

CHASING OUR COSMIC DAWN



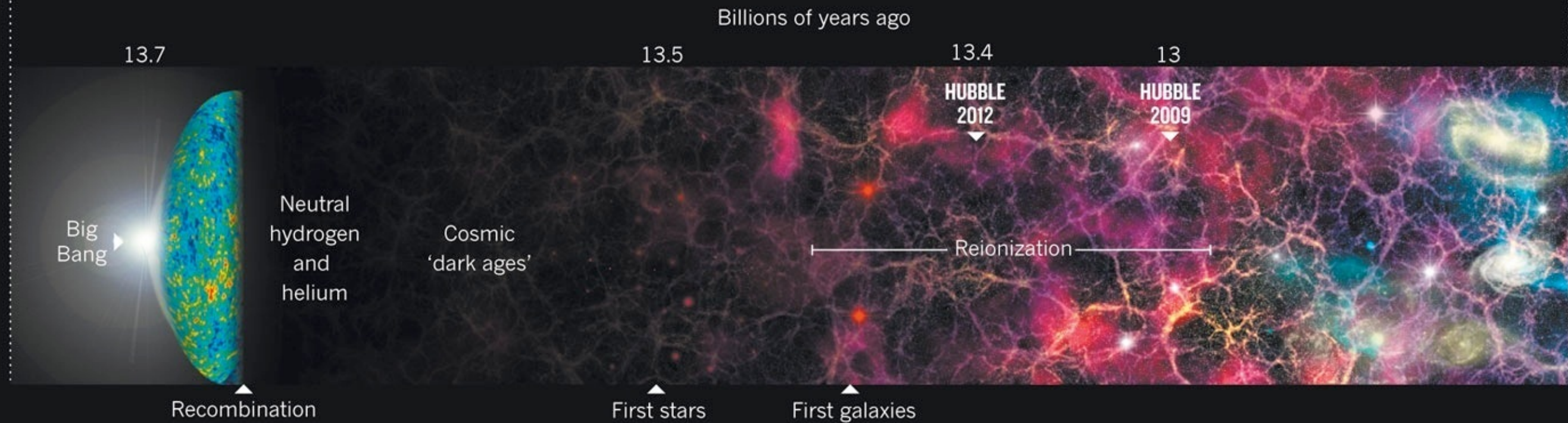
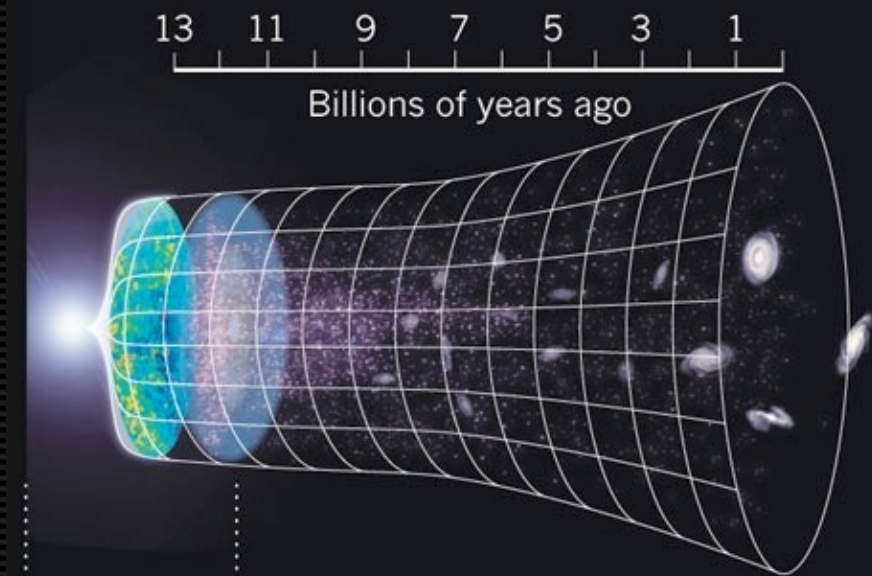
OPENING THE 21CM COSMOLOGICAL WINDOW ON THE UNIVERSE

DANIEL C. JACOBS

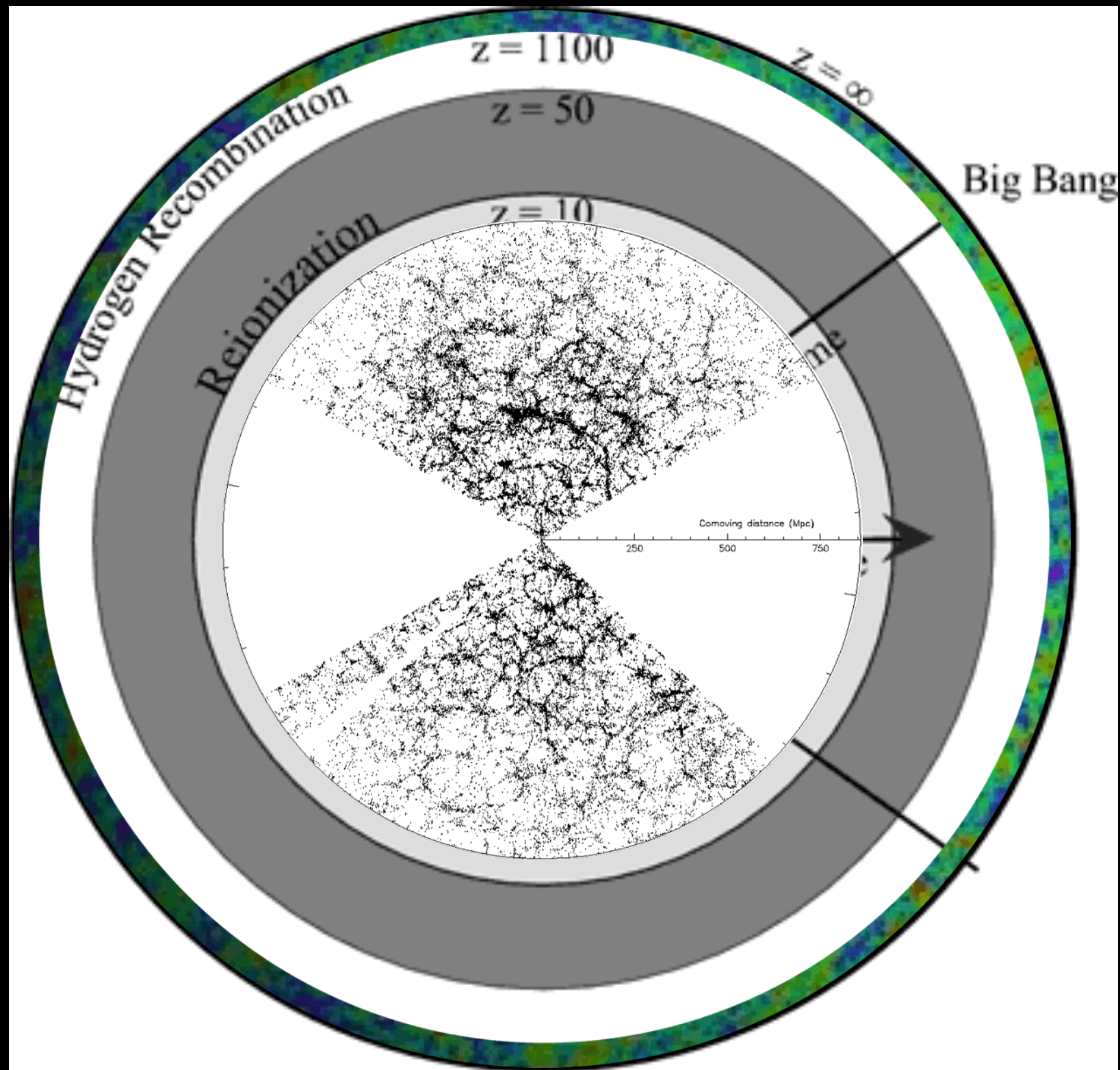
NSF POSTDOCTORAL FELLOW, ARIZONA STATE UNIVERSITY

DAWN'S EARLY LIGHT

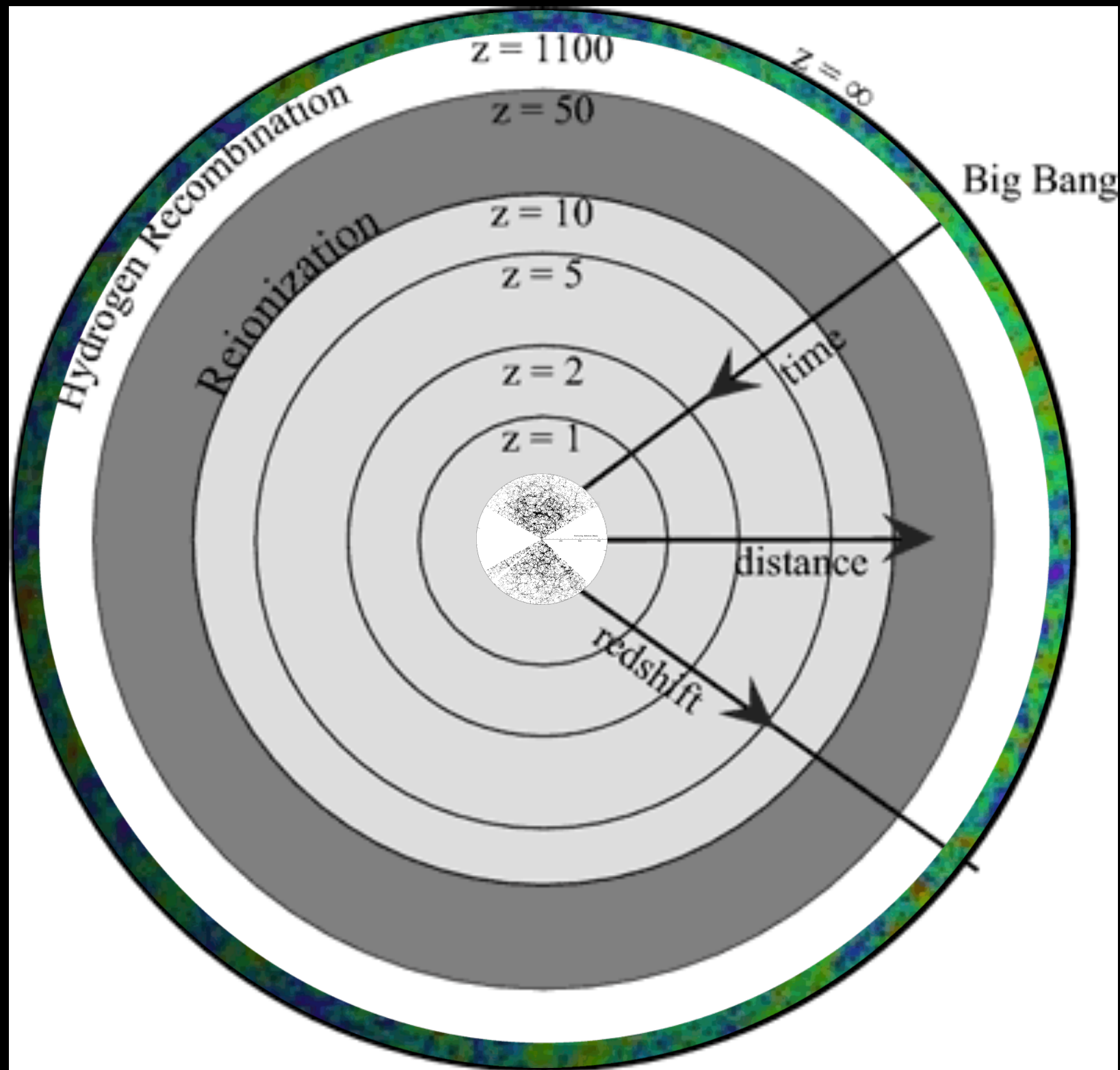
The Big Bang generated a haze of primordial hydrogen and helium. After about 370,000 years, cosmic expansion cooled it enough for electrons and protons to form neutral atoms ('recombination'). During the resulting 'dark ages', when the Universe had no stars to light it, gravity magnified slight fluctuations in density and caused the neutral gas to clump. The densest clumps eventually became the first stars and galaxies. Their ultraviolet light ionized the remaining neutral gas ('reionization'), allowed light to stream freely into space, and brought the dark ages to an end.



THE LARGE SCALE UNIVERSE



THE LARGE SCALE UNIVERSE

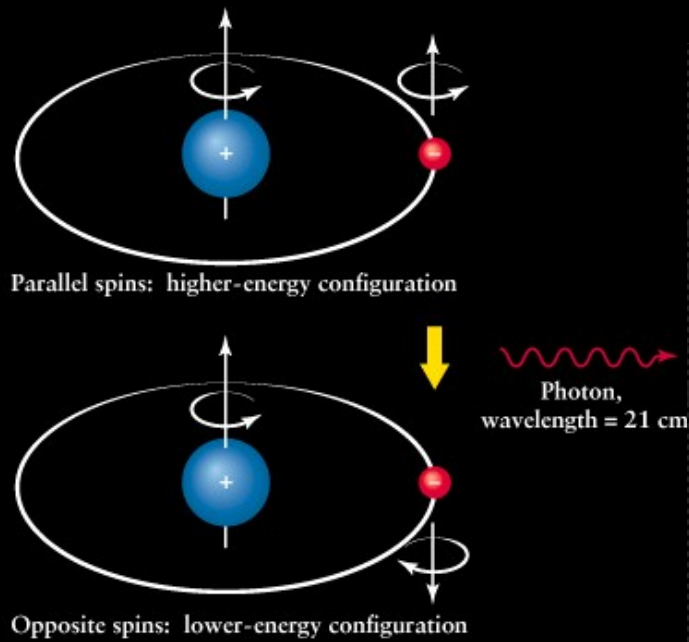




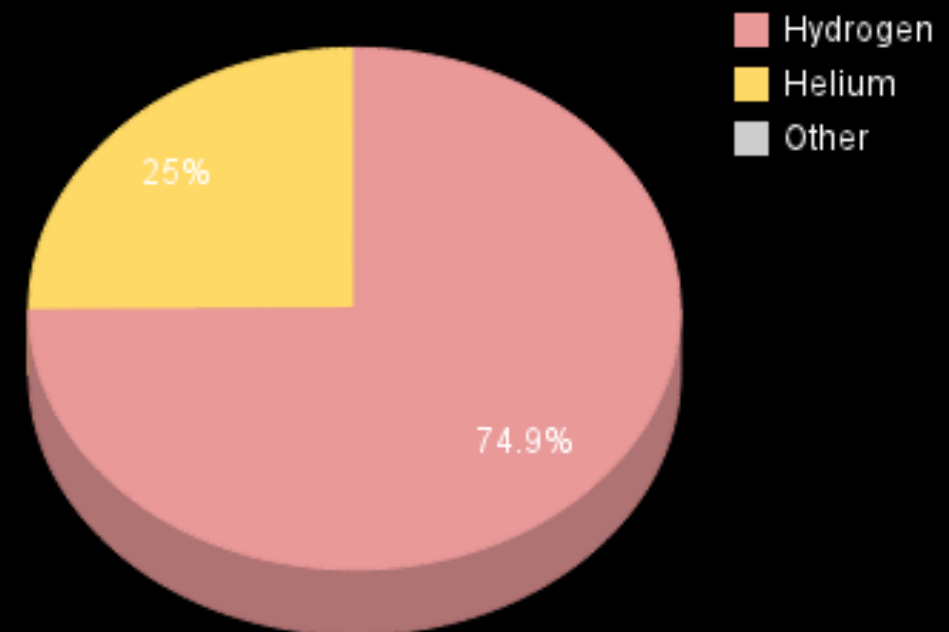
Credit: M.Alvarez (CITA)
& R. Kaehler (Stanford)

DAWN'S EARLY

The Big Bang generates
After about 370,000 yr
electrons and protons
During the resulting "light
light it, gravity magnify
the neutral gas to clump
the first stars and gas
remaining neutral gas
freely into space, and



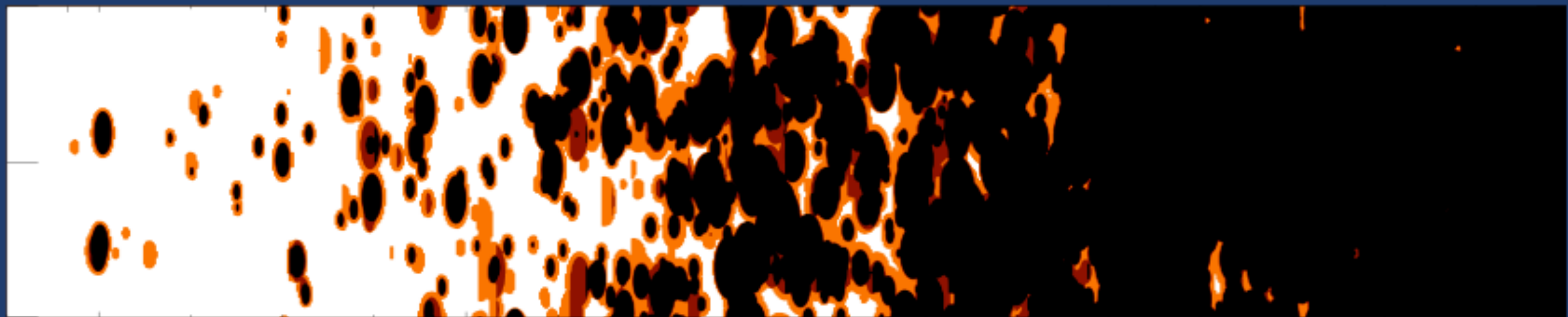
Baryons in the Universe



12

Redshift

6



100MHz

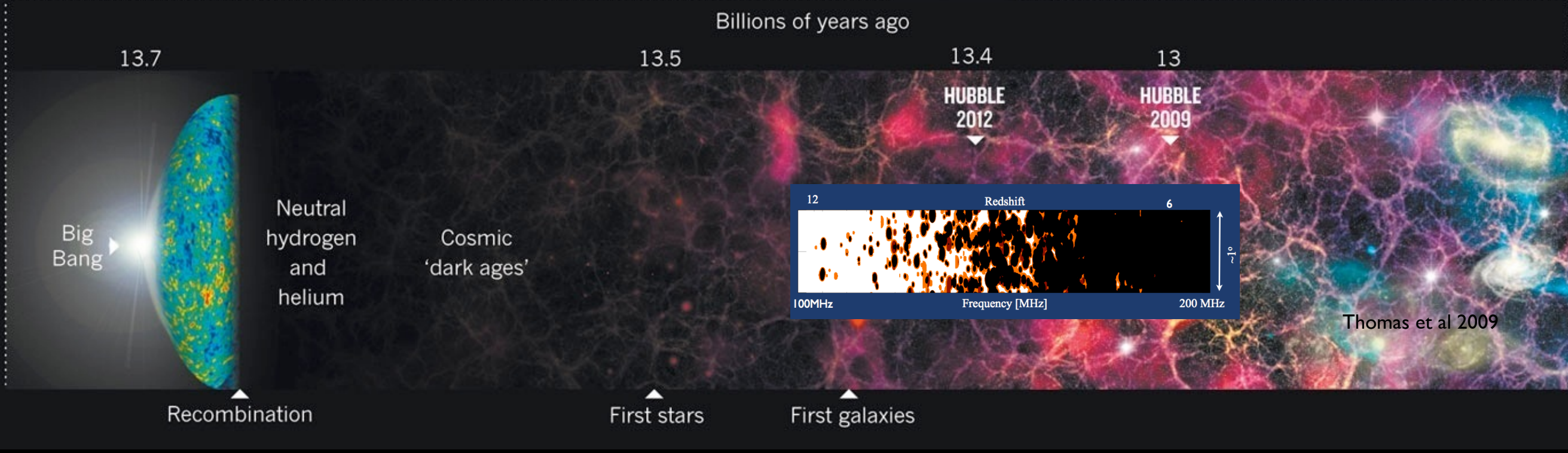
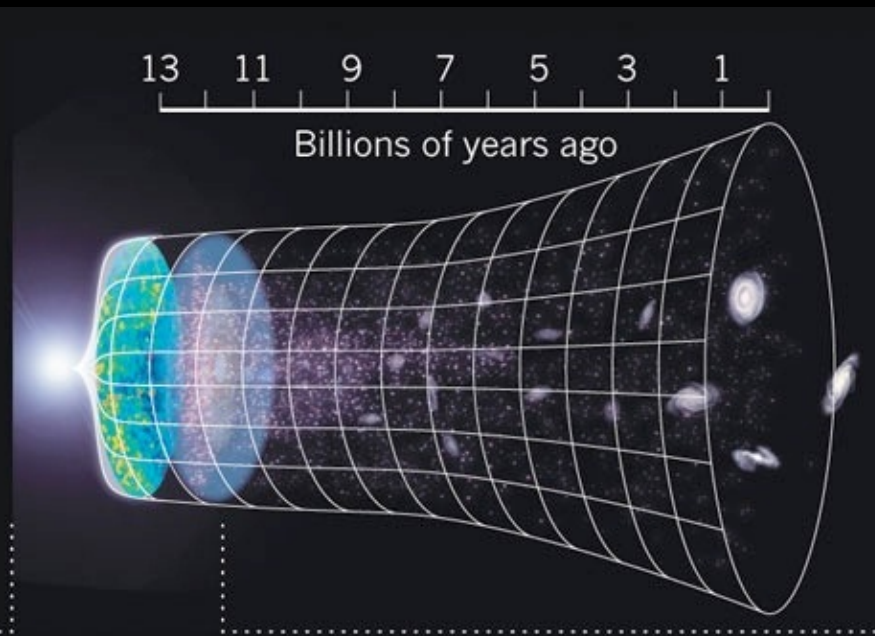
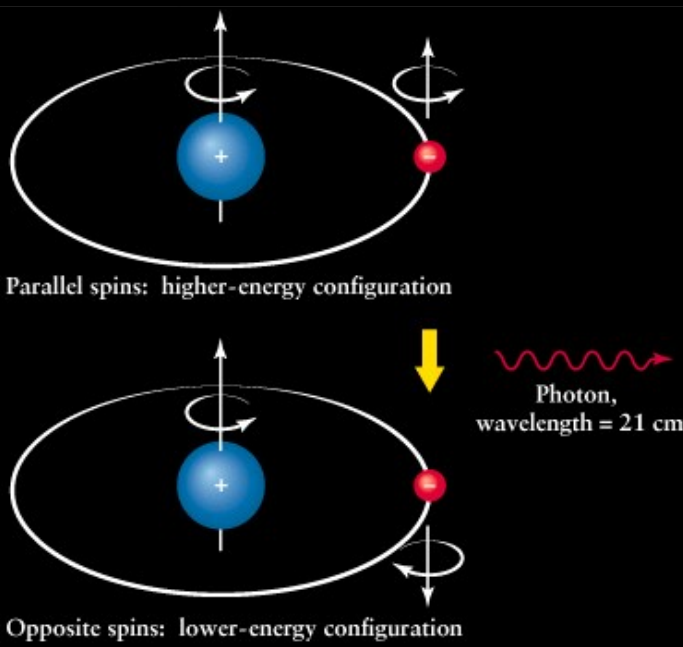
Frequency [MHz]

200 MHz

Cowen 2013

DAWN'S FA

The Big Bang gave birth to the universe. After about 370,000 years, electrons and protons combined to form neutral hydrogen. During the resulting 'dark ages', gravity began to pull the neutral gas together, eventually forming the first stars and galaxies. The remaining neutral gas eventually broke apart and was blown away into space, leaving behind a vast, empty void.

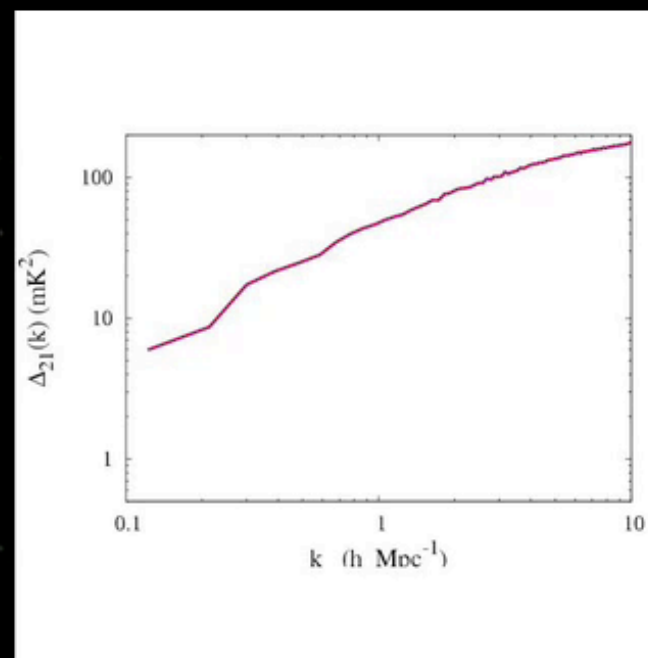




M.Alvarez (CITA)
& R. Kaehler (Stanford)



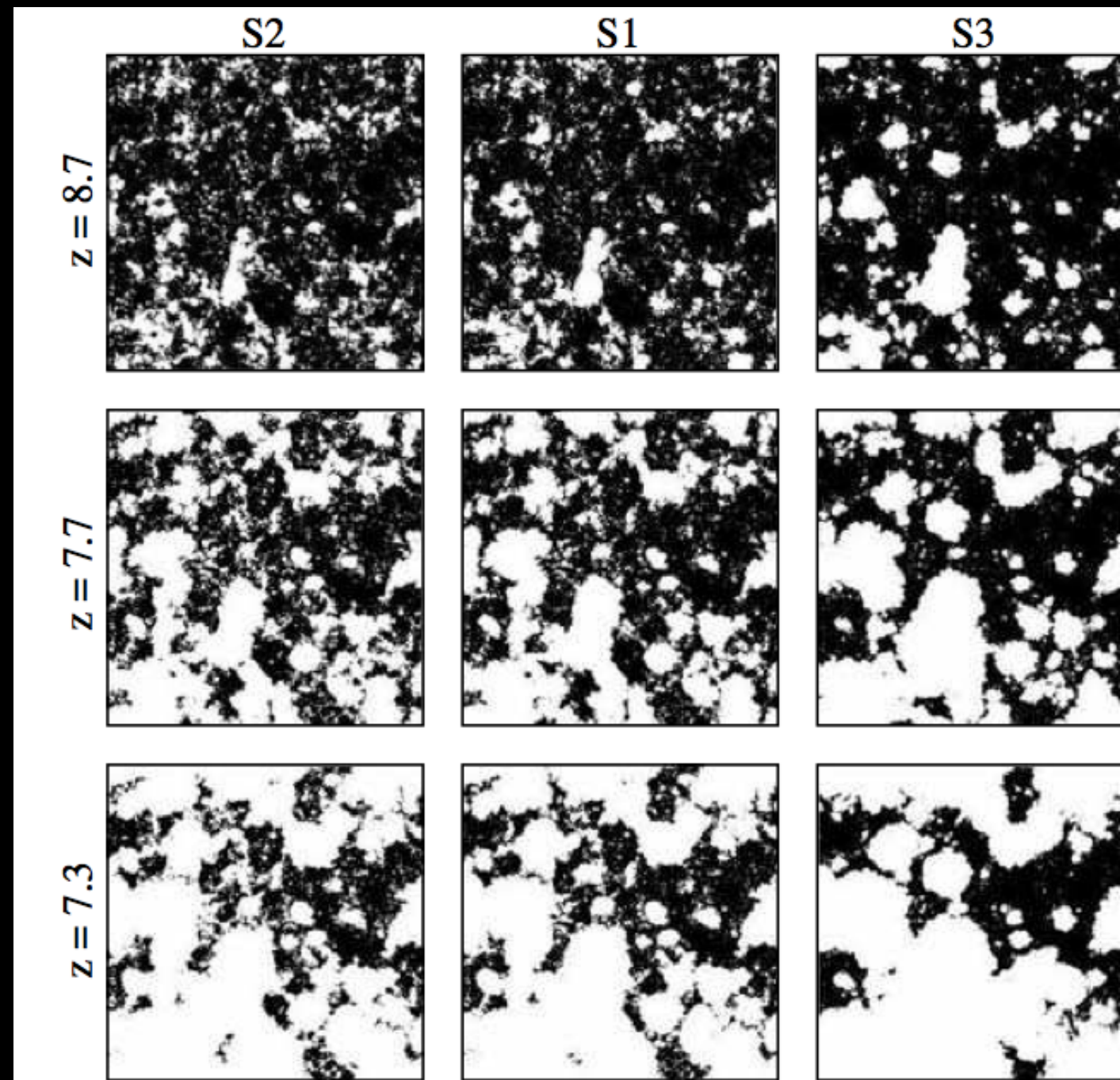
$z=11.1$



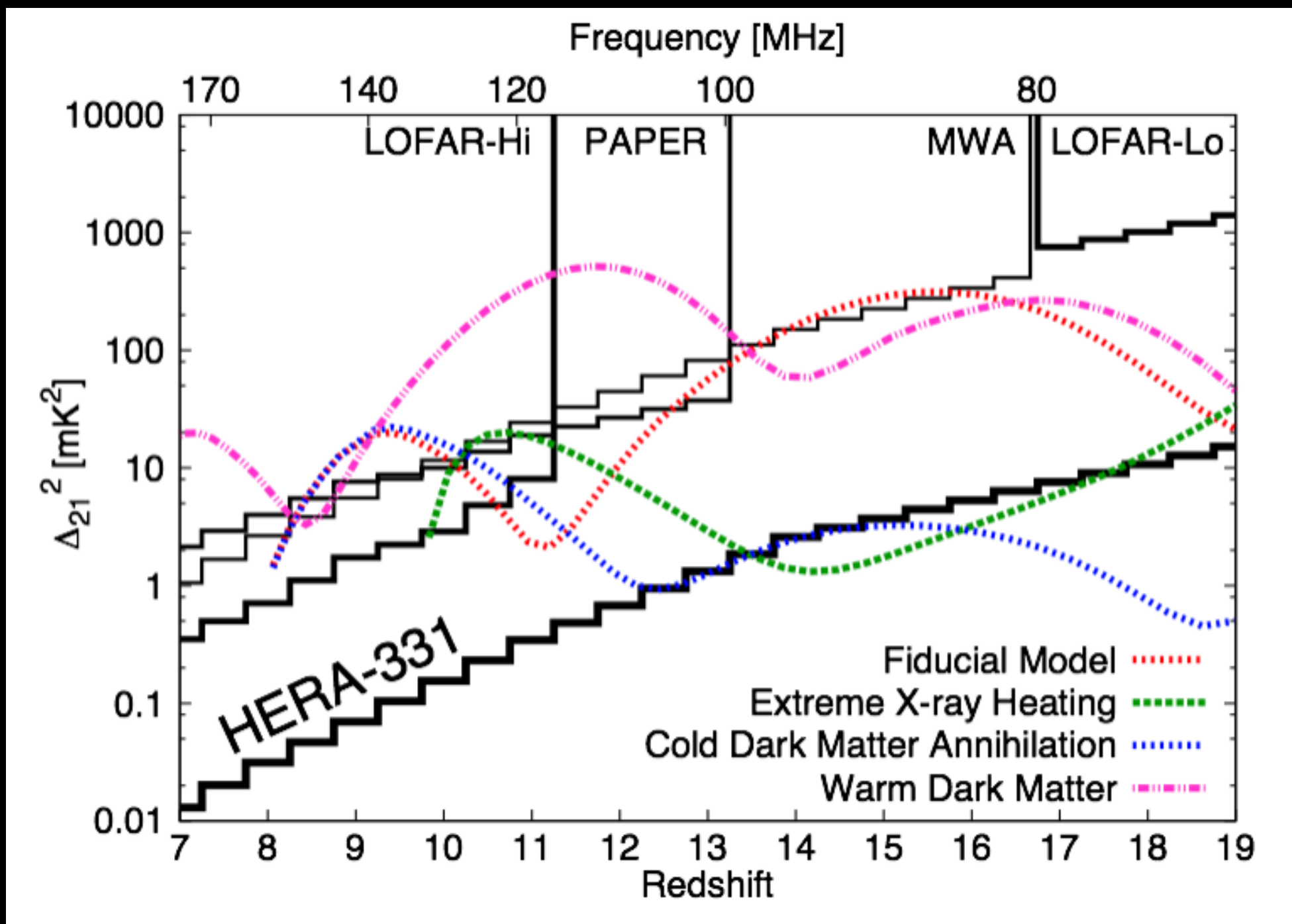
M. Mcquinn (Berkeley)

IMAGING

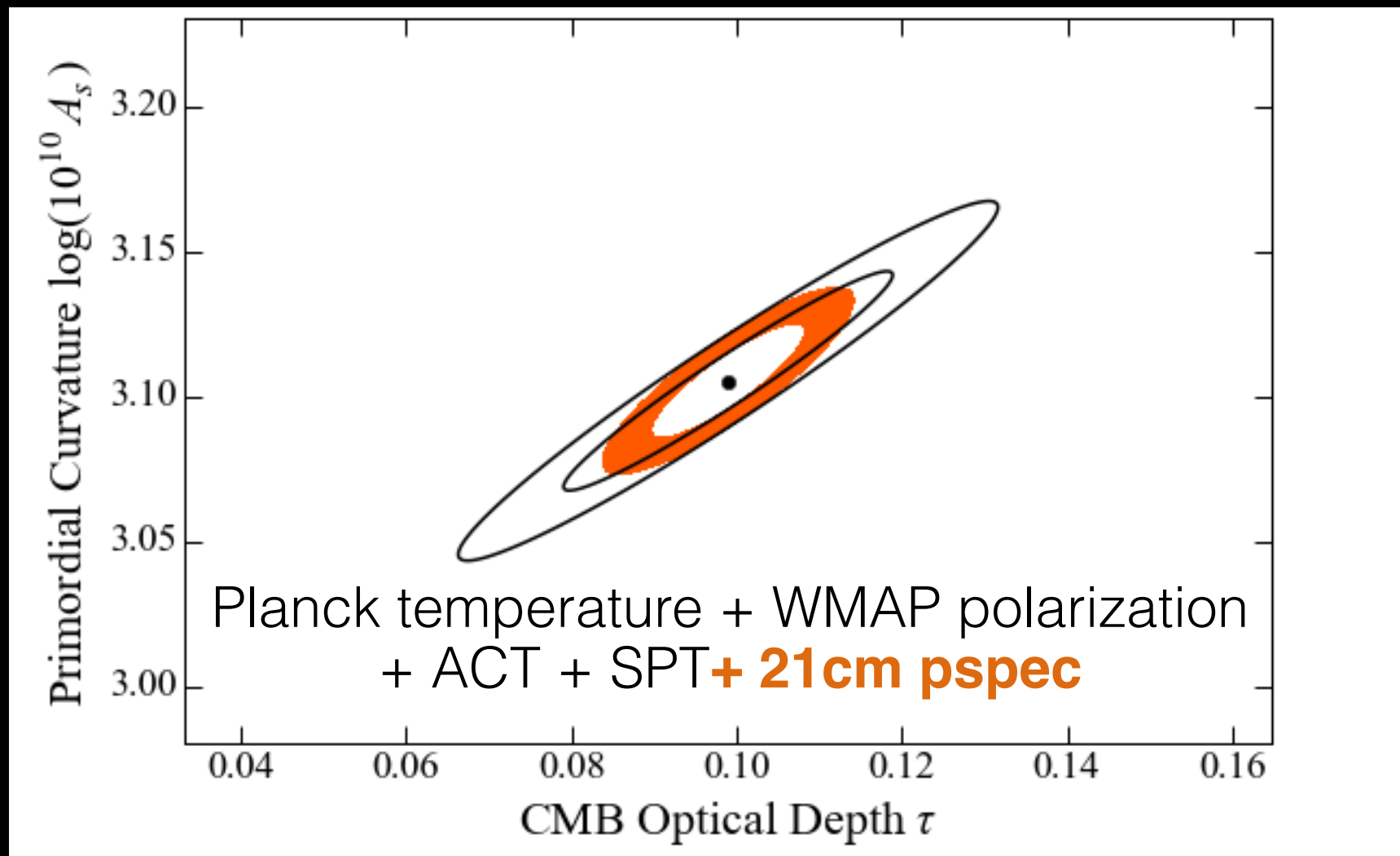
- signal amplitude $\sim 20\text{mK}$
- first generation sensitivity: 80mK
- SKA sensitivity: 4mK
- near future: statistical measures



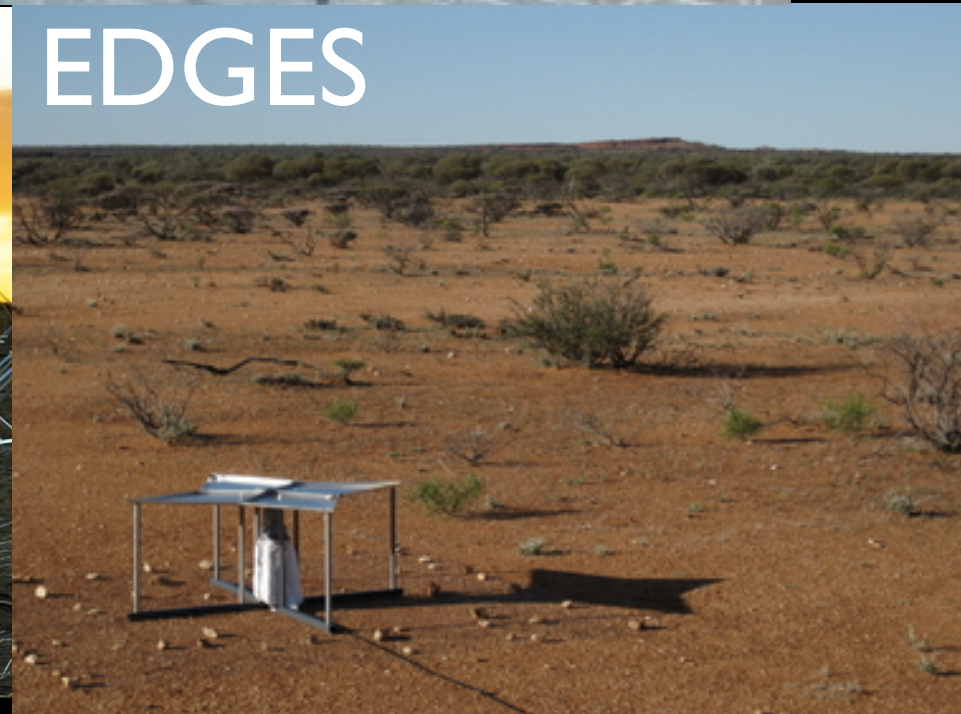
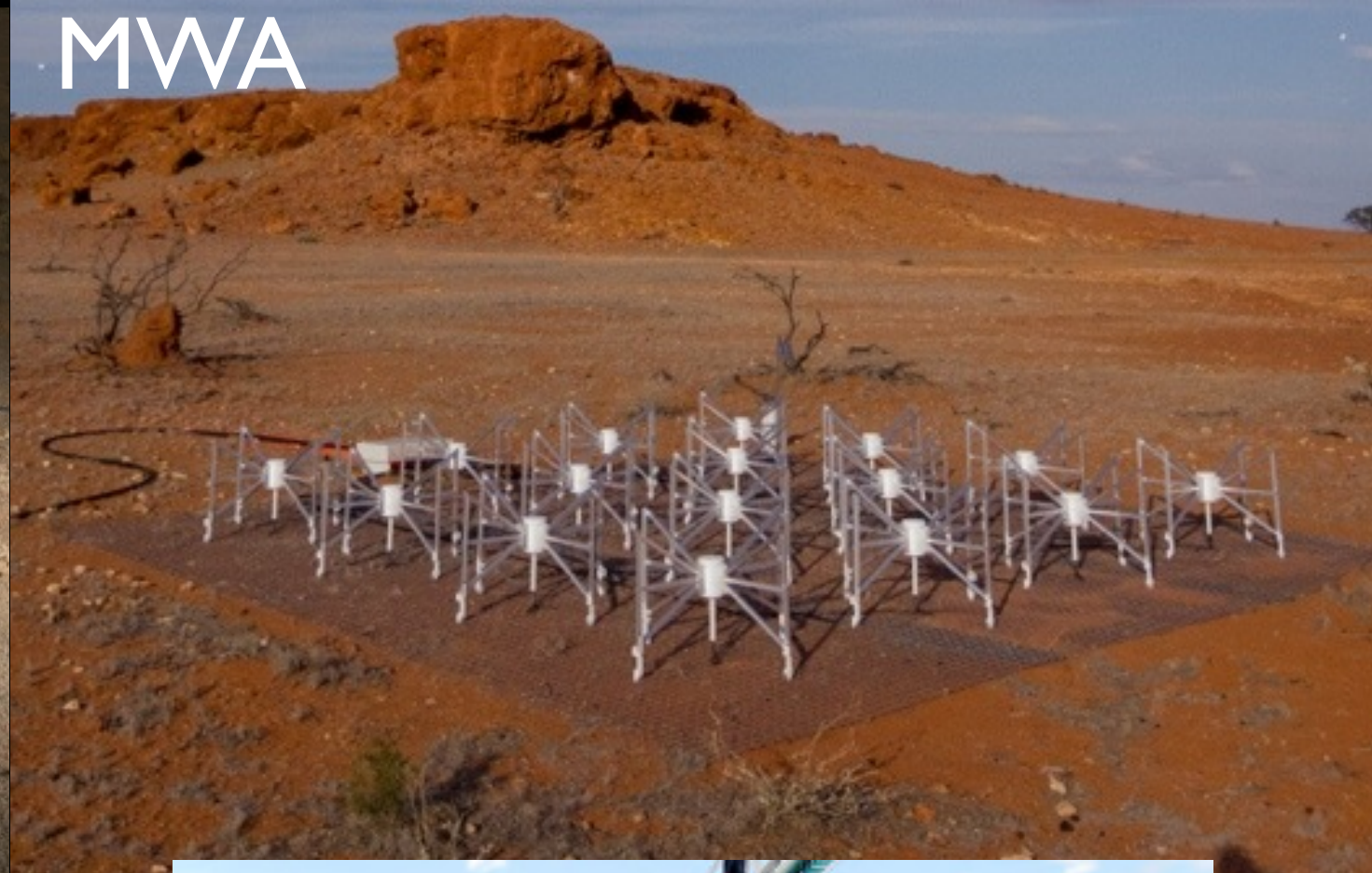
McQuinn et al. 2007 MNRAS 377



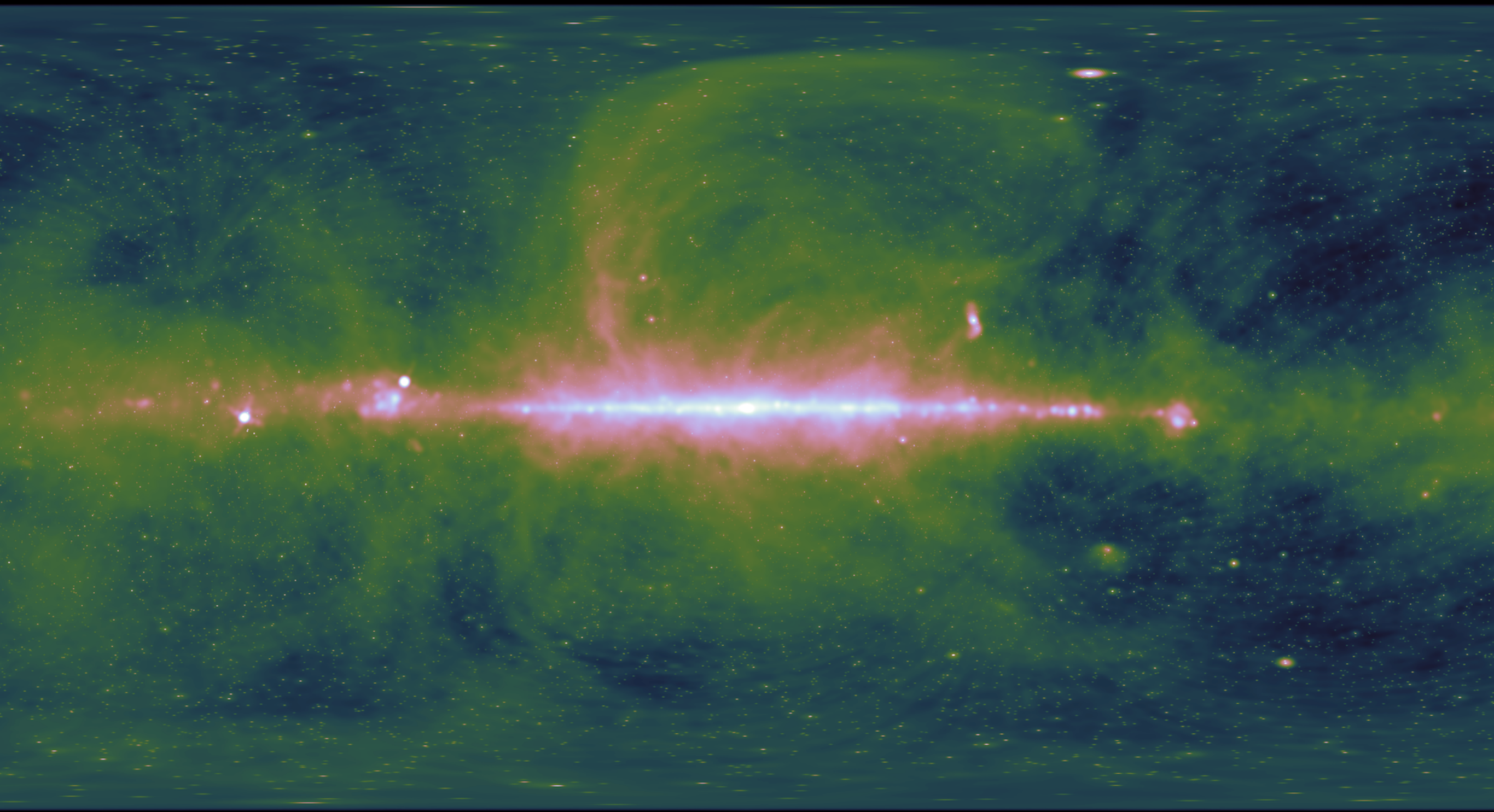
Mesinger et al 2014



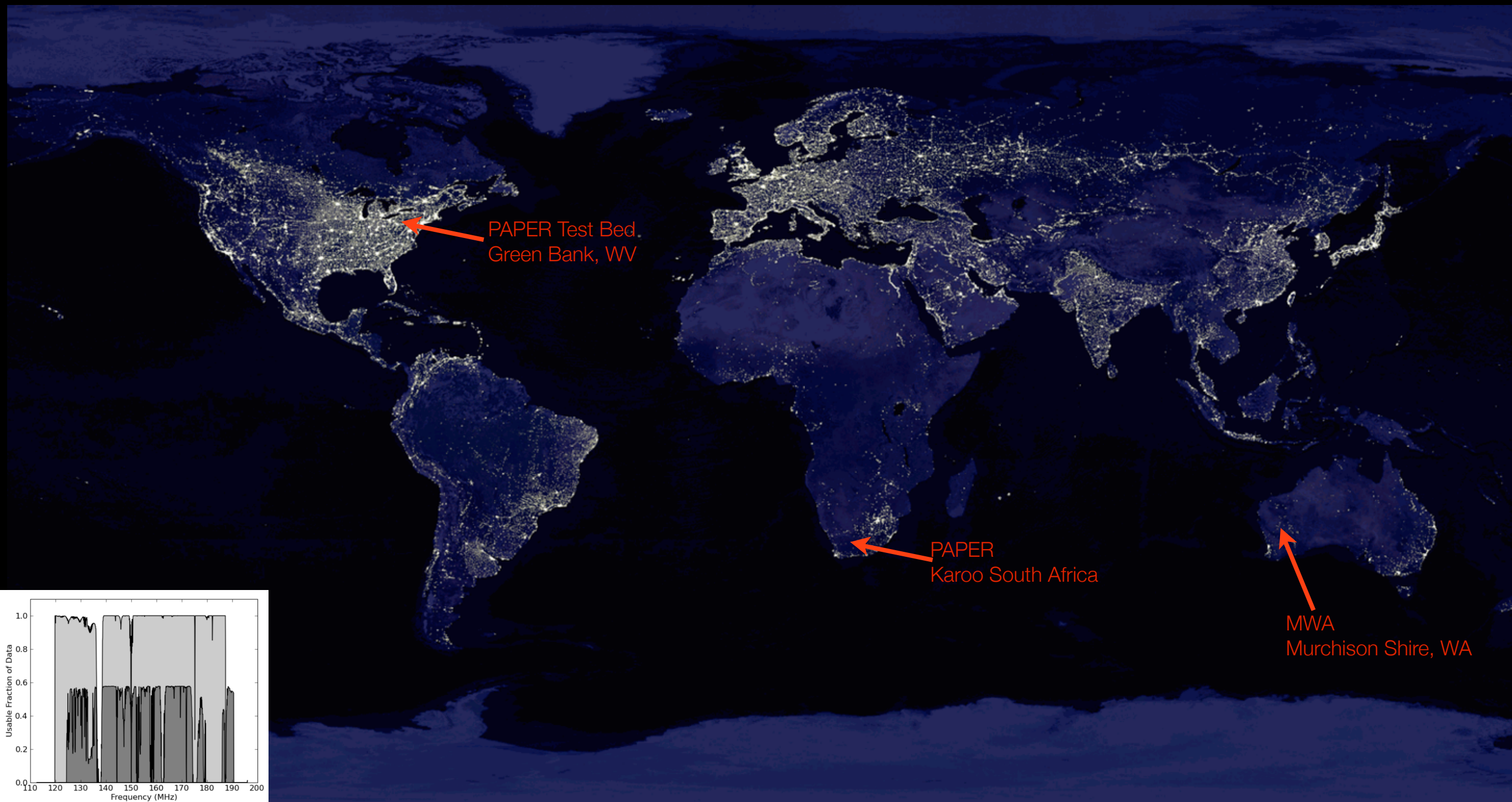
Liu et al in prep



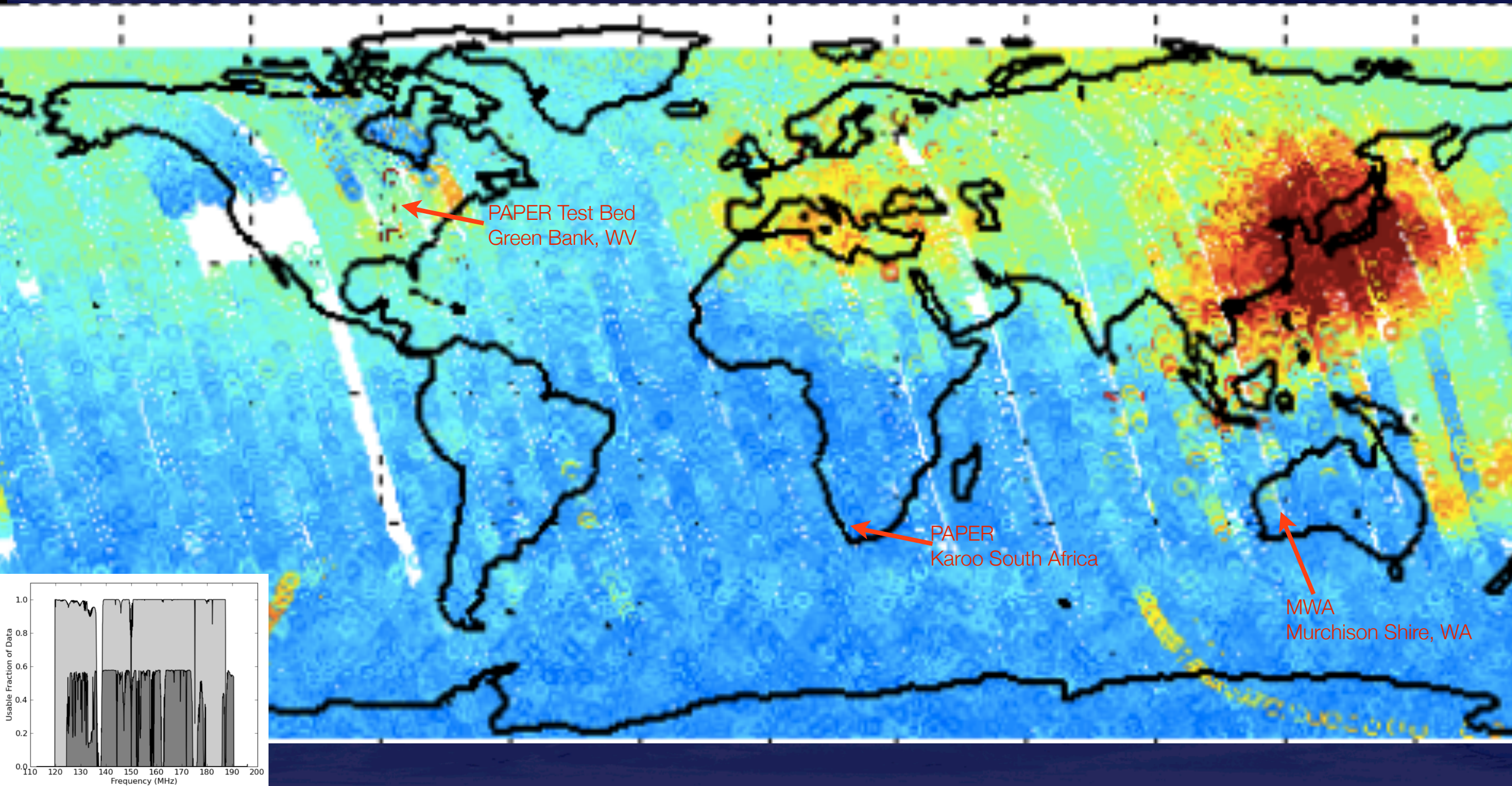
CHALLENGES

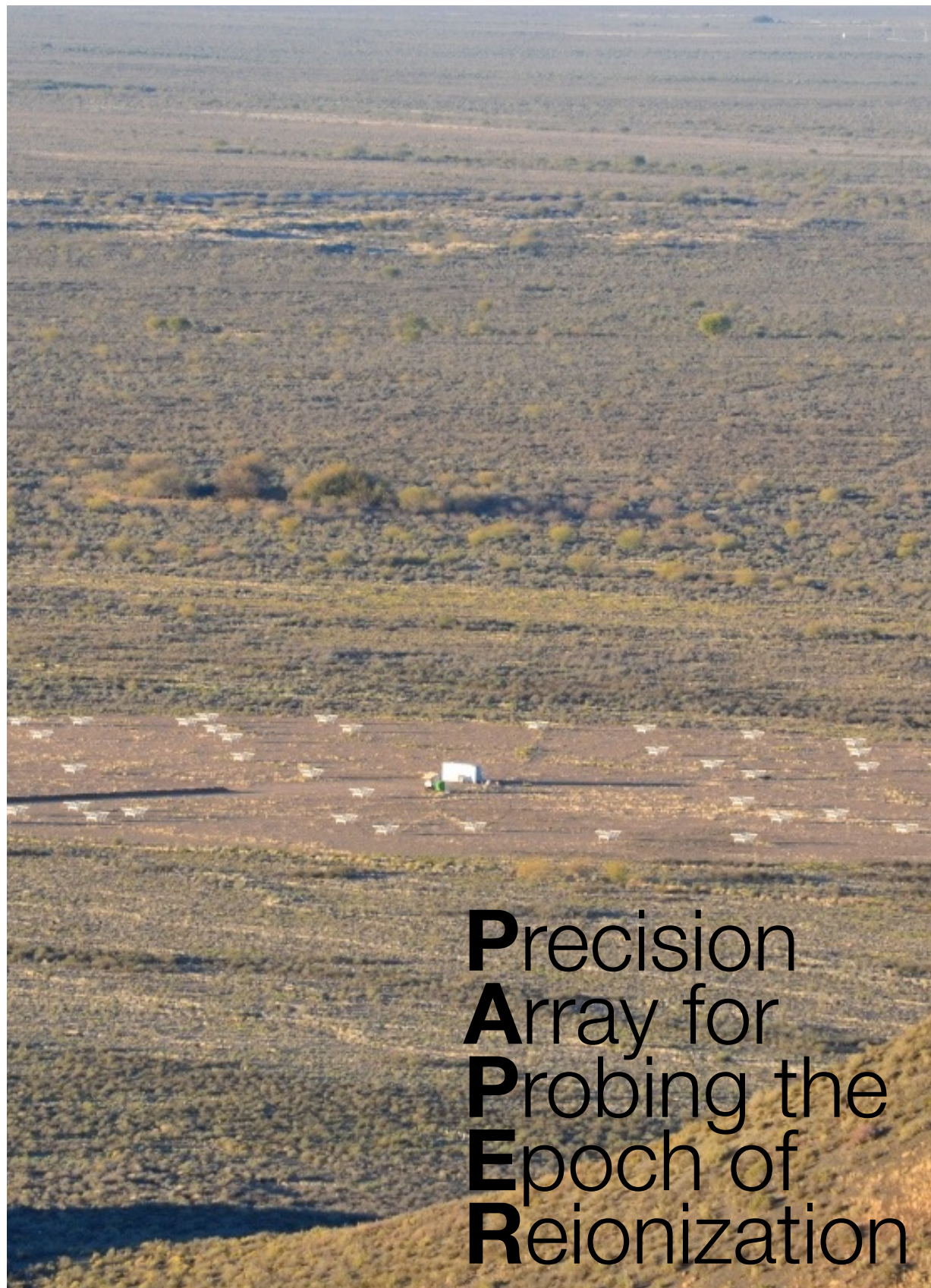


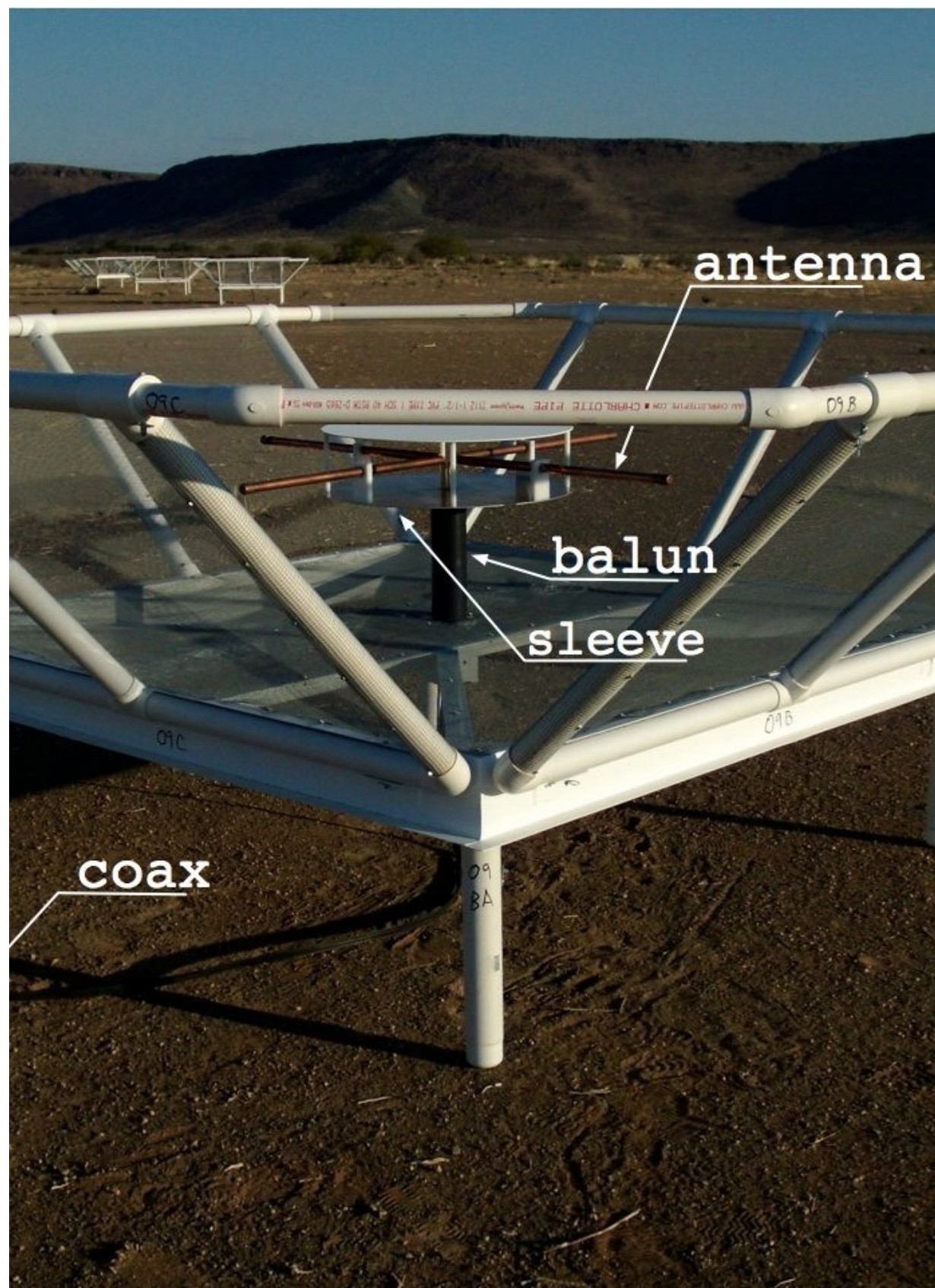
RADIO FREQUENCY INTERFERENCE



HUMAN INTERFERENCE





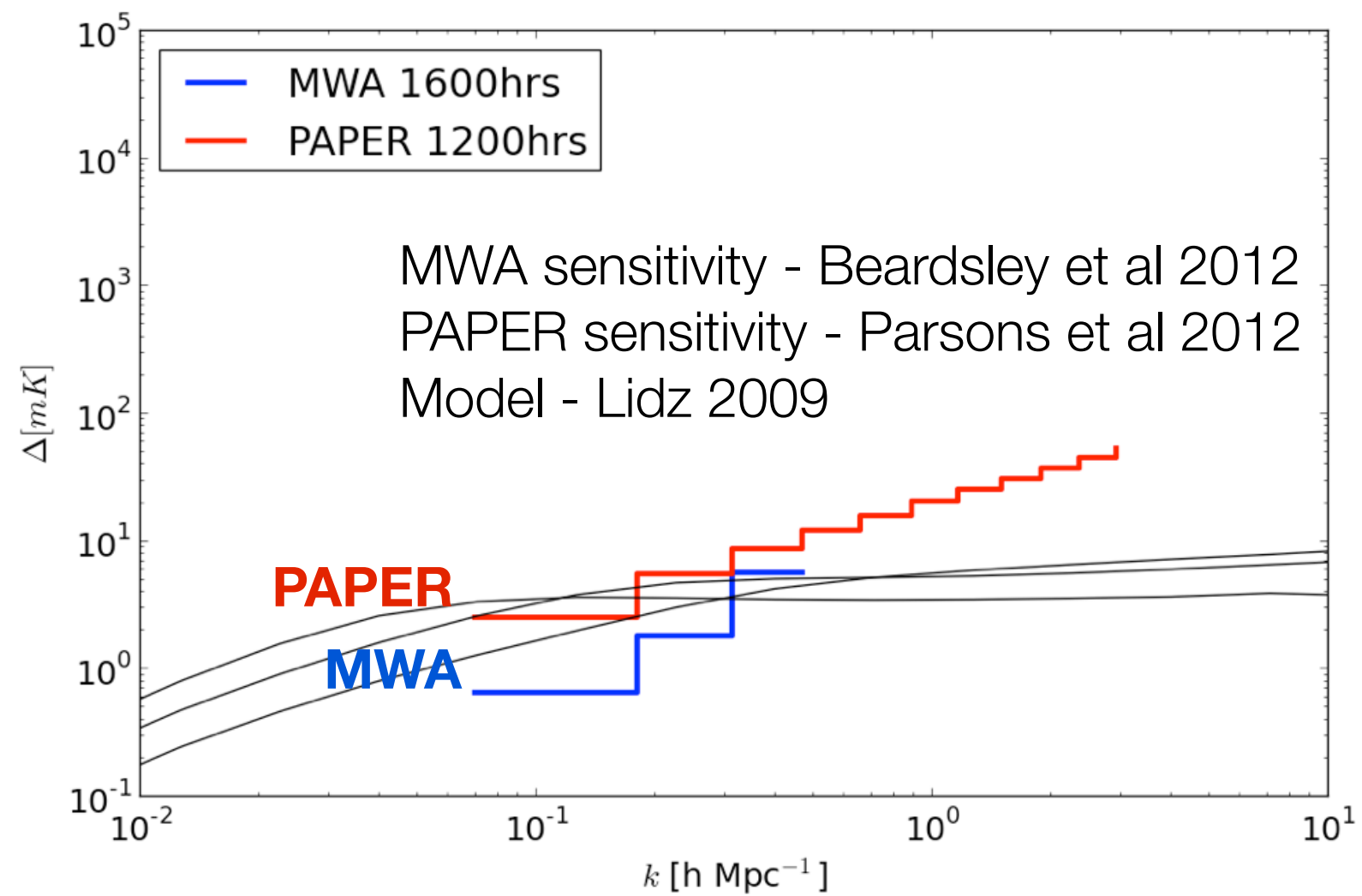


PAPER and MWA close up





	PAPER	MWA
Antenna	dipole	phased dipole tiles
antenna positions	grid	radial
spectrum	100-200MHz	80-300MHz
location	Karoo Desert (SKA-South Africa)	Western Australia (SKA-Australia)
field of view	60 degrees	30 degrees
Strength	systematic rejection	imaging capability
Weakness	limited sensitivity	uneven spectral coverage



PAPER AND MWA

DEEP INTEGRATION VS REMOVING FOREGROUNDS

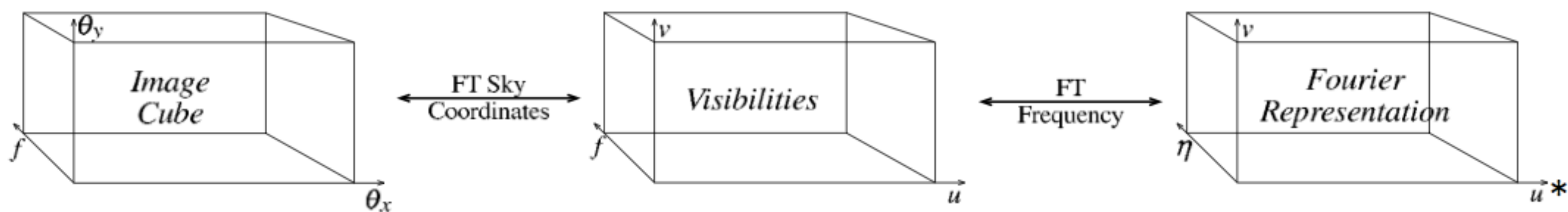


Filtering/Covariance

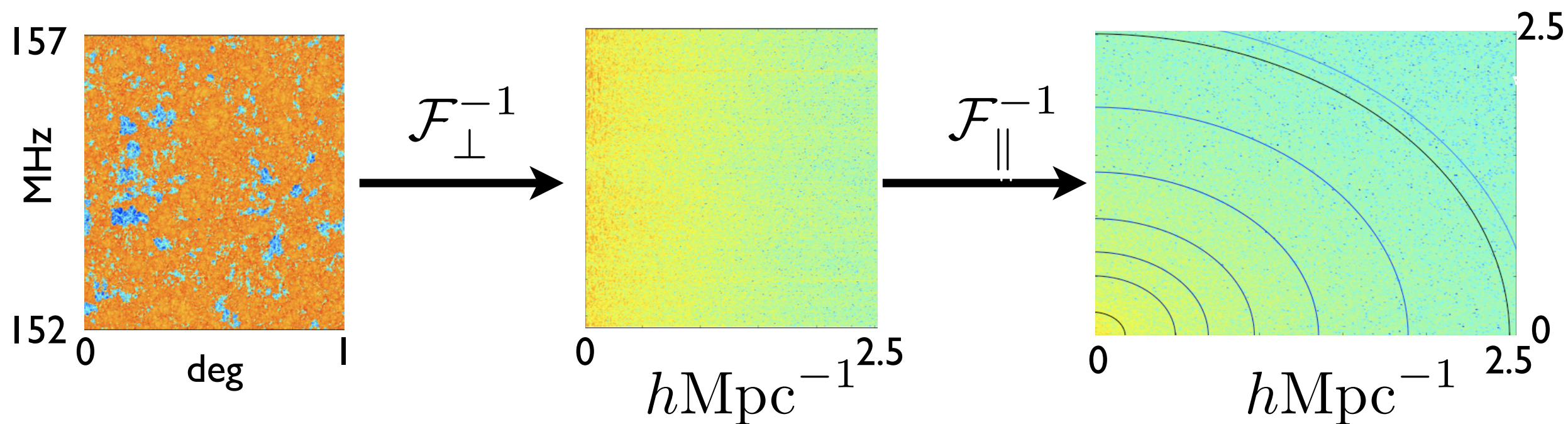


Direct Subtraction

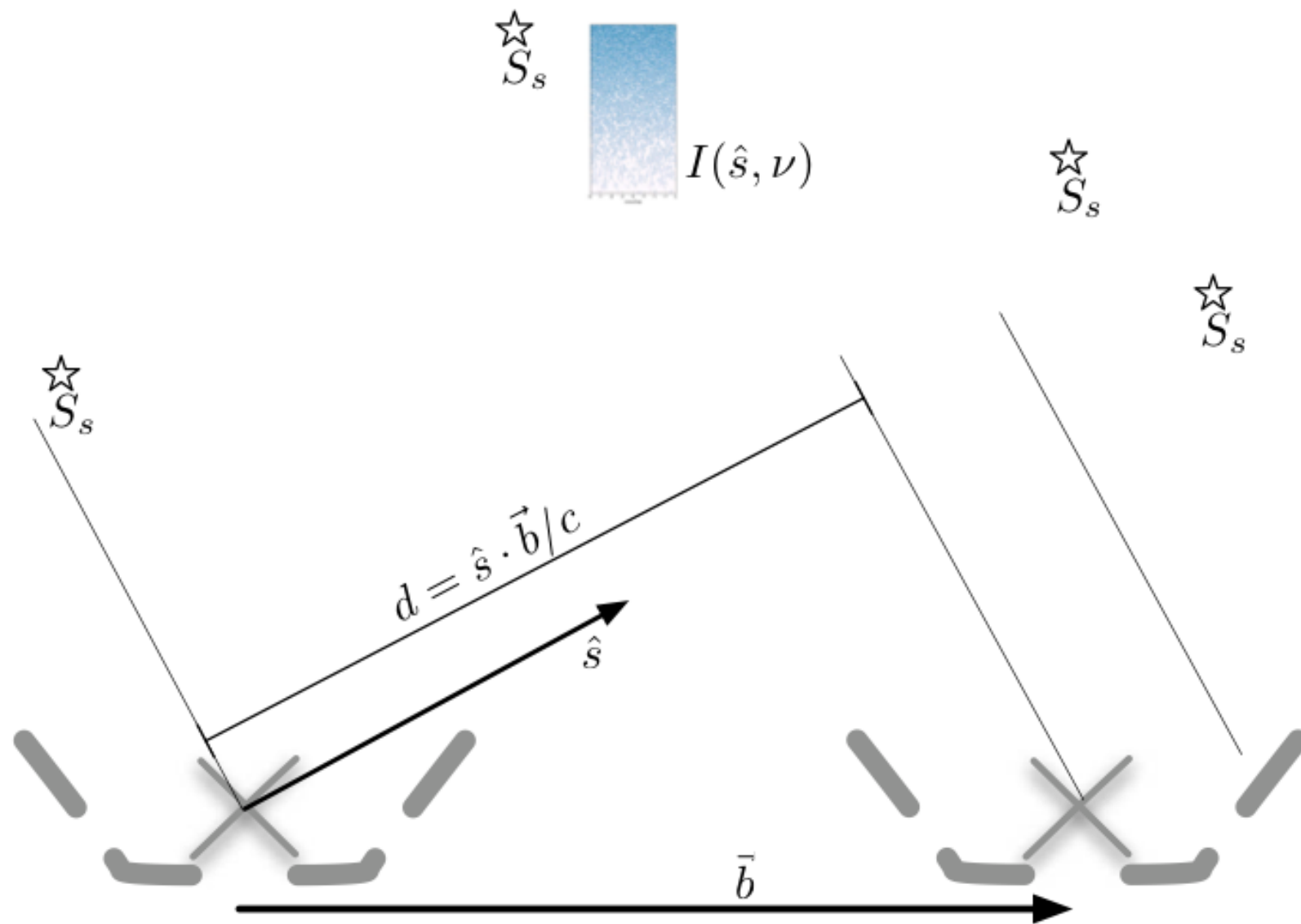
HI 21cm



Morales, 2006 AJ 619



Interferometry 101

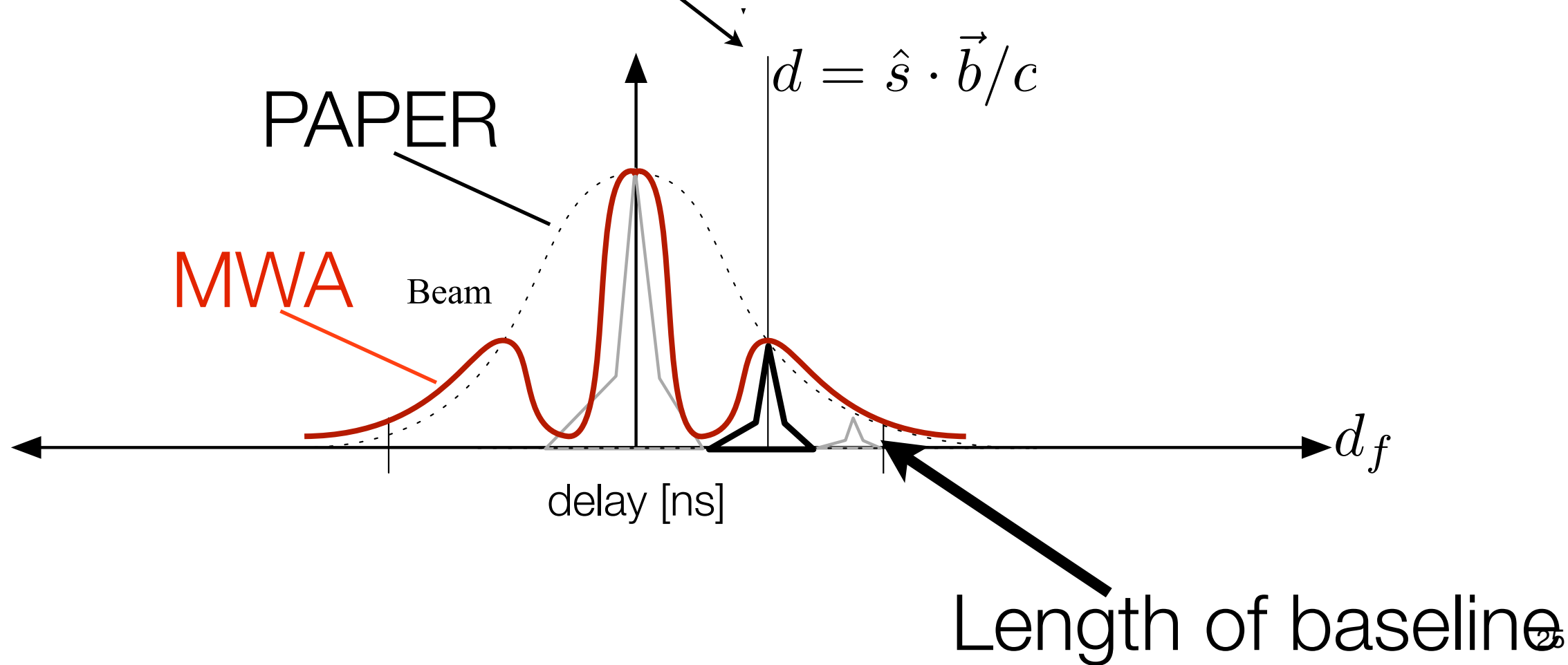


$$V_{ij} \approx \underbrace{\sum_s S_s e^{-2\pi i d_s \nu}}_{\text{Point Sources (wide band)}} + \underbrace{\int I(\hat{s}, \nu) e^{-2\pi i \hat{s} \cdot \vec{b} \nu / c} d\Omega}_{\text{EoR (Narrow band)}}$$

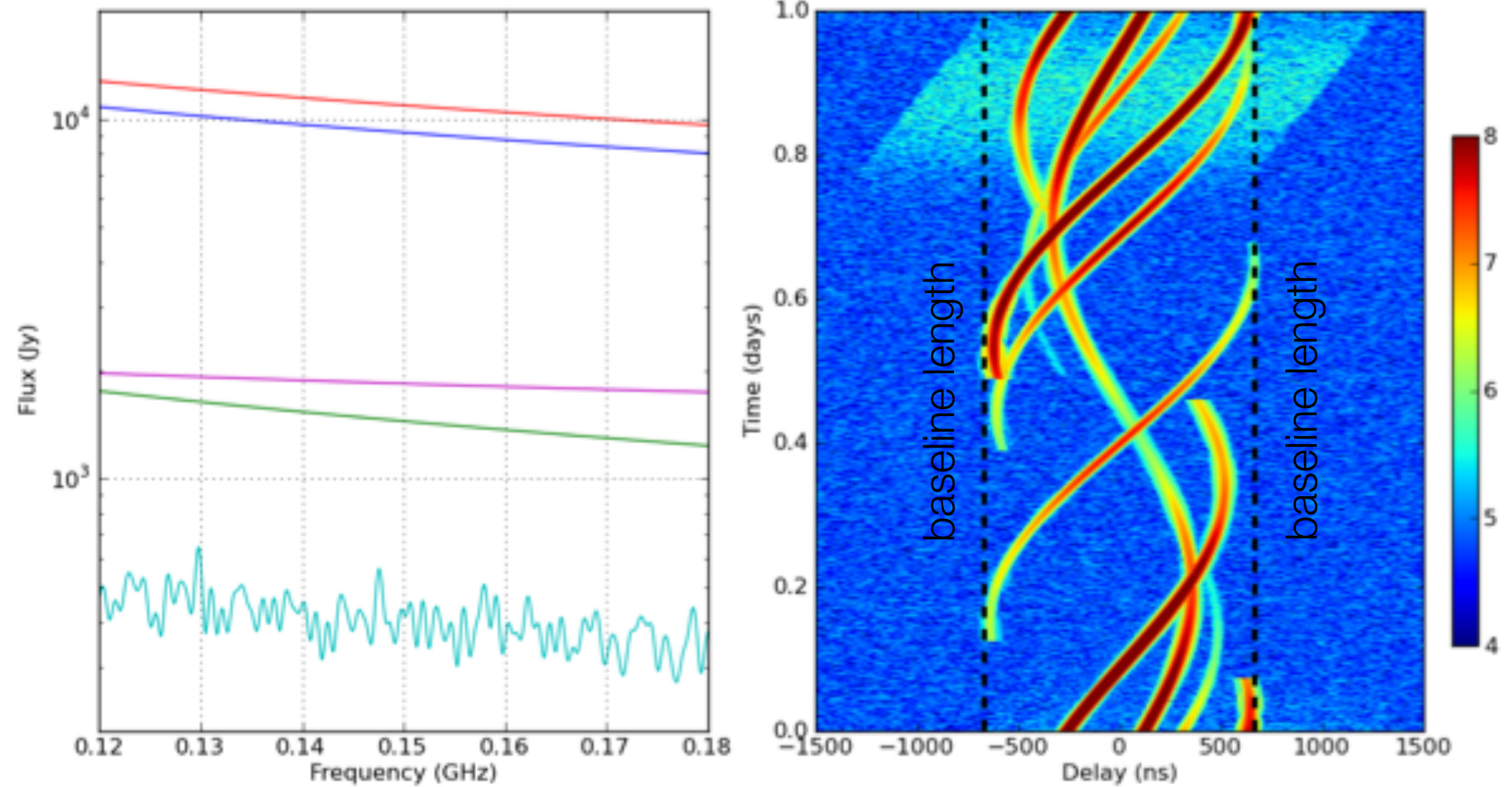
F it

$$\mathbf{FT}(V_{ij} \approx \sum_s S_s e^{-2\pi i d_s \nu} + \int I(\hat{s}, \nu) e^{-2\pi i \hat{s} \cdot \vec{b} \nu / c} d\Omega)$$

Point Sources (wide band) EoR (Narrow band)

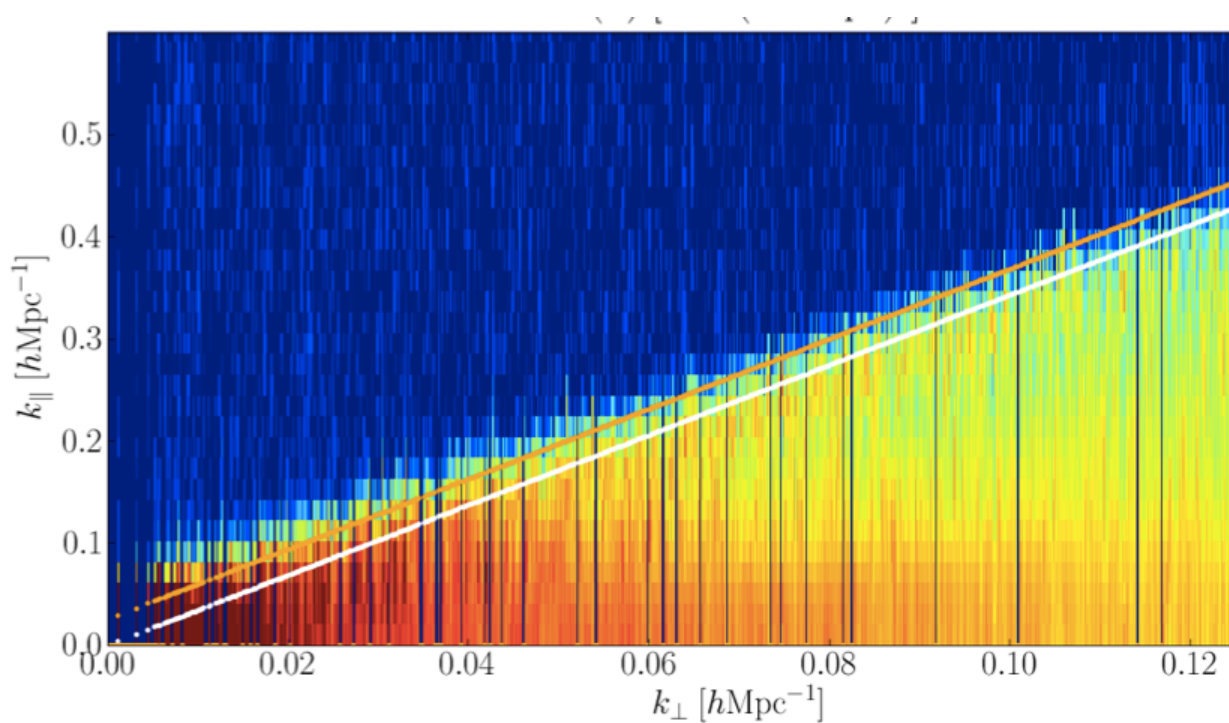


Foregrounds on a single baseline



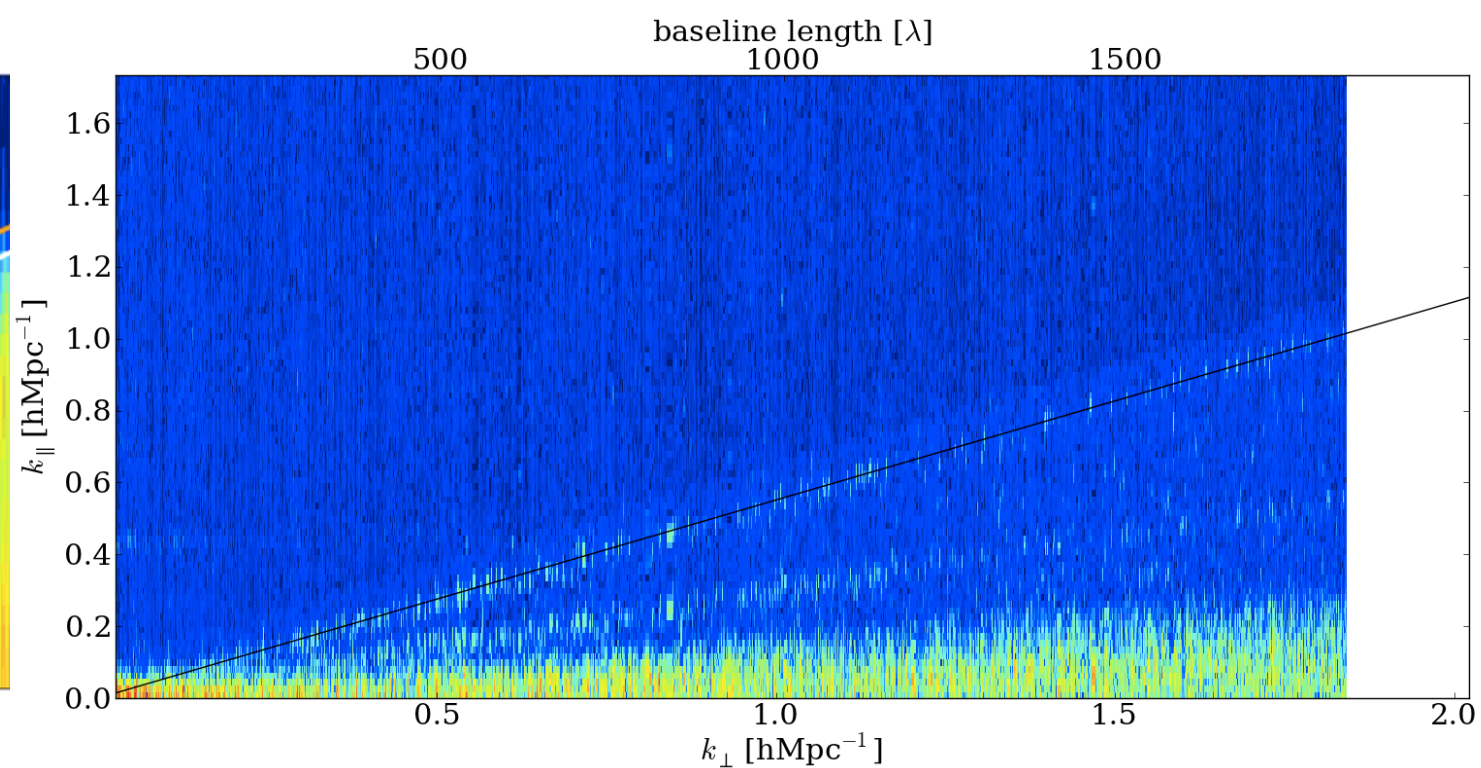
Foregrounds

PAPER

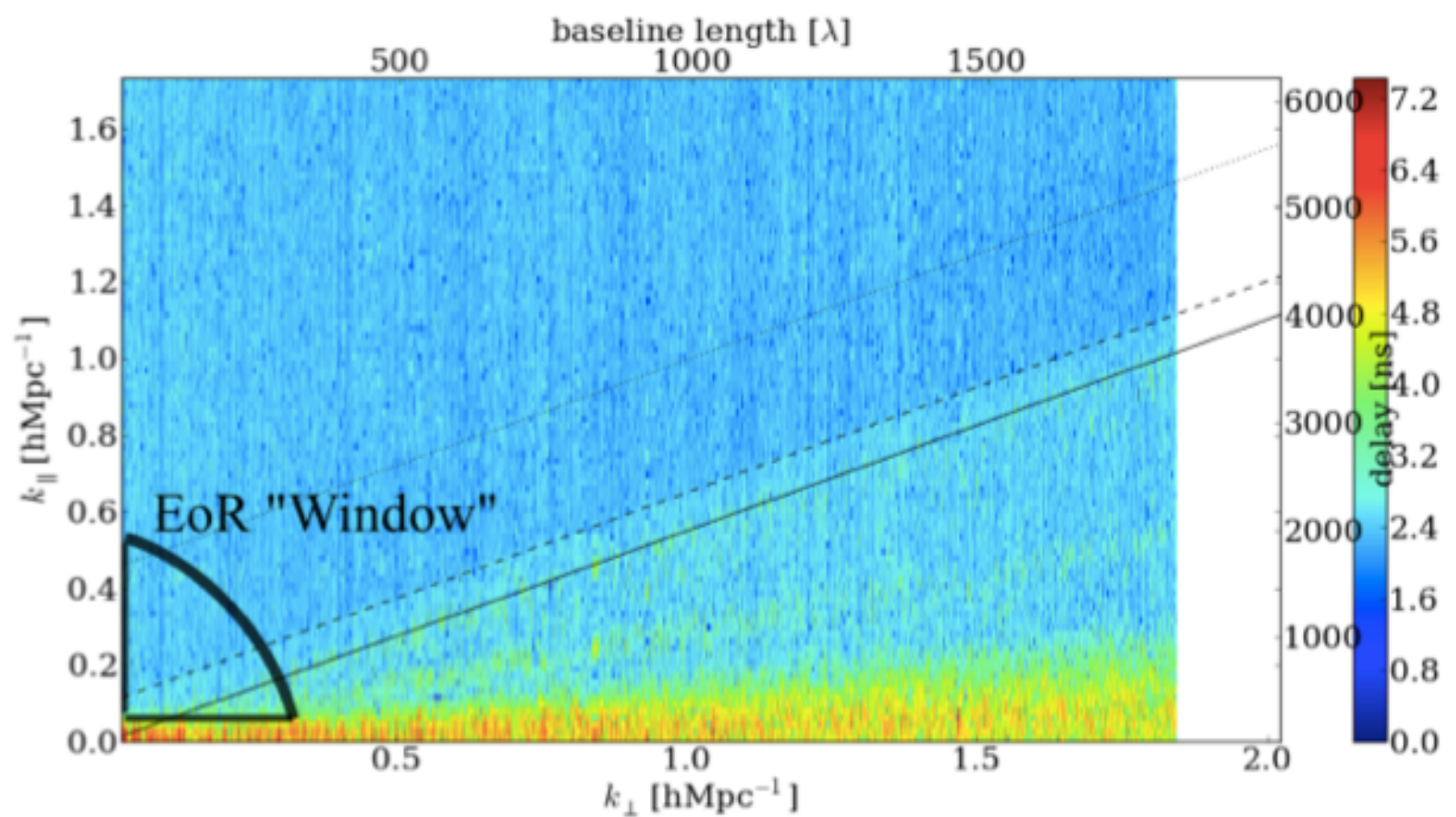
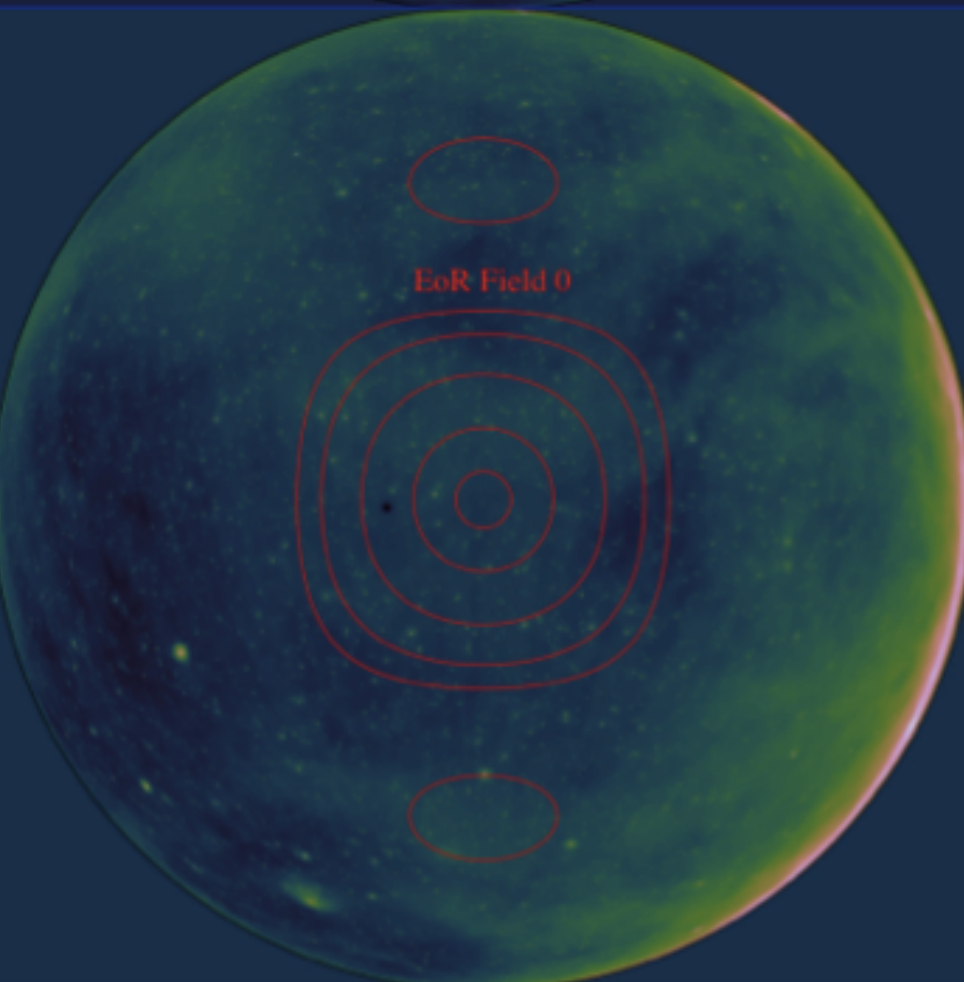
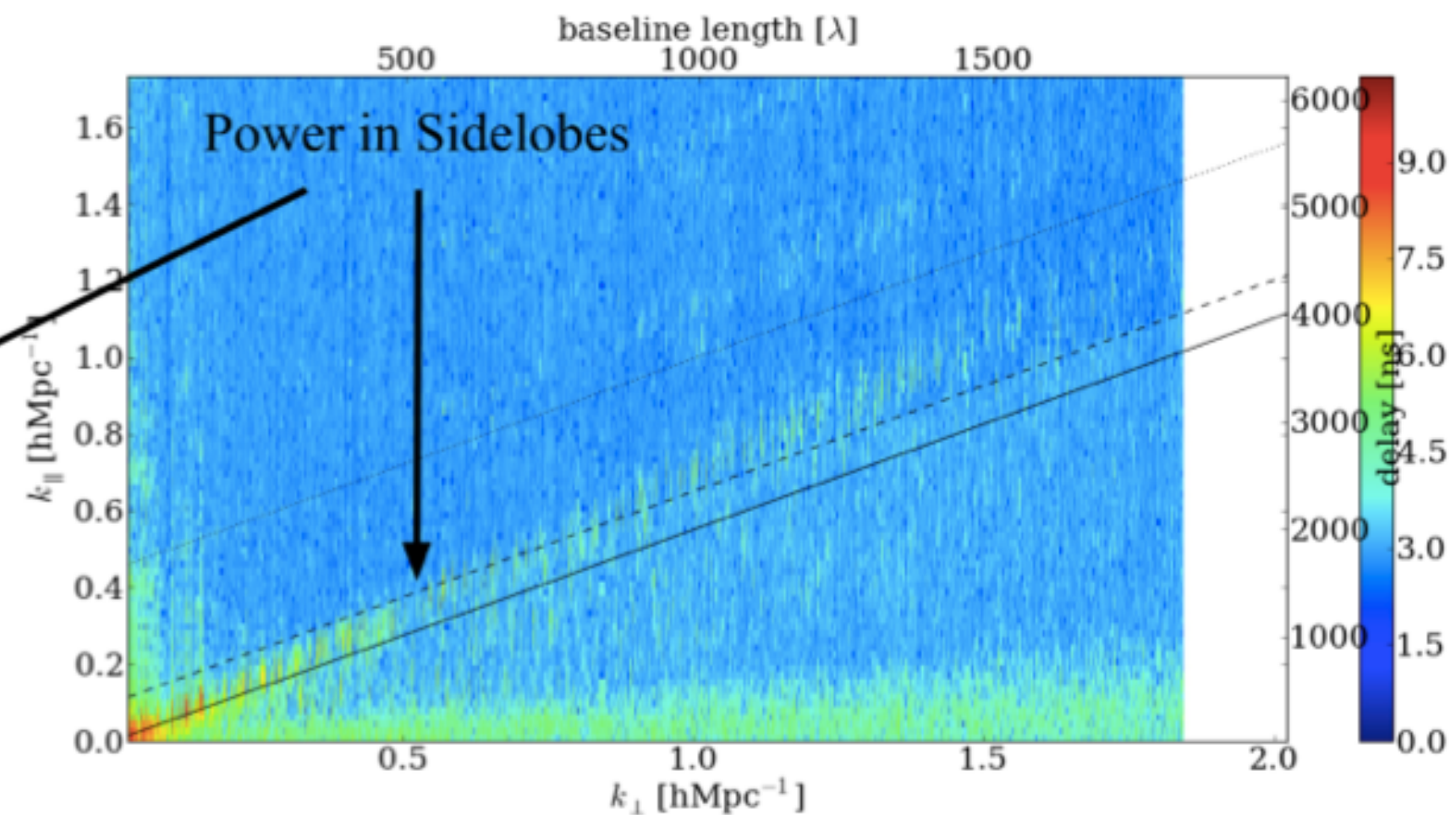
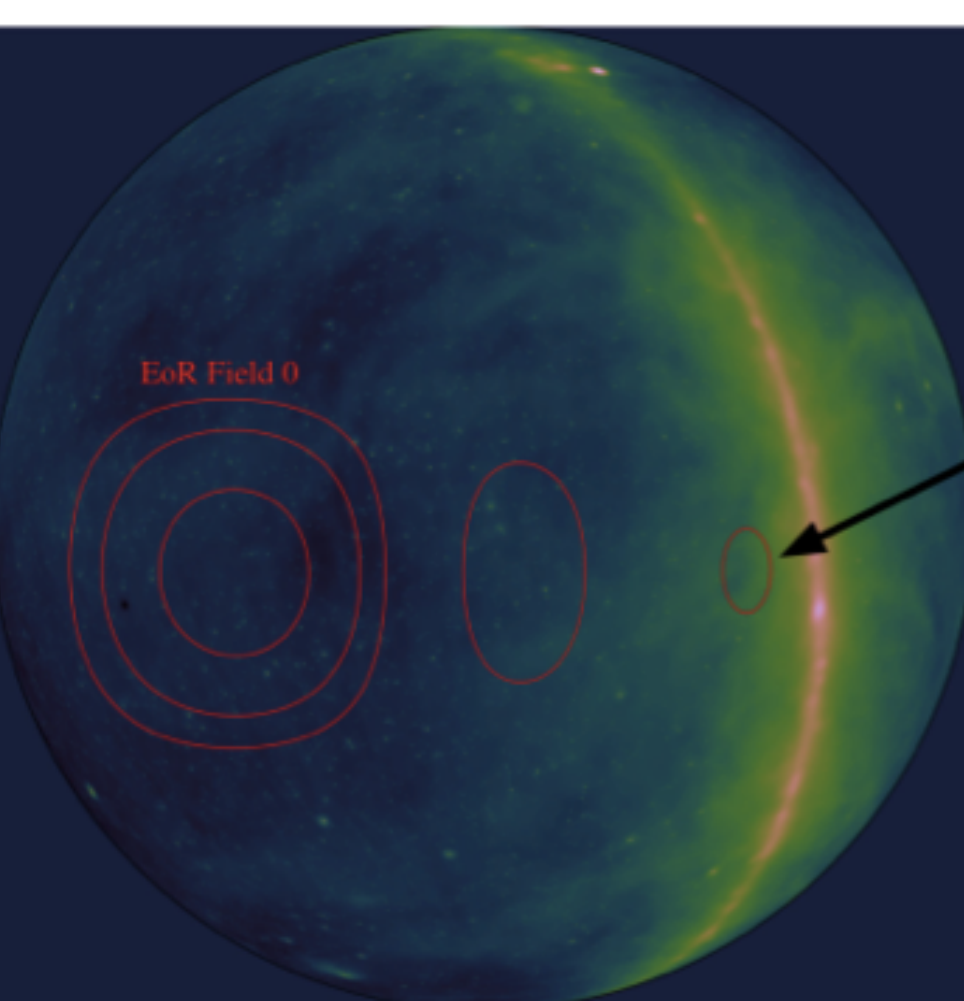


Pober et al 2013

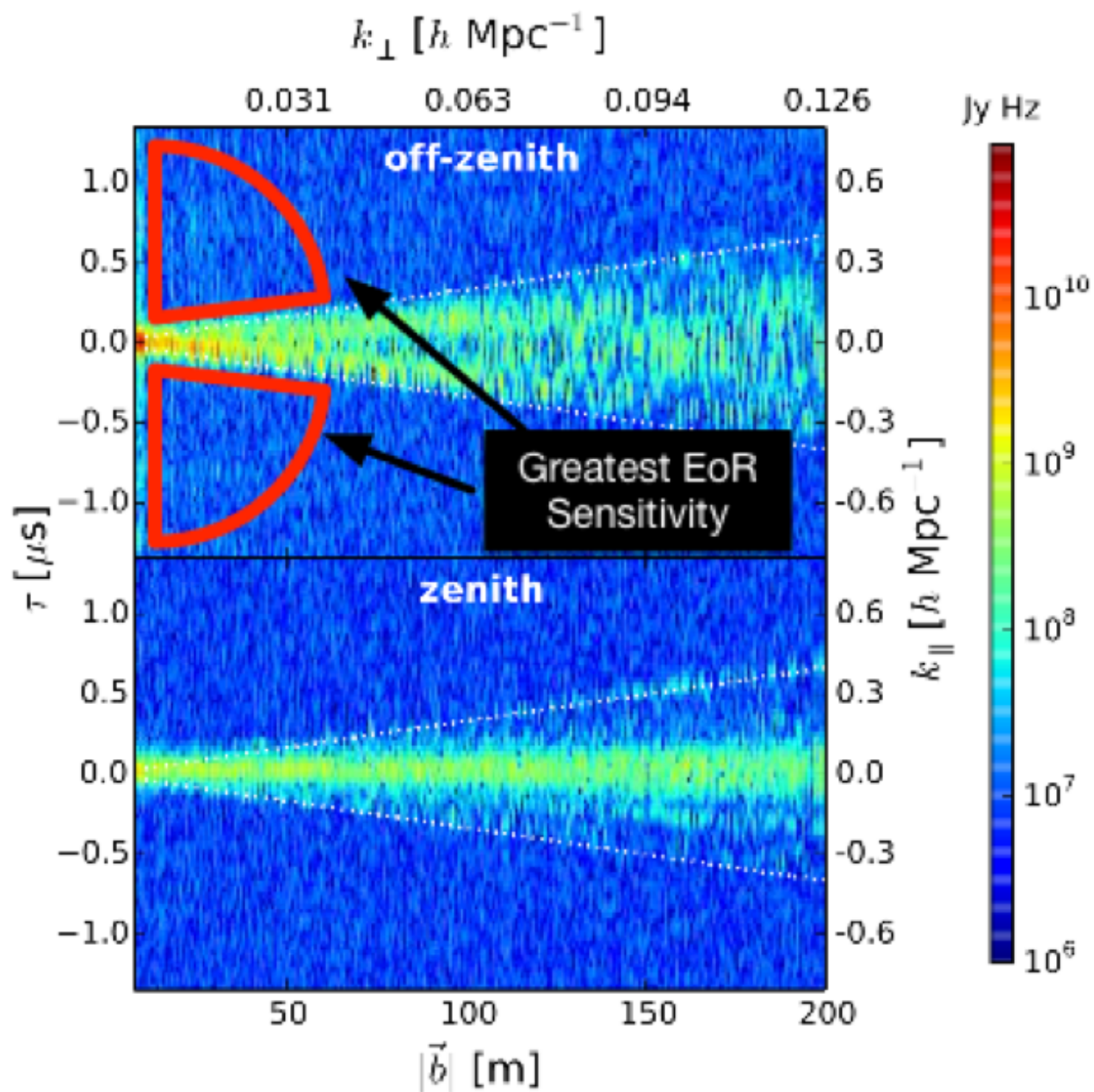
MWA



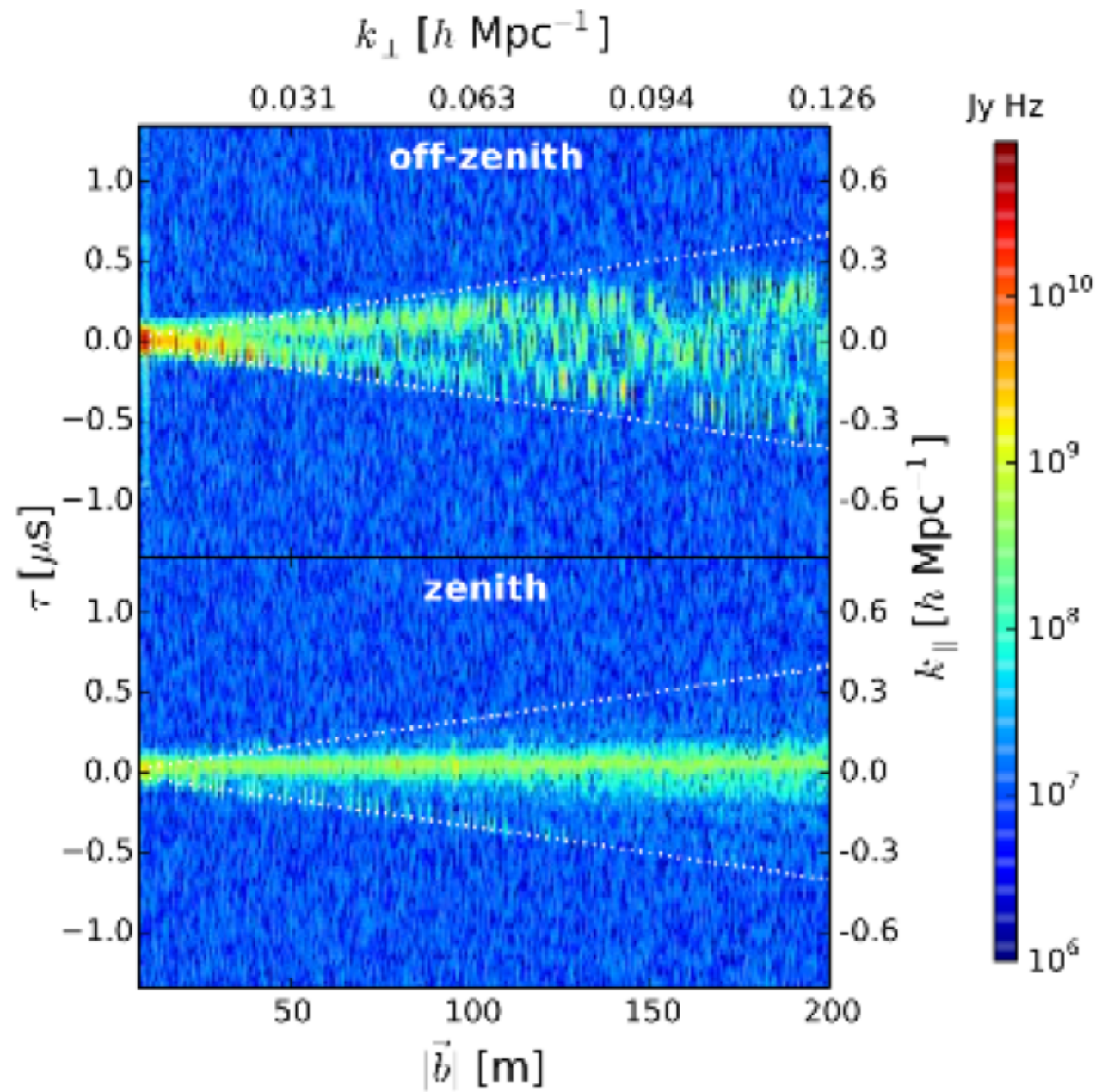
August 23, 2013



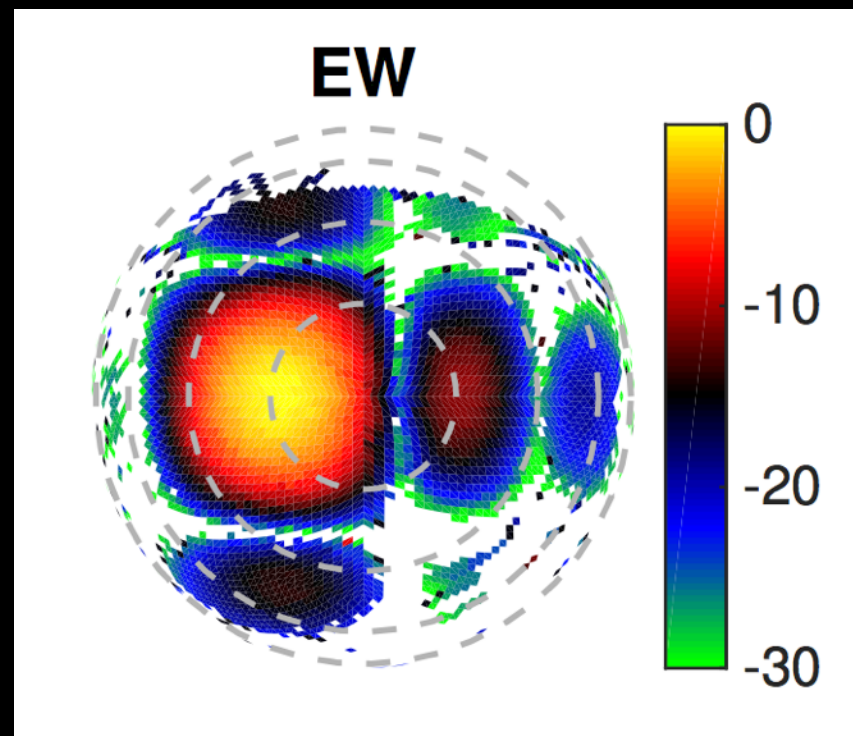
Data



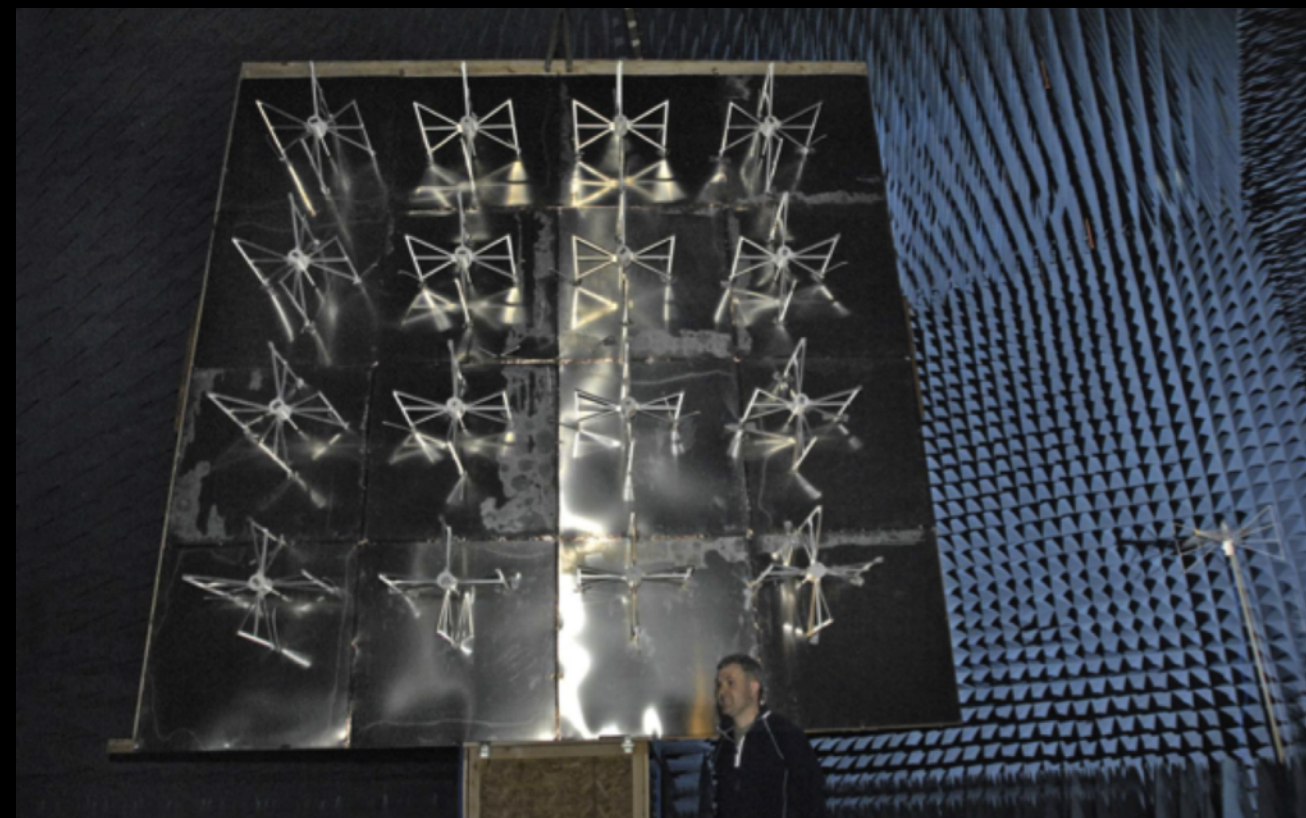
Simulation



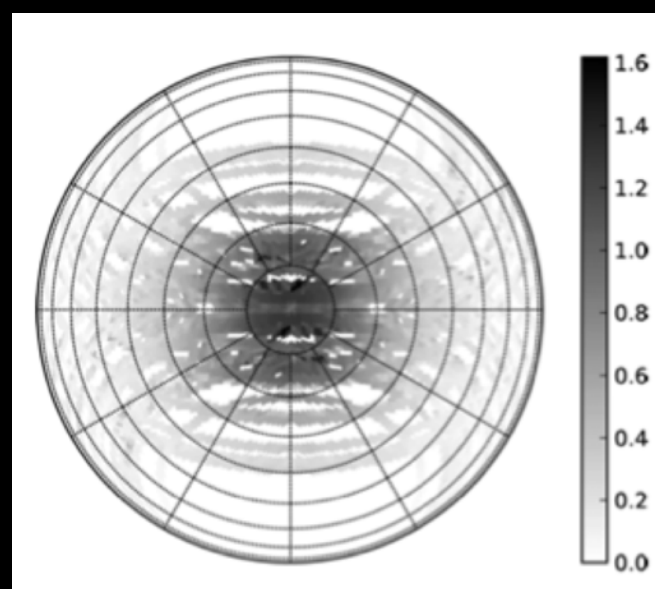
Thyagarajan et al (acceptance imminent)



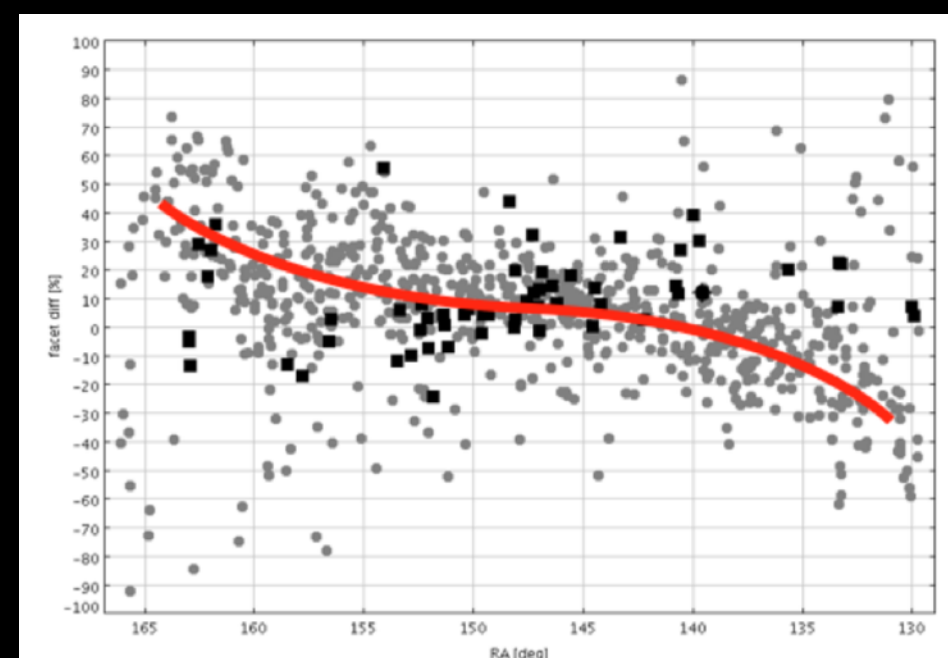
Neben / ORBCOMM



MIT/Lincoln Labs



Pober et al 2012



Jacobs 2013

EXTERNAL CALIBRATOR FOR
HI OBSERVATORIES

ECHO



DONALD C. BACKER

PRECISION ARRAY FOR PROBING THE EPOCH OF REIONIZATION

Parsons (UCB)

Deboer

MacMahon

Dexter

Ali

Cheng

Liu

Aguirre (UPenn)

Kohn

Moore

Jacobs (ASU)

Bernardi (SA)

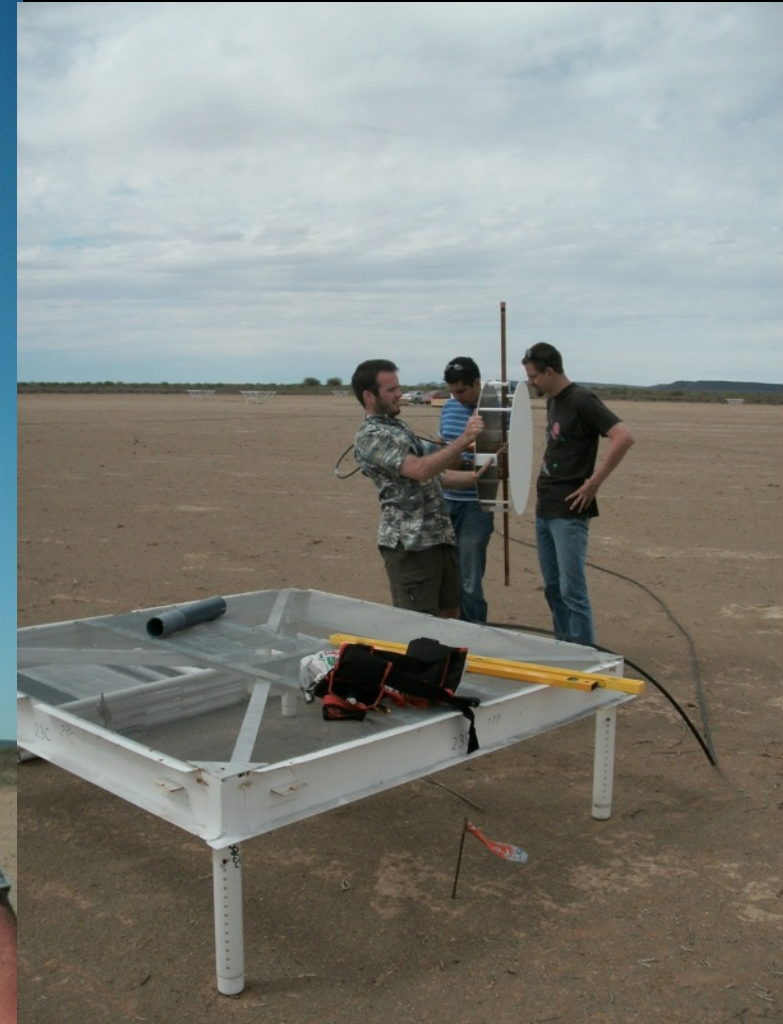
Carilli (NRAO)

Bradley (UVa)

Pober (UWa)



PAPER Construction





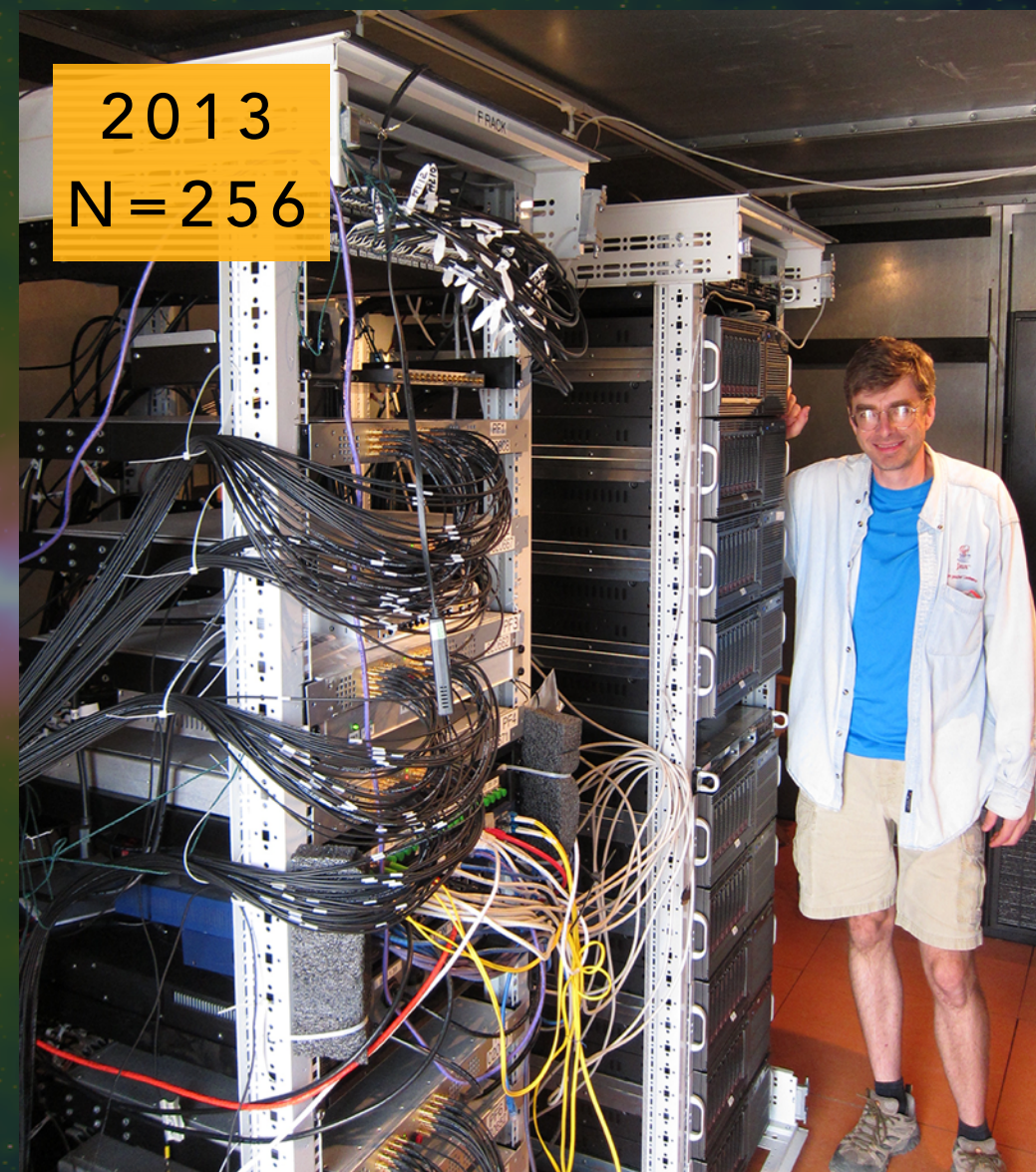
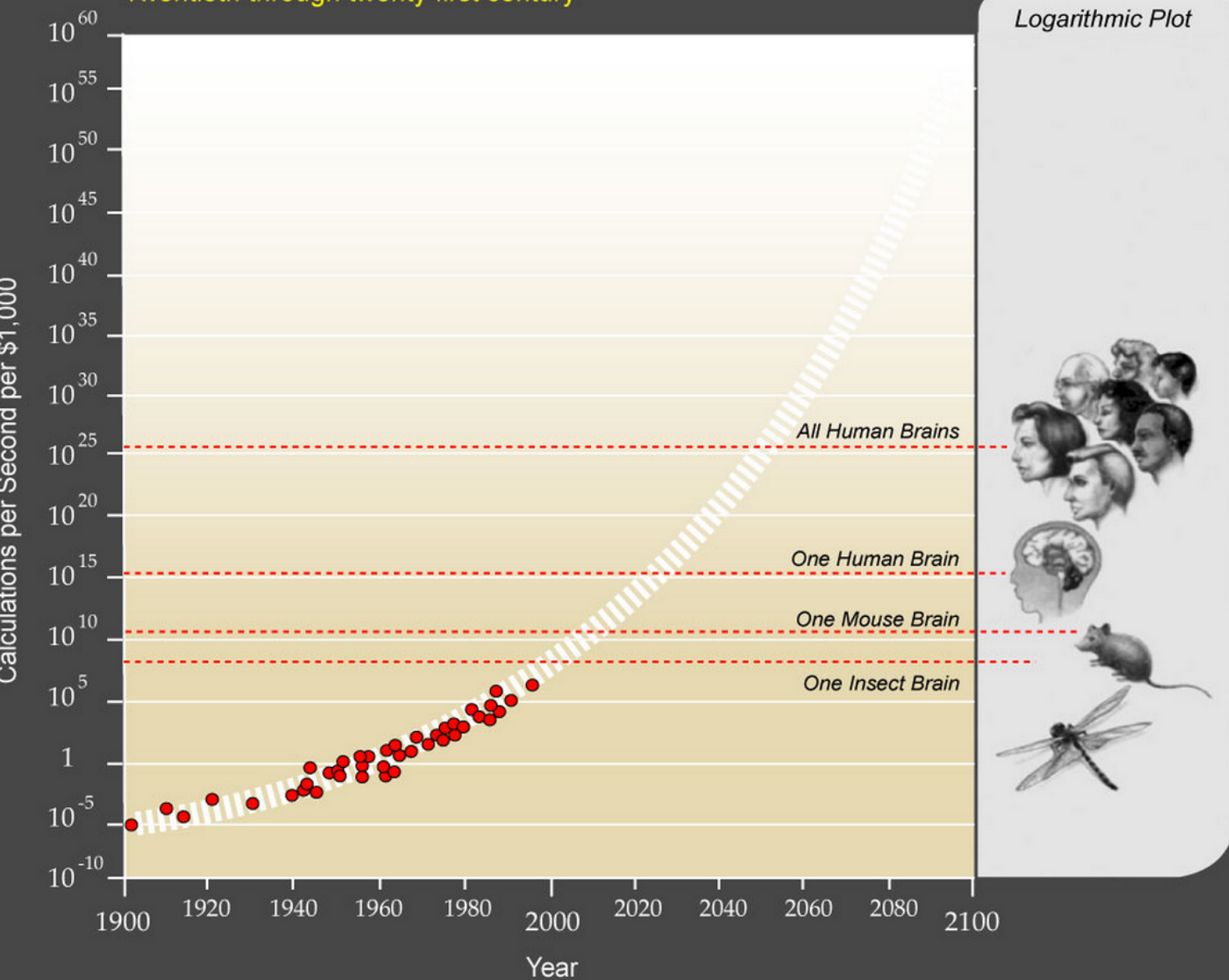


PSA I 6

2009

$$O(N^2)$$

Exponential Growth of Computing Twentieth through twenty first century







PSA32 Grid

2012

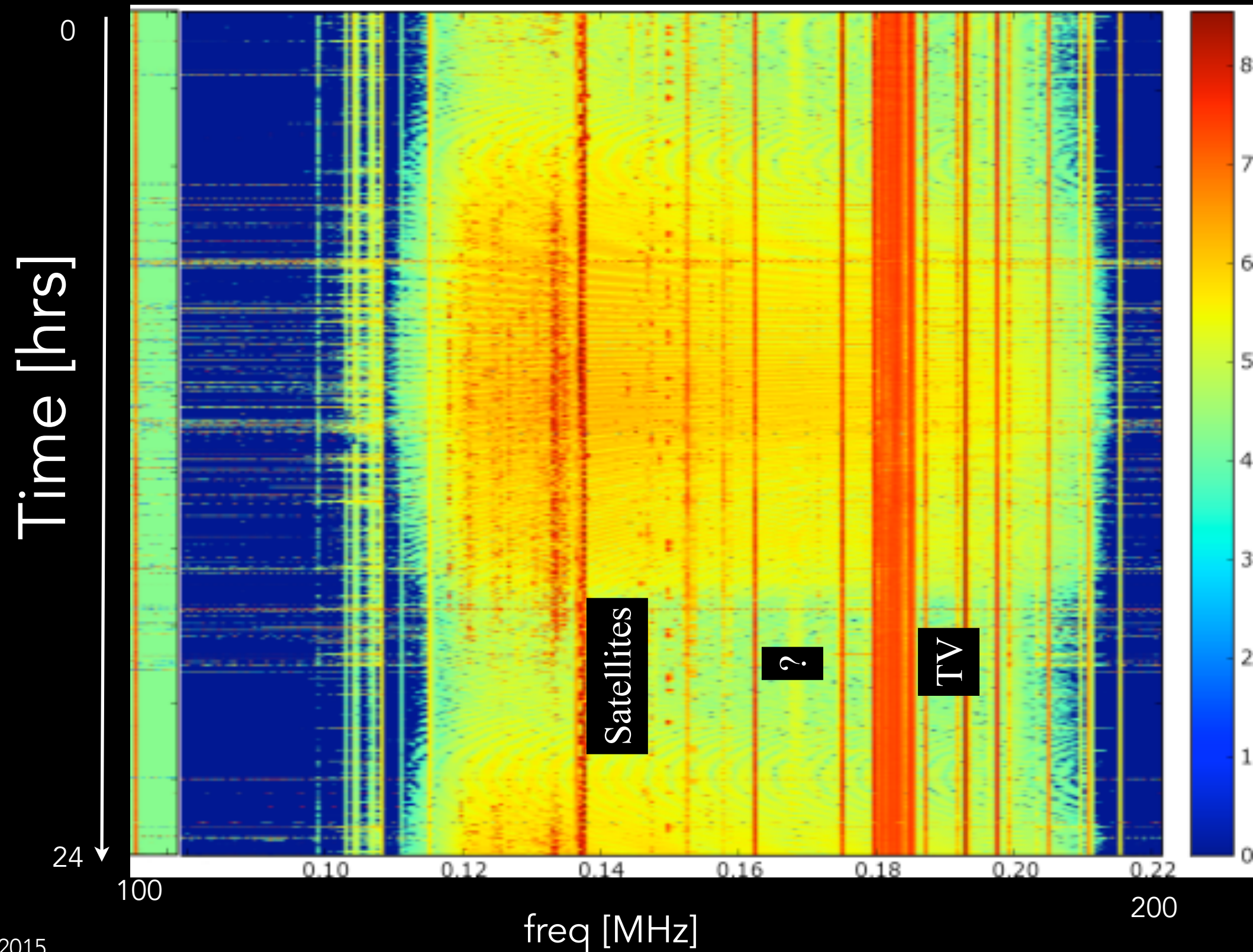


PSA64

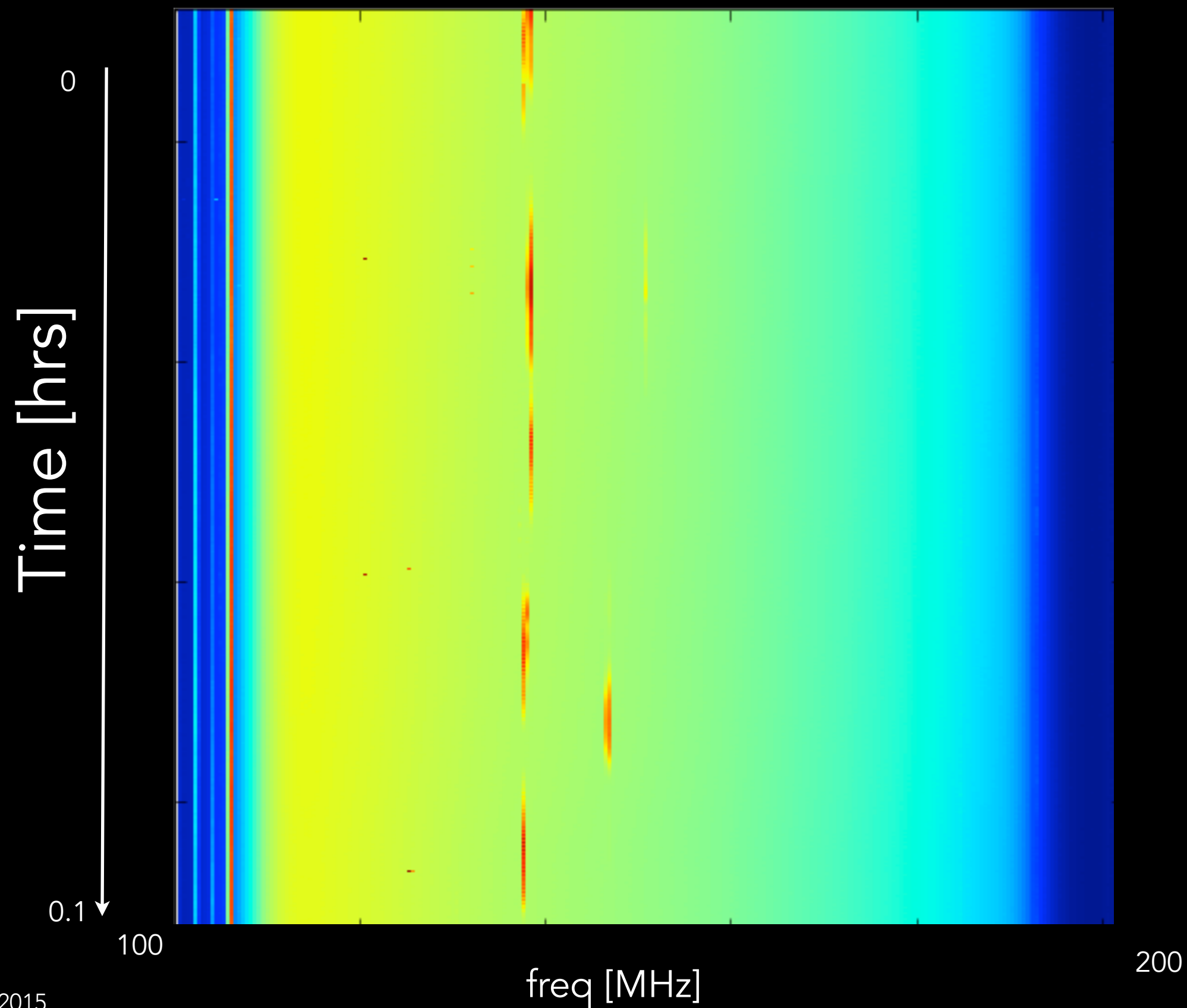
2011



PAPER GREEN BANK



PAPER SOUTH AFRICA



YEAR 1 PAPER



PAPER STATUS

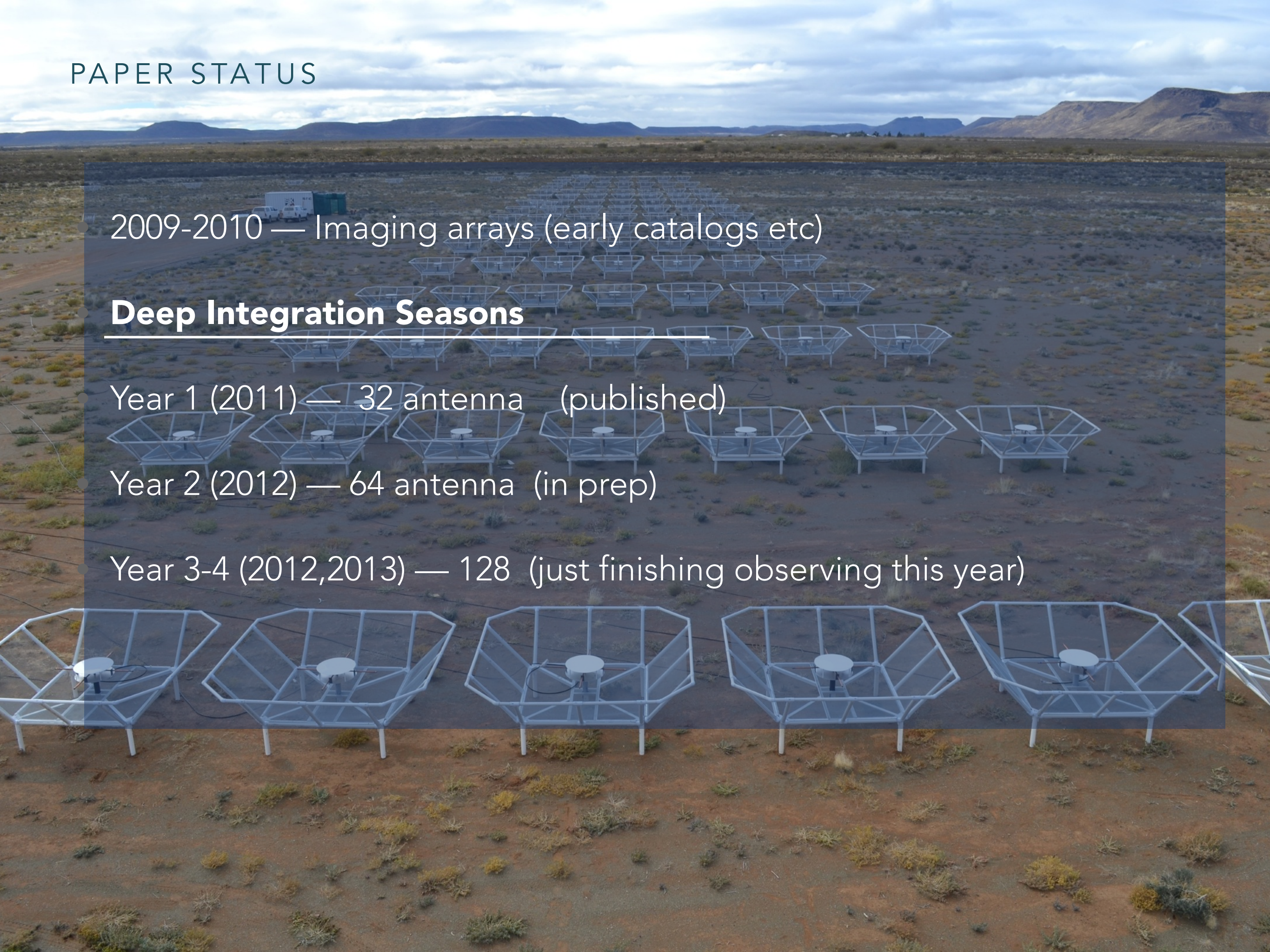
2009-2010 — Imaging arrays (early catalogs etc)

Deep Integration Seasons

Year 1 (2011) — 32 antenna (published)

Year 2 (2012) — 64 antenna (in prep)

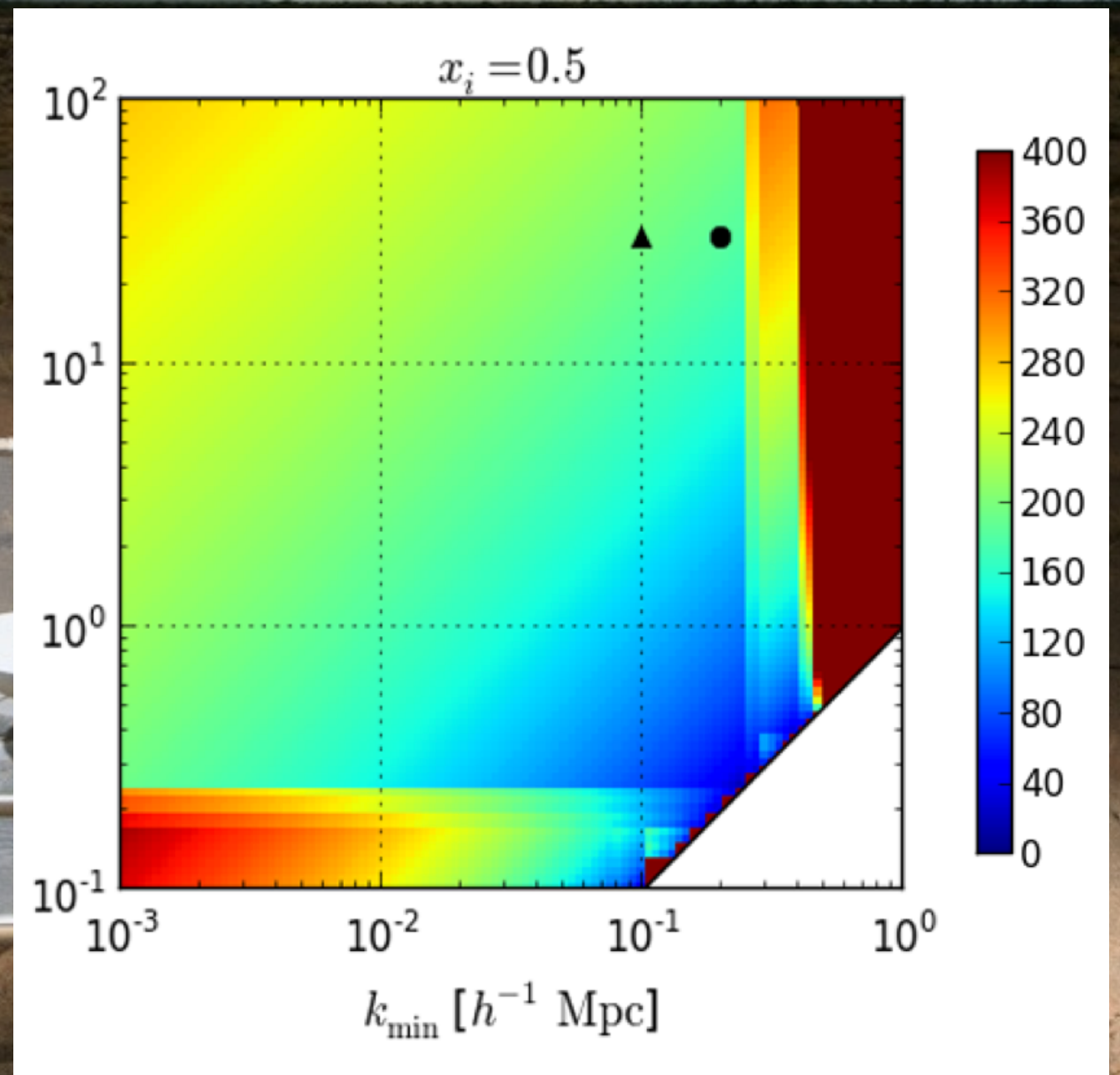
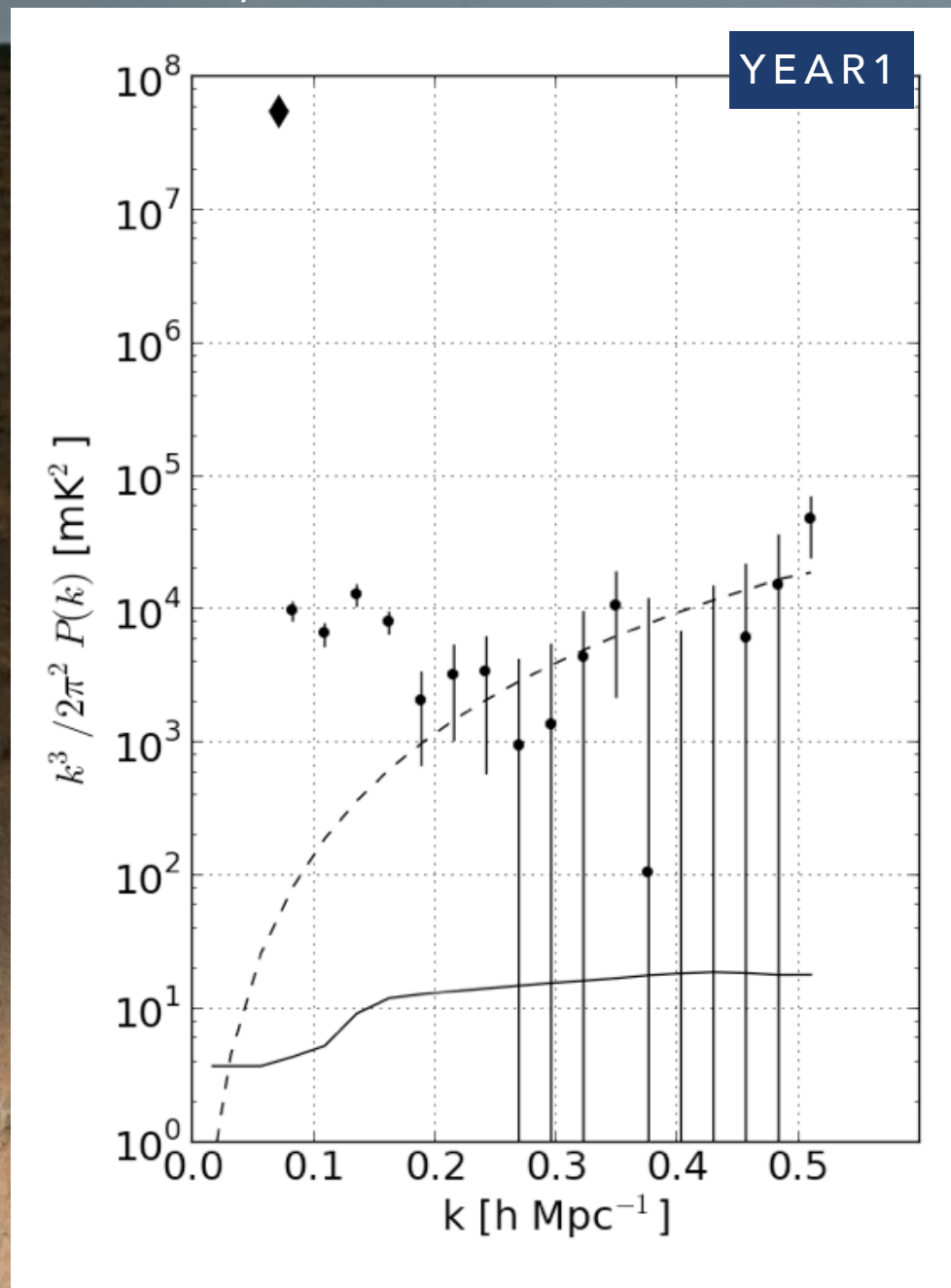
Year 3-4 (2012,2013) — 128 (just finishing observing this year)

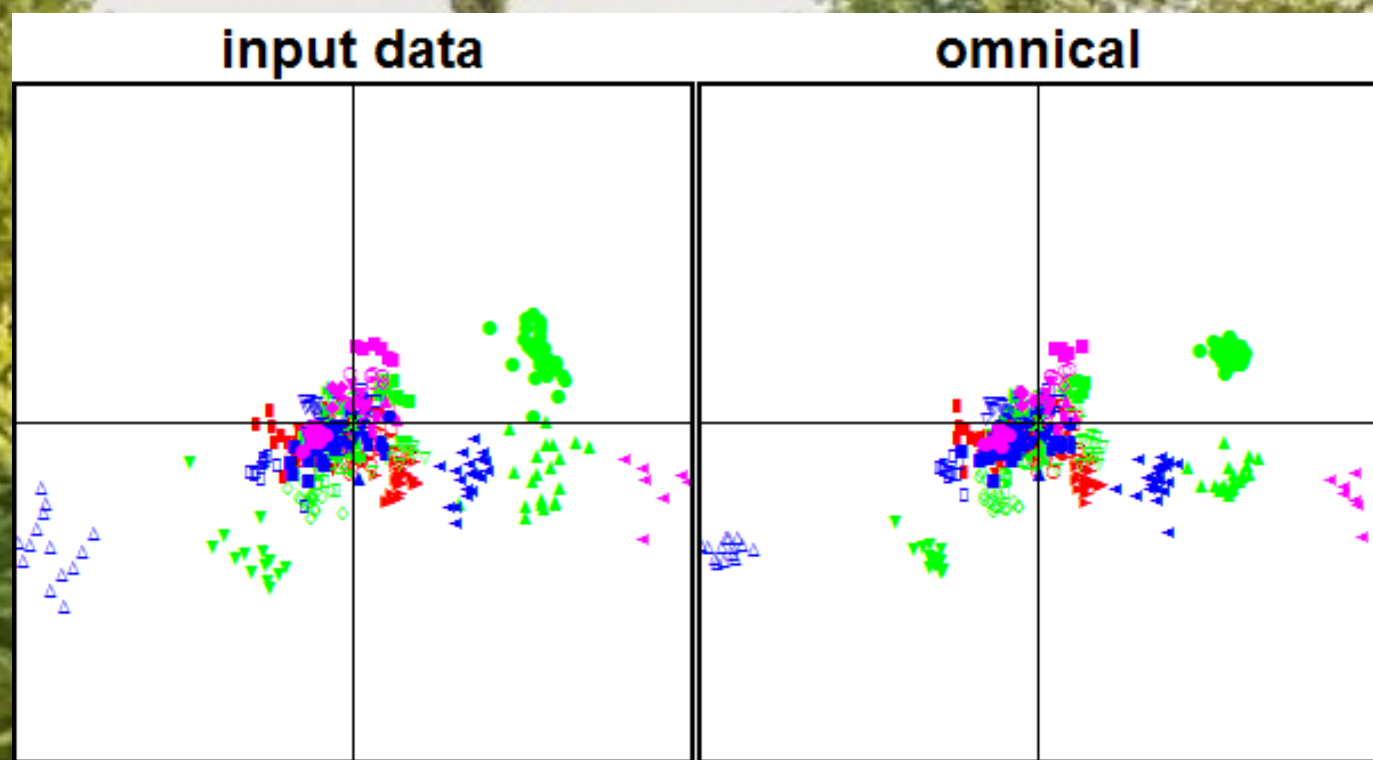


YEAR 1 PAPER

Parsons 2014, Jacobs 2015

(Heating from
early objects) > 0





Omniscope

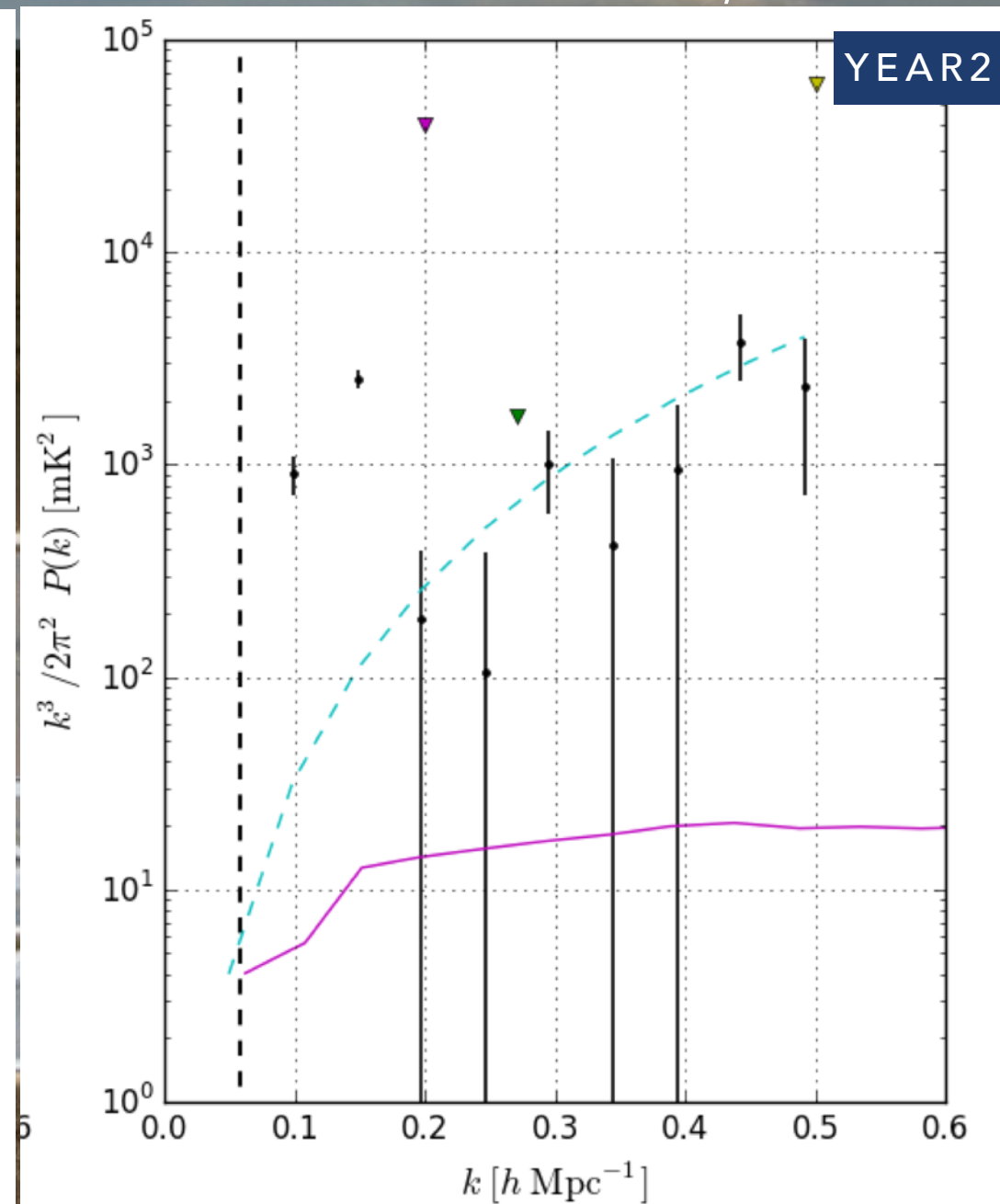
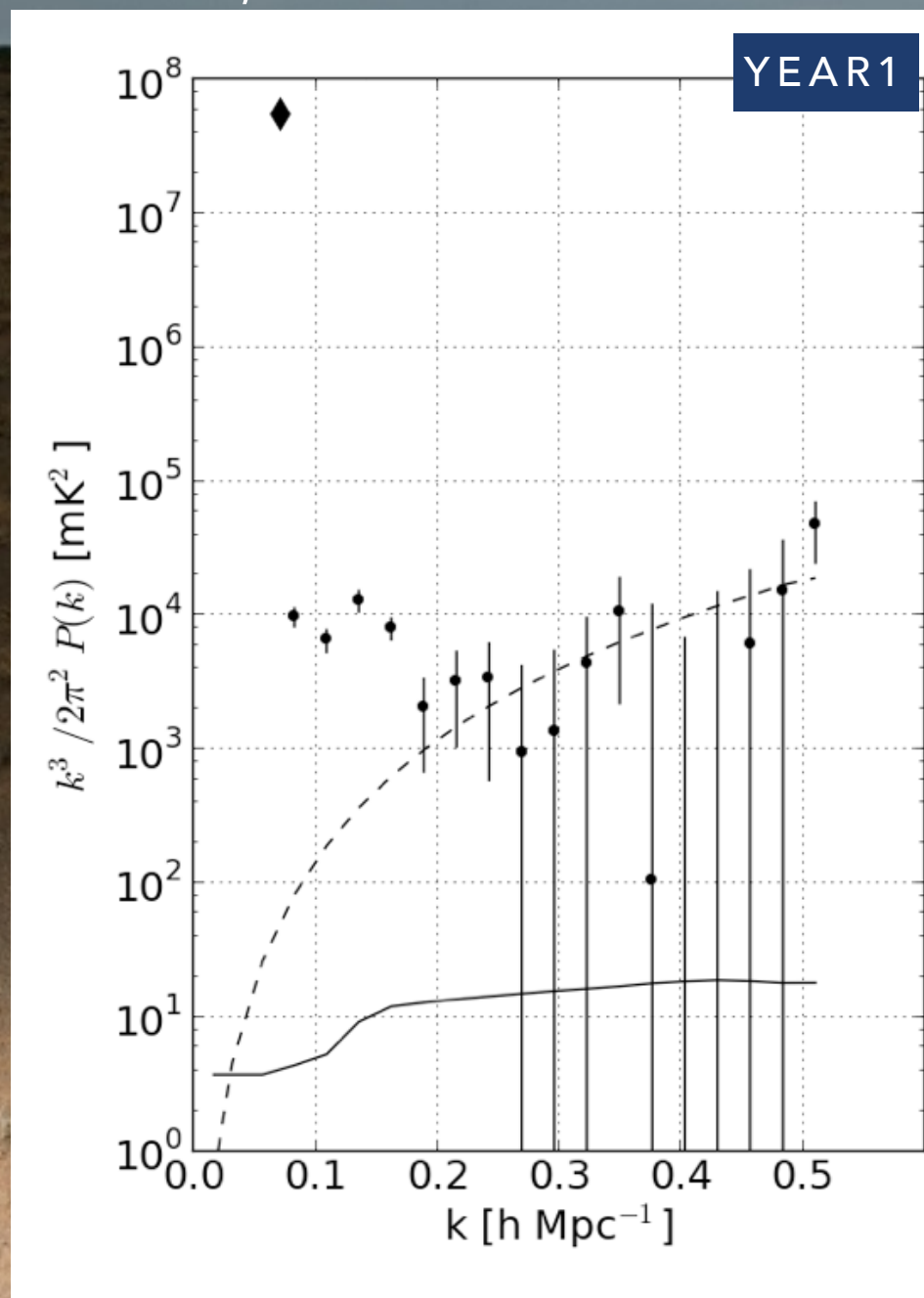
Zheng et al 2014



YEAR 2 PAPER RESULTS

Parsons 2014, Jacobs 2015

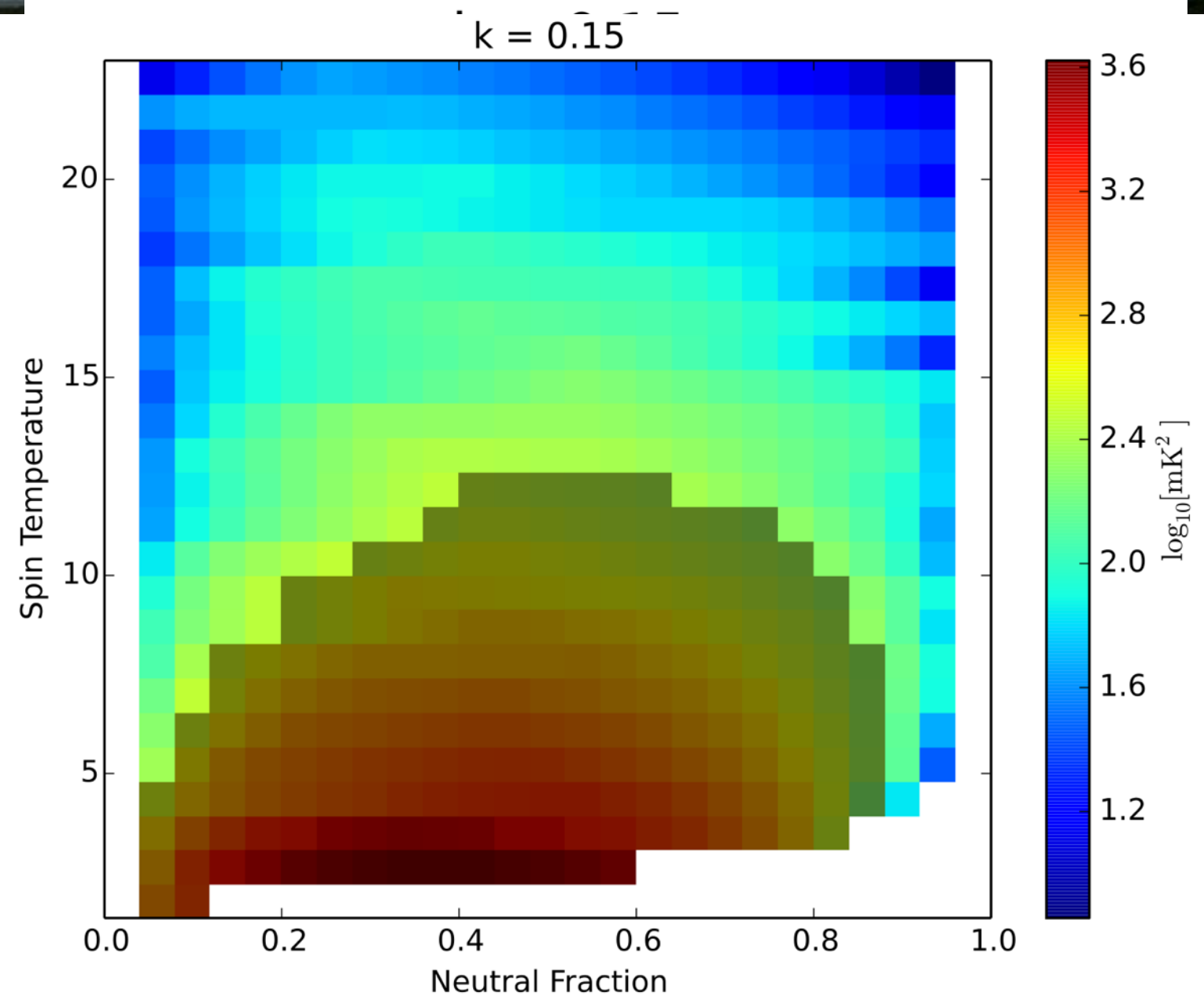
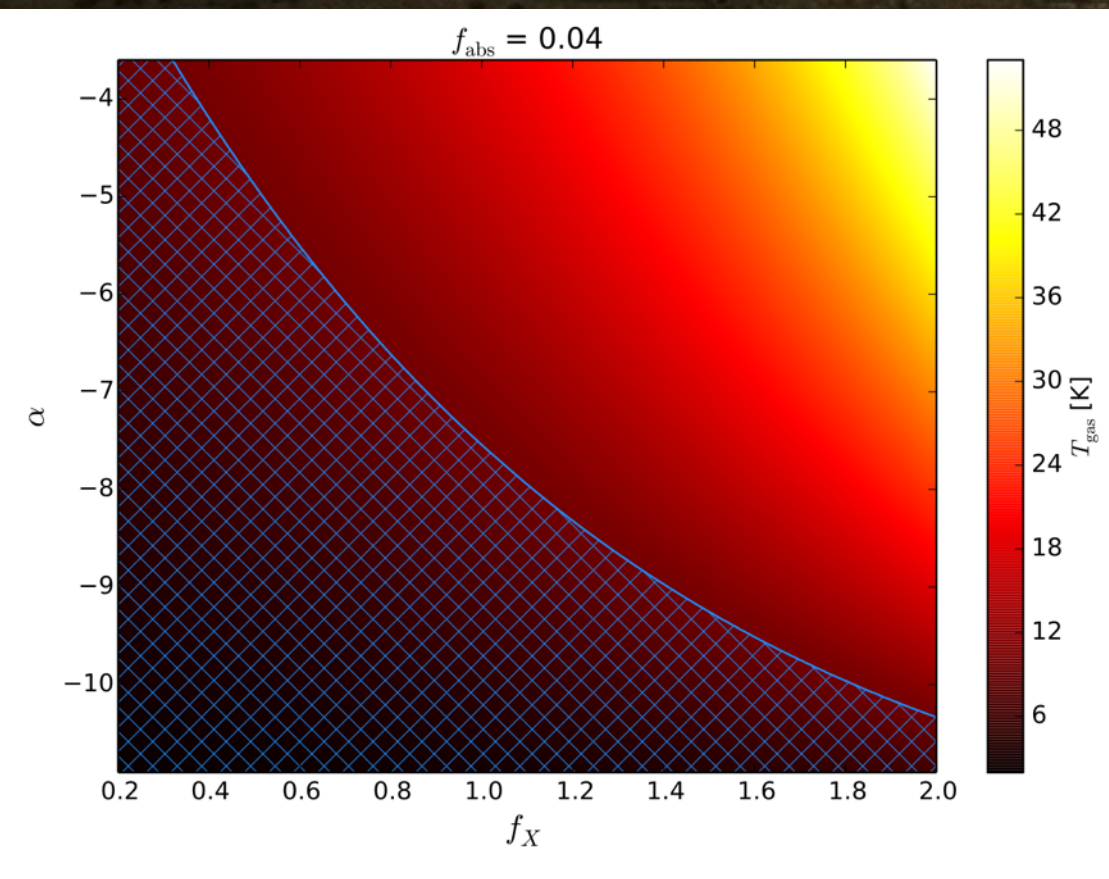
Ali, et al 2015



[ARXIV.ORG/ABS/1502.06016](https://arxiv.org/abs/1502.06016)

PAPER YEAR 2 RESULTS

$$\delta T_b(\nu) \approx 9x_{\text{HI}}(1+\delta)(1+z)^{\frac{1}{2}} \left[1 - \frac{T_{\text{CMB}}(z)}{T_S} \right] \left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right] \text{ mK}$$



Pober et al (imminent)

FEATURES

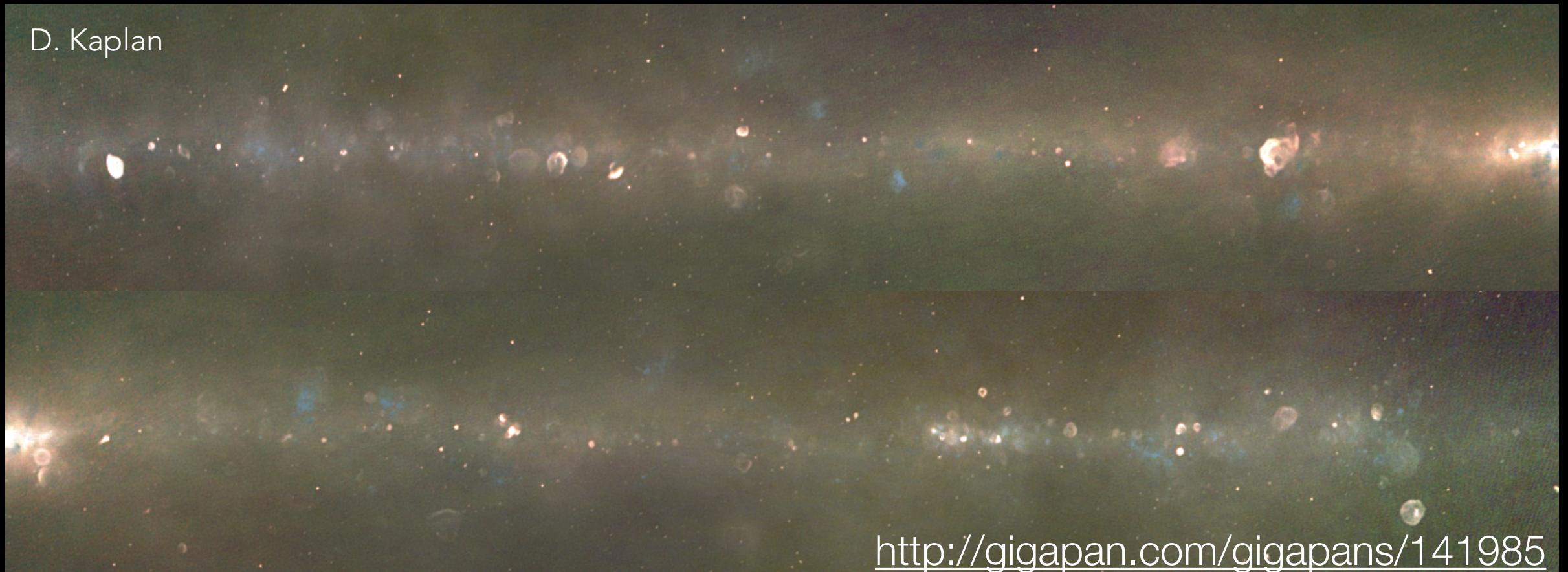
A glimpse of COSMIC DAWN

Murchison
Widefield
Array

MWA SCIENCE

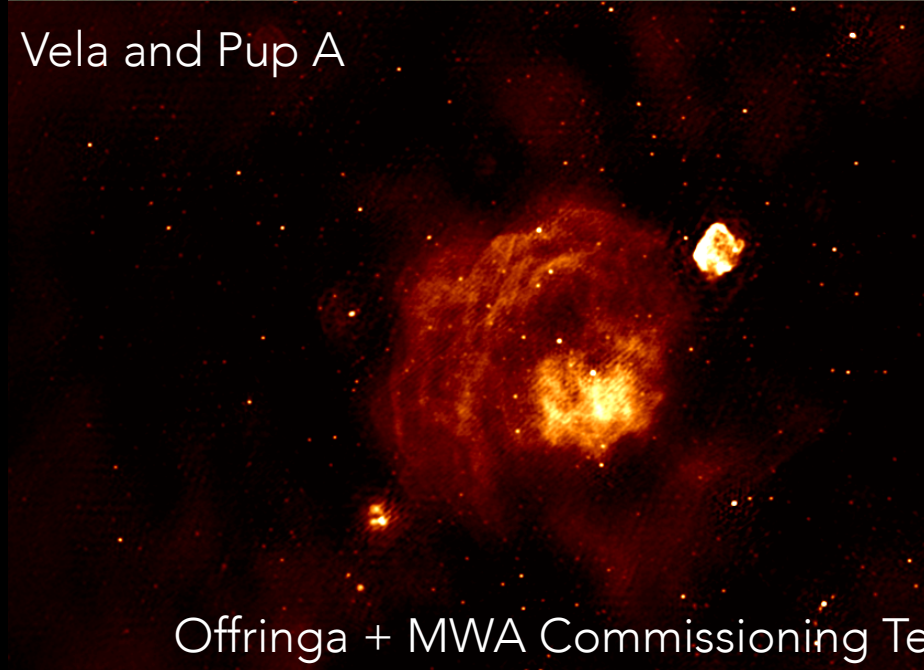
80 degrees

D. Kaplan

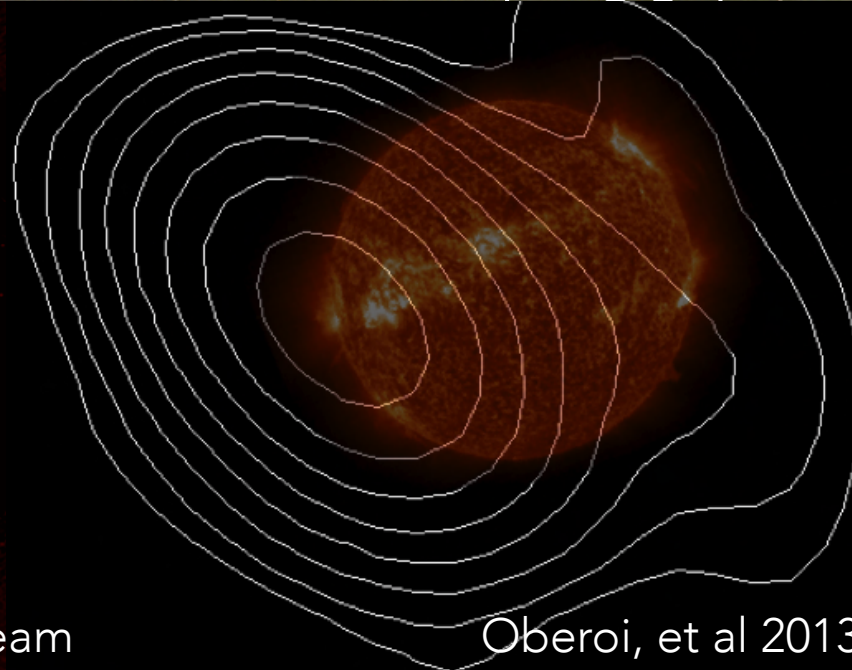


<http://gigapan.com/gigapans/141985>

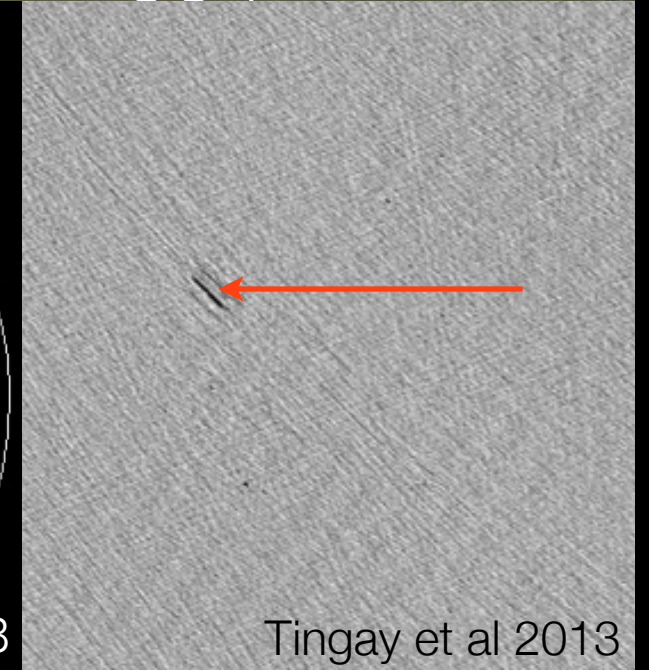
Vela and Pup A



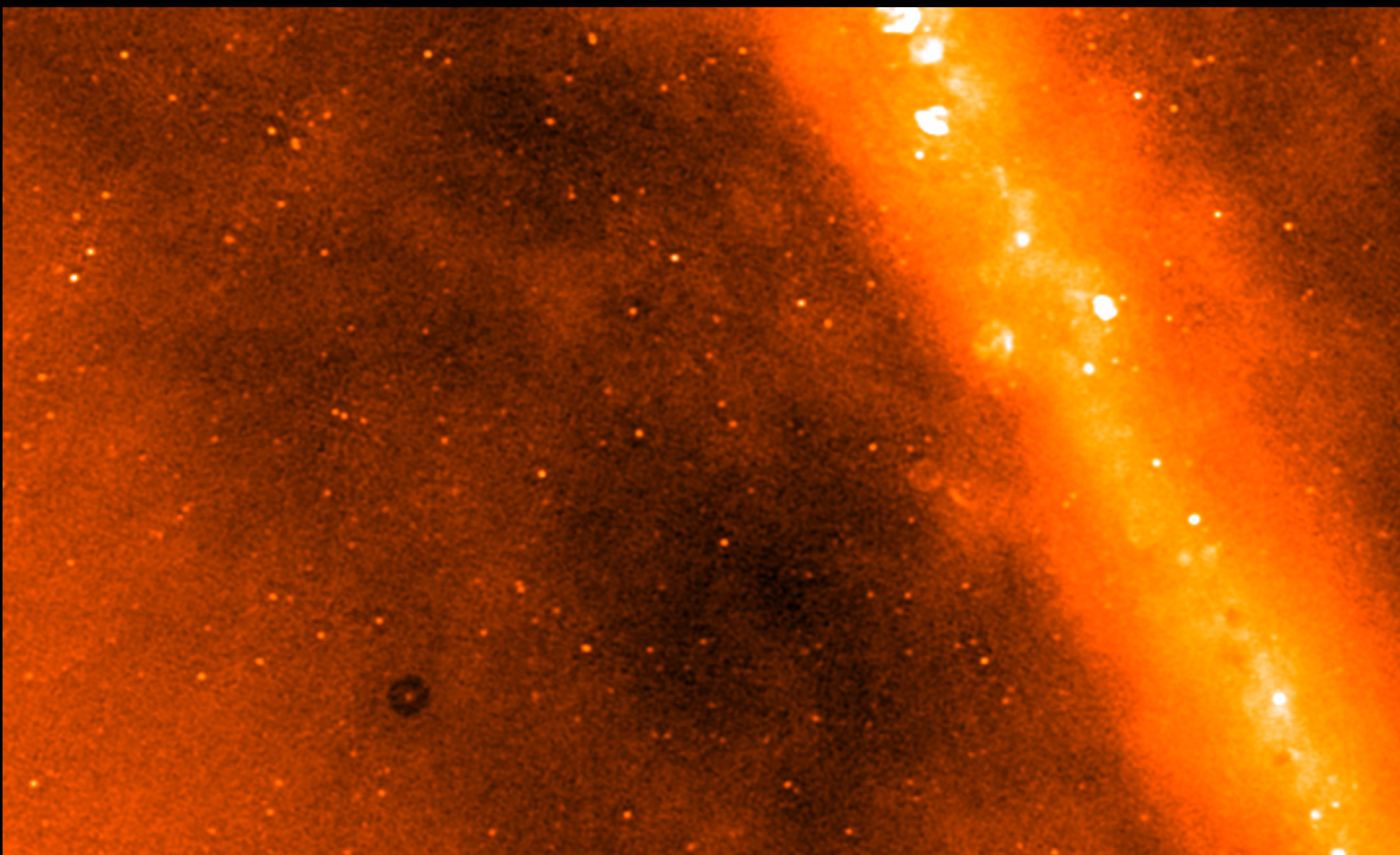
Offringa + MWA Commissioning Team

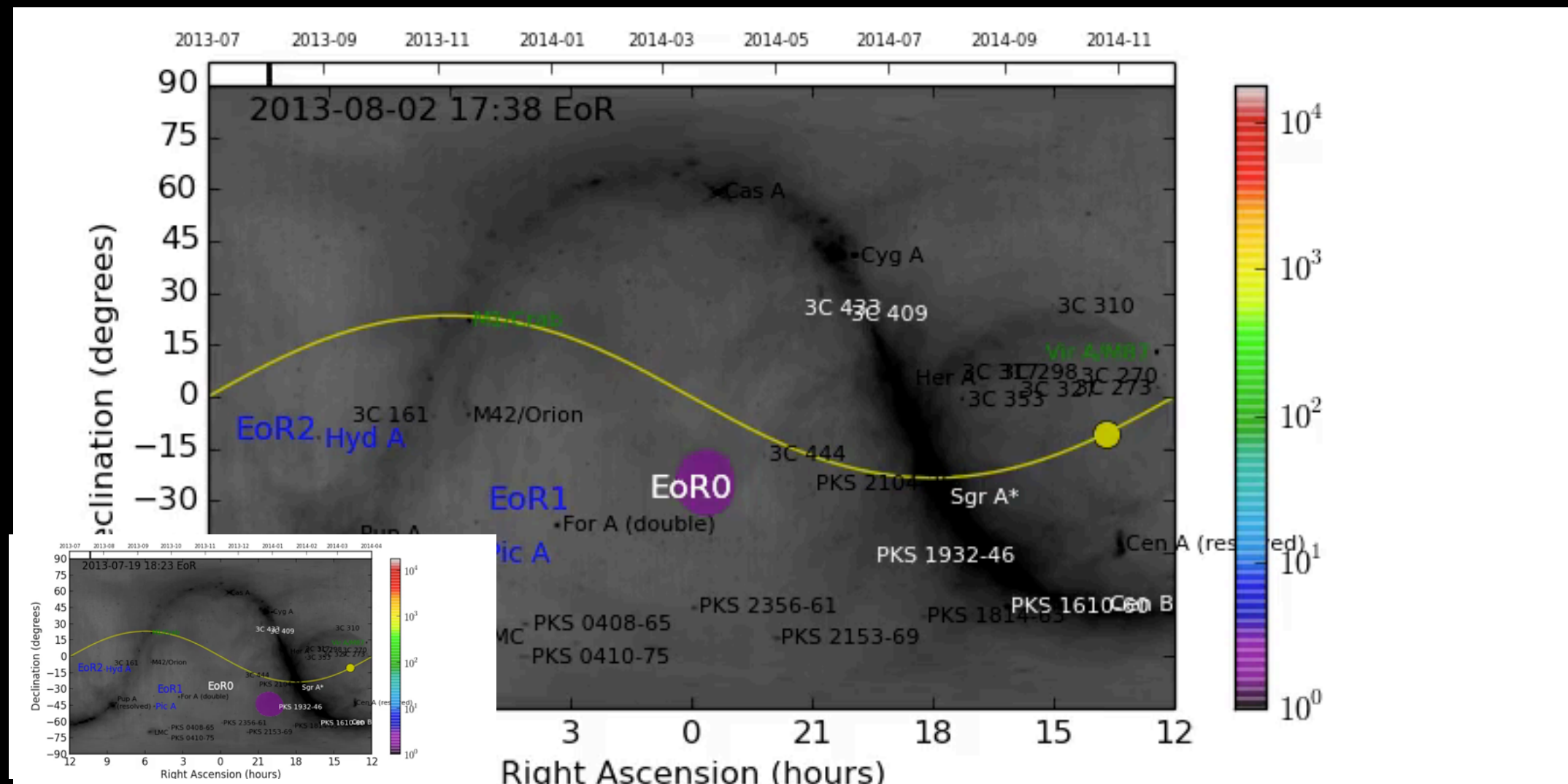


Oberoi, et al 2013



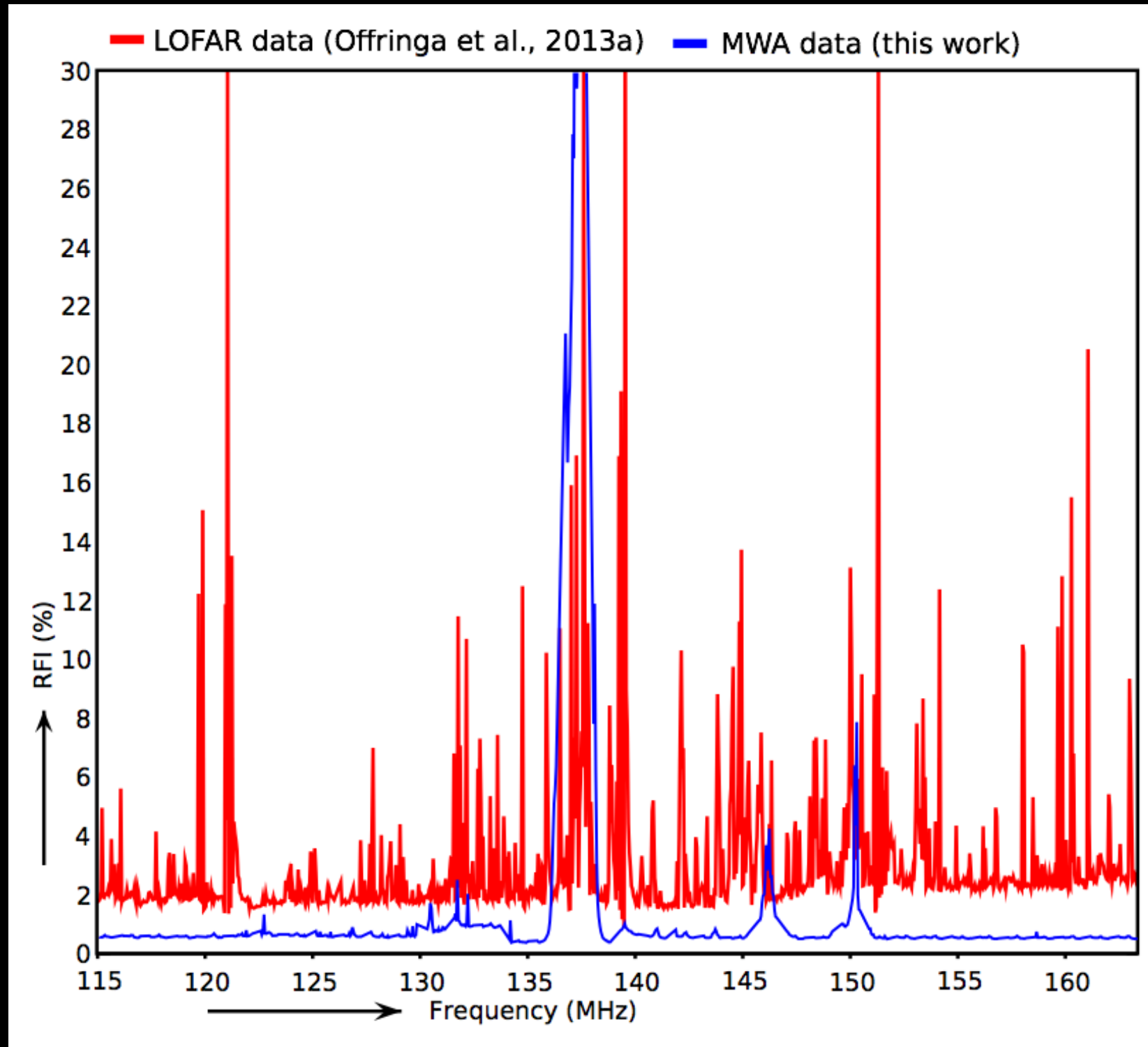
Tingay et al 2013





	EOR0	EOR1	TOTAL
LOW ($9 > Z > 7.3$)	253	322	575
HIGH ($7.4 > Z > 6.1$)	345	168	513
TOTAL	598	490	1088 HOURS

MWA INTERFERENCE



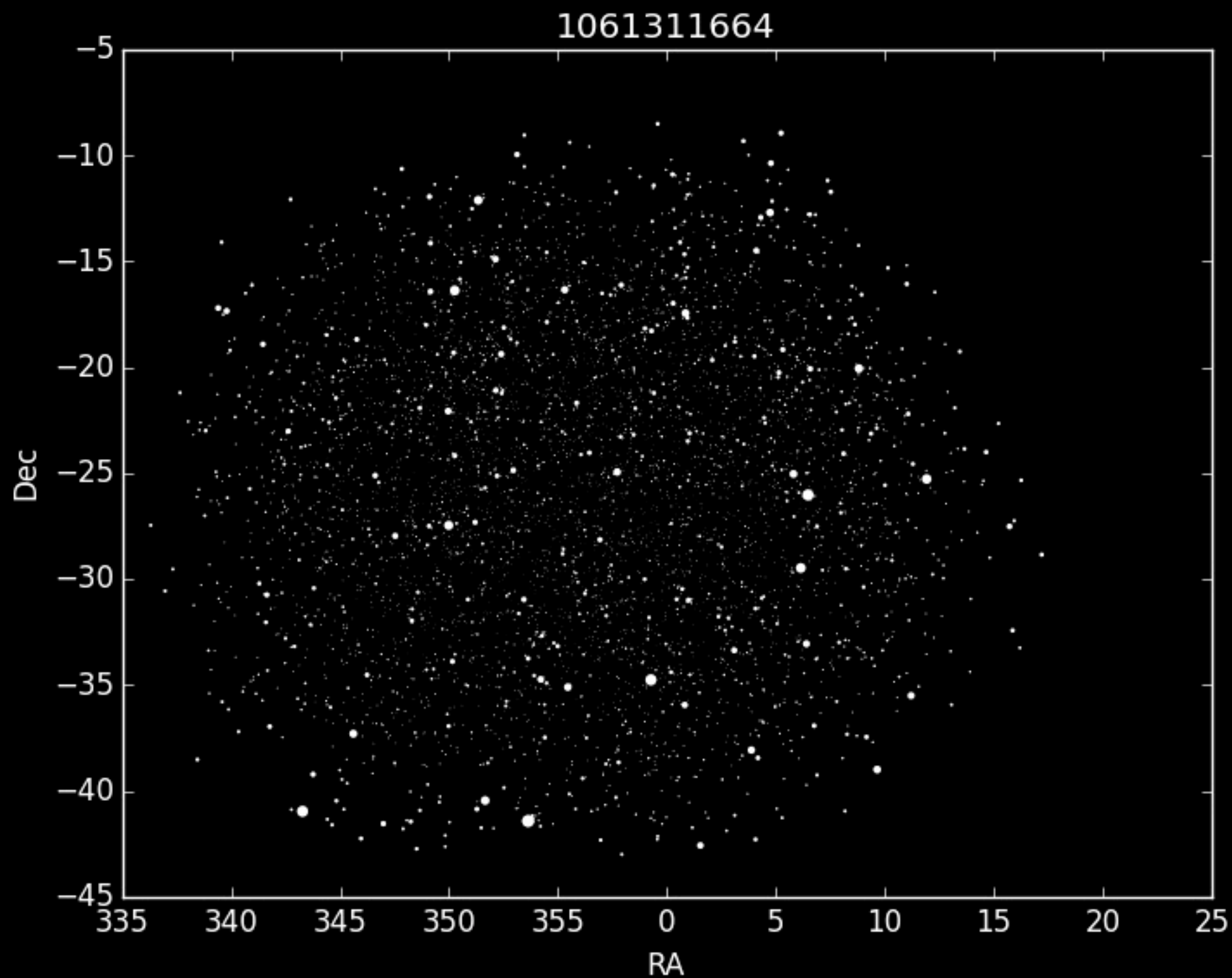
Offringa et al (in review)



Abraham Neben
MIT

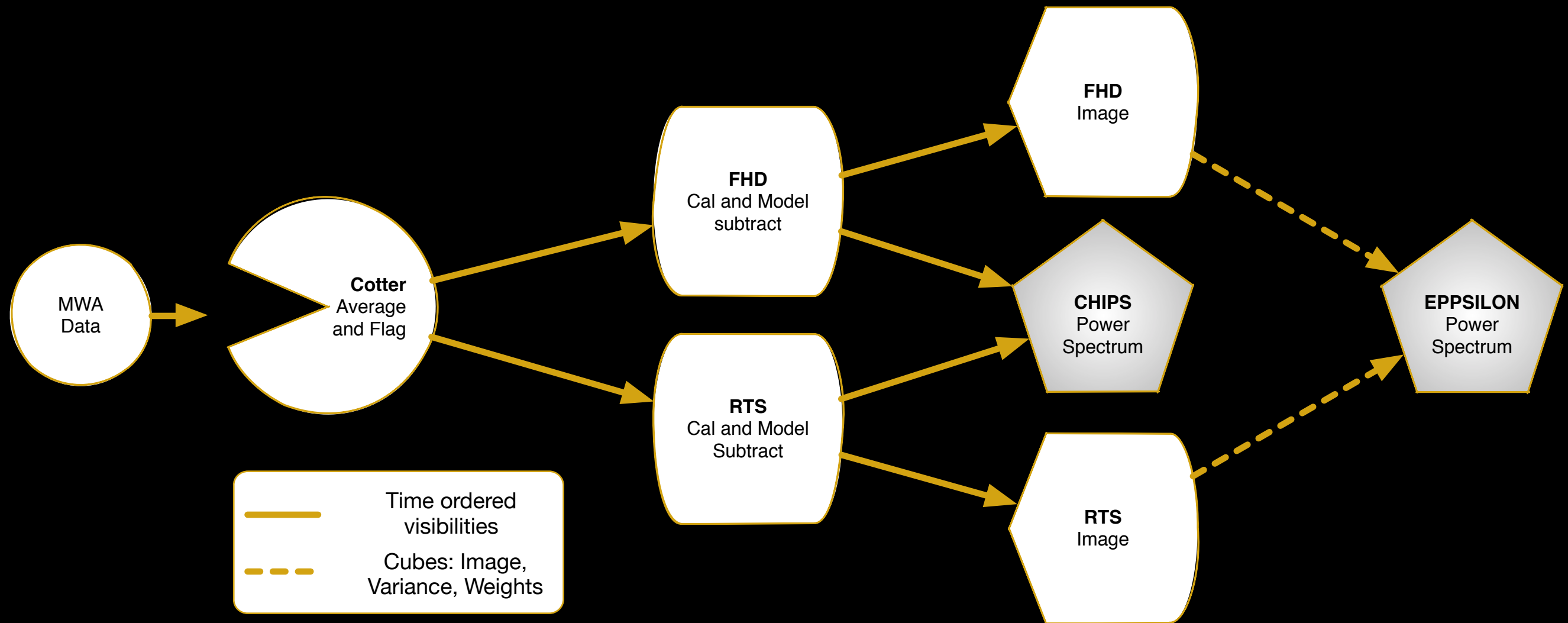
CARROLL 2014

C



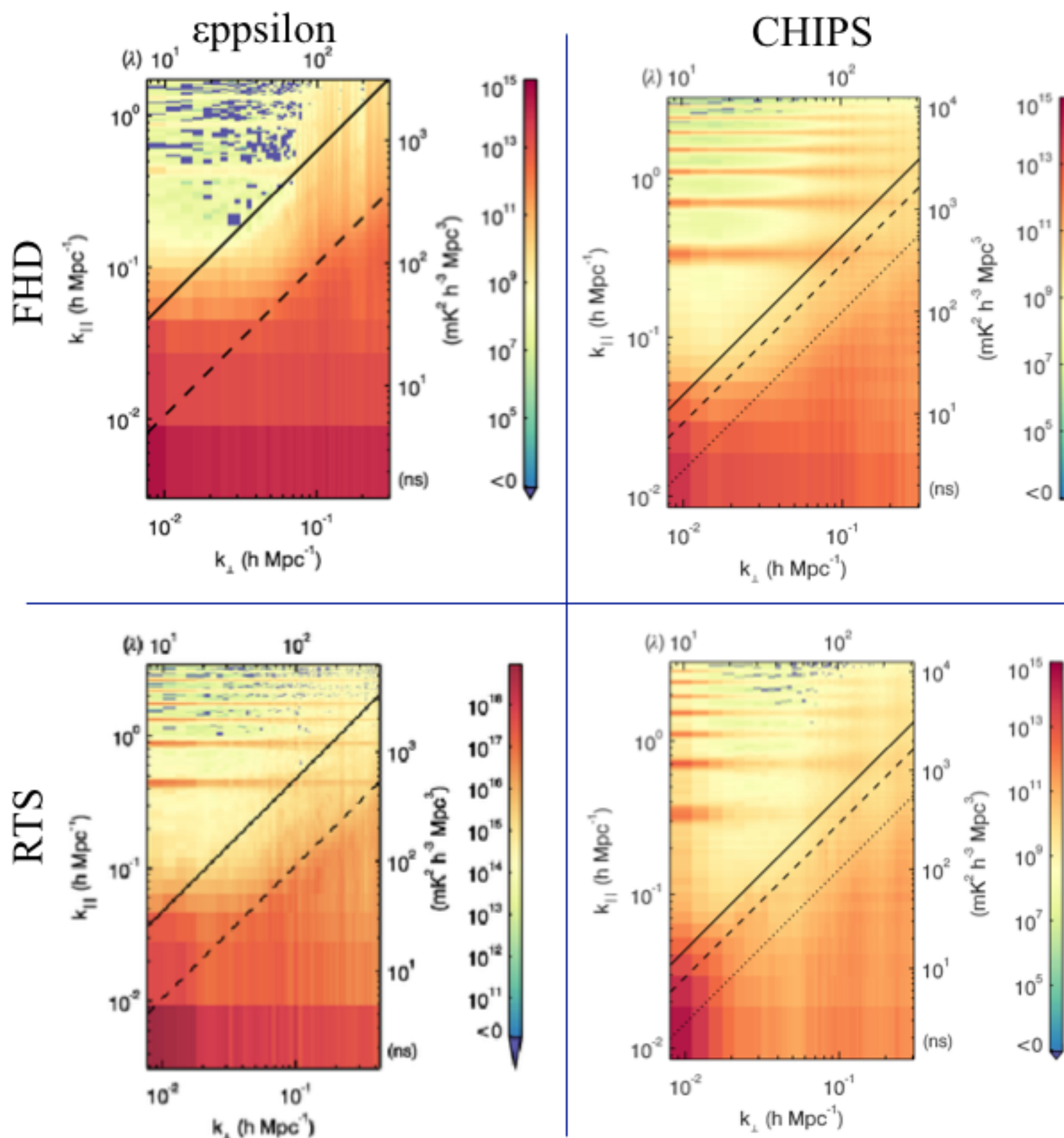
See poster 144.47 on Monday

THE MWA COMPARISON FRAMEWORK



Foreground Removal

Power Spectrum Method

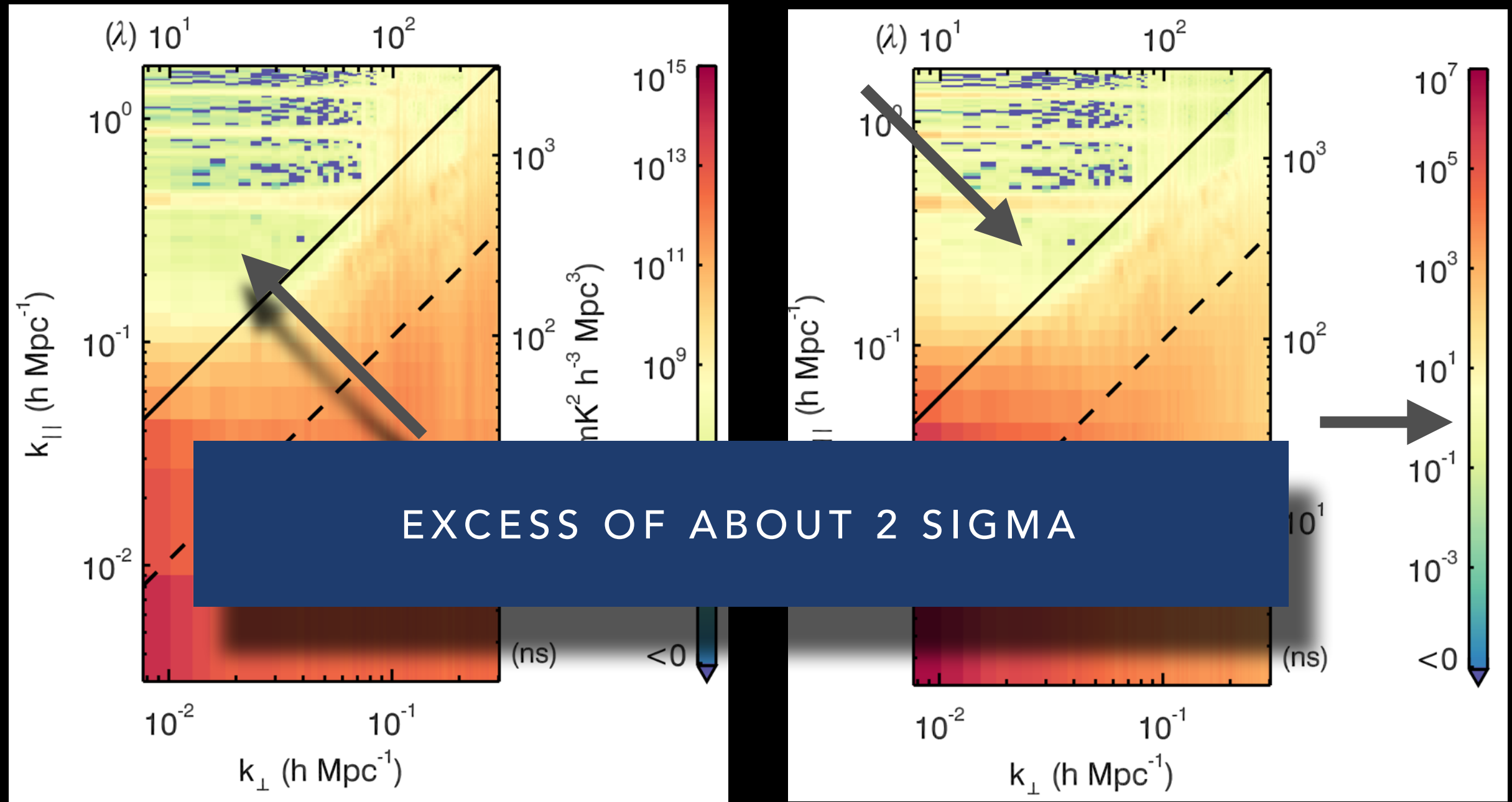


PRELIMINARY!

POWER SPECTRUM - 40 HOURS

power spectrum

power/error



Beardsley, in prep

FOREGROUND FILTERED SENSITIVITY

Different foreground scenarios

Instrument	Pessimistic	Moderate	Optimistic
PAPER	1.17	2.02	4.82
MWA	0.60	2.46	6.40
LOFAR NL Core	1.35	2.76	17.37

SNR to fiducial model



HYDROGEN EPOCH OF REIONIZATION ARRAY

Parsons (UCB) Aguirre (UPenn) Sievers (UKZN)

Morales (UW) Furlanetto (UCLA) Bowman (ASU)

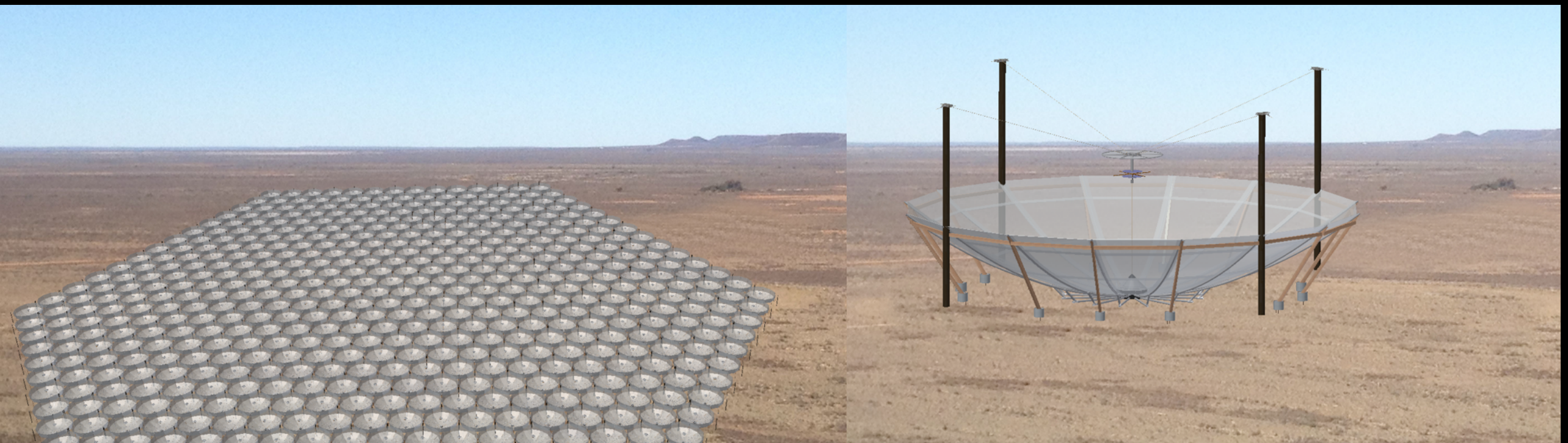
Hewitt (MIT-Kavli) Tegmark (MIT) Jacobs (ASU)

Carilli (NRAO\Cavendish) DeBoer (UCB)

SKA - South Africa

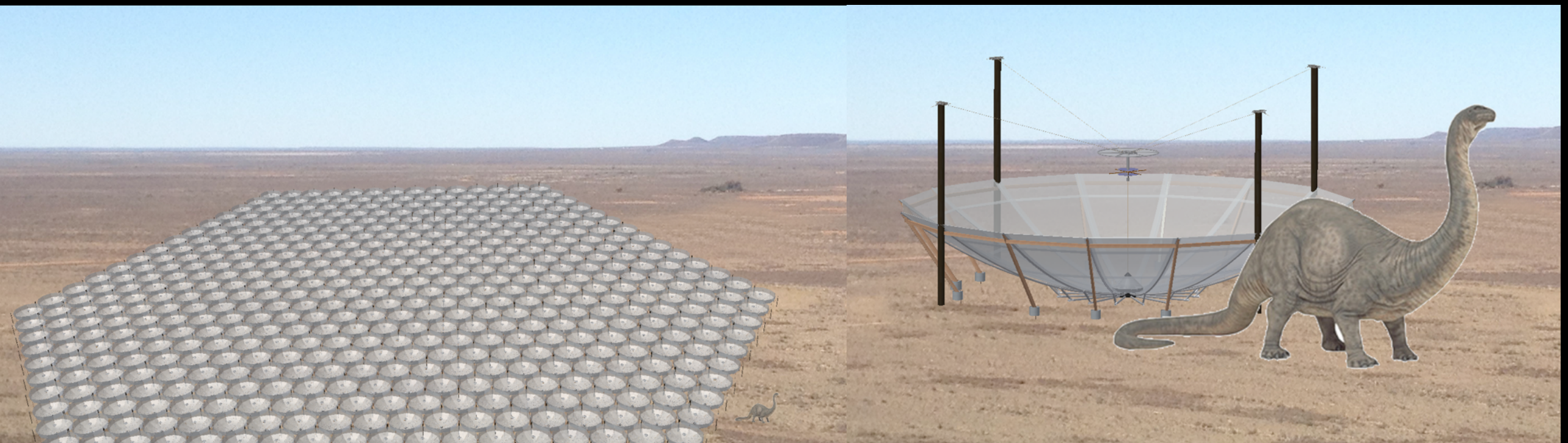
HYDROGEN EPOCH OF REIONIZATION ARRAY

- 14m transit dish, 331 element array
- PAPER feed
- MWA-type node architecture
- Fast focus minimizes chromaticity
- Joint MWA - PAPER enterprise
- 0.1 km²



HYDROGEN EPOCH OF REIONIZATION ARRAY

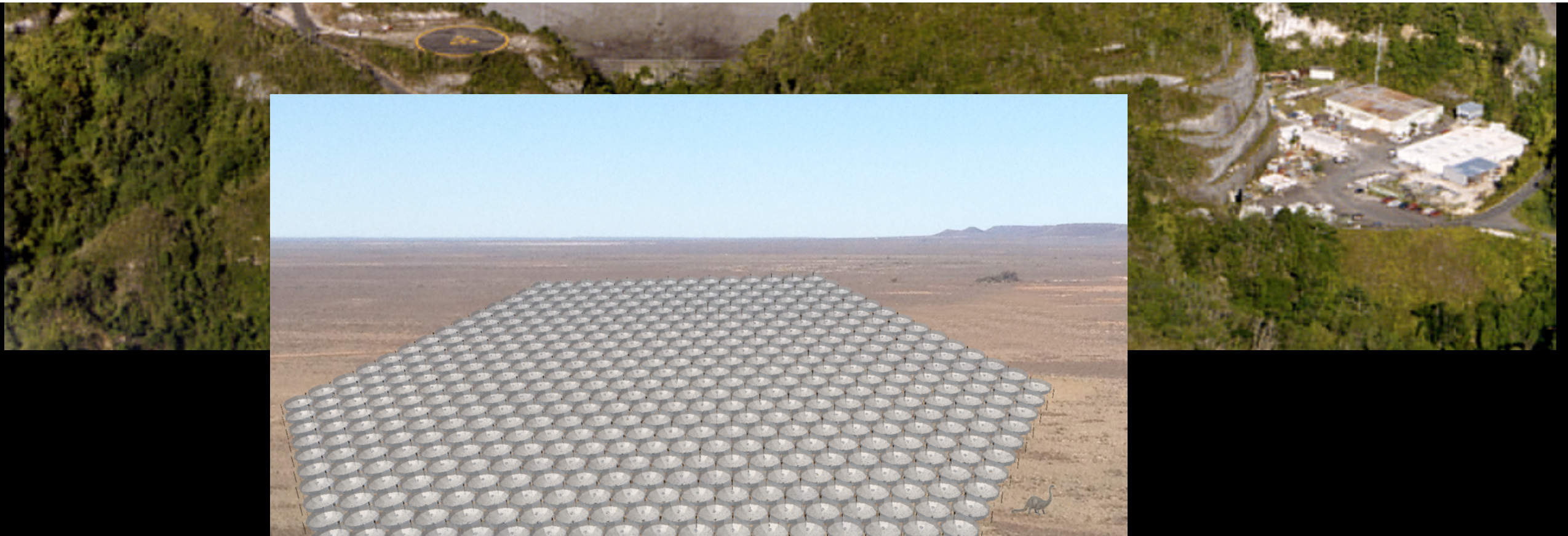
- 14m transit dish, 331 element array
- PAPER feed
- MWA-type node architecture
- Fast focus minimizes chromaticity
- Joint MWA - PAPER enterprise
- 0.1 km^2



DETECTION OF REASONABLE EOR MODELS UNDER VARIOUS FOREGROUND ASSUMPTIONS

Instrument	Pessimistic	Moderate	Optimistic
PAPER	1.17	2.02	4.82
MWA	0.60	2.46	6.40
LOFAR NL Core	1.35	2.76	17.37
HERA	32.09	38.20	133.15
SKA1 Low Core	10.01	35.95	218.27

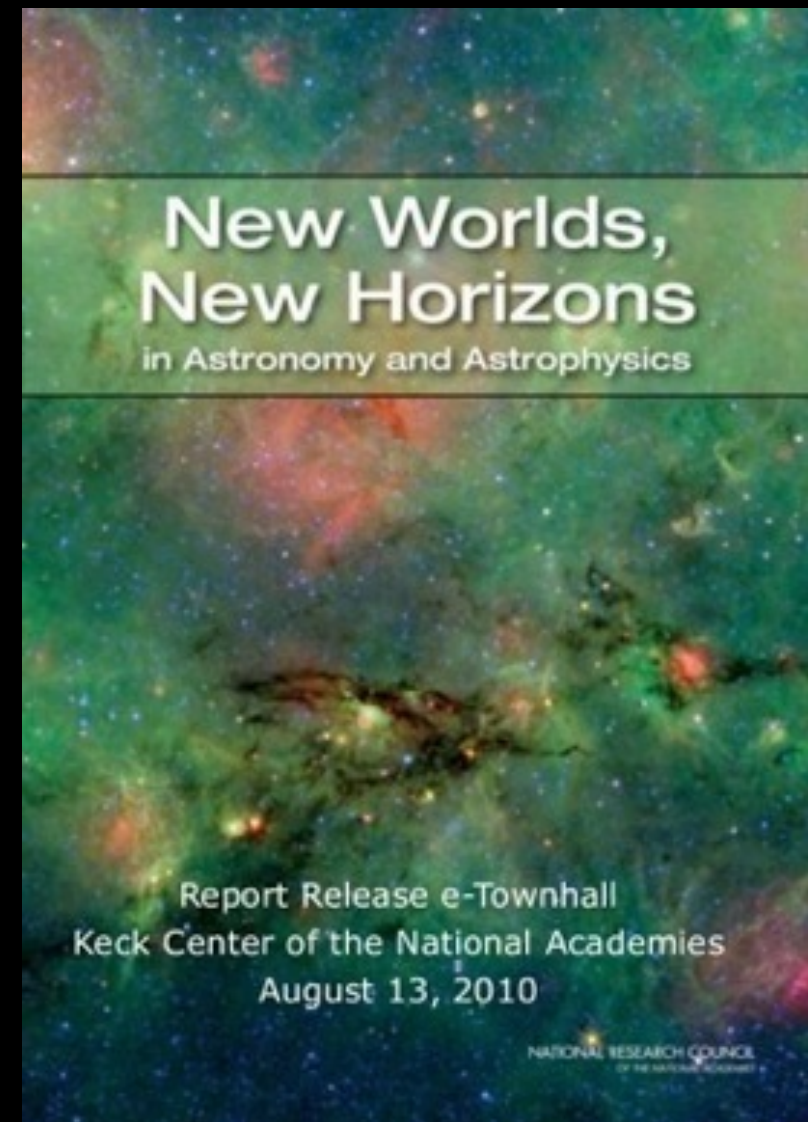
SNR to fiducial model



*scale approximate

HERA HISTORY

- 2010 Decadal white-paper estimated cost \$80M
- Ranked highest in radio projects and targets multiple top level focus areas
- 2011/2012 cost reduced to \$20M
- 2013 NSF “Mid-Scale”, funded for two years to begin construction
- Next proposal cycle Q3 2015

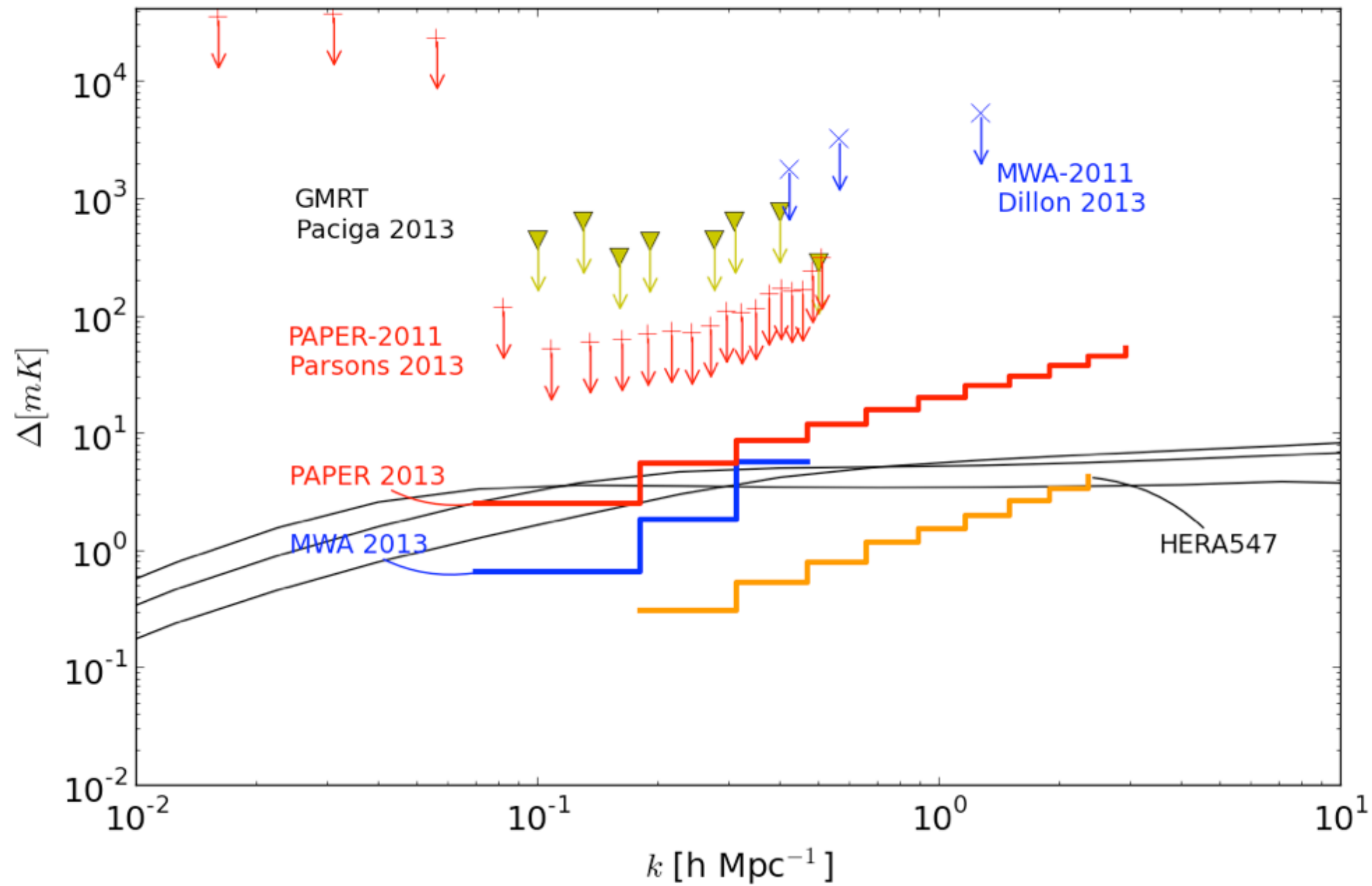




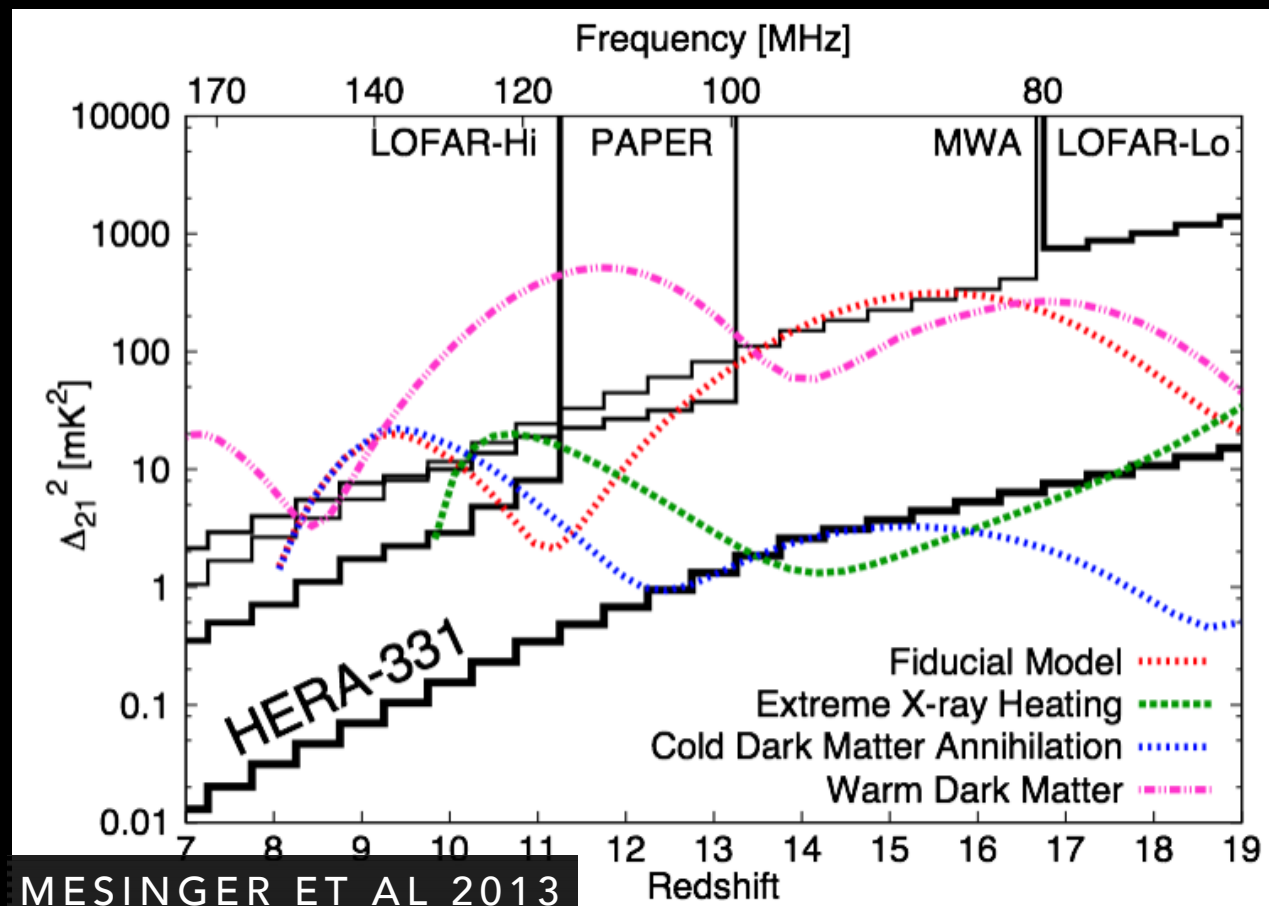
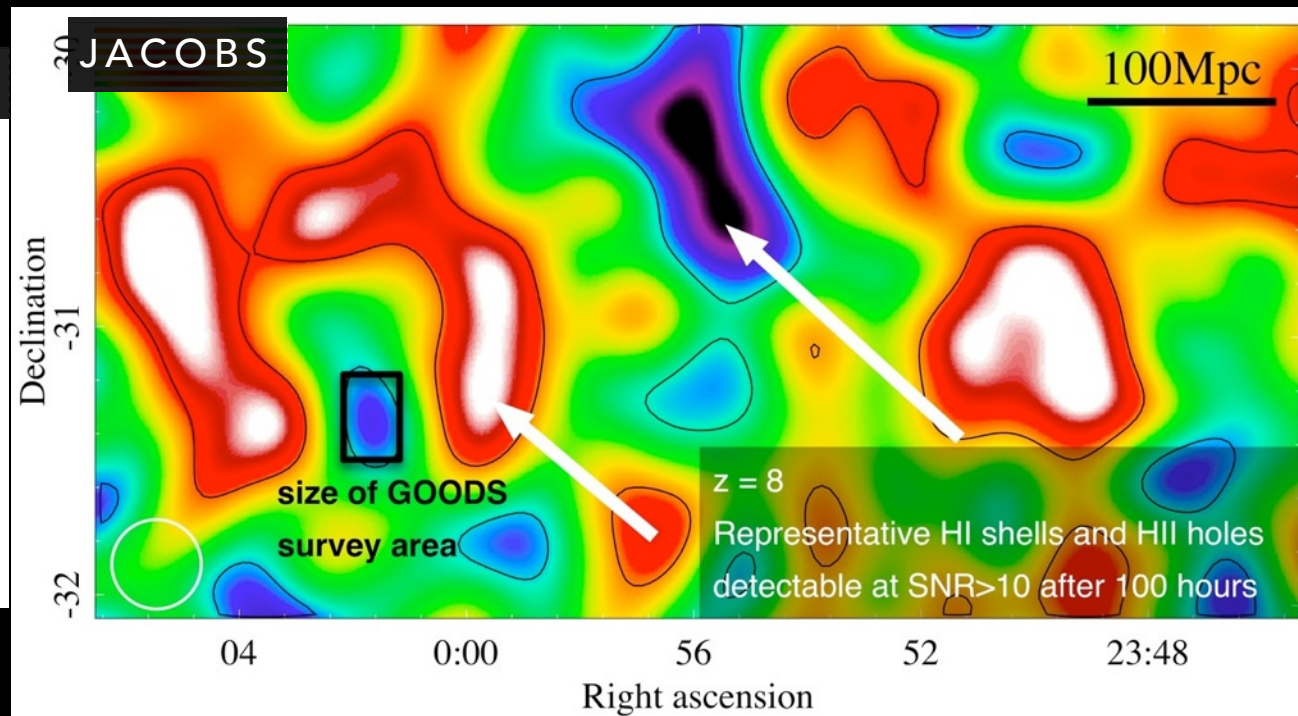
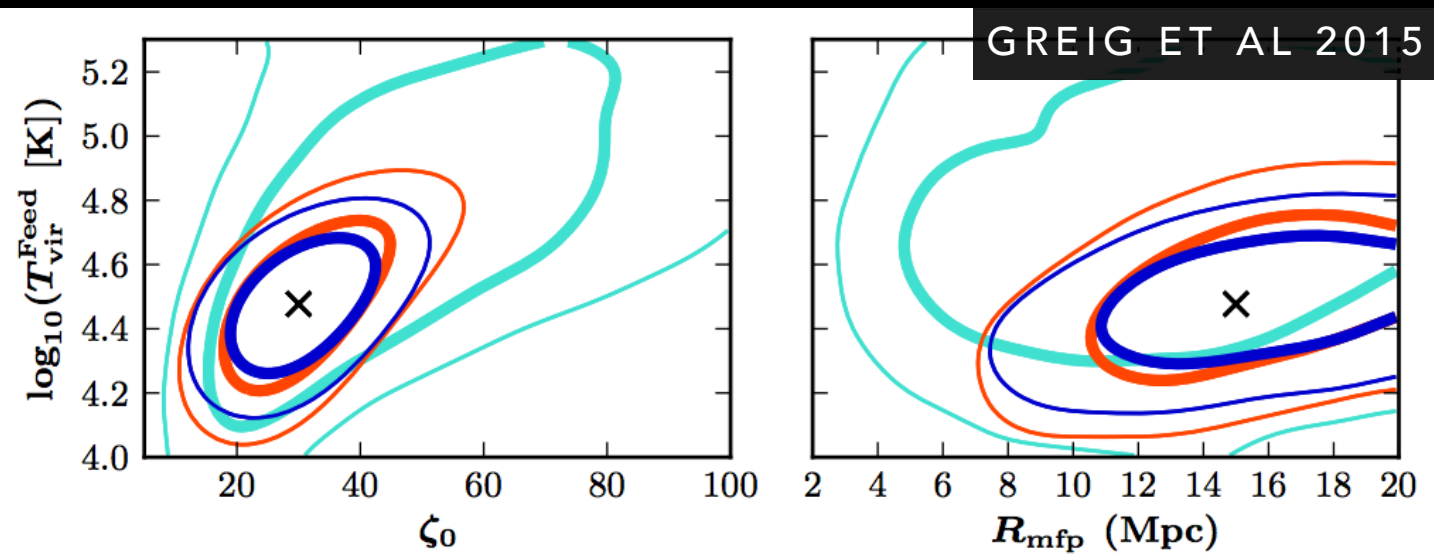
KAROO ARRAY
PROCESSING BUILDING

QUARTERS

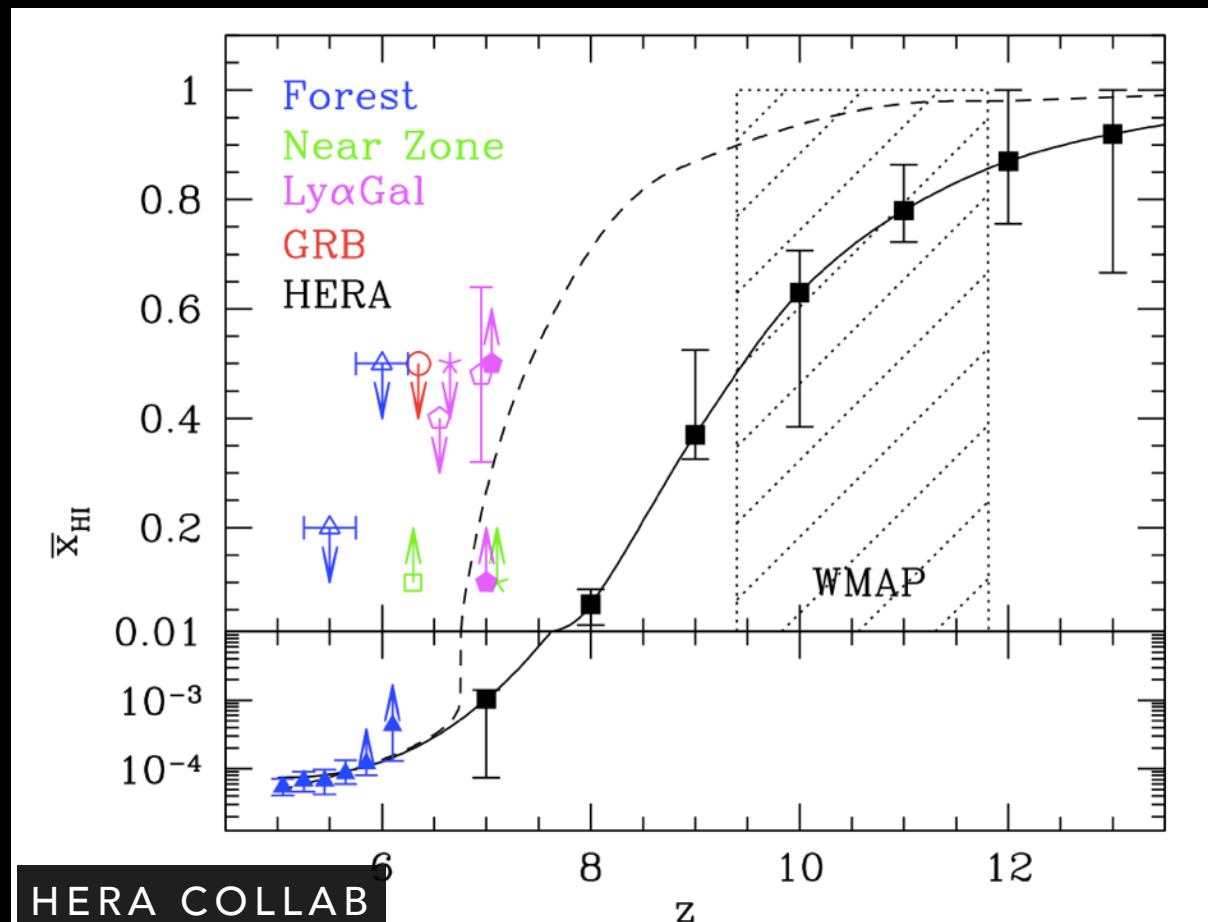
HERA SENSITIVITY



HERA CAPABILITIES



MESINGER ET AL 2013



HERA COLLAB

THANK YOU!



LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.



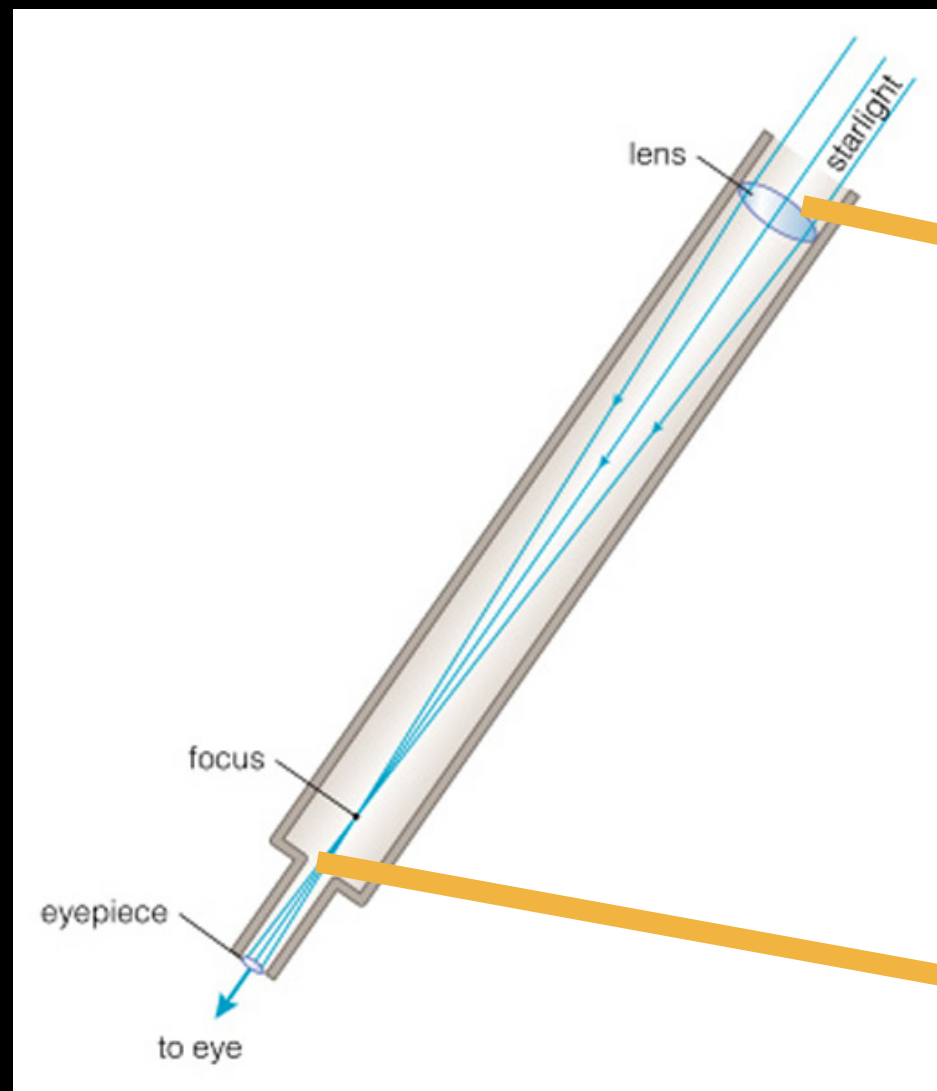
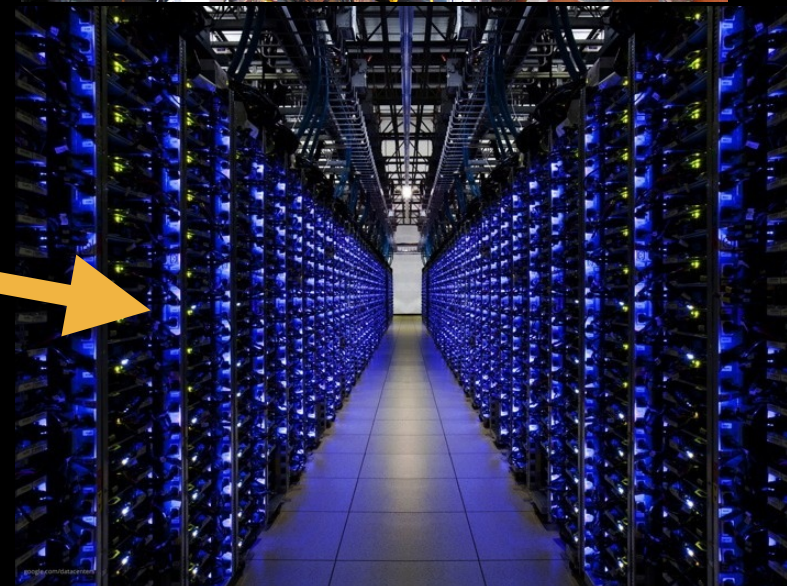
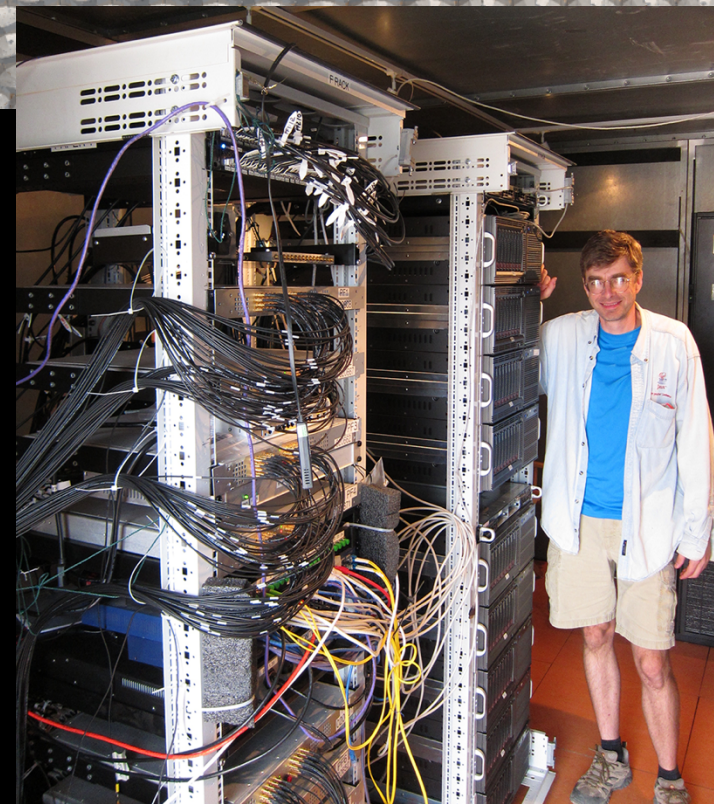
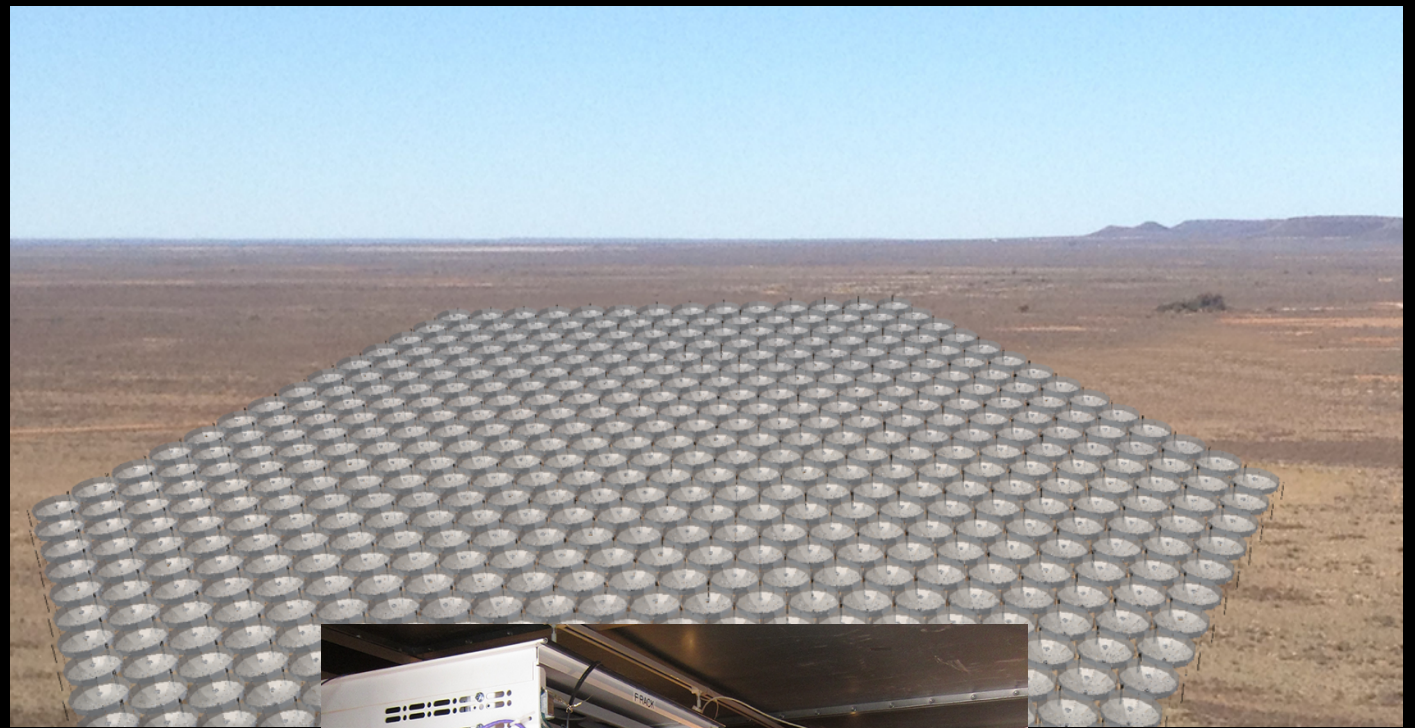
Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million years
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-years
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters

JEAN-FRANCOIS PODEVIN (*illustration*); STEVEN FURLANETTO, AARON SOKASIAN AND LARS HERNQUIST *Harvard University (simulations)*

HERA IS

IS A **SOFTWARE** TELESCOPE





- Primary beam uncertainty is the current leading cause of foreground contamination

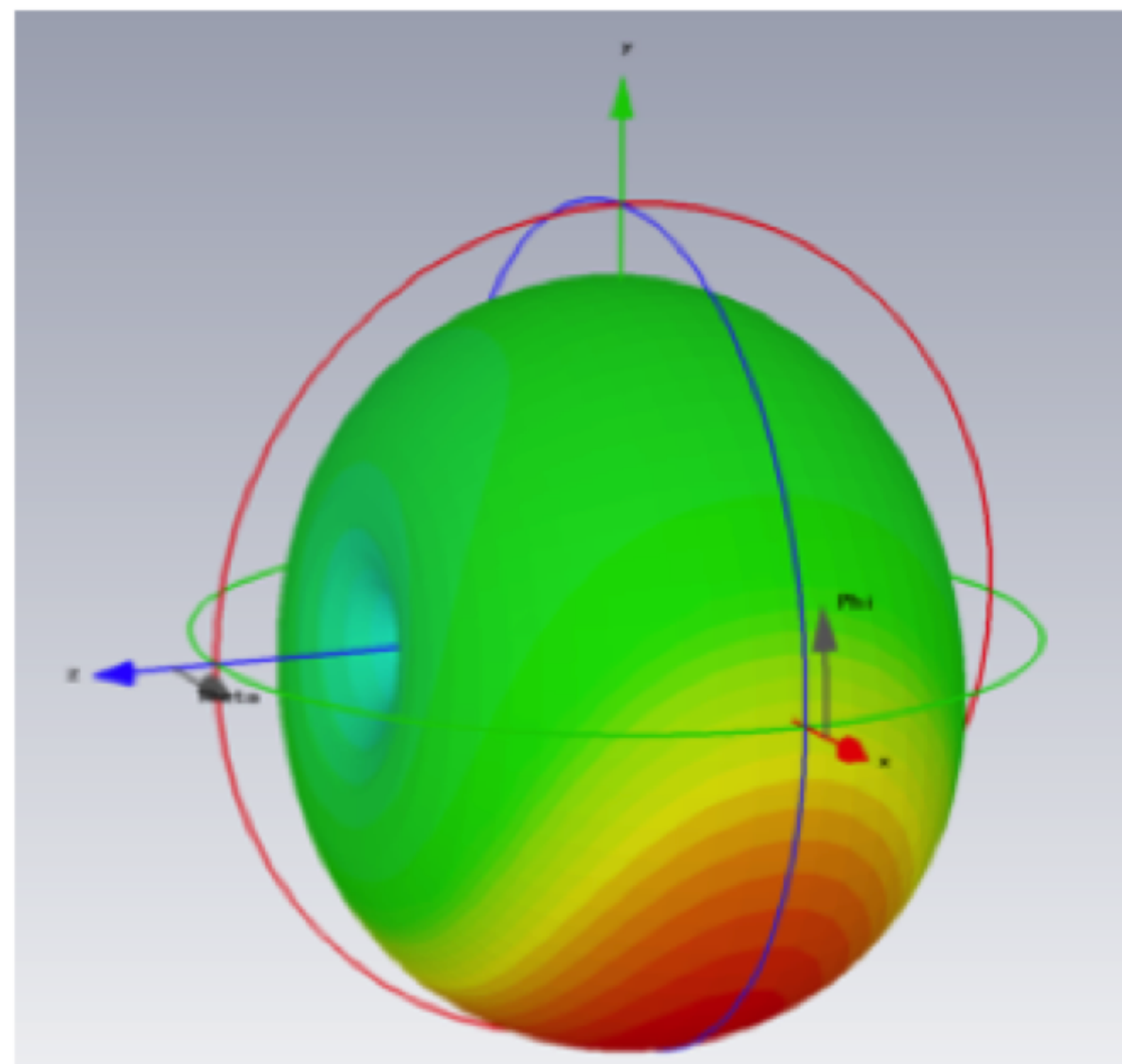
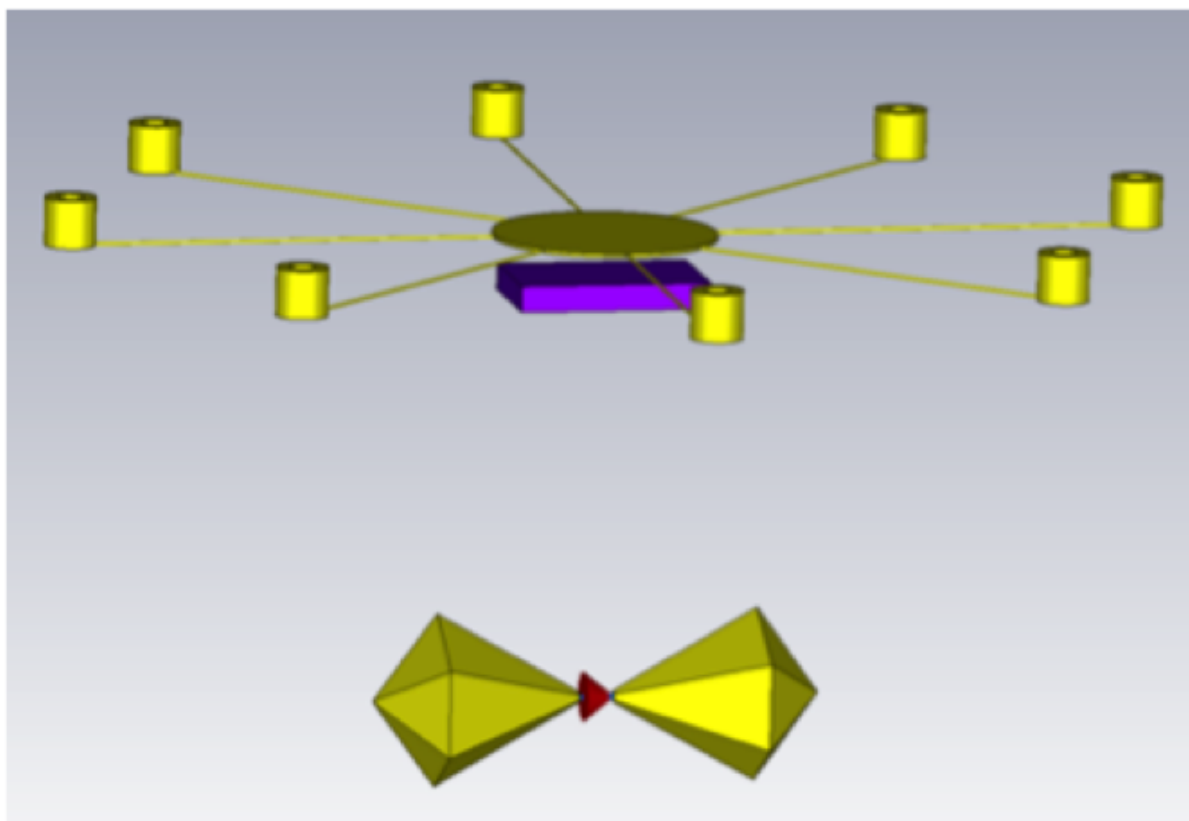
ECHO Project (ATI 2013, Jacobs PI)

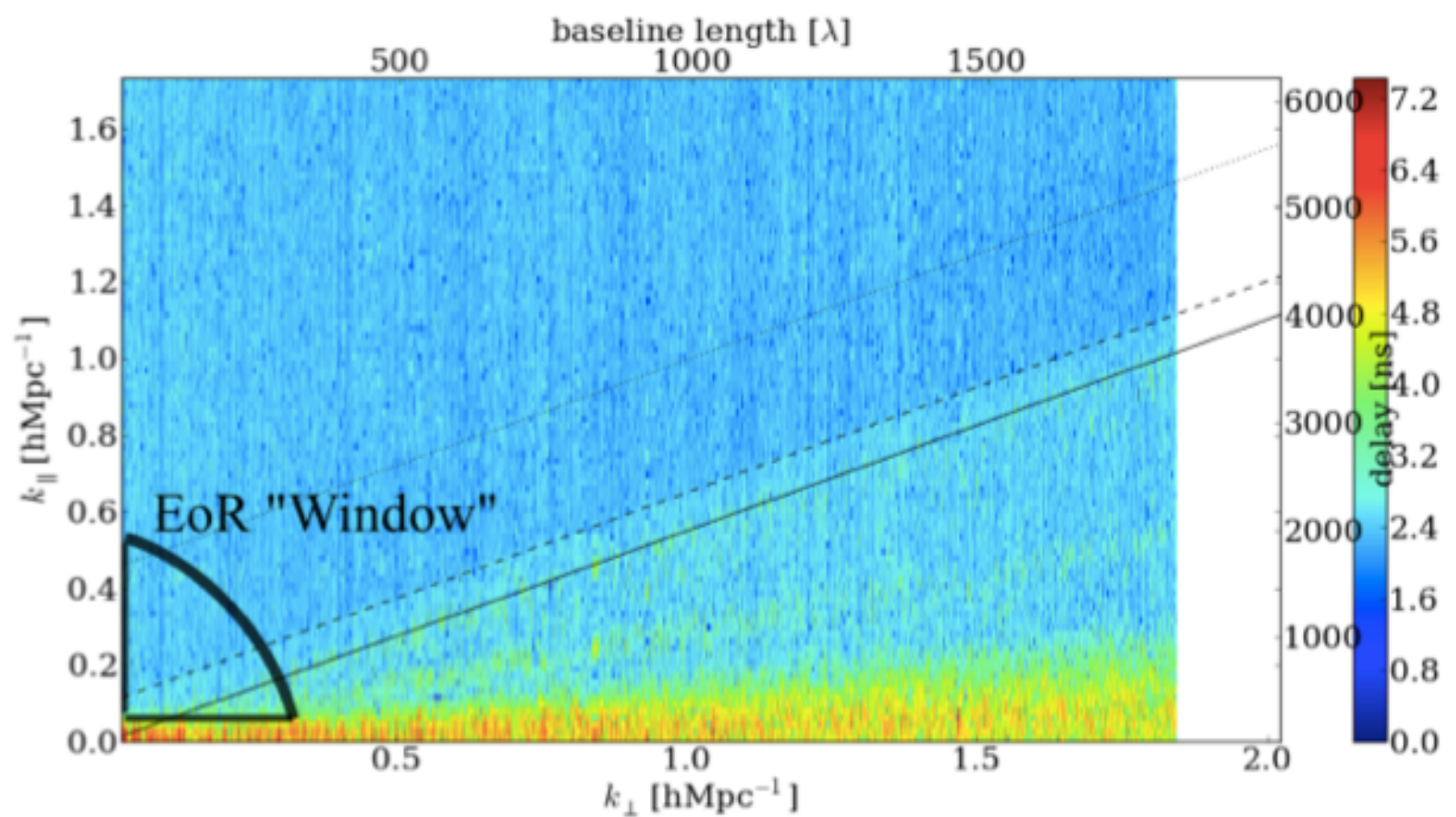
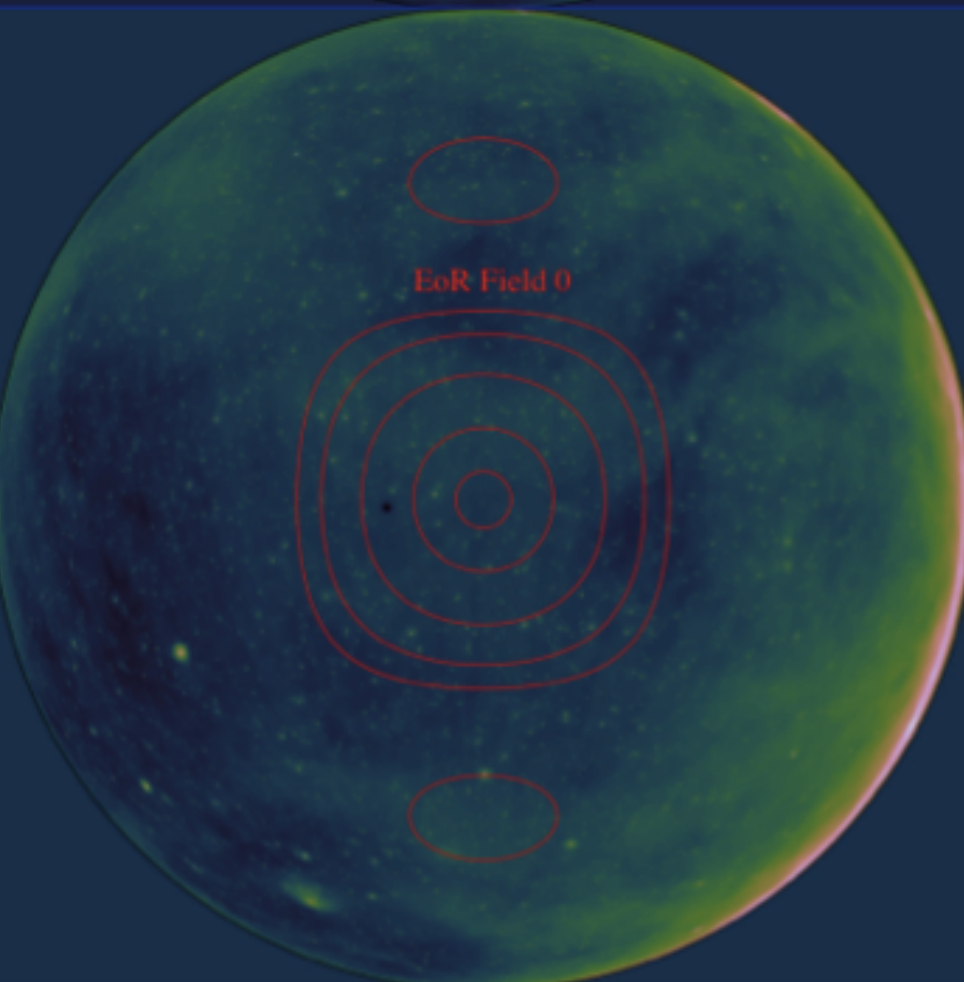
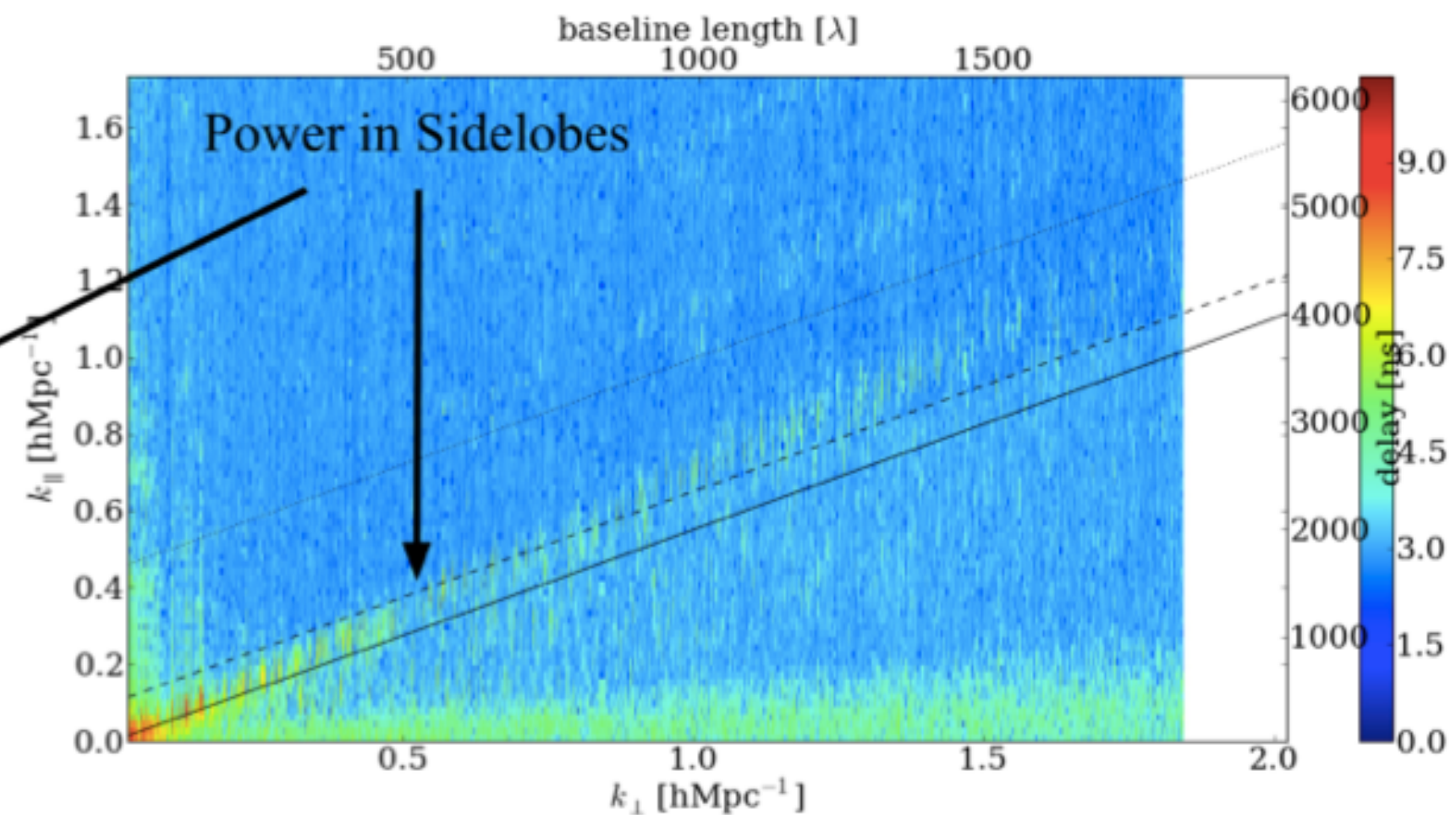
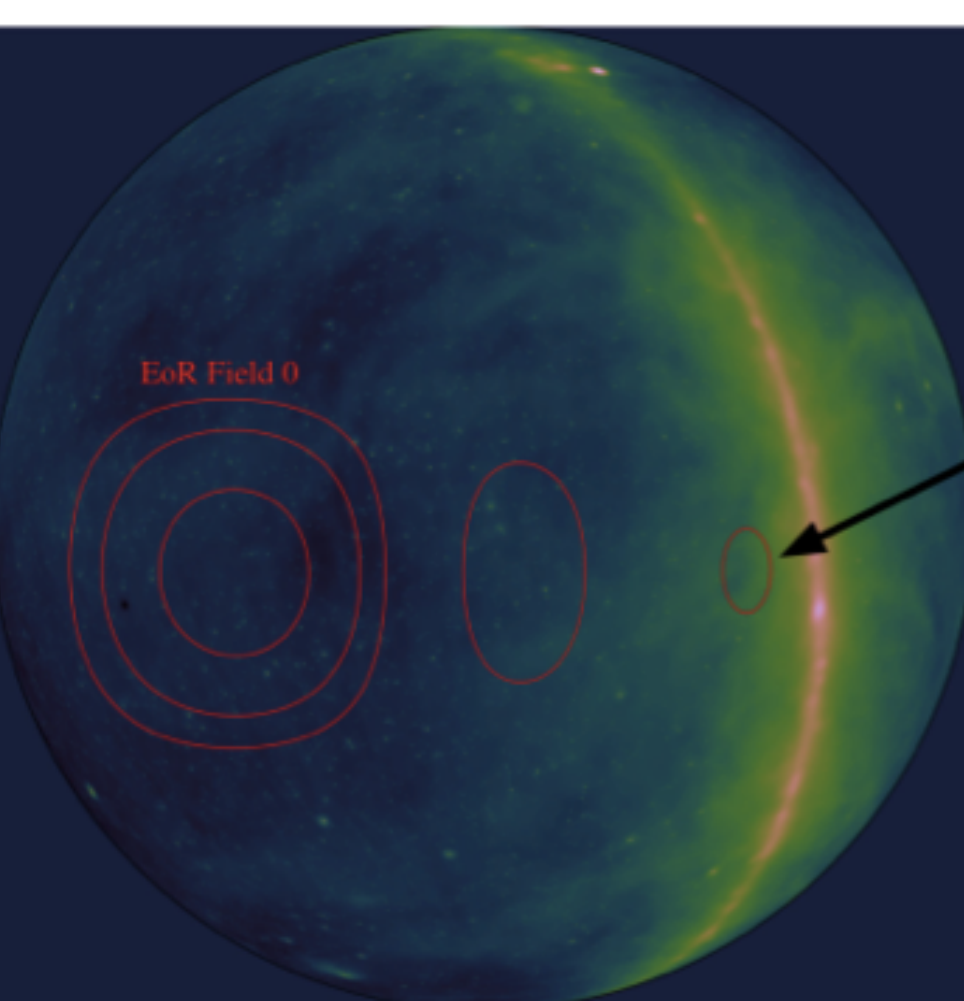
- This uncertainty is identified by simulating only 200 seconds of data. More is needed!

NSF CDSE (Prop.)

- Time-to-science is currently averaging 2.5 years. Telescope is half in the computer, but the expertise is still weighted towards the i.

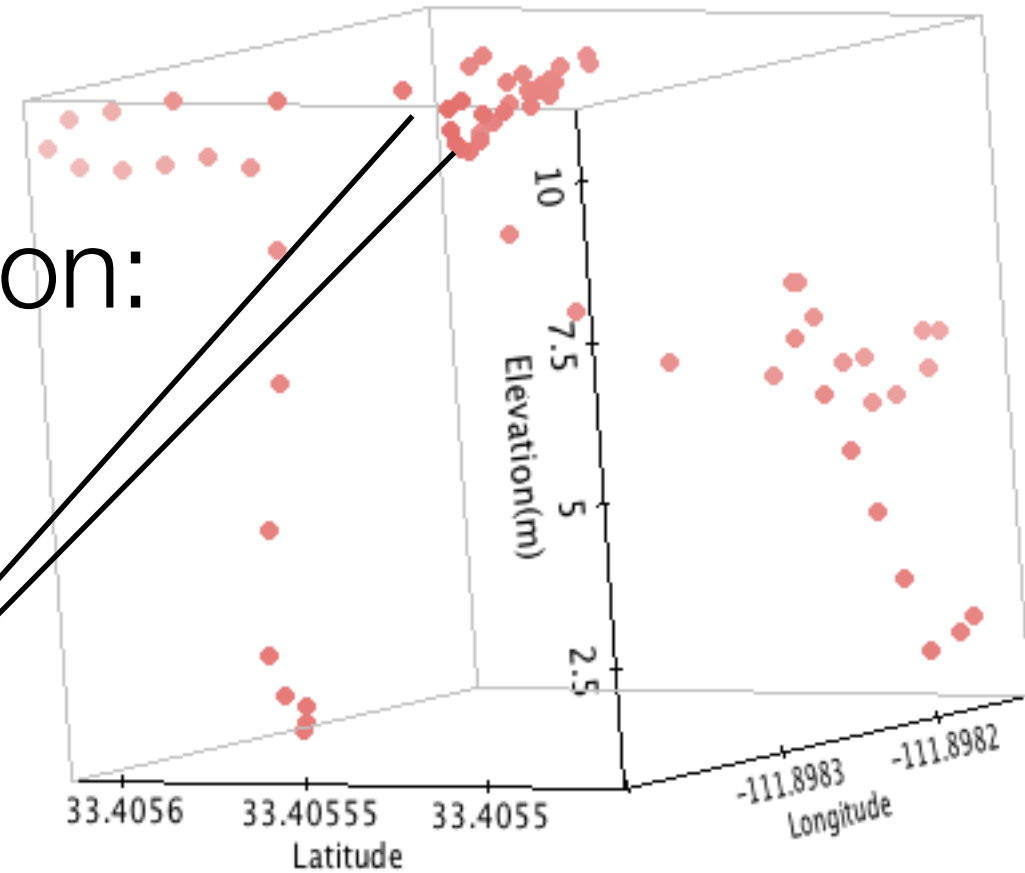
Workflow industrialization.





Stability test

Beam map precision:
3.7deg



Hover
 $dx=4.5m$
 $dy=6.5m$
 $dz=0.422$

Beam mapping flight test

- Flight mode 1: Hover
- Flight mode 2: constant beam contours
- Flight mode 3: Experimental

