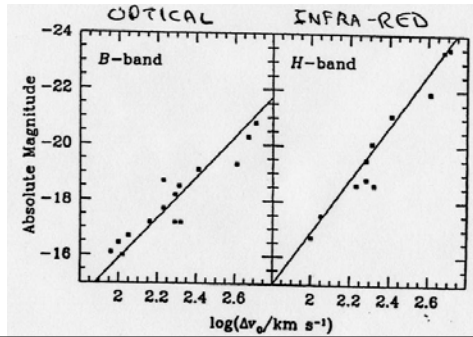
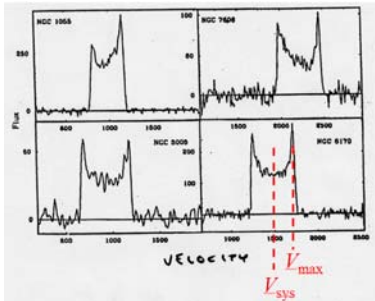


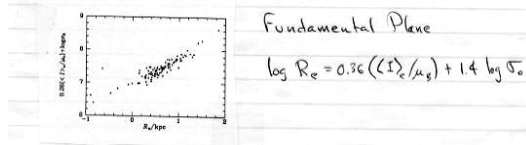
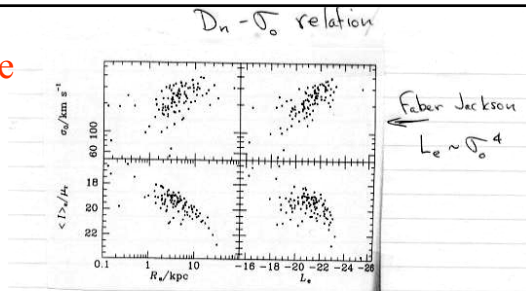
Tully-Fisher relation

- virial theorem: $v^2 \sim GM/r$
- assume $L \propto M \implies L-v$ correlation expected
- for spiral galaxies, $L - v$ correlation easily measured using H I 21cm profiles, optical/IR photometry.
- must apply $\sin i$ correction
- infrared Tully-Fisher: IR measurements minimize scatter due to absorption \implies tighter correlation



E galaxy fundamental plane

- another $L-v$ correlation due to $M-L$ correlation.
- Faber-Jackson relation is first approximation
- fundamental plane gives best precision, but $D_n - \sigma_0$ is used more often.
- $\sigma_0 \rightarrow D_n$
- angular size = D_n /distance
- 15% scatter in resulting distance to any one galaxy.

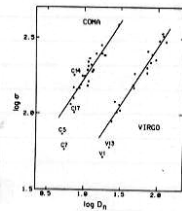


$$\log R_e = 0.36 (\langle I_e \rangle / \mu_g) + 1.4 \log \sigma_0$$

DEFINE
 D_n = diameter containing mean surface brightness
 $I_n = 20.75 \mu_g$

FUNDAMENTAL PLANE
 $\implies D_n = 2.05 \left(\frac{\sigma_0}{\text{km s}^{-1}} \right)^{1.23}$

Linear Size - σ_0 relation \rightarrow distance



Surface brightness fluctuations

- same galaxy seen at any distance will have same surface brightness.

N = number of stars in angular area θ^2

n = number of stars per unit absolute area

$$\text{Surface brightness} = I = \left(\frac{L}{4\pi D^2}\right) N = \underbrace{\left(\frac{L}{4\pi D^2}\right)}_{\text{flux per star}} \underbrace{n (D\theta)^2}_{\text{\# stars in } \theta^2} = \frac{Ln\theta^2}{4\pi}$$

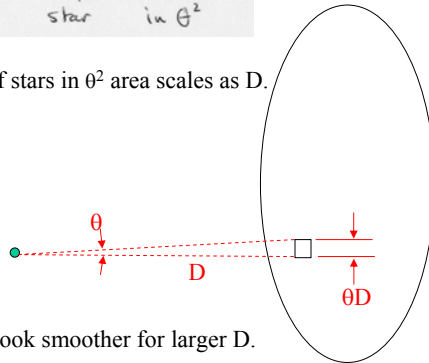
- But standard deviation of number of stars in θ^2 area scales as D .

$$N = n (D\theta)^2$$

$$\sigma_N = \sqrt{N} = \sqrt{n} D\theta$$

$$\sigma_I = \left(\frac{L}{4\pi D^2}\right) \sigma_N = \frac{L n^{1/2} \theta}{4\pi D}$$

$$\frac{\sigma_I^2}{I} = \frac{\langle L \rangle}{4\pi D^2}$$



- So surface brightness distributions look smoother for larger D .

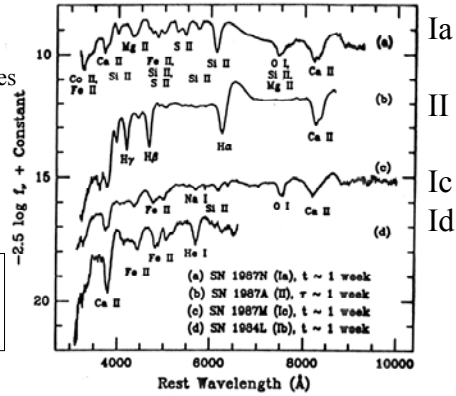
Type Ia Supernovae



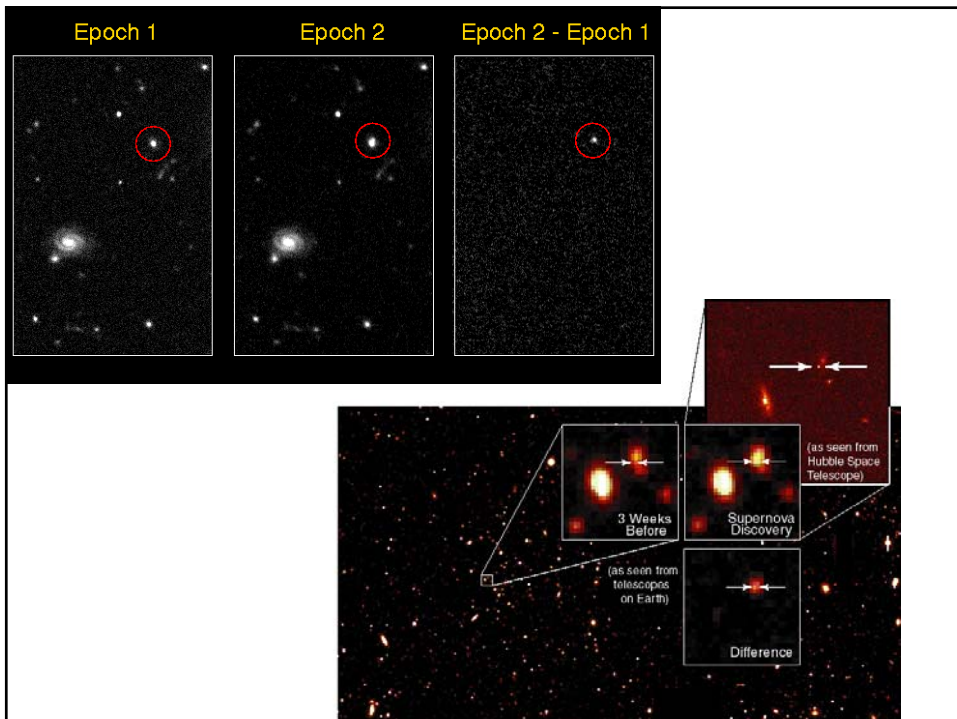
Type Ia Supernovae

- Type I - no H in spectra
 - Type Ia - strong Si, S, Ti, Ca Mg lines
 - Type Ib/c - strong He, Na, Ca
- Type II - strong H lines

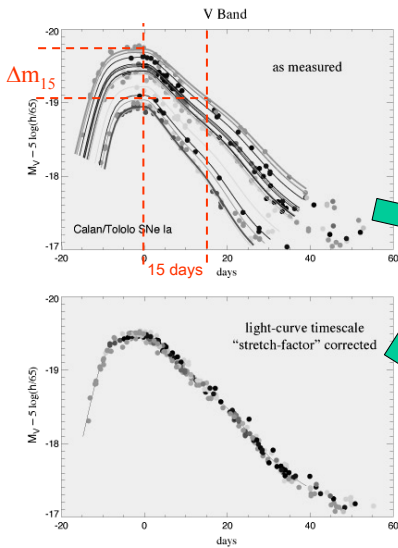
Spectra taken 1 week after maximum.



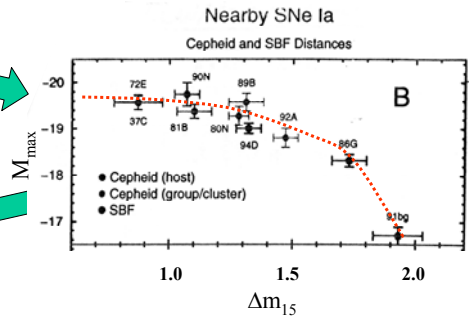
- Types II, Ib, Ic: core collapse & explosion of $M > 10M_{\odot}$ star.
- Type Ia: thermonuclear detonation of massive ($\sim 1.4M_{\odot}$) white dwarfs.
 - Great uncertainty about details.



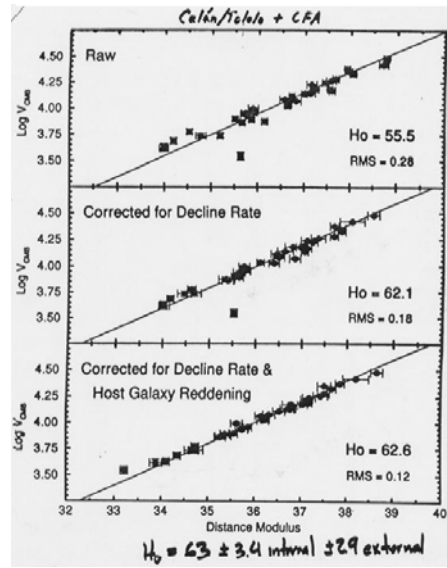
Low Redshift Type Ia Template Lightcurves

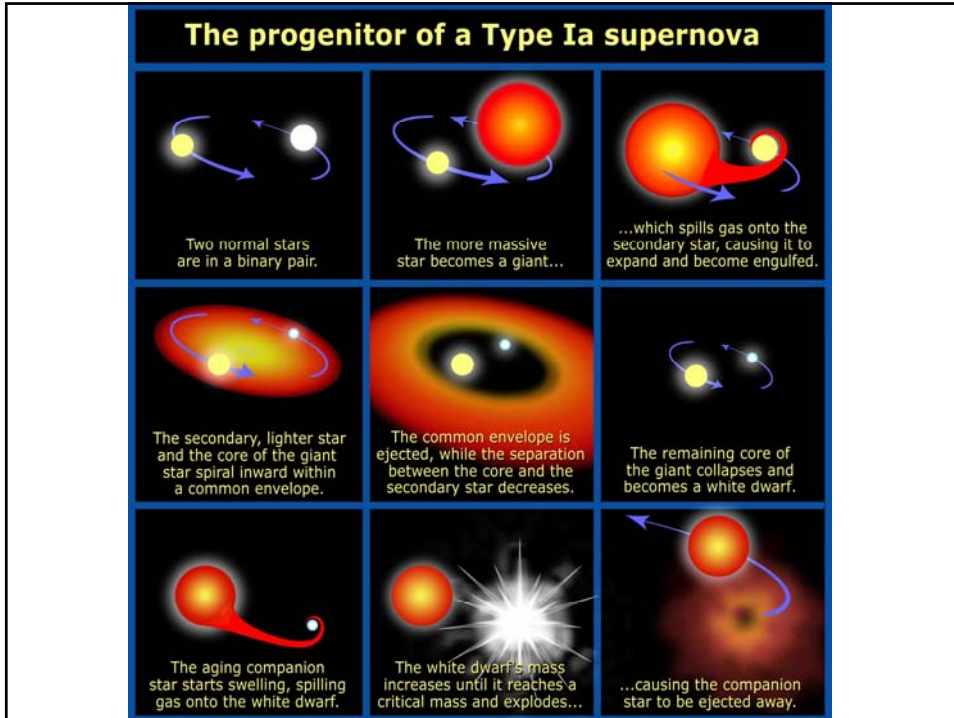


SN Ia as Standard Candles



Velocity ↑





Type Ia Supernovae

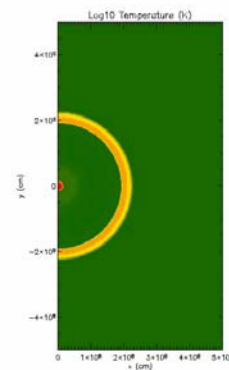
- Neighbor star dumps too much mass onto a white dwarf.
- Increased density \rightarrow runaway heating through C + C burning
 - Overwhelms $\gamma \rightarrow \nu + \bar{\nu}$ cooling
- Heating rate faster than dynamical timescale
 - White dwarf interior cannot peacefully respond to pressure increase.
- *Deflagration*
 - leading to *detonation*?



Type Ia Supernovae as “standard candles”.

- Always happens when mass goes just past limit for heating-cooling balance.
 - \rightarrow Supernova always has same luminosity.

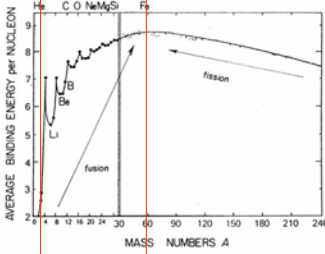
- Get distance from $\text{Flux} = \frac{L}{4\pi r^2}$



Deflagration simulation

Size = 0.000 ps
number of blocks = 1114, AMR levels = 7

SN Ia as Standard Candles

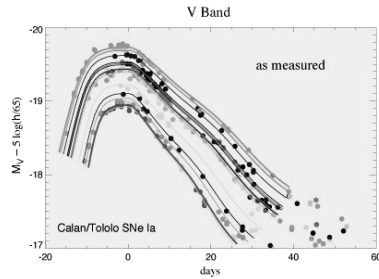
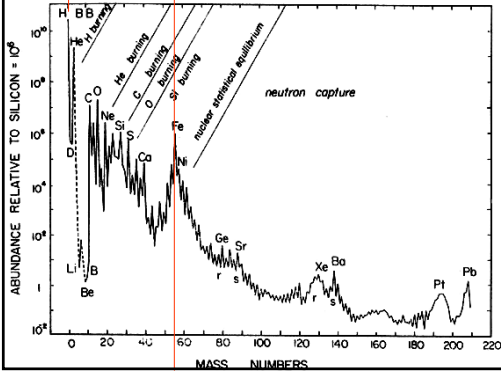


Light output powered by radioactive decay:



Amount of Ni determines both luminosity *and* opacity.

- So luminosity and fading timescale are correlated.

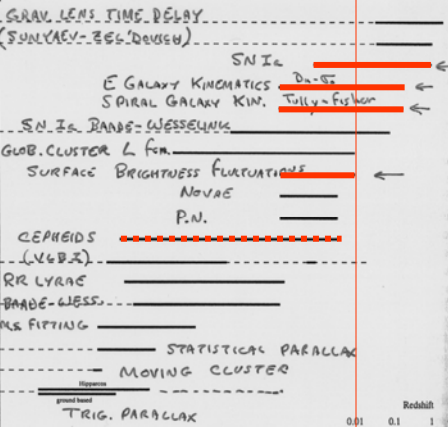


The Cosmic Distance Ladder and the HST Key Project

Distance Determination

- Gravitational lens time delay
- Suzuki-Zel'dovich
- Supernovae Ia standard candles
- Elliptical galaxy kinematics
- Spiral galaxy kinematics
- Supernovae
- Baade-Wesselink
- Globular cluster luminosity function
- Surface brightness fluctuations
- Novae as standard candles
- Planetary nebula luminosity function
- Cepheids PL and PLC relations
- VLB proper motions
- RR Lyrae stars as standard candles
- Statfit Baade-Wesselink
- Main sequence fitting
- Statistical parallax
- Moving cluster
- Trigonometric parallax

DISTANCE (PC) →



ground based

Redshift

Distance (pc)

HYADES

GALACTIC CENTER

MAGELLANIC CLOUDS

M31

LOCAL GROUP

VIRGO CLUSTER

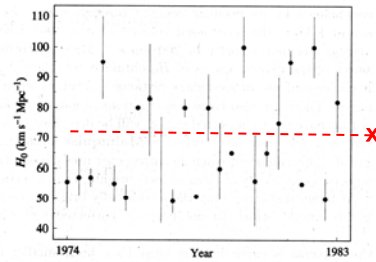
COMA CLUSTER

HUBBLE FLOW

Objects/scales

HST Key Project on Extragalactic Distance Scale

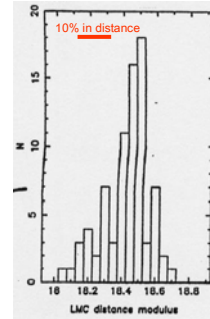
- Mould et al. 2000, ApJ 529, 786
- Measured Cepheids in 18 spirals
 - $D < 25$ Mpc, $v < 1800$ km/s
 - also used 7 more galaxies from other sources
- Distances to Cepheids relative to LMC distance
- Used these to calibrate secondary distance indicators
 - Tully-Fisher
 - Fundamental plane
 - Surface brightness fluctuations
 - Type Ia supernovae
- Secondary distance indicators ==> coverage to 10^4 km/s
- Goal is to measure H_0



$$H_0 = 71 \pm 6 \text{ km/s/Mpc}$$

TF:	71	± 4 (random)	± 4 (systematic)
FP:	78	8	10
SBF:	69	4	6
SN:	68	2	2

- Uncertainties:
 - Correction for large scale flows
 - Distance to LMC.
Taken to be 50 kpc $\pm 6.5\%$



Distribution of published LMC distance moduli