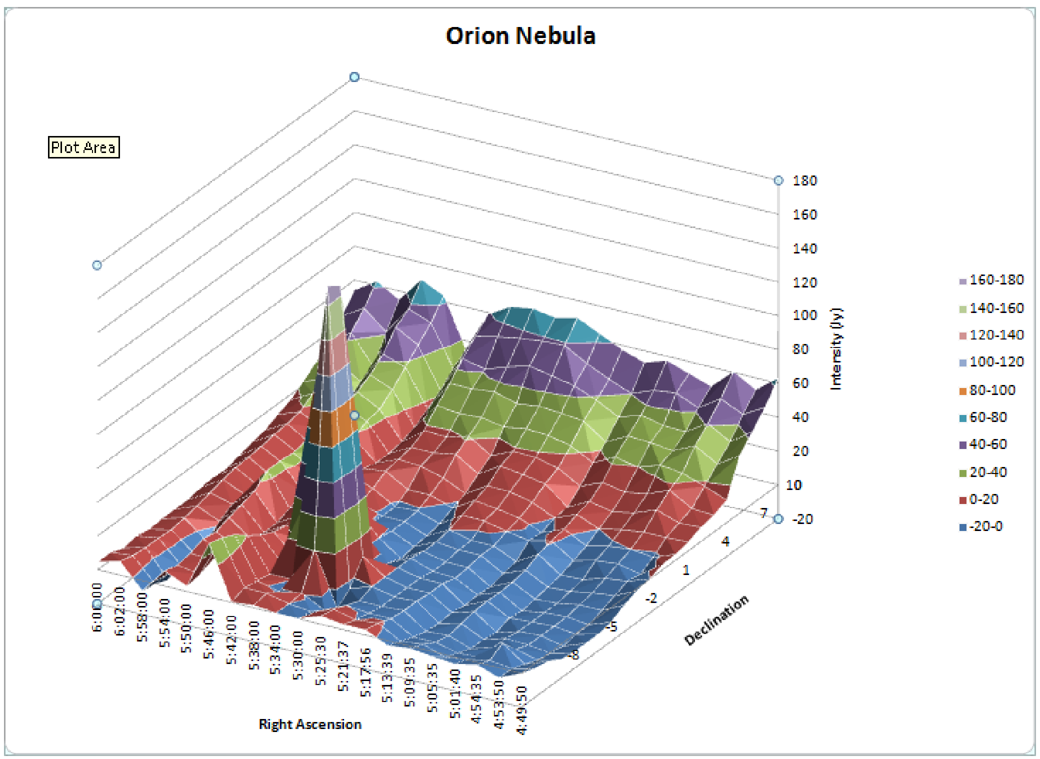
# (Astro)Physics 343 Lecture # 13: cosmic microwave background (and cosmic reionization!)

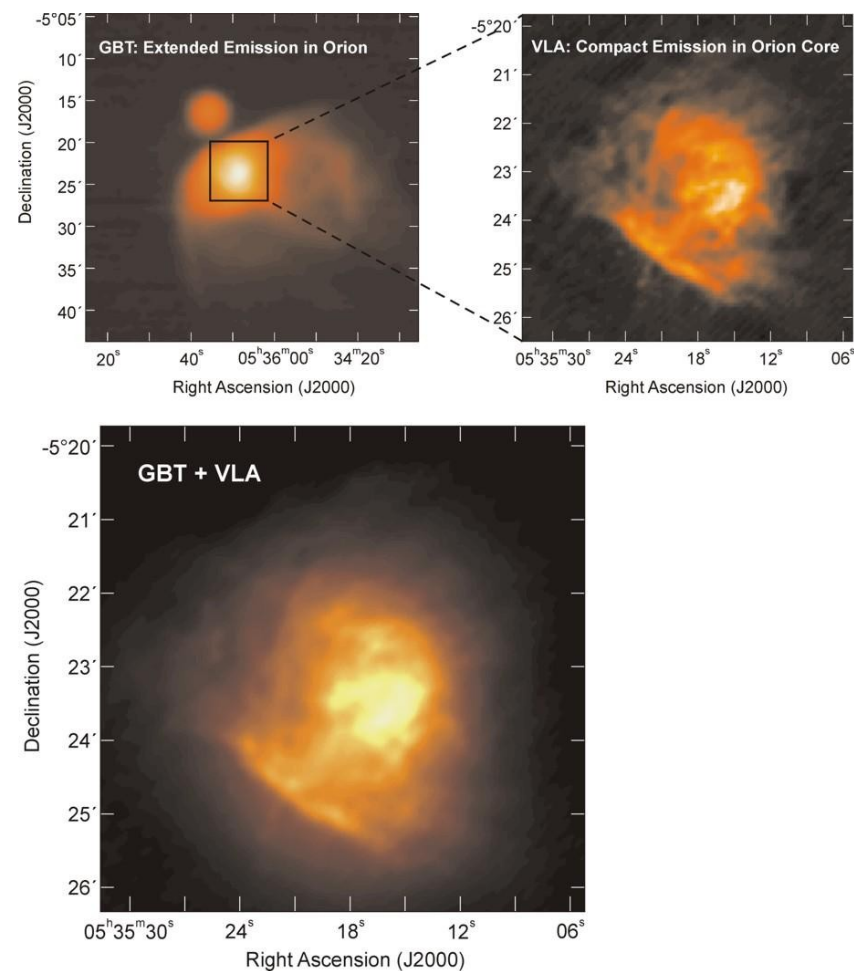
# Welcome back!


**(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)**

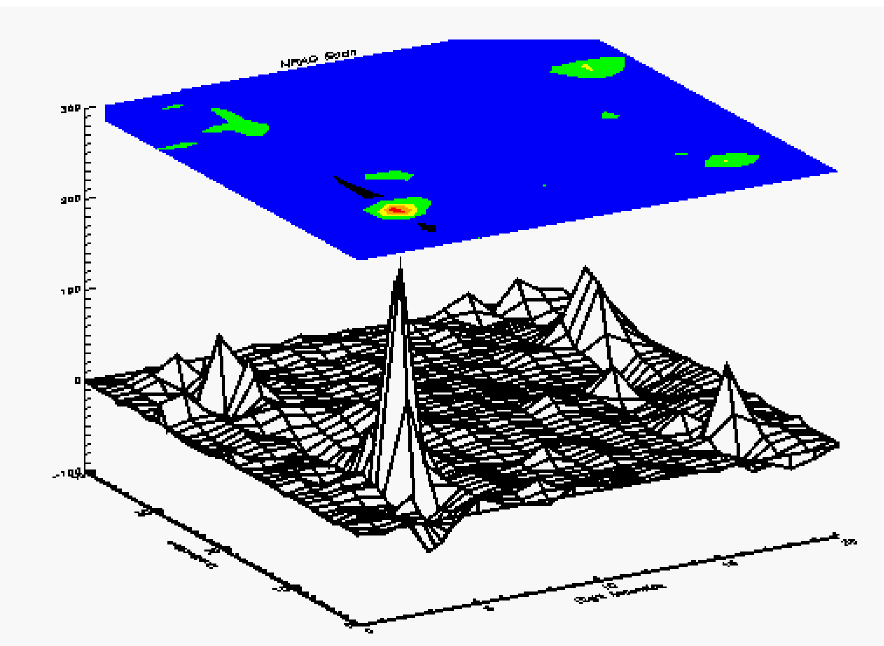


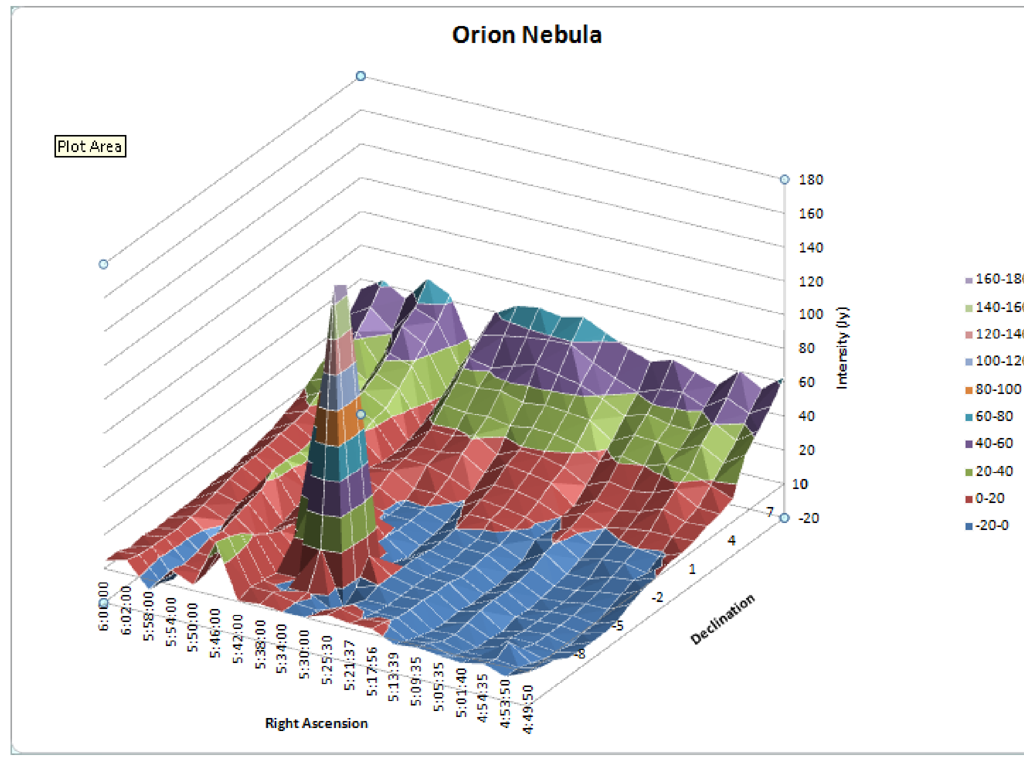

**Orion A mapped at 8.4 GHz with GBT and VLA (courtesy D. Shepherd)**

# 2008 vs. 2009

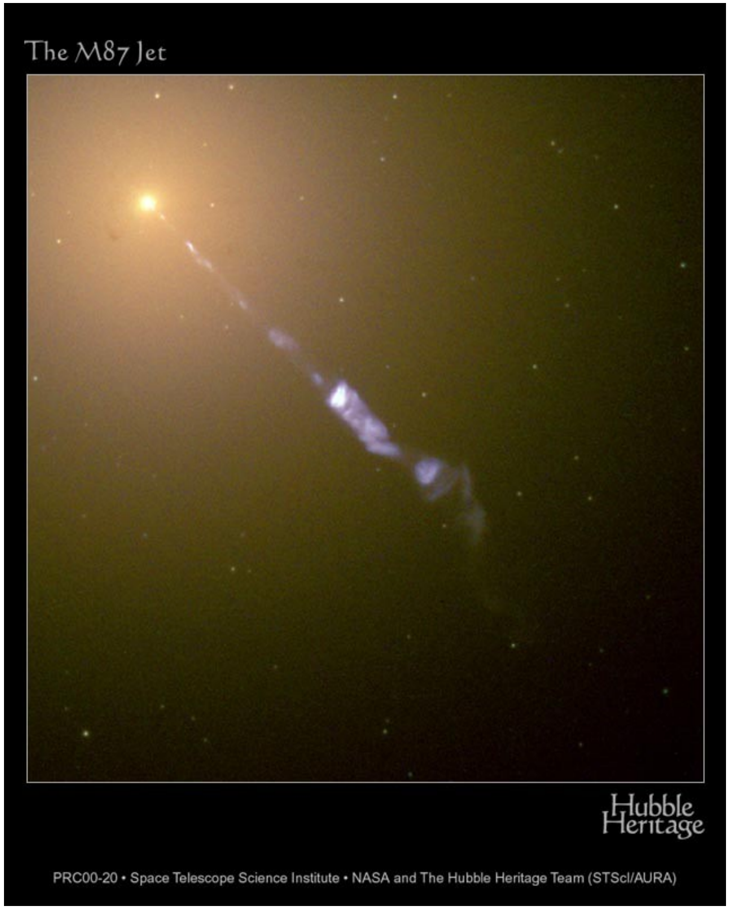
## Rutgers 2008

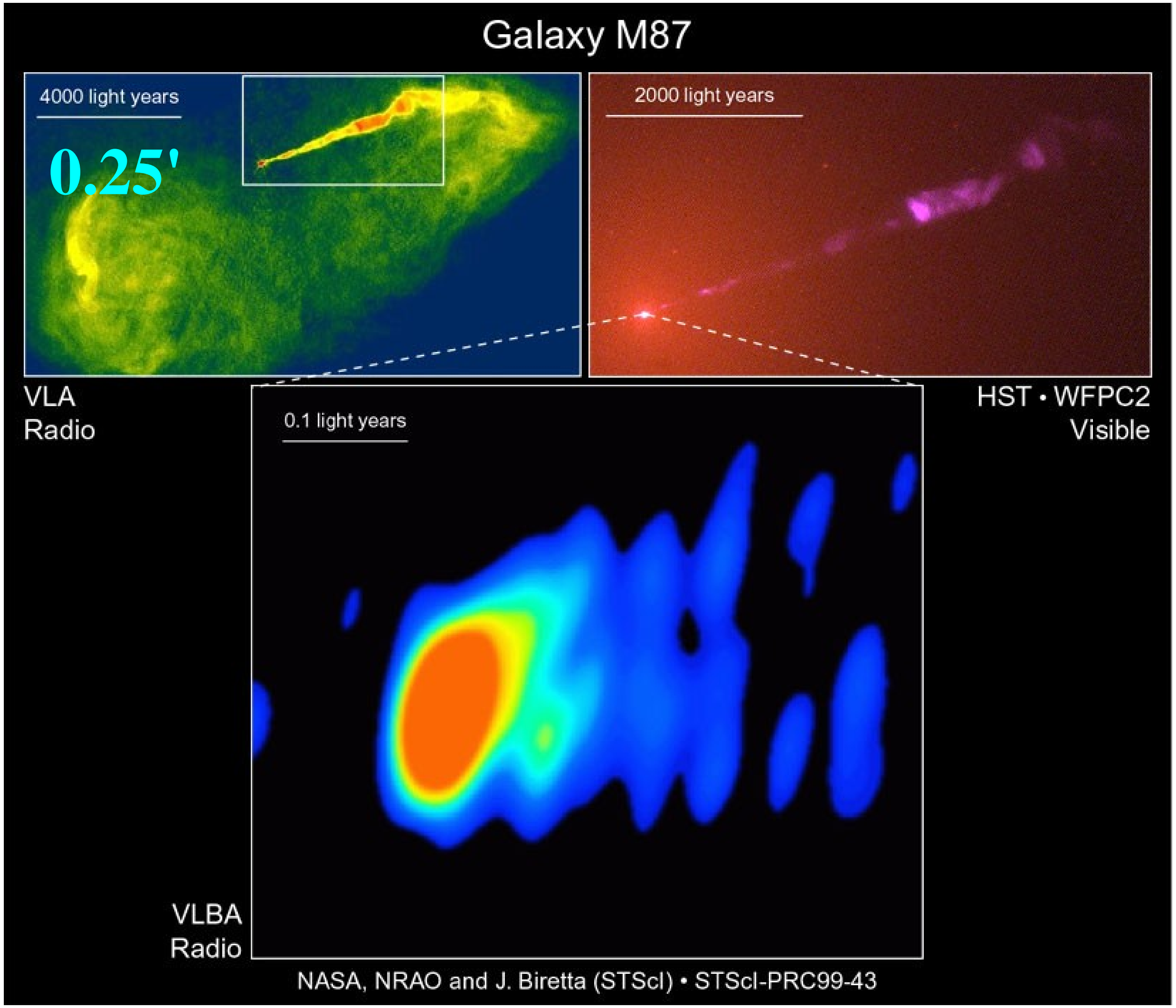


## Rutgers 2009



# M87: brightest elliptical in Virgo cluster



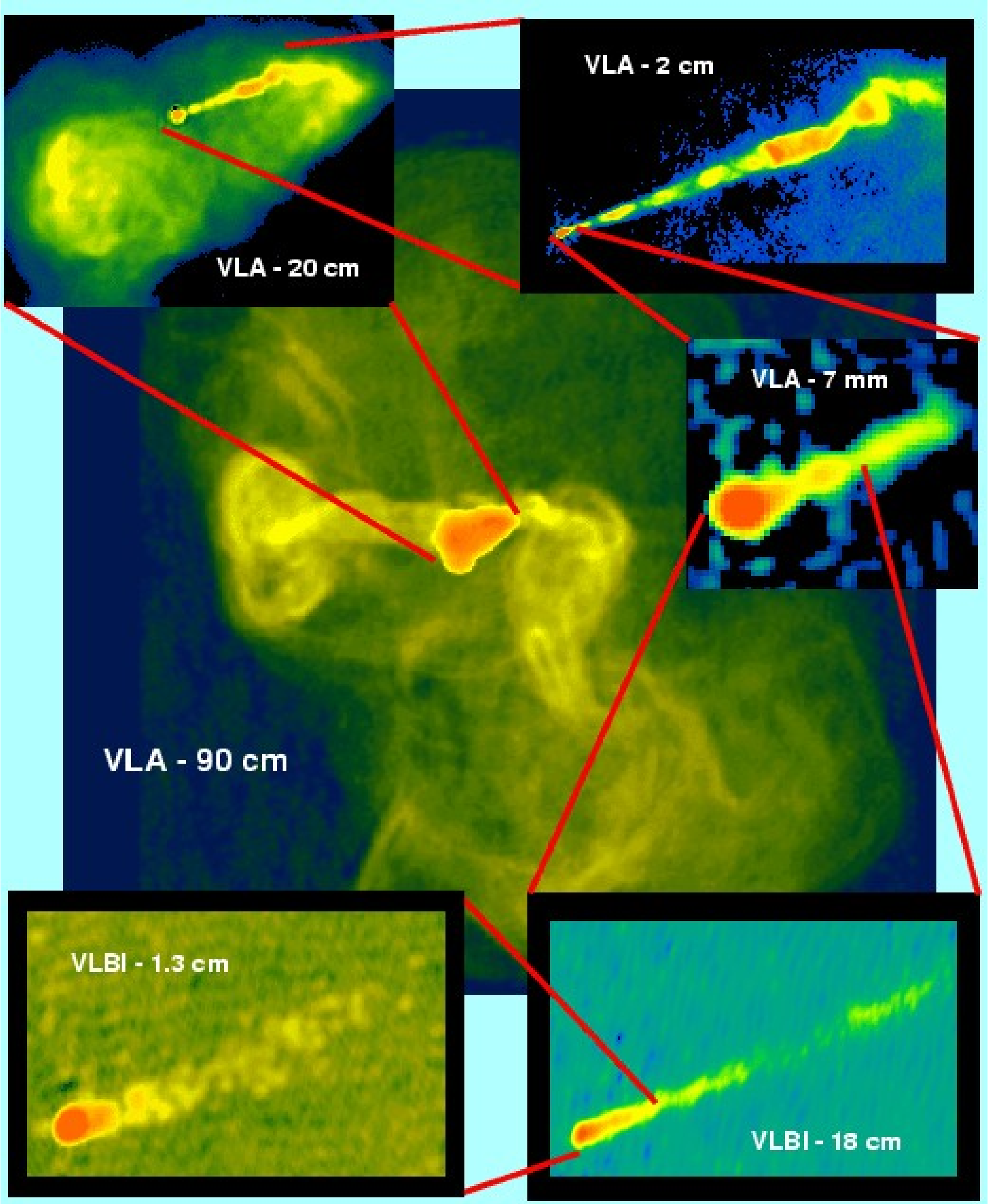




**Courtesy NASA/STScI.**

# M87: multiple radio views

**Courtesy F. Owen.**

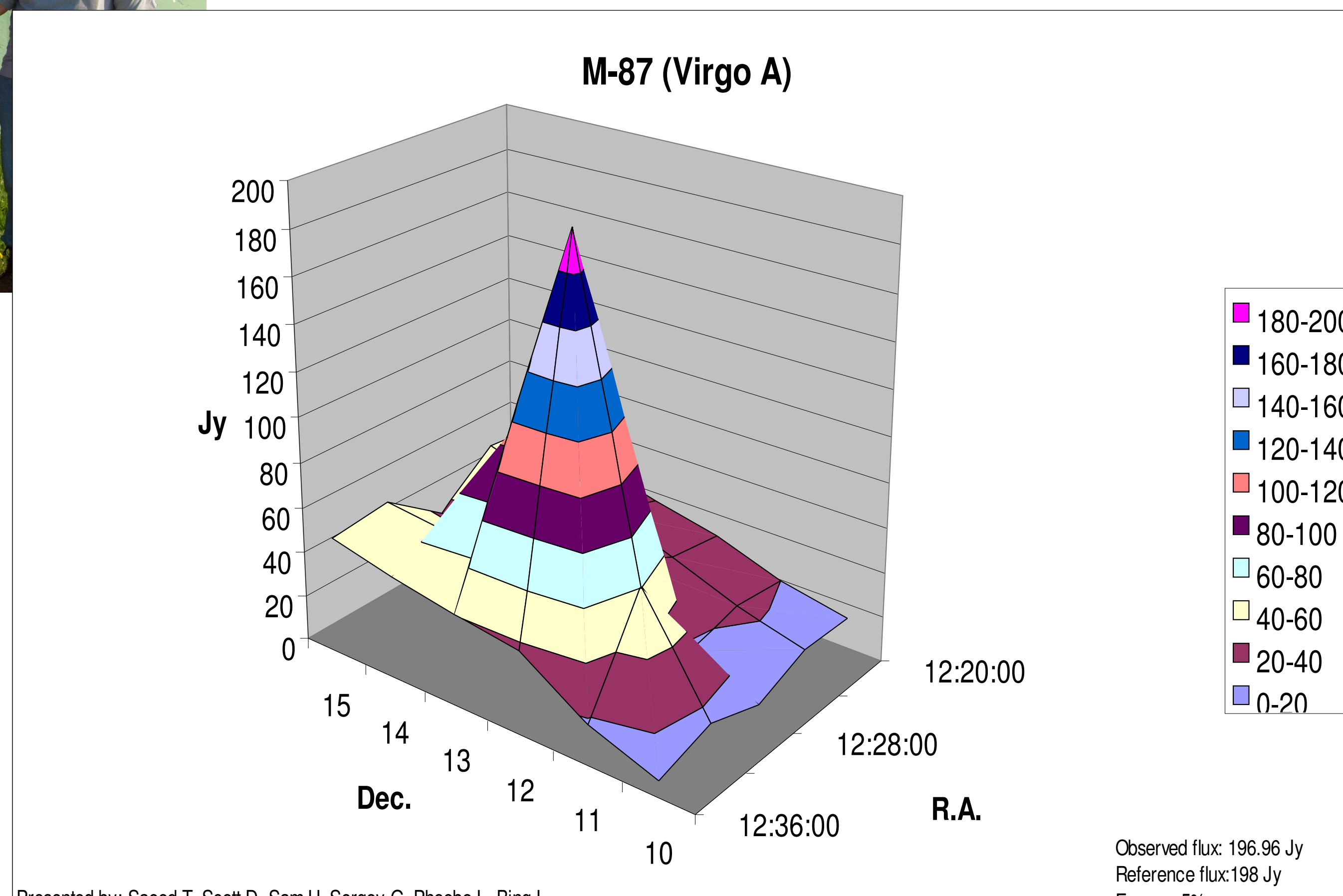
**http://www.aoc.nrao.edu/~fowen/M87.html**



# Results: M87


**Peak optical position:**

**12:30:49.4 +12:23:28 (J2000)**




**Team Rutgers:**

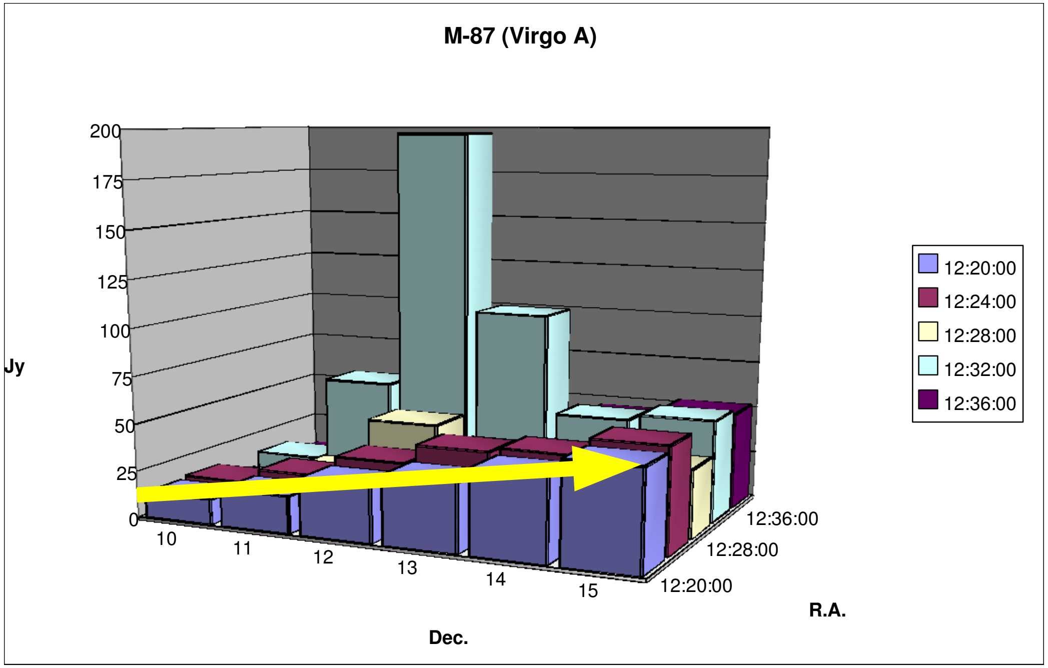
**1.4 GHz peak at**

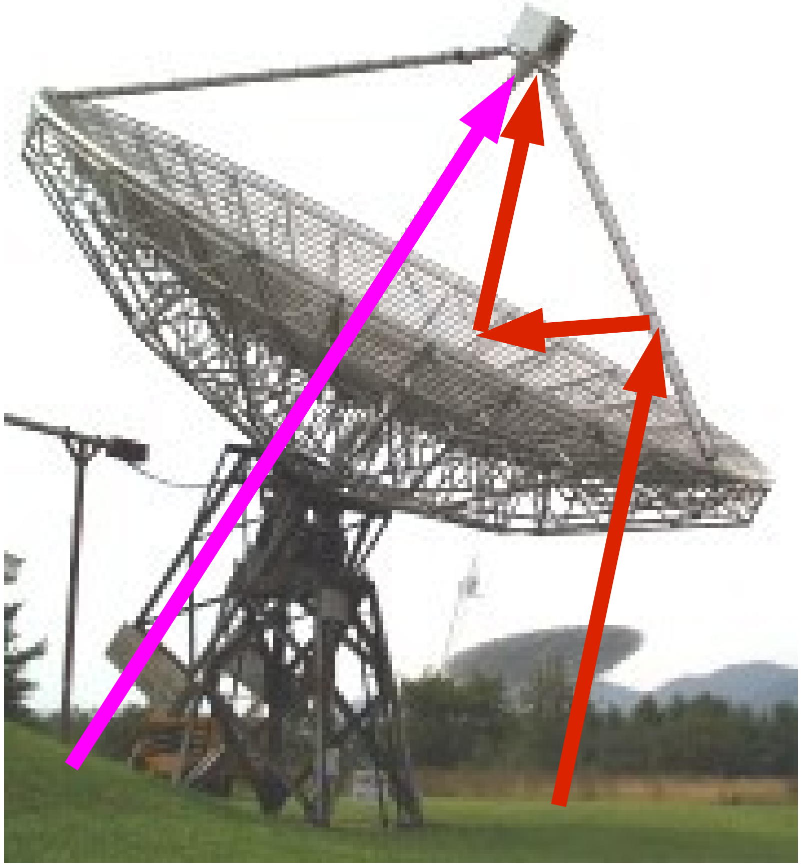
**12:32.0 +12.0 (J2000)**

**Very nearly 200 Jy!**

# Spillover

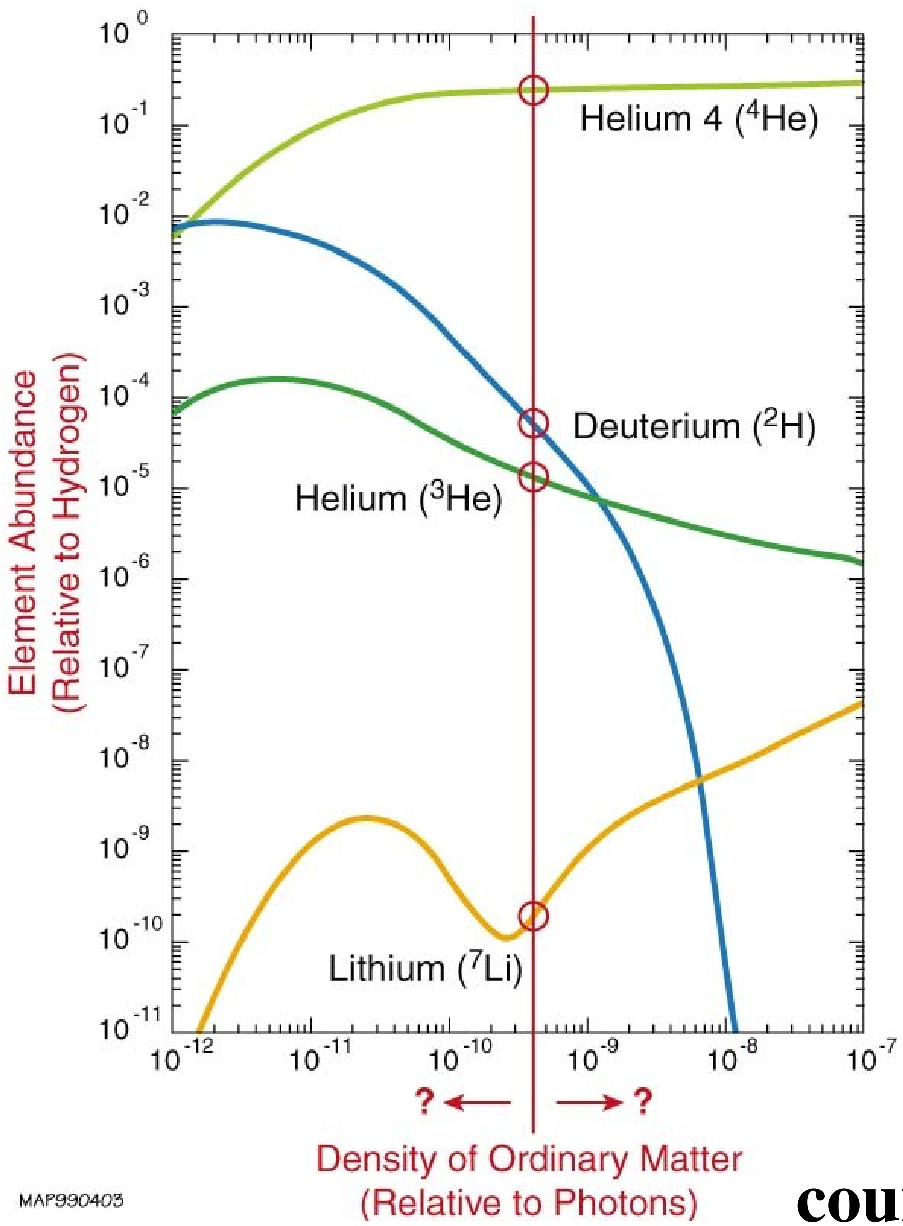
**Higher intensity at higher declination, also seen in Orion data!**



**"Spillover" occurs when emission from "behind" telescope enters main beam due to reflection off supports and/or the fact that the feed "sees" beyond the edge of the dish.**

# Consensus cosmology: the Big Bang

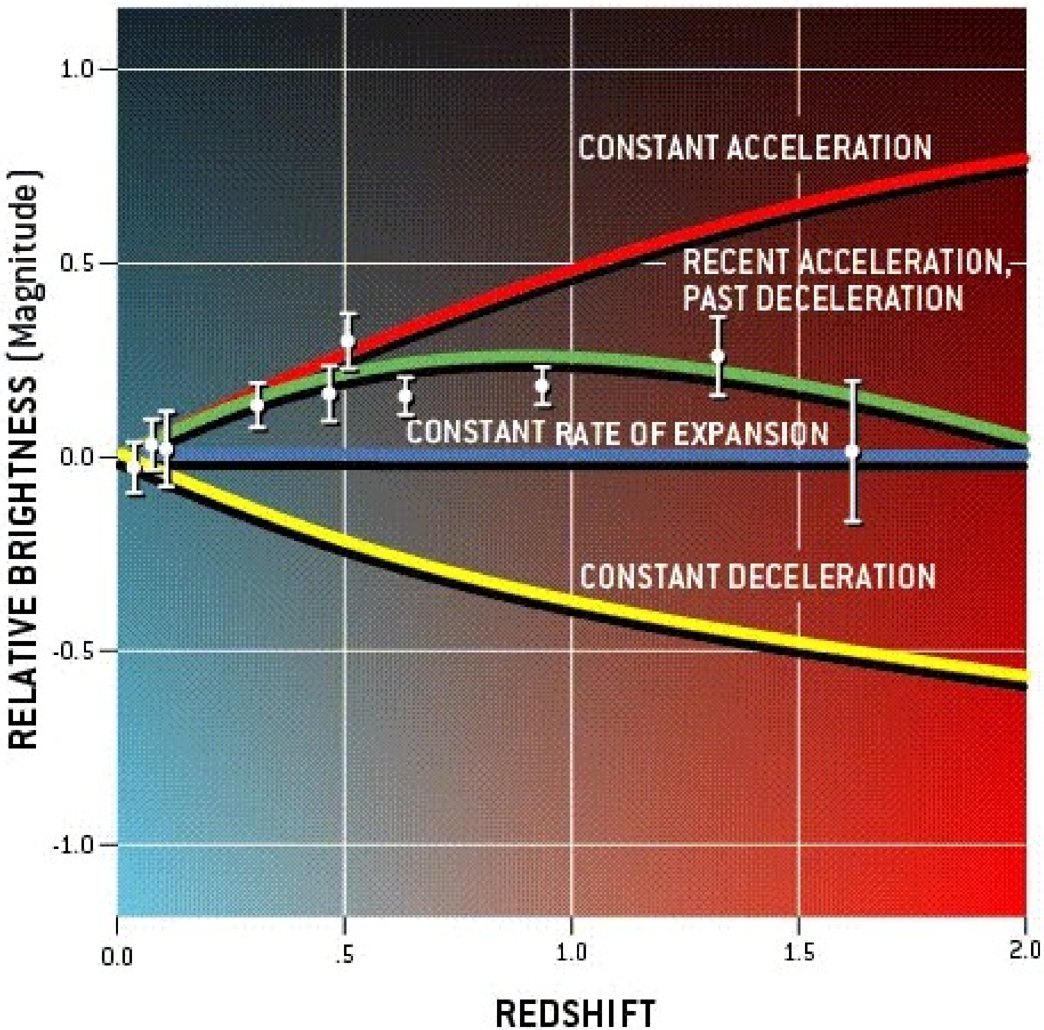



courtesy NASA

**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

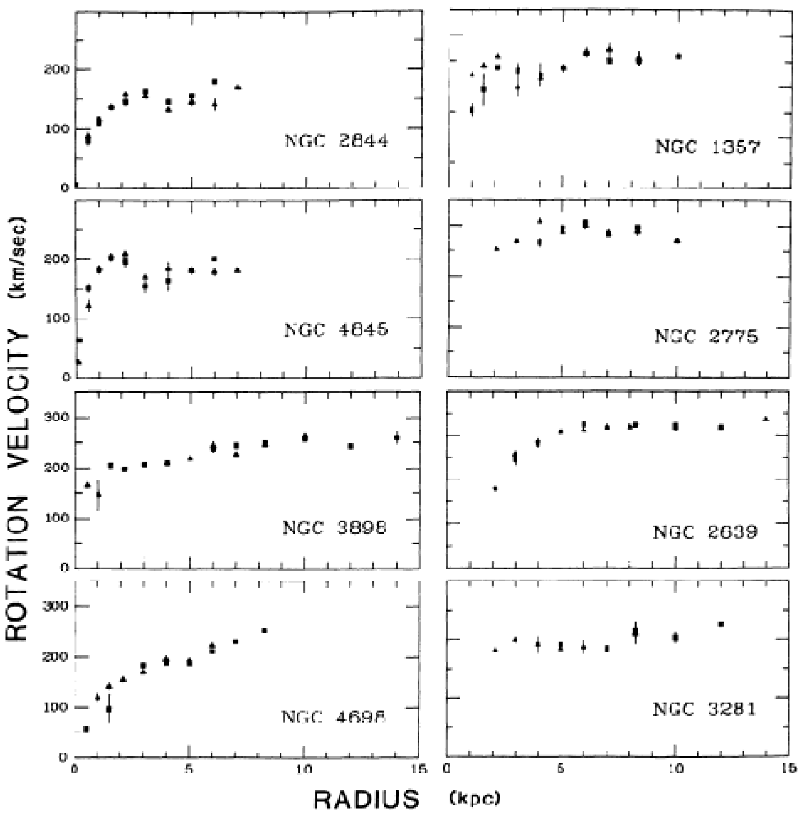



**Riess & Turner (2004)**

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

**⋆ supernovae at $z \sim 0.5$ are fainter ⇔ more distant than expected for a constant expansion rate**

# Consensus cosmology: Dark matter



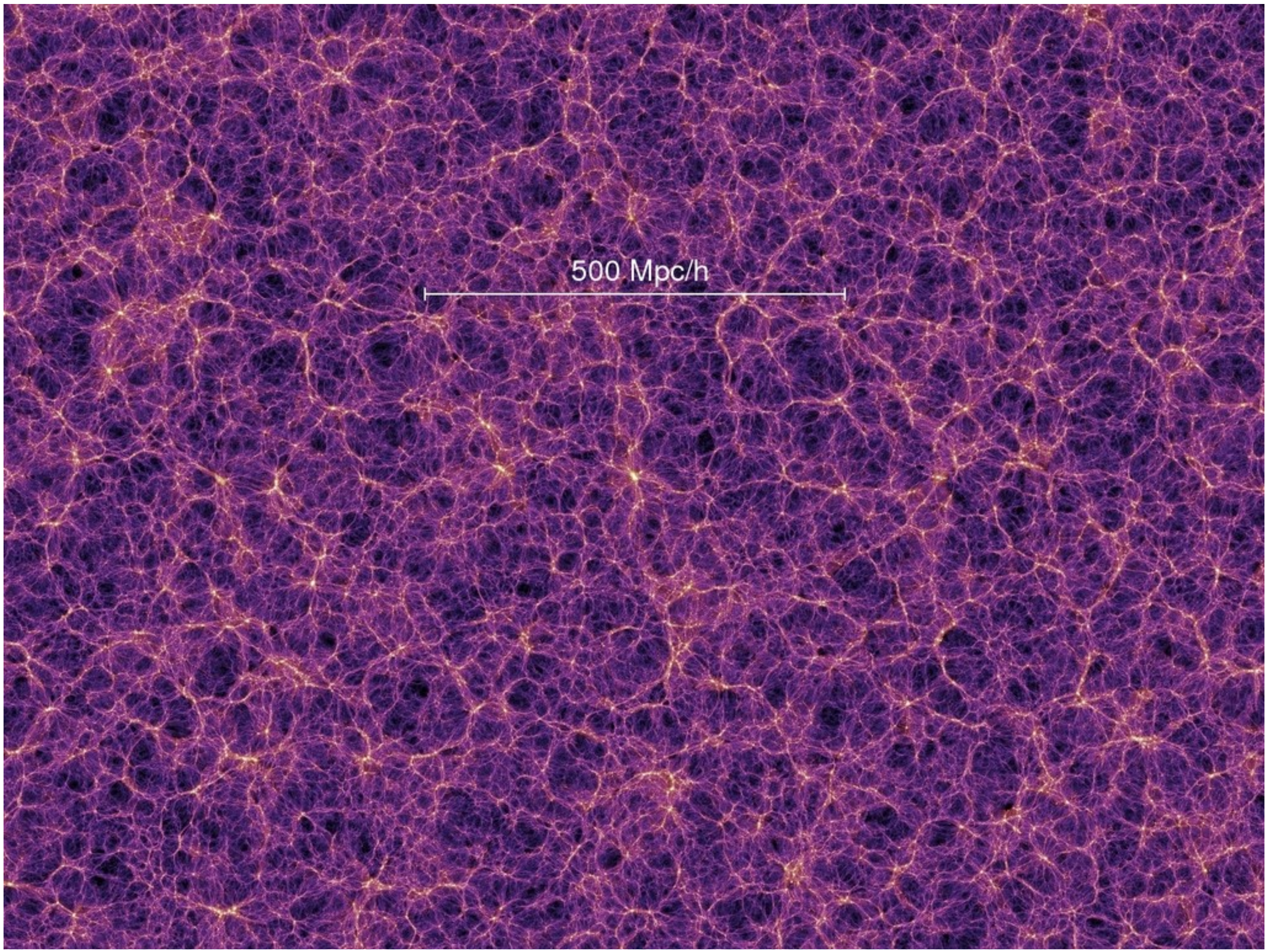

**Rubin et al. (1985)**

**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**

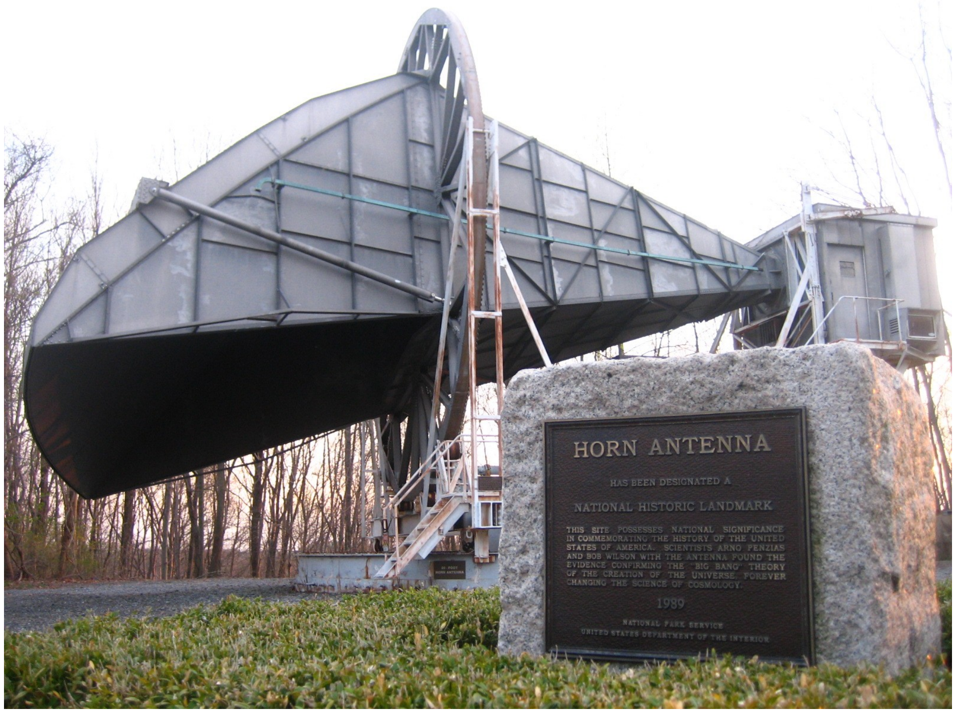
**(3) Gas is reionized: some combination of the first stars and the first active galactic nuclei reionize the cosmic gas.**

# 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.**

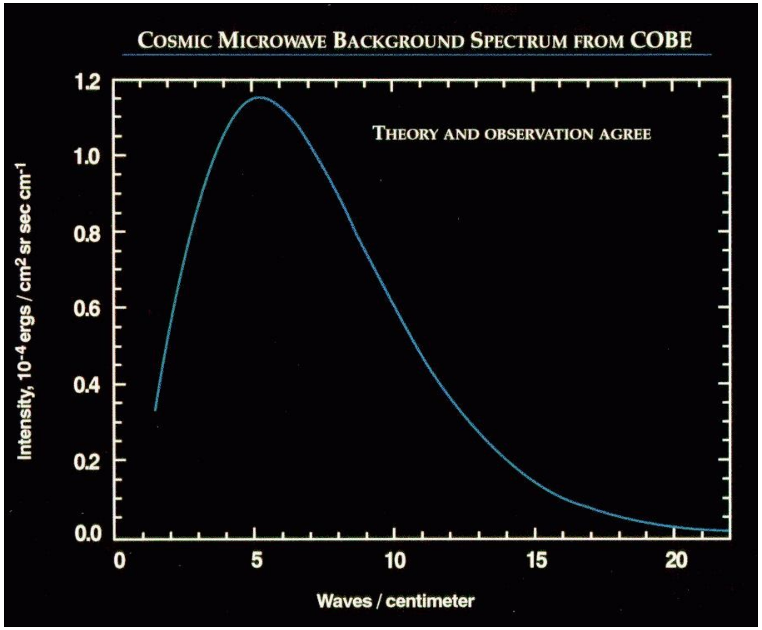
**First discovered with a New Jersey radio telescope: in 1964, by Arno Penzias & Bob Wilson (signal was neither instrument noise nor pigeon droppings!).**



# 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.**

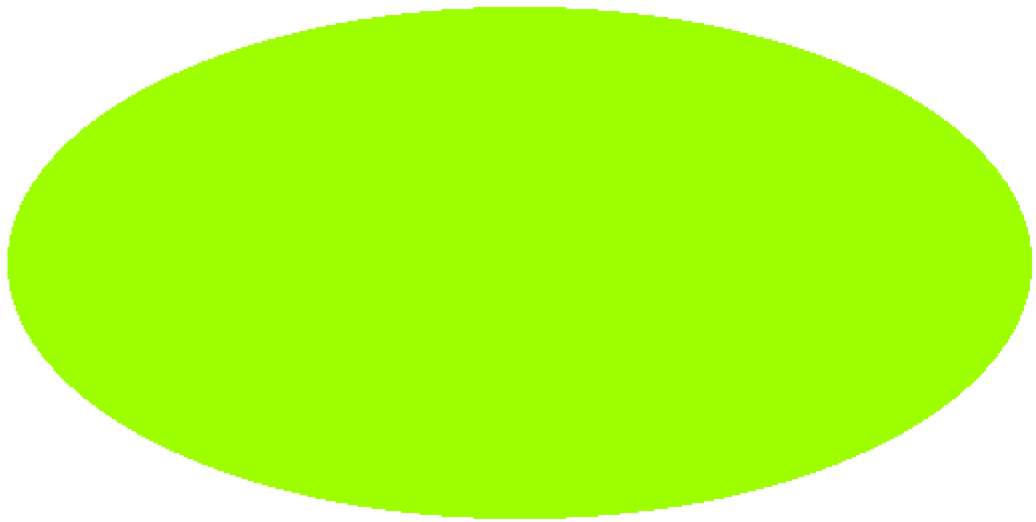



**courtesy NASA**

**This is the cosmic microwave background (CMB).**

# Smoothness of CMB = evidence of inflation

***COBE*** **map of CMB across entire sky is extremely smooth (i.e., $T_{\mathrm{CMB}} \simeq 2.73$ K in all directions).**



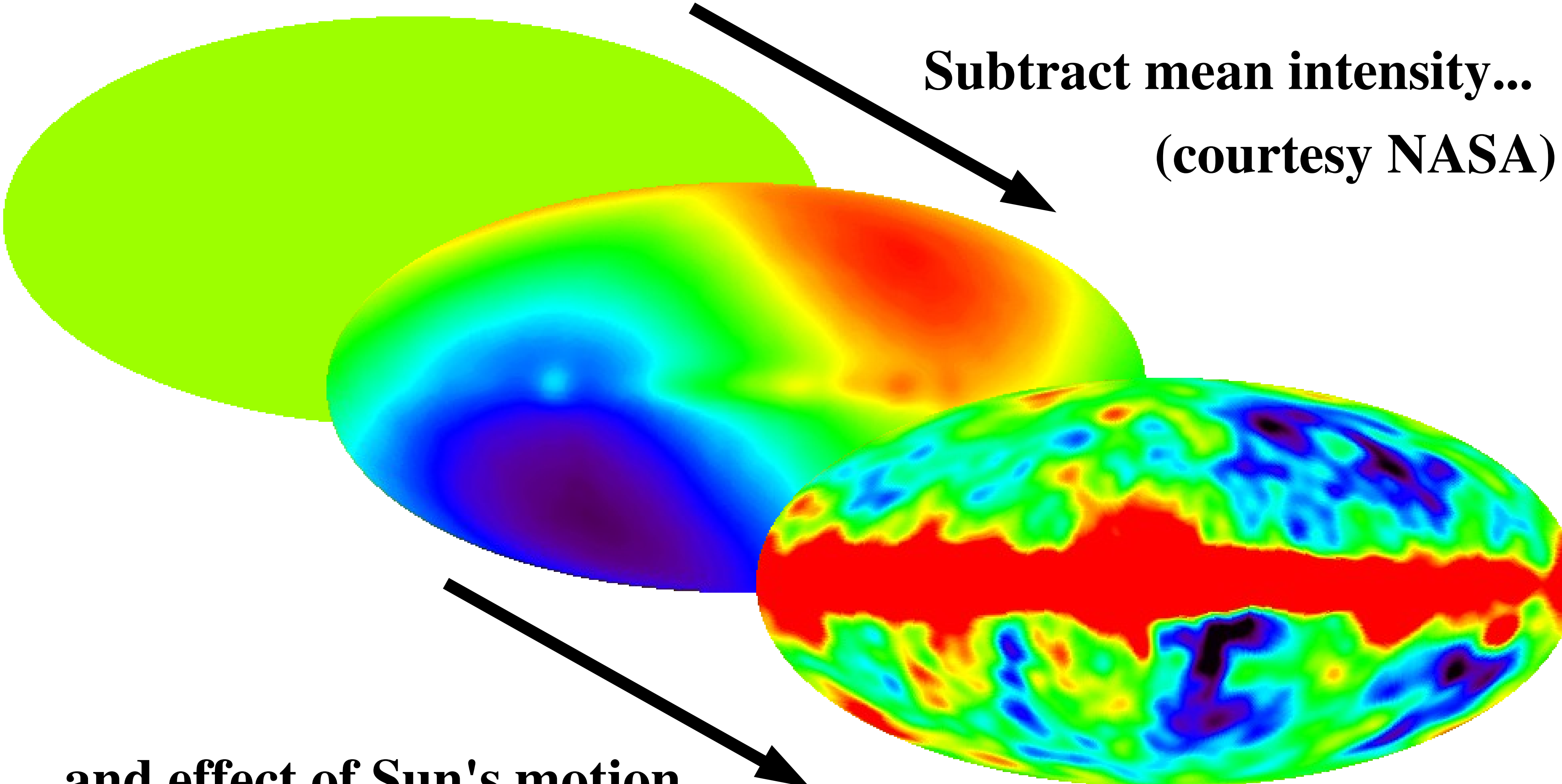
**This is evidence of inflation: an episode of exponential growth very early in the universe's history, in which a small region at a nearly uniform temperature "inflated" to become the entire observable universe.**

# Deviations from a perfect blackbody

**Looking deeper, *COBE* showed CMB is not perfectly smooth!**

**Subtract mean intensity...**

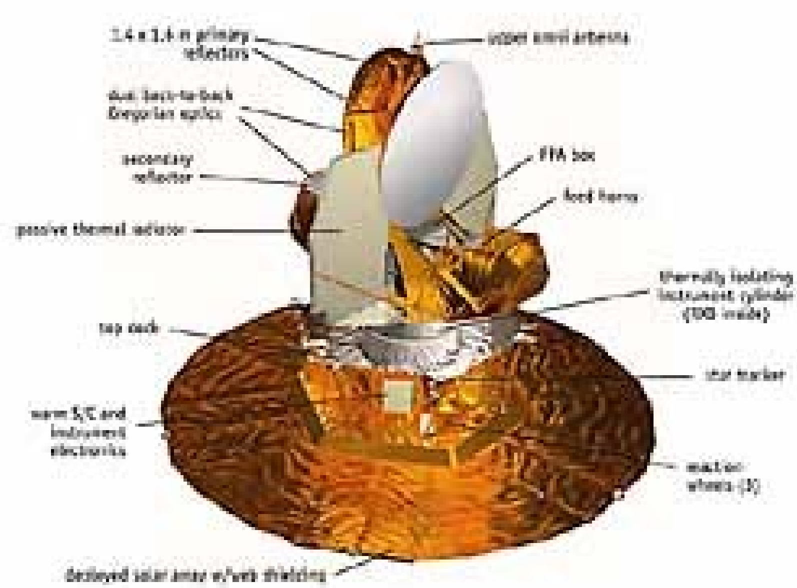
**(courtesy NASA)**

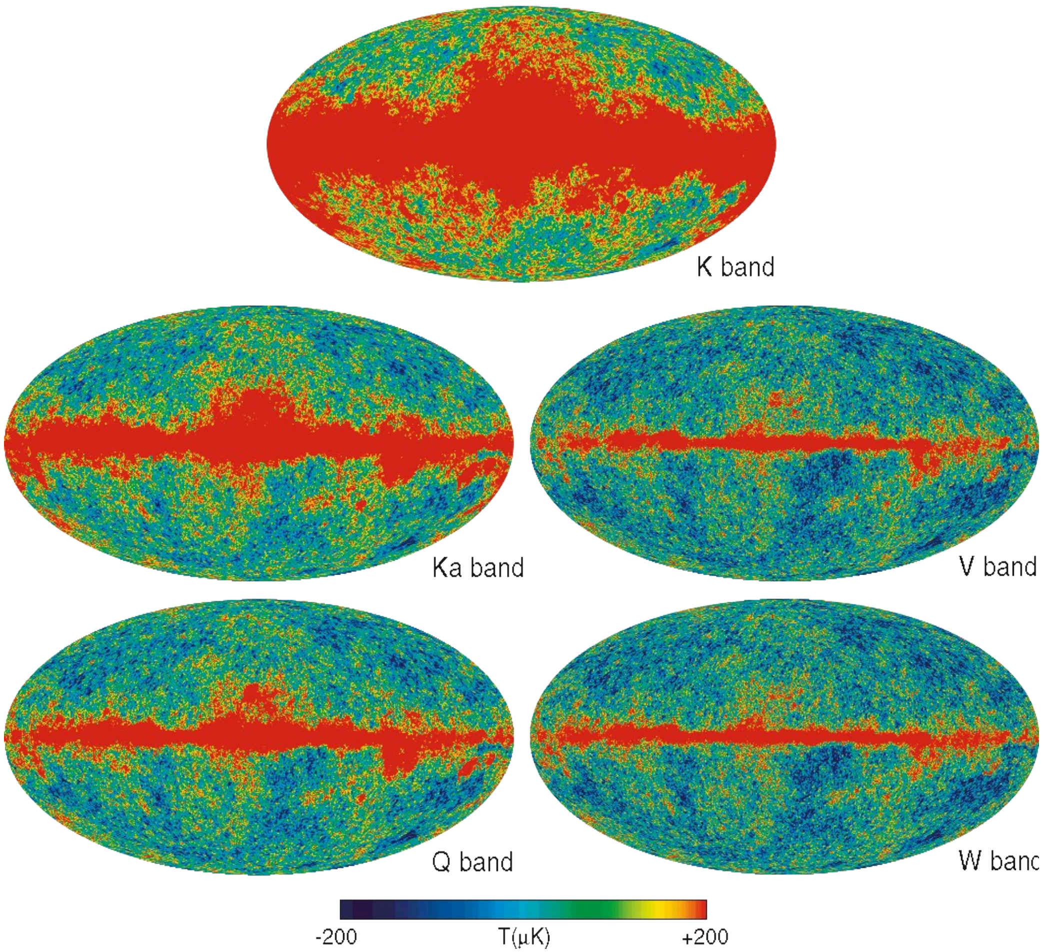


**...and effect of Sun's motion...**

# Correcting for Galactic foregrounds

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

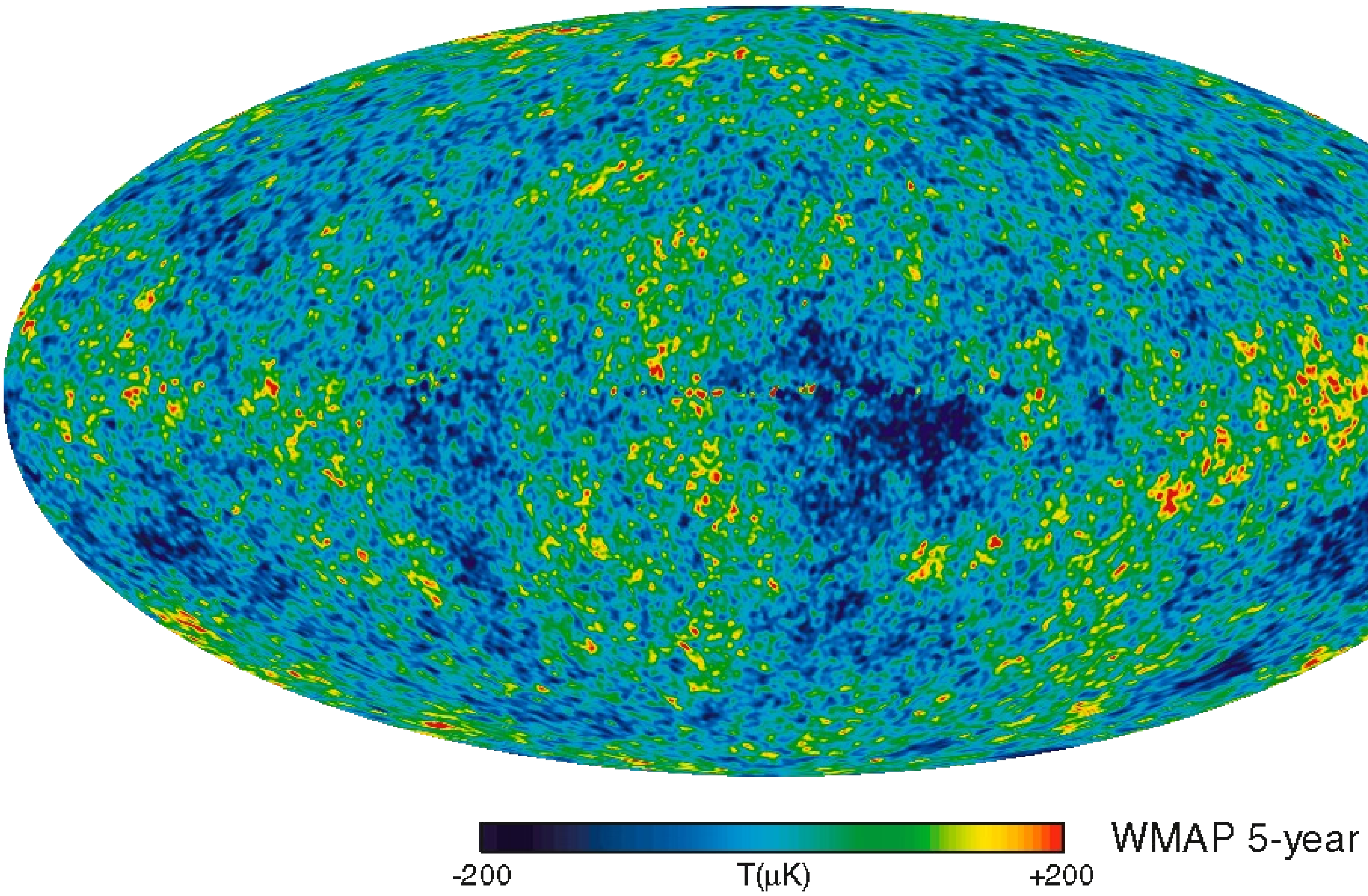


# Primordial fluctuations

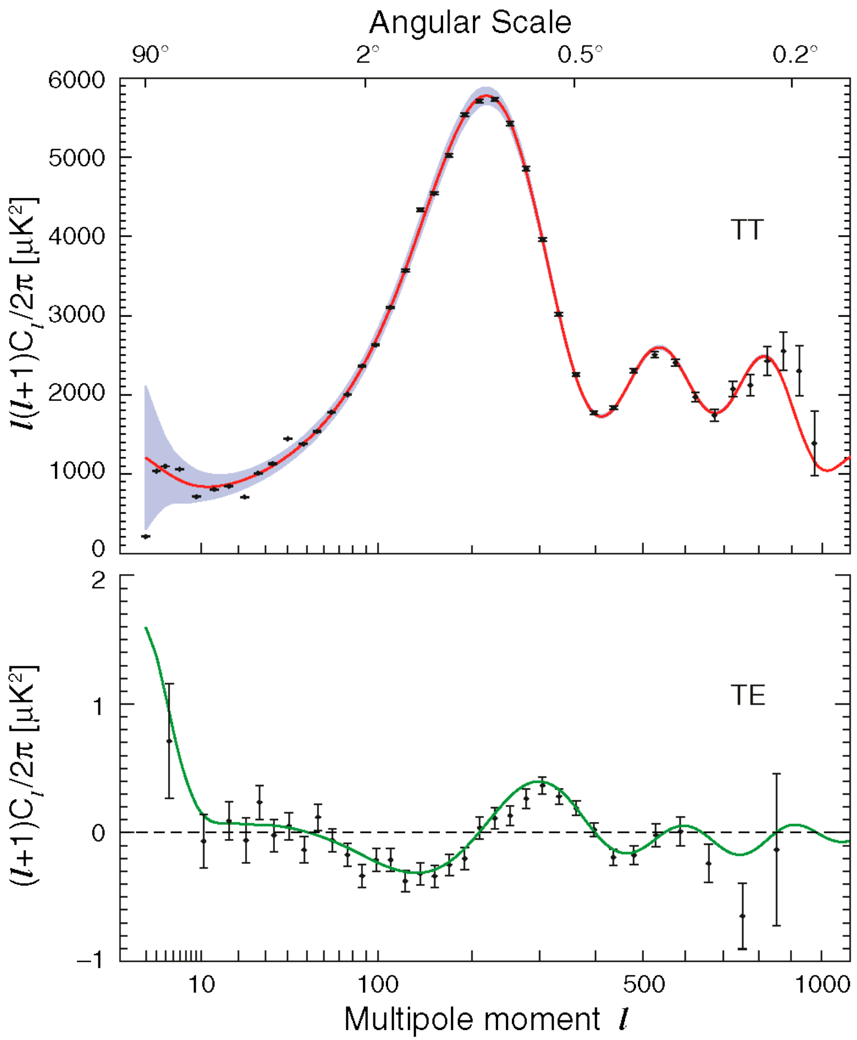
**...allowing removal of the Milky Way's emission and isolation of**

**CMB temperature fluctuations ↔ matter density fluctuations.**



# The "spectrum" of the CMB fluctuations

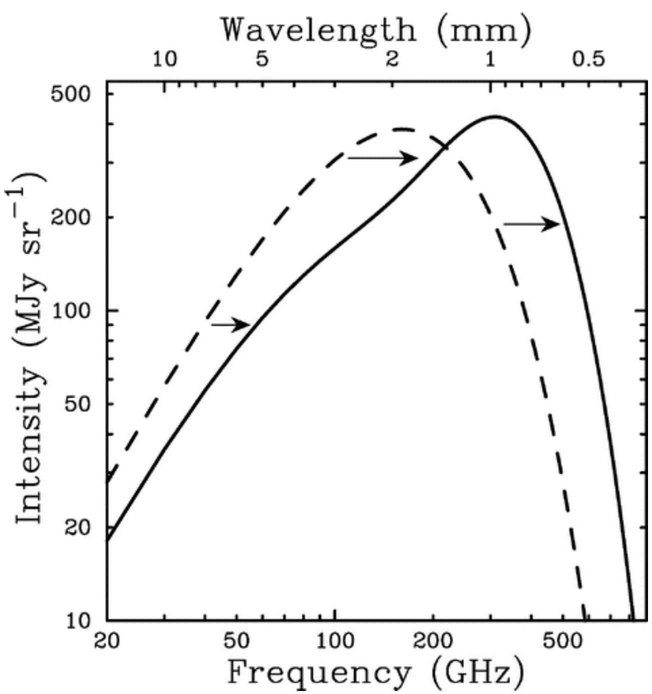
**Power spectrum of the CMB is like its Fourier transform, showing the characteristic angular scales on which the rippliness of the CMB is strong.**



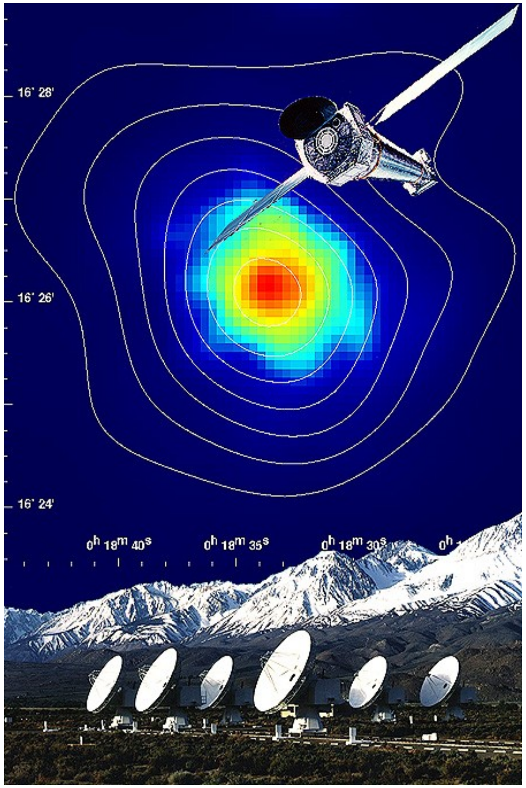

**The power spectrum depends sensitively on cosmological parameters (dark matter, dark energy, etc.).**

# 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.**

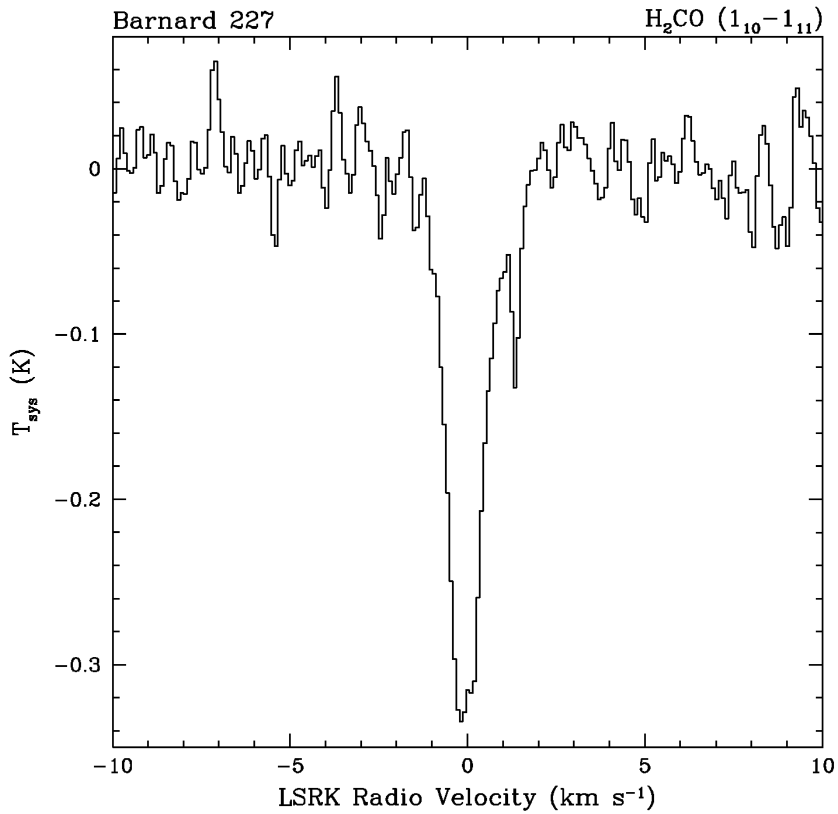



**This is the Sunyaev-Zeldovich Effect (SZE) being exploited at Rutgers via the ACT project.**



# 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.**

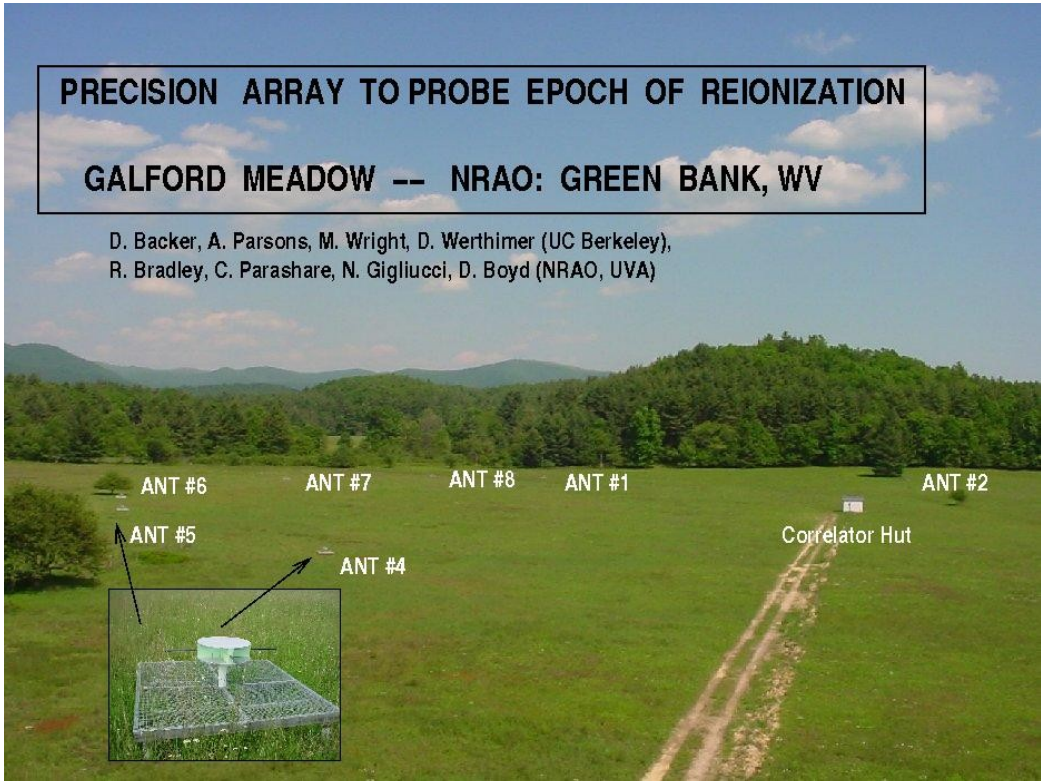
**We still don't know what causes reionization, or how: quasars (i.e., AGN)? galaxies? individual stars?**

**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)...**

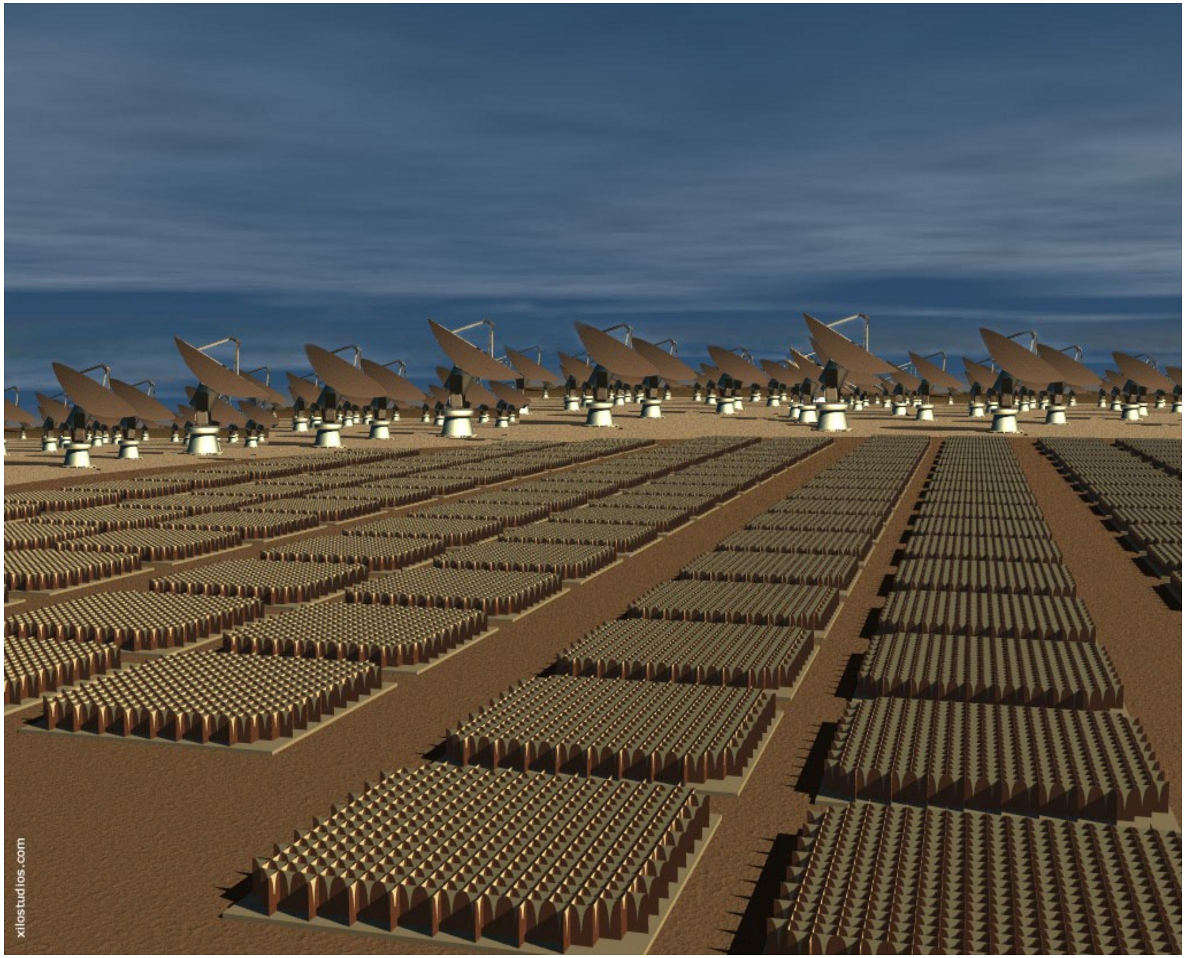
**16 → 64 antennas operating at 100–200 MHz (↔ $z$ = 6–13).**




**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...**

# Quiz

# Topic(s) of student choice lecture

**Current suggestions that are related to radio astronomy:**

- **+ modified Newtonian dynamics and HI rotation curves**
- **+ pulsars**
- **+ megamasers and (indirect) constraints on dark energy**
- **+ ???**

# Please finish the decision-making process...

# Information for evaluations

**Instructor's name: Andrew Baker**

**Course title: Obs. Radio Astron.**

**College/Course/Section:**

**01:750:343:01**

**Law**
**Patel**
**Patterson**
**Shah**
**Spassova**

**01:105:343:01**

**Brady**
**Demarest**
**Galkin**
**Heiblim**
**Llamas**
**Rodriguez**
**Salmon**
**Tarabichi**