**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.
Surface brightness fluctuations

- same galaxy seen at any distance will have same surface brightness.
  \[ N = \text{number of stars in angular area } \theta^2 \]
  \[ n = \text{number of stars per unit absolute area} \]

Surface brightness \( \Sigma = \frac{1}{4\pi} \log \left( \frac{N}{\theta^2} \right) = \frac{L_n \theta^2}{4\pi} \)

- But standard deviation of number of stars in \( \theta^2 \) area scales as \( D \).

- 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

- Types II, Ib, Ic: core collapse & explosion of M > 10M☉ star.

- Type Ia: thermonuclear detonation of massive (~1.4M☉) white dwarfs.
  - Great uncertainty about details.

Spectra taken 1 week after maximum.
Type Ia Supernovae

• Neighbor star dumps too much mass onto a white dwarf.
• Increased density $\rightarrow$ runaway heating through $\text{C + C}$ burning
  • Overwhelms $\gamma \rightarrow \nu + \nu$ 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 $\text{Flux} = \frac{L}{4\pi r^2}$
SN Ia as Standard Candles

Light output powered by radioactive decay:

\[ ^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \]

Amount of Ni determines both luminosity and opacity.

- So luminosity and fading timescale are correlated.

The Cosmic Distance Ladder and the HST Key Project
HST Key Project on Extragalactic Distance Scale

- 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 $H_0$
  \[
  H_0 = 71 +/- 6 \text{ km/s/Mpc}
  \]

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- Uncertainties:
  - Correction for large scale flows
  - Distance to LMC.
  - Taken to be 50 kpc +/- 6.5%