Mapping the Milky Way

- Q: What is a good distance indicator? What criteria should we use to judge it, since we don’t actually know distances *a priori*?

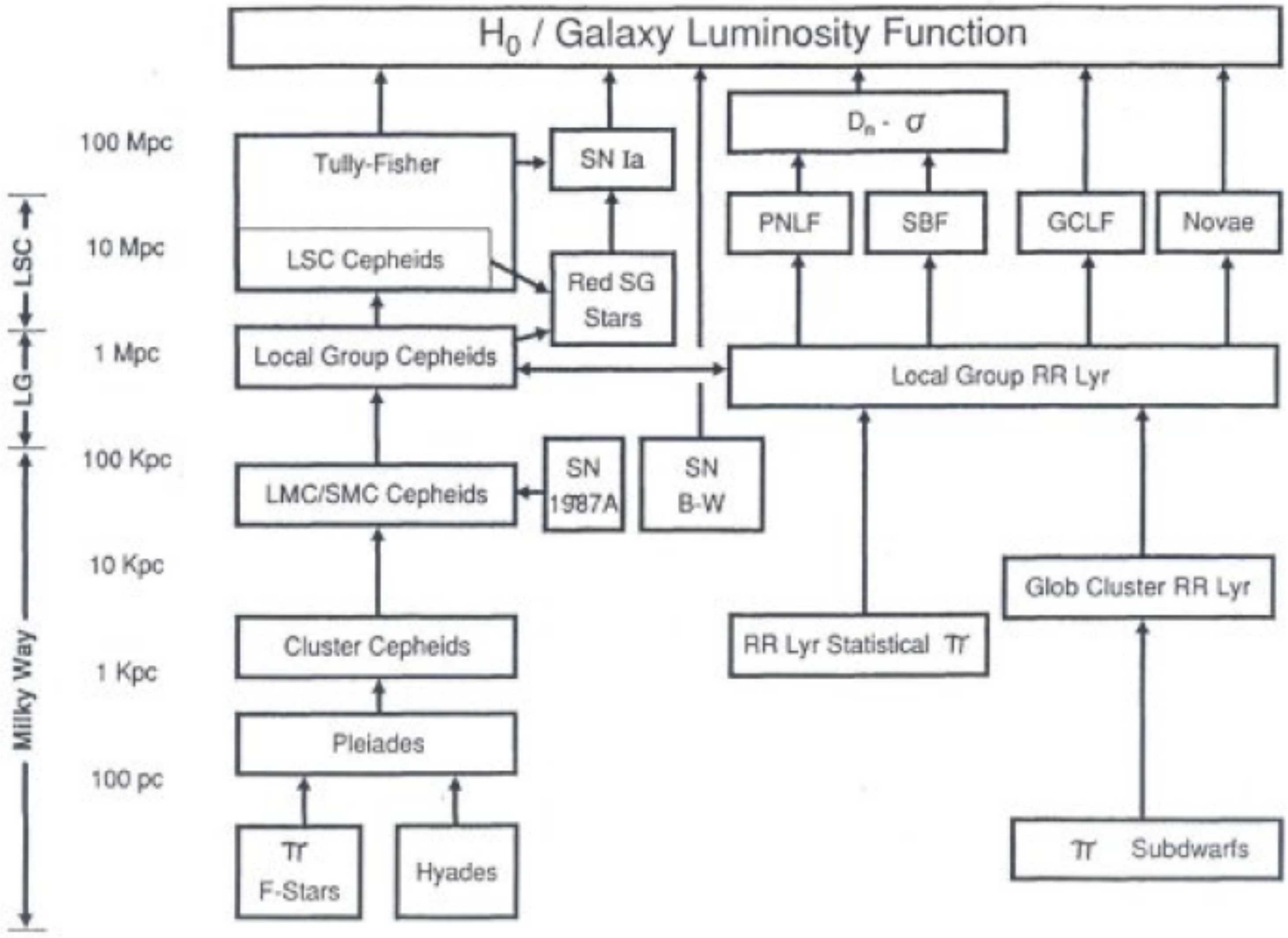
Possible criteria:

-- We understand the physical basis of the indicator (ie what contributes to the absolute magnitude of a Type 1a SN)

-- We think that it works (at least it passes all the tests we can think of) but we don’t really understand why (eg Tully-Fisher)

Which is more important?

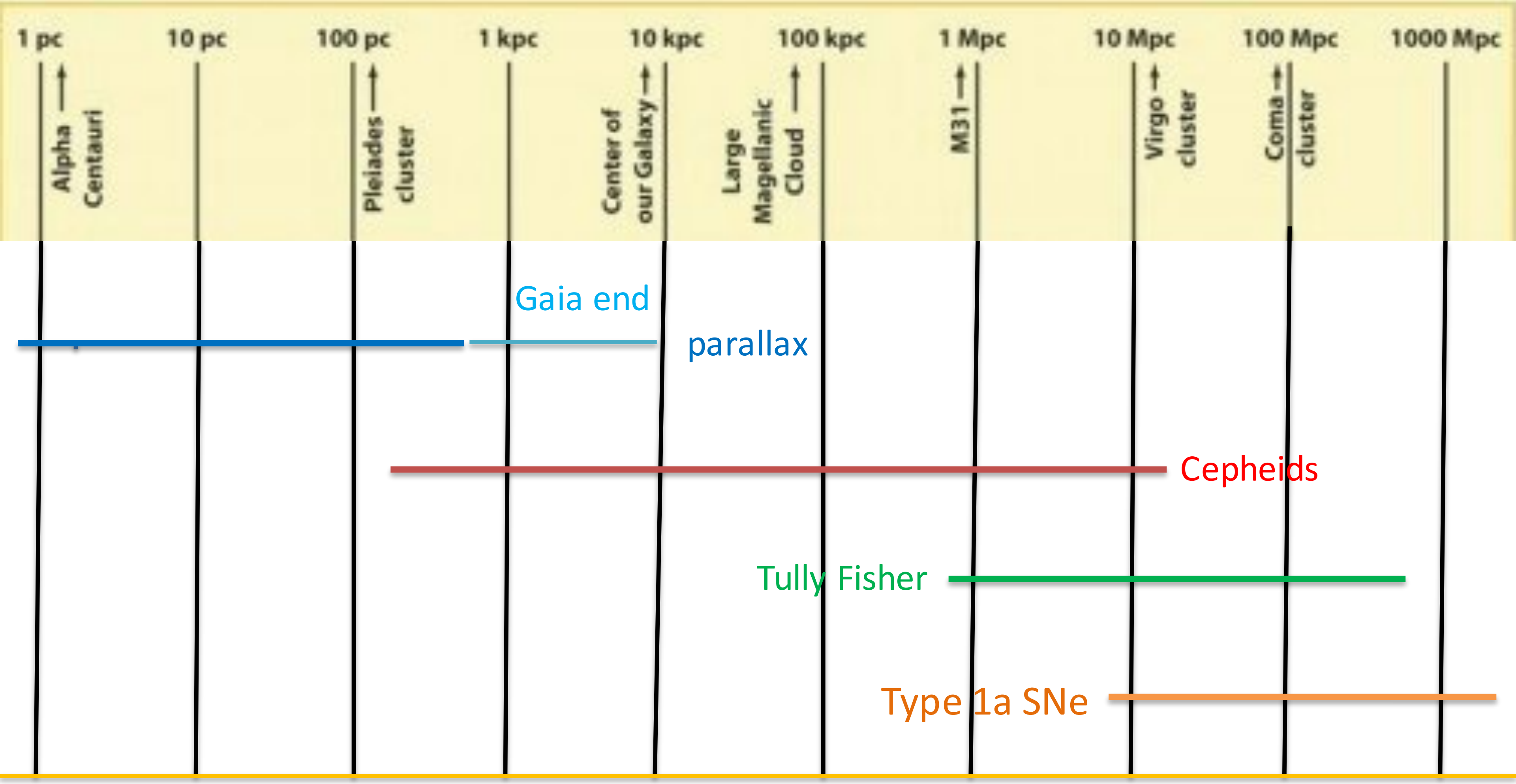
The distance ladder (Jacoby et al 92)



Pathways to Extragalactic Distances

—In this diagram we illustrate the various modern routes which may be taken to arrive at H_0 and the genealogy and approxima

The distance ladder simplified



Absolute vs Relative Distance Indicators

absolute distance indicators dont require the 'distance ladder' – the shaky structure that is constructed to give distances via parallax, then other indicators

Q

What are examples of each sort?

Relative vs absolute indicators

- Parallax is an absolute indicator: we just need to know the Earth’s orbital radius and use geometry to get the distance to a star which is near enough to detect its parallax
- Main sequence fitting uses stars with distances from an absolute indicator (parallax) to work out distances to clusters with similar properties to the parallax stars so this is a relative indicator

Another relative indicator

- The Tully-Fisher technique relates the orbital velocity of galaxy disks to their luminosity.

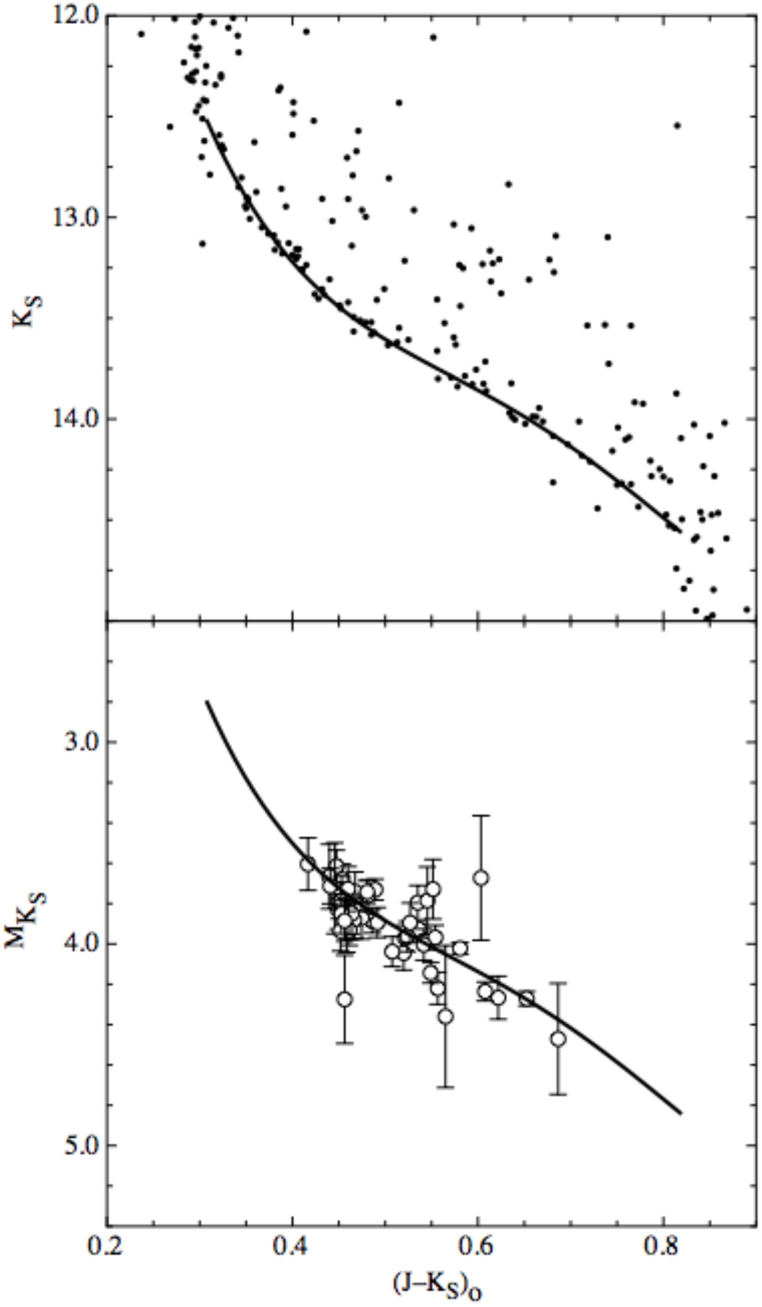
-- in order to use this, we need to calibrate the relation via Cepheids in the same galaxy

-- in order to use Cepheids we need to calibrate their P-L relation via main sequence fitting of clusters containing Cepheids, ie by tying back to parallax stars

Main sequence fitting

If we have the color-magnitude diagram of a cluster (M67 is shown) and also have stars with known distances from parallax then we can deduce the distance of the cluster

Q: what is your estimate of M67's distance?



Sarajedini et al 09

Main sequence fitting: complications

Q What determines the position of a cluster main sequence in a CMD ?

→ [Fe/H]

→ reddening

→ sometimes age

Isochrones?

- Can also use isochrones directly, if you are confident that the stellar models are accurate and the transformation from L to Mv is accurate
- Q: How would one derive a transformation from a star’s luminosity to its absolute magnitude in a given passband?

Isochrones?

- Can also use isochrones directly, if you are confident that the stellar models are accurate and the transformation from L to Mv is accurate
- Q: How would one derive a transformation from a star's luminosity to its absolute magnitude in a given passband?

A: use synthetic spectra plus filter passbands to relate bolometric luminosity to say Mv

Problem : position of zero-age main sequence depends on stellar metallicity because of line-blanketing

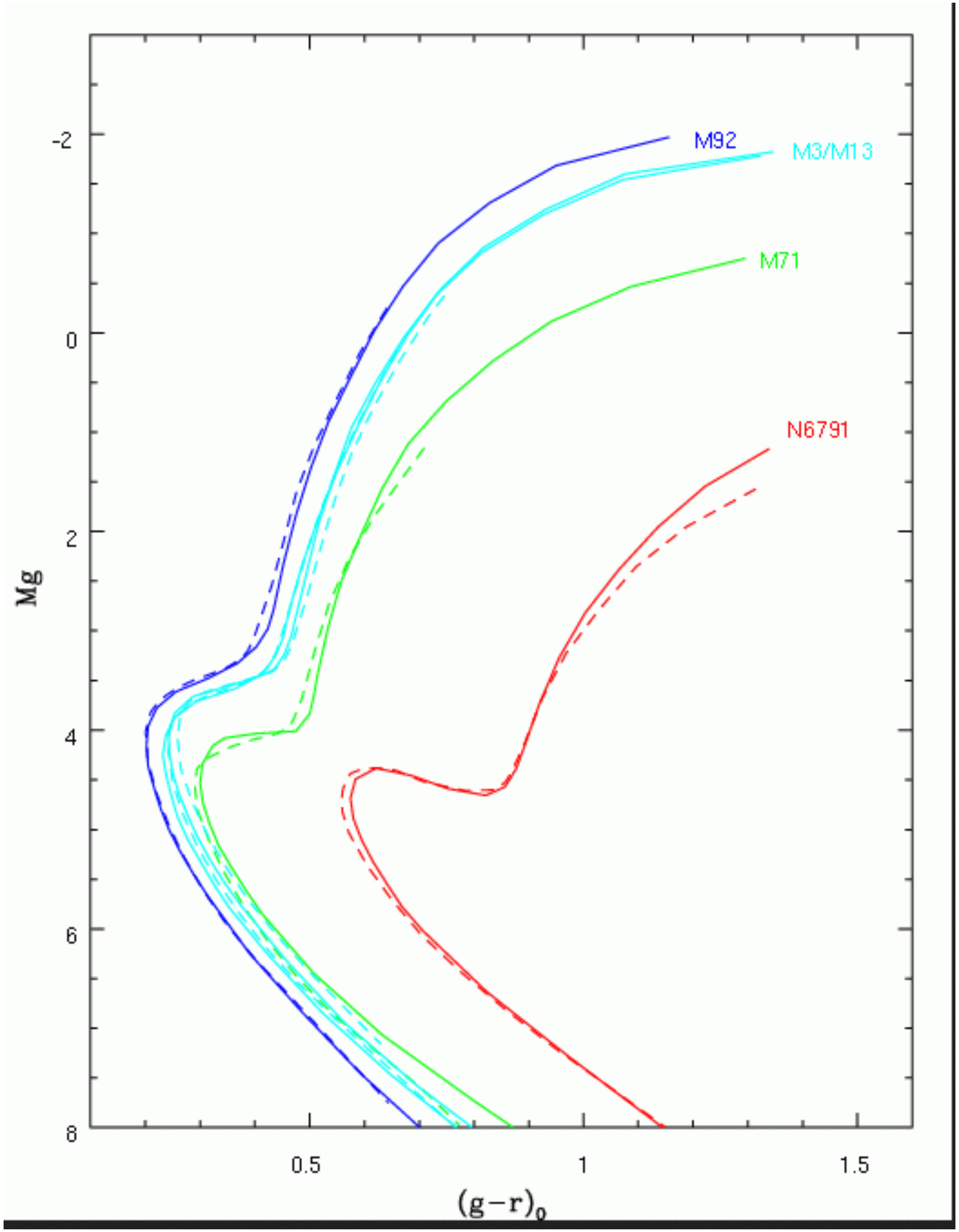
(see Mihalas & Binney p116)

Very metal-poor stars have spectra that are close to black bodies.

SDSS CMDs for old clusters in the Milky Way.

[Fe/H] values from top to bottom are

M92	-2.4
M13	-1.6
M71	-0.8
NGC 6791	+0.3



Metallicity vs stellar color

Line blanketing: Metal lines are more common in the UV and blue of stellar spectra than in the red, so a metal-richer star has less UV light than a metal poor one

Opacity: more metals absorb energy from the interior of the star, making stars "swell up", giving them cooler (redder) temperatures.

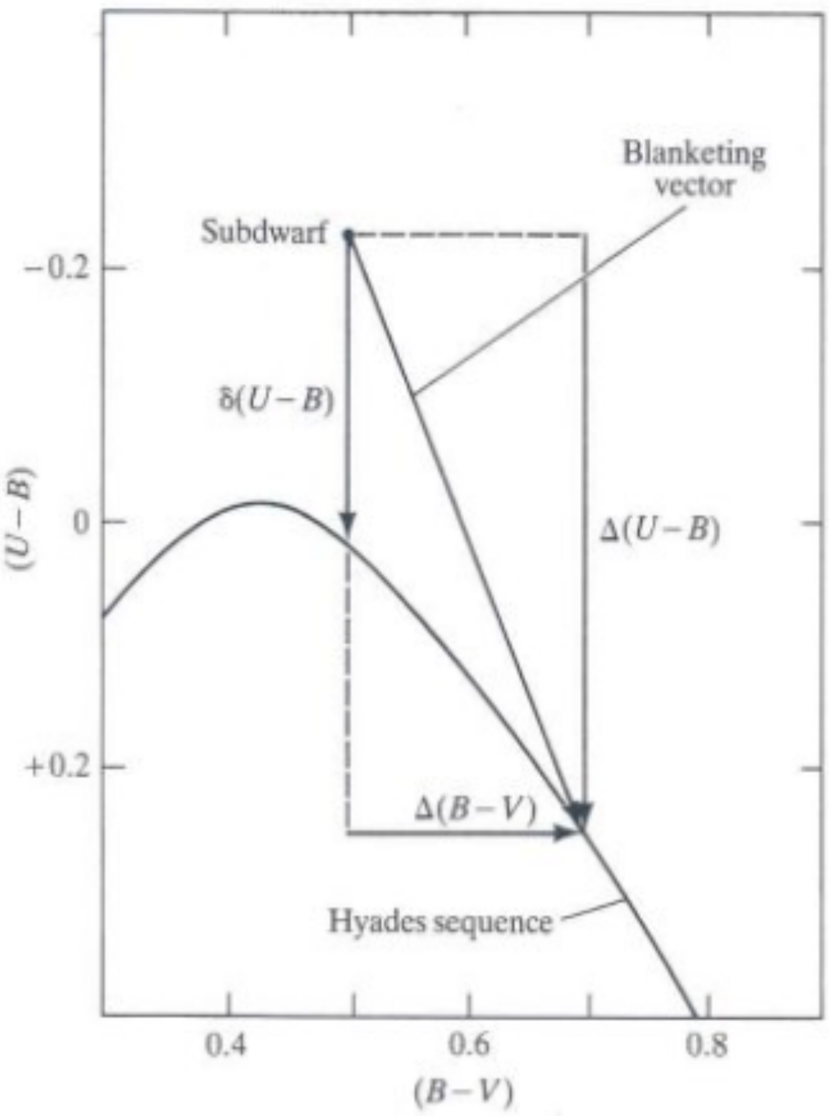


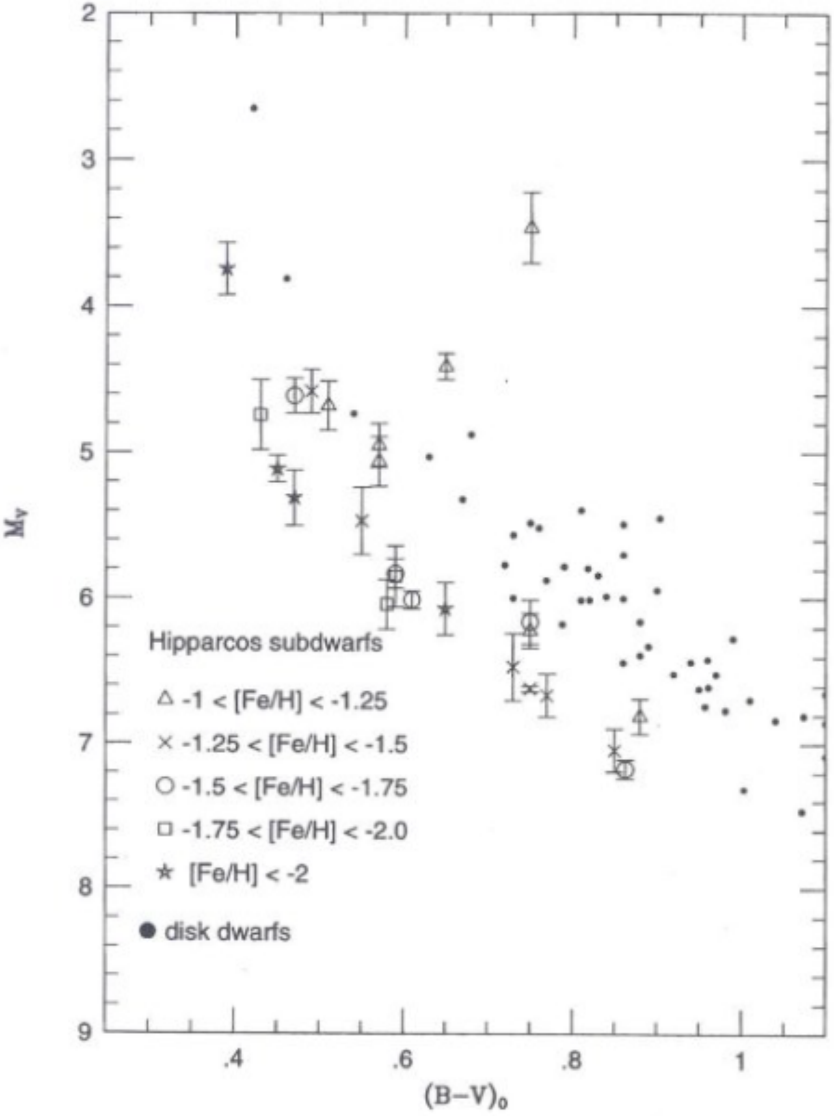
Figure 3-10. Blanketing vector in two-color diagram for a metal-deficient subdwarf. The subdwarf has an ultraviolet excess $\delta(U - B)$ compared to a Hyades

Main sequence fitting for subdwarfs

Halo stars are rare. So metal-poor subdwarfs are rare

They are all shown on the plot to the right (Reid 1997)

(note error bars)



Reid 1997

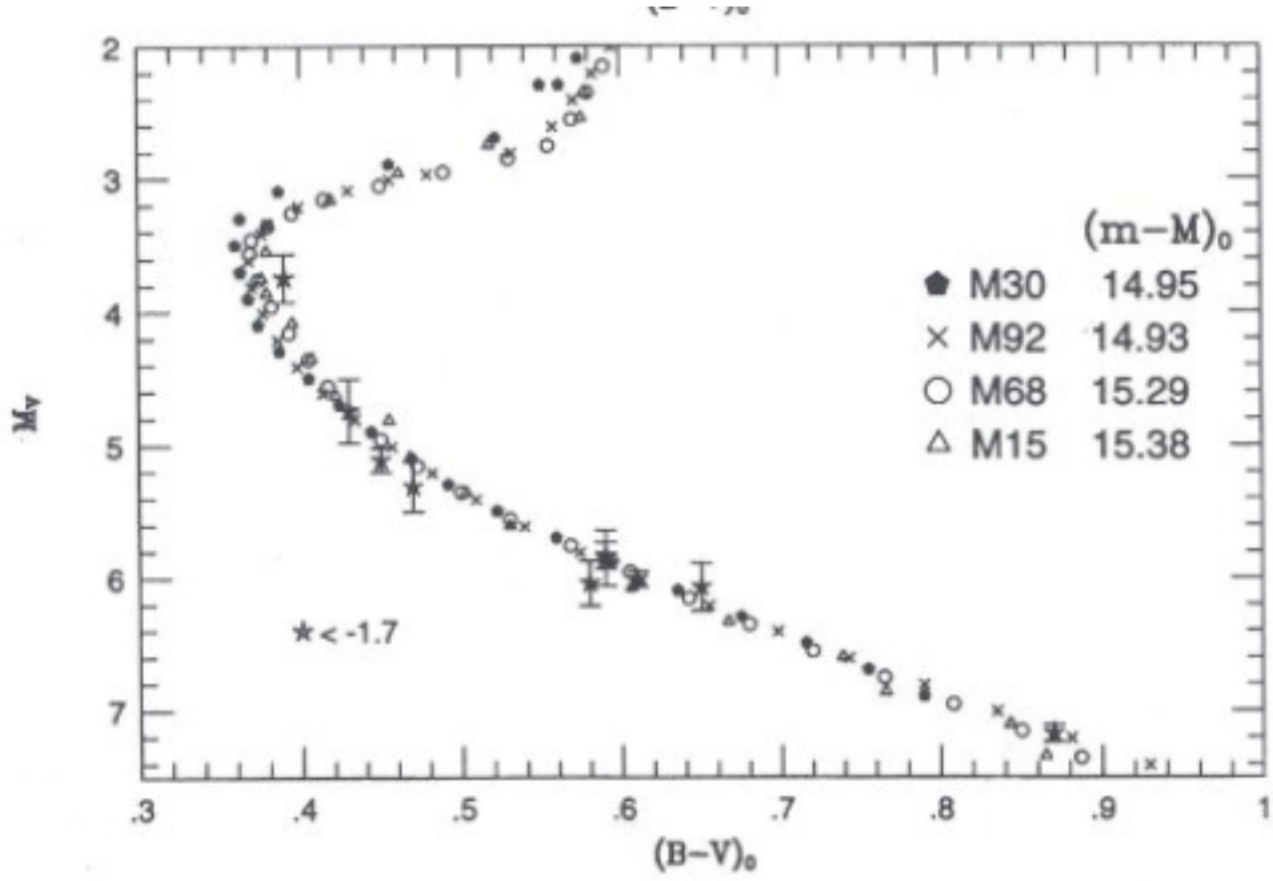


FIG. 5. Main-sequence fitting for the four metal-poor globular clusters.

Q: How well defined is a relation based on 8 stars?

BUT: Gaia DR1 has increased number of stars with parallax!

And there will be more coming in later data releases….

Cepheids as distance indicators

- Cepheids are particularly useful as distance indicators because they show a period/luminosity relation

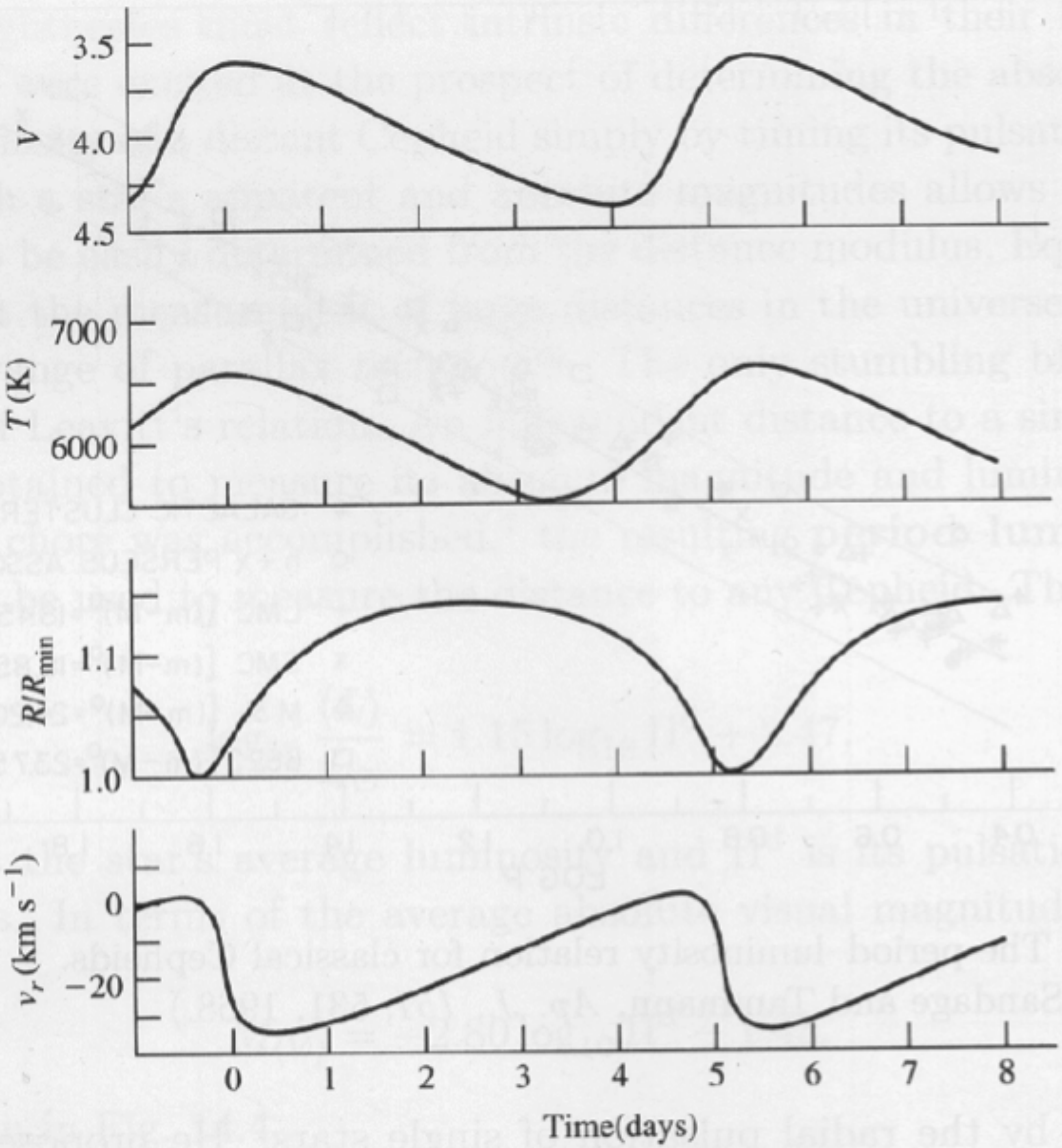
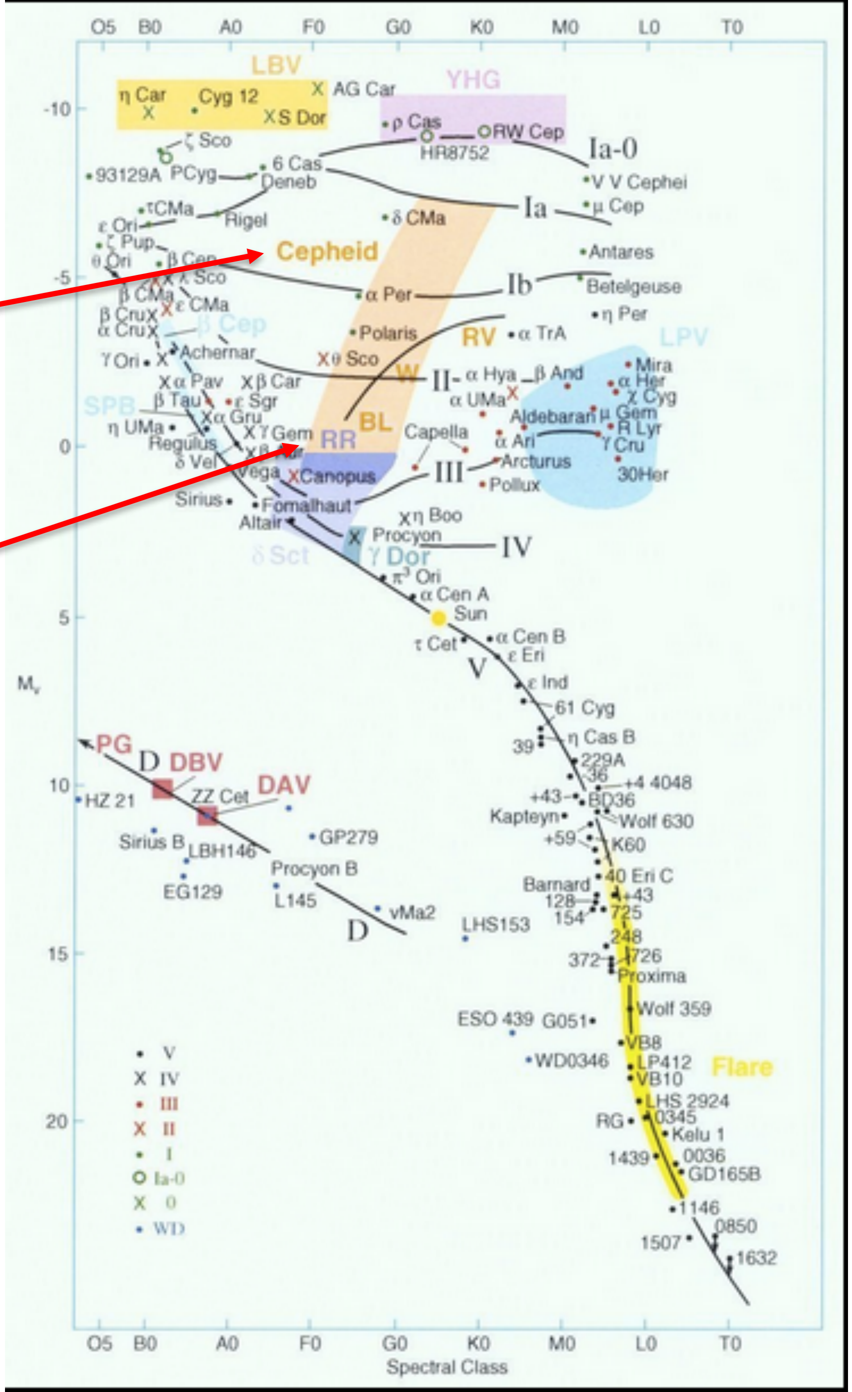


Figure 14.5 Observed pulsation properties of δ Cephei.

Cepheids are evolved massive stars; RR Lyraes are equivalent for lower mass



From *The Cambridge Encyclopedia of Stars*, J. B. Kaler, Cambridge University Press, 2006. C

Cepheids as standard candles

- bright ($M_V = -2$ to -7, young, massive stars passing thru instability strip)

  (visible to ~ 15 Mpc with HST) (Virgo cluster)

- easily detected via variability, esp. in optical

- we understand physics of pulsation

BUT

Young disk stars can have dusty surroundings

RS Pup (HST)

Basis of P-L relation:

- more luminous stars have longer period

$P^2 \propto \frac{R^3}{M}$ (Newton) (Kepler)

$L \propto M^k$ (more massive stars have denser, hotter cores & are much more luminous)

$L \propto R^2 T^4$

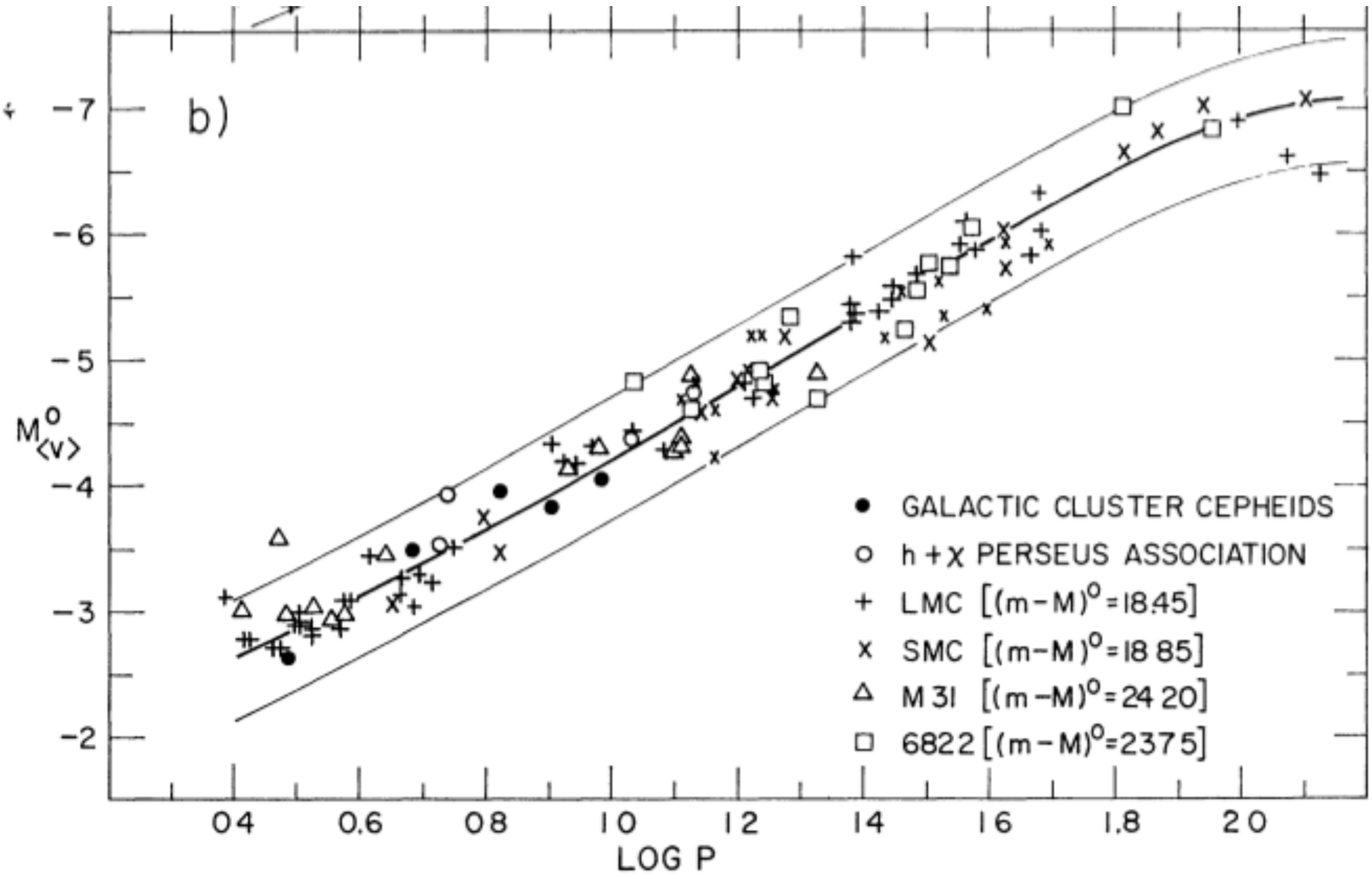
P-L relation continued

Eliminating mass gives a relation between period, luminosity & temp. (color)

ie P-L-C relation

P-L relation has more scatter but easier to measure

Example of a P-L relation



Sandage and Tamman 1968

Calibration of P-L or P-L-C relation

- Cepheids in LMC useful

  Why ?

  However, is there a metallicity dependence ?

  (LMC has lower mean metallicity than Milky Way, M81, large spirals)

- Milky Way Cepheids:
  - few (~20 in open clusters)
  - cluster Cepheids calibrated via mainsequence fitting, ~10% distance error
  - field stars calibrated via Baade-Wesselink

  - metallicity!
  - most Milky-Way Cepheids have shorter periods, while most HST (Virgo) cepheids have long periods

$\boxed{Q}$ Why?

110 HST orbits to get Cepheid parallaxes from Fine Guidance Sensors

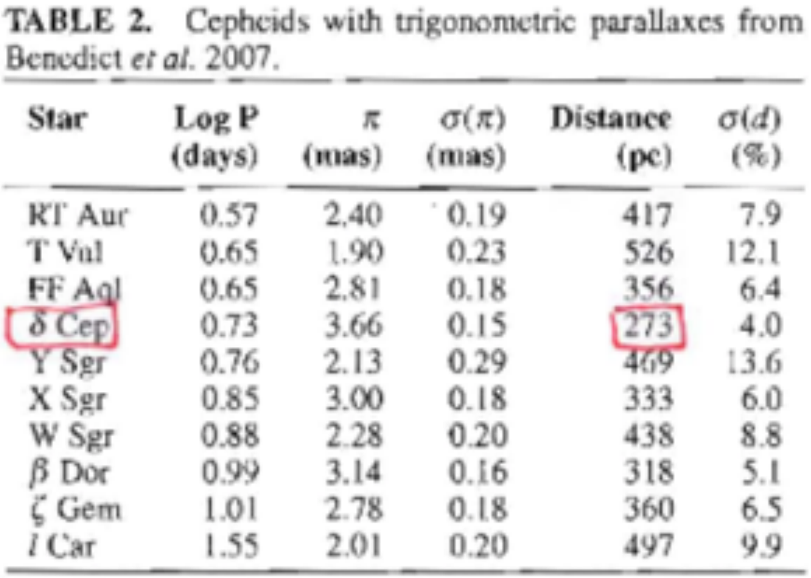


TABLE 2. Cepheids with trigonometric parallaxes from Benedict *et al.* 2007.

Star	**Log P (days)**	π (mas)	$\sigma(\pi)$ (mas)	**Distance (pc)**	$\sigma(d)$ (%)
RT Aur	0.57	2.40	0.19	417	7.9
T Vul	0.65	1.90	0.23	526	12.1
FF Aql	0.65	2.81	0.18	356	6.4
δ Cep	0.73	3.66	0.15	273	4.0
Y Sgr	0.76	2.13	0.29	469	13.6
X Sgr	0.85	3.00	0.18	333	6.0
W Sgr	0.88	2.28	0.20	438	8.8
β Dor	0.99	3.14	0.16	318	5.1
ζ Gem	1.01	2.78	0.18	360	6.5
l Car	1.55	2.01	0.20	497	9.9

Baade-Wesselink method: an absolute distance indicator for variable stars:

(See Binney and Merrifield)

$$\underset{\text{luminosity}}{L} = \sigma \underset{\text{effective temperature}}{T_{\mathrm{eff}}^{4}} \cdot 4\pi \underset{\text{stellar radius}}{R^{2}}$$

Fundamental Properties of Stars

Temperature (T)

Radius (R)

Chemical Composition

Mass (M)

Surface Gravity (g)

Luminosity (L)

Density (ρ)

Age

$$g = GM/R^2$$

$$L \propto R^2\,T^4$$

$$\rho \propto M/R^3$$

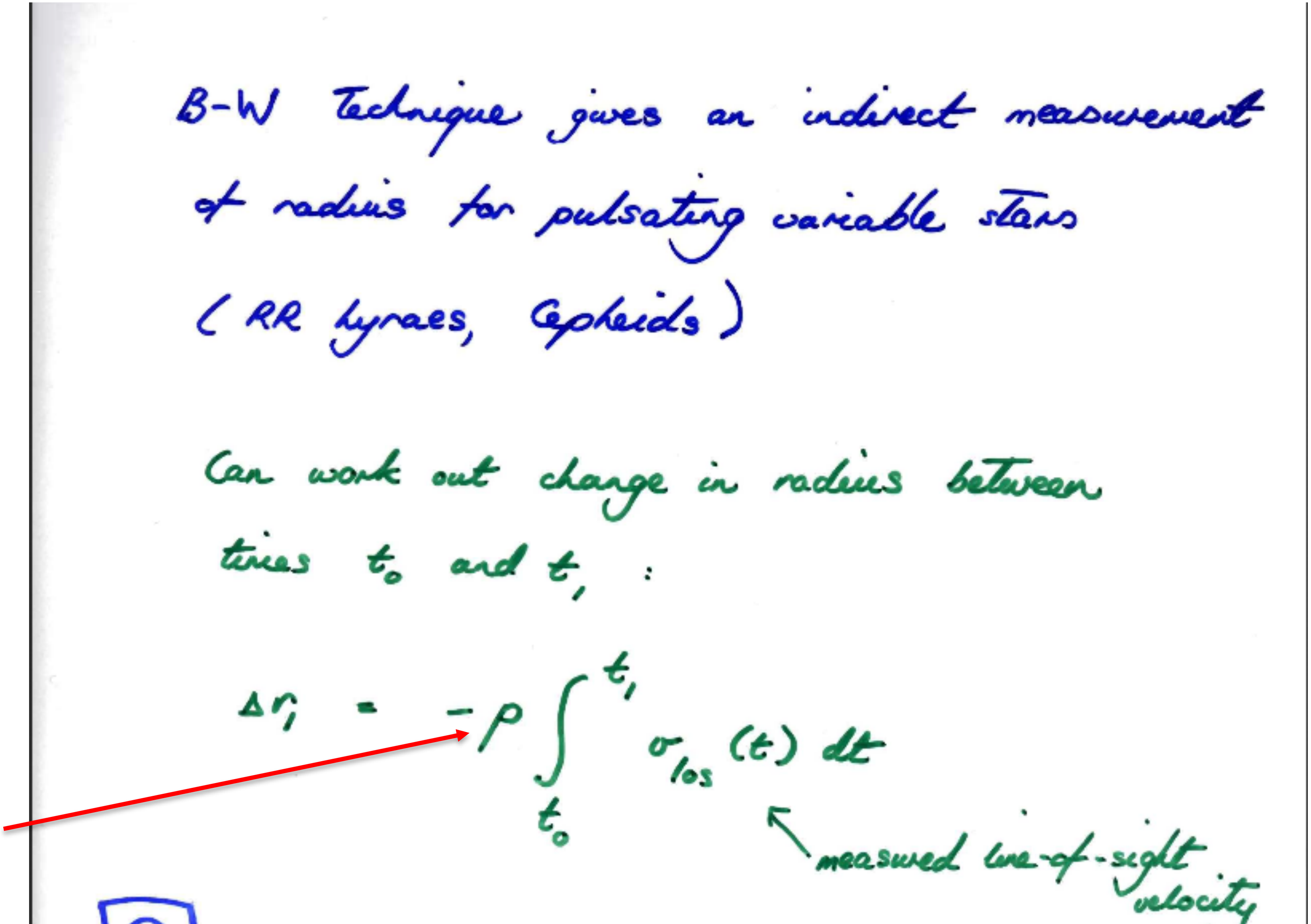
Dan Huber U Hawaii

Teff is relatively straightforward to measure

Q: How?

Radius is more challenging since stars are so far away. Recently more stellar radii are becoming available via interferometry (angular radius) and asteroseismology (linear)

V = dR/dt! Use velocity curve



B-W Technique gives an indirect measurement of radius for pulsating variable stars (RR Lyraes, Cepheids)

Can work out change in radius between times t_0 and t_1 :

$$\Delta r_1 = -p \int_{t_0}^{t_1} v_{los}(t)\, dt$$

measured line-of-sight velocity

NB!

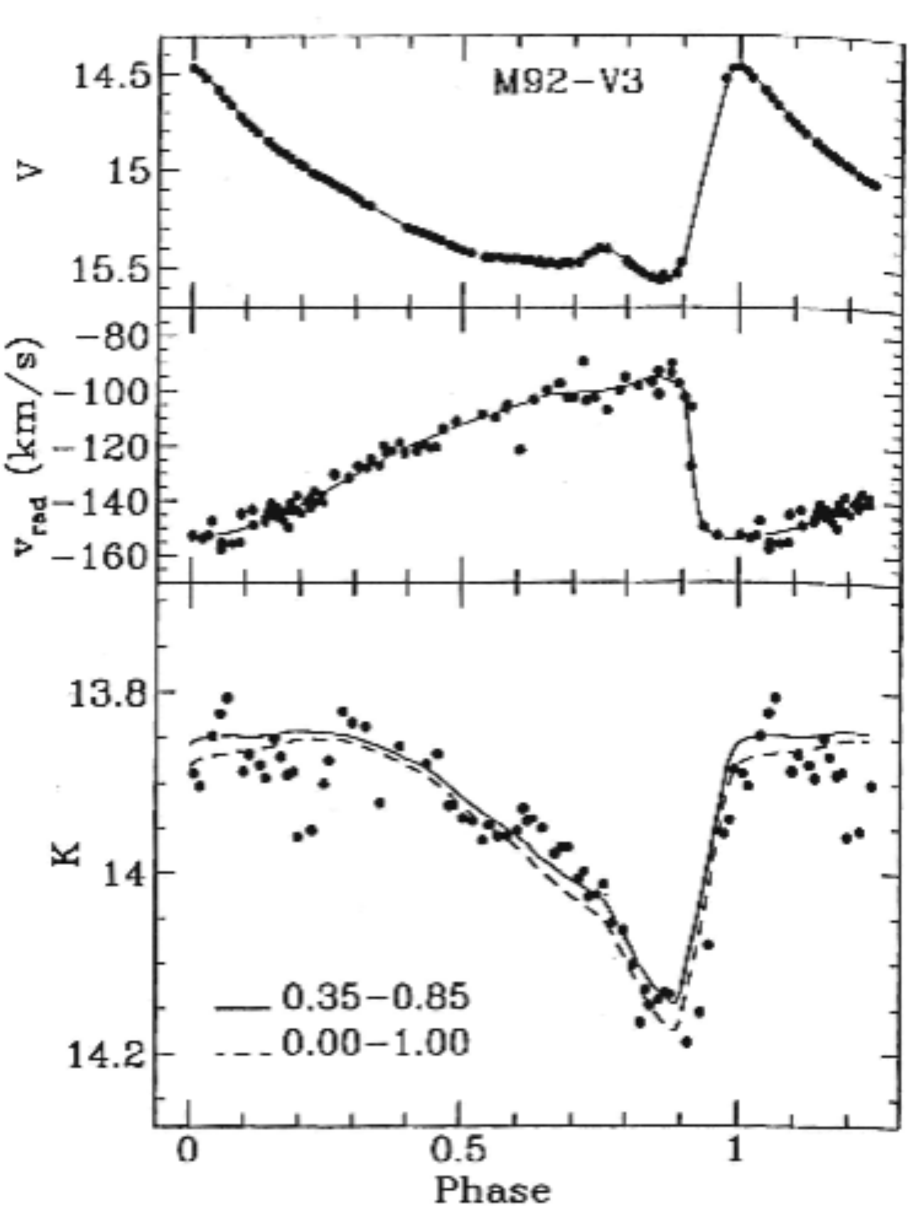
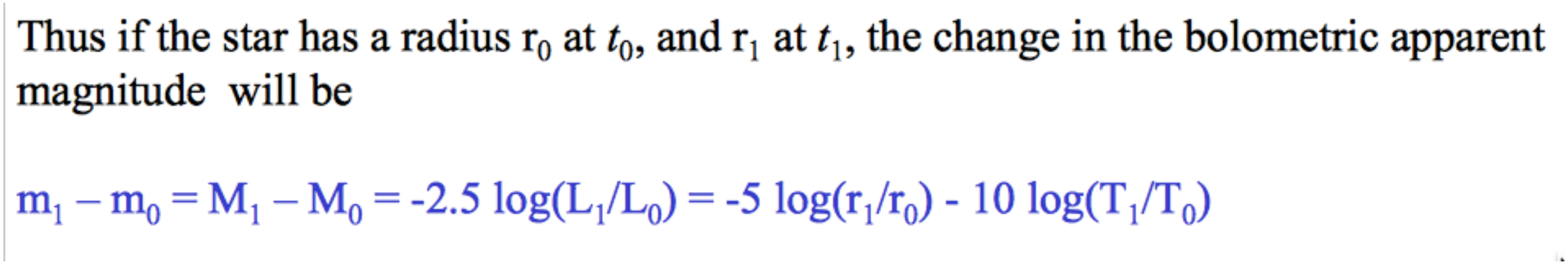


Fig. 4. V light curve, radial velocity curve and *K* band light curve for M 92-V 3. The individual points refer to the observed data except that

RR Lyrae changes in apparent magnitude and radial velocity

How do we get the stellar radius?

- We have the difference in radii at different phases from the velocity curve
- We get the ratio of radii from the following:



Thus if the star has a radius r_0 at t_0, and r_1 at t_1, the change in the bolometric apparent magnitude will be

$$m_1 - m_0 = M_1 - M_0 = -2.5 \log(L_1/L_0) = -5 \log(r_1/r_0) - 10 \log(T_1/T_0)$$

With both the ratio and the difference of the two radii we can derive the star’s radius velocity

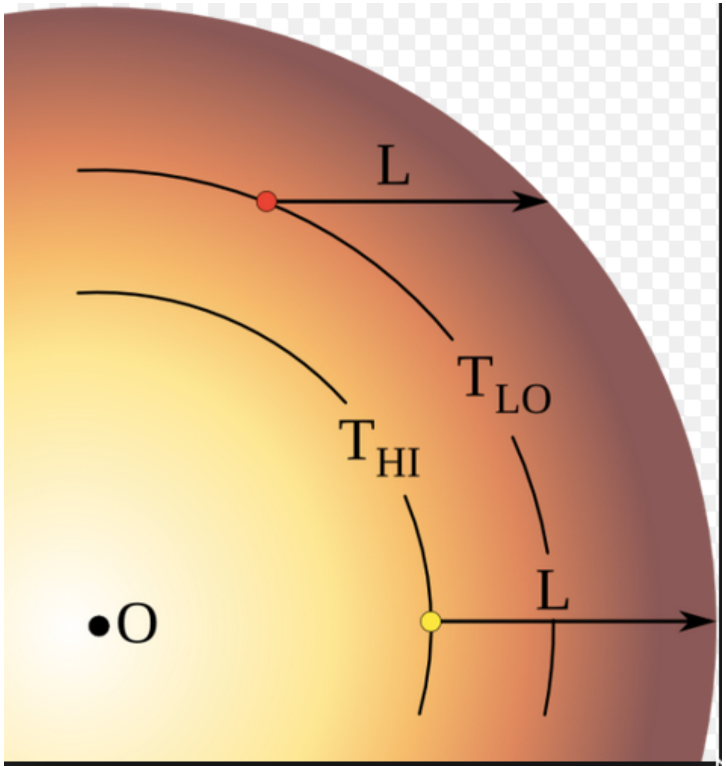
$\boxed{Q}$ why can't we just integrate the velocity curve directly? what is this ρ?

Hint: what do we measure when we measure v_{los}? How ~~[illegible]~~ could a velocity study of the Sun be better than one of an unresolved star?

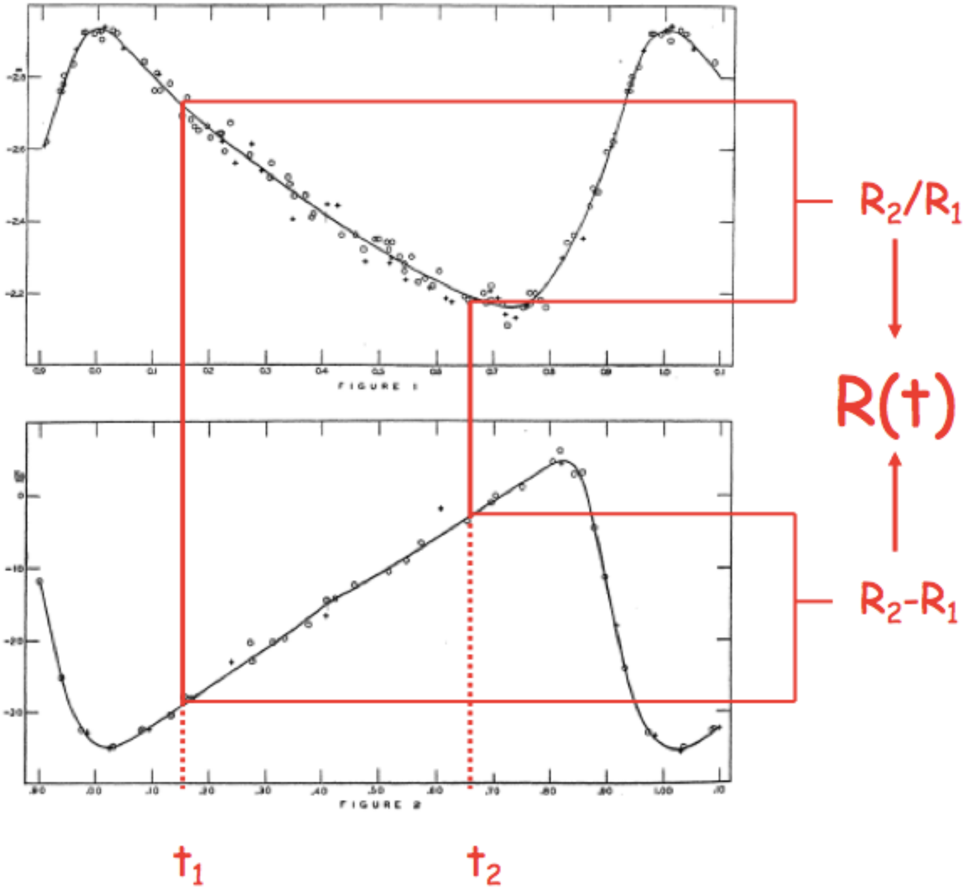
- A: Since the star is pulsating radially and since we measure only the line-of-sight velocity, we will get a strong contribution from the center of the stellar disk, and none at all from the edges.
- To derive p we need to integrate the component of velocity we see across the stellar disk. But effects like limb darkening make this non-trivial

Limb darkening review

We see about one optical depth into a star. At the center this is further down in the star and so it looks hotter and brighter there than at the edge



Baade Wesselink summary



Apparent magnitude

Velocity

R_2/R_1

$R(t)$

$R_2 - R_1$

t_1

t_2

Light and radial velocity curve of δCephei (Schwarzchild, M. 1938)

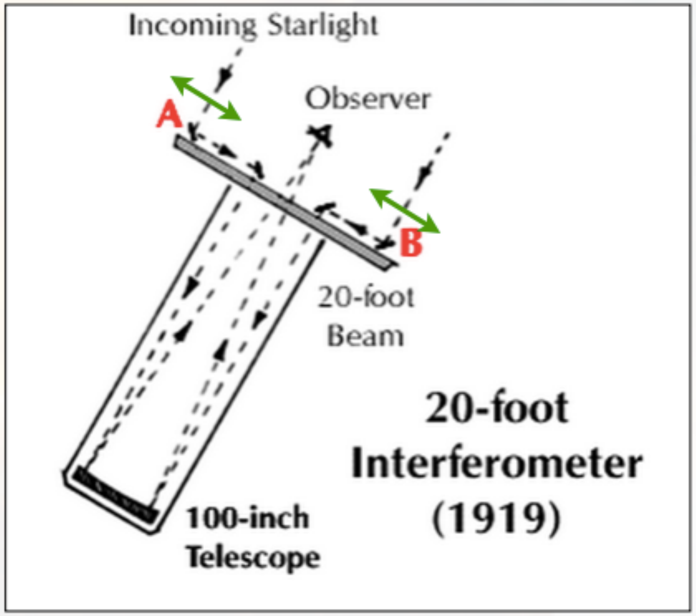
Dan Li University of Florida

Checks of B-W (and calibrating p)

A variation on B-W uses interferometry to measure angular radius, and integration of the velocity curve plus p-factor to give difference in linear radius. Good agreement with classical B-W

Some interferometry is done with CHARA array at Mt Wilson, CA; some with the Very Large (8m) Telescopes in Paranal, Chile

Early Days: the Michelson interferometer



Albert Michelson measured the angular size of Betelgeuse to be ~0.05 arcseconds ~ $1\text{x}10^{-5}$ degrees; combined with it's parallax, the radius was determined to be 150 x 10^{6} km (roughly the perihelion distance of Mars) - the first stellar diameter measurement!

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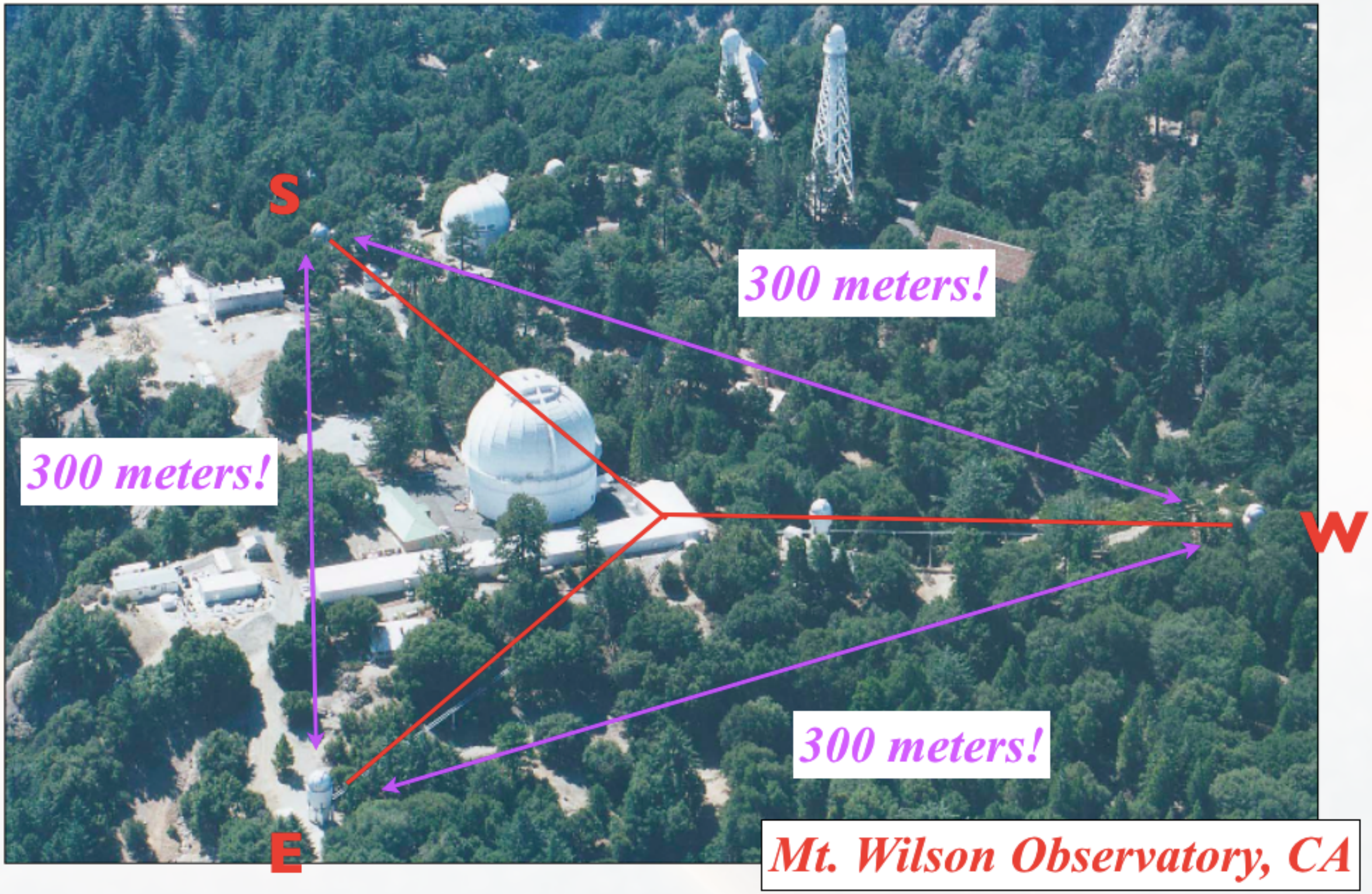
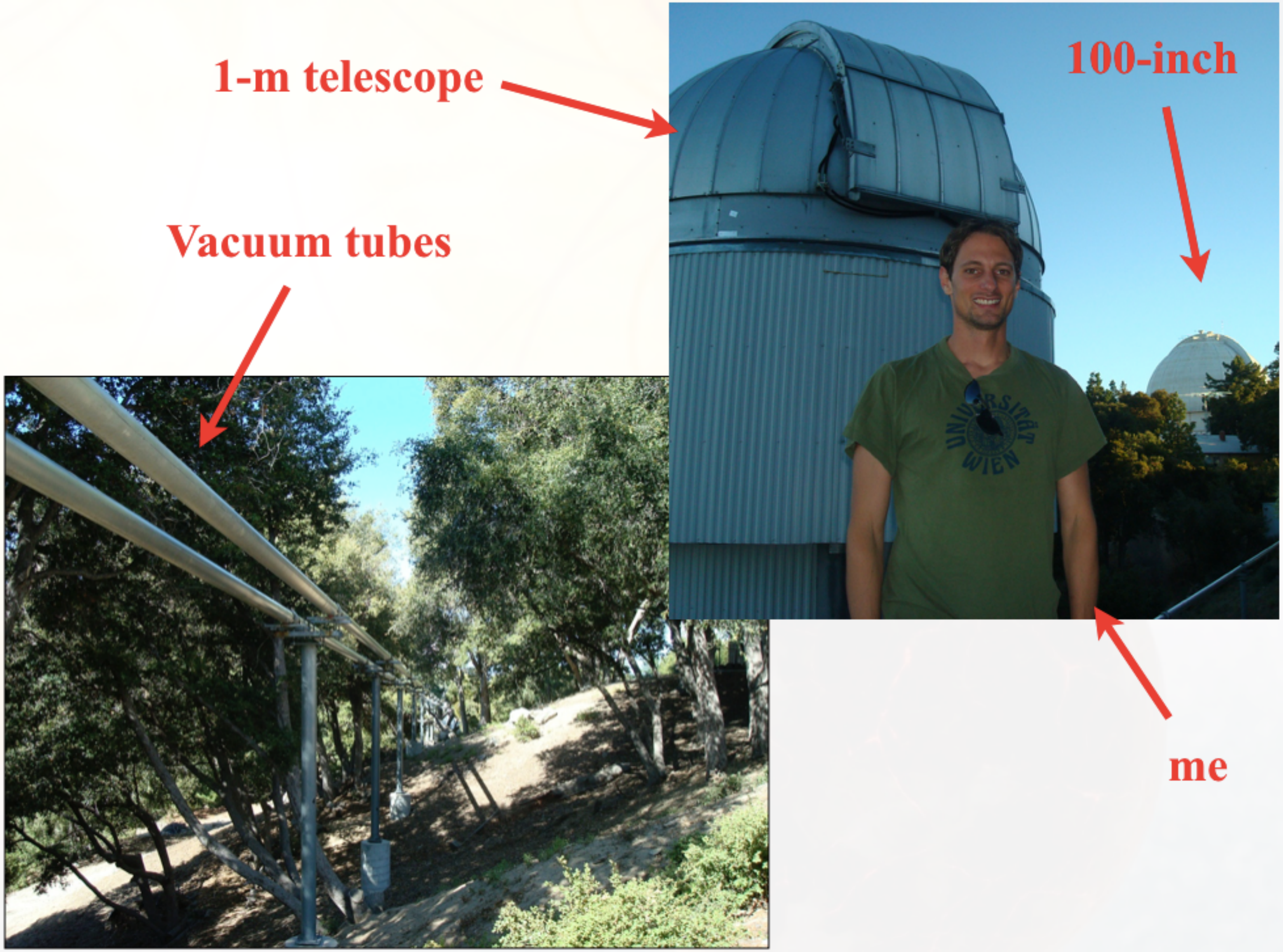
Center for High-Angular Resolution Astronomy



Daniel Huber



1-m telescope

100-inch

Vacuum tubes

me

Dan Huber

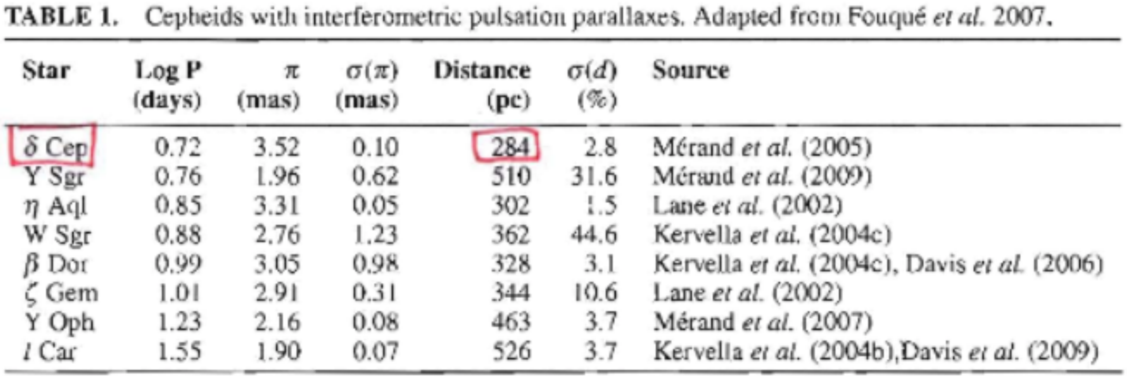


TABLE 1. Cepheids with interferometric pulsation parallaxes. Adapted from Fouqué *et al.* 2007.

Star	Log P (days)	π (mas)	$\sigma(\pi)$ (mas)	Distance (pc)	$\sigma(d)$ (%)	Source
δ Cep	0.72	3.52	0.10	284	2.8	Mérand *et al.* (2005)
Y Sgr	0.76	1.96	0.62	510	31.6	Mérand *et al.* (2009)
η Aql	0.85	3.31	0.05	302	1.5	Lane *et al.* (2002)
W Sgr	0.88	2.76	1.23	362	44.6	Kervella *et al.* (2004c)
β Dor	0.99	3.05	0.98	328	3.1	Kervella *et al.* (2004c), Davis *et al.* (2006)
ζ Gem	1.01	2.91	0.31	344	10.6	Lane *et al.* (2002)
Y Oph	1.23	2.16	0.08	463	3.7	Mérand *et al.* (2007)
ι Car	1.55	1.90	0.07	526	3.7	Kervella *et al.* (2004b),Davis *et al.* (2009)

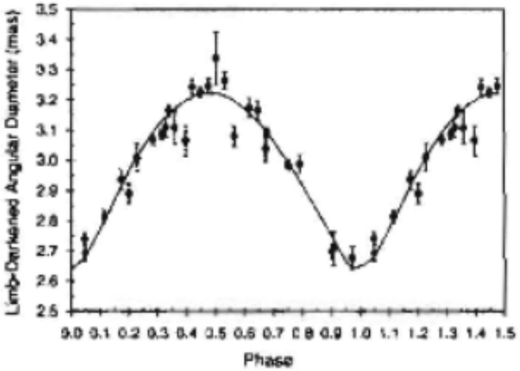
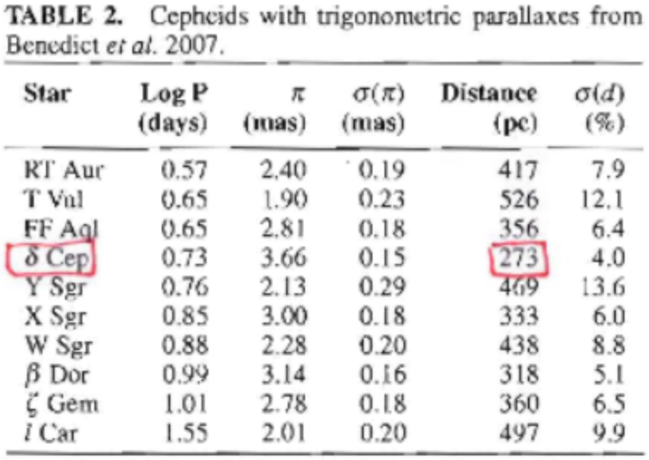


FIGURE 3. Observed angular diameters (points) of ι Car compared to scaled linear displacements (smooth curve). Data from SUSI. Figure from Davis *et al.* (2009).



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ζ Gem	1.01	2.78	0.18	360	6.5
ι Car	1.55	2.01	0.20	497	9.9

- Comparison of Cepheid distances via interferometry-based BW and HST parallaxes
- Good agreement between HST parallaxes and B-W!!

Another absolute method: light echos

SN 1987A in the LMC was a type II SN with progenitor a blue supergiant which had a mass loss event which gave off a circular shell before it went supernova

At the time of the SN this shell was 0.2 pc away. It was photoionized by the SN's UV flux (when it arrived!) and the ring observed by HST some 3.5 years after its explosion… HST image gives us the angular extent of the ring

HST image

Light travel time

- UV monitoring of SN1987A by IUE (an early UV satellite) showed that the light curve of the narrow emission lines (from the photoionized ring) had a delay of several months after the SN explosion
- The delay was caused by the light travel time to the ring and so we can measure the distance to the LMC using the angular size and the speed of light
- Details of geometry in homework…..

Workaday distance estimates for field stars

- Photometric ‘parallax’: since any star spends most of its time on the main sequence, assume that the stars you are interested in are main sequence stars, measure a color, and derive absolute magnitude from an empirical or theoretical ZAMS
- Some more sophisticated versions of this estimate metallicity from stellar colors too
- Q: what bias might be problematical with the assumption about a star being on the main sequence?

Spectroscopic “parallax” for field stars

- Use spectrum to estimate [Fe/H] and luminosity class (luminosity can be tough)
- Use stellar color and fiducial or isochrone to read off absolute magnitude
- Then use m-M = 5 log d (in pc) – 5

(or estimate reddening and add that in; above

Galactic latitude |b|=5 one can use estimate from Schlegel et al 1998 who calibrated the far-IR emission of IRAS with COBE data)