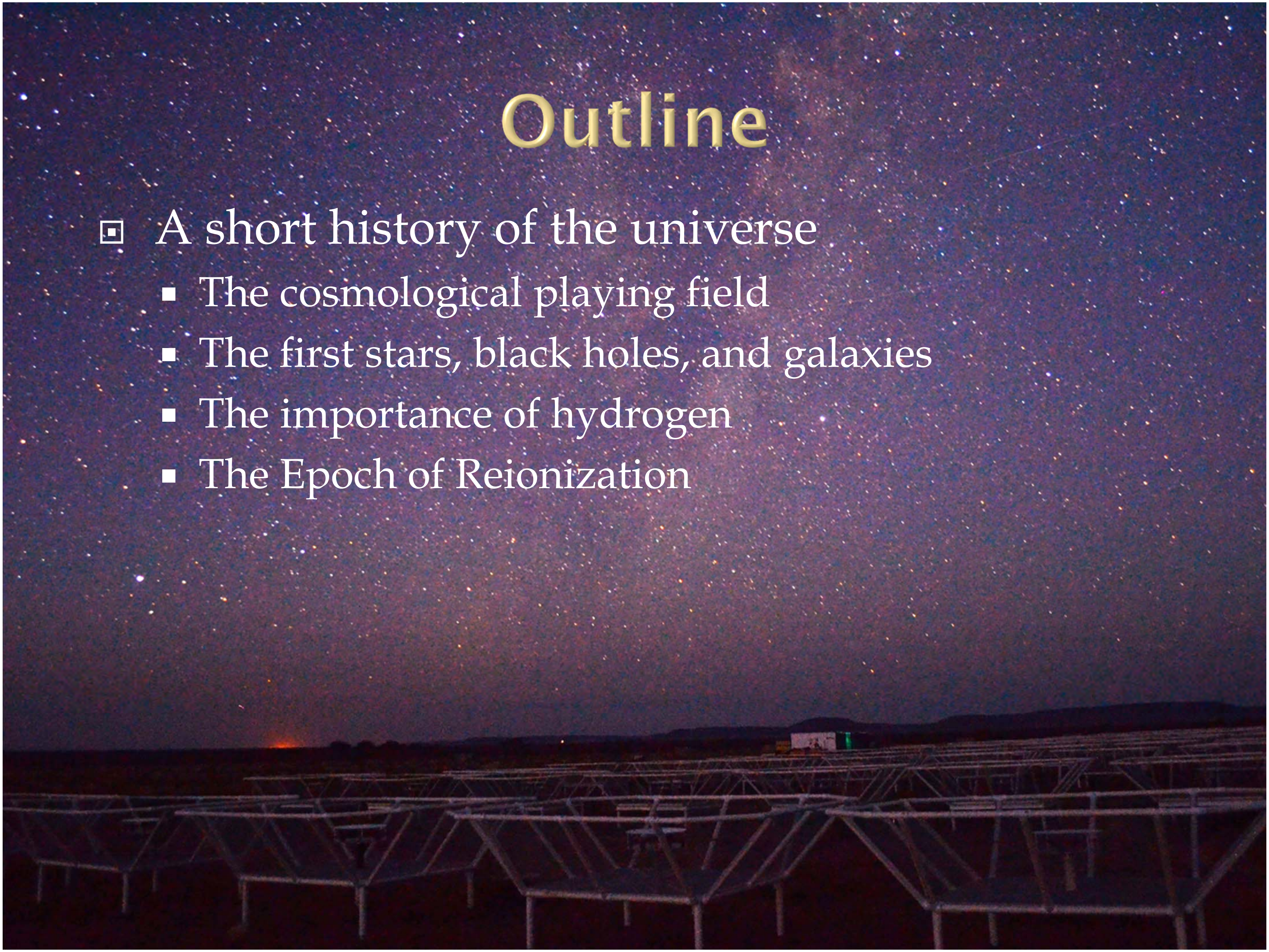
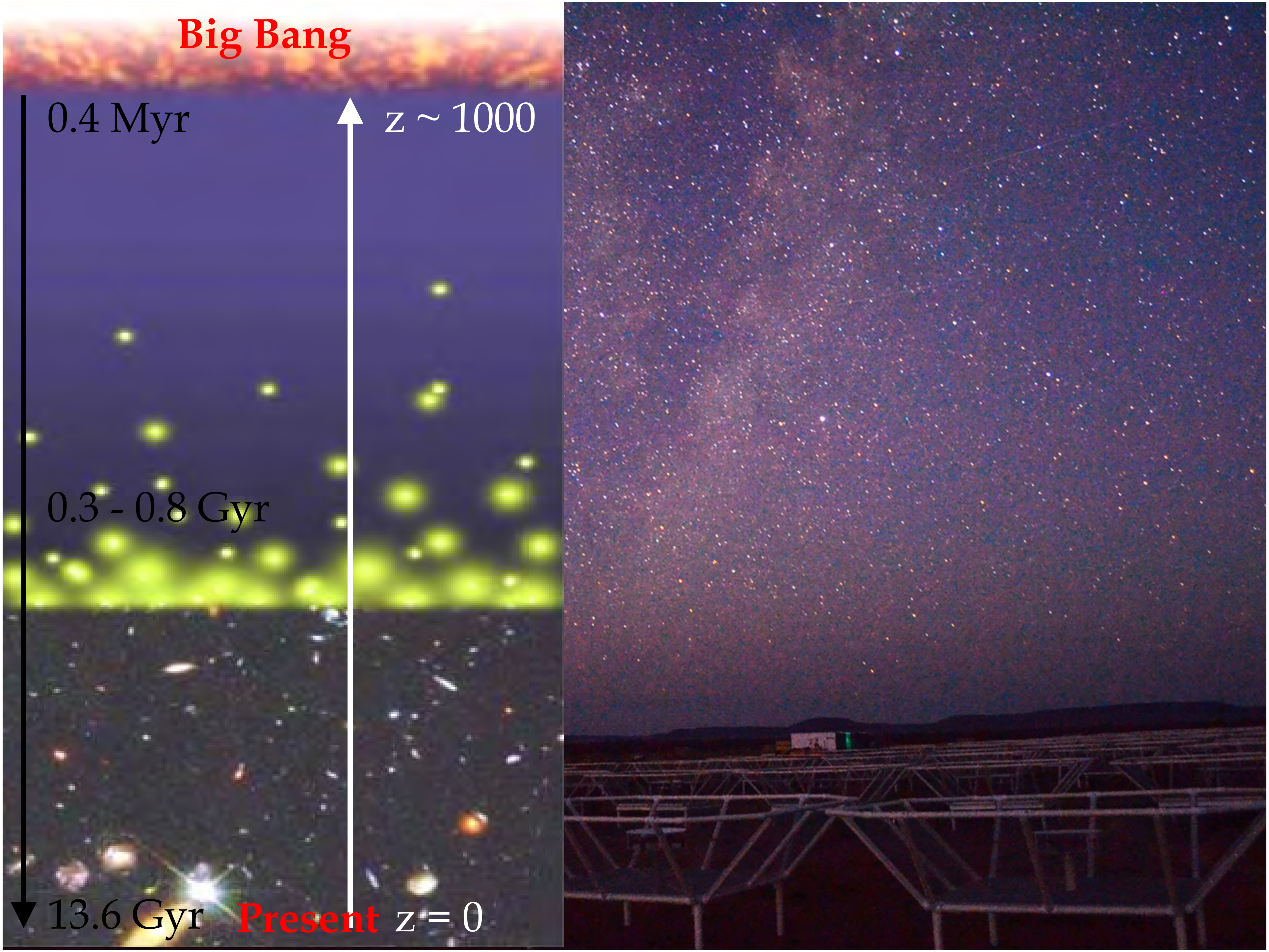
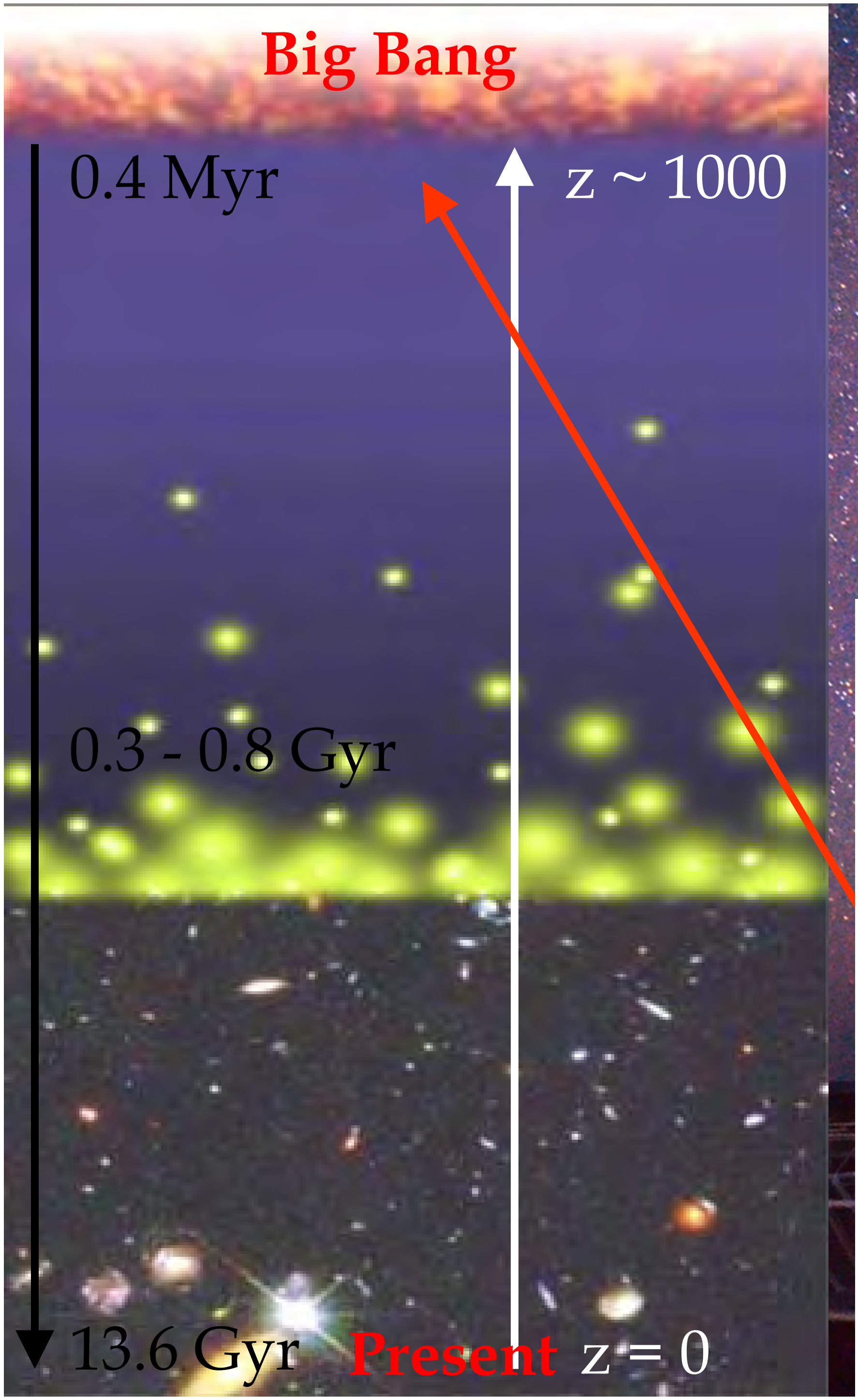


Outline

- A short history of the universe
  - The cosmological playing field
  - The first stars, black holes, and galaxies
  - The importance of hydrogen
  - The Epoch of Reionization

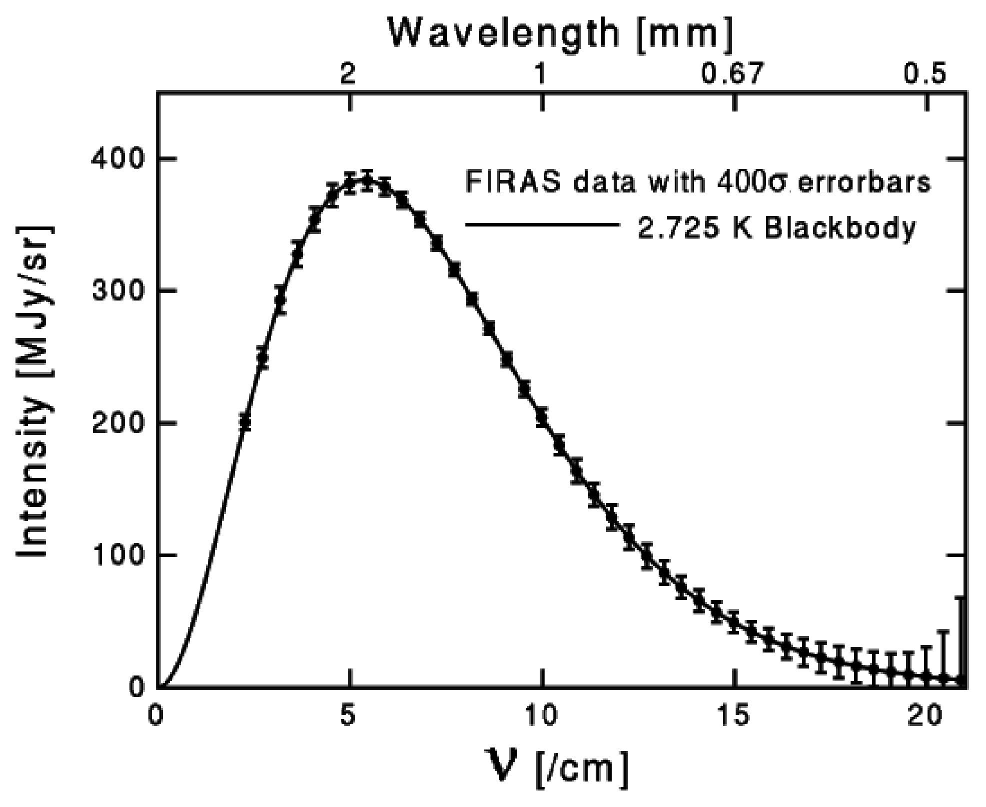

Big Bang
0.4 Myr
z ~ 1000
0.3 - 0.8 Gyr
13.6 Gyr
Present
z = 0

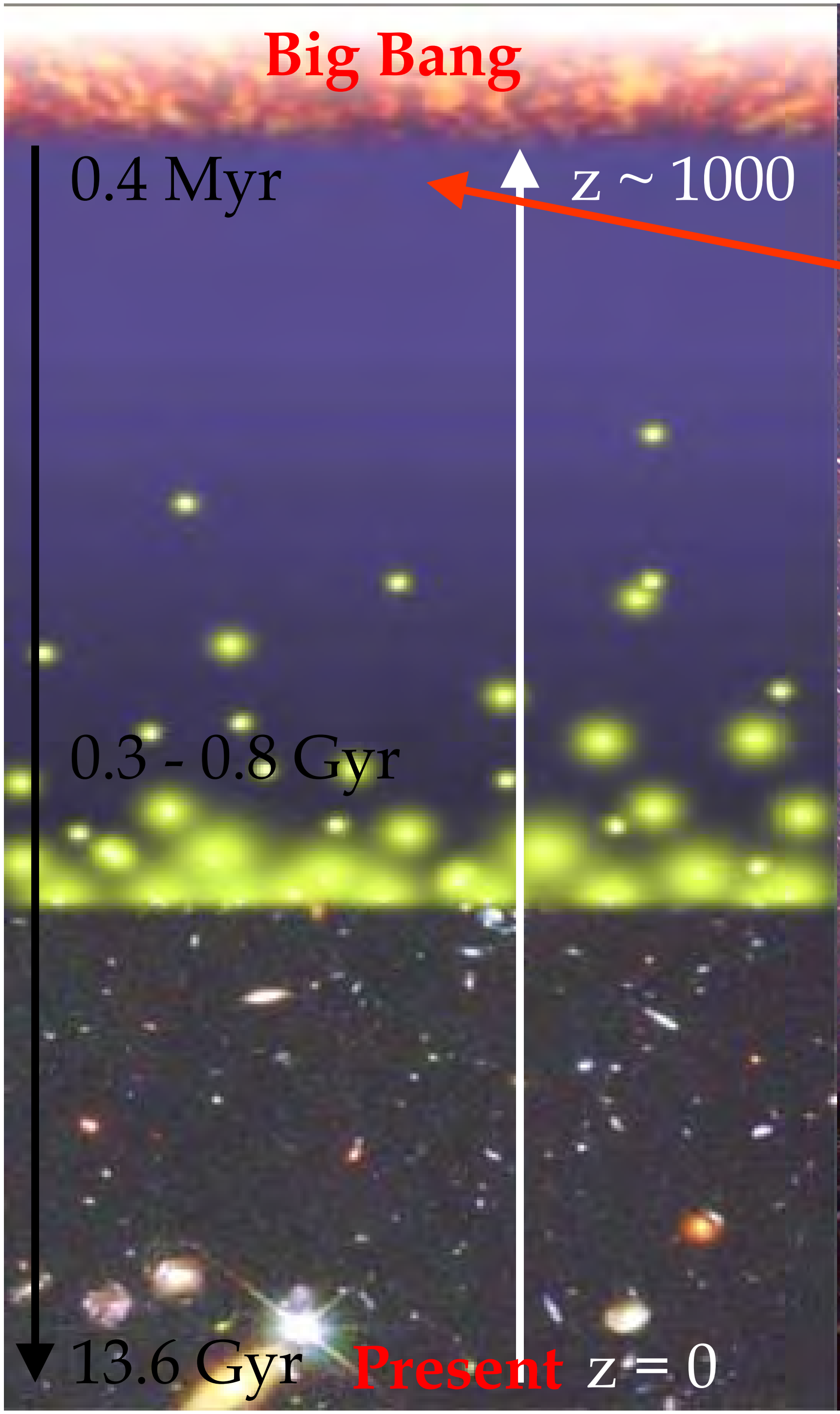


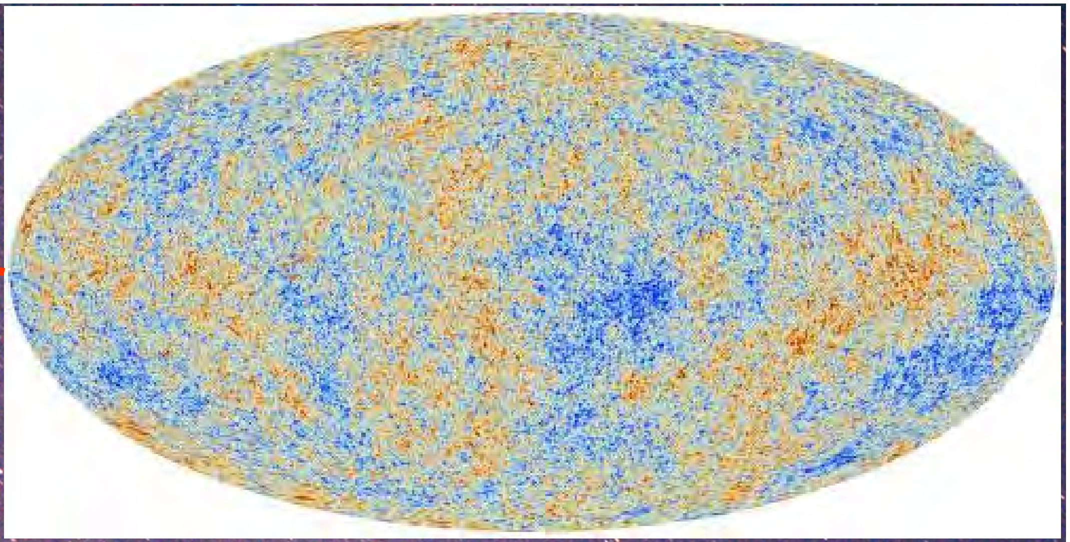
Cosmic microwave background radiation (CMB)

Blackbody radiation which cools as the universe expands

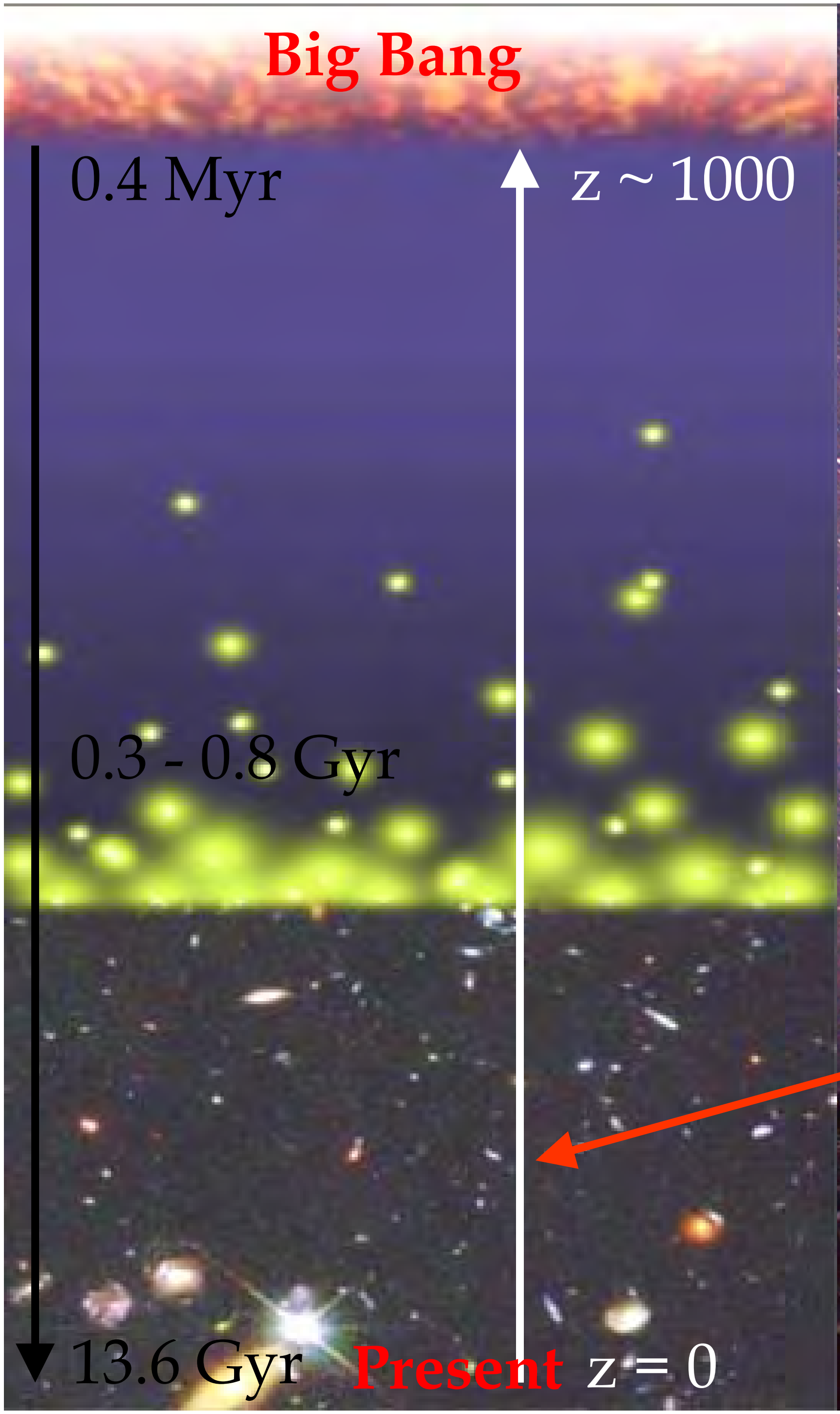
Temperature was bout 3000 K when the universe was 400,00 years old and is 3 K today





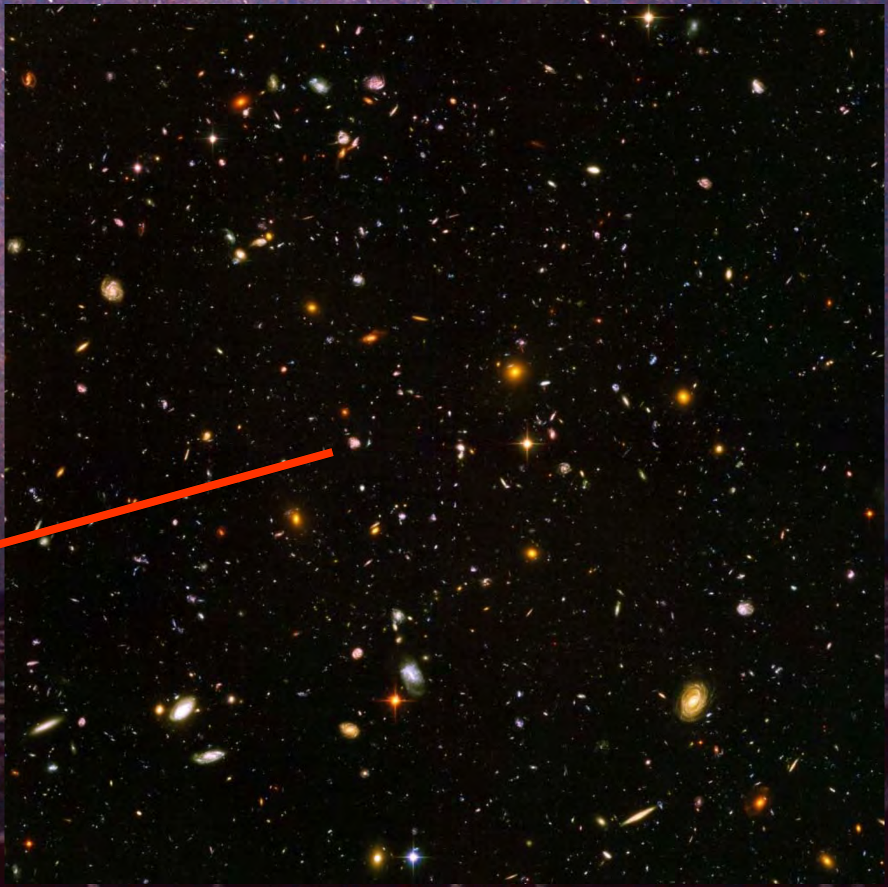


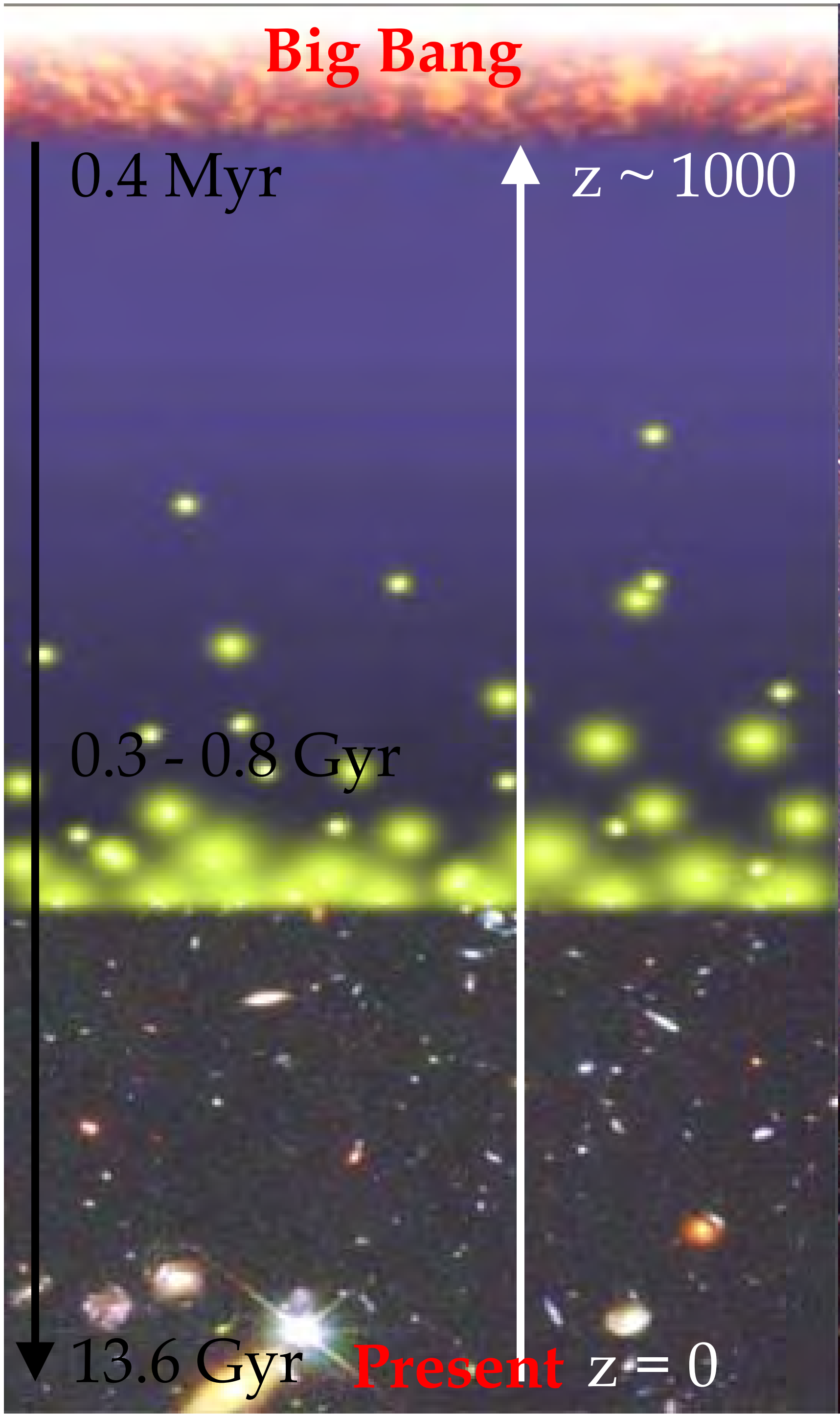
The spatial fluctuations in the CMB temperature of 1 part in 10^5 track matter overdensities which gravitationally collapse to form structures today (galaxies, clusters of galaxies): we know the initial conditions of *structure formation* in the universe



The “Realm of the Galaxies”

This is the universe you know: stars , planets, and galaxies, and clusters of galaxies: the *structure of the universe*





What happened in between?

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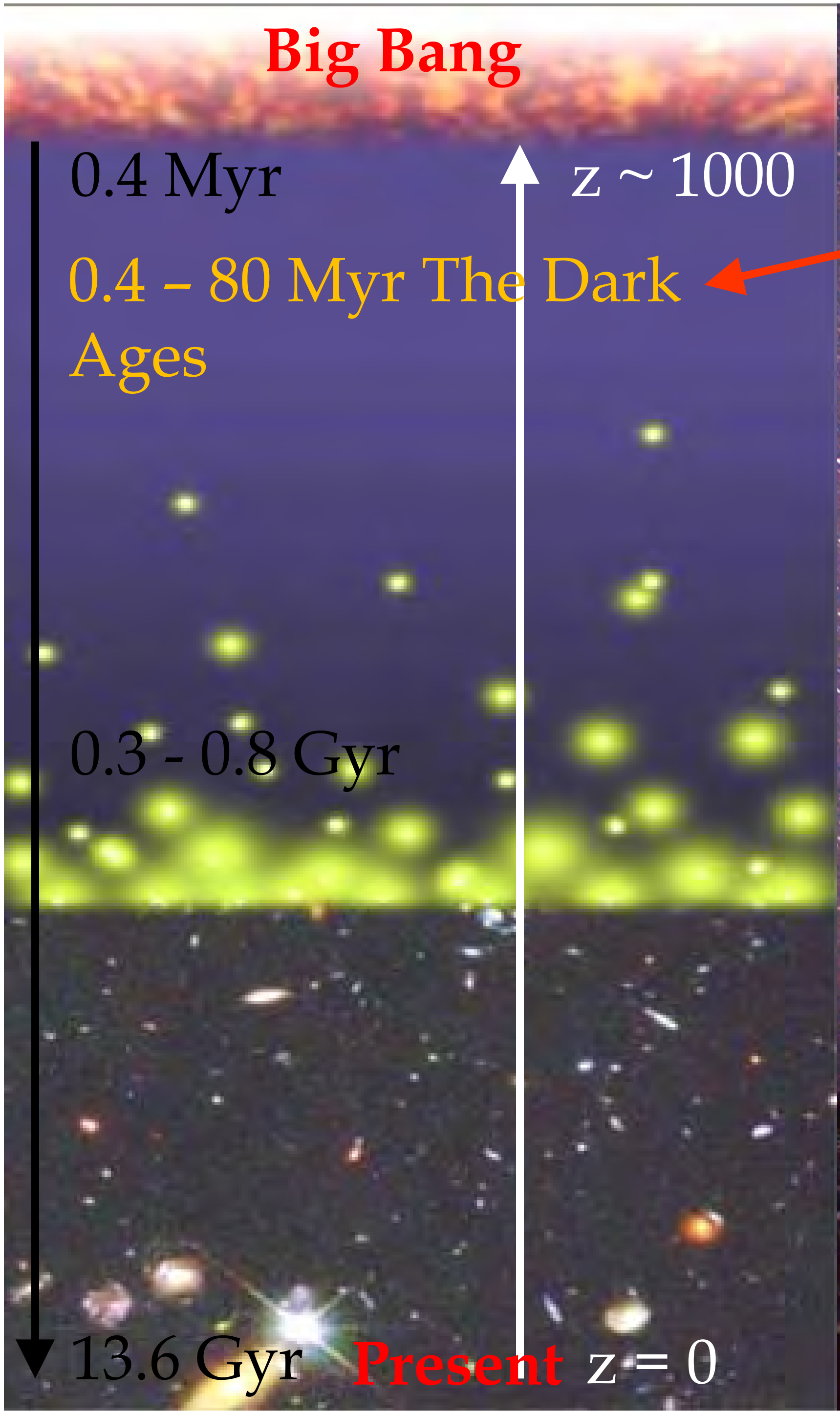
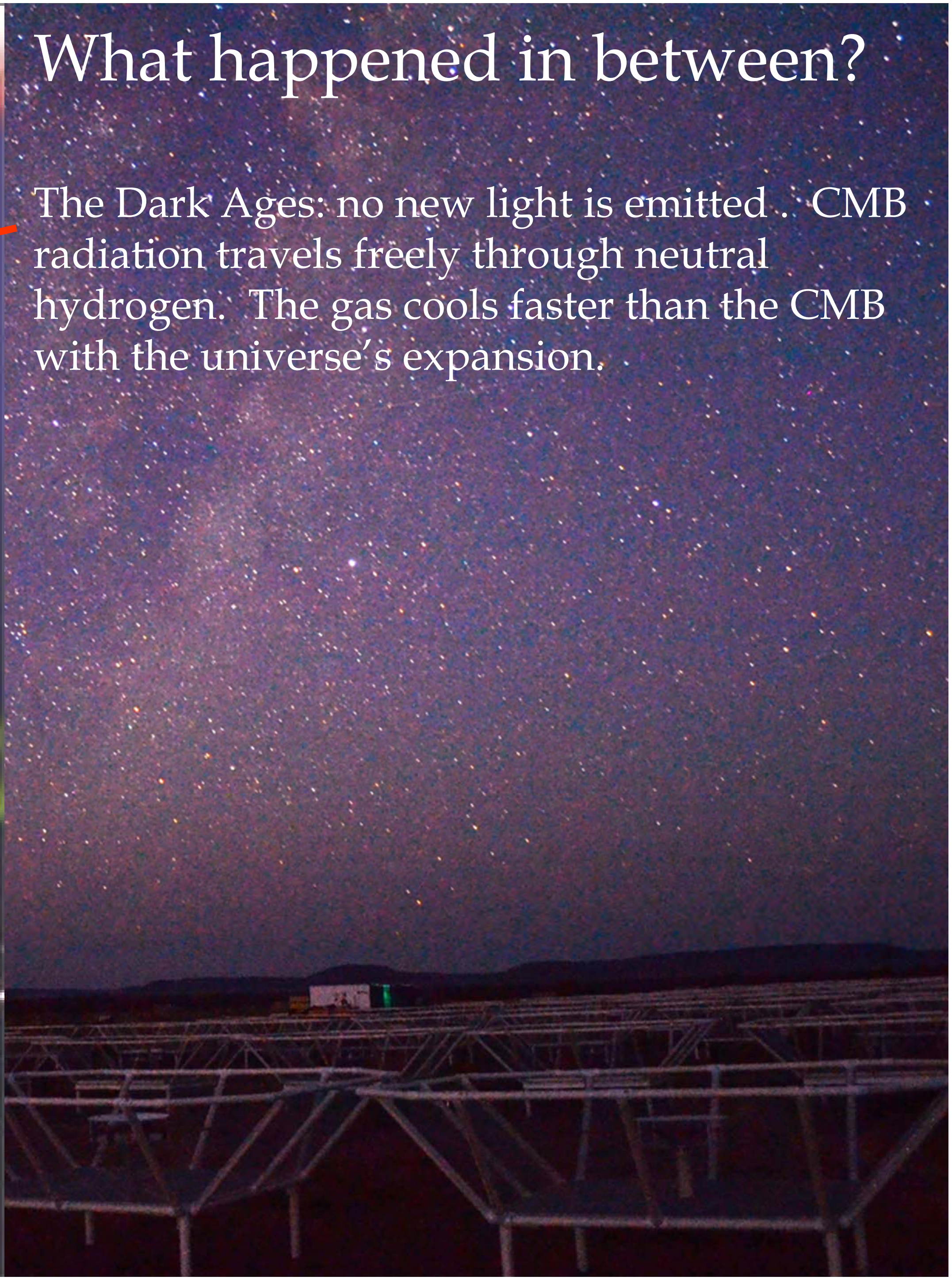


The Dark Ages: no new light is emitted .. CMB radiation travels freely through neutral hydrogen. The gas cools faster than the CMB with the universe’s expansion.



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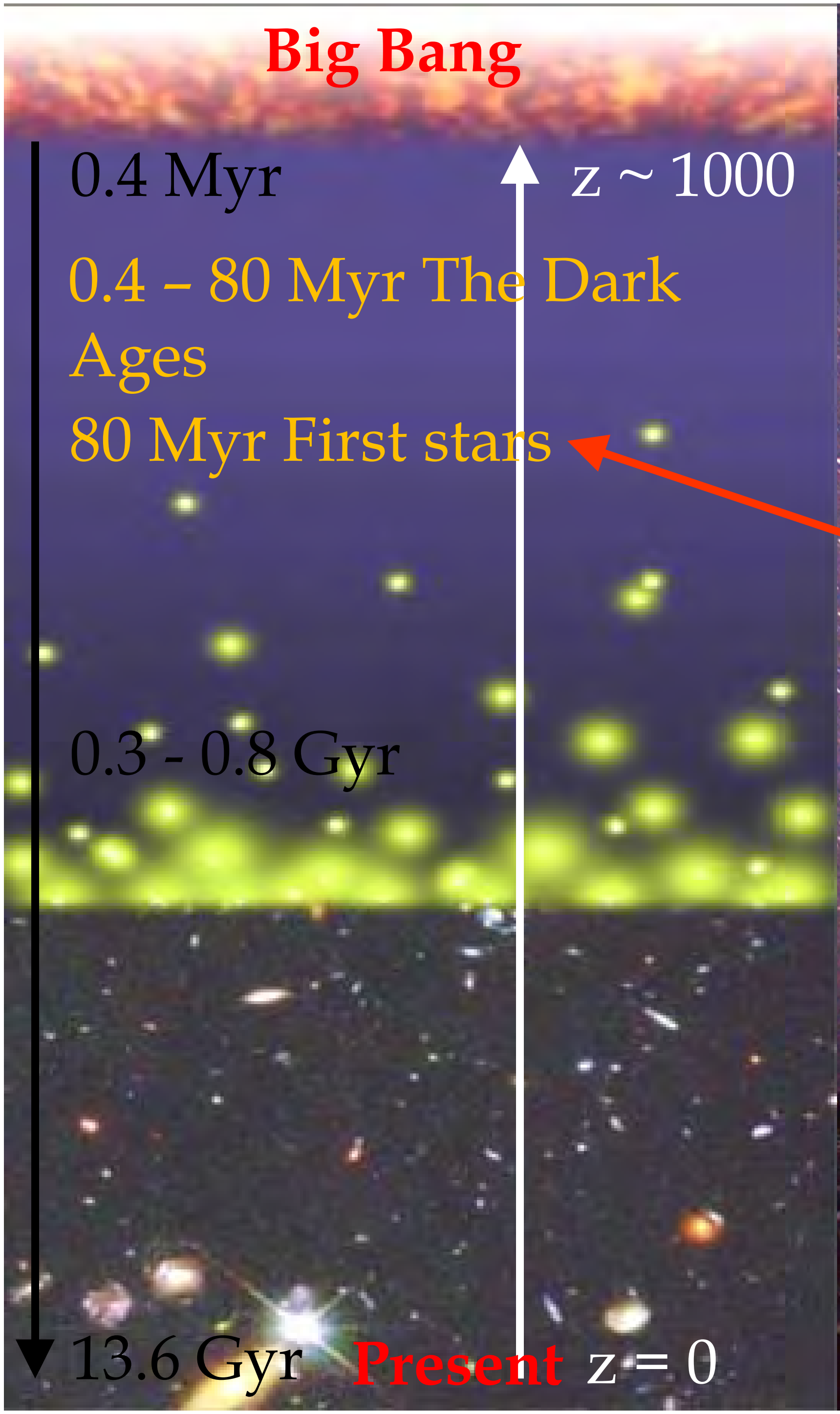


Big Bang

0.4 Myr

z ~ 1000

0.4 – 80 Myr The Dark Ages

80 Myr First stars

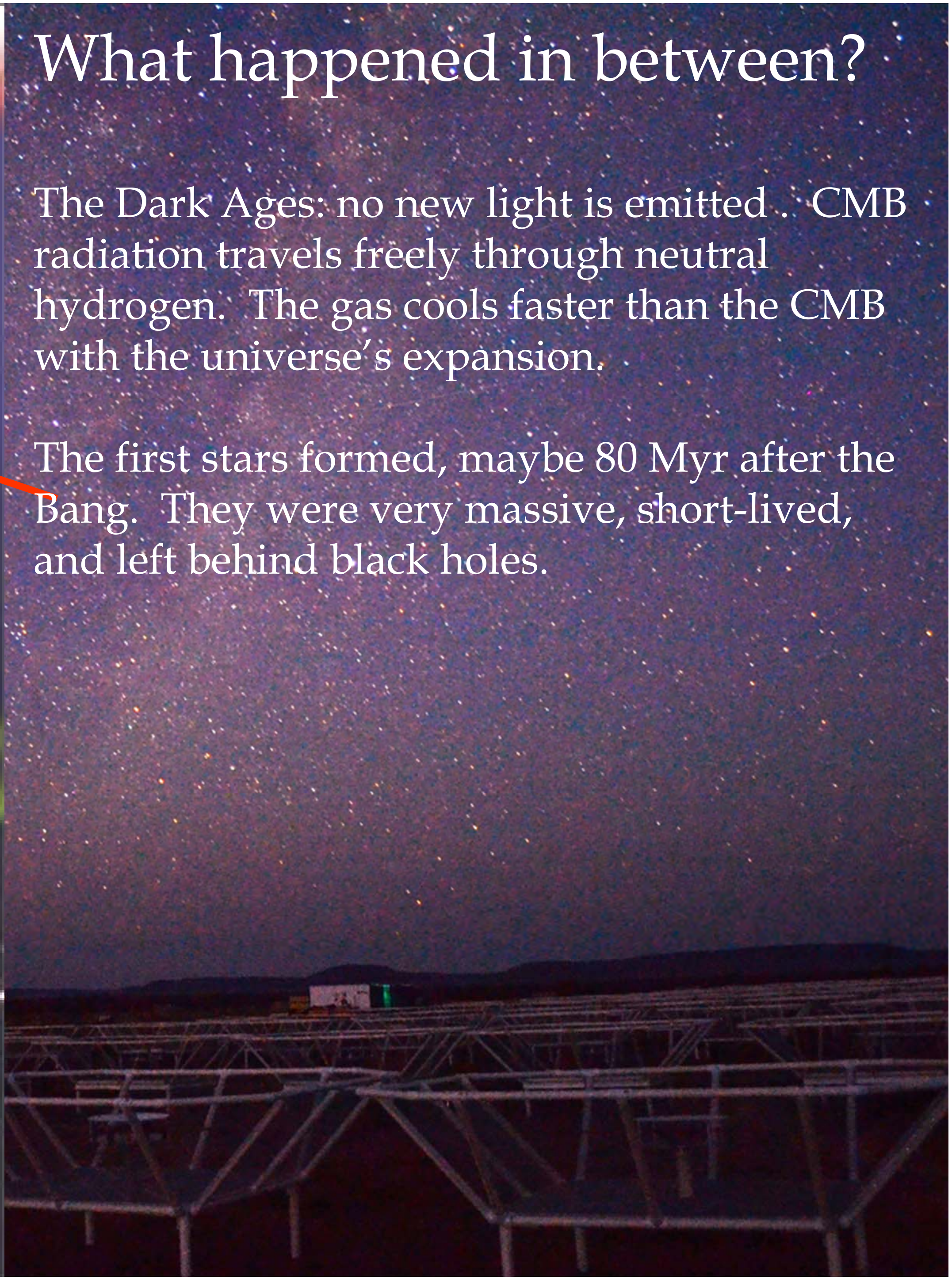
0.3 - 0.8 Gyr

13.6 Gyr

Present z = 0

The Dark Ages: no new light is emitted.. CMB radiation travels freely through neutral hydrogen. The gas cools faster than the CMB with the universe's expansion.

The first stars formed, maybe 80 Myr after the Bang. They were very massive, short-lived, and left behind black holes.



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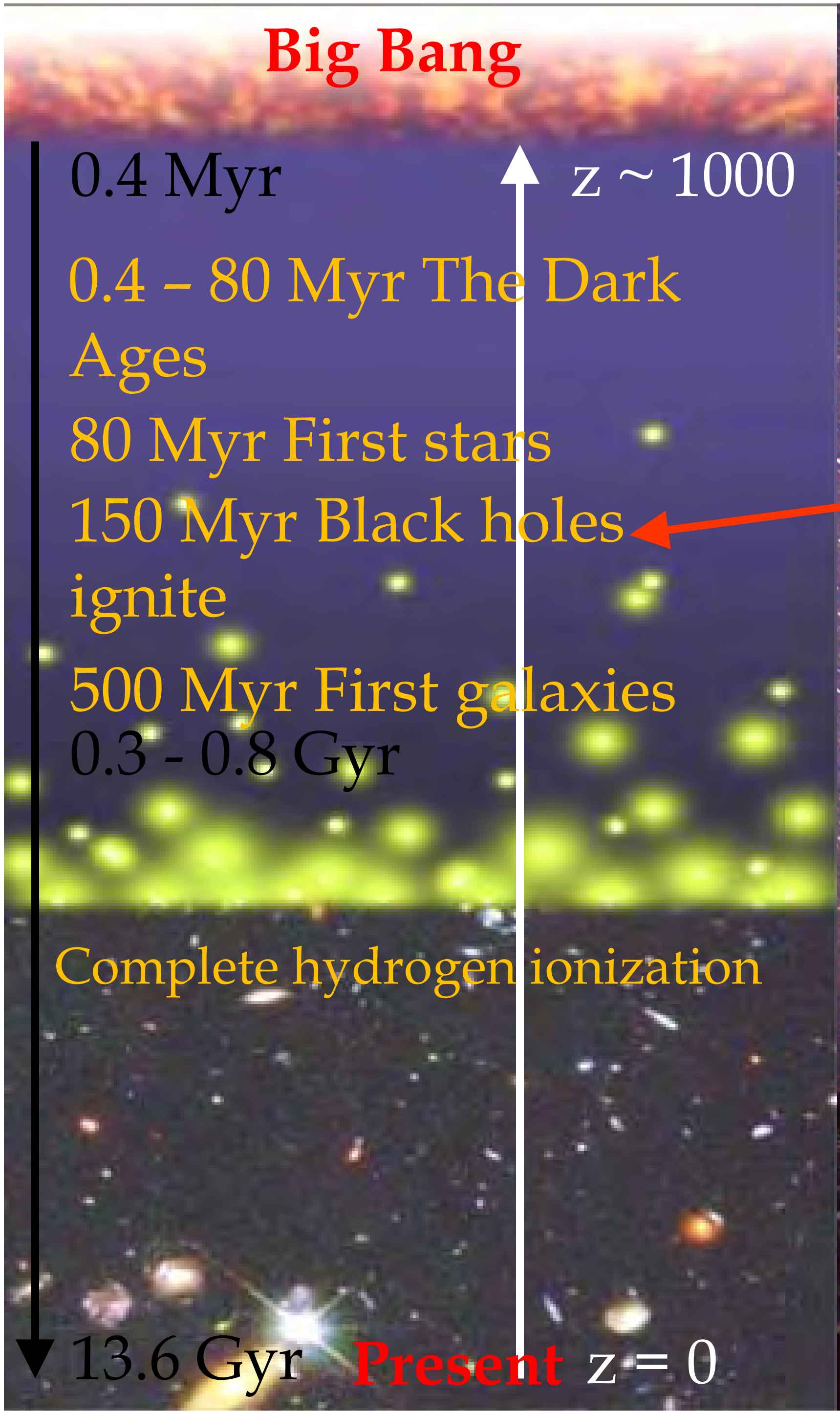

Big Bang

0.4 Myr

z ~ 1000

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80 Myr First stars

150 Myr Black holes ignite

500 Myr First galaxies

0.3 - 0.8 Gyr

Complete hydrogen ionization

13.6 Gyr

Present z = 0

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Large aggregations of stars form: the first galaxies

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What happened in between?

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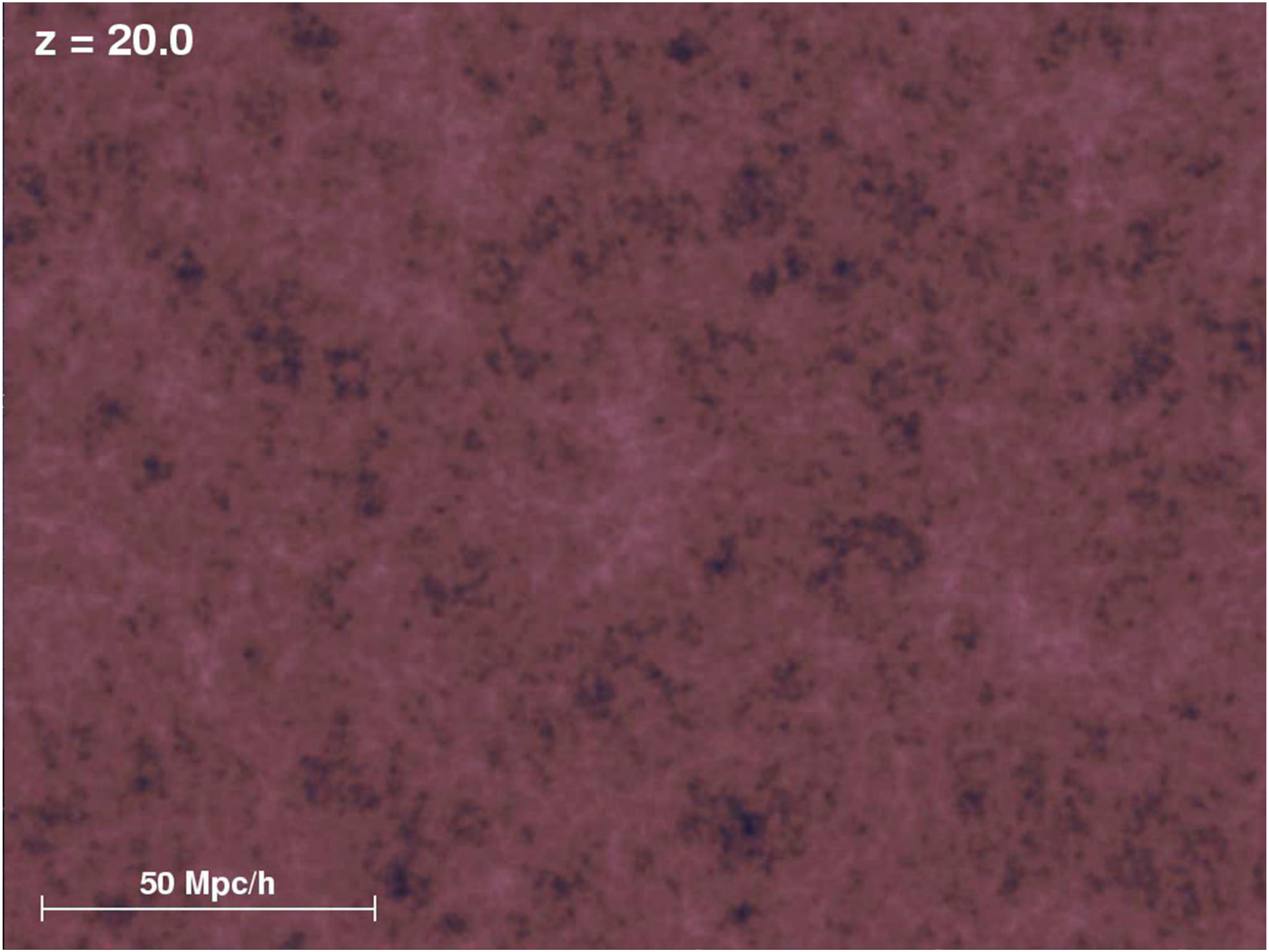
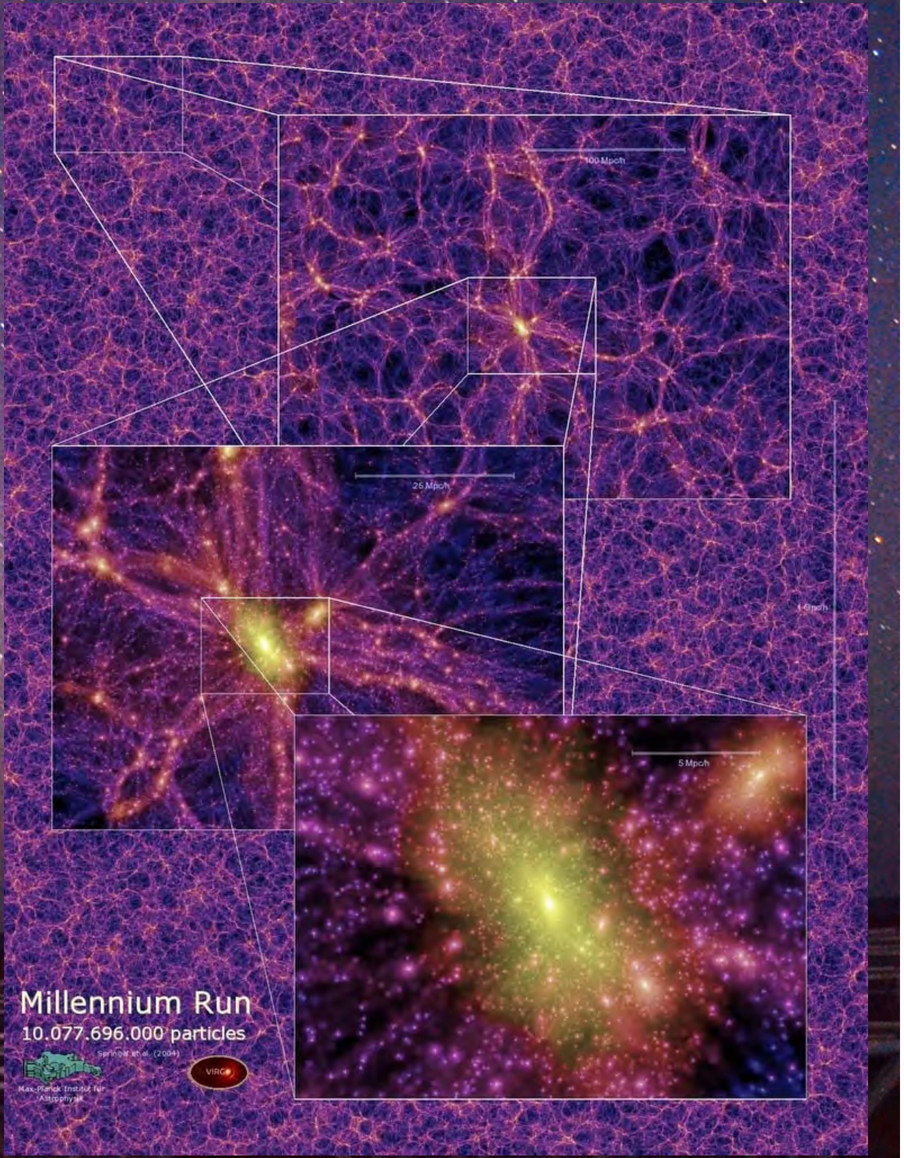
Large aggregations of stars form: the first galaxies

The light from galaxies eventually ionizes the bulk of the hydrogen in the universe, which lives between them


z = 20.0
50 Mpc/h

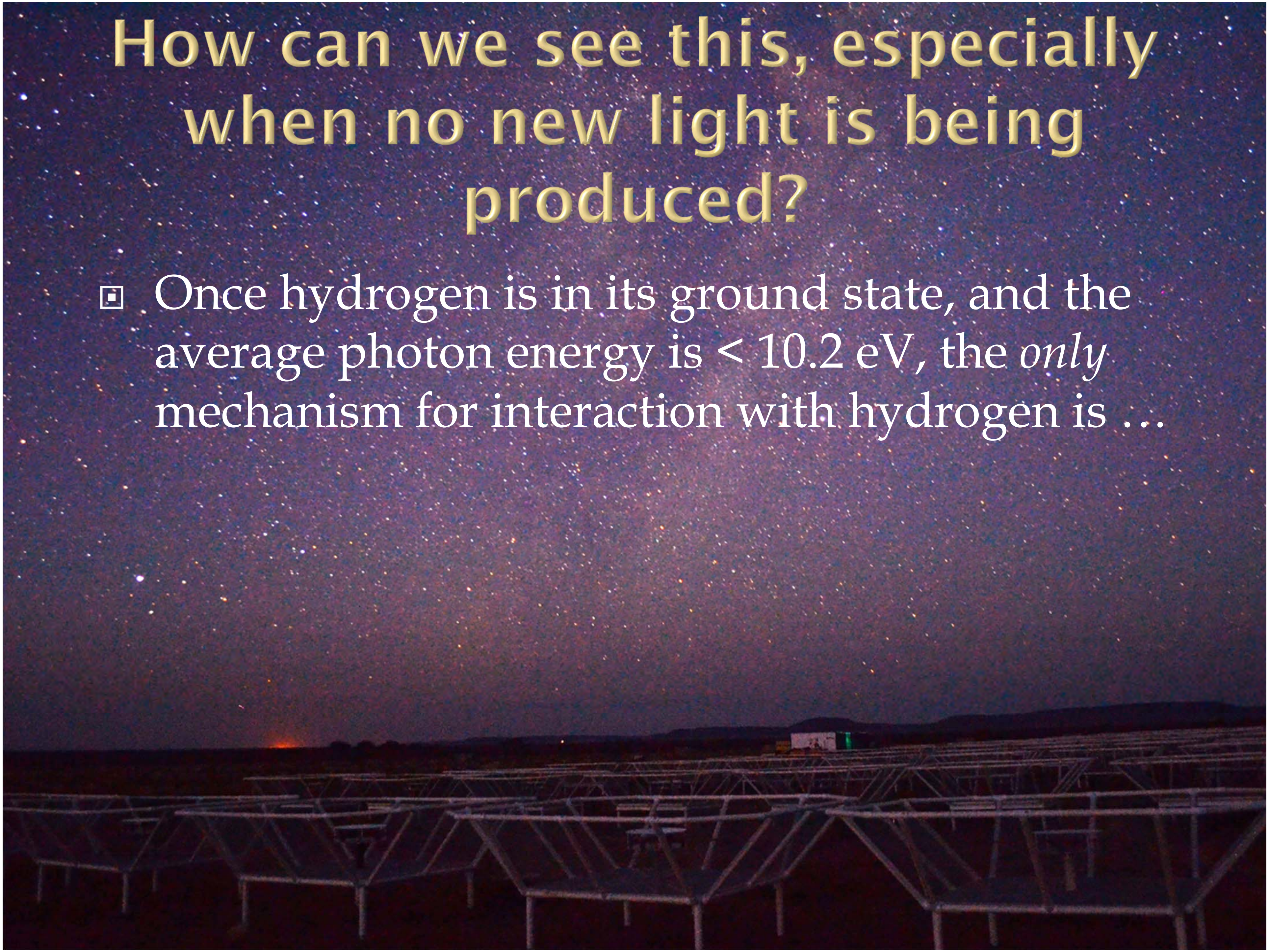
It's a good story, but between the CMB and 500 Myr, we have almost no direct observational evidence: we have just a theory of the evolution of dark matter and computer simulation.

We would like to see this happen!



How can we see this, especially when no new light is being produced?

- Once hydrogen is in its ground state, and the average photon energy is < 10.2 eV, the *only* mechanism for interaction with hydrogen is …



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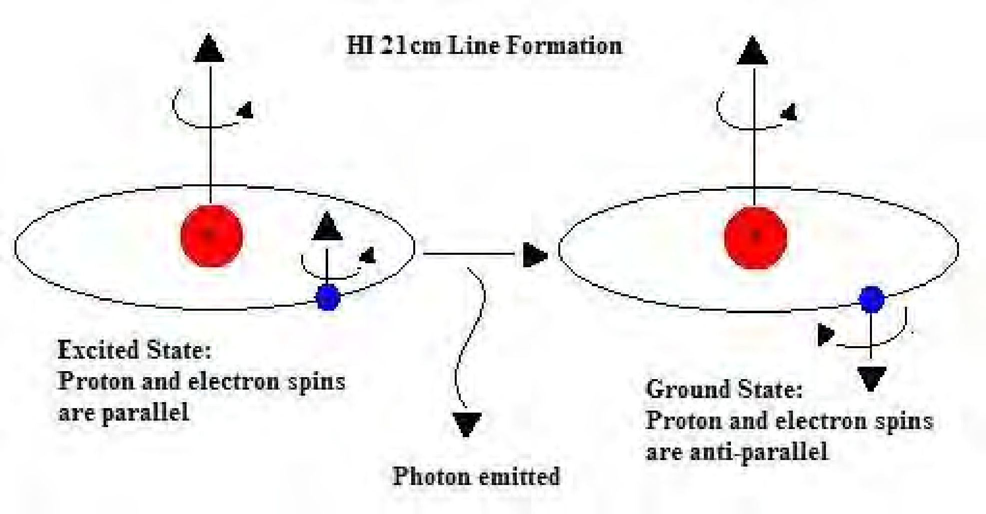
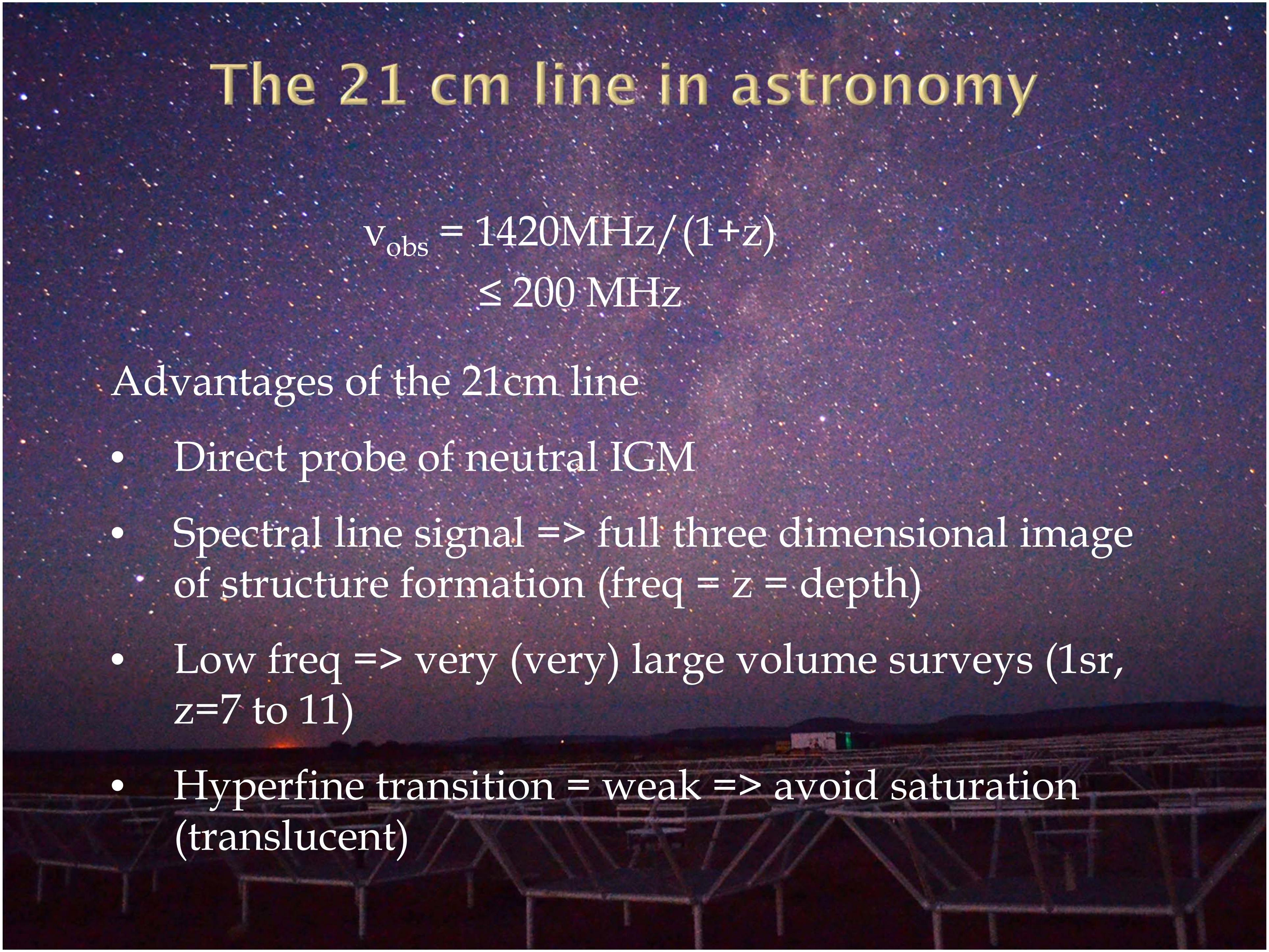
The hyperfine splitting of the hydrogen ground state



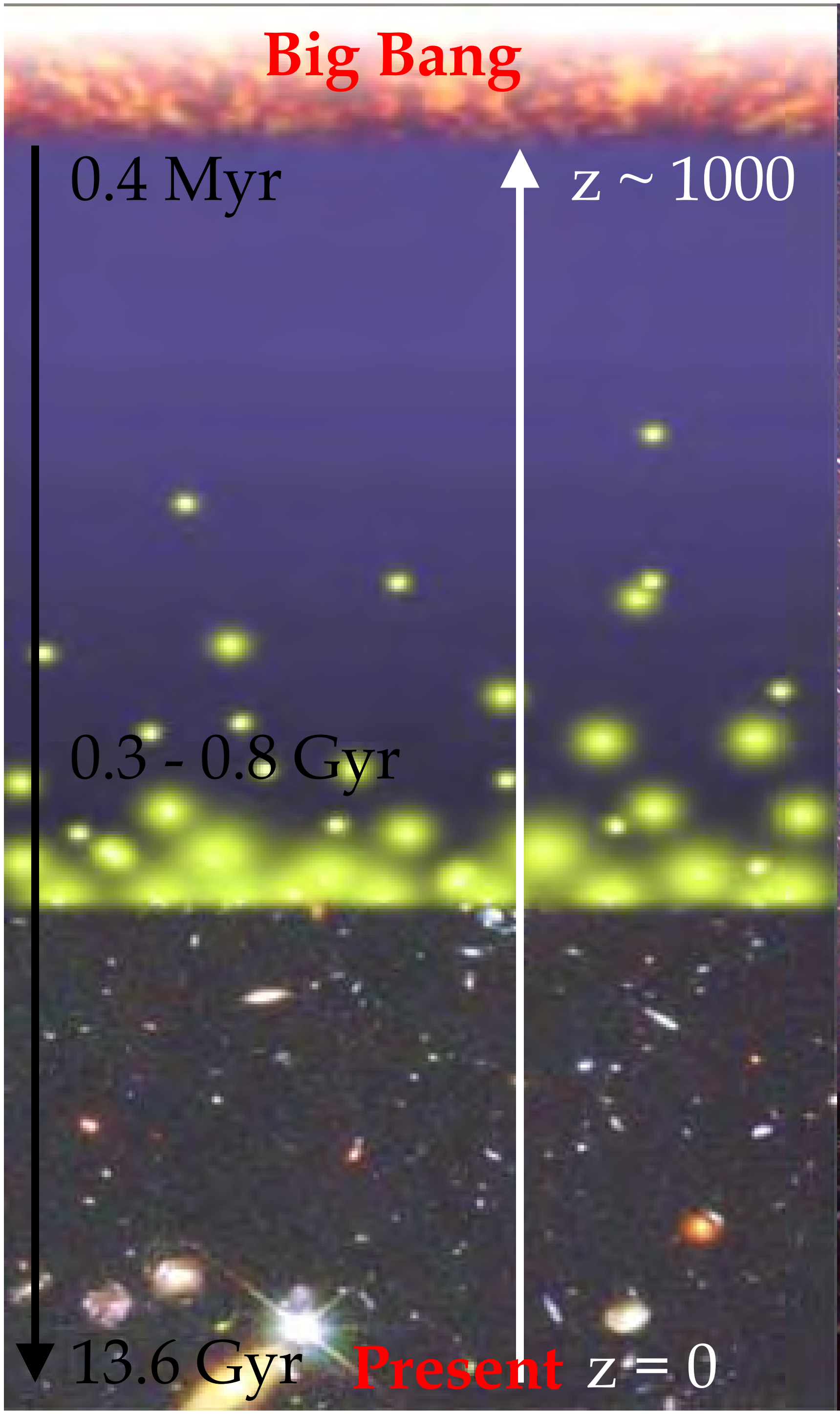
The 21 cm line in astronomy

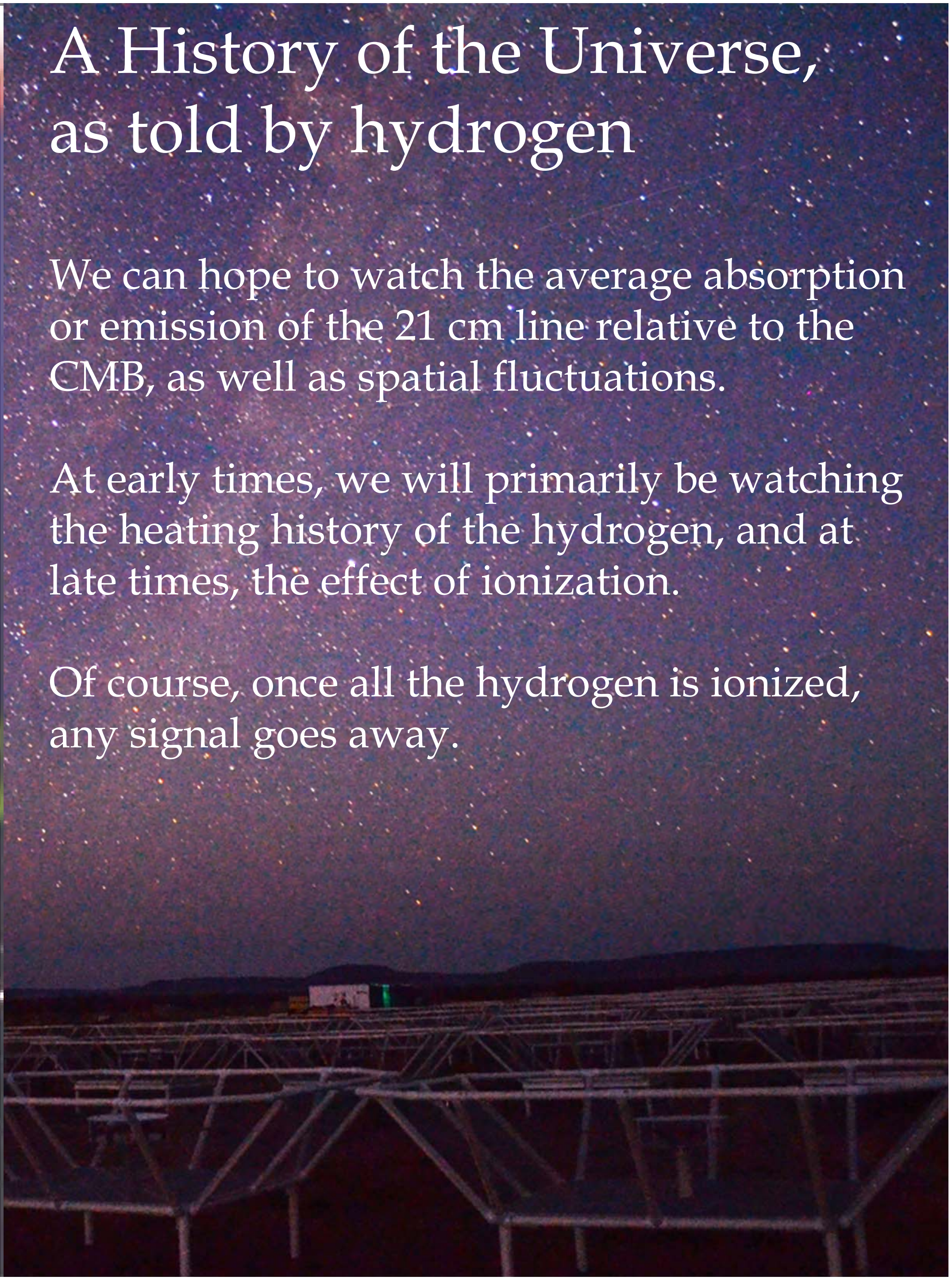


$$\nu_{obs} = 1420\mathrm{MHz}/(1+z)$$
$$\leq 200\ \mathrm{MHz}$$

Advantages of the 21cm line

- Direct probe of neutral IGM
- Spectral line signal => full three dimensional image of structure formation (freq = z = depth)
- Low freq => very (very) large volume surveys (1sr, z=7 to 11)
- Hyperfine transition = weak => avoid saturation (translucent)



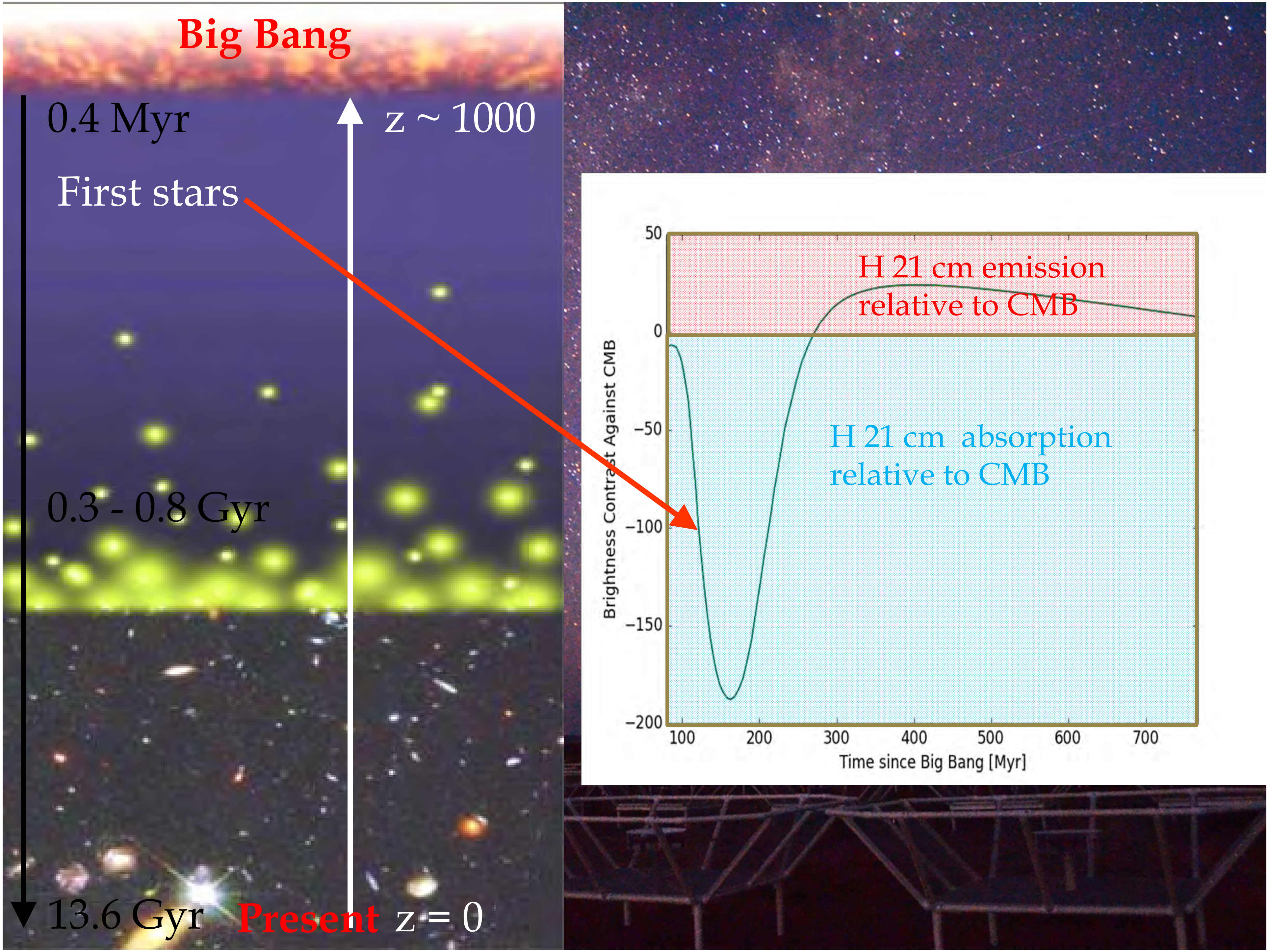


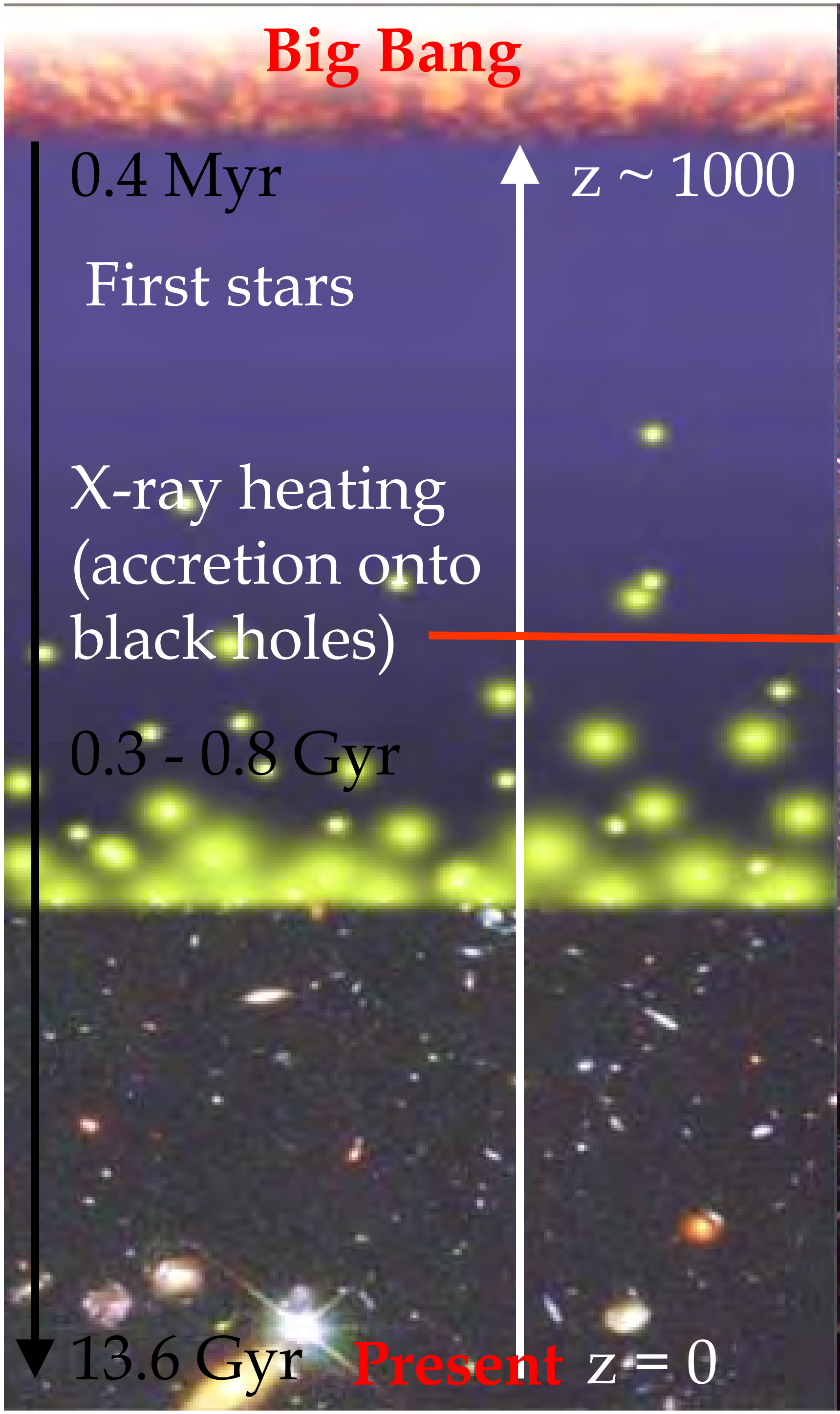
A History of the Universe, as told by hydrogen

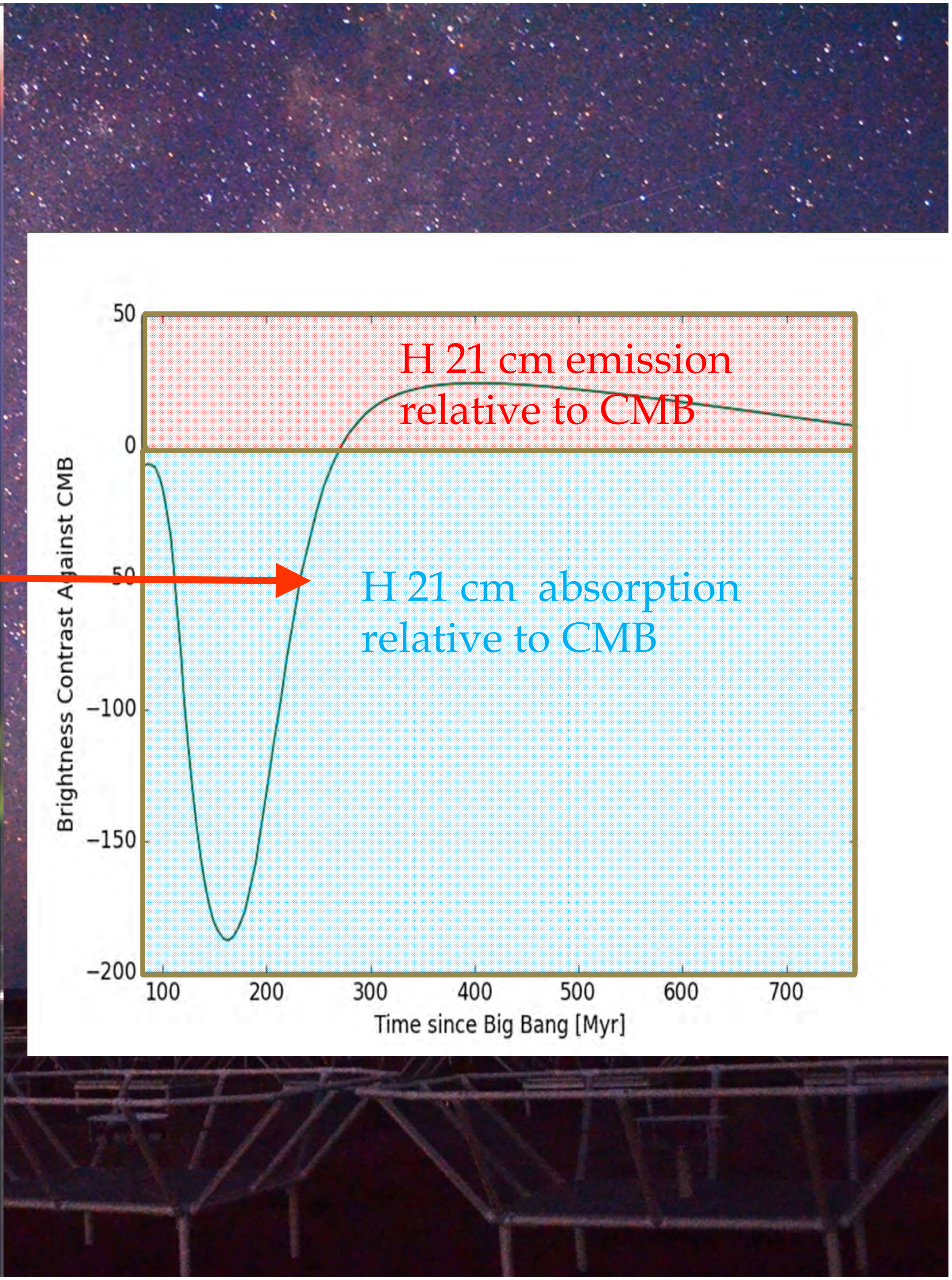
We can hope to watch the average absorption or emission of the 21 cm line relative to the CMB, as well as spatial fluctuations.

At early times, we will primarily be watching the heating history of the hydrogen, and at late times, the effect of ionization.

Of course, once all the hydrogen is ionized, any signal goes away.


Big Bang
0.4 Myr
z ~ 1000
First stars
0.3 - 0.8 Gyr
13.6 Gyr
Present
z = 0
H 21 cm emission relative to CMB
H 21 cm absorption relative to CMB
Brightness Contrast Against CMB
50
0
−50
−100
−150
−200
100
200
300
400
500
600
700
Time since Big Bang [Myr]


Big Bang
0.4 Myr
z ~ 1000
First stars
X-ray heating
(accretion onto
black holes)
0.3 - 0.8 Gyr
13.6 Gyr
Present
z = 0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relative to CMB
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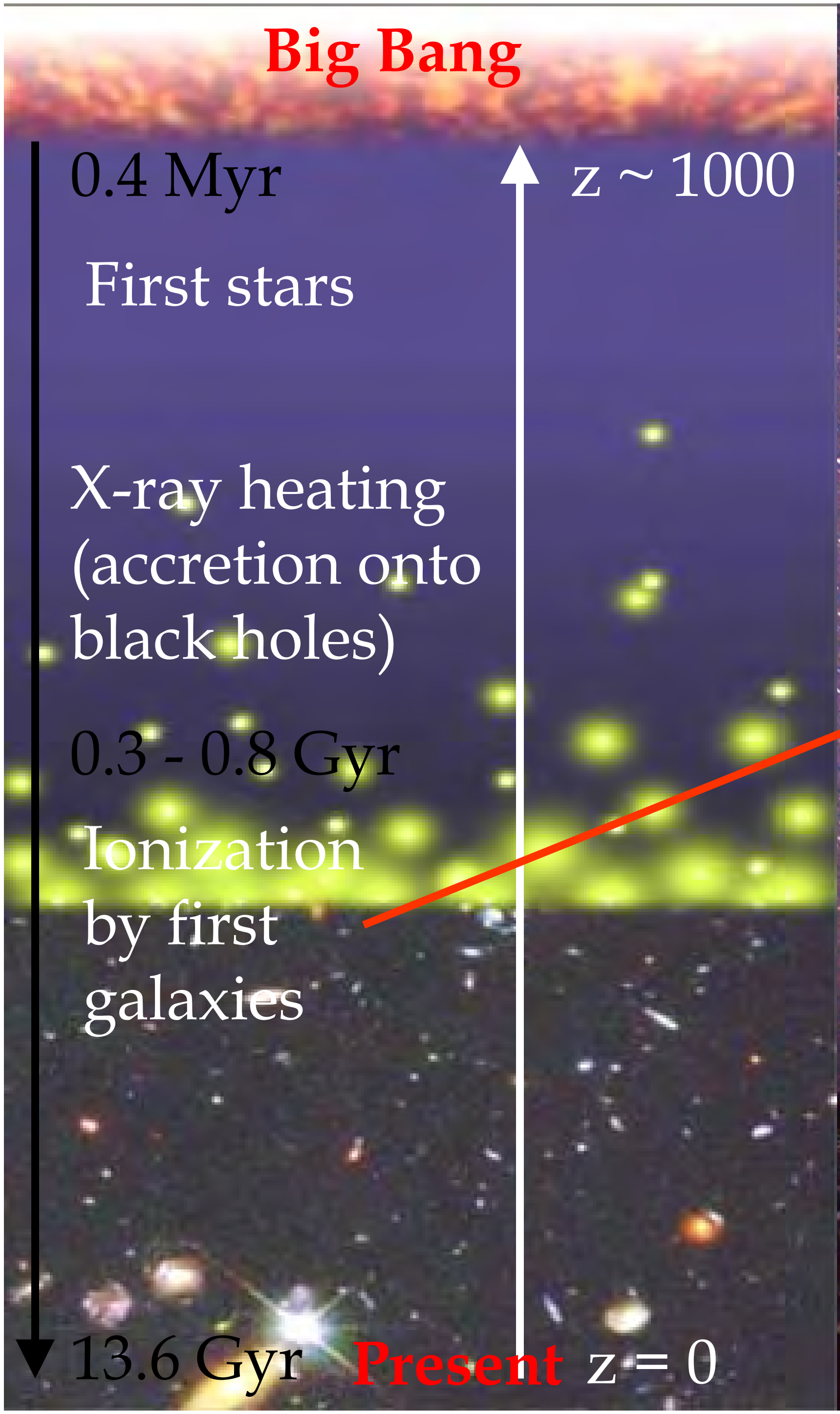


Big Bang

0.4 Myr

z ~ 1000

First stars

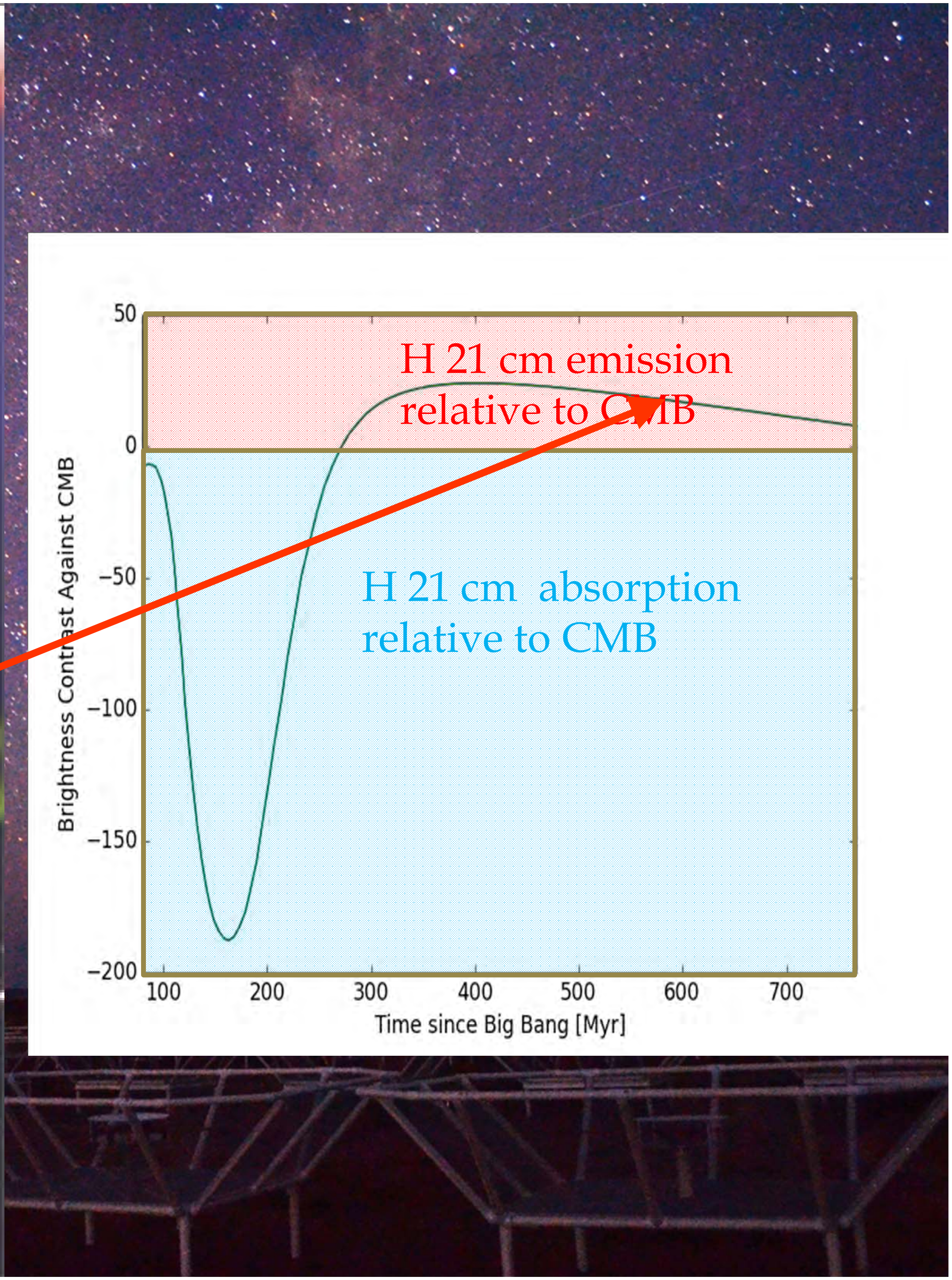
X-ray heating (accretion onto black holes)

0.3 - 0.8 Gyr

Ionization by first galaxies

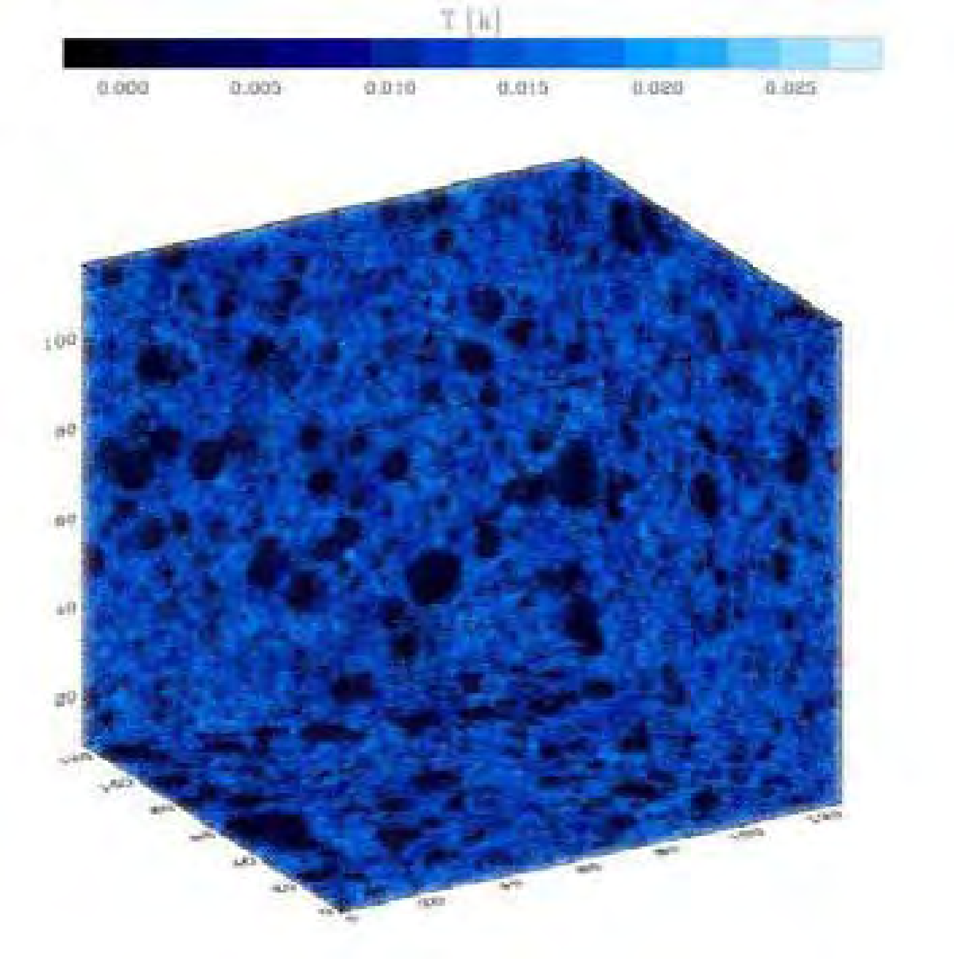
13.6 Gyr

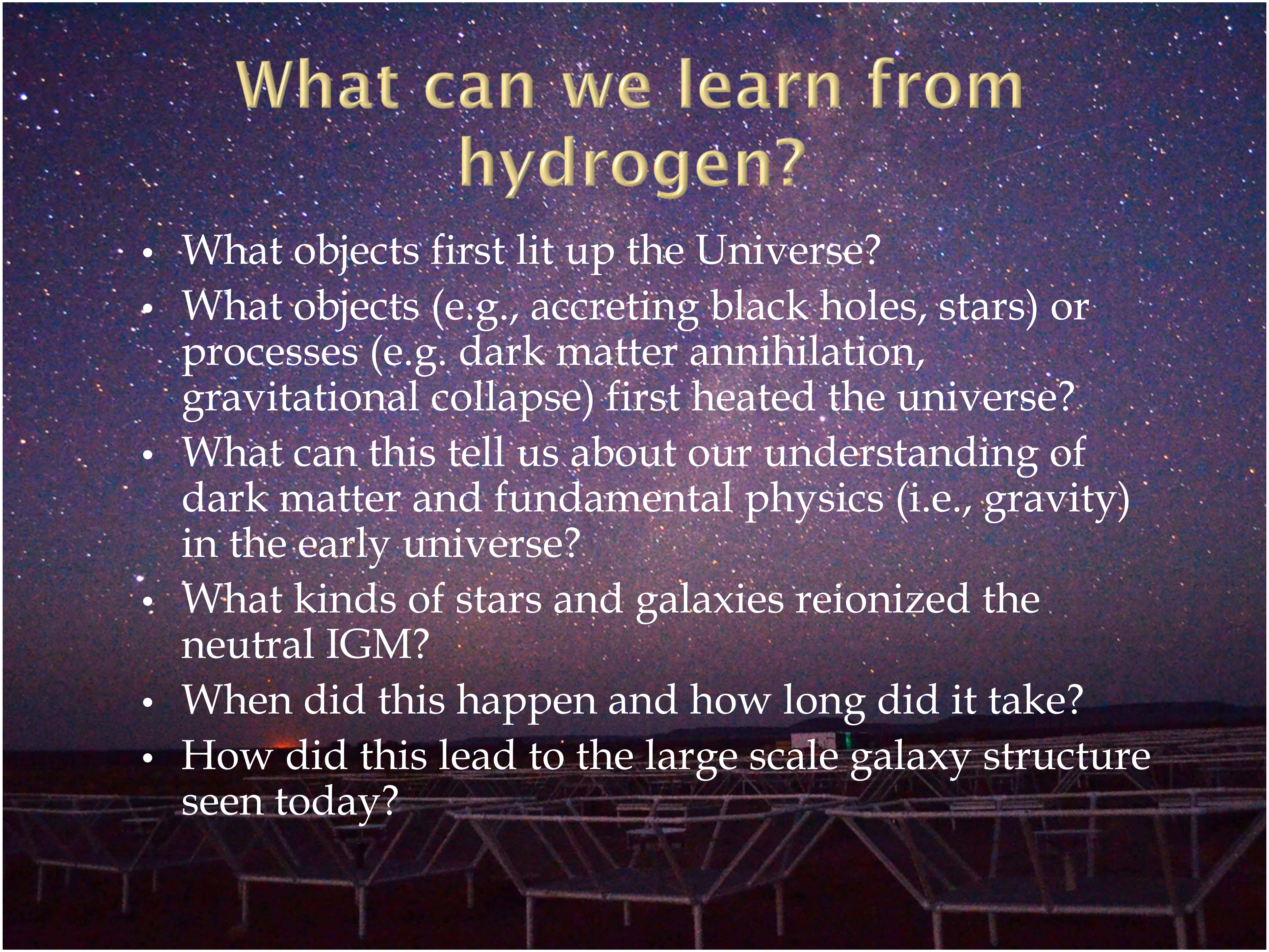
Present z = 0



21 cm tomography holds great cosmological promise

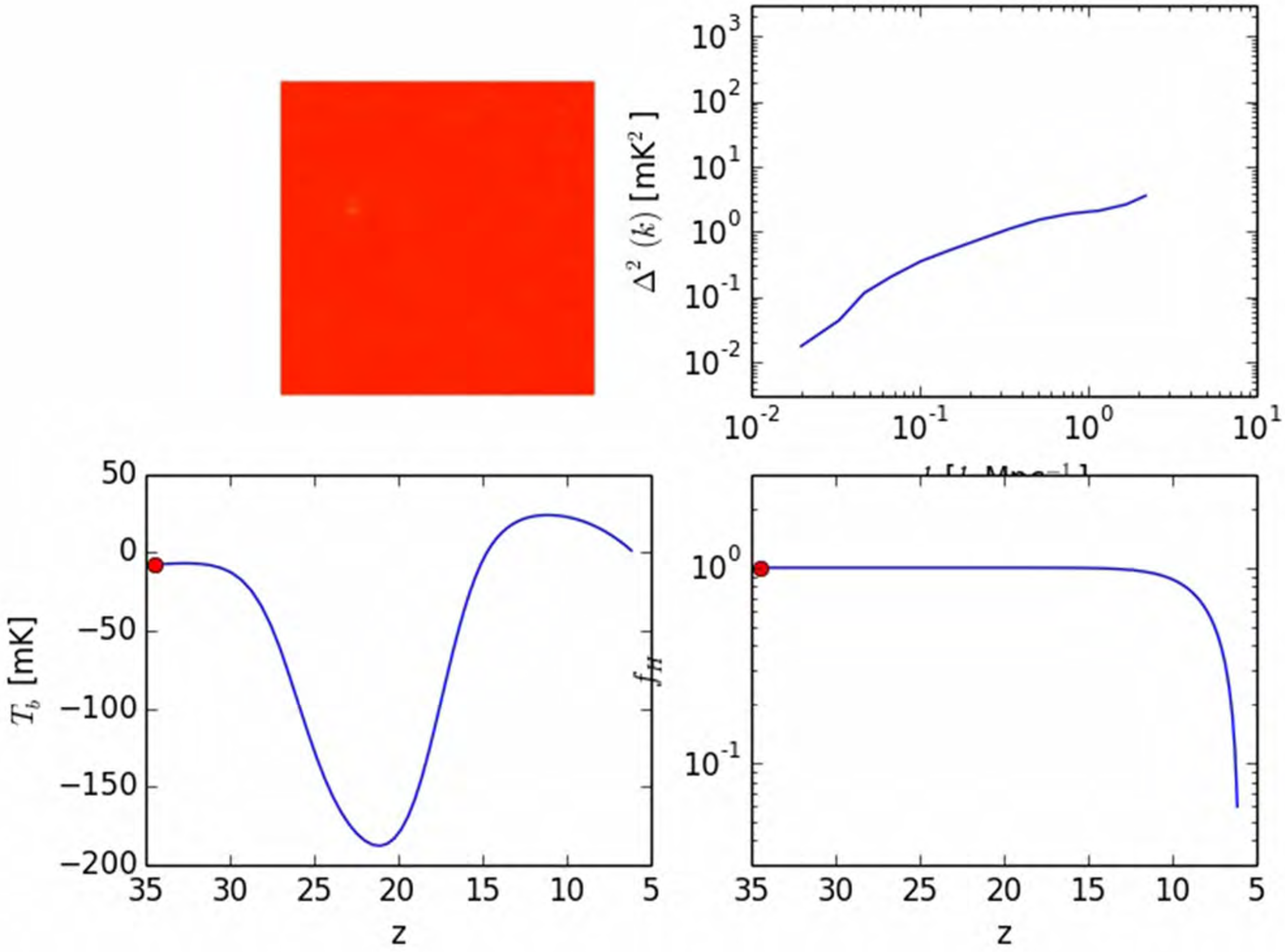
- As a line emission, the signal is intrinsically *three dimensional*
- probes linear structure formation down to scales well below those accessible by the CMB
- 21 transition is optically thin: we see through the whole cube
- We can see if those simulations are right!





What can we learn from hydrogen?

- What objects first lit up the Universe?
- What objects (e.g., accreting black holes, stars) or processes (e.g. dark matter annihilation, gravitational collapse) first heated the universe?
- What can this tell us about our understanding of dark matter and fundamental physics (i.e., gravity) in the early universe?
- What kinds of stars and galaxies reionized the neutral IGM?
- When did this happen and how long did it take?
- How did this lead to the large scale galaxy structure seen today?


$\Delta^2(k)$ [mK^2]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
T_b [mK]
50
0
−50
−100
−150
−200
35
30
25
20
15
10
5
z
f_H
10^{0}
10^{-1}
35
30
25
20
15
10
5
z

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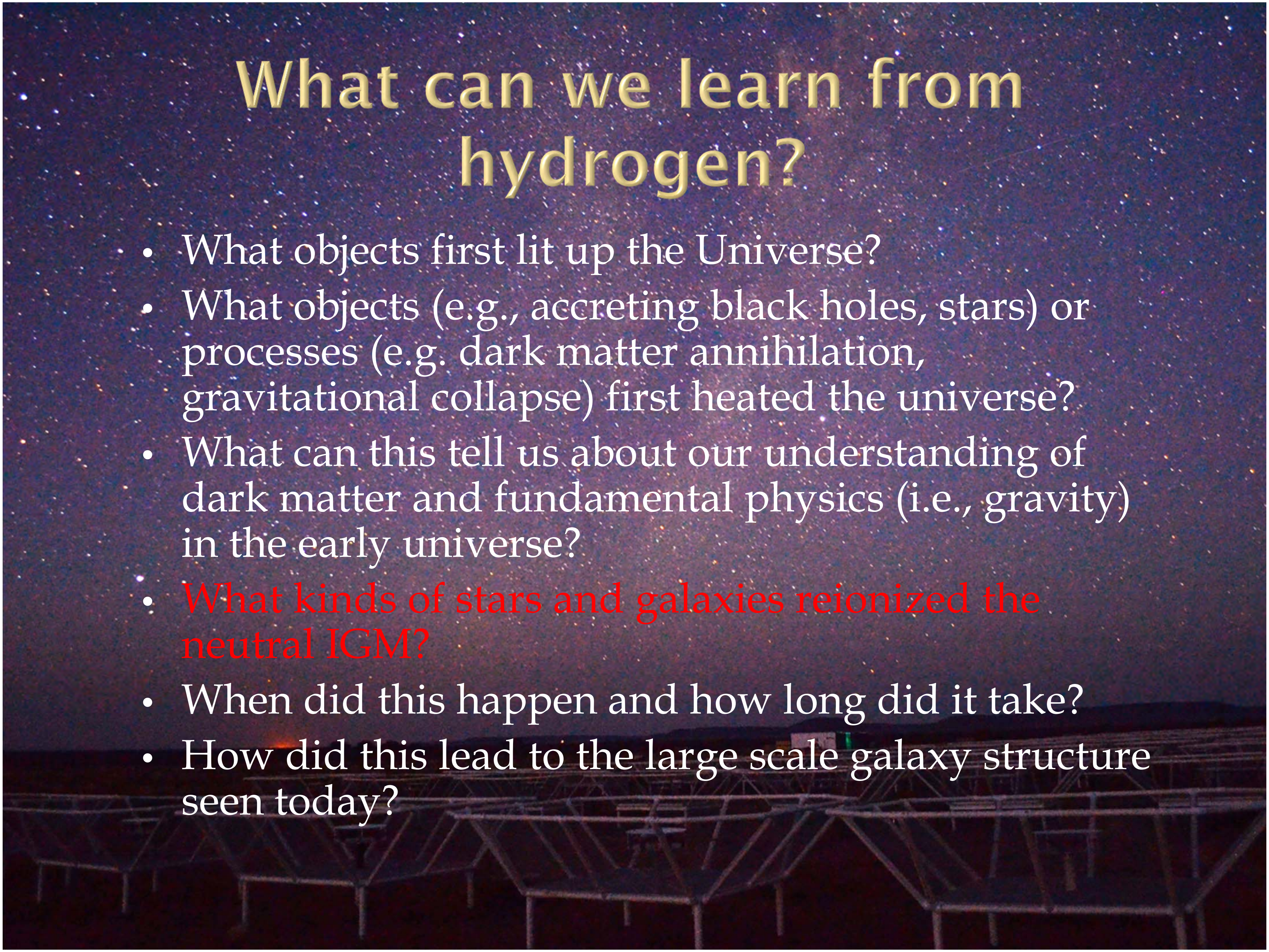

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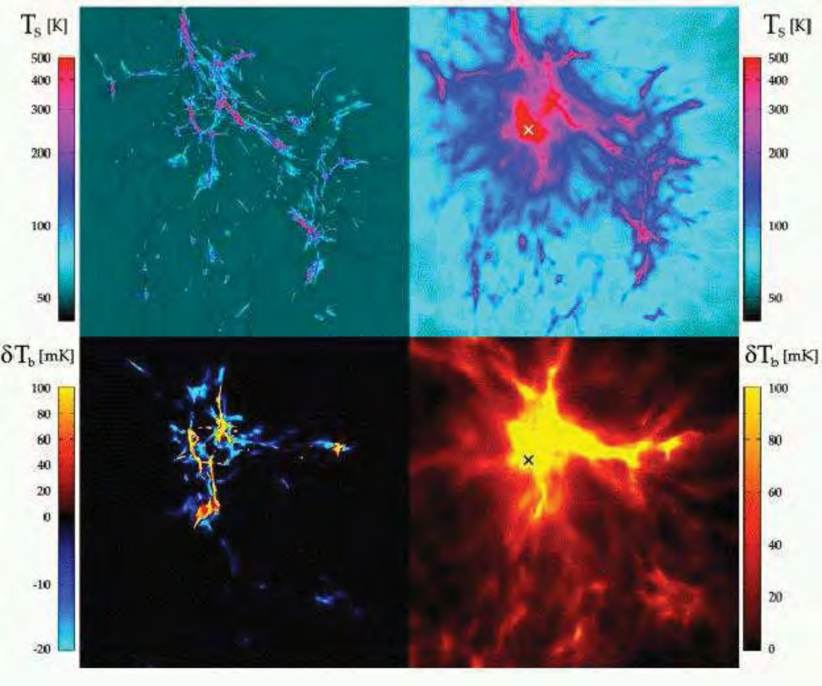
What were the like galaxies which reionized the universe?



- All indications from (very!) sparse measurements are that they were much less massive and star forming than present galaxies
- They were highly disturbed by collisions and mergers
- We may not be able to see them even with advanced telescopes
- But we can still see their effects on hydrogen, and learn about star formation within them

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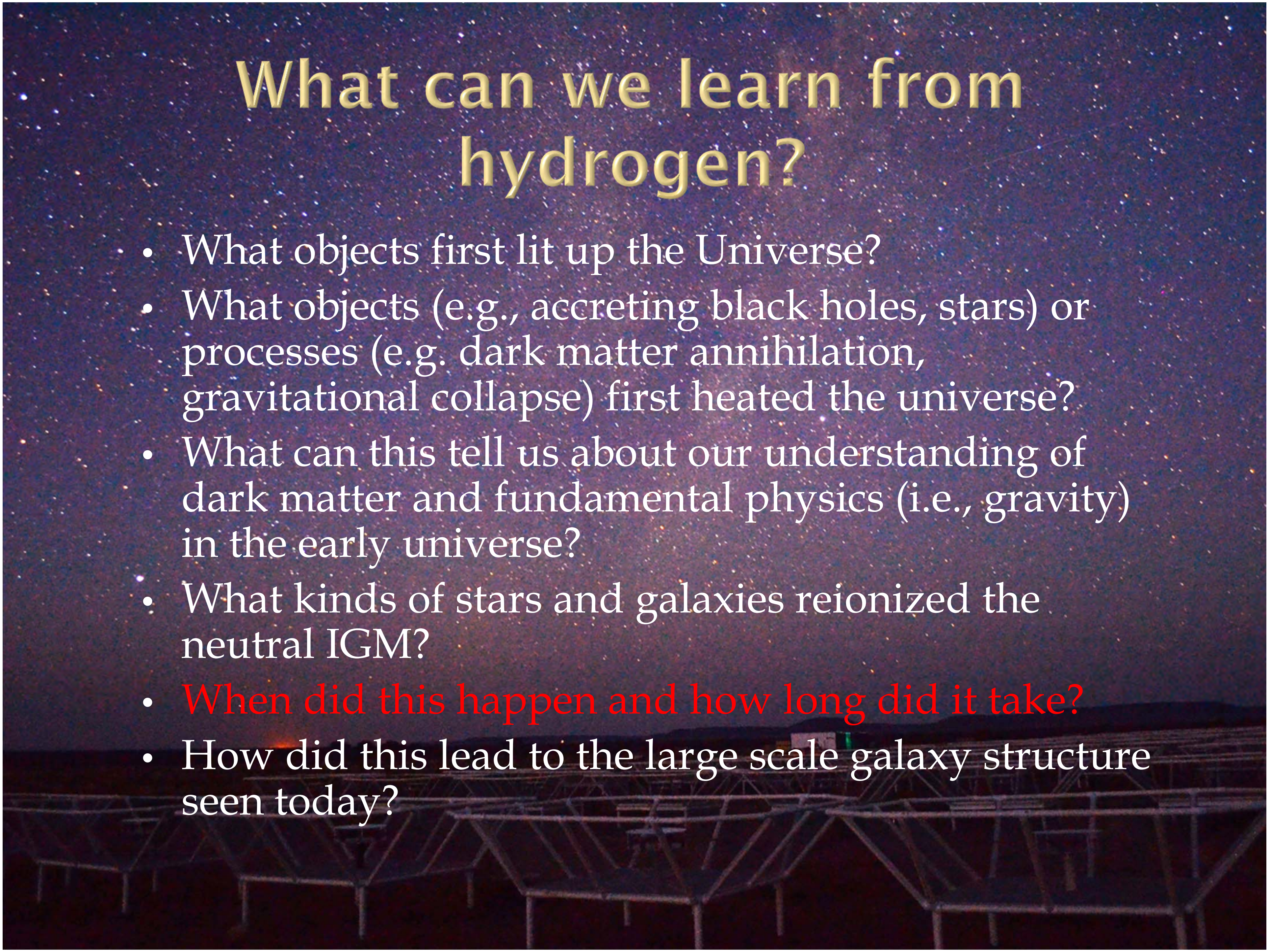
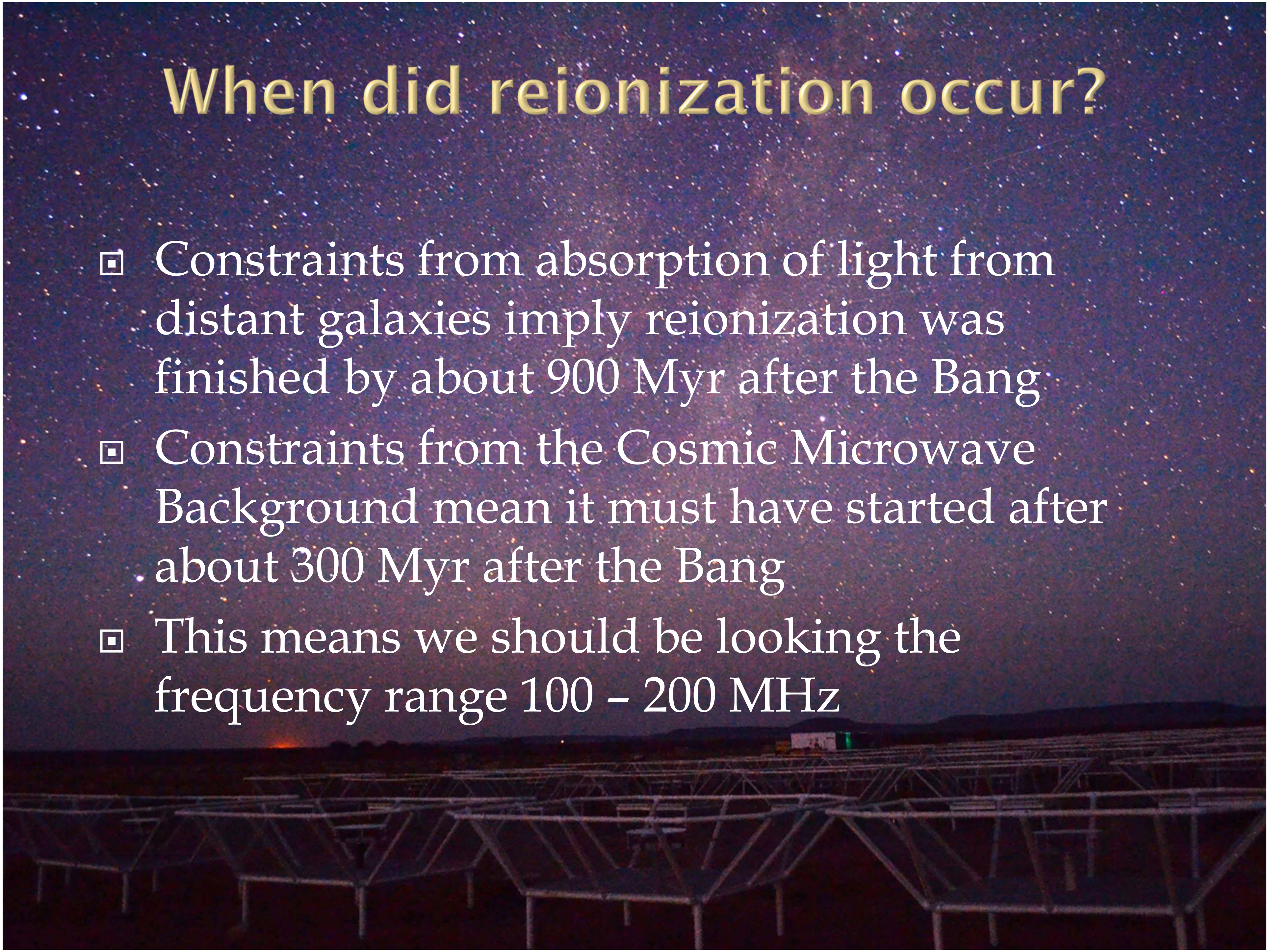


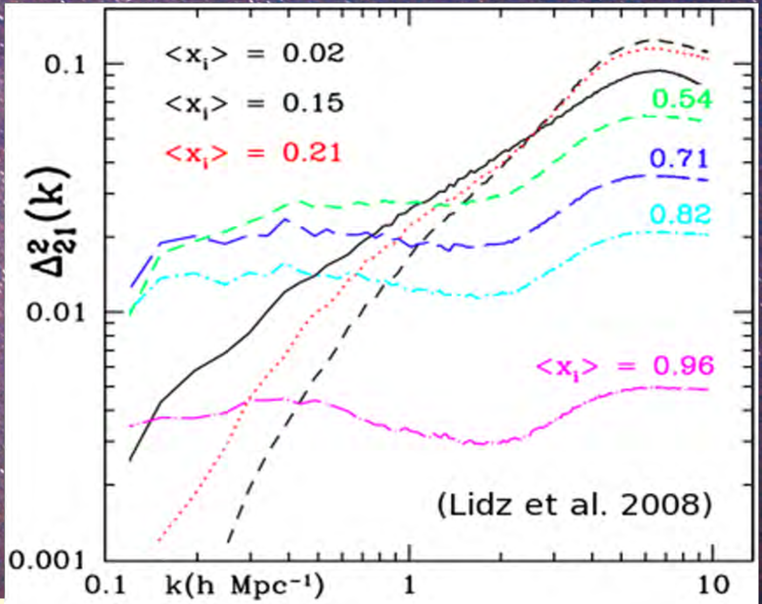


When did reionization occur?

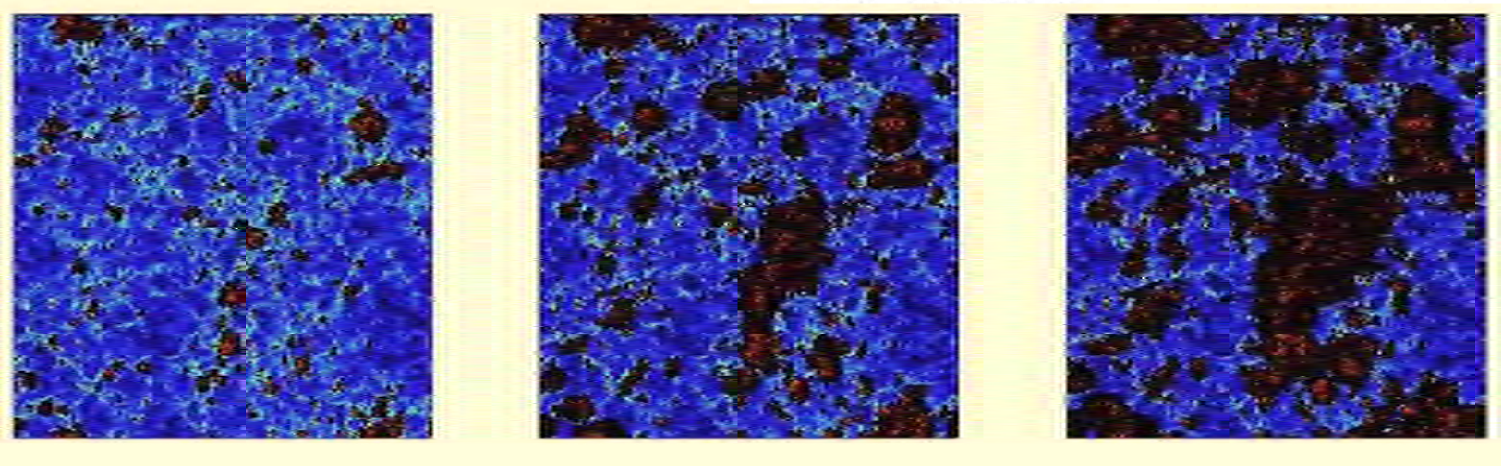
- Constraints from absorption of light from distant galaxies imply reionization was finished by about 900 Myr after the Bang
- Constraints from the Cosmic Microwave Background mean it must have started after about 300 Myr after the Bang
- This means we should be looking the frequency range 100 – 200 MHz

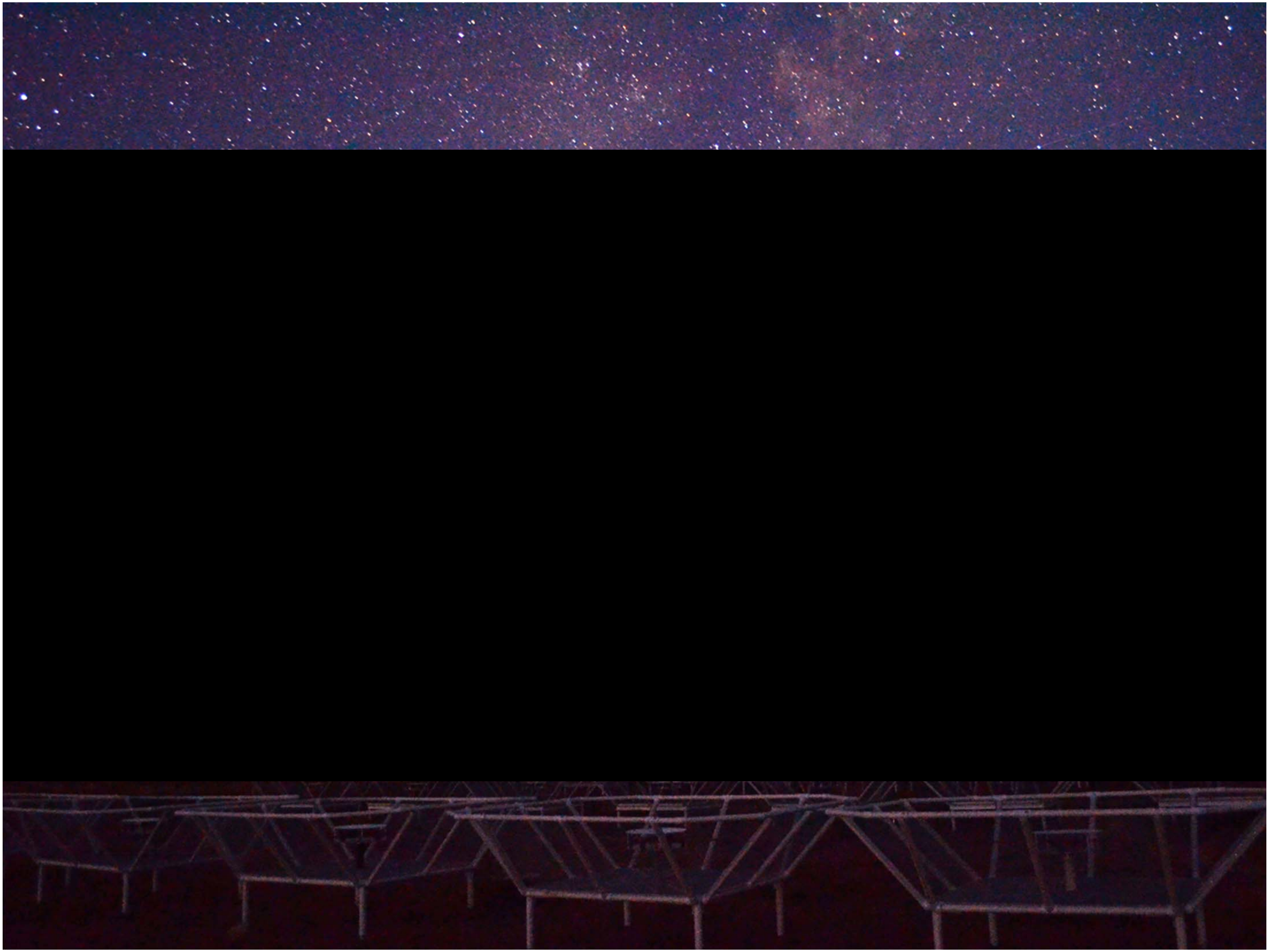
The first experiments will attempt to measure the power spectrum of 21 cm fluctuations during reionization

- The power spectrum evolves with redshift (time) in a characteristic way
- The fluctuations are on scales of 10's of Mpc (10's of arcminutes observed)
- The detection will be statistical



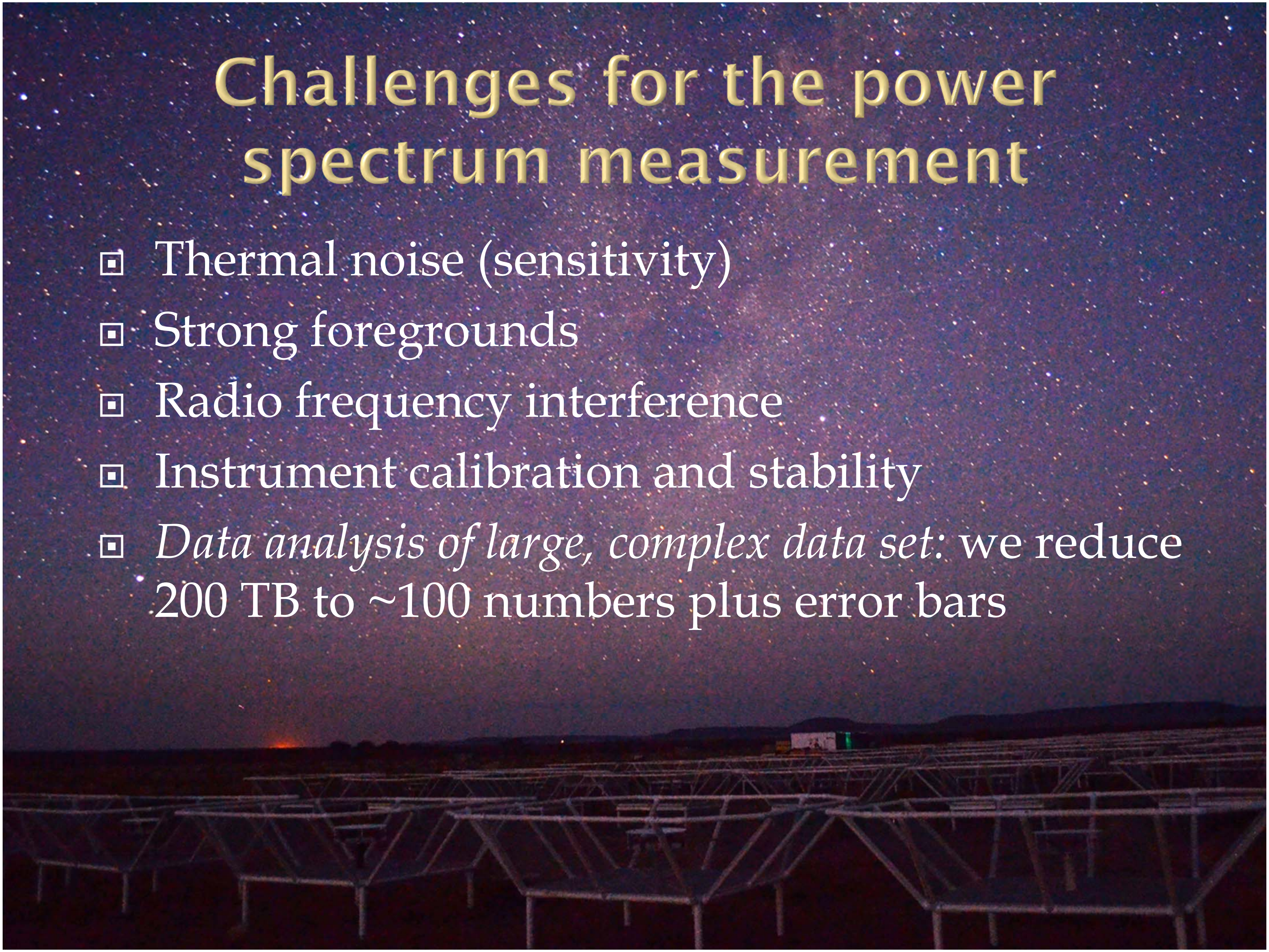
(Lidz et al. 2008)





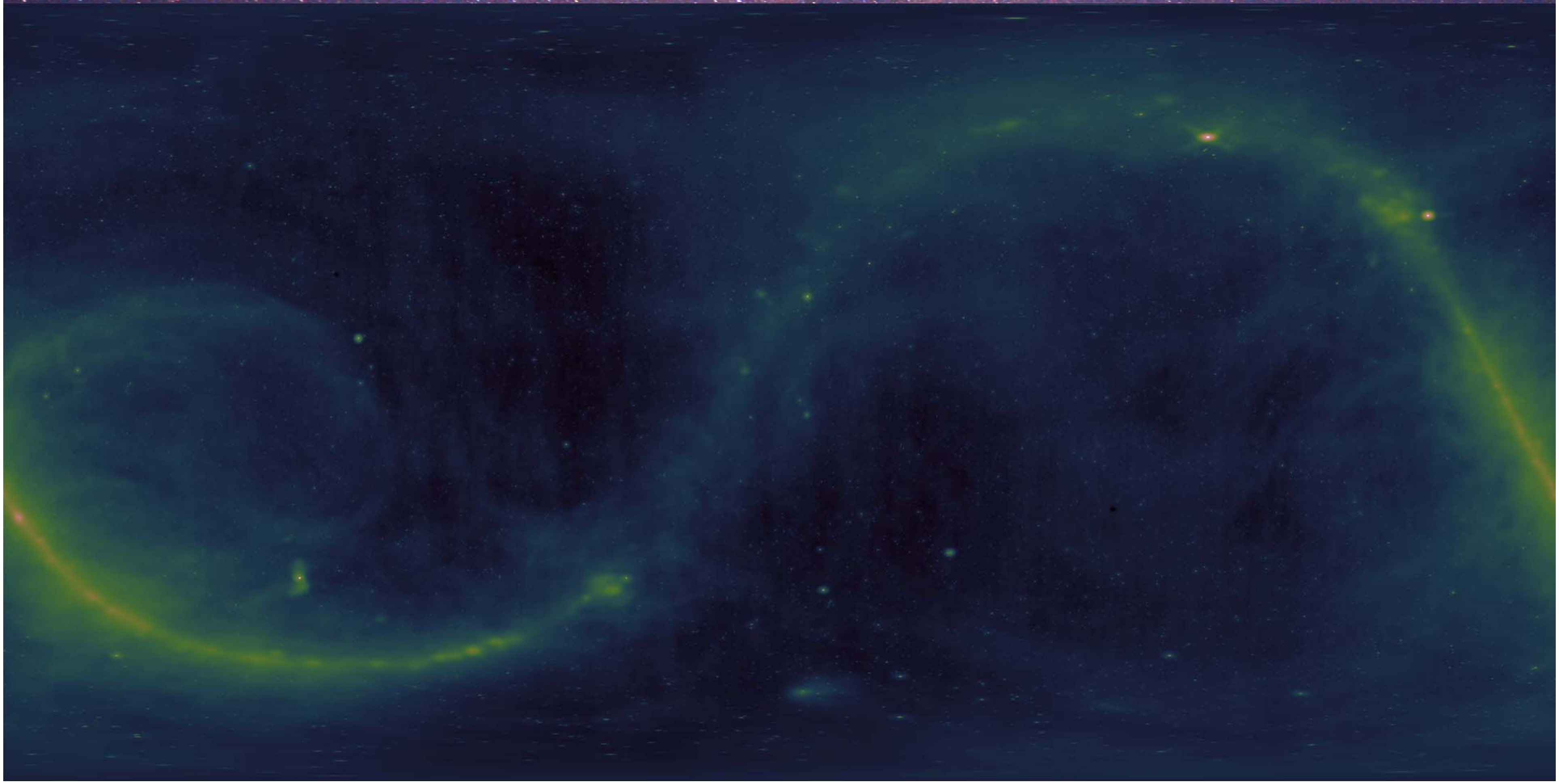
Challenges for the power spectrum measurement

- Thermal noise (sensitivity)
- Strong foregrounds
- Radio frequency interference
- Instrument calibration and stability
- *Data analysis of large, complex data set:* we reduce 200 TB to ~100 numbers plus error bars



Foregounds

Our Galaxy and every accreting black hole and star-forming region between us and the epoch of reionization is orders of magnitude brighter than our signal



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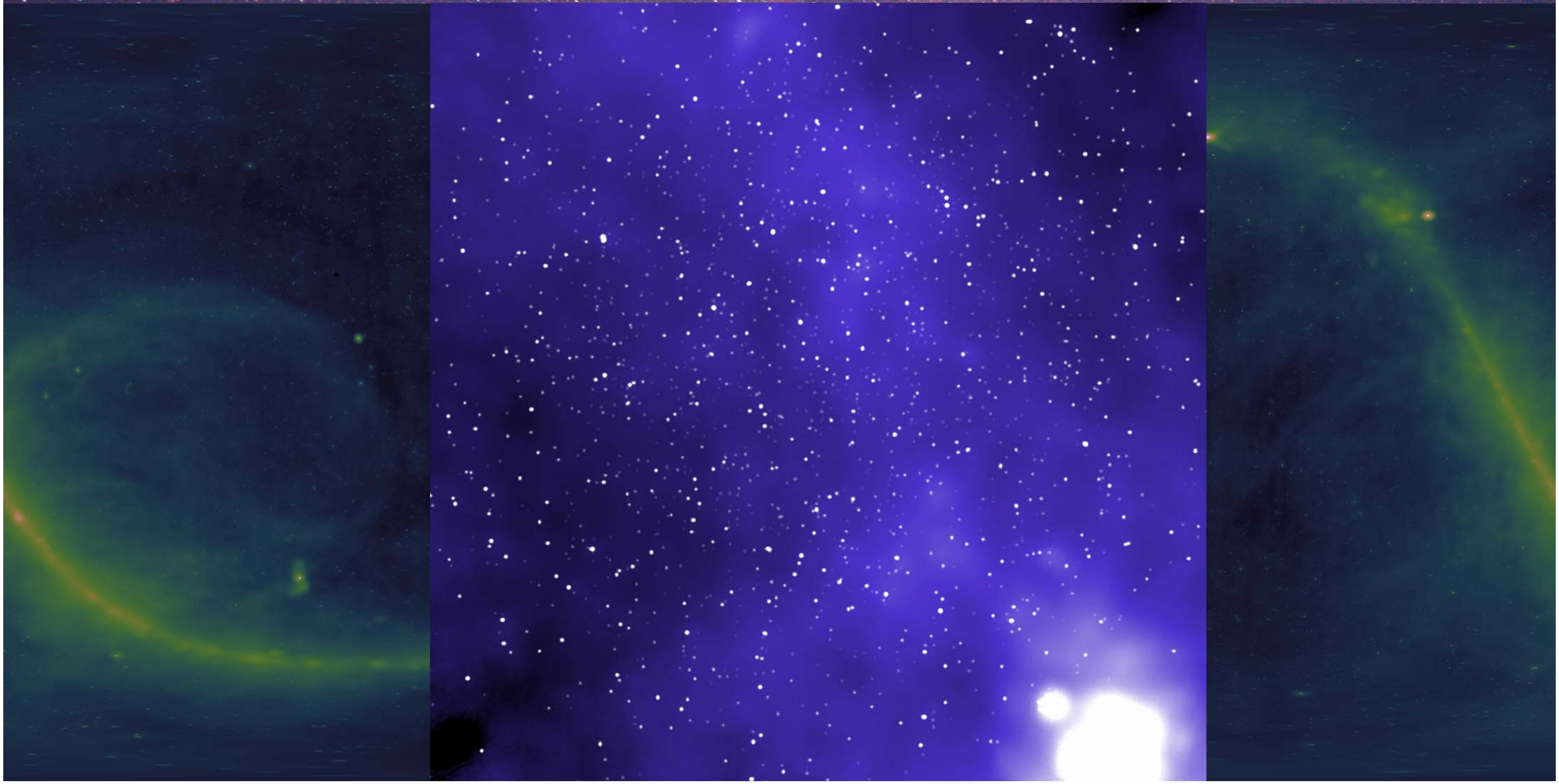

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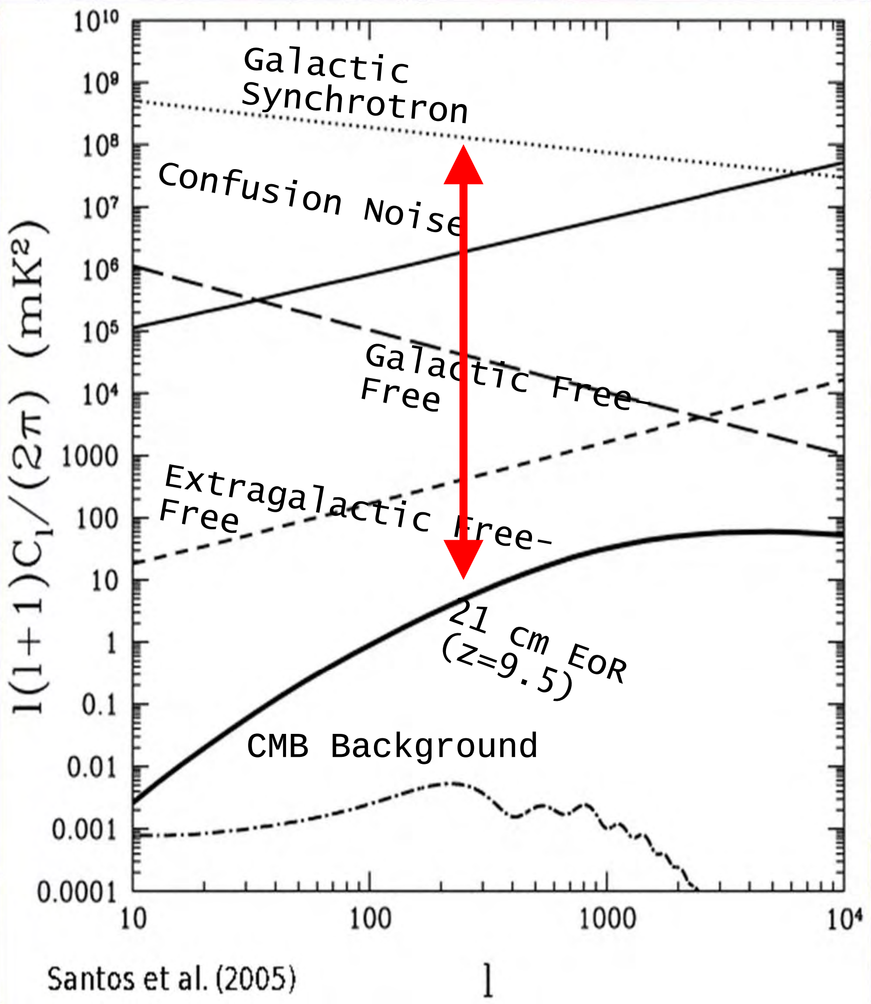

Santos et al. (2005)

We have a lever, though: the foregrounds are spectrally smooth, but our signal is not

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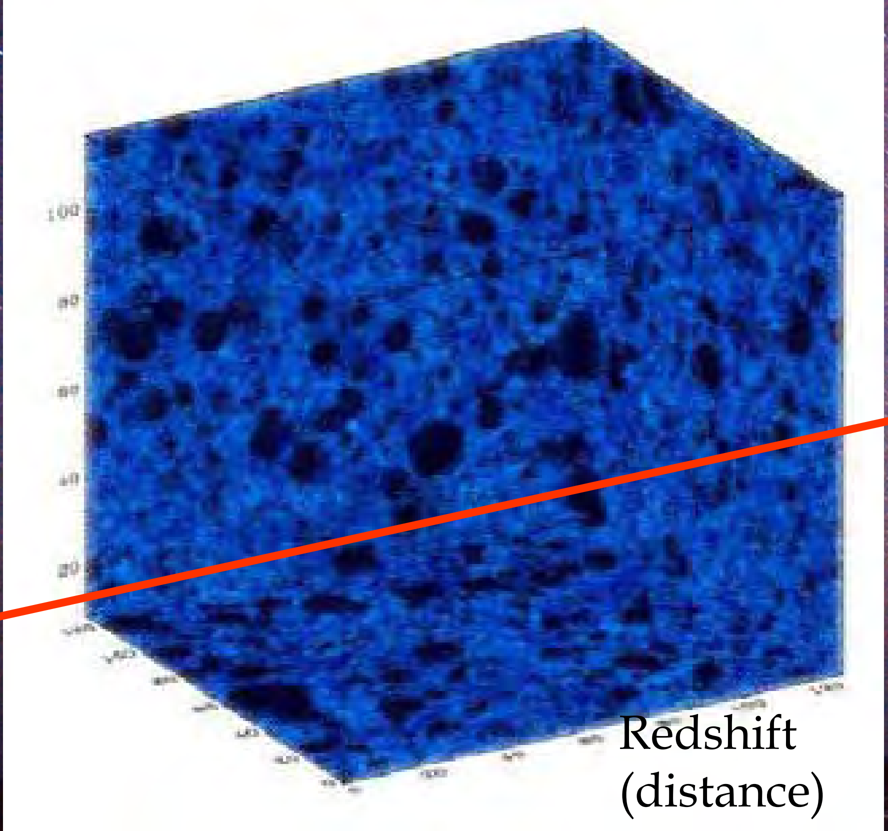

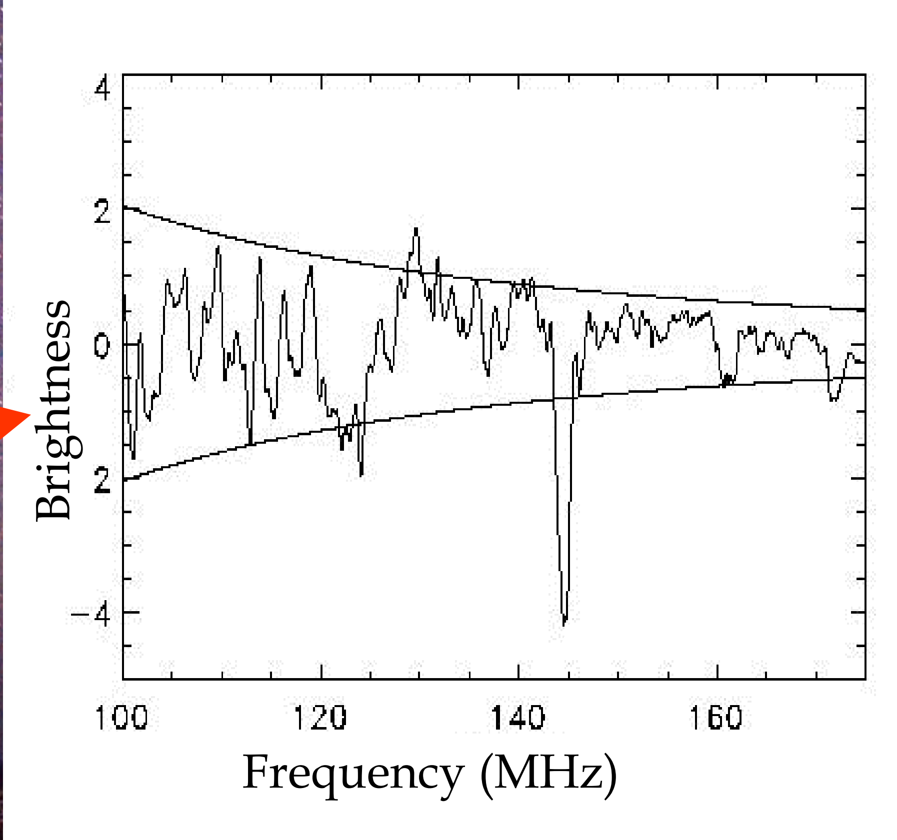

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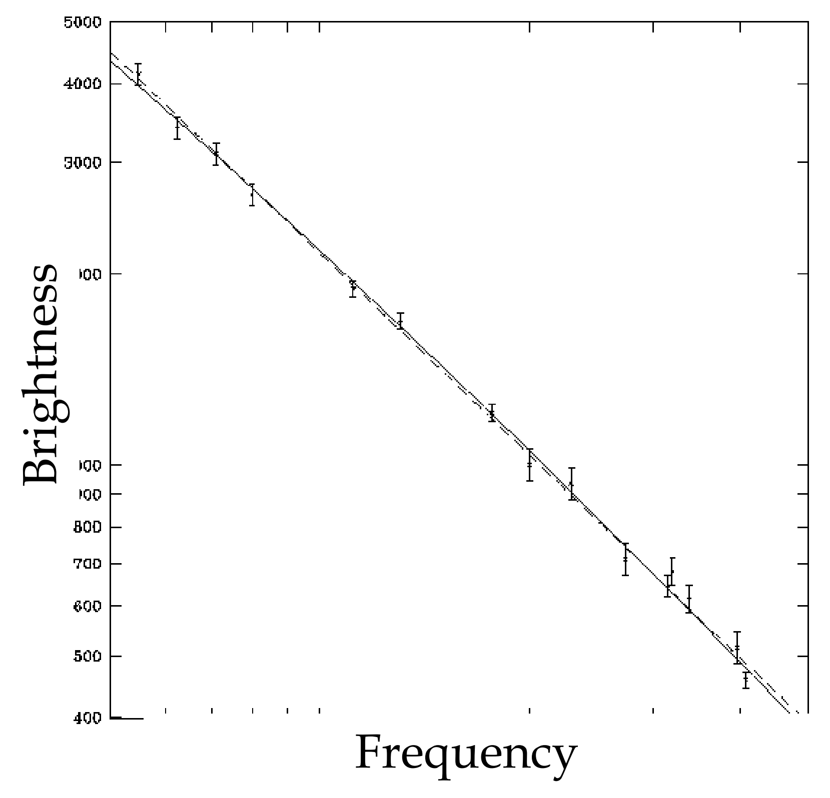
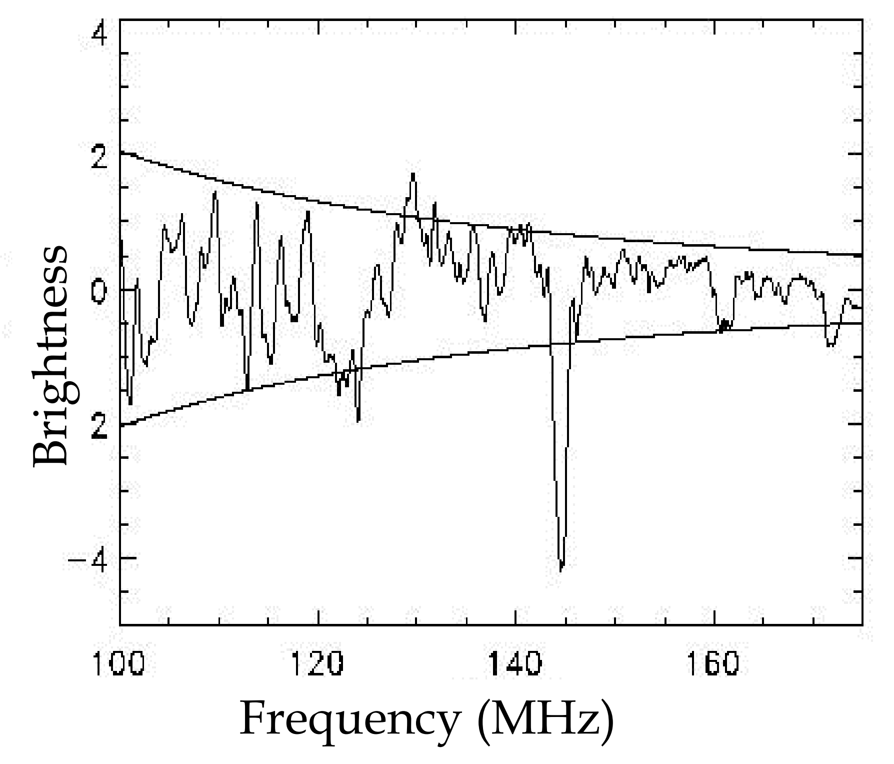
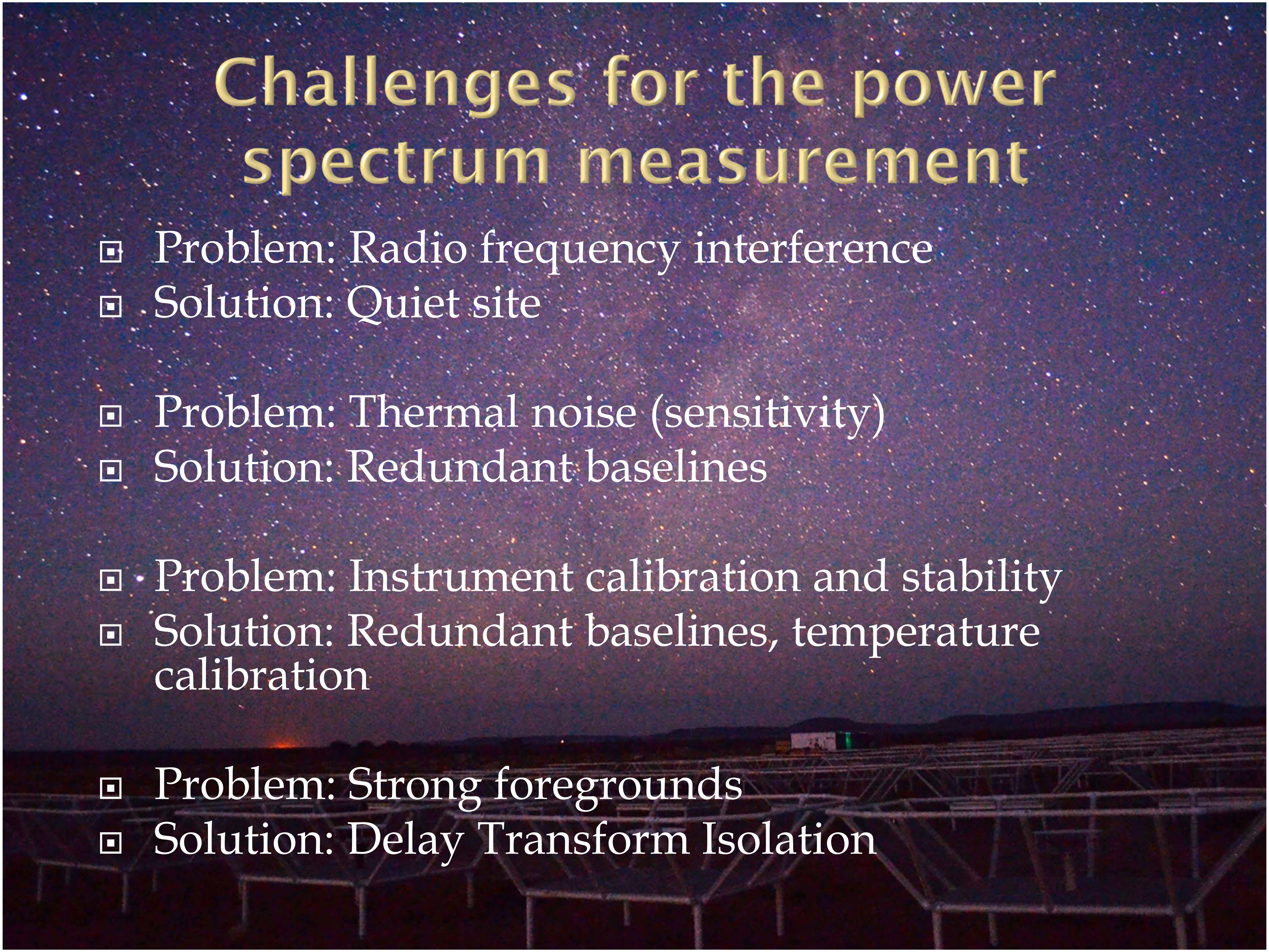






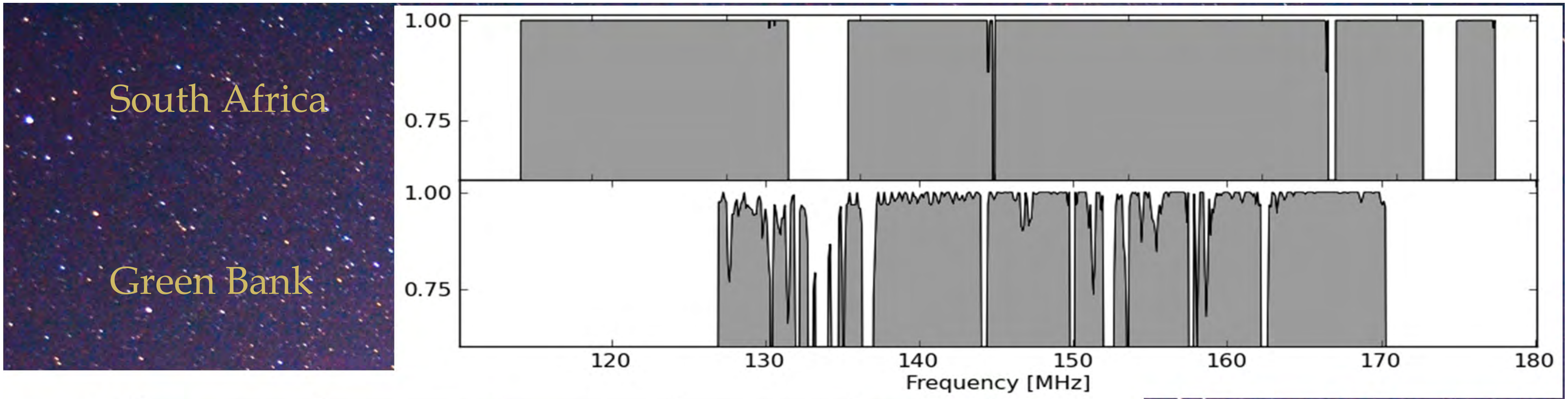
Challenges for the power spectrum measurement

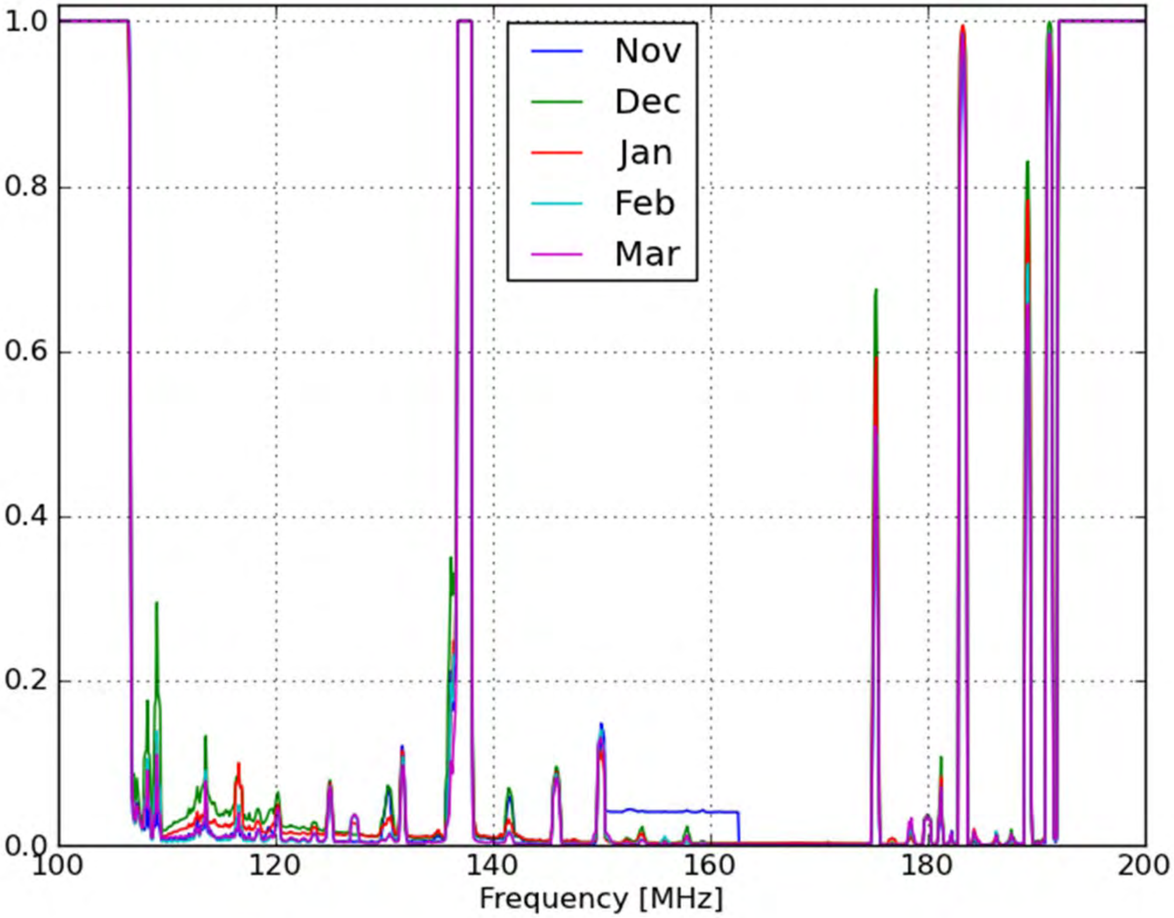
- Problem: Radio frequency interference
- Solution: Quiet site

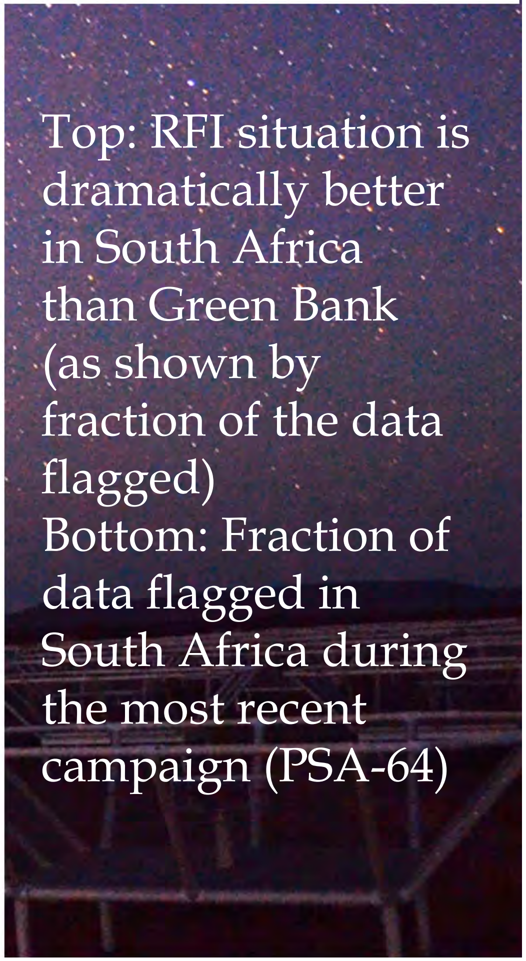
- Problem: Thermal noise (sensitivity)
- Solution: Redundant baselines

- Problem: Instrument calibration and stability
- Solution: Redundant baselines, temperature calibration

- Problem: Strong foregrounds
- Solution: Delay Transform Isolation

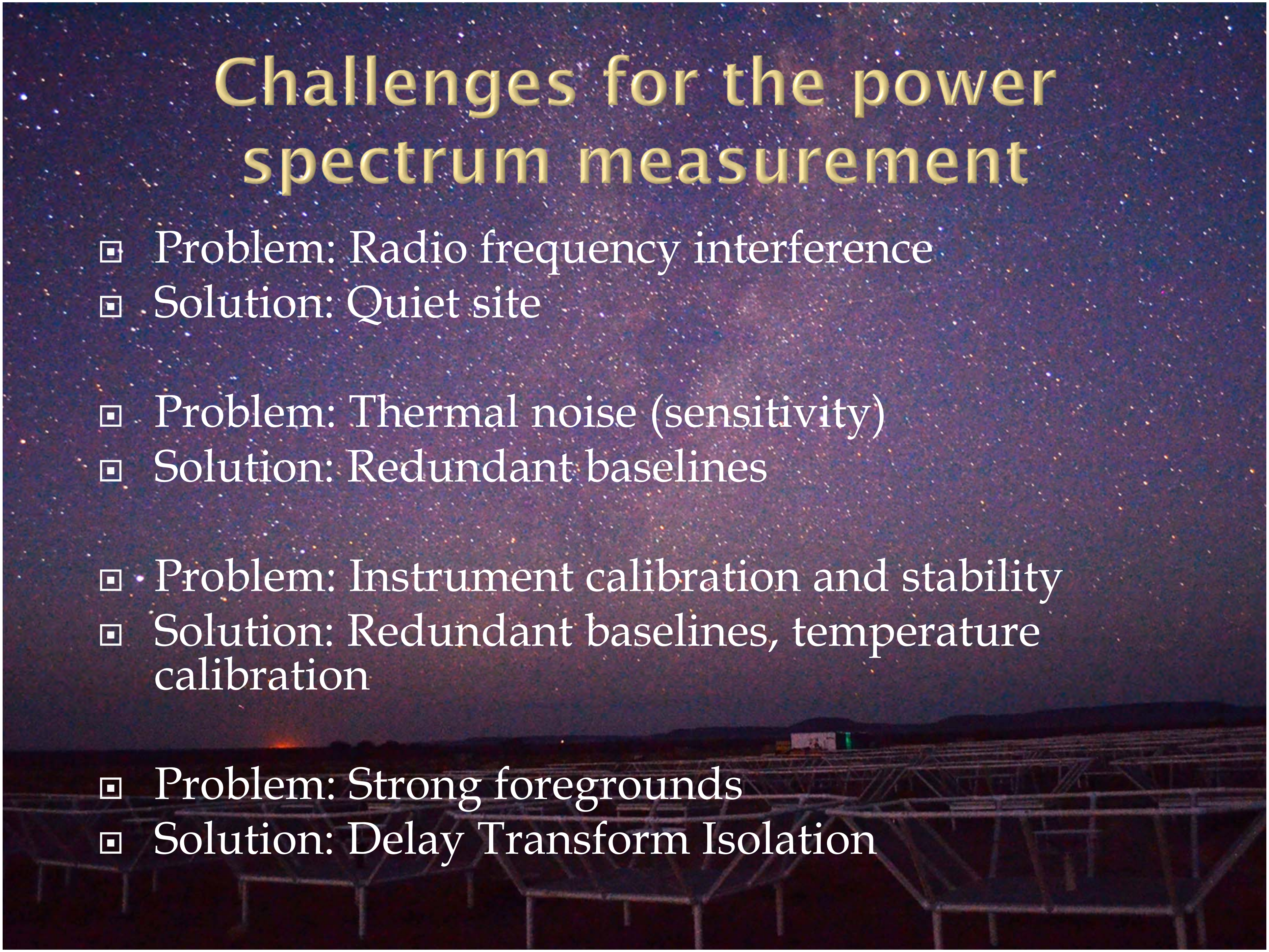






Top: RFI situation is dramatically better in South Africa than Green Bank (as shown by fraction of the data flagged)

Bottom: Fraction of data flagged in South Africa during the most recent campaign (PSA-64)



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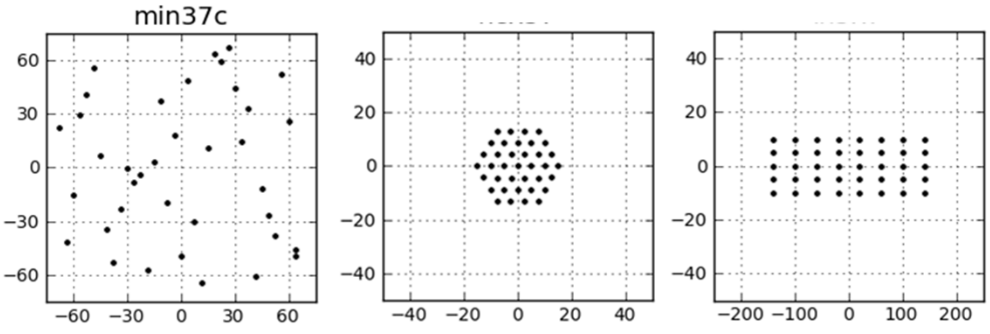
- Problem: Thermal noise (sensitivity)
- Solution: Redundant baselines

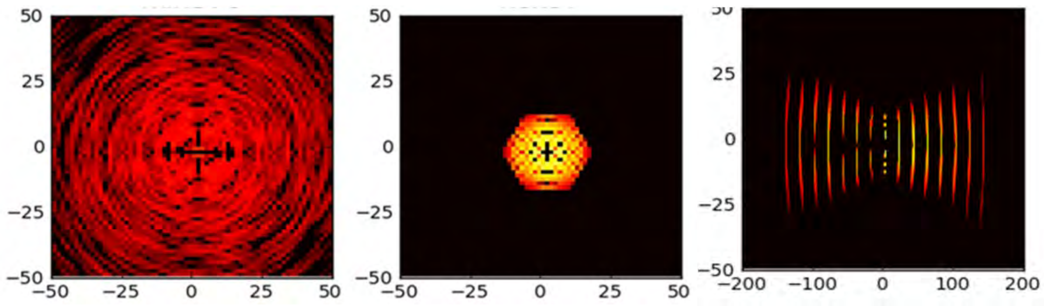
- Problem: Instrument calibration and stability
- Solution: Redundant baselines, temperature calibration

- Problem: Strong foregrounds
- Solution: Delay Transform Isolation

Configuration



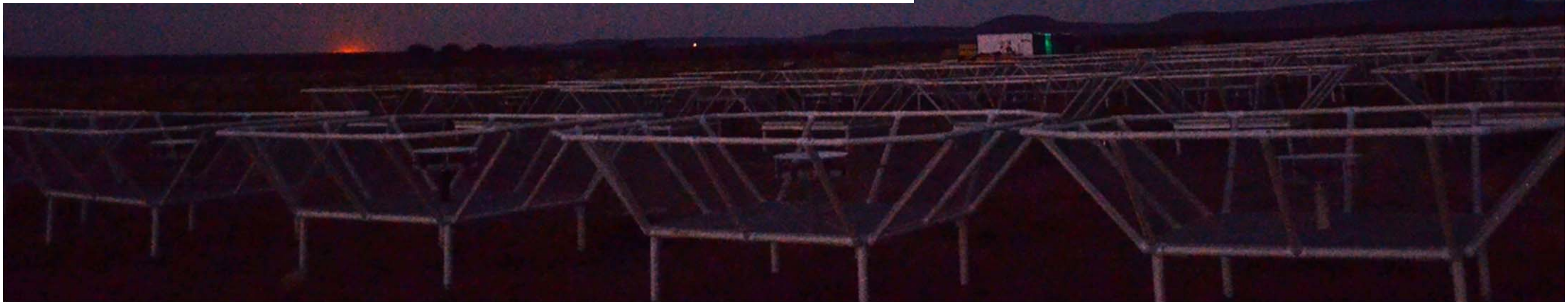
Physical configuration



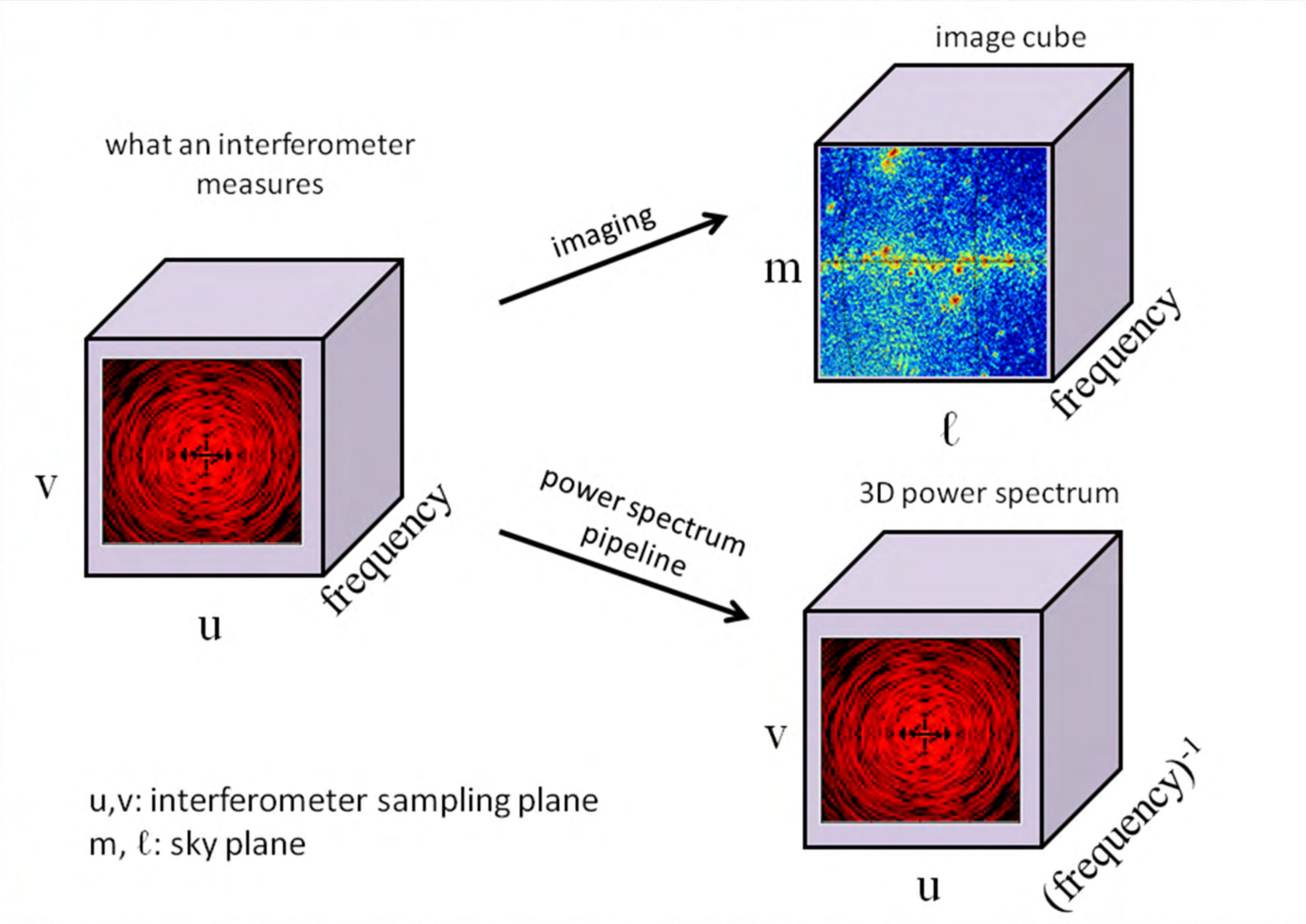
Fourier space coverage

Each baseline of an interferometer measures one point in the Fourier plane of the transform of an image.

Dense Fourier sampling produces good images.

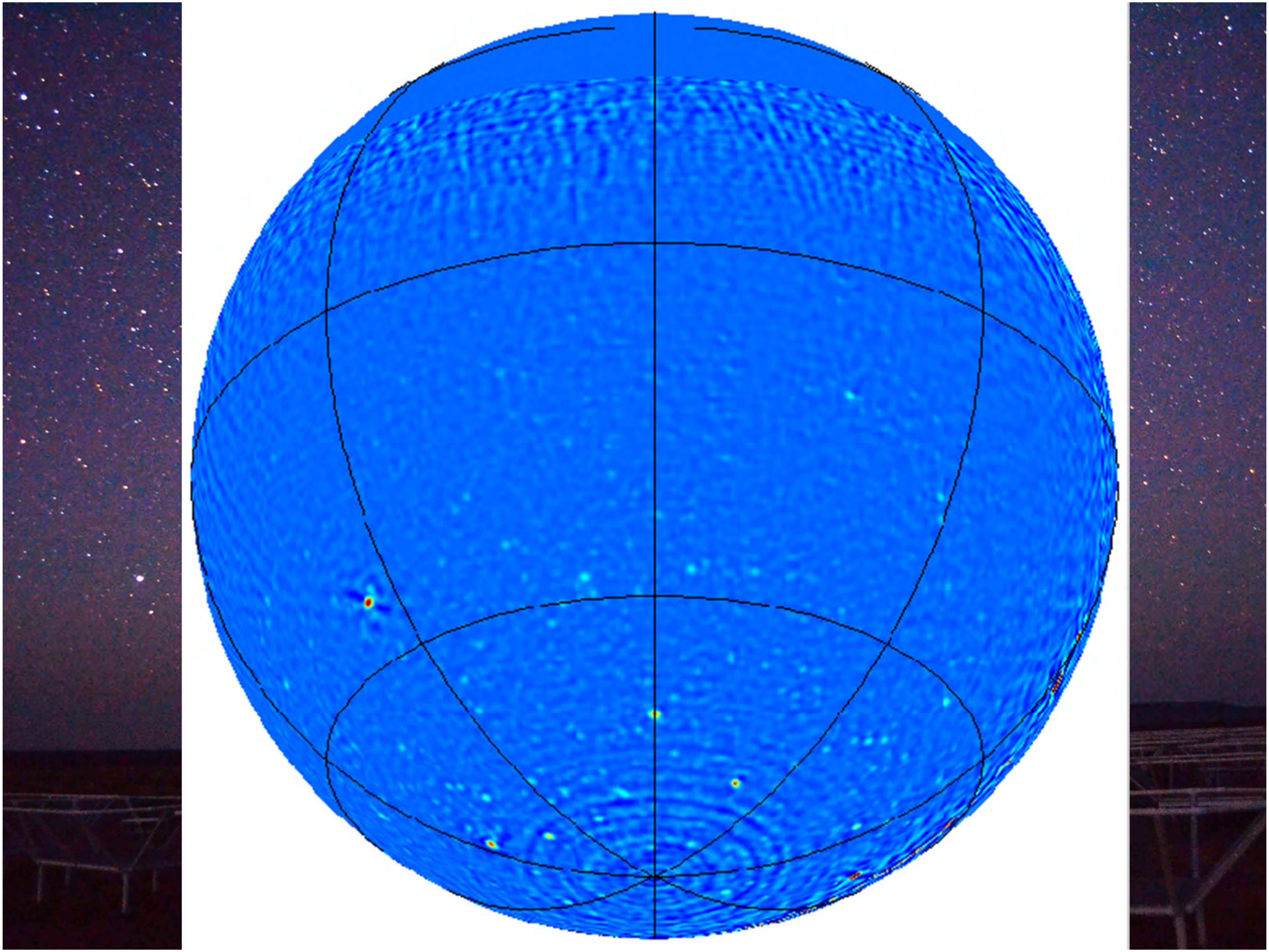


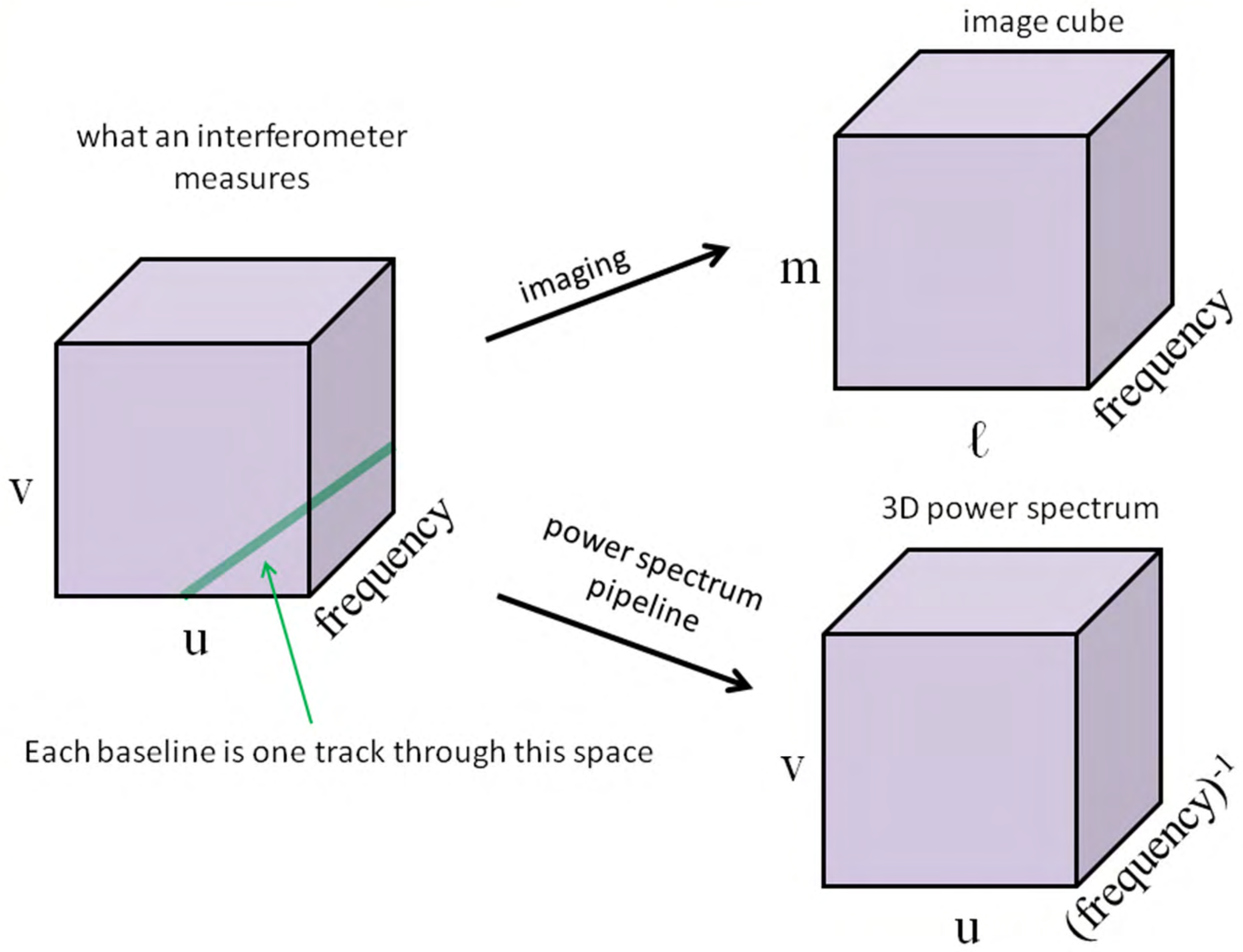
Interferometric Imaging



u,v: interferometer sampling plane
m, ℓ: sky plane

(PAPER does image! Jacobs et al 2011, 2013; Stefan et al 2013)





what an interferometer measures

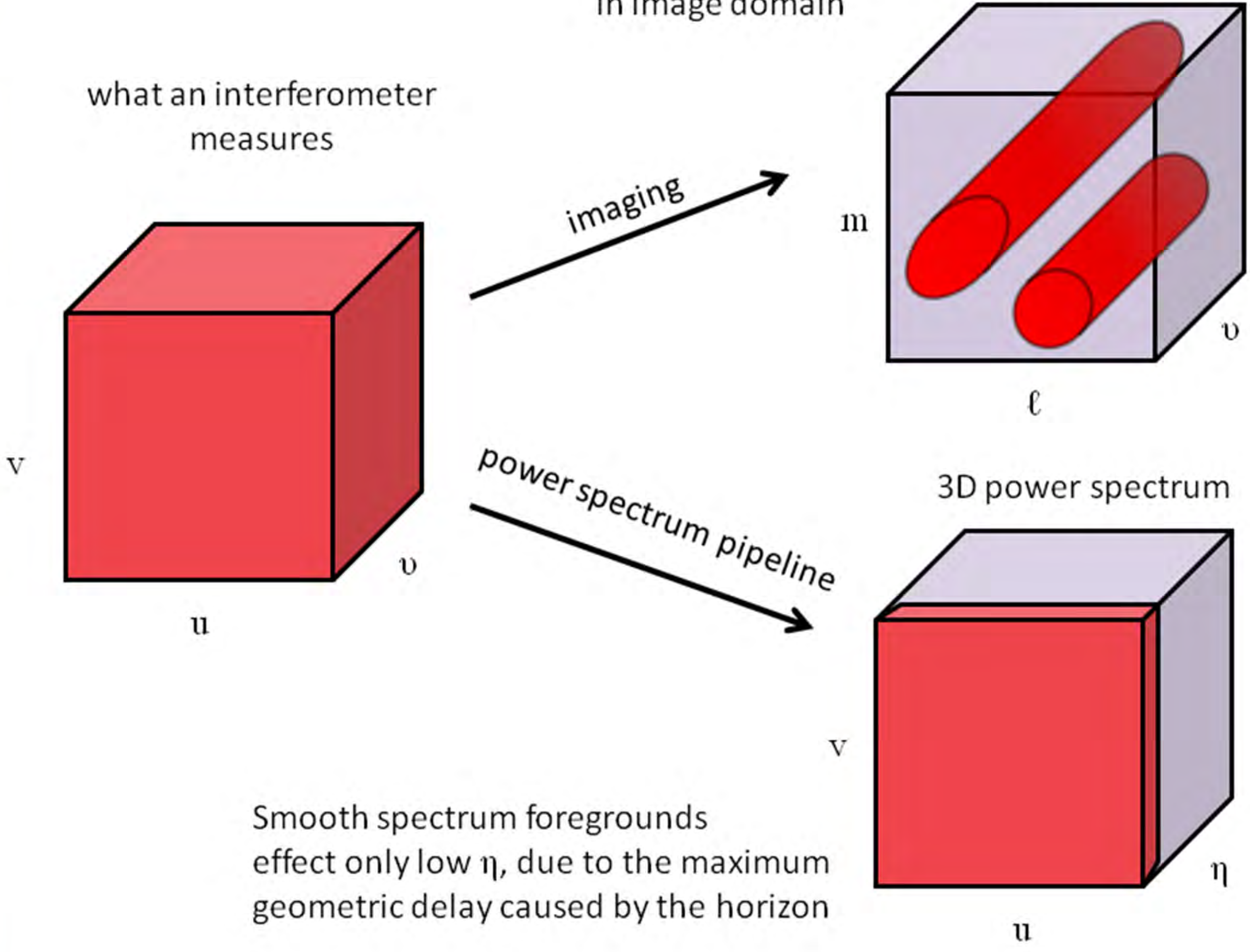
Each baseline is one track through this space

imaging

image cube

power spectrum pipeline

3D power spectrum



what an interferometer measures

Foregrounds localized in image domain

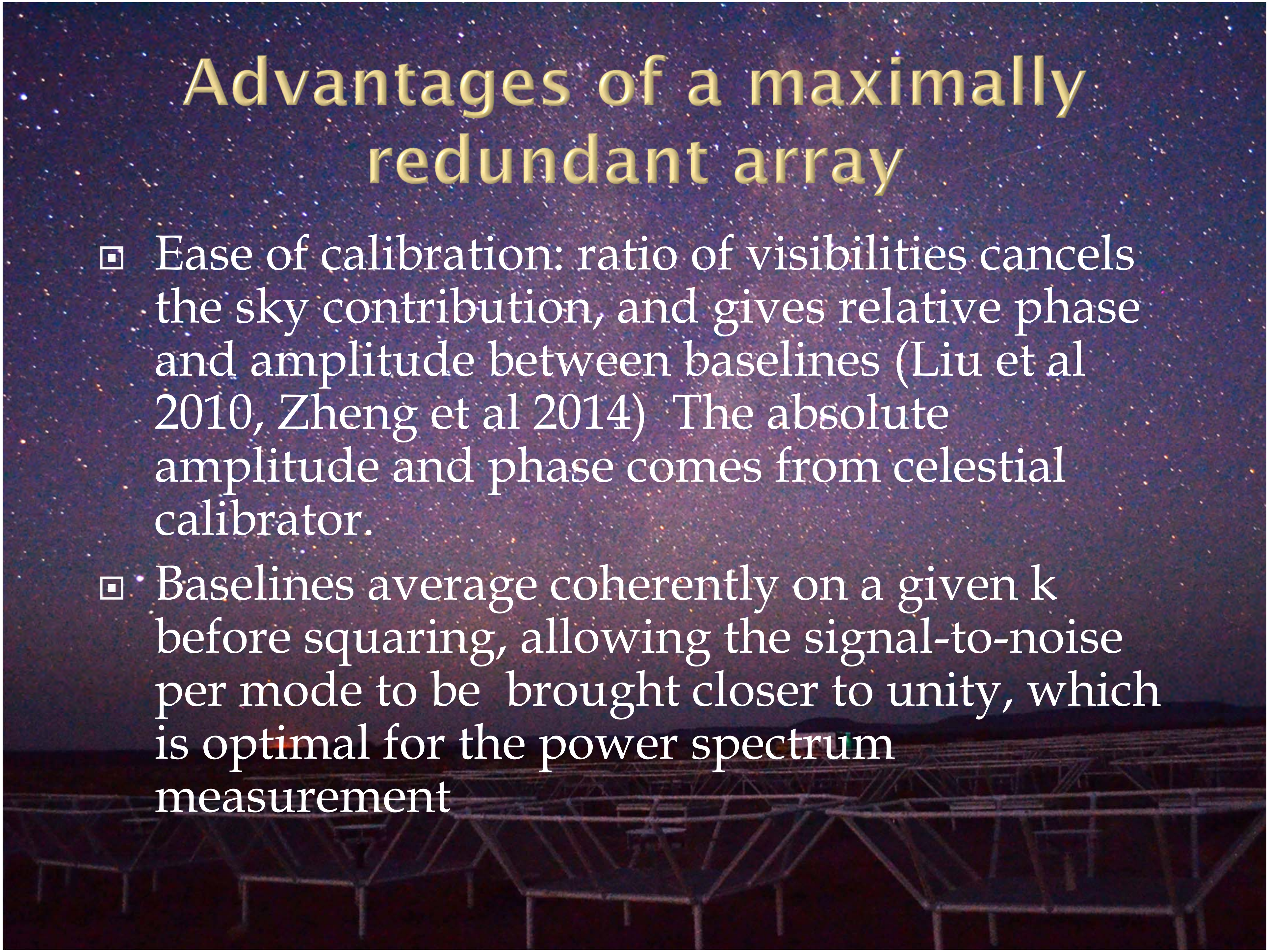
imaging

image cube

power spectrum pipeline

3D power spectrum

Smooth spectrum foregrounds
effect only low η, due to the maximum
geometric delay caused by the horizon

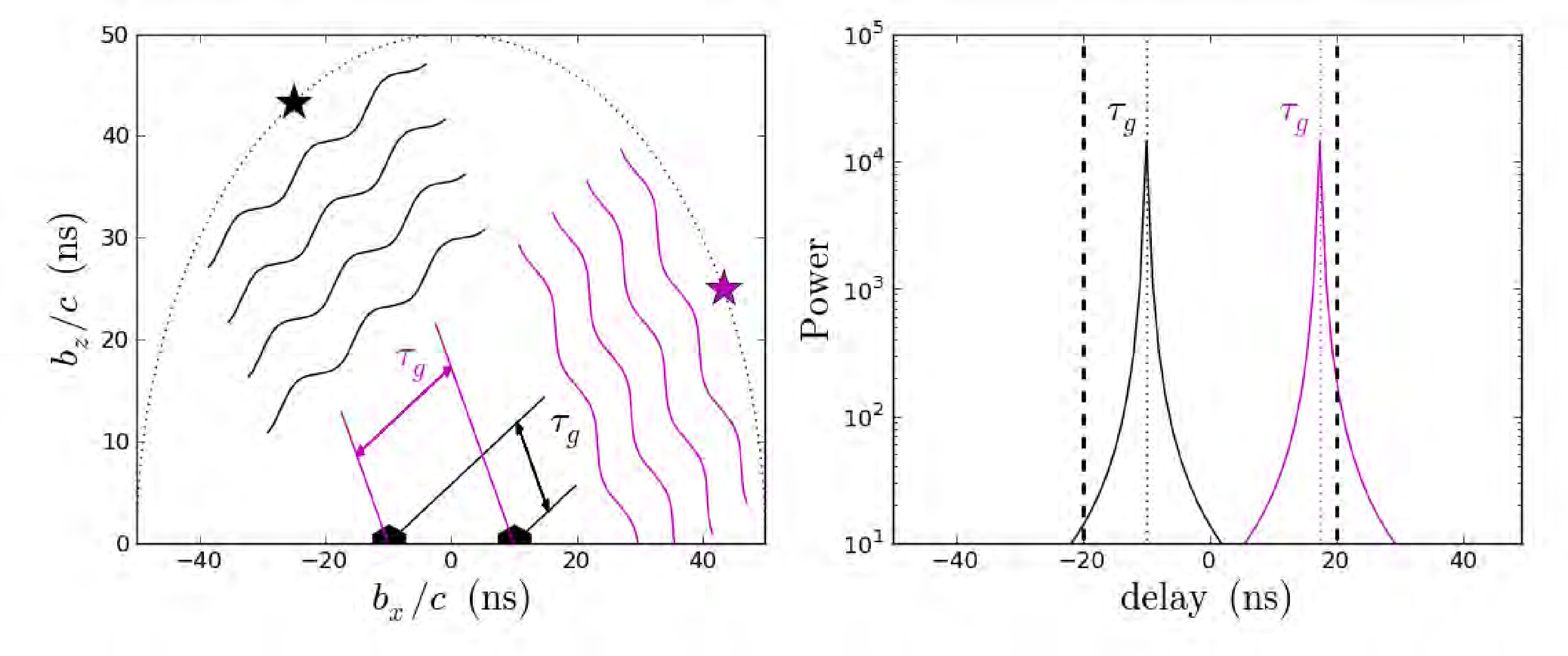


Advantages of a maximally redundant array

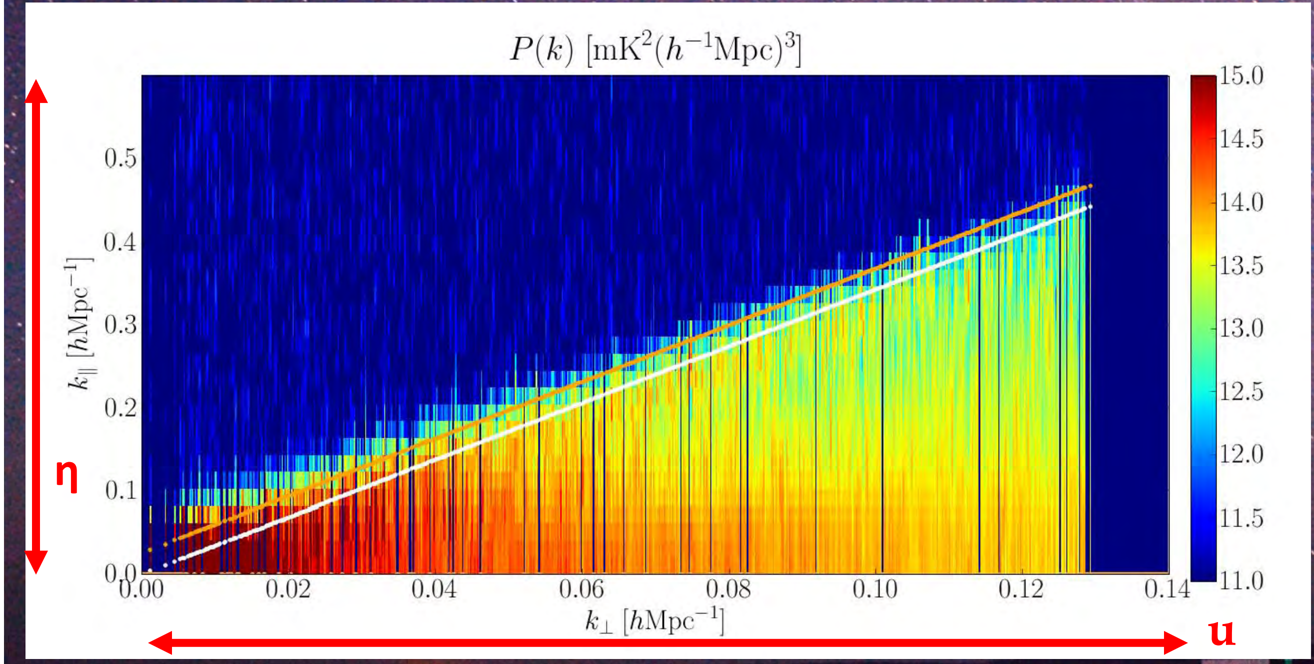
- Ease of calibration: ratio of visibilities cancels the sky contribution, and gives relative phase and amplitude between baselines (Liu et al 2010, Zheng et al 2014) The absolute amplitude and phase comes from celestial calibrator.
- Baselines average coherently on a given k before squaring, allowing the signal-to-noise per mode to be brought closer to unity, which is optimal for the power spectrum measurement

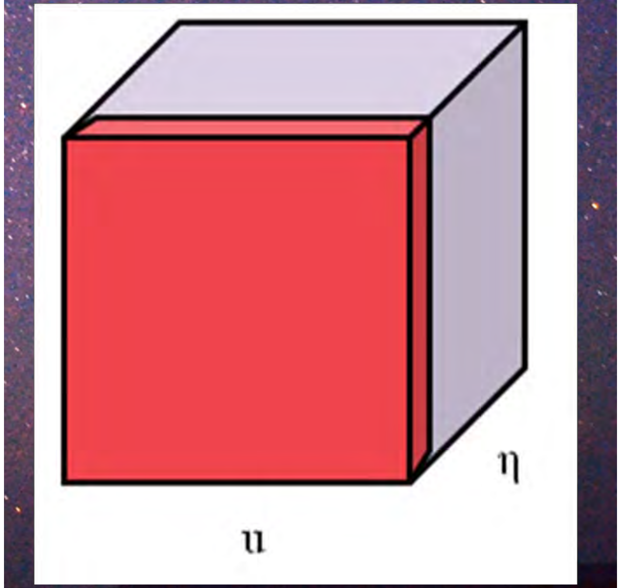
The Delay Transform

- Delay space: Fourier transform of frequency axis
- Point sources map to (nearly) delta functions if they are *smooth* in frequency space
- The central delay is then the geometric delay set by the baseline length
- The width in delay space is a measure of the frequency coherence of the spectrum
- Delay space is very nearly *k_parallel*-space
- Note the *maximum* geometric delay caused by the horizon



Foregrounds in k-space

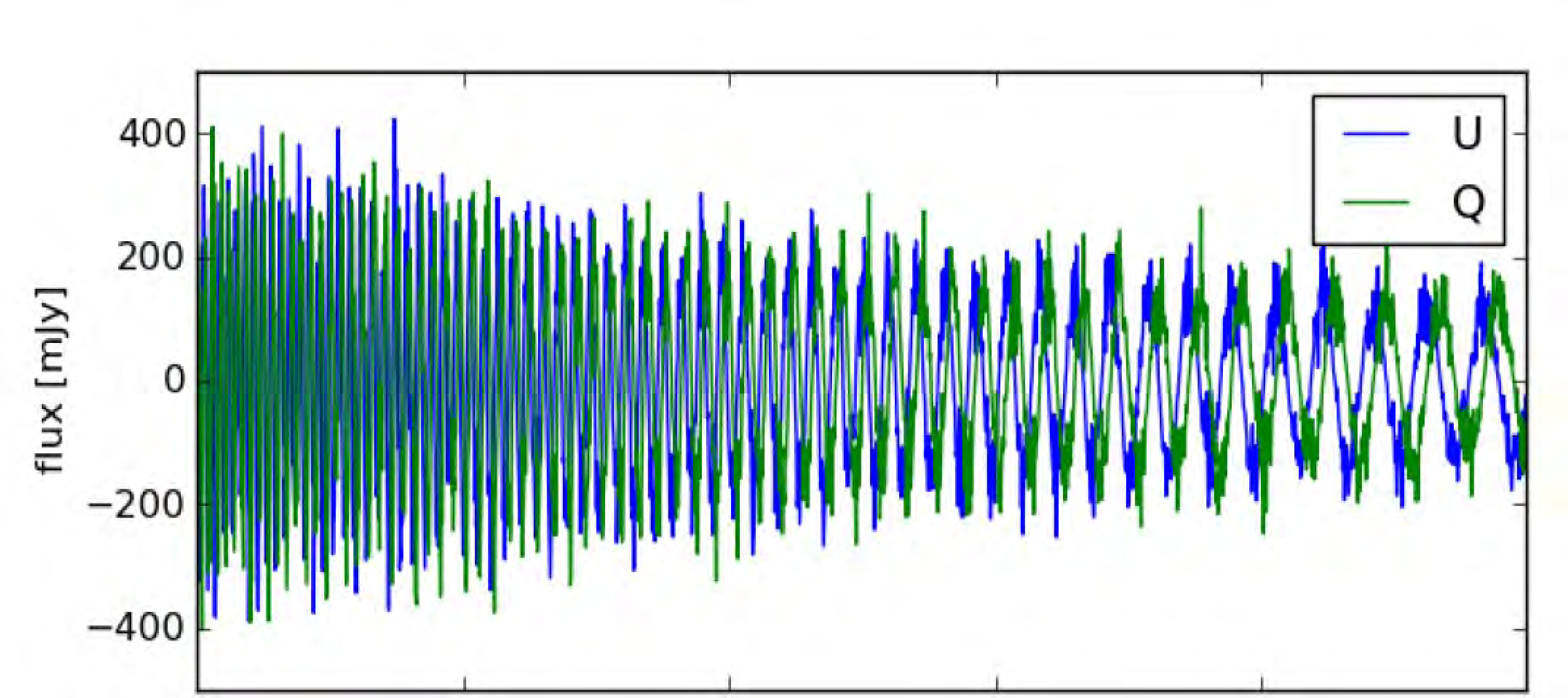




Polarization Effects on EoR

- Faraday rotation of polarized sources could introduce frequency dependent structure. Individual sources produce a periodic signal as a function of ν^{-2} Leakage of this signal could produce non-smooth structure.

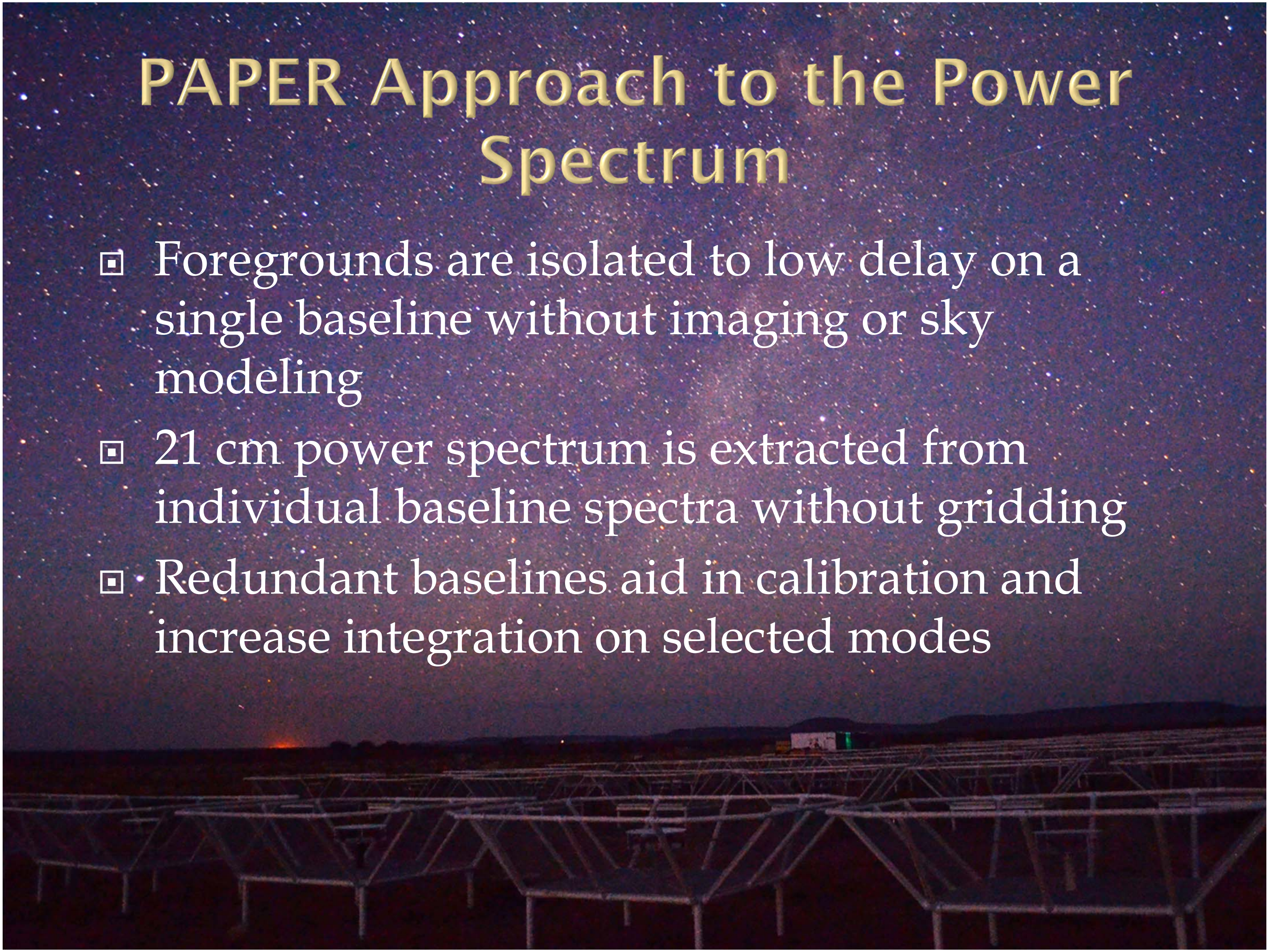
$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n_e B_{\parallel} ds$$



Polarization effects are mitigated by:

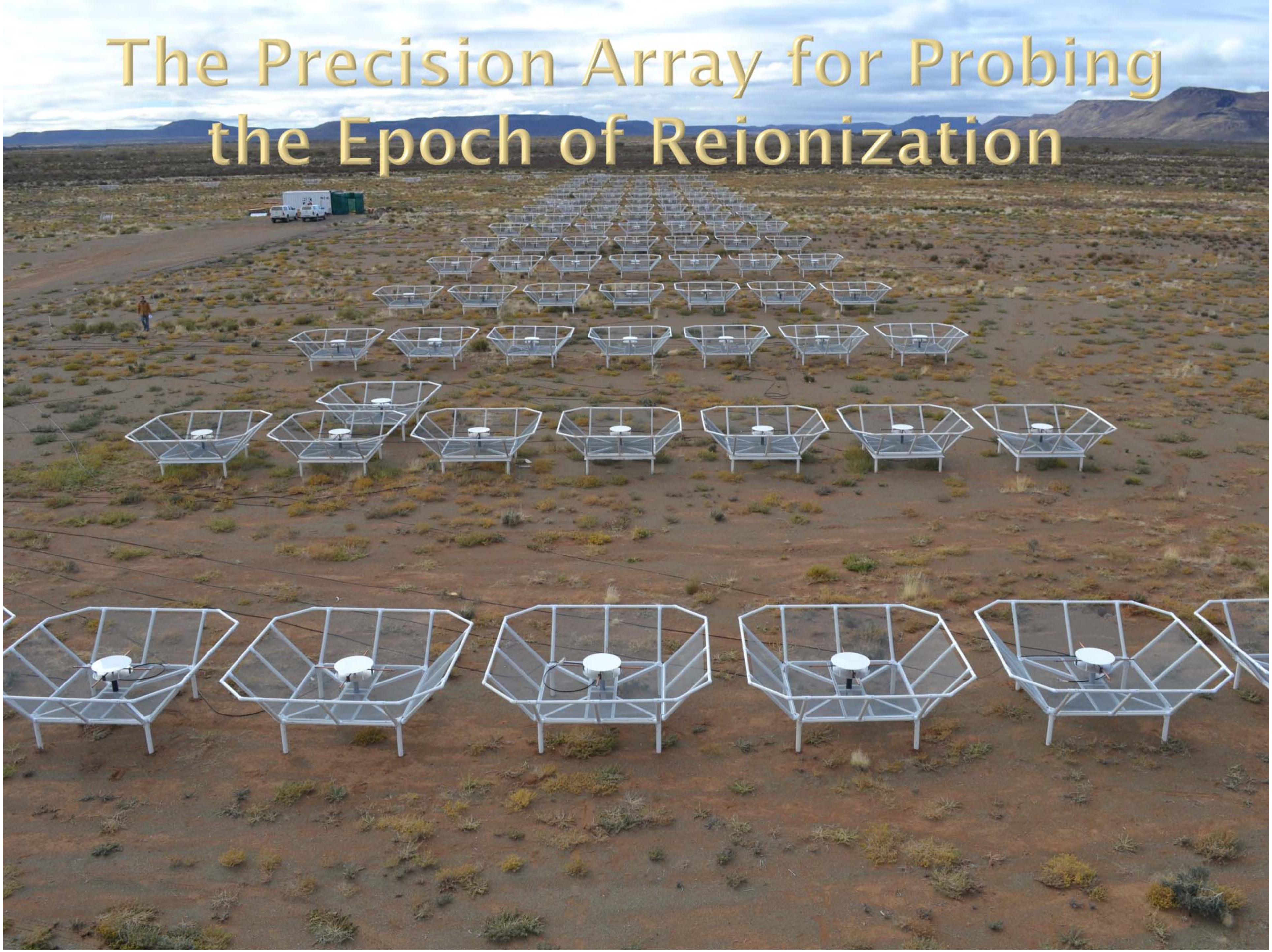
- Low intrinsic polarization of sources
- Precision calibration made possible in maximum redundancy array

PAPER Approach to the Power Spectrum



- Foregrounds are isolated to low delay on a single baseline without imaging or sky modeling
- 21 cm power spectrum is extracted from individual baseline spectra without gridding
- Redundant baselines aid in calibration and increase integration on selected modes

The Precision Array for Probing the Epoch of Reionization



The PAPER Instrument

- A radio interferometer
- 128 antennas each receiving both linear polarizations
- 100-200 MHz bandwidth
- Easily reconfigurable (unburied TV cable)
- Large, smooth primary beam covering most of the sky
- Science operations in South Africa

The PAPER Team

UVa / NRAO

Rich Bradley
Pat Klima
Formerly:
Nicole Gugliucci
Chaitali Parashare

NRAO-GB

Ford
Lacasse
Greenberg
Treacy
Klopp

UC Berkeley

Aaron Parsons
Adrian Liu
Jonnie Pober
(now at UW)
Zaki Ali
Carina Cheng
Dave De Boer
Dave MacMahon
Matt Dexter

SKA-SA

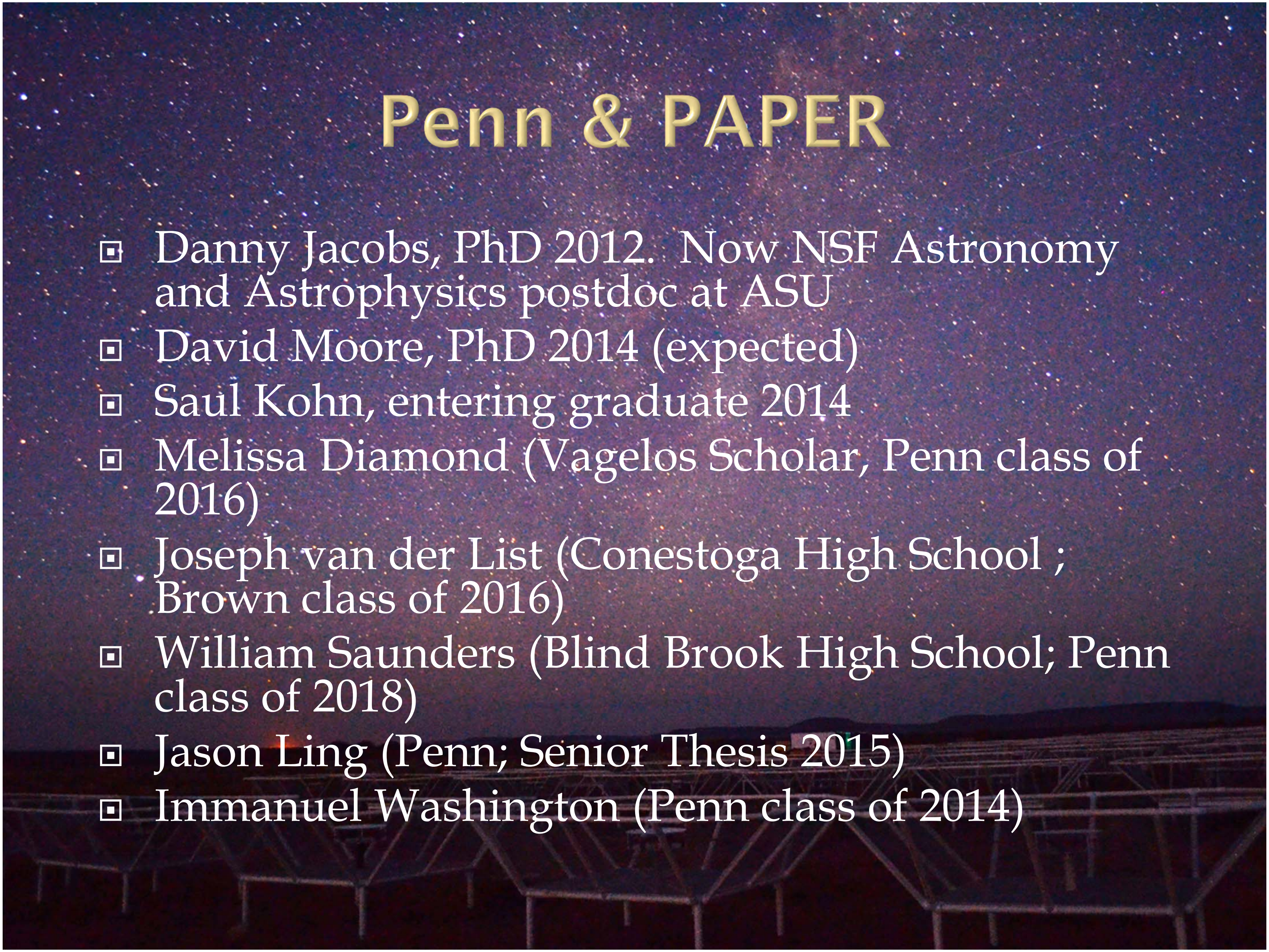
William Walbrugh
Jason Manley

U. Penn.

James Aguirre
Danny Jacobs
(now at ASU)
David Moore

Cambridge

Chris Carilli
Irina Stefan



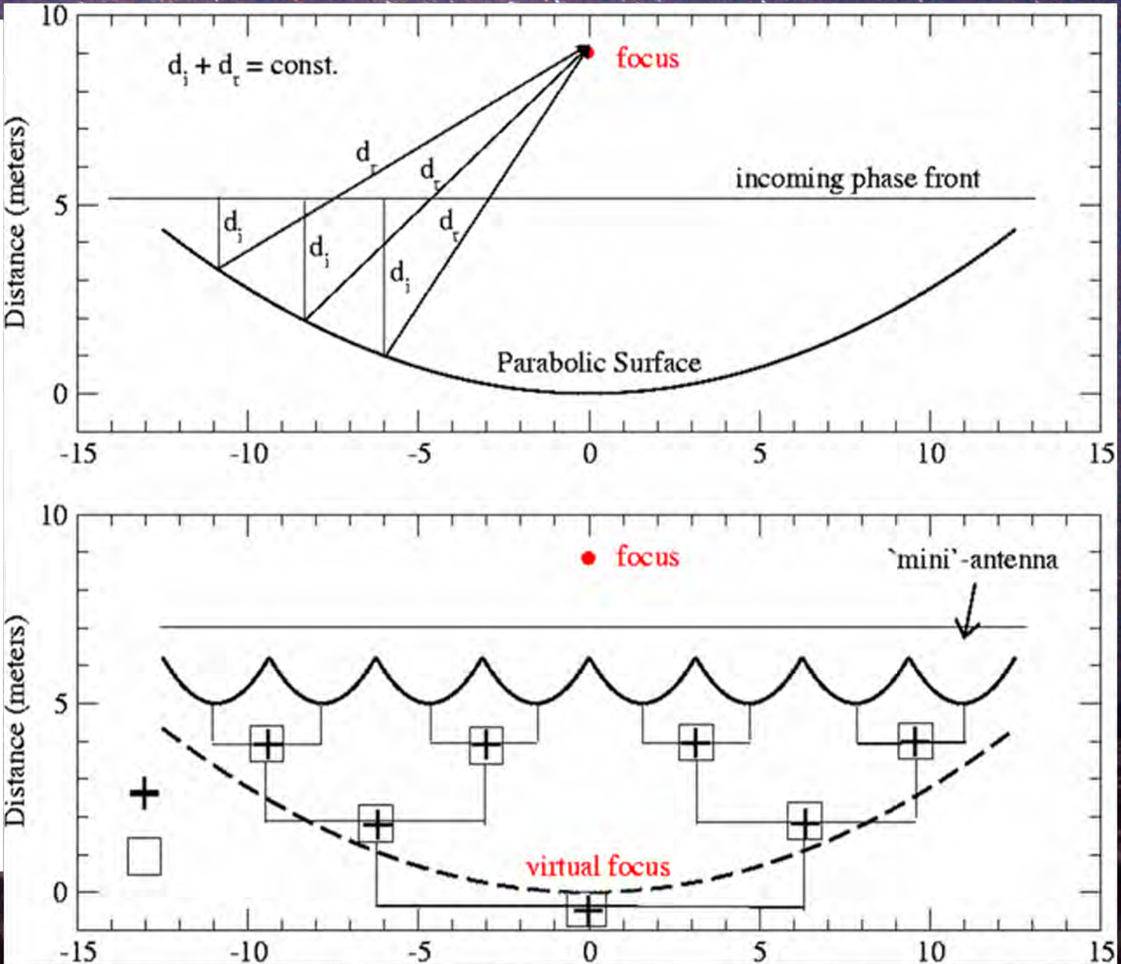
Penn & PAPER

- Danny Jacobs, PhD 2012. Now NSF Astronomy and Astrophysics postdoc at ASU
- David Moore, PhD 2014 (expected)
- Saul Kohn, entering graduate 2014
- Melissa Diamond (Vagelos Scholar, Penn class of 2016)
- Joseph van der List (Conestoga High School ; Brown class of 2016)
- William Saunders (Blind Brook High School; Penn class of 2018)
- Jason Ling (Penn; Senior Thesis 2015)
- Immanuel Washington (Penn class of 2014)

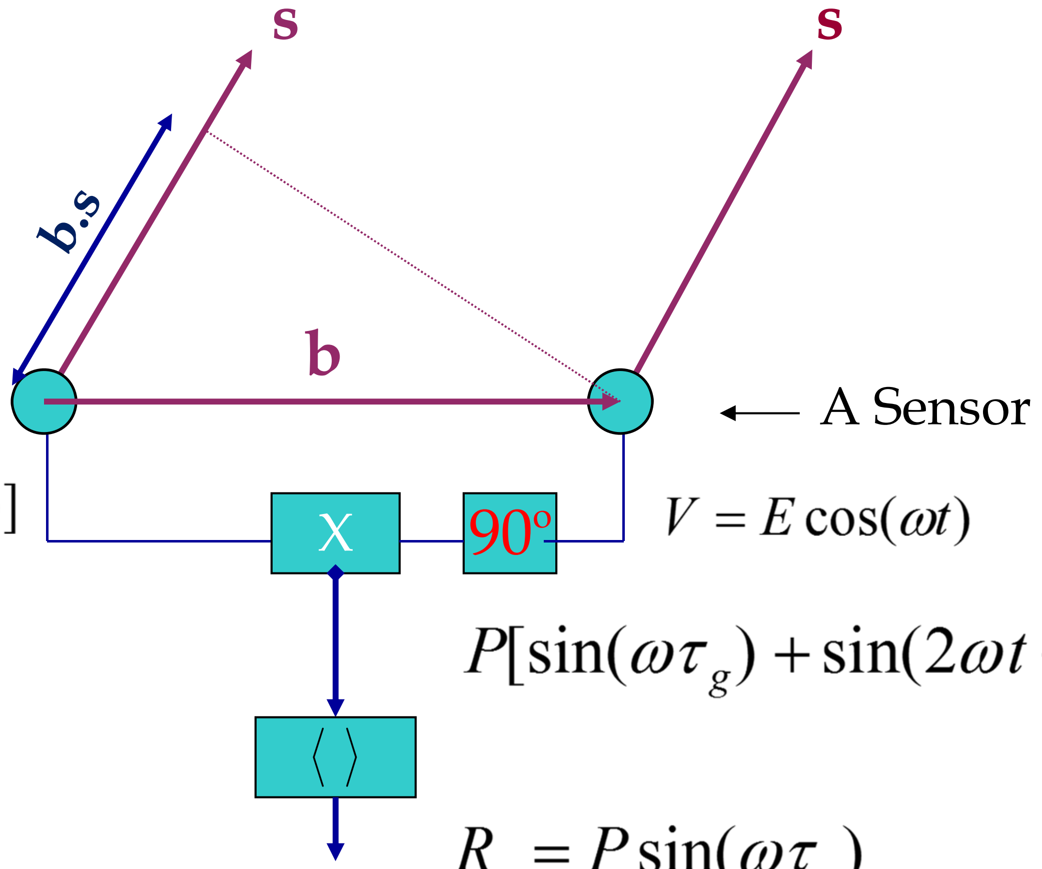
Aperture Synthesis

In order to gain the resolution of one large telescope without having to build a single large dish, we can use *aperture synthesis.*

This is done by sequentially combining pairs of signals from a "virtual antenna". If we break the aperture into N sub-apertures, there will be N(N–1)/2 pairs to combine.



A baseline's measurement



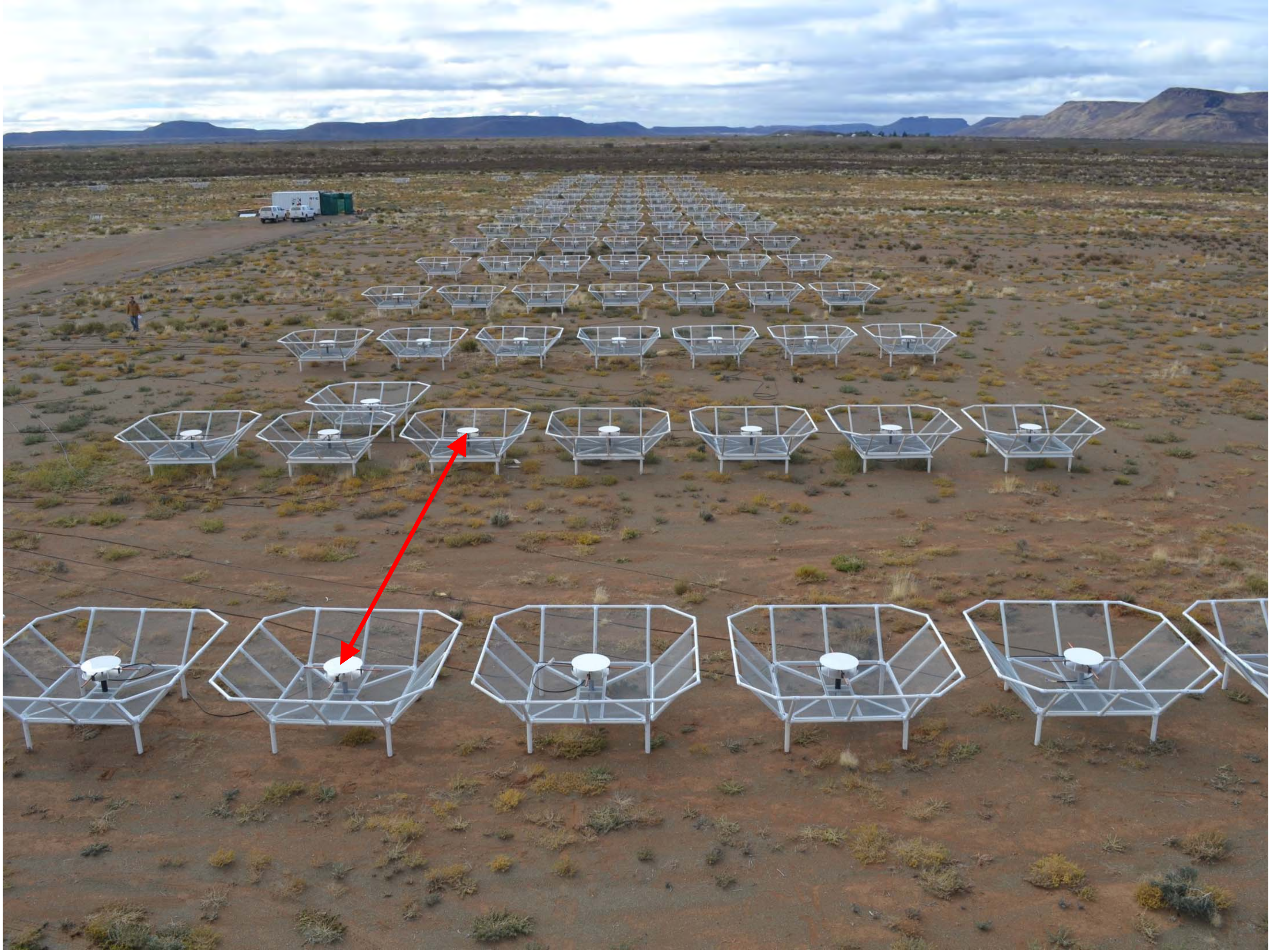
$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$

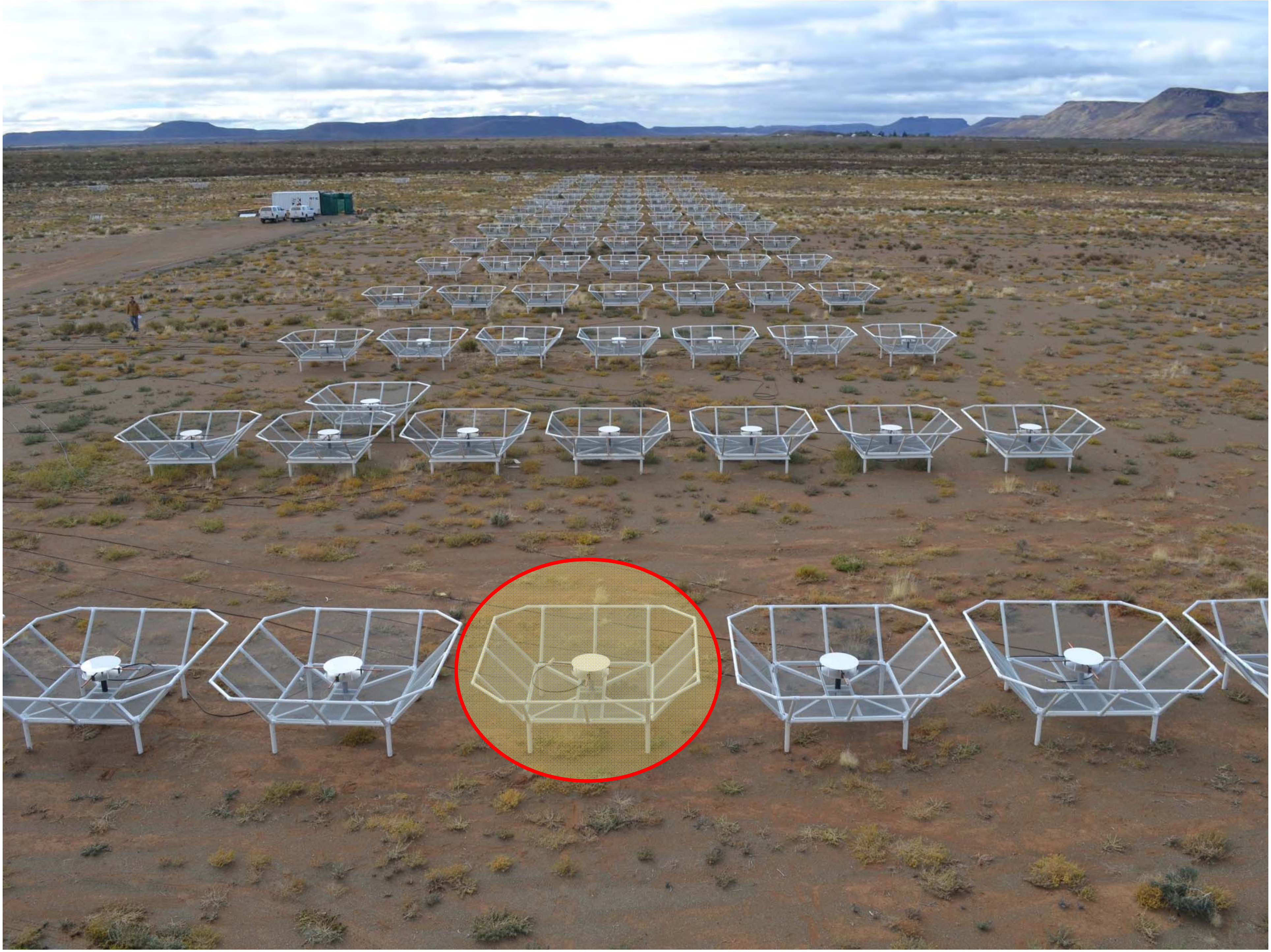
$$V = E \cos[\omega(t - \tau_g)]$$

$$V = E \cos(\omega t)$$

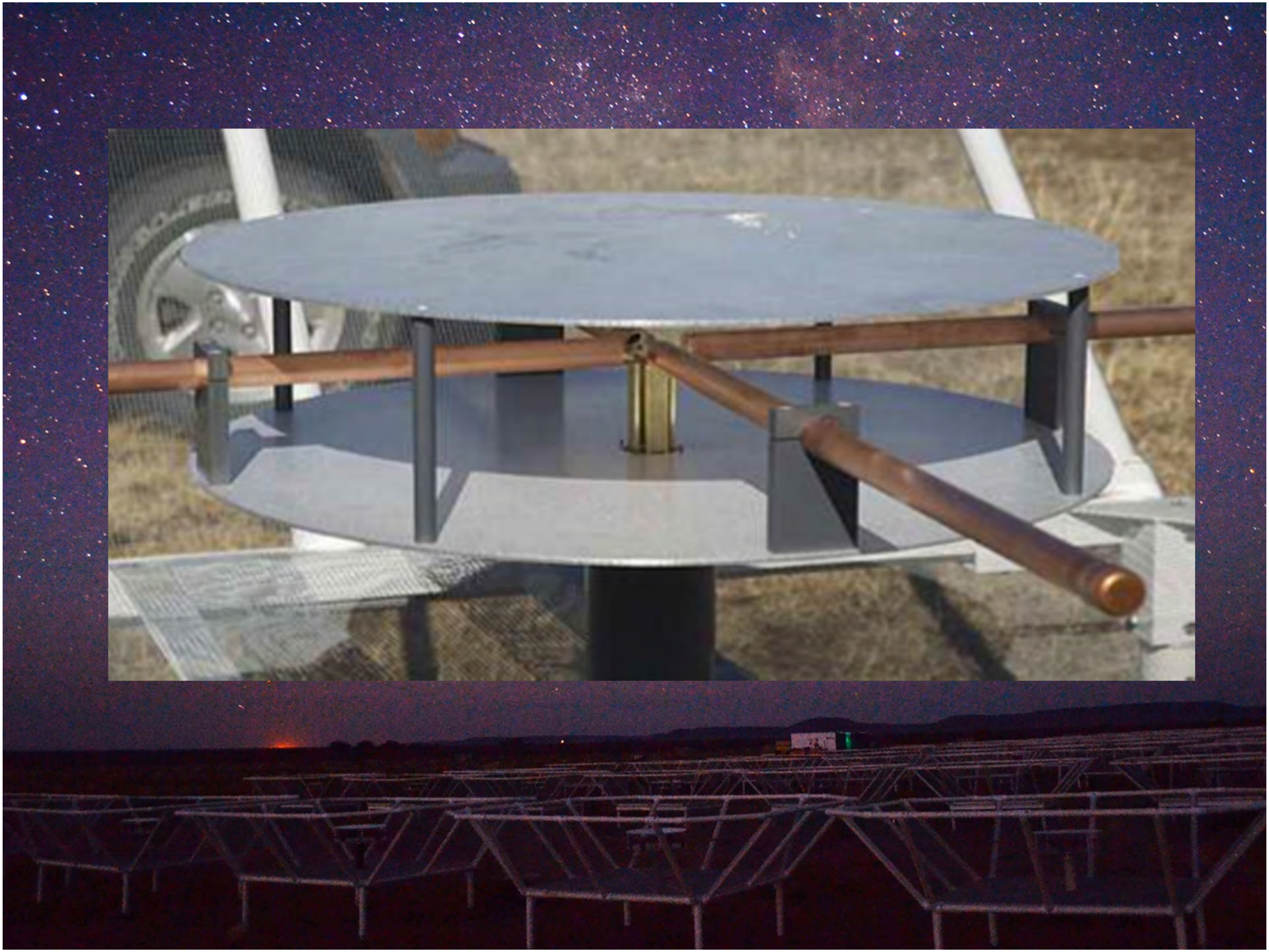
$$P[\sin(\omega\tau_g) + \sin(2\omega t - \omega\tau_g)]$$

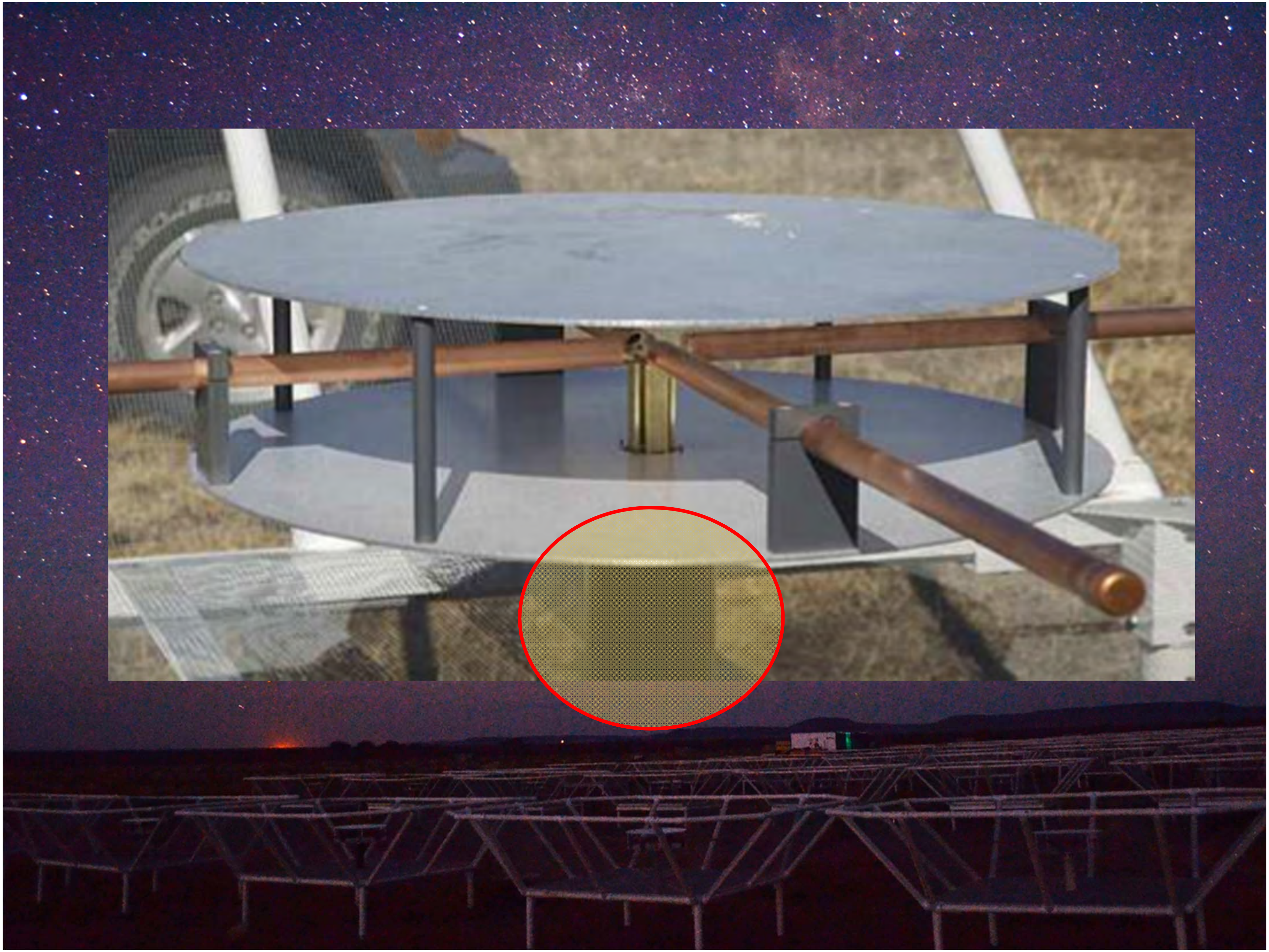
$$R_s = P \sin(\omega\tau_g)$$

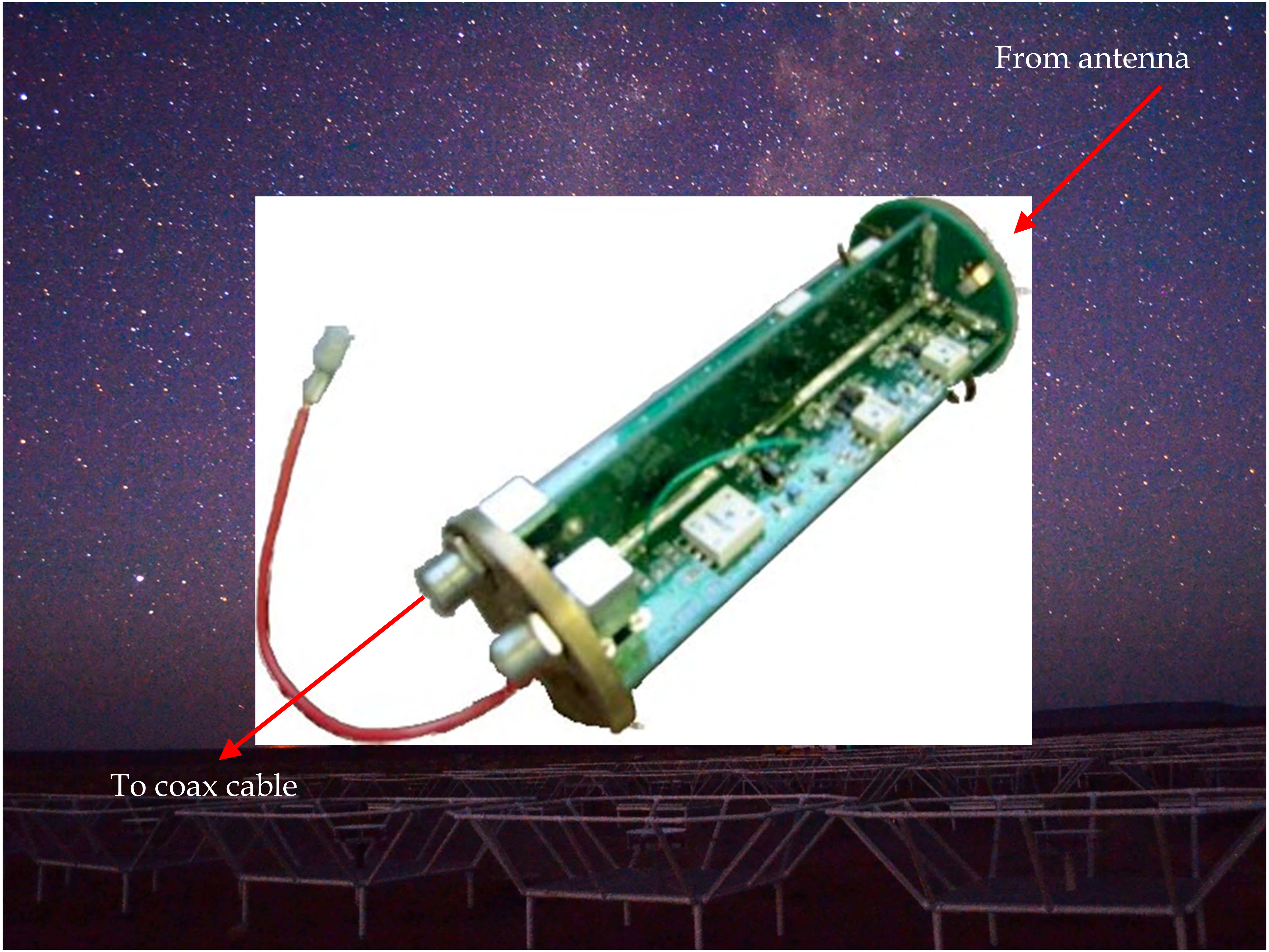


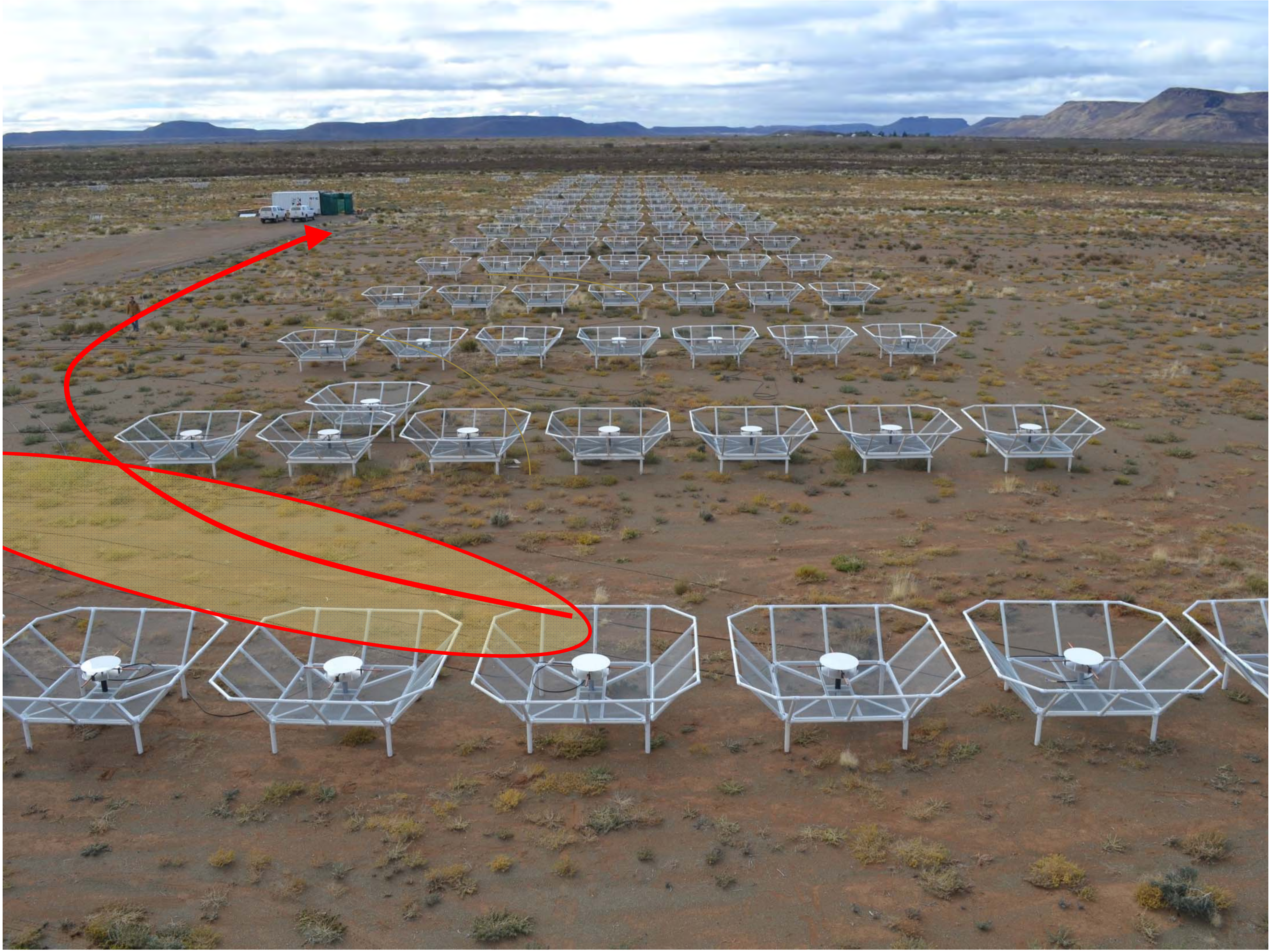


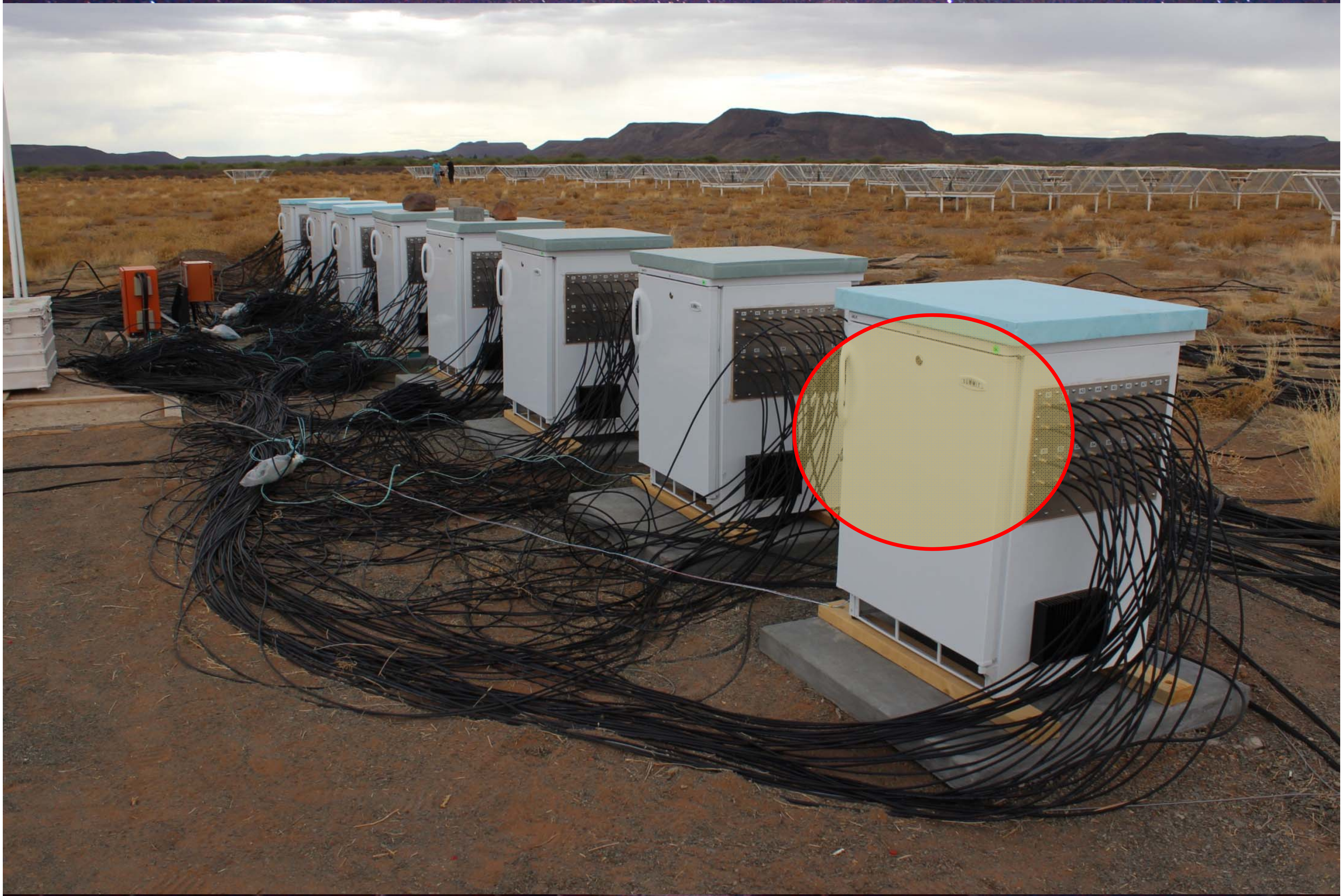
Danny Jacobs David Moore

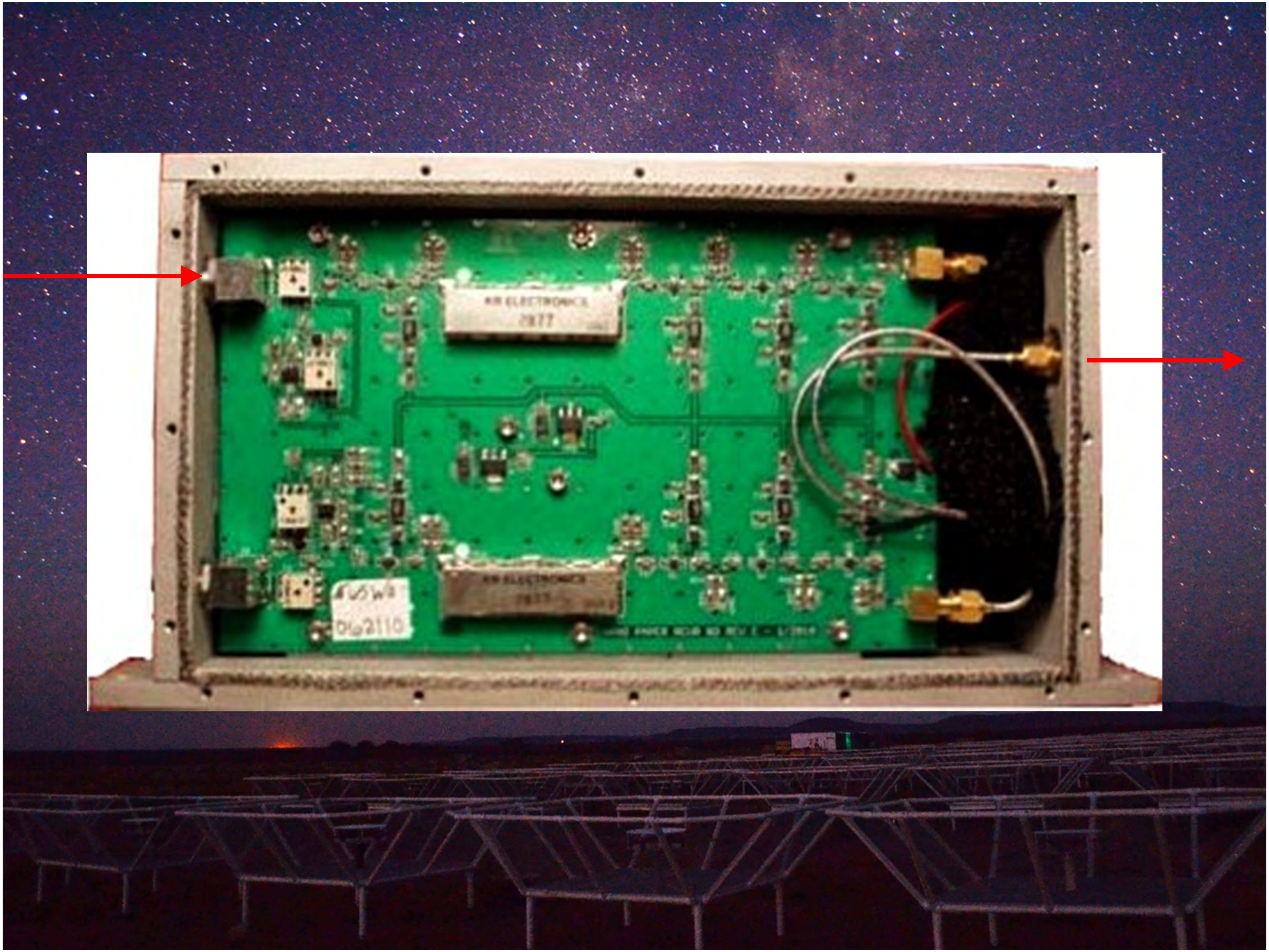




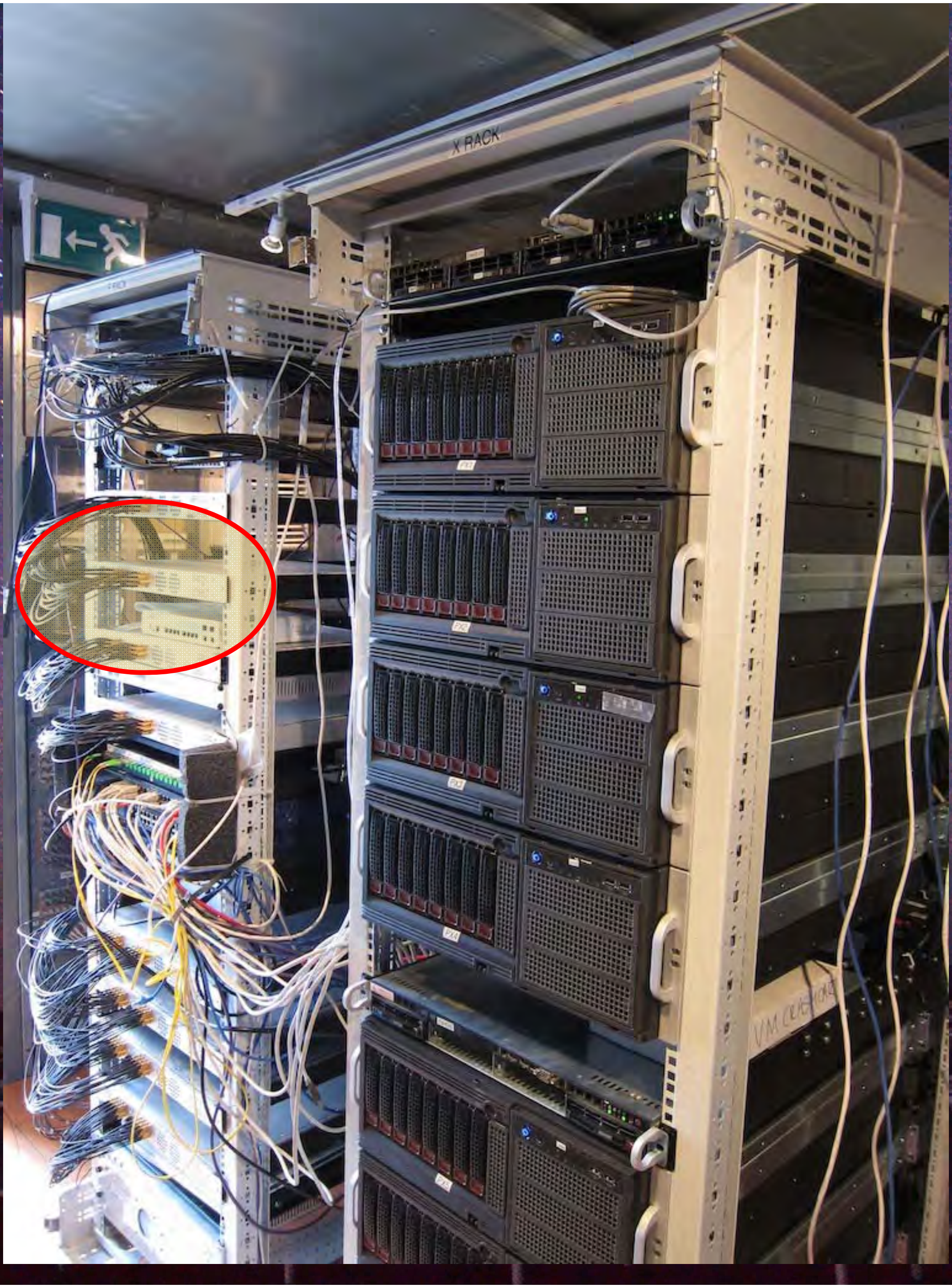

From antenna
To coax cable





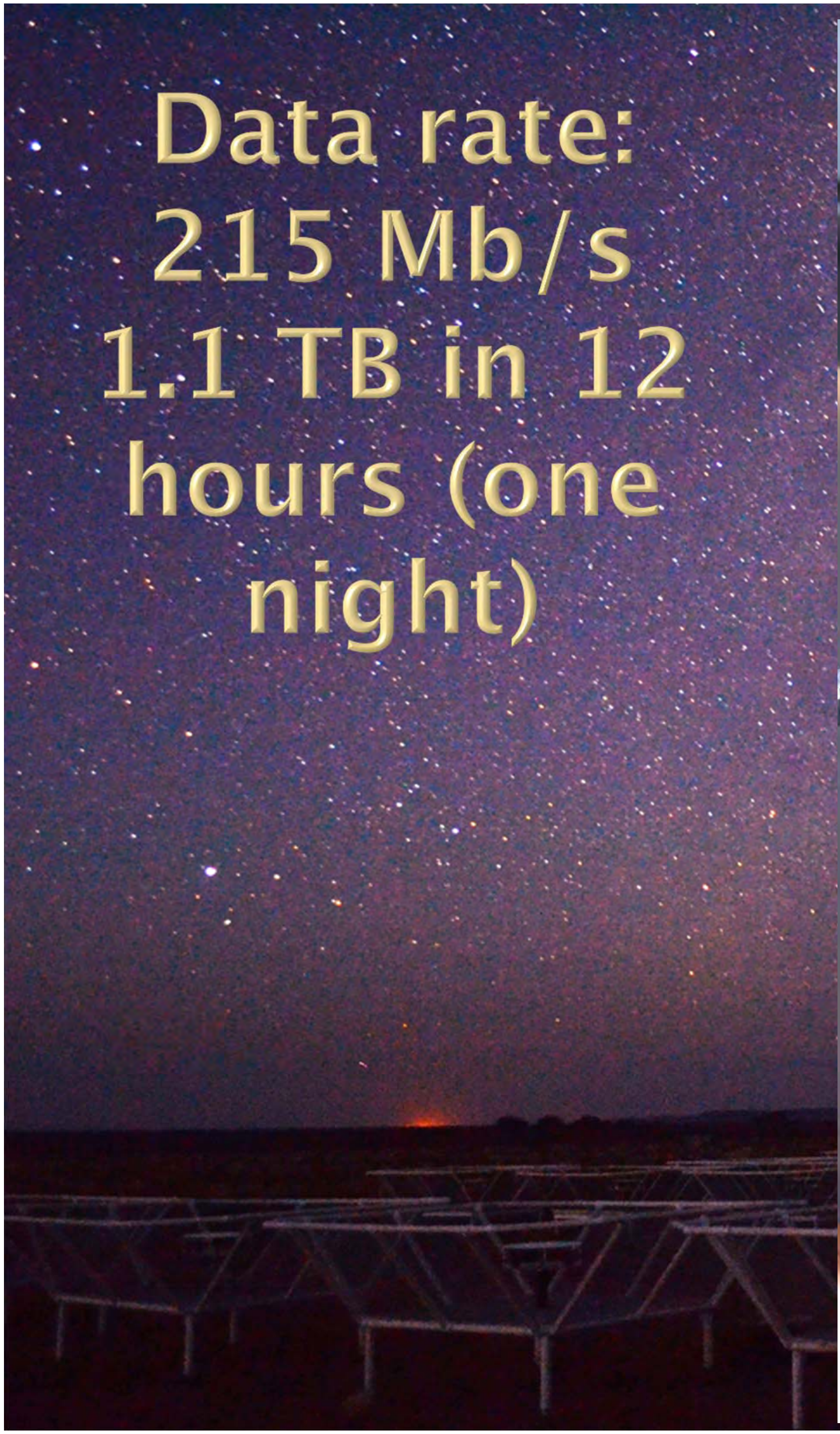

AR ELECTRONICS
2877
#65WB
062110


X RACK



X RACK


1020668
D023
D022



Data rate:
215 Mb/s
1.1 TB in 12 hours (one night)

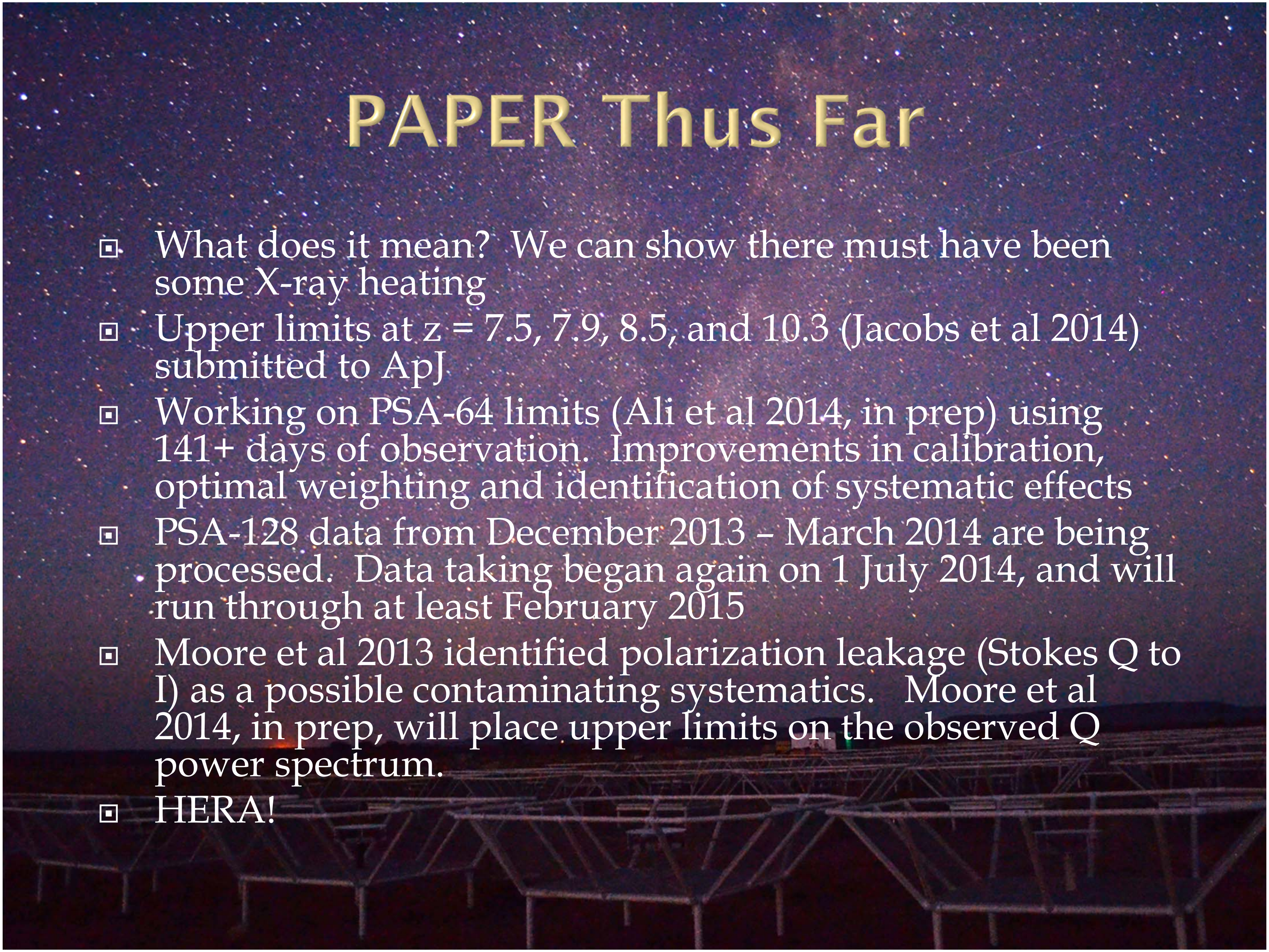
Computing & Storage

Penn leads the computing for PAPER

Computing cluster at Penn: 22 nodes, 200 cores

Data compression in South African done with small 4-node cluster, plus 110 TB RAID storage

- 140 TB of storage space using Dell HPC NFS Storage Solution (NSS), with 10 Gbe connection to compute nodes and parallel access, with full RAID backup



PAPER Thus Far

- What does it mean? We can show there must have been some X-ray heating
- Upper limits at z = 7.5, 7.9, 8.5, and 10.3 (Jacobs et al 2014) submitted to ApJ
- Working on PSA-64 limits (Ali et al 2014, in prep) using 141+ days of observation. Improvements in calibration, optimal weighting and identification of systematic effects
- PSA-128 data from December 2013 – March 2014 are being processed. Data taking began again on 1 July 2014, and will run through at least February 2015
- Moore et al 2013 identified polarization leakage (Stokes Q to I) as a possible contaminating systematics. Moore et al 2014, in prep, will place upper limits on the observed Q power spectrum.
- HERA!

Advanced Analysis Techniques for Transit Arrays

with Application to PAPER and HERA

James Aguirre

University of Pennsylvania

The Fundamental Visibility Equation

Our most general form of the visibility which we wrote down was

$$V(\nu,u,v,w) = \int A(\nu,l,m)\mathcal{S}(\nu,l,m)\mathrm{e}^{-i(ul+vm+w\sqrt{1-l^2-m^2}}\frac{dldm}{\sqrt{1-l^2-m^2}}$$

Here A is the primary beam of the antenna pair, $\mathcal{S}$ is the pattern of emission on the sky, ν is the frequency of observation.
For transit arrays, we will find it easier to think about re-writing this in the celestial coordinate system.

New Coordinate System

We define a coordinate system where $\hat{z}$ points along the earth's rotation axis, and $\hat{x}$ and $\hat{y}$ lie in the equatorial plane. We can choose $\hat{x}$ to point in the direction of RA=0. (θ, ϕ) will represent the usual spherical coordinates. We are taking the sky as fixed, and the positions of the primary beam and the baseline vector move with respect to it as a function of t.

We recall that we can write a unit vector on the sphere as

$$\hat{s} = \cos\phi \sin\theta \hat{x} + \sin\phi \sin\theta \hat{y} + \cos\theta \hat{z}$$

Then in this coordinate system, the baseline vector will be

$$\mathbf{b} = b_x \cos(\omega_e t) \hat{x} + b_y \sin(\omega_e t) \hat{y} + b_z \hat{z}$$

where ω_e is the angular velocity of the Earth's rotation, and $t = 0$ corresponds to the array pointed at $RA = 0$ (that is, LST=0).

Direction Cosines in Terms of (θ, ϕ)

The direction cosines are defined as

$$\sin(\theta) = l^2 + m^2$$

$$\tan\phi = \frac{m}{l}$$

From this it is clear that we can write

$$ul + vm + wn = ul + vm + w\sqrt{1 - l^2 - m^2} =$$

$$\frac{b_x}{\lambda}\cos\phi\sin\theta + \frac{b_y}{\lambda}\sin\phi\sin\theta + \frac{b_z}{\lambda}\cos\theta$$

Now, we notice that $\frac{\nu}{c} = \frac{1}{\lambda}$, so

$$\begin{aligned} \frac{b_x}{\lambda}\cos\phi\sin\theta + \frac{b_y}{\lambda}\sin\phi\sin\theta + \frac{b_z}{\lambda}\cos\theta &= \\ \frac{\mathbf{b}(0)}{\lambda}\cdot\hat{s} &= \mathbf{b}\cdot\hat{s}\nu/c \end{aligned}$$

And finally

$$\frac{dldm}{\sqrt{1-l^2-m^2}} = \sin\theta d\theta d\phi \equiv d\Omega$$

This now gives us, explicitly

$$V(\nu, t; \mathbf{b}) = \int_0^{2\pi} \int_0^{\pi} A(\nu, t; \theta, \phi) \mathcal{S}(\nu; \theta, \phi) \mathrm{e}^{-i\mathbf{b}\cdot\hat{s}\nu/c} \sin(\theta) d\theta d\phi$$

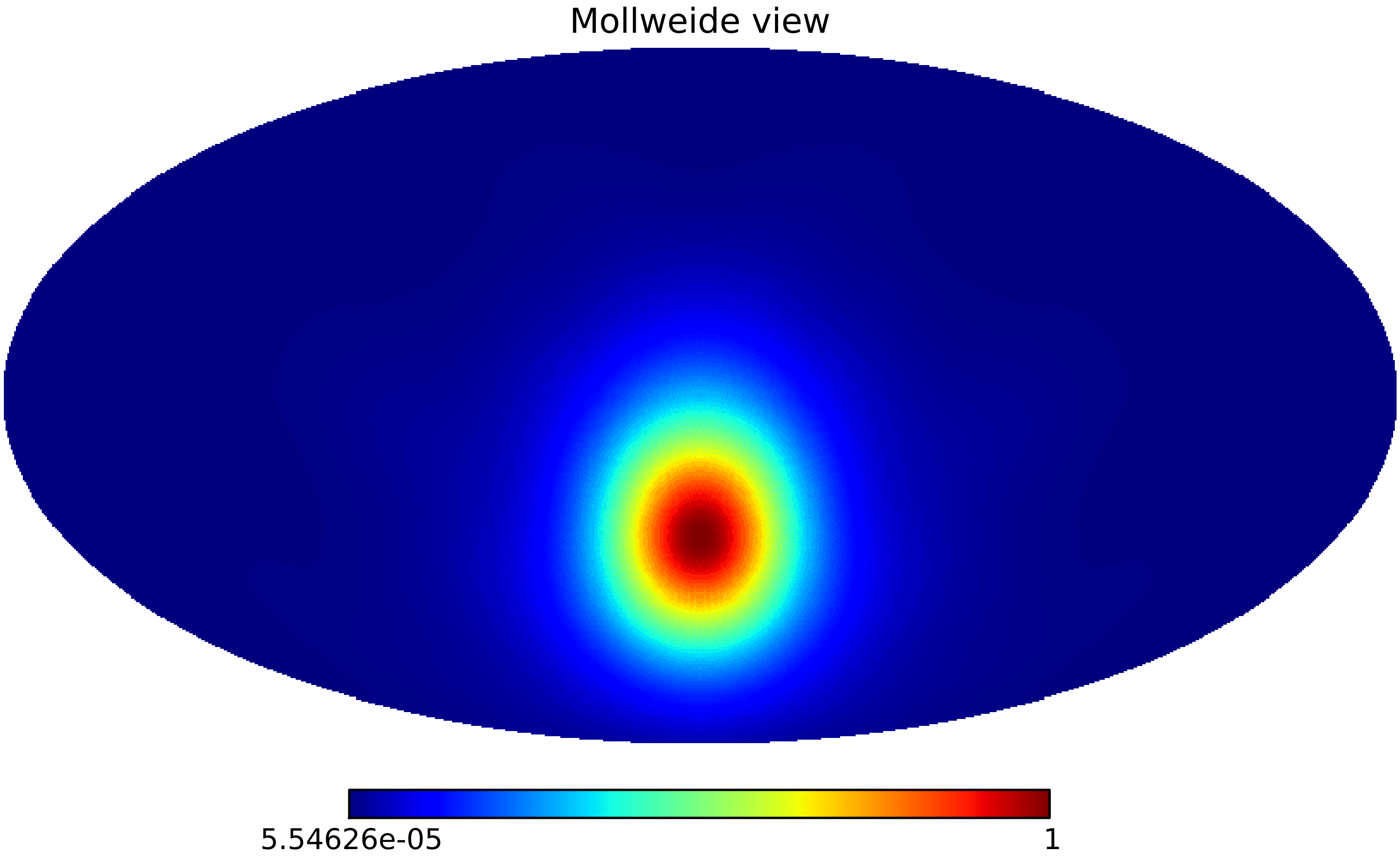
Moving the Primary Beam

We are now almost in a position to evaluate the visibility integral (numerically) for any sky, frequency, and time, except that we need to account for how the primary beam moves as the earth rotates. We will simply write it as

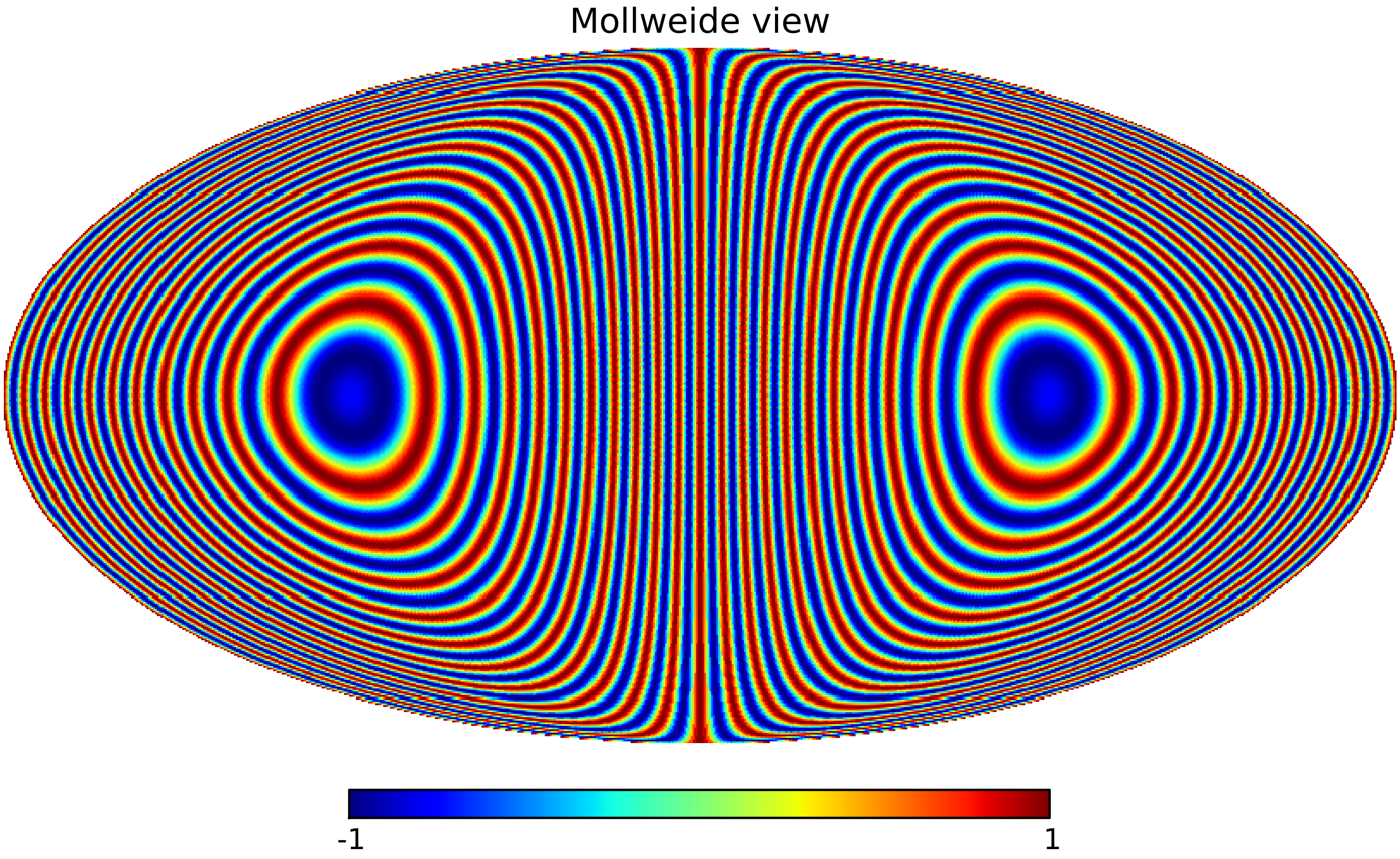
$$A(t) = A(\Omega - \Omega_0(t))$$

where $\Omega_0(t) = (\theta_0, \omega_e t)$ where θ_0 is the co-latitude of the array and $\omega_e t$ is the LST, i.e., $\Omega_0(t)$ is the local zenith of the array (where it is looking at time t).
You will notice that this is a kind of shift of the function, and indeed we can use a sophisticated form of the shift theorem (for spherical harmonics) to evaluate $A(t)$ in practice.

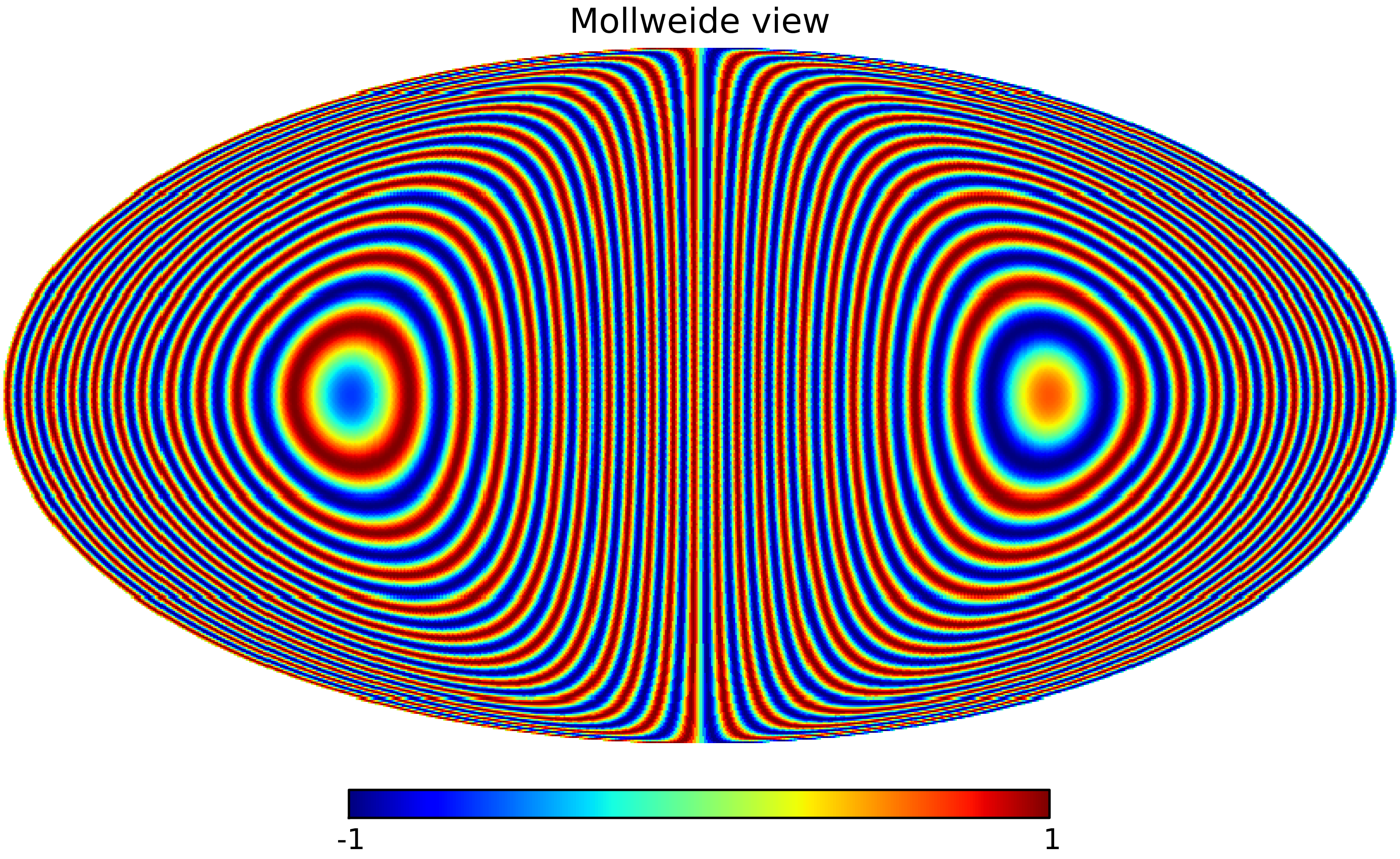
The Beam $A(\Omega)$



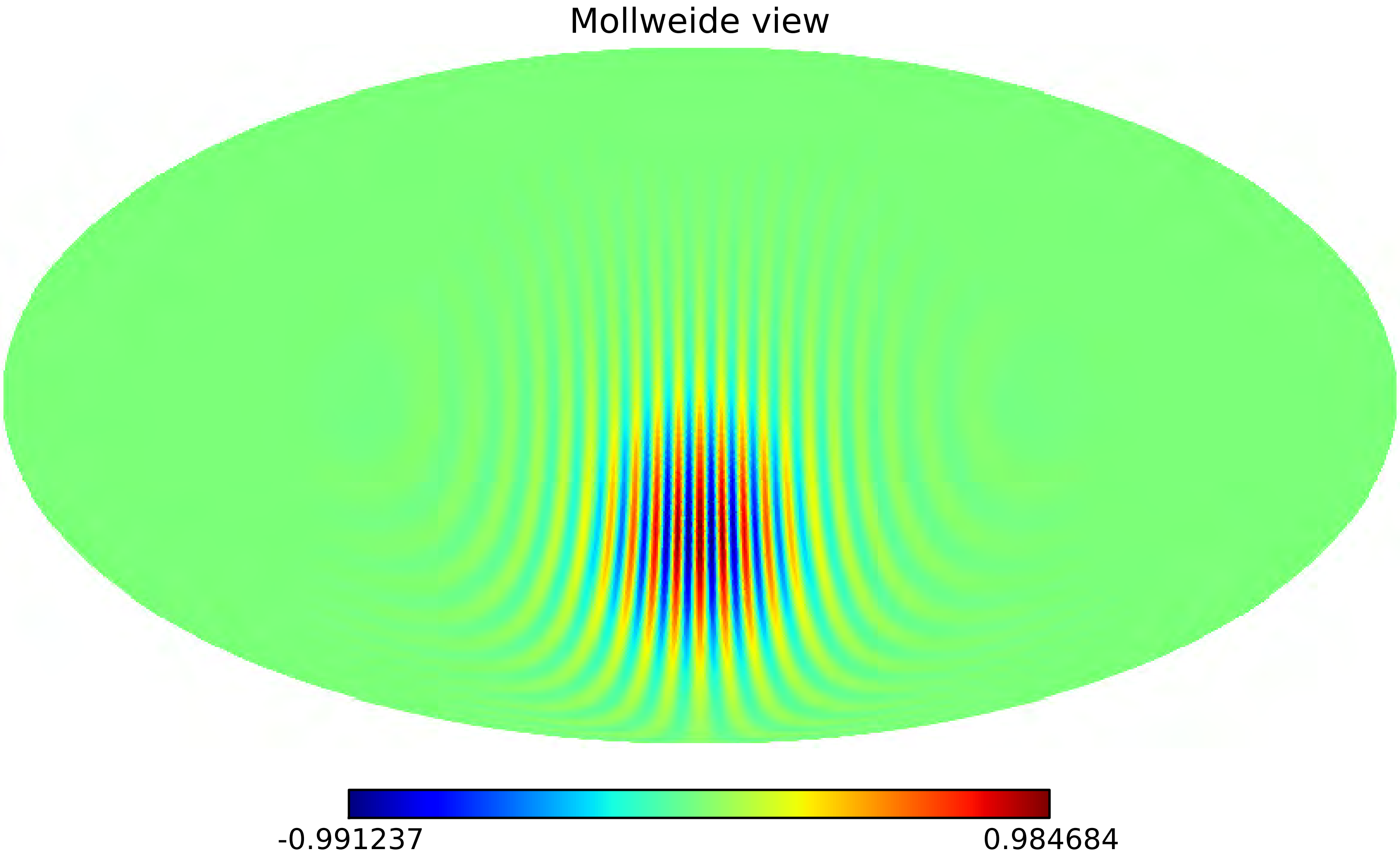
The Fringe Re[$\mathrm{e}^{-i\mathbf{b}\cdot\hat{s}\nu/c}$]



The Fringe Im[$\mathrm{e}^{-i\mathbf{b}\cdot\hat{s}\nu/c}$]



$A(\Omega)$ ***Re[***$\mathrm{e}^{-i\mathbf{b}\cdot\hat{s}\nu/c}$***]***



The Time-Frequency Visibility

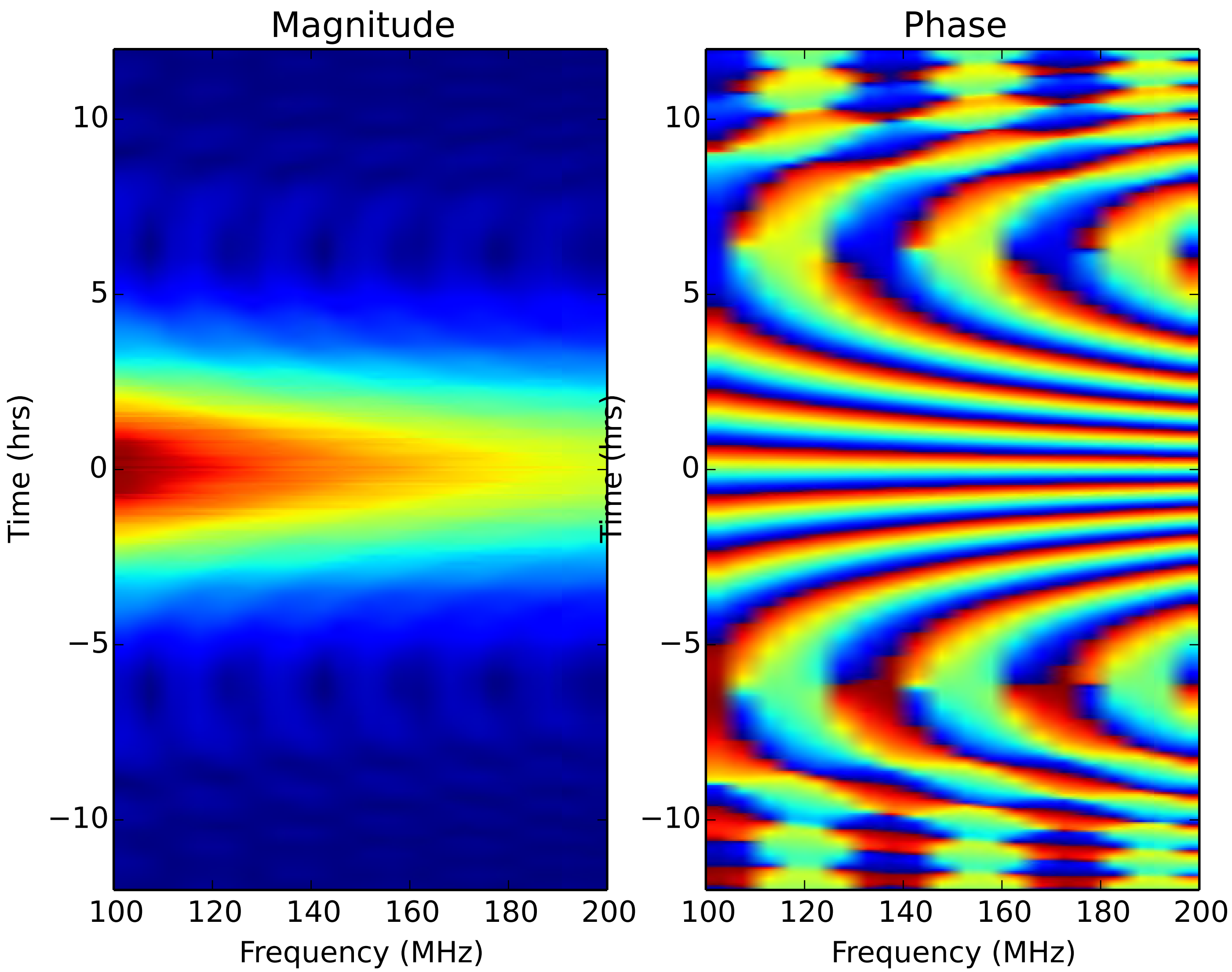
Let's write the visibility for a single baseline down in a compact form as

$$V(\nu, t; \mathbf{b}) = \int A(\nu, \Omega - \Omega_0(t)) \mathcal{S}(\nu, \Omega) \mathrm{e}^{-i\mathbf{b}(t)\cdot\hat{s}\frac{\nu}{c}} d\Omega$$

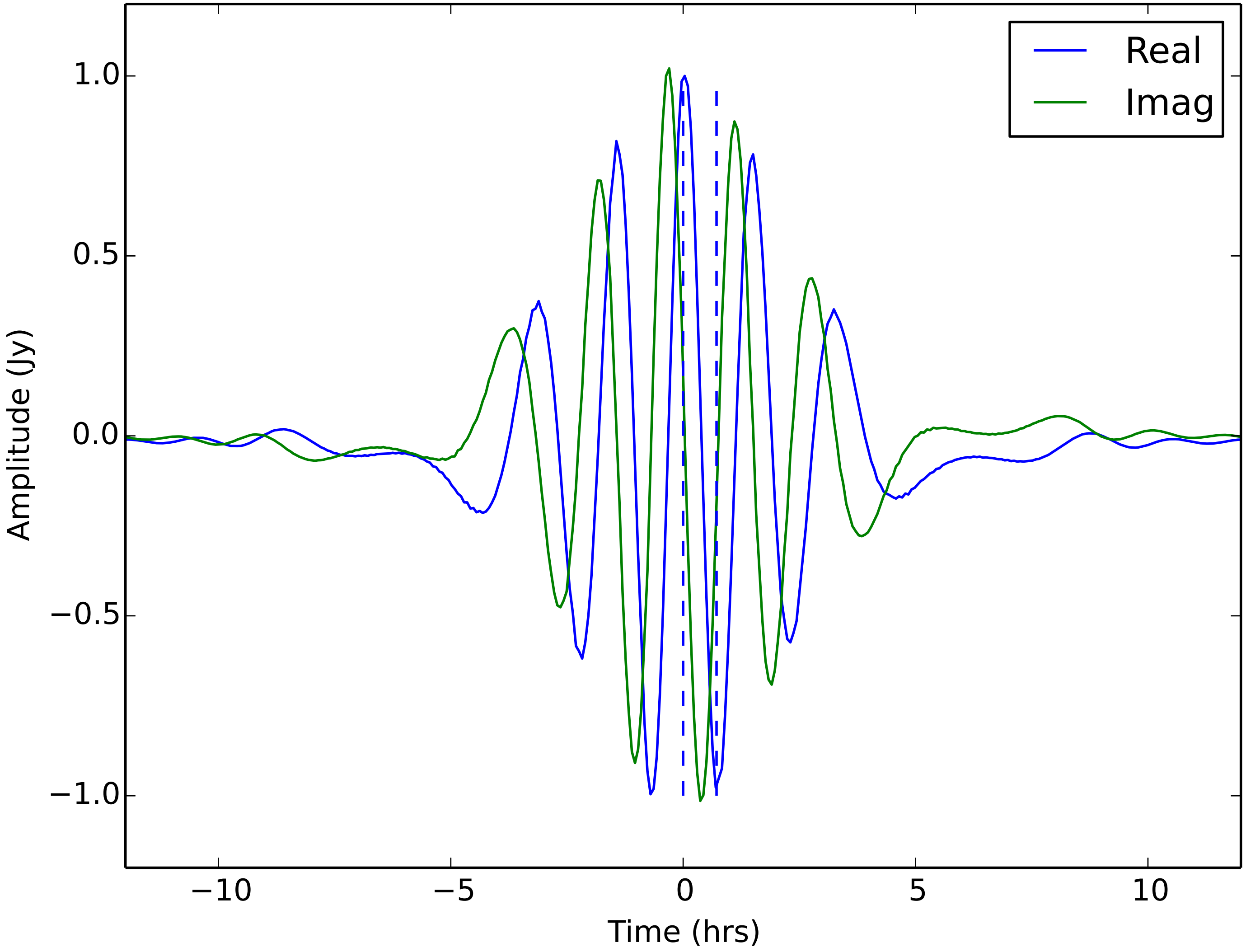
What does this look like as a function of ν and t for a given baseline?
Let's consider a point source

$$\mathcal{S}(\nu, \Omega) = \mathcal{S}_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha} \delta(\Omega - \Omega_s)$$

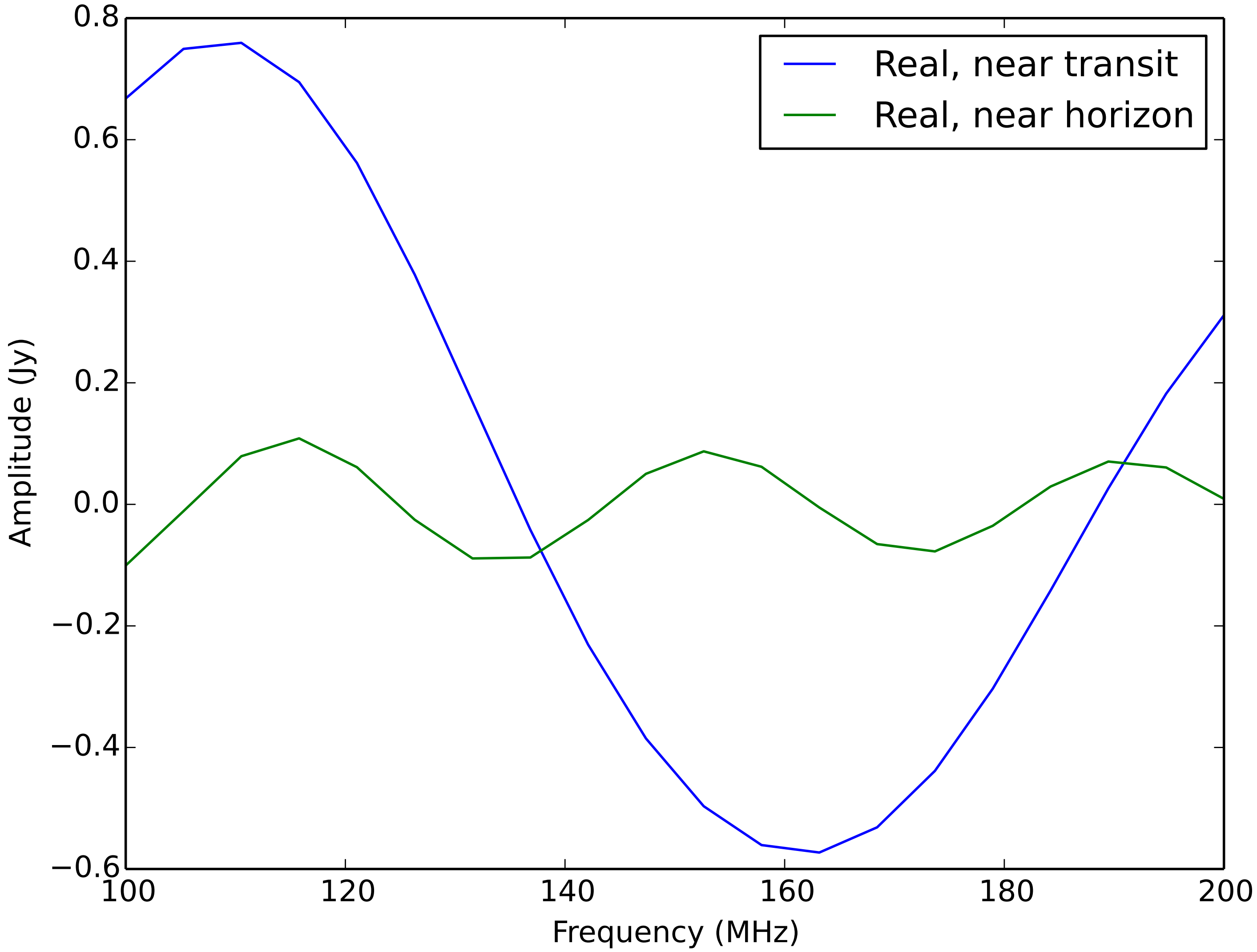
One Point Source



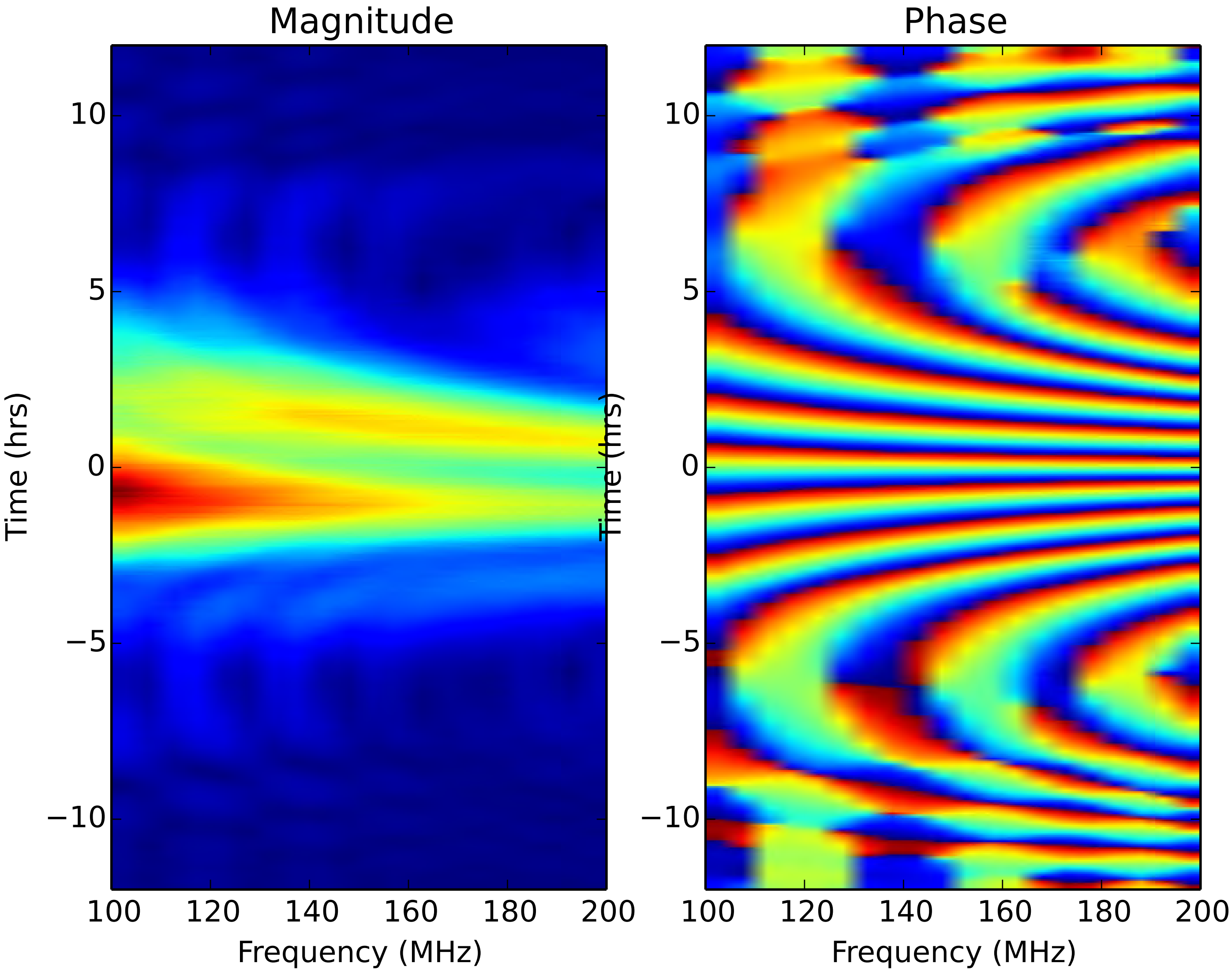
One Point Source



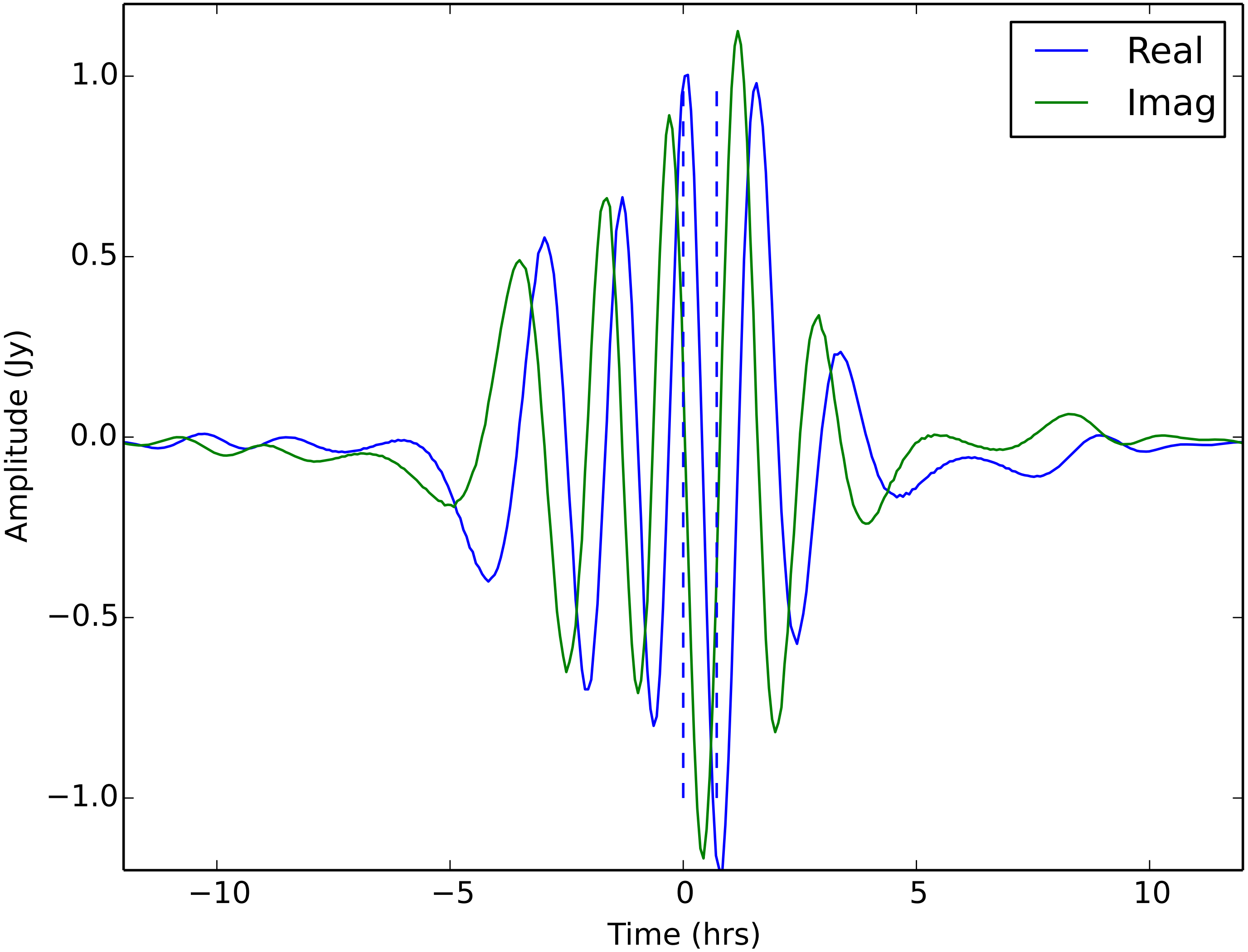
One Point Source



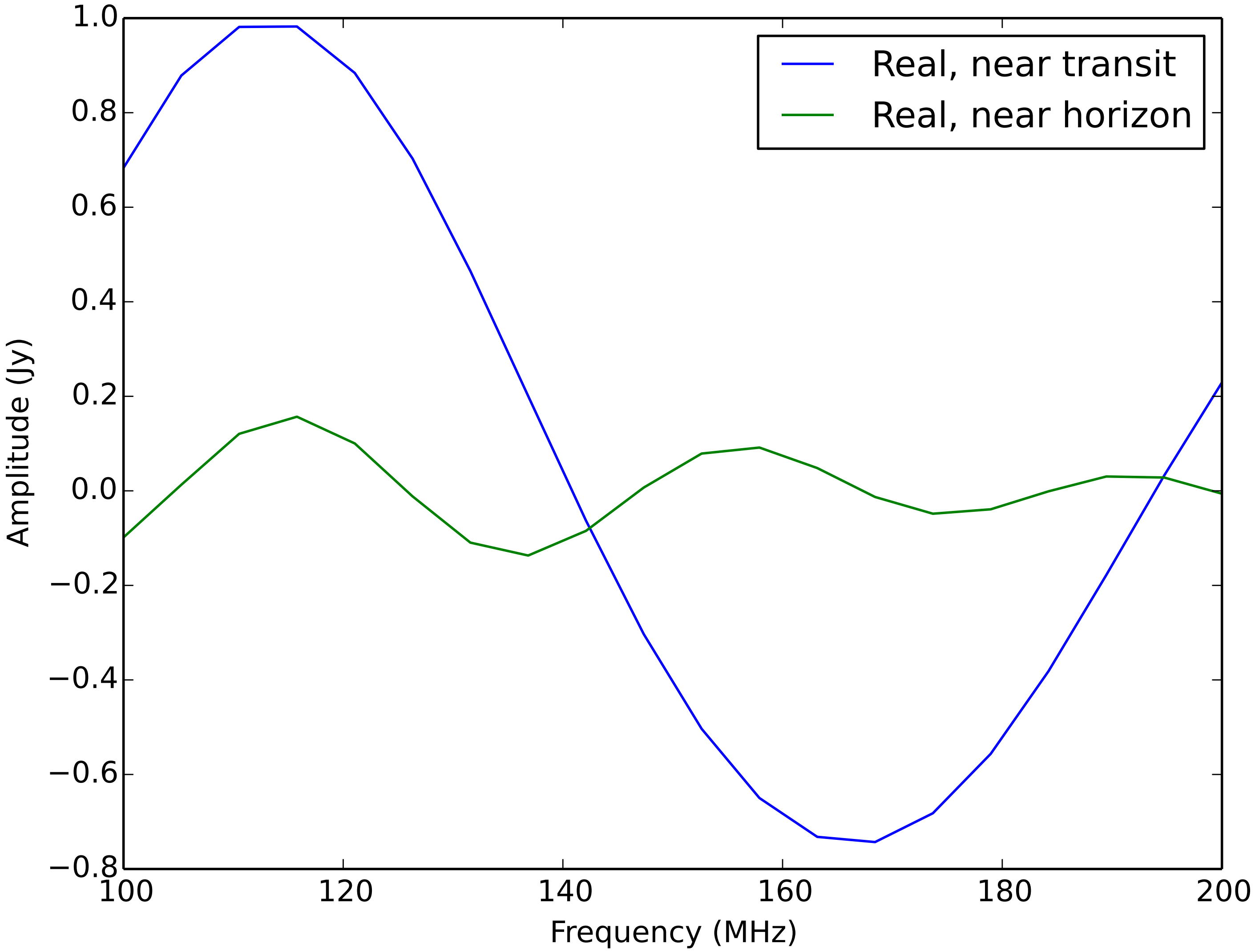
Two Point Sources



Two Point Sources



Two Point Sources



What is the period of the oscillations in time and frequency?
Let’s consider the following operations:

$$\mathcal{F}_\nu[V(\nu,t)](\tau,t) = \int V(\nu,t)\mathrm{e}^{-i\nu\tau}d\nu$$

$$\mathcal{F}_t[V(\nu,t)](\nu,f) = \int V(\nu,t)\mathrm{e}^{-itf}dt$$

Since the oscillatory part of $V(\nu, t)$ is

$$\mathrm{e}^{-i\mathbf{b}(t)\cdot\hat{s}\frac{\nu}{c}}$$

at fixed *time* the maximum rate at which the fringe will oscillate is

$$\tau_{max} = \frac{|\mathbf{b}|}{c}\ \mathrm{seconds}$$

which corresponds to an oscillation every

$$\frac{2\pi c}{|\mathbf{b}|}\ \mathrm{Hz}$$

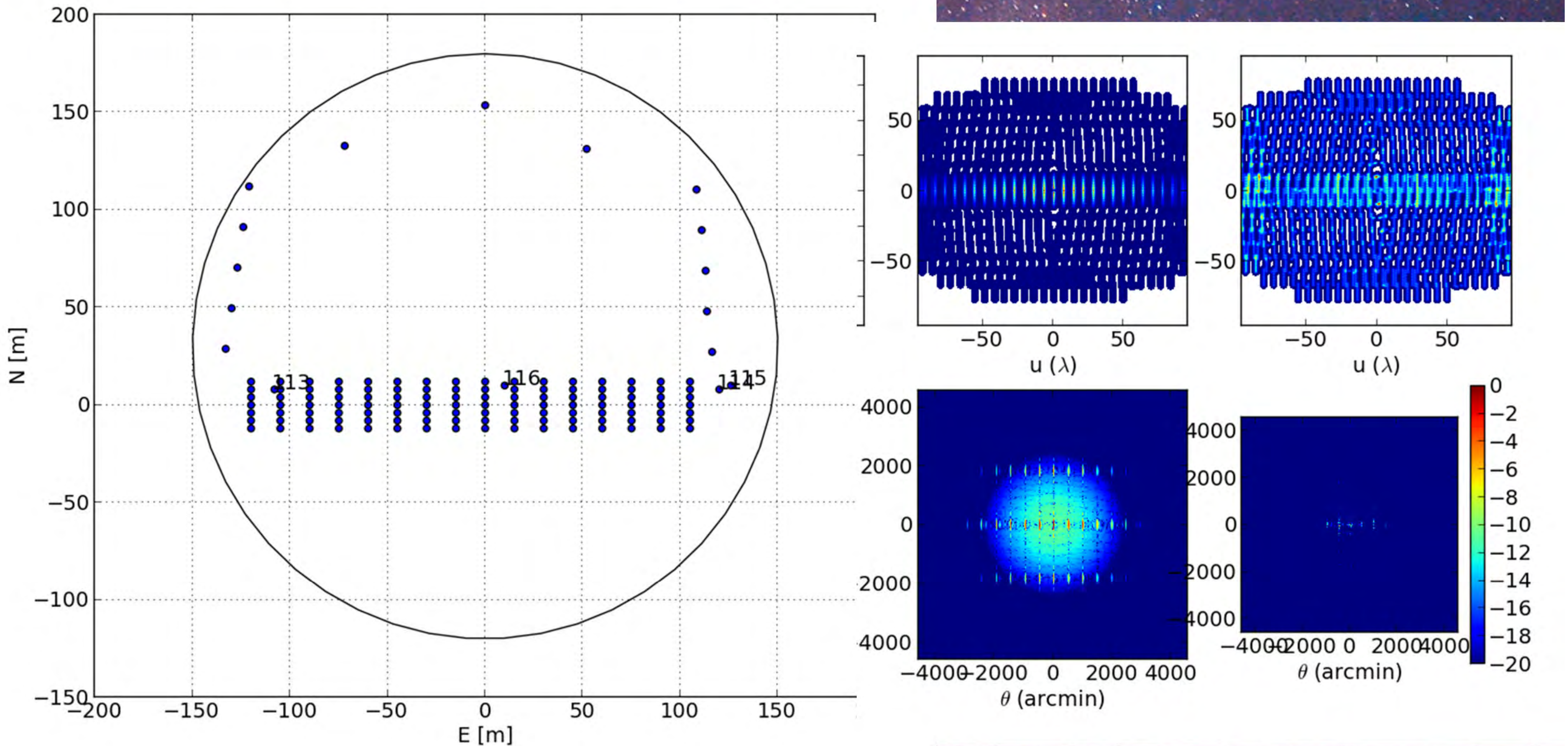
Similarly, at fixed *frequency* the maximum rate at which the fringe will oscillate depends on the rate at which $\mathbf{b}$ is changing (which depends on the Earth's rotation rate):

$$f_{max} = \frac{|\mathbf{b}|}{c}\nu\frac{\omega_e}{2\pi}\ \mathrm{Hz}$$

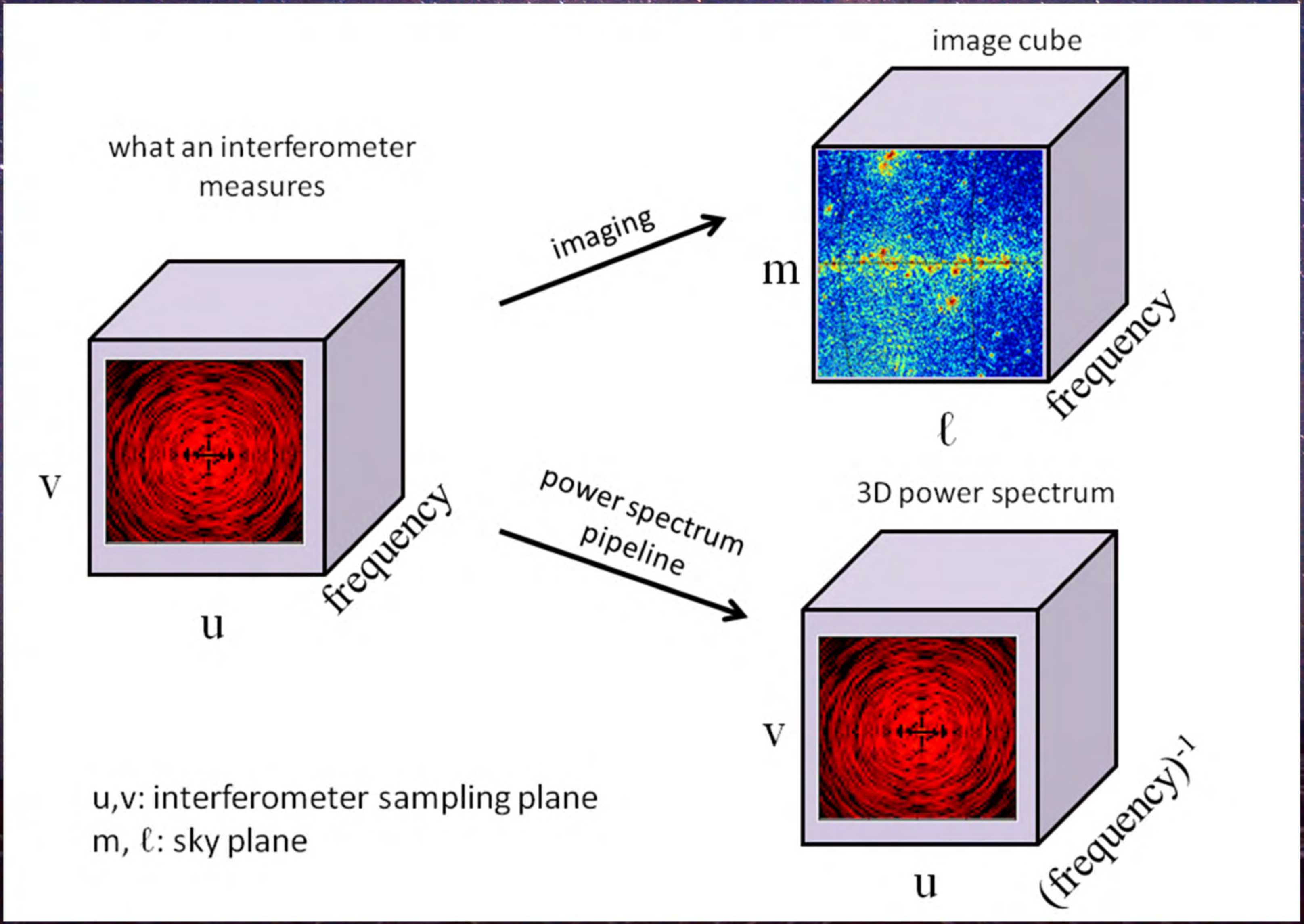
which corresponds to an oscillation every

$$\left(\frac{|\mathbf{b}|}{c}\nu\frac{\omega_e}{2\pi}\right)^{-1}\ \mathrm{seconds}$$

PSA-128 Configuration



Interferometric Imaging



what an interferometer measures

v

u

frequency

imaging

image cube

m

ℓ

frequency

power spectrum pipeline

3D power spectrum

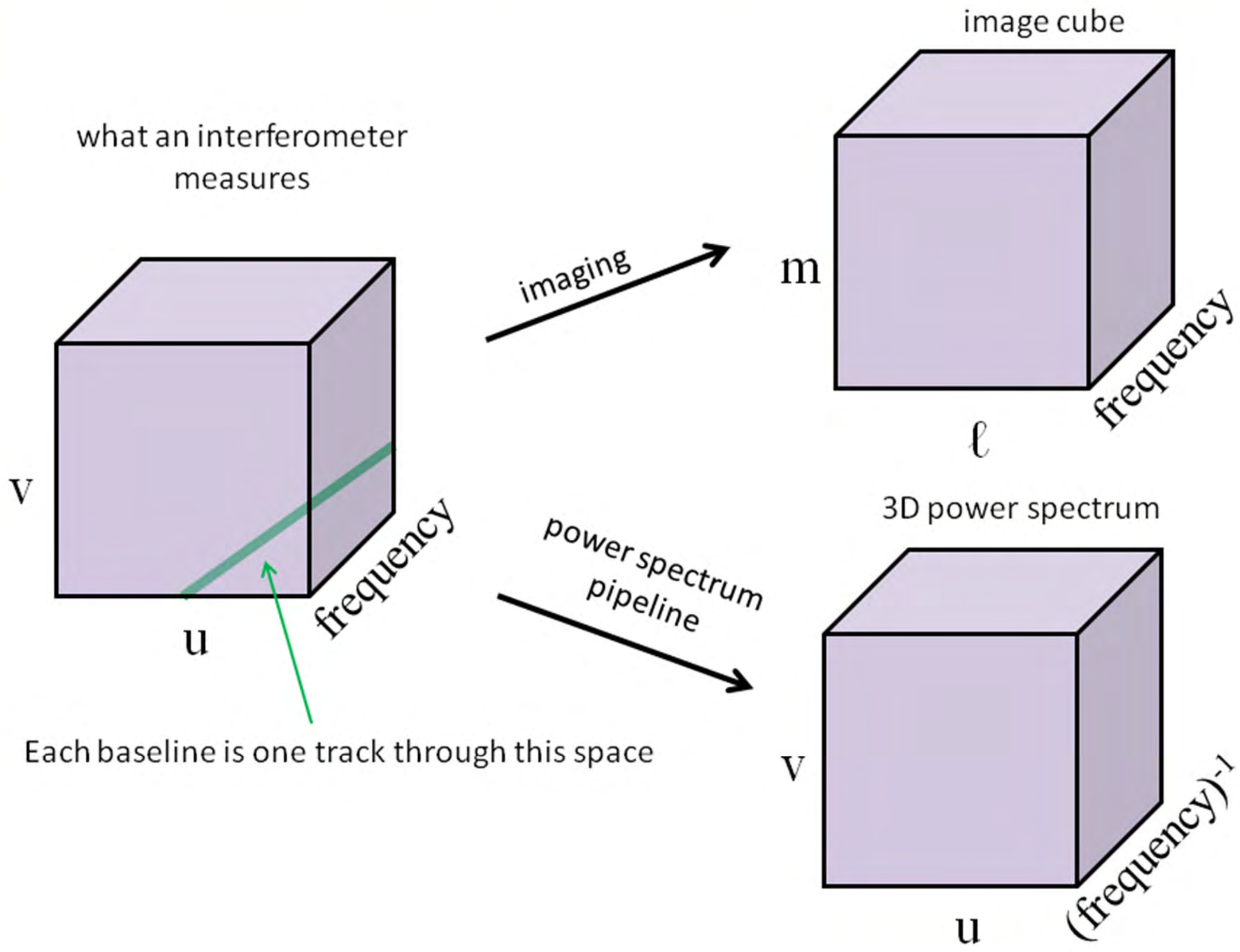
v

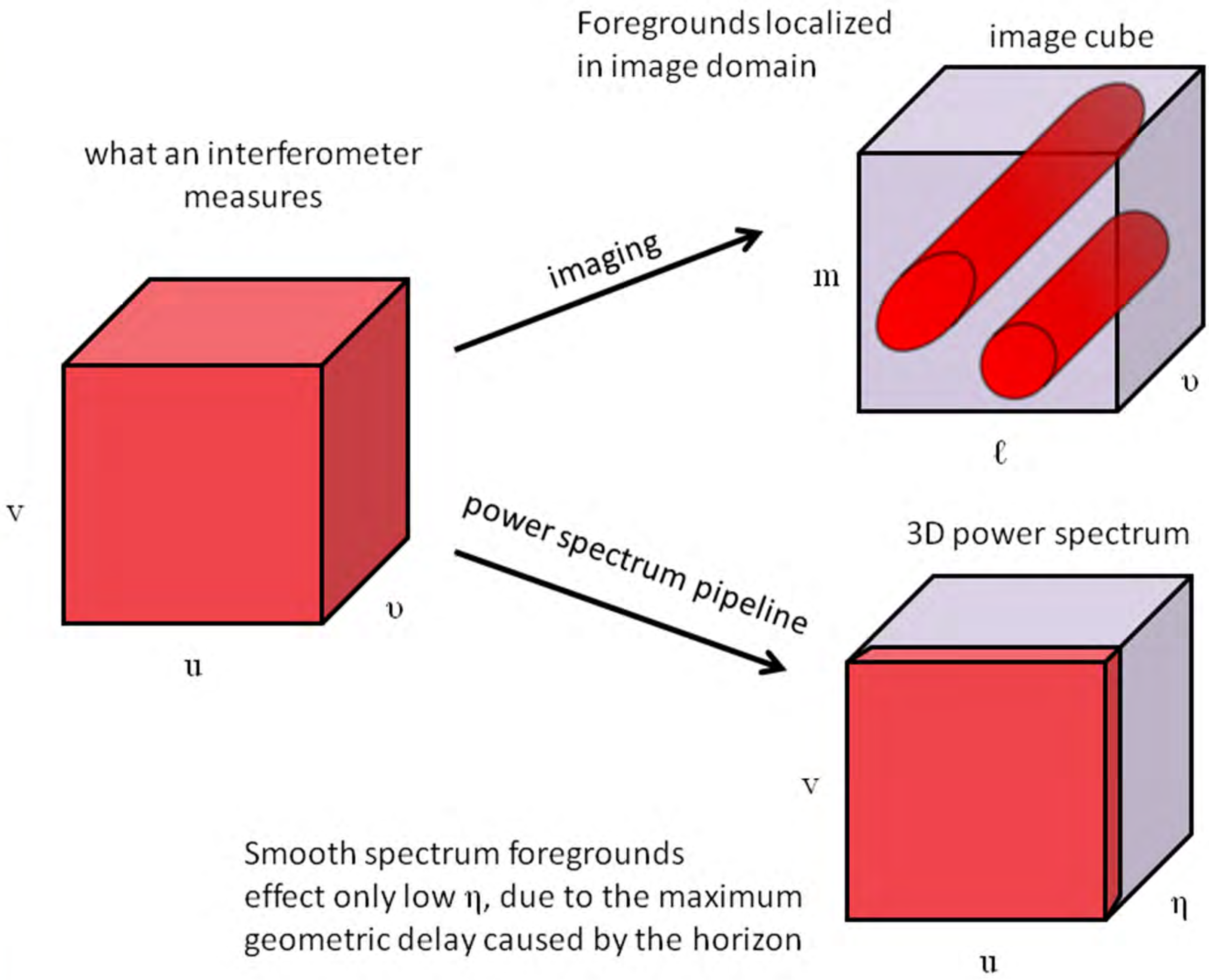
u

$(\text{frequency})^{-1}$

u,v: interferometer sampling plane
m, ℓ: sky plane

(PAPER does image! Jacobs et al 2011, 2013; Stefan et al 2013)


what an interferometer measures
v
u
frequency
Each baseline is one track through this space
imaging
image cube
m
ℓ
frequency
power spectrum pipeline
3D power spectrum
v
u
(frequency)$^{-1}$



what an interferometer measures

imaging

Foregrounds localized in image domain

image cube

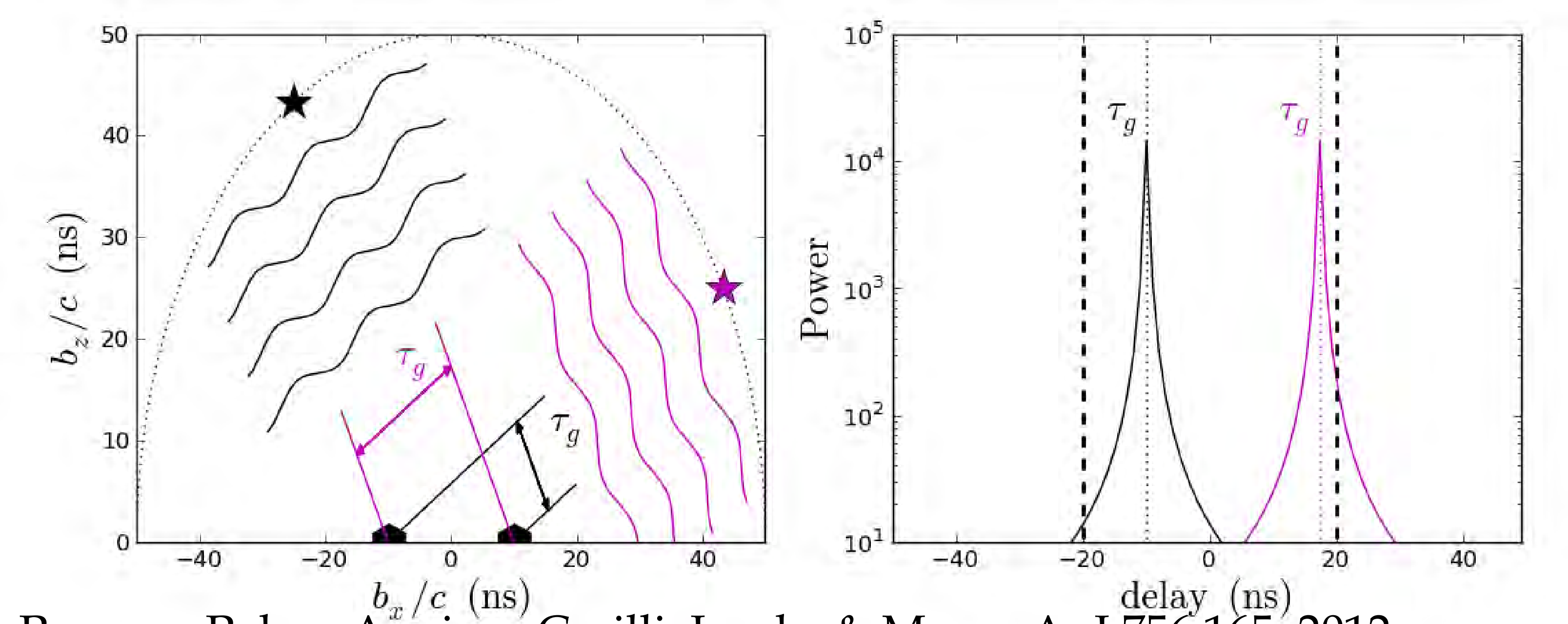
power spectrum pipeline

3D power spectrum

Smooth spectrum foregrounds
effect only low η, due to the maximum
geometric delay caused by the horizon

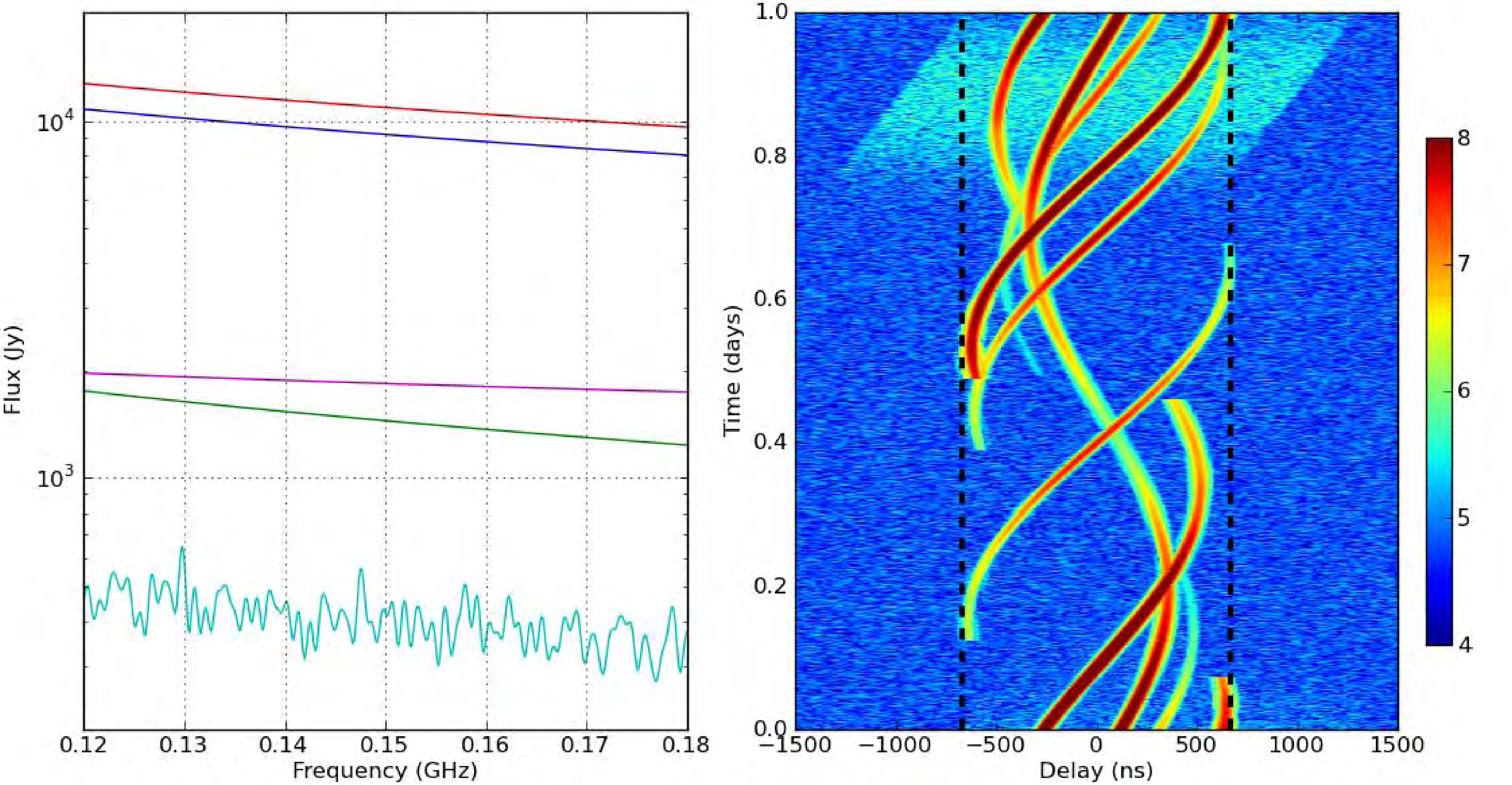
The Delay Transform

- Delay space: Fourier transform of frequency axis
- Point sources map to (nearly) delta functions if they are *smooth* in frequency space
- The central delay is then the geometric delay set by the baseline length
- The width in delay space is a measure of the frequency coherence of the spectrum
- Delay space is very nearly *k_parallel*-space
- Note the *maximum* geometric delay caused by the horizon



Parsons, Pober, Aguirre, Carilli, Jacobs & Moore ApJ 756 165, 2012

Example Spectra in Delay Space



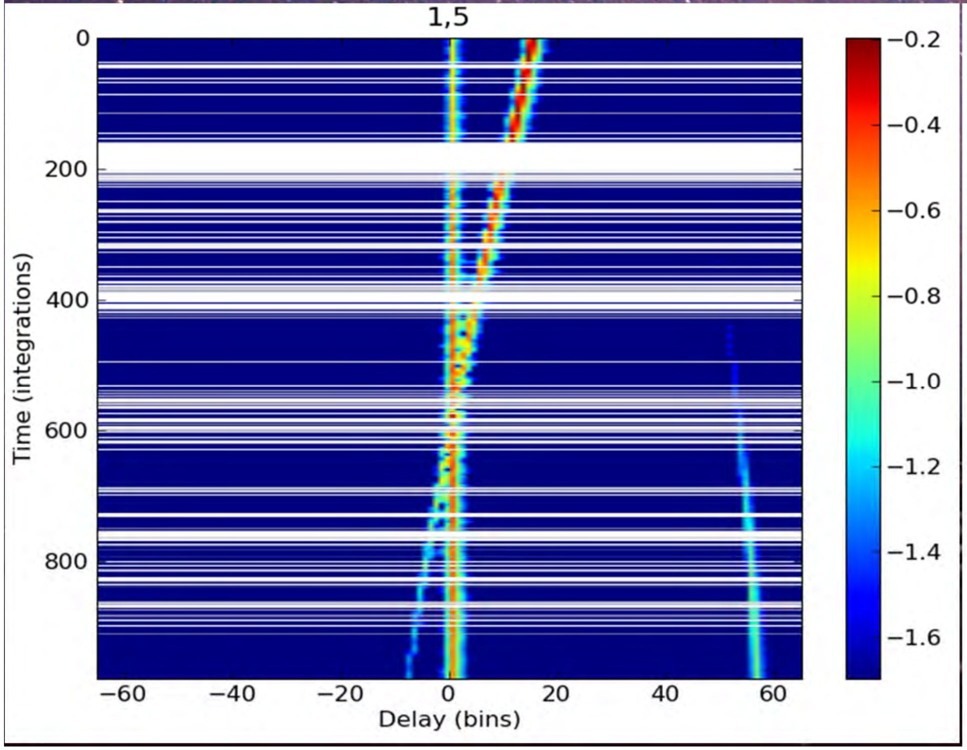
Delay/Delay-Rate Transform:

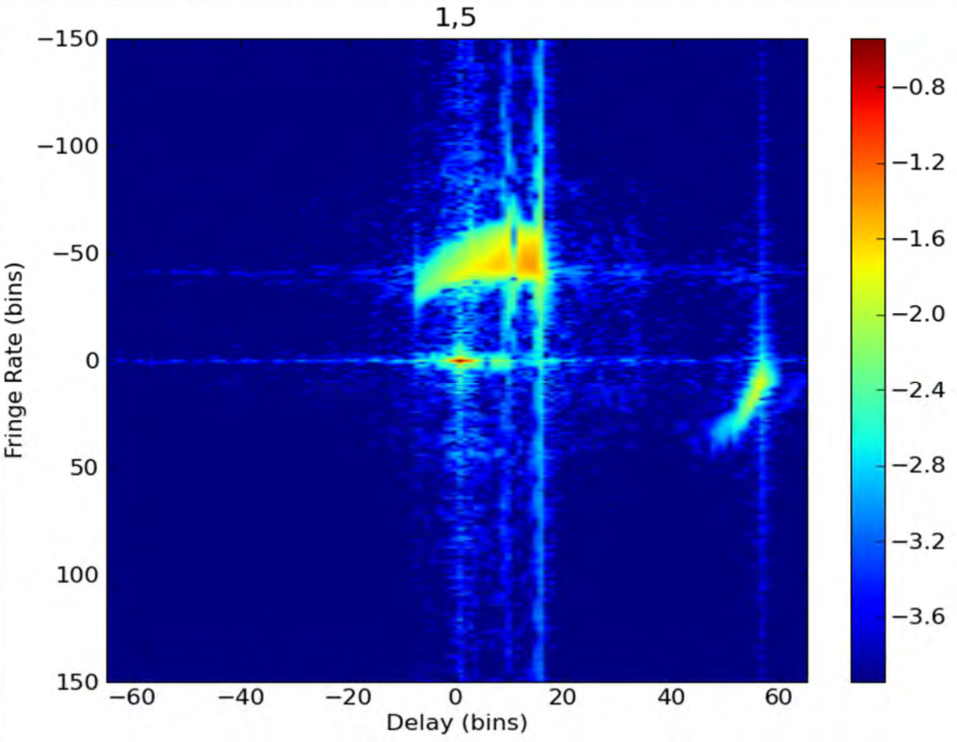
Pseudo-imaging and Compression

Example: 1 hour of data with Cas A, Cyg A, Tau A

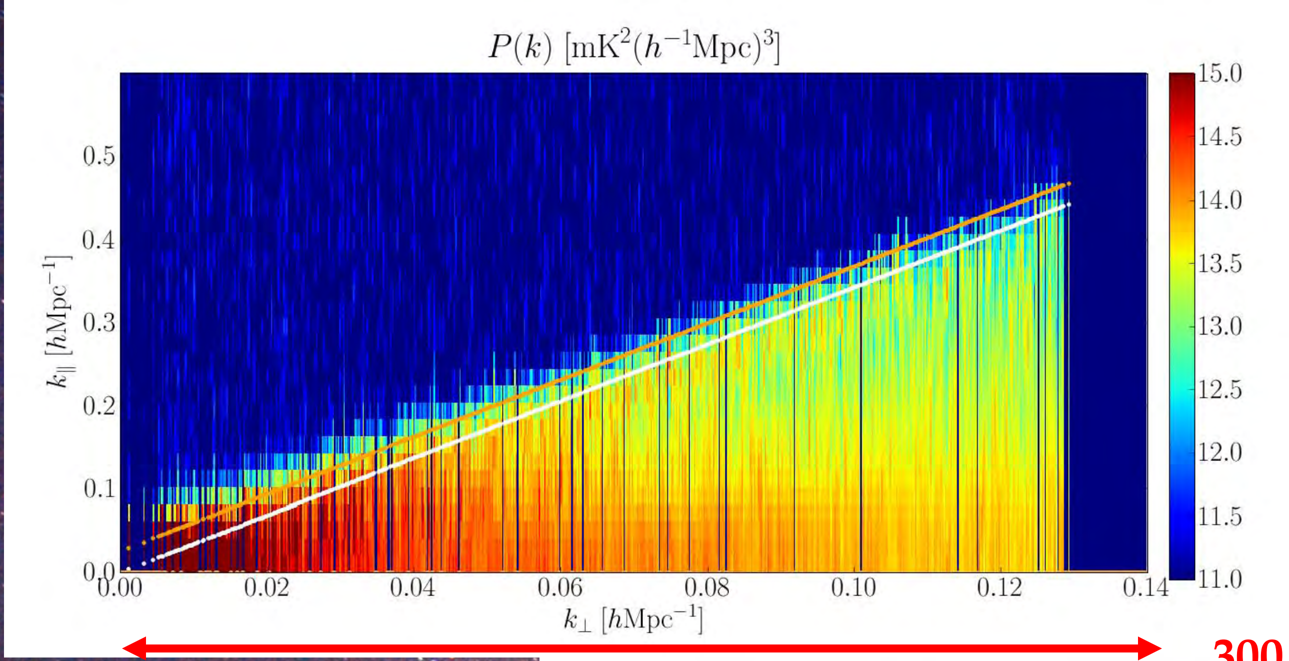
- Phase to a source (here, Cas A)
- FFT of frequency axis = "Delay Image"
- FFT of time axis = "Delay/Delay-Rate"
- Cas A is confined to a region near origin
- PSF determined by bandpass + time variabliity

Useful as a form of optimized compression, specific to baseline length



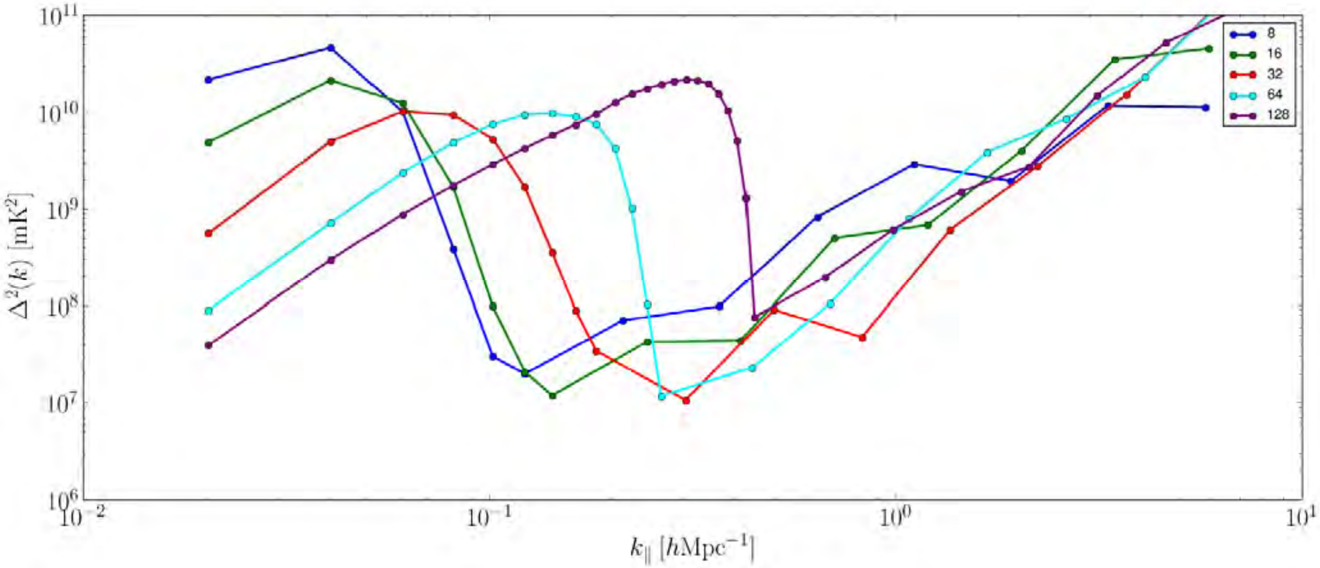


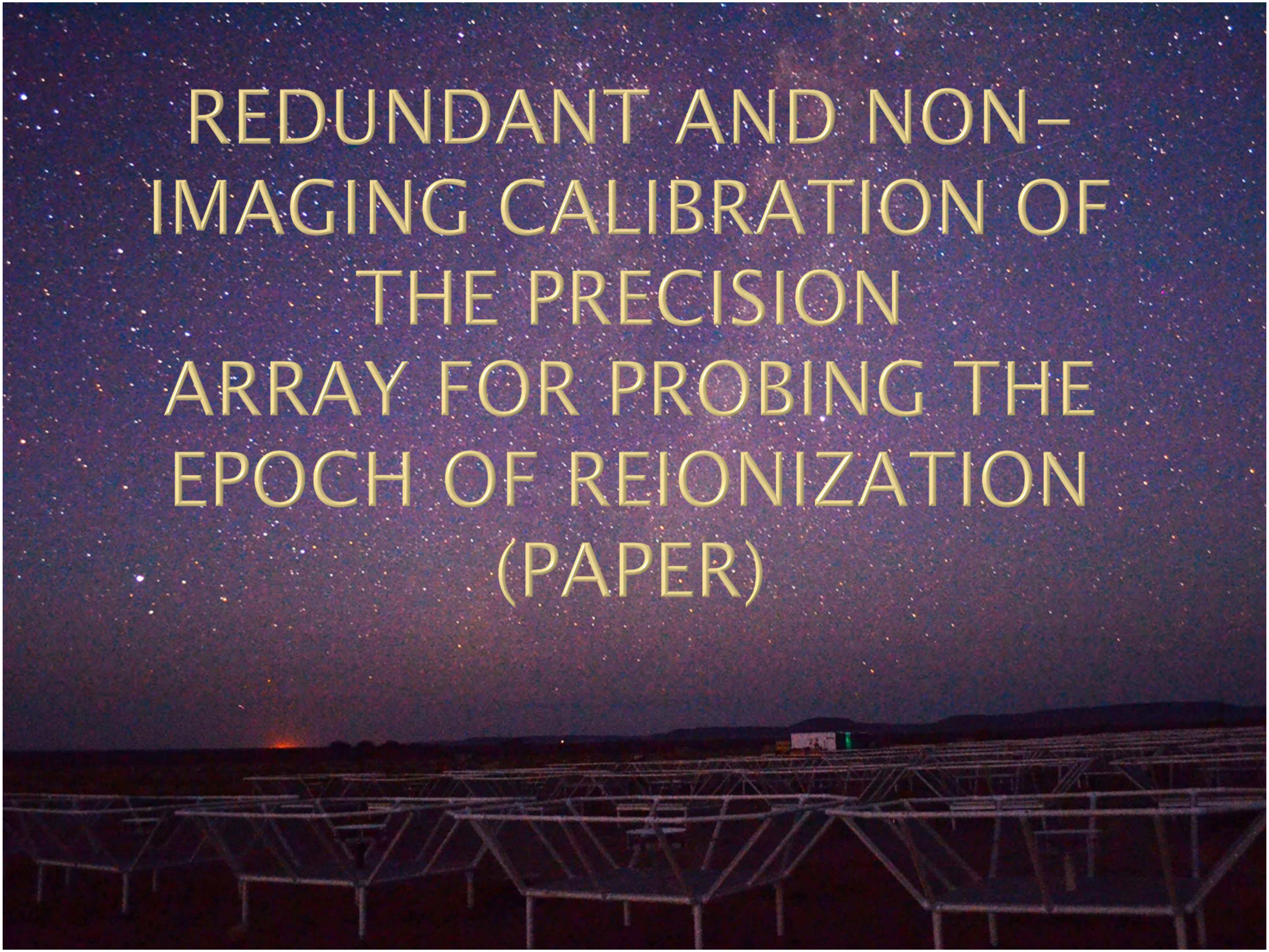
Foregrounds in k-space



300 m

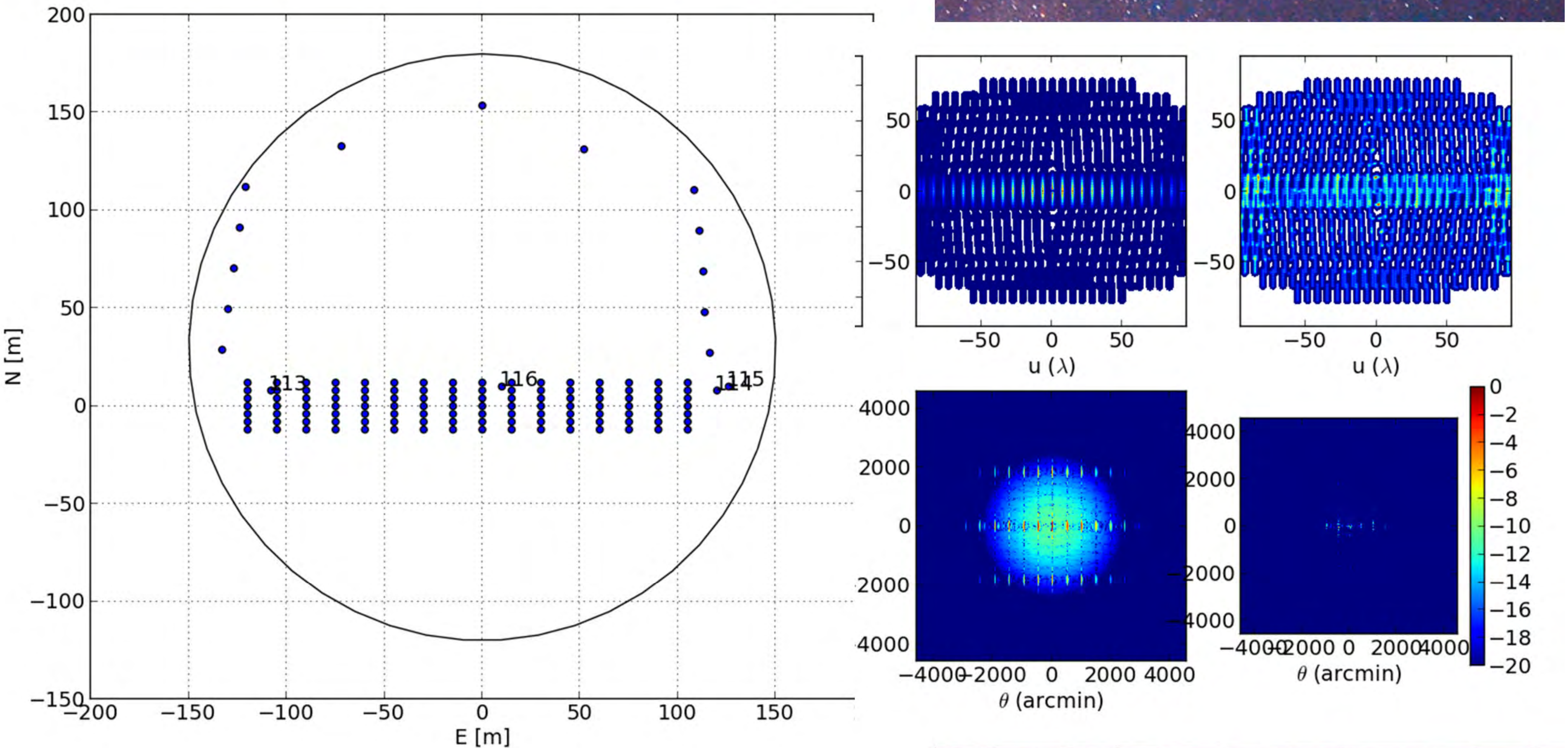
Pober et al 2013
ApJ 768 L36





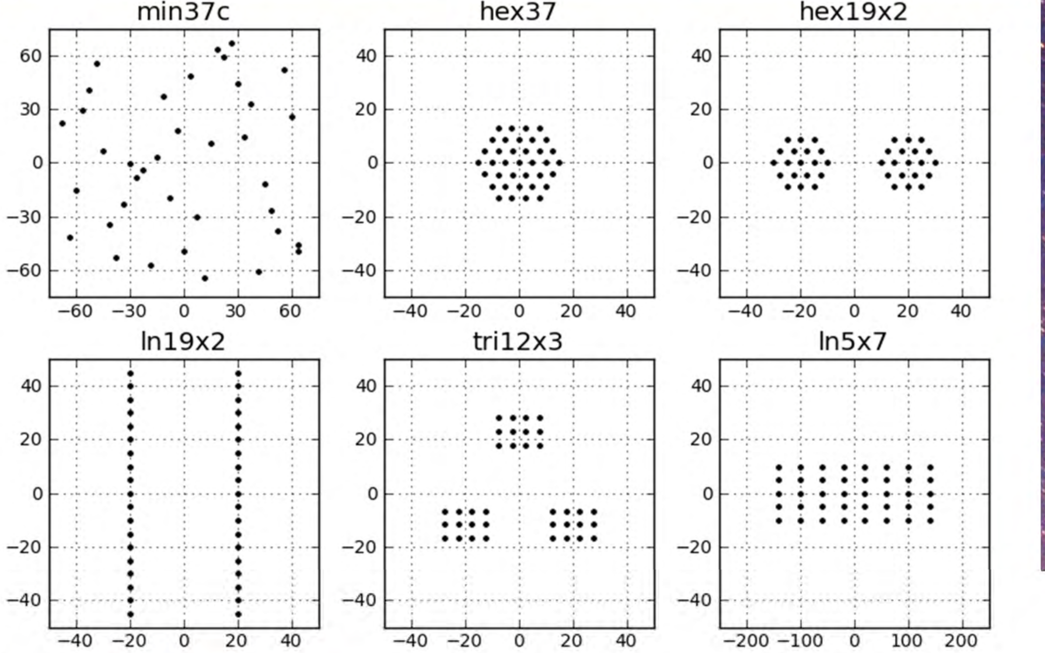
REDUNDANT AND NON-IMAGING CALIBRATION OF THE PRECISION ARRAY FOR PROBING THE EPOCH OF REIONIZATION (PAPER)

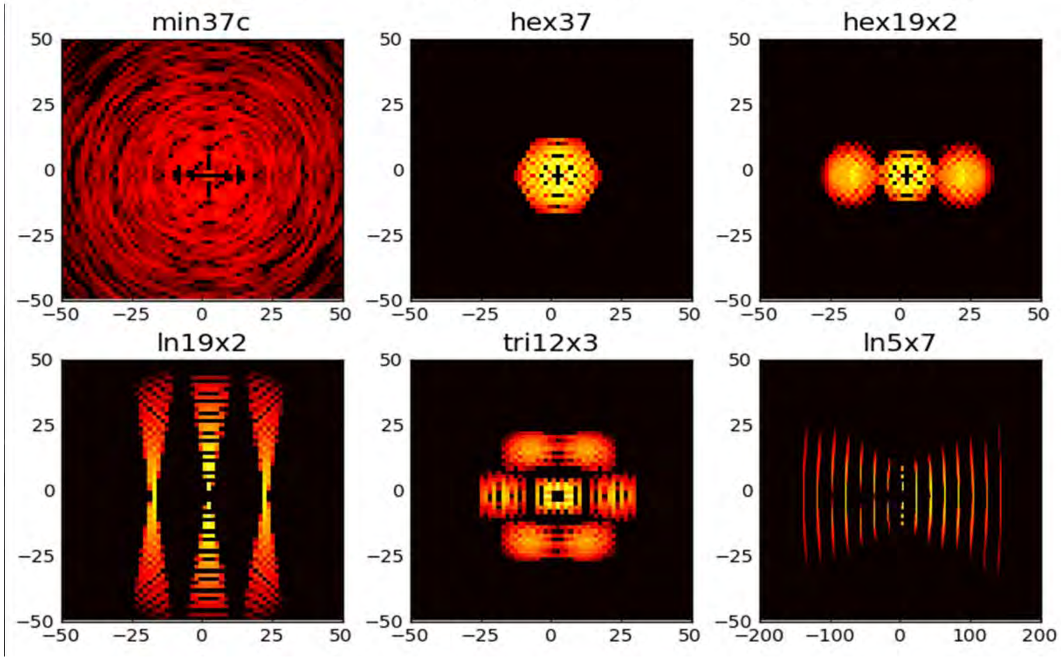
PSA-128 Configuration

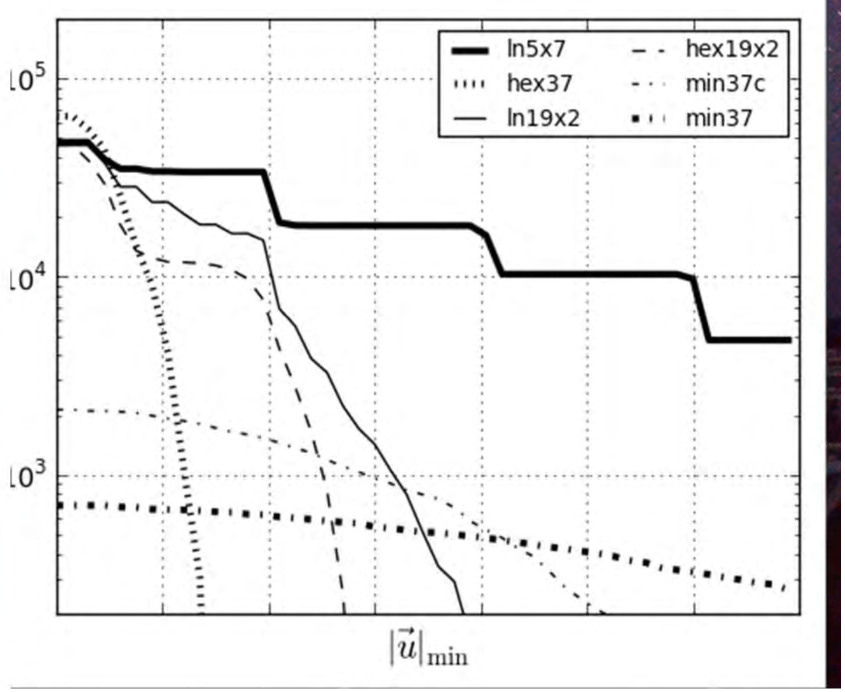


Why redundnancy?

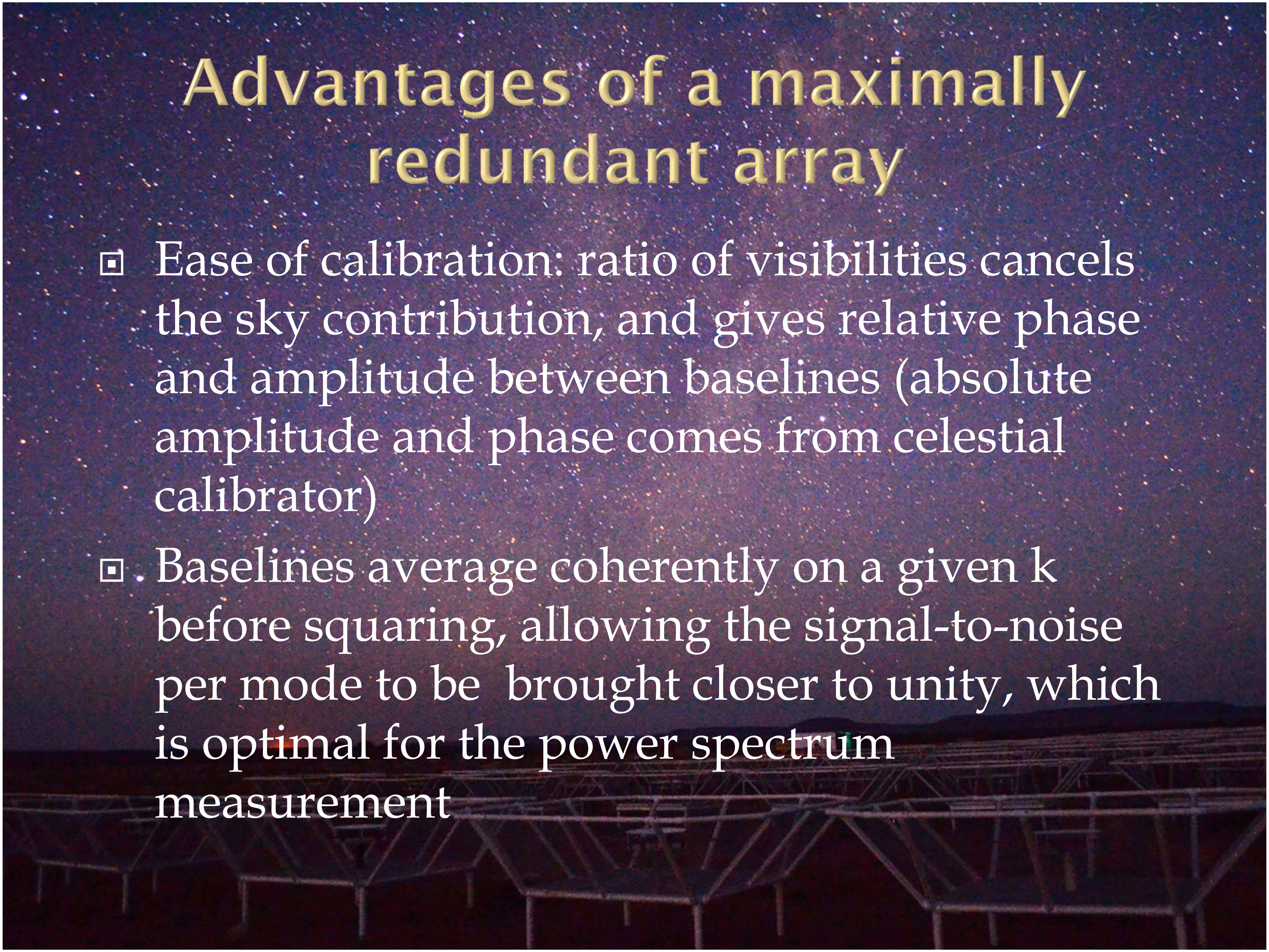
A Sensitivity and Array-Configuration Study for Measuring the Power Spectrum of 21cm Emission from Reionization
Parsons, Pober, McQuinn, Jacobs & Aguirre Apj 753 81, 2012





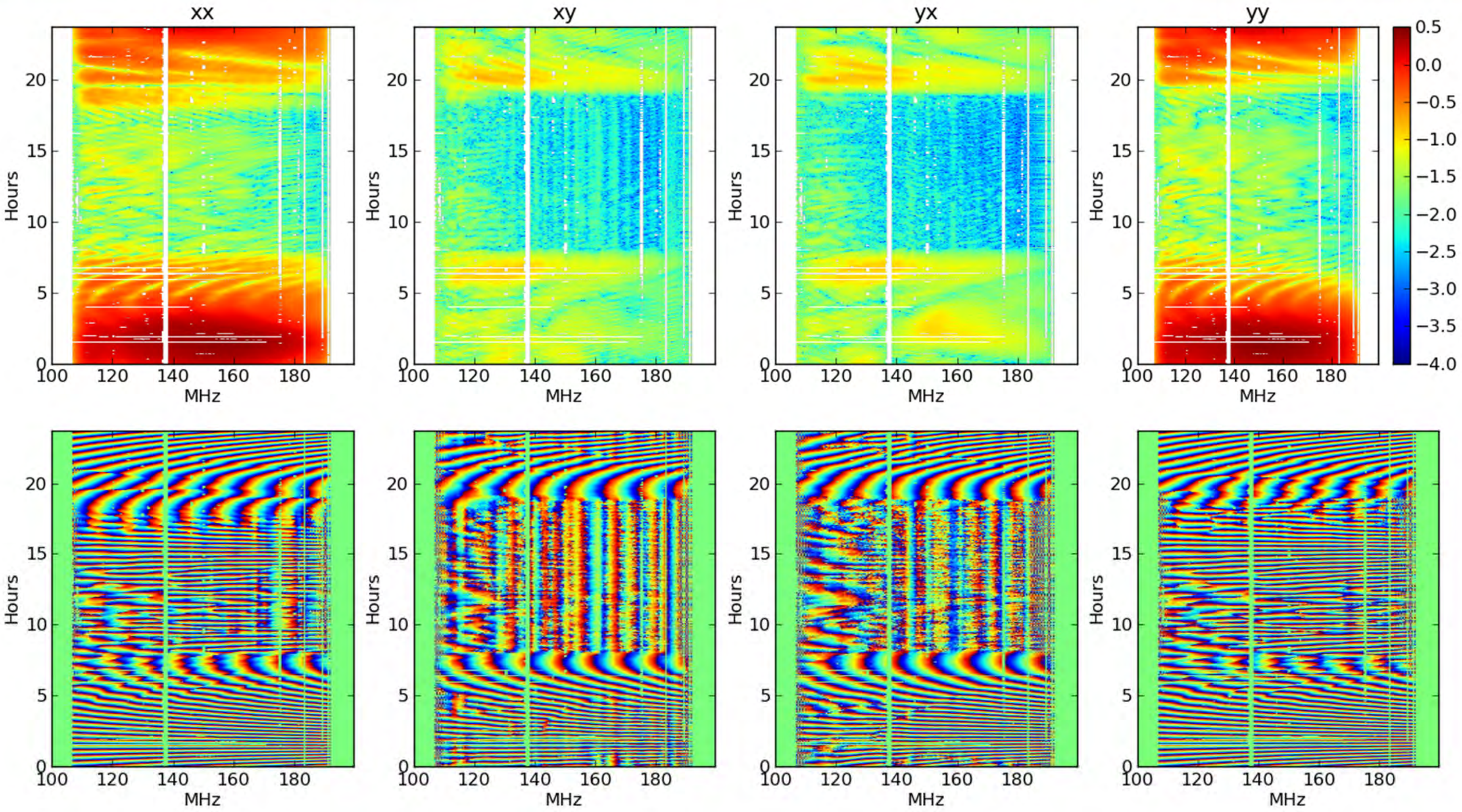


Advantages of a maximally redundant array



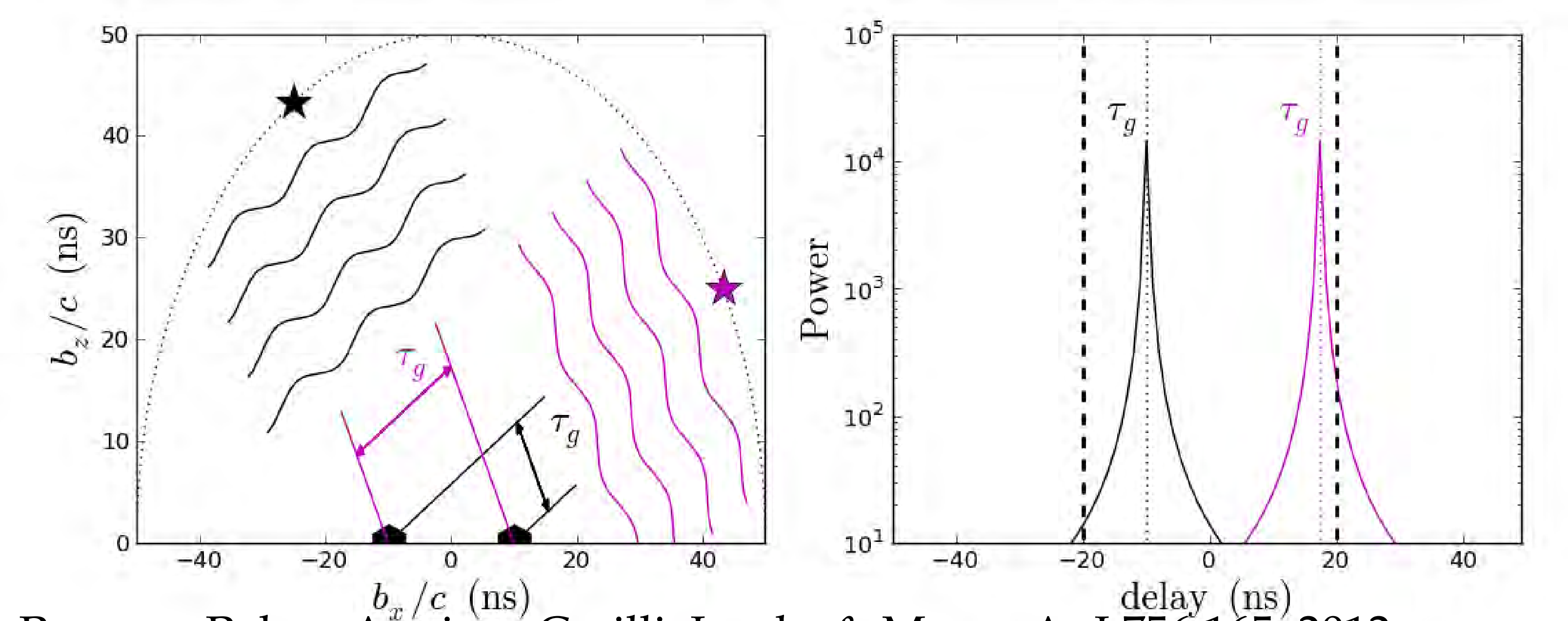
- Ease of calibration: ratio of visibilities cancels the sky contribution, and gives relative phase and amplitude between baselines (absolute amplitude and phase comes from celestial calibrator)
- Baselines average coherently on a given k before squaring, allowing the signal-to-noise per mode to be brought closer to unity, which is optimal for the power spectrum measurement

With sparse uv coverage, the fundamental analysis unit becomes the *individual baseline* "waterfall" visibility



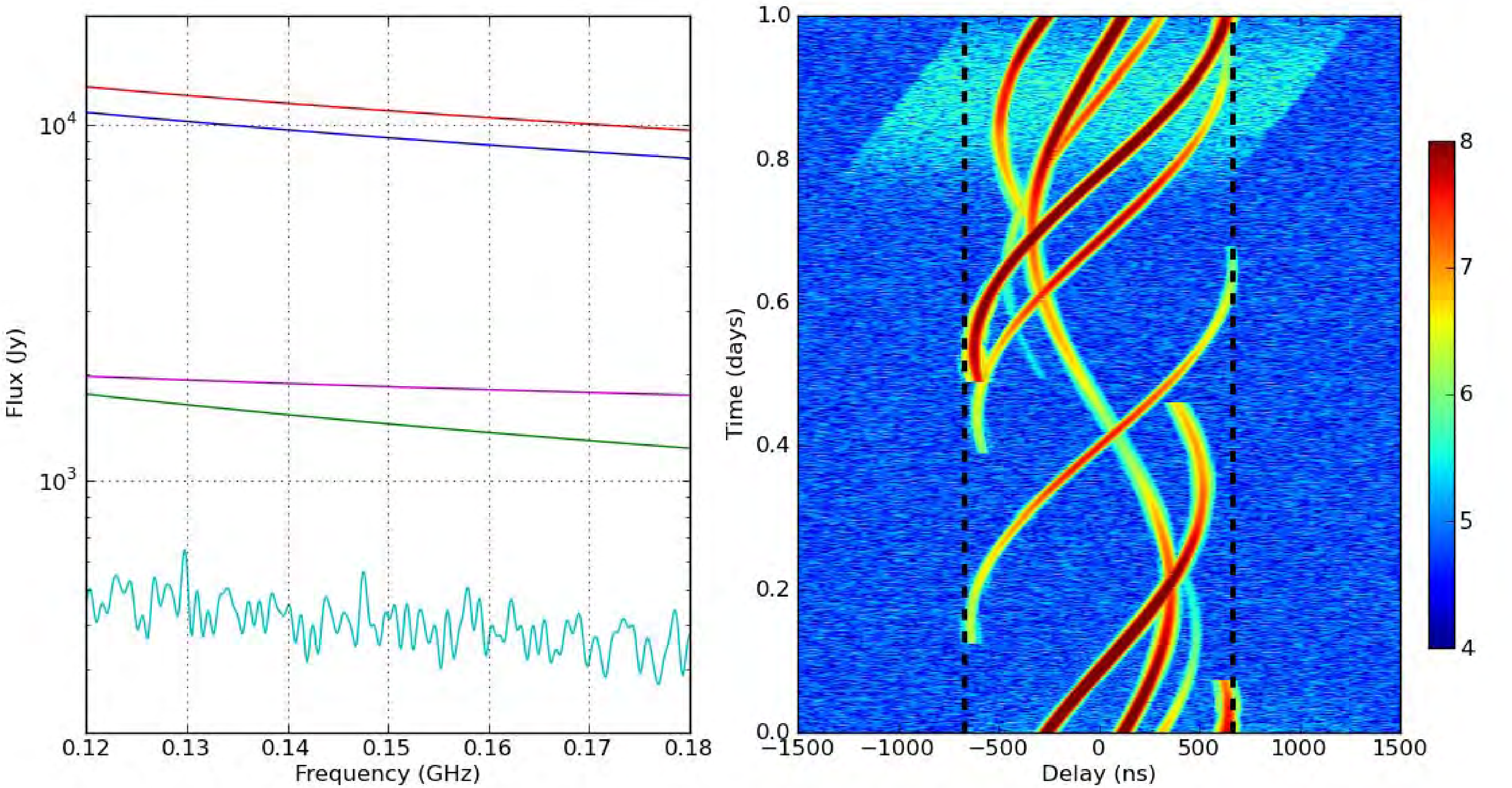
Interferometry without Imaging: The Delay Transform

- Delay space: Fourier transform of frequency axis
- Point sources map to (nearly) delta functions if they are *smooth* in frequency space
- The central delay is then the geometric delay set by the baseline length
- The width in delay space is a measure of the frequency coherence of the spectrum
- Delay space is very nearly *k_parallel*-space
- Note the *maximum* geometric delay caused by the horizon



Parsons, Pober, Aguirre, Carilli, Jacobs & Moore ApJ 756 165, 2012

Example Spectra in Delay Space



Delay/Delay-Rate Transform:

Pseudo-imaging and Compression

Example: 1 hour of data with Cas A, Cyg A, Tau A

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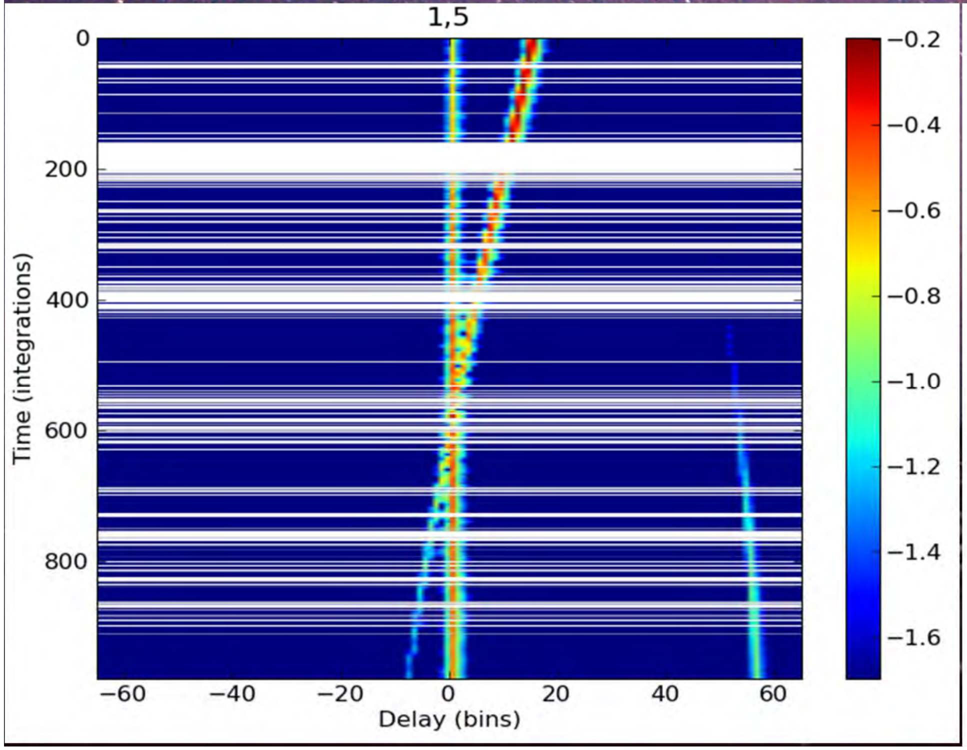
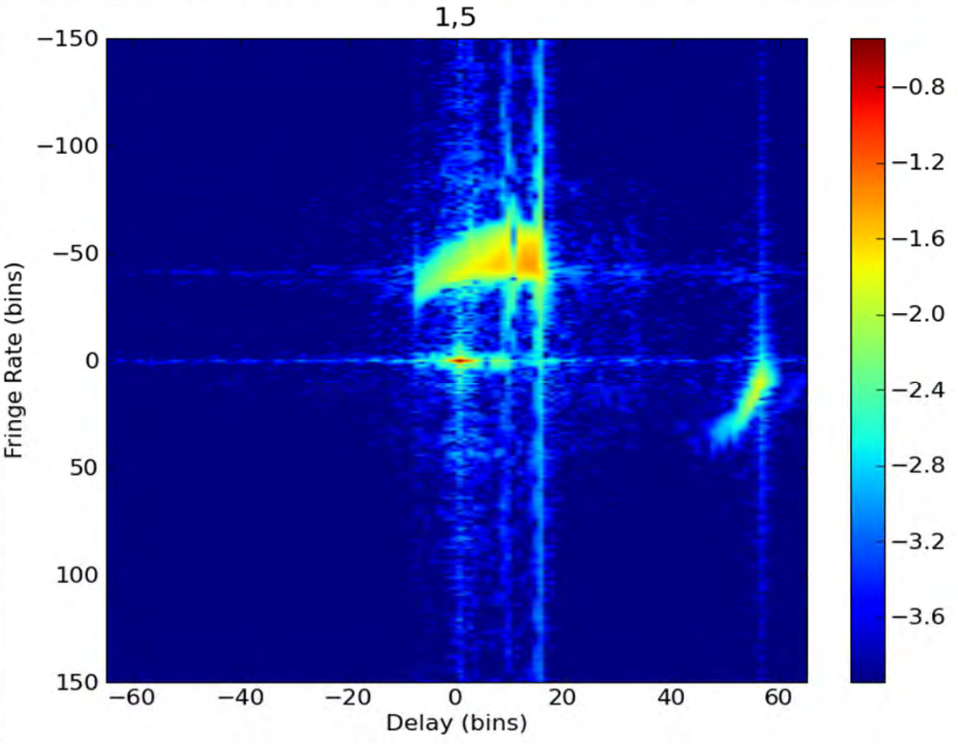
- PSF determined by bandpass + time variabliity

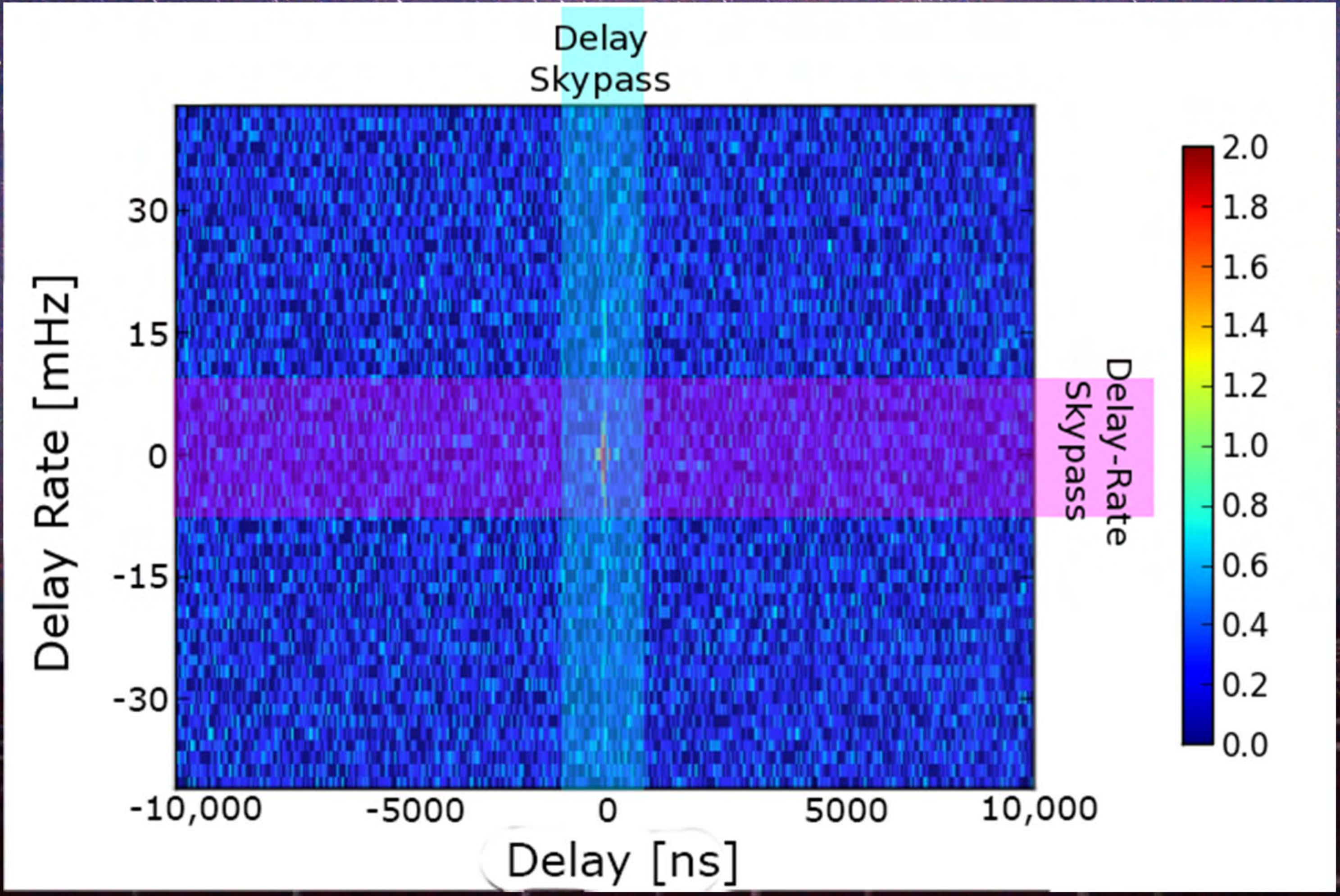
Useful as a form of optimized compression, specific to baseline length



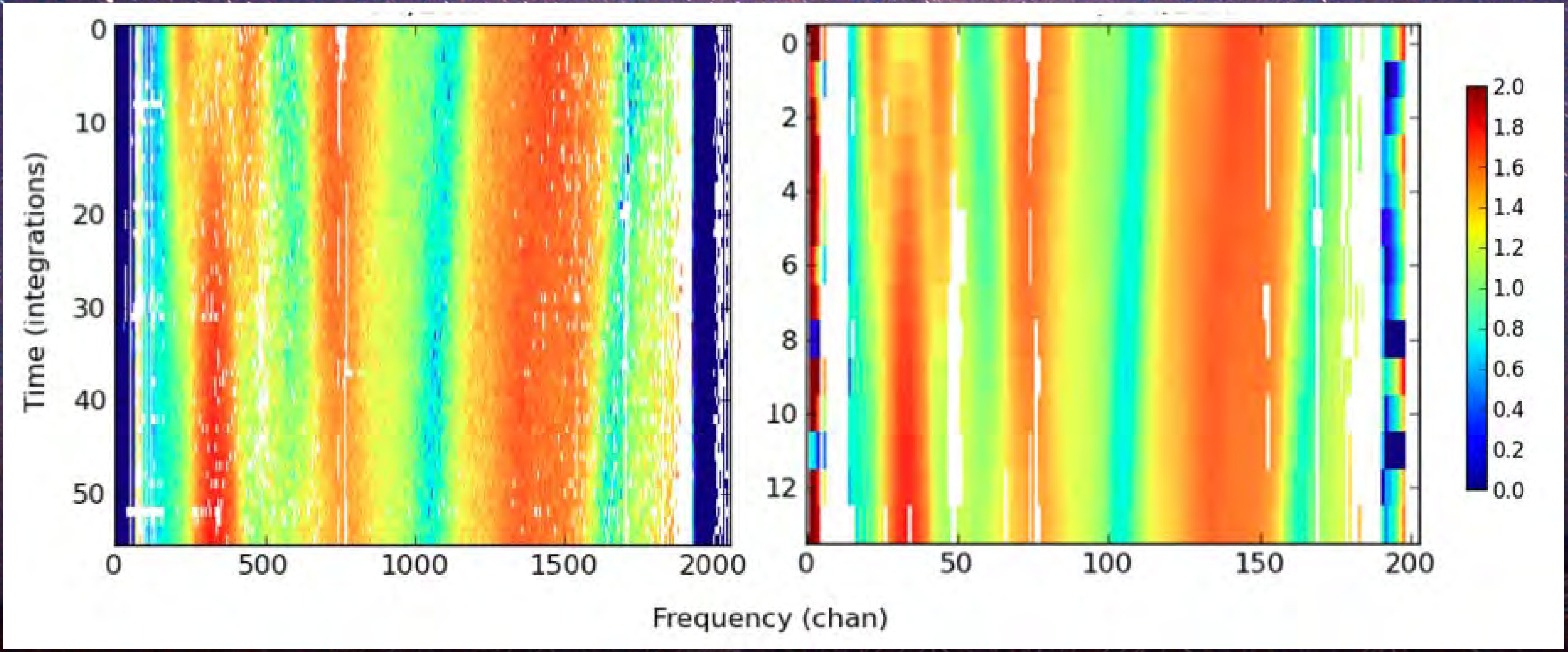


Compression

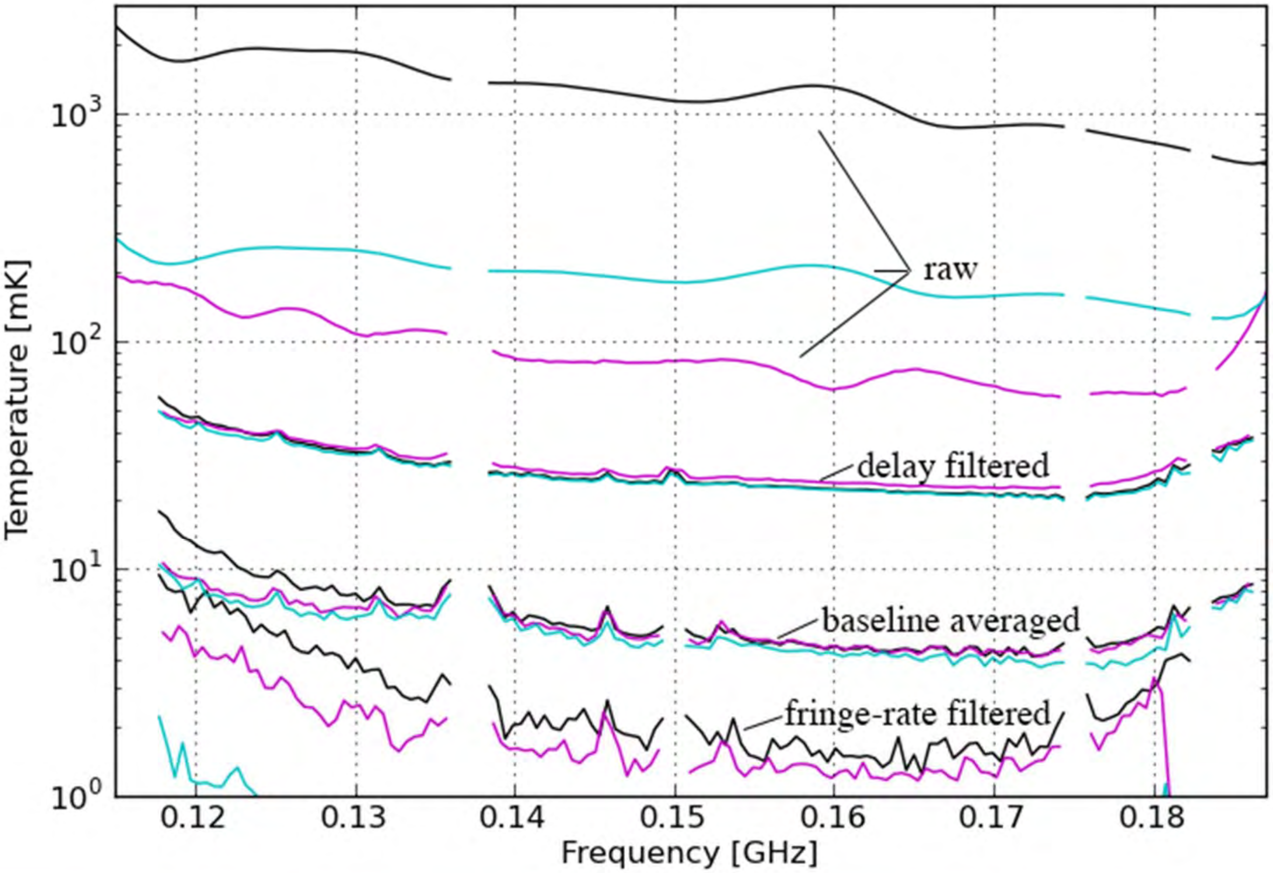
The key is that signal only lives in a small region of the delay / delay rate space

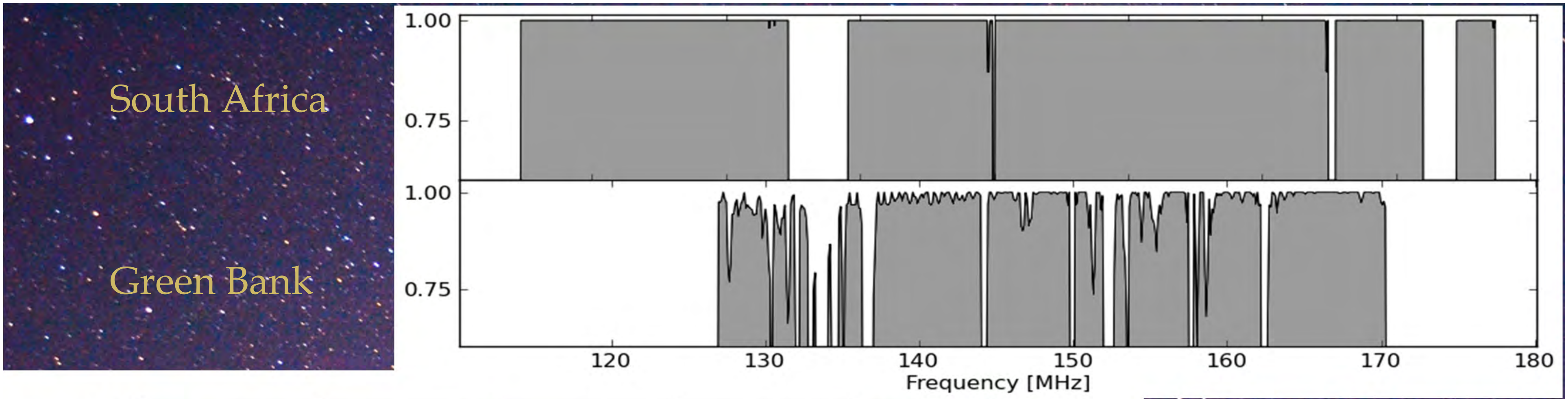


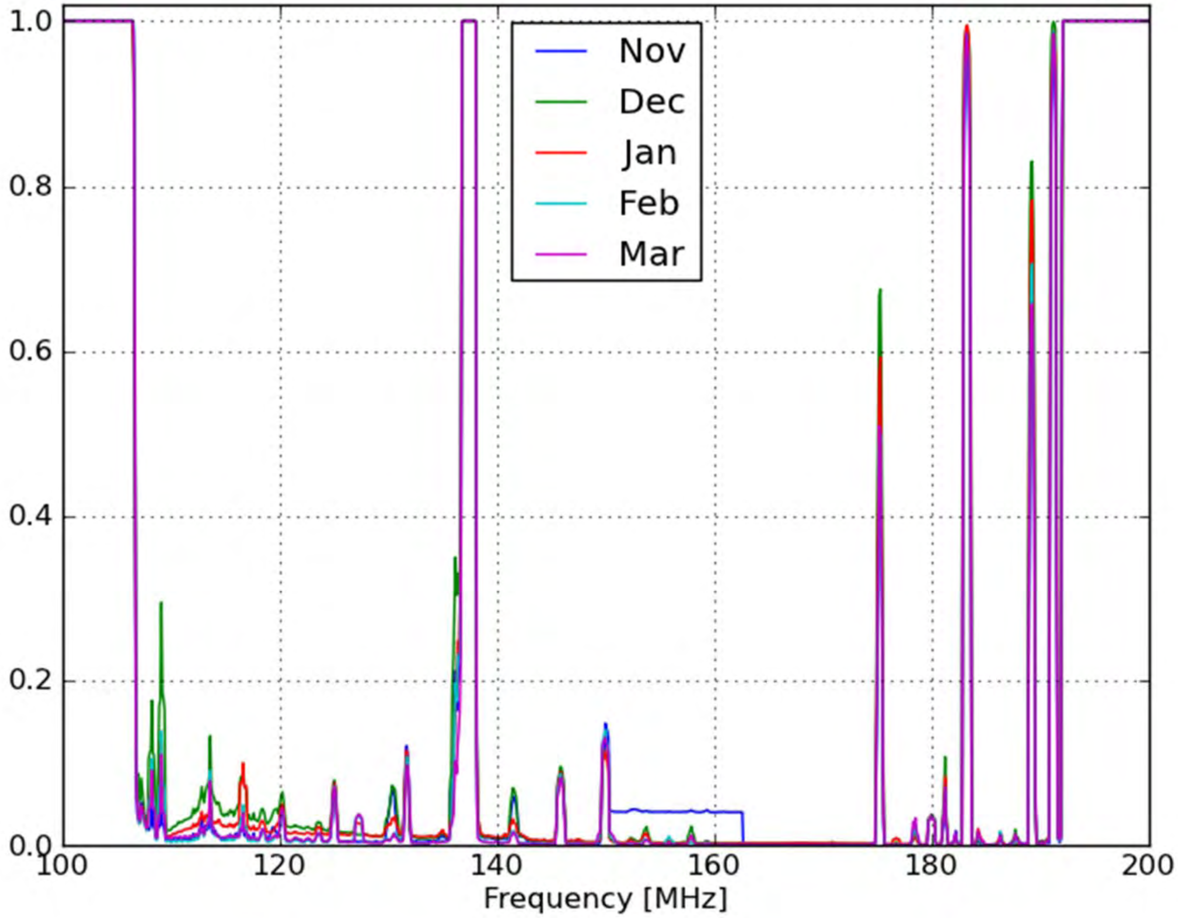
Compression dramatically reduces the number of spectral and time channels, without loss of signal



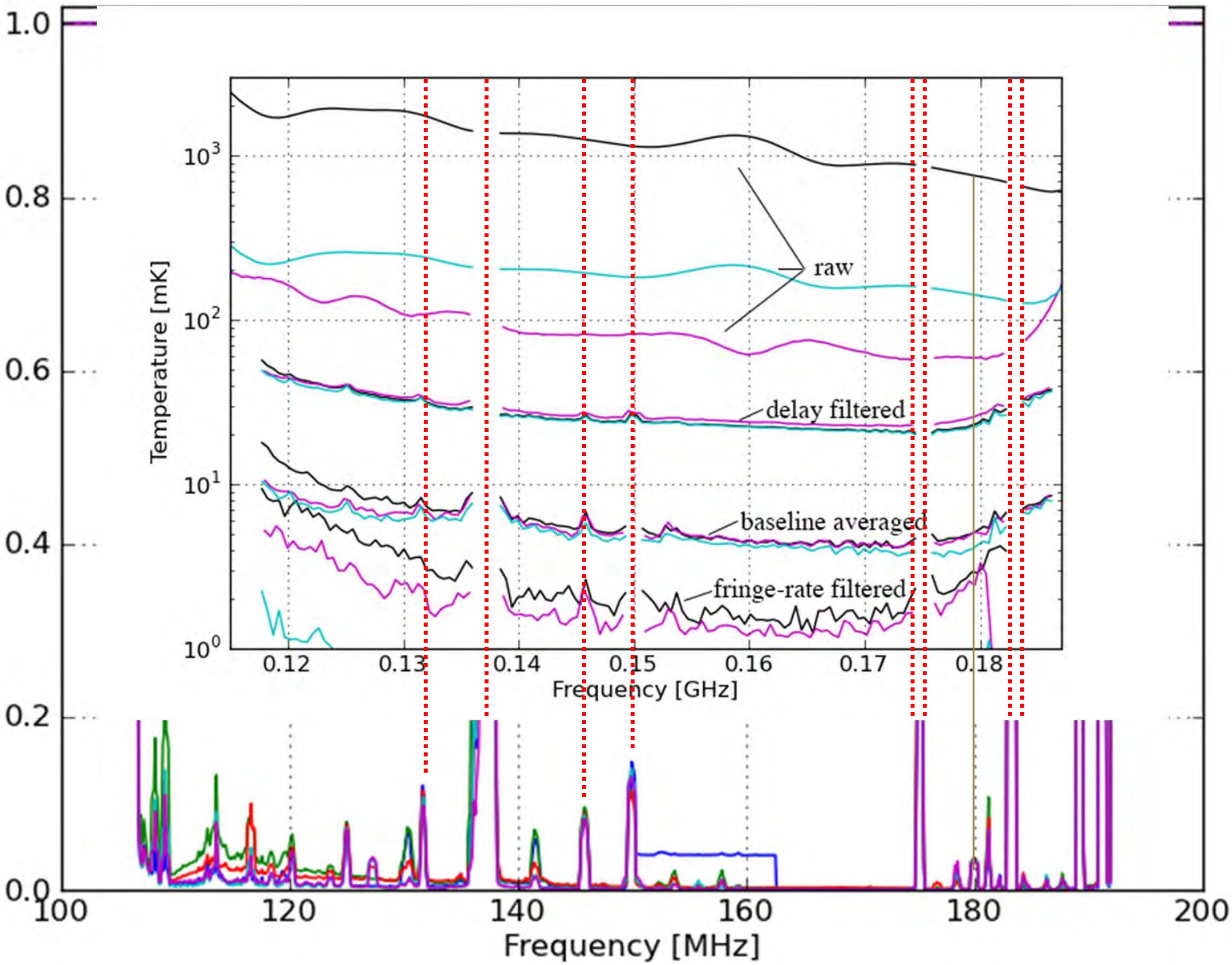
RFI gaps create problems in applying Fourier methods, but these can be overcome







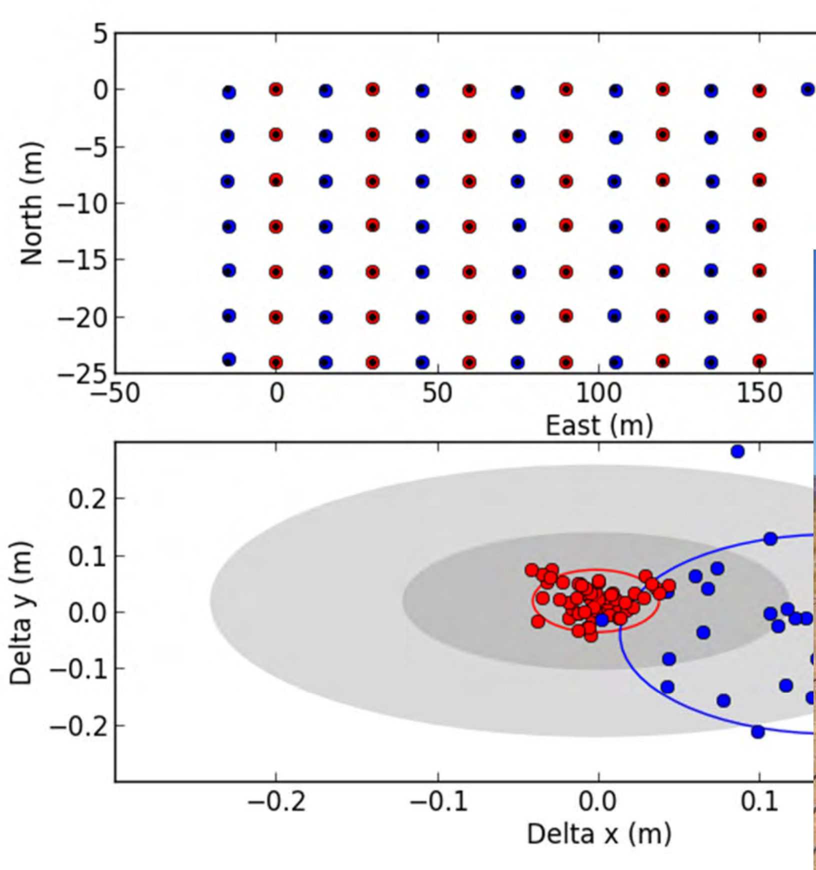
Top: RFI situation is dramatically better in South Africa than Green Bank (as shown by fraction of the data flagged)
Bottom: Fraction of data flagged in South Africa during the most recent campaign (PSA-64)



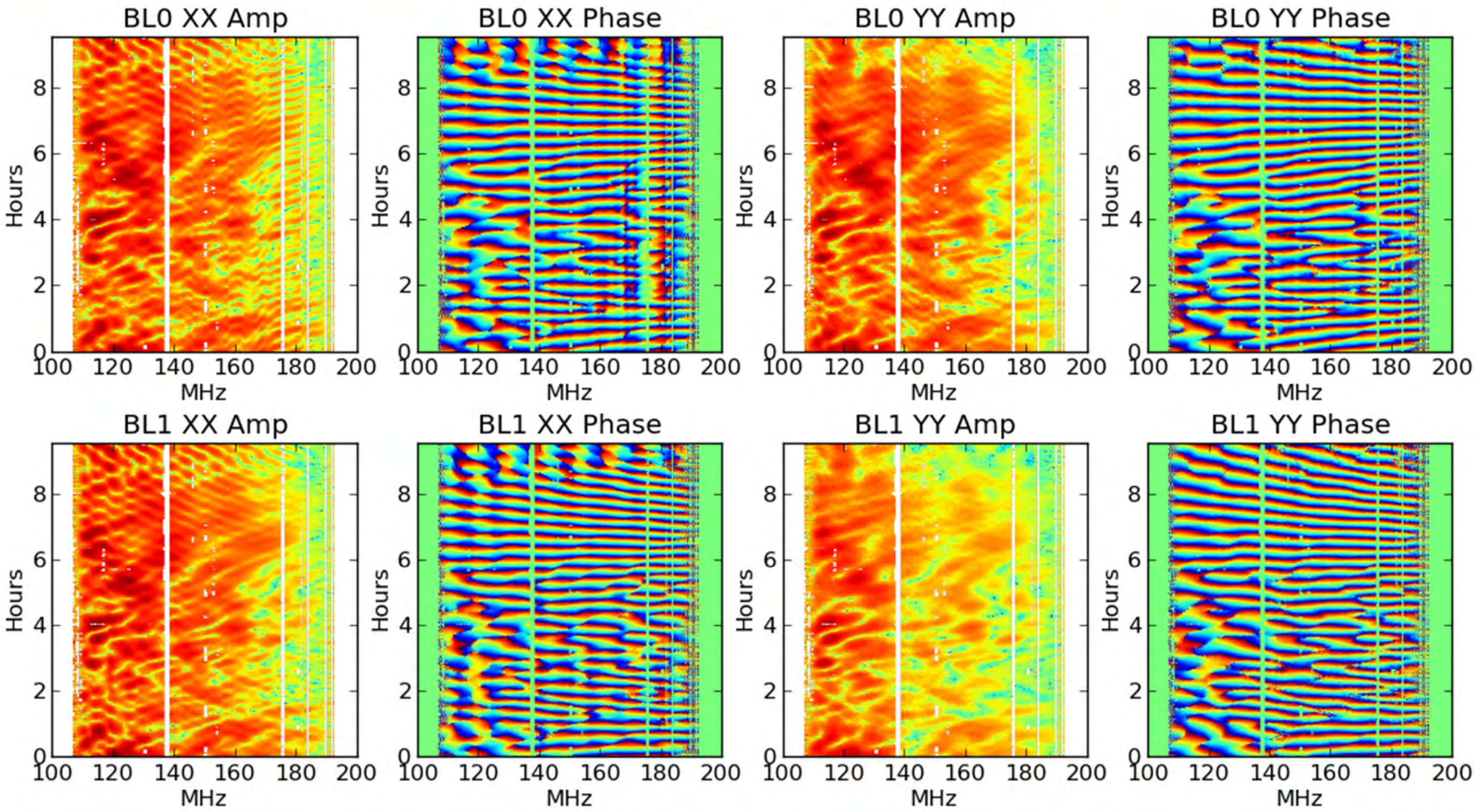
1.0
0.8
0.6
0.4
0.2
0.0
100
120
140
160
180
200
Frequency [MHz]
Temperature [mK]
10^3
10^2
10^1
10^0
raw
delay filtered
baseline averaged
fringe-rate filtered
0.12
0.13
0.14
0.15
0.16
0.17
0.18
Frequency [GHz]

Redundancy in position

Antennas can be positioned accurately to ~2 cm RMS with GPS and some legwork



Redundant baselines really are pretty redundant


BL0 XX Amp

BL0 XX Phase

BL0 YY Amp

BL0 YY Phase

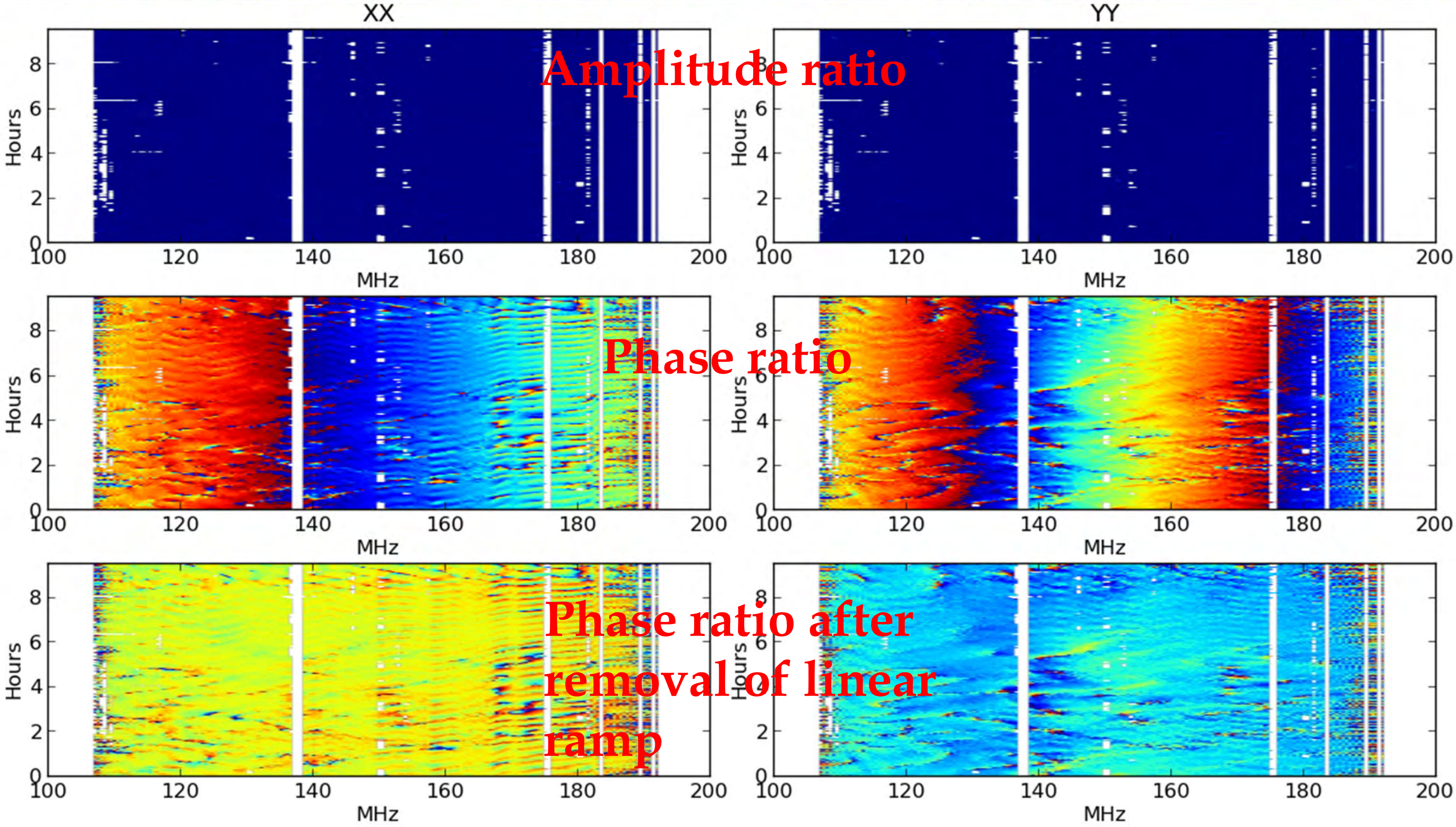
BL1 XX Amp

BL1 XX Phase

BL1 YY Amp

BL1 YY Phase

Calibration from *ratios* of redundant baselines



Amplitude ratio

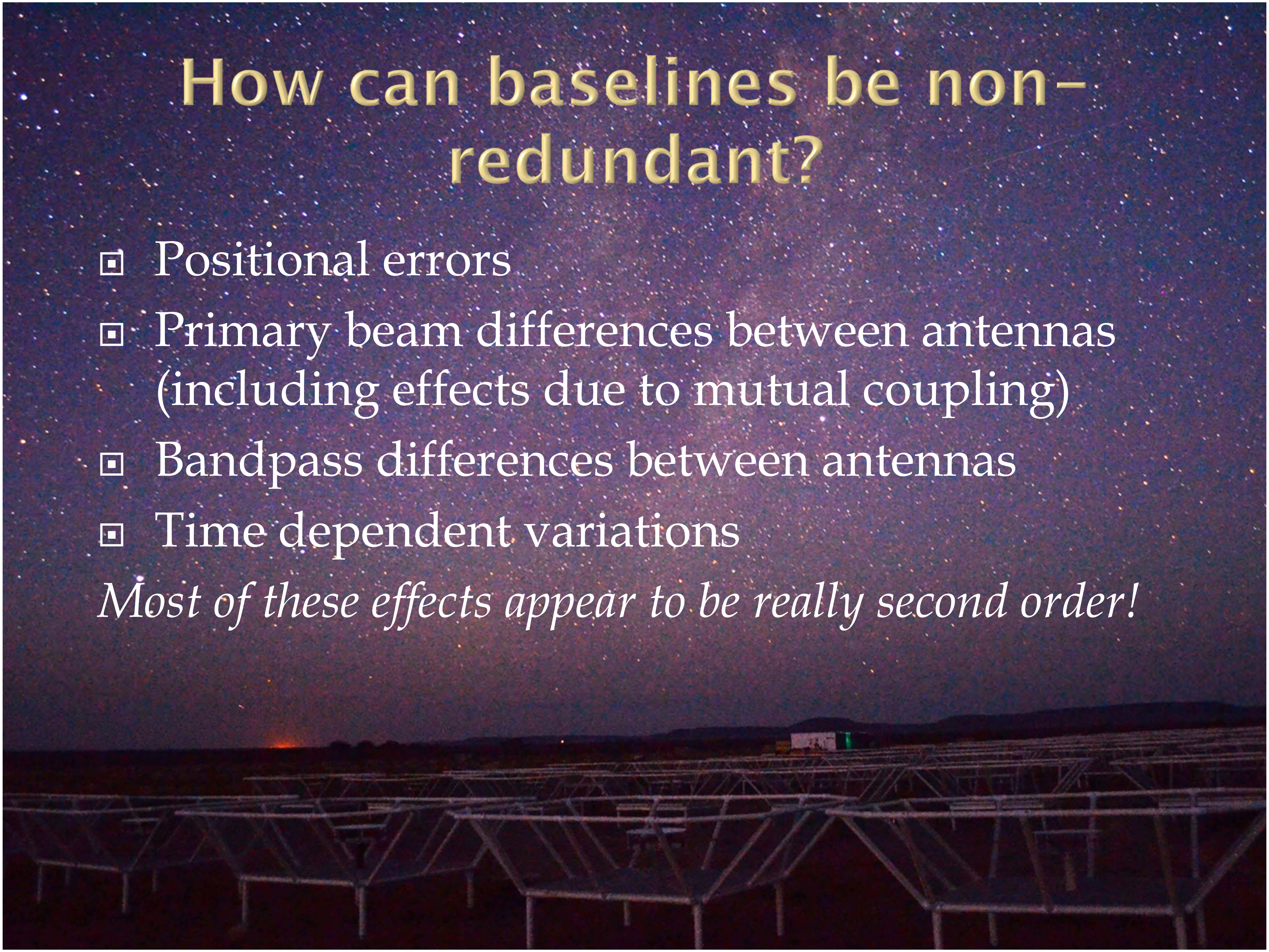
Phase ratio

Phase ratio after removal of linear ramp

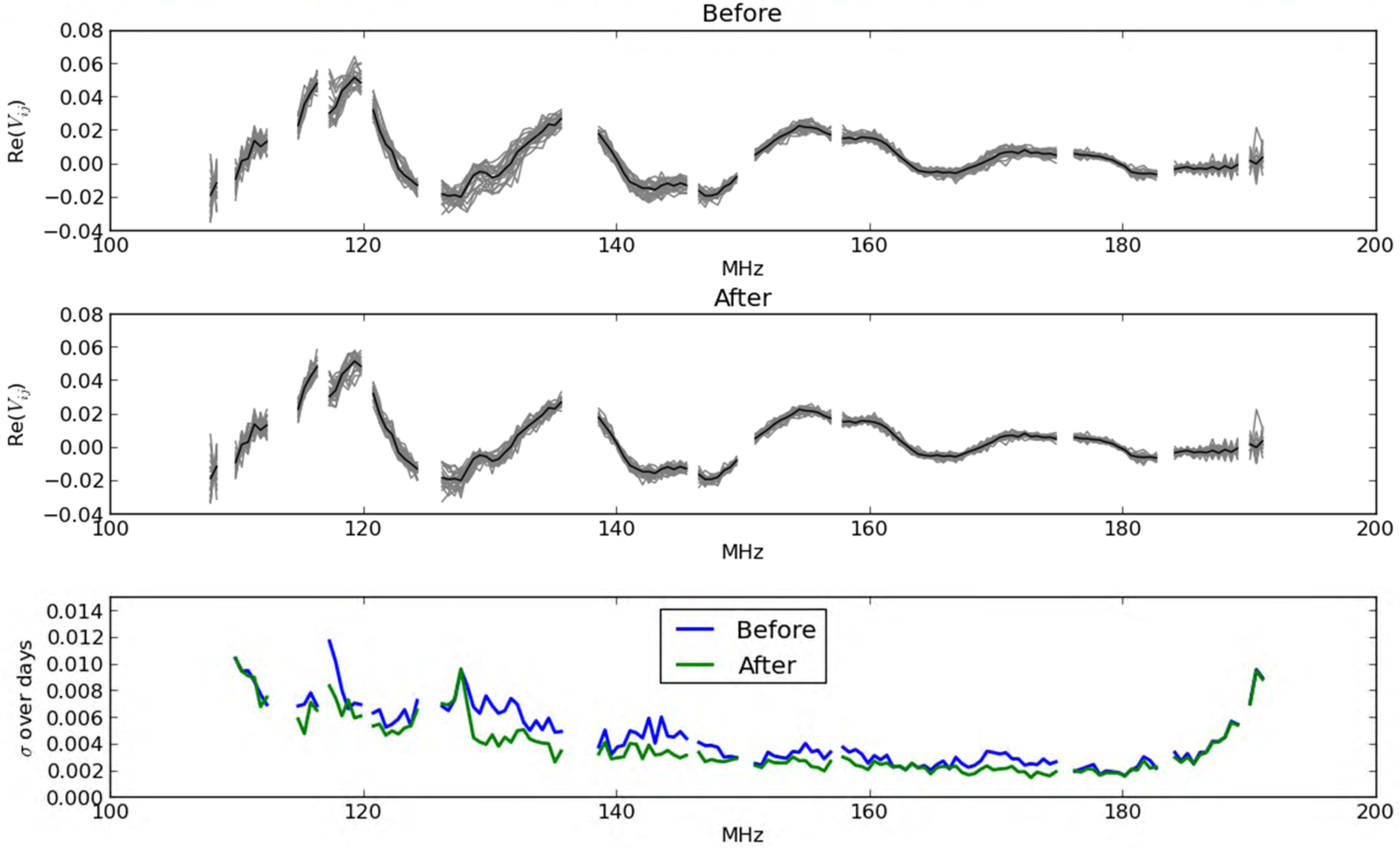
How can baselines be non-redundant?

- Positional errors
- Primary beam differences between antennas (including effects due to mutual coupling)
- Bandpass differences between antennas
- Time dependent variations

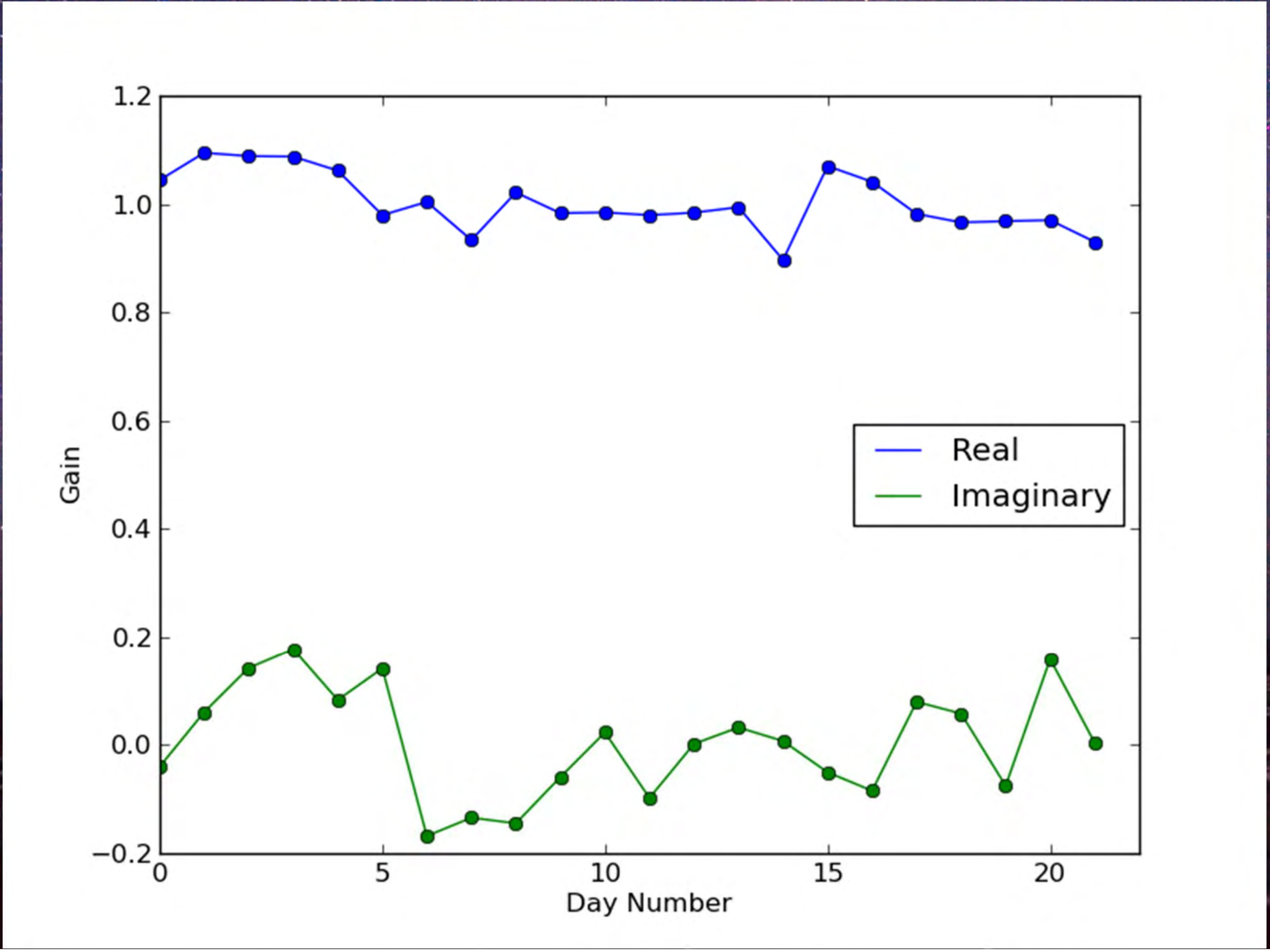
Most of these effects appear to be really second order!



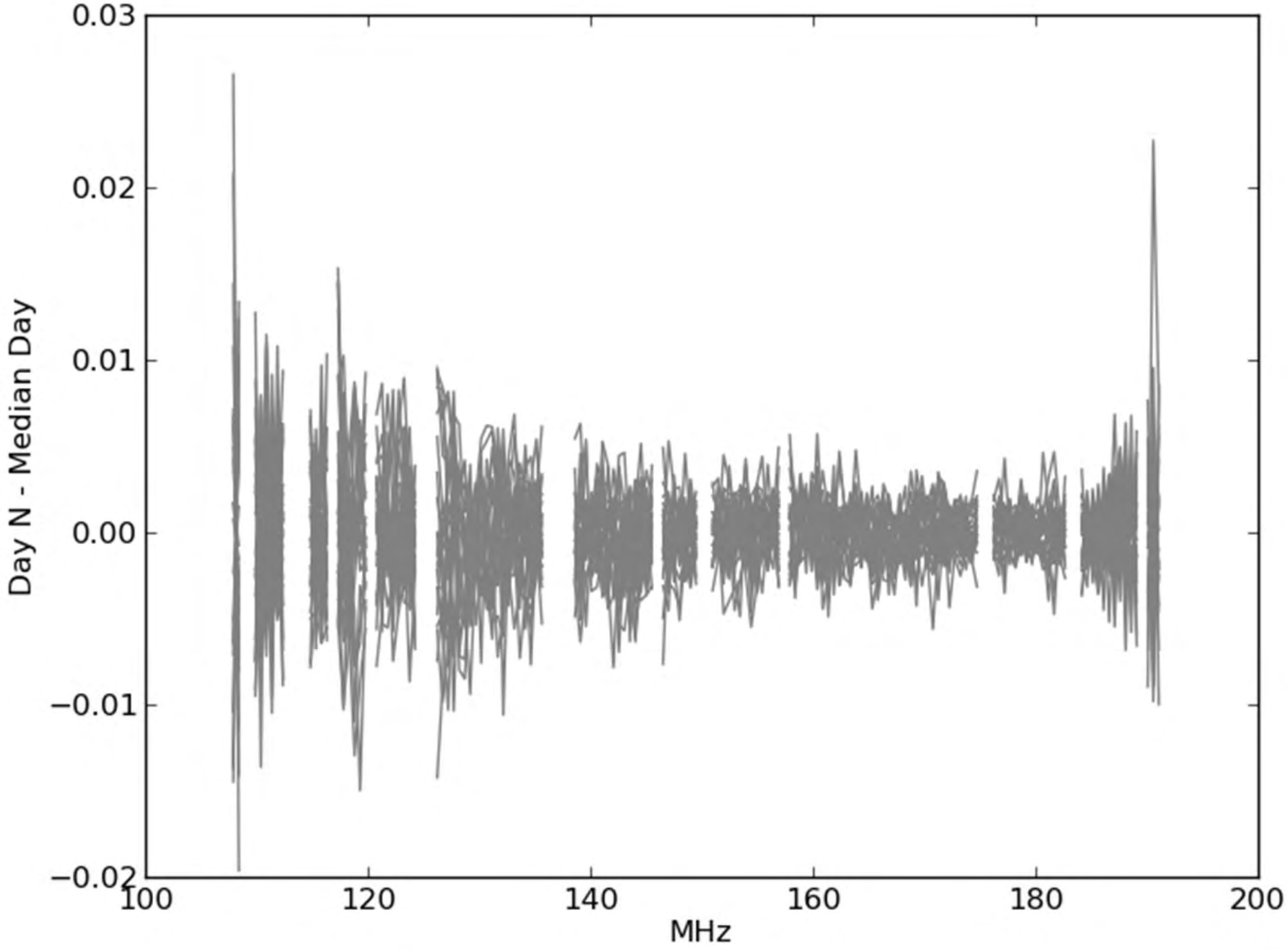
Time stability is quite good

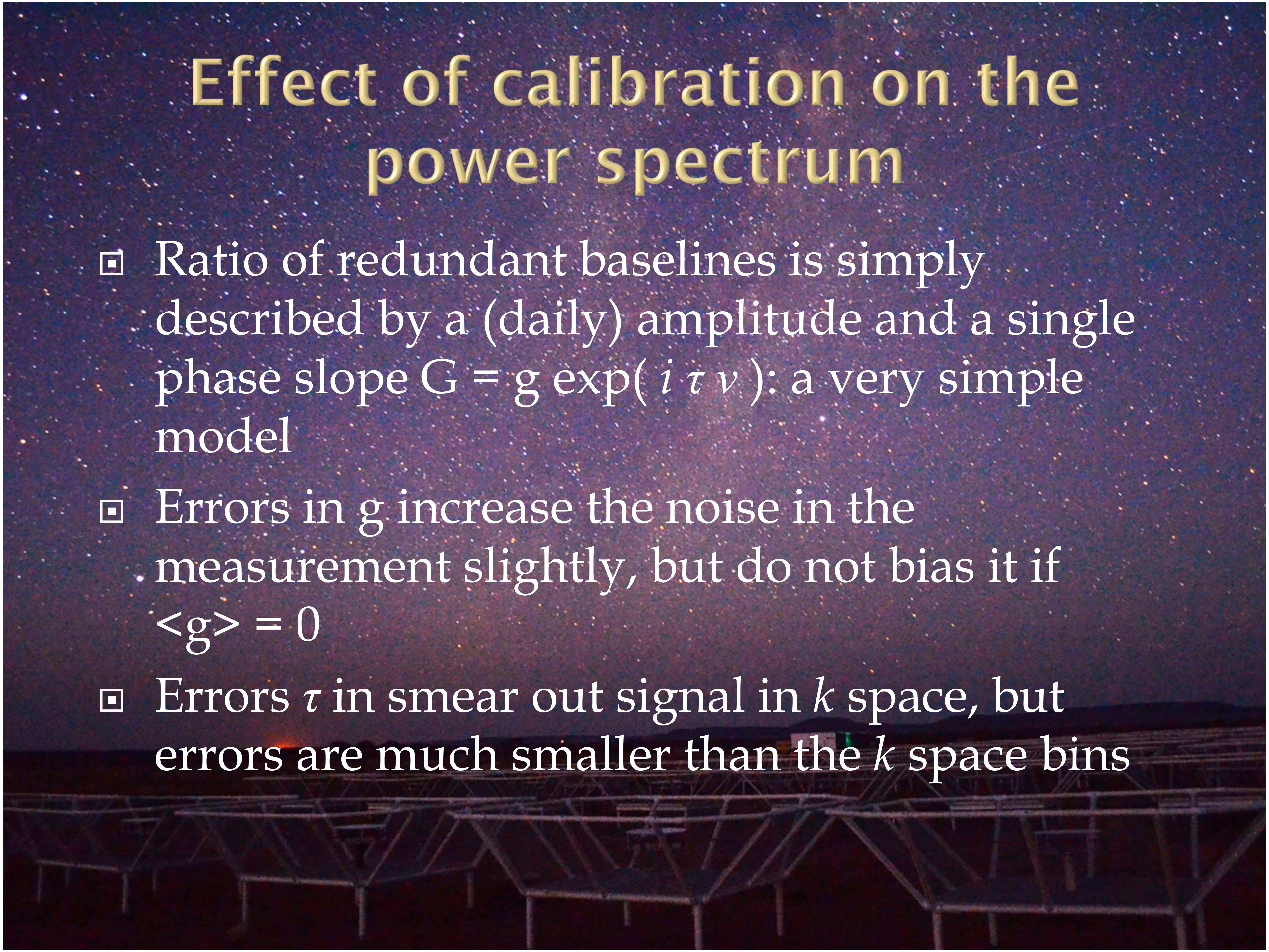


Day-to-day gain variations are small



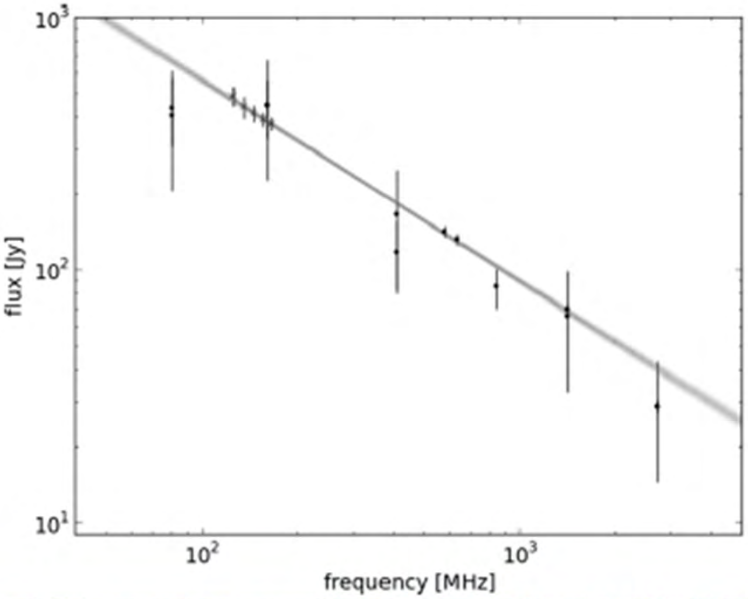
Differencing over days approximates the noise

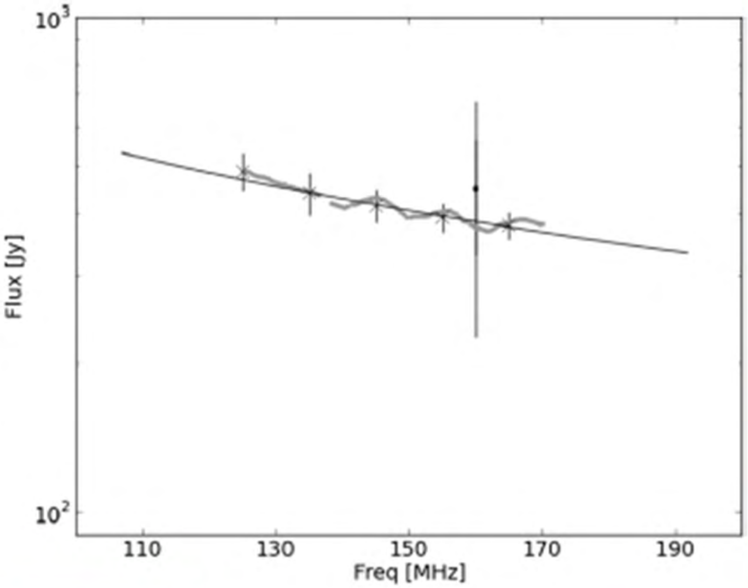


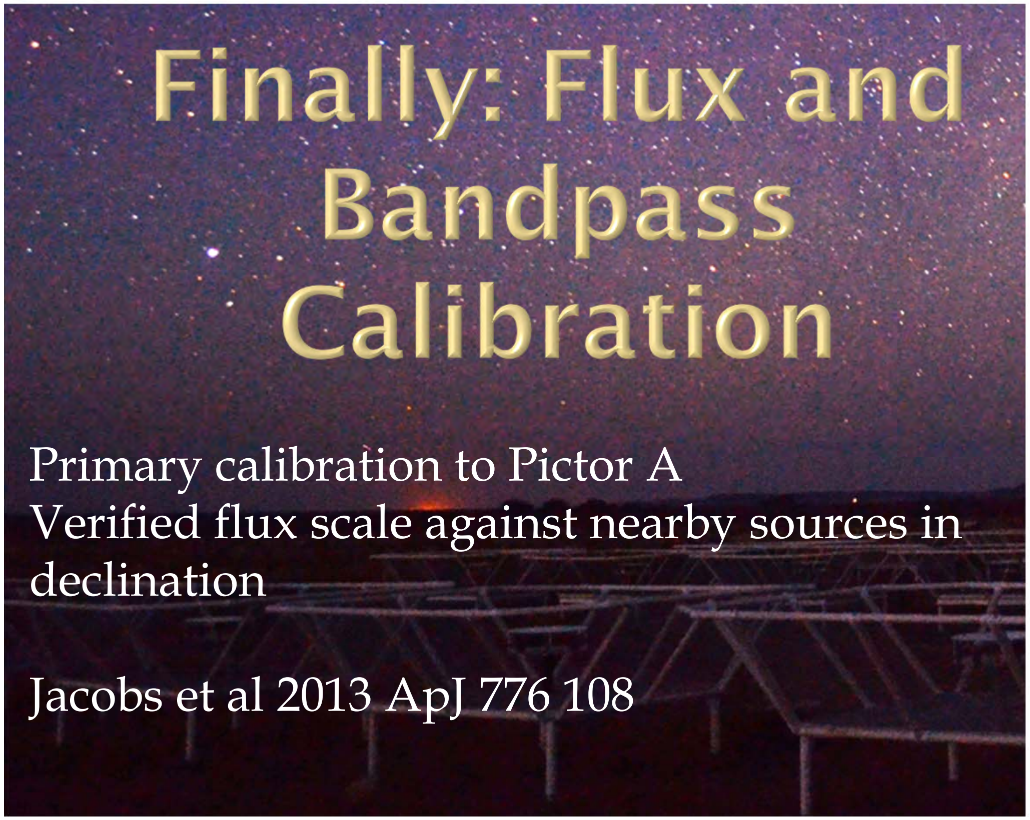


Effect of calibration on the power spectrum

- Ratio of redundant baselines is simply described by a (daily) amplitude and a single phase slope $G = g \exp(i \tau \nu)$: a very simple model
- Errors in g increase the noise in the measurement slightly, but do not bias it if $\langle g \rangle = 0$
- Errors τ in smear out signal in *k* space, but errors are much smaller than the *k* space bins



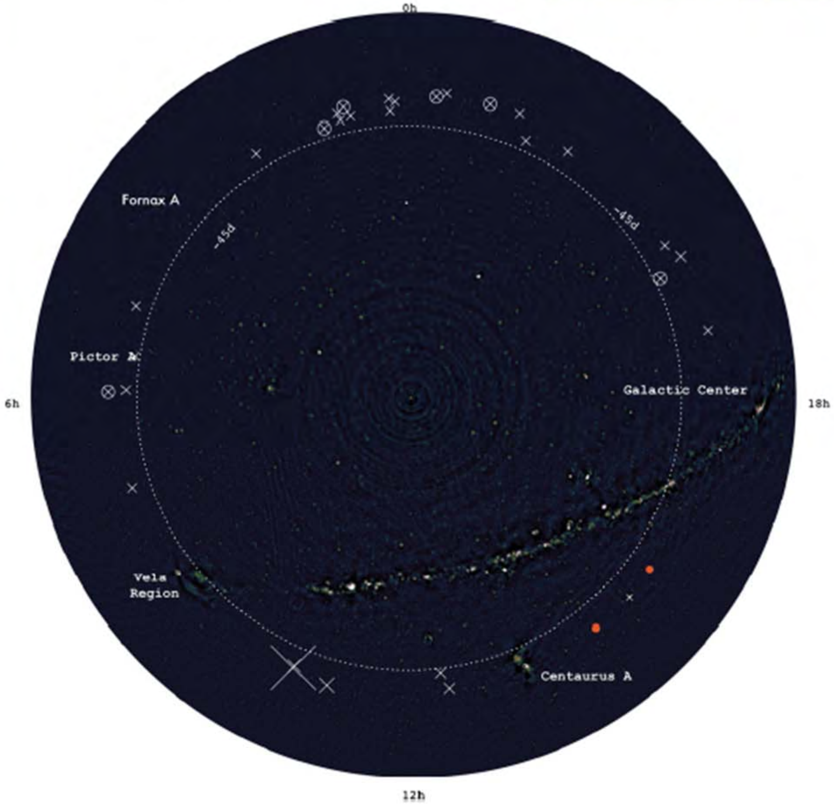




Finally: Flux and Bandpass Calibration

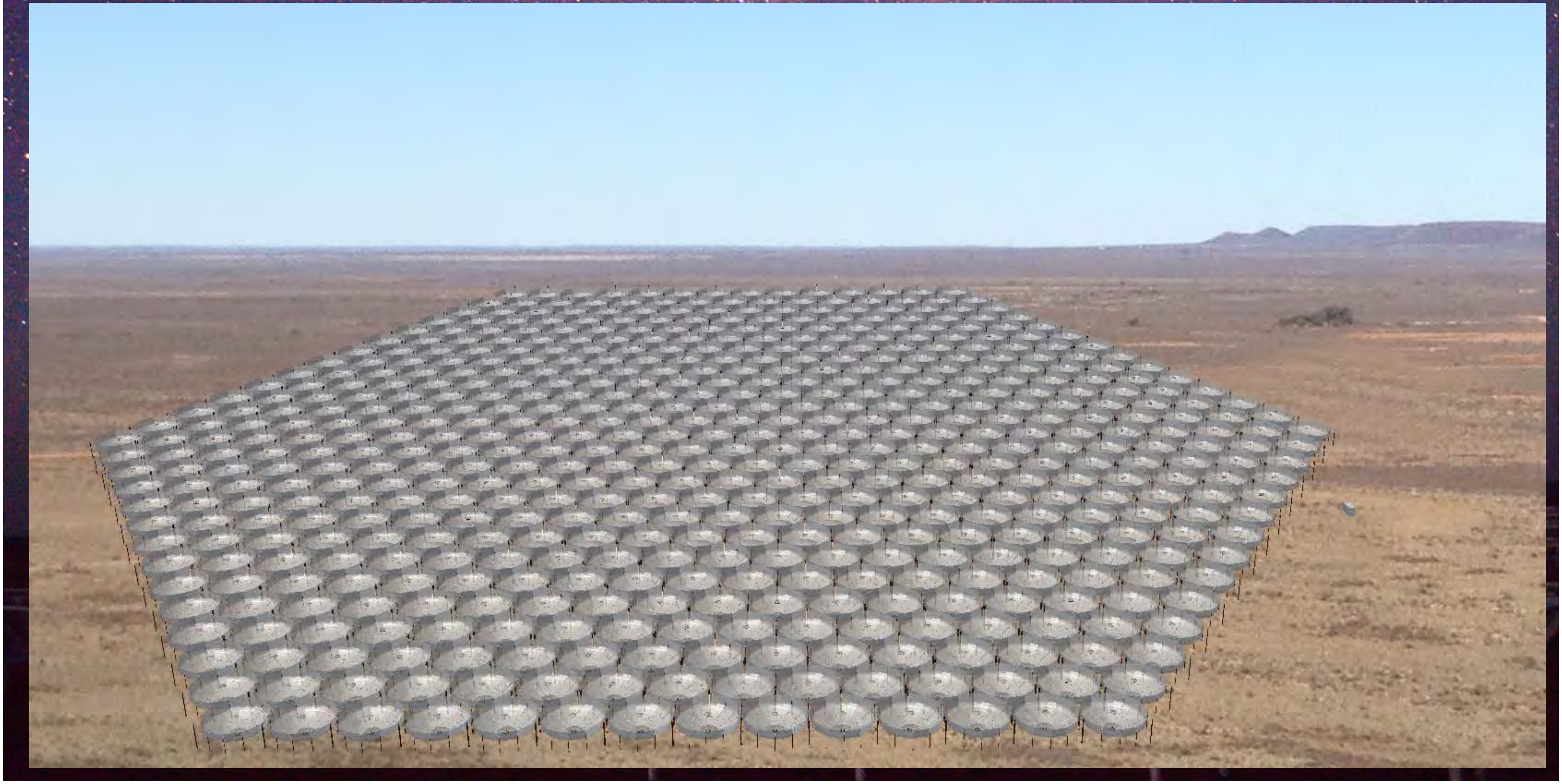
Primary calibration to Pictor A
Verified flux scale against nearby sources in declination

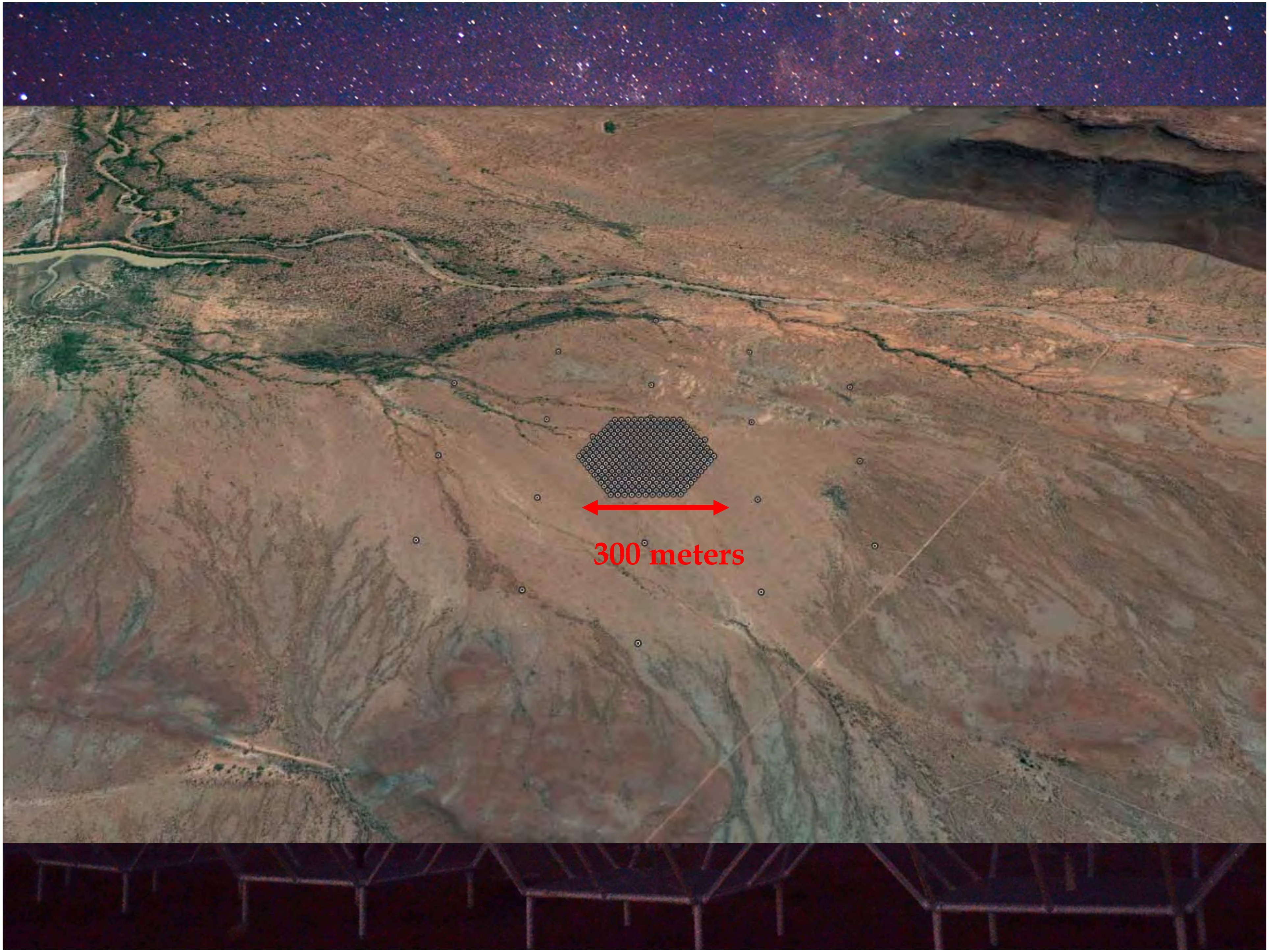
Jacobs et al 2013 ApJ 776 108



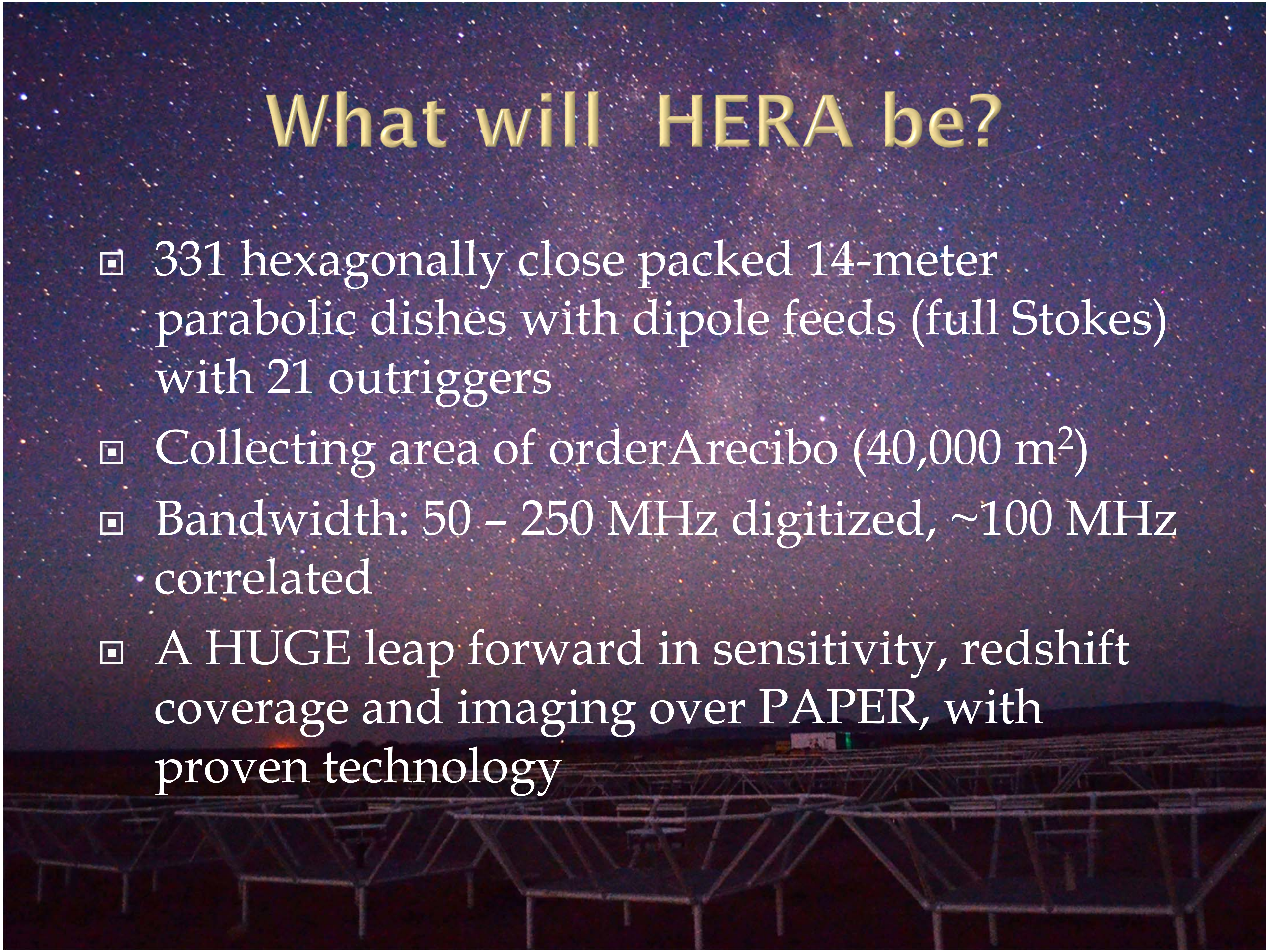
HERA

Hydrogen Epoch of Reionization Array

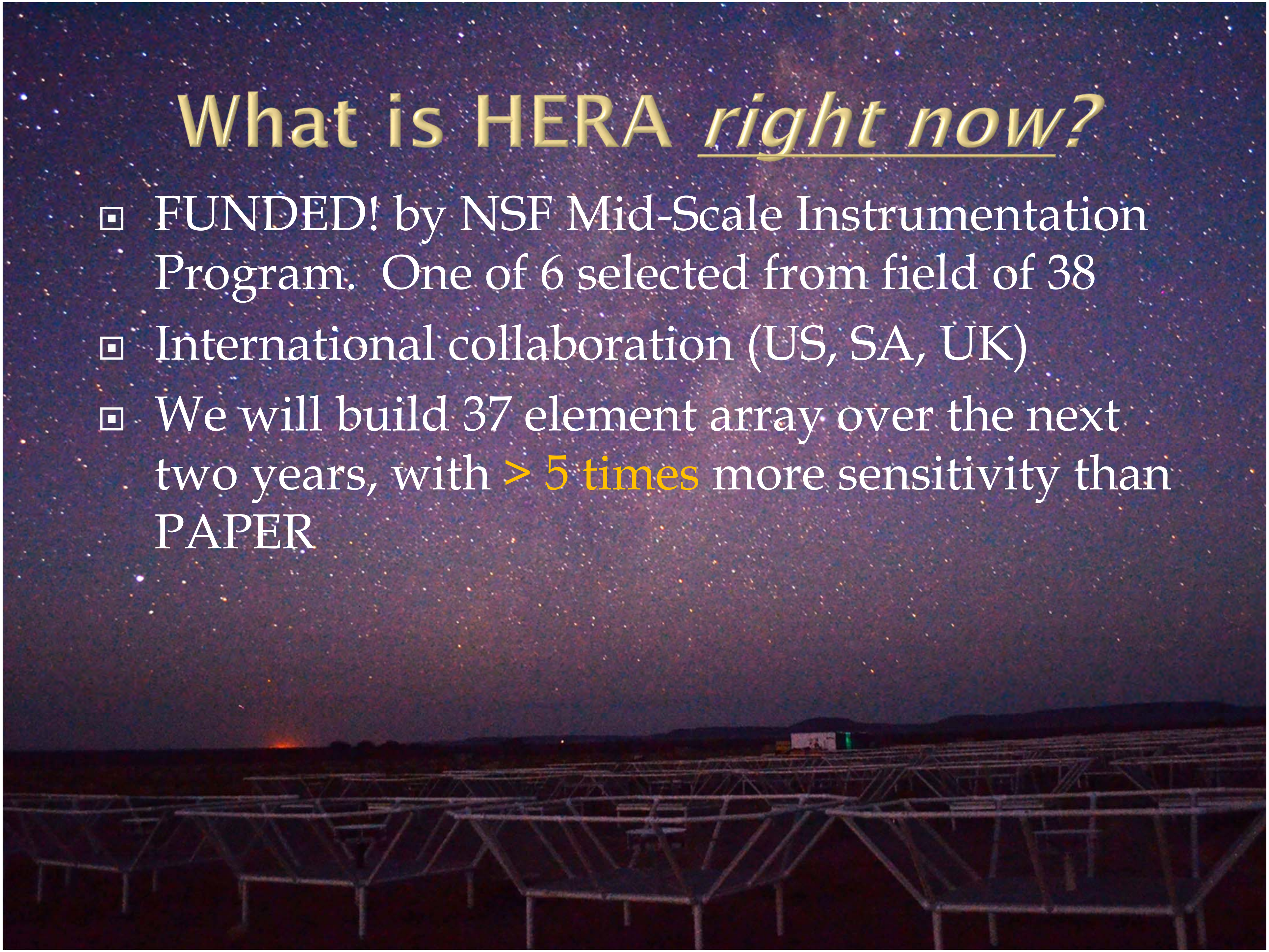



300 meters

What will HERA be?



- 331 hexagonally close packed 14-meter parabolic dishes with dipole feeds (full Stokes) with 21 outriggers
- Collecting area of orderArecibo (40,000 m^2)
- Bandwidth: 50 – 250 MHz digitized, ~100 MHz correlated
- A HUGE leap forward in sensitivity, redshift coverage and imaging over PAPER, with proven technology



What is HERA *right now?*

- FUNDED! by NSF Mid-Scale Instrumentation Program. One of 6 selected from field of 38
- International collaboration (US, SA, UK)
- We will build 37 element array over the next two years, with > 5 times more sensitivity than PAPER

Berkeley
PI: Aaron Parsons
David DeBoer
Adrian Liu
Dan Werthimer
Zaki Ali

Arizona State University
Judd Bowman
Danny Jacobs

Cambridge / NRAO
Chris Carilli

University of Kwa-Zulu Natal
Cynthia Chiang
Jon Sievers

UCLA
Steve Furlanetto

MIT
Jackie Hewitt
Max Tegmark
Josh Dillon

NRAO
Rich Bradley

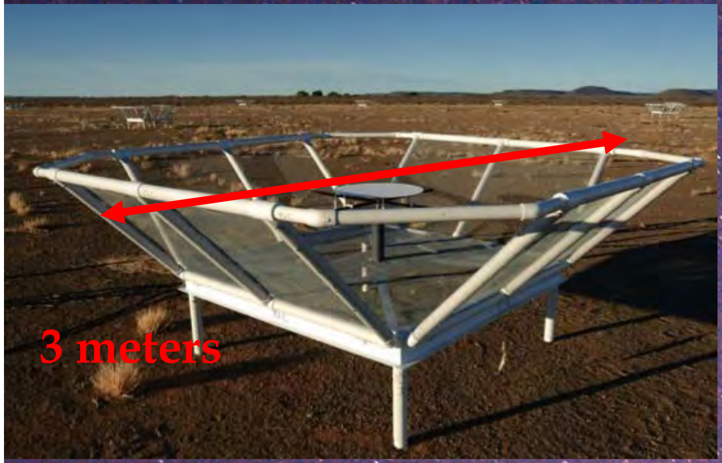
University of Pennsylvania
James Aguirre
David Moore

SKA-SA
Gianni Bernardi

University of Washington
Miguel Morales
Jonnie Pober

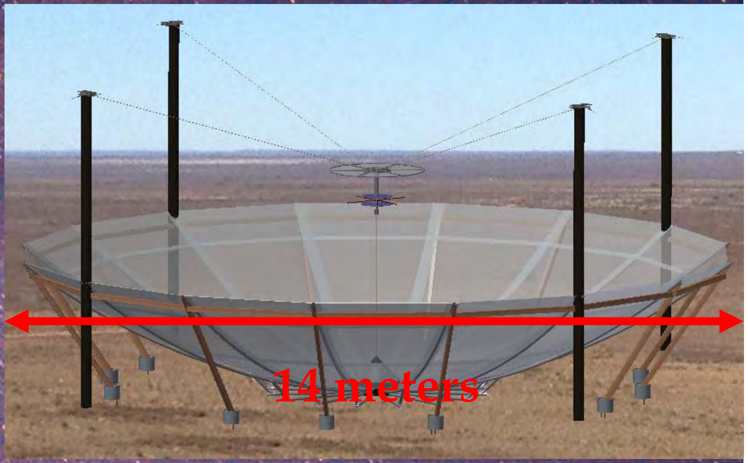
PAPER → HERA

4 m^2 collecting area per element

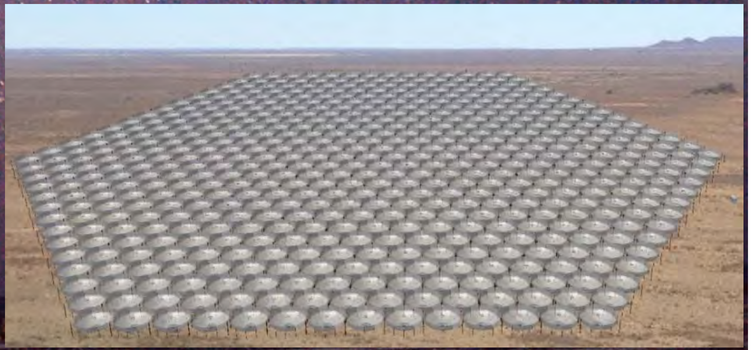


128 antennas
X m total collecting area

108 m^2 collecting area per element

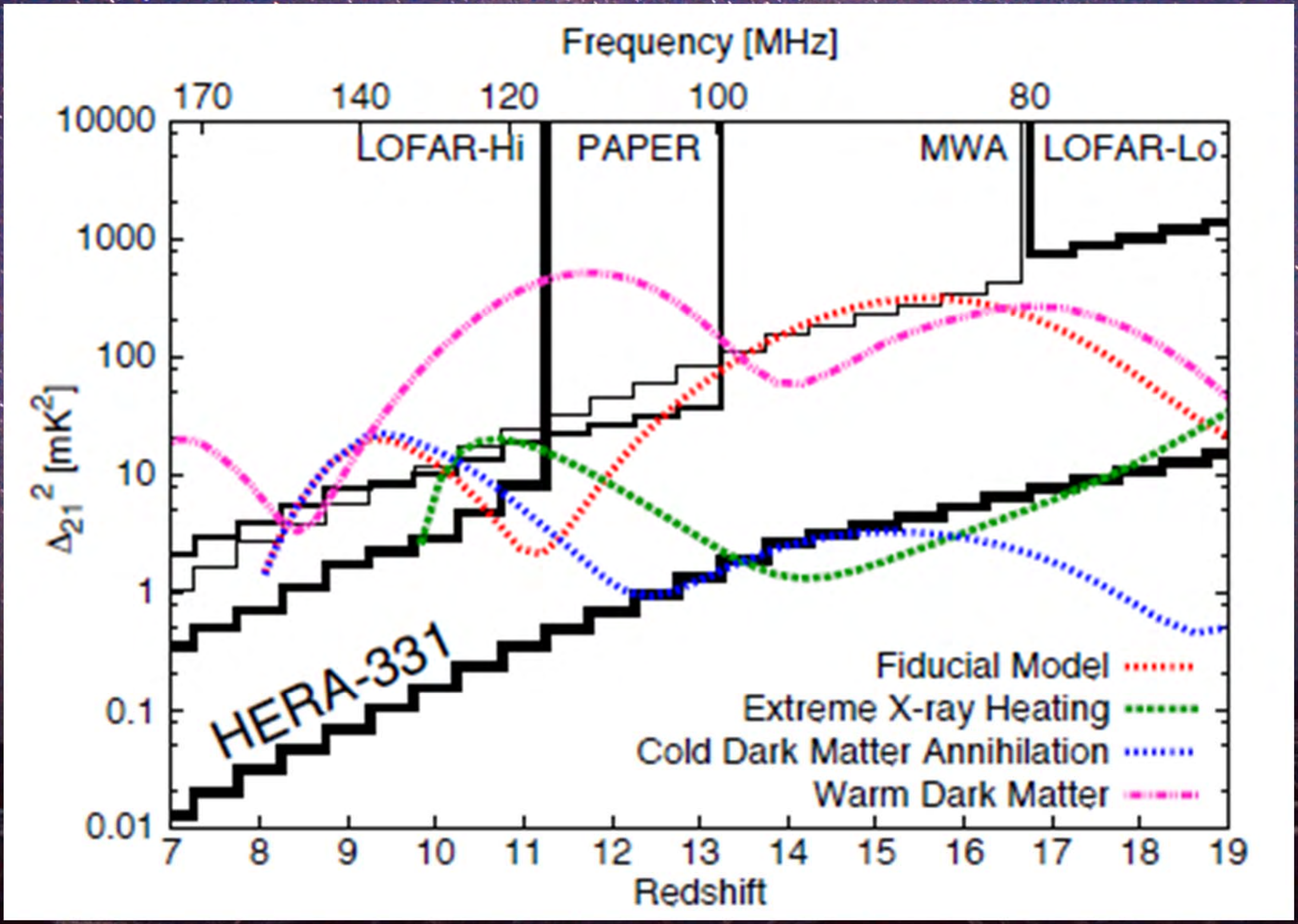


352 antennas
38,000 m^2 total collecting area



Useful frequency range increased down to 70 MHz (z ~ 20)

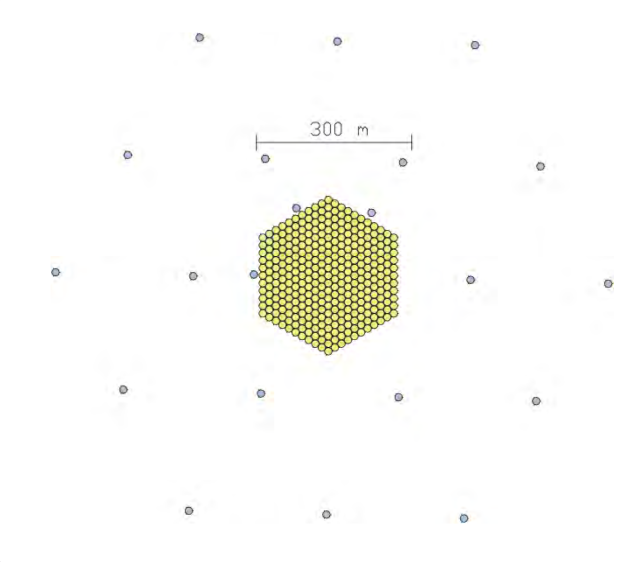
The Early Universe with HERA



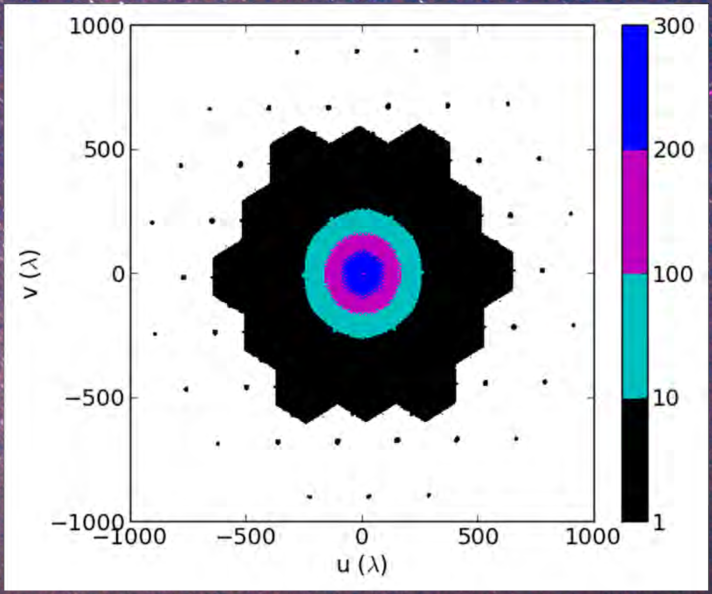
Mesinger et al 2013

HERA will be a powerful imaging instrument

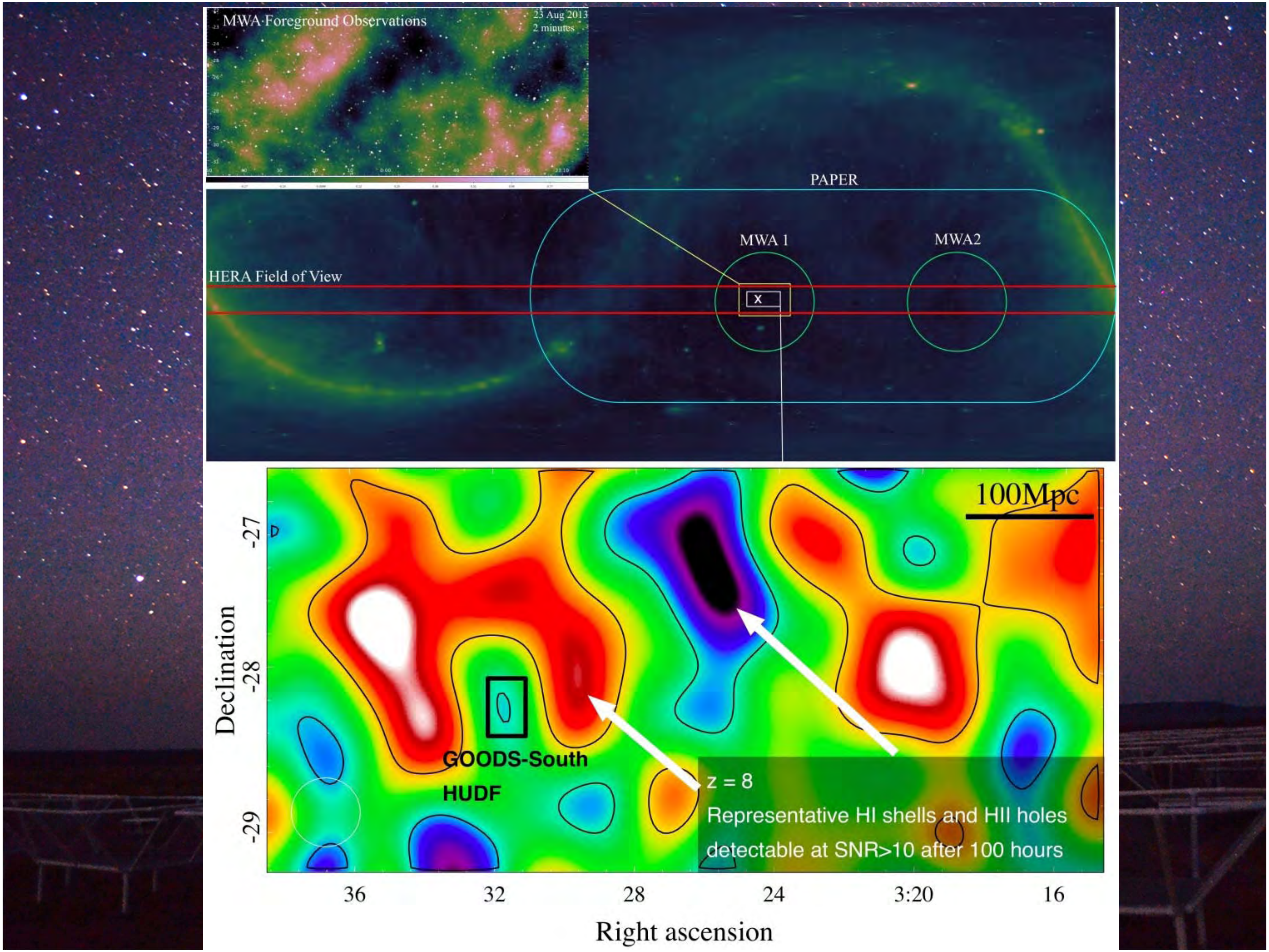
Physical configuration



Fourier plane coverage



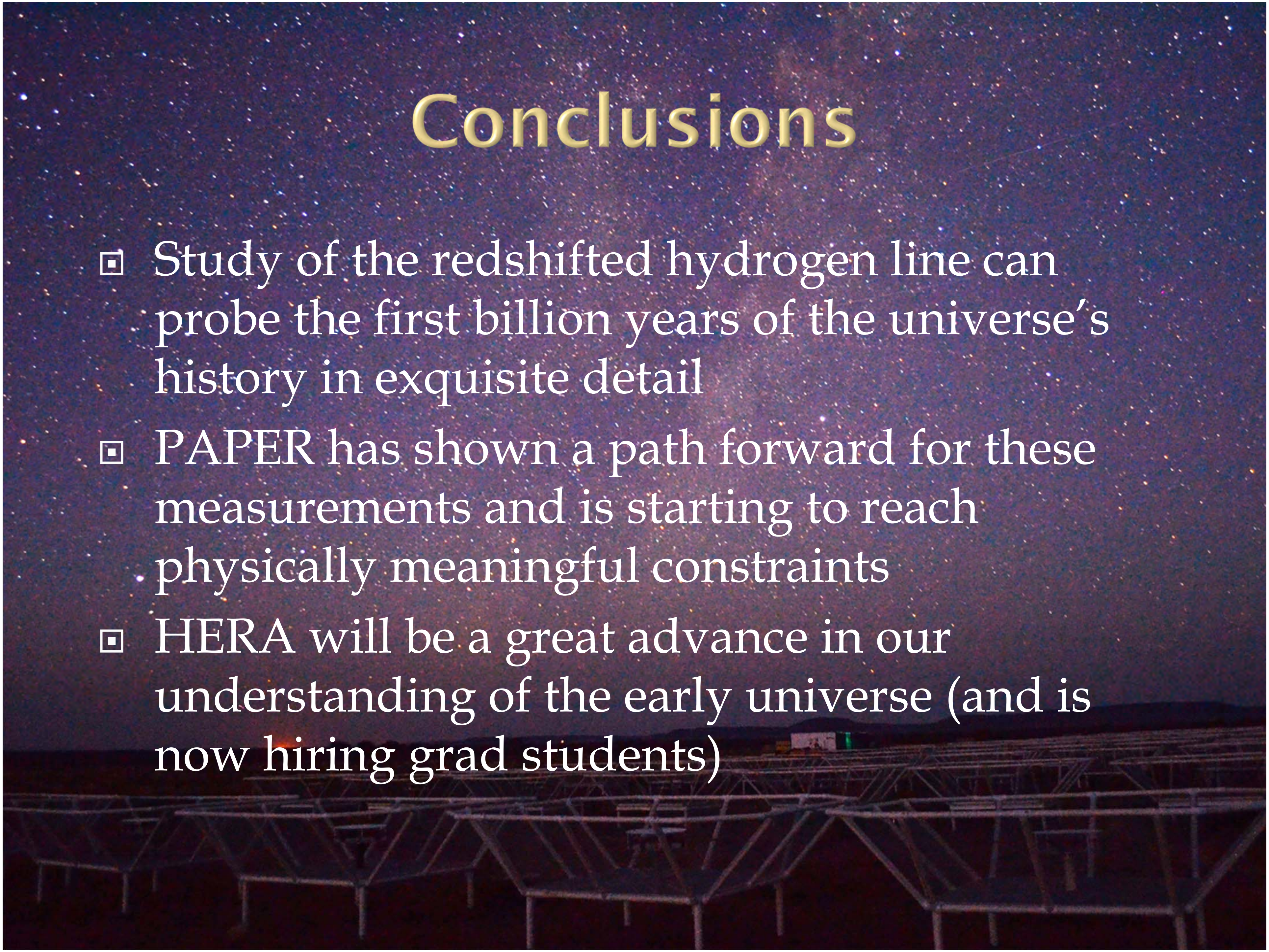
The final configuration of 331 antennas in dense core, with 21 outriggers, gives excellent uv coverage and a well-behaved synthesized beam



z = 8

Representative HI shells and HII holes detectable at SNR>10 after 100 hours

Conclusions



- Study of the redshifted hydrogen line can probe the first billion years of the universe's history in exquisite detail
- PAPER has shown a path forward for these measurements and is starting to reach physically meaningful constraints
- HERA will be a great advance in our understanding of the early universe (and is now hiring grad students)