A “Mark 6” Recording System for the VLBA Upgrade

Jon Romney

NRAO, Socorro

New Initiatives Workshop

2004 December 13

Original Concept

Implement Mark 5B Initially

- Required to operate at 1 Gbps.

Develop Own Upgrade, “Mark 6”

- Goals: 4 Gbps by 2009. Rate a subset of EVLA capacity.
- Other development efforts not known, had to plan for own development in 2007-08.
- Cost estimates.
  - M&S: $2.6M [primarily disk drives]
  - Labor: 10+4 work-months

New Concept

Implement Mark 5A Initially

- Mark 5B still not yet available.

Exploit Developments Elsewhere

- Conduant Corporation (developer / vendor for Mark 5) expecting to announce new "Amazon" unit next quarter.
  - Enhanced version of current "Big River" unit.
  - Based on significantly upgraded "Streamstore" board.
  - Record rate capacity ≥ 3.2 Gbps; already 80% of goal for 2009.
  - Cost predicted to be "similar to" Mark 5.
- Haystack Observatory Mark 5B I/O board.
  - Will limit throughput at 2 Gbps (onto 16 disk drives).

NRAO Options for 4 Gbps

- Successor to Conduant Amazon Unit
  - Will very likely be available by 2009, with capacity » 4 Gbps.
- Mark 5B I/O Board Possible Bottleneck
  - Possible that Haystack will develop own "Mark 6", ≥ 4 Gbps.
    - But Mark 4 correlator design limits throughput to 2 Gbps.
    - Quite possible that EVLA correlator will be only system requiring VLBI data at 4 Gbps.
- NRAO could …
  - Develop own "Mark 6" I/O board.
  - Collaborate with or contract with Haystack to develop it.

End

The VLBA Spacecraft Navigation Pilot Project

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Introduction

- NRAO Just Completed ~Year-Long Project
- Funded by NASA
- Major Components
  - Feasibility study.
    - Viability of VLBA spacecraft navigation measurements demonstrated.
    - Operational reliability yet to be demonstrated.
    - Variety of details still to be studied.
  - Implementation studies.
    - Almost all planned studies completed, with a few exceptions.
    - Additional work, beyond project goals, completed in many cases.

Motivation:
Opportunity to Augment VLBA

New Instrumentation

- Required to support spacecraft navigation functions.
- Ka-band receivers.
- Mark 5 recording system, up to 1 Gbps sustained capacity.
- E-VLBI capability.

Upgraded Operational Infrastructure

- Allowing brief spacecraft navigation observations with minimal impact on astronomy program.

Broader User Base

Navigation Feasibility Study

Collaborative Effort …

with various groups at JPL:

Navigation / Delta-DOR / Missions.

Test Observations

Standard VLBA phase-referencing technique.

Imaged by NRAO personnel.

Total delays delivered to JPL for further analysis.

13 VLBA observations, including both Mars Exploration Rovers, in final week before each landed on Mars.

Navigation Feasibility Study

	VLBA Spacecraft Navigation Pilot Project								
				Test Observations					
				Target		Reference	---- Primary	Reference ----	
ObsCode	Start Date & Time	Duration	Stations	Spacecraft	Declination	Calibrators	Flux	Distance	Precision
TS020	[UT]	[h:m]			[deg]		[mJy]	[deg]	[nrad]
A	2003/12/19 22:30	3:00	9.5	MER-A	2	1	250	2.2	2
				MER-B	2	1	250	2.8	2
B	2004/1/3 22:30	3:00	10	MER-B	5	1	381	3.6	4
C	2004/1/8 15:09	3:10	10	Stardust	-20	3	200	7.2	4
D	2004/1/19 22:12	3:15	9.5	MER-B	9	3	700	3.2	2
E	2004/1/21 22:12	3:15	10	MER-B	9	3	700	2.6	2
F	2004/1/23 22:12	3:15	9	MER-B	10	3	700	2.5	2
G	2004/3/24 10:30	6:24	6.5	Stardust	-21	3	200	7.4	7
H	2004/4/9 19:14	6:43	10	MGS	23	3	266	3.7	4
				Odyssey	23	3	266	3.7	4
I	2004/4/25 19:15	6:44	9	MGS/Ody	24	3	---	---	---
J	2004/5/20 18:00	8:08	9	MGS	24	3	200	3.6	2
				Odyssey	24	3	200	3.6	2
K	2004/6/30 15:00	5:38	10	Cassini	22	4	750	5.4	9
L	2004/8/23 16:30	4:28	10	Odyssey	9	3	180	2.6	2
M	2004/9/8 13:00	5:38	9	Cassini	21	4	350	3.1	2

Navigation Feasibility Study

Essential Conclusions

- Pilot Project achieved a priori goal, 1 nrad positional accuracy (200 μas).
- NRAO spacecraft images within 1-4 nrad of well-determined orbits.
- JPL analysis found inclusion of VLBA total delays halved formal error of overall orbit fit.
- Accuracy limited primarily by catalog precision and atmosphere.
- JPL acknowledged VLBA observations can provide valuable complement to DSN in-house VLBI technique.

Navigation Feasibility Study

“Quasi-Operational” Spacecraft Navigation

- One day after formal end of Pilot Project, NRAO received request from Cassini mission for VLBA spacecraft navigation measurements.
- Goal: help measure mass of Saturnian satellite Iapetus. Huygens probe will pass close to Iapetus en route to Titan.
- Target of Opportunity observation organized; 5 runs of 1 or 3 hours over 7 days; same reference calibrators used.
- Analysis in process at JPL.

Implementation Studies

Navigation Implementation Study

- Scheduling/correlator software upgrades.
- New AIPS tasks.

Mark 5 Implementation Study

- Station/correlator control software upgrades to support Mark 5A.
- Partial design of Playback Interface hardware replacement, for eventual upgrade to Mark 5B.

VLBA Ka-Band System Design Study

- Receiver similar to EVLA design; feed similar to GBT.
- X/Ka-band dual-frequency dichroic system option.

Current Project Status

Pilot Project Completed

Final report submitted	2004/12/1
Wrap-up meeting held at JPL	2004/12/10

Follow-on Project(s) Under Discussion

- Continued technical studies.
  - Establish reliability of VLBA spacecraft navigation observations.
  - Develop approach to integration into VLBA and JPL operations.
- Implementation of new equipment and catalog.
  - Mark 5 recording system.
  - Ka-band receivers.
  - Ka-band calibrator catalog.

Thanks to these NRAO Personnel

Project Manager

Jon Romney

Navigation Feasibility & Implementation Studies

John Benson
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Craig Walker
Bob Zavala

Mark 5 Implementation Study

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Barry Clark
Juan Cordova
Mike Revnell
Bruce Rowen

Ka-Band Implementation Study

Bob Hayward
Ylva Pihlstroem
Marian Pospieszalski
Sivasankaran Srikanth
Jon Thunborg
John Webber

End

New Initiatives in Cosmic Microwave Background Studies

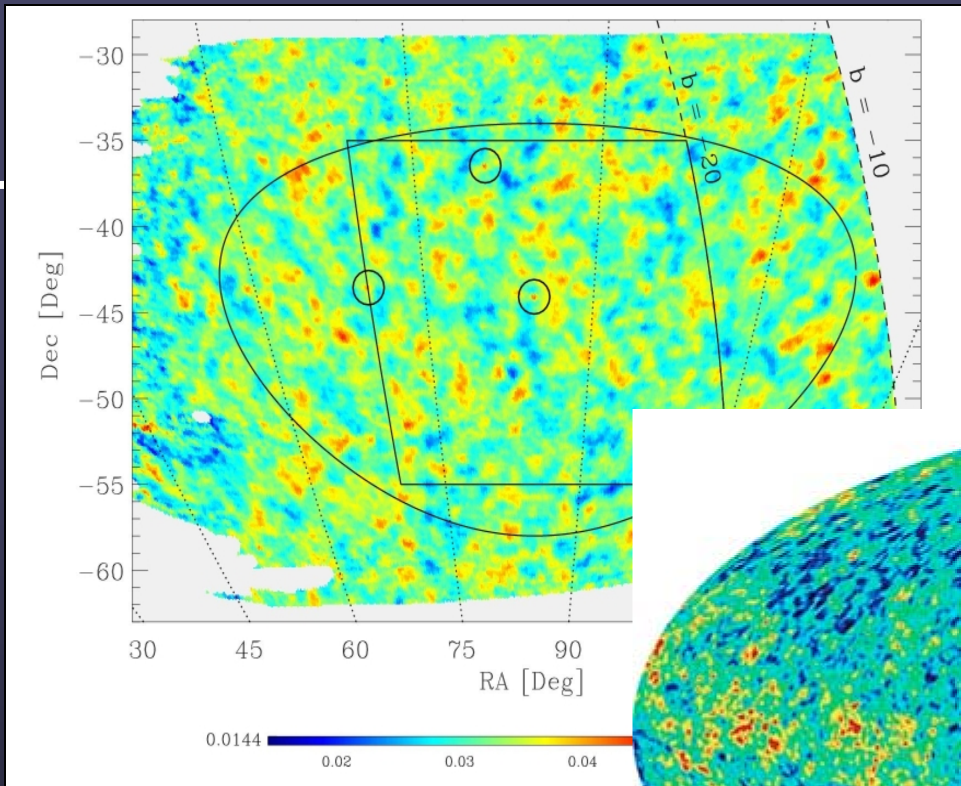
Steven T. Myers

National Radio Astronomy Observatory

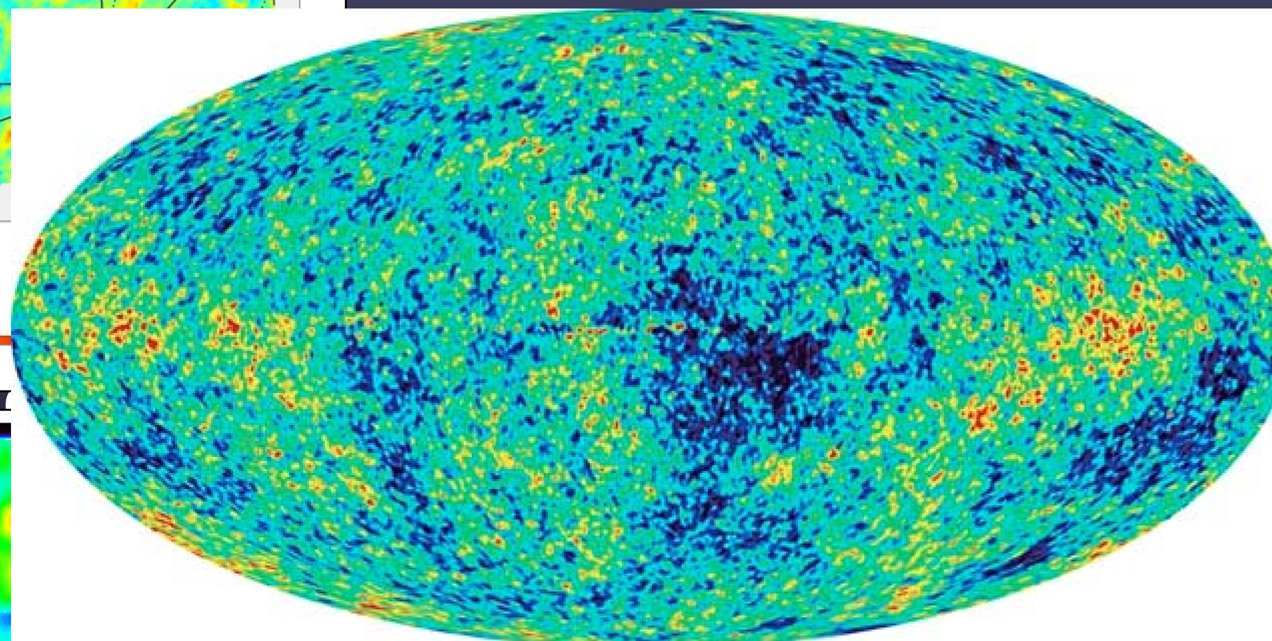
Socorro, NM

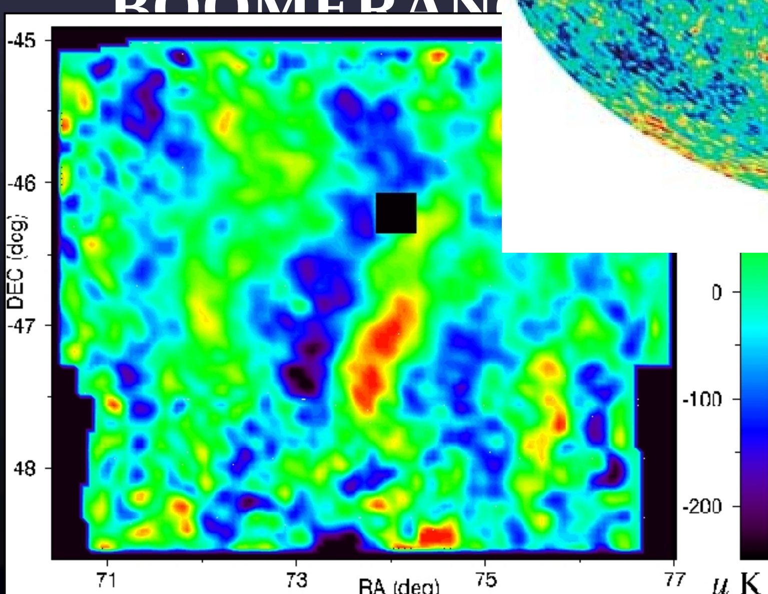
Where we are

WMAP Satellite



BOOMERANG

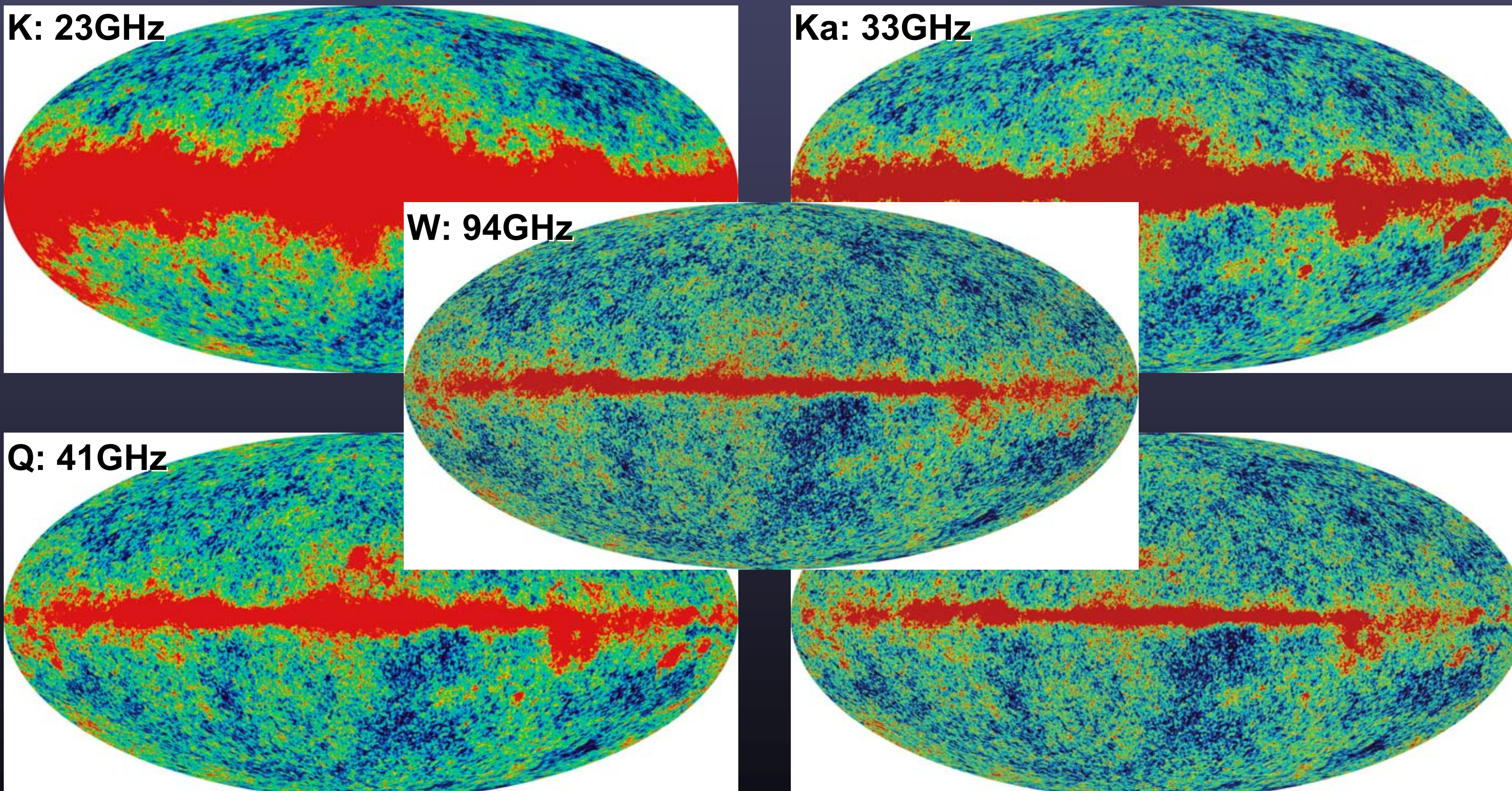




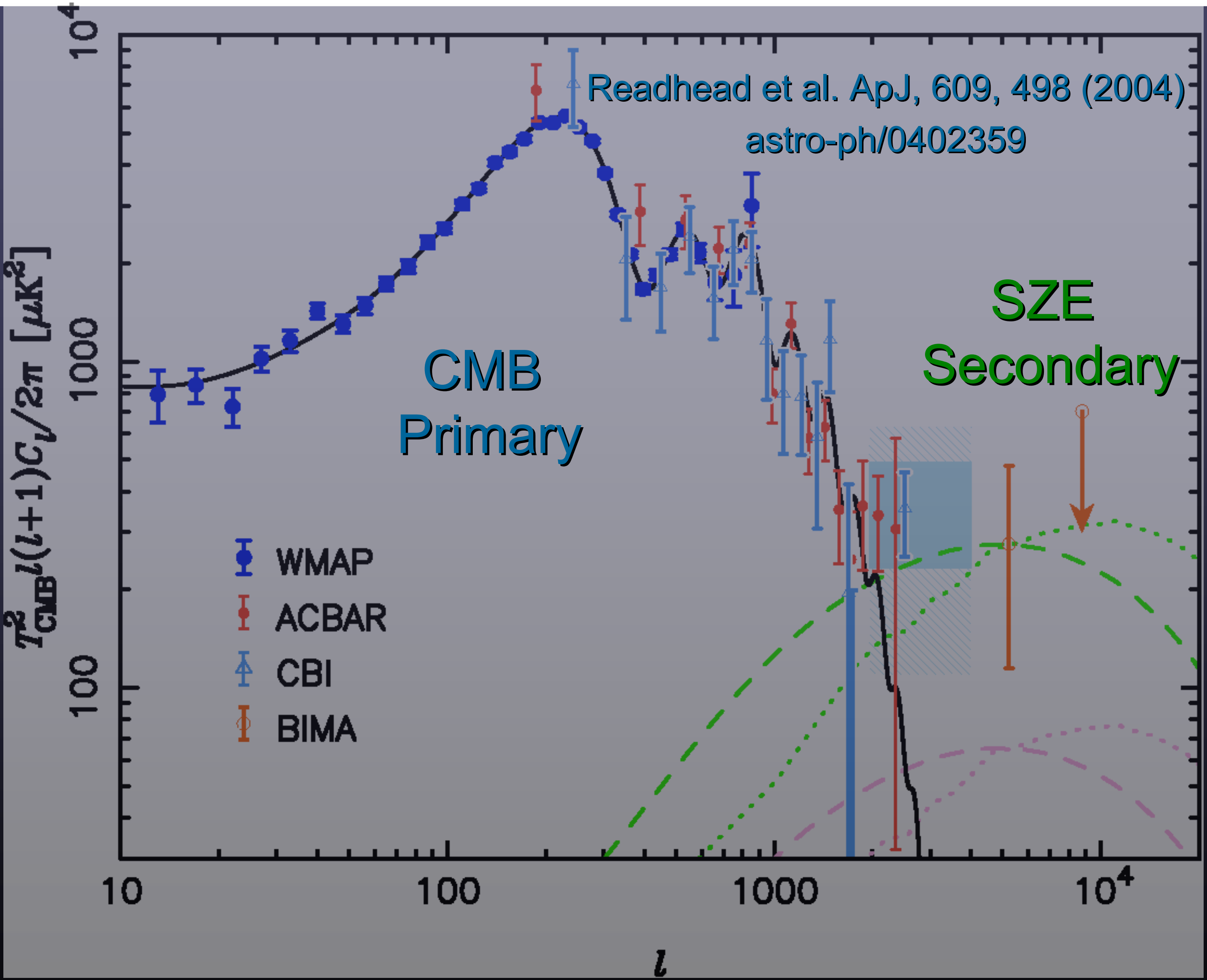
ACBAR

WMAP: 5-band images of the sky

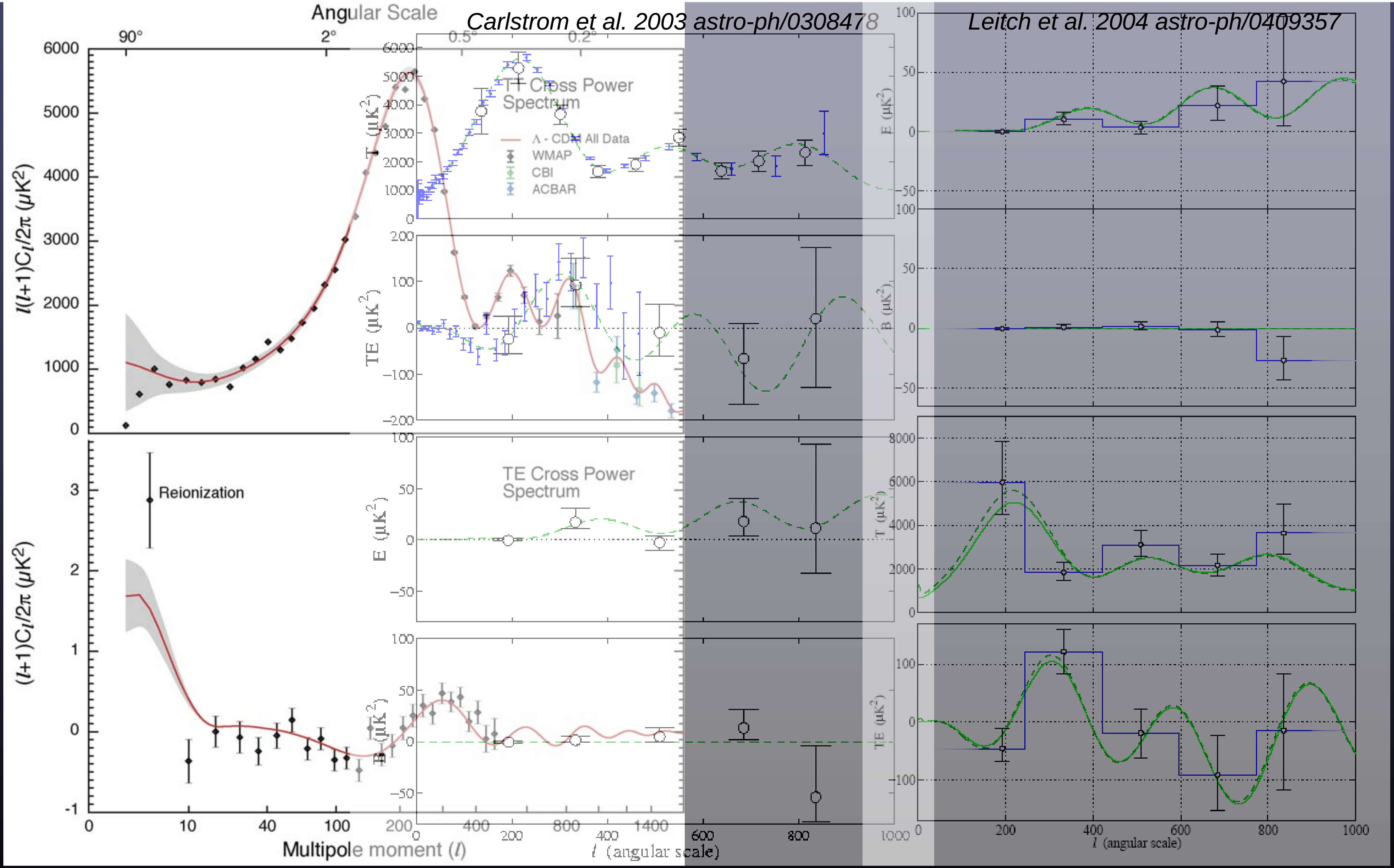
- HEALpix maps:



CBI 2000+2001, WMAP, ACBAR, BIMA

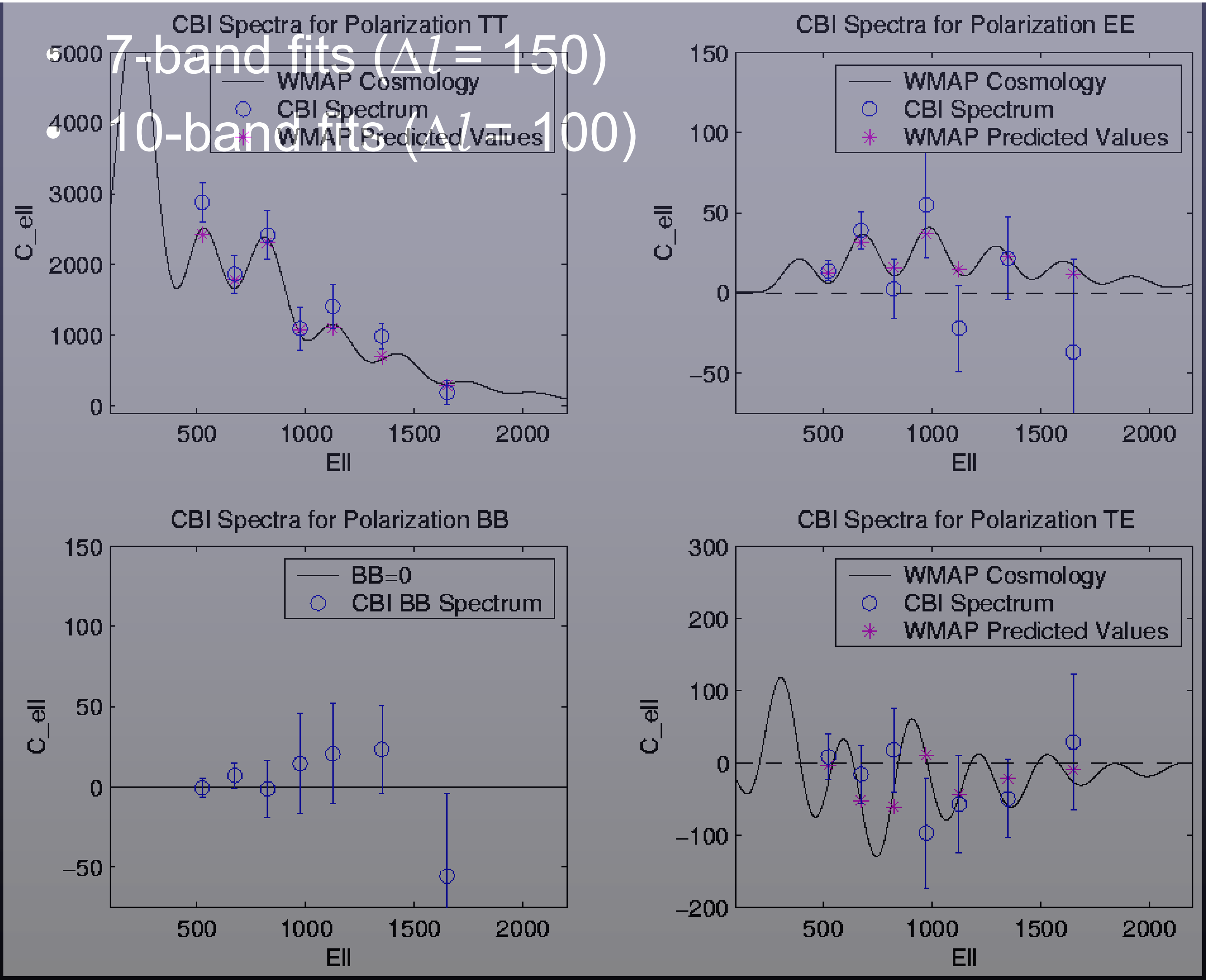


Polarization: WMAP & DASI

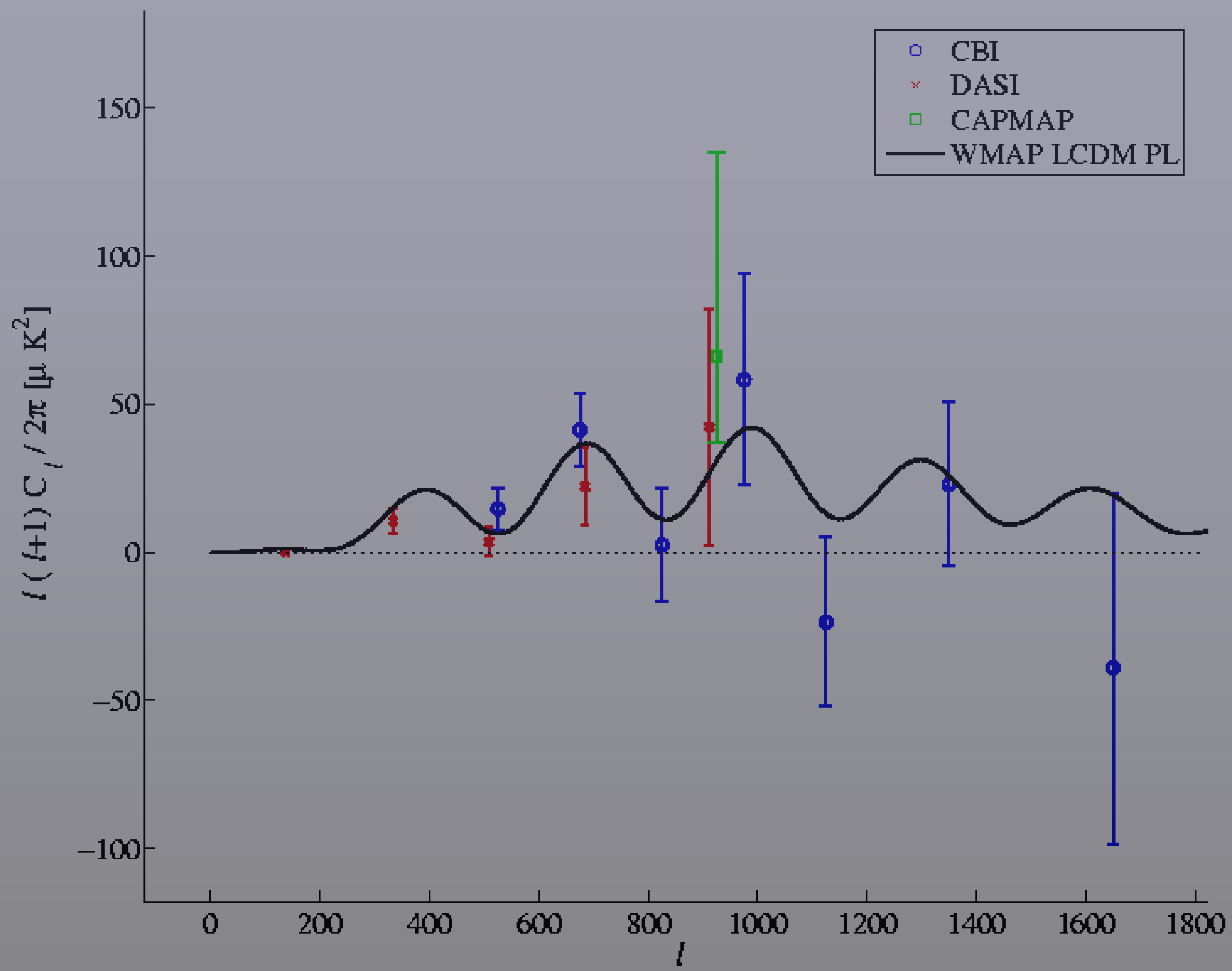


New: CBI Polarization Power Spectra

- 7-band fits ($\Delta l = 150$)
- 10-band fits ($\Delta l = 100$)

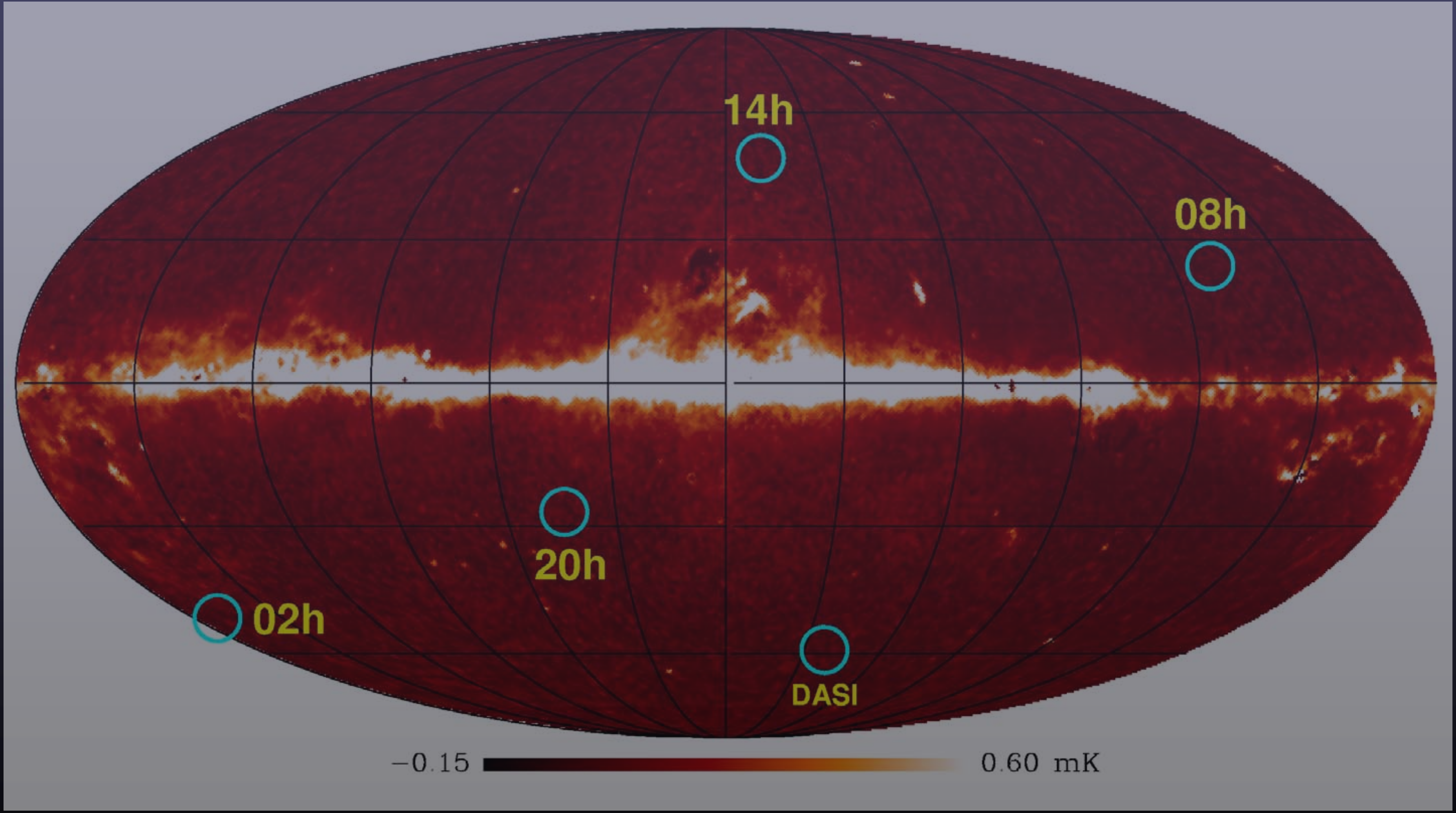


New: CBI, DASI, Capmap EE



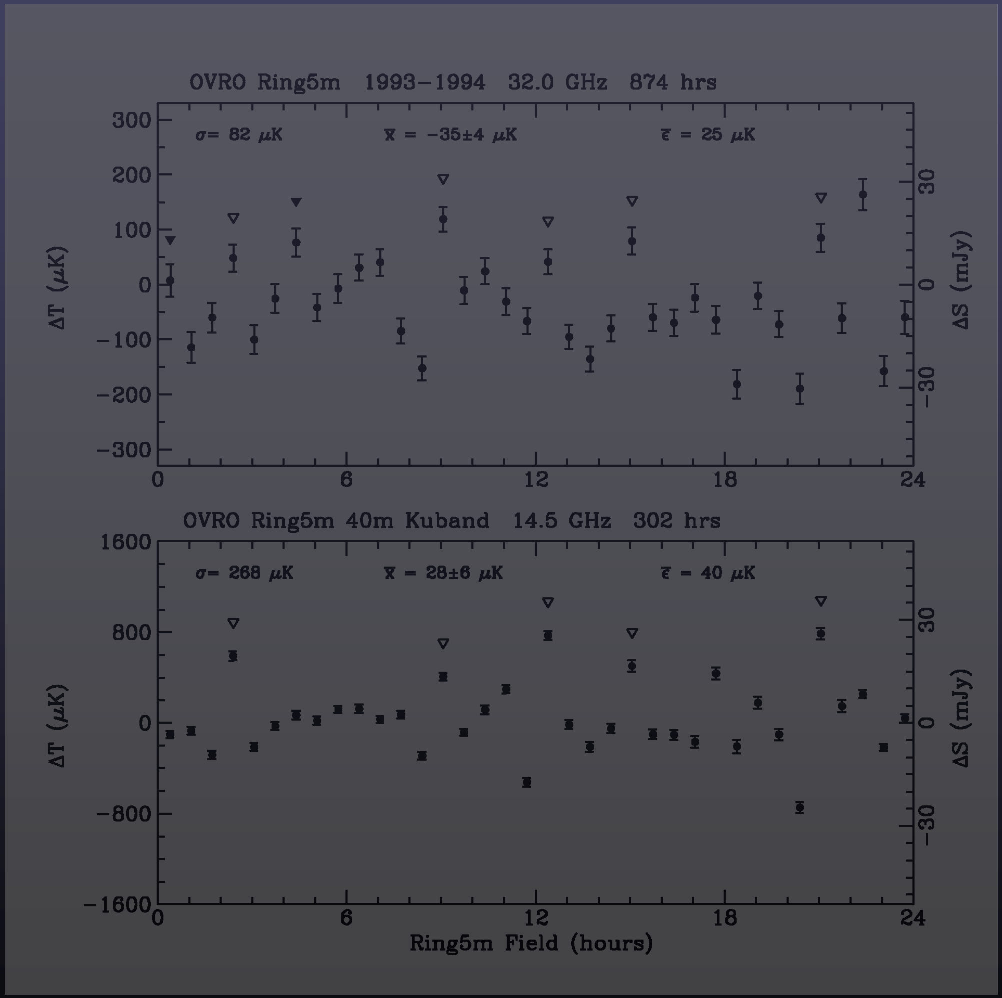
Foregrounds - CBI & DASI Fields

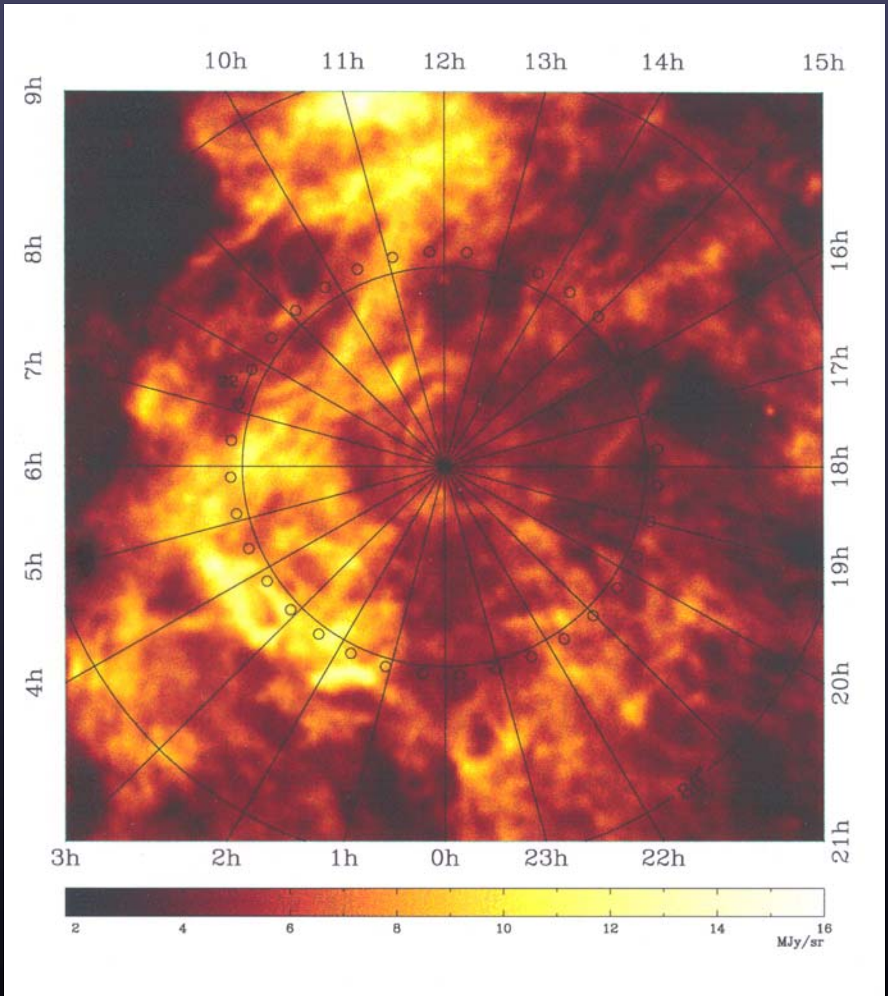
galactic projection – image WMAP “synchrotron” (Bennett et al. 2003)



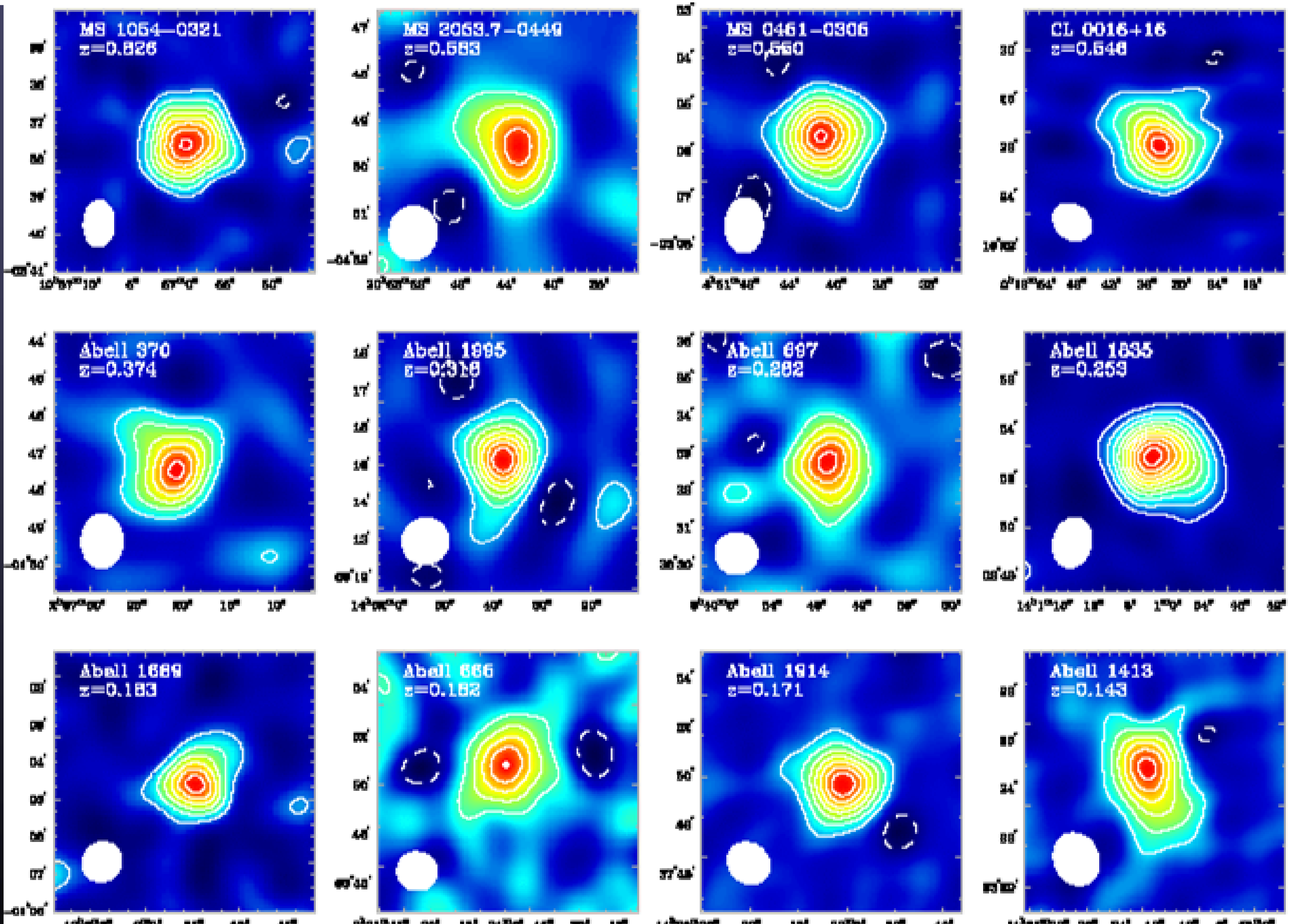
Anomalous Microwave Emission

- Spinning dust or very hot HII? seen in NCP region





SZE Sample from 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03

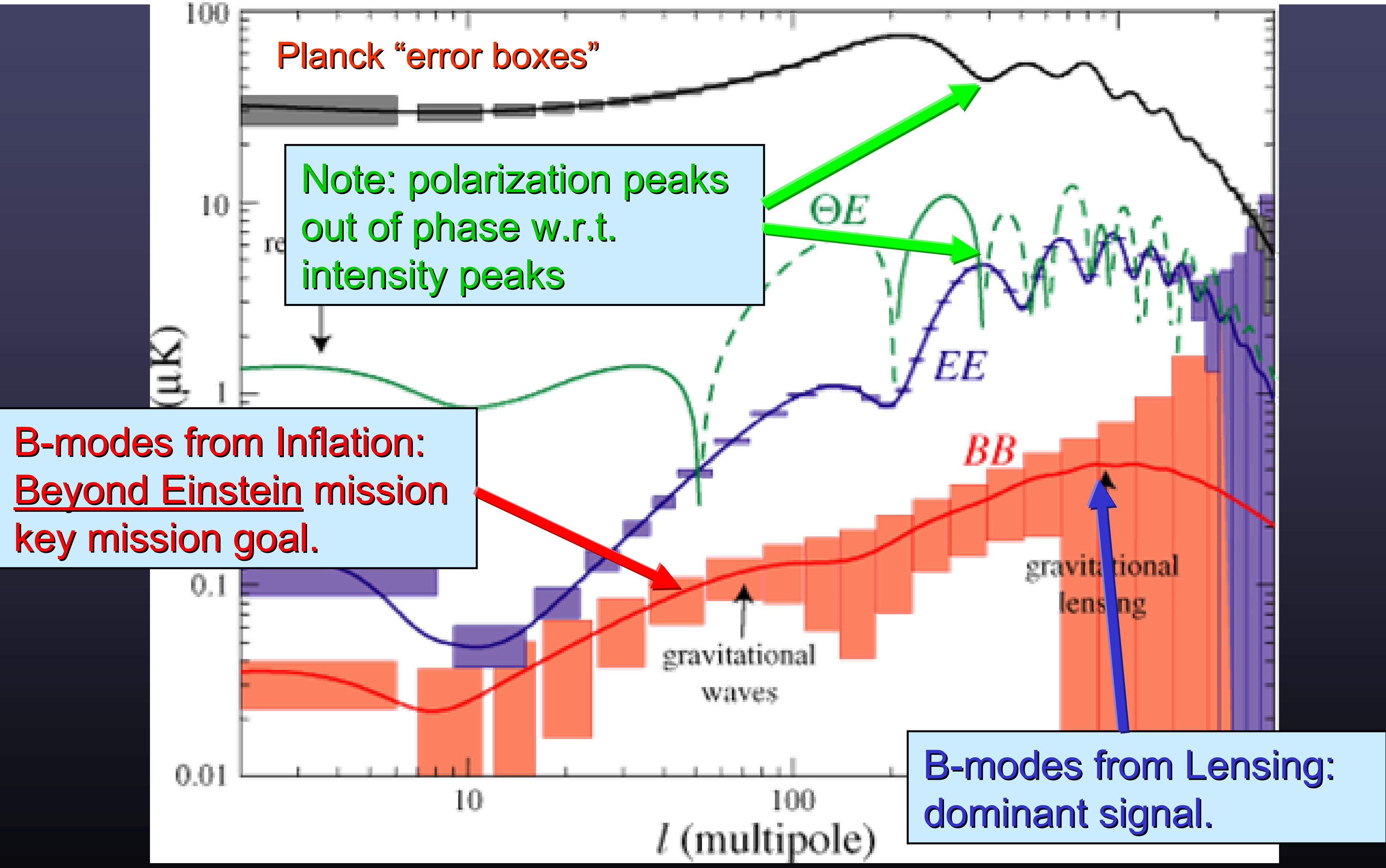


Summary

- CMB temperature power spectrum measured
- CMB polarization power spectrum measured
- SZE secondary possibly detected
- SZE imaging “routine”
- Foregrounds (other than point sources) not yet limiting

Where we need to go

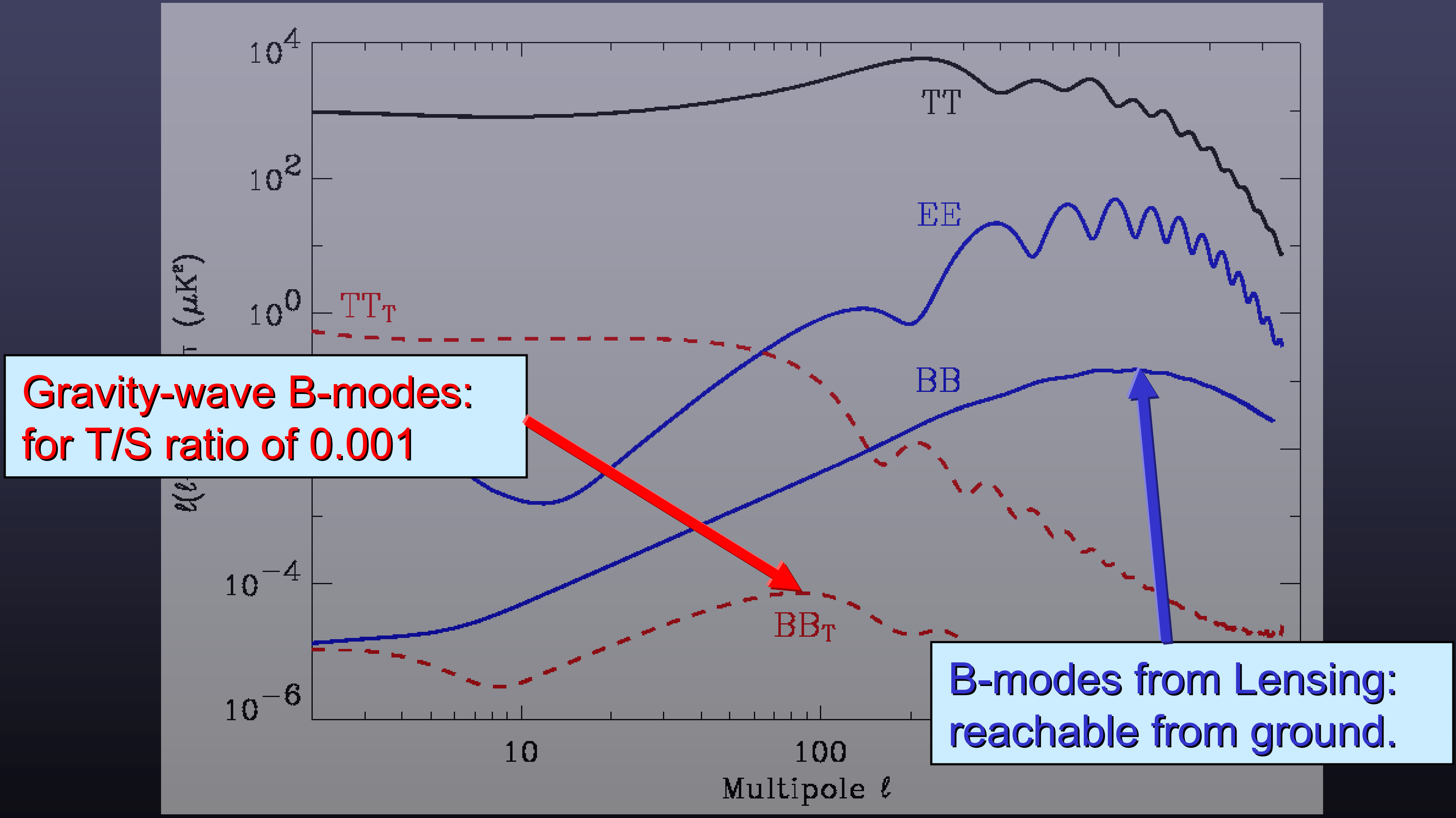
Planck Projections



Hu & Dodelson *ARAA 2002*

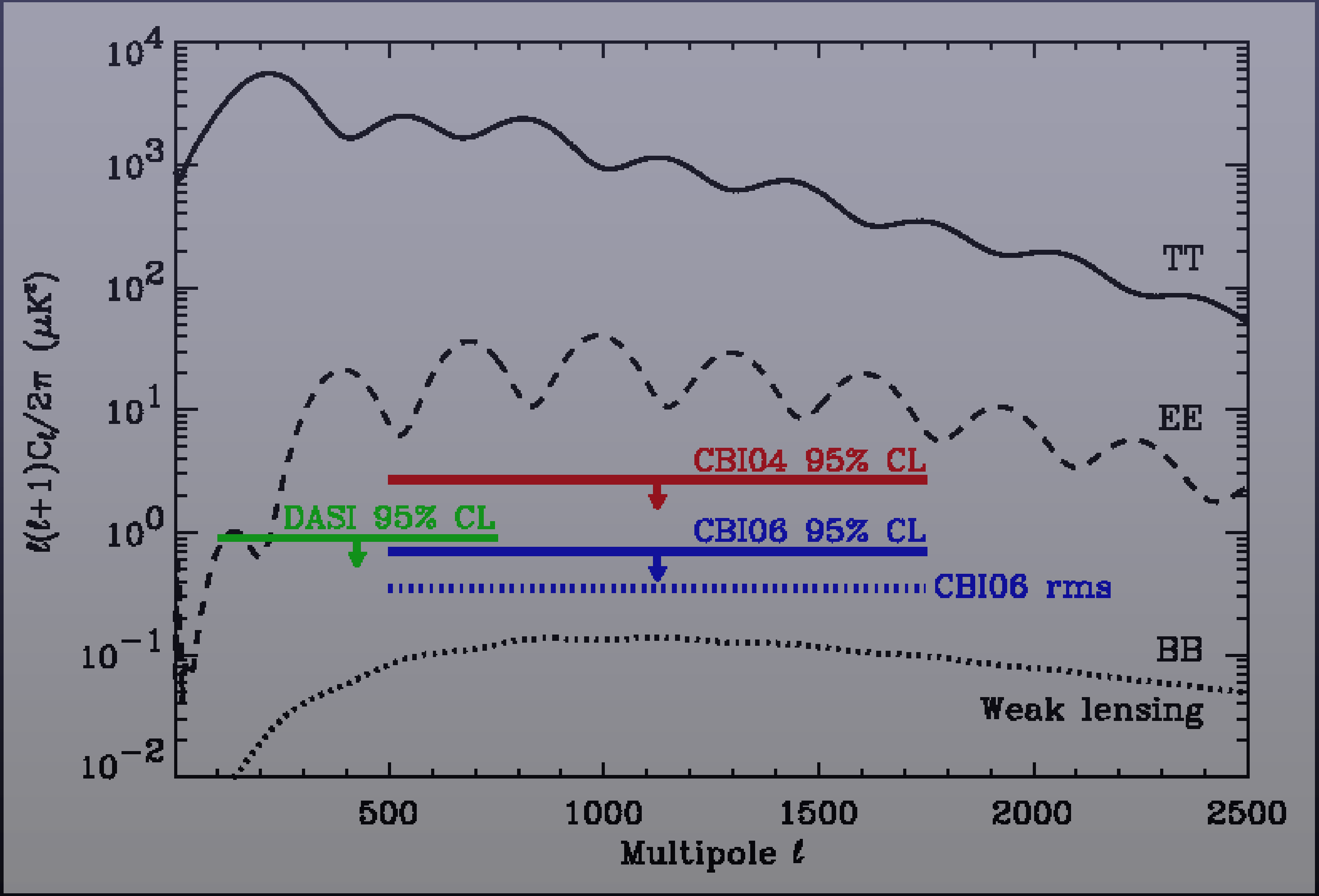
Intermediate l goals

- The goal: EE and BB (lensing)



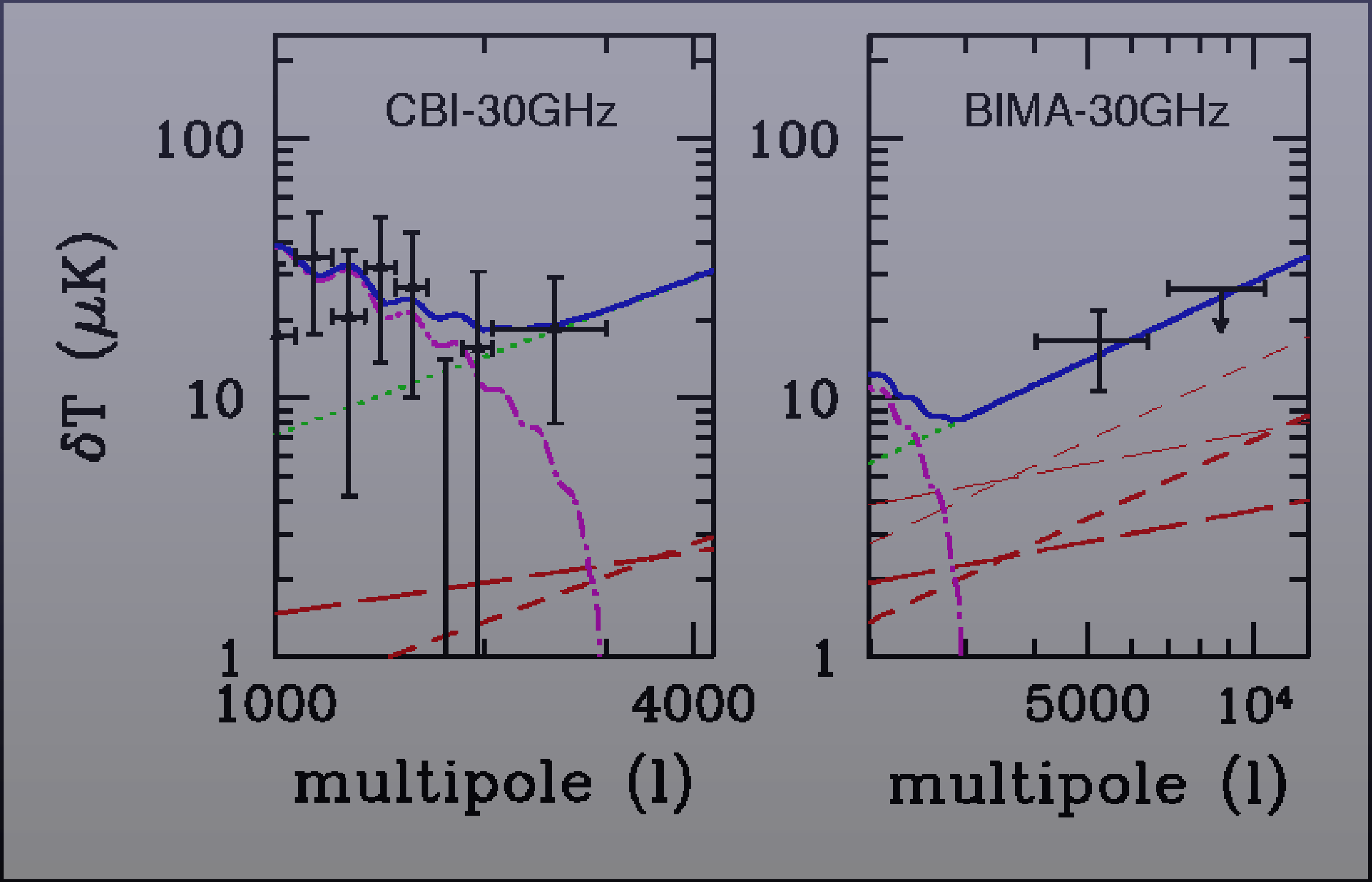
Foreground Projections

- Will BB (lensing) be foreground limited?



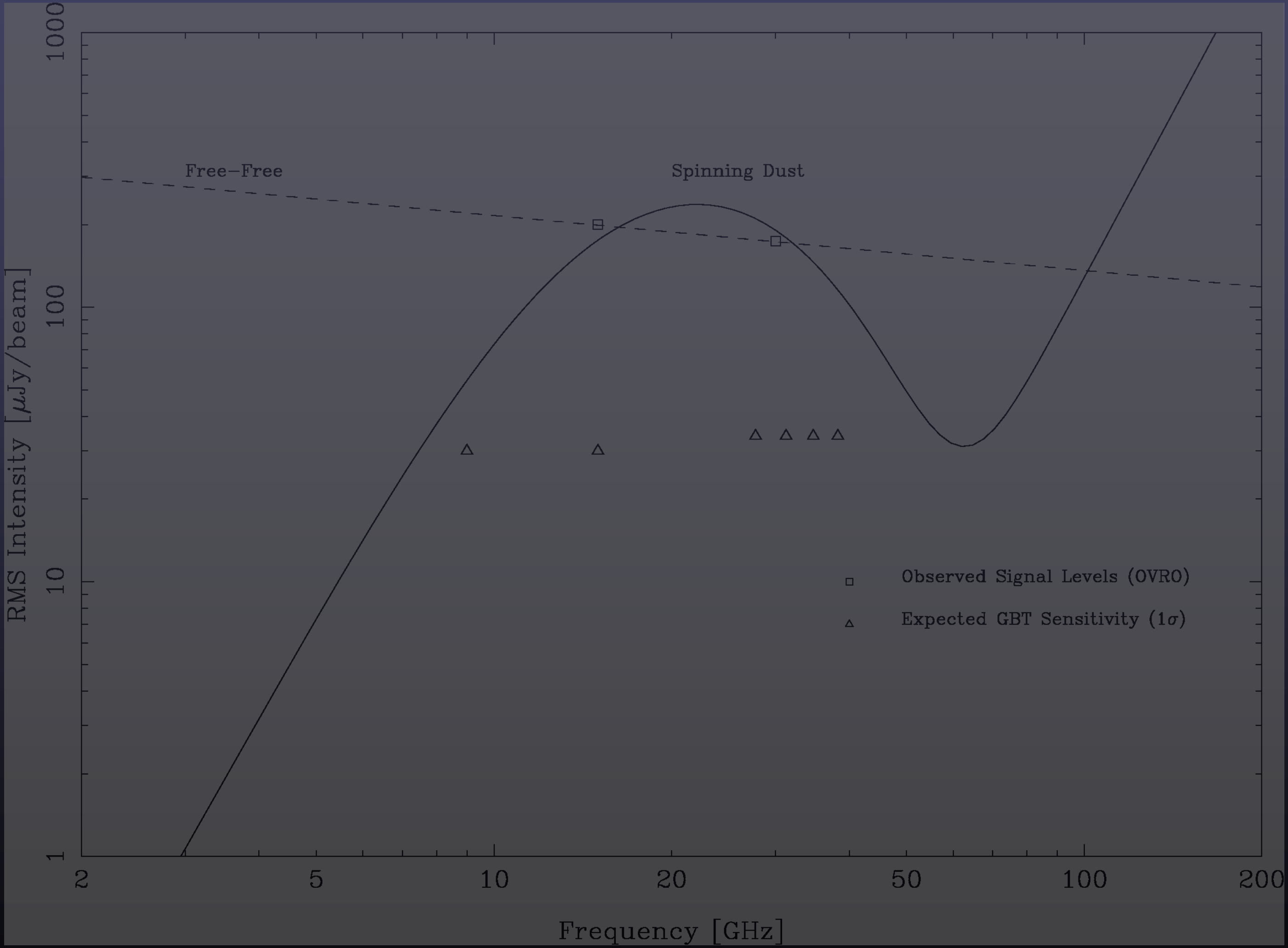
Point Source Foregrounds

- High-frequency population unknown at mJy levels
  - Toffolatti et al. 2004 (astro-ph/0410605) in dispute:

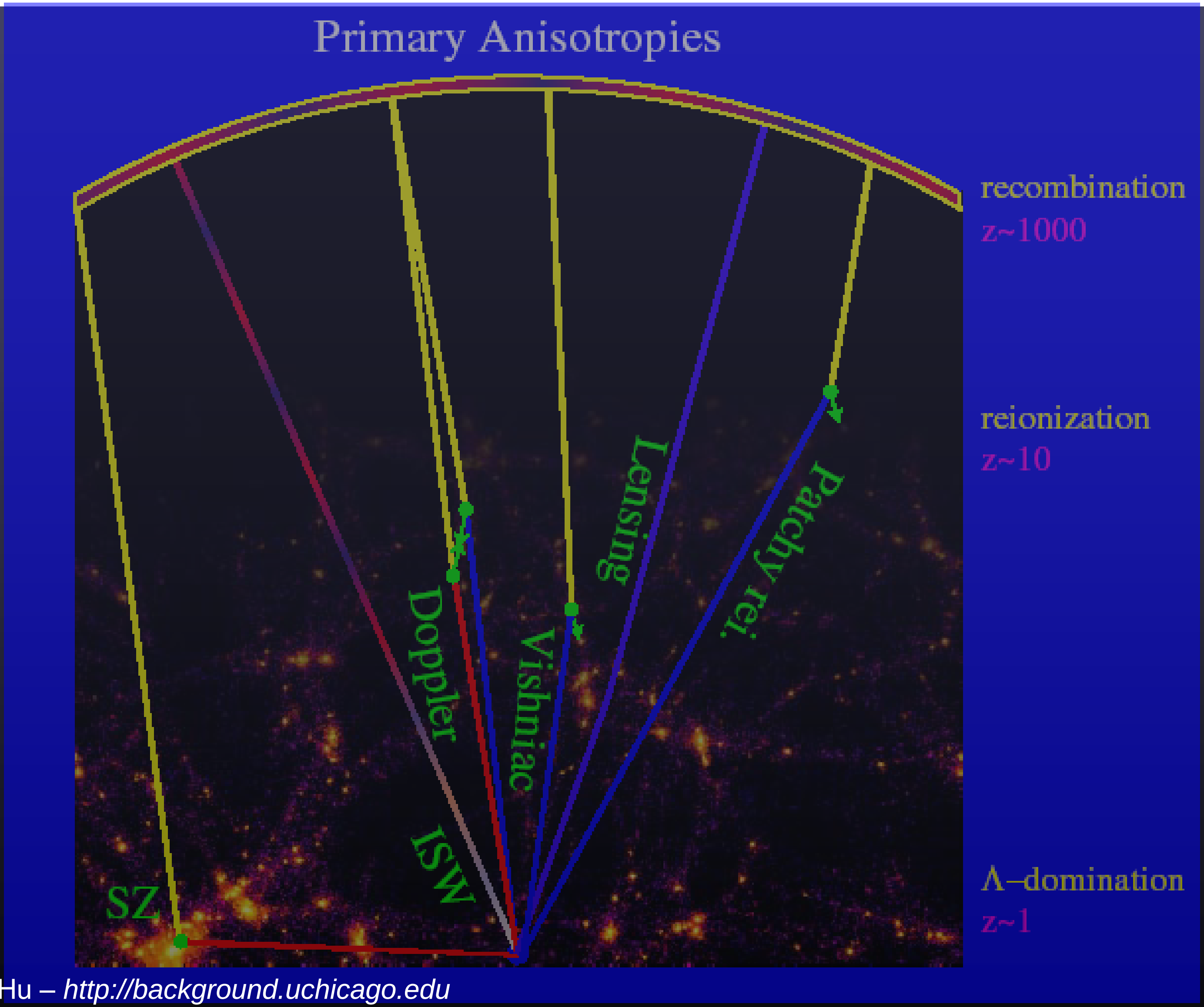


Diffuse Foregrounds

- Spinning dust (Draine, Lazarian, et al.) – not confirmed



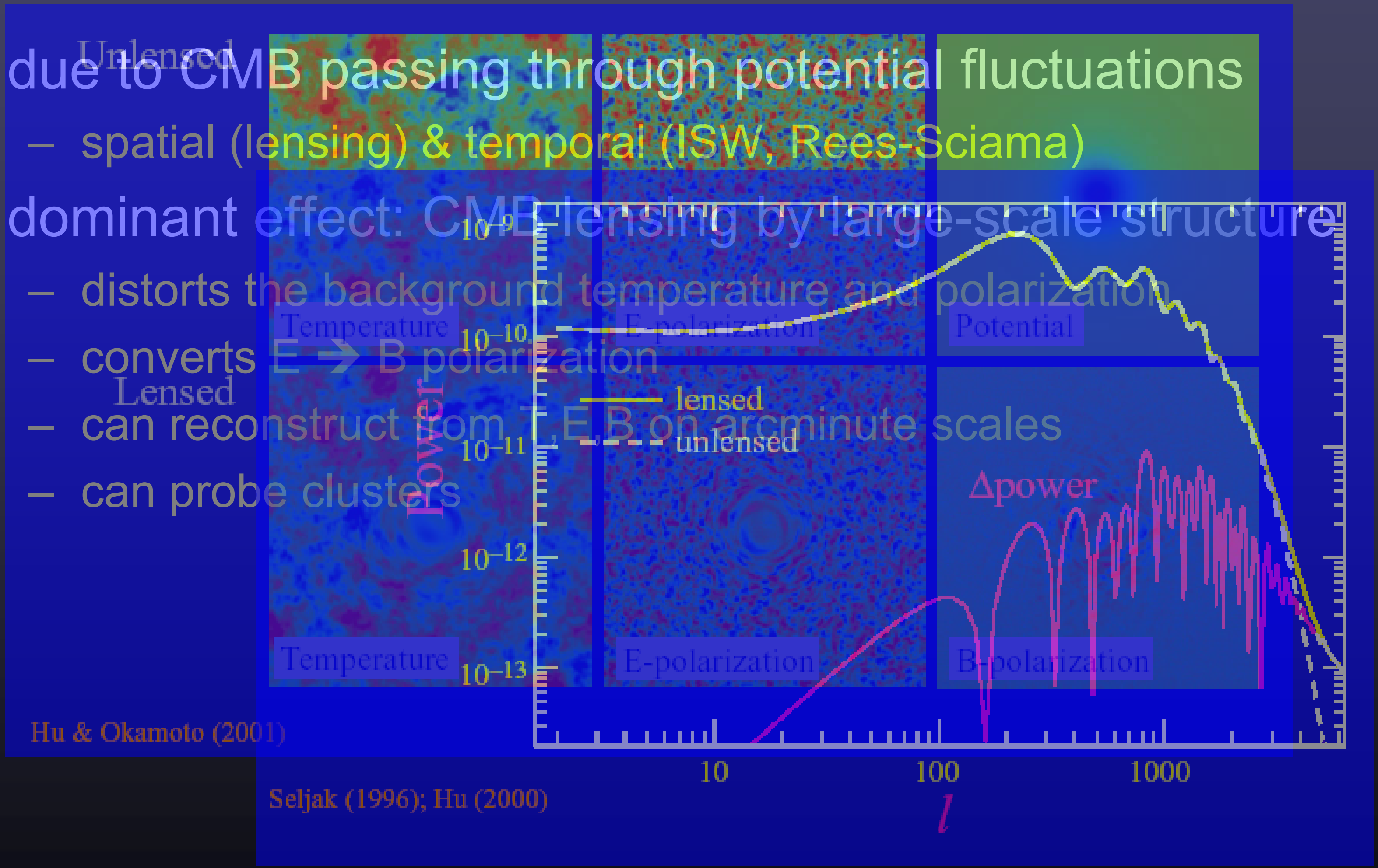
Secondary Anisotropies



Courtesy Wayne Hu – *http://background.uchicago.edu*

Gravitational Secondaries: Lensing

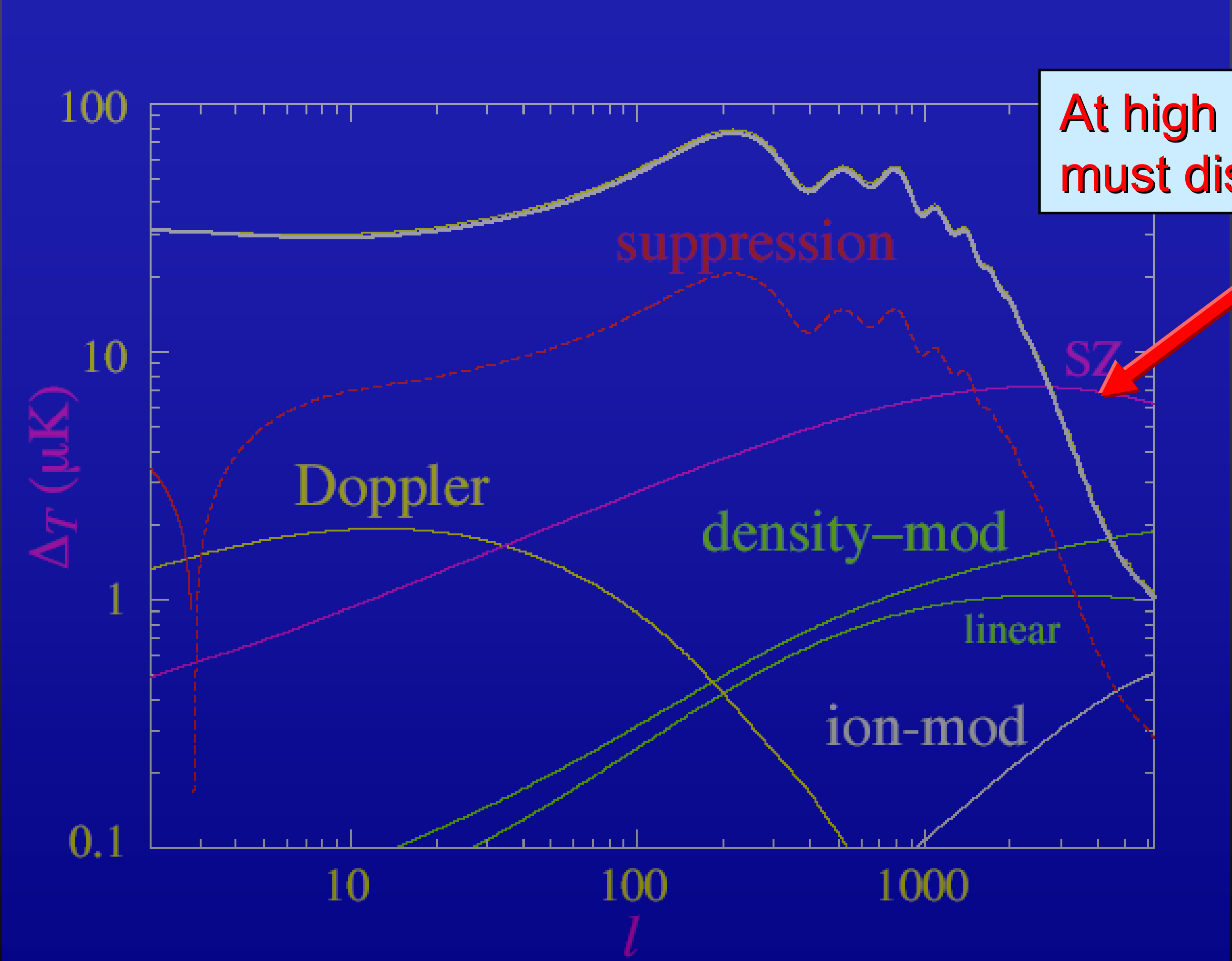
- due to CMB passing through potential fluctuations
  - spatial (lensing) & temporal (ISW, Rees-Sciama)
- dominant effect: CMB lensing by large-scale structure
  - distorts the background temperature and polarization
  - converts E → B polarization
  - can reconstruct from T,E,B on arcminute scales
  - can probe clusters



Courtesy Wayne Hu – *http://background.uchicago.edu*

Scattering Secondaries

- Due to variations in density, velocity, ionization:

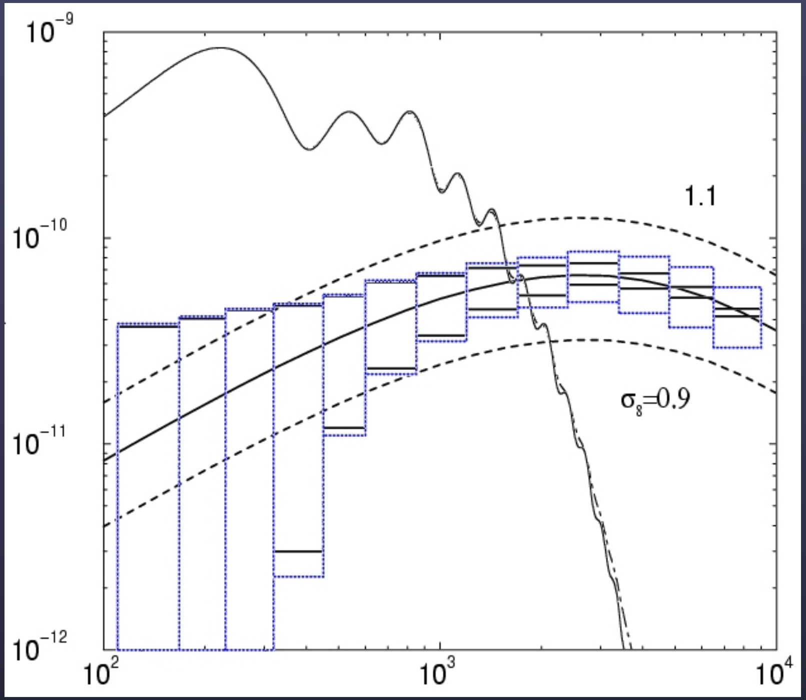


At high l: SZ dominant, must disentangle others

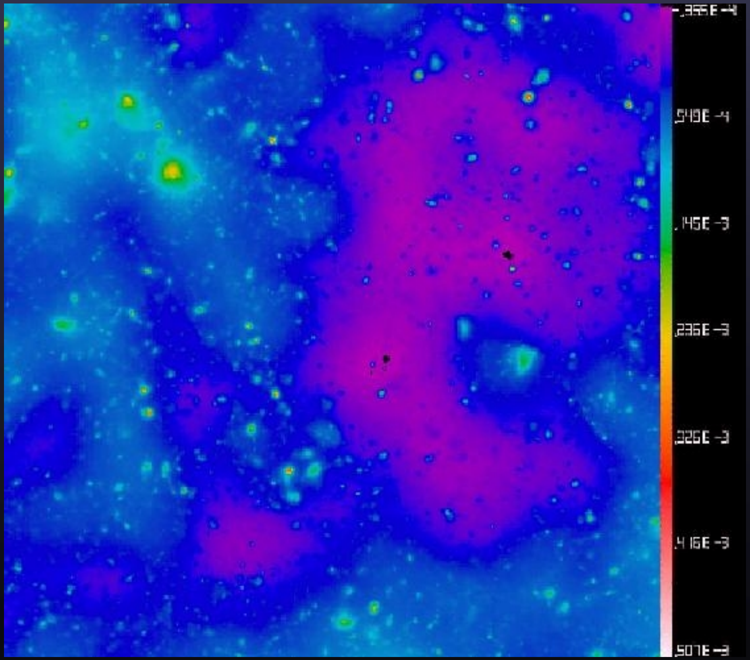
Courtesy Wayne Hu – *http://background.uchicago.edu*

e.g. SZE Secondary Anisotropies

- Spectral distortion of CMB
- Dominated by massive halos (galaxy clusters)
- Low-z clusters: ~ 20'-30'
- z=1: ~1' → expected dominant signal in CMB on small angular scales
- Amplitude highly sensitive to σ_8



A. Cooray (astro-ph/0203048)



P. Zhang, U. Pen, & B. Wang (astro-ph/0201375)

Goals & Requirements

- Primary anisotropies: non-Gaussianity
  - sensitive wide-field images
- Primary anisotropies: BB polarization
  - degree scales: all-sky, satellites; but lensing foreground
- Secondary anisotropies: SZE & EE/BB lensing
  - moderate sized fields, can be done from ground, multi-band
- other secondaries very difficult (but possible)
  - need spectral information and cross-correlation with templates
- foregrounds: will likely limit the sensitivity of observations
  - need multi-wavelength surveys for correction or templates
  - knowledge of mJy source populations at 30-100 GHz
  - not glamorous but necessary!

Future CMB Instruments

Current & Future “CMB” Experiments

- CMB Polarization:

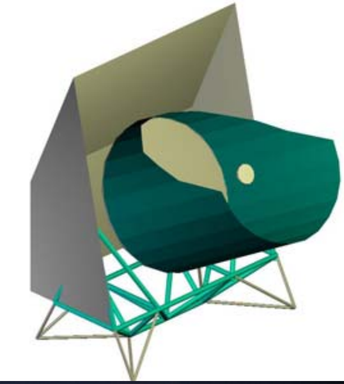
Comparison of Experiments

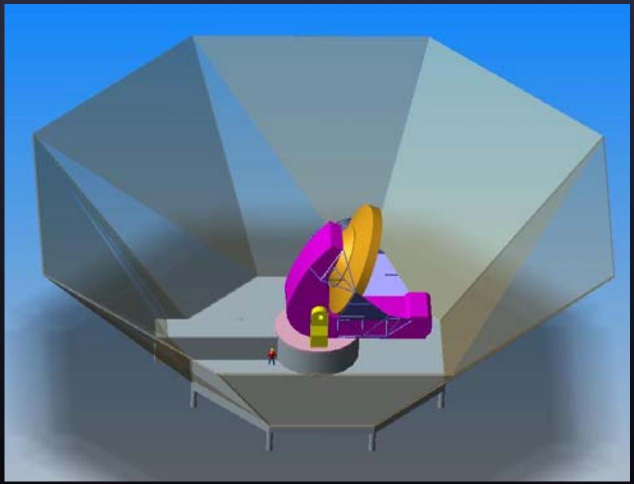
Experiment	FWHM [°]	ν [GHz]	Detectors: N	Detectors: Type	Pol. Modulation	Site	References
In progress							
CBI	0.75	30	13	HEMT	Multiplying interf.	Chile	Readhead2004,Padin2002
CAPMAP	0.06–0.14	40,90	4,12	MMIC-LNA	Phase Switched LO	NJ	Barkats2004
Maxipol	0.17	140,420	12,4	Bolometer	1◁2-wave plate	Balloon	Johnson2003
B2K	0.11–0.16	145,245,345	(4,2,2)×2	Bolometer	Spatial	Balloon	Montroy2003
WMAP	0.21–0.82	22,30,40,60,90	(1,1,2,2,4)×2	HEMT	Scan	L2	Kogut2003
In development							
KUPID	0.2	12–18	1	HEMT	RF Phase Switch	NJ	Gundersen2003
QUaD	0.07	100,150	(12,19)×2	PSB	1◁2-wave plate	SP	Bowden2004,Church2003
BICEP	1,0.7	100,150	(16,32))×2	PSB	Faraday Switch	SP	Keating2003
Planck	0.23–0.55	30,44,70	(2,3,6))×2	MMIC-LNA	Scan	L2	Lawrence2003
	0.08-0.15	100,143,217,353	(4,4,4,4)×2	PSB			Lemarre2003
MBI	1.4	90,180,270		Bolometer	Adding Interf.		Tucker2003
SPORT	7	22,32,90	1,1,2	HEMT	RF Phase Switch	Space St.	Carretti2002
AMiBA		90	19	MMIC-LNA	Multiplying Interf.	Hawaii	Lo2000
CLOVER	0.25	90,150,220	(256,256,256)×2	PSB	Scan	Dome C	Taylor2004
QUIET				MMIC Pol.	RF Phase Switched	Chile	Gaier2003
Large scale	0.15–0.35	90,40	794,91				
Small	0.06-0.14	90 or 40	397 or 91				

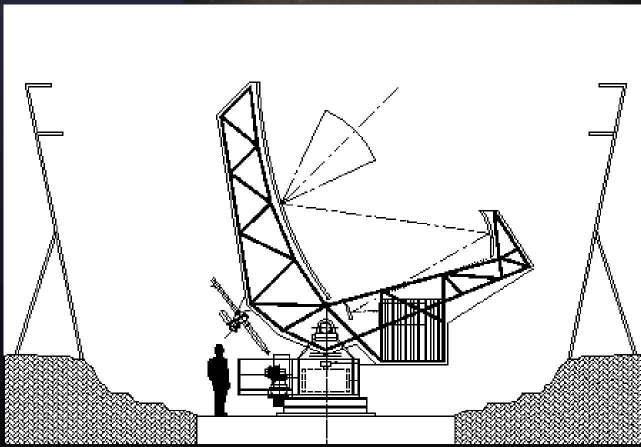
  - PSB based instruments (Planck HFI, QUad, BICEP, etc.)
  - MMIC based instruments (Planck LFI, QUIET, etc.)

Current & Future “CMB” Experiments

- Other:
  - SZA [8x3.5m], SPT [8m] (Carlstom) – cluster counts
  - ACT [6m] (Penn/Princeton) – CMB, cluster counts
  - BLAST [1.9m] (Penn/Toronto/UBC) – sub-mm counts
  - APEX [12m] (MPI) – dusty galaxies
  - Atacama 25-meter (Cornell/Caltech) – FIR/sub-mm



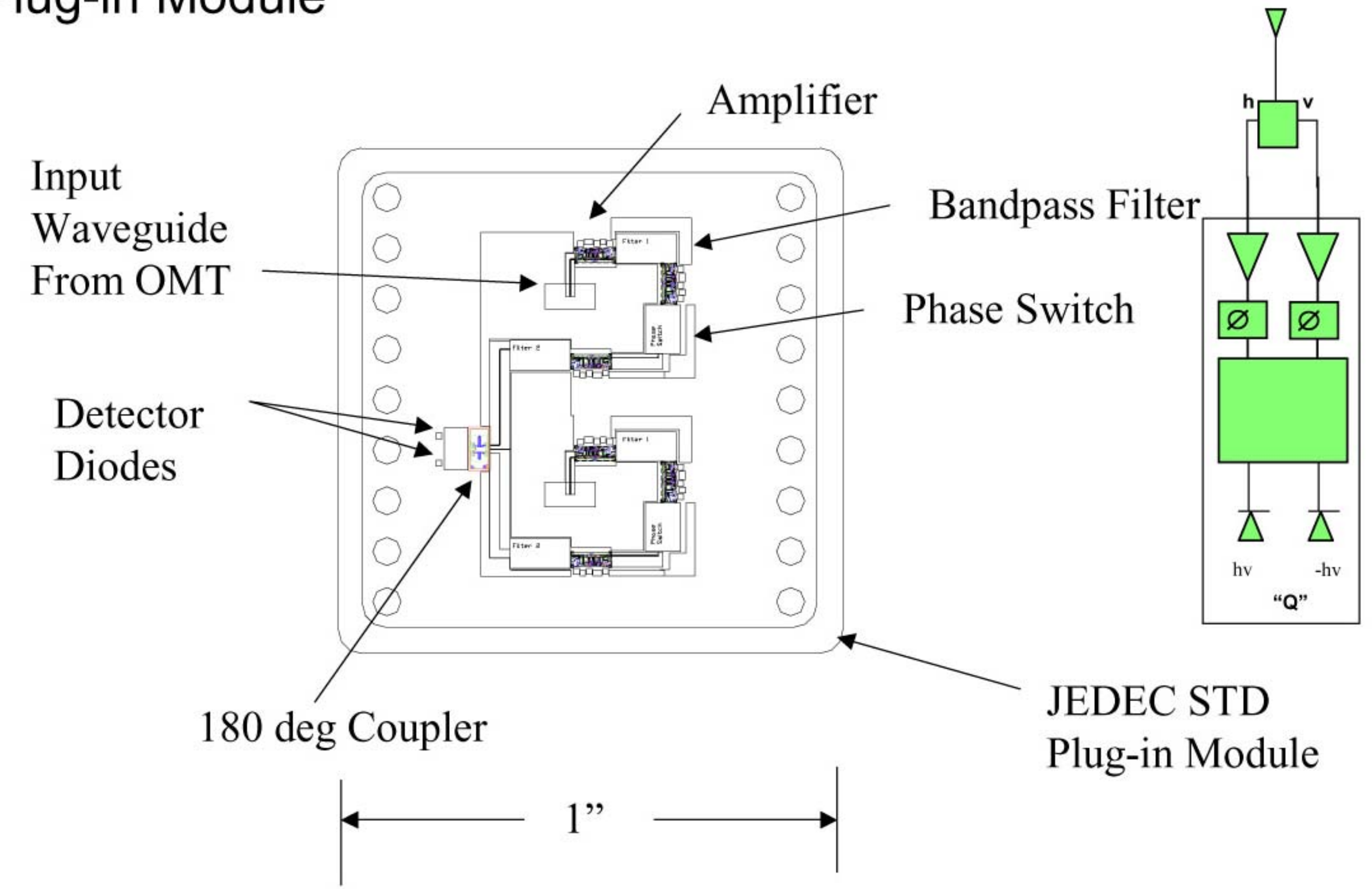




MMIC Array Technology

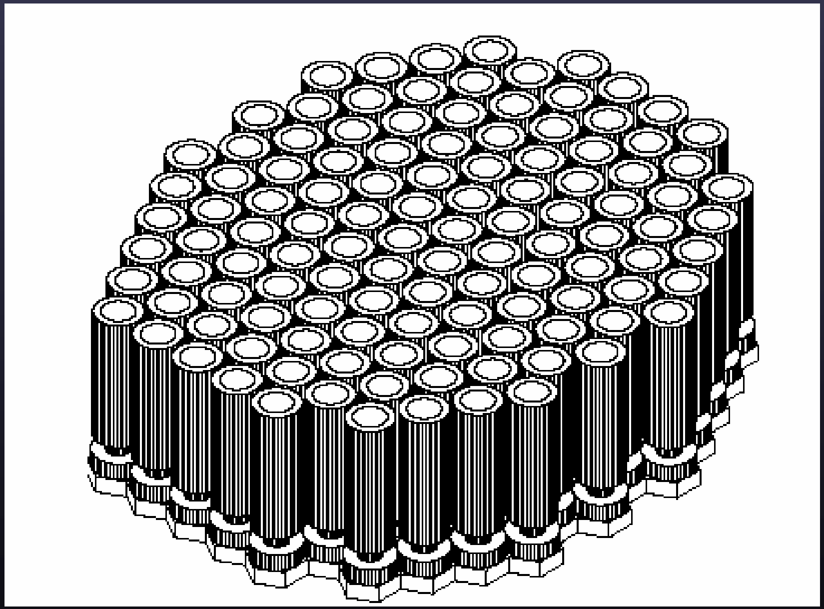
- Allows fabrication of large-format heterodyne arrays:

Array element:Complete 100 GHz Polarimeter receiver in a Plug-in Module



QUIET

- JPL (Todd Gaier)
- test on CBI platform as 100-element horn array
- aim for 1000-element array on 6-8m telescope
- cross-correlation for polarization

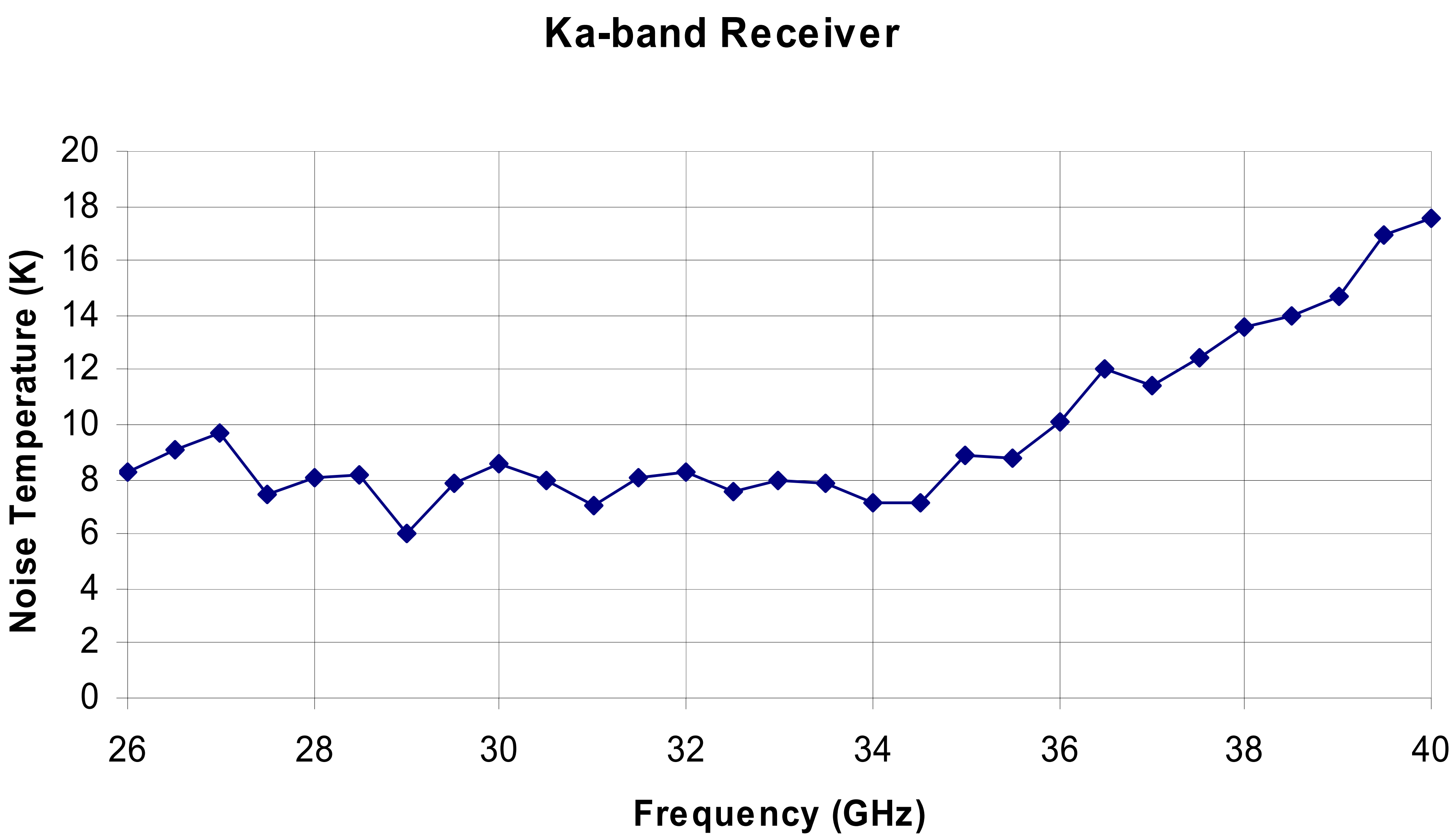


NRAO & CMB

What is NRAO doing for CMB?

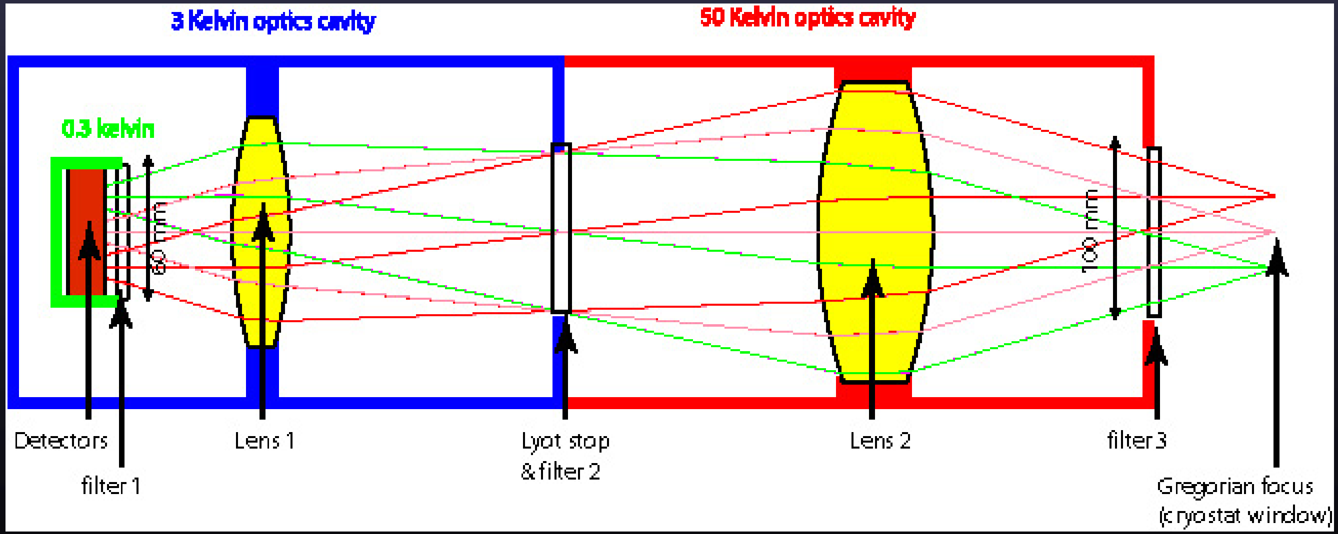
- HEMT development & fabrication (Pospiesalski)
- CBI science & analysis (Myers, Mason)
- GBT Ka-band follow-up of foregrounds (Mason, CIT)
- GBT Penn Array (Mason, UPenn)
- foregrounds with VLA & GBT (various)

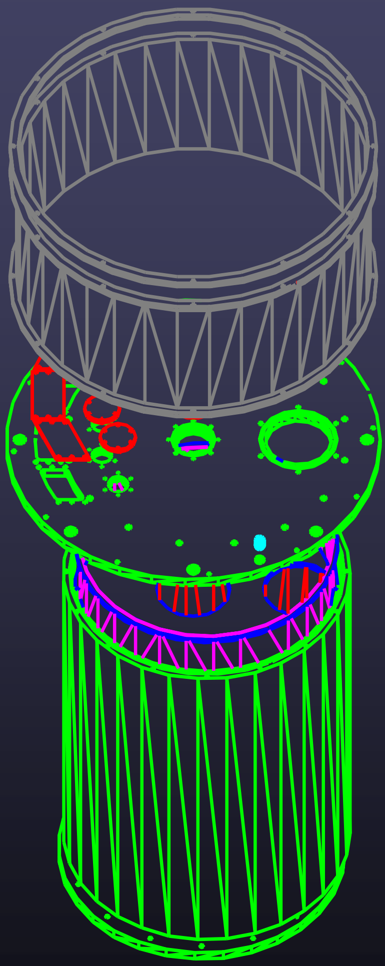
CBI Upgrade: New NRAO HEMTs



Penn Array Receiver

- 86 to 94 GHz bandpass initially
- 8 by 8 array of TES bolometric detectors
- beam: 8’’ fwhm
- A fully sampled (0.5fλ) focal plane
- Background limited detectors





GBT: PennArray In 1 hour

Observing mode	Sky coverage	Sensitivity (1σ)
Point source (switching)	32″ × 32″	2.5 μJy

- Photometric redshifts for known sources
- Observations of the galactic center
- Measuring the albedo of known Trans-Neptunian objects

Observing mode	Sky coverage	Sensitivity (1σ)
Slow scanning	5′ × 5′	25 μJy

- High resolution maps of the Sunyaev-Zel'dovich effect
- Understanding the physics of star and planet formation
- Studies of centimeter-sized dust grains in the Solar system

Observing mode	Sky coverage	Sensitivity (1σ)
Fast scanning	1° × 1°	290 μJy

- Large area surveys : bright point sources, galactic plane etc

The SZE with Penn Array

With Nobeyama 45m

80″ resolution @21GHz

0.5 mJy/beam

34 hour integration

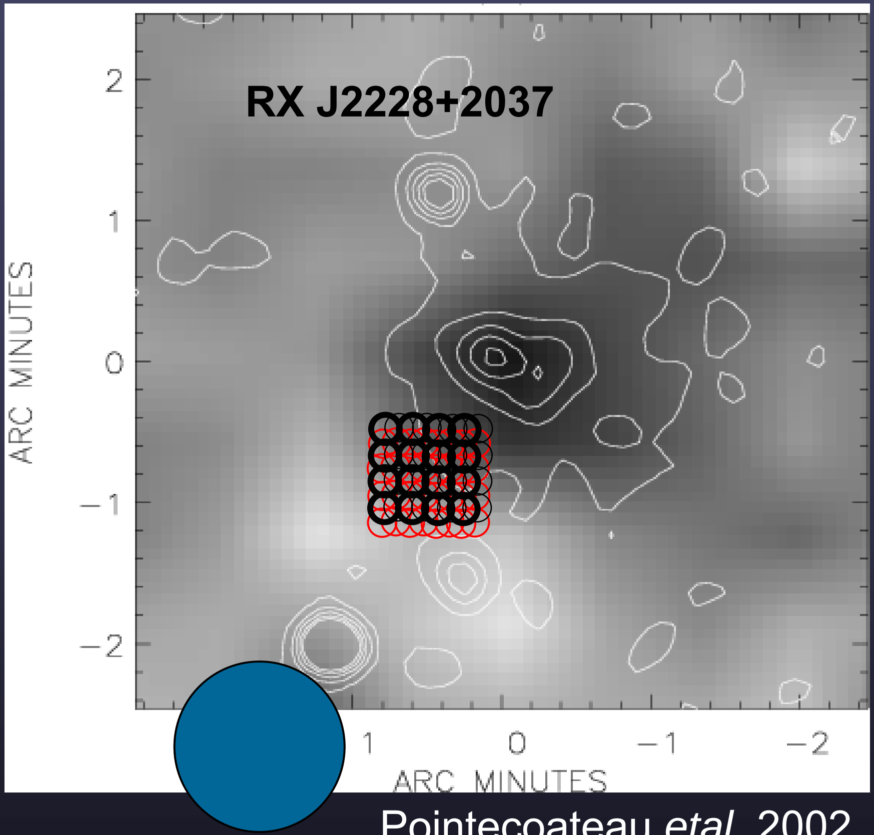
With the GBT

8″ resolution @90GHz

0.05 mJy/beam

15 minute integration

Z~0.08 → 8''=8 kpc !

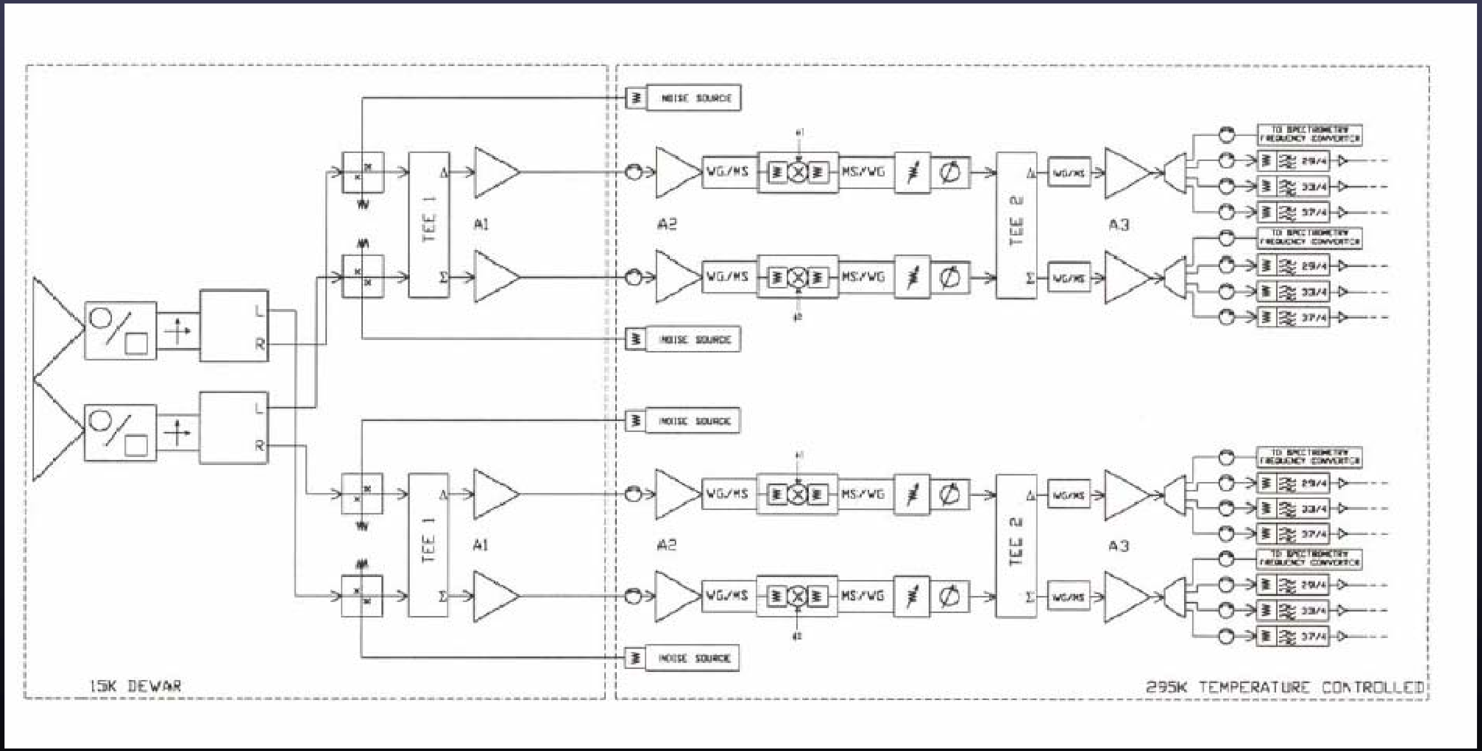


Pointecoateau *etal.* 2002

→ 8 μJy in 10 hours
5'×5' map
SNR ~5 in core of nearby cluster

GBT 1-cm Receiver

- Frequency range 26-40 GHz
- MAP-style balanced radiometers (1/f rejection)
- Two-horn, dual polarization, 0.25 mJy in 1 sec
- Caltech backend → fast switching (also 3mm Rx)

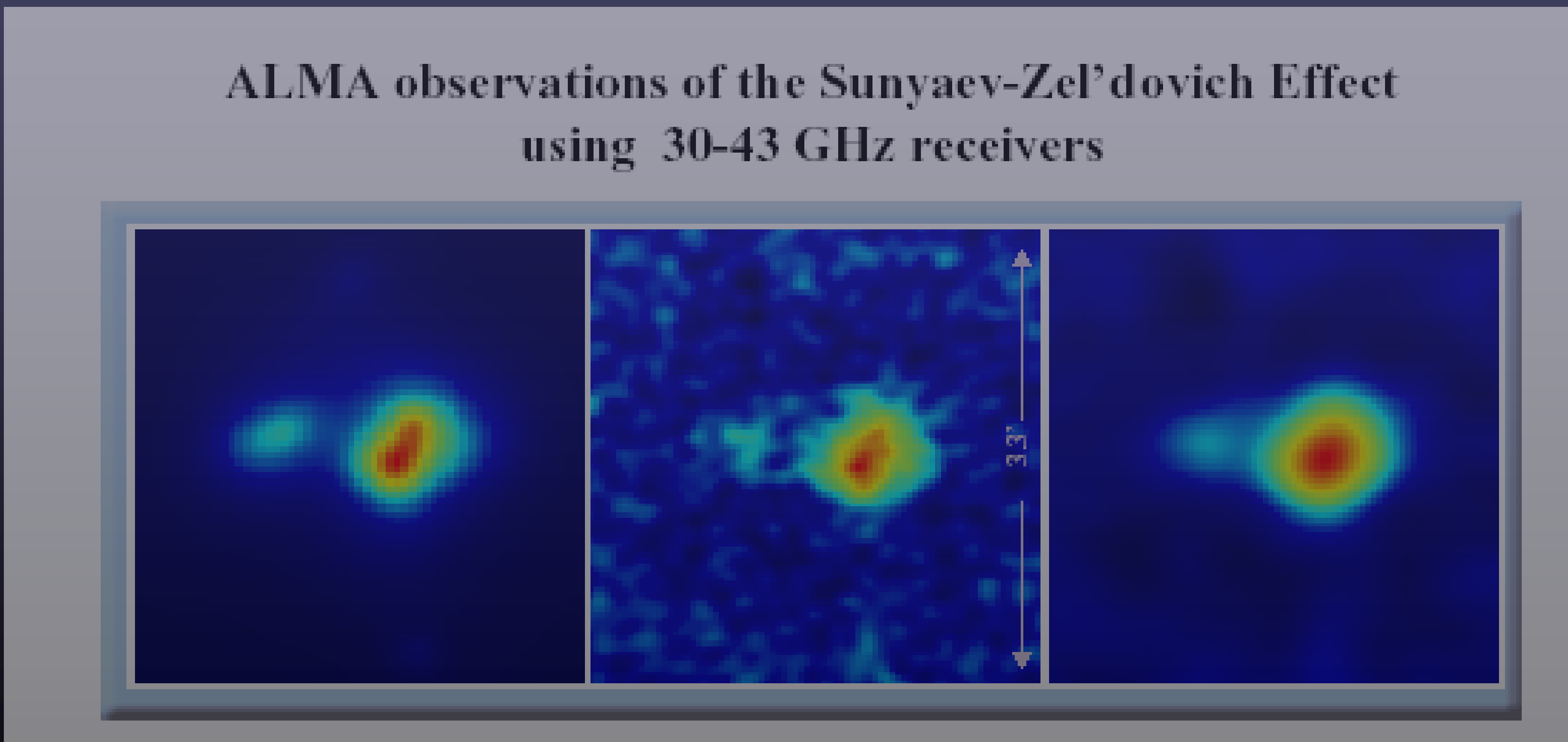


What could NRAO do in CMB?

- MMIC development & fabrication
- contribute to CBI operations
- GBT foreground surveys (C,X,Ku)
- GBT Mega-pixel Array (bolometer or heterodyne)
- ALMA 30 GHz
- EVLA E-configuration
- join a big CMB project (ground and/or space)
- sky surveys (EVLA,GBT,ALMA) for foregrounds

ALMA Cosmology

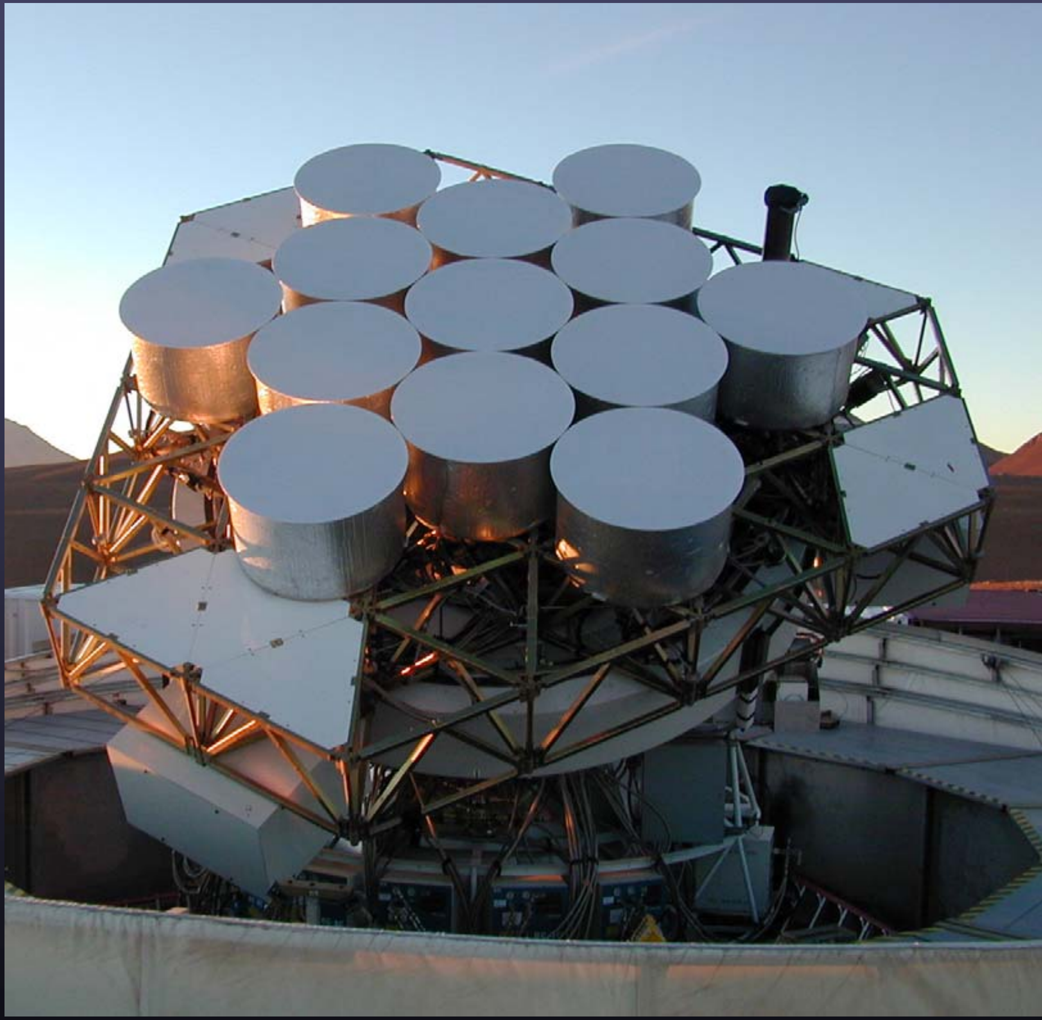
- Sub-mm galaxies identification and followup
- High-resolution CMB & SZE at 30 GHz



CBI

The Cosmic Background Imager

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys 20 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin
- Rotatable platform

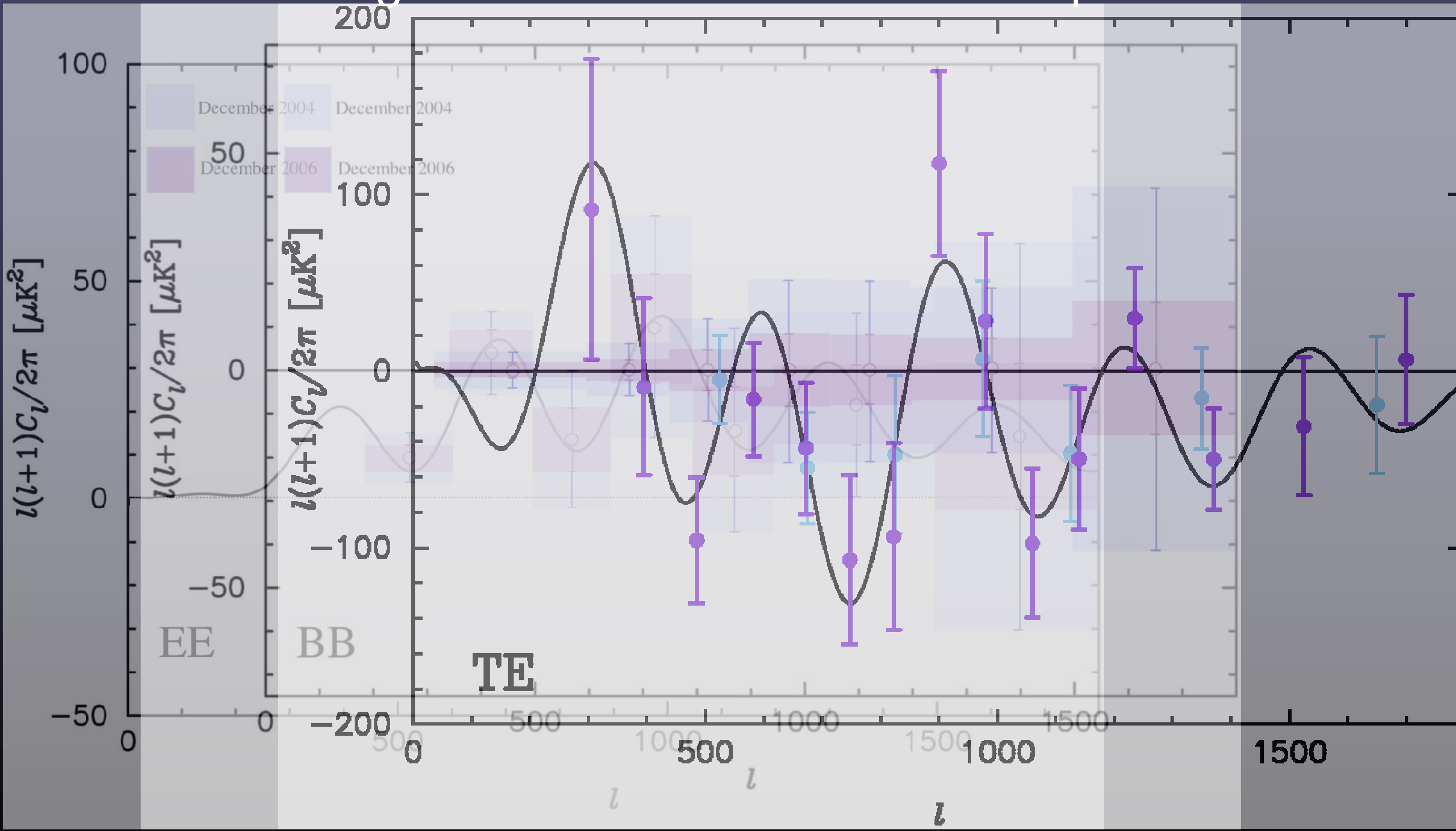


CBI Status & Future

- It is working well!
- Significant gains projected through 2006
- Currently unfunded (in debt)
- NSF proposal submitted Nov04, but funding gap
- Shutdown in Jan 2005 (need ~200K$)
- Already NRAO involvement (Myers, Mason, Pospiesalski)

CBI Projections

- Run through 2006: EE 2.7× & BB 3.5× improvement



New Initiatives

New Initiatives in CMB: Small

- GBT: Continuum receivers
  - Upgrade C, X, Ku (& possibly K) to balanced design
  - Enables sensitive continuum mapping (CMB foregrounds)
- EVLA E-configuration & ALMA 30 GHz
  - Increases surface brightness sensitivity
  - complementary (EVLA@15 GHz = ALMA@30 GHz)
  - Enables SZE and diffuse foreground studies
- CBI support
  - modest investment to keep Chile operations running
  - Caltech looking for partners (at 200K$ level)
  - CBI partner automatically part of QUIET
  - NSF funding future (CBI & QUIET) uncertain, but our support could make a large difference

New Initiatives in CMB: Large

- GBT: Mega-pixel array
  - build on experience from PennArray
  - large bolometer camera
  - or large heterodyne focal-plane array
  - Enables deep 3mm imaging or spectroscopy
  - bolometer: best mapping performance, highest sensitivity
  - heterodyne: allows spectroscopy, imaging more difficult
  - do we just buy the camera, or invest in development ourselves?
- New technology investment
  - build (or buy up!) major lab for MMIC or bolometer development
  - bolometers: several existing big groups (NIST,Goddard,UCB,JPL)
  - MMIC: JPL (currently unfunded)
  - or something different…

New Initiatives in CMB: Interferometry

- CBI, DASI, & VSA have demonstrated the utility of interferometry for CMB (particularly for polarization)
- sensitivity limited by number of elements
  - would need 100's of elements
  - could combine FPA and interferometer for multi-beaming
- would require massive wide-band correlators
  - development of inexpensive large-scale correlators
  - of interest to other next generation big arrays (e.g. SKA)
- would be competing against bolometer & MMIC arrays
  - but interferometer polarization systematics much cleaner!
- risky & expensive, but worth exploring…

New Initiatives in CMB: Other

- Beyond our current portfolio (ALMA,EVLA,GBT)
  - complementary telescopes, e.g. Atacama 25-m
  - space missions
  - instruments on other telescopes, e.g. SCUBA-2
- Partnership
  - what do we bring to the table (other than $$)?
  - what do we get (other than observing time)?

New Initiatives in CMB: Sky Surveys

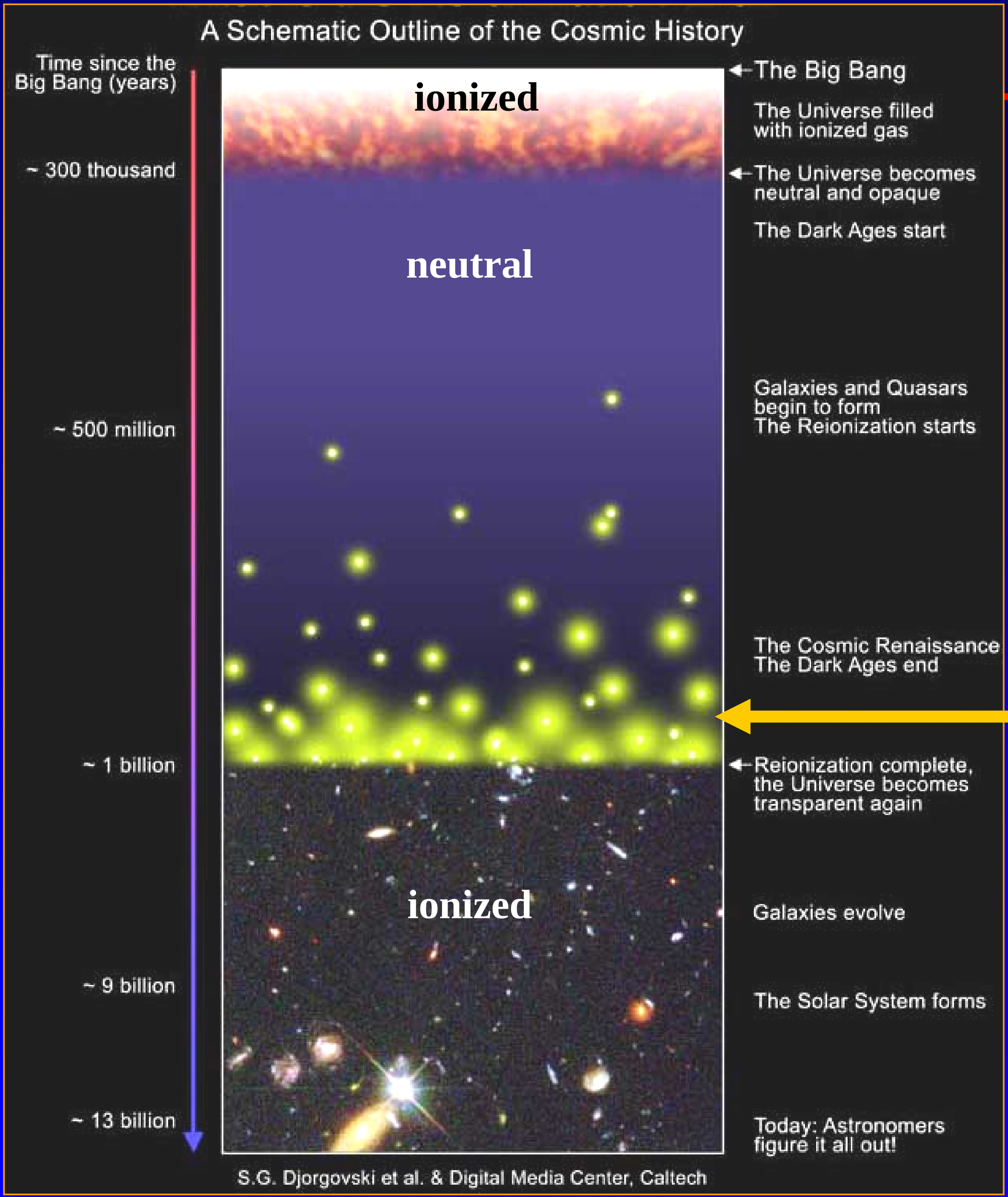
- Needed for CMB foreground templates
  - high-frequency source population & polarization unknown!
- EVLA
  - NVSS & FIRST insufficient
  - C or X band survey at mJy level (plus deeper S & L surveys)
  - OTF scanning (need to cover $>10^4$ sq. degrees)
  - wide-band continuum mapping (algorithm development necessary)
  - start early in EVLA lifetime (don't wait!)
  - enables other projects (e.g. gravitational lens surveys)
  - E-configuration diffuse polarized emission survey also possible
- GBT
  - 3mm Penn Array survey
  - mega-pixel camera surveys if instrumented

Conclusions

- Few easy or clear answers
- "Sure" "crazy-not-to" winners
  - EVLA sky surveys! start in 2009 (or before)
  - better GBT continuum receivers (C-K bands)
    - make sure enough funds & manpower available!
- "Sure" "find someway to do it" winners
  - GBT mega-pixel camera (3mm bolometer array)
  - EVLA E-configuration
  - ALMA 30 GHz
- Riskier
  - major investment in bolometer or MMIC technology development
  - develop technology for large-scale CMB interferometry!
  - completely new telescopes (e.g. Atacama 25-m)

History of IGM

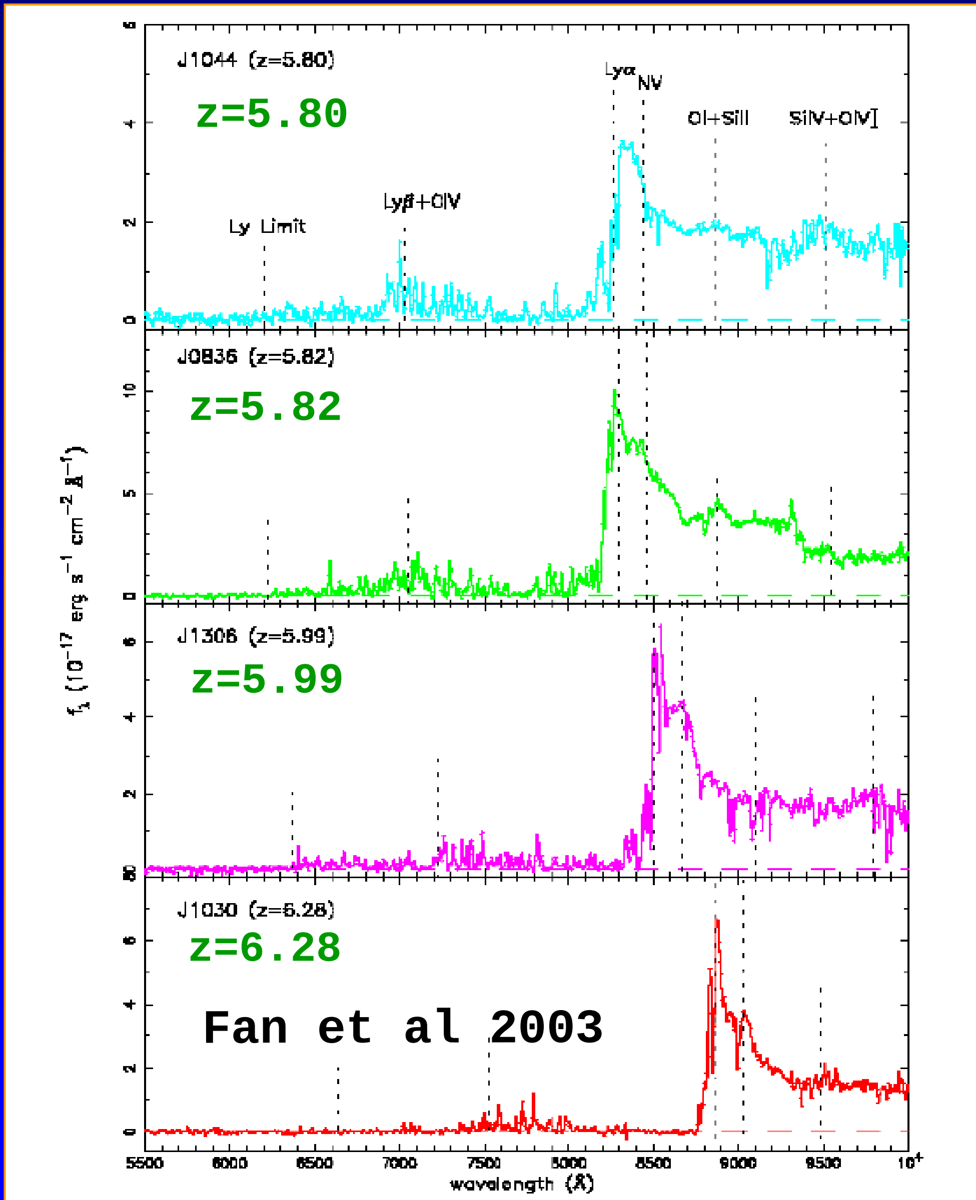
C.Carilli (NRAO) NNIW Dec 04



Epoch of Reionization (EoR)

- **bench-mark in cosmic structure formation indicating the first luminous structures**

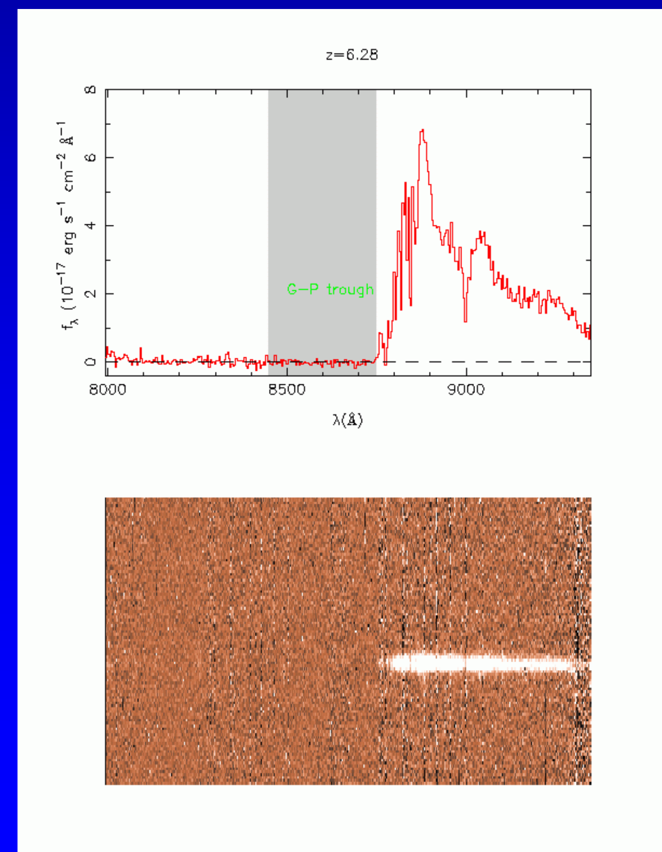
The Gunn Peterson Effect



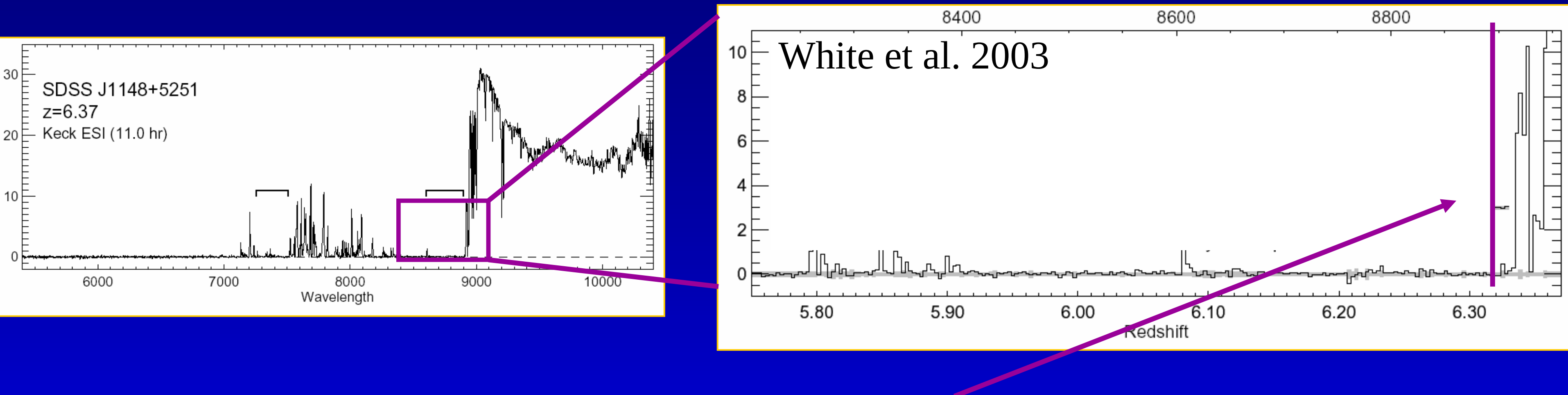
Fast reionization at z=6.3

=> opaque at $\lambda_{obs} < 0.9\mu m$

f(HI) > 0.001 at z = 6.3



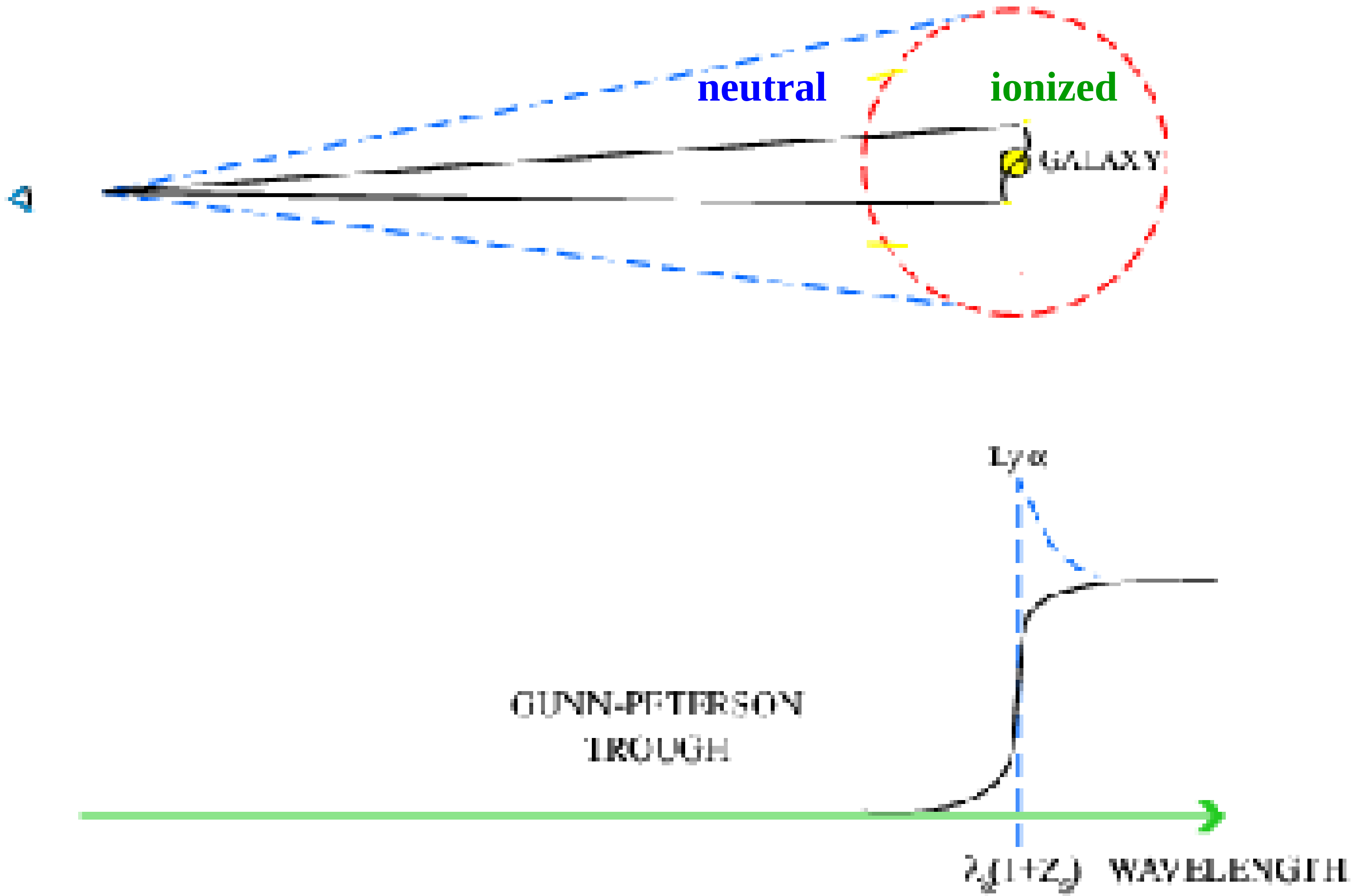
Cosmic Stromgren Spheres: proximity effect (Wyithe et al. 04)



Z_host(CO) = 6.419; Z_gp = 6.32 => photons leaking 6.32<z<6.419

'time bounded' Stromgren sphere: R = 4.7 Mpc =>

- t_qso= 1e5 R^3 f(HI)= 1e7yrs for f(HI) = 1 or
- **f(HI) > 0.1** at z>6.2 for t_qso = t_fid > 1e6 yrs



Loeb & Rybicki 2000

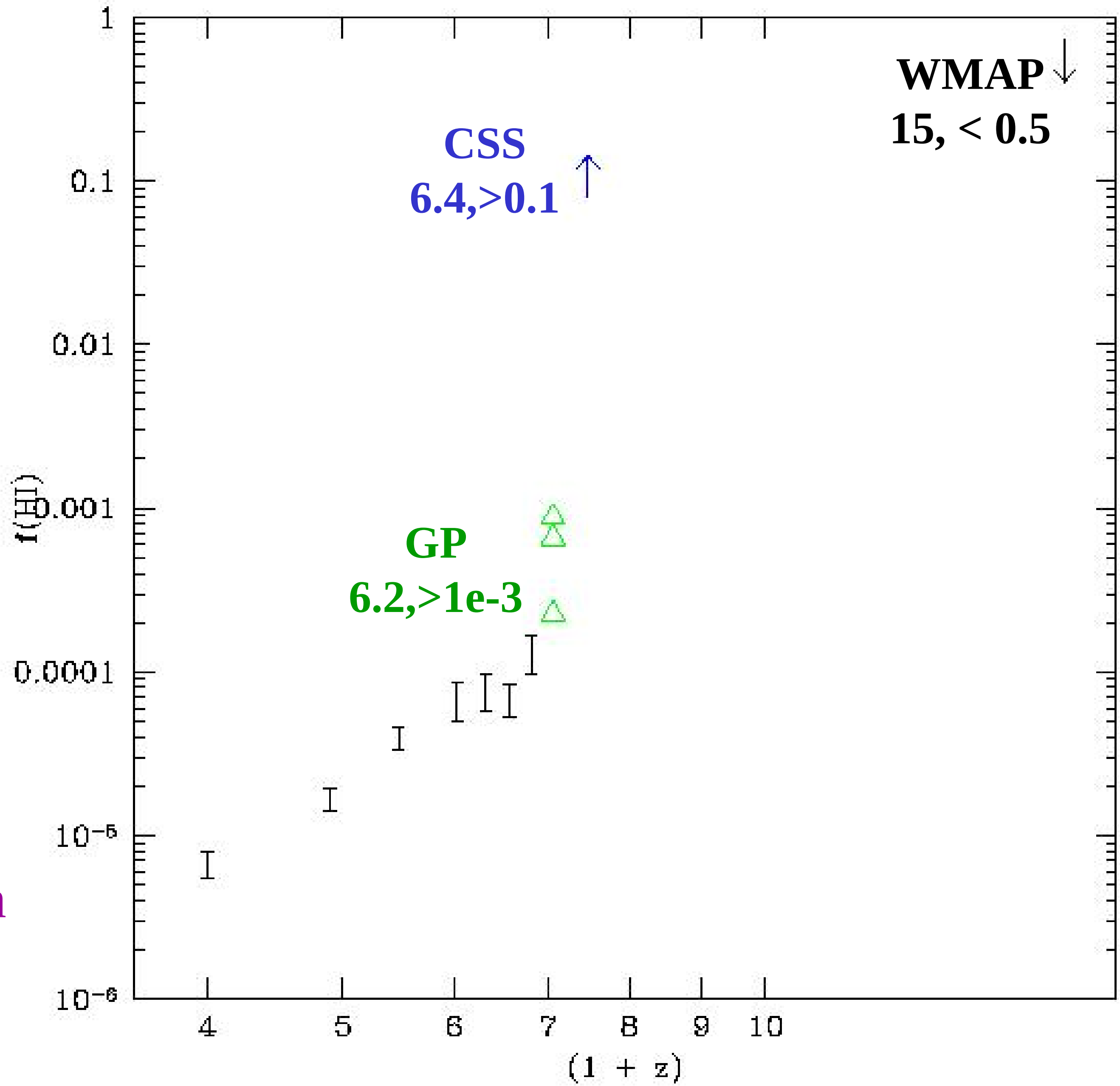
Complex reionization z=6.3 to 17?

• GP => fairly fast at z=6.2

• CSS => very fast at z=6.2?

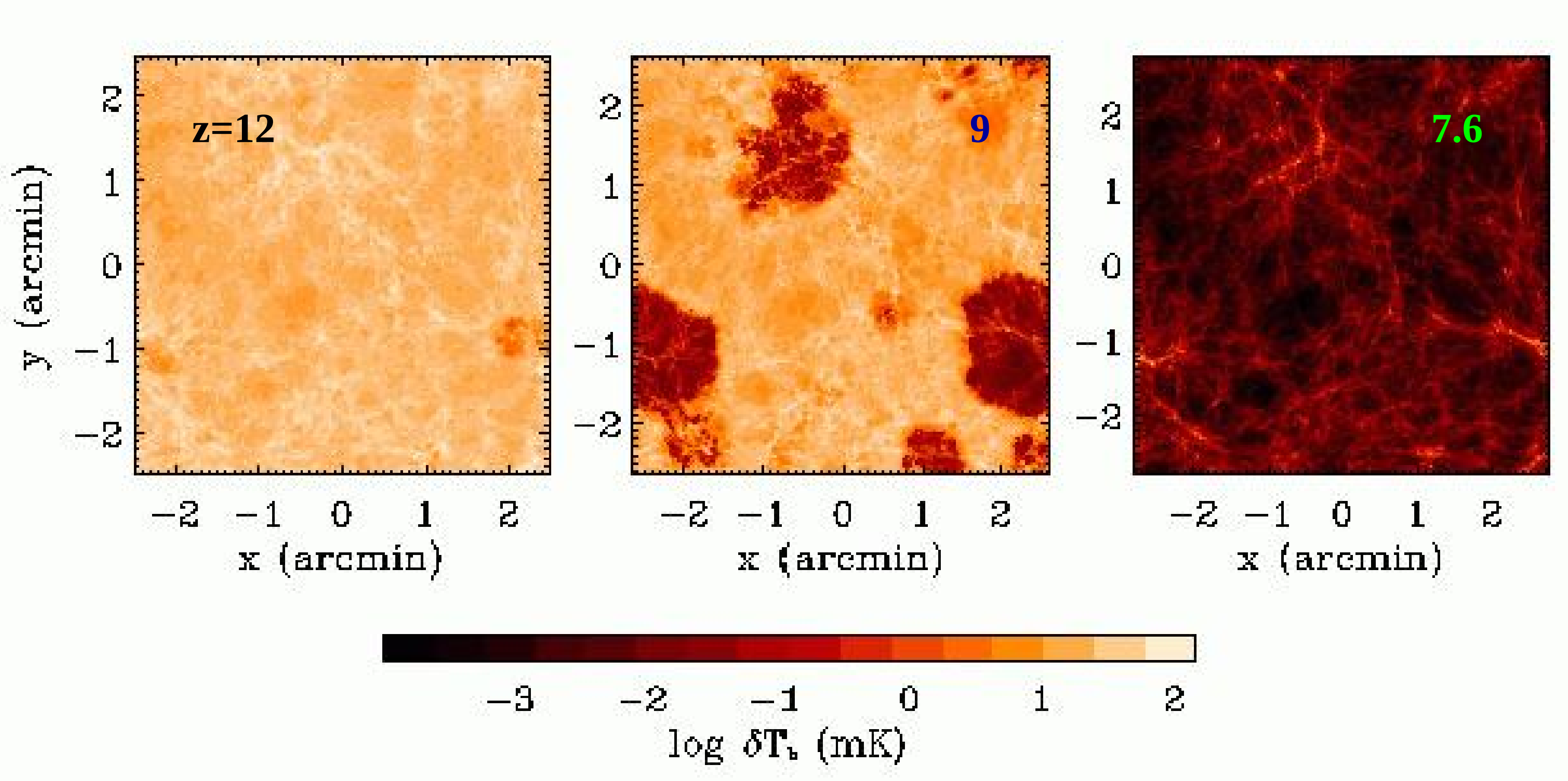
•WMAP=>complex to z=17?

See also Cosmic Stromgren Surfaces (Mesinger & Haiman 04), but cf. Ly γ, Oh & Furlanetto 05



HI 21cm Tomography of IGM at 100 – 200 MHz

Zaldarriaga + 2003



- $\Delta T_B(2') = 10$'s mK
- SKA rms(100hr) = 4mK
- LOFAR rms (1000hr) = 80mK

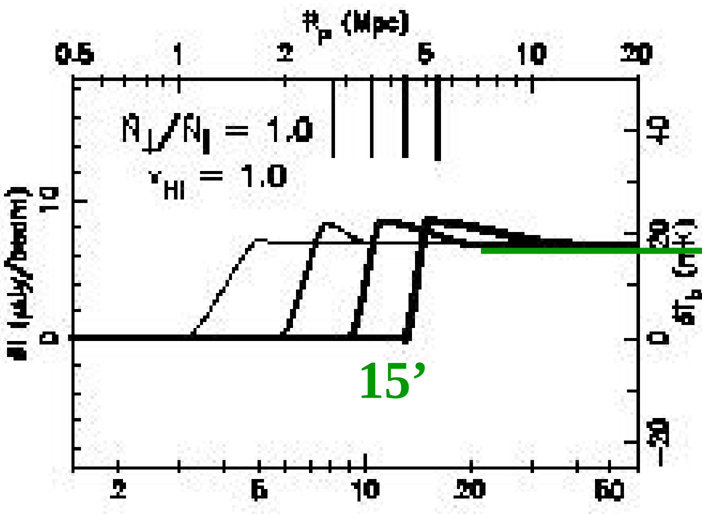
VLA-VHF: 180 – 200 MHz
prime focus dipole (CfA/NRAO)

- Leverage: existing telescopes, IF, correlator, operations
- $110K D+D/construction (CfA)
- Labor (CfA/NRAO)

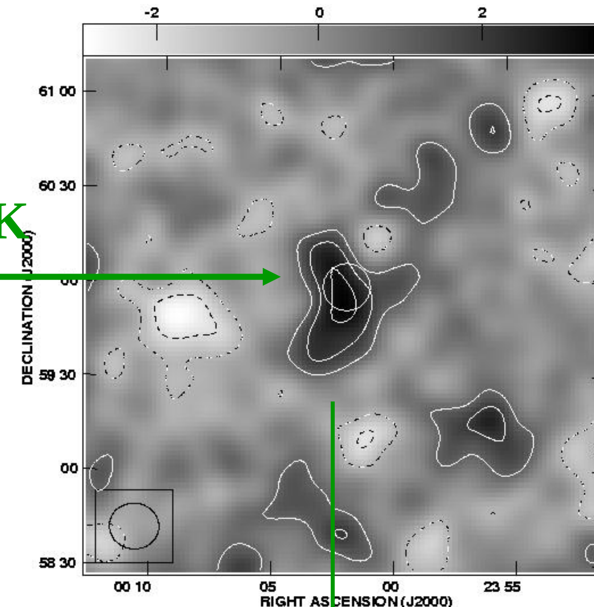
Table 1. Personnel & Responsibilities

Personnel	Inst.	Background[a]	Responsibility
L. Greenhill	SAO	sci	Project scientist and manager; data analysis
R. Blundell	SAO	sci/eng	Lead for SAO receiver lab activities
E. Tong	SAO	eng	Antennas and electronics design
R. Kimberk	SAO	eng	Construction and lab testing; deployment
S. Leiker	SAO	eng	Construction and lab testing; deployment
C. Carilli	NRAO	sci	Prototype testing; commissioning calibration and measurement; data analysis
R. Perley	NRAO	sci/eng	Prototype testing; commissioning calibration and measurement; data analysis
A. Loeb	Harvard	sci	Theory and modelling
M. Zaldarriaga	Harvard	sci	Theory and modelling
S. Furlanetto	CalTech	sci	Theory and modelling

Main Experiment: Cosmic Stromgren spheres around z=6 to 6.5 SDSS QSOs (Wyithe & Loeb 2004)

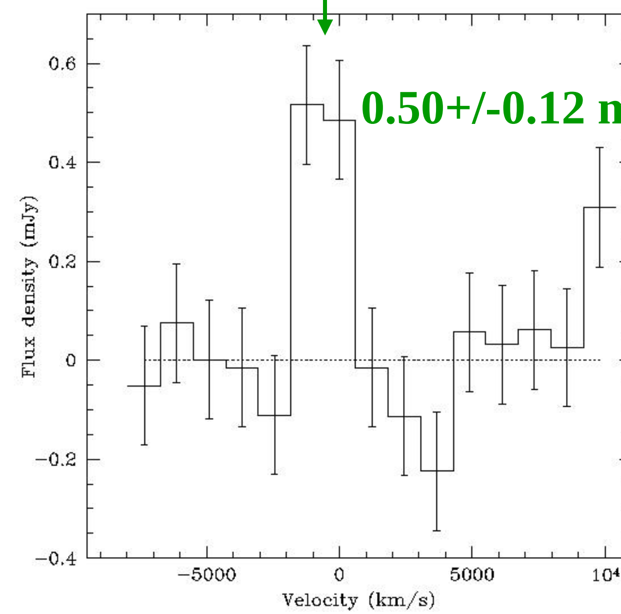


20 f(HI) mK

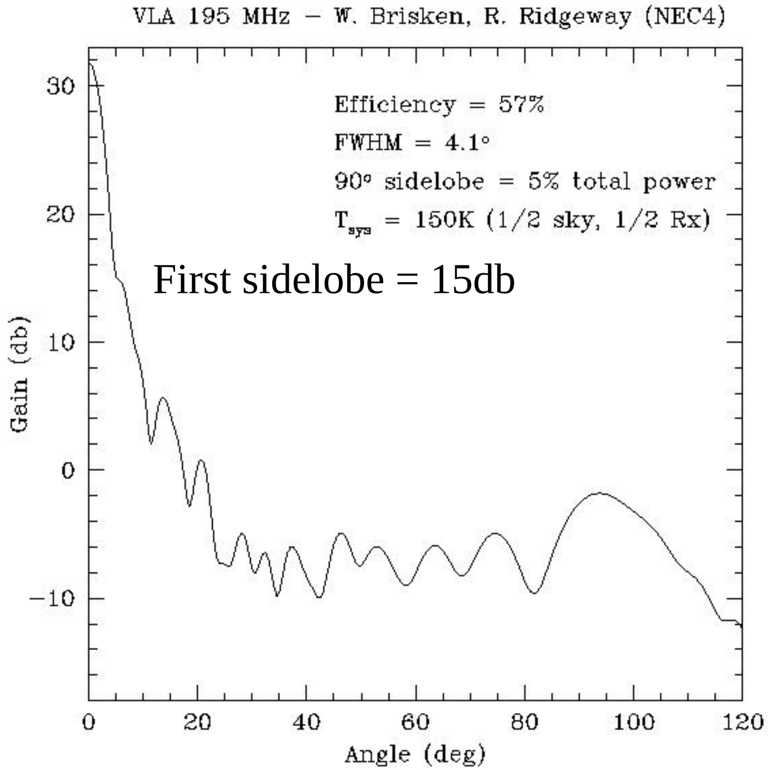


VLA-VHF
190MHz
250hrs

- VLA spectral/spatial resolution well matched to expected signal: 7’, 1000 km/s
- Set first hard limits on f(HI) at end of cosmic reionization (f(HI) < 0.3)
- Easily rule-out cold IGM (T_s < T_cmb): signal = 360 mK



System/Site characteristics



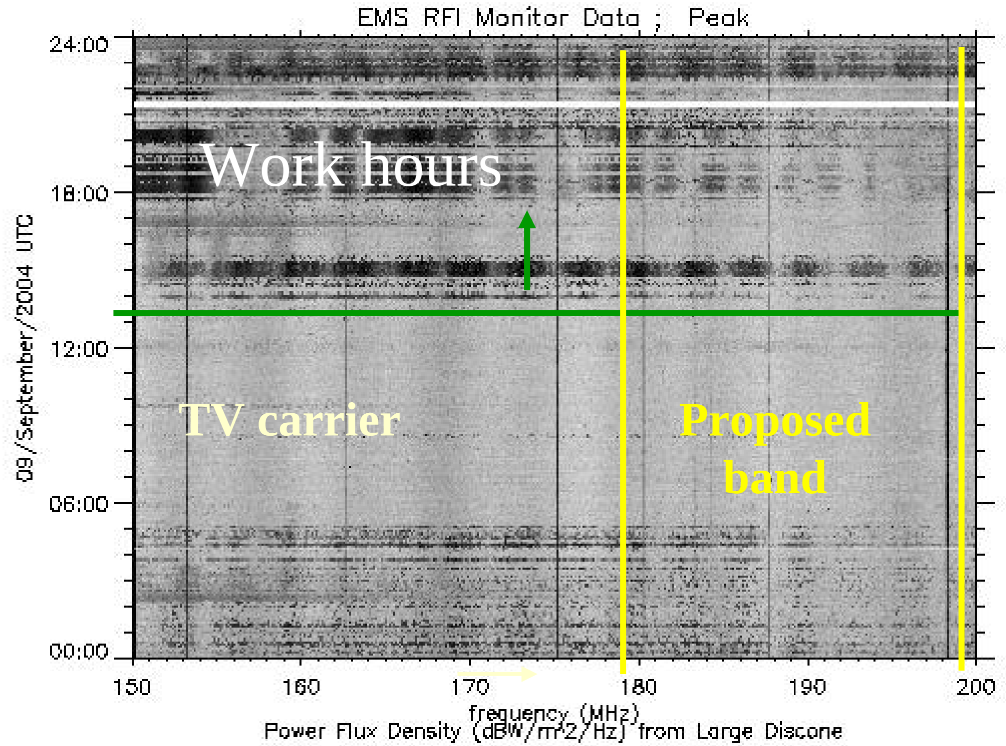
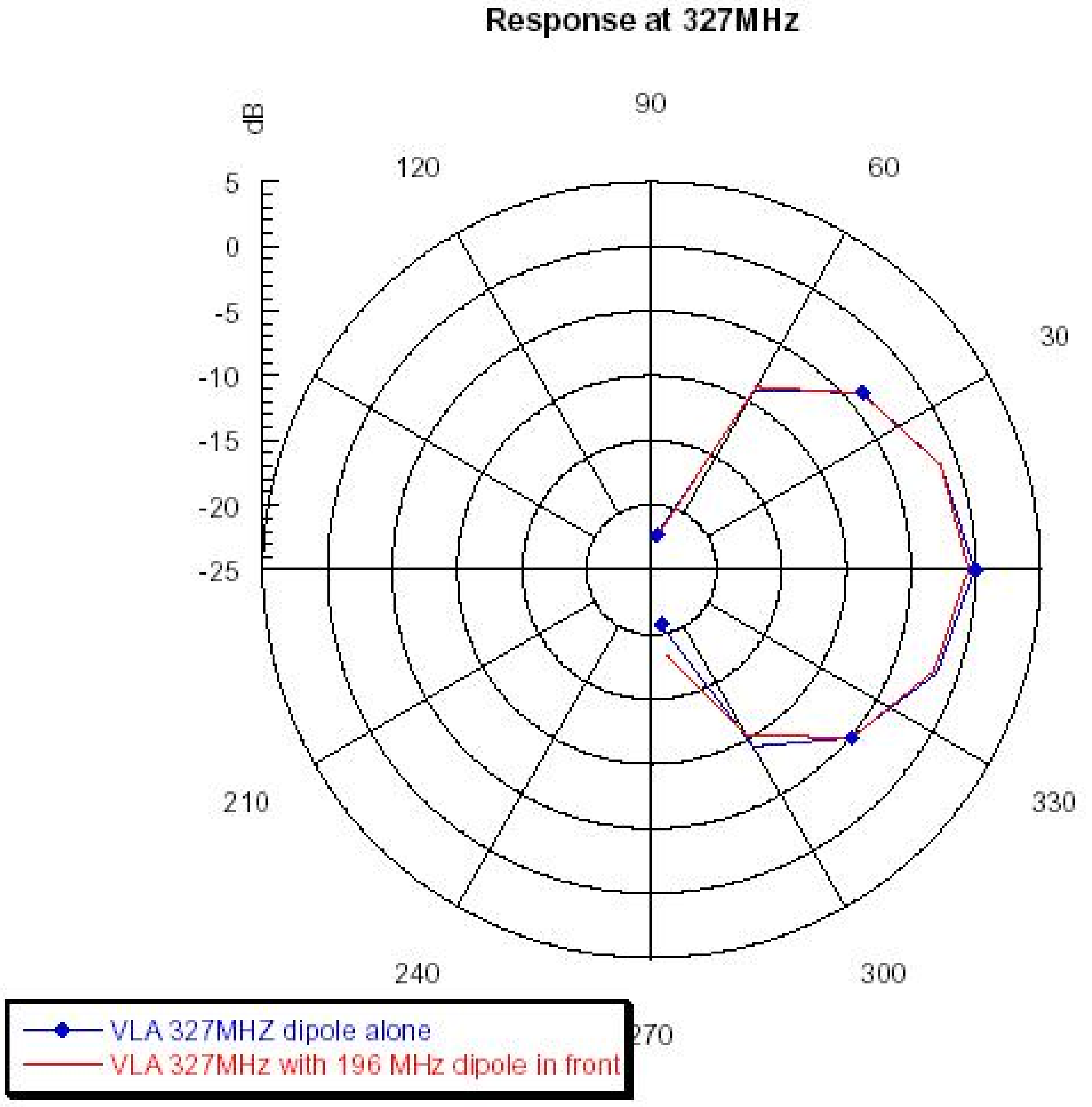


Table 1. VLA Low Frequency Systems

Band [MHz]	Passband [MHz]	A_e	T_{rx} [K]	T_{sky} [K]	D/λ	RMS(10min) [mJy]	Δ/λ	Focus loss	FoV† [°]	$(\mathrm{FoV}/\mathrm{scaled\ rms})^2$ $[(°)^2\ \mathrm{mJy}^{-2}]$
74	73-74.5	0.15	···	10^2	6	150	0.10	0.01	9.3	0.004
VHF	178-202	0.50	60*	100	16	2	0.27	0.08	3.5	0.43
320	305-337	0.40	100*	25	27	1.4	0.43	0.24	2.1	0.11
1400	1240-1700	0.55	30	3	125	0.06	···	···	0.5	0.25



0.5db loss (12%) at 327 due VHF

Challenges and ‘mitigation’: VLA-VHF CSS

- Ionospheric phase errors – Freq^-2 ; 4deg FoV; 1km B_{max}
- Sky temp = 100 (ν/200 MHz)^-2.6 K
- Confusion (in-beam) – spectral measurement (eg. Morales & Hewitt 2004); mJy point source removal w. A array; precise position and redshift
- Wide field problems – polarization, sidelobes, bandpass – all chromatic **?**
- RFI – “interferometric excision” (but D array); consistently ‘clean’ times in monitor plots (but very insensitive measure) **?**
- Effect on P/L **?**

Timeline: Funding proposal accepted SAO Aug04

- Observing proposal NRAO Sept 04
- P/VHF feed tests SAO Dec 04
- M+T doc. for NRAO Dec04
- Construct 10:1 scale model SAO Dec 04

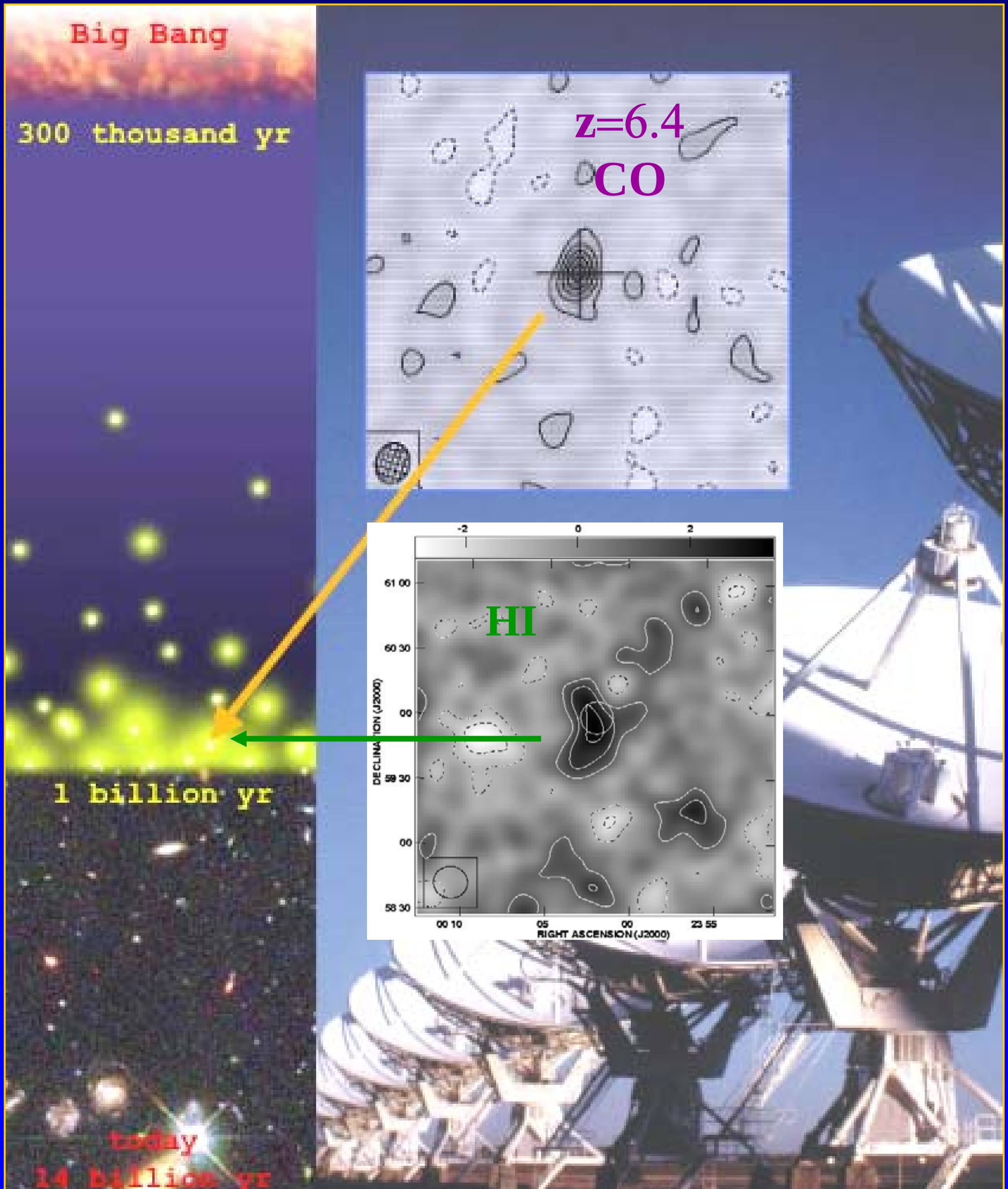
- Construct/deliver prototype SAO Jan05
- Single dish tests: RFI, impact L/P, T_{sys}, beam, eff… VLA Jan-Feb 05
- Interferometric tests 4 ants Mar-Apr 05
- Final design choice (fixed/deployable) Apr 05
- Full const/installation May – Aug 05
- First exp (150hr) D array Q4 05
- Large proposal: D array, Q1 07

Probing Cosmic Reionization with the VLA

- High freq: Study physics of the first luminous sources – mol gas + star form/AGN

- VHF: study process of reionization via CSS → set first hard constraints on f(HI) (<0.3) during the EoR

- Legacy: free new Rx band, potentially 'band of choice' at low frequencies



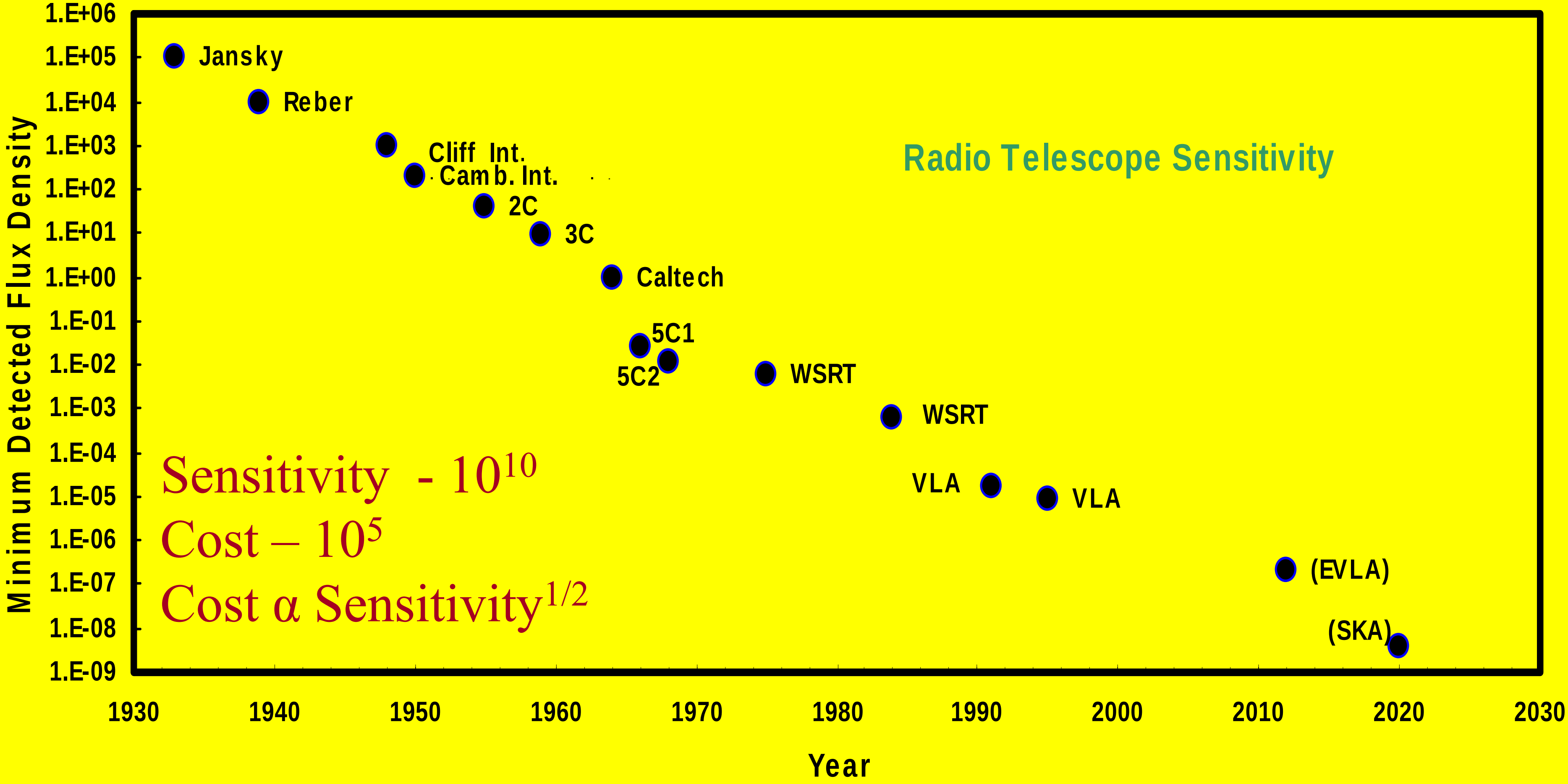
The Square Kilometre Array

- What?
- Why?
- How?
- Where?
- When?
- Who?
- How Much?
- Issues and problems

Official SKA design goals

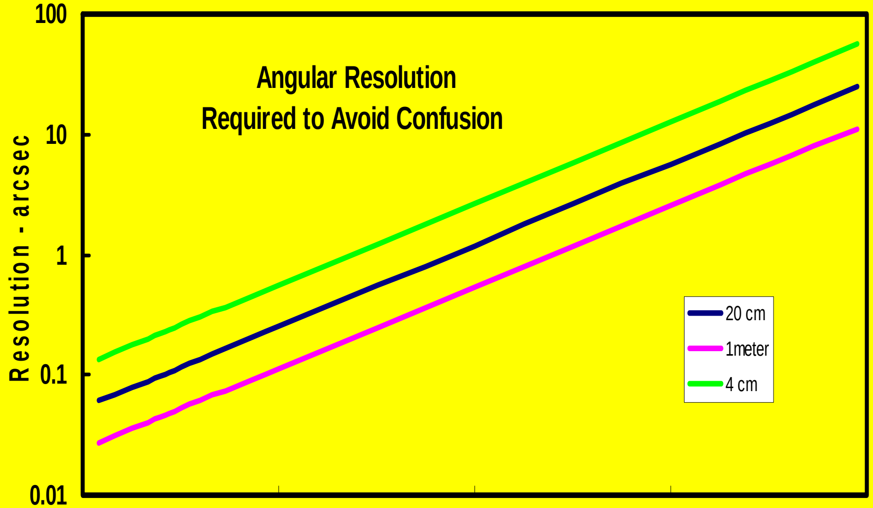
- Aeff/Tsys: 2 x 10^4 m^2/K

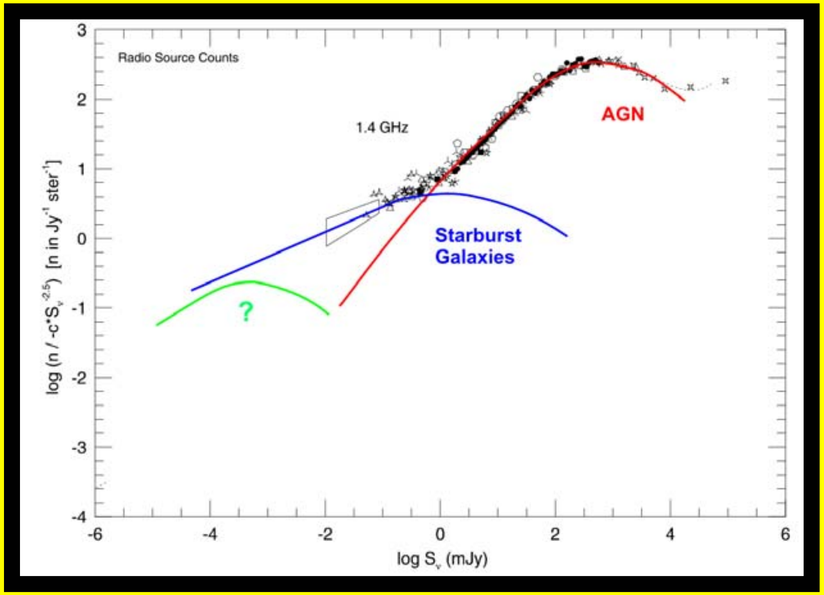
  (T_{sys} = 0.2Jy) ($T_{sys/VLA}$ = 16Jy)
- σ = 50 nanoJy rms - 1 hour
- Angular resolution: 0.1 arcsec or better @ 1.4 GHz
- Frequency range 300 MHz - 30 GHz
- Imaging Field of View: 1 square deg. @ 1.4 GHz
- Number of instantaneous pencil beams: 100
- Number of pixels: 10^8
- Surface brightness: 1K @ 0.1 arcsec (continuum)
- Instantaneous bandwidth: 0.5 + f/5 GHz
- Minimum number of spectral channels: 10^4
- Number of widely spaced, simultaneous frequency bands: 2
- Polarisation purity: -40 dB
- Dynamic range: 10^{6-7}

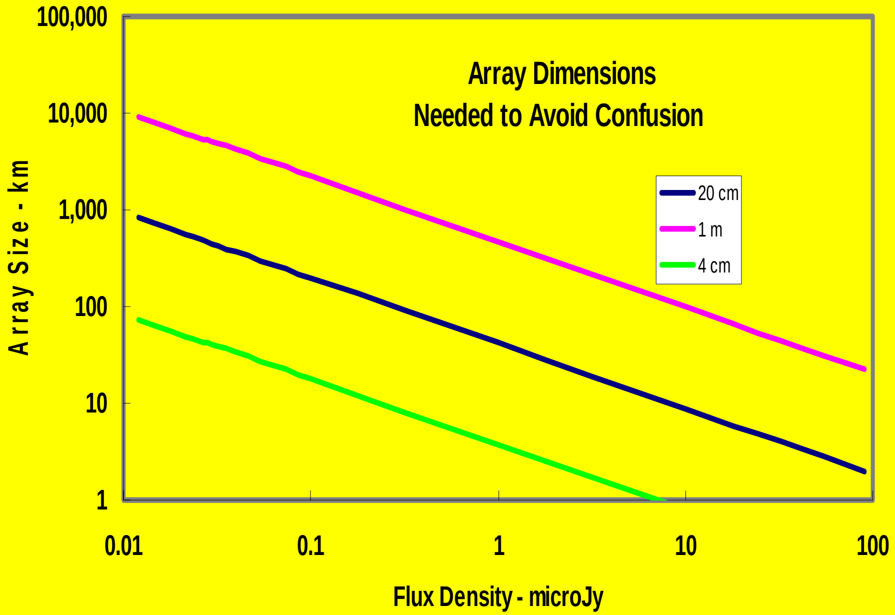


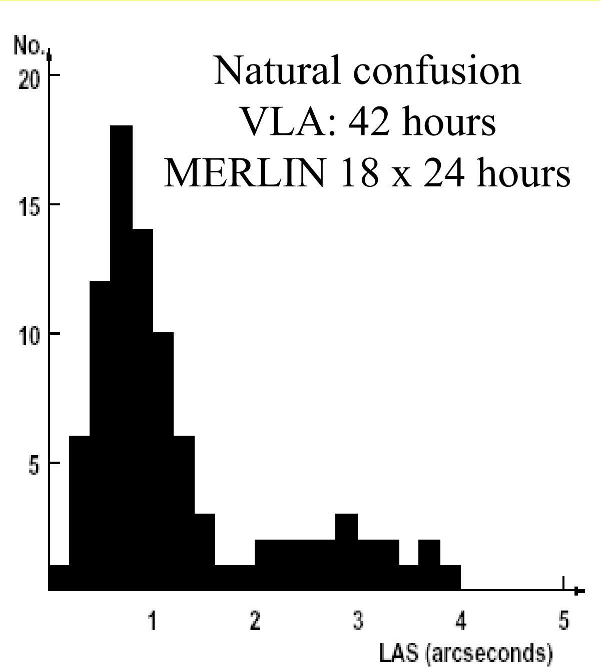
Radio Telescope Sensitivity
Minimum Detected Flux Density
Year
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Jansky
Reber
Cliff Int.
Camb. Int.
2C
3C
Caltech
5C1
5C2
WSRT
WSRT
VLA
VLA
(EVLA)
(SKA)
Sensitivity - 10^{10}
Cost – 10^{5}
Cost α Sensitivity$^{1/2}$

Confusion may be a problem









Key Science Goals

http://www.aoc.nrao.edu/~ccarilli/DHAPS.shtml

- The Cradle of Life
- Probing the Dark Ages
- Origin and evolution of cosmic magnetism
- Strong field tests of gravity (pulsars & black holes)
- Evolution of galaxies and large scale structure
- Exploration of the unknown

Astronomy is an observational science. We cannot do experiments. We can only observe, and we should not be afraid discovering something new. Today's hot new issues (fads) are tomorrow's old issues.

The excitement of the SKA will be not in the old questions it will answer but in the new questions it will raise.

Radio Astronomy Discoveries

- Cosmic radio noise
- Non thermal radiation
- Solar radio bursts
- Jupiter radio bursts
- Rotation of Mercury
- Internal heat source in giant planets
- Giant molecular clouds
- Cosmic masers
- Extrasolar planetary systems
- Radio Galaxies (black holes)
- Cosmic evolution
- Quasars
- Relativistic jets
- Pulsars (neutron stars)
- Gravitation lensing
- Gravitational radiation
- Cosmic Microwave Background

Why radio?

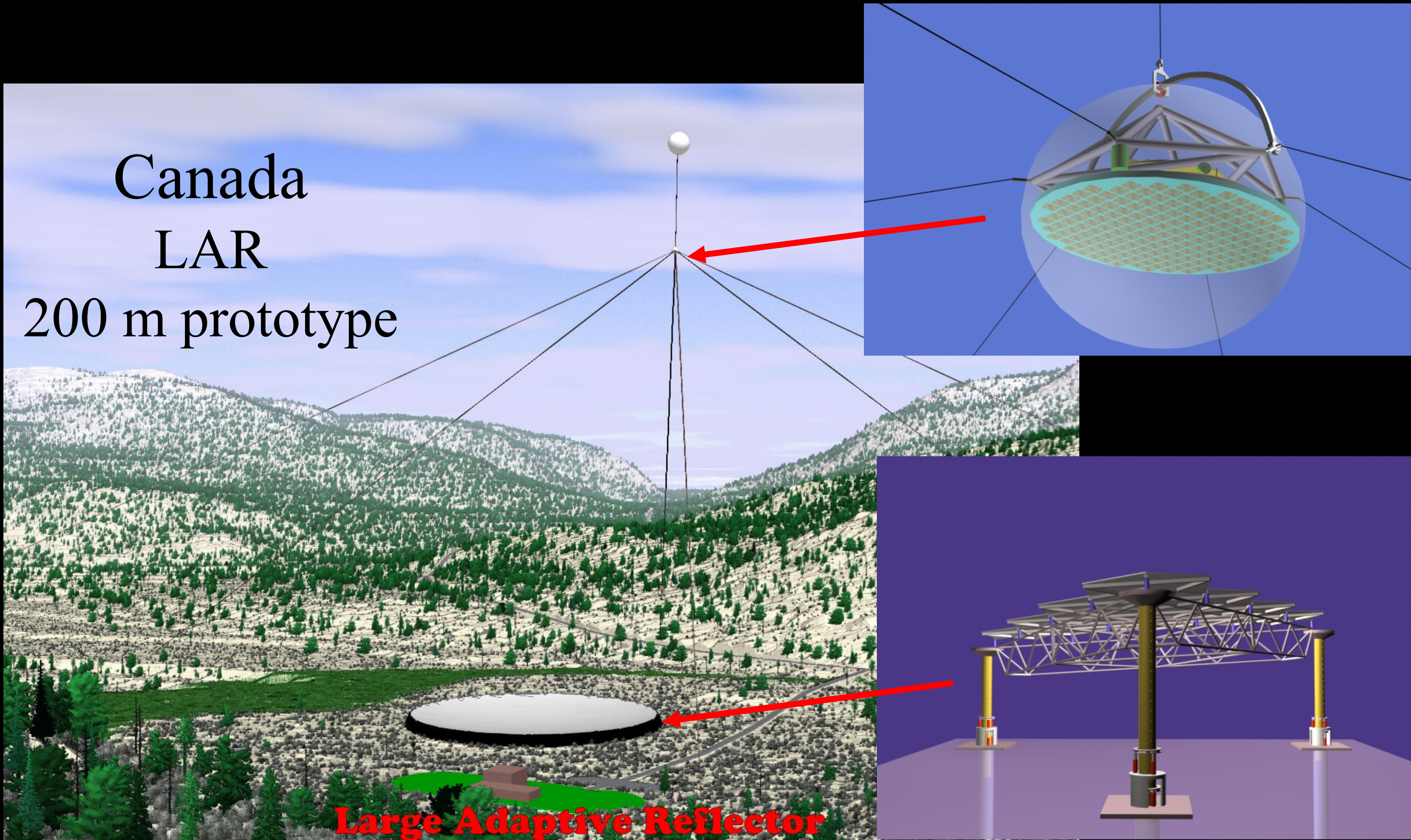
- The sky is nearly empty, so we can use unfilled apertures.
- Long coherent integration times are possible
- We can build amplifiers and split the signal without loss
- High resolution diffraction limited imaging is possible with post processing so that adaptive optics at radio frequencies involves no precision moving parts
- But, large radio telescopes are needed! Even moderate sized radio telescopes are uninteresting.

How to build the SKA

- *Brute force* – Replace all EVLA antennas (27 VLA + 8 NMA + 10 VLBA) with 45 GBTs. Use EVLA infrastructure - fiber, correlator, receivers, computers, software: *Cost about \$ 5 x* 10^9
- *Be Clever!*


Square Km Array
Europe
USA
India
Australia
China
Canada

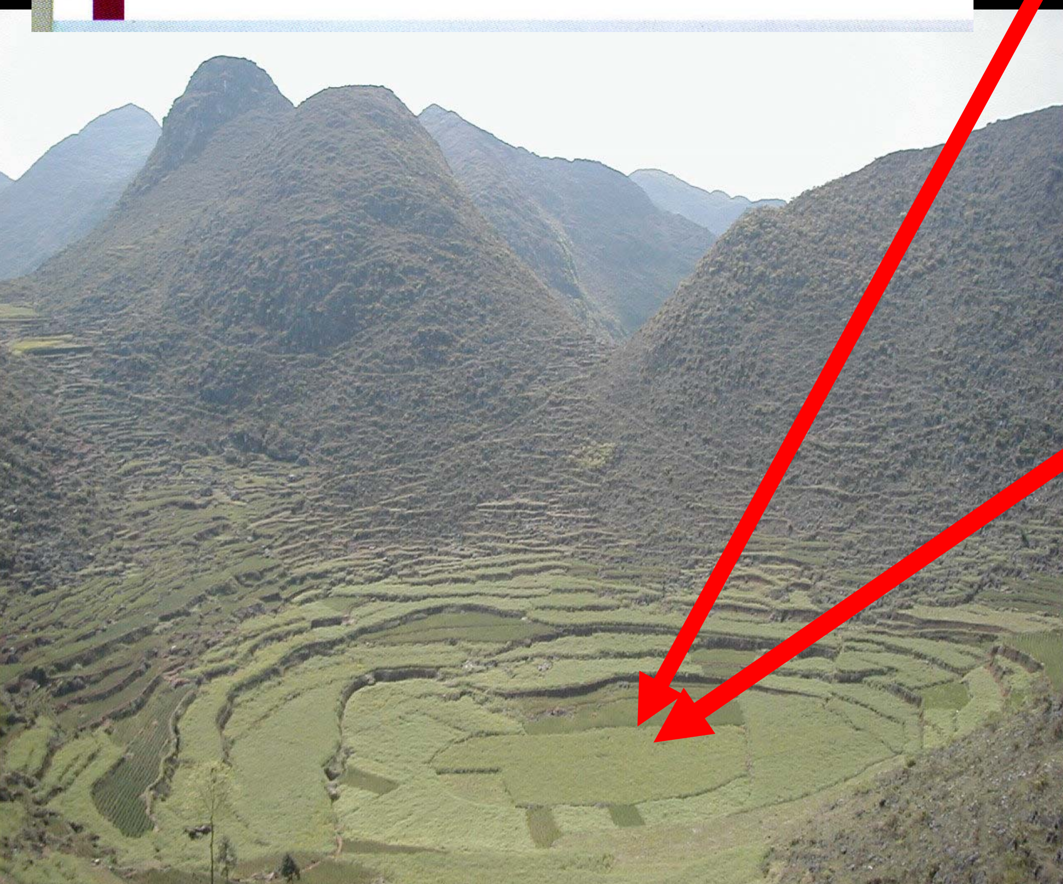

Europe
SKADS (€ 32 M)
1 x 500 m² array at WSRT
3 x 100 m²
Upgrade of Bologna Cross
32
SKA


Canada
LAR
200 m prototype
Large Adaptive Reflector

Australia
MNRF

MWA (son of LOFAR)
with
Haystack
80-300 MHz

China



FAST

Five hundred meter Aperture Spherical Telescope

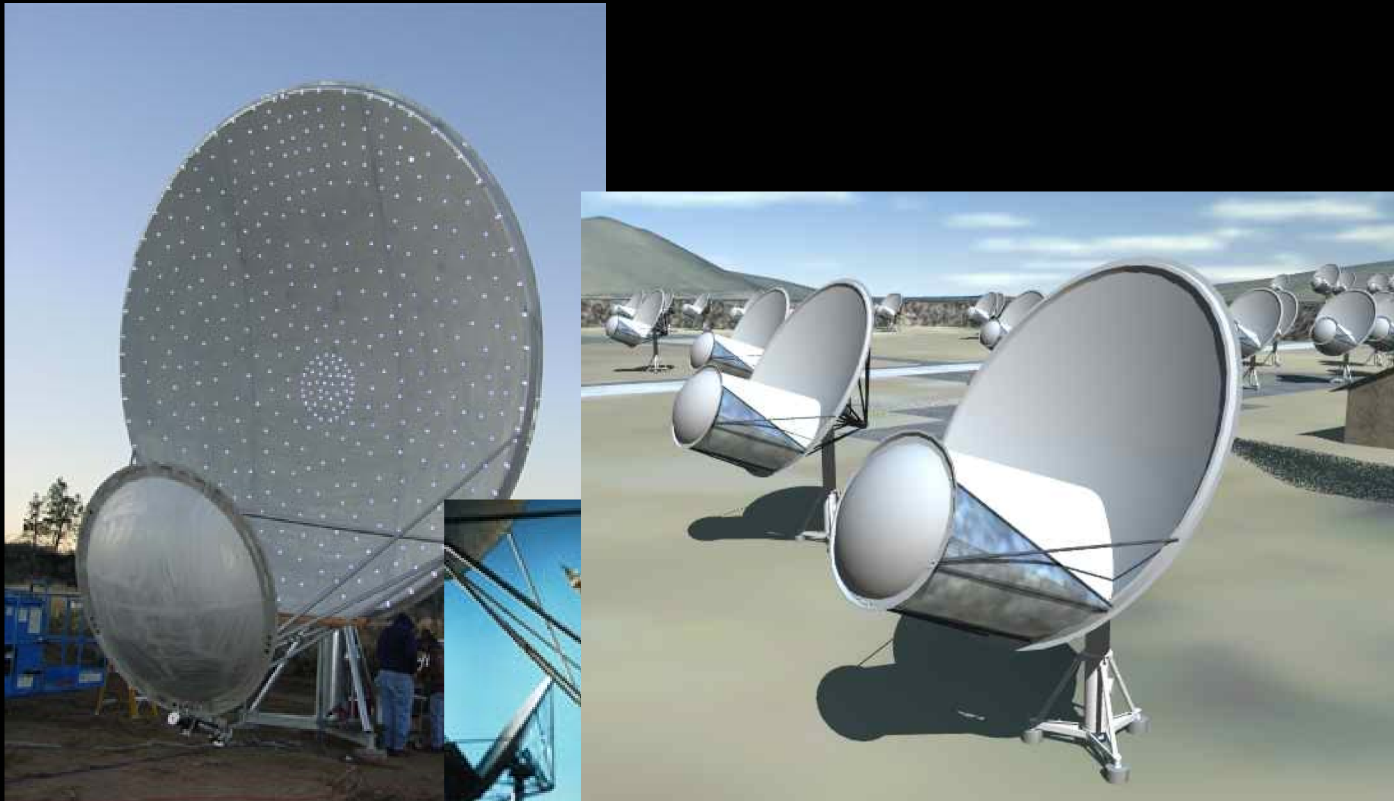
U.S. Consortium Concept
ATA type Synthesis Array
Large N/Small D

Why parabolic dishes?
- experience
- sky coverage
- frequency coverage

Why large N?
- collecting area
- dynamic range
- baseline diversity
- snapshot mode
- self-calibration
- RFI excision

Why small D?
- field-of-view
- minimizes cost?

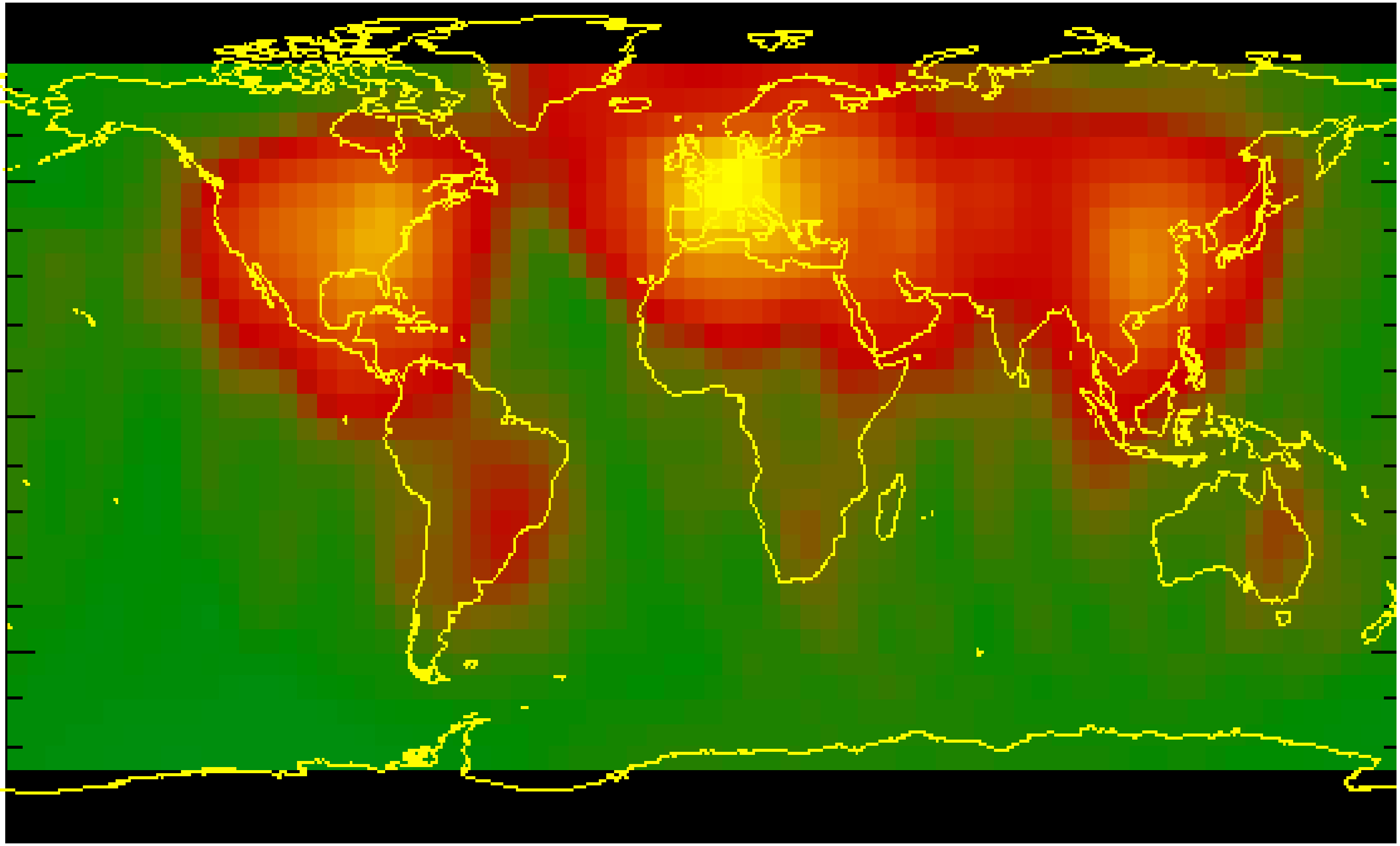
4400 x 12 m dishes



Where will the SKA be built?

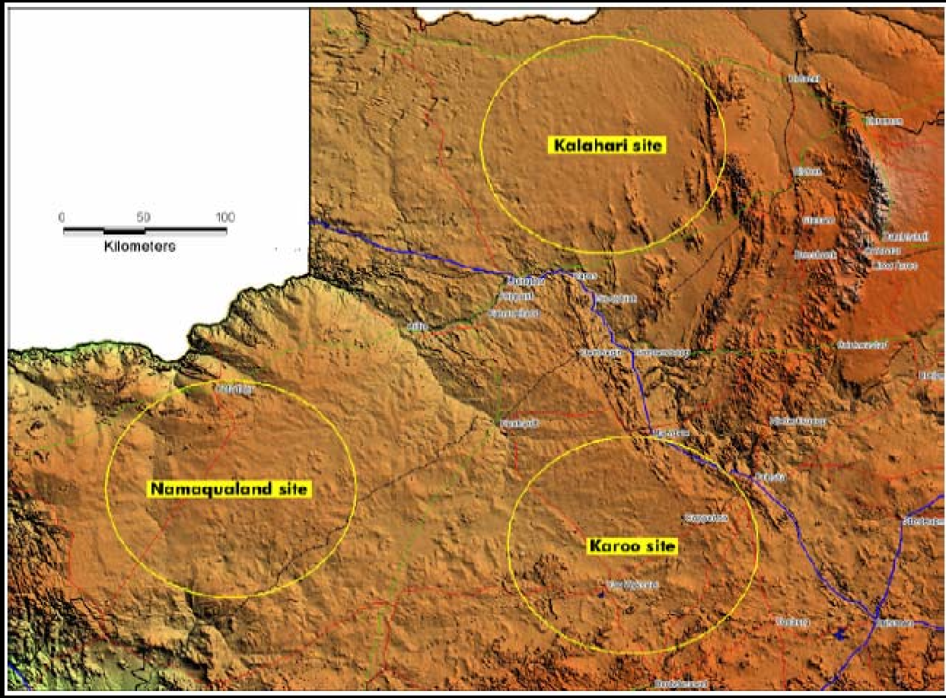
- RFI environment (low population density)
- Troposphere stability (high dry desert site)
- Southern hemisphere – Galactic Center
- Political issues – who has the money. He who has the gold rules!
- 6 preliminary proposals submitted
  - U.S, Australia, South Africa, China, Argentina, (Brazil)
- Siting RFP issued September, 2004
- Site proposals due December 31, 2005
- 2006 Site selection or down-selection

Distribution of RFI



Mileura Station, WA

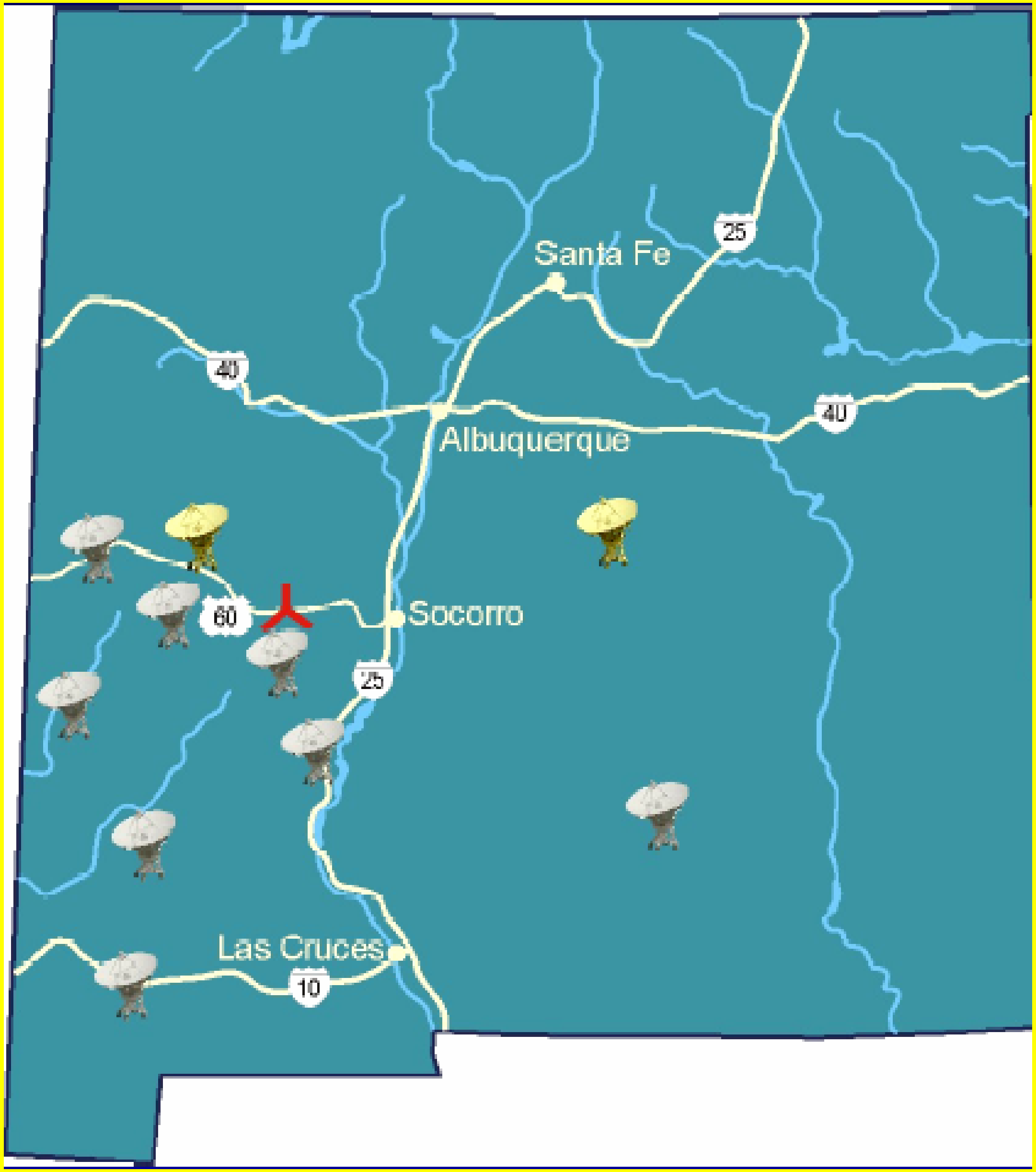
Northern Cape Province, South Africa

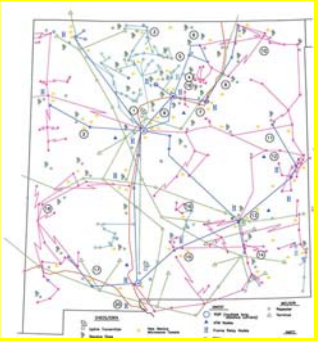


Potential Sites in China


Argentine Site

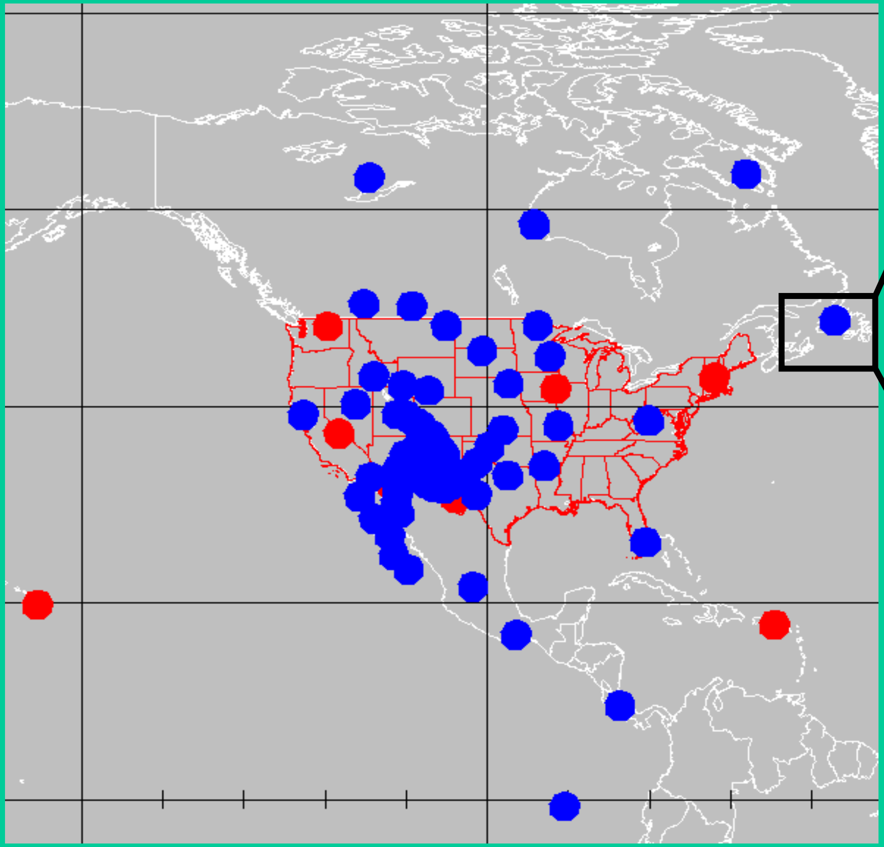
VLA+NMA+VLBA

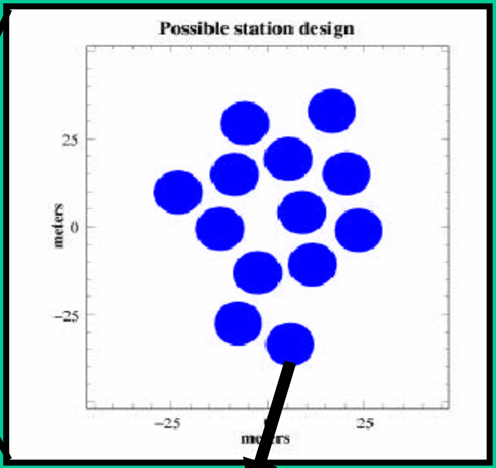




- Infrastructure
- Roads
- Fiber
- Schools
- Medical facilities
- Scientists/Engineers
- Federal Labs, Nat. Obs
- VLA
  - Long term site data
  - Good phase stability
  - RFI?
  - Political situation?

US – Large-N/Small-D



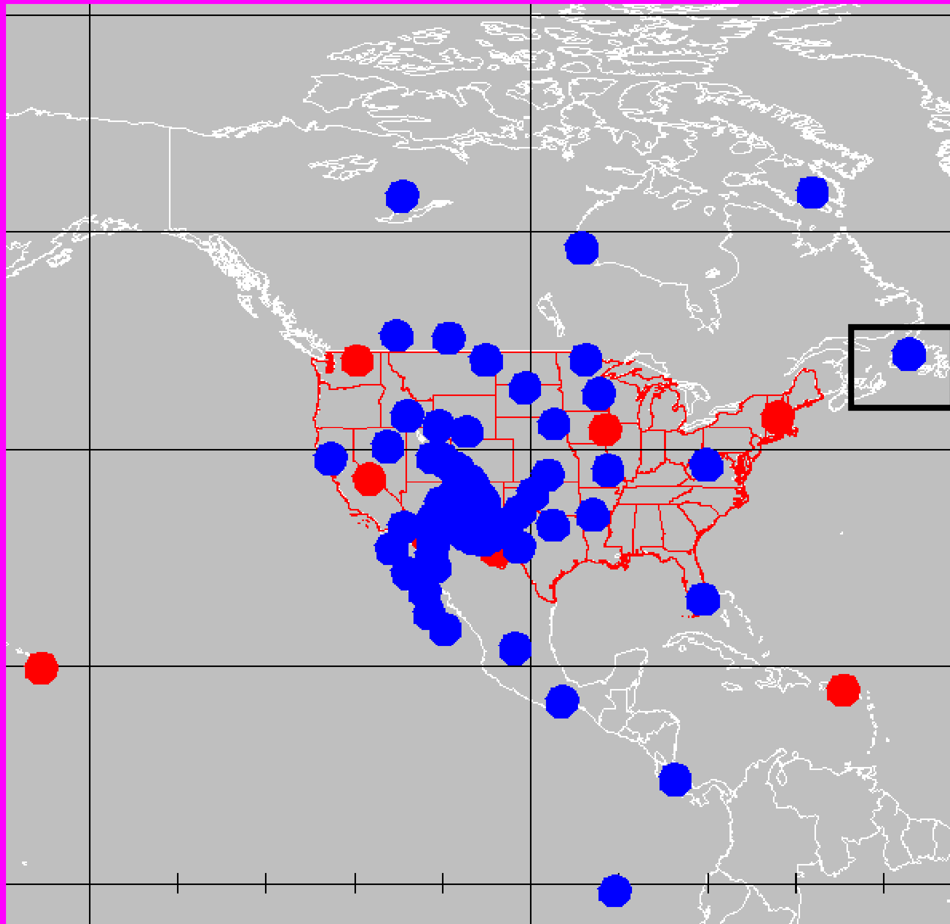


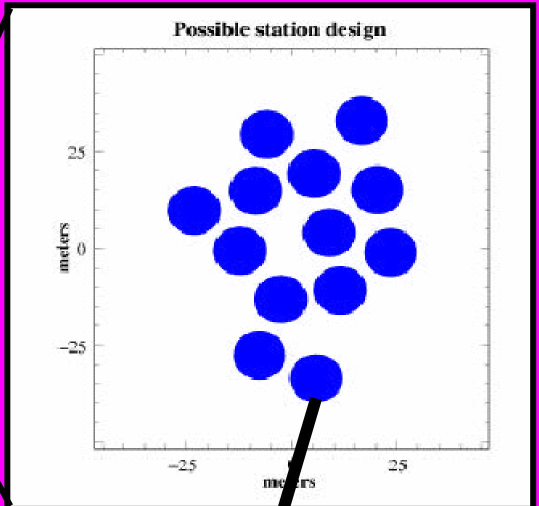
84 stations
35-350 km

76 stations
350-3500 km

Inexpensive, hydroformed dishes

2320 x 12m antennas within 35 km core





US SKA Configuration

Resolution 0.01 arcsec
@ 21 cm

Centrally condensed
Scale free array
2320 ant inside 35 km
84 stations: 35 to 350 km
76 stations: 350 to 3500 km

Scale free configuration adopted to accommodate a wide range of scientific goals, but this is controversial

When

- **1994** **IAU/URSI Large radio telescope WG formed**
- **1998** **Green Bank Workshop**
- **1999** **Formation of U.S. SKA Consortium**
- **2000** **MOU signed by six groups, ISSC formed**
- **2002** **Seven design concepts (white papers) received by ISSC**
- **2004 Sept:** **Siting RFP**
- **2005 Dec 31:** **Site proposals due**
- **2006** **Site selection or down-selection**
- **2008** **Facility definition, plan pathfinder/prototype/demonstrator**
- **2009** **Start pathfinder construction (5-10% SKA)**
- **2011** **Propose SKA construction**
- **2012** **Start construction**
- **2015** **First Science**
- **2020** **Full operation**

SKA Project Organization

International SKA Steering Committee (ISSC)

22 members representing 12 countries

Chair: Phil Diamond (MERLIN)

- 6 European (UK, Germany, Netherlands, UK, Italy, +1)
- 6 United States (Tarter, Welch, Terzian, Kellermann, Preston, Cordes, +1)
- 2 Canada
- 2 Australia
- 2 Asia (China, India)
- 1 (South Africa)
- 1 At-large member (Ekers)

Engineering Working Group
Chair: Peter Hall (Australia)
Antennas
Software & Computing – Tim Cornwell
Signal Transmission
RF Systems
Signal processing – Larry D'Addario
Interference mitigation
Systems Engineering – Dick Thompson
Industrial liaison

International Project Office
Director: Richard Schilizzi
Project Engineer: Peter Hall

- 2004 Budget: $185 K for Project Director
  - 1/3 from U.S.
    - 50 K from NSF grant to U.S. Consortium
    - 12 K from member dues to Consortium
- 2005 Budget: $707K Euro = $947K
  - Project Director
  - Project Engineer (currently supported by Australia)
  - RFI testing (currently supported by ASTRON)
  - 1/3 from U.S. or $315K
    - $150K available from NSF grant and consortium funds

US SKA Consortium*

Chair: Yervant Terzian (Cornell)
Vice Chair: Jack Welch (UCB)

Caltech/JPL
Cornell/NAIC
Harvard/Smithsonian CfA
MIT/Haystack
NRAO (KIK, RCW)
NRL
SETI Institute
Virginia Tech
University of Minnesota
University of New Mexico
UC Berkeley
University of Illinois
University of Wisconsin

*Each institution pays $3 K per year in dues for EPO, travel, IPO

US SKA Prototype Activities

Allen Telescope Array (SETI)	DSN Array	EVLA
310 6m dishes f = 0.5-11GHz 2003: First antenna 2004: 3-elements? 2005: 32-elements? 2006 or 7: 200 elements Goal: 351 elements	3 x 3600 x 12m dishes f = 8/32GHz 2003 6m prototype 2005 2x6m interferometry + 1 x 12 m 2008 6 x12m x 3 sites 2013 400x12mx3 sites =1200 Expensive? Symmetric Antennas	45 x 25m antennas f = 1-50 (90) GHz (VLA+NMA+VLBA) 2001 Start Upgrade 2006 Start NMA construction 2012 EVLA I Operation 2012 EVLAII Operation

Long Wavelength Array

U.S. SKA Technology Development Program

- **U.S. development program is currently supported via a 3 year $1.5M grant to Cornell – June 2002 to June 2005**
- **U. S. Technology Development Program $ 32 M proposed to NSF over 5 years. Managed by NAIC.**
  - Antennas, Feeds, Optics, Receivers – Weinreb, JPL
  - Digital signal transport and processing – Cappallo, Hsk
  - System analysis and design – Jones, JPL
  - Operations and costing – Goldsmith, NAIC
  - ATA test facility – Bock? UCB
  - Site Proposal Preparation (due end of 2005) - UNM?
  - EPO – Tarter, SETI
  - International Project Office, exchange rate problem, NSF problem
- **TDP competing with FASR, LWA, LSST, and TMT**
- **TDP funding not likely to receive full 32M; gap is likely**
- **Time scale (2005-2009) of TDP is a problem**
  - **2008 Concept selection**
  - **2006 Site selection**
- **TDP Review was held at the NSF on October 26**
  - **Unclear goals of TDP – does not lead to construction**
  - **Unclear management, what right has the ISSC to decide anything?**
  - **Cost and value of prototype hydroformed dish**

Other SKA development programs

Australia

Major National Research Funding Program

HIFAR (AUD 100M)

MWA (AUD 50)

Site proposal (WA)

Europe (SKADS)

Square Km Array Design Studies

€ 32M (€ 14/10M EC),

34 Institutions in 13 “European” Countries - 5 year program

Netherlands, UK, Paris, Bologna, MPIfR, Spain, Russia, Canada, South Africa, Poland, Sweden, Australia

South Africa, Australia & Argentina have major funding for site proposal

Canada – LAR

NRAO and the SKA

- NRAO staff are heavily involved in the international SKA program. ISSC, EWG, SWG
- NRAO organized the first meeting of U.S. scientists interested in the SKA
- NRAO is a member of the U.S. SKA Consortium
- The U.S. LNSD White paper was prepared at NRAO
- NRAO has tried to keep a low profile in the organization of U.S. SKA activities. NRAO is not part of NSF TDP proposal
  - Zero sum game for NRAO
  - The planning and design of new facilities is part of our job. Most of the areas where we plan to contribute are spin-offs from EVLA development
    - Wide field high dynamic range imaging, data management, and archiving
    - Long distance data transmission
    - Site proposal – NMA sites
    - Building the scientific case

How much will it cost?

4400 x 12 m antennas	$ 660 M
Receivers	170
Data transmission	40
Civil costs (central site)	65
Civil costs (outer configuration)	135
Signal processing	80
Computing hardware	80 (500?)
Software development (660 man years)	50
Non-recurring engineering	60
Contingency (20%)	270
Total	**$1,610 M**

How much will it cost to operate

Operations Staff	36 FTE's	$ 1.8 M/year
Scientific Staff	30	3.0
Computing Hardware Support	10	0.9
Computing systems plus M/C	40	4.0
Data management	10	1.2
Central engineering	150	12.0
Distributed engineering	240	19.2
Administration	50	4.0
Fiber rental		10+???
M&S		15.4
Upgrades (3% construction)		50.0
User support (3% construction)		50.0
Total annual operating cost		**$ 171.5**

Who is going to Pay for it?

- Default plan
  - U.S. 1/3
  - Europe 1/3
  - RoW (Canada, Australia, Asia, Africa) 1/3
- Problems with this plan
  - U.S. funding must wait until EVLA, LSST, ATSC, and TMT (aka GSMT)
  - NSF not interested in divesting control/power
  - European priority with OWL
  - Canada: may depend on choice of concept
  - Australia, South Africa may depend on site

Technical challenges for the SKA

- Constructing a cost effective SKA
  - Antenna elements
  - Low cost high reliability radiometers
  - High data rate signal transfer (100 x EVLA
  - Correlator
  - Wide field high dynamic range imaging
  - RFI mitigation
  - Data management and archiving
- Confusion levels - natural confusion
- Reliable and cost effective operations

Logistical, administrative, cultural, financial challenges

Funding an international project?

- SKA was international from the start
- Different funding/management cultures in each country

- Who is responsible for
  - Setting policy?
  - Fiscal accountability?
  - Program management?
  - Banking Issue
- Should there be
  - Strong central management – e.g., NRAO/AUI, ESO
  - Weak central management with power shared among partners – e.g., ALMA
- Intellectual Property Rights/ITAR/visas
- Continued broad participation after site and concept selection.
- Rationalization of construction schedule with U.S. TDP and European SKADS technology development schedules, and with expected funding profile.
- Competition from national ambitions (SKA demonstrators/prototypes)
  - US (ATA, EVLA, LWA, FASR)
  - Australia (HIFAR, MWA)
  - China (FAST)
  - Canada (LAR)
  - Europe (e-MERLIN, LOFAR)
- The SKA has been a catalyst for a wide range of technical investigations with applications to radio astronomy and space craft tracking.

Some SKA scenarios

- Build on EVLA = VLA/NMA/VLBA by increasing collecting area and using existing infrastructure, e.g., roads, power, fiber, skilled scientists and engineers currently in New Mexico.
  - This approach is probably decades away
- Build a low frequency ($\nu < 1$ GHz) array on a radio quiet site in Western Australia which complements the EVLA
  - Who will pay for it?
    - **U.S. (NSF) should contribute as we need a facility for $\nu < 1$ GHz**
    - **RoW has been using VLA, Green Bank, Arecibo for free**
      - **Time for the RoW to provide their share**
      - **Will we have an open skies policy in the ALMA era**
- NSF to negotiate with NASA for time on DSN array with NSF supported instrumentation for radio astronomy

Whither NRAO?

- Continue to muddle along with the crowd, write reports, go to meetings in exotic places.
- Assert leadership
- Forget it for the present. We have too many other things to do.

Resources for further study

Science Case:

http://www.aoc.nrao.edu/~ccarilli/DHAPS.shtml

International SKA:

http:/www.skatelescope.org/

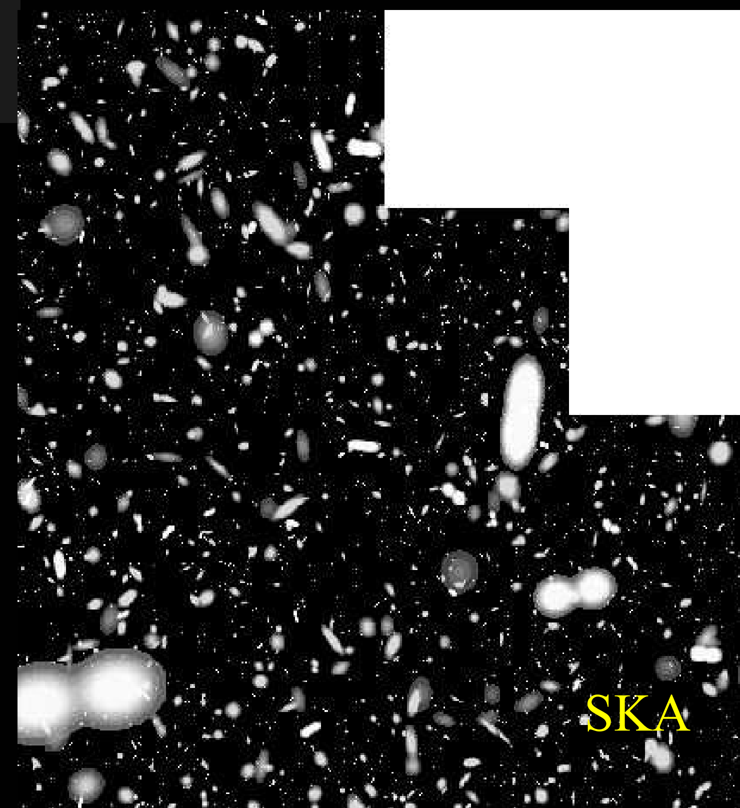
U.S. SKA

http://astrosun2.astro.cornell.edu/research/projects/ska/main.shtml

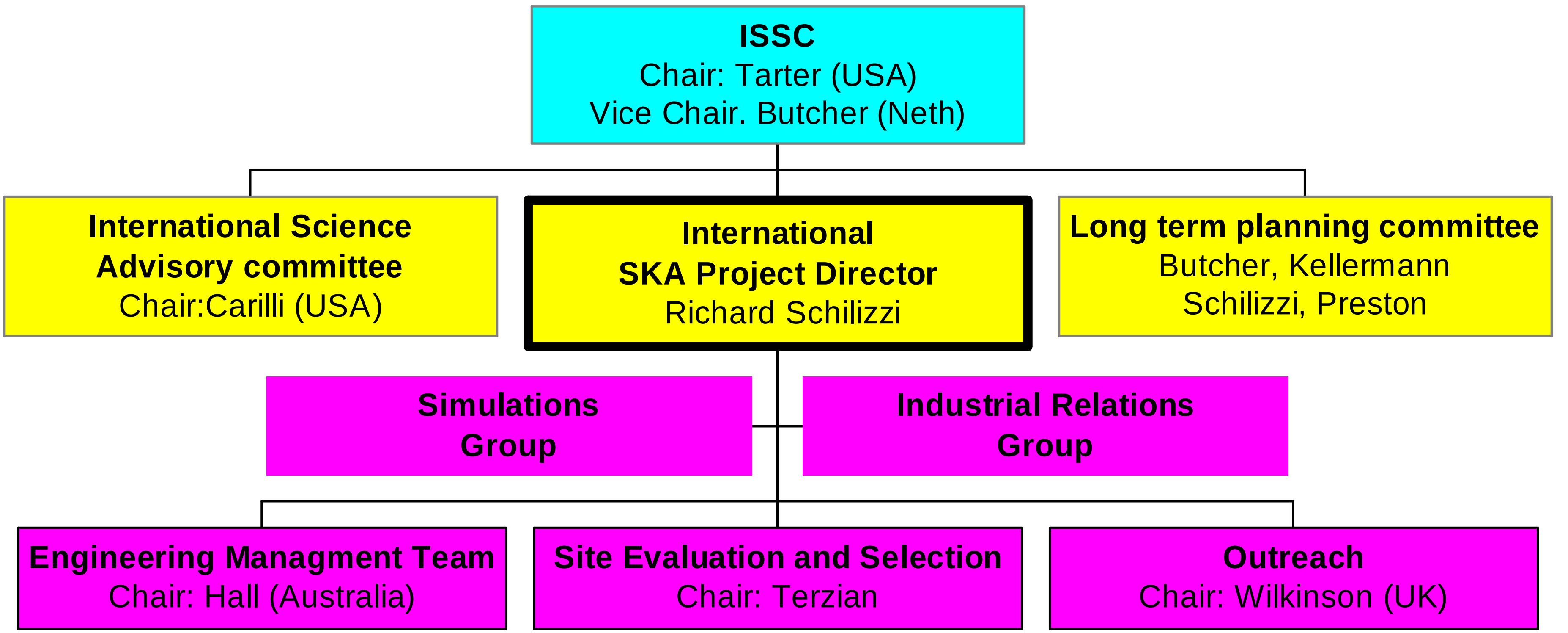
LNSD

U.S. Site Proposal

Hubble Deep Field



Current SKA Management Structure

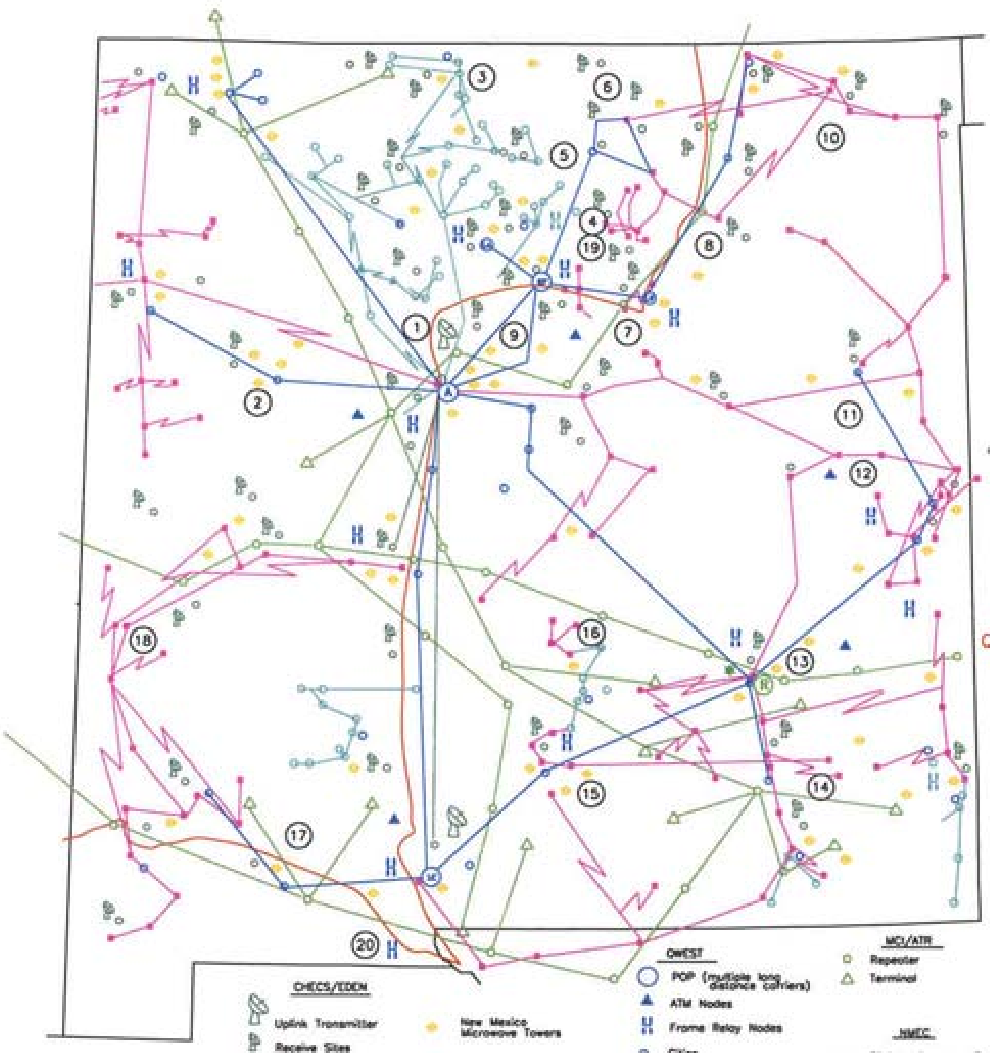


U.S. SKA Plan

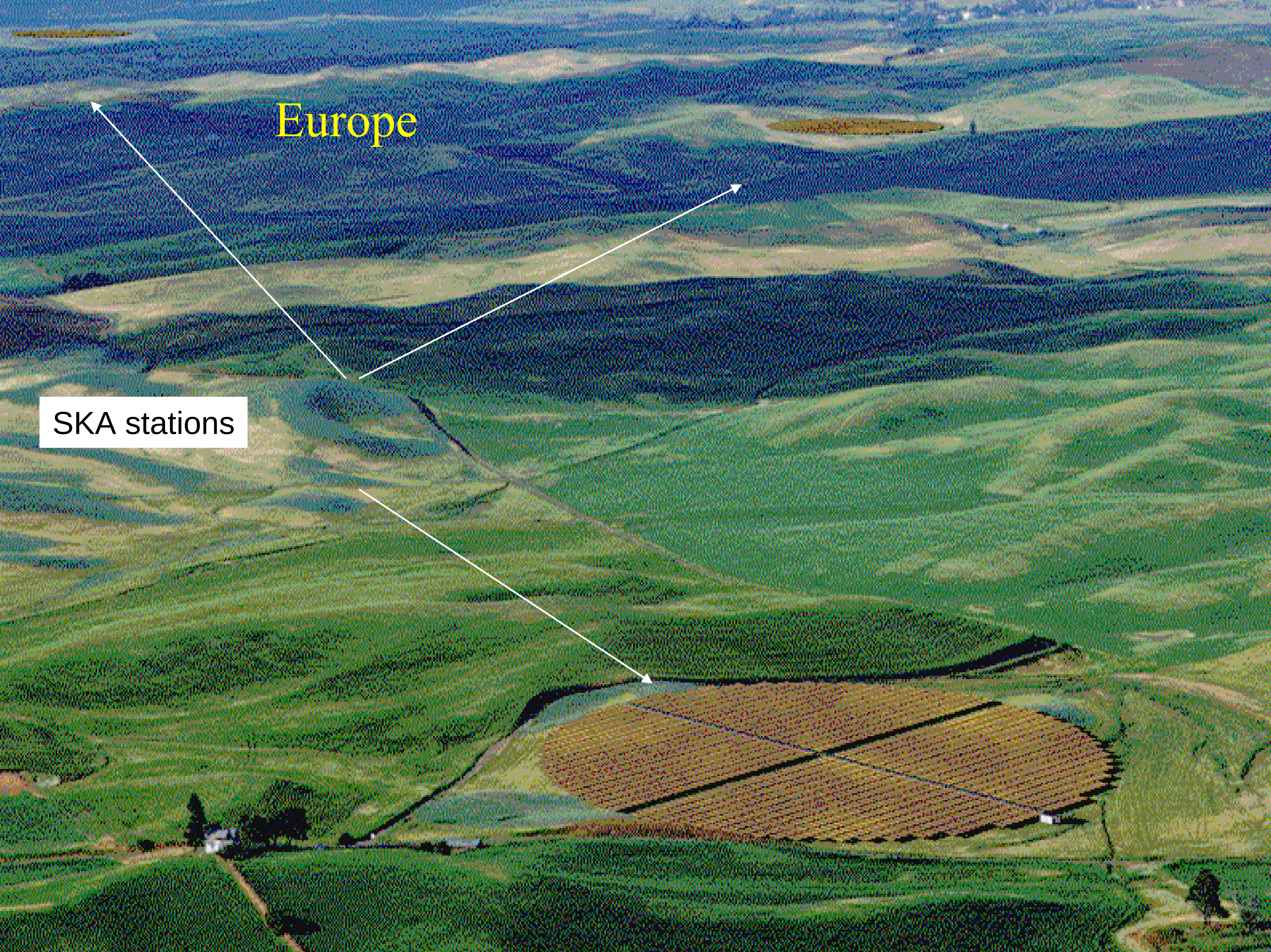
- Complete ATA
- Continue DSN Prototype
- Develop new technologies with NSF funds
- Build LOFAR in U.S. South West (NM)
- Complete EVLA
- Grow SKA in the US Southwest using new antenna technology

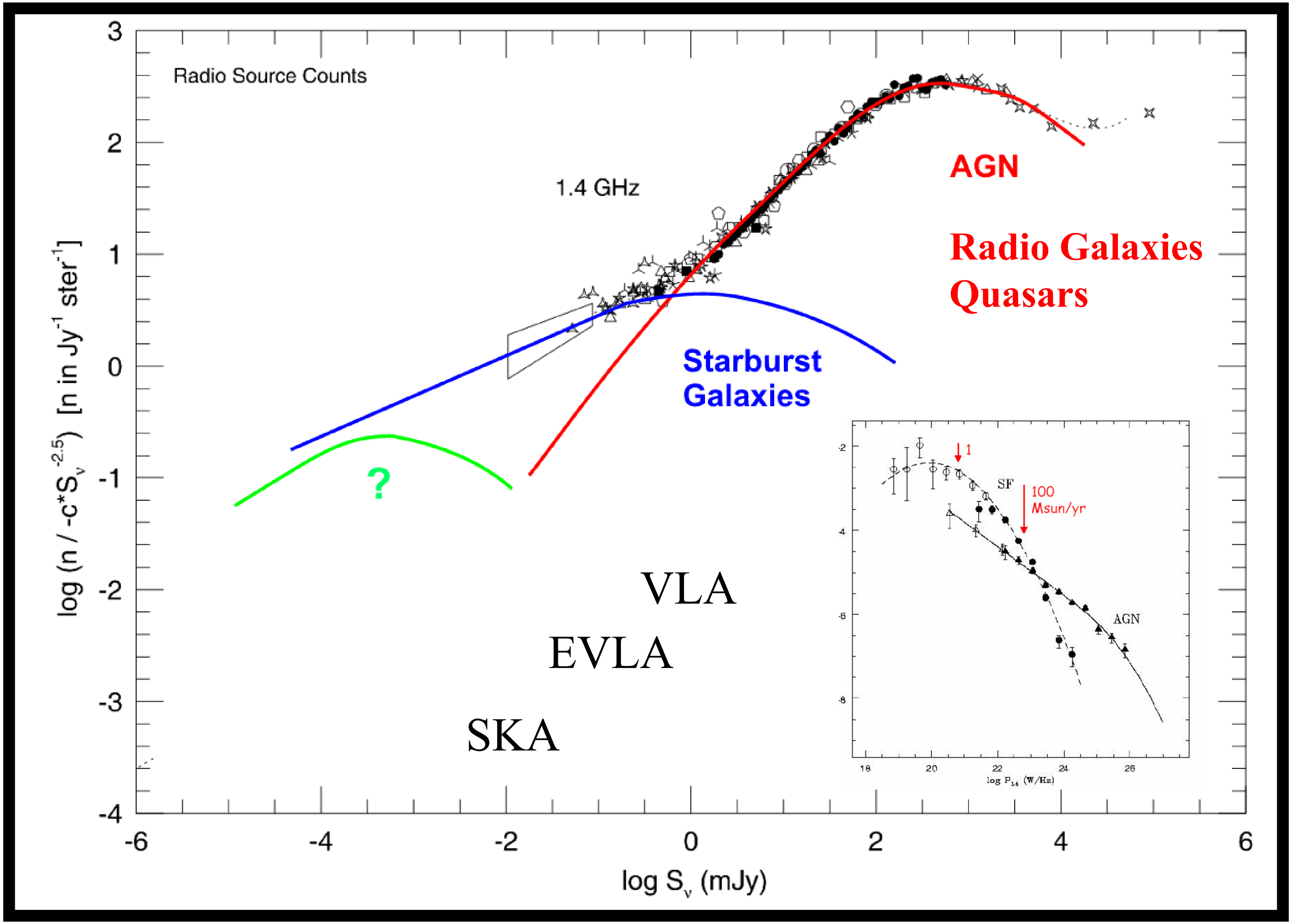
SKA Goal – 40 x improvement in sensitivity over EVLA

- First epoch of star formation and galaxy formation at z = 1
  - Molecules at z >> 1
- NanoJy continuum surveys
  - 25 nJy rms in 1 hour
  - Normal Galaxies at z = 1
- Spiral galaxies HI at z =1
  - CO at z=5
- Transient radio sources
  - Giant pulses, flares
  - ISS – high resolution observations of pulsars, GRBs
- Radio galaxies, quasars, BH and relativistic beam physics
  - Acceleration near MBHs
- Magnetic fields
  - Jets, galaxies, clusters, Faraday rotation
- Cosmic (H_2O) masers
  - Geometric distance beyond the local flow
- Stars of all types - thermal
- Solar System
  - Asteroids, TNOs, radar
- Census of MilkyWay Pulsars
- SETI



New Mexico fiber installation

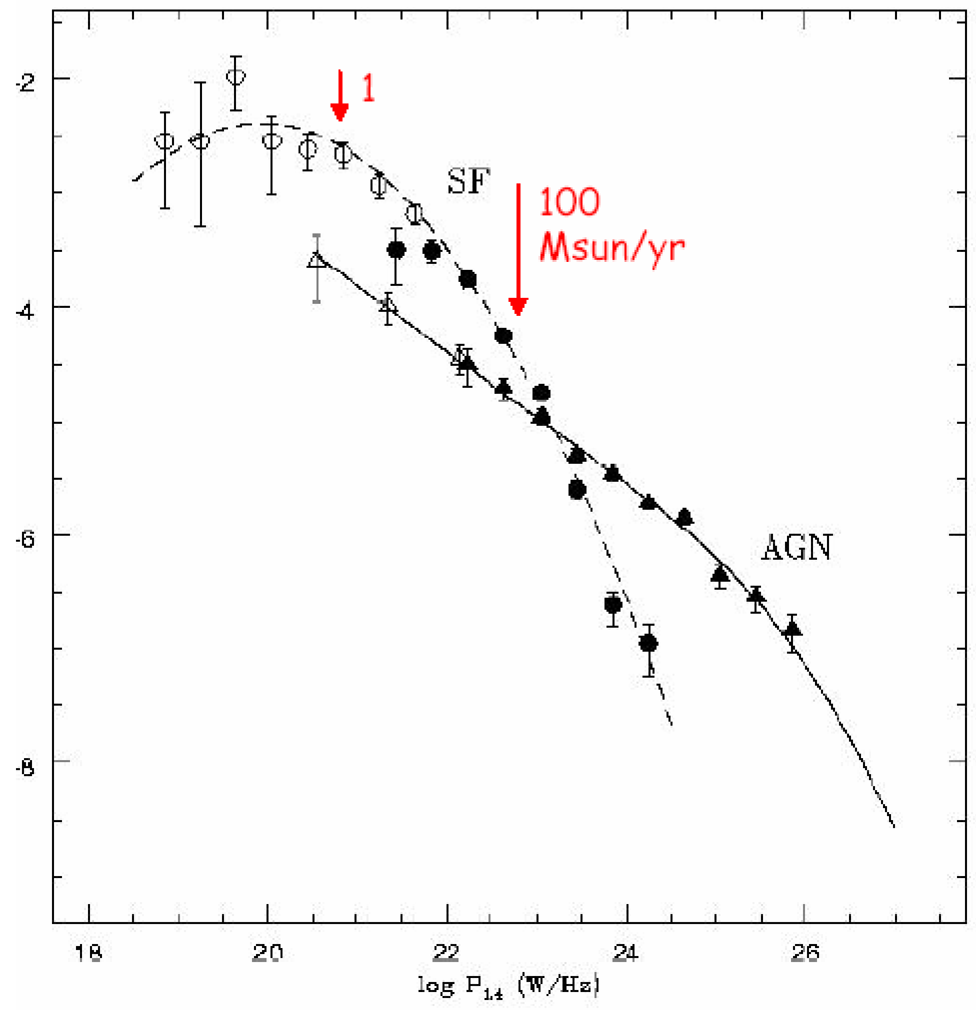

Europe
SKA stations



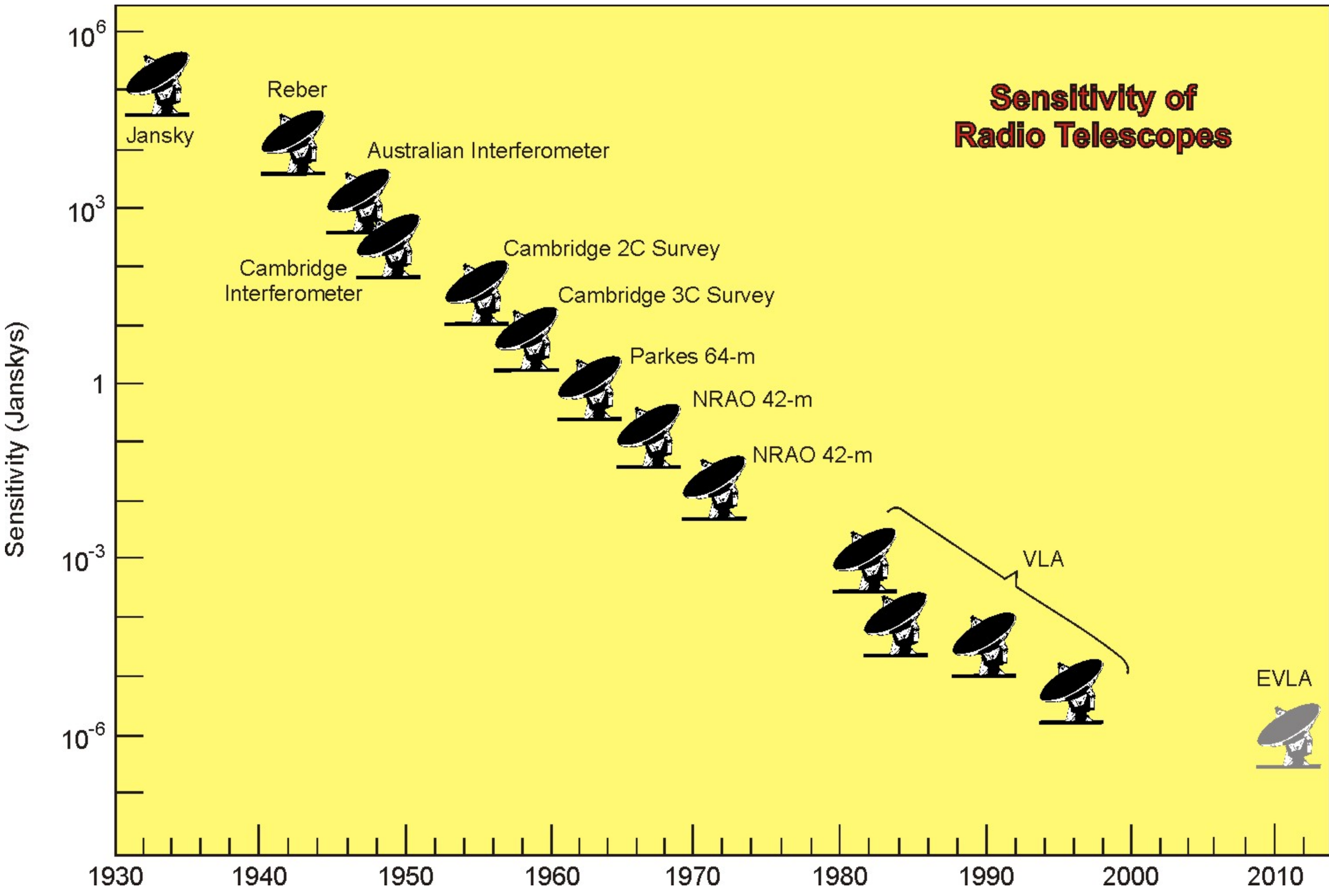
Radio Source Counts
1.4 GHz
AGN
Radio Galaxies
Quasars
Starburst
Galaxies
?
VLA
EVLA
SKA
log (n / -c*S_ν^-2.5) [n in Jy^-1 ster^-1]
log S_ν (mJy)
SF
AGN
1
100
Msun/yr
log P_14 (W/Hz)

U.S. Proposal
North American Array
Most of collecting area is in New Mexico
About half the collecting area near VLA site

- Large, high, dry, site (VLA) is ideal
- Extensive infrastructure already in place in NM
  - Land, roads, fiber, personnel, universities, federal labs, national observatories
- Existing long term site studies for VLA/NMA/LOFAR – excellent sites
- Co-location with VLA+NMA+VLBA allows phased development
- Long term rfi situation unclear



-2
-4
-6
-8
18
20
22
24
26
log P$_{1.4}$ (W/Hz)
1
100
Msun/yr
SF
AGN



Sensitivity of
Radio Telescopes
Sensitivity (Janskys)
10^6
10^3
1
10^{-3}
10^{-6}
Jansky
Reber
Australian Interferometer
Cambridge
Interferometer
Cambridge 2C Survey
Cambridge 3C Survey
Parkes 64-m
NRAO 42-m
NRAO 42-m
VLA
EVLA
1930
1940
1950
1960
1970
1980
1990
2000
2010

LOFAR
The Low Frequency Array
Haystack, Astron, NRL, SWC*

Frequency: 10-240 MHz
Size: 400 km. 100 patches
Resolution : 2-20 arcsec
Elements: 2 x 13,000 dipoles
Sky coverage: Multiple beams
Location:
- SW United States (NM)
- Western Australia
- Netherlands

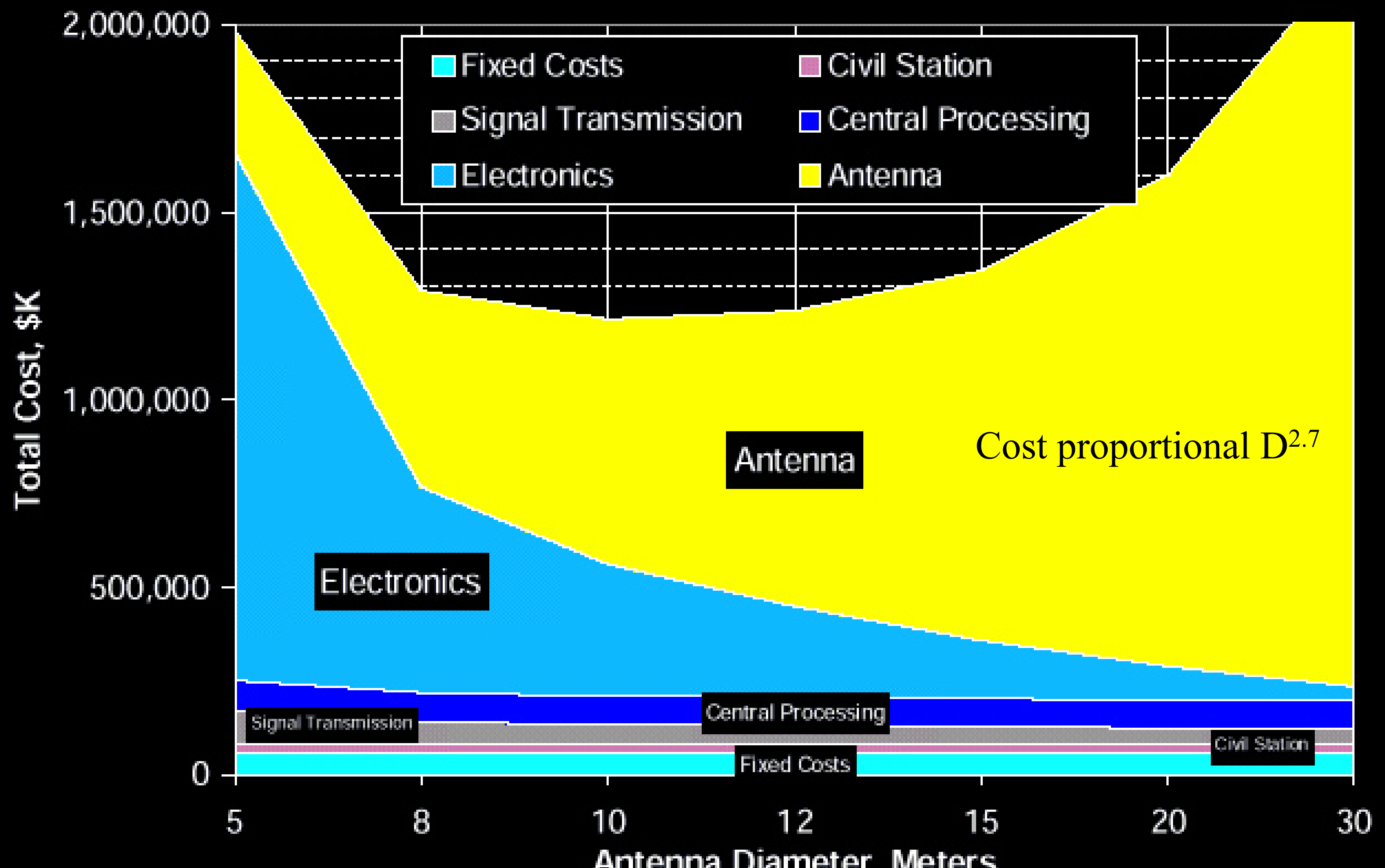
Time Table
- PDR June 2003
- Site Selection late 2003
- Initial Operations 2006
- Full Operations 2008

*UNM, LASL,U Tex, NMS, NM Tech

By products of SKA Development

- In other countries, e.g., Australia and Canada, there are major industrial components.
- In the U.S. an NSF grant to the SKA Consortium has revitalized university research in radio astronomy instrumentation.

SKA Cost Breakdown by Subsystem vs Antenna Diameter
Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^3 K$, 2001 Electronics Cost = $54K per Element



SKA History

- First Discussions: 1991
- 1994 URSI---IAU Large Radio Telescope WG formed
- 1997 S&T Workshop, Leiden, Netherlands
- 1998 S&T Workshop, Calgary, Alberta, Canada
- 1998 S&T Workshop, Green Bank, WV
- 1999 S&T Workshops, Leiden & Dwingeloo, Netherlands
- 2000 S&T Workshop, Manchester, UK
- 2000 ISSC formed, MOU signed at IAU GA
- 2001 S&T Workshop, Berkeley, CA, USA
- 2002 S&T Workshops, Bologna, Italy, Groningen, Netherlands
- 2003 S&T Workshop, Geraldton, WA, Australia, July, 28-31

A Foot Print of Time

A lasting impression….

DDP116 at the Green Bank Interferometer

It is said to be BGC's footprint


DDP-116
DDP-116