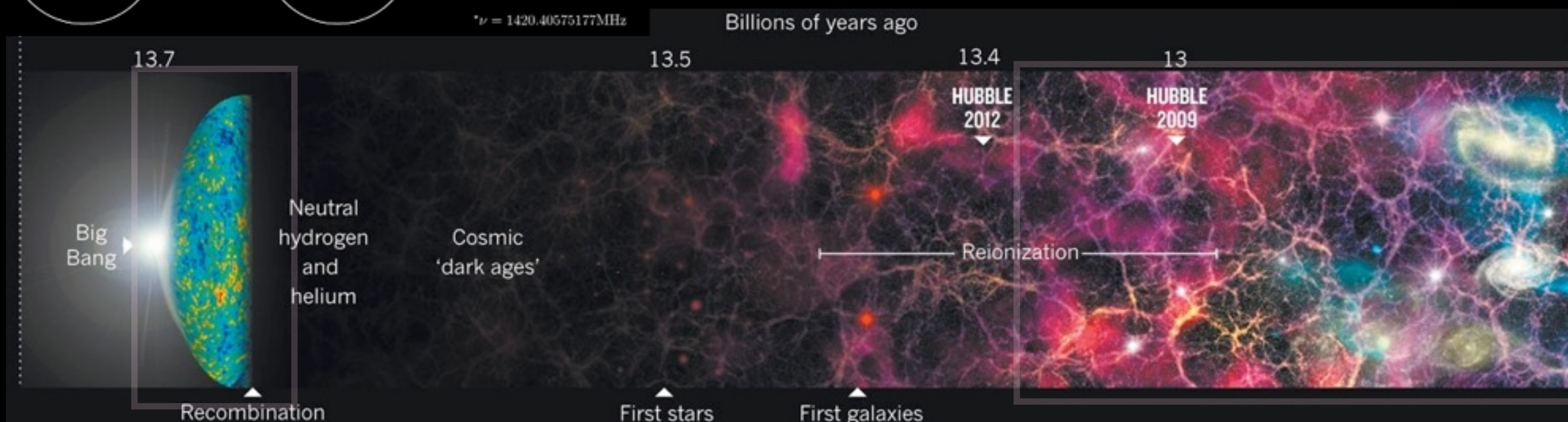
21 CM COSMOLOGY

DANIEL C. JACOBS
NSF POSTDOCTORAL FELLOW, ARIZONA STATE UNIVERSITY

Dark Ages and Cosmic Reionization

- Dark Ages   z>~15
  - Onset of non-linearity.
  - Birth of stars, galaxies, quasars, metals.
  - Last frontier!

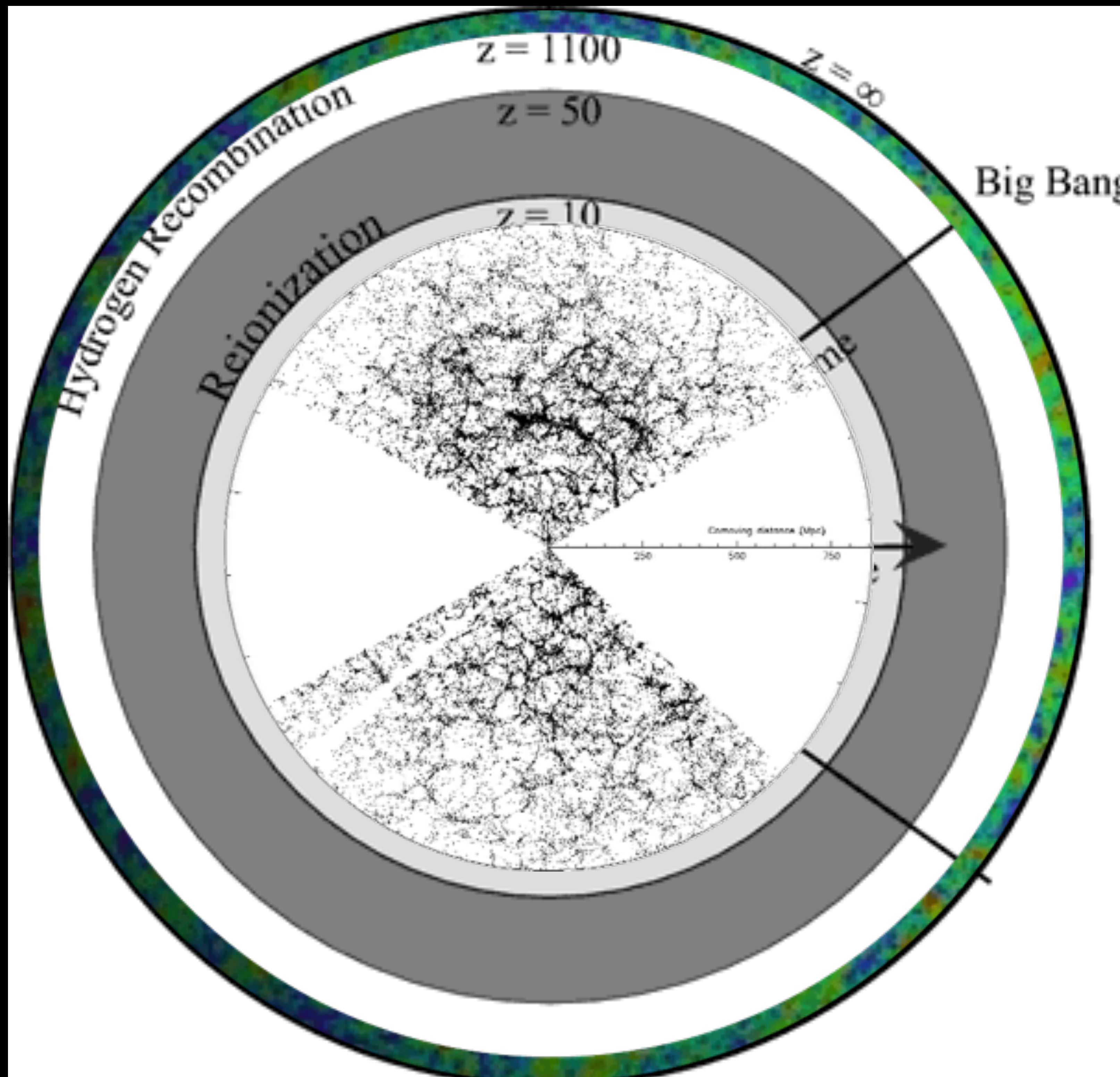
- Reionization 6~<z~<15
  - Last great phase change (affects 75% of the baryonic matter)
  - sensitive to early star and quasar formation
  - an unambiguous cosmological milestone



1100   20   8   6

Cowen 2013

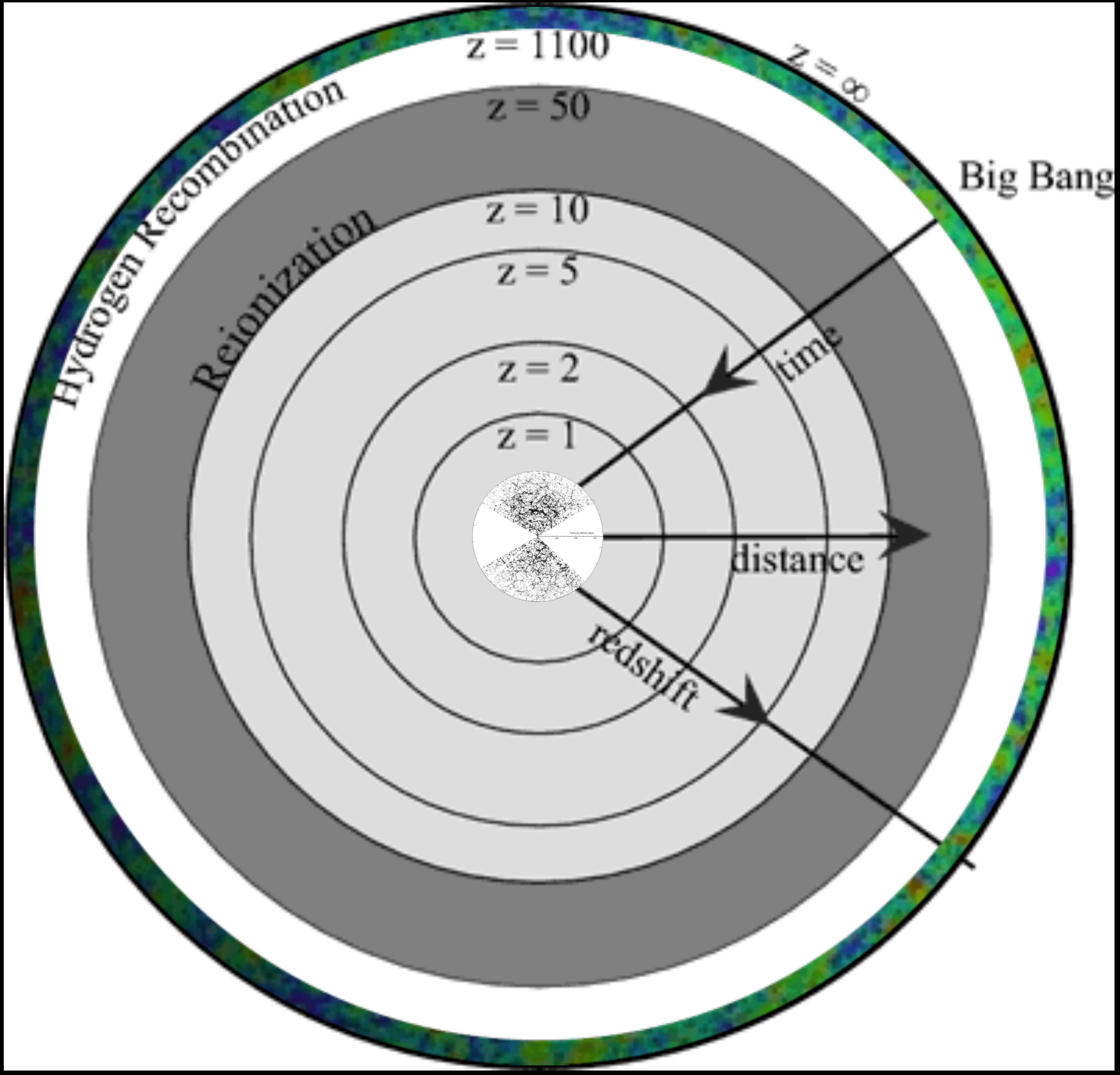
THE LARGE SCALE UNIVERSE



D. Jacobs, 2015

Adapted from Loeb, 2012

THE LARGE SCALE UNIVERSE

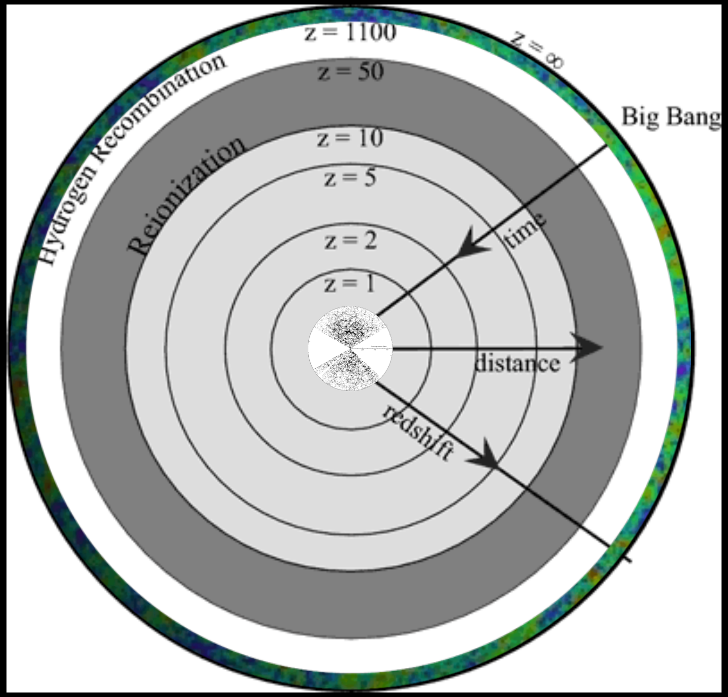


D. Jacobs, 2015

Adapted from Loeb, 2012

21CM COSMOLOGY

- Precision Cosmology
  - at high z, linear pre-reionization 10^16 modes (compared to 10^7 CMB)
    initial conditions, neutrino mass
  - at low z, emission in wells, intensity mapping, BAO and lensing
    dark energy eq. of state or other models
- Astrophysical
  - can see times prior to formation of emitters (opens up the dark ages to exploration)
  - probes reionization directly



D. Jacobs, 2015

REIONIZATION IN 21CM

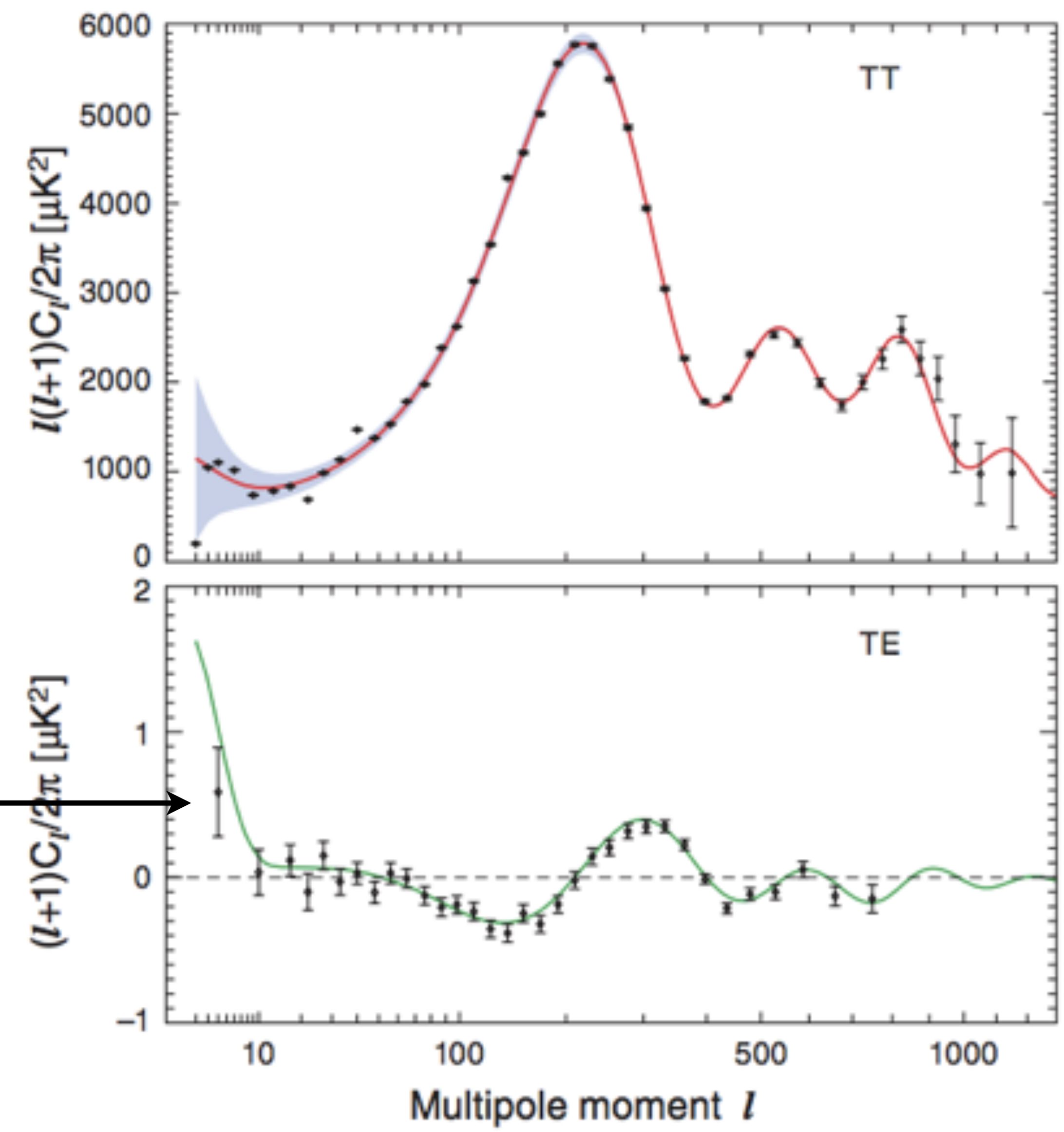
- pre-21cm probes
- 21cm cosmology
- foregrounds
- current results
- the future

CMB and Reionization

- electrons in ionized universe scatter the polarized CMB
- l<10 (horizon at reionization)
- small optical depth (a weak ~1% signal)

$$\tau_e = 0.087 +/- 0.015$$

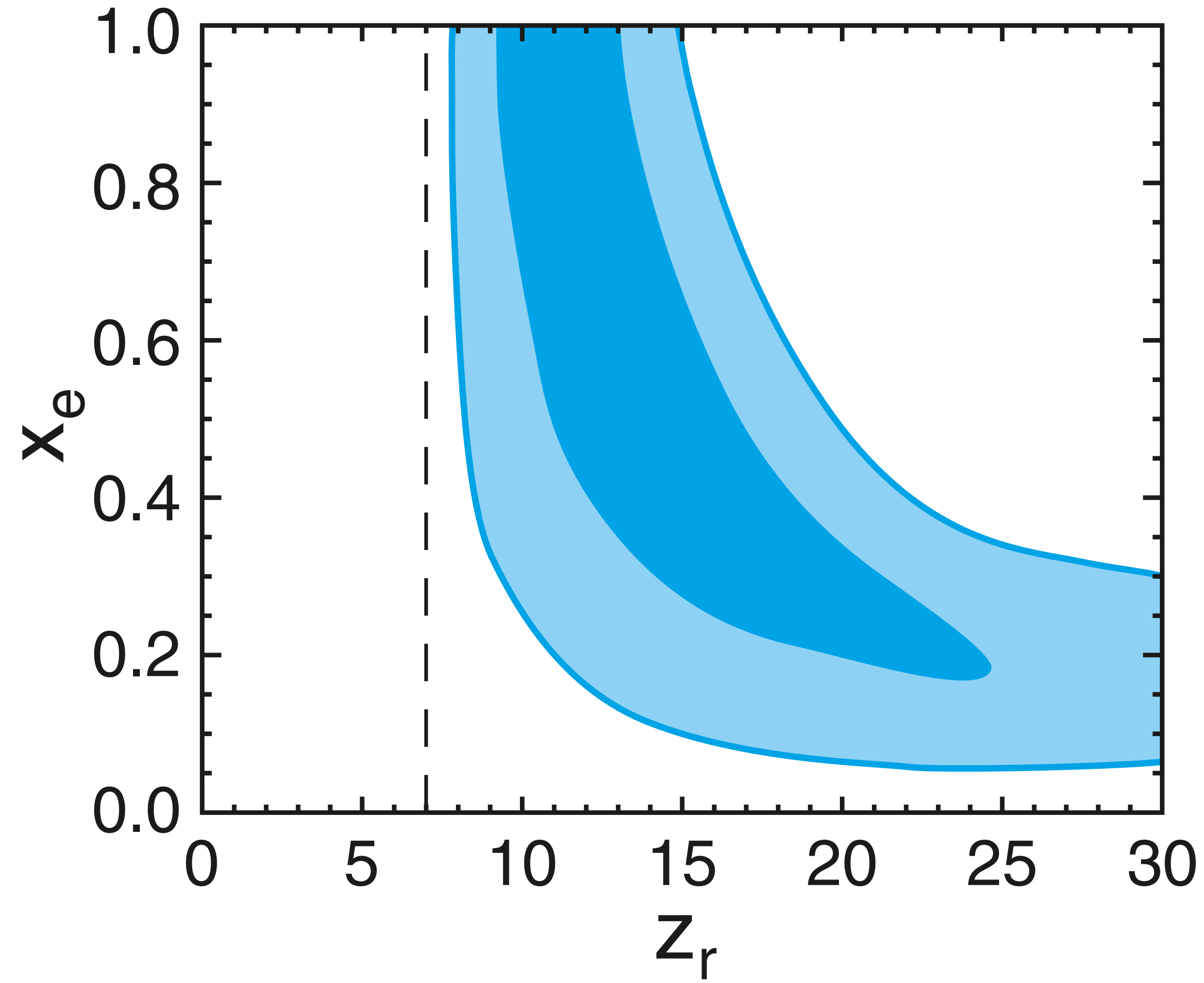
WMAP 7



http://loco.lab.asu.edu/danny_jacobs

implications of optical depth

- difficult to get reionization earlier than z<15
- z<13, just about anything goes
- the earlier it starts, the longer it goes on.



Dunkley ea 2009 ApJ 180, 306

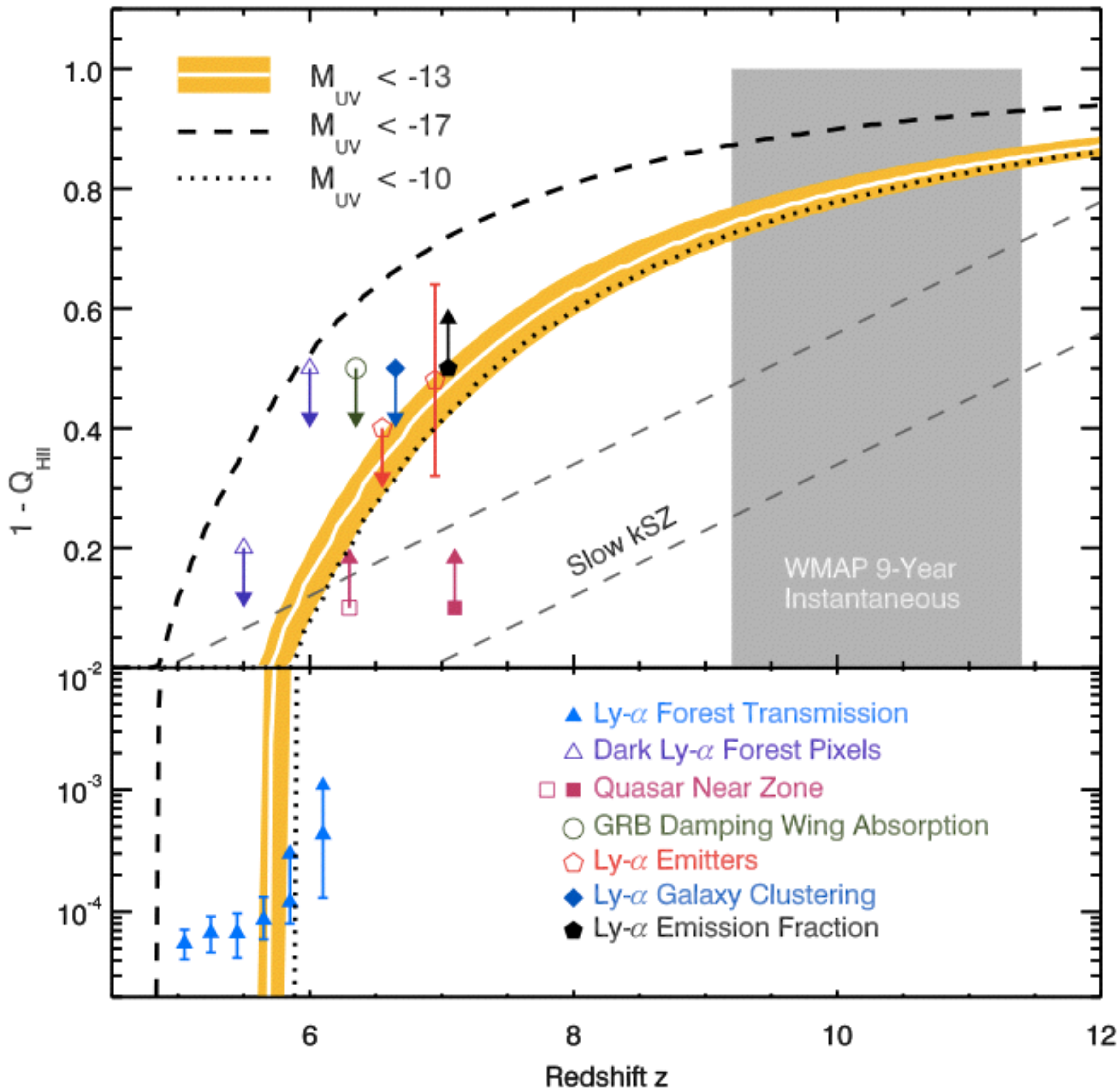
CMB constraints

- electrons in ionized universe scatter the polarized CMB
- l<10 (horizon at reionization)
- small optical depth (a weak ~1% signal)

$$\cancel{\tau_e = 0.087 +/- 0.015} \xrightarrow{\text{WMAP 7}} z_{\rm reion} \simeq 10.5 \pm 1.1$$

$$\cancel{\tau_e = 0.066 \pm 0.012} \xrightarrow{\text{Planck (Feb 2015)}} z_{\rm reion} \simeq 8.8 \pm 1.2$$

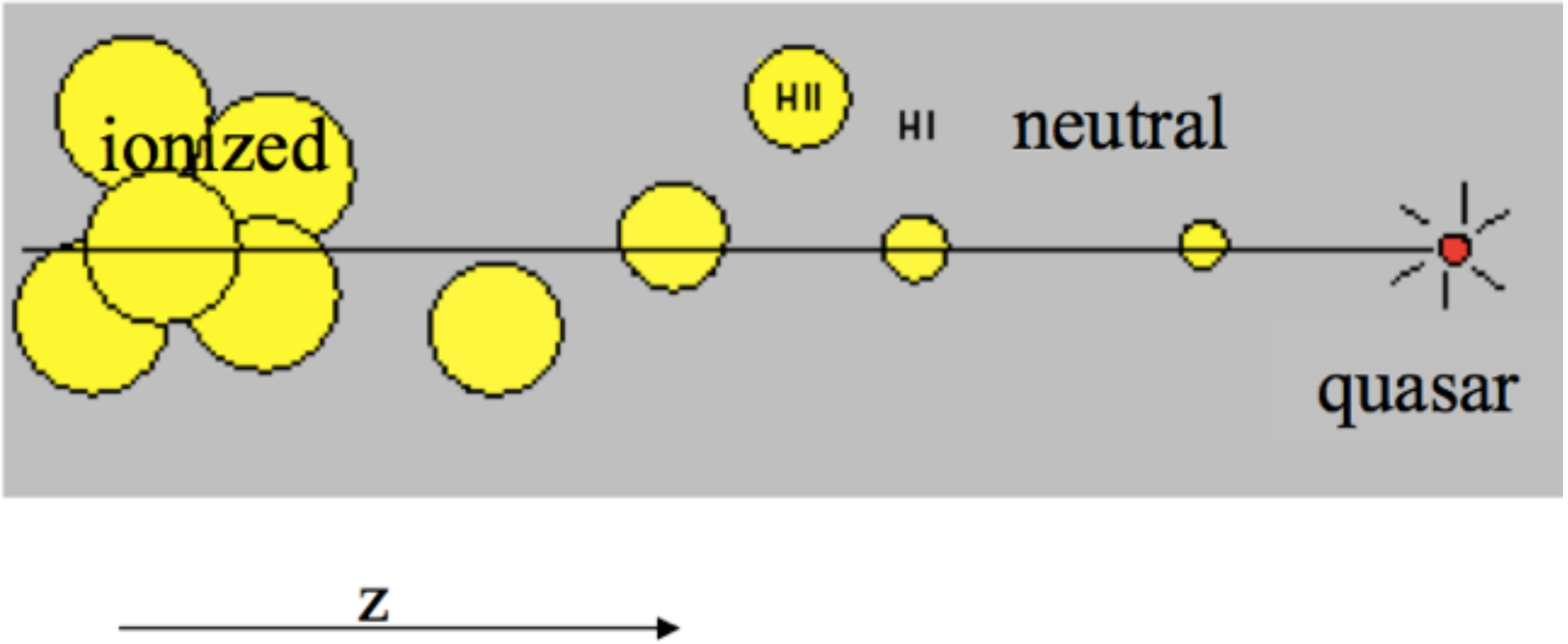
$$\tau_e = 0.078 \pm 0.012 \xrightarrow{\text{Planck (July 2015)}} z_{\rm reion} \simeq 9.9 \pm 1.8$$

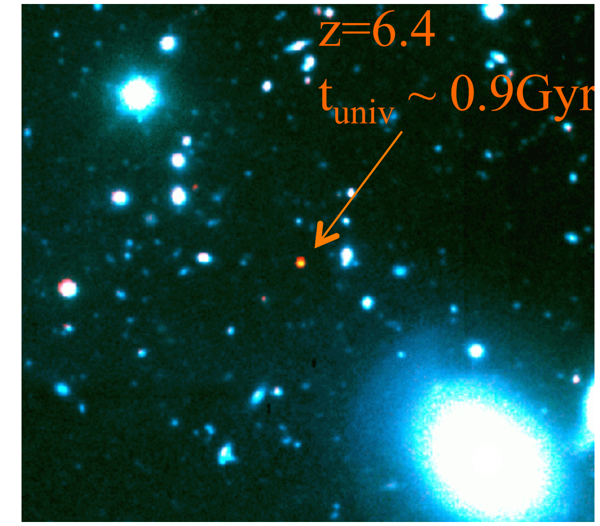


Robertson et al 2013

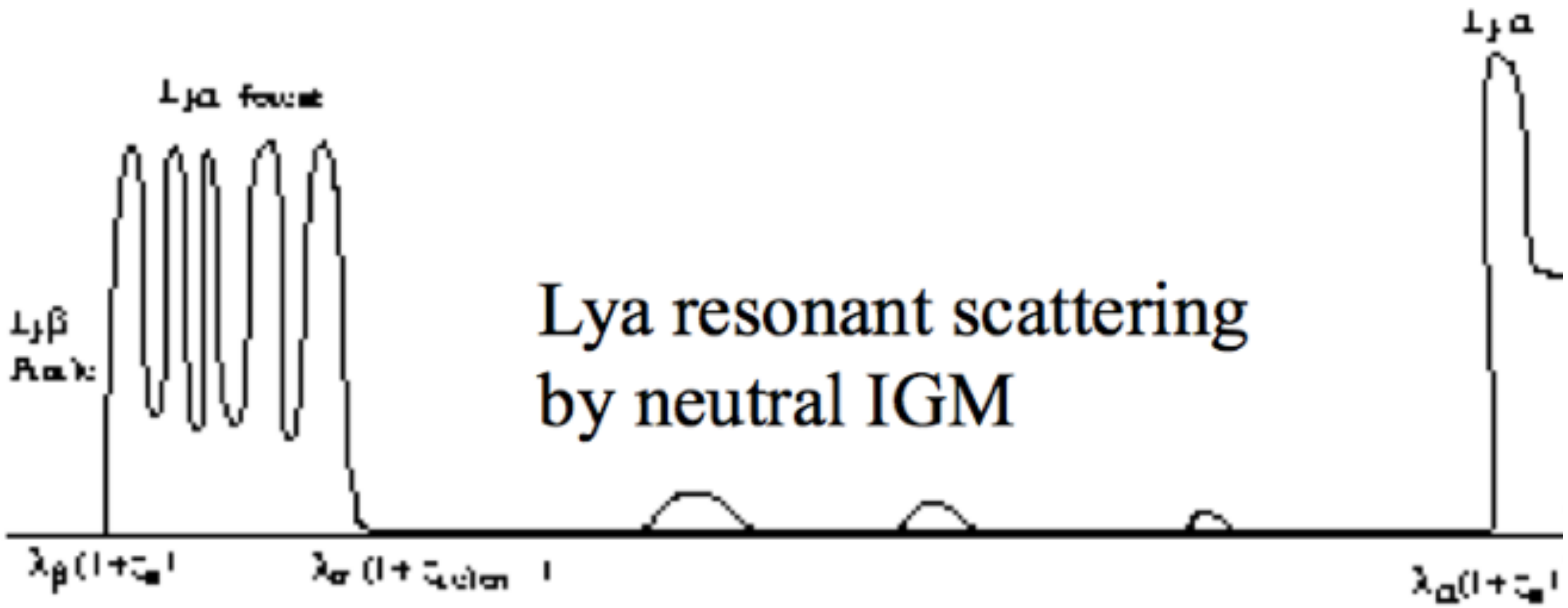
Robertson ea 2013

Gunn - Peterson Absorption





Spectrum



Gunn and Peterson 1963; Barkana and Loeb 2001

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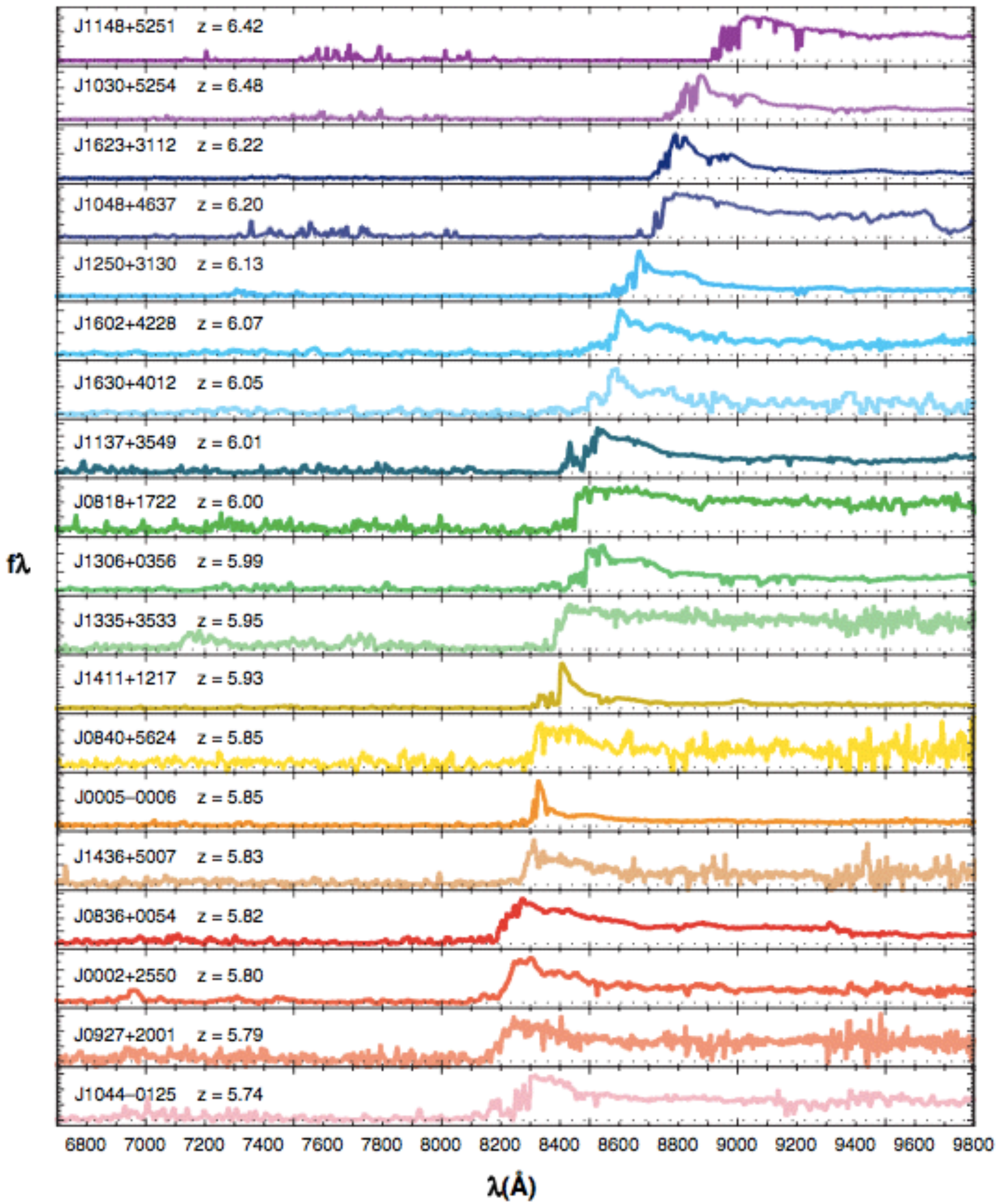
6.42

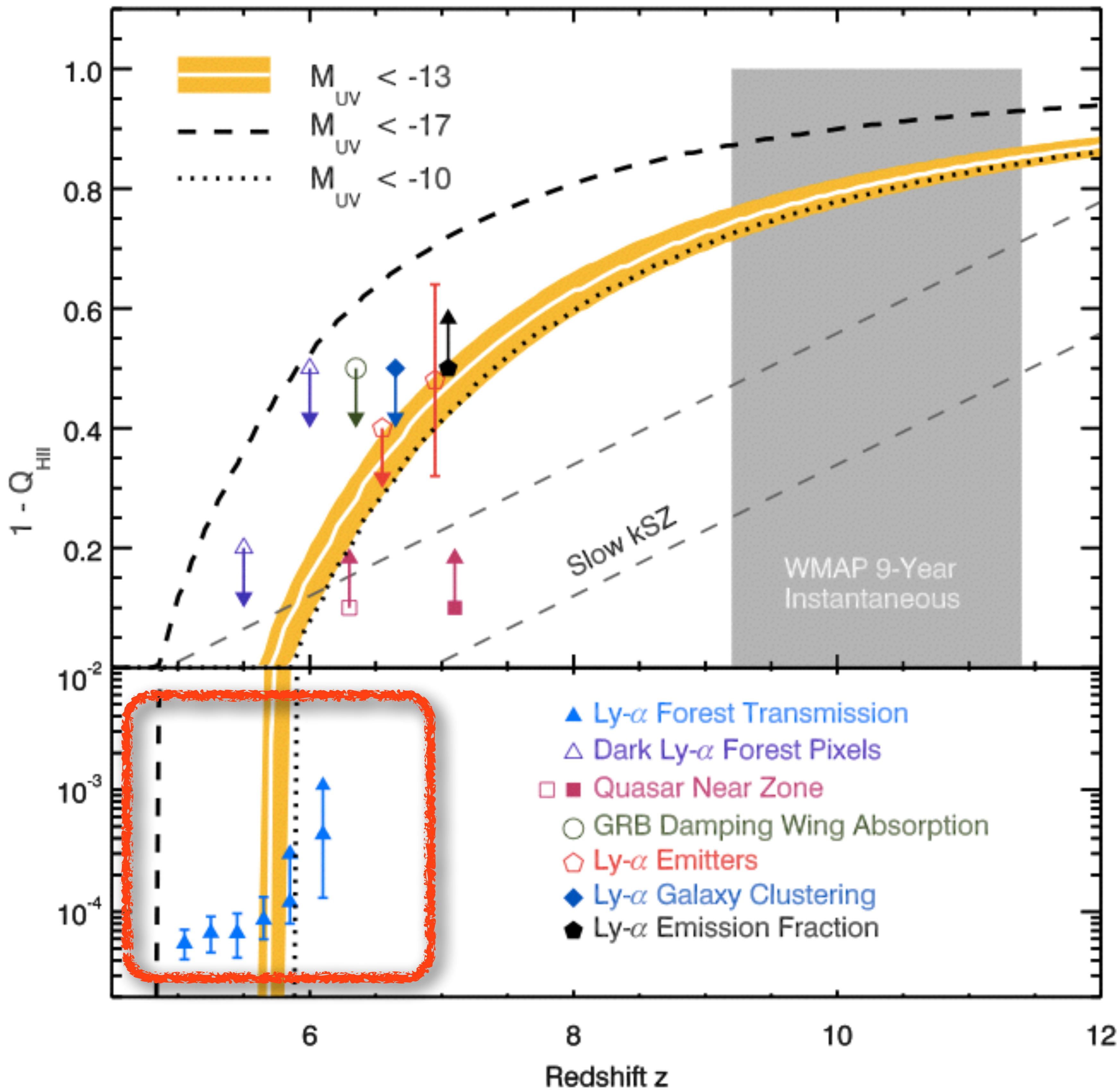


5.74

redshift

- SDSS quasars
- opaque at z>6
- reionization?

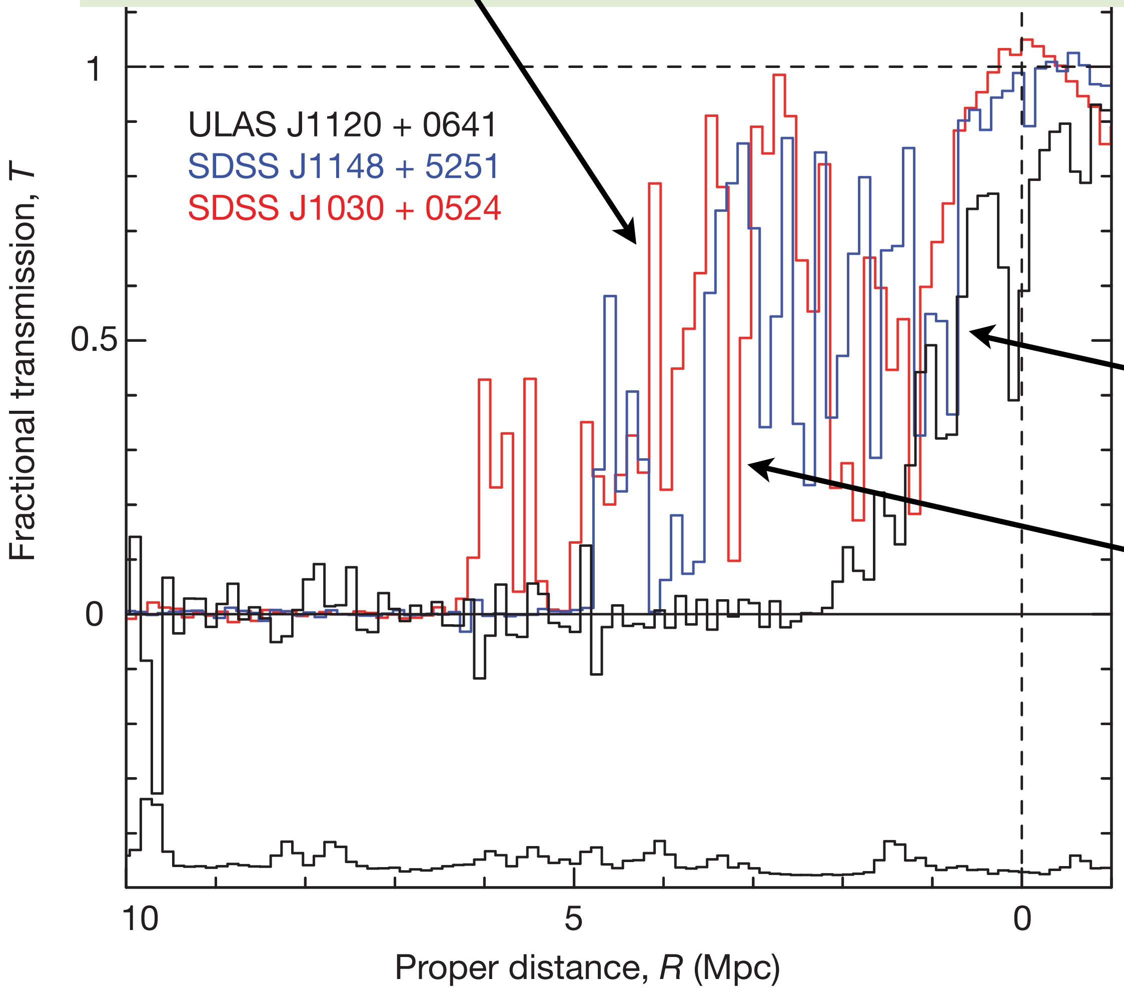
Fan, Carilli, Keating 2006



Robertson ea 2013

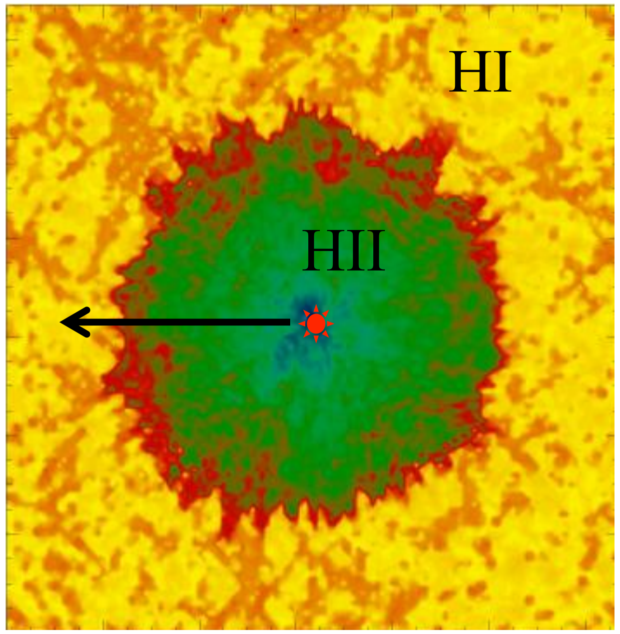
Quasar Near Zones

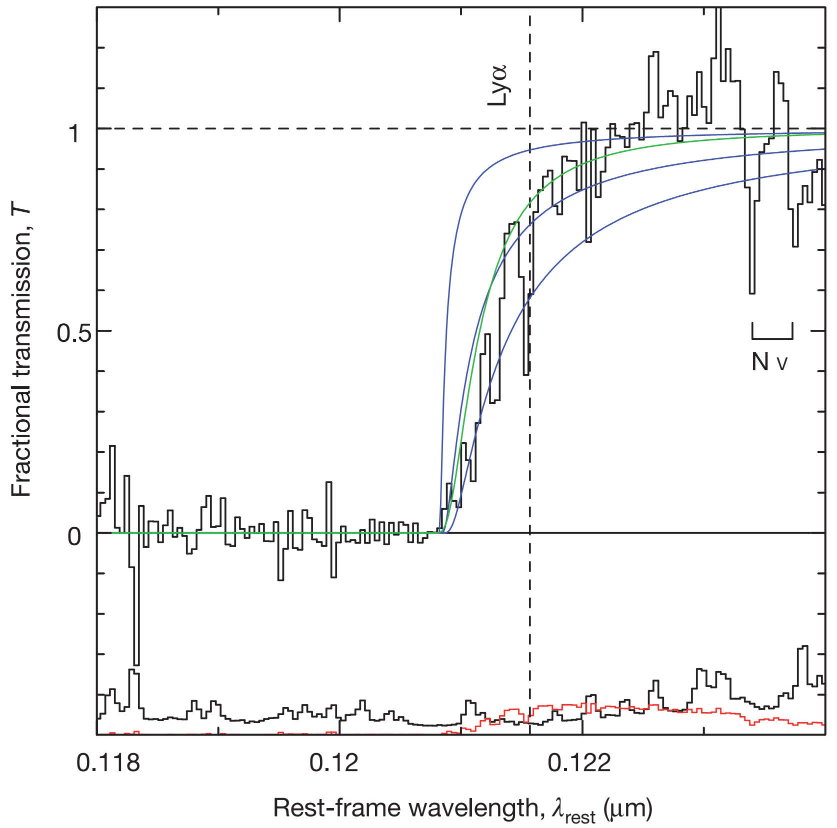
lack of absorption right near the quasar

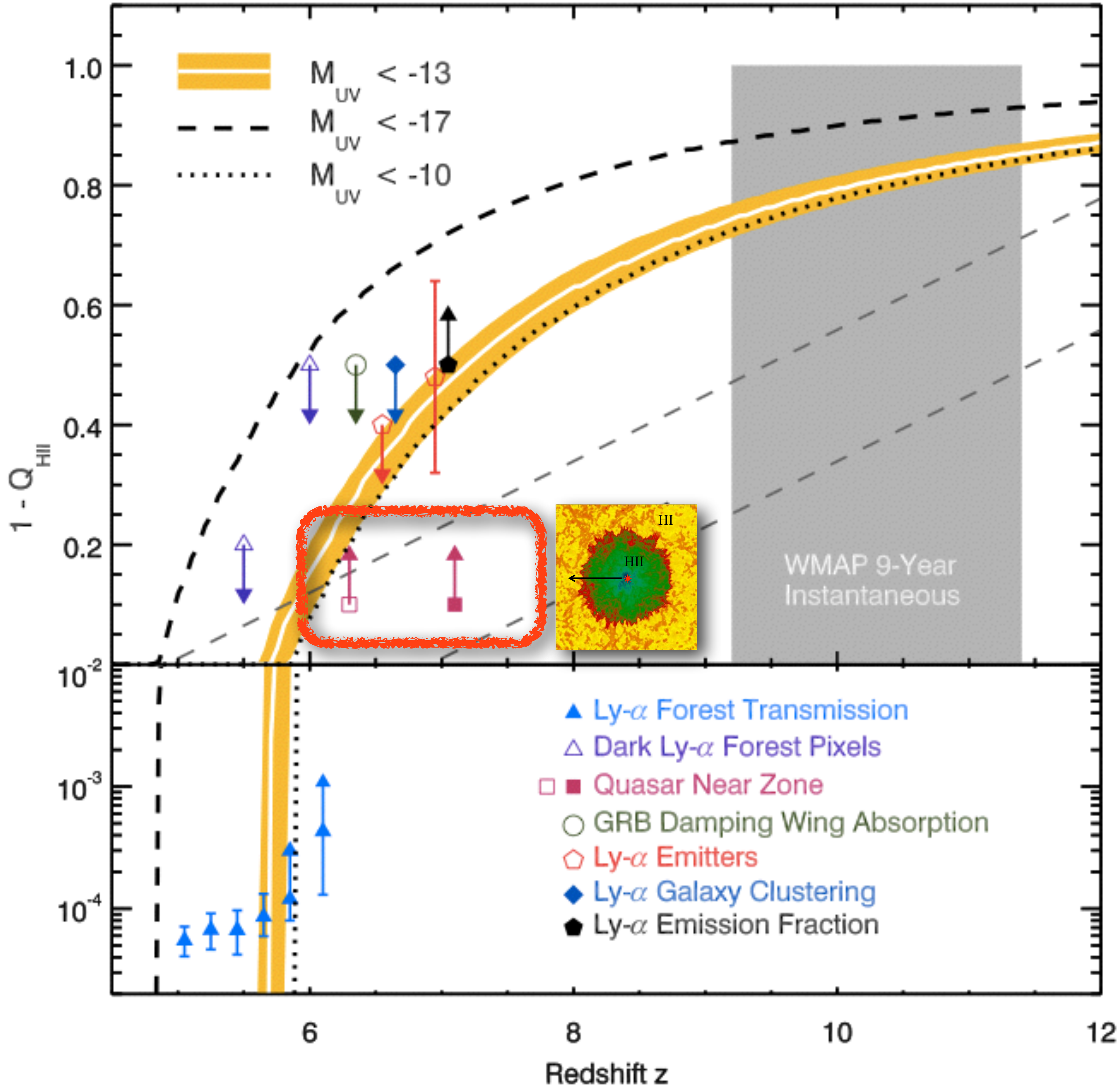


z=7.1

z=6.4







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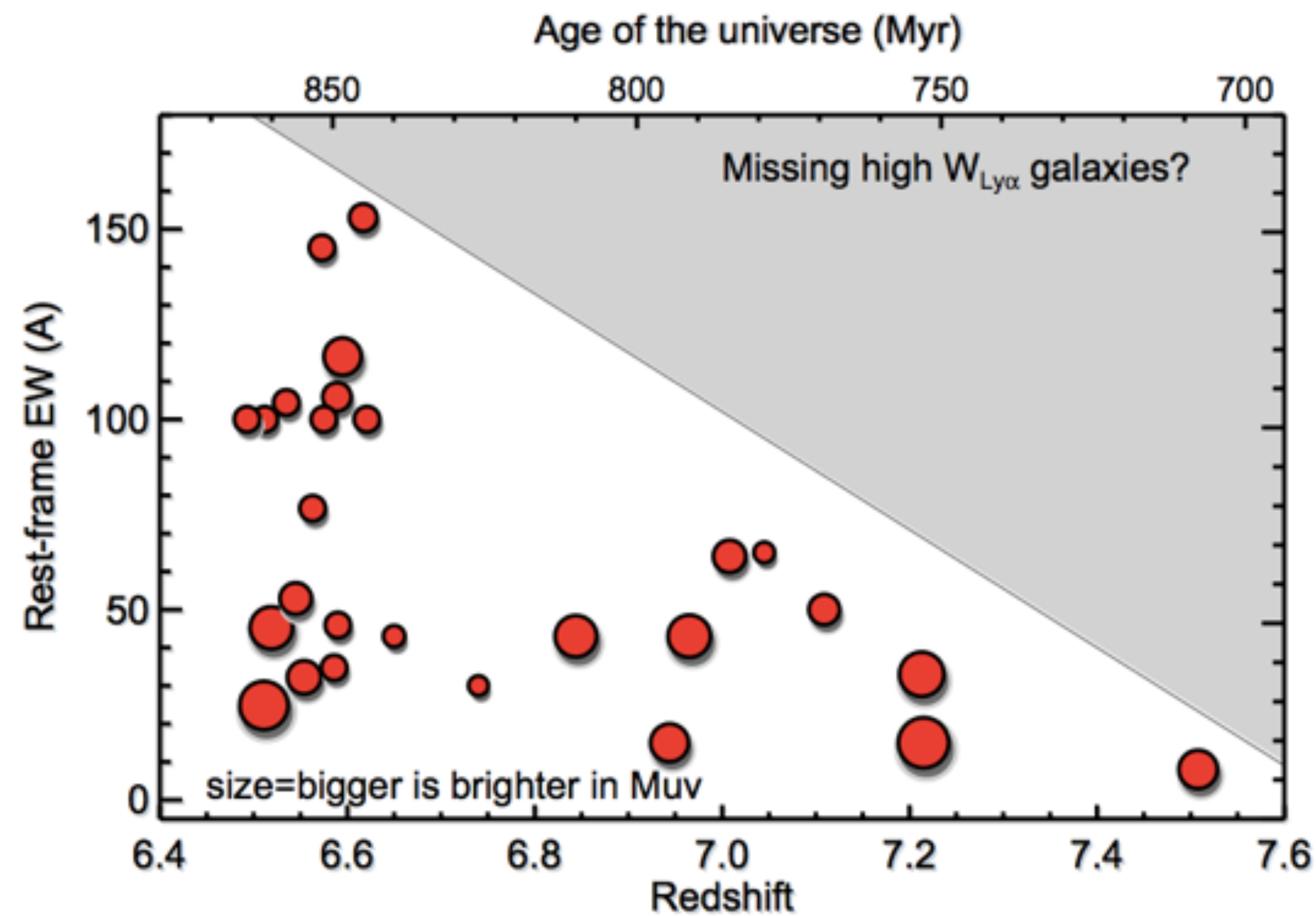
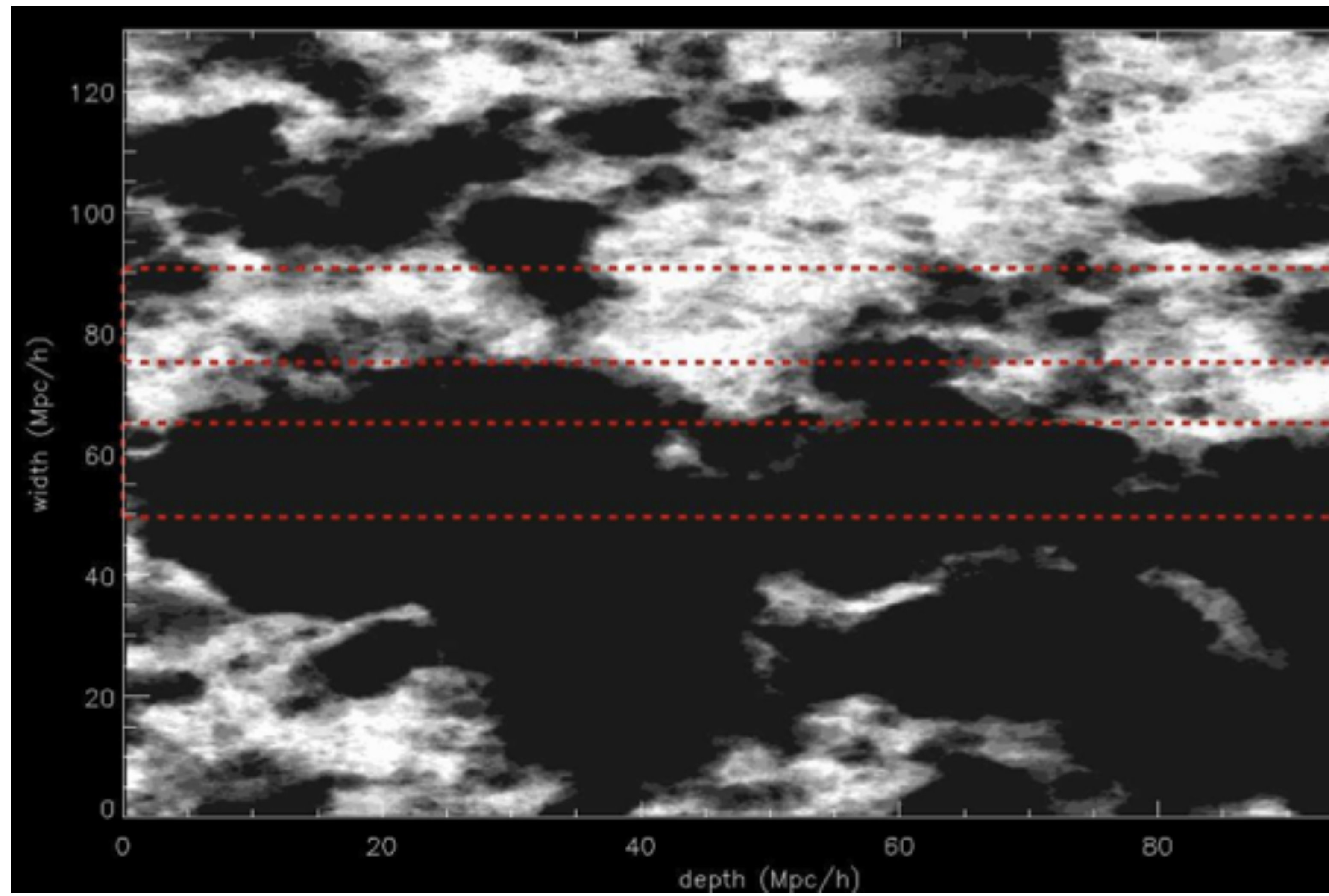
More missing Lyalpha photons

- accounting for selection effects and likely evolution scenarios
- the number of lyalpha emitters drops with increasing redshift
- Explanation:
    - A) fewer such galaxies
    - B) absorption
      Modeling suggests patchy reionization and neutral fraction>0.3 at z~8



What do objects tell us?

- survey volumes are small compared to patchiness scale
- 3D simulations with current surveys have x_HI>0.05 at z=7



Taylor and Lidz, 2014 MNRAS 437 2542

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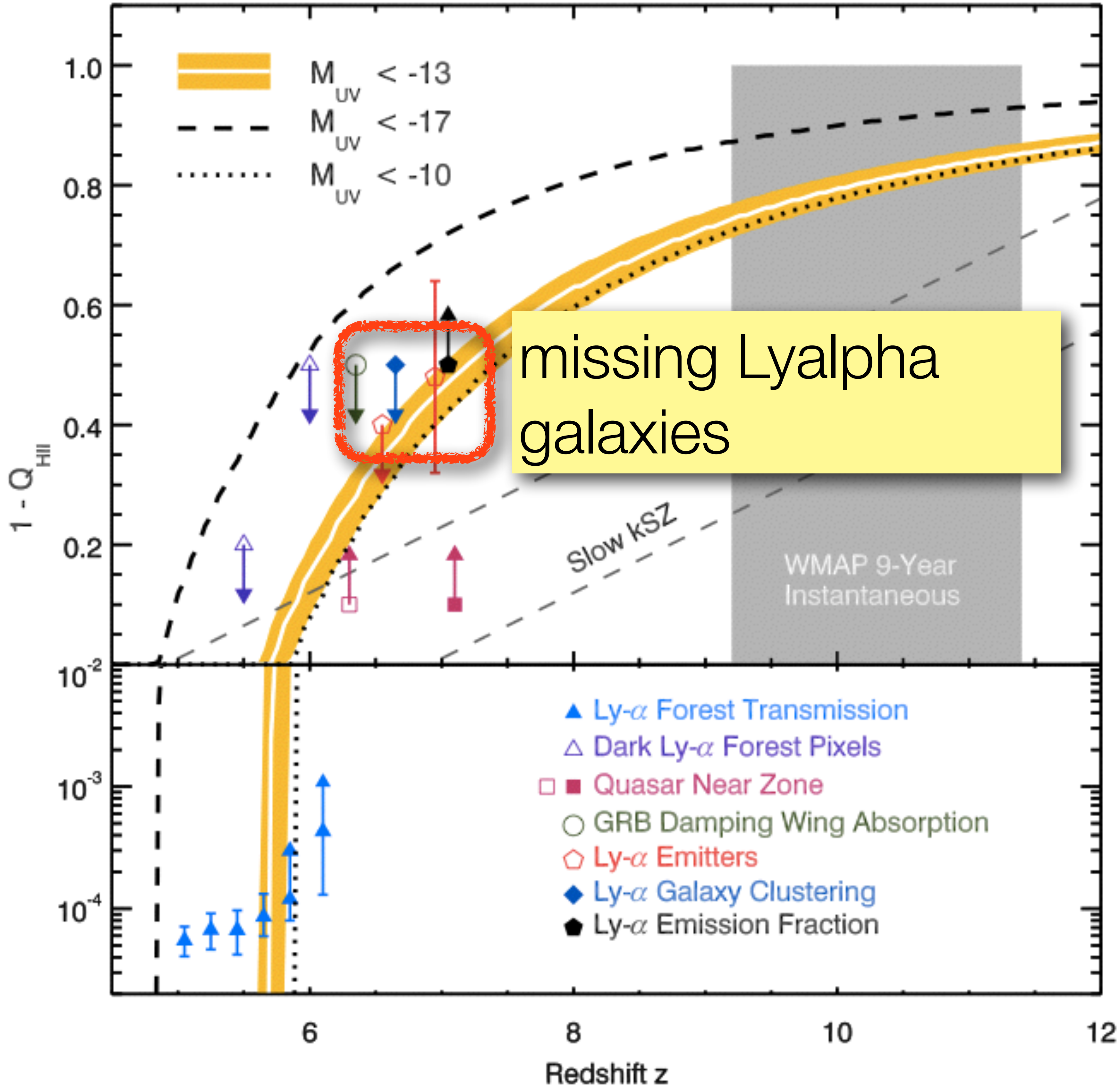

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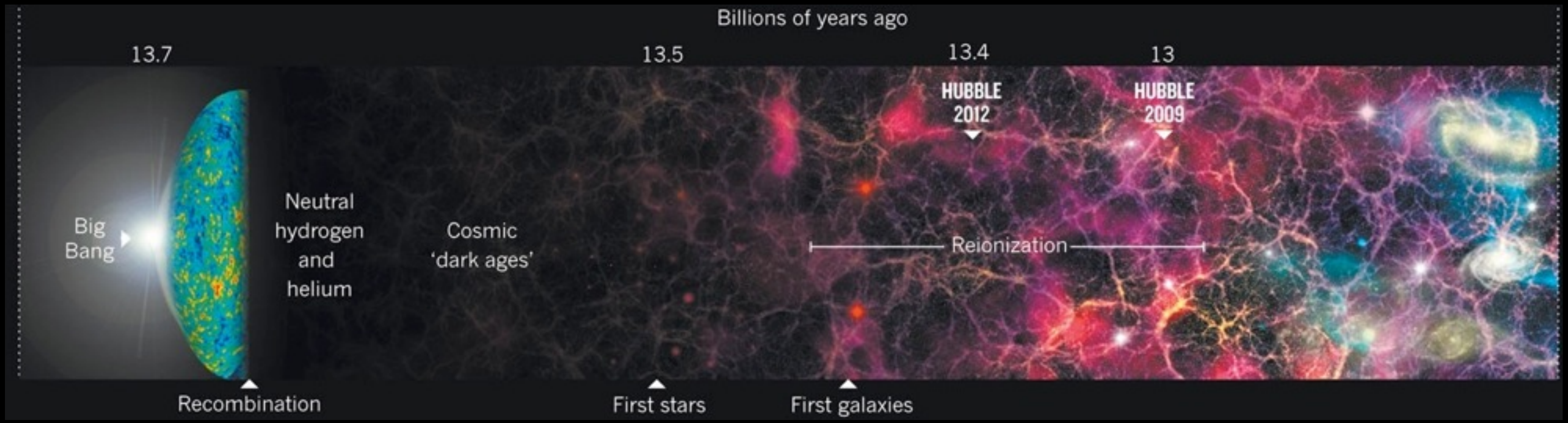
Dark Ages and Cosmic Reionization

current non-21cm measurements:

galaxy model dependent

highly sample limited

best probe only works at low HI densities



1100 20? 8? 6

Cowen 2013

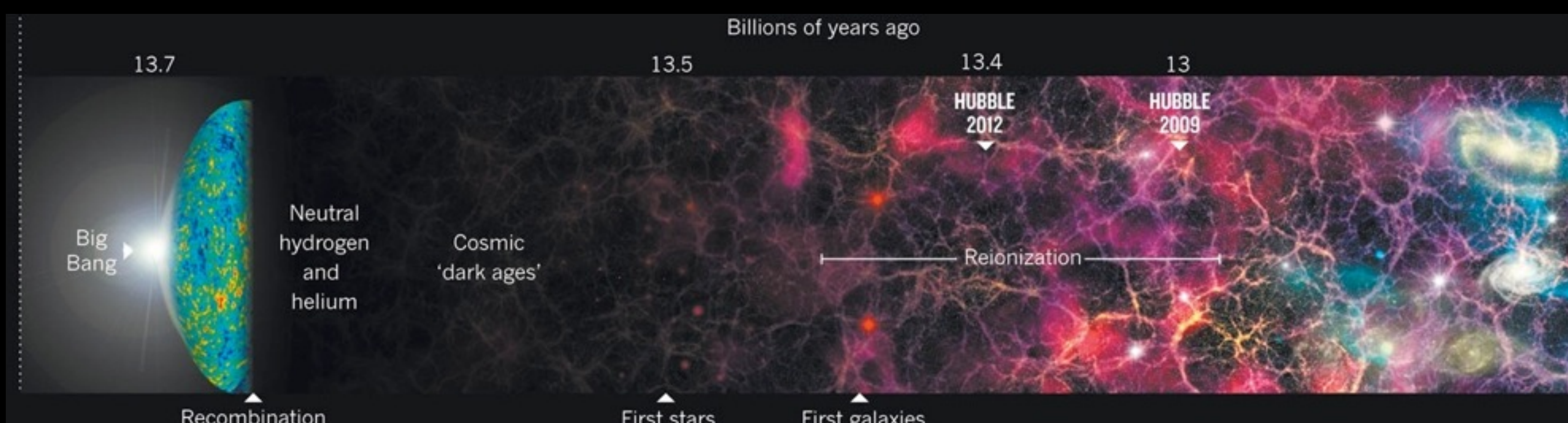
Dark Ages and Cosmic Reionization

current non-21cm measurements:

- galaxy model dependent
- highly sample limited
- best probe only works at low HI densities

21cm:

- Directly probes HI
- narrow spectral line,
  - (frequency maps directly to redshift)
- can theoretically survey all visible universe
- optically thin (cubes!)

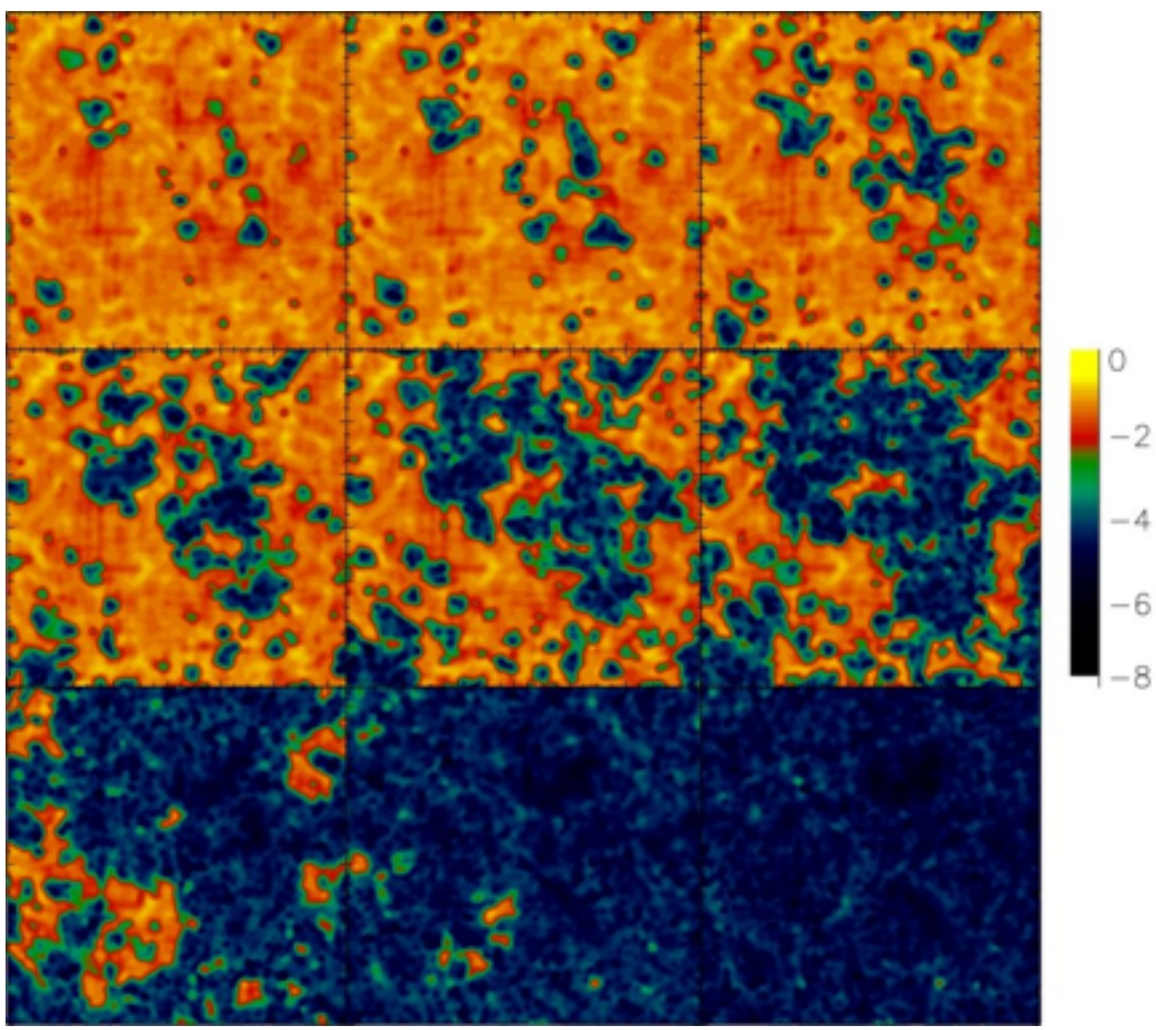


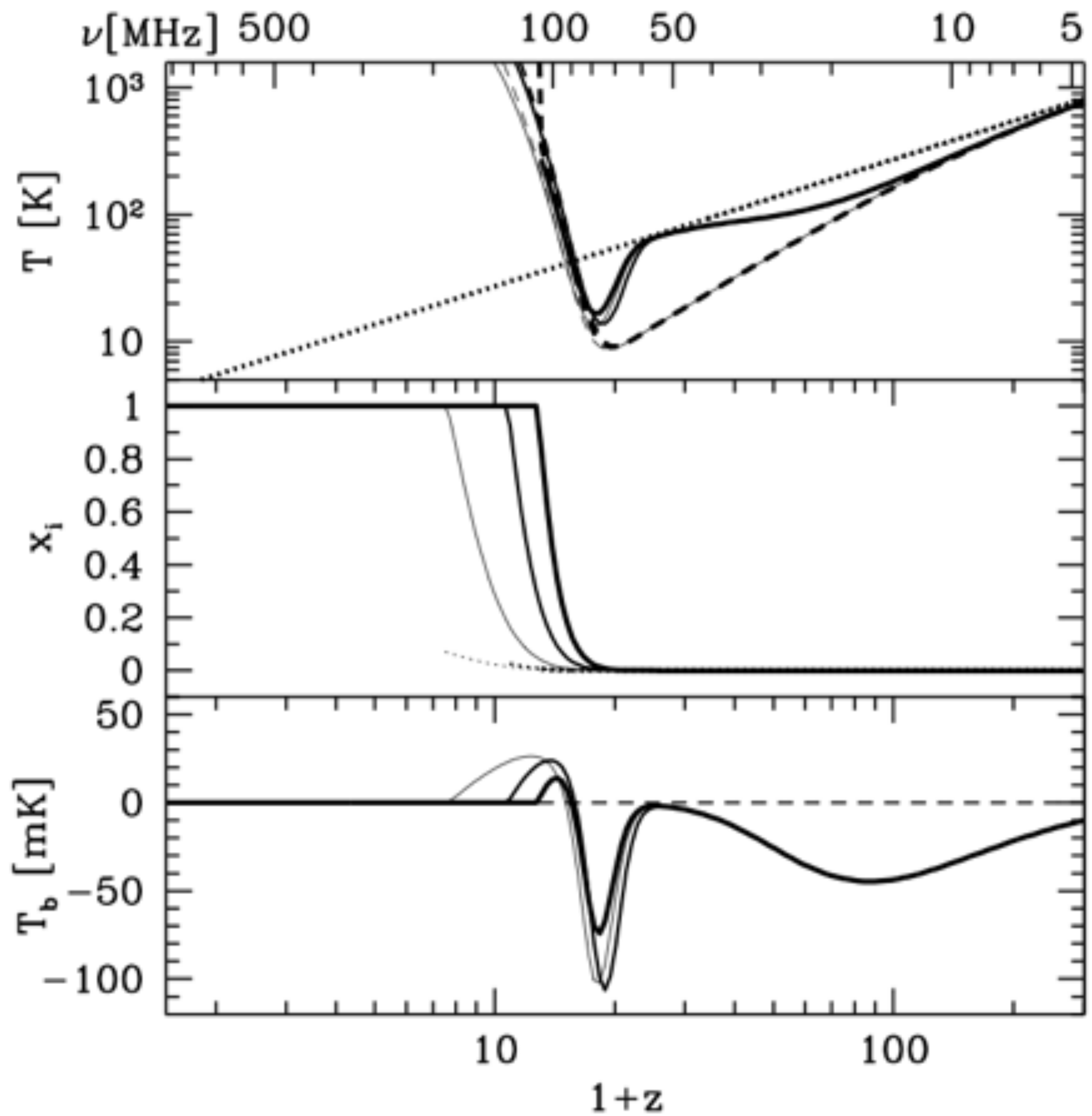
1100 20? 8? 6

Cowen 2013

21cm Observables

- Two features to measure: the global signal and the fluctuations
  global signal: **single antenna.** dark ages dynamics and reionization
  fluctuations: **interferometer** can distinguish different models of reionization and late dark ages





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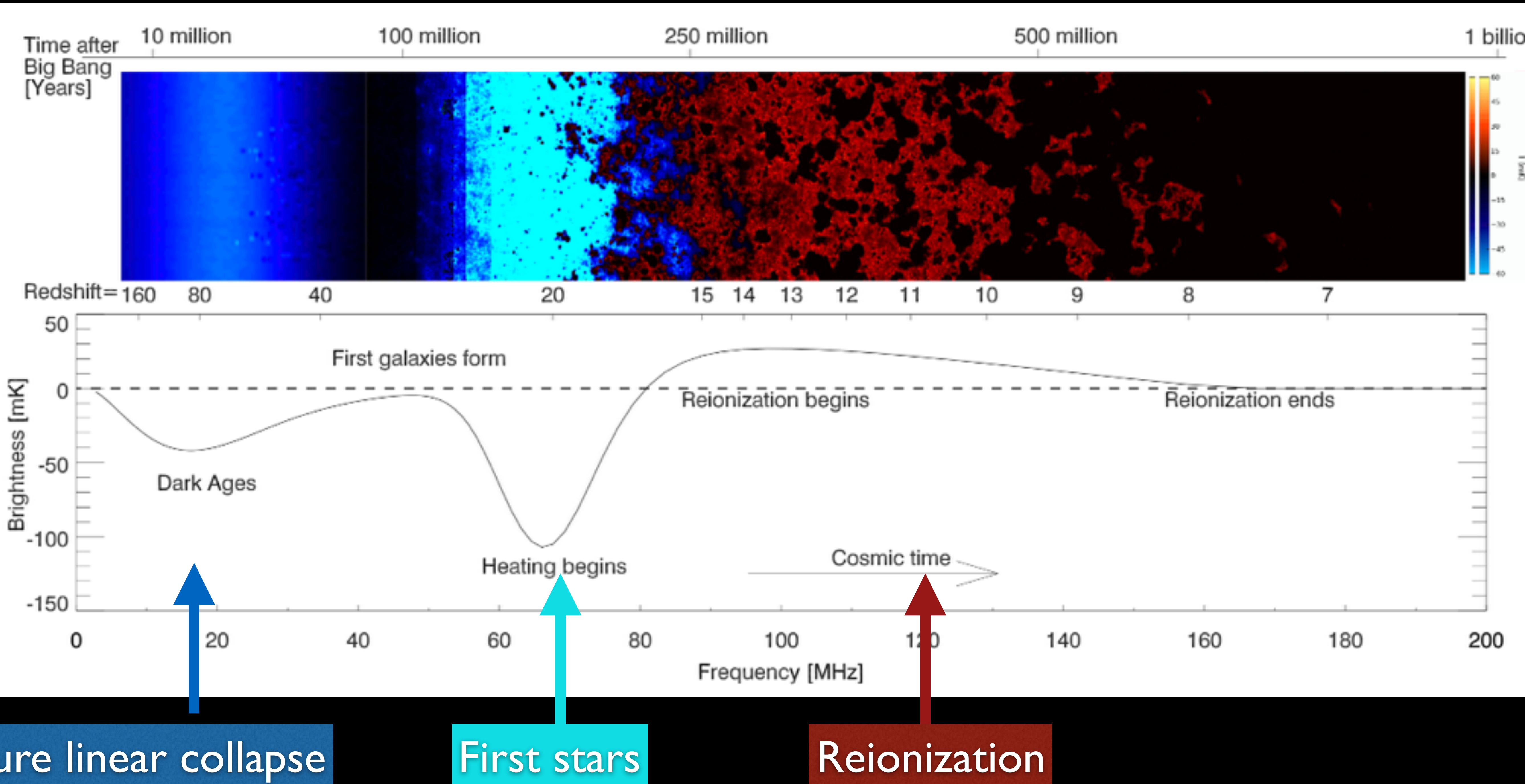
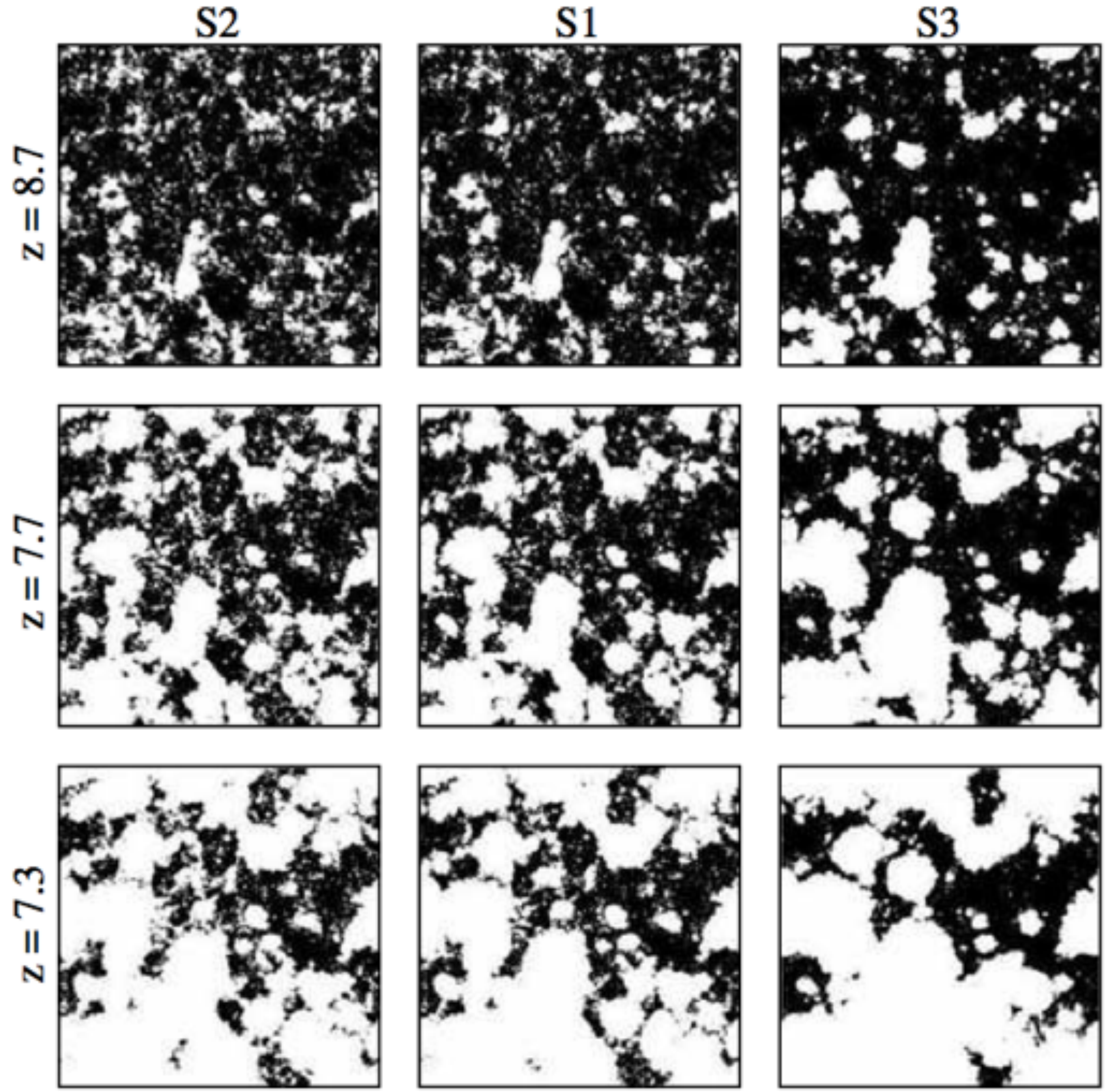
GLOBAL TEMPERATURE



D. Jacobs, 2015

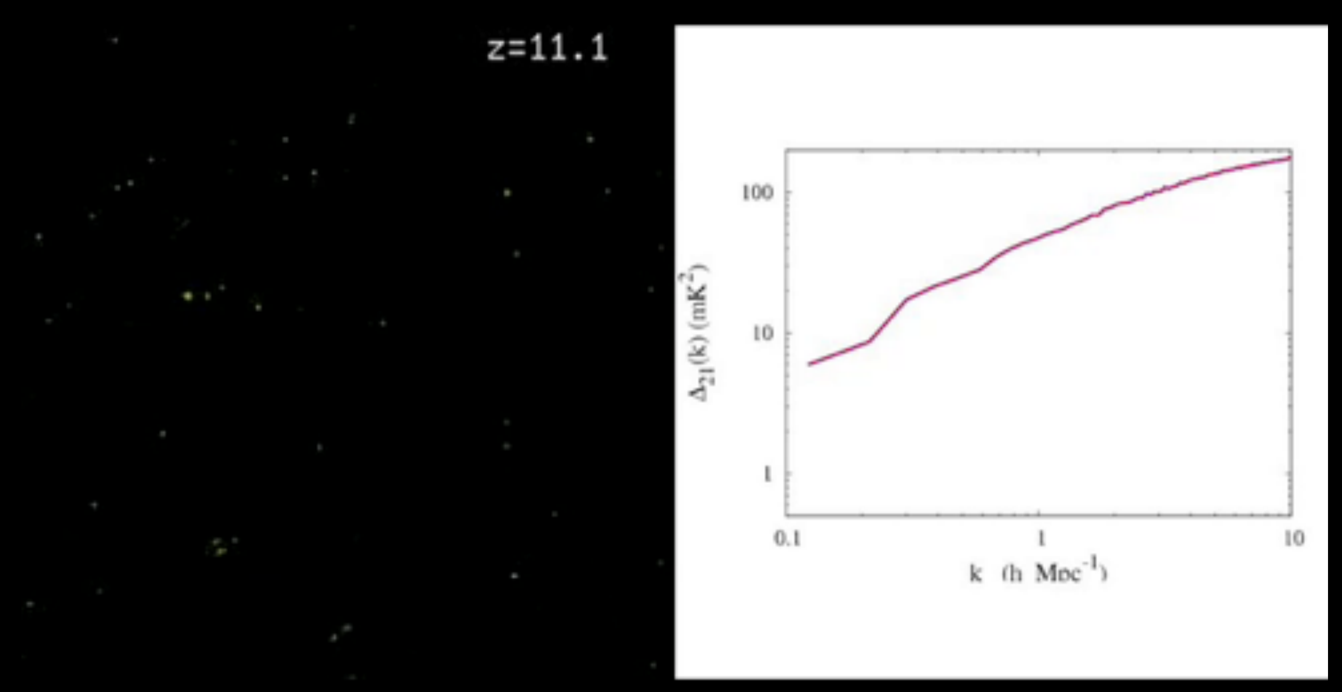
imaging

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



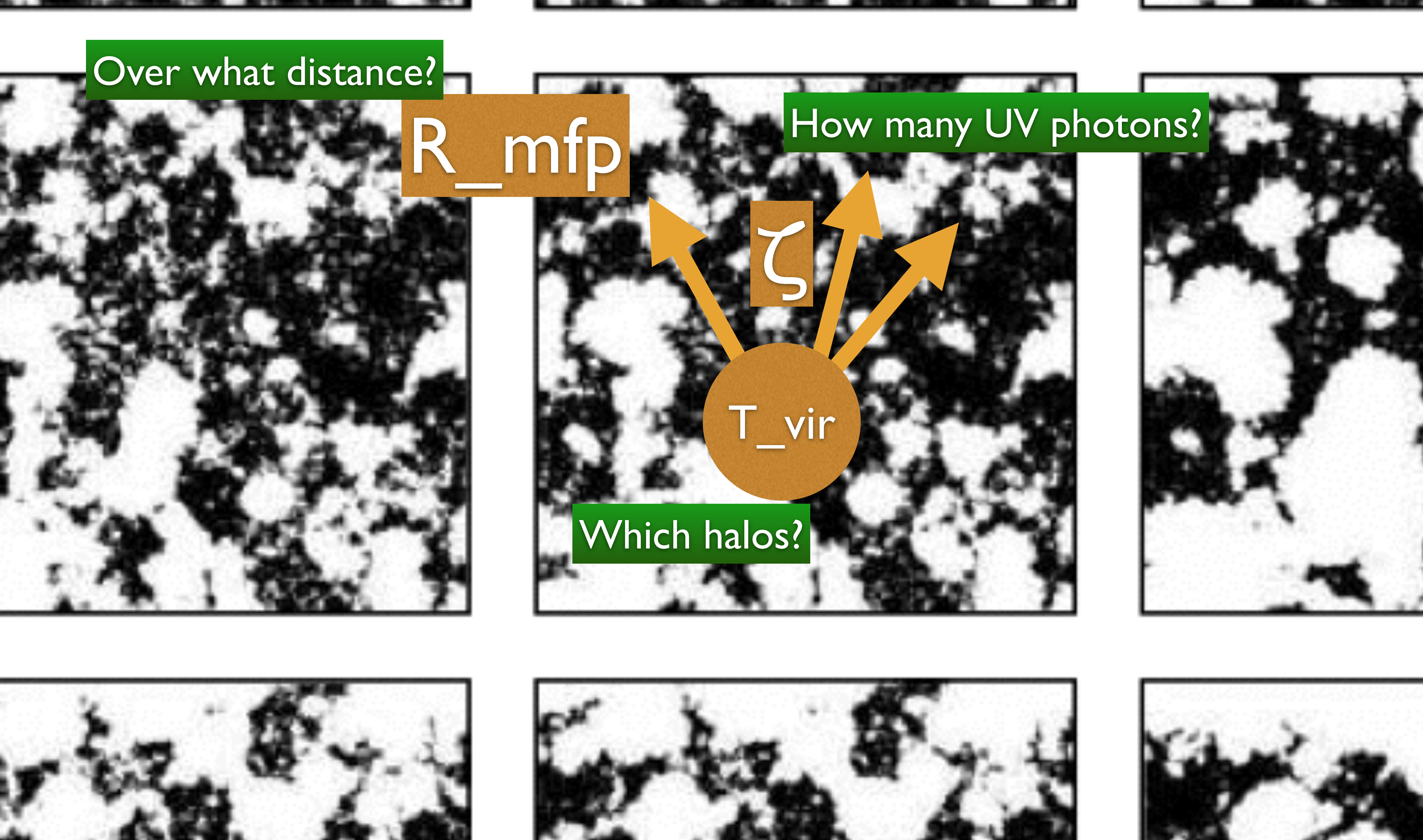
McQuinn ea 2007 MNRAS 377

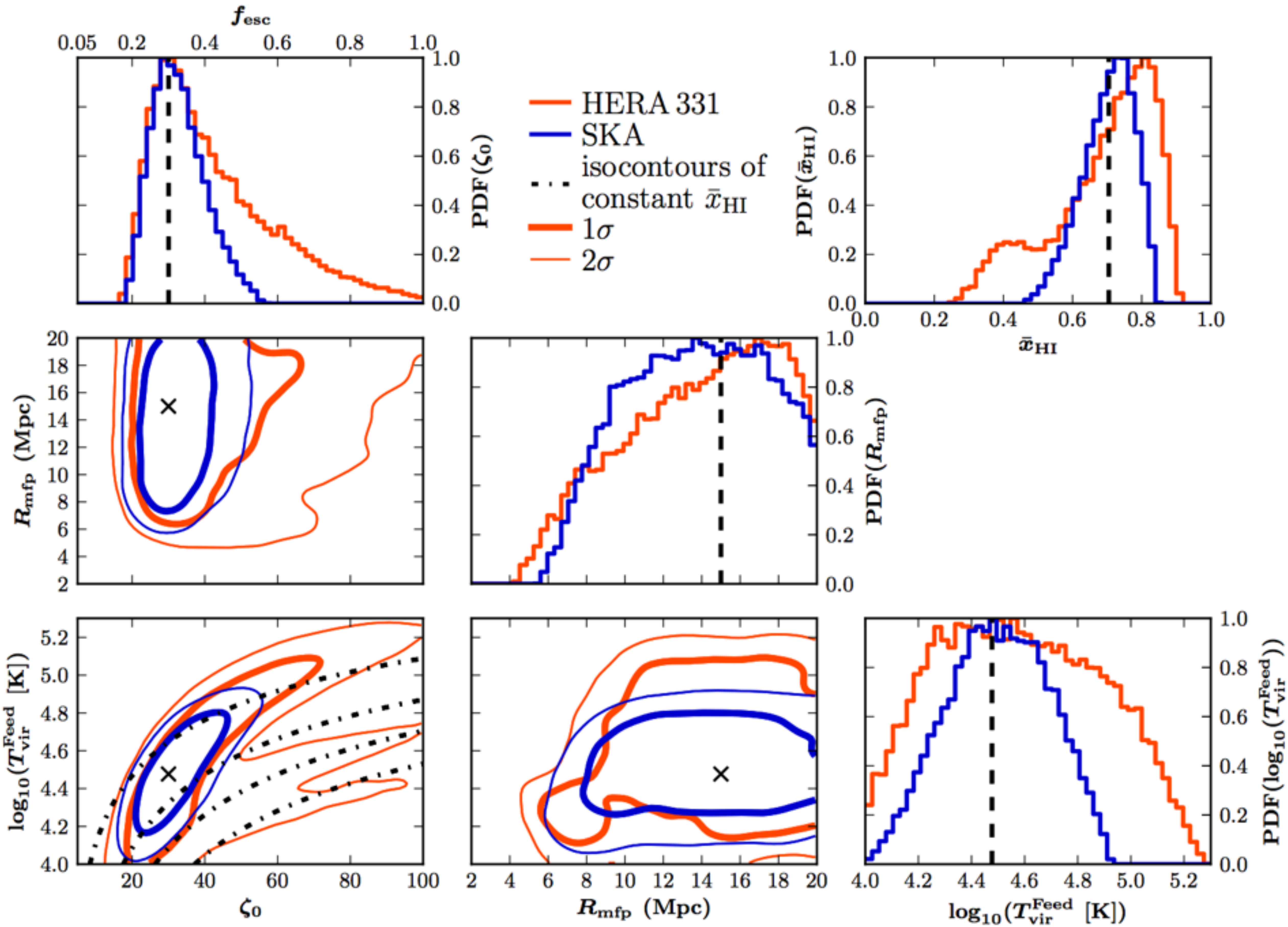
Credit: M. Alvarez (CITA)
& R. Kaehler (Stanford)



Credit: M. Mcquinn (Berkeley)

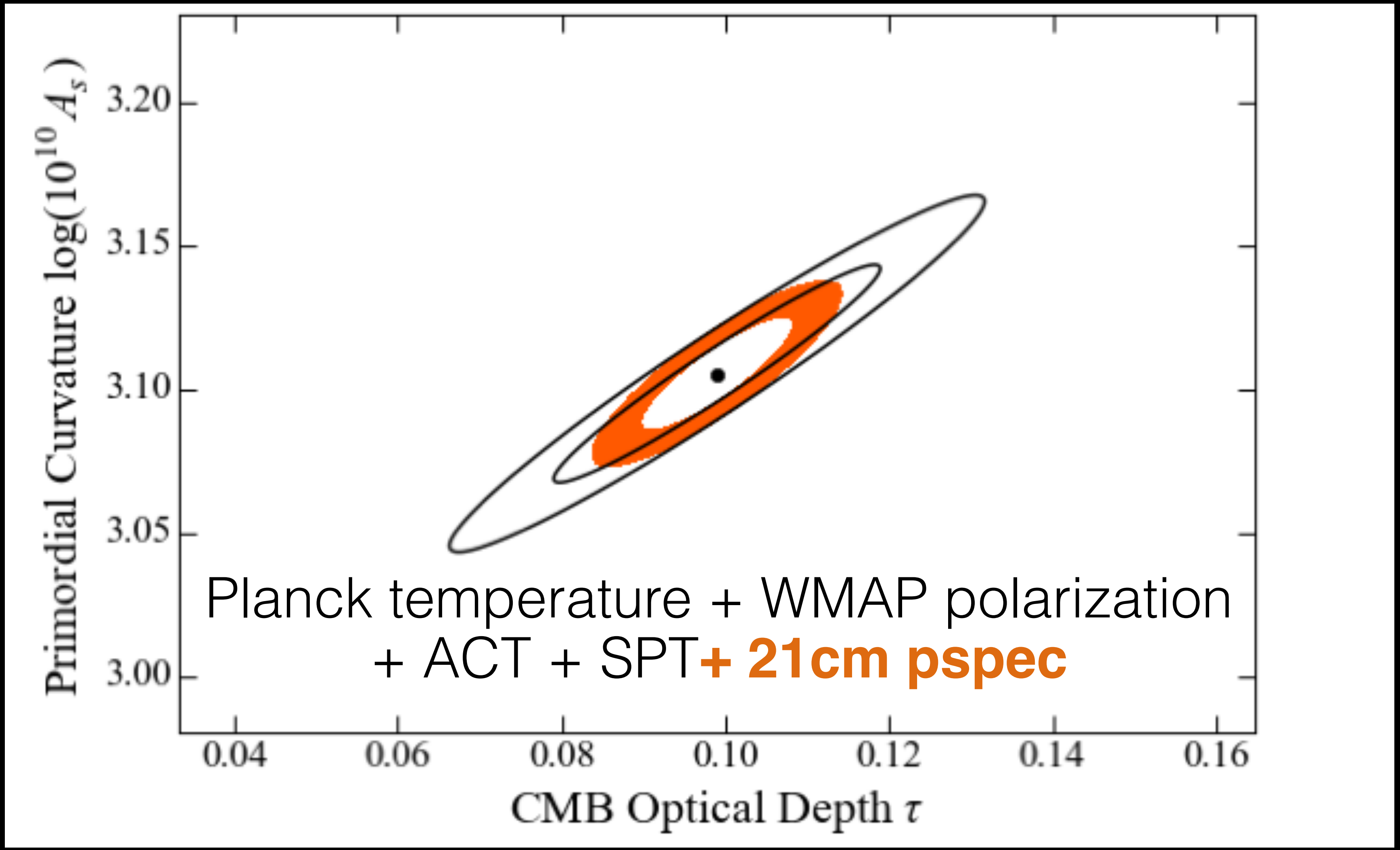
Reionization physics in a nutshell



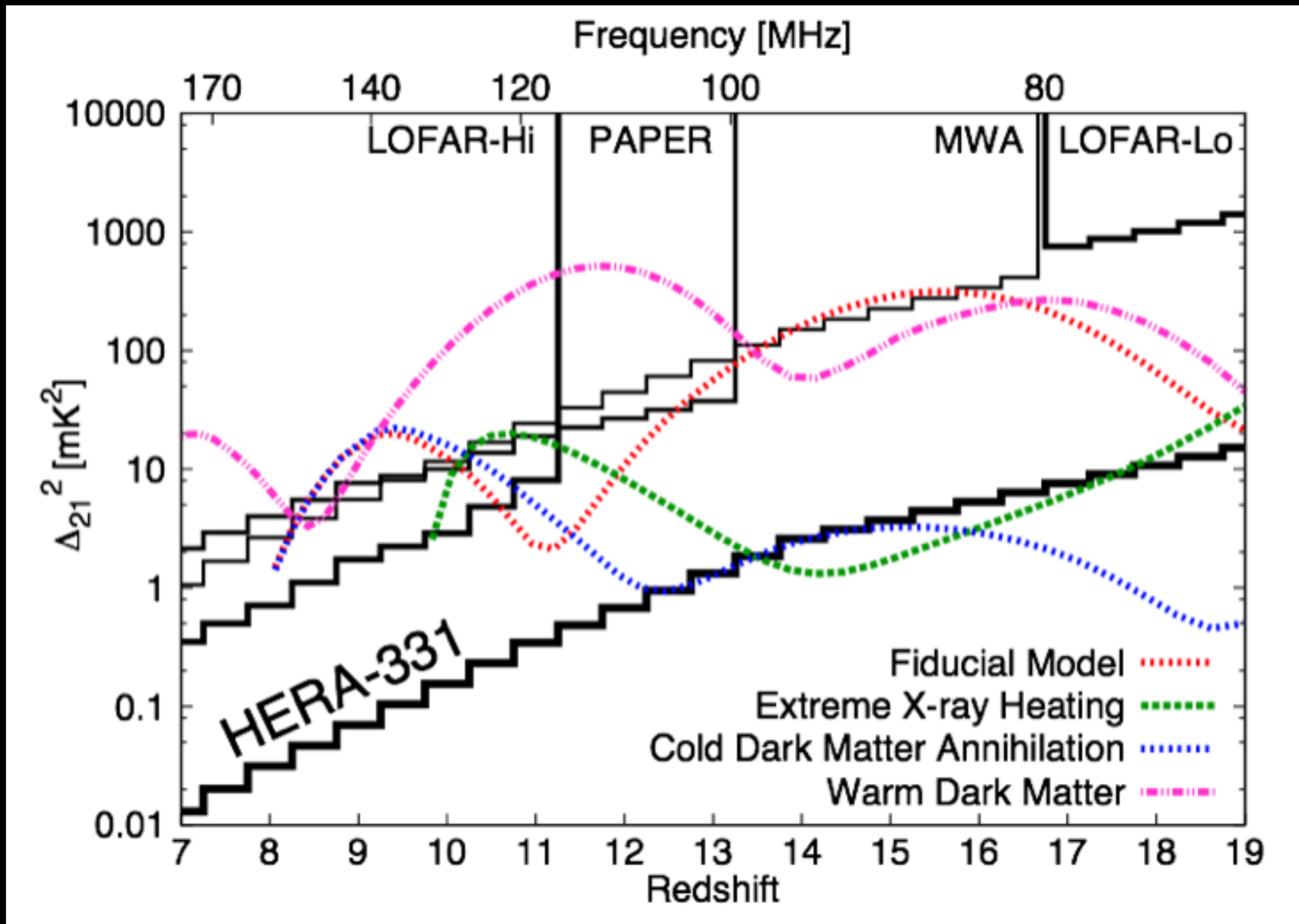


Grieg and Mesinger, MNRAS 2015, arXiv:1501.06576

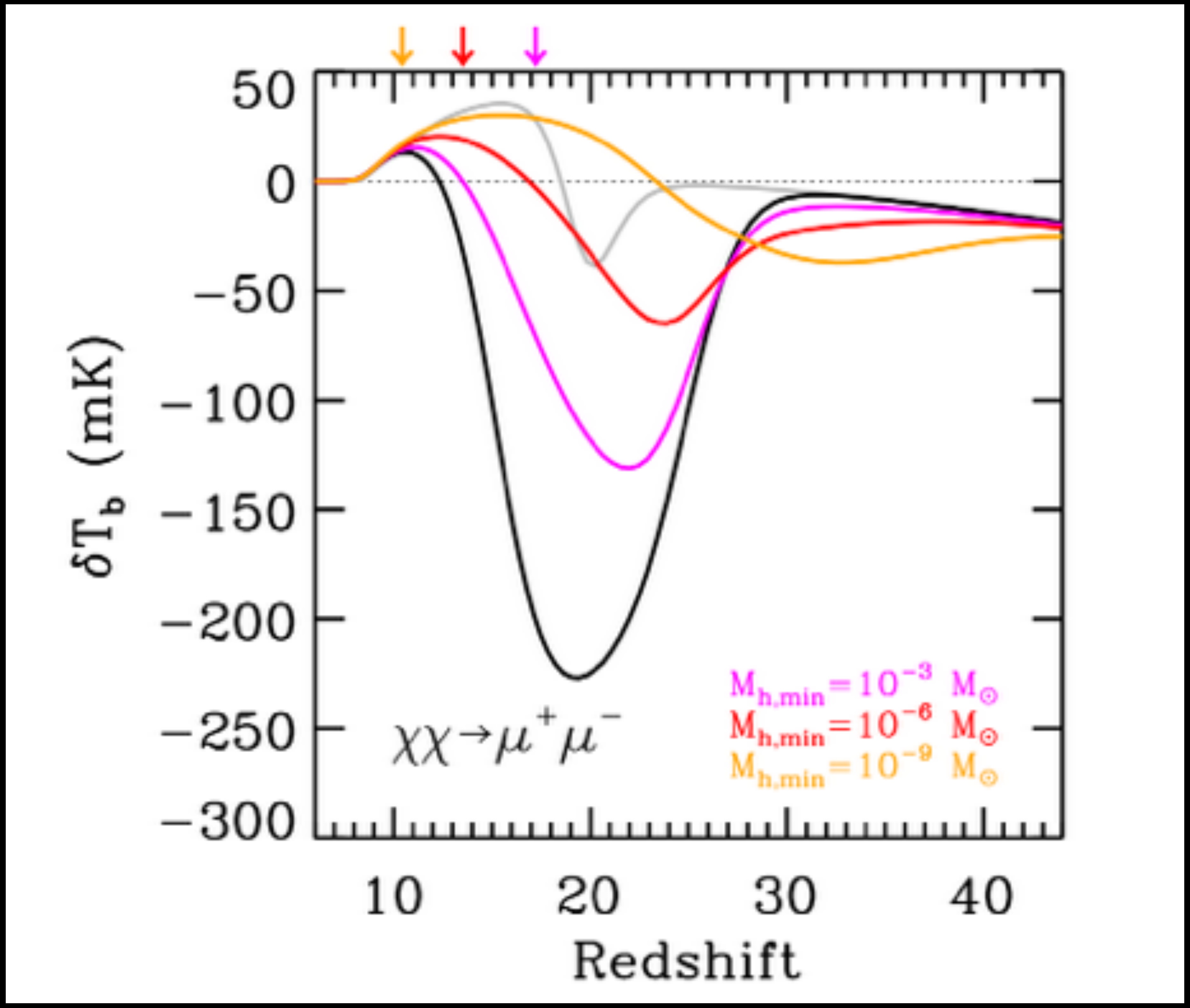
CONSTRAINING CMB COSMOLOGY



Liu et al in prep

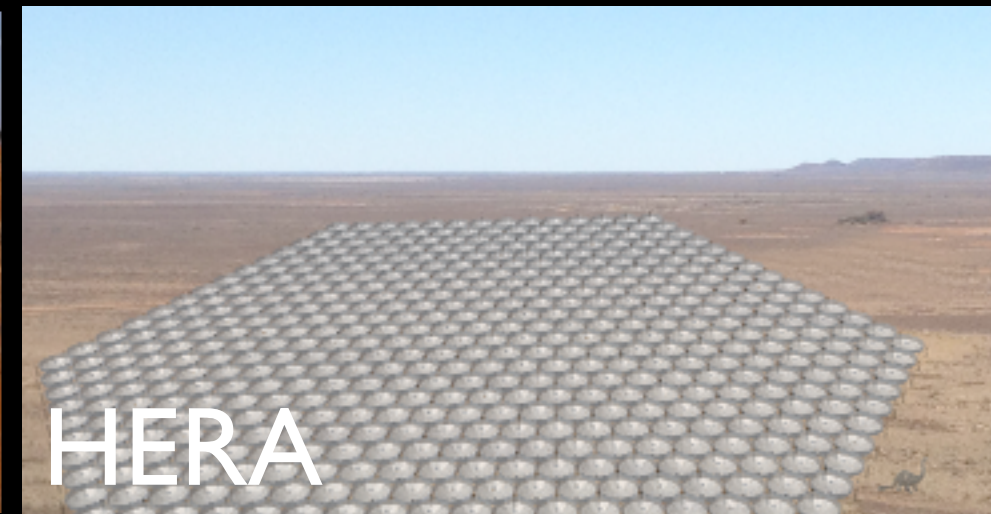


Mesinger et al 2014



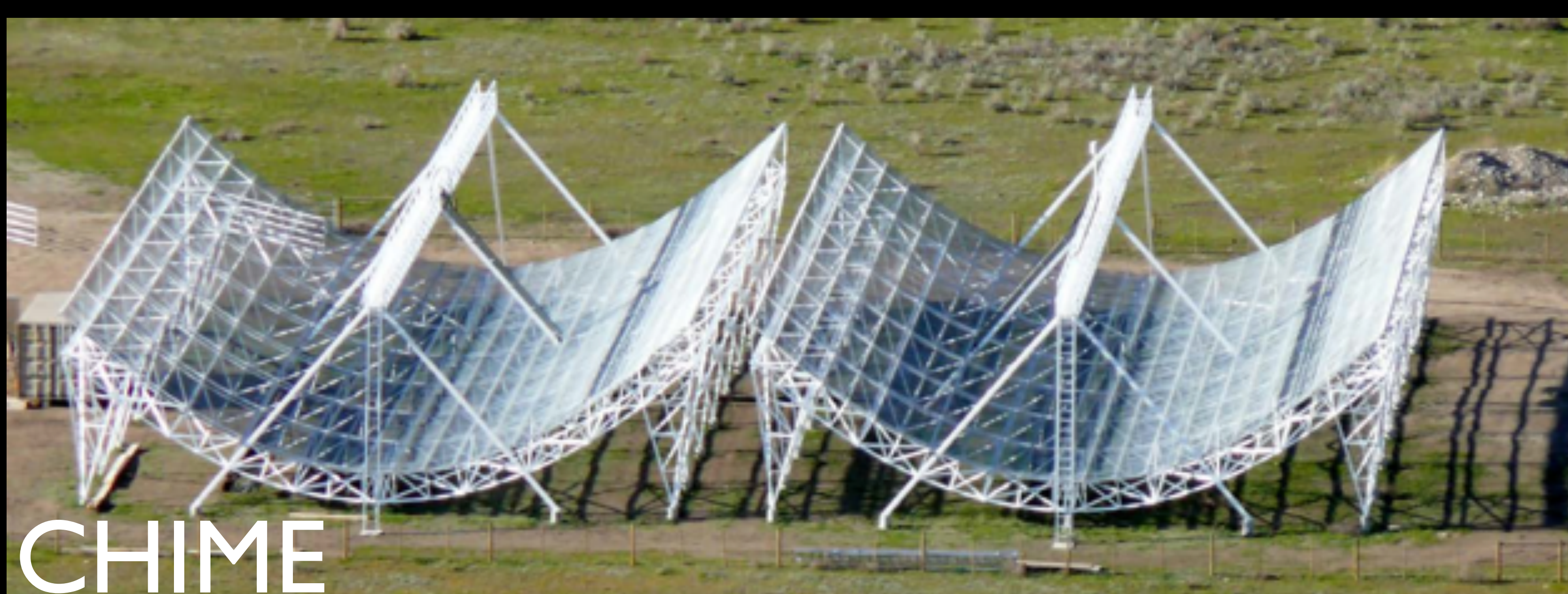
Evoli et al 2014


LOFAR

MWA

HERA

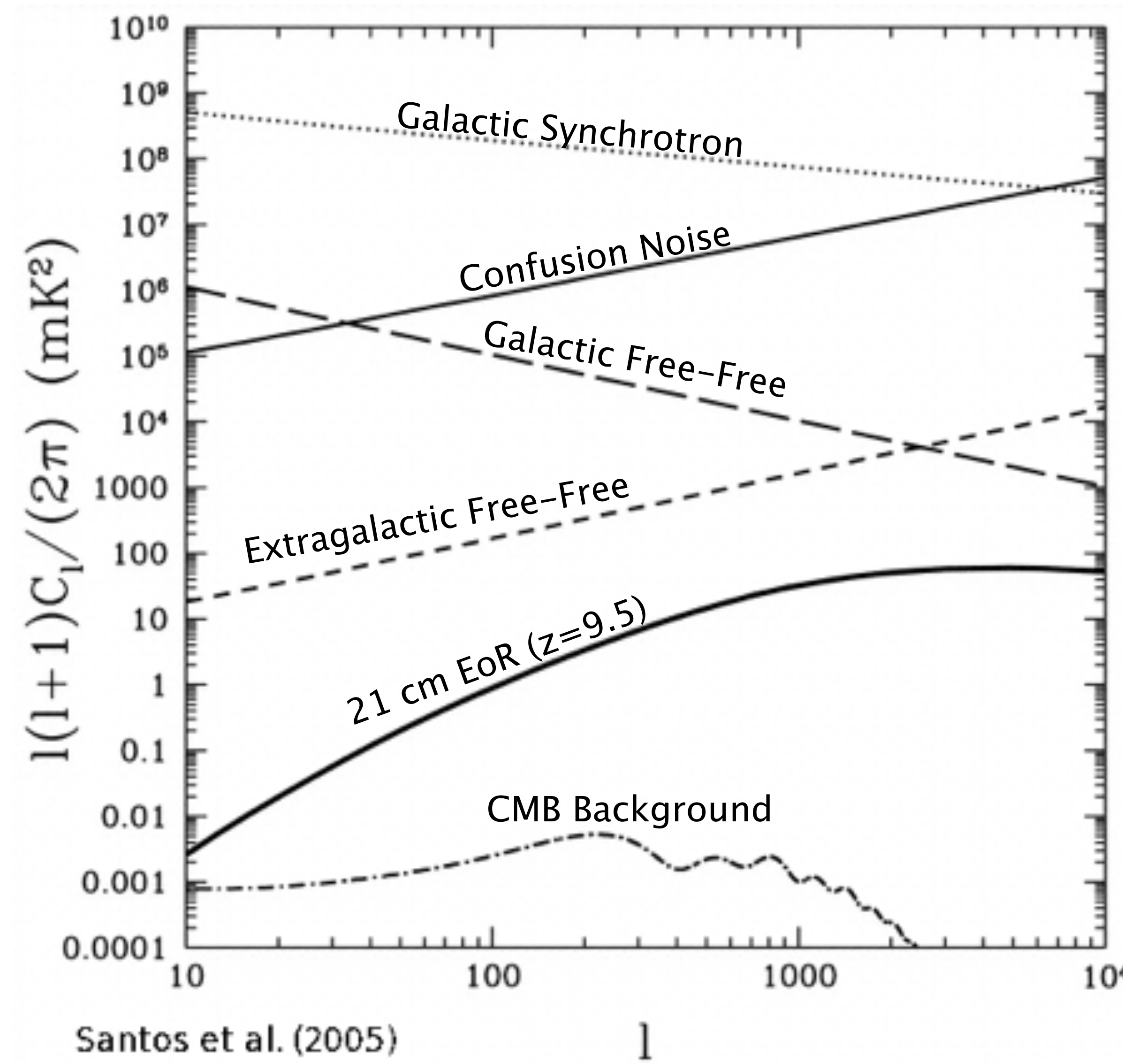
PAPER

LWA & CDA

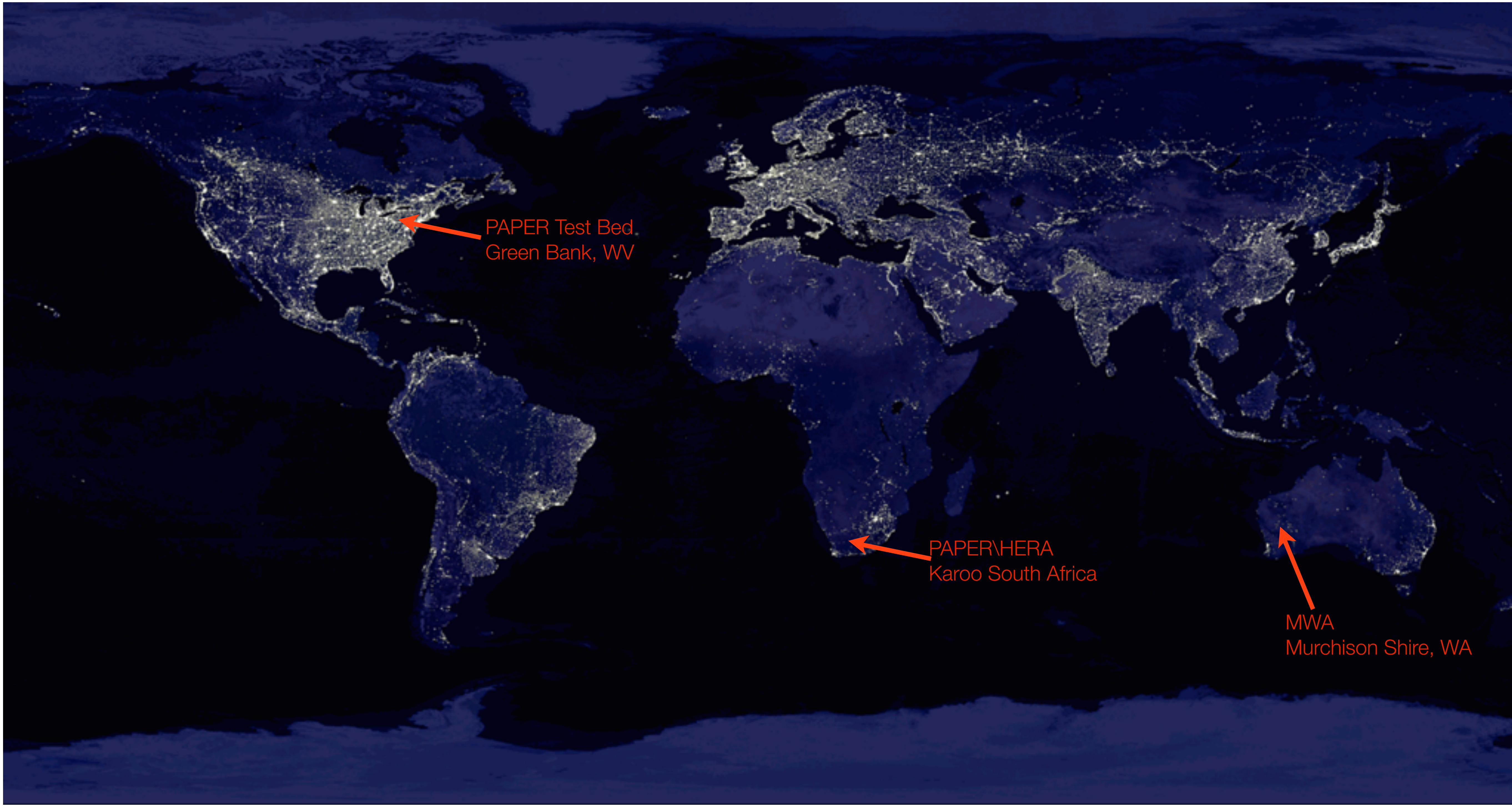
EDGES

CHIME

Challenges

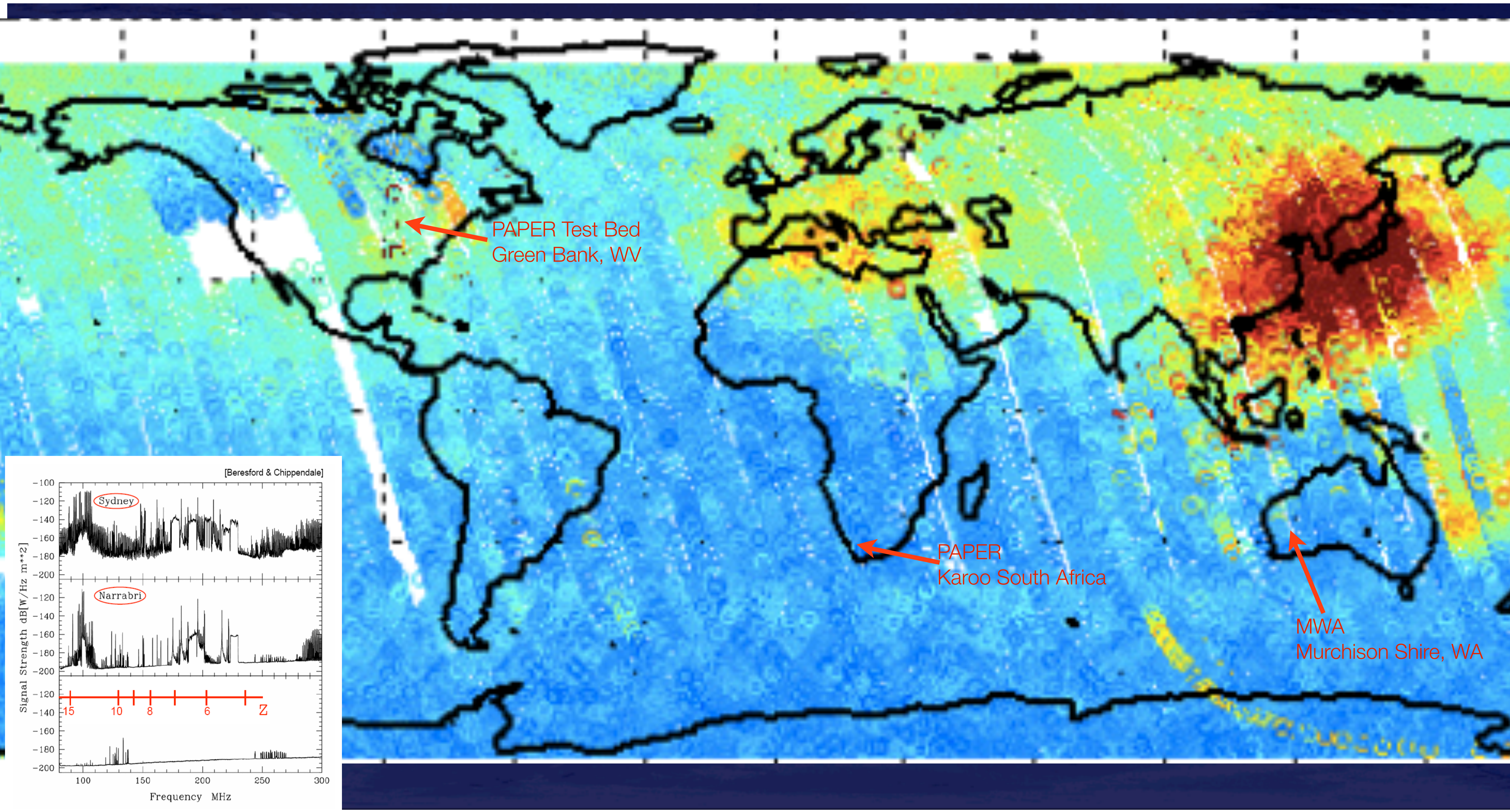
- Foregrounds
    - 9 orders of magnitude in mK^2
    - spectrally smooth (unlike 21cm line)
- Interference
- Sensitivity



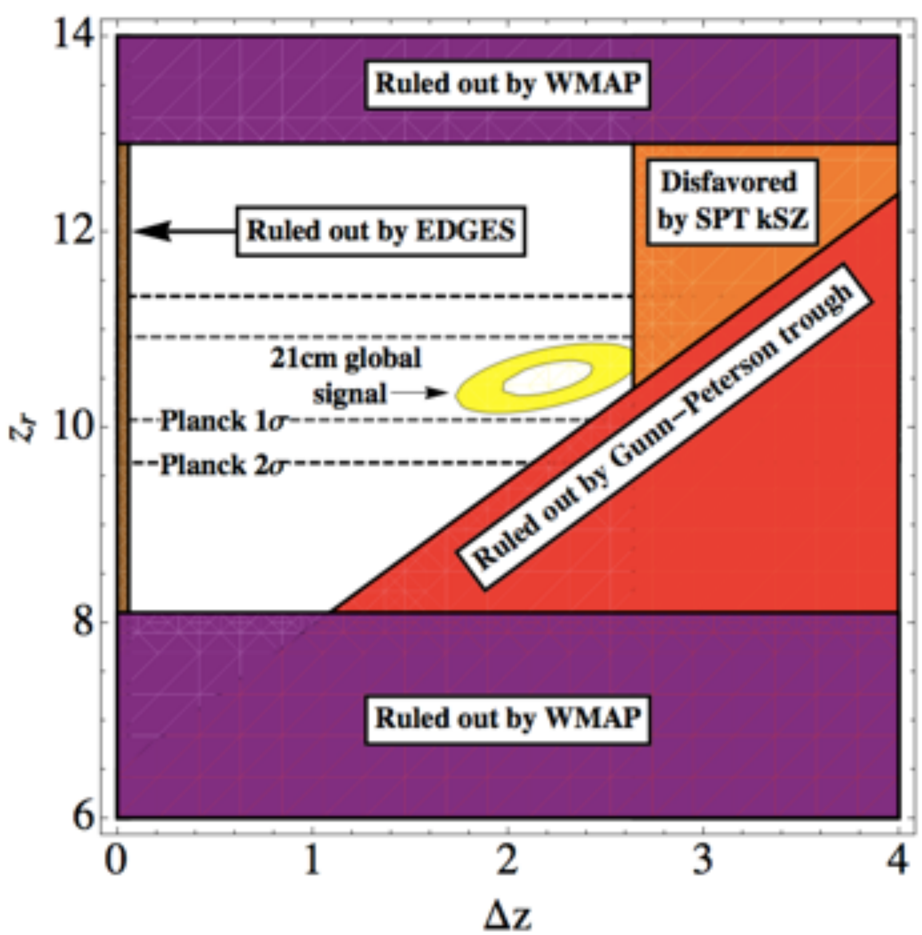
Radio Frequency Interference

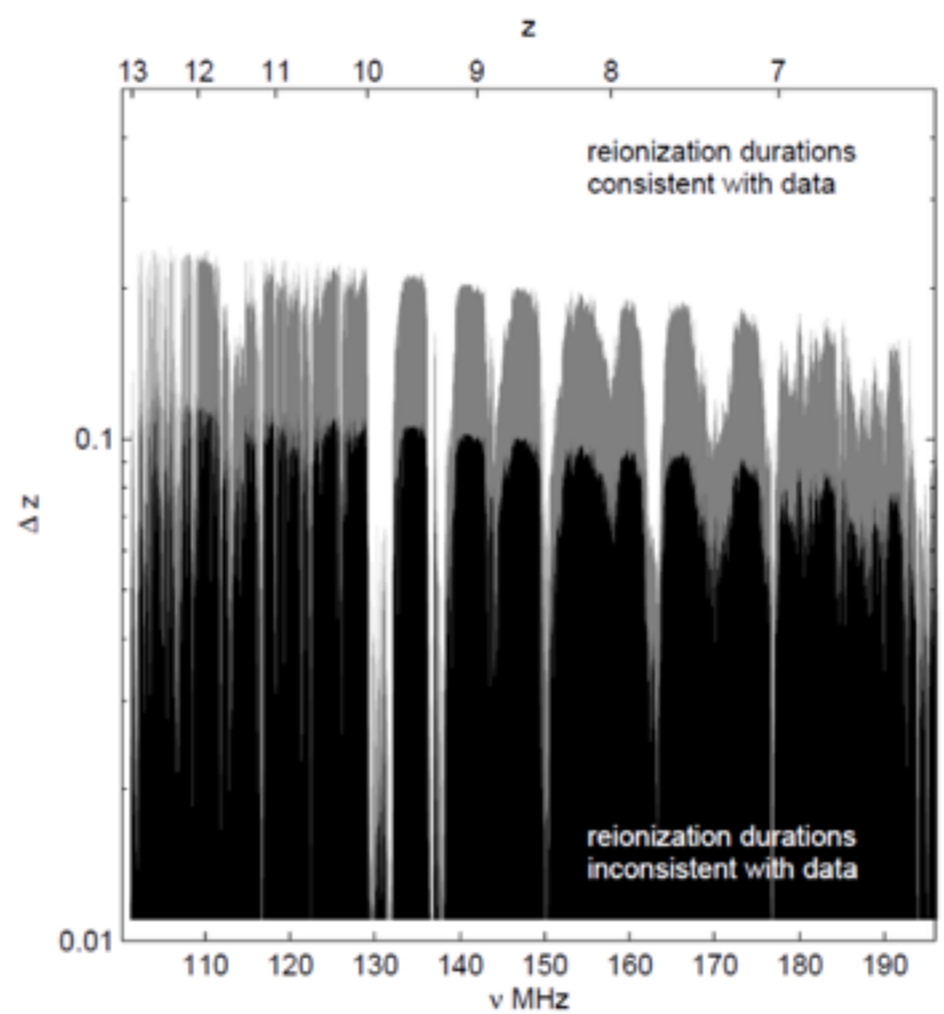


Human Interference



EDGES



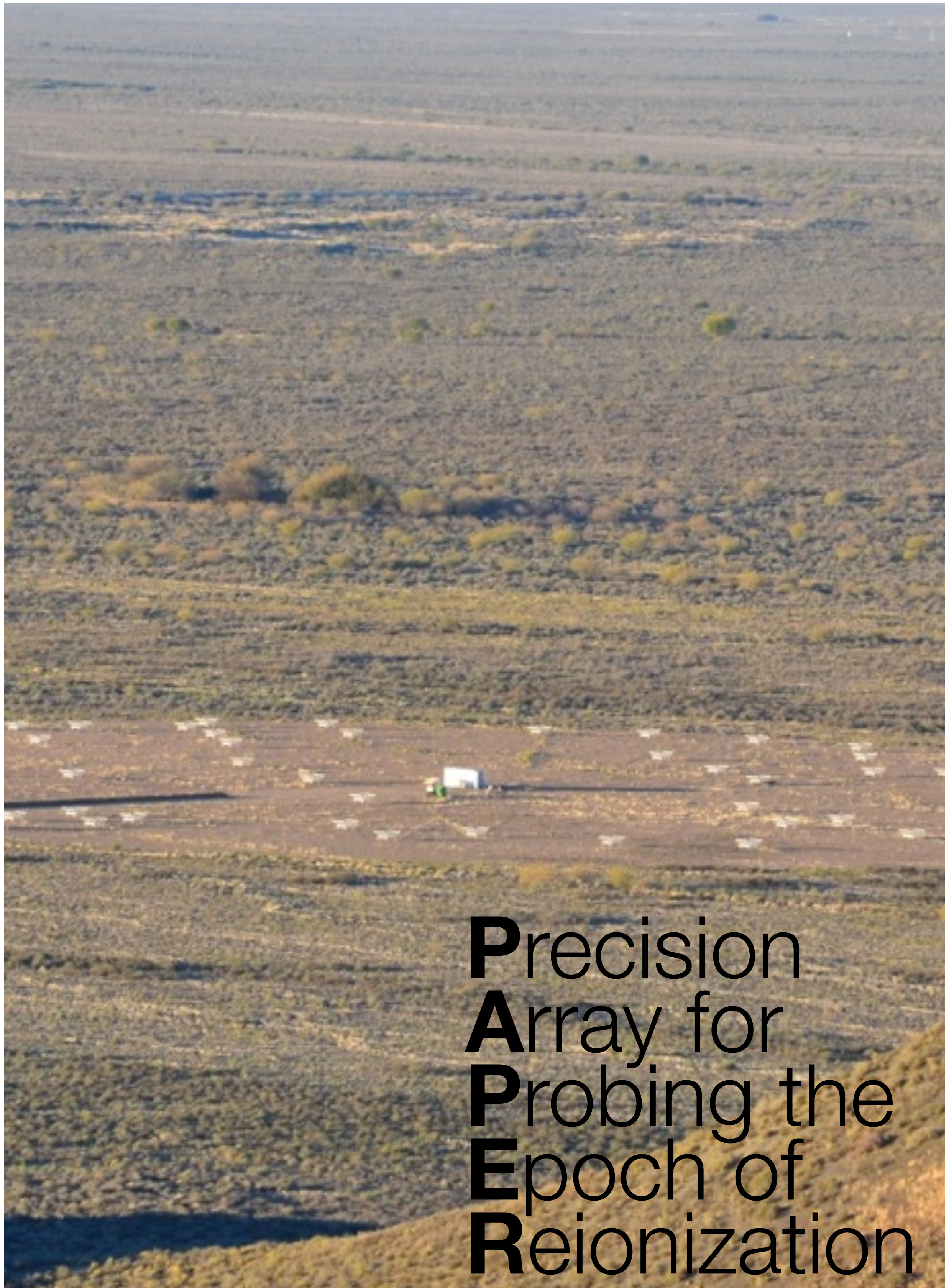


Liu, Pritchard, Tegmark, Loeb 2013

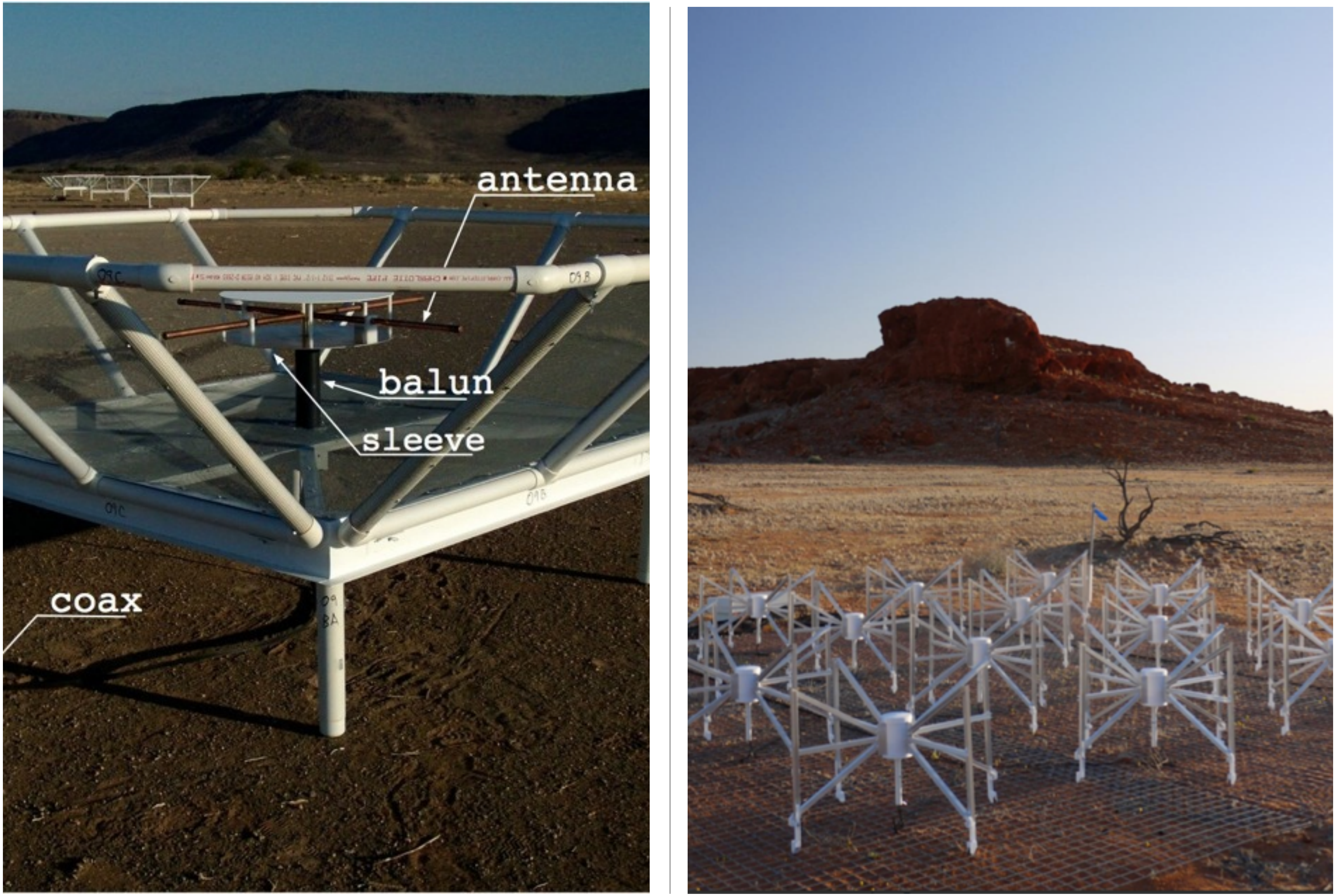
EDGES update 2015

- Rogers et al. 2015 – confirmation of ionospheric model and first-ever direct detection (as far as we can find) of electronic thermal emission from ionosphere.
- Mozdzen et al. 2015 (submitted) – beam chromaticity model shows foreground subtraction is very sensitive to beam pattern. New "blade" dipole design deployed to minimize effects.
- Current observing campaign began October 2014. Looking promising… :) should improve on previous limits
- Two wavelength bands now: 50-100 MHz (First Light) and 100-200 MHz (reionization) -- *you can see the low-band antenna halfway to the hut in the picture. It is a scaled copy of the high-band antenna*

http://loco.lab.asu.edu/danny_jacobs



MWA
MURCHISON
WIDEFIELD
ARRAY



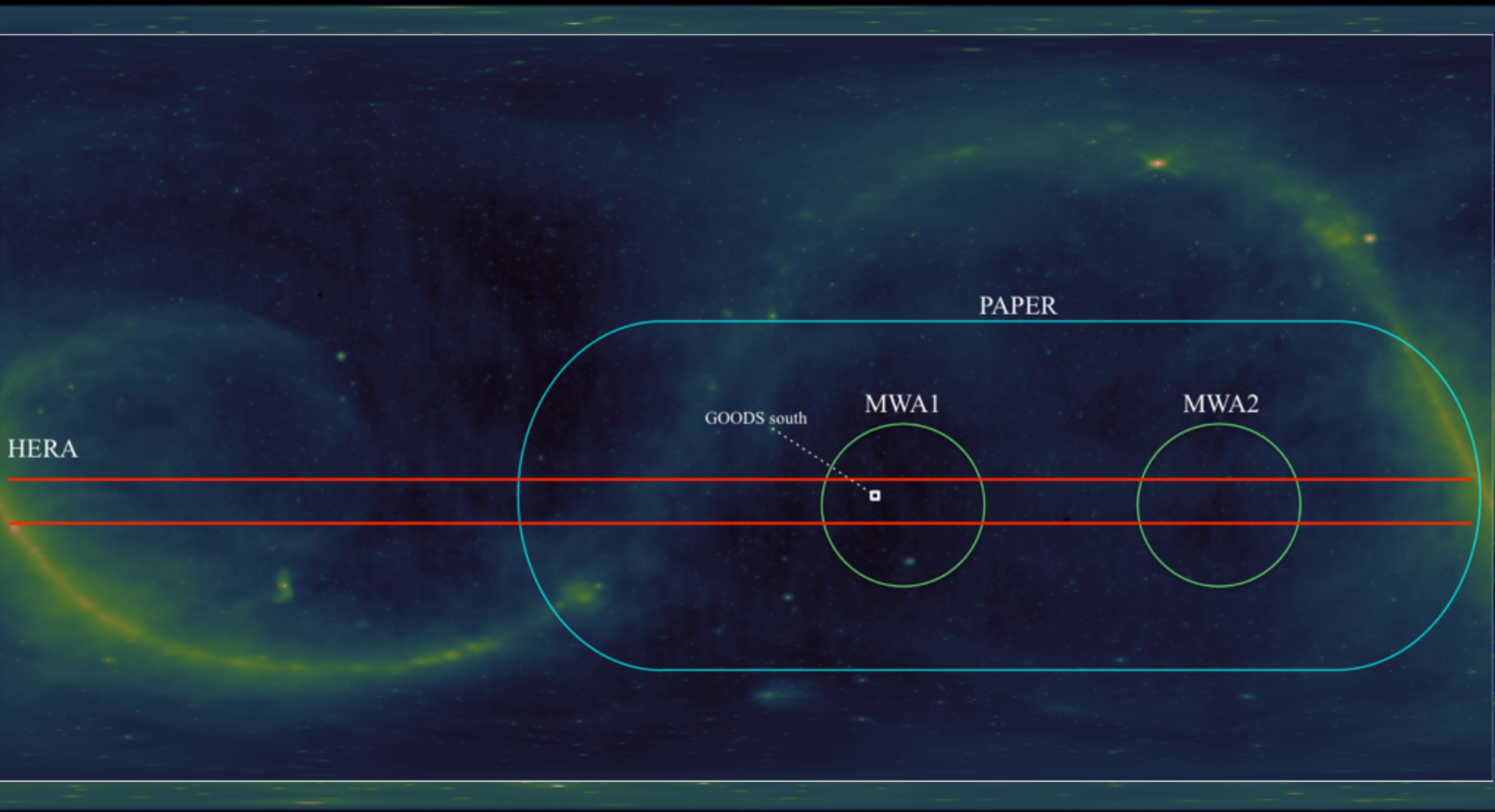
PAPER and MWA close up

MWA
MURCHISON
WIDEFIELD
ARRAY

	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

MWA and PAPER

FIELDS OF VIEW




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


Richtersveld
National Park
Upington
Riemvasmaak
Community
Conservancy
Kimberley
Bloemfontein
Maputsoe
Maseru
Mafeteng
PAPER
South
Africa
575 km
Addo Elephant
National Park
East London
Port
Elizabeth
Worcester
Cape Town
Cape Town

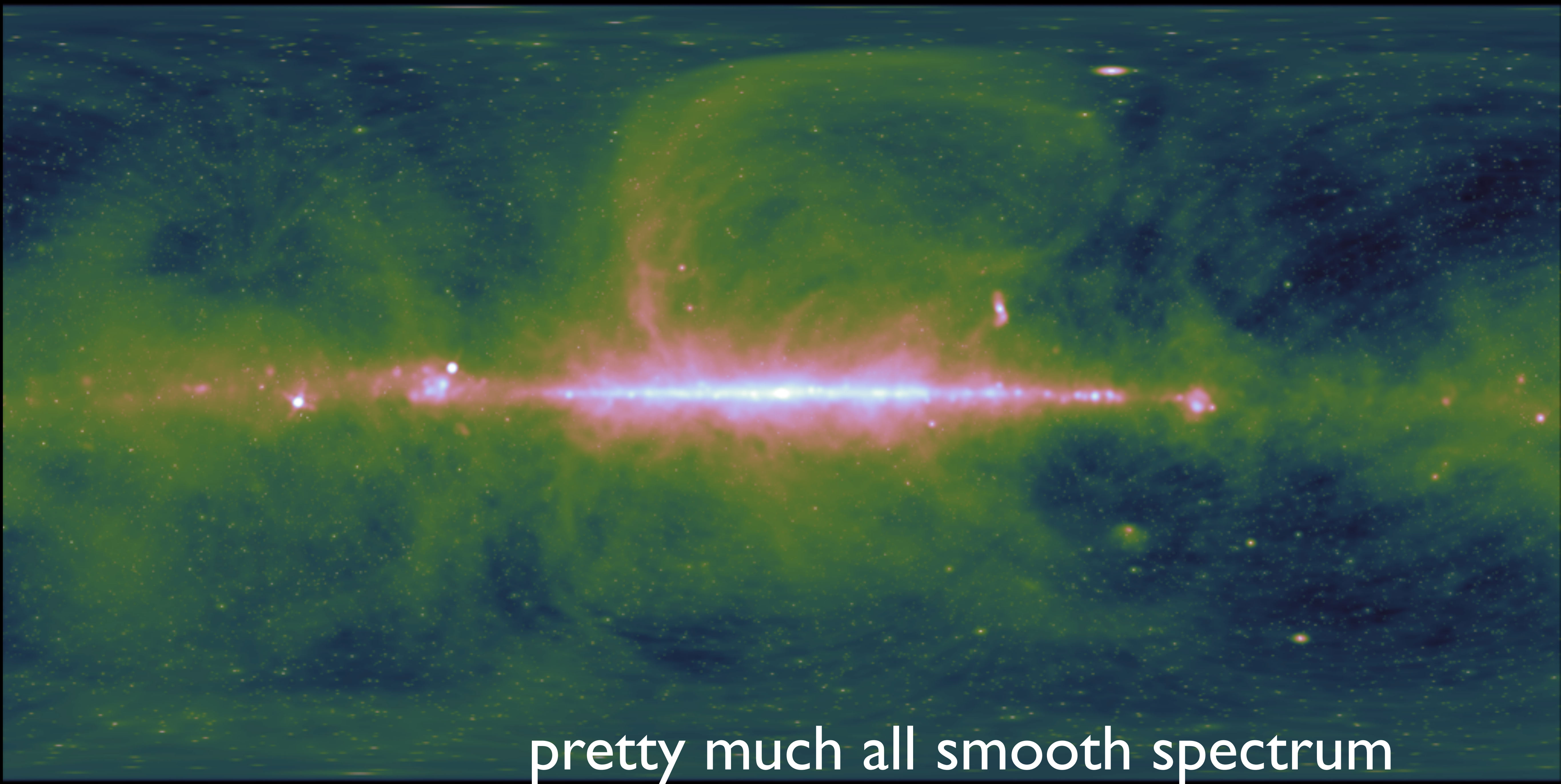
First Gen Reionization Sensitivity

	Avoidance		Subtraction	
Instrument	Drift	Track	Drift	Track
PAPER 128	1.56	—	4.46	—
MWA 128	0.66	0.86	2.50	3.15
LOFAR	0.70	1.90	7.48	12.22

Name of the game: Noise (not foreground) limited measurements

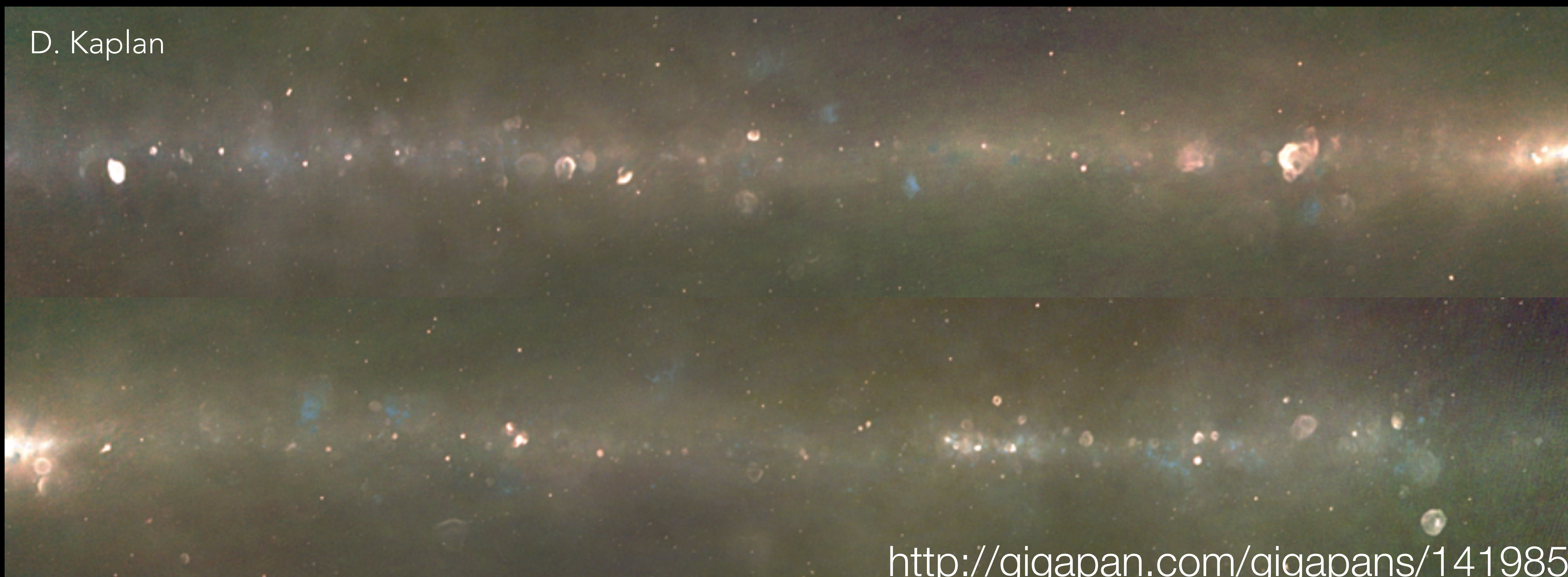
HERA Memo #4, J. Pober (reionization.org/memos/)

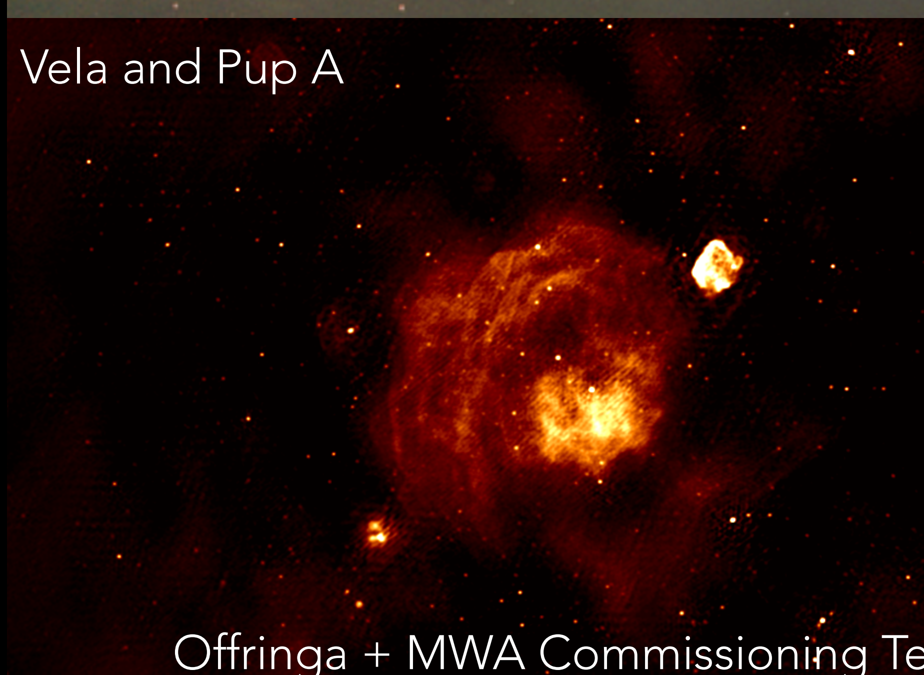
Foregrounds

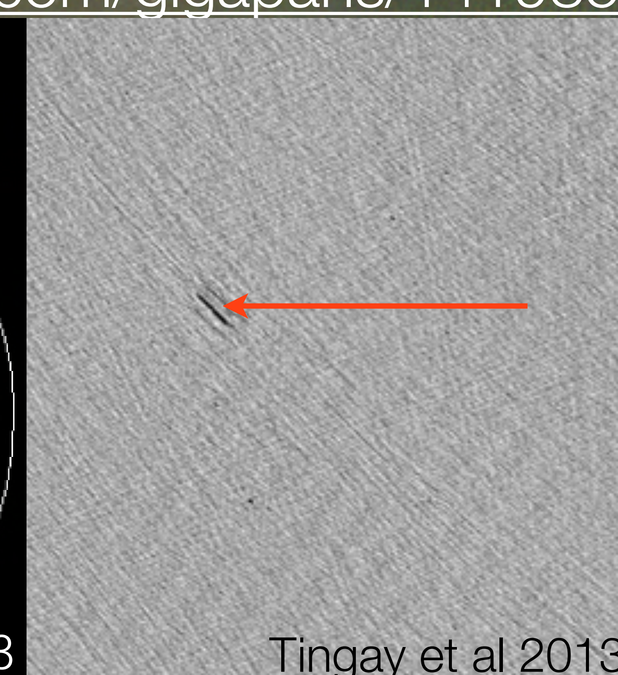


MWA SCIENCE

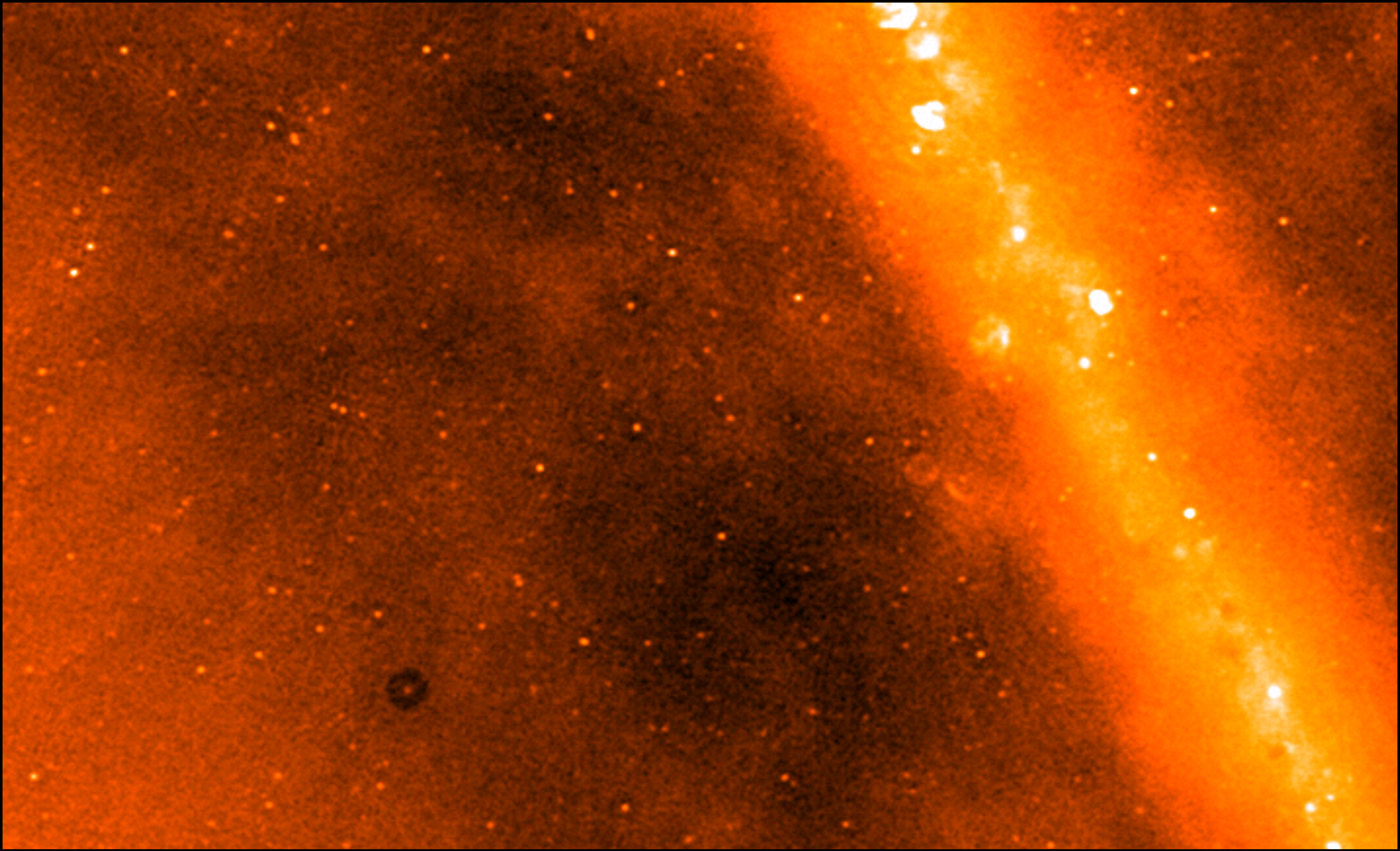
80 degrees







mwatelescope.org



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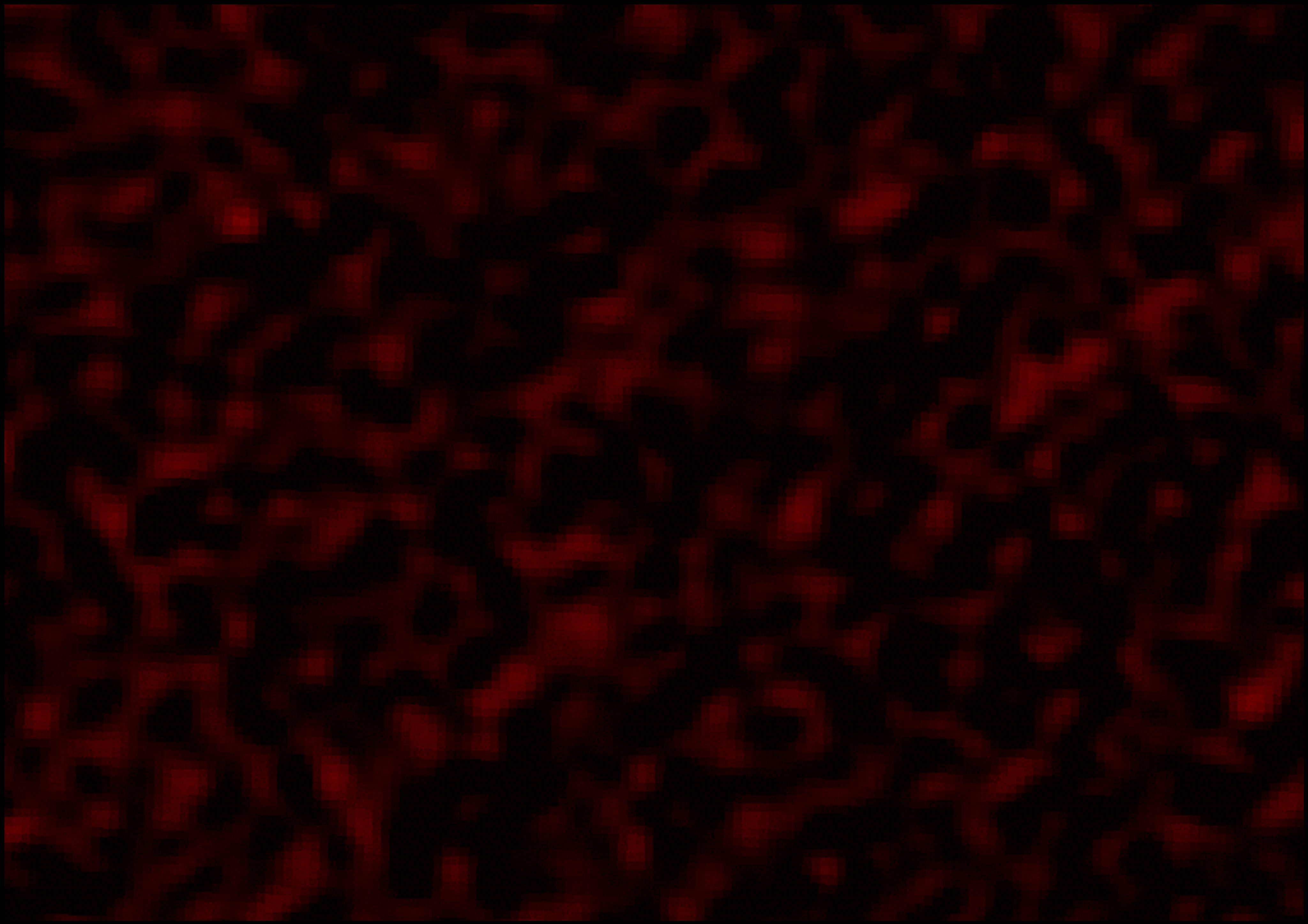
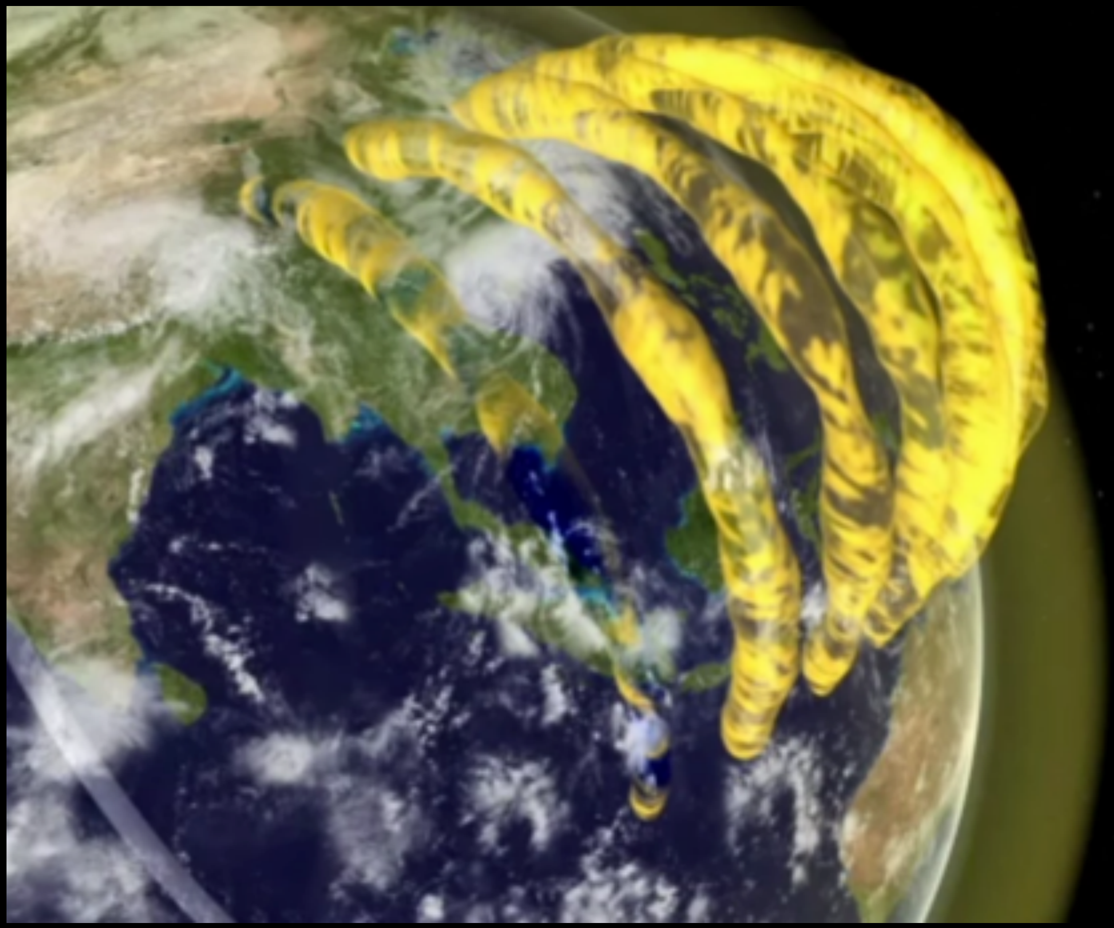
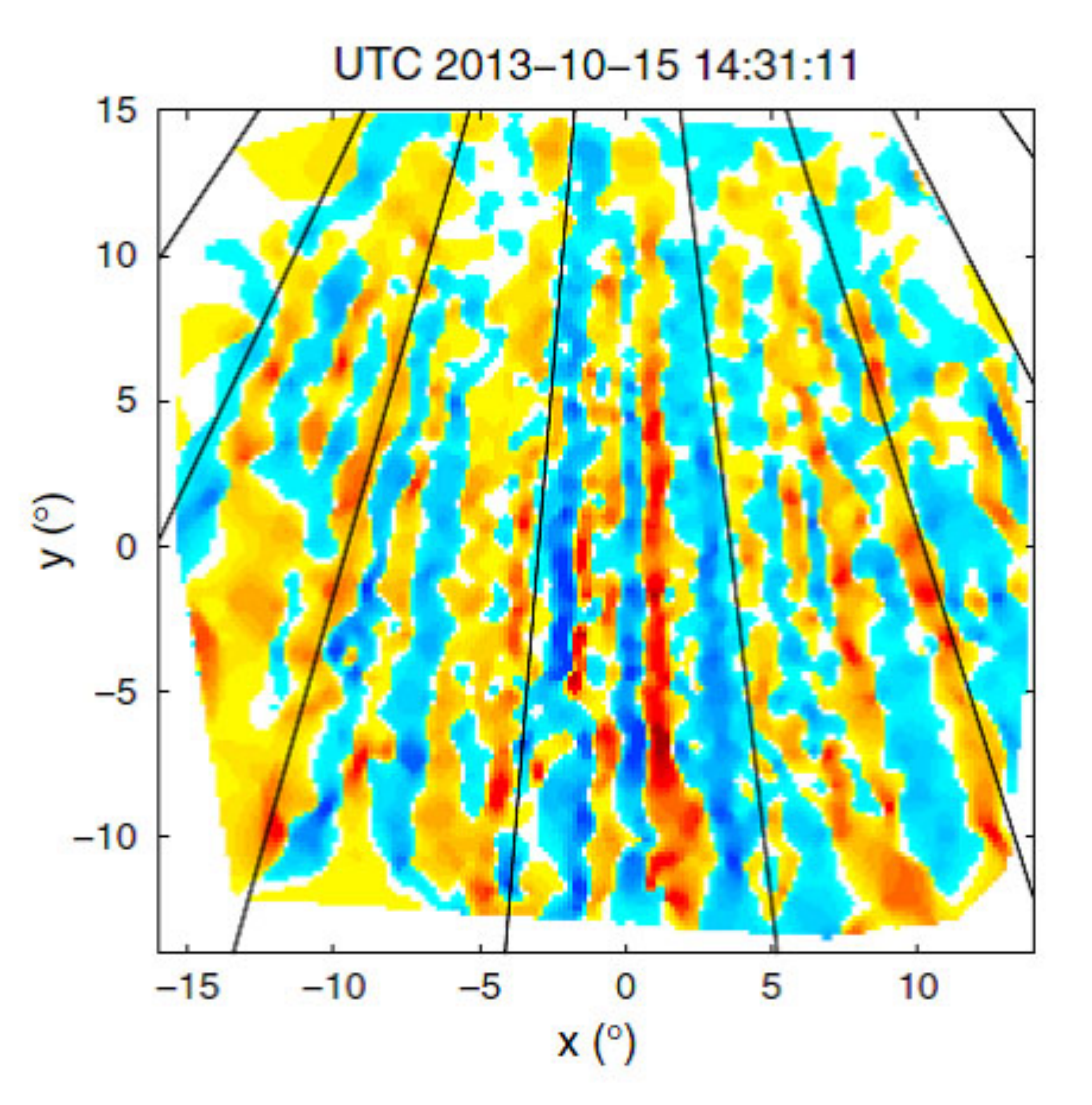


mwatelescope.org



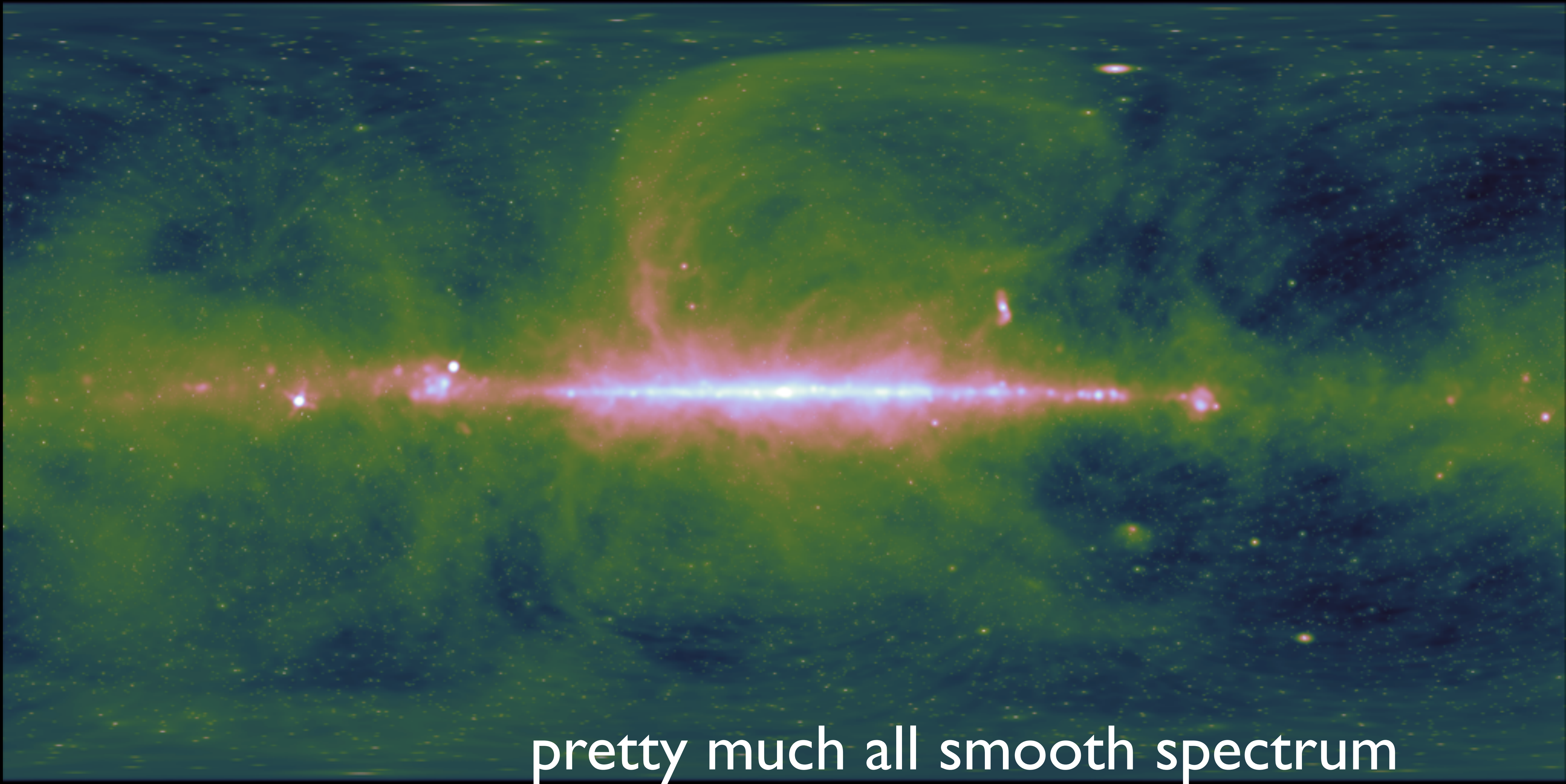
https://youtu.be/ymZEOihlIdU

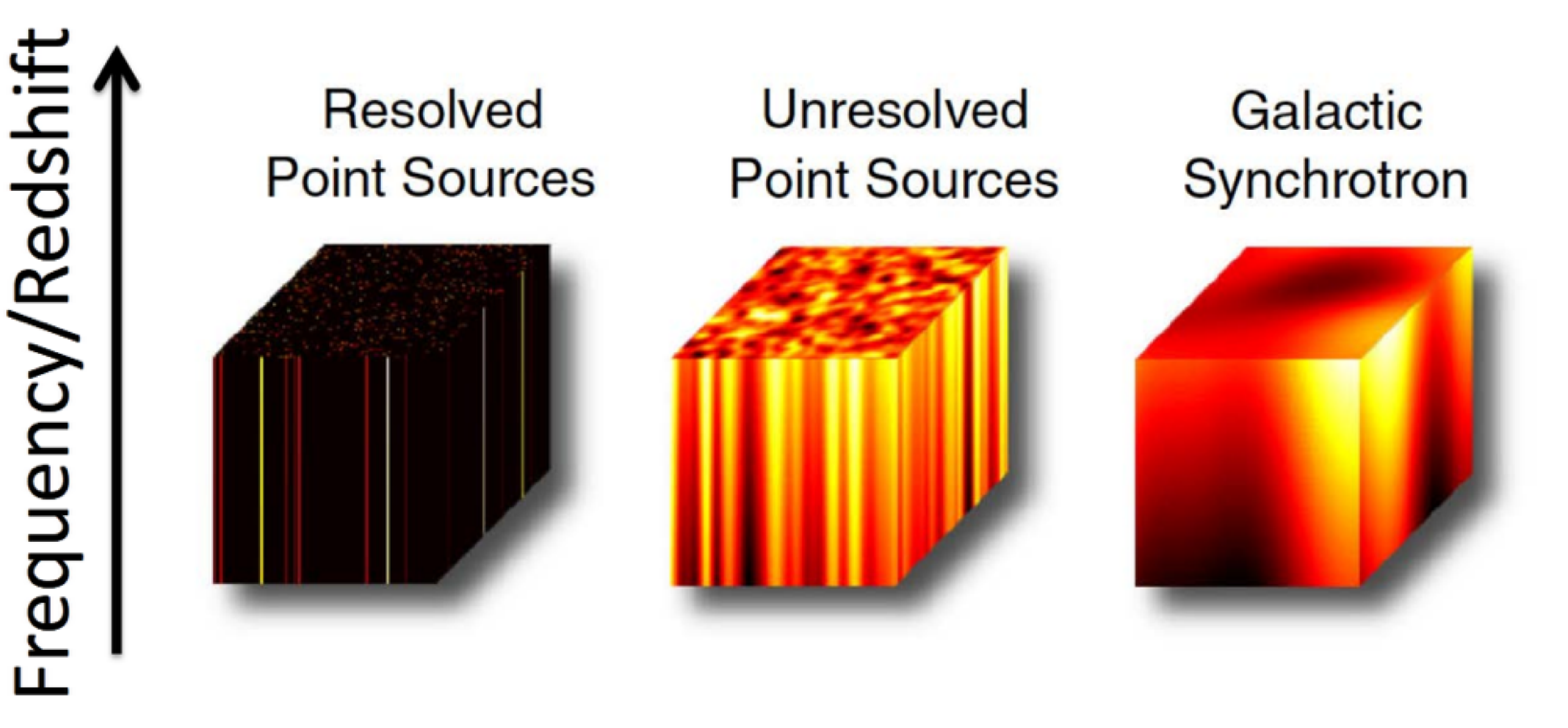


Loi et al GRL, 2015

mwatelescope.org

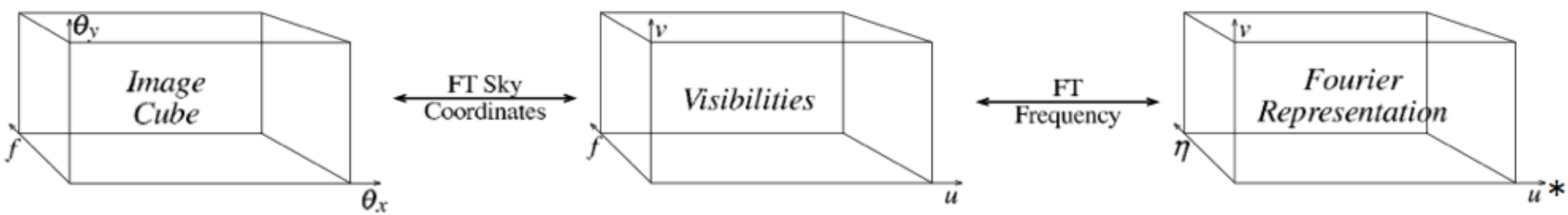
Foregrounds



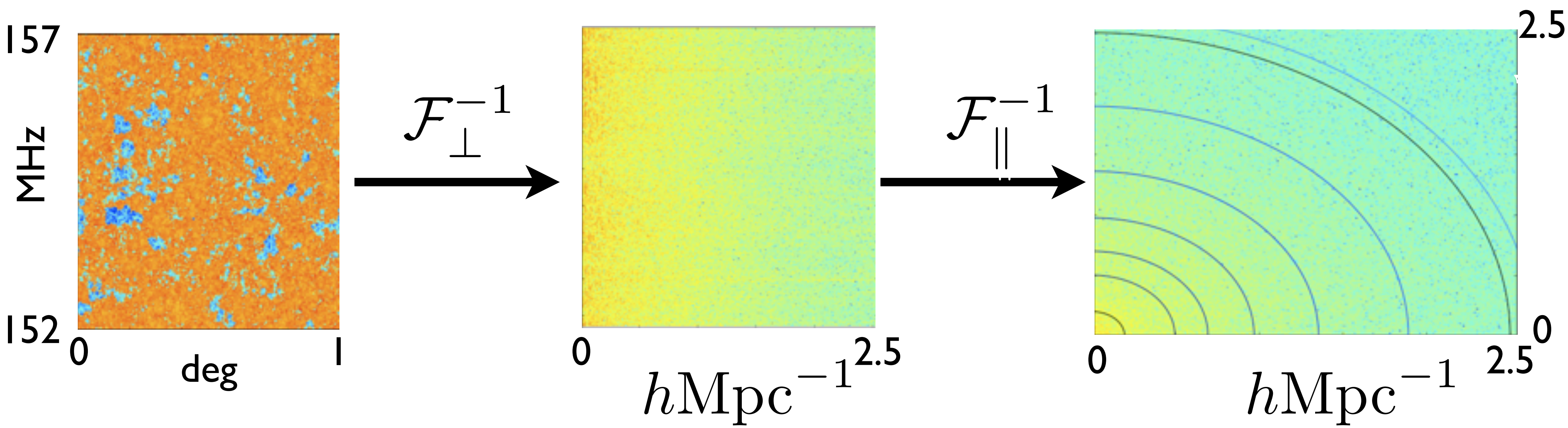


Dillon, Liu, Tegmark 2013

HI 21cm

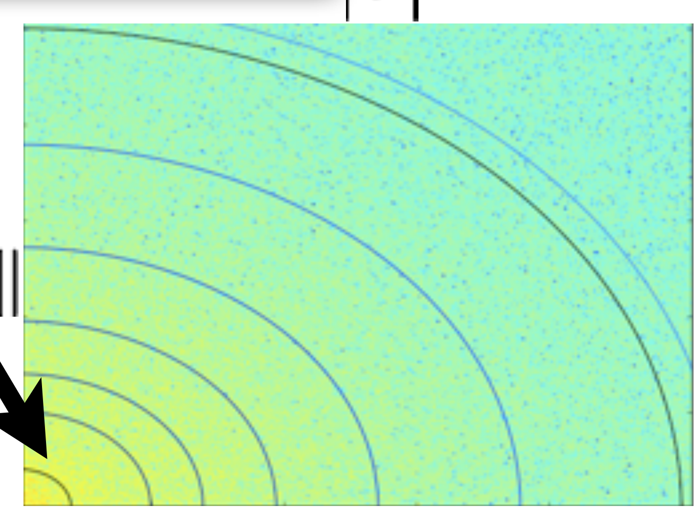


Morales, 2006 AJ 619



units

Signal brightest at short spacings and large spectral scales



Foregrounds!

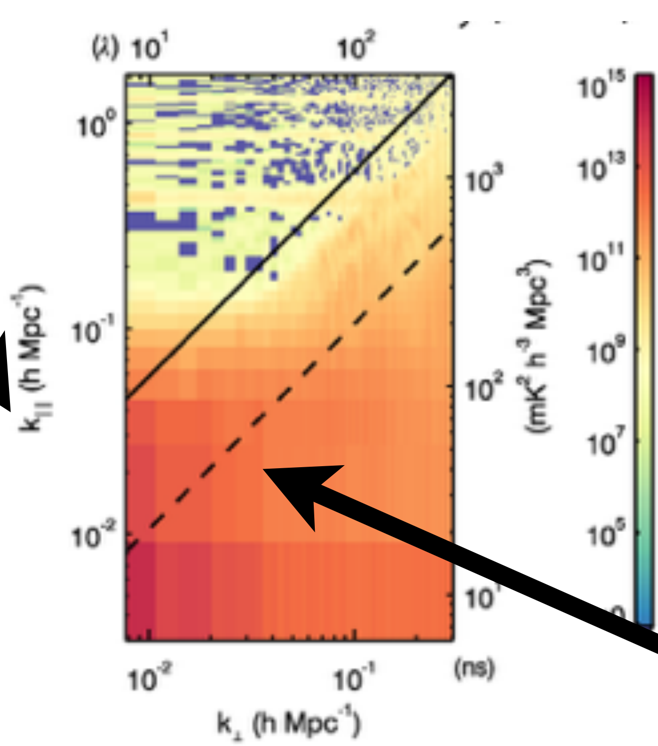
Signal brightest at short spacings and large spectral scales

baseline length $[\lambda]$

$|\vec{b}|$

$k_{||}$

$[h\mathrm{Mpc}^{-1}]$



τ

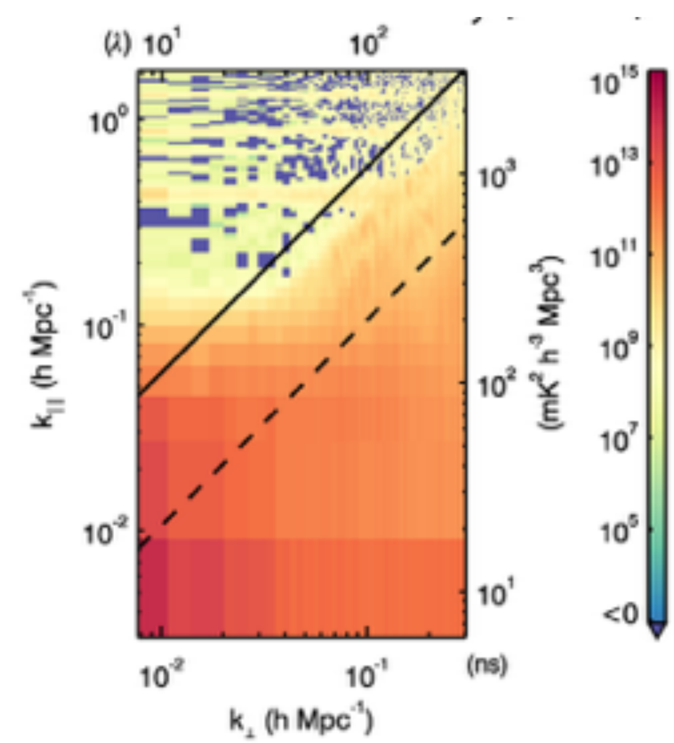
(spectral) [ns]

$k_{\perp}$

Foregrounds make a 'wedge'

Foreground Lessons

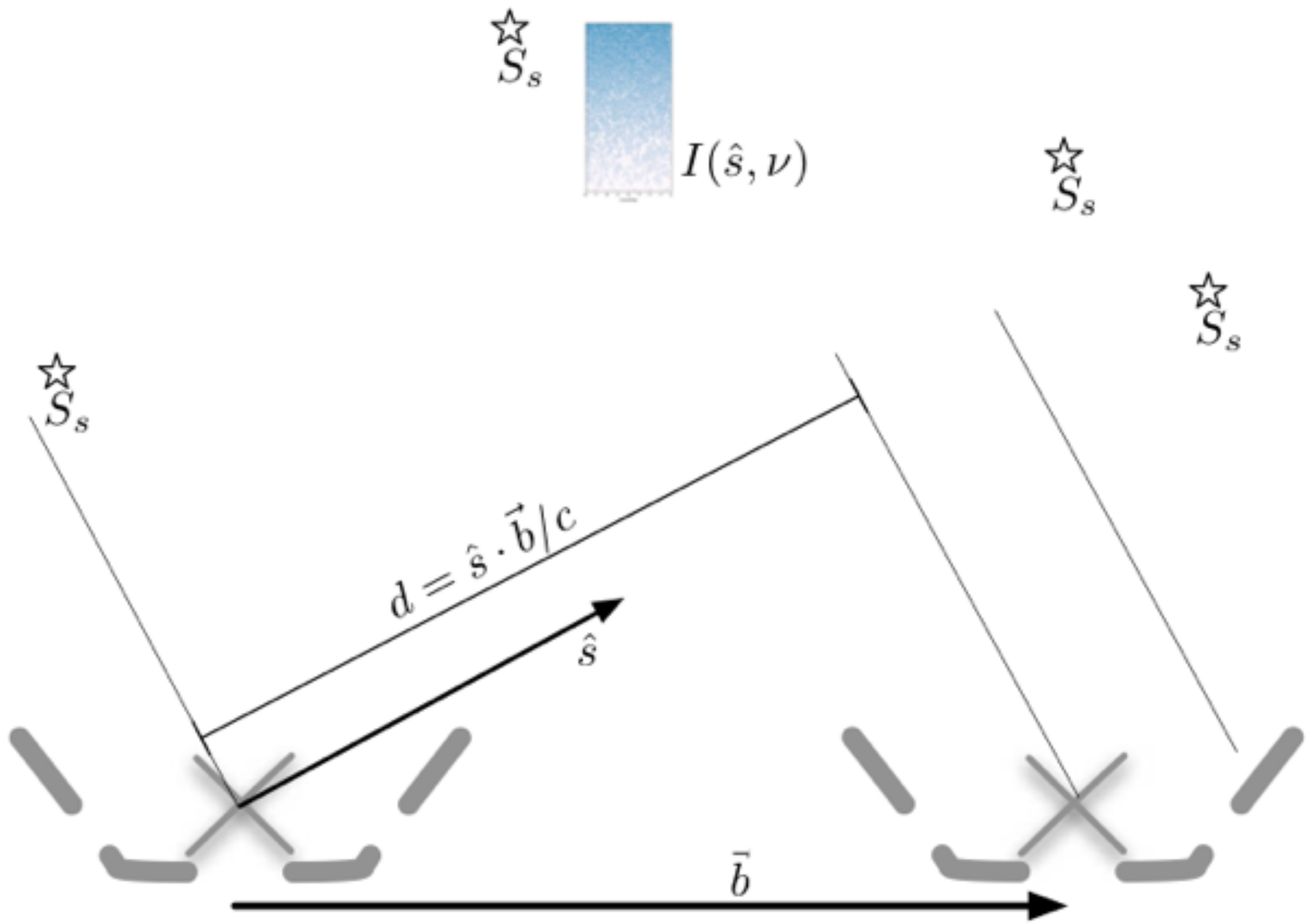
- Avoidance is easiest but least sensitive
- Source subtraction is best but is also the hardest
- Sources at the horizon are the first hurtle
- the galaxy is probably showing up on long baselines
- averaging baselines without care can lead to spectral issues
- modeling of covariance can put foregrounds into errors instead of a bias



http://loco.lab.asu.edu/danny_jacobs


DELAY SPECTRUM:
AVOIDANCE WITHOUT GRIDDING

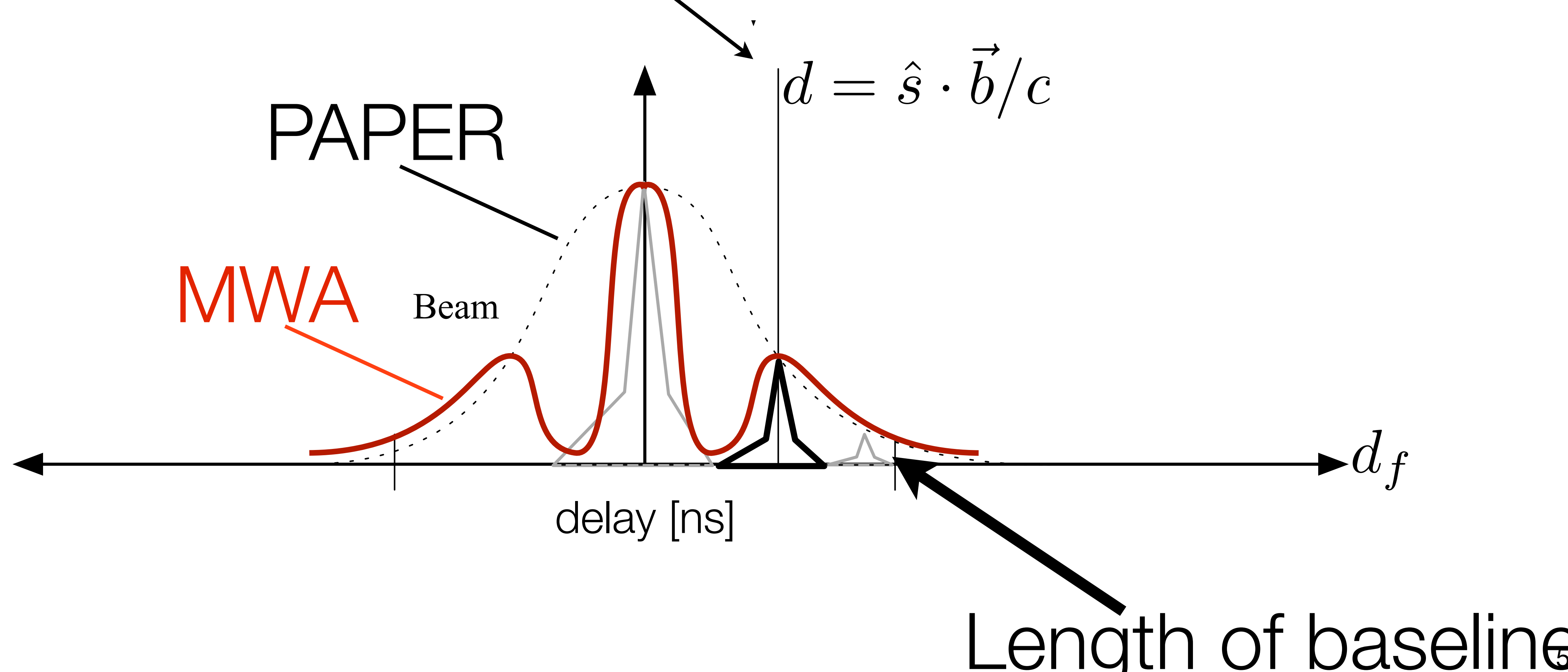
Interferometry 101



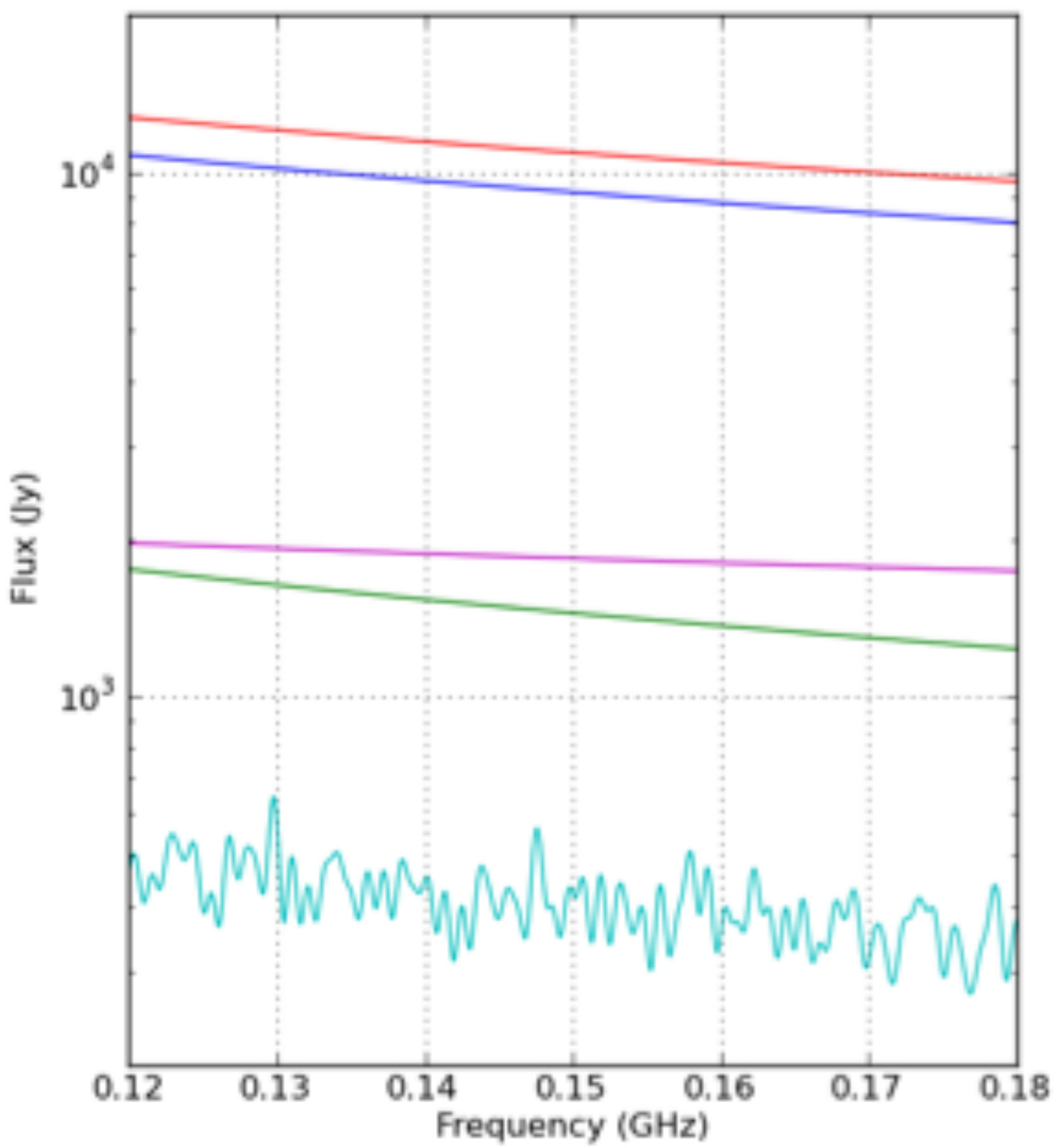
$$V_{ij} \approx \underbrace{\sum_s S_s s^{-2\pi i d_s \nu}}_{\text{Point Sources (wide band)}} + \underbrace{\int I(\hat{s}, \nu) e^{-2\pi i \hat{s} \cdot \vec{b} \nu / c} d\Omega}_{\text{EoR (Narrow band)}}$$

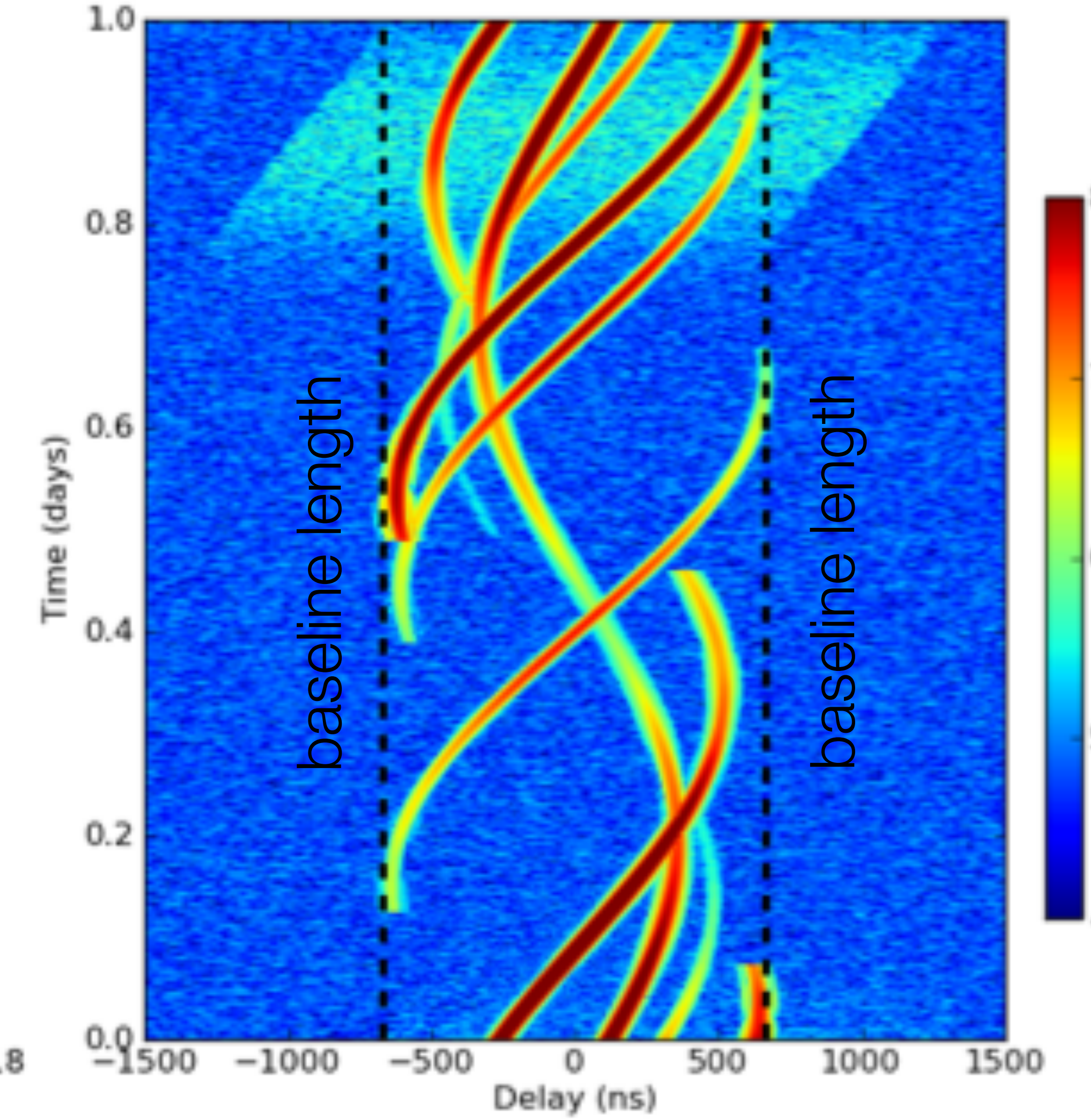
The delay spectrum (a 1D power spectrum)

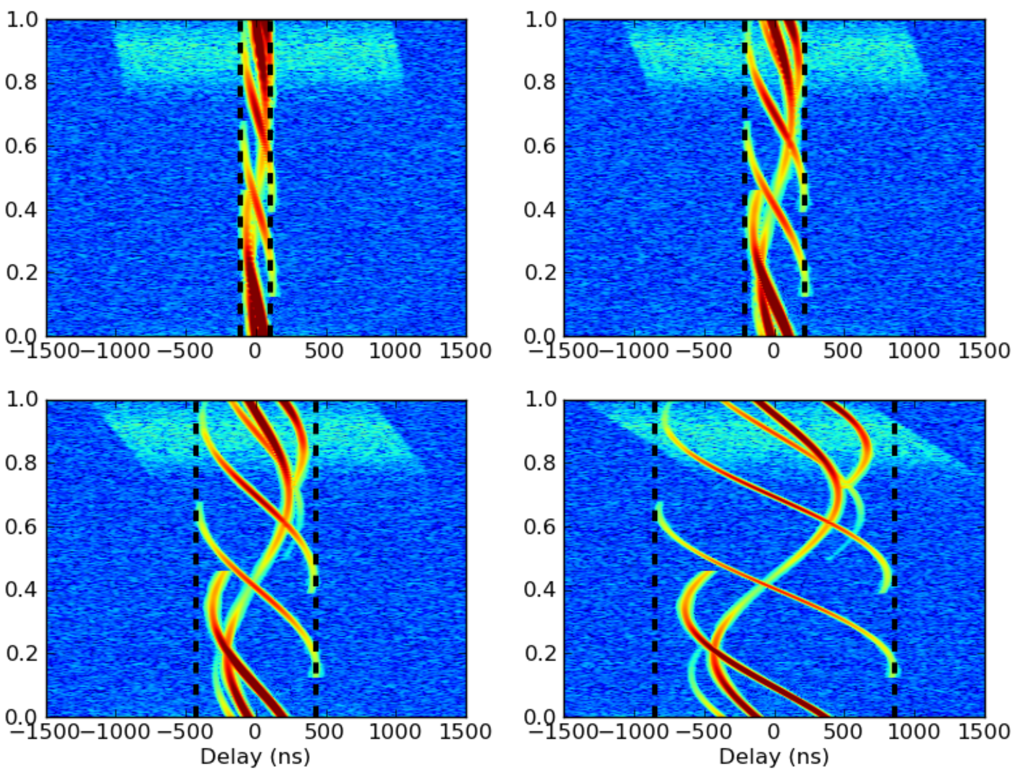
$$\mathbf{FT}\Big(V_{ij} \approx \underbrace{\sum_s S_s e^{-2\pi i d_s \nu}}_{\text{Point Sources (wide band)}} + \underbrace{\int I(\hat{s},\nu) e^{-2\pi i \hat{s}\cdot\vec{b}\nu/c} d\Omega}_{\text{EoR (Narrow band)}} \Big)$$

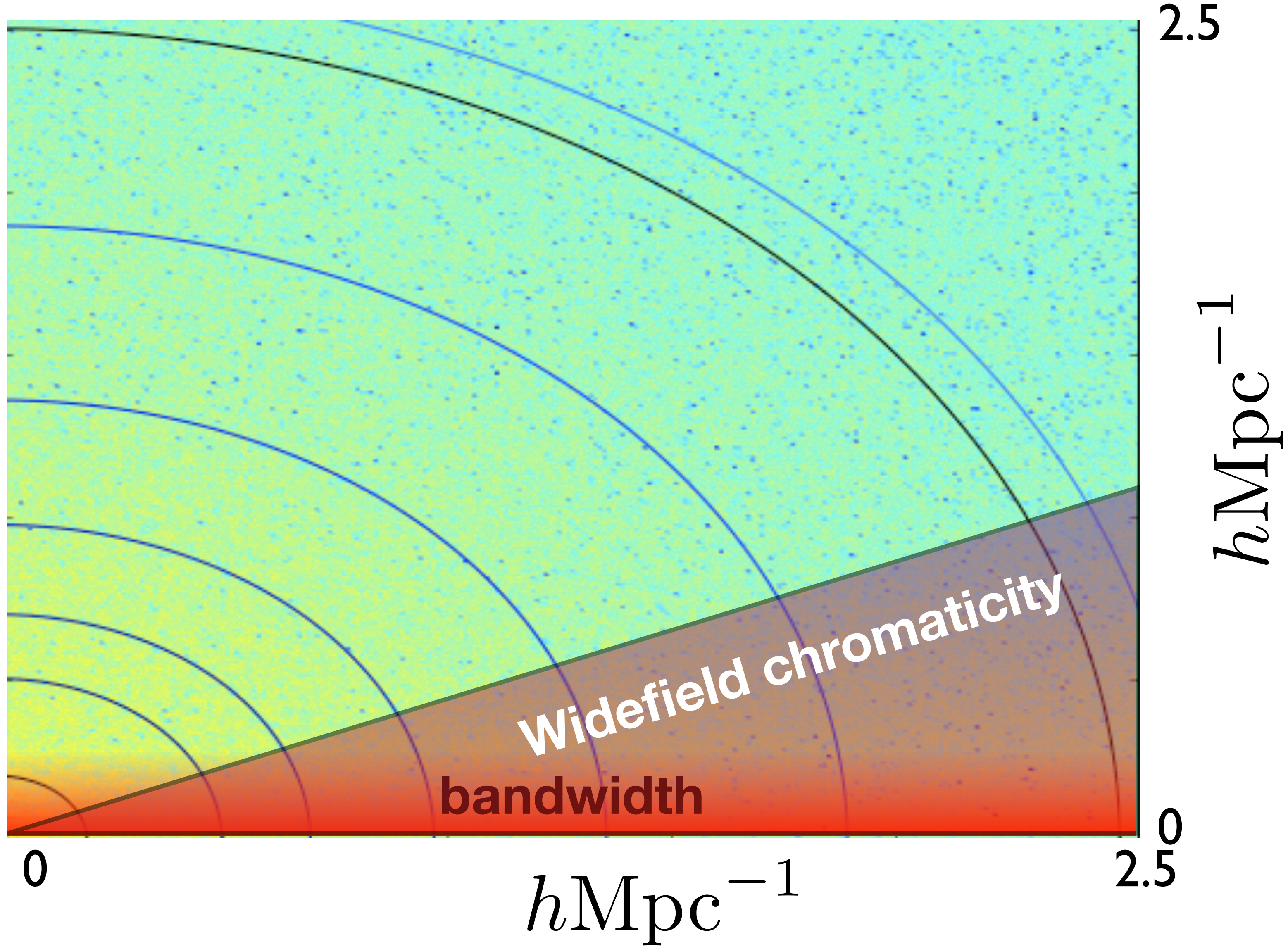


Foregrounds on a single baseline





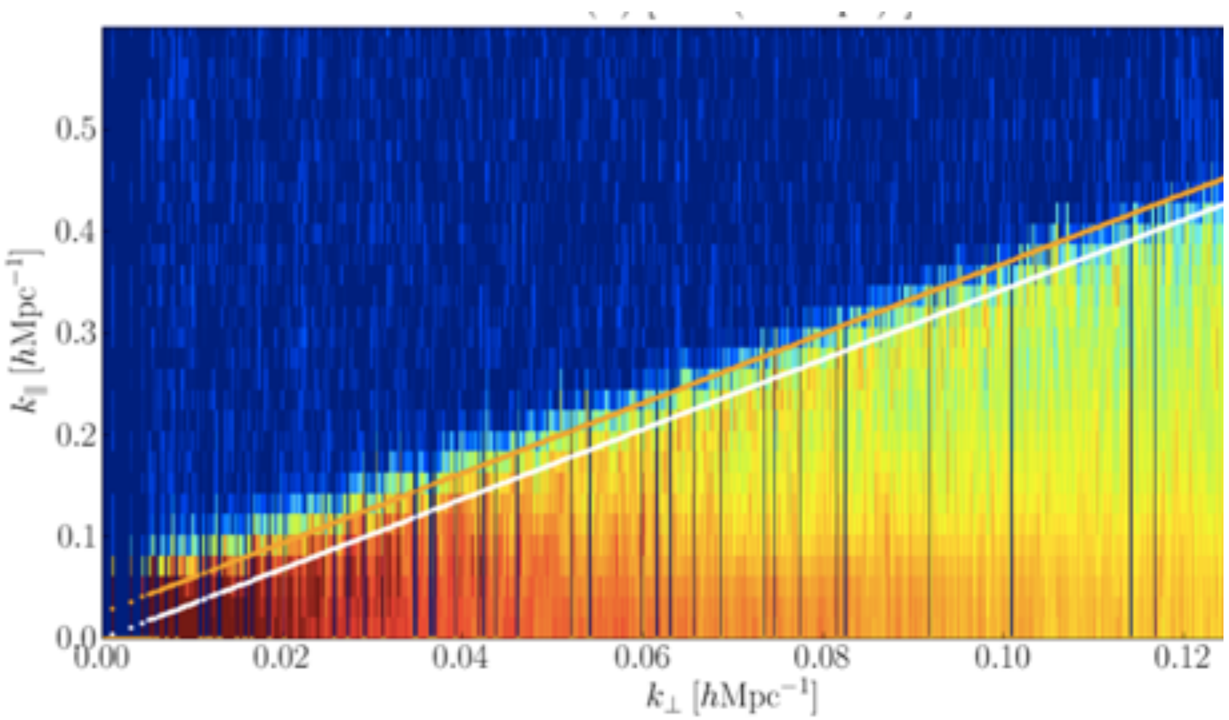


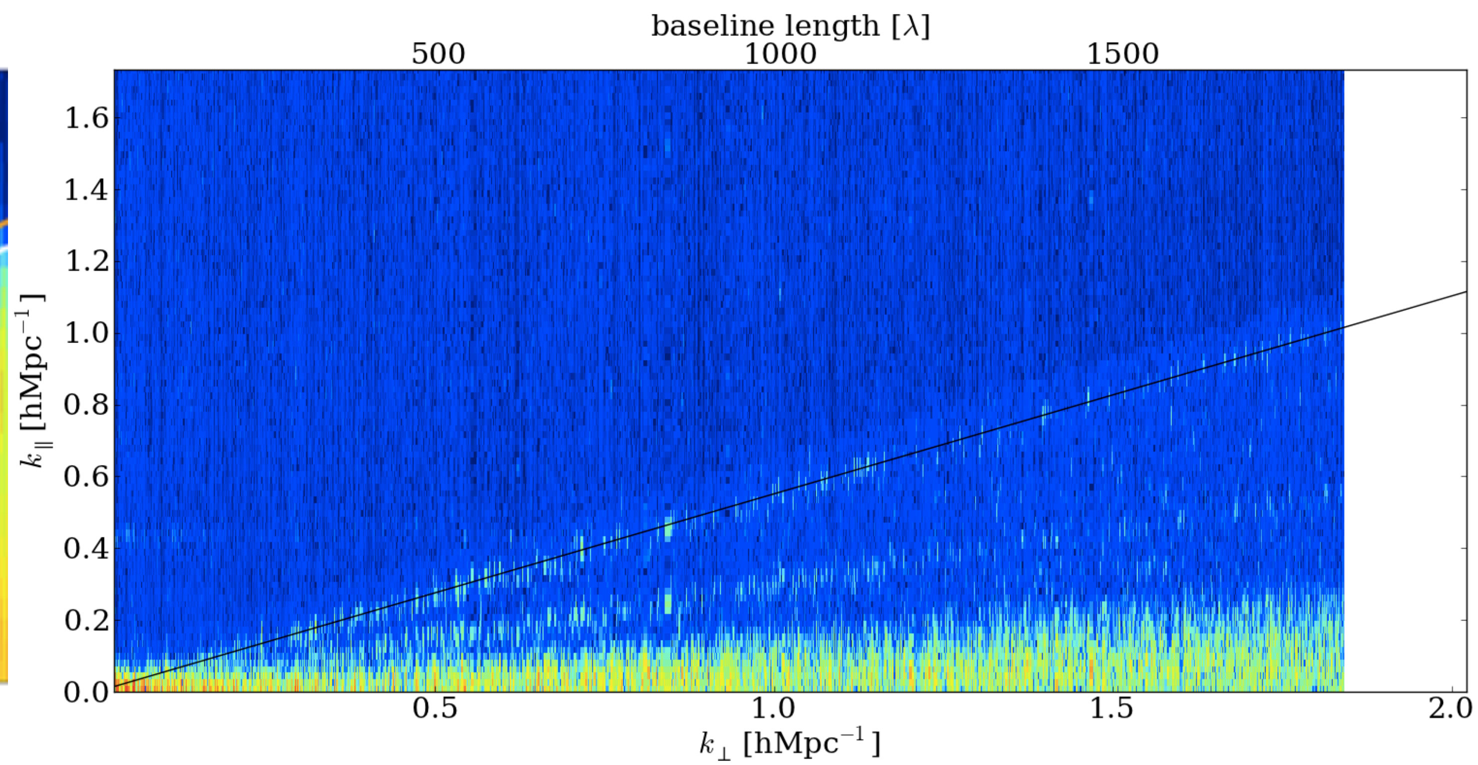


http://loco.lab.asu.edu/danny_jacobs

PAPER

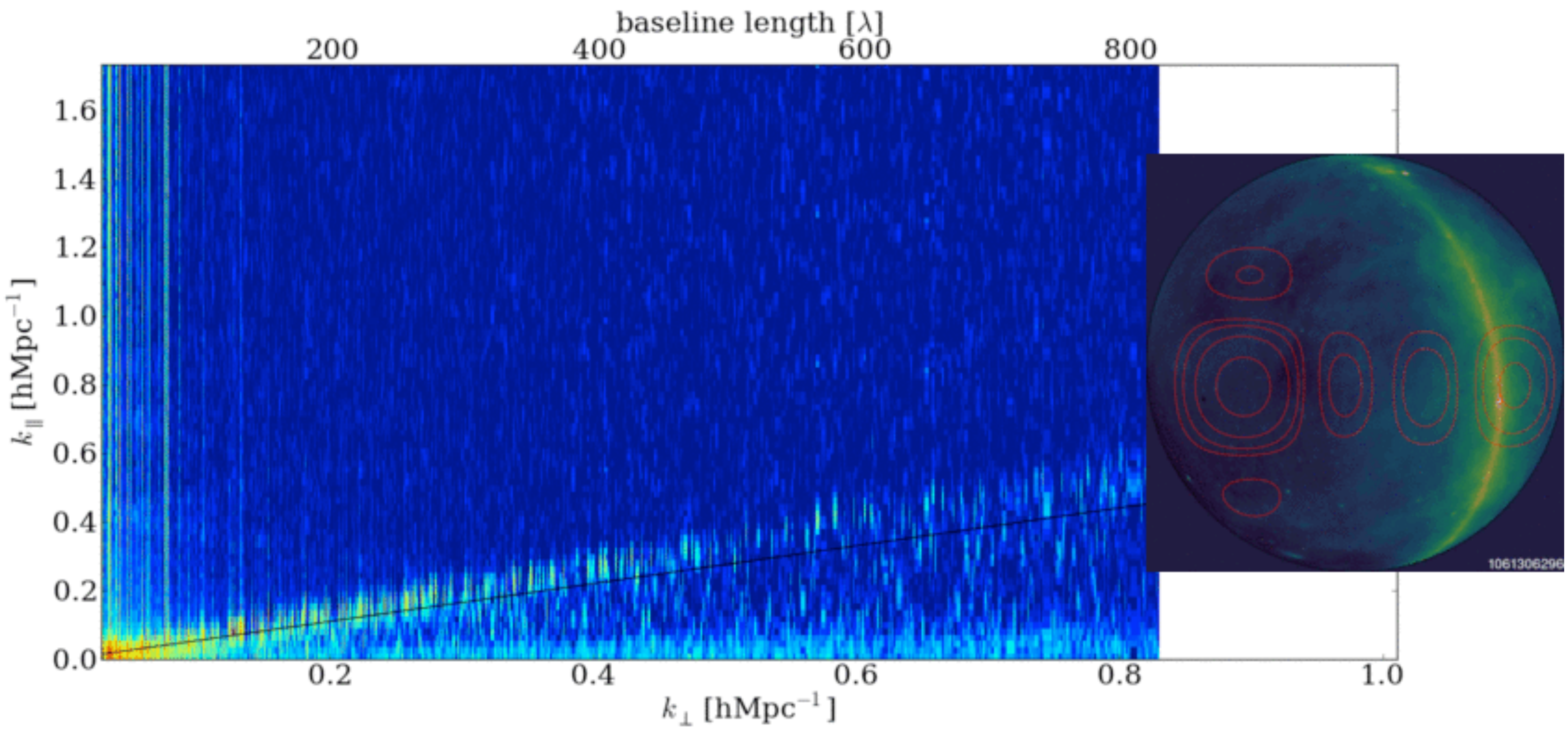
MWA



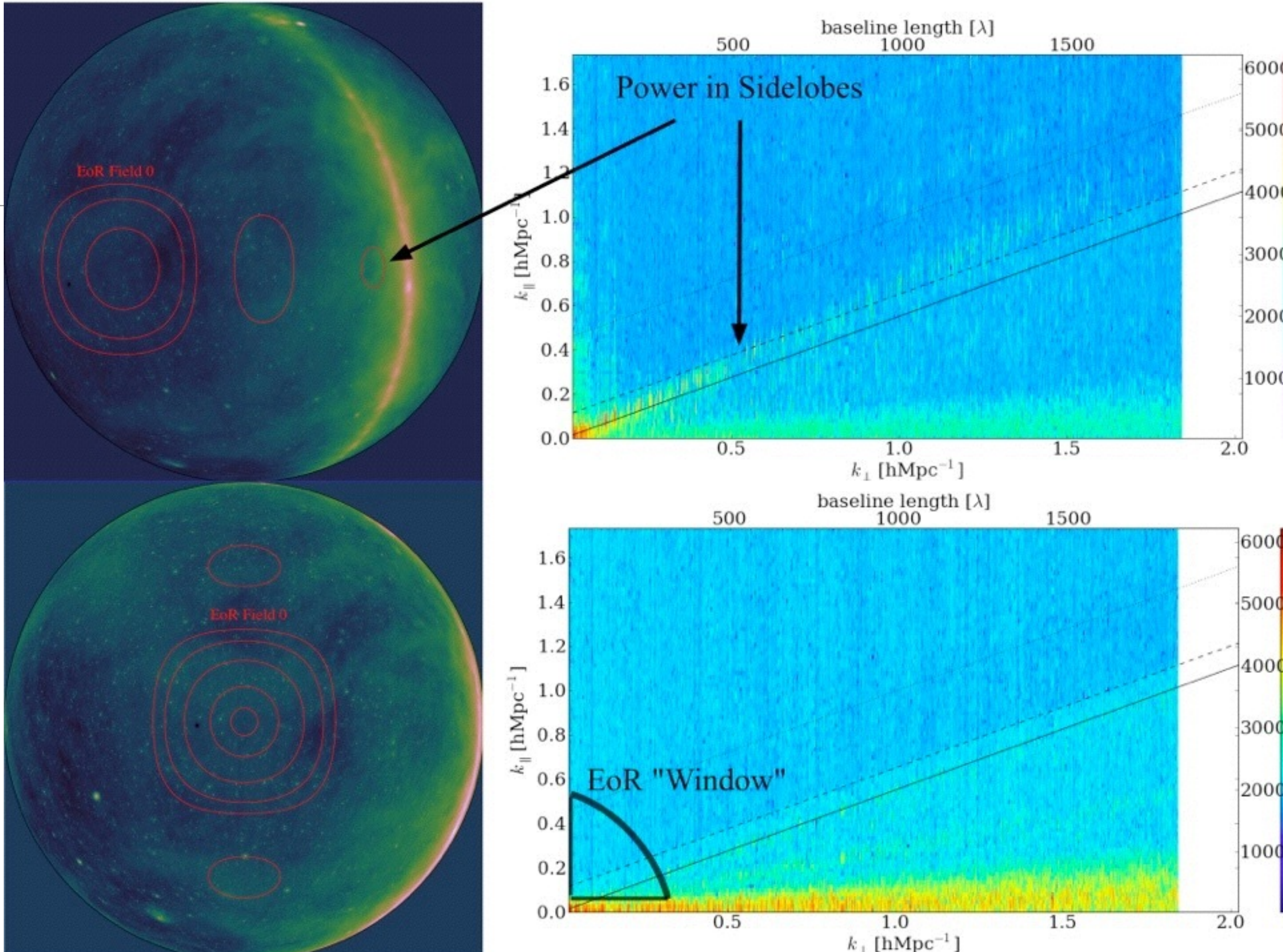


Pober et al 2013

August 23, 2013

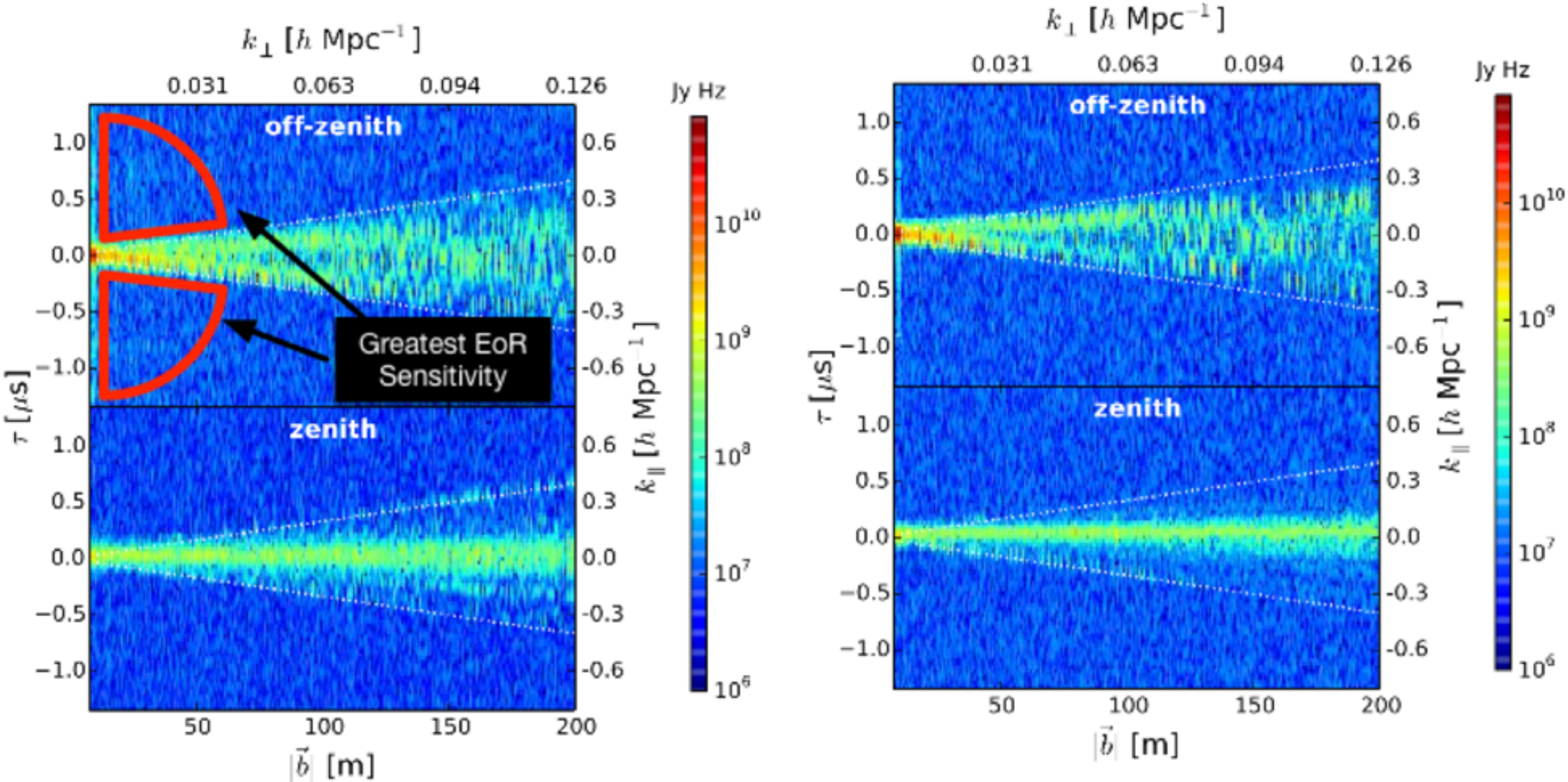


baseline length [λ]
200
400
600
800
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$k_{\parallel}$ [hMpc^{-1}]
0.2
0.4
0.6
0.8
1.0
$k_{\perp}$ [hMpc^{-1}]
1061306296


EoR Field 0
baseline length [λ]
500
1000
1500
Power in Sidelobes
$k_{\parallel}$ [hMpc^{-1}]
$k_{\perp}$ [hMpc^{-1}]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0.5
1.0
1.5
2.0
EoR Field 0
EoR "Window"

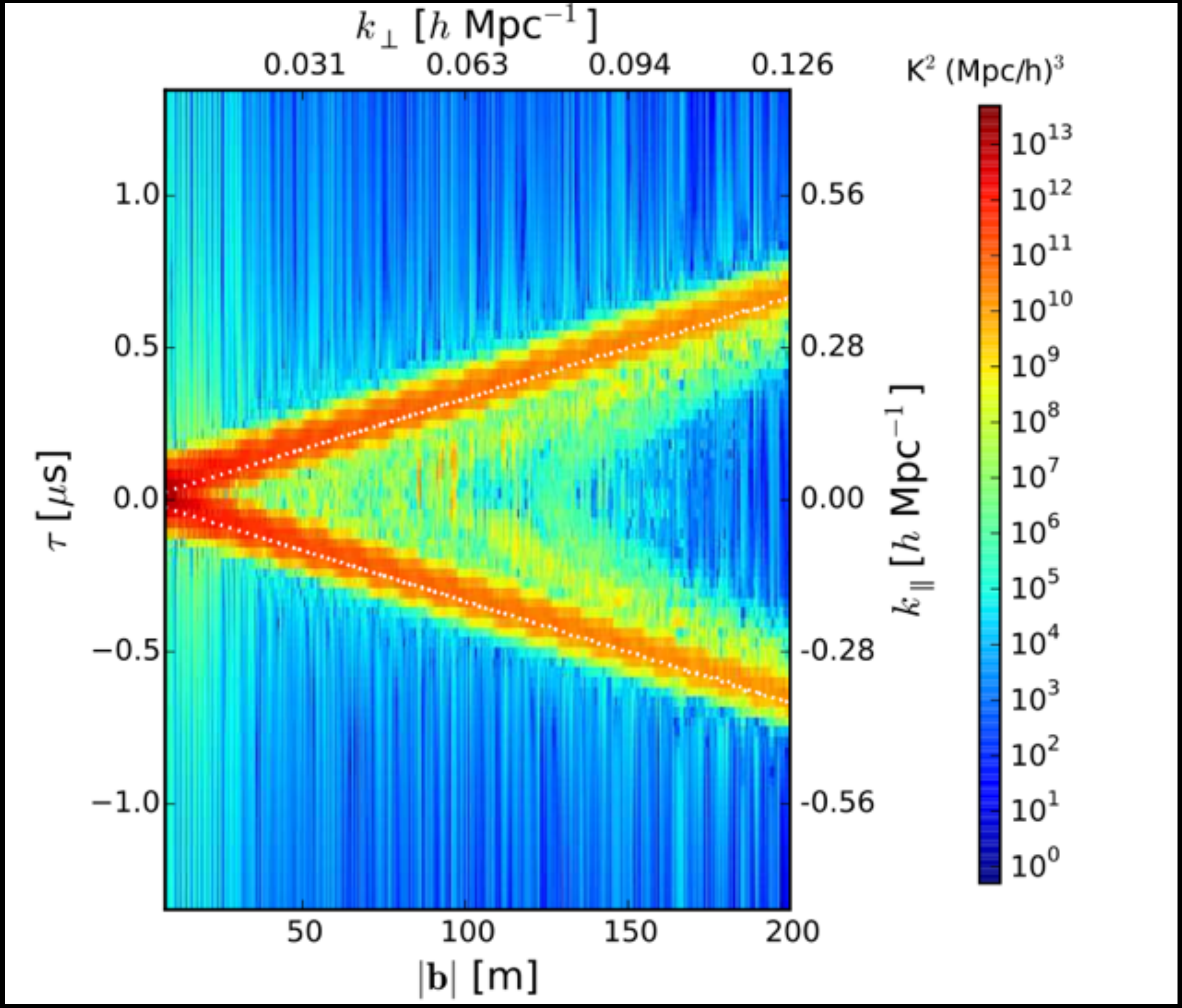
http://locc

Widefield Foregound simulation



arxiv:1502.07596 Thyagarajan et al 2015a,b
arXiv:1506.06150

MEAN FOREGROUNDS

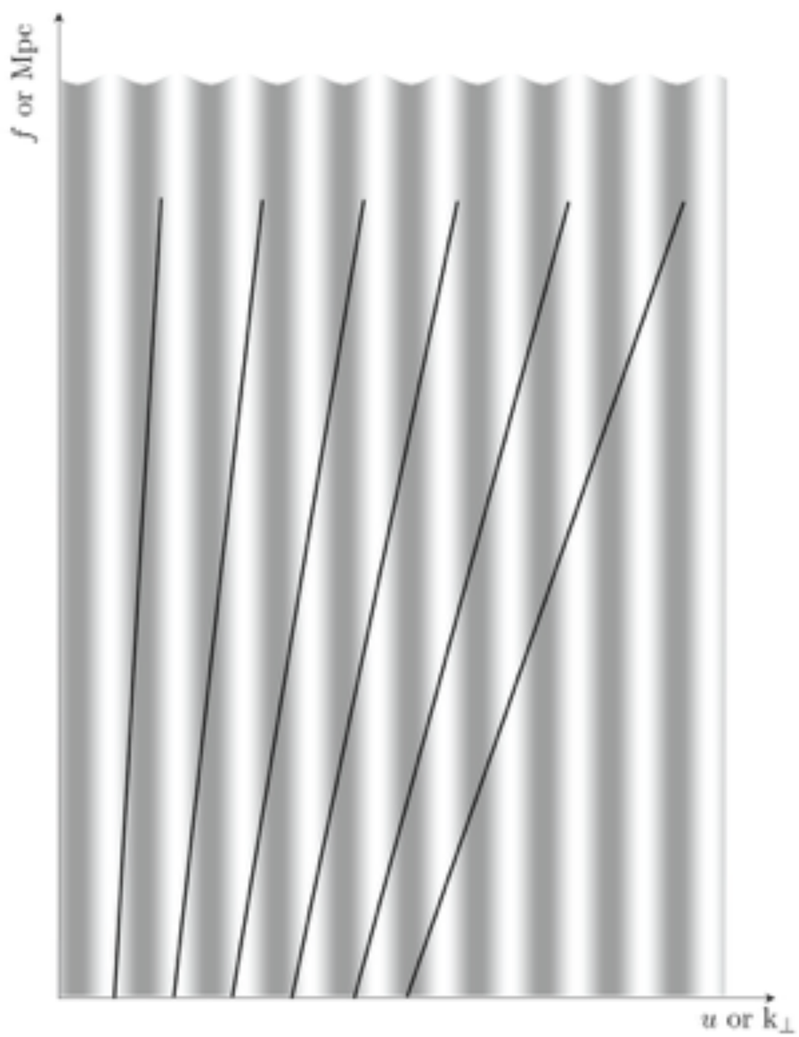


arxiv:1502.07596 Thyagarajan et al 2015a,b
arXiv:1506.06150

MAKING CUBES

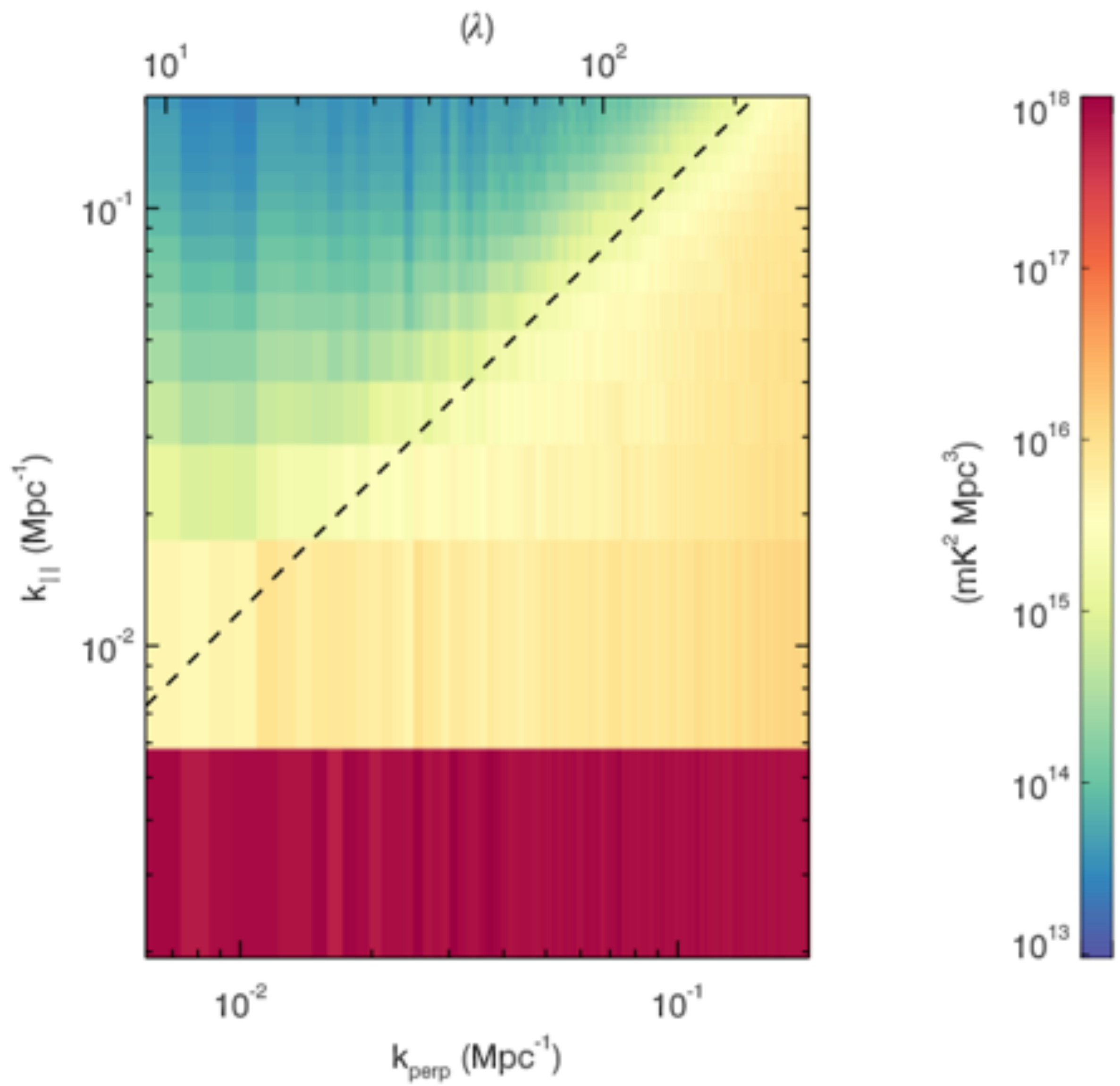
Gridding leakage

uv gaps move with frequency



Morales, Hazelton, et al 2012

wedge-like leakage

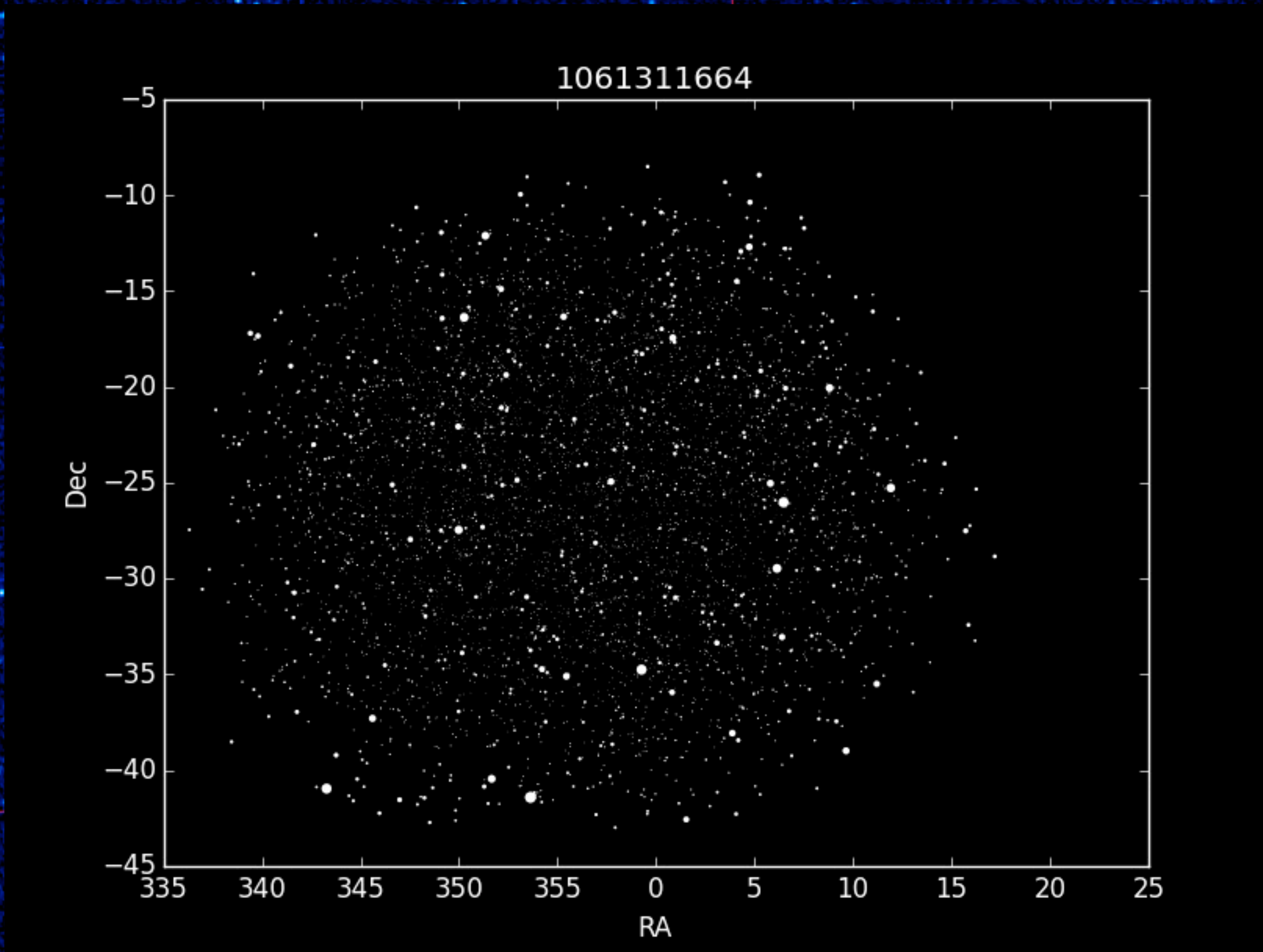


Hazelton, et al 2013

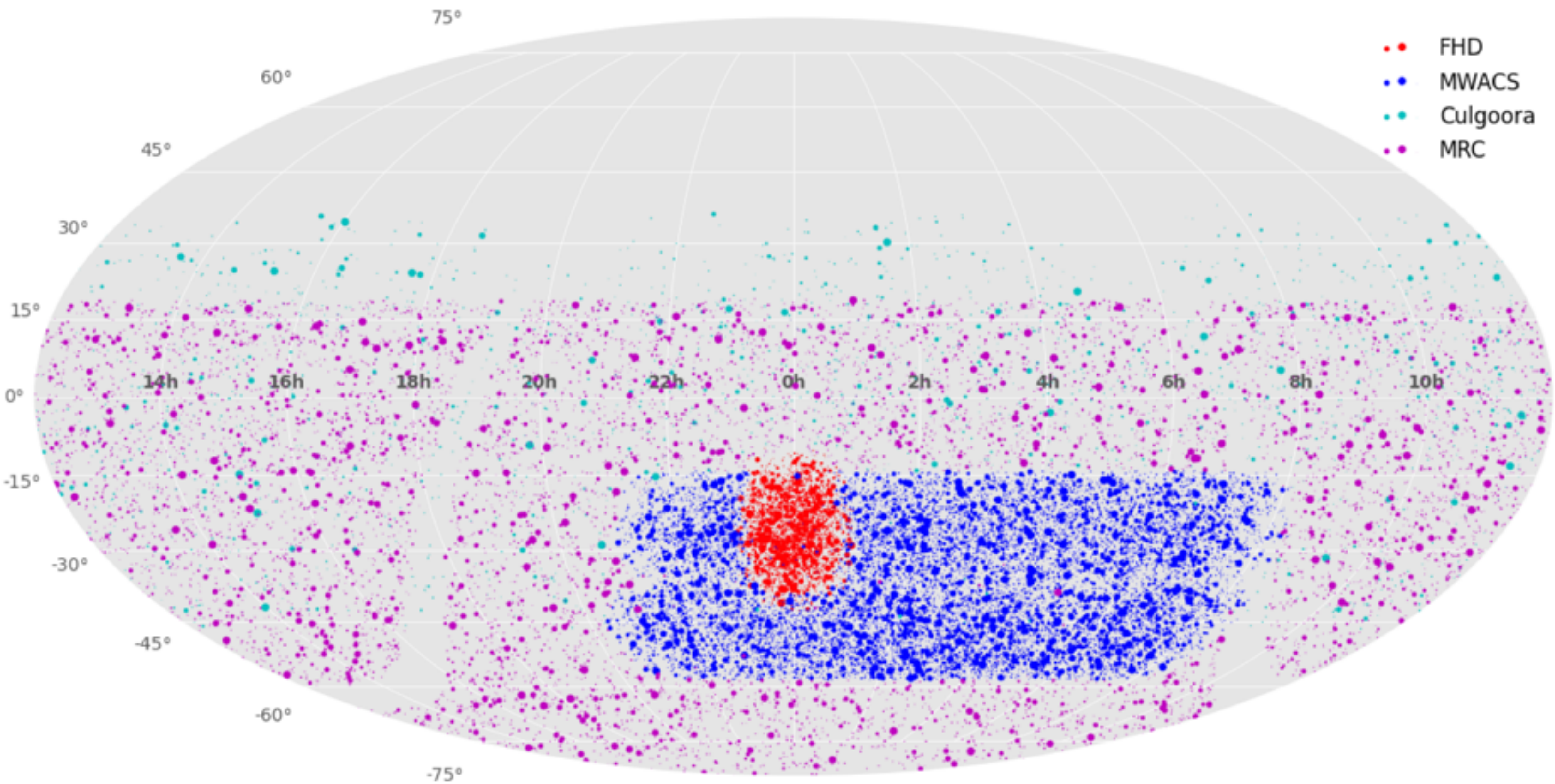
http://loco.lab.asu.edu/danny_jacobs

CARROLL 2014

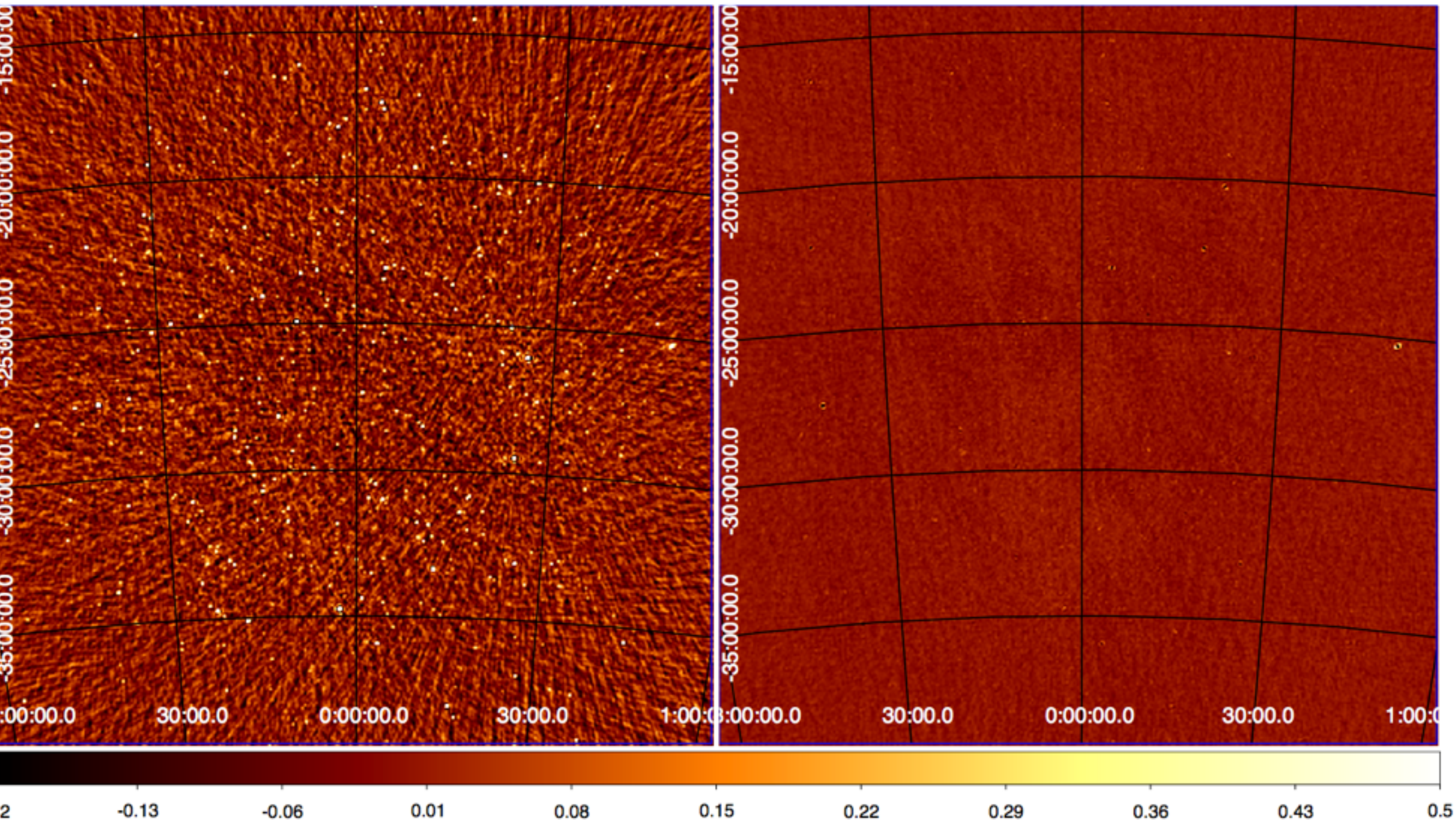
C



FOREGROUND CATALOG

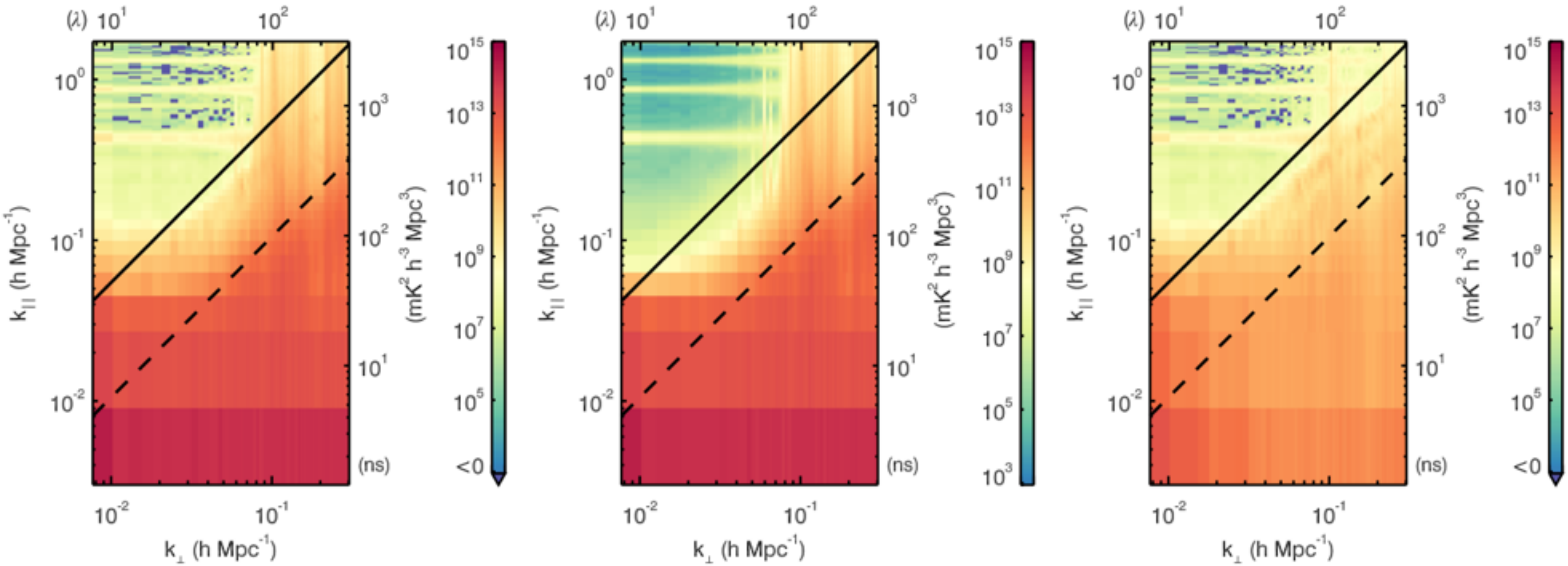


by P. Carroll (UW)

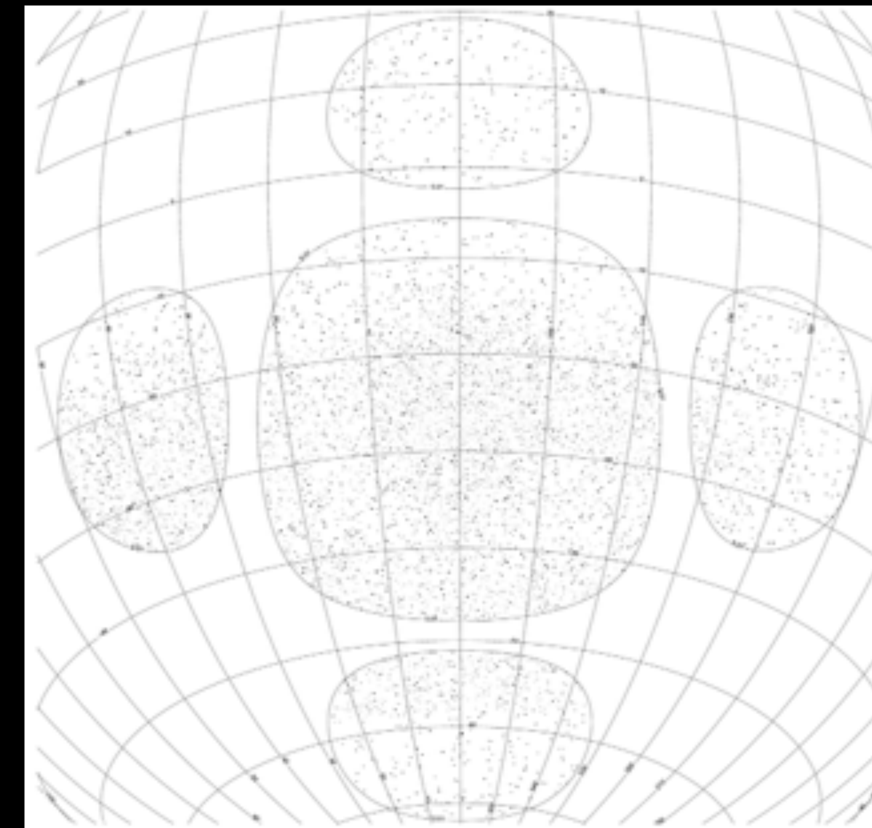


http://loco.lab.asu.edu/danny_jacobs

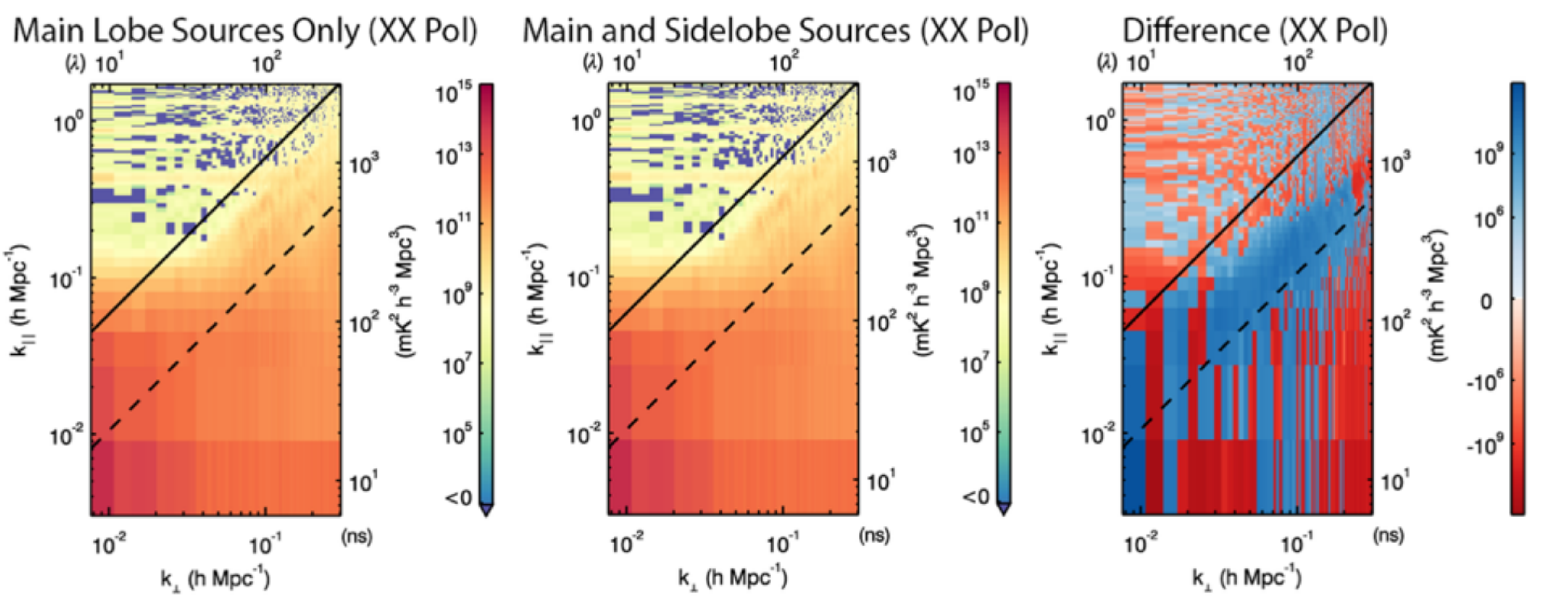
Data - Model = Residual



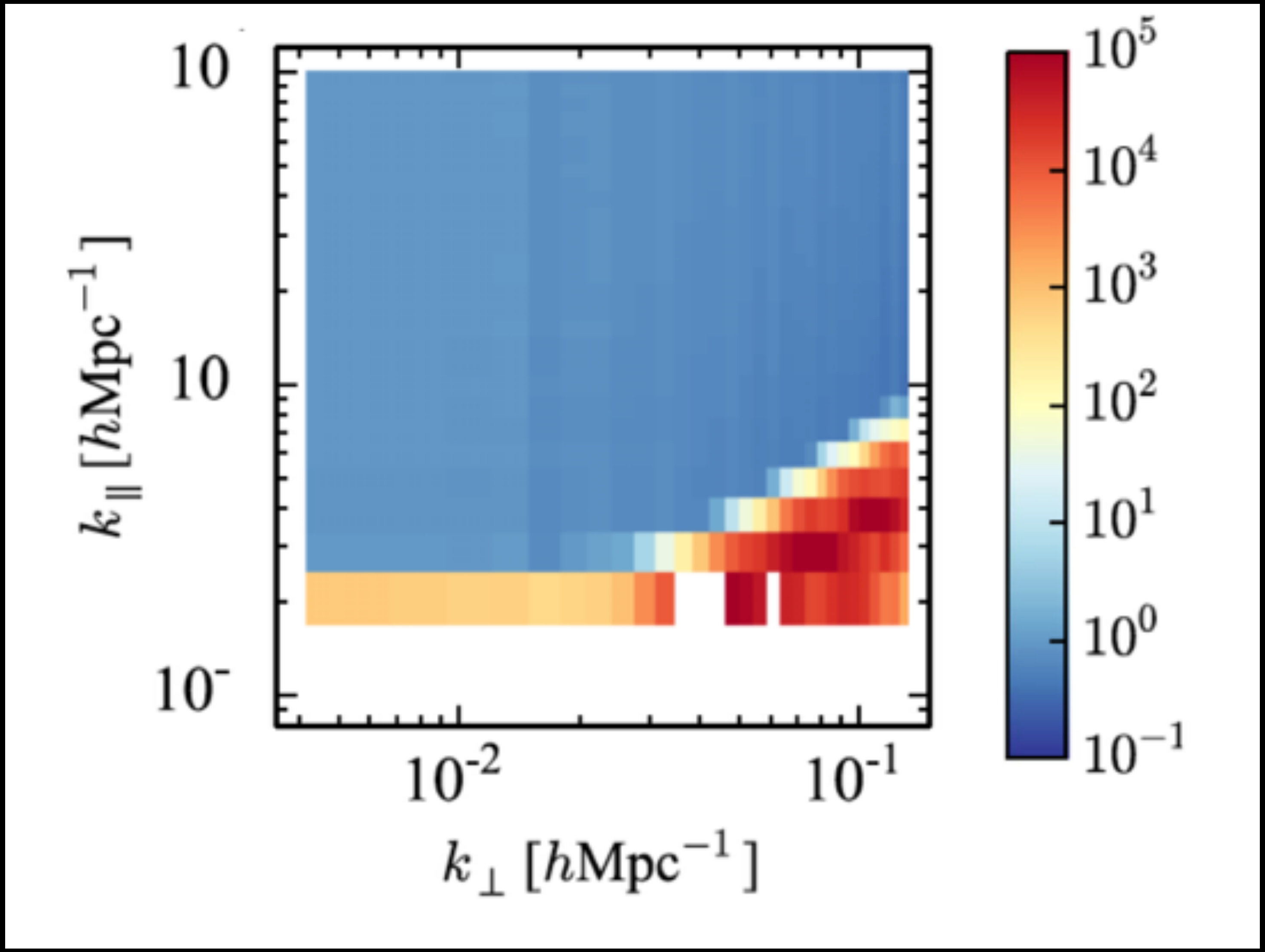
SUBTRACTING SOURCES NEAR THE HORIZON



Using FHD imager, Sullivan et al, ApJ 2012, arXiv:1209.1653
Pober et al (in prep)

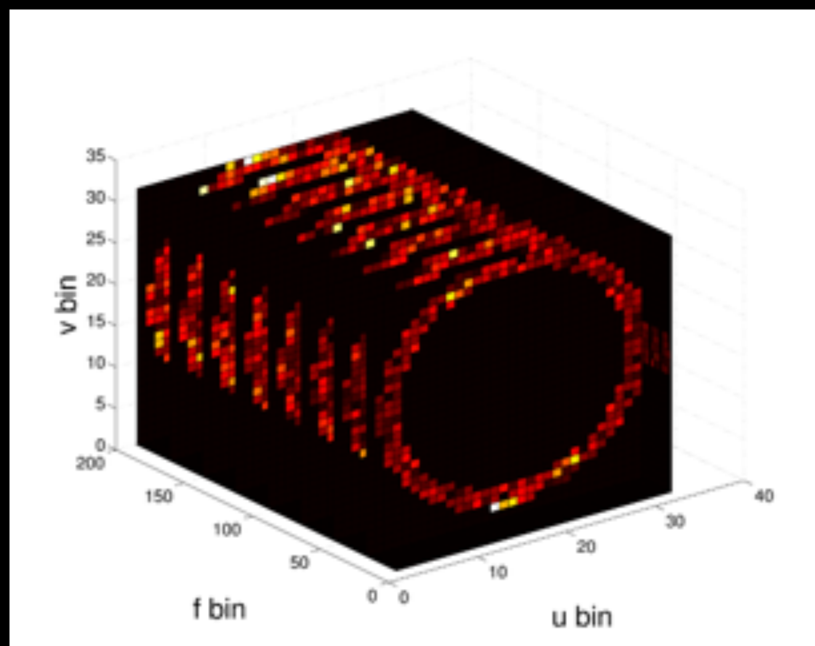


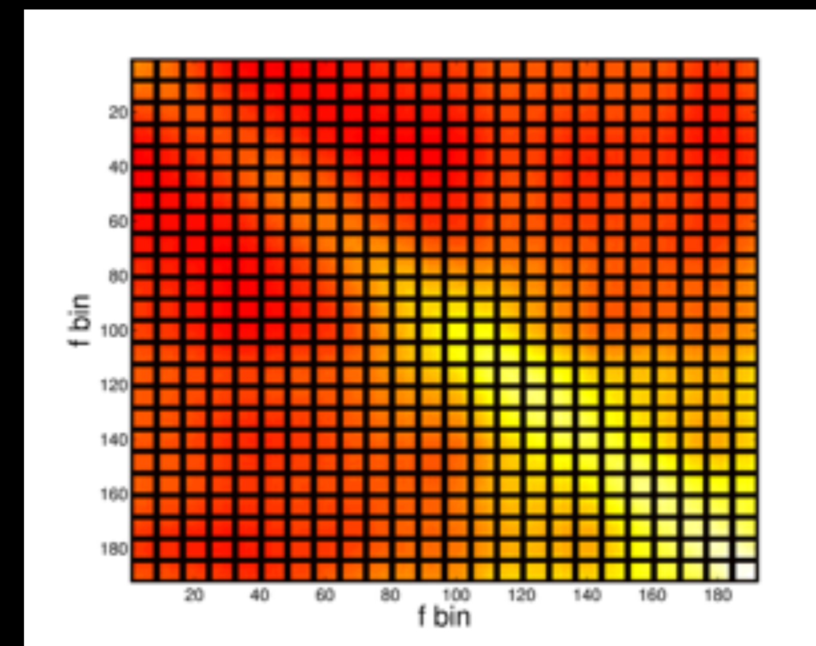
POWER SPECTRUM FOREGROUND CONTAMINATION REDUCTION

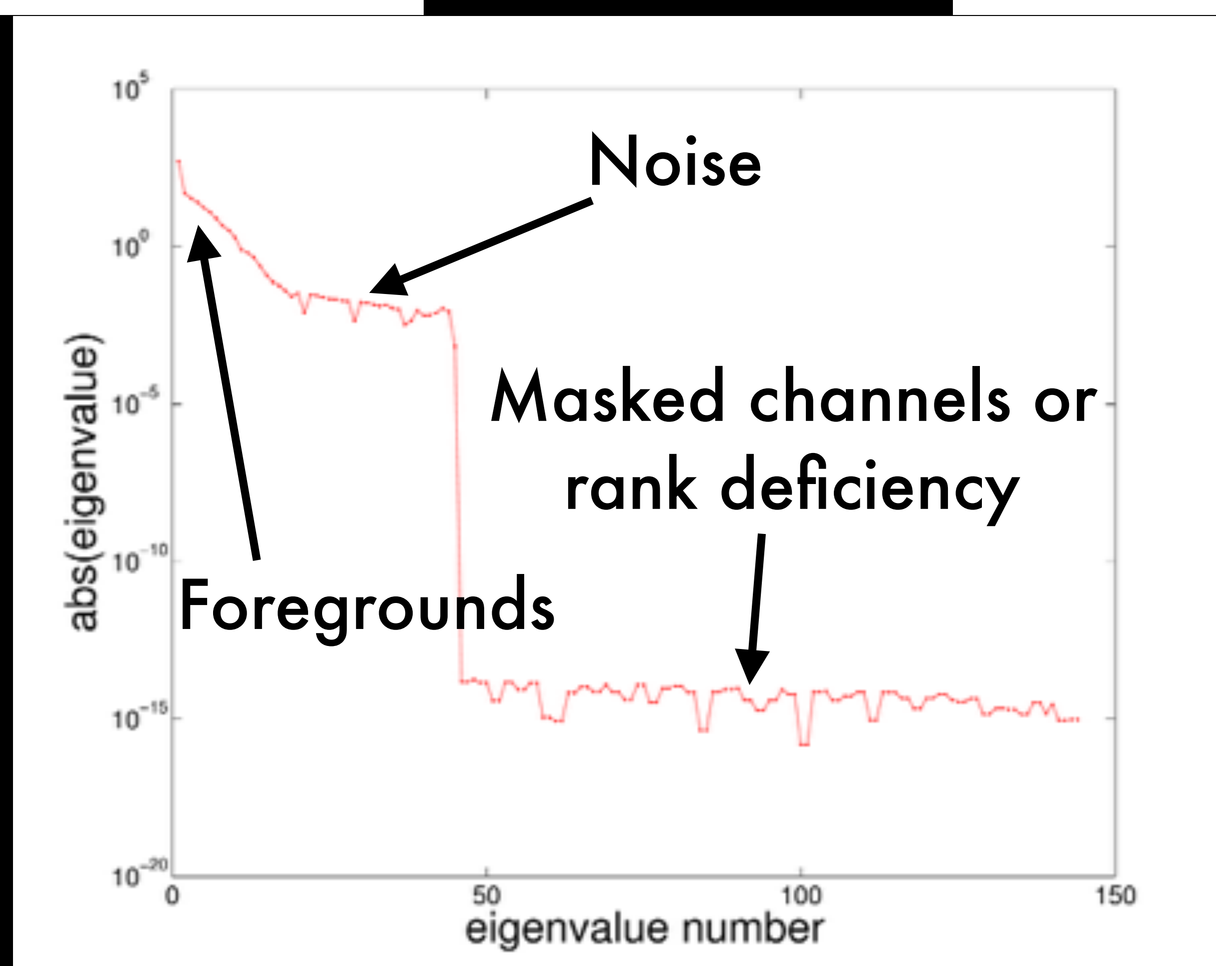


Liu, Parsons, Trott PrD 2014a&b

EMPIRICAL COVARIANCE ESTIMATION/MINIMIZATION



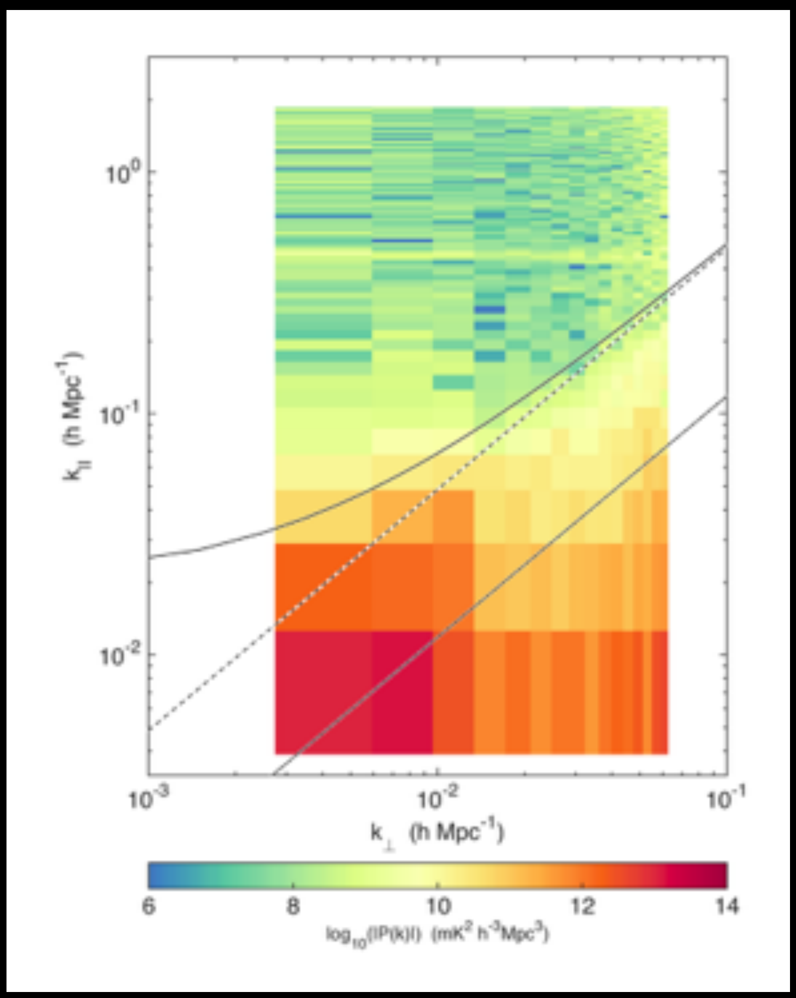


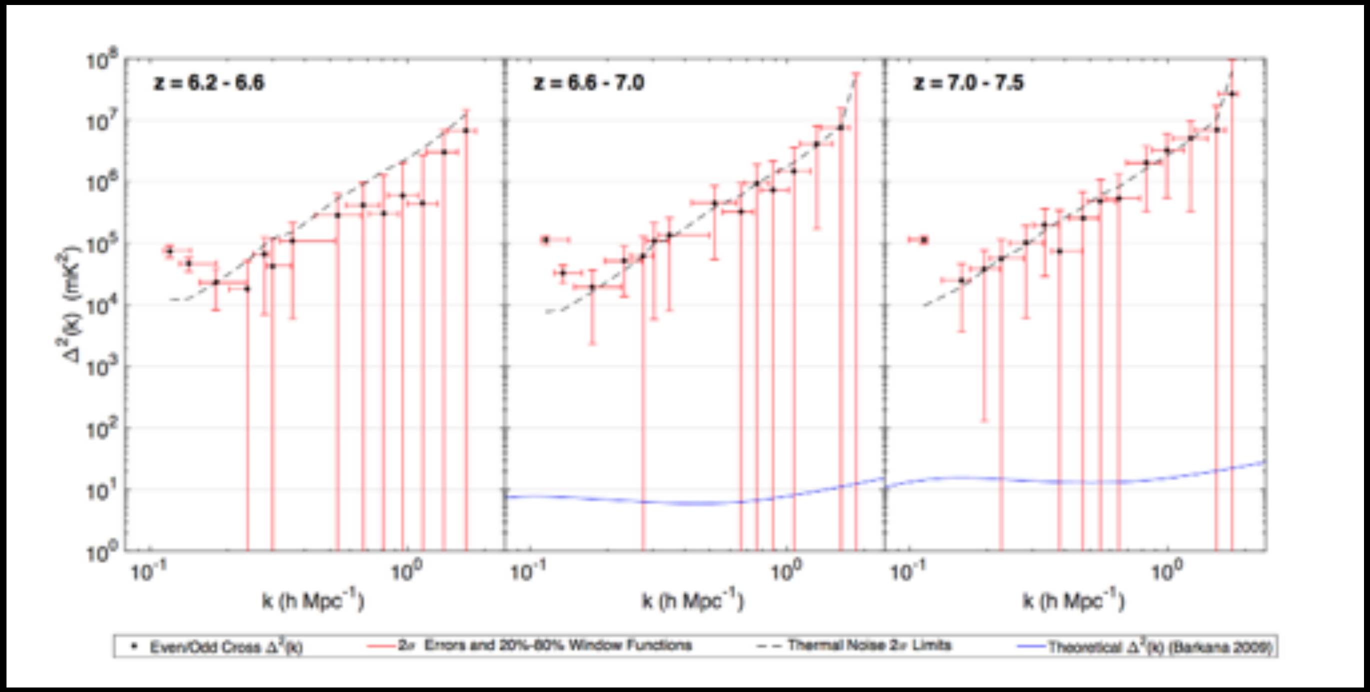


Dillon et al PrD 2015, arxiv:1506.01026

D. Jacobs, 2015

EMPIRICAL COVARIANCE ESTIMATION/MINIMIZATION



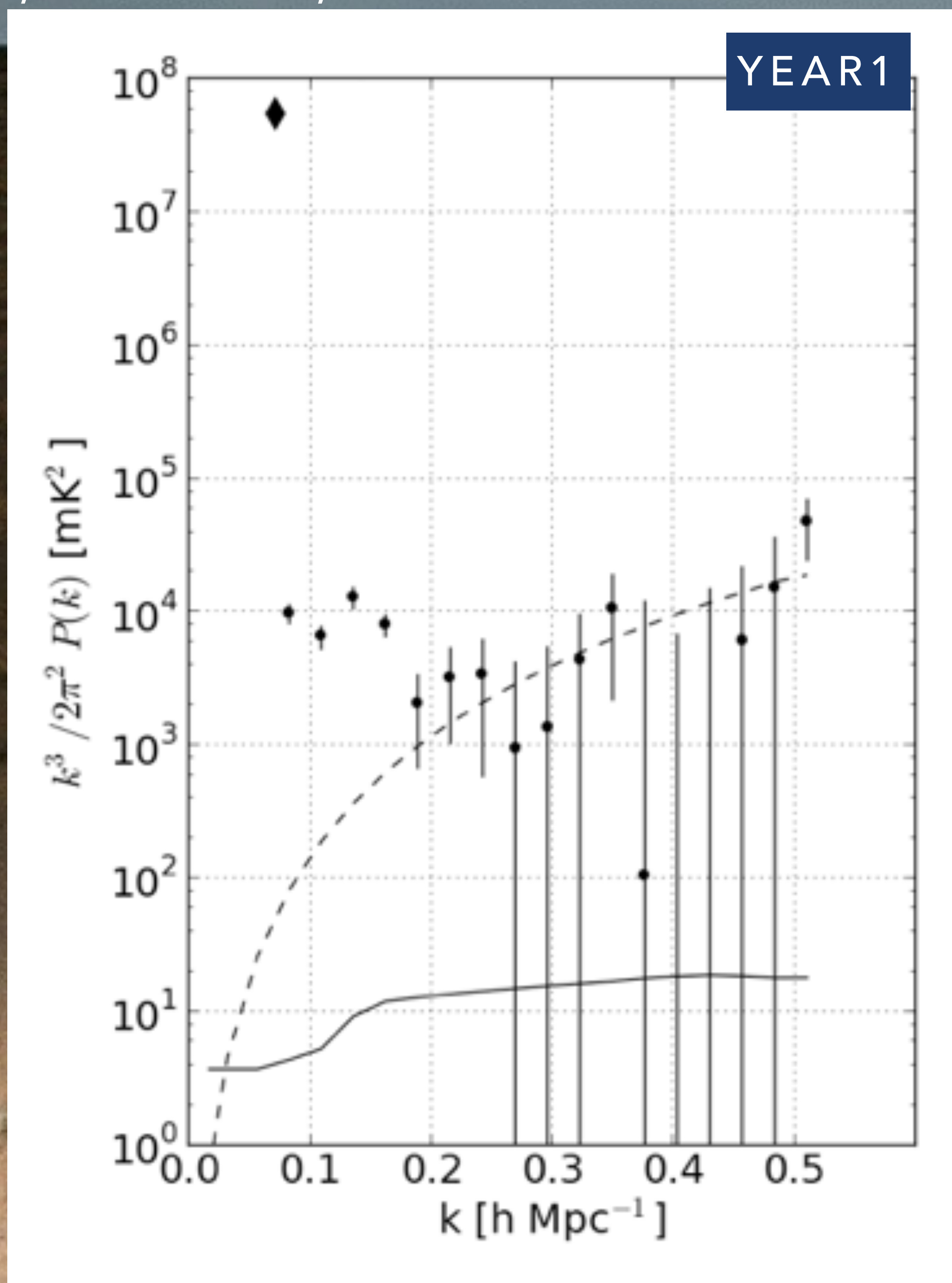


Dillon et al PrD 2015,
arxiv:1506.01026

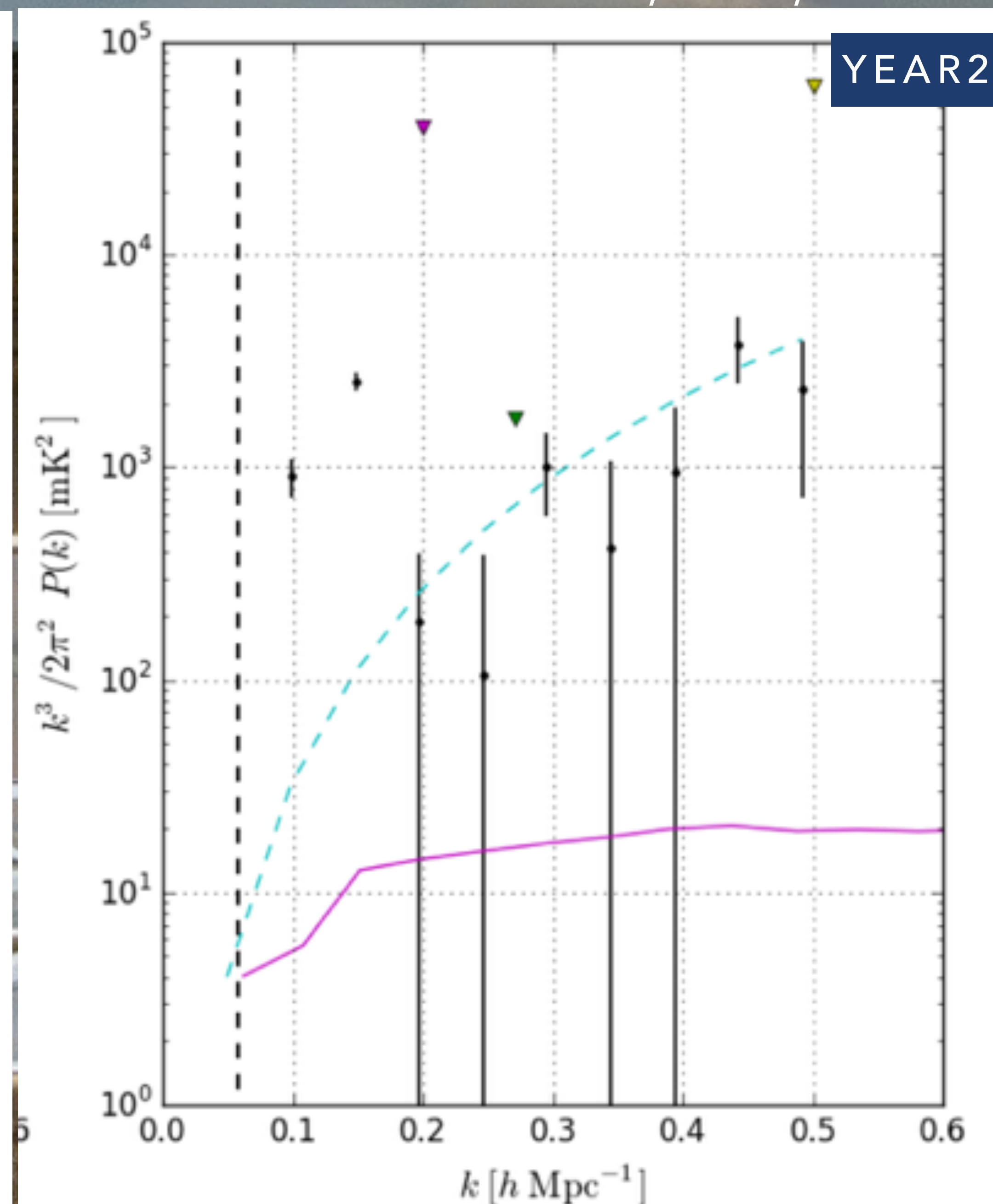
D. Jacobs, 2015

YEAR 2 PAPER RESULTS

AP, **DCJ**, et al 2014, Jacobs 2015



Ali, **DCJ**, et al 2015



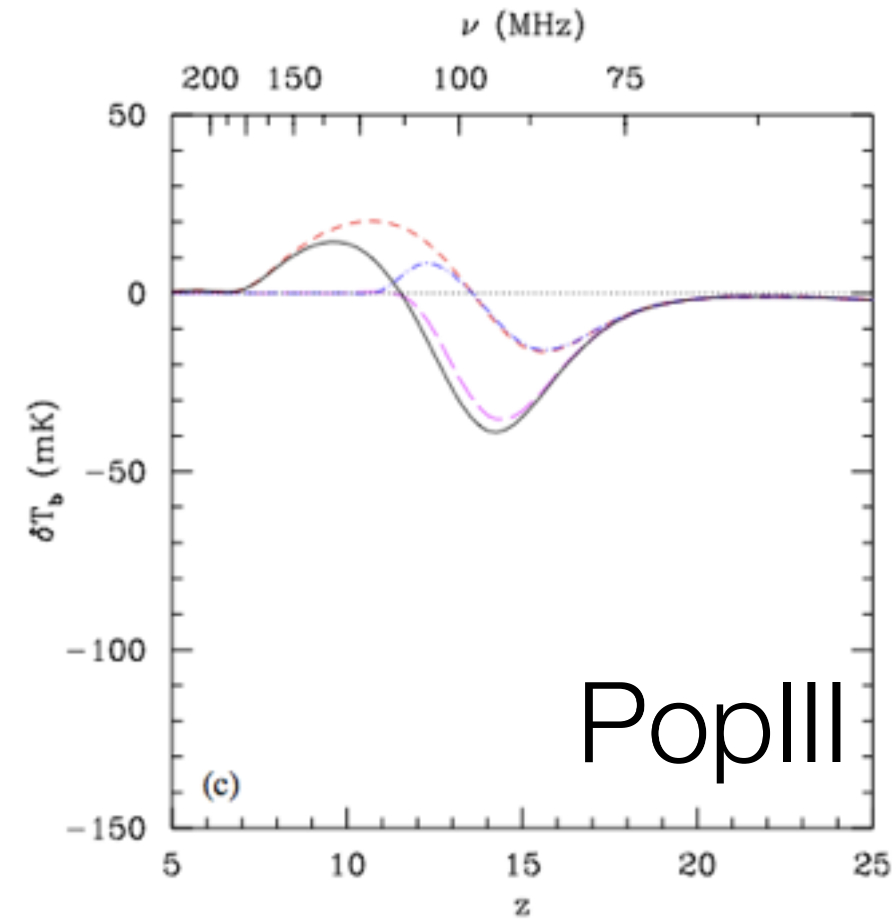
ARXIV.ORG/ABS/1502.06016

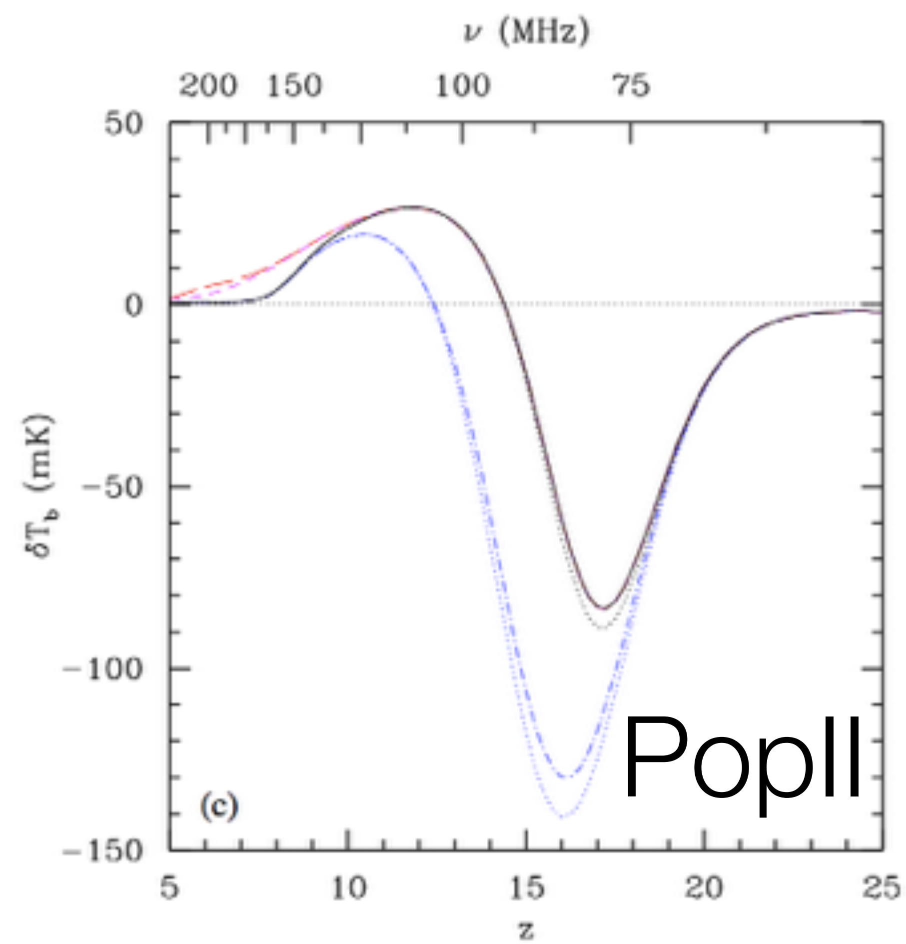
Early Heating.

- order of events uncertain, inc xray heating
- If it didn't happen. -> HI in deep absorption
- Low X-Ray luminosity (but enough Lya for WF)
- Global amplitude constraint (450K at z=8, EDGES)

$$\Delta^2_{21}(k) = \langle T_b \rangle^2 \Delta^2_i(k)$$

- Pop II vs Pop III

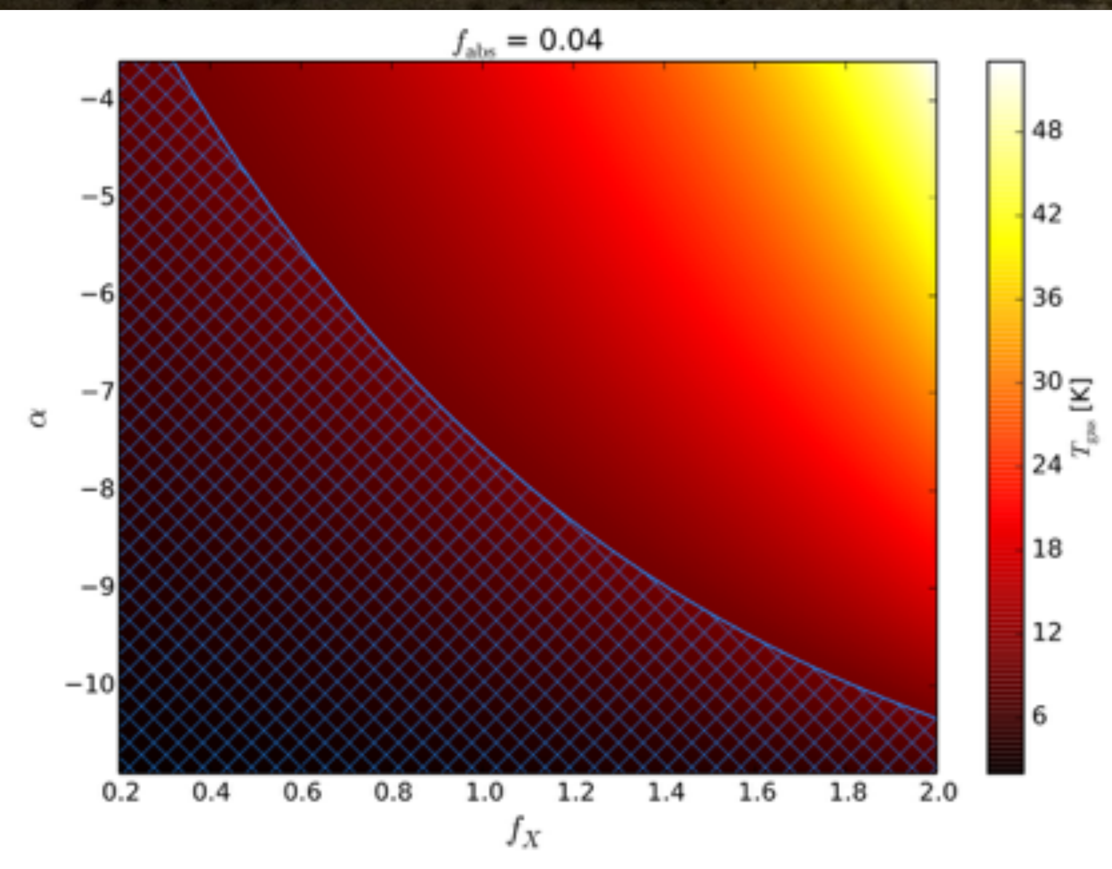


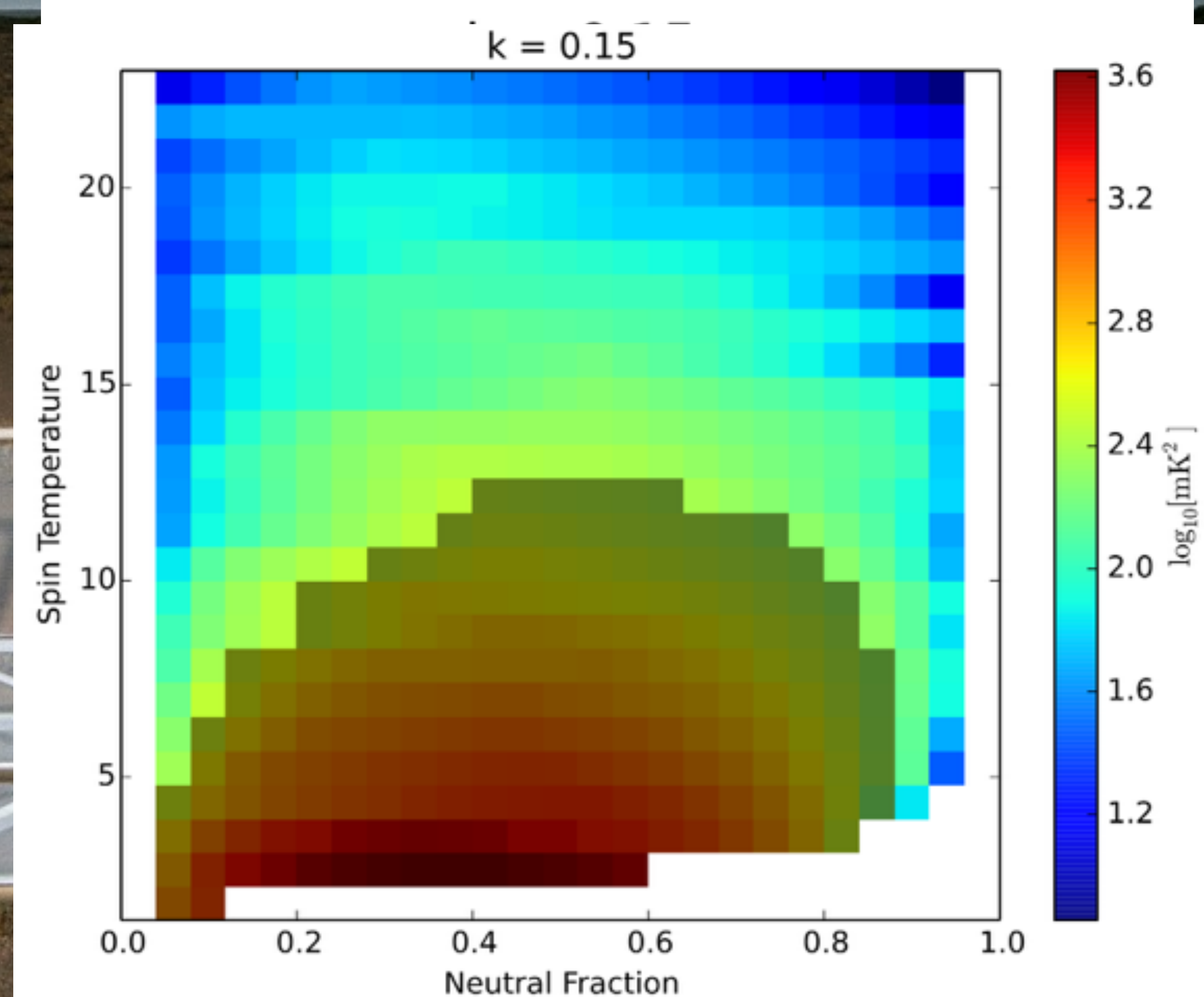


Furlenetto, Oh, Briggs 2006

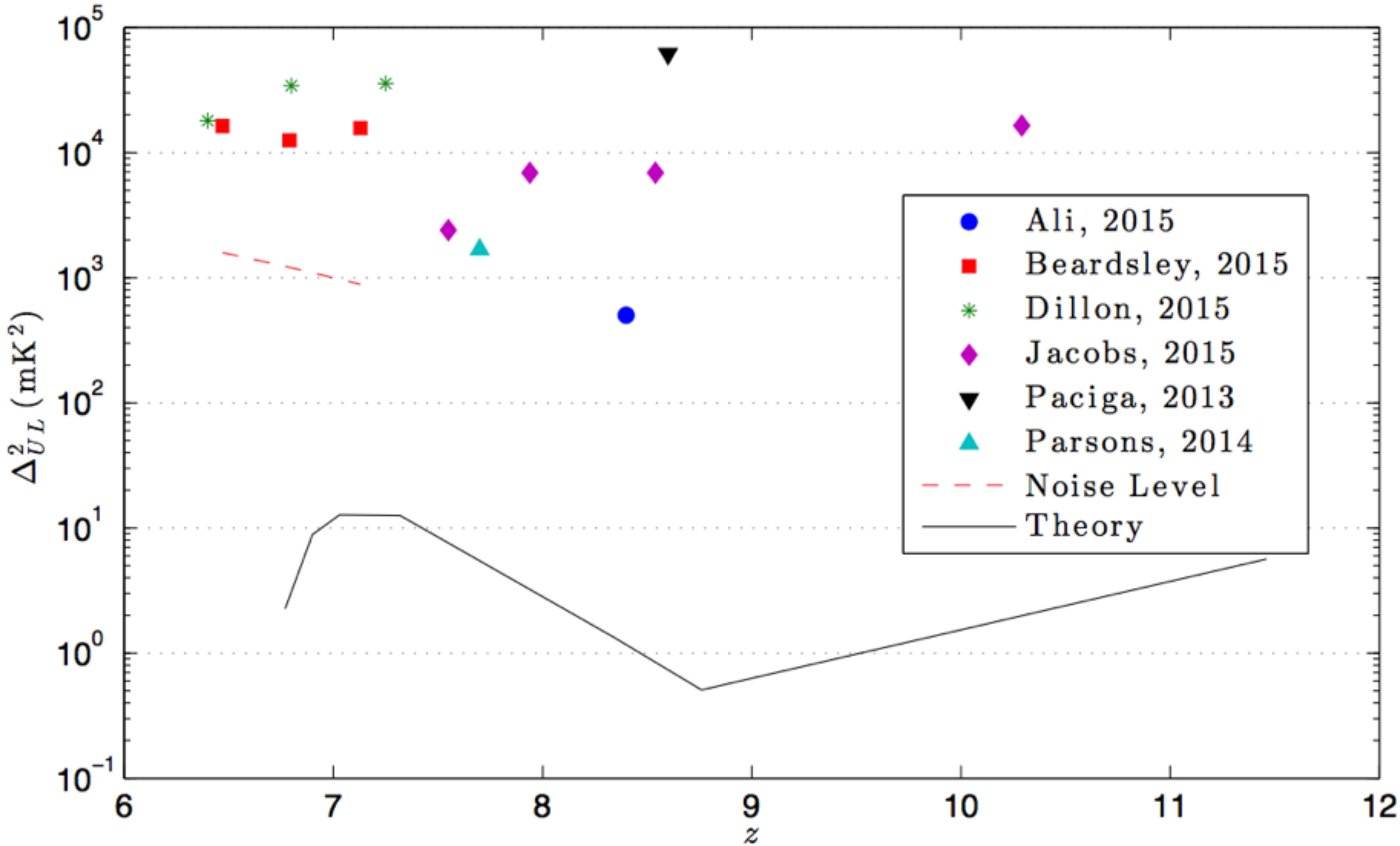
PAPER YEAR 2 RESULTS

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





Pober, **DCJ**, et al http://arxiv.org/abs/1503.00045



Beardsley 2015, thesis

http://loco.lab.asu.edu/danny_jacobs

HYDROGEN EPOCH OF REIONIZATION ARRAY

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

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

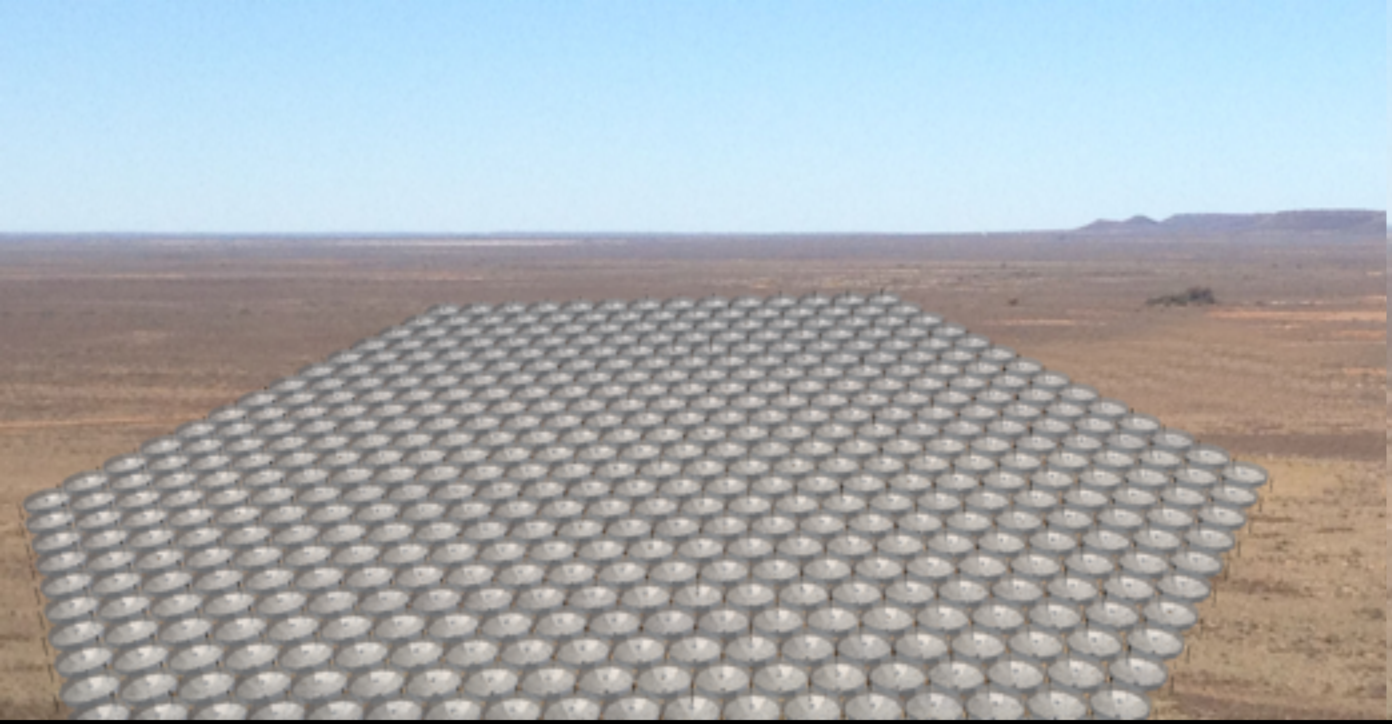
Hewitt (MIT-Kavli) Tegmark (MIT) Jacobs (ASU)

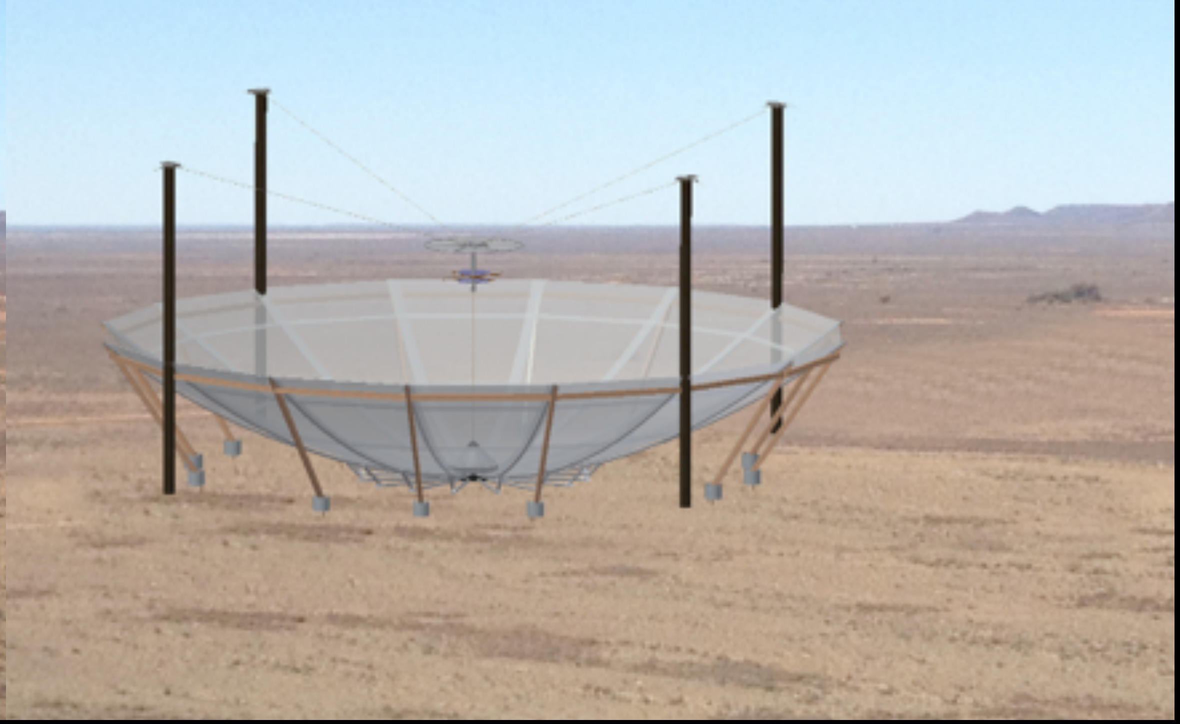
Carilli (NRAO\Cavendish) Bernardi (SKA -SA)

REIONIZATION.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





HYDROGEN EPOCH OF REIONIZATION ARRAY

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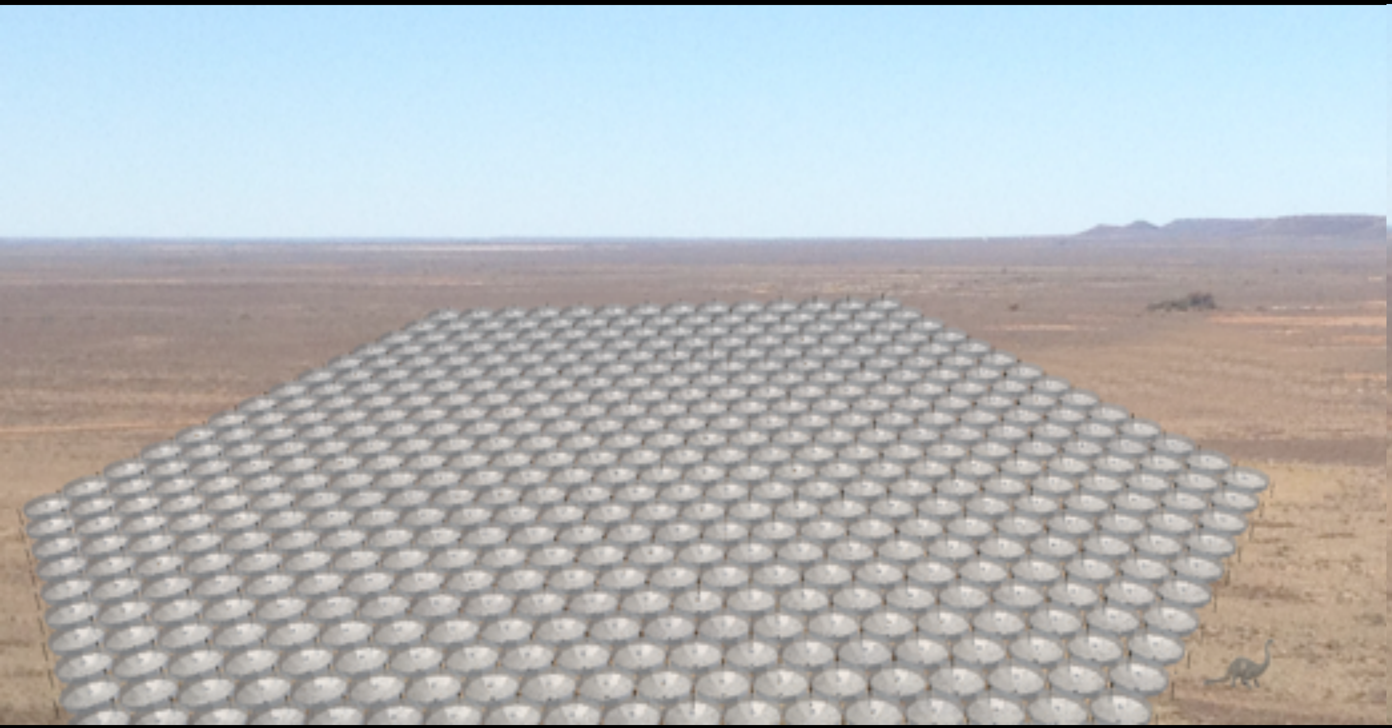
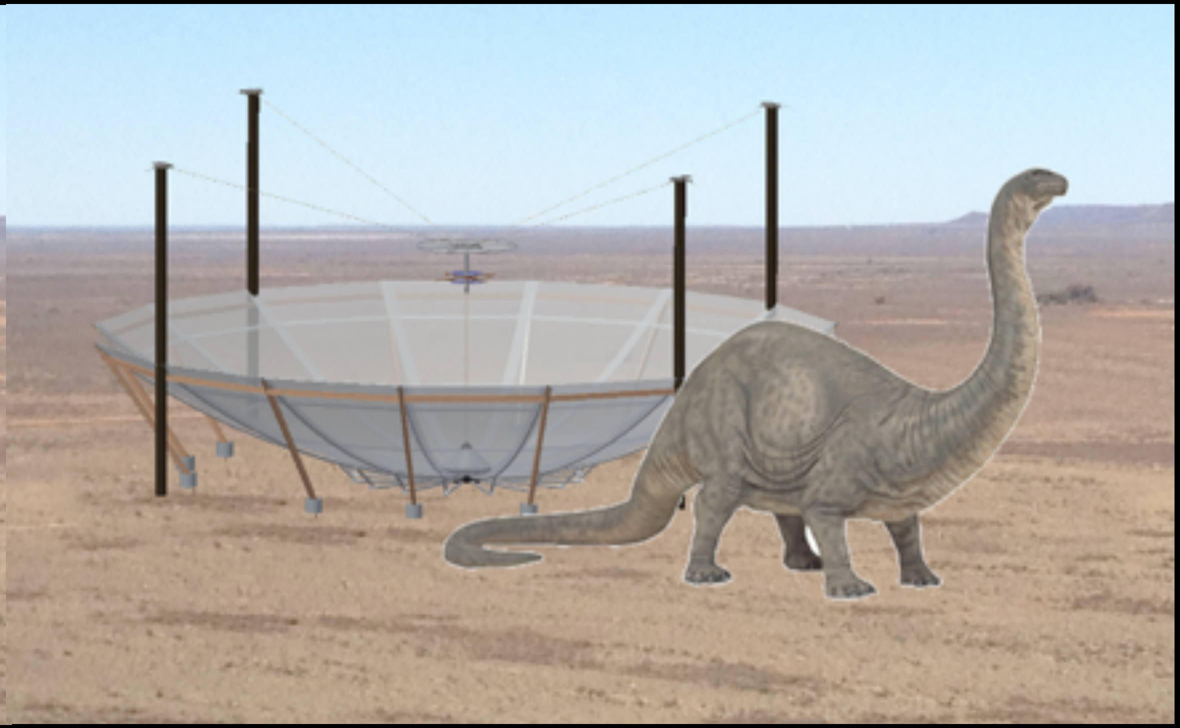


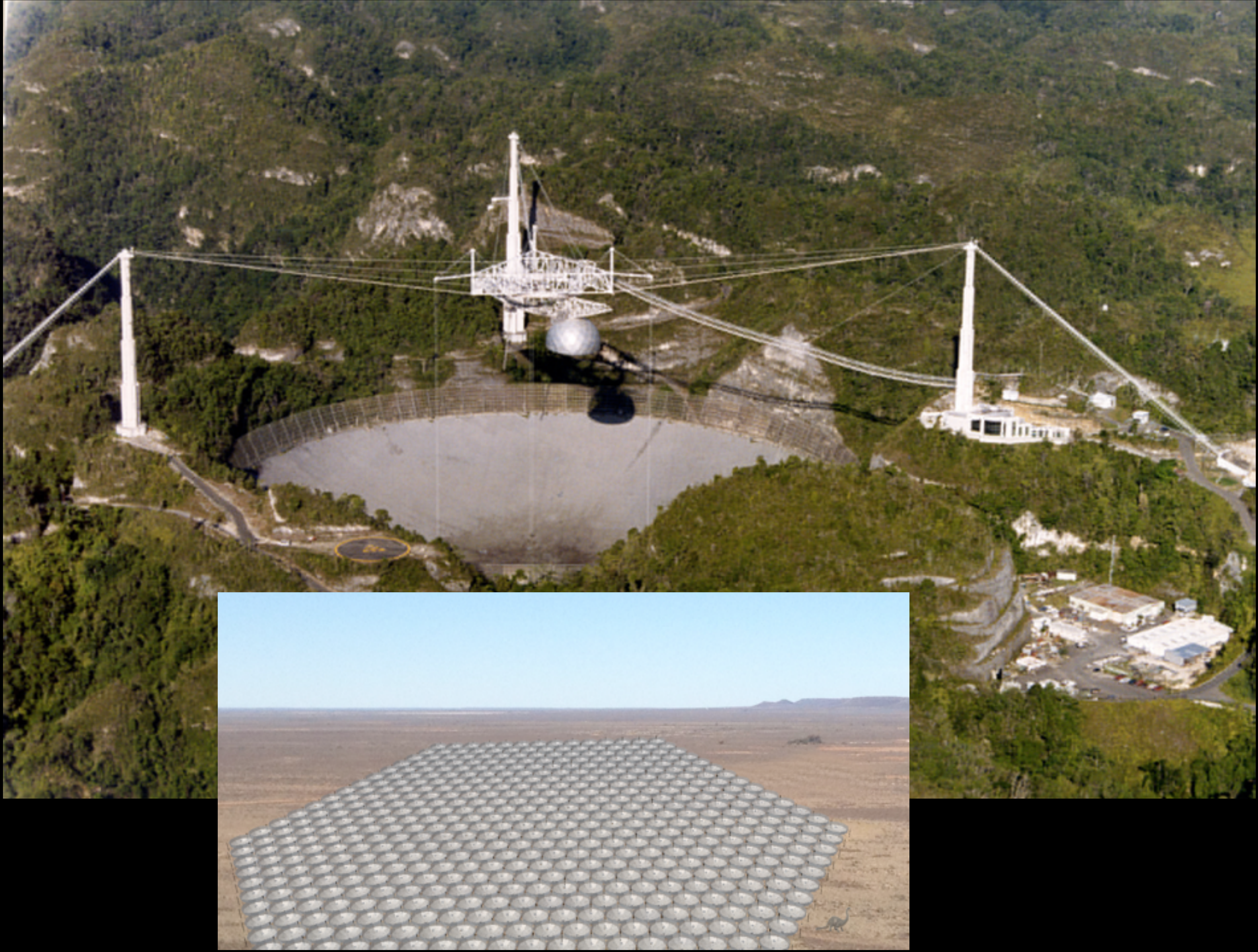


UCLA

NRAO

Penn

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI



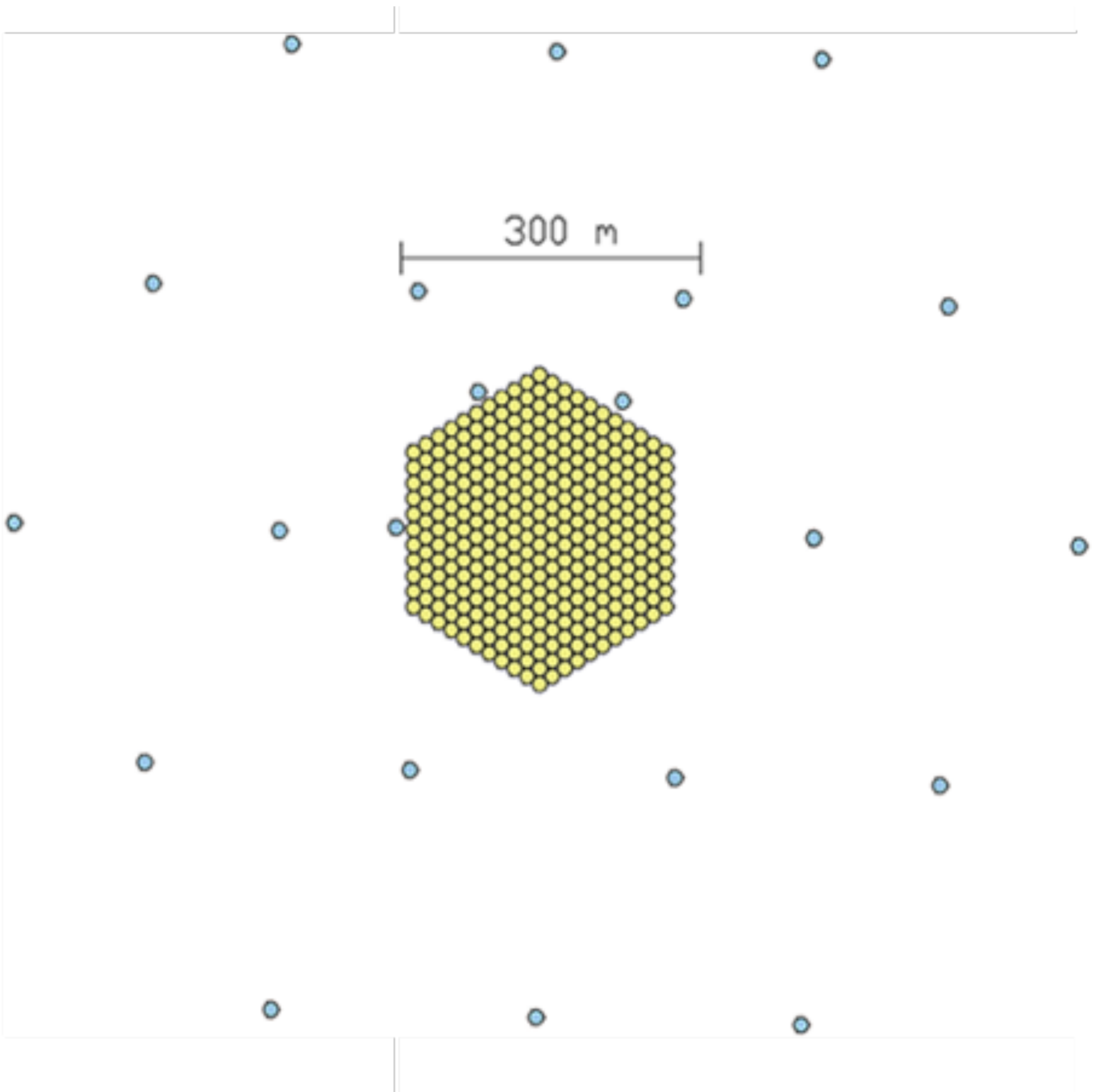
*scale approximate

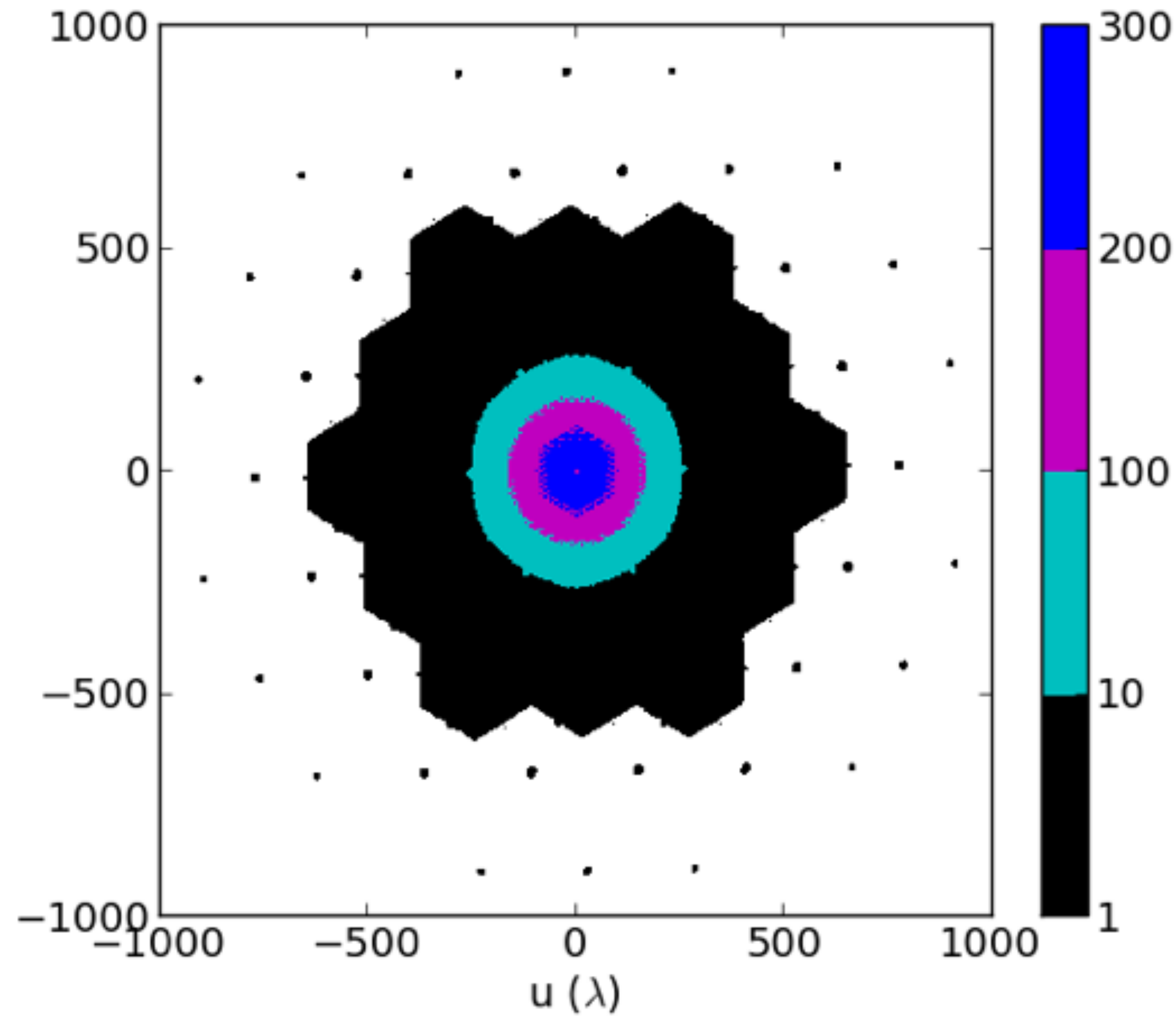
Next Gen Reionization Sensitivity

	Avoidance		Subtraction	
Instrument	Drift	Track	Drift	Track
PAPER 128	1.56	—	4.46	—
MWA 128	0.66	0.86	2.50	3.15
LOFAR	0.70	1.90	7.48	12.22

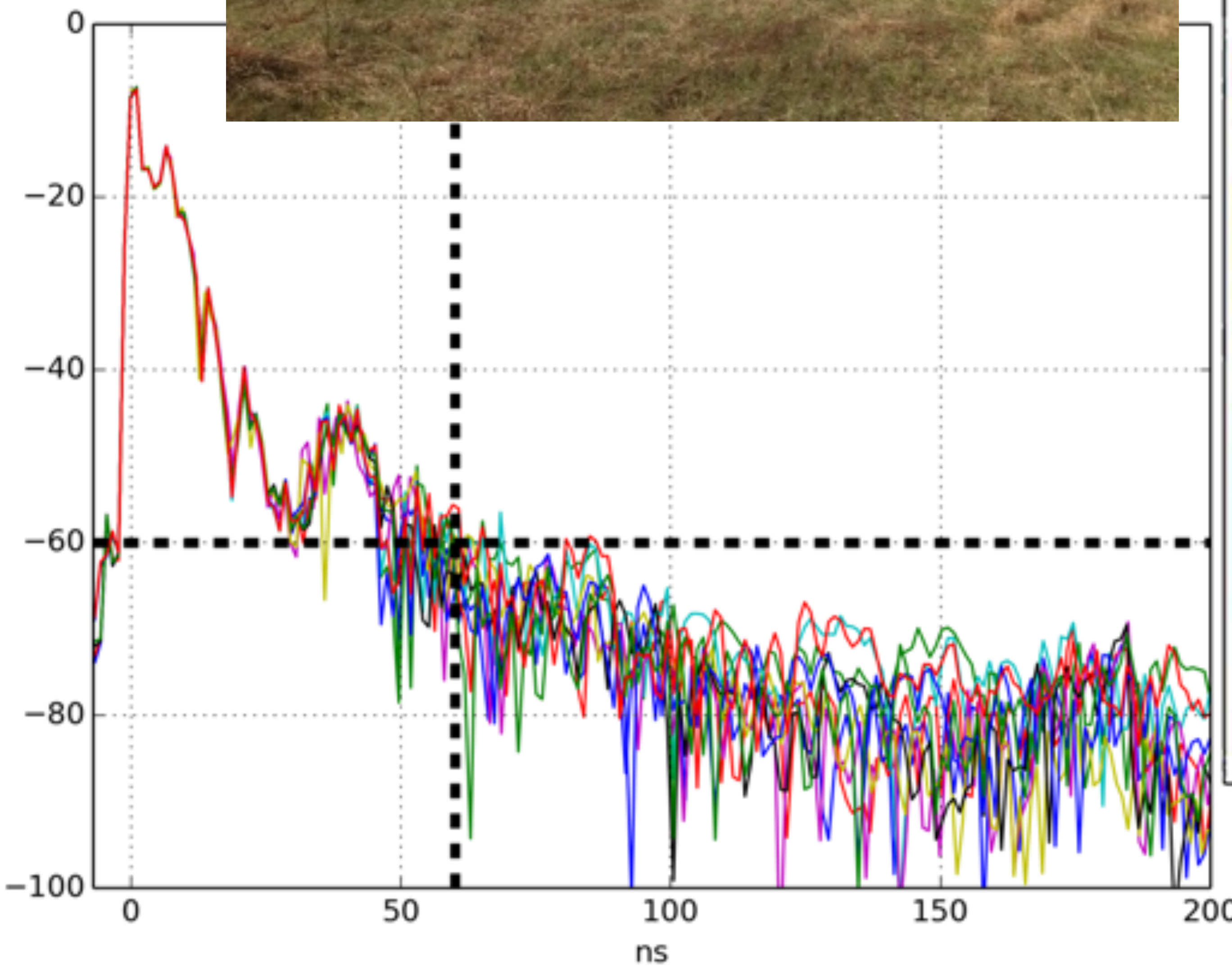
HERA Memo #4, J. Pober (reionization.org/memos/)

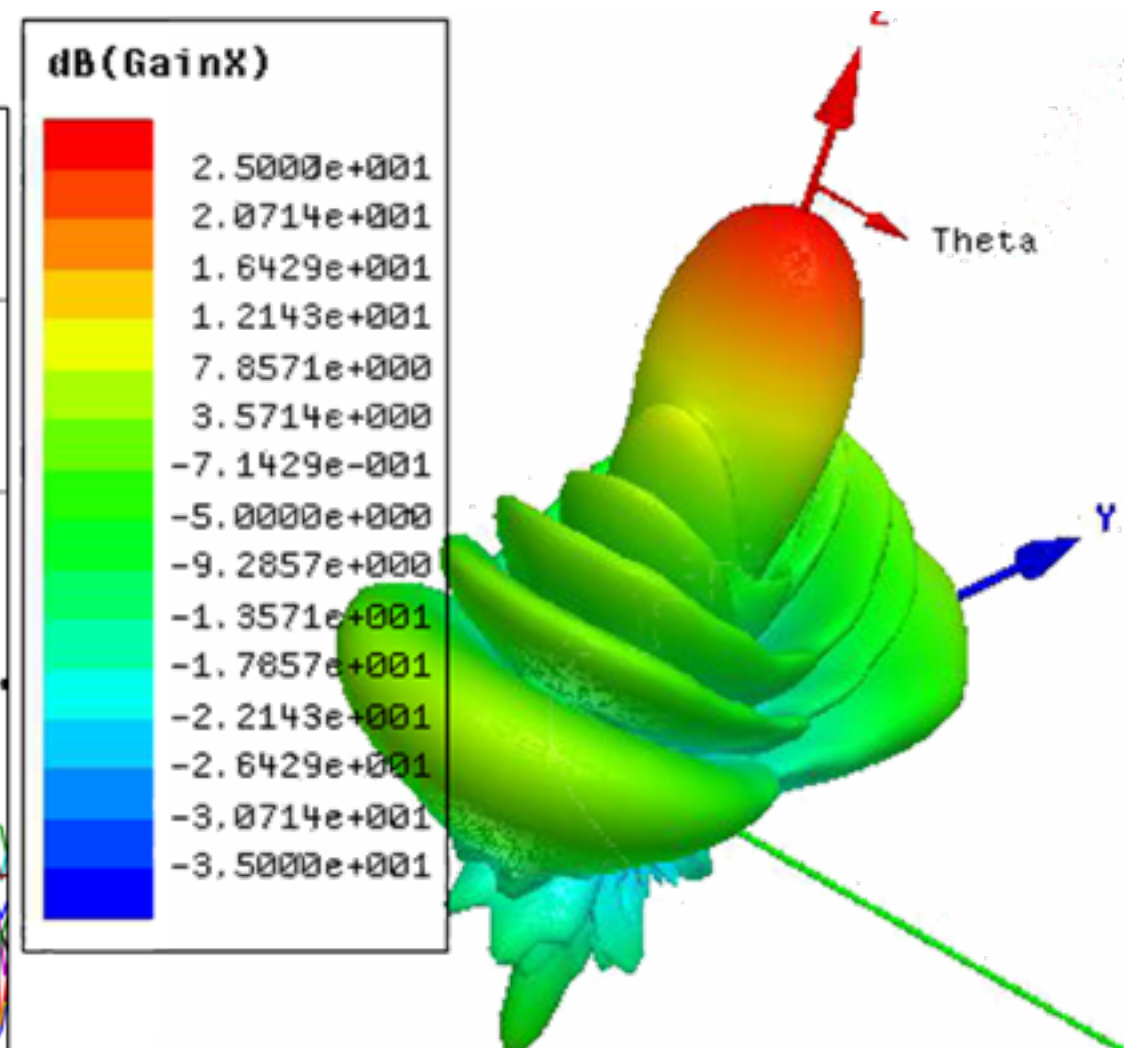
HERA uv coverage



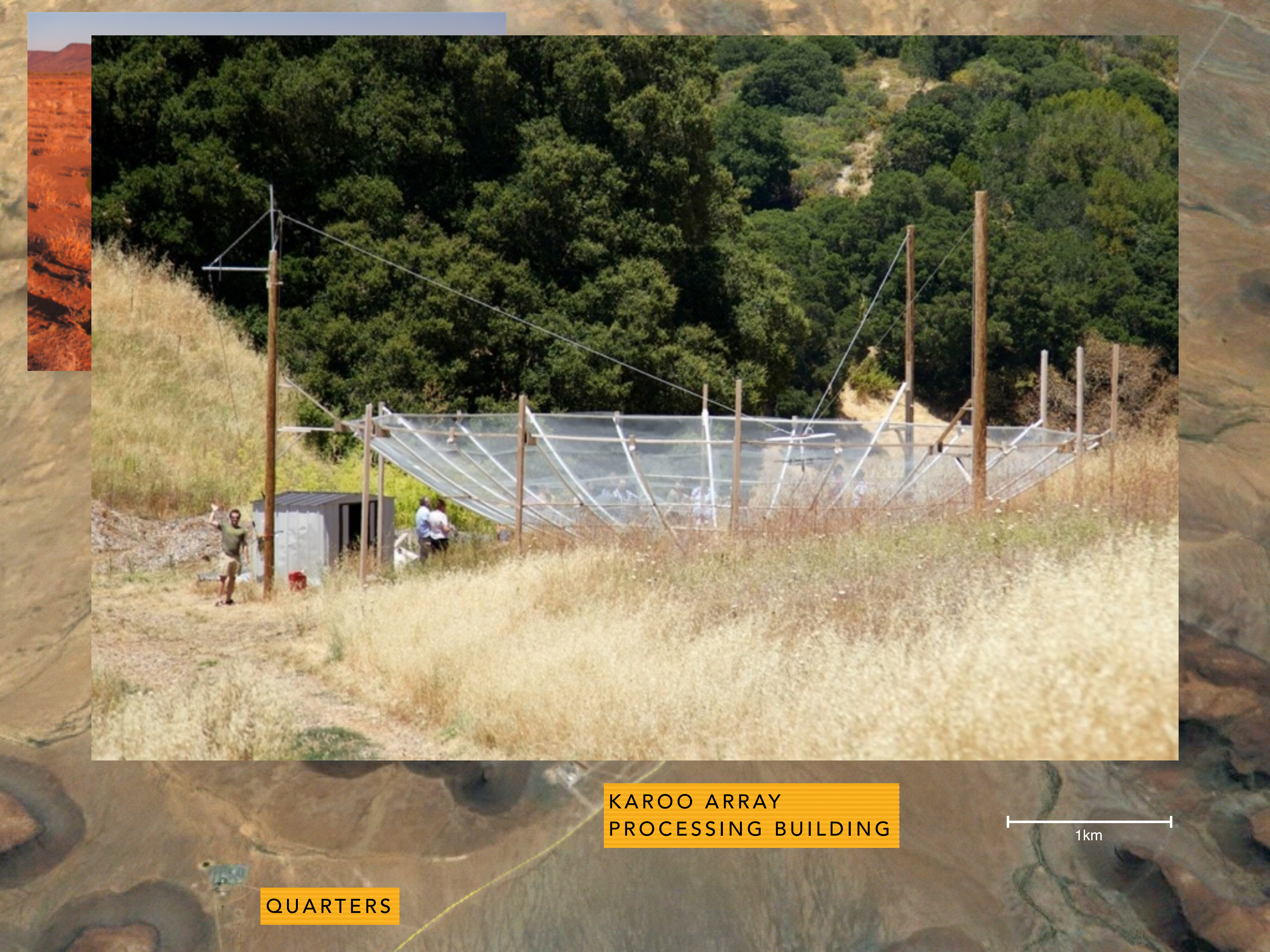


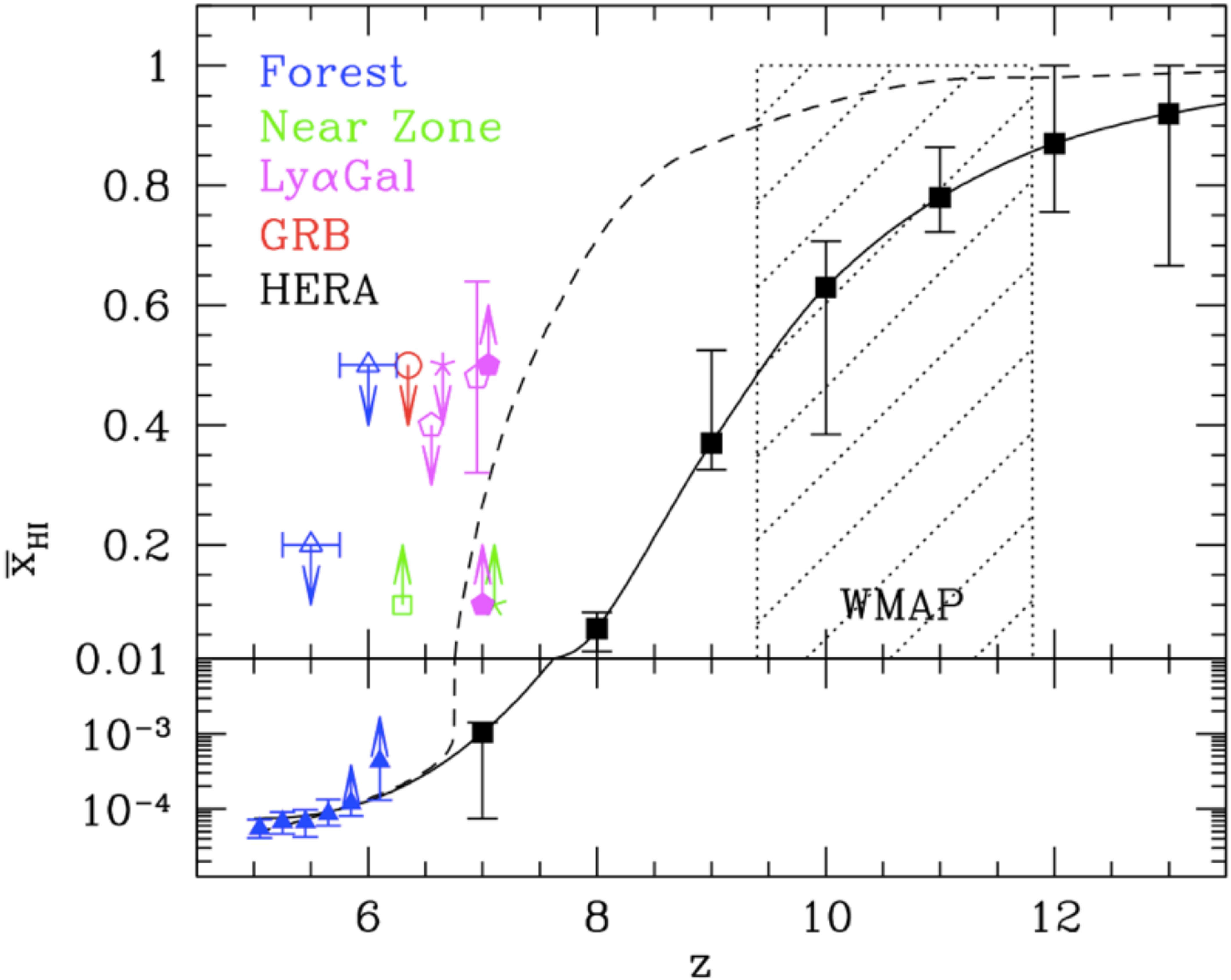
Danny Jacobs





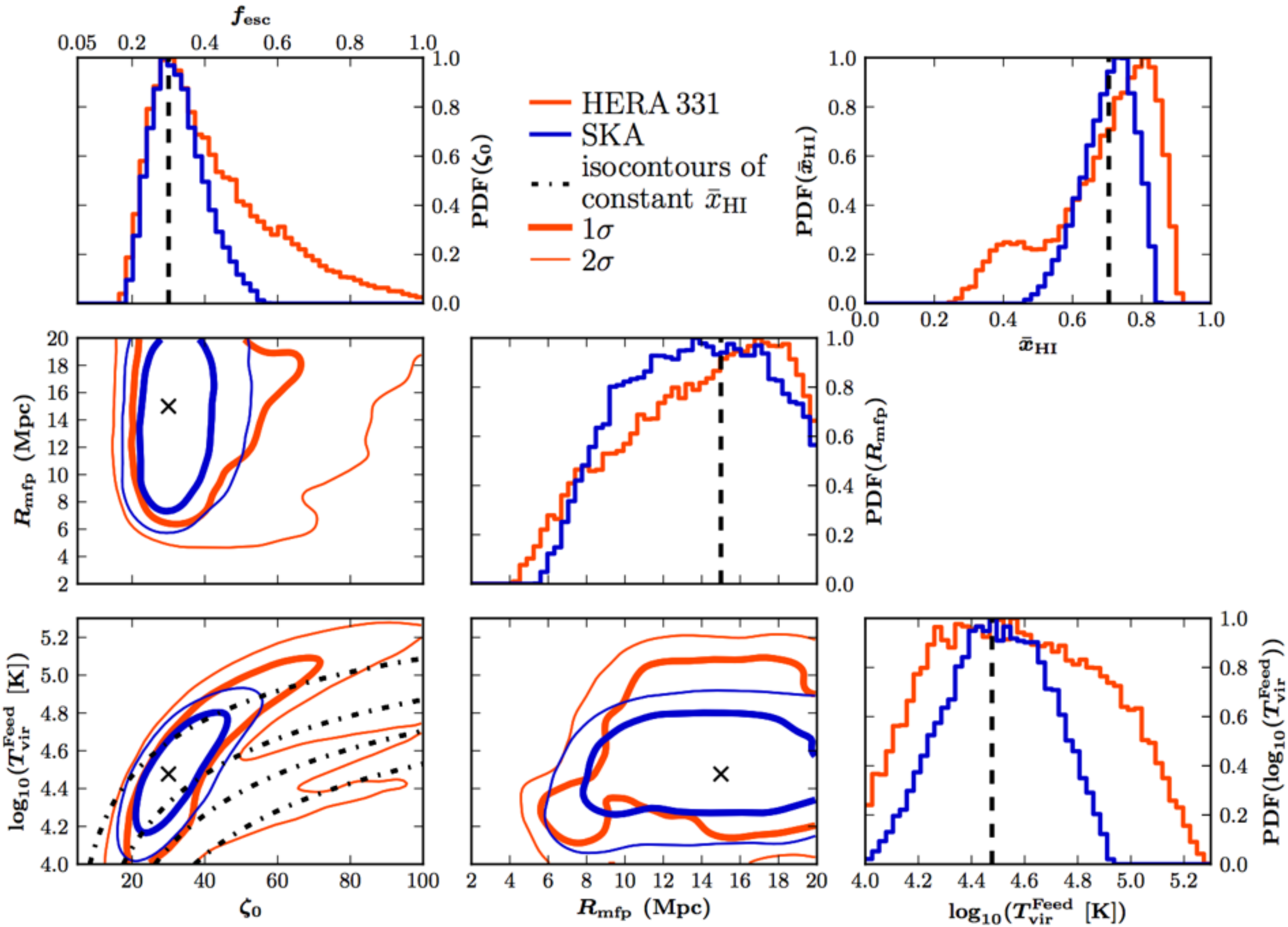
http://loco.lab.asu.edu/danny_jacobs


KAROO ARRAY
PROCESSING BUILDING
QUARTERS
1km

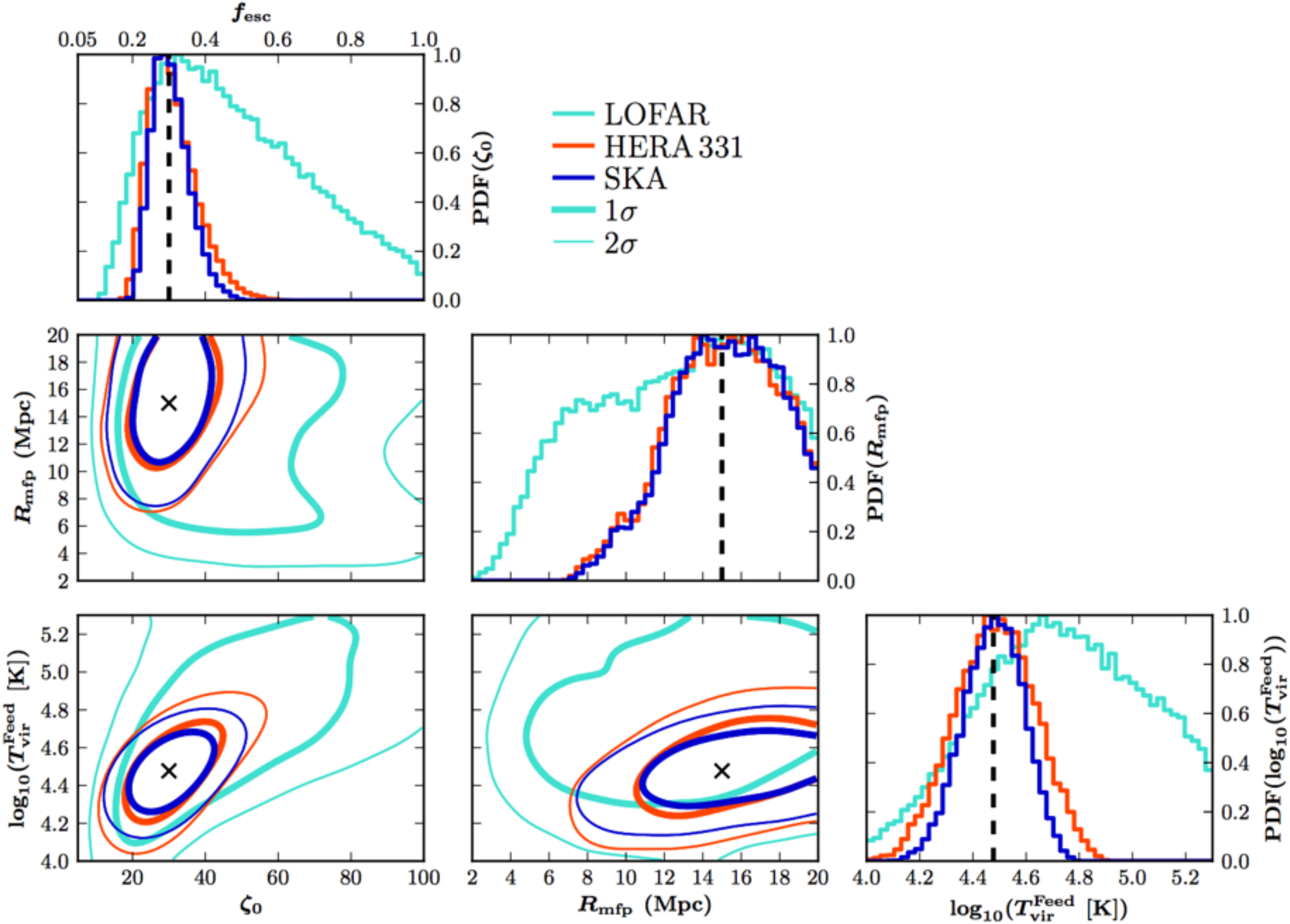


Forest
Near Zone
LyαGal
GRB
HERA
WMAP
1
0.8
0.6
0.4
0.2
0.01
10^{-3}
10^{-4}
$\overline{x}_{HI}$
6
8
10
12
z

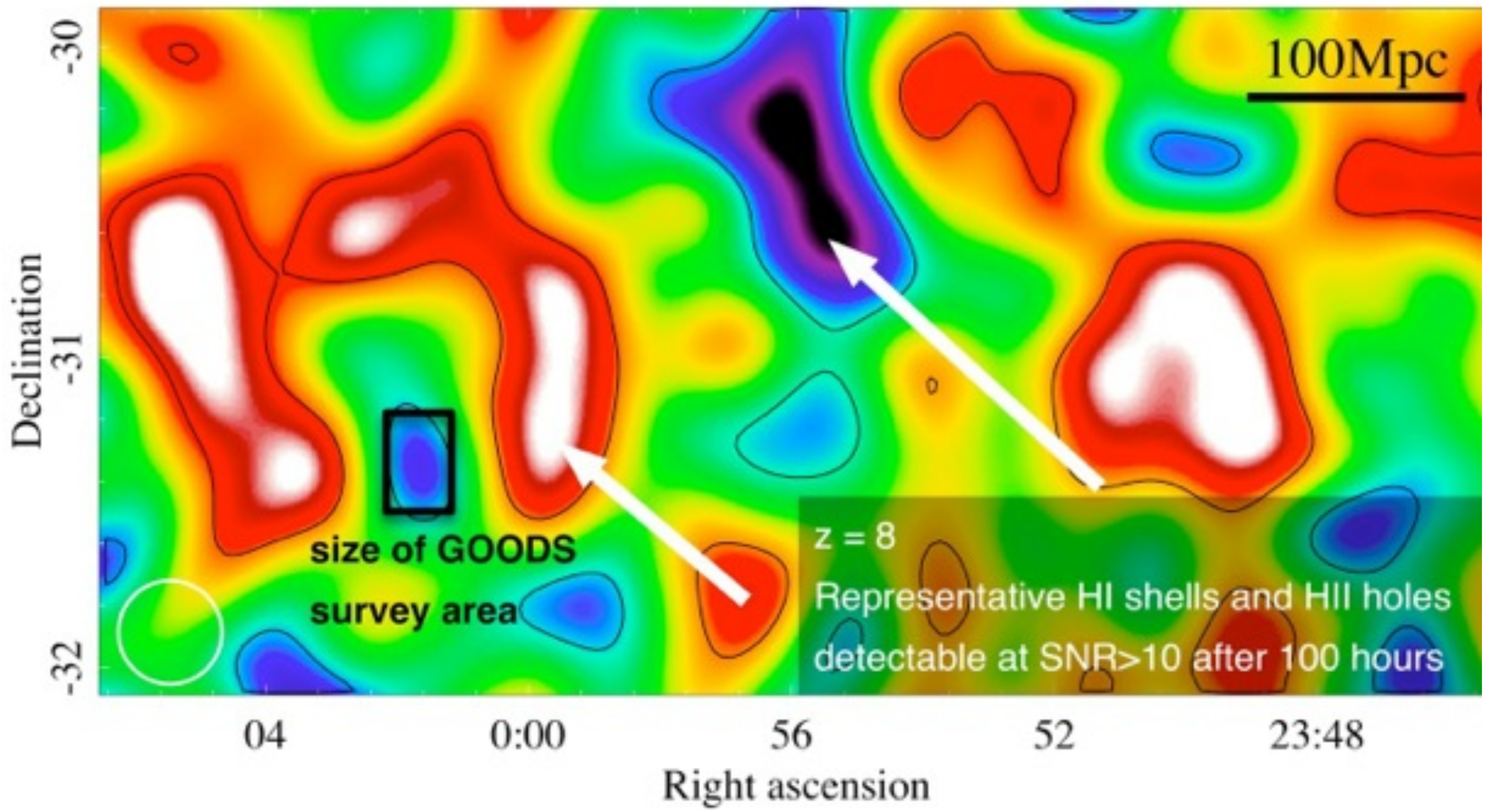
ht



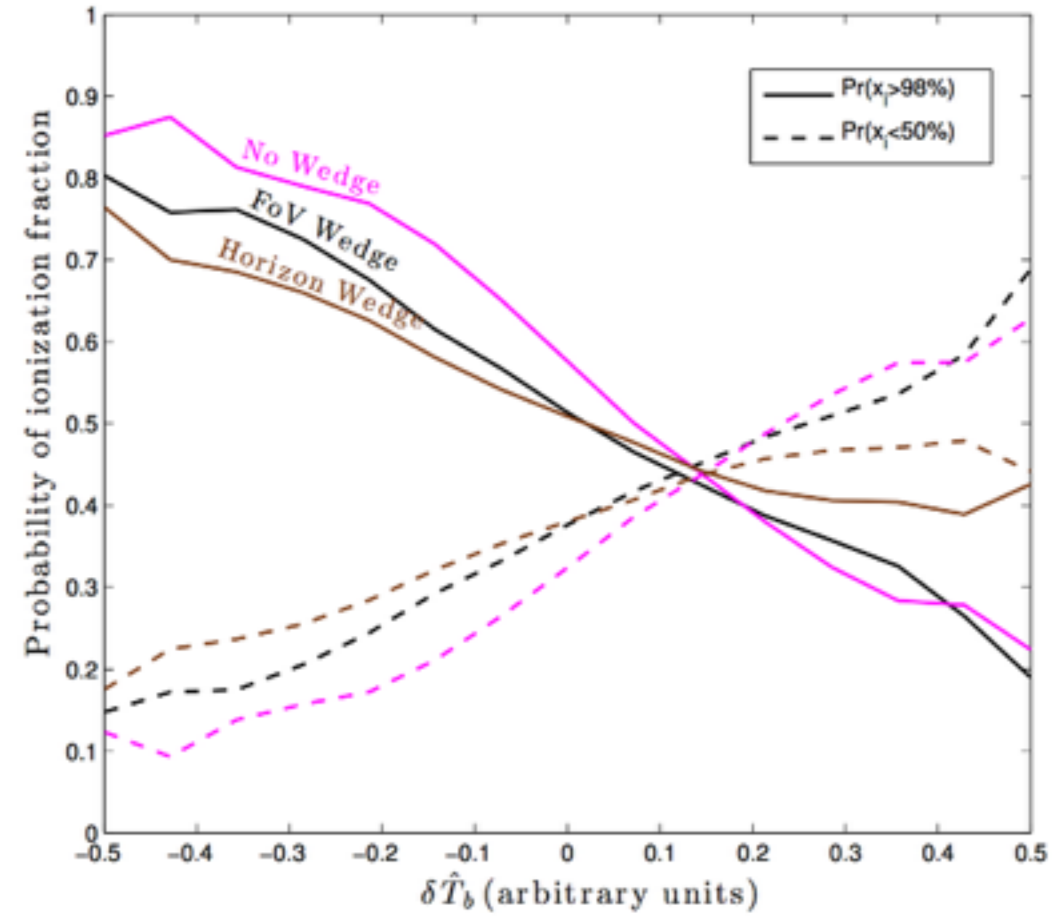
Grieg and Mesinger, MNRAS 2015, arXiv:1501.06576



Grieg and Mesinger, MNRAS 2015, arXiv:1501.06576

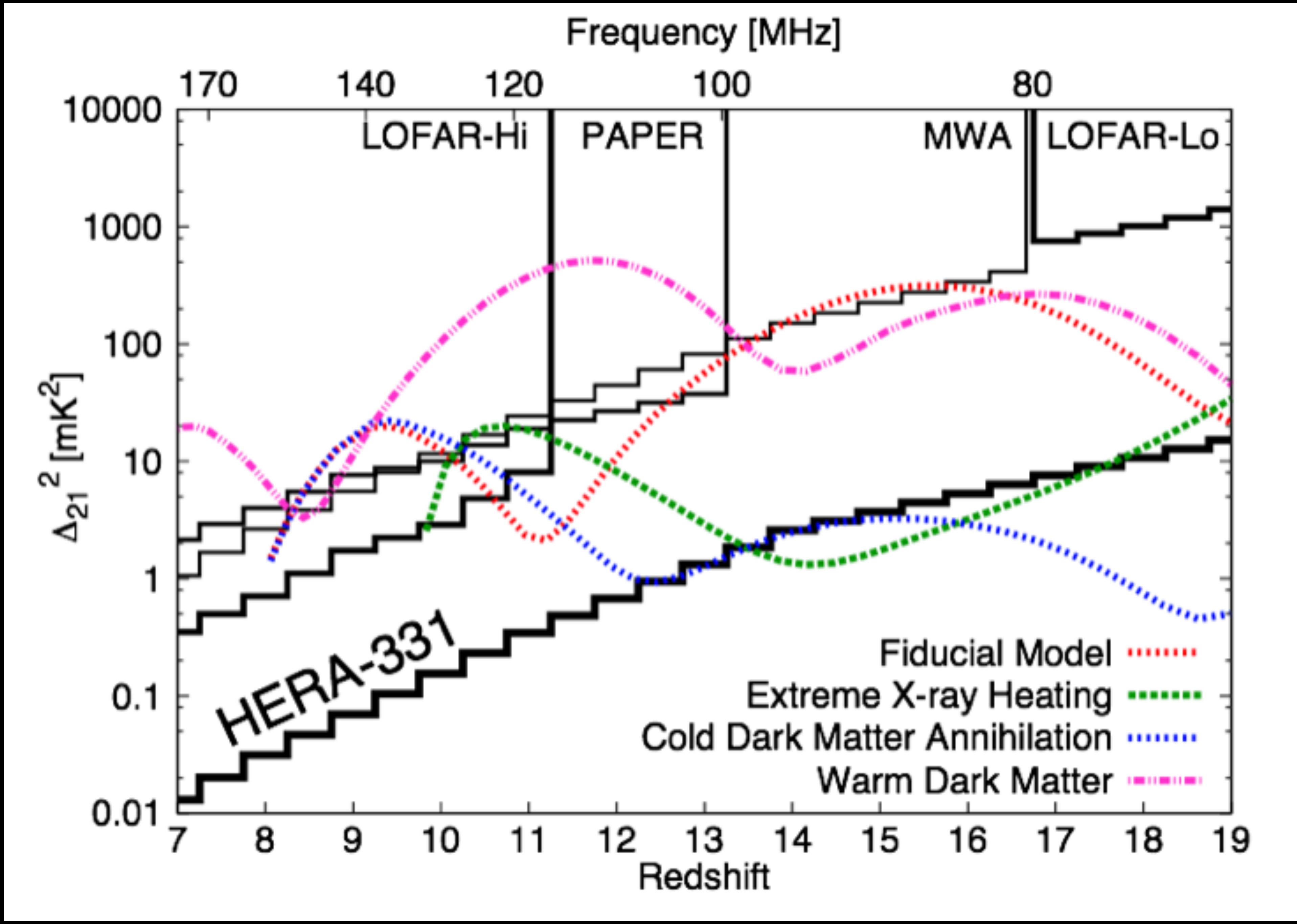


HERA memo #0, D. Jacobs, reionization.org/memos/



Beardsley et al, ApJ 2015

EPOCH OF XRAYINATION



Summary

- Reionization and the Dark Ages are the last unexplored parts of the cosmological timeline. Significant focus of both Cosmology and Astronomy fields. Difficult with traditional methods/objects.

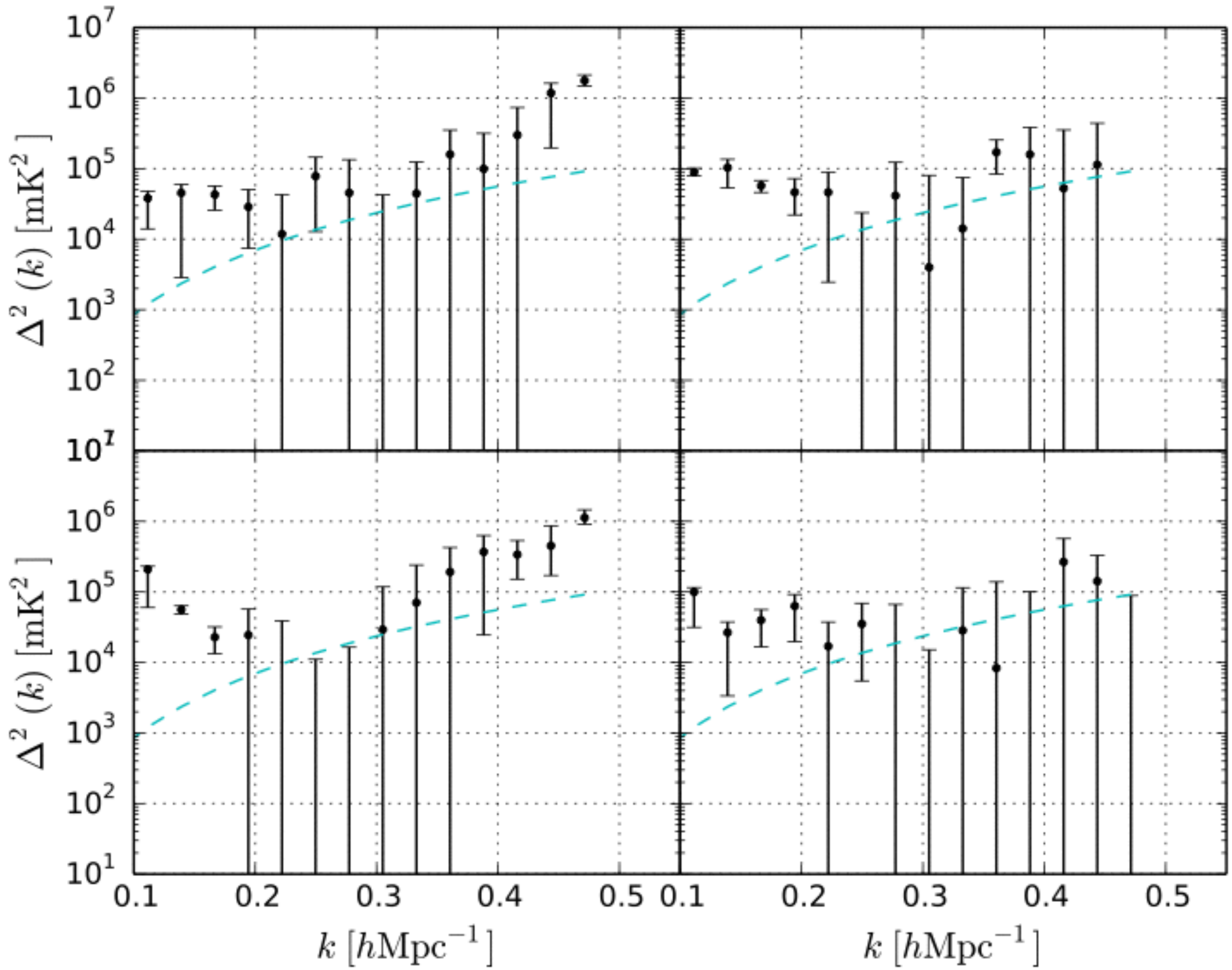
- 21cm can probe both regions. Made possible by modern electronics & computing

- MWA and PAPER (2005-2016) observing now. Already constraining pathological models.

- HERA (2015-2020): will pin down reionization timeline, distinguish between plausible models, and provide first images

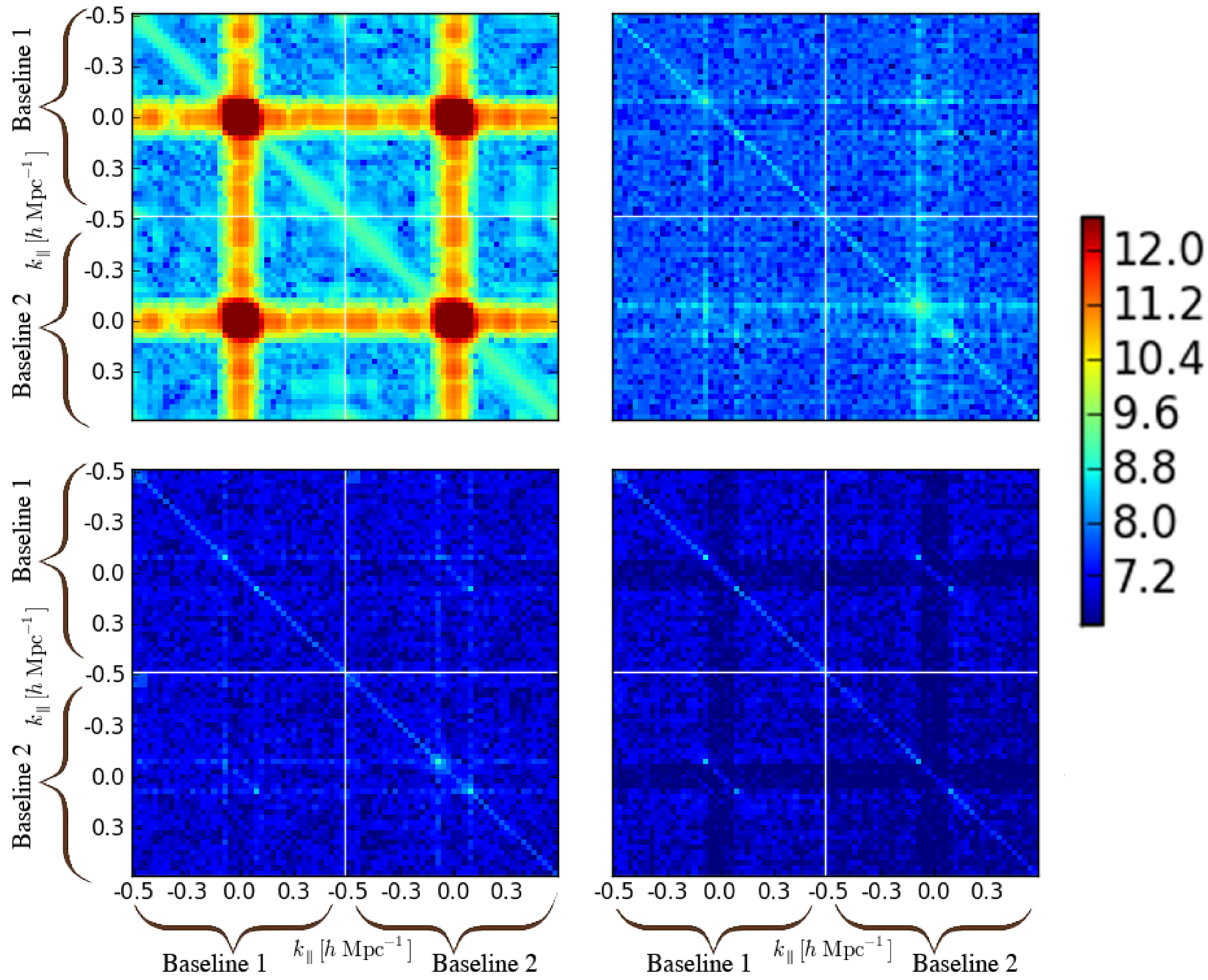
- SKA Low (2021+) full tomographic imaging to 10Mpc scales

Thank you!



http://loco.lab.asu.edu/danny_jacobs

Correlated stuff

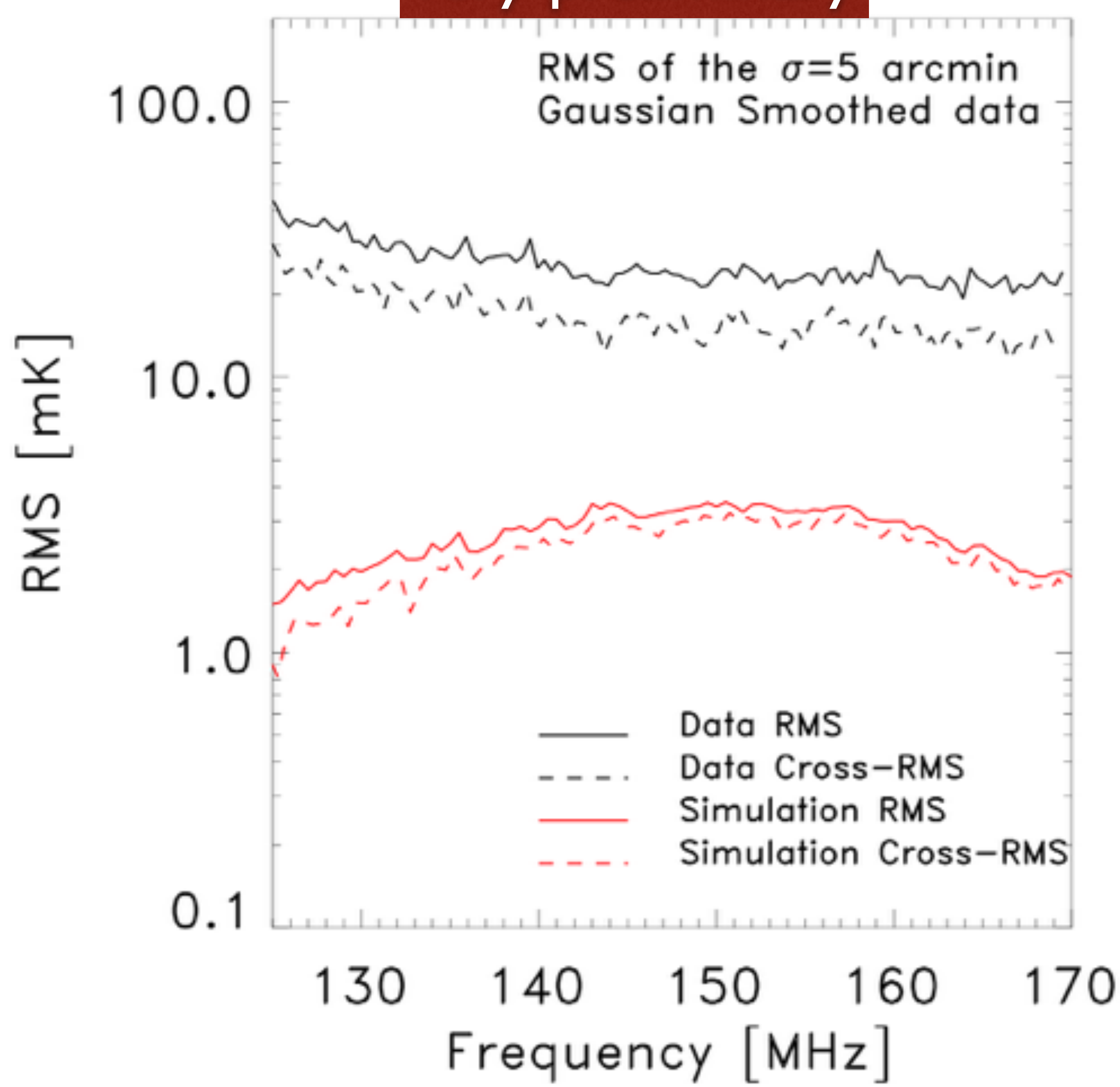


LOFAR status

- Best images have 10^6 dynamic range, 6arcsec resolution and 10s of uJy RMS (this is very very low)

- Currently working on:
  - Polarization leakage (in preps Jelic ea, Khan ea)
  - ionospheric effects (Vedanthan - arxiv: 1412:1420, Mevius)
  - effects of self-cal and imaging (Patil ea, Yattawatta ea)

very preliminary

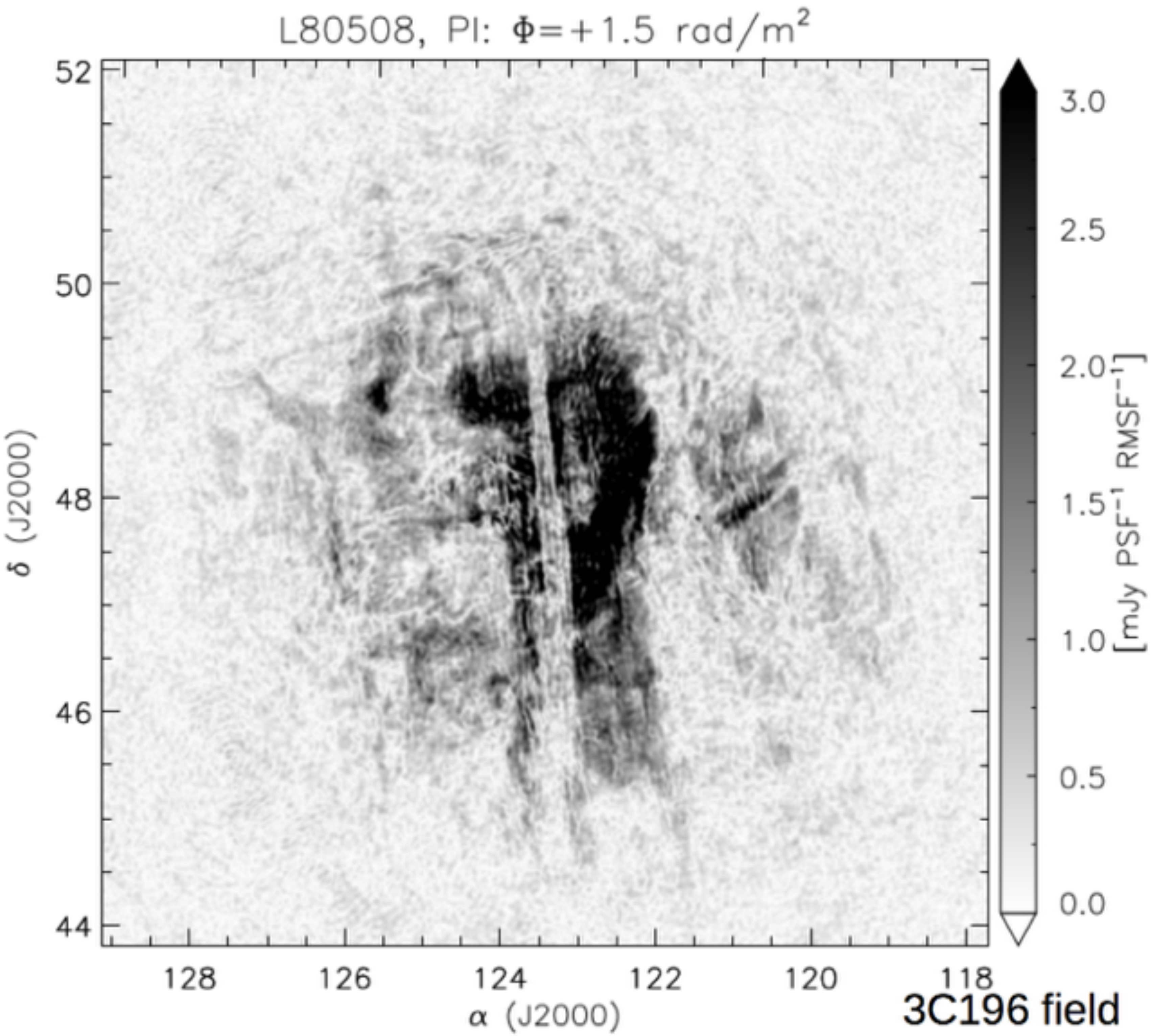


http://loco.lab.asu.edu/danny_jacobs

LOFAR Polarization Sneak preview

- 1-10K of polarized signal
- Mostly diffuse, low RM

Jelic et al (in prep)



3C196 field

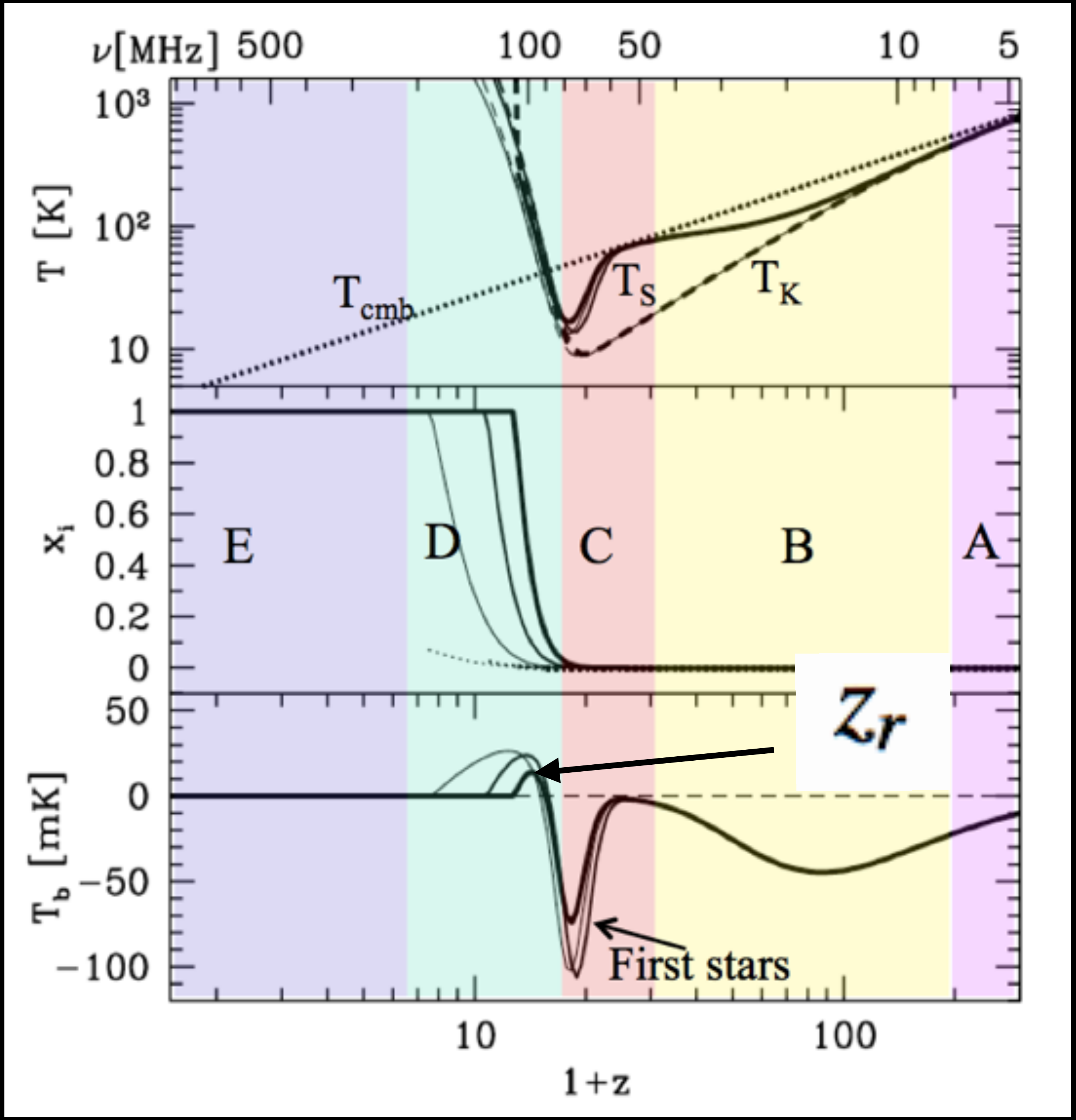
A. z>200: $T_{CMB} = T_K = T_S$ by residual e-, photon, and gas collisions. No signal.

B. z~30 to 200: gas cools as $T_k \approx (1+z)^2$ vs. $T_{CMB} \approx (1 + z)$, but $T_S = T_K$ via collisions => absorption, until density drops and $T_S \rightarrow T_{CMB}$

C. z~20 to 30: first stars => Lyα photons couples T_K and T_S => 21-cm absorption

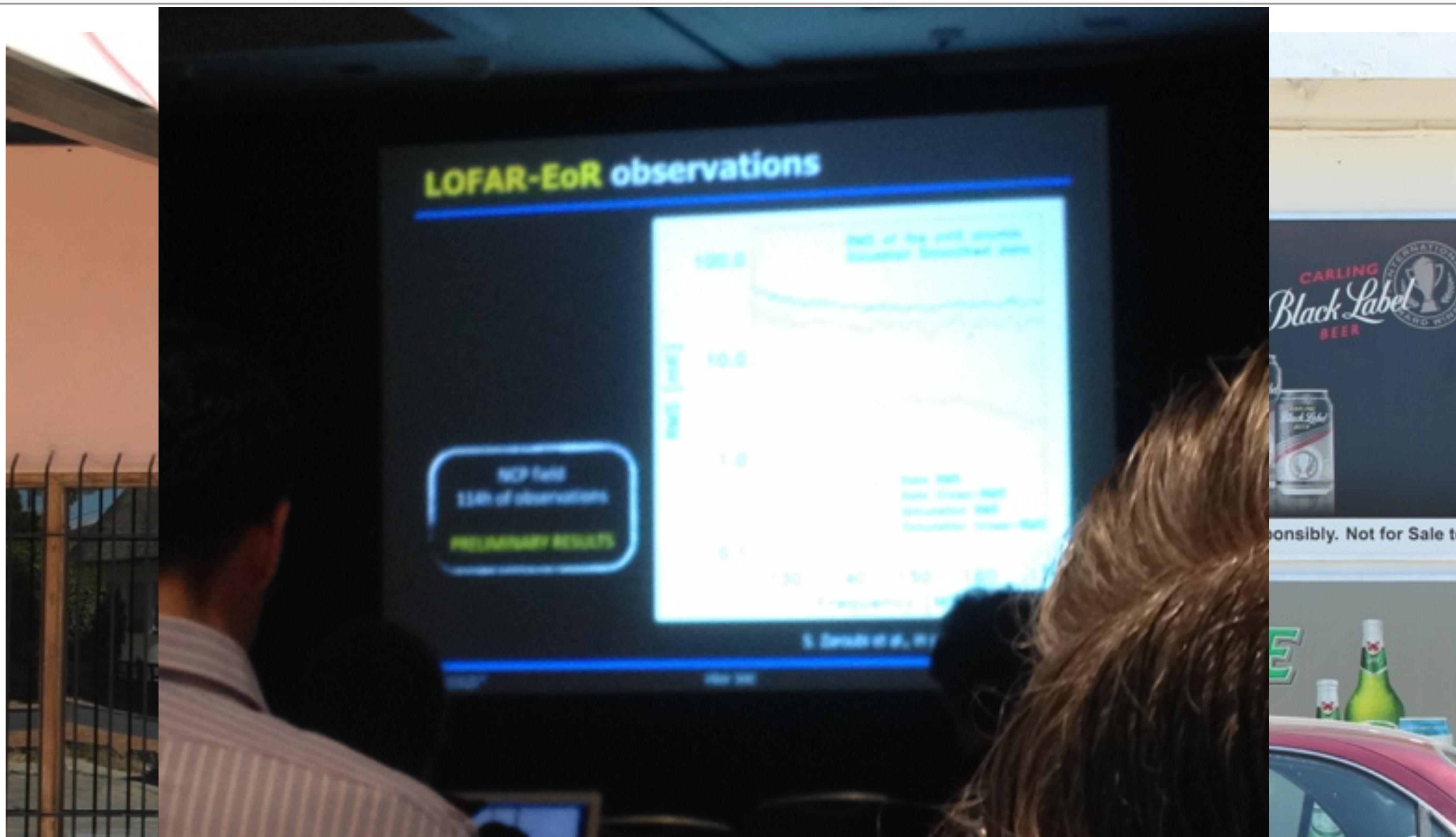
D. z~6 to 20: IGM warmed by hard X rays => $T_K > T_{CMB}$. T_S coupled to T_K by Lya. Reionization is proceeding => bubble dominated

E. IGM reionized



after a similar slide by carilli

LOFAR Update

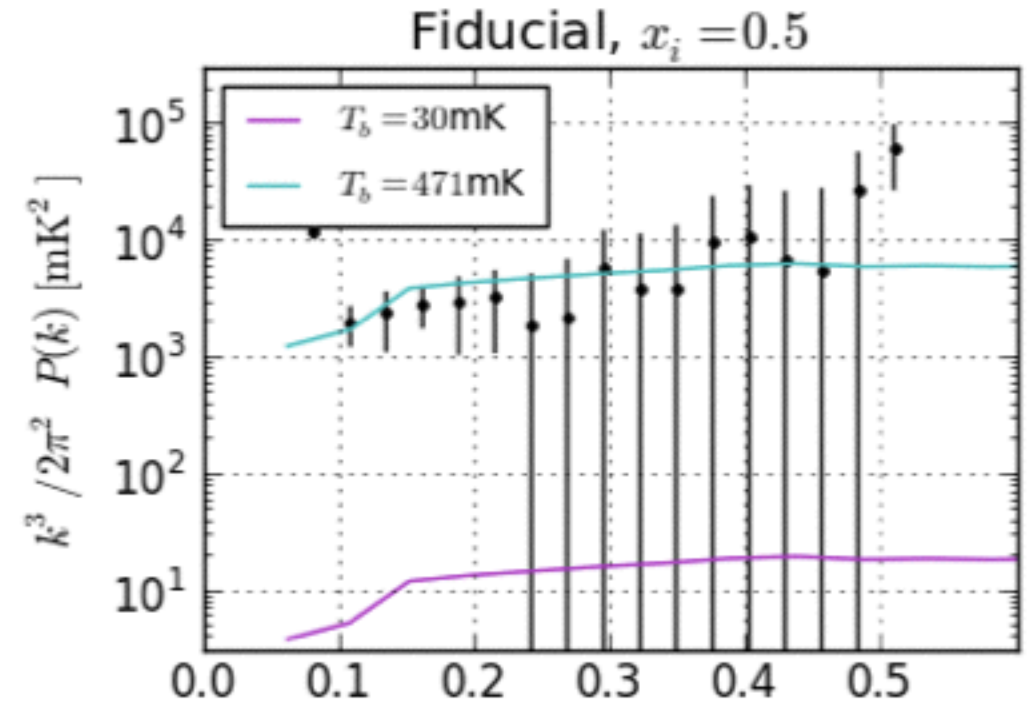


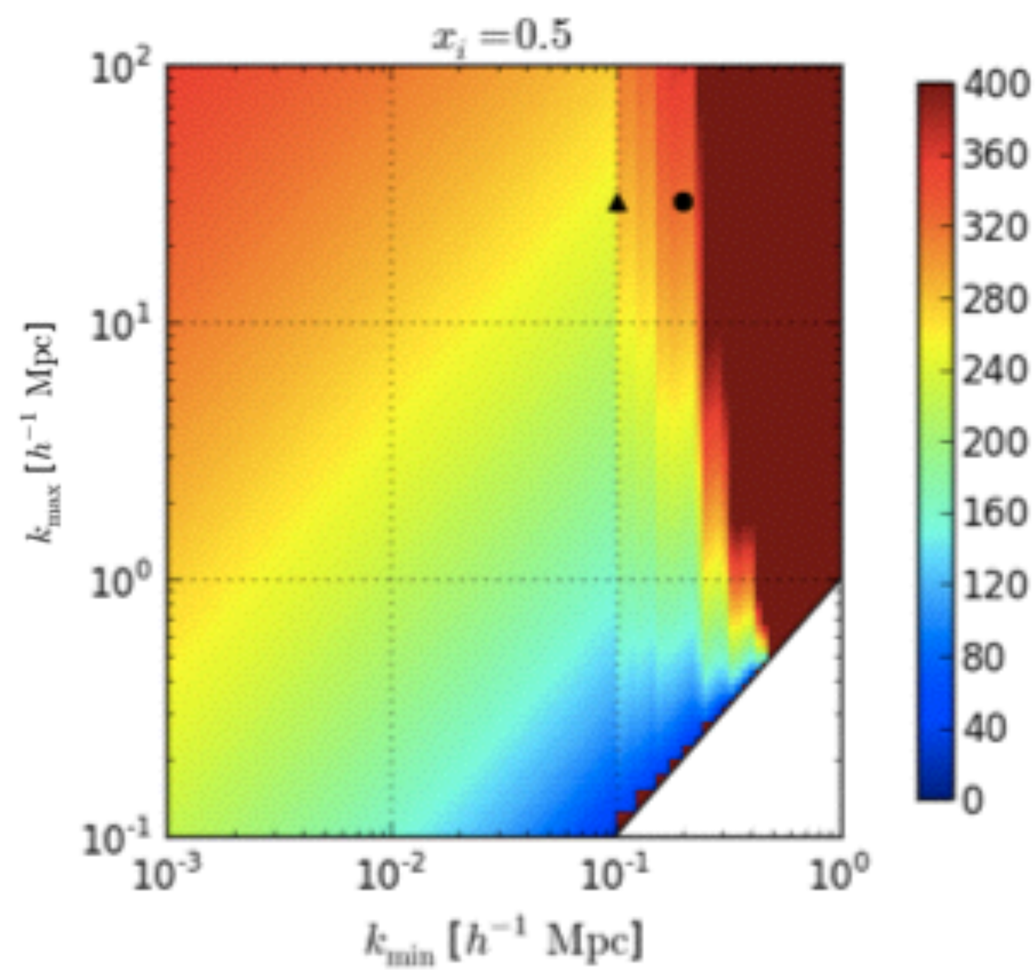
Variance Statistic: Patil 2014 arxiv:1401.4172
Noise limited at 6hrs: Yatawatta A&A 550 136
Foreground methods: Chapman et al 2012 MNRAS, 2013 MNRAS

Actual Science

- Gas must be heated to within 400K of the CMB. (As determined by the lowest lowest k bins)

- If the power spectrum is "peaky". It must be even much hotter still.





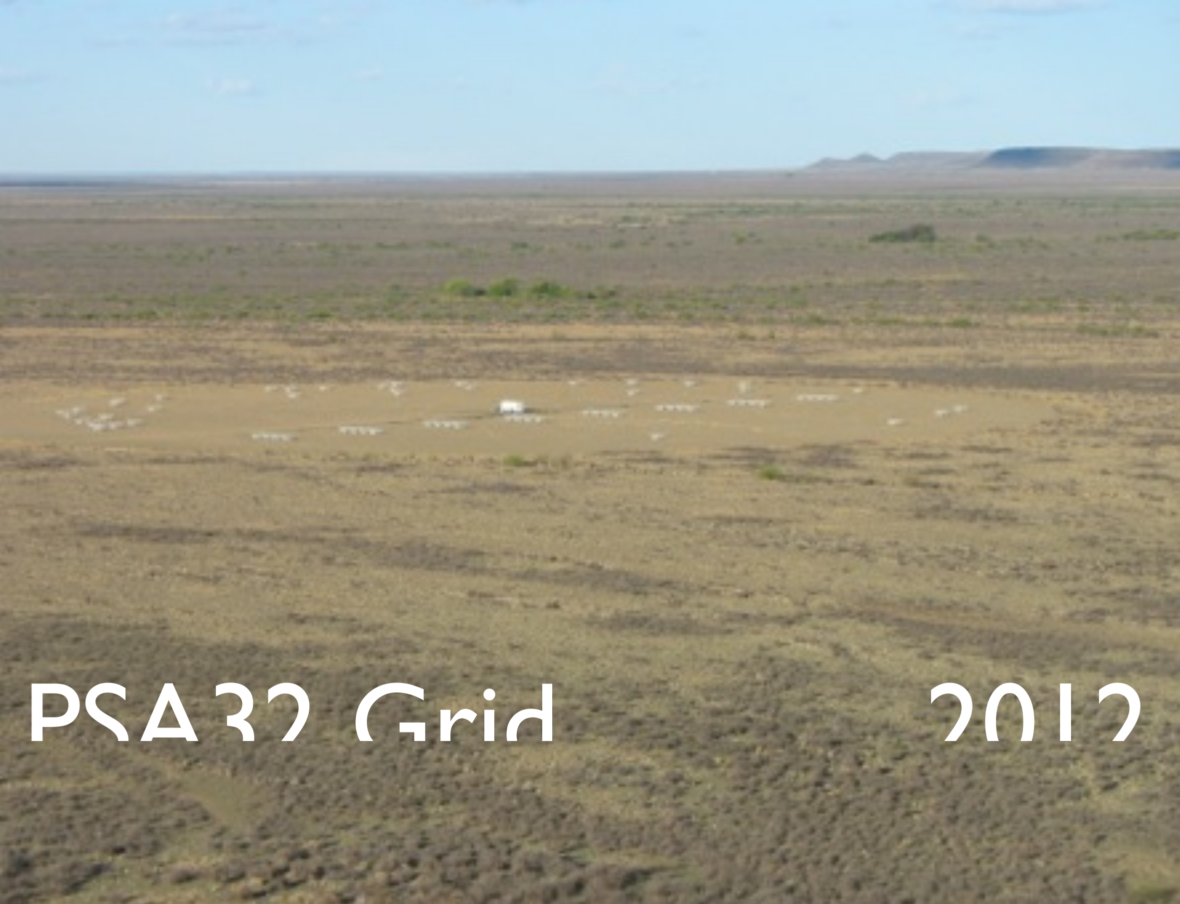
PAPER Construction

The Karoo Array Telescope is hosting PAPER at its site


PSA16
2009


SSC


SSC
SK


PSA32 Grid
2012


PSA64
2011