

Galaxies and Active Galactic Nuclei



Bits of C&M Chaps. 23, 24 and 25



1995: Hubble deep field taken with WFPC2 on HST during 150 orbits. 2.5 arc minutes across. 3000 galaxies. 1/28,000,000 of the total area of the sky.



2004: Hubble Ultra Deep Field (1/10 moon's extent) taken with ACS on HST during 400 orbits. 3 arc minutes across. 10,000 galaxies => 1000 billion galaxies over entire sky.

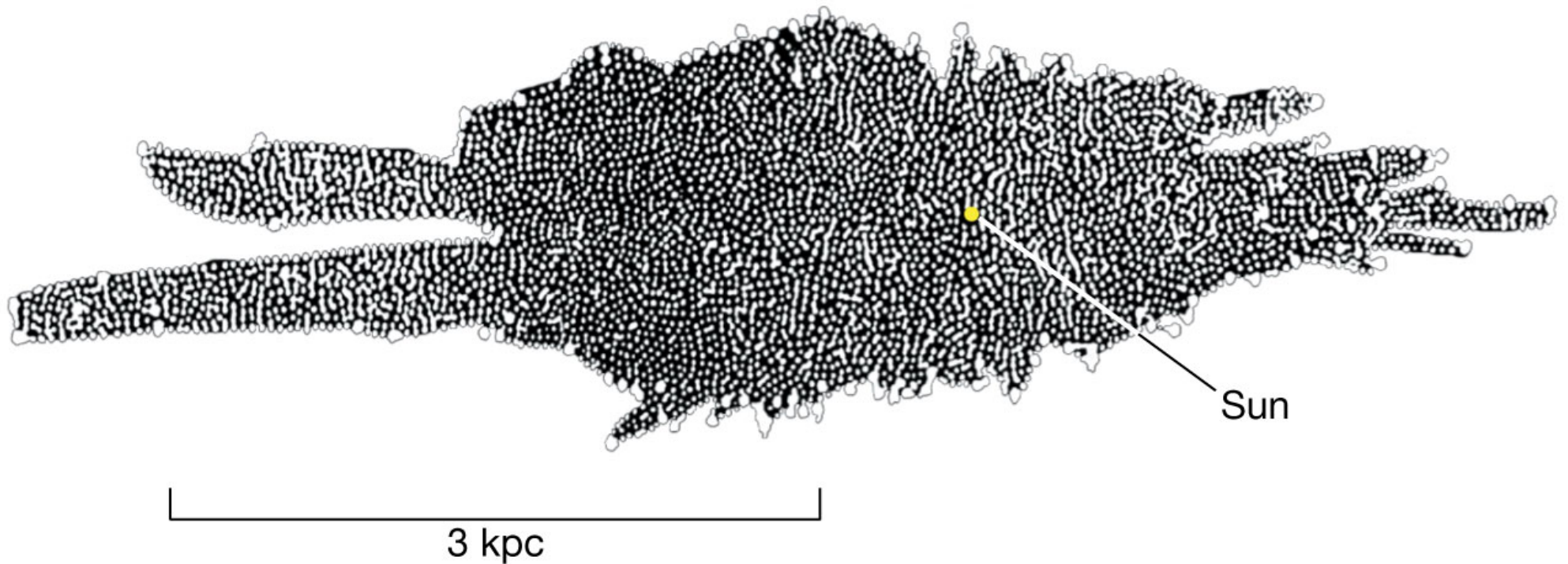
Hubble eXtreme Deep Field (HXDF) image in Sept. 2012. 23 days in the centre of the HUDF, adding an extra 5500 galaxies



From 1920 to the present day we have gone from knowing only one galaxy, to identifying trillions.



From geocentrism to heliocentrism, Galileo showed (early 1600s) that the Milky Way is a blur of unresolved stars.



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Mid 1800s, William Herschel counted stars to sketch the Milky Way. Put sun at the centre! Problem: dust blocks our view!

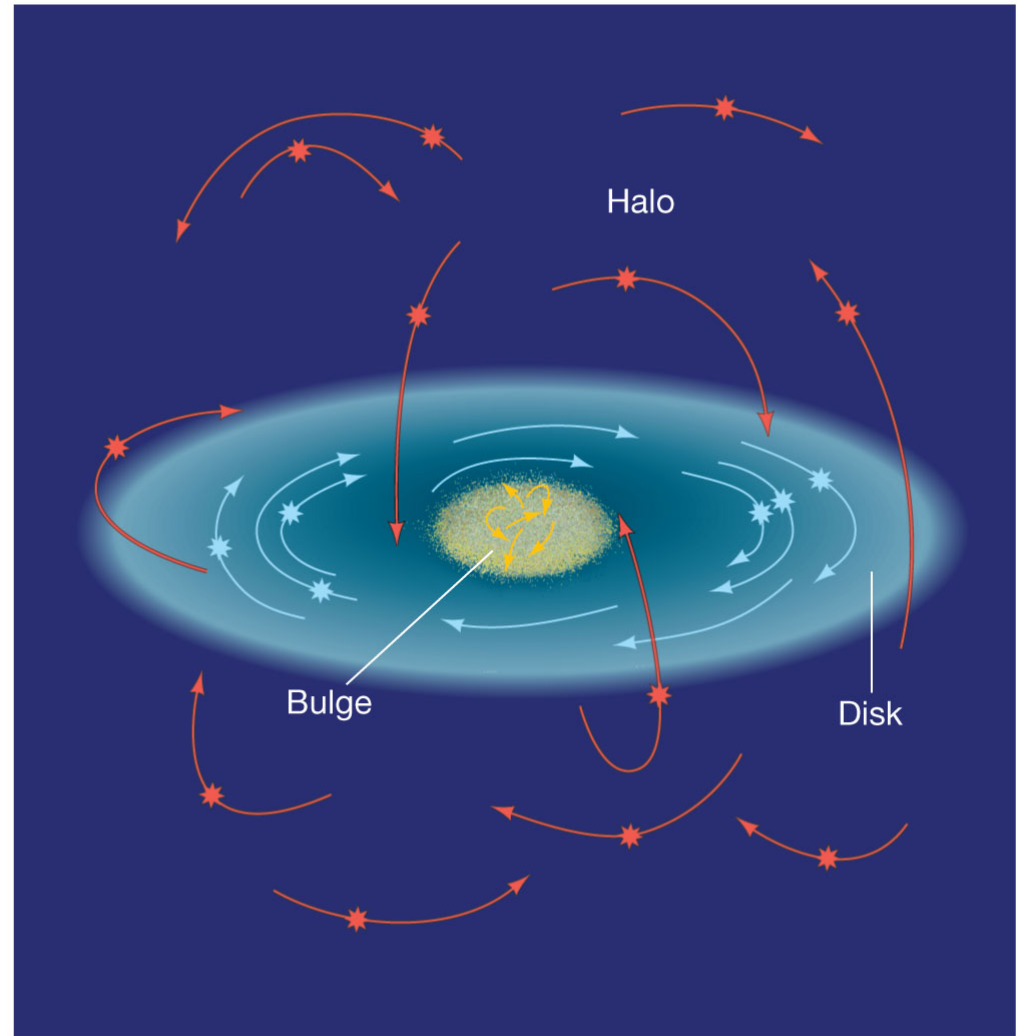
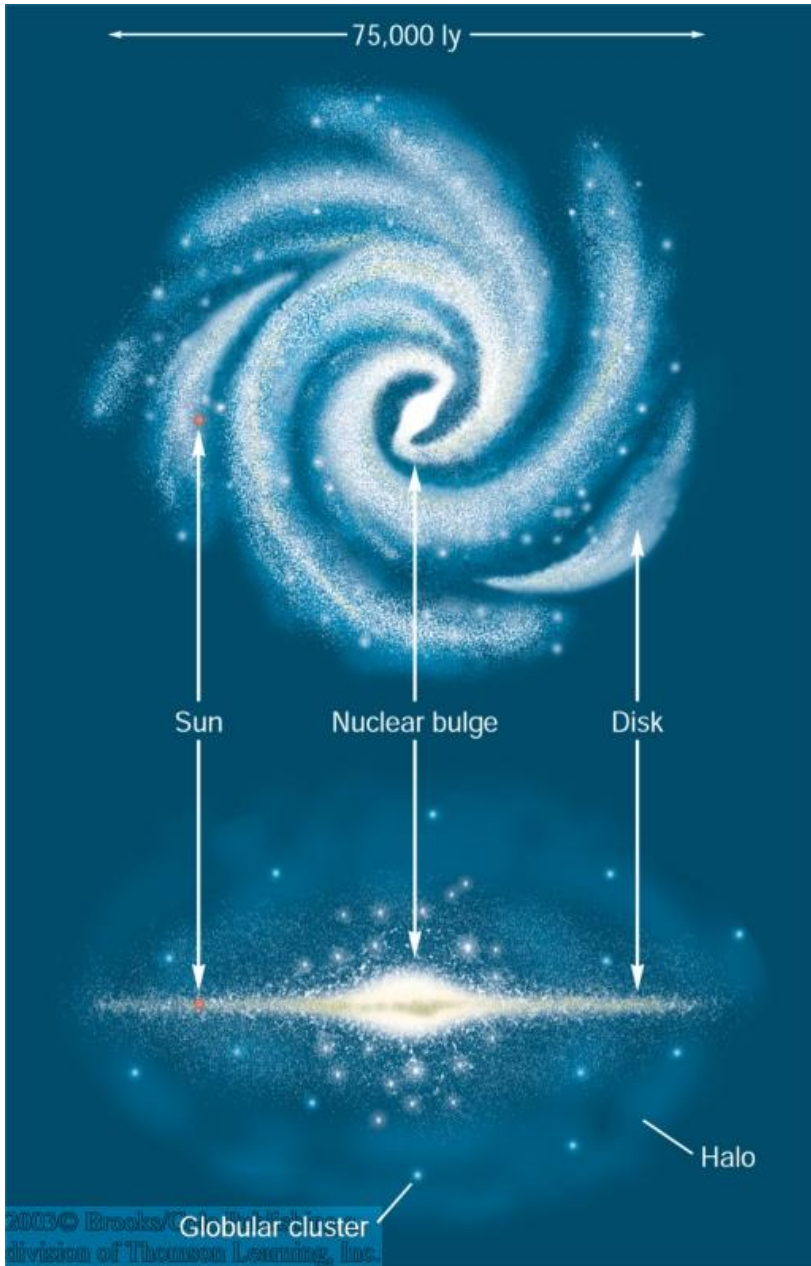
View from the inside!



View from the outside?



The Structure of the Milky Way

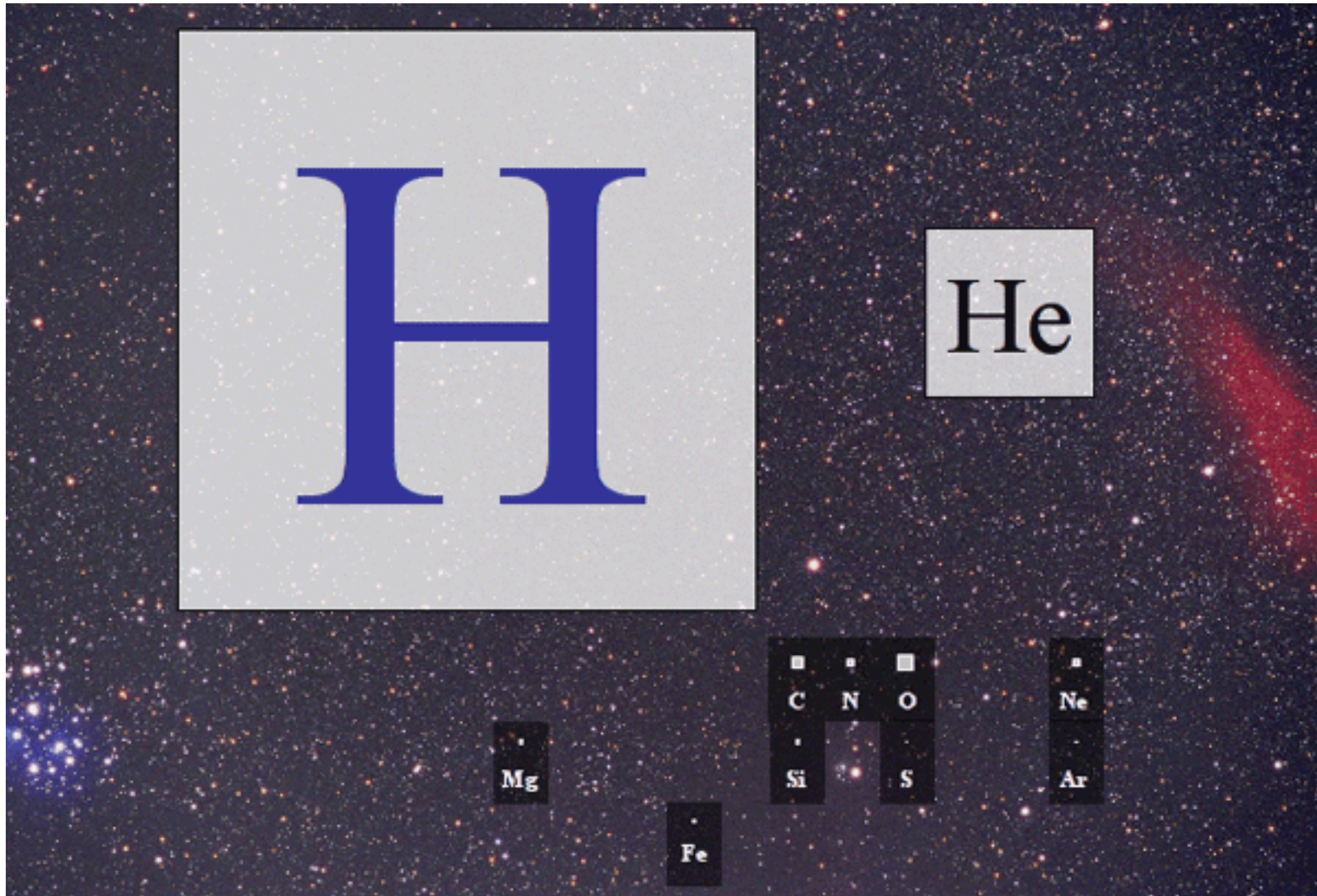


Aside: elements from a chemist's perspective

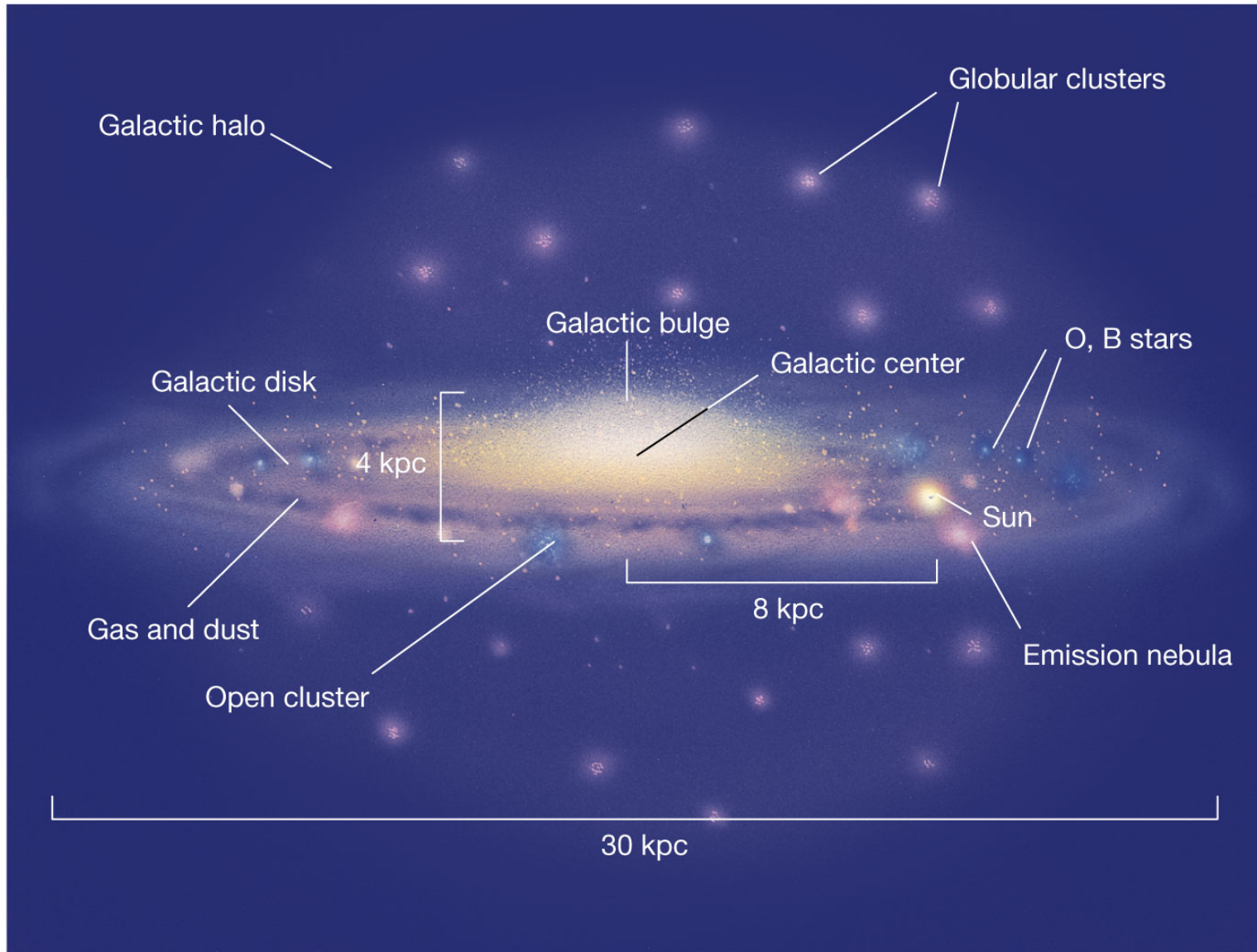
Periodic Table of the Elements

																		18 VIIIA 8A
1 1IA 1A																	2 He Helium 4.00260	
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797	
11 Na Sodium 22.989769	12 Mg Magnesium 24.304	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.4527	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.921595	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9062	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29	
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium (209, 9824)	85 At Astatine 209, 9811	86 Rn Radon 222, 9119	
87 Fr Francium 223, 9187	88 Ra Radium 226, 9234	89-103 Actinide Series	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (270)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (285)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (284, 9049)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (288)	117 Uus Ununseptium (289)	118 Uuo Ununoctium (289)	
			57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	
			89 Ac Actinium 227, 9291	90 Th Thorium 232, 9091	91 Pa Protactinium 231, 9293	92 U Uranium 238, 9298	93 Np Neptunium 237, 9402	94 Pu Plutonium 244, 9404	95 Am Americium 243, 9504	96 Cm Curium 247, 9606	97 Bk Berkelium 247, 9707	98 Cf Californium 251, 9808	99 Es Einsteinium 252, 9909	100 Fm Fermium 257, 9910	101 Md Mendelevium 258, 101	102 No Nobelium 259, 102	103 Lr Lawrencium (260)	
			Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides						

Aside: elements from an astronomer's perspective



Stellar populations in the Galaxy:



Mapping spiral arms: stars.



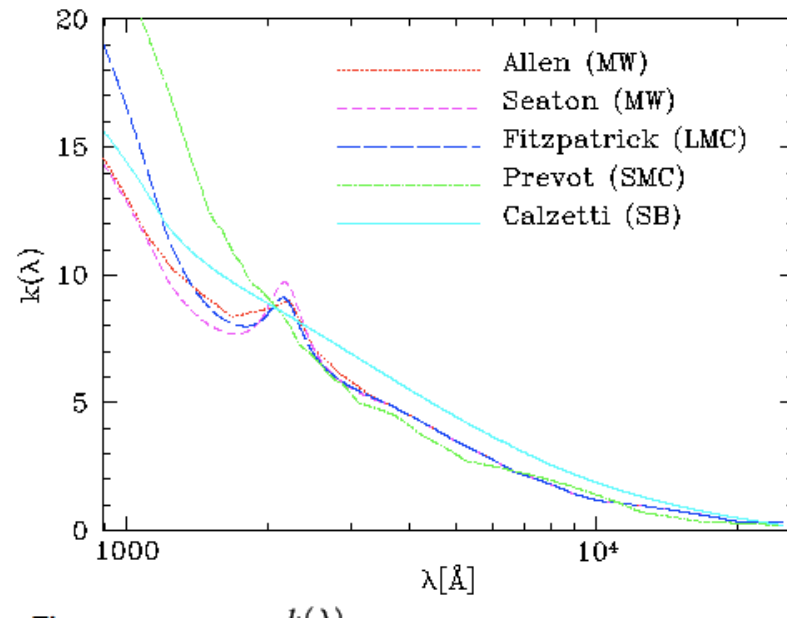
Nice and bright, but...

We live in the disk and it is dusty: we can only see about 1kpc.



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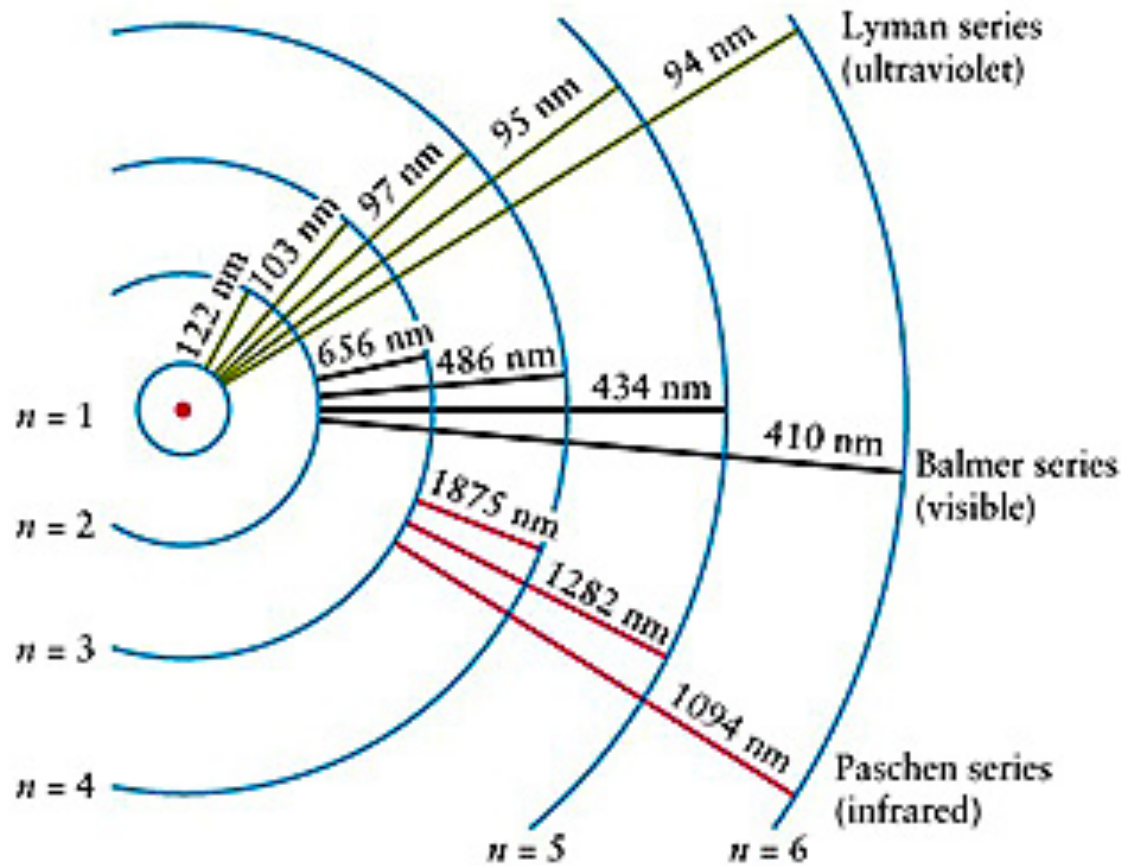
Galactic extinction laws:



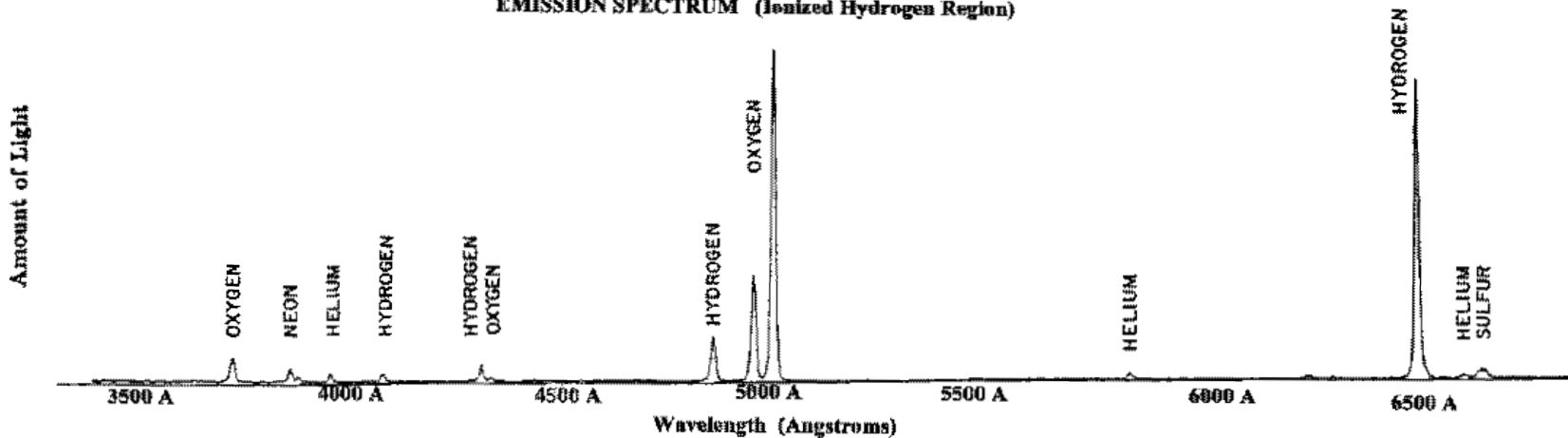
Mapping spiral arms: gas near hot stars.



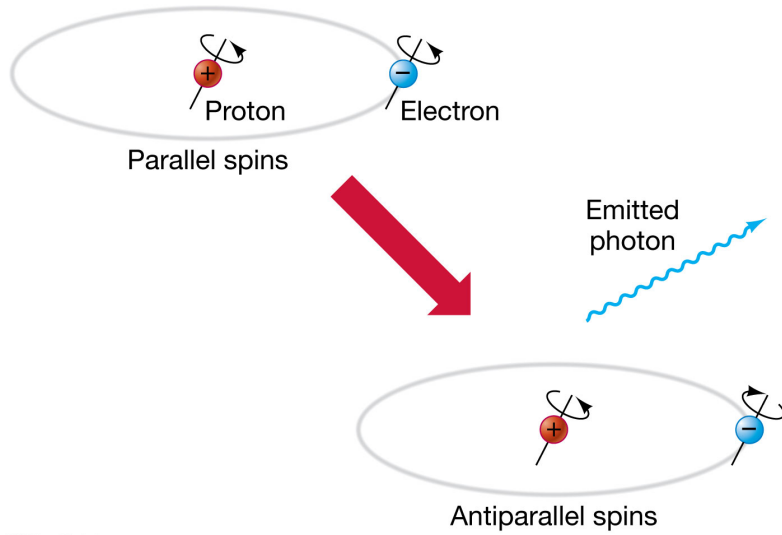
Strongest emission lines are in the optical, so still suffer from interstellar extinction.



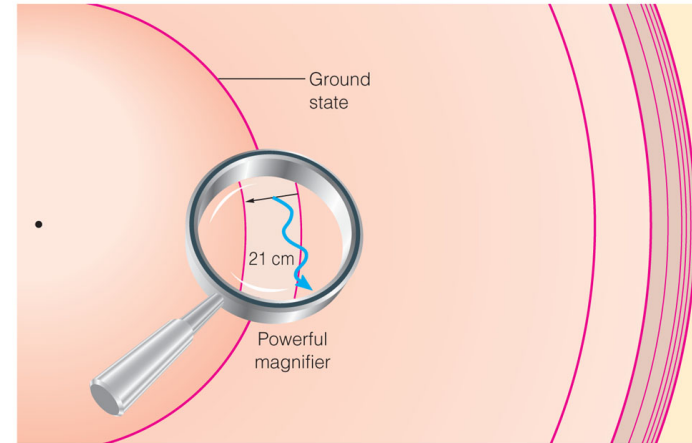
EMISSION SPECTRUM (Ionized Hydrogen Region)



Mapping spiral arms: gas. HI 21cm immune to dust.



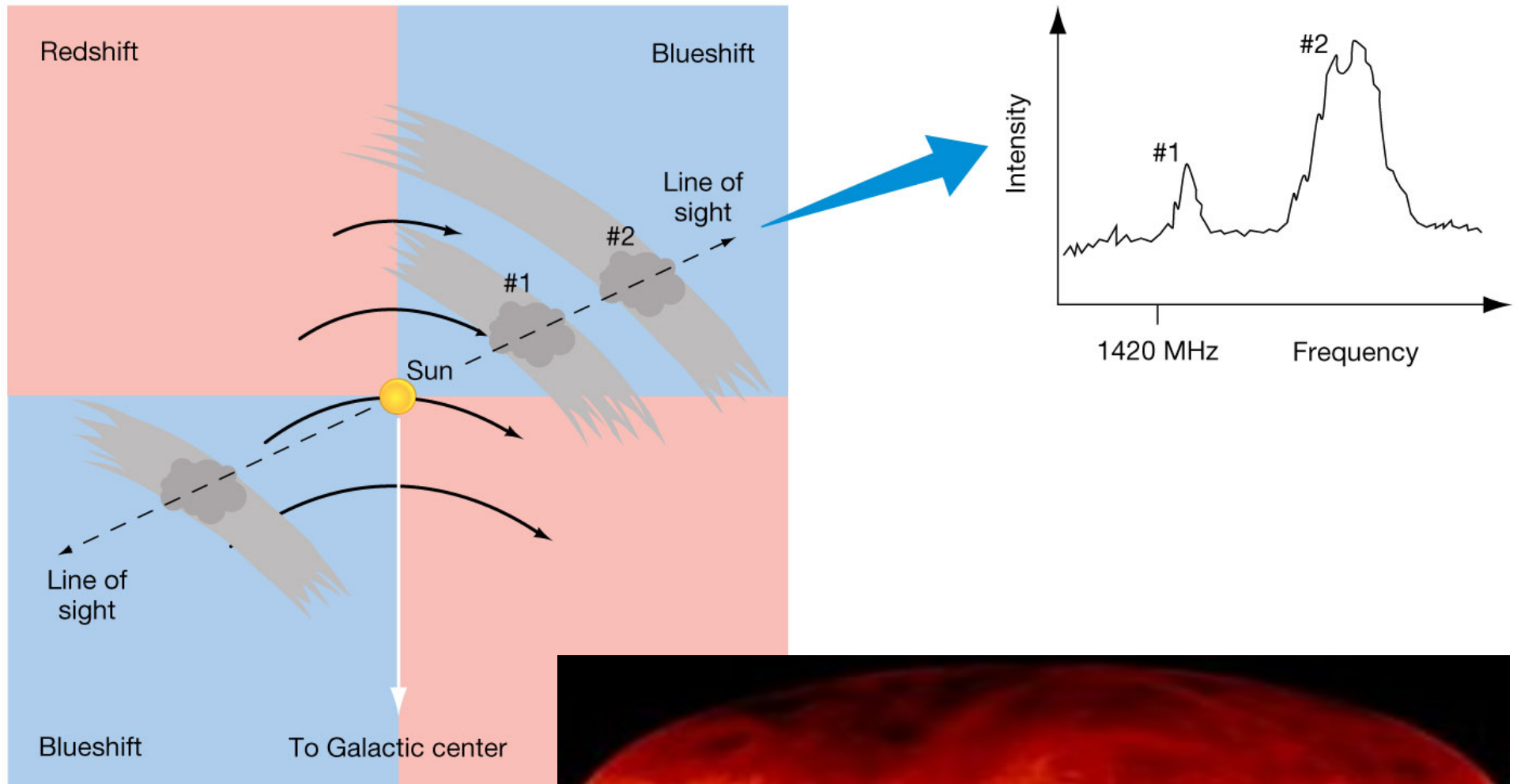
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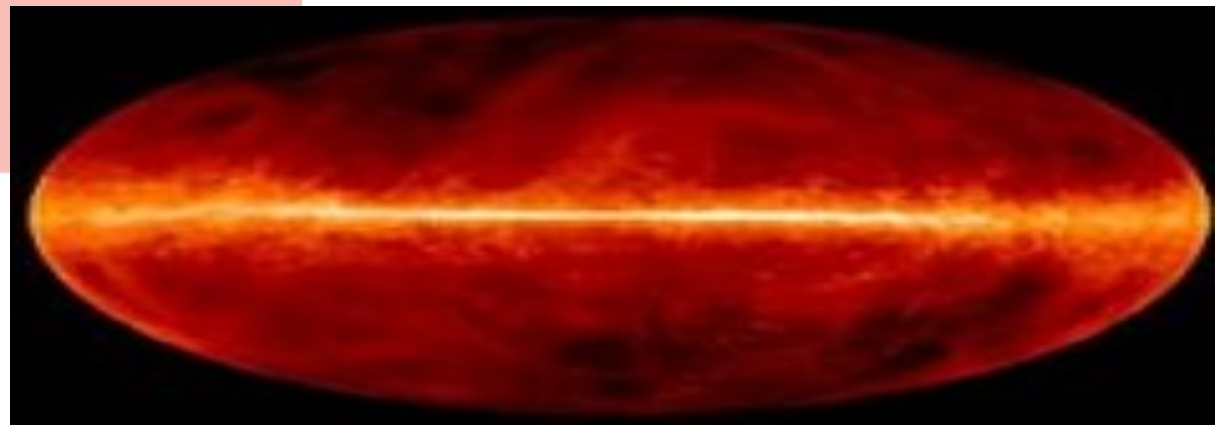
© 2005 Brooks/Cole - Thomson



Mapping spiral arms: gas. HI 21cm immune to dust.



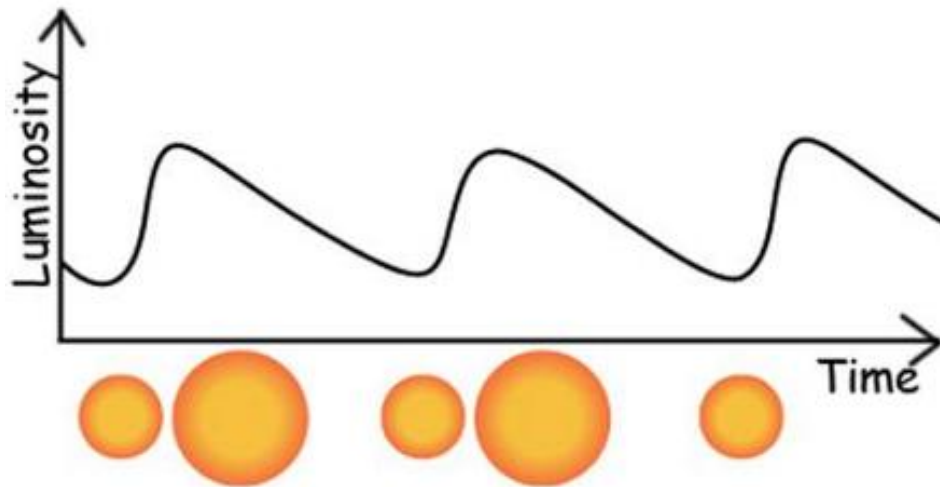
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Can also map star-forming galaxies in the IR.

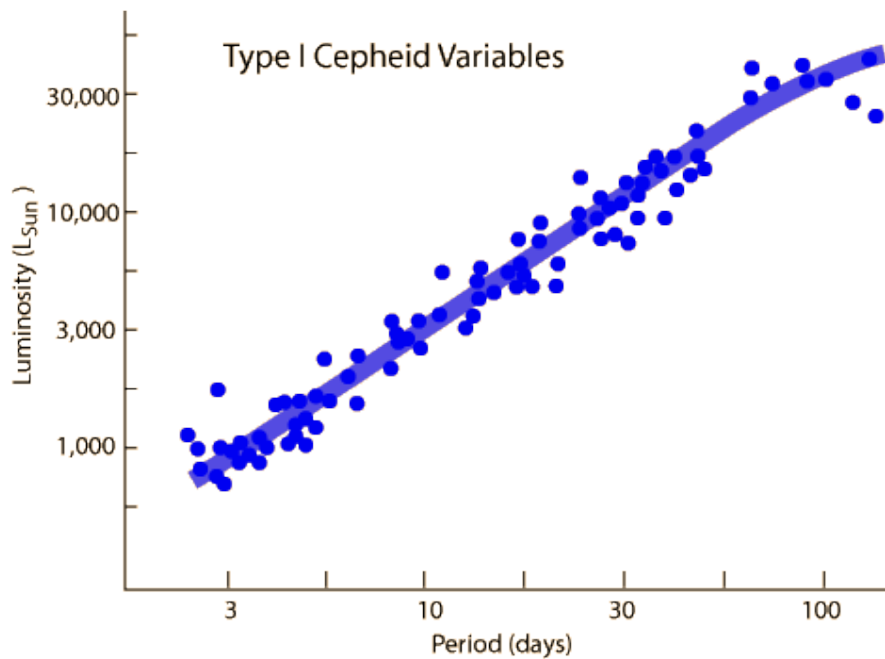


Measuring the size of the Milky Way

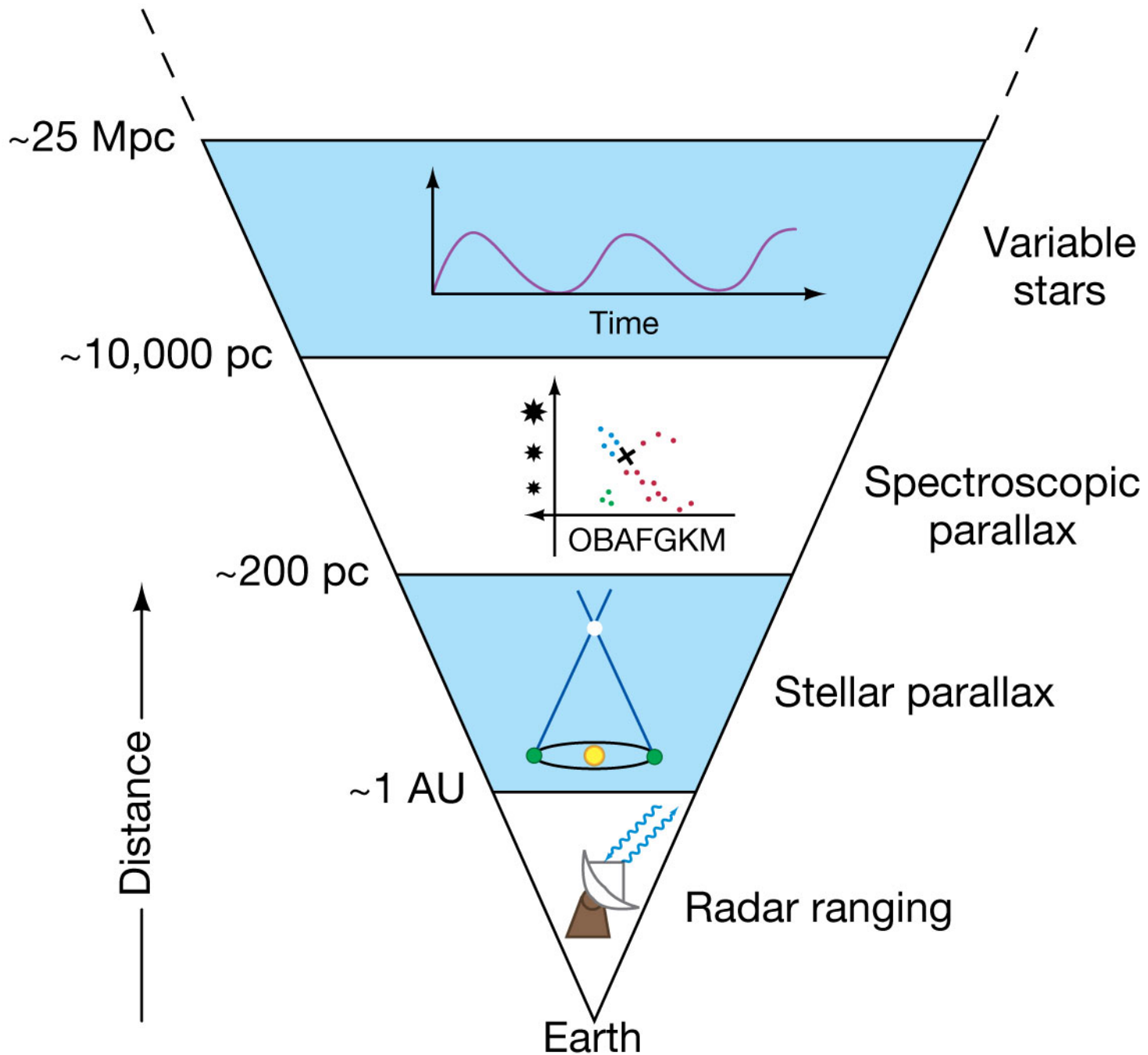


Cepheid variable stars pulsate.

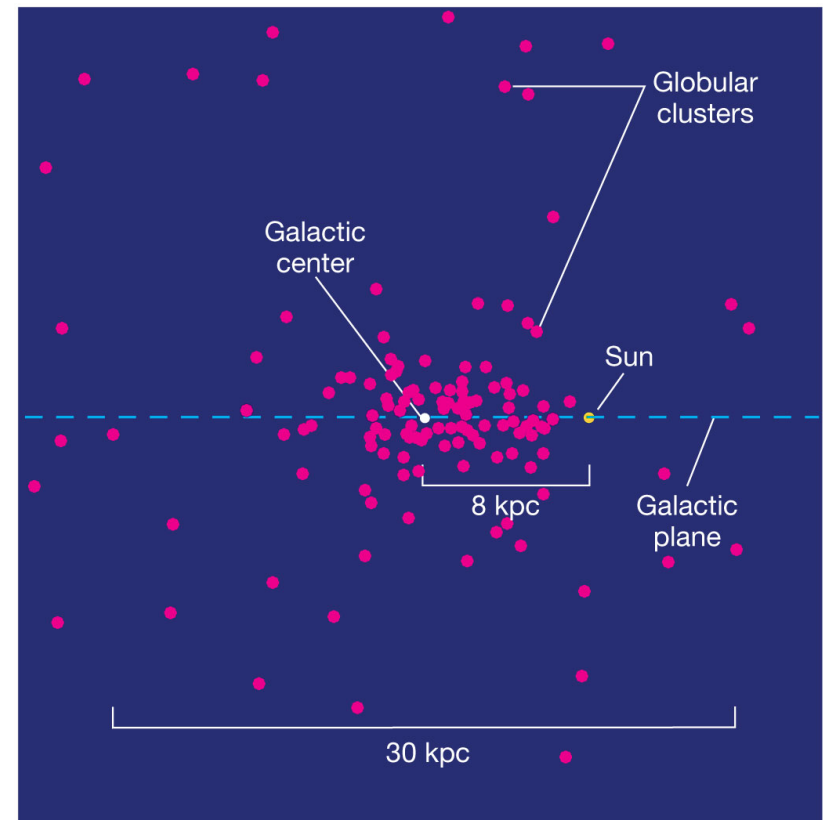
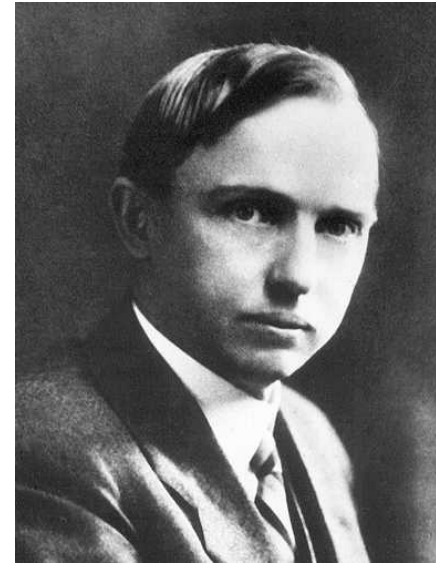
Period-luminosity relation discovered by Henrietta Swan-Leavitt c 1910. Distance measure beyond parallax.







Early 20th century, the extent of the Milky Way determined by Harlow Shapley using distances to globular clusters. Spherically distributed over many kpc. Sun not at centre.



Weighing the Galaxy with Kepler's 3rd Law

$$P^2 = a^3 / M, \text{ where } P \text{ in years, } a \text{ in AU and } M \text{ in solar units}$$

Example: What mass is contained in the Galaxy within the radius of the sun's orbit if the sun's period around the Galaxy is 240 million years at a radius of 8.5 kpc?

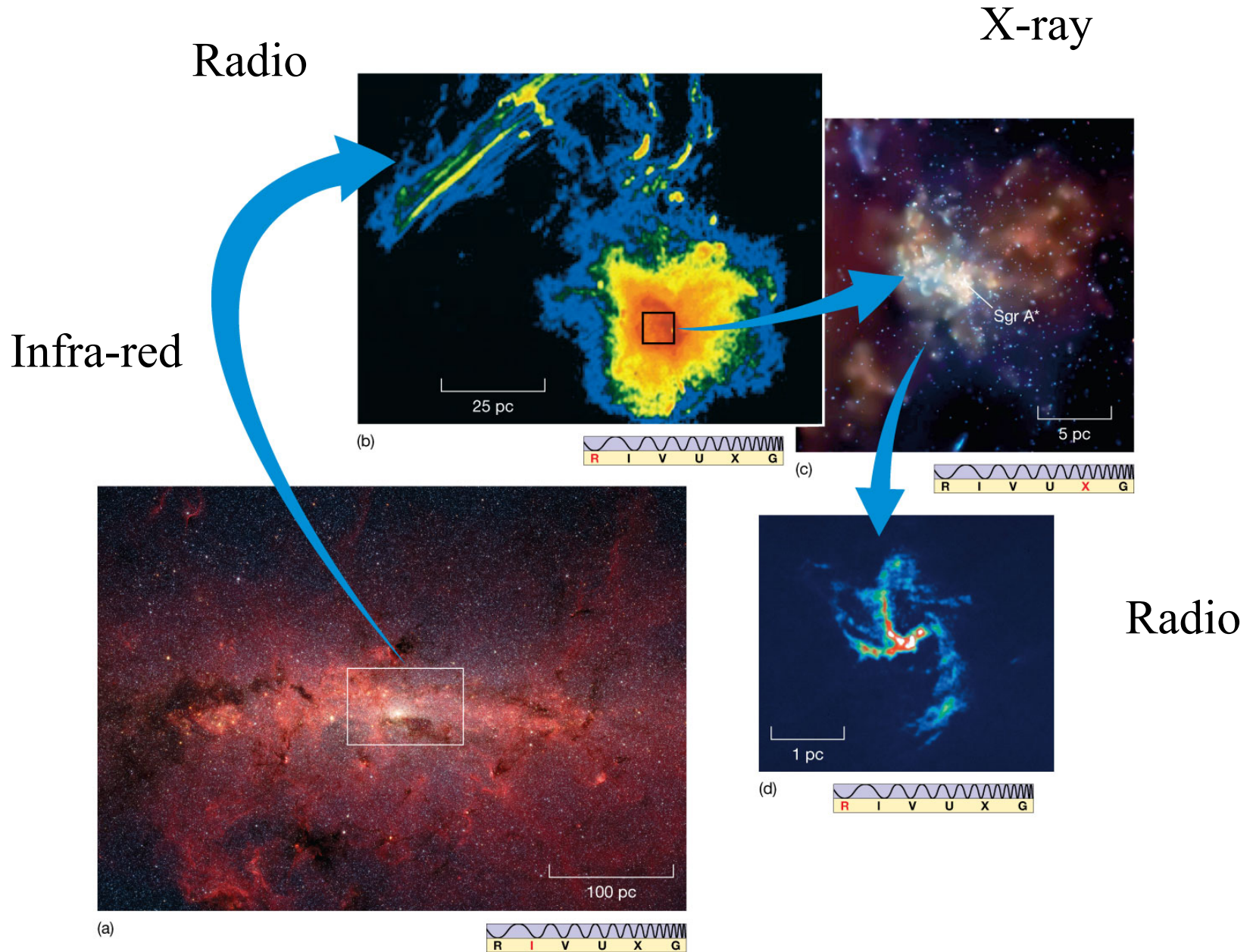
$$8.5 \text{ kpc} = 1.75 \times 10^9 \text{ AU.}$$

$$M = a^3 / P^2 = (1.75 \times 10^9)^3 / (240 \times 10^6)^2$$

$$= 0.9 \times 10^{11} \text{ solar masses}$$

If we take into account the mass outside the sun's orbit, we would find a mass of at least 2×10^{11} solar masses, i.e. 200 billion solar masses.

The Galactic Centre



1995.50

S0-16

S0-2

S0-3

S0-1

S0-19

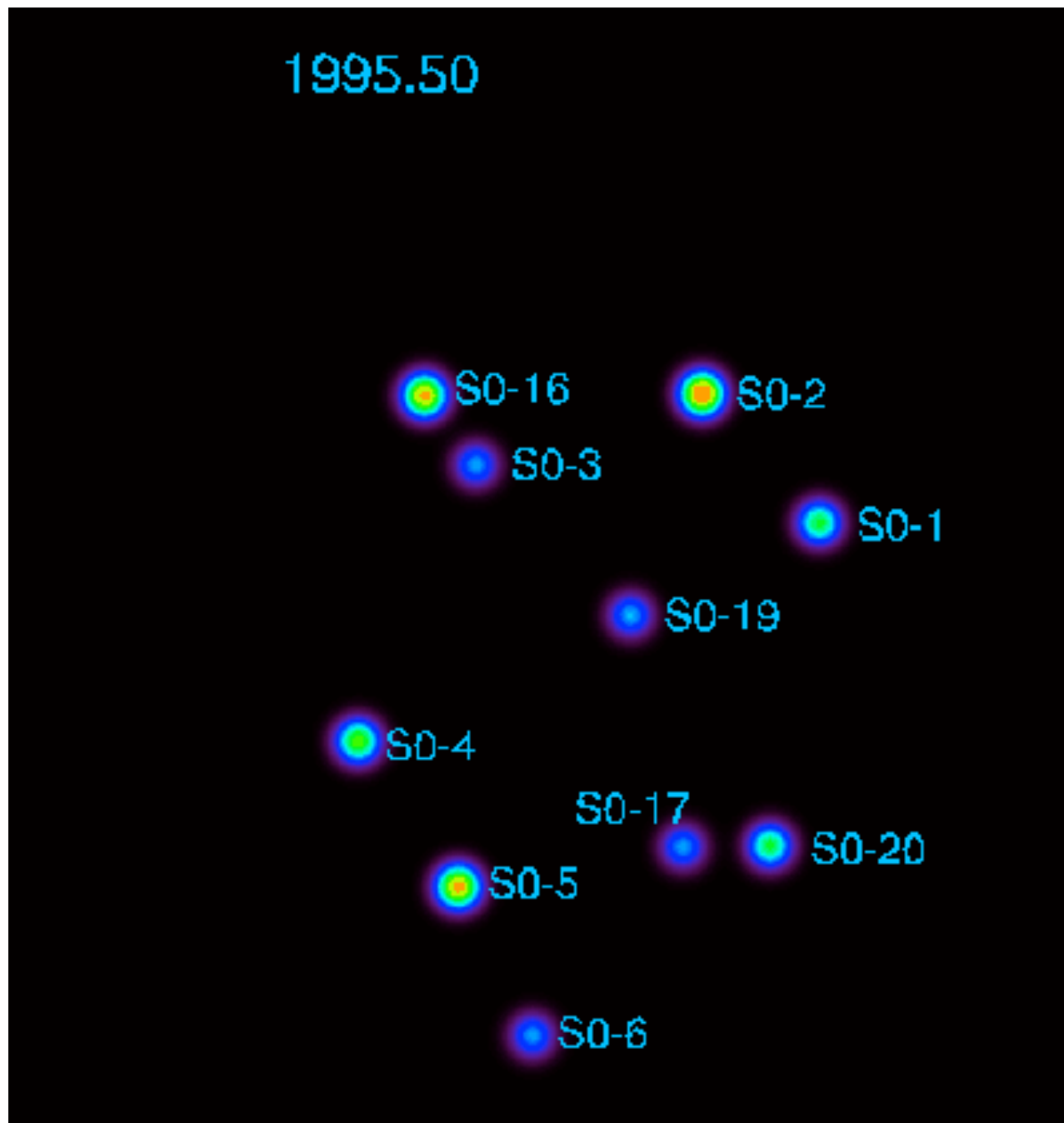
S0-4

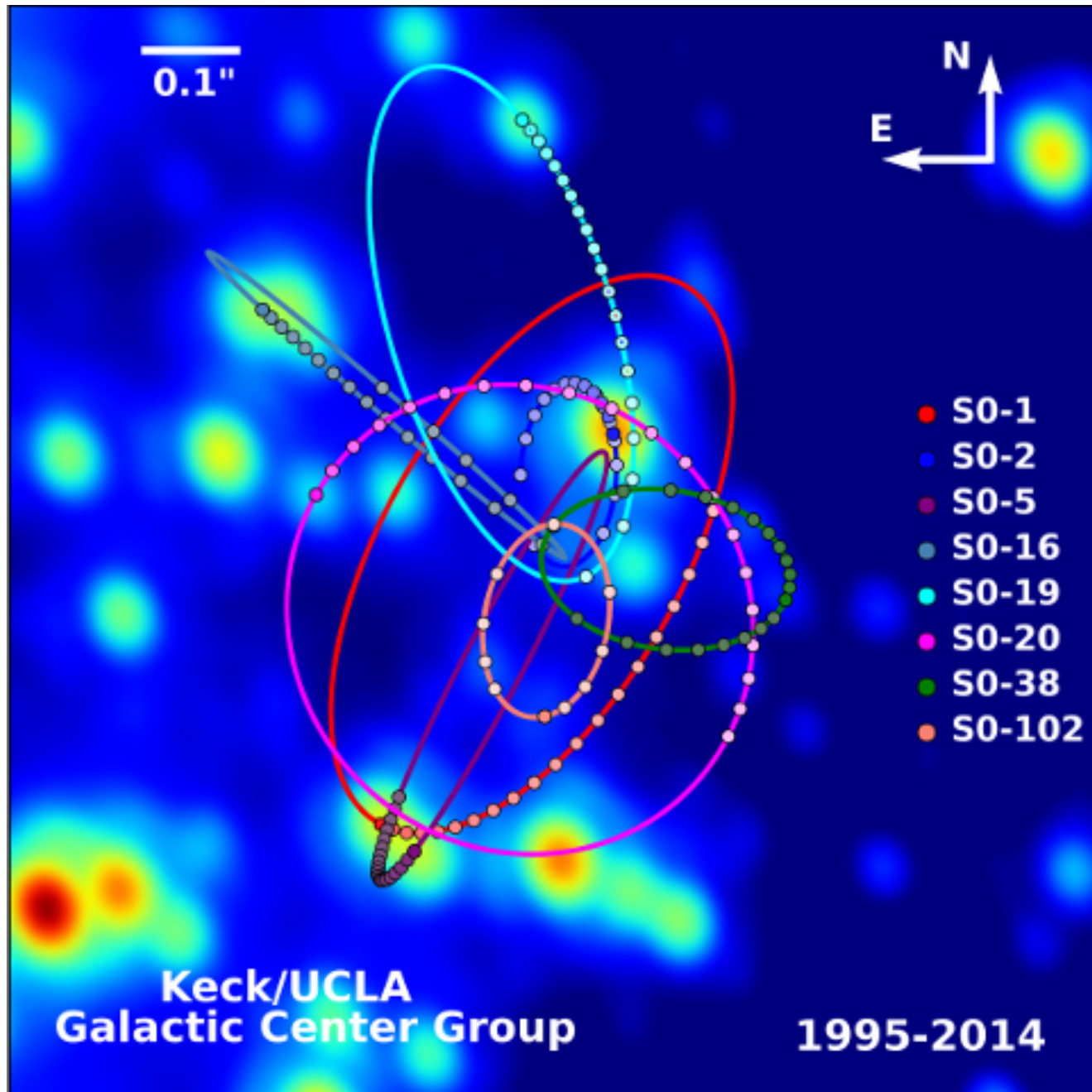
S0-17

S0-5

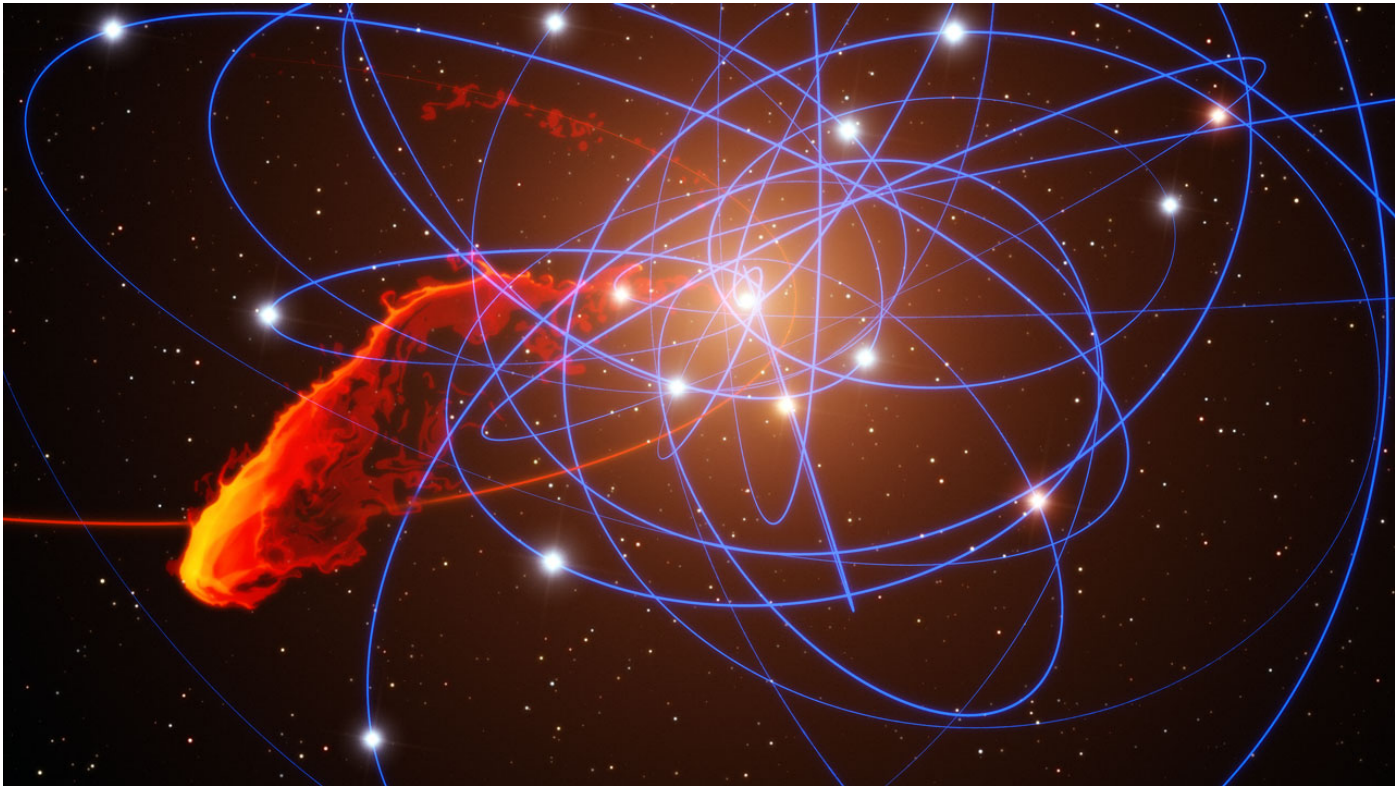
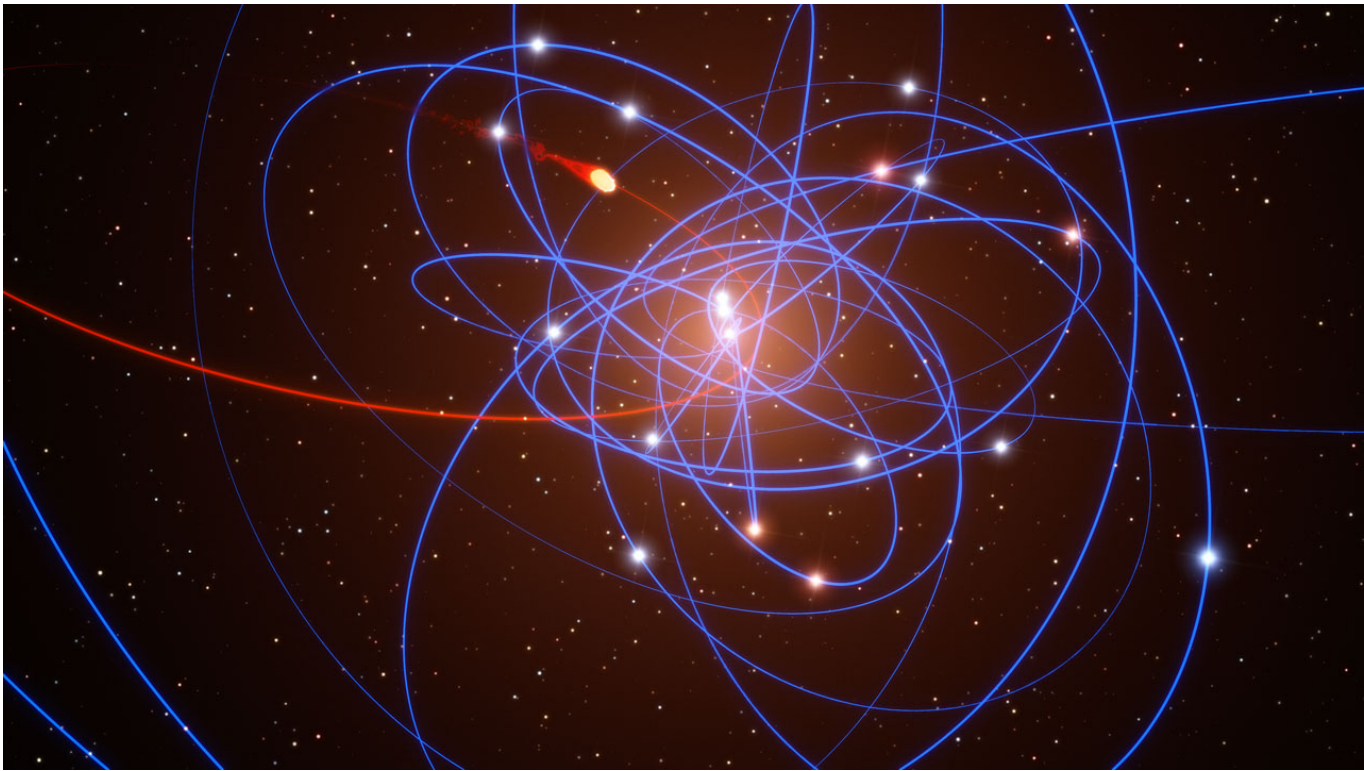
S0-20

S0-6

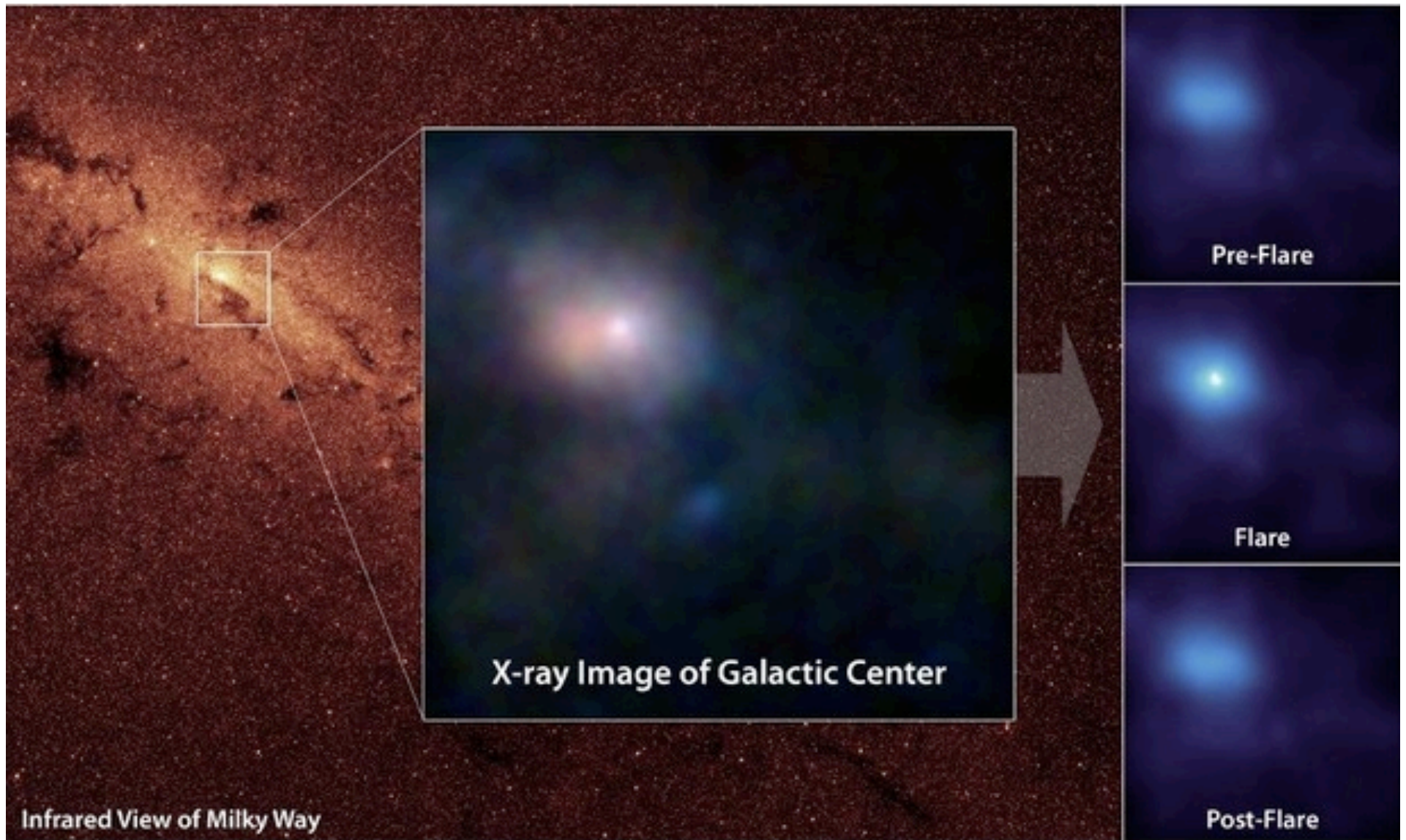




<http://www.galacticcenter.astro.ucla.edu/>



New NASA X-ray telescope, NuSTAR detects flares as the black hole “burps”.



The first (unintentional) catalog of **extra-galactic** objects by Charles Messier in the mid 1700s: 100 fuzzy objects that were not comets!

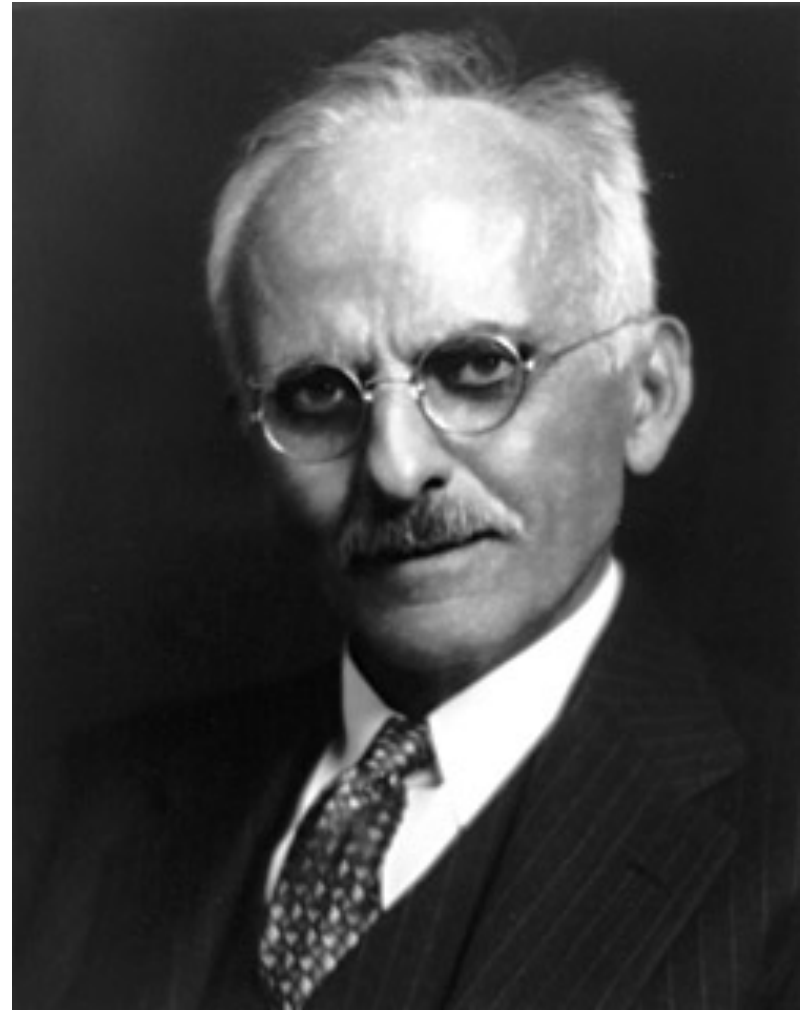


The Leviathon of Parsonstown

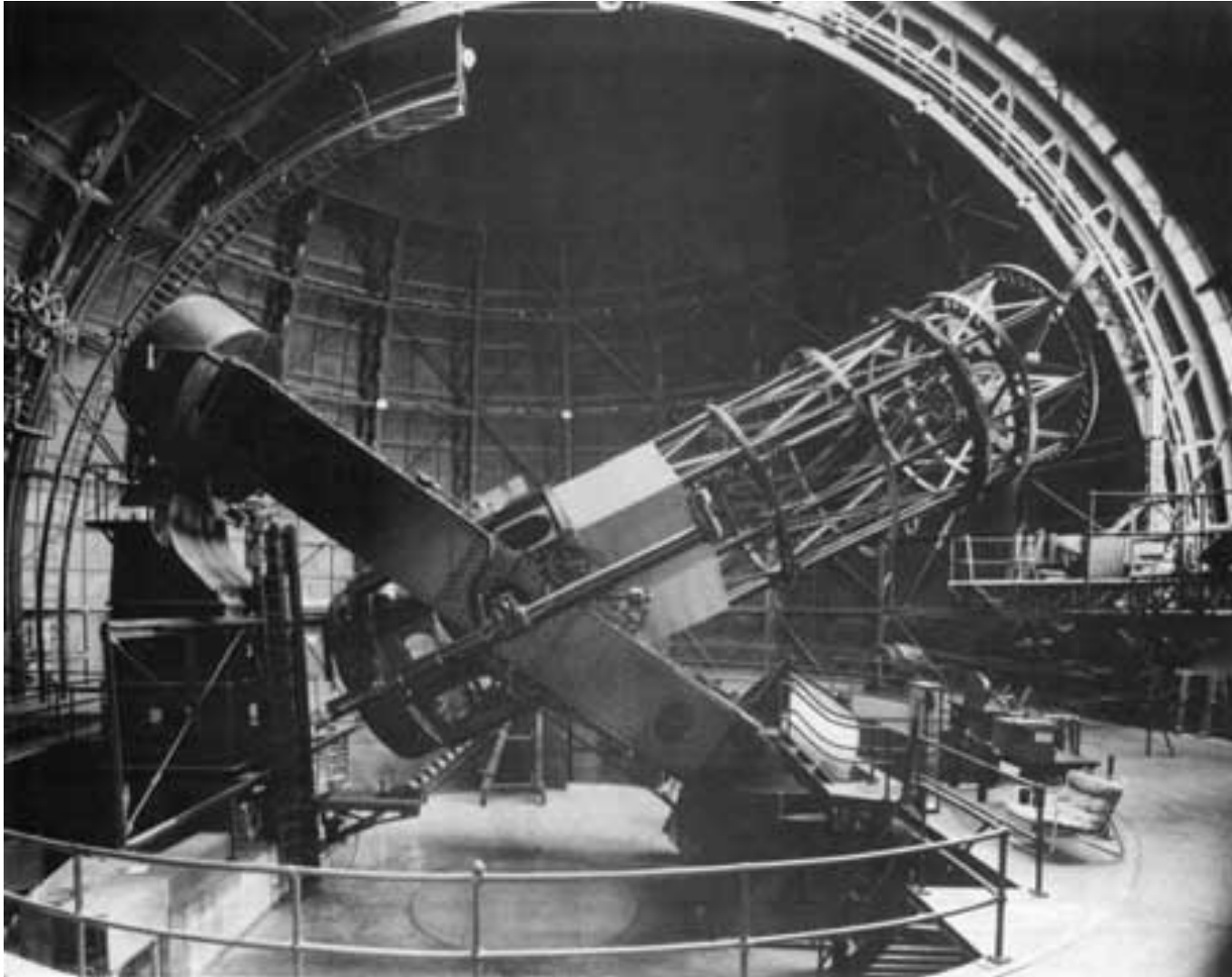




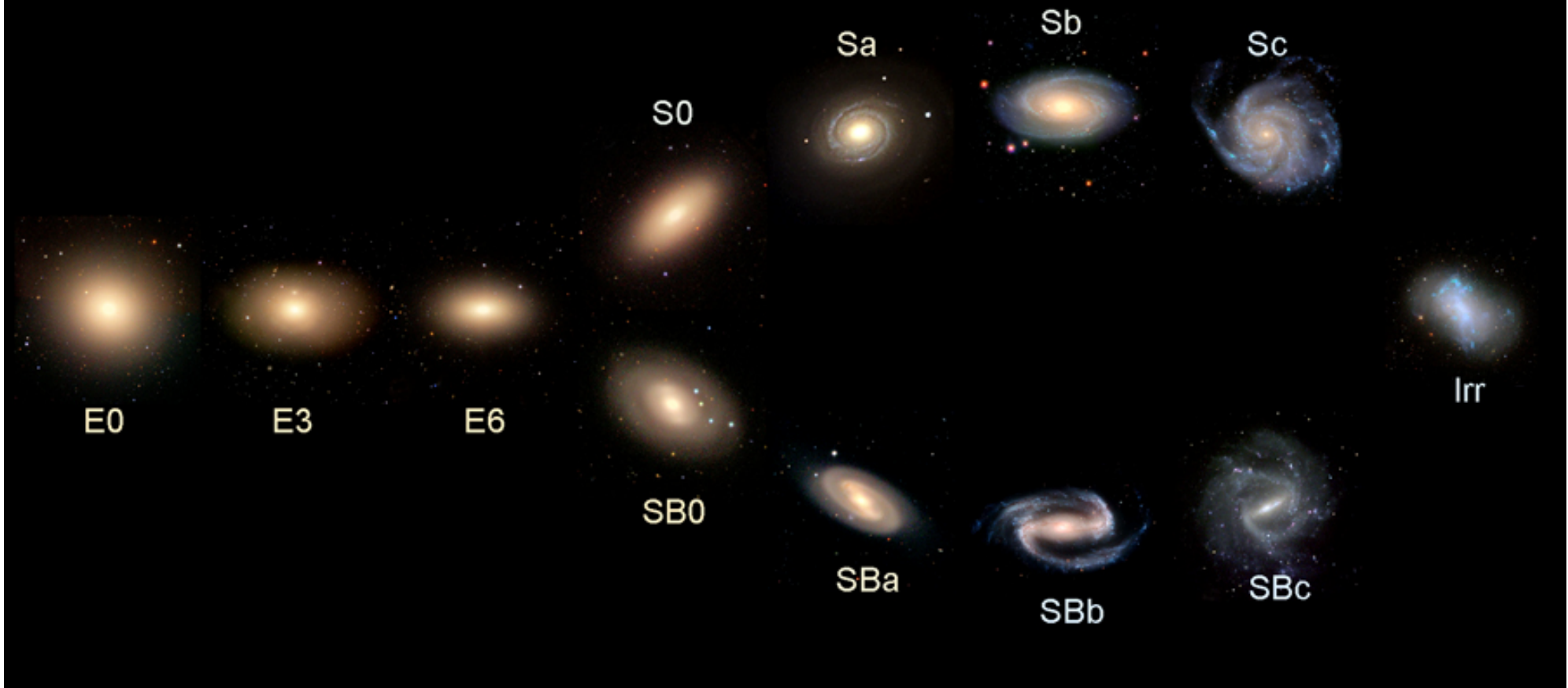
The nature of nebulae: The Shapley-Curtis debate (1920)



Edwin Hubble settled the Great Debate in 1923.

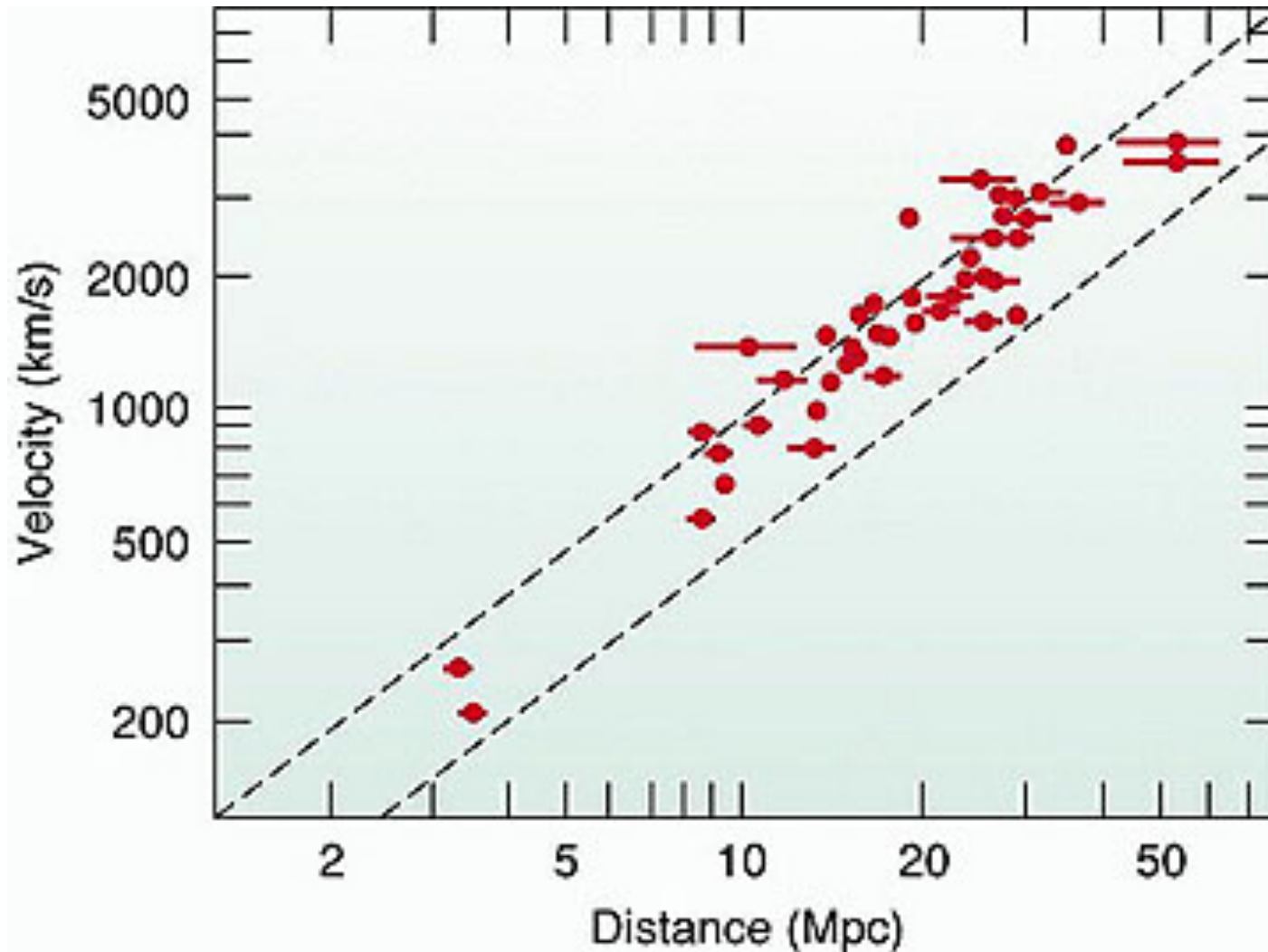


Hubble's Galaxy Classification Scheme

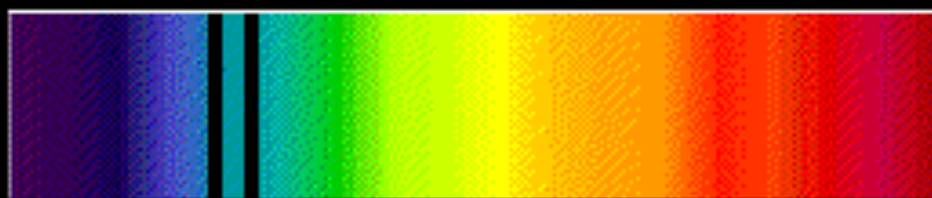


The Hubble Law

$$V \text{ (km/s)} = H \text{ (km/s/Mpc)} \times D \text{ (Mpc)}$$

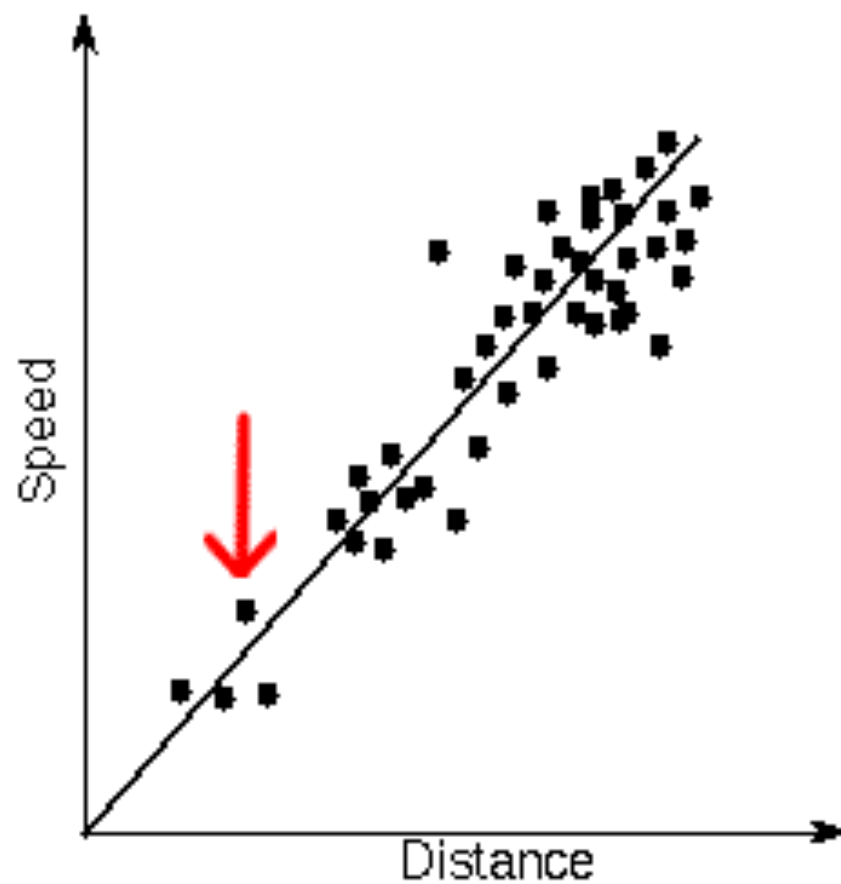


Where H is a constant that describes the gradient of the slope, and is called the **Hubble constant (km/s/Mpc)**.



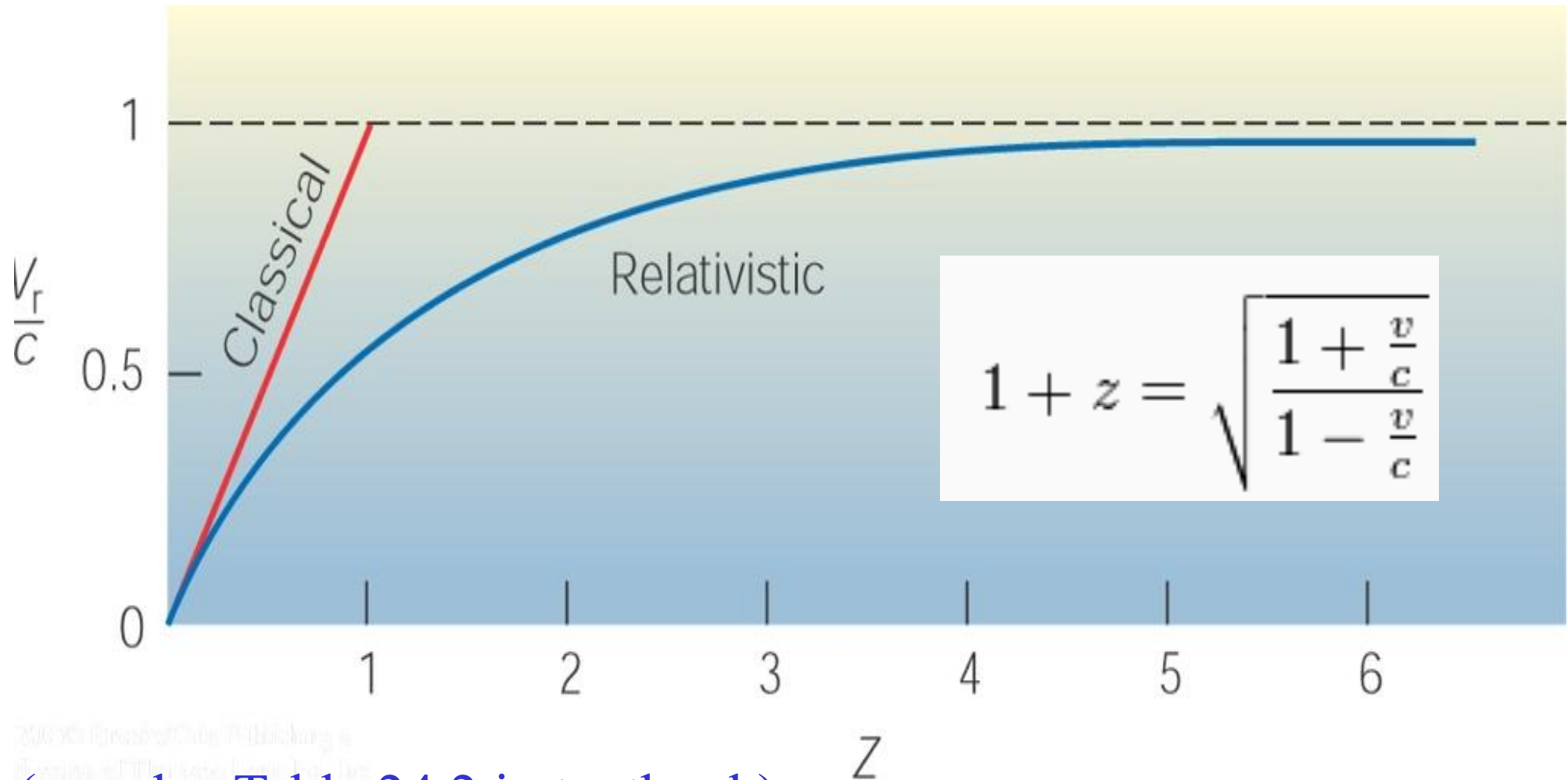
Hubble Law

$$\text{recession speed} = H_0 \times \text{distance}$$



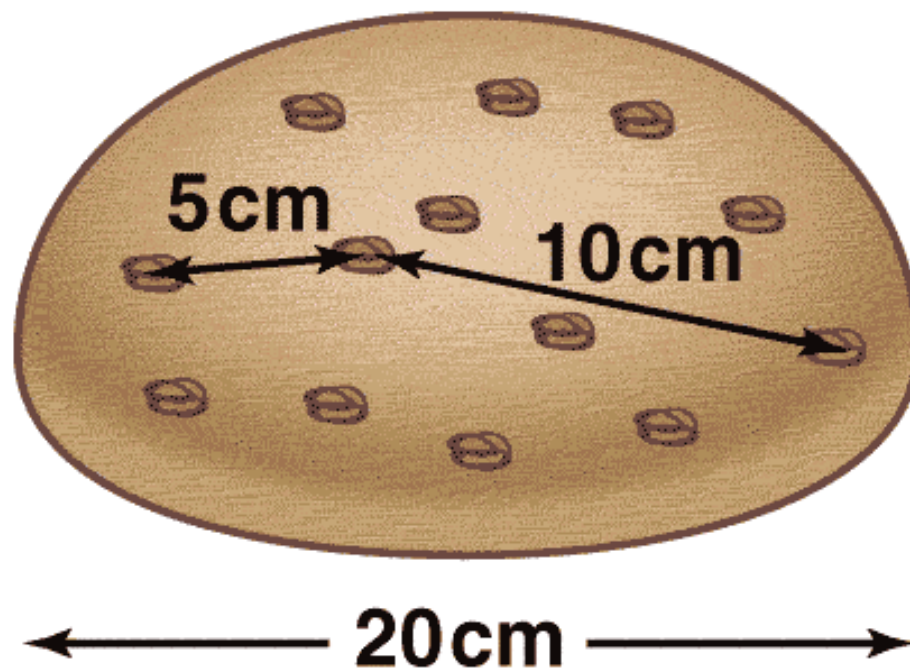
Redshift

$$\frac{\text{Change in wavelength}}{\text{Original wavelength}} = \frac{\text{velocity}}{\text{light speed}} = \frac{\Delta\lambda}{\lambda_0} = \text{redshift} = z$$



(see also Table 24.2 in textbook)

Implication of Hubble law - the Universe is expanding!



Example: A galaxy has its H alpha line shifted from 656 nm to 664 nm, what is the distance to the galaxy, assuming $H = 70 \text{ km/s/Mpc}$?

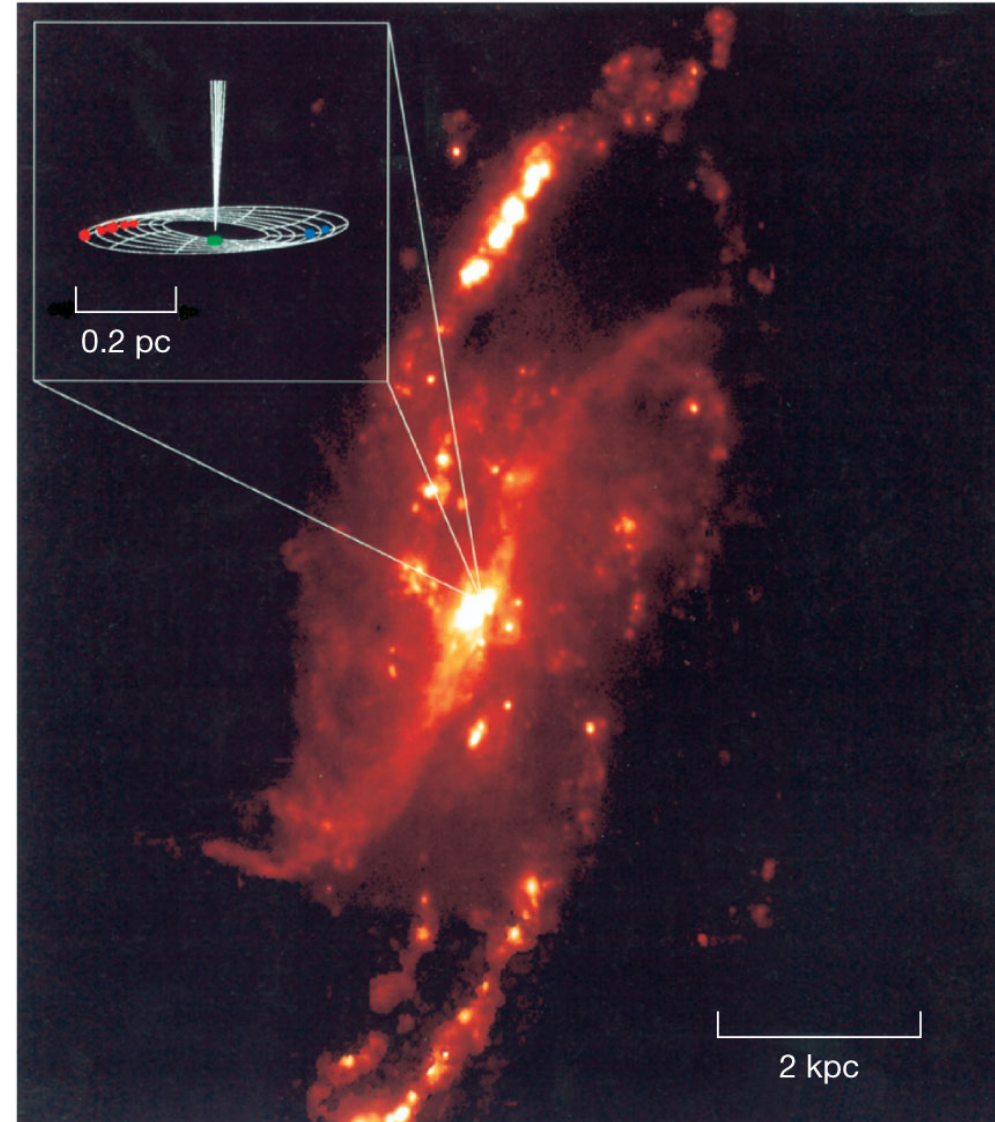
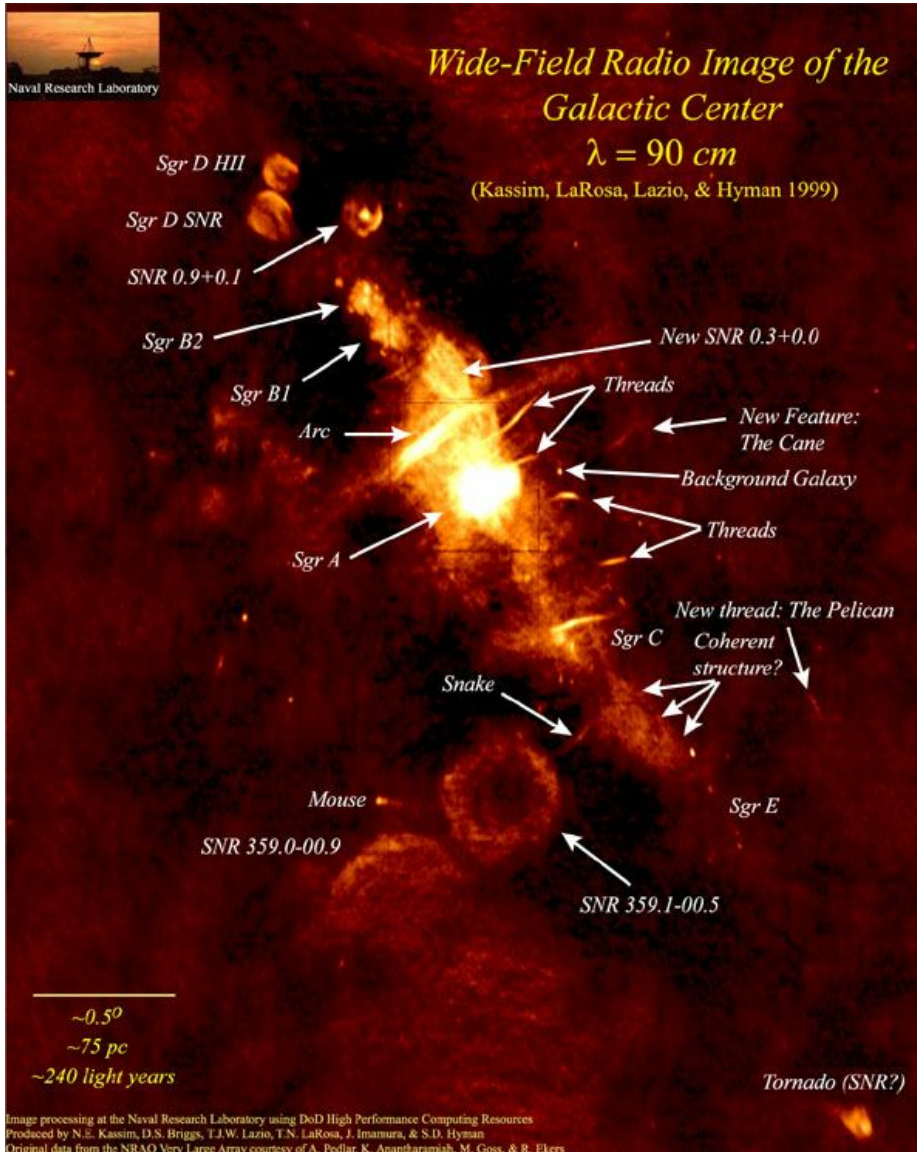
$$\text{Using Doppler equation: } \frac{v}{c} = \frac{\Delta\lambda}{\lambda_{\text{rest}}}$$

$$\frac{664-656}{656} \times 3 \times 10^5 = 3.66 \times 10^3 \text{ km/s}$$

$$V = Hd$$

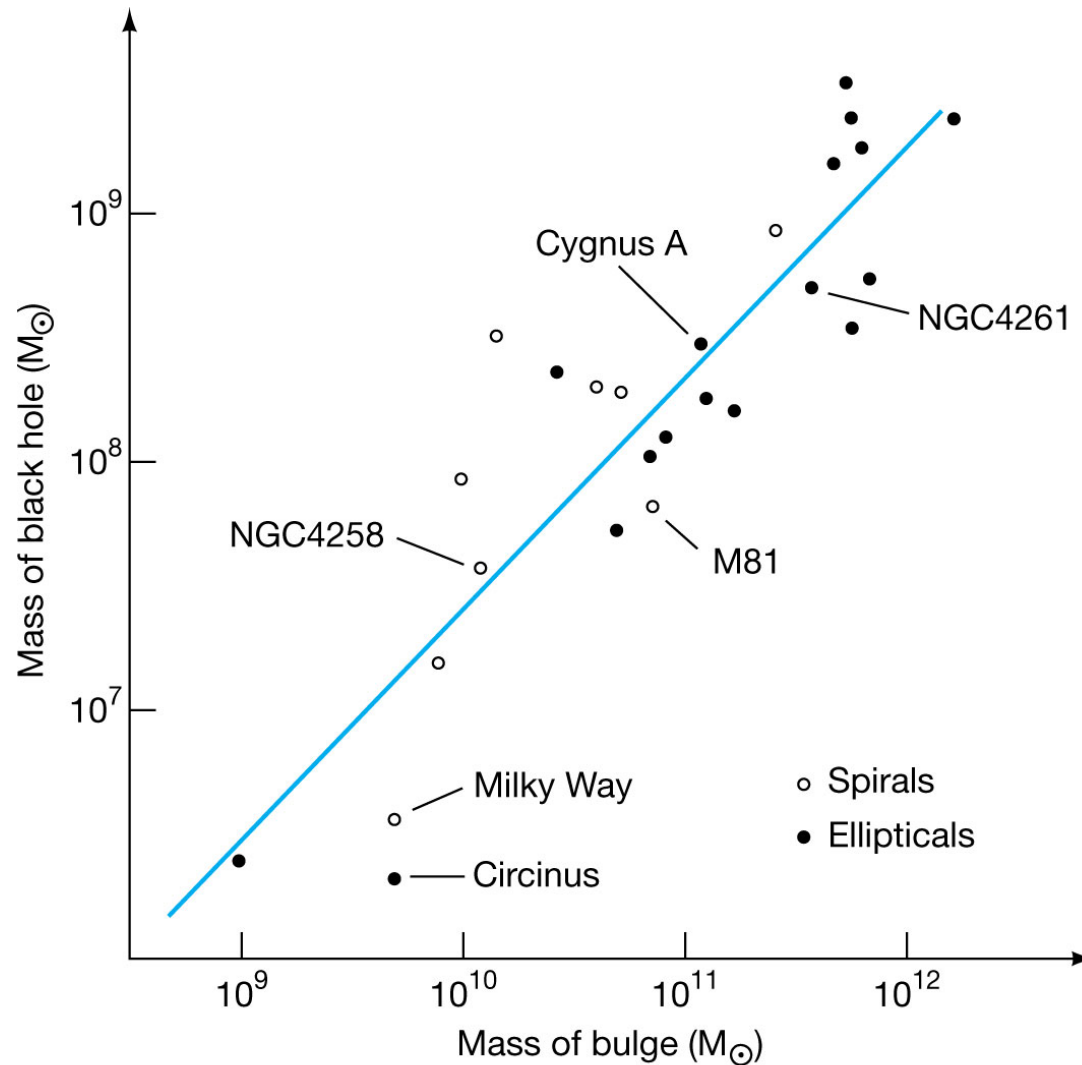
$$D = 3.66 \times 10^3 / 70 \\ = 52 \text{ Mpc}$$

Central supermassive black holes



Structure around Galactic centre

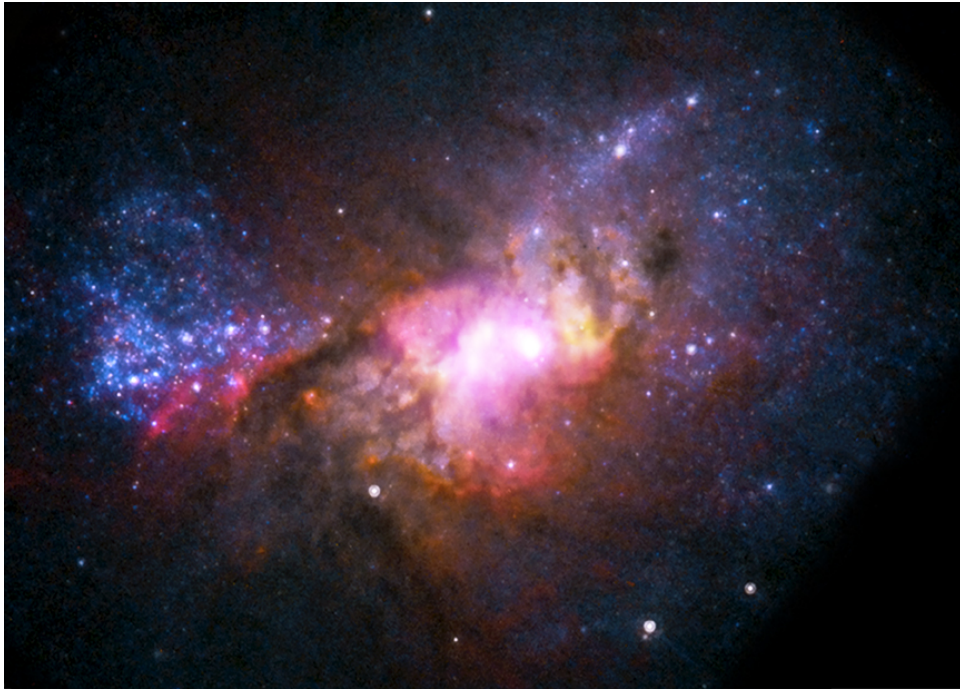
Gas disk at centre of spiral NGC 4258



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All (massive) galaxies have central supermassive black hole whose mass is proportional to the mass of the stars in the bulge - remarkable!

Low mass galaxies which don't have bulges shouldn't have black holes, but...



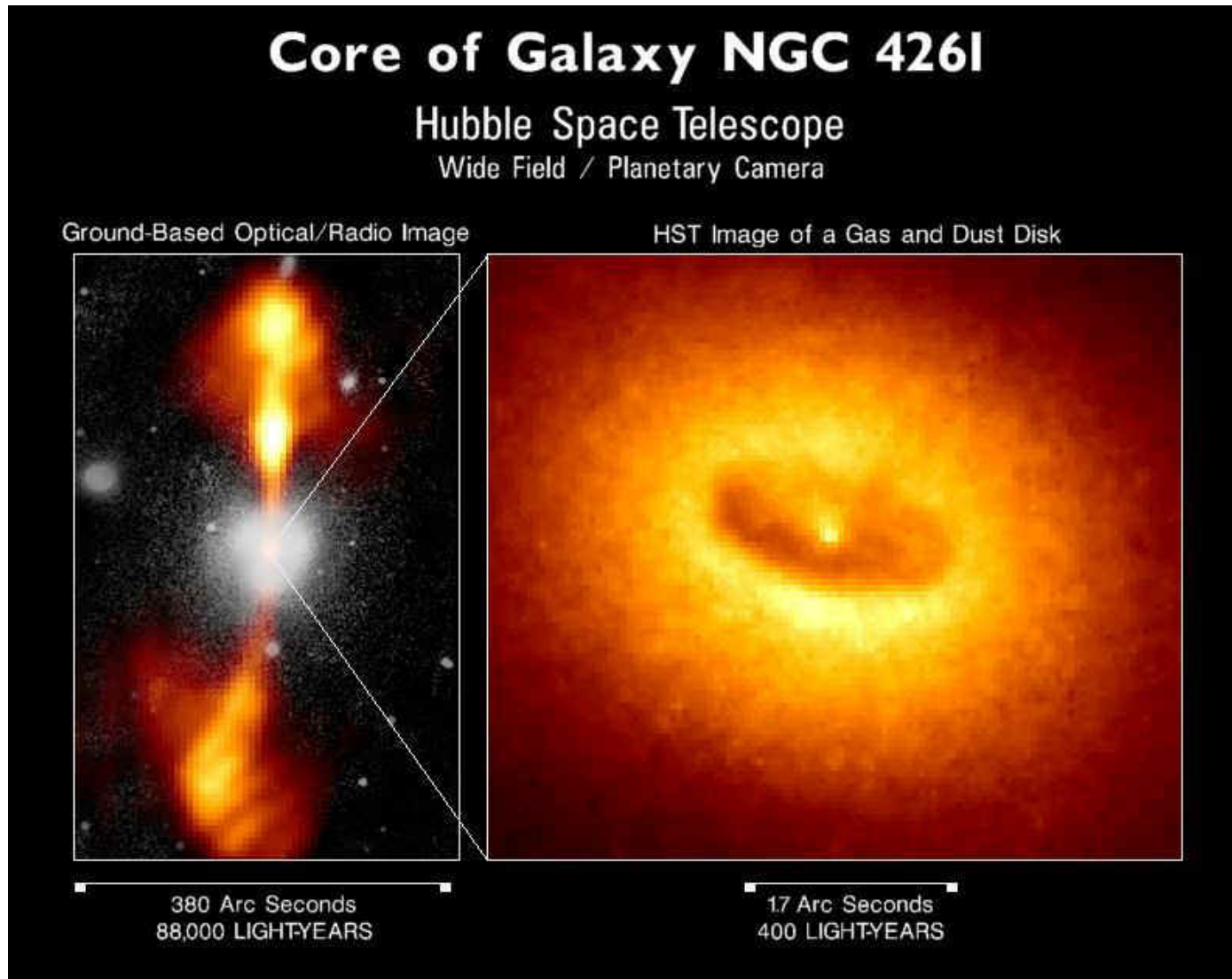
This dwarf has a 2 million solar mass BH.



This bulgeless galaxy has clear signs of nuclear activity.

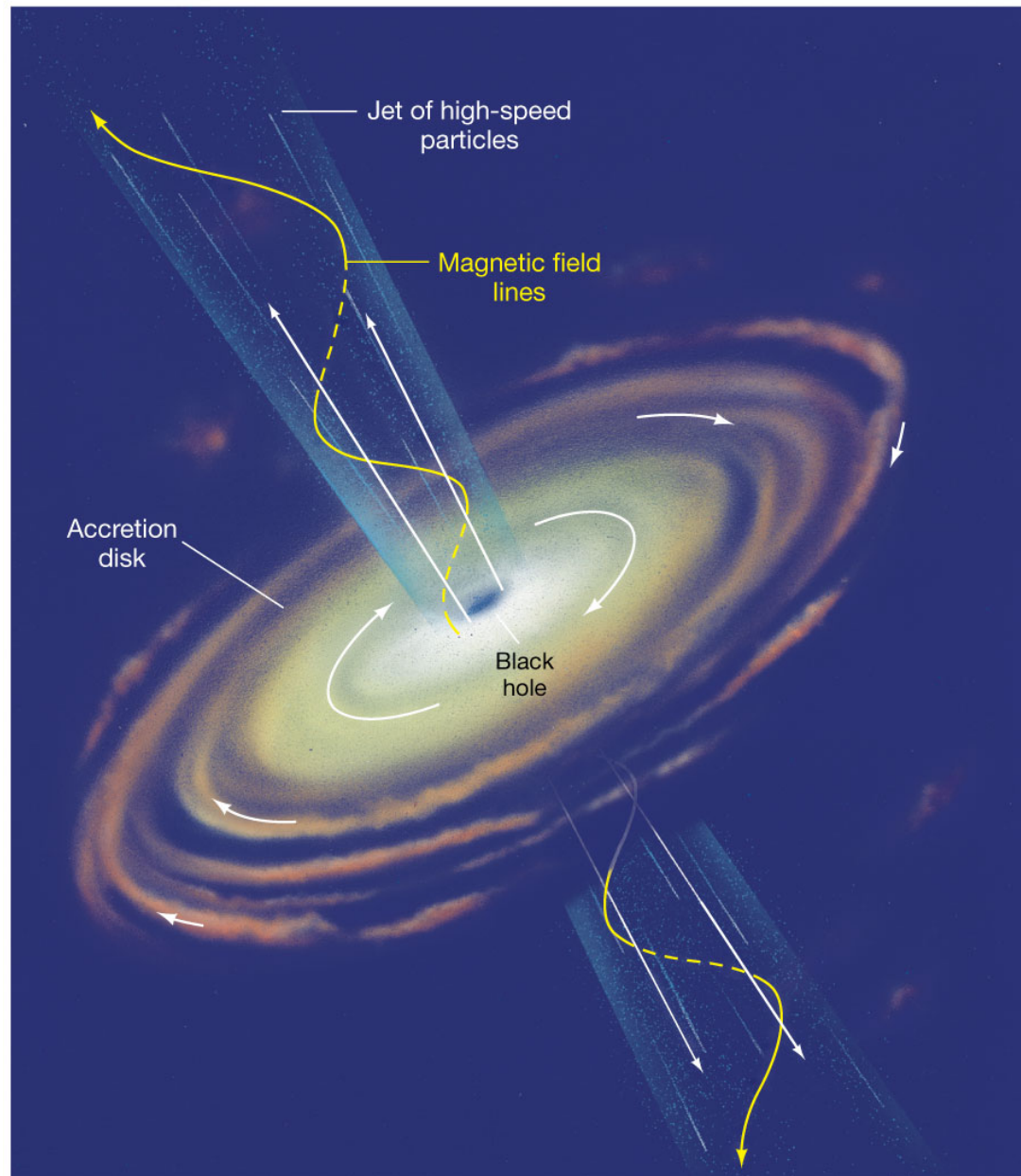
Nuclear star clusters as seed black holes?

Active galaxies - when the black hole gets fed

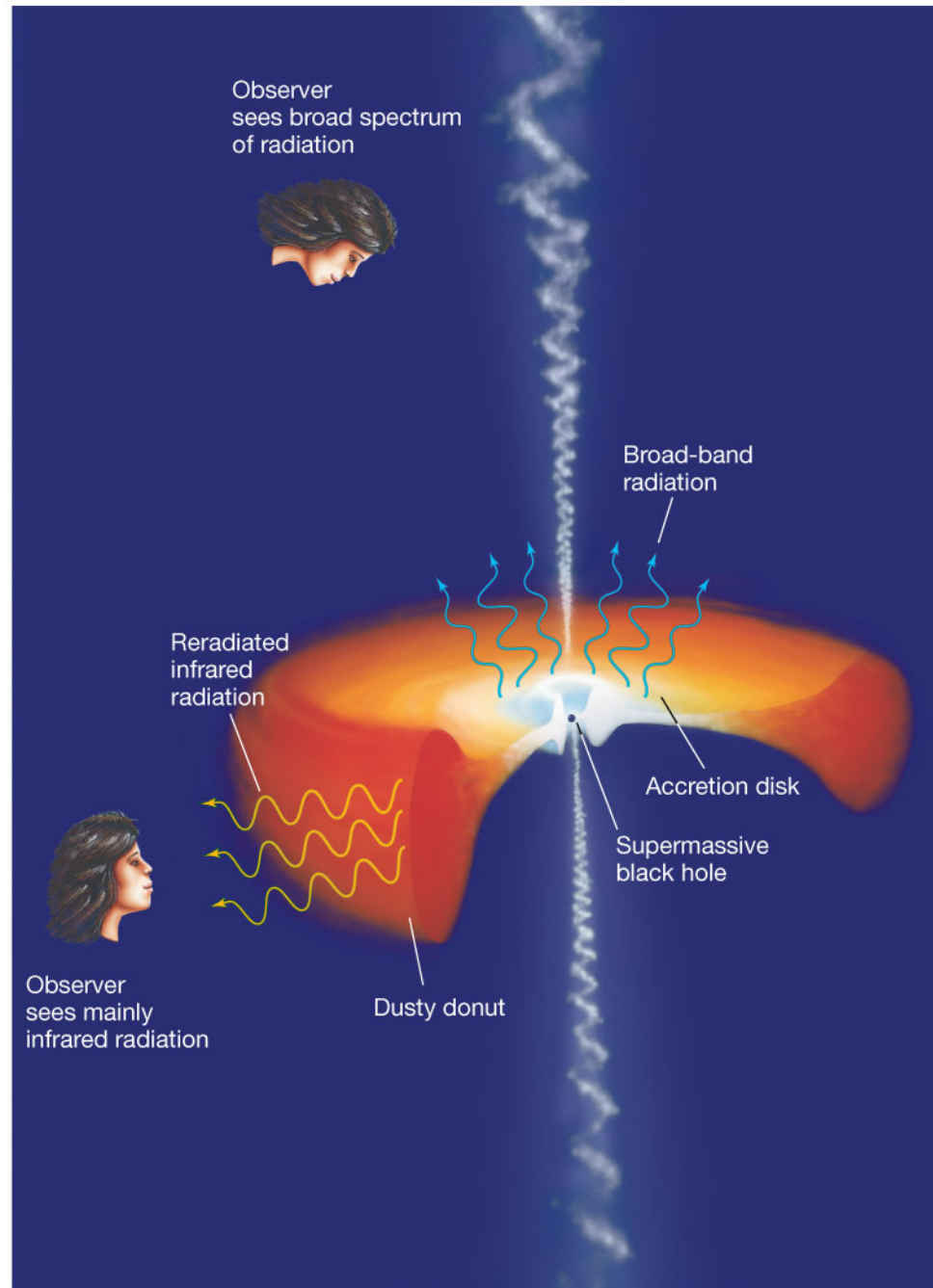


Galaxies in which the black hole is “switched on” and producing large amounts of energy are referred to as active galaxies, and the cores themselves are called **active galactic nuclei (AGN)**.

AGN fuelling: **accretion disks**. Processes in the accretion disk/jet makes black hole “visible”.



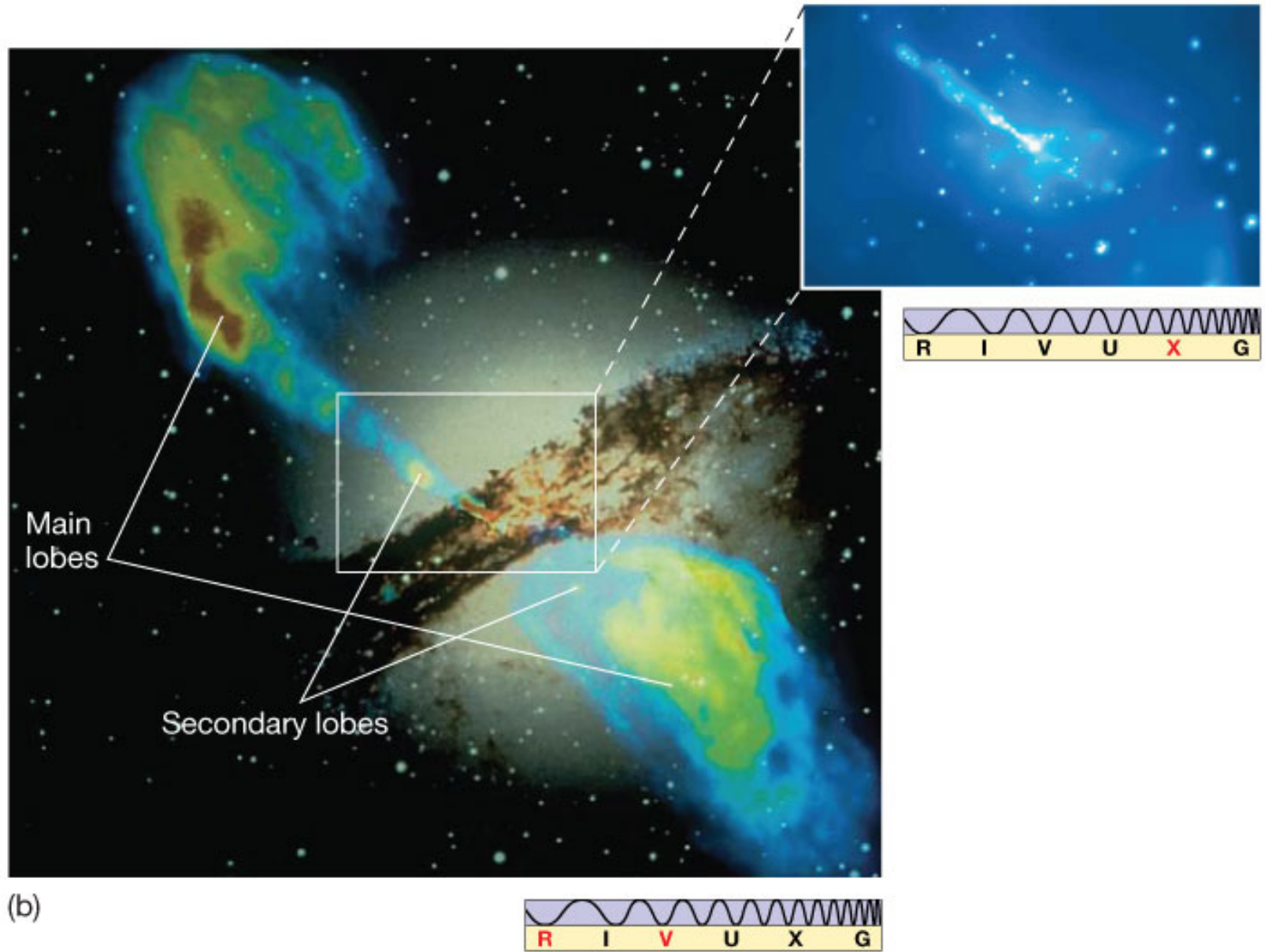
The “unified model”



AGN detection methods: Radio jets, most common in massive ellipticals, “radio galaxies”.

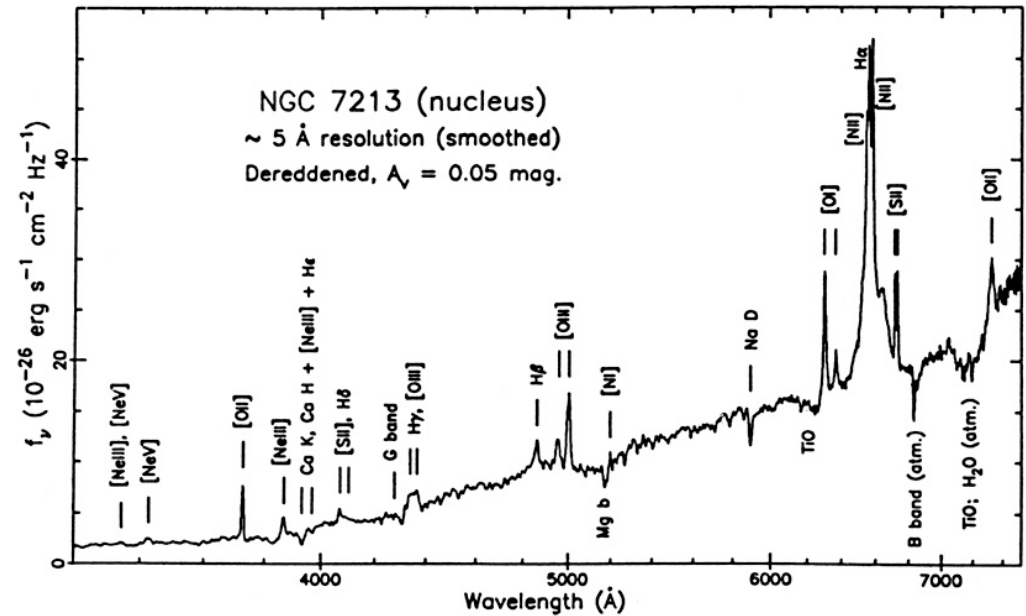
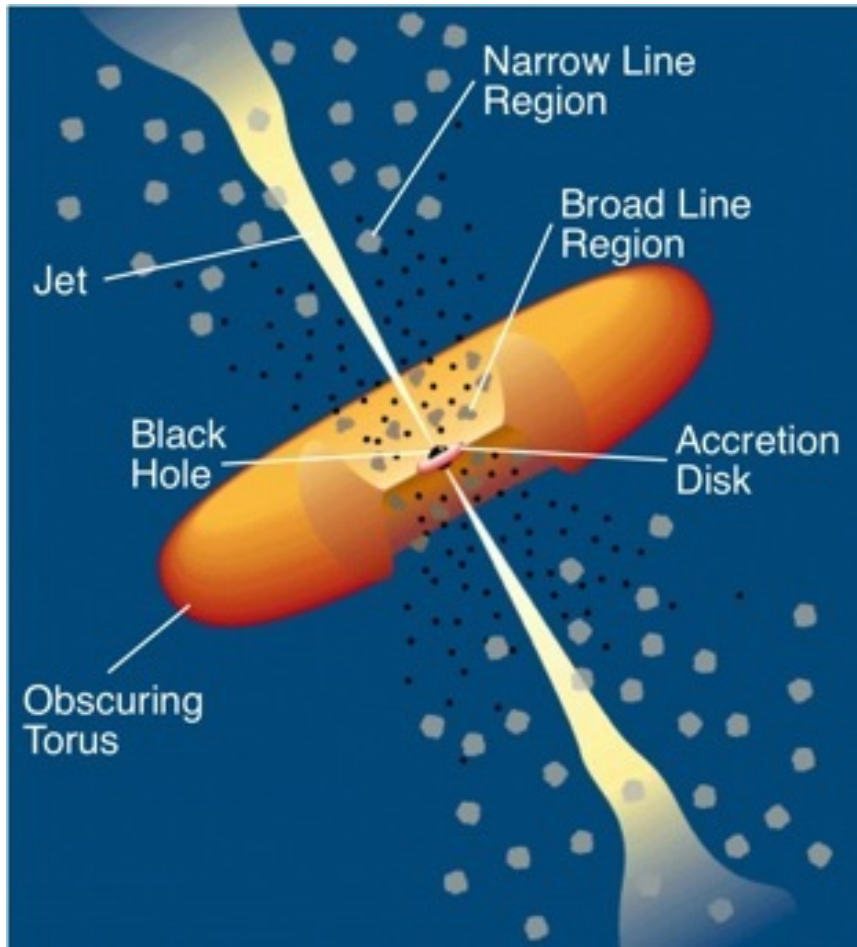


AGN detection methods: X-ray emission detected around accretion disk.



(b)

AGN detection methods: spectroscopy of broad emission lines:

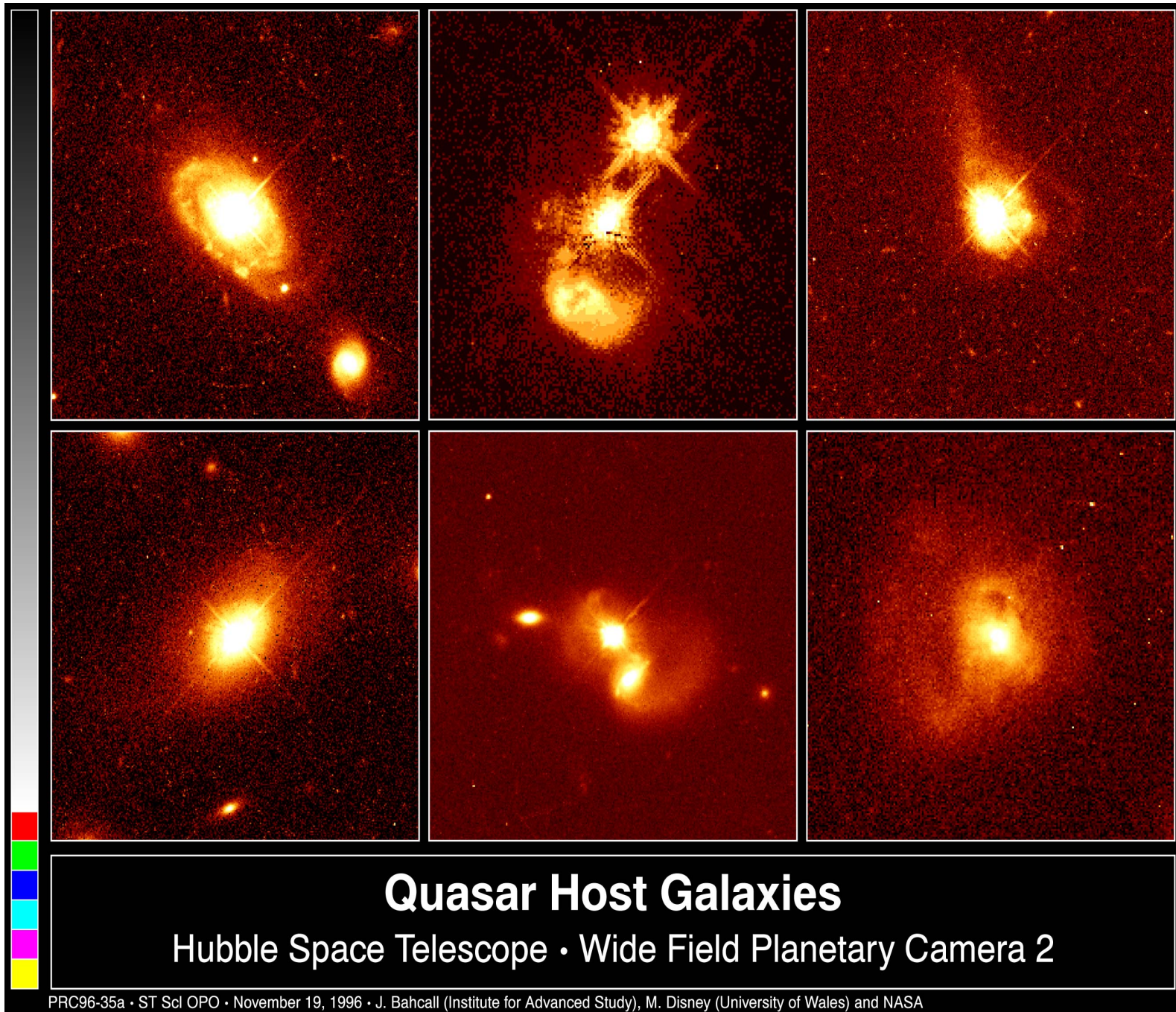


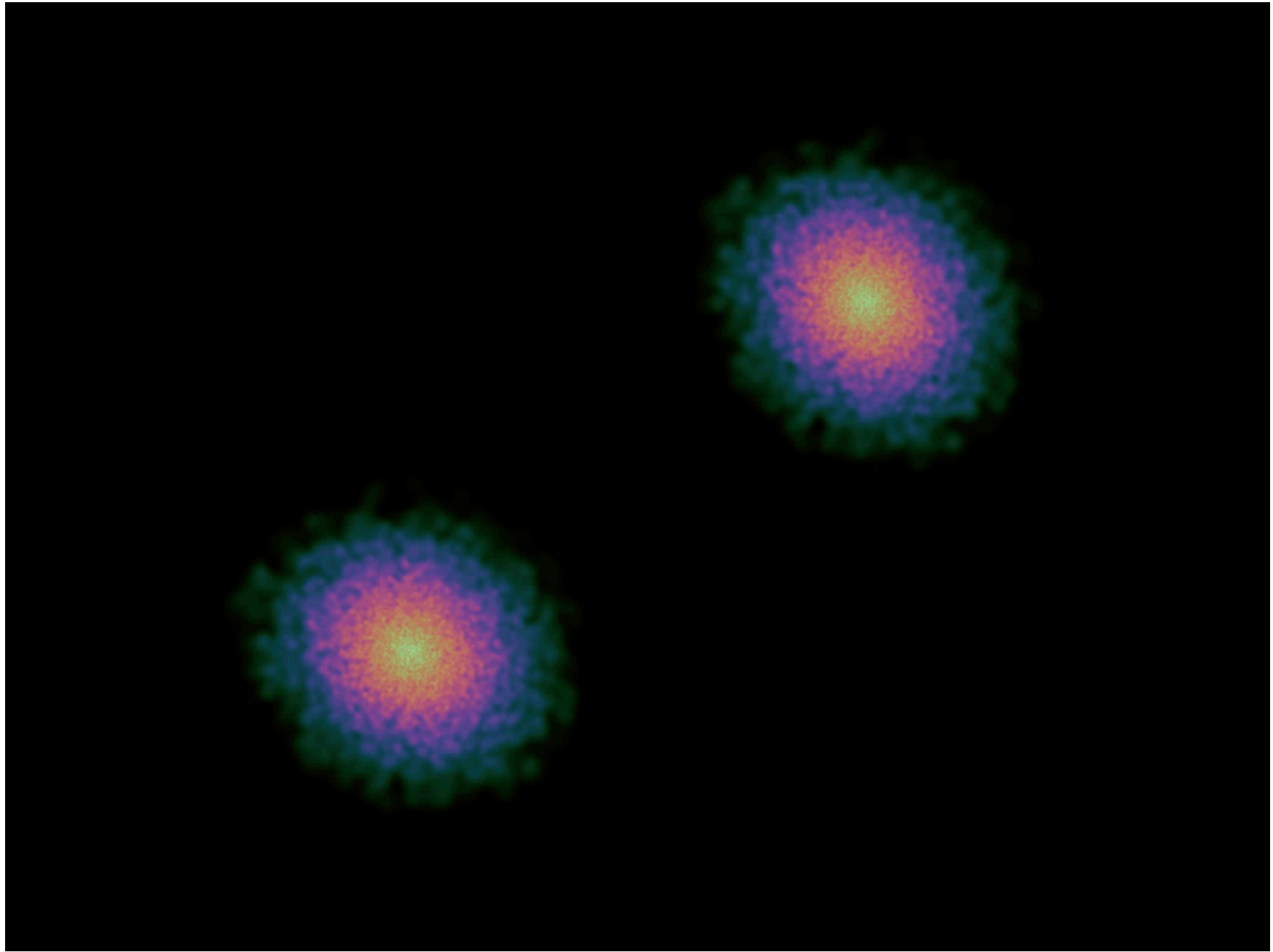
Why are lines broad in this region?

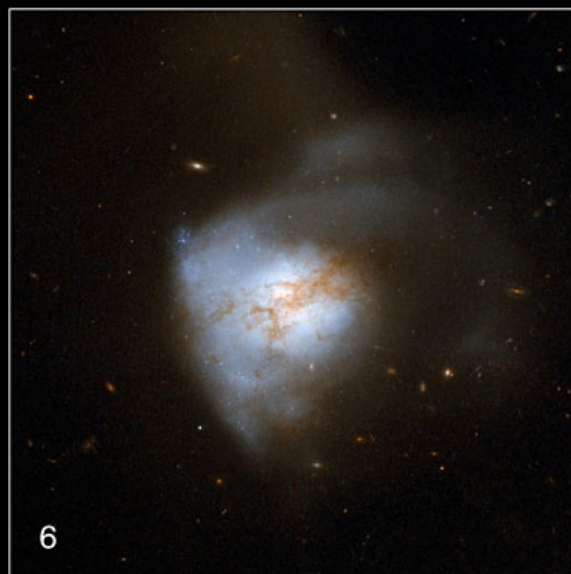
Not all AGN are in massive ellipticals, they can also be found in spirals, where they tend to be classified as lower luminosity **Seyfert galaxies**.

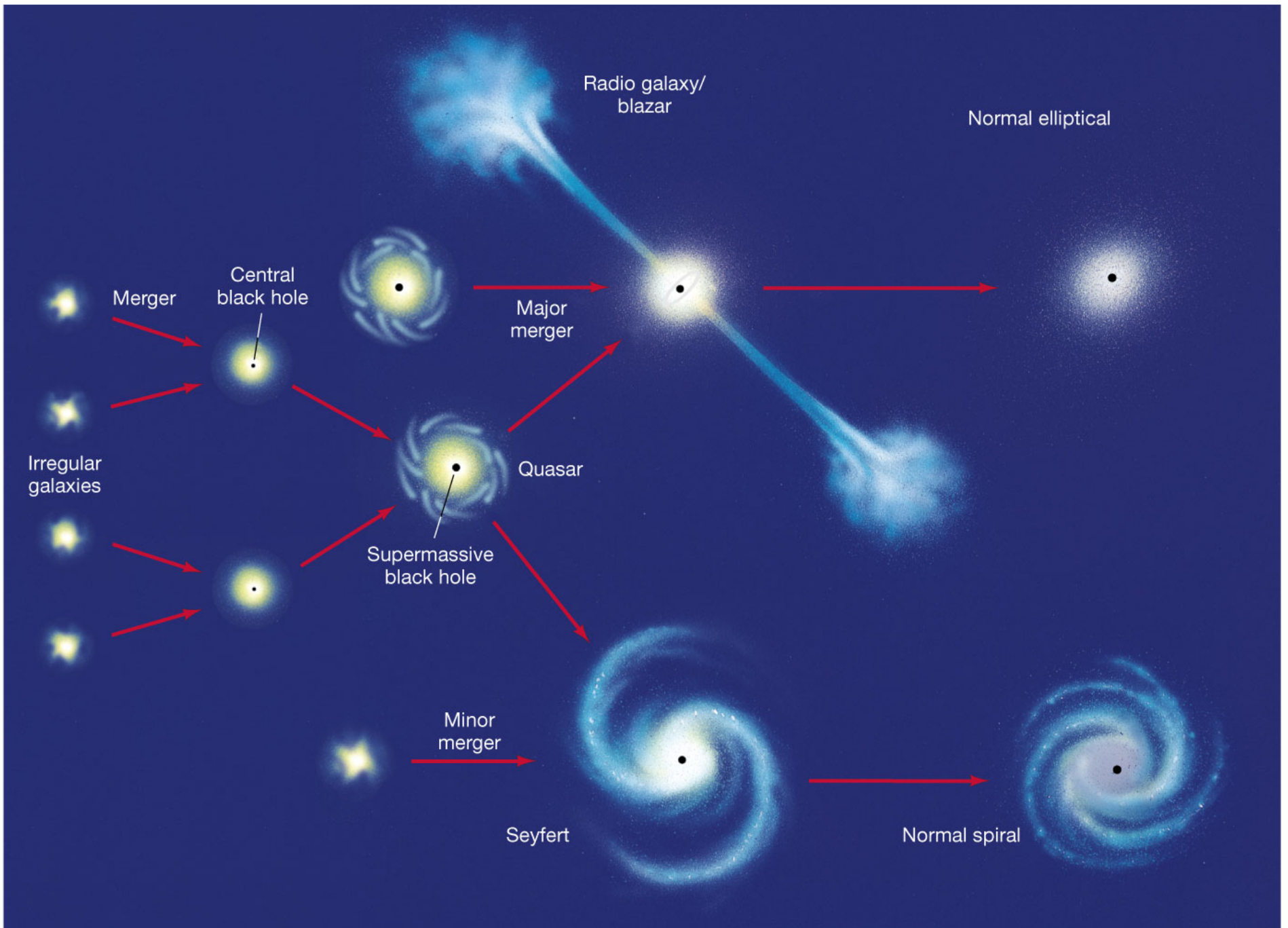


Quasars - a clue to what switches black holes on.







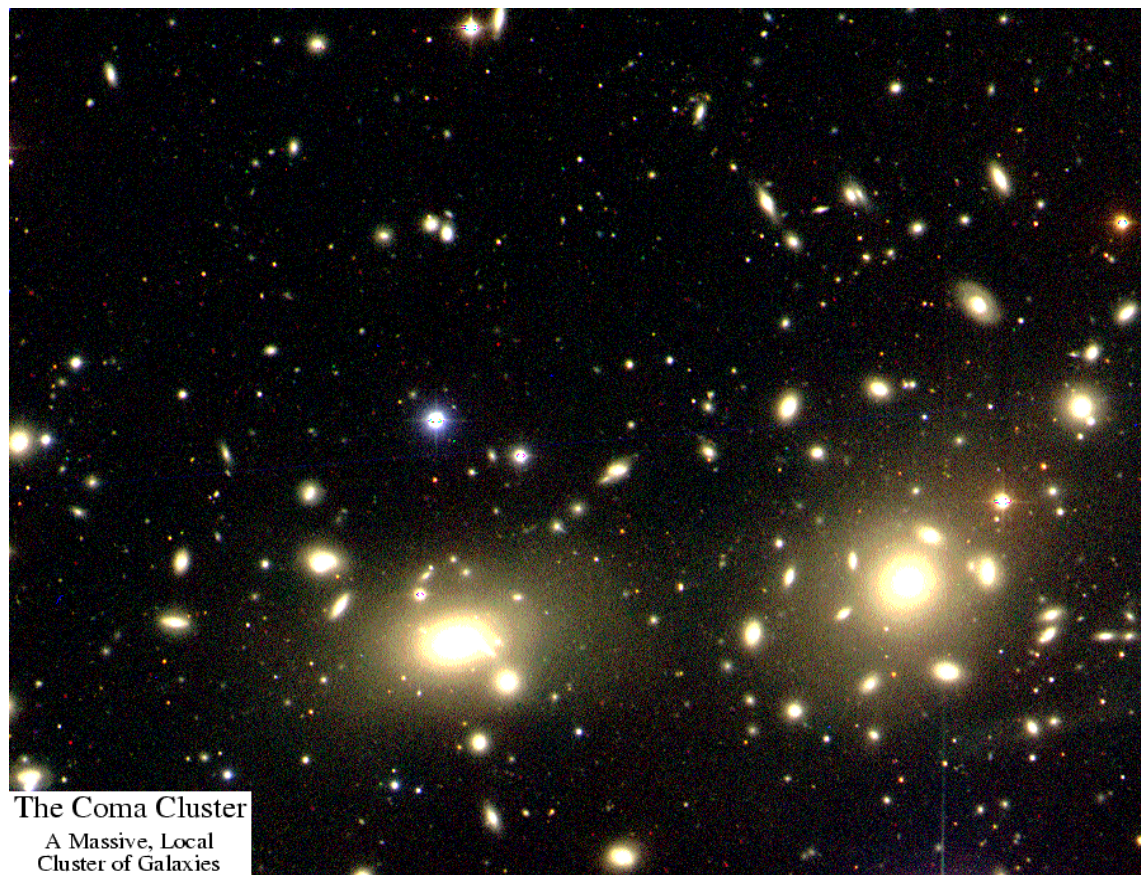
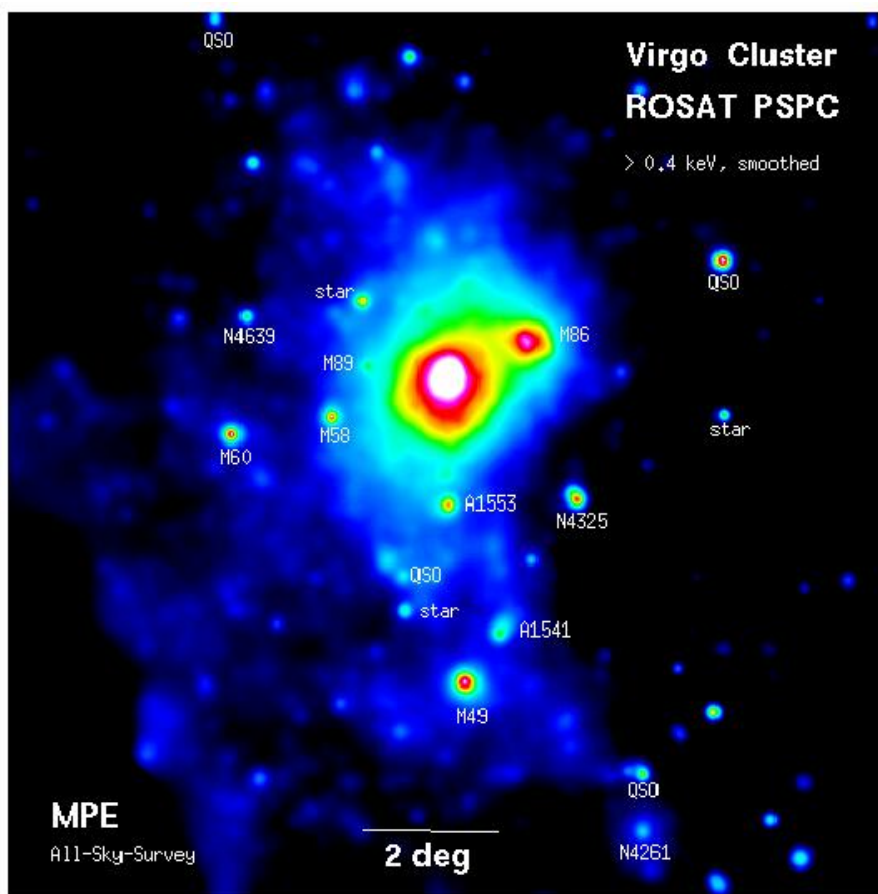


Galaxy Clusters and Large Scale Structure

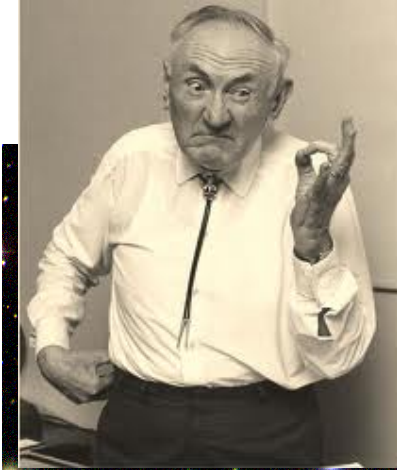


Local Group of galaxies has 2 big spirals (Milky Way and Andromeda), the two Magellanic Clouds (Large and Small) and about 50 other galaxies spanning 10 million light years (3 Mpc).

Galaxy Clusters



Something fishy in the Coma cluster (Zwicky 1933)



Distance to Coma ~ 100 Mpc

Angular size ~ 0.5 deg.

Apparent mag $\sim +9$ mags

$$\text{Diameter} = \frac{0.5 \times 3600 \times 100}{206265}$$

Diameter ~ 1 Mpc

Absolute magnitude of Sun ~ -5 , so apparent mag of Sun at 100 Mpc:

$$m = -5 + 5 \log(1e8) + 5 = 40$$

Coma is 31 mags brighter than Sun: $2.5^{31} = 2.5 \times 10^{12}$ times brighter!

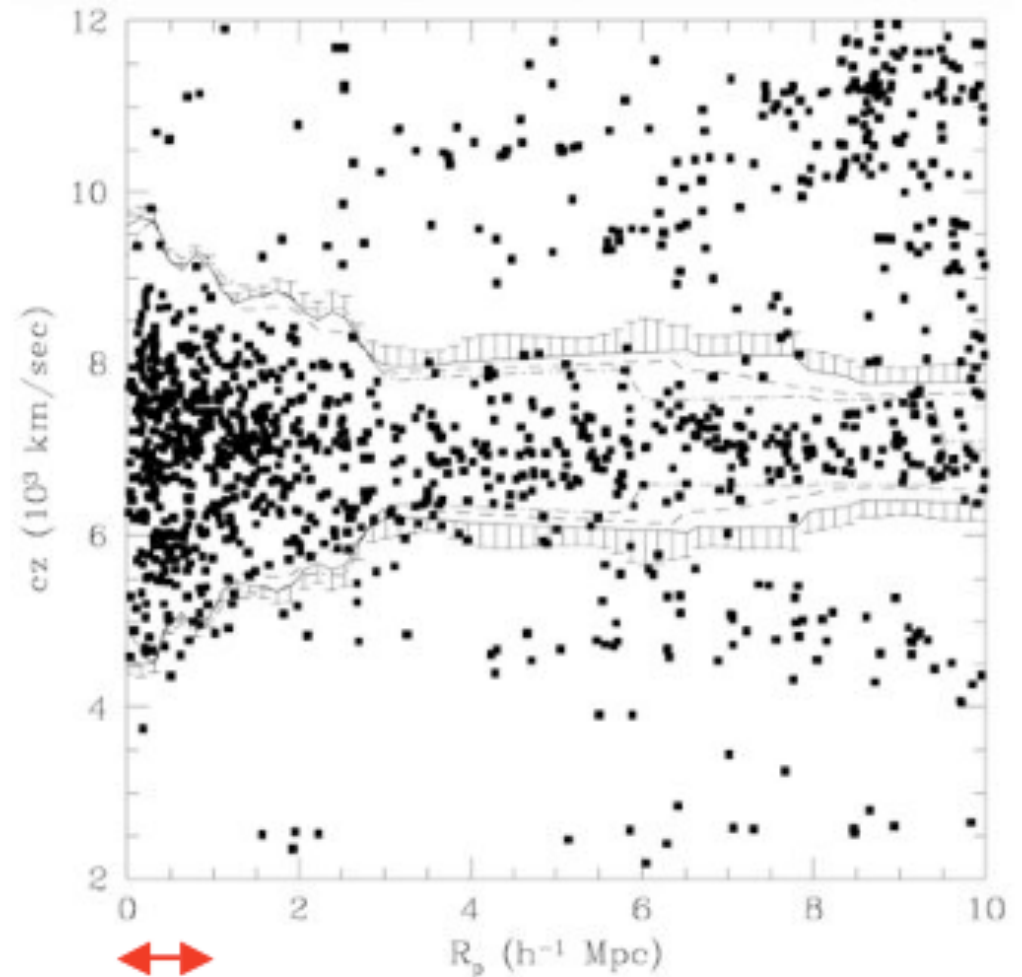
Luminosity of Coma cluster is $\sim 2.5 \times 10^{12}$ solar luminosities, so probably contains about 2.5×10^{12} stars (average stellar mass is about 1 solar mass).

Galaxy radial velocities in Coma have a dispersion (spread) about 1000 km/s within 1 Mpc.

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$\rightarrow M \sim \frac{v^2 r}{G}$$

± 1000 km/s



1 Mpc

Galaxy radial velocities in Coma have a dispersion (spread) about 1000 km/s within 1 Mpc.

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

V (1000 km/s) in m/s

$$\rightarrow M \sim \frac{v^2 r}{G}$$

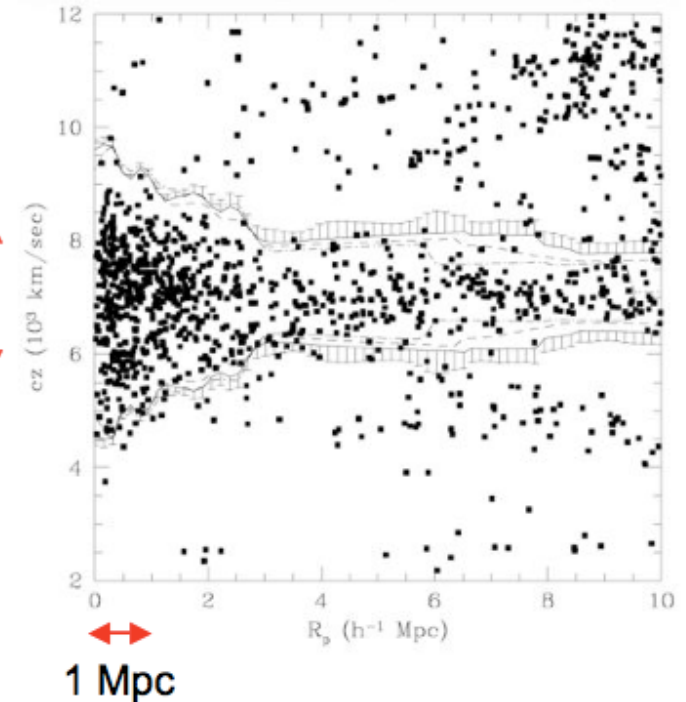
±1000 km/s

R (1Mpc) in m

$$M = \frac{(1e6)^2 \times 3.08e12}{6.67e-11}$$

$$= 4.6e44 \text{ kg}$$

$$\sim 2.5 \times 10^{14} \text{ solar masses}$$



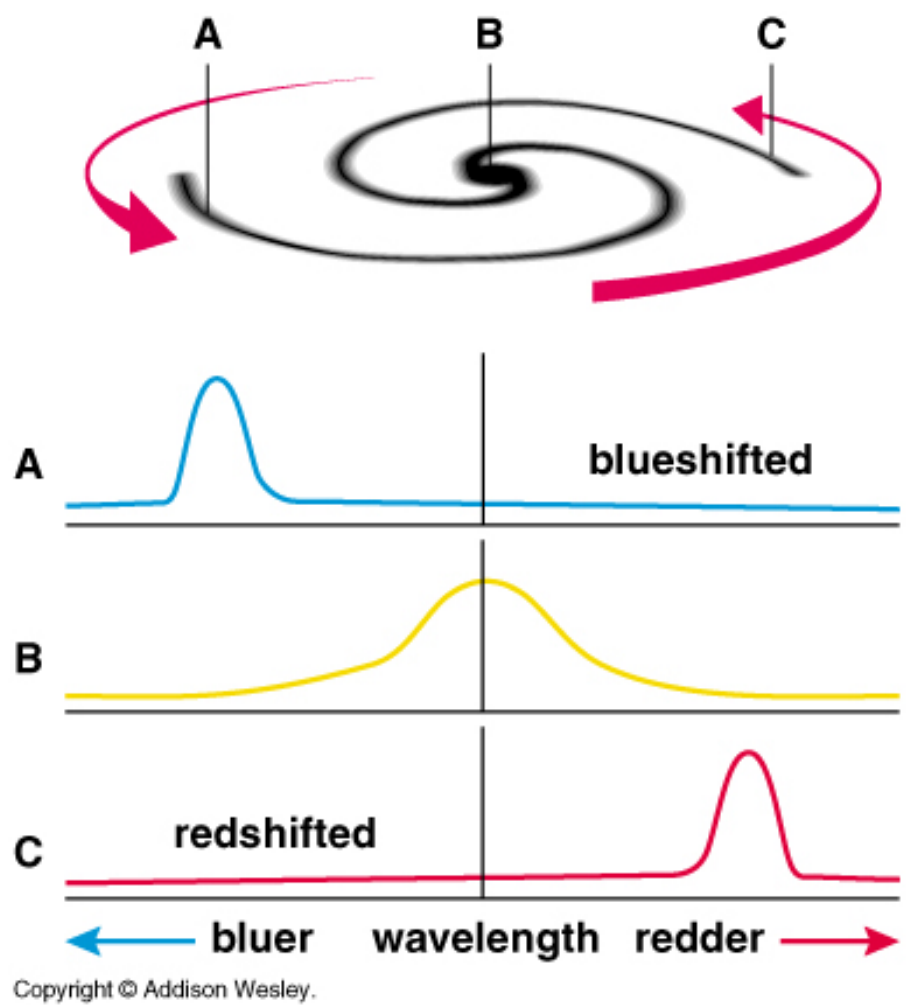
For each solar mass, expect a solar luminosity but for Coma:

$$\frac{2.5 \times 10^{14} \text{ solar mass}}{2.5 \times 10^{12} \text{ solar luminosities}} = 100 \text{ times more mass than light!}$$

(accurate virial theorem treatment gives x400)

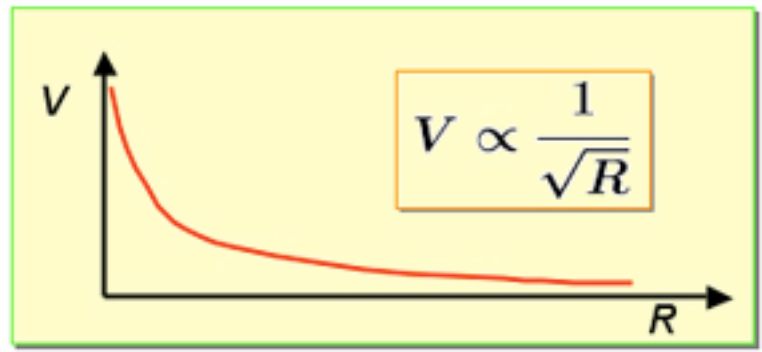
First evidence of dark matter largely ignored for 40 years!!

Dark Matter Inferred from Galaxy Rotation Curves



Measure velocity from Doppler shift as a function of radius. From equating gravity and centripetal forces:

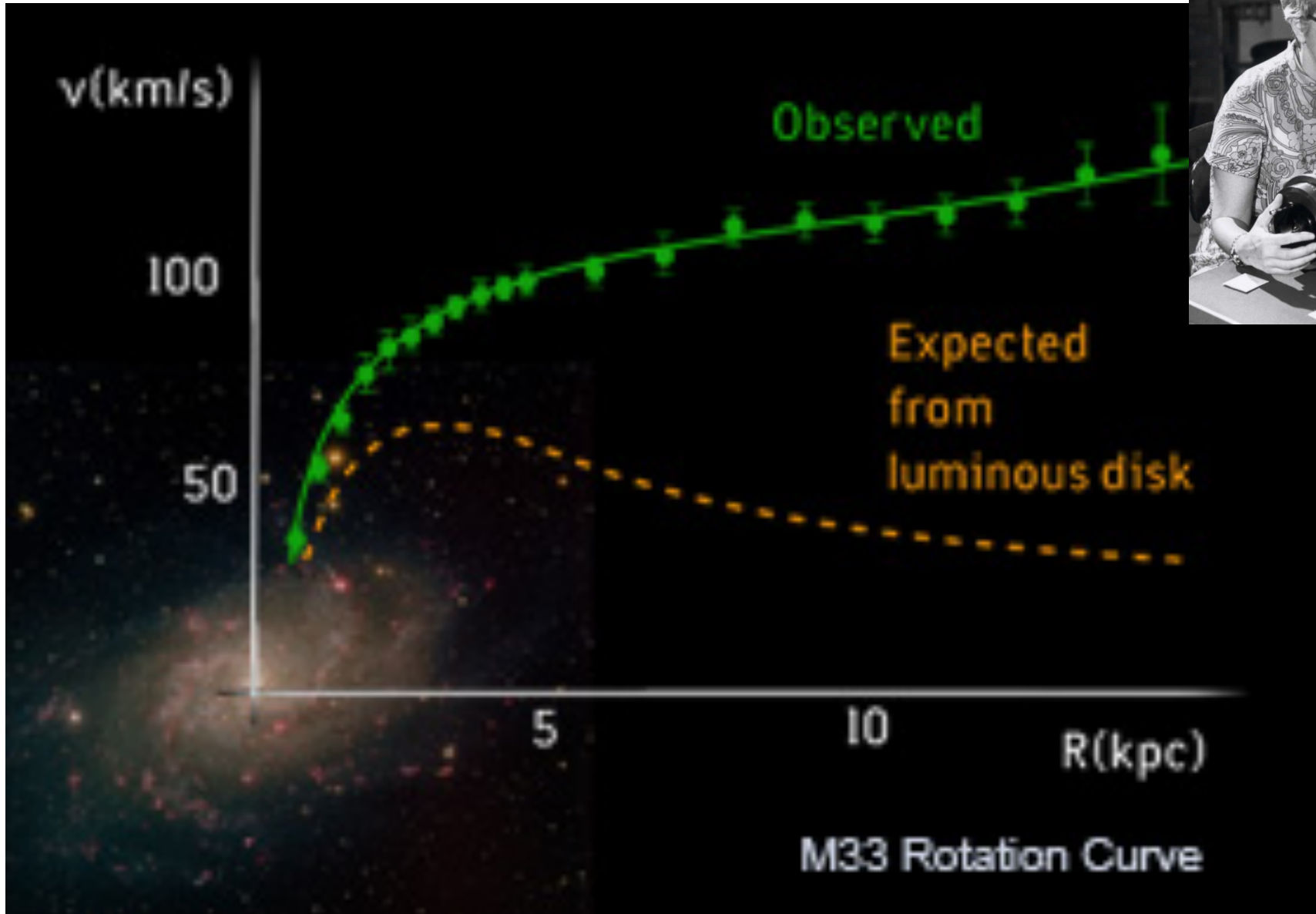
$$V^2 = GM / R$$

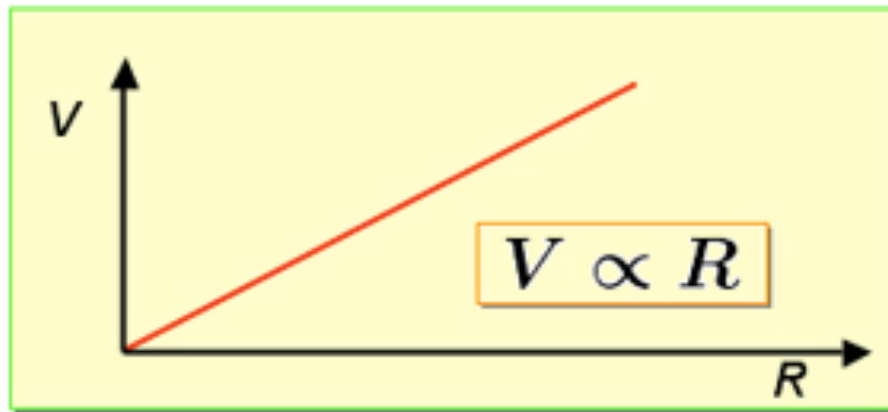


Kepler's 3rd law also predicts $V^2 \propto 1/R$

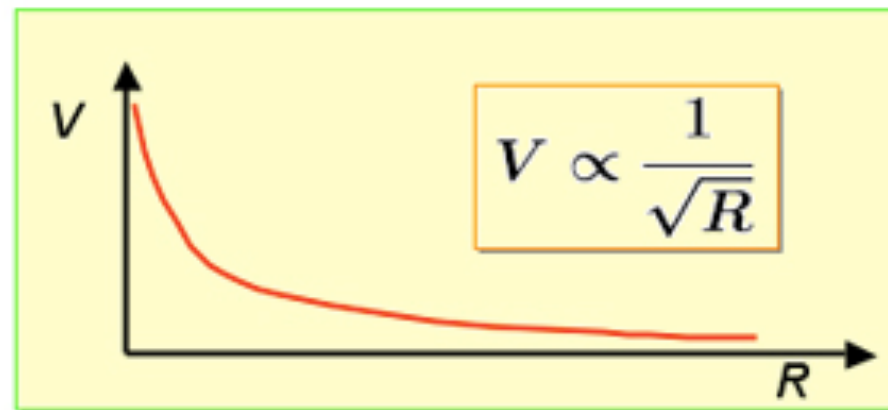
Actual rotation curves are flat (constant velocity beyond stellar disk), or even rising!!

Vera Rubin c1970

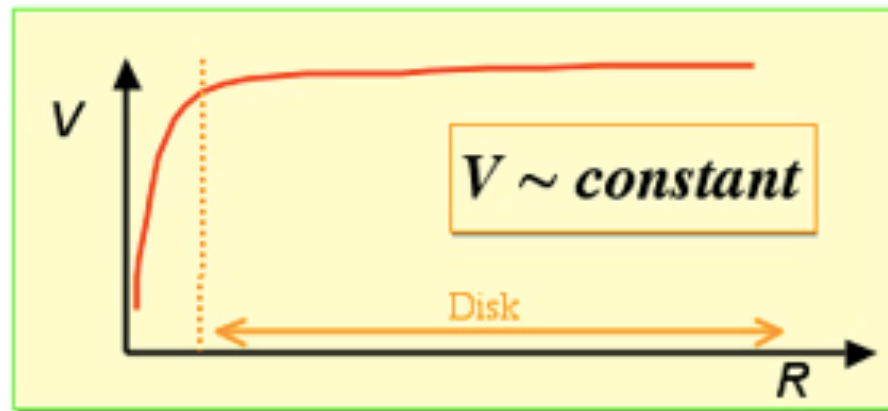




Solid Body
Rotation



Keplerian
Rotation



Galactic
Rotation

What does it mean to have constant velocity at large R?

Let M_R = mass enclosed within R,

$\rho(R)$ = density at R

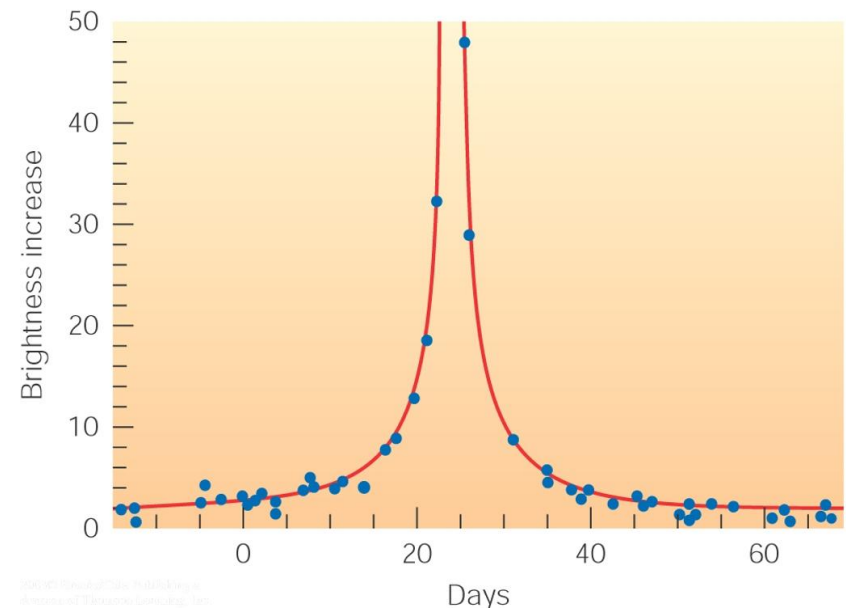
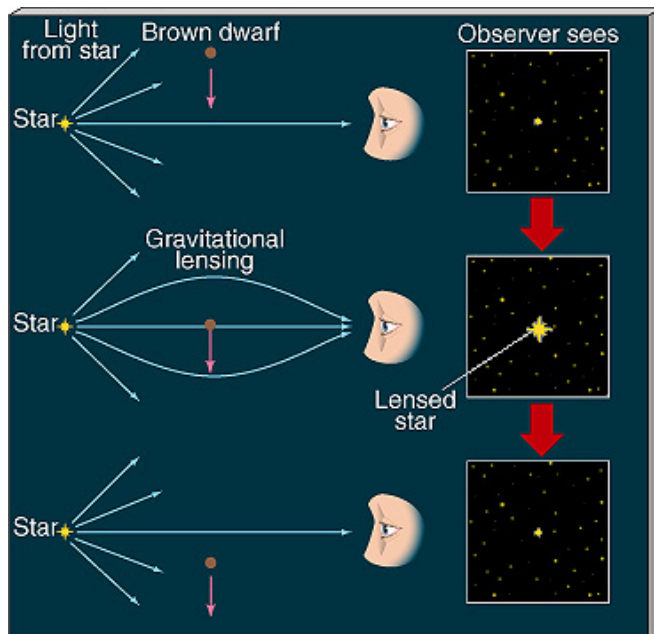
$$v^2 = \frac{GM_R}{R} = \text{constant} - \text{what does this mean?}$$

Answer: $M_R \propto R$

Mass keeps on increasing with radius!

What is dark matter?

- **Stars** - No! Would be visible.
 - **Gas** - No! Seen in emission (21cm, CO mm, Xray, etc.) and absorption.
 - **Stellar remnants** (white dwarfs, neutron stars) - No!
- Microlensing experiments.



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Microlensing experiments.
- **Stellar mass BHs** - No! Lensing.
- **Massive BHs** - No! Would see X-rays, gravitational effects.
- **Exotic particles** - probably, but not sure what!!

80-90% of matter in galaxies is dark!!!!