NORMAL AND STARBURST GALAXIES
PAUL NANDRA

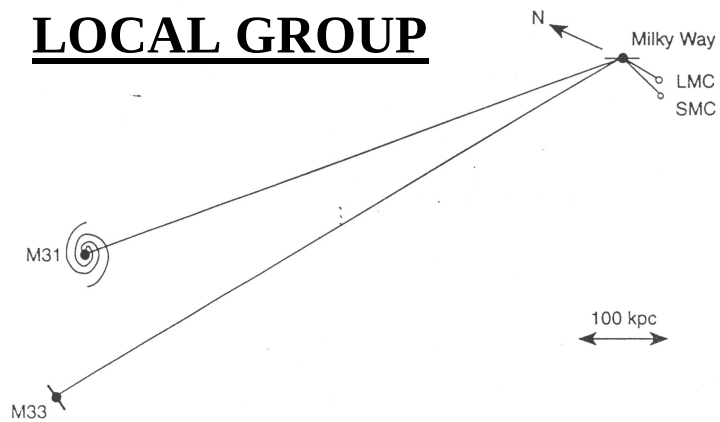
OVERVIEW

- Classification
- General properties
- X-ray properties
- Starburst Galaxies
- Hot gas in ellipticals
- Rotation curves, dark matter and black holes

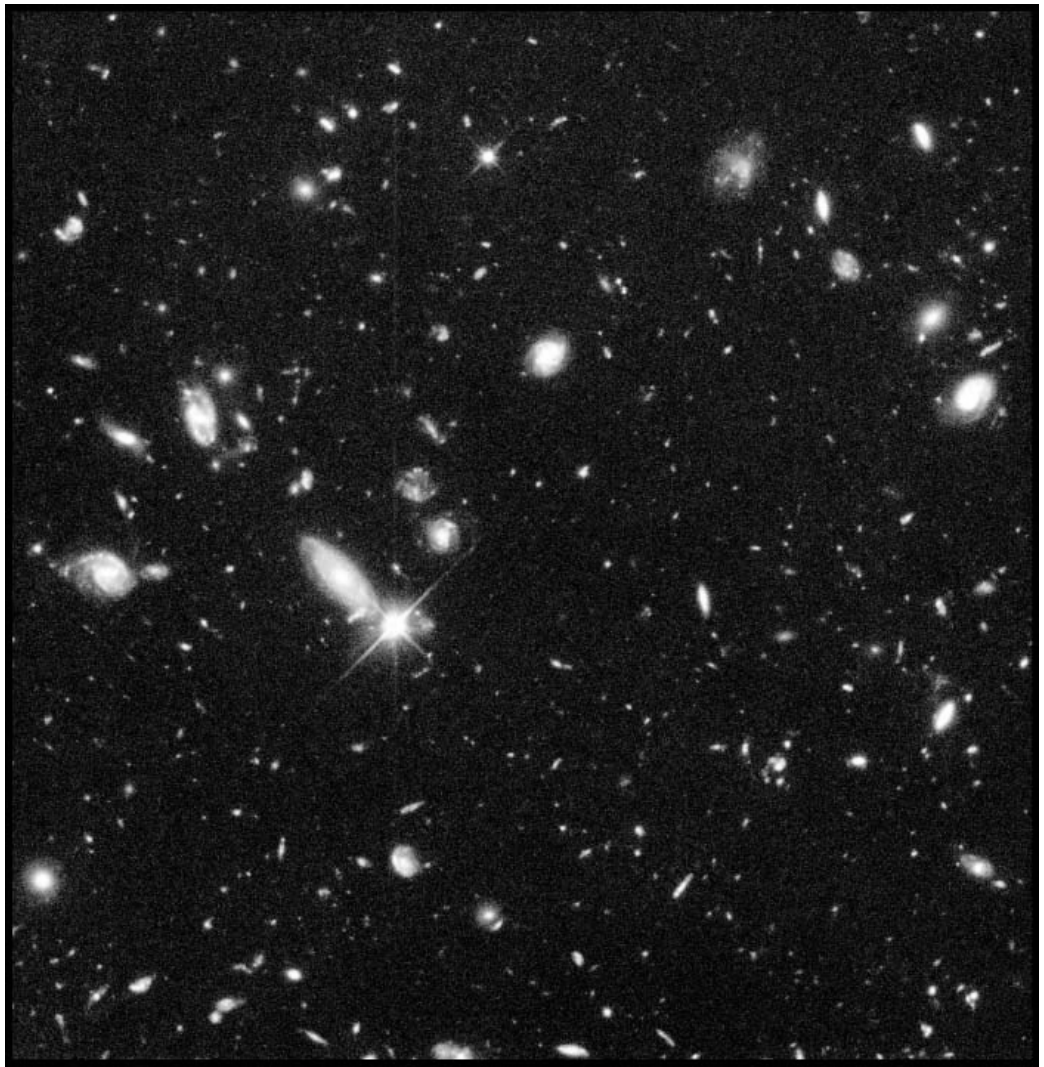
THE SHAPLEY-CURTIS DEBATE
(e.g. Shu in "The Physical Universe")

- Until about 1920, distances to "faint nebulosities we now know as galaxies were unknown, as was their nature
- Controversy was resolved in 1923 by Edwin Hubble who observed Cepheid variables in M31 (The Andromeda Galaxy). He inferred a distance of $d = 2 \times 10^6$ light years – definitely outside our galaxy.
- There are now estimated to be $>10^{10}$ galaxies in the observable universe

LOCAL GROUP



LMC = Large Magellanic Cloud
SMC = Small Magellanic Cloud
M31 = Andromeda Galaxy



Hubble Deep Field HST • WFPC2

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

MORPHOLOGICAL CLASSIFICATION OF NEABY GALAXIES

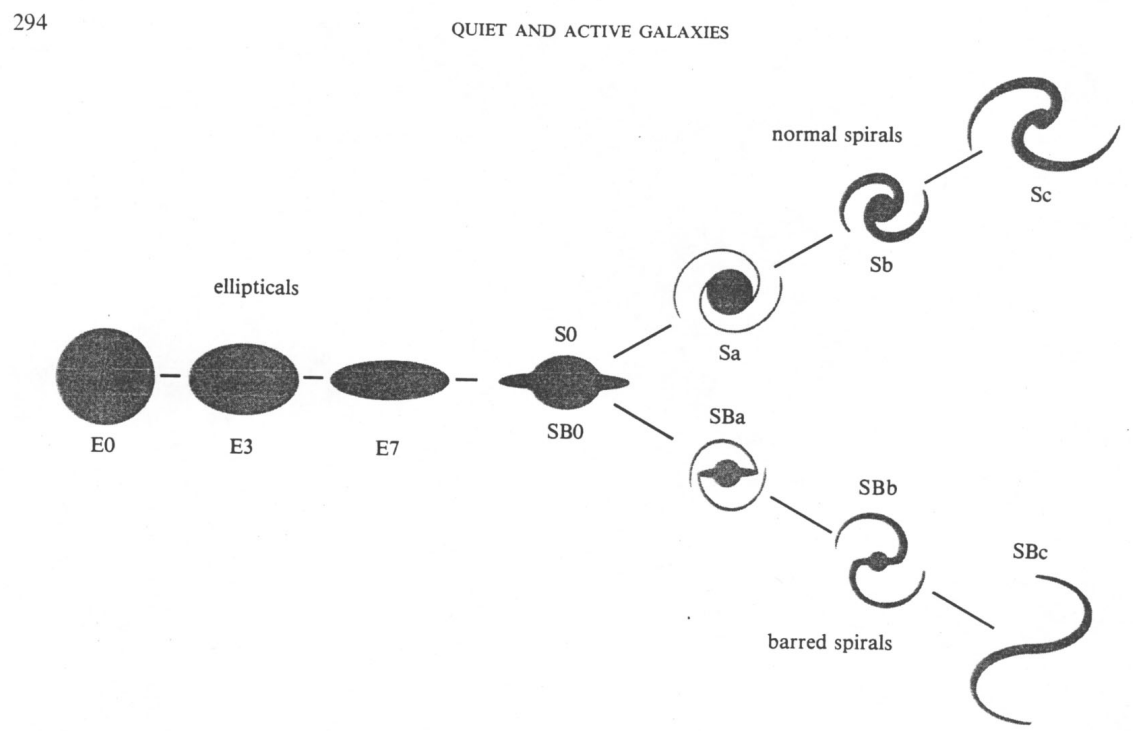
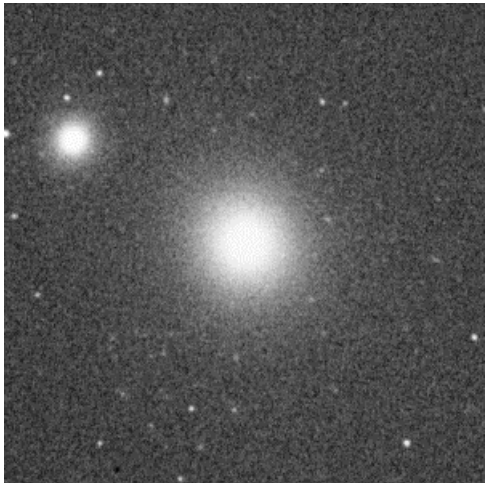


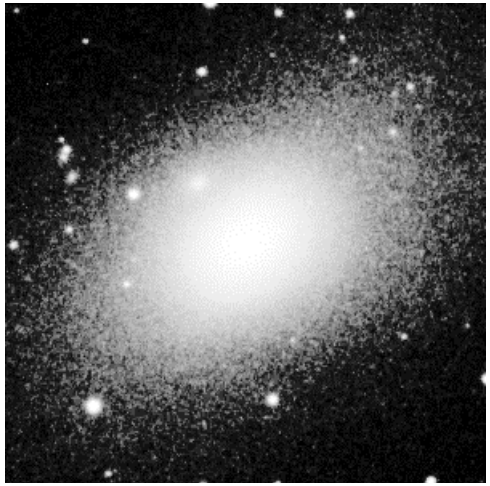
Figure 13.7. Hubble's tuning-fork diagram for the classification of regular galaxies.

Morphology less certain for distant (forming?) galaxies at high redshift like HDF

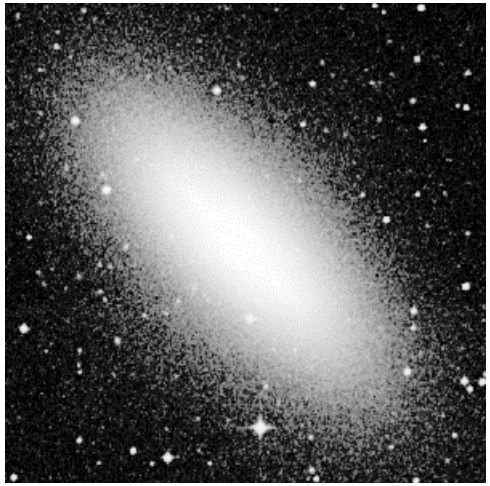
ELLIPTICAL GALAXIES



NGC 4278
E1



NGC 4406
E3

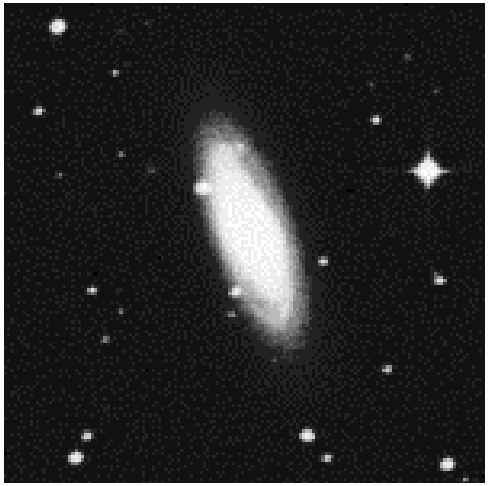


NGC 3115
E7

En=10(1-b/a)
a=major axis
b=minor axis

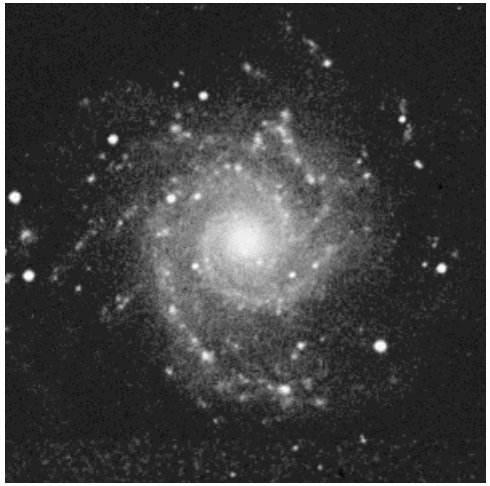
http://skyview.gsfc.nasa.gov/

SPIRAL GALAXIES



NGC 2811
Sa

NGC 3031
Sb



NGC 628
Sc

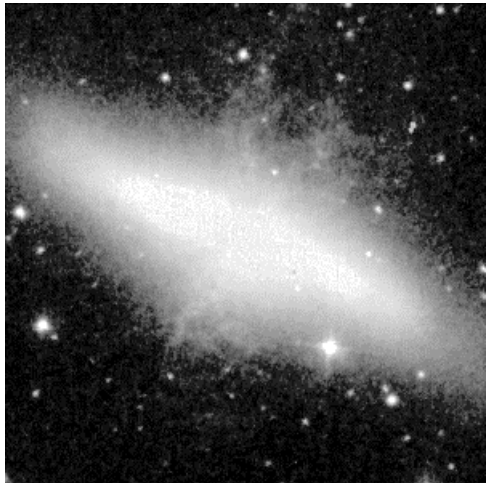
Sa → Sc:
large → small bulge
tight → loose arms

http://skyview.gsfc.nasa.gov/

EVEN MORE GALAXIES

NGC 1300
SBb

NGC 6822
Irregular



M82
Starburst

En=10(1-b/a)
a=major axis
b=minor axis

http://skyview.gsfc.nasa.gov/

SPIRALS vs. ELLIPTICALS

- *Ellipticals:* no evidence for young stars in – mostly old, metal poor ("pop II") stars. *Spirals:* young, metal rich stars ("pop I") in spiral arms and pop I+II in bulge
- Thought to be little gas and dust in ellipticals
- Stellar velocities in spirals dominated by rotation. This causes the flattening. In ellipticals mostly random velocities, so rotation does not account for E-sequence flattening (rather anisotropy).
- No spiral structure in ellipticals

PROPERTIES OF GALACTIC TYPES

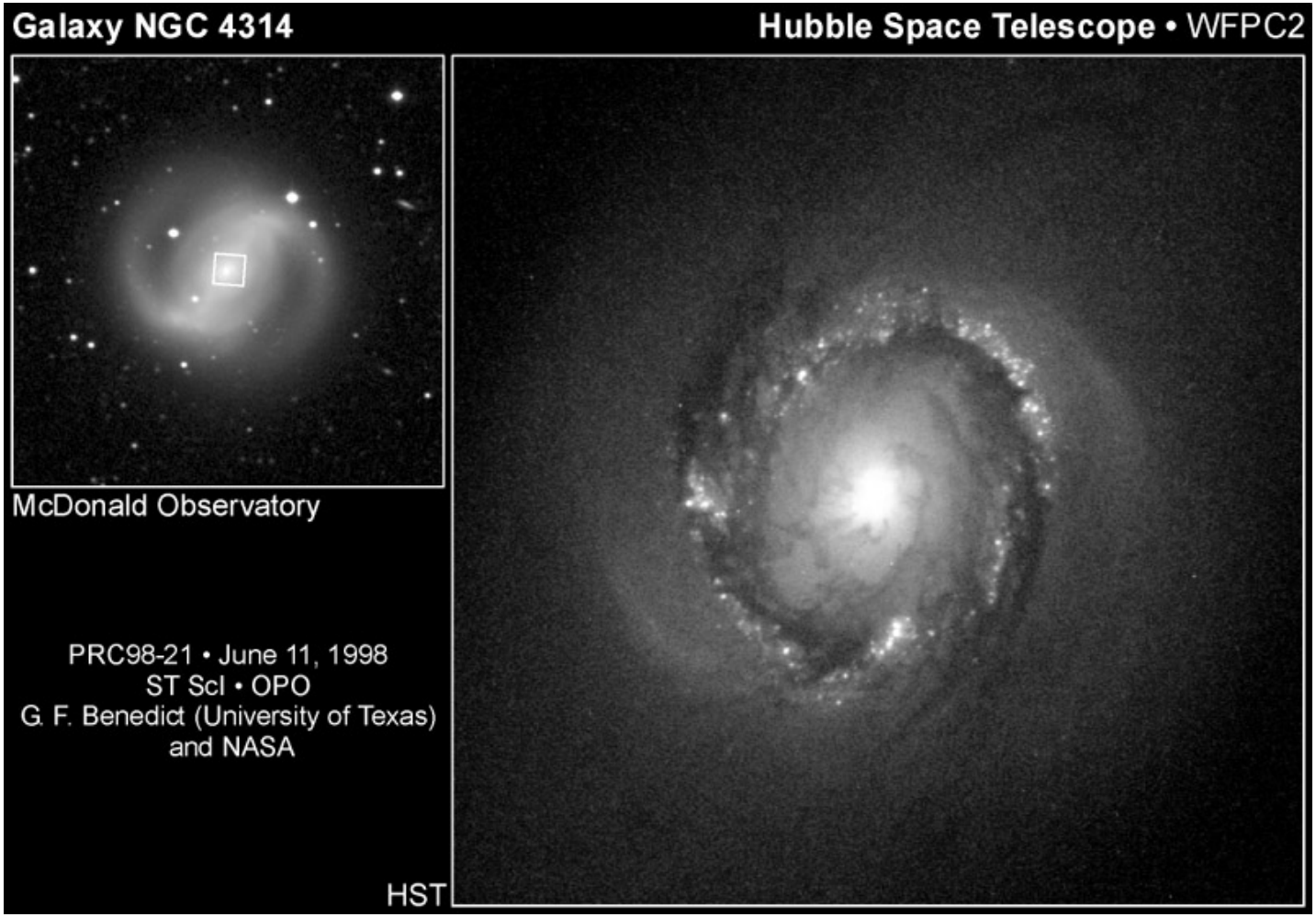
Adapted from Table 21-2 in *Discovering Astronomy*,Robbins, Jefferys & Shawl 1995 (John Wiley and Sons, Inc: New York)

Property	**Elliptical**	**Spiral**	**Irregular**
ISM			
Gas	Little	Substantial	Substantial
Dust	Very little	Substantial	Yes
Stars			
Star formation	Very little	Yes	Yes
Population I*	No	Yes	Yes
Population II	Yes	Yes	No
Oldest stars	10^{10} years	10^{10} years	10^{10} years
Youngest stars	10^{10} years	Newly formed	Newly formed
Spectral types	G-K	A-K	A-F
Other			
Rotation	Low or none	High	Yes and no
Color	Reddish	Blueish disk, reddish halo/bulge	Blueish
Macroscopic (c.f. Milkyway)**			
Diameter	0.03-10	0.3-3	0.05-0.5
Luminosity	5×10^{-5}-10	0.01-2	10^{-4}-10^{-2}
Mass	10^{-5}-50	0.01-2	10^{-3}-0.5

*Pop I: young, disk, metal rich
Pop II: old, nucleus, halo, metal poor

**D_{MW} ~ 30kpc ~ 10^{26} cm
L_{MW} ~ 1.3 10^{10} L_{sun} ~ 5 10^{43} erg s^{-1}
M_{MW} ~ 2 10^{11} M_{sun} ~ 4 10^{44} g

STAR FORMATION IN SPIRAL ARMS



SURFACE BRIGHTNESS PROPERTIES

- De Vaucoulers found empirical law for surface brightness of ellipticals:

$$L(r)=L(0)\ \exp[-(r/r_0)^{1/4}]$$

r=distance from center

L(0)=Central surface brightness

r_0=scale length

Also obeyed in spiral bulges; large variation in r_o, as galaxies have a wide range of sizes - but not much in L(0)

Typical number: $L(0)\sim 2 \times 10^4\ L_{sun}/(\text{lt yr})^2$

This does not hold for dwarf galaxies, however

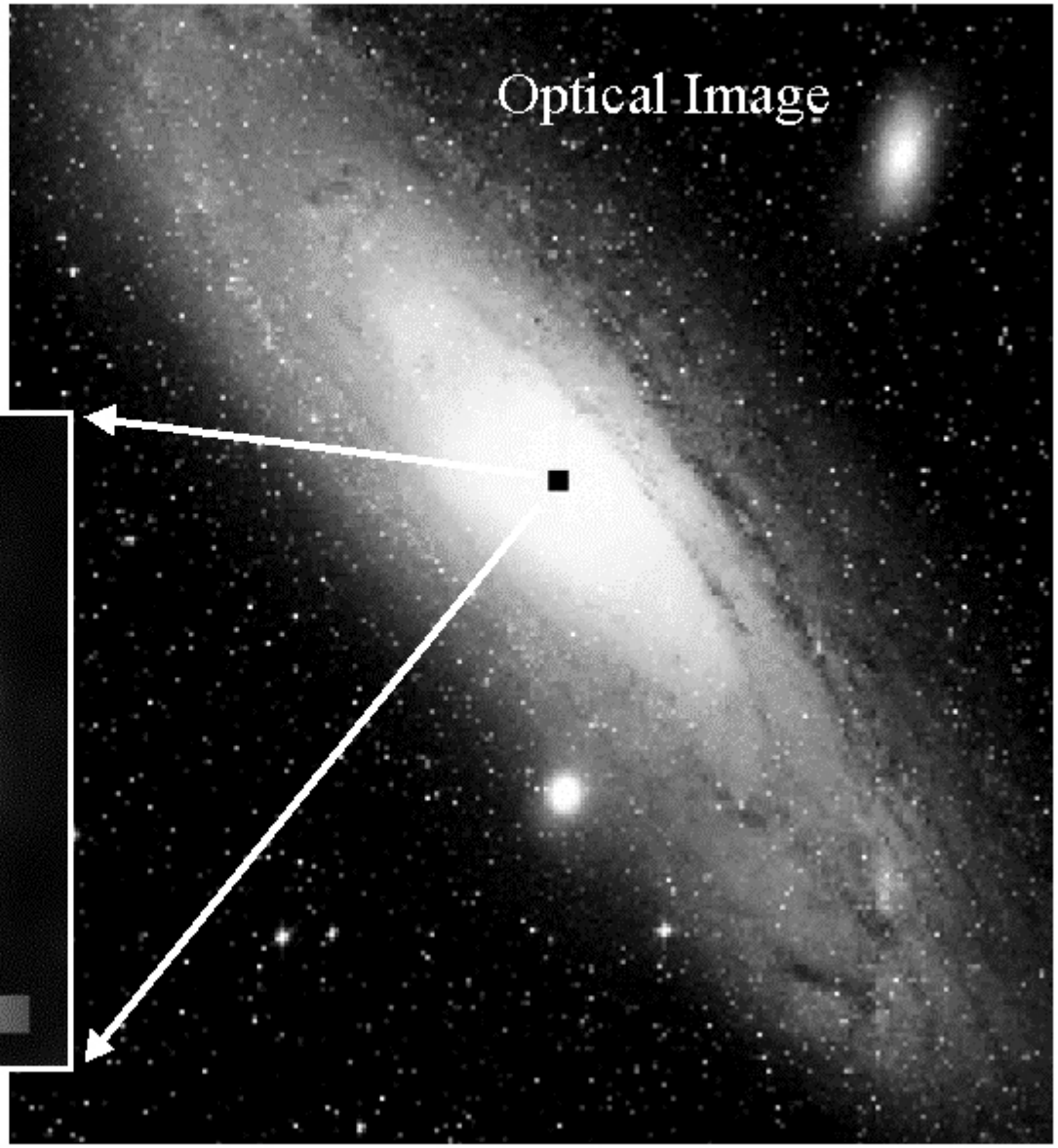
- In spiral disks the azimuthally averaged surface brightness follows

$$L(r)=L(0)\ \exp(-r/r_0)$$

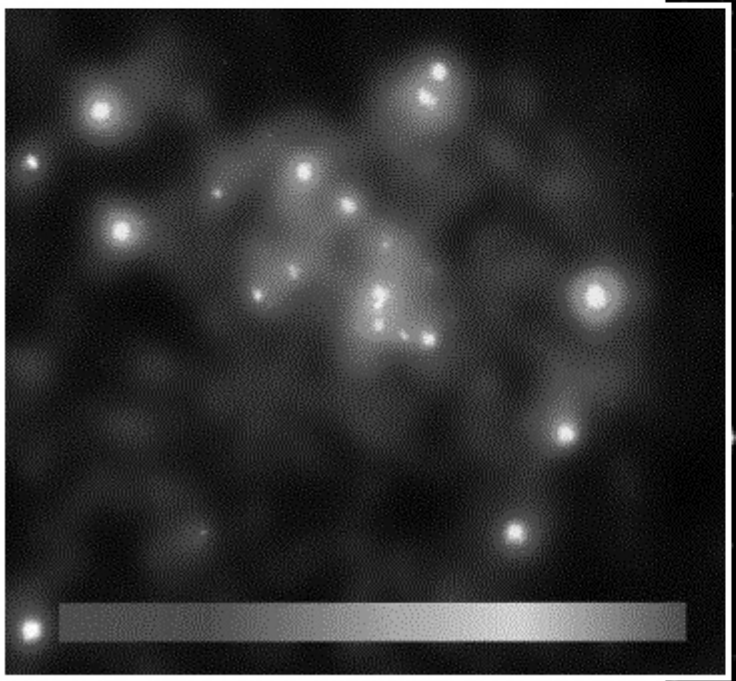
X-ray emission of galaxies

- Typical galaxy luminosity $L_X \sim 10^{39\text{-}40}$ erg s^{-1}
- Diffuse emission from hot gas
  - starforming and elliptical galaxies
- Accreting binaries (Black holes, Neutron stars, white dwarfs) $L_X \sim 10^{38}$ erg s^{-1} or even more!
- Supernova remnants ($L_X \sim 10^{36}$ erg s^{-1})
- A few of these bright X-ray sources typically dominate the general emission of normal/active stars (10^{26} – 10^{33} erg s^{-1})

M31: The Andromeda Galaxy



Chandra
X-ray Image



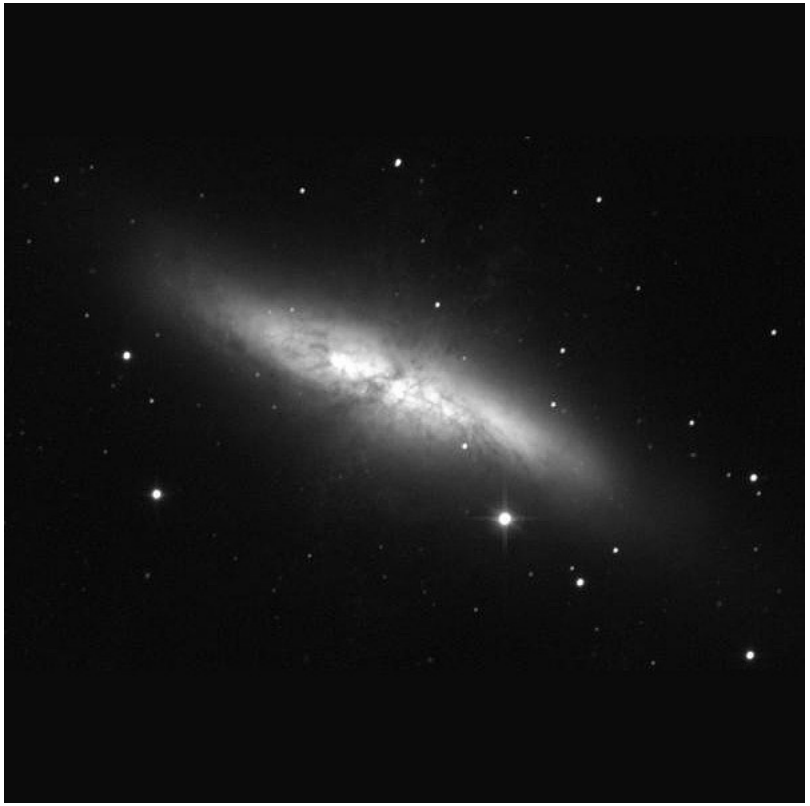
1 million K 20 million K

DISCRETE X-RAY SOURCES

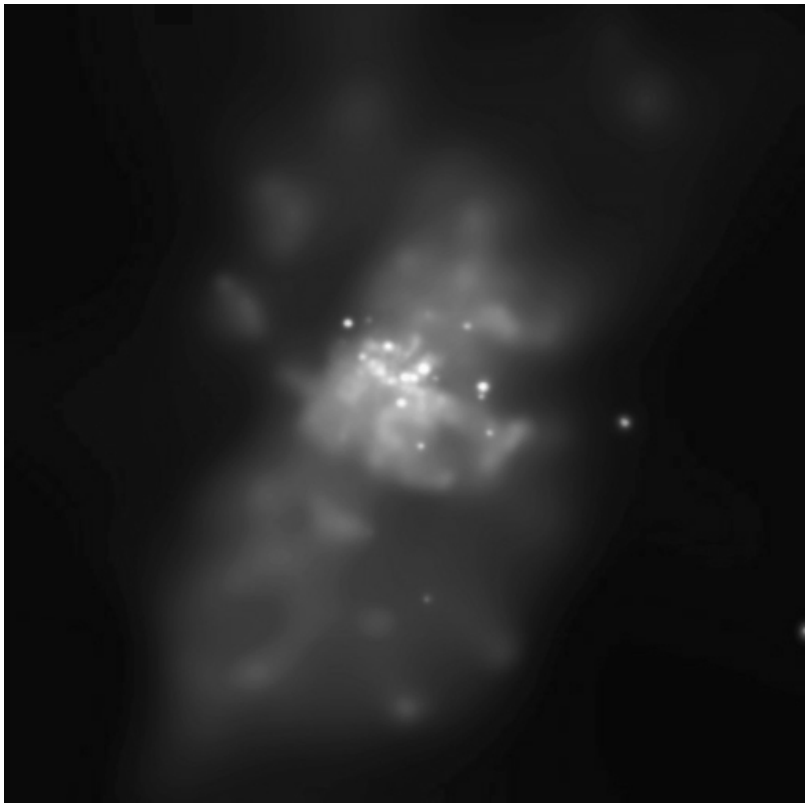
- Accreting binaries: Matter heated to X-ray temperatures due to gravitational potential
  - Black hole binaries (e.g. Cygnus X-1)
  - Neutron star binaries (LMXB, HMXB)
  - White dwarf (e.g. Cataclysmic Variables)
- Supernova remnants: matter heated to X-ray temperatures by shocks

STARBURST GALAXIES: M82

Optical



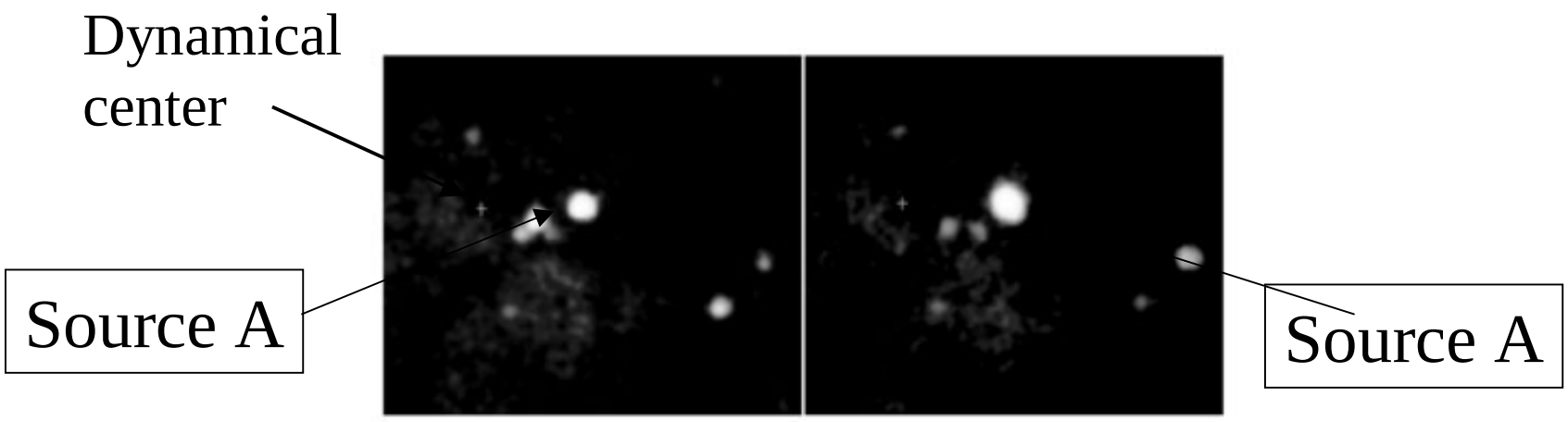
X-ray



X-ray point sources: SNR and binaries

Diffuse emission: Starburst-driven “superwind”

CHANDRA OBSERVATION OF M82



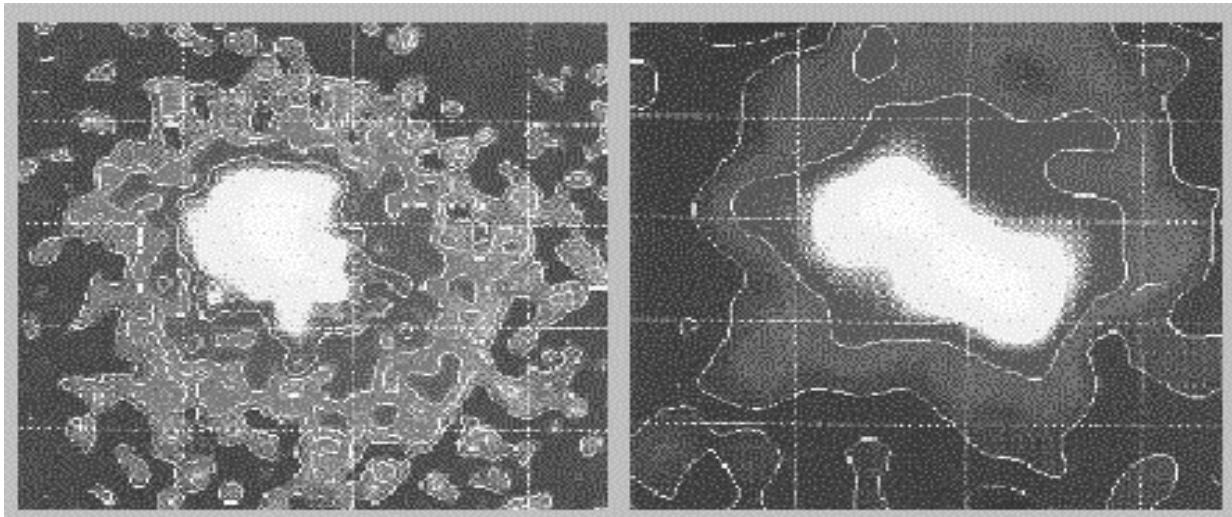
- Source A dominates the hard (2-10 keV) emission of M82
- It is VARIABLE on short time scales
- It is OFFSET from the dynamical center
- ***What is it?***

M82/Source A: Facts and Questions

- M82:
  - redshift z=0.000677
- Source A:
  - Offset = 9 arcsec
  - Var. time scale = 90 days
  - Flux = 1.4 10^{-10} erg cm^{-2} s^{-1}
- General
  - Hubble const. H_0=50 km s^{-1} Mpc^{-1}
  - Speed of light c = 3 x 10^{10} cm s^{-1}
- Formulae
  - $D_L = cz/H_0$ (luminosity distance)
  - $F = L/4\pi D_L^2$ (flux)
  - R = c t (light travel distance)
  - L_{edd} = 1.3 x 10^{38} $M/M_\odot$ erg s^{-1} (Eddington luminosity)

- How far away is M82?
- How far is source A from the center of M82?
- What is the luminosity of source A?
- What is the limit on the mass of source A from its luminosity?
- What is the limit on the size of source A from variability?
- *What is the limit on the mass of source A from variability?*

DIFFUSE GAS IN ELLIPTICALS



X–ray maps of the elliptical galaxy NGC4472, in 0.7 – 4 keV (left) and 4 – 10 keV (right), obtained with the *Asca* Observatory. The X–ray emission indicates the presence of hot plasmas of temperature 10 – 20 million K. The plasma is thought to be confined gravitationally, and total mass necessary for the confinement can be derived from the X–ray data. The total mass thus estimated significantly exceeds the estimated mass of stars and various gaseous components, thus providing evidence for the dark matter in these galaxies.

DIFFUSE GAS IN ELLIPTICALS

- Hot gas is confined gravitationally
  - Gas pressure balanced by gravitational "pressure" of mass in galaxy
- Implies missing mass or "*DARK MATTER*"
  - Census of mass in stars and gas is less than the mass required to confine the gas (2-5 times)
- Also implied from galaxy rotation curves

VIRIAL THEOREM

- In a gravitationally bound system (like a galaxy), the kinetic energy is equal to ½ the potential energy:

$$\frac{1}{2} mv^2 = \frac{1}{2} GMm/r \quad (KE = \frac{1}{2} PE)$$

OR

$$M(r) = r\, v^2/G$$

ROTATION CURVES

- By determining velocity as a function of radius v(r) one can determine the mass within that radius M(r). This can be compared to the mass in stars or gas.
- Velocities are measured by the Doppler width (broadening) of spectral lines ($v/c = \Delta\lambda/\lambda$):
  - E.g. 21cm hydrogen emission line
- This measures the line-of sight velocity. 3-dimensional velocity $v_{3d}=\sqrt{3}\, v_{los}$
  - Gives spread of random velocities of stars in ellipticals
  - Or rotational velocity of stars/gas in spirals
  - These should satisfy the virial theorem
- If galaxy is spatially unresolved, this width corresponds to maximum velocity
- If galaxy is spatially resolved, we get the rotation curve, v(r)

FINDING: ROTATION CURVES OF GALAXIES STAY FLAT AT LARGE RADII …but visible mass (light) falls of exponentially ⇒ **"DARK MATTER"**

ROTATION CURVE FOR MILKYWAY

Problems/Issues:

- Correction of order unity is required to account for the unknown 3-dimensional mass distribution. $M=rv^2/G$ strictly applicable to spherically symmetrical system
- Measurements of v are non-trivial as, e.g. lines from individual stars are broadened
- Only angular distance can be measured directly, not r, which depends on the (uncertain) distance to the galaxy

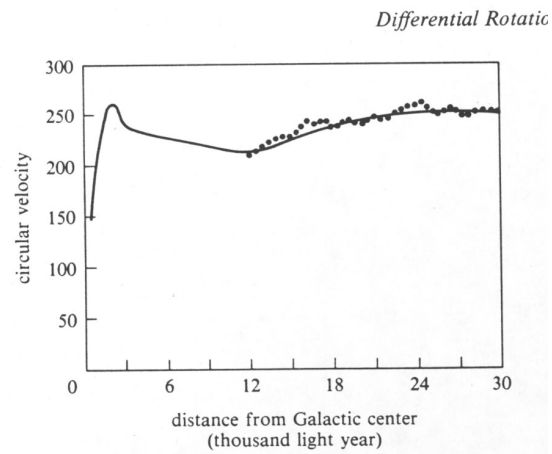
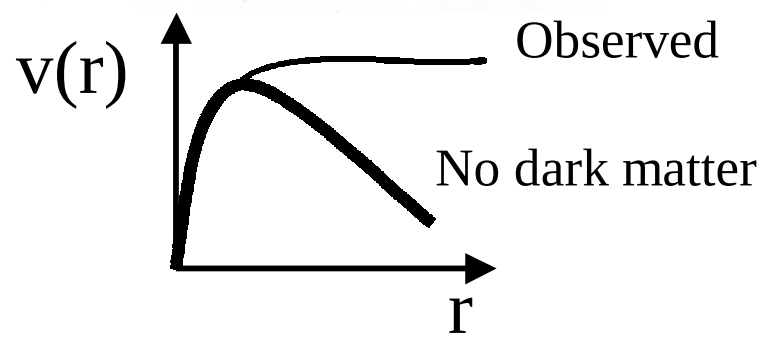


Figure 12.15. The rotation curve of the Galaxy obtained from 21-cm observations of the atomic hydrogen gas interior to the solar circle.

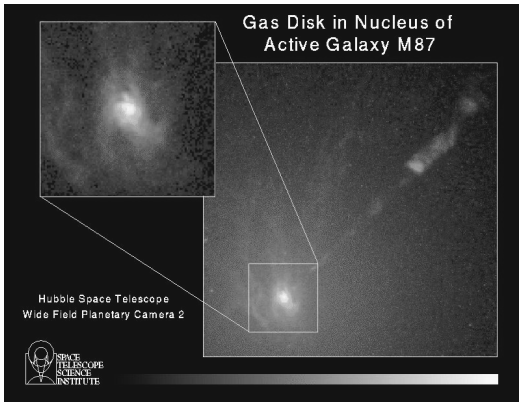


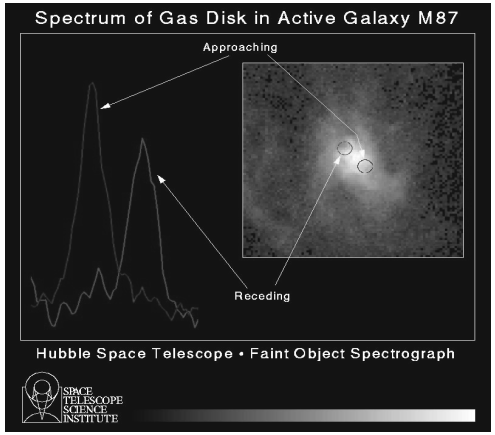
DARK MATTER CANDIDATES

- MACHOs: Massive Compact Halo Objects (e.g. black holes, brown dwarfs, dark stars?)
- WIMPs: Weakly Interacting Massive Particles (e.g. massive neutrinos)
- Exotic particles (undiscovered subatomic particles)
- Law of gravitation wrong at large distances (e.g. MOND – Modified Newtonian Dynamics)
- More…

DYNAMICS OF INNERMOST REGIONS

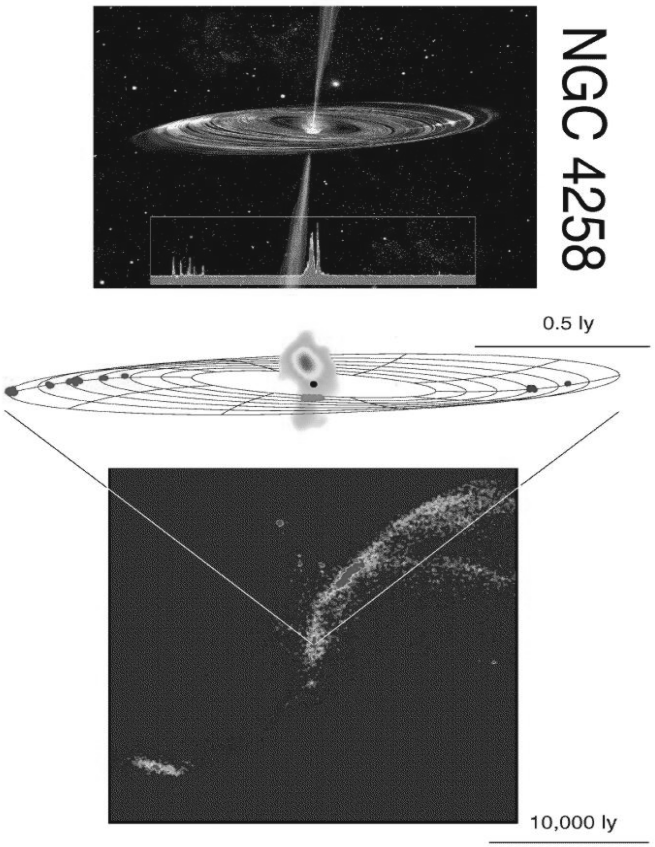
- Requires very high angular resolution (e.g. Hubble Space telescope or radio interferometry)
- M87: observed rotation of gas disk around nucleus
- Velocities rise in central region
- Inferred 1 billion solar masses from the rotation: **BLACK HOLE?**





KEPLERIAN ROTATION

- NGC 4258: Water MASER emission in a disk of molecular gas rotating around the centre of the galaxy.
- Disk observed at very high inclination (edge on)
- Inferred Keplerian rotation law for the orbiting gas.
- Implies 30 million solar masses within ~1 pc



ARE THERE BLACK HOLES IN ALL GALAXIES?