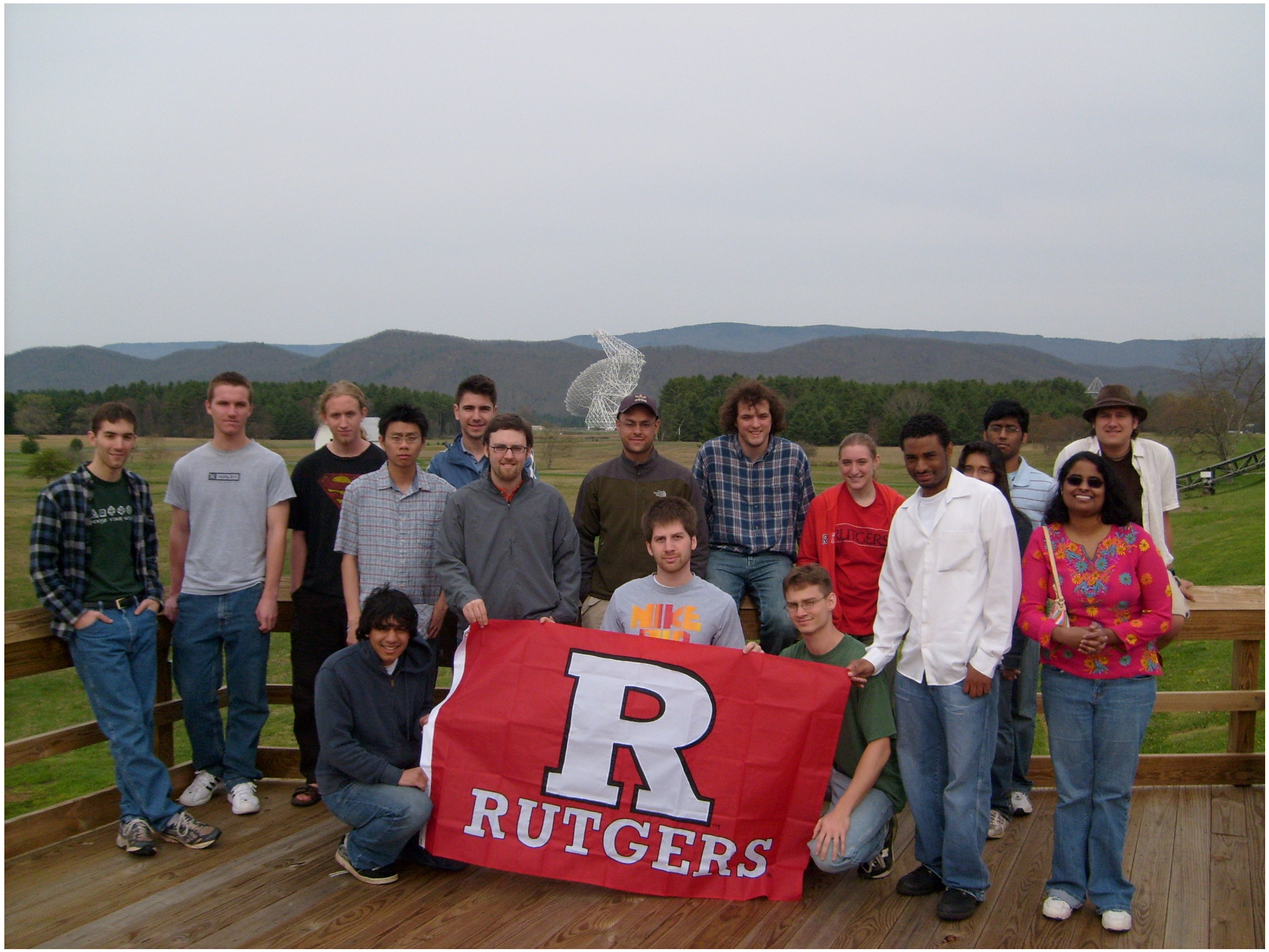
(Astro)Physics 343 Lecture # 13: cosmic microwave background (and cosmic reionization!)

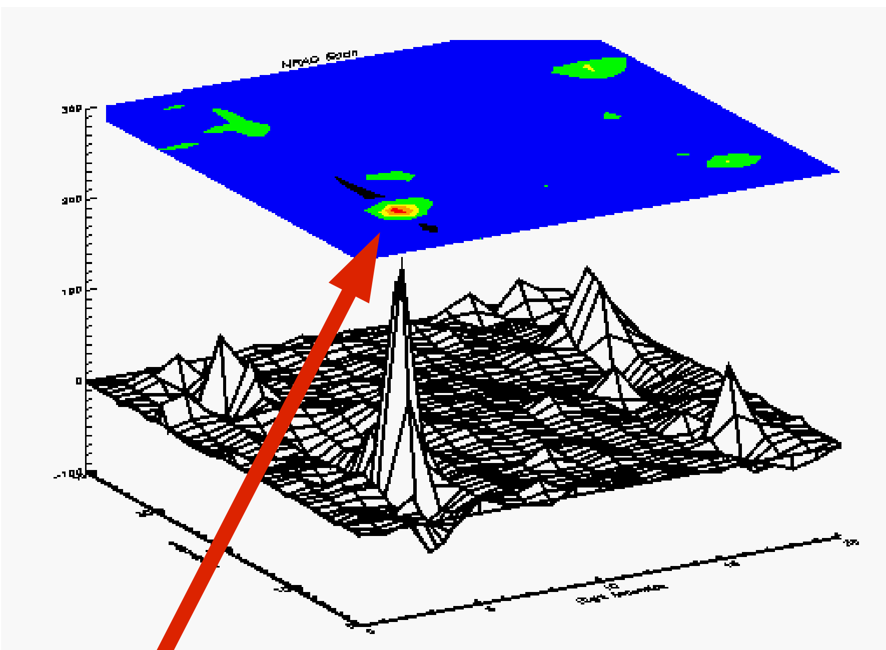
Welcome back!

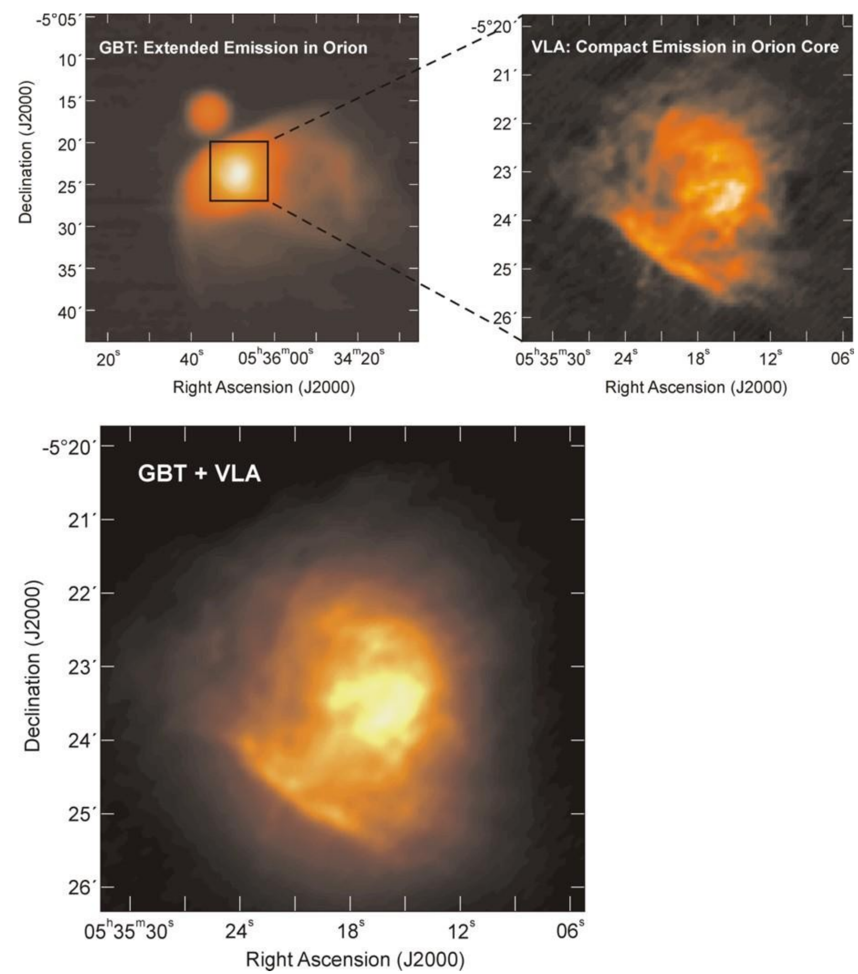


(four pictures on class website; add your own to http://s304.photobucket.com/albums/nn172/rugbt/)

Results: Orion

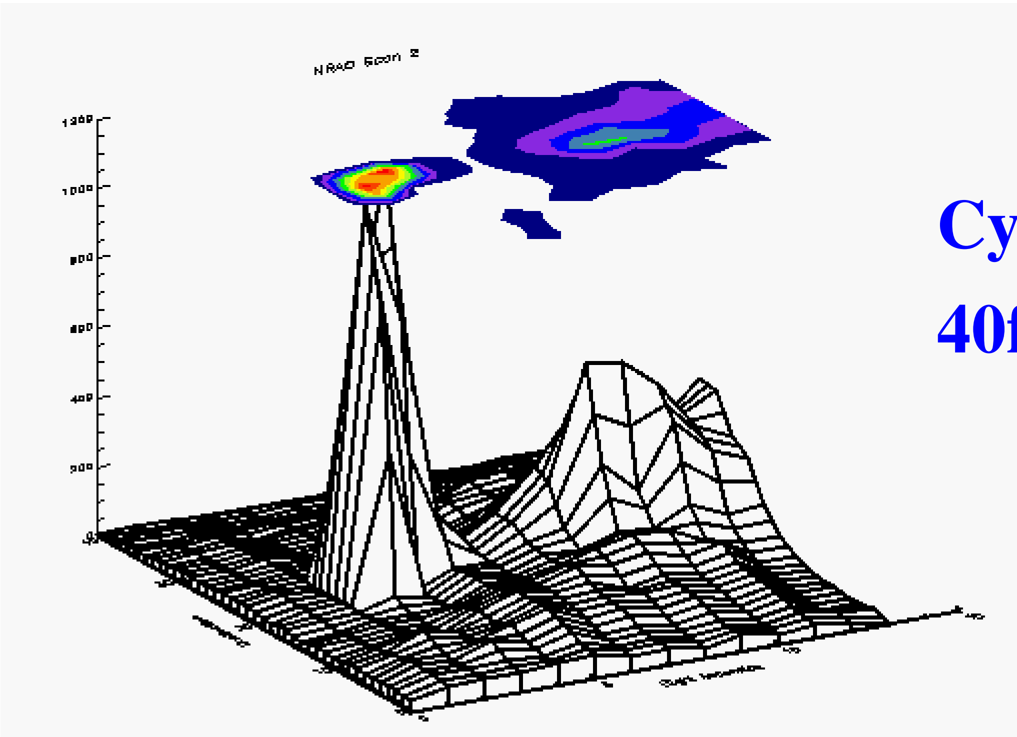
Orion region mapped with 40ft telescope (Team Rutgers)





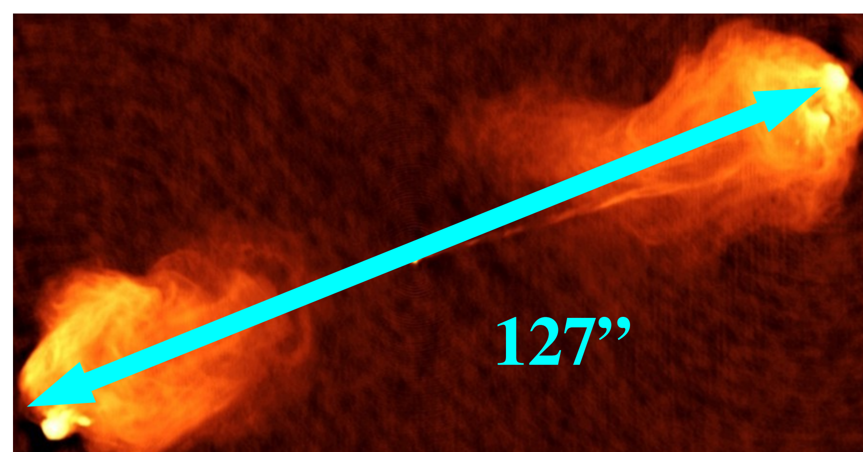
Orion A mapped at 8.4 GHz with GBT and VLA (courtesy D. Shepherd)

Results: Cygnus

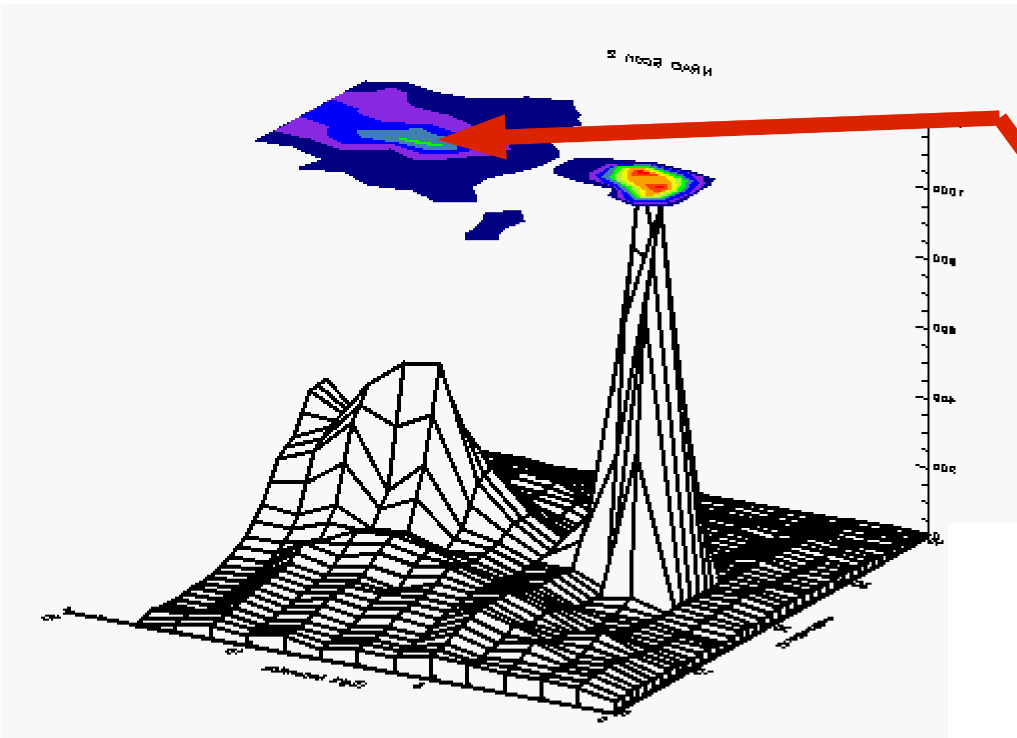


Cygnus region mapped with 40ft telescope (Team Rutgers)

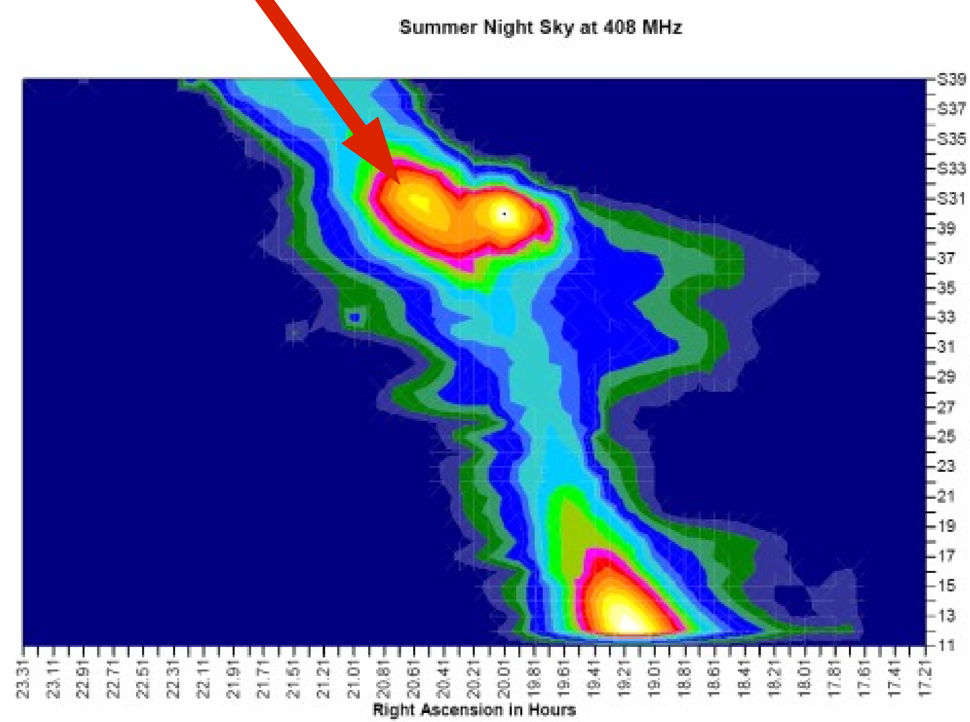
Cygnus A radio galaxy mapped with VLA (Perley et al. 1984)



Results: Cygnus A + Cygnus X region

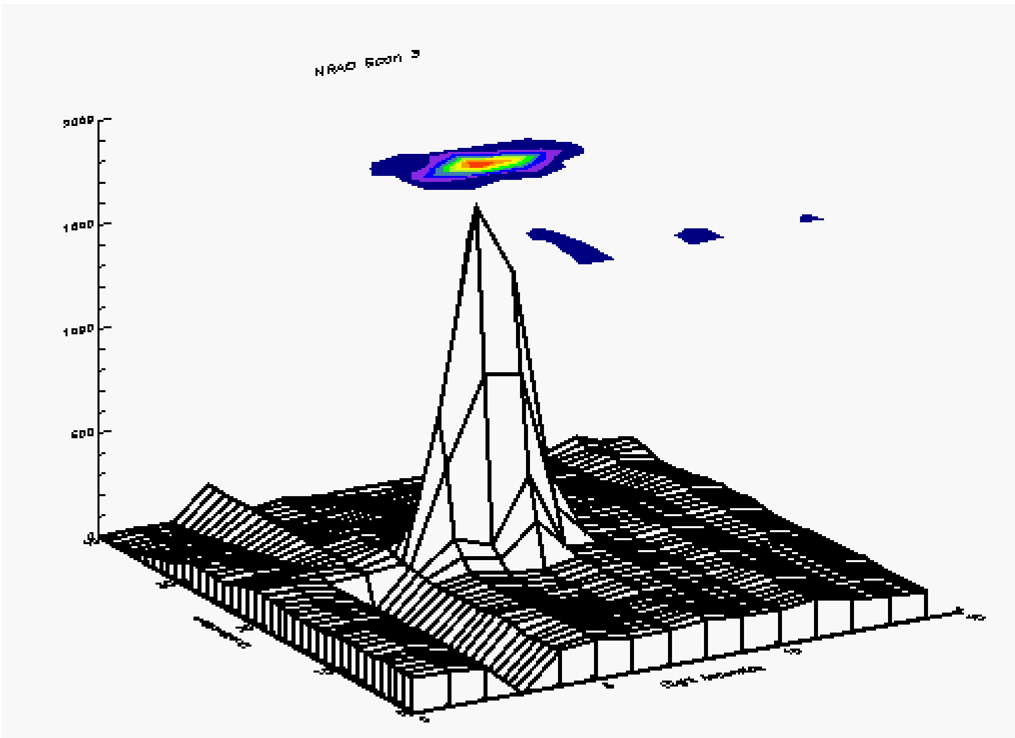


Extended star-forming region?

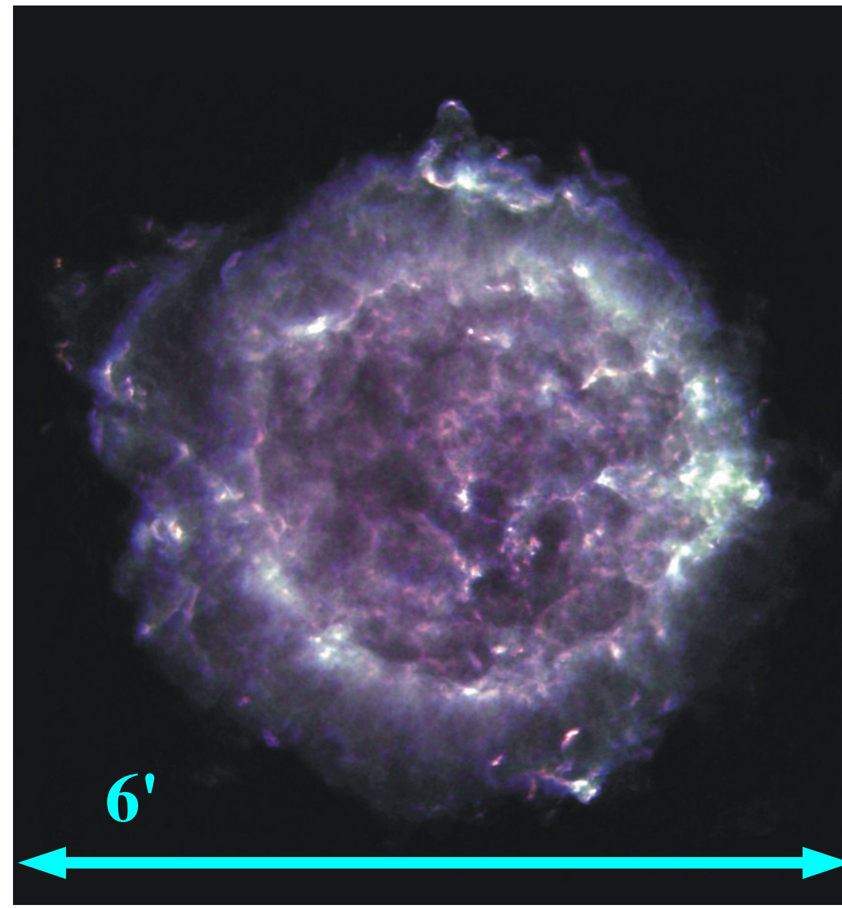


http://www.408mhzsurvey.org.uk/

Results: Cassiopeia A



Cass A supernova remnant mapped with 40ft telescope (Team Rutgers)

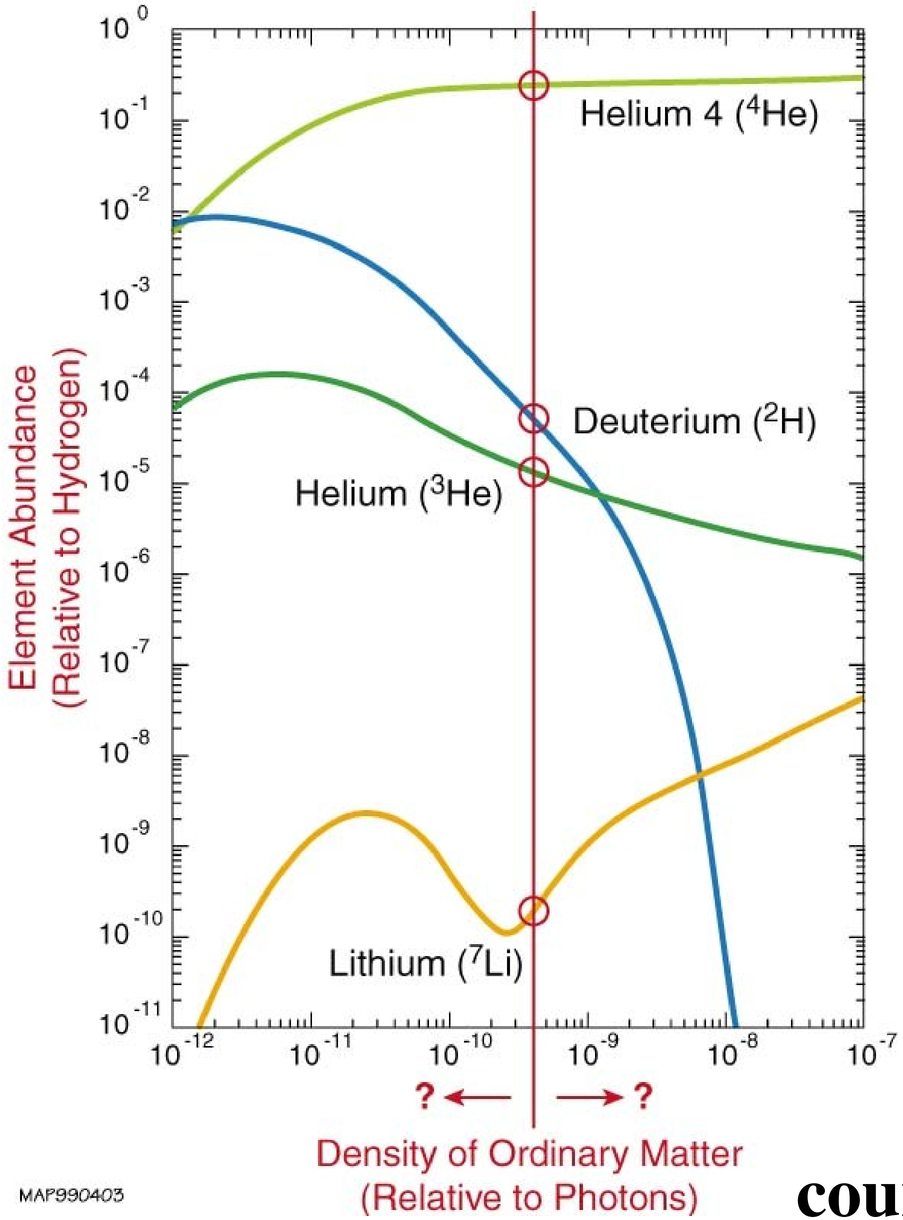


Cass A mapped at {1.4,5.0,8.4} GHz by VLA (courtesy T. Rector)

Showcase image(s)?

At least one map will go on permanent display... but only after we've confirmed source match(es) with exact coordinates!

Consensus cosmology: the Big Bang



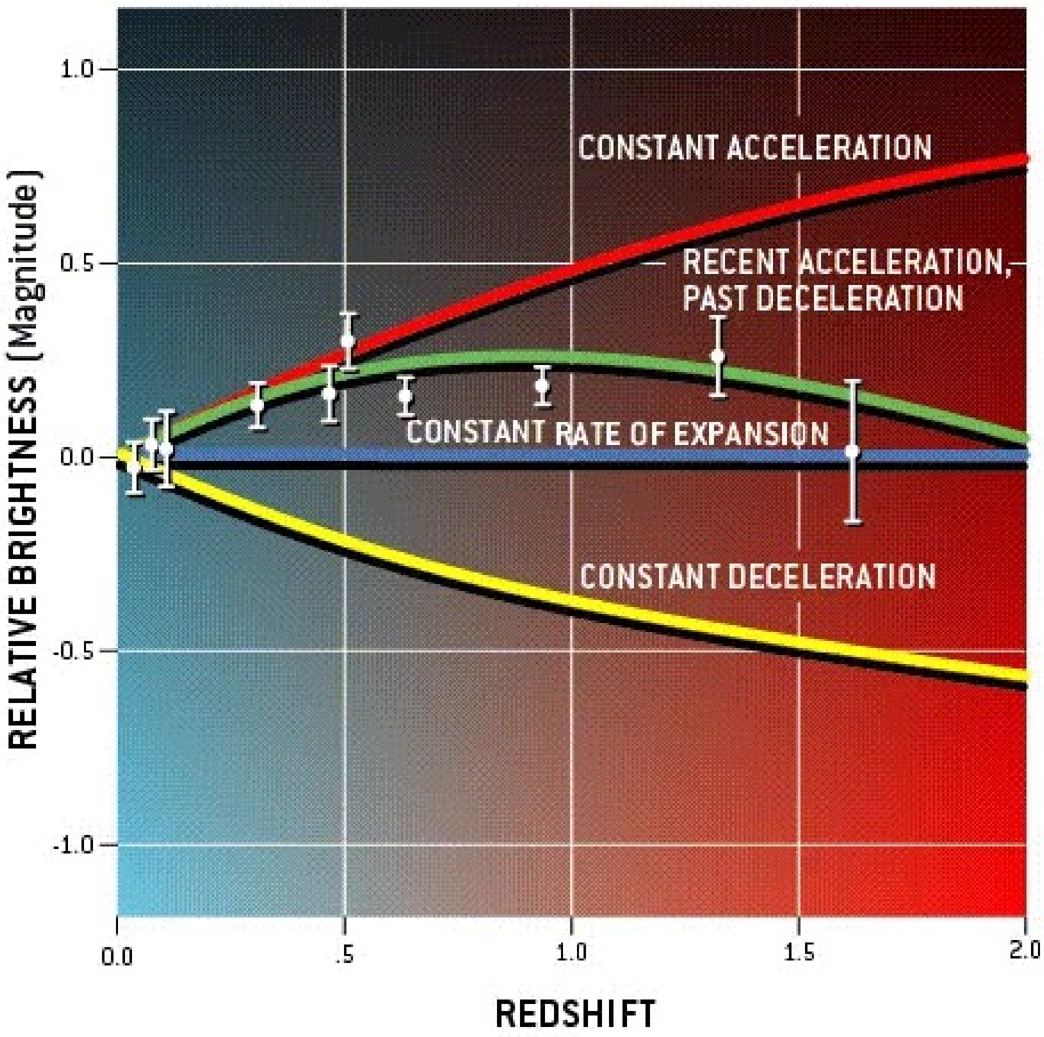
courtesy NASA

Universe was initially in a **hot, dense state** from which it began expanding at the moment of the Big Bang (about 13.7 Gyr ago).

★ primordial element abundances (first 3 minutes)

★ ongoing expansion (locally, $D \propto z$)

Consensus cosmology: Dark energy

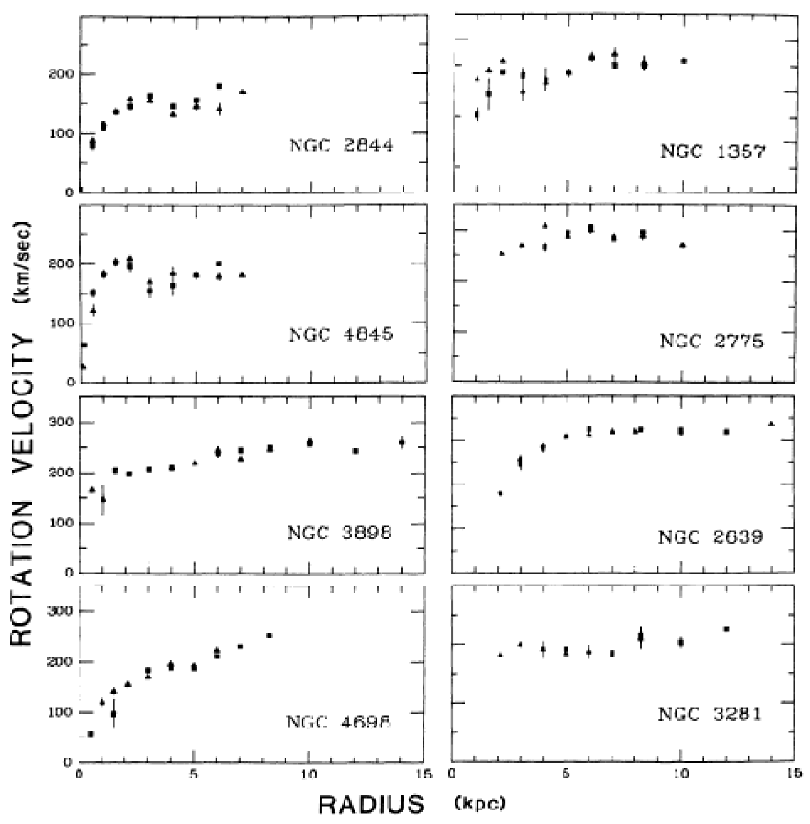


Riess & Turner (2004)

Expansion has recently been accelerated by a "dark energy" of unknown origin.

⋆ supernovae at z ~ 0.5 are fainter ⇔ more distant than expected for a constant expansion rate

Consensus cosmology: Dark matter

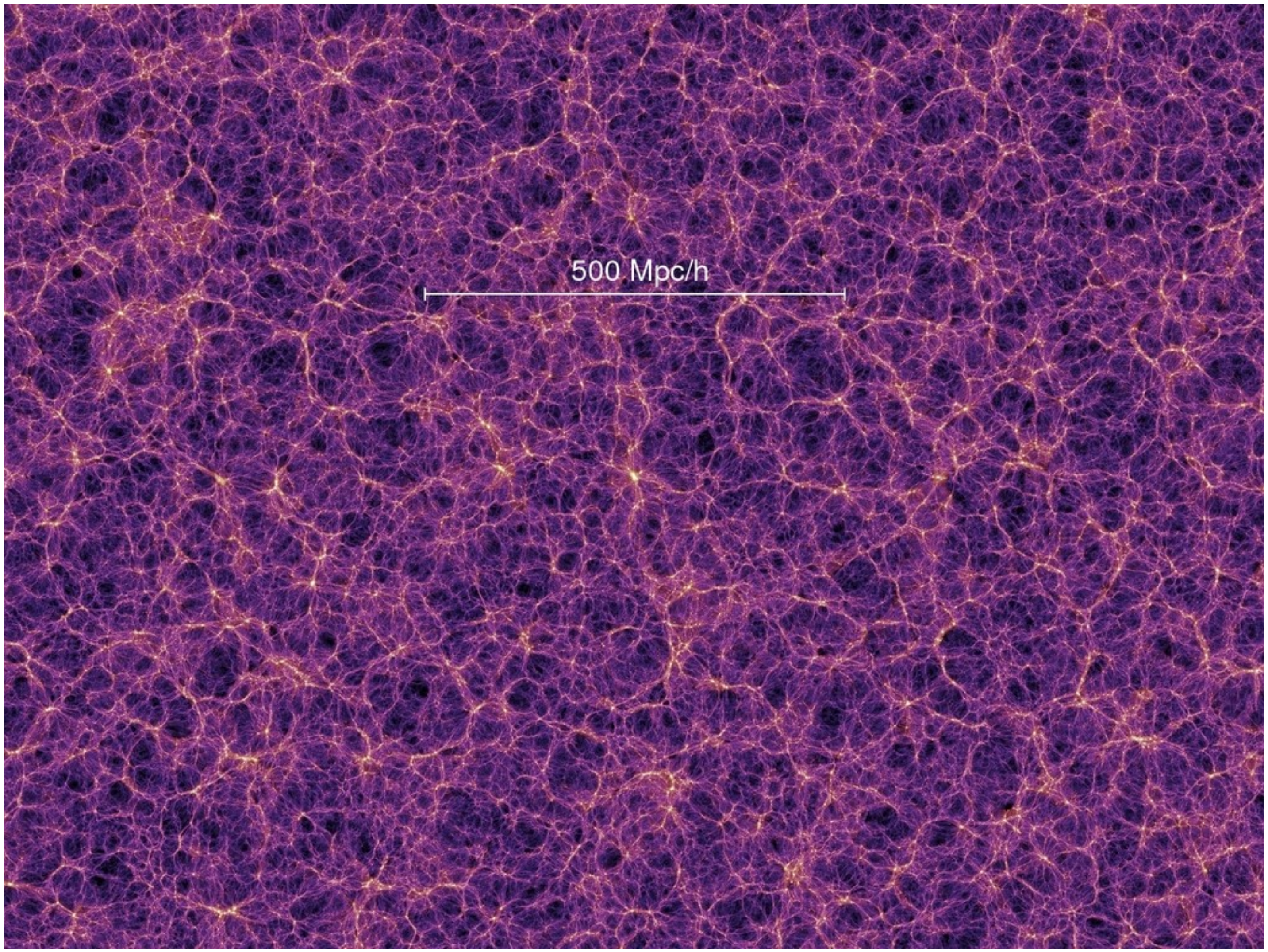


Rubin et al. (1985)

Just 17% of the universe's matter is ordinary, "baryonic" material (protons, electrons, etc.). The remaining 83% is non-baryonic "cold dark matter" (CDM) that has only gravitational effects.

★ **"extra" mass required to explain galaxy rotation curves**

Dark matter drives galaxy formation



Springel et al. (2005): 10 billion particle *N*-body simulation

What happens to baryonic gas?

(1) Gas is ionized; photons are constantly interacting with the plasma via Thomson scattering (free charges radiate when an electromagnetic wave impinges on them).

RECOMBINATION

(2) Gas is neutral: once temperature of gas drops to ~3000 K, electrons and protons recombine; photons fly!

REIONIZATION

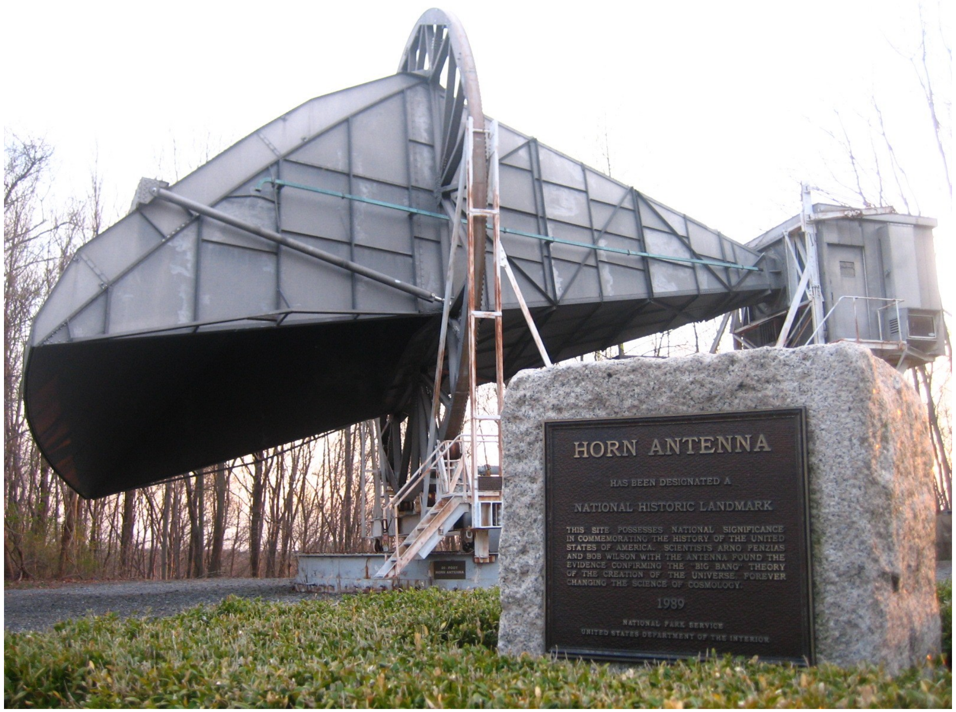
(3) Gas is reionized: some combination of the first stars and the first active galactic nuclei reionize the cosmic gas.

Recombination leads to cosmic background

Happened at $z \sim 1088$, about 379,000 years after Big Bang.

Photons that have just decoupled from matter at this redshift will fly to us from all sides, creating a cosmic background.

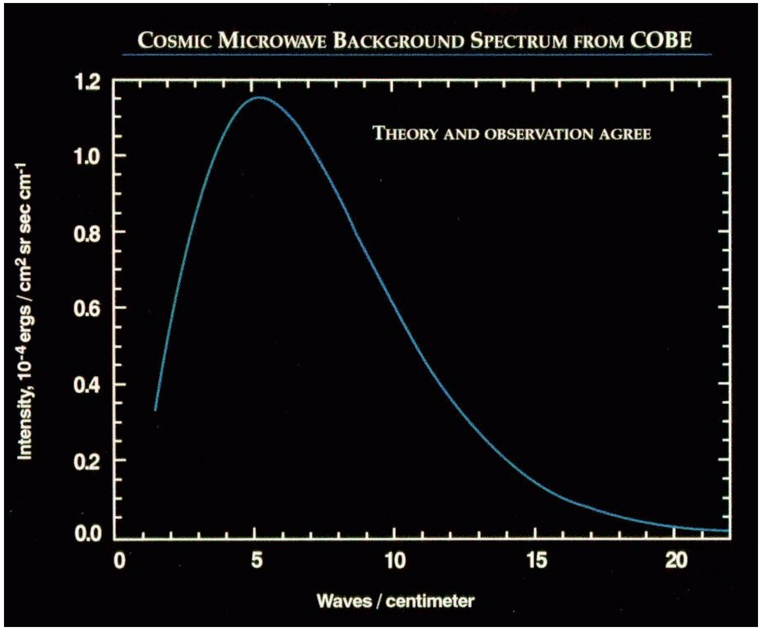
First discovered with a New Jersey radio telescope: in 1964, by Arno Penzias & Bob Wilson (signal was neither instrument noise nor pigeon droppings!).



The cosmic *microwave* background

Photons should retain a blackbody spectrum whose temperature corresponds to the gas they were last in equilibrium with: 3000 K/(1 + z) → 2.725 K today.

Cosmic Background Explorer (*COBE*) confirmed that this was the case using radio observations, thereby winning the 2006 Nobel Prize for John Mather and George Smoot.



courtesy NASA

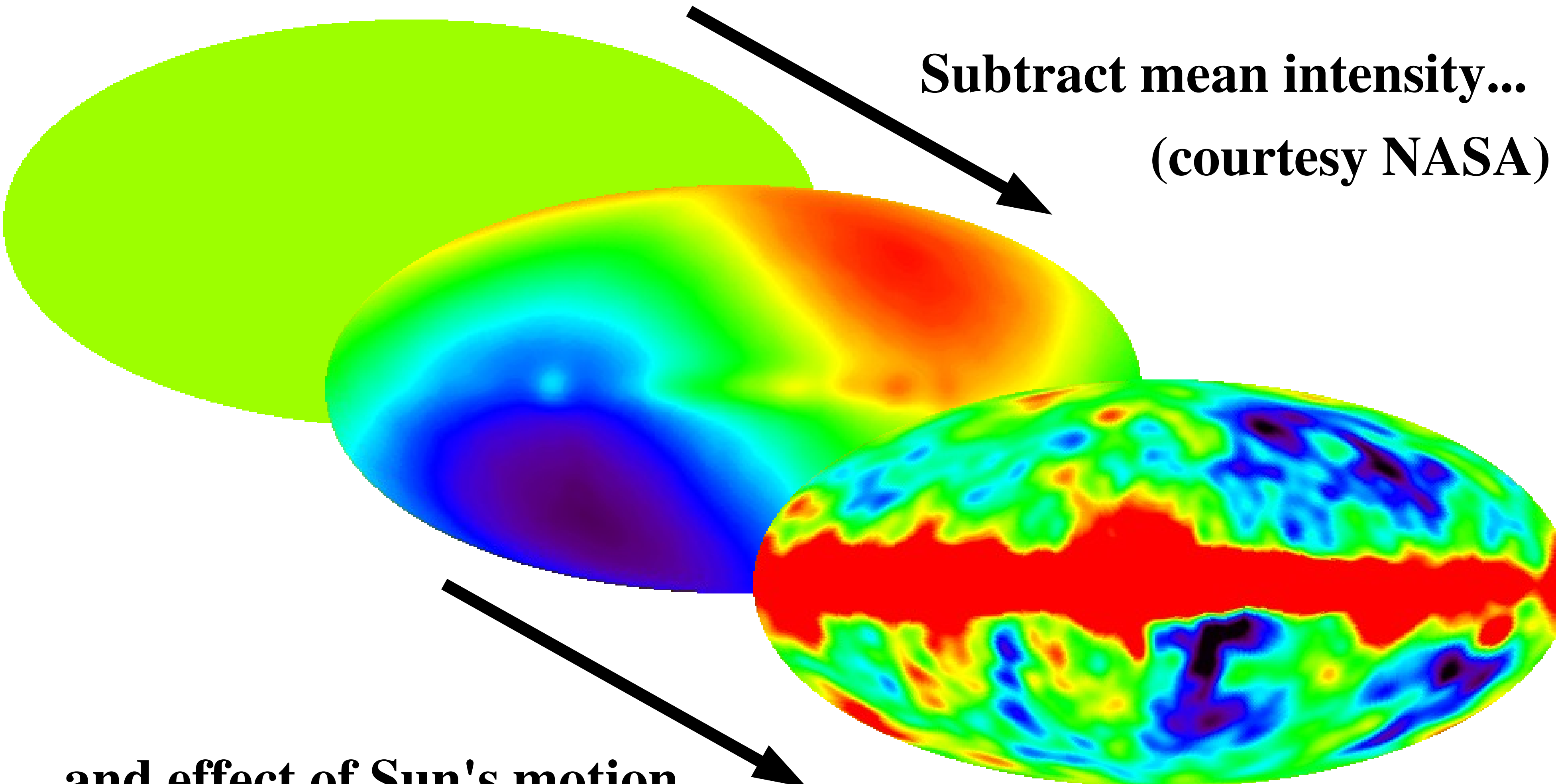
This is the cosmic microwave background (CMB).

Deviations from a perfect blackbody

In fact, *COBE* demonstrated that the CMB is not perfectly smooth!

Subtract mean intensity...

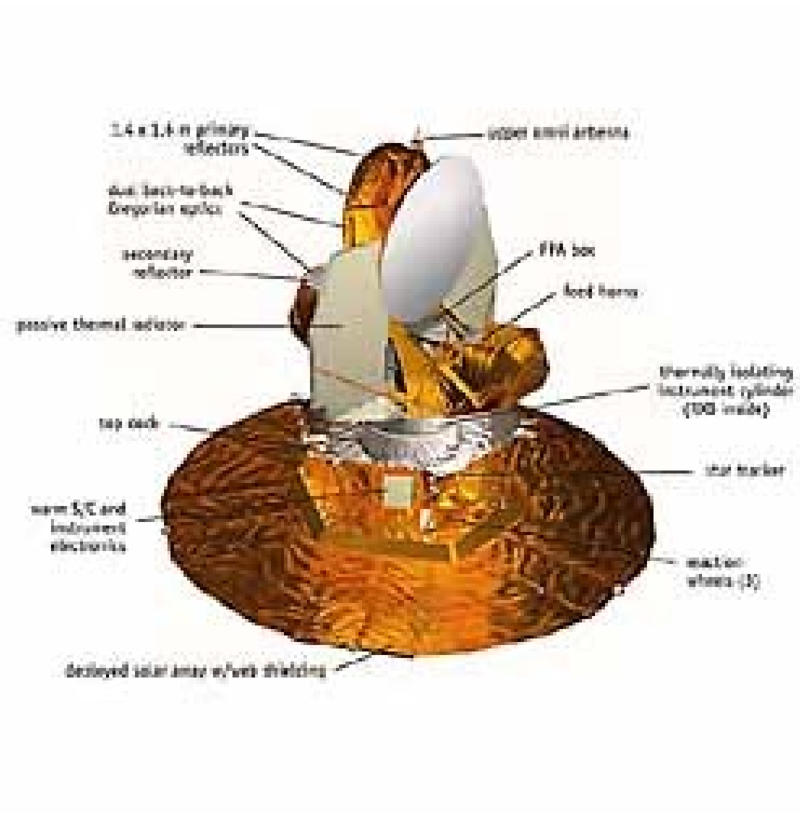
(courtesy NASA)

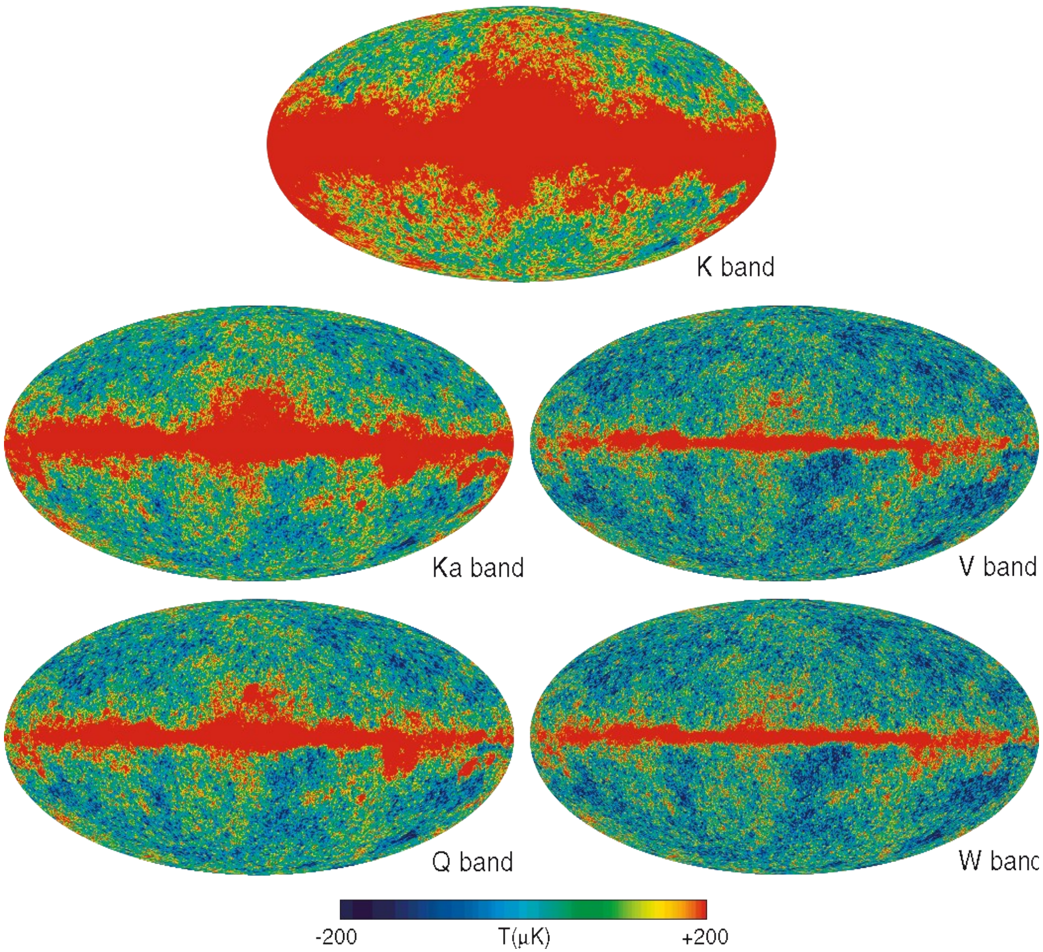


...and effect of Sun's motion...

<u>Correcting for Galactic foregrounds</u>

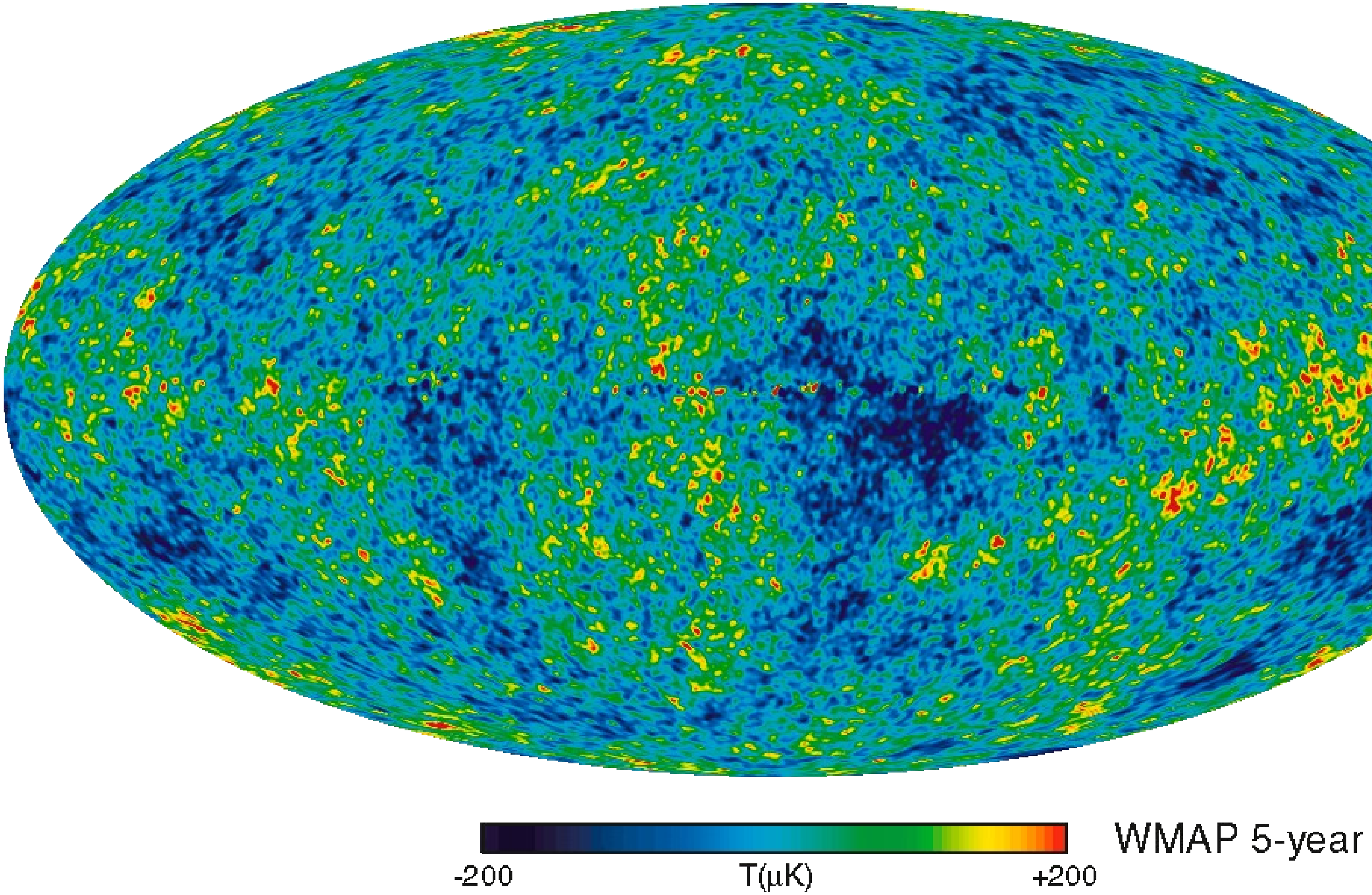
A more recent mission: the Wilkinson Microwave Anisotropy Probe (*WMAP*) has five bands ranging from 22–90 GHz...





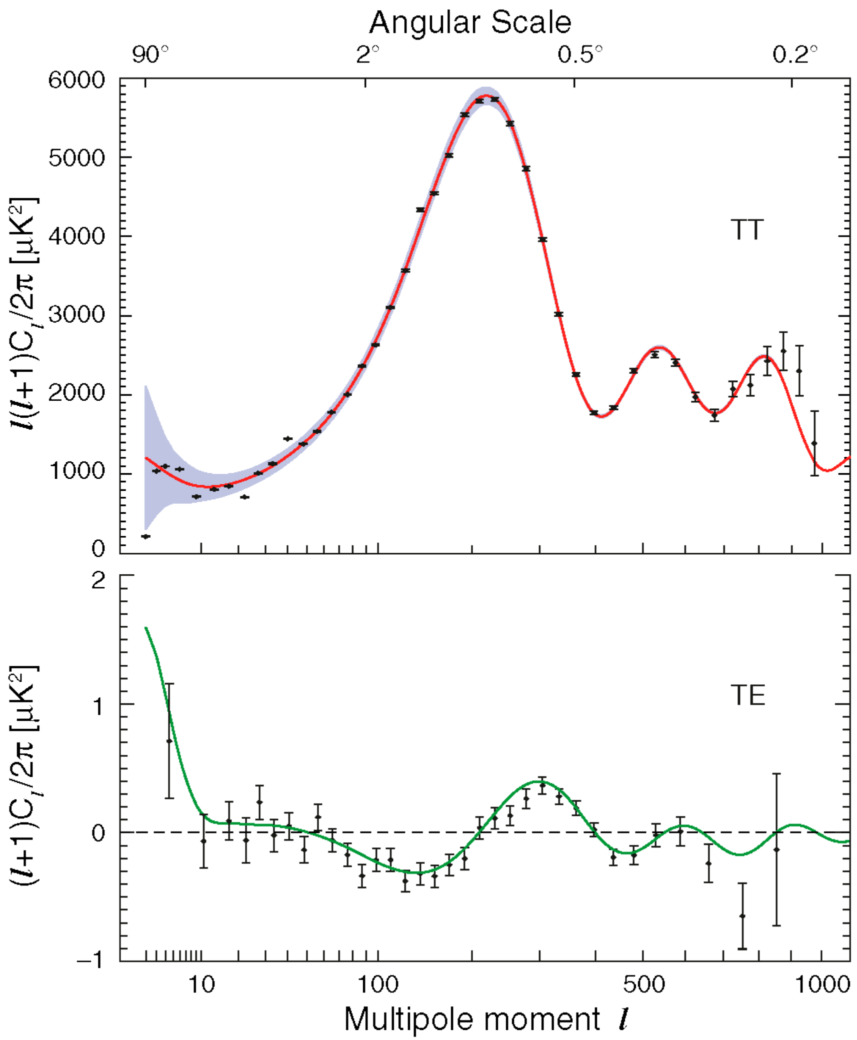
Primordial fluctuations

...allowing removal of the Milky Way's emission and isolation of CMB temperature fluctuations ↔ matter density fluctuations.



The "spectrum" of the CMB fluctuations

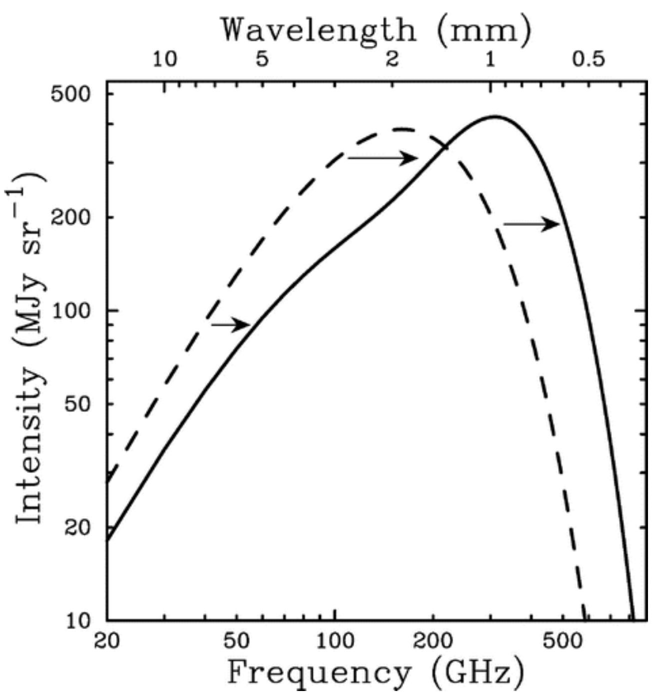
Power spectrum of the CMB is like its Fourier transform, showing the characteristic angular scales on which the rippliness of the CMB is strong.



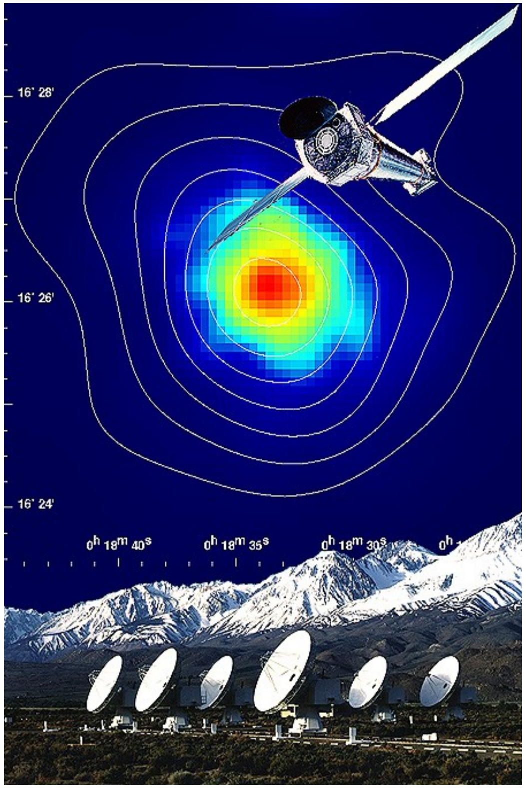
The power spectrum depends sensitively on cosmological parameters (dark matter, dark energy, etc.).

What can intervening matter do to the CMB?

Case #1: CMB photons pass through the hot gas in a cluster of galaxies and gain energy. The CMB spectrum's shift to higher energy leads to a *lower* radio flux along the line of sight to the cluster, i.e., a hole in the CMB.

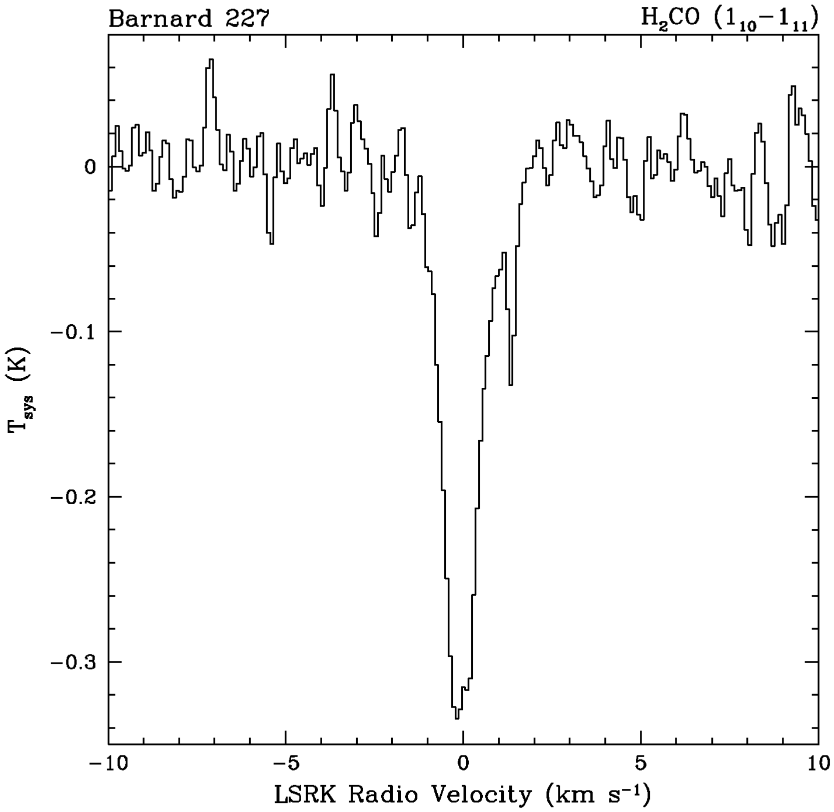


This is the Sunyaev-Zeldovich Effect (SZE) being exploited at Rutgers via the ACT project.



What can intervening matter do to the CMB?

Case #2: CMB photons pass through dense gas that contains a large number of formaldehyde (H_2CO) molecules. Due to its complex energy level structure, H_2CO can end up in an "anti-inverted state," with more molecules in ground state than expected for thermal equilibrium. CMB photons can then be absorbed, leaving a hole!



courtesy J. Darling

A few words about reionization

Recombination happens at z ~ 1088 (as stated earlier).

Reionization occurs over an extended period: z ~ 6–11, corresponding to 150 Myr – 1 Gyr after the Big Bang.

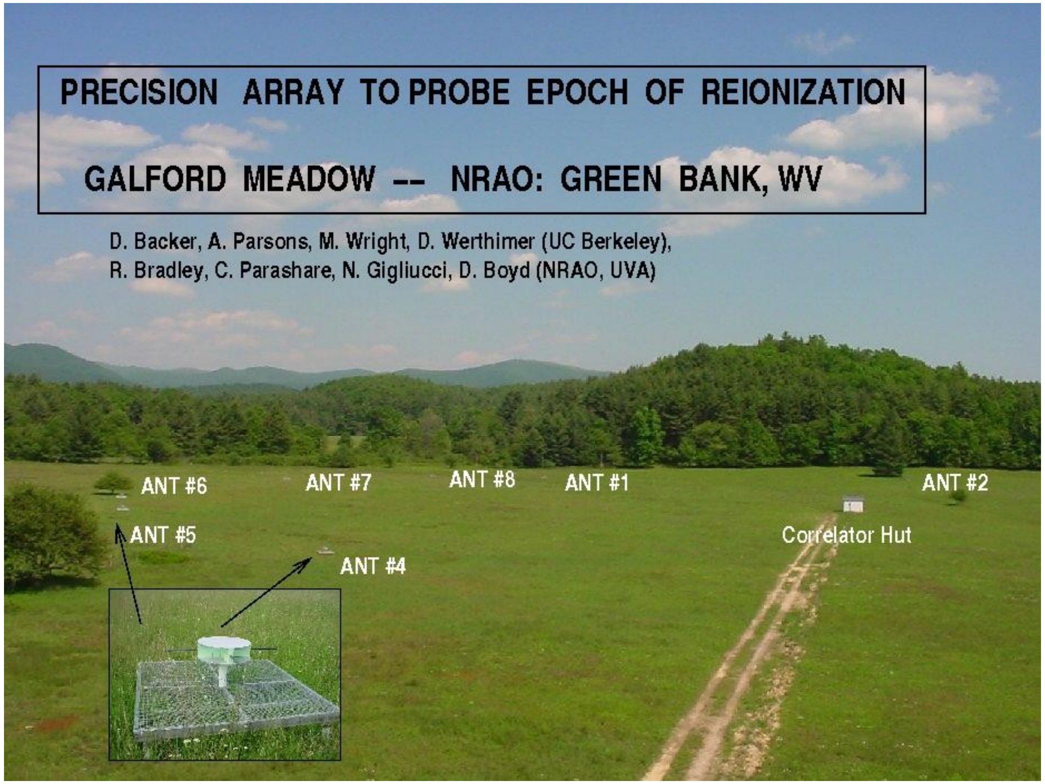
We still don't know what causes reionization, or how: quasars (i.e., AGN)? galaxies? individual stars?

Maybe looking for the last surviving clumps of HI will help...

Looking for highly redshifted HI

An example of a reionization experiment: PAPER (the Precision Array to Probe the Epoch of Reionization)...

8 antennas operating at 100–200 MHz (↔ z = 6–13).

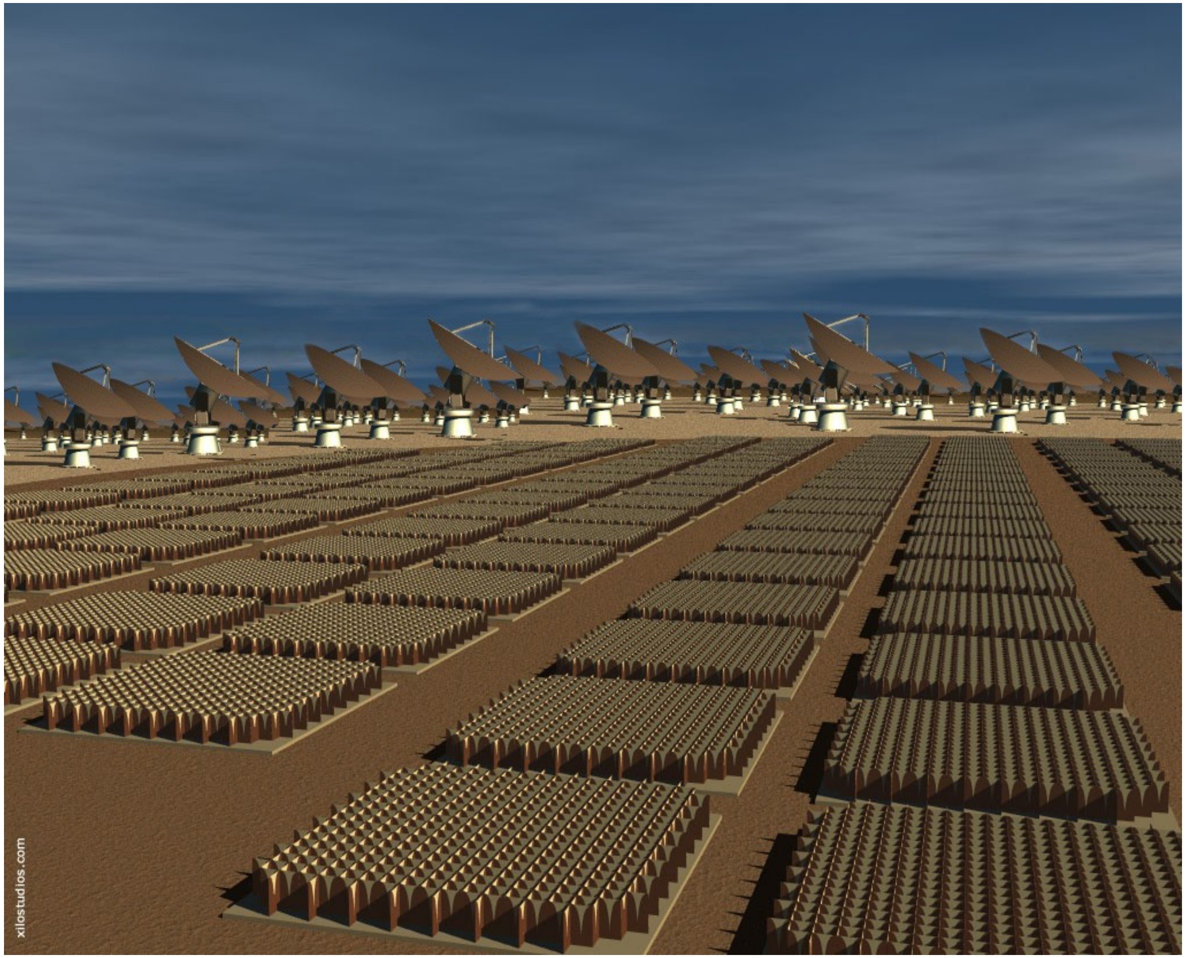


Testing at Green Bank in NRQZ before moving to Australia.

Looking farther ahead: the SKA

The SKA (Square Kilometer Array) will be built in Australia or South Africa (once money is available); at least one part of it will be focused on reionization science.

Artist's conception...



Topic of student choice lecture?

BATTLESTAR

Information for evaluations

Instructor's name: Andrew Baker

Course title: Obs. Radio Astron.

College/Course/Section:

01:105:343:01

Baghal

Kanarek

Matthews

Ng

Patel

Suszko

Tomczak

01:750:343:01

Crews

Golugula

Jain

Karanam

Merced

Shappee

Stelling

Urbanowicz