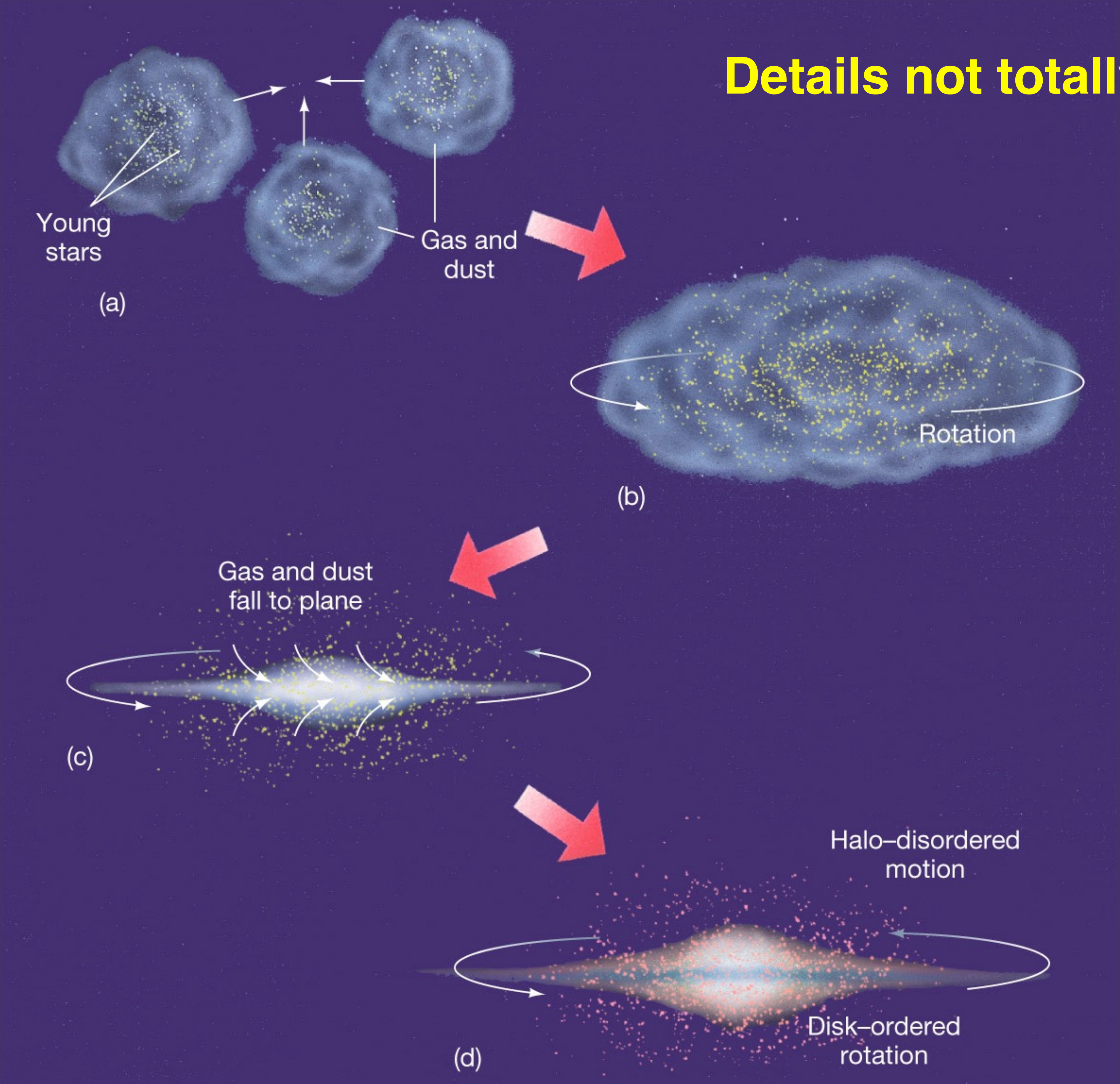
Halo formation and satellite galaxies

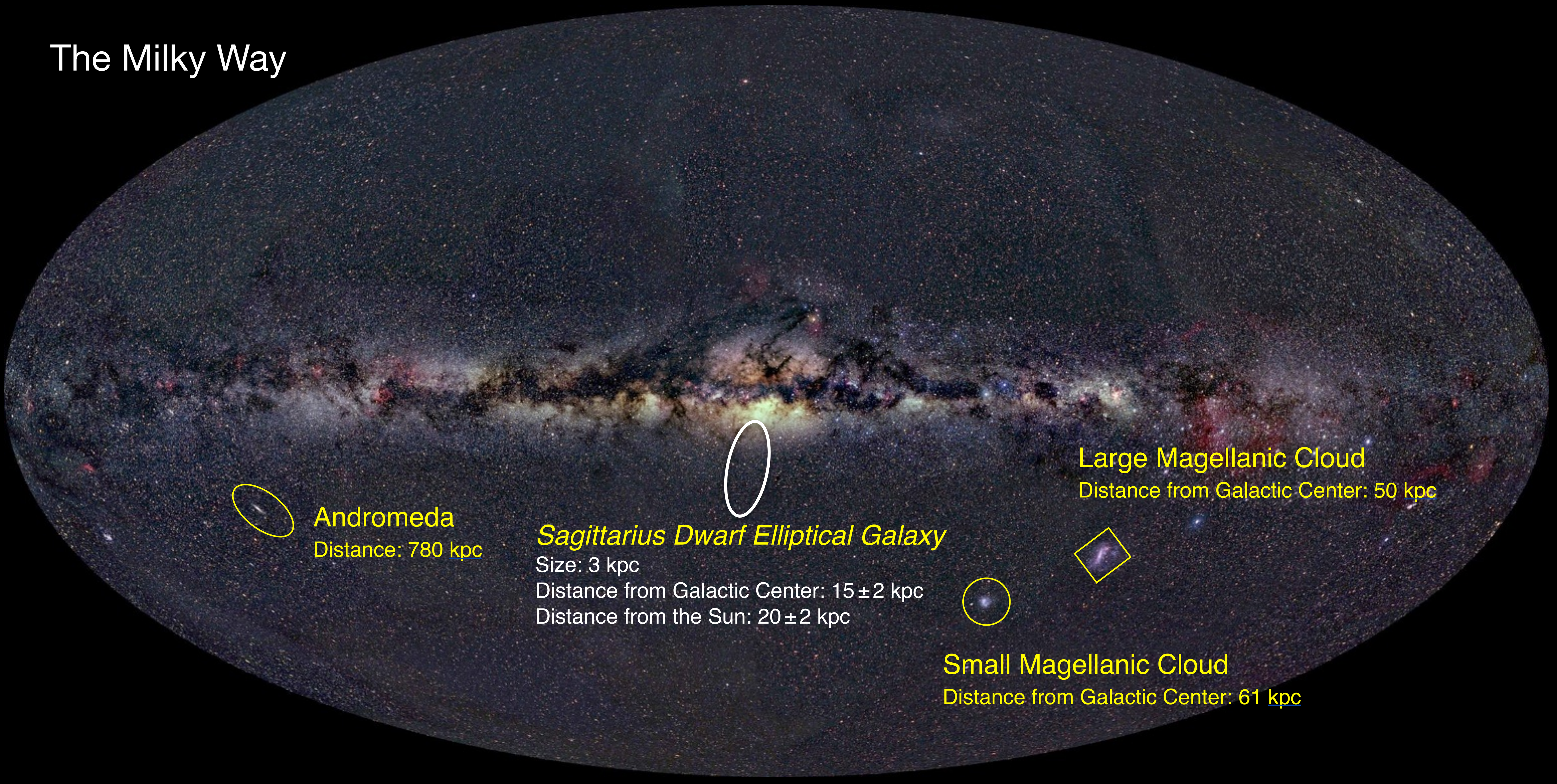
Formation of the Milky Way
(more than 10 billion years ago)

Details not totally known



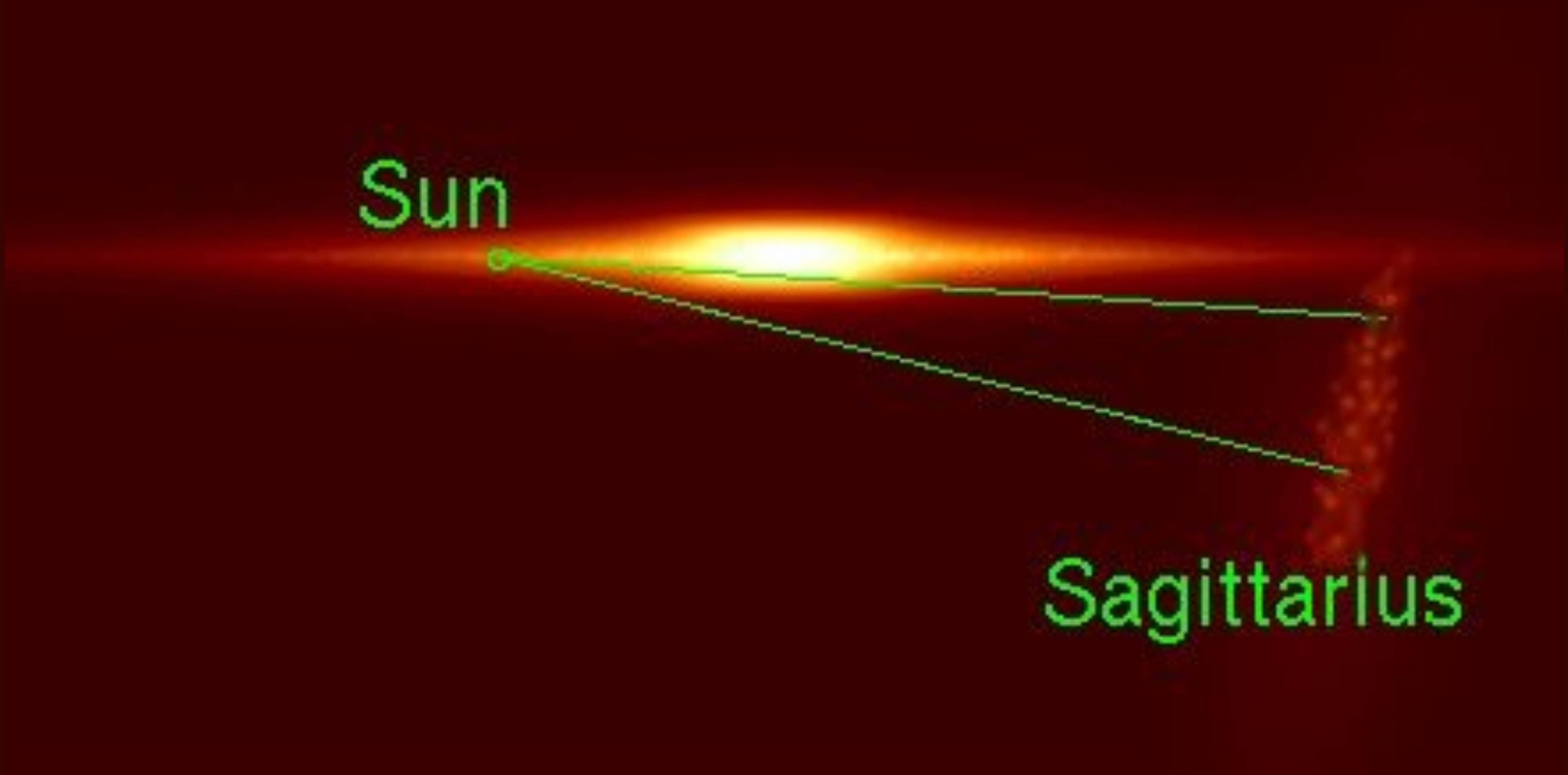
Closest galaxy to the Milky Way: *Sagittarius Dwarf Elliptical Galaxy* (*SagDEG*)

(discovered in 1994, opposite side of the galactic core from Earth)



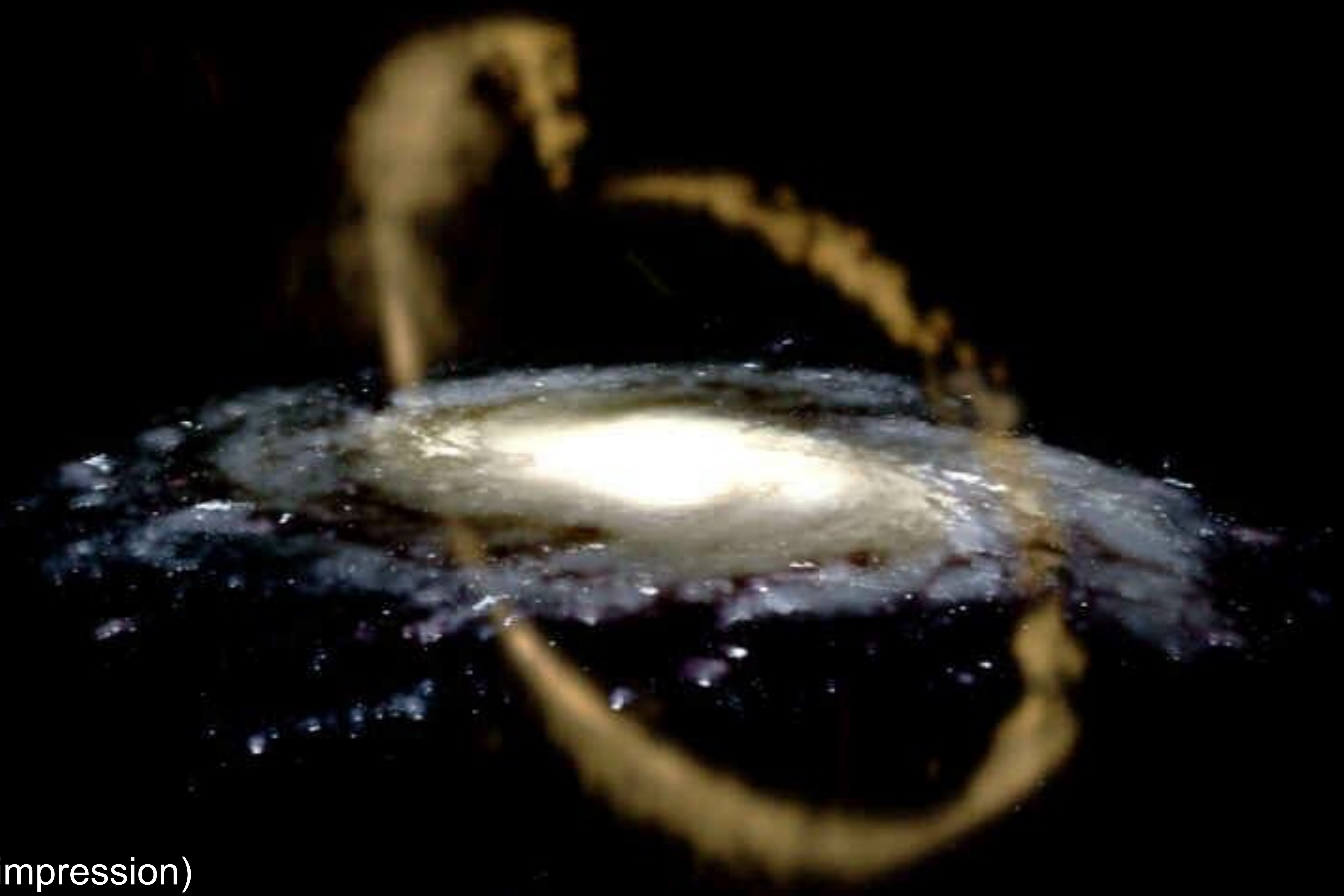
SagDEG is old & metal poor galaxy with little interstellar dust and composed largely of Population II stars, best seen in near infrared

Sagittarius Dwarf Elliptical Galaxy



Sagittarius Dwarf Elliptical Galaxy

- It started as a round shape
- It passed through plane of Milky Way several times in the past
- Now ripped apart into a long stellar stream



(artist's impression)

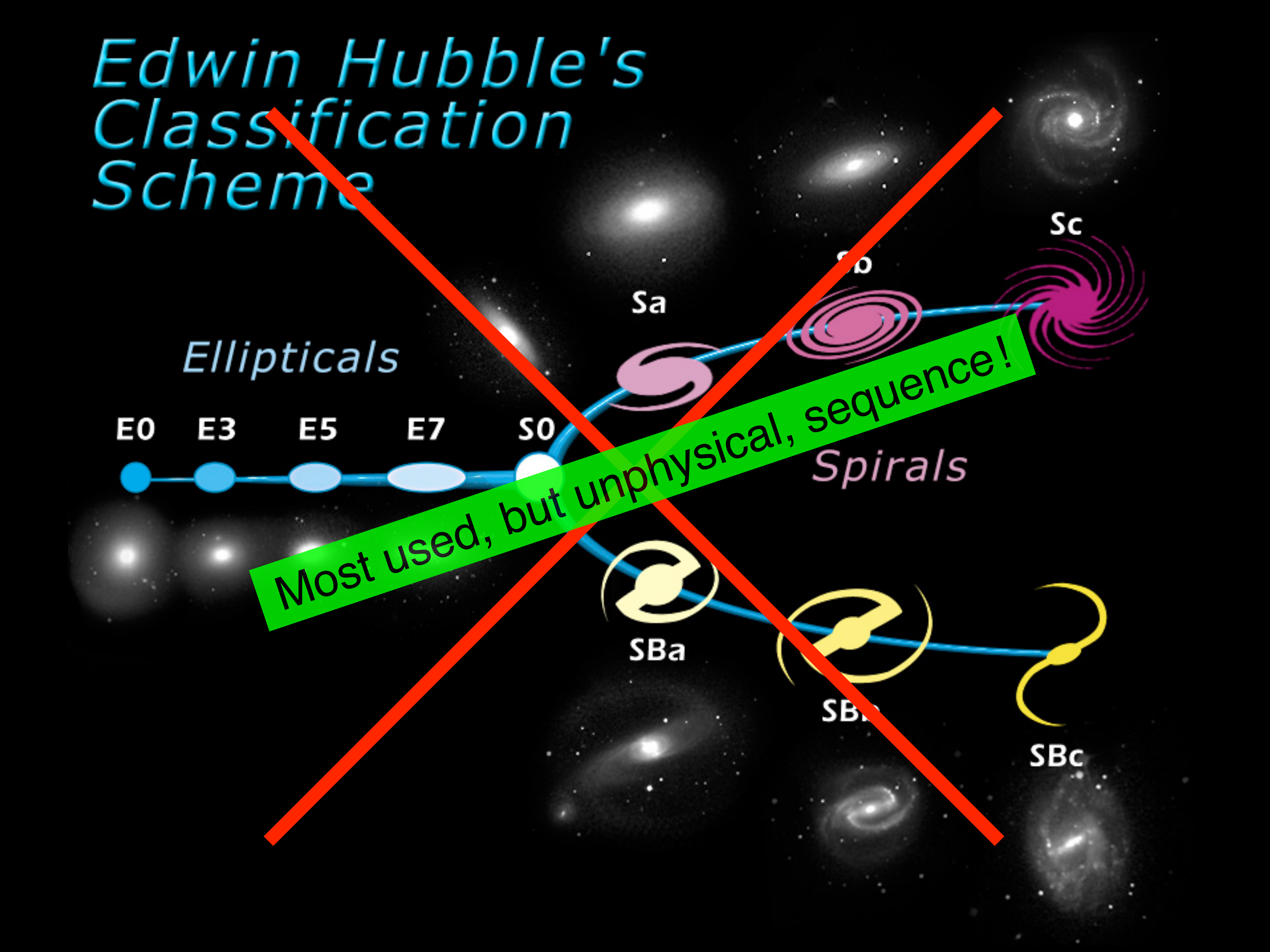
Classification of galaxies

Classification of galaxies according to their morphology

Elliptical galaxy

Spiral galaxy

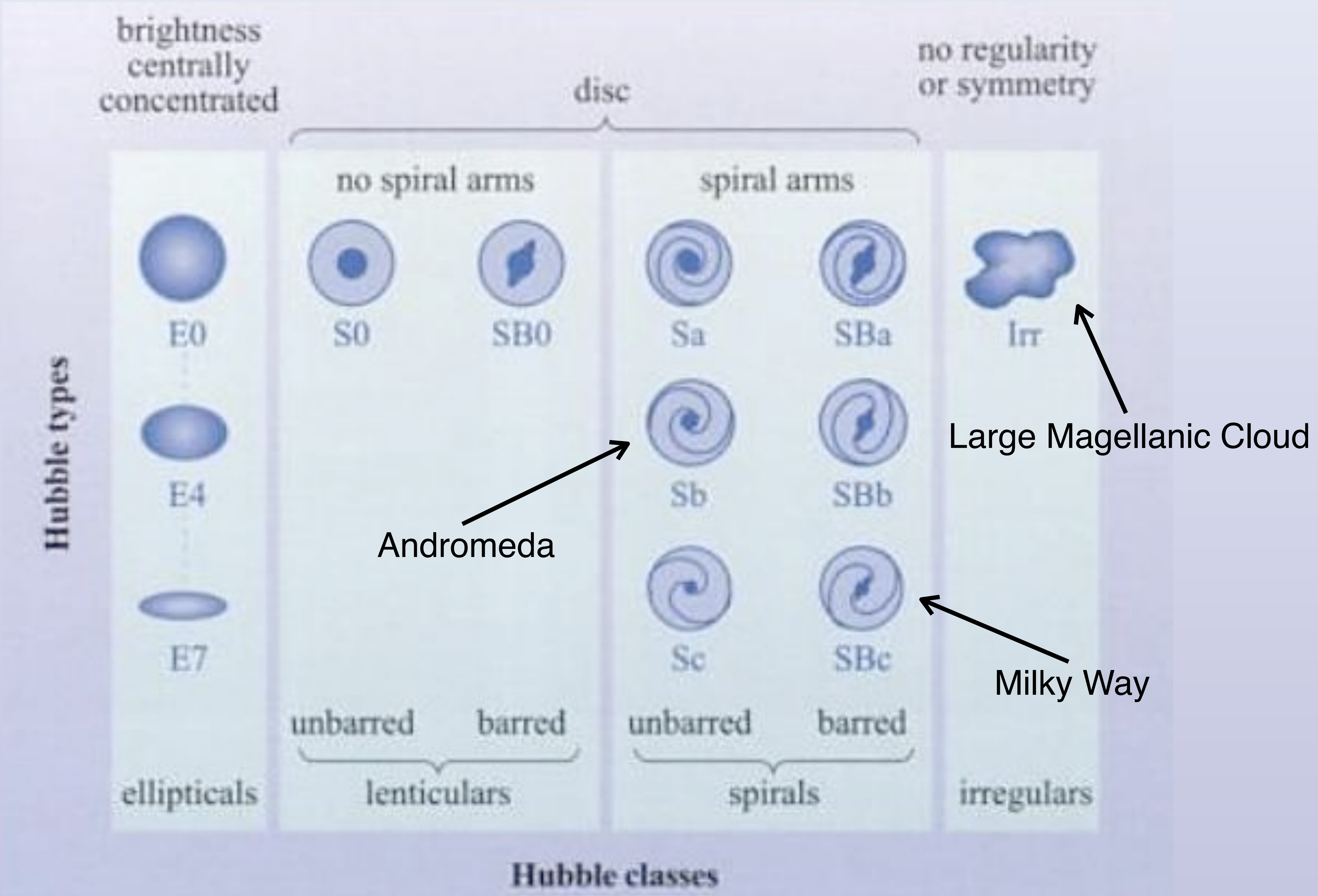
Irregular galaxy

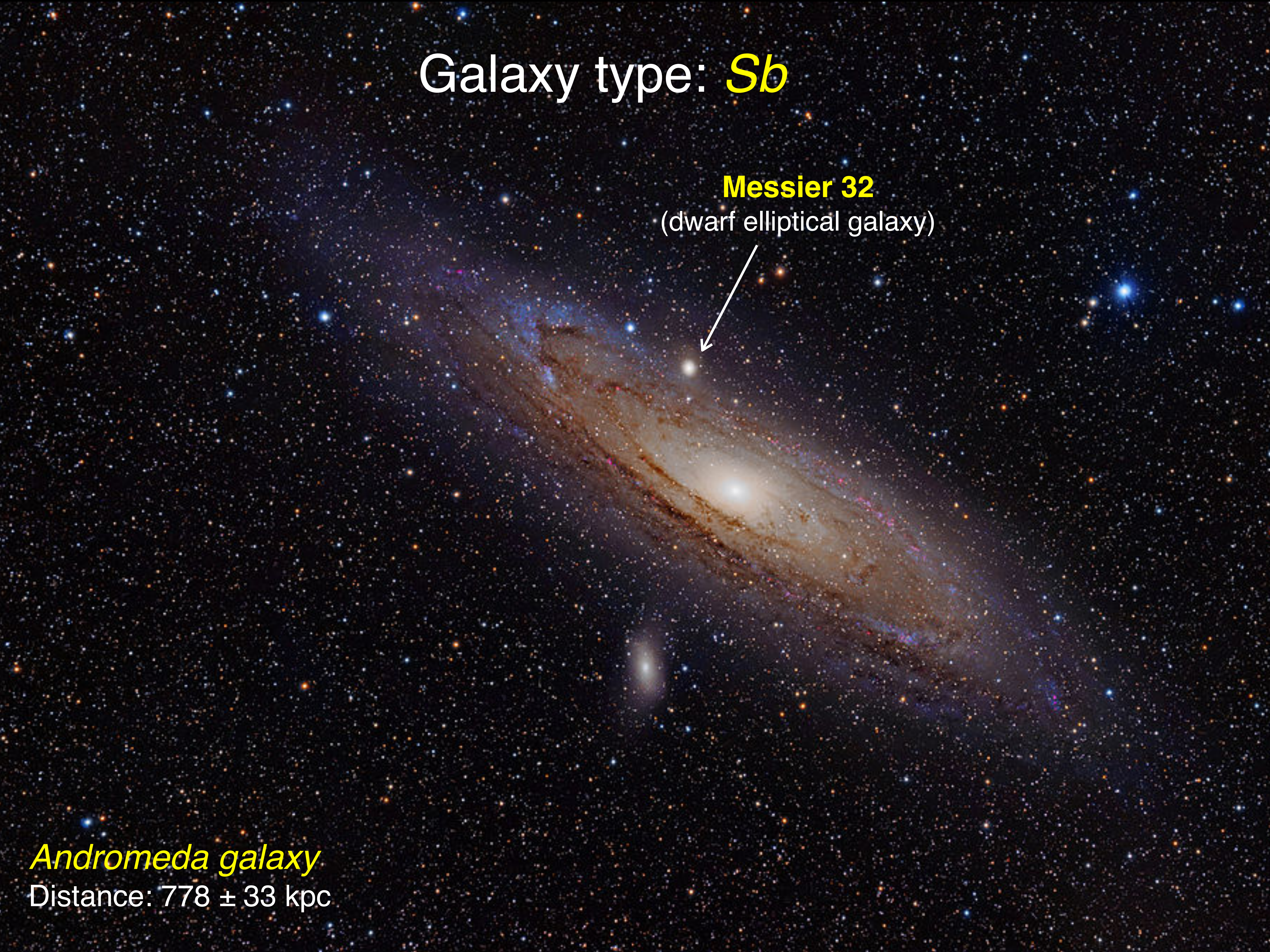


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sc
Spirals
SBa
SBc
Most used, but unphysical, sequence!

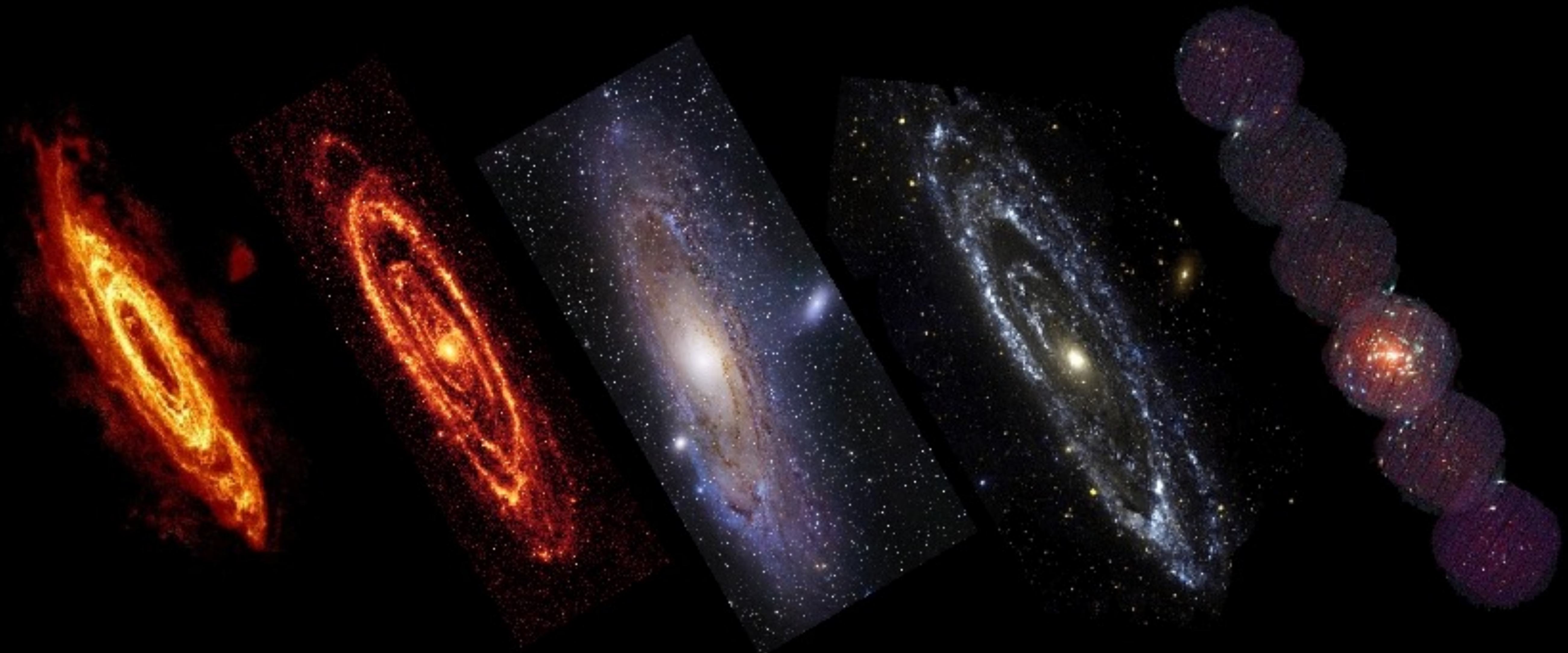
Classification scheme for galaxies

(from De Vaucouleurs 1959)




Galaxy type: *Sb*
Messier 32
(dwarf elliptical galaxy)
Andromeda galaxy
Distance: 778 ± 33 kpc

Andromeda galaxy



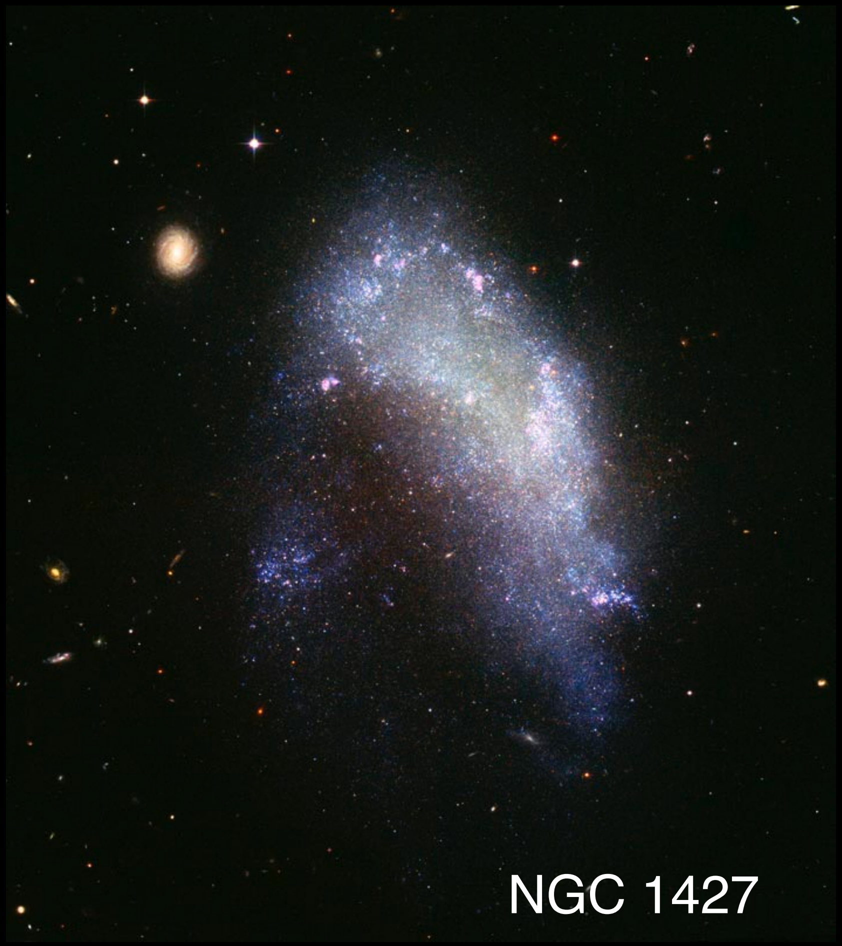
Radio   Infrared   Visible   Ultra-violet   X-ray

Spiral galaxies

Edge on spiral galaxy

Face on spiral galaxy

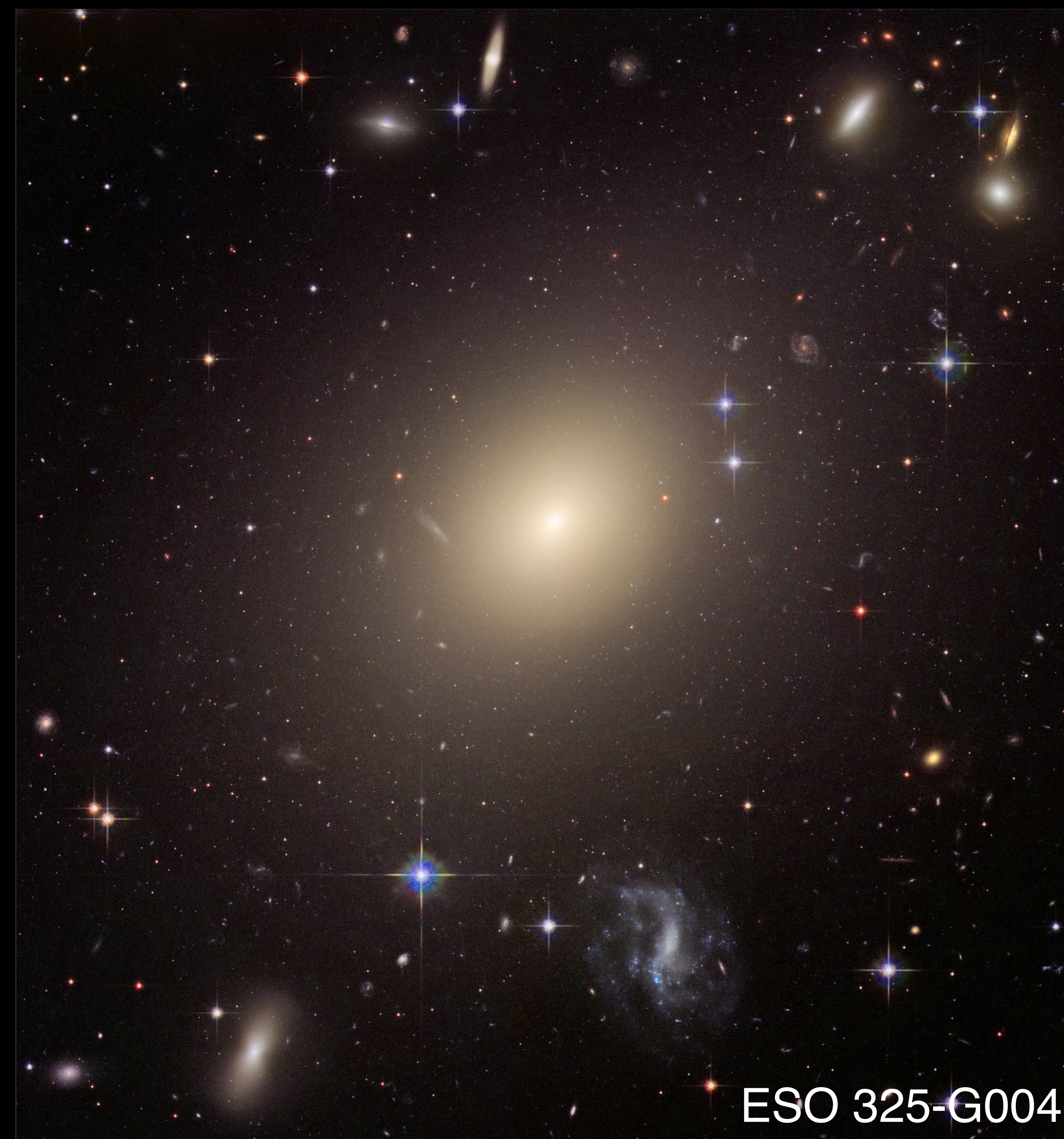
Irregular galaxies



Two elliptical galaxies, which one is larger?

Dwarf elliptical galaxy

Giant elliptical galaxy

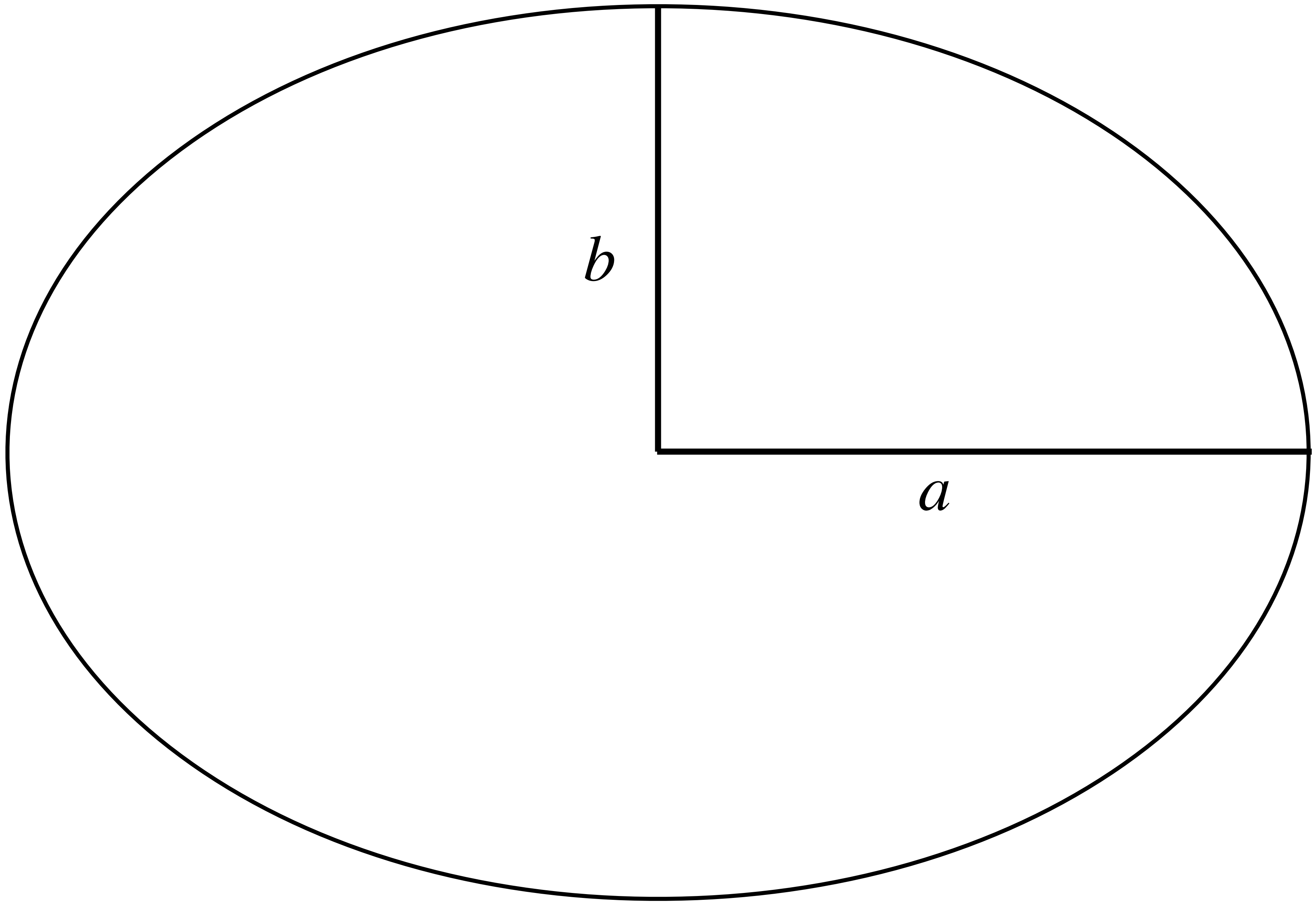


Lenticular galaxies

Type S0

Type SB0

Classification of elliptical galaxies: *E0, E1 ... E7*



$$f = (a-b)/a \times 10$$

For $a = b \longmapsto f = 0$, spherical galaxy *E0*

Most flat elliptical galaxies: *E7*

Typical elliptical galaxies: *E3*

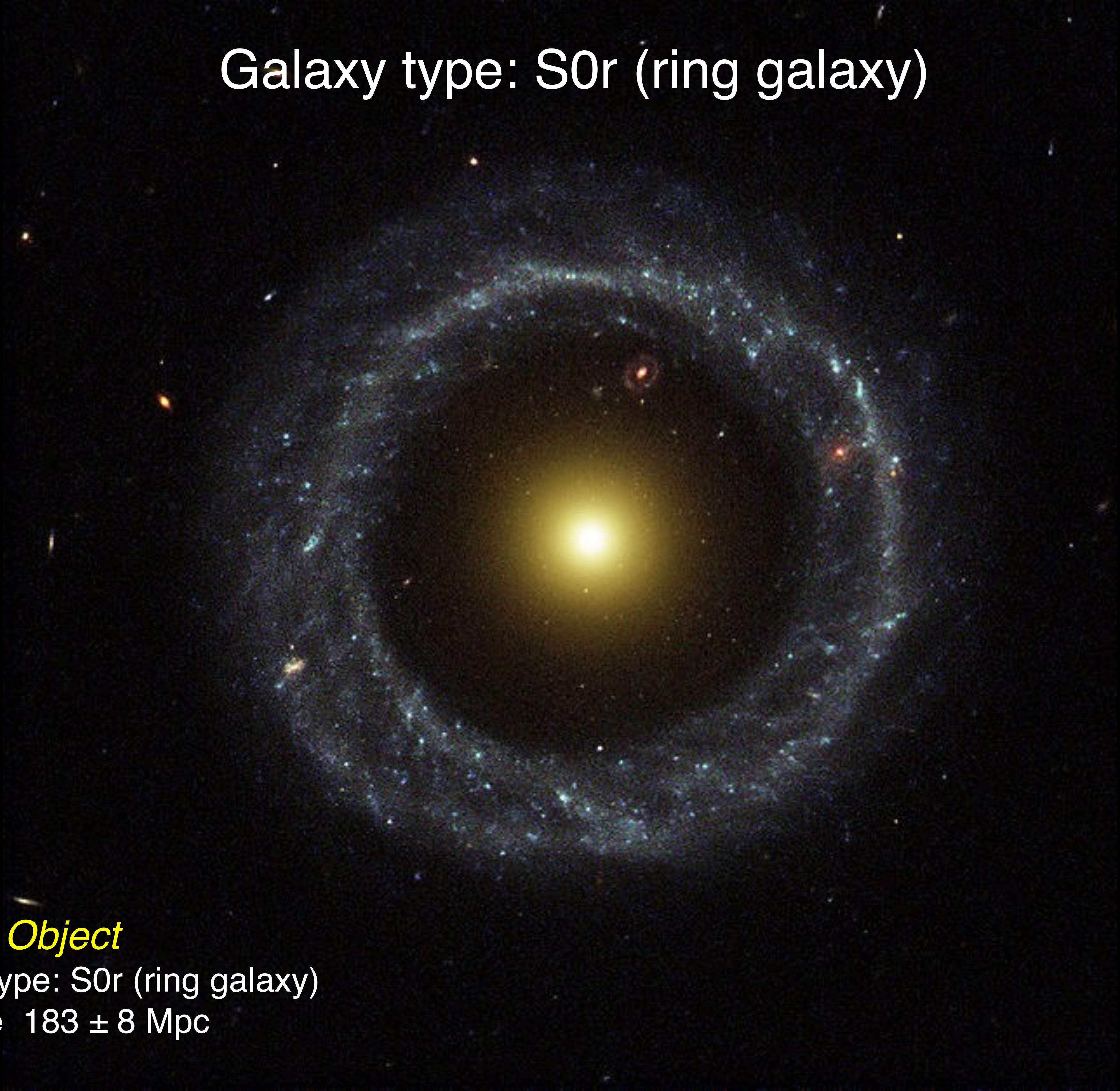
Elliptical galaxies

Type E0

Type E4

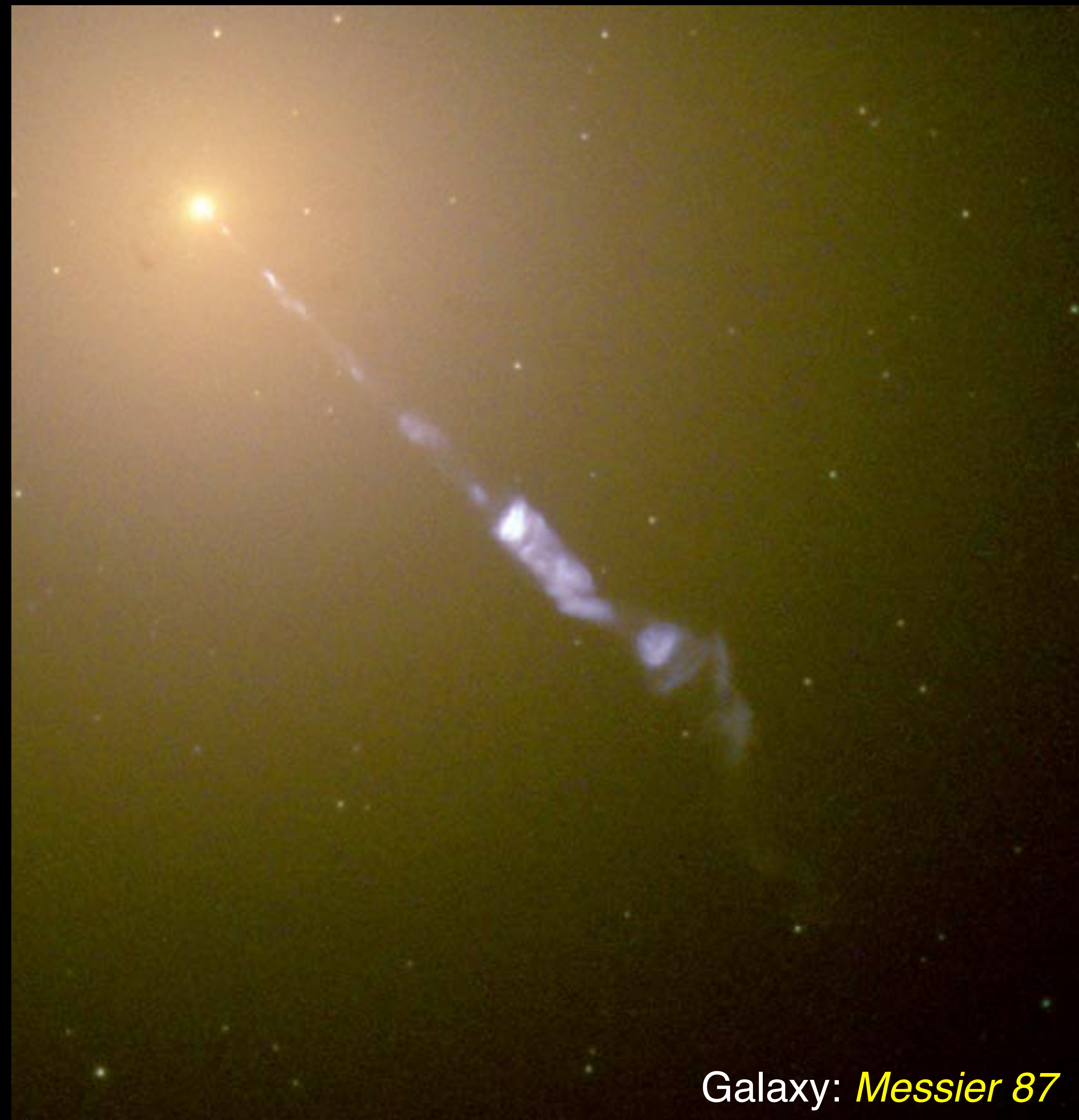
Type E5

Galaxy type: S0r (ring galaxy)



Hoag's Object
Galaxy type: S0r (ring galaxy)
Distance 183 ± 8 Mpc

Peculiar galaxies have abnormal features

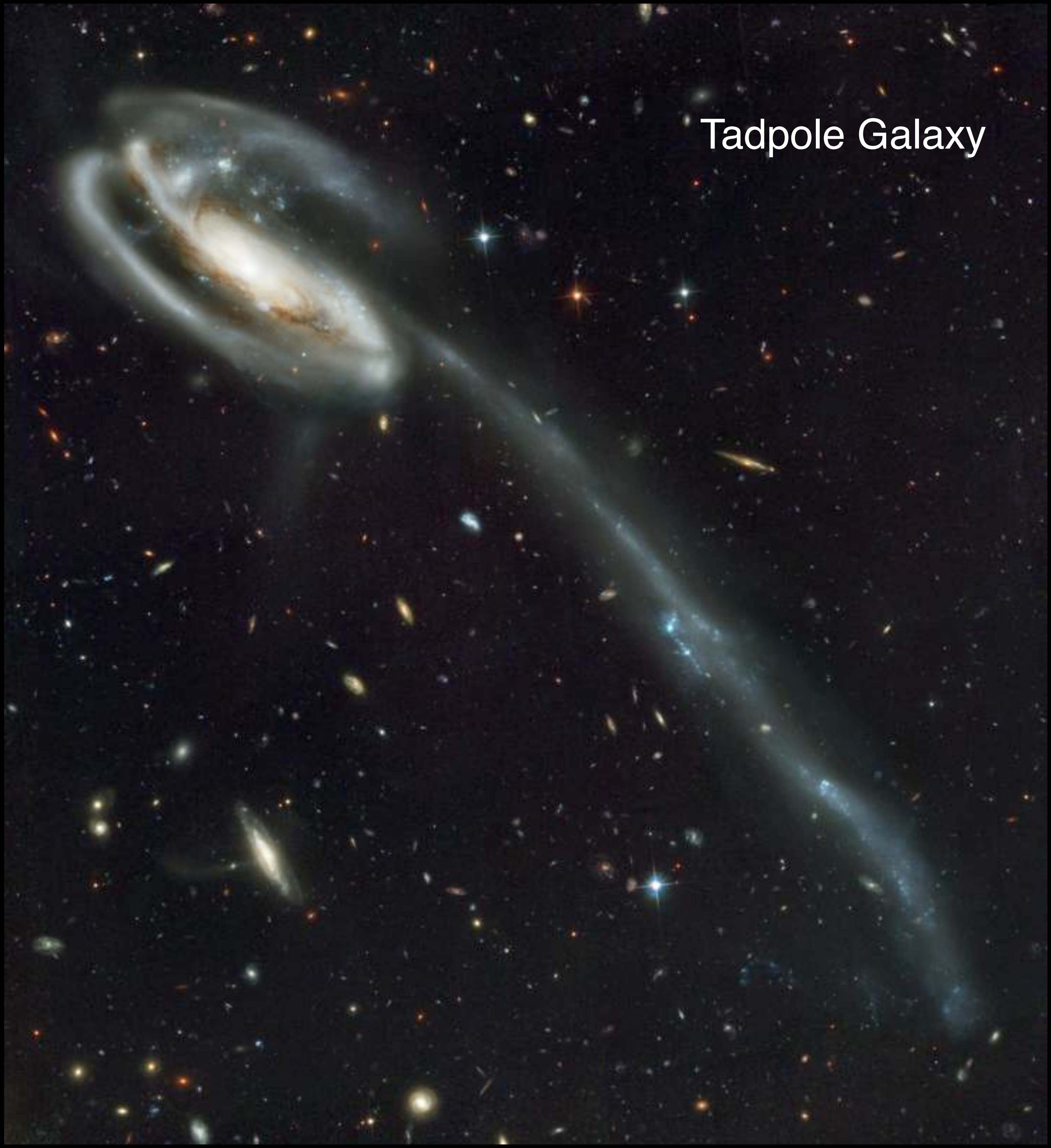


Galaxy: *Messier 87*

Peculiar elliptical galaxy with jet
(origine: supermassive black hole at center)

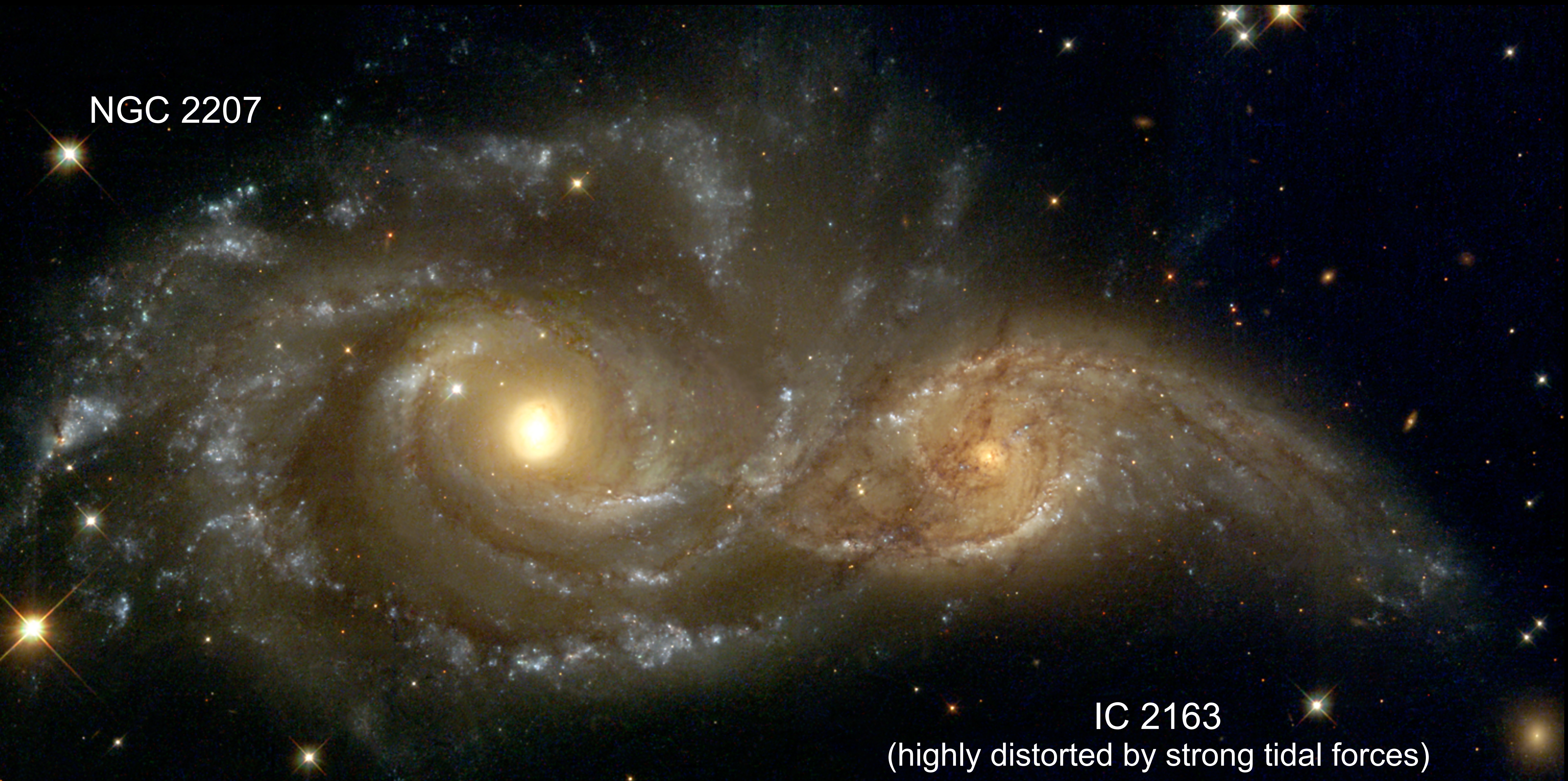
Galaxy type: E0 pec
Distance: 16.40 ± 0.50 Mpc

Peculiar galaxies have abnormal features



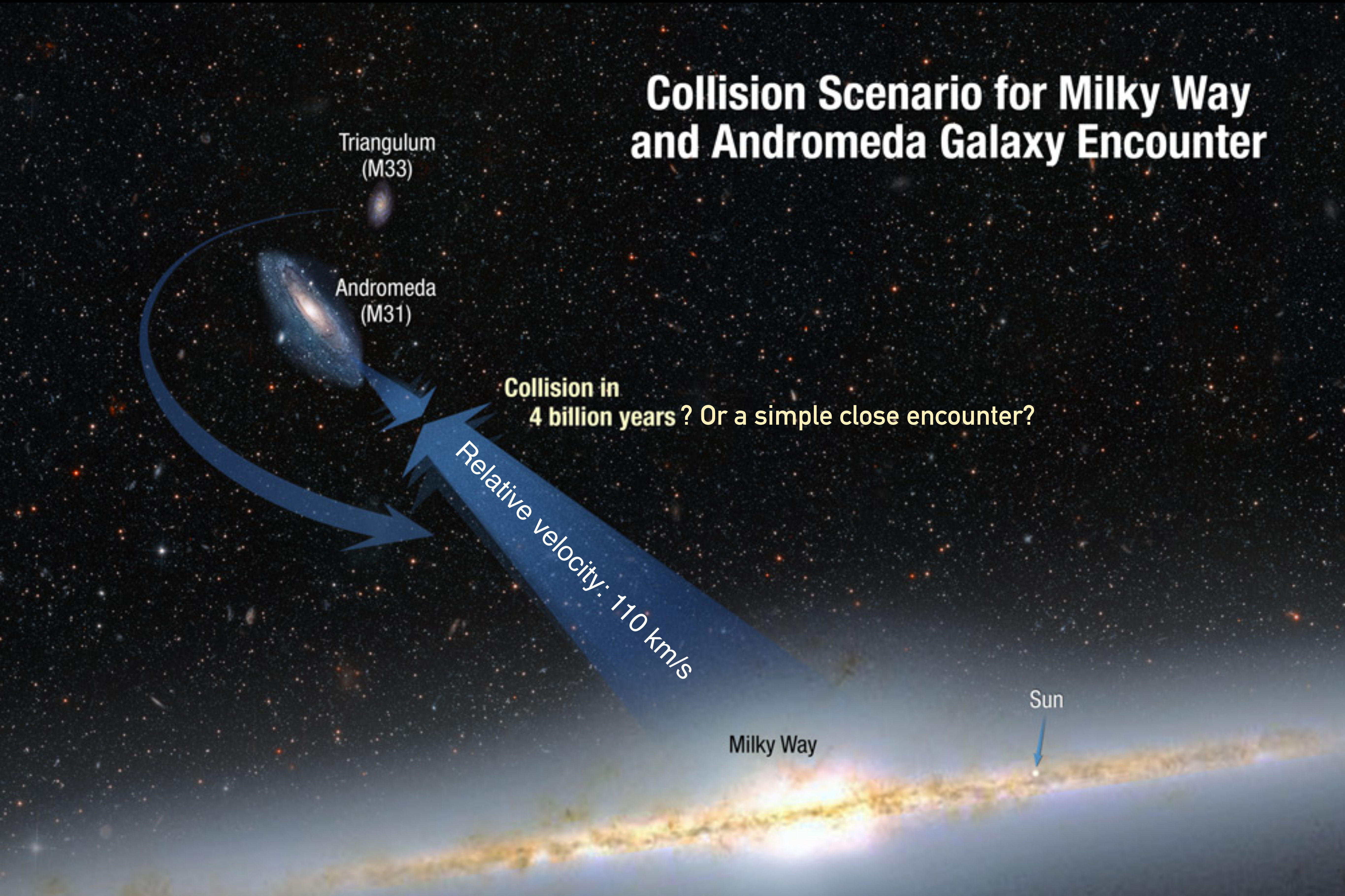
Interacting galaxies
Galaxy type: SB pec
Distance: 130 Mpc

Peculiar galaxies have abnormal features

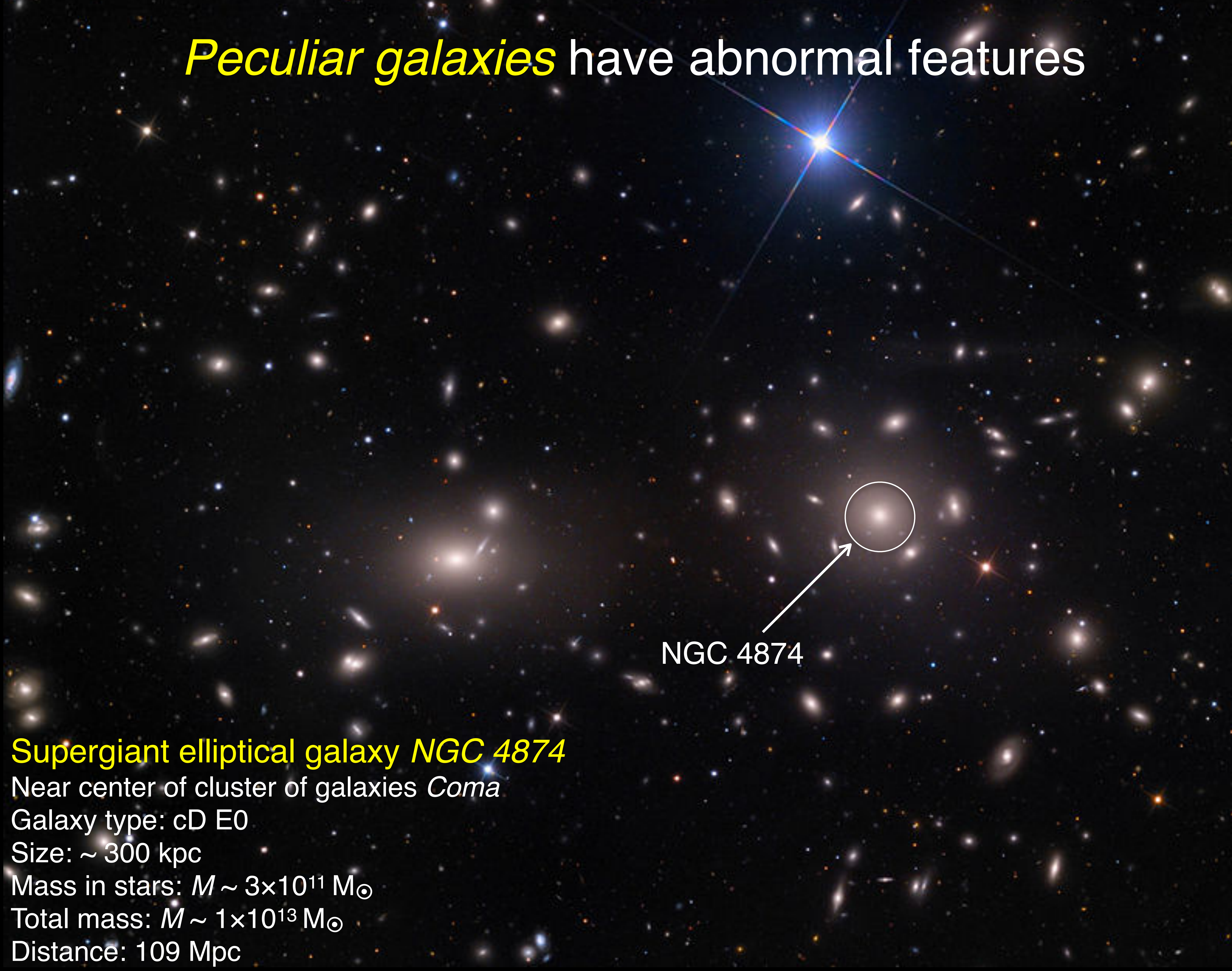


Colliding galaxies
(early phase of interaction)
Distance: 24.9 ± 12 Mpc

Galaxy collision: final faith of Andromeda & Milky Way



Peculiar galaxies have abnormal features



Supergiant elliptical galaxy *NGC 4874*

Near center of cluster of galaxies *Coma*

Galaxy type: cD E0

Size: ~ 300 kpc

Mass in stars: $M \sim 3\times10^{11}\ M_\odot$

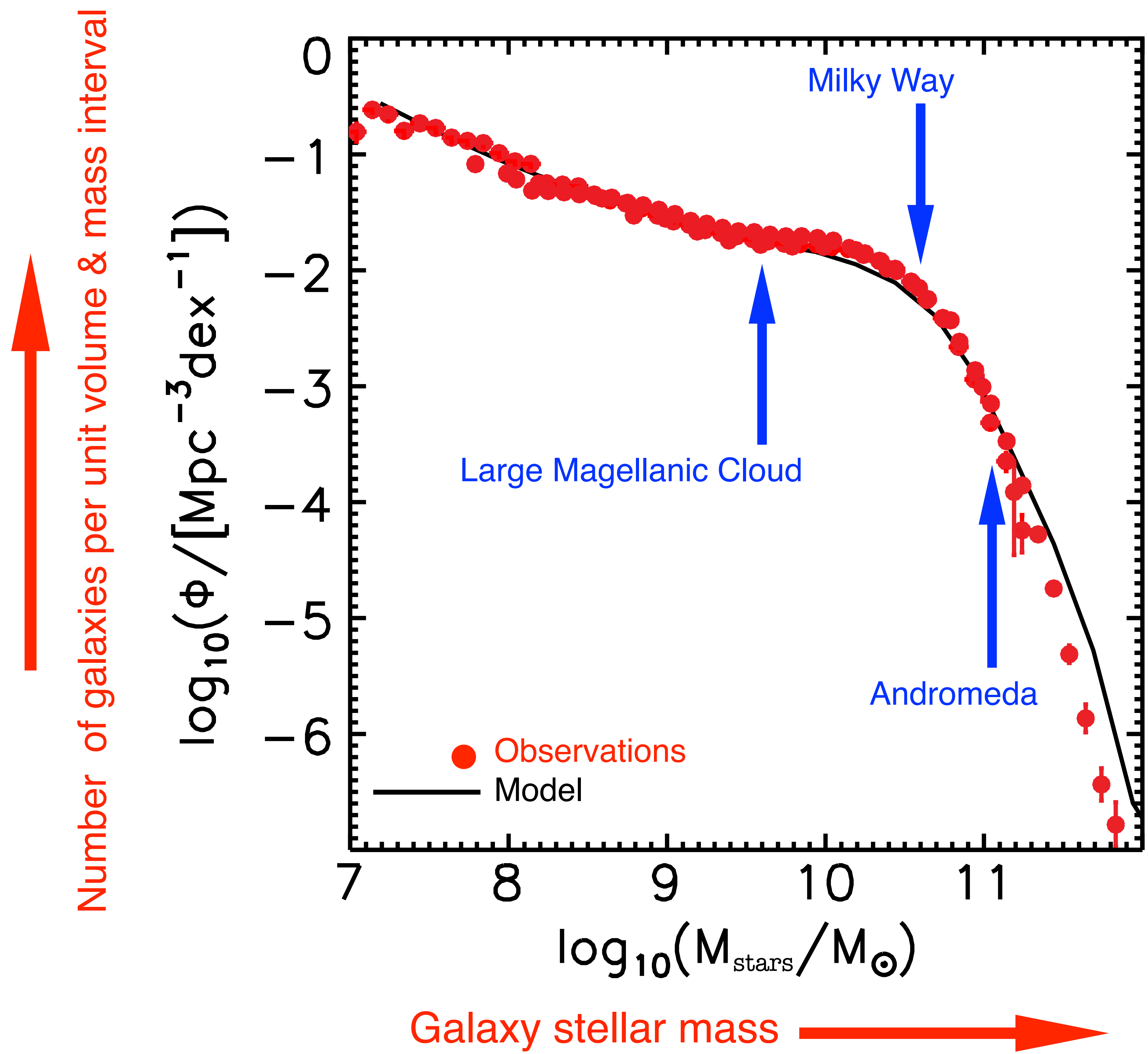
Total mass: $M \sim 1\times10^{13}\ M_\odot$

Distance: 109 Mpc

Properties of galaxies with **different morphologies**

Property	Ellipticals	Spirals	Irregulars
Fraction	$\gtrsim$ 60%	$\lesssim$ 30%	$\lesssim$ 15%
Total mass	$10^5 - 10^{13}\ M_\odot$	$10^9 - 10^{12}\ M_\odot$	$10^7 - 10^{10}\ M_\odot$
Luminosity	$10^5 - 10^{11}\ L_\odot$	$10^9 - 10^{11}\ L_\odot$	$10^7 - 10^{10}\ L_\odot$
Diameter	$(0.01 - 5)\ d_{MW}$	$(0.02 - 1.5)\ d_{MW}$	$(0.05 - 0.25)\ d_{MW}$
Molecular & atomic gas	low	5 – 15 %	15 – 25 %

Stellar mass function of galaxies in nearby universe



Measuring the mass of galaxies

Method 1: rotation curve of spiral galaxies

Spiral galaxy *Messier 33* (*Triangulum Galaxy*)
Galaxy type: Scd
Distance: 730 - 940 kpc

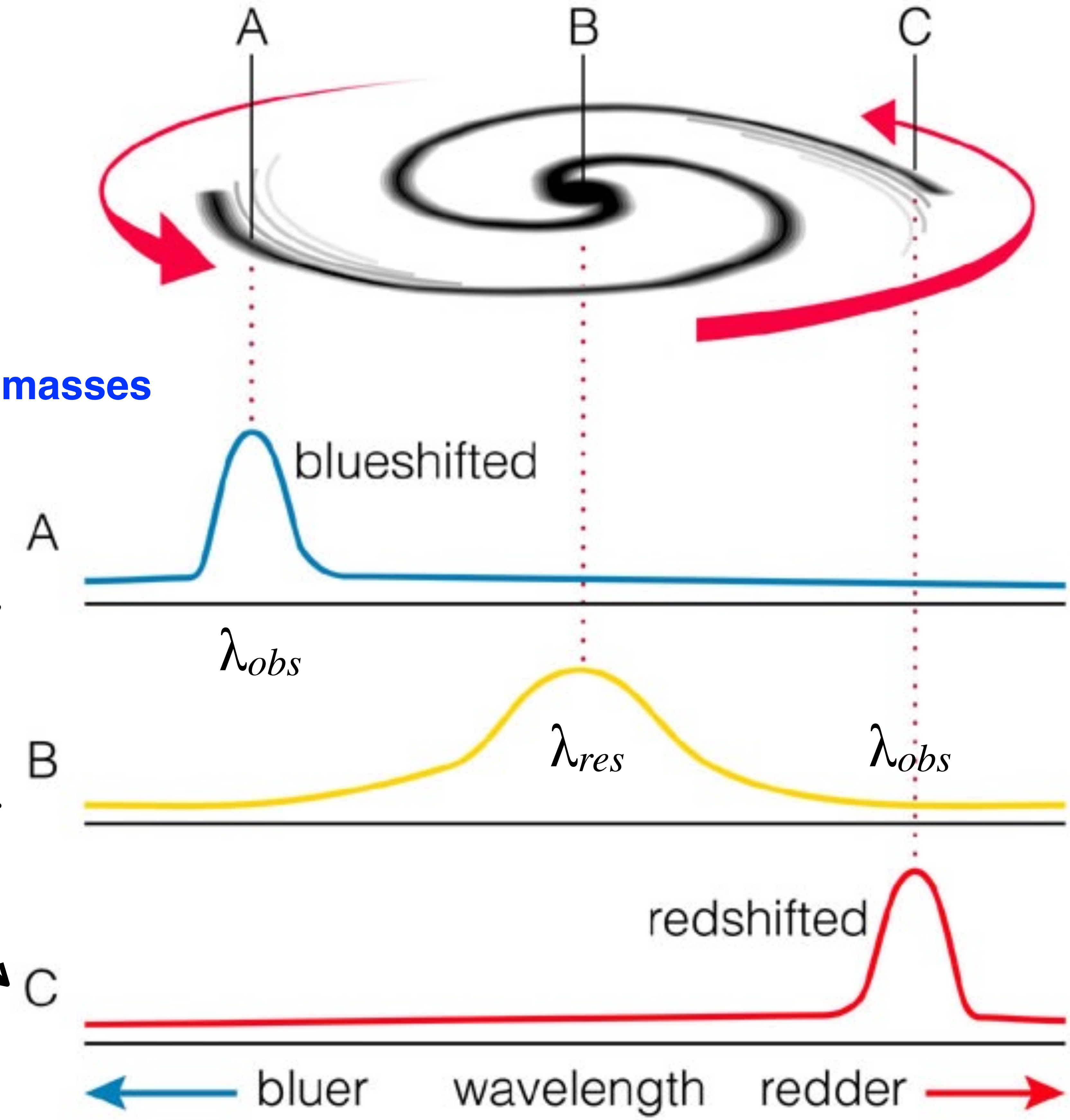
Method 1: rotation curve of spiral galaxies

Velocity from Doppler shift:

$$\frac{v}{c} = \frac{\lambda_{obs} - \lambda_{res}}{\lambda_{res}}$$

Larger velocities imply larger masses

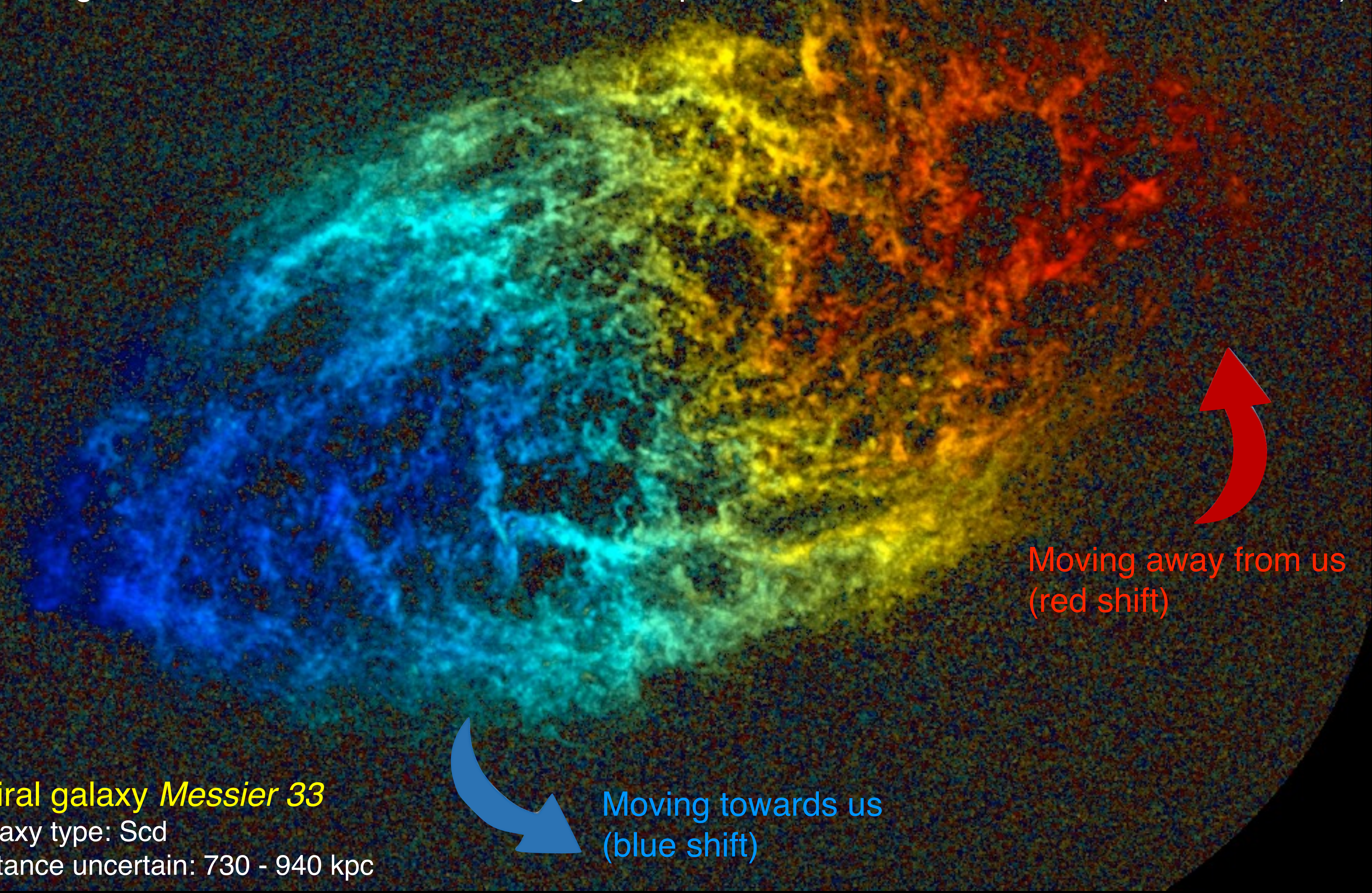
Emission line in spectra of a galaxy



Hydrogen emission at λ = 21 cm of spiral galaxies to measure Doppler shift

⟹ *rotation velocity* at large distance from center

Result: galaxies can rotate so fast if a large component made of invisible matter (dark matter)

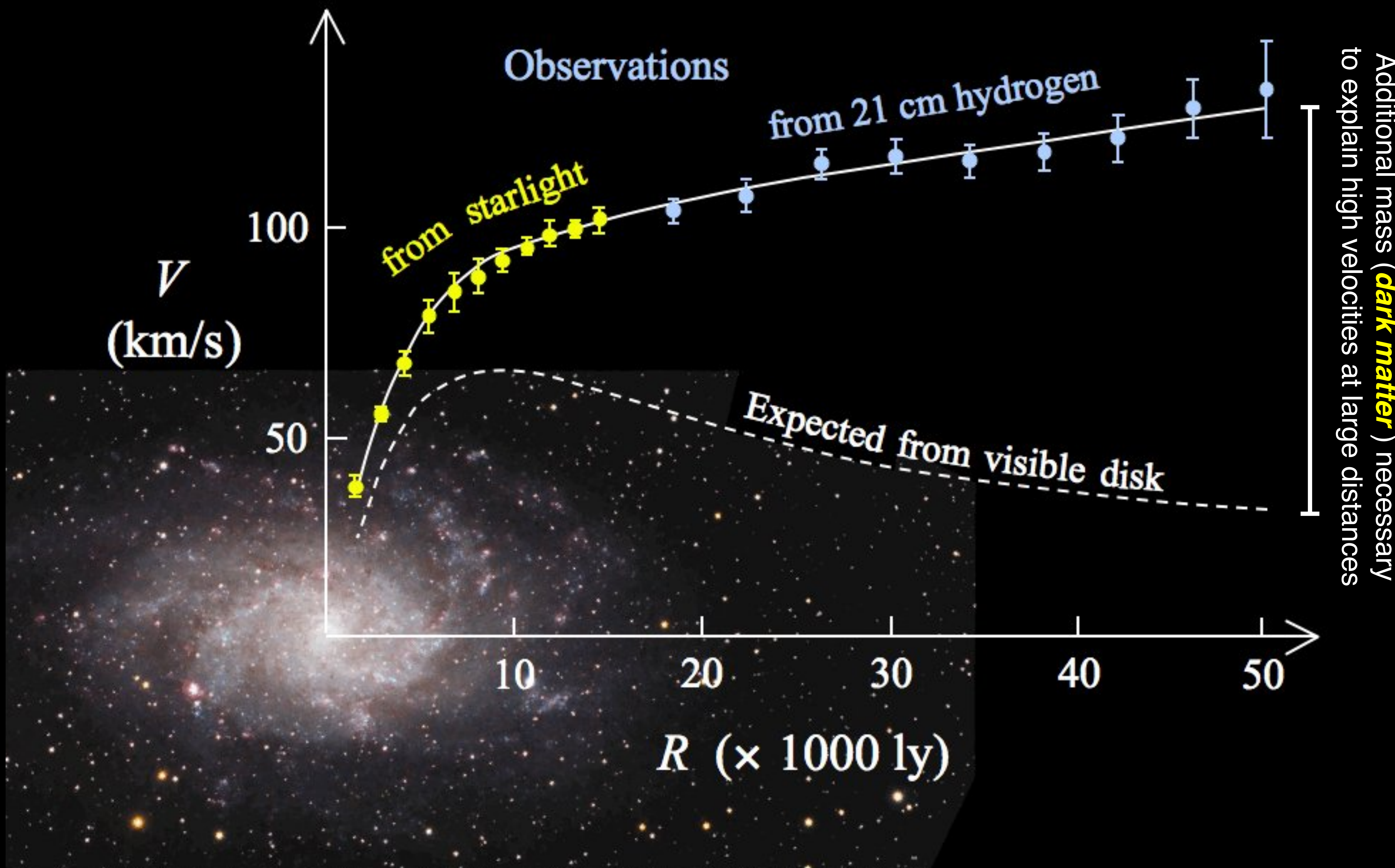


Spiral galaxy *Messier 33*

Galaxy type: Scd

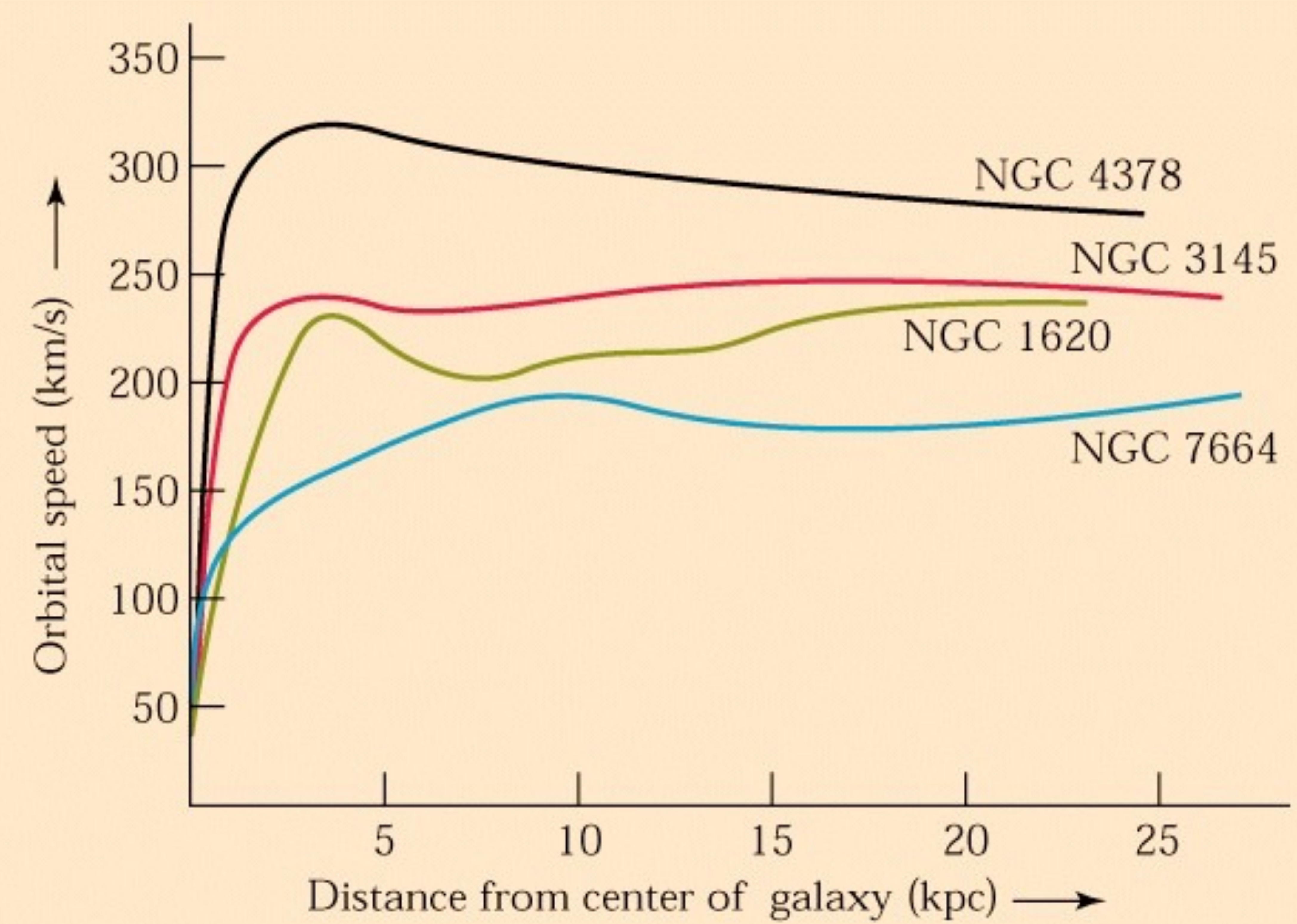
Distance uncertain: 730 - 940 kpc

Hydrogen emission at λ = 21 cm of spiral galaxies to measure Doppler shift

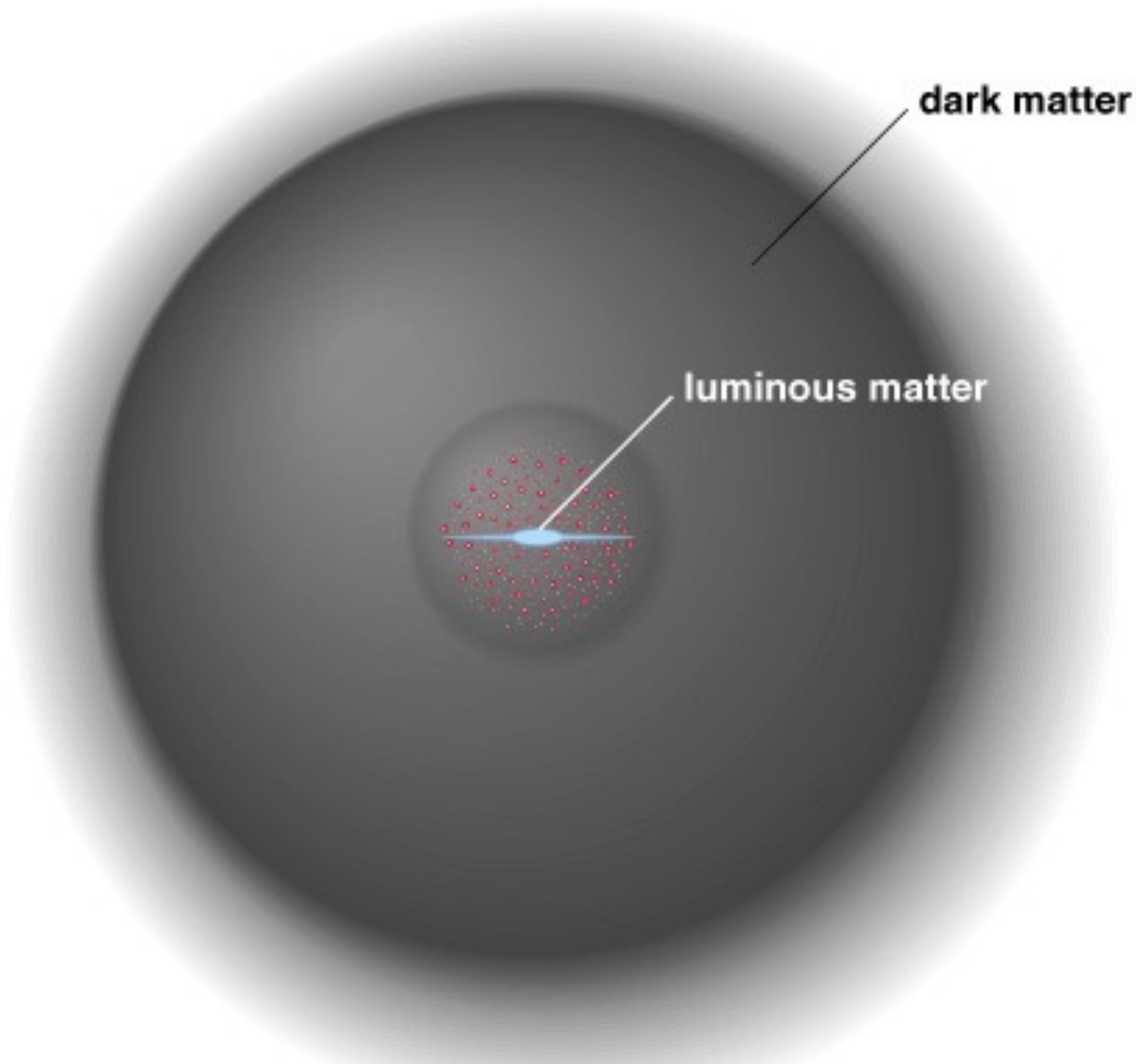


Rotation curve of *Messier 33*
Total mass: $M = 5\times10^{10}\ M_{\odot}$

Rotation curves of nearby spiral galaxies



Matter of spiral galaxies dominated by ***Dark Matter Halo***



Dark matter halo**:** hypothetical large envelope surrounding galactic disk of matter that is **not made of atoms** and that **does not emit light**

Method 2: velocity dispersion of stars in elliptical galaxies

For *virial theorem*, kinetic energy of stars related to gravitational potential:

$$E_k = -E_g/2$$

large $\Delta v \Longrightarrow$ large M

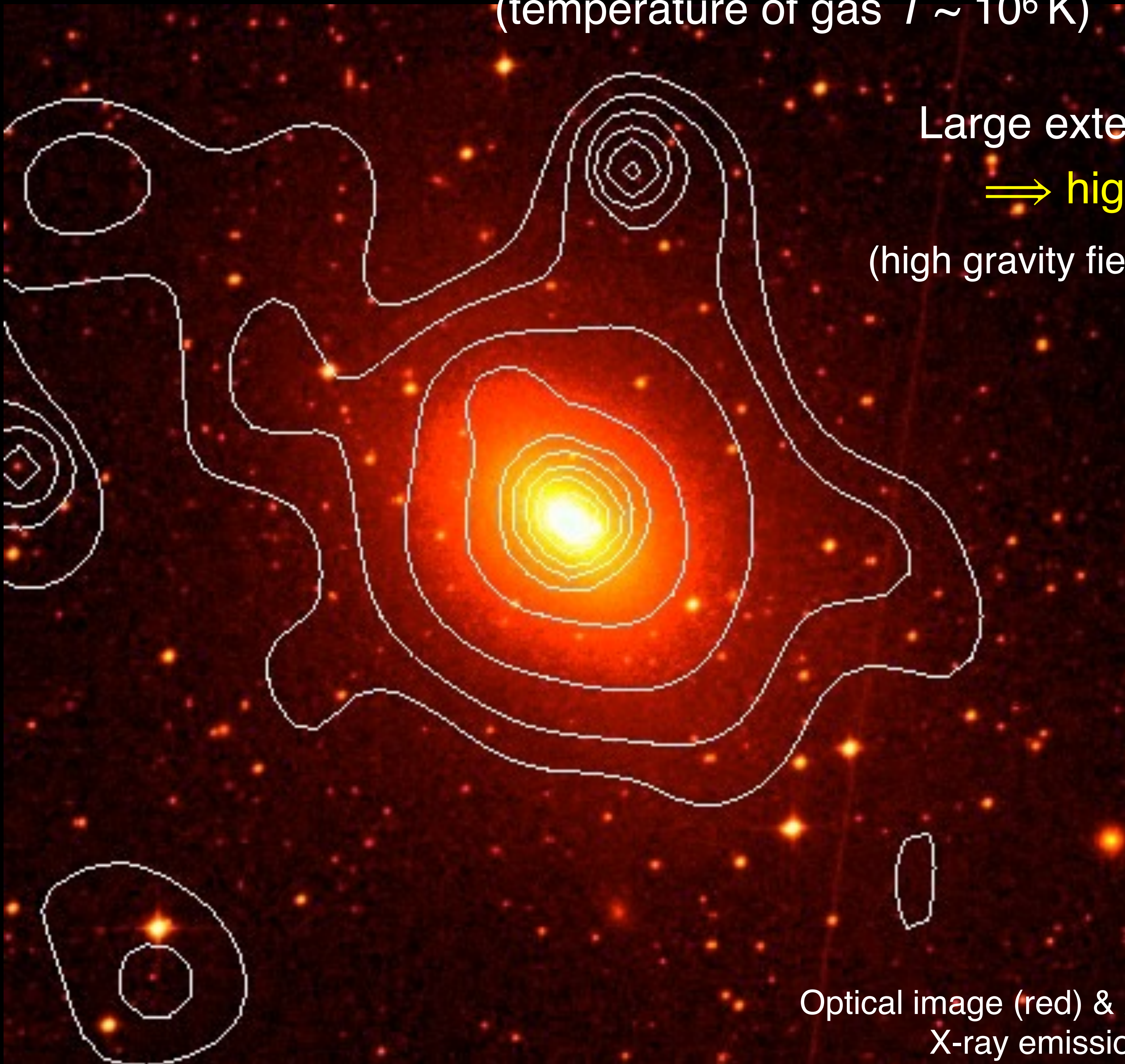
$$\Delta v \propto (M/R)^{1/2}$$

M & R: mass & radius of galaxies

Doppler shift of many stars $\Longrightarrow$ velocity dispersion Δv

Method 3: X-ray image of elliptical galaxies

(temperature of gas $T \sim 10^6$ K)



Large extent of X-ray emission

$\Longrightarrow$ high T $\Longrightarrow$ large M

(high gravity field prevents gas to escape)

Optical image (red) & X-ray emission (white contours)
X-ray emission larger than stellar component

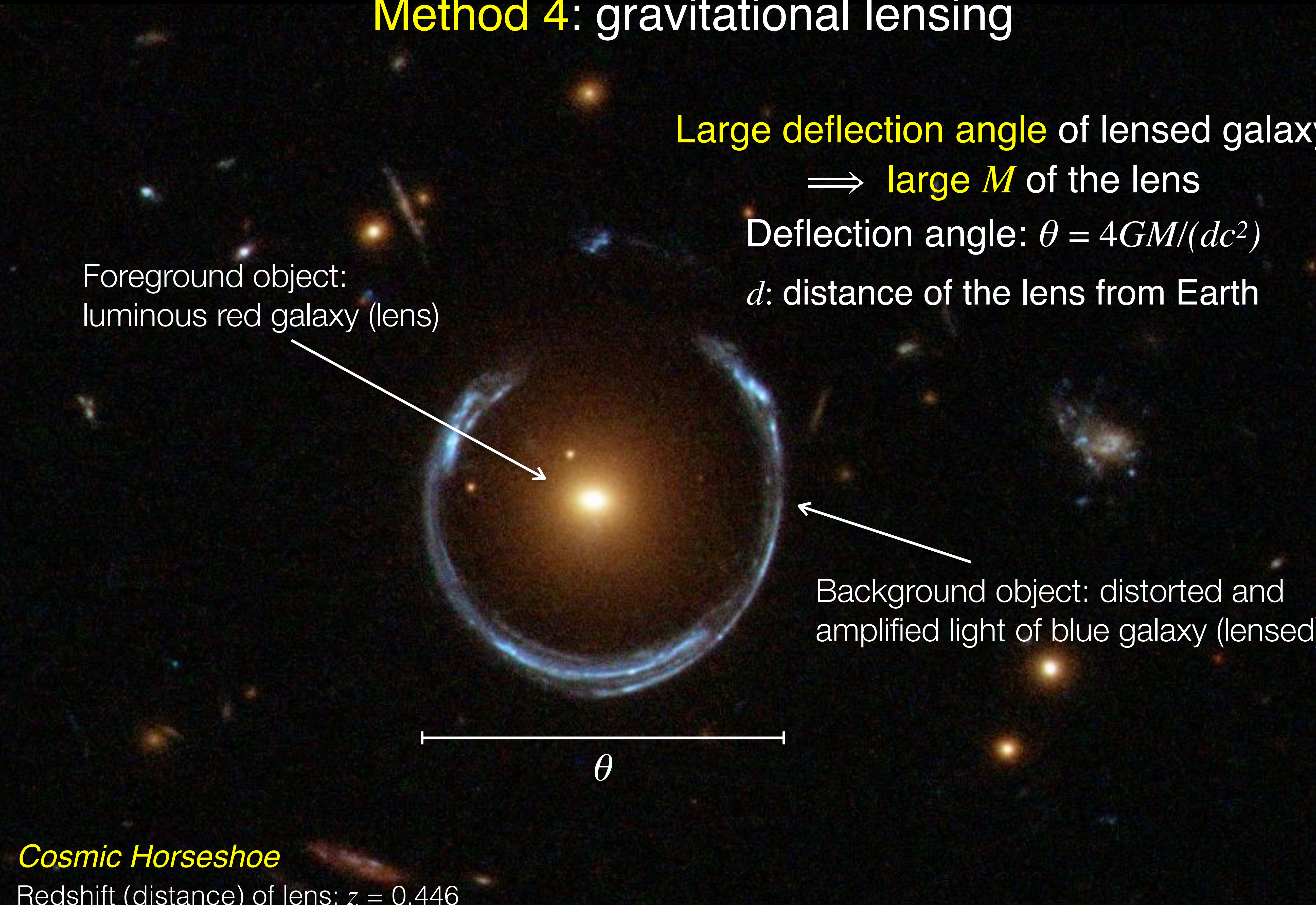
Method 4: gravitational lensing

Large deflection angle of lensed galaxy

$\Longrightarrow$ large M of the lens

Deflection angle: $\theta = 4GM/(dc^2)$

d: distance of the lens from Earth



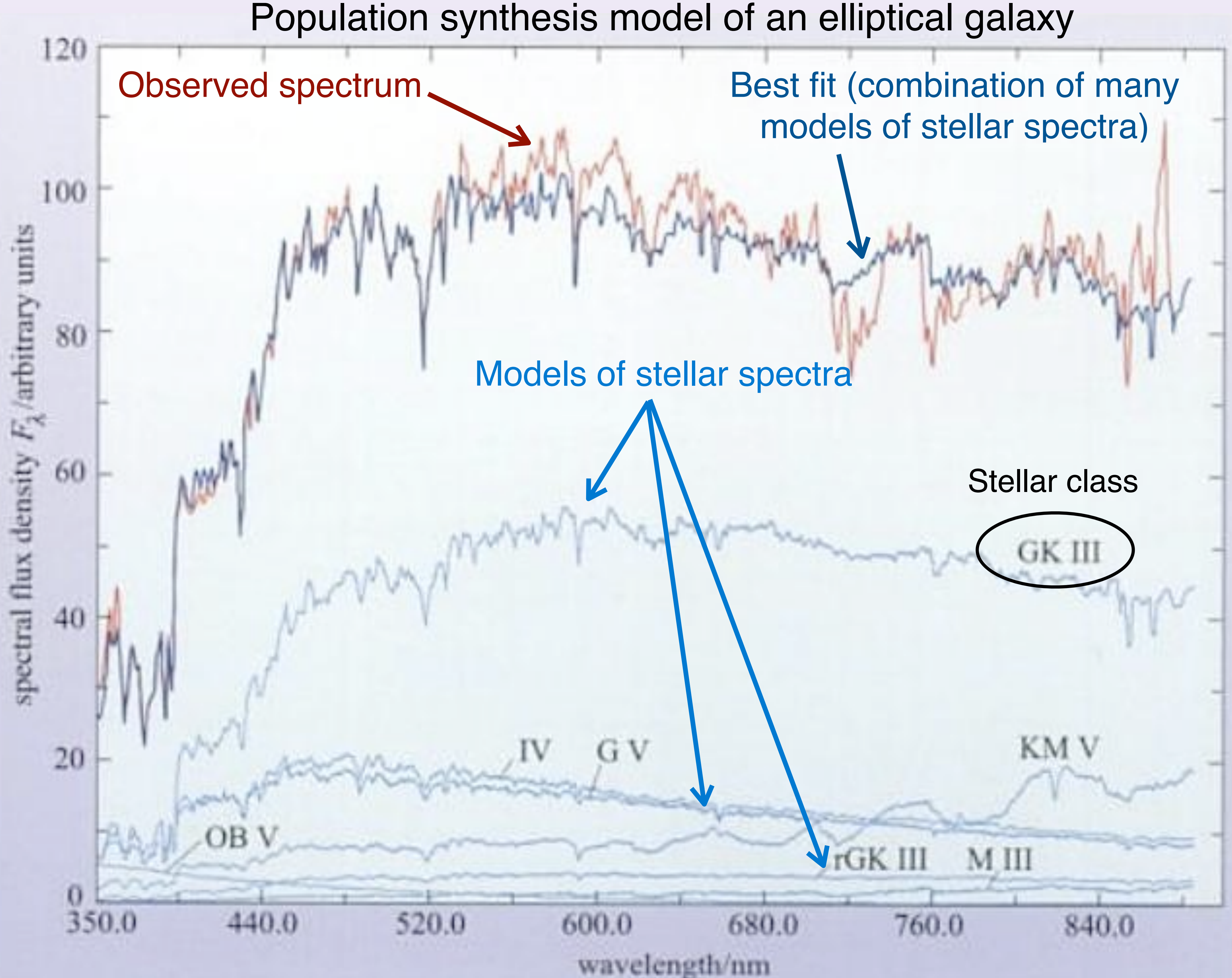
Cosmic Horseshoe

Redshift (distance) of lens: z = 0.446

Redshift lensed galaxy: z = 2.379

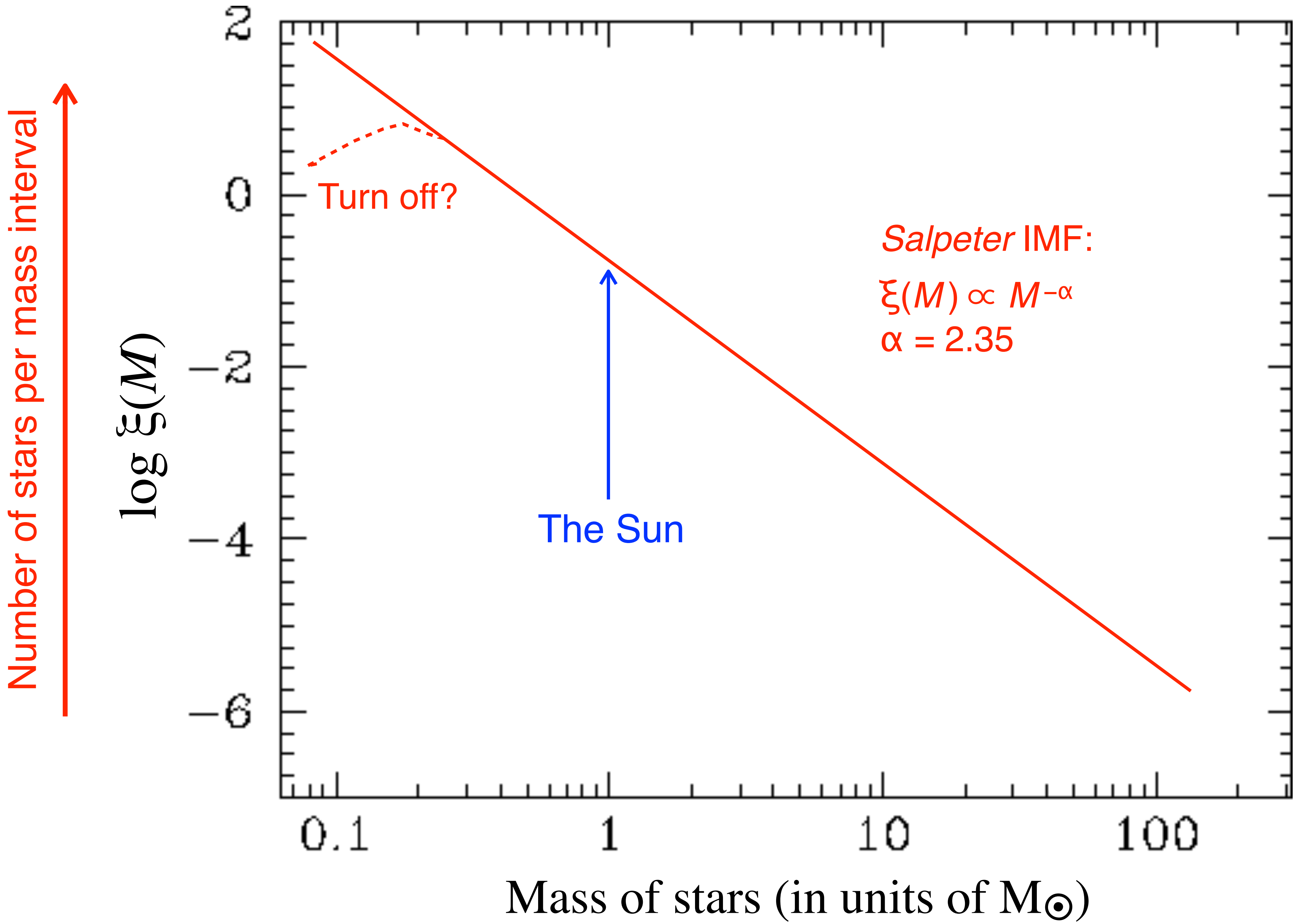
Method 5 (stellar component only): *population synthesis model* of galaxies

Population synthesis model of an elliptical galaxy



Total number of stars in best fit necessary to explain observations gives stellar mass

Stellar mass depends on *initial mass function* (IMF) for stars



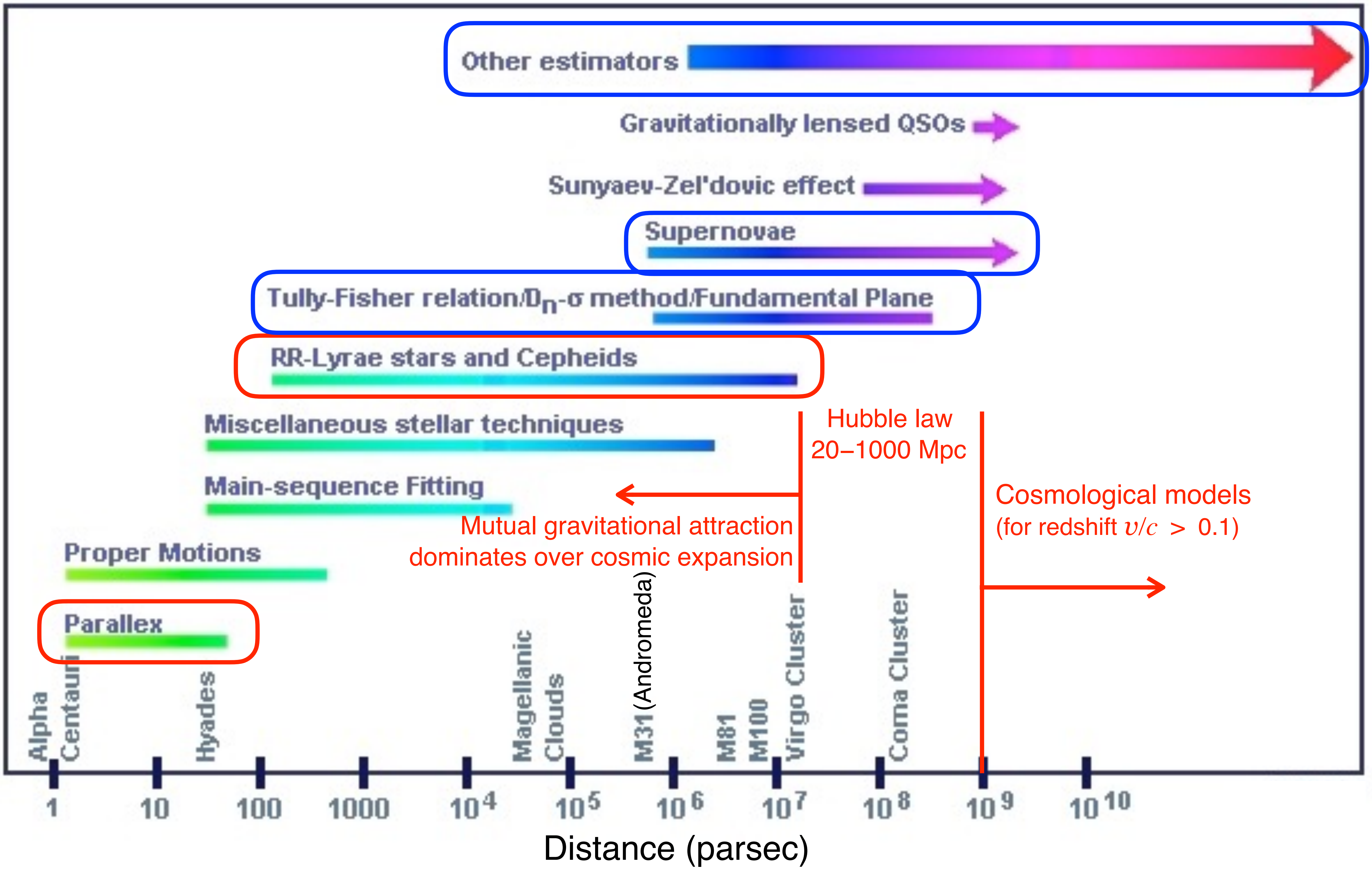
Corollary 1: stellar mass of galaxies dominated by **small** (then cold) stars
Corollary 2: stellar mass best estimated using near **infrared** observations

Distance of galaxies

Astronomical distances: found from one method to calibrate other methods

$\Longrightarrow$ from near universe to largest distances

Distance ladder



Distances measured from **standard candles**

(same class of objects have similar luminosity L)

$$F = \frac{L}{4\pi d^2}$$

Observed flux (measured on Earth) → F

Emitted power (known for standard candles) → L

Distance can be derived → d

$\downarrow\uparrow$

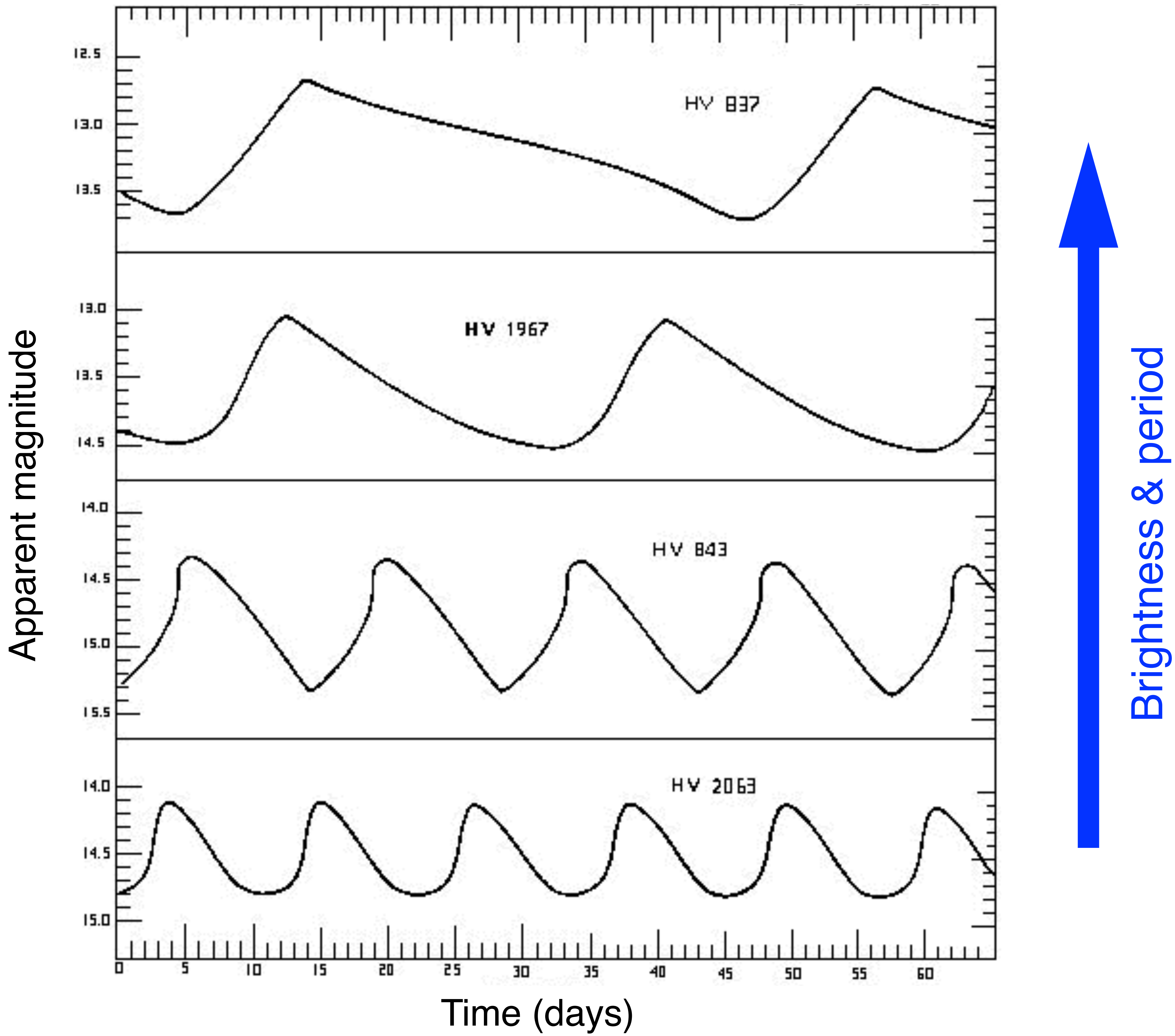
$$M = m - 5\log(d) + 5$$

Absolute magnitude (known for standard candles) → M

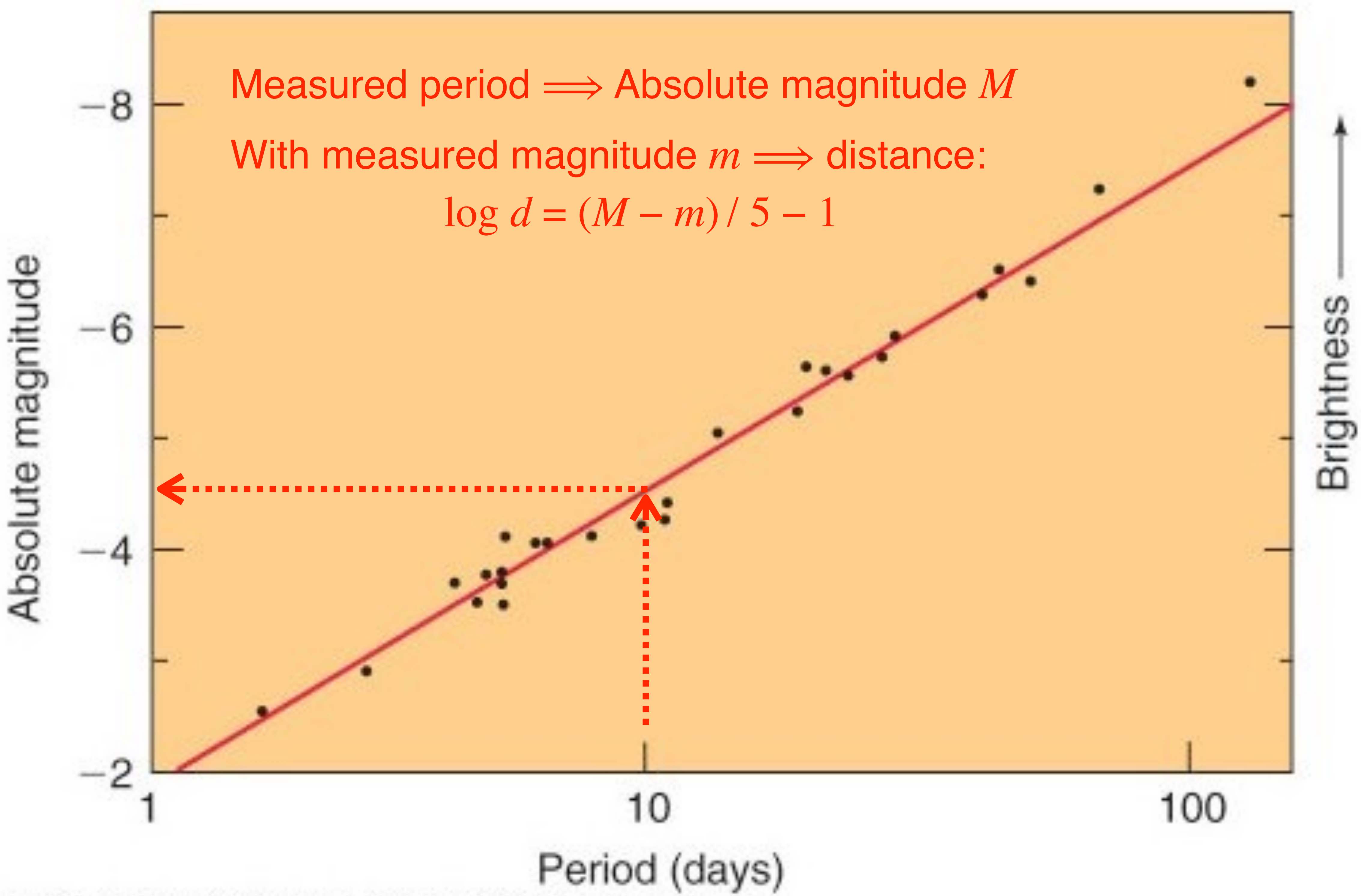
Observed magnitude → m

Distance (in parsec) can be derived → d

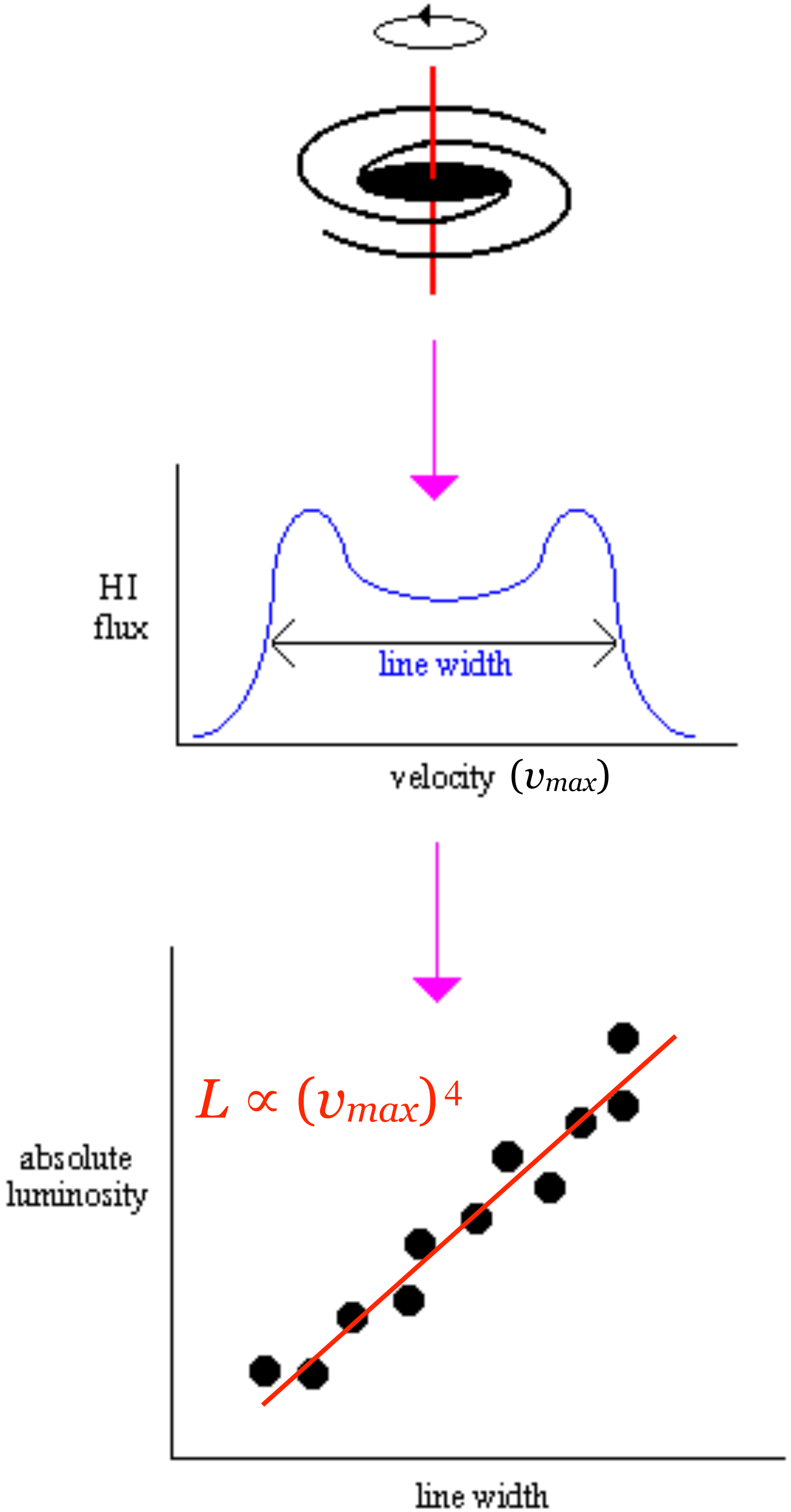
Cepheid variable stars as standard candles



Cepheid variable stars as standard candles



Tully-Fisher relation



spiral galaxies rotate, and the rotation speed is proportional to the mass of the galaxy

measurements of neutral hydrogen (HI) display a ''double–horned'' profile, where the width of the line indicates the mass

Measured line width $\Longrightarrow$ rotational velocity $v_{\max}$

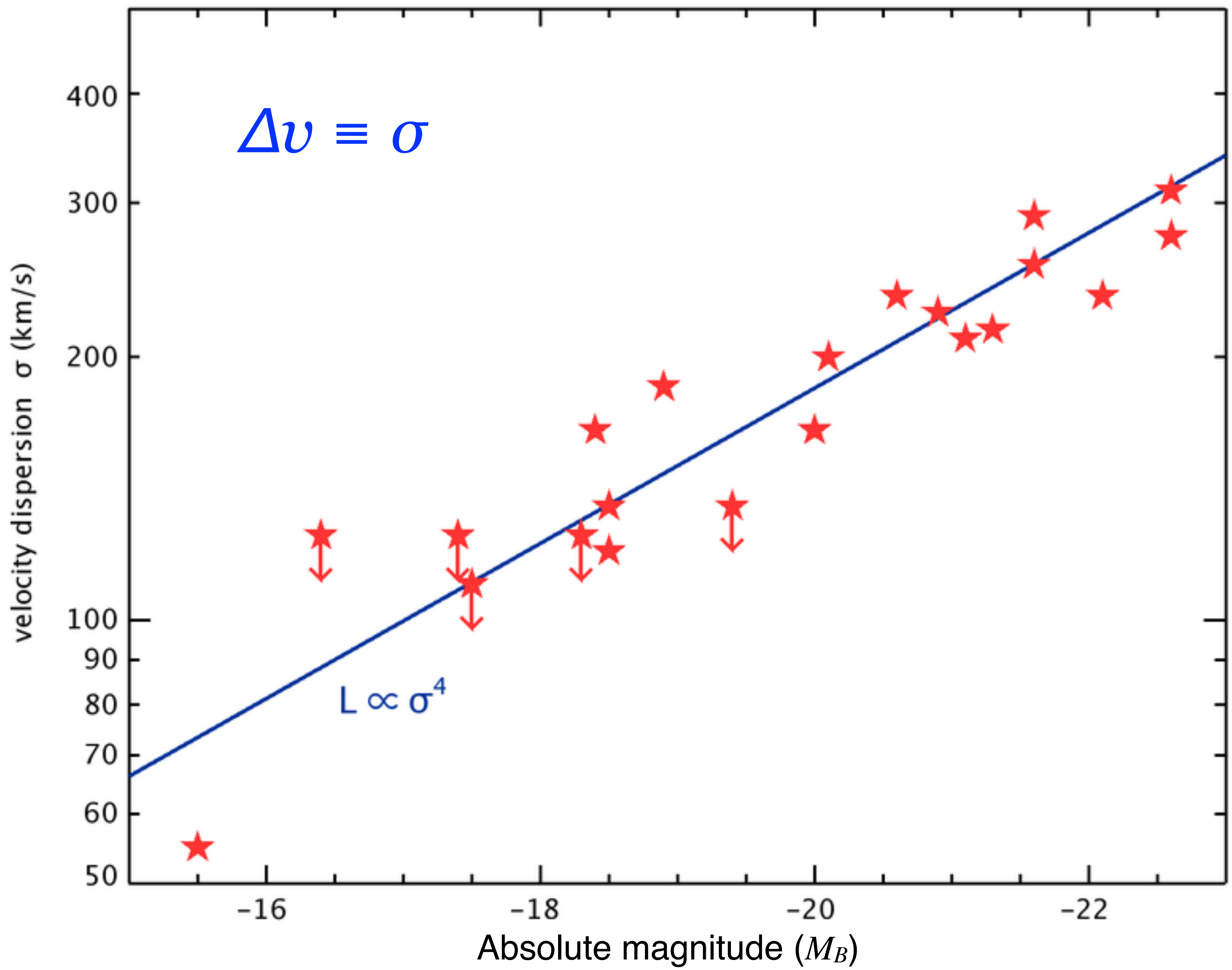
With Tully-Fisher relation $\Longrightarrow$ luminosity L

And measured flux F $\Longrightarrow$ **distance:**

$$d = [L/(4\pi F)]^{1/2}$$

a plot of line width versus absolute luminosity of a galaxy is called the Tully–Fisher relation. When calibrated using galaxies with Cepheid distances, the TF relation is used to determine Hubble's constant.

Faber-Jackson relation in elliptical galaxies



Equivalent to Tully-Fisher relation seen for spiral galaxies

Redshift and expansion of the Universe

Expansion of the Universe & the ***Hubble law***

More distant galaxies moving away from Milky Way faster than closer galaxies

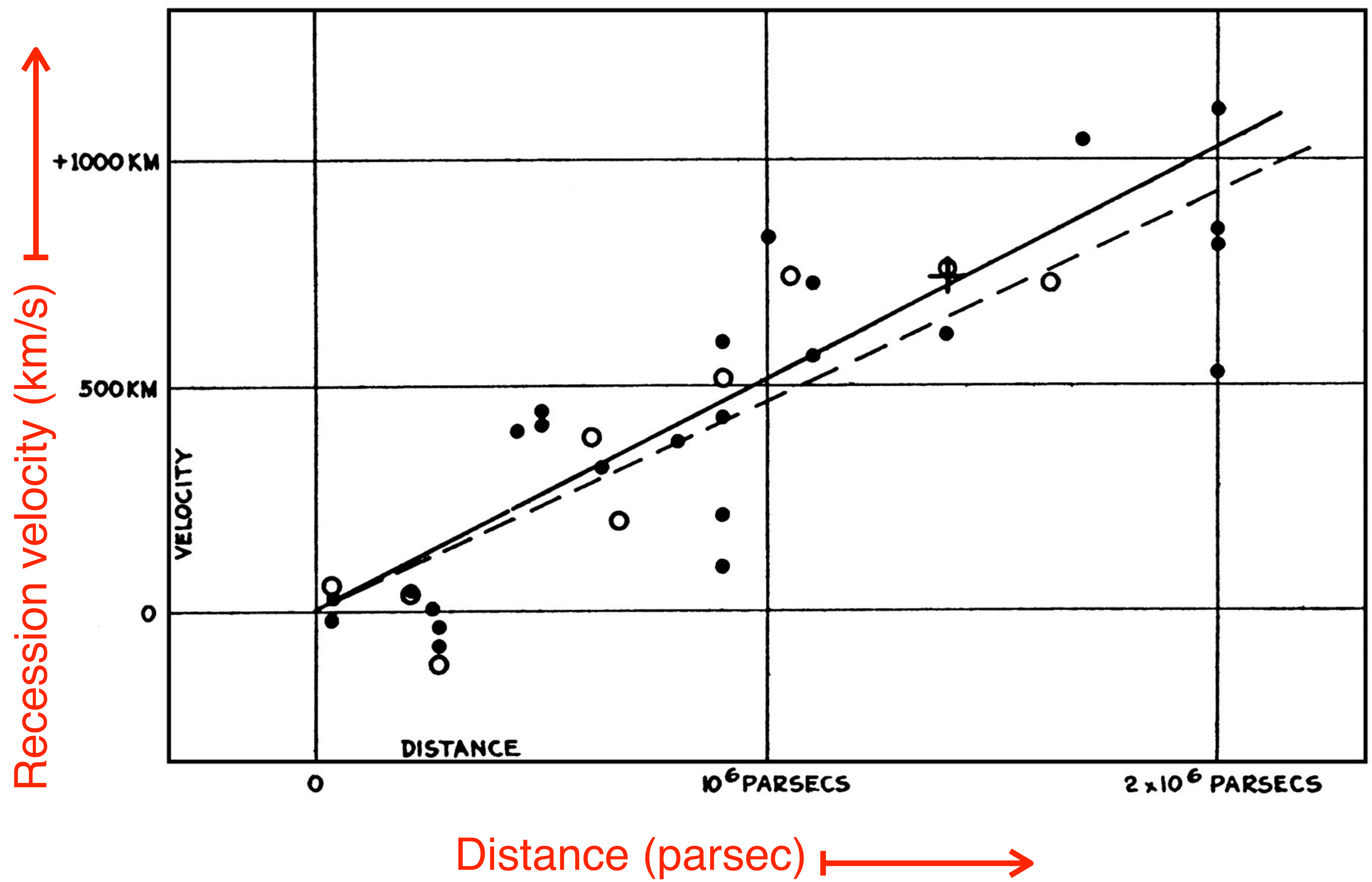
Georges Lemaître (1927):
Recession velocity v proportional to their distance d

Edwin Hubble (1929):
Experimental confirmation that $v \propto d$

The Universe must Be Expanding!

Since 2018 called **Hubble-Lemaître law**

Hubble's original data of "*Extra-Galactic Nebulae*" (1929)



Hubble-Lemaître law: $\upsilon = H_o \times d$

υ: velocity

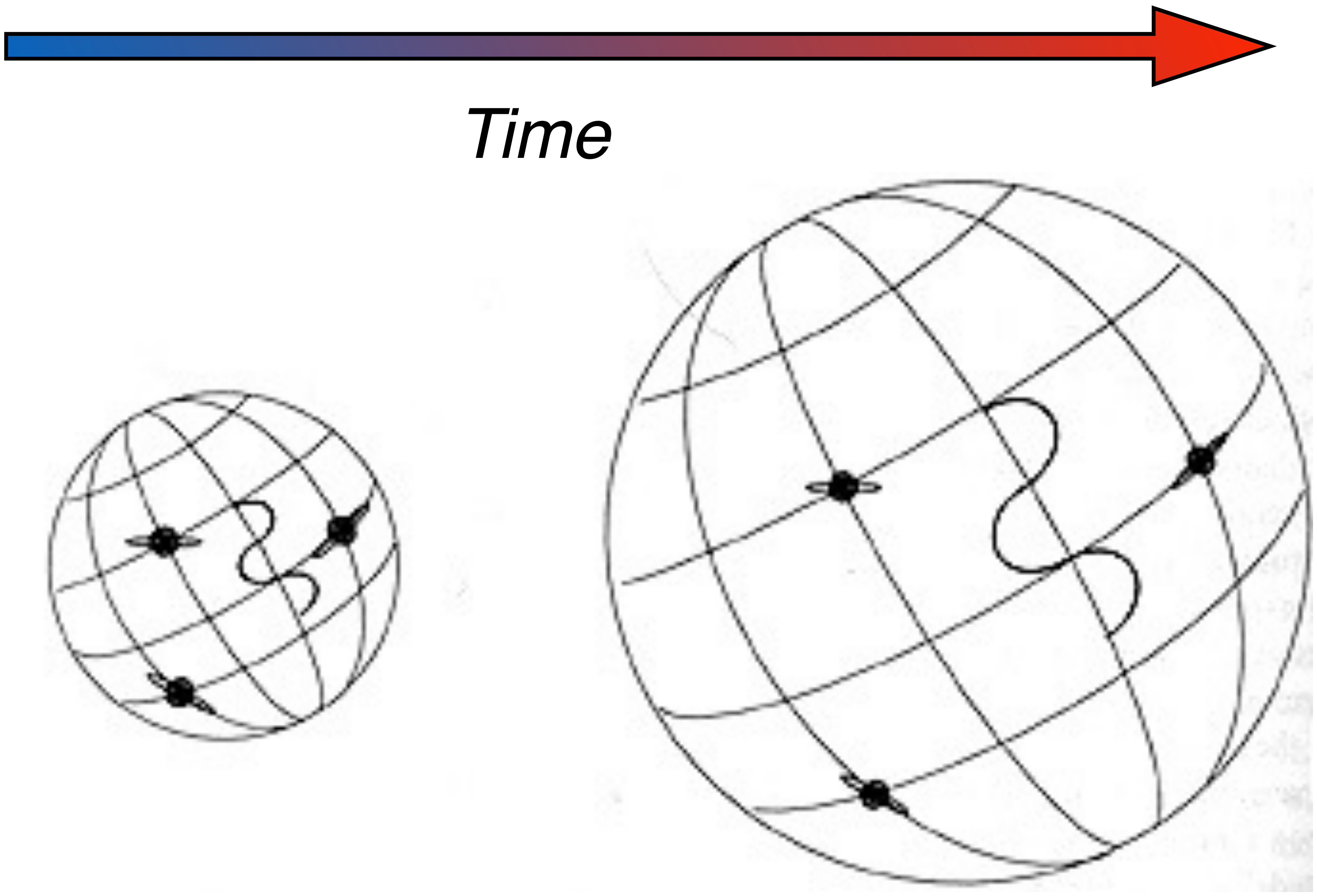
H_o: Hubble constant

d: distance

First measured expansion rate: $H_o = 500$ km s^{-1} Mpc $^{-1}$

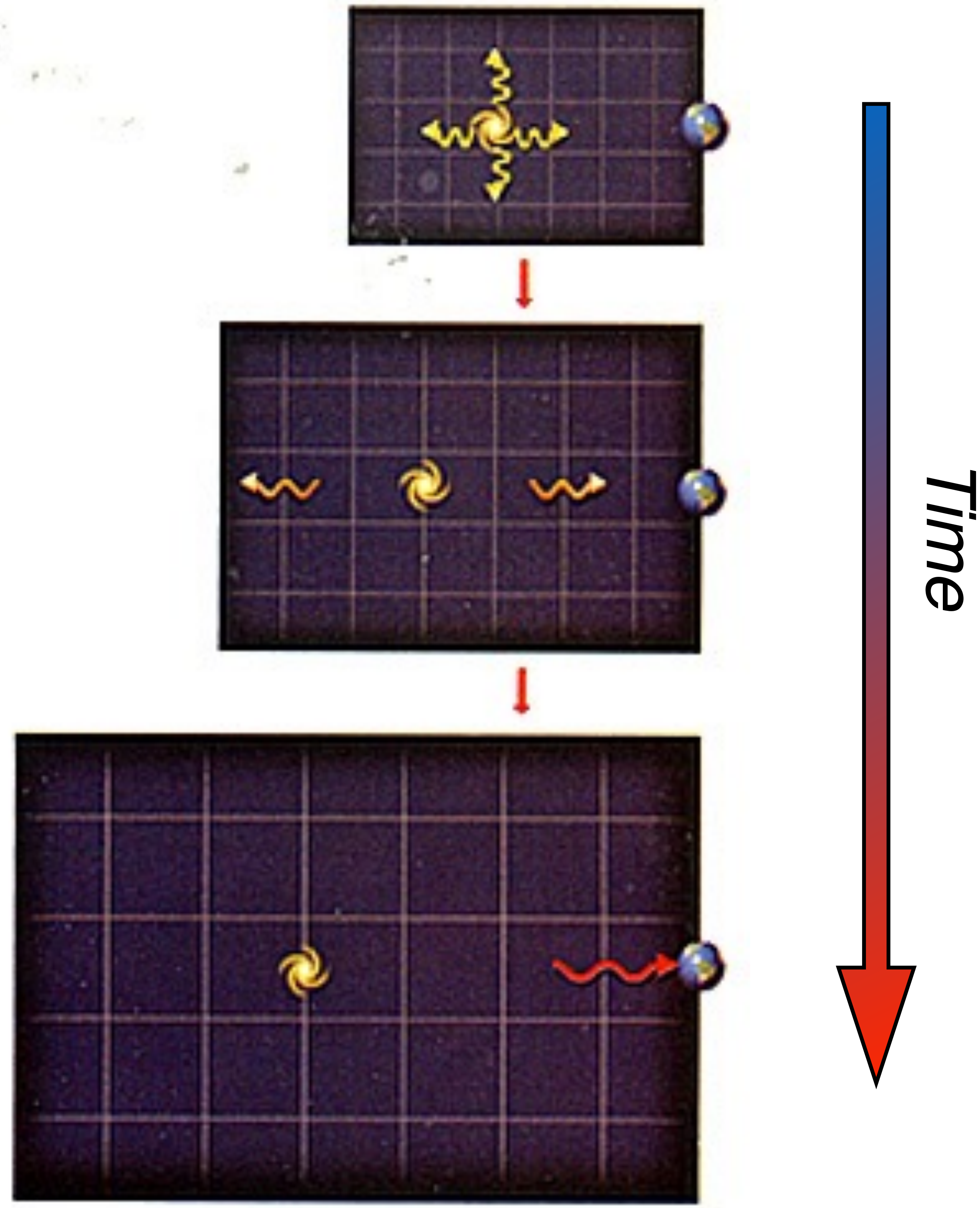
Measured today: $H_o \simeq 70$ km s^{-1} Mpc $^{-1}$

Expansion of of the Universe

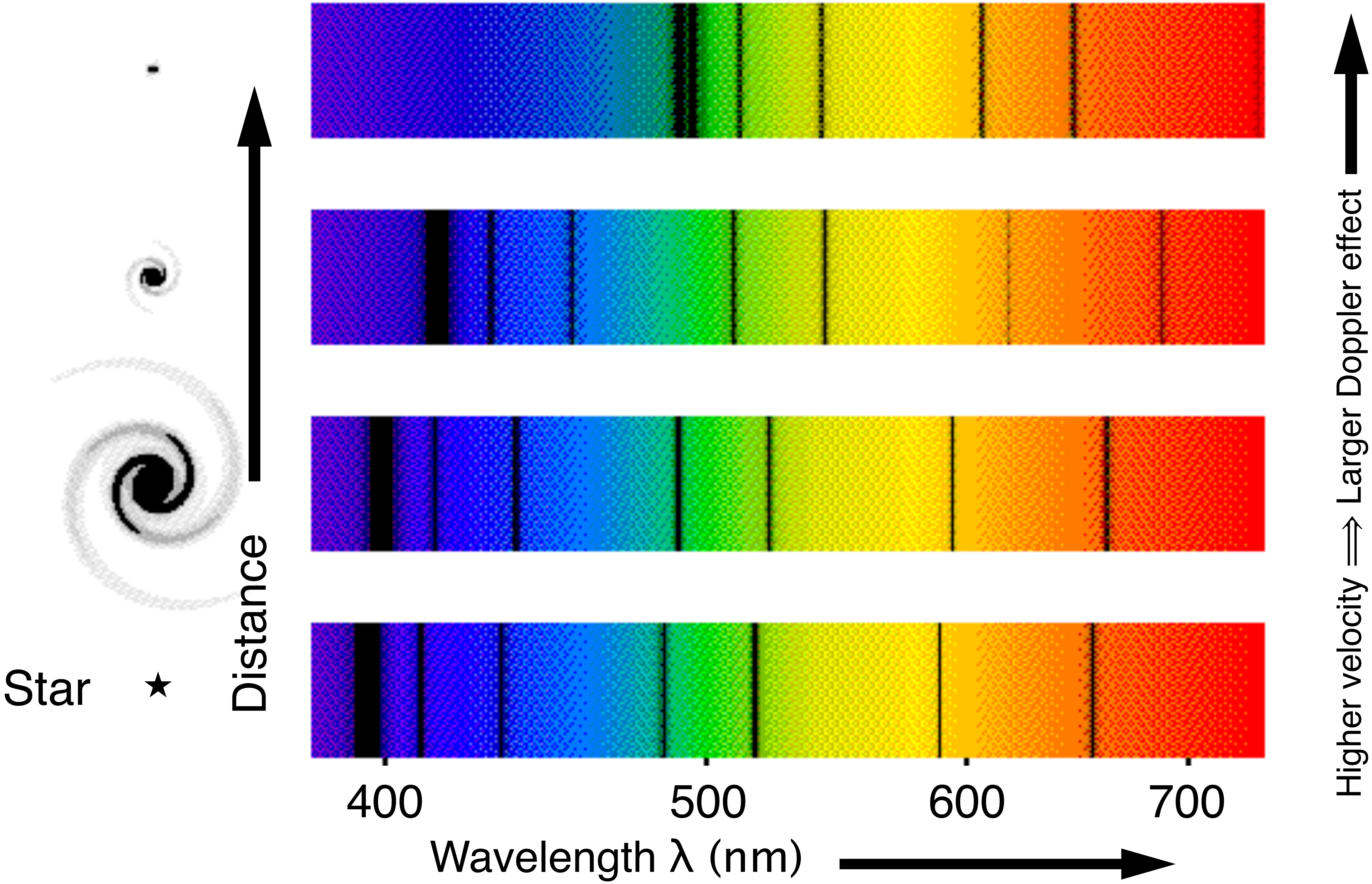


Wavelength of cosmic radiation is stretched $\Longrightarrow$ Universe gets colder

Expansion of of the Universe & **cosmological redshift**

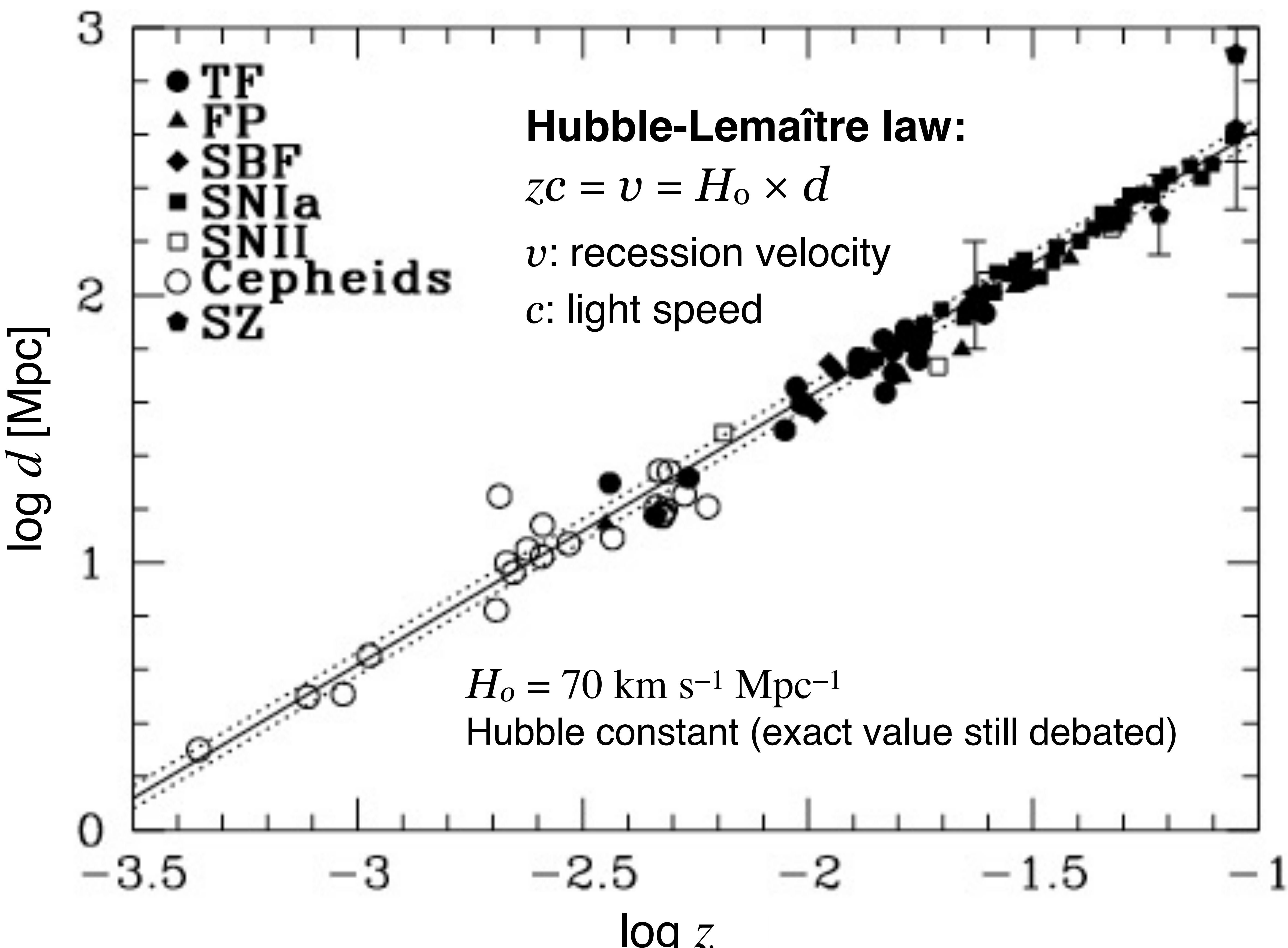


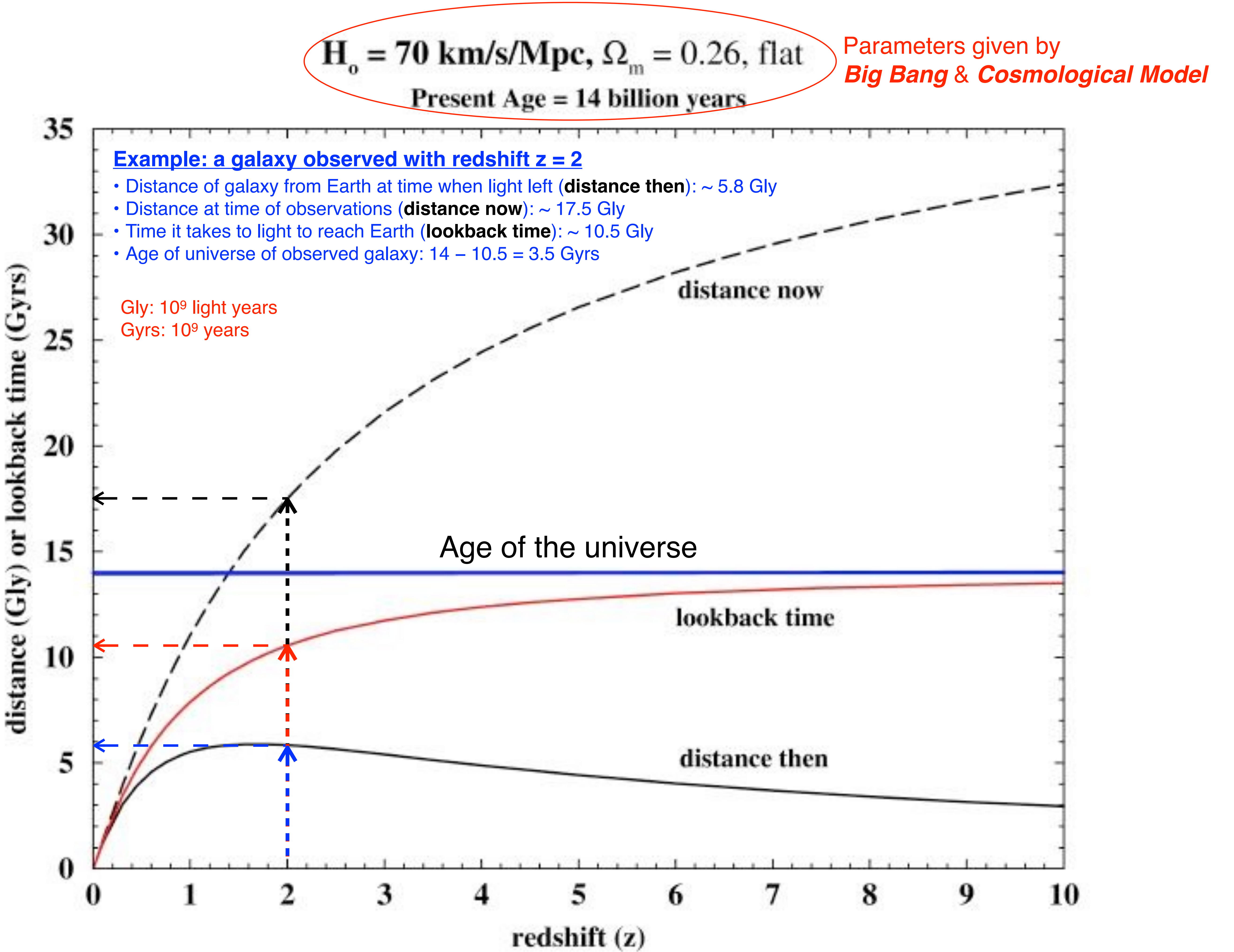
Redshift is Doppler effect due to expansion of the universe

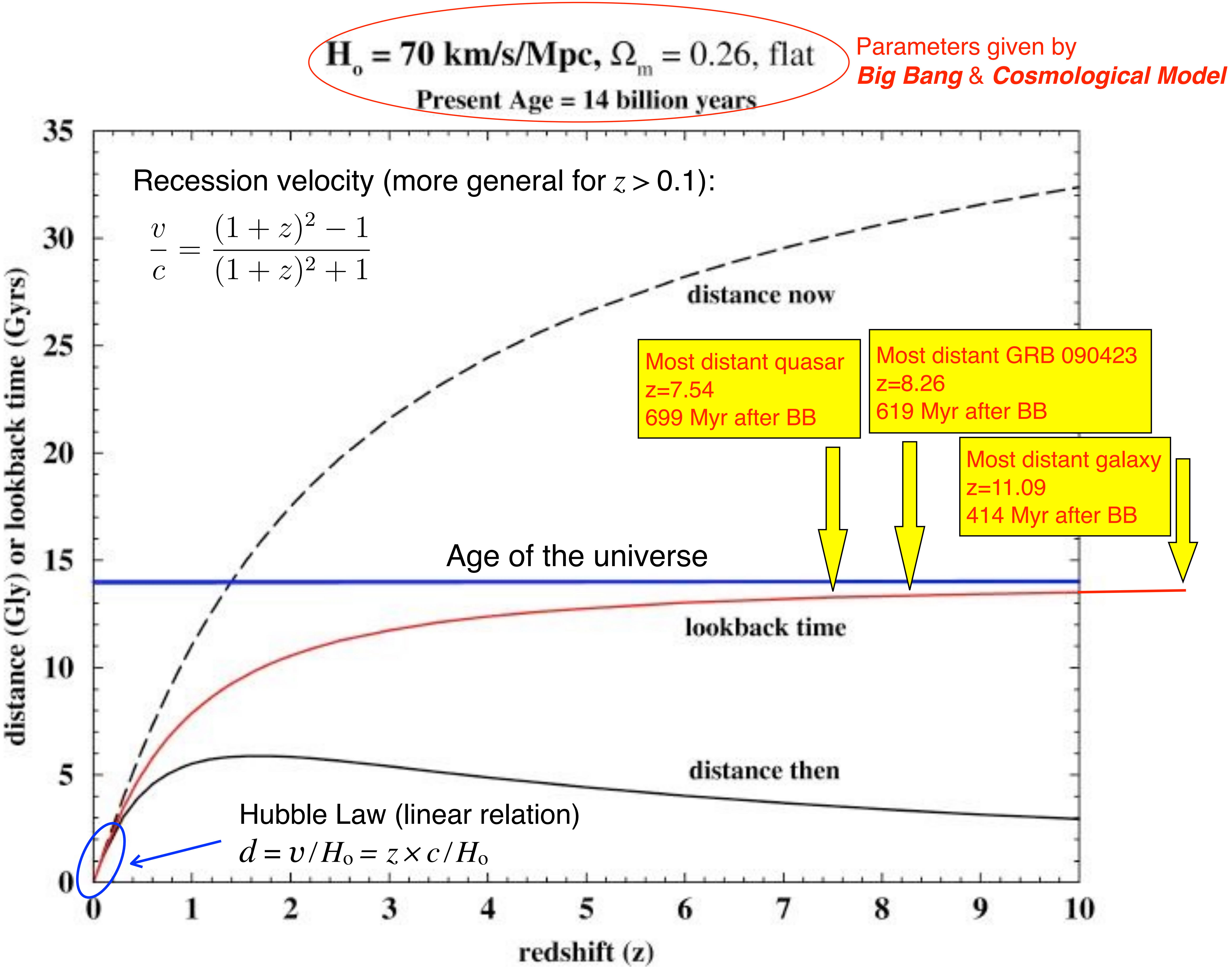


redshift ⟶ $$\frac{\lambda_o - \lambda_r}{\lambda_r} \equiv z \simeq \frac{v}{c}$$ ⟵ linear approximation (valid for $z < 0.1$)

Distance d vs. redshift z




H$_o$ = 70 km/s/Mpc, Ω_m = 0.26, flat
Present Age = 14 billion years
Parameters given by
Big Bang & Cosmological Model
Example: a galaxy observed with redshift z = 2
• Distance of galaxy from Earth at time when light left (distance then): ~ 5.8 Gly
• Distance at time of observations (distance now): ~ 17.5 Gly
• Time it takes to light to reach Earth (lookback time): ~ 10.5 Gly
• Age of universe of observed galaxy: 14 – 10.5 = 3.5 Gyrs
Gly: 10^9 light years
Gyrs: 10^9 years
distance now
Age of the universe
lookback time
distance then
distance (Gly) or lookback time (Gyrs)
redshift (z)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9
10



H_o = 70 km/s/Mpc, Ω_m = 0.26, flat
Present Age = 14 billion years
Parameters given by
Big Bang & Cosmological Model
Recession velocity (more general for z > 0.1):
$\frac{v}{c} = \frac{(1+z)^2 - 1}{(1+z)^2 + 1}$
distance now
Most distant quasar
z=7.54
699 Myr after BB
Most distant GRB 090423
z=8.26
619 Myr after BB
Most distant galaxy
z=11.09
414 Myr after BB
Age of the universe
lookback time
distance then
Hubble Law (linear relation)
$d = v/H_o = z \times c/H_o$
distance (Gly) or lookback time (Gyrs)
redshift (z)
0
5
10
15
20
25
30
35
1
2
3
4
6
7
8
9

Accelerated expansion of the Universe

Supernovae Type Ia as standard candles to measure cosmological distances

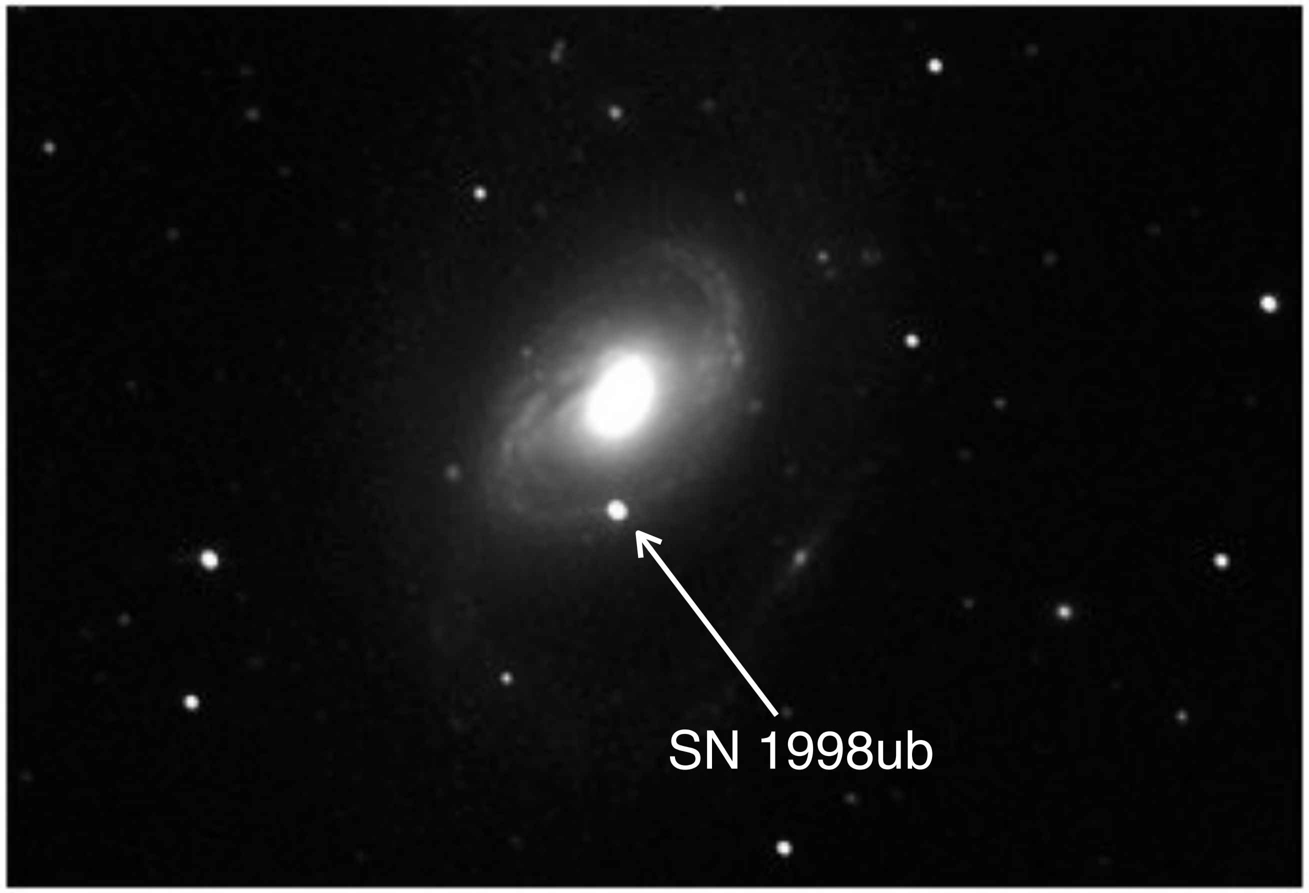
Saul Perlmutter

Brian Schmidt

Adam Riess

Nobel Prize 2011: ”For the discovery of the accelerating expansion of the Universe through observations of distant supernovae”

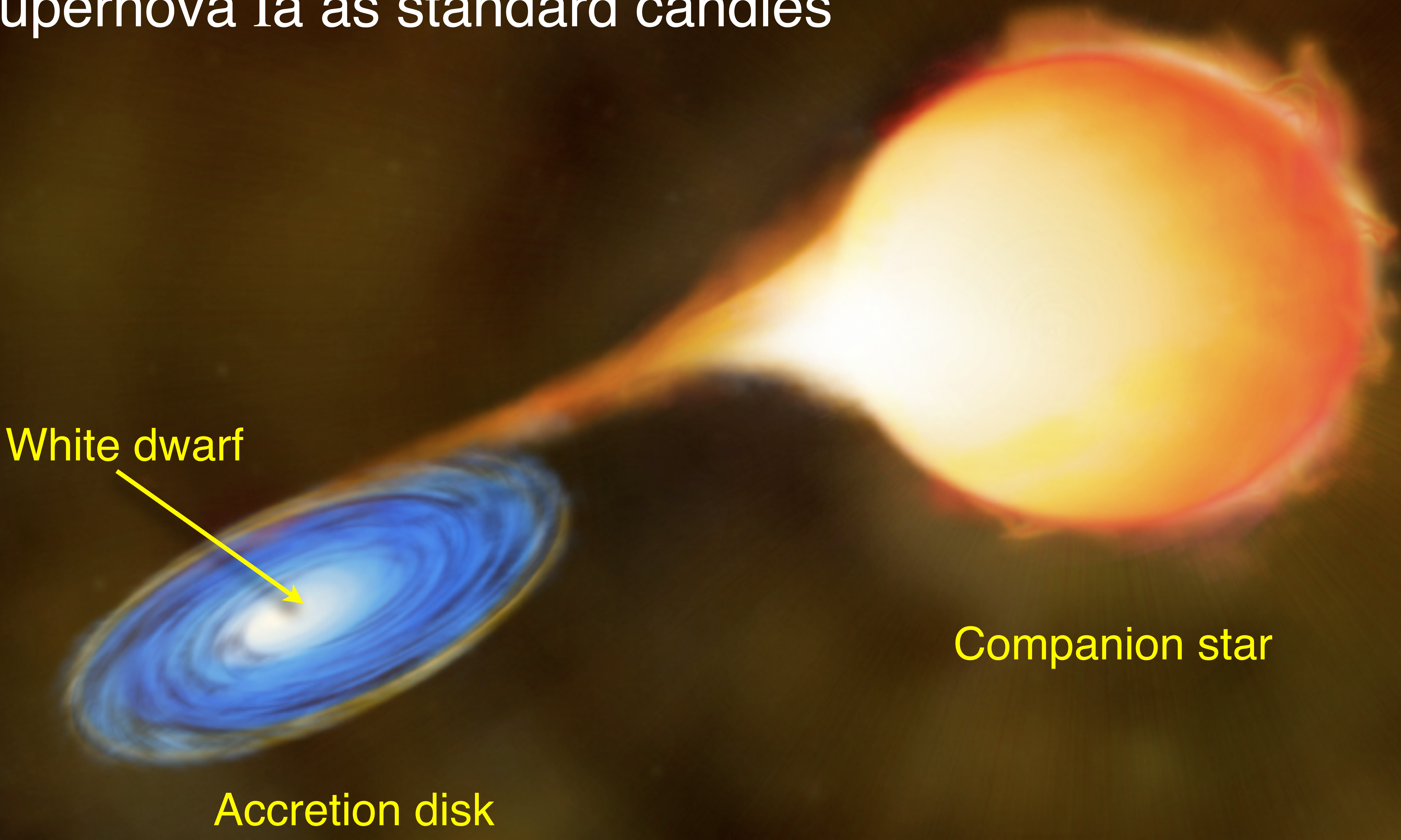
Supernovae Type Ia as standard candles



Galaxy ***Messier 96***, observed on 17/05/1998, shows supernova event

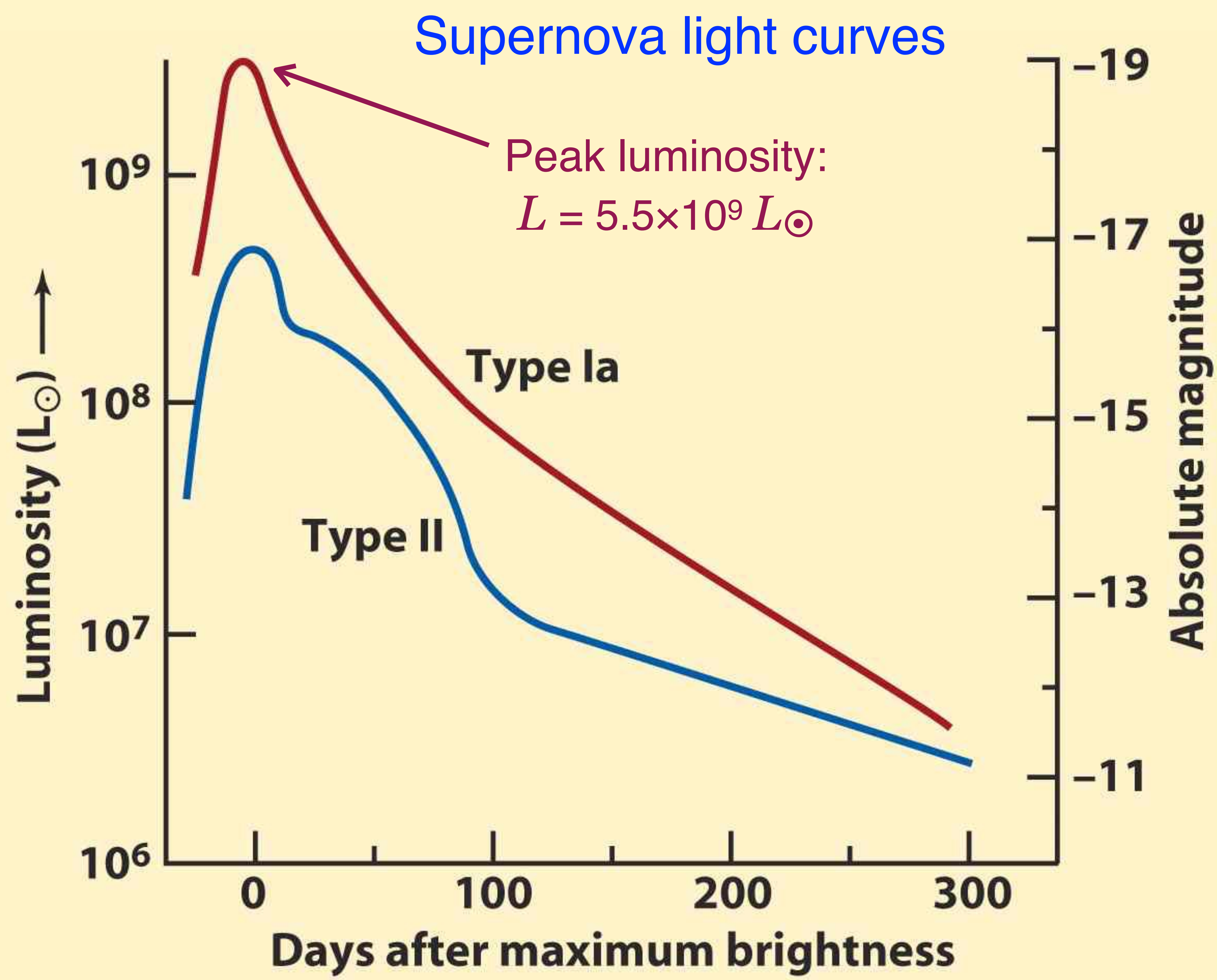
Same galaxy ***Messier 96*** observed 2 years before (15/04/1996)

Supernova Ia as standard candles



Standard candle because explosion occurs when mass of white dwarf reaches a particular value: *Chandrasekhar limit* $M = 1.4\ M_{\odot}$

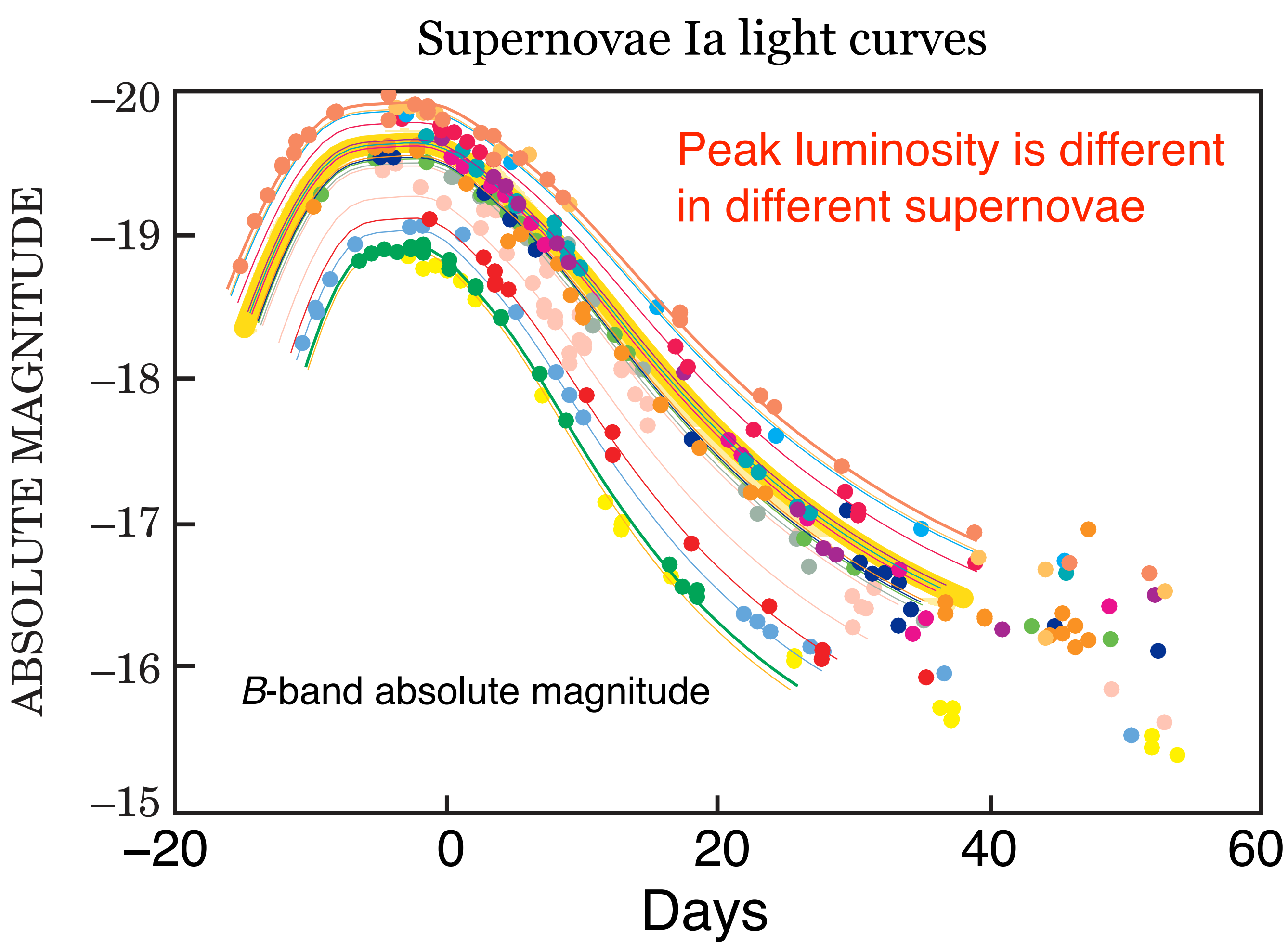
Supernovae Type Ia have similar luminosity at peak



Supernovae Type Ia as standard candles

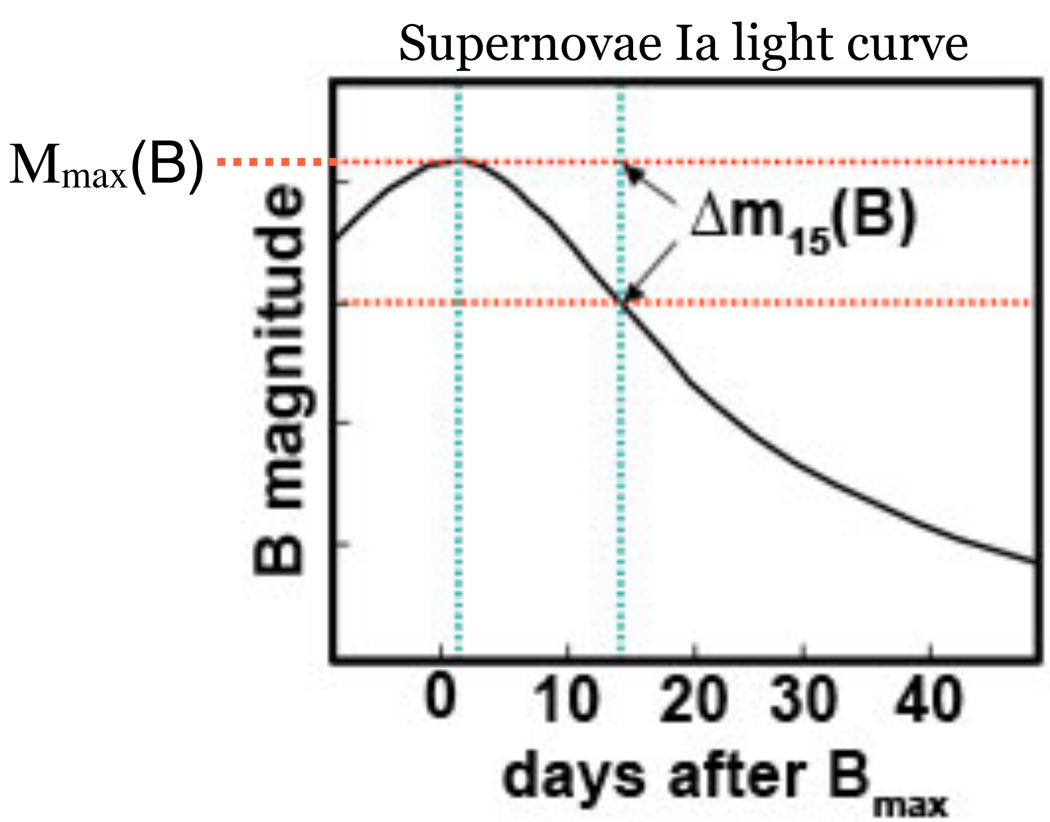
Observed distance of a standard candle

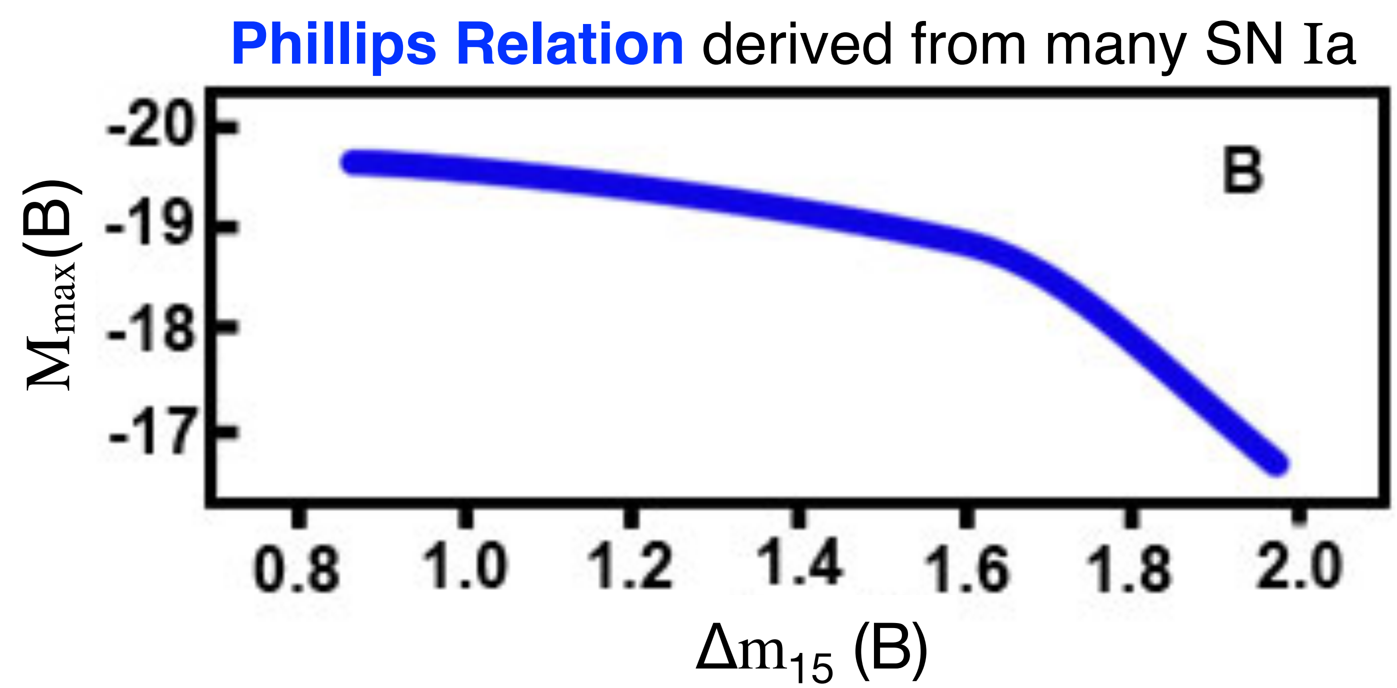
$$d = [L / (4\pi F)]^{1/2}$$



- Peak is wider in time for brighter supernovae
- ***Phillips Relation*** to infer the “intrinsic absolute brightness” (“standard candle”) of SN Ia

Supernovae Type Ia as standard candles

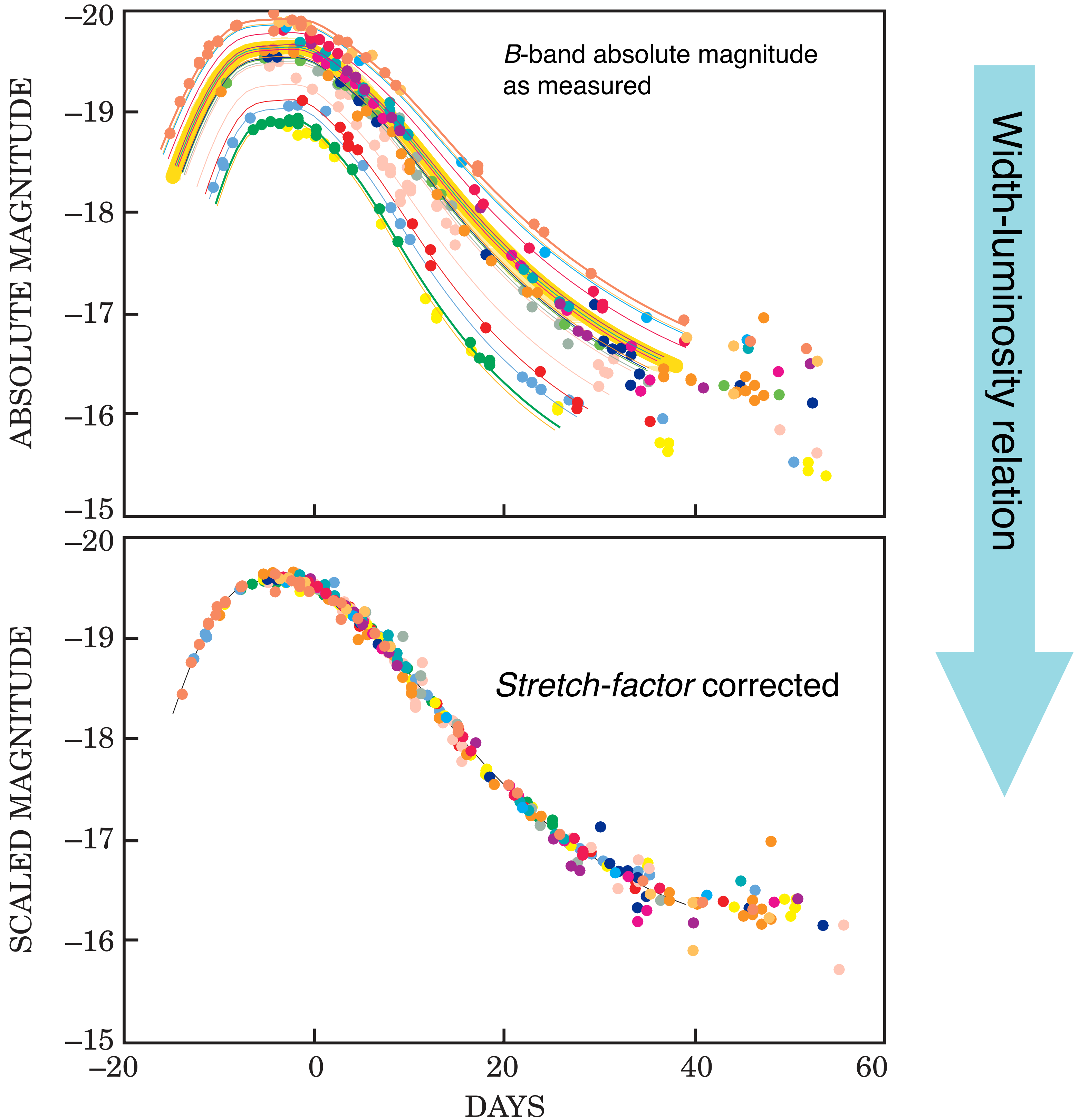




Δm_{15}(B): *B*-band observed magnitude drop in 15 days after maximum

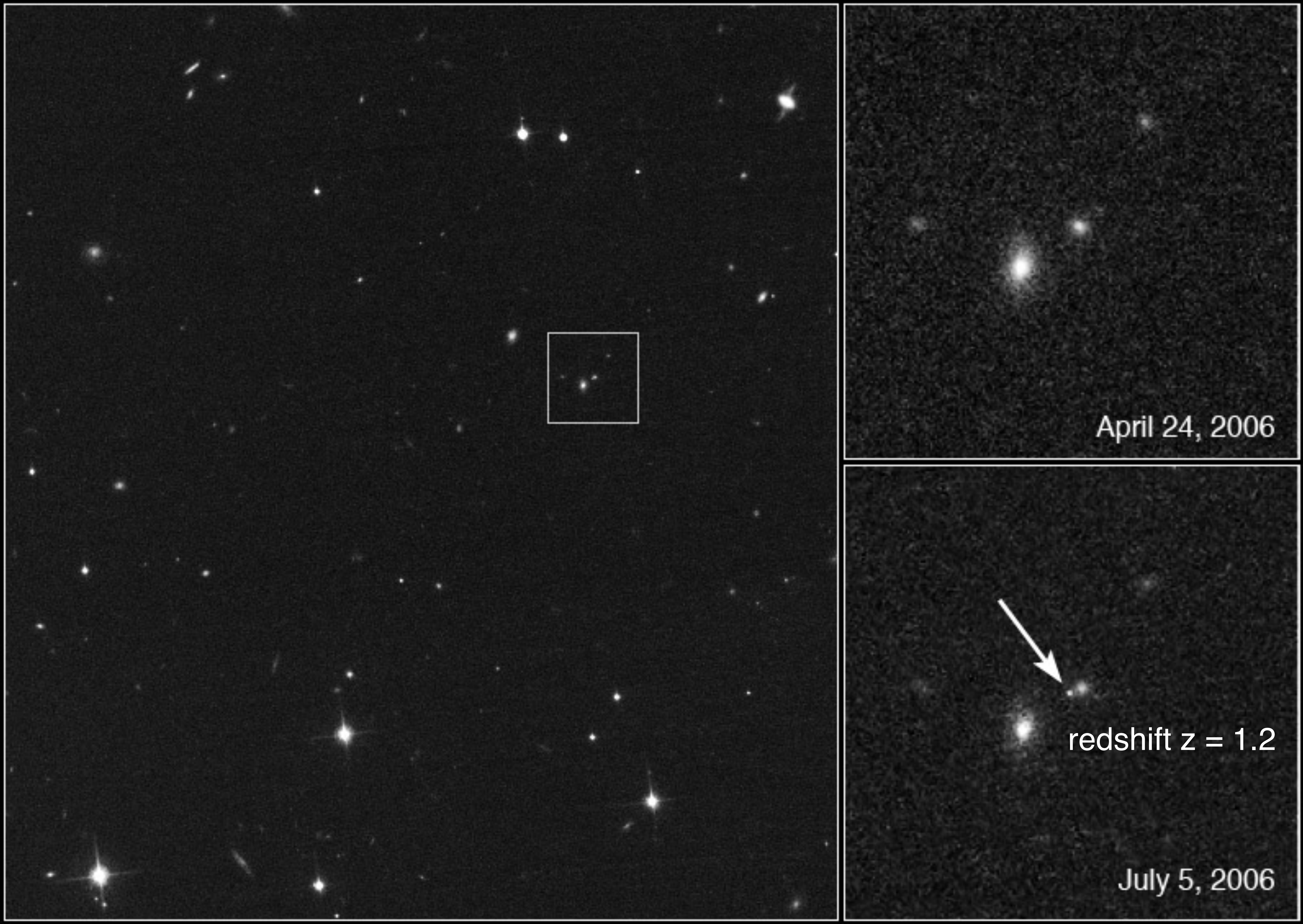
M_{max}(B): *B*-band absolute magnitude at peak

Supernovae Type Ia as standard candles



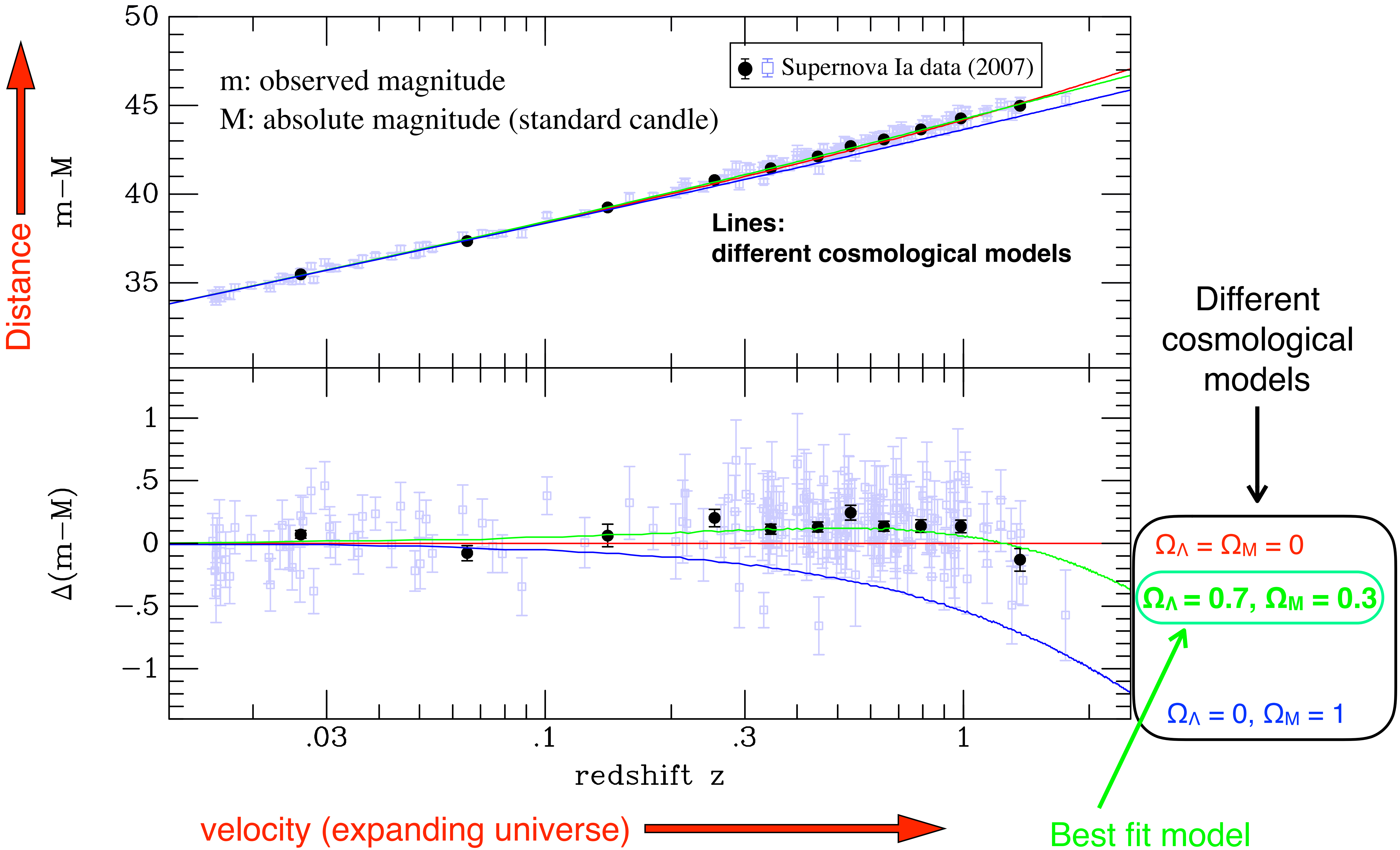
After this correction, supernovae Ia are real standard candles

Supernova Ia are bright $\Longrightarrow$ can be detected at **high distance**

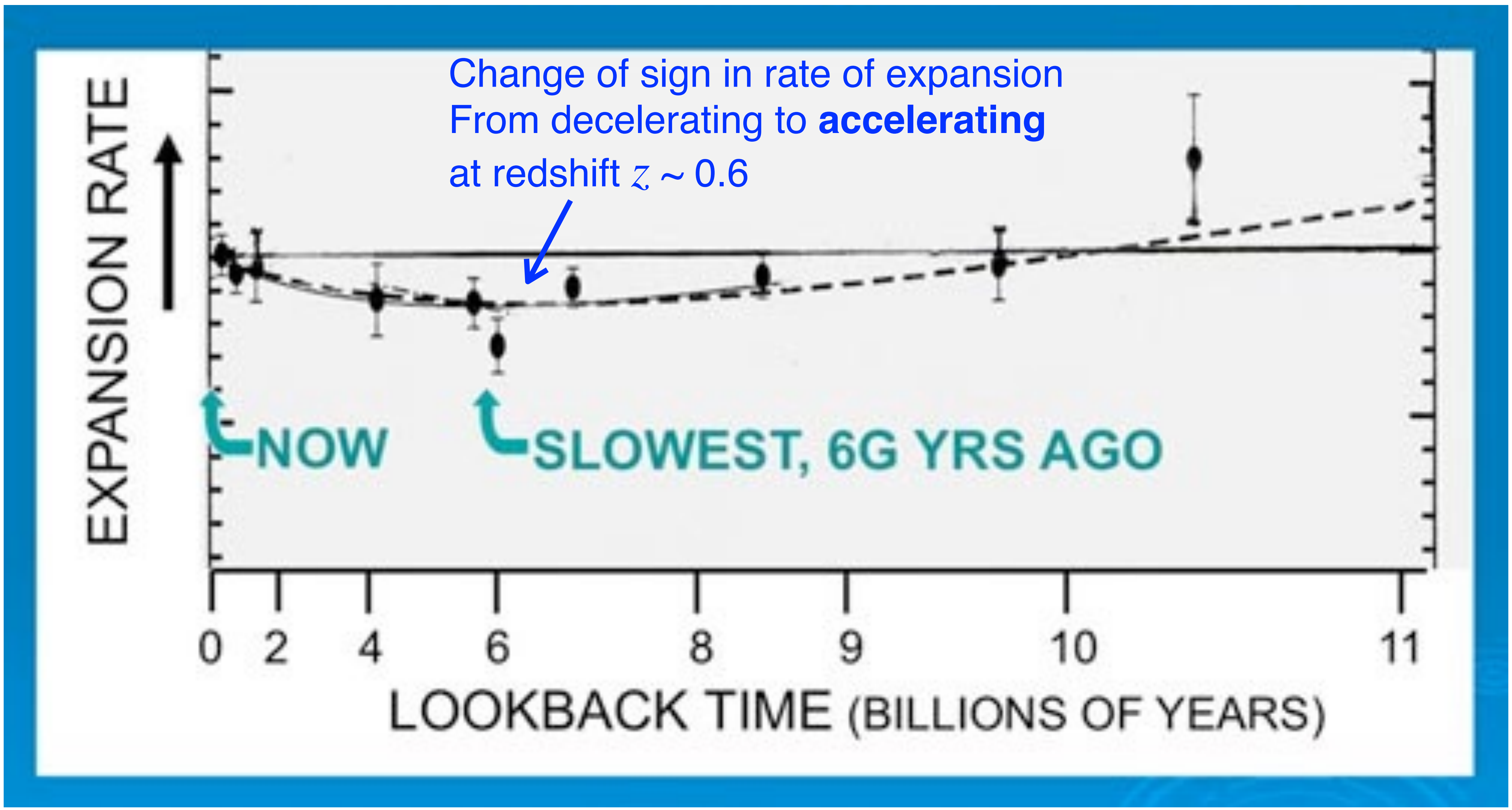


Most distant supernova Ia ever detected

Supernovae type Ia and cosmology: **the accelerating Universe**



The accelerating expansion of the Universe



Time since *Big Bang*