

**ASTR 1040: Stars & Galaxies**



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 Lecture 23 Tues 7 Apr 2020  
 zeus.colorado.edu/astr1040-toomre

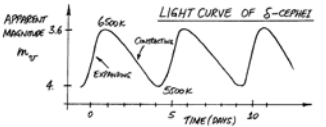
**Our wide world (universe) of Galaxies**

- The rich range of galaxies: **spiral, barred spirals, ellipticals, and irregulars**
- Hubble's scheme to **classify galaxies**
- Examine how **distance can be estimated** by overlapping methods – **major challenge**
- **Expanding universe:** Hubble's discovery #2
- Finish reading **Chap 20 "Galaxies and Foundations of Modern Cosmology"**
- Focus with care: **20.2 'Measuring Cosmic Distances' and 20.3 'Hubble's Law'**
- Mid-Term Exam 3: **Tues Apr 21 (Lect 27)**

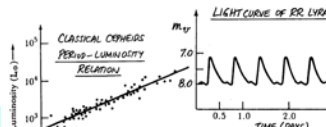
**REPEAT A STORY**

**Cepheid variable stars as distance indicators: "standard candle"**

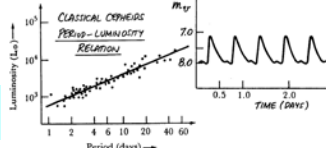
**PULSATING VARIABLE STARS**  
 STARS BECOME UNSTABLE TO LARGE-AMPLITUDE PULSATIONS AS THEY EVOLVE ACROSS "INSTABILITY STRIP"  
 AS STARS PULSATE, THEY EXPAND AND CONTRACT, CHANGING BRIGHTNESS AS THEY DO ...




**LIGHT CURVE OF 5-CEPHEID**



**LIGHT CURVE OF RR LYRAE**



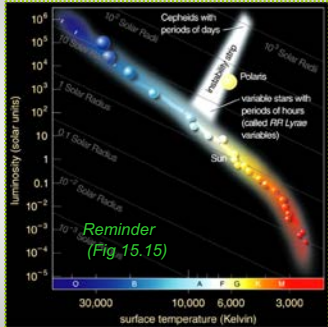
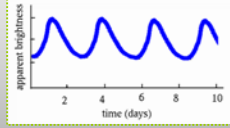
**CLASSICAL CEPHEIDS PERIOD-LUMINOSITY RELATION**



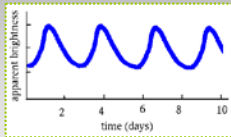
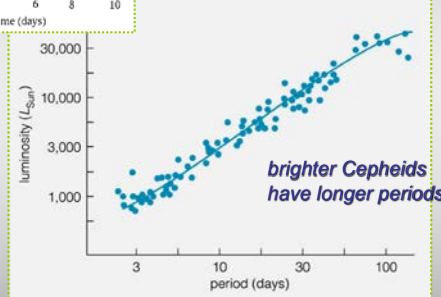
**Vital discovery by Henrietta Leavitt (1912)**

**Cepheid stars in H-R diagram**

- **"Instability strip"** -- region in H-R diagram with large, bright stars
- Outer regions of star are unstable and tend to pulsate
- **Star expands and contracts, getting brighter and fainter**

**Cepheid variable stars**





**Period - Luminosity relation**

*brighter Cepheids have longer periods*

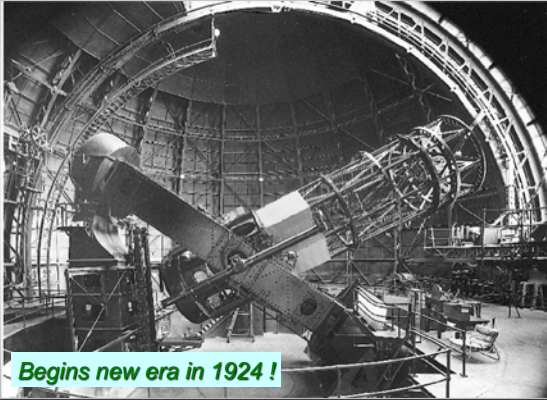
**Andromeda found to be far outside Milky Way – another "island universe": galaxy!**

- **Edwin Hubble in 1924 identified Cepheids in Andromeda (M31) → showed they were far outside of Milky Way!**
- **Now known distance: 2.54 million ly (778 kp)**
- His first big discovery (more to come) ...



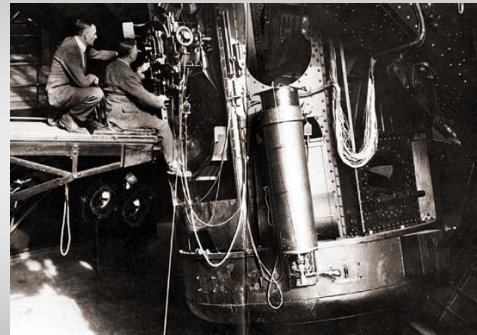
**Hubble using new 100" Hooker telescope at Mt. Wilson (above LA)**

100" Hooker telescope at Mt Wilson



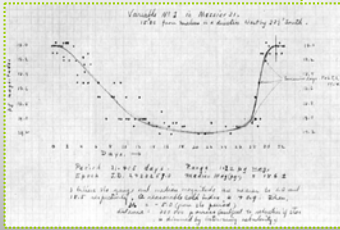
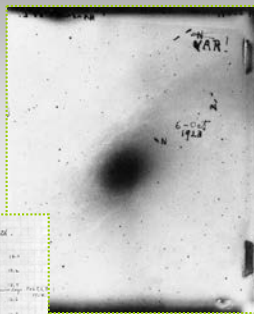
Begins new era in 1924!

Andromeda found to be far outside Milky Way – another "island universe" galaxy!



Hubble (and Jeans) at new 100" Hooker telescope on Mt. Wilson

Edwin Hubble in 1924 identified Cepheids in Andromeda (M31) → showed they were far outside of Milky Way!



Andromeda – M31 (Sb)

NGC205

M32

First galaxy shown by Hubble (1924) to be a distinct "island universe"

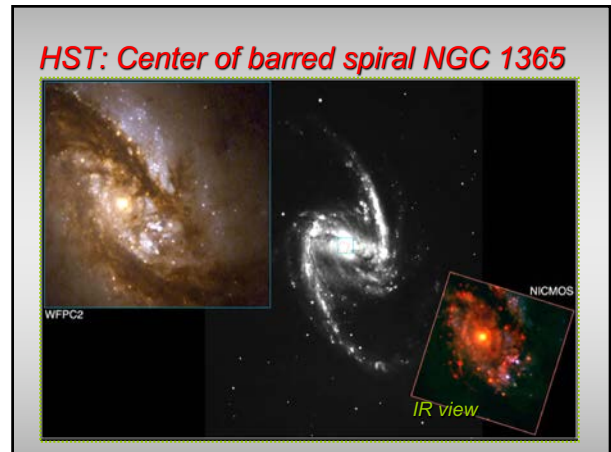
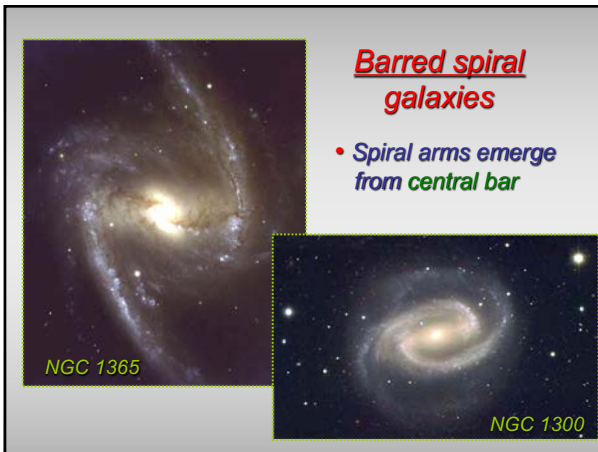
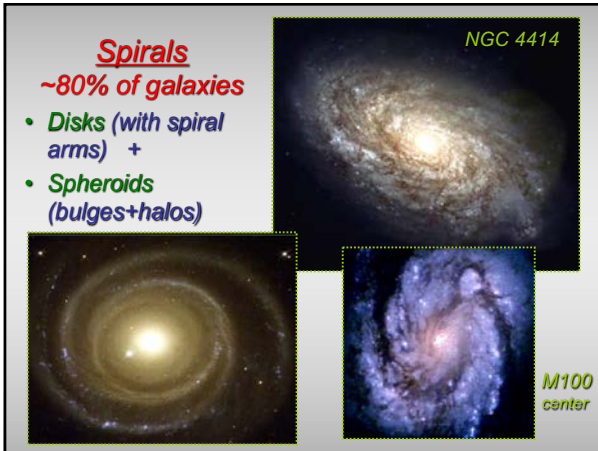
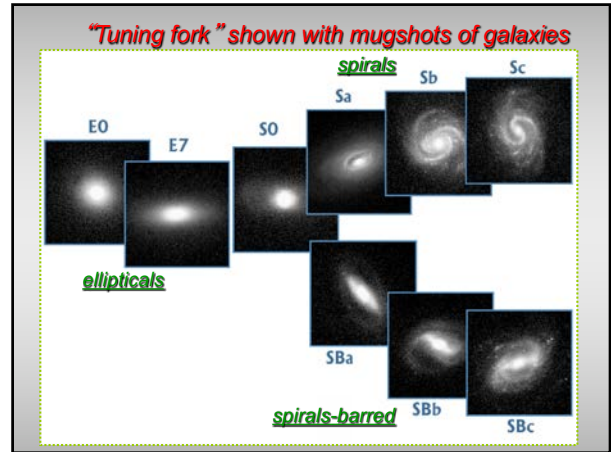
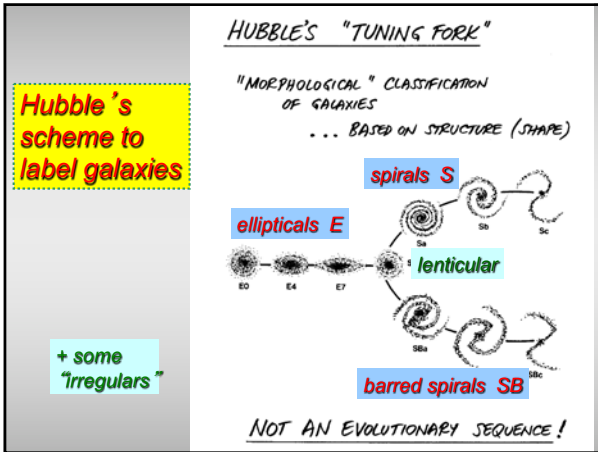
2.54 million ly away 260,000 ly in diameter

LATEST IR IMAGING



M31 from WISE + M32 (below) + M110 (NGC 205)

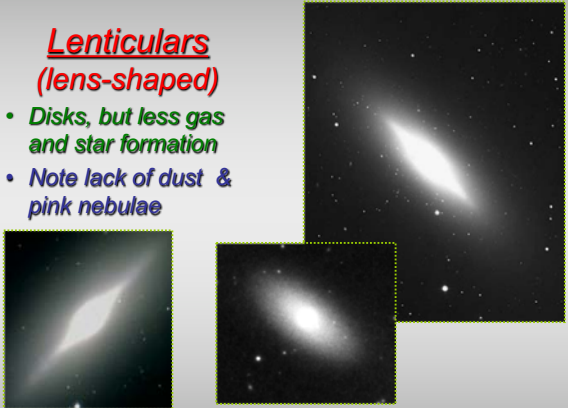
Questions or Comments






**Lenticulars**  
**(lens-shaped)**

- Disks, but less gas and star formation
- Note lack of dust & pink nebulae



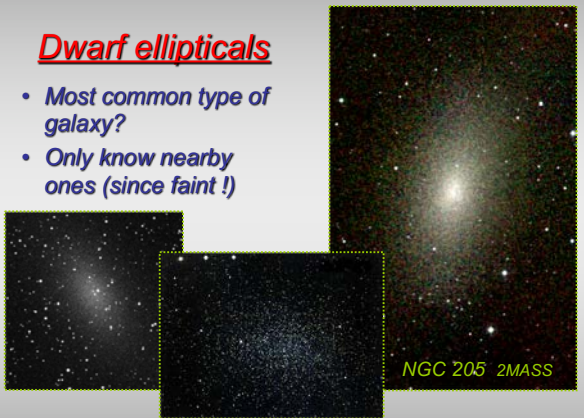
**Ellipticals**  
**~15% of galaxies**

- Round or slightly flattened
- **Very little cold gas, dust, or young stars**
- **Reddish color = old stars (red giants, red main sequence)**



**Dwarf ellipticals**


- Most common type of galaxy?
- Only know nearby ones (since faint !)



NGC 205 2MASS

**Irregulars**

- **Galaxies in transformation?**  
Often LOTS of star birth



M82  
NGC 674

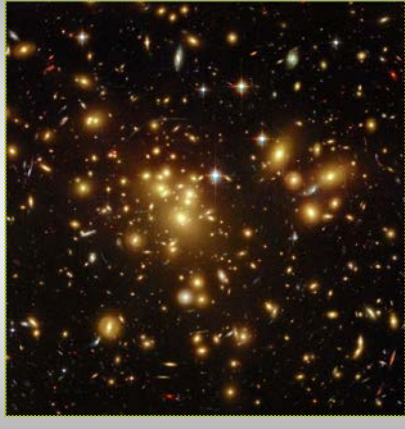
**Where do spirals and ellipticals live?**

- **Spirals** – mostly in groups (3-10 galaxies)

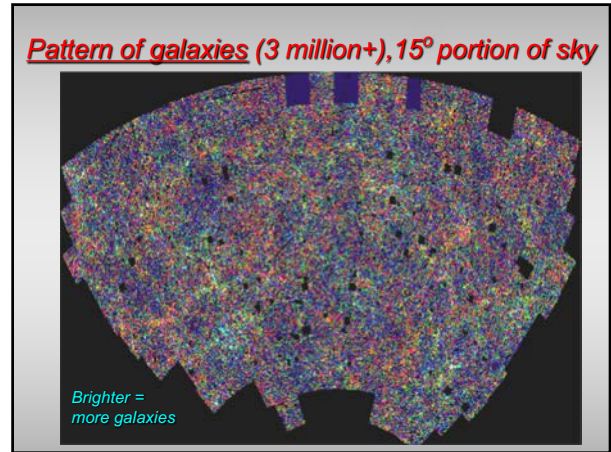
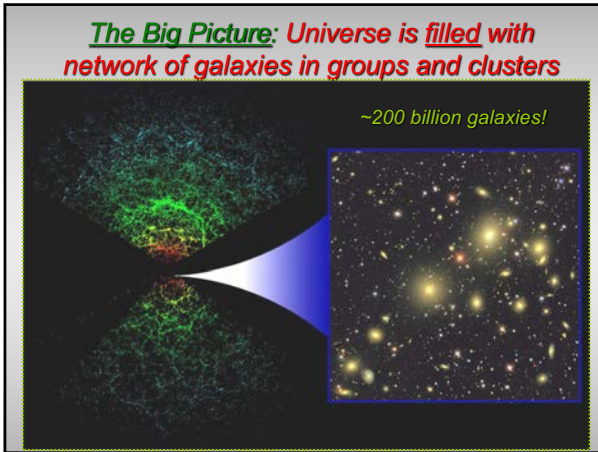


HST: Hickson CG 87

- **Ellipticals** - most often in **dense clusters of galaxies** (involve 100's to 1000's)
- Often a few massive "CD" galaxies near center



HST: Abell 1689



**Poll 1 -- Shapes of galaxies**

- How might you classify this galaxy?

- A. Sa
- B. SBb
- C. E
- D. SO

**Our "local group" of galaxies**

**3 spirals:**  
 Andromeda (M31)  
 Milky Way  
 Triangulum (M33)

**2 irregulars:**  
 LMC  
 SMC

**16+ dwarfs**

**OUR "LOCAL GROUP" OF GALAXIES**  
 ... IN OUR NEAR NEIGHBORHOOD

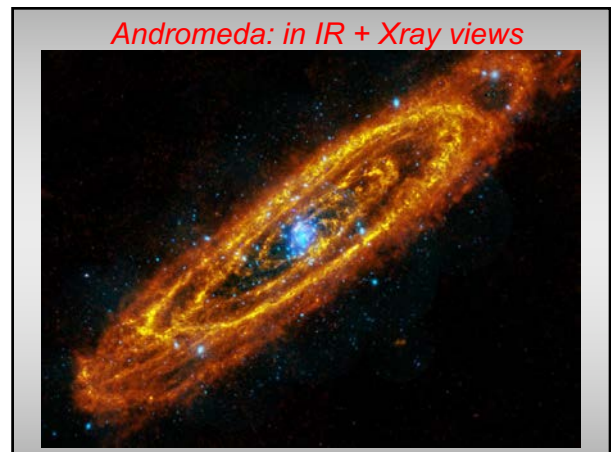
**LARGEST: 3 SPIRAL GALAXIES**  
 ANDROMEDA M31 S1 1/2 M<sub>SOL</sub>  
 OUR GALAXY (MILKYWAY) SB 1 \*  
 TRIANGULUM M33 SC 1/5 \*

**2 IRREGULAR GALAXIES**  
 LARGE MAGELLANIC CLOUD (LMC) 1/8 \*  
 SMALL " " (SMC) 1/50 \*

**10 DWARF ELLIPTICAL GALAXIES**  
**2 DWARF IRREGULAR GALAXIES**  
**4 SMALL ELLIPTICALS** ~ 21 GALAXIES


**Biggest is Andromeda (Sb - M31)**

- Andromeda is ~2.5 million light years away (780 kpc) (or ~35 MW diameters), has ~1.5 mass of MW
- We see her as "she" was 2.54 million years ago, not as she is today! - this is lookback time
- Oops! she may crash into MW in about 2+ billion years




**Triangulum (M33)**

- 1/5 mass of MW, spiral classified as Sc
- Several bright (pink) star forming regions



**Large & Small Magellanic Clouds**



LMC

SMC



LMC has 30 Doradus, home of SN 1987A

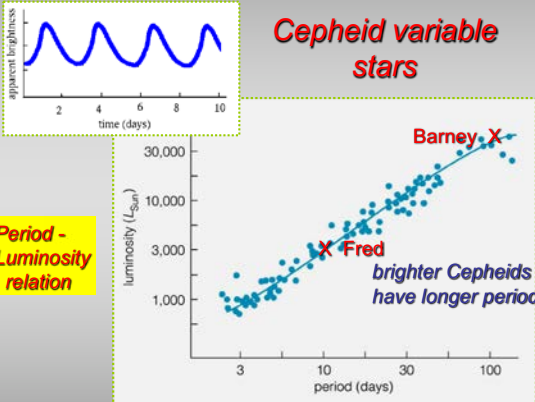
**Questions or Comments**

**Poll 3: Cepheids**

Two Cepheid stars, Fred and Barney, have the same apparent brightness. Fred has a period of 10 days, and Barney of 100 days. Which is closer?

- Fred
- Barney
- They are both the same distance
- Not enough information to tell

**Cepheid variable stars**



apparent brightness

time (days)

luminosity ( $L_{sun}$ )

period (days)

Barney X

Fred X

brighter Cepheids have longer periods

Period - Luminosity relation



**Hubble: next showed universe appeared to be expanding!**

- **Vesto Slipher (1912)** reported that most galaxies showed Doppler redshifts
- **Edwin Hubble**, using new 100" telescope, started busily measuring galaxy redshifts
- **Hubble (1929)** announced that redshifts of galaxies appear to increase with distance from us
- This was startling: suggests an **EXPANDING UNIVERSE!**

**Hubble and recession of galaxies: measured many redshifts**

Further away, greater redshift!

Hubble guessed their distances by size and brightness – underestimated by factor 10!

**HUBBLE'S DISCOVERY OF RECESSION OF GALAXIES**

**HUBBLE'S LAW:**  
 DOPPLER VELOCITY (RECESSION) = HUBBLE CONSTANT x DISTANCE

**Hubble showed universe appears to be expanding!**

**Hubble's Law:  $v = H_0 d$**

Velocity of Recession (Doppler Shift) (km/sec) = Hubble's Constant (km/sec/Mpc) x Distance (Mpc)

Hubble's (1929) original:

Scatter here from random velocities of nearby galaxies, unreliable distance estimates

**Poll 3 Hubble Constant**

**From Hubble's original plot, what is the Hubble Constant?**

Velocity (km/s)

Distance (parsecs)

A. 100 km/s  
 B. 500 km/s  
 C. 500 km/s/Mpc  
 D. 1000 km/s  
 E. 1000 km/s/Mpc

**Best current values for expansion**

$H_0 = 71 \pm 4$  km/s/Mpc

**"HUBBLE CONSTANT"**

Hubble (1929) plot extended only to 2 Mpc,  $H_0$  was ~500!

**UNIVERSE EXPANDS ON THE LARGE SCALE**

**LIKE EXPANDING RAISIN BREAD!**

**THIS COULD EXPLAIN HUBBLE'S VELOCITY-DISTANCE LAW**

... CLUSTERS OF GALAXIES APPEAR TO BE MOVING AWAY FROM ALL OTHERS! (TRUE ON AVERAGE)

**Balloon analogy for expanding universe**

- On an expanding balloon, no galaxy is at the "center" of expansion; no edge
- Expansion happens into a higher dimension (2-D surface into a 3-D space)
- Is our 3-D space expanding through a 4<sup>th</sup> dimension?

Questions or Comments

**Mapping the universe: need distances to galaxies!**

- Identify (and calibrate) properties of galaxies that could serve as "STANDARD CANDLES" -- beyond direct measure by trigonometric parallax
- 1. Make some measure of an object which identifies its luminosity (like period in Cepheid)
- 2. Use this luminosity and measure apparent brightness to infer distance to it

**DISTANCE ESTIMATE 1**

**Main-Sequence Fitting**

- Start with cluster A (upper) whose distance known via parallax
- Compare with other cluster B (lower)
- Get distance to B from brightness difference

Distances up to ~200,000 light years

**Main Sequence Fitting often compared to nearby Hyades Cluster (M45)**

Only 151 ly away

Close enough to get distance estimate through parallax

**DISTANCE ESTIMATE 2**

**Cepheid variable stars**

**Period - Luminosity relation**

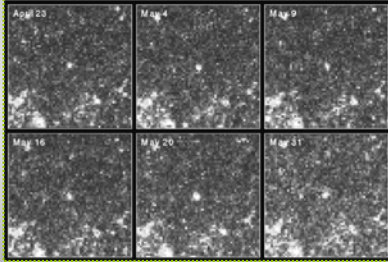
brighter Cepheids have longer periods



**DISTANCE ESTIMATE 2**

**Cepheids variables as standard candles**

1. Measure period of variability
2. From period-luminosity relation, infer the luminosity
3. Compare with apparent brightness and thus determine distance

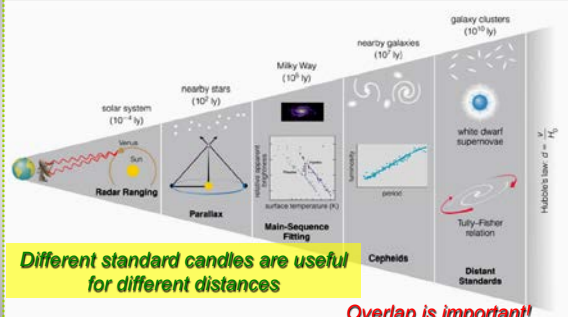


Cepheid variable in M100 (HST)

**Number of Fuzzier Distance Estimators**

- **A.** Apparent brightness of (resolved) **red and blue supergiants**
- **B.** Size and brightness of **H II regions** (emission nebulae) or **starbirth regions**
- **C.** **Intercompare** distances so deduced for specific galaxies (overlapping rungs in 'distance ladder' or 'chain')

**Distance ladder to measure universe**



Different standard candles are useful for different distances

Overlap is important!

**"Distance ladder"**

**Overlapping "standard candles"**

ABSOLUTE MAGNITUDE $M$	BRIGHTEST OBJECT/METHOD	CAUSE TO "BRIDGE"	MEASURING DISTANCE
-6	MAIN SEQ FITTING	200,000 ly	
-6	ANDROMEDA (M31) 3MG 14MG	CEPHEID VARIABLE (TRIAS)	20 MEG (TRIAS) 6 Mpc
-8	VEGA CLUSTER 4MG 15MG	RED SUPERGIANT	100 MEG (MAGELLAN) 30 Mpc
-8		RED SUPERGIANT	50 MEG 15 Mpc
-9		BLUE STG	80 MEG 25 Mpc
----- NO INDIVIDUAL CANDLES -----			
-10	GIORGIO CLUSTERS	130 MEG	40 Mpc
-12	H II REGIONS	300 MEG	95 Mpc
-20	SUPERNOVA EXPLOSION	10 BLG	3 Bpc
	TULLY-FISHER RELATION		

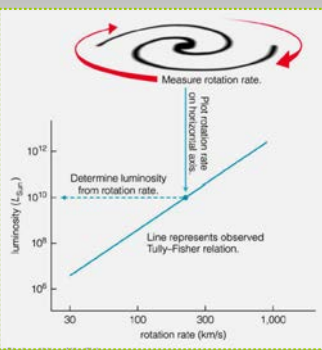
**DISTANCE ESTIMATE 3**

**Tully-Fisher Relation**

- Fast rotation speeds in spiral galaxies
- → more mass in galaxy
- → higher luminosity

Measure rotation speeds to infer luminosity


Need bright "edge-on" spirals, estimate tilt



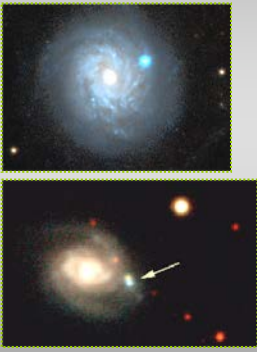
**DISTANCE ESTIMATE 4**

**Even brighter: White dwarf supernovae**

- "Standard explosion" = fusion of 1.4 solar masses of material
- Nearly the same amount of energy released

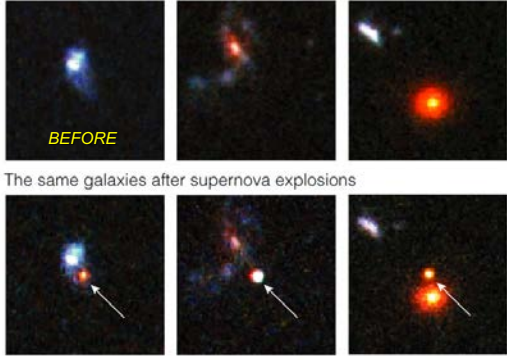


**Bright enough to be seen halfway across observable universe**



**Useful for mapping the universe to the largest distances**

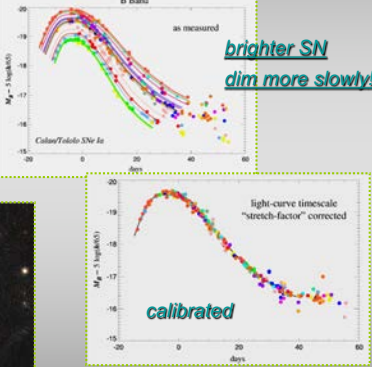
**Supernovae in very distant galaxies**



The same galaxies after supernova explosions

**White dwarf supernovae** DISTANCE ESTIMATE 4


- **Carbon fusion explosion:** mass transfer in binary takes white dwarf 'over the edge'
- **Roughly same amount of energy released (calibrate)**



*brighter SN dim more slowly!*

*light-curve timescale "stretch-factor" corrected*

*calibrated*



**Measuring big distances to galaxies**

**"STANDARD CANDLES" -- important ones in 'distance ladder'**

- 0. Parallax
- 1. Main-sequence fitting
- 2. Cepheid variables
- 3. Tully-Fisher relation
- 4. White dwarf supernovae

**Brightness ~ Luminosity / (Distance)<sup>2</sup>**