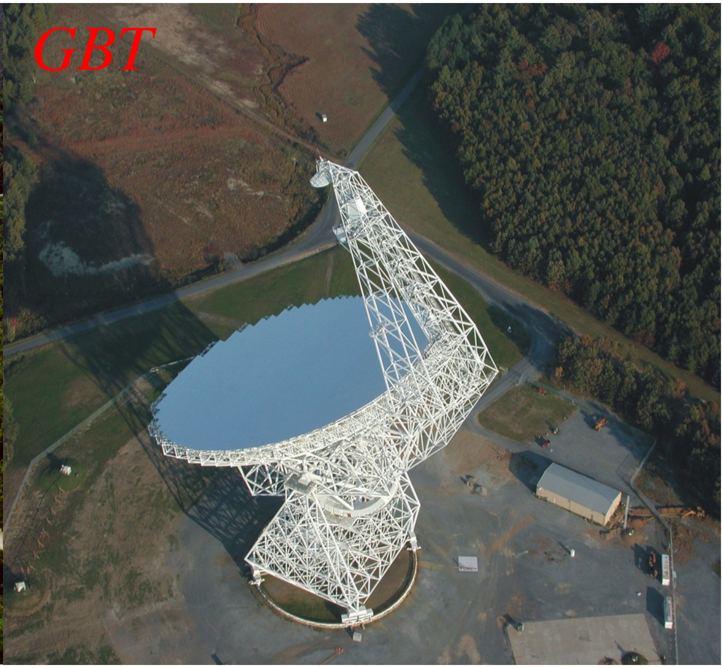
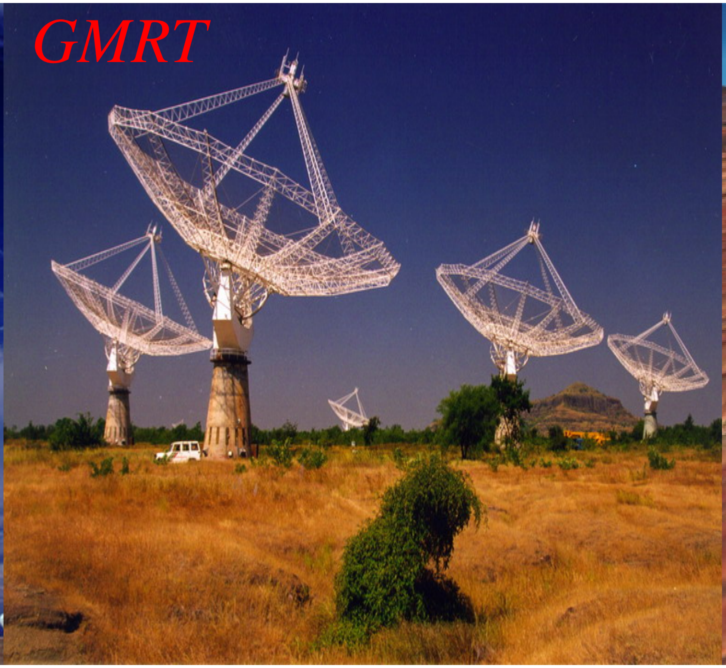
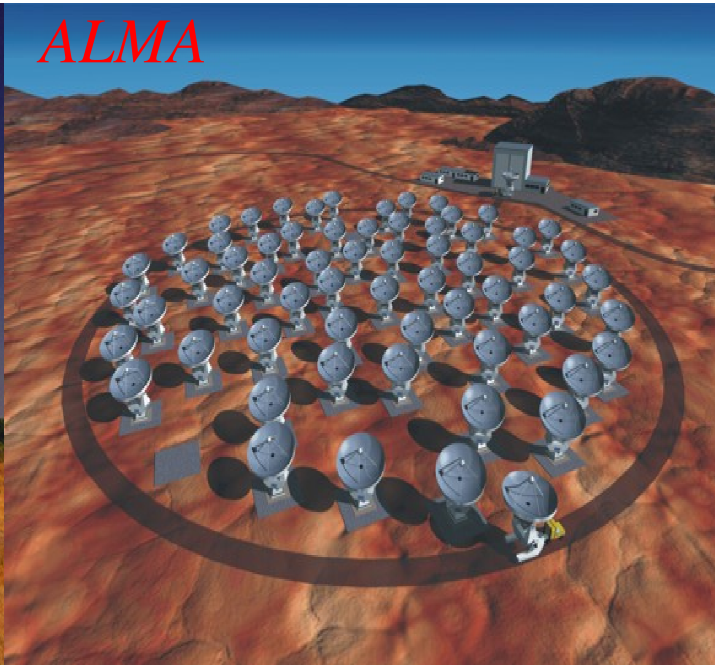
Science at Radio Frequencies

Nissim Kanekar *(NCRA-TIFR)*



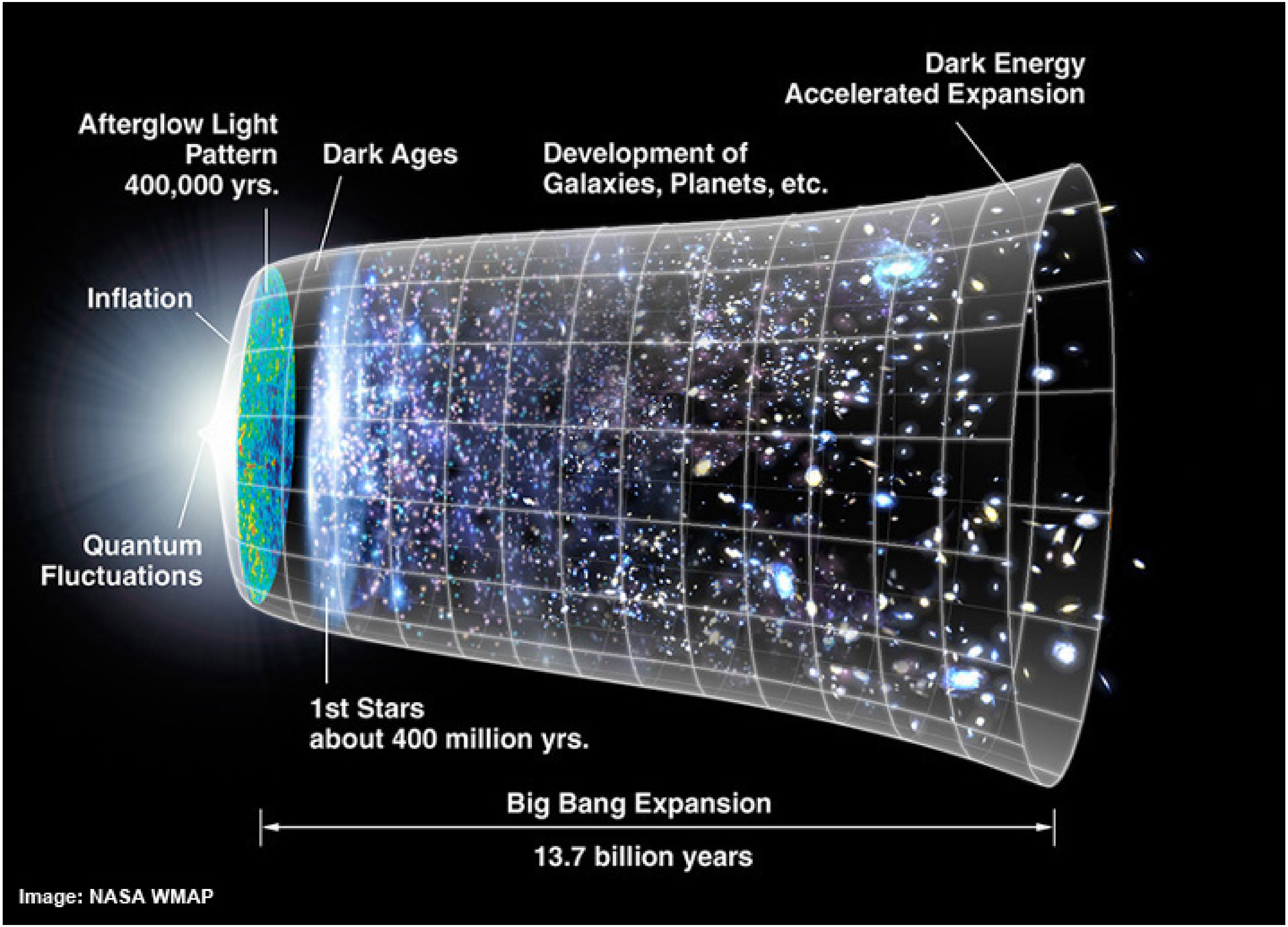




OUTLINE

- Theme: Probes of general relativity and cosmology.
- The Cosmic Microwave Background.
- HI-21cm imaging studies: Rotation curves and dark matter.
- Water megamasers: The distance scale of the Universe.
- Pulsar timing studies: Tests of general relativity.
- Radio astronomy of the next decade.

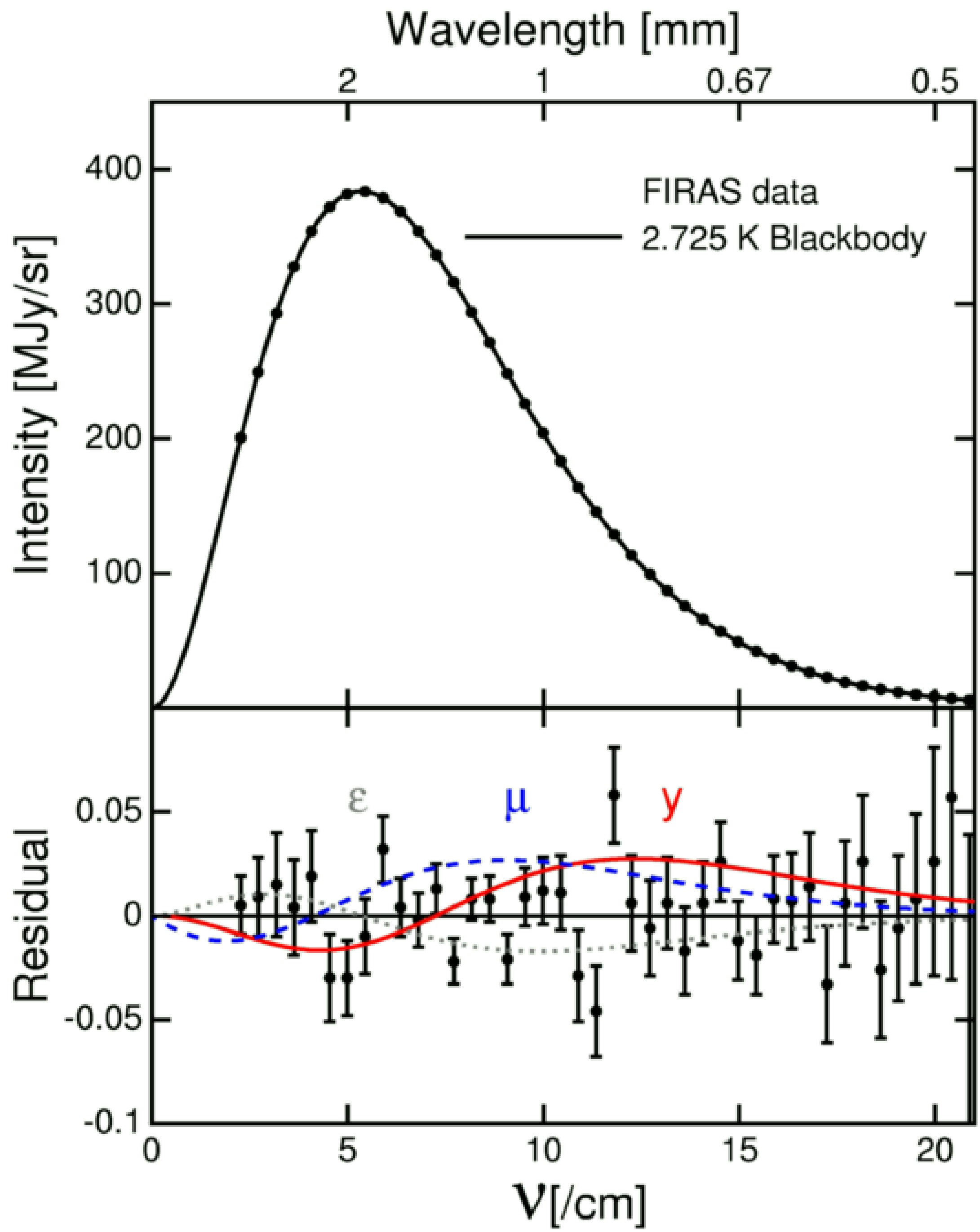
A Brief History of (Nearly) Everything



(Courtesy: NASA)

Cosmic Microwave Background

- Universe ionized at $z > 1100$
  ⇨ Radiation "trapped" by scattering off electrons.
- After recombination, few electrons: radiation free-streams away. Predicted to be visible in all directions, with T ~ 5 K!
  (Alpher & Hermann 1948; Gamow 1948)
- Detected by Penzias & Wilson in 1964, with T ~ 2.7 K: Strong evidence for a homogenous, isotropic Universe!
  (Penzias & Wilson 1965)
- $T_{CMB} = 2.725 \pm 0.004$ K
  (Mather et al. 1994)
- Best known black body in the Universe!



(Mather et al. 1994)

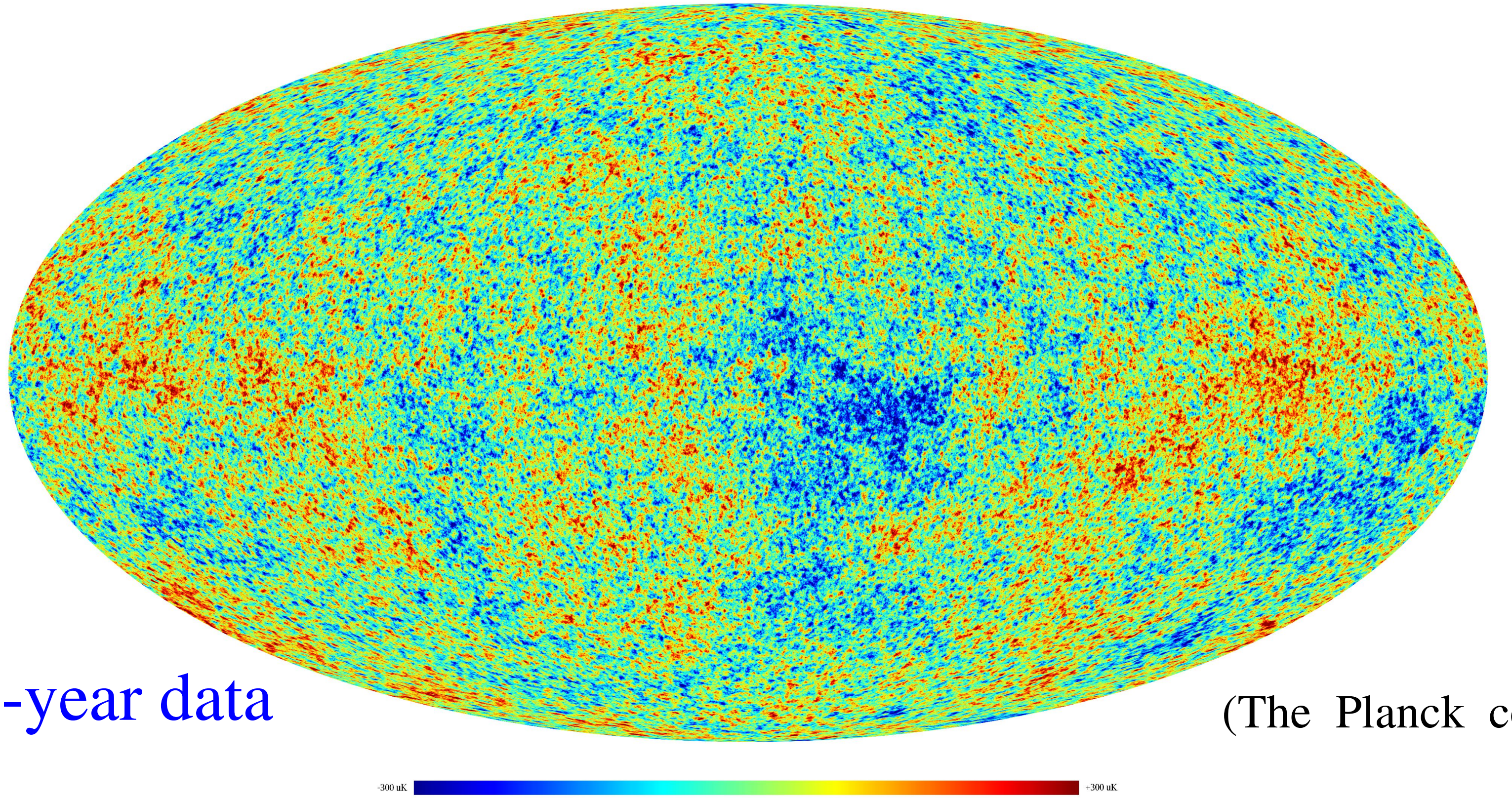
CMB ANISOTROPIES

- Anisotropies in the CMB trace density inhomogeneities at the epoch of recombination ! First detected by the COBE satellite in 1992!

(Smoot et al. 1992)

- Today: Detailed modelling of CMB anisotropies gives the best constraints on the cosmological model (e.g. WMAP, Planck...).

- -200 μK – +200 μK: Extremely low anisotropies, 1 part in 10,000!

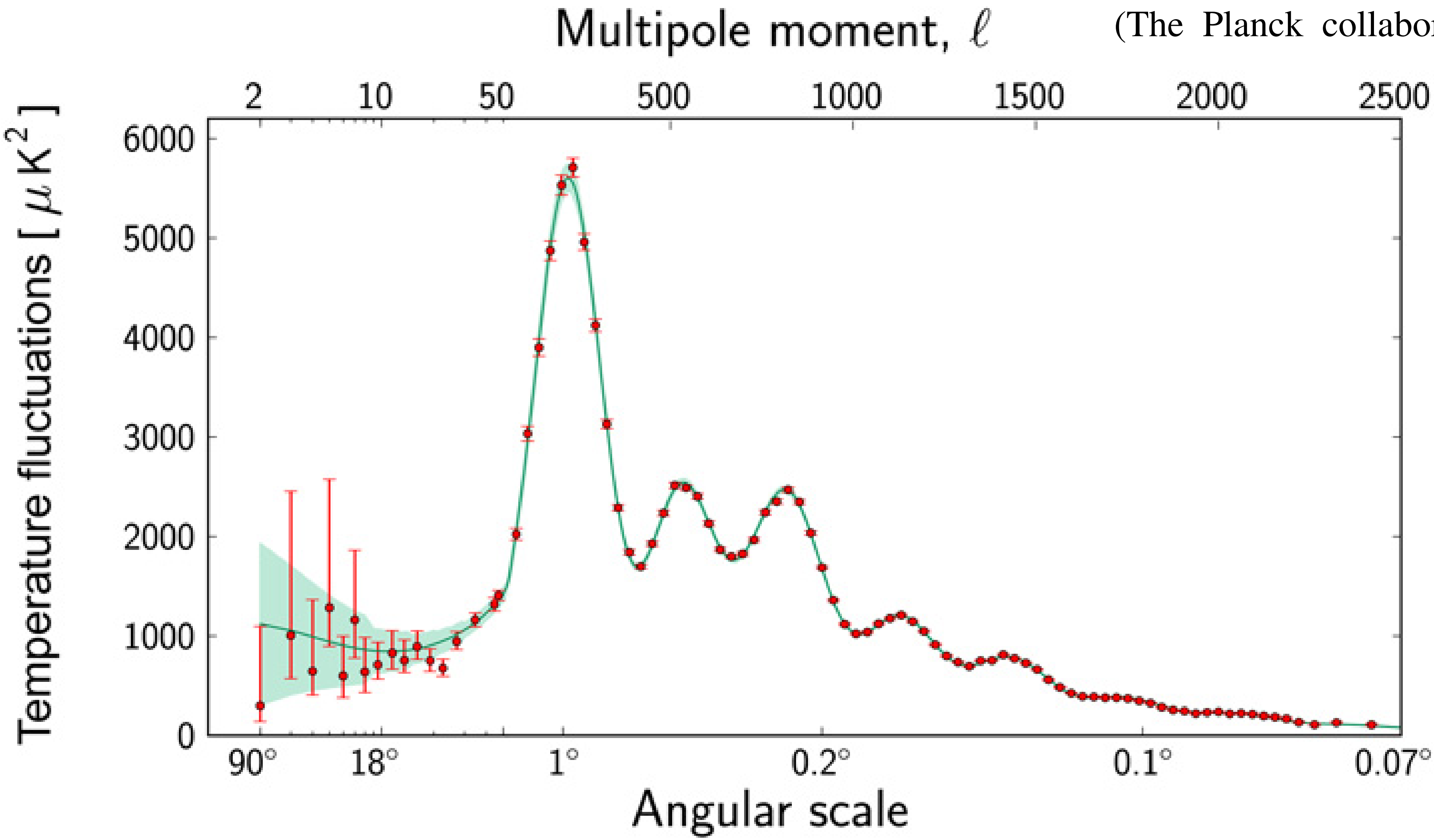


Planck 2-year data

(The Planck collaboration)

CMB ANISOTROPIES

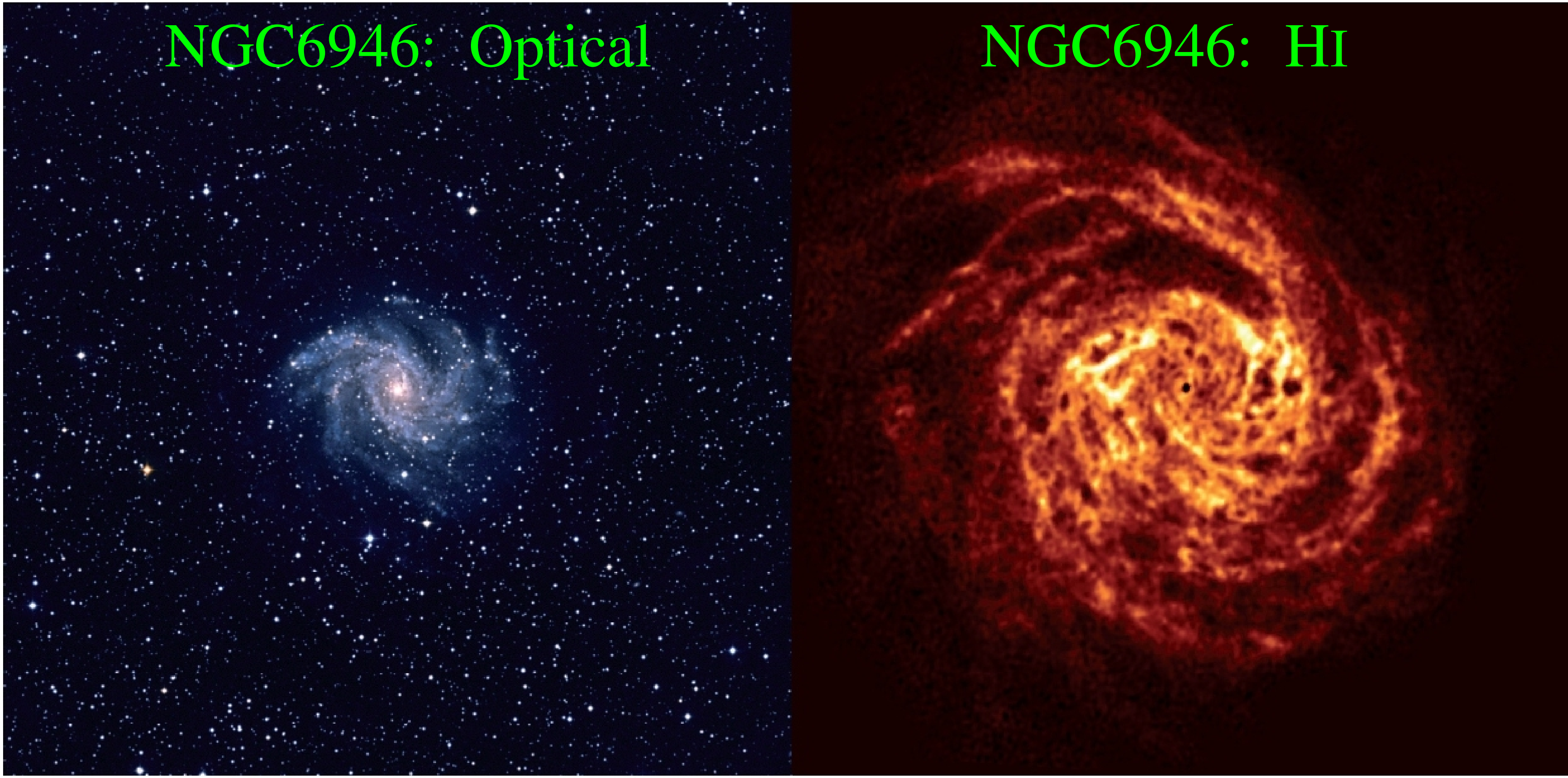
(The Planck collaboration)



- "Acoustic" peaks, due to oscillations in the photon-baryon fluid!

- Precision cosmology! A flat ΛCDM model gives an excellent fit:
  $H_0 = 67.3$ km/s/Mpc, $\Omega_{baryon} = 0.05$, $\Omega_{DM} = 0.27$, $\Omega_{DE} = 0.68$, $w=-1$.

Gas in Galaxies: Why Do We Care ?



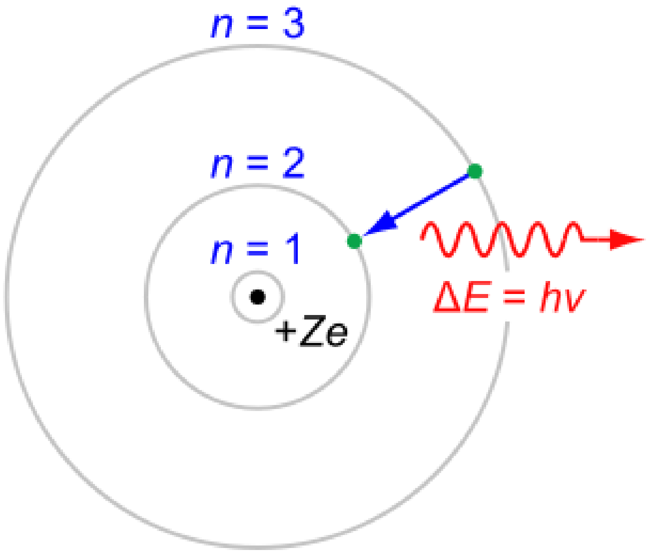
(Boomsma, Ph.D. thesis)

- Gas in galaxies is typically more widespread than stars.

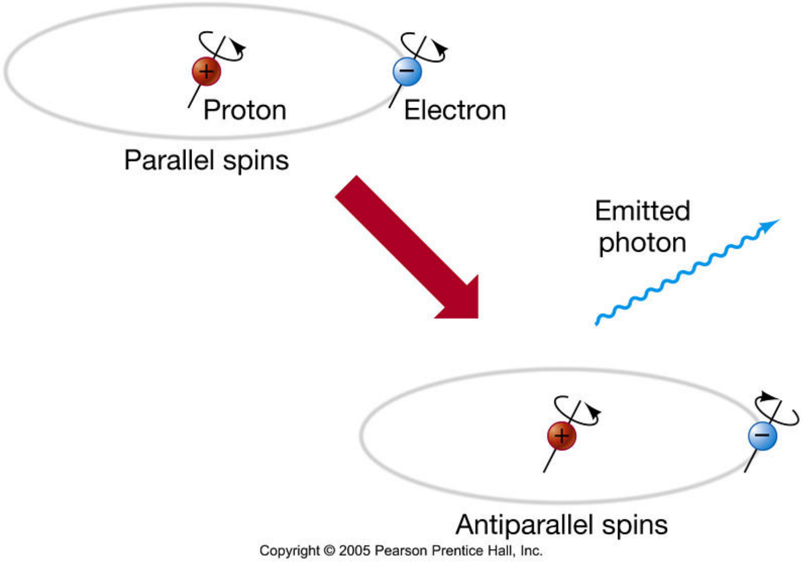
- Spectroscopic studies of the atomic gas are sensitive to the gas kinematics and, hence, to the large-scale galaxy dynamics.

Spectral Lines in Atomic Hydrogen

"Rydberg states"



"HI-21cm Hyperfine line"



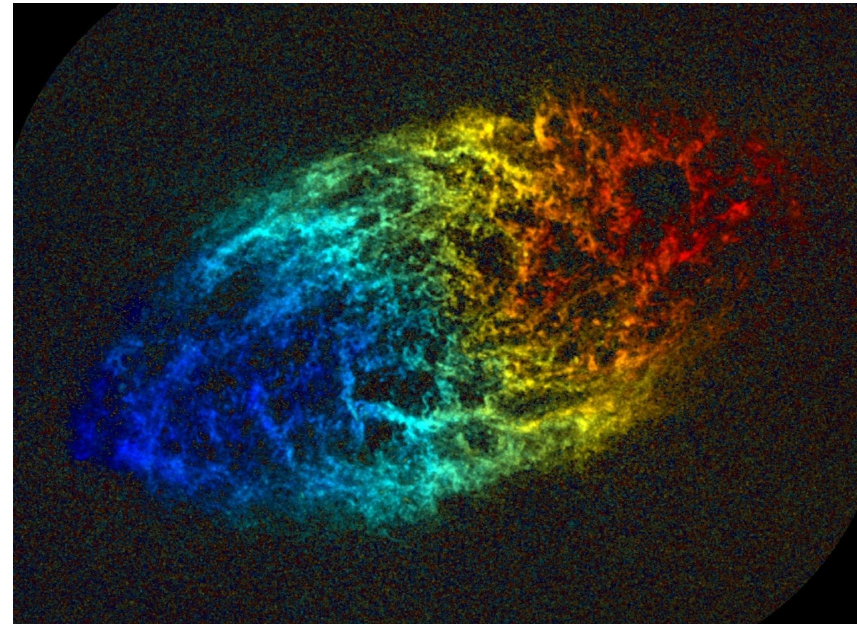
(Courtesy: NRAO)

- Strong electric dipole lines:
  A-coefficient, $A_{21} \sim 10^{8}\ s^{-1}$.
- UV, optical frequencies:
  $(h\nu/k) \sim 10^5$ K ⇨
  $(n_2/n_1) \approx 0$!

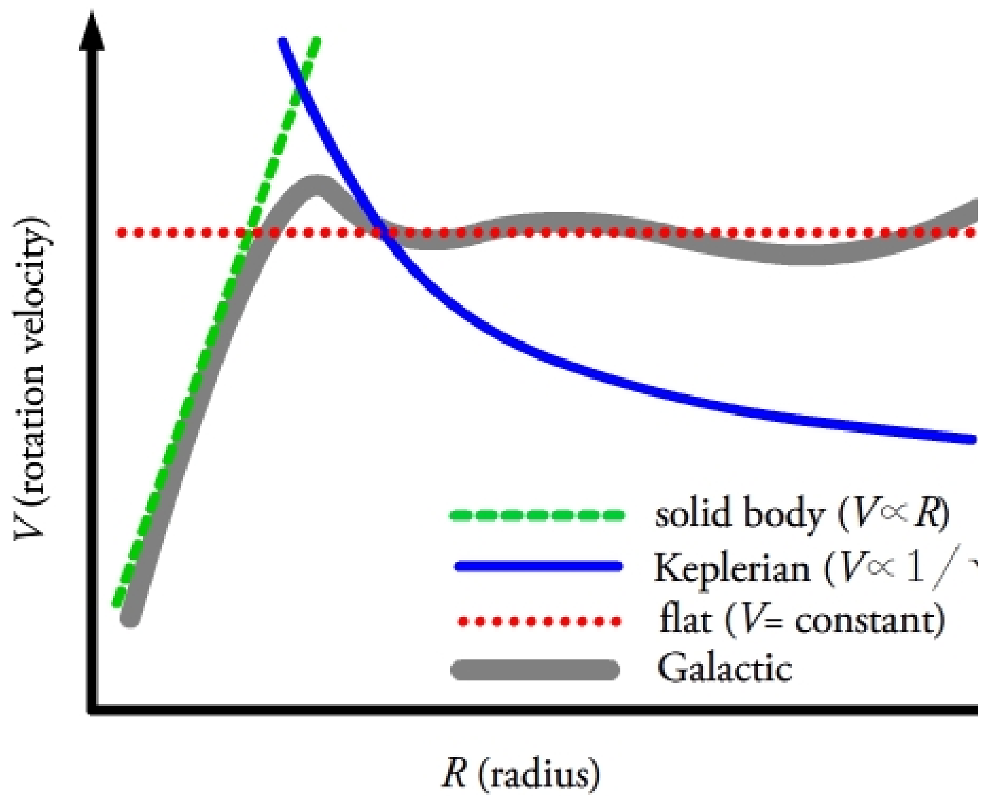
- Weak magnetic dipole lines:
  A-coefficient, $A_{21} \sim 10^{-15}\ s^{-1}$.
- $\nu = 1420.40575$ MHz:
  $(h\nu/k) \sim 0.07$ K ⇨
  $(n_2/n_1) \sim 3 \times [1 - 0.07/T_s]$

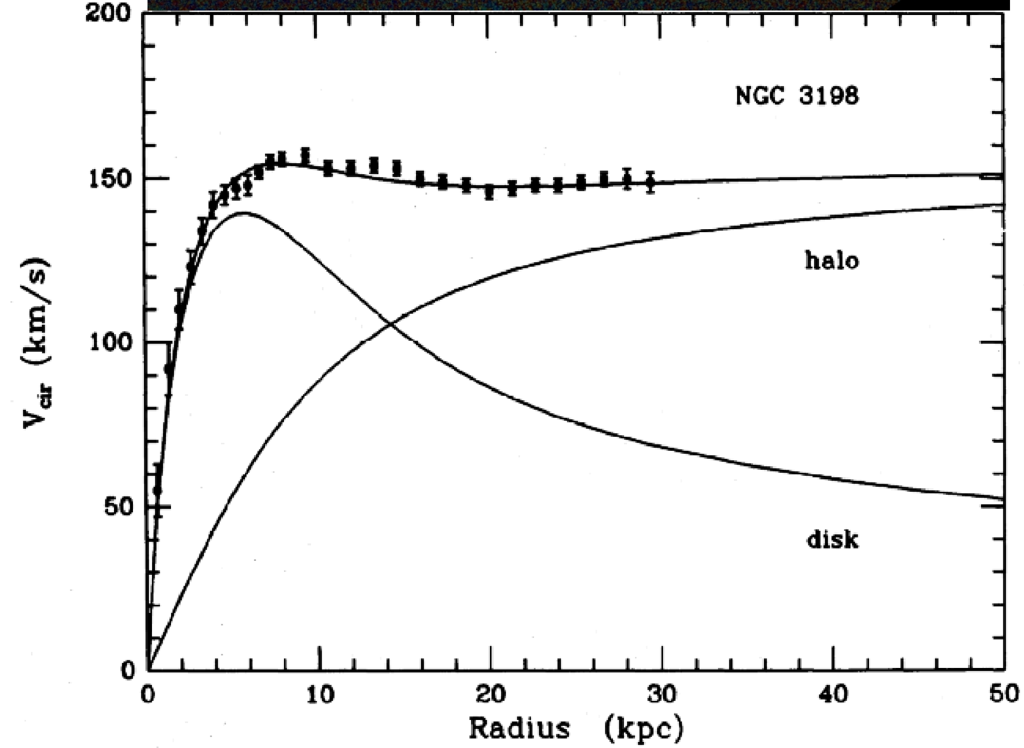
- The weakness of the HI-21cm line is actually its strength!

Galaxy Rotation Curves



- For circular orbits of gas/stars in a rotating galaxy:
  Rotation velocity, $V = [GM/R]^{1/2}$.
  ⇨ $V \propto R^{-1/2}$ at large R, as most mass is in the inner regions.

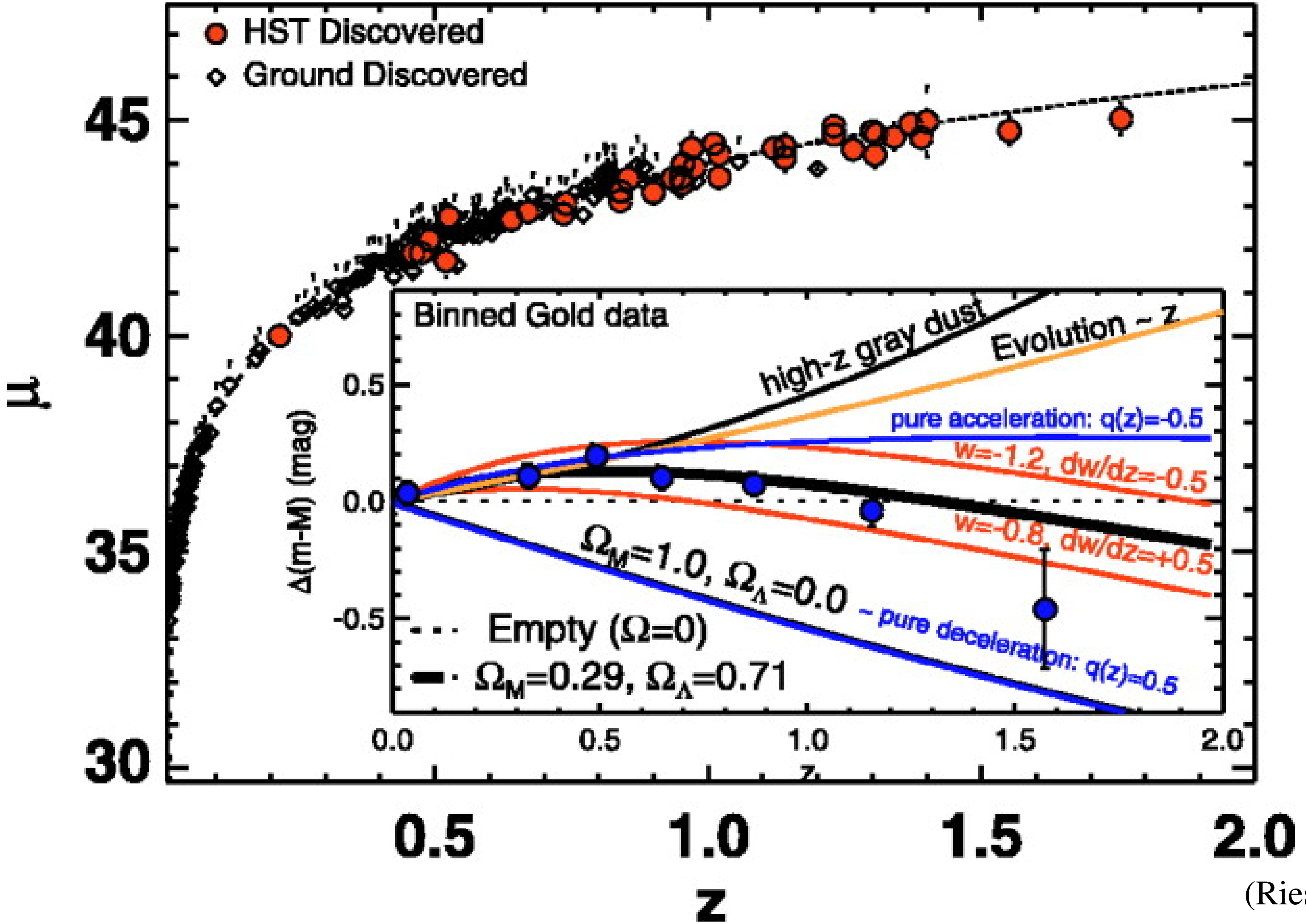




But,... Flat rotation curves ⇨ Mass increases with radius!

⇨ Dark Matter! Non-baryonic!!!

The Cosmological Distance Scale



(Riess et al. 2007)

- High-z type Ia supernovae are *dimmer* than expected from their redshift, for a flat Universe with no dark energy!
  ⇨ Larger distances! ⇨ Requires an *accelerating* Universe!

THE COSMOLOGICAL DISTANCE SCALE

- Estimates of cosmological distances require bright standard candles, objects of known luminosity that can be detected at high distances. E.g. Cepheid variables, type Ia supernovae, ...

- The distance estimates have to be built from multiple candles: e.g. Cepheid variables can be detected in the Milky Way and nearby galaxies, but not at high redshifts; Type Ia supernovae are rare in the nearby Universe, but can be detected at high redshifts.

- First calibrate the luminosity of Cepheids by observing them in nearby galaxies. Then search for Type Ia supernovae in galaxies that are intermediate in distance so that one can detect Cepheids in them. Galaxies with Type Ia supernovae are then monitored to search for Cepheids, to measure their distance and calibrate the Type Ia supernova luminosities.

- The final error on the Type Ia supernova distances thus depends on the Cepheid calibration! This is the dominant source of error.

H_2O MEGAMASERS: THE DISTANCE SCALE

- 22 GHz water megamasers arise in accretion disks that rotate around the central black holes of bright active galactic nuclei.

(e.g. Claussen et al. 1984)

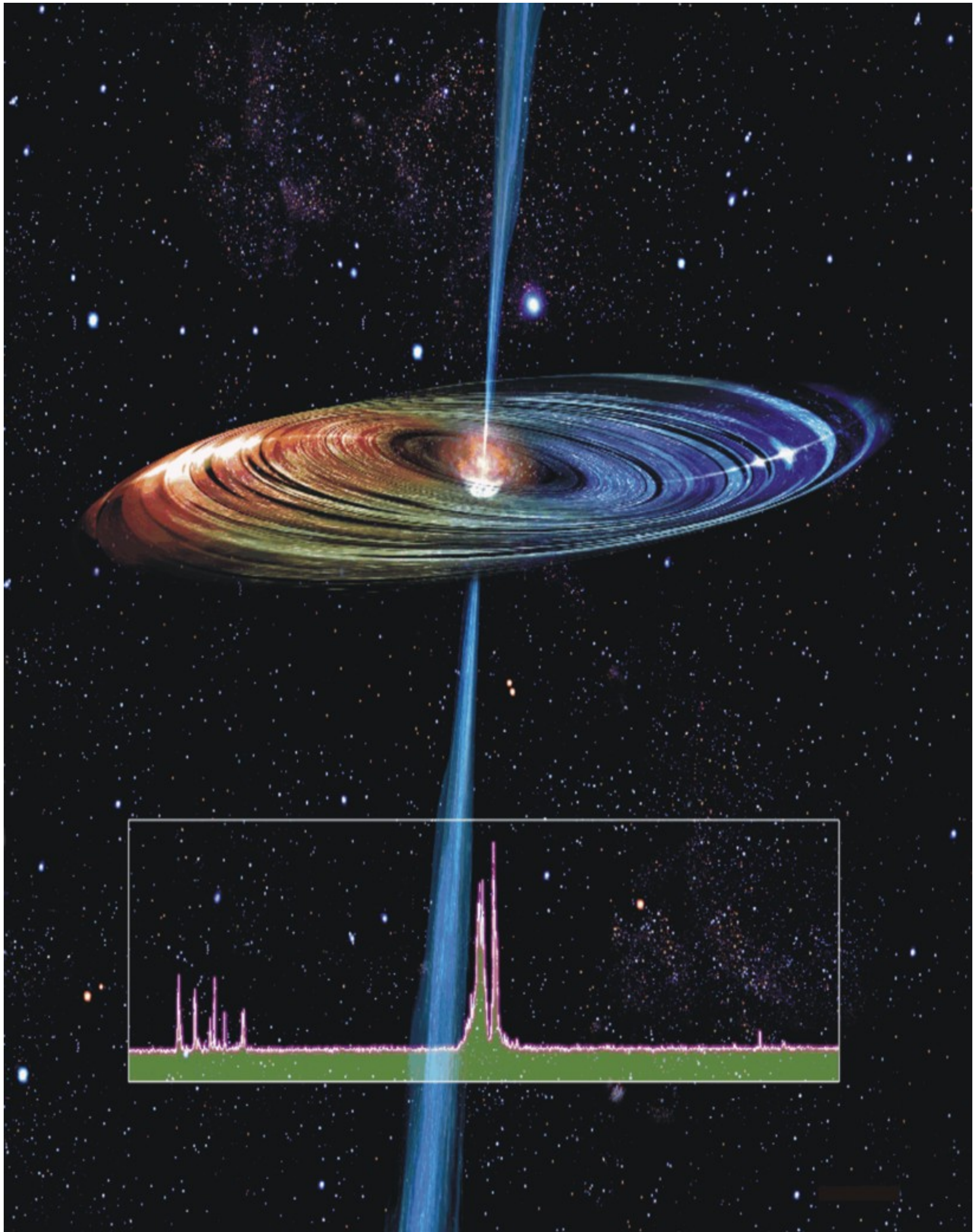
- VLBI studies: The megamaser emission consists of multiple lines, each arising from small regions (of size ~ 0.1 pc) in the disk. The line velocities trace the disk rotation!

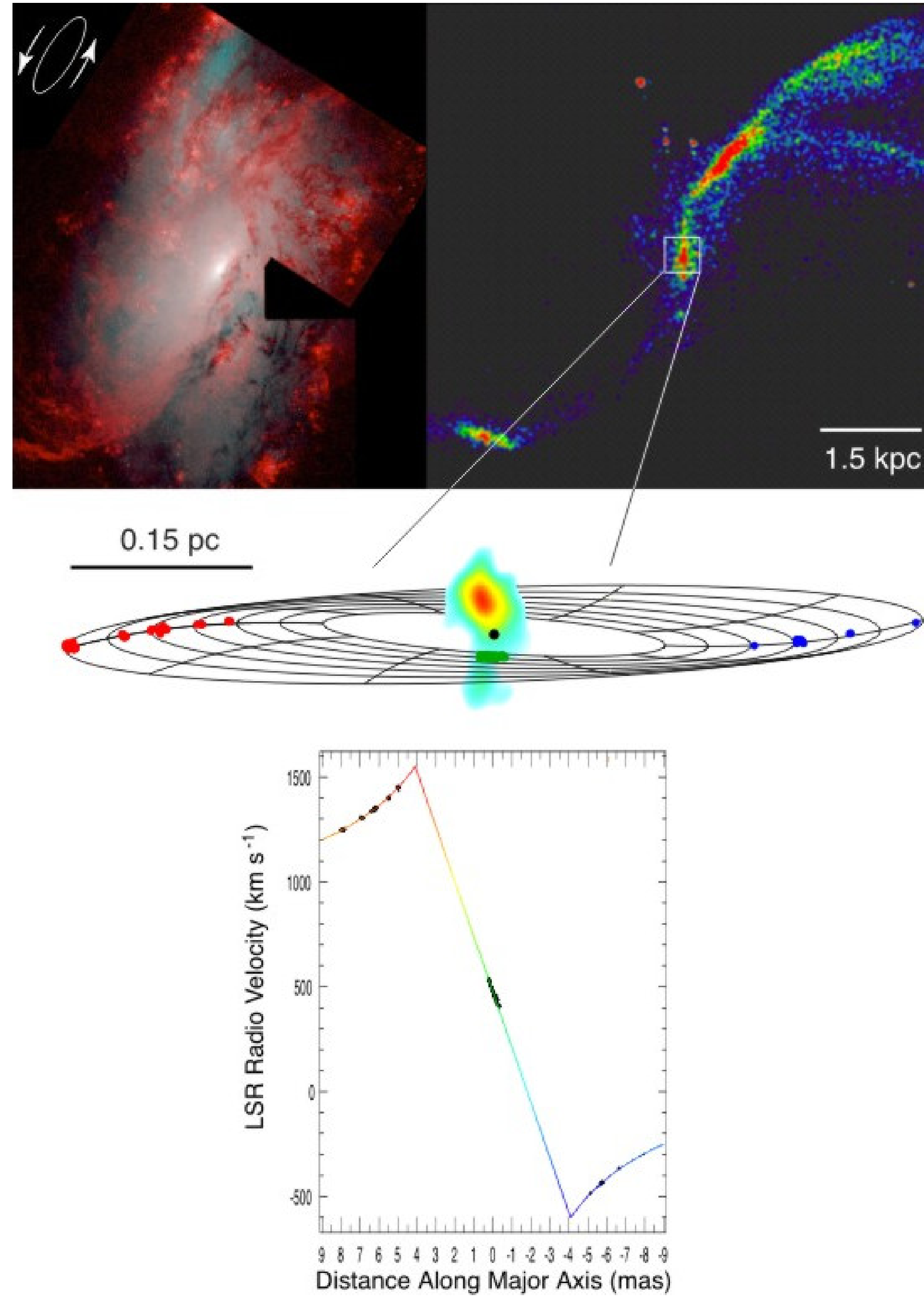
(e.g. Haschick et al. 1990)

- The H_2O megamasers in NGC4258: Lovely Keplerian rotation!!! Very slight warp in the disk!

(Moran et al. 1995)

H_2O MEGAMASERS: THE DISTANCE SCALE





(Courtesy Mark Reid and NRAO)

H_2O Megamasers: The Distance Scale

- VLBA monitoring of the H_2O megamasers in NGC4258 with angular resolutions of 0.2 mas, along with GBT monitoring to measure the accelerations of different lines: Map the rotation of the megamasers and determine their distance from the central black hole. From the measured angular distance, determine the distance of NGC4258 from us: 7.60 ± 0.22 Mpc (3%!).

  (e.g. Moran et al. 1995; Herrnstein et al. 1999; Humphreys et al. 2013)

- Detect Cepheids in NGC4258: Calibrate the Cepheid scale to 3%!
  ⇨ Measure both H_0 and Type Ia supernovae distances to 3%!

  (e.g. Riess et al. 2011; Humphreys et al. 2013)

- *En passant*, measure the black hole mass: $4 \times 10^7 \, M_\odot$!

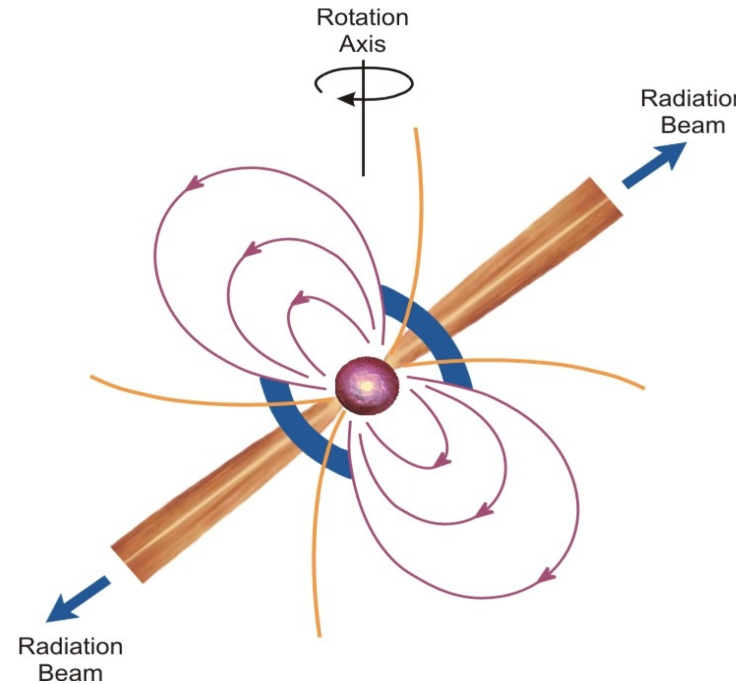
  (e.g. Moran et al. 1995; Humphreys et al. 2013)

- Megamaser Cosmology Project: 72 megamasers, 17 BH masses!
  Hubble constant, $H_0 = 69.0 \pm 3.8$ km/s/Mpc (preliminary).

  (e.g. Reid et al. 2013)

Pulsars: Testing GR via Timing Studies

- Pulsars are rotating neutron stars, detected as a stream of regular pulses (period ~ 1.4ms – 8s) as the lighthouse beam sweeps across us.



- Pulsar timing studies: Measure the time of arrival of each pulse, relative to the average pulse profile. Predict the times of arrival, based on a model of the pulsar, the measured period and the period derivative, the location and mass of a possible companion, etc.

- The differences between the model and observed times of arrival are called the pulsar timing residuals. These contain the signature of any unmodelled systematic effects (e.g. arising from deviations from General Relativity).

Pulsars: Testing GR via Timing Studies

- Binary neutron stars: Different orbital/spin parameters in GR and other theories. Can also generally test for deviations from Keplerian motion. So far, results match GR predictions to within 0.1% ! Best current pair: the double pulsar, 0737-3039A/B.

  (e.g. Kramer et al. 2006)

- Pulsar Timing Array: Possible to indirectly detect a background of gravitational waves (GWs) by regular timing of a network of (> 20) milli-second pulsars over ~ 10 years. This is because a GW passing over the earth would produce a correlation between the timing residuals in different pulsars. Coalescing black holes at the centres of galaxies are good candidates for detection.

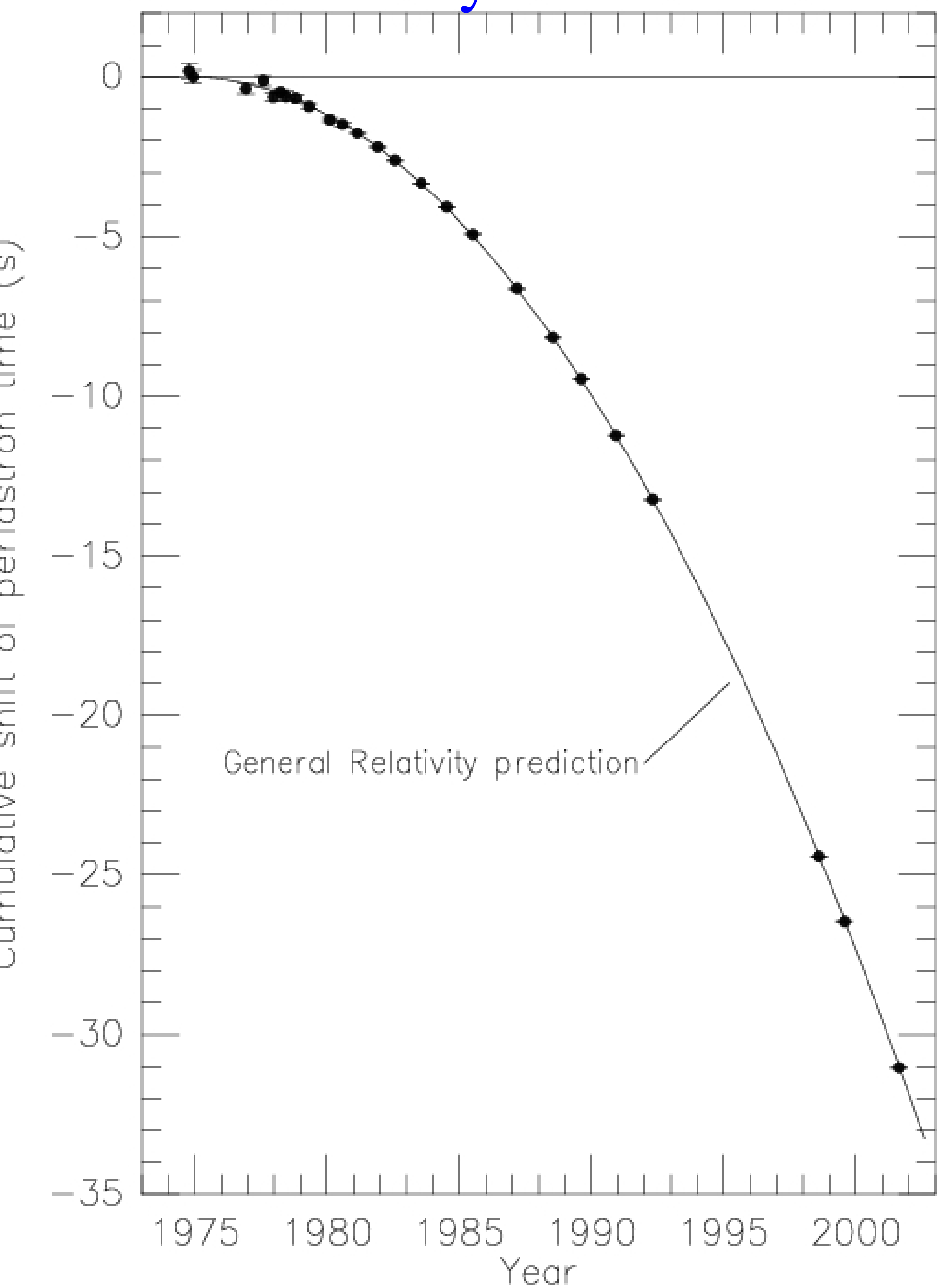
  (e.g. Manchester 2006)

- NS-BH companions: Measure mass & spin of the black hole, as well as deviations from GR in the strong-field regime ⇨ Searches for pulsars orbiting the Galactic Centre!

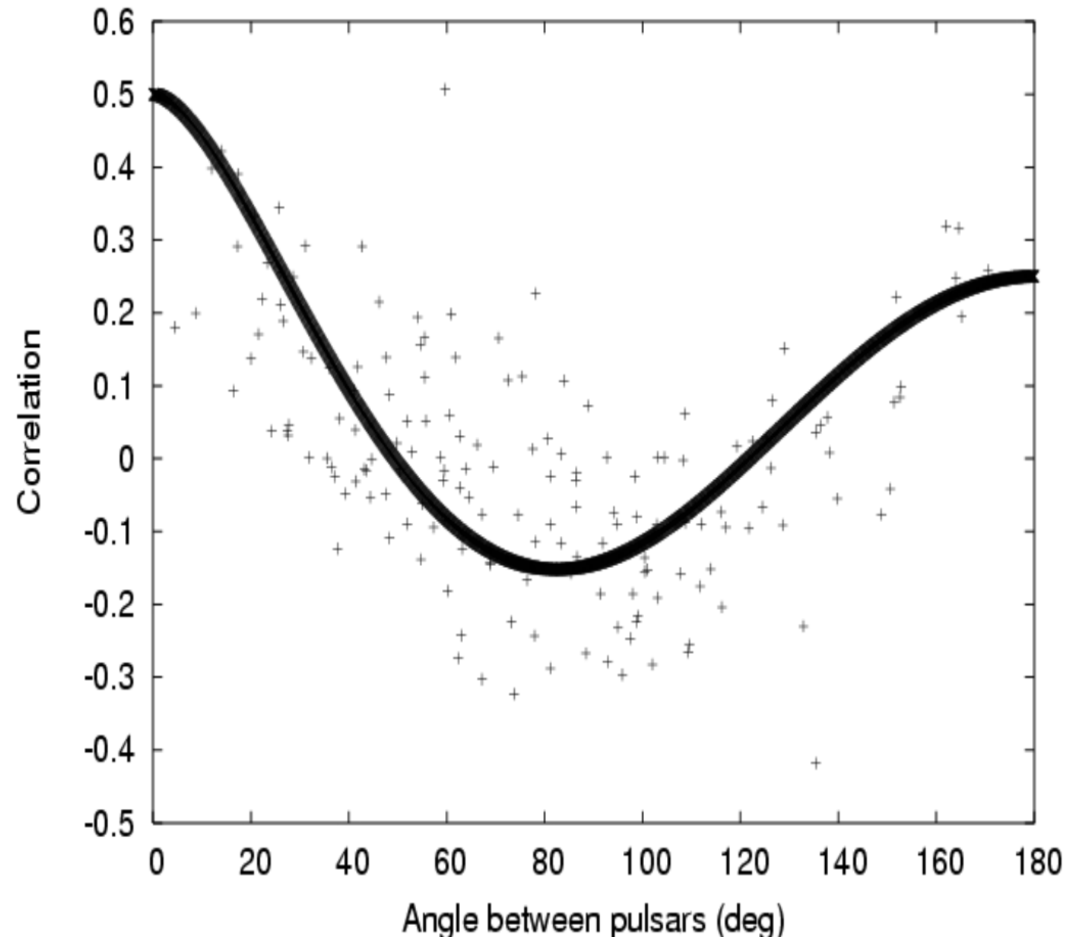
  (e.g. Macquart et al. 2010)

PULSARS: TESTING GR VIA TIMING STUDIES

Orbital decay for B1913+16.



(e.g. Weisberg & Taylor 2002)



Pulsar Timing Array: Correlation between timing residuals of different pulsars.

(e.g. Hobbs et al. 2009)

Radio Astronomy: Now and Tomorrow

- CMB: Evidence for the Big Bang! Precision cosmology today!
- HI-21cm galaxy velocity fields: Evidence for dark matter!
- H_2O megamasers: The cosmological distance scale!
- Pulsar binaries: Indirect detection of gravitational waves!

- Mapping HI-21cm emission from the Epoch of Reionization!
- Pulsars orbiting a black hole: GR in the strong-field regime!
- VLBI studies of emission at the event horizon of a black hole!
- Direct observations of planet formation around young stars!

ALMA imaging of gas disks around stars

- Gas being transferred from the outer disk of GG Tau-A to the inner disk ⇨ Longer lifetime for the latter! Planet formation!

Sub-mm Galaxies: A New Population

- 1997: Star formation rate peaks at $z \sim 1$, and then drops sharply at higher redshifts. Based on ultraviolet imaging studies.

- Ultraviolet light arises from massive stars, but can be obscured by dust; UV light is hence not a good SF tracer in dusty regions.

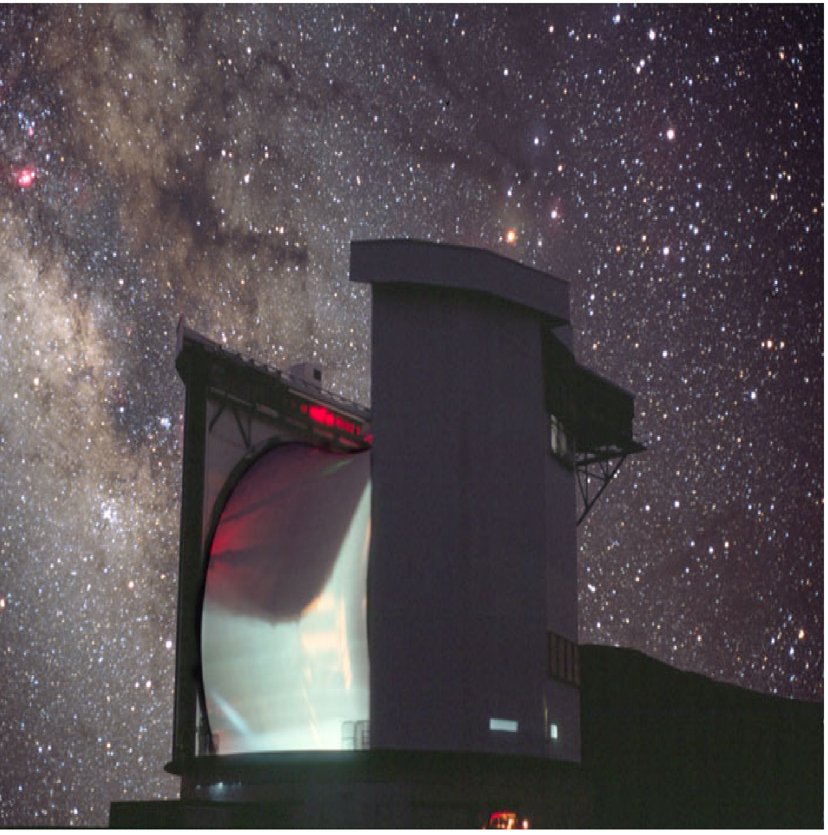
- The heated dust re-radiates in the far-IR bands. Dusty galaxies are hence very bright in the far-IR. If such galaxies are at high redshifts, the peak of the emission redshifts to the sub-mm band.

- Until the late nineties, there were no sub-mm telescopes! No idea that there are high-z galaxies where dust obscuration prevents the escape of almost all the optical/ultraviolet radiation!

(e.g. Blain et al. 2002)

- And then SCUBA came along...

SUB-MM GALAXIES

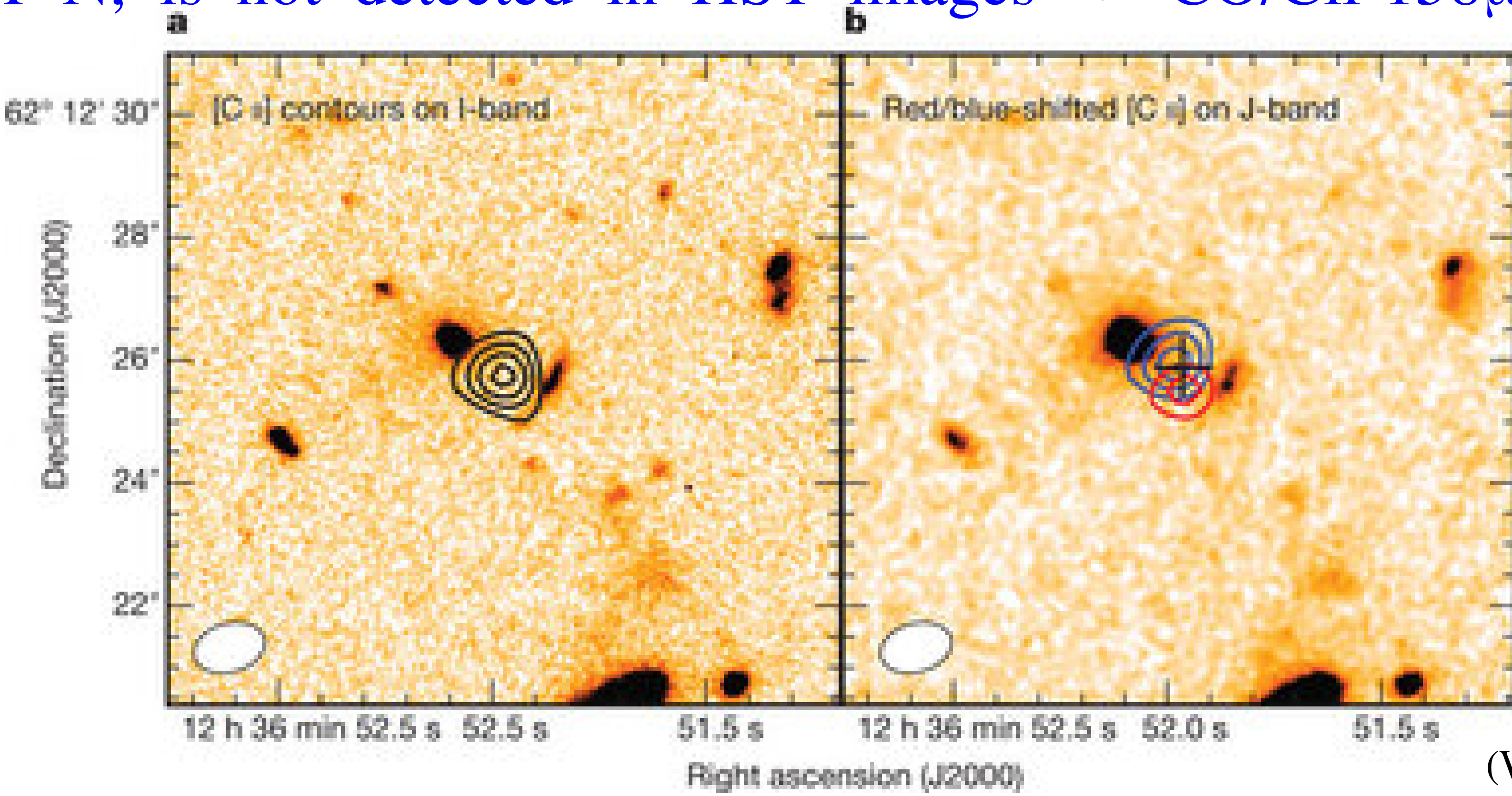


(Hopkins & Beacom 2006)

- JCMT-SCUBA surveys: Unknown population of UV-faint, starburst galaxies, identified as sub-mm galaxies (SMGs). Massive galaxies, rich in molecules and dust!
  (e.g. Hughes et al. 1998)
- SMGs dominate the star formation rate of the universe at $z > 0.7$!
  (e.g. le Fl'och et al. 2005; Hopkins & Beacom 2006)

SUB-MM GALAXIES (SMGS)

- Extremely high stellar mass, ~ 3.7×10^{11} $M_\odot$, molecular gas mass, $M_{MOL} \sim 3 \times 10^{10}$ $M_\odot$, and SFR ~ 1000 $M_\odot$ yr^{-1} !
- Detected out to $z \sim 5.2$! Could be a problem for the ΛCDM model if detected at higher redshifts!
- Hard to measure optical redshifts! HDF850.1, brightest SMG in the HDF-N, is not detected in HST images ⇨ CO/CII-158μm lines!



(Walter et al. 2012)

The Negative K-Correction for SMGs

(From Robert Decarli)

- Negative K-correction: As easy to detect an SMG at 1 – 3 mm at $z \sim 8$ as at $z \sim 1$!
- ~ 100 SMGs known at $z \sim 2 - 4$, with a few out to $z \sim 5$.

The Epoch of Reionization

- After recombination at $z \sim 1100$ until $z \sim 30$, the Universe contains mostly neutral hydrogen.

- *If* this neutral hydrogen is present between galaxies at $z \sim 0 - 3$, quasar spectra would show strong Lyman-α absorption at all wavelengths $\lambda < 1215.7 \times (1 + z_{QSO})$ ⇨ The Gunn-Peterson trough!

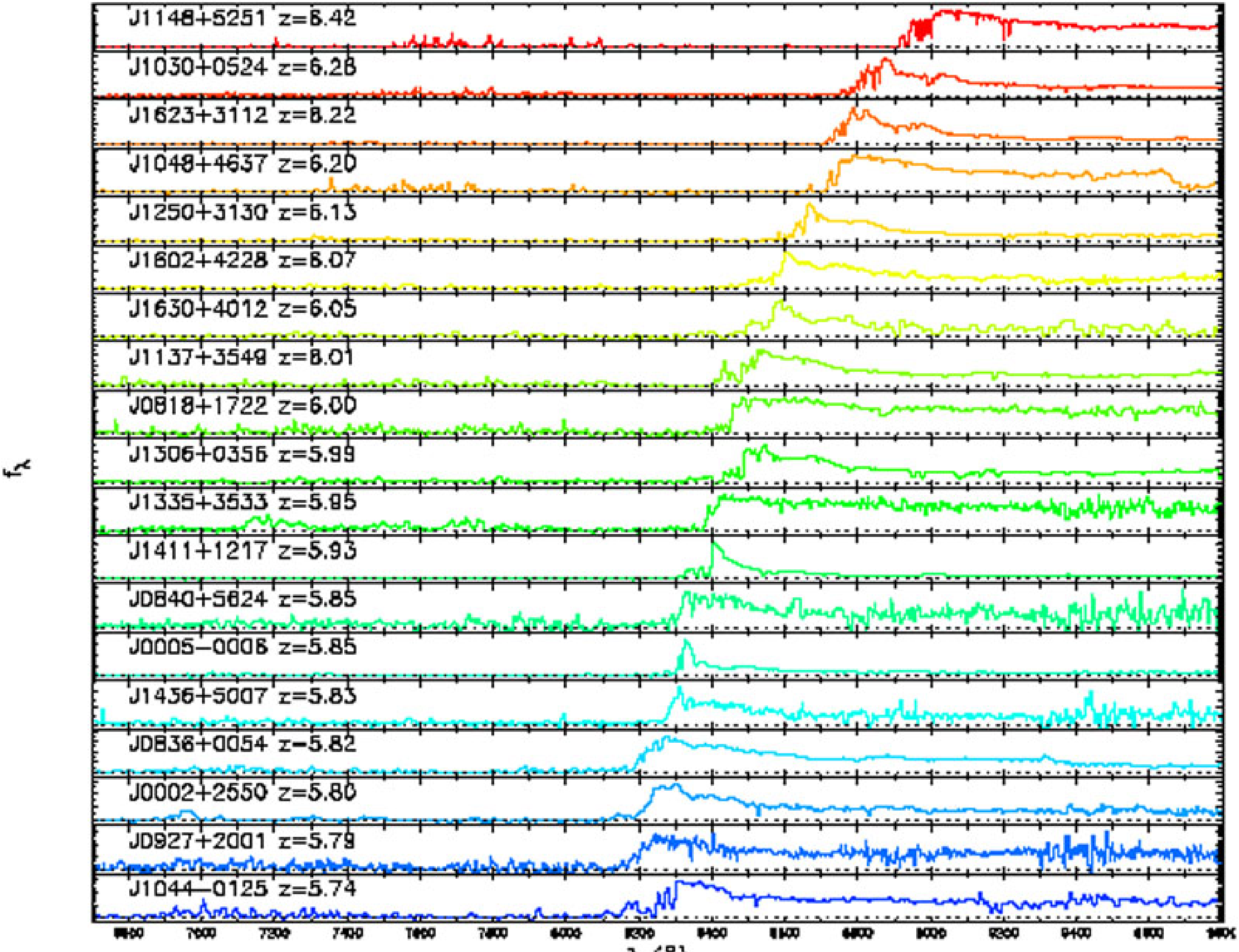
  (Gunn & Peterson 1965)

- Lack of Gunn-Peterson trough in quasar spectra at $z < 6$: Hydrogen between galaxies is mostly ionized at $z < 6$. Gunn-Peterson trough detected in quasar absorption spectra at $z >\sim 6$!!!

  (Becker et al. 2001; Fan et al. 2002)

- Reionization by UV photons from first stars/quasars at $z \sim 6.5 - 12$. Epoch of Reionization: The last phase transition in the Universe!

- Next frontier of cosmology: Multiple radio telescopes currently being used, built, or planned, to study the EoR! Includes the GMRT, LOFAR, MWA, PAPER, SKA...



(Fan et al. 2002, 2006)

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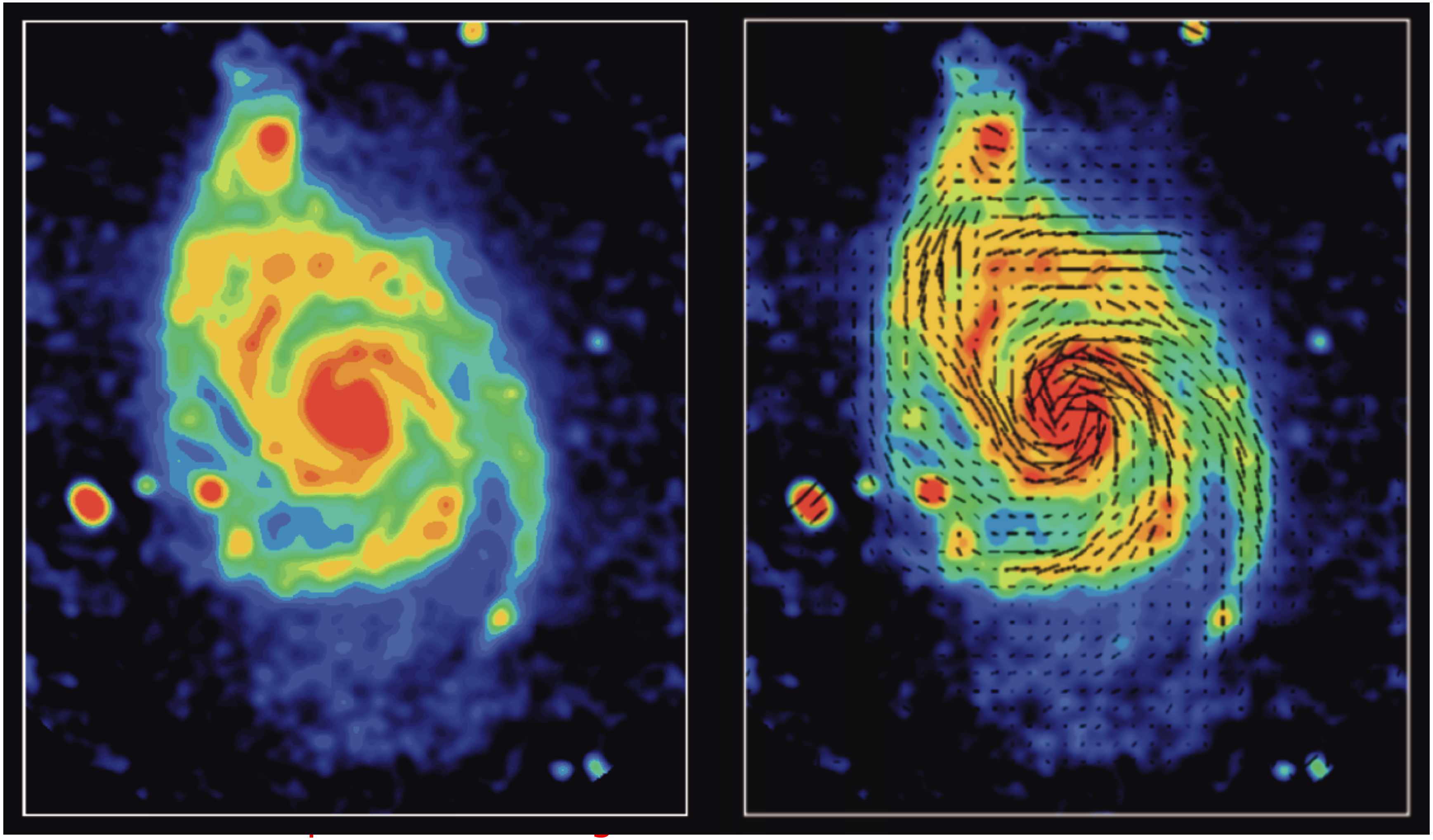
Magnetic Field Orientation in Galaxies



Radio Continuum

Beck, Horellou, Neininger

Lines=Magnetic Field Orientation

www.nrao.edu/imagegallery

(from Hibbard 2010)