Lezione Fermi 14

Luciano Maiani, AA 14-15

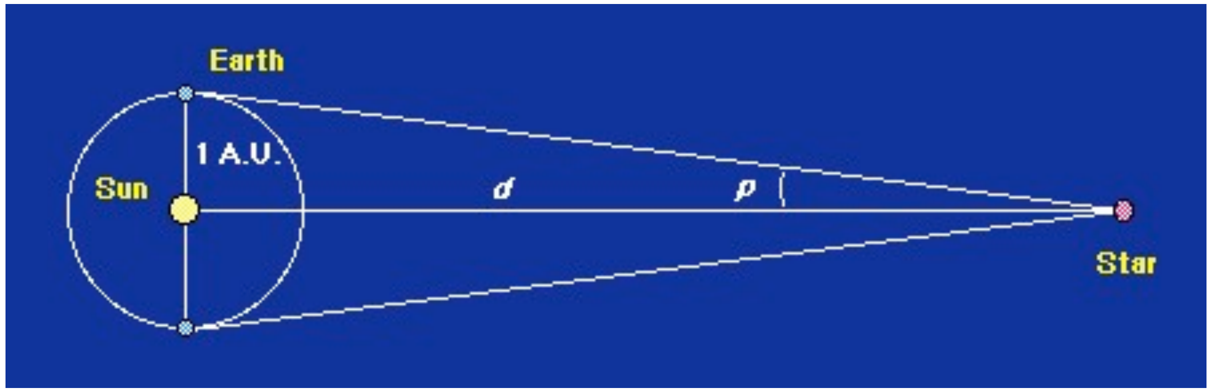
La Scala delle Distanze Cosmiche

Sommario

1. Parallasse stellare
2. Stelle variabili
3. Parallasse spettroscopica
4. La Relazione di Tully e Fisher
5. Maser galattici
6. Supernovae Ia
7. Vista d'insieme
8. Le dimensioni delle cose nel Cosmo
9. Determinazioni recenti della Costante di Hubble

1. Parallasse Stellare

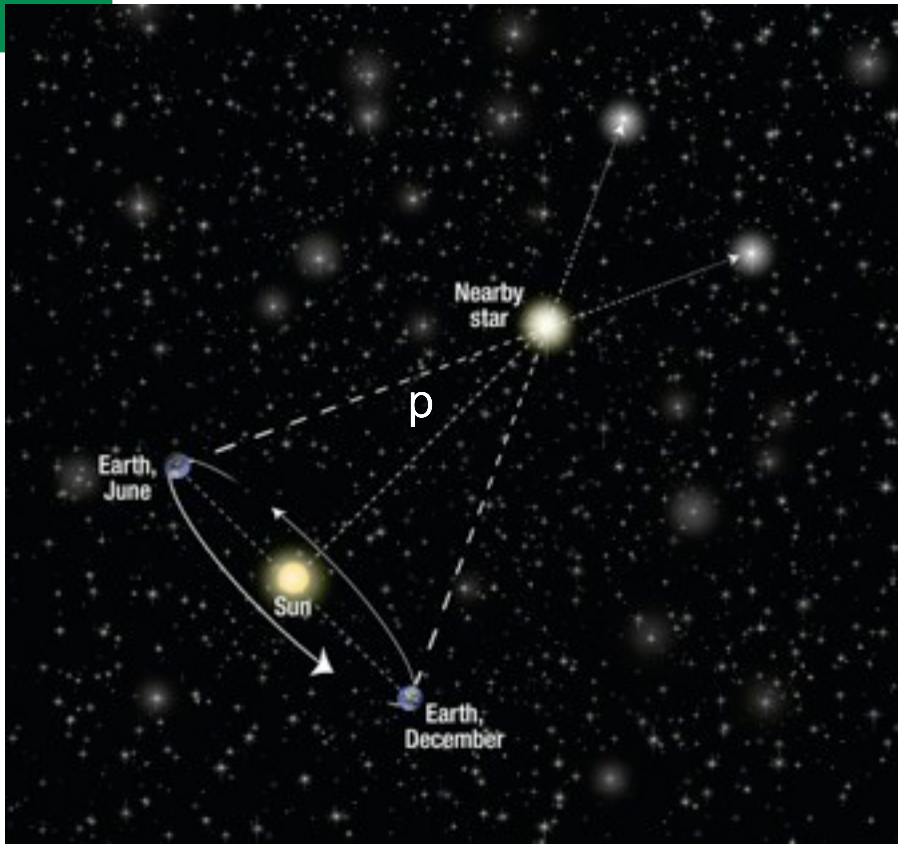
- La luce proveniente da un astro a distanza finita vista da due punti di osservazione diversi, ci appare provenire da direzioni diverse. La "parallasse", p, e' la differenza degli angoli sotto cui vediamo l'astro, divisa per due.



- L'ipotesi e' che la luce viaggi in linea retta, un'ipotesi che gli astronomi greci usarono per determinare il raggio della Terra (Eratostene) e il rapporto tra le distanze Terra-Sole e Terra-Luna (Aristarco).
- Il metodo risente di numerosi errori. Sulla Terra, prima di tutto, le differenze di temperatura e gli effetti di turbolenza dell'atmosfera, che influenzano la traiettoria dei raggi luminosi
- inoltre, se l'astro e' lontano, p e' sempre piu' piccolo e occorrono metodi moto precisi per osservarlo.
- Gli astronomi greci non riuscirono a rilevare differenze tra la direzione delle stelle nel corso dell'anno, anche noi le chiamiamo "stelle fisse", e conclusero che la Terra e' ferma al centro dell'Universo (non tutti).
- In tempi moderni, dalla Terra si apprezzano parallassi di 0.01 secondi d'arco, che limita la misura con un 10% di errore alle stelle distanti qualche parsec
- I telescopi orbitanti hanno rivoluzionato il campo e aumentato la portata del metodo di diversi ordini di grandezza.

Parallasse Stellare

$$p = 1 \text{ arcsec} \rightarrow d = 1 \text{ parsec} = 3.36 \text{ light} - \text{year}$$



Hipparcos- ESA in the Laboratory

- **Limitations**

- If the stars are too far away, the parallax can be too small to measure accurately.

In general, the greater the distance, the smaller the parallax, and so the less precise the distance measurement will be. The smallest parallax measurable from the ground is about 0.01-arcsec. This means that from the ground, the method of Trigonometric Parallaxes has the following limitations.good out to 100 pc

- only get 10% distances out to a few parsecs.
- only a few hundred stars are this close

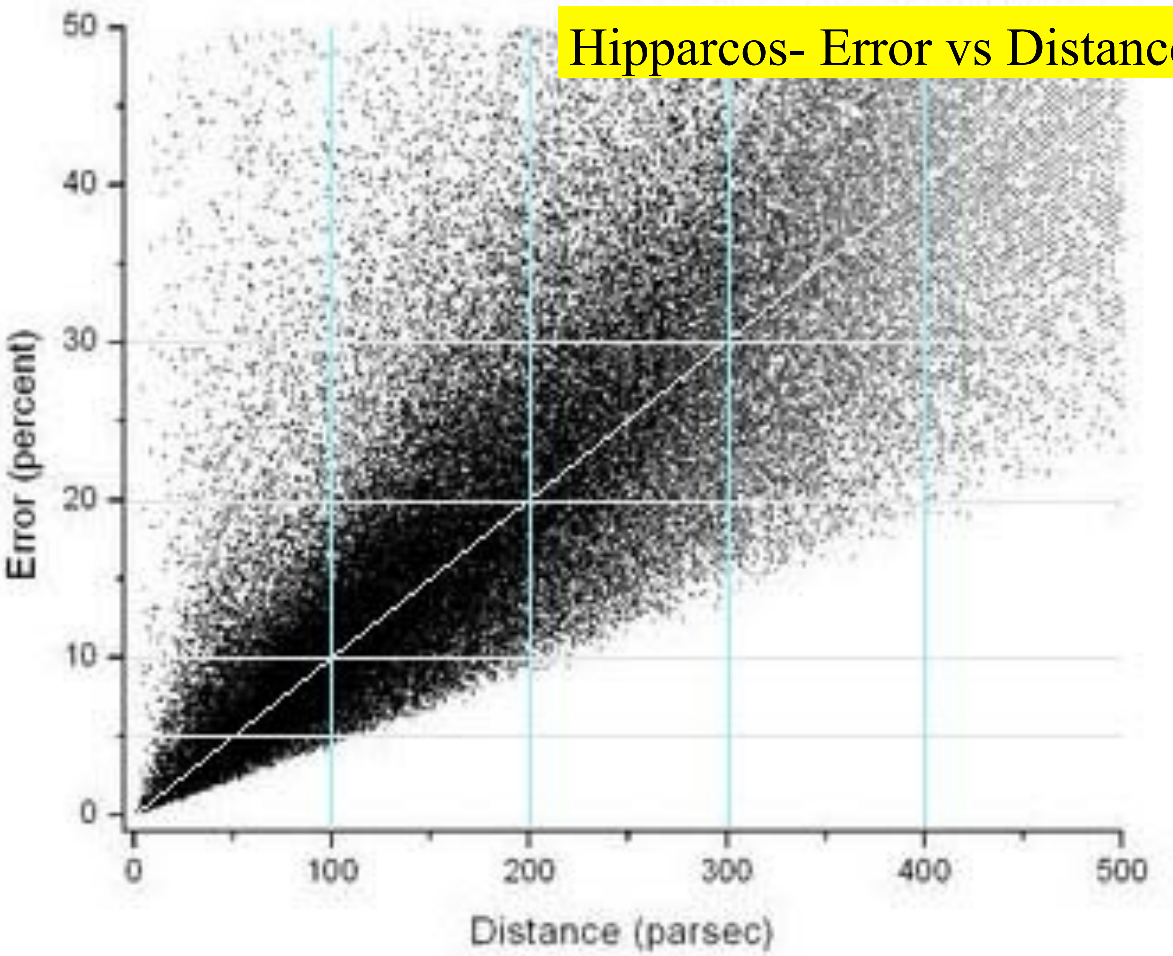
- **Hipparcos**

The Hipparcos satellite (launched by the European Space Agency in 1989) measured precision parallaxes to an accuracy of about 0.001-arcsec.

- Hipparcos measured parallaxes for about 100,000 stars
- Got 10% accuracy distances out to about 100 pc
- Good distances for bright stars out to 1000 pc.

Hipparcos represented a great leap in our knowledge of the distances (and motions) of nearby stars. The catalog was just released in late 1997, and is already having an impact on many areas of astronomy that rely in accurate distances.

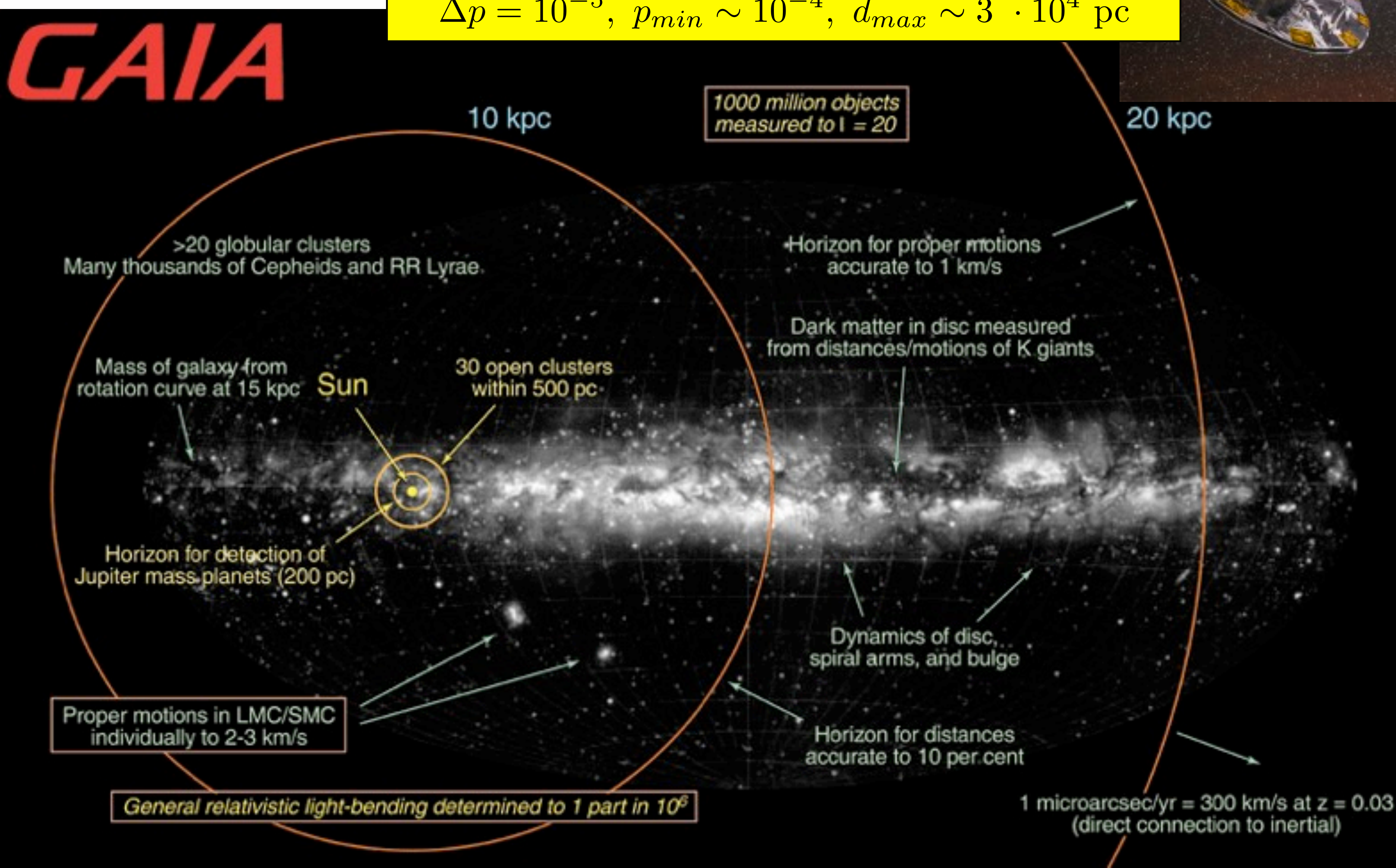
Hipparcos- Error vs Distance



Gaia is a European follow-up mission to Hipparcos that was launched on 19 December 2013, reaching its orbital station at the Earth/Sun L2 point in January 2014, and began science operations in July 2014. Its goal is to conduct what amounts to a Galactic census. Gaia is undertaking an all-sky survey of the Galaxy that build up high-precision angular measurements through repeated measurements. The final Gaia data catalog will not be completed until about 2020.Mission Goals:

- Measure positions and motions for about 1 Billion Stars
- Measure parallaxes for >200 Million Stars
- Max precision of 10 microarcseconds
- This means 10% or better distances out to 10,000pc

$$\Delta p = 10^{-5},\ p_{min} \sim 10^{-4},\ d_{max} \sim 3\ \cdot 10^{4}\ \text{pc}$$



2. Stelle variabili: le Cefeidi

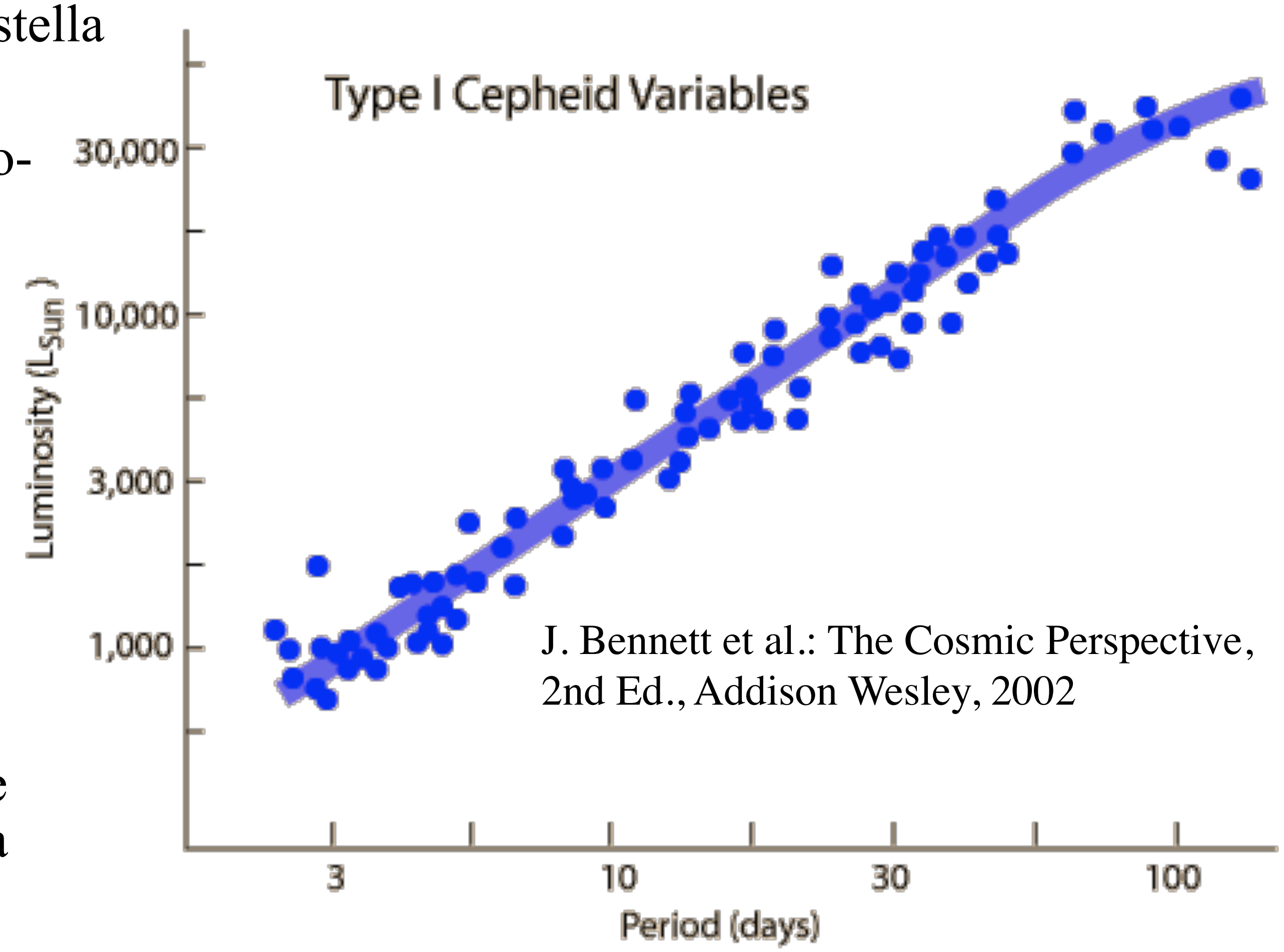
- 1784. E. Pigott scopre la variabilita' di Eta-Aquilae. Pochi mesi dopo, J. Goodricke osserva la variabilita' di Delta-Cephei, stella eponima della classe
- 1908. Henrietta Swan Leavitt stabilisce la relazione periodo-luminosita' delle Cefeidi, studiando un migliaio di stelle variabili nella Nube di Magellano

$$L_{app} = \frac{L_0}{4\pi D^2}, \; L_{abs} = \frac{L_0}{4\pi(10\ pc)^2}$$

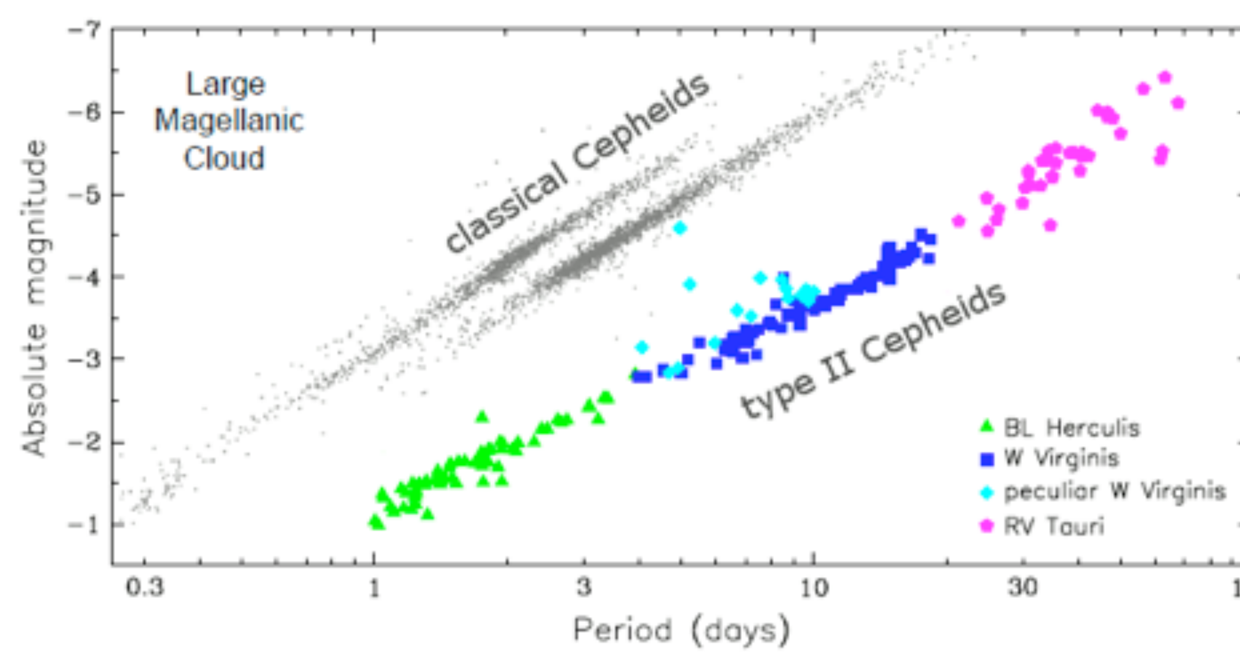
$$L_{abs} = \frac{L_{app} D^2}{(10pc)^2} \quad \text{ovvero}: \; D = 10pc\sqrt{\frac{L_{abs}}{L_{app}}}$$

- L_{abs} si ricava dal periodo, L_{app} si misura, si trova D.

- 1924. Edwin Hubble, usando le stelle cefeidi, stabilisce che la nebulosa Andromeda e' un "universo isola" distinto dalla nostra Galassia
- 1929. E. Hubble e M. Humason, usando le cefeidi come "candela standard" per misurare le distanze e l'effetto Doppler per la velocita', stabiliscono che le galassie si allontanano da noi con velocita' proporzionale alla distanza , la "legge di Hubble"
- 1940. Walter Baade scopre che ci sono due tipi di Cefeidi con relazione periodo-luminosita' diverse, tipo I e tipo II (meno luminose) e rivaluta la distanza di Andromeda di un fattore circa 4
- I due tipi si distinguono per le caratteristiche dello spettro:
  - Cepheid I: Population I, metal rich, simili al Sole
  - Cepheid II: Population II, metal poor



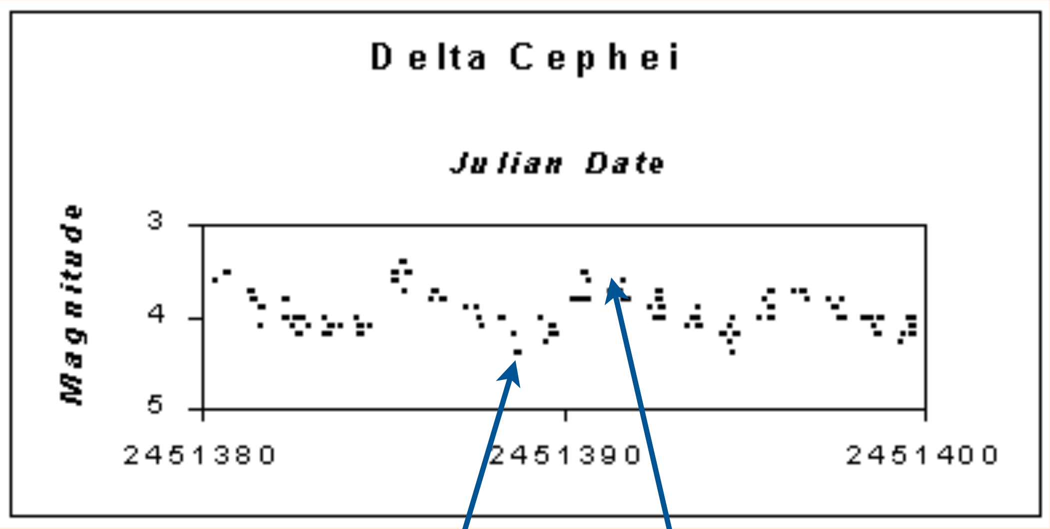
J. Bennett et al.: The Cosmic Perspective, 2nd Ed., Addison Wesley, 2002



Cefeidi: come funziona

- 1917. Eddington propone il meccanismo a valvola
- 1953. A. S. Zhevakin identifica l'Elio come il gas che agisce da valvola

- al minimo di luminosita' l'Elio degli strati esterni e' caldo e doppiamente ionizzato, He^{++}, quindi opaco: la pressione di radiazione lo spinge verso l'esterno, la luminosita' aumenta;
- espandendosi, l'Elio si raffredda e diventa ionizzato una volta, He^{+}. L'opacita' diminuisce, la pressione di radiazione e' meno efficace, il gas si comprime, la luminosita' diminuisce
- la compressione scalda il gas e aumenta la ionizzazione, quindi l'opacita': il ciclo riprende.



This composite light curve is described as being composed of almost 750 observations from 35 observers. Despite the apparent scatter, the long term reproducibility of this pattern has led to a value of 5.366 days for the period of delta Cephei. Many Cepheids have periods that are known to the second according to AAVSO.

Luminosita' al minimo, gas caldo, He^{++}

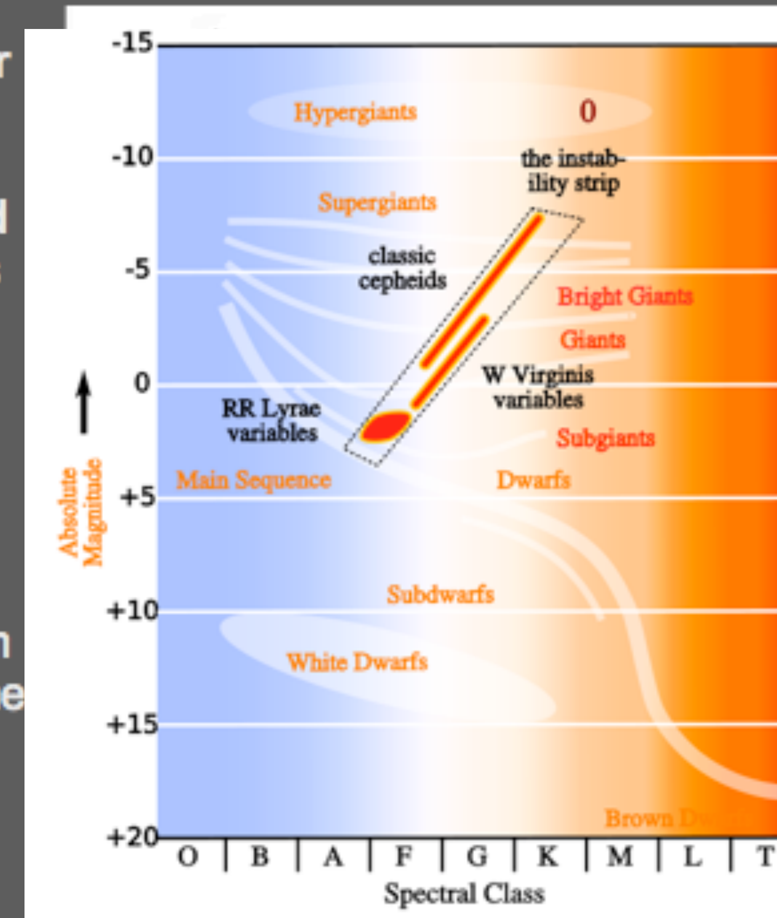
Luminosita' al massimo, gas freddo, He^{+}

Stelle variabili: RR-Lyrae

- Stelle variabili con periodo piu' corto delle Cefeidi con una relazione periodo-luminosita' definita

A short-period, yellow or white giant pulsating variable; RR Lyrae stars belong to Population II and are often found in globular clusters (hence one of their older names – **cluster variables**) or elsewhere in the galactic halo. They have periods of 0.2 to 2 days, amplitudes of 0.3 to 2 magnitudes, and spectral types of A2 to F6. Some of them have similar light curves to those of Cepheid variables (earning them the now-obsolete name of **cluster Cepheids** or **short-period Cepheids**) and, like Cepheids, obey a period-luminosity relation that enables them to serve as reliable distance indicators. RR Lyrae variables, however, are older, less massive, and fainter (with luminosities typical around 45 L_{sun}) than Cepheids.

Two subgroups are recognized: RRAB, which pulsate in the fundamental mode, and RRC, which pulsate in the first overtone. Type RRAB shows an asymmetric light curve, with a steep rise and a more gradual decline, while type RRC varies roughly sinusoidally and with an amplitude of less than 0.8 magnitude. The presence of scatter and large amplitude variations in the light curves are often the signature of double-mode pulsation and the Blazhko effect in some of these variables.

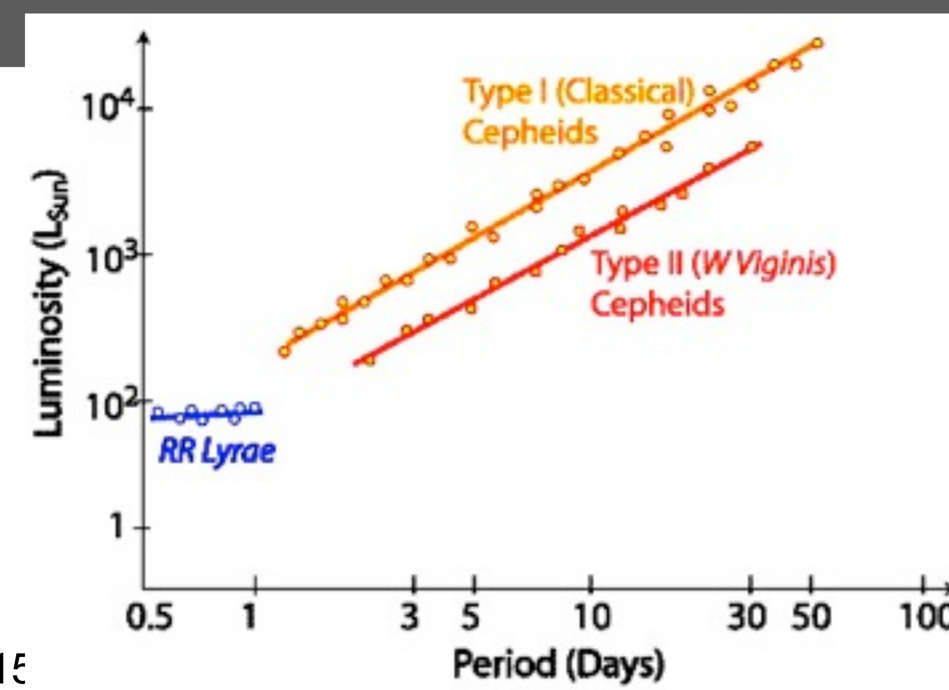


Spectral classification

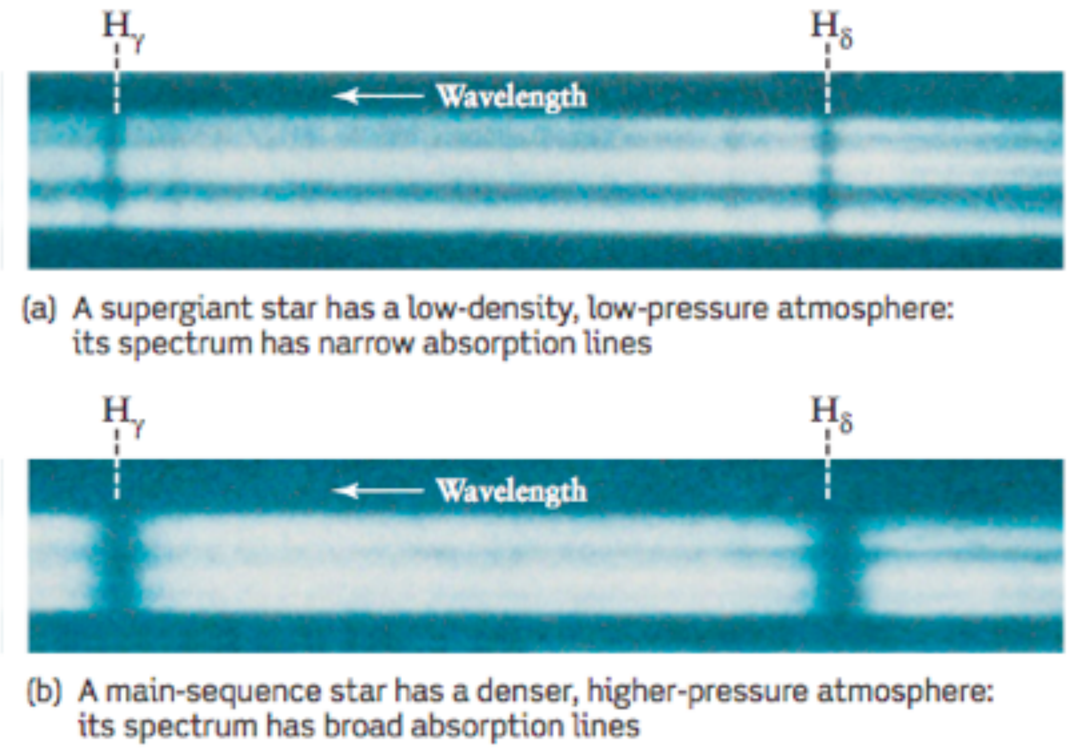
The Hubble Space Telescope has identified several RR Lyrae candidates in globular clusters of the Andromeda galaxy[5] and has measured the distance to the prototype star RR Lyrae.

Kepler space telescope provided constant coverage of a single field with accurate photometric data. In addition, RR Lyrae itself was in Kepler field of view.[6]

The Gaia mission is expected to greatly improve knowledge of RR Lyraes by providing homogeneous spectrographic information of a large population of such stars.[7]



3. Parallasse spettroscopica



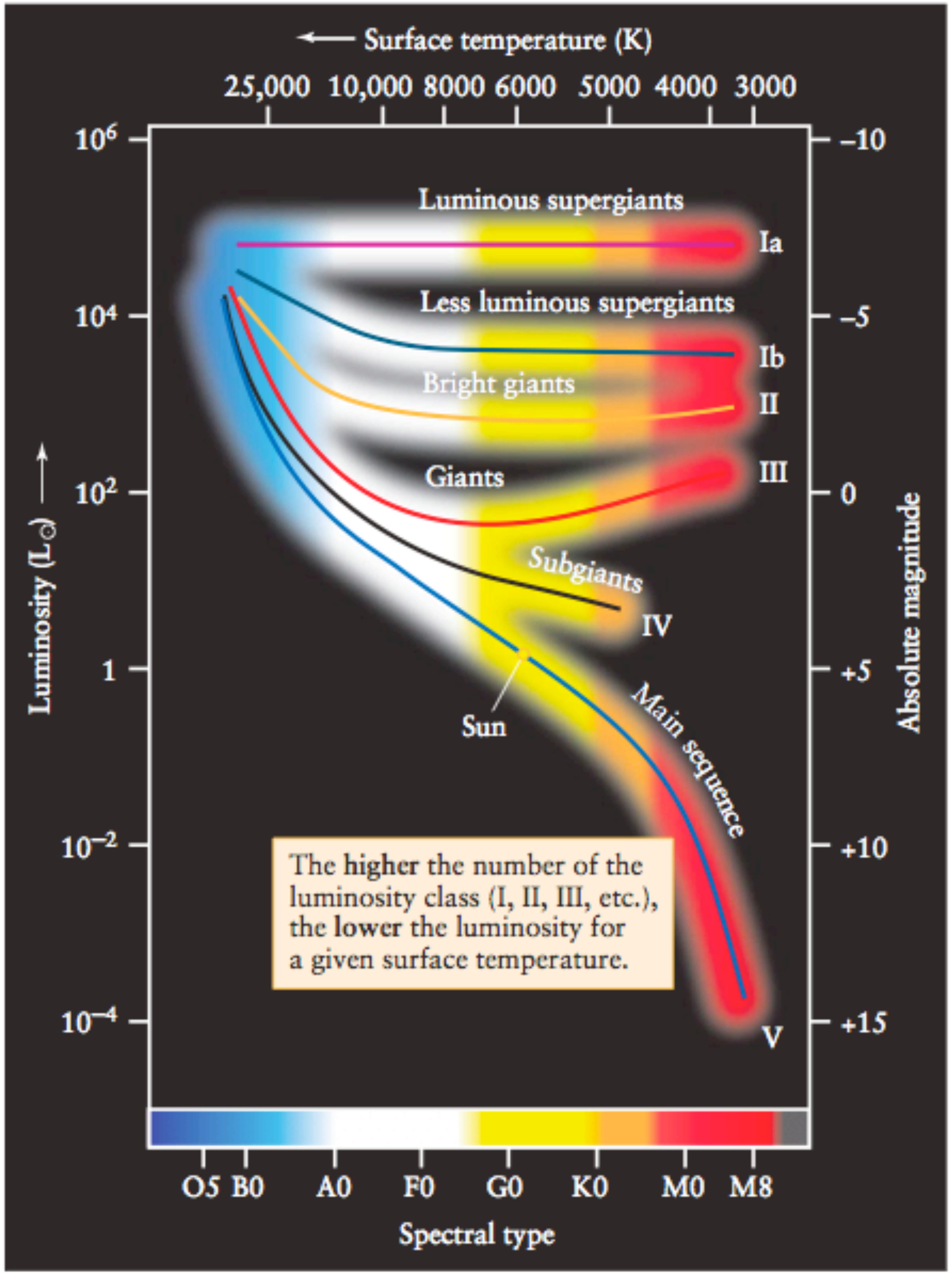


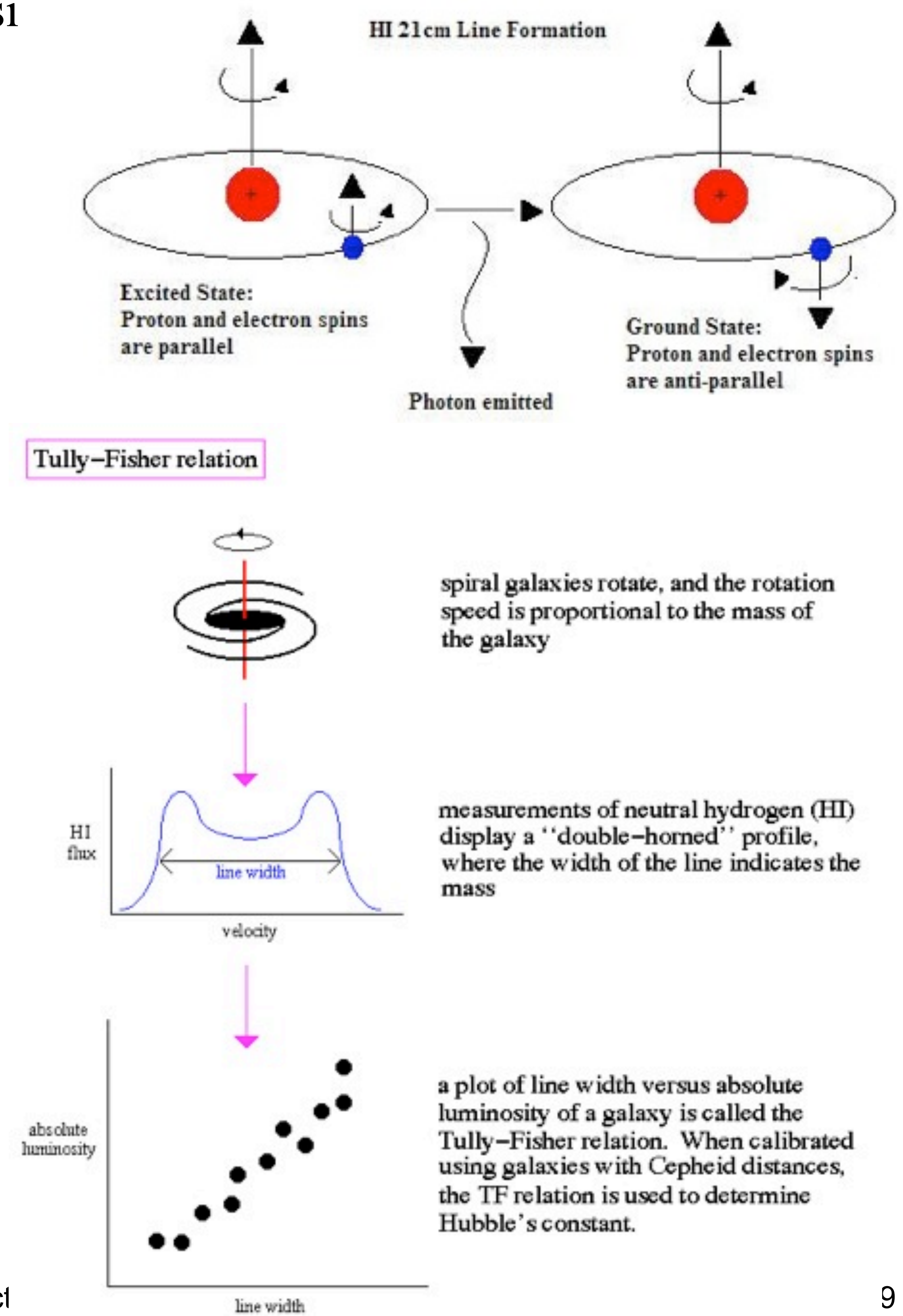
Figure 17-17

Luminosity Classes The H-R diagram is divided into regions corresponding to stars of different luminosity classes. (White dwarfs do not have their own luminosity class.) A star's spectrum reveals both its spectral type and its luminosity class; from these, the star's luminosity can be determined.

- Dallo spettro e dal colore si risale alla classe di luminosita' della stella
- per stelle della Sequenza Principle, dato il colore, si risale alla luminosita' vera, M
- se conosciamo la luminosita' apparente della stella, m, otteniamo il modulo di distanza
  - M-m= -5 log(D/(10 pc))
- ovvero D: ***Parallasse Spettroscopica***
- vale fino a circa 10 kpc (cioe' all'interno della Galassia)

4. La Relazione Tully-Fisher

- Le galassie a spirale ruotano e dei due lembi uno si avvicina e uno si allontana
- Le masse di gas idrogeno che ruotano con la galassia emettono onde radio di lunghezza d'onda 21 cm.
- La frequenza e' spostata verso il basso (eff. Doppler, per allontanamento) e verso l'alto (eff. Doppler, per avvicinamento) e la riga complessiva si allarga.
- La galassia ruota tanto piu' velocemente quanto piu' e' massiva
- e la luminosita' intrinseca cresce con la massa
- Quindi: la larghezza della riga 21 cm da' una misura della luminosita' intrinseca (effetto Tully-Fisher, scoperto negli anni '70)
- Calibrando la relazione T-F su Galassie la cui distanza e' misurata dalle Cefeidi, si puo' ottenere, dall'allargamento della riga 21, cm la luminosita' assoluta, quindi la distanza di galassie troppo lontane per distinguere le Cefeidi



5. Maser galattici

- MASER= Microwave amplification by stimulated emission of radiation
- nelle galassie ci sono nubi di molecole molto estese.
- L'intenso flusso di luce dalle stelle produce un'inversione di popolazione: numero di molecole in stati eccitati superiore al numero di quelle nello stato fondamentale,
- le differenze di energia dei livelli molecolari corrisponde a lunghezze d'onda nelle nelle microonde
- si produce il fenomeno dell'emissione stimolata (A. Einstein, 1917)

$$E_{i+1} - E_i = h\nu; \quad h\nu + M_{i+1} \to M_i + 2h\nu,$$

- le nubi diventano sorgenti intense di microonde, proprio come avviene nei MASER artificiali, precursori del LASER

Within a few million years the light from bright stars will have boiled away this molecular cloud of gas and dust. The cloud has broken off from the Carina Nebula. Newly formed stars are visible nearby, their images reddened by blue light being preferentially scattered by the pervasive dust. This image spans about two light-years and was taken by the Hubble Space Telescope in 1999.

Maser come “candela standard”

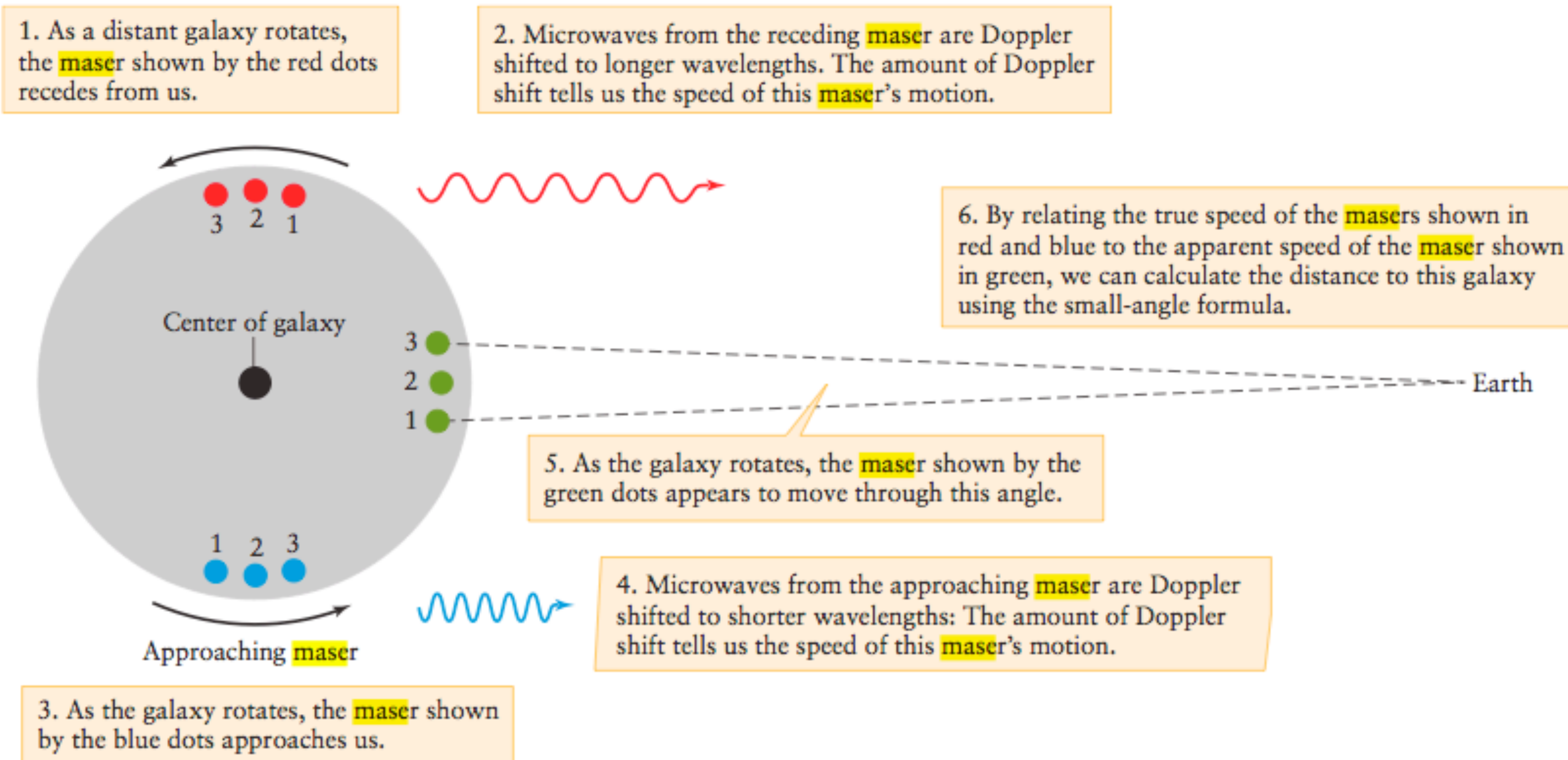


Figure 24-15

Measuring the Distance to a Galaxy Using Masers This drawing shows interstellar clouds called masers (the colored dots) moving from position 1 to 2 to 3 as they orbit the center of a galaxy. The redshift and blueshift of microwaves from the masers shown in red and blue tell us their orbital speed. By relating this to the angle through which the masers shown in green appear to move in a certain amount of time, we can calculate the distance to the galaxy.

6. Supernovae Ia

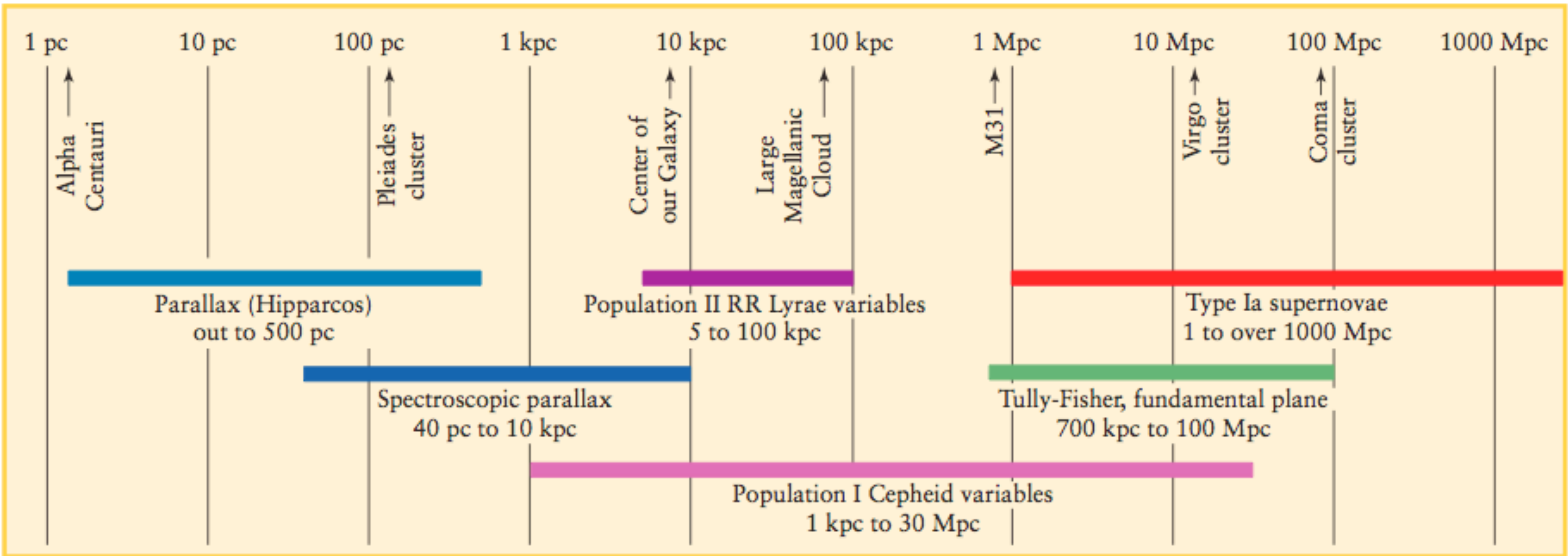
- Abbiamo visto, Lez. 5 e Lez. 11, che nelle nane bianche che acquistano per accrezione una massa superiore alla massa di Chandrasekar si innesca una fusione nucleare esplosiva sostenuta dalla fusione del Carbonio

- $C^{12} + C^{12} \rightarrow Mg^{24} + \gamma$
- $\rightarrow Mg^{23} + N$
- $\rightarrow Na^{23} + P$
- $\rightarrow Ne^{20} + He^{4}$
- $\rightarrow O^{16} + 2He^{4}$

- in queste condizioni, la nana bianca diventa una ***supernova termonucleare***, Supernova Ia, di cui possiamo dedurre la luminosita' assoluta dalla curva di luce, e quindi ricavare la distanza dalla luminosita' apparente
- le Supernovae Ia sono visibili anche nelle galassie lontane e forniscono una candela standard per distanze dell'ordine del Miliardo di pc (Gpc)

7. Vista d'insieme

- ne parleremo dopo le vacanze....



8. Le dimensioni delle cose nel Cosmo

- galassia: dimensioni lineari∼ 50 kpc, M∼ (0.5-1) 10^{12} $M_\odot$
- distanza intergalattica ∼ 1 Mpc, es. la distanza di Andromeda (M31)
- cluster di galassie: il piu' vicino e' il Virgo cluster
  - 2000 galassie
  - d∼10 Mpc, diametro∼ 5 Mpc
- le galassie hanno velocita' particolari (peculiar velocities), ad es. il nostro gruppo locale si muove verso il Virgo cluster per attrazione gravitazionale,
- ***Il moto di Hubble.*** Su distanze maggiori, le galassie mostrano un moto coerente di allontanamento, il, segnalato dallo spostamento verso il rosso delle righe spettrali: $v=H_0\,d$
- $H_0 \sim 70$ km/sec /Mpc
- $1/H_0$= tempo di Hubble ∼ 14 Miliardi di anni

$$\mathrm{Mpc/km} = (3.09\cdot 10^{16}\ \mathrm{m}\cdot 10^6)/(10^3\ \mathrm{m}) \sim 3\cdot 10^{19};$$
$$H_0^{-1} \sim 1/70\ \mathrm{sec}\cdot\mathrm{Mpc/km} \sim 1.4\cdot 10^{-2}\cdot 3\cdot 10^{19}/(3\cdot 10^7)\ \mathrm{yrs} =$$
$$= 14\cdot 10^9\ \mathrm{yrs}$$

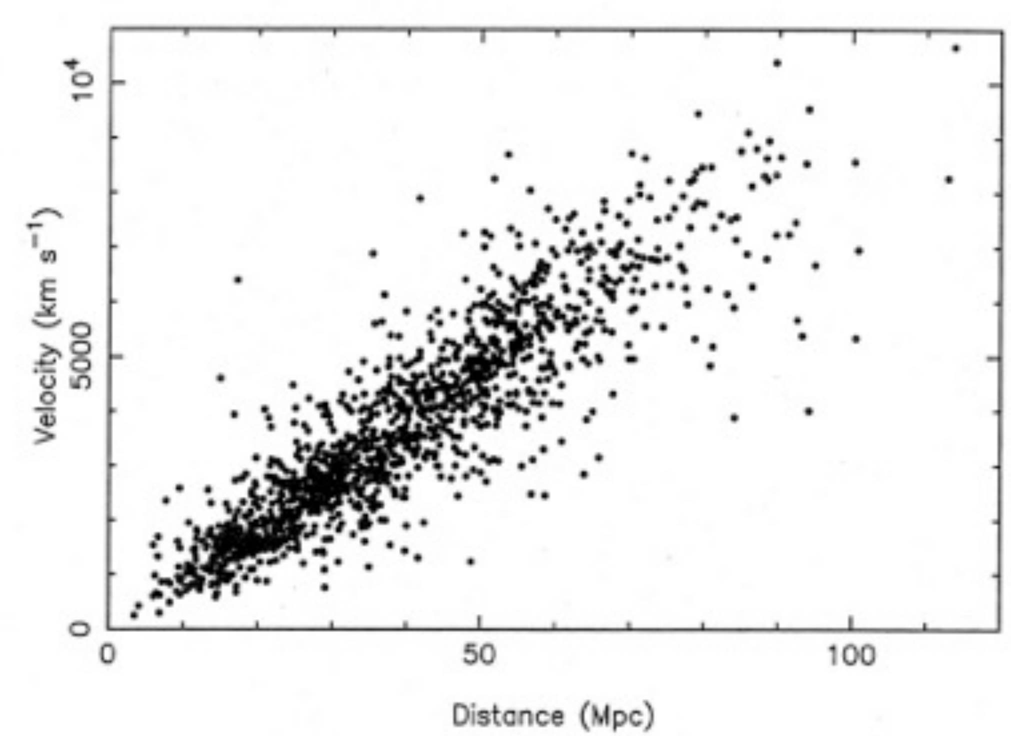


Figure 2.5 A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The x-axis scale assumes a particular value of H_0.]

Virgo Cluster

Common Name: The Virgo Cluster
Other Names: M91
RA: 12 25 1
Dec +12 53
Constellation: Virgo
Distance: 60 million light years
Magnitude: 8.9 (M86)

Notes:
The Virgo Cluster with its some 2000 member galaxies dominates our intergalactic neighborhood, as it represents the physical center of our Local Supercluster (also called Virgo or Coma-Virgo Supercluster), and influences all the galaxies and galaxy groups by the gravitational attraction of its enormous mass.
It has slowed down the escape velocities (due to cosmic expansion, the `Hubble effect') of all the galaxies and galaxy groups around it, thus causing an effective matter flow towards itself (the so-called Virgo-centric flow). Eventually many of these galaxies have fallen, or will fall in the future, into this giant cluster which will increase in size due to this effect. Our Local Group has experienced a speed-up of 100..400 km/sec towards the Virgo cluster. Current data on the mass and velocity of the Virgo cluster indicate that the Local Group is probably not off far enough to escape, so that its recession from Virgo will probably be halted at one time, and then it will fall and merge into, or be eaten by the cluster, see our Virgo Cluster & Local Group page.

Because of the Virgo Cluster's enormous mass, its strong gravity accelerates the member galaxies to considerably high peculiar velocities, up to over 1500 km/sec, with respect to the cluster's center of mass. Investigations over the past decades have revealed a quite complex dynamic structure of this huge irregular aggregate of galaxies. The Virgo cluster is close enough that some of its galaxies, which happen to move fast through the cluster in our direction, exhibit the highest blue-shifts (instead of cosmological redshifts) measured for any galaxies, i.e. are moving toward us: The record stands for IC 3258, which is approaching us at 517 km/sec. As the cluster is receding from us at about 1,100 km/sec, this galaxy must move with over 1,600 km/sec through the Virgo Cluster's central region. Analogously, those galaxies which happen to move fastest away from us through the cluster, are receding at more than double redshift than the cluster's center of mass: The record is hold by NGC 4388 at 2535 km/sec, so that this galaxy moves peculiarly in the direction away from us at over 1,400 km/sec.
Ref: Quoted from http://www.seds.org/Messier/more/virgo.html

In the above photo, there are some 10 galaxies, M86 the largest centre left, above and to the left is M84, to the lower left of M86 is NGC4402, to the right of M84 isNGC 4388, etc.
M86 is travelling towards us as it is blue shifted. It is a giant elliptical or lenticulargalaxy. A dwarf companion galaxy can be seen on the image below taken with the canon camera.
Ngc 4402 is an edge on spral galaxy

Telescope: Meade LX200GPS 14"
Camera: SBig ST-8
Filters: CBVR
Exposure:
Date: 2006
Where: Tenby Observatory, Coonabarabran
Lat: 31 16 35.05 S, Long 149 11 33.99 E, Elevation 547metres

9. Determinazioni recenti della Costante di Hubble

Date published	Hubble constant (km/s)/Mpc	Observer	Citation	Remarks / methodology
2013-03-21	67.80 ±0.77	Planck Mission	[13][14][15][16][17]	The ESA Planck Surveyor was launched in May 2009. Over a four-year period, it performed a significantly more detailed investigation of cosmic microwave radiation than earlier investigations using HEMT radiometers and bolometer technology to measure the CMB at a smaller scale than WMAP. On 21 March 2013, the European-led research team behind the Planck cosmology probe released the mission's data including a new CMB all-sky map and their determination of the Hubble constant.
2012-12-20	69.32 ±0.80	WMAP (9-years)	[18]	
2010	$70.4^{+1.3}_{-1.4}$	WMAP (7-years), combined with other measurements.	[19]	These values arise from fitting a combination of WMAP and other cosmological data to the simplest version of the ΛCDM model. If the data are fit with more general versions, H_0 tends to be smaller and more uncertain: typically around 67 ±4 (km/s)/Mpc although some models allow values near 63 (km/s)/Mpc.[20]
2010	71.0 ±2.5	WMAP only (7-years).	[19]	
2009-02	70.1 ±1.3	WMAP (5-years). combined with other measurements.	[21]	
2009-02	$71.9^{+2.6}_{-2.7}$	WMAP only (5-years)	[21]	
2006-08	$77.6^{+14.9}_{-12.5}$	Chandra X-ray Observatory	[22]	
2007	$70.4^{+1.5}_{-1.6}$	WMAP (3-years)	[23]	
2001-05	72 ±8	Hubble Space Telescope	[24]	This project established the most precise optical determination, consistent with a measurement of H_0 based upon Sunyaev-Zel'dovich effect observations of many galaxy clusters having a similar accuracy.
prior to 1996	50–90 (est.)		[25]	
1958	75 (est.)	Allan Sandage	[26]	This was the first good estimate of H_0, but it would be decades before a consensus was achieved.