

Discussions with Ger have  
time nor place.





# The “Infamous” CD/EoR SKA white paper

Exp Astron (2013) 36:235–318  
DOI 10.1007/s10686-013-9334-5

ORIGINAL ARTICLE

## Reionization and the Cosmic Dawn with the Square Kilometre Array

Garrelt Mellema · Léon V. E. Koopmans · Filipe A. Abdalla · Gianni Bernardi ·  
Benedetta Ciardi · Soobash Daiboo · **A. G. de Bruyn** · Kanan K. Datta ·  
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Mario G. Santos · Dominik J. Schwarz · Benoit Semelin · Harish Vedantham ·  
Sarod Yatawatta · Saleem Zaroubi

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**Abstract** The Square Kilometre Array (SKA) will have a low frequency component (SKA-low) which has as one of its main science goals the study of the redshifted 21 cm line from the earliest phases of star and galaxy formation in the Universe. This

The same *lessons learned* from LOFAR-EoR have played a major role in an SKA WP that was written in 2012.



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21 cm signal provides a new and unique window both on the time of the formation of the first stars and accreting black holes and the subsequent period of substantial ionization of the intergalactic medium. The signal will teach us fundamental new things about the earliest phases of structure formation, cosmology and even has the potential to lead to the discovery of new physical phenomena. Here we present a white paper with an overview of the science questions that SKA-low can address, how we plan to tackle these questions and what this implies for the basic design of the telescope.

**Keywords** Cosmology: Observations · Dark ages · Reionization ·  
First stars · Diffuse radiation · Intergalactic medium · Radio lines:  
General · Techniques: Interferometric

The same *lessons learned* from LOFAR-EoR have played a major role in an SKA WP that was written in 2012.



# SKA1-Low inspired by LOFAR

Table 2 SKA1-low – Log-Periodic Dipoles

<b>Aperture Array</b>		
Lower Frequency	50 MHz	Dual polarization (2 orthogonal)
Upper Frequency	300 MHz	Single element covering full range
Number of antennas per station	289	Log-Periodic-Dipole antennas
Total physical aperture	$8.0 \times 10^5 \text{ m}^2$	
Area per antenna	$2.25 \text{ m}^2$	
Element filling factor in station	0.7	Areal filling factor
Dense/Sparse Transition	111 MHz	$A_e$ per element is equal to packing density
<b>Array Configuration</b>		
Station Diameter	35 m	
Number of stations	911 stations	866 in core; 45 in spiral arms
Core (radius <600 m)	~50% (~433 st'ns)	Fractional total number of core stations
Core (radius <1000 m)	~75% (650 st'ns)	"
Spiral Arms	~4% (45 stations)	15 stations per spiral arm
Av'g St'n filling factor (radius <220 m)	0.91	Stations must be close-packed or overlapped to radius of 650 m.
<b>Station Beam Forming</b>		
Number of beams	1	"Average" number of beams per pol'n required to 300 MHz
Instantaneous bandwidth per beam	250 MHz	Assumes full bandwidth is available (50-300 MHz)
<b>Digital Outputs</b>		
Sample streams	2	Max - sub-bands
bits per sample	8	Sent from Beamformers
<b>Signal Transport System</b>		
Data rate per station	10 Gb/s *	Optical fibre to signal processor
Radius < 3000 m	8.7 Tb/s	866 stations
3 km < Radius < 50 km	450 Gb/s	45 stations
<b>Signal Processing System</b>		
Fine Frequency channels**	$2.5 \times 10^5$	Channel Bandwidth = 1 kHz
Complex Correlations	$4.1 \times 10^{11}$	$911^2/2$ baselines x (1 bms x 4 pol'n prod's x $2.5 \times 10^5$ chans
Complex Correlations: Spiral Arms	$0.4 \times 10^{11}$	$(911^2 - 866^2) / 2$ baselines
Core (radius <3 km) Dump Time	~10.6 s	Station diameter = 34 m; max baseline = 6 km
Minimum Dump Time	~0.6 s	Station diameter = 34 m; max baseline = 100 km
<b>Science Computing System</b>		
Input data rate (1 kHz channels)	$842 \times 10^9$	Byte $\text{s}^{-1}$ av'ge from correlator (4-Byte x 2 for complex) (3.8 corr's/10.6 s + 0.3 corr's/0.6 s) x $10^{11}$ x 8 (8-Byte complex)
Input data rate (100 kHz channels)	$8.4 \times 10^9$	Assumes some preprocessing at 1 kHz, then averaging

$A=0.8 \text{ km}^2$ ; 50% in a 600m core  
75% in a 1000m core  
4% outer 15 stat  
to 45 km radius

Station=size = 35m diameter

Freq: 50-300MHz

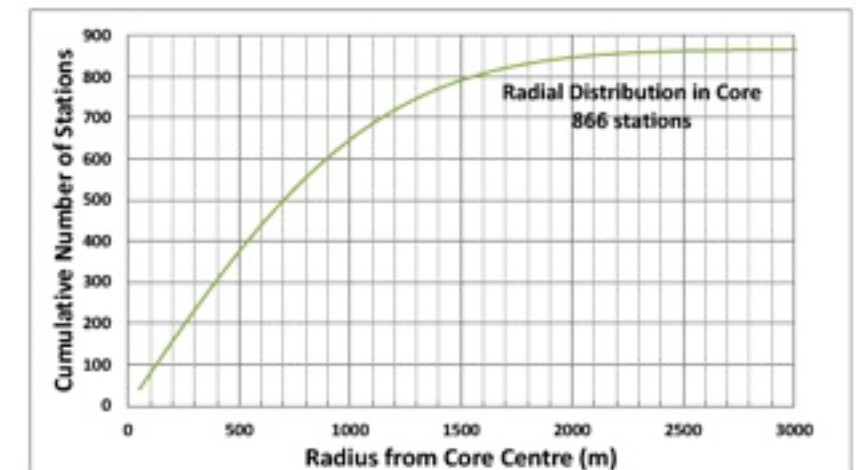
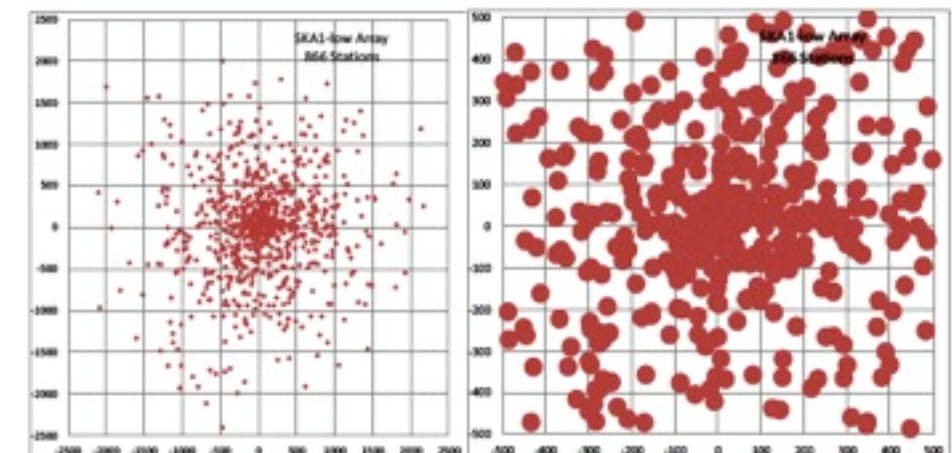


Figure 3 Cumulative collecting area as a function of core radius in the SKA1-low array.





# The first SKA Science Assessment Workshop: March 2013

Major involvement of Ger in the current SKA CD/EoR Science Team and leading several of its “Tigre Teams” -> Memo’s on long baselines and redundancy.





# Ger was influential in writing several memo's for the RfC of the SKA CD/EoR Science Team

## Request for (no) Change by the CD/EoR SKA SWG, plus supporting material

Oct. 5, 2013

**CD/EoR Science Team:** L.V.E. Koopmans (chair), F. Abdalla, J. Aguirre, K. Ahn, A. Parsons, I. van Bemmell, G. Bernardi, F. Briggs, A.G. de Bruyn, T.-C. Chang, L. Greenhill, G. Mellema, M. Morales, U.-L. Pen, J. Pritchard (vice-chair), M. Santos, B. Semelin, T. Tsutomu, R.L. Webster

Study of the Cosmic Dawn and Epoch of Reionization, or HI at high redshifts more generally, is one of the two main science drivers of SKA in phase 1 (SKA memo 125). The current SKA1 baseline design (SKA-TEL-SKO-DD-001-1\_BaselineDesign1) already closely matches the science requirements needed to successfully detect and study the redshifted 21-cm emission of neutral hydrogen over a redshift range of  $\sim 6$  to  $\sim 25$ , as extensively discussed in Mellema, Koopmans et al. (2013, Exp.Ast. 36, 235).

In March 2013 a science-assessment workshop was held at the SKA office to discuss the baseline-design for SKA1 with many of its stakeholders. A number of questions were raised during the workshop on changes and/or modifications to the current baseline design, as summarized and listed in Appendix A.

Based on extensive discussions during and since the workshop, and during subsequent telecons by the CD/EoR science team, we conclude the following:



SKA: It's happening and the impact of LOFAR(-EoR) is being felt in many ways...



SKA Science & Engineering meeting Oct. 2013



**What about beyond SKA?**





*A White paper for a low-frequency radio interferometer mission to explore the cosmological Dark Ages for the L2, L3 ESA Cosmic Vision program*

**24/05/2013**

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# DEX

## DARK AGES EXPLORER

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This project will not  
happen before ~2030  
maybe my retirement!



Ger has inspired and lead many new ideas and developments in the field of EoR (HI) observations: in LOFAR, SKA ... and beyond!

*I hope (expect!) you will keep playing a leading role in the future!*



LOFAR

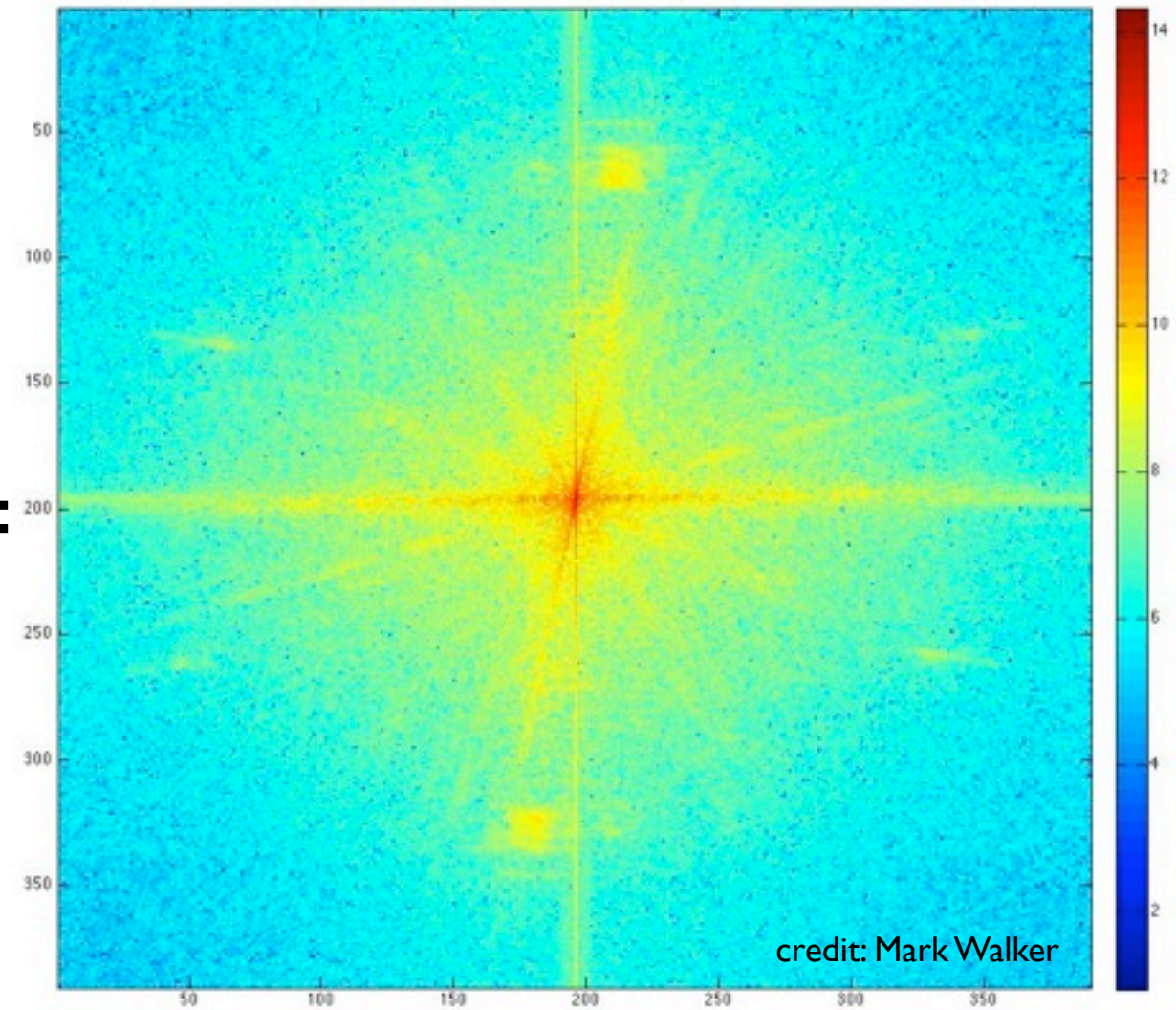
SKA →



Thanks Ger for all the advise and inspiration!

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