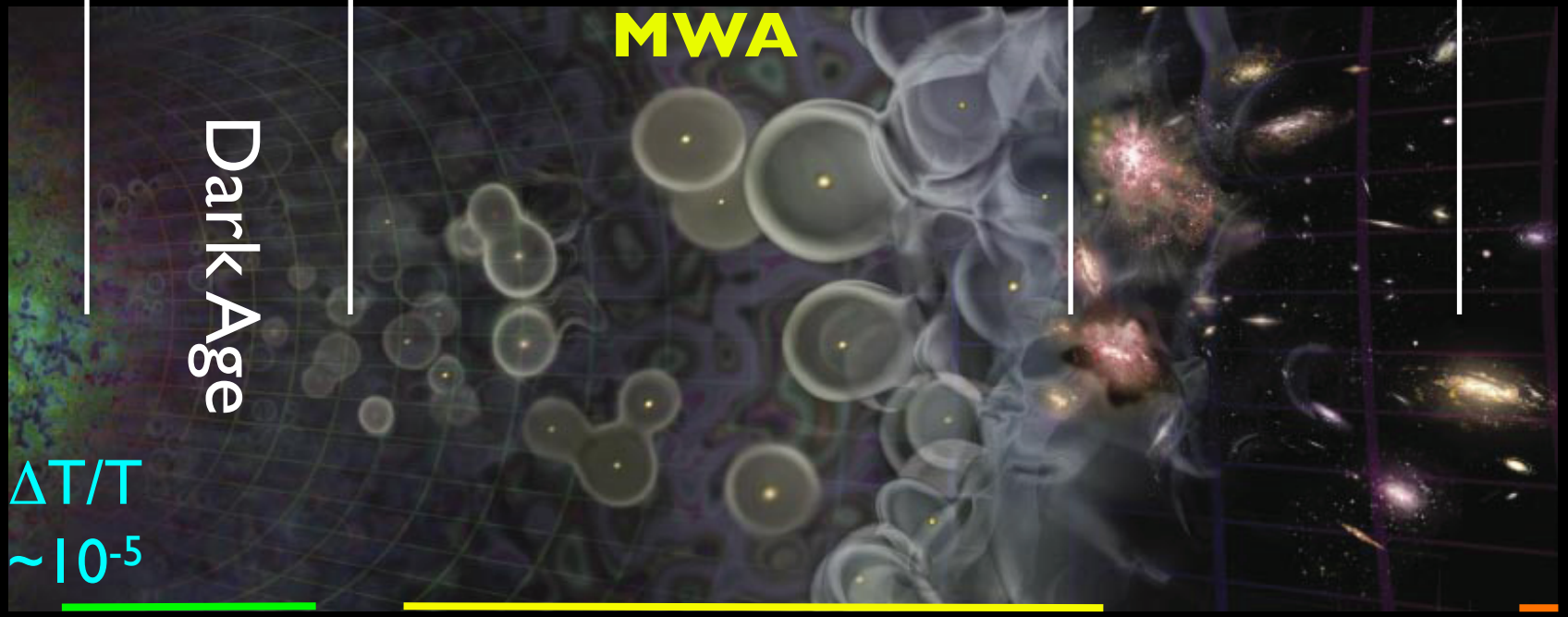
Hydrogen EoR Arrays: MWA to SKA

Lincoln Greenhill
Harvard / Smithsonian

Talks: Wed. PM– Adami; Thus AM–Pritchard; Several–re LOFAR

The Cosmological Record



Complements
- near-IR spectroscopy of quasars etc
- redshifted 21 cm sky maps of the IGM

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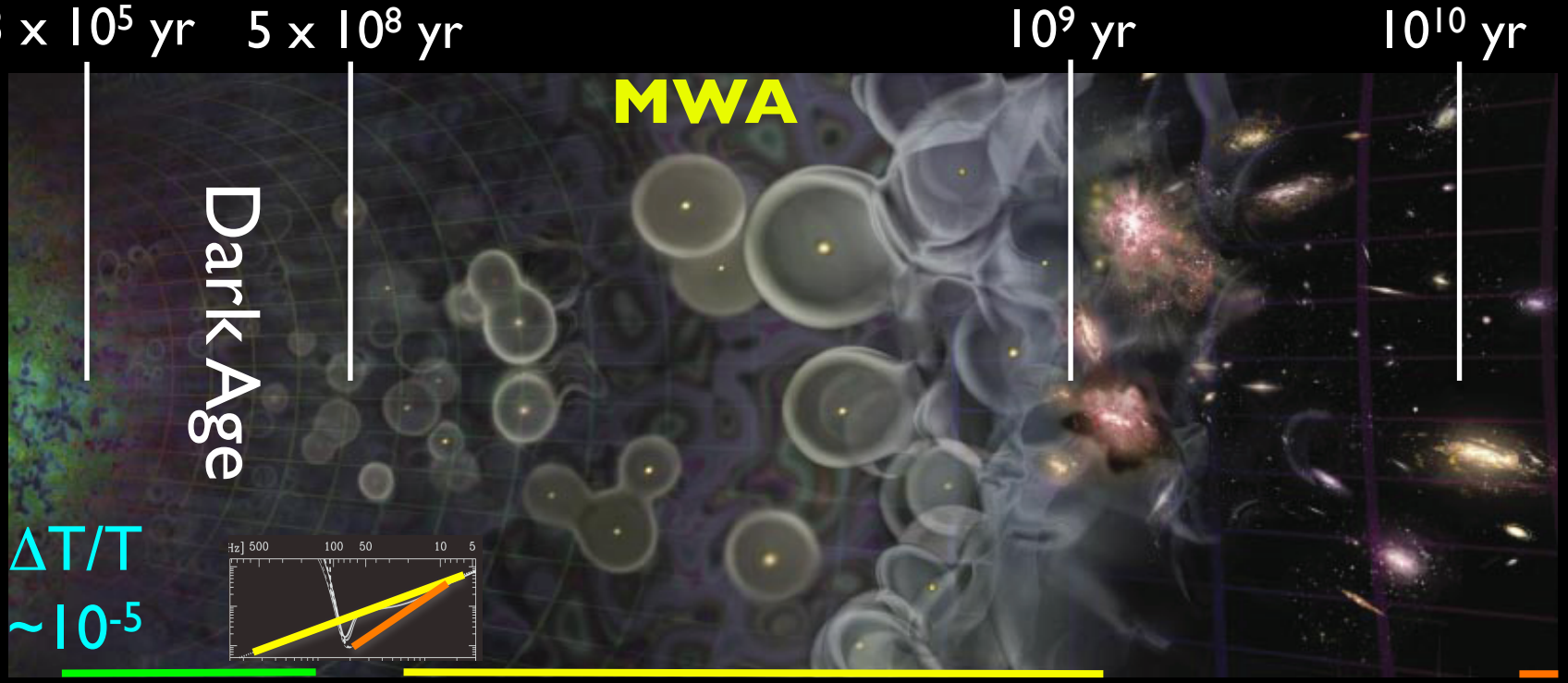
The Cosmological Record



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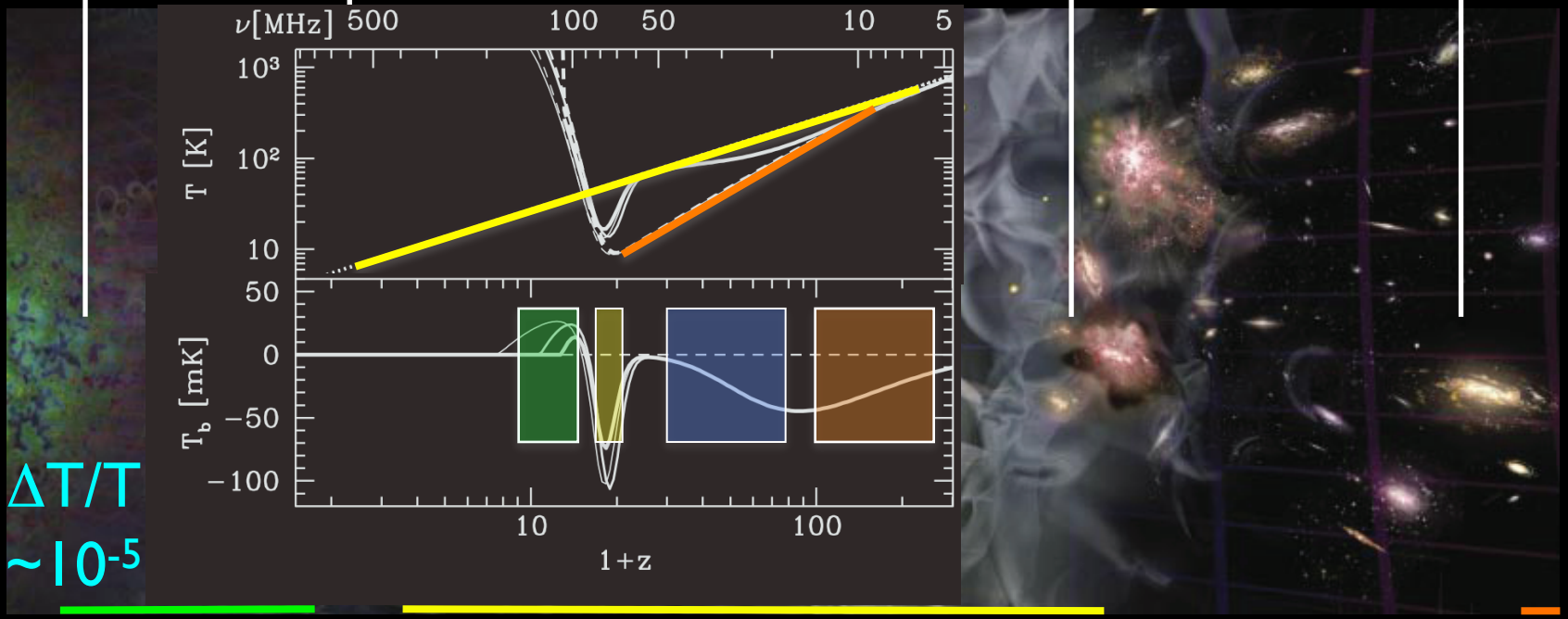
The Cosmological Record

3×10^5 yr 5×10^8 yr 10^9 yr 10^{10} yr



H/He

Epoch of Reionization

Epoch of Experimentation

Complements
- near-IR spectroscopy of quasars etc
- redshifted 21 cm sky maps of the IGM

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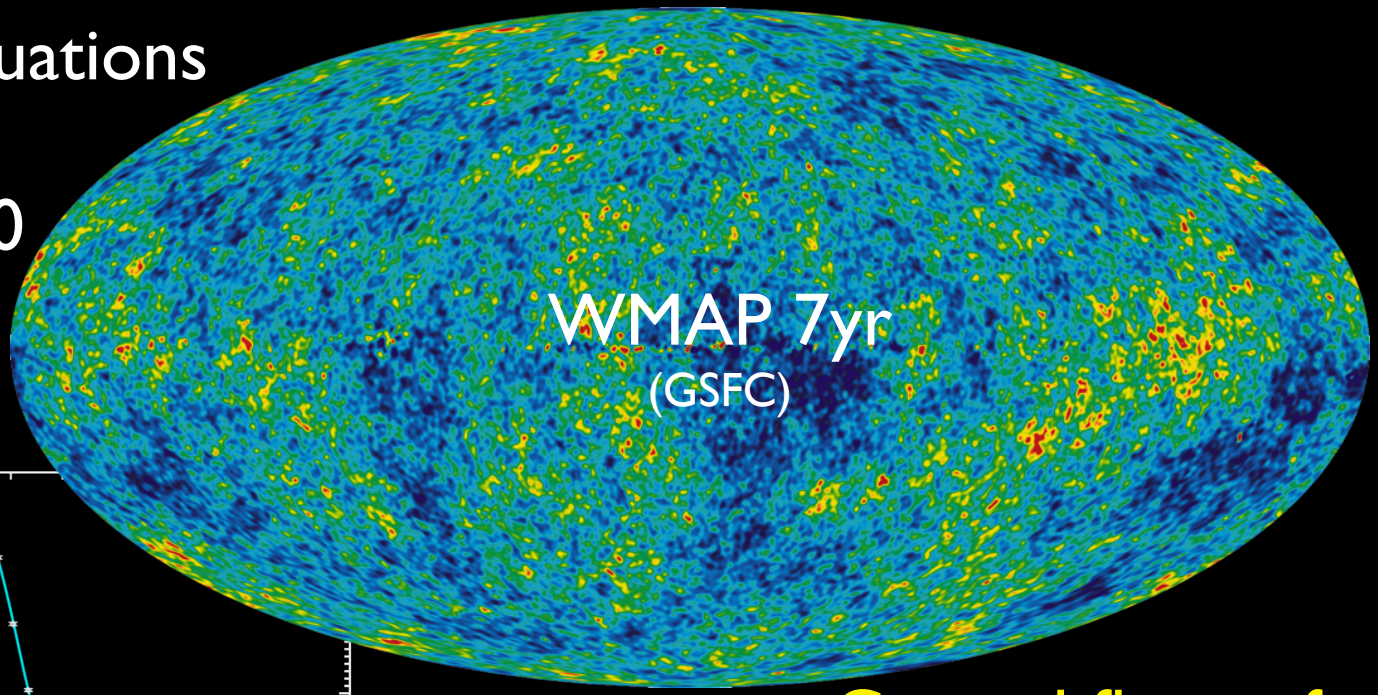
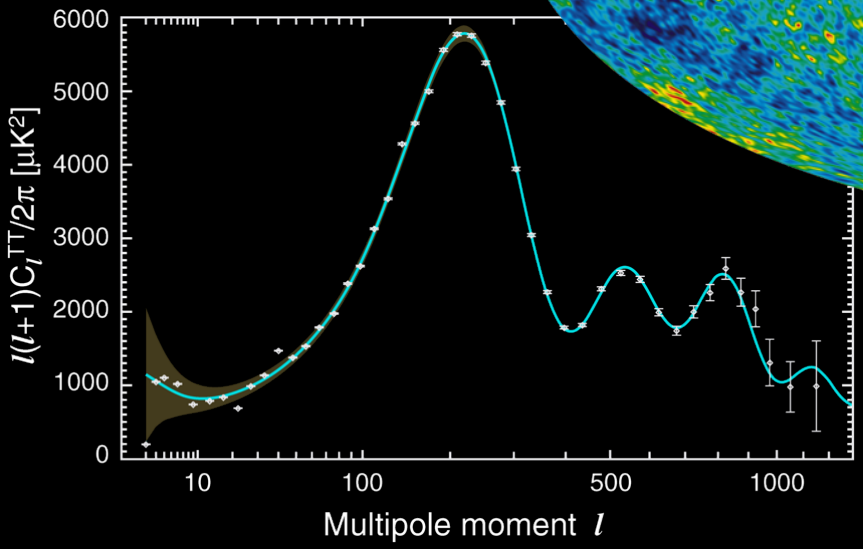
"The EOR is like the CMB but better..."

CMB temp. fluctuations touch just one redshift, z ~ 1100





Ground floor of a
20± year "scientific industry"
(working with industry)

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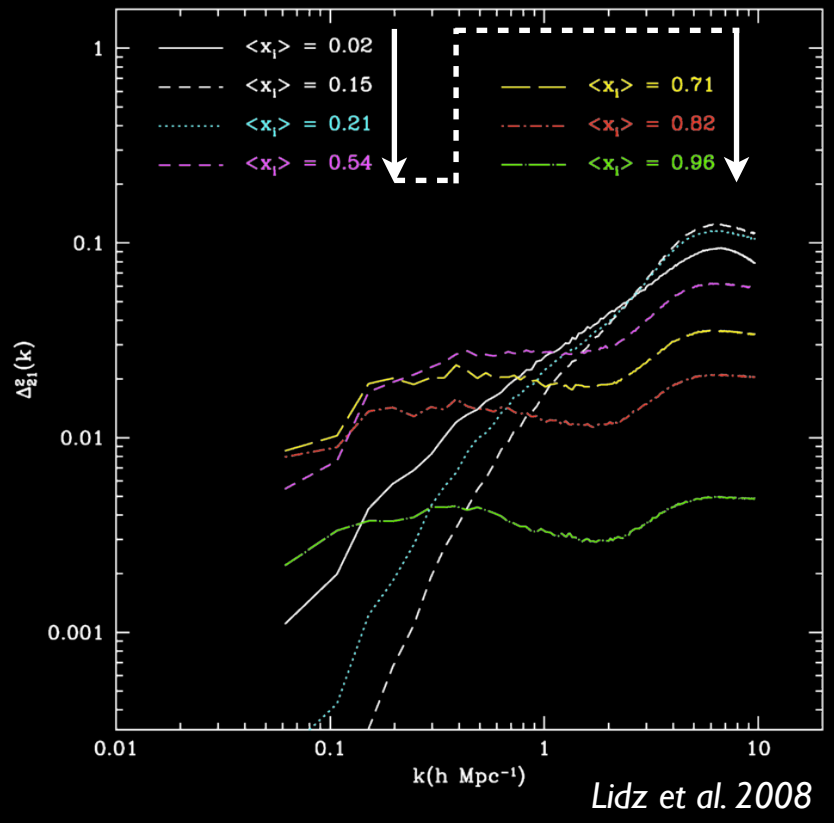
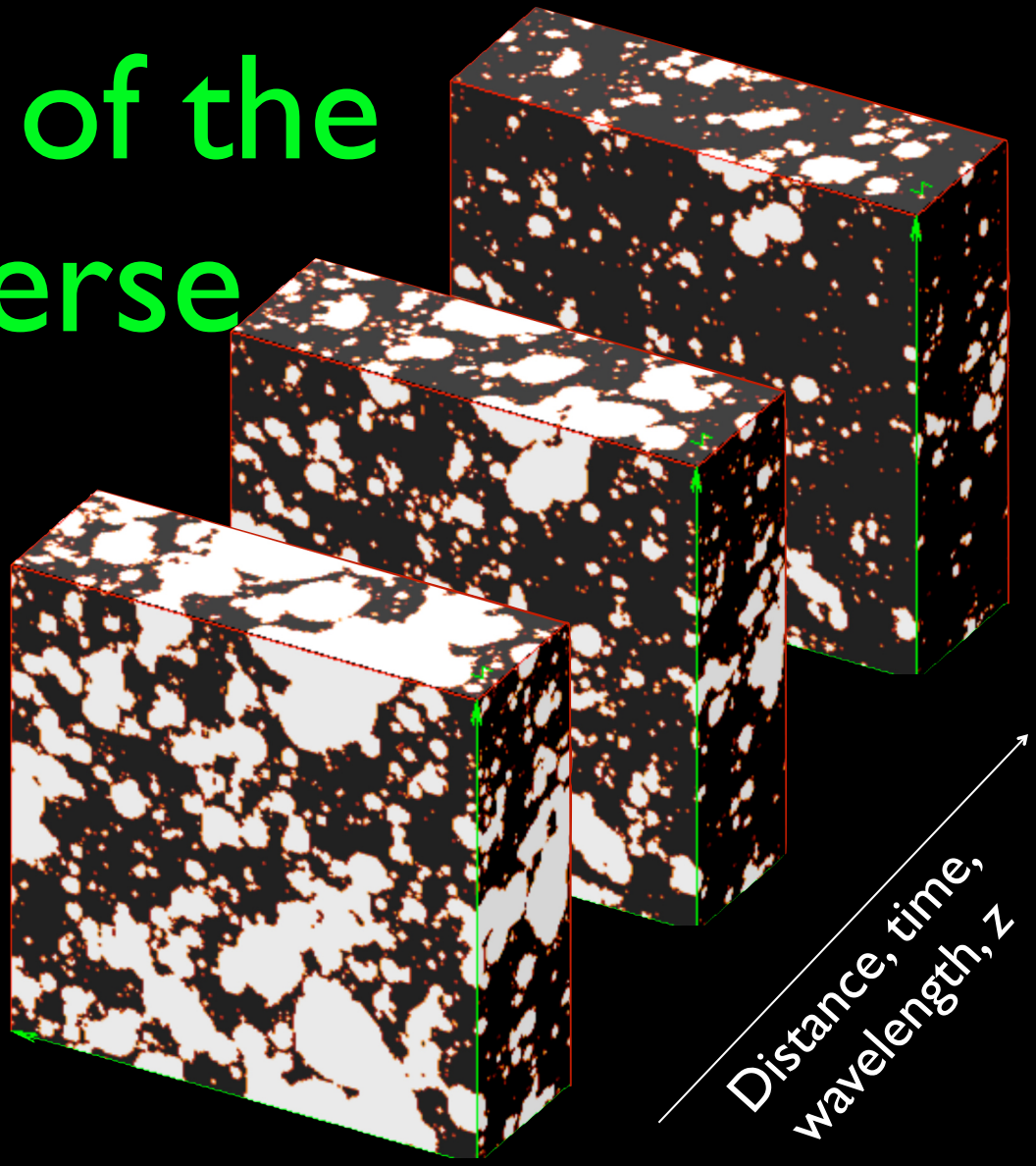
Tomography of the Early Universe



Lidz et al. 2008



- Slicing the early universe
- More distant gas appears at longer wavelength

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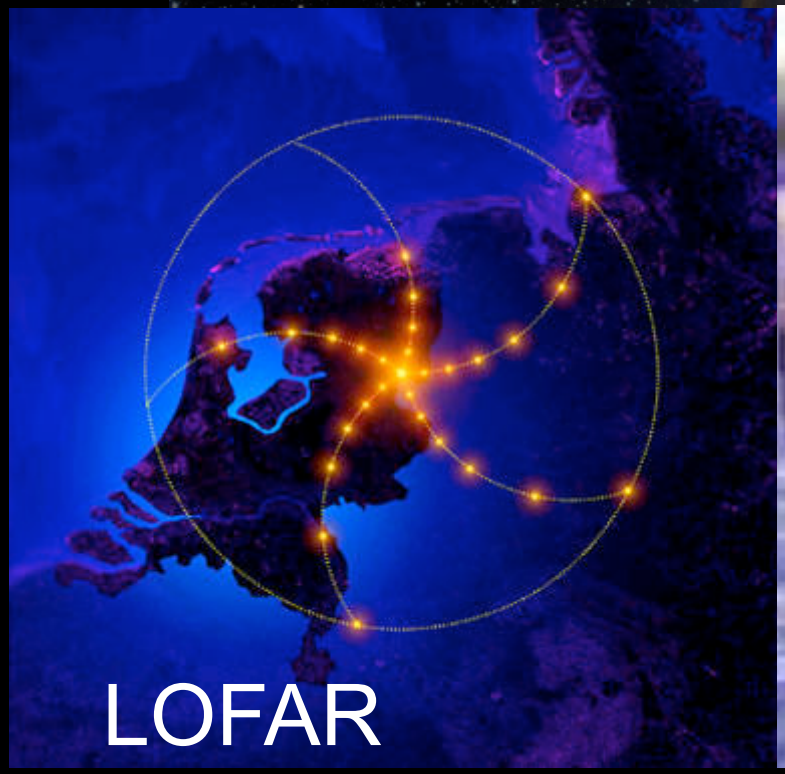
EOR Dipole Arrays

Pathfinders to SKA-lo

The EOR is SKA-lo key science



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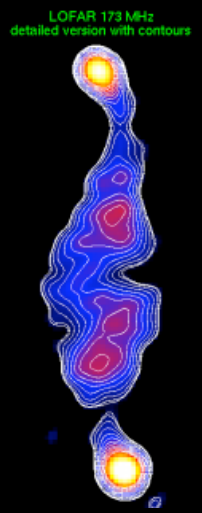
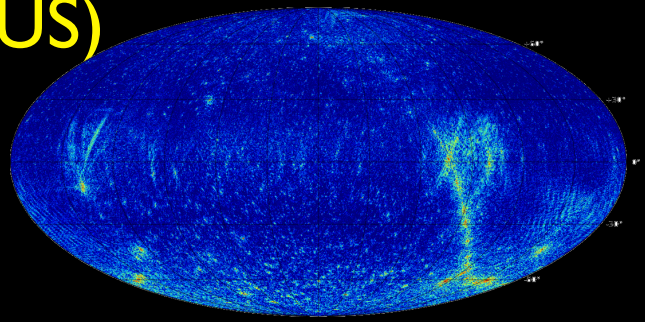
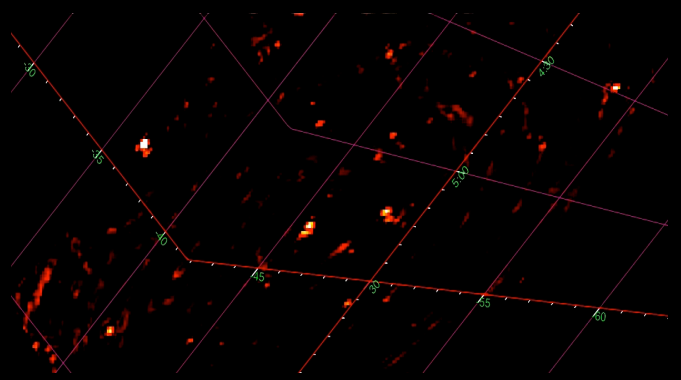
Status

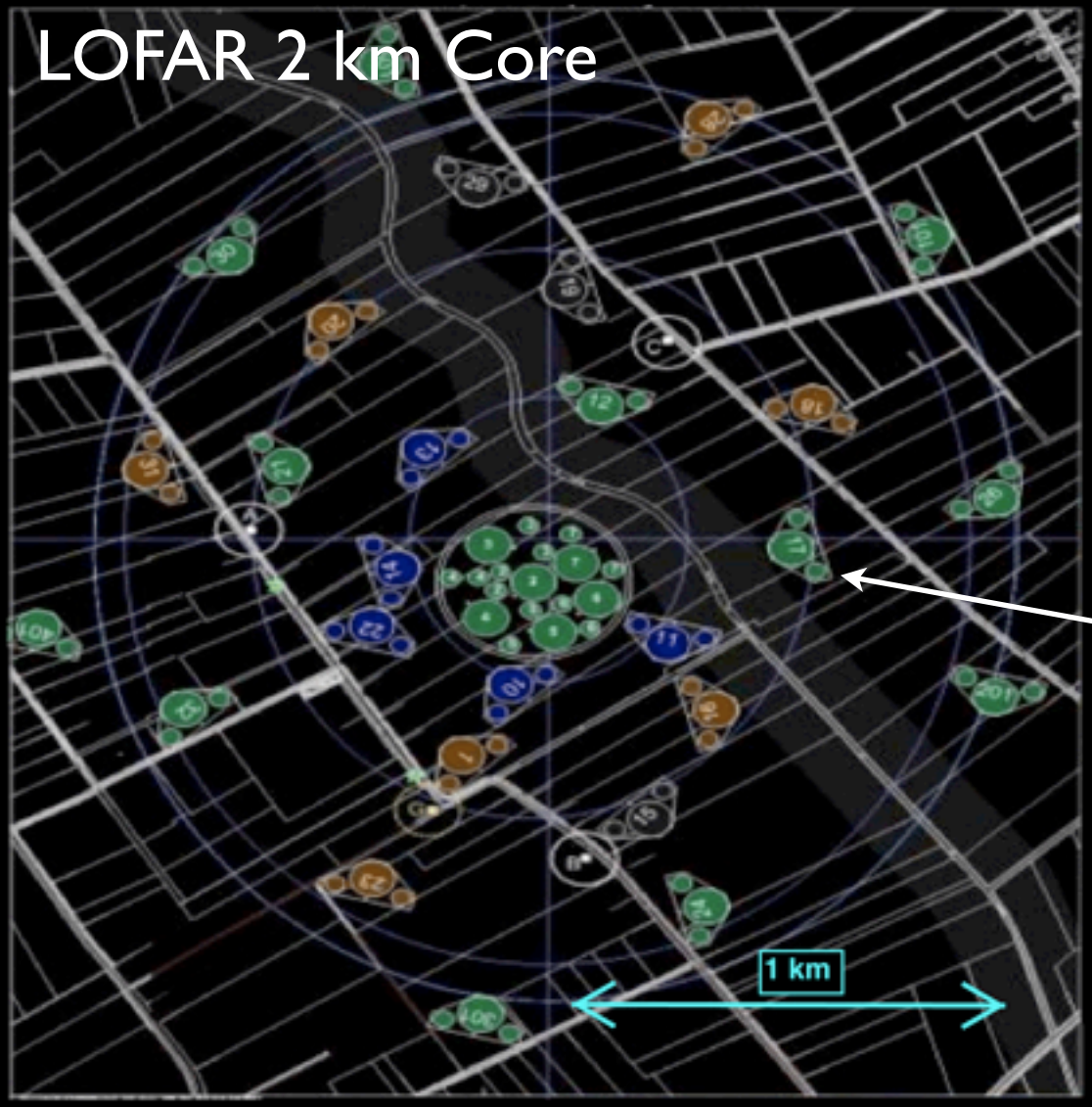
- LOFAR
  - *O*(15) core stations (Dec. 09 forecast)
  - narrow and wide-field imaging
- PAPER
  - 32 dipoles in the Karoo (+16 in US)
  - full-sky map
- MWA
  - 32 stations at Boolardy
  - imaging with *O*(30°) FOV





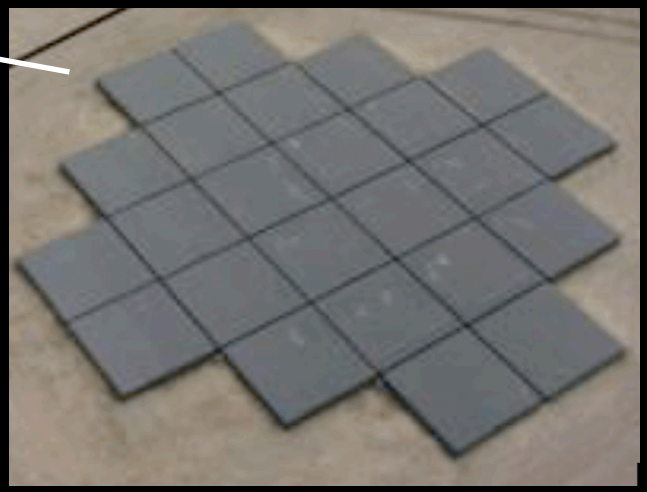


Different approaches in attacking the EOR – RF hierarchies...computing...science analysis



Hierarchy: LOFAR

[4x4]x24x28



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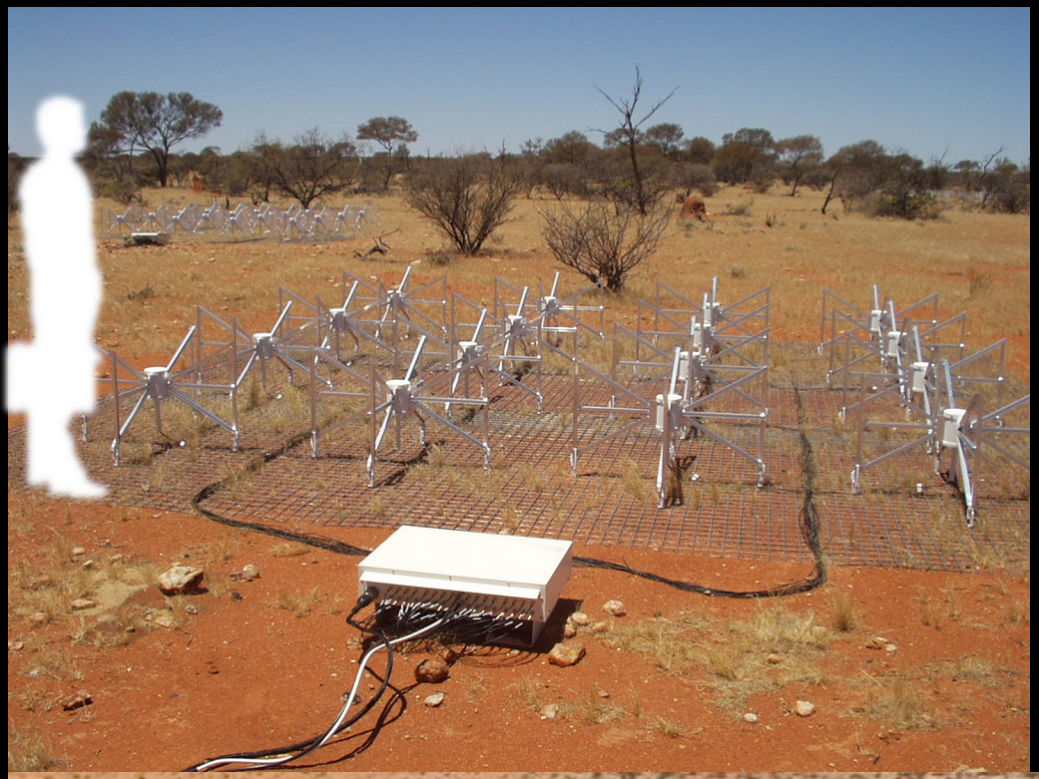


Hierarchy: MWA

[4x4]x24x28

[4x4]x512

5% prototype

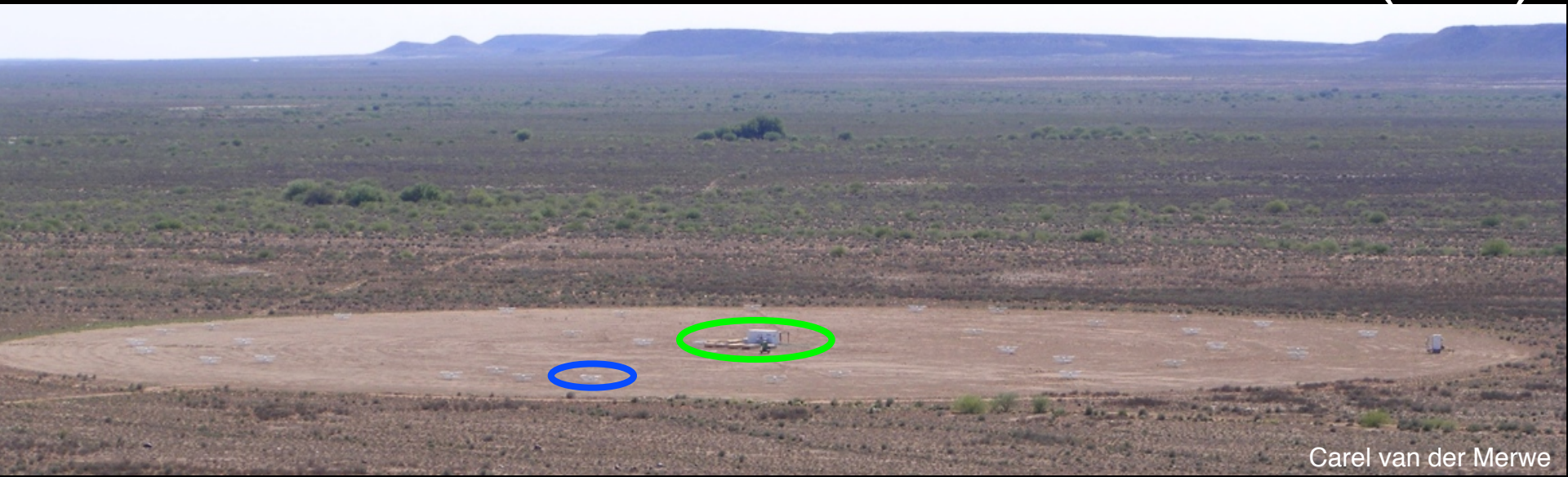
400m

Hierarchy: PAPER

[4x4]x24x28

[4x4]x512

1 x *O*(512)



Differentiation

	PAPER	MWA	LOFAR
Hierarchy	1x32➟512	[4x4]x512	[4x4]x24x36
FOV	*O*(100°)	*O*(30°)	O(2°) x 8
Correlation	large-N FPGA CASPER	large-N FPGA custom	CPU
Cal/Im	post real-time	real-time	post real-time
Calibration	iterative	one-pass	iterative
Imaging	synthesis ➟ ?	Filled aperture T-avg'd snapshot	synthesis
Engine	CPU	GPU	CPU/GPU
Rate	?	10-100 TF s^{-1}	10-100 TF s^{-1}
Analysis vol.	?	~0.5 PB season^{-1}	~0.1 PB season^{-1}

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MWA Status

US/AUS/IN collaboration

Proj. Dir.: Whitney
Proj. Sci: Greenhill
Board Chair: Gaensler

MIT-Haystack
MIT campus
Smithsonian
Harvard U.
U. Melb.
Curtin U.

U. WA
U. Tas
U. Sydney
ANU
Raman Research Inst.
CSIRO

also contributions from individuals/groups at UWisc, UWash, CalTech

Thanks: field, engineering, and test teams, real-time calim team (CfA) – D. Mitchell, G. Bernardi, S. Ord, R. Edgar, M. Clark, & R. Wayth

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MWA Distinctions

- Largest yet large-N array (N > 500)
  - full $O(N^2)$ cross-correlation of apertures ➟ HUGE FOV: 10^3 deg^2
- Real-time calibration and imaging
  - O(100) Gb s^{-1} from correlator
  - can't record raw data (3 PB wk^{-1}@10^h dy^{-1})
  - real-time primary beam & ionosphere correction
- Union of FPGA and GPU technologies
  - correlator ~200 Top s^{-1} (MAC)
  - real-time cal / image system ~100 TFlop s^{-1} theoretical
  - pipeline meets required 8^s cadence with simulations in lab
- Enforced time averaging of images (~1 Gb s^{-1}) output
  - massive forward modeling task; std. deconvolution not possible

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MWA Status

- 5% prototype has completed Test & Verification program: *Feb'10*
- 1st full-sky survey *yesterday*
- 1st EOR field characterizations...*right now*
- entering science phase with 5% array
- build out in ~ 1 year from Q4 2010

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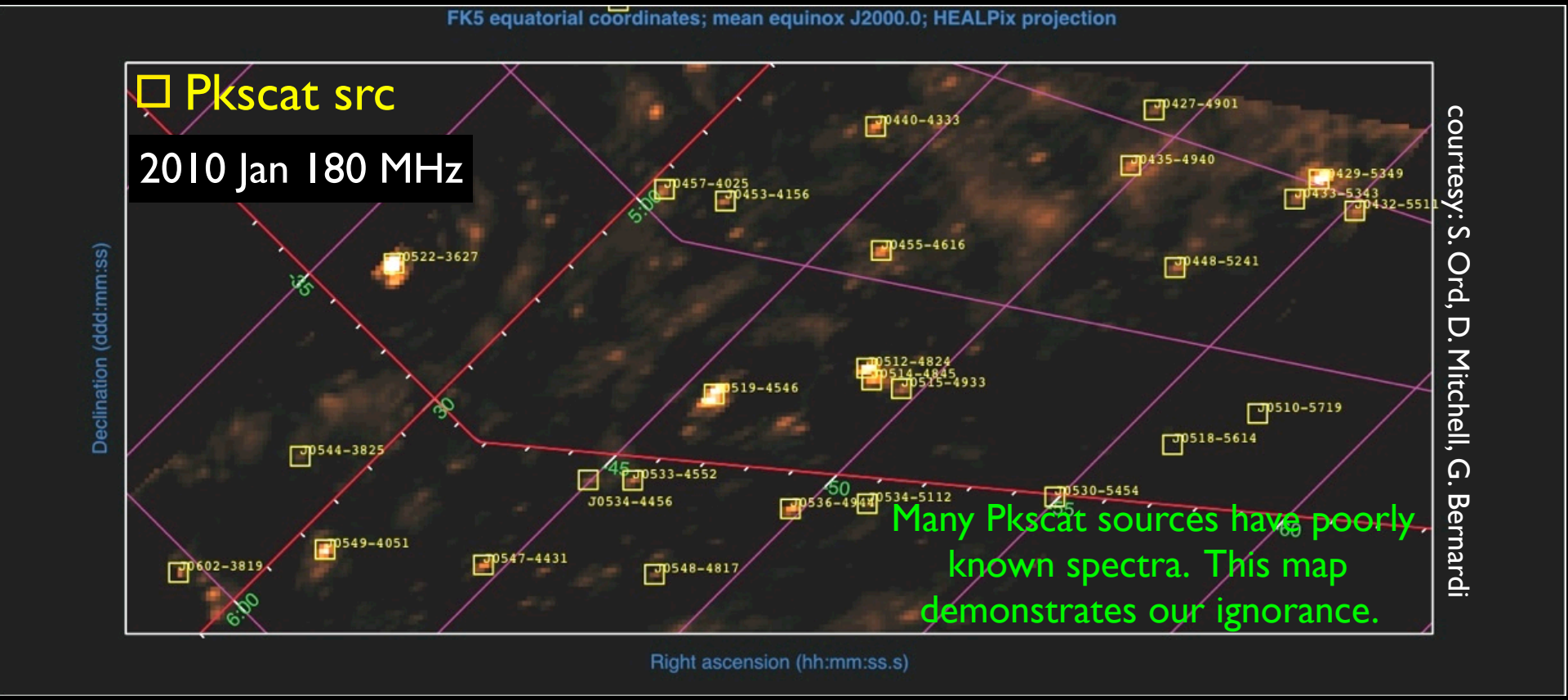
32T Integrations



Pictor A subtracted in real-time

FOV~20°, BW=30 MHz, T=6-8^{h}

3^{m} snapshots co-added, no deconvolution

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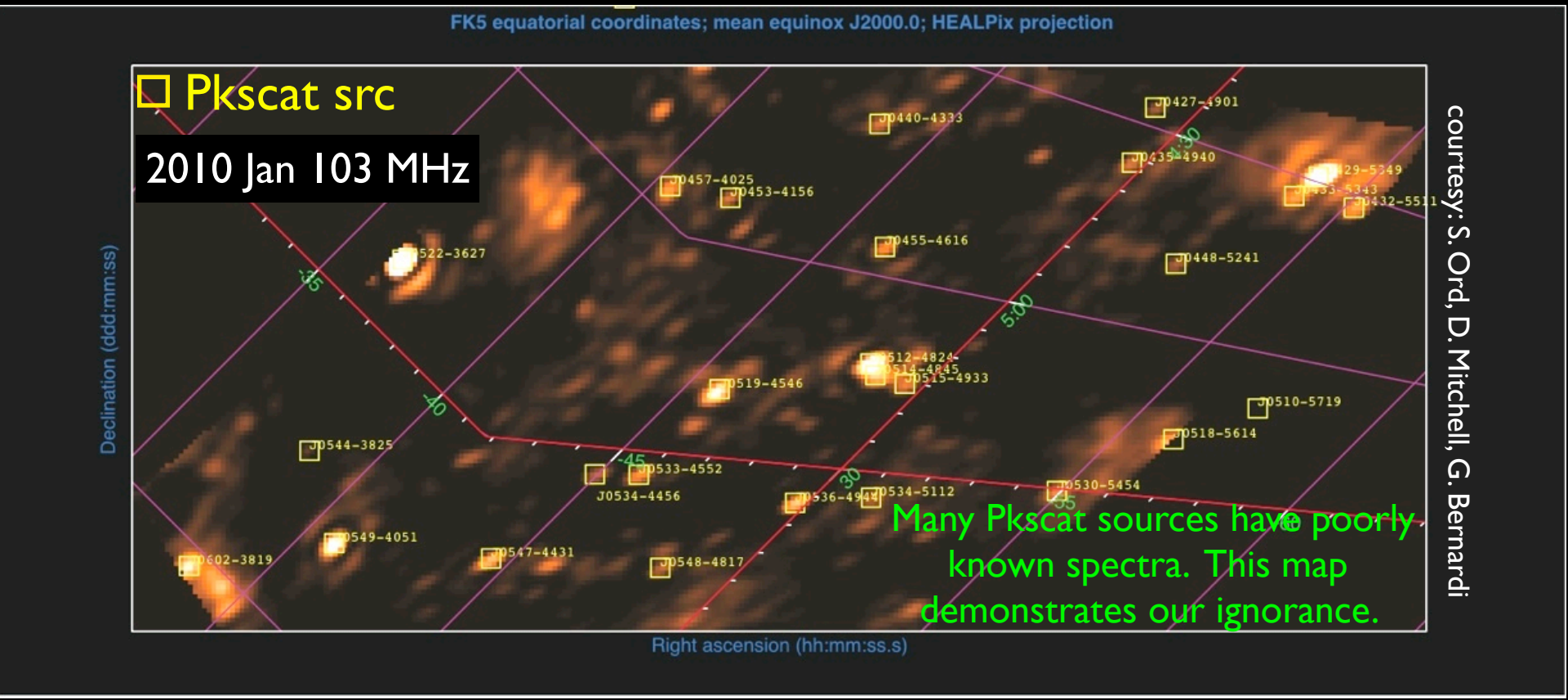
32T Integrations



Pictor A subtracted in real-time

FOV~20°, BW=30 MHz, T=6-8^{h}

3^{m} snapshots co-added, no deconvolution

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Pathway to SKA

- HERA concept
  - Hydrogen Epoch of Reionization Array
    - progression 10^4 m^2 ➟ 10^5 m^2 ➟ 10^6 m^2
    - ☞ *HERA dovetails with SKA-lo* ☜
  - US/Astro2010 white paper
    - MWA - PAPER hybrid as strawman
    - 2 RFIs; 1 Q&A (Backer / Greenhill)
- Formulated w/ Astro2010 in mind
  - simple argument, broad appeal ➟EOR-only
  - simple traceable costing
  - US audience: sponsors, panels, community
  - emphasis on 2nd stage since more tangible

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Pathway to SKA

TABLE I: Technical Progression of Dark Age & Reionization Arrays

Instrument	Phase	A_{eff} (km^2)	No. Elements	FOV (°)	Goal†	B_{max}	B_{fill}
PAPER	2010–14	0.003	128-512	60	PS Detection		
MWA	2010–14	0.01	512	20-40	PS Detection	1.5 km	0.3 km
HERA II	2015-19	0.1	5000	20-60*	PS Characterization	3 km?	1.5 km
HERA III	2020–	$O(1)$	$O(50000)$	(20-60)‡	Structure Imaging	5 km?	5 km

➡ SKA

up to ~15000 for bare dipoles

†– PS: Power Spectrum. *– Field of view depends on detailed trade-off study following HERA-I efforts. ‡– HERA-III parameters will depend on experience gained by mid-decade.

Backer et al. 2009

HERA-II is not necessarily just a 10% prototype.
Designs, uses, and cost-benefit may pivot between HERA-II and III, e.g.,
(i) basic characterization of the science signal may not come until HERA-II
(ii) new, possibly breakthrough DSP (nlogn) may not be ready until after HERA-II

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HERA Build-Out Scenario

- GOAL: 100x larger EOR array than today's
- 3 technical / engineering approaches
  - all, some, or none may work on their own

Phs Ia
- build & operate arrays in parallel
  - lessons learned: LOFAR, MWA, PAPER

Phs Ib
- extant arrays as testbeds for EOR
  - deploy next-gen prototypes & techniques

Phs II
- build & operate 10x EOR array(s): HERA-II
- development cycle

Phs III
- build & operate single 100x array: HERA-III
- generalize (e.g., MWA / LOFAR examples) ➟ SKA-lo

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EOR Design Choices

- Large uncertainties hinder design and path selection
  - must wait until LOFAR, MWA, and PAPER deliver
- Longest baseline, B_{max}
- Max. size of filled aperture plane, B_{fill}
- Correlation $O(n^2)$ vs Direct $O(n\log n)$ signal processing
- Real-time cal/imaging vs iterative calibration
  - Image manipulation vs visibility manipulation
- Hierarchy of RF hardware / monolithic FOV
- Heterogeneous computing model (FPGA, GPU, massCPU)
- Input data rate - correlators don't nec. compress volumes
- Output data rate - accum. large images / large visibility sets
- Storage - exabyte? rolling petabyte?

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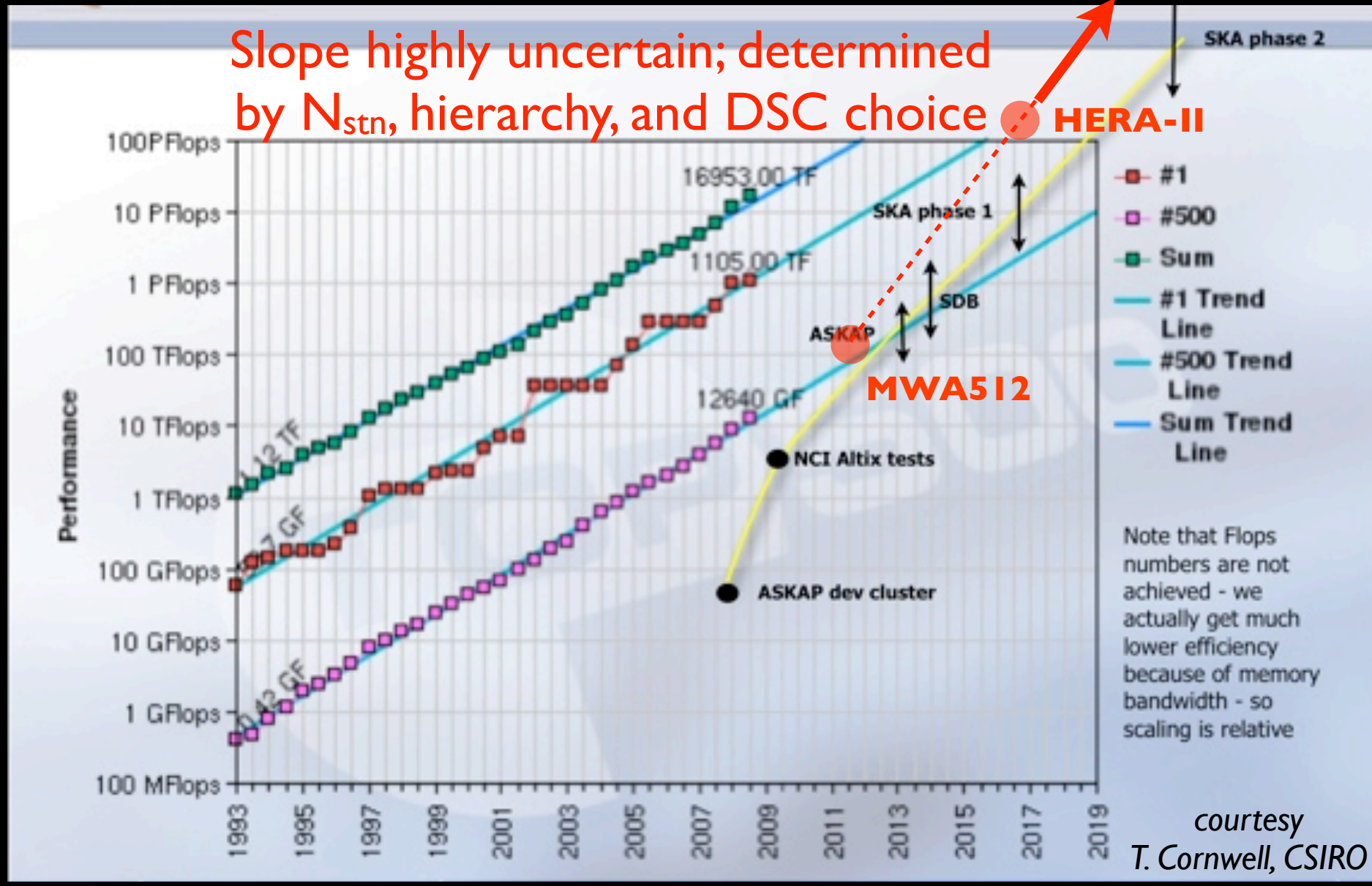
SKA-lo computing may scale as or more rapidly than SKA-mid



Summary

- big science questions (e.g.,)
  - How/when did the 1st generations of stars form?
  - What were they; how did the population evolve?
- epoch of experimentation; ground floor
  - LOFAR, MWA, PAPER
- HERA progression: pathfinders to SKA-lo
  - many open configuration questions
  - array specs: anyone's guess
  - only field experience will tell

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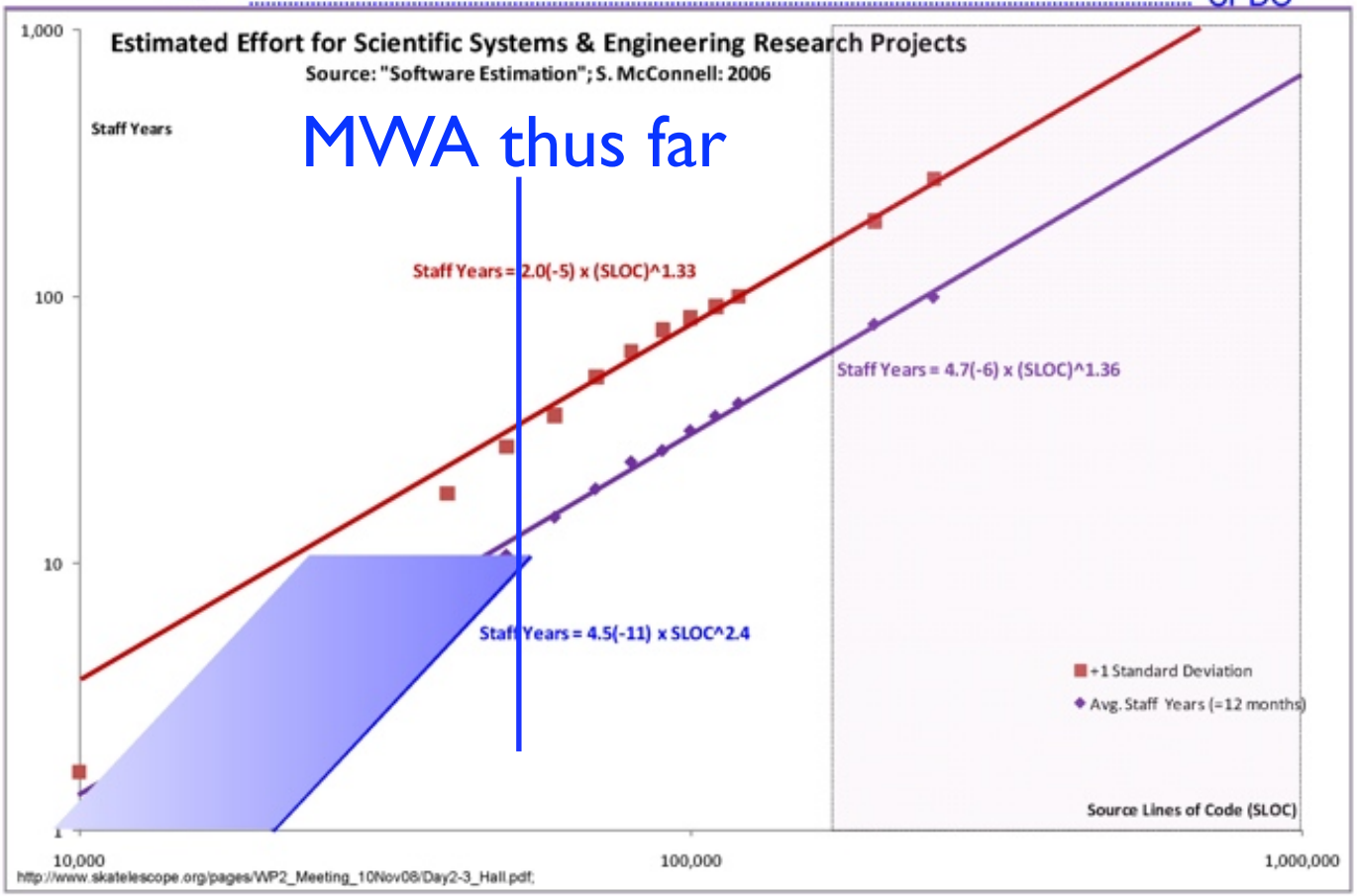
end

Legacy: ~30 to ~700+ staff years effort?

SPDO



Why are dipole arrays challenging?

- big, bright, messy sky
  - broad field of view of dipoles
  - linearly polarized components
  - fore / back-ground $10^{5\text{-}6}$: 1
- dipole elements
  - 100% linearly polarized
  - fixed on the ground (non-tracking)
  - sparsely distributed, inefficient, large numbers
- ionospheric variability & structure
- data rate

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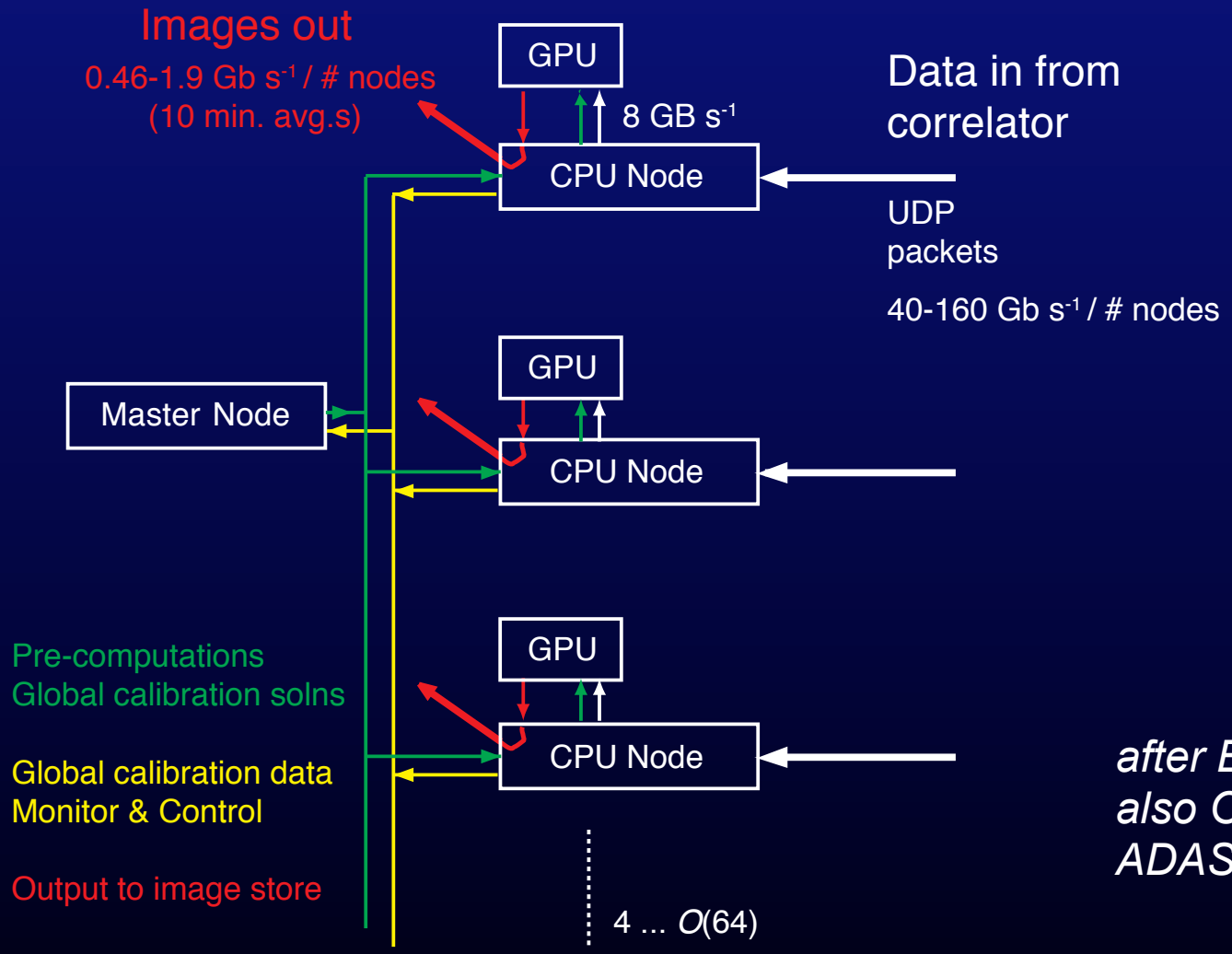
Heterogeneous Computing



after Edgar et al. also Ord et al. ADASS08

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3 LAYER COMPU-TING

Loop ~100 sources
Creation of, and arithmetic with, many vectors of length ~130,000.
Many 2×2 matrix operations inside loops over source and baseline (~10^7).

Grids ~1024×1024 ($4N_{freq}$)
Each populated via convolutions with 130,000 different kernels.
Kernels ~17×17

No = $4N_{freq}$
~1024×1024

Grids ~1024×1024 ($4N_{freq}$)
~10^6 Ax=b solutions (4×4) per N_{freq}.
~10^6 pixel mappings per N_{freq}.

$ops \propto N_{src} N^2_{ant} N_{freq}$ ± $ops \propto N^2_{kern} N^2_{ant} N_{frq}$ $ops \propto N_{freq}$ $ops \propto N^2_{pix} N_{freq}$

Compute Node j

calibrator loop

splat

2D FFT

resample & avg.

GPU_j

updated every few minutes

updated every 8 s

from correlator

1 gigE

Σ vis.

CPU_j

MPI link

update gridder kernels

compute frequency dependent effects

ionospheric & primary beam parameters

4x4 matrix/pix. and pixel info.

Master Node

calibrator selection

MPI synch. multi-chan. source fits

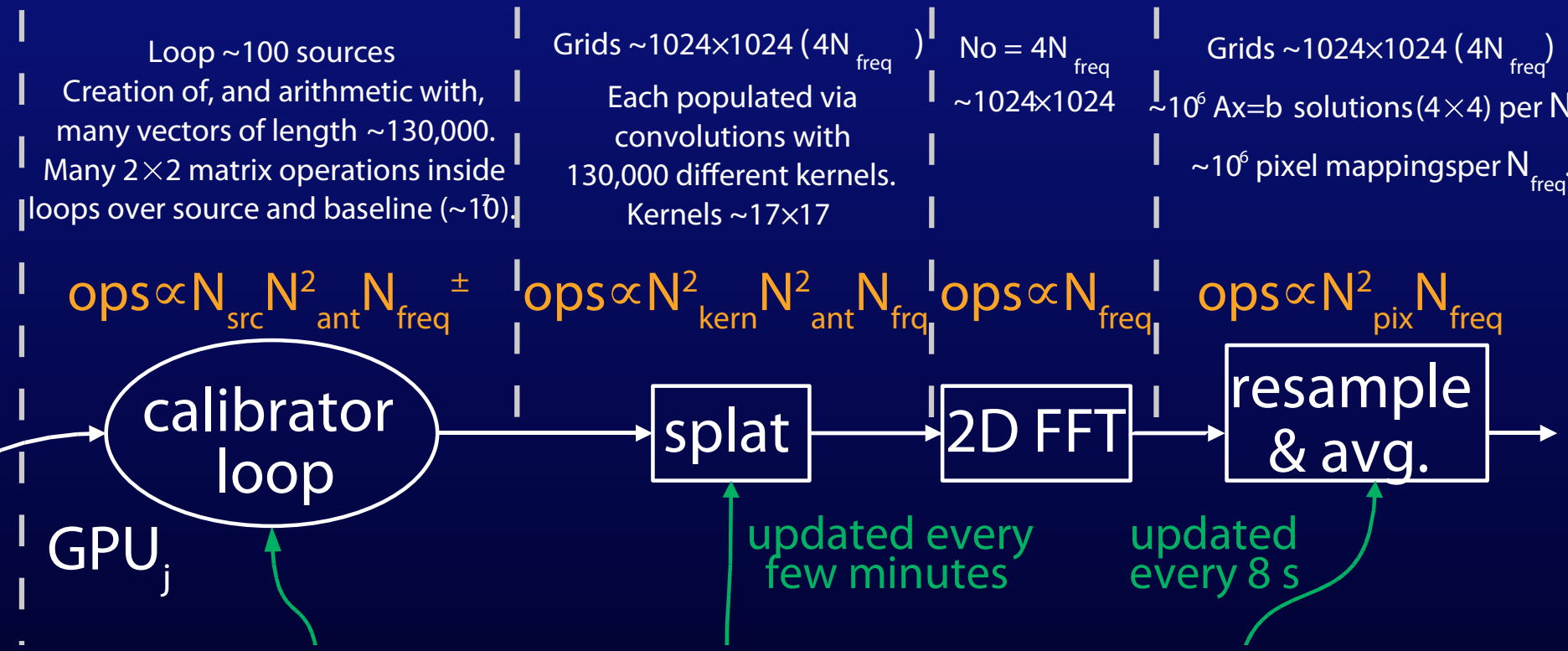
LSQ cal. fits (multi-source)

pre-computation of pixel positions and instrumental polarization

Thread 1: 8 s integrate new data

Thread 2: 8 s process previous interval

(D. Mitchell : CfA)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Each populated via convolutions with 130,000 different kernels.
Kernels ~17×17
No = 4N freq
~1024×1024
Grids ~1024×1024 (4N freq)
~10^6 Ax=b solutions (4×4) per N freq
~10^6 pixel mappings per N freq.
ops∝N src N^2 ant N freq ±
ops∝N^2 kern N^2 ant N frq
ops∝N freq
ops∝N^2 pix N freq
calibrator loop
splat
2D FFT
resample & avg.
GPU j
updated every few minutes
updated every 8 s

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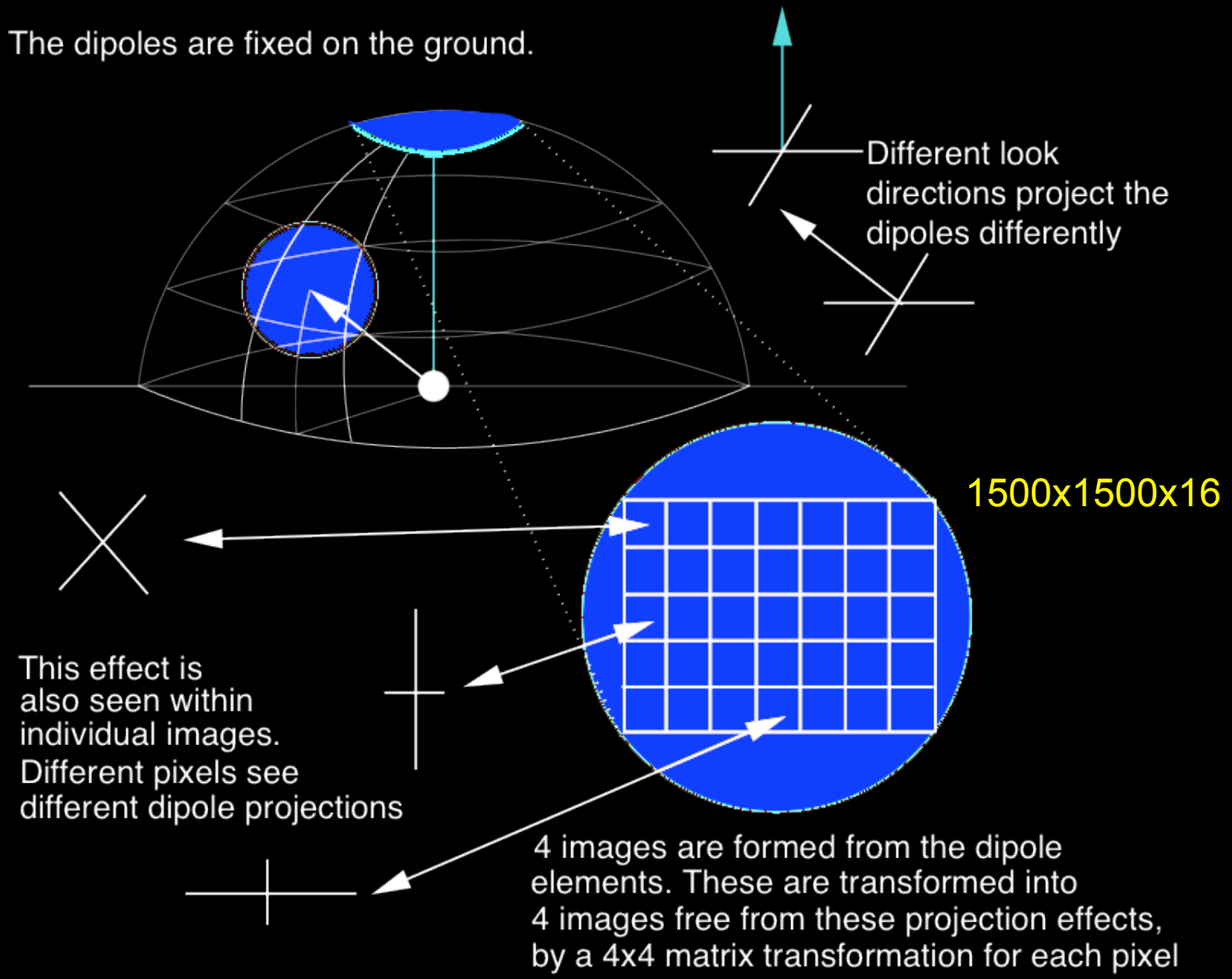
Conversion to instrument independent Polarization



courtesy S. Ord

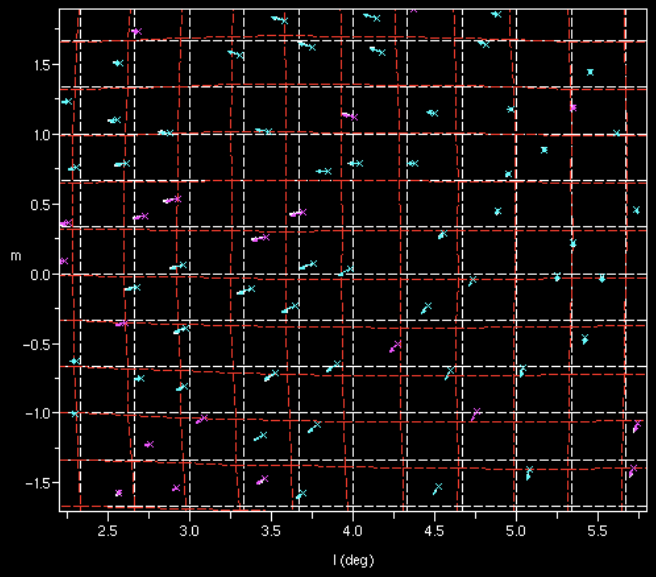
Repair of Ionospheric Distortion

Use the observed source refraction to distort the pixel boundaries used when regridding.

- $w_i = d^{-\alpha}$ ($w_i = 0$ if $d > d_{max}$)
- $M^T M = \lambda^2 I$ (minimise local shear)
- $M^T M = I$ (minimise local scaling)

Interpolation function: At each vertex minimise $\sum_i w_i \left| p'_i M - q'_i \right|^2$

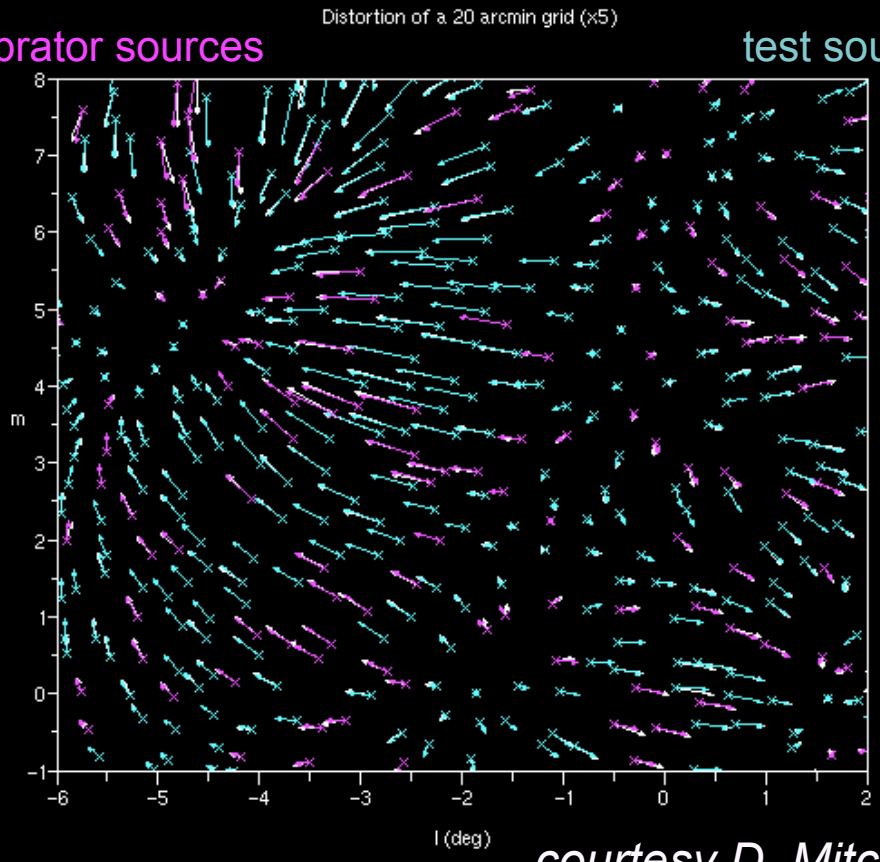
Refracted grid



Ideal grid

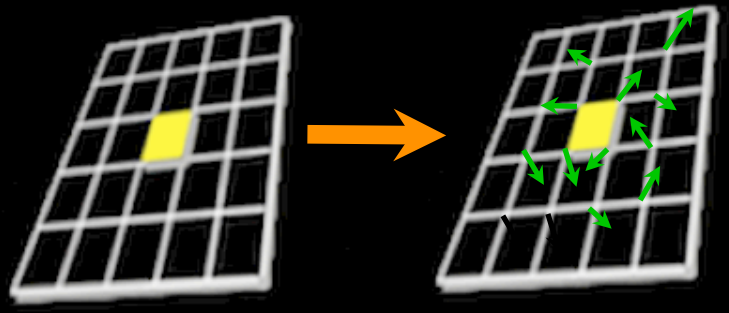
calibrator sources

test sources

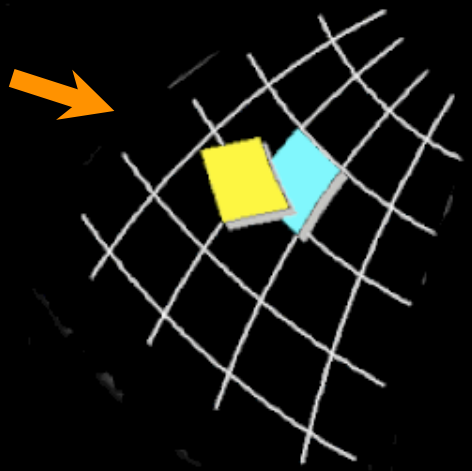


courtesy D. Mitchell

Re-pixelization



Involves double precision non-linear coordinate transformation

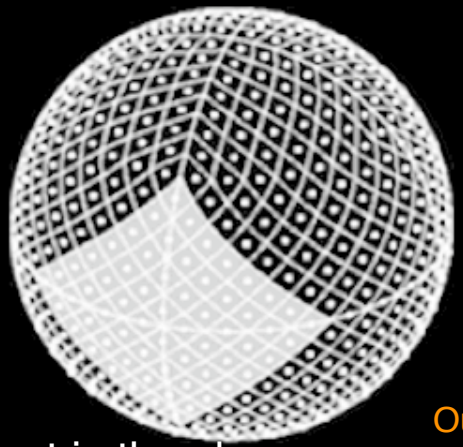


The pixels are projected into a curved sky coordinate frame

Double precision calculation of polygon intersections

Best flux conservation requires the precise calculation of input and output pixel overlaps.

Output pixels are taken from the HEALPIX pixelisation of the sphere to allow efficient indexing and storage

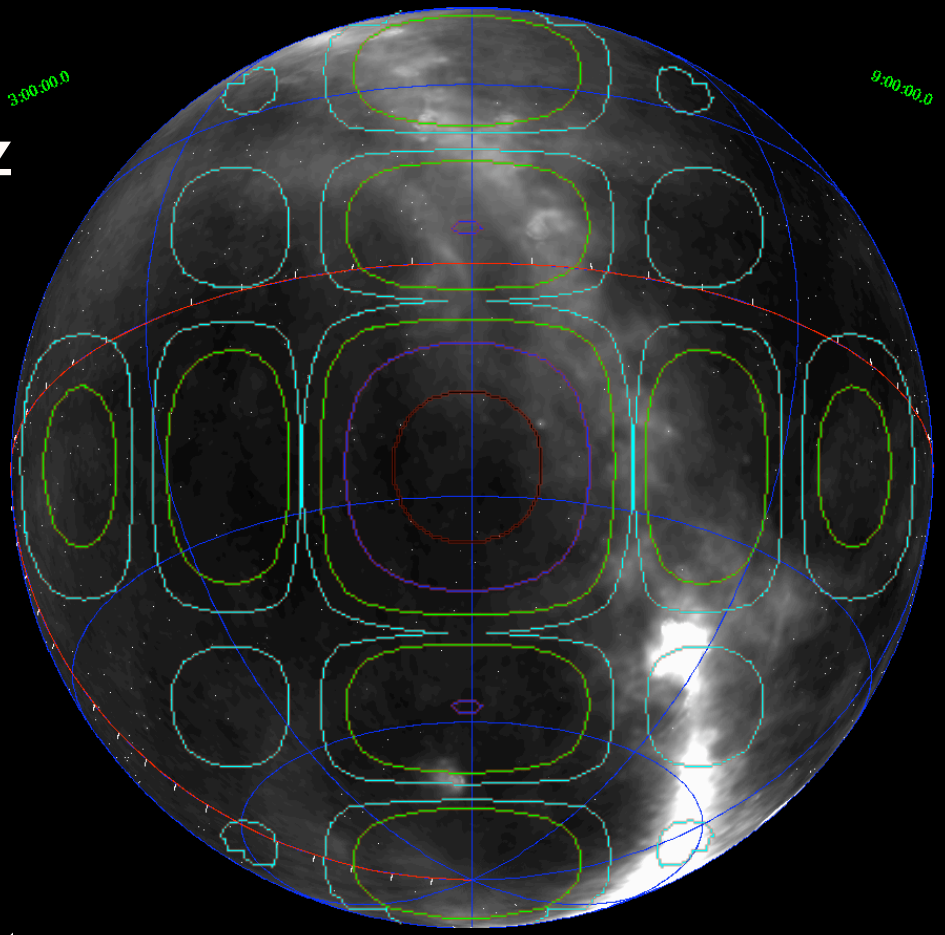


Final output is the sky brightness distribution in an all-sky pixelisation. No further reprojection is required

Simplifications are possible (interpolation/ flat sky/straight pixel edges)

courtesy S. Ord

model 140 MHz
radio sky



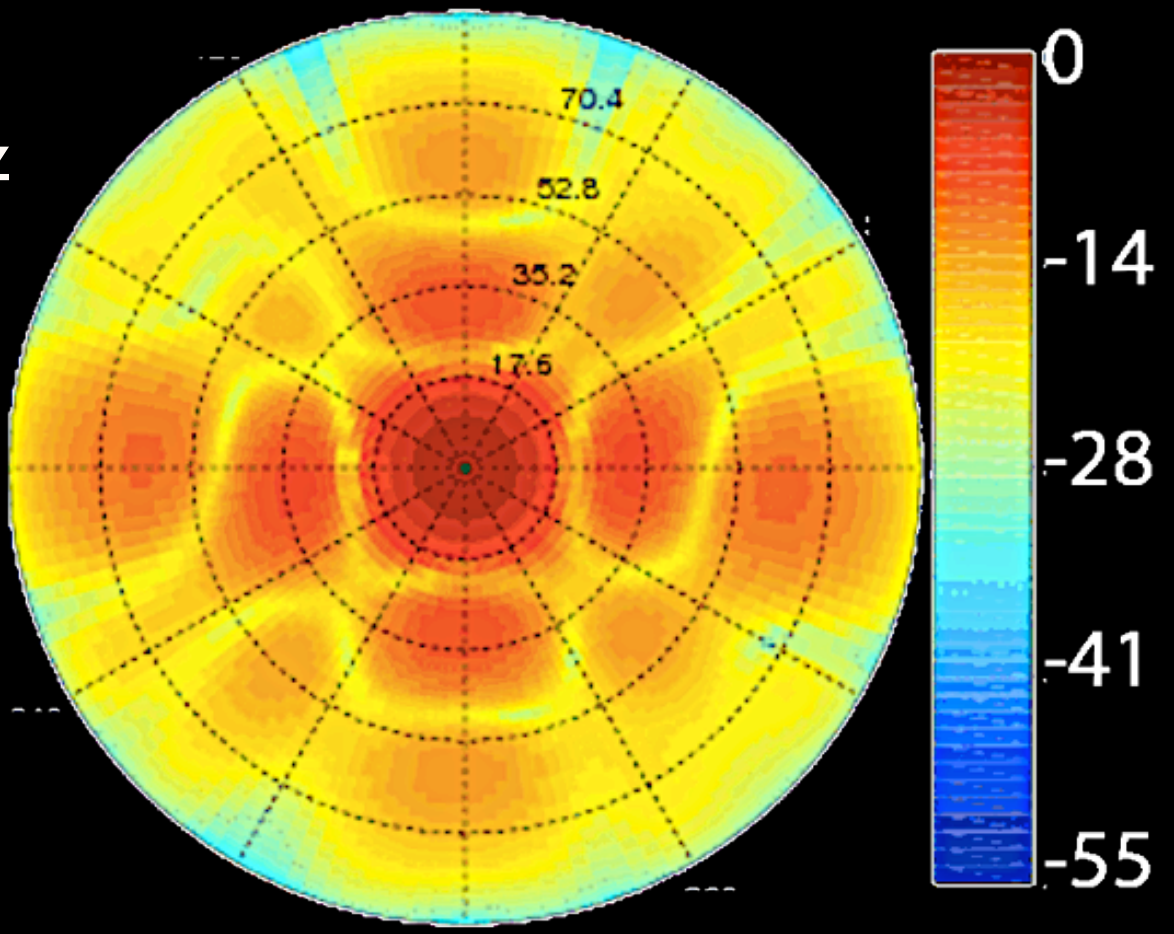
Primary Beam

- complicated
- time variable
- tile dependent
- calibration dependent
- requires fix in gridding
- different for each visib.

3,10, 20 & 30 dB
contours @ 200 MHz

courtesy S. Ord, D. Mitchell

model 140 MHz
radio sky



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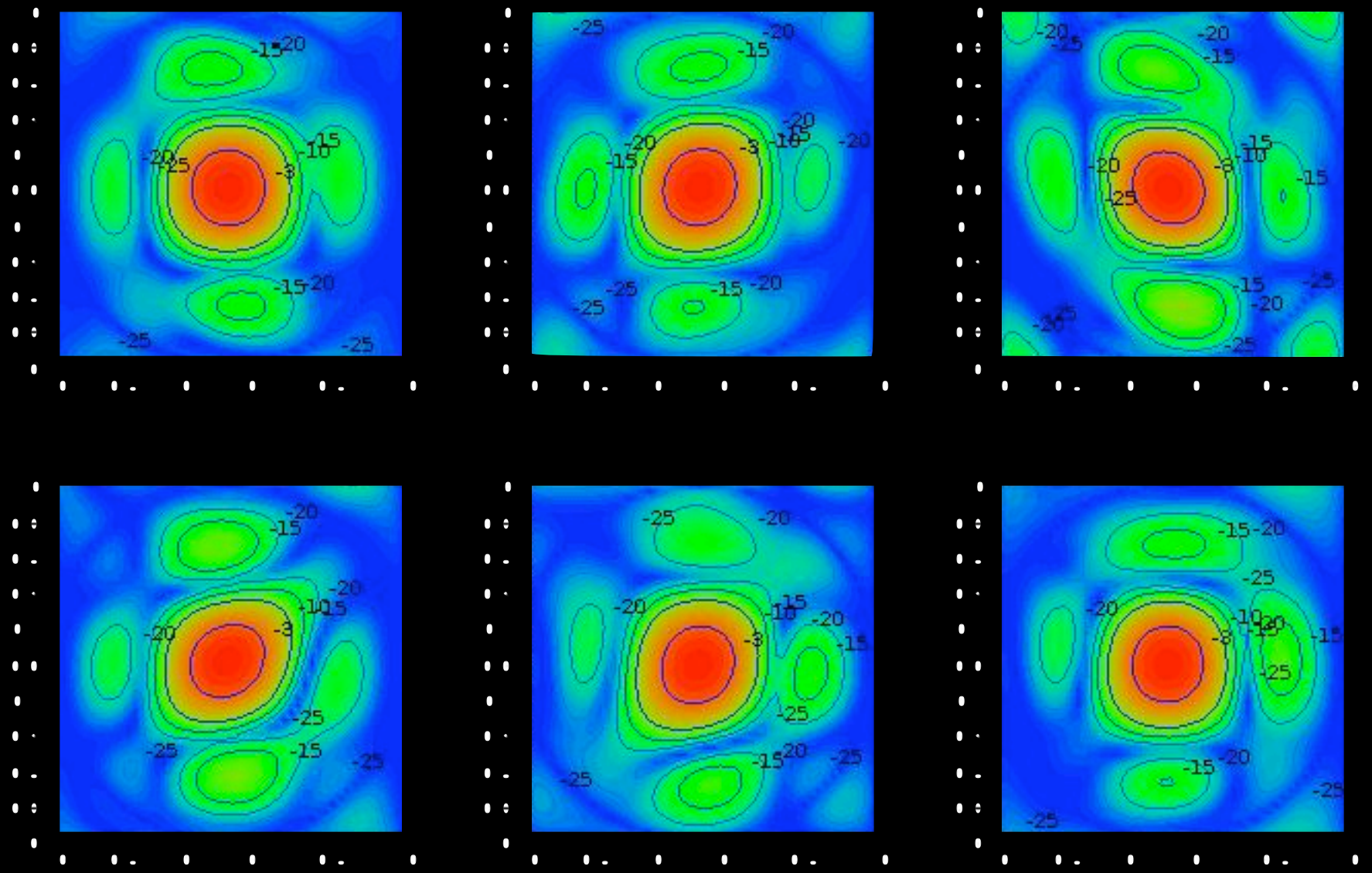


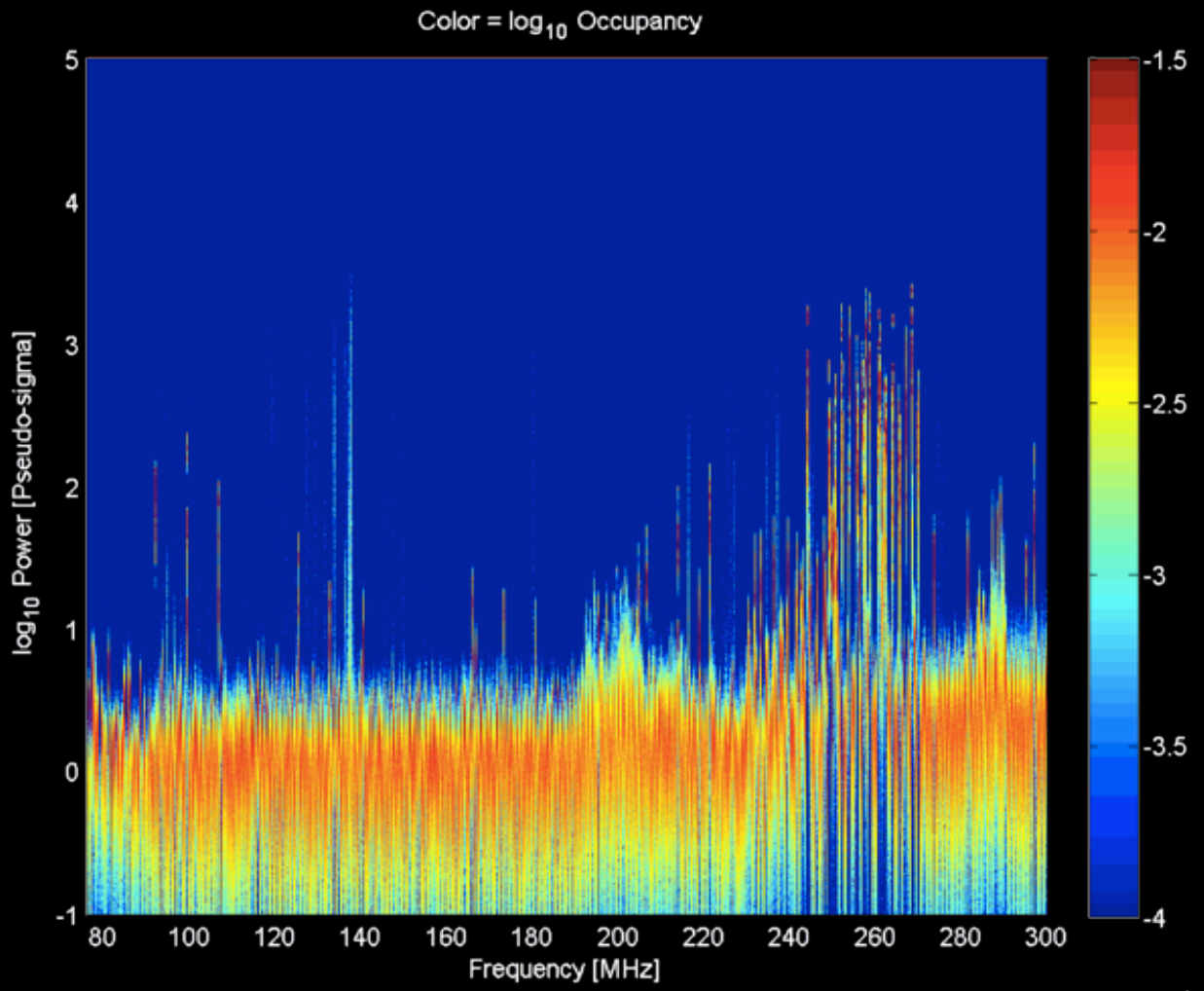
30% perturbation in voltage cal (10% in power)
10 degrees perturbation in phase, dipole to dipole

courtesy D. Mitchell

RFI Environment

Occupancy

- Relatively clean environment for EoR studies
  - Pwr vs ν
  - color: occupancy
  - 11/13–11/16/07
  - Acquiris back-end



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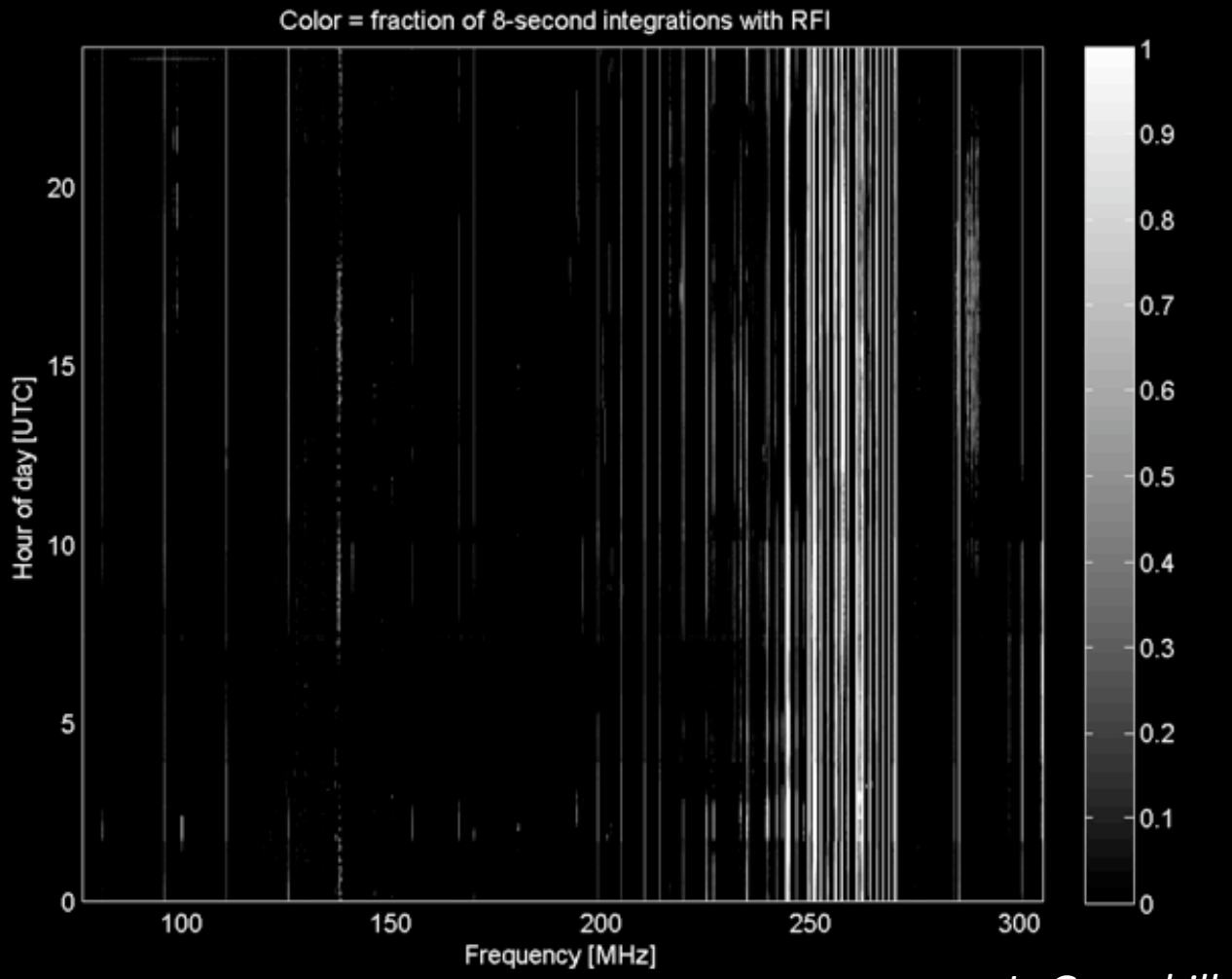
RFI Environment

Timing

- Relatively clean environment for EoR studies
  - time vs ν
  - grays: % > 15σ
  - 11/13–11/16/07
  - Acquiris back-end



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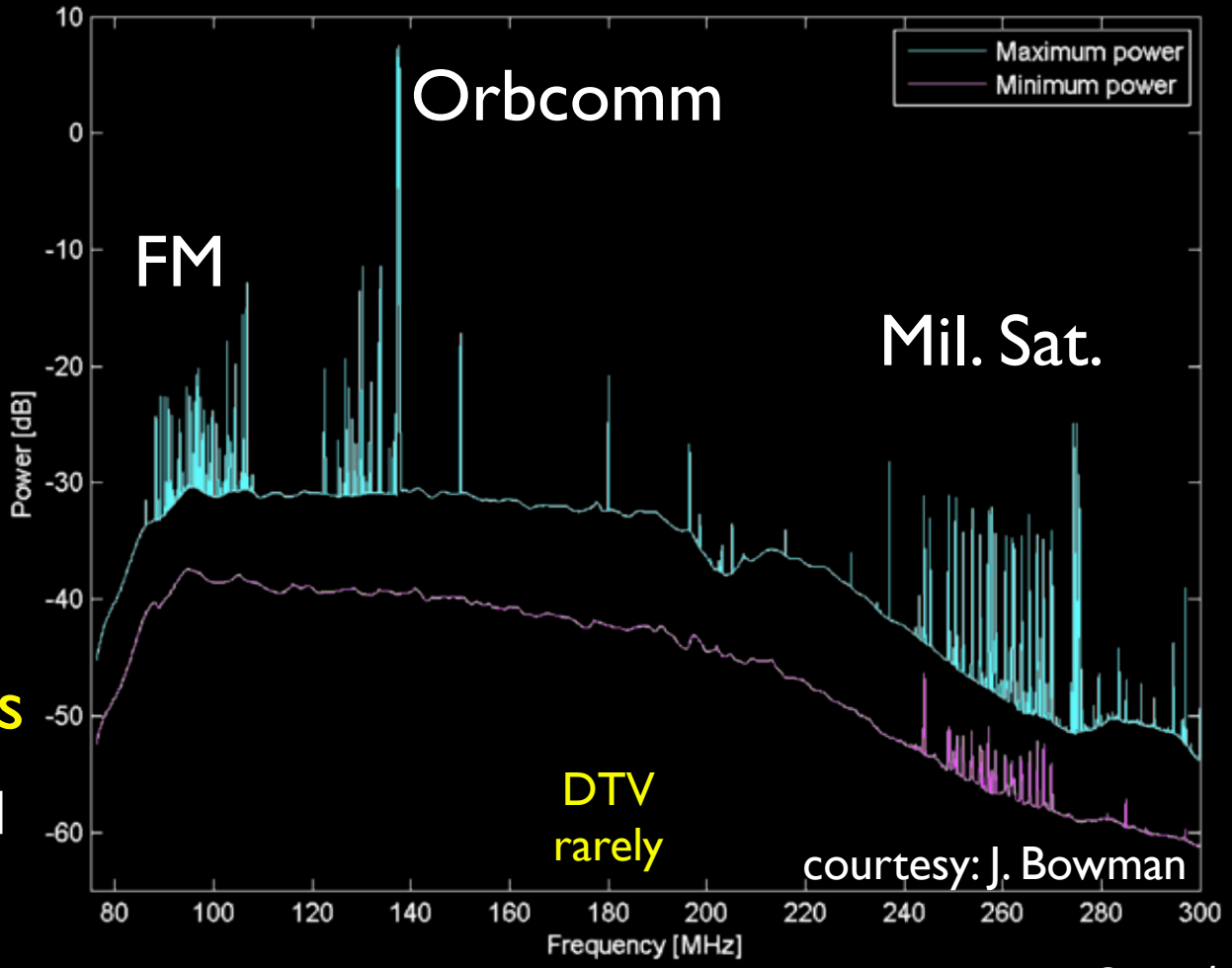
RFI: The Driver

- Relatively clean environment for EoR studies
  - max & min
  - 11/13–11/16/07
  - offset due to GC
- RFI not contemporaneous
  - Acquiris back-end



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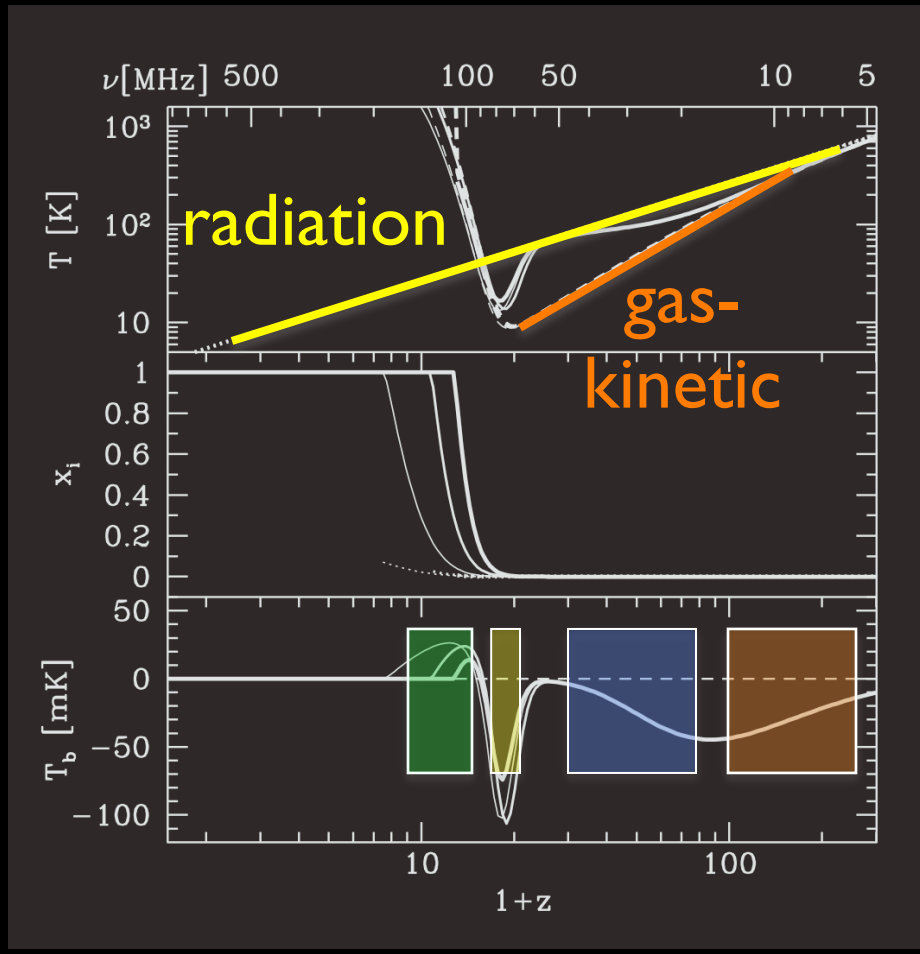
Temperature Evolution

- Radiation T_r cools
- Gas T_{spin} & $T_{kinetic}$ coupled
- T_{spin} decouples
- Lyα couples T_{spin} - $T_{kinetic}$
  - Wouthuysen-Field effect
- IGM heated (Xray, Lyα)
  - start with nearby universe
  - linear regime is ultimate goal



Pritchard & Loeb 2008

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HI λ21cm

- forbidden hyperfine transition: $1^2s_{1/2}$ states
- $n_1/n_o = g_1/g_o \; e^{-0.068K/T_s}$
- $T_S = [T_{CMB} + y_\alpha T_k + y_c T_k] / [1 + y_\alpha + y_c]$
  - Lyα and collisional coupling via y_i
  - Field 58; Madau et al. 98...
- Brightness temp. depends on T_S (not T_k)

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δT_b

- $T_b \sim 28\ \text{mK}\ (1+\delta) h^2\ x_{HI}\ [\ 1 - T_S / T_{CMB}]$

  $* [\Omega_b / 0.02]\ [\Omega_m / 0.24]^{-1/2} [(1+z)/10]^{1/2}$

  - δ: density deviation from mean
  - T: temperatures, Brightness, Spin and CMB
  - x_{HI}: neutral fraction of HI

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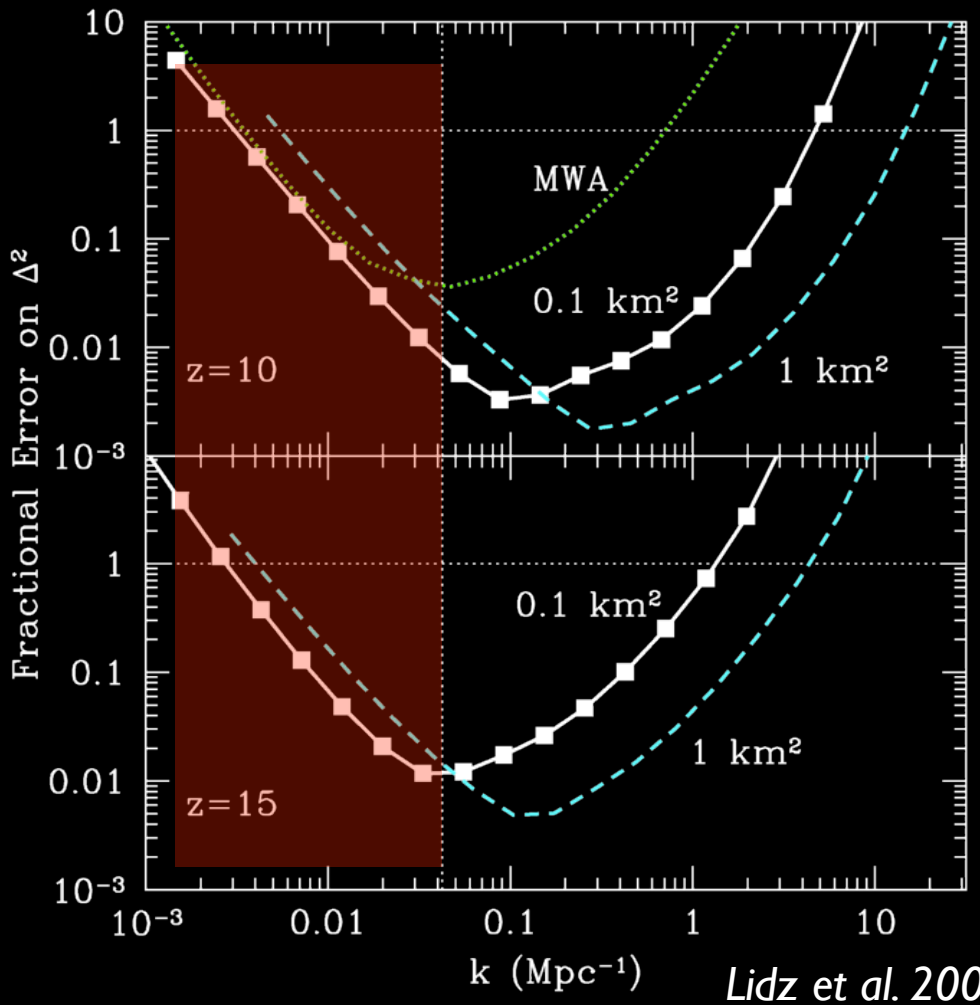
Sensitivity Trends

- Fiducial arrays
- MWA vs 10%SKA
  - Filled SKA core
  - 3 km SKA baselines
    - MWA
    - x10 (0.1 km^2)
    - x100 (1 km^2)
- 1000^h 8 MHz



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Lidz et al. 2008

MWA Calibration & Imaging

- 8^{s} cadence — *O*(50,000) lines
- 48 servers; 96 GPUs
- 40 Gb s^{-1} input; *O*(2) Gb s^{-1} output (minimum)
- O(20) Tflop s^{-1} — > O(100) desired
- 40 kW (*goal*) — ~1 GFlop/W
- 5 racks
- off-the-grid operational capability (*diesel / solar*)
  - max ambient on site — 50°C
  - air cooling — limited water (*except during floods*)
  - university support base — 600 km distant
  - nearest small city — 300 km distant (*220 km unpaved*)

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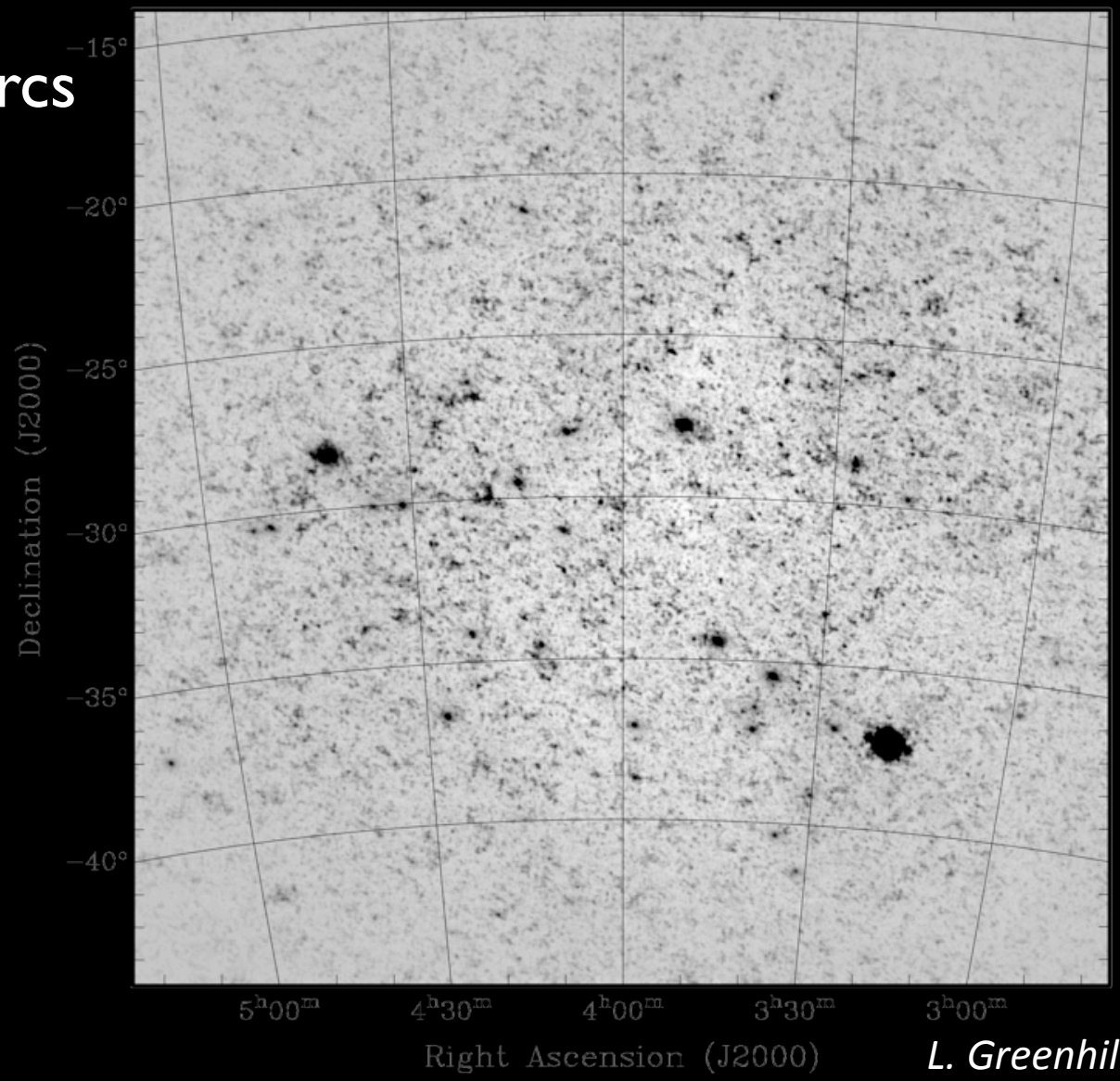
512T MWA-RTS Snapshots

- RTS peels strong srcs
- Stokes I
- Parkes catalog
  extrapolated to 160
- Diffuse emission
  (*Costa et al. 2008*)
- 160 MHz
- 8^{s} (clean image!)



no. peeled = 0
scale 2–5 Jy bm^{-1}
peak 360 Jy bm^{-1}

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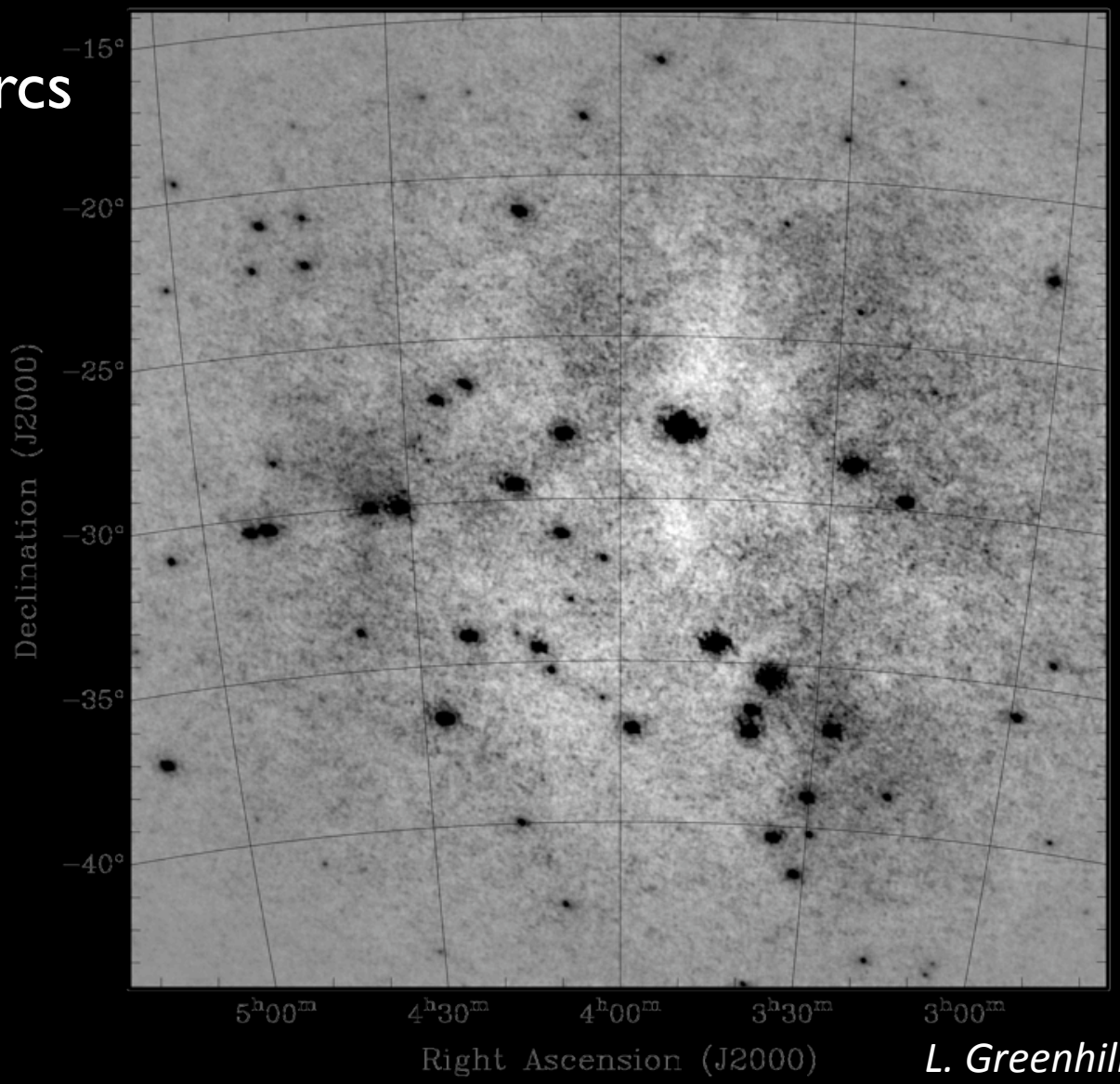
512T MWA-RTS Snapshots

- RTS peels strong srcs
- Stokes I
- Parkes catalog
  extrapolated to 160
- Diffuse emission
  (*Costa et al. 2008*)
- 160 MHz
- 8^s (clean image!)



no. peeled = 2
scale -1–1 Jy bm^{-1}
peak 50 Jy bm^{-1}

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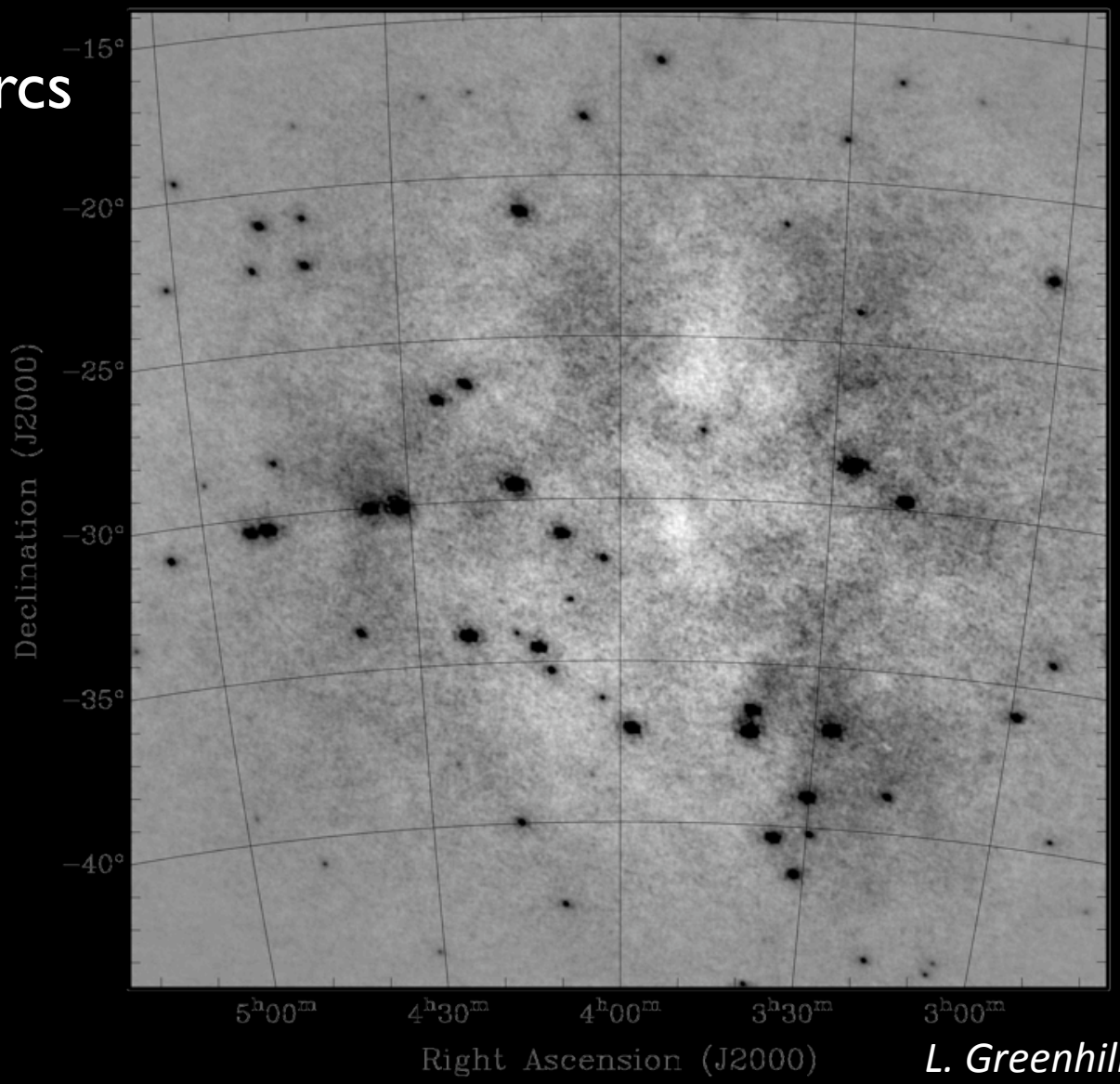
512T MWA-RTS Snapshots

- RTS peels strong srcs
- Stokes I
- Parkes catalog
  extrapolated to 160
- Diffuse emission
  (*Costa et al. 2008*)
- 160 MHz
- 8^s (clean image!)



no. peeled = 10
scale -1–1 Jy bm^{-1}
peak 50 Jy bm^{-1}

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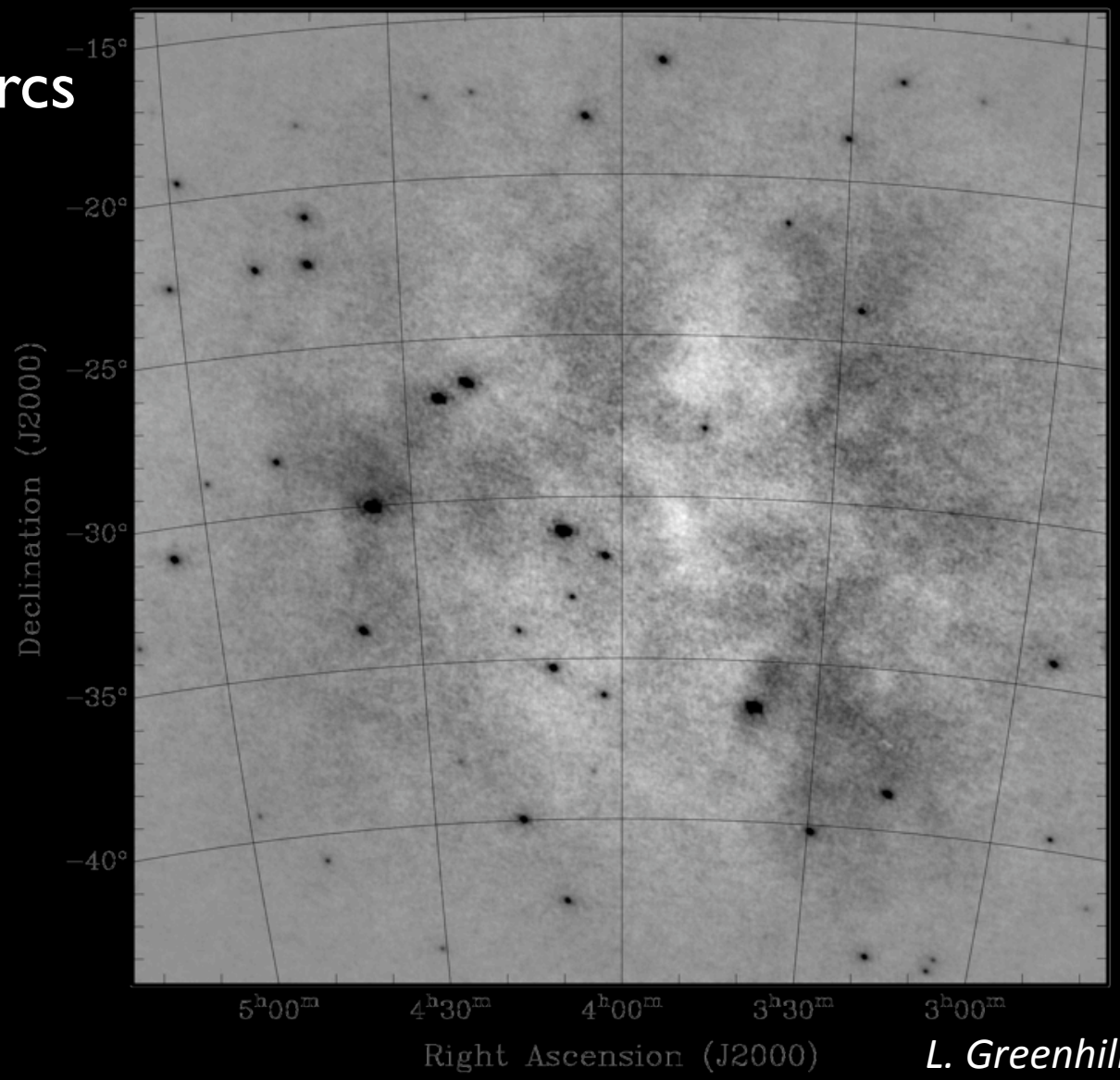
512T MWA-RTS Snapshots

- RTS peels strong srcs
- Stokes I
- Parkes catalog
  extrapolated to 160
- Diffuse emission
  (*Costa et al. 2008*)
- 160 MHz
- 8^s (clean image!)



no. peeled = 30
scale -1–1 Jy bm^{-1}
peak 13 Jy bm^{-1}

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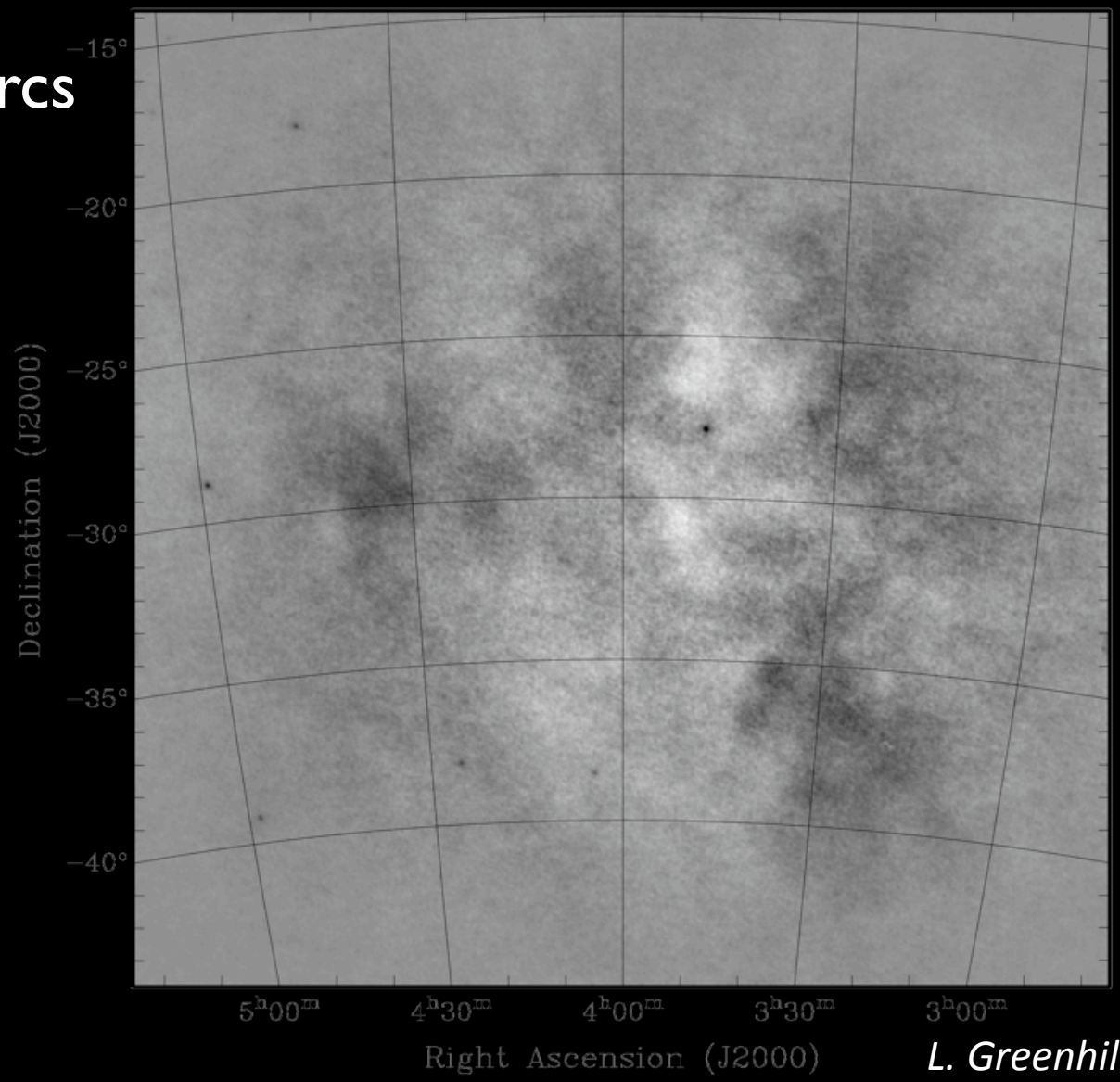
512T MWA-RTS Snapshots

- RTS peels strong srcs
- Stokes I
- Parkes catalog
  extrapolated to 160
- Diffuse emission
  (*Costa et al. 2008*)
- 160 MHz
- 8^{s} (clean image!)



no. peeled = 100
scale -1–1 Jy bm^{-1}
peak 1.5 Jy bm^{-1}

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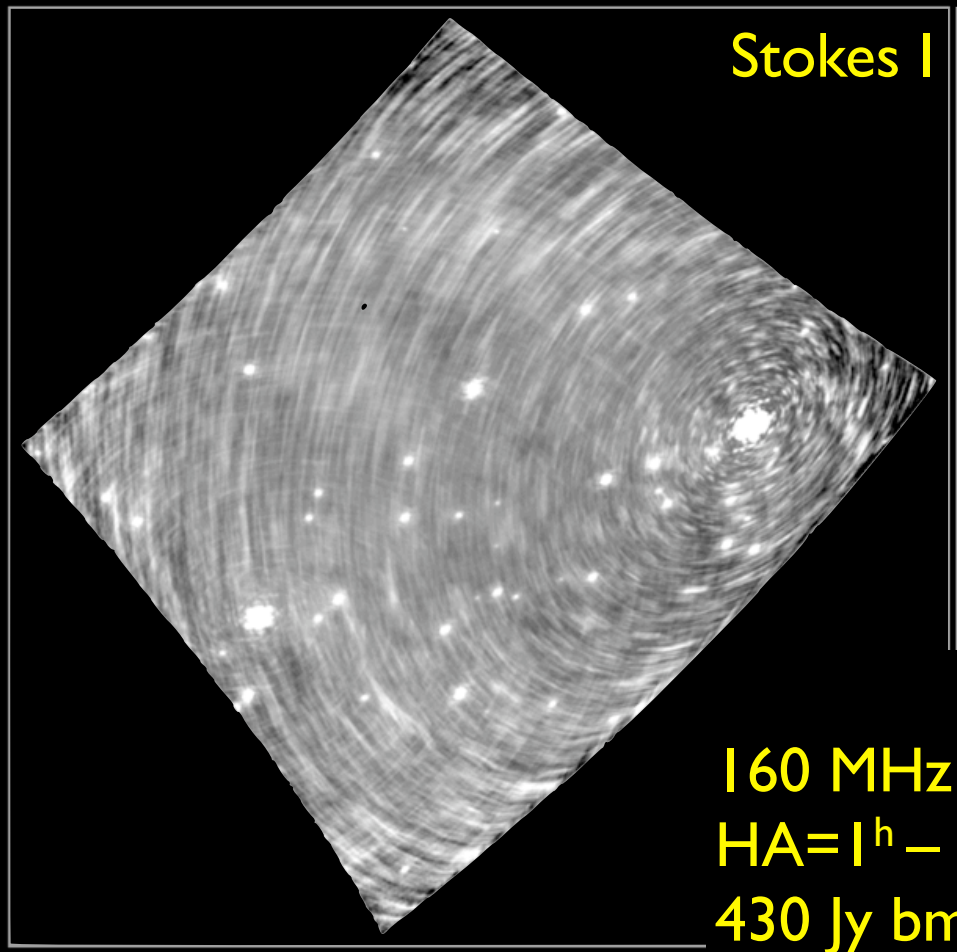
512T MWA-RTS Integration



160 MHz
HA=1^h – 0^h
430 Jy bm^{-1} pk
-2–2 Jy bm^{-1}

courtesy: S. Ord, D. Mitchell, G. Bernardi

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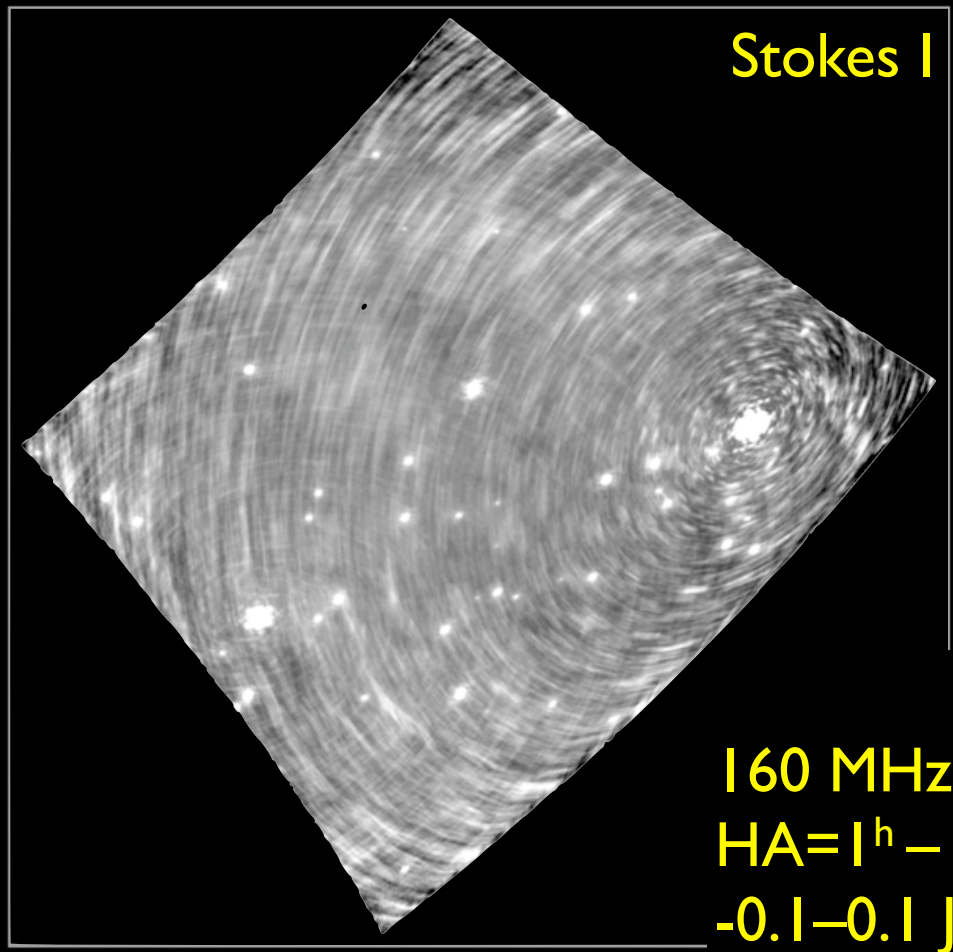
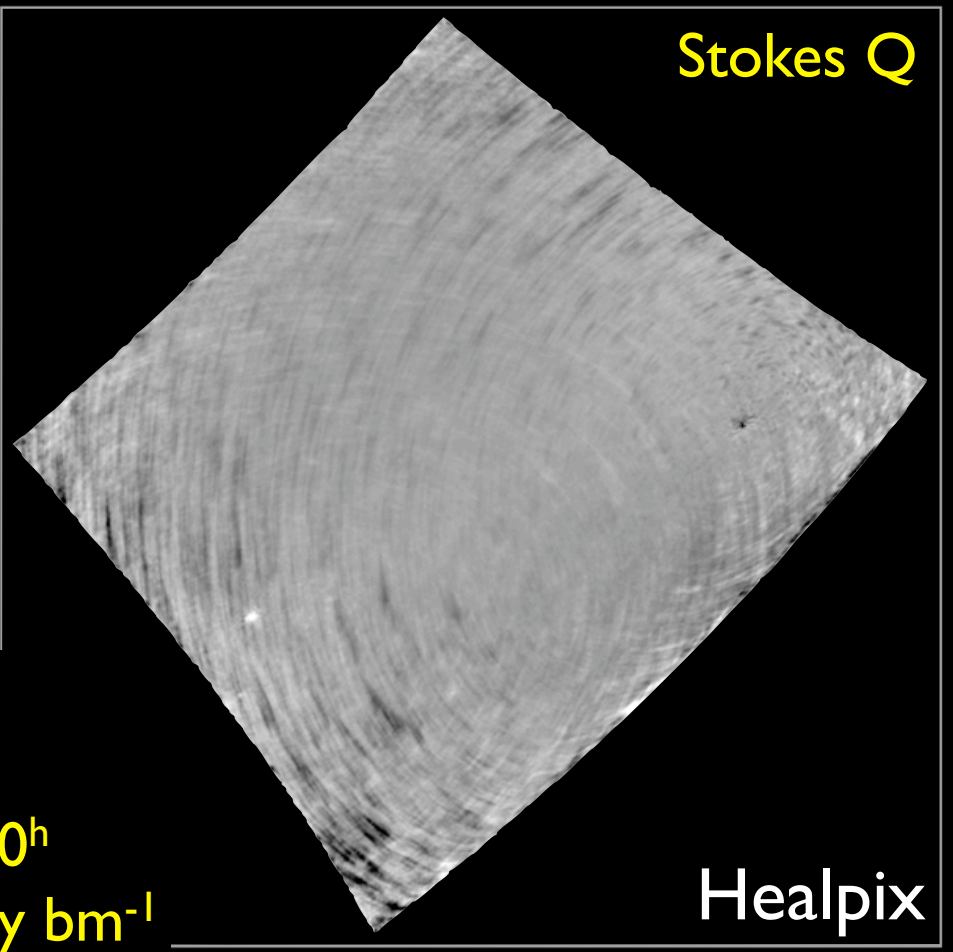
512T MWA-RTS Integration





160 MHz
HA=1^h – 0^h
-0.1–0.1 Jy bm^{-1}

instr. pol. @ edge < 0.1%

Healpix

courtesy: S. Ord, D. Mitchell, G. Bernardi

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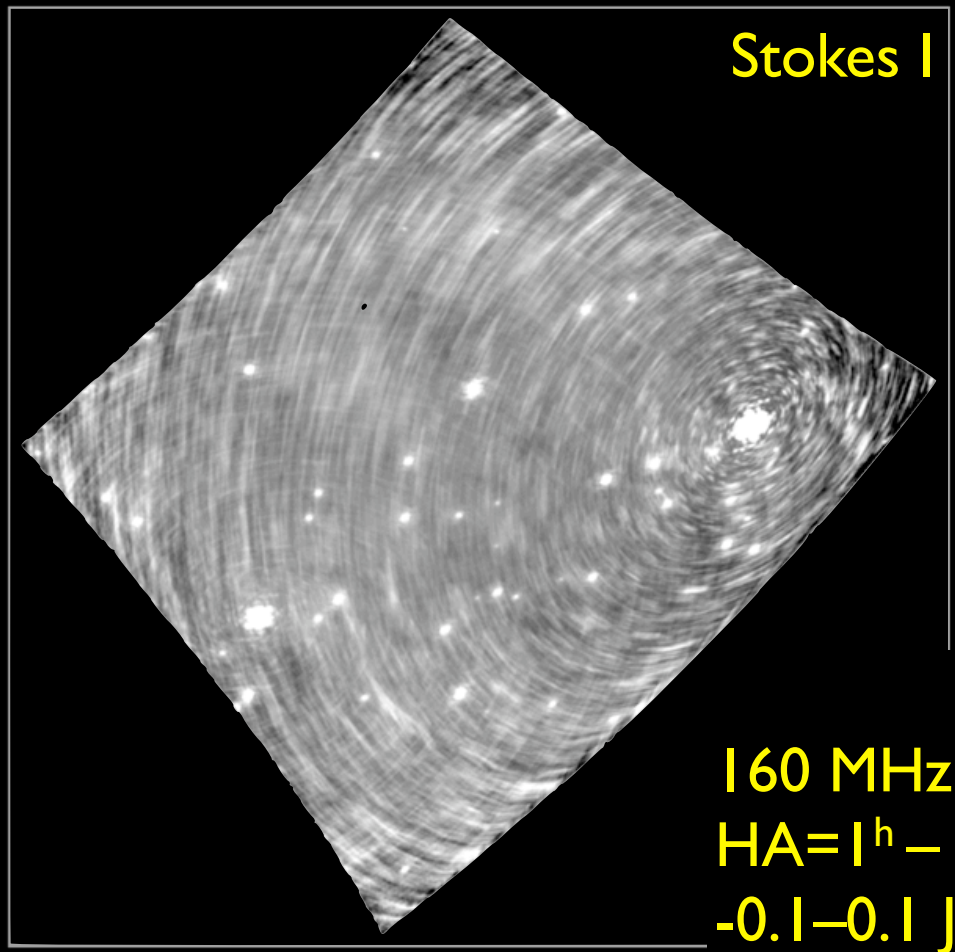
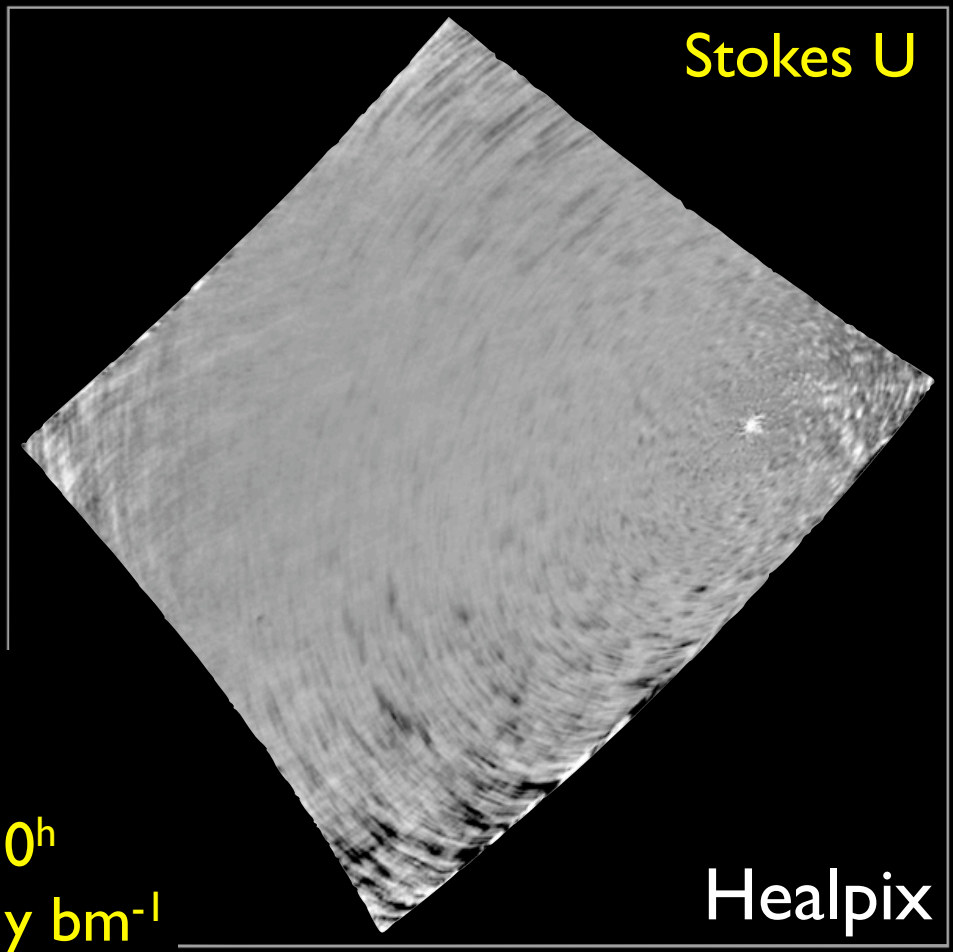
512T MWA-RTS Integration





160 MHz
HA=1^h – 0^h
-0.1–0.1 Jy bm^{-1}

instr. pol. @ edge < 0.1%

Healpix

courtesy: S. Ord, D. Mitchell, G. Bernardi

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512T RTS Processing

- this alone requires *O*(20) TFlop s^{-1} (continuous)
- maxtrix-heavy calibration
- gridding data prior to FFT
  - large N
- conversion of polarization coordinates
  - time-varying projection calculation; large
- rubber-sheet distortion
  - ionosphere $\propto \nu^2$
- pixel re-sampling
  - curved boundaries

All GPU friendly
first e2e GPU real-time pipeline

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Broome
NORTHERN
TERRITORY
Tennant Creek
Port Hedland
Dampier
Yarrie
Karratha
WESTERN
AUSTRALIA
Newman
Alice Springs
Paraburdoo
Yulara
Carnarvon
Meekatharra
planned fiber link
Boolardy Station
Shire of Murchison
Pop: O(100)
Area: 41,173 km²
Leonora
Geraldton
Coober Pedy
SOUTH AUSTRALIA
Kalgoorlie
Ceduna
Port Augusta
Perth
Fremantle
Whyalla
Bunbury
Esperance
Port Lincoln
Adelaide
Albany

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You go where the population is low .....
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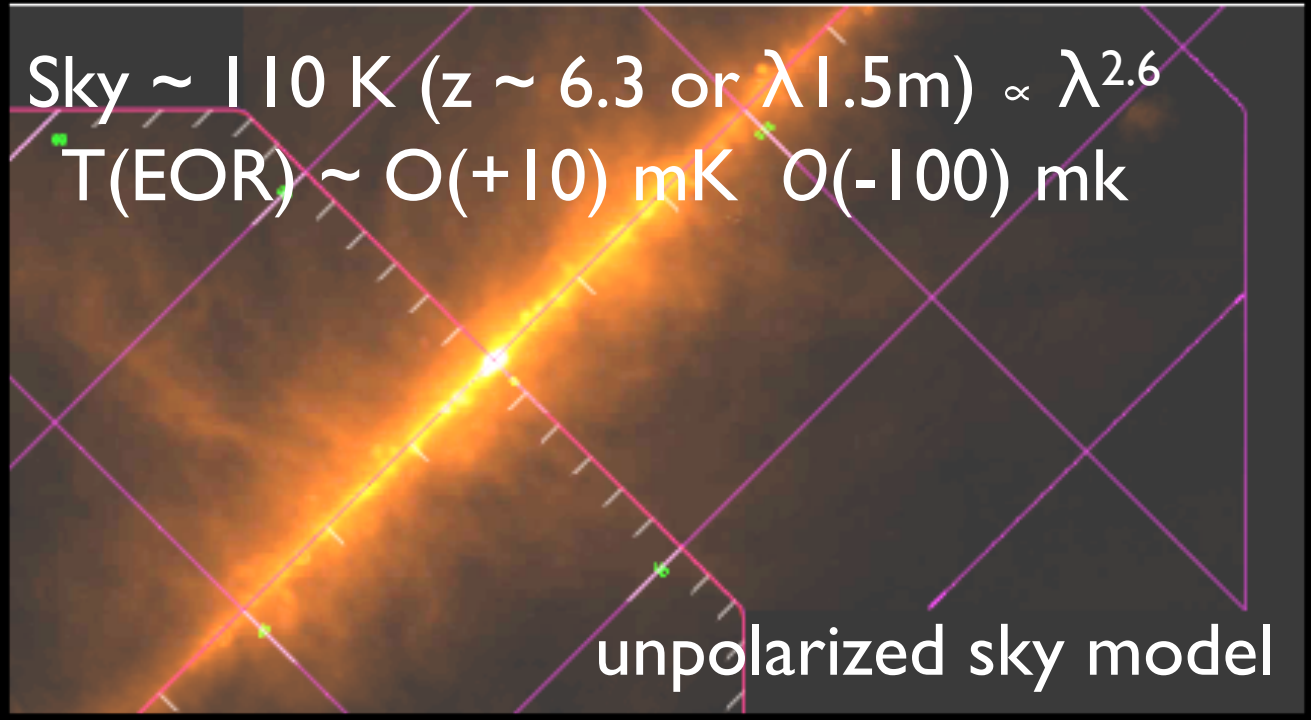
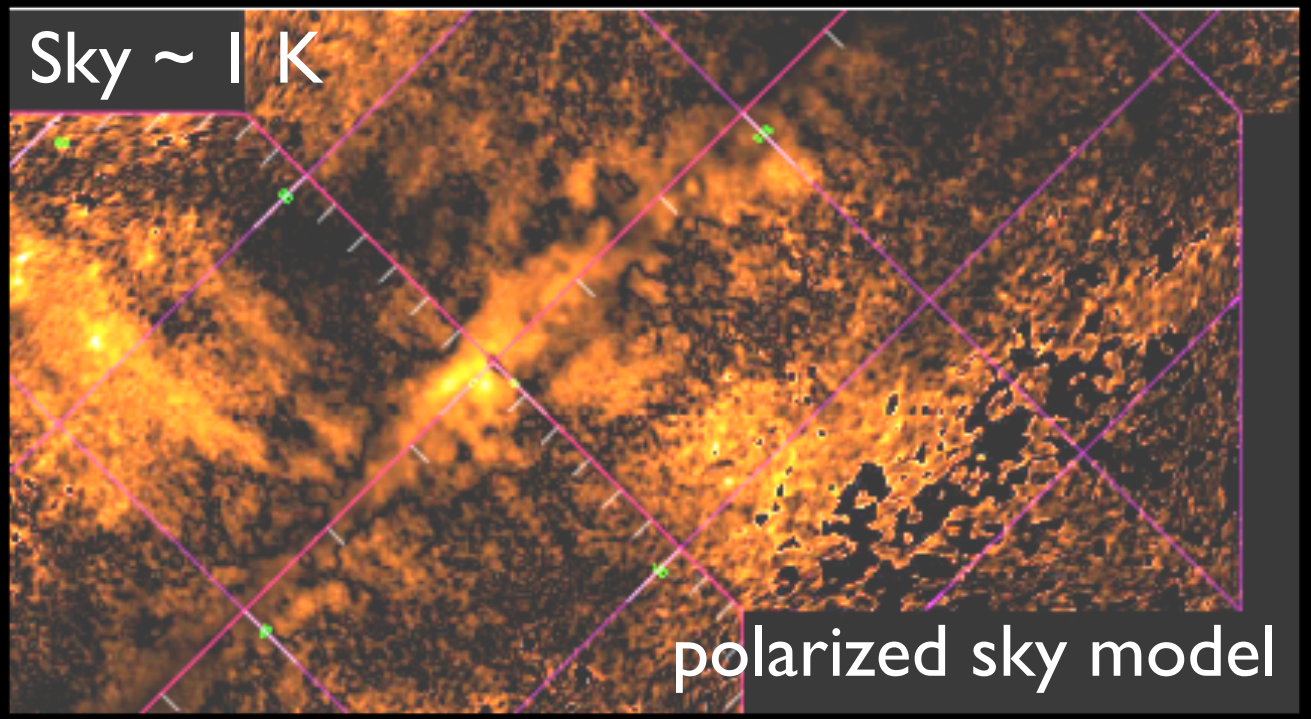
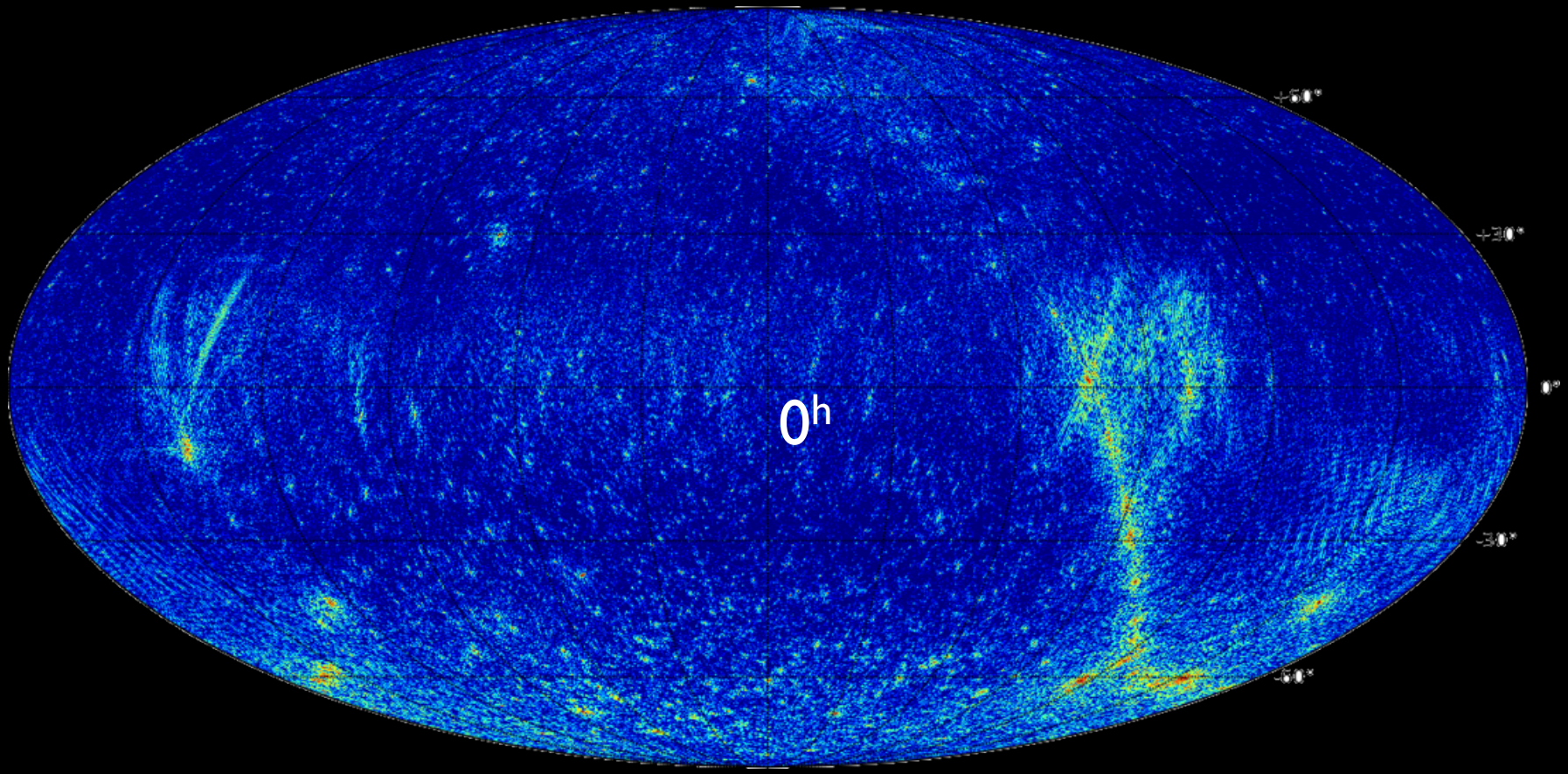
FOREGROUNDS CHALLENGE





Steve Ord (CfA)

PAPER 2010



32 dipoles (S) 16 dipoles (N)

$\log_{10}$ 0.1-100 Jy

MWA Specifications

- Science: EOR, Helio/Space Physics, Transients
- Tuning = 80-300 MHz
- $BW_{inst.}$ = 30.72 MHz.....$\Delta\nu$ = 40 kHz
- $BsIn_{max}$ = 1.5 km..... some 3 km stat'ns
- FOV = 10 – 40° (x 1).....$\Delta\theta$ = 3–10′
- Apertures = 512 tiles..... 5x5m, 4x4 dipoles
  - N_{tot} = 8000 crossed dipoles.....10,800 m^2 / 240K (z~8)
  - Beamforming: analog @ tiles.....also voltage beams
- $\Delta t = 8^s$
- Stokes = I,Q,U
- "fix it in software" *HPC is integral !*

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Next Stop...512T

	32T	512T
cadence	8^s (0.05^s)	8^s (0.5^s)
ops	co-add snaps	fwd model 10^m avgs
size	0.3 km	1.5 km (3 km)
FOV	10-40°	10-40°
cal src / FOV	*O*(1)	*O*(50)
iono. corr.	none	MLS ($\tau \geq 8^s$)
dipole / tile	static / 2 parm	dynamic / 32^+ parm
beam corr.	image	uv plane
ch / RTC	192	10
data rate	1.5 gb s^{-1}	40 gb s^{-1}
computing	*O*(2) TFlop s^{-1}	*O*(150) TFlop s^{-1}

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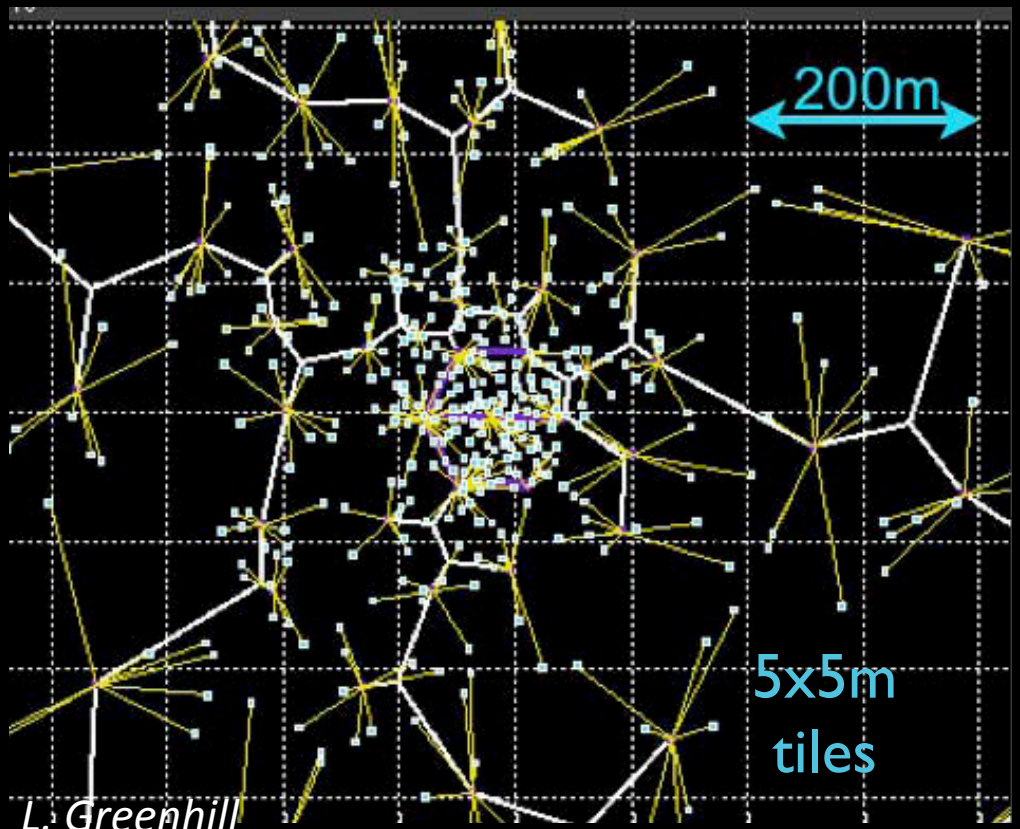
HI Array Drivers-Challenges

Drivers	MWA	LOFAR
sensitivity	$O(10^4)$ dipoles < 1.5 km	$O(10^5)$ dipoles < 2± km
dynamic range	full-correlation dispersed dipoles snapshot processing data rates snapshots FPGA/GPUs massive fwd modeling	clustering of dipoles station phasing limited-correlation synthesis multiple beams needed DNR/cal. trade off extensibility?
FOV		

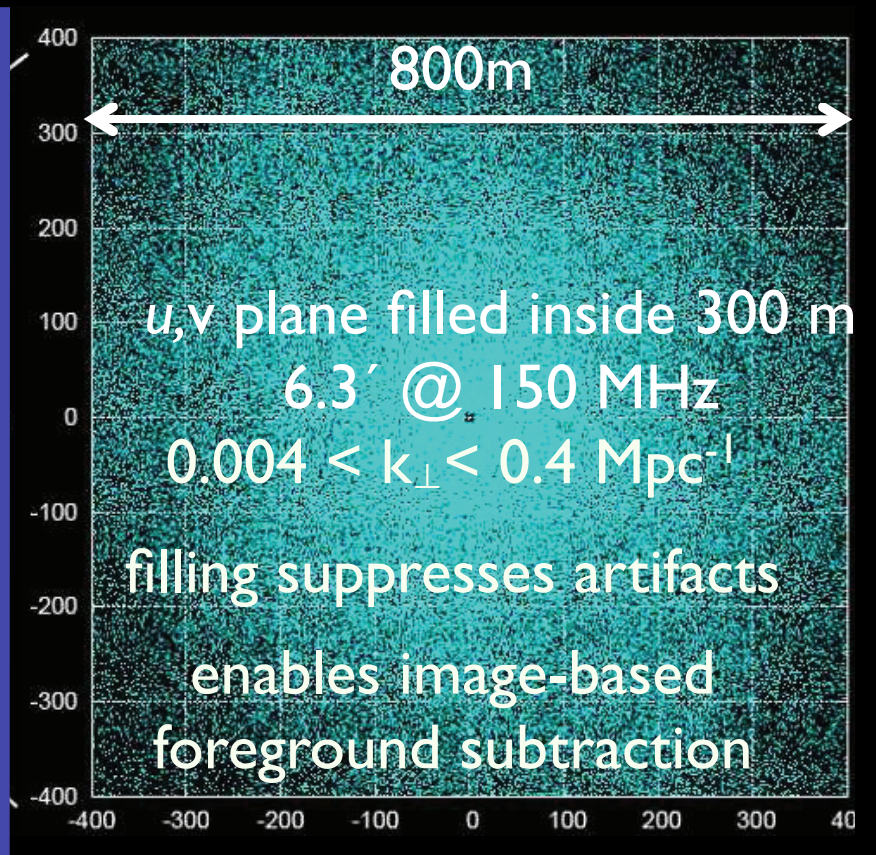
MWA – Large-N array

snap shot instrument - SKA model?

dipole layout areal filling



antenna spacings



HPC as Linchpin

	LOFAR (c)	MWA 512T	HERA-II
Correlation	44 TFlop s^{-1} (BlueGene/P)	160 TFlop s^{-1}	16 - 120 PFlop s^{-1}
Calibration/ imaging		150 TFlop s^{-1}	5 - 70 PFlop s^{-1}

- array characteristics
  - N: antennas or tiles – B: bandwidth (# of ch.)
  - F: field of view – S: array geographic size
- correlation
  - $\propto k_0 N^2 F B + k_1 N B$
- calibration & imaging
  - $\propto k_3 N^2 B + k_4 B (F S)^{1-2}$
- MWA-style EOR processing: reqs. not firmly in hand

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