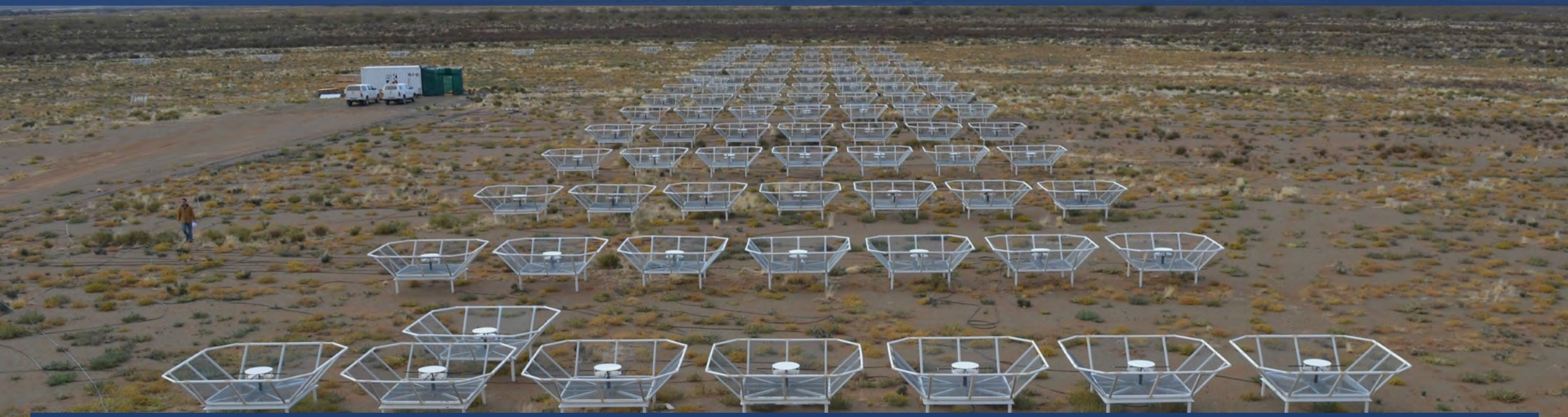
WORK SUPPORTED BY THE NATIONAL SCIENCE FOUNDATION

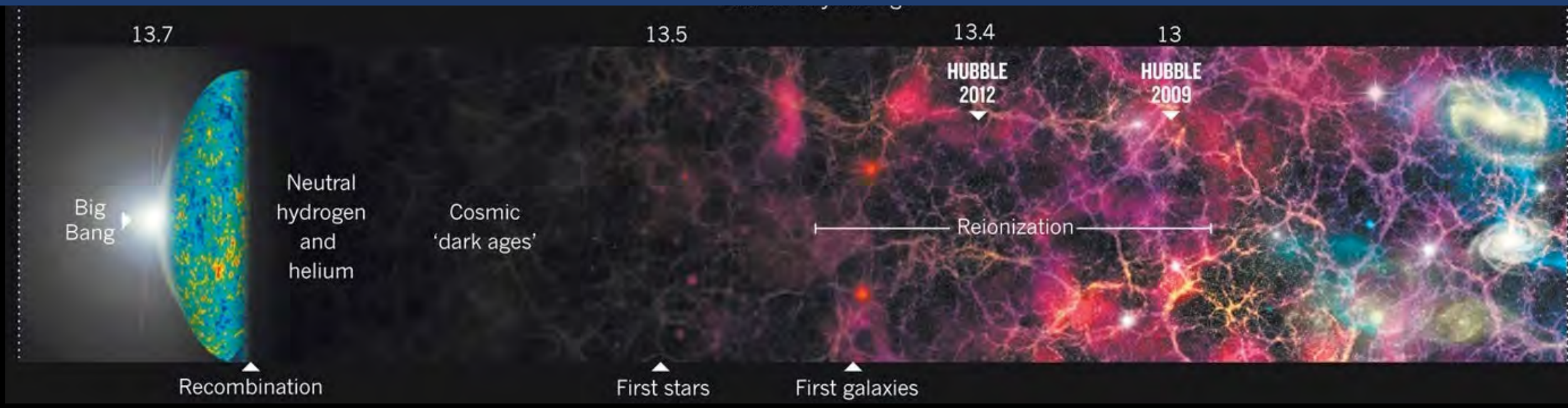


21 CM COSMOLOGY WITH PAPER, MWA AND HERA

DANIEL C. JACOBS
NSF POSTDOCTORAL FELLOW, ARIZONA STATE UNIVERSITY
ON BEHALF OF THE MWA, PAPER AND HERA COLLABORATIONS

A GRAPHICAL PREVIEW

A GRAPHICAL PREVIEW



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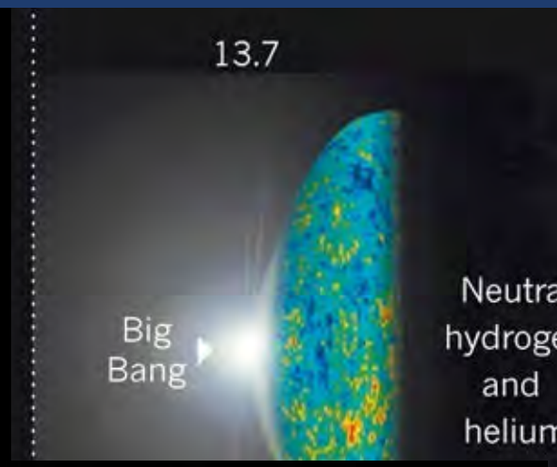

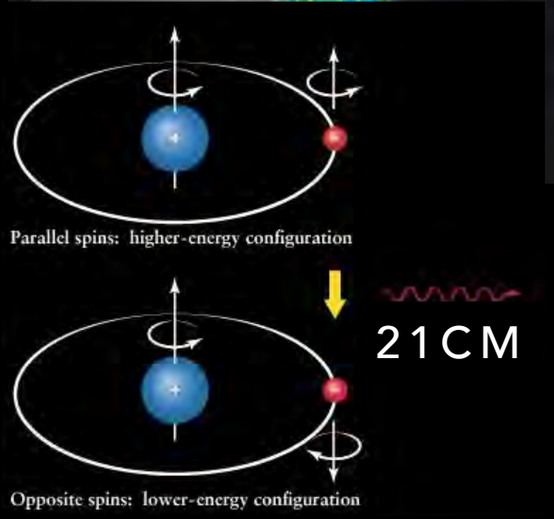

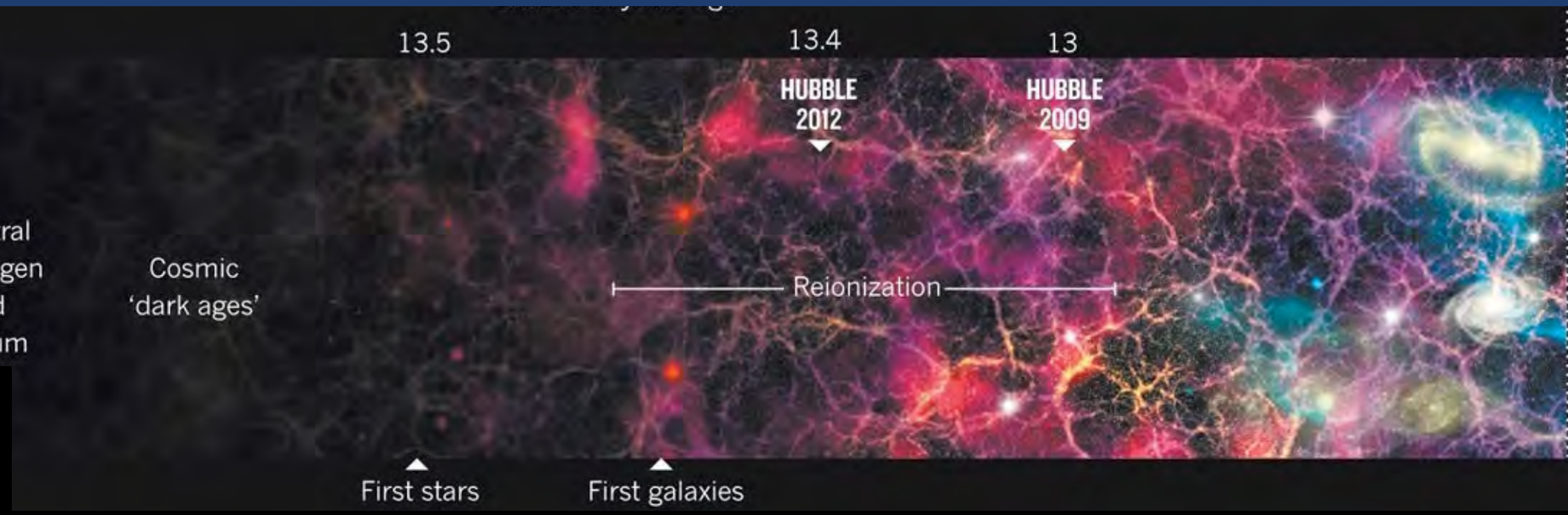

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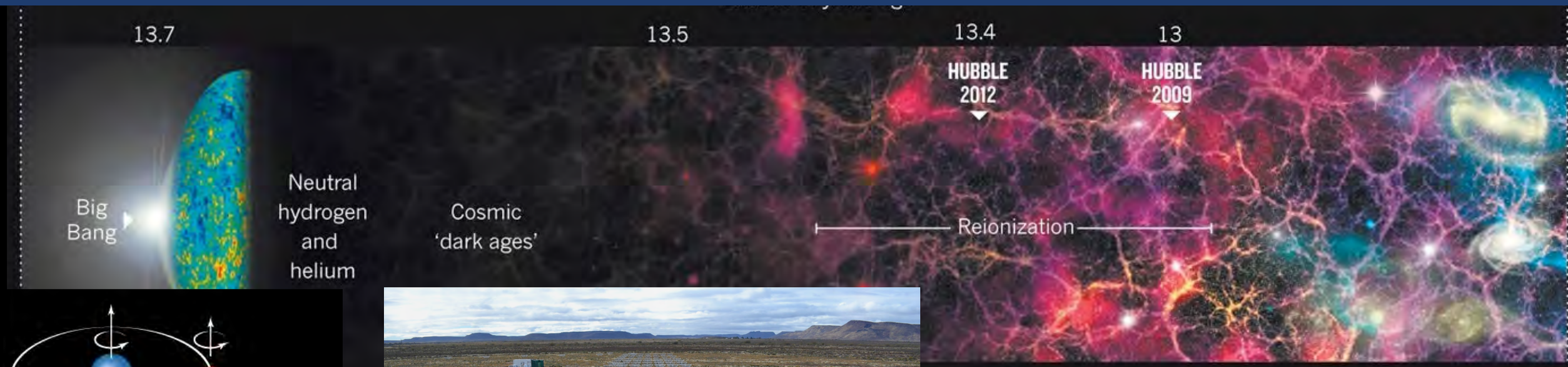

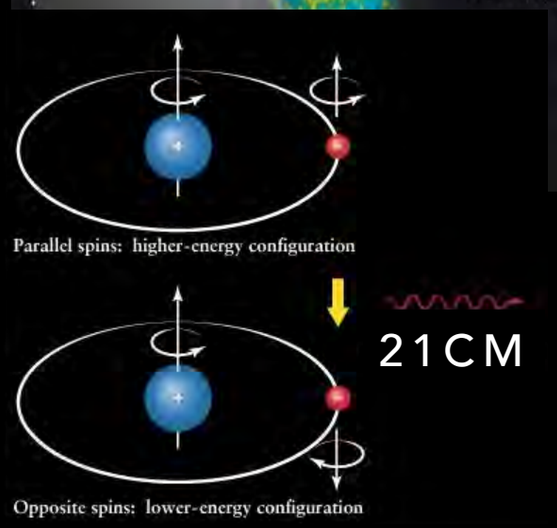

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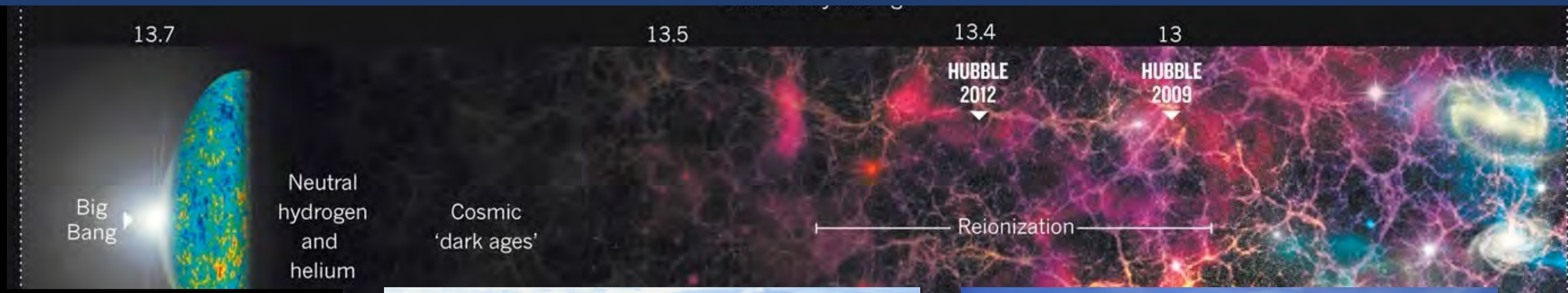

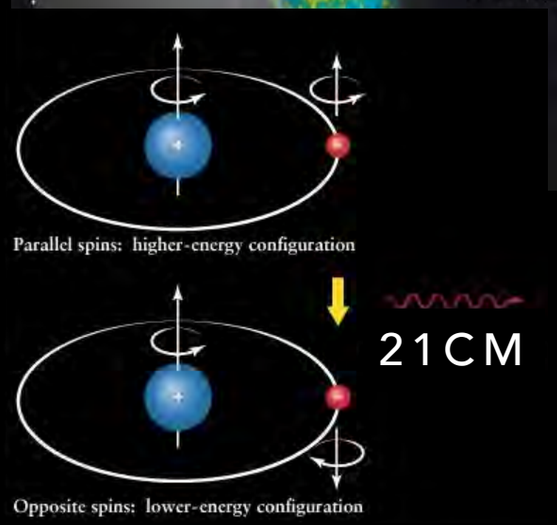

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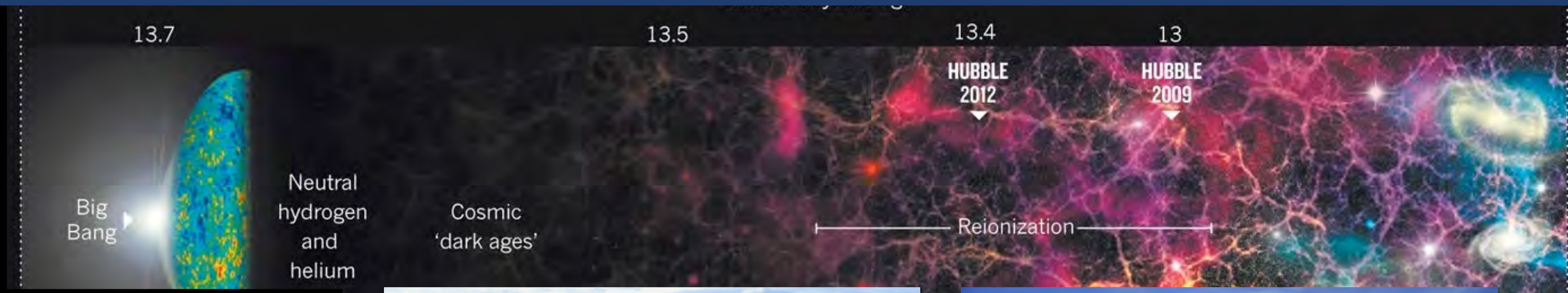

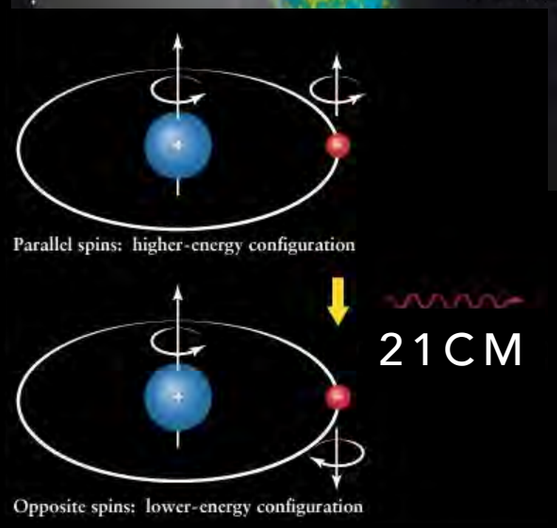

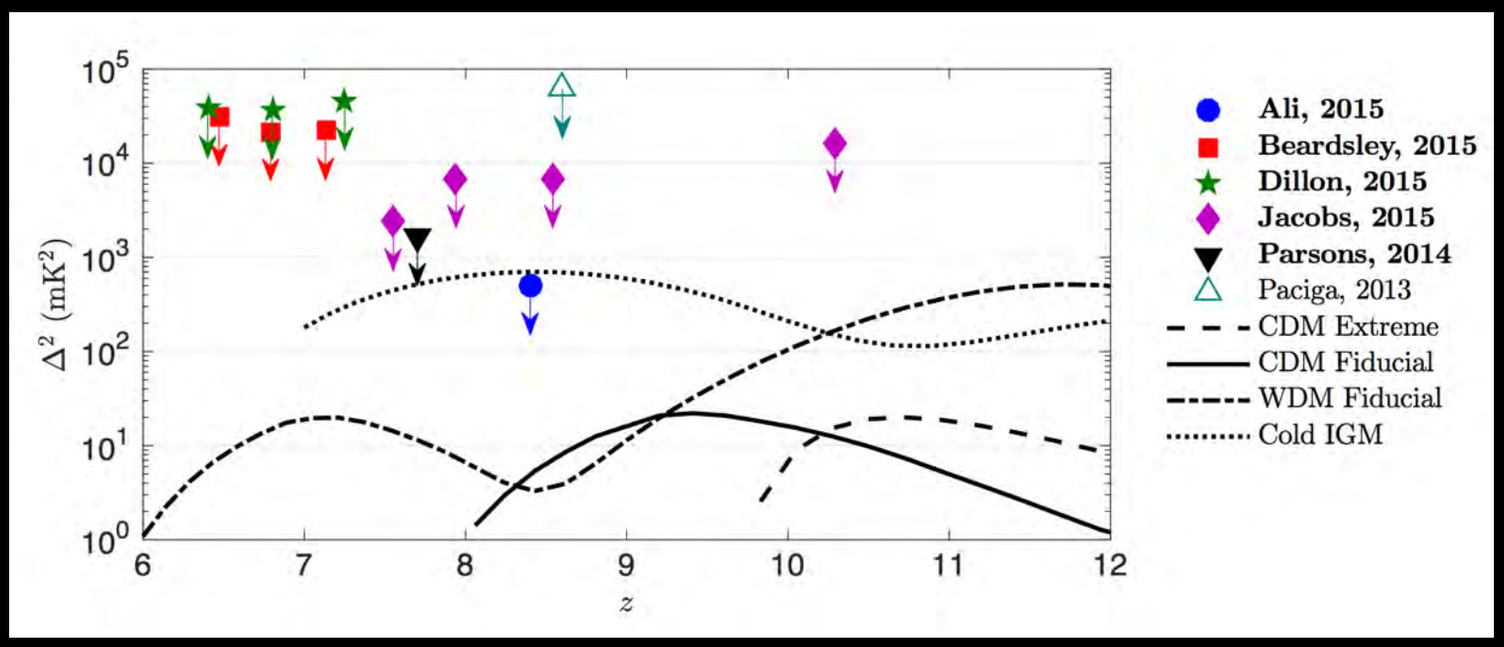

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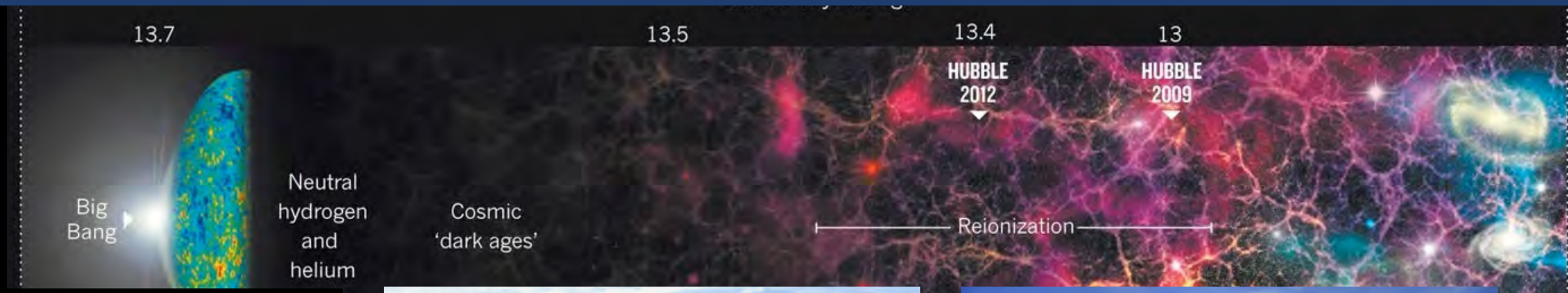
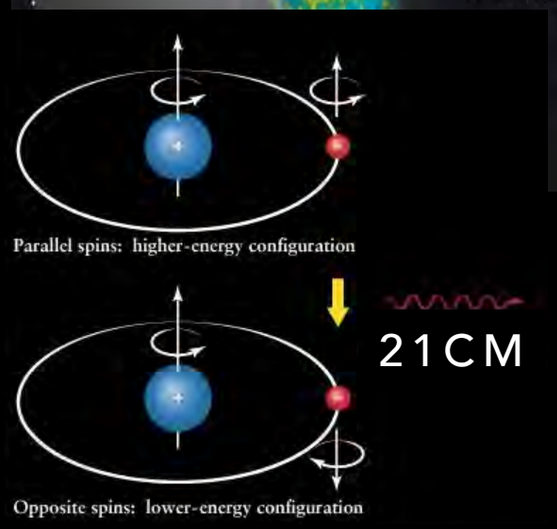
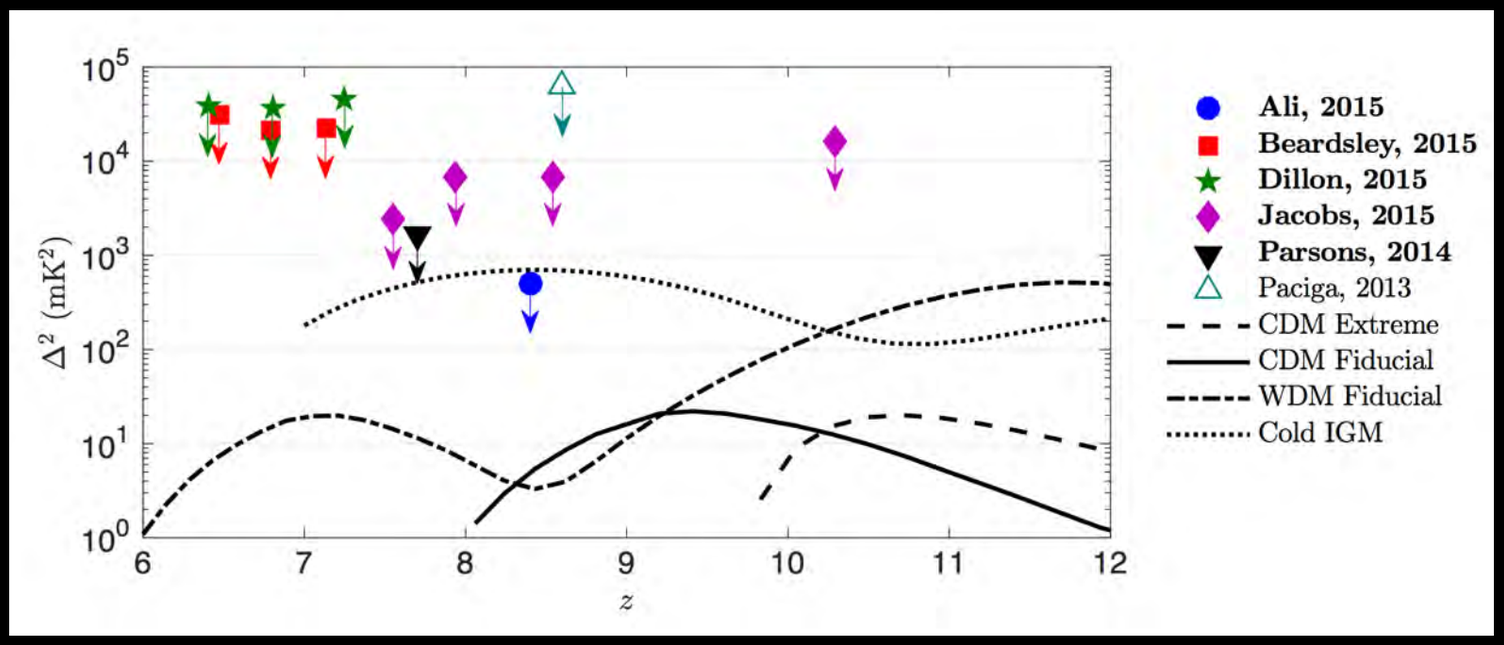






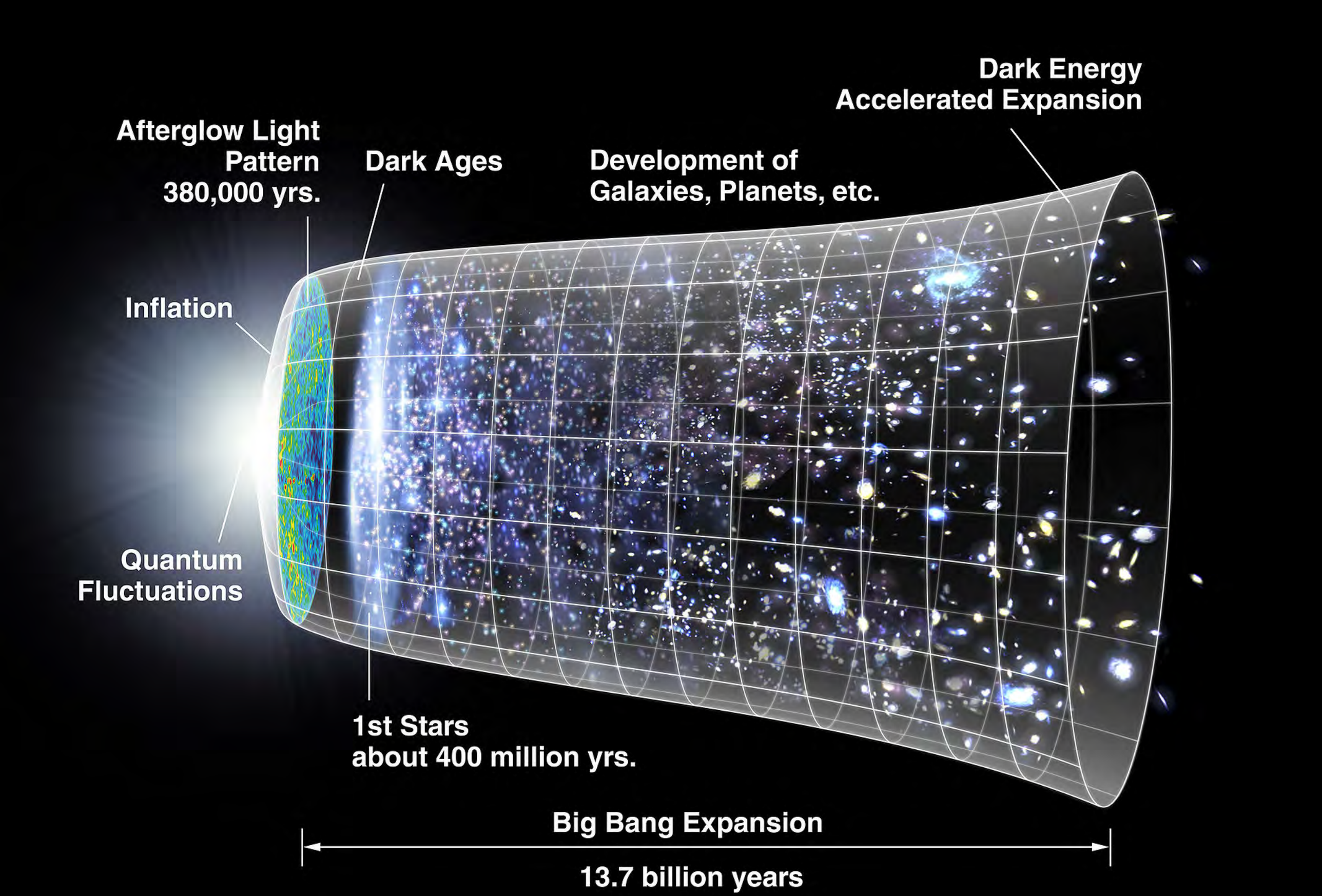
Science Questions

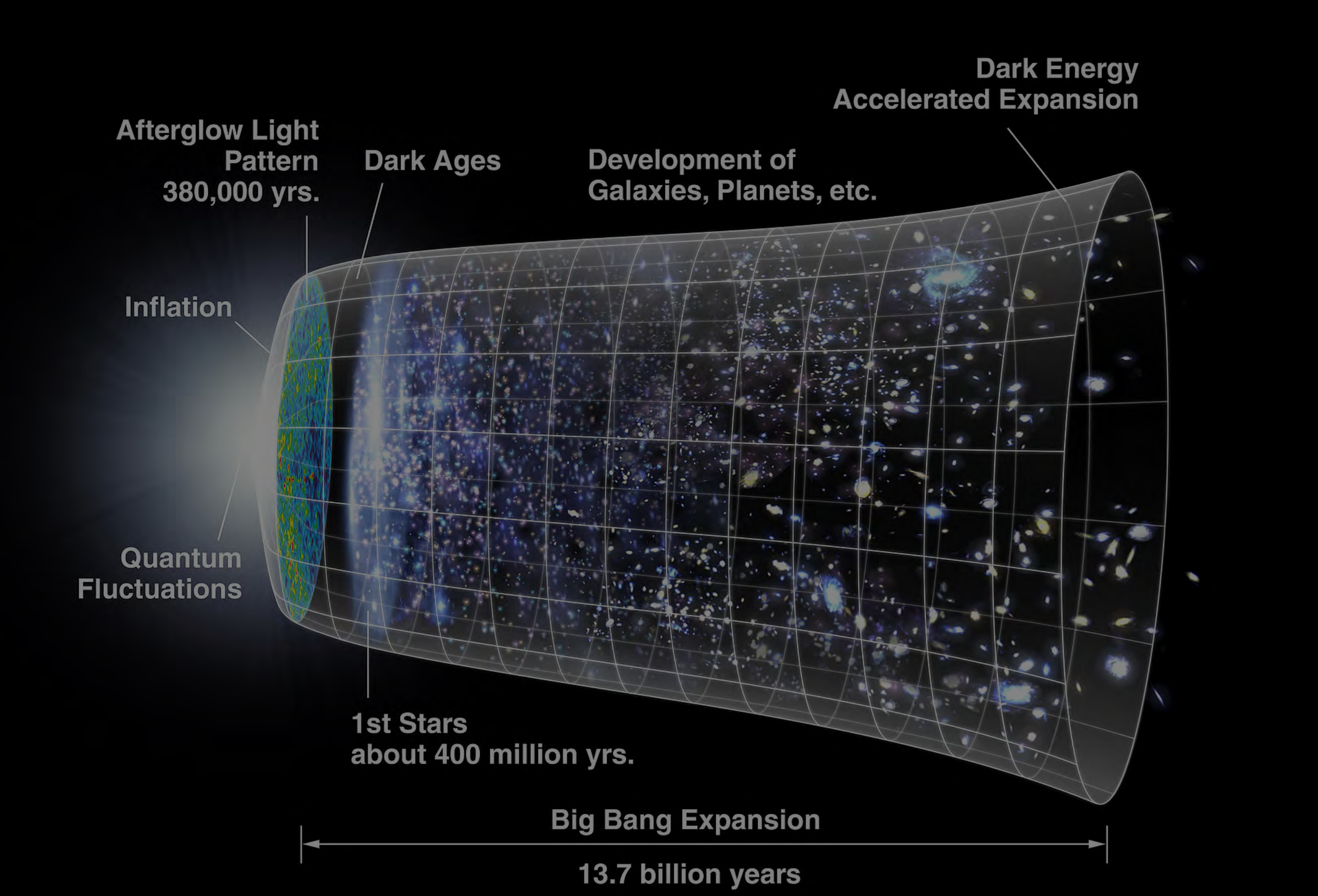
- Transition to Nonlinearity
- Dark Matter Annihilation
- Parameters of first Astrophysics (black holes, galaxies, AGN)
- Direct measurement optical depth (CMB tau)

Experimental Activities

- **Major contributor to MWA** (PI* of NSF portion, $300k)
- **Core member of PAPER**
- **Founding member of HERA**, (lead of several subsystems; convert to PI* as Faculty)
- **ECHO project** (NSF supported, Jacobs PI, ~$96k)
- **SPARCS cubesat** (Systems Engineer on NASA APRA proposal)

*NSF rules required Bowman as official PI


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years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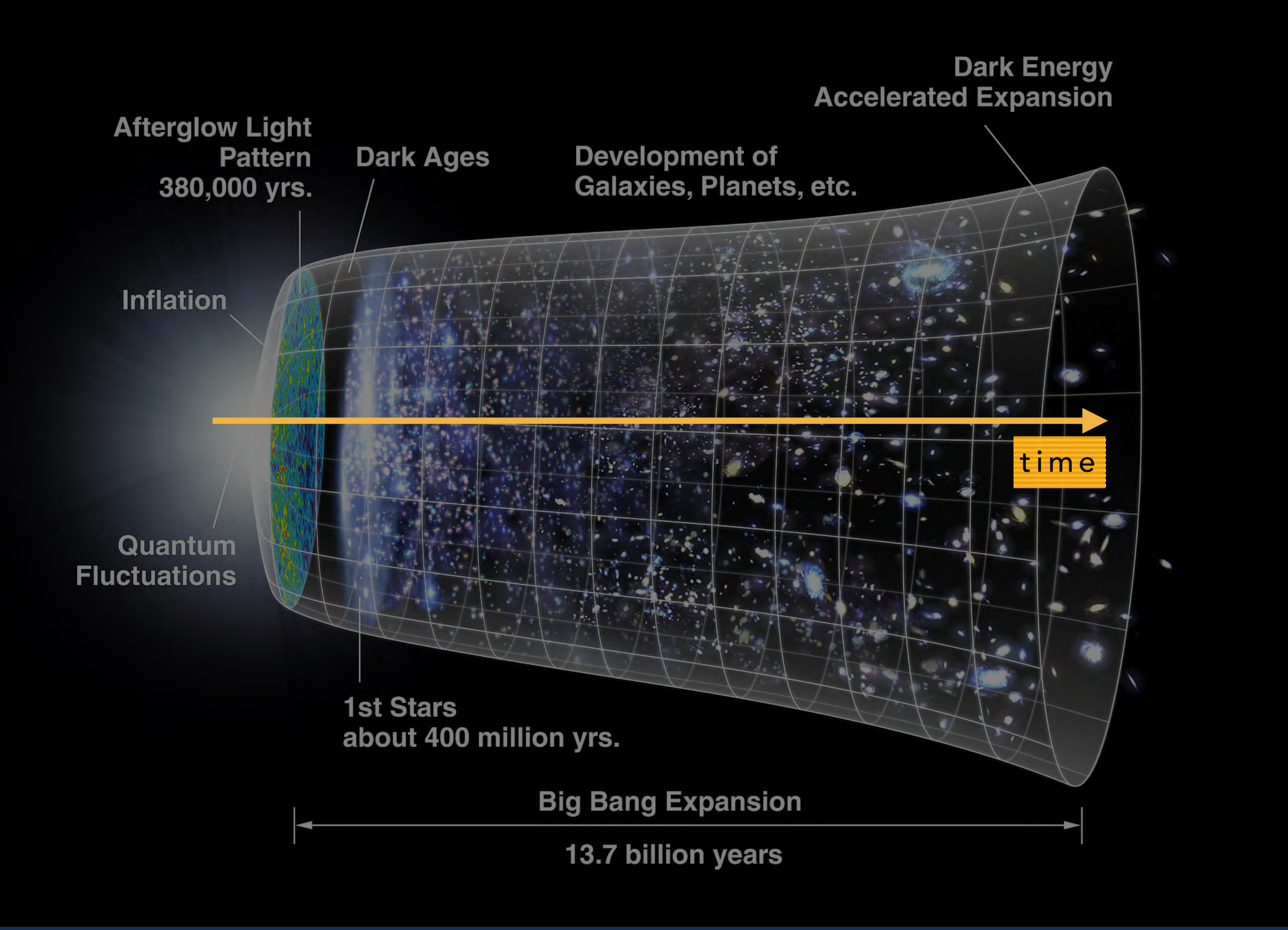
Dark Energy
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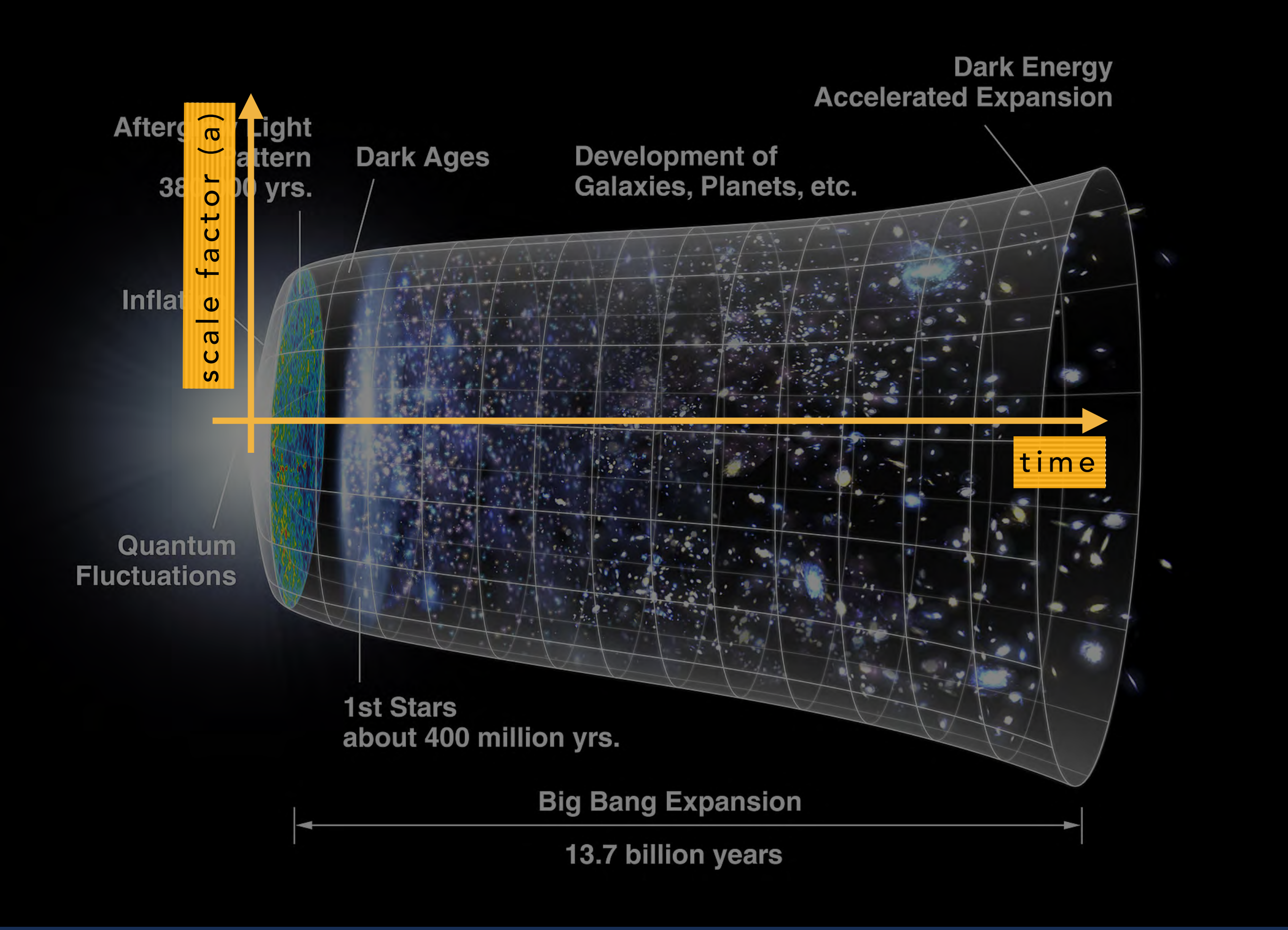
Dark Energy
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Development of
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scale factor (a)
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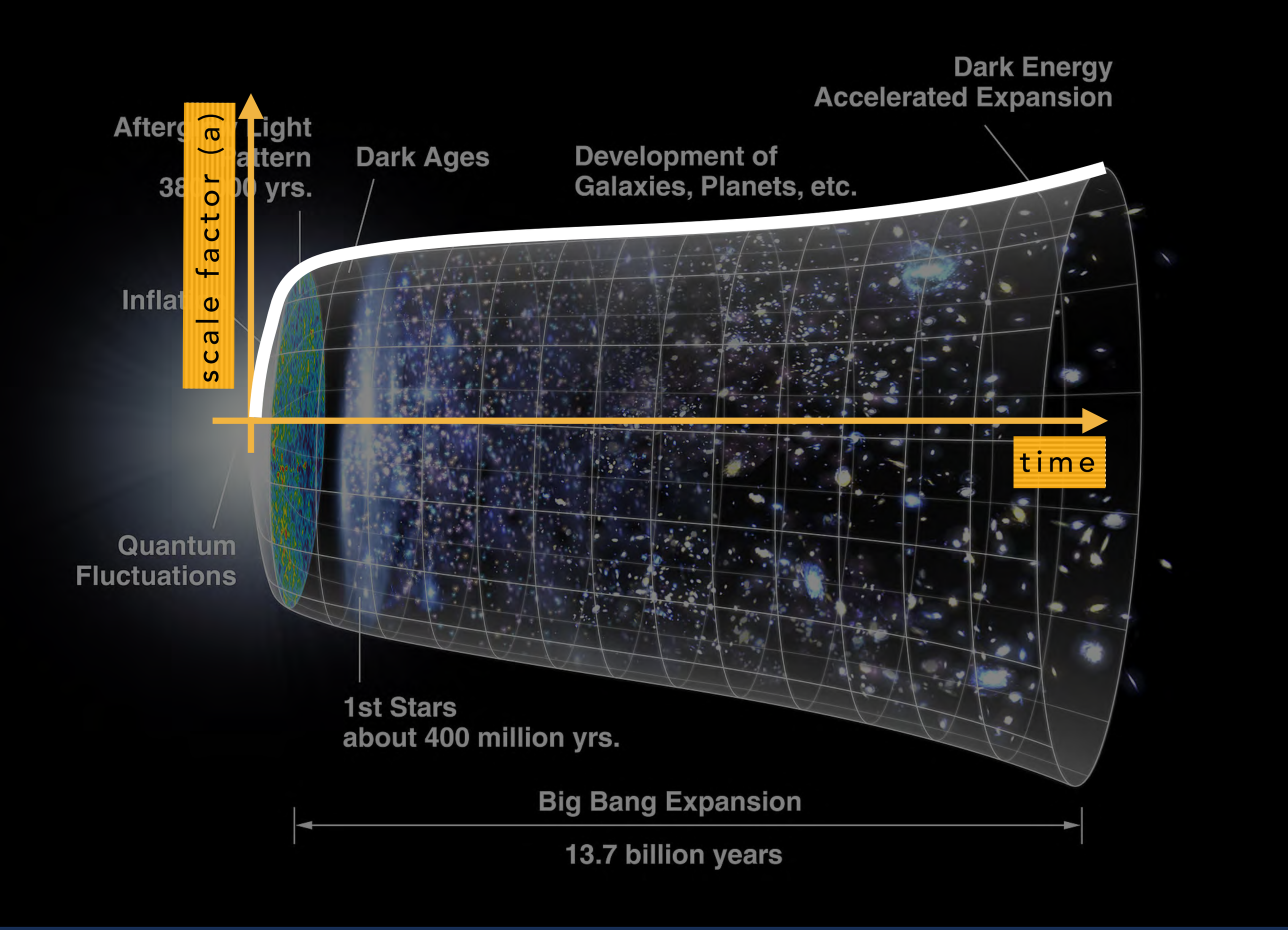
Dark Energy
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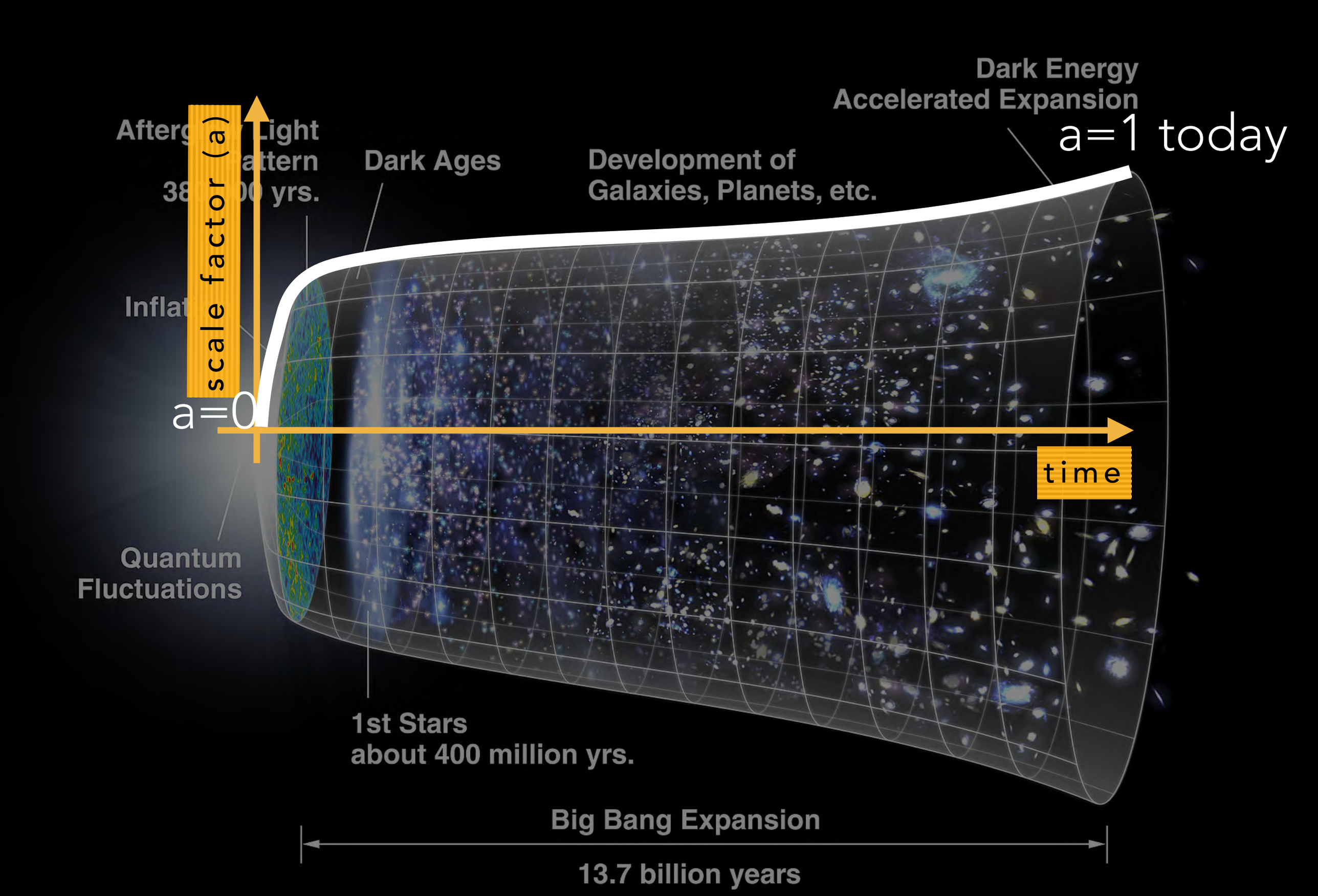

Dark Energy
Accelerated Expansion
a=1 today
Dark Ages
Development of
Galaxies, Planets, etc.
scale factor (a)
a=0
time
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Dark Energy
Accelerated Expansion

a=1 today

Dark Ages

Development of
Galaxies, Planets, etc.

Aftergl Light
attern
38 00 yrs.

Inflat

Quan
Fluctuat s

scale factor (a)

a=0

time

redshift (z)

z=1100 @ CMB

1st Stars
about 400 million yrs.

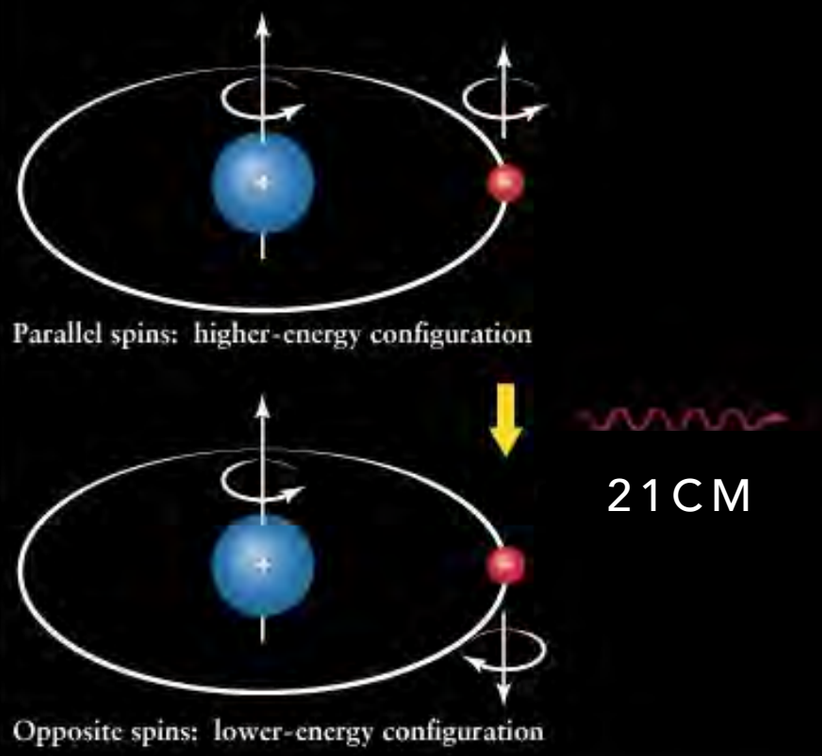
z=0 today

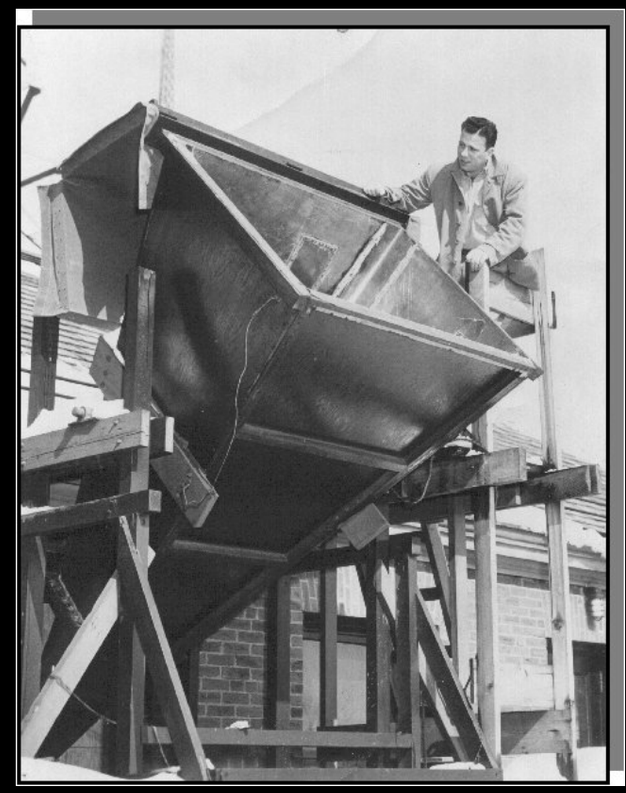
Big Bang Expansion

13.7 billion years

time

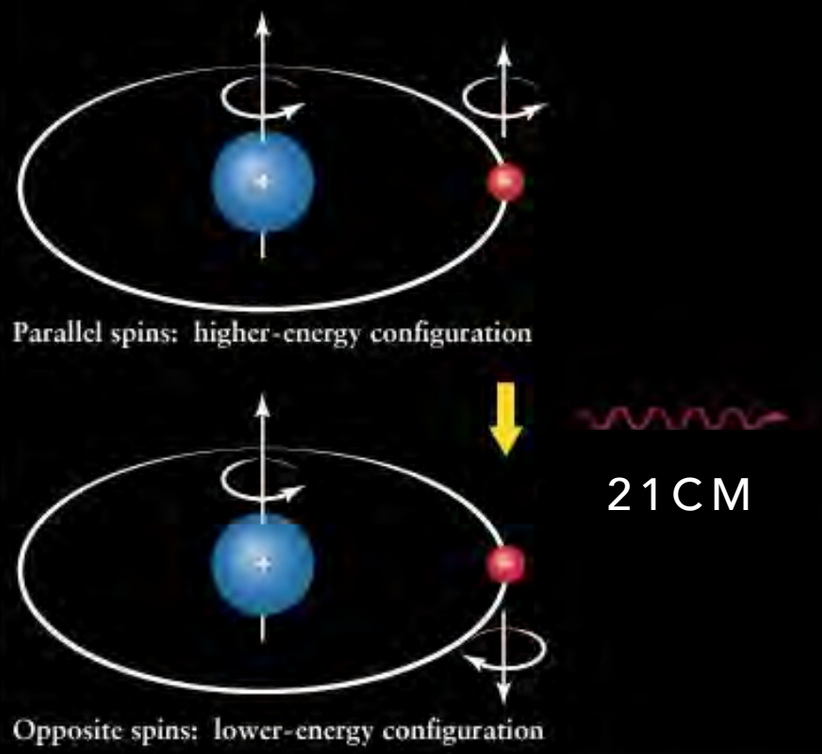
HYDROGEN 21 CM

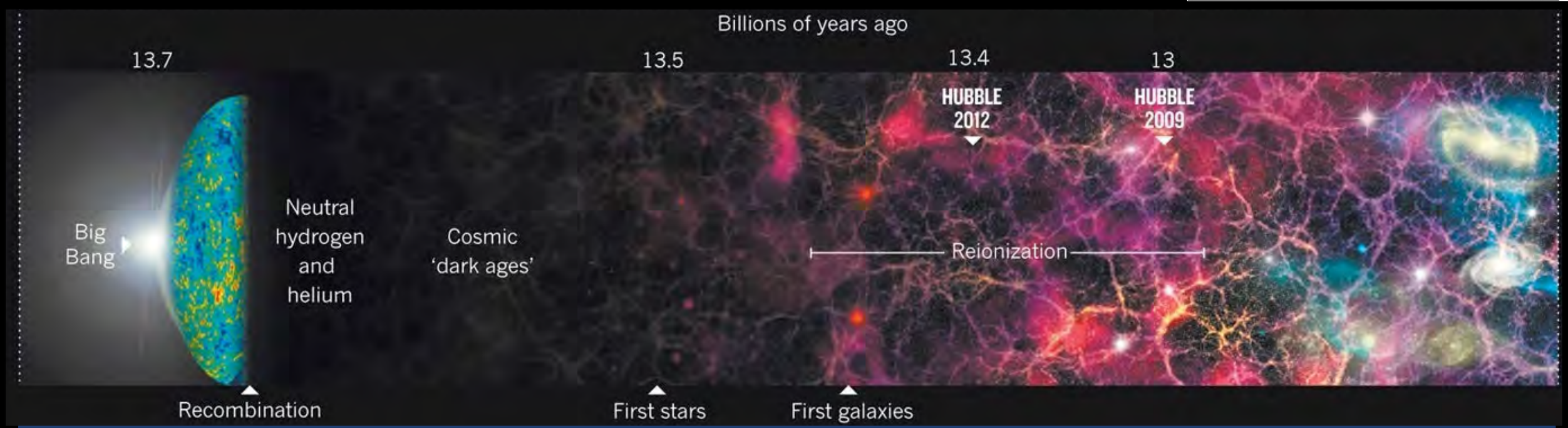




- Most abundant element in the universe
- First detected in 1951 by Ewan and Purcel
- ground state hyperfine
- narrow spectral line (ultra precise redshifts)
- optically thin (3d cubes)
- a historically powerful tool (eg discovery of Dark Matter)

HYDROGEN 21 CM





frequency	1.3MHz	67MHz	100MHz	200MHz	400MHz
redshift (z)	1100	20	12	6	2

reionization.org loco.lab.asu.edu/danny_jacobs mwatelescope.org eor.berkeley.edu

EVENTS ON THE COSMIC TIMELINE

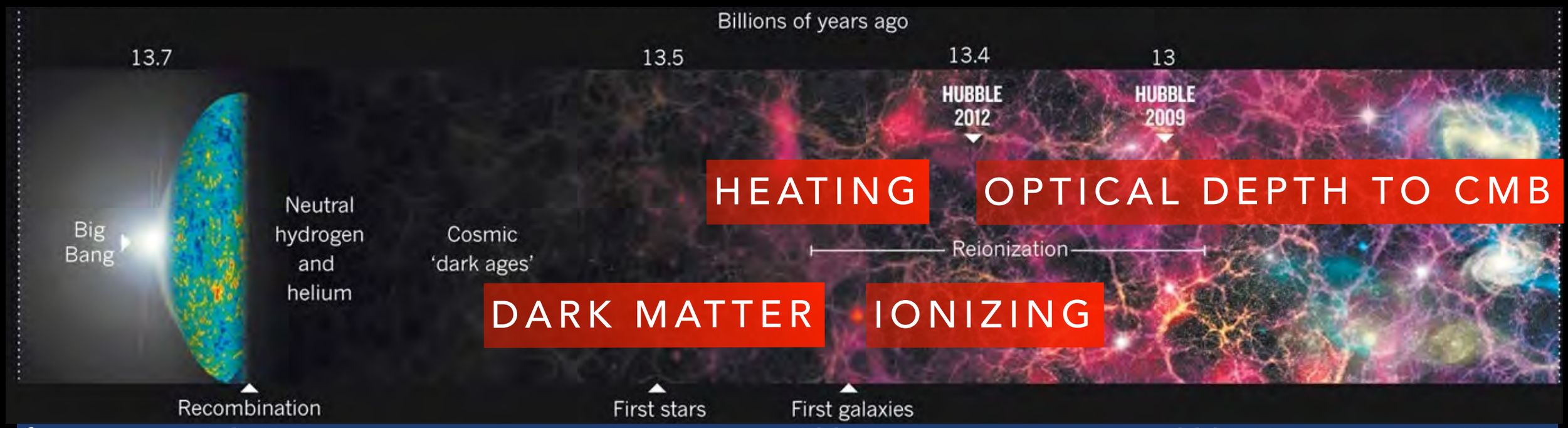
Dark matter dominated

1st Stars

1st Galaxies

Reionization

Hydrogen in galaxies



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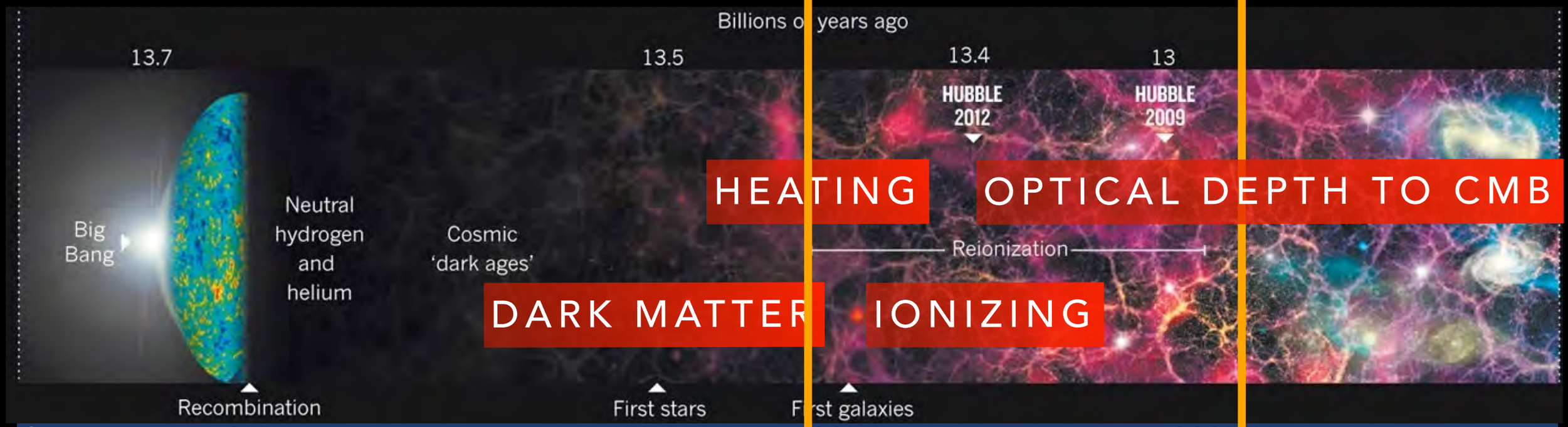


HEATING

OPTICAL DEPTH TO CMB

DARK MATTER

IONIZING

frequency	1.3MHz	67MHz	100MHz	200MHz	400MHz
redshift (z)	1100	20	12	6	2

PHYSICS ACCESSIBLE TO 21 CM MAPPING ACROSS THE TIMELINE

Dark Ages

- Transition to Nonlinearity
- Black holes and First Stars
- Dark Matter Annihilation

REionization

- First Galaxies
- First AGN
- Direct Measurement Optical depth (CMB tau)

Dark Energy

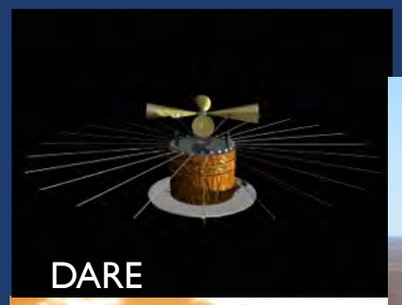
- Baryon Acoustic Oscillations (dark energy probe)
-

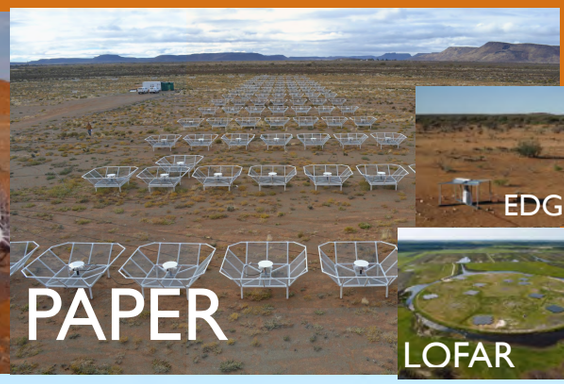
frequency	1.3MHz	67MHz	100MHz	200MHz	400MHz
redshift (z)	1100	20	12	6	2

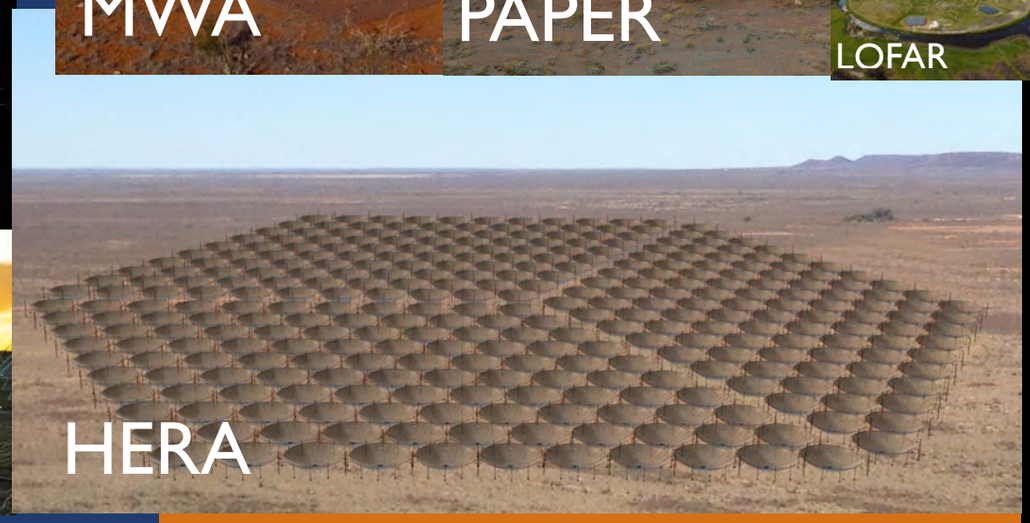
DARK AGES

REIONIZATION

INTENSITY MAPPING





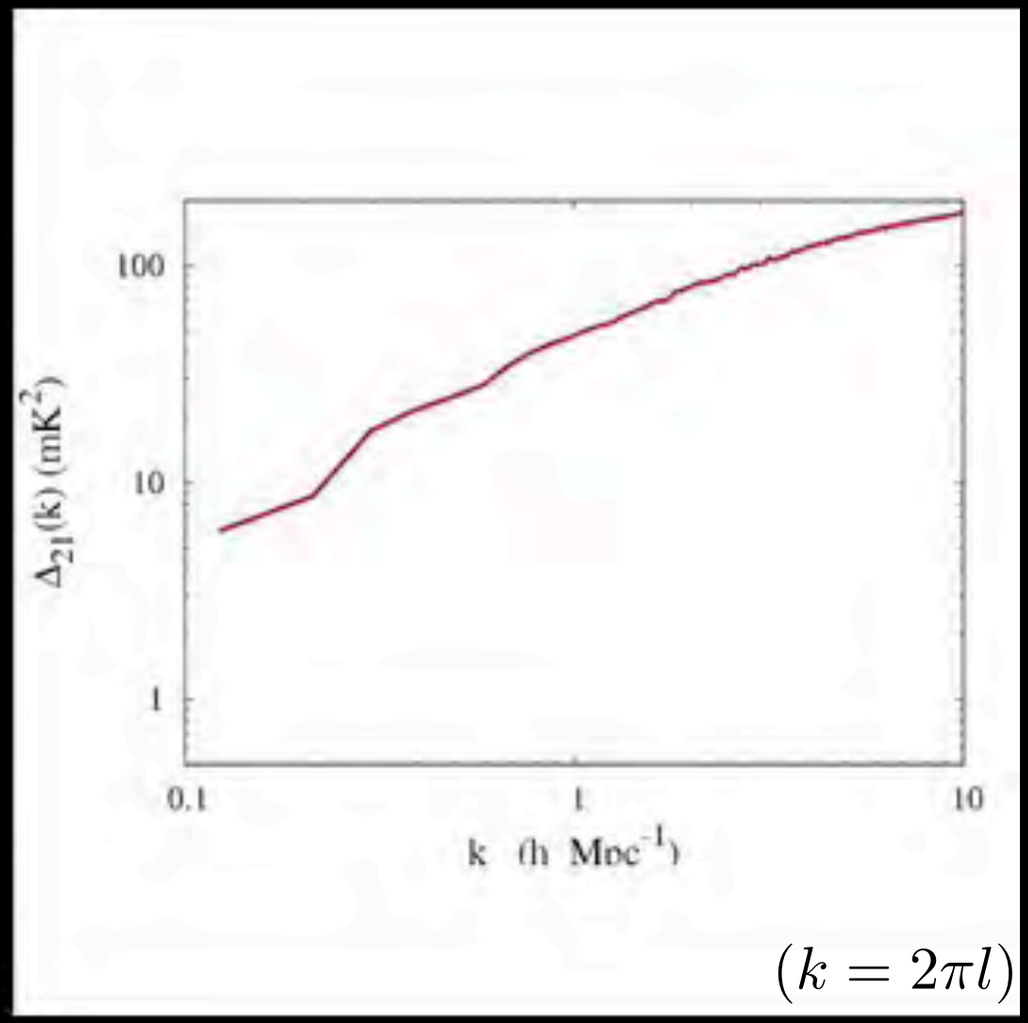


frequency	1.3MHz	67MHz	100MHz	200MHz	400MHz
redshift (z)	1100	20	12	6	2

M. Alvarez (CITA)
& R. Kaehler (Stanford)

M. Alvarez (CITA)
& R. Kaehler (Stanford)

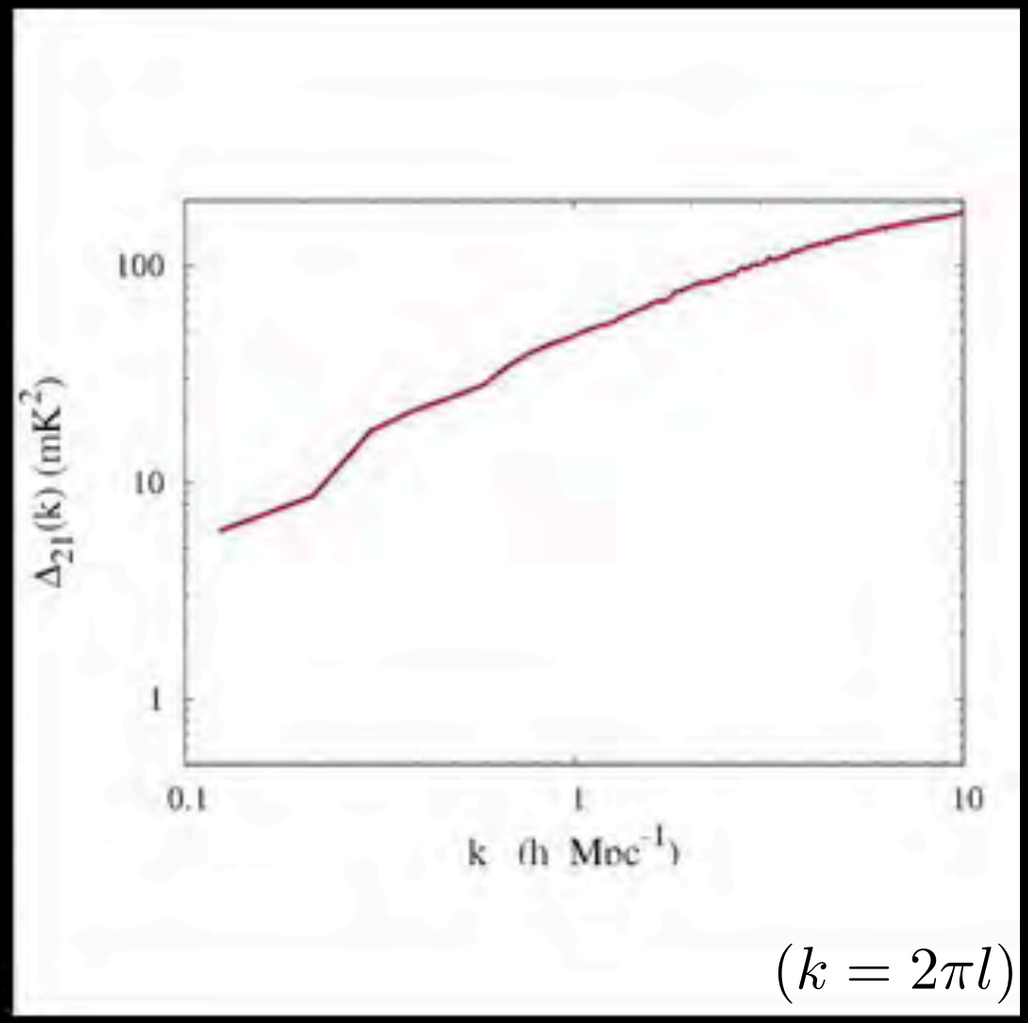
z=11.1



$(k = 2\pi l)$

M. Mcquinn (U.Washington)

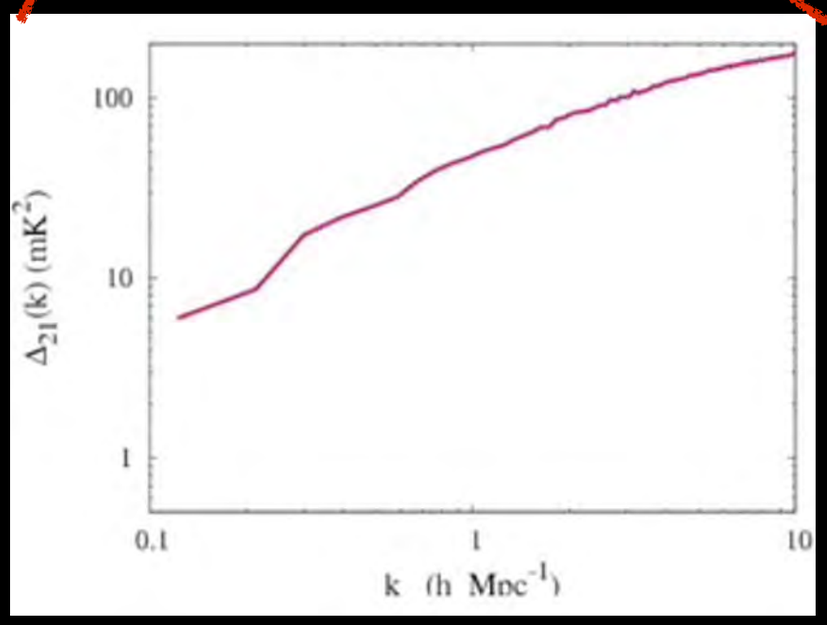
z=11.1

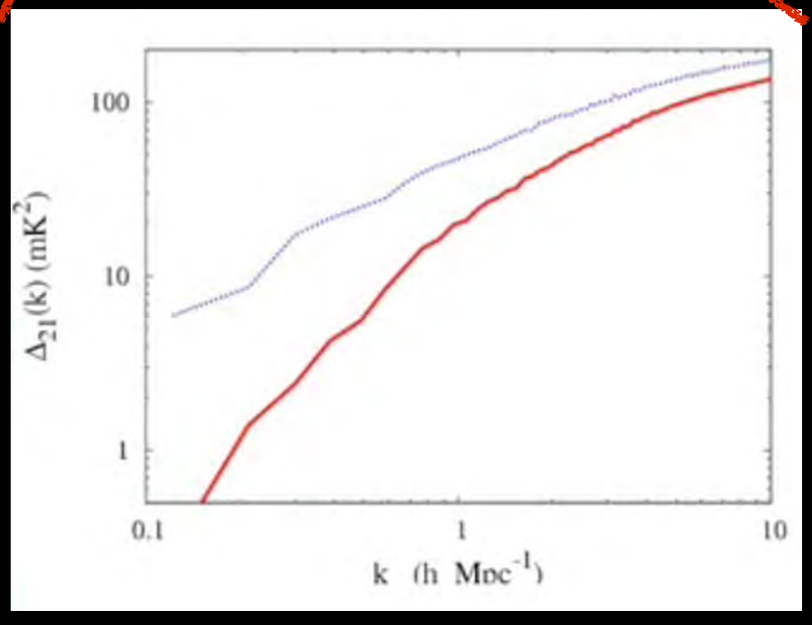


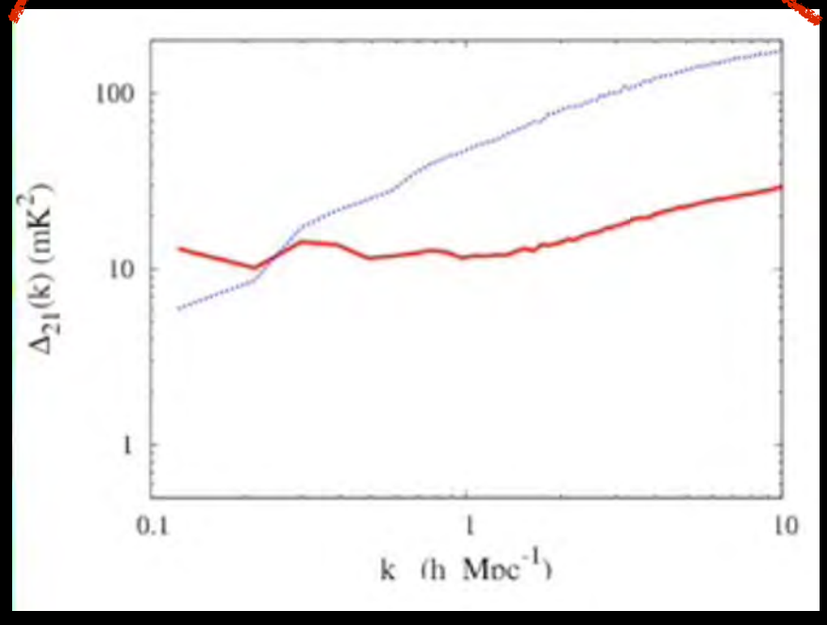
$(k = 2\pi l)$

M. Mcquinn (U.Washington)

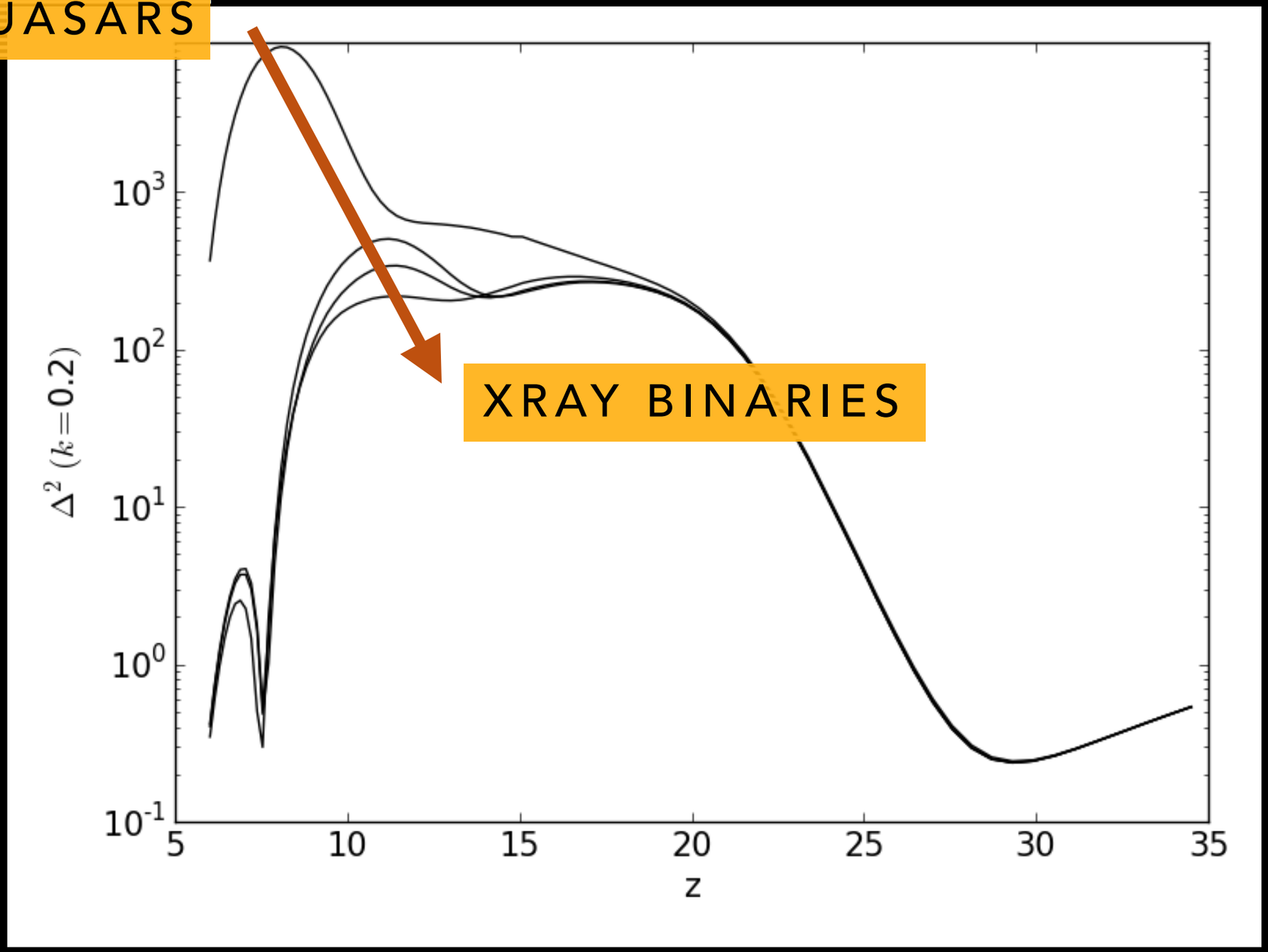

12
Redshift
6
~1°
100MHz
Frequency [MHz]
200 MHz


100
10
1
0.1
1
10
$\Delta_{21}(k)$ (mK^2)
k (h Mpc^{-1})


100
10
1
0.1
1
10
$\Delta_{21}(k)$ (mK^2)
k (h Mpc^{-1})


100
10
1
0.1
1
10
$\Delta_{21}(k)$ (mK^2)
k (h Mpc^{-1})

HEAT TYPE CHANGES POWER SPECTRUM EVOLUTION



1ST GEN 21CM TELESCOPES

Common attributes:

- Dipole arrays
- 100-200MHz (1.5 to 3m operating wavelength)
- Direct digitization (no mixers)
- Isolated, desert environments
- Large numbers of elements (128 tiles vs 27 VLA dishes)

1ST GEN 21CM TELESCOPES

1ST GEN 21CM TELESCOPES

Common challenges:

- Field of view defined by a dipole response (much wider than a high gain dish)
- Very large correlation data products (TB a night, PB a year)

PRECISION ARRAY FOR PROBING THE EPOCH OF REIONIZATION (PAPER)

PRECISION ARRAY FOR PROBING THE EPOCH OF REIONIZATION (PAPER)

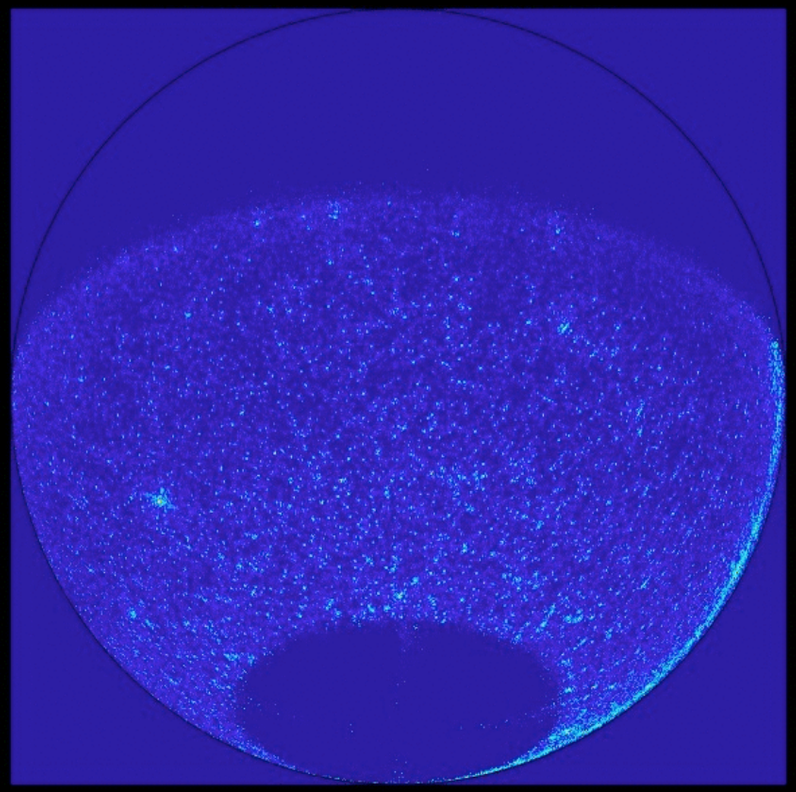
Location: Karoo Desert, South Africa
Experimental Array optimized for power spectrum

Parsons, Pober, McQuinn, **Jacobs**, and Aguirre, 2012
Parsons, Pober, Aguirre, Carilli, **Jacobs**, and Moore, 2012

128 single dipoles with ground screens

PAPER RESULTS

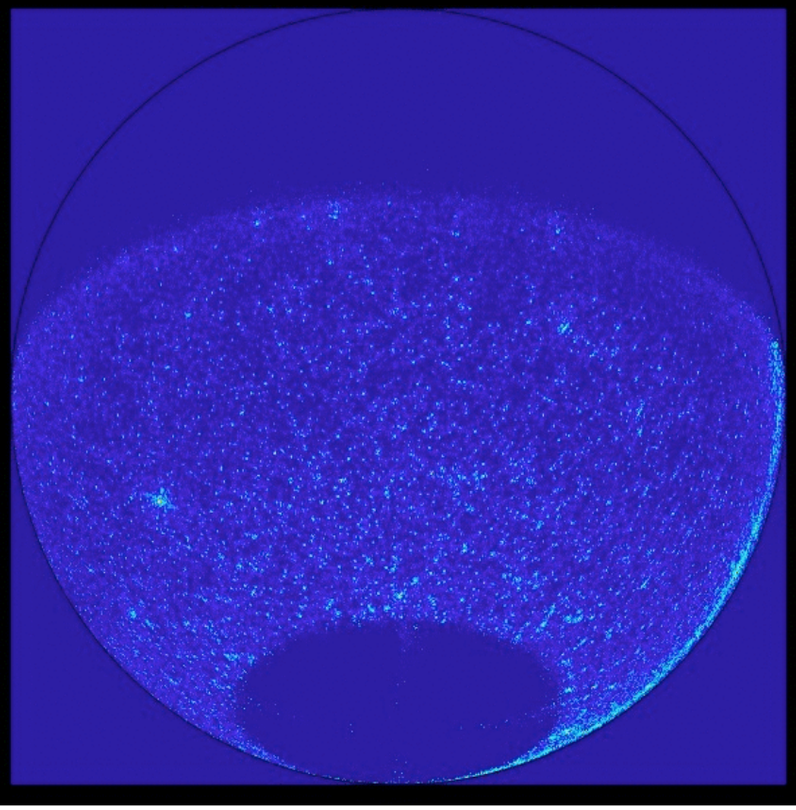
Catalogs



Bright source catalog	**Jacobs**, et al 2012
Catalog accuracy	**Jacobs**, et al 2013
Flux calibration standard	**Jacobs**, et al 2014

PAPER RESULTS

Catalogs



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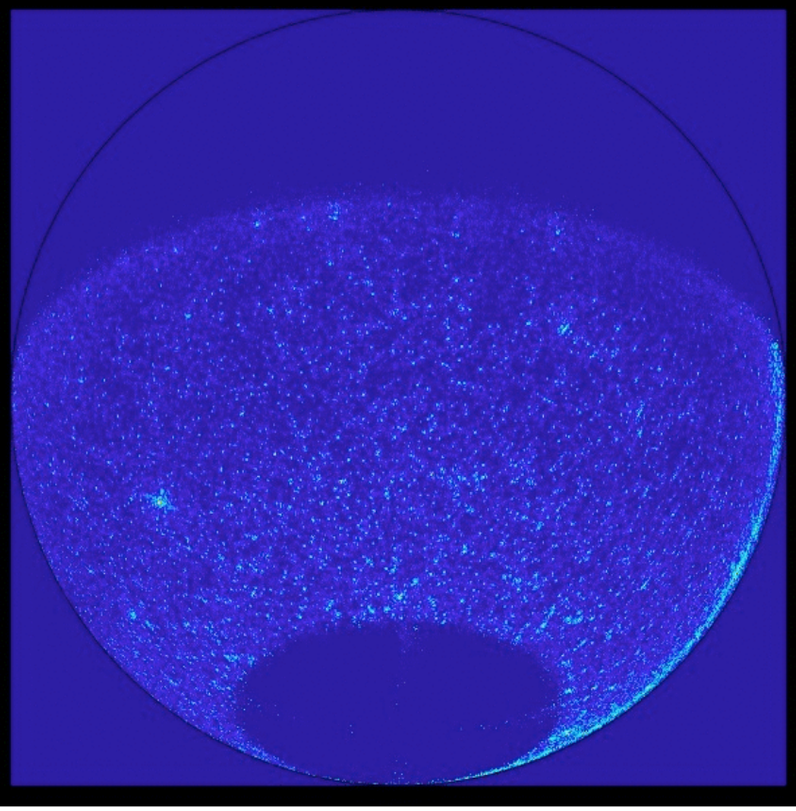
LIMITED BY THE ACCURACY OF DIPOLE RESPONSE MODEL

PAPER RESULTS

Catalogs



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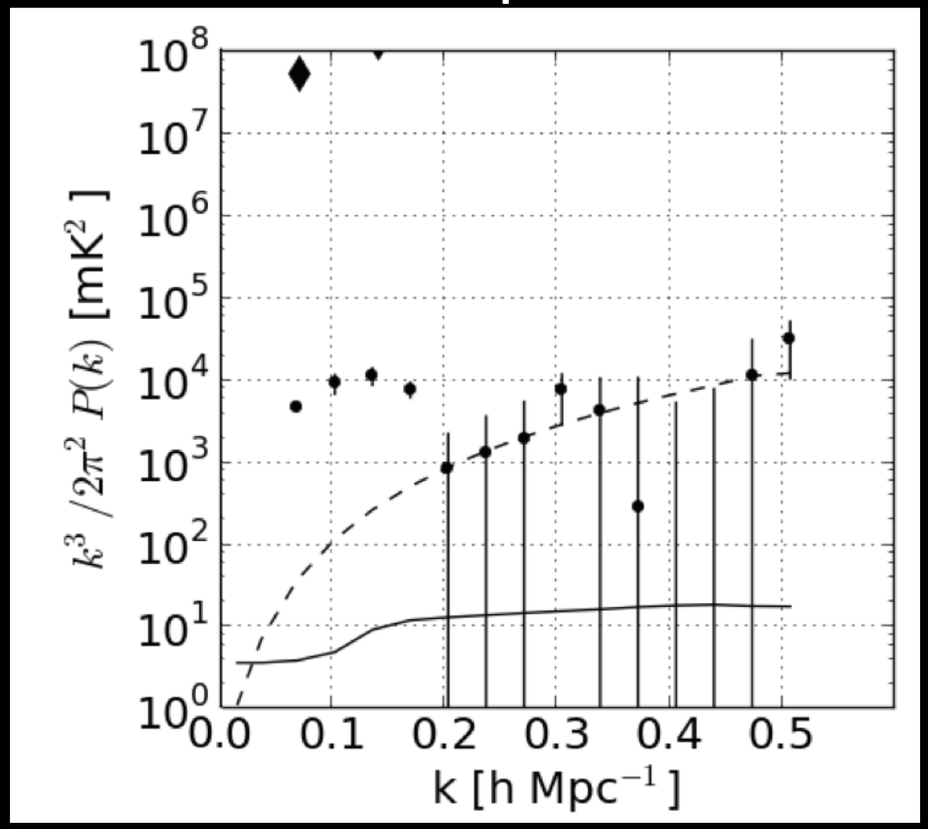
LIMITED BY THE ACCURACY OF DIPOLE RESPONSE MODEL

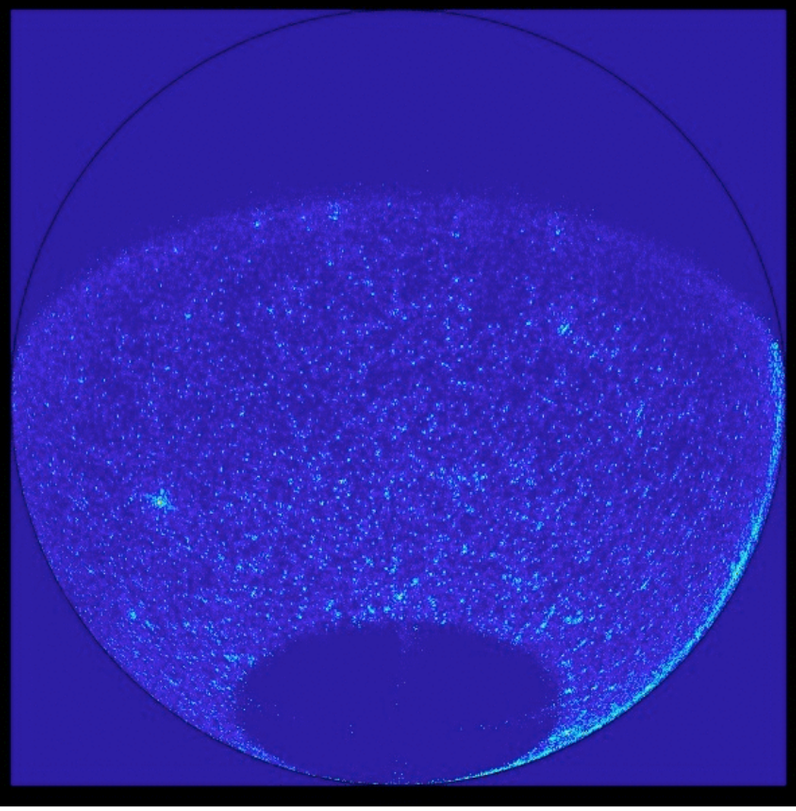
Power spectra



Year 1 power spectrum	Parsons,…,**Jacobs** et al 2014
Year 1 multi-redshift limits	**Jacobs**, et al 2015
Year 2 power spectrum	Ali,… **Jacobs**, et al 2015
Year 2 multi-redshift limits	Kolopanis, **Jacobs**, et al 2016

PAPER RESULTS

Catalogs



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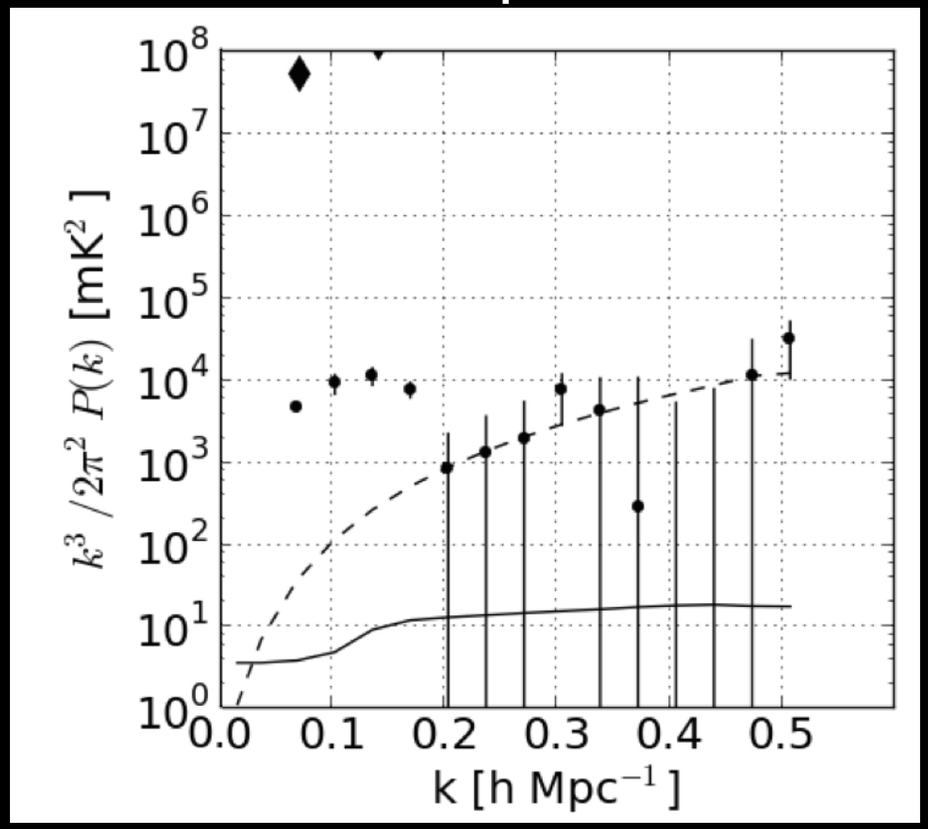
LIMITED BY THE ACCURACY OF DIPOLE RESPONSE MODEL

Power spectra



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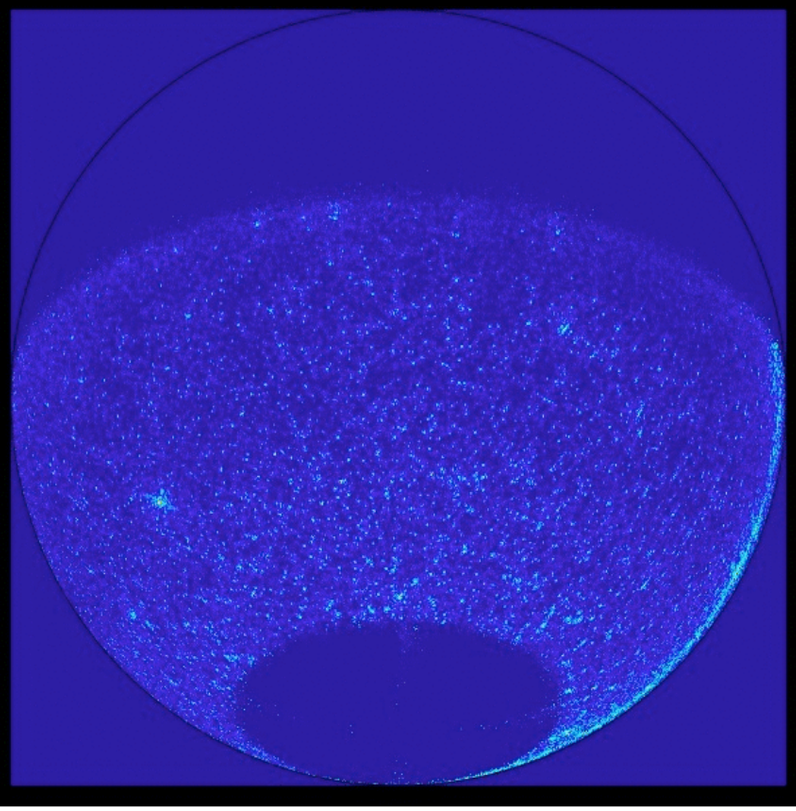
IN COLLABORATION REVIEW

PAPER RESULTS

Catalogs



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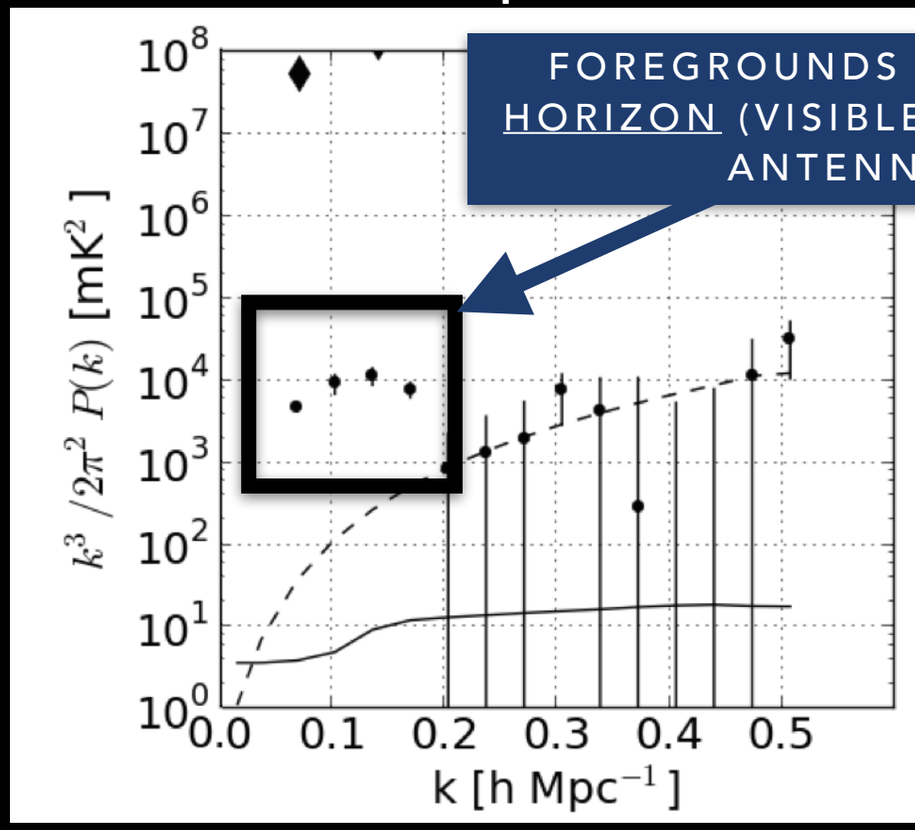
Power spectra

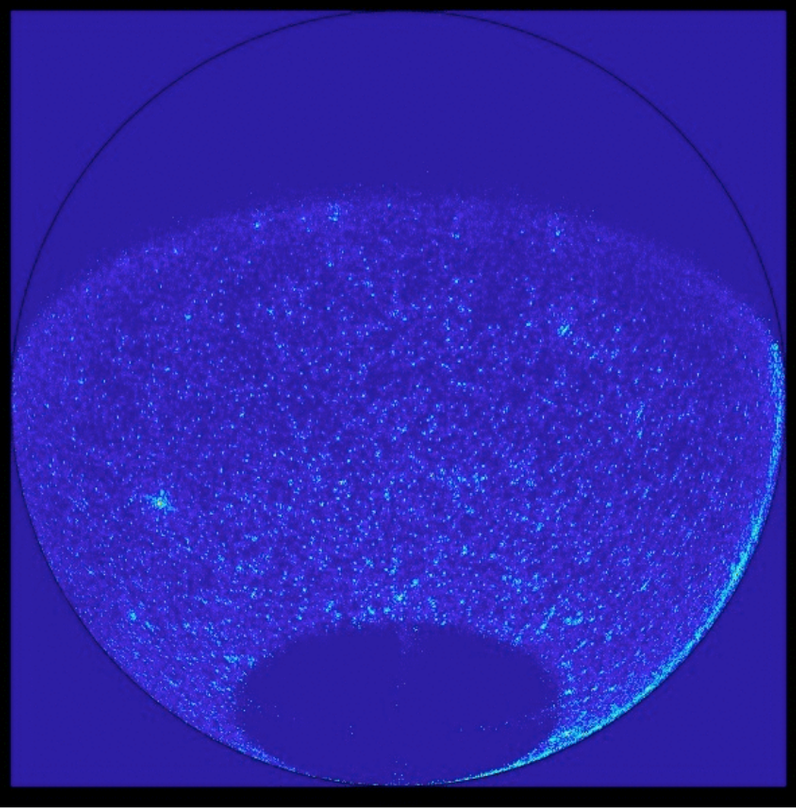


Year 1 power spectrum	Parsons,…,**Jacobs** et al 2014
Year 1 multi-redshift limits	**Jacobs**, et al 2015
Year 2 power spectrum	Ali,… **Jacobs**, et al 2015
Year 2 multi-redshift limits	Kolopanis, **Jacobs**, et al 2016

IN COLLABORATION REVIEW

PAPER RESULTS

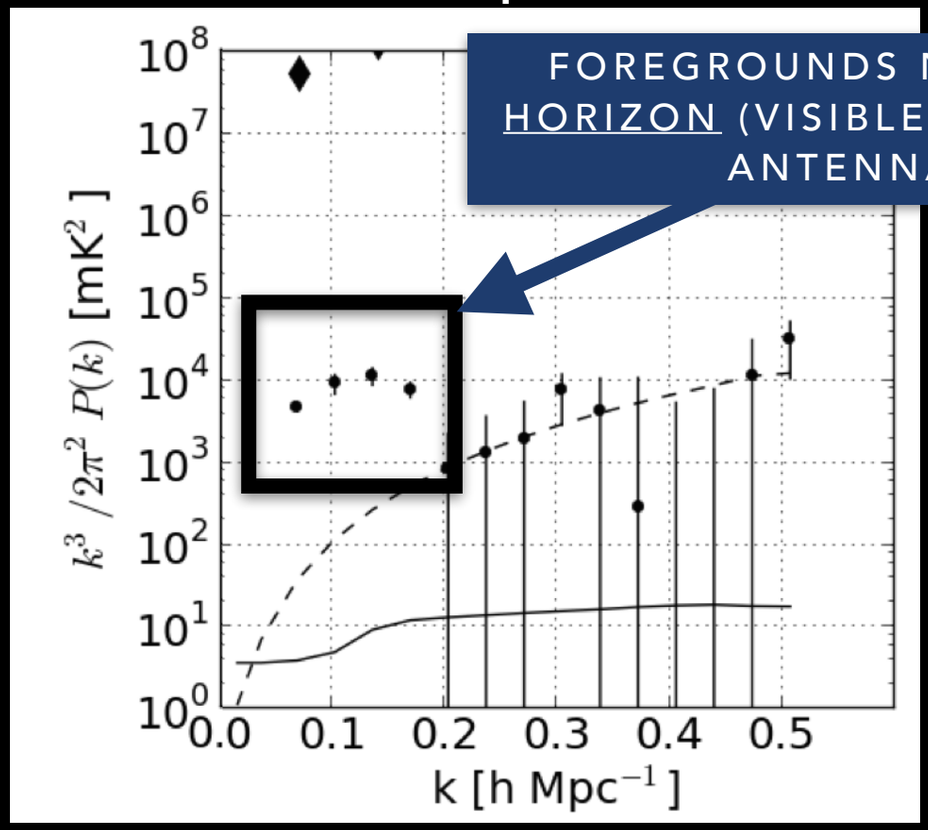
Catalogs



Bright source catalog	**Jacobs**, et al 2012
Catalog accuracy	**Jacobs**, et al 2013
Flux calibration standard	**Jacobs**, et al 2014

LIMITED BY THE ACCURACY OF DIPOLE RESPONSE MODEL

Power spectra



Year 1 power spectrum	Parsons,…,**Jacobs** et al 2014
Year 1 multi-redshift limits	**Jacobs**, et al 2015
Year 2 power spectrum	Ali,… **Jacobs**, et al 2015
Year 2 multi-redshift limits	Kolopanis, **Jacobs**, et al 2016

IN COLLABORATION REVIEW

physics grad student, ASU

MURCHISON WIDEFIELD ARRAY

MURCHISON WIDEFIELD ARRAY

Location: Western Australia
Pre-cursor to Square Kilometer Array
128 phased array tiles

MWA EoR Results Summary

(**Jacobs** et al, 2016 in review)

Productive, Open time instrument
40% of time on 21cm science,
(Jacobs et al, observing)

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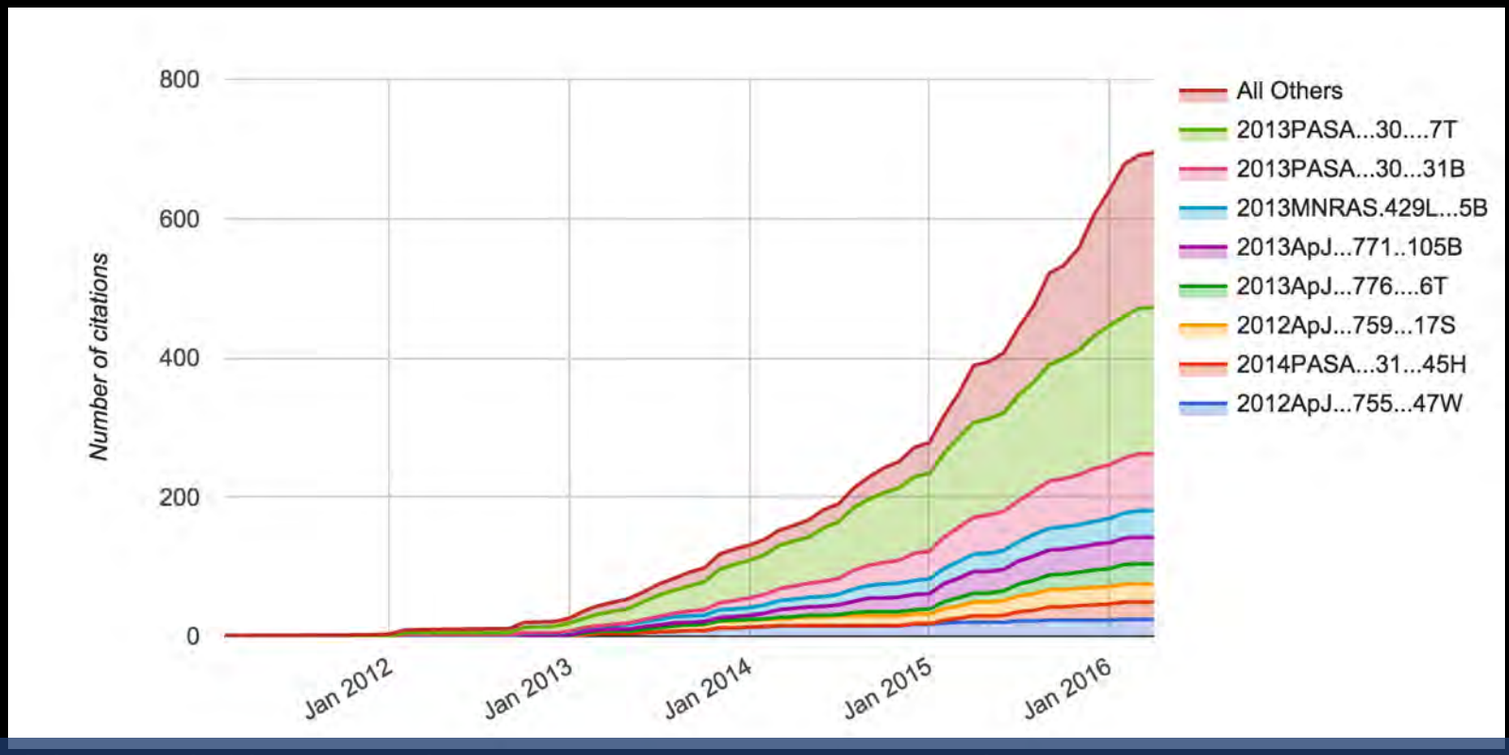
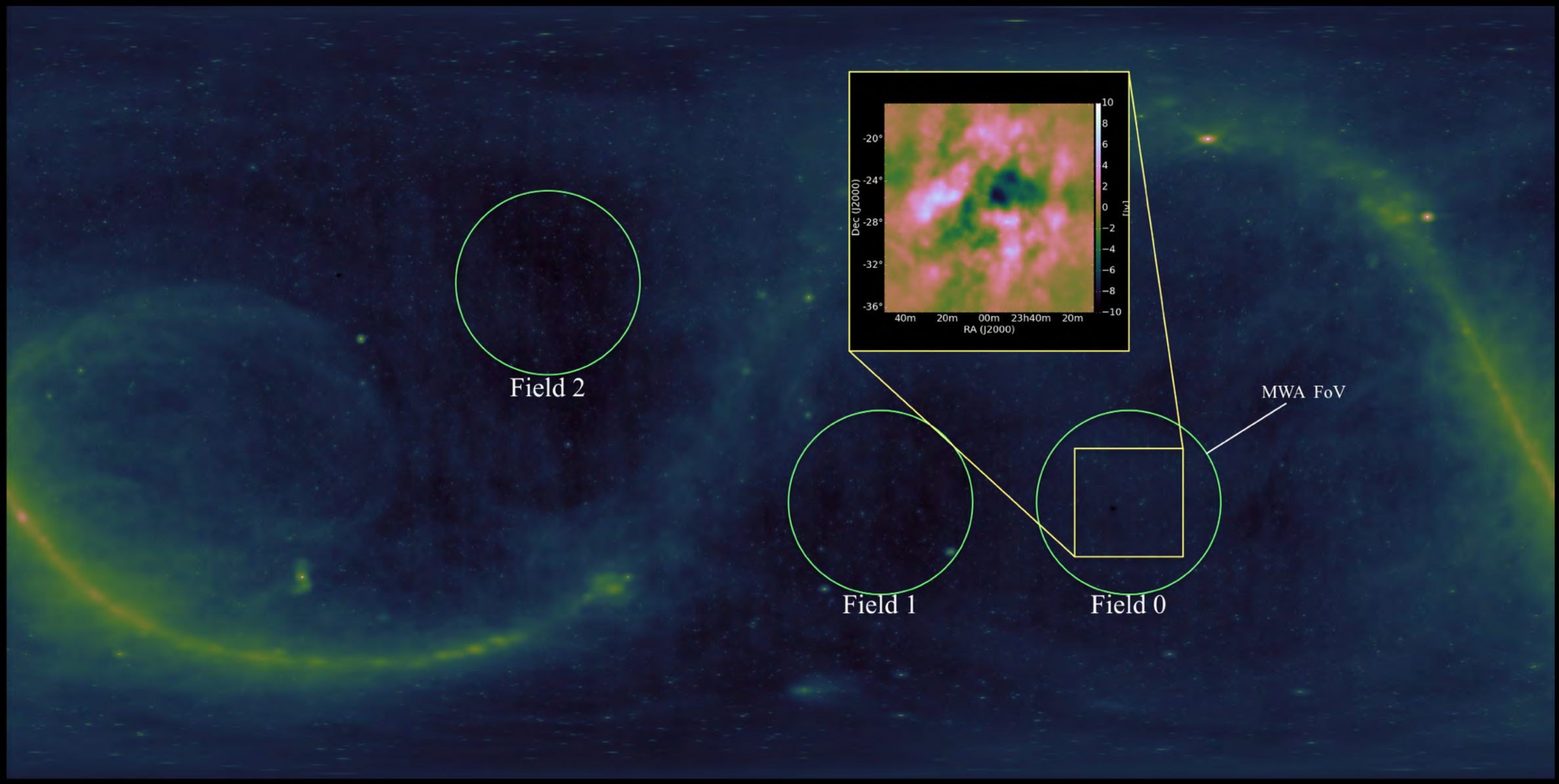


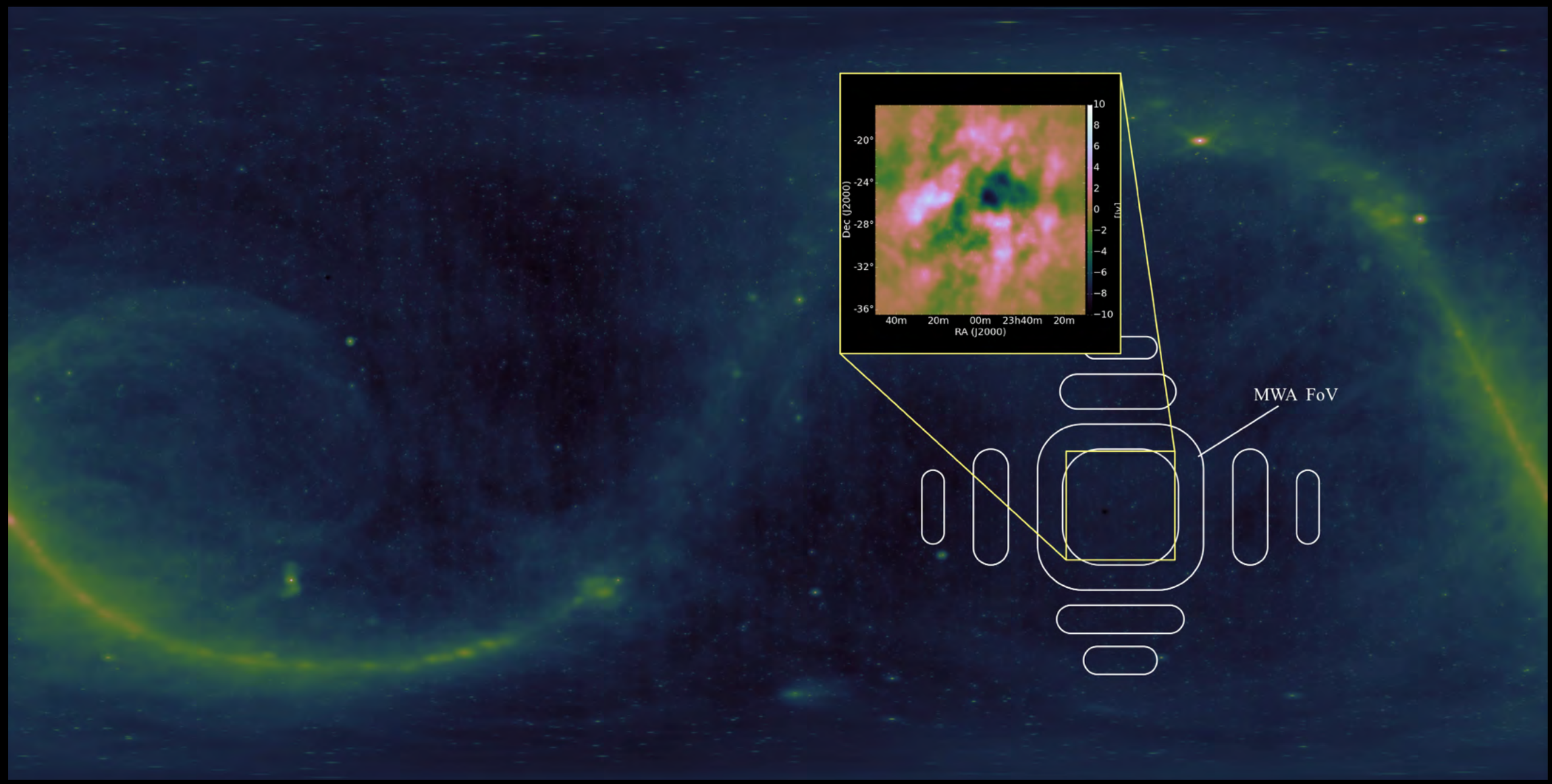
MWA REIONIZATION RESULTS

NSF Astronomy and Astrophysics Grant 1410719, Jacobs PI

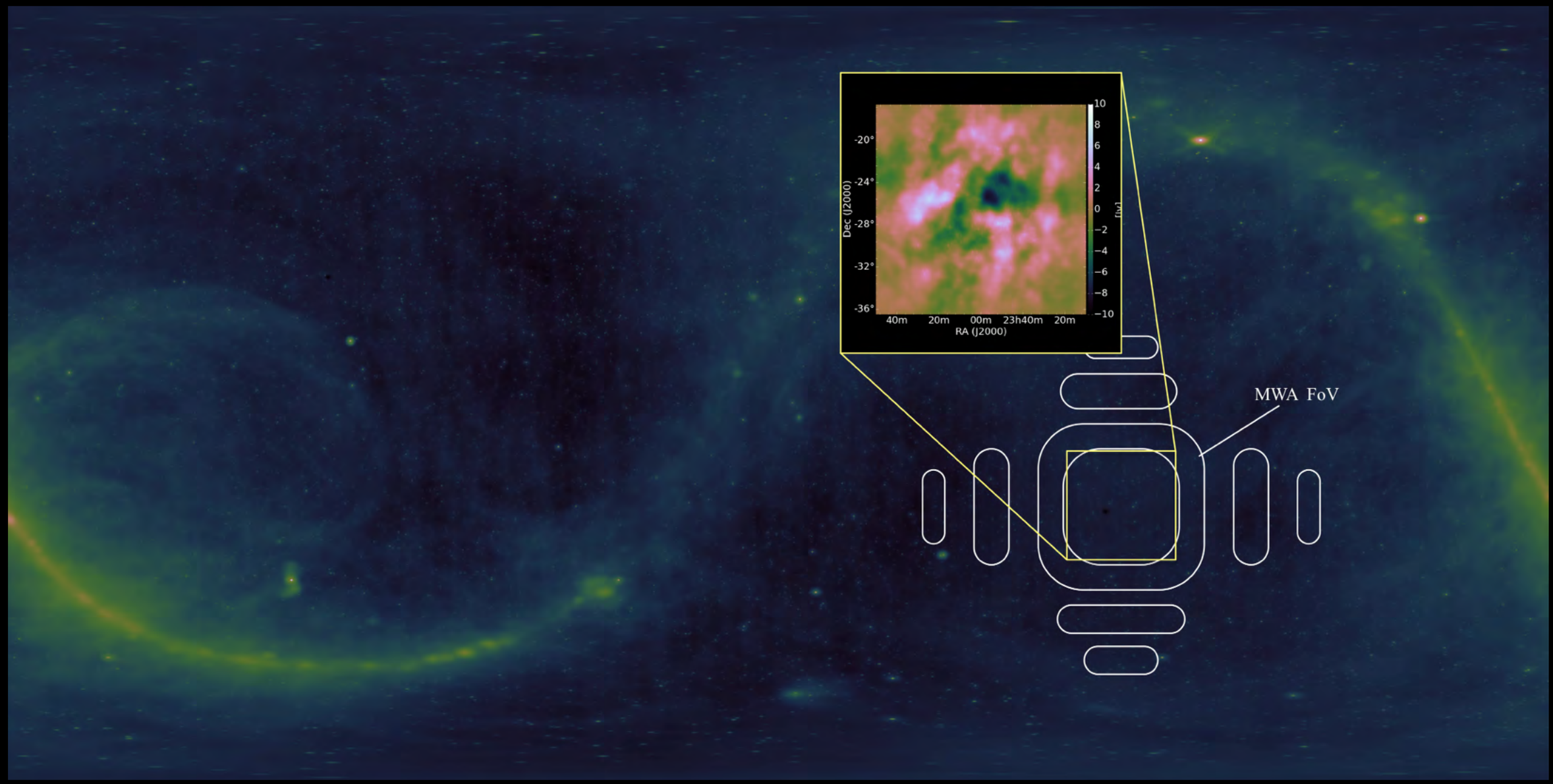


MWA REIONIZATION RESULTS

NSF Astronomy and Astrophysics Grant 1410719, Jacobs PI



MWA REIONIZATION RESULTS

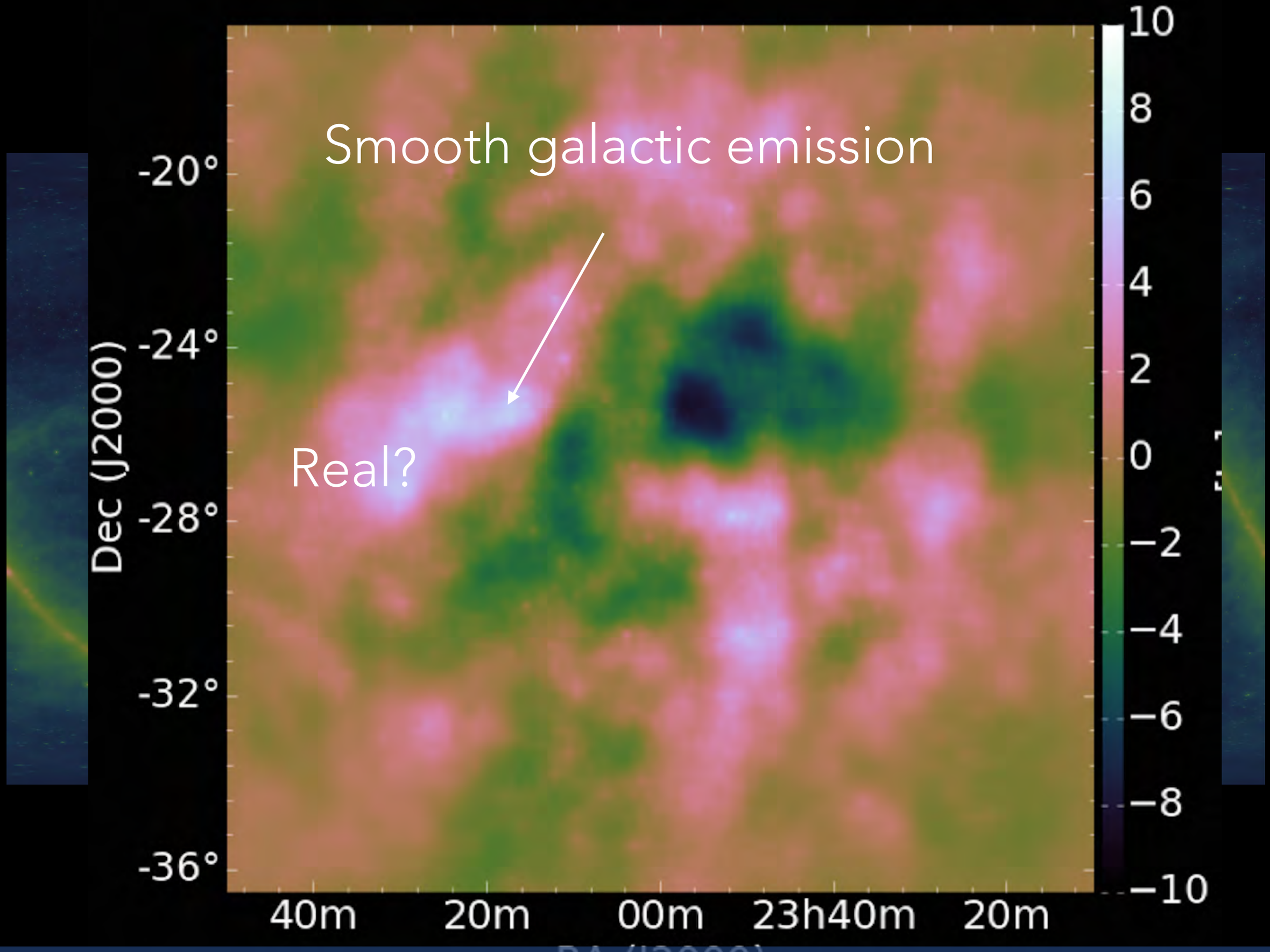


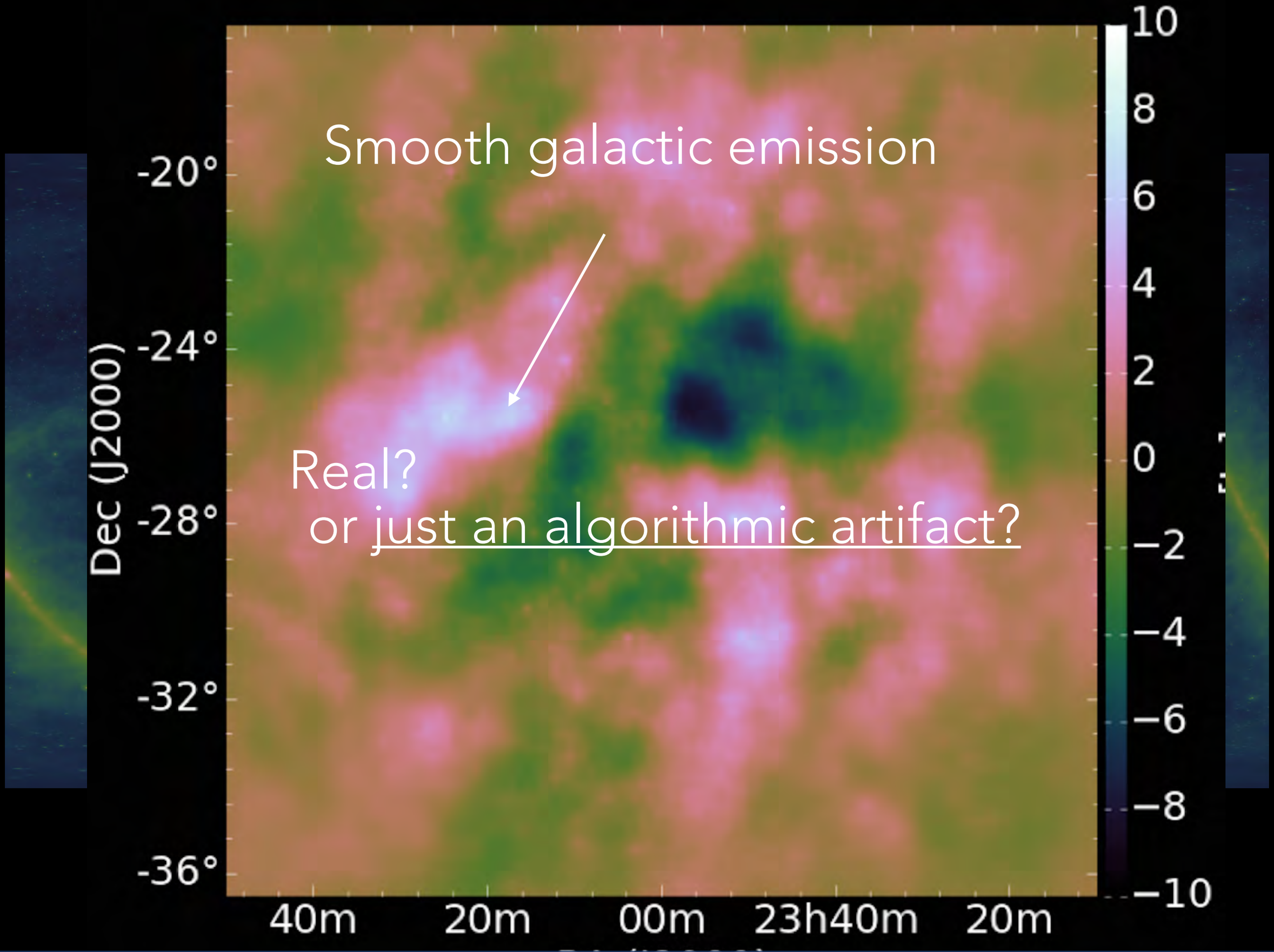
Smooth galactic emission

-20°
-24°
-28°
-32°
-36°
Dec (J2000)

40m
20m
00m
23h40m
20m
RA (J2000)

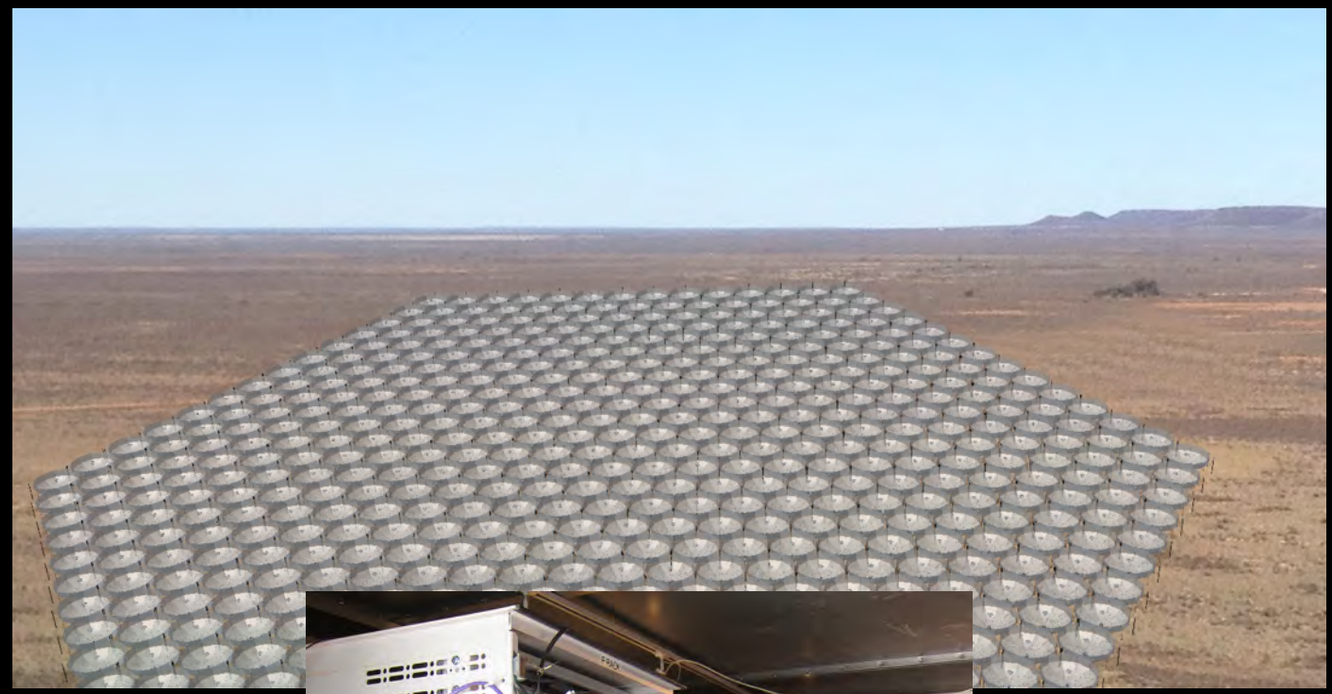
10
8
6
4
2
0
−2
−4
−6
−8
−10

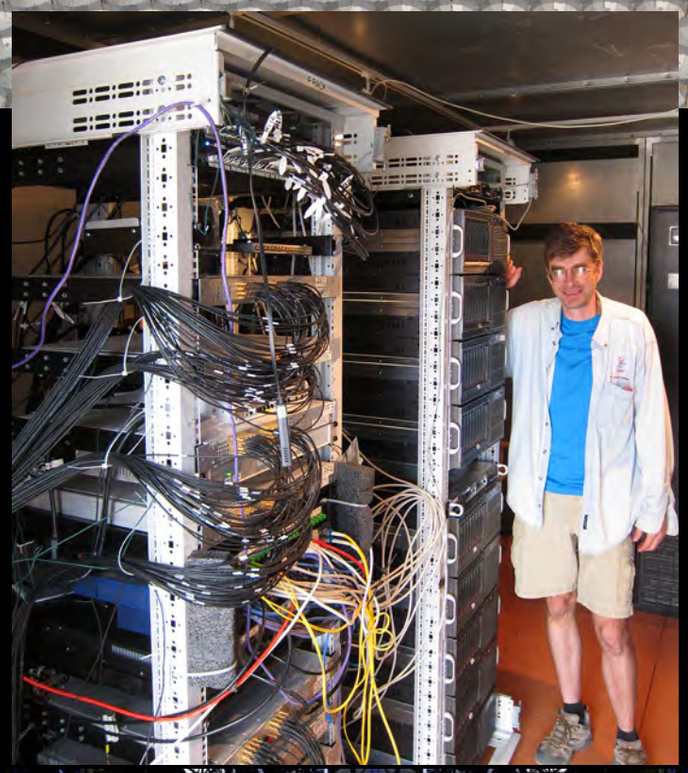

Smooth galactic emission
Real?
-20°
-24°
-28°
-32°
-36°
Dec (J2000)
40m
20m
00m
23h40m
20m
RA (J2000)
10
8
6
4
2
0
−2
−4
−6
−8
−10

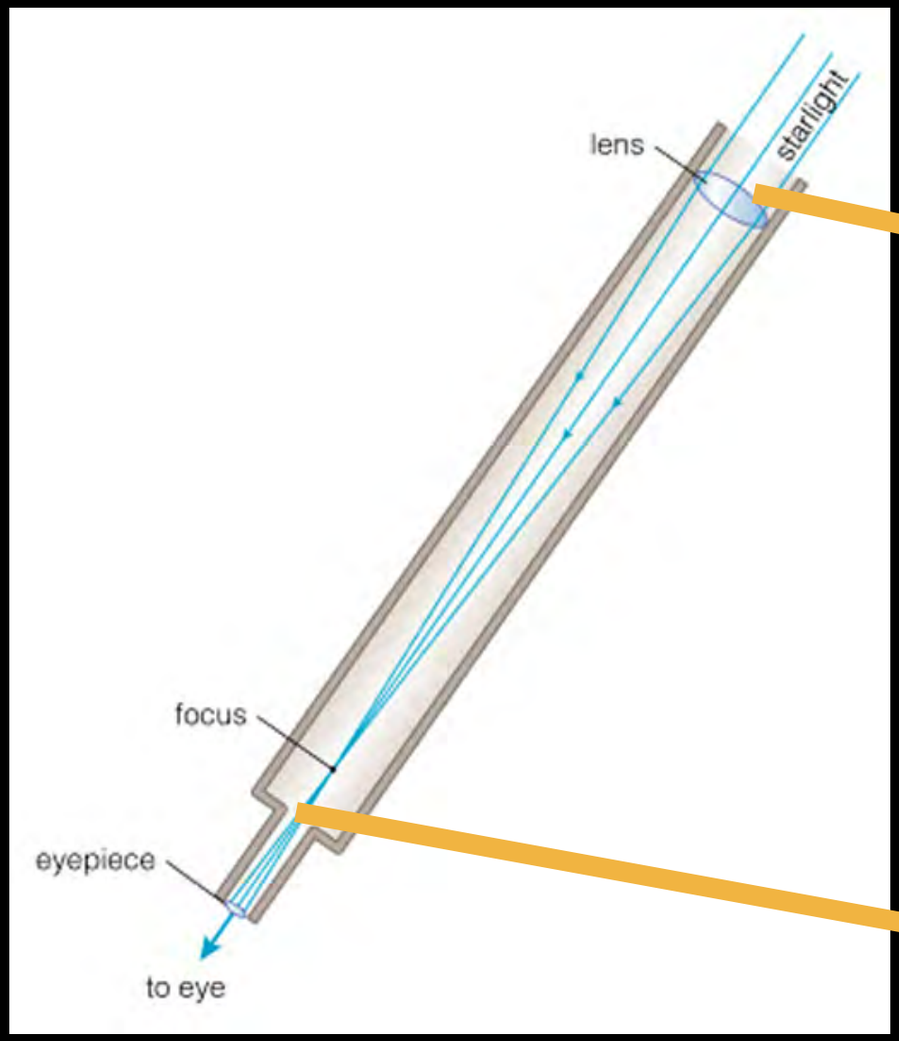

Smooth galactic emission
Real?
or just an algorithmic artifact?
-20°
-24°
-28°
-32°
-36°
Dec (J2000)
40m
20m
00m
23h40m
20m
RA (J2000)
10
8
6
4
2
0
−2
−4
−6
−8
−10

BIG INTERFEROMETERS

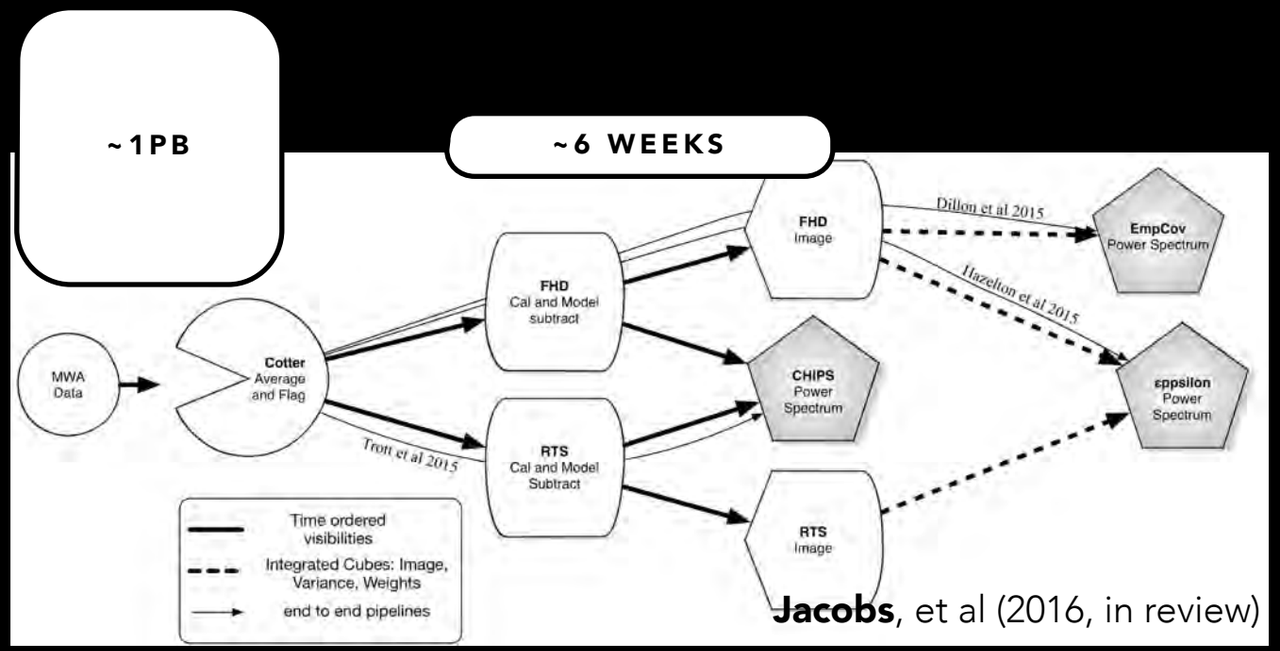
ARE **SOFTWARE** TELESCOPES





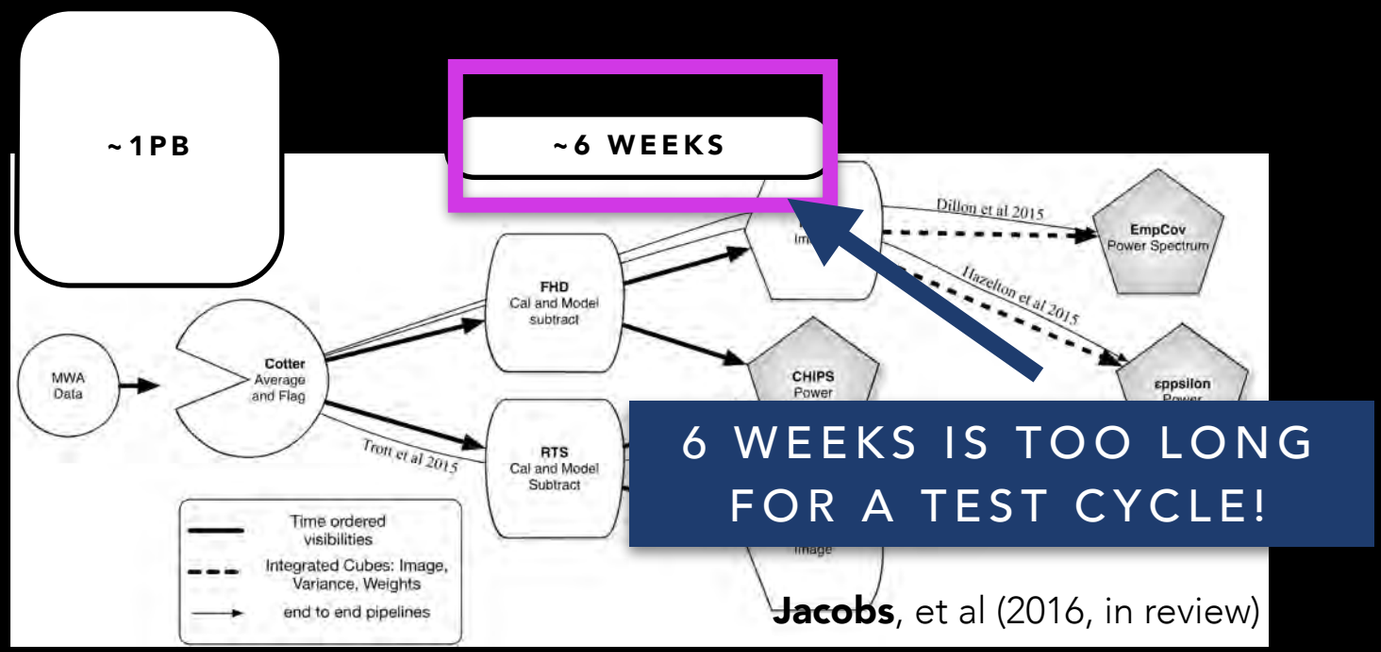

lens
starlight
focus
eyepiece
to eye

PROVING OUT THE MWA PIPELINE



Jacobs, et al (2016, in review)

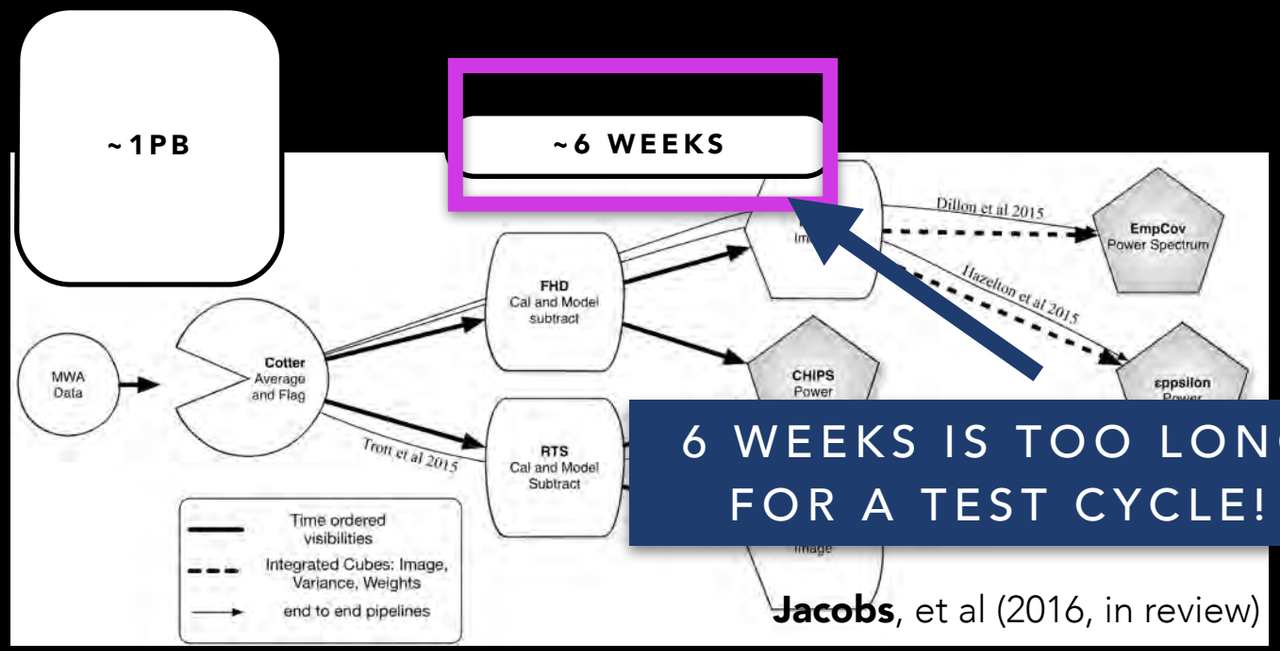
PROVING OUT THE MWA PIPELINE



6 WEEKS IS TOO LONG FOR A TEST CYCLE!

Jacobs, et al (2016, in review)

PROVING OUT THE MWA PIPELINE



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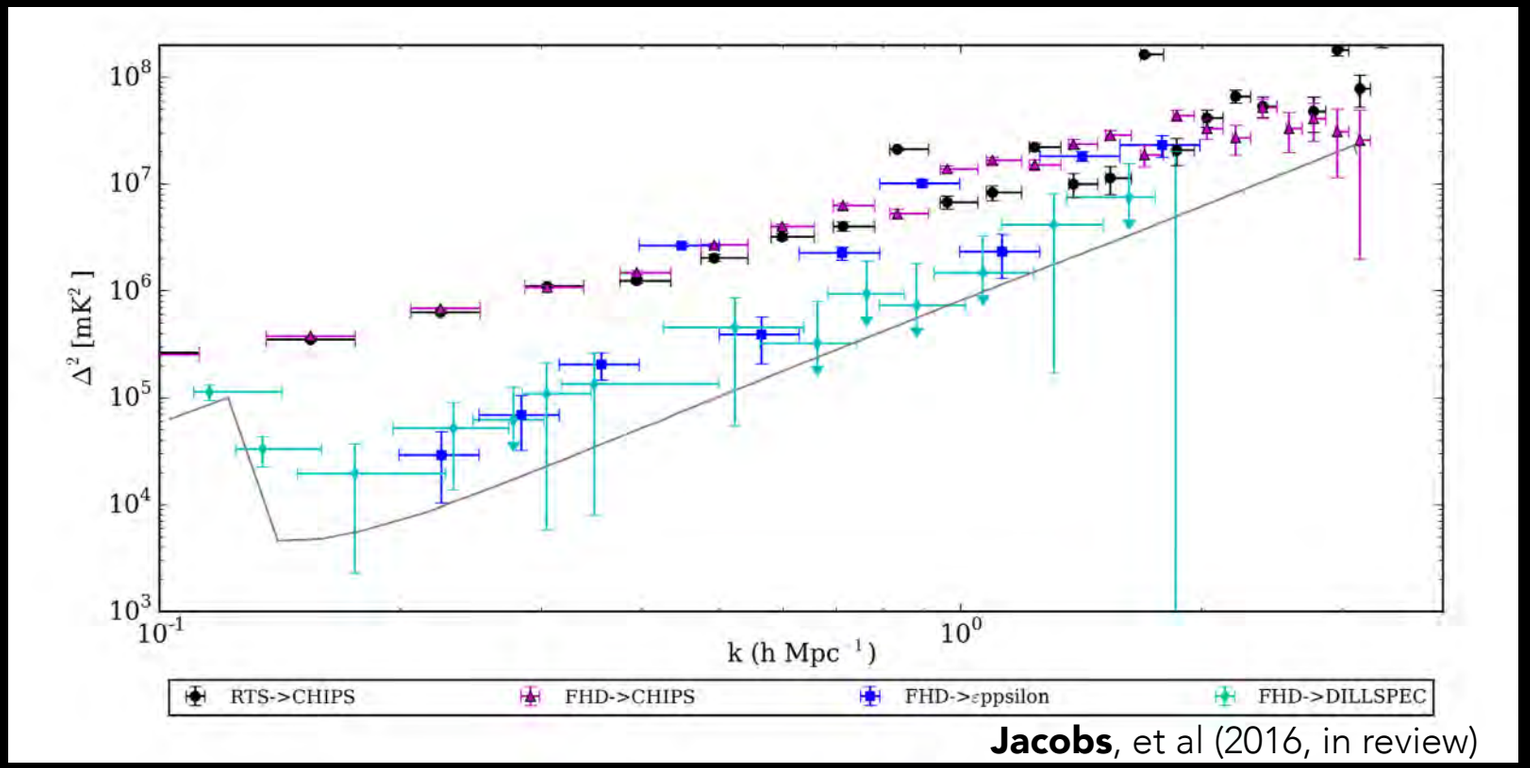
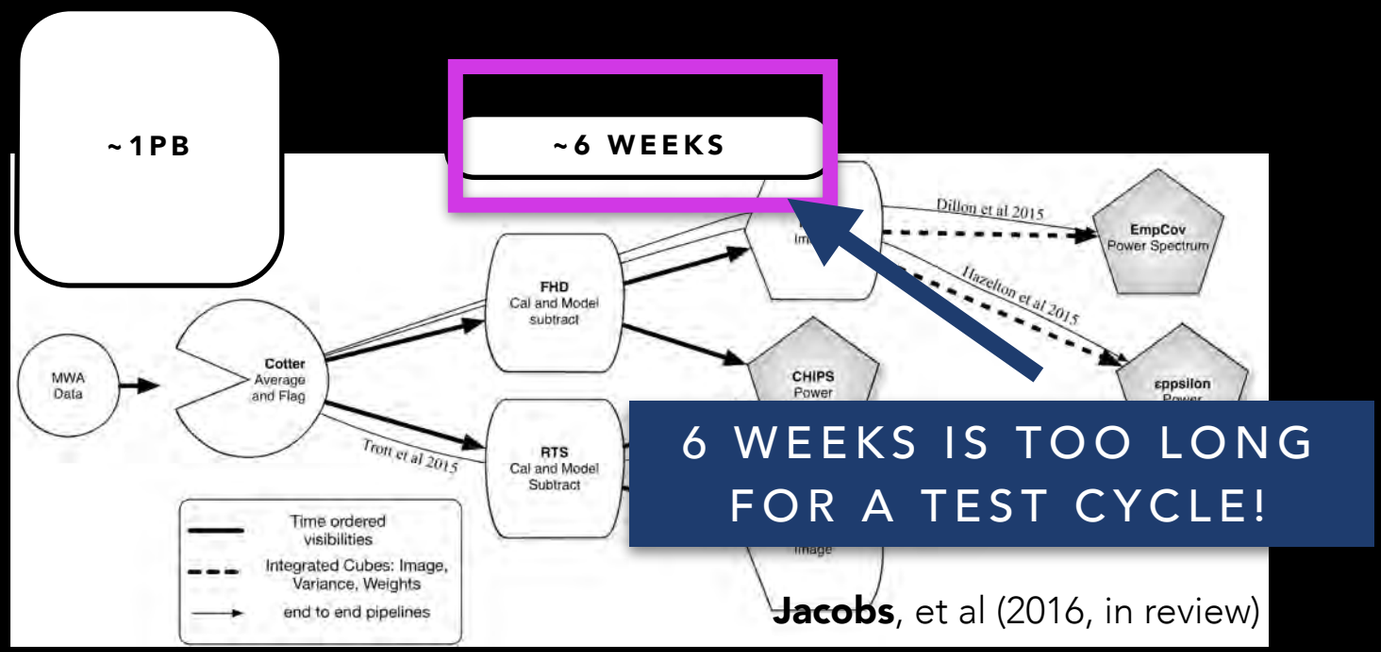
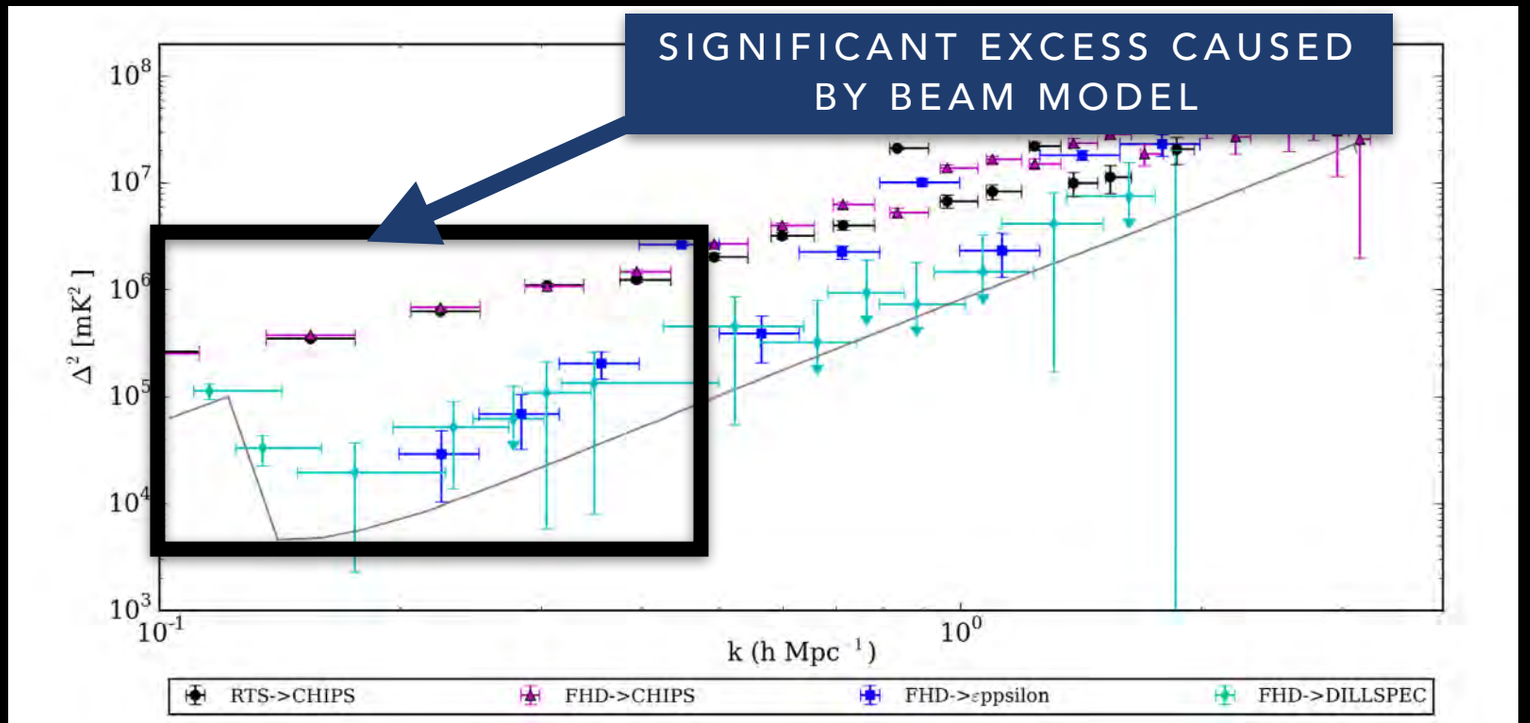


Jacobs, et al (2016, in review)

PROVING OUT THE MWA PIPELINE

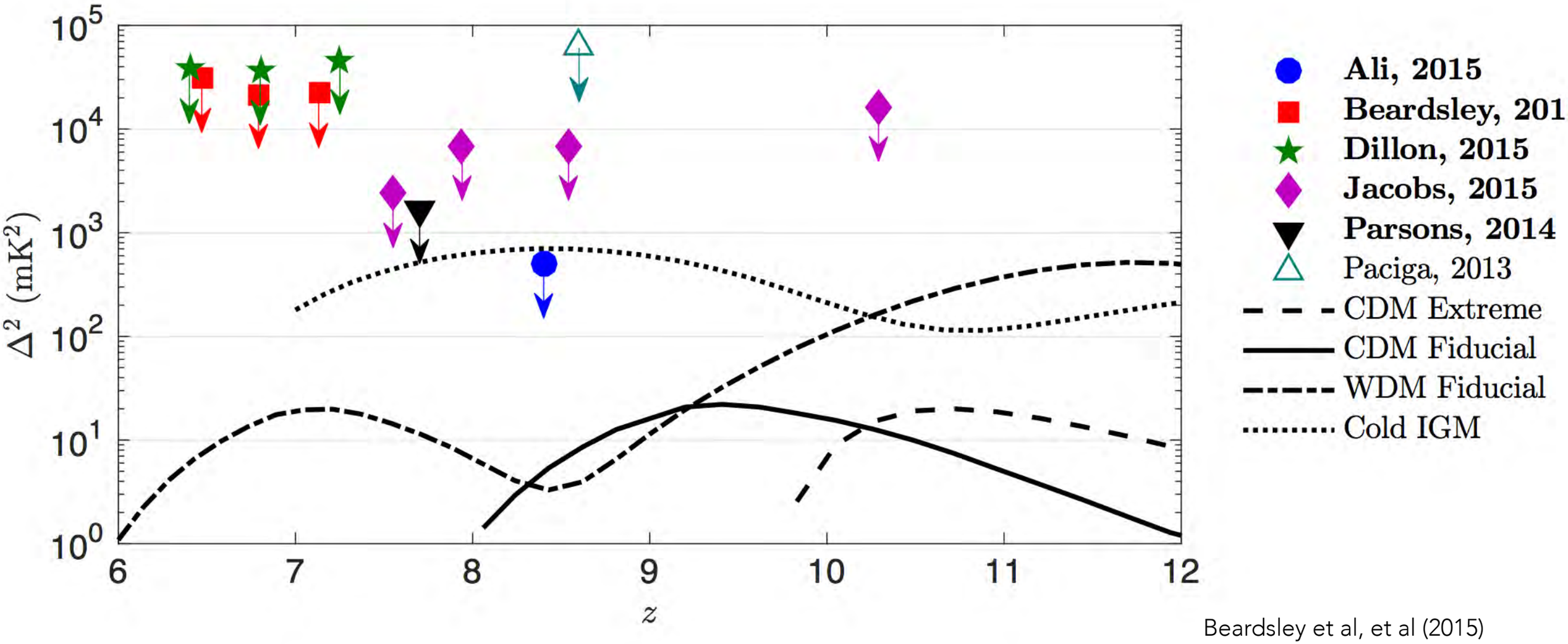


Jacobs, et al (2016, in review)



Jacobs, et al (2016, in review)

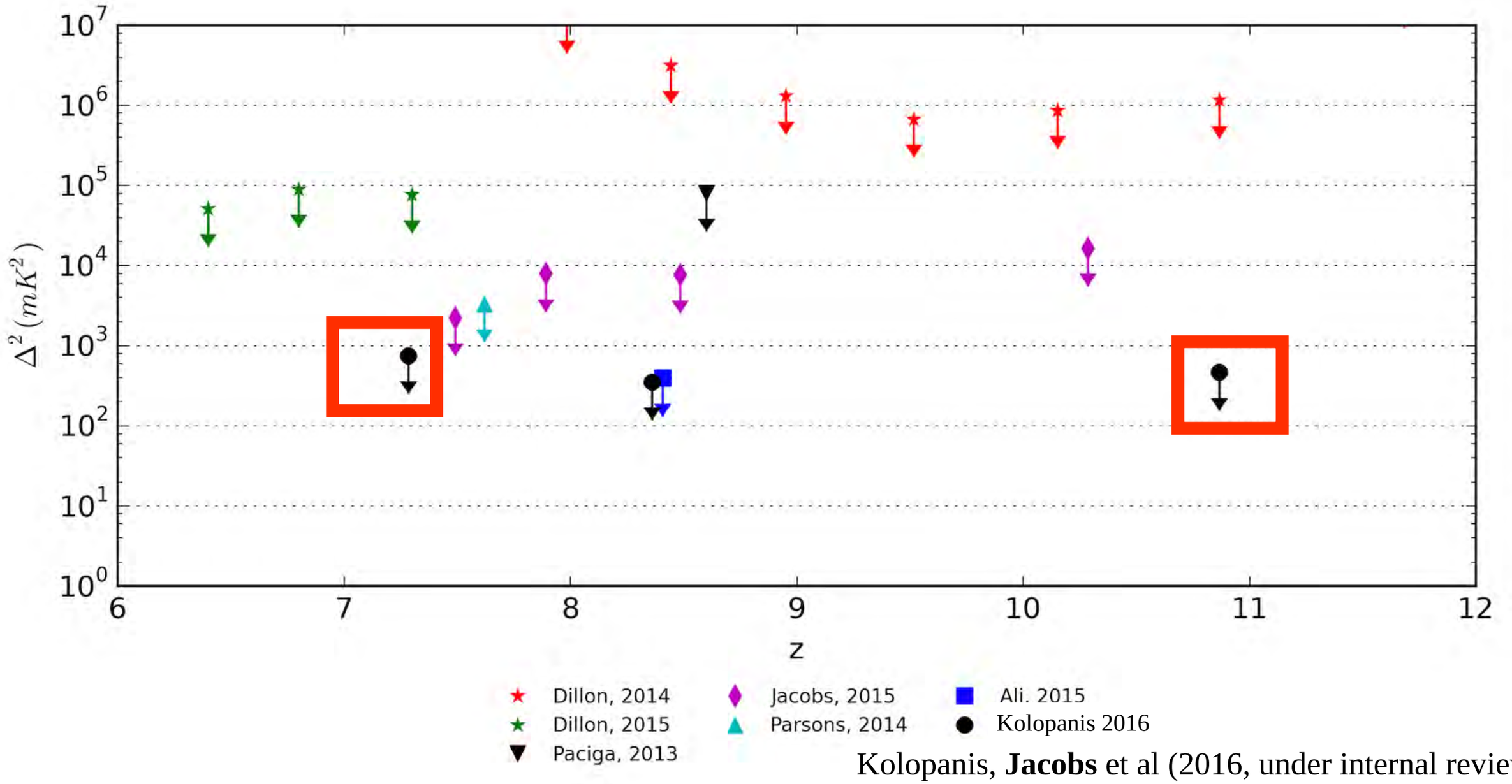
ALL CURRENT LIMITS: MWA AND PAPER



Beardsley et al, et al (2015)

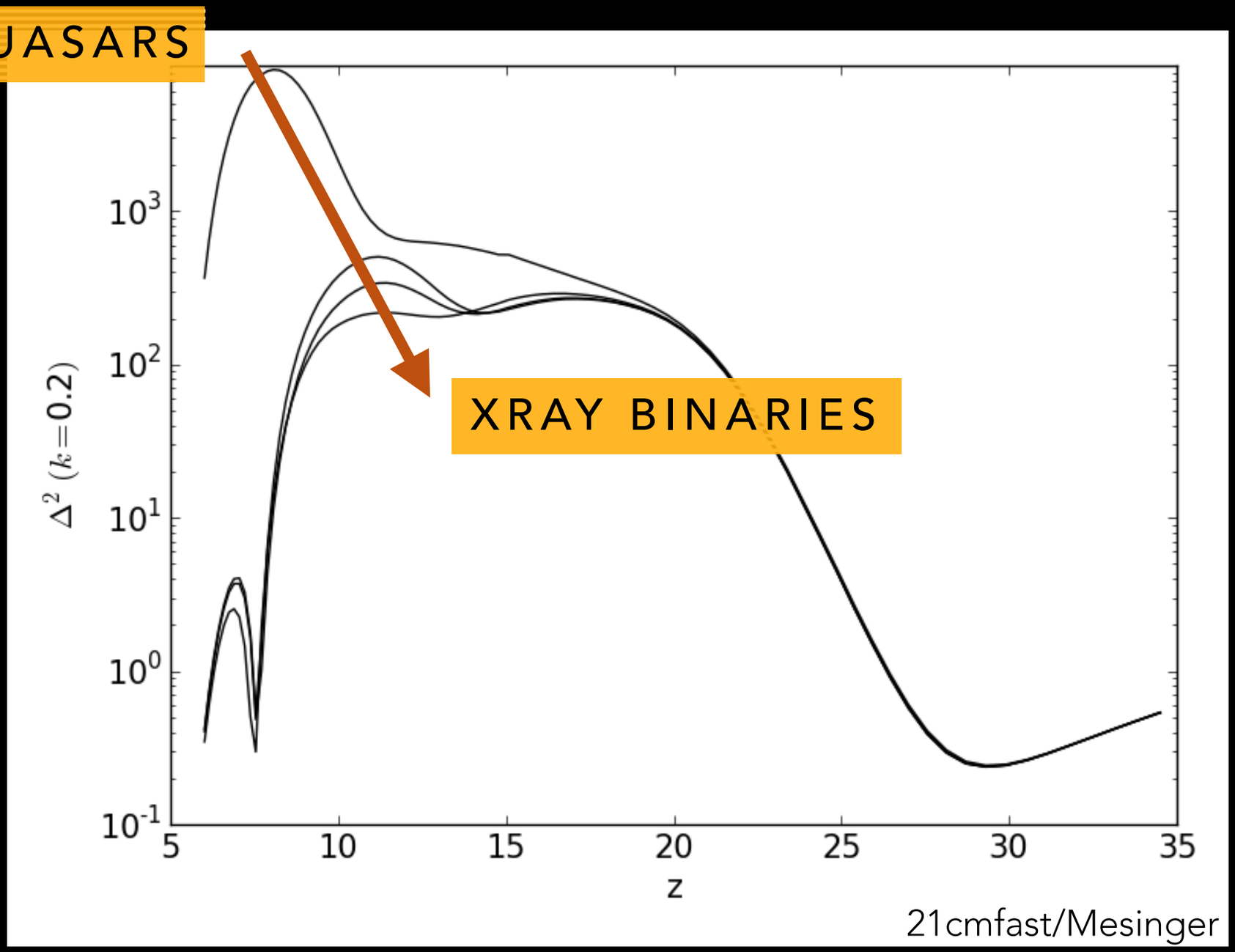
COLD IGM RULED OUT. XRAYS FROM FIRST STARS!

ADDING LATEST PAPER YEAR 2 DATA



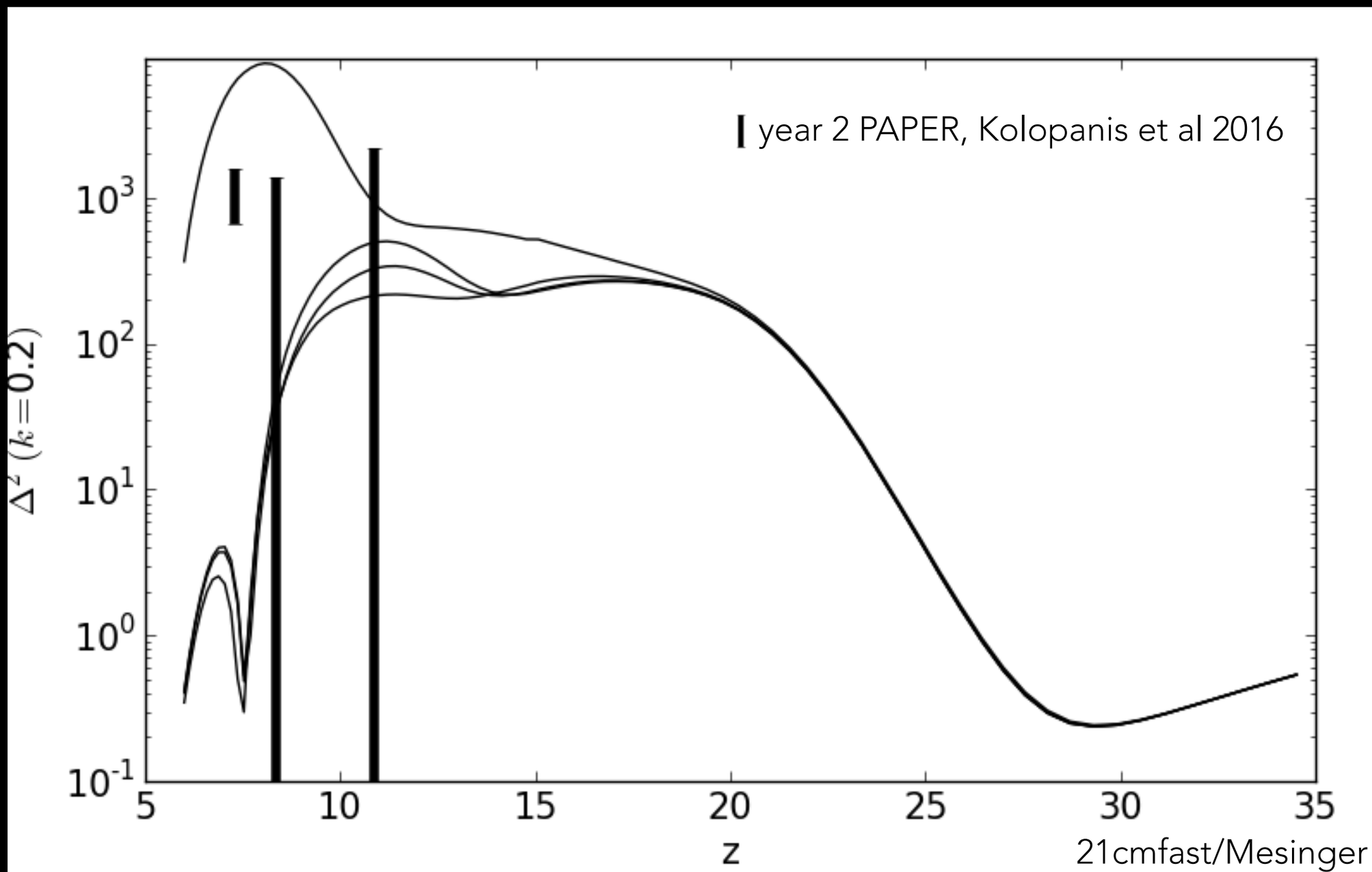
Kolopanis, **Jacobs** et al (2016, under internal review)

DETECTING THE FIRST HEAT

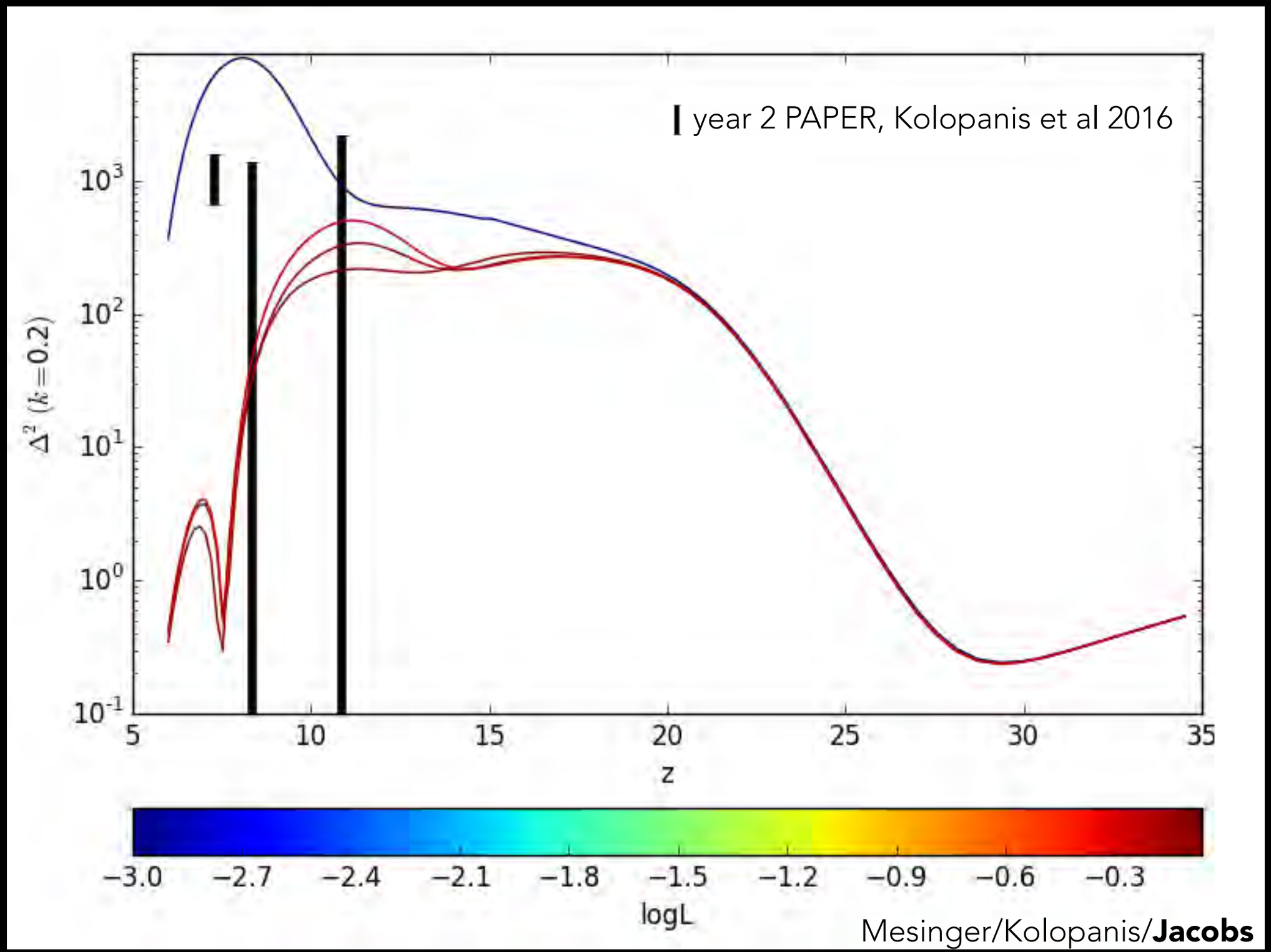


21cmfast/Mesinger

DETECTING THE FIRST HEAT

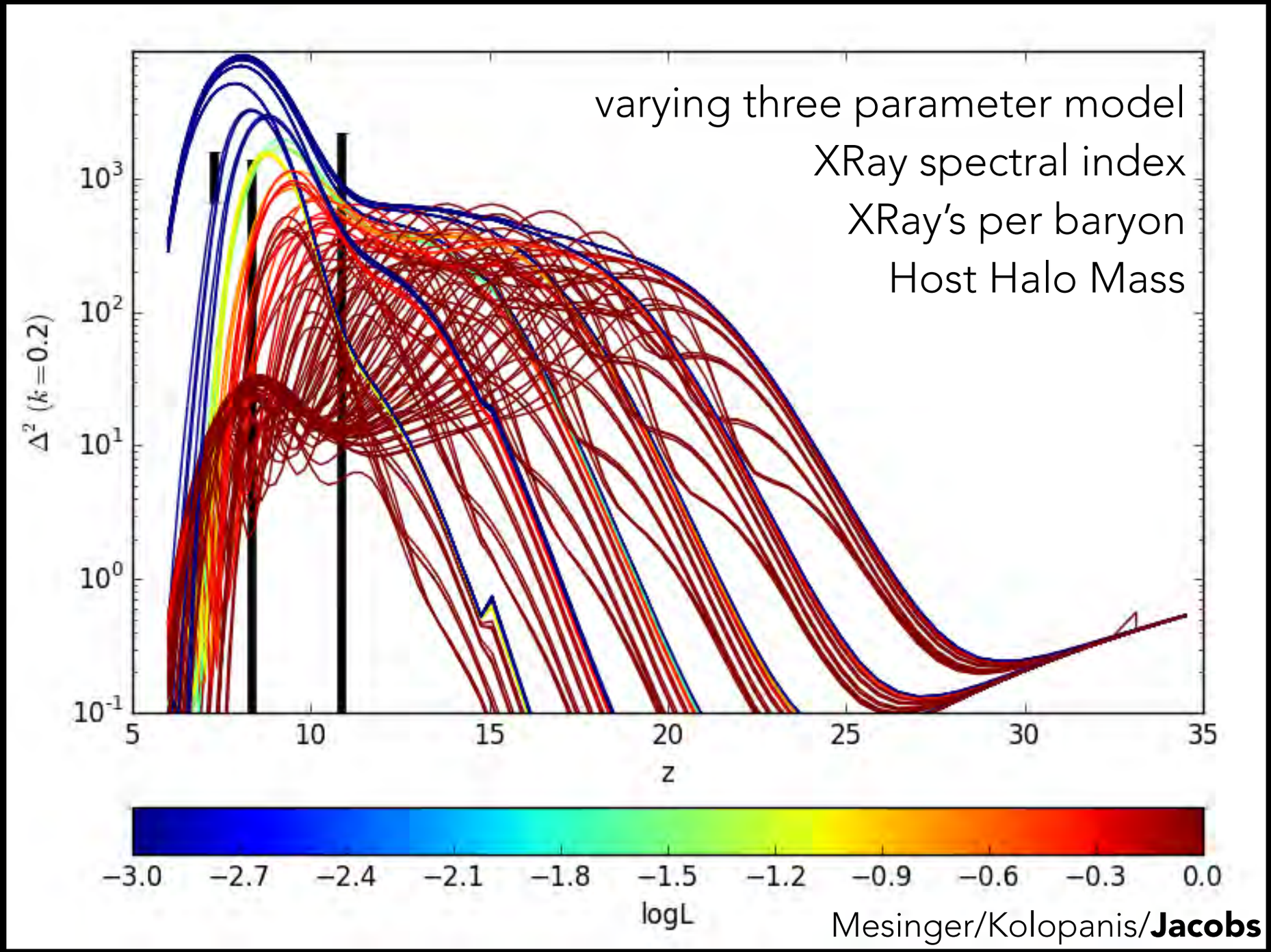


DETECTING THE FIRST HEAT

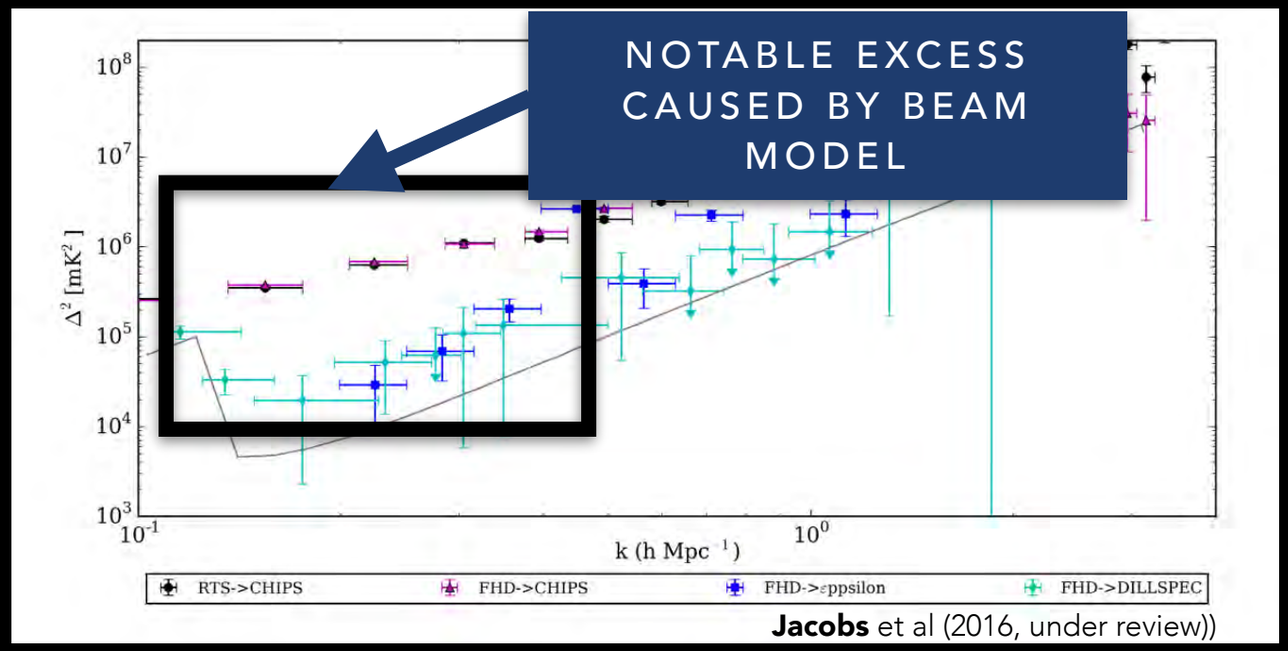


Mesinger/Kolopanis/**Jacobs**

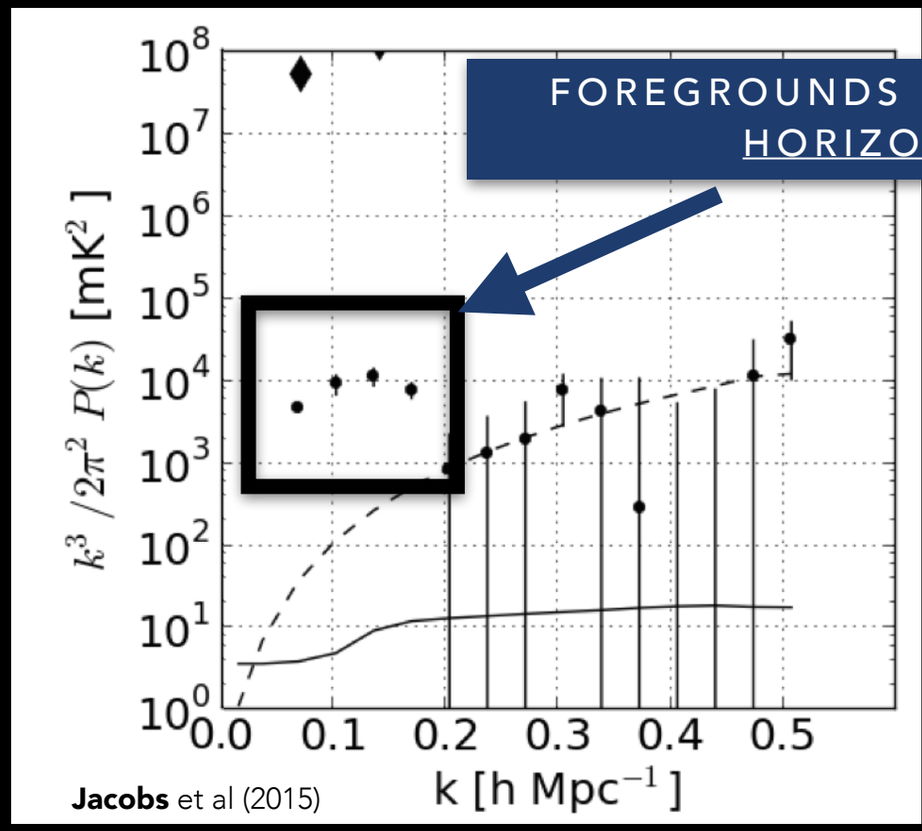
RULING OUT MORE HEATING SCENARIOS



FOREGROUND EXCESSES POINT TO BEAM MODEL INACCURACIES

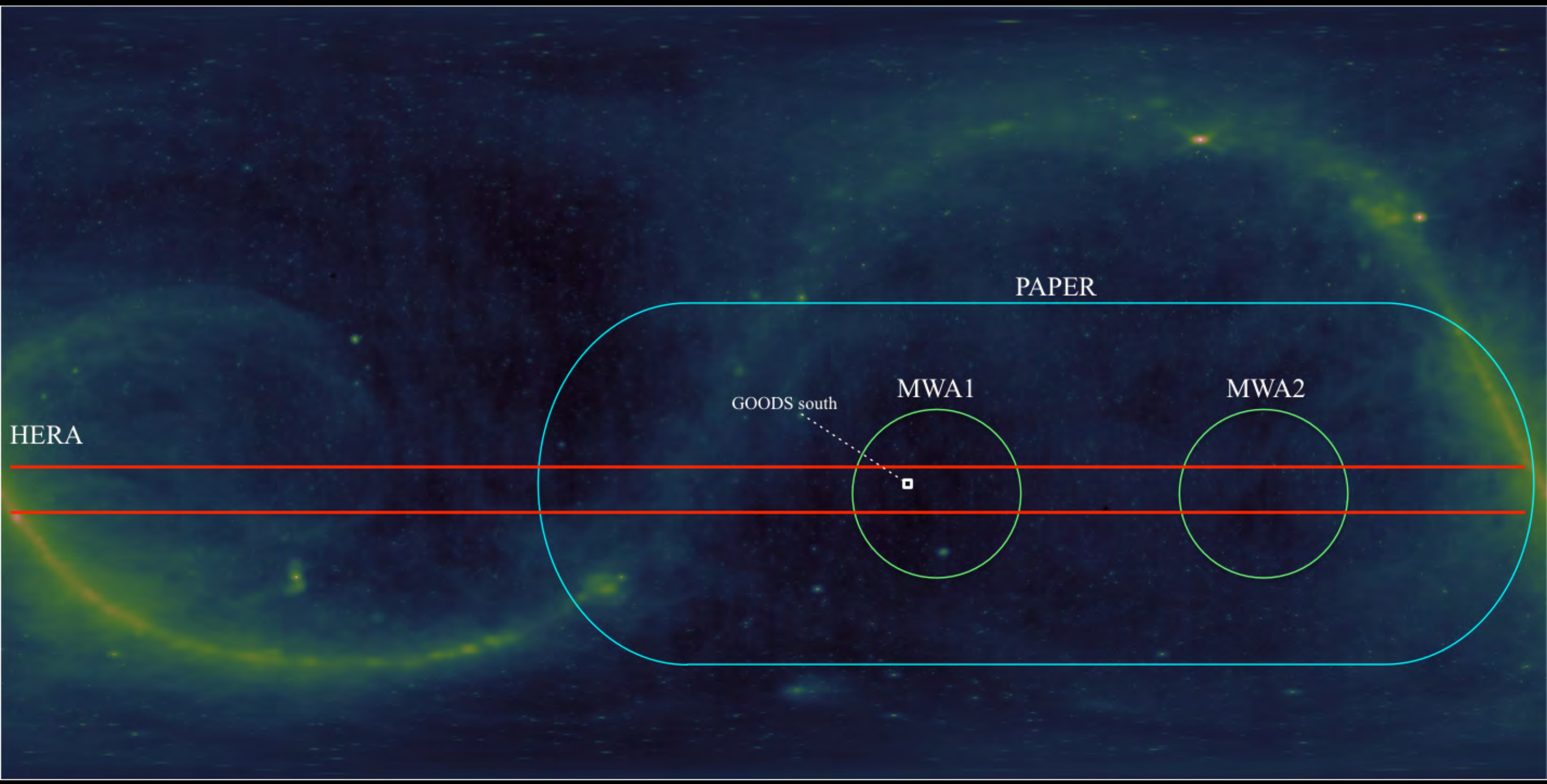


Jacobs et al (2016, under review))

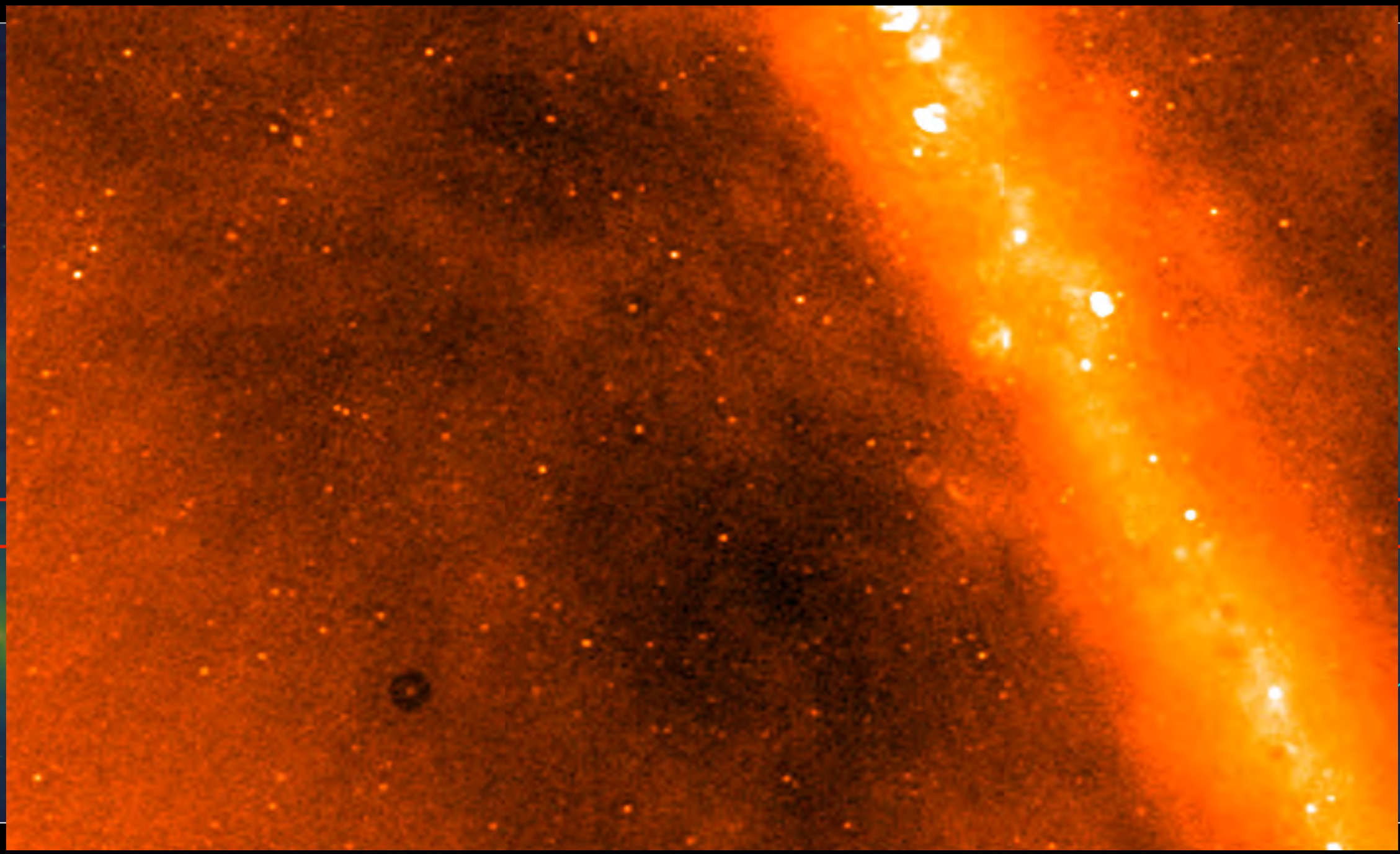


Jacobs et al (2015)

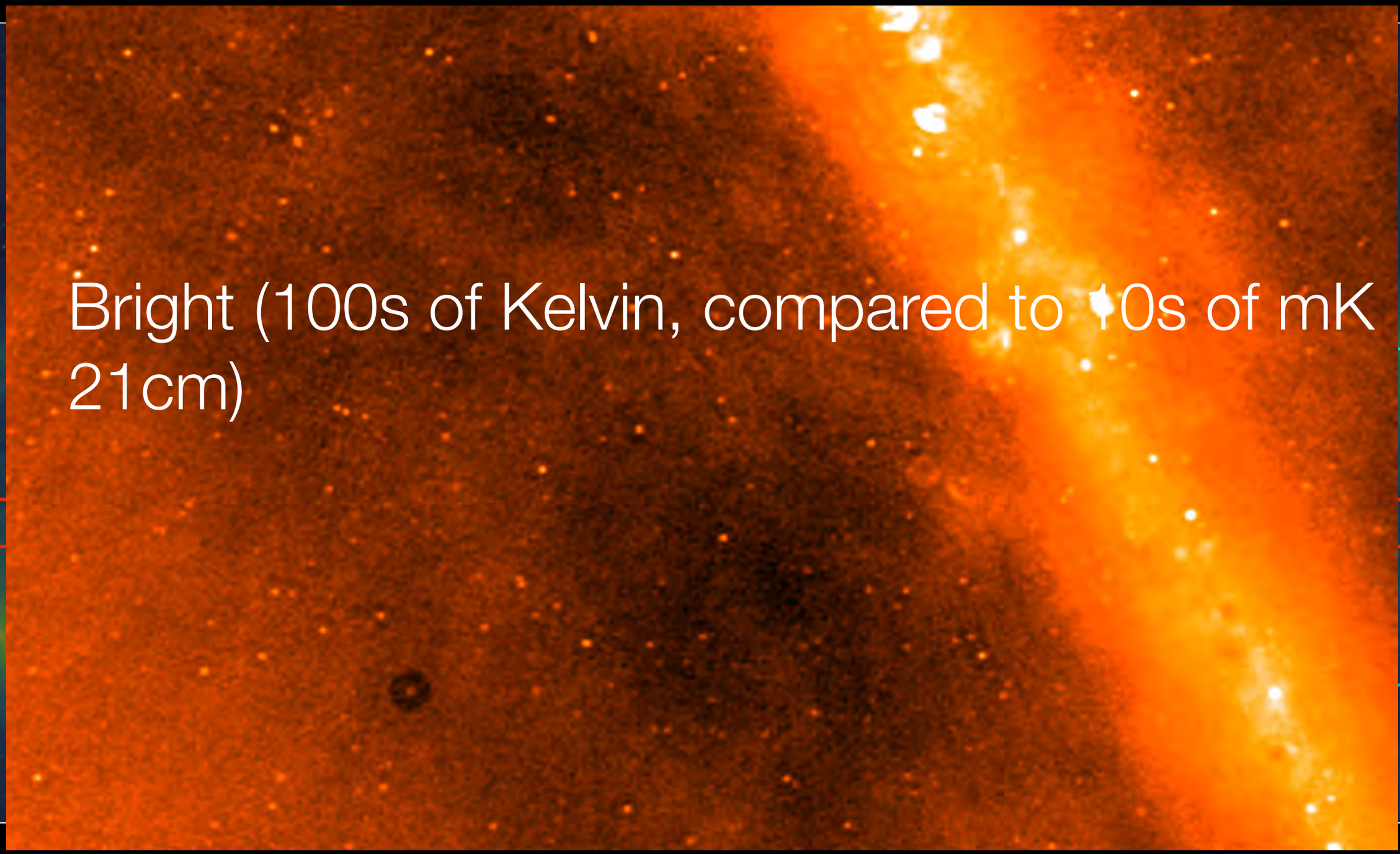
Foreground - Beam mixing



Foreground - Beam mixing

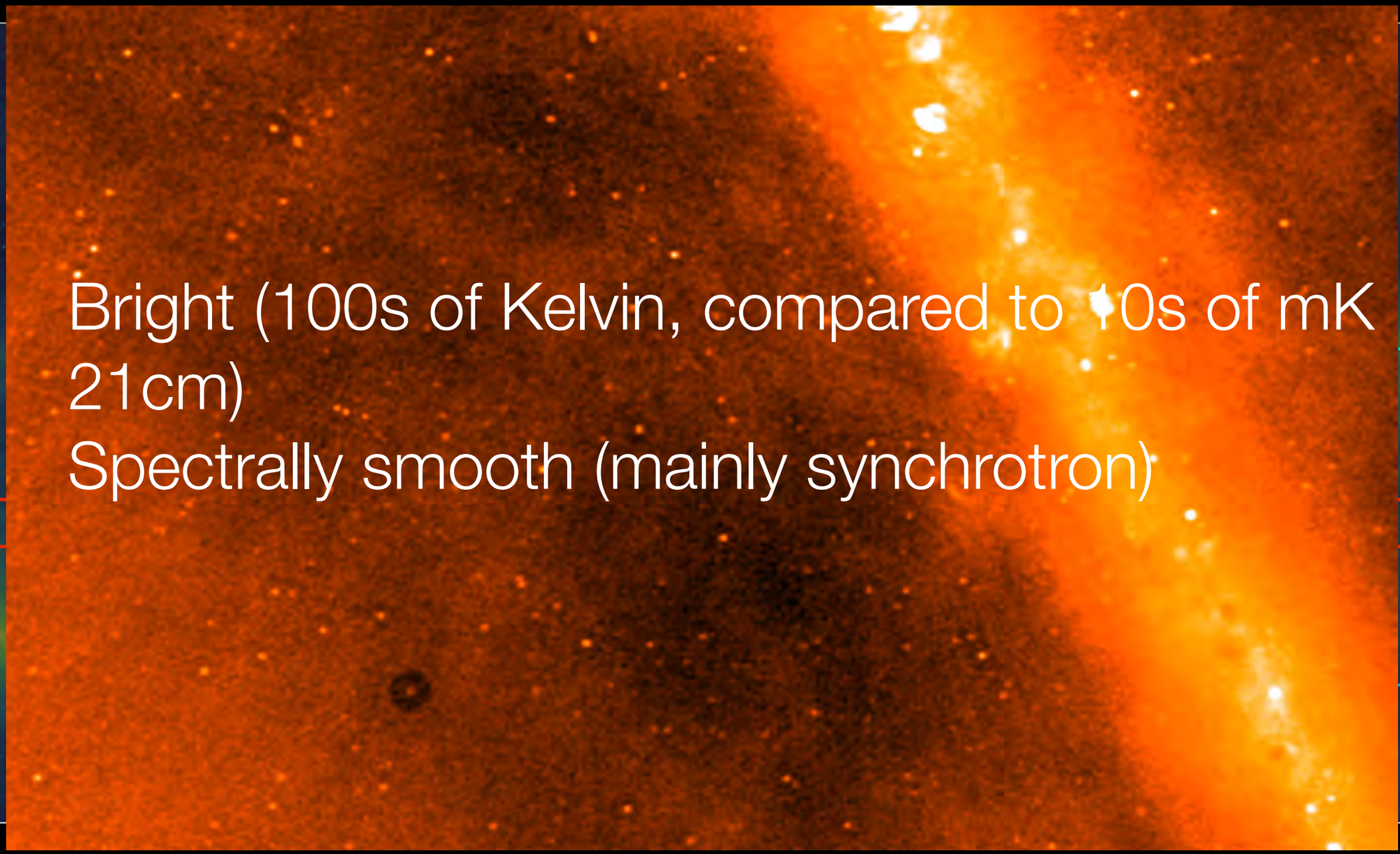


Foreground - Beam mixing

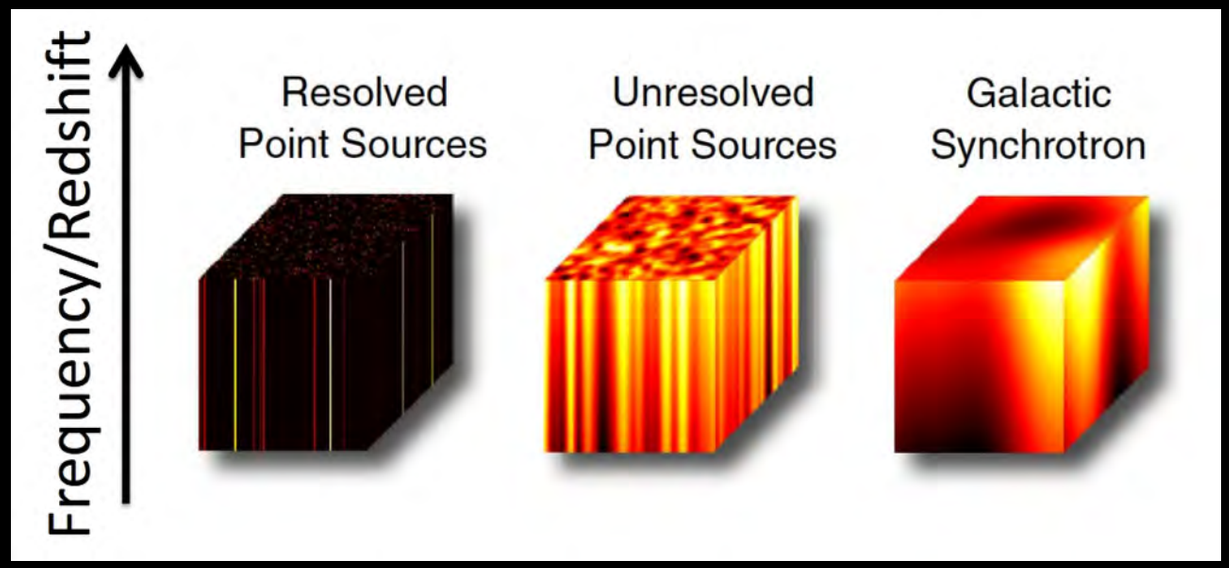


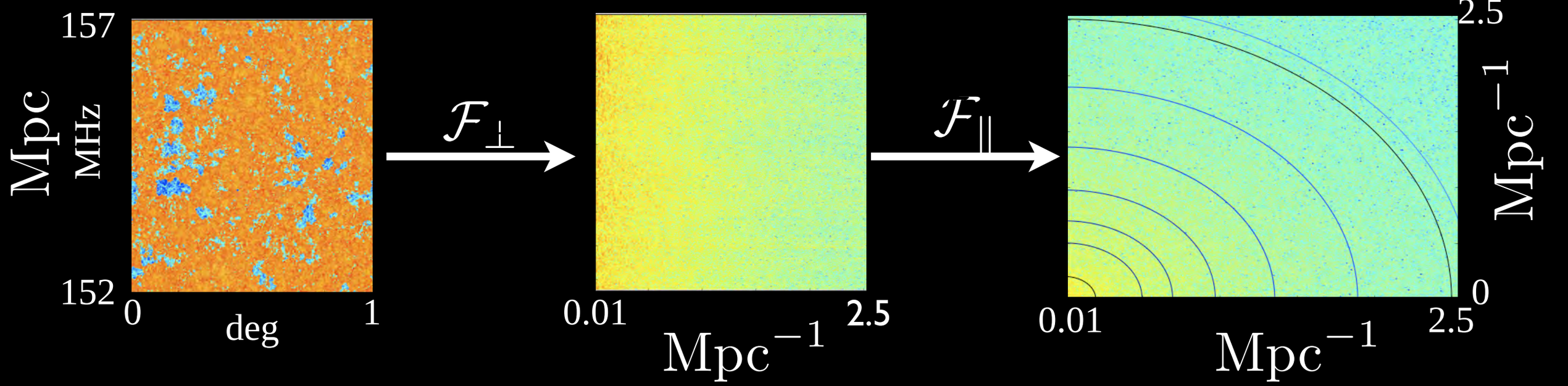
HERA

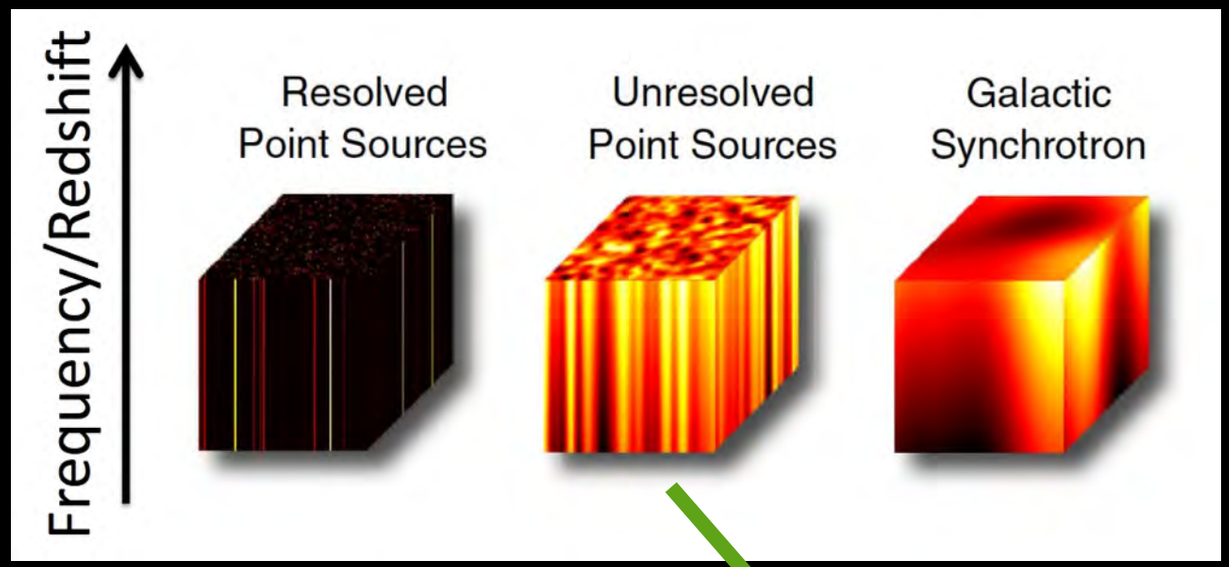
Foreground - Beam mixing

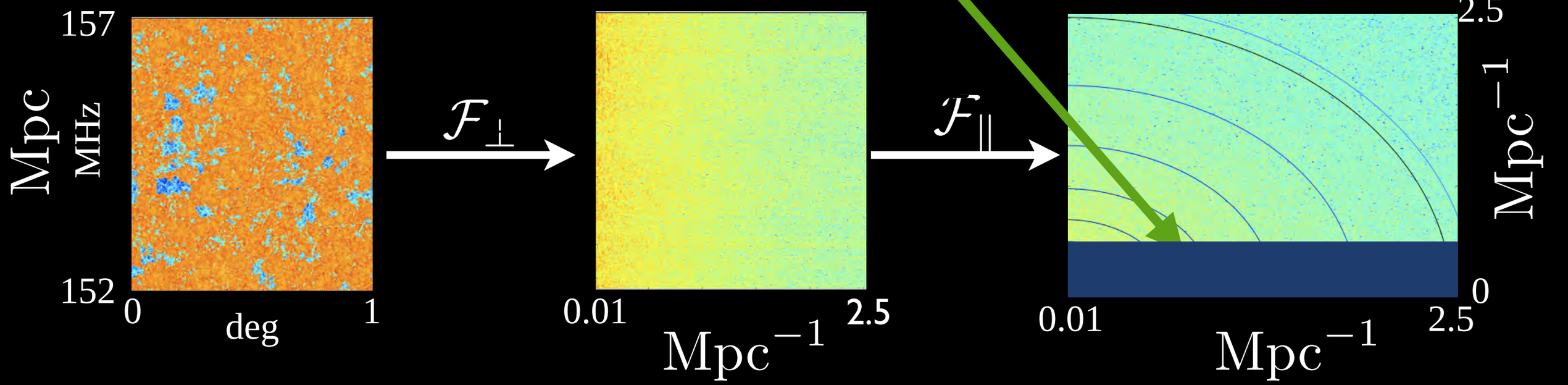


HERA


Frequency/Redshift
Resolved
Point Sources
Unresolved
Point Sources
Galactic
Synchrotron


157
152
Mpc
MHz
0
deg
1
$\mathcal{F}_\perp$
0.01
2.5
Mpc^{-1}
$\mathcal{F}_\parallel$
0.01
2.5
Mpc^{-1}
2.5
0
Mpc^{-1}


Frequency/Redshift
Resolved
Point Sources
Unresolved
Point Sources
Galactic
Synchrotron


157
152
Mpc
MHz
0
deg
1
$\mathcal{F}_\perp$
0.01
2.5
Mpc^{-1}
$\mathcal{F}_\parallel$
0.01
2.5
Mpc^{-1}
2.5
0
Mpc^{-1}

DETAILED INSTRUMENTAL SIMULATION

composite sky model

image available online: loco.lab.asu.edu/danny_jacobs/

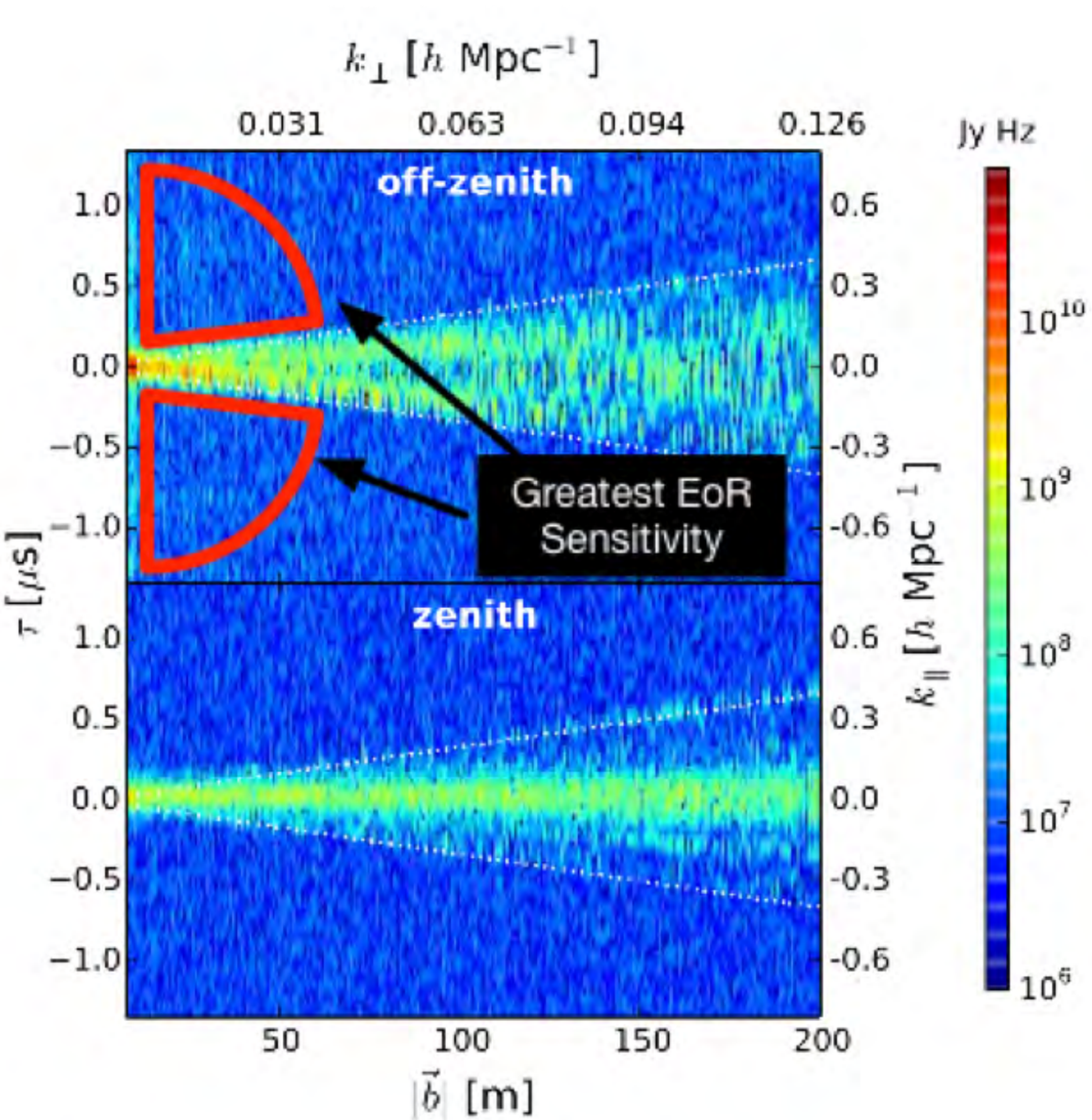
apply instrument model

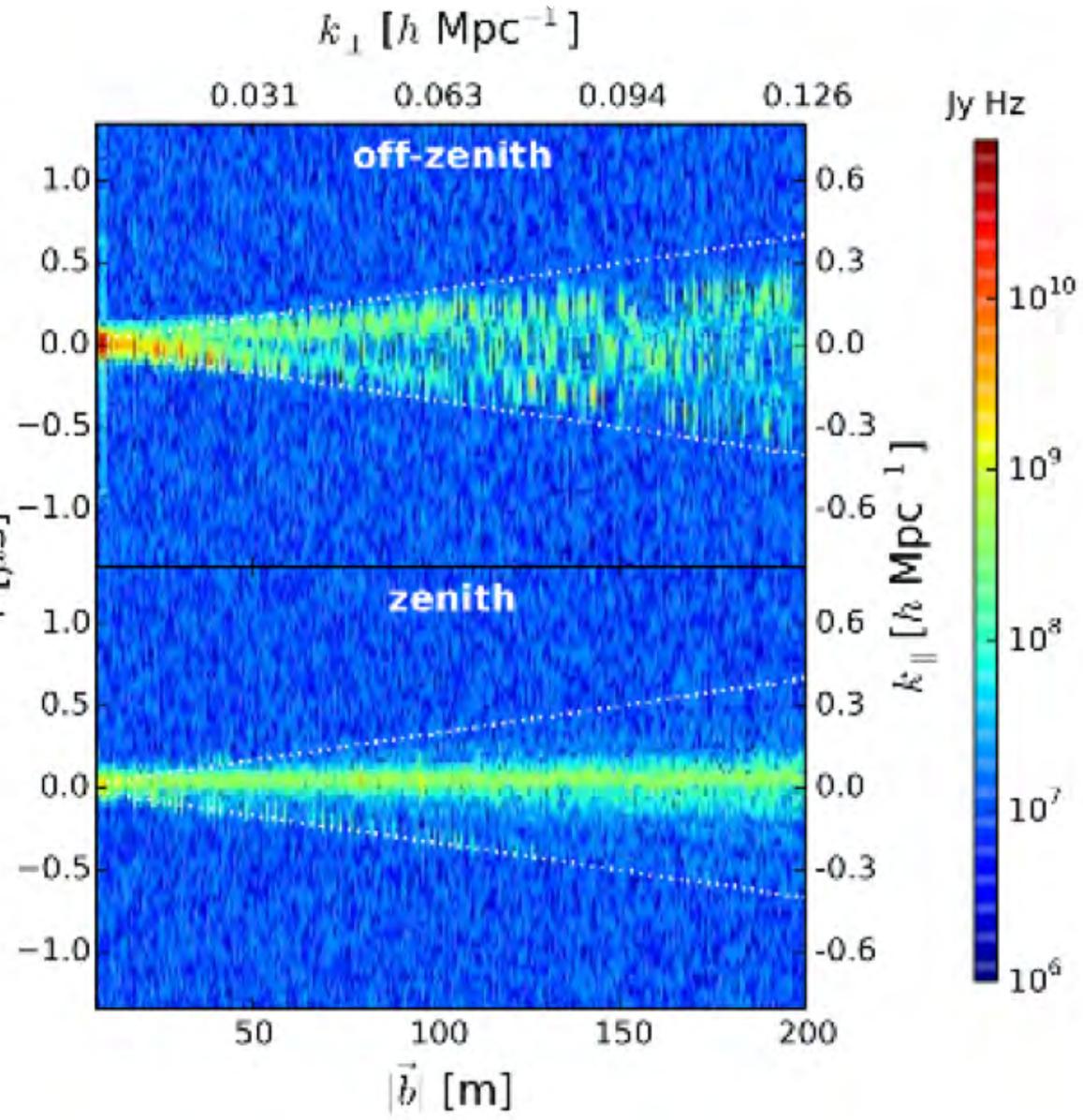
https://github.com/dannyjacobs/PRISim

Thyagarajan, **Jacobs**, et al 2015a

Thyagarajan, **Jacobs**, et al 2015b

Widefield Foreground simulation vs data

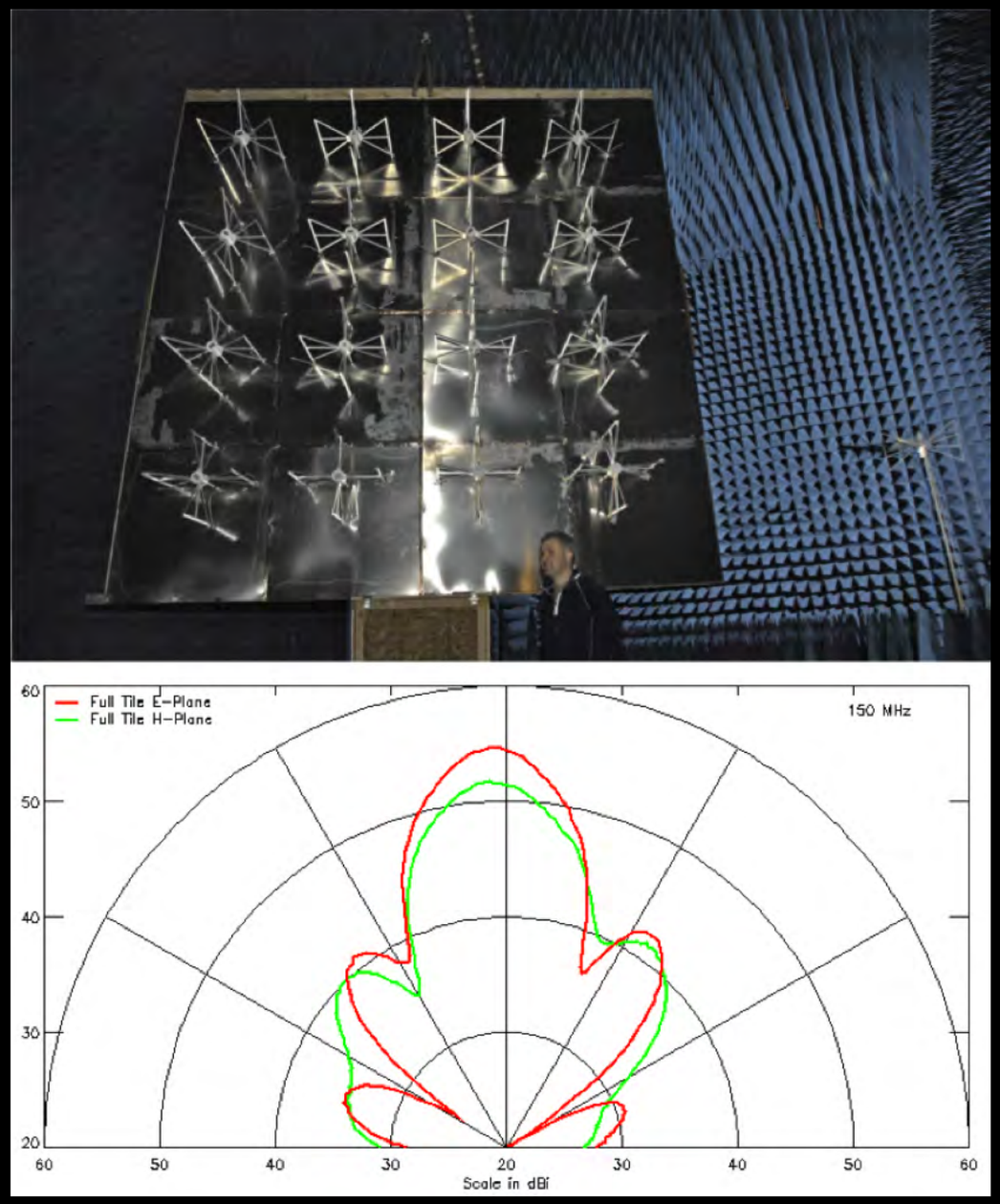




https://github.com/dannyjacobs/PRISim

Thyagarajan, **Jacobs**, et al 2015a
Thyagarajan, **Jacobs**, et al 2015b

PRIMARY BEAM UNCERTAINTY IS NOT NEW



HERA beam requirement

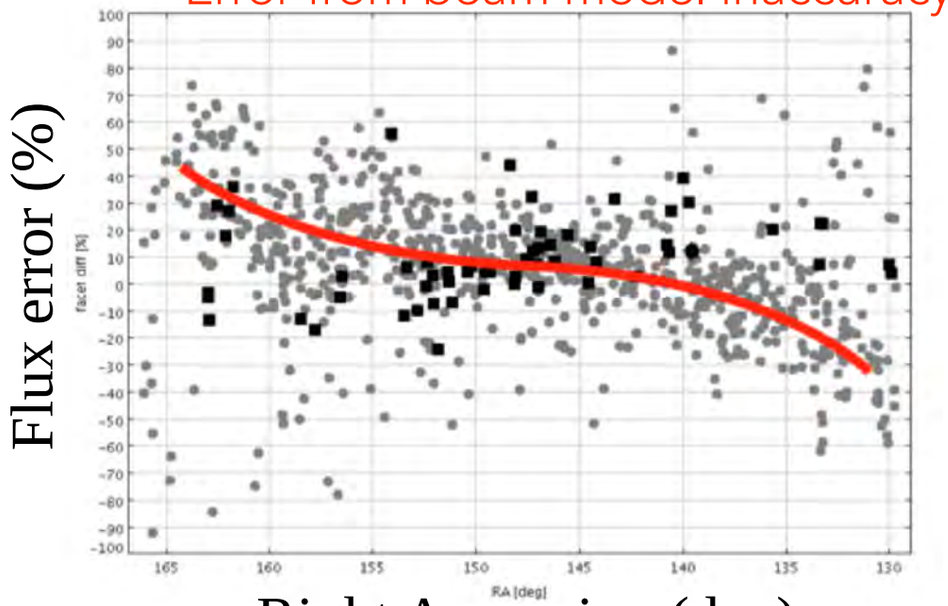
1% at -40 dB

CHIME

0.1% on FWHM (Newburgh et al 2014)

MWA catalog error

Error from beam model inaccuracy



Jacobs et al 2013

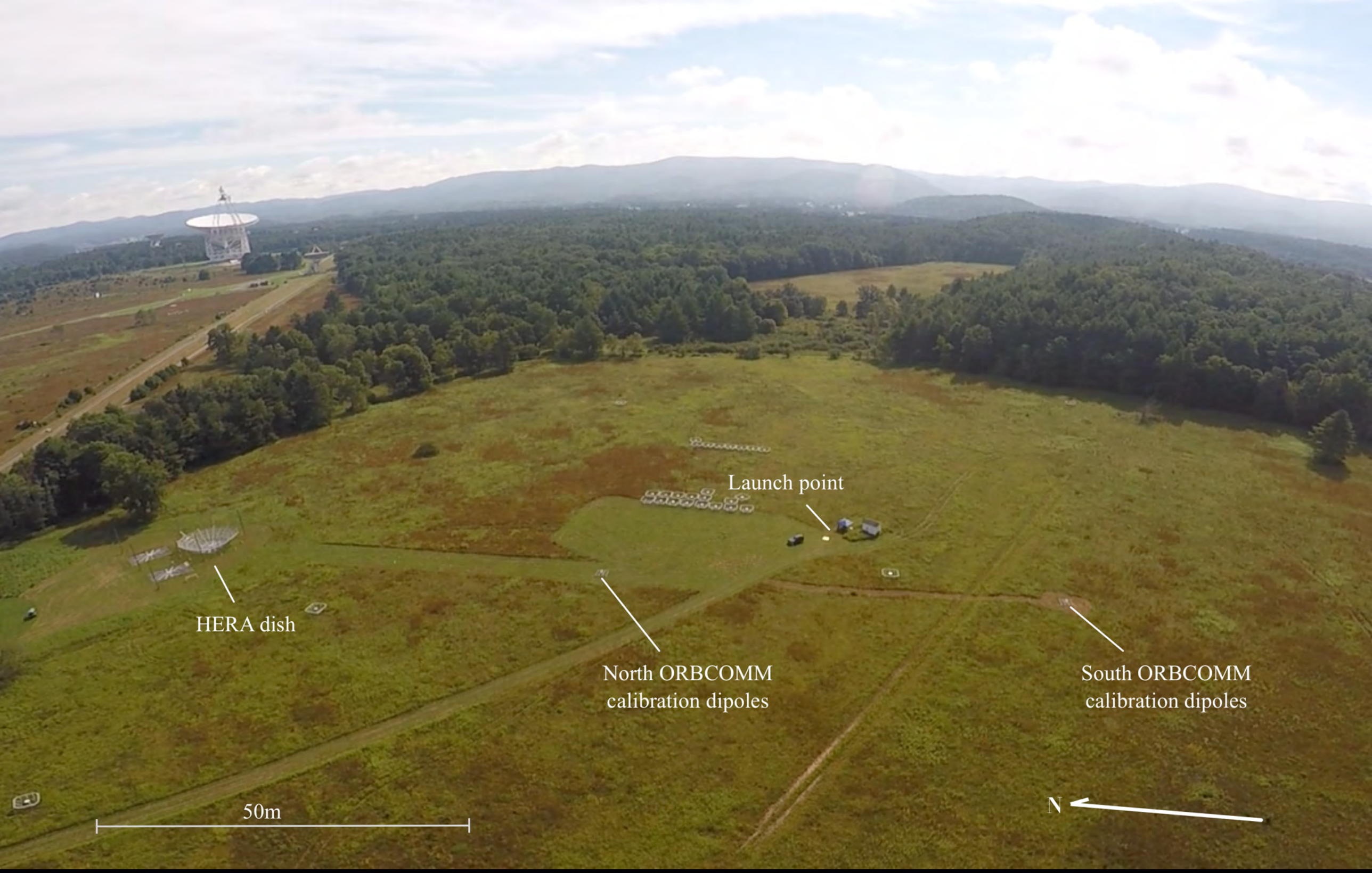
EXTERNAL CALIBRATOR FOR HYDROGEN OBSERVATORIES | ECHO

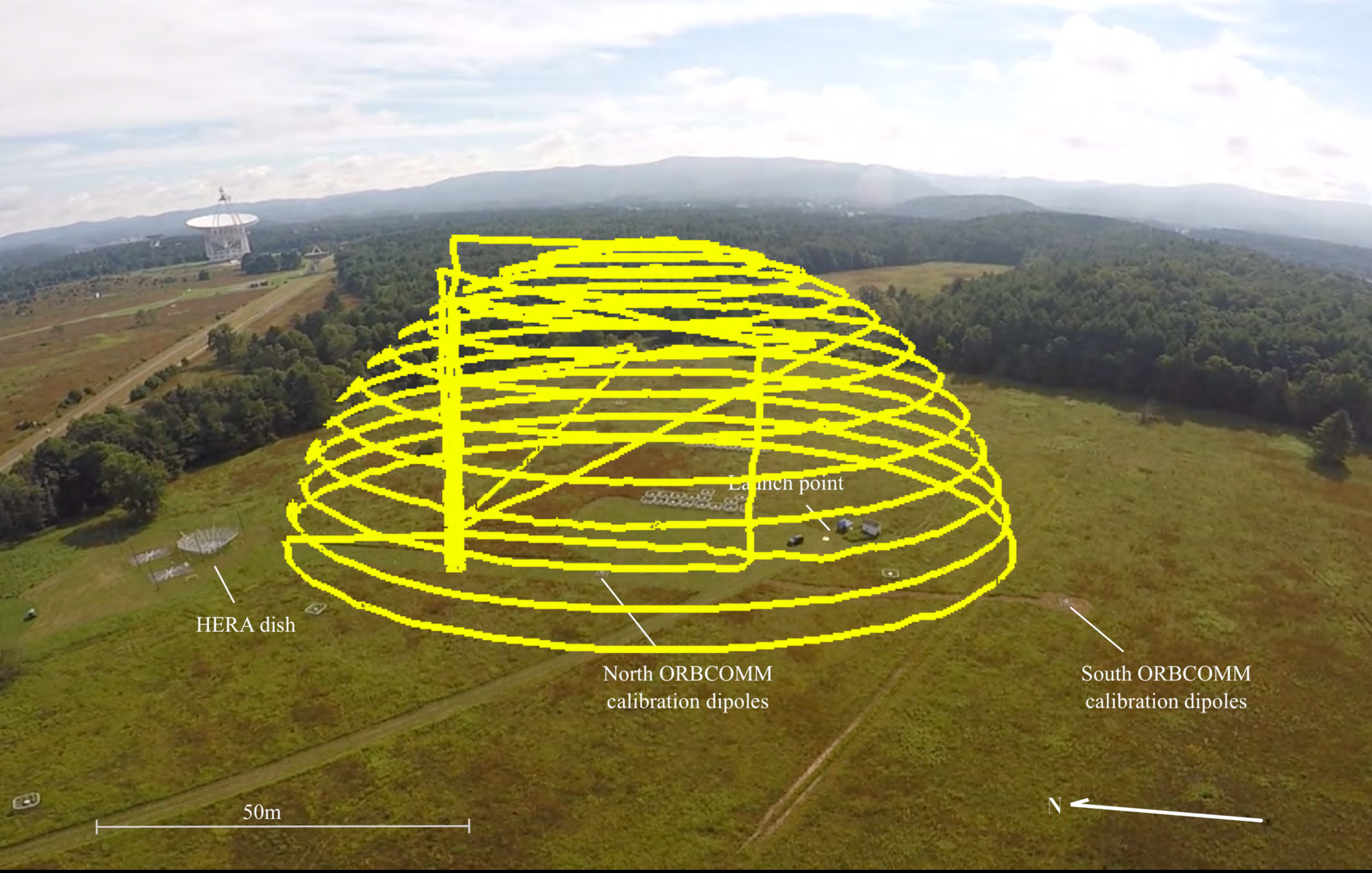
NSF Advanced Technology and Instrumentation Program

Jacobs PI

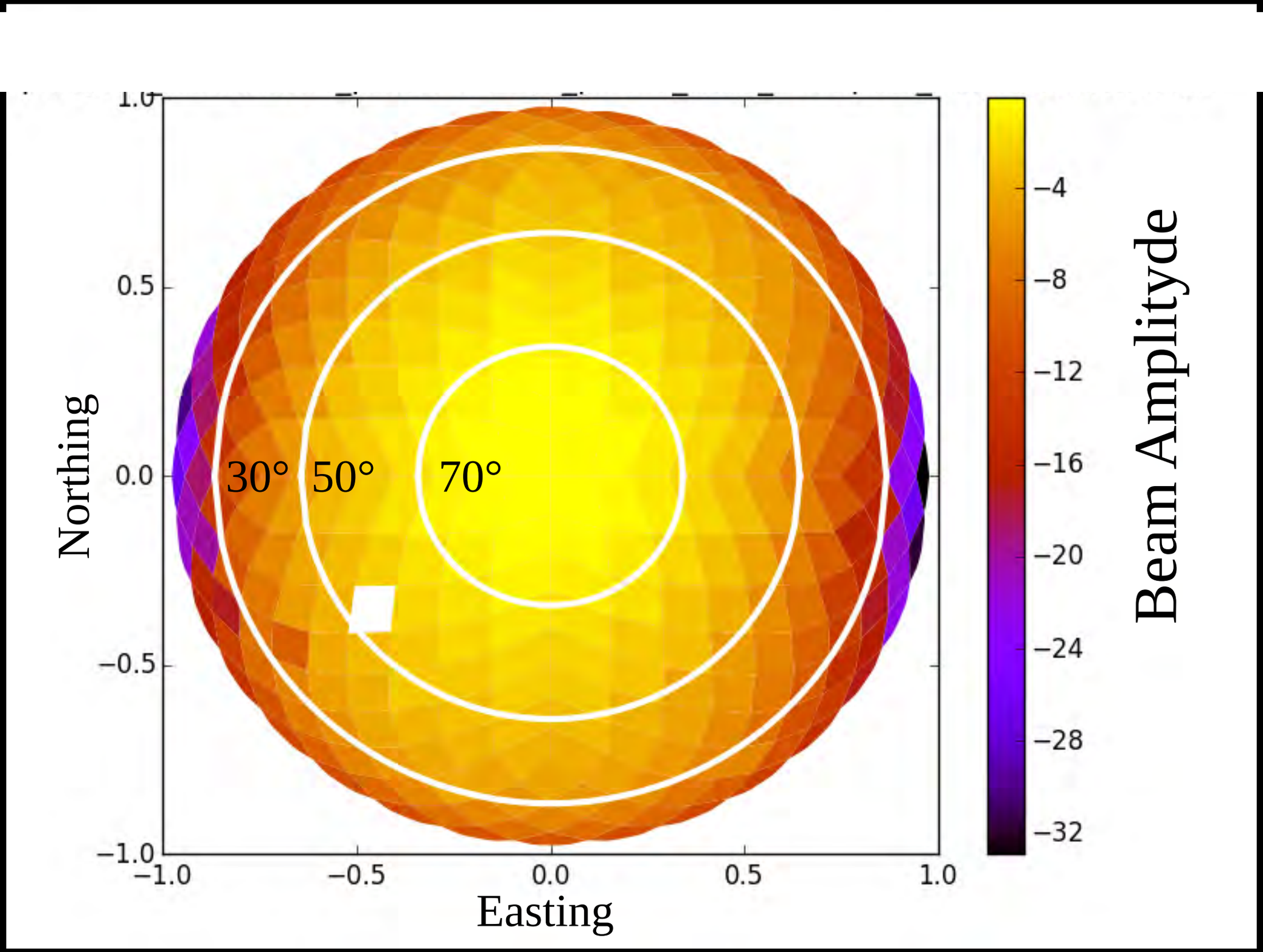
ECHO DIAGRAM

Transmits 100-200MHz
Calibration signal

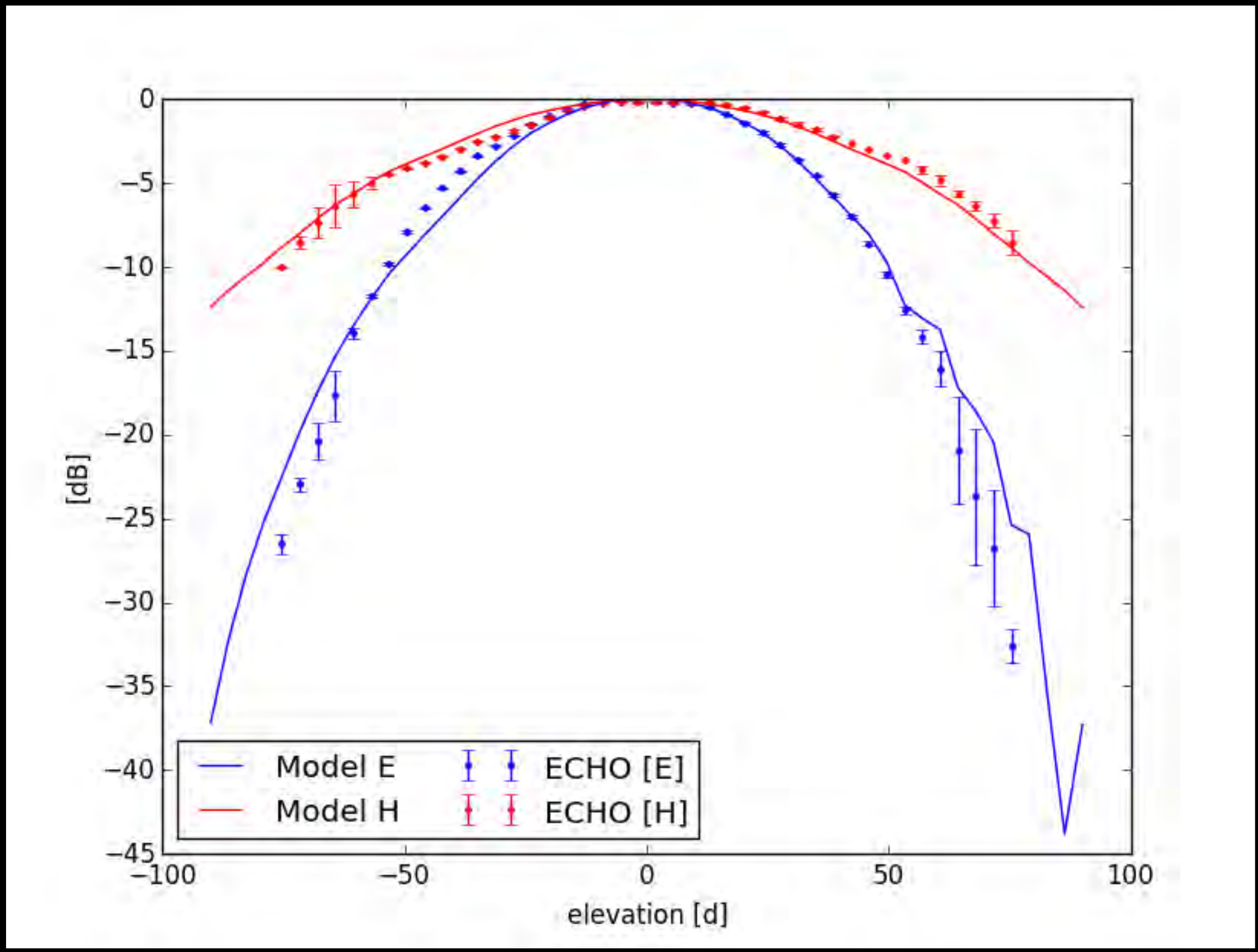

Launch point
HERA dish
North ORBCOMM
calibration dipoles
South ORBCOMM
calibration dipoles
50m
N


Launch point
HERA dish
North ORBCOMM
calibration dipoles
South ORBCOMM
calibration dipoles
50m
N

EXAMPLE MAP


1.0
0.5
0.0
−0.5
−1.0
Northing
30°
50°
70°
−1.0
−0.5
0.0
0.5
1.0
Easting
−4
−8
−12
−16
−20
−24
−28
−32
Beam Amplityde

ECHO CAL DIPOLE TEST



ECHO STUDENTS

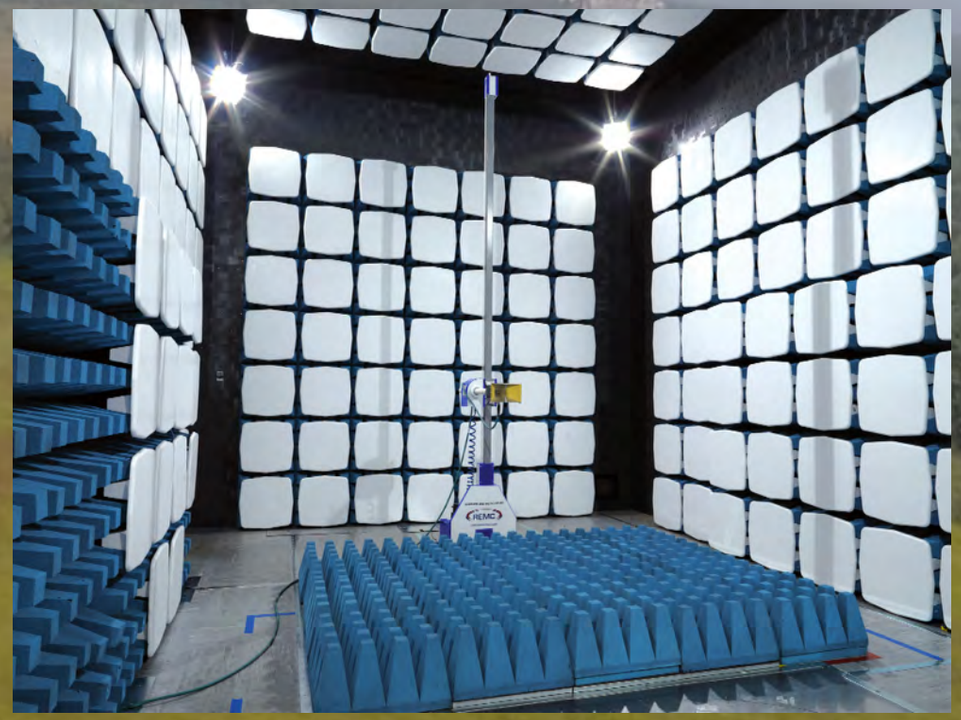
D.Jacobs (PI)

Students: J. Burba, L. Turner, B. Stinnett, M. Busch, M. Leatham, V. Serrano, M. Denney, D. Nelson, A. Neben, K. Johnson

loco.lab.asu.edu/danny_jacobs/ECHO

ECHO: CURRENT/FUTURE WORK

- Anechoic chamber measurements
- Electromagnetic simulation
- FPGA-based transmitter
- Guest Instruments
- Integration with: HERA (next field trip Feb 27) In talks with: LWA, CHIME, HIRAX, SPT?



HYDROGEN EPOCH OF REIONIZATION ARRAY (HERA)

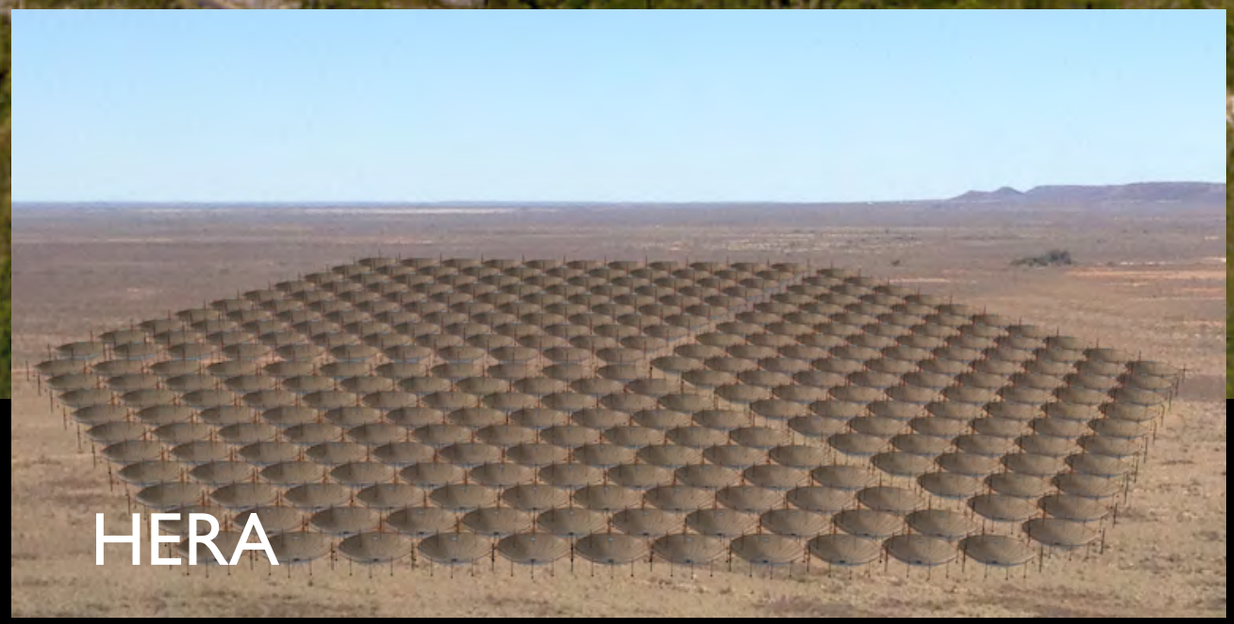
Location: Karoo Desert, South Africa
High sensitivity on Reionization and late Dark Ages
350 14m dishes

Goal: High SNR Power spectra and first images

(HERA memo #0, D. Jacobs)

Expanded redshift range: from 13 to 20 via Moore Foundation
Supported by the NSF Mid-Scale program, construction under way.

HYDROGEN EPOCH OF REIONIZATION ARRAY (HERA)


HERA

HERA PRIMARY SCIENCE

1. Detect and characterize reionization 21cm emission at high significance

2. Constrain global parameters of First Astrophysics

3. Direct measurement of CMB optical depth (tau)

4. First true survey images suitable for cross-comparison

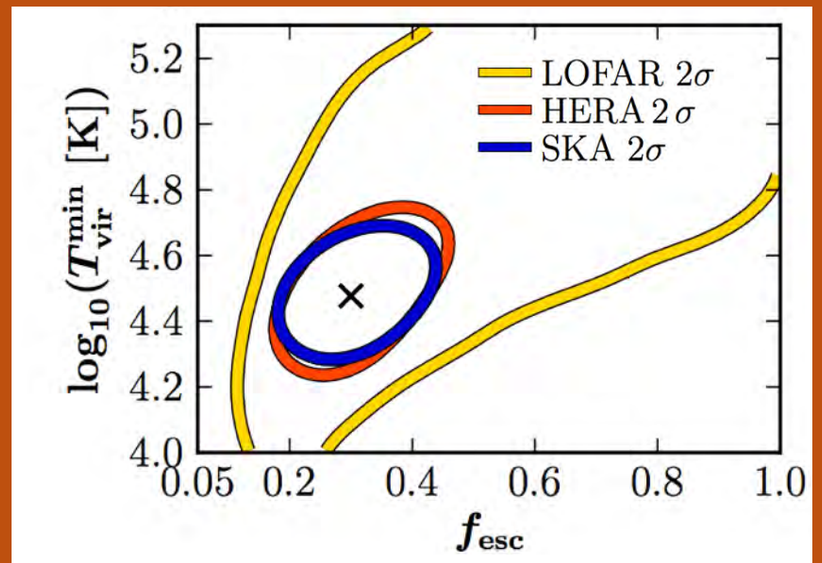
HERA PRIMARY SCIENCE

1. Detect and characterize 21cm emission at high significance

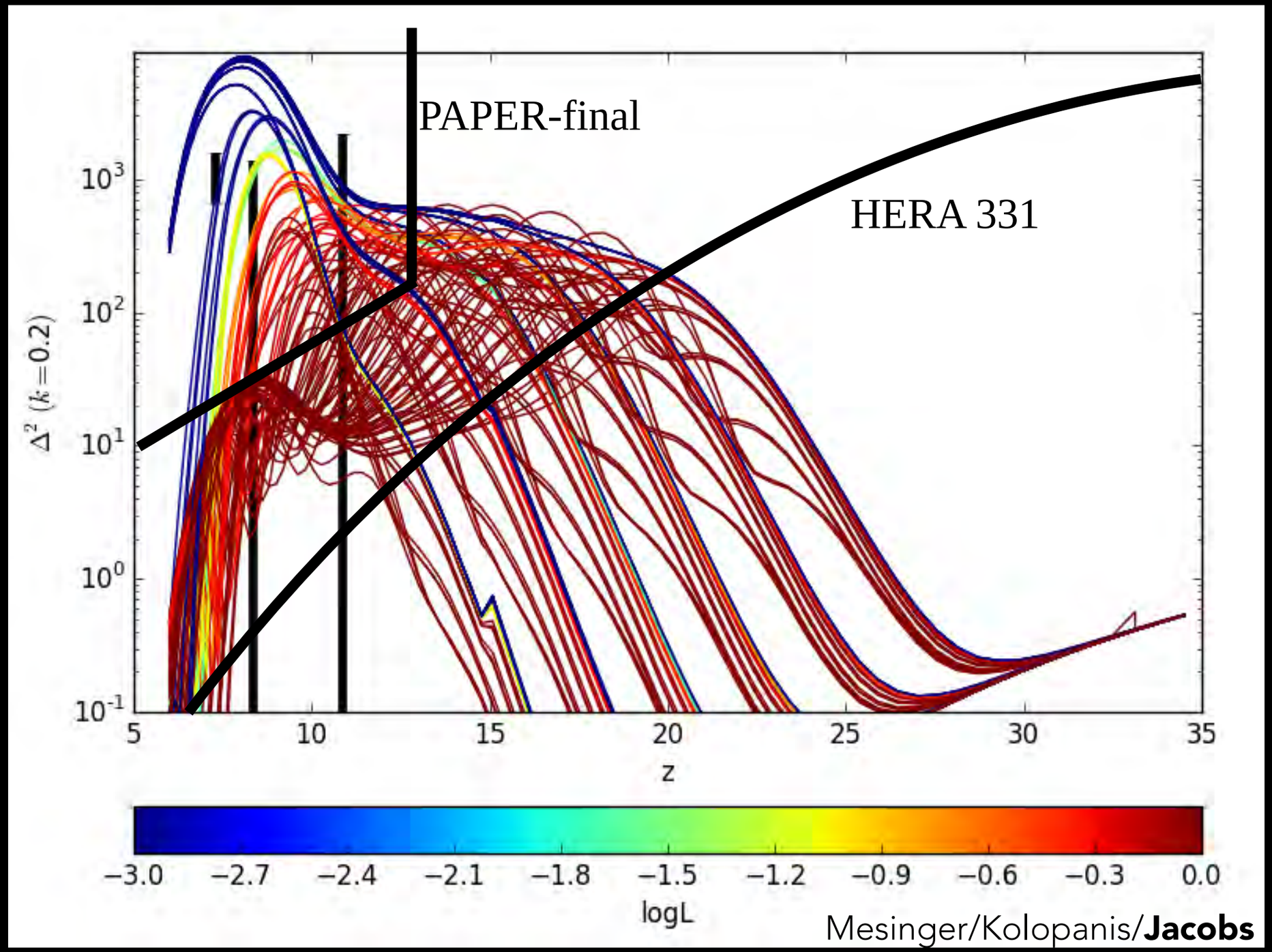
Instrume	SN
PAPER 128	1.56
MWA 128	0.66
LOFAR	0.70
HERA 37	5.67
HERA 331	38.75
MWA 256[a]	2.40
SKA1 Low[b]	21.23

Pober, HERA memo #4

2. Constrain global parameters of First Astrophysics

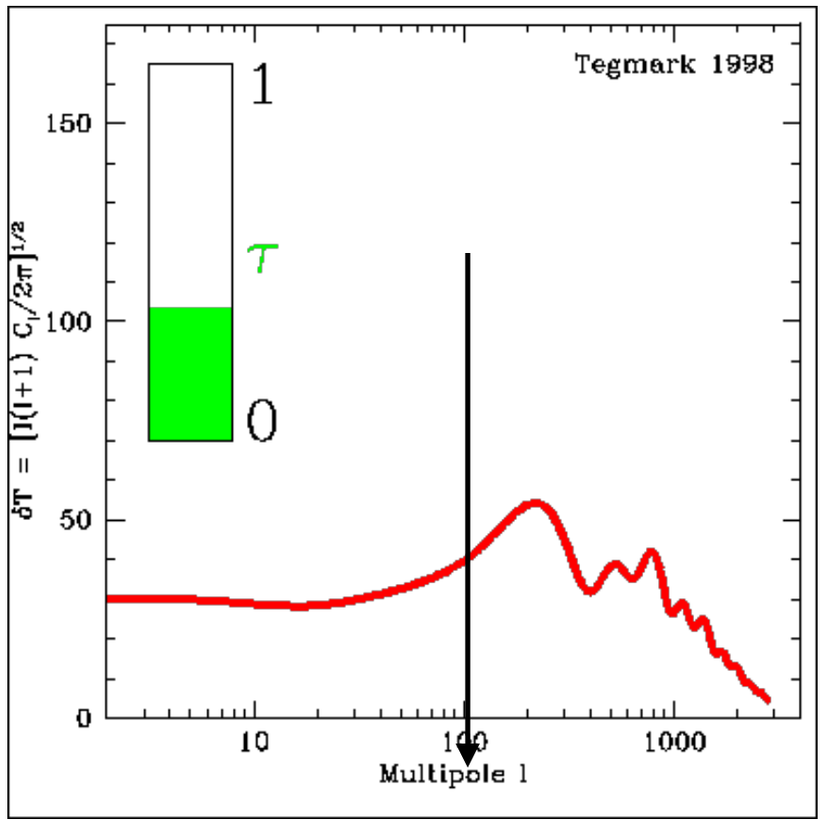


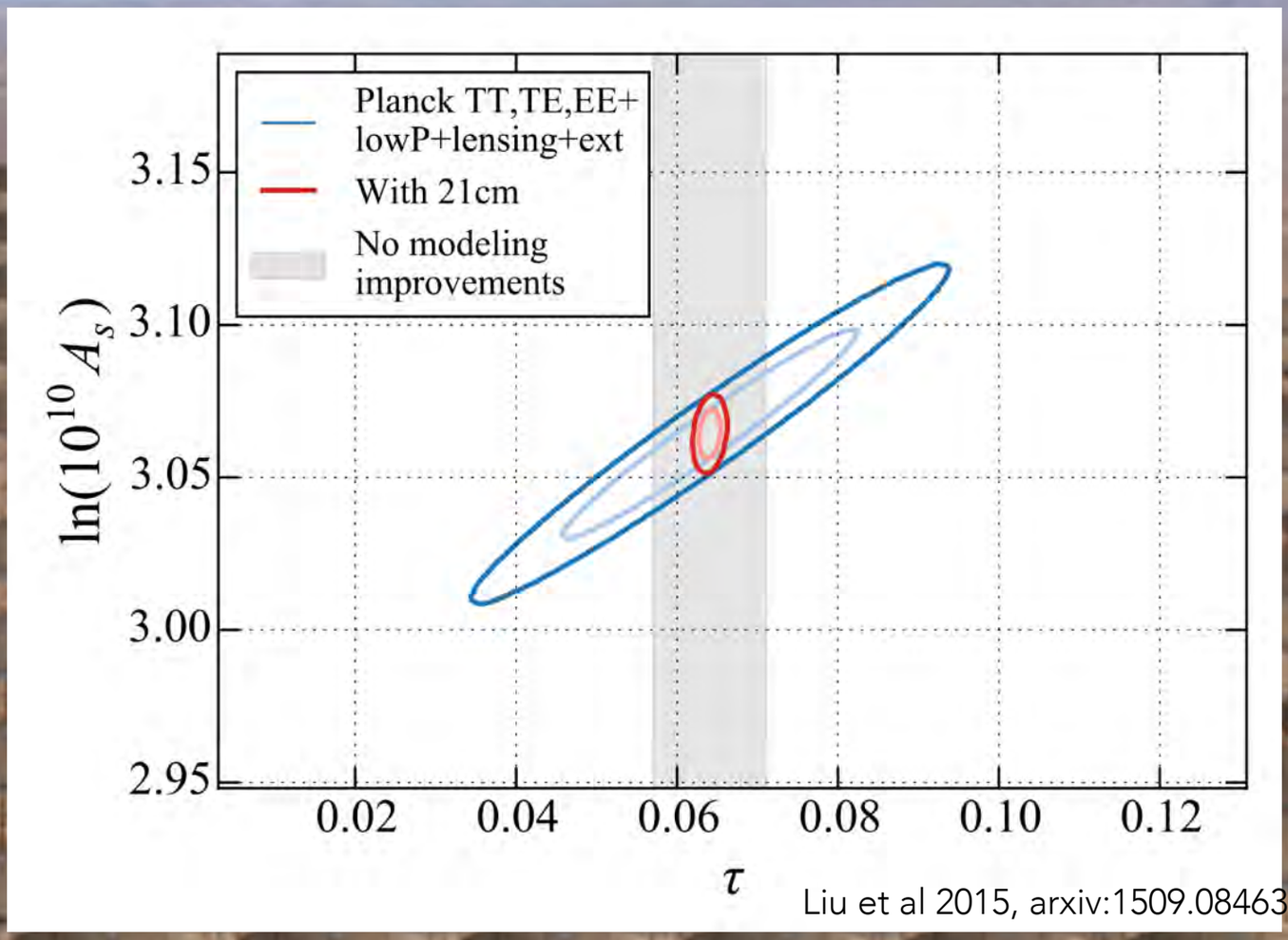
Grieg et al, 2015



Mesinger/Kolopanis/**Jacobs**

3. Direct measurement of CMB optical depth (tau)

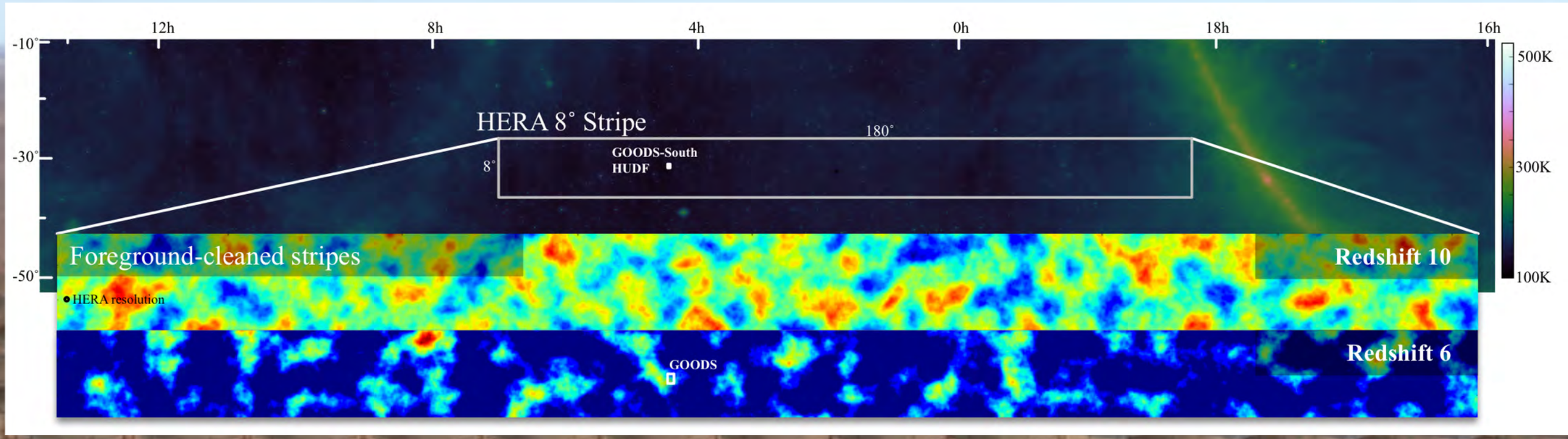




Liu et al 2015, arxiv:1509.08463

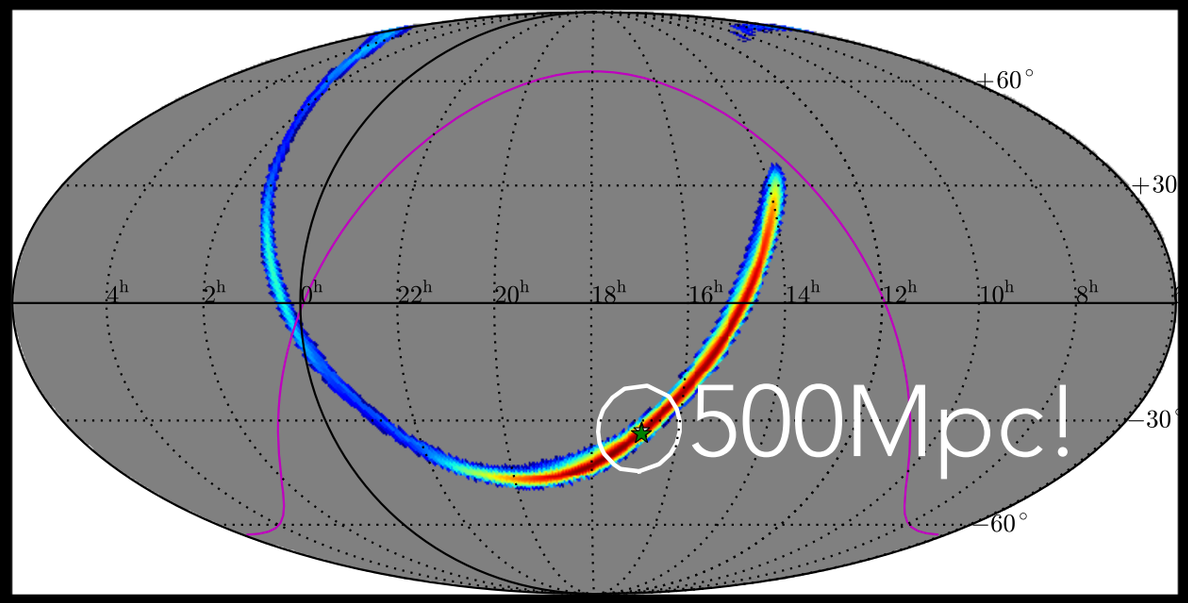
ERA

4. First true survey images suitable for cross-comparison

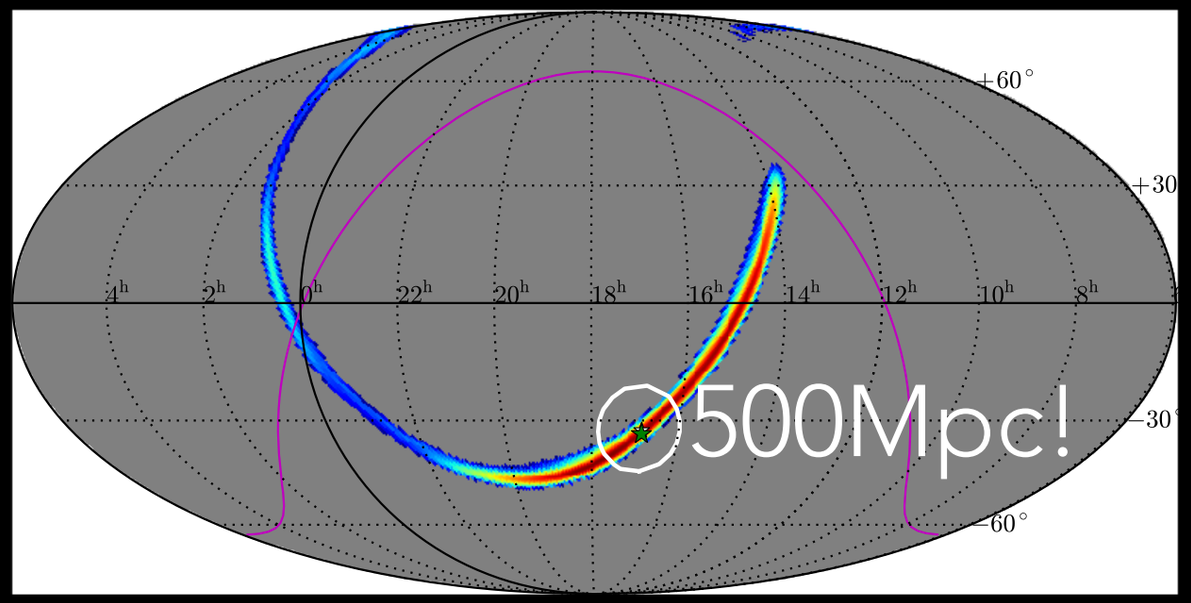


ERA

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)



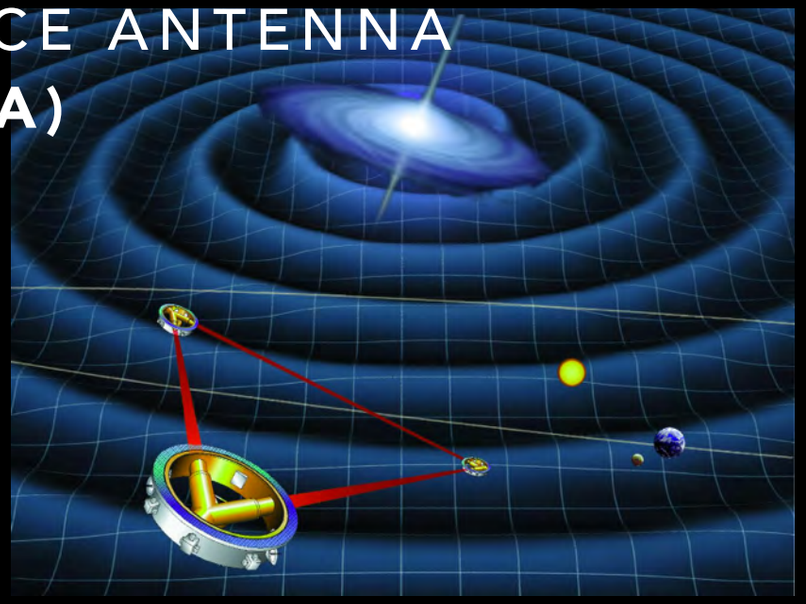
We can use inspirals as cosmological probes only if we associate the gravitational event with an electromagnetic counterpart.

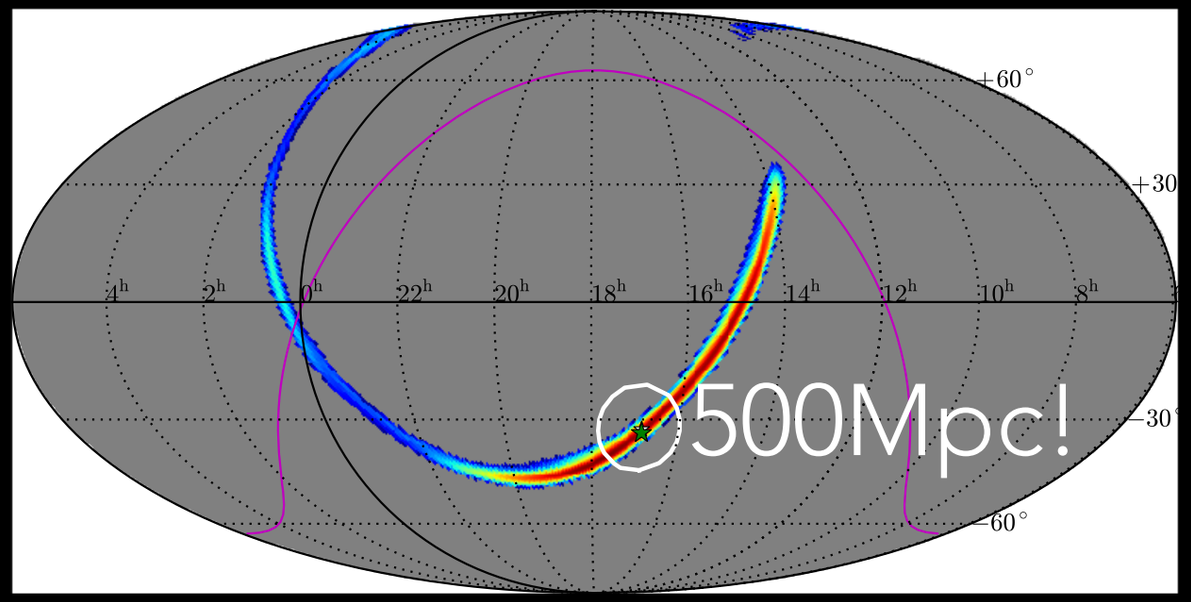


LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY **(LIGO)**

We can use inspirals as cosmological probes only if we associate the gravitational event with an electromagnetic counterpart.

LASER INTERFEROMETRIC SPACE ANTENNA **(LISA)**





LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

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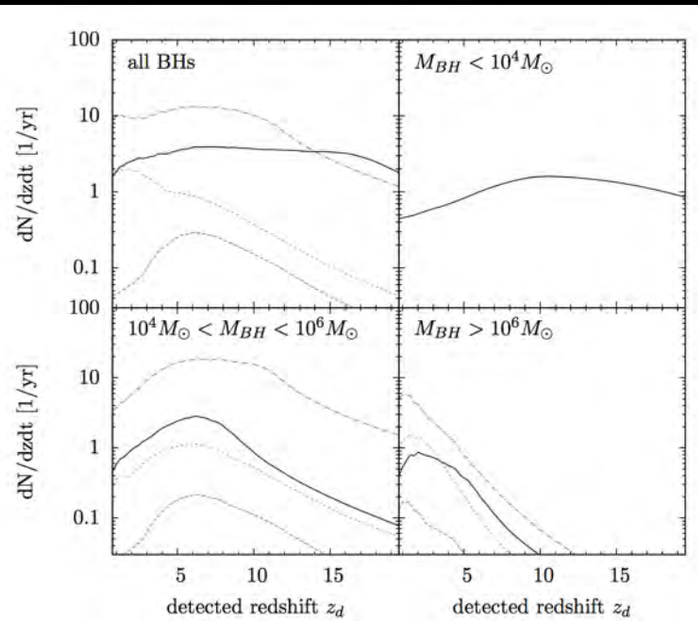
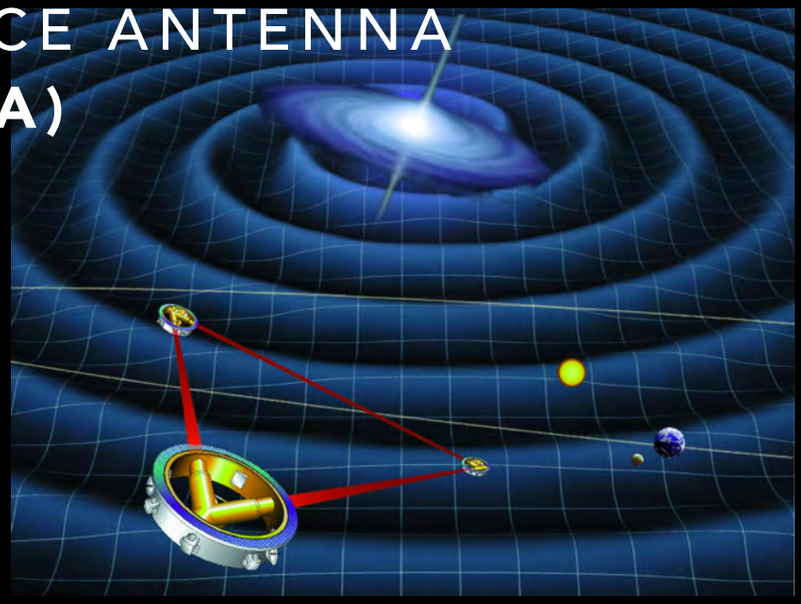


Plowman, **Jacobs**, et al 2010

LASER INTERFEROMETRIC SPACE ANTENNA (LISA)



A SECOND PROBE AT HIGH REDSHIFT!

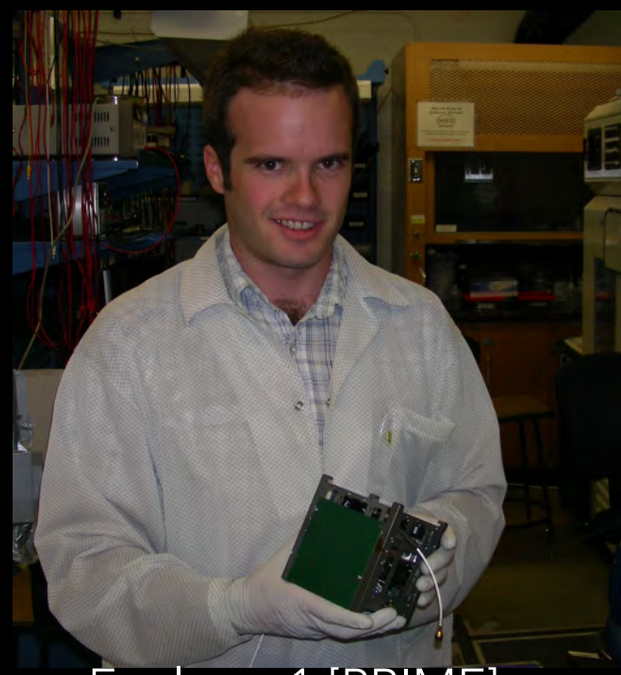
EXOPLANETS! CUBESATS!

SPARCS M-Dwarf activity monitor

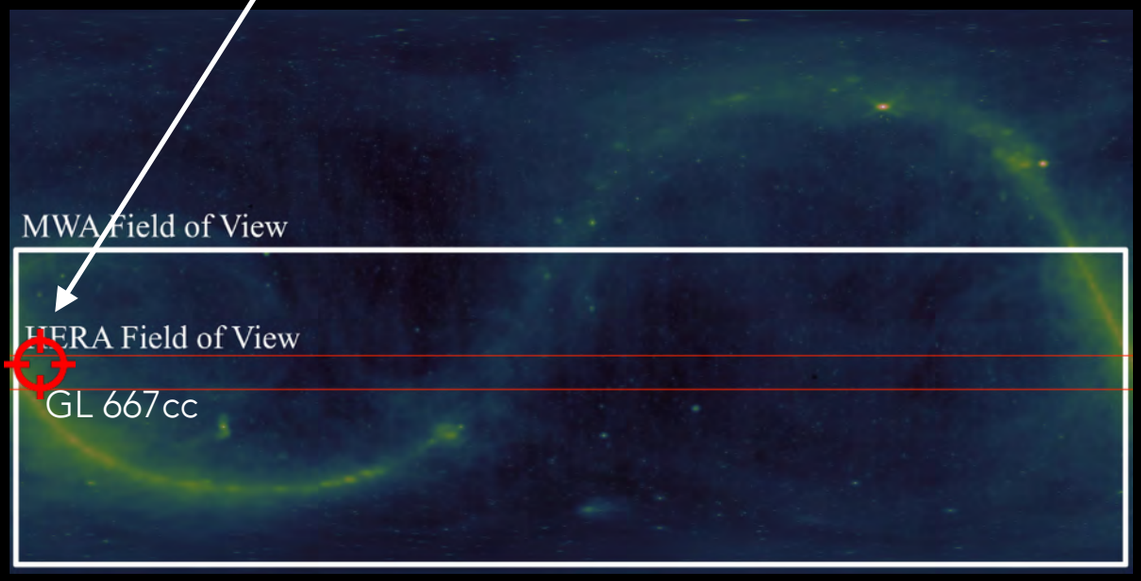
Planet around an active M-dwarf
Stellar activity drives the atmosphere

GL 667cc (artists conception)

6u cubesat, long term UV monitor



Explorer 1 [PRIME]
Launched October 2011,
Project Manager: D.Jacobs



HERA "Exo-Flares" search

Monitoring for Extrasolar stellar coronal mass ejections

HYDROGEN EPOCH OF REIONIZATION ARRAY

Parsons (UCB)
Aguirre (UPenn)
Bernardi (SKA-SA)
Bowman (ASU)
Carilli (NRAO/ Cambridge)
Furlanetto (UCLA)
Hewitt (MIT-Kavli)
Jacobs (ASU)
Loeb (Harvard)
Pober (Brown)
Sievers (UKZN)

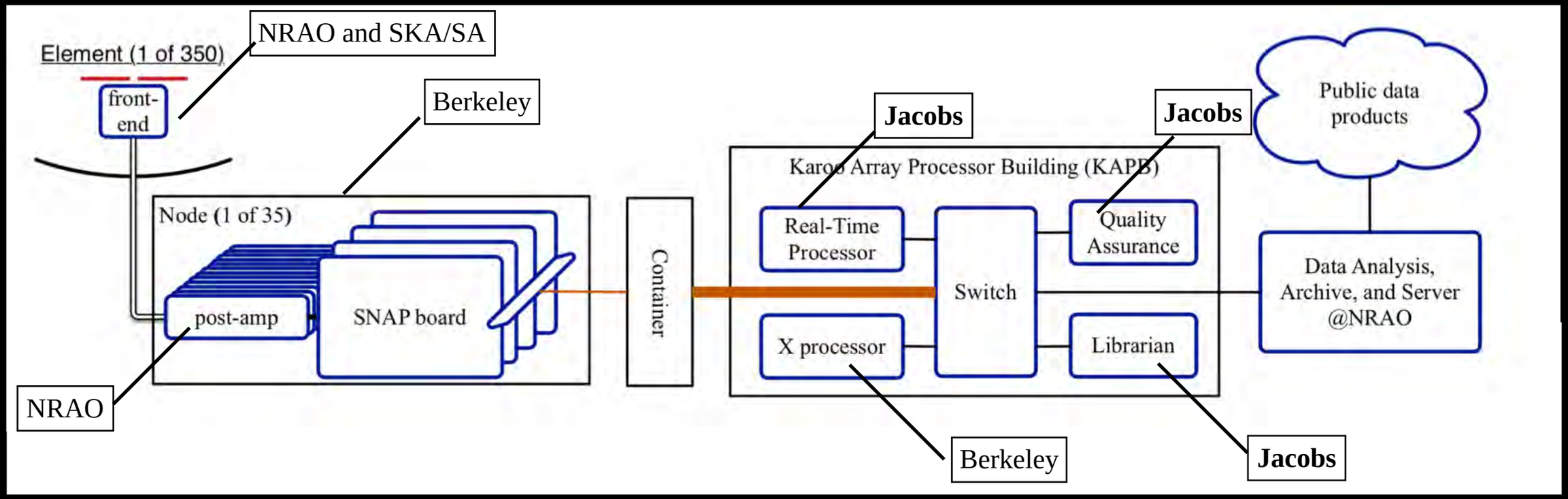
REIONIZATION.ORG

JACOBS LAB HERA RESPONSIBILITIES

Data archive: 1.5 PB of storage, autonomously managed

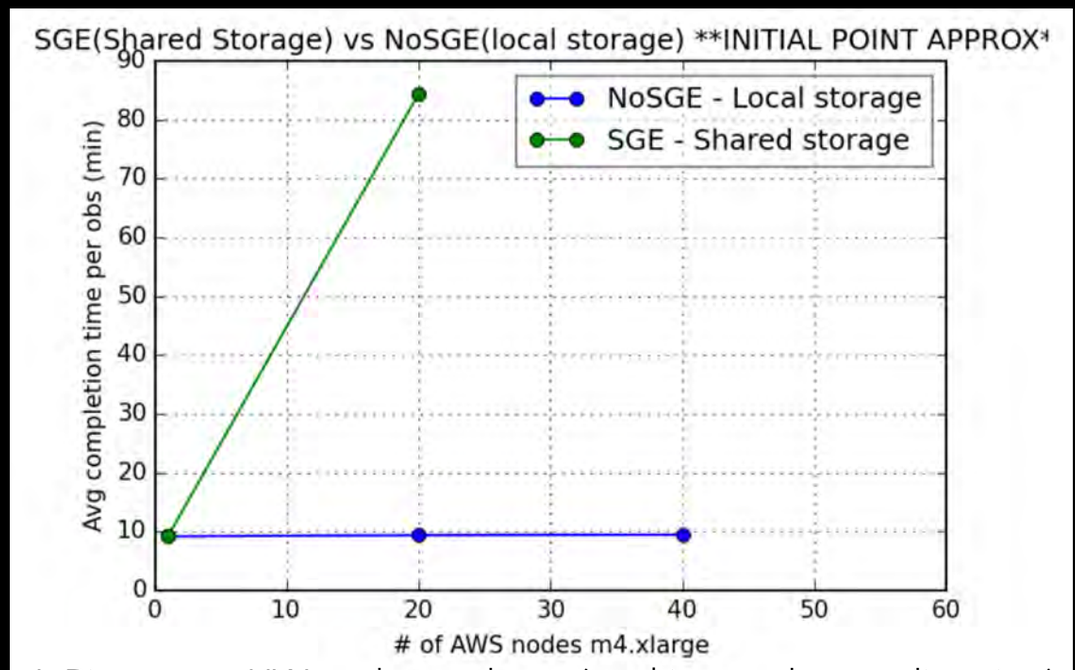
Online processing: executes automated calibration workflow in the field

- Builds on successful PAPER and MWA deployments
- ~15 node, 200 disk system
- Custom python-based software stack
- Cluster built in US, deployed on site

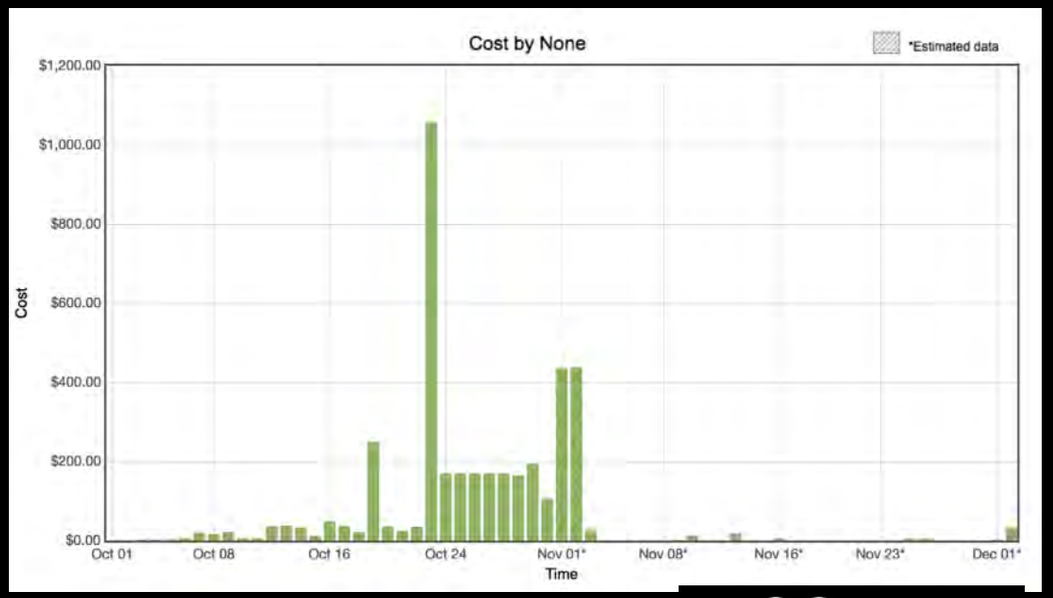


ACCELERATED OFFLINE ANALYSIS

- widefield imaging/foreground subtraction is under heavy development
- needs testing on a large amount of data
- typical run: 50TB of data in ~6 weeks on dedicated cluster
- with Amazon/XSEDE burst resources, same run ~**48 hours**
- Developed AstroTaskr for portable workflow execution https://github.com/HERA-Team/still_workflow



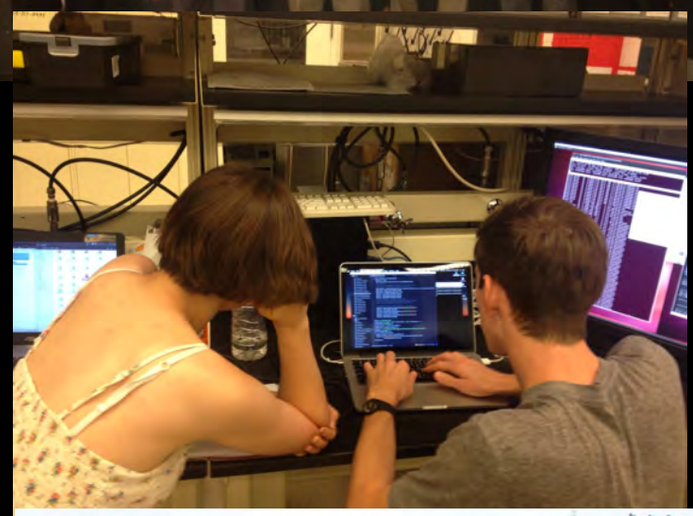
J. Ringuette, UW undergraduate (working under my direction)



supported by: amazon web services™

CURRENT/UPCOMING JACOBS LAB PROJECTS

- Instrument simulation (PRISim)
  Thyagarajan, Jacobs et al 2015a,b and Jacobs, et al, 2015
- ECHO #3 construction, lab characterization
- ECHO mapping of HERA, extension to CHIME, LWA, HYRAX, et al. (field work)
- HERA analog signal chain characterization
  ala HERA memo #10, Jacobs et al 2015
- HERA online systems
  processing cluster, deploy on site, commissioning and operations
- HERA commissioning analysis,
  Jacobs, et al 2010, Jacobs et al 2014, Kolopanis et al 2016
- cloud data processing
  Jacobs, et al 2016



BIG PICTURE INSTRUMENT TIMELINE

- HERA construction (2016-2019)

- MWA upgrade
  Phase II: 2016-2018 antenna doubling
  Phase III: 2018-2020 x6 increase in bandwidth

- SKA Phase Low: Phase I (construction start ~2018)

Thank you!

AMPLIFIER CHARACTERIZATION AND IMPROVEMENT

2014

2016

ANALOG SIGNAL CHAIN VERIFICATION

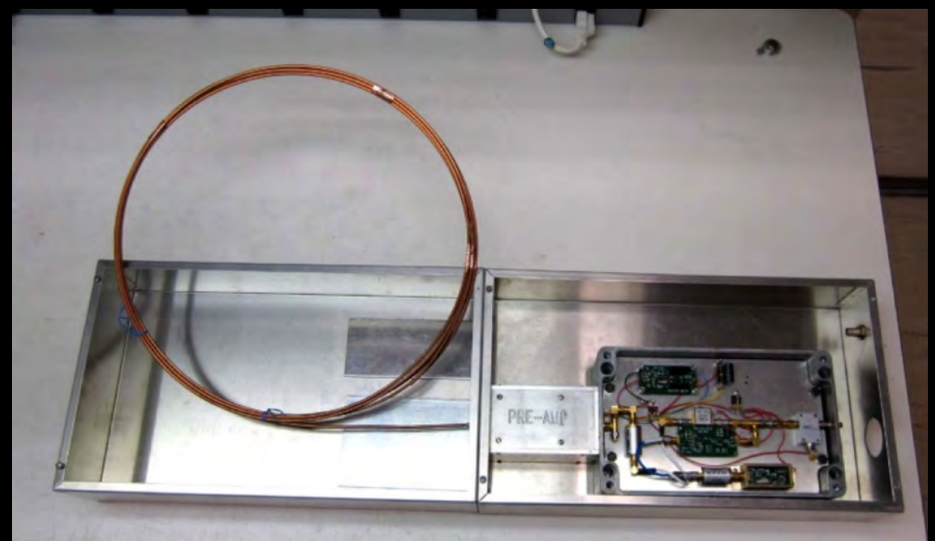
- System Temperature

(HERA memo #10, Jacobs et al 2015)

- Cross-coupling and reflections

Jacobs et al 2011

EDGES Absolute Calibration with "Sky Simulator"
(curtesy Alan Rogers,MIT and Judd Bowman,ASU)



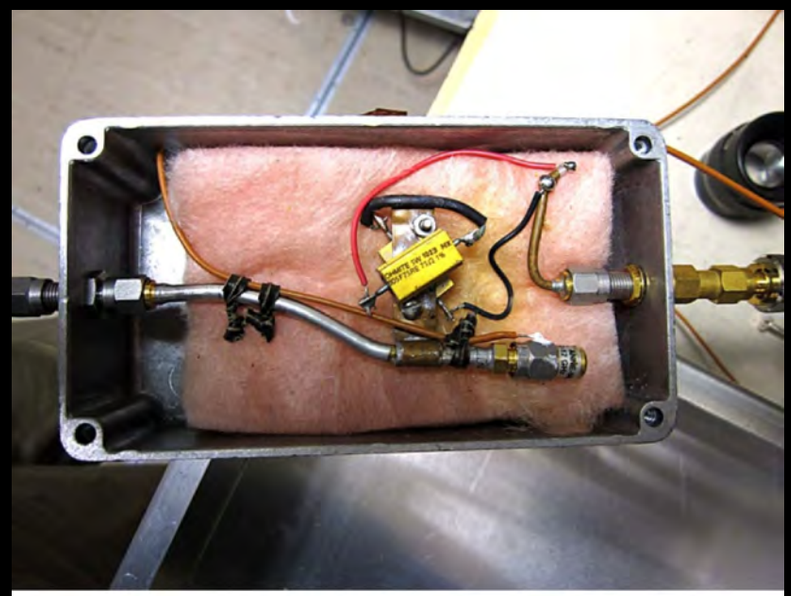
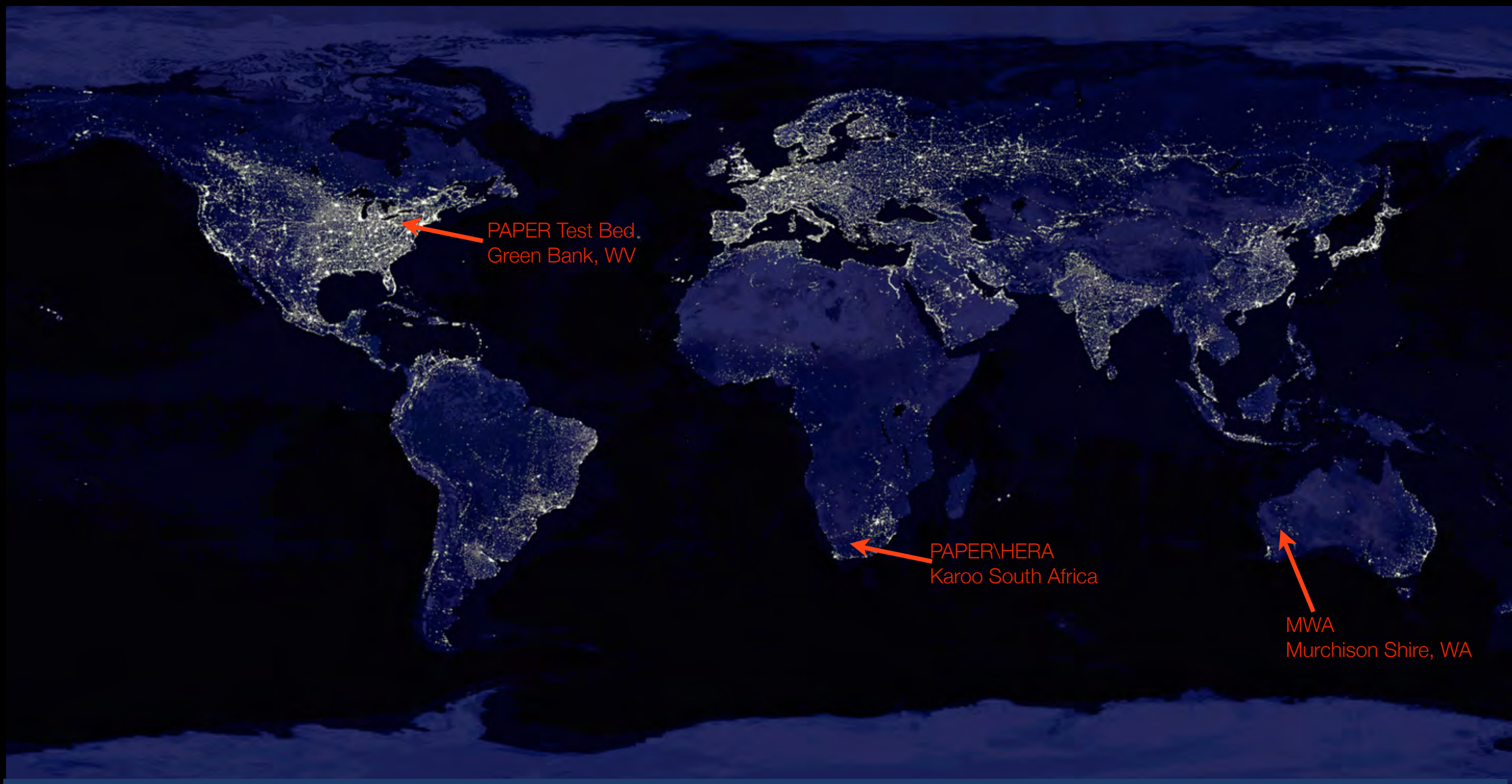


Fig. 1C. Hot/Cold load

RADIO FREQUENCY INTERFERENCE

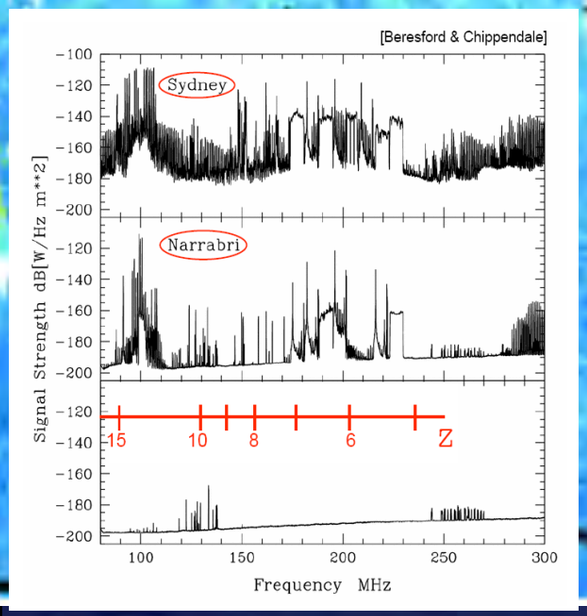


RADIO FREQUENCY INTERFERENCE

PAPER Test Bed
Green Bank, WV

PAPER
Karoo South Africa

MWA
Murchison Shire, WA

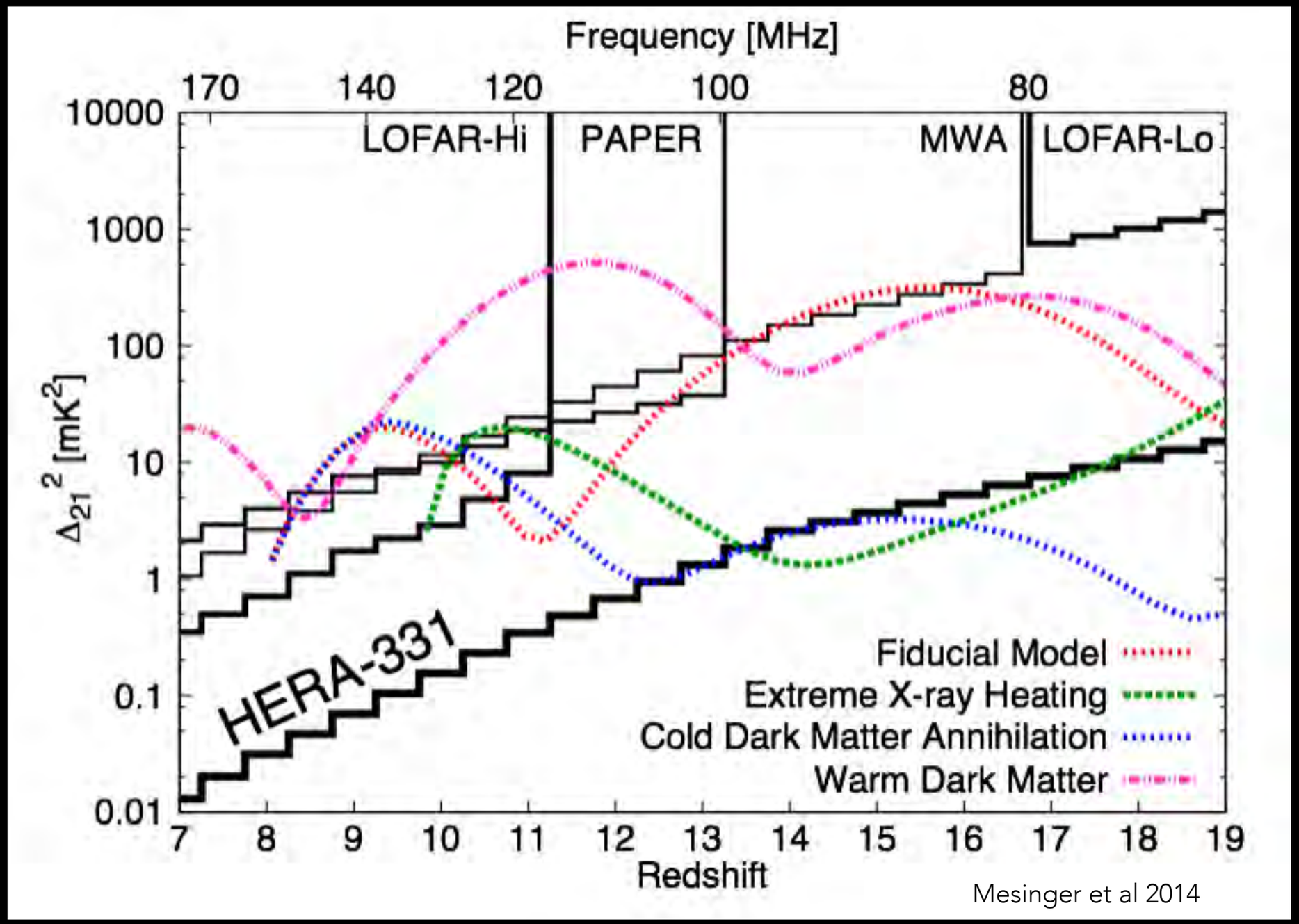



MWA
Murchison
Radio-astronomy
Observatory
Western
Australia
800km
Perth
Armadale
Rockingham
Mandurah
Bunbury
Busselton
Albany


Richtersveld
National Park
Upington
Kimberley
Kroonstad
Welkom
Bloemfontein
Maputsoe
Maseru
Mafeteng
Mohale's
Hoek
Reinvasmaak
Community
Conservancy
PAPER/HERA
South
Africa
575 km
Addo Elephant
National Park
Graaff-Reinet
Cape Town
Port
Elizabeth
Cape Town

DARK AGES AND BEYOND

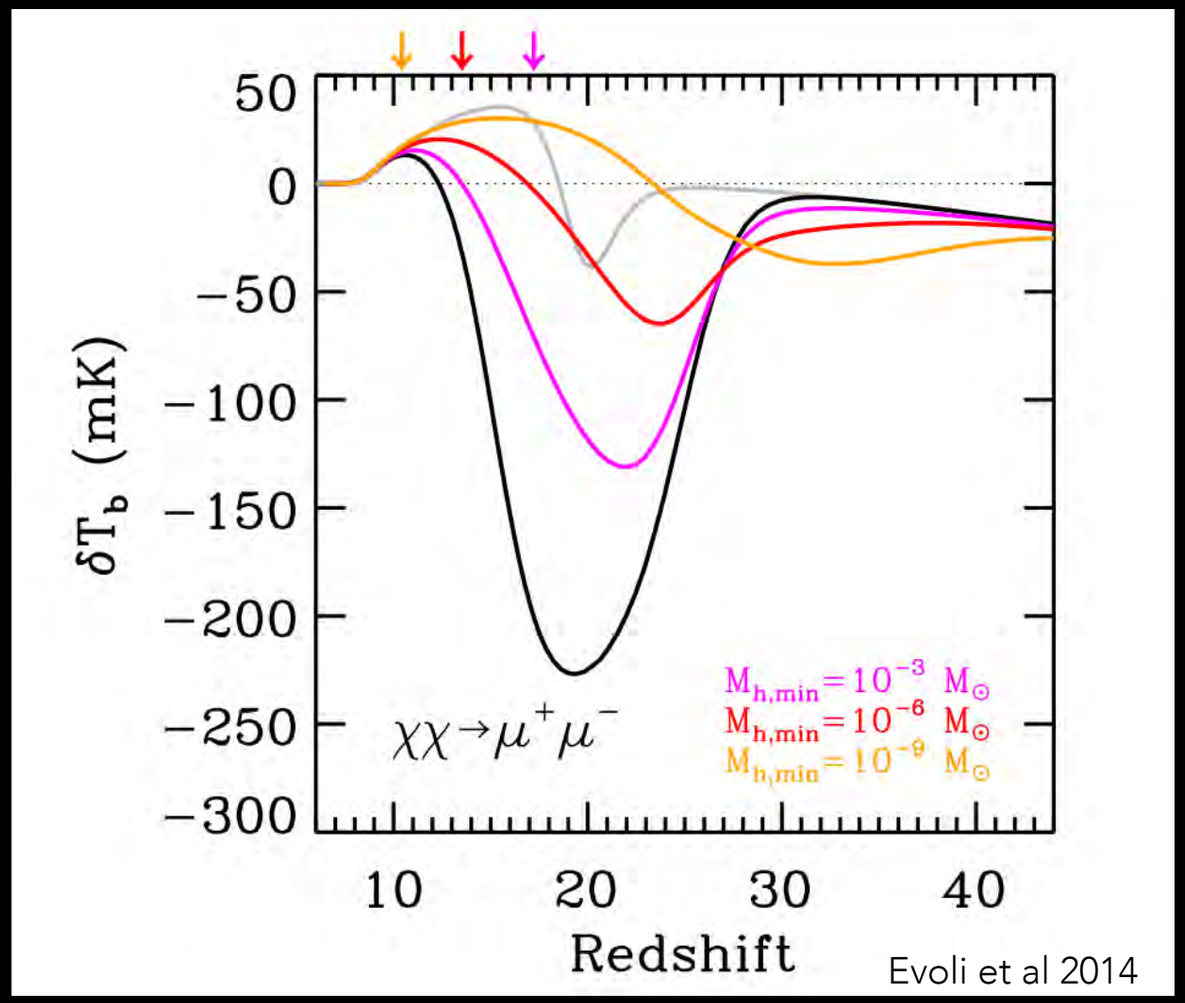
DARK AGES: DARK MATTER



Mesinger et al 2014

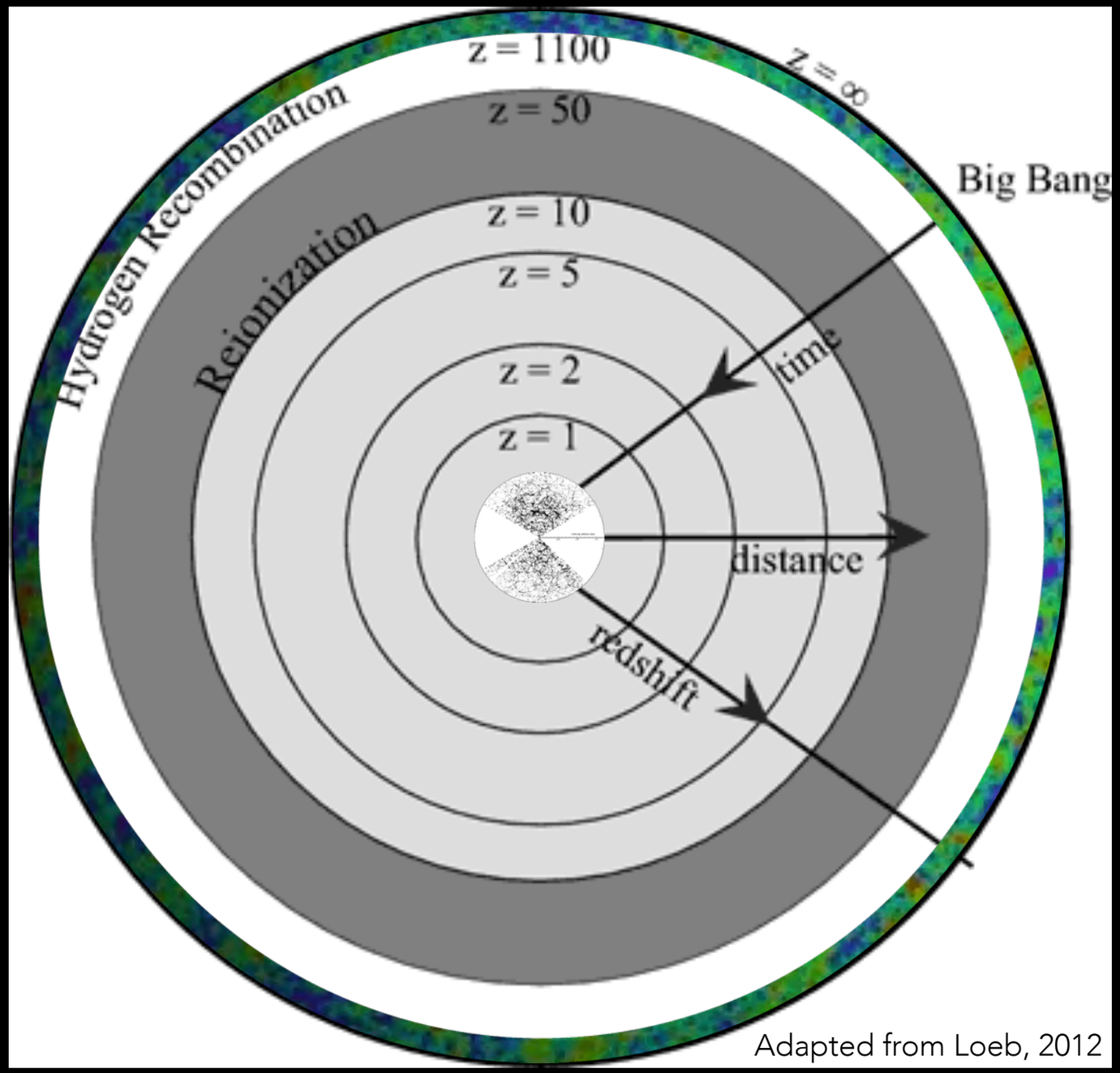
DARK AGES: DARK MATTER

Cross section drives power spectrum



Evoli et al 2014

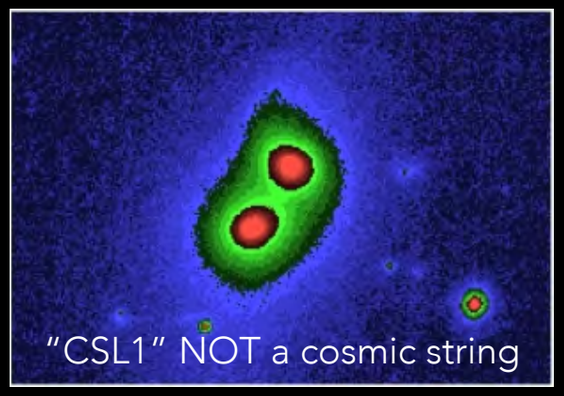
21 CM OPENS 10^12 MORE MODES



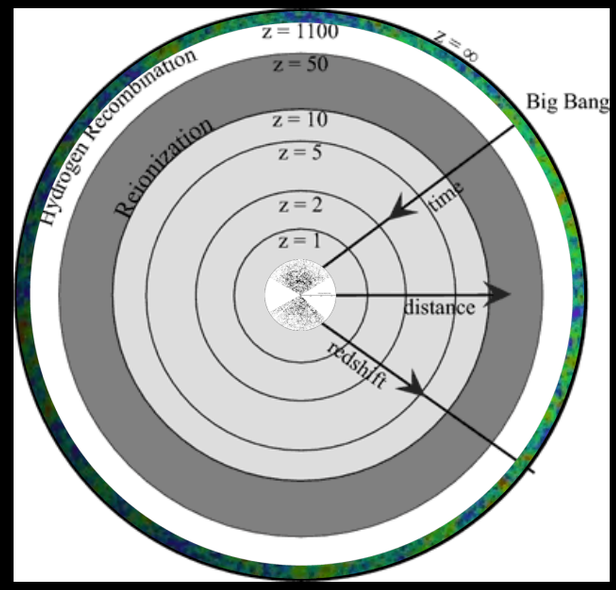
Adapted from Loeb, 2012

21 CM OPENS 10^12 MORE MODES

Cosmic Strings
Pagano and Brandenberger, 2012



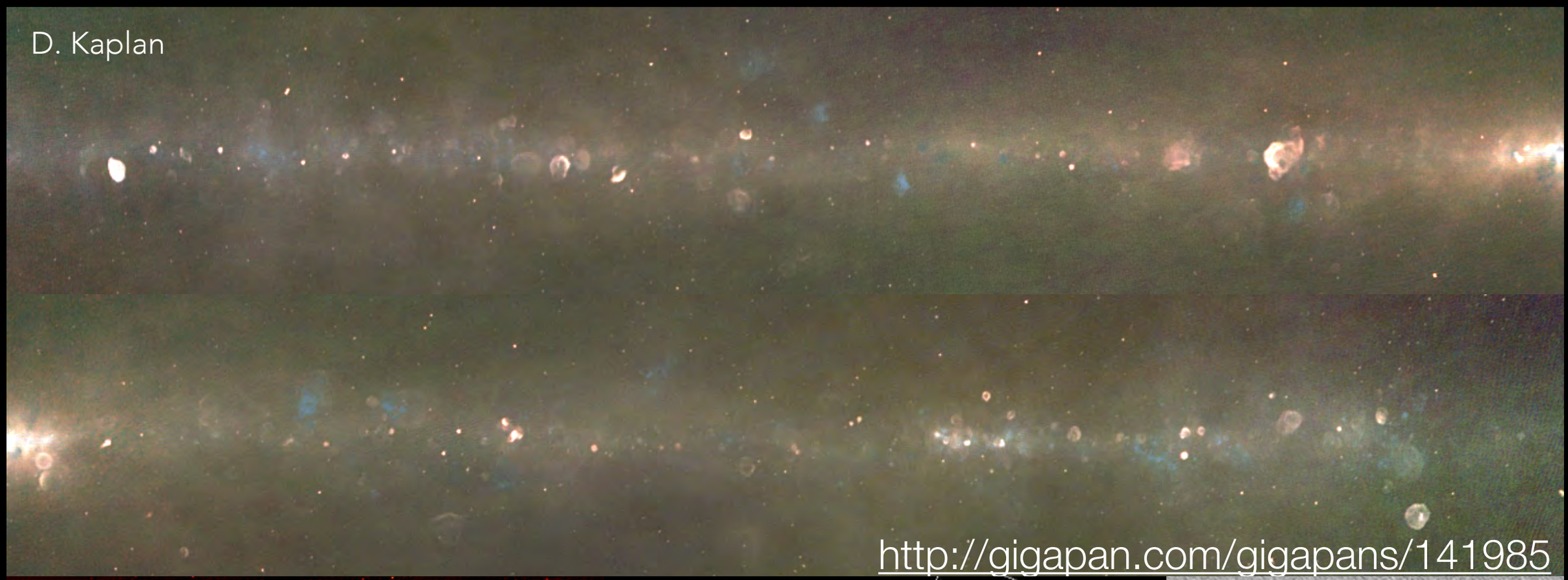
Primordial Non-gaussianity
Joudaki et al 2011



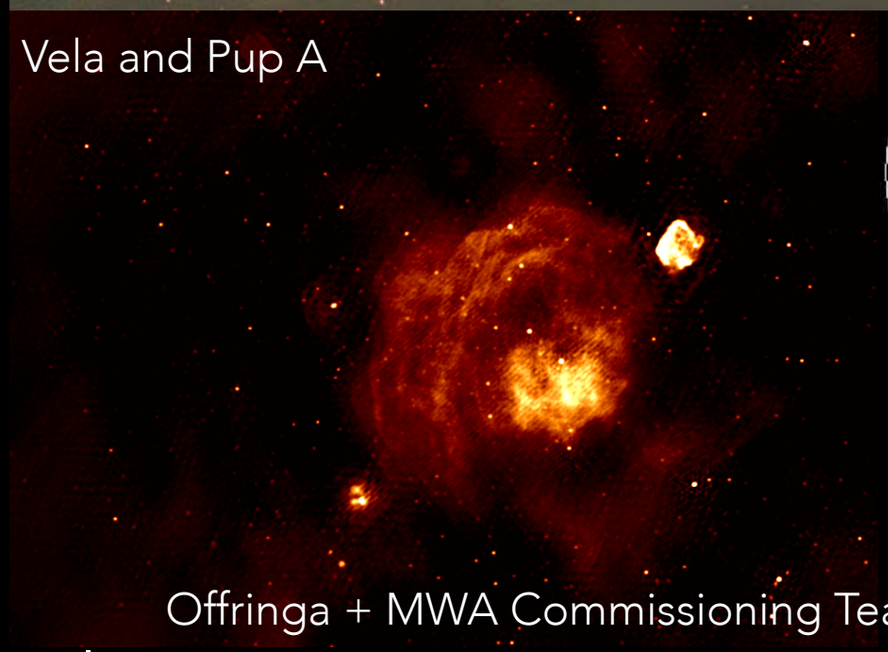
Adapted from Loeb, 2012

MWA SCIENCE

80 degrees

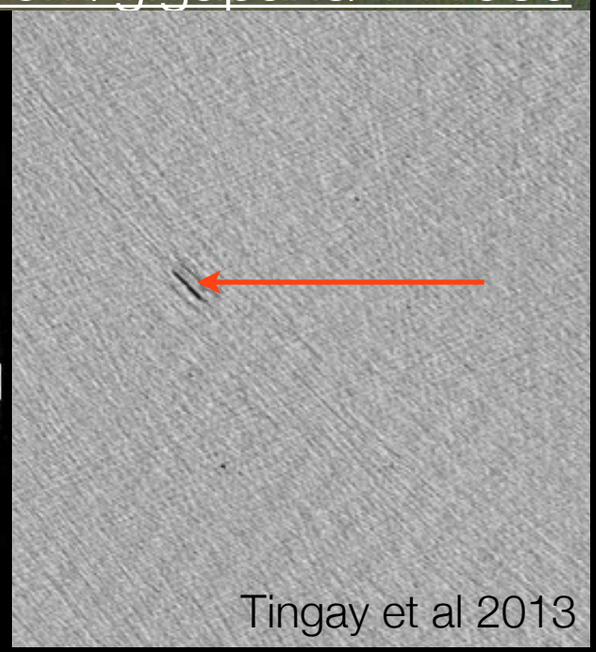


http://gigapan.com/gigapans/141985



Offringa + MWA Commissioning Team

Oberoi, et al 2013

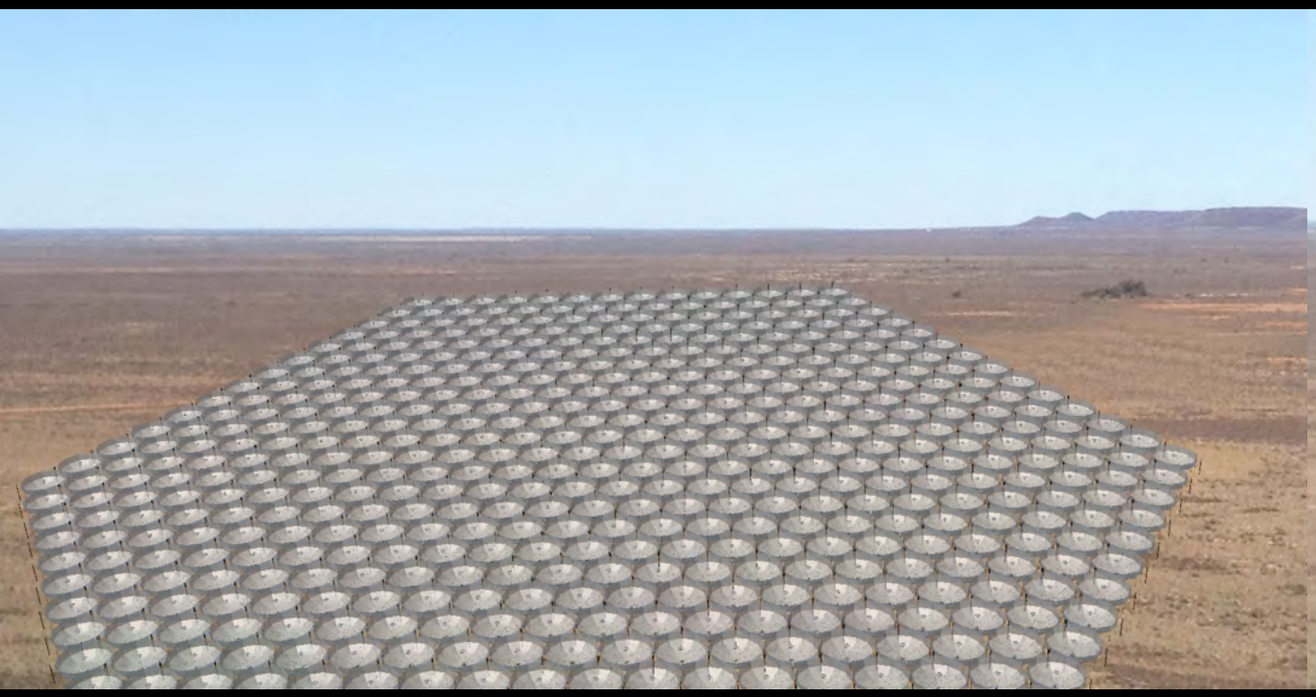


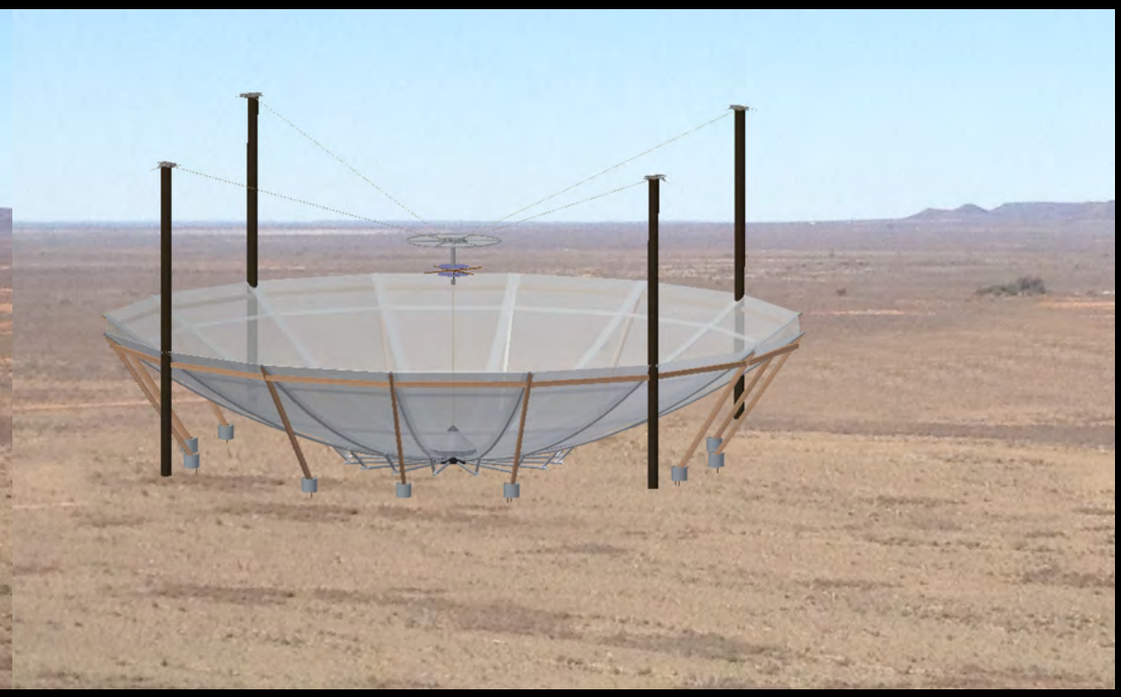
Tingay et al 2013

mwatelescope.org

HYDROGEN EPOCH OF REIONIZATION ARRAY

- 14m transit dish, 331 element array
- PAPER feed
- MWA-type node architecture
- Fast focus minimizes chromaticity
- Joint MWA - PAPER enterprise
- 0.1 km^2





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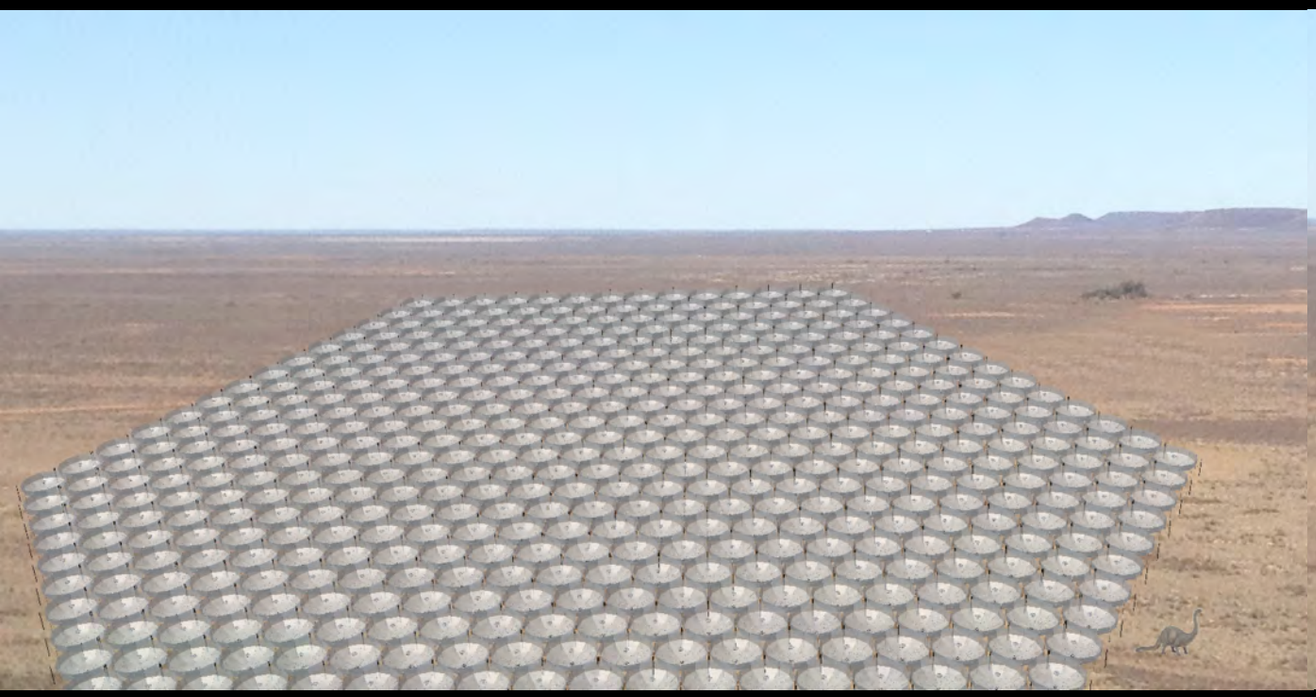
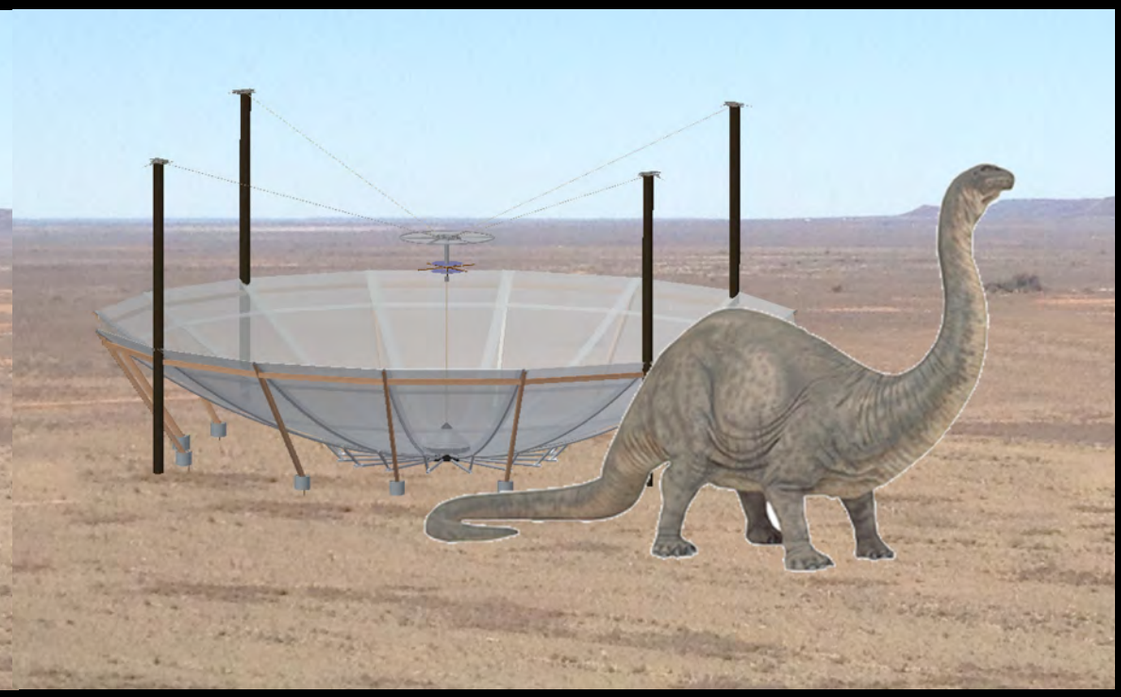
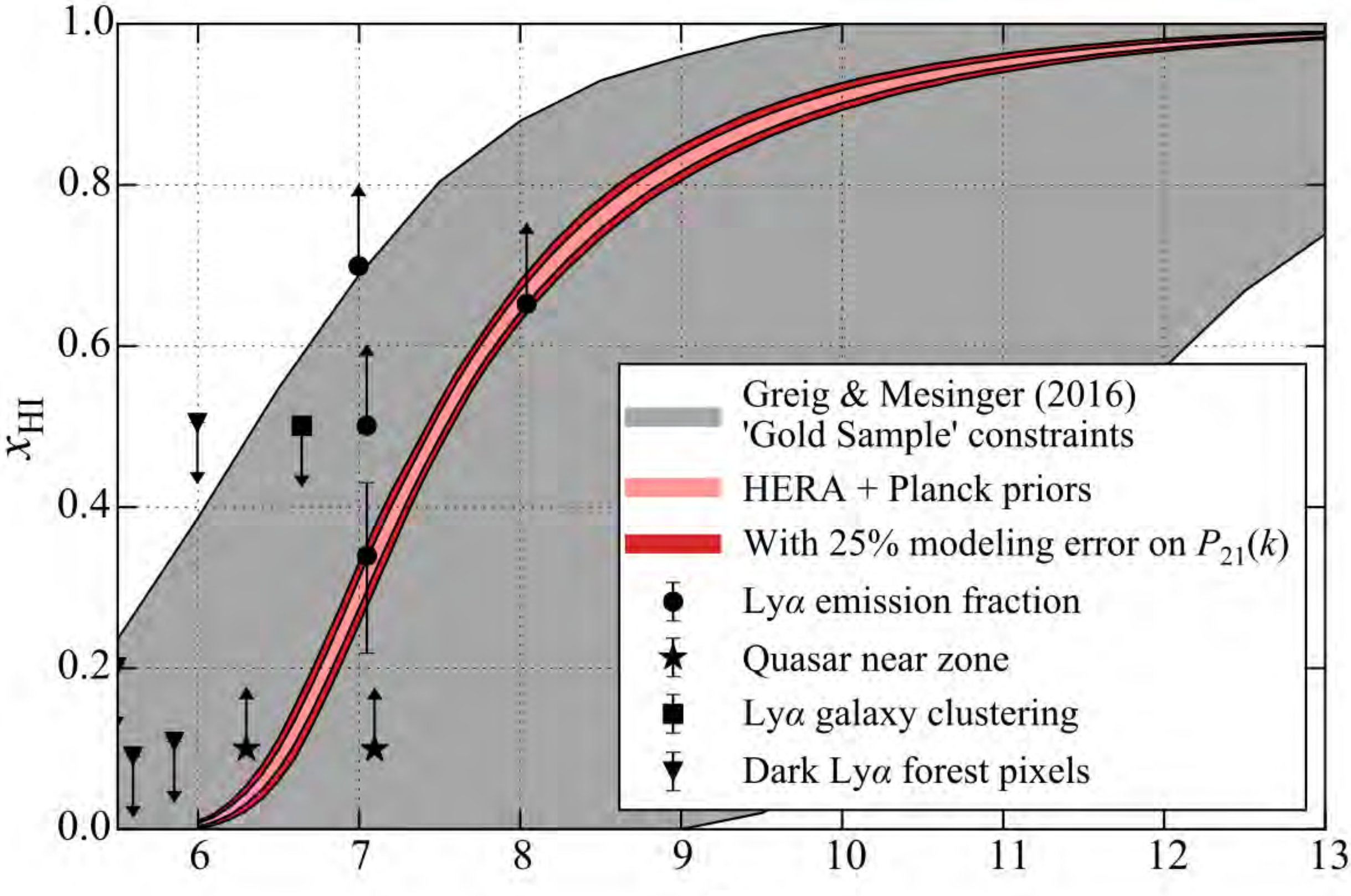
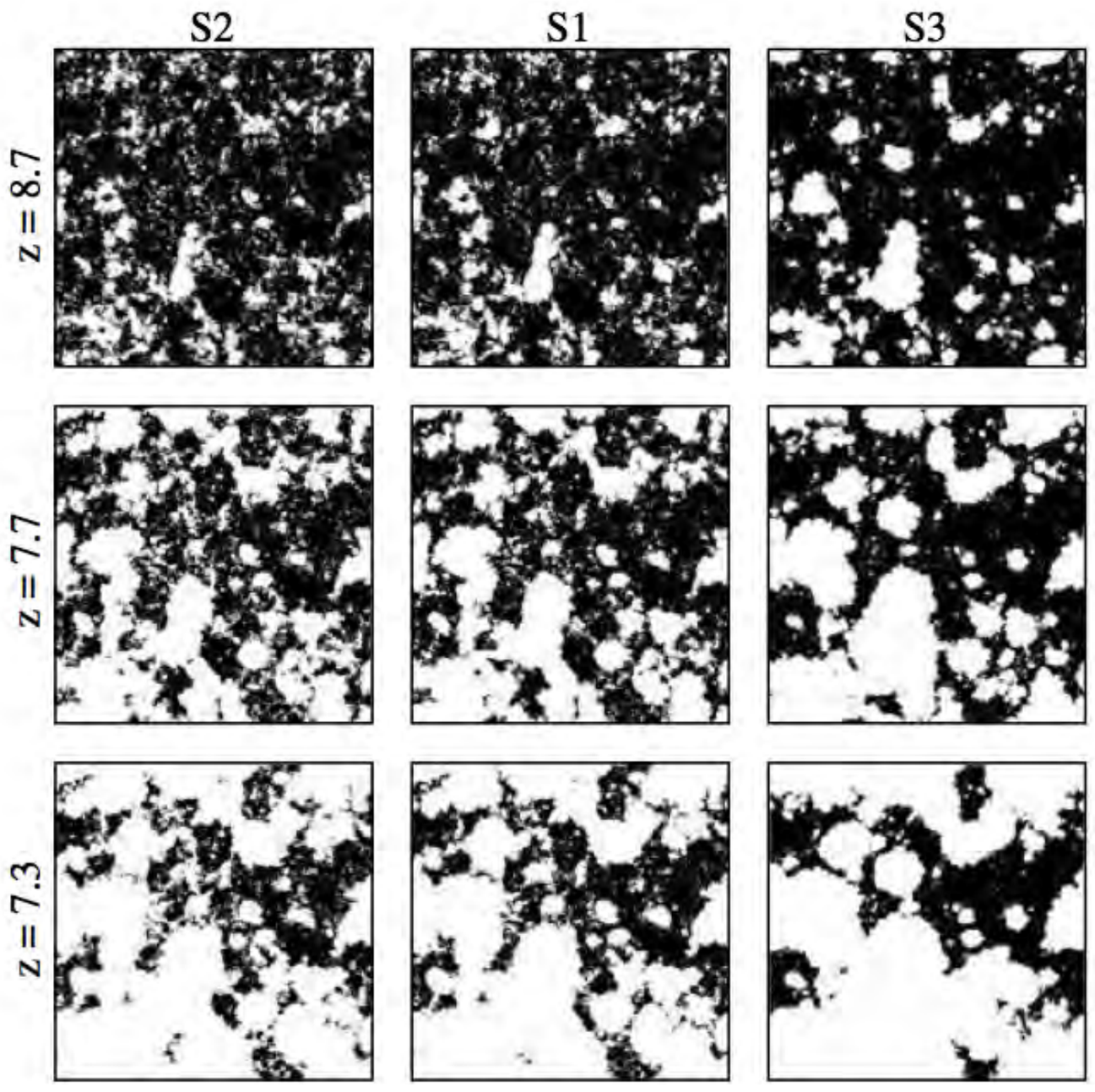





1.0
0.8
0.6
0.4
0.2
0.0
$x_{\rm HI}$
6
7
8
9
10
11
12
13
z
Greig & Mesinger (2016)
'Gold Sample' constraints
HERA + Planck priors
With 25% modeling error on $P_{21}(k)$
Lyα emission fraction
Quasar near zone
Lyα galaxy clustering
Dark Lyα forest pixels

imaging

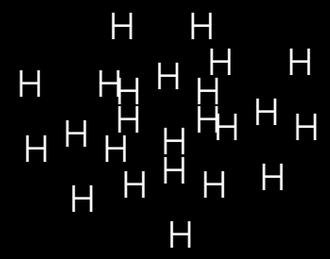
- signal amplitude ~20mK
- first generation sensitivity: 80mK
- SKA sensitivity: 4mK
- near future: **statistical measures**

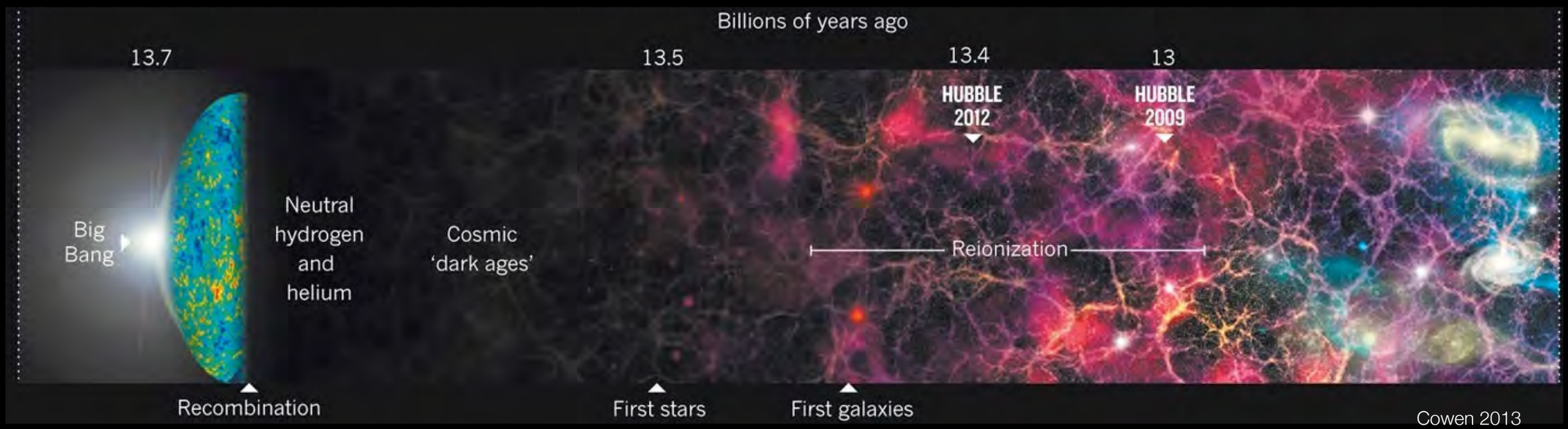


McQuinn ea 2007 MNRAS 377

CMB photons recombined Hydrogen

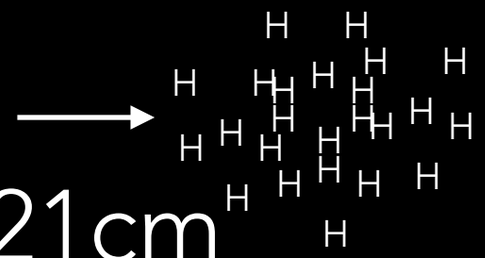
2 mm



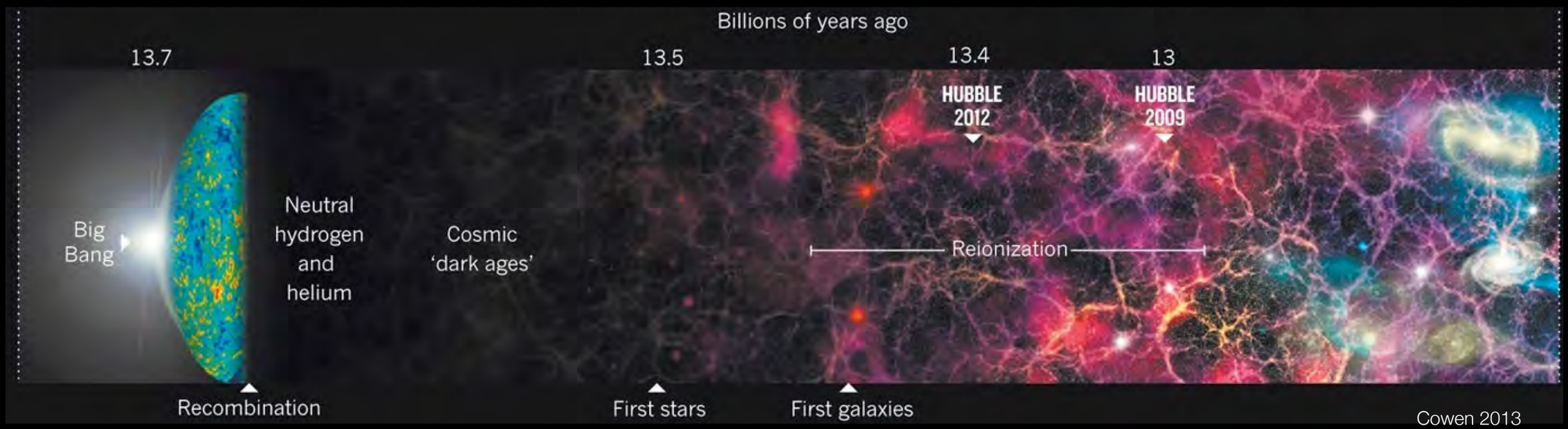


320kya — 500Mya — Now

recombined Hydrogen



21cm



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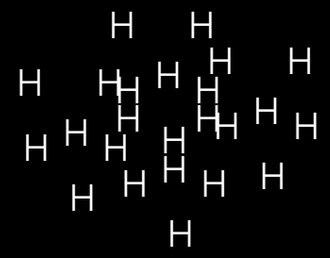
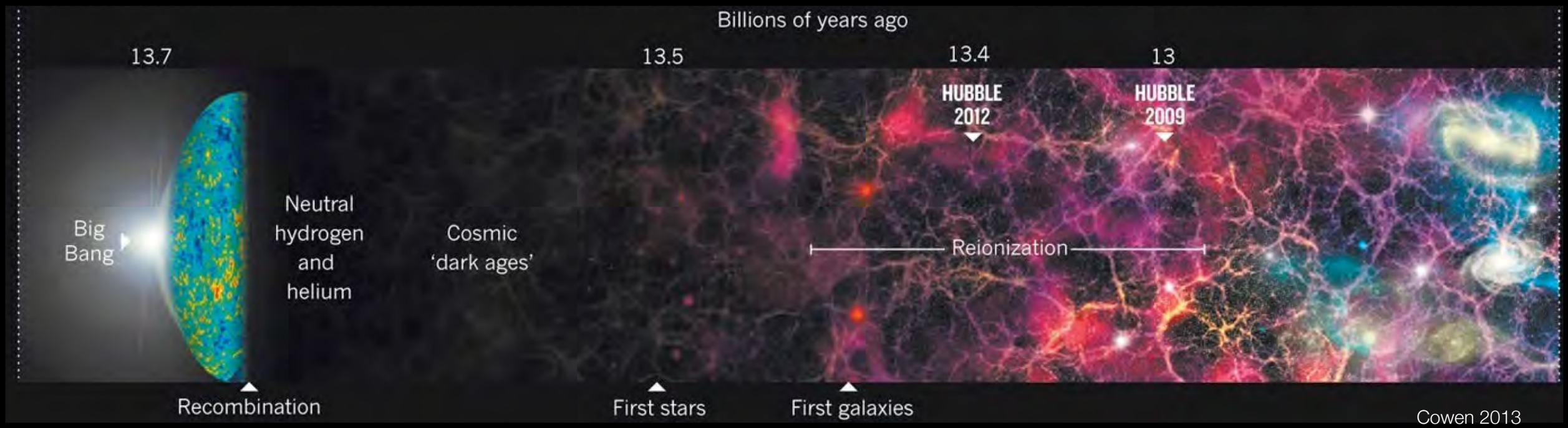


~3m



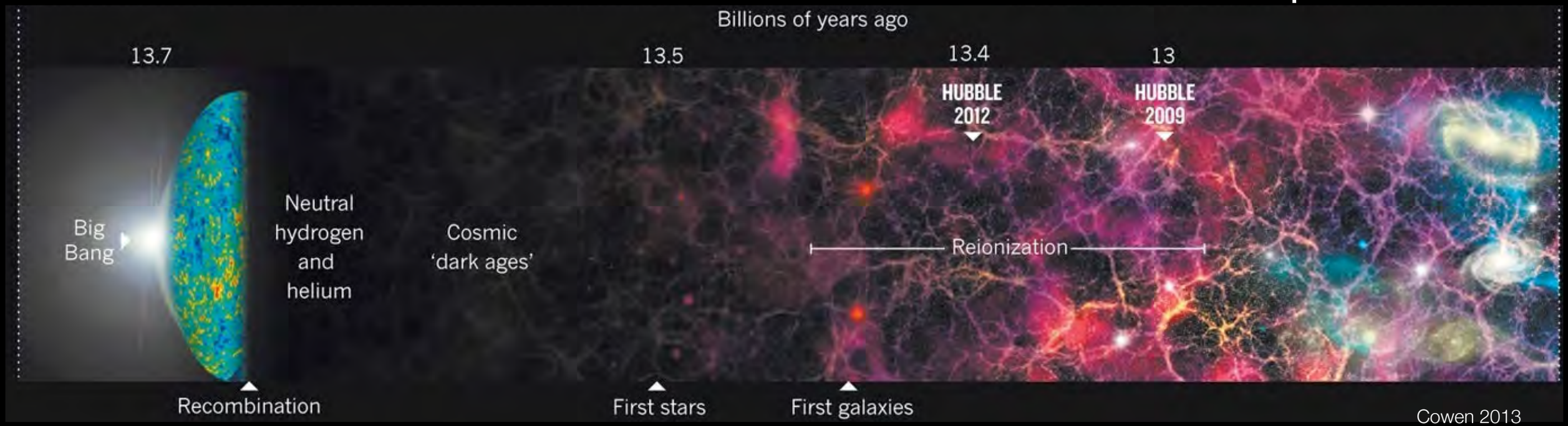
ionization fraction

matter density

$$T_b = 27 x_{\rm HI} \left(1 + \frac{4}{3}\delta_b\right) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2} \times \left(\frac{T_S - T_\gamma}{T_S}\right) {\rm mK},$$

CMB Temp

H temperature



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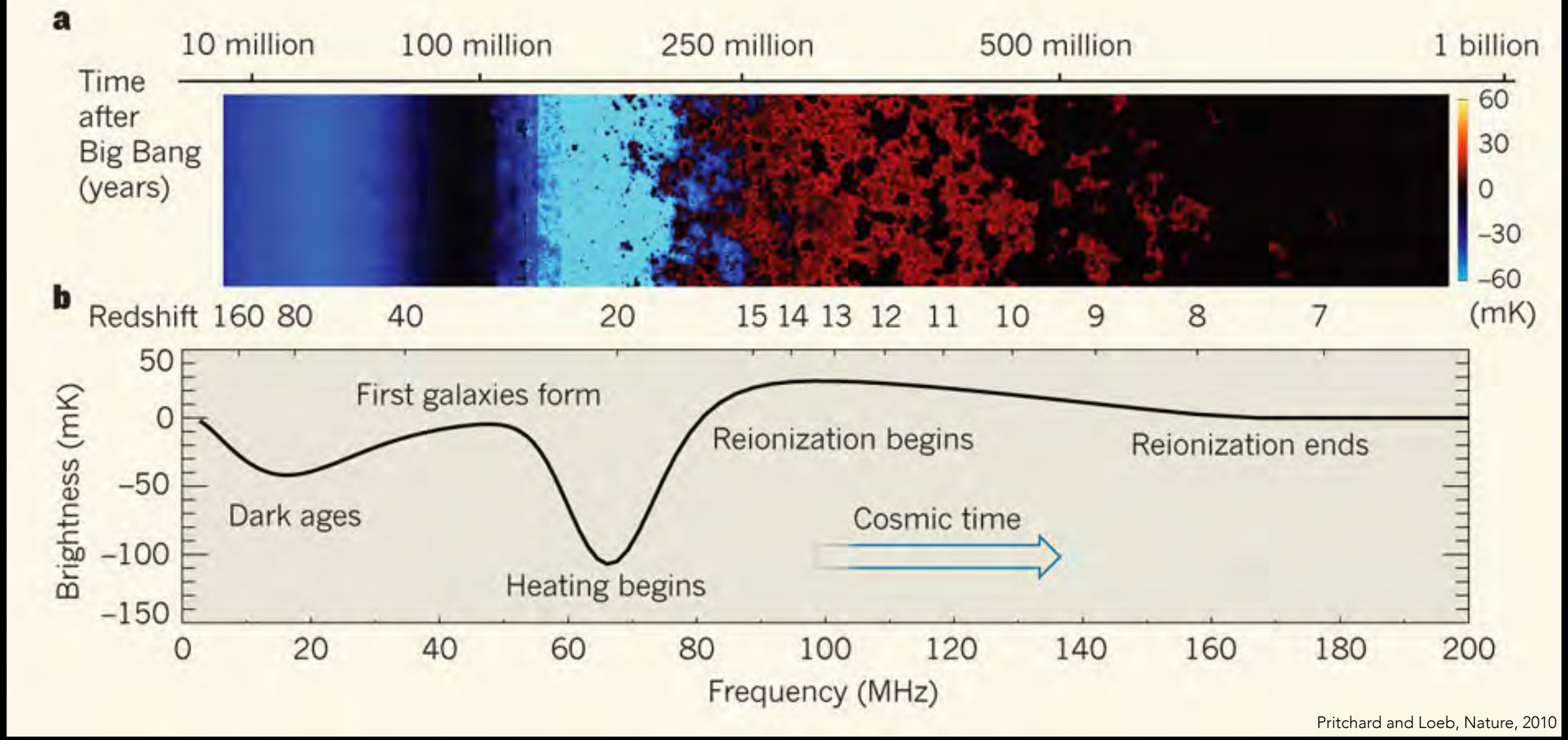
Pritchard and Loeb, PrD, 2008



Pritchard and Loeb, Nature, 2010

$$T_b = 27 x_{\rm HI} \left(1 + \frac{4}{3}\delta_b\right) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2} \times \left(\frac{T_S - T_\gamma}{T_S}\right) \text{mK},$$

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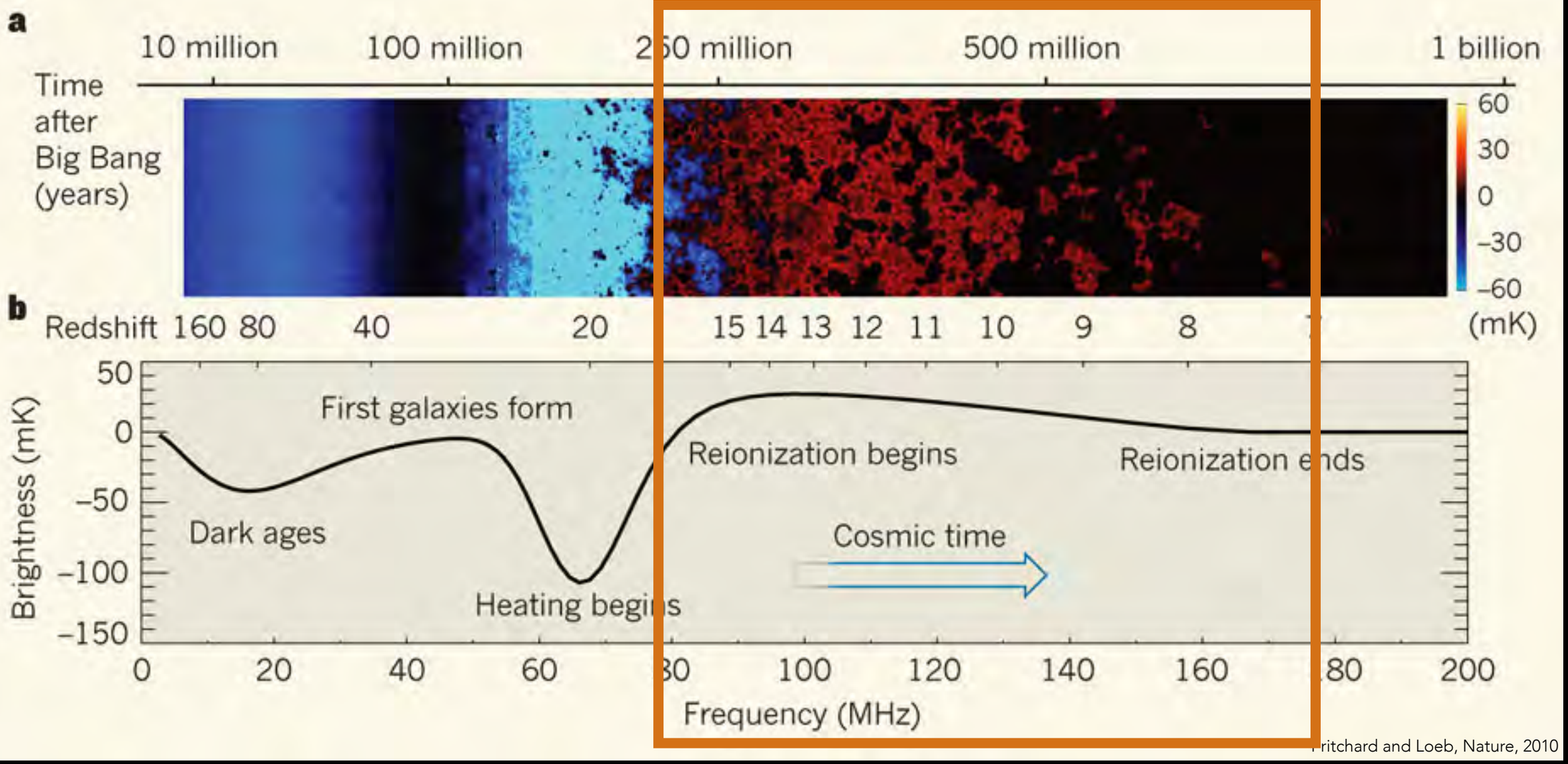
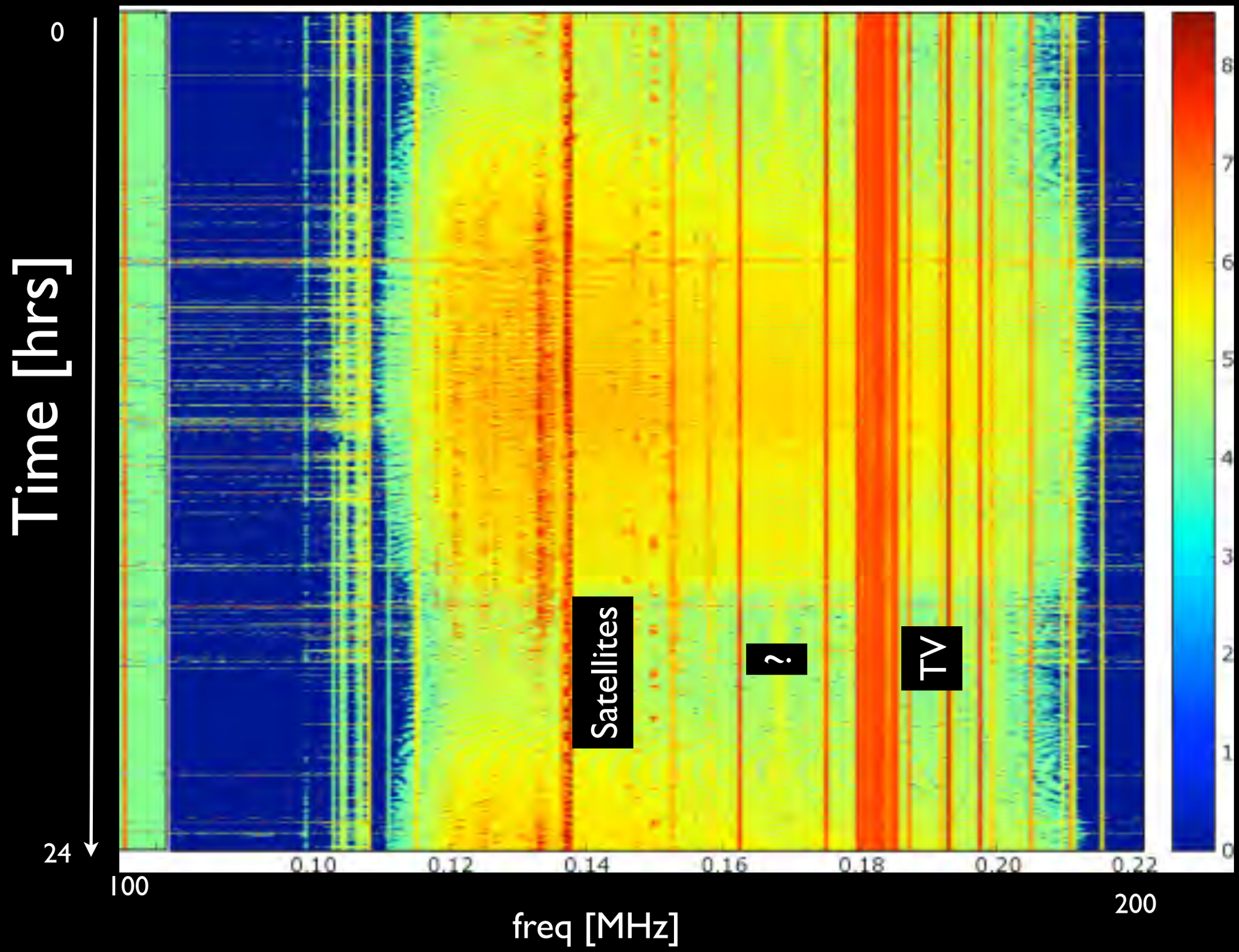
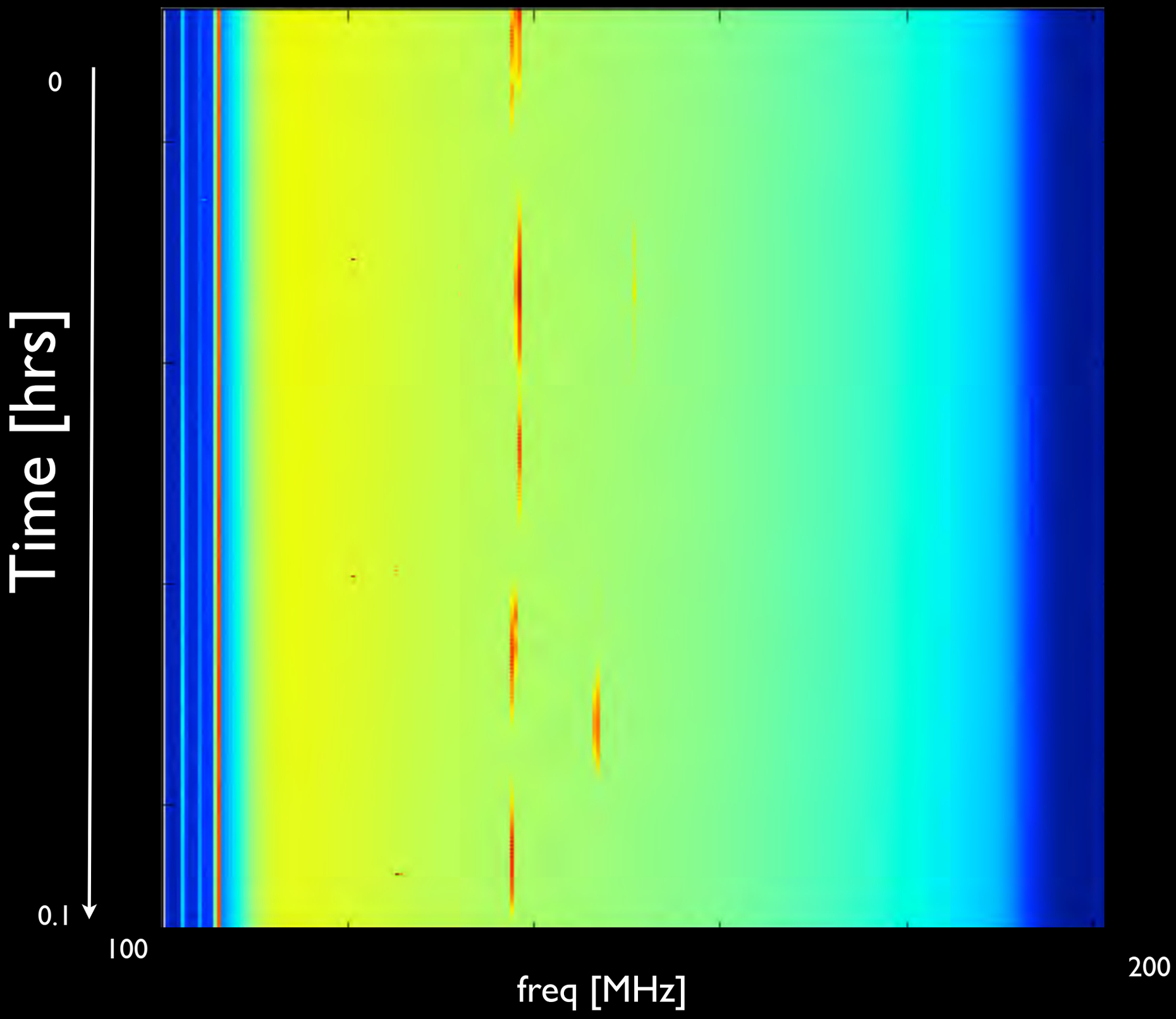


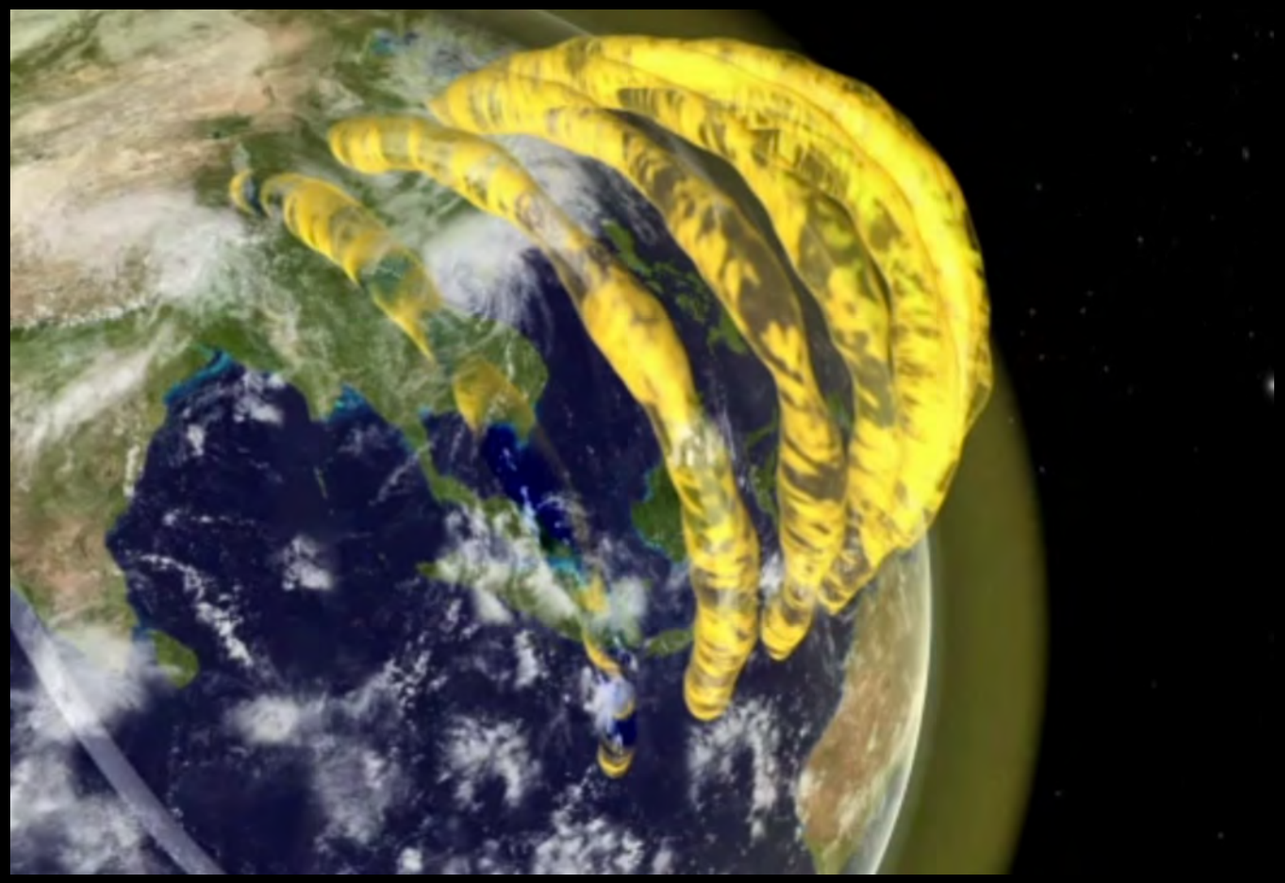
Pritchard and Loeb, Nature, 2010

PAPER Green Bank

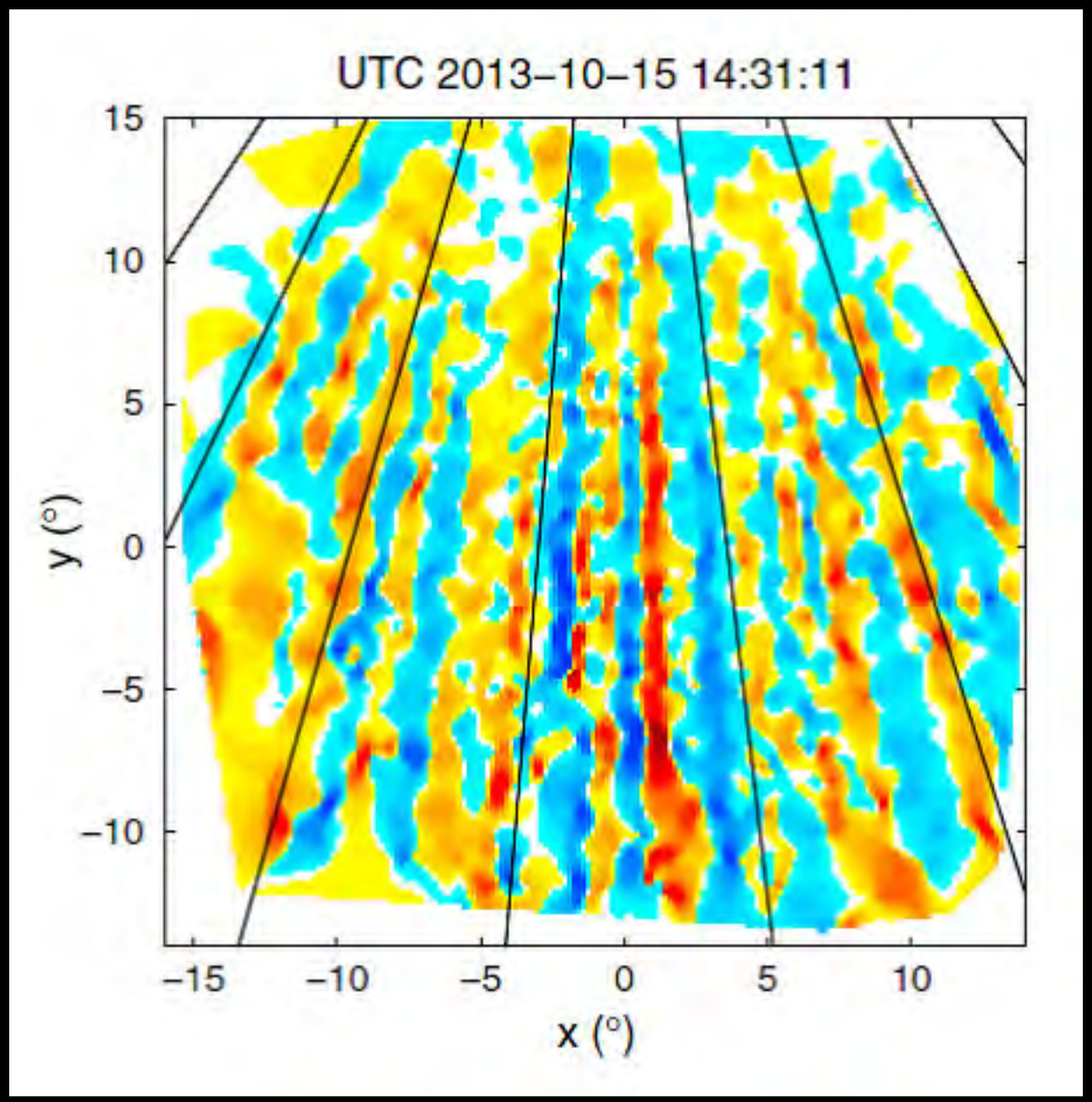


PAPER South Africa





https://youtu.be/ymZEOihlIdU

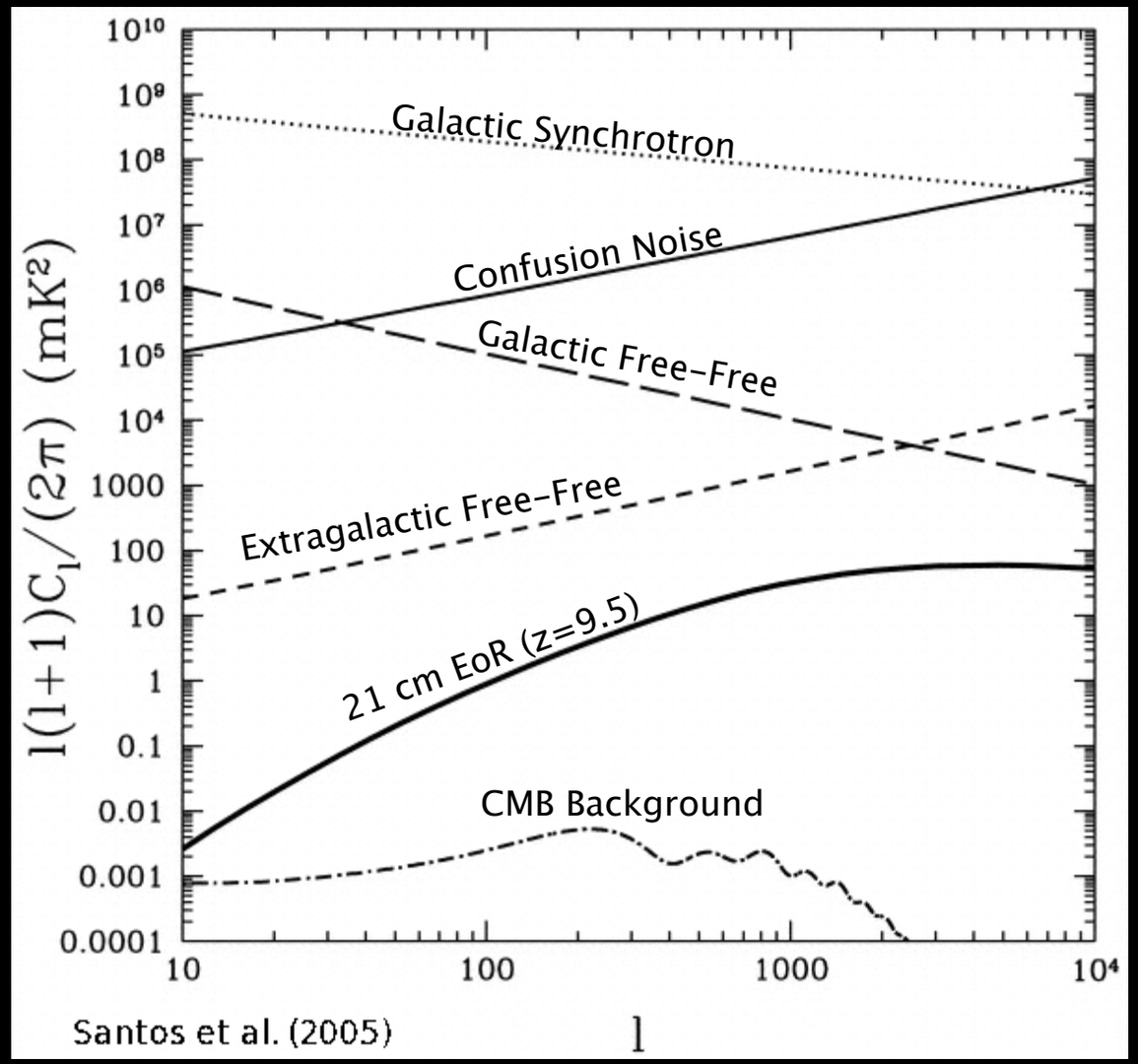


Loi et al GRL, 2015

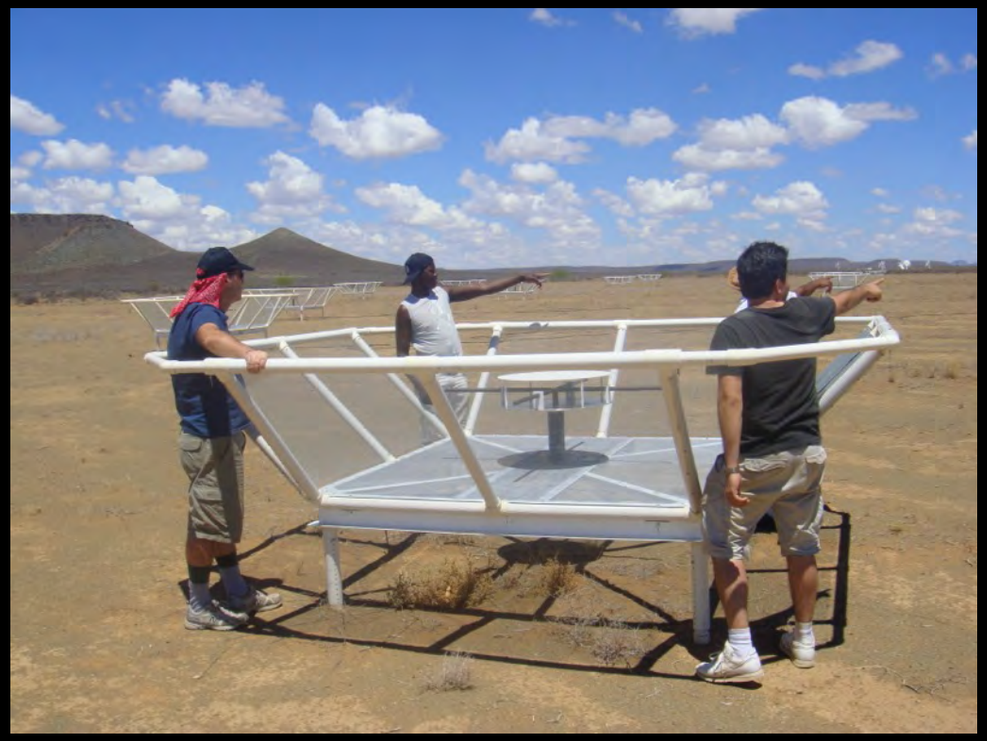
mwatelescope.org

CHALLENGES

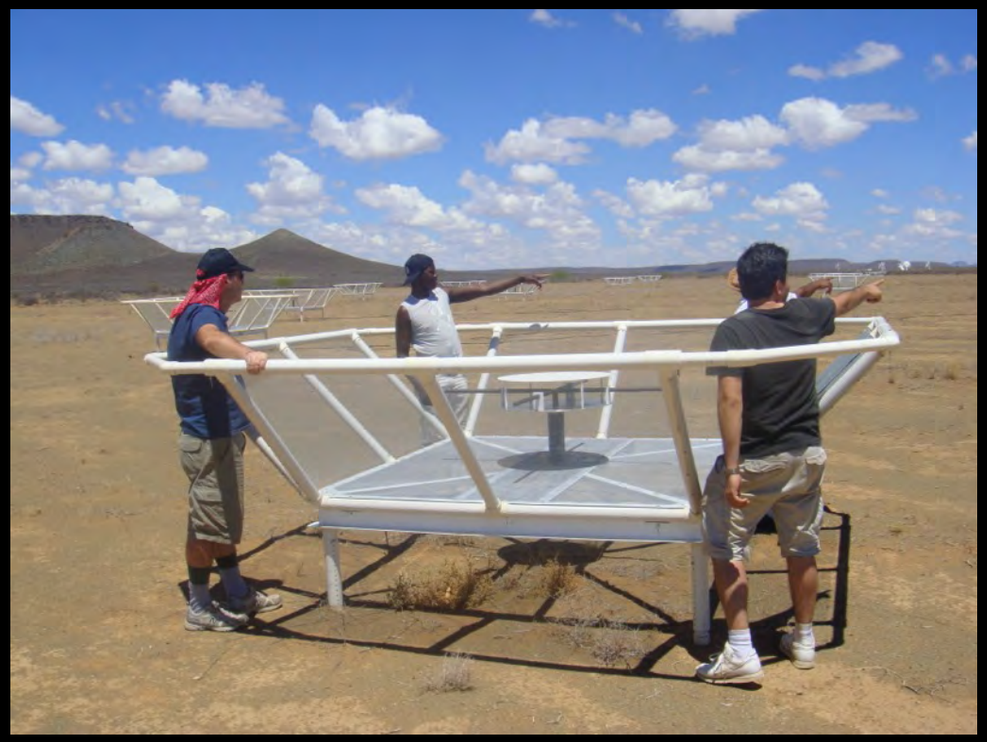
- Interference
- Sensitivity
- Foregrounds
  - 9 orders of magnitude in mK^2
  - spectrally smooth (unlike 21cm line)



SENSITIVITY



SENSITIVITY



EXPERIMENTAL DEVELOPMENTS

Hardware limitations

UNCERTAIN PRIMARY BEAM

ANALOG CROSS-COUPLING

SLOW ANALYSIS FEEDBACK

Current Projects

EXTERNAL CALIBRATOR

ANALOG VERIFICATION

REAL TIME CALIBRATION

ACCELERATED OFFLINE PROCESSING

*BIG DATA

EXTERNAL CALIBRATOR FOR HYDROGEN OBSERVATORIES

NSF Advanced Technology and Instrumentation Program

Jacobs PI

EXTERNAL CALIBRATOR FOR HYDROGEN OBSERVATORIES

NSF Advanced Technology and Instrumentation Program

Jacobs PI

Source: VCO synthesizer (137-2GHz)

EXTERNAL CALIBRATOR FOR HYDROGEN OBSERVATORIES

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Jacobs PI

Drone: 3DR X8

Source: VCO synthesizer (137-2GHz)

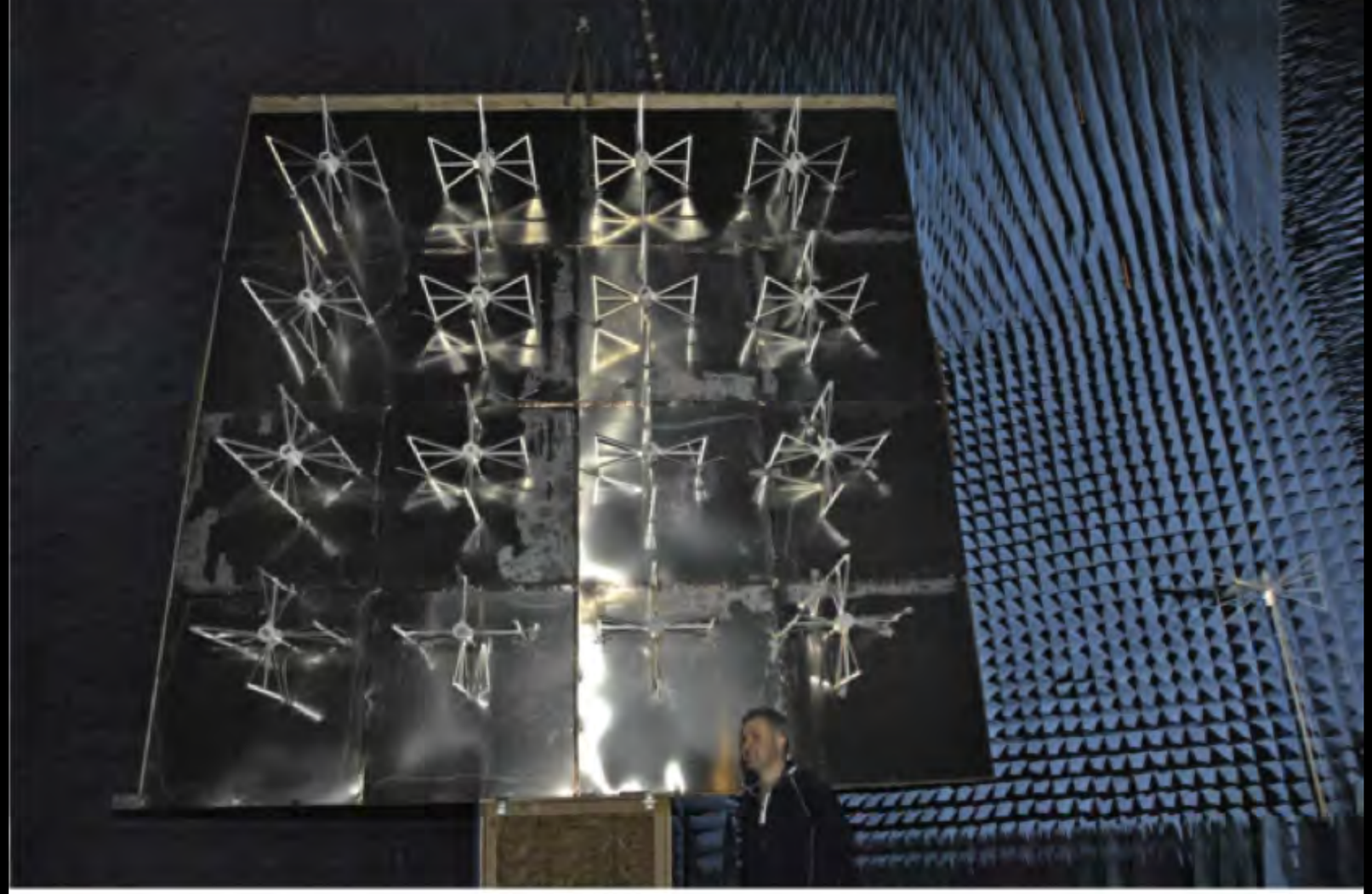
EXTERNAL CALIBRATOR FOR HYDROGEN OBSERVATORIES

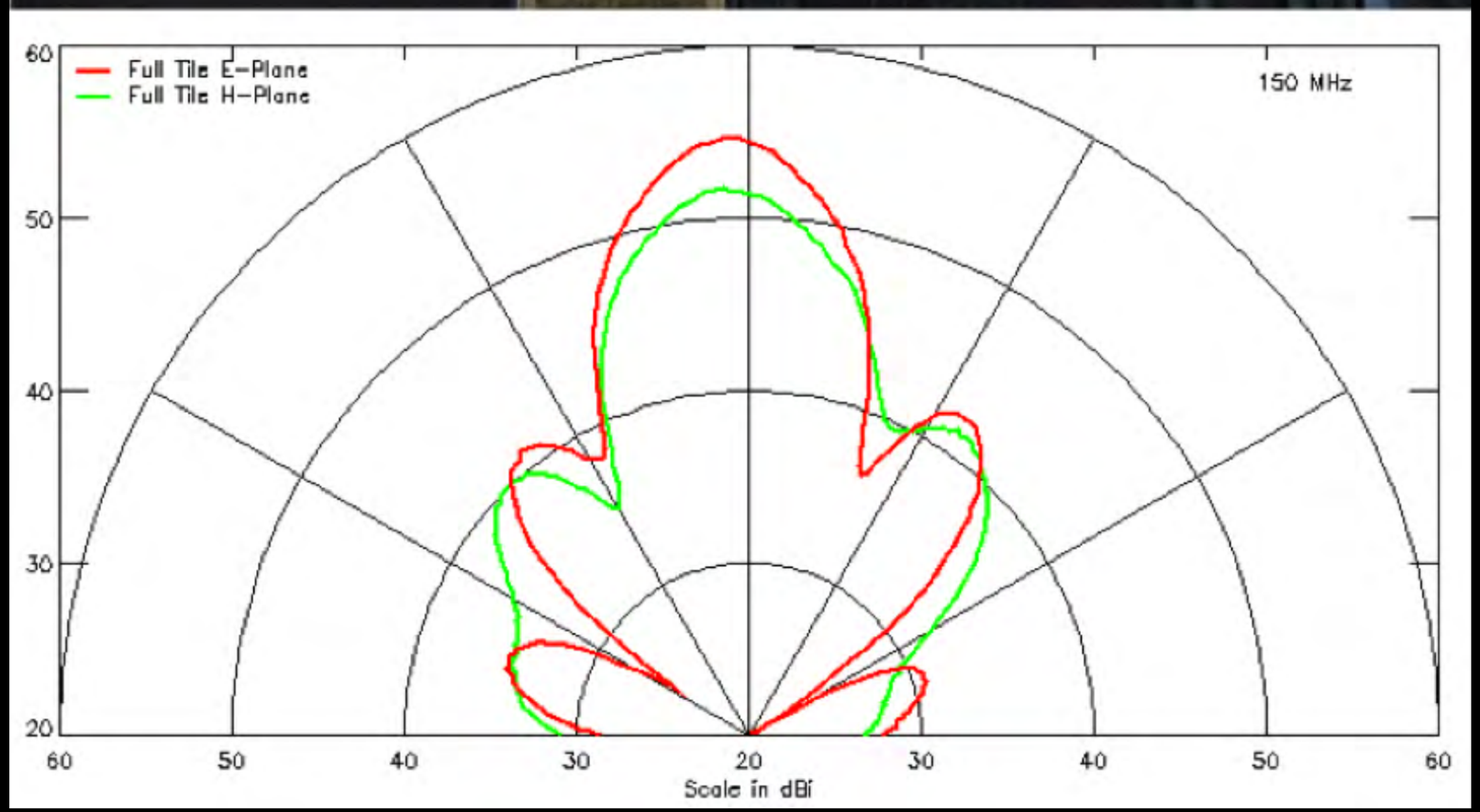
NSF Advanced Technology and Instrumentation Program
Jacobs PI

Source: VCO synthesizer
(137-2GHz)

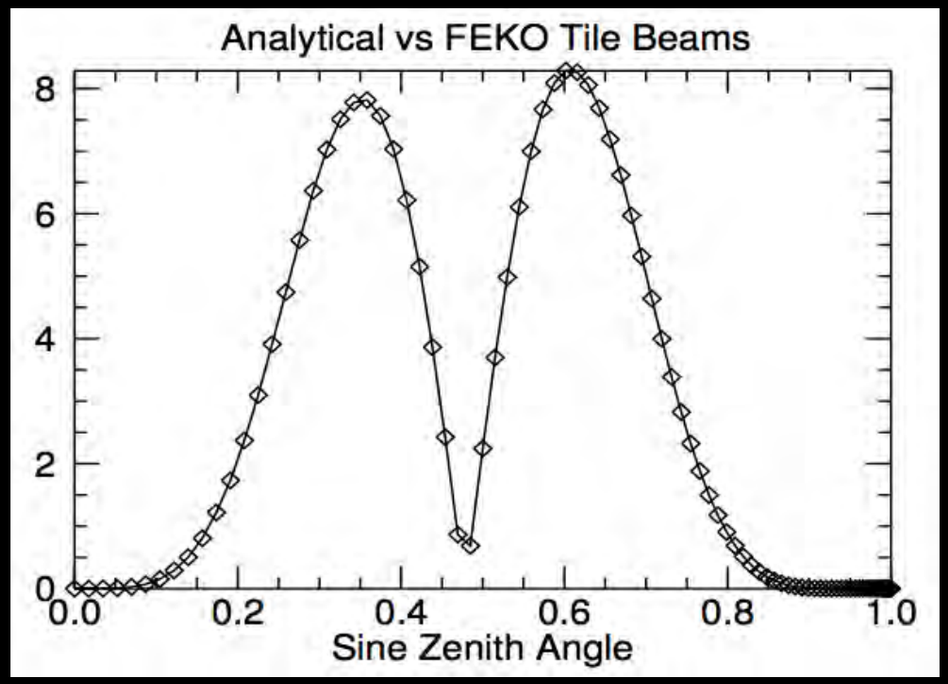
Drone: 3DR X8

Antenna: Bicolog bowtie
100-2Ghz



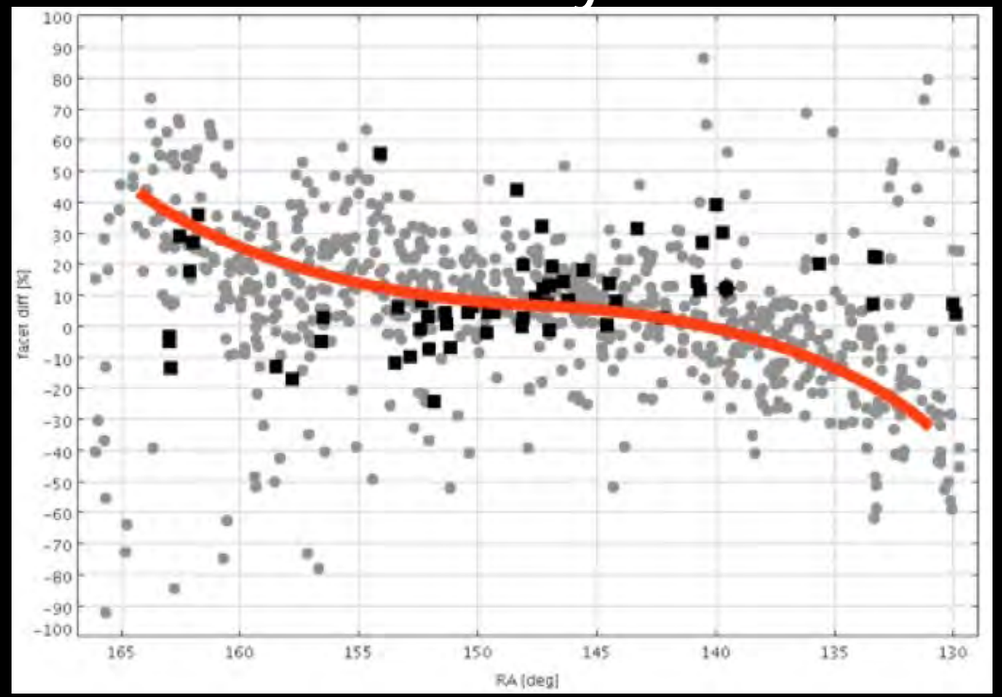

Full Tile E-Plane
Full Tile H-Plane
150 MHz
60
50
40
30
20
60
50
40
30
20
30
40
50
60
Scale in dBi

Model Variance



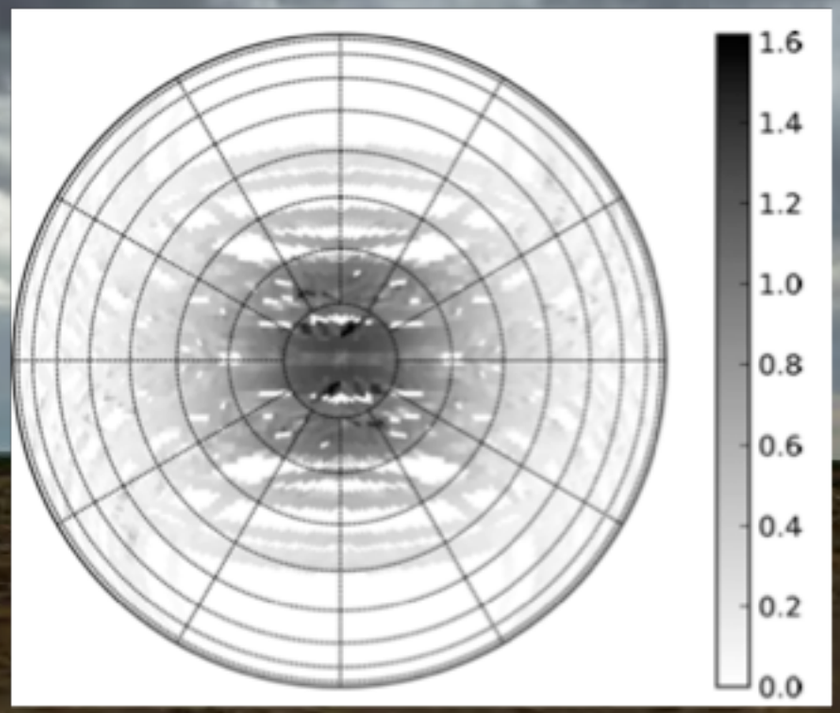
Analysis by Ben McKinley et al

Flux uncertainty



Jacobs et al 2013

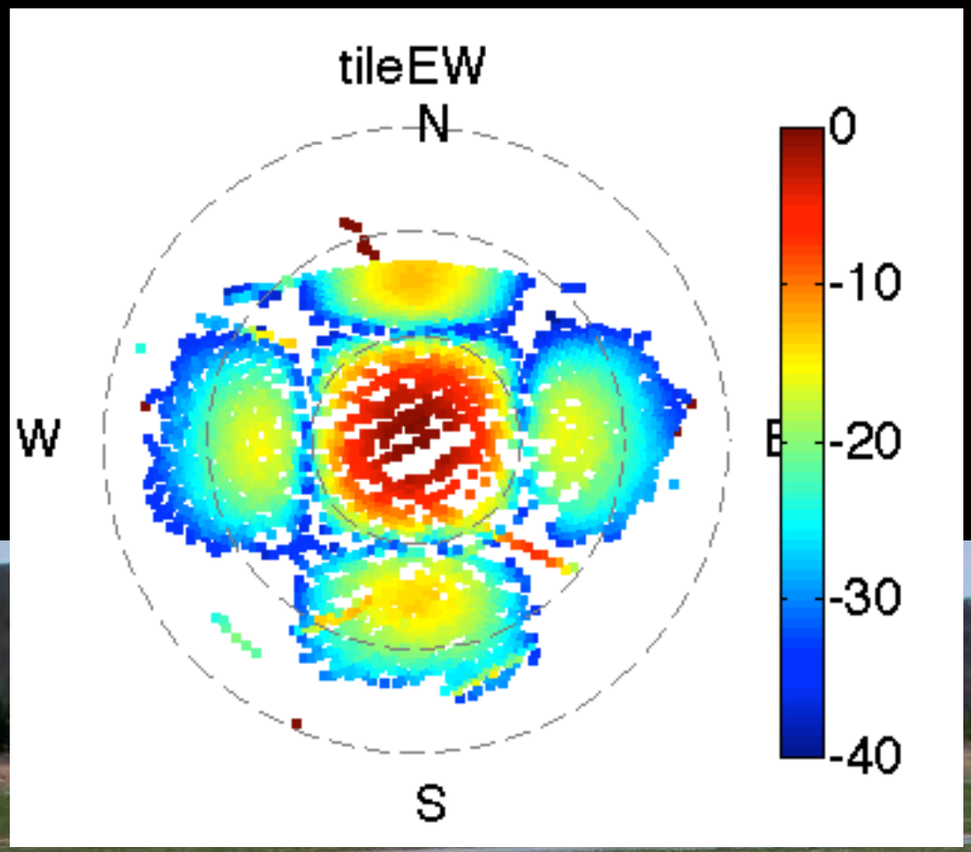
see also Sutinjo et al, Rad Sci, 2015

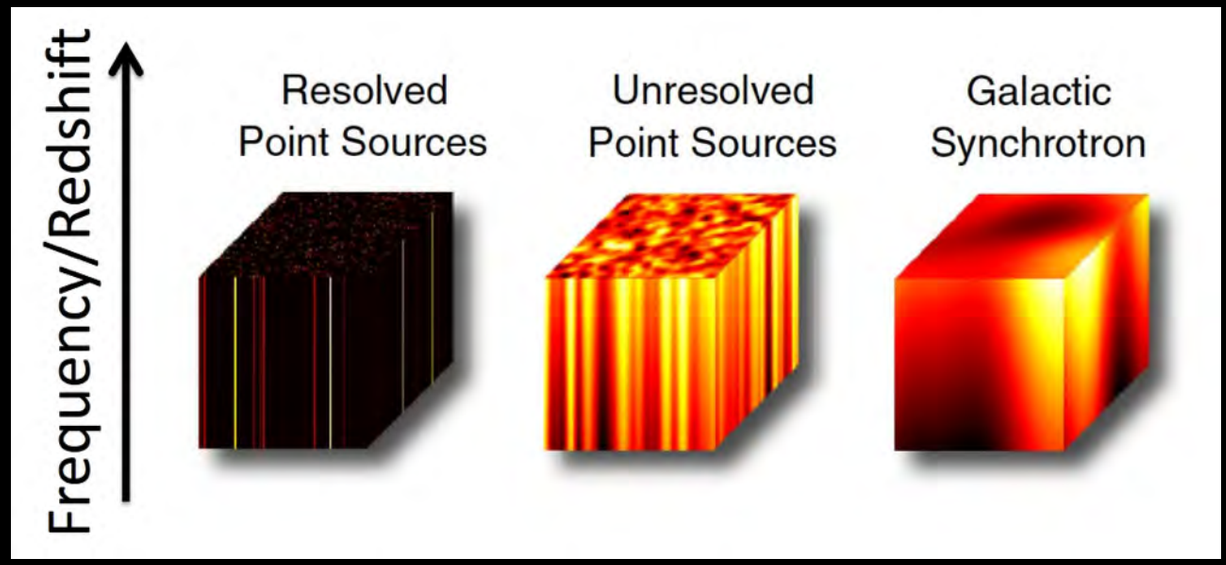


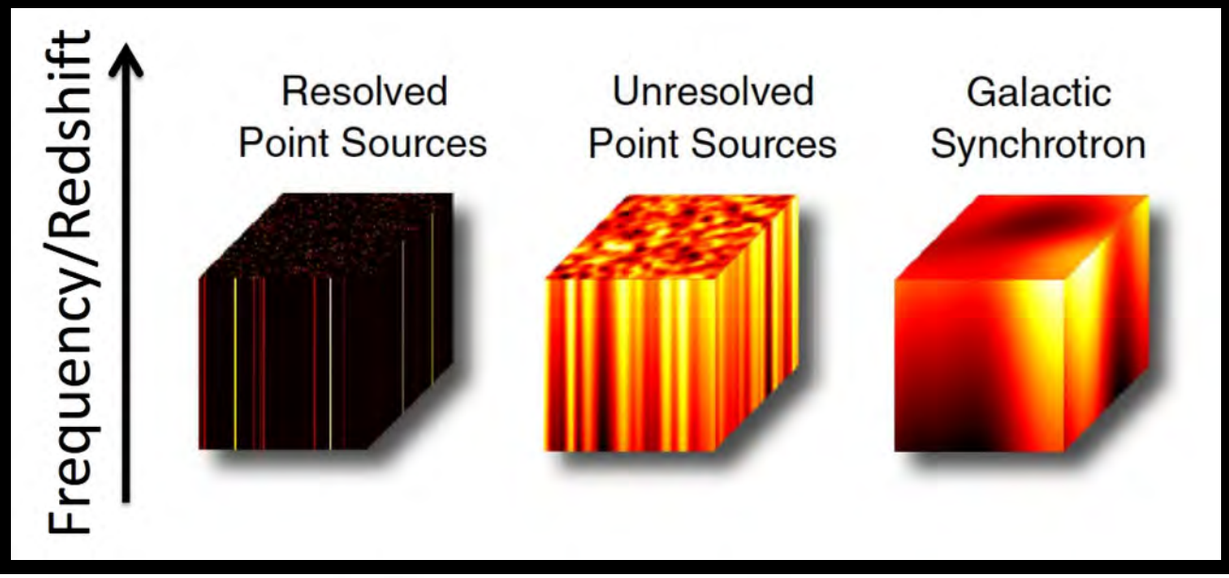
Pober et al, AJ, 2012, v143

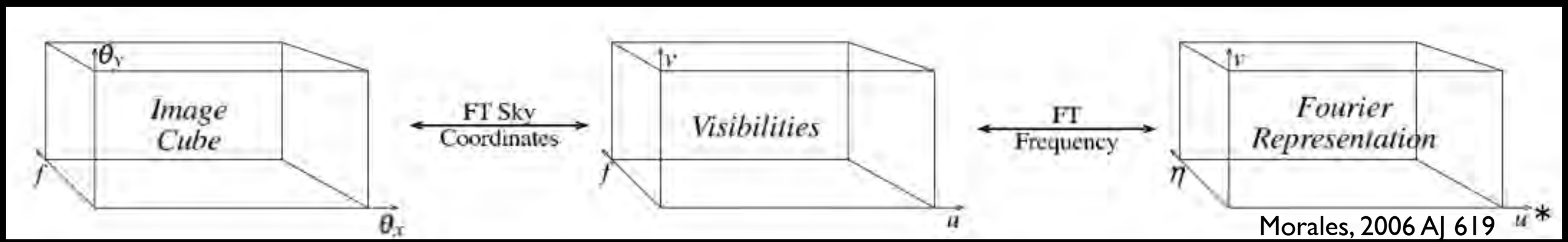
Using ORBCOMM

Neben et al Radio Science, 2015, vol 50

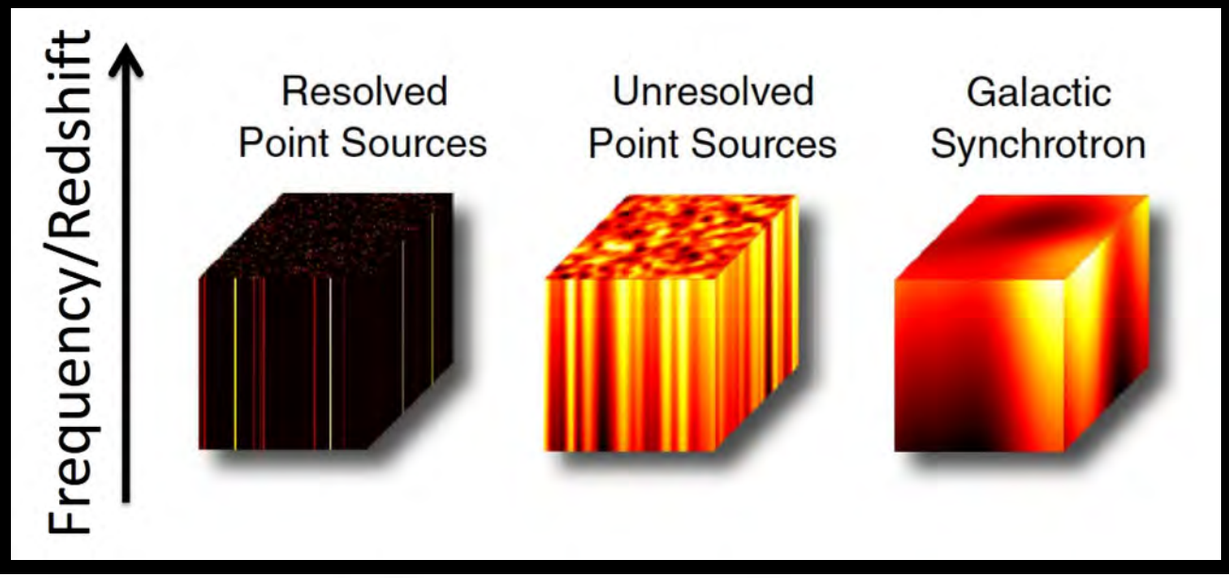


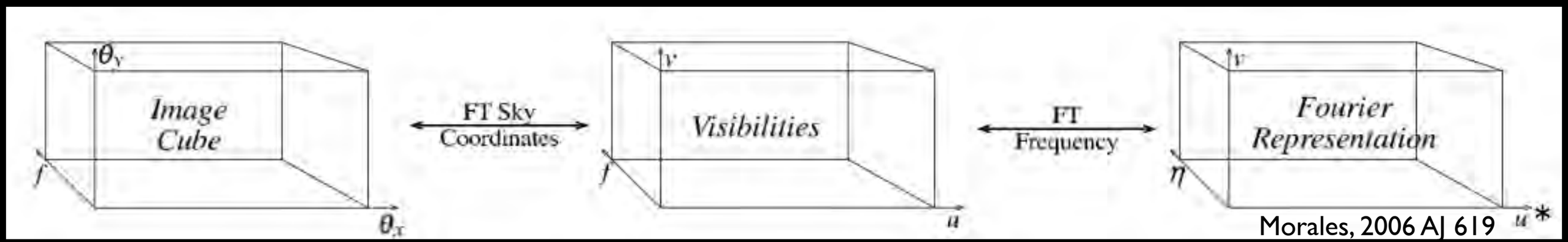

Frequency/Redshift
Resolved
Point Sources
Unresolved
Point Sources
Galactic
Synchrotron



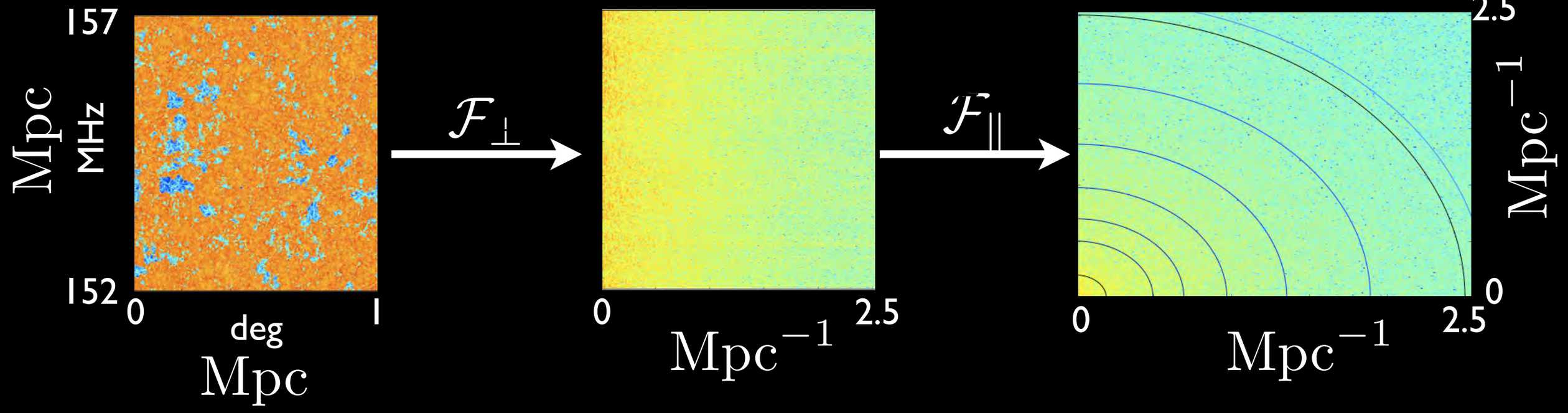


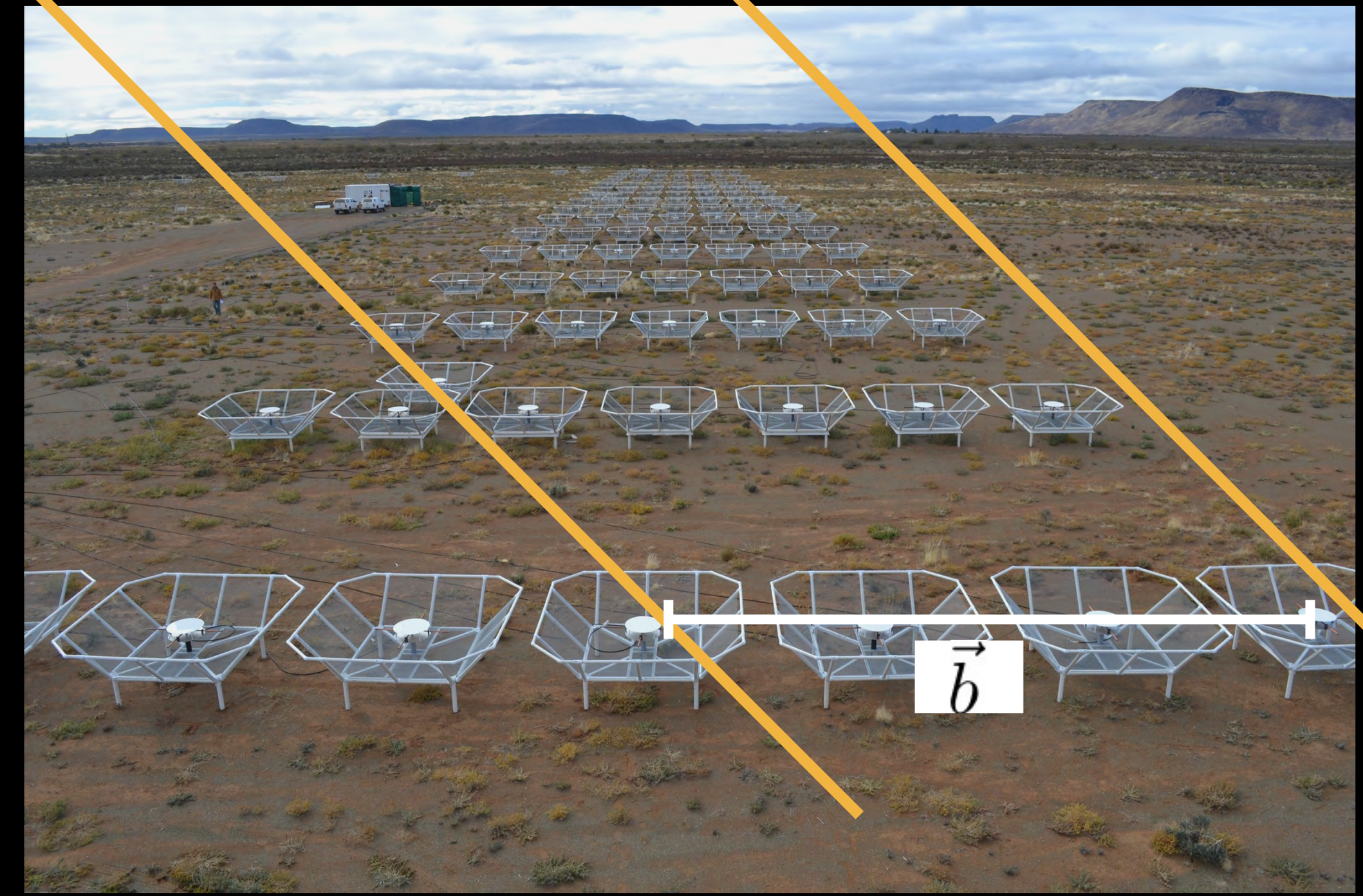
Morales, 2006 AJ 619

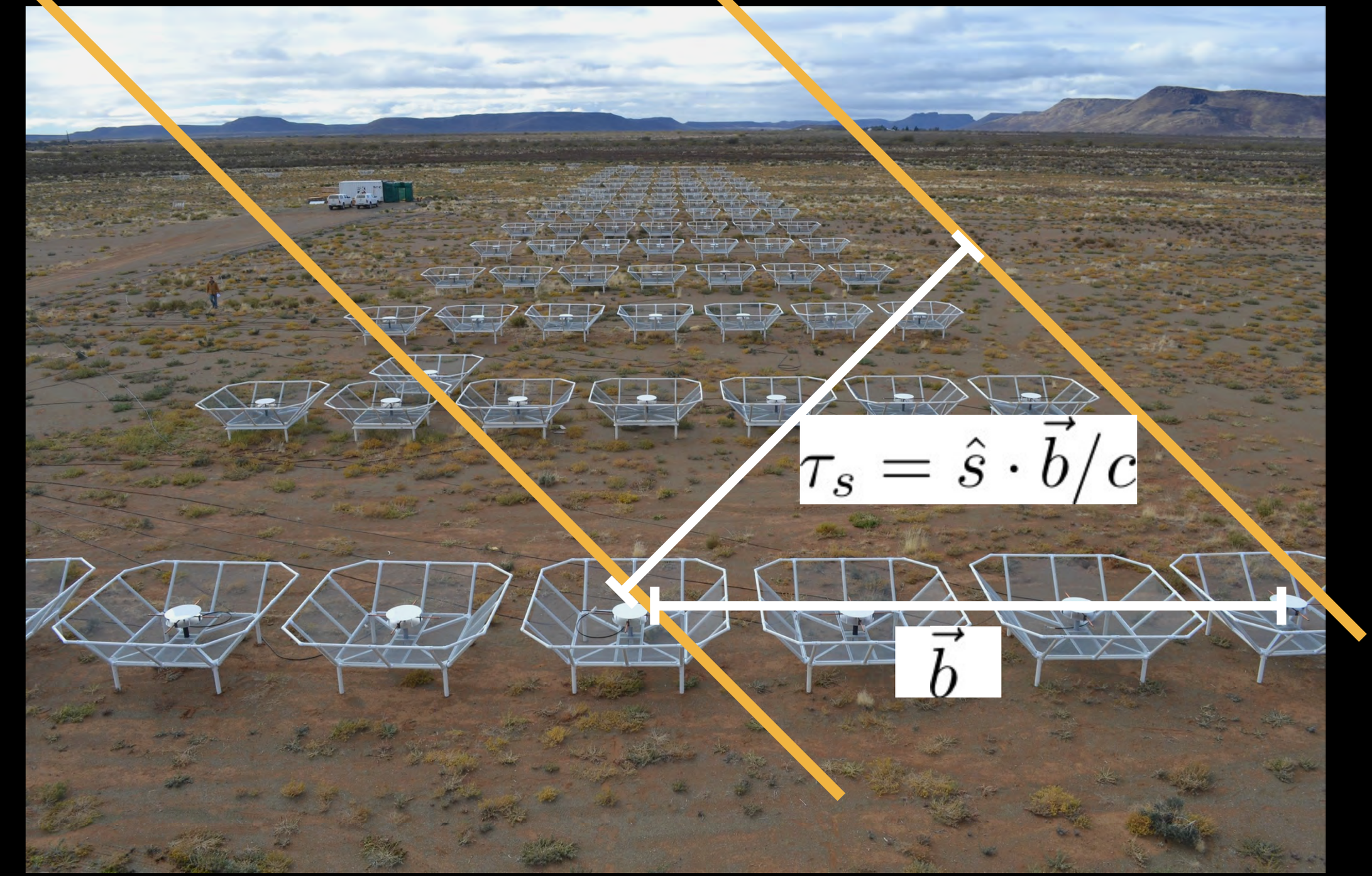


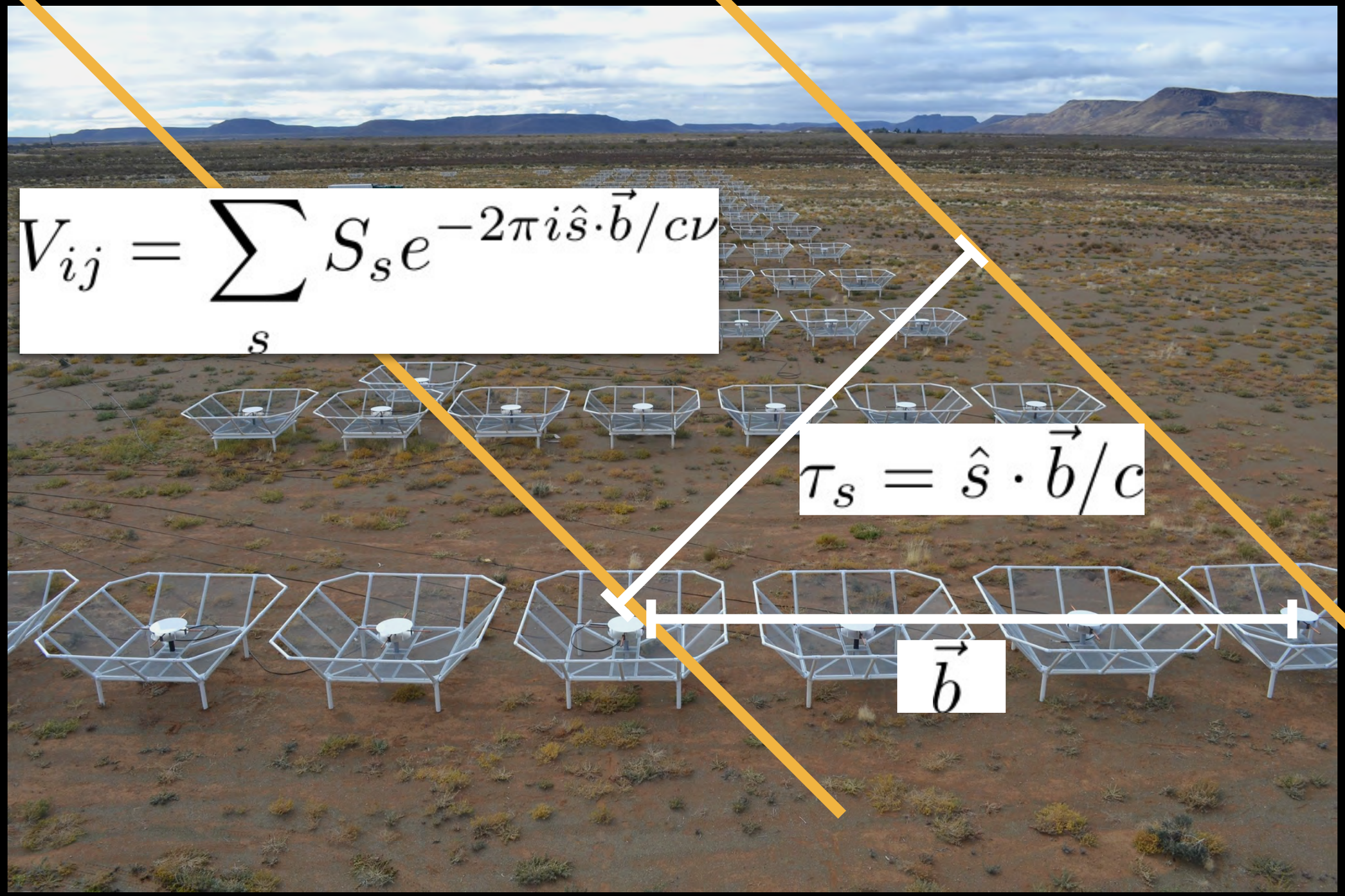


Morales, 2006 AJ 619

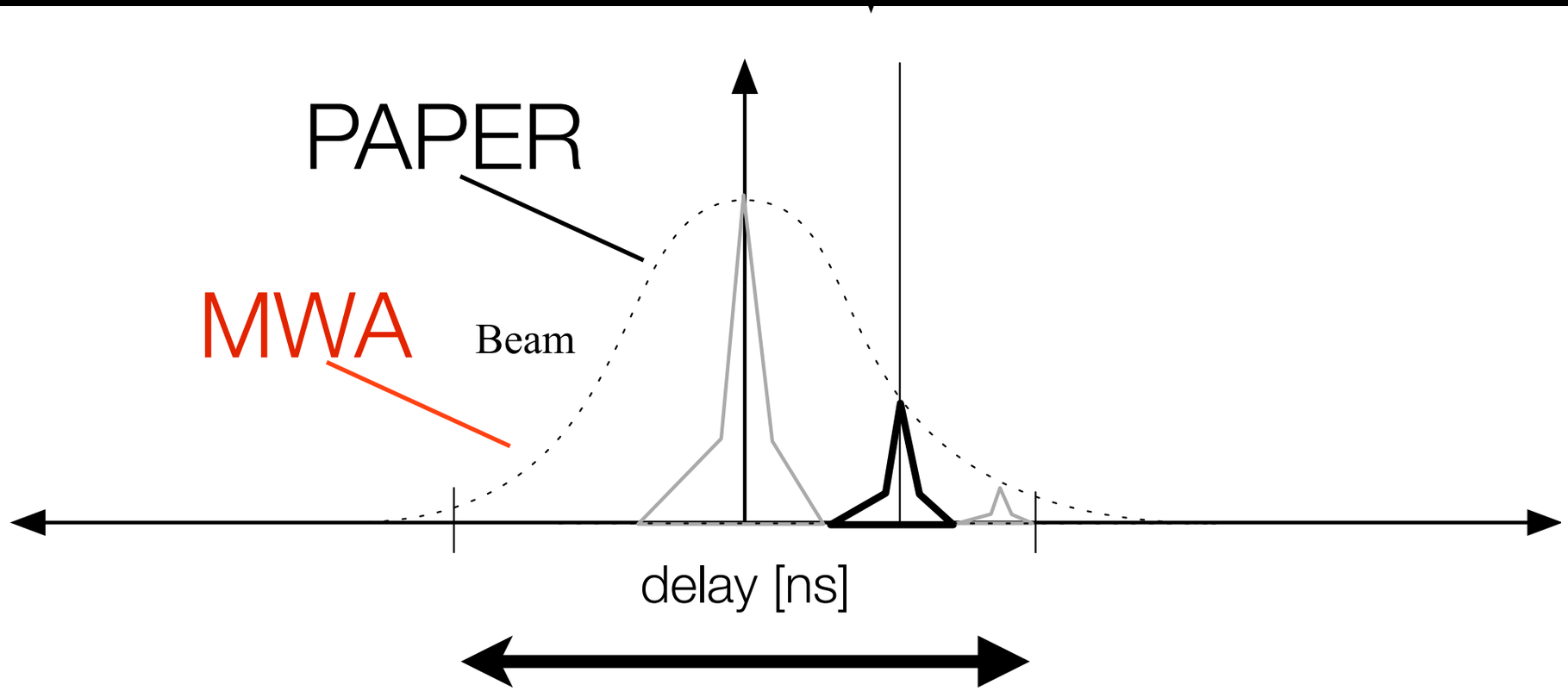



S
$\vec{b}$

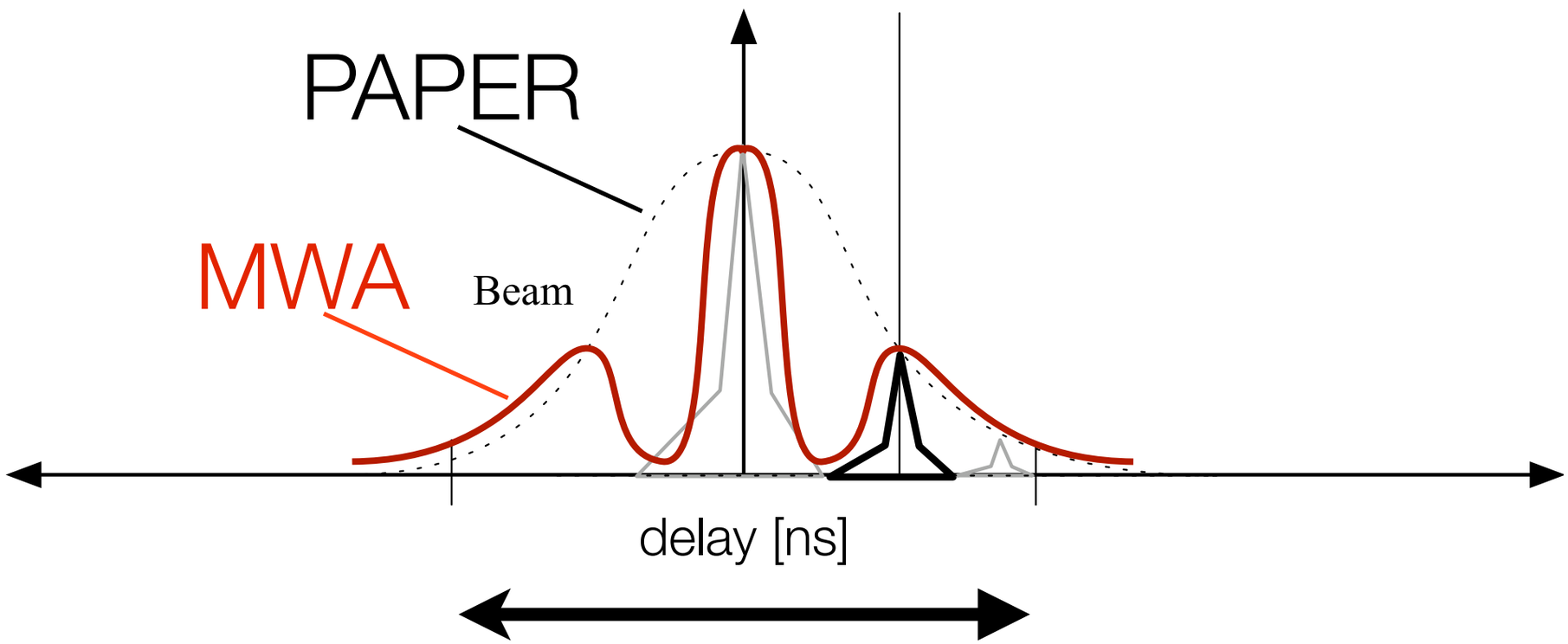

S
$\tau_s = \hat{s} \cdot \vec{b}/c$
$\vec{b}$


$V_{ij} = \sum_s S_s e^{-2\pi i \hat{s}\cdot\vec{b}/c\nu}$
$\tau_s = \hat{s}\cdot\vec{b}/c$
$\vec{b}$

THE DELAY SPECTRUM (A 1D POWER SPECTRUM)

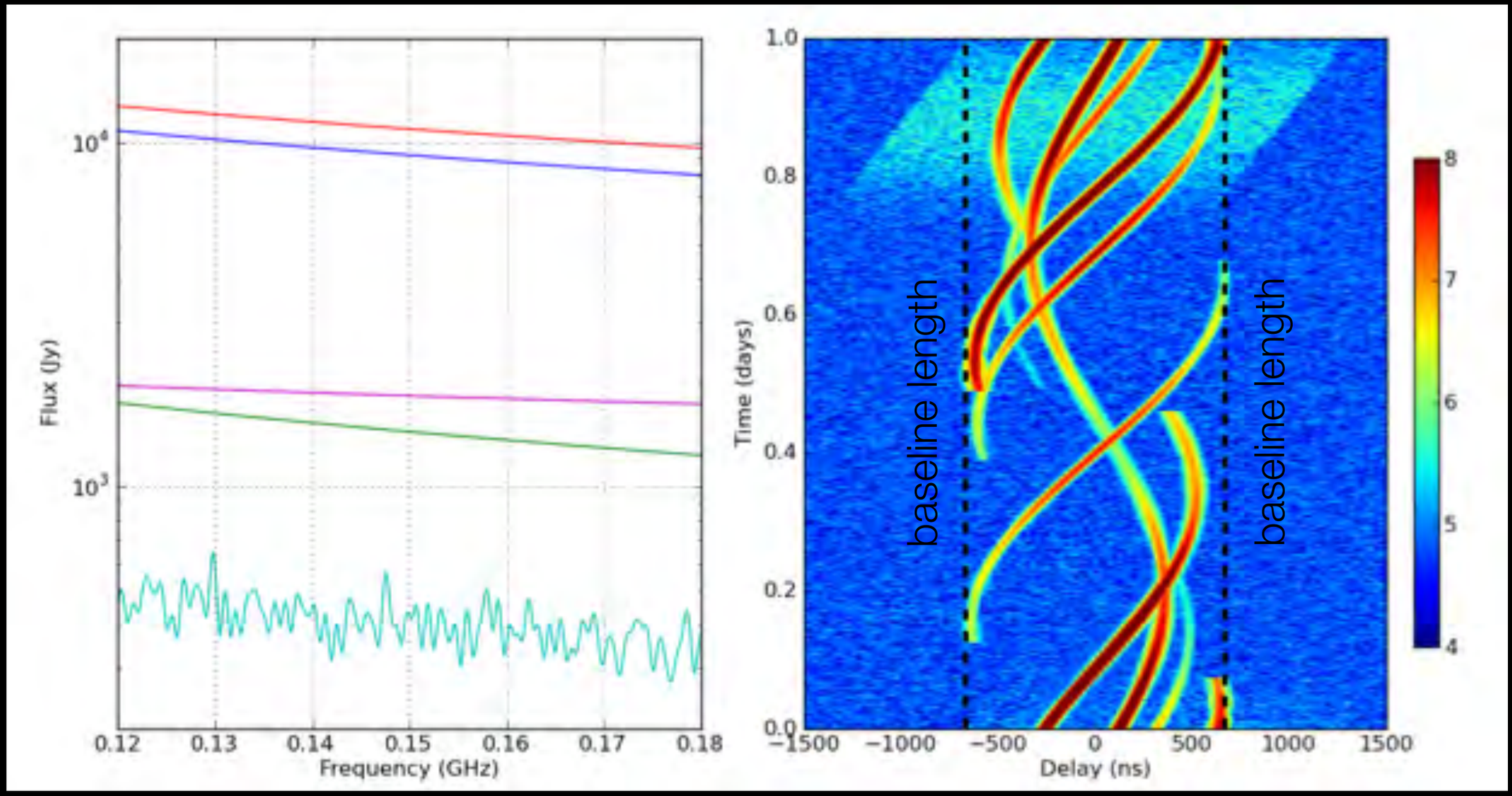


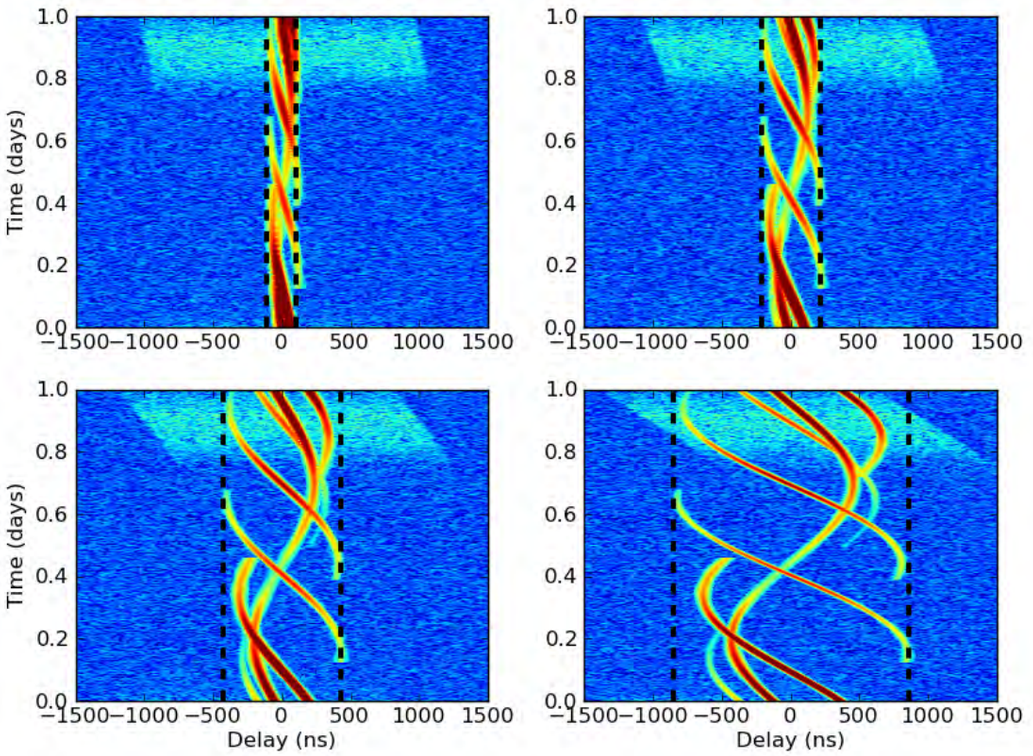
THE DELAY SPECTRUM (A 1D POWER SPECTRUM)

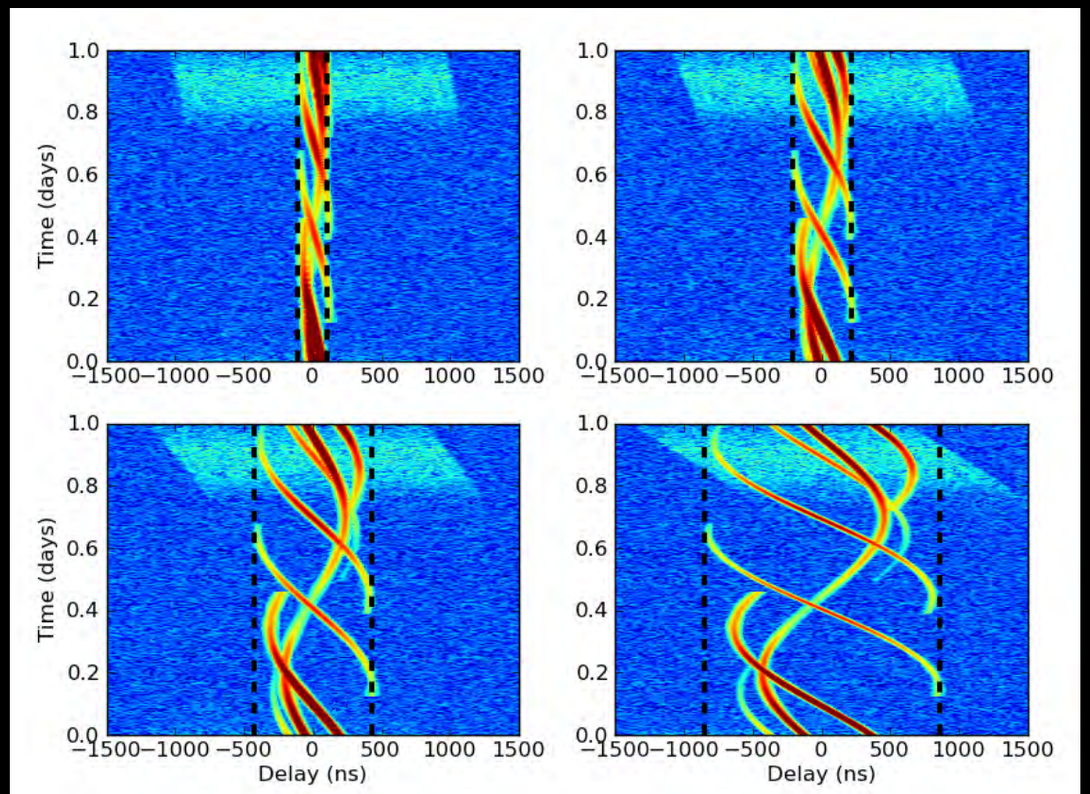


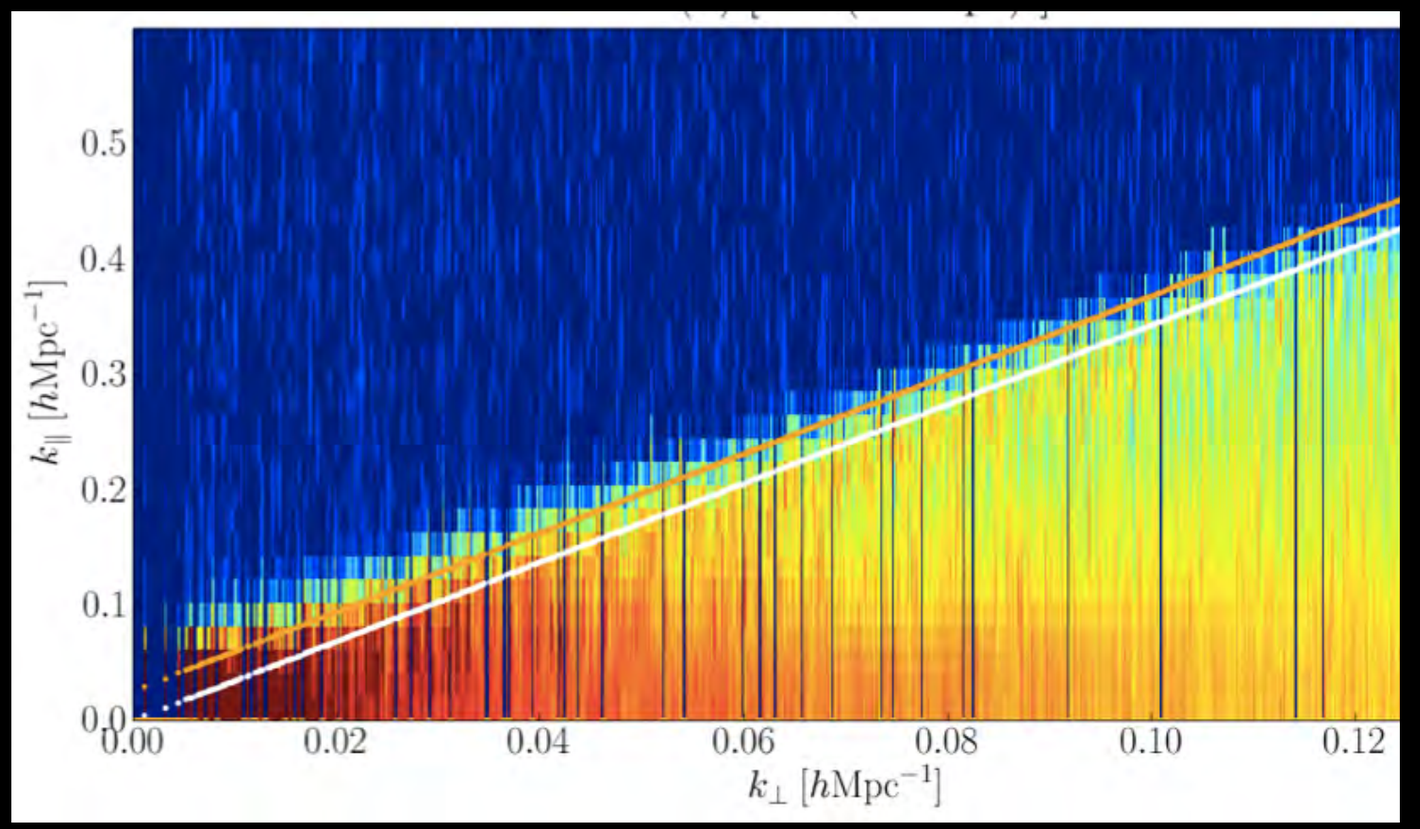
Light travel time between antennas

FOREGROUNDS ON A SINGLE BASELINE




Time (days)
Delay (ns)
1.0
0.8
0.6
0.4
0.2
0.0
−1500 −1000 −500 0 500 1000 1500





Pober,…, **Jacobs**, et al 2013

Longer baselines are more chromatic

Portable planetarium outreach

Portable planetarium outreach:student training

Public outreach

MEETINGS HOSTED