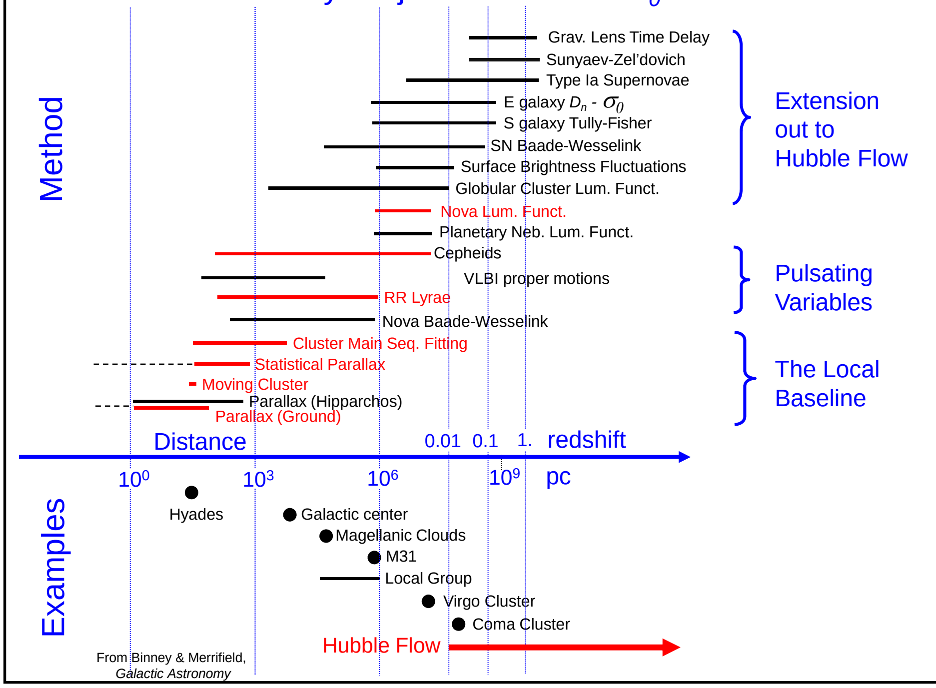
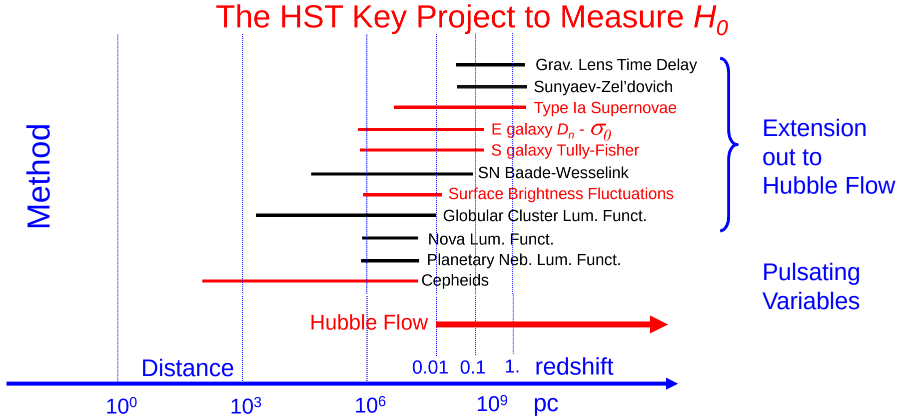
The HST Key Project to Measure H_0



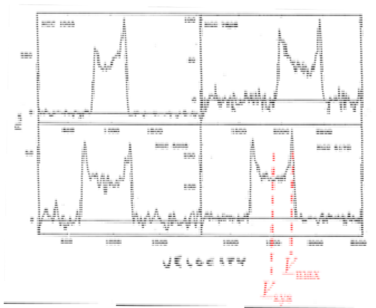
The HST Key Project to Measure H_0

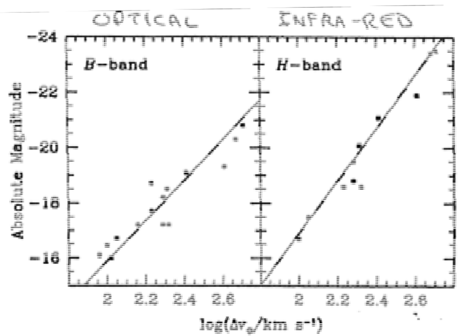


- Mould et al. 2000, ApJ 529, 786
- Measured Cepheids in 18 spirals
  - D < 25 Mpc, v < 1800 km/s
  - also used 7 more galaxies from other sources
- Distances to Cepheids relative to LMC distance
- Used these to calibrate secondary distance indicators
  - Tully-Fisher
  - Fundamental plane
  - Surface brightness fluctuations
  - Type Ia supernovae

Tully-Fisher Relation

- L-v correlation
- for spiral galaxies, v easily measured using H I 21cm (radio) profiles.
- must apply sin i correction for inclination.
- infrared Tully-Fisher: IR measurements minimize scatter in L due to absorption ==> tighter correlation
- F/L ➔ distance





E Galaxy Fundamental Plane The D_n - σ_0 relation

- Define:

  D_n = angular diameter at which surface brightness reaches
  I_n = 20.75 B-mag/arcsec^2

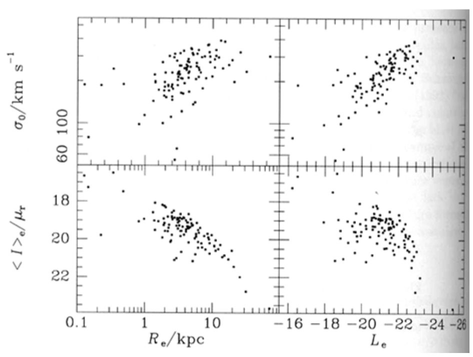
- Observations show that linear size (in kpc) corresponding to D_n is tightly correlated with σ_0

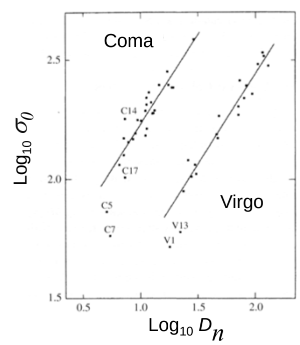
- D_n - σ_0 relation combines radius, surface brightness and internal velocity dispersion σ_0

  ➔ *The Fundamental Plane strikes again!*

- Angular size = D_n = (linear size)/distance

- 15% scatter in resulting distance to any one galaxy.





[CO Fig. 27.5]

Surface brightness fluctuations

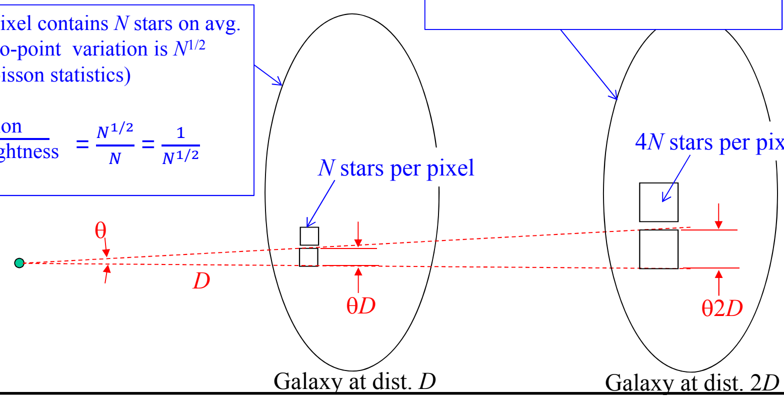
- Same galaxy seen at any distance will have same surface brightness.
  - Flux from each star drops as $1/D^2$
  - But number of stars in each pixel grows as D^2.
- But surface brightness distributions look smoother for larger *D*.

- Each pixel contains $4N$ stars on avg.
- Point-to-point variation is $(4N)^{1/2}$ (Poisson statistics)

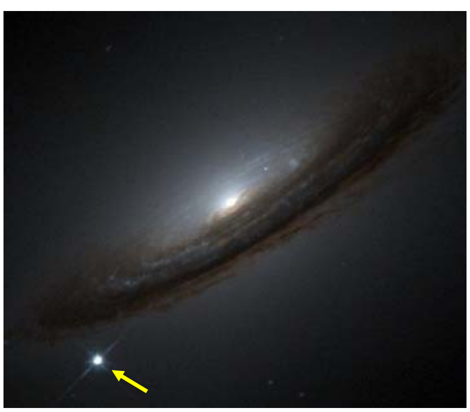
$$\frac{\text{Variation}}{\text{Avg.Brightness}} = \frac{(4N)^{1/2}}{4N} = \frac{1}{2N^{1/2}}$$

- Each pixel contains N stars on avg.
- Point-to-point variation is $N^{1/2}$ (Poisson statistics)

$$\frac{\text{Variation}}{\text{Avg.Brightness}} = \frac{N^{1/2}}{N} = \frac{1}{N^{1/2}}$$



Type Ia Supernovae



Core collapse supernovae
- Massive stars ($M > 8$ or10 M_{sun})
- Wide range in M ➔ wide range in L
- Not useful as "standard candles"

Type Ia supernovae
- White dwarf with $M \sim 1.4\ M_{sun}$
- L can be precisely calibrated.
- Good standard candles.

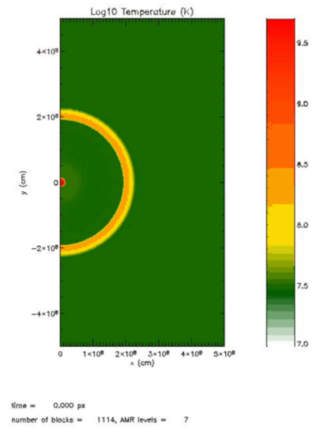
Type Ia Supernovae

- Something dumps too much mass onto white dwarf.
- Increased density ➔ runaway heating through C + C burning
- Heating rate faster than dynamical timescale
  - White dwarf cannot peacefully respond to pressure increase.
- *Deflagration*
  - leading to *detonation*?

Type Ia Supernovae as "standard candles".

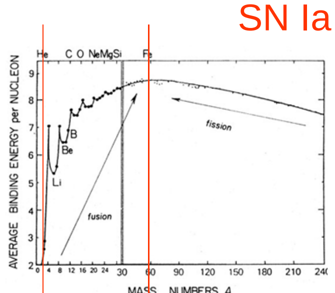
- Always happens when mass goes just past limit for heating-cooling balance.

  ➔ Supernova always has ~ same luminosity (factor 10).
- Get distance from $\text{Flux} = \dfrac{L}{4\pi r^2}$



Deflagration simulation

SN Ia as Standard Candles

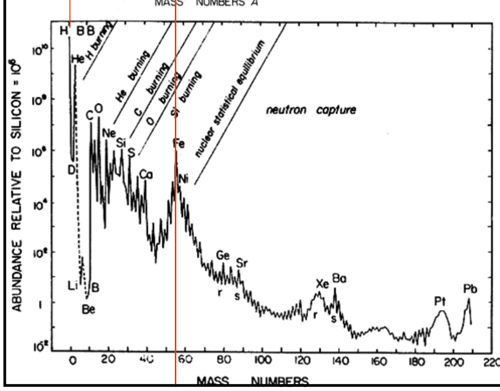


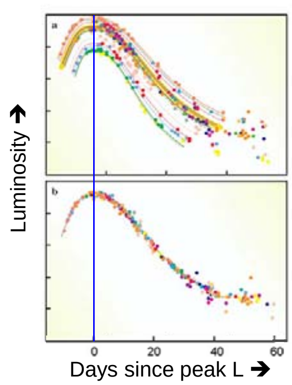
Light output powered by radioactive decay:

^{56}Ni ➔ ^{56}Co ➔ ^{56}Fe

Amount of Ni determines both luminosity *and* opacity.

- So luminosity and fading timescale are correlated.



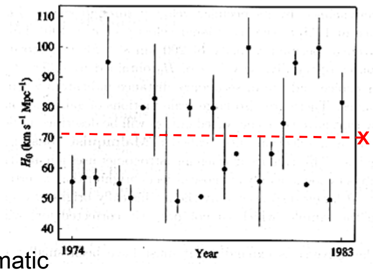


Observed range in *L* and *fading timescale.*

After correcting for *L - timescale* correlation.

The HST Key Project to Measure H_0

- Measured Distances to Cepheids.
  - relative to LMC distance.
- Used these to calibrate secondary distance indicators in same galaxies.

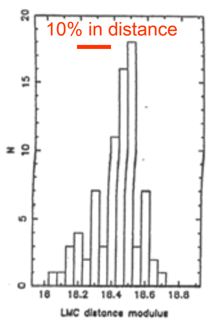


	value	random	systematic
Tully-Fisher	71	± 4	± 4
$D_n - \sigma_0$	78	8	10
Surface Brightness Fluct.	69	4	6
Type Ia SNe	68	2	2

Average: $H_0 = 71 \pm 6$ km/s/Mpc

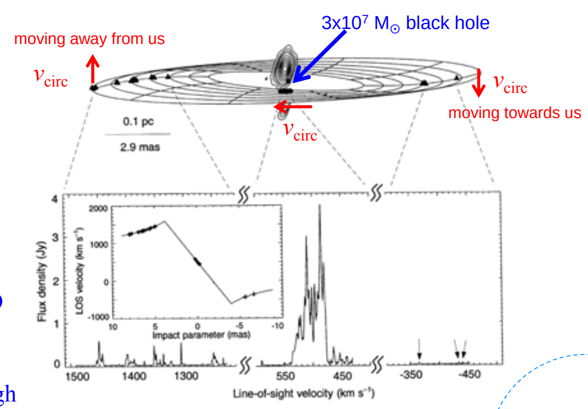
- Uncertainties:
  - Correction for large scale flows
  - Distance to LMC.

    Taken to be 50 kpc ± 6.5%



Distribution of published LMC distance moduli

Megamaser Galaxies

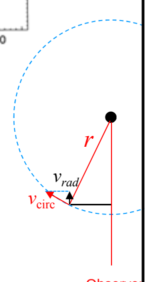


- Radio telescope observes H_2O emission line.
- Maser (stimulated emission) when there is long path through gas at same radial velocity (as seen by us).

  ➔ Intense brightening of beam.
- Radio VLBI measurements of maser proper motion $d\theta/dt$ and v_r

- Keplerian rotation around BH.
- Proper motion of maser knot

  $= d\theta/dt = v_{circ} / D$
- Also use acceleration $dv_{rad}/dt = v^2/r$
  - Compare r to angular size of orbit.



D = 7.2 Mpc

Latest Result: $H_0 = 73.8 \pm 2.6$ km s^{-1} Mpc^{-1}

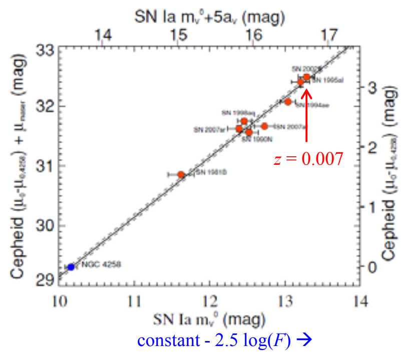
Nobel Prize ↘

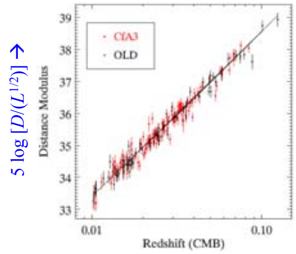
The Astrophysical Journal, 730:119 (18pp), 2011 April 1 doi:10.1088/0004-637X/730/2/119

A 3% SOLUTION: DETERMINATION OF THE HUBBLE CONSTANT WITH THE *HUBBLE SPACE TELESCOPE* AND WIDE FIELD CAMERA 3*

Adam G. Riess[1,2], Lucas Macri[3], Stefano Casertano[2], Hubert Lampeitl[4], Henry C. Ferguson[2], Alexei V. Filippenko[5], Saurabh W. Jha[6], Weidong Li[5], Ryan Chornock[7], and Jeffrey M. Silverman[5]

- Recalibrated Cepheid P-L relation in 3 ways:
  - Distance to Megamaser galaxy NGC4258.
  - Better parallaxes to MW Cepheids.
  - Improved distance to LMC.
- Calibrated luminosities of 8 "nearby" SN Ia using Cepheids in same galaxies.
- Determined H_0 from Hubble diagram for existing sample of 253 SN Ia with redshift $z \le 0.1$





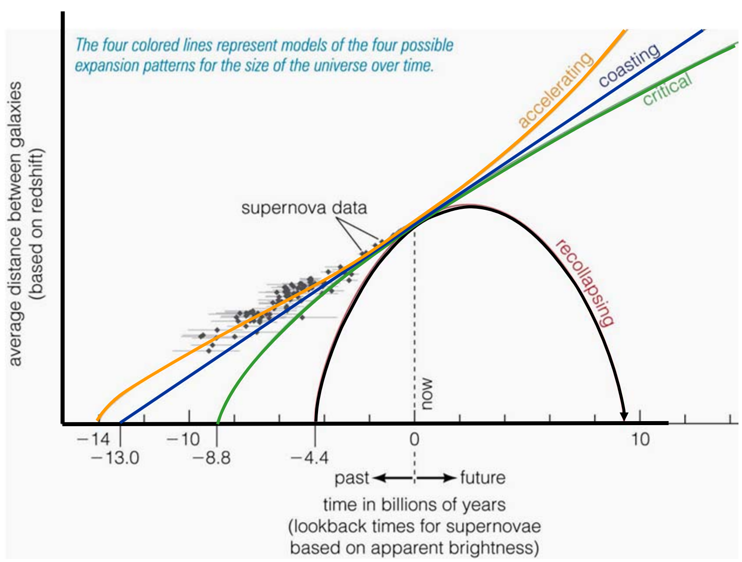
Distance modulus:

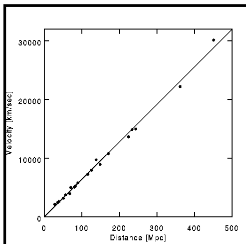
$(m\text{-}M) = 5 \log(D/10 \text{ pc})$

$L / F \propto D^2$

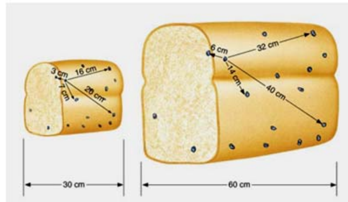
[CO pg. 62]

Sneak Preview

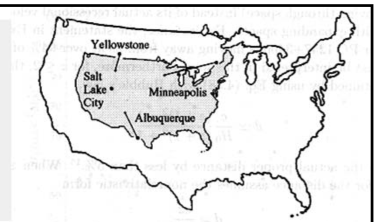




Redshift vs distance



As seen from a Wonder Bread raisen

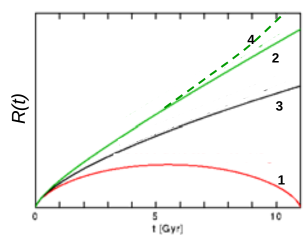


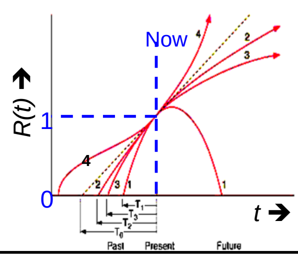
As seen from Utah

The Expanding Universe [CO 29.1]

R(t) = scale factor = 1/(1+z)

R(t) vs. *t*





The Cosmological Principle:

At any given time, the universe is the same everywhere.

Universe is

- Homogeneous
- Isotropic

Cosmological Principle: Universe is homogeneous & isotropic

Newtonian Cosmology

- Energy:

Kinetic + Potential = Total

[29.1]

$$\frac{1}{2}mv^2 - \frac{GM_r m}{r} = -\frac{1}{2}mkc^2\varpi^2$$

$$\frac{1}{2}mv^2 - \frac{G\frac{4}{3}\pi r^3\rho m}{r} = -\frac{1}{2}mkc^2\varpi^2$$

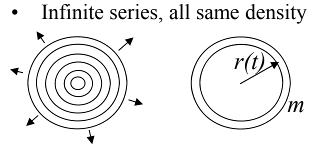
$$\frac{1}{2}m\left(\frac{dR}{dt}\varpi\right)^2 - \frac{4}{3}\pi G\rho m(R\varpi)^2 = -\frac{1}{2}mkc^2\varpi^2$$

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

[29.10]

Friedman eq'n:

- Nested, expanding shells
  - Infinite series, all same density *ρ(t)*



  - Follow single shell, mass *m*

[29.3]

- **r(t) = (Scale factor) x (co-moving coordinate)**

$$r(t) = R(t)\varpi$$

$$\frac{dr(t)}{dt} = v(t) = \frac{dR(t)}{dt}\varpi$$

- **Define: Total Energy** $= -\frac{1}{2}mkc^2\varpi^2$

Why???

Cosmological principle ➔

For bound universe, each nested shell must simultaneously have KE➔0

$$E = -\frac{4}{3}\pi G\rho m R^2\varpi^2 \propto m\varpi^2$$

Other forms of the Friedman Equation:

Kinetic + Potential = Total

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$ [29.10]

$$\left(\frac{dR}{dt}\right)^2 - \frac{8\pi G\rho_o}{3R} = -kc^2$$ [29.11]

$$\left(H^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$ [29.9]

- Define: $R(t_o) = 1$
- Conservation of mass:

$R^3(t)\rho(t) = R^3(t_o)\rho(t_o) = \rho_o$ [29.5]

- Hubble's law: [29.7]

$v(t) = H(t)\, r(t)$

But also: $r(t) = R(t)\, \varpi$

$$v(t) = \frac{dR(t)}{dt}\varpi$$

$$H(t) = \frac{v(t)}{r(t)} = \frac{\frac{dR(t)}{dt}\varpi}{R(t)\varpi} = \frac{1}{R}\frac{dR(t)}{dt}$$ [29.8]

The Critical Density

Kinetic + Potential = Total

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$ [29.10]

$$\left(\frac{dR}{dt}\right)^2 - \frac{8\pi G\rho_o}{3R} = -kc^2$$ [29.11]

$$\left(H^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$ [29.9]

$$E = -\frac{1}{2}mkc^2\varpi^2$$

$$\text{Energy per unit mass} = -\frac{1}{2}kc^2\varpi^2$$

$k > 0$ ➔ negative E, shells will collapse back
$k = 0$ ➔ E = 0, each shell has exactly escape velocity.
$k < 0$ ➔ positive E, shells expand forever

Critical density

$k = 0$ ➔ $H^2 = \frac{8}{3}\pi G\rho_c$

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$ [29.15]

$\rho_{c,o} = 1.88 \times 10^{-26}\, h^2$ kg m^{-3} [27.15]

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} \qquad \boxed{\Omega_o = \frac{\rho_o}{\rho_{c,o}}}$$ [29.18] [29.19]

The Critical Density

Kinetic + Potential = Total

[29.10]

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

[29.11]

$$\left(\frac{dR}{dt}\right)^2 - \frac{8\pi G\rho_o}{3R} = -kc^2$$

For k=0:

$$\left(\frac{dR}{dt}\right)^2 = \frac{8\pi G\rho_{c,0}}{3R}$$

$$\int_0^R \sqrt{R'}\, dR' = \sqrt{\frac{8\pi G\rho_{c,0}}{3}} \int_0^t dt'$$

$$R = \left(\frac{3}{2}\right)^{\frac{2}{3}} \left[\sqrt{\frac{8\pi G\rho_{c,0}}{3}}\, t\right]^{\frac{2}{3}}$$

$$= \left(\frac{3}{2}\right)^{2/3} \left(\frac{t}{t_H}\right)^{2/3}$$

$$E = -\frac{1}{2} mkc^2\varpi^2$$

Energy per unit mass $= -\frac{1}{2}kc^2\varpi^2$

$k > 0$ ➔ negative E, shells will collapse back
$k = 0$ ➔ E = 0, each shell has exactly escape velocity.
$k < 0$ ➔ positive E, shells expand forever

Critical density

$$\frac{8\pi G\rho_{c,0}}{3} = H_o^2 = \frac{1}{t_H^2}$$

$k = 0$ ➔ $H^2 = \frac{8}{3}\pi G\rho$

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$ [29.15]

$\rho_{c,o} = 1.88 \times 10^{-26}\, h^2$ kg m^{-3} [27.15]

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} \qquad \Omega_o = \frac{\rho_o}{\rho_{c,o}}$$ [29.18] [29.19]

Homework: [CO 29.7]
= max size + lifetime of closed U.
Due Oct. 18

The Critical Density

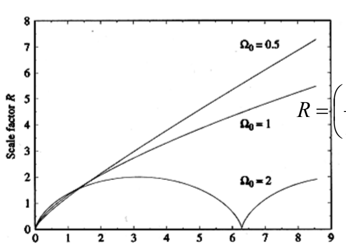
Kinetic + Potential = Total

[29.10]

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

[29.11]

$$\left(\frac{dR}{dt}\right)^2 - \frac{8\pi G\rho_o}{3R} = -kc^2$$



$$R = \left(\frac{3}{2}\right)^{\frac{2}{3}} \left(\frac{t}{t_H}\right)^{\frac{2}{3}}$$

[Fig. 29.5]

For Ω≠1, see parametric solutions in CO [29.32-29.39]

$$E = -\frac{1}{2} mkc^2\varpi^2$$

Energy per unit mass $= -\frac{1}{2}kc^2\varpi^2$

$k > 0$ ➔ negative E, shells will collapse back
$k = 0$ ➔ E = 0, each shell has exactly escape velocity.
$k < 0$ ➔ positive E, shells expand forever

Critical density

$$\frac{8\pi G\rho_{c,0}}{3} = H_o^2 = \frac{1}{t_H^2}$$

$k = 0$ ➔ $H^2 = \frac{8}{3}\pi G\rho$

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$ [29.15]

$\rho_{c,o} = 1.88 \times 10^{-26}\, h^2$ kg m^{-3} [27.15]

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} \qquad \Omega_o = \frac{\rho_o}{\rho_{c,o}}$$ [29.18] [29.19]

All Universes ~ “flat” ($\rho \sim \rho_c$) at early times.

- Homework problem 29.9 will show:

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} = 1 + \frac{kc^2}{(dR/dt)^2} \qquad (29.194)$$

Homework:
[CO 29.9]
Due Oct. 18

and that $dR/dt \rightarrow \infty$ as $t \rightarrow 0$

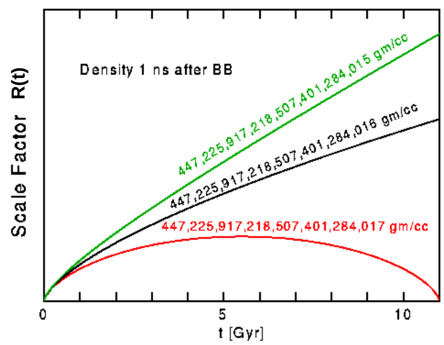
implying $\rho(t) \rightarrow \rho_c(t)$ as $t \rightarrow 0$ for all values of k.

Consequences:

1. For small t, it is OK to use:

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = 0$$

2. Even tiny departures from flatness ($\rho = \rho_c$) at small t would have grown into impossibly large departures from flatness by present time.



Including Pressure

[pp. 1160-1161]

- For a fluid undergoing *adiabatic* expansion (no transfer of heat):

Homework:
[CO 29.12]
= derive acceleration eqn.
Due Oct. 18

Work done is $dU = -PdV$

$$\frac{dU}{dt} = -\frac{4}{3}\pi P \frac{d(r^3)}{dt}$$

$$u = \frac{U}{\frac{4}{3}\pi r^3} \quad \Rightarrow \quad \frac{d(r^3 u)}{dt} = -P\frac{d(r^3)}{dt}$$

$$\rho = \frac{u}{c^2} \quad \Rightarrow \quad \frac{d(r^3\rho)}{dt} = -\frac{P}{c^2}\frac{d(r^3)}{dt}$$

$$\frac{d(R^3\rho)}{dt} = -\frac{P}{c^2}\frac{d(R^3)}{dt}$$

Friedman Equation (Energy)

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right]R^2 = -kc^2$$

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right]R^3 = -kc^2 R$$

Time derivative + algebra

Acceleration Equation (Force): $\dfrac{d^2R}{dt^2} = -\dfrac{4}{3}\pi G\left(\rho + \dfrac{3P}{c^2}\right)R$