Title: Experimental Windows on the Expansion History of the Universe

Date: Oct 17, 2008 11:00 AM

URL: http://pirsa.org/08100036

Abstract: I\'ll discuss three promising upcoming experimental measurements that will probe the expansion history of the universe: (1) growth bases tests of Dark Energy with the Sunyaev-Zeldovich Effect, including new results from the South Pole Telescope and APEX-SZ, (2) inflationary constraints that will be provided by the next generation of CMB-polarization experiments, with prospects from EBEX, and (3) standard ruler measurements from Baryon Acoustic oscillations, including an introduction to an ambitious new Canadian Hydrogen Intensity Mapping initiative called CHIME. The talk will build on the PI-presentation last week from SPT-collaborator Jeff McMahon. I\'ll focus on the experimental aspects of each measurement, it\'s interface to theory, and spend most of the time on (3) CHIME.

Experimental Windows on the Expansion History of the Universe

Matt Dobbs

McGill CosmoloGy Instrumentation Laboratory MCgIL

http://mcgillcosmology.ca

1. Growth-based D.E. Test
2. Inflationary Expansion Test
3. Scale-based D.E. Test

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What we built, what we're building, and what we're gonna build.

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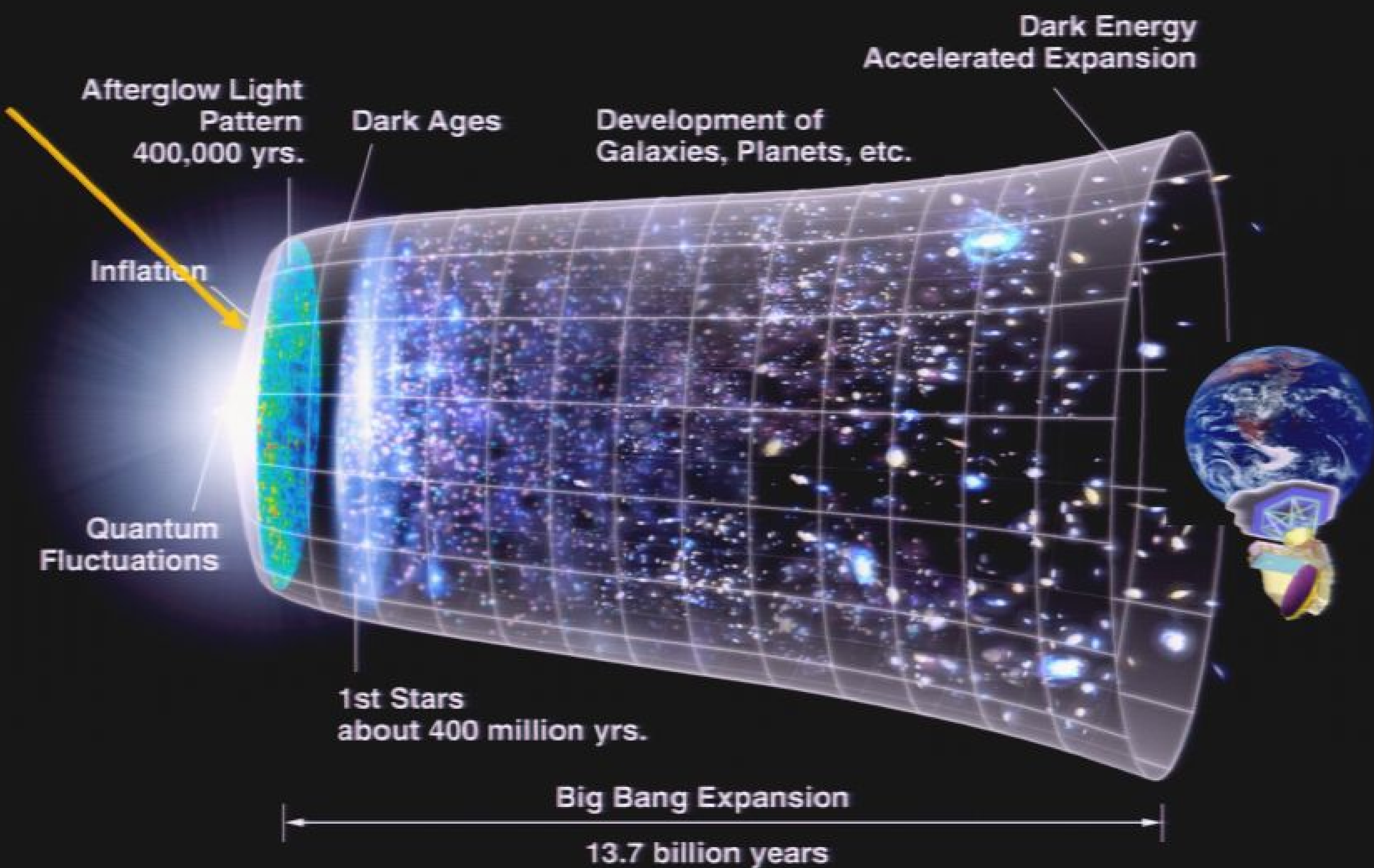
Inflationary Expansion Tests

EBEX

Observational Cosmology

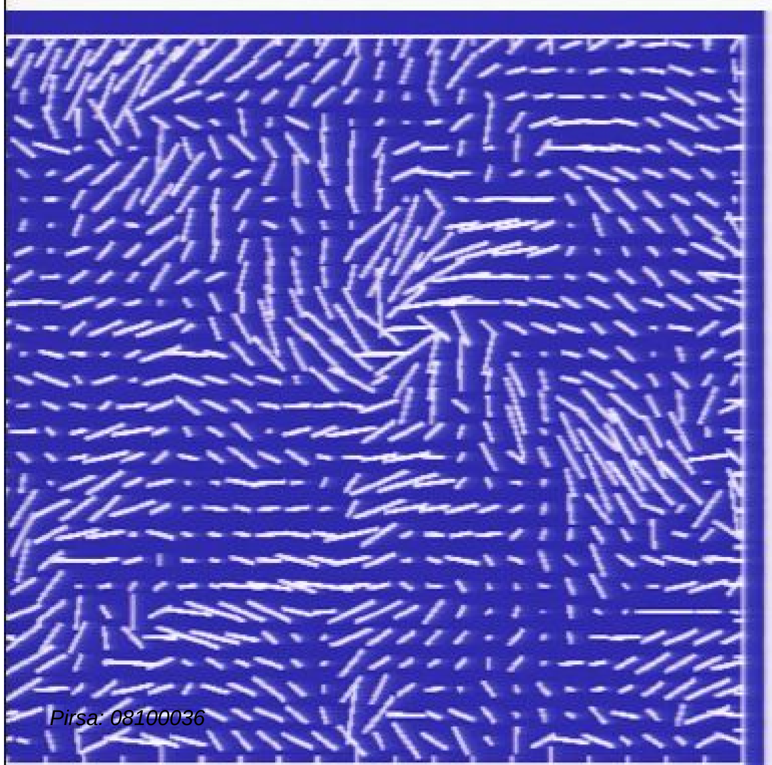


Gravity Waves from Inflation

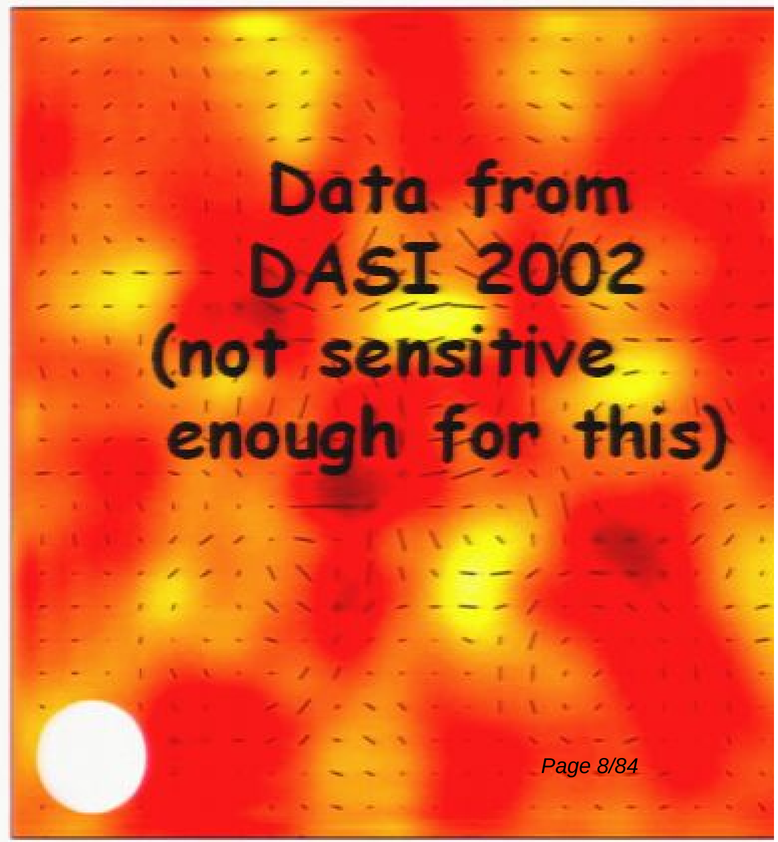
- ***inflationary gravity wave background*** (IGB) provides fingerprint of inflation (10^{16} GeV)
- imprinted on CMB as curl component of polarization signal

Gravity Waves from Inflation

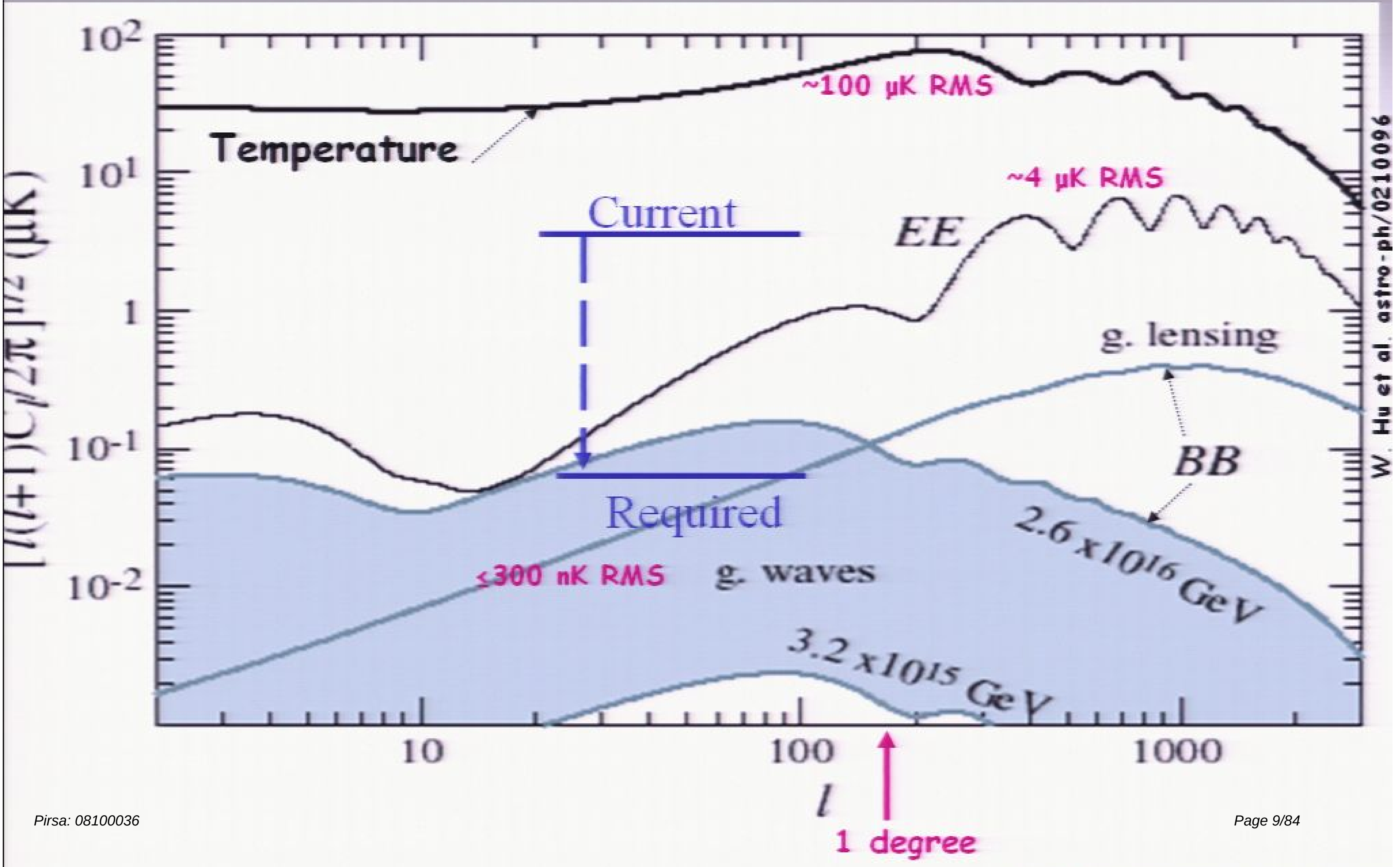
- gravity wave signature encoded in CMB POLARIZATION
- *the catch:*
  - → factor ≤ 10^{-2} smaller than the temperature anisotropy.



Example of what gravity waves would look like



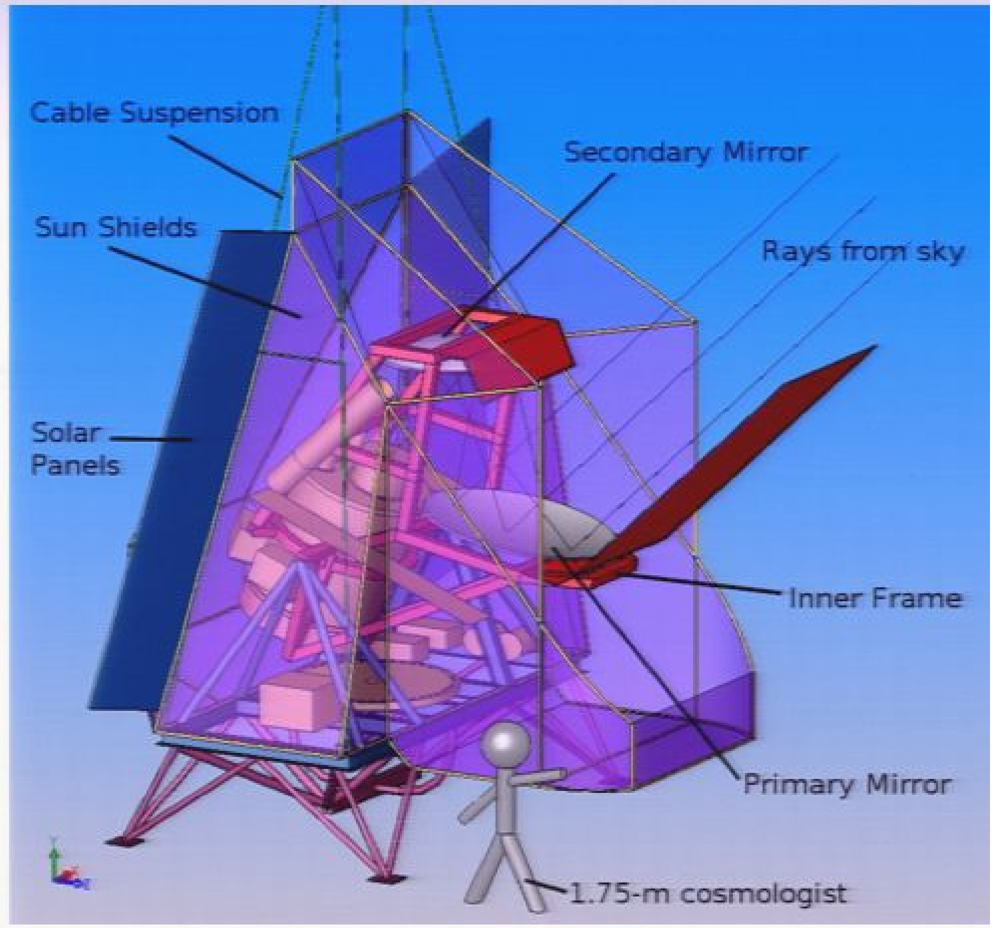
CMB Polarization



EBEX

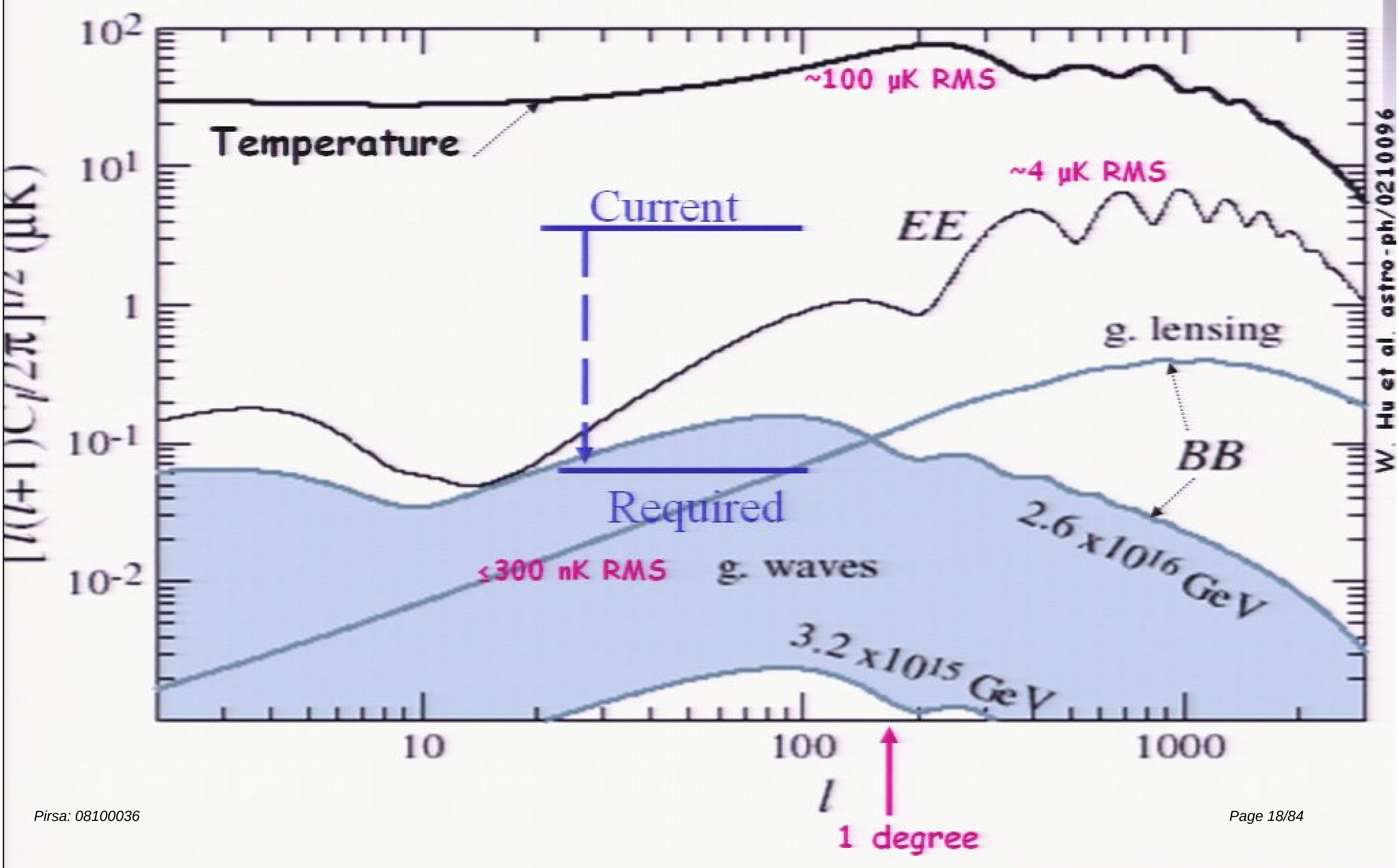
- 2-3 week Antarctic balloon flight
- 800, 400, 300 **spiderweb** TES detectors at 150, 250, 420 GHz
- **Frequency** MUX readout
- Polarimetry with ***polychromatic*** *half wave plate* + wire grid
- Dragone **Telescope**, clear aperture

- Resolution: **8'** at all frequencies
  - *420 deg²* 700 nK/ 8' pixel
- Science focus
  - ***20 < ell < 400***
  - Go after B-modes
  - Measure dust foreground accurately.



APC-Paris, Brown, Cardiff, Columbia, Harvard, Lawrence Berkeley National Lab, McGill, SISSA, UC Berkeley, U. Minnesota, Weizmann Institute

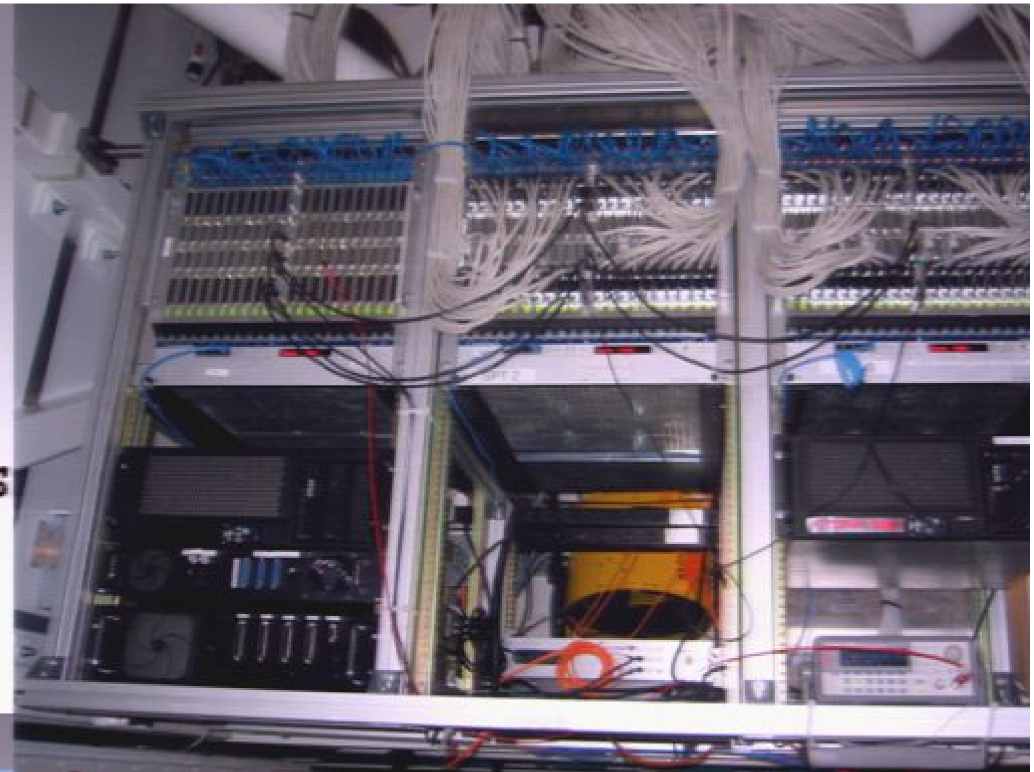
CMB Polarization



At the McGill Cosmology Instrumentation Lab

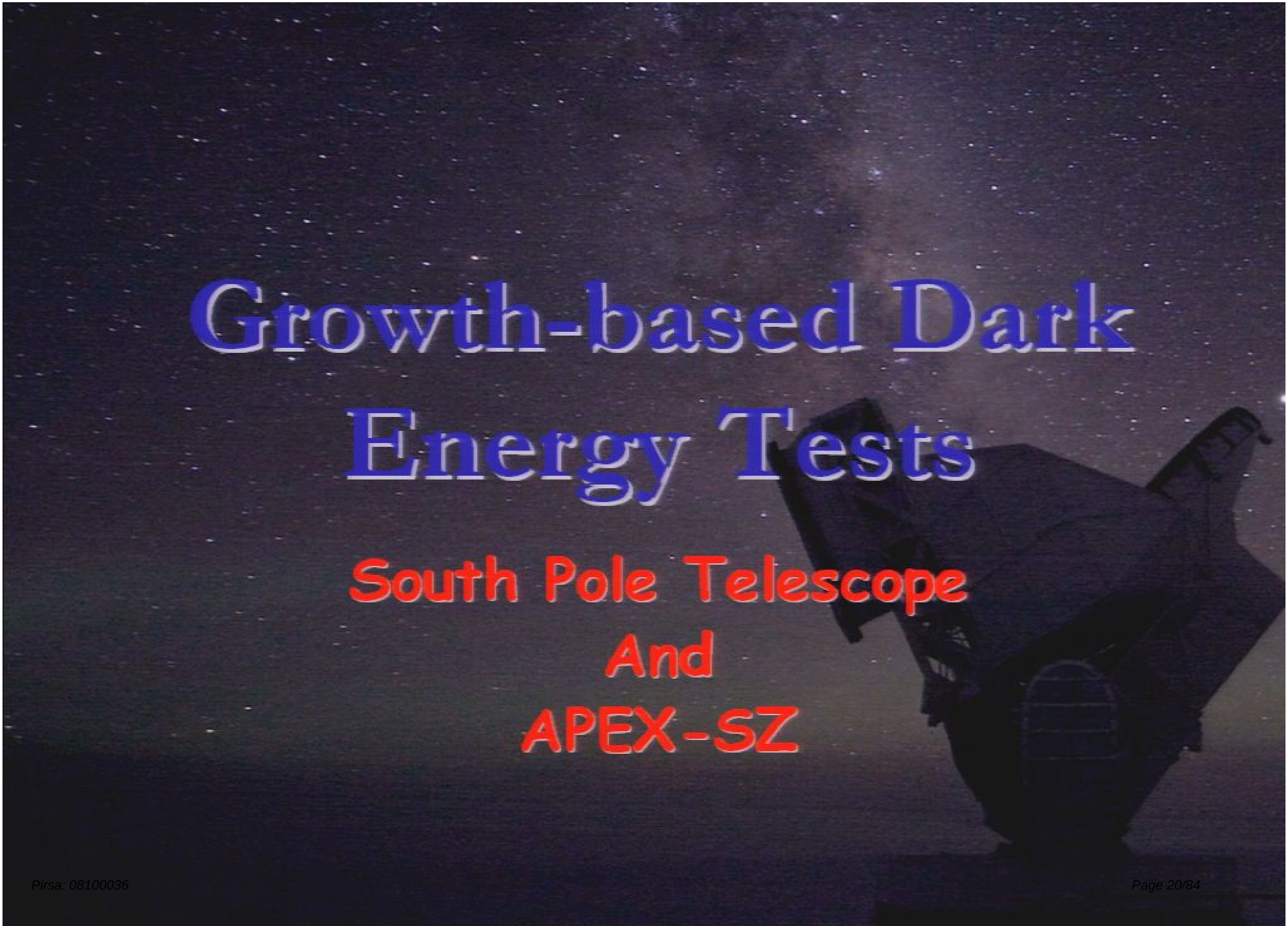
We specialize in detector readout:

- Cold superconducting electronics
- Warm FPGA electronics



Circa 2006
Electronic readout system for the South Pole Telescope.

Circa 2008
Electronic readout system for a NASA balloon borne CMB telescope.


Growth-based Dark
Energy Tests
South Pole Telescope
And
APEX-SZ

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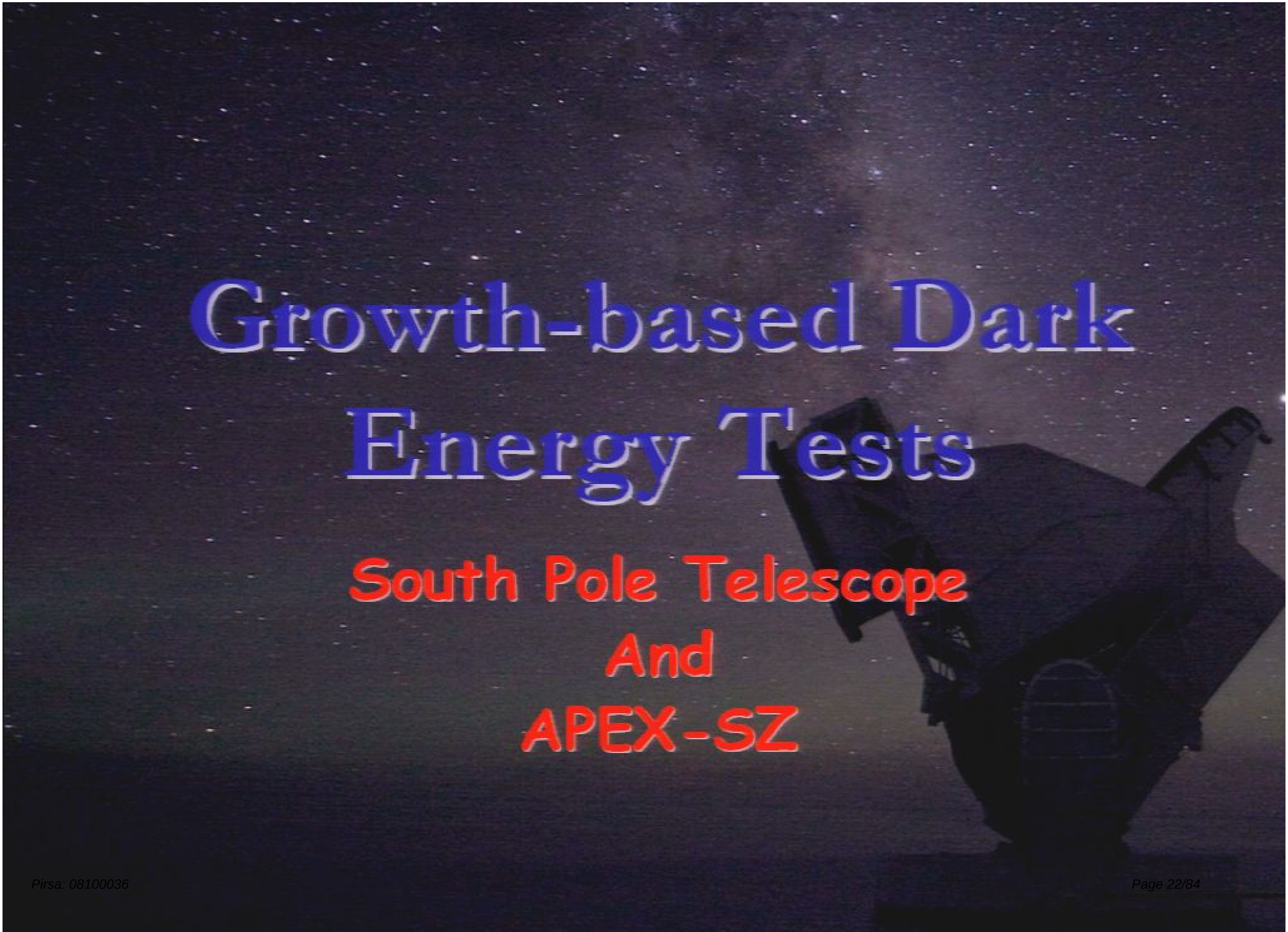
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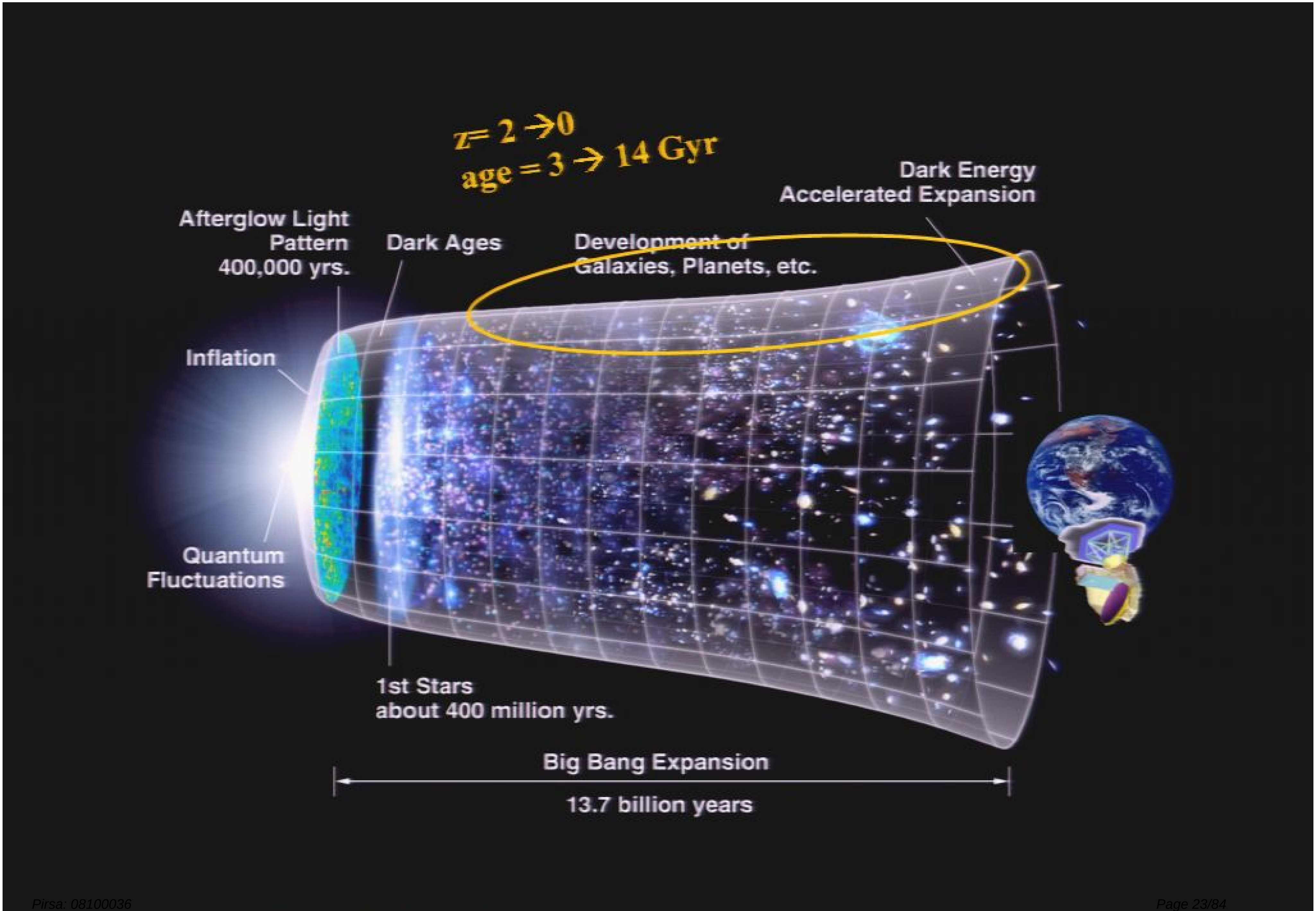


slide adapted from NASA publicity figure)

The Sunyaev Zel'Dovich Effect

- Proportional to the total thermal energy of cluster

SZE Flux : $S \propto \frac{1}{d_A(z)^2} \int n_e T_e dl$

- Surface Brightness Independent of redshift

Dark Energy Constraints with Clusters of Galaxies

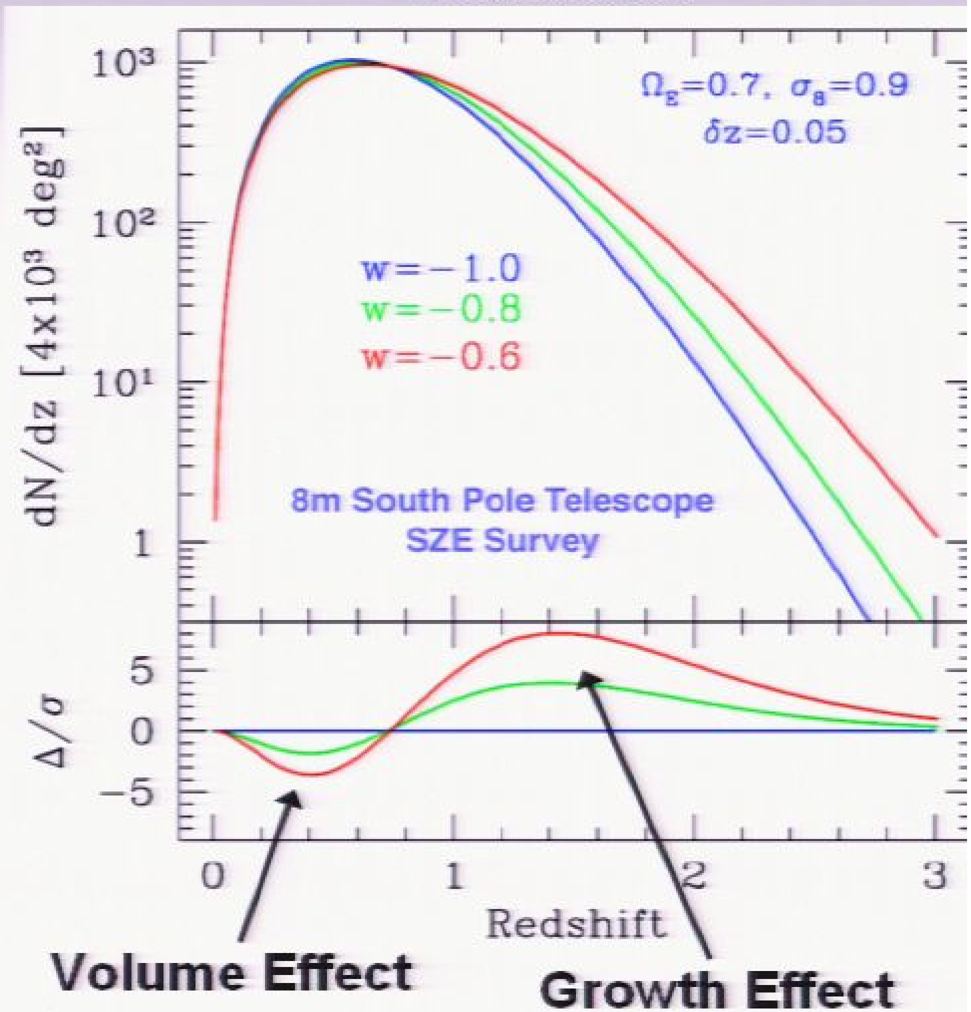
Cluster Abundance, dN/dz

$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Depends on:
Matter Power Spectrum, *P(k)*
Growth Rate of Structure, *D(z)*

Depends on:
Rate of Expansion, *H(z)*

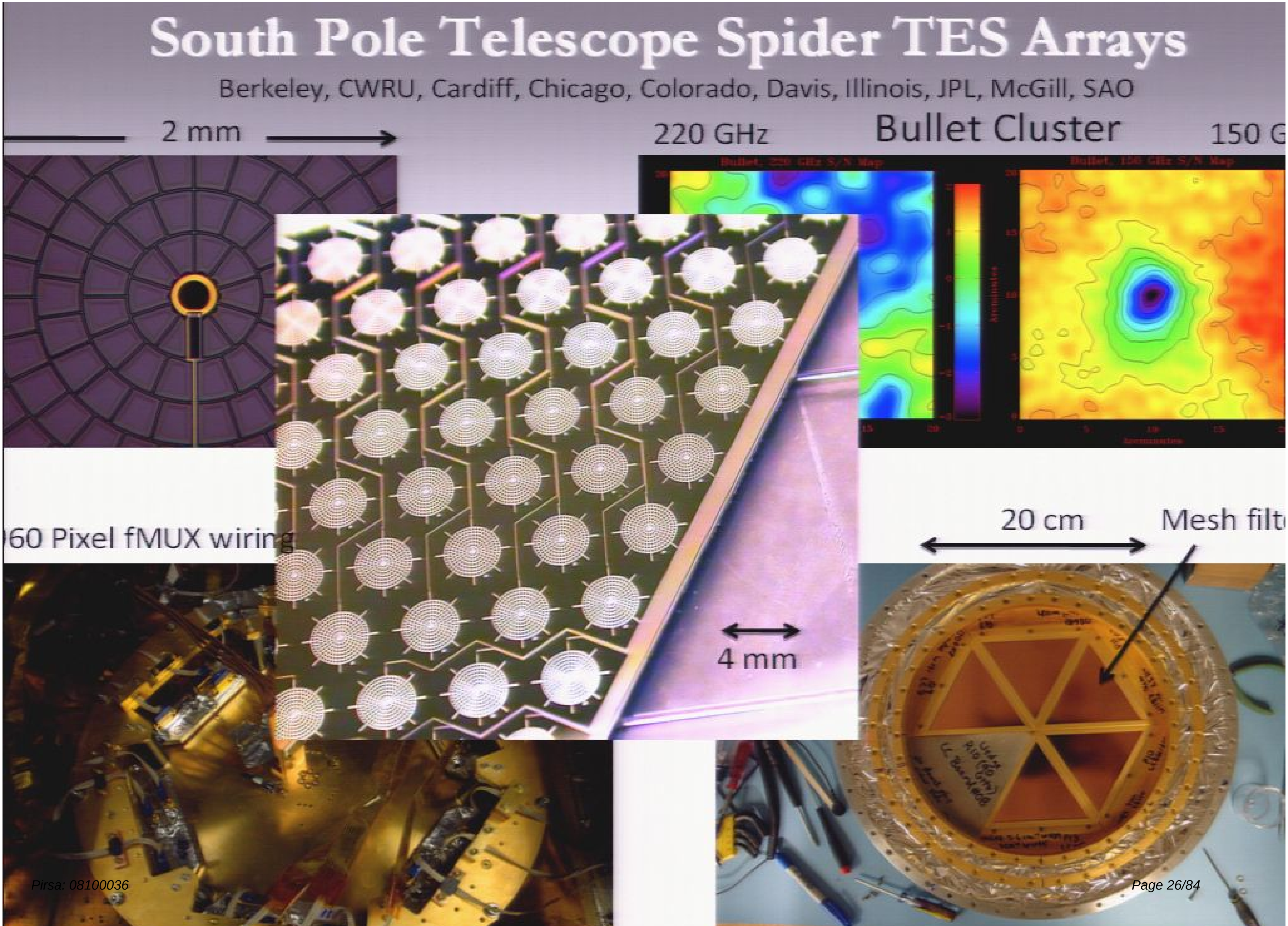
Credit: Joe Mohr



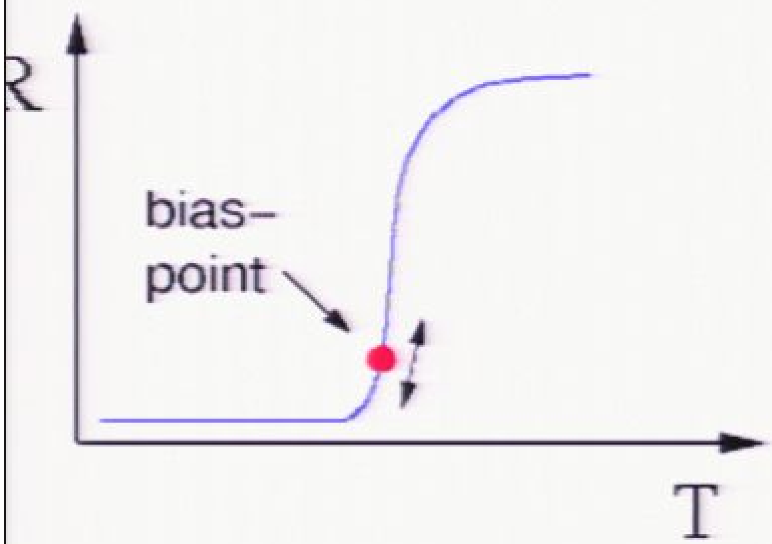
For fixed Ω_{DE} and increasing w:

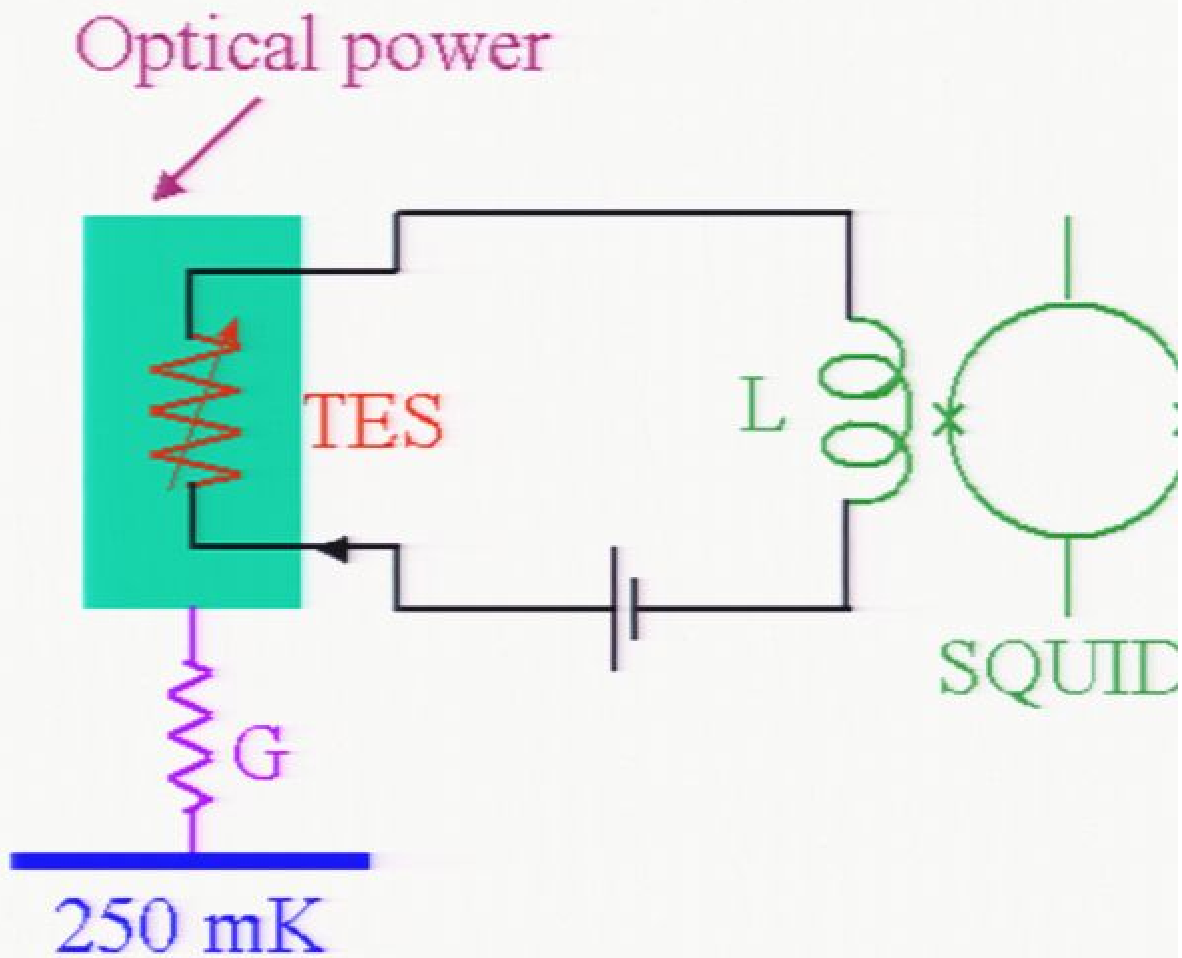
1. Fewer clusters at low redshift, due to decreased volume surveyed

2. More clusters at high redshift, due to decreased growth rate


South Pole Telescope Spider TES Arrays
Berkeley, CWRU, Cardiff, Chicago, Colorado, Davis, Illinois, JPL, McGill, SAO
2 mm
220 GHz
Bullet Cluster
150 G
960 Pixel fMUX wiring
4 mm
20 cm
Mesh filt

Transition-Edge Sensor (TES) Bolometers

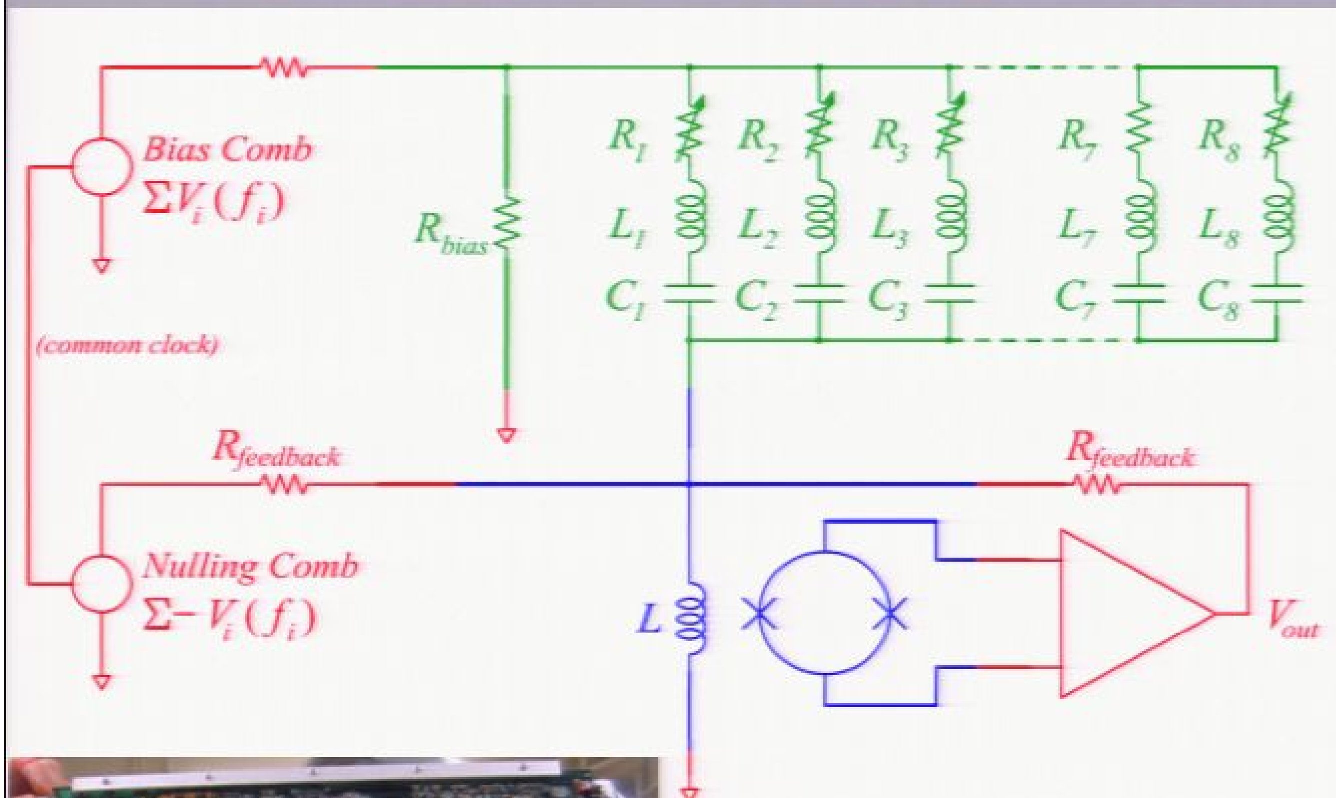


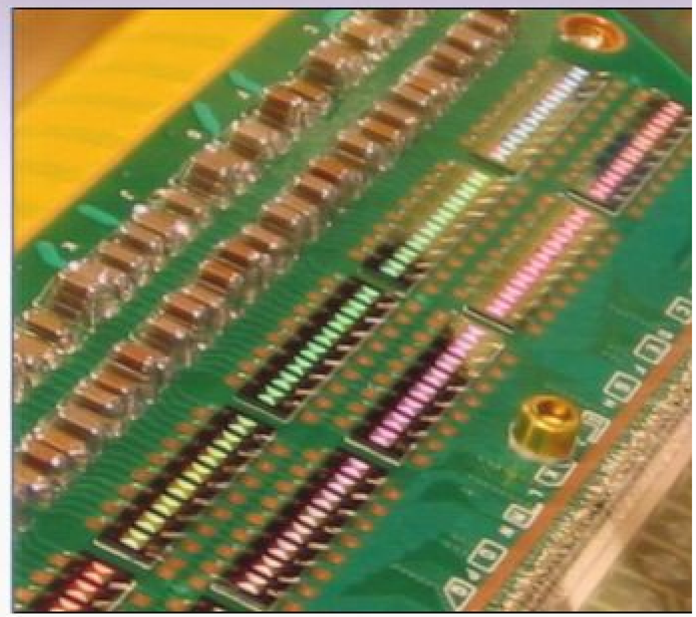


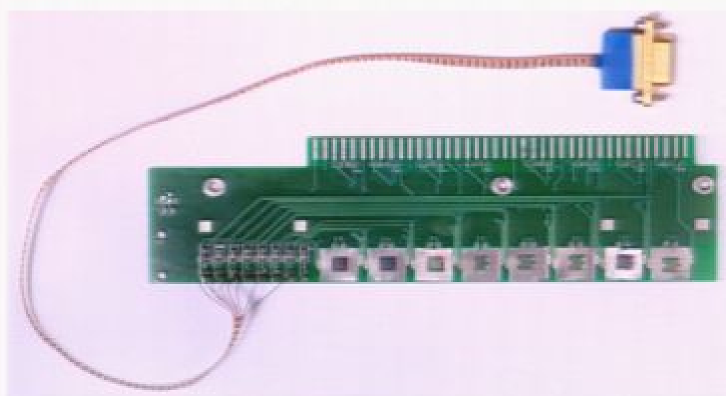
$$P_{bias} = V_{bias}^2 \; / \; R$$

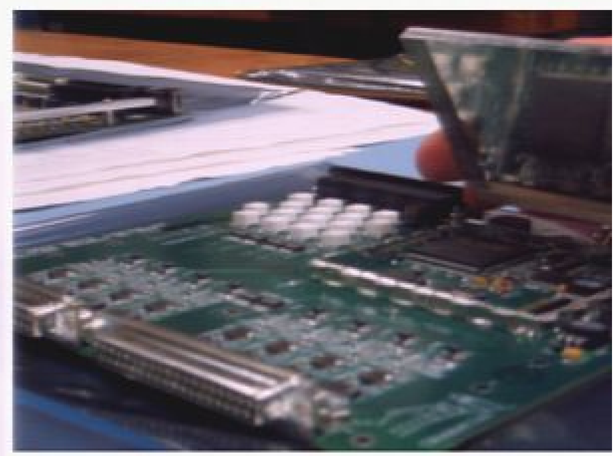
$$P_{total} = P_{bias} + P_{photon} \approx \text{constant}$$

Frequency-domain multiplexer

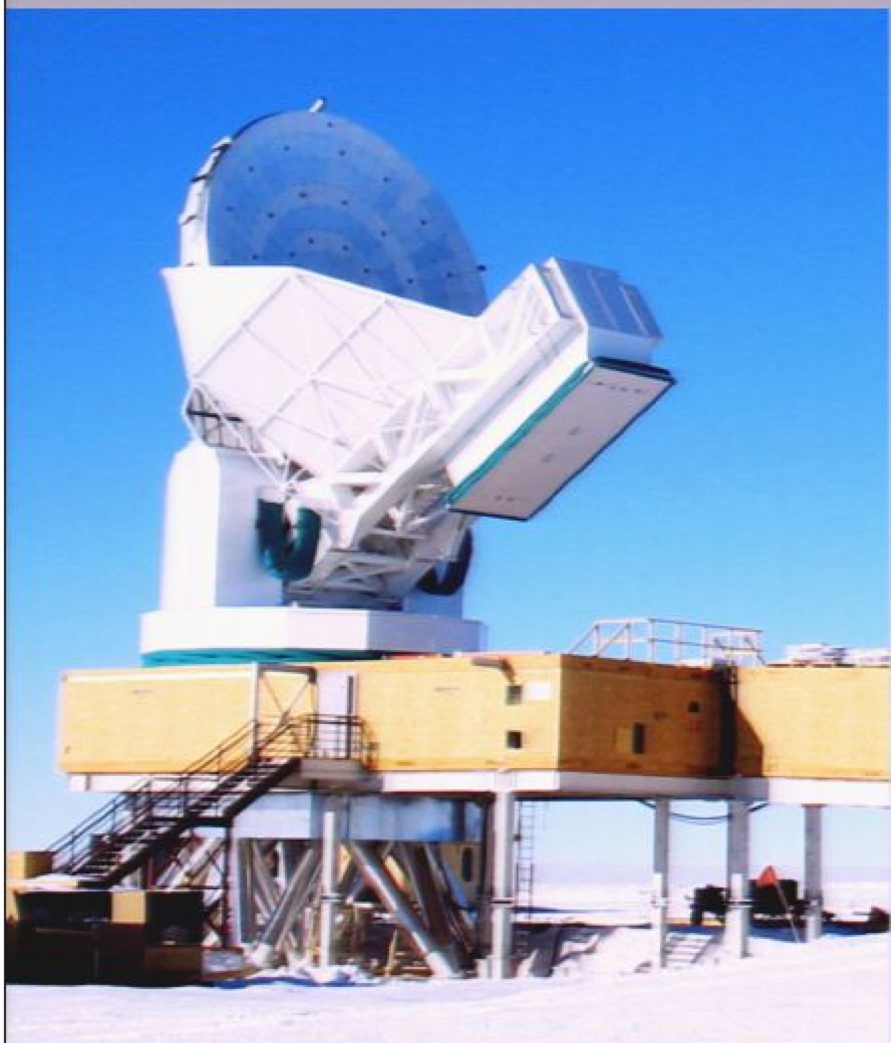








The South Pole Telescope (SPT)



Sub-millimeter Wavelength Telescop

- 10 meter telescope (1' FWHM beam 150 GHz)
- Off-axis Gregorian optics design
- 20 microns RMS surface accuracy
- 1 arc-second pointing
- Fast scanning (up to 4 deg/sec in azimuth)

SZ receiver:

- 1 sq. deg FOV
- ~960 background limited pixels
- Observe in 3+ bands between 90-22 GHz simultaneously with a modula focal plane

Funded by NSF

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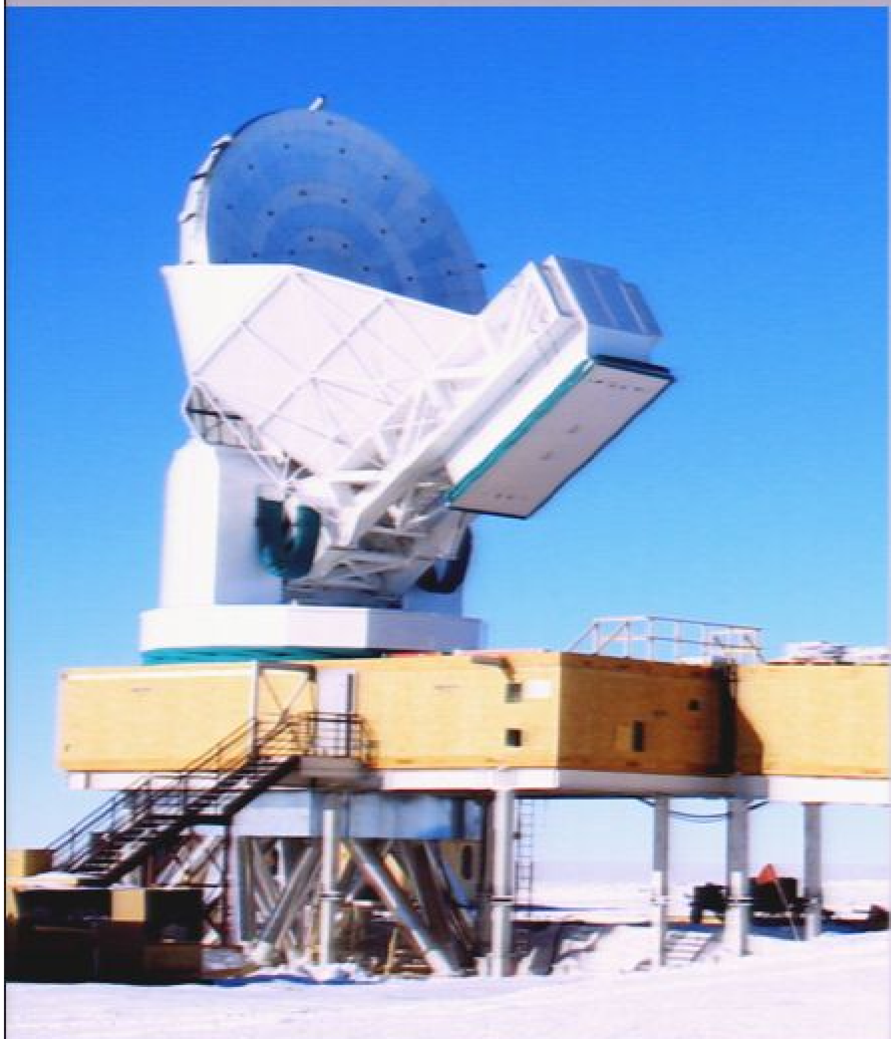

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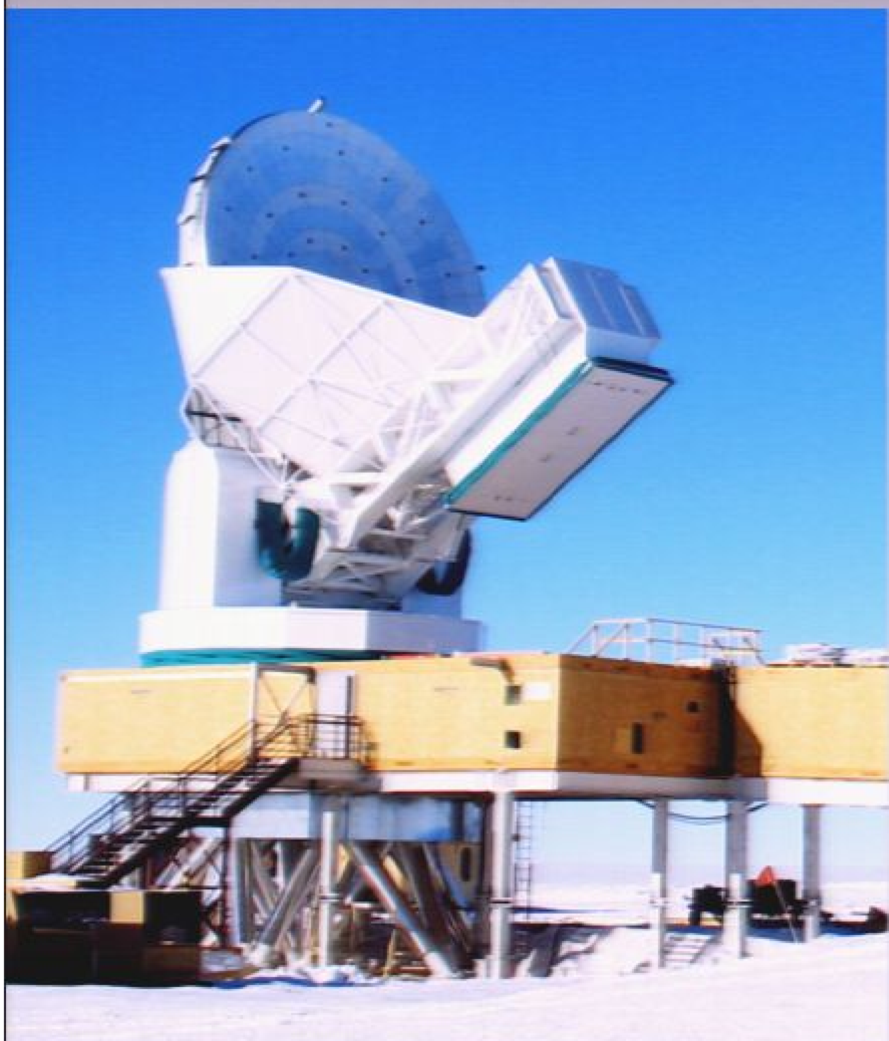

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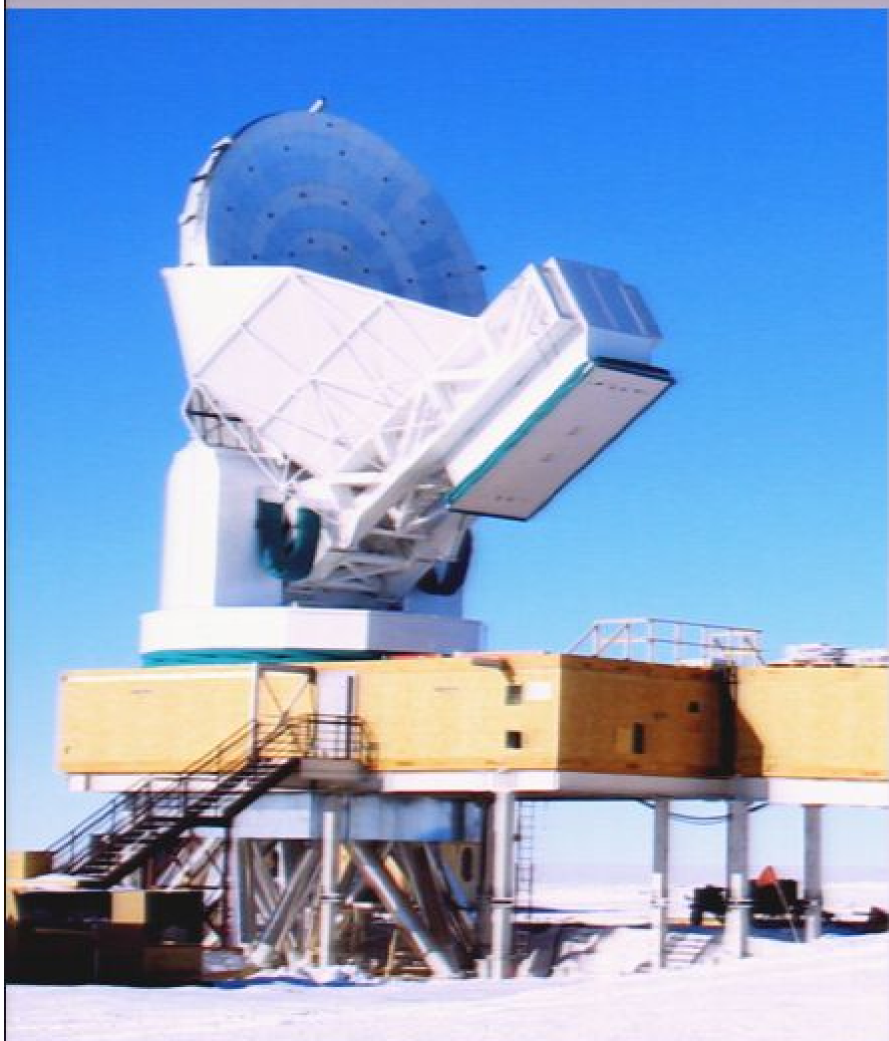

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KICP
Kavli Institute for Cosmological Physics at the University of Chicago

Berkeley University of California

Astronomy University of Illinois at Urbana-Champaign

Case Western Reserve University

McGill

The University of Chicago

Harvard-Smithsonian Center for Astrophysics

Berkeley Lab

Cardiff University
Prifysgol Caerdydd

UC Davis University of California

Colorado University of Colorado at Boulder

SPT Collaboration

SPT 2nd Season Focal Plane Stats

$Band$ (GHz)	$Num.of$ $Bolos$	NET_{RJ} $(\mu K s^{1/2})$
90	~ 35	~ 800
150	~ 350	~ 220
220	~ 200	~ 280

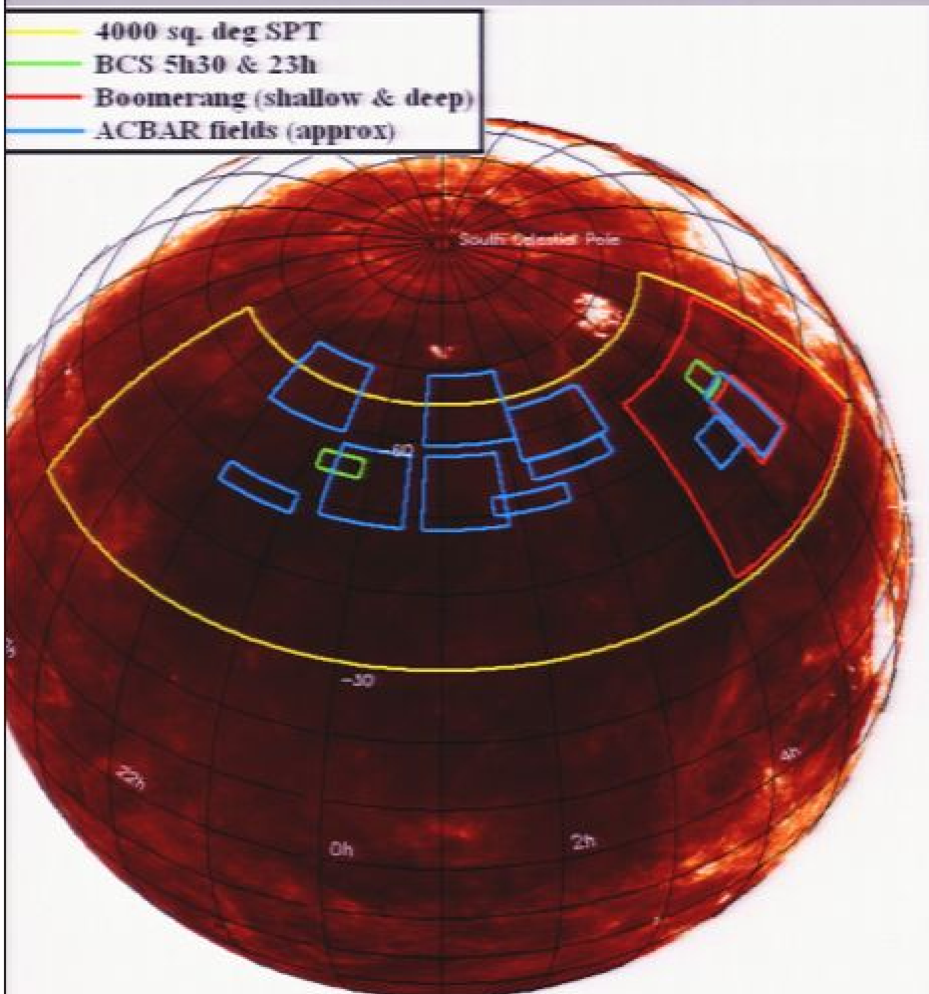
(For comparison, ACBAR had 16 bolometers at 150 GHz with NET of ~ 210 uK s^1/2)

•150 and 220 GHz essentially background limited

•90 GHz sensitivity is lacking (fab error)

•Will add 2 new 90 GHz wedges in December 2008

SPT observing regions

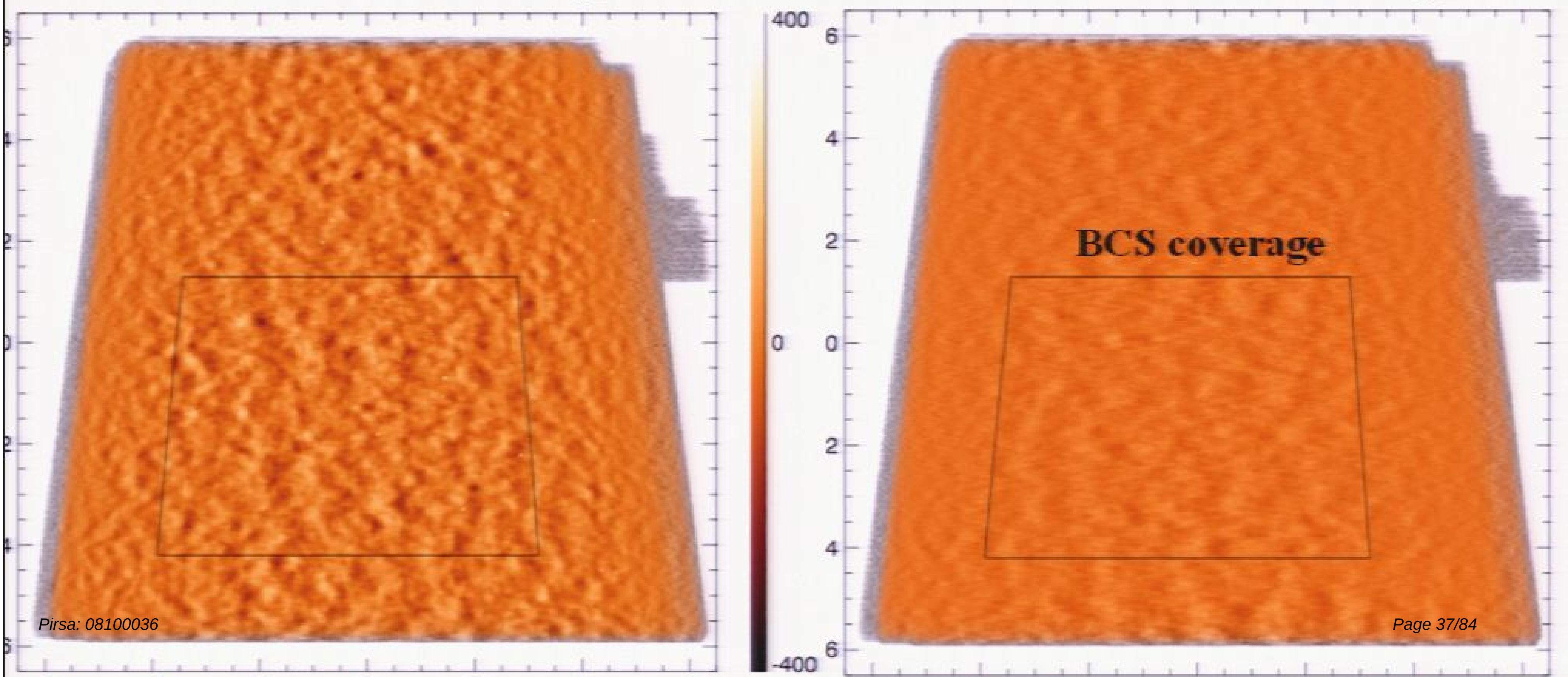


- 1st year (mostly engineering)
  - 60 sq. degrees in BCS 5hr
    - 40uK/arcmin pixel
  - 5 sq. degrees inside previous region
    - 15uK/arcmin
- 2nd year
  - 100 sq degree 5hr
    - 17 uK/arcmin at 150 GHz
  - 100 sq degree 23hr
    - < 15 uK/arcmin at 150 GHz
  - 11 x deep Targeted clusters images
  - 500 sq degree Wmap calibration scan
    - 20 hrs of observation gives 2% cal

First Survey Field RA~ 23 Hours

- Mapped with interleaved azimuth raster scans
- ~800 hours of observation
- 100 deg^2 ~17 uK/arcmin pixel
- 60 deg^2 overlap with BCS

150 GHz L+R map **150 GHz L-R map**



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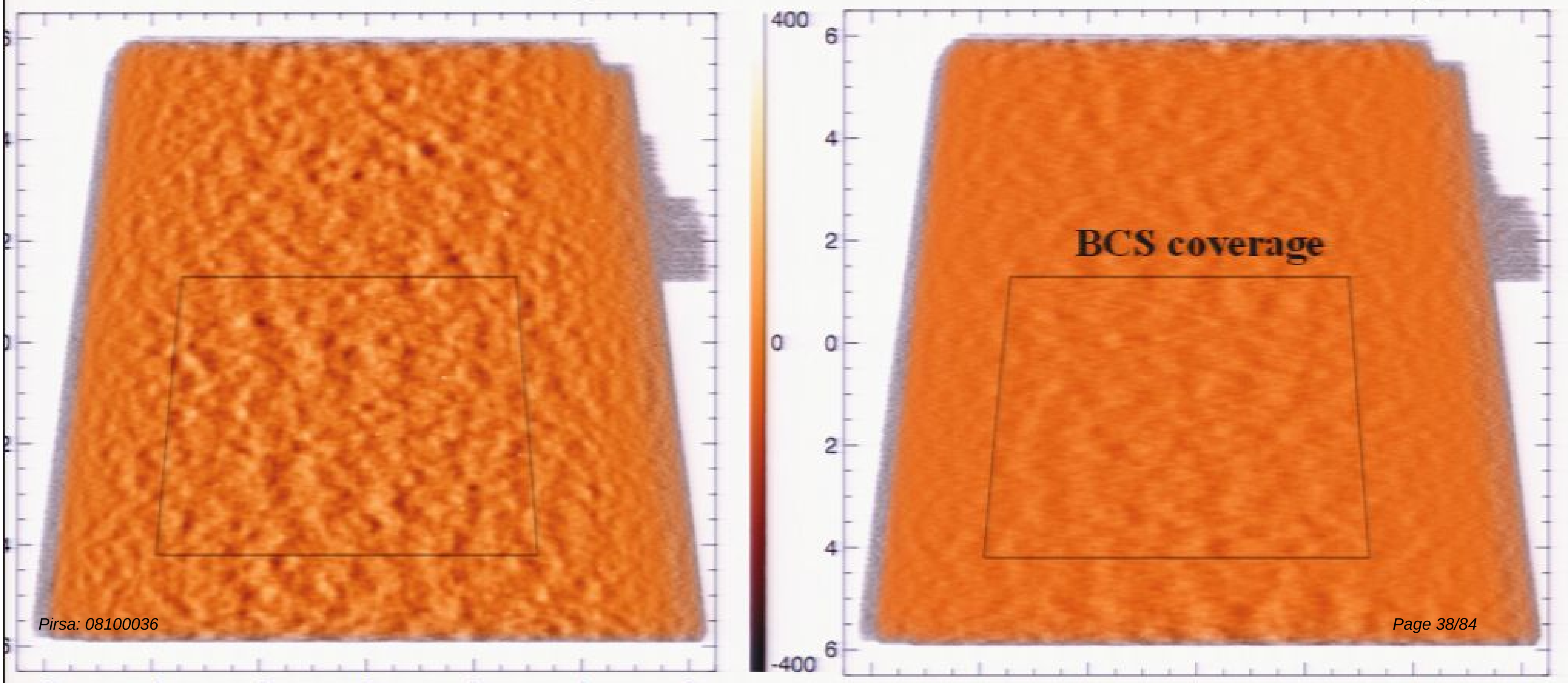

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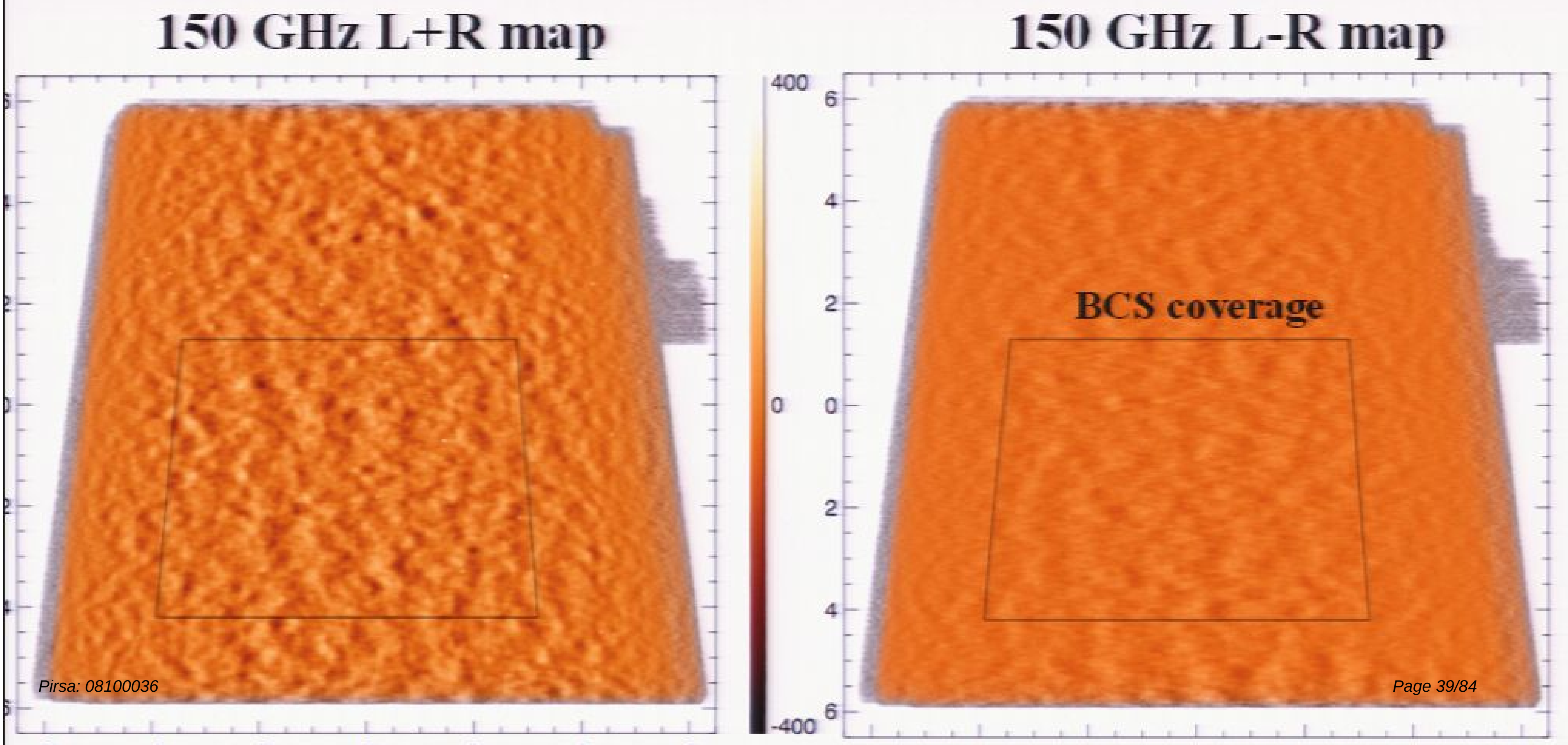

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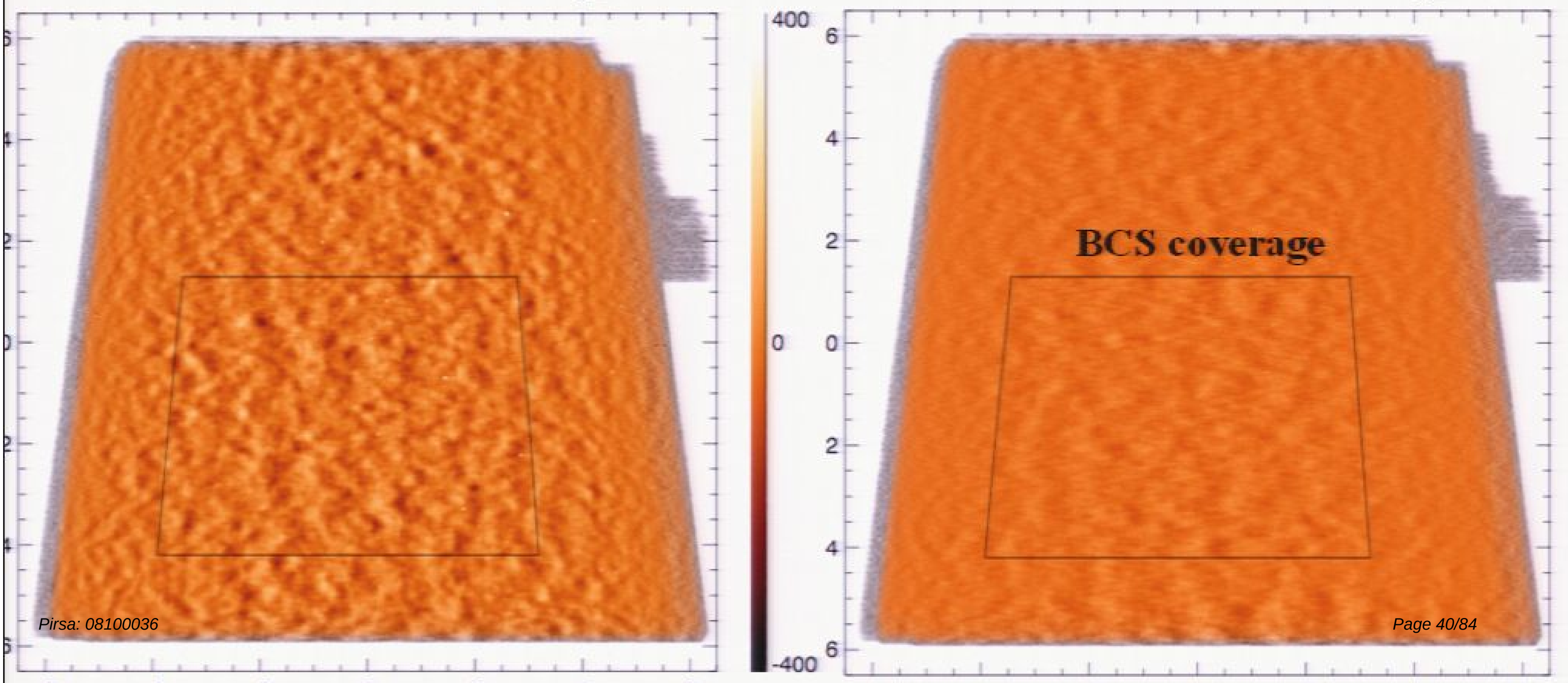
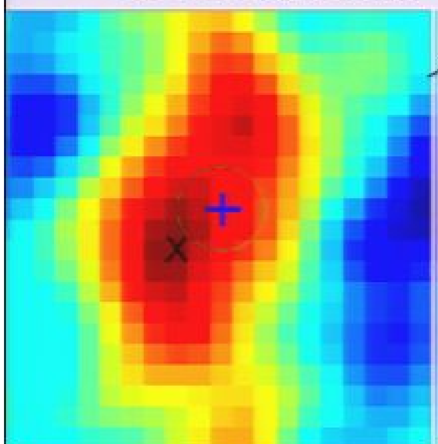
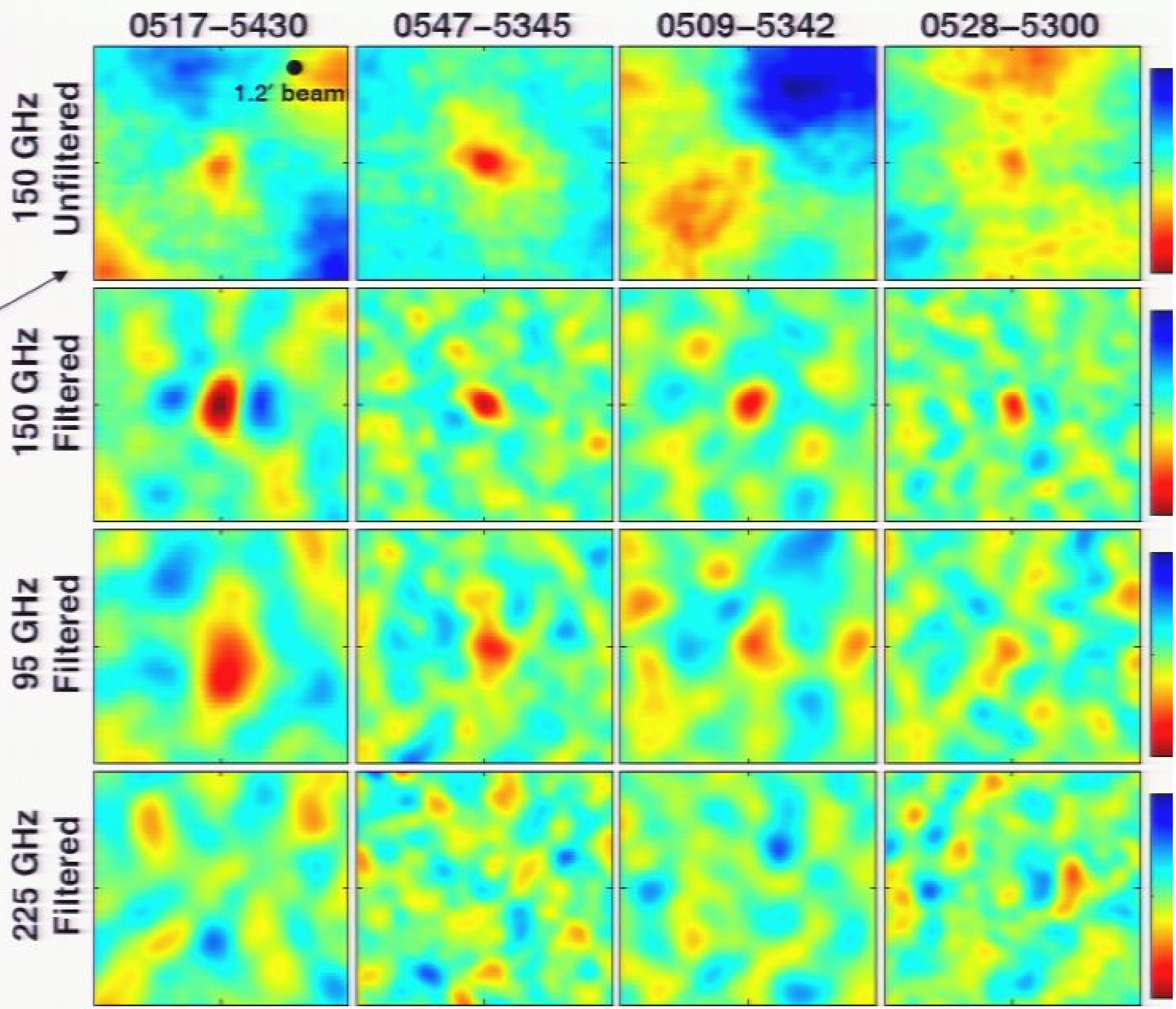


Four most significant 150 GHz decrements in 40 deg² 23 Hr BCS field



(R)EFLEX x-ray cluster
(R)XCJ0516.6-5430)



$$\psi = \frac{S^T N^{-1}}{\sqrt{S^T N^{-1} S}}$$

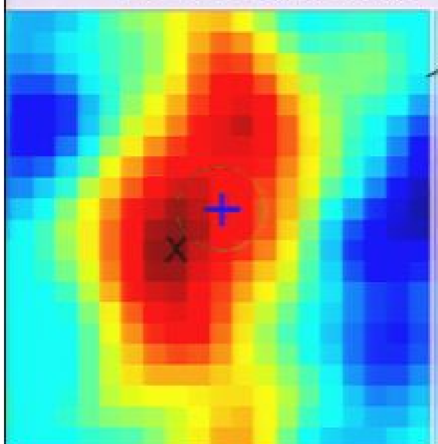
ID	R.A.	decl.	SNR at: 150 GHz	95 GHz	225 GHz	best
SPT-CL 0517-5430	79.144	-54.506	-8.8	-3.4	-0.4	1.
SPT-CL 0547-5345	86.650	-53.756	-7.4	-3.9	1.9	0.
SPT-CL 0509-5342	77.333	-53.702	-6.0	-3.4	0.1	1.2

Pseudo-color Optical Confirmations

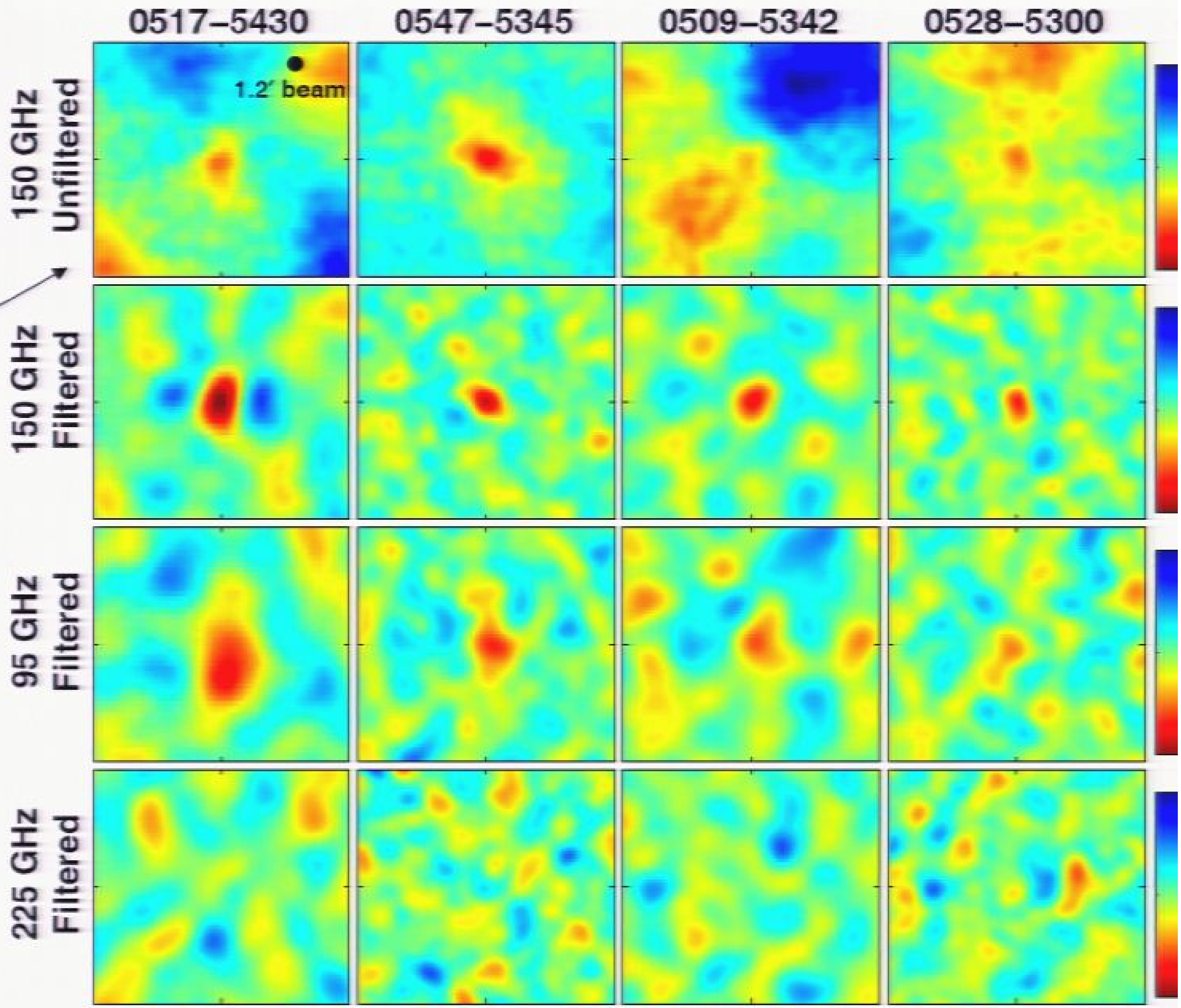
CHIME

Canadian Hydrogen Intensity Mapping Experiment

Four most significant 150 GHz decrements in 40 deg^2 23 Hr BCS field



REFLEX x-ray cluster
(RXCJ0516.6-5430)



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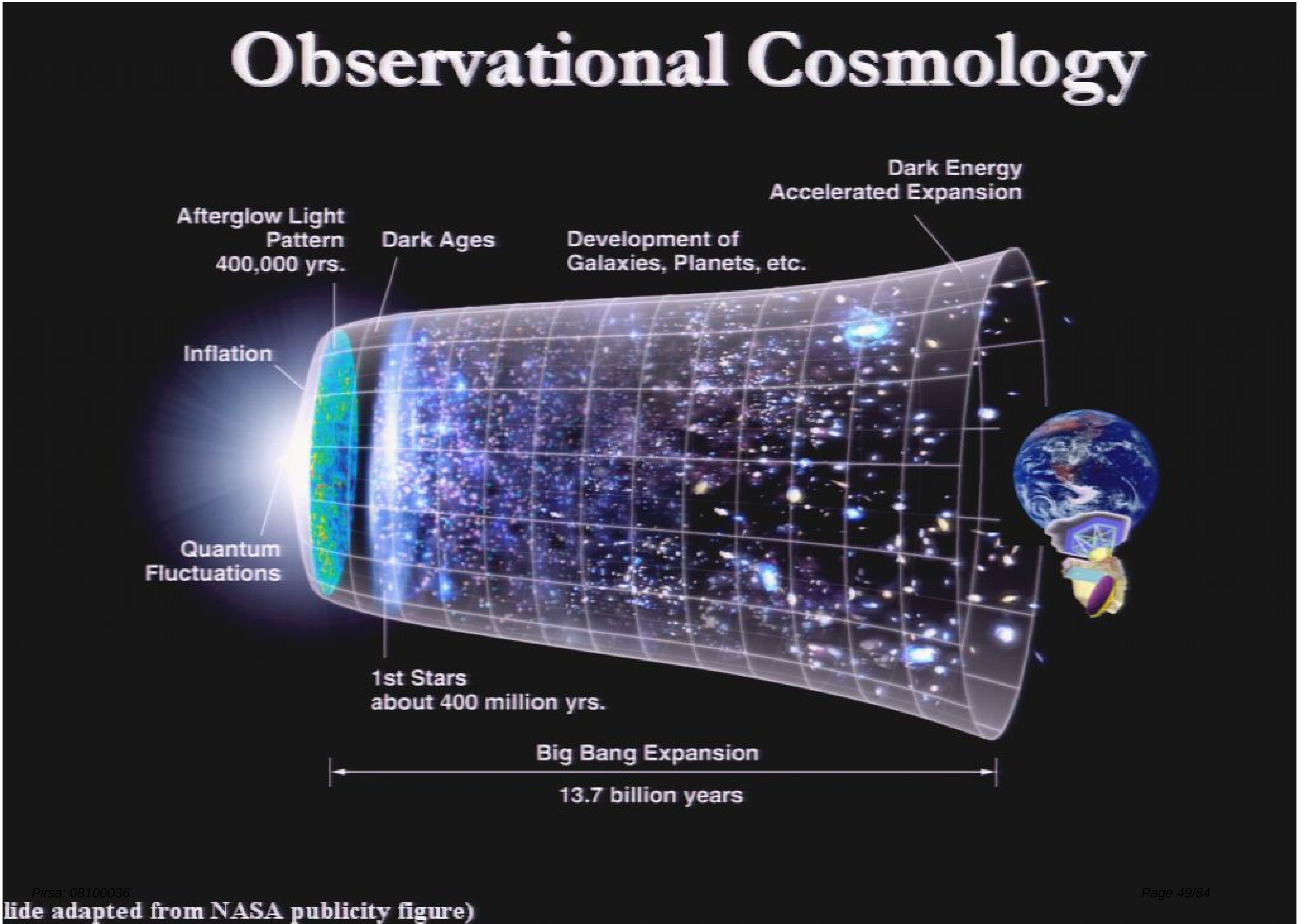
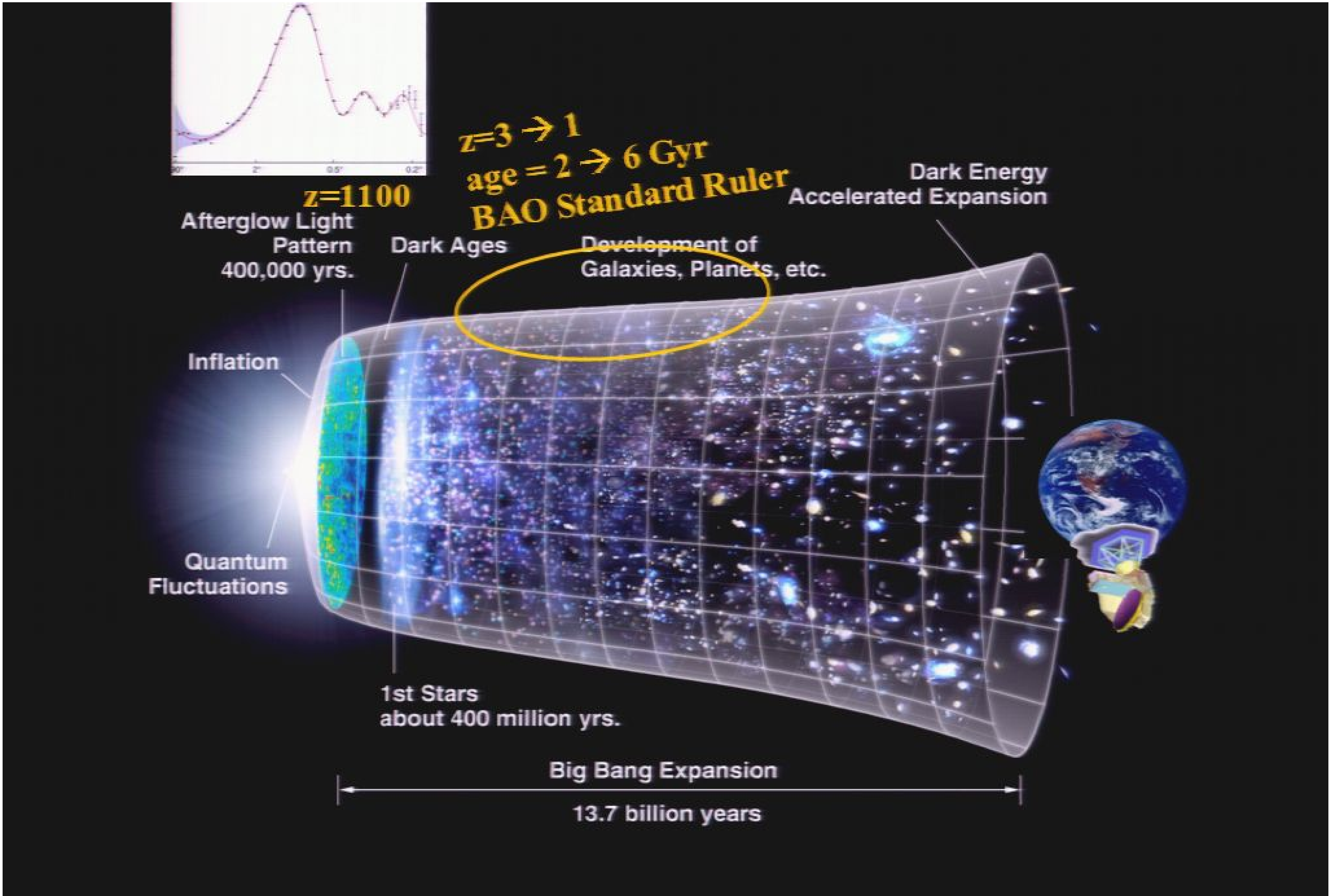
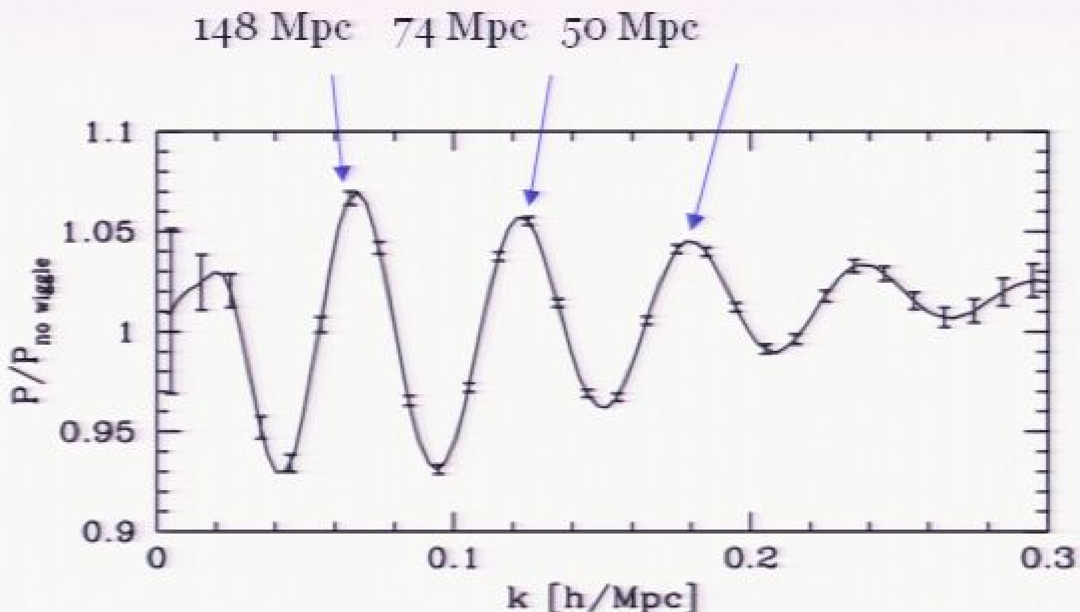

Observational Cosmology
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
lide adapted from NASA publicity figure)

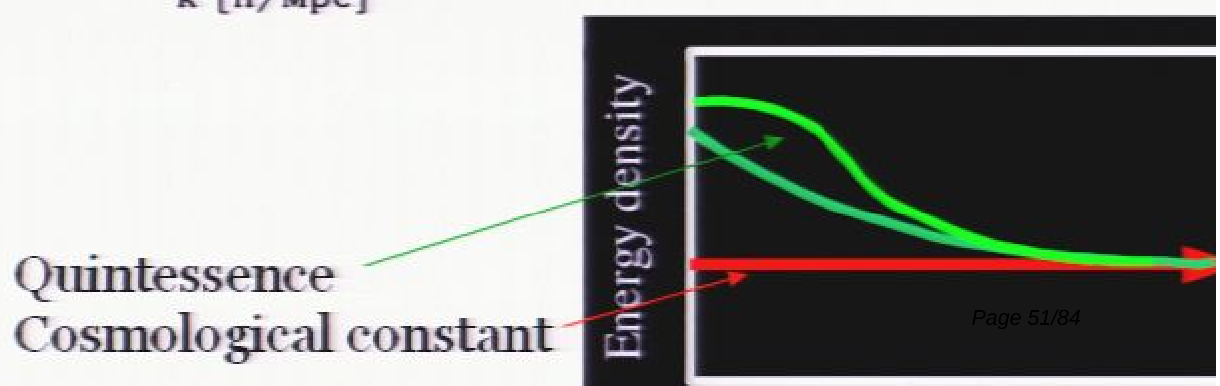


slide adapted from NASA publicity figure)

Cosmic Sound

- BAO → ~100 Mpc scales.
- ~Linear Physics



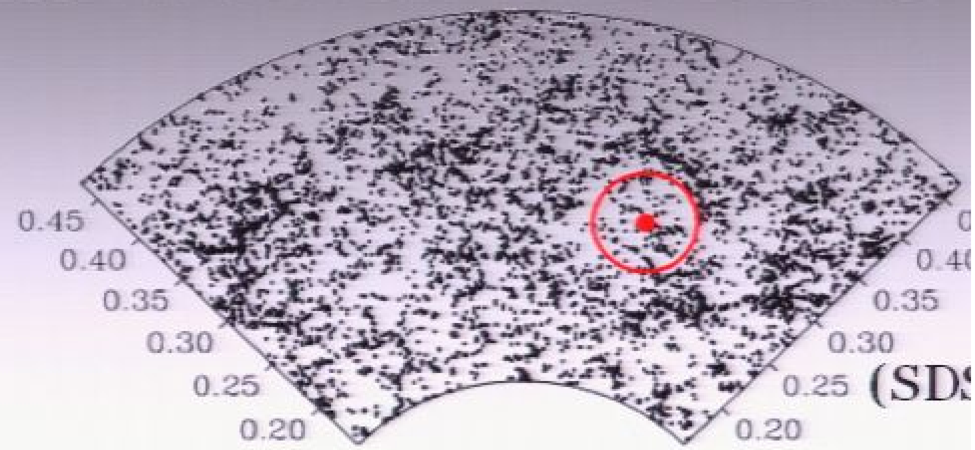


Galaxies: traditional tracer for BAO

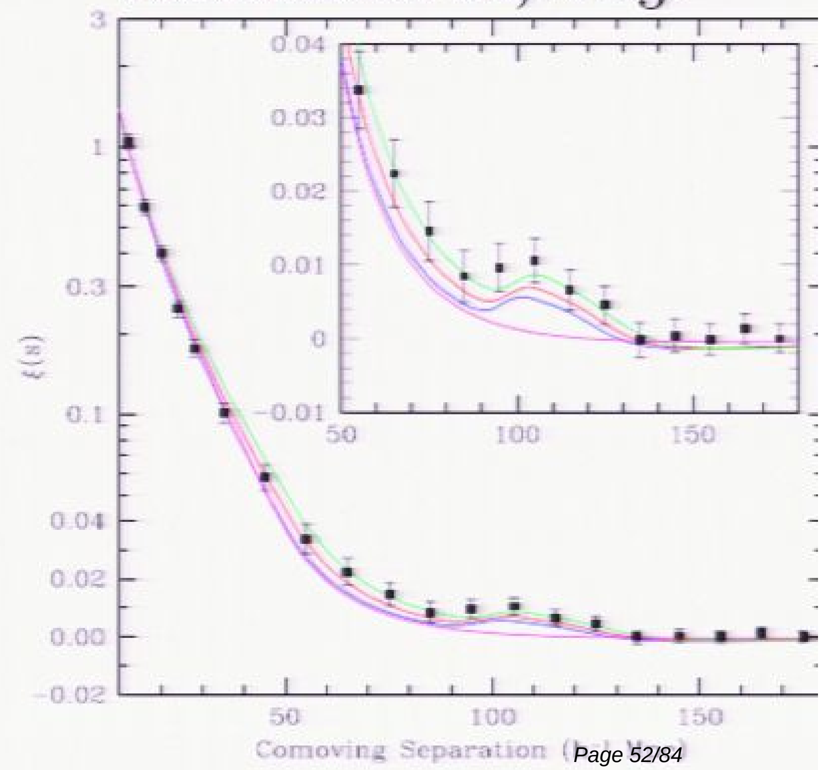
- Nearby ($z \approx 0.3$) BAO signal seen by SDSS & 2df

- ~1% (2 Gpc^3/h^3) of the universe has been mapped with optical light from galaxies.

- Galaxy surveys are expensive
- Rely on (non-linear) galaxies as tracers for BAO

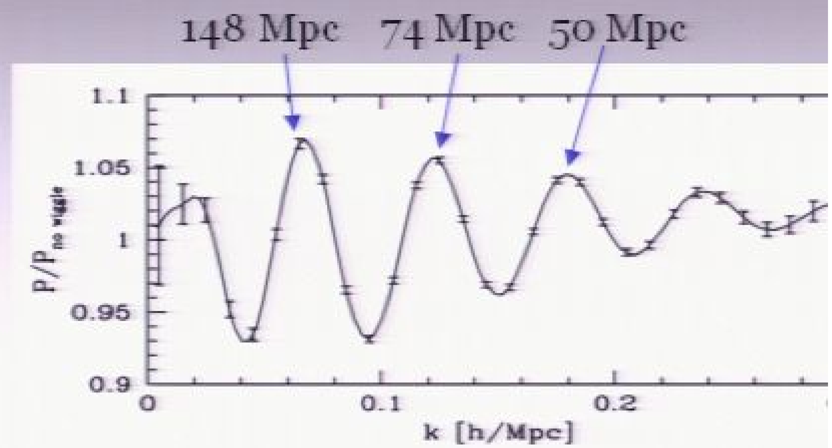


Eisenstein *et. al.*, 2005.



Cosmic Sound

- Acoustic oscillations are on large (co-moving) scales.
- No need to see individual galaxies… integrate over large swaths of sky with <~ degree beams.



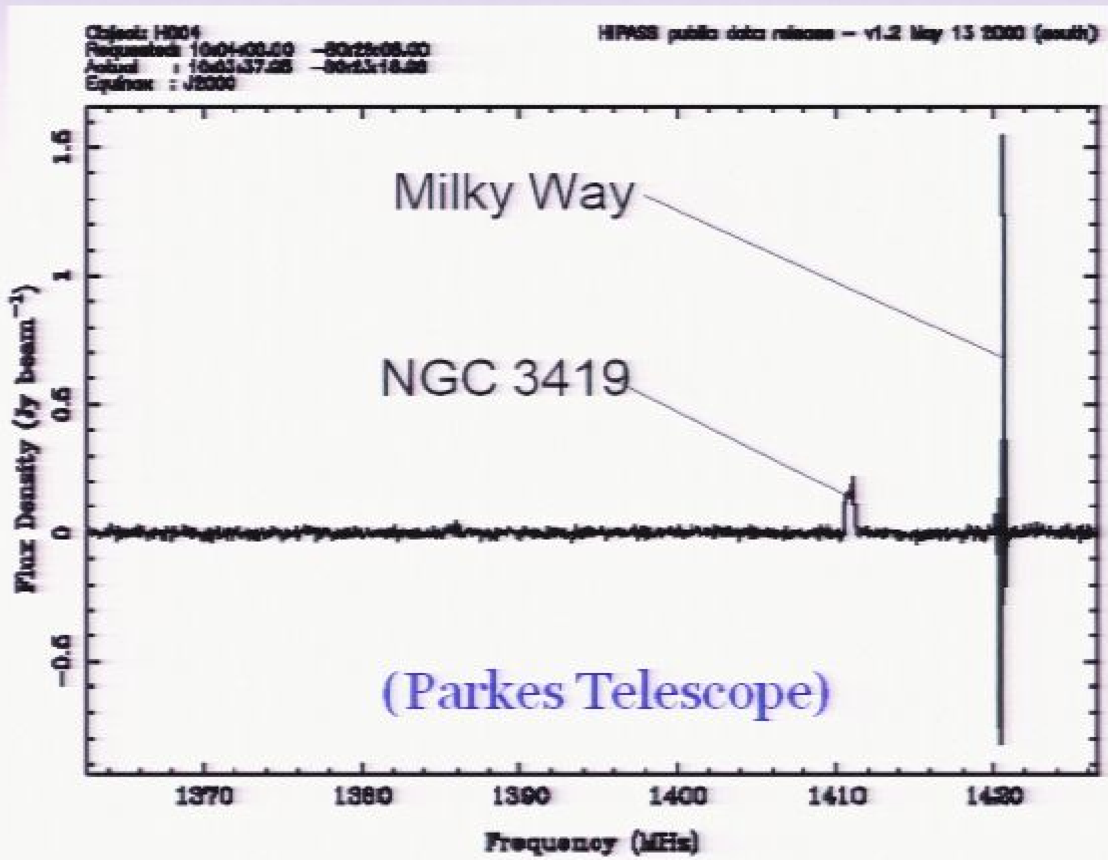
- … but need redshift signature.

→ 21cm (1420 MHz) Hydrogen Hyperfine Transition

- Traces matter beautifully, and provides redshift (3d mapping)

- ***Hydrogen Intensity Mapping***
  - Measure BAO in angular directions in redshift shells.
  - Measure BAO in radial direction as function of redshift.
  - 10,000 m^2 collection area adequate.

21 cm Hydrogen Line



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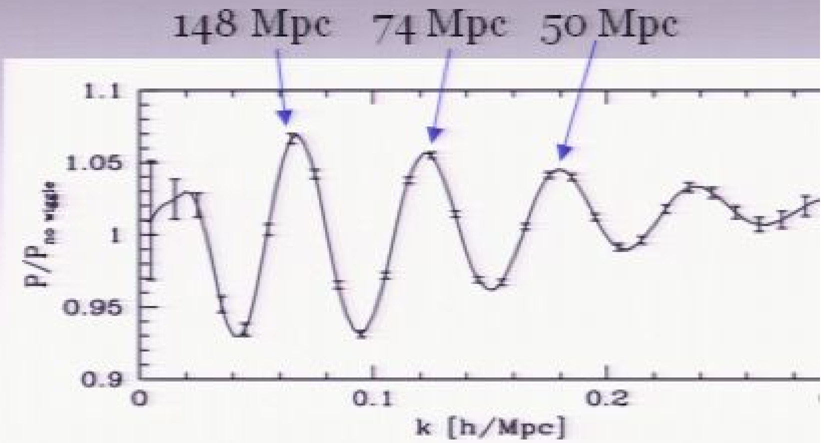

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21cm Intensity Mapping

- Goal:
  - maximize mapping speed
  - Bag enough photons (large collection area) for good sensitivity

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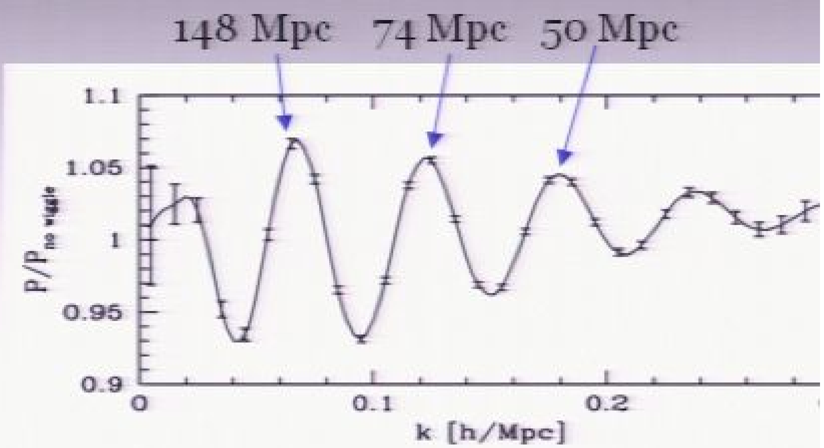

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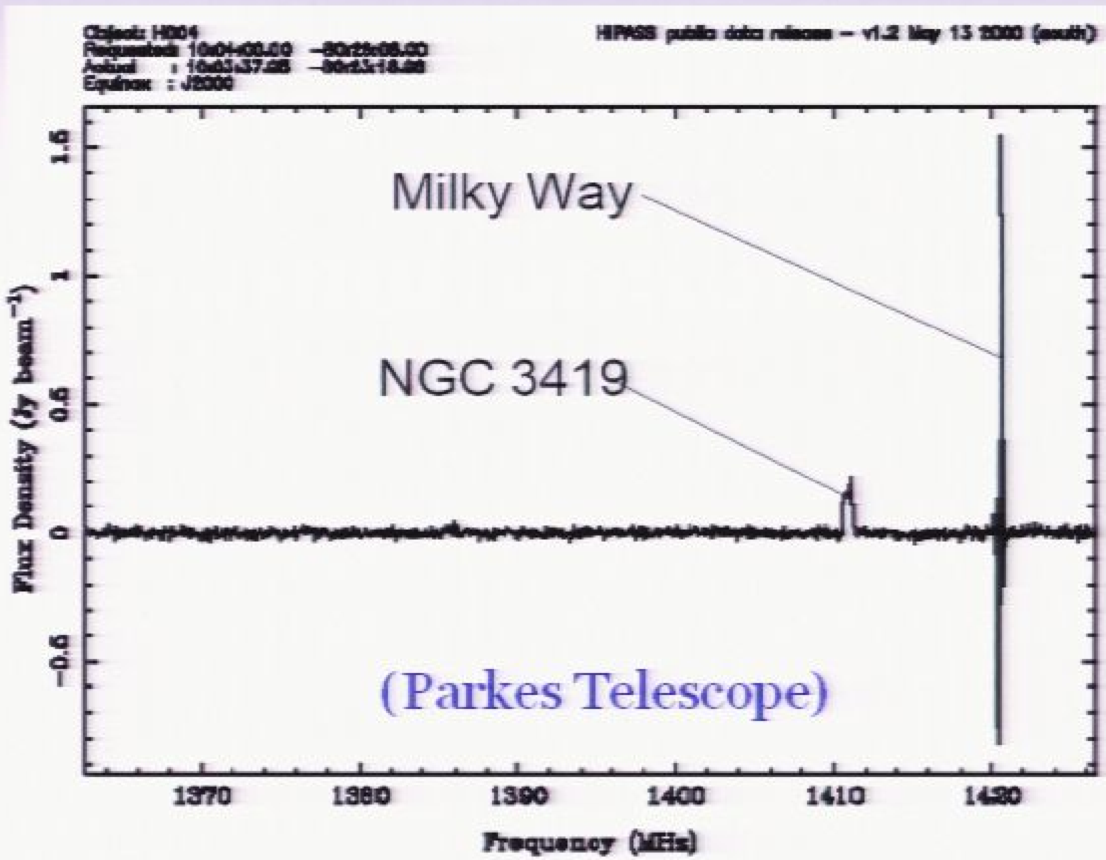

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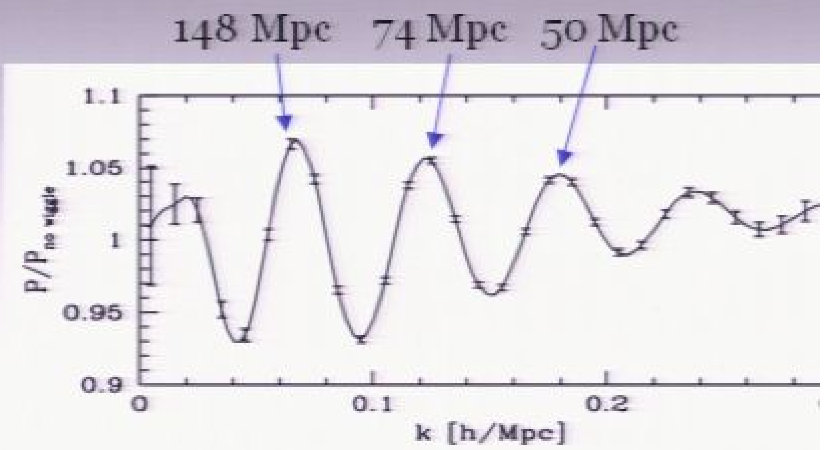

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→ 21cm (1420 MHz) Hydrogen Hyperfine Transition

- Traces matter beautifully, and provides redshift (3d mapping)

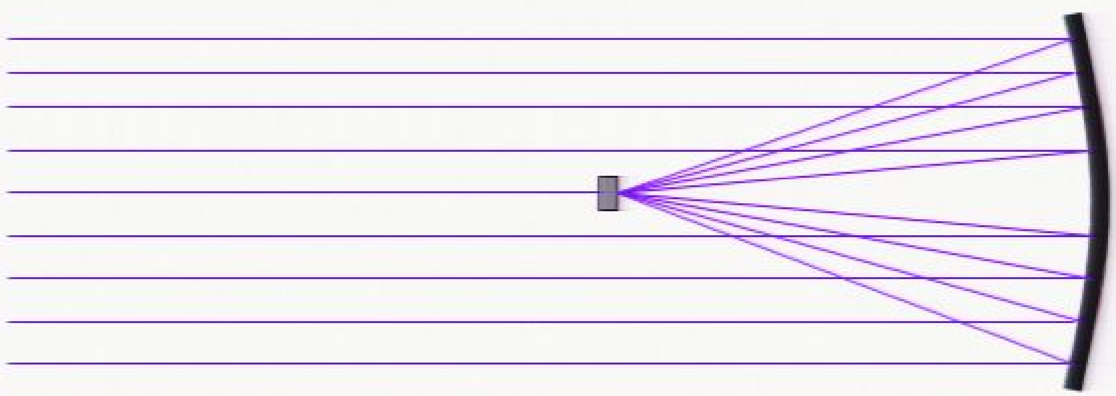
- ***Hydrogen Intensity Mapping***
  - Measure BAO in angular directions in redshift shells.
  - Measure BAO in radial direction as function of redshift.
  - 10,000 m^2 collection area adequate.

21cm Intensity Mapping

- Goal:
  - maximize mapping speed
  - Bag enough photons (large collection area) for good sensitivity

FFT Telescope Cartoon

- Traditional reflector serves to adjust phase of plane-wave rays, such that light collected across a large area arrives coherently at detector.



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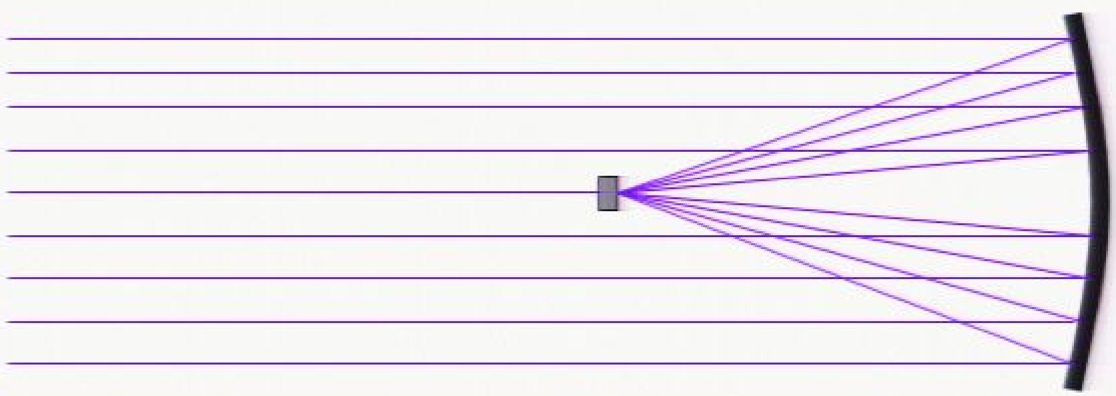

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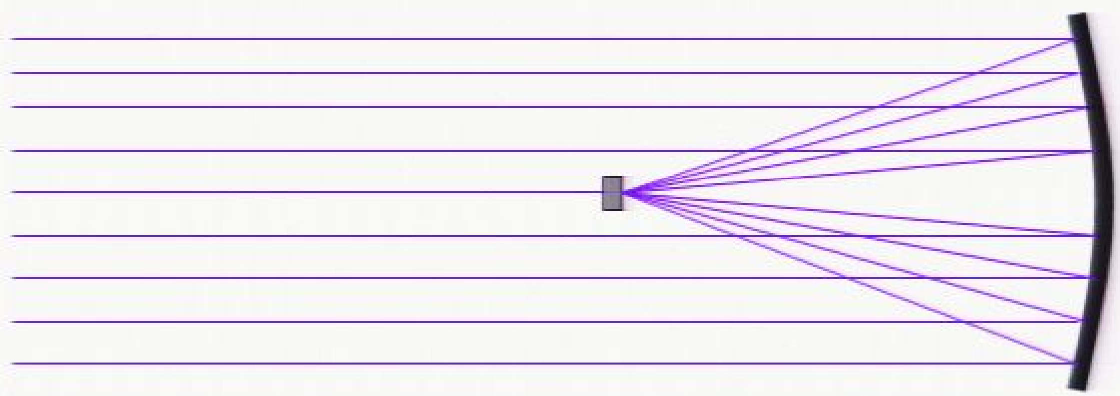


FFT Telescope Cartoon

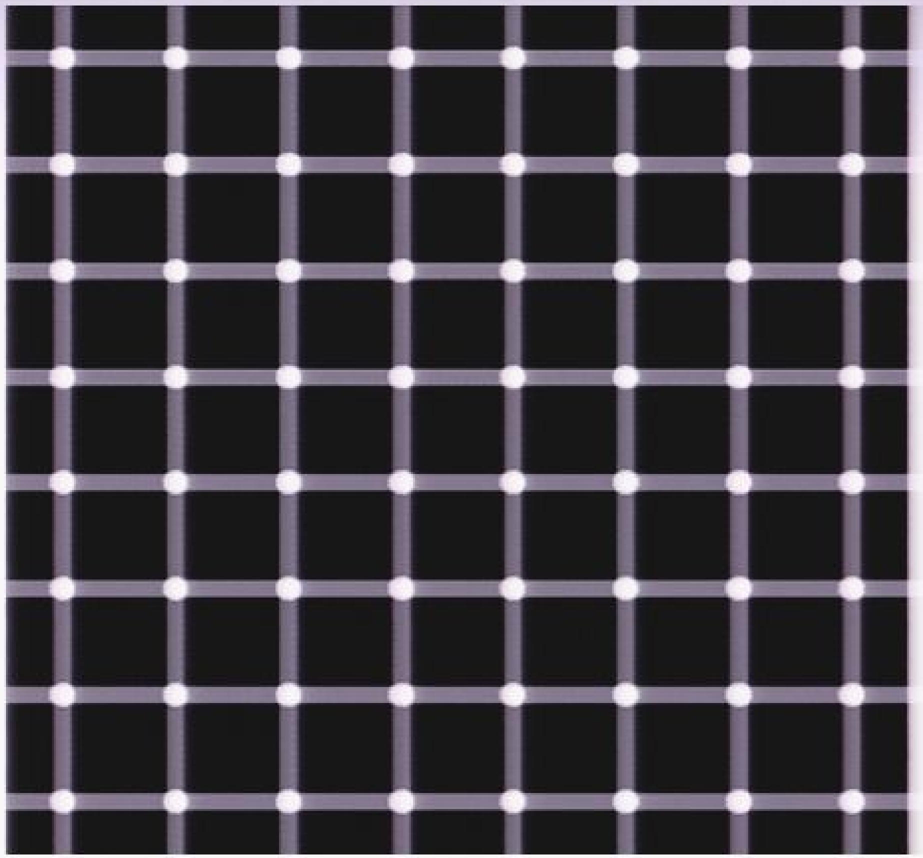
- If receivers were cheap,

  I could pepper them along the reflector, and add their signals together with just the right delay- and achieve the same net signal and point to the same place on the sky.
- I need to Nyquist sample the wavefront.
- I can apply my delay in analog (i.e. cable lengths), or digitally after conversion.

FFT Telescope Cartoon

- I can also lay them out in a line – applying any delay I like (e.g. the delay configuration that makes this indistinguishable from the reflector).
- If I apply my delays digitally – I can apply more than one delay configuration – and look at more than one point on the sky.
- A Fourier transform of the receiver time streams, provides an image of the sky.
- If I use uniform spacing – and Nyquist sample the waveform, I can look at all points on the sky simultaneously using an FFT.

FFT Telescope



- Nyquist sample
- Equal spacing
- All sky
- Summing
- Beamsize

Cylindrical Telescopes

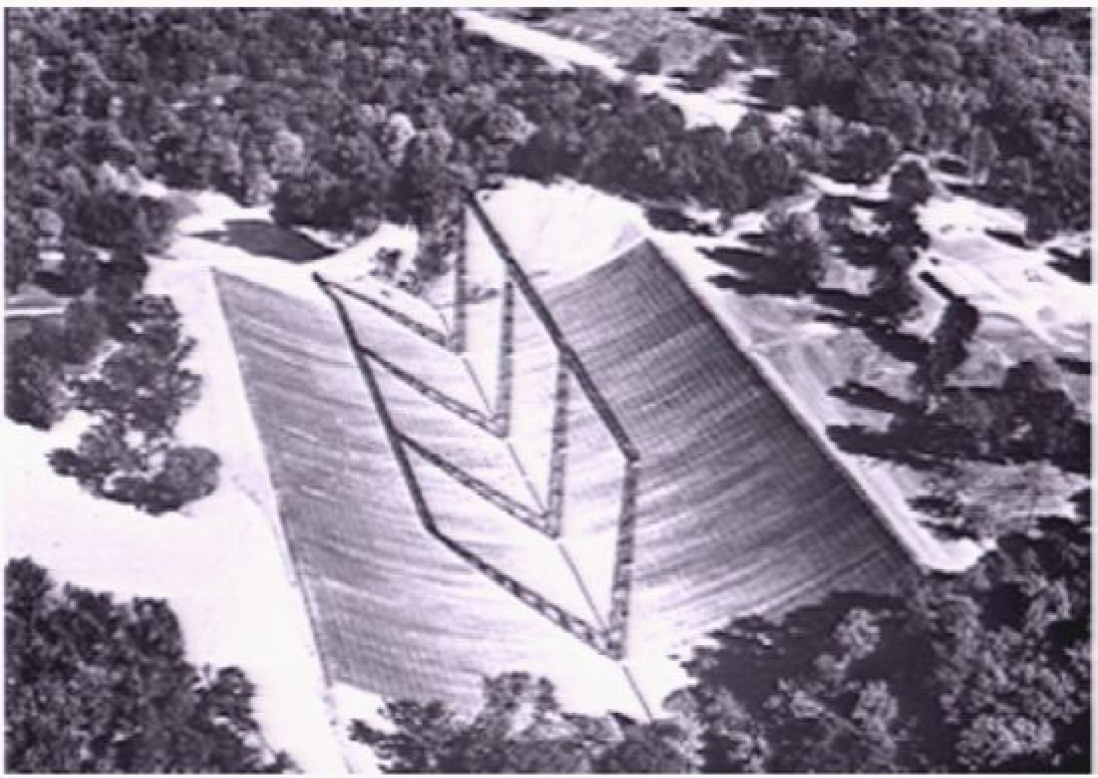
- FFT telescope in N-S direction
  - Possibility of full-sky FoV.

- Traditional reflector in E-W direction
  - λ/D = 60cm/20m = 1.7 degree FoV
  - Allow sky to drift over-head.

(Carnegie Mellon Prototype Cylinder)

Cylinder History

- Popular 1960-1980
- Lost favor with advent of cryogenically cooled pre-amplifiers.
- Room temp amplifiers with 20K noise temp now available.



Illinois 400 ft Telescope ca. 1960

(slide from Jeff Peterson)

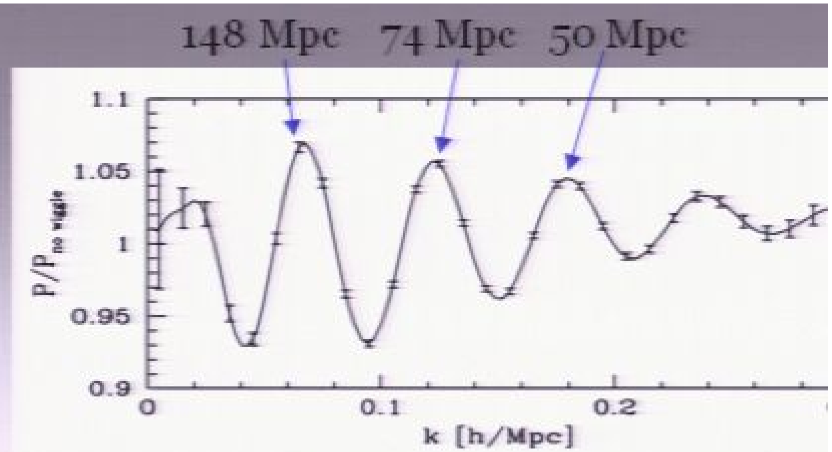
CHIME

- Array of five 20x100m cylinders → 10,000 m^2 area.
- Oriented North-South
  - Survey sky as it sky drifts overhead without any moving parts or the associated maintenance.

- Instrumented every 25 cm with dual polarization broadband antennae
- (driven by communications industry) Modern low noise amplifiers achieve ~20K noise.
  - Room temperature → no cryogenics

CHIME

Map 100 Gpc^3/h^3



CHIME Experiment Parameters

Observing Frequency	800 to 400 MHz
Observing Wavelength	38 to 76 cm
Redshift	$z \approx 0.8$ to 2.5
System Noise Temperature	$\leq$ 50K
Beam size	0.26° to 0.53°
Field of View, N-S	52° to 105°
Field of View, E-W	1.3° to 2.5°
Cylinder Size	100m × 20m
Number of Cylinders	5
Collecting Area	10,000 m^2
Antenna Spacing	26 cm
Number of Antennae per Cylinder	390
Number of Dual-Polarization Antennae	1950
Number of Antennae Summed before Digitization	2
Number of Digitizers	1950
Bandwidth of Channeled outputs	1 MHz

age = 7 → 2.6 Gyr

10 → 45 Mpc resoluti

bandwidth ~2→4 MI

CHIME Core Collaboration

UBC

- Mark Halpern
- Kris Sigurdson
- Siegfried Stiemer

McGill U

- Matt Dobbs
- David Hanna

U Toronto / CITA

- Dick Bond
- Ue-li Pen

HIA, DRAO

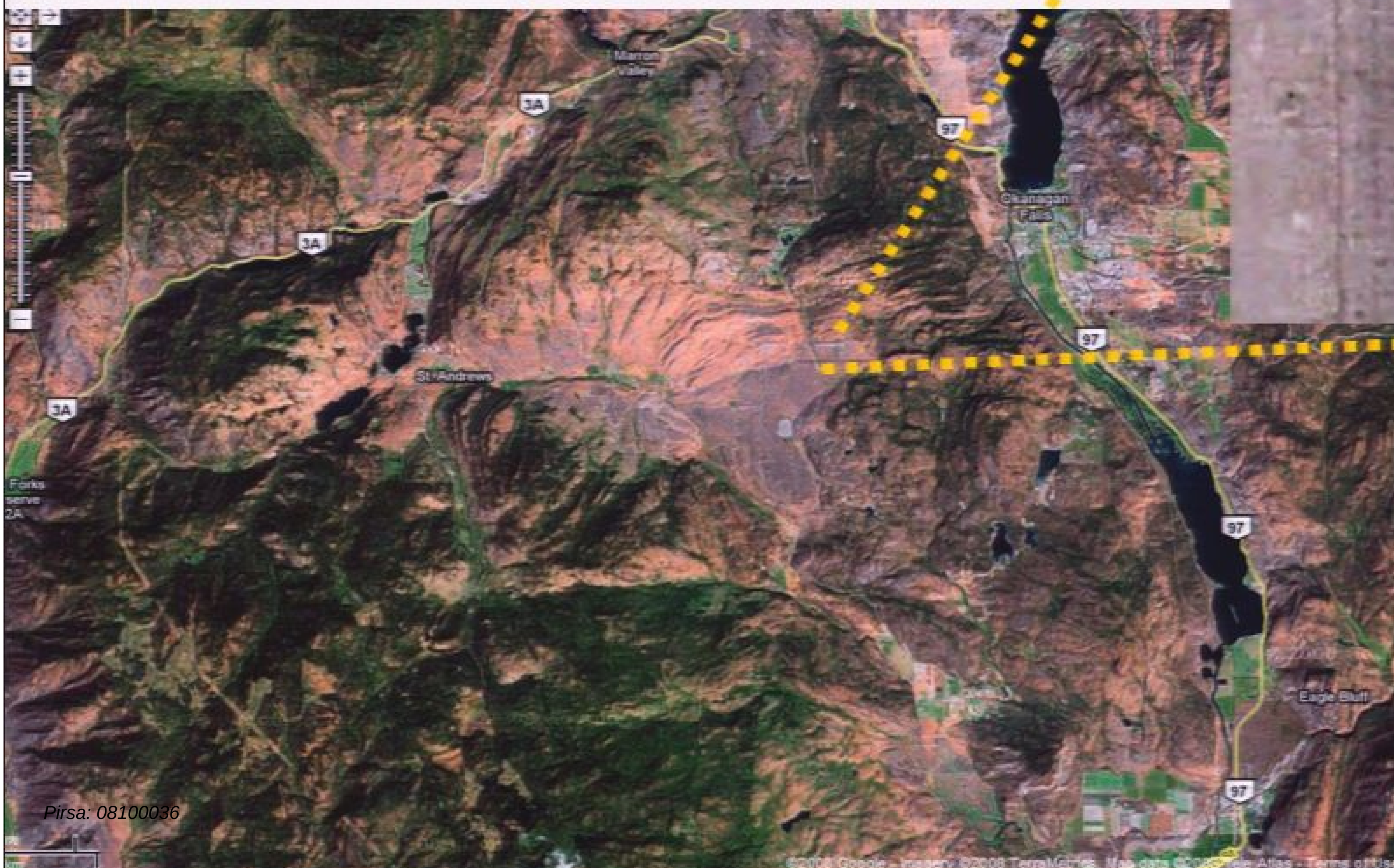
- Tom Landecker

Carnegie Mellon U

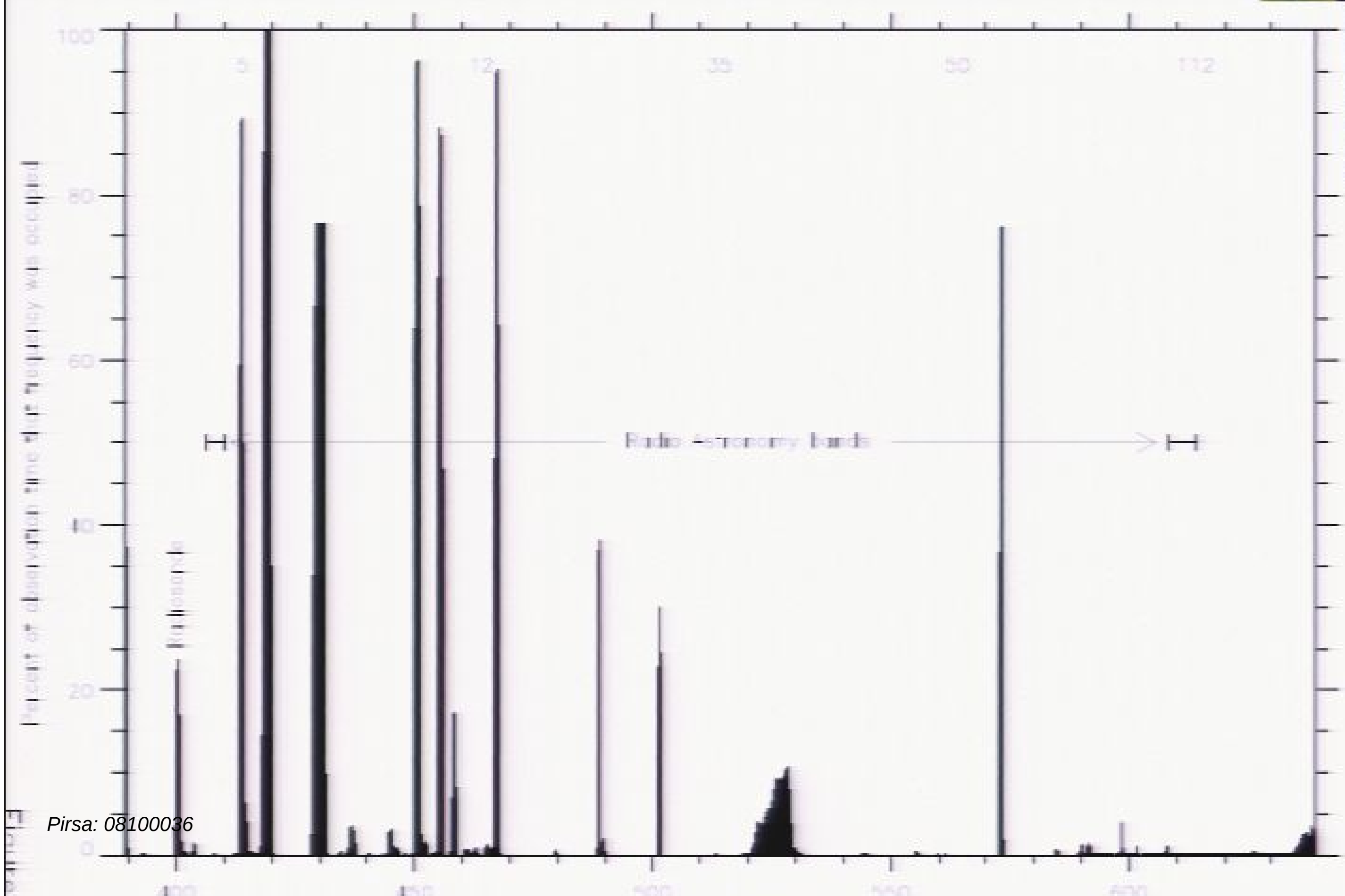
- Jeff Peterson

Dominion Radio Astrophysical Observatory

- Near Penticton, BC
- RF quiet zone, protected by federal law.
- Shielded from locally generated RF by surrounding mountains.



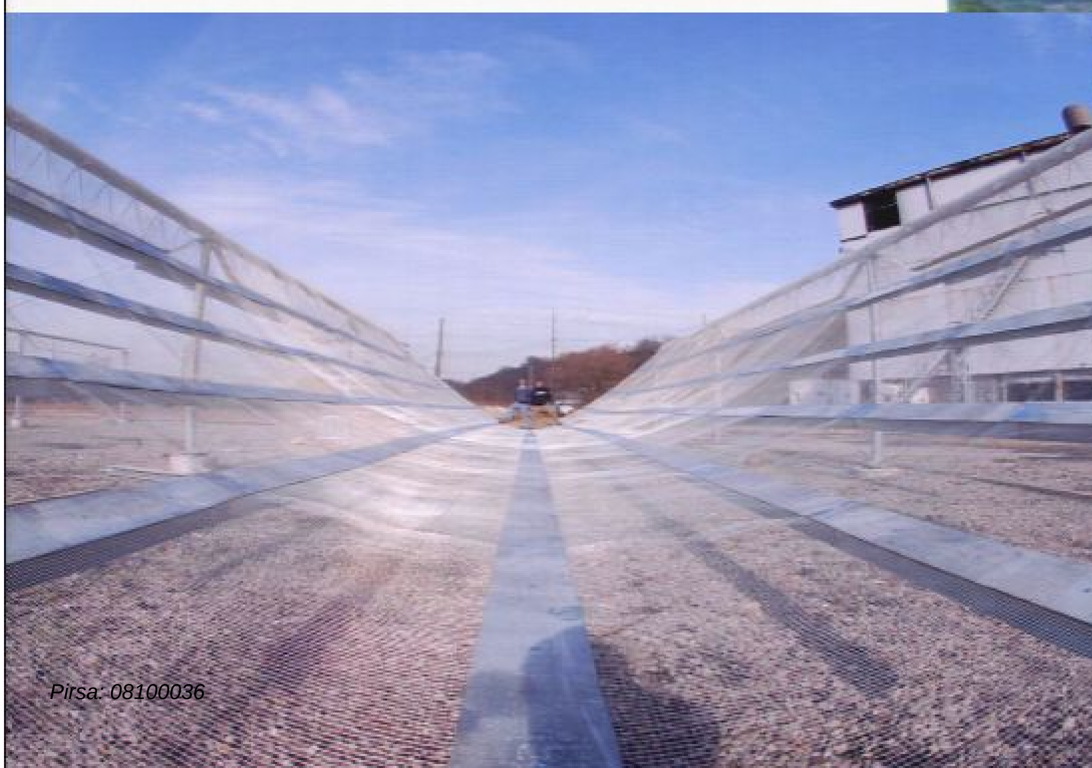
Earth-bound Interference at DRAO



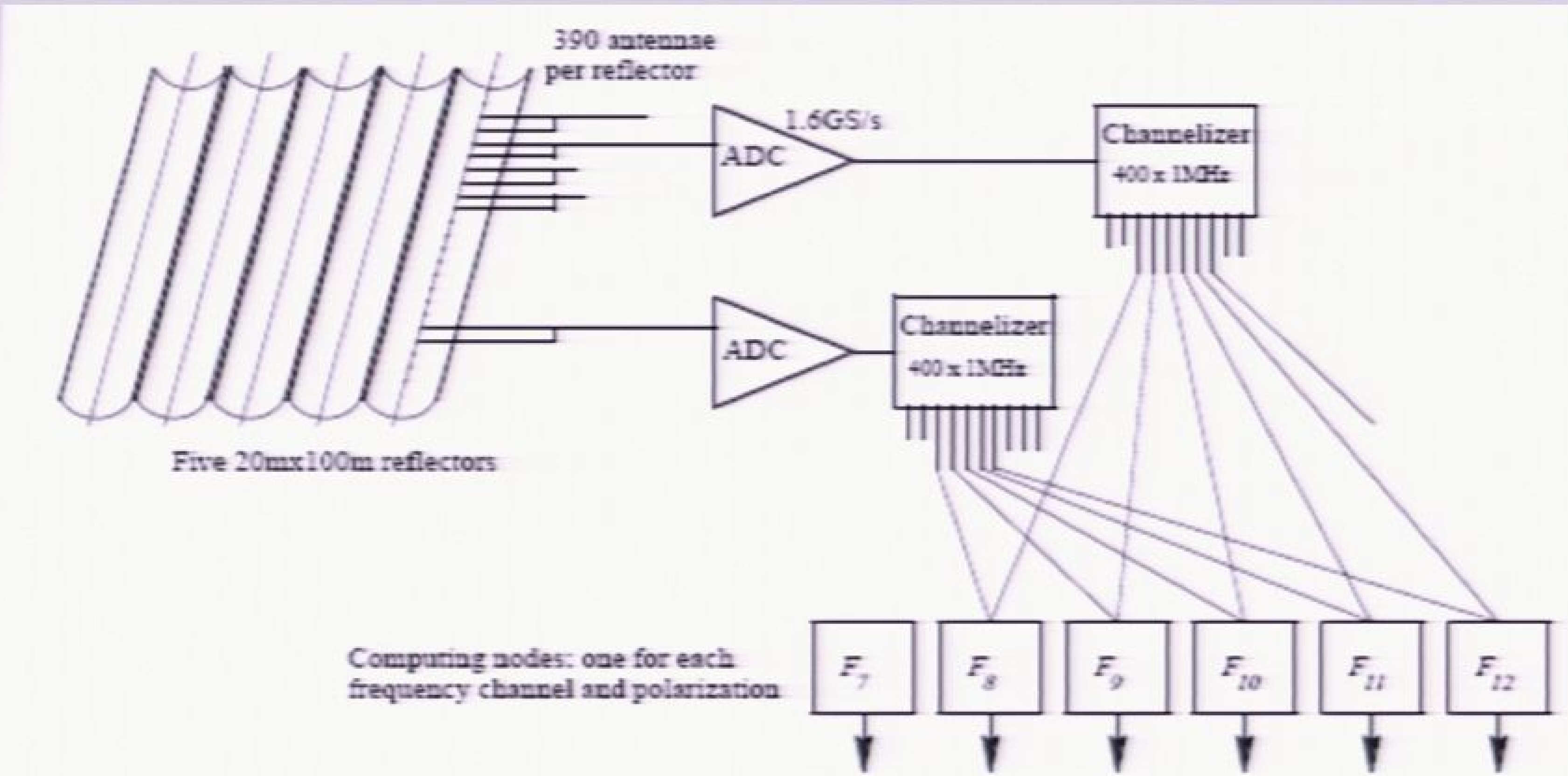
John Galt, 2002

Cylinder Prototype & CHIME Testbed

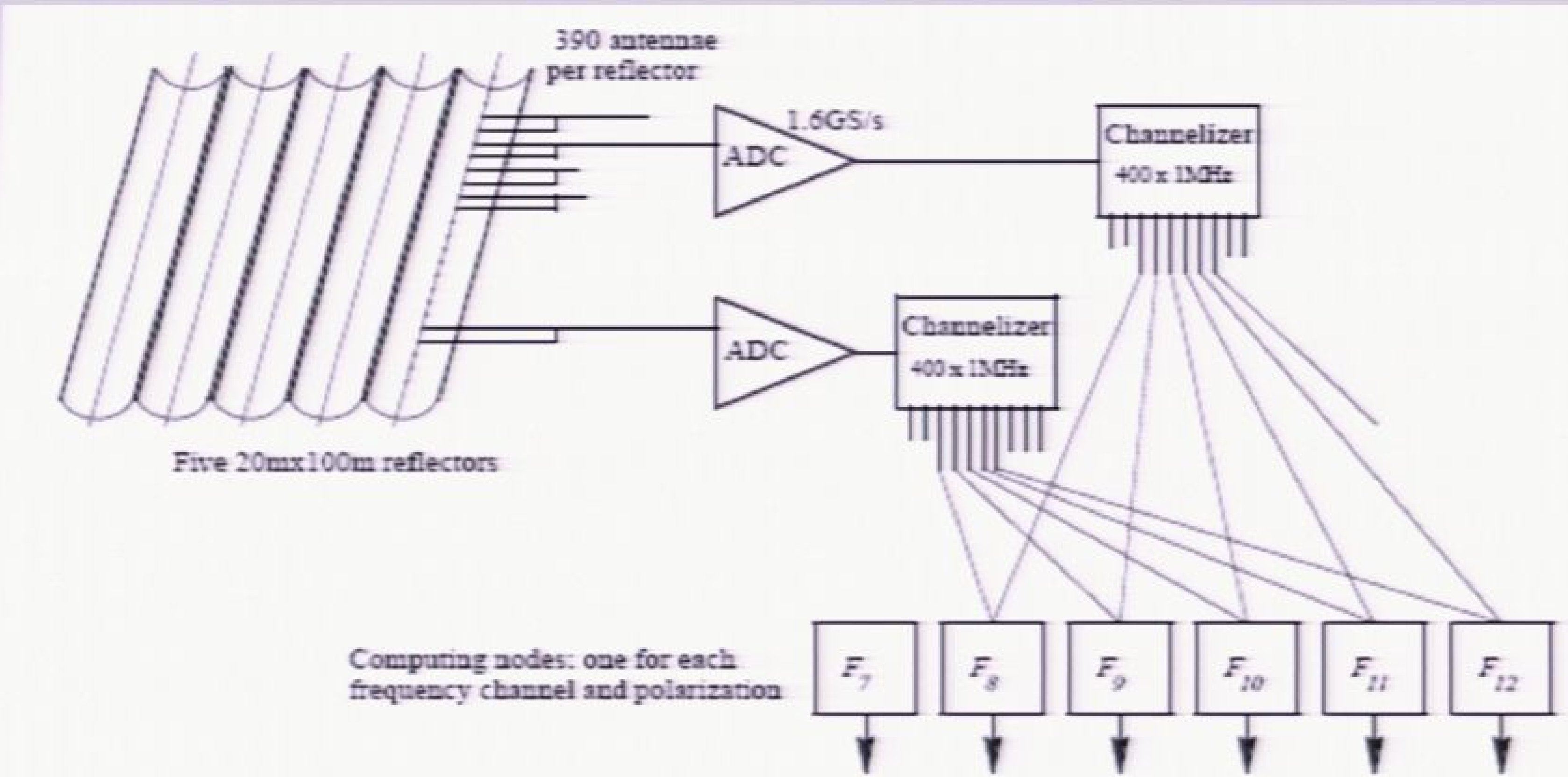
- Three 10 x 30m cylinders at Carnegie Mellon
- Led by: Jeff Peterson / Ue-Li Pen / Kris Sigurdson



CHIME Dataflow

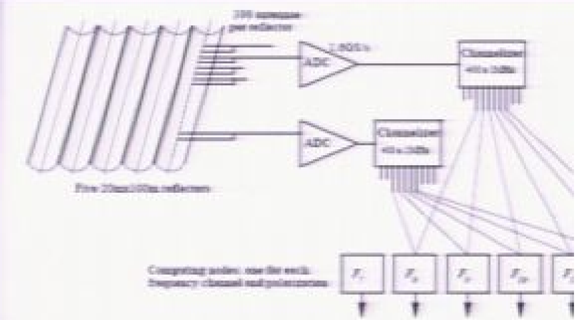


CHIME Dataflow



Channelization, Correlation

- Stage 1: (near antenna), firmware based FFT divides waveform up into 400 bands, each 1 MHz wide (from 400-800 MHz).
  - Each band corresponds to a redshift shell.



- Stage 2: PC or GPU-based FFT correlates signals separately for each frequency band along the cylinder N-S direction.
  - "embarrassingly parallel"
  - Uniform antenna spacing → Efficient N log(N) operation.

Tremendous real-time data rate!
1.6 Terasamples/sec.

- Stage 3: PC or GPU-based processors correlate signals between cylinders
  - Low pass filter data from each sky pixel to slow (several Hz) data rate and write to disk.

Tiny data rate to disk.
~4 GB/day

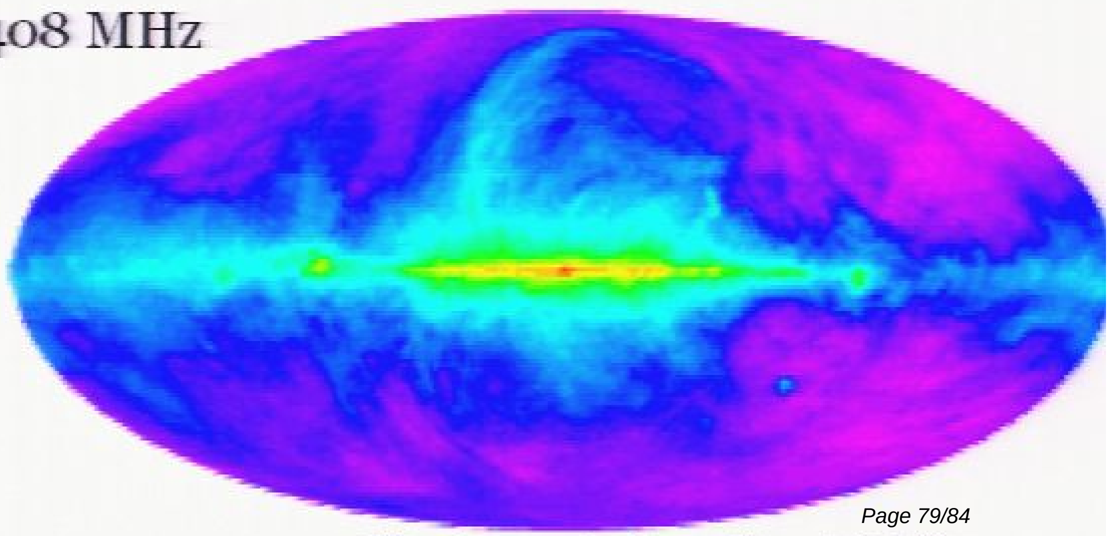
Hardware Challenges

- Mass-produce broadband Antenna/LNA
- Digitize and channelize antenna waveforms
- Transport data from Stage 1→2.
  - Data throughput 1.6 Terasamples per second
  - → Need (really) fast network.

Foregrounds

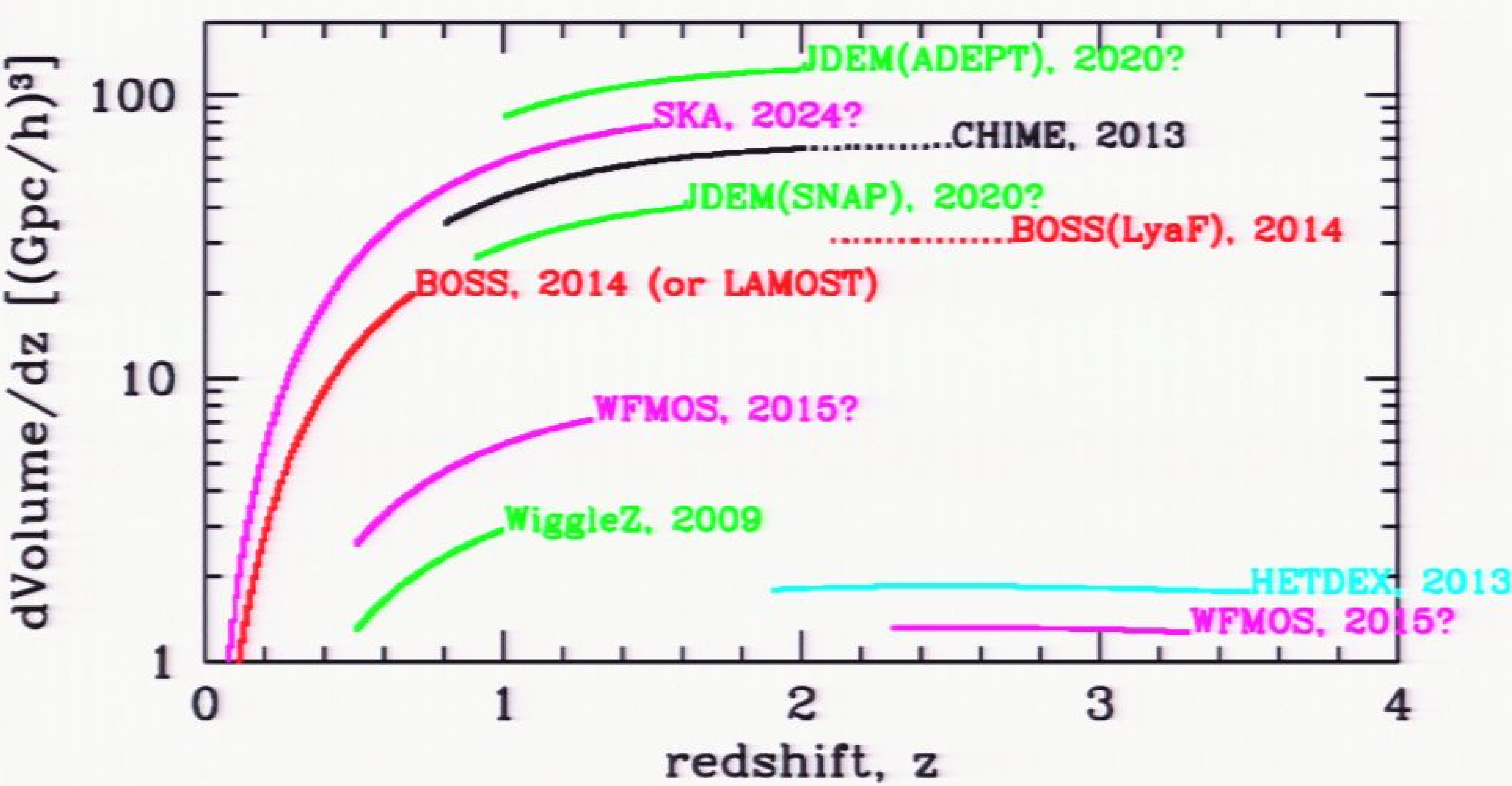
- Broad-band extragalactic emission from point sources
- Galactic emission (primarily synchrotron)
  - Emission is smooth in frequency space → remove lion's share with simple high-pass filter.
  - Global Magneto-Ionic Medium Survey (GIMIMS).

408 MHz



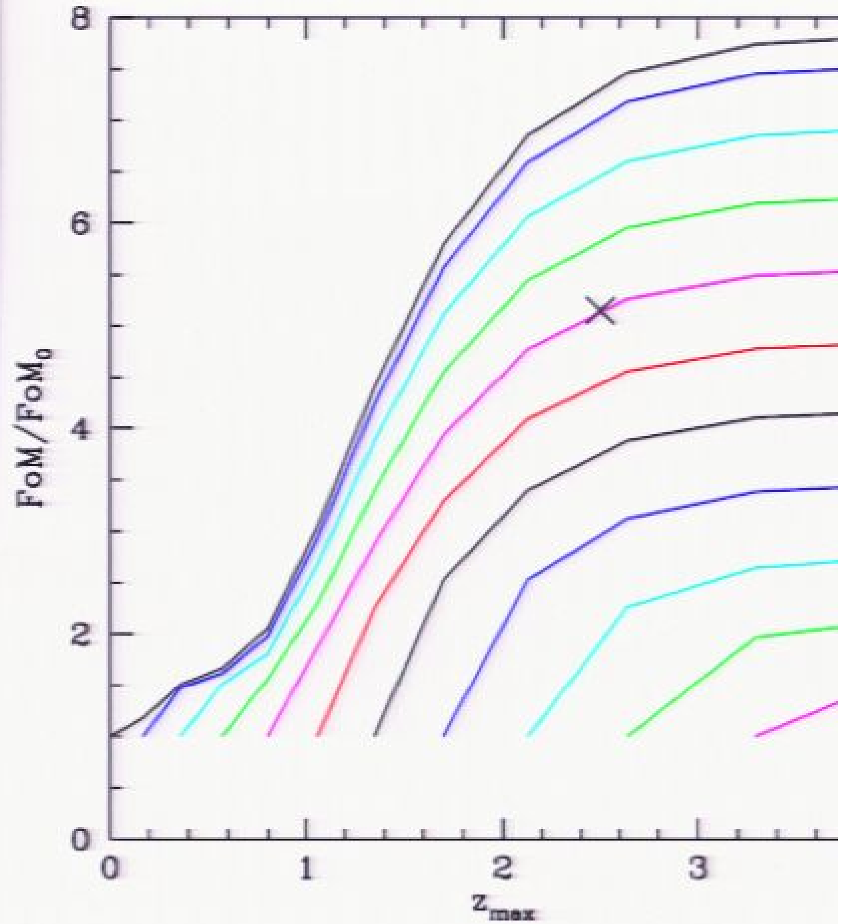
Haslam, et al., 1982, *A&AS*, **47**, 1.

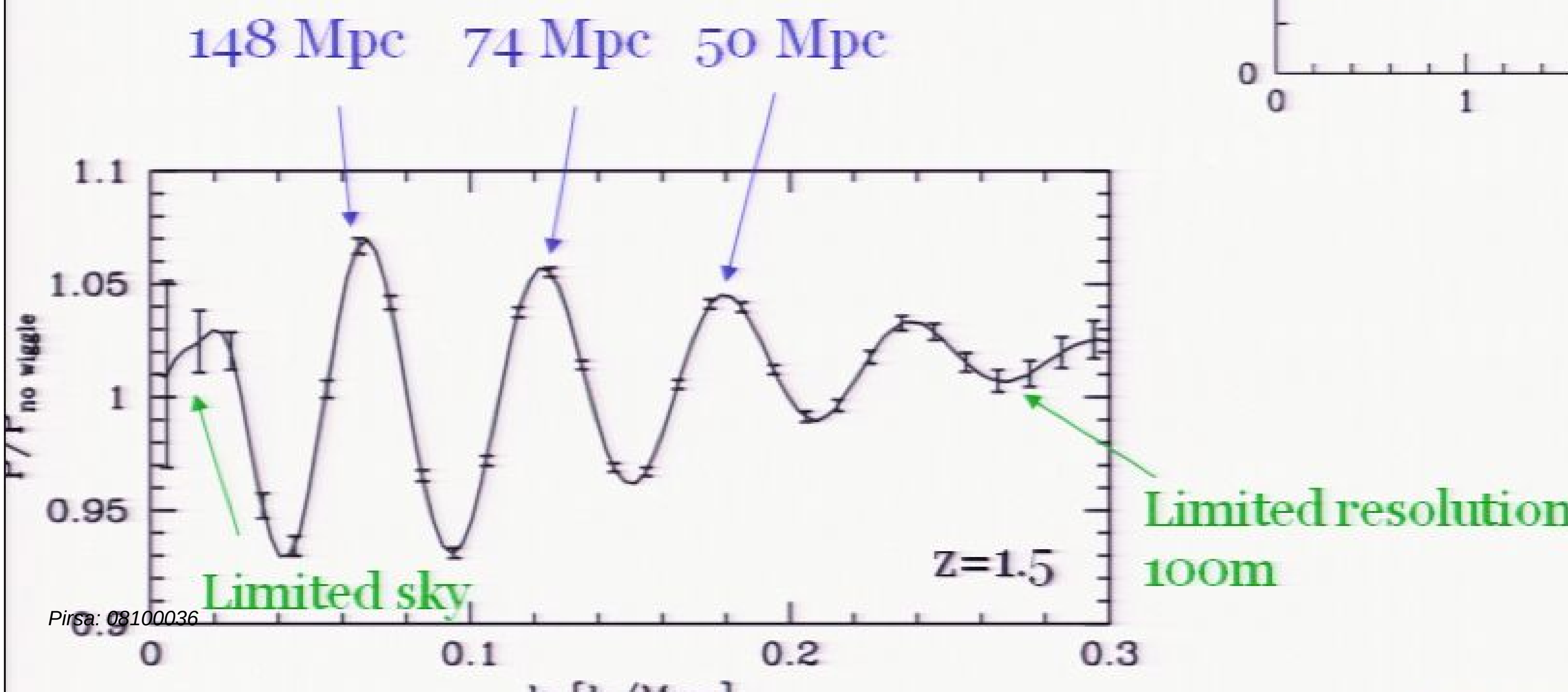
CHIME Capability



CHIME

- Map 100 Gpc^3/h^3
- 2 years of observations
- Improve uncertainty on DE parameters (w,w') by a factor of 5 ("Figure of Merit")





CHIME Ancillary Science

- *Chime will map the polarization and intensity of 40% of the sky with great sensitivity in a poorly explored frequency band.*
  - Galactic Magnetic fields
    - Complementary to Global Magneto-Ionic Medium Survey (GIMIMS),300-1800 MHz
    - Much deeper observations in subset of band.
  - Find and monitor Pulsars across massive sky area
    - Need real-time detection and monitoring software that extracts this data before the final averaging to Hz data rates.
    - Not intended for precision pulsar timing → but discover new objects.
  - Detect and monitor thousands of previously unknown Radio Transien
  - ...

Summary

- New windows are opening now on the expansion history of the universe
  - Inflationary gravity waves, through CMB polarization
  - Growth-based dark energy tests, such as Sunyaev-Zeldovich
    - (beautiful) Proof-of-concept cluster detections from South Pole Telescope submitted for publication last week.
  - The BAO standard rulers

- A new Canadian consortium is building a new FFT cylinder experiment purpose built for the cosmic sound measurement.
  - Proposal submitted.
  - Still a lot of theory work to do... chip in!

(Warning) Advertisement:
Graduate Student and postdoc fellowship opportunities available at McGill…