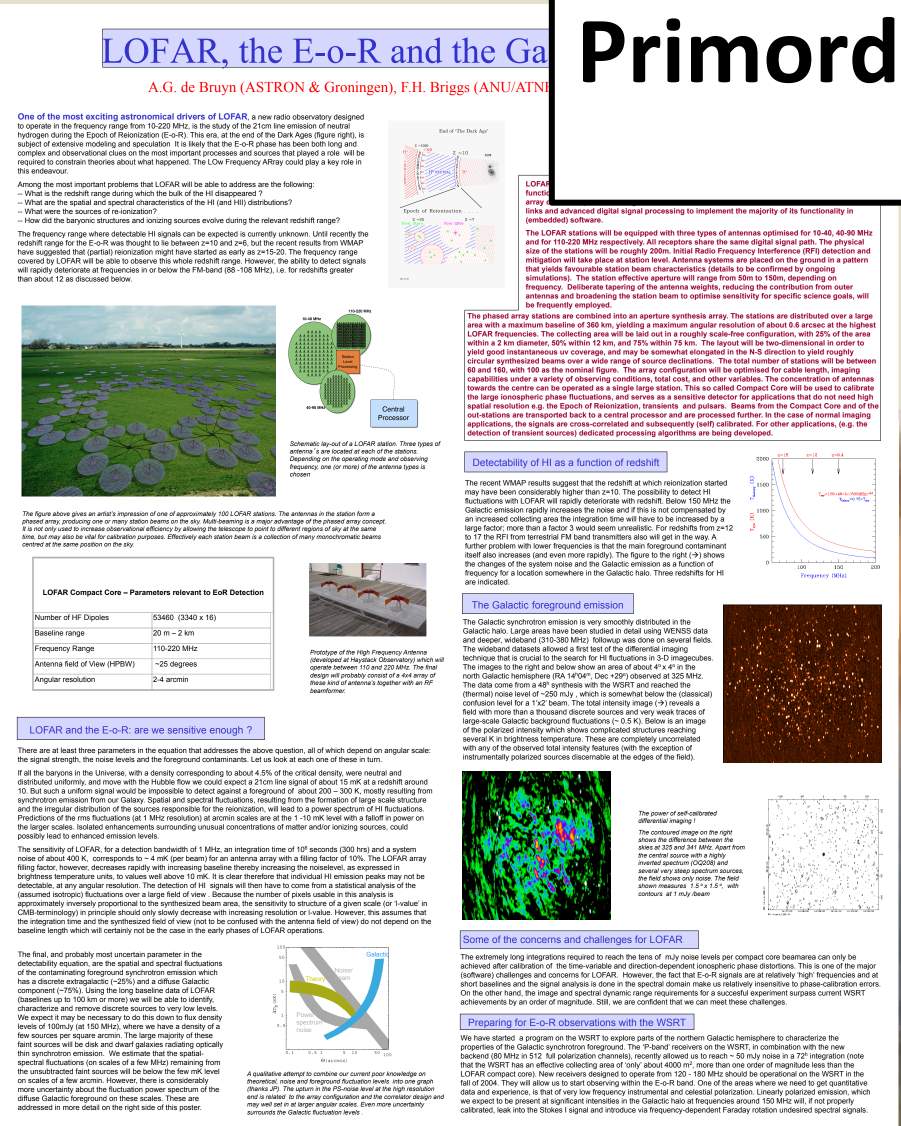
Primordial Hydrogen: EoR++

Frank Briggs



4-7 November 2013

Groningen, the Netherlands

IAU216, Sydney, 14-17 July 2003

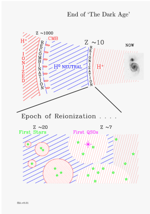
LOFAR, the E-o-R and the Galactic foreground

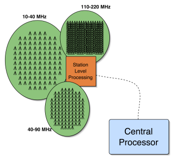
A.G. de Bruyn (ASTRON & Groningen), F.H. Briggs (ANU/ATNF), M.P. van Haarlem (ASTRON)

One of the most exciting astronomical drivers of LOFAR, a new radio observatory designed to operate in the frequency range from 10-220 MHz, is the study of the 21cm line emission of neutral hydrogen during the Epoch of Reionization (E-o-R). This era, at the end of the Dark Ages (figure right), is subject of extensive modeling and speculation It is likely that the E-o-R phase has been both long and complex and observational clues on the most important processes and sources that played a role will be required to constrain theories about what happened. The LOw Frequency ARray could play a key role in this endeavour.

Among the most important problems that LOFAR will be able to address are the following:
-- What is the redshift range during which the bulk of the HI disappeared ?
-- What are the spatial and spectral characteristics of the HI (and HII) distributions?
-- What were the sources of re-ionization?
-- How did the baryonic structures and ionizing sources evolve during the relevant redshift range?

The frequency range where detectable HI signals can be expected is currently unknown. Until recently the redshift range for the E-o-R was thought to lie between z=10 and z=6, but the recent results from WMAP have suggested that (partial) reionization might have started as early as z=15-20. The frequency range covered by LOFAR will be able to observe this whole redshift range. However, the ability to detect signals will rapidly deteriorate at frequencies in or below the FM-band (88 -108 MHz), i.e. for redshifts greater than about 12 as discussed below.





Schematic lay-out of a LOFAR station. Three types of antenna's are located at each of the stations. Depending on the operating mode and observing frequency, one (or more) of the antenna types is chosen

The figure above gives an artist's impression of one of approximately 100 LOFAR stations. The antennas in the station form a phased array, producing one or many station beams on the sky. Multi-beaming is a major advantage of the phased array concept. It is not only used to increase observational efficiency by allowing the telescope to point to different regions of sky at the same time, but may also be vital for calibration purposes. Effectively each station beam is a collection of many monochromatic beams centred at the same position on the sky.

LOFAR Compact Core – Parameters relevant to EoR Detection

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Prototype of the High Frequency Antenna (developed at Haystack Observatory) which will operate between 110 and 220 MHz. The final design will probably consist of a 4x4 array of these kind of antenna's together with an RF beamformer.

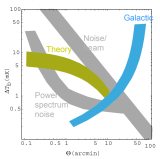
LOFAR and the E-o-R: are we sensitive enough ?

There are at least three parameters in the equation that addresses the above question, all of which depend on angular scale: the signal strength, the noise levels and the foreground contaminants. Let us look at each one of these in turn.

If all the baryons in the Universe, with a density corresponding to about 4.5% of the critical density, were neutral and distributed uniformly, and move with the Hubble flow we could expect a 21cm line signal of about 15 mK at a redshift around 10. But such a uniform signal would be impossible to detect against a foreground of about 200 – 300 K, mostly resulting from synchrotron emission from our Galaxy. Spatial and spectral fluctuations, resulting from the formation of large scale structure and the irregular distribution of the sources responsible for the reionization, will lead to a power spectrum of HI fluctuations. Predictions of the rms fluctuations (at 1 MHz resolution) at arcmin scales are at the 1 -10 mK level with a falloff in power on the larger scales. Isolated enhancements surrounding unusual concentrations of matter and/or ionizing sources, could possibly lead to enhanced emission levels.

The sensitivity of LOFAR, for a detection bandwidth of 1 MHz, an integration time of 10^6 seconds (300 hrs) and a system noise of about 400 K, corresponds to ~ 4 mK (per beam) for an antenna array with a filling factor of 10%. The LOFAR array filling factor, however, decreases rapidly with increasing baseline thereby increasing the noiselevel, as expressed in brightness temperature units, to values well above 10 mK. It is clear therefore that individual HI emission peaks may not be detectable, at any angular resolution. The detection of HI signals will then have to come from a statistical analysis of the (assumed isotropic) fluctuations over a large field of view . Because the number of pixels usable in this analysis is approximately inversely proportional to the synthesized beam area, the sensitivity to structure of a given scale (or 'l-value' in CMB-terminology) in principle should only slowly decrease with increasing resolution or l-value. However, this assumes that the integration time and the synthesized field of view (not to be confused with the antenna field of view) do not depend on the baseline length which will certainly not be the case in the early phases of LOFAR operations.

The final, and probably most uncertain parameter in the detectability equation, are the spatial and spectral fluctuations of the contaminating foreground synchrotron emission which has a discrete extragalactic (~25%) and a diffuse Galactic component (~75%). Using the long baseline data of LOFAR (baselines up to 100 km or more) we will be able to identify, characterize and remove discrete sources to very low levels. We expect it may be necessary to do this down to flux density levels of 100mJy (at 150 MHz), where we have a density of a few sources per square arcmin. The large majority of these faint sources will be disk and dwarf galaxies radiating optically thin synchrotron emission. We estimate that the spatial-spectral fluctuations (on scales of a few MHz) remaining from the unsubtracted faint sources will be below the few mK level on scales of a few arcmin. However, there is considerably more uncertainty about the fluctuation power spectrum of the diffuse Galactic foreground on these scales. These are addressed in more detail on the right side of this poster.



A qualitative attempt to combine our current poor knowledge on theoretical, noise and foreground fluctuation levels into one graph (thanks JP). The upturn in the PS-noise level at the high resolution end is related to the array configuration and the correlator design and may well set in at larger angular scales. Even more uncertainty surrounds the Galactic fluctuation levels .

LOFAR Low Frequency Array

The LOFAR consortium consists of ASTRON, MIT-Haystack and NRL (see www.lofar.org).

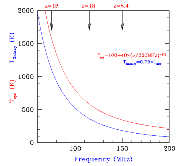
LOFAR is an aperture synthesis array composed of phased array stations that perform the same function as individual dishes in conventional synthesis radio telescopes (e.g. the Westerbork array or the VLA). It uses a large number of low-cost antennas and relies on broad-band data links and advanced digital signal processing to implement the majority of its functionality in (embedded) software.

The LOFAR stations will be equipped with three types of antennas optimised for 10-40, 40-90 MHz and for 110-220 MHz respectively. All receptors share the same digital signal path. The physical size of the stations will be roughly 200m. Initial Radio Frequency Interference (RFI) detection and mitigation will take place at station level. Antenna systems are placed on the ground in a pattern that yields favourable station beam characteristics (details to be confirmed by ongoing simulations). The station effective aperture will range from 50m to 150m, depending on frequency. Deliberate tapering of the antenna weights, reducing the contribution from outer antennas and broadening the station beam to optimise sensitivity for specific science goals, will be frequently employed.

The phased array stations are combined into an aperture synthesis array. The stations are distributed over a large area with a maximum baseline of 360 km, yielding a maximum angular resolution of about 0.6 arcsec at the highest LOFAR frequencies. The collecting area will be laid out in a roughly scale-free configuration, with 25% of the area within a 2 km diameter, 50% within 12 km, and 75% within 75 km. The layout will be two-dimensional in order to yield good instantaneous uv coverage, and may be somewhat elongated in the N-S direction to yield roughly circular synthesized beams over a wide range of source declinations. The total number of stations will be between 60 and 160, with 100 as the nominal figure. The array configuration will be optimised for cable length, imaging capabilities under a variety of observing conditions, total cost, and other variables. The concentration of antennas towards the centre can be operated as a single large station. This so called Compact Core will be used to calibrate the large ionospheric phase fluctuations, and serves as a sensitive detector for applications that do not need high spatial resolution e.g. the Epoch of Reionization, transients and pulsars. Beams from the Compact Core and of the out-stations are transported back to a central processor and are processed further. In the case of normal imaging applications, the signals are cross-correlated and subsequently (self) calibrated. For other applications, (e.g. the detection of transient sources) dedicated processing algorithms are being developed.

Detectability of HI as a function of redshift

The recent WMAP results suggest that the redshift at which reionization started may have been considerably higher than z=10. The possibility to detect HI fluctuations with LOFAR will rapidly deteriorate with redshift. Below 150 MHz the Galactic emission rapidly increases the noise and if this is not compensated by an increased collecting area the integration time will have to be increased by a large factor; more than a factor 3 would seem unrealistic. For redshifts from z=12 to 17 the RFI from terrestrial FM band transmitters also will get in the way. A further problem with lower frequencies is that the main foreground contaminant itself also increases (and even more rapidly). The figure to the right (→) shows the changes of the system noise and the Galactic emission as a function of frequency for a location somewhere in the Galactic halo. Three redshifts for HI are indicated.



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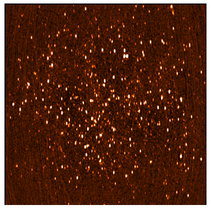
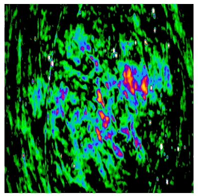
The Galactic synchrotron emission is very smoothly distributed in the Galactic halo. Large areas have been studied in detail using WENSS data and deeper, wideband (310-380 MHz) followup was done on several fields. The wideband datasets allowed a first test of the differential imaging technique that is crucial to the search for HI fluctuations in 3-D imagecubes. The images to the right and below show an area of about 4° x 4° in the north Galactic hemisphere (RA 14^h04^m, Dec +29°) observed at 325 MHz. The data come from a 48^h synthesis with the WSRT and reached the (thermal) noise level of ~250 mJy , which is somewhat below the (classical) confusion level for a 1'x2' beam. The total intensity image (→) reveals a field with more than a thousand discrete sources and very weak traces of large-scale Galactic background fluctuations (~ 0.5 K). Below is an image of the polarized intensity which shows complicated structures reaching several K in brightness temperature. These are completely uncorrelated with any of the observed total intensity features (with the exception of instrumentally polarized sources discernable at the edges of the field).





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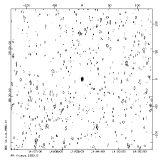
The contoured image on the right shows the difference between the skies at 325 and 341 MHz. Apart from the central source with a highly inverted spectrum (OQ208) and several very steep spectrum sources, the field shows only noise. The field shown measures 1.5° x 1.5°, with contours at 1 mJy /beam



Some of the concerns and challenges for LOFAR

The extremely long integrations required to reach the tens of mJy noise levels per compact core beamarea can only be achieved after calibration of the time-variable and direction-dependent ionospheric phase distortions. This is one of the major (software) challenges and concerns for LOFAR. However, the fact that E-o-R signals are at relatively 'high' frequencies and at short baselines and the signal analysis is done in the spectral domain make us relatively insensitive to phase-calibration errors. On the other hand, the image and spectral dynamic range requirements for a succesful experiment surpass current WSRT achievements by an order of magnitude. Still, we are confident that we can meet these challenges.

Preparing for E-o-R observations with the WSRT

We have started a program on the WSRT to explore parts of the northern Galactic hemisphere to characterize the properties of the Galactic synchrotron foreground. The 'P-band' receivers on the WSRT, in combination with the new backend (80 MHz in 512 full polarization channels), recently allowed us to reach ~ 50 mJy noise in a 72^h integration (note that the WSRT has an effective collecting area of 'only' about 4000 m^2, more than one order of magnitude less than the LOFAR compact core). New receivers designed to operate from 120 - 180 MHz should be operational on the WSRT in the fall of 2004. They will allow us to start observing within the E-o-R band. One of the areas where we need to get quantitative data and experience, is that of very low frequency instrumental and celestial polarization. Linearly polarized emission, which we expect to be present at significant intensities in the Galactic halo at frequencies around 150 MHz will, if not properly calibrated, leak into the Stokes I signal and introduce via frequency-dependent Faraday rotation undesired spectral signals.

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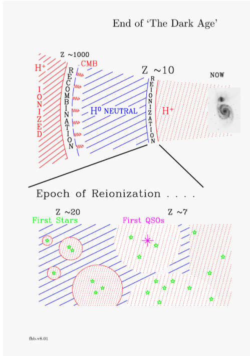

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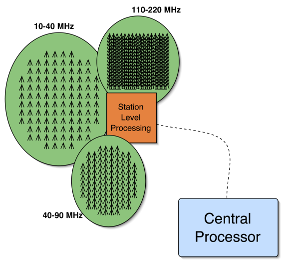

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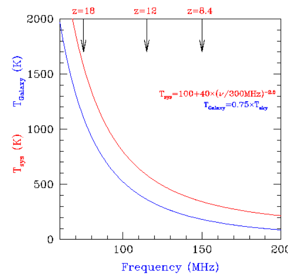

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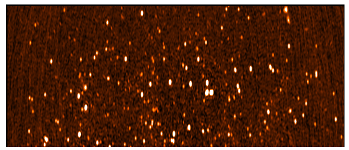

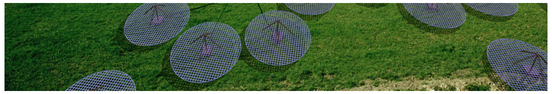

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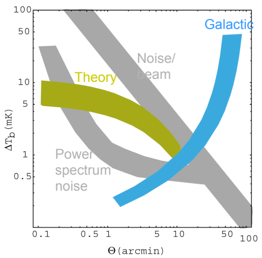

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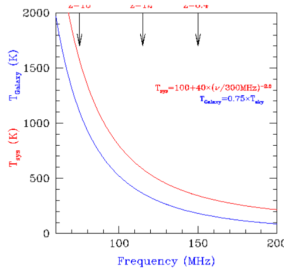

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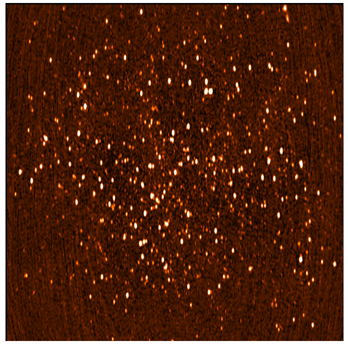

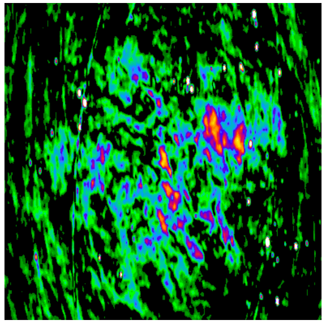

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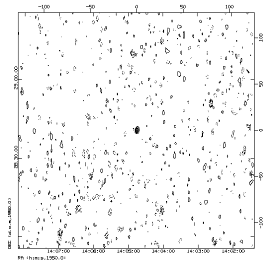


Some of the concerns and challenges for LOFAR

The extremely long integrations required to reach the tens of mJy noise levels per compact core beamarea can only be achieved after calibration of the time-variable and direction-dependent ionospheric phase distortions. This is one of the major (software) challenges and concerns for LOFAR. However, the fact that E-o-R signals are at relatively 'high' frequencies and at short baselines and the signal analysis is done in the spectral domain make us relatively insensitive to phase-calibration errors. On the other hand, the image and spectral dynamic range requirements for a succesful experiment surpass current WSRT achievements by an order of magnitude. Still, we are confident that we can meet these challenges.

Preparing for E-o-R observations with the WSRT

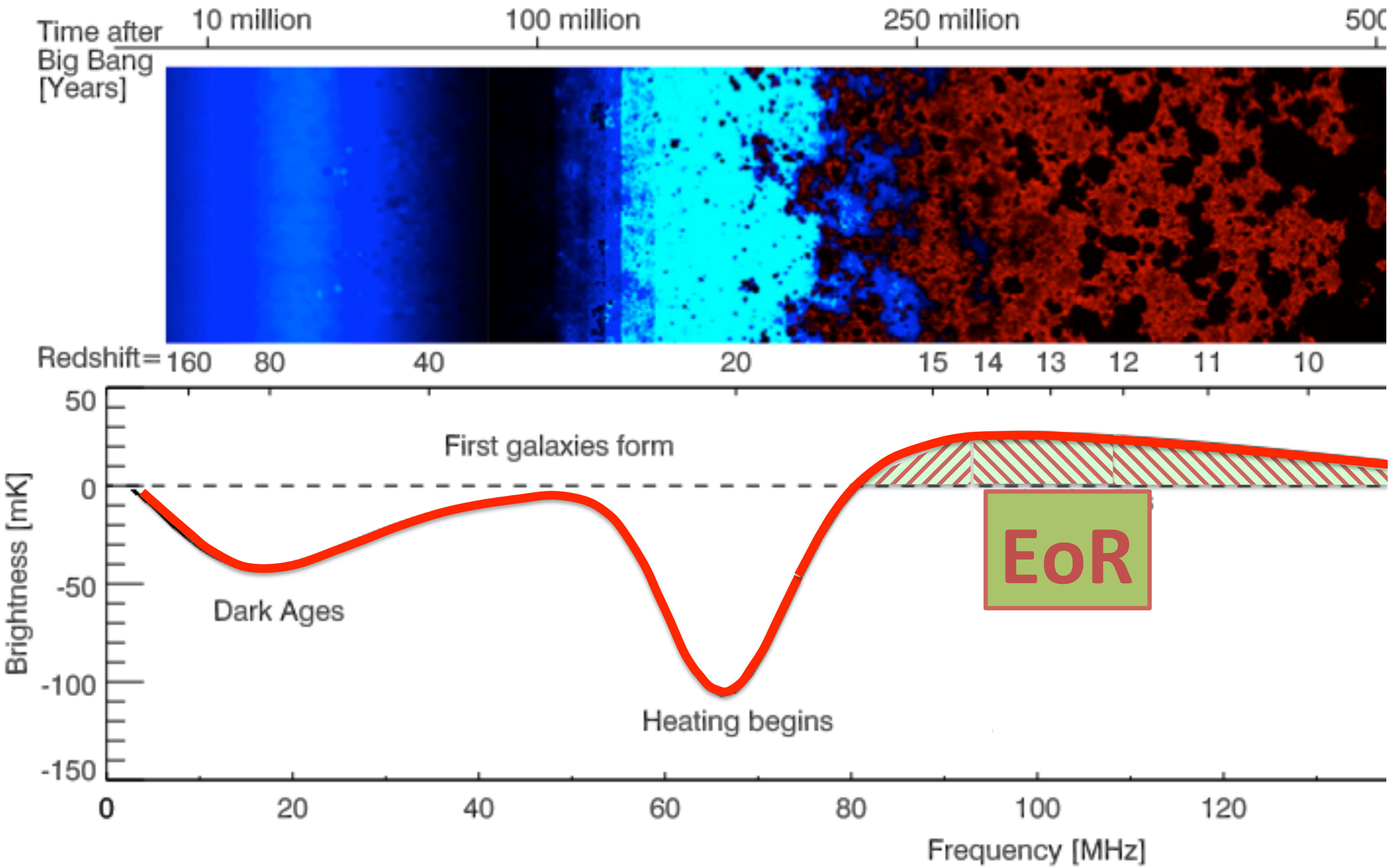
We have started a program on the WSRT to explore parts of the northern Galactic hemisphere to characterize the properties of the Galactic synchrotron foreground. The 'P-band' receivers on the WSRT, in combination with the new backend (80 MHz in 512 full polarization channels), recently allowed us to reach ~ 50 mJy noise in a 72^h integration (note that the WSRT has an effective collecting area of 'only' about 4000 m^2, more than one order of magnitude less than the LOFAR compact core). New receivers designed to operate from 120 - 180 MHz should be operational on the WSRT in the fall of 2004. They will allow us to start observing within the E-o-R band. One of the areas where we need to get quantitative data and experience, is that of very low frequency instrumental and celestial polarization. Linearly polarized emission, which we expect to be present at significant intensities in the Galactic halo at frequencies around 150 MHz will, if not properly calibrated, leak into the Stokes I signal and introduce via frequency-dependent Faraday rotation undesired spectral signals.

A story of **Primordial HI**…

Radio Spectrum from 0 – 200 MHz:

absorption & emission in 21cm line

Pritchard & Loeb 2012



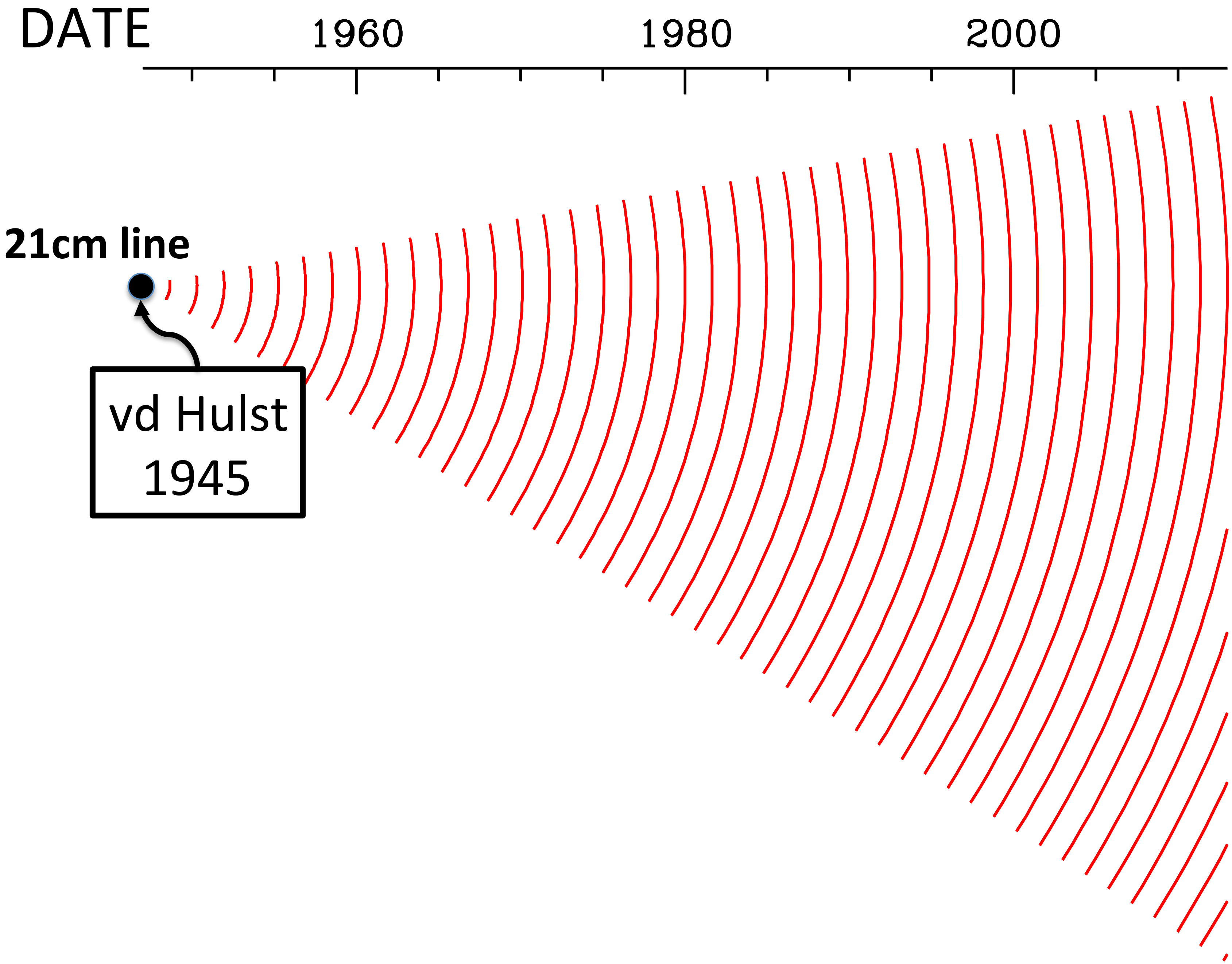
A **story** of **Primordial HI**…

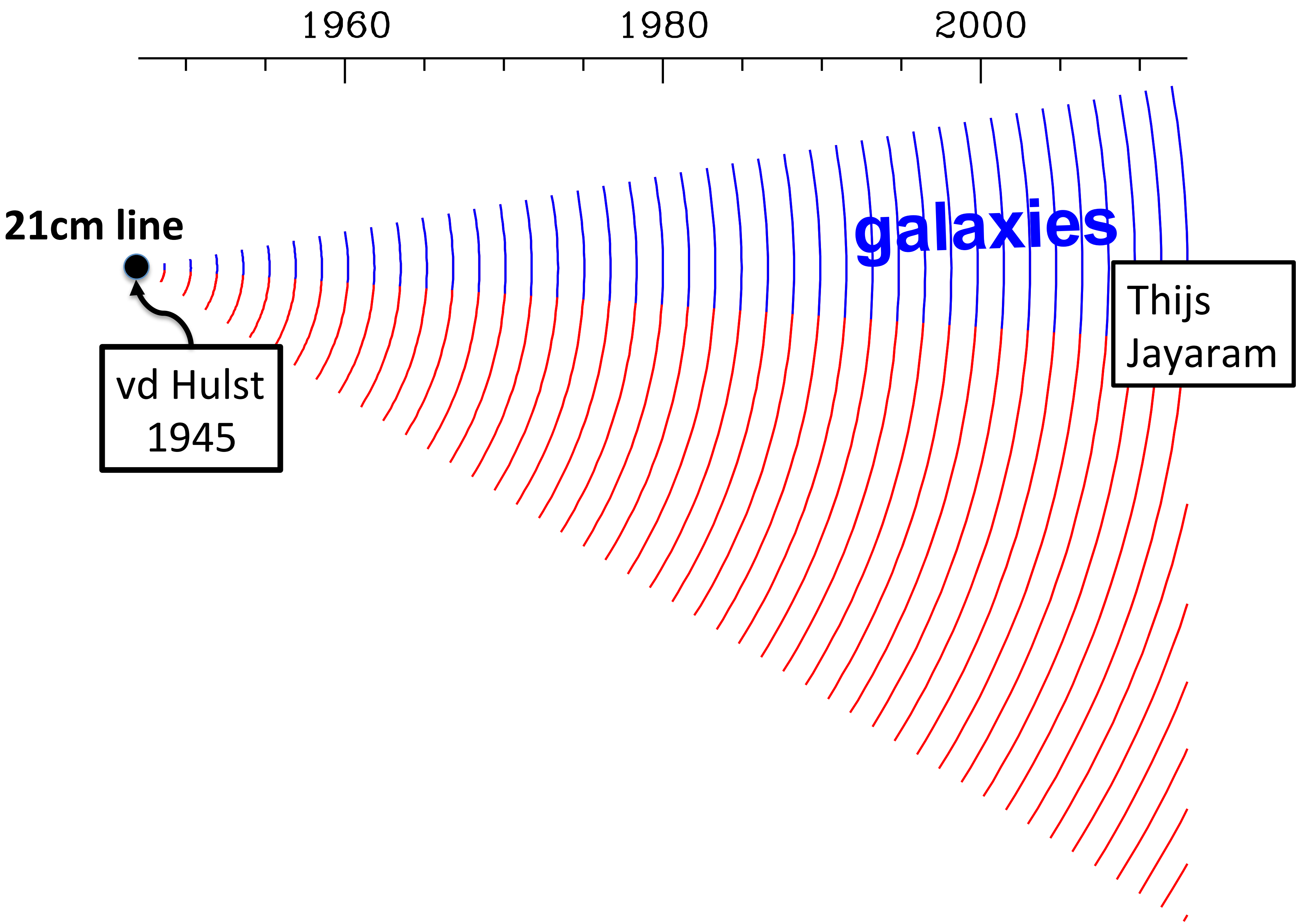
(spinning a yarn?)

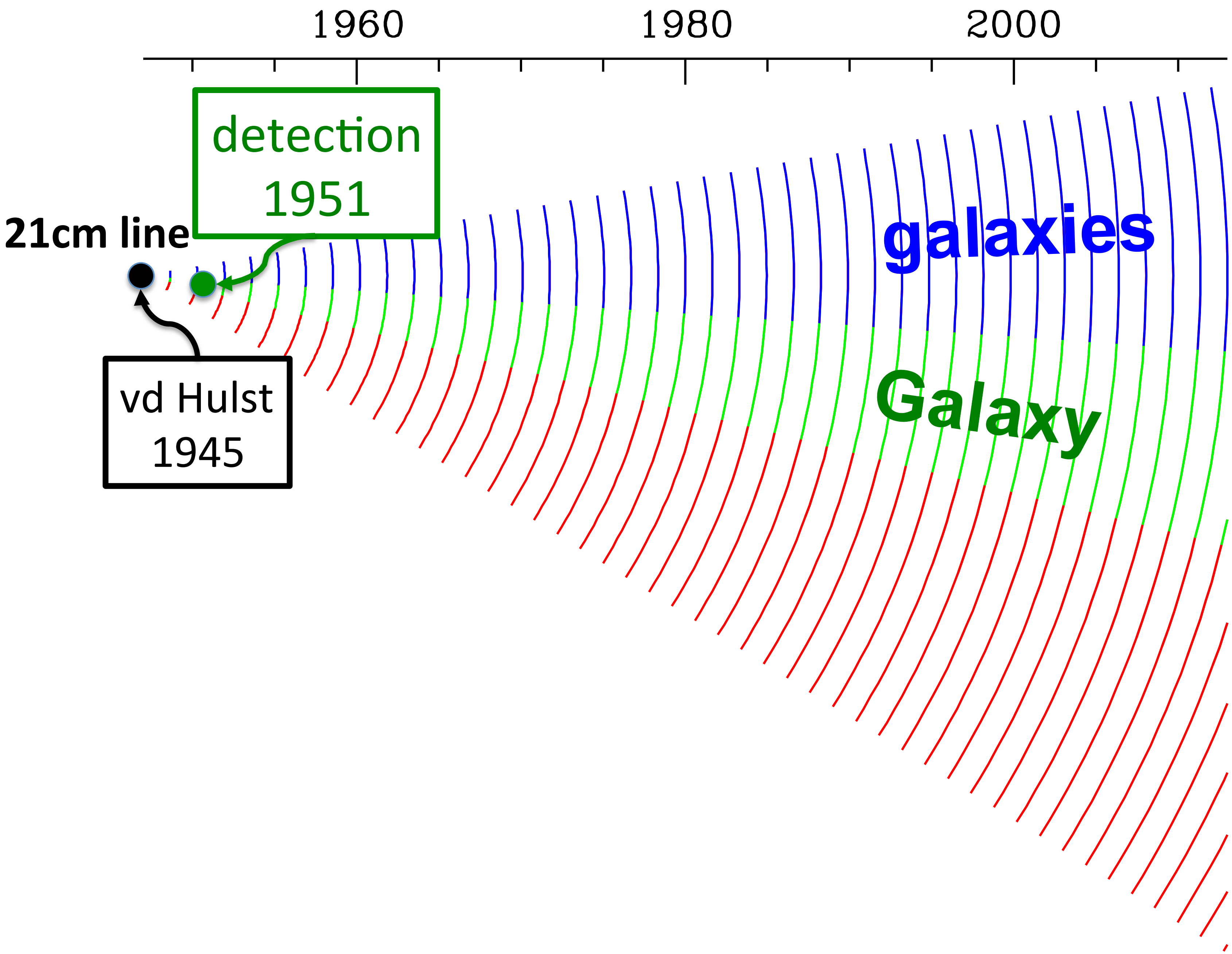
- Most observations have been **motivated** by **theoretical** argument

- **Few surprises** …
  (but very important one)

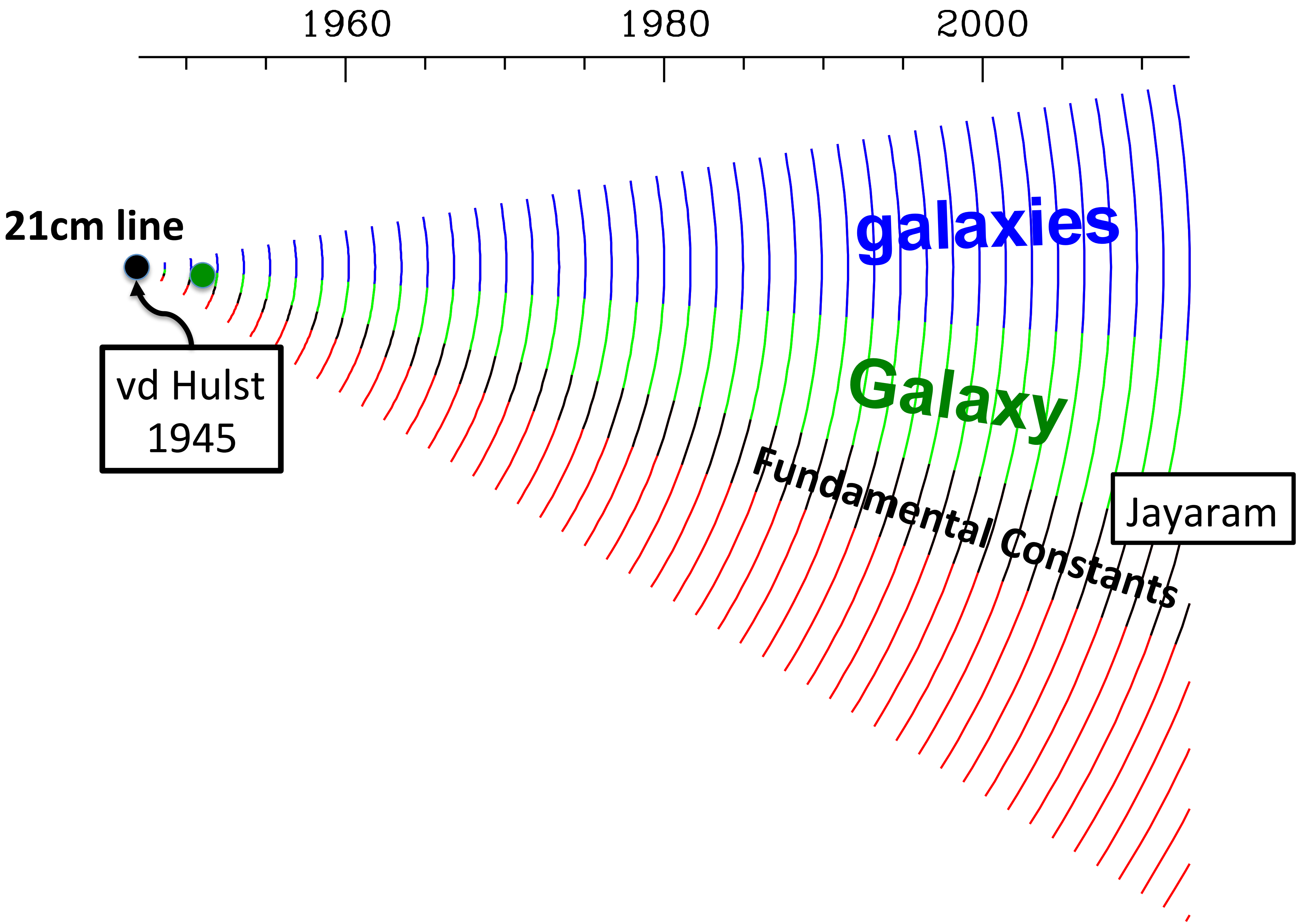
- A few key papers that stimulated **WAVEs of enthusiasm** & observational efforts…
  - Identify a few sources
  - Follow the waves…

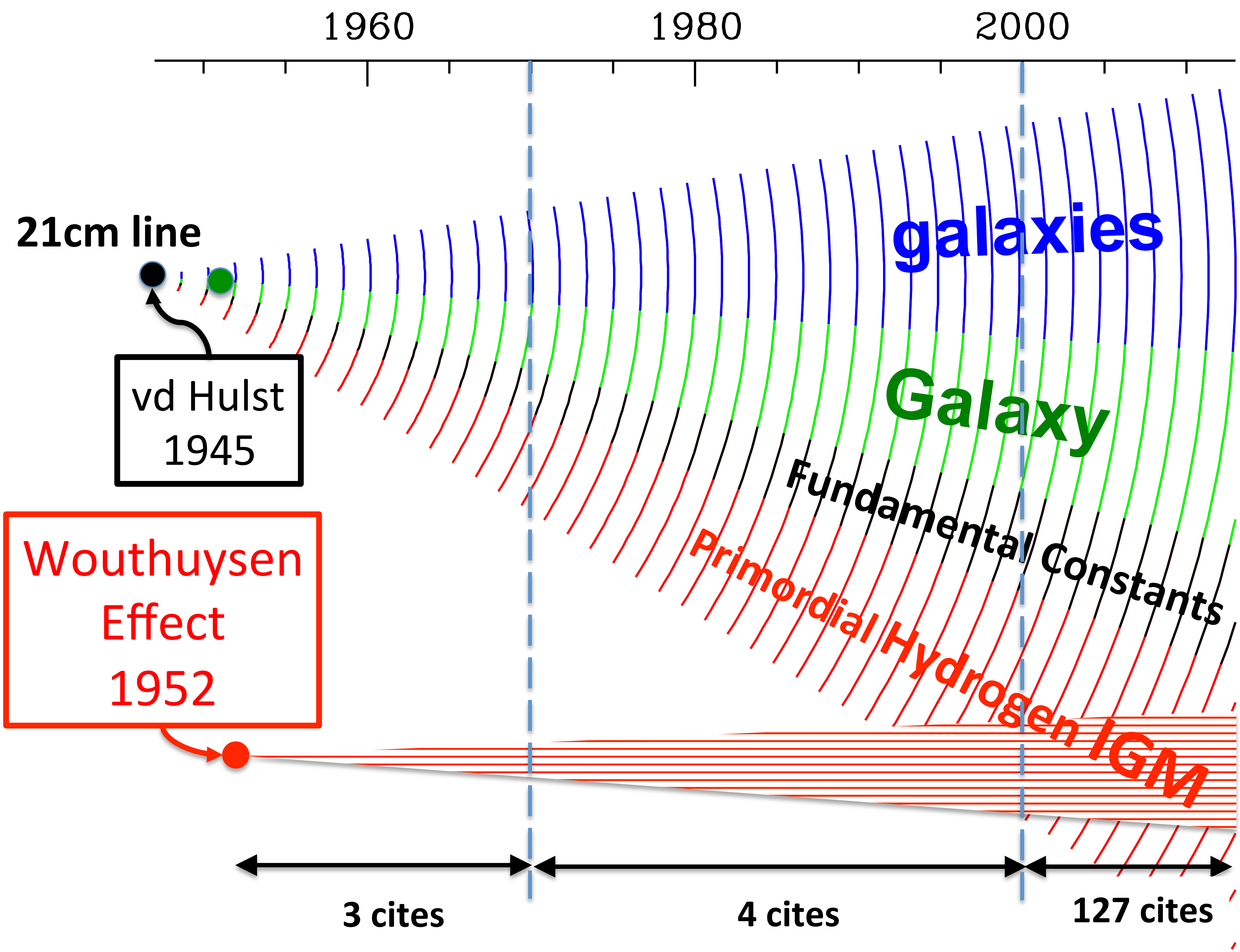

DATE
1960
1980
2000
21cm line
vd Hulst
1945


1960
1980
2000
21cm line
galaxies
vd Hulst
1945
Thijs
Jayaram



1960
1980
2000
detection
1951
21cm line
vd Hulst
1945
galaxies
Galaxy

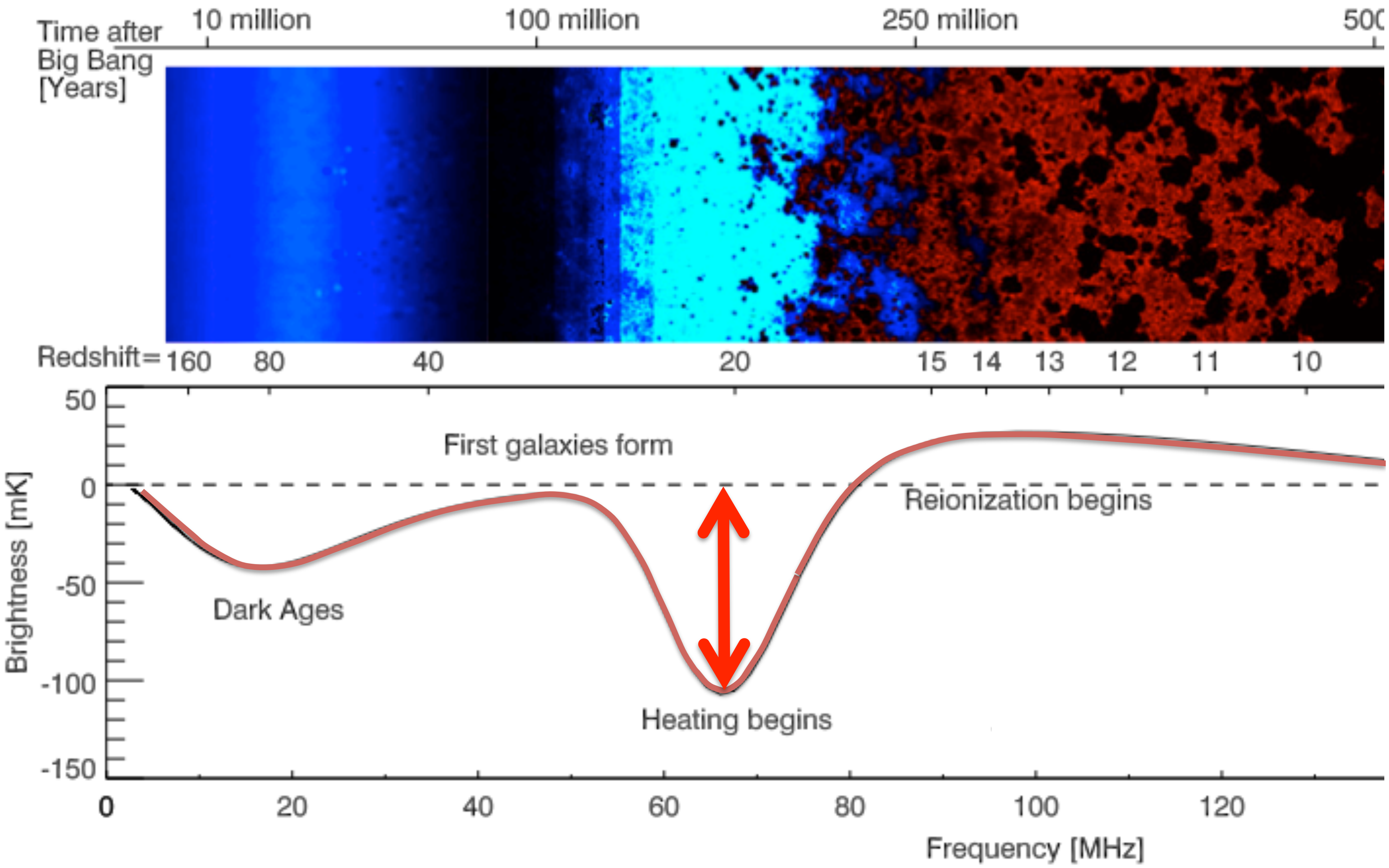

1960
1980
2000
21cm line
vd Hulst
1945
galaxies
Galaxy
Fundamental Constants
Jayaram

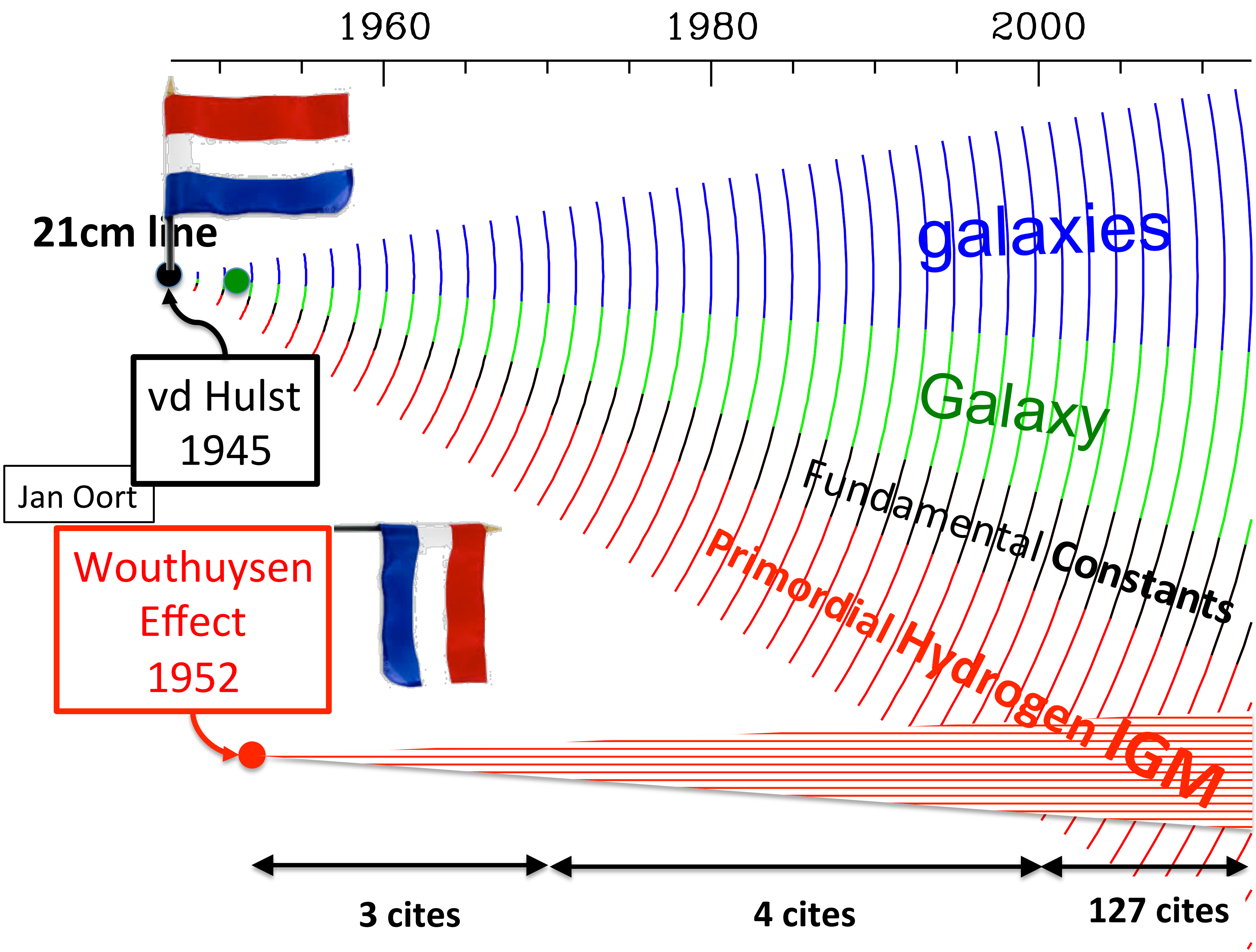

1960
1980
2000
21cm line
vd Hulst
1945
galaxies
Galaxy
Fundamental Constants
Primordial Hydrogen
IGM
Wouthuysen
Effect
1952
3 cites
4 cites
127 cites

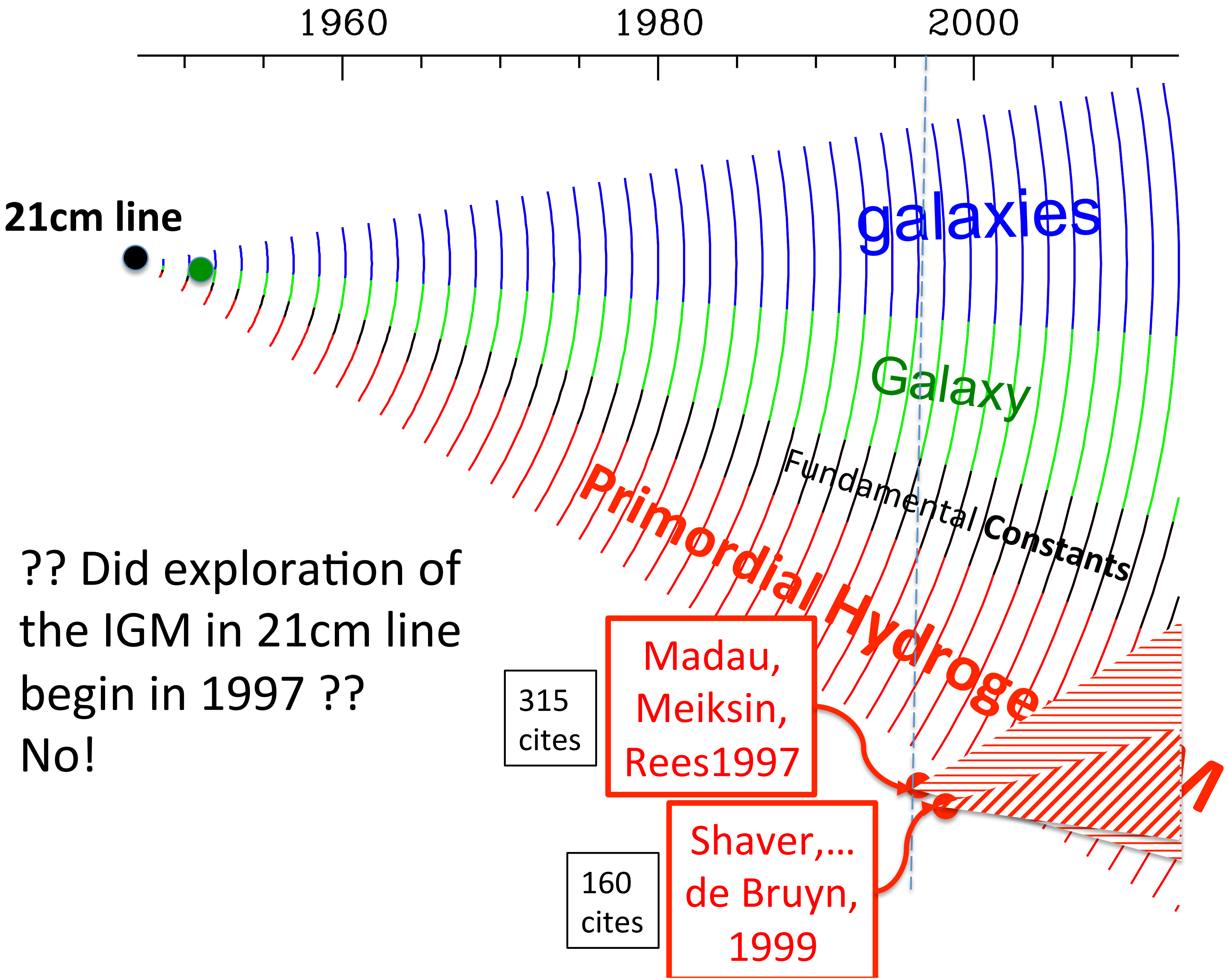
Radio Spectrum from 0 – 200 MHz:

absorption & emission in 21cm line

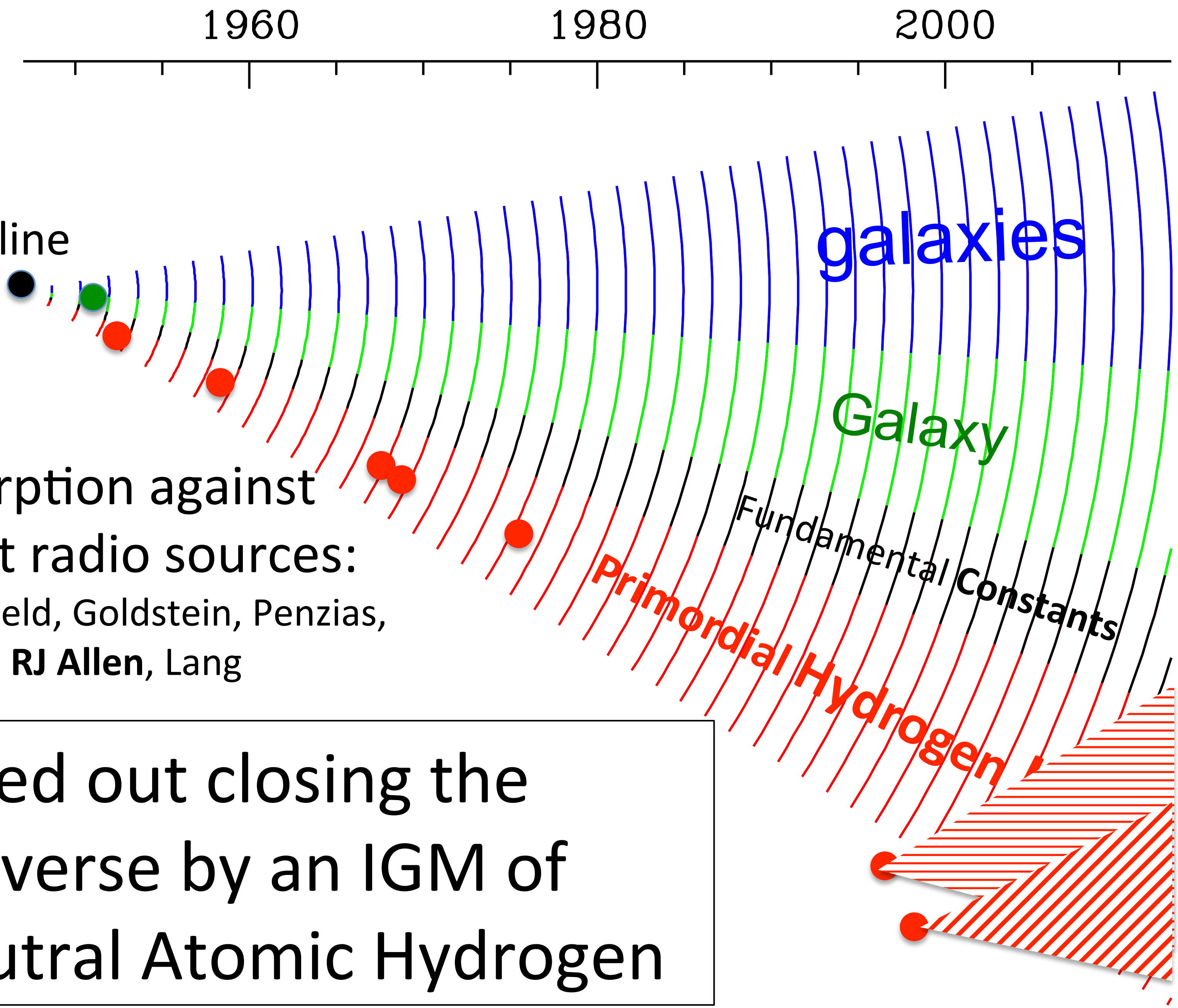
Pritchard & Loeb 2012




1960
1980
2000
21cm line
vd Hulst
1945
Jan Oort
Wouthuysen
Effect
1952
galaxies
Galaxy
Fundamental Constants
Primordial Hydrogen IGM
3 cites
4 cites
127 cites



?? Did exploration of the IGM in 21cm line begin in 1997 ??
No!

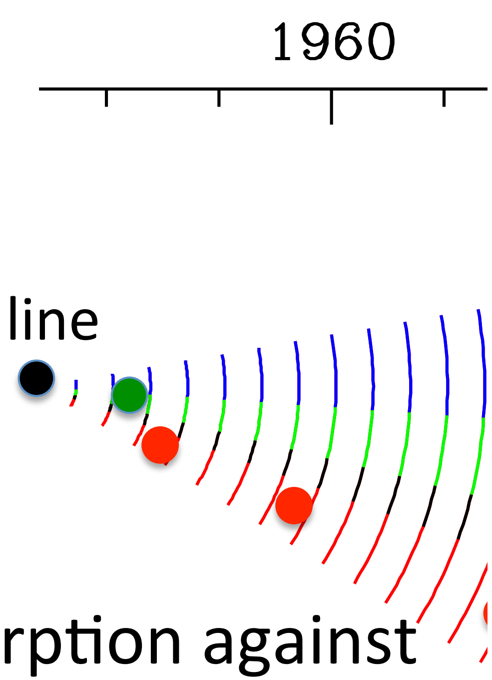


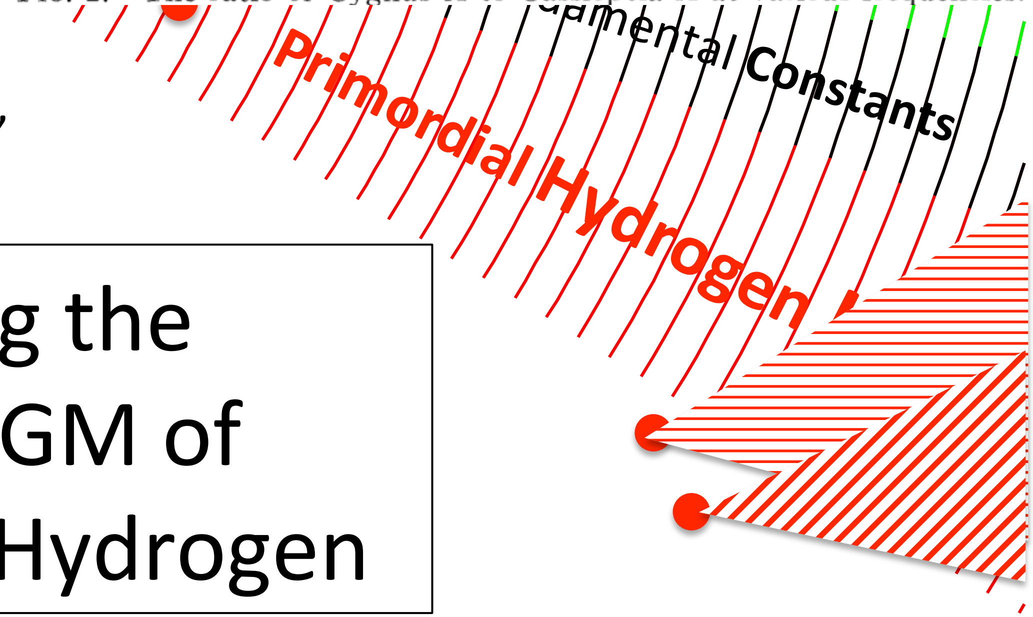
21cm line

Absorption against bright radio sources:

Wild, Field, Goldstein, Penzias, Wilson, **RJ Allen**, Lang

Ruled out closing the Universe by an IGM of Neutral Atomic Hydrogen





21cm line

Absorption against bright radio sources:
Wild, Field, Goldstein, Penzias, Wilson, **RJ Allen**, Lang

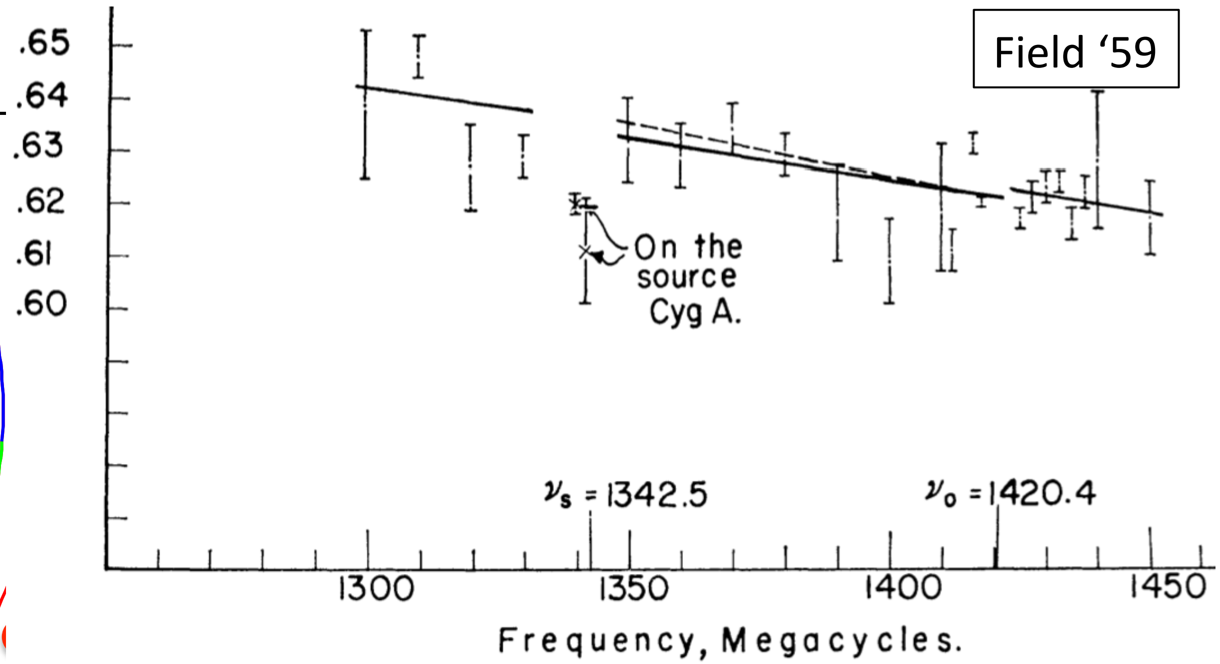
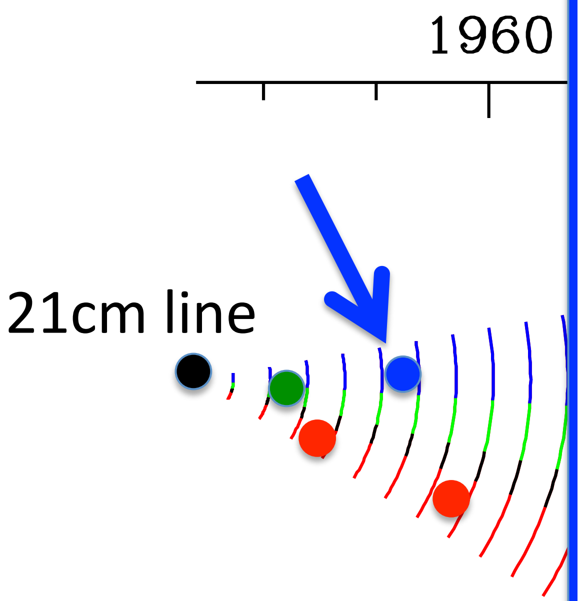
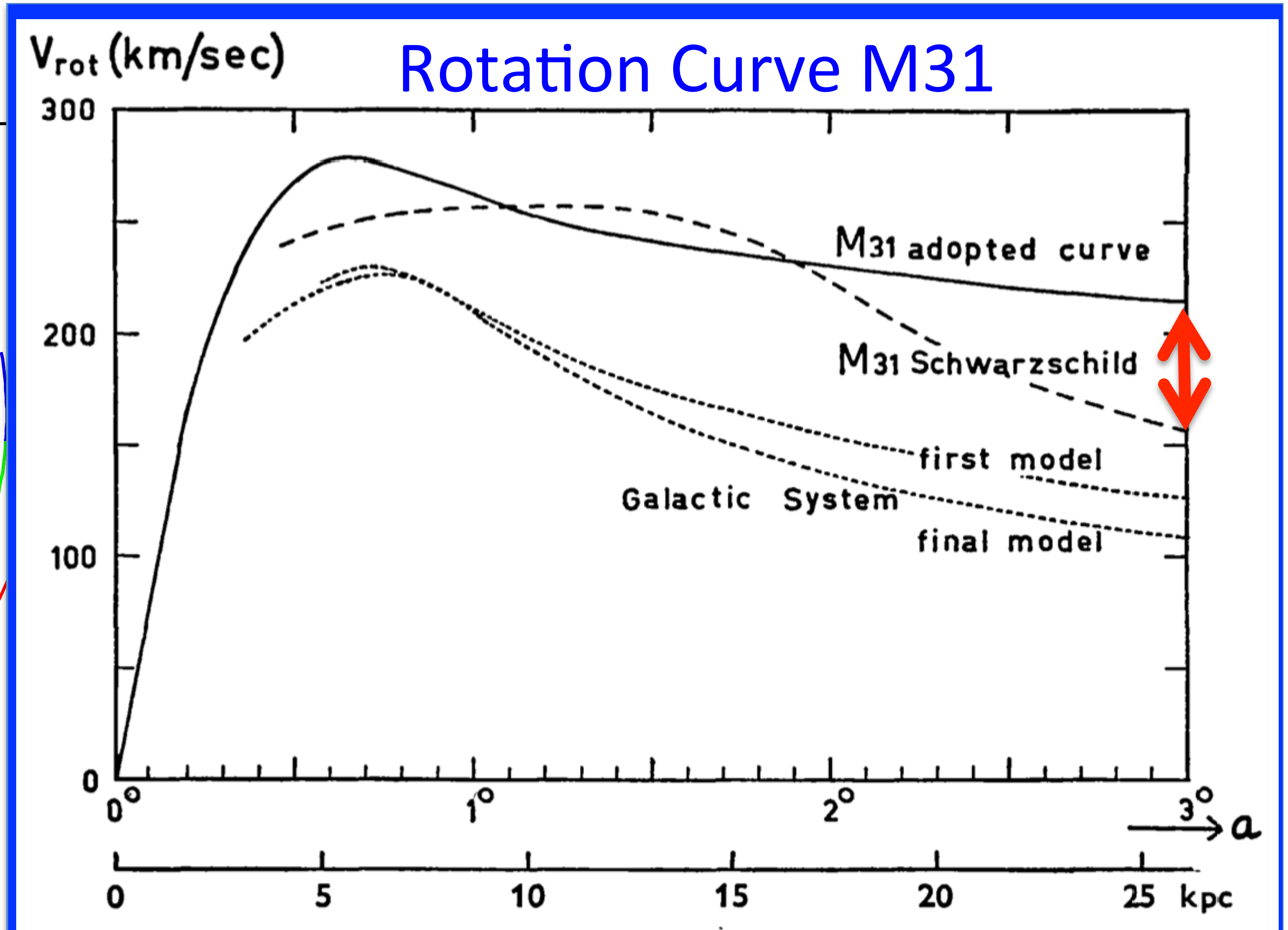


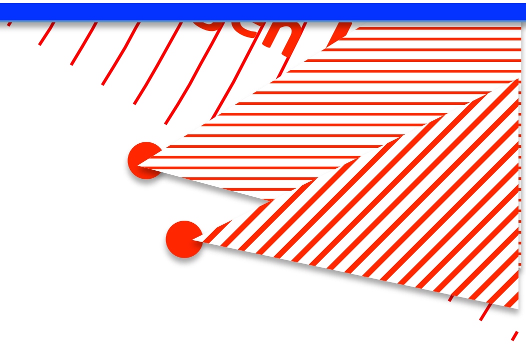
FIG. 2.—The ratio of Cygnus A to Cassiopeia A at various frequencies. The points

Ruled out closing the Universe by an IGM of Neutral Atomic Hydrogen

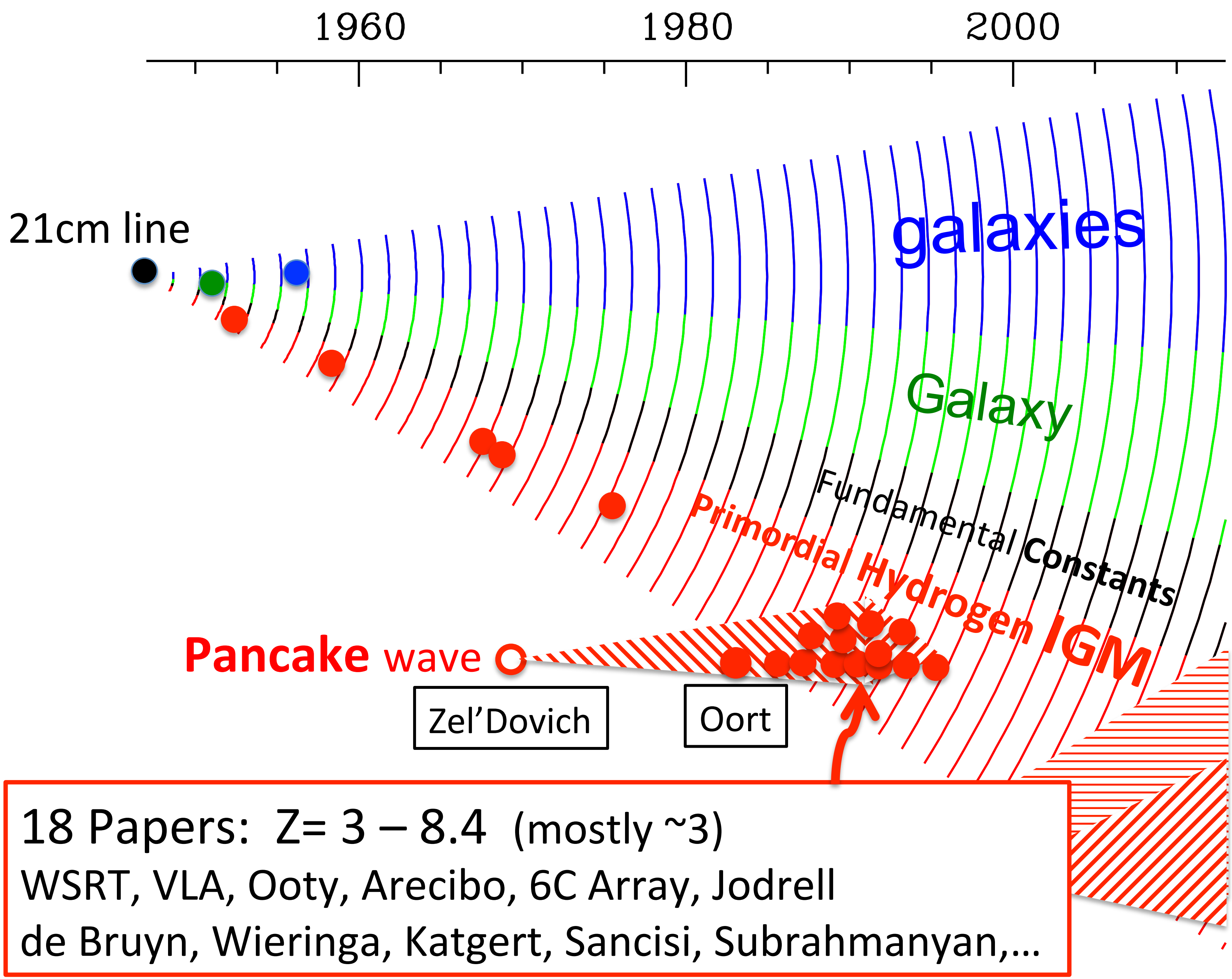




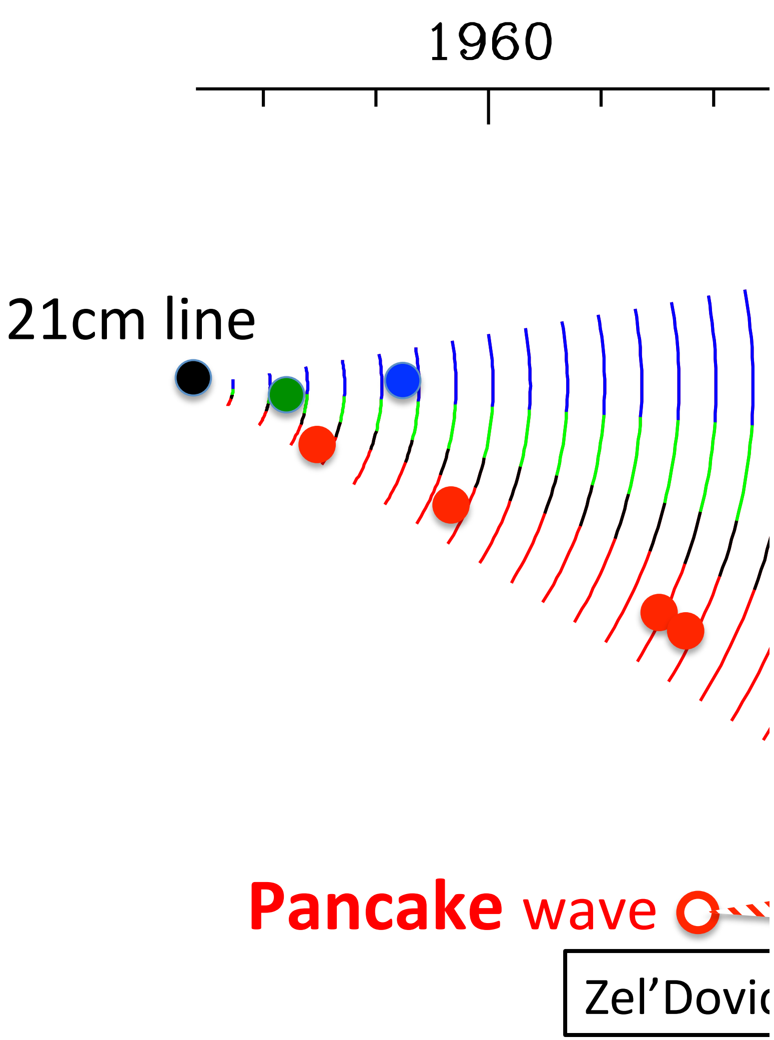
Rotation laws of M31 and the Galactic System.



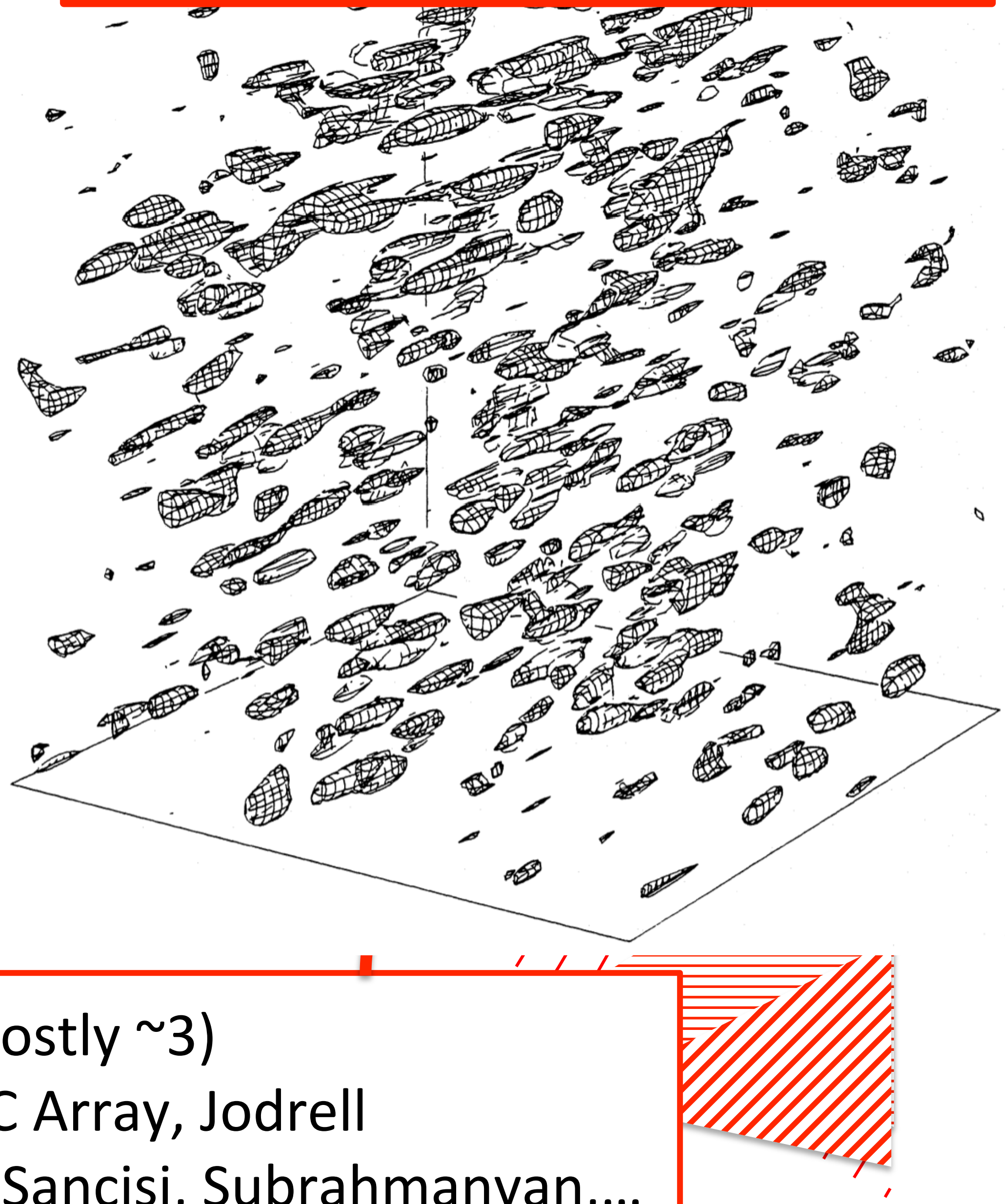
1957 van de Hulst,
Raimond, van Woerden



1960
1980
2000
21cm line
galaxies
Galaxy
Fundamental Constants
Primordial Hydrogen IGM
Pancake wave
Zel'Dovich
Oort
18 Papers: Z= 3 – 8.4 (mostly ~3)
WSRT, VLA, Ooty, Arecibo, 6C Array, Jodrell
de Bruyn, Wieringa, Katgert, Sancisi, Subrahmanyan,...



Upper limits approx 10^{13} Msolar HI



18 Papers: Z= 3 – 8.4 (mostly ~3)
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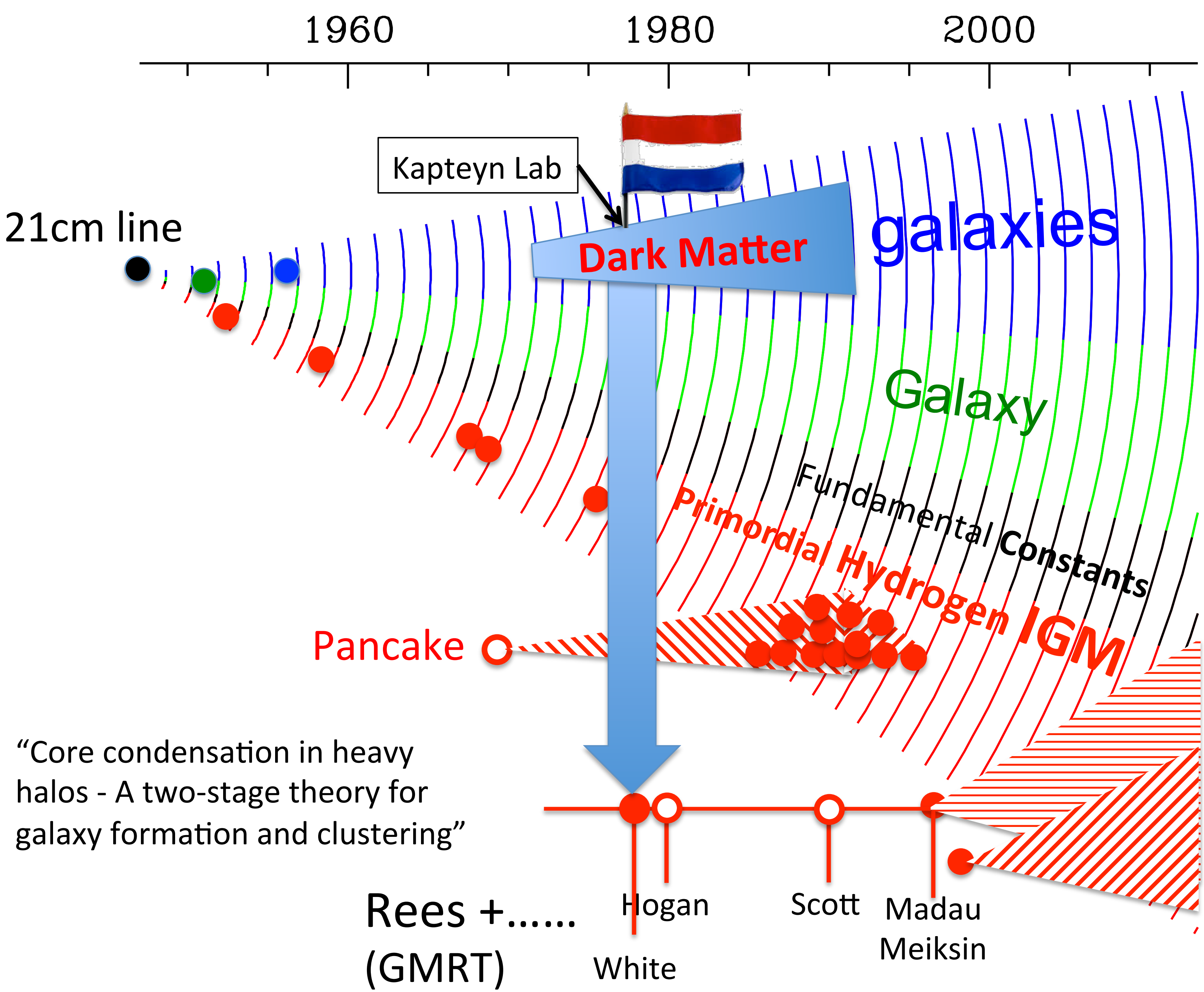
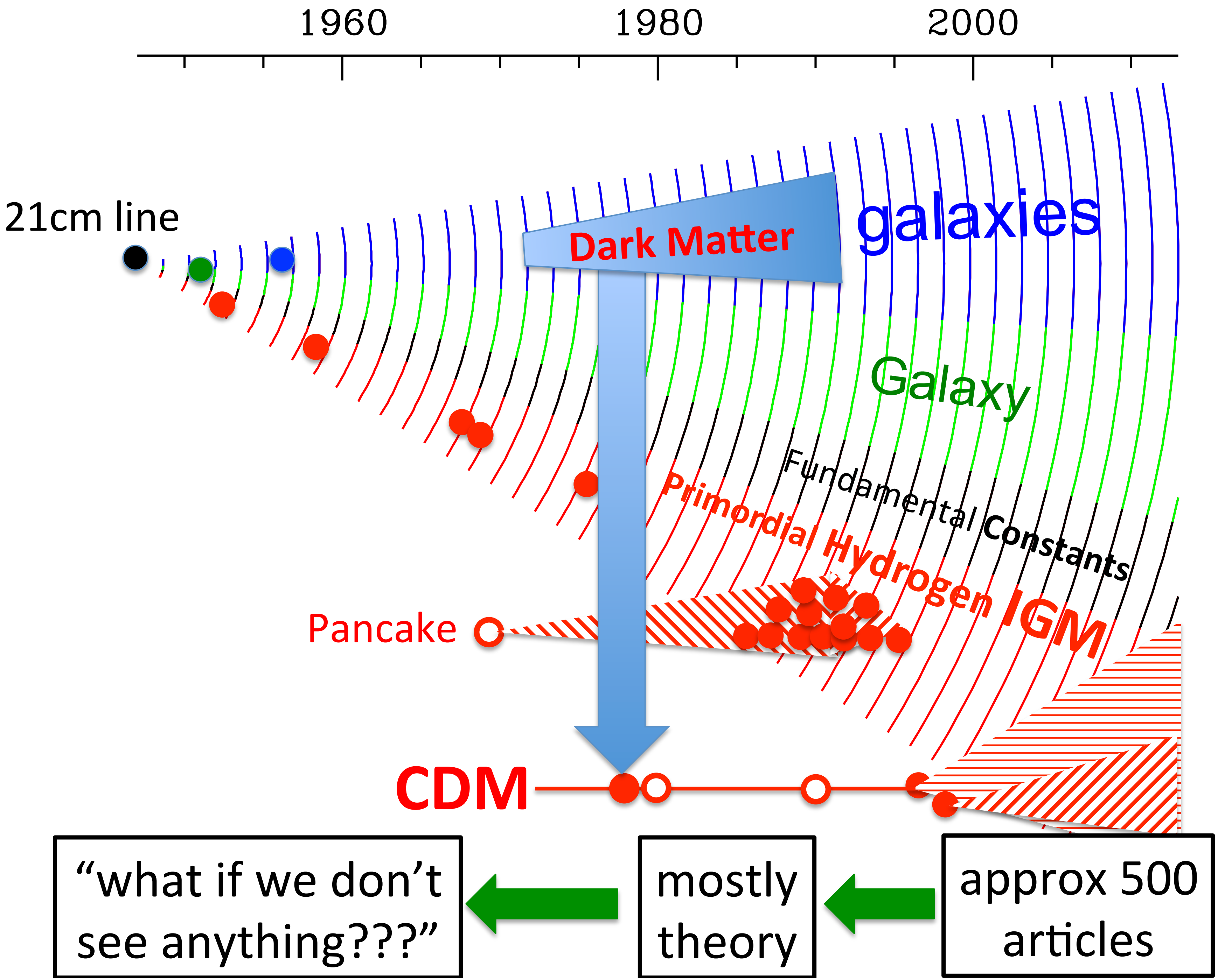
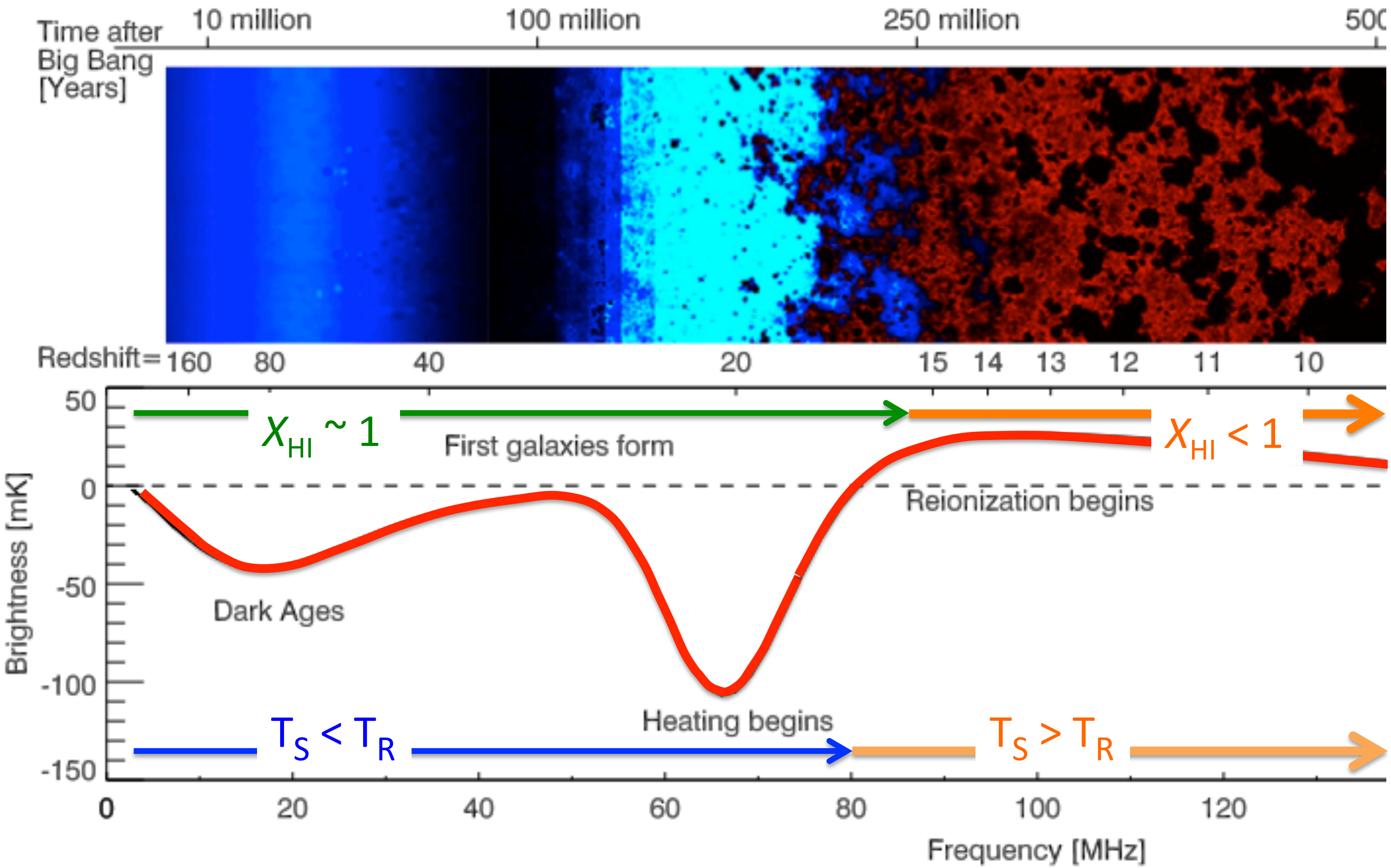


1960
1980
2000
Kapteyn Lab
21cm line
Dark Matter
galaxies
Galaxy
Fundamental Constants
Primordial Hydrogen IGM
Pancake
"Core condensation in heavy halos - A two-stage theory for galaxy formation and clustering"
Rees +......
(GMRT)
Hogan
White
Scott
Madau
Meiksin

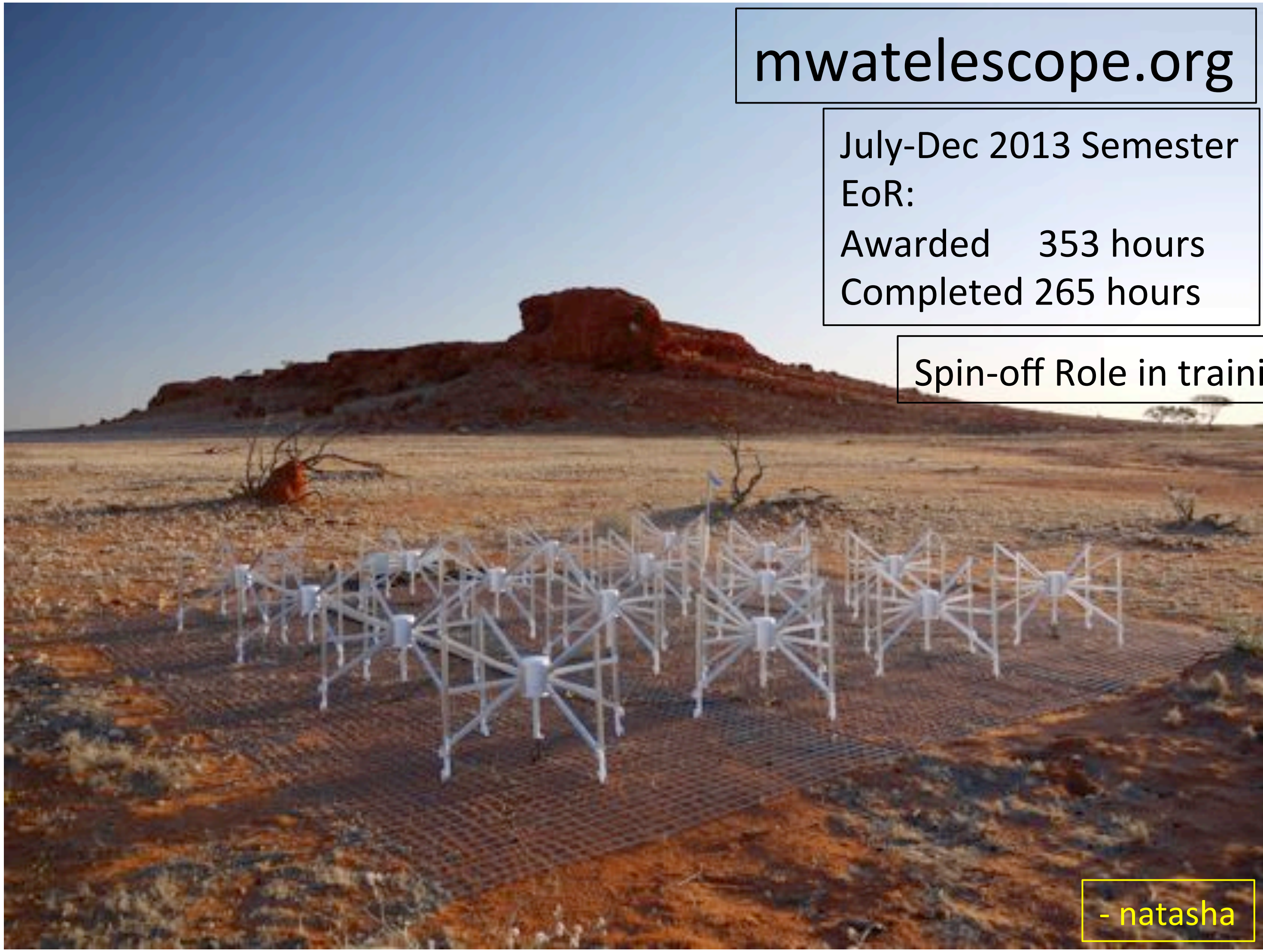

1960
1980
2000
21cm line
Dark Matter
galaxies
Galaxy
Fundamental Constants
Primordial Hydrogen IGM
Pancake
CDM
“what if we don’t see anything???”
mostly theory
approx 500 articles

Radio Spectrum from 0 – 200 MHz:

absorption & emission in 21cm line



Winding up !


mwatelescope.org
July-Dec 2013 Semester
EoR:
Awarded 353 hours
Completed 265 hours
Spin-off Role in training
- natasha

Winding up !

Coherent wave:

- creative thought
- curiosity
- Enthusiasm
- Investment of Global Wealth

Winding up !

Coherent wave:

- creative thought
- curiosity
- Enthusiasm
- Investment of Global Wealth

Value of confession ?

- Telescopes grow on trees
- … tool or toy?
- Both…

Winding up !

Coherent wave:

- creative thought
- curiosity
- Enthusiasm
- Investment of Global Wealth

Value of confession ?

- Telescopes grow on trees
- … tool or toy?
- Both…

With society's investment comes:

- Responsibility (wise use of resources)
- Obligation (give back to/share with society)

I look forward to the remainder of the programme with great pleasure

Again, congratulations to Ger on his successes and best wishes for the future

Wound up !