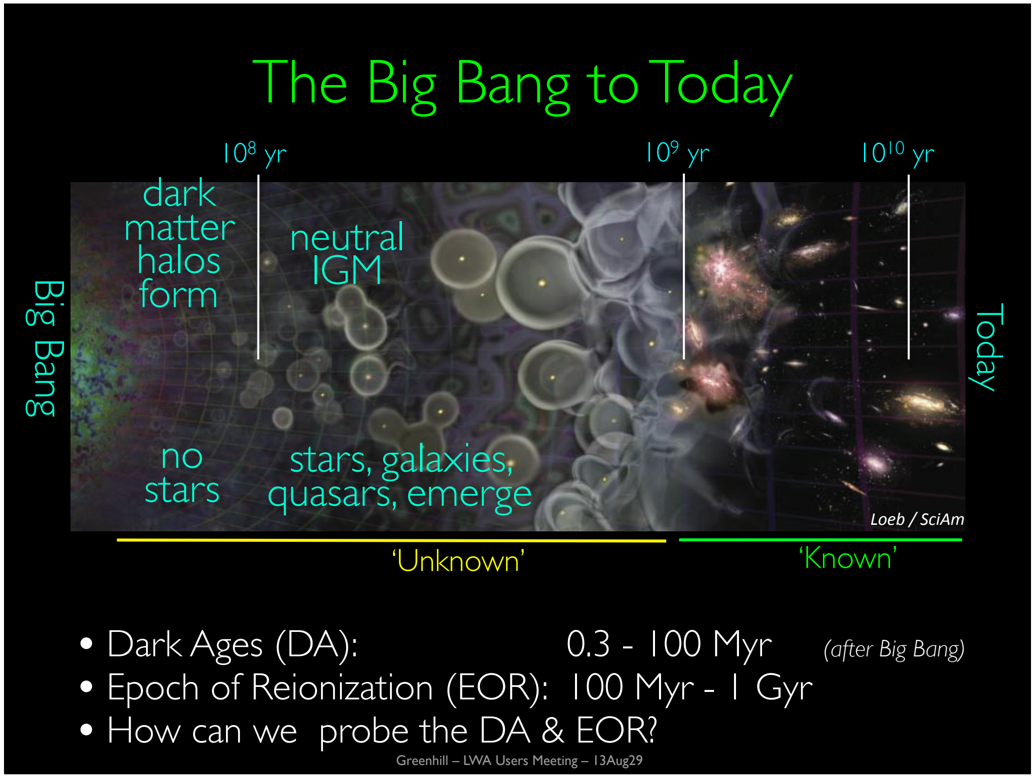
Enabled by confluence of discovery & innovation

- HI cosmology
  - dark ages → transition → widespread reionization
  - predicted signatures on the sky (spectral, angular)
- CASPER: commodity FPGA-driven DSP
- GPU computing as engine for DSP
- cuWARP: wide-field polarized dipole-array calibration & imaging libraries (GPU enabled)
  - sub-set developed by Harvard group for MWA
- LWA

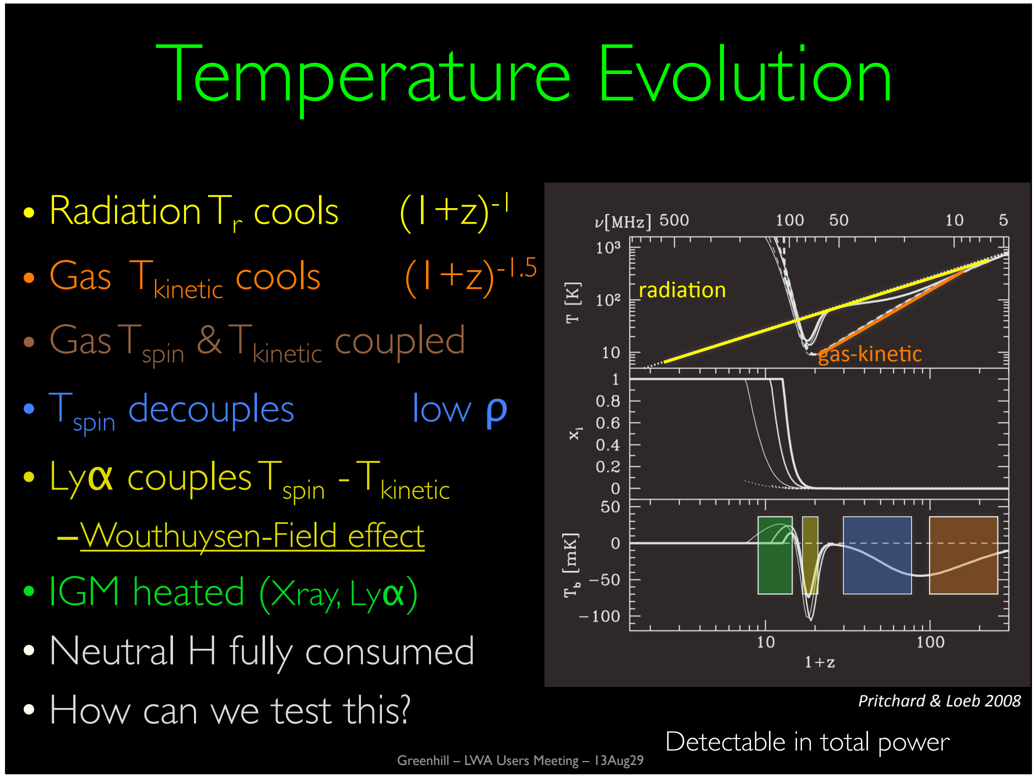


THEORY IS UNCONSTRAINED

Swiss cheese universe

H/He

heating, ionization, pumping among levels

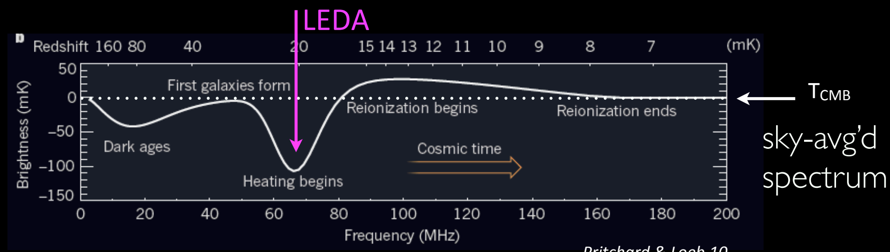


HI SIGNAL GOES THROUGH SEVERAL PHASES DURING THE DARK AGE AND EMERGENCE.

Top: Evolution of temperature over redshift.
Bottom: Deviation of spin temp which regulates 21cm line
Mddle: ioniZation fraction.

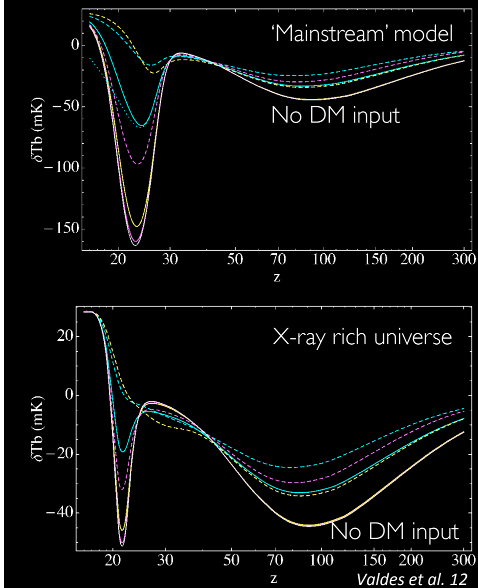
M-wave inVestigations move left to right.
Today: green / yellow w/ single dishes green: arrays
Tomorrow – or next week : blue/red.

Target



Pritchard & Loeb 10

A Range of Possible Spectra



Valdes et al. 12

- DM annihilation injects energy into the IGM and changes T_s
  - discriminant among DM models?
- Relative motion DM vs baryonic…
  - Tseliakhovich & Hirata 10
  - McQuinn & O'Leary 12
  - Visbal et al. 12
  - Fialkov et al. 12

Variation in halo abundance, gas content, ... X-ray emission & heating

LEDA Summary

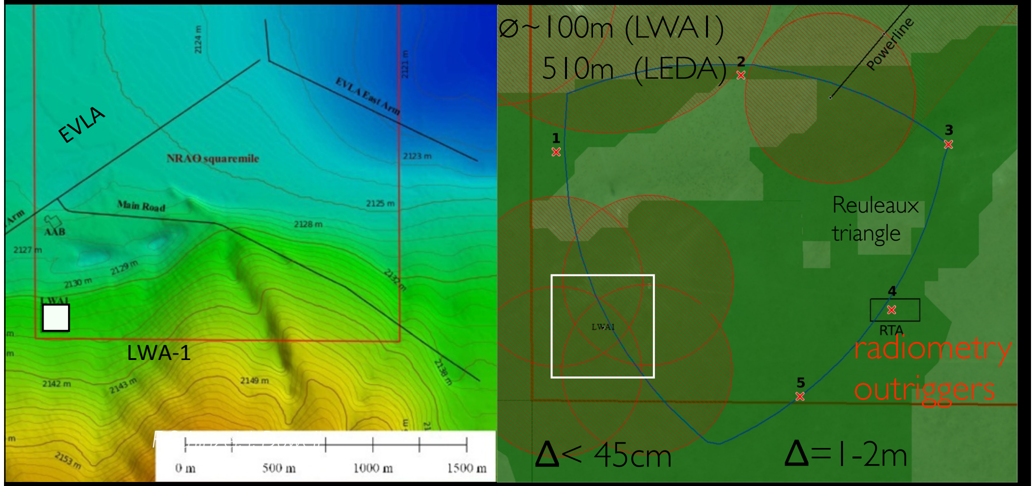
- LEDA targets Cosmic Dawn HI science from the ground
  - constrain thermal history of IGM at z ~ 20
  - constrain initial conditions for Reionization
- measure or constrain the sky-averaged spectrum
- supplement radiometry calibration using array-based deliverables
  - dipole gain patterns
  - ionospheric fluctuations
  - sky models
  - redundant measurement

LEDA Summary

- add full-correlation back-end to an LWA station
  - 512 inputs, 60 MHz, 2400 ch., 240 Gb s^{-1} (internal)
- add outrigger antennas for radiometry
- apply a generalized GPU-native ME package for cal/im

- set the stage for trivial scaling to $O(10^3–10^4)$ elements
- set a foundation for power spectrum measurements at redshifts ~ 20

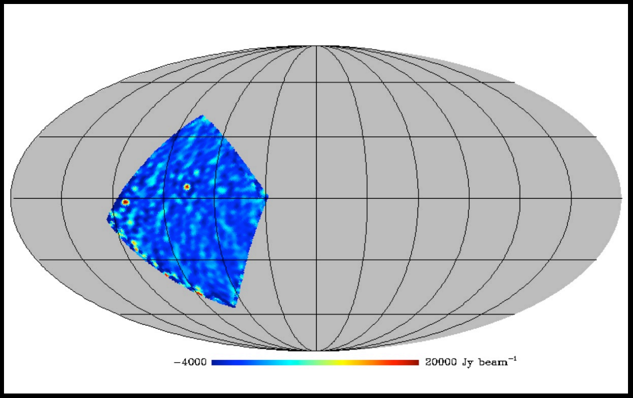
Aperture *ab initio*



c.2012.5

Schinzel

LEDA32 First Light



- 26 signal paths: 12 Sep 25
- 90° CygA / CasA field
  - 6dB FOV ~ 130°

FPGA-GPU computing cluster correlates 12 LWA1 antennas in dual polarization.

First field demonstration correlator architecture and application of CuWarp pipeline.

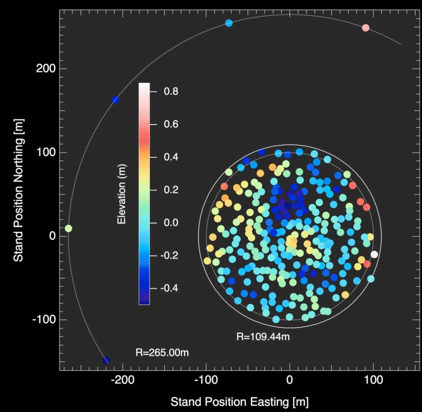
Kocz & Bernardi

One Year Later: LEDA512

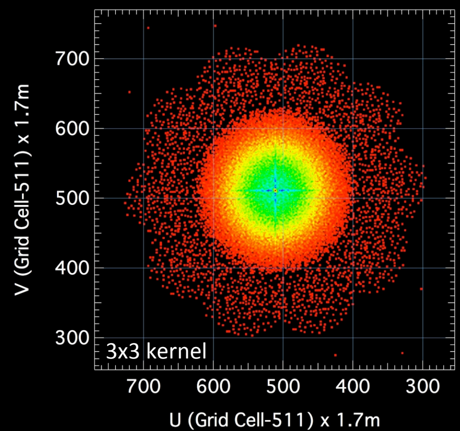
251 dual polz antenna core + 5 outriggers

LOL

One Year Later: LEDA512



- RMS ~ 22 cm
  - < **λ**/15
- Pk-Pk ~ [-49, +82] cm
- outriggers are not outliers



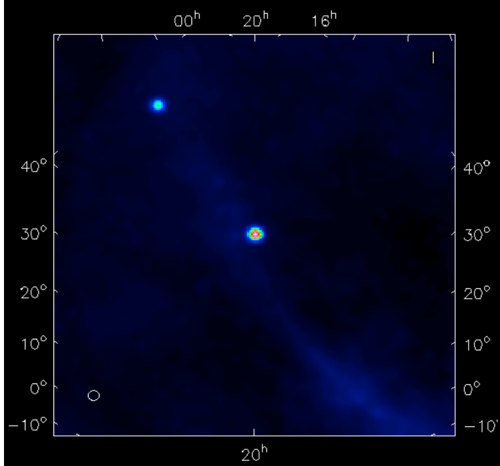
- 100% filled to 155m, instantaneously
  - ➡ diffuse emission: 1.3° - 3.7° spacing
  - ➡ point sources: 0.74° - 2.2° spacing

LOL Specifications

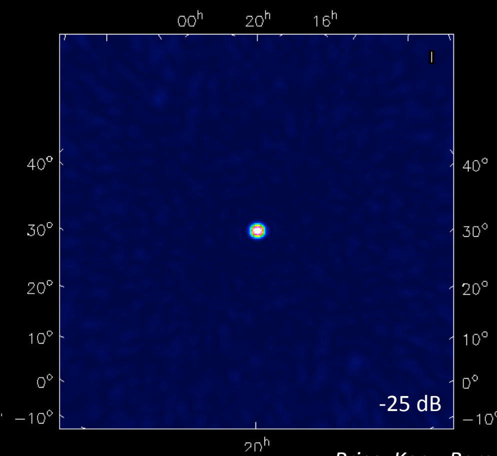
LEDA at OVRO LWA (as built)

fringe spacing Minimum CORE (N=251) CORE-outriggers (N=5) FULL	 4.8m 212m 373m 504m	λ3.4m - 10m 55′ - 2.7° 31′ - 1.5° 23′ - 1.1°
Stokes-I confusion (min.) CORE CORE-outriggers	 0.9 - 1.9 Jy 0.3 - 0.6 Jy	
Collecting area	~5000 m^2 (62 MHz; zenith)	
Filled aperture ⌀ (instant.)	155m	
Outrigger-outrigger spacing	166m	
Mutual coupling (gain deviation)	O(a few %) TBC	
Correlated inputs	512	
Correlated bandwidth	59 MHz	
Computation	16.9 Top s^{-1} (~½ eVLA @ 8 GHz BW)	

One Year Later: LEDA512



CASA image: Cyg/Cas A (self-cal)
47.00 MHz; 8.53^s; 2.616 MHz

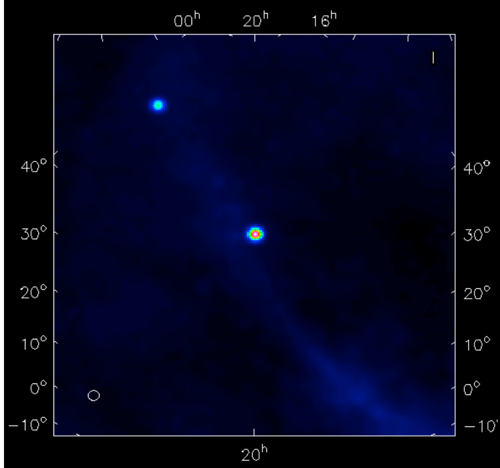


PSF

Price, Kocz, Barsdell
HOT OFF THE PRESS

LOL

One Year Later: LEDA512



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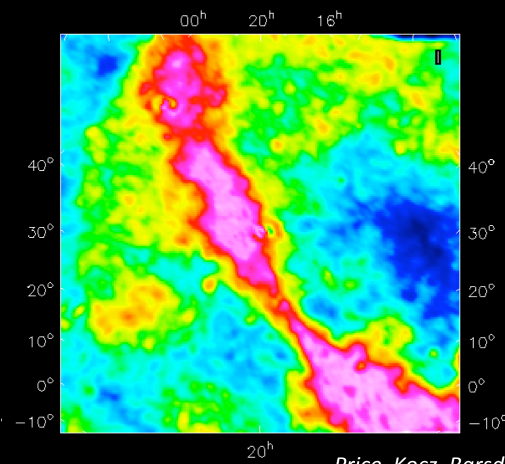
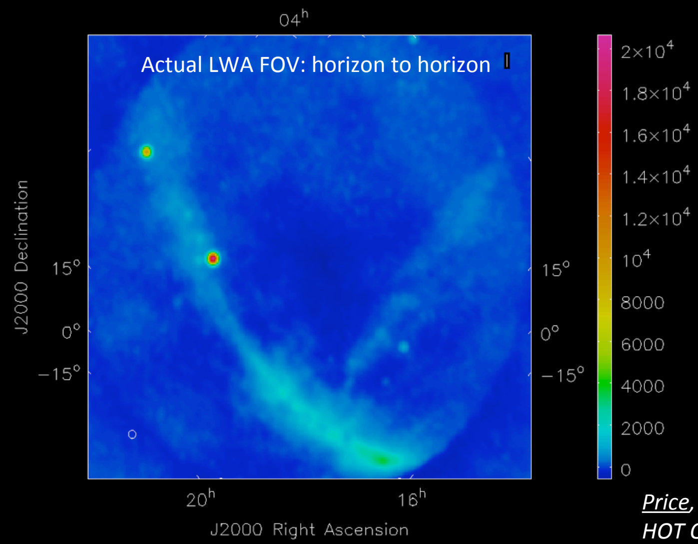


Residuals

<u>Price</u>, Kocz, Barsdell
HOT OFF THE PRESS

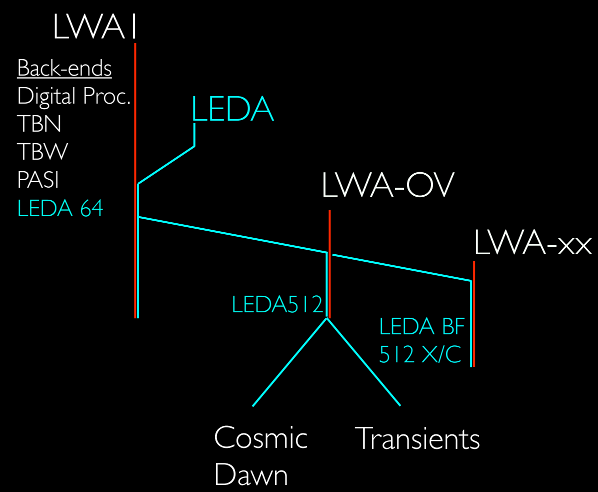
LOL

One Year Later: LEDA512



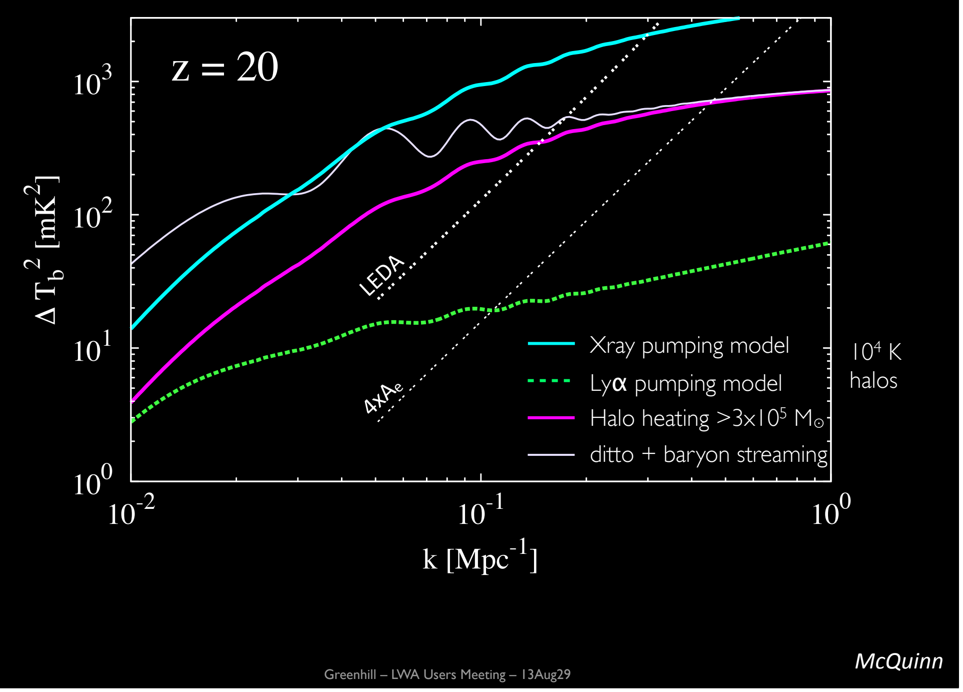
<u>Price</u>, Kocz, Barsdell
HOT OFF THE PRESS

LEDA bridges LWA sites and Science



Evolution

- Sky-average HI spectrum
  - winter 2013/14 science season
  - constraints or detection
  - continuation into 2014/15
- Angular power spectrum
  - LEDA platform for development (h/w & technique)
  - array expansion by increments (?)
    - LEDA2048 scale is practical to build today.



z = 20
Δ T_b^2 [mK^2]
k [Mpc^-1]
10^0
10^1
10^2
10^3
10^-2
10^-1
10^0
LEDA
4xA_e
Xray pumping model
Lyα pumping model
Halo heating >3x10^5 M⊙
ditto + baryon streaming
10^4 K
halos
McQuinn

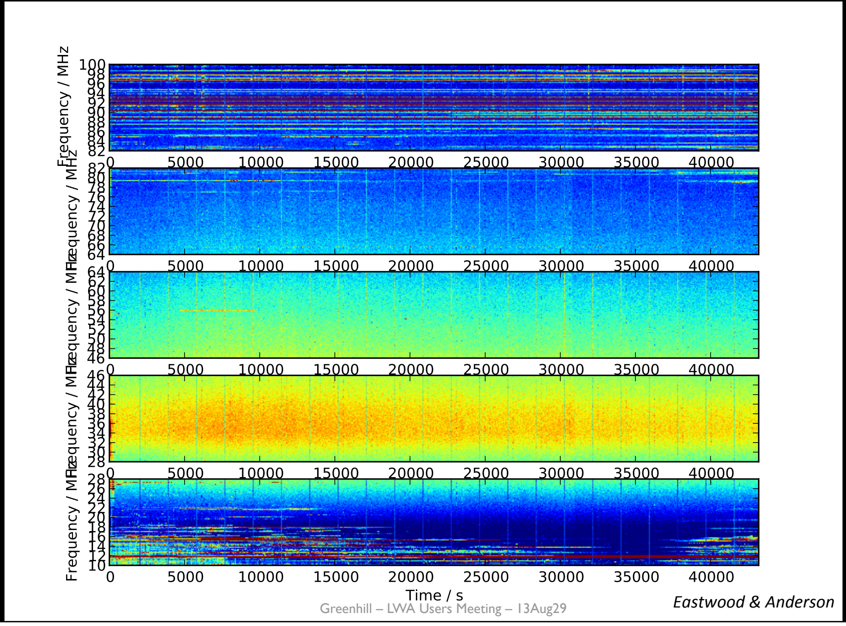
Summary

- LEDA is targeting ground-based Cosmic Dawn HI science
  - constrain thermal history of IGM at $z \sim 20$
  - constrain initial conditions for Reionization
- LEDA provides a general purpose back-end for LWA stations
  - correlation
  - beam forming
- A 512 input O(100 MHz) FPGA/GPU correlator is
  - Demonstrated
  - Easy
  - Embarrassingly scalable to O(5000) antennas (current GPUs)
  - Affordable
  - Compact
  - Energy efficient
    - 'LEDA2048' correlation would draw < 20 kW in Q4CY14 (GM110 GPUs)
  - Fast to build
  - A platform for DSP experimentation in a general purpose programming environment

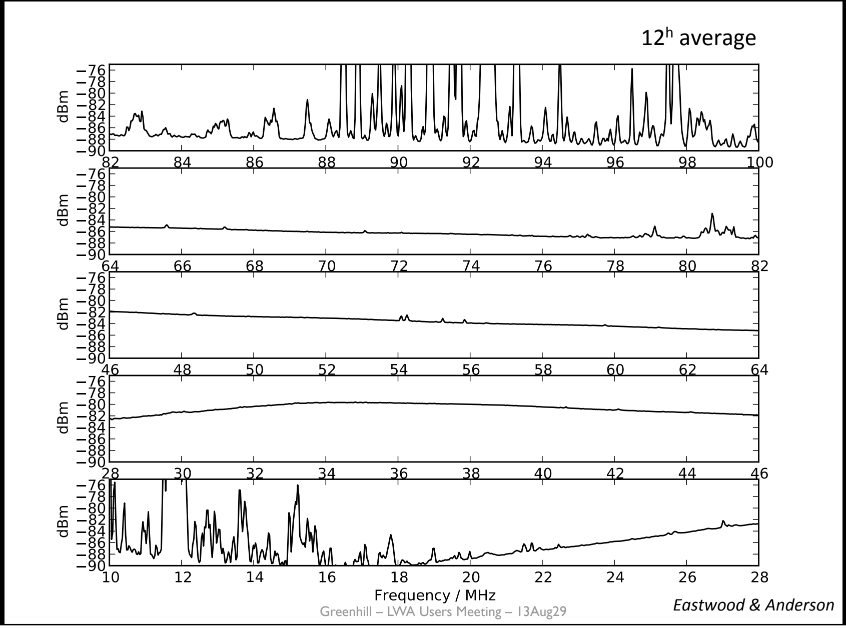
– end –

– backup slides –

RF Environment



RF Environment

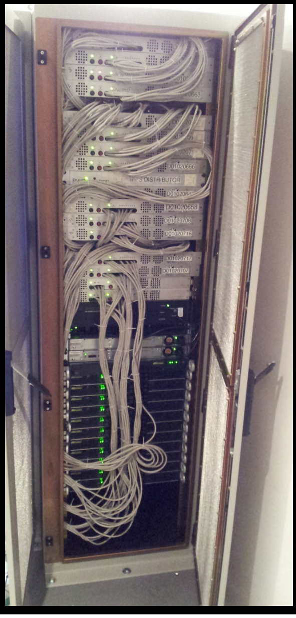


LEDA Technical Innovation

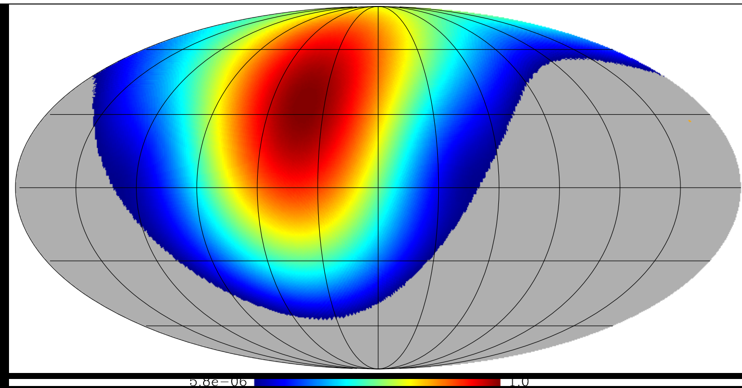
- design optimizations for LWA-OV
- heterogeneous FPGA/CPU/GPU correlator (1^{st} light 9/12)
  - simplified corner turn, unidirectional data flow
  - application of general purpose HPC hardware
  - embarrassingly simple & fast correlator scaling
  - low full cost (parts, systems, FTEs)
- high-density sampler card (16 x 250 MSa s^{-1} @ 8 bit)
- optimization of Harvard-X for Kepler GK110
- PSRDADA applied to 40-gE data capture (GPUs)
- RF shielded rack configuration for HPC hardware
- foundation for future LWA beamforming back-ends

LEDA512 Correlator Footprint

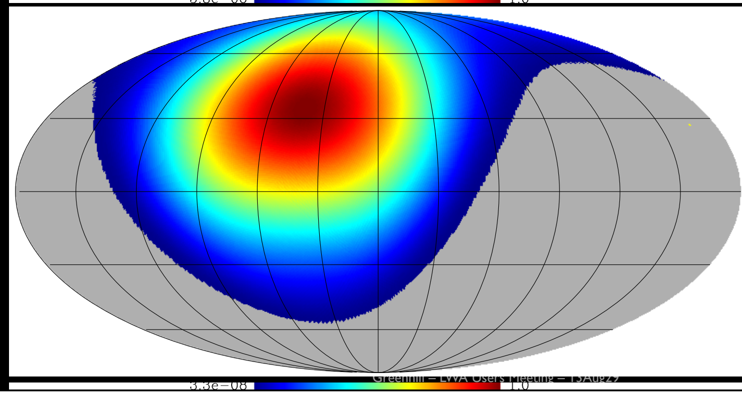
- Compute: 17 TOp s^{-1} 240 Gb s^{-1}
- Rack: 1
- Power: 9.0 kW
  - 1.6 kW FPGA/network
  - 7.4 kW GPU servers (170W/GPU)
- Manpower: 13±1 person-month
  - dev. to deploy: LEDA32 to LEDA512
  - 512 build/integration: 6 weeks
  - 512 deployment: < 5 days
- Pile of Parts: $200-250K
  - GK110 Tesla GPU, e5-2670 CPUs
  - ROACH2/Virtex6, 40-gE



Know your gain pattern...

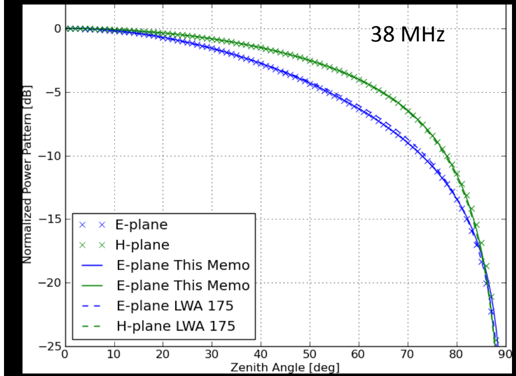


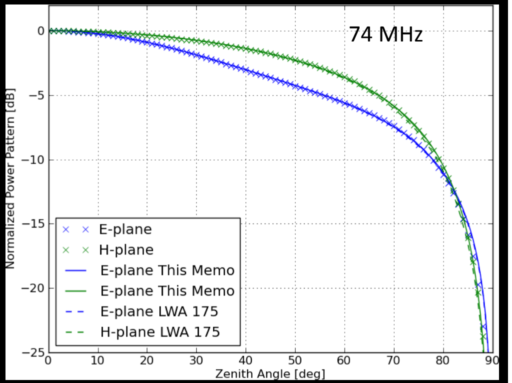
Dipole pattern



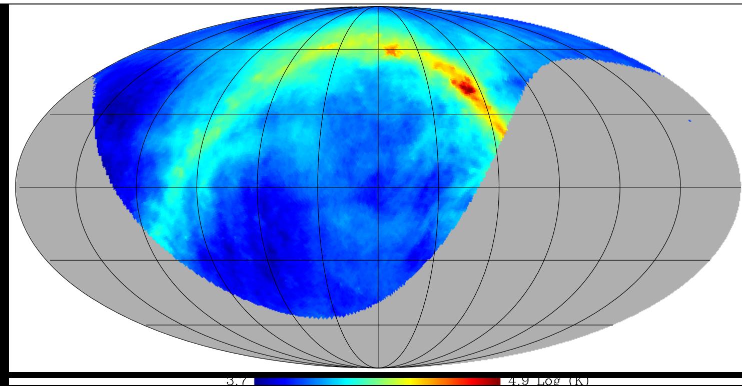
LWA pattern

‘Real’ LWA Gain Patterns

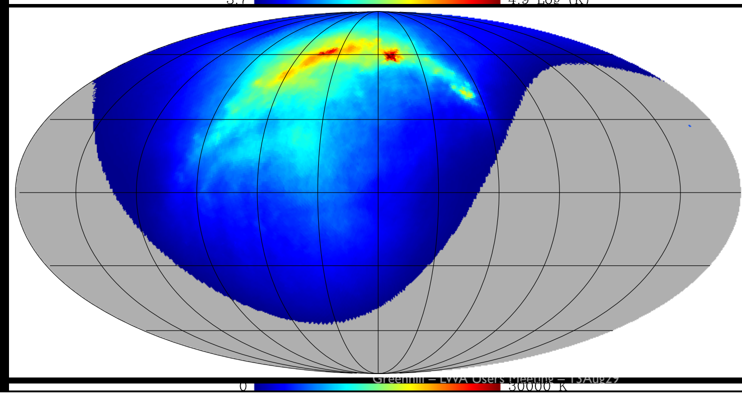




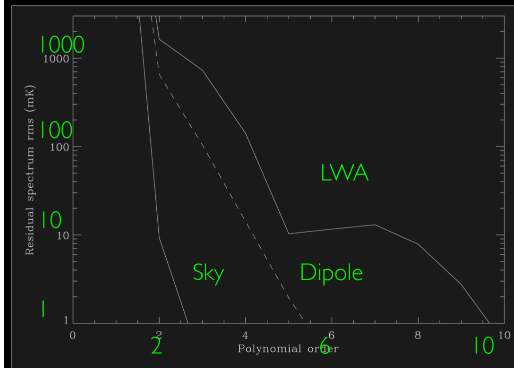
Smooth, slowly varying, but still departs from ideal dipole pattern



Model @
40 MHz
Cost et al. 08

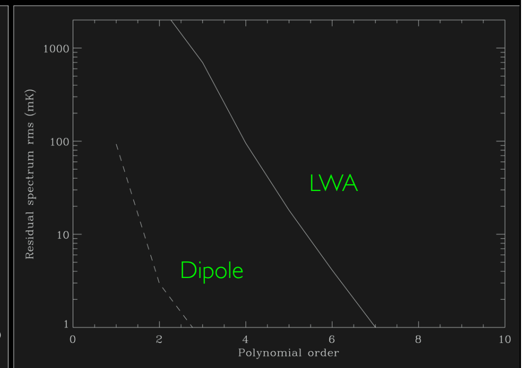


×
dipole pattern
(example)



- Angle-avg model sky x pattern
- Fit polynomial
- Compute RMS

Sky spectrum is not nec. well approximated by a low order polynomial for some instruments



- Subtract ‘templated’ sky model
- Fit polynomial
- Compute RMS

Sky spectrum is not nec. well approximated by a low order polynomial for some instruments