Challenges for Accessing the 21cm Signal Below 100 MHz

Motivation

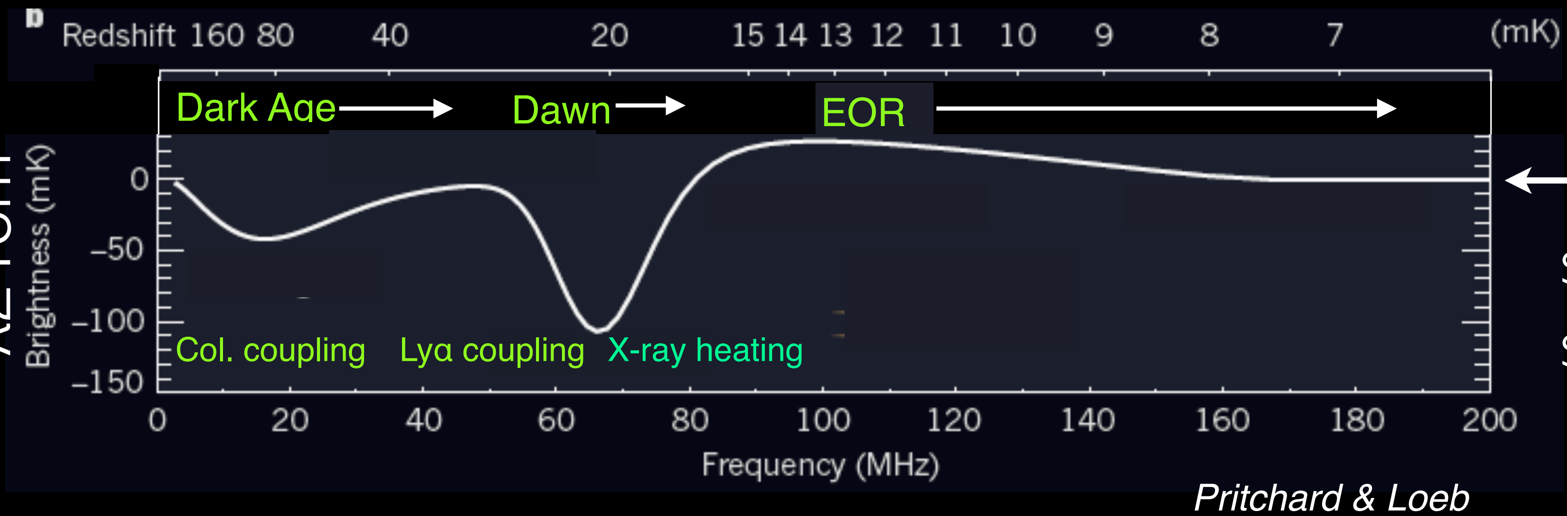
- Focus: Cosmic Dawn
  – $15 < z < 25$
  – pre-galactic, neutral medium
  – "Epoch of Starlight," "Epoch of Heating"
  – direct inference re true Dark Age
- Sky-averaged λ21cm spectrum
  – LWA/LEDA: Large-aperture Expt. to Detect the Dark Age
- Power spectrum measurement
  – LWA/OV
  – DAT (optimized hybrid array concept)
  – complements HERA prime band: 100-200 MHz
- Common thread: "hybrid" calibration schemes

Physics

- Test theories of fundamental processes **before reionization astrophysics**
- Set boundary conditions for Reionization and Dark Age

Physics	Process	Effect	Observable
Wouthuysen-Field	21cm-Lyα coupling	$T_S \rightarrow T_k < T_{CMB}$	absorption
Black hole formation	X-ray deposition	$T_S \uparrow$ f(E)	transition to emission
BAO	Dark matter / baryon drift	SF suppression in light haloes (LHS)	absorption profile early/late
Dark matter	Annihilation, WDM	DA heating, ionization, LHS	dilution, ν-shift of signal
Star formation	Lyman-Werner bckgnd Spread of metals	SF efficiency $\uparrow\downarrow$ in light haloes	absorption profile early/late

Tracer



λ21cm

T_{CMB}

sky-avg'd spectrum

- Mode
  - 0^{th} : all-sky, frequency spectrum
  - N^{th} : fluctuations, 2D / 3D power spectrum
- Challenge: calibration
  - advantage to optimized, purpose-built instruments

Some Basic Variables

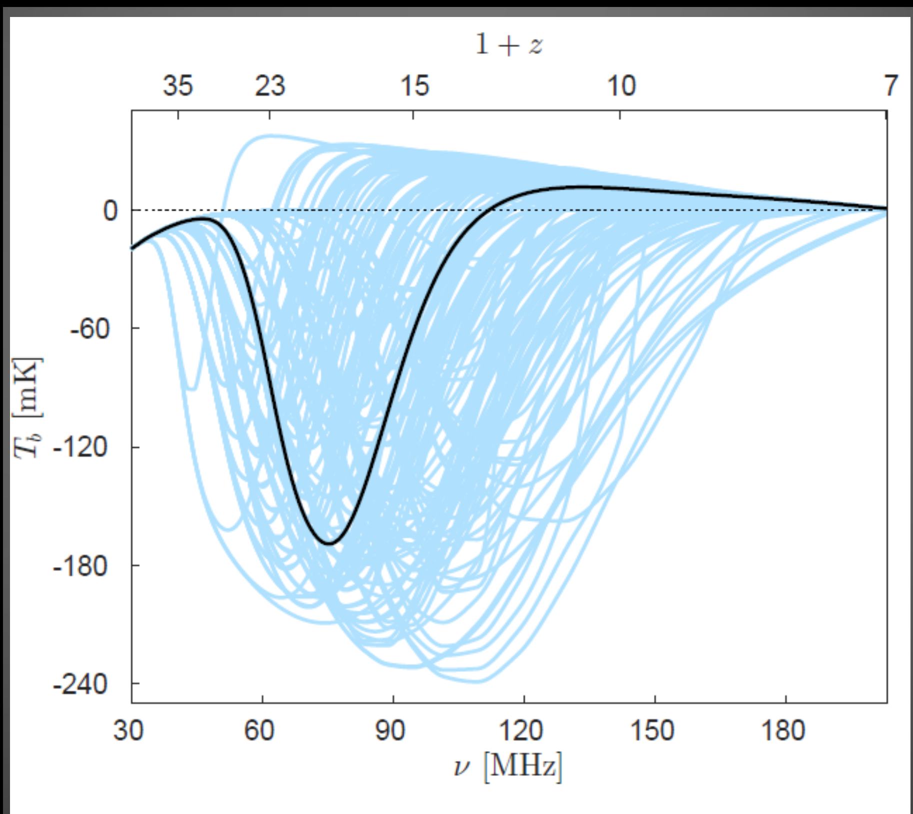
- Cooling
  - H_2 , H , metals
- Heating
  - hard vs soft X-rays, onset epoch
  - mini-quasars

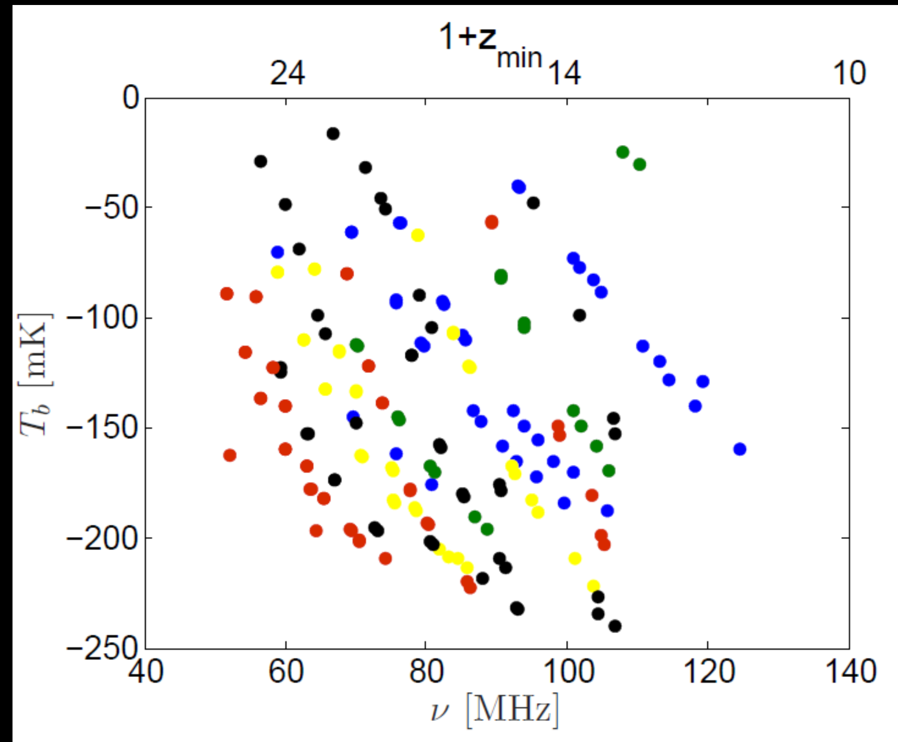
- Lyα escape

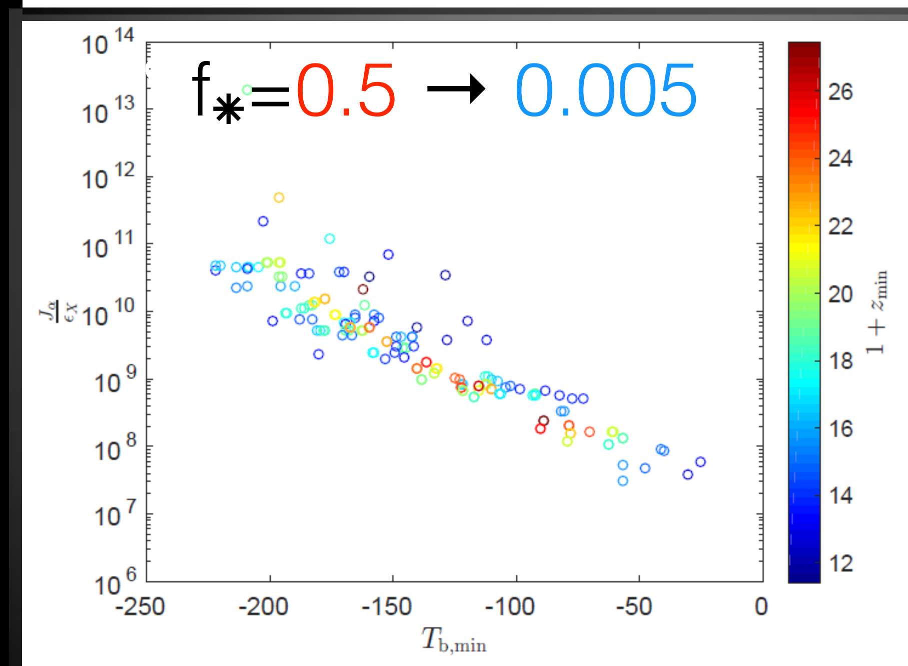
- Lyman Werner feedback efficiency
- Baryon-DM drift (BAO)
- DM heating
- DM halo "sterilization" processes

No reionization physics, galaxy assembly,…

Unvarnished Range of Predictions







- Not just a matter of "turning" points

courtesy Cohen, Barkana, Fialkov

Why is the 0-mode easy

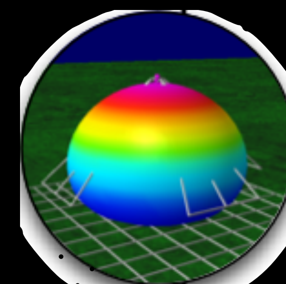
- Narrow absorption feature
- Potentially O(100) mK
- Variants on Dicke switching
- Readily available RF componentry

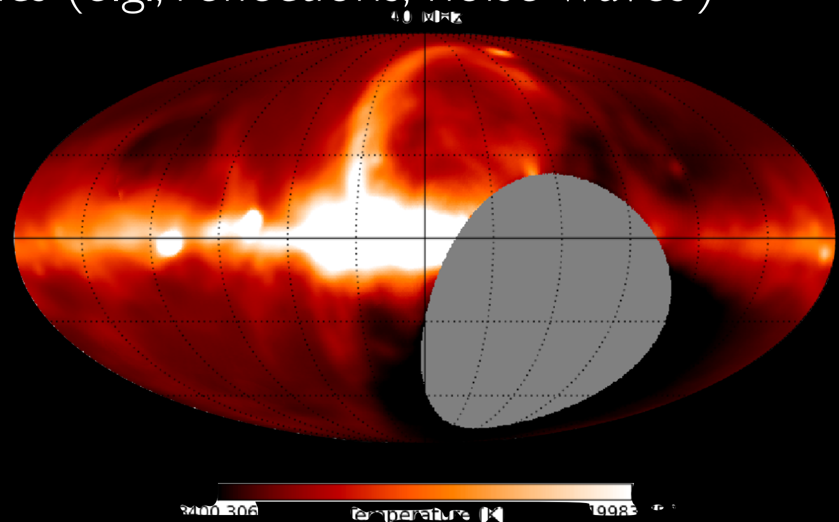
Why is the 0-mode hard

- Bandpass: detection demands 1:10^5 cal.
  - no features that mimic the science signal
- Limited applicability of differential techniques
- Sky model: diffuse synchrotron dominates
  - need good fidelity on large angular scales; pt. srcs secondary
- Gain patterns: should be measured in situ
  - E&M models are not ultimate authority
  - m-wave dipoles respond to the environment trivia
- Signal path reflections, self-noise, impedance response…
  - RF elements' responses to signal path trivia
- Ionosphere (?): static and dynamic
- FM radio (and TV)

0-mode Expt. Requirements

- Low RFI occupancy (ν, t)
- Isolated, simple broadband antenna
  - "slowly" varying, smooth gain pattern and efficiency variations (ν, θ, φ, t)
    - measurement vs. simulation
- Noise-temperature calibration
  - ≥ 2 temperature calibration sources
    - high noise calibration stability (e.g., LEDA's O($1{:}10^{-5}$) $°C^{-1}$ in total power)
- Means to measure RF systematics (e.g., reflections, 'noise waves')
- Monitoring of the ionosphere
- Sky model

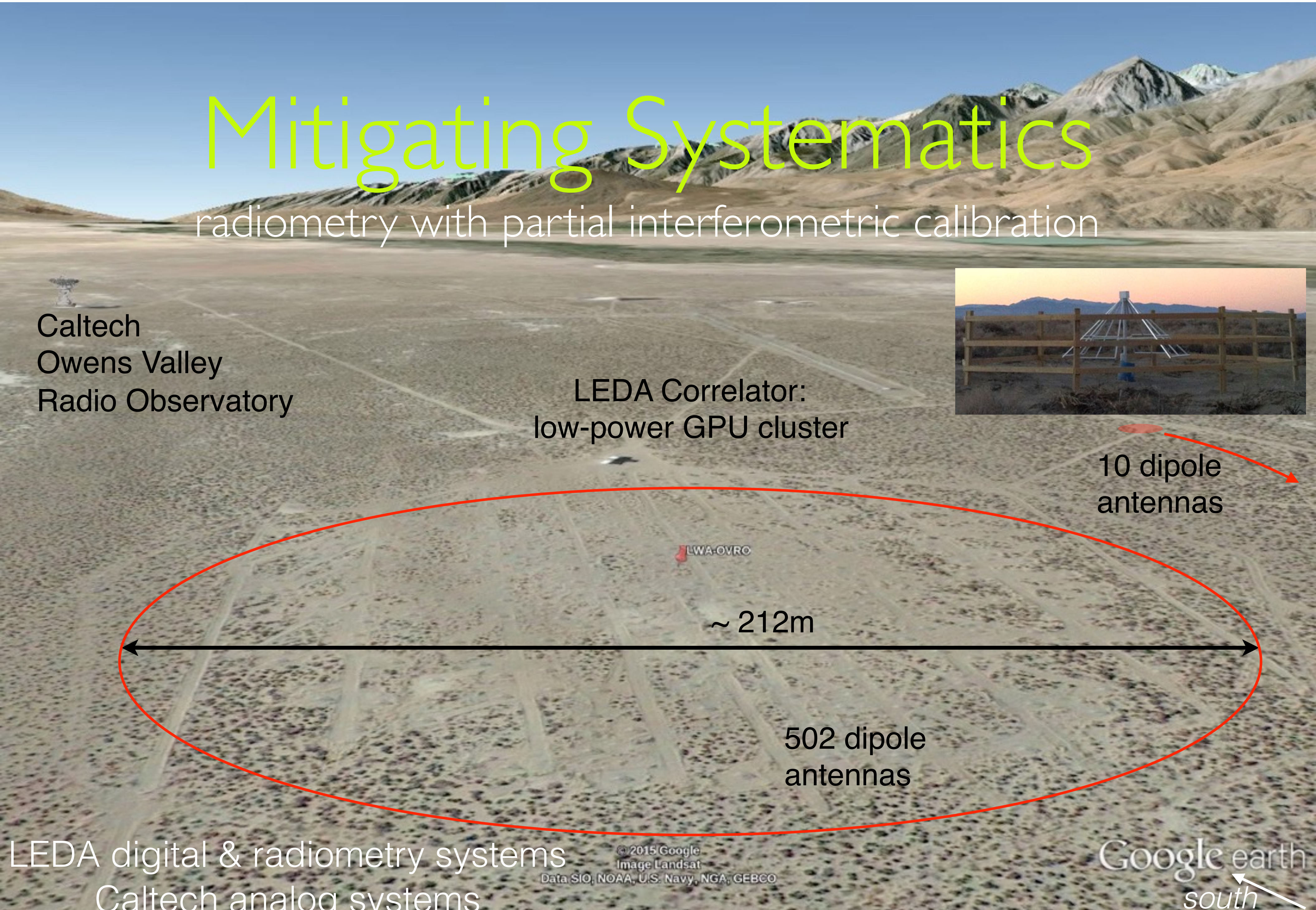




Dowell et al. 16

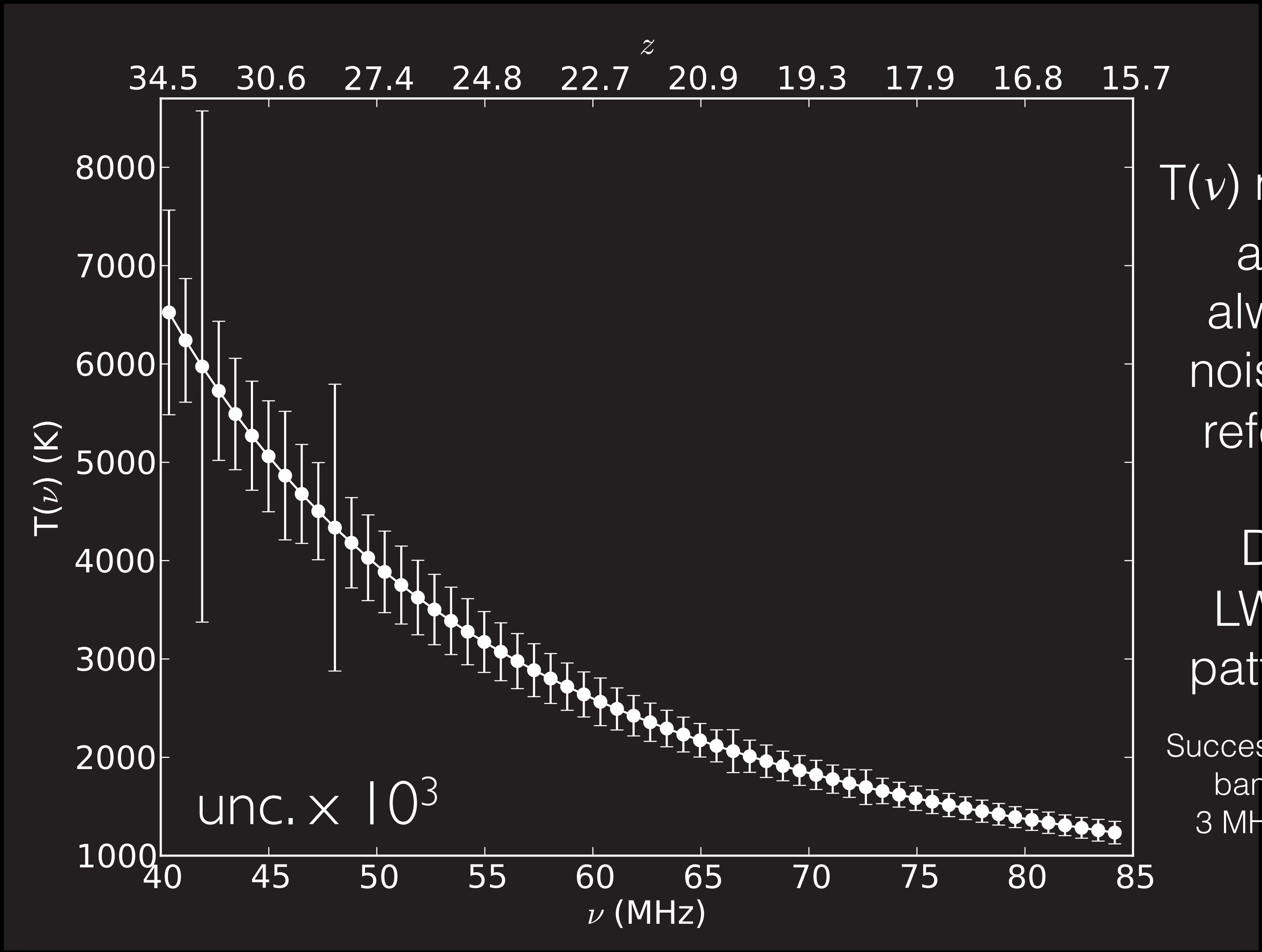
Mitigating Systematics

radiometry with partial interferometric calibration



Greenhill / Barsdell

LEDA Calibrated Spectrum



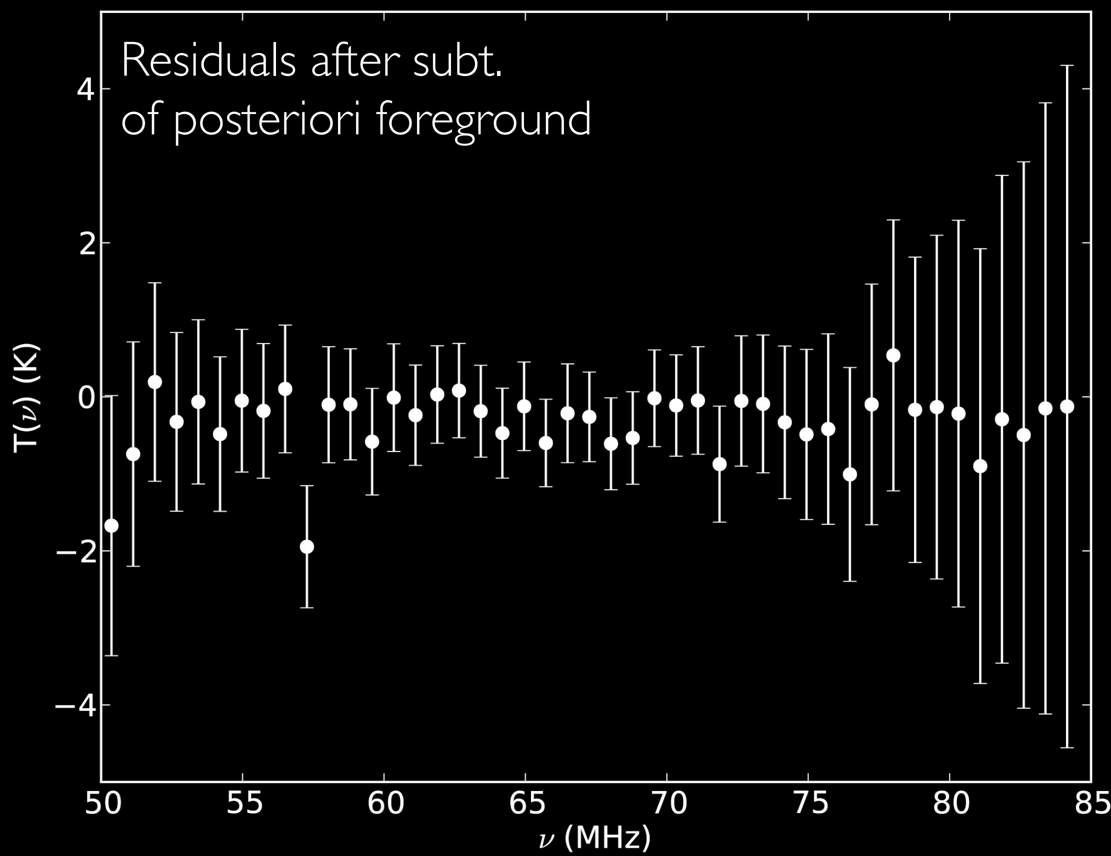
T(ν) measured against always-on noise diode references

Default LWA gain pattern sim.

Successful obs. in TV bands and just 3 MHz shy of FM;

(Bernardi, Zwart, Price, LG et al. 16)

LEDA Trial MCMC Analysis



HIBAYES pipeline *(new)*
uses MultiNEST (Buchner+ '14)

Season 2 data (2^h)
9:30 < LST < 11:30
2016 Feb 12
FE v. (n-1)

RMS = 470 mK
(nonBayesian analysis: 423 mK)

$-890 < A_{HI} < 0$ mK (95% CL)

$\sigma_{HI} > 6.5$ MHz ($\Delta z > 1.9$ @ $z \simeq 20$)

Detection <u>should</u> require 400^h

(Bernardi, Zwart, Price, LG et al. 16)

Fluctuations

Leverage on Same Basic Variables

- Cooling
  - H_2 , H , metals
- Heating
  - hard vs soft X-rays, onset epoch
  - mini-quasars

- Lyα escape

- Lyman Werner feedback efficiency
- Baryon-DM drift (BAO)
- DM heating
- DM halo "sterilization" processes

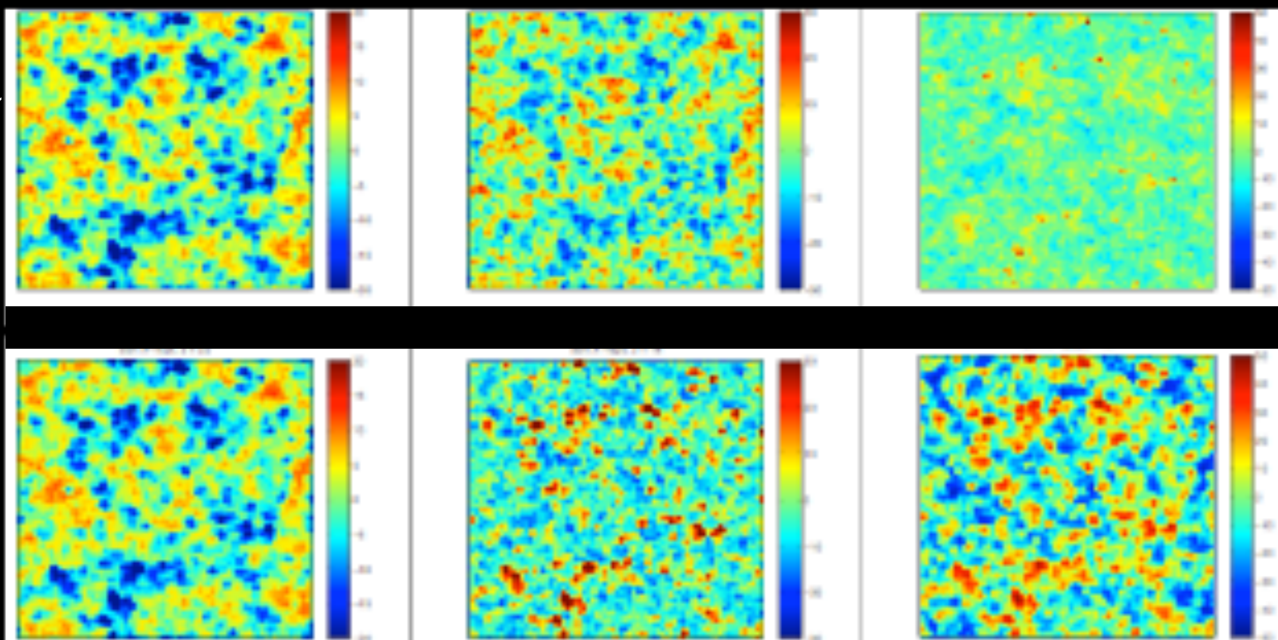
No reionization physics, galaxy assembly,…

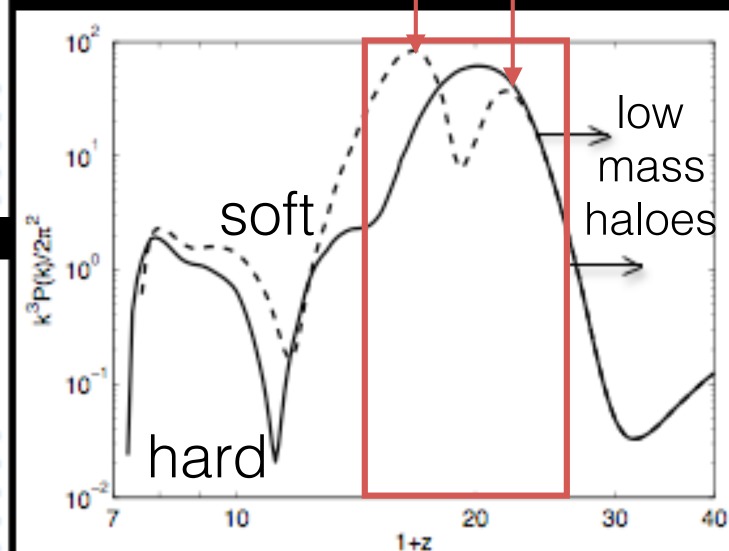
Fluctuations

e.g., X-ray hardness effects

Hard (E>1 keV)

Soft





384x384 Mpc

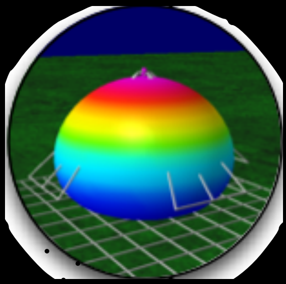
–50→+50 K

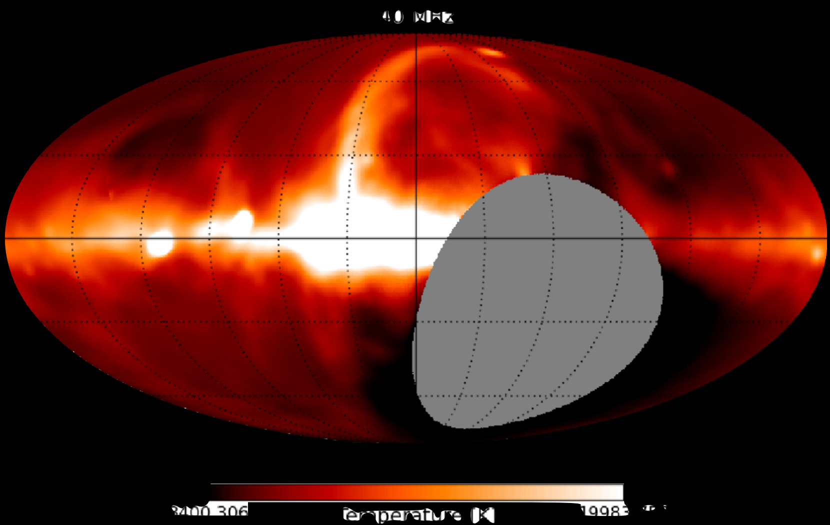
k = 0.1 cMpc^{-1}

courtesy Fialkov

N-mode Expt. Requirements

- Optimized, purpose-built array: 1 octave in frequency
- Low RFI occupancy (ν, t)
- Gain pattern & bandpass measurement using astronomical data
  - "slowly" varying, smooth variation (ν, θ, φ, t)
  - accounting for mutual coupling
  - compact array and outriggers
- Capacity to measure / correct the ionosphere using astronomical data
  - refraction
  - scintillation
  - absorption/emission
- Minimum scattering w/in antenna farm
- Internal noise-temperature calibration
- Accurate diffuse emission sky model

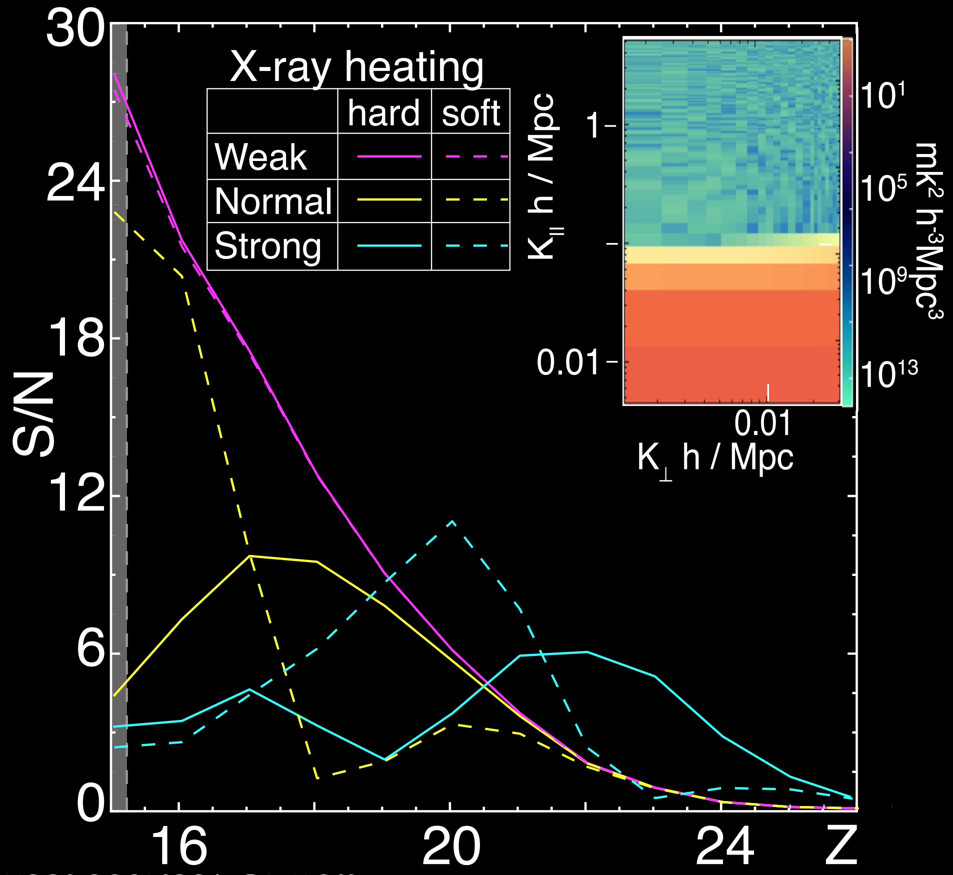




Dowell et al. 16

- Options now for power-spectrum array
  - 16 < z < 25
  - Minimally redundant array: LWA-OV (Eastwood, Hallinan, Greenhill+)
    - "go with what you have"
    - spherical harmonic decomposition of sky (after Shaw)
  - Maximally redundant, large-N_A: "Dark Age Telescope"
    - hybrid approach (cf. LEDA) for versatility in calibration
    - design-ready
- DAT as straw man
- Proximate to beamforming / imaging array (e.g., LWA1)
  - peeling + foreground avoidance
  - "regularized" gen.-2 LWA antenna, coplanar
  - O(100°) FOV
  - x/c multiple beams, long non-redundant baselines
  - characterization of ionosphere
  - monitoring / characterization of sky model

DAT Sensitivity



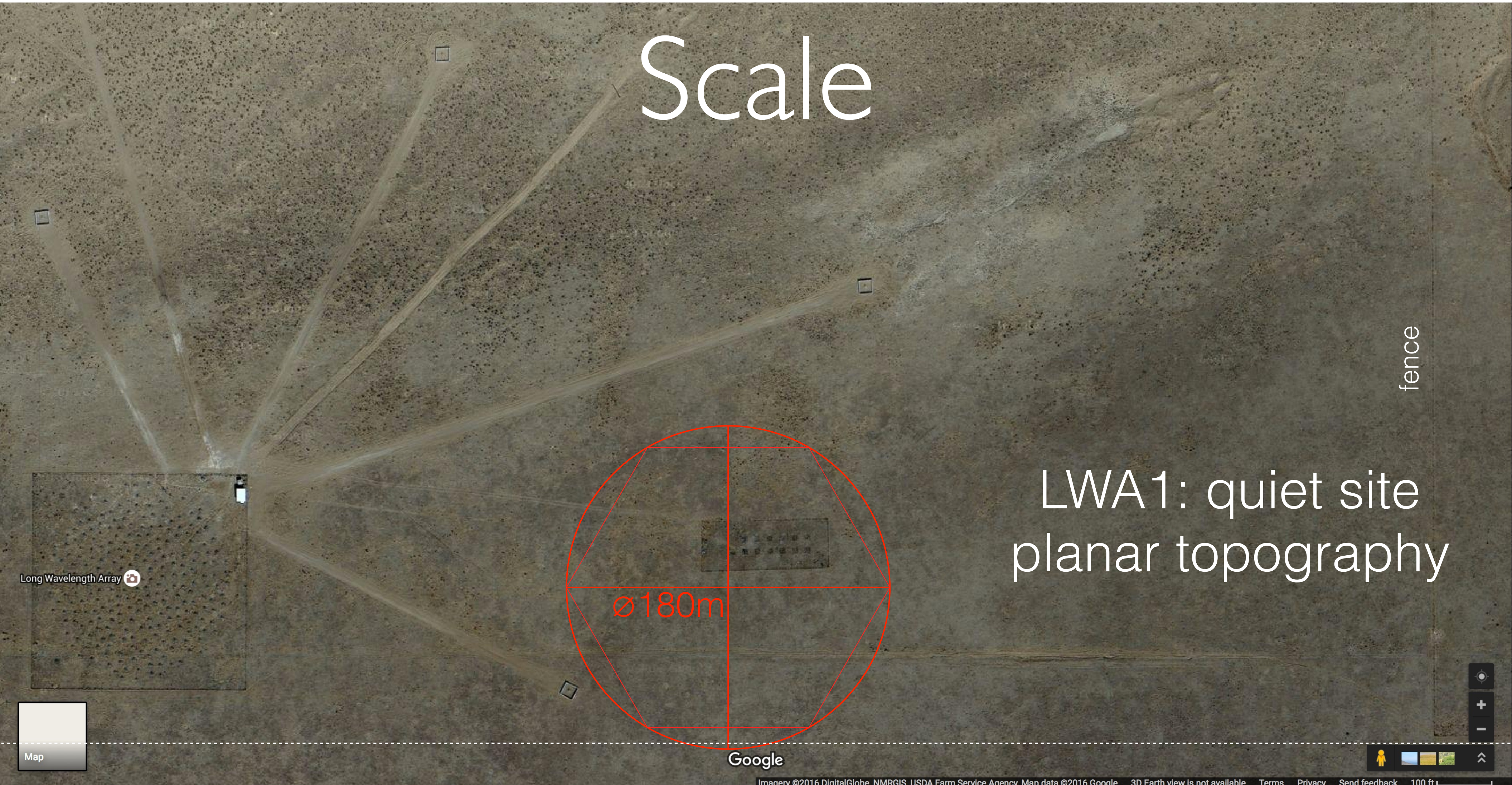
Sample capability of a stage-II system

271 ant. & ⌀180m:

3000^h (2 yr)

foreground filter: $k_{||} > 0.08$

Scale



Hexagons¶	127 ants. ⌀120m	external cal: 4 LWA1 bms.
	169 ants. ⌀140m	plus LEDA outriggers
	217 ants. ⌀160m	
	271 ants. ⌀180m¶	

¶ Assumes 2λ spacing at 60 MHz (z=22.7)

DAT Specifications

Science band Cal. band	60-87 MHz (15-23) 30-87 MHz
N_{ant}	303
configuration	hexagonal, redundant + ext. dense array (LWA1)
antenna-type	"regularized, horizon-blind LWA" consistent gain patterns coplanarity to a few cm
max. spacing	180m
min. spacing	2λ @ 60 MHz
Tsys	1200 - 3000 K (T_{rx}=500 K)
Power / data rate (via LWA1 infrastructure)	< 8.5 kW /

Table 1 – DAT Specifications

Item	Specification	Driver
Bands: Science Calibration	60-87 MHz ($15<z<23$) 30-87 MHz	Cosmological models
N_{ant}	128 – 271 (new) 24 (existing) 156 – 299 (total)	S/N=10-30 in 3000h Long baselines
$N_{SignalPath}$	320 – 606 (incl. LWA1 beams)	2 x $(N_{ant})_{total}$
New installation	hexagonal redundant array & LWA-style shelter	Maximal redundancy, efficient packing
Diameter	≤ 180m	N_{ant} & spacing
Min. spacing	≥ 2λ @ 60 MHz	coupling
Coplanarity(¢)	±10 cm	
LWA1-DAT separation	> 360m O.C. ≲ 1 km	Confusion Ionosphere
Tsky T_{rx}	1200 - 3000 K 500 K	Sky-noise dominance
Antenna type	LWA-like*	Cost control
RF/pwr/digital cabling	Direct burial	Safety/stability/$
Power(¶)	< 5 kW < 7 kW	128 ant. scenario 271 ant. scenario
Data rate out(§)	< 1 Gb s^{-1}	LWA ops model
HVAC	2 x 3t	LWA-SV model

(¢) After grading. Modified LWA antenna design to permit fine height adjustment to ~1 cm informed by laser survey.
(*) Modified ground screen to assure repeatable gain patterns, antenna to antenna, reduce horizon response, and narrow gain pattern.
(¶) Via cable from LWA1 transformer.
(§) Fiber cable link to LWA1 shelter. Piggybacking on LWA1 10 GbE cable to control building.

Summary

- Motivation
  - Cosmic Dawn window
    - $16 < z < 25$
    - Epoch of starlight & Epoch of heating
    - establish boundary conditions on EOR & Dark Age
- Challenges …
- Calibration is paramount
  - optimized, dedicated, 1-octave instruments
  - hybrid calibration
    - radiometry w/ interferometric calibration
    - tandem redundant and non-redundant arrays
    - DAT

– end –