Lecture 6: Galaxy Dynamics (Basic)

- Basic dynamics of galaxies
  - Ellipticals, kinematically hot random orbit systems
  - Spirals, kinematically cool rotating system
- Key relations:
  - The fundamental plane of ellipticals/bulges
  - The Faber-Jackson relation for ellipticals/bulges
  - The Tully-Fisher for spirals disks
- Using FJ and TF to calculate distances
  - The extragalactic distance ladder
  - Examples

Elliptical galaxy dynamics

- Ellipticals are triaxial spheroids
- No rotation, no flattened plane
- Typically we can measure a velocity dispersion, σ
  - I.e., the integrated motions of the stars
- Dynamics analogous to a gravitational bound cloud of gas (I.e., an isothermal sphere).
- I.e.,

$$-\frac{dp}{dr} = \frac{GM(r)\rho(r)}{r^2}$$

HYDROSTATIC EQUILIBRIUM

PRESSURE FORCE PER UNIT VOLUME

GRAVITATIONAL FORCE PER UNIT VOLUME

Check Wikipedia "Hydrostatic Equilibrium" to see deriiation.

Elliptical galaxy dynamics

- For an isothermal sphere gas pressure is given by:

$$p = \rho(r)\sigma^2$$

$$\rho(r) \propto \frac{1}{r^2}$$

$$\Rightarrow \frac{\sigma^2}{r^3} \propto \frac{GM(r)}{r^4}$$

$$M(r) \propto \sigma^2 r$$

Reminder from Thermodynamics:
P=nRT/V=ρT,
E=(3/2)kT=(1/2)mv^2

$$\left(M(r) = \frac{2\sigma^2 r}{G} \right)$$

3

Elliptical galaxy dynamics

- As E/S0s are centrally concentrated if σ is measured over sufficient area M(r)=>M, I.e.,

$$\text{Total Mass} \propto \sigma^2 r$$

- σ is measured from either:
  – Radial velocity distributions from individual stellar spectra
  – From line widths in integrated galaxy spectra

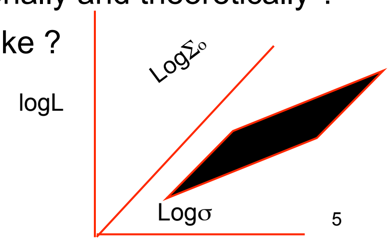
[See Galactic Astronomy, Binney & Merrifield for details on how these are measured in practice]

4

Elliptical galaxy dynamics

- We have three measureable quantities:
  - L = luminosity (or magnitude)
  - R_e = effective or half-light radius
  - σ = velocity dispersion
- From these we can derive Σ_o the central surface brightness (nb: one of these four is redundant as its calculable from the others.)
- How are these related observationally and theoretically ?
- I.e., what does: $L \propto \Sigma_o^x \sigma_v^y$ look like ?

THE FUNDAMENTAL PLANE



5

Fundamental Plane Theory

IF $\sigma_v^2 \propto M/R_e$ (I.e., stars behaving as if isothermal sphere)

& $L \propto \Sigma_o R_e^2$ Surf. Brightness definition

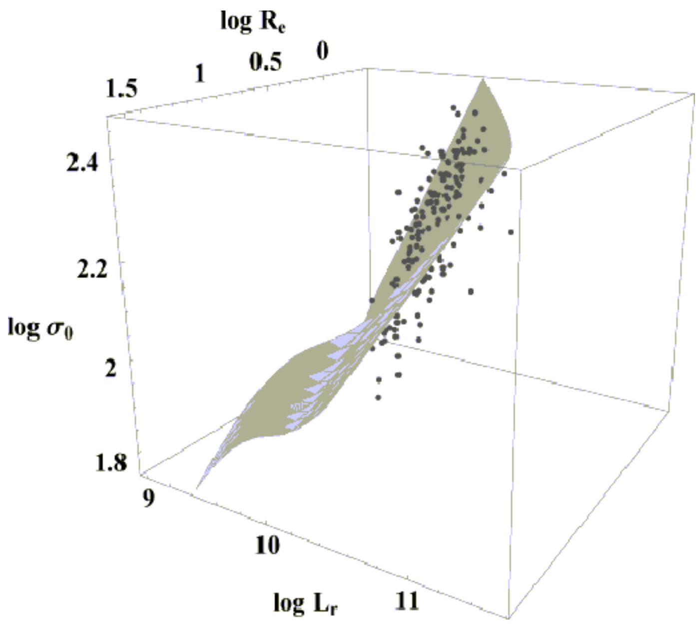
=> $L \propto \Sigma_o^{-1} \sigma^4$ i.e., if $M \propto L$

For $M/L \propto M^a$ i.e., $M \propto L^{(\frac{1}{1-a})}$

$$\sigma^2 \propto \frac{L^{(\frac{1}{1-a})}}{L^{\frac{1}{2}}} \Sigma_o^{\frac{1}{2}}$$

$L^{1+a} \propto \Sigma_o^{a-1} \sigma_v^{4-4a}$ If a=0, $M \propto L$ and $L \propto \Sigma_o^{-1} \sigma_v^4$

Hence E/S0 galaxies are expected to lie upon a plane in a 3D plot of logL v logΣo v logσ = the fundamental plane of ellipticals and bulges



7

Fundamental Plane Observations

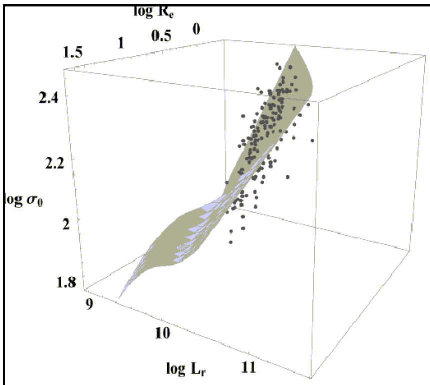
Observationally: $L \propto \Sigma_o^{-0.7} \sigma_v^3$

Which implies: $M/L \propto M^{0.25}$

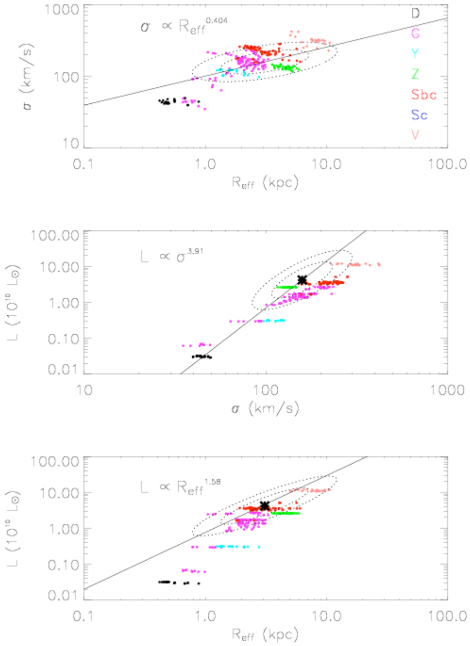
Tighest projected correlation is known as the ***Faber-Jackson relation:*** $L \propto \sigma_v^3$

Or in edge on projection:

$$L \propto \Sigma_o r_e^2$$
$$r_e^2 \propto \Sigma_o^{-1.7} \sigma^3$$
$$r_e \propto \Sigma_o^{-0.85} \sigma_v^{1.5}$$
$$\log r_e \propto 0.34 \mu_o + 1.5 \log \sigma_v$$
$$\log r_e \propto 1.5[\log \sigma_v + 0.23 \mu_o]$$
$$\log r_e \propto \log \sigma_v + 0.23 \mu_o$$



- Faber-Jackson relation →



Can use FJ to measure distances

- Example: A galaxy with M=-21 mag at d=100Mpc has a σ_v=200km/s. A second galaxy has σ_v=220km/s and m=19 mags. What is its distance ?
- Answer: Use:

$$L \propto \sigma_v^3$$
$$M \propto -2.5\log(\sigma_v^3) \propto -7.5\log\sigma_v$$
$$M = k - 7.5\log\sigma_v$$
$$k = -3.74, M = -3.74 - 7.5\log\sigma_v$$

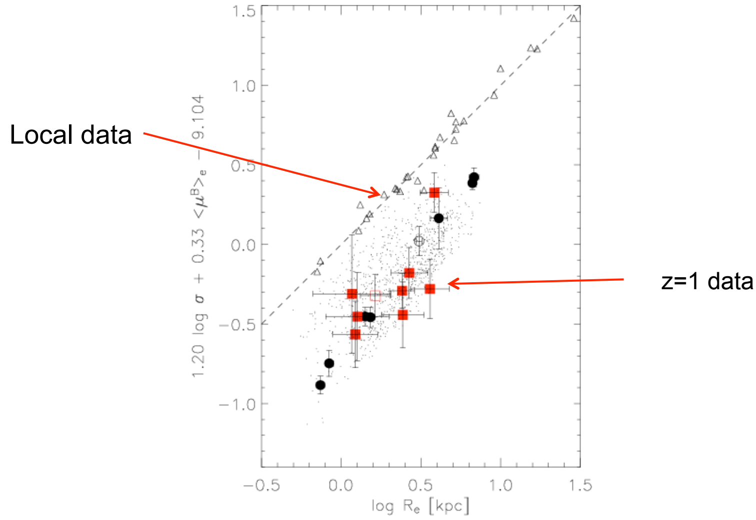
For G2:

$$M = -21.3$$
$$d = 10^{0.2[m-M-25]}$$
$$d = 1148\,Mpc$$

FJ relation is used as a distance indicator

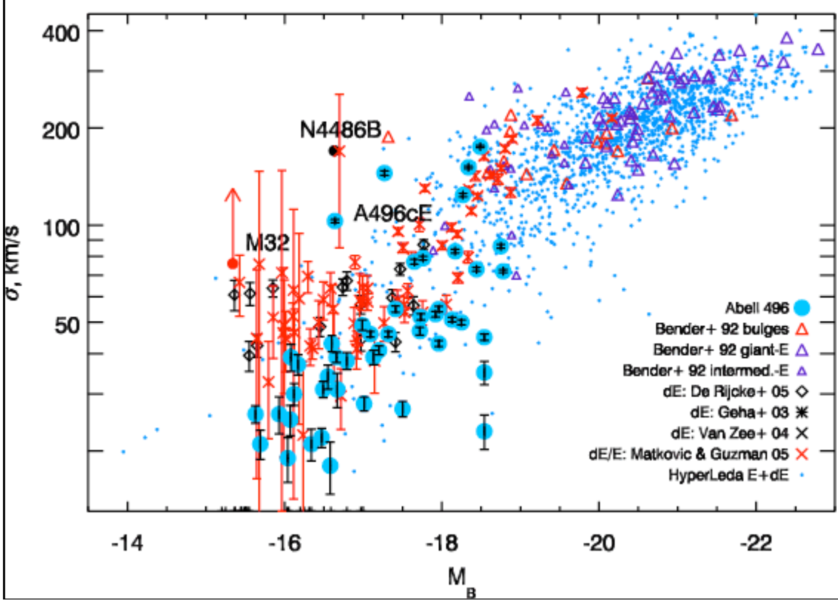
FP is used to monitor the evolution of ellipticals to z~1.5

Evolution of FP?
Unveils evolution of ellipticals?



de Serego Alighieri et al 2005, A&A

Ellipticals and bulges?



Spiral galaxy dynamics

- Spiral galaxies are dominated by rotation.
- Balance centripetal force with gravity:
- =>

$$\frac{GM(r)}{r^2} = \frac{v_c^2}{r}$$

VIRIAL THEOREM (Grav.=Centripetal force)

$$M(r) = \frac{v_c^2 r}{G}$$

$$\Sigma_o \propto \frac{L}{r^2}$$

- If Σo is constant for all disks: $L \propto r^2$
- If M/L is constant: $M \propto L$
- =>

$$L \propto v_c^2 L^{\frac{1}{2}}$$

$$L \propto v_c^4$$

$$M \propto -10 \log v_c$$ ← THE TULLY FISHER RELATION

122 R. Giovanelli: *The I–Band Tully–Fisher relation*

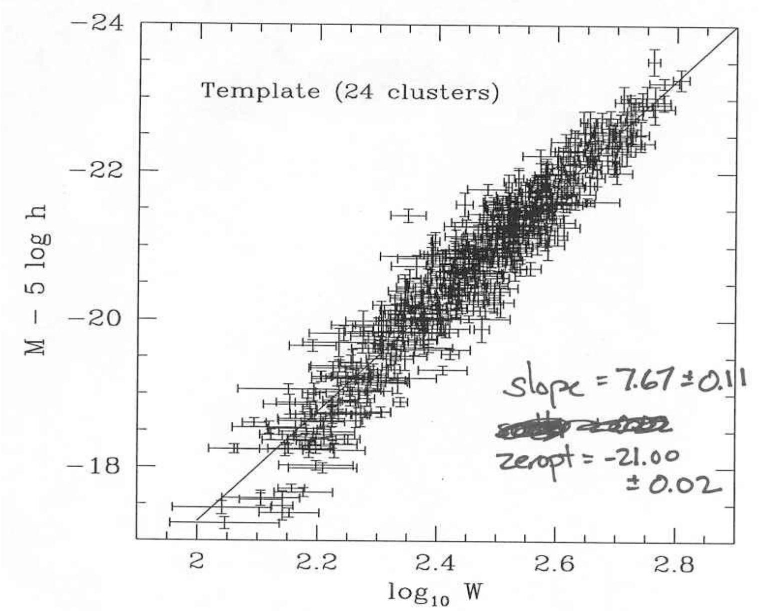


FIGURE 4. Template relation based on 555 galaxies in 24 clusters.

14

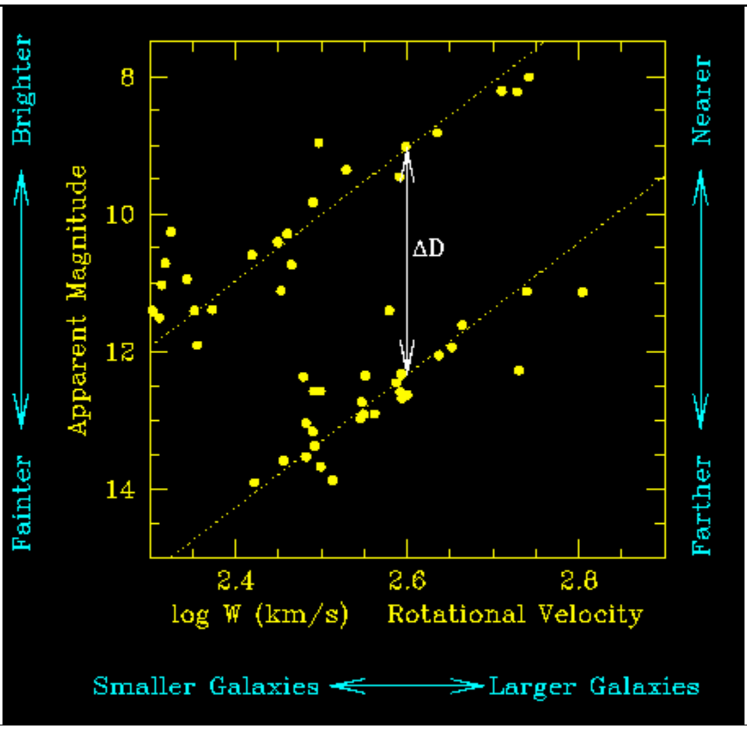
Observed Tully-Fisher relation

$$M_B = -7.48 \log v_c - k_B^{TF}$$

$$M_H = -9.50 \log v_c - k_H^{TF} \quad (k_h=-2.8)$$

- I.e., longer wavelengths optimal as observed relation close to theory.
- Problem:
  - Want galaxy face-on to measure M accurately
  - Want galaxy edge-on to measure v accurately
- Optimal inclination for TF observations = 45 degrees
- Near-IR better as dust extinction much less
- Velocities often obtained from HI (21cm line)

15



16

Using TF to measure distances

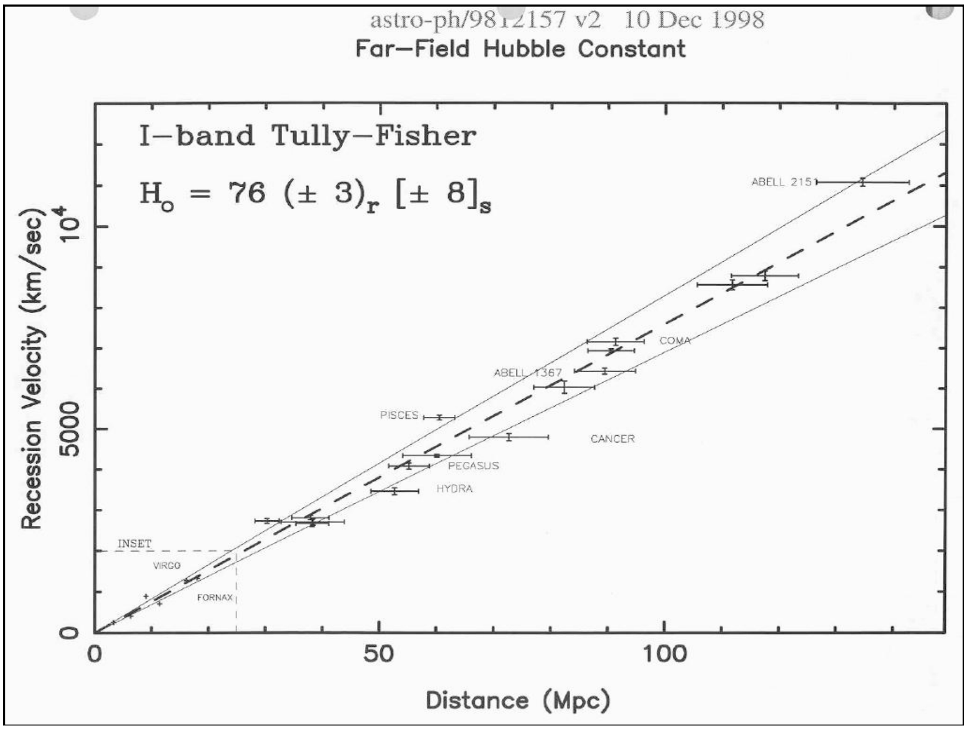
- Example: A spiral galaxy has a measured rotation of 300 km/s, a major-minor axis ratio of 1.74 and an apparent magnitude of 18.0 mags (H-band). If its spectroscopic redshift is z=0.15 deduce the Hubble constant ?

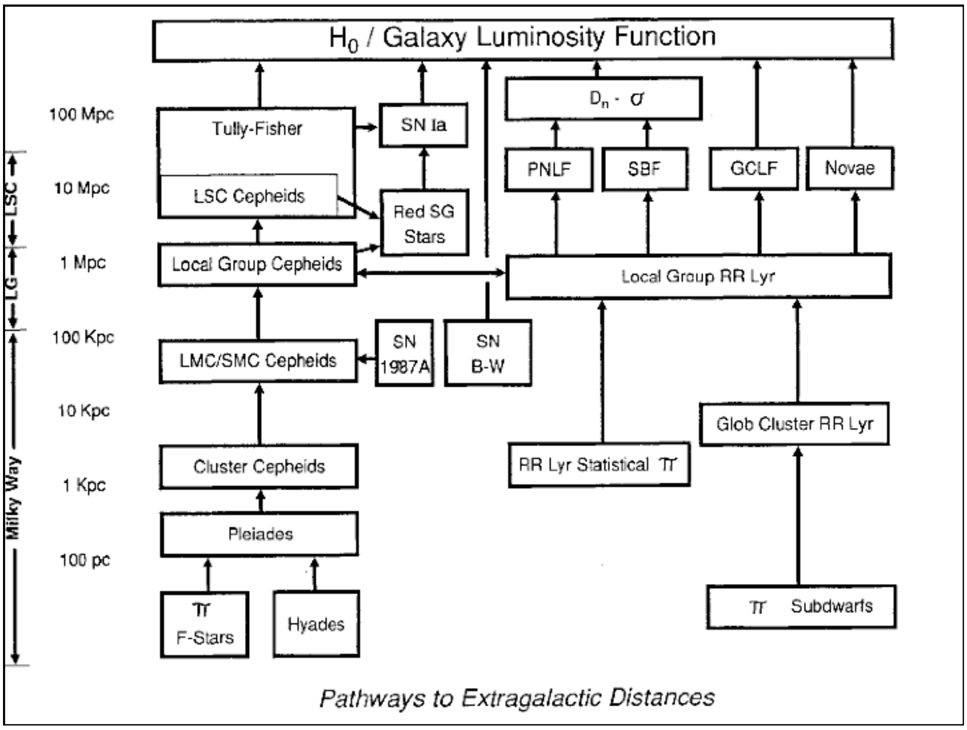
$$\cos(i) = 0.57, i = 55\deg$$
$$v_c = 300/\sin(i), v_c = 366 km/s$$
$$M_H = -9.50\log(v_c) - k_H^{TF}$$
$$M_H = -21.55 mag$$
$$d = 10^{0.2[m - M_H - 25]}$$
$$d = 813 Mpc$$

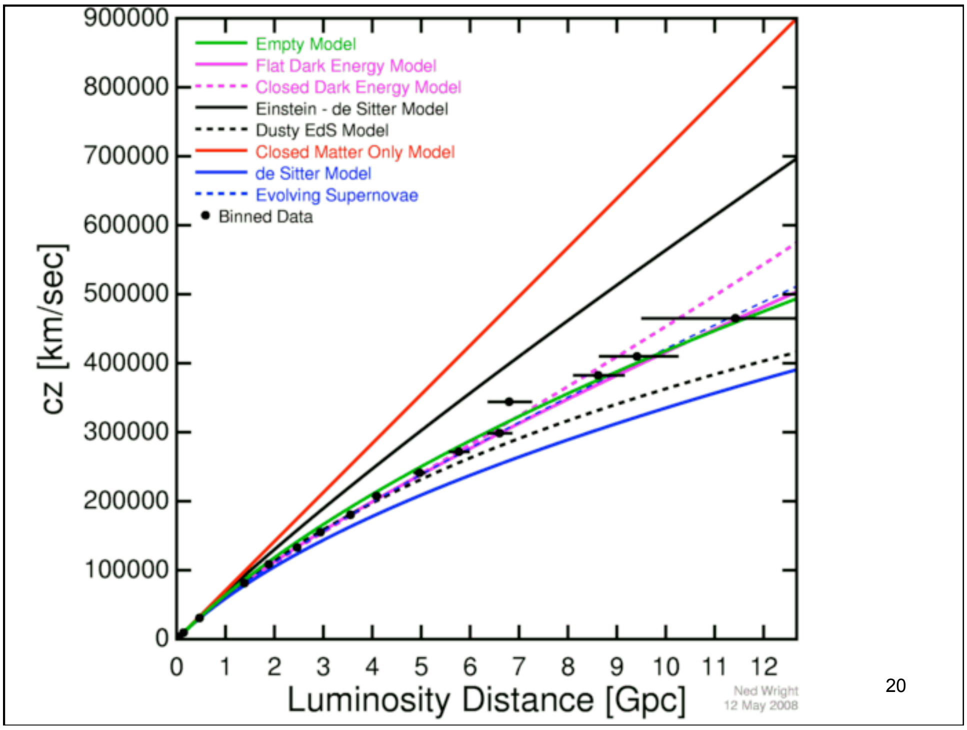
If z=0.15 and assume v_{pec}=0:

$$H_o = \frac{cz}{d} = 55 km/s/Mpc$$

17




H0 / Galaxy Luminosity Function
100 Mpc
10 Mpc
1 Mpc
100 Kpc
10 Kpc
1 Kpc
100 pc
LSC
LG
Milky Way
Tully-Fisher
LSC Cepheids
SN Ia
Red SG Stars
Dn - σ
PNLF
SBF
GCLF
Novae
Local Group Cepheids
Local Group RR Lyr
LMC/SMC Cepheids
SN 1987A
SN B-W
Glob Cluster RR Lyr
Cluster Cepheids
RR Lyr Statistical π
Pleiades
π F-Stars
Hyades
π Subdwarfs
Pathways to Extragalactic Distances


Empty Model
Flat Dark Energy Model
Closed Dark Energy Model
Einstein - de Sitter Model
Dusty EdS Model
Closed Matter Only Model
de Sitter Model
Evolving Supernovae
Binned Data
cz [km/sec]
Luminosity Distance [Gpc]
Ned Wright
12 May 2008

20

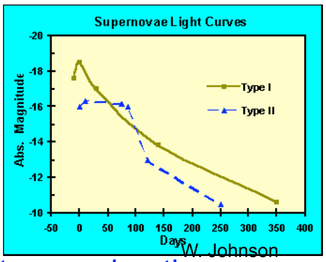
Supernovae Type Ia

- an ideal standard candle is very bright, and of known brightness (at least for some observable time)
- type Ia supernovae fit this description:
  - when they explode, they reach a large absolute magnitude that varies little from supernova to supernova
- a type Ia supernova occurs in a binary star system where gas from a red giant overflows onto a white dwarf
  - when a critical mass is reached the white dwarf can no longer be supported and collapses, then rebounds

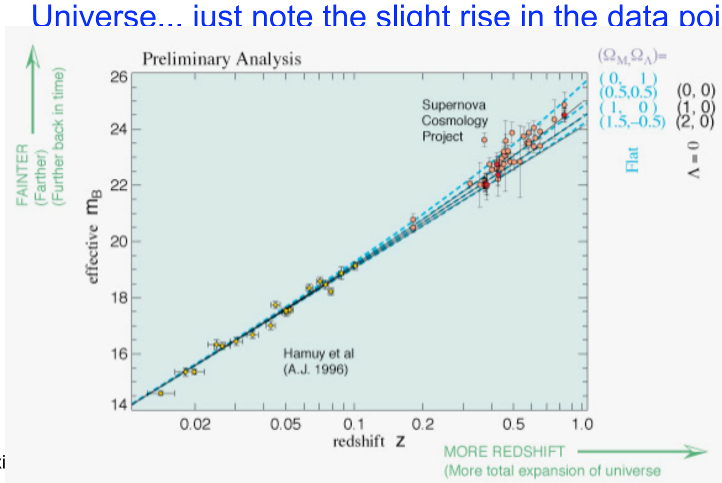
    (type II supernovae are single stars that collapse when nuclear fusion ceases... Ia vs Ib depends on if the companion has hydrogen in the atmosphere)

Acceleration of the Universe

- Type Ias can be seen over such large distances one can measure the change in H with t (or z)
  - assume their peak luminosity L is constant
  - then the measured flux is just $F = L / 4 \pi d^2$
  - from Hubble's law: $d = v / H_0$
  - if Hubble's law applies at large distances, i.e. the Universe has always expanded at the same rate, then the flux should decrease steadily with redshift
- the Supernova Cosmology project set out to discover if this is actually the case (http://www-supernova.lbl.gov/public/)

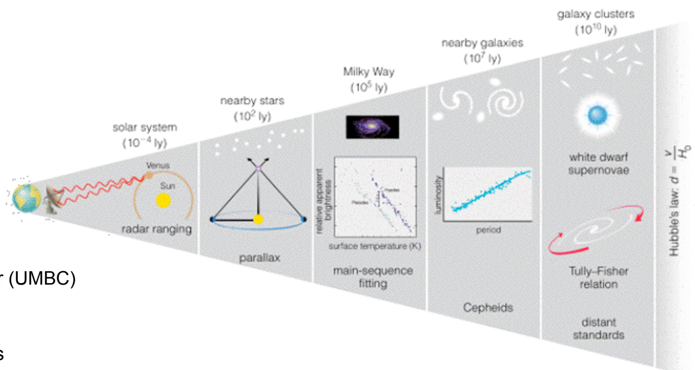


- in fact, the most distant Ia supernovae appear to be a bit *fainter* than predicted (distance to large)
  - results for 42 supernovae shown in the plot
  - the lines show different ideas about the history of the Universe... just note the slight rise in the data points



the distance ladder

- Lastly... remember that absolute distances can have big errors! Most of the methods are ‘bootstrapped’ to another method for closer objects (e.g. Hubble’s law). When we get to the scale of the whole Universe, this series of potential errors could build up to be pretty big!



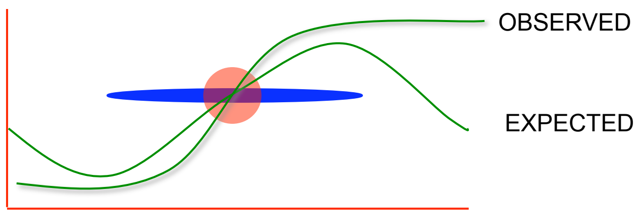
J. Fisher (UMBC)

Rotation curves

- If $v_c^2 \propto \frac{M}{r}$ we expect at large radii that M = constant

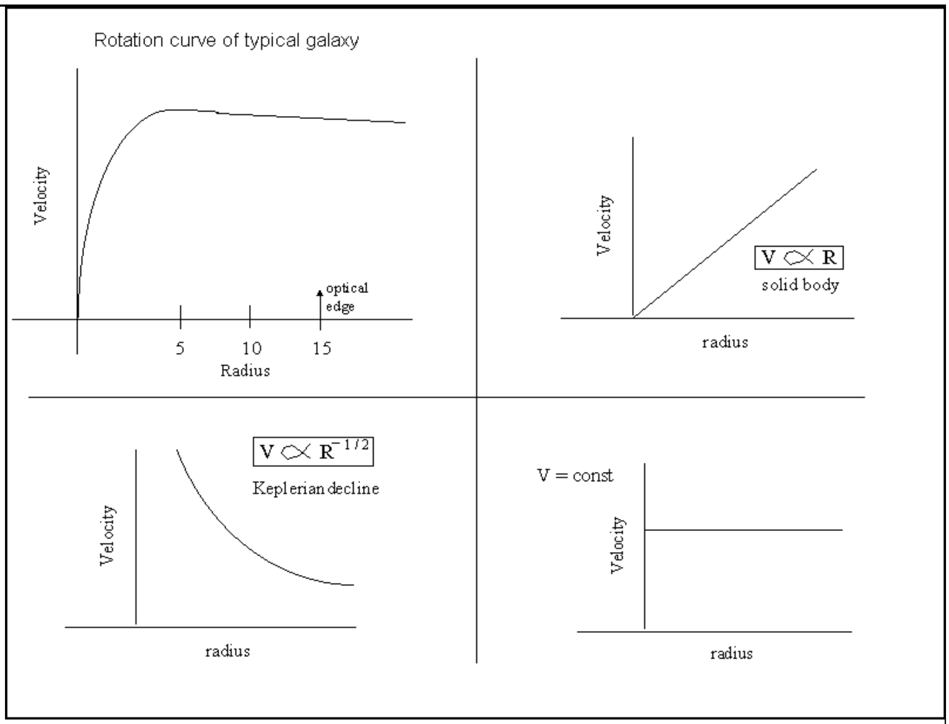
$\therefore v_c \propto r^{-\frac{1}{2}}$

- I.e., rotation curve (v versus r) should decrease:



- Conclusion: substantial mass at large radii but not luminous as there are no stars at these radii.

25



The dark matter distribution

- What kind of mass distribution gives v independent of r ?

$$v_c^2 = \frac{M(r)G}{r}, \therefore M(r) \propto r$$

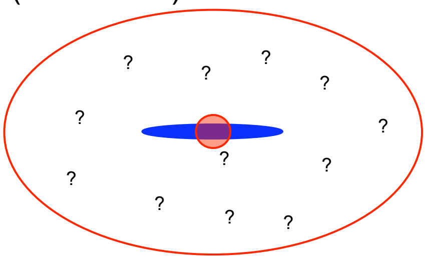
$$\rho(r) = \frac{M(r)}{V} \propto \frac{1}{r^2}$$

More formally:

$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM}{dr}$$

same answer

- I.e., consistent with an isothermal sphere of non-luminous (non-stellar) or "Dark Matter"



DM CANDIDATES:
COLD DUST
IONISED PLASMA
HI CLUMPS
COLD DARK MATTER
WIMPS
MACHOS
MOND