Sterrenstelsels en Kosmologie

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Aim:

To provide a ‘complete’ and modern overview of our current knowledge of galaxies and cosmology


History of the Universe
PRESENT
SUN FORMS
5
HELIUM REIONIZATION
QUASAR ERA
11
FIRST GALAXIES
HYDROGEN
REIONIZATION
13
DARK AGES
BIG BANG
13.7 BILLIONS OF YEARS

Today

- Organization
  - Material, exercises, examination, schedule
- Overview (Schneider: Sect. 1.1 +1.2)
  - What is out there?
    - The Galaxy and galaxies
    - The multi-wavelength view of galaxies
    - Large scale structure: galaxies, voids
    - Distant universe
    - Active galaxies
  - Expanding universe
  - Early Universe
- Main questions to address
- Overview lecture series
- Homework 1.

Organisation

Material

Basic Book

- Peter Schneider: Extragalactic Astronomy and Cosmology, An introduction, Springer-Verlag 2006 (PS)

Background Books

- Binney and Tremaine: 'Galactic Dynamics' (BT)

Introduction into theory of galaxy dynamics, i.e. potential theory, orbits, distribution functions, equilibria, disks, mergers, etc.

Level of BT is very high (advanced Master course), but this means they remain useful throughout your career.

Stephen Serjeant: Observational Cosmology, Cambridge University press,
ISBN: 9780521192316, Publication date: September 2010 (SS)
Very new book. it covers a broad range of topics.

Handouts
http://www.strw.leidenuniv.nl/~rottgering/Site/Galaxies_lectures_2012.html

Opgaven

- zijn bedoeld om te zorgen dat de studenten de gegeven stof doornemen en kunnen checken of ze de inhoud begrepen hebben.
- het is de bedoeling dat de opgaven het volgen van het vak en het tentamen doen makkelijker maken.Het netto resultaat zou **tijdwinst** moeten zijn.
- Moeten worden ingeleverd bij het volgende college.
- Jesse is altijd bereid te helpen, maar ga voor het weekend naar hem toe.
- Niet tijdig inleveren: cijfer is een 1 (ongeveer 1/3 punt minder op uiteindelijke tentamen resultaat)
- Laat het me ***tijdig*** weten als het een keer voorkomt dat het maken van opgaven niet in jullie drukke schema past: we kunnen dan of een keer overslaan of een individuele regeling treffen.

Cijfer

- Cijfers voor de opgaven tellen mee voor 30 % voor tentamen cijfer

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7	13	nm1				SK	
8	20	nm1				SK	
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11	12	nm1				SK	
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14	apr 2	nm1				SK	
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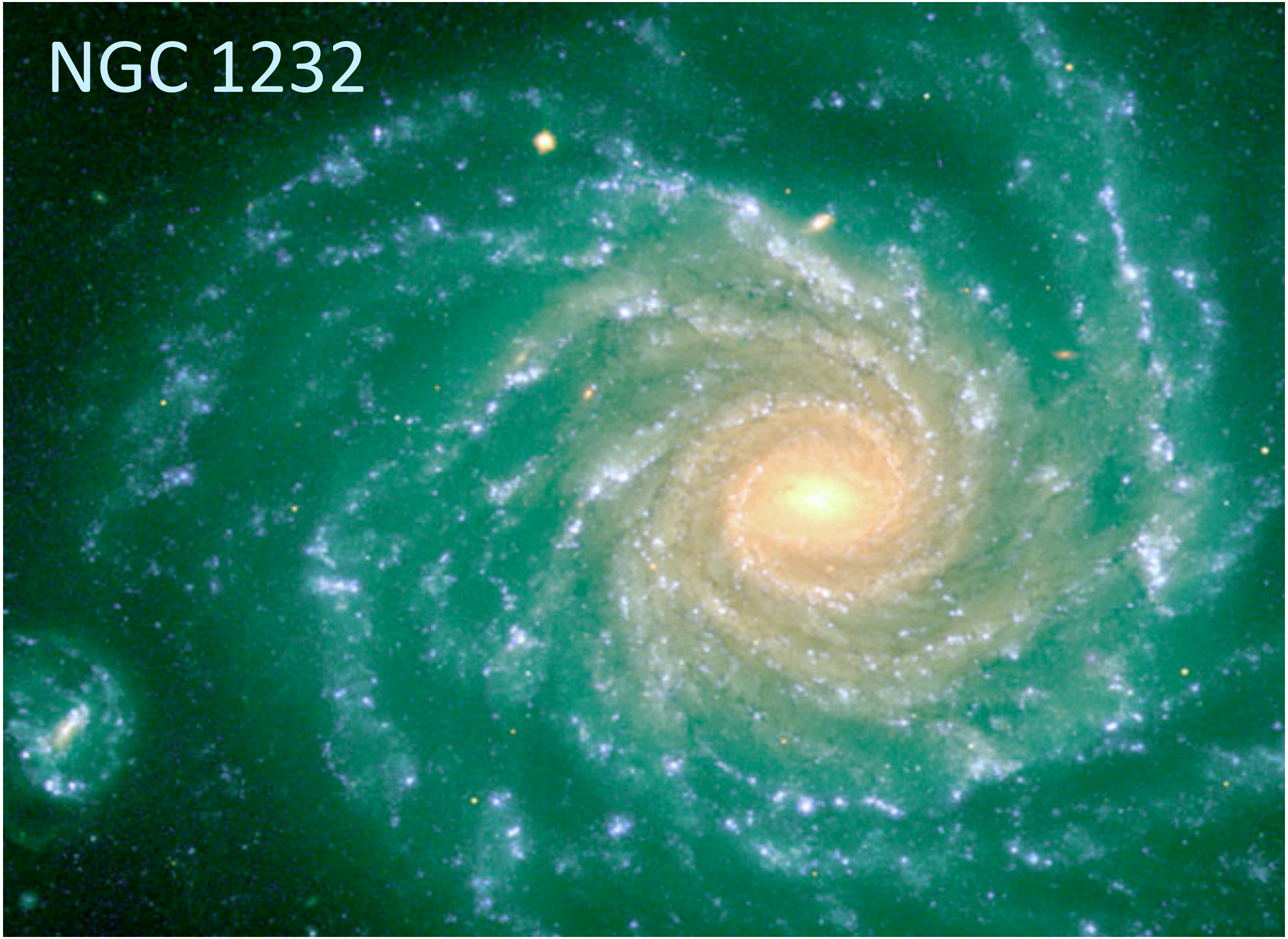
16	16	nm1				SK	
17	23	nm1				SK	
18	30	Koninginnedag					
19	mei 7	nm1				SK	
20	14	nm1				SK	
21	21	nm1				SK	

14 Lectures

- Overview (<u>Schneider: Sect. 1.1 +1.2</u>)
  - What is out there?
    - The Galaxy and galaxies
    - The multi-wavelength view of galaxies
    - Large scale structure: galaxies, voids
    - Distant universe
    - Active galaxies
  - Expanding universe
  - Early Universe

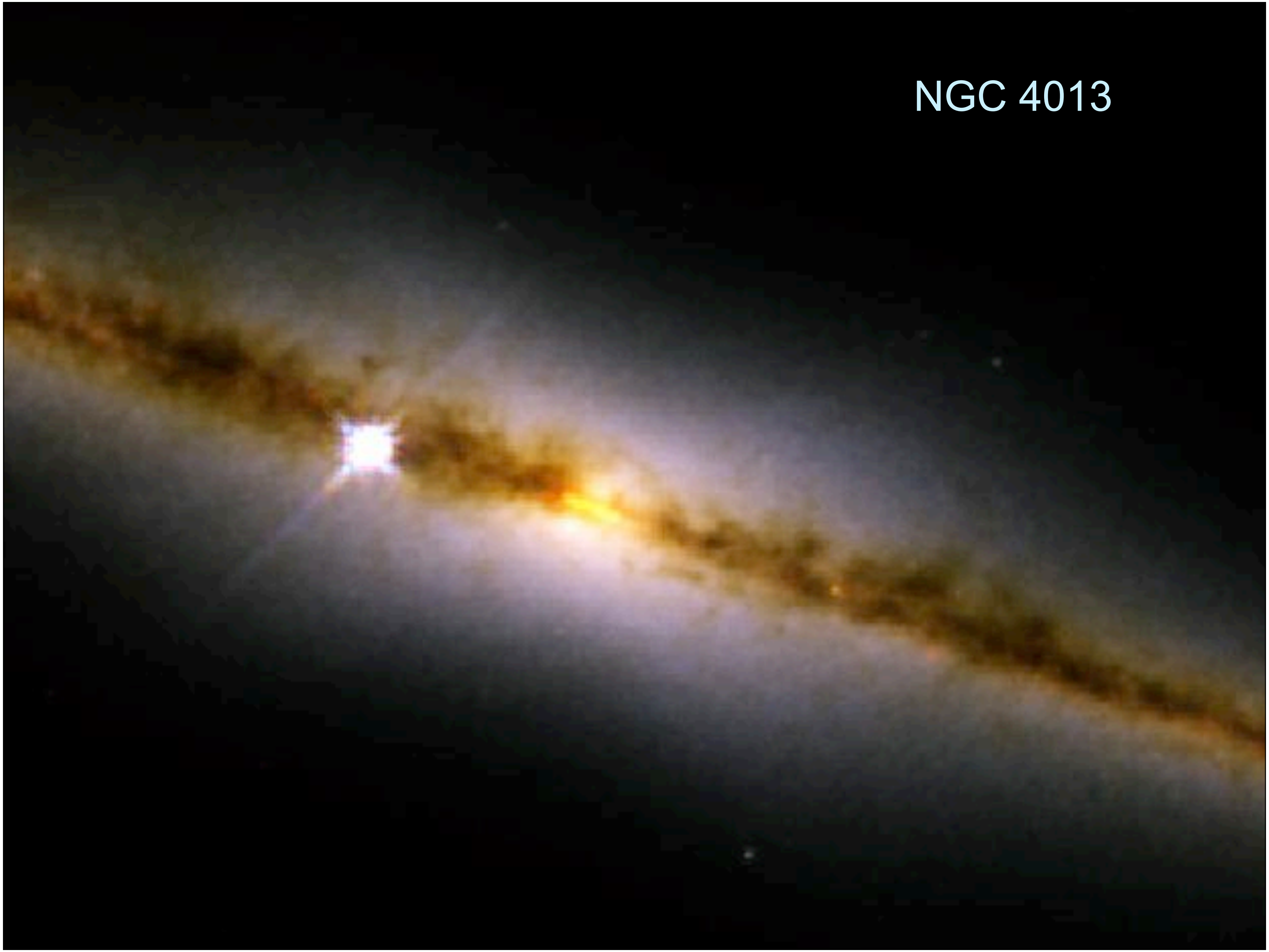
The Galaxy and galaxies

- A panorama of the Milky Way, as seen from Death Valley, 2005.
- see: http://en.wikipedia.org/wiki/Milky_Way


NGC 1232

Face-on spiral: NGC 1232

- VLT image: 6.8 x 6.8 arcmin, 60 kpc at 30 Mpc
- If this was our galaxy:
  - our sun at 8.0 kpc,
  - orbiting at ~220 km/s,
  - taking 230 million years
- bright blue knots: young stars
- patchy regions: absorption by dust in the Inter Stellar Medium (ISM)
- red glow: old stars, mainly in the bulge
- galaxy to the left: distorted companion galaxy


NGC 4013

NGC 4013

- observed edge-on by Hubble
- disk obscured by dust
- central bulge

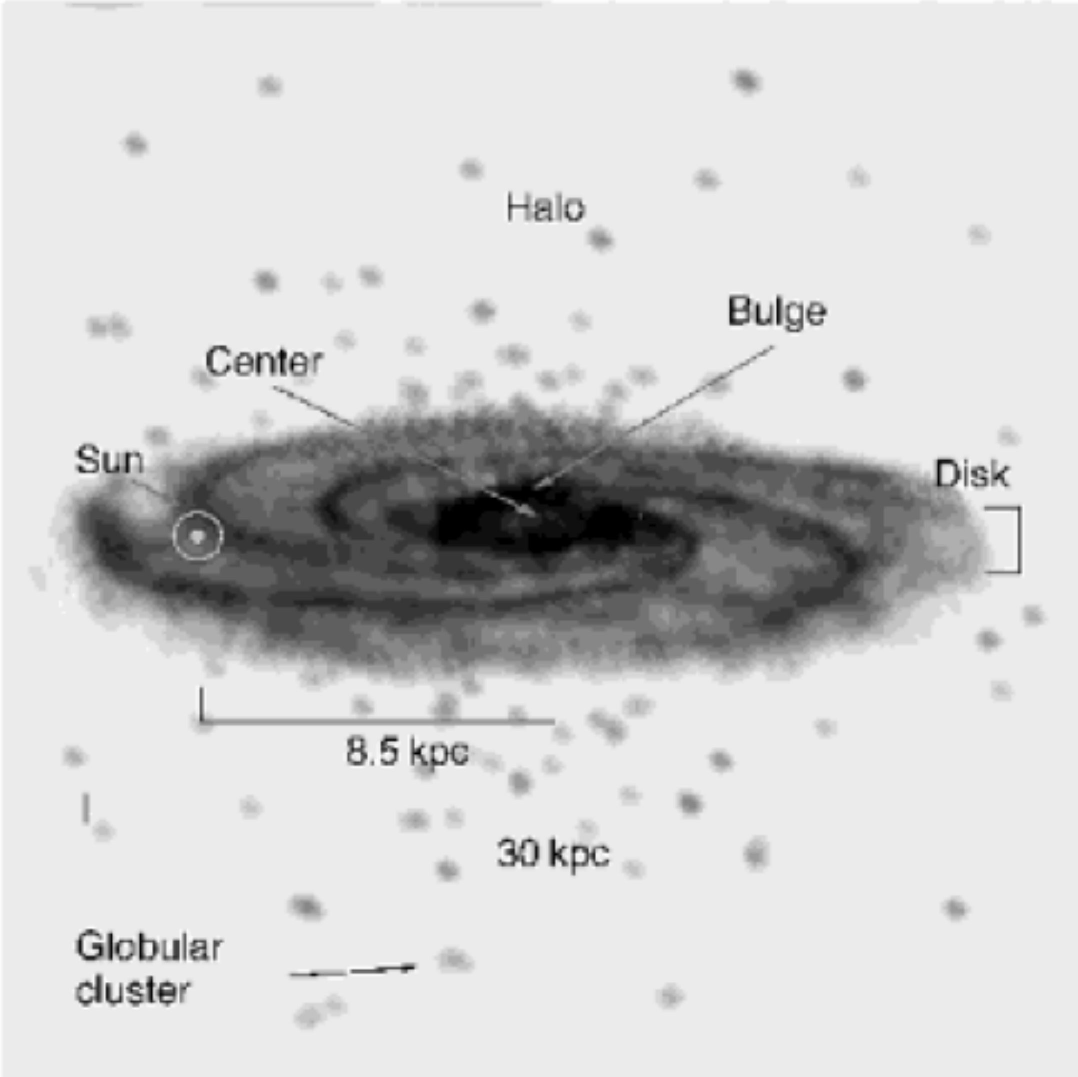
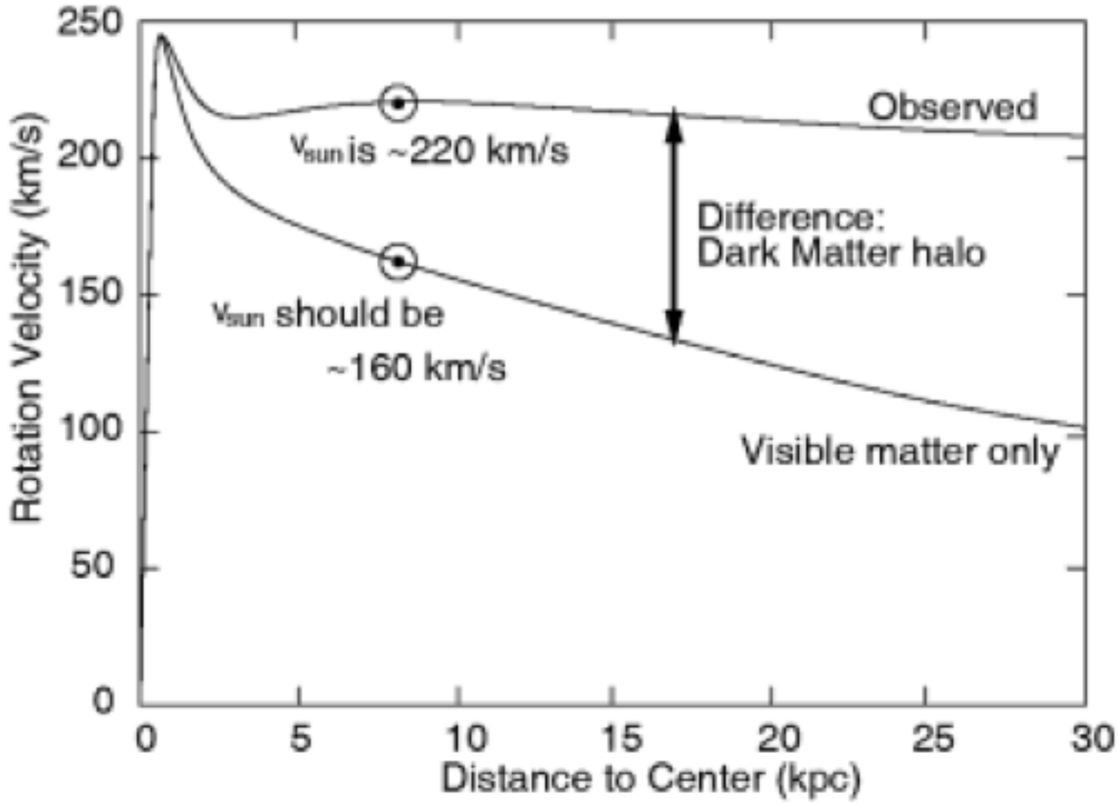


Fig. 1.3. Schematic structure of the Milky Way consisting of the disk, the central bulge with the Galactic center, and the spherical halo in which most of the globular clusters are located. The Sun orbits around the Galactic center at a distance of about 8 kpc

The Galaxy

- thin disk of young stars and gas with a radius of 20 kpc and a scale height of 300 pc.
- ~ 1 kpc thick disk which contains an older stellar population compared to the thin disk
- a central bulge of old stars
- spherical halo containing most of the globular clusters and some of the oldest stars (12 Gyr)
- central massive BH of 3×10^6 solar masses

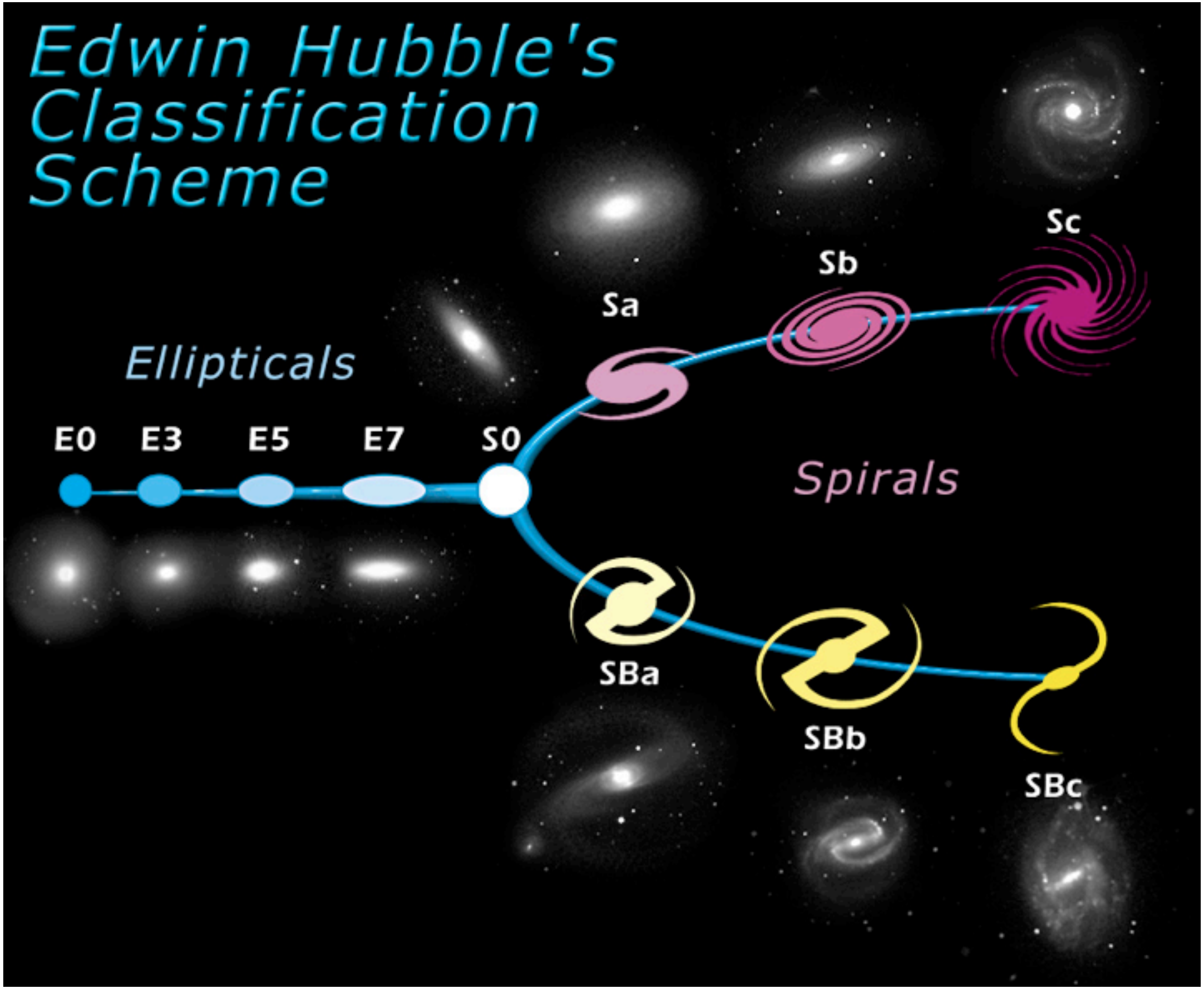
Rotation and dark matter



- Rotation velocity:

$$V_0 = \sqrt{\frac{GM(r_0)}{R_0}}$$

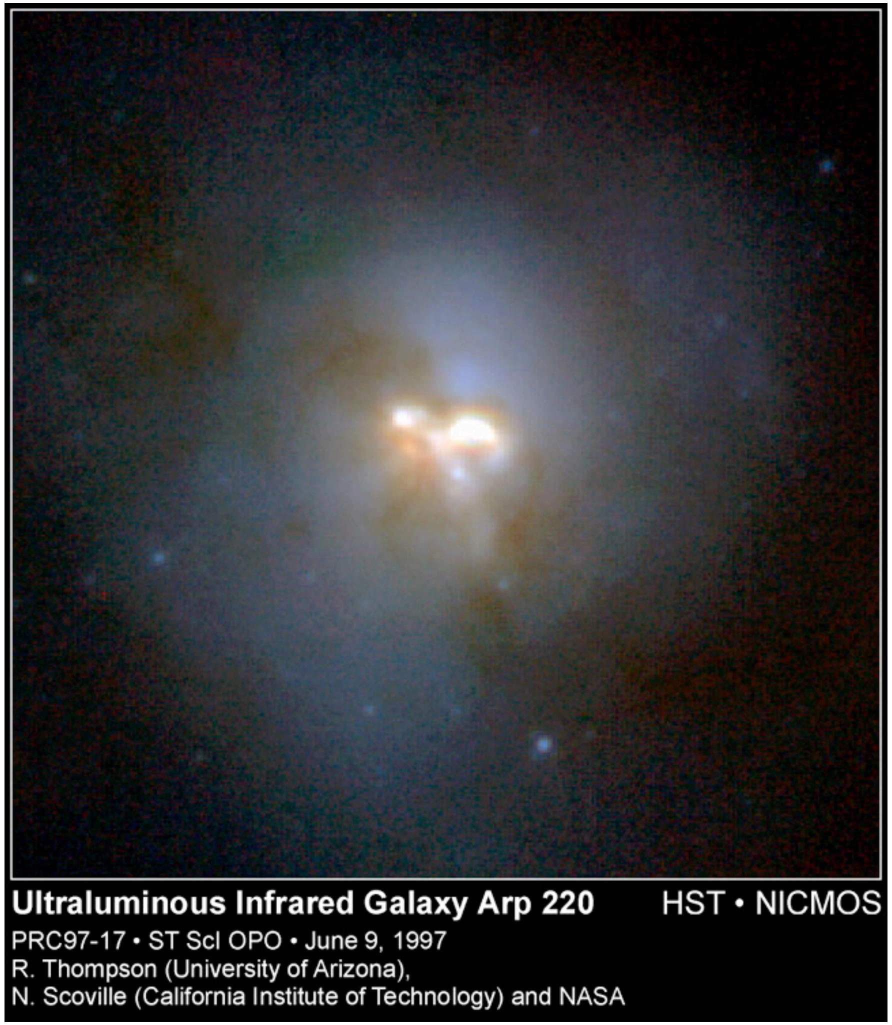
- visible matter gives for the sun at Ro = 8 kpc 160 km/s
- We measure 220 km/s due to ‘dark matter’
- Nature of matter unknown.
  - weakly interacting particles?
  - free floating rocks?


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

The world of galaxies

- Main types
  - spirals, late type galaxies
    - star formation taking place
    - flat rotation curve: large amount of dark matter
  - ellipticals, early type galaxies
    - mainly old stars
- Additional types
  - S0: disk-like but with old stars
  - irregular galaxies
  - dwarf galaxies
  - starburst galaxies
  - active galaxies

Arp 220:
prototypical starbursting galaxy



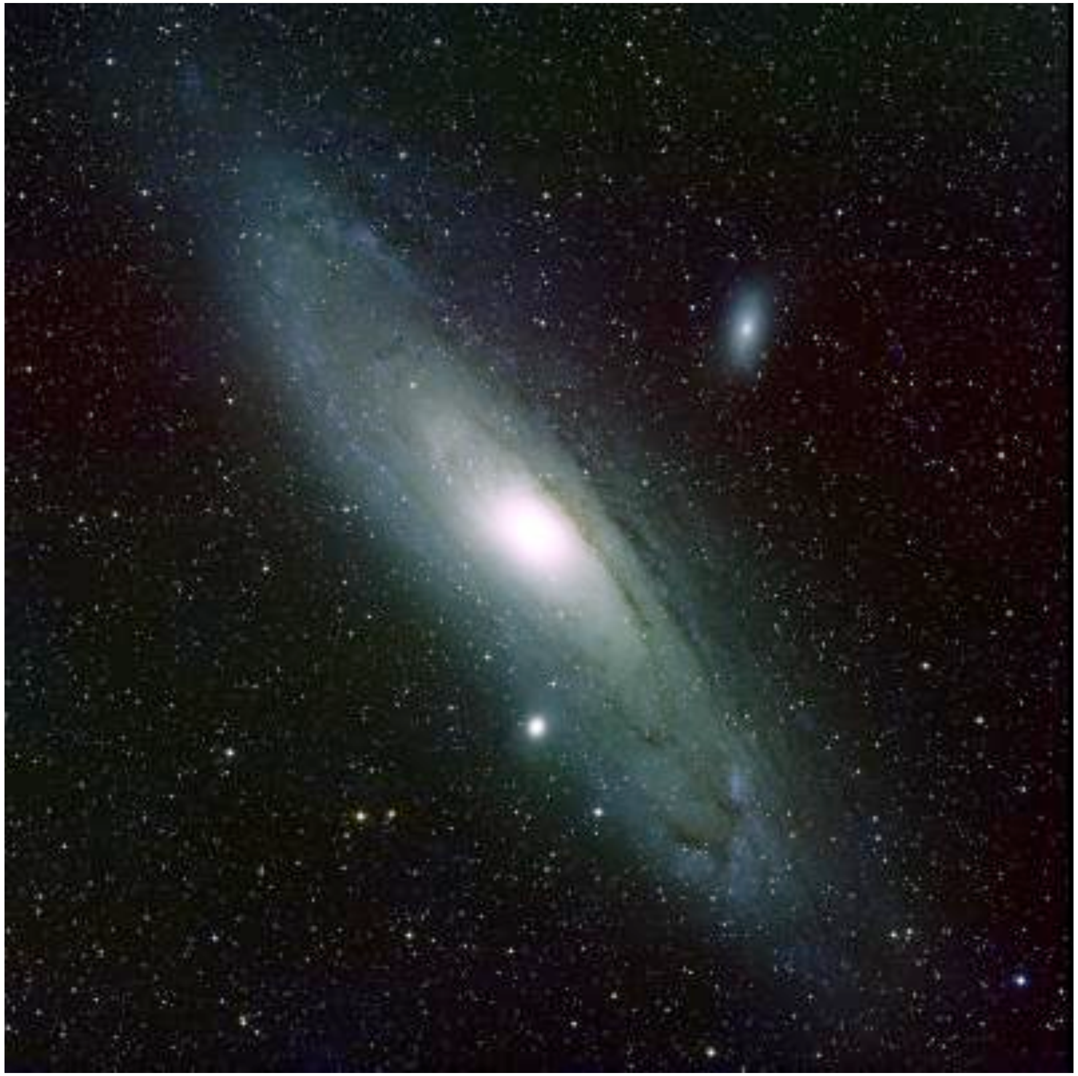
Starburst galaxies

- galaxies that from stars typically at rates of 10 - 300 Mo/yr (Cf our galaxy ~2 M/yr).
- extremely luminous at far-Infrared wavelength, up to 98 % from of the luminosity in this spectral region. This is due to dust emission. The dust is heated by young stars.
- often merging systems

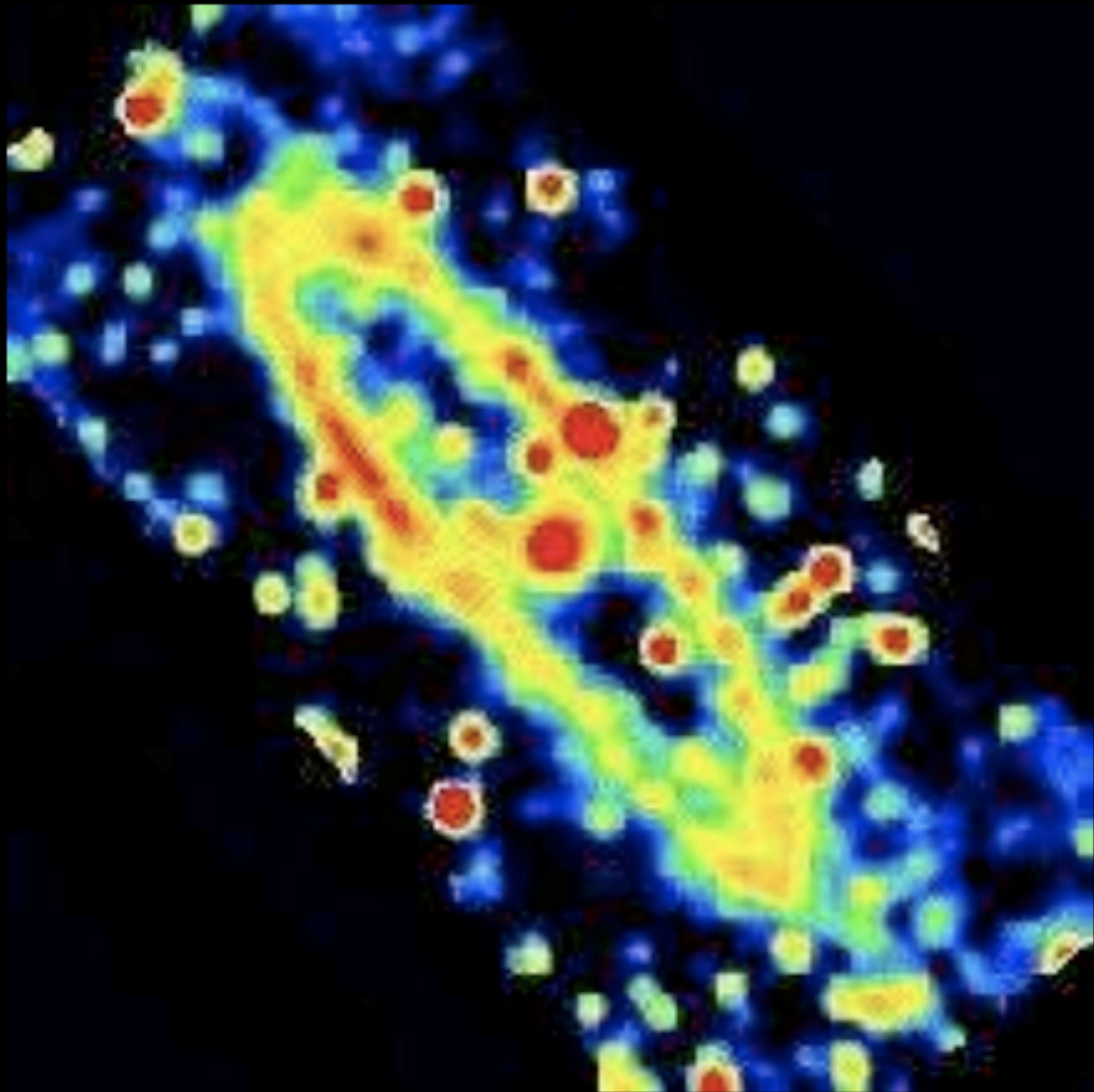
Multi-wavelength view:

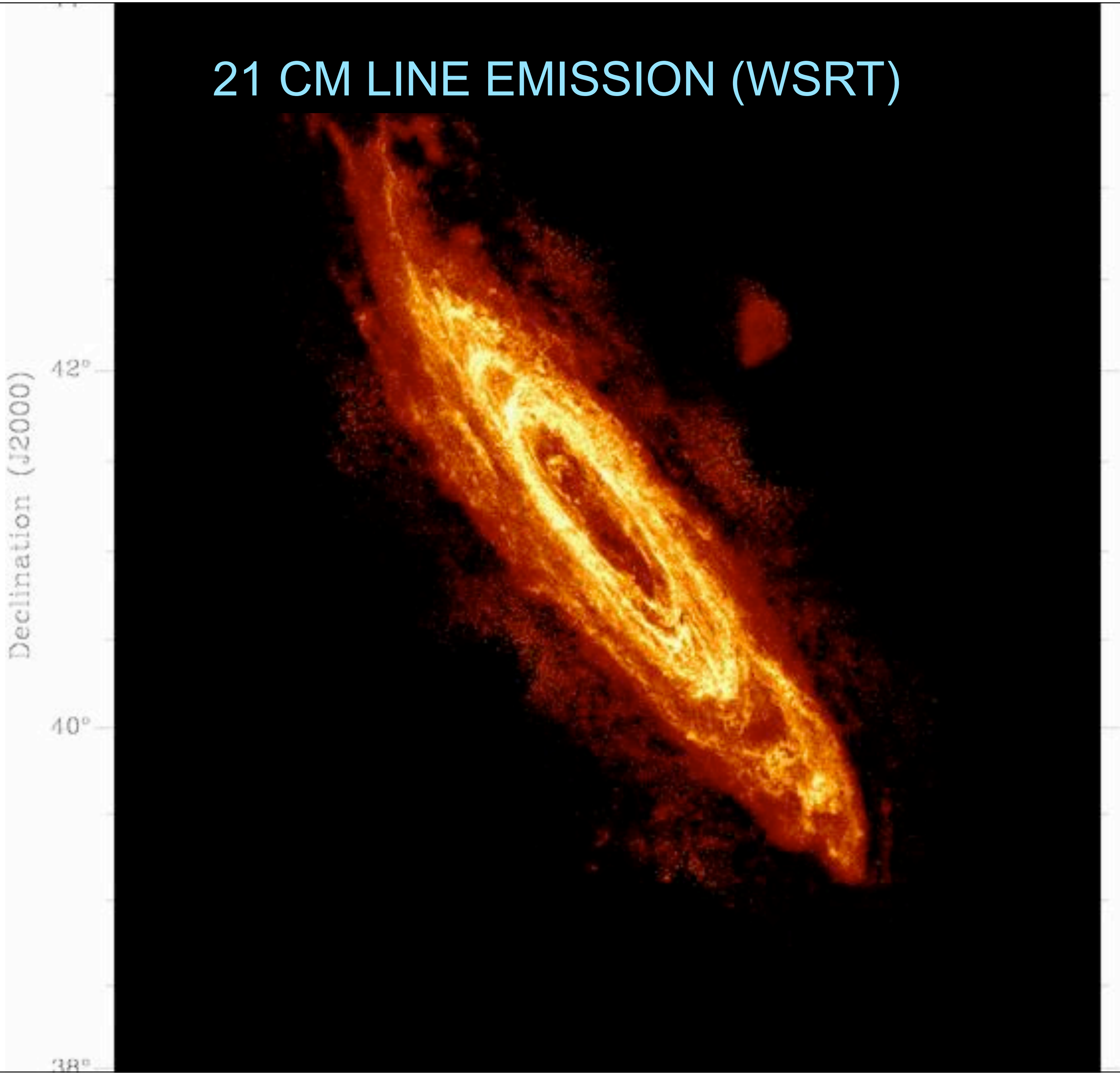
Galaxies emit over the entire electromagnetic spectrum

M31

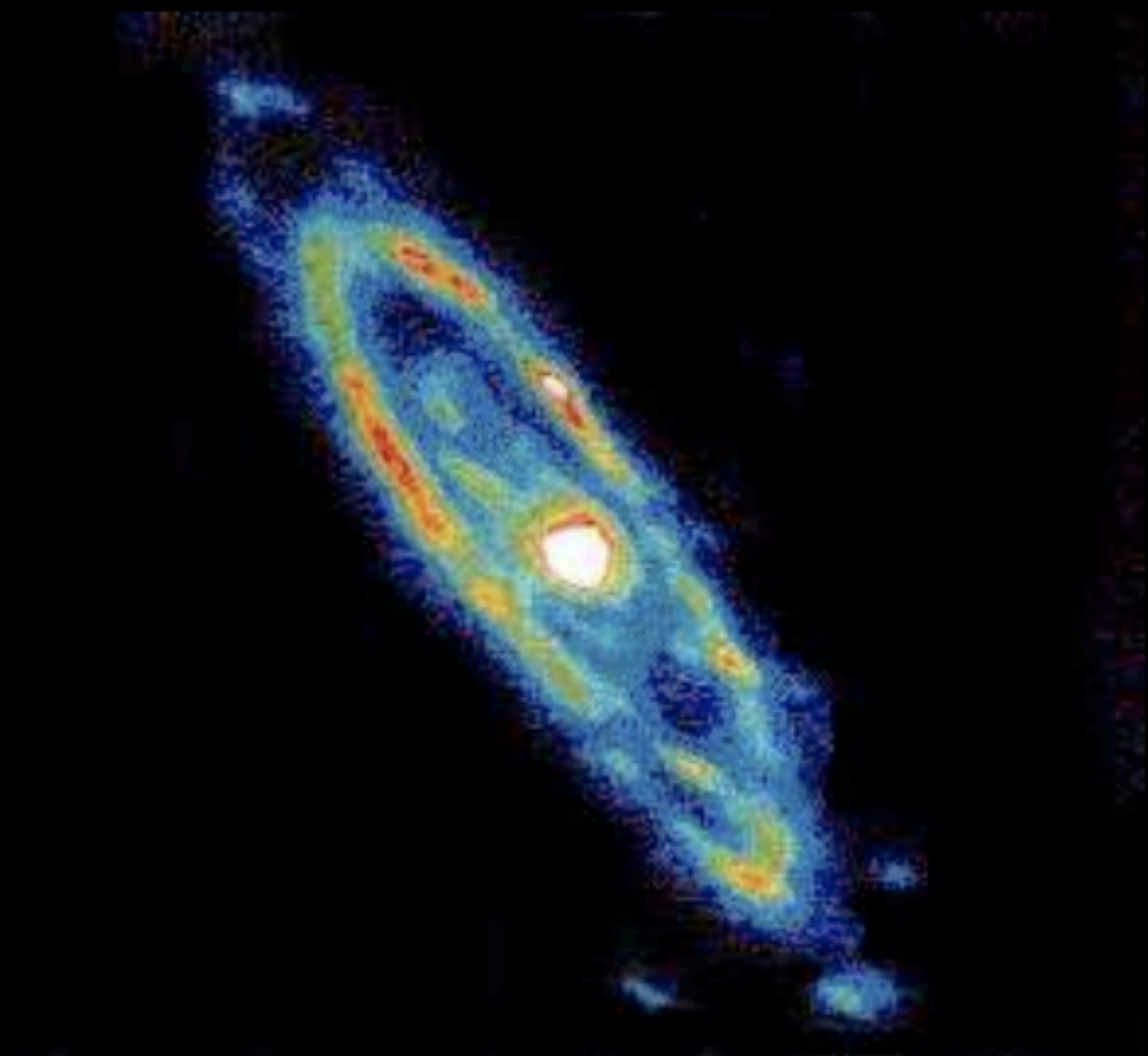


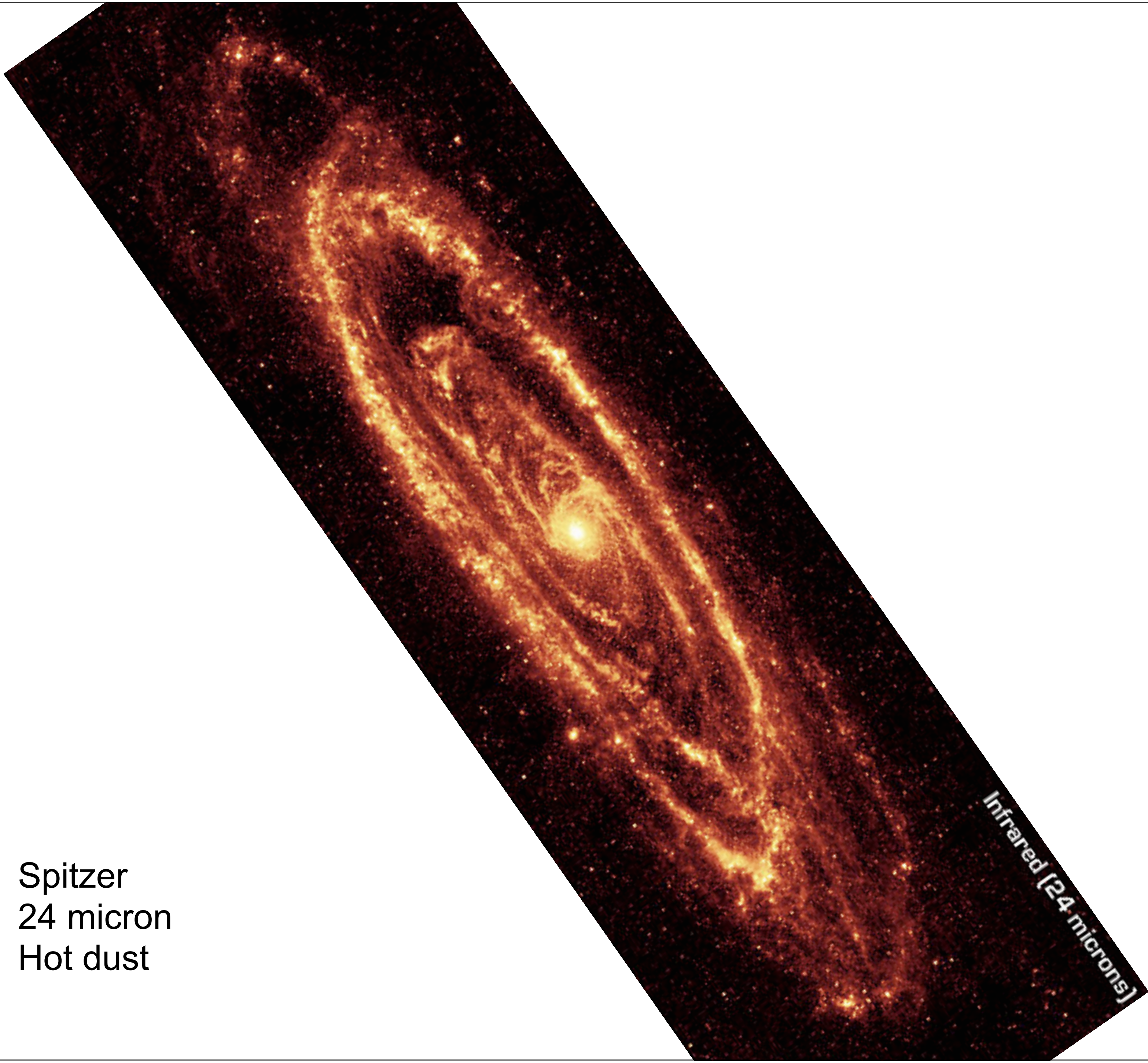
RADIO CONTINUUM EMISSION AT 6 CM




21 CM LINE EMISSION (WSRT)
Declination (J2000)
42°
40°
38°

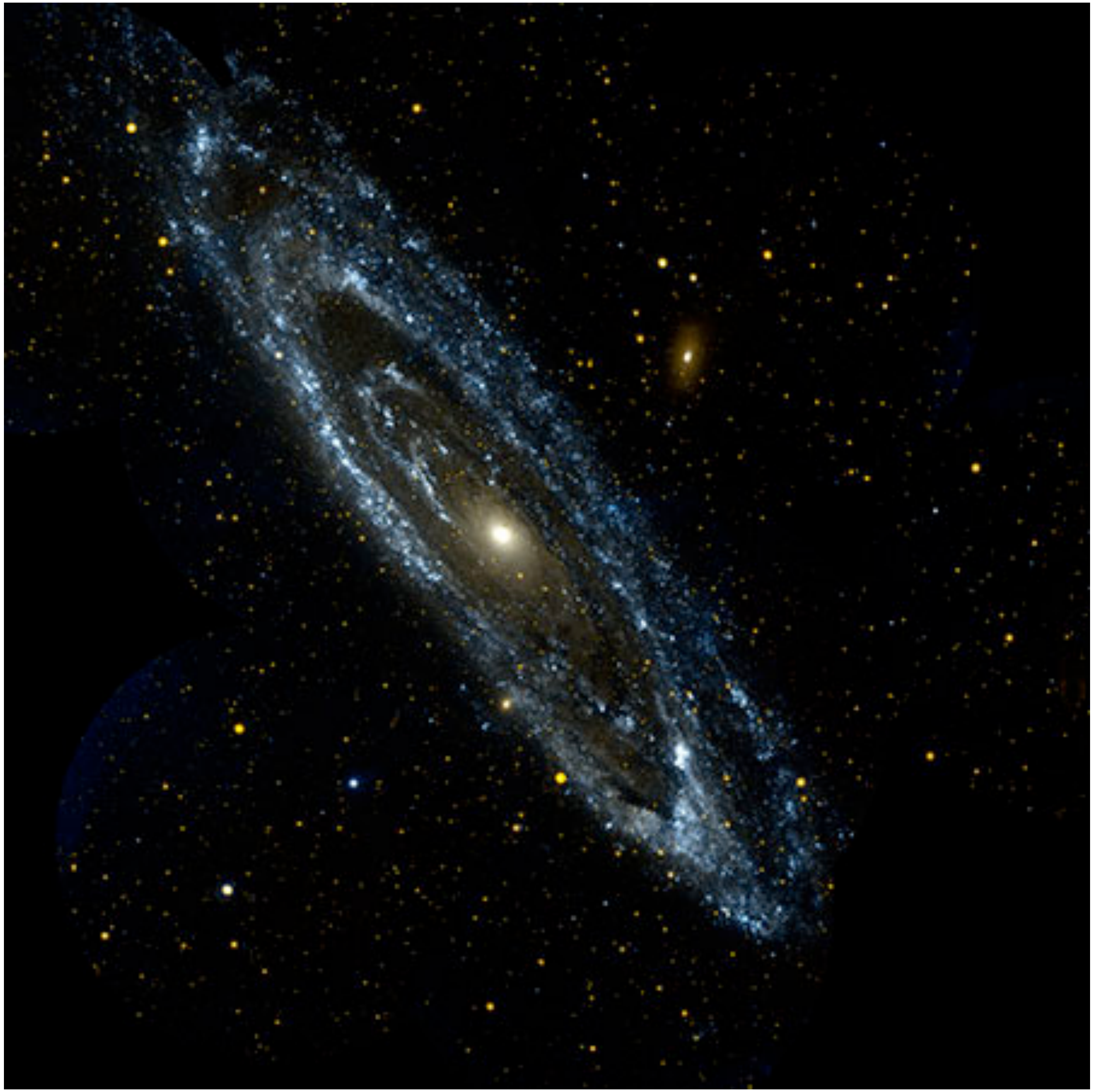
M31 IRAS 100 micron



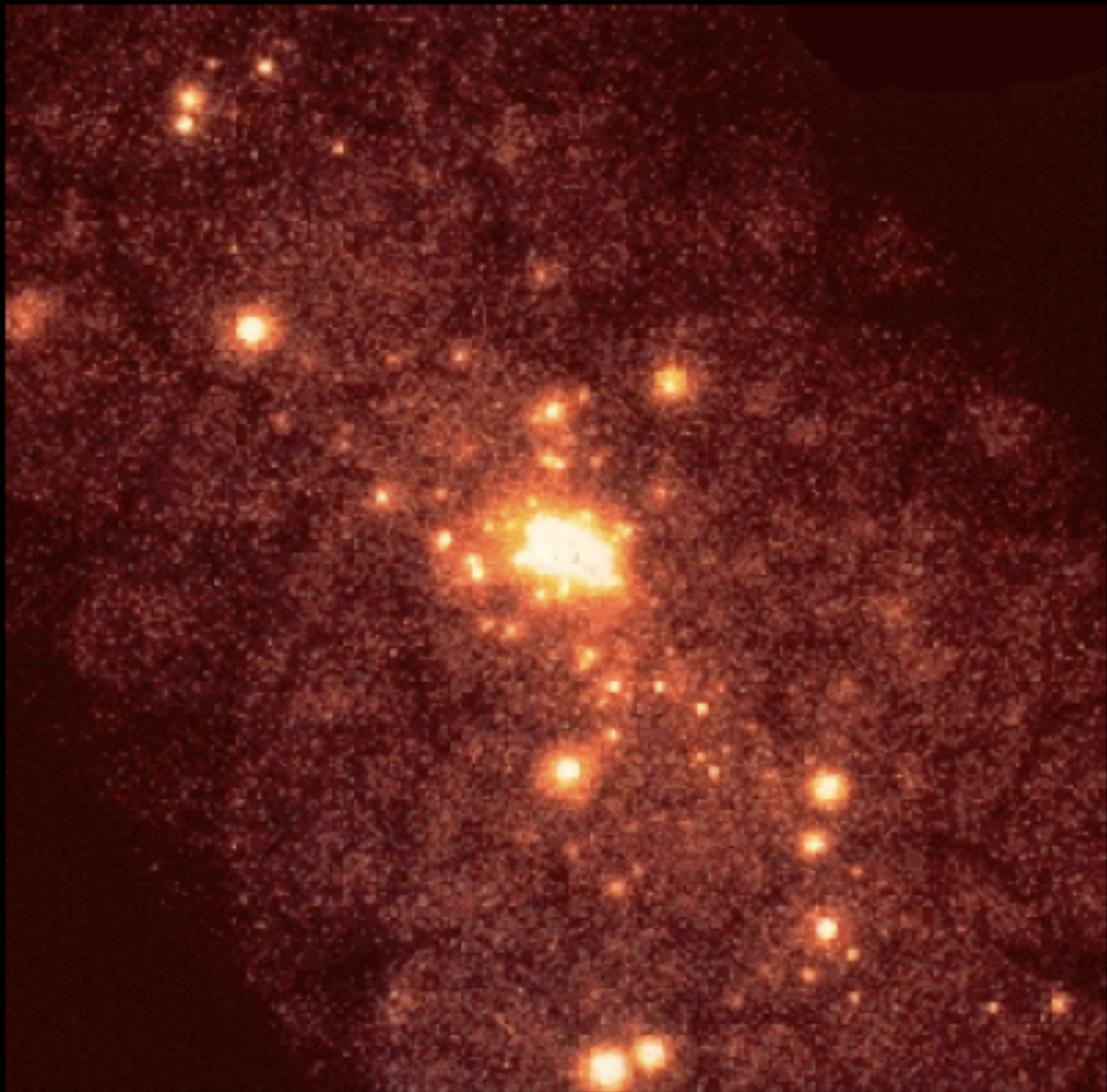


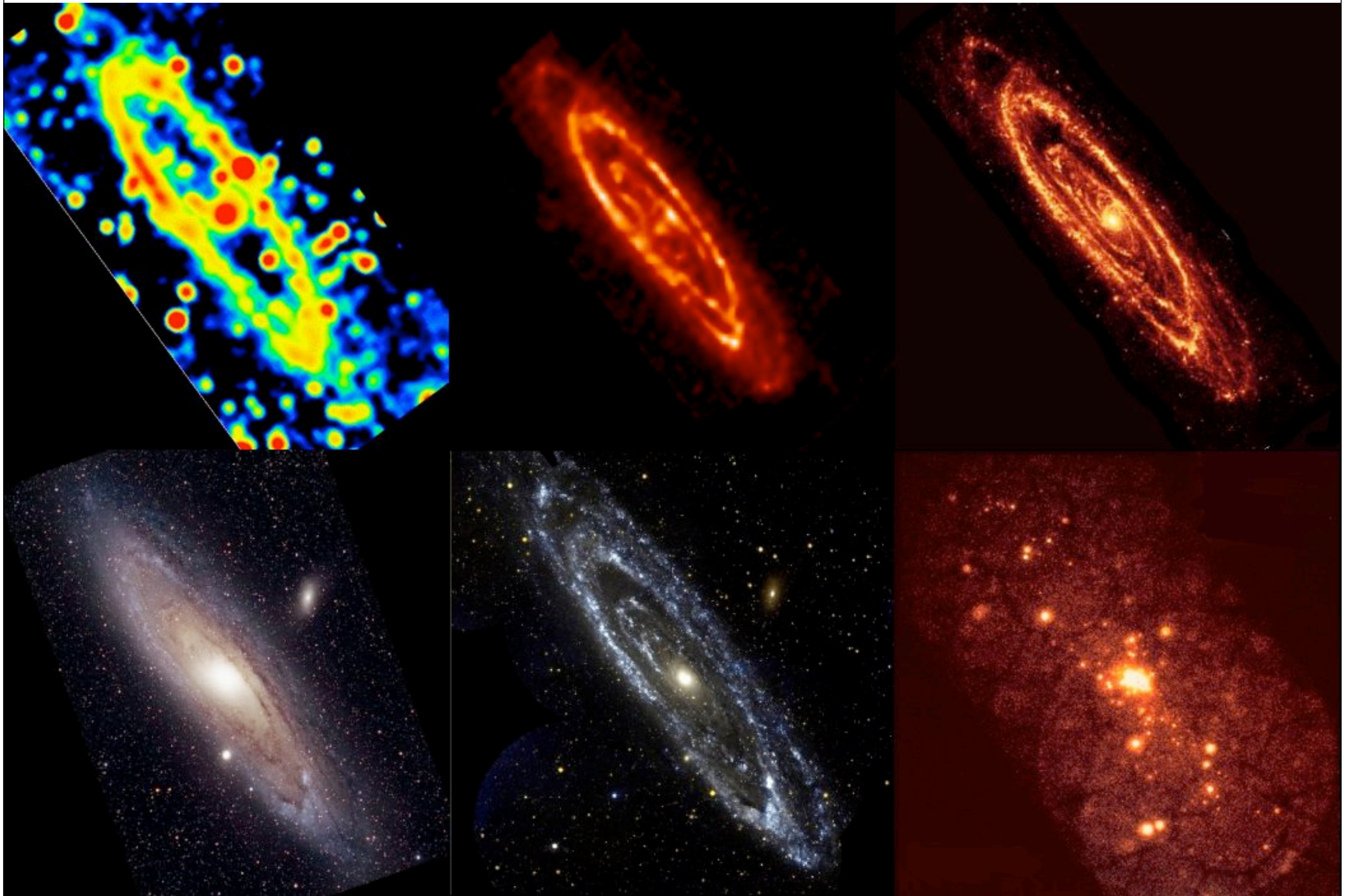
Spitzer
24 micron
Hot dust

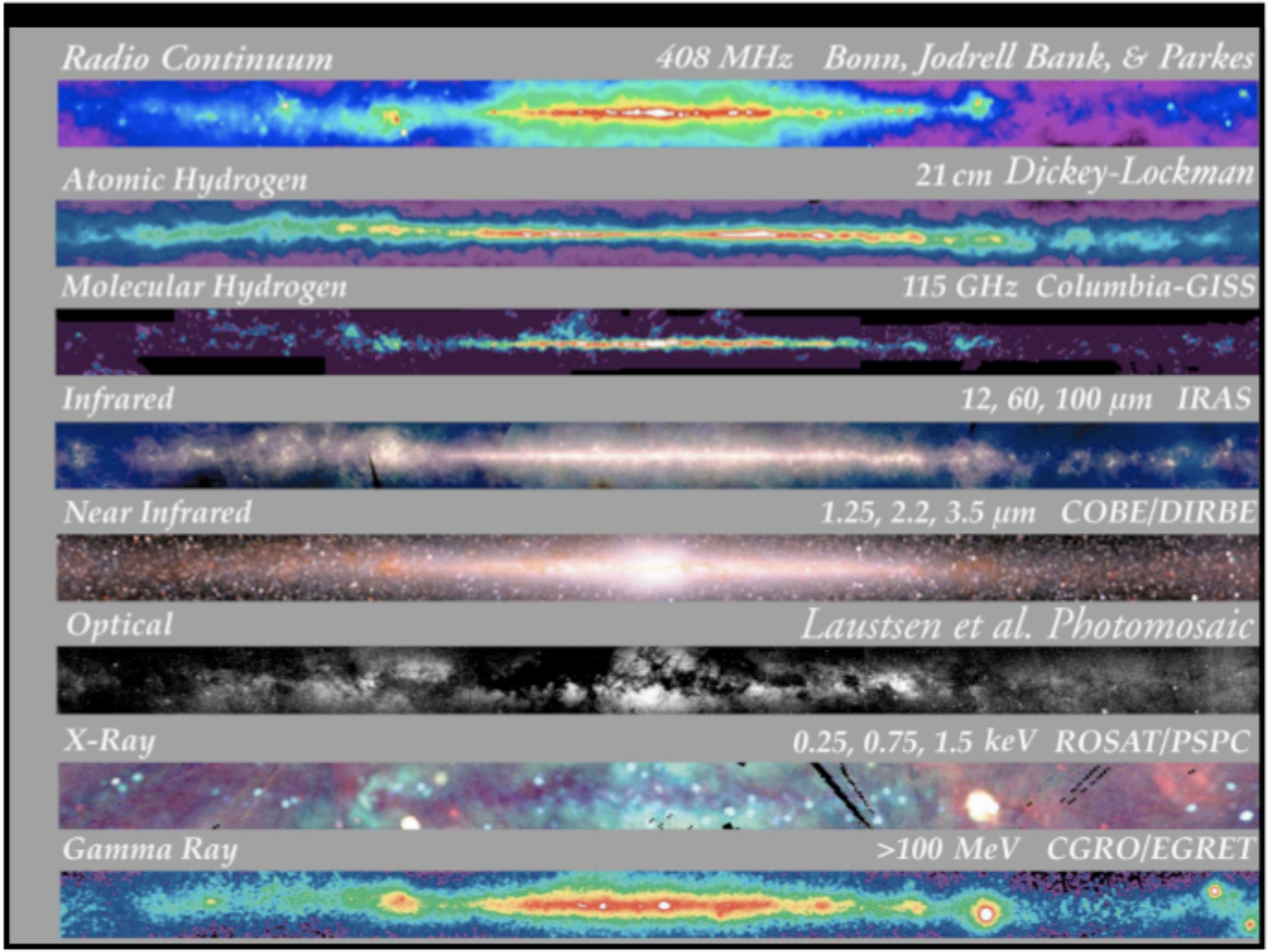
Galex
UV image



M31 Xray (center)




Radio
cold dust
hot dust
Optical
UV
X-ray (center)


Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen
21 cm Dickey-Lockman
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET

Galaxies emit in many wavelengths

Radio:

- Smooth continuum emission following spiral arms: free-free emission due to warm gas
- Compact emission regions identified as supernova remnants
- Line emission: HI 21 cm, CO, molecular lines from cold gas

Infrared:

- Continuum emission from dust, heated by young stars in starforming regions

Near Infrared:

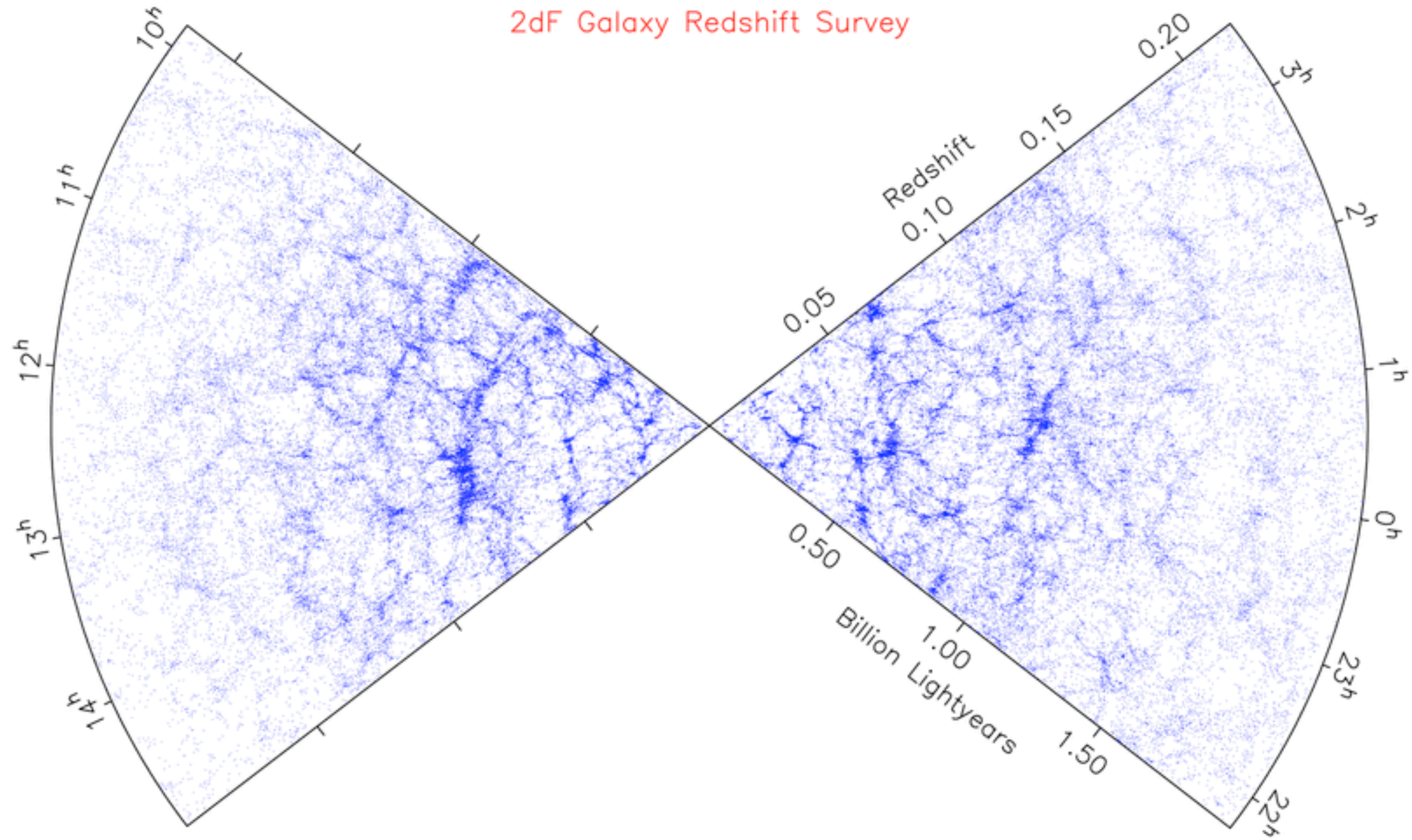
- Red super giants, modest extinction

Optical-UV:

- Visible stars, dust absorption
- Emission lines from hot (10^4 K) gas
- Stellar absorption lines

- X-Ray:
  - (Double) stars, neutron stars
  - Very hot gas

Large scale structure: voids, filaments and clusters



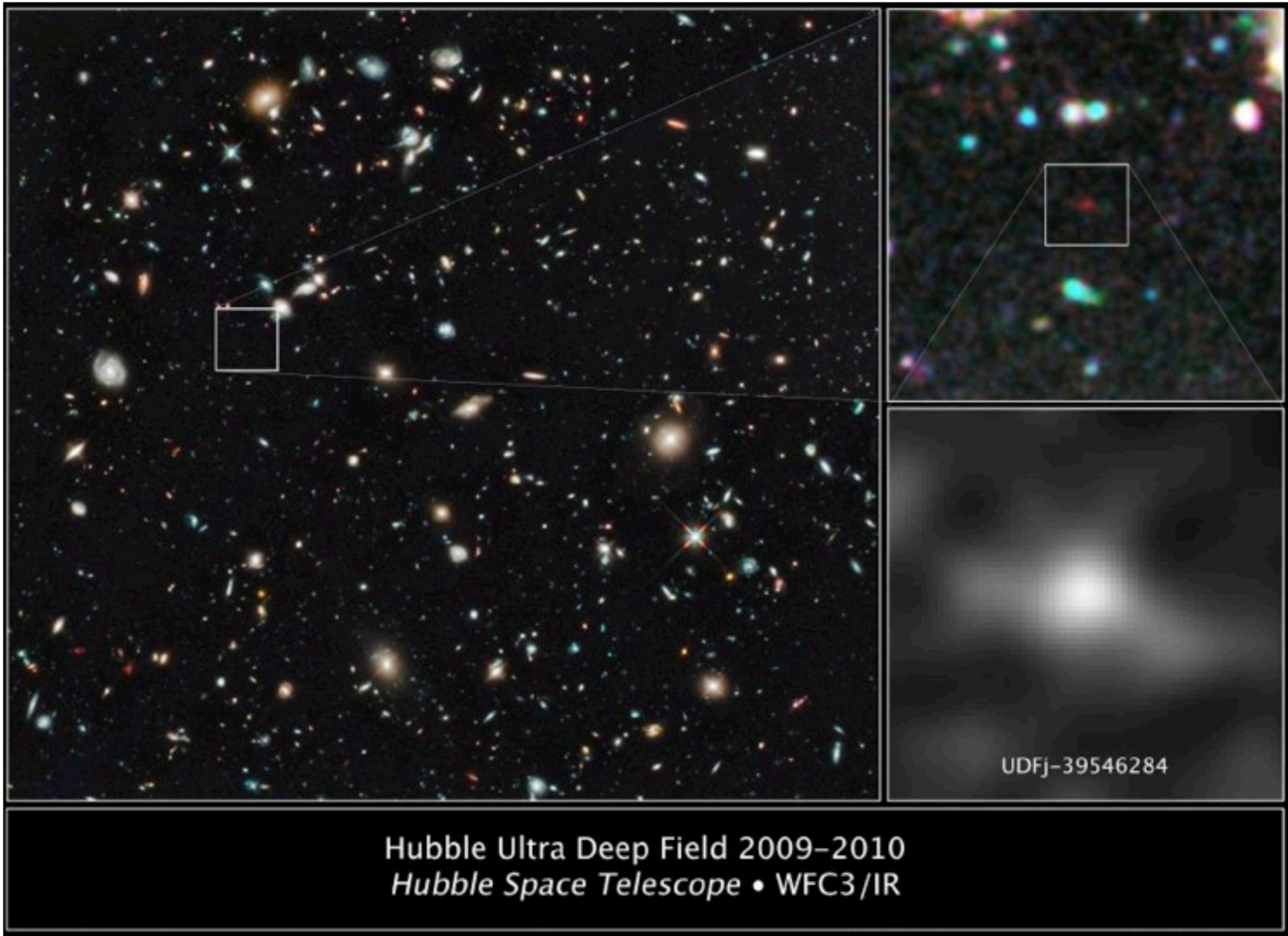
The 2dF Galaxy Redshift Survey (2dFGRS obtained good redshifts for 221414 galaxies over an area of 1500 square degree, see, http://www2.aao.gov.au/2dfgrs/Public/Survey/description.html. See also fig. 8.2 from Scheider


Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC
ASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07


Clusters of galaxies

- Properties
  - Velocity dispersion ~1000 km/s
    - young: $t_{\rm dyn} \sim \frac{2R}{v} \sim \frac{1000\,{\rm km/s}}{2\,{\rm Mpc}} \sim 2 \times 10^9 {\rm yr}$
    - virial theorem: most massive structures have masses: $3\times10^{14} - 3\times10^{15}$ M$\odot$ within 2 Mpc
  - Hot X-ray radiating gas with T $\sim 3 \times 10^7$ K
  - Mostly ellipticals
- Closest: the Coma cluster
  - 90 Mpc distance, 1000 luminous galaxies, 85 % ellipticals
- Important objects for study:
  - Number density is directly related to fluctuation in the Early universe
  - Interaction of gas and galaxies strongly influences galaxy properties.

Galaxies in the Early universe:


UDFj-39546284
Hubble Ultra Deep Field 2009-2010
Hubble Space Telescope • WFC3/IR

Most Distant Galaxy Candidate Ever Seen in Universe The farthest and one of the very earliest galaxies ever seen in the universe appears as a faint red blob in this ultra-deep–field exposure taken with NASA's Hubble Space Telescope. This is the deepest infrared image taken of the universe. Based on the object's color, astronomers believe it is13.2 billion light-years away.

The most distant objects in the universe appear extremely red because their light is stretched to longer, redder wavelengths by the expansion of the universe. This object is at an extremely faint magnitude of 29, which is 500 million times fainter that the faintest stars seen by the human eye.

The dim object is a compact galaxy of blue stars that existed 480 million years after the Big Bang, only four percent of the universe's current age. It is tiny and considered a building block of today's giant galaxies. Over one hundred such mini-galaxies would be needed to make up our Milky Way galaxy.

The Hubble Ultra Deep Field infrared exposures were taken in 2009 and 2010, and required a total of 111 orbits or 8 days of observing. The new Wide Field Camera 3 has the sharpness and near-infrared light sensitivity that matches the Advanced Camera for Surveys' optical images and allows for such a faint object to be selected from the thousands of other galaxies in the incredibly deep images of the Hubble Ultra Deep Field.

Credit: NASA, ESA, G. Illingworth (University of California, Santa Cruz), R. Bouwens (University of California, Santa Cruz and LeidenUniversity), and the HUDF09 Team

http://www.nasa.gov/mission_pages/hubble/science/farthest-galaxy.html

Active galaxies

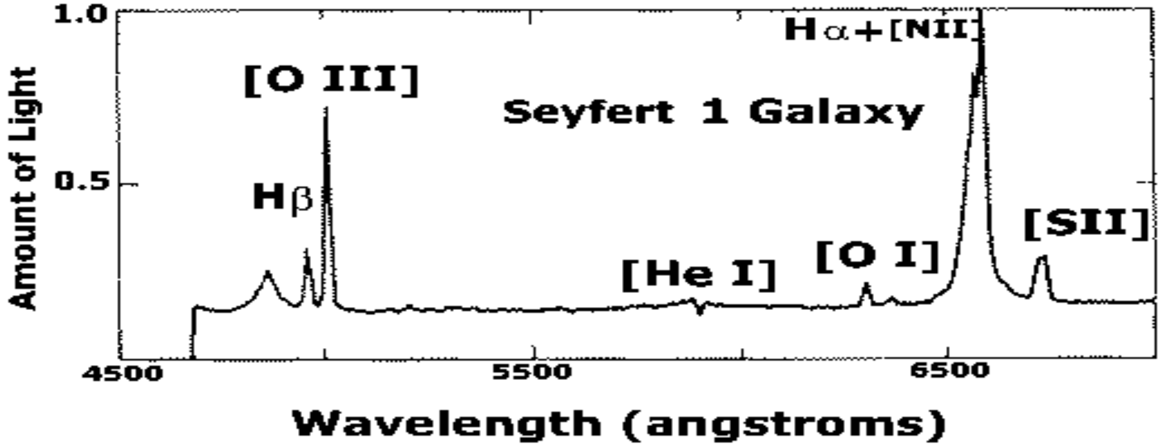
Seyfert galaxies

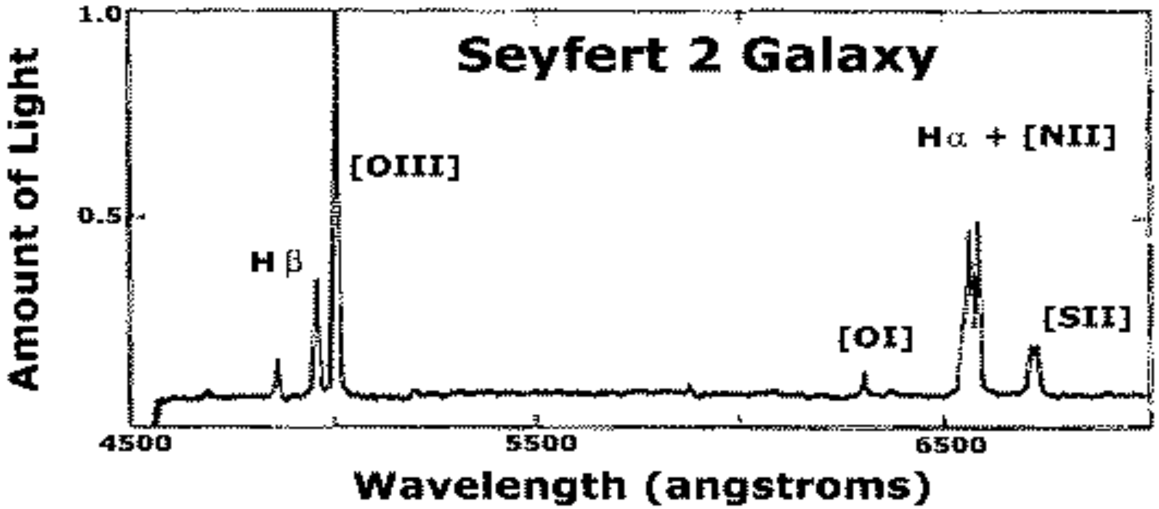
1943, Carl Seyfert: certain nearby spiral galaxies have very bright, pinpoint nuclei and unusual spectra with very strong, often broad, emission lines

Most if not all Seyfert galaxies are in spirals

Seyfert galaxy NGC 7742
http://antwrp.gsfc.nasa.gov/apod/ap981023.html

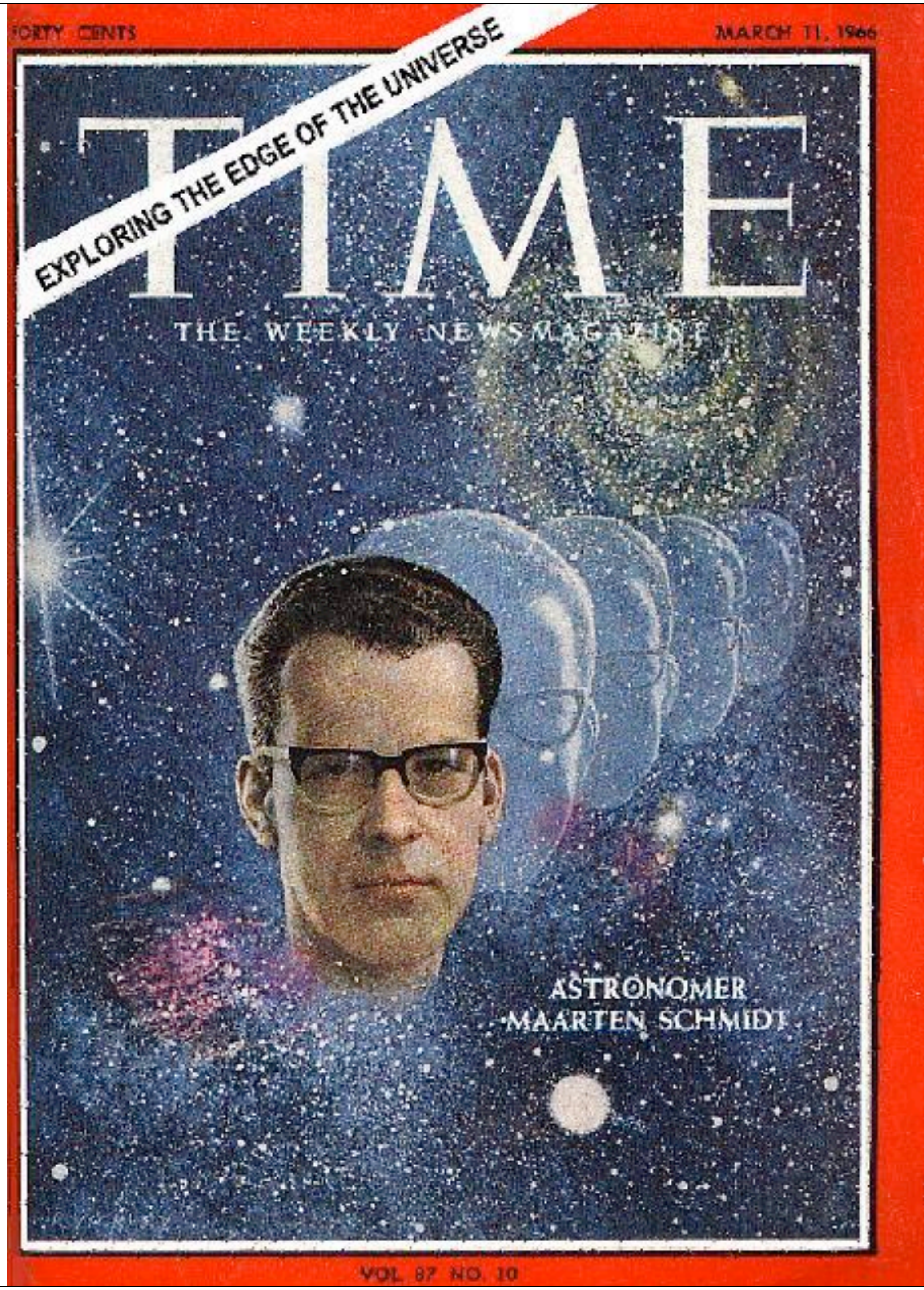
Seyfert galaxies have very strong emission lines





3C 273

The "First" Quasar



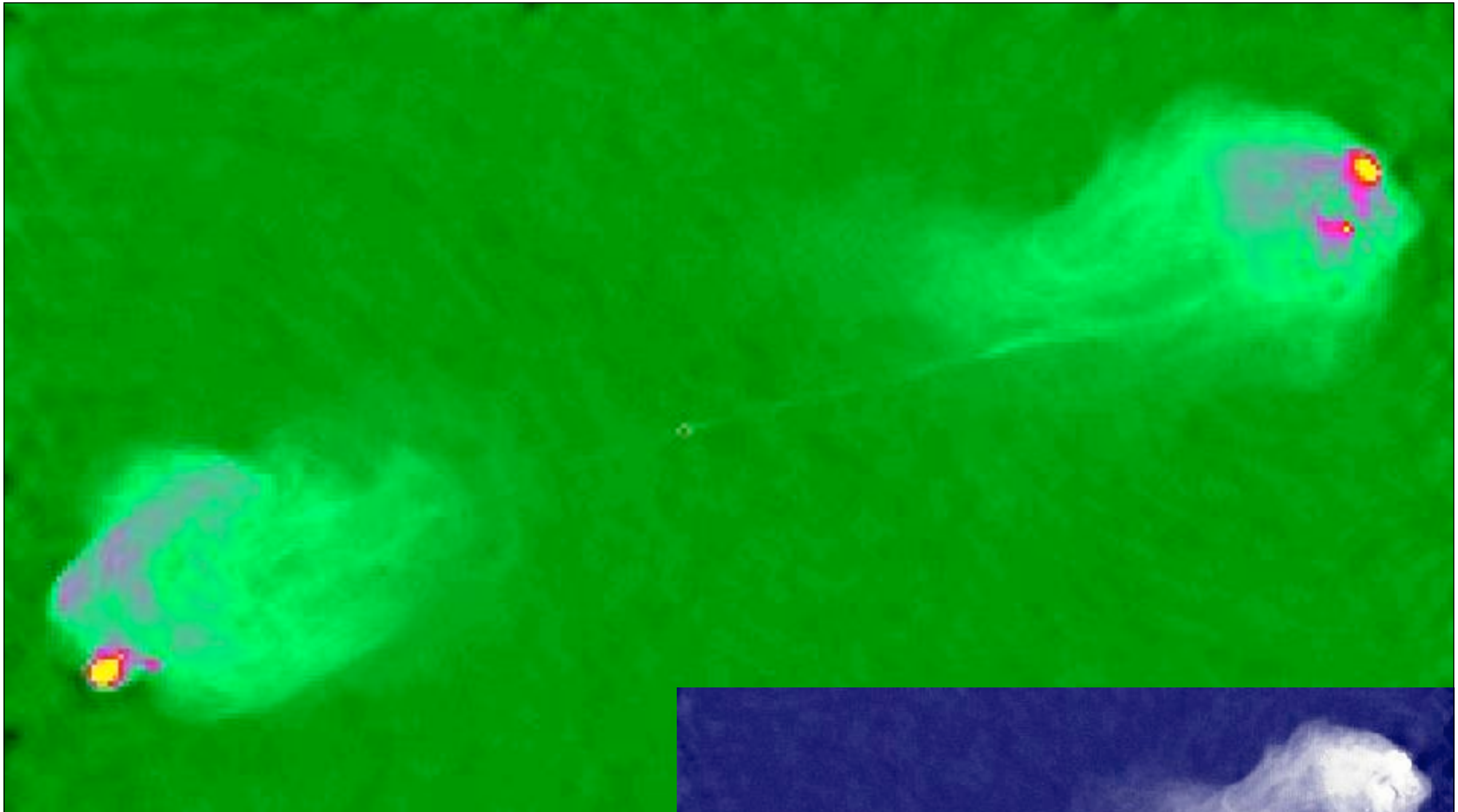
Seyferts versus quasars

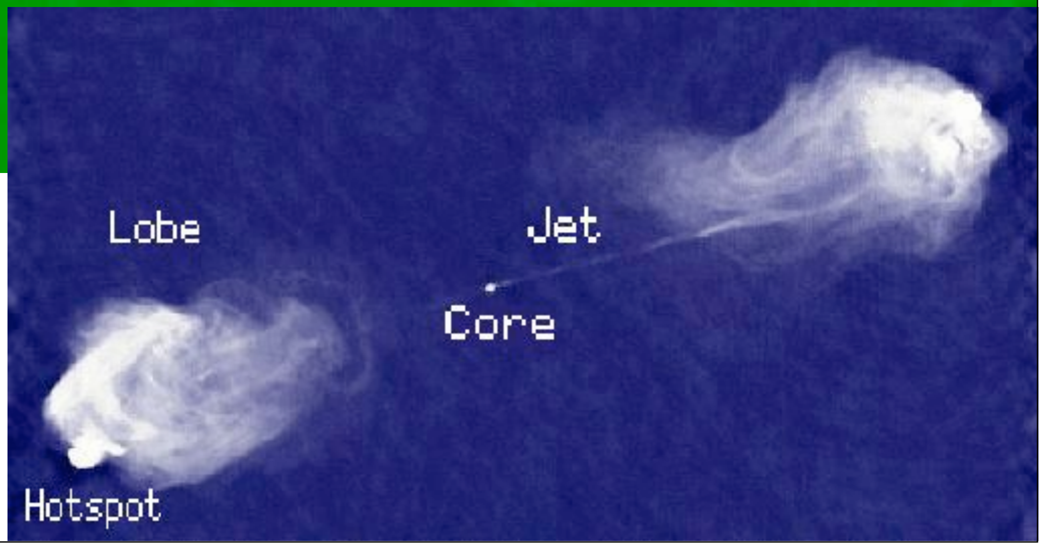
- Spectra similar to Seyfert I
- QSOs are the more luminous counter parts of seyferts
  - QSO: Nuclear magnitudes $M_B < -21.5$
- Identification
  - QSO's: unresolved at ~ 1 arcsec scales
  - Seyferts: well resolved and identified with spirals

Central Black hole

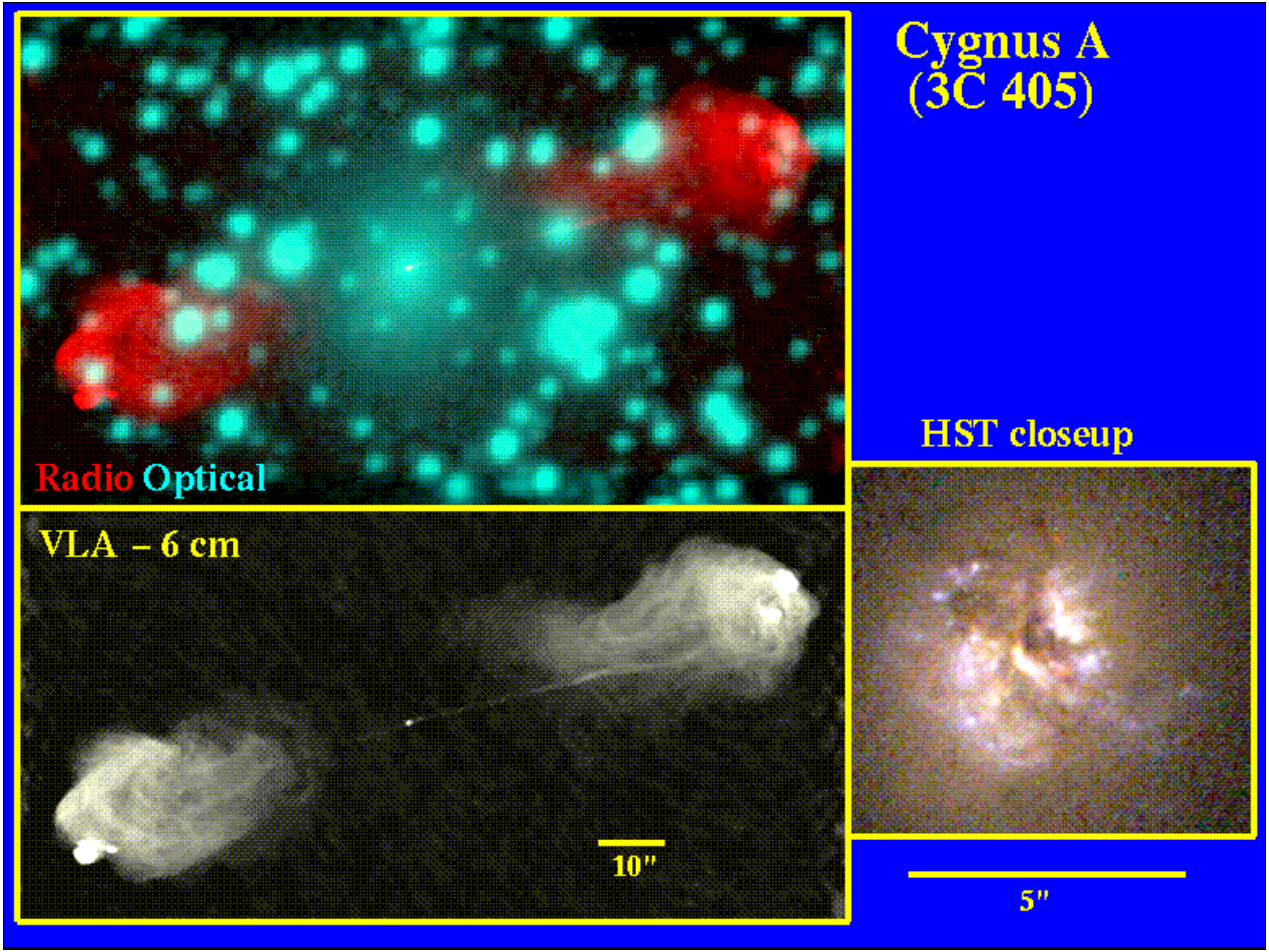
- Luminosity of quasars up to a 1000 times our galaxy
- Variable: luminosity comes from a small region

- Conclusion: energy from matter falling into massive black hole, converting gravitational potential energy into kinetic energy. Friction lead to heat, which is partly reradiated.





Cygnus A



Cygnus A
(3C 405)
Radio Optical
VLA – 6 cm
10"
HST closeup
5"

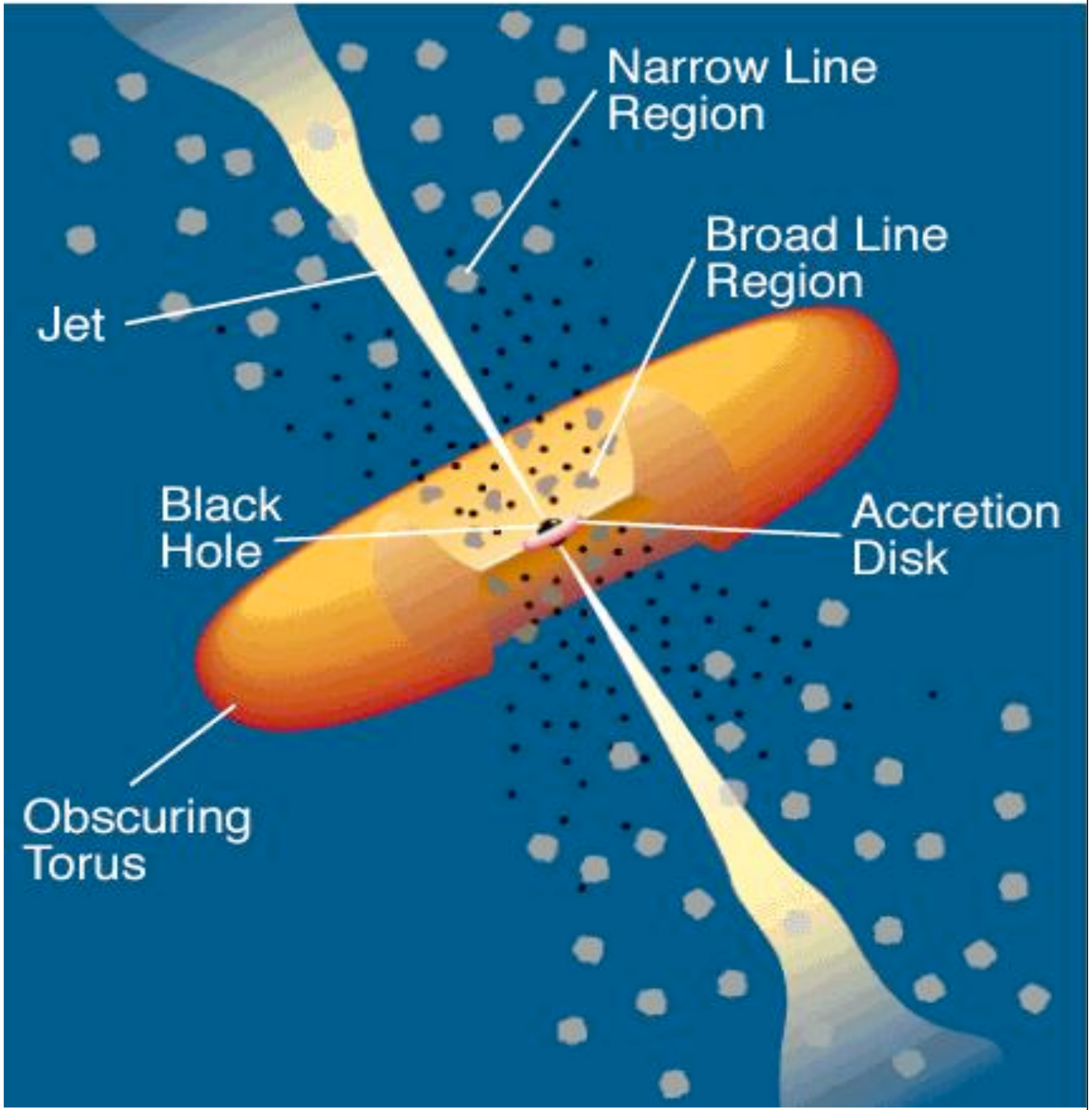
Radio Galaxies

- Mid-1950s: powerful radio sources are frequently associated with giant elliptical galaxies.
- First radio galaxy identified was Cygnus A
- Intense beams or *jets*, moving with highly-relativistic speeds are transporting the electrons and magnetic field out to the radio lobes.
- The *radio lobes* are believed to be produced when the *jets* ram into intergalactic gas clouds. The radio emission is due to synchrotron emission and comes principally from giant radio lobes, well outside the visible portions of the galaxy, sometimes extending up to 1 Mpc.
- The jets can end in *hotspots*, intensity maxima at the extremities of the lobes. They have typical linear sizes of 1 kpc. Location where the jet hits the ambient medium
- Frequently there is also a *radio core*, coincident with the galaxy nucleus.

Building blocks

Unification:

observed properties depend on viewing angle



Active Nuclei

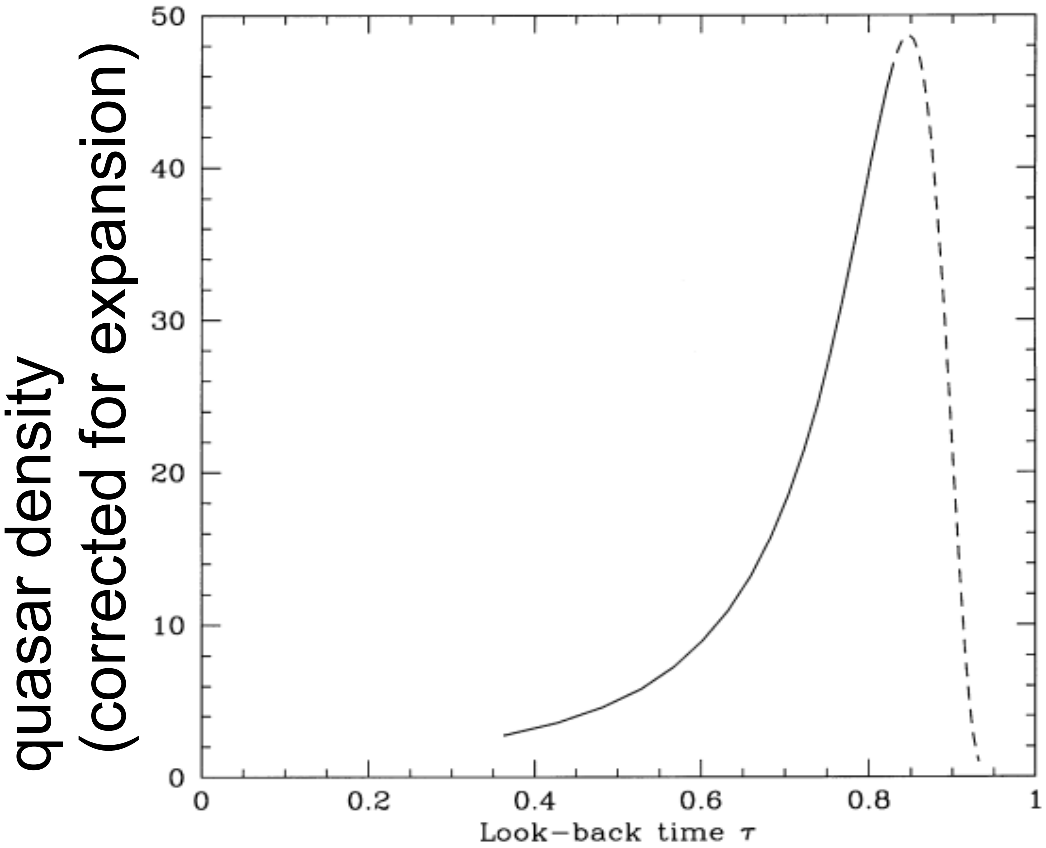
− produce emission at all wavelengths
  Radio: core, jets, lobs
  Infrared: Continuum emission presumably by a dusty torus
  Optical-UV: Blue core+Emission lines
  X-Ray: emission from accretion disk

− Many length scales:
  - from very close to the nucleus (~pc)
  - to the largest scale (> 1Mpc)

− Main types: quasars, Seyfert galaxies, radio galaxies

− (observed) properties depend on orientation, age, black-hole mass, spin (?), host galaxy, environment

Quasars: dinosaurs of the past



Redshifts and the expanding universe

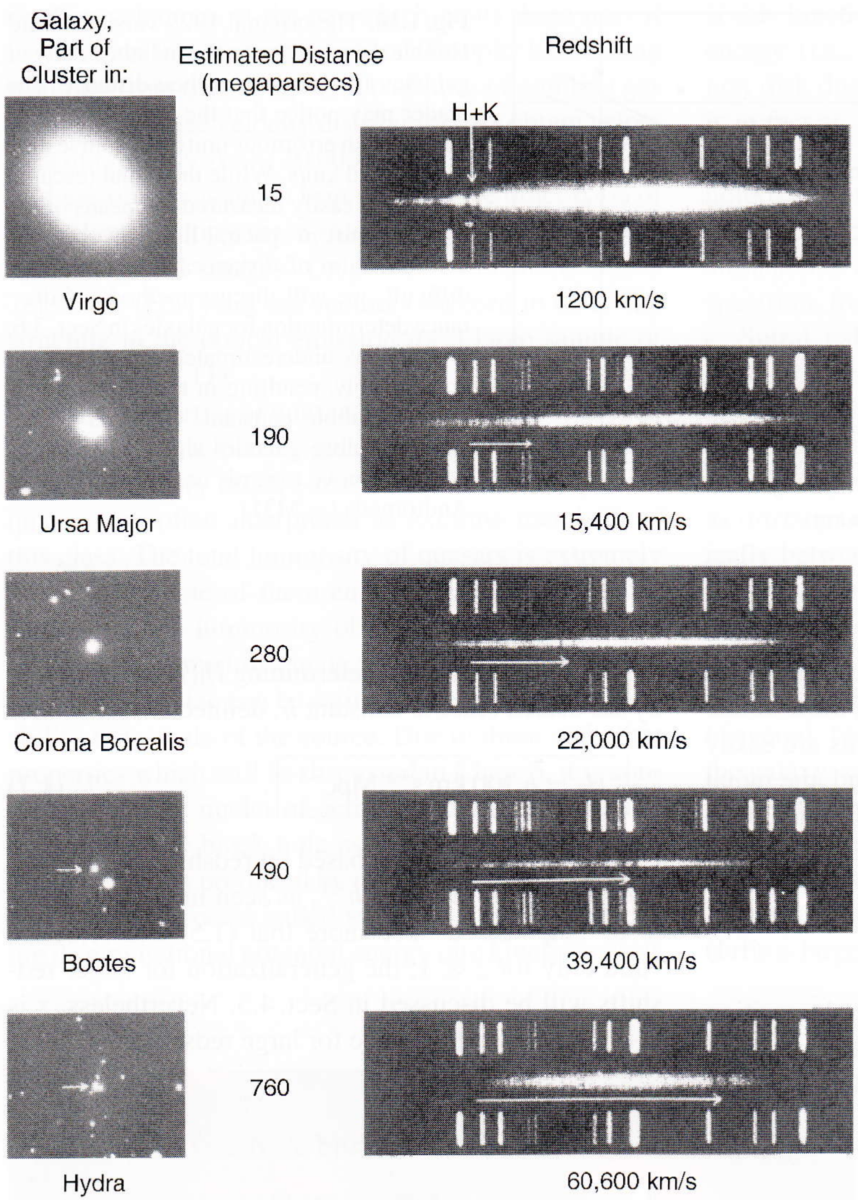


Fig. 1.9. The spectra of galaxies show characteristic spectral lines, e.g., the H + K lines of calcium. These lines, however, do not appear at the wavelengths measured in the laboratory but are in general shifted towards longer wavelengths. This is shown here for a set of sample galaxies, with distance increasing from top to bottom. The shift in the lines, interpreted as being due to the Doppler effect, allows us to determine the relative radial velocity – the larger it is, the more distant the galaxy is. The discrete lines above and below the spectra are for calibration purposes only

1929 Hubble diagram

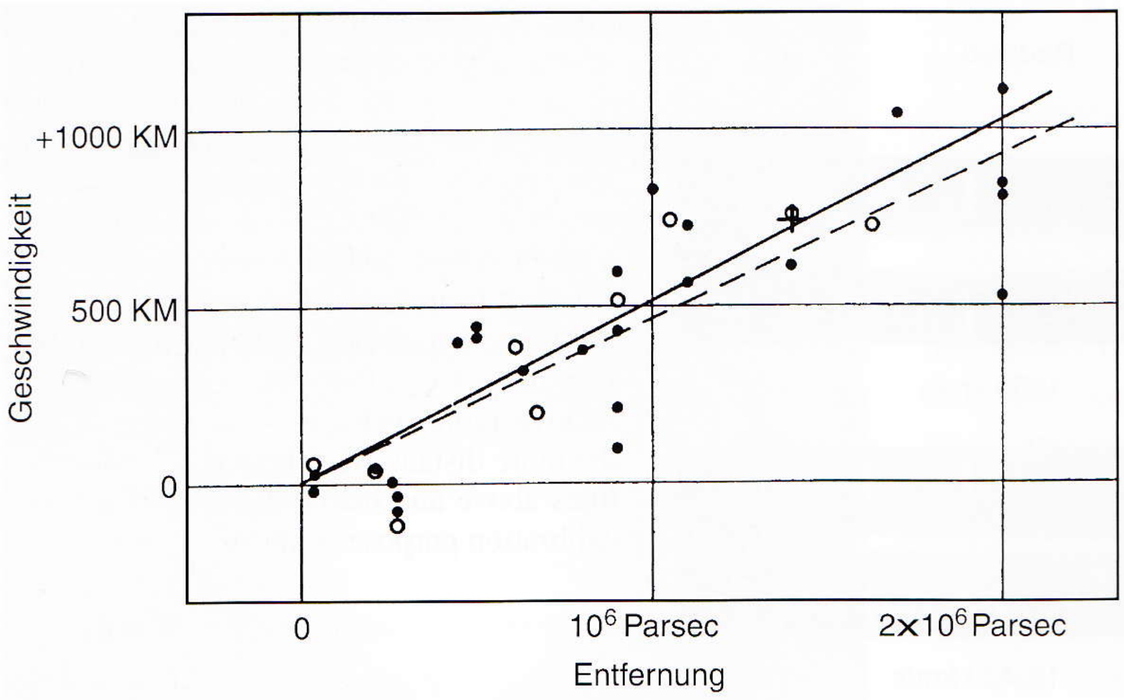
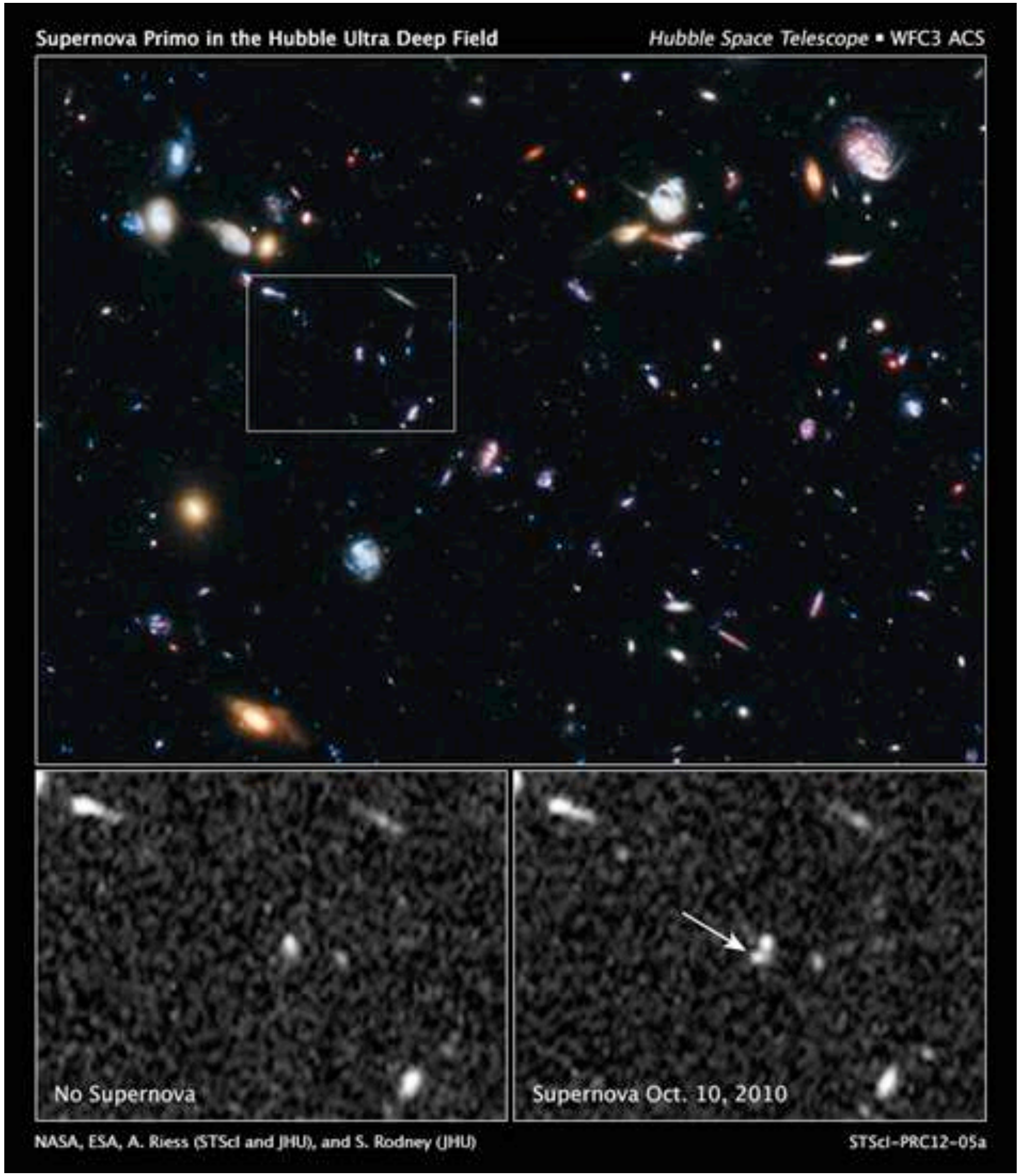
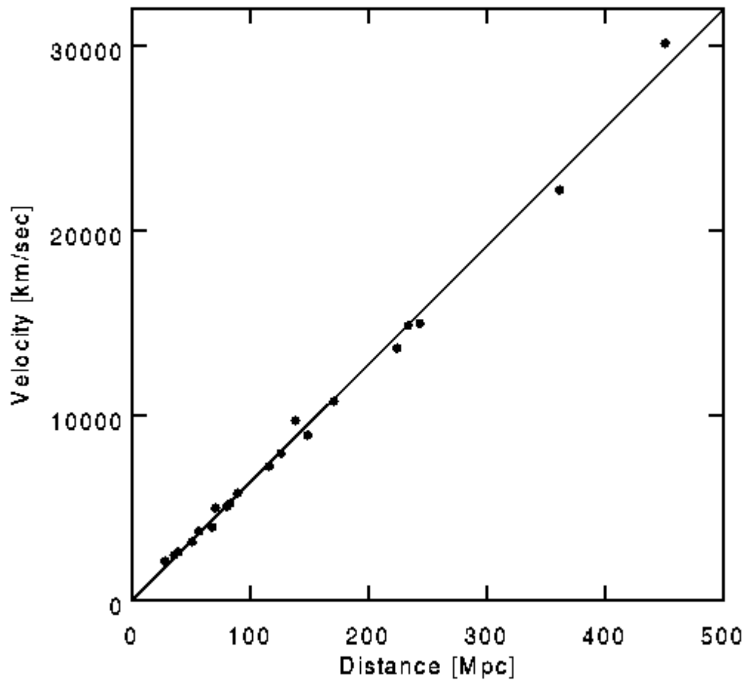


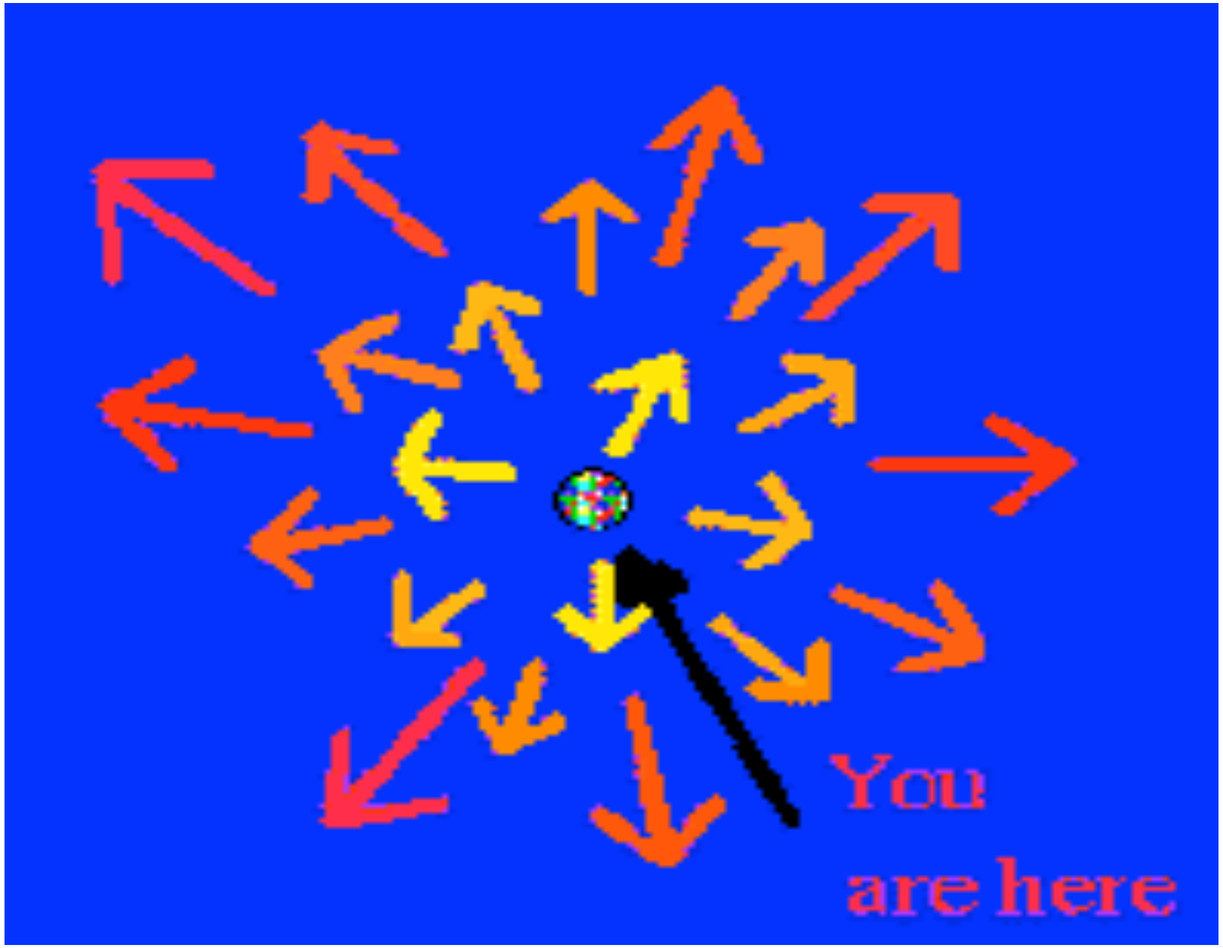
Fig. 1.10. The original 1929 version of the Hubble diagram shows the radial velocity of galaxies as a function of their distance. The reader may notice that the velocity axis is labeled with errornous units – of course they should read km/s. While the radial (escape) velocity is easily measured by means of the Doppler shift in spectral lines, an accurate determination of distances is much more difficult; we will discuss methods of distance determination for galaxies in Sect. 3.6. Hubble has underestimated the distances considerably, resulting in too high a value for the Hubble constant. Only very few and very close galaxies show a blueshift, i.e., they move towards us; one of these is Andromeda (= M31)





- Hubble diagram using supernova data assuming supernovae are standard candles (Riess 1996)

Expanding universe



- In our local universe it is observed that the universe expands following the 'Hubble law'
- (*) Hubble law: $v = H_0 D$

  v: velocity [km/s], D: distance [Mpc], Hubble constant H_0 = 73 km/s/Mpc*

  * Spergel, D.N. et al. 2007. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology. ApJS 170, 377-408.
- Distances are difficult to measure, but velocities are easy
- (**) Define redshift:

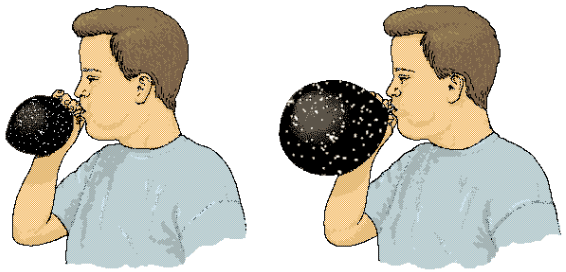
$$z := \frac{\lambda_{\mathrm{obs}} - \lambda_0}{\lambda_0}, \qquad \lambda_{\mathrm{obs}} = (1+z)\lambda_0$$

- Combining (*) and (**): from a measured redshift follows a distance:

$$D \approx \frac{zc}{H_0} \approx 4100z\,\mathrm{Mpc}$$

Expanding universe

- Space it self is expanding, there is NO center of expansion

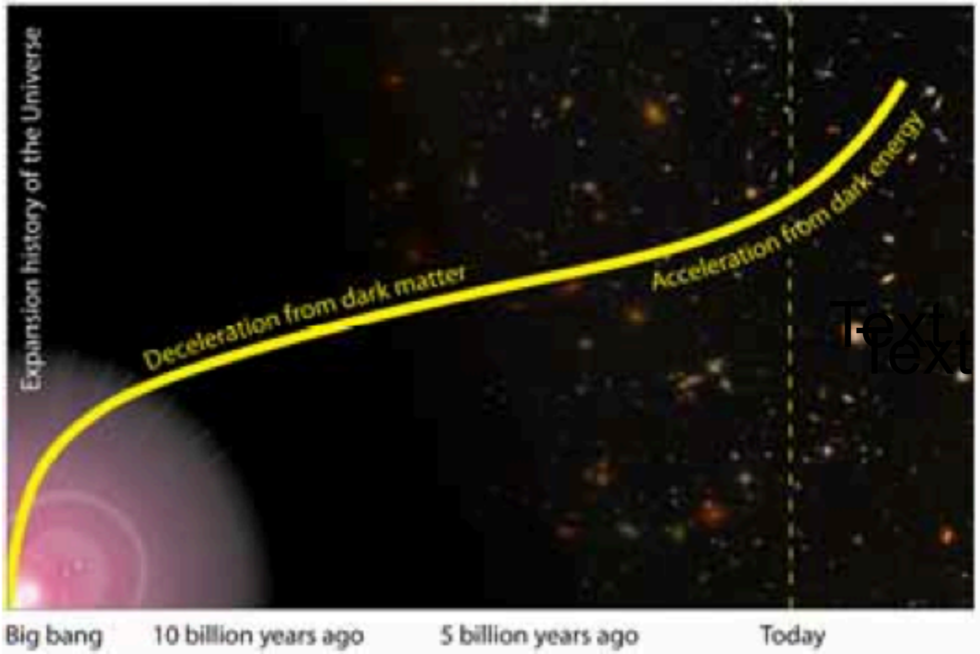


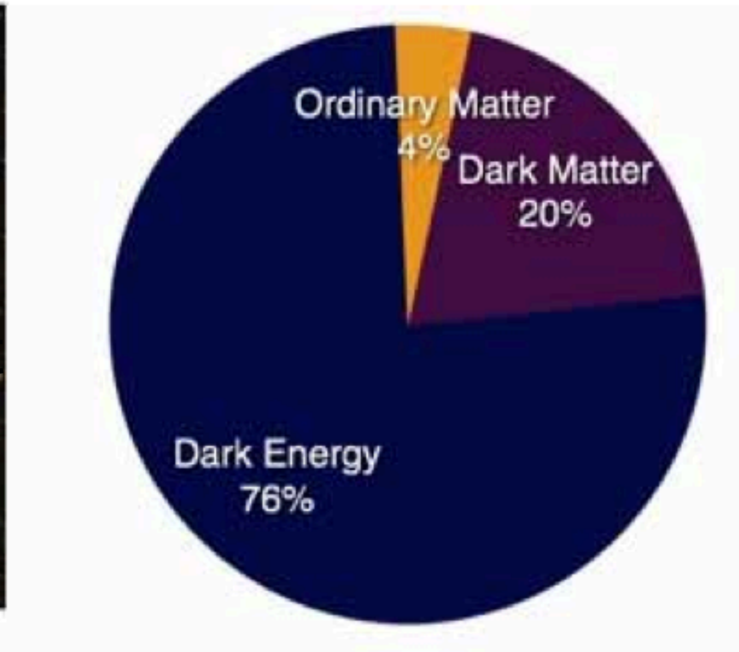
Draw spots on a balloon to represent galaxies in the universe.

As you blow up the balloon, the "galaxies" move further apart.

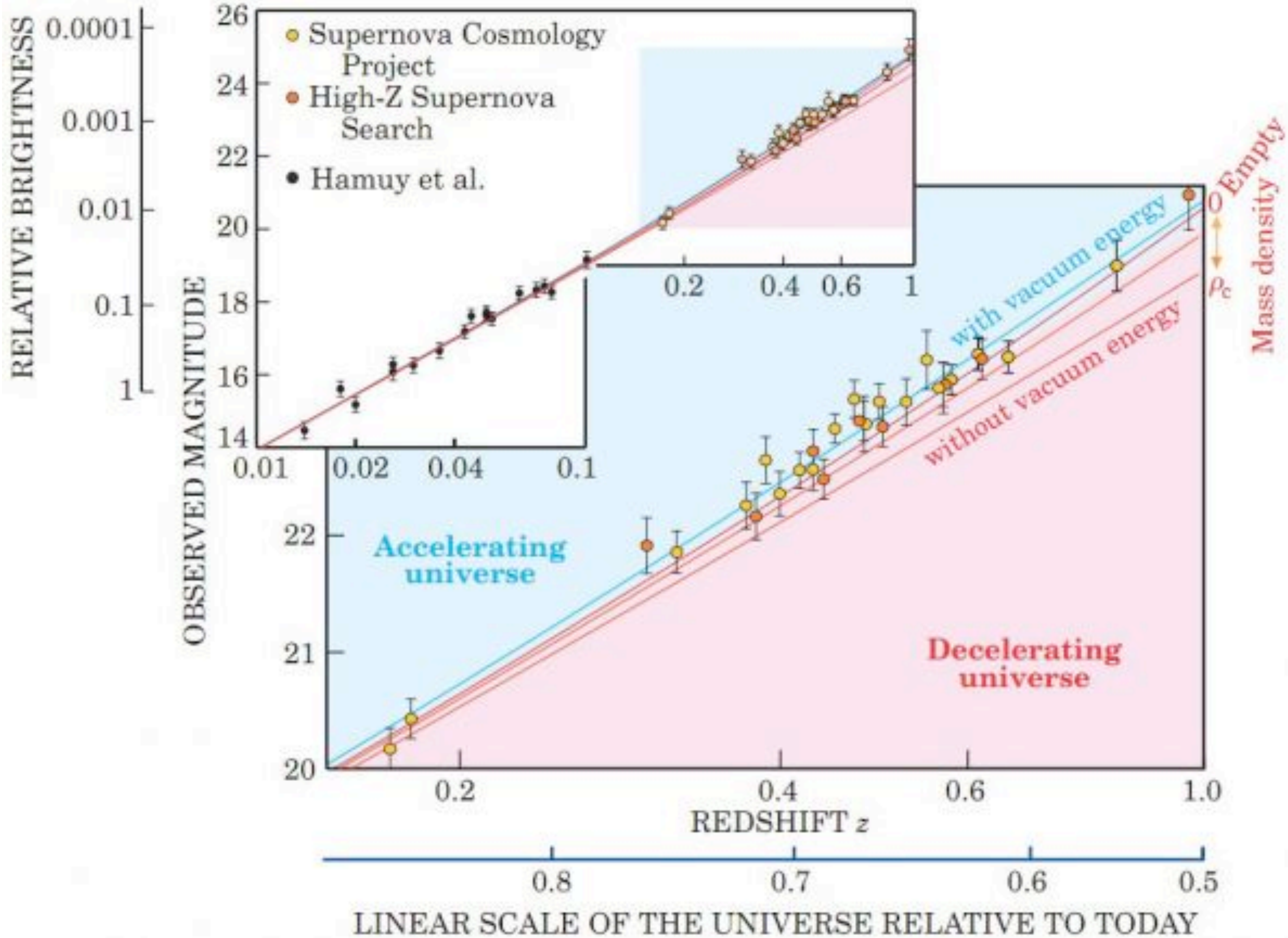
- General relativity gives a good description, but with Newtonian dynamics we will find a good approximation
- With description of the expansion we can determine:
  - the age of the universe
  - mass and energy density of the universe
- and with a measured recession velocity of a galaxy, we can determine:
  - the age of the universe when the galaxy emitted the photons we receive now
  - its distance and physical size

Dark matter decelerates expansion
Dark energy accelerates expansion





nature dark matter and dark energy profound mystery

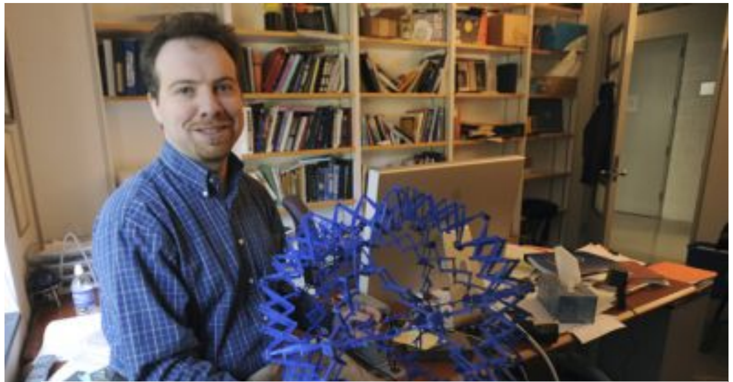


http://physicsforme.wordpress.com/2011/10/04/supernovae-dark-energy-and-the-accelerating-universe/

SCIENCE - SCITECH

Three Americans Share 2011 Nobel Peace Prize in Physics

Published October 04, 2011 | Associated Press



AP Photo/The John D. and Catherine T. MacArthur Foundation, Gail Burton

The Royal Swedish Academy of Sciences says American Saul Perlmutter, U.S.-Australian citizen Brian Schmidt and U.S. scientist Adam Riess (pictured here in 2008) share the 2011 Nobel Prize in physics. The trio were honored Tuesday, Oct. 4, 2011 "for the discovery of the acclerating expansion of the universe through observations of distant supernovae."

STOCKHOLM – Three U.S.-born scientists won the Nobel Prize in physics Tuesday for discovering that the universe is expanding at an accelerating pace, a stunning revelation that suggests the cosmos will eventually freeze to ice.

The Royal Swedish Academy of Sciences said American Saul Perlmutter would share the 10 million kronor ($1.5 million) award with U.S.-Australian Brian Schmidt and U.S. scientist Adam Riess. Working in two separate research teams during the 1990s -- Perlmutter in one

Primordial nucleosynthesis

Time since the Big Bang	Reactions	Description
< 1 s	$p + e^- \rightleftharpoons n + \nu_e$, $n + e^+ \rightleftharpoons p + \overline{\nu}_e$	Neutron–proton freeze-out sets the subsequent neutron–proton ratio.
$\sim$1–100 s	$n \rightarrow p + e^- + \overline{\nu}_e$	Neutrons then decay.
$\sim$100–200 s	$p + n \rightleftharpoons D + \gamma$	The reason why there are any neutrons left in the Universe is nuclear reactions that create stable deuterium nuclei, which allow further reactions.
$\sim$200–1000 s	$D + n \rightarrow {}^3_1H + \gamma$, ${}^3_1H + p \rightarrow {}^4_2He + \gamma$, $D + p \rightarrow {}^3_2He + \gamma$, ${}^3_2He + n \rightarrow {}^4_2He + \gamma$, $D + D \rightarrow {}^3_2He + n$, $D + D \rightarrow {}^3_1H + p$, ${}^3_1H + D \rightarrow {}^4_2He + n$, ${}^3_2He + D \rightarrow {}^4_2He + p$	Deuterium burning exceeds deuterium creation. The net effect of these deuterium burning reactions is $D + D \rightarrow {}^4_2He + \gamma$.

Serjeant, p. 51

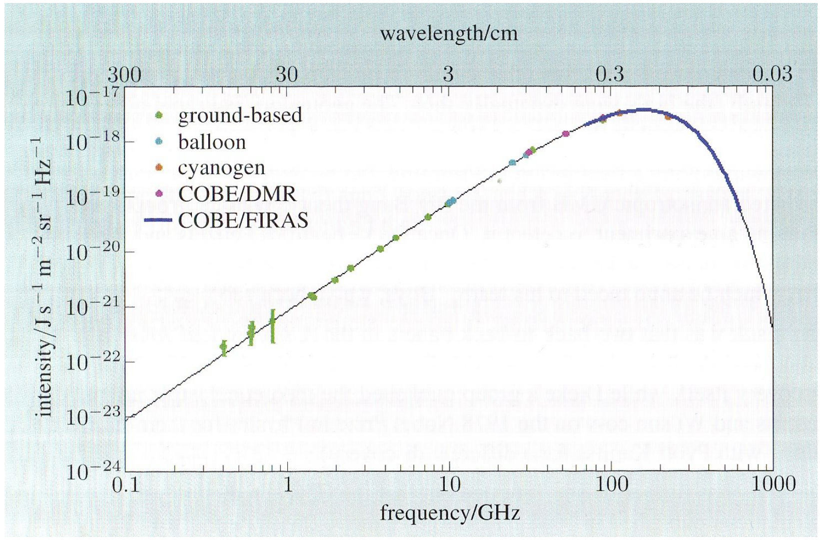
About 1/4 of the baryonic mass is predicted to be He^{4}, formed 3 minutes after the big bang. This is consistent with observations.

Early universe

- Temperature of radiation field in the universe inversely proportional to scale of universe: when the universe was 10 times smaller, then the temperature was 10 times higher.
- Observed is the Cosmic microwave background:

  Fits an almost perfect black-body

  curve with T=2.725 ± 0.001K



Serjeant, p. 41

- 380,000 years ago, the universe was a 1000 times smaller and T=3000K: most hydrogen was ionised and photons were continuously scattered by electrons
- Around this time, hydrogen recombined and the universe was opaque
- Subsequent expansion lowered the temperature T of the photons down to T=3 K in the present universe.

Mapping the CMB

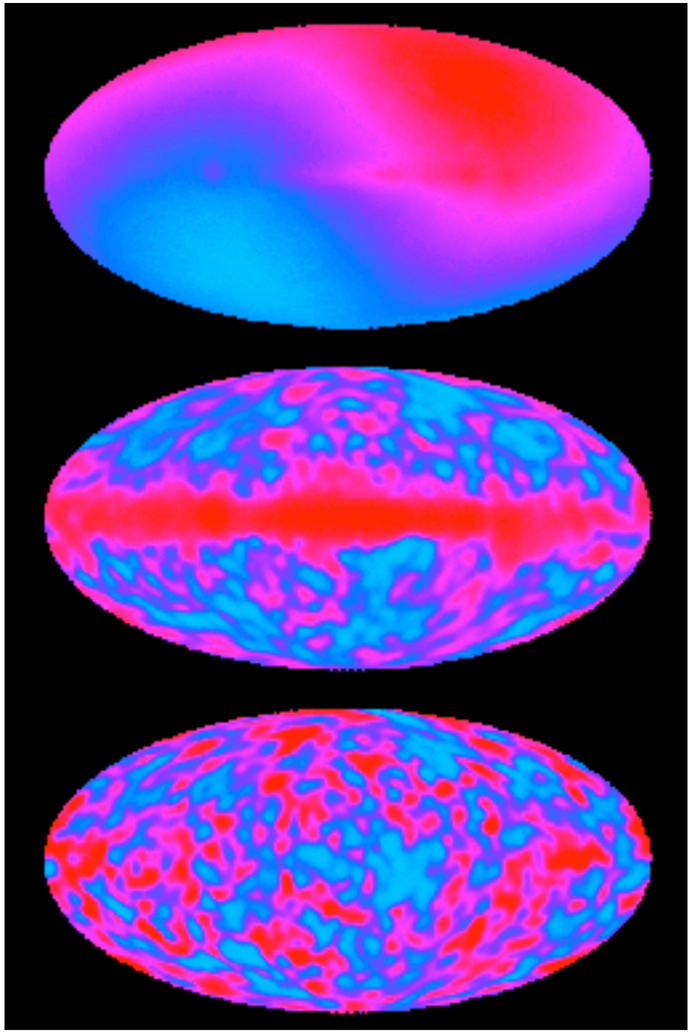


Fig. 1.17. Temperature distribution of the cosmic microwave background on the sky as measured by the COBE satellite. The uppermost image shows a dipole distribution; it originates from the Earth's motion relative to the rest-frame of the CMB. We move at a speed of $\sim 600\,\mathrm{km/s}$ relative to that system, which leads to a dipole anisotropy with an amplitude of $\Delta T/T \sim v/c \sim 2 \times 10^{-3}$ due to the Doppler effect. If this dipole contribution is subtracted, we get the map in the middle which clearly shows the emission from the Galactic disk. Since this emission has a different spectral energy distribution (it is not a blackbody of $T \sim 3\,\mathrm{K}$), it can also be subtracted to get the temperature map at the bottom. These are the primordial fluctuations of the CMB, with an amplitude of about $\Delta T/T \sim 2 \times 10^{-5}$

Large scale structure in the universe evolved from small density fluctuations imprinted in the cosmic microwave background

Cosmology as a triumph of the human mind

- Validity models
  - up to when the universe was 10^{-6} sec old, T=10^13 K
  - GR tested in binary pulsars with scales of 10^{11} cm and over the scale of the universe 10^{23} cm, ie over 10^{17} orders of magnitude.
- Discussion: why should the physical laws apply in the distant universe?

Main questions on the content of the Universe:

What is the structure of galaxies ?
- Of what components are they made off ?
- How is this distributed?
- What are the motions?

How do AGN work?
- What kind of AGN exist?
- What components are they made off?
- What physical processes play a role?
- How are they fed?
- What is their impact on their environment?
- How are the family relations?-> unifications

What are the properties of matter between galaxies?

What is the structure of Clusters of galaxies
- Of what components are they made off ?
- How are these distributed?
- What are their motions?

What is a good description of Large Scale structure?

Key questions

Origin?
Evolution?

Brief content of the course I

1) Introduction and Overview - 30 jan

2) Space and Time I - 6 feb

Expanding Universe, Newtonian derivation of the Friedmann-Lemaitre expansion equations, components of matter in the Universe

3) Space and Time II - 13 feb

Consequences Expanding Universe: Necessity of the a Big Bang, Redshift, Age of the universe, Distances in the universe.

4) Early Universe - 20 feb

Thermal history, Decoupling Neutrinos, Pair Annihilation, Primordial nuclear synthesis, Cosmic microwave background, Reionization

5) The local Universe I - 27 feb

Hubble tuning fork,

Ellipticals: classification, brightness profiles, composition,
dynamics, evolution

Spiral galaxies: classification, brightness profiles, composition,
rotation curves and dark matter,

Stellar content, star formation rate, star formation history,
population synthesis

Luminosity functions

Scaling relations: Tully-Fisher relation, Faber-Jackson relation, Fundamental plane, D_n-sigma

6) The Local Universe II - 5 maart

Statistical relations: Morphology-density relation, colour - magnitude diagram, mass - size

Black holes in the center of Galaxies: Searches, some properties, relation properties black hole and hosting galaxy

AGN zoology, building blocks, unification, some important results

Clusters of galaxies, general properties, cooling flows

Large scale structure of the universe: : clusters, filaments, voids,

(optional: two point correlation functions, baryon wiggles)

7) Gravitational forces and potentials - 12 maart

Poisson equation; Potential for spherical systems; Newton's Theorems; Simple potentials

8) Stellar dynamics - 19 maart

Importance of (stellar) dynamics
Equations of motion, Do stars collide? Virial Theorem, Application:
Galaxy masses, Binding Energy and Formation of Galaxies, Scaling Relations,
Relevant Time scales

9) Orbits - 2 april

Orbits in spherical potentials, Constants and Integrals of motion,
Spherical and other potentials, Schwarzschild's method

10) Collisionless Boltzman equation - 16 april

Derivation, spherical systems, isotropic models, several examples.

11) Jeans equations - 23 april

Derivation, spherical models, isotropic models

Example: influence of central black hole on dynamic signatures.

Distant AGN: luminosity functions

AGN zoology, building blocks, unification, some important results

13) Galaxy formation - 14 mei

Modeling galaxy formation and evolution: merger trees, cooling, feedback, mergers, feedback.

Confronting observations with models.

Possible additional topic: Ly-alpha forest and damped Ly-alpha systems.

14) Summary - 21 mei

Brief content of the course II

8) March 14: *Collisionless Boltzman equation*

9) March 28: *Jeans equations*

10) April 4: *Isotropic and anisotropic models, some applications*

11) April 18: *The distant optical universe*
Source counts, Cold dark matter and structure formation, Population synthesis, Photometric and spectroscopic redshifts, Luminosity functions, Active galaxies, Surveys

12) May 9: *Distant multi-wavelength universe*
Infrared background light, sub-mm galaxies, Infrared galaxies, Star formation rates, Cosmic starformation history and stellar mass assembly, Downsizing, Feedback

13) May 23: *Black holes*
What are black holes?, Eddington limit, Accretion efficiency, Cosmic mass density, Finding BHs, Magorrian relation, X-ray background, Feedback, Merging black holes

14) May 30 (if time permits): *Intervening universe*
Lymanα-forest, Damped Lyα systems

1. Home work questions

1. What value did Spergel et al. 2007 find for the age of the universe? What was the error?

   See: Spergel, D.N. et al. 2007. Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology. ApJS 170, 377-408.

2. Have a look at

   http://www.esa.int/SPECIALS/Herschel/SEMY1K0SDIG_0.html

   Braun, R. et al. 2009, ApJ, 695, 937B A Wide-Field High-Resolution H I, Mosaic of Messier 31. I. Opaque Atomic Gas and Star Formation Rate

   at what wavelength has M31 the largest observed angular size?

3. Find a recent press release on an HST deep field.

   What colours were used to produce the image?

   What angular size on the sky did the image have?

   How many galaxies could be detected?

4. What is the angular size of the largest radio source know?

   How does it compare to the moon?

5. Find the original data from the original 1929 paper for Fig 1.10 (page 10) in Schneider and remake the plot using IDL. Give a printout of the program.
6. Give three questions that you would like to see discussed in this lecture series.