# COSMOLOGY WITH THE HI-21CM LINE


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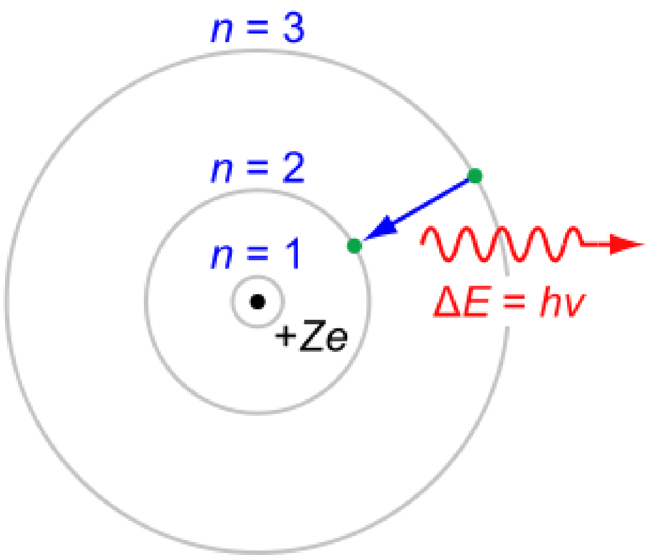
(Image: B. Premkumar)

# OUTLINE

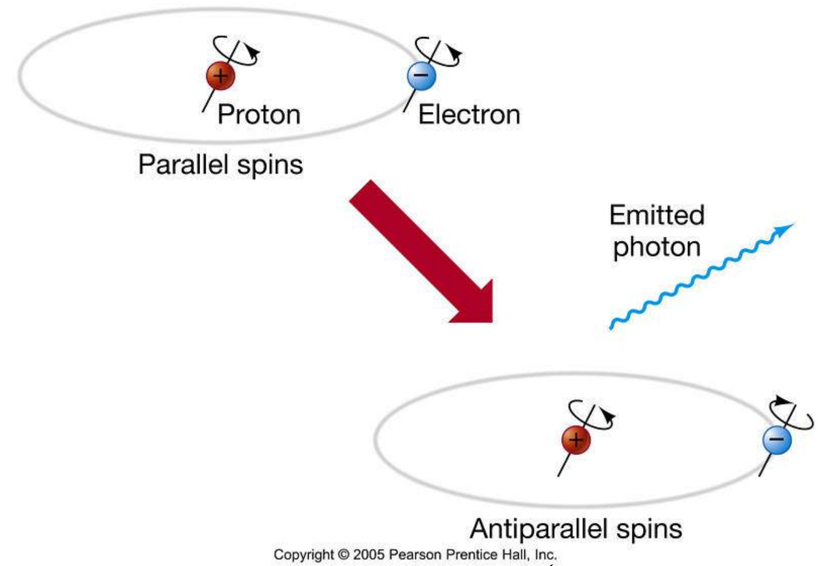
- Spectral lines in atomic hydrogen: the HI-21cm transition.
- Why do we like it so much ?
- HI-21cm emission and absorption studies.
- A (very) brief history of the Universe.
- Cosmological issues.
- Cosmology with the HI-21cm line.

# SPECTRAL LINES IN ATOMIC HYDROGEN

"Rydberg states"




"HI-21cm Hyperfine line"

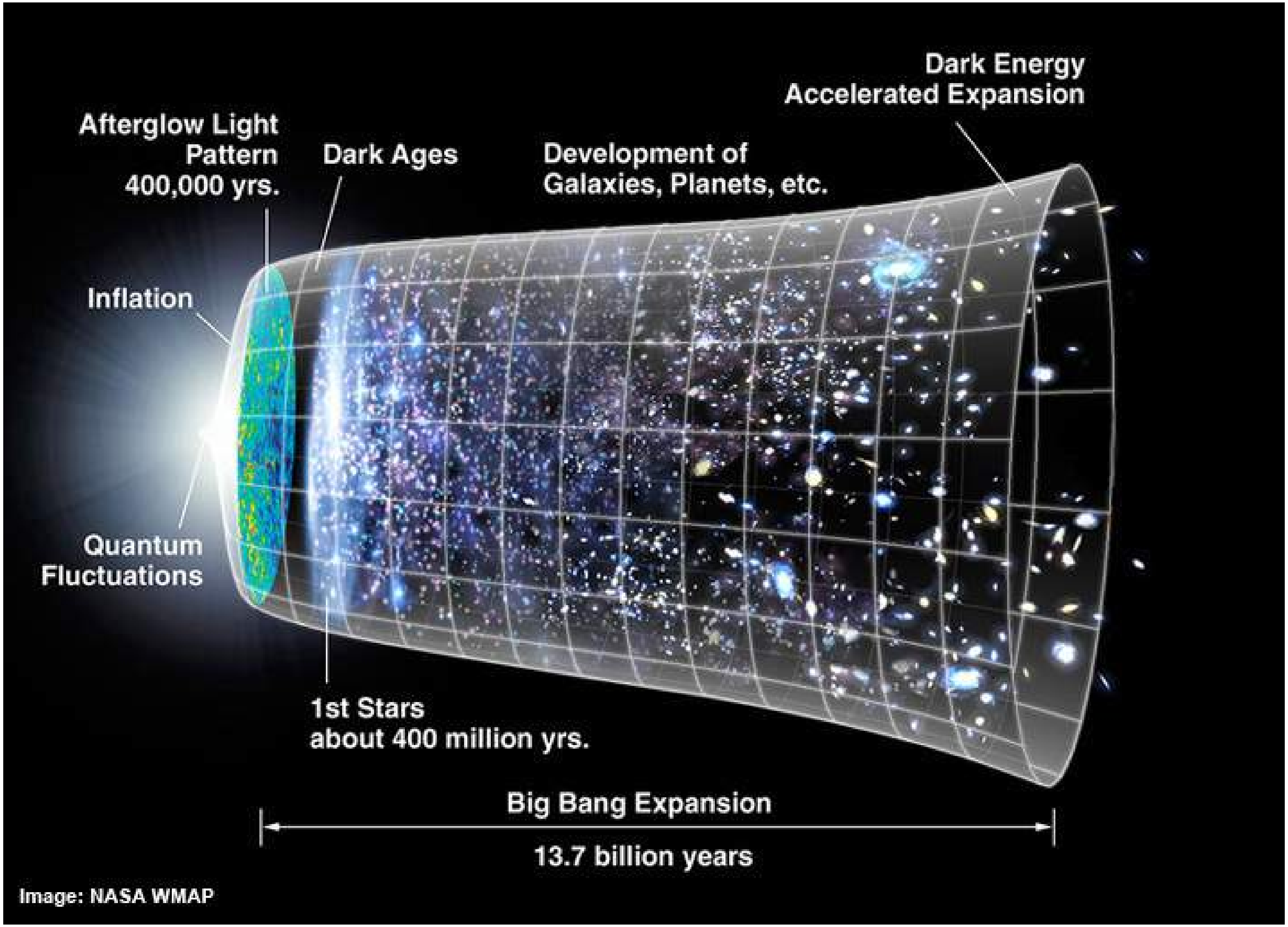



(Courtesy: NRAO)

- Strong electric dipole lines: A-coefficient, $A_{21} \sim 10^{8}\ \mathrm{s}^{-1}$.
- UV, optical frequencies: $(h\nu/k) \sim 10^5$ K ⇨ $(n_2/n_1) \approx 0$!
- Weak magnetic dipole lines: A-coefficient, $A_{21} \sim 10^{-15}\ \mathrm{s}^{-1}$.
- $\nu = 1420.40575$ MHz: $(h\nu/k) \sim 0.07$ K ⇨ $(n_2/n_1) \sim 3 \times [1 - 0.07/T_s]$

- The weakness of the HI-21cm line is actually its strength!

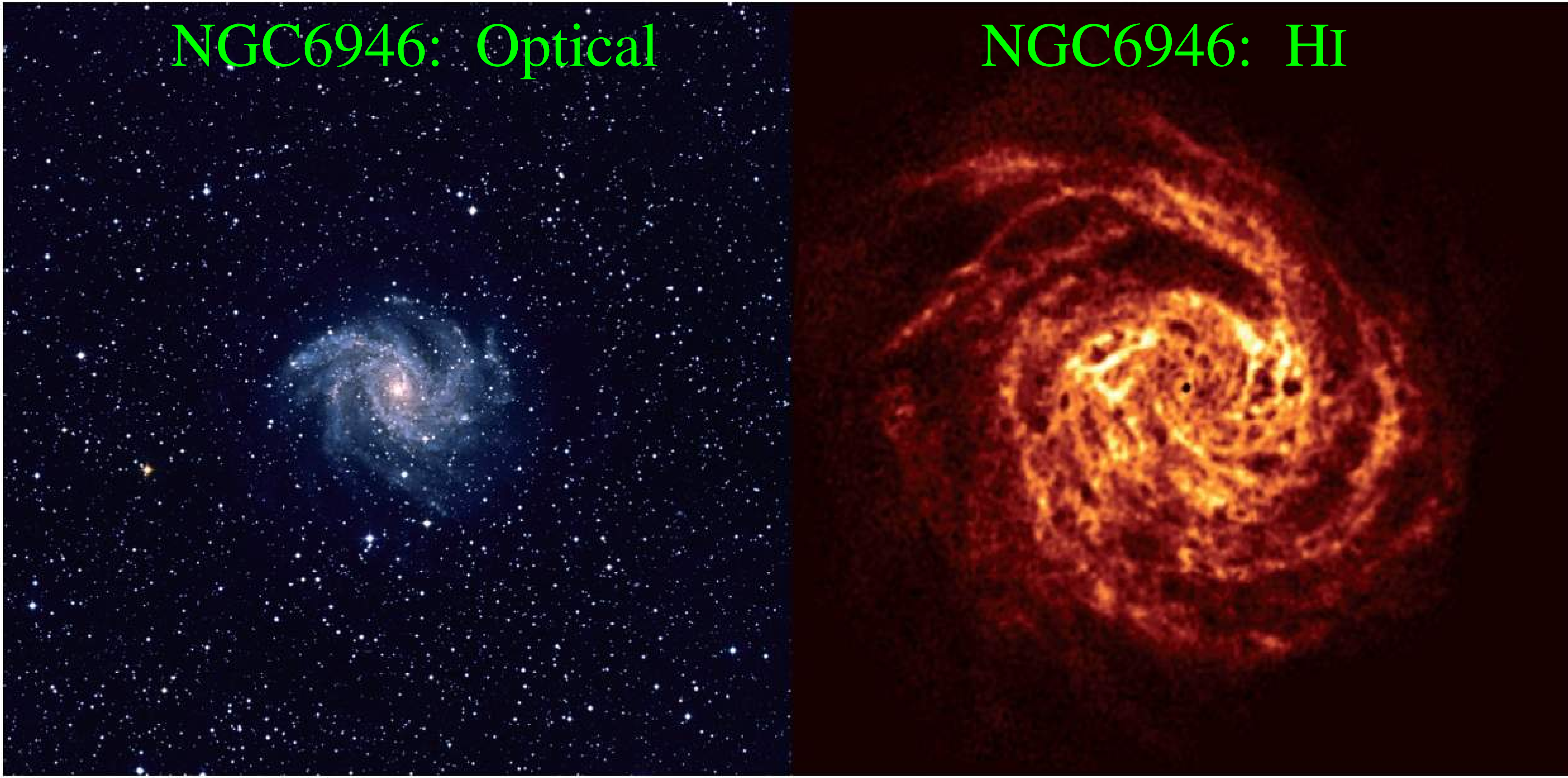
# WHY DO WE CARE ?




(Courtesy: NASA)

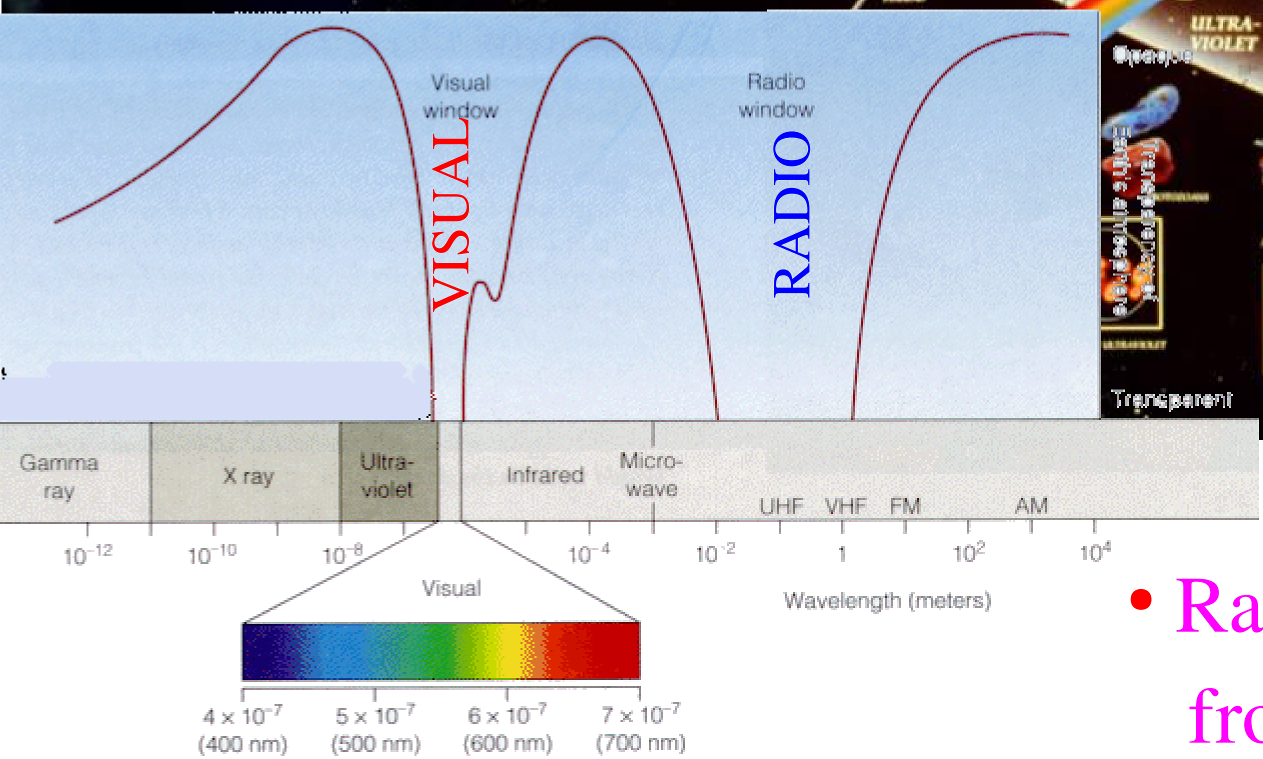
- ~75% of the Universe's baryons are hydrogen (HI, HII, $H_2$).
- Most hydrogen in normal galaxies is in the atomic phase.

# Why Do We Care ?




(Boomsma, Ph.D. thesis)

- Gas in galaxies is typically more widespread than stars.
- Spectroscopic studies of the atomic gas are sensitive to the gas kinematics and, hence, to the galaxy dynamics.

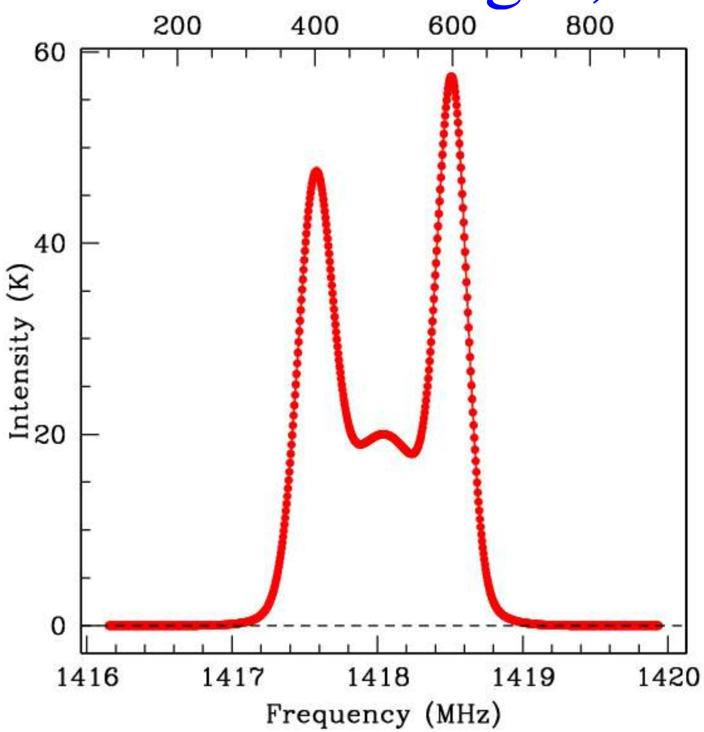

(Courtesy: NASA)

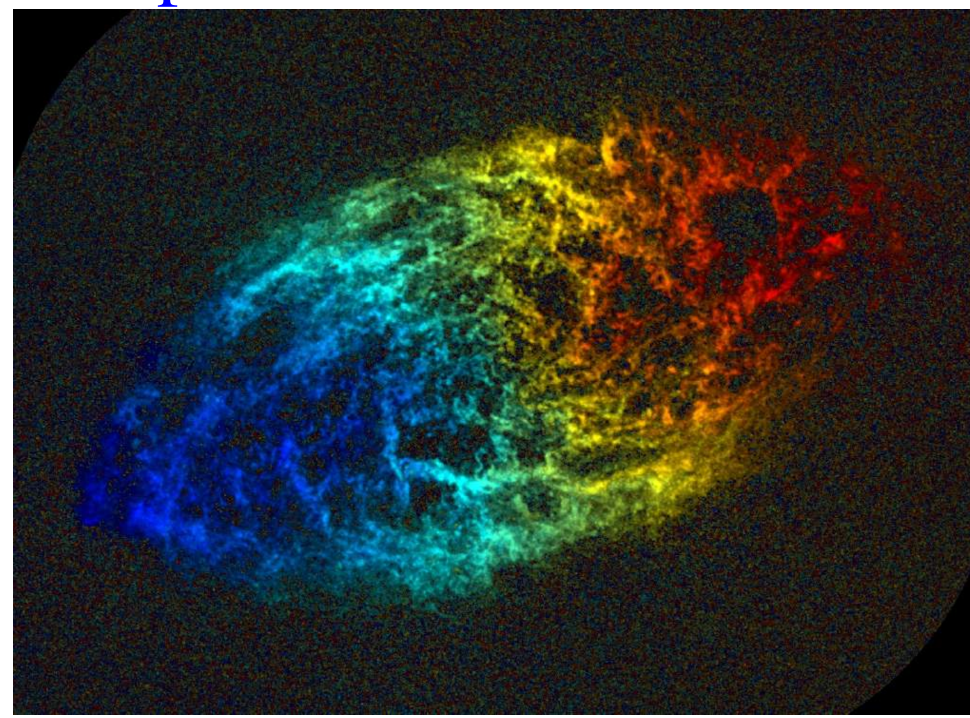
- Radio waves do not suffer from dust extinction!

# FREQUENCIES AND VELOCITIES

- If the gas is moving towards an observer, spectral lines are "blueshifted", to lower observed wavelengths.

⇨ Line wavelength, width and shape contain information !



- HI-21cm lines have a width and shape, determined by the gas kinetic temperature and any internal motions.
- In equilibrium, the lines have a Gaussian shape!

  Cold gas ⇨ Narrow lines. Warm gas ⇨ Wide lines.

# HI-21CM ABSORPTION & HI-21CM EMISSION

- HI-21cm *emission*: Line strength depends on the amount of gas!

  $N_{HI} = 1.8 \times 10^{18} \times \int T_B \, dV$

  $T_B$ : Line brightness temperature.

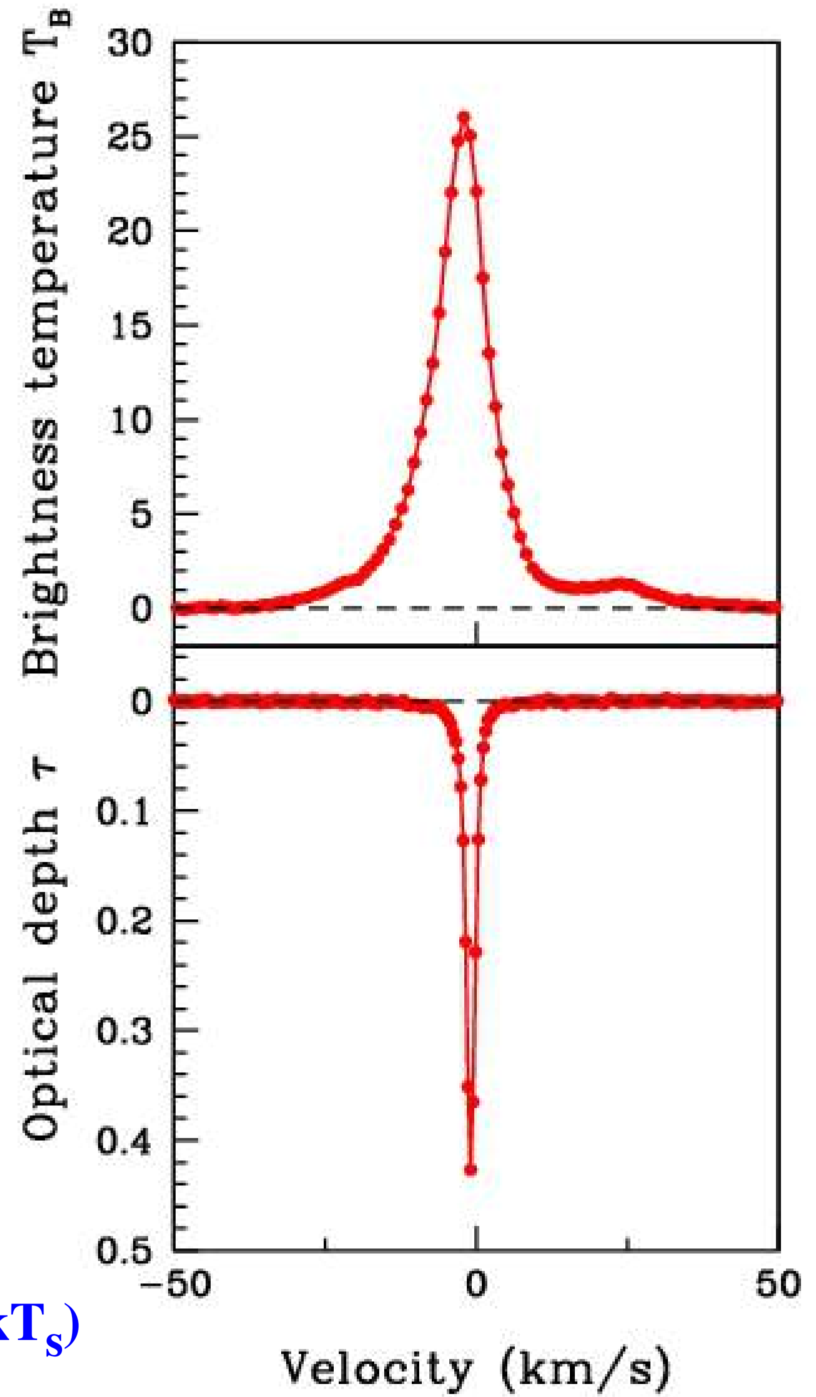
  $N_{HI}$: HI column density: $\int n \, ds$.

- HI-21cm *absorption*: Line strength depends on both the amount of gas and the gas temperature!

  $N_{HI} = 1.8 \times 10^{18} \times T_S \times \int \tau dV$

  $\tau$ : Optical depth: $I(\nu) = I_0 \, e^{-\tau(\nu)}$

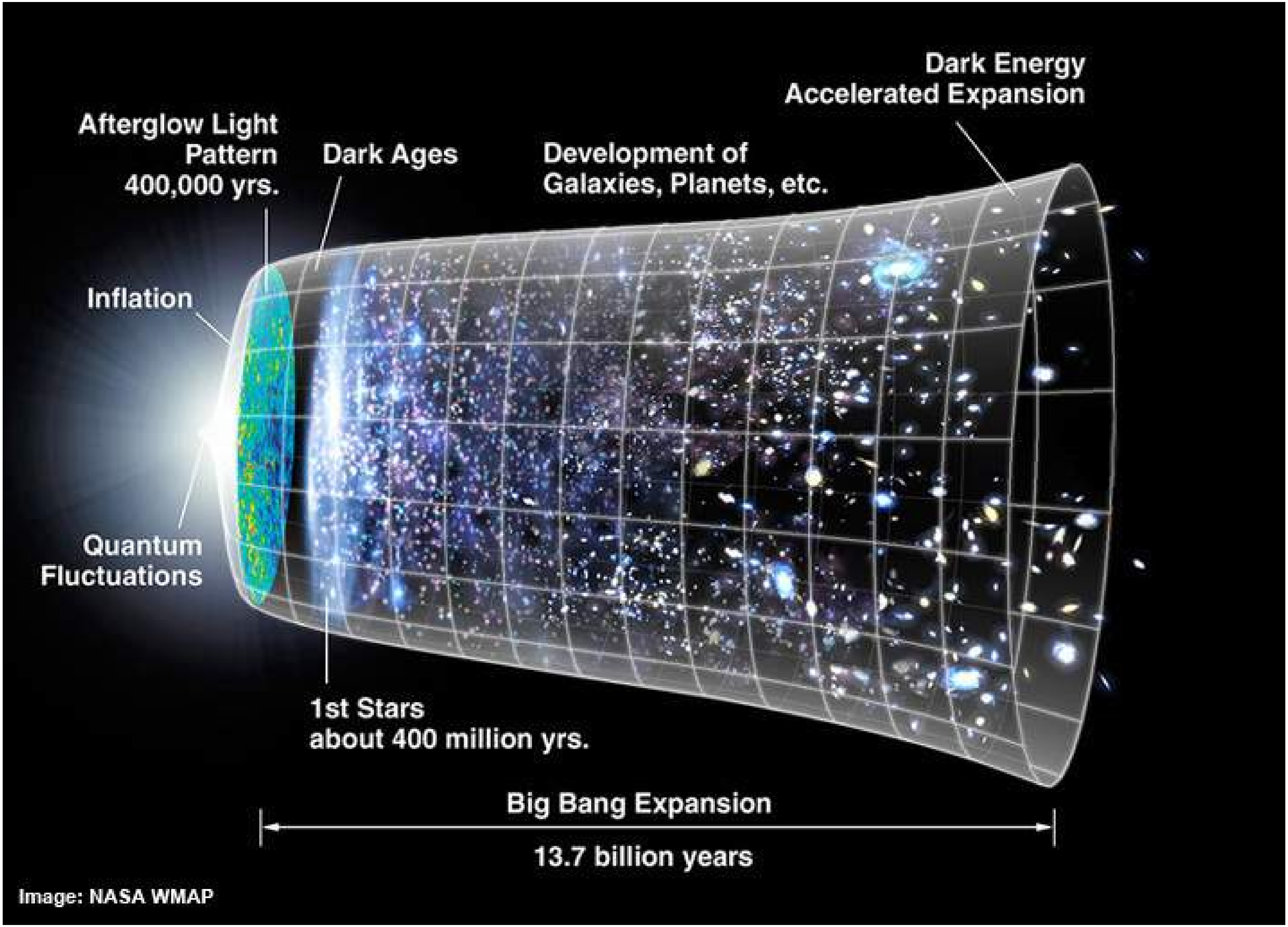
  $T_S$ : Spin temperature; $[n_2/n_1] \propto e^{(-h\nu/kT_S)}$



# Summary - I

- Hydrogen is the dominant species in the Universe.
- Gas in galaxies extends far beyond the stars!
- The weakness of the HI-21cm line is a *good* thing!
  Most atoms not in the ground state ⇨ Emission studies.
  Line strength ∝ HI column density ⇨ Gas kinematics!
- Line widths depend on gas temperature:
  Cold gas ⇨ Narrow lines. Warm gas ⇨ Wide lines.
- Absorption strength proportional to amount of gas & inversely proportional to temperature.
- Emission strength proportional to total amount of gas.

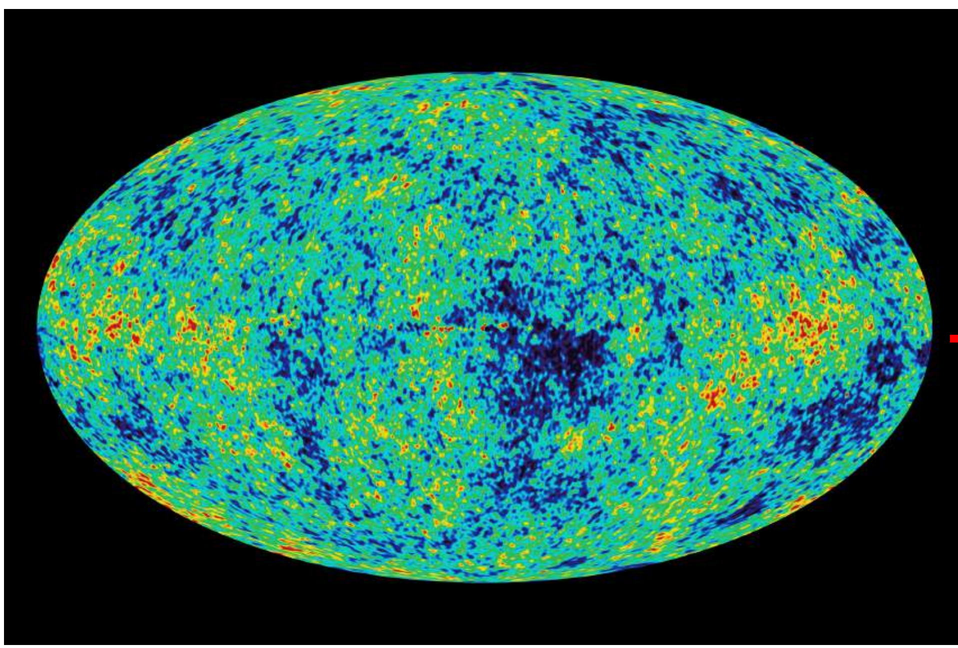
# A Brief History of (Nearly) Everything




(Courtesy: NASA)

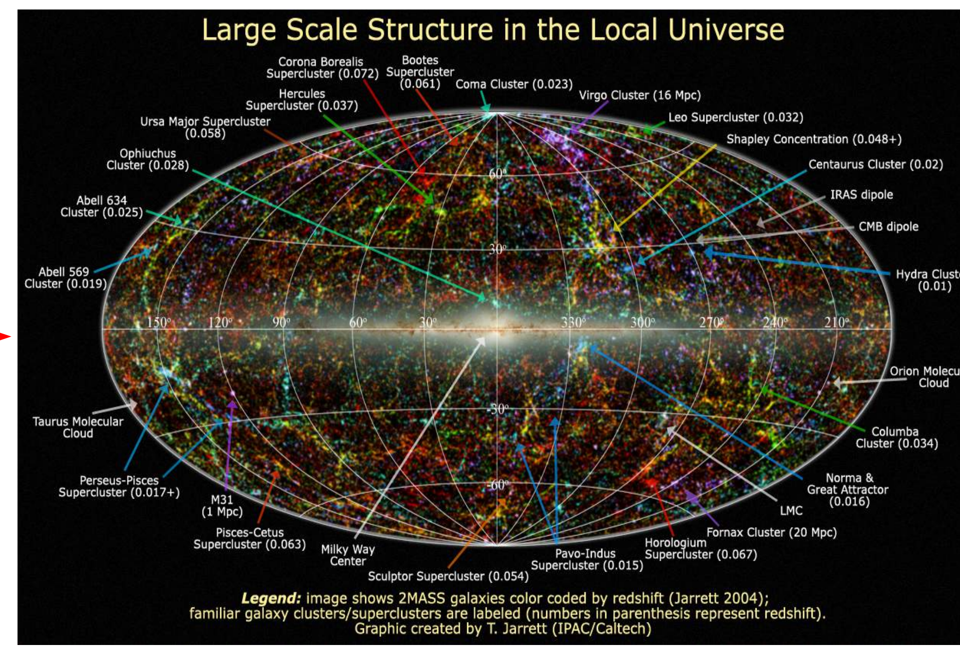
# Cosmological Issues

- What are the main constituents of the Universe ?
  Baryons, dark matter, dark energy, ... ?
- The last cosmological frontier: the Epoch of Reionization.
- How do galaxies and their constituents form and evolve ?



Microwave Background, $z \sim 1100$

$\delta = (\rho - \rho_0)/\rho_0 \sim 10^{-5}$




Local large-scale structure, $z \sim 0$

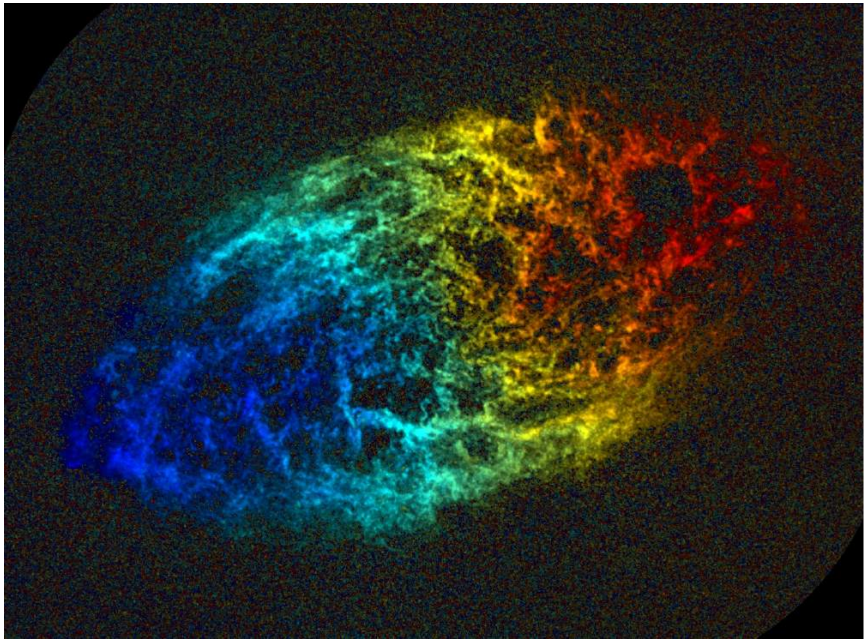
$\delta = (\rho - \rho_0)/\rho_0 \sim 10^2 - 10^3$

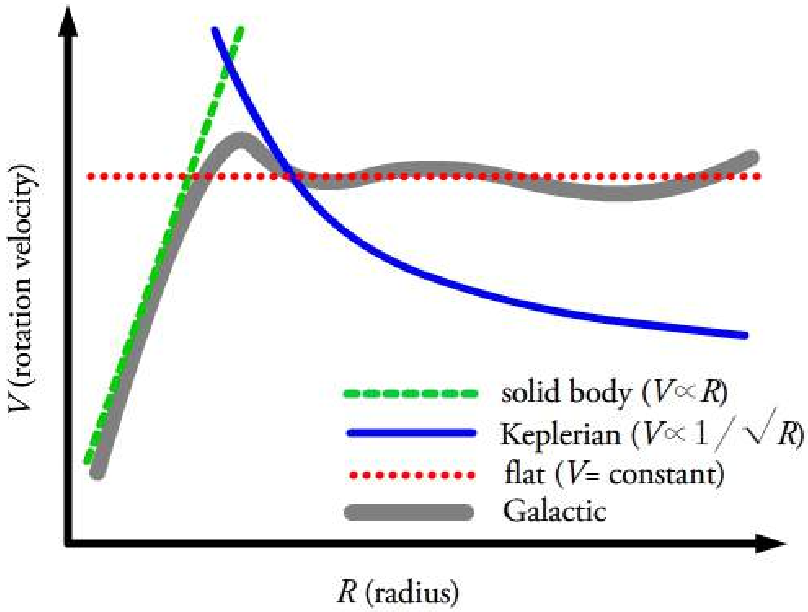
# COSMOLOGY WITH THE HI-21CM LINE

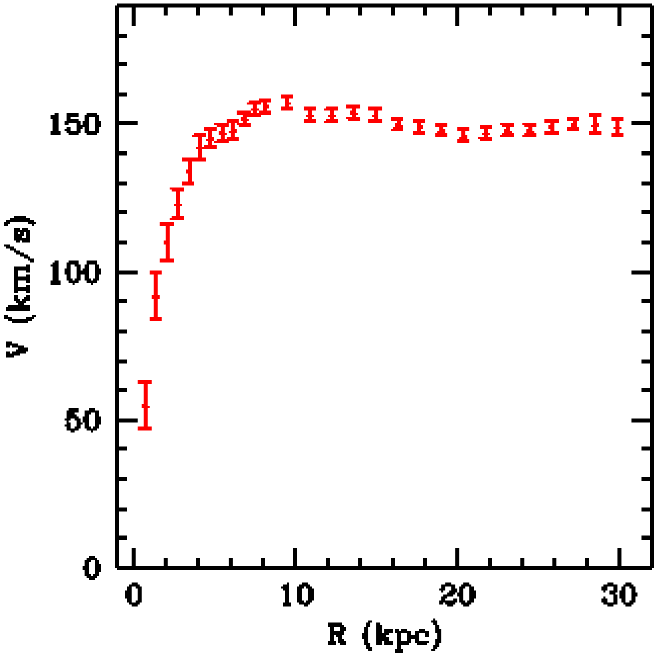
- HI in nearby galaxies: A universal dark matter profile ?
- HI in high-redshift galaxies:
  The evolution of gas in galaxies (size, temperature, etc.).
  Measuring the mass density in neutral gas.
- HI at ludicrously high redshift: the Epoch of Reionization.
- And now for something completely different:
  Fundamental constant evolution.

# HI Emission from Nearby Galaxies

- Direct measurements of HI mass, velocity field & dynamical mass.
- For circular orbits, $V = [GM/R]^{1/2}$. Should have $V \propto R^{-1/2}$ at large R, as most mass is in inner regions.






But... Flat rotation curves ⇨ Dark Matter! (e.g. Begeman 1989, A&A)

# DARK MATTER DENSITY PROFILES ?

- Simulations predict that dark matter halos of galaxies have a universal "NFW" form, with $\rho(r) \propto 1/[r(a+r)^2]$.
  ⇨ At low $r$, a "cuspy" profile, $\rho(r) \propto 1/r$

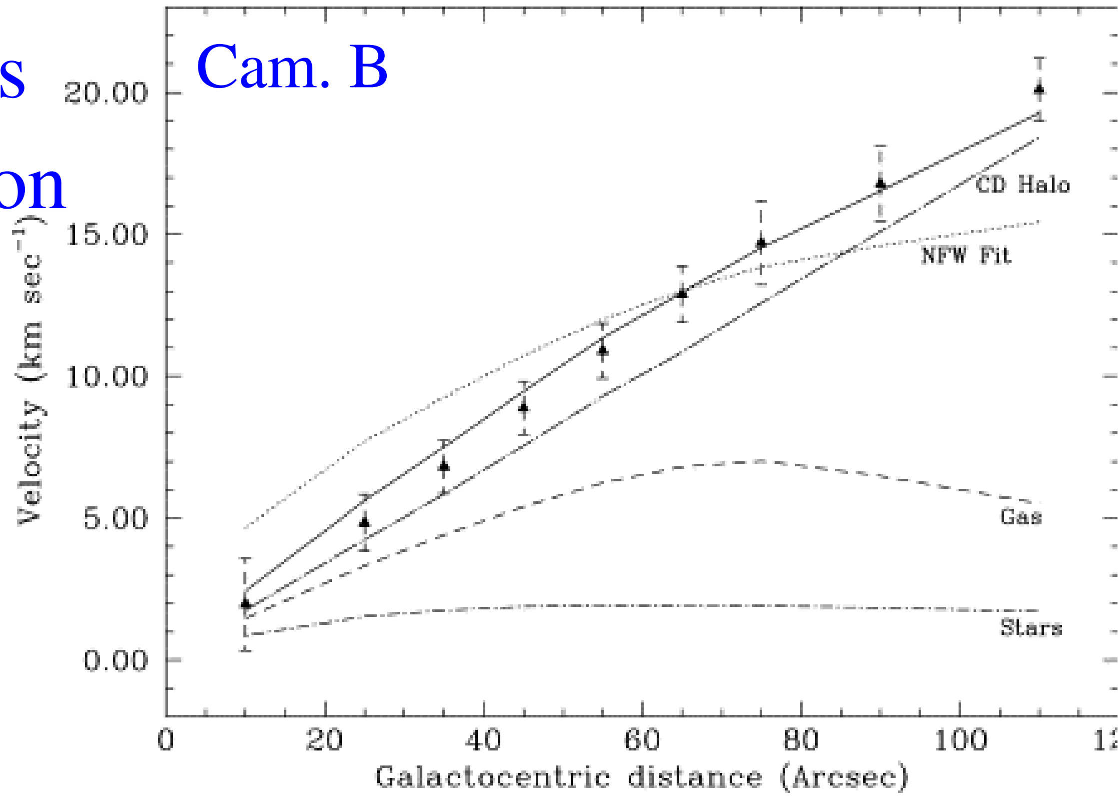
(Navarro et al. 1997, ApJ)

- Test by mapping HI-21cm emission from galaxies, to obtain circular velocity versus distance ("rotation curve").

- Dwarf galaxies good targets due to low baryonic fraction at low radius.

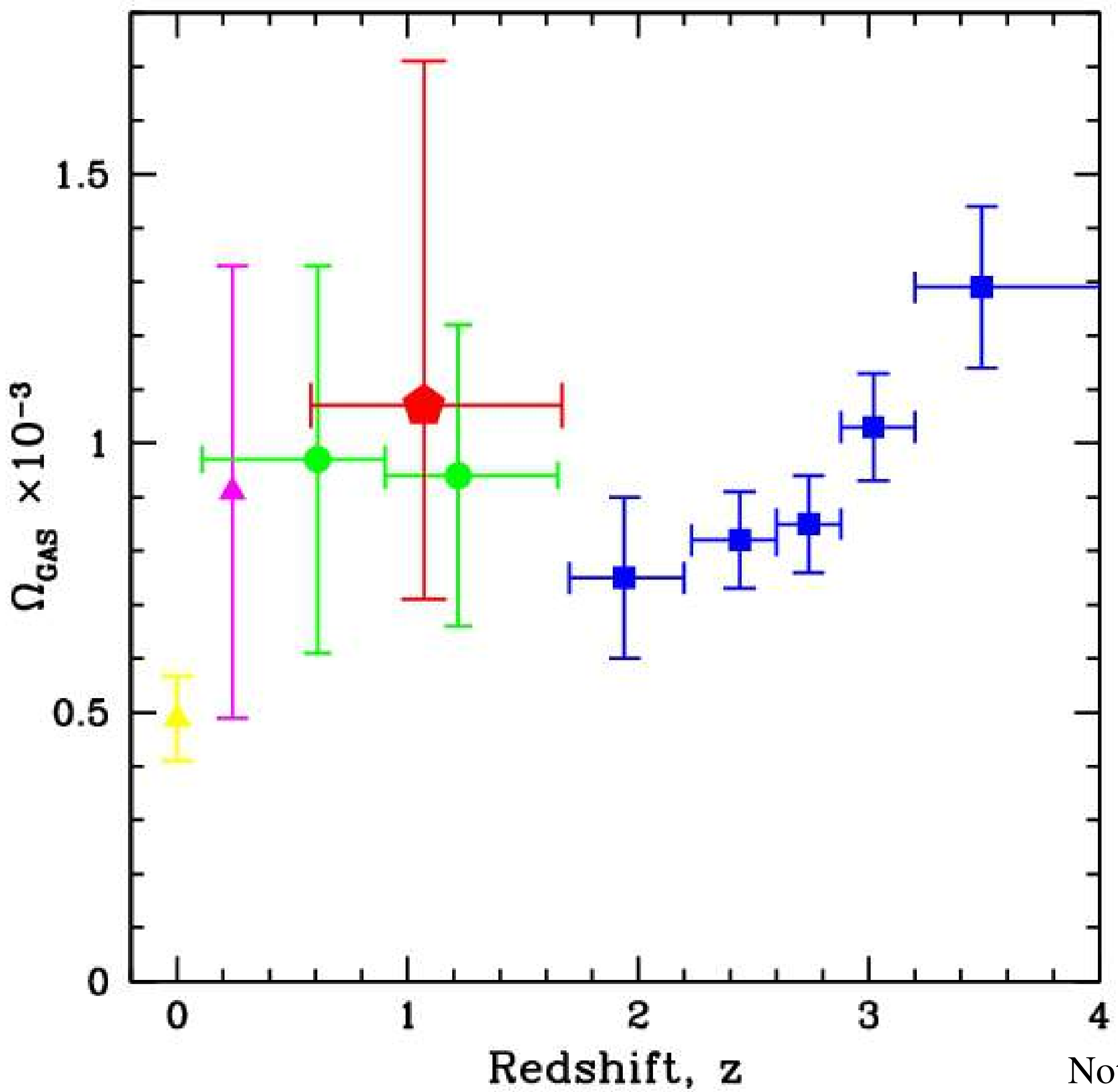
- A cuspy halo is *not* a good fit for Cam. B, and other dwarf galaxies.

(Begum et al. 2003, New Astr. Rev)



# HI IN HIGH-REDSHIFT GALAXIES

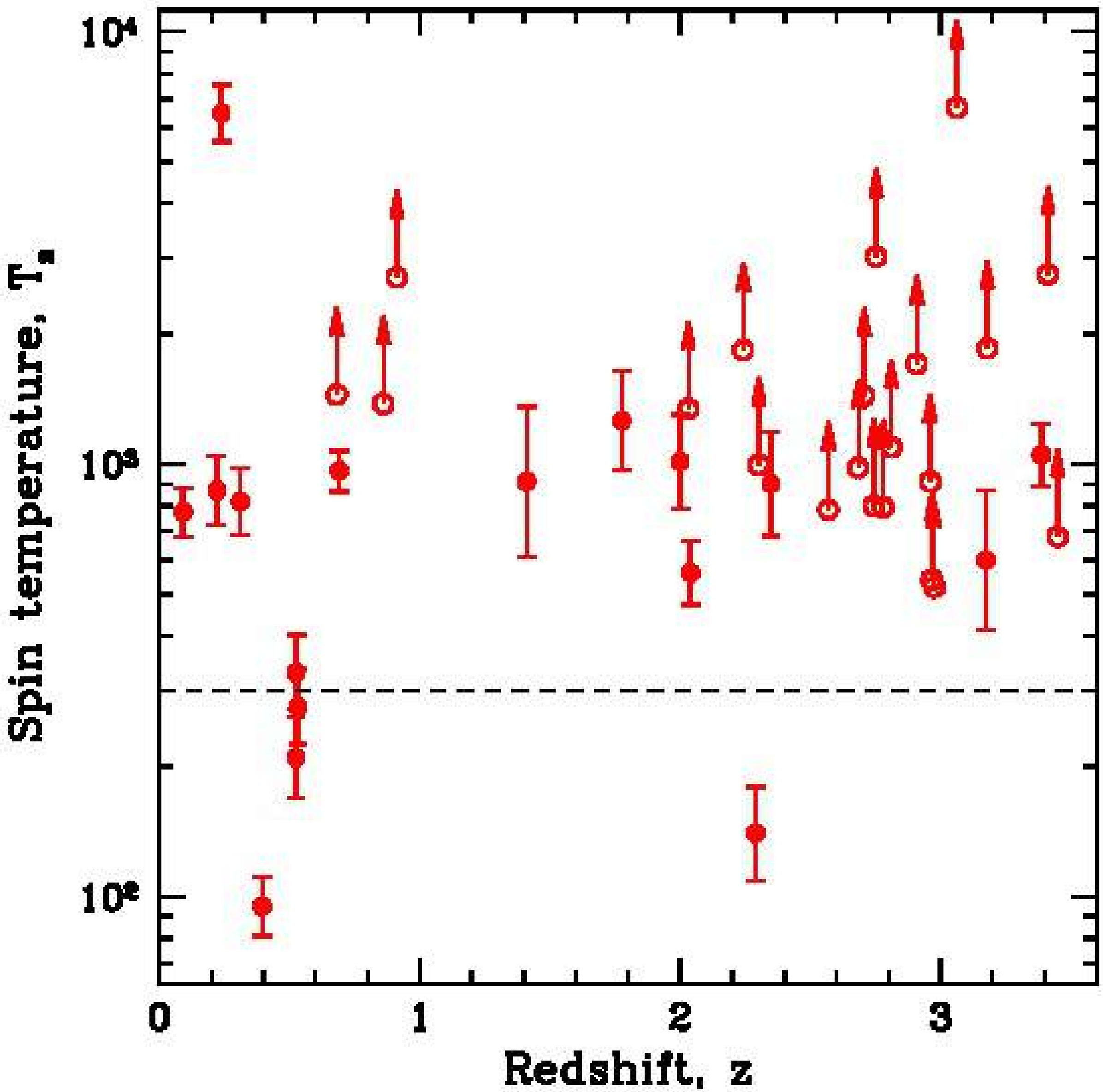
- Evolution of the cosmological mass density of neutral gas.




(Zwaan et al. 2005, A&A; Noterdaeme et al. 2009, A&A; NK et al. 2009, MNRAS)

# HI IN HIGH-REDSHIFT GALAXIES

- Temperatures are systematically higher in high-$z$ galaxies.
  - ⇨ High-$z$ galaxies are small systems, dwarfs not spirals!



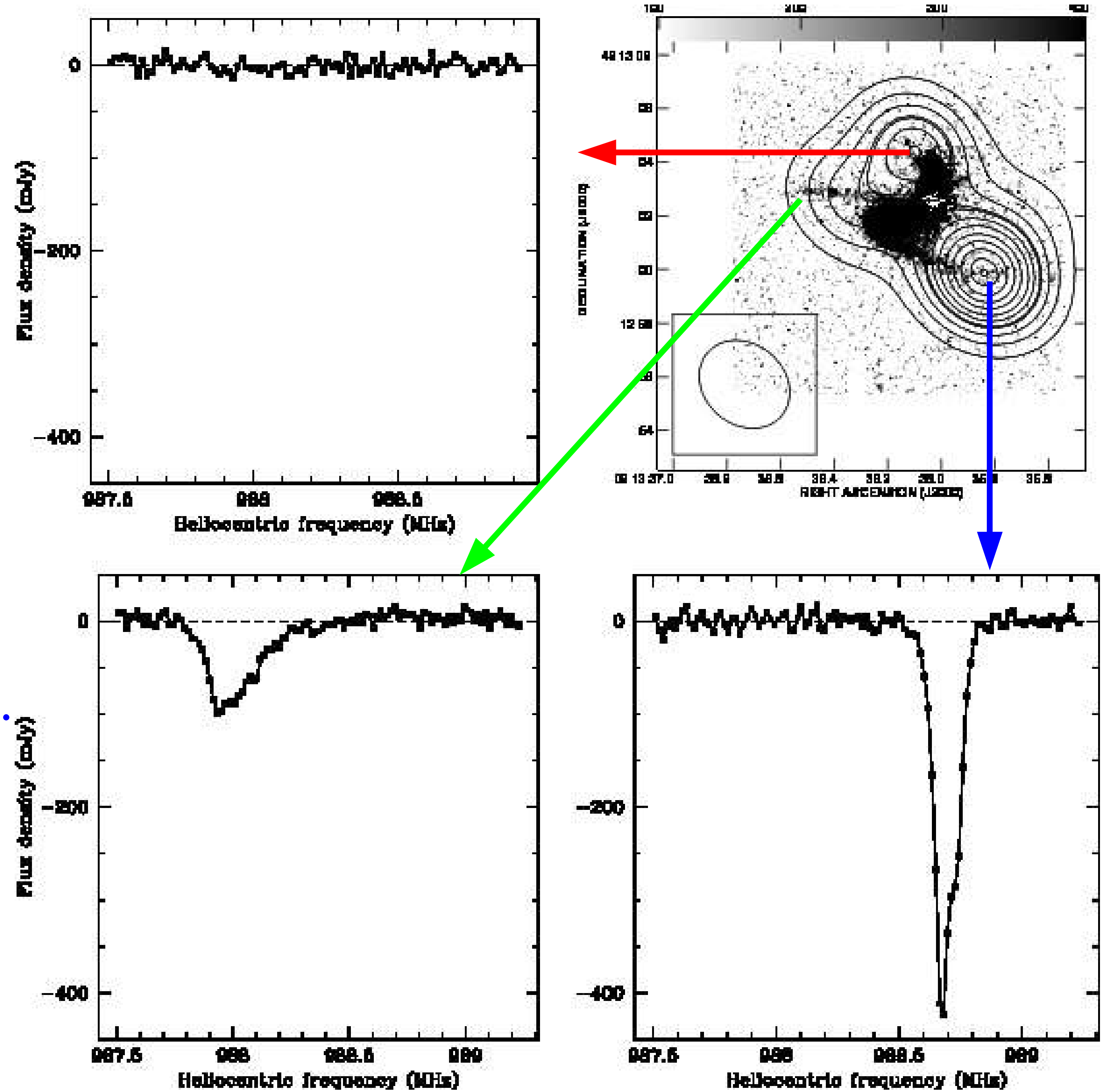

(NK et al. 2013)

# MAPPING HI-21CM ABSORPTION:

Measure the size of high-$z$ galaxies.

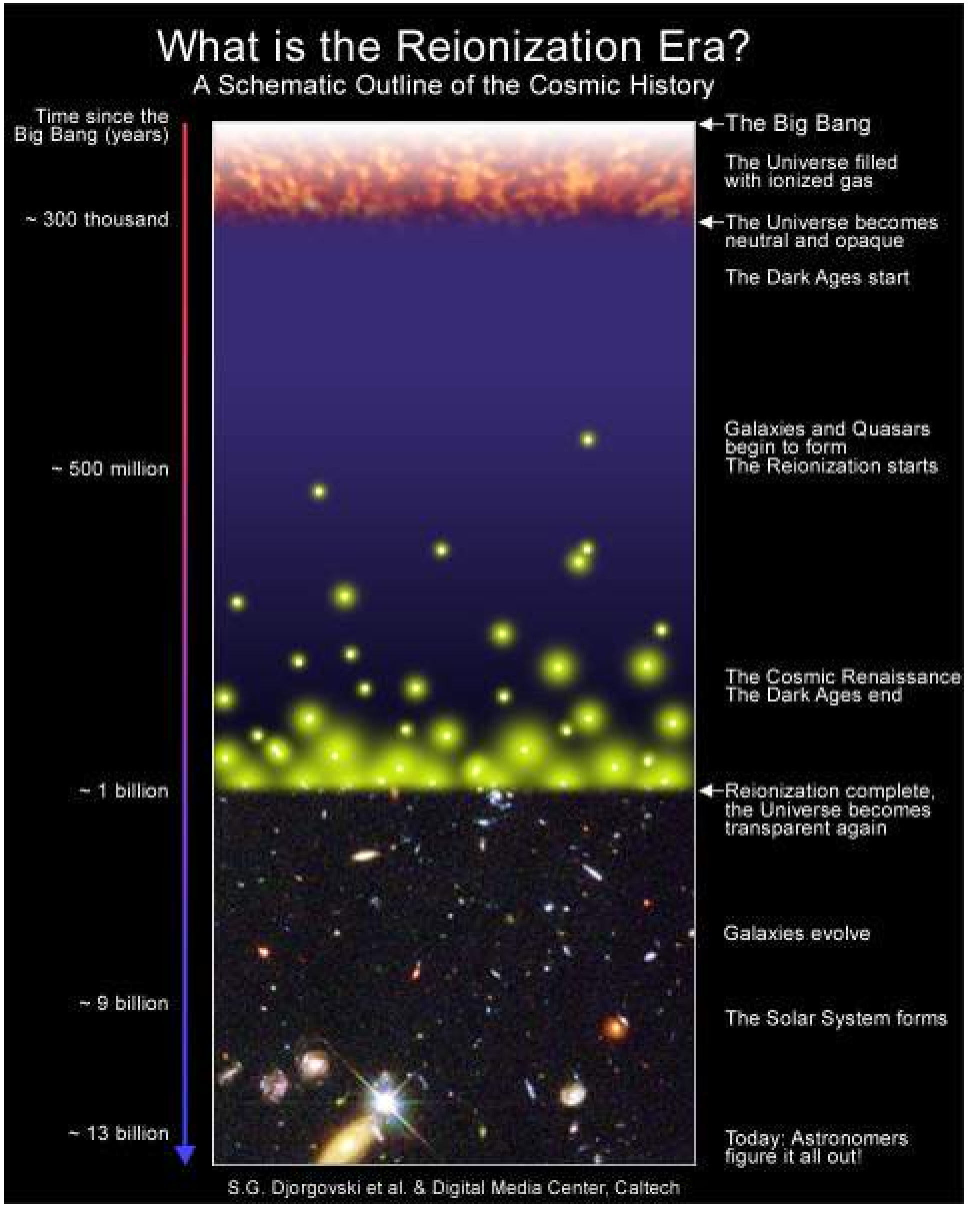
Galaxy at $z$~0.44 toward 3C196:

Absorption found far beyond spiral arms: Size > 80 kpc.




(NK & Chengalur 2013)

# HI FROM THE EPOCH OF REIONIZATION

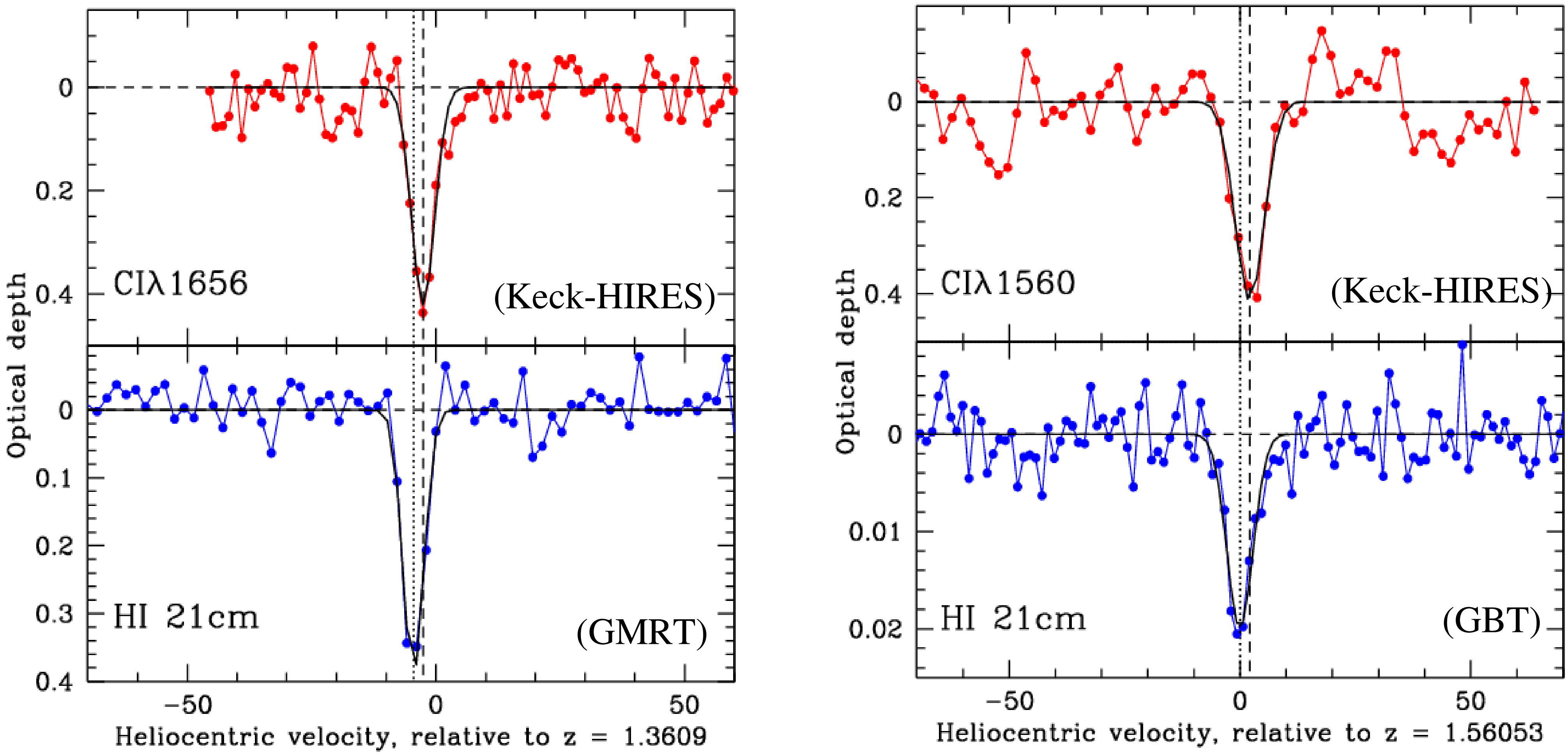



(Courtesy: MIT-Haystack)

- Last phase transition in the Universe; probe of cosmology!
- HI-21cm from the EoR: New telescopes: LOFAR, MWA...

# Fundamental Constant Evolution

- HI-21cm frequency $\propto \alpha^2$ ; CI frequency $\propto \alpha^0$.
- If $\alpha$ changes with time, $\nu_{21}(z) \neq \nu_{21} \Rightarrow z_{21} \neq z_{CI}$.




$$[\Delta\alpha/\alpha] = [+3.4 \pm 0.5\ (stat.) \pm 3.3\ (syst.)] \times 10^{-6}$$

(NK et al. 2010, ApJL)

# What can HI-21cm Spectroscopy do for You ?

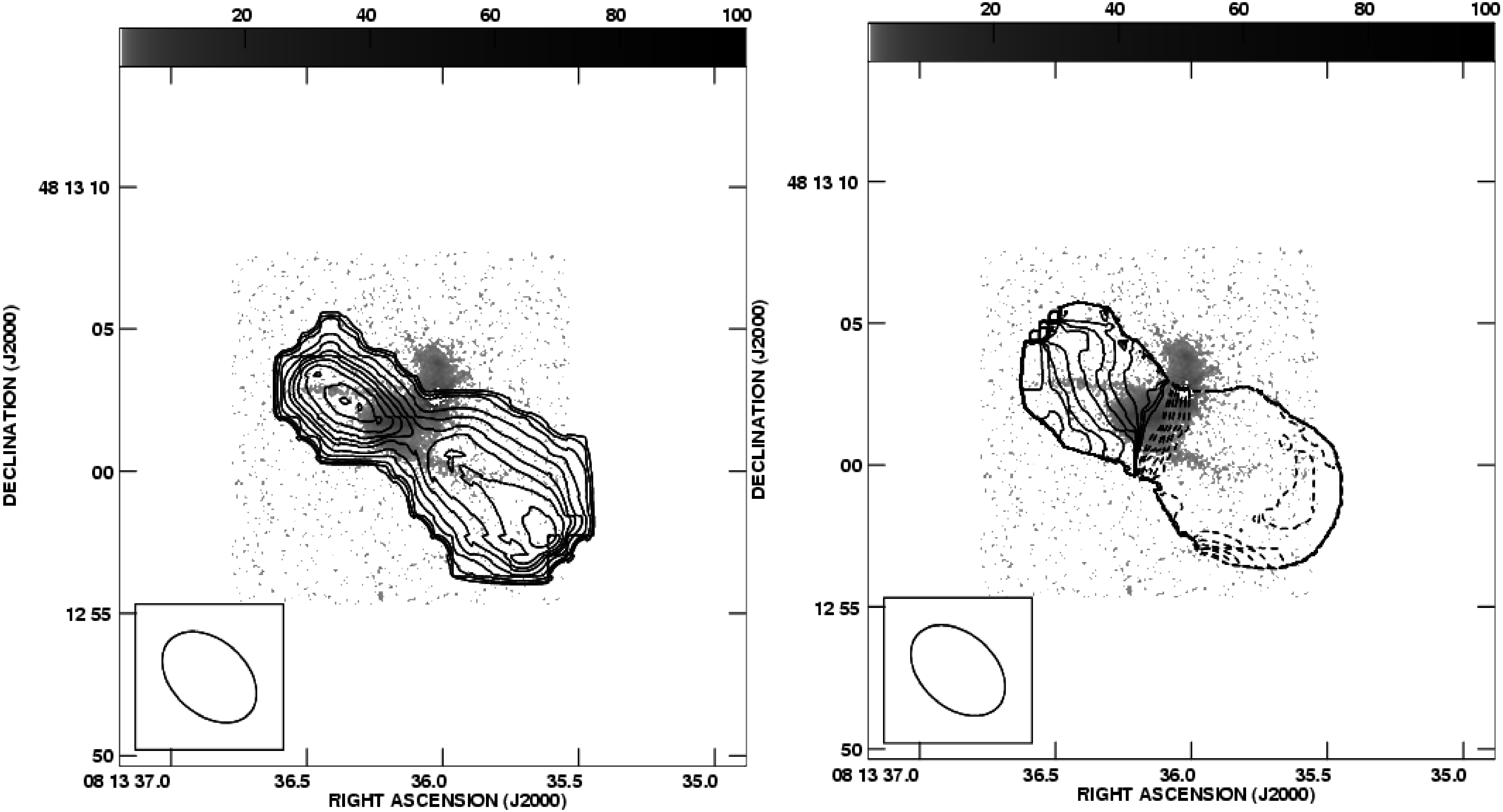
- HI-21cm absorption studies of galaxies toward background radio-loud quasars: gas temperature, size, kinematics.
- HI-21cm emission mapping of local galaxies: rotation curves, dark matter density profiles.
- Deep HI-21cm emission images of clusters and groups: Mass density in neutral gas.
- Critical probe of the Epoch of Reionization! Independent and sensitive test of the cosmological model.
- Probing fundamental constant evolution with spectral lines.

# THE GIANT METREWAVE RADIO TELESCOPE

Govind Swarup

# $z \sim 0.437$ DLA towards 3C196:

HI-21cm absorption extends far beyond the optical spiral arms ⇨ Transverse size > 80 kpc!




(NK & Chengalur 2010)

# HI-21cm Absorption v/s HI-21cm Emission

- Absorption or emission ? If we observe an HI cloud of temperature $T_C$ towards a quasar of temperature $T_{Bg}$, the observed line brightness temperature is

$$T_B = T_C [ 1 - e^{-\tau} ] + T_{Bg} e^{-\tau}$$

- If $T_{Bg} >> T_C$ ⇨ Absorption: $T_B \approx T_{Bg} e^{-\tau}$
- If $T_C >> T_{Bg}$ ⇨ Emission : $T_B \approx T_C [ 1 - e^{-\tau} ]$

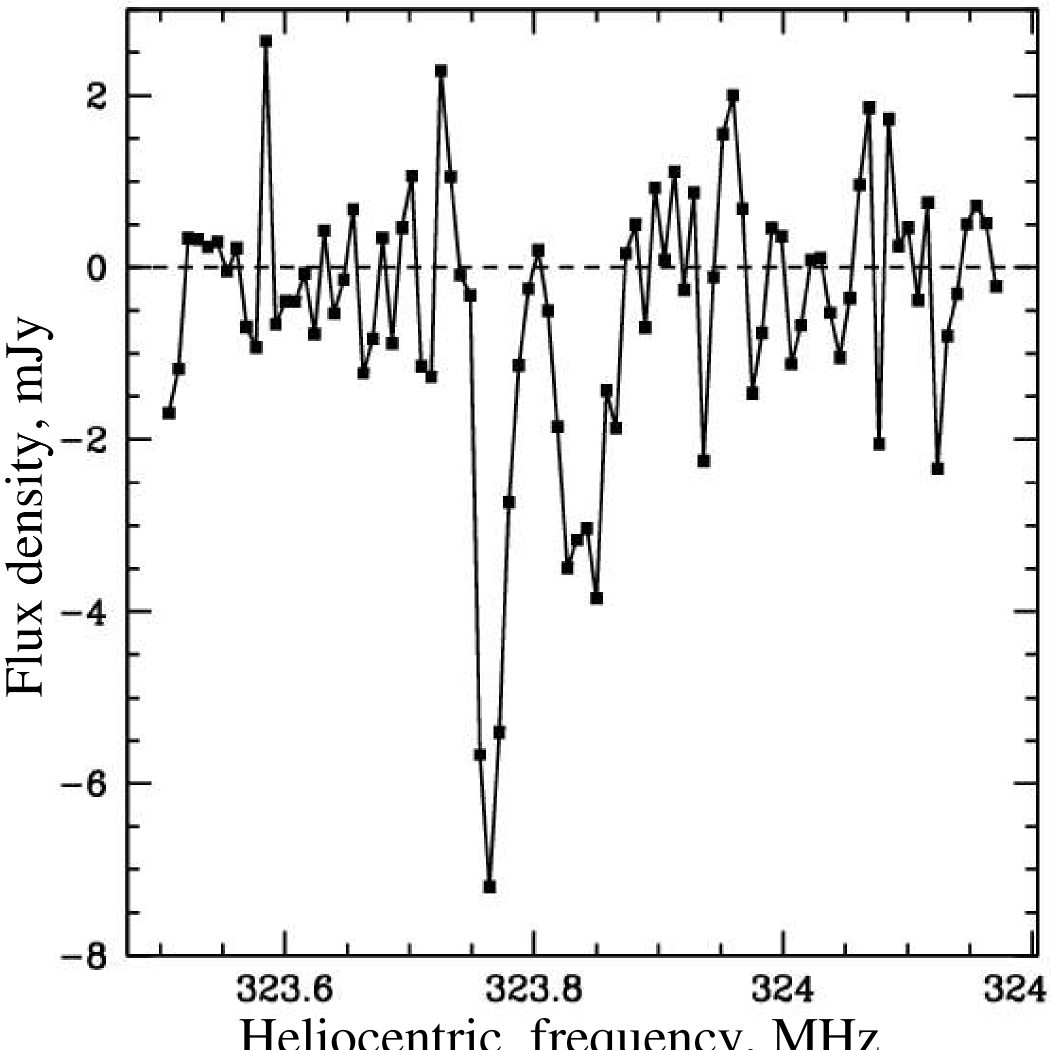
Evolution of gas in galaxies: HI-21cm absorption studies.

For galaxies towards radio quasars ⇨ Gas temperature!

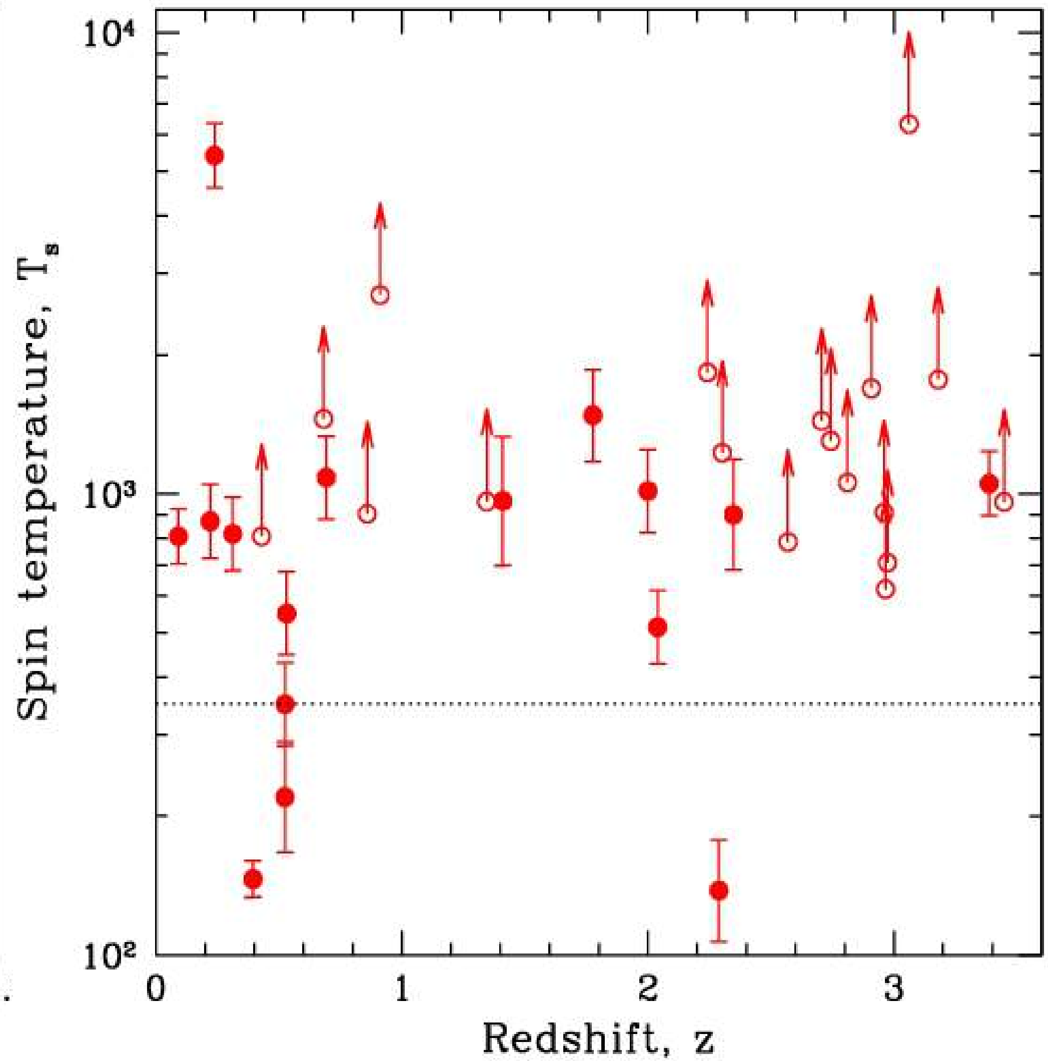
Temperatures are systematically higher in high-$z$ galaxies.

⇨ High-$z$ galaxies are small systems, dwarfs not spirals!

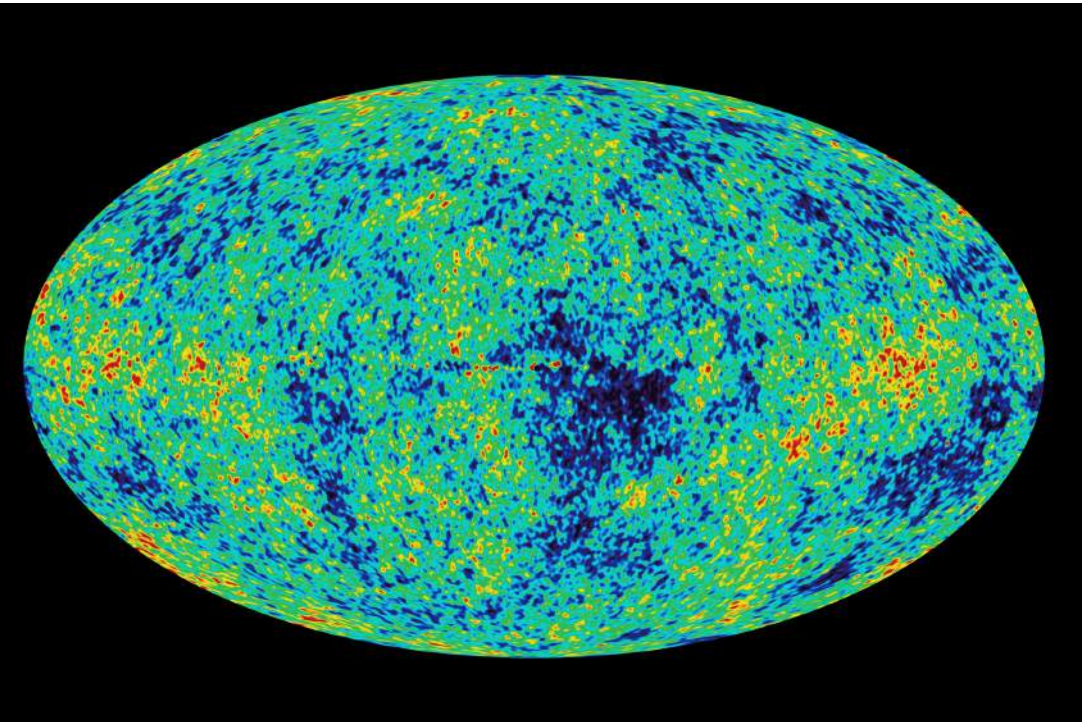
(NK et al. 2007, MNRAS)




(NK et al. 2009, ApJL)



# Galaxy Formation and Evolution



(Courtesy: NASA/WMAP)

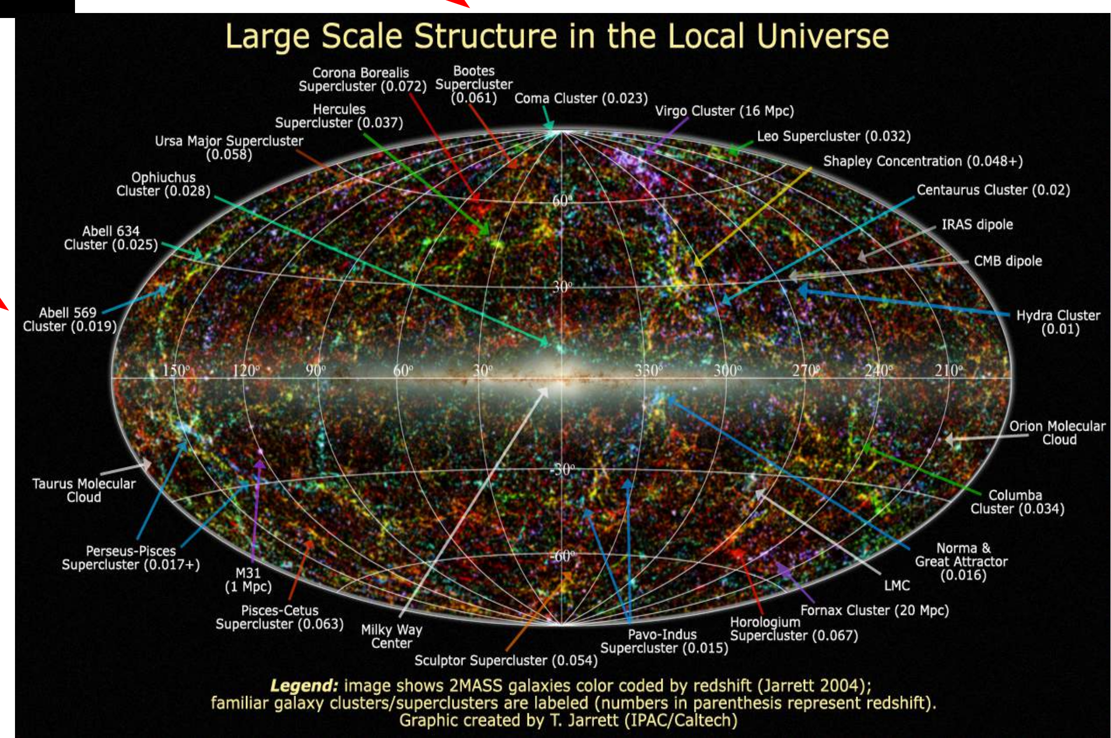
Cosmic Microwave Background

Redshift, $z \sim 1100$.

Tiny differences in density:

$\delta = (\rho - \rho_0)/\rho_0 \sim 10^{-5}$

(Jarrett 2004, PASA)




Local large-scale structure:

$z \sim 0$.

Huge differences in density:

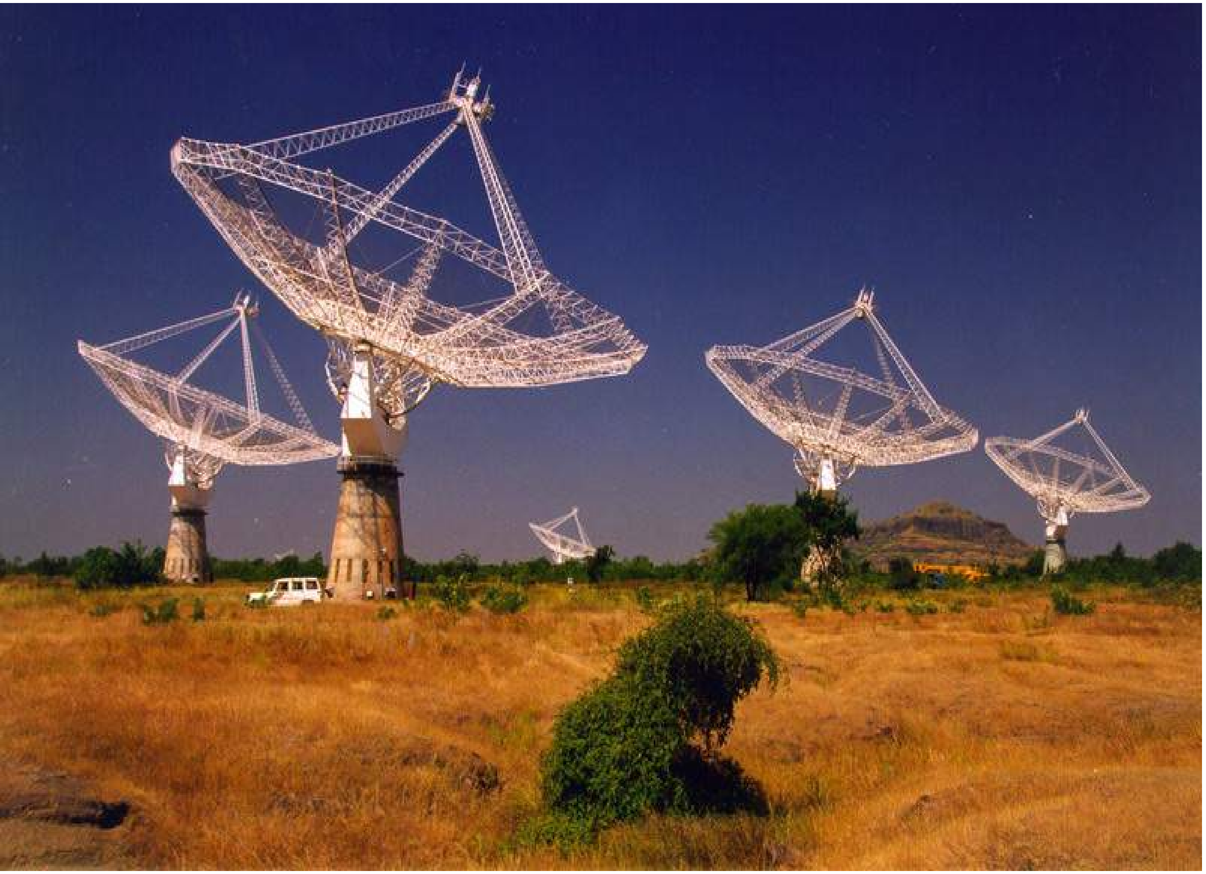
$\delta = (\rho - \rho_0)/\rho_0 \sim 10^2 - 10^3$

# The Giant Metrewave Radio Telescope

(Swarup et al. 1991, Curr.Sci.)

- Size does matter (I): Sensitivity $\propto$ Telescope area.

  Size does matter (II): Angular resolution $\propto$ 1/Diameter.



Govind Swarup

- An "Interferometer": 30 antennas, 45m diameter, Y-array with a maximum separation of 25 km.
- Collecting area: 30 antennas; Resolution: 25-km telescope!
- 5 frequency bands at 150, 233, 327, 610 and 1420 MHz.
- Most sensitive telescope in the world below 1 GHz!

# DARK MATTER DENSITY PROFILES ?

- Simulations predict that dark matter halos of galaxies have a universal "NFW" form, with $\rho(r) \propto 1/[r(a+r)^2]$.

  ⇨ At low $r$, a "cuspy" profile, $\rho(r) \propto 1/r$

  (Navarro et al. 1997, ApJ)

- Can test this by mapping HI-21cm emission from gas in galaxies, to obtain the circular velocity ("rotation curve") as a function of distance from the galaxy centre.

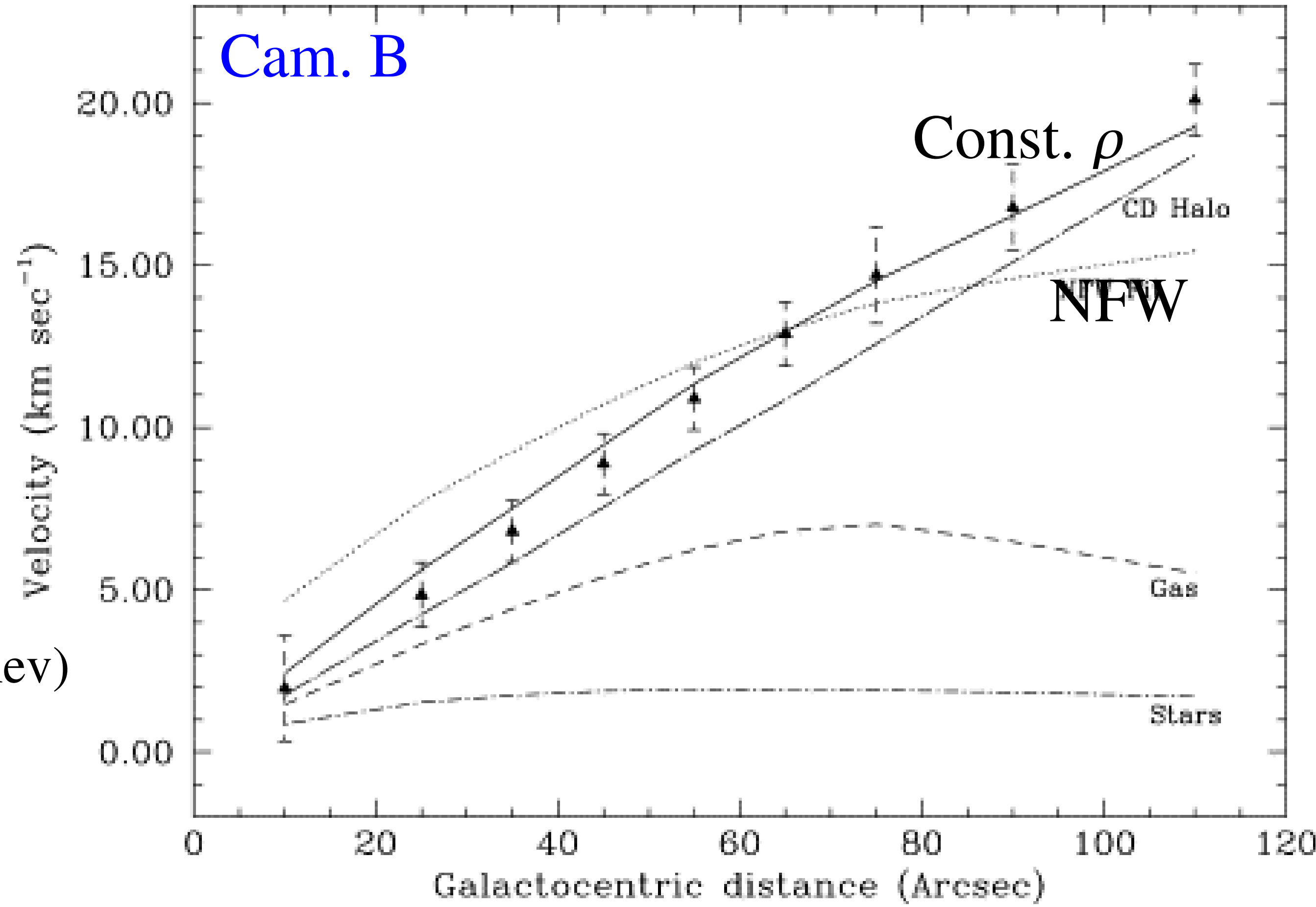
- Dwarf galaxies especially good for searches for density cusps, as their baryonic fraction at low $r$ is very small.

  (Begum, Chengalur et al.)

# DARK MATTER DENSITY PROFILES ?

- Faint Irregular Galaxy GMRT Survey (FIGGS): Large sample of faint dwarf galaxies. (Begum, Chengalur et al.)

- A cuspy halo does *not* give a good fit for Cam. B, or a few other dwarfs.
(Begum et al. 2003, New Astr. Rev)




- Could stellar explosions modify the density profile by dumping energy in the centres of dwarfs ?
(Governato et al. 2010, Nature)

# WHERE DO WE GO FROM HERE ?

- Upgrading the GMRT: the eGMRT!
- Increasing collecting area: More antennas!
- Increase baseline length: Better angular resolution OR More antennas at short baselines: low surface brightness HI emission (e.g. at $z \sim 1.4$).
- Wide field of view: Focal plane arrays at 610 MHz. Large-area surveys for HI at $z \sim 1.4$.
- Larger bandwidth: 400 MHz (32 MHz today).
- New receivers: Uniform frequency coverage 0.15 – 1.5 GHz