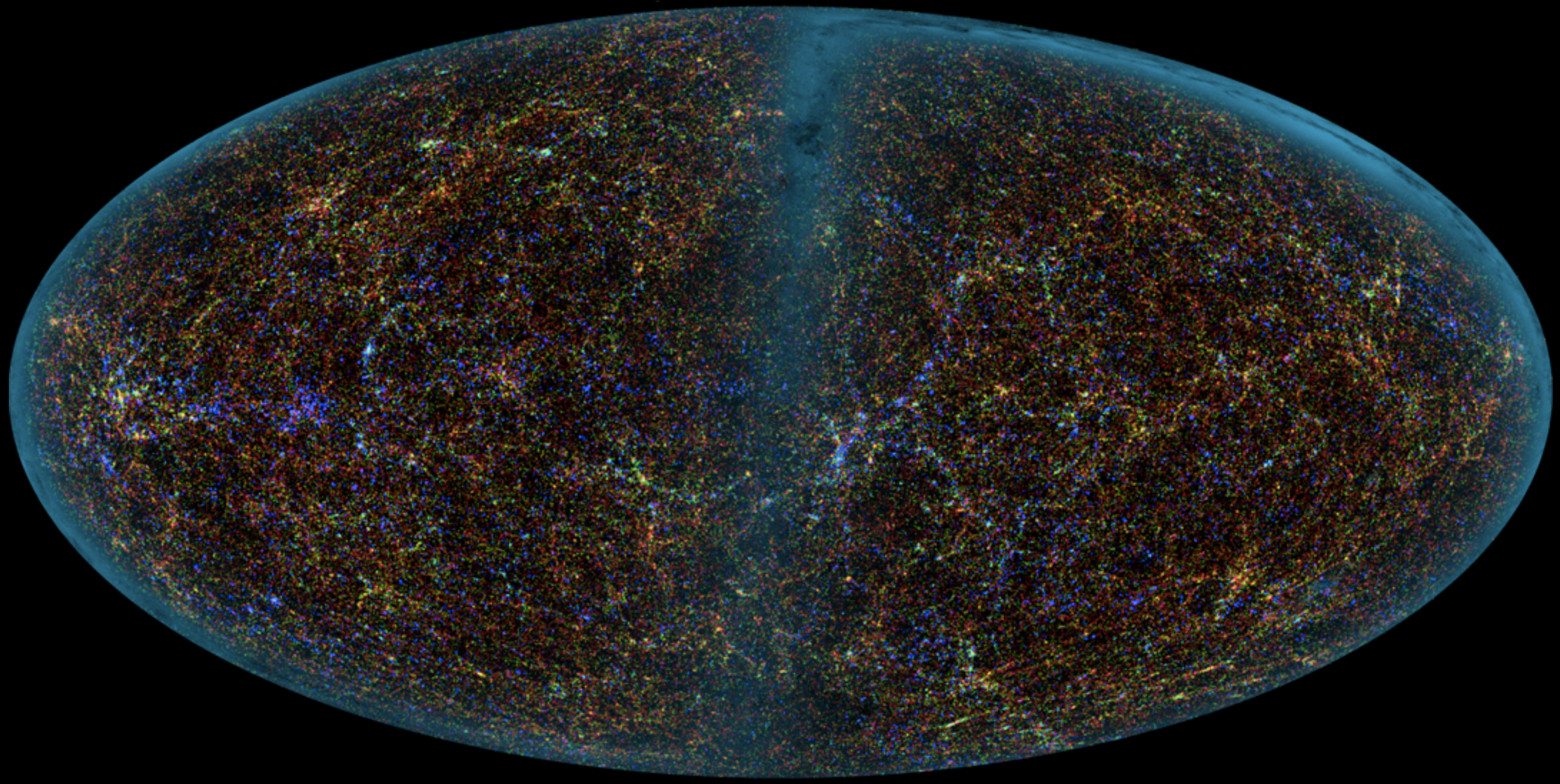
Cosmology
and Large Scale Structure



<u>Today</u>
Distance Scale
secondary indicators

Homework 3 due one week from today

3 October 2024

http://astroweb.case.edu/ssm/ASTR328/

Distance Scale

So why do we need to get this right?

Astrophysics:

- turn observed properties of objects (apparent magnitude, angular size) into intrinsic properties of objects (luminosity, physical size)

Measure H_0:

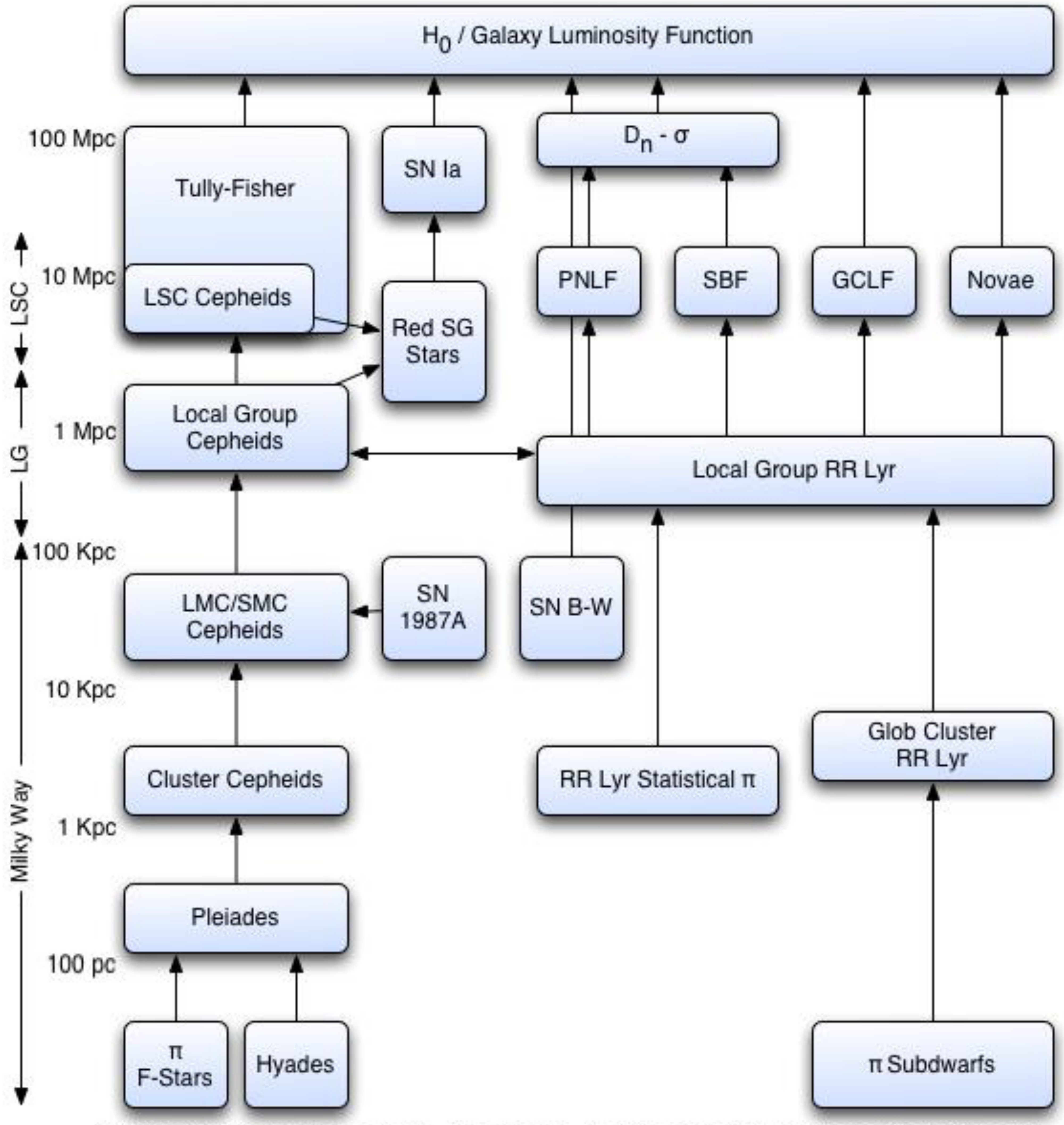
- Cosmological parameter, want local, independent confirmation of cosmological measurements at high redshift.
- Once measured, can use it as a distance indicator (Hubble distance: $d=v/H_0$)

Measure peculiar motions in the universe:

- $v_{obs} = H_0 d + v_{pec}$
- if we know distance *independent* of redshift, we can look for large scale velocity structure in the universe

Important Complications:

- An accurate measure of H_0 means getting out to a distance where $v_{pec} << H_0 d$.
- Local galaxies do *not* have useful Hubble distances, due to [peculiar motions]() and [Virgocentric flow]().
- Distances *within* clusters (ie with accuracies of +/- few Mpc) are *not knowable* via Hubble's law.
- Need *several* distance estimators to reduce systematic errors between methods.



Adapted by Stuart Robbins from: Jacoby et al. *A Critical Review of Selected Techniques for Measuring Extragalactic Distances.* PASP, **104** (1992).

physics of pulsating stars

calibration band-pass dependent

Pulsations of one Cepheid in many bands

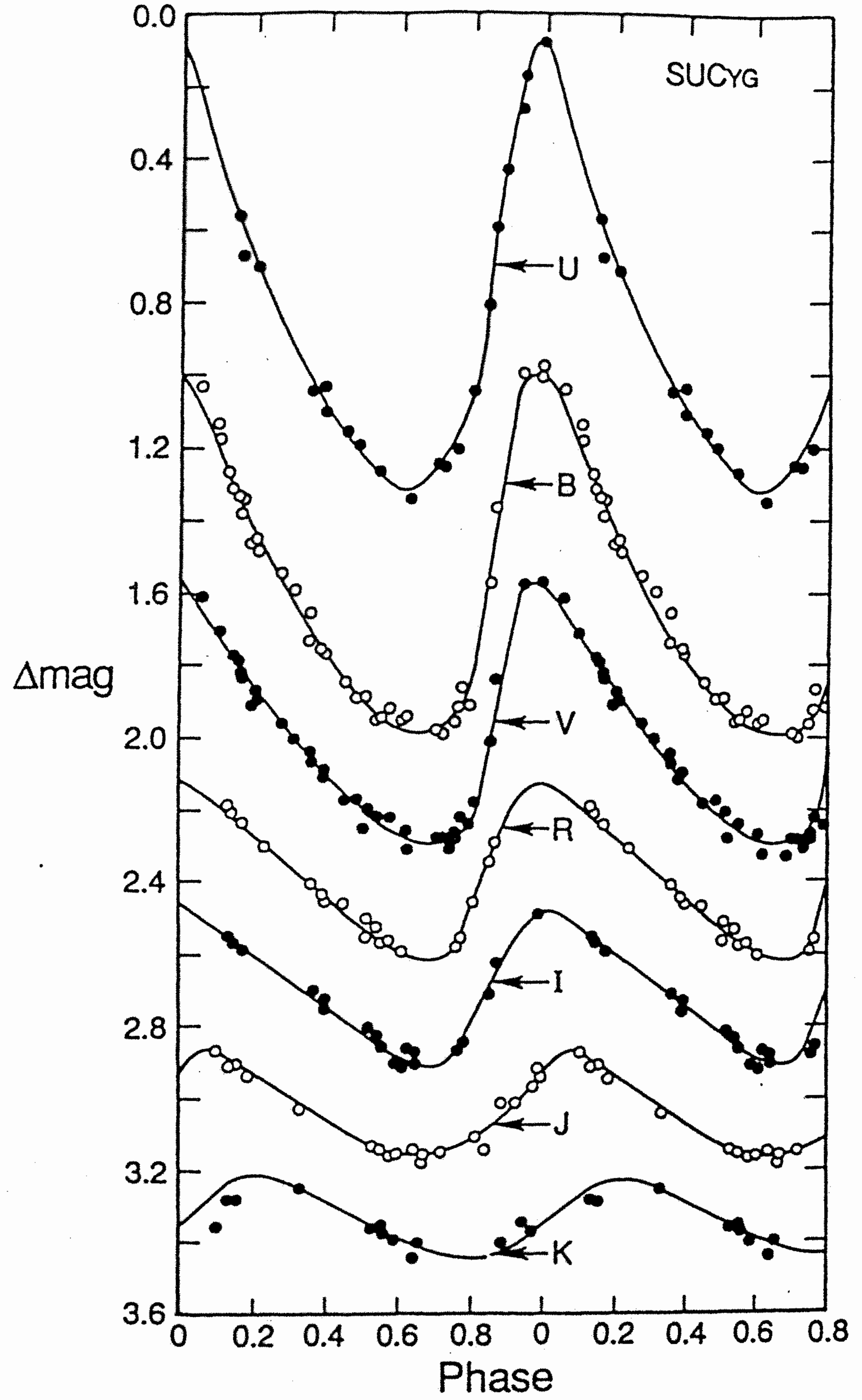
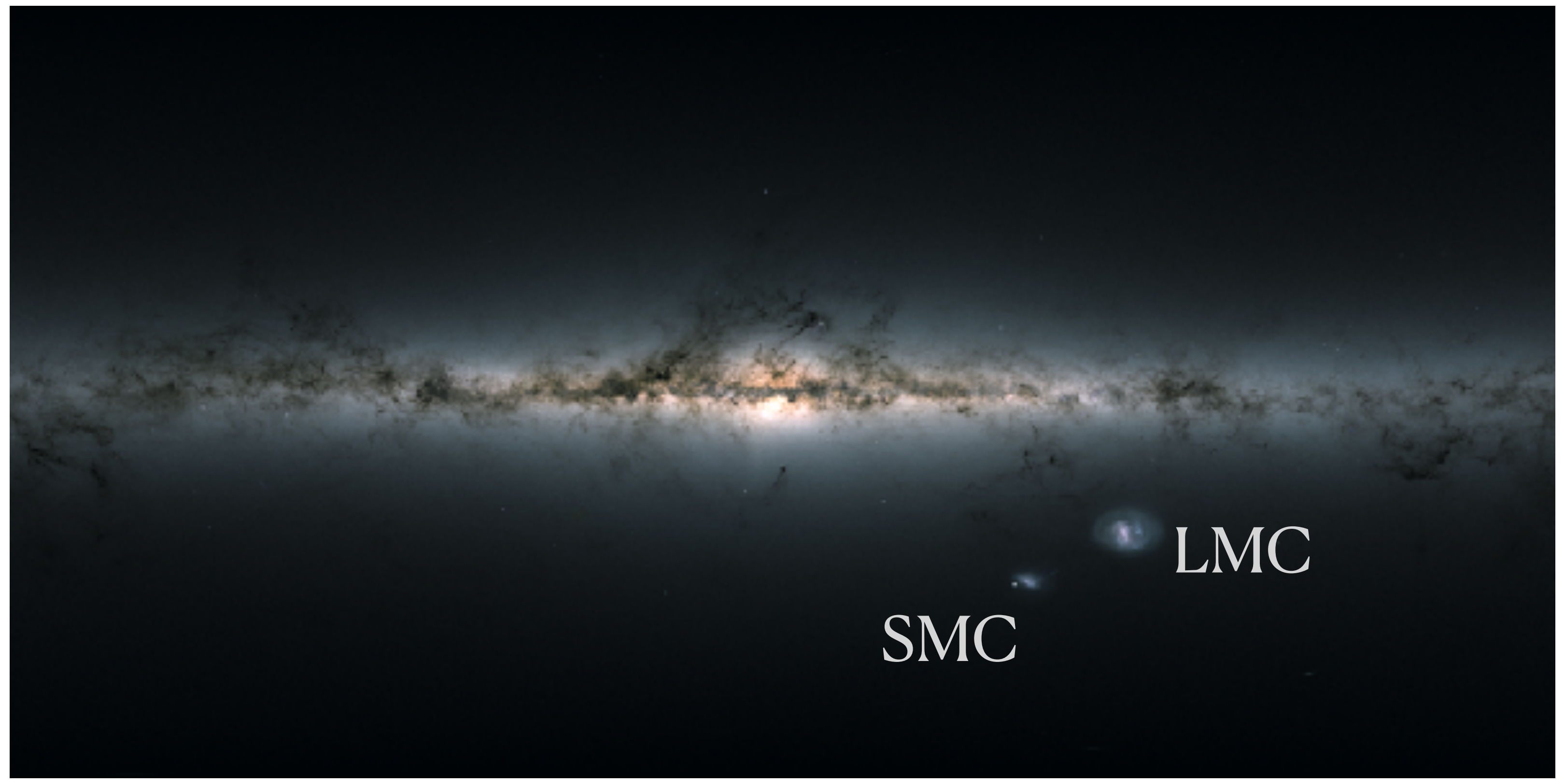


FIG. 5–Variations of amplitude and phase of maximum seen in the light curve of a typical Galactic Cepheid as a function of increasing wavelength. Note the monotonic drop in amplitude, the progression toward more symmetric light variation, and the phase shift of maximum toward later phases, all with increasing wavelength. Upper light curves are for short wavelengths (ultraviolet, blue, and visual); lower light curves are for long wavelengths (red and near-infrared out to $K = 2.2$ microns).



P-L relations in many bands

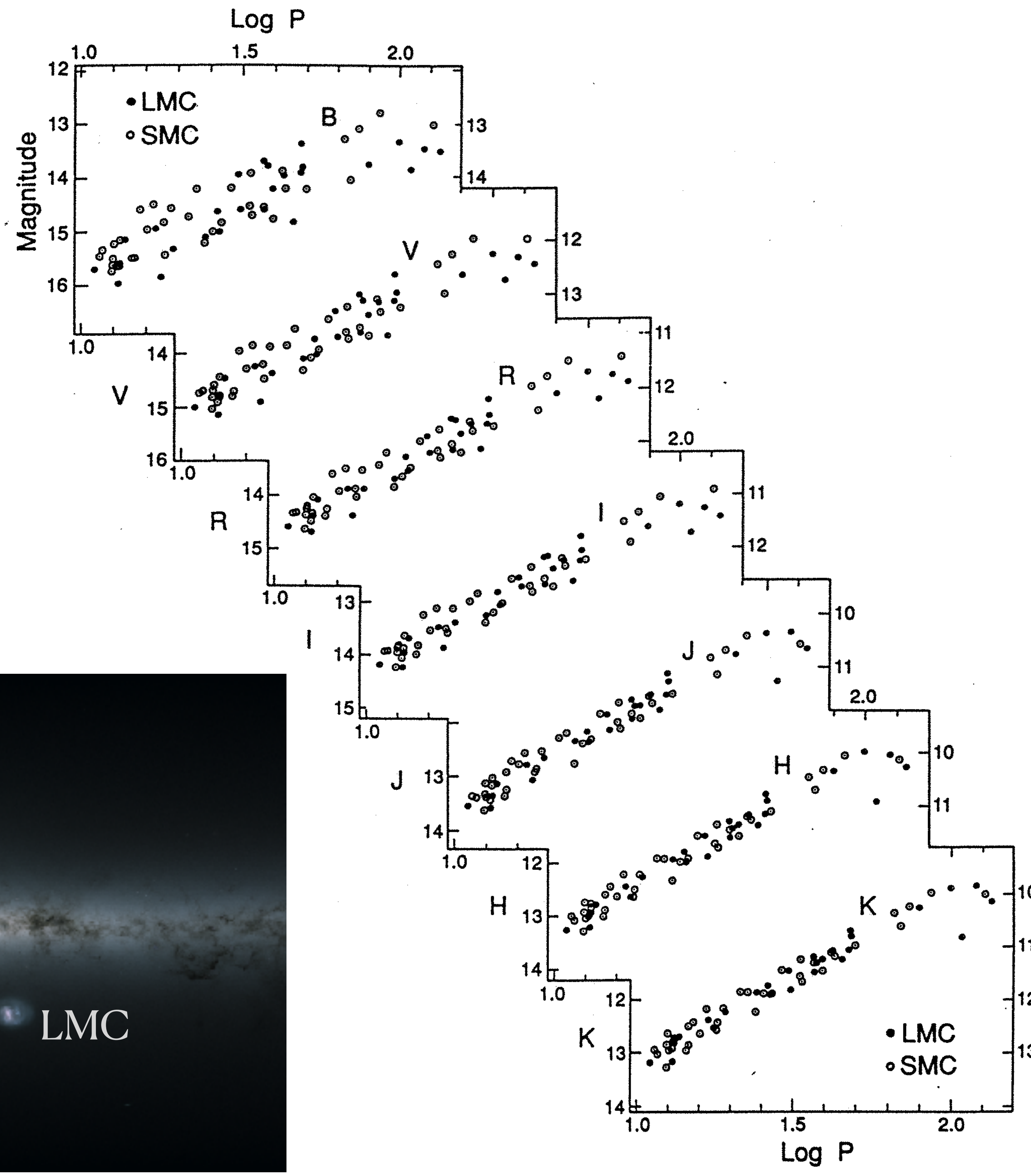
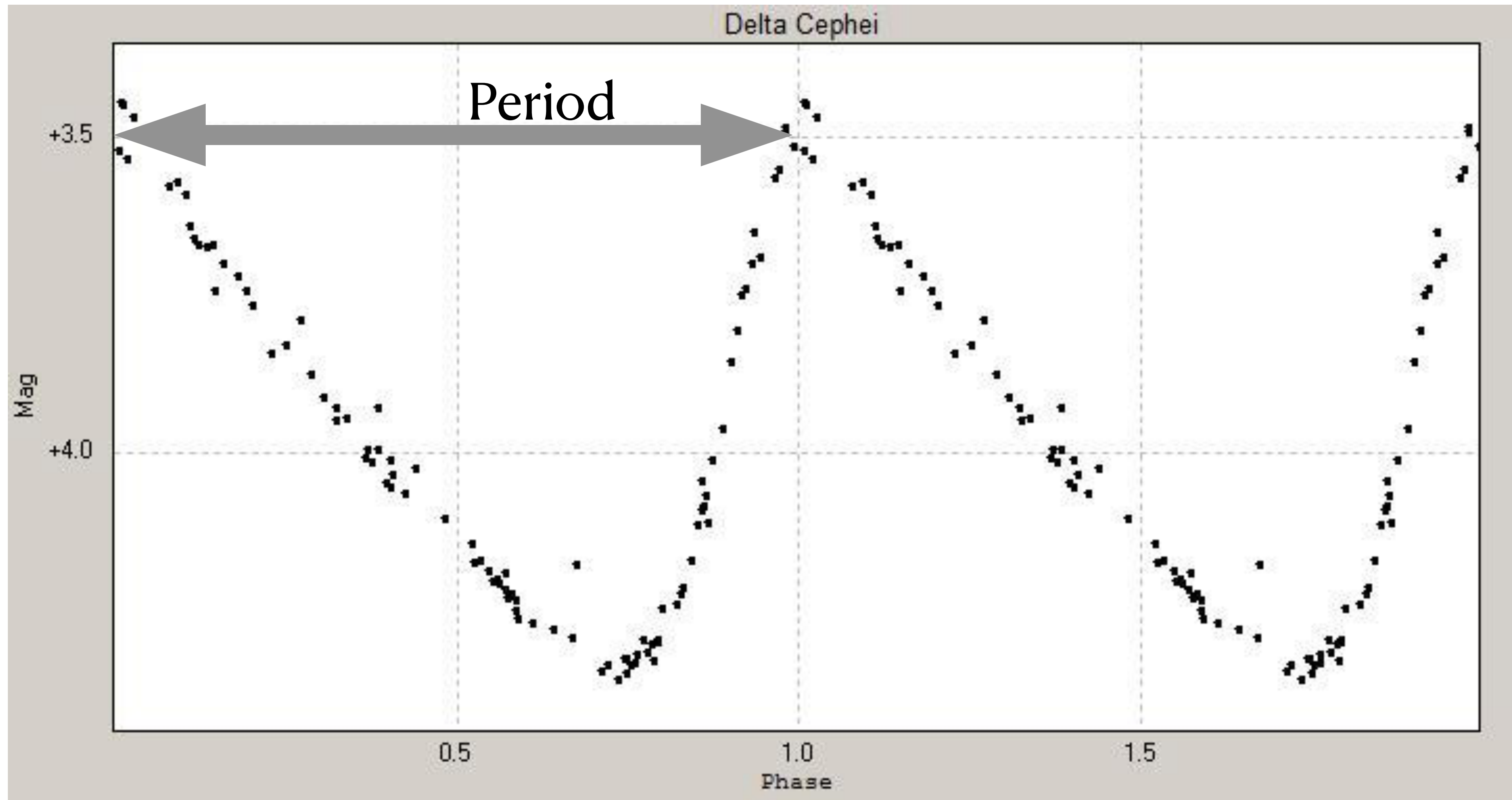


FIG. 4–Magellanic Cloud Cepheid period-luminosity relations at seven wavelengths, from the blue to the near-infrared, constructed from a self-consistent data set (Freedman & Madore 1992). LMC Cepheids are shown as filled circles; SMC data, shifted to the LMC modulus, are shown as open circles. Note the decreased width and the increased slope of the relations as longer and longer wavelengths are considered.

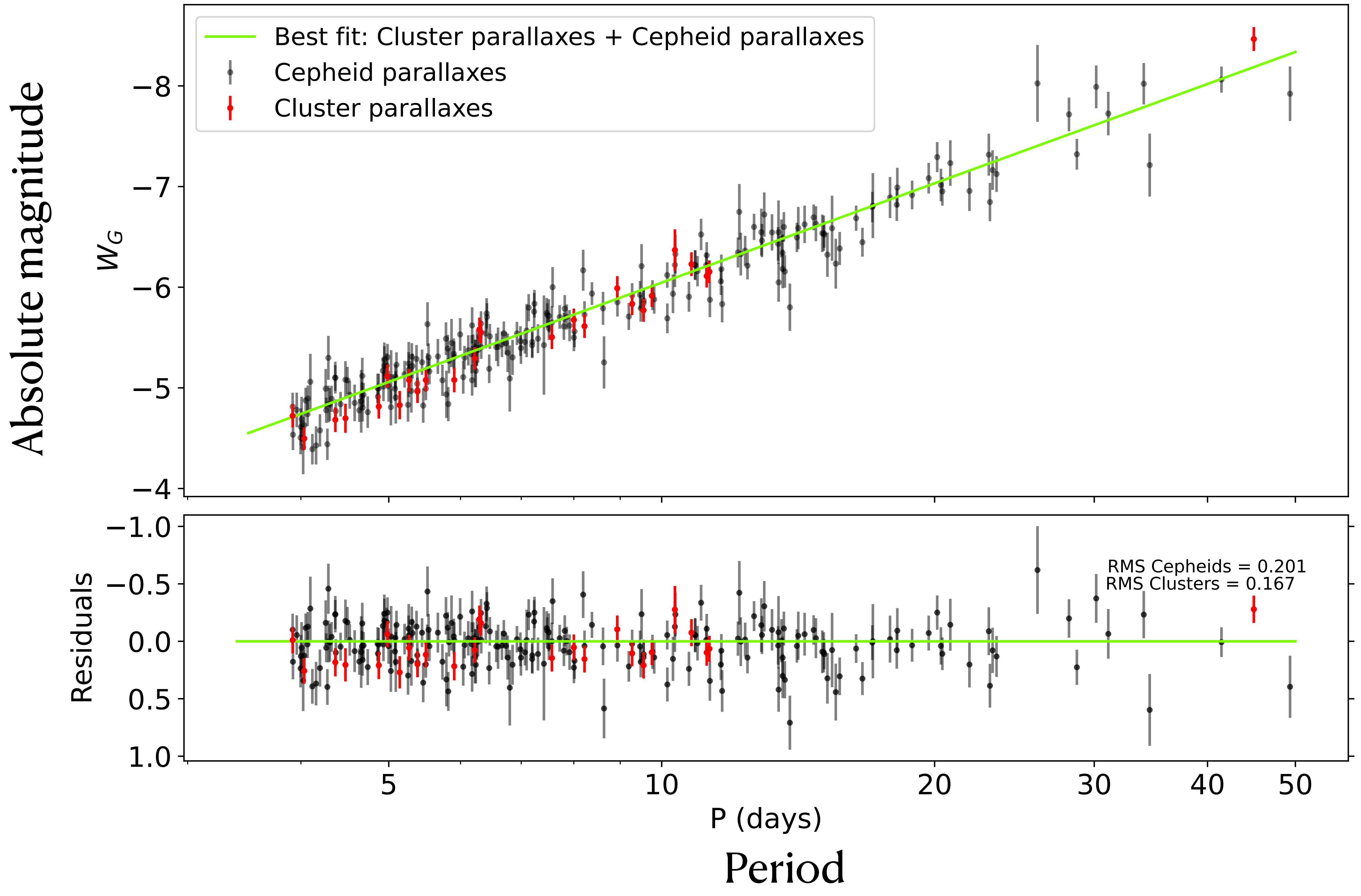
Distance Scale

- Bright Star Standard Candles
  - Cepheids, RR Lyraes
  - calibrate by
    - parallax
    - main sequence fitting of clusters containing these stars



Cruz Reyes & Anderson 2023 (A&A 672, A85)

Cepheid P-L relation from Gaia



Bright Cepheids have long periods;
faint Cepheids have short periods.

Discover through repeated observation.
Measure period, infer luminosity from P-L relation.
Apply inverse square law, accounting for extinction A:

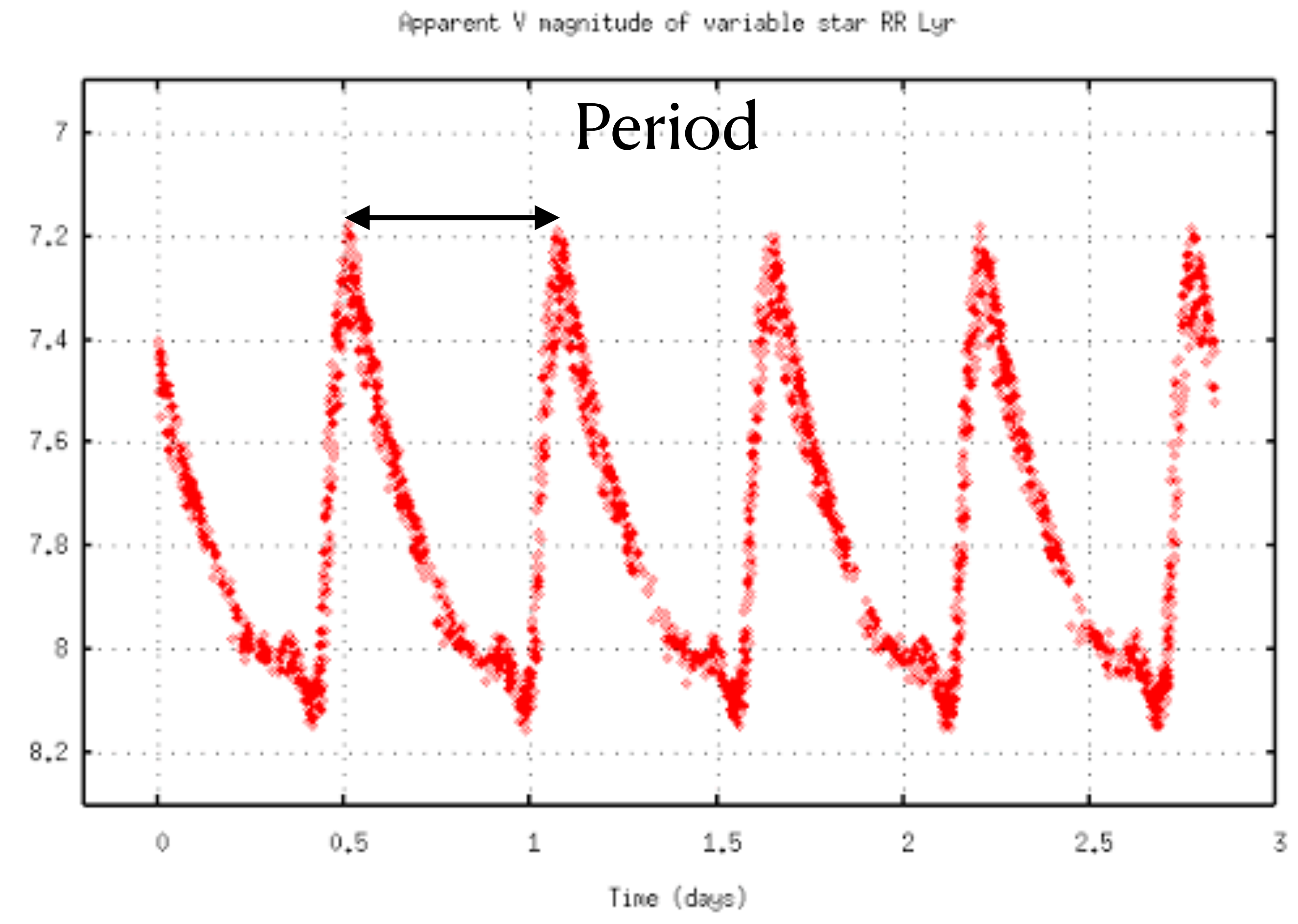
$$m_K - M_K = 5\log(d) - 5 + A_K$$

calibration band-pass dependent

metallicity dependent

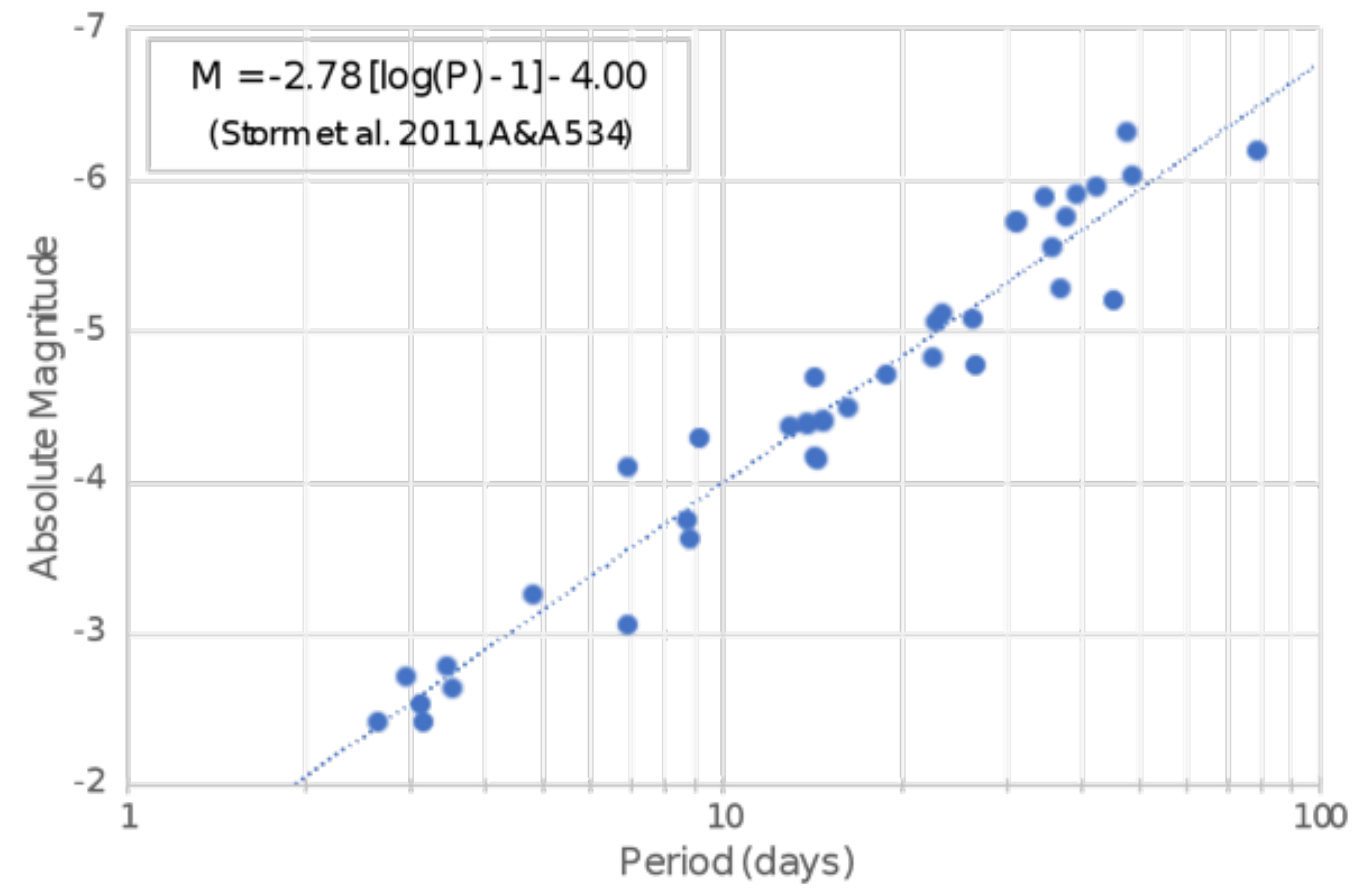
Distance Scale

- Bright Star Standard Candles
  - Cepheids, RR Lyraes
  - calibrate by
    - parallax
    - main sequence fitting of clusters containing these stars



RR Lyrae P-L relation

Absolute magnitude



Period

Bright RR Lyraes have long periods;
faint RR Lyraes have short periods.

Discover through repeated observation.
Measure period, infer luminosity from P-L relation.
Apply inverse square law, accounting for extinction A:

$$m_K - M_K = 5\log(d) - 5 + A_K$$

calibration band-pass dependent: $M_V = -4.12 - 2.88(\log P - 1)$

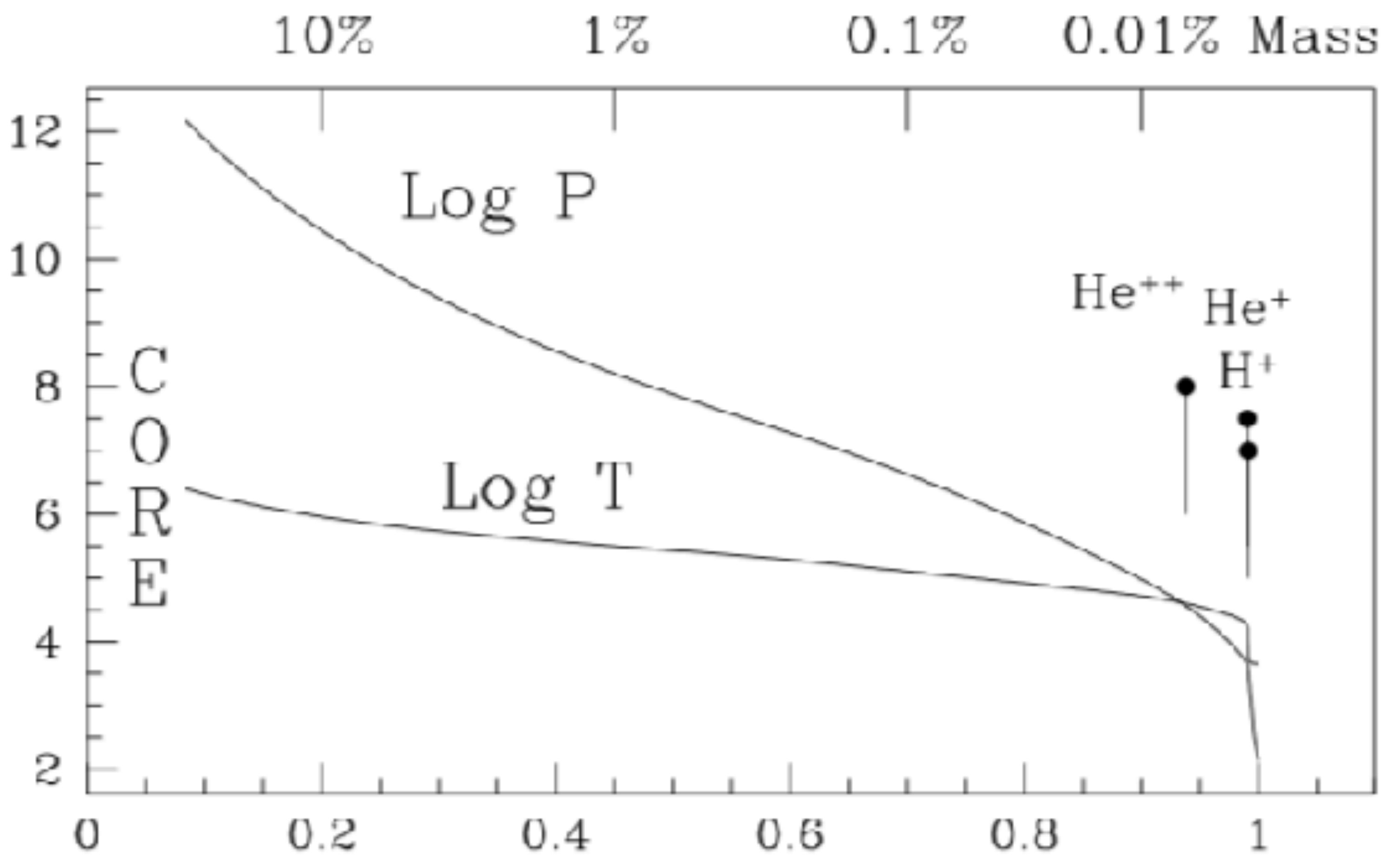
metallicity dependent

Distance Scale

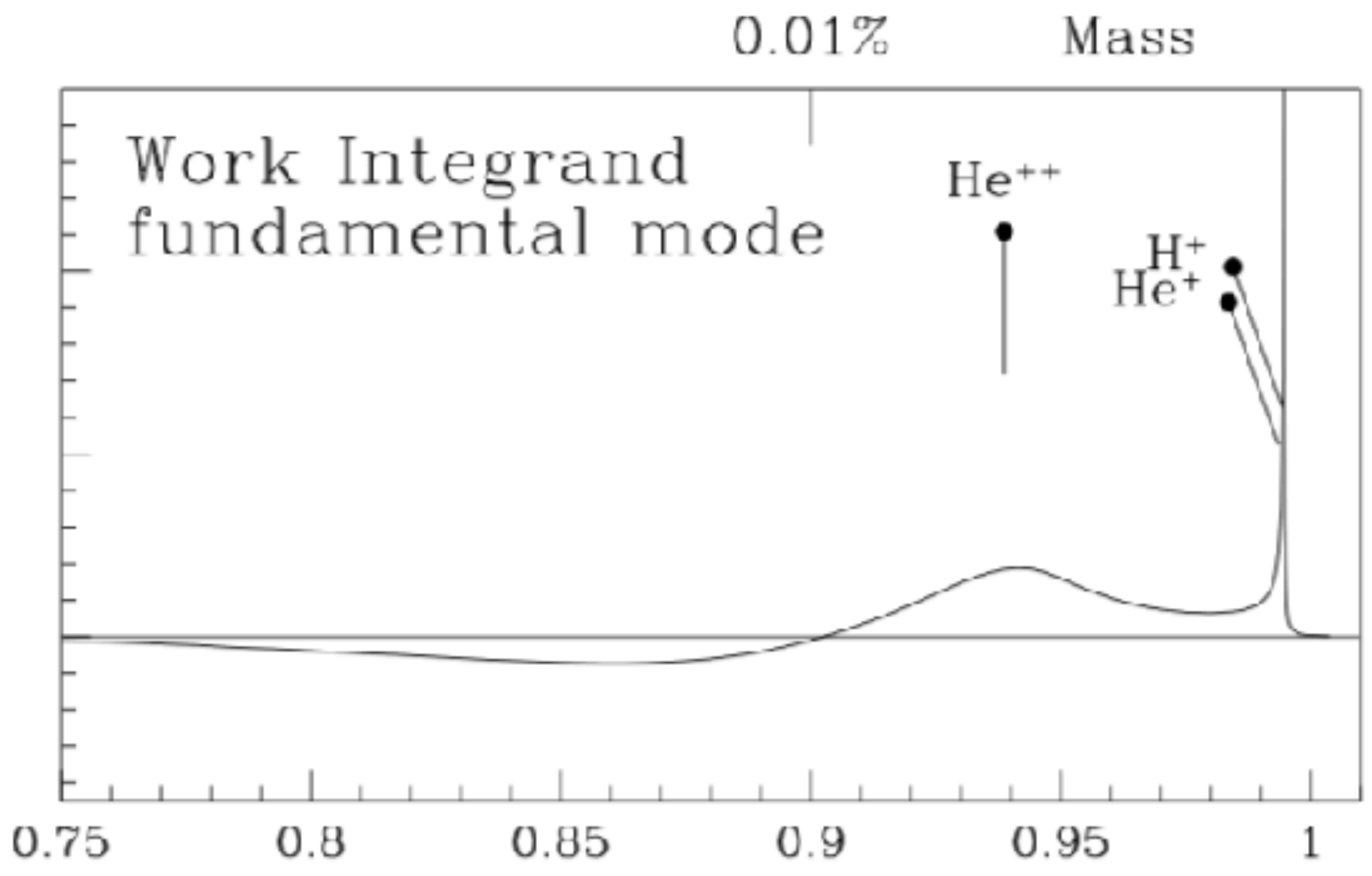
- Bright Star Standard Candles
  - Cepheids, RR Lyraes
    - pulsating stars

Oscillations driven by opacity instability that occurs when the He+ edge is near enough to the surface that there is insufficient pressure to contain it.

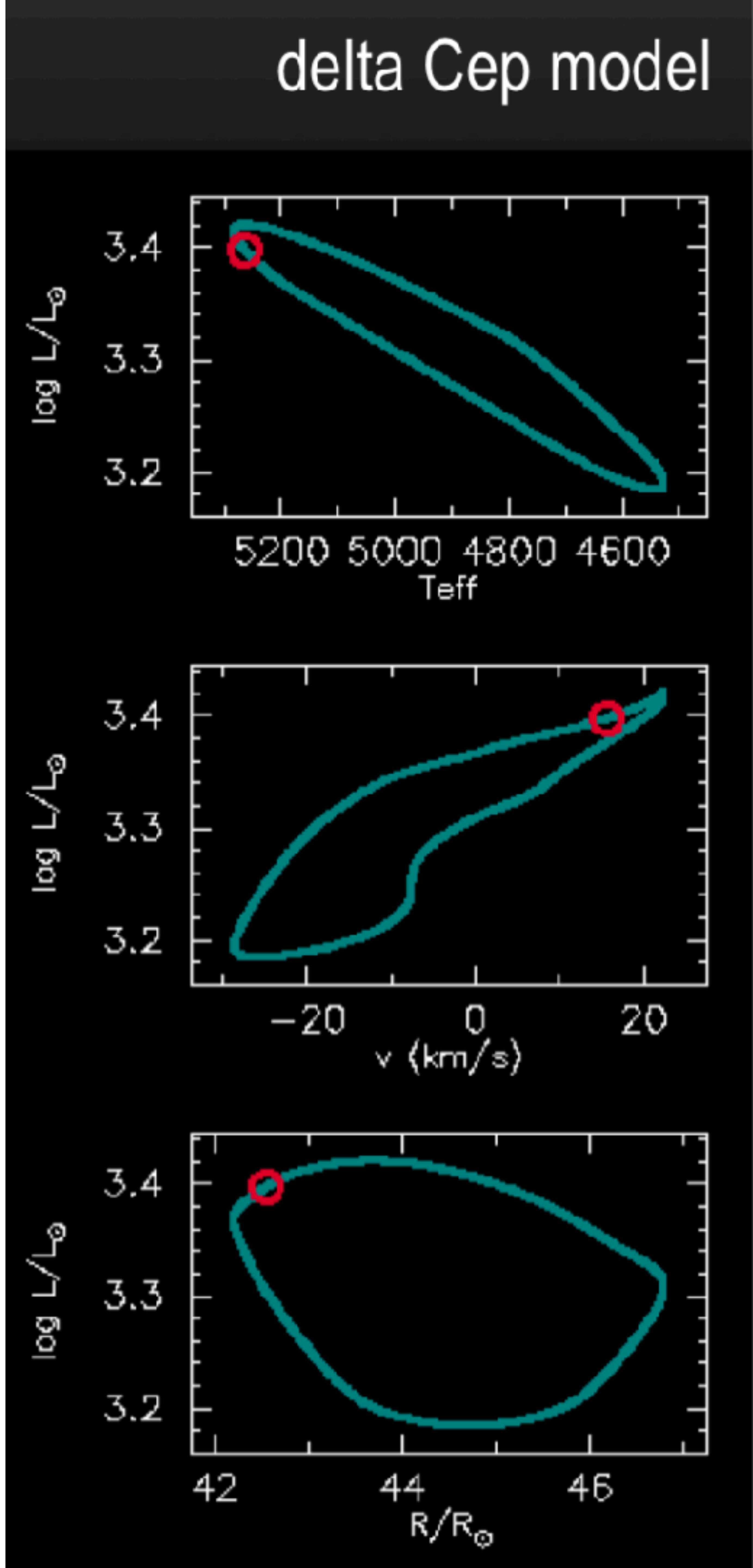
The opacity goes up instead of down with increasing temperature across the $He^+ \leftrightarrow He^{++}$ transition.



R/R_*

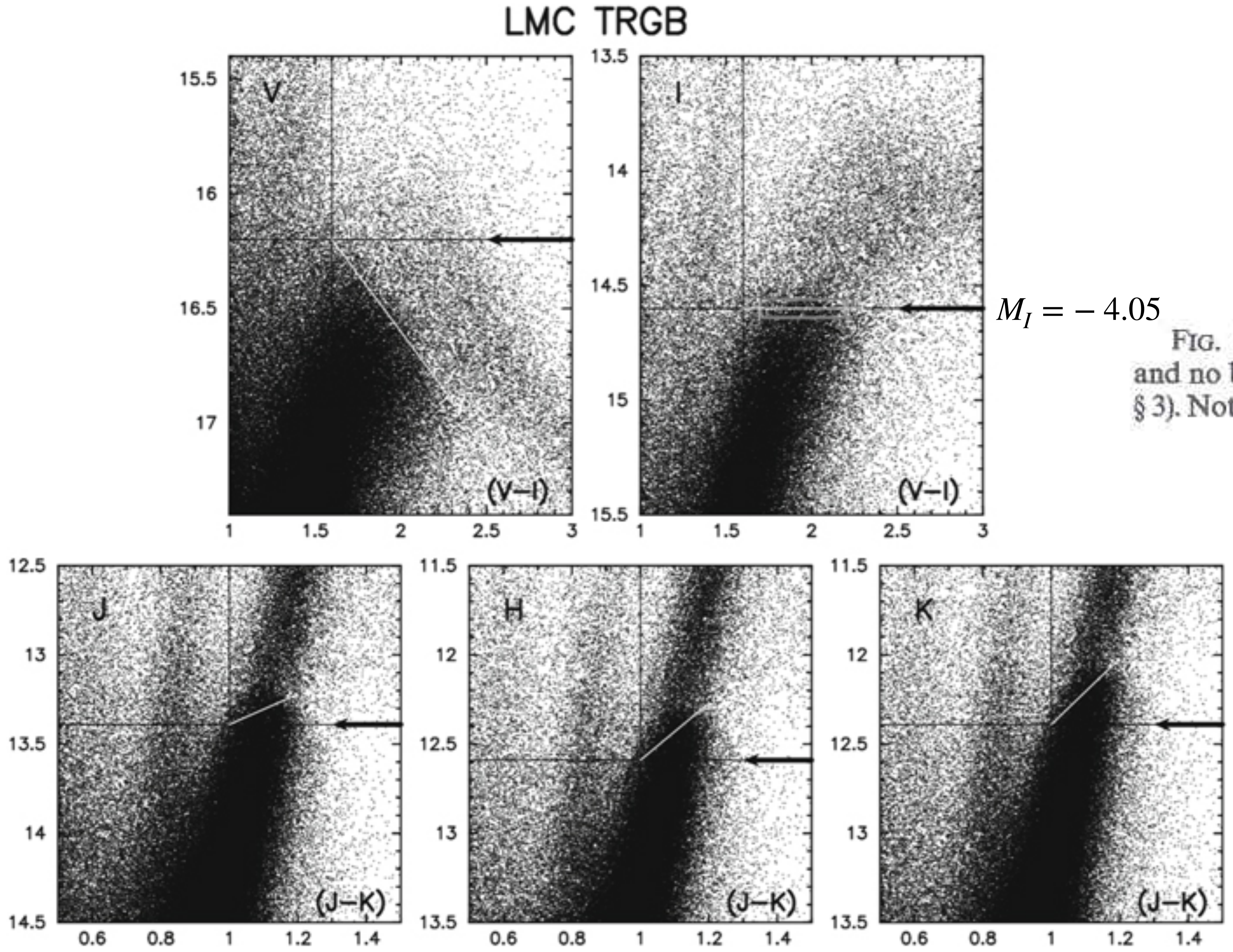


R/R_*



Distance Scale

- Bright Star Standard Candles
  - TRGB
  - calibrate by
    - main sequence fitting of clusters or an entire galaxy like the LMC



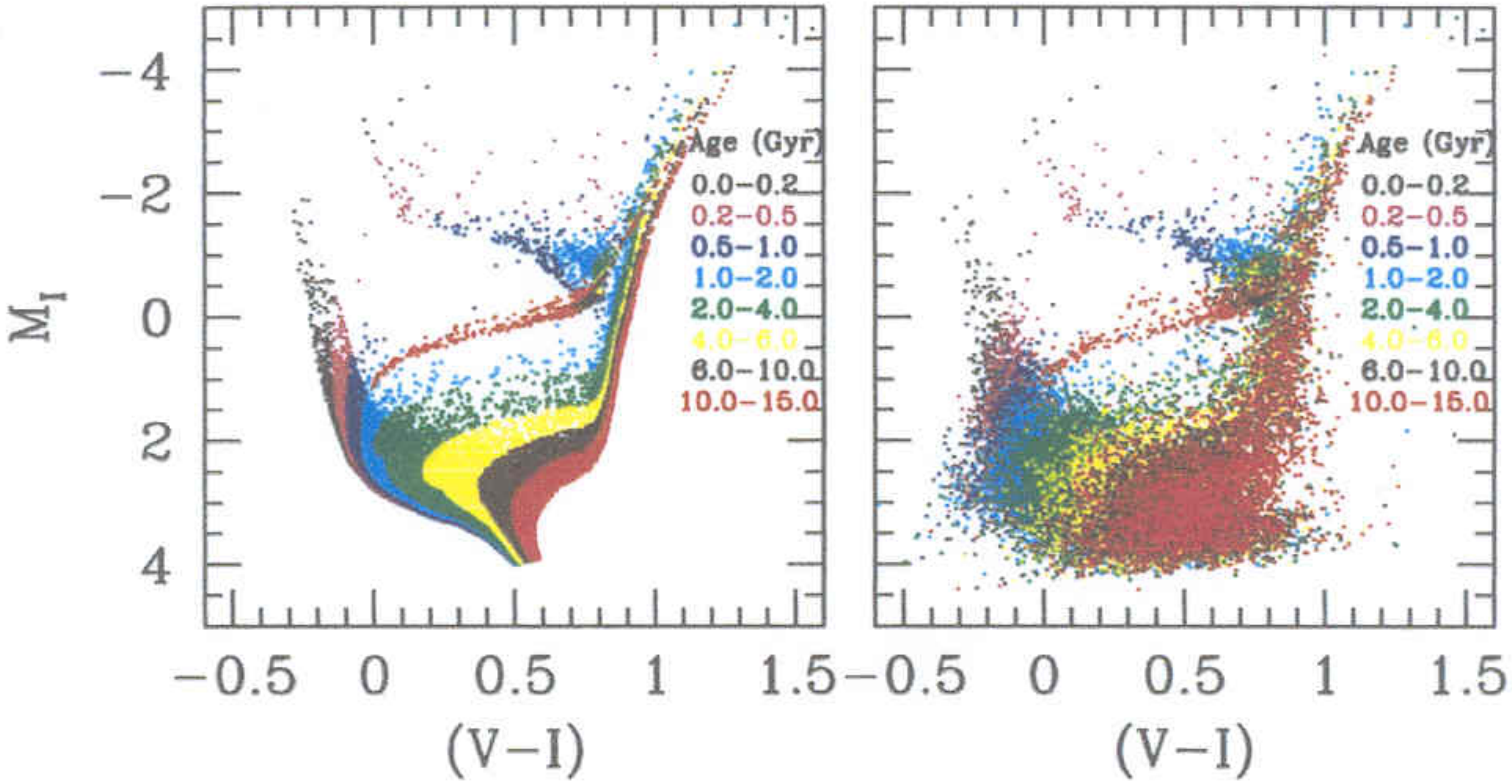


FIG. 2.—Set of partial models for a synthetic CMD computed with constant SFR(t) from 15 Gyr ago to the present, $Z = 0.0004$, Kroupa et al. (1993) IMF, and no binary stars. The left panel shows the theoretical synthetic CMD, while in the CMD of the right panel observational errors have been simulated (see § 3). Note the sequence of ages in both the MS and the subgiant branch and, although less definite, also in the RC and HB.

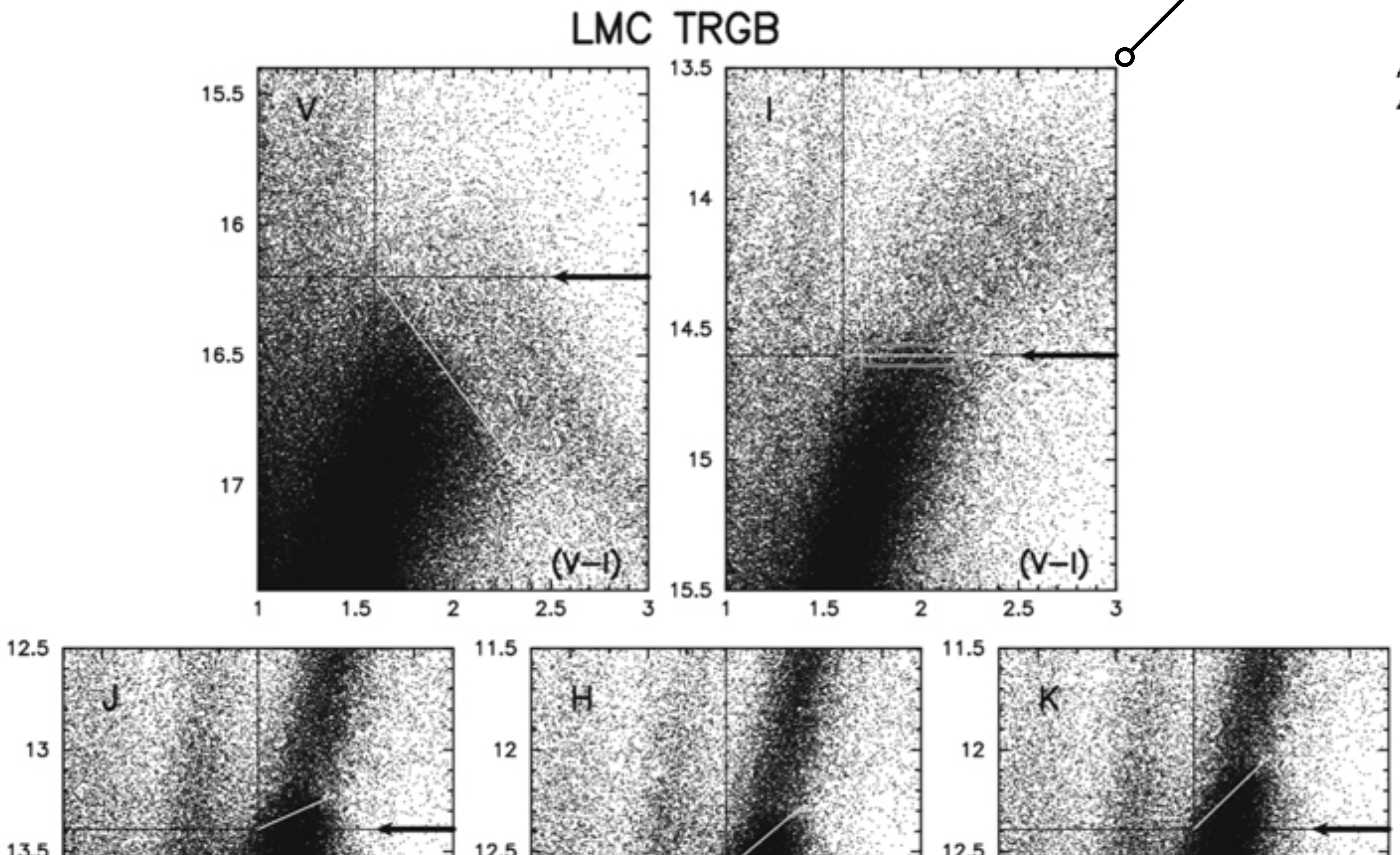
Works best in the I-band for low metallicity systems, where

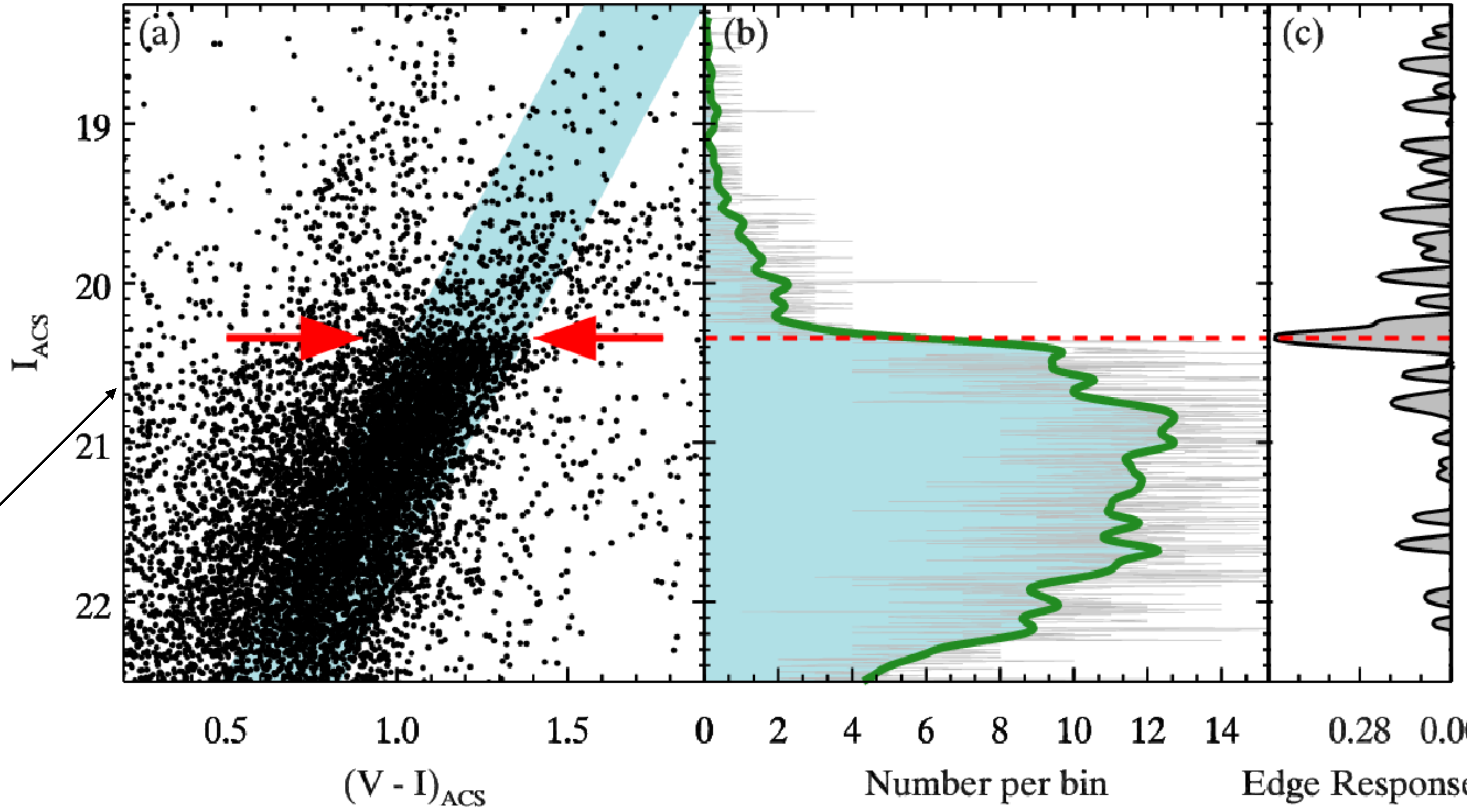
$$\text{TRGB} \quad M_I = -4.05$$

In general, both bandpass and metallicity dependent.

Distance Scale

- Bright Star Standard Candles
  - TRGB
  - calibrate by
    - main sequence fitting of clusters or an entire galaxy like the LMC





Works best in the I-band for low metallicity systems, where

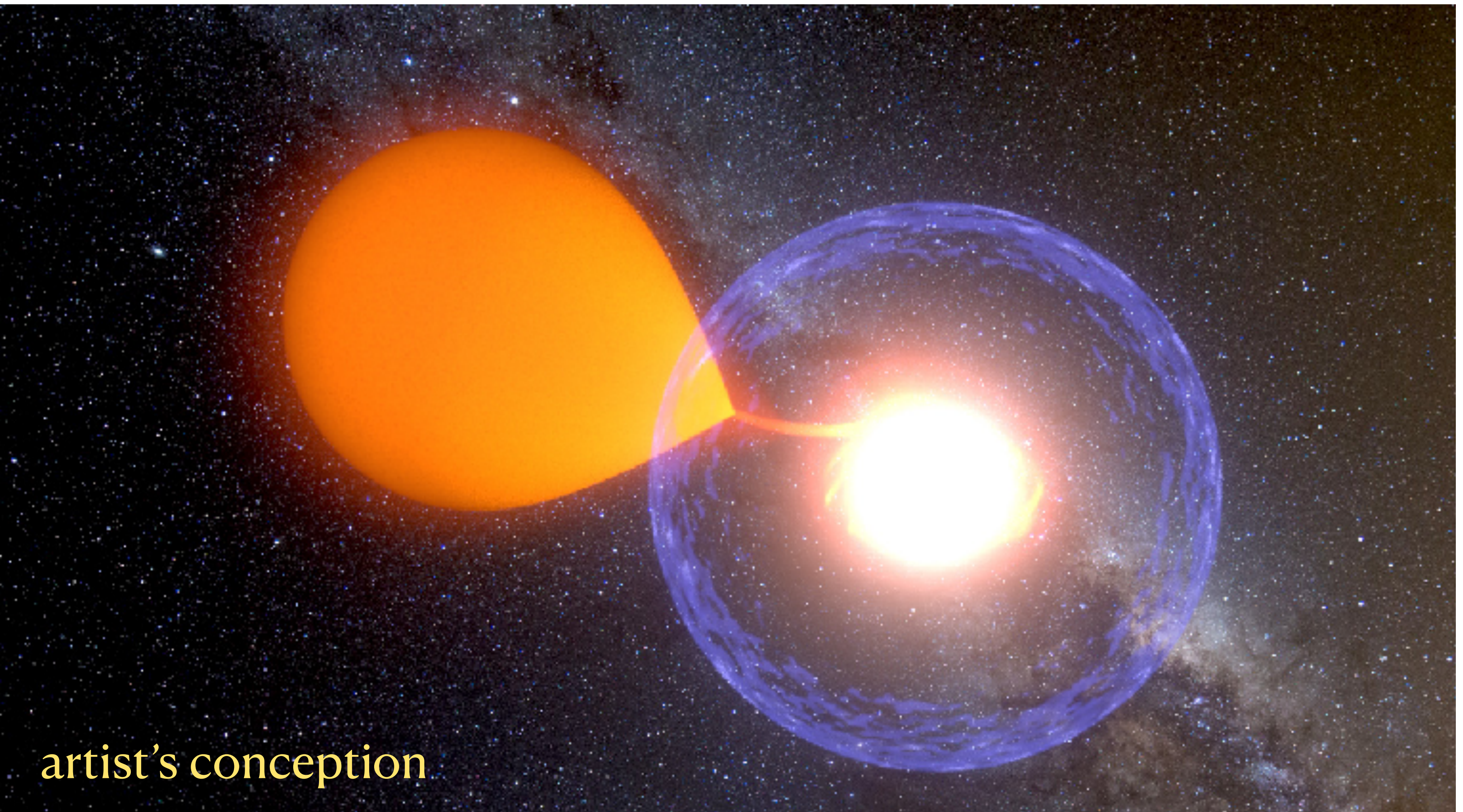
TRGB $M_I = -4.05$

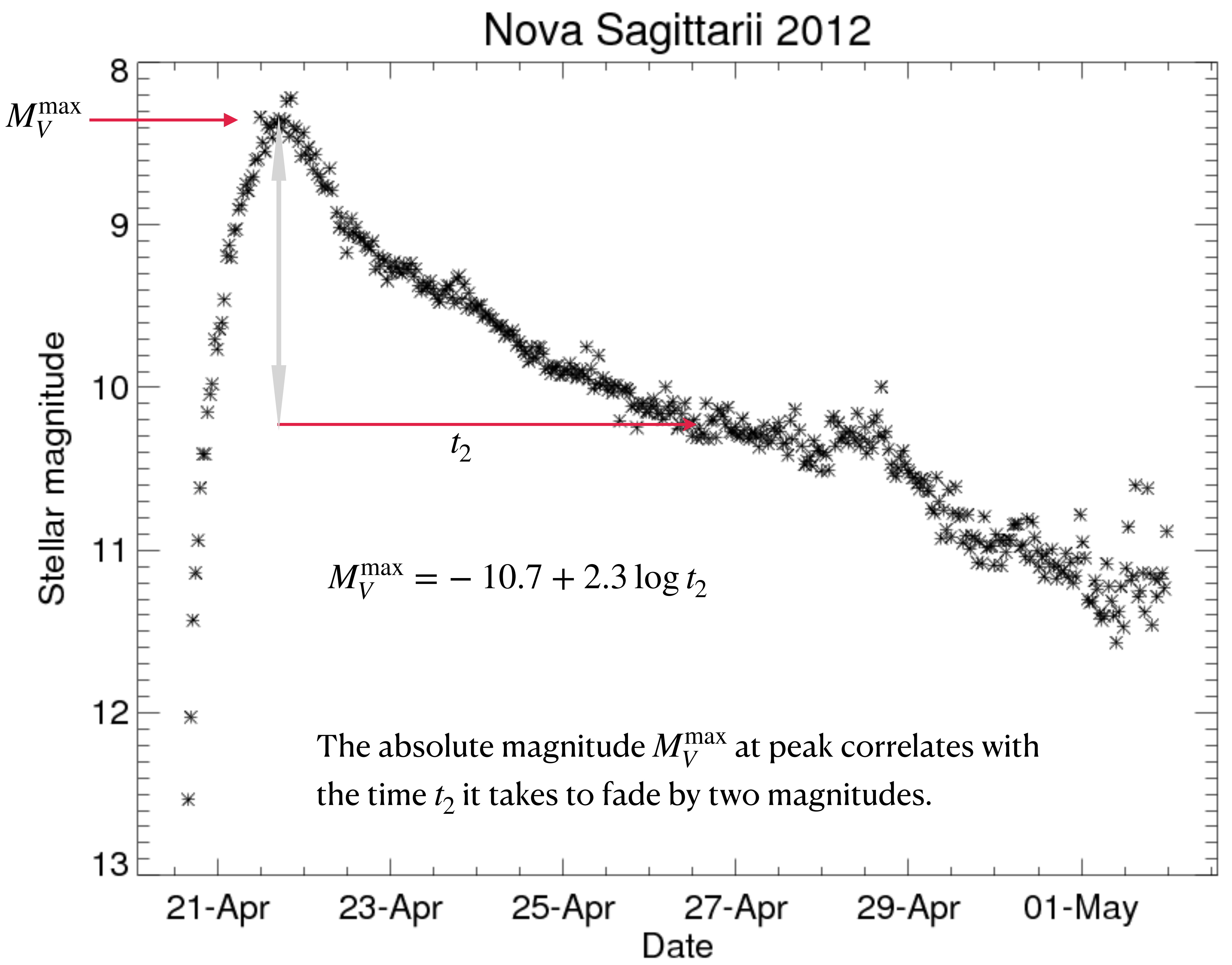
In general, both bandpass and metallicity dependent.

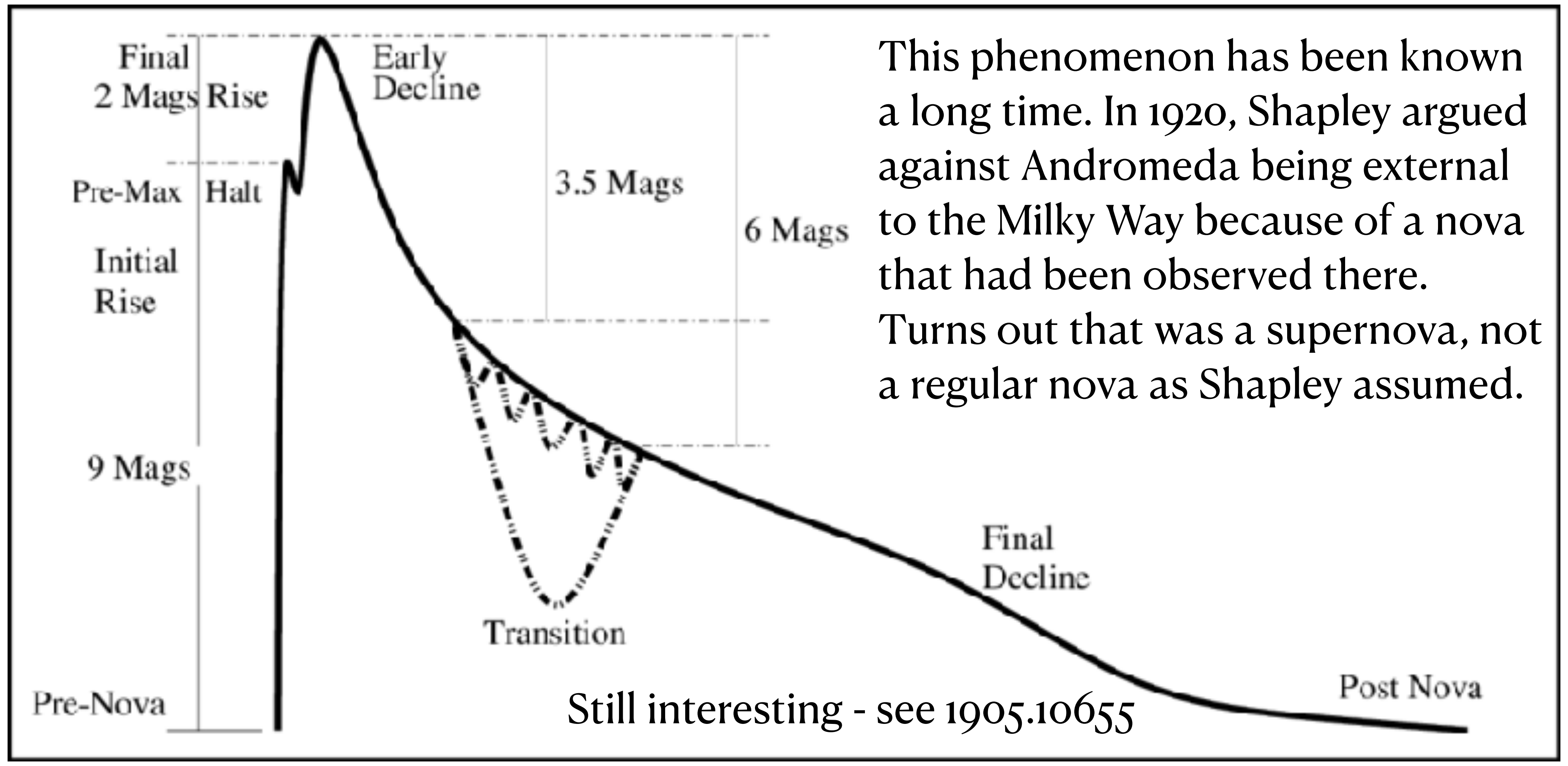
Distance Scale

- Secondary Distance Indicators
  - Novae
    - fuel ignition on surface of white dwarf

A white dwarf in a binary can accrete gas from its partner if it fills its Roche lobe after evolving into a giant. The accumulated material can reach a critical point where H to He fusion is ignited in the layer on the surface of the white dwarf. This flashes brightly as a nova and promptly self-extinguishes. Only the surface is affected, so the process can repeat (repeating novae are known).







This phenomenon has been known a long time. In 1920, Shapley argued against Andromeda being external to the Milky Way because of a nova that had been observed there. Turns out that was a supernova, not a regular nova as Shapley assumed.

Still interesting - see 1905.10655

Distance Scale

- Secondary Distance Indicators
  - Planetary nebulae
    - sharp edge in [O III] luminosity function

Planetary nebulae (PN) are the last stage of stellar evolution for low mass stars when they expel their outer layers into space, leaving behind the core as a white dwarf. For a brief period, the core is hot enough to ionize the departing gas. PN can be recognized by their strong [O III] emission. Their [O III] luminosity function has a strong cut off, which makes a serviceable distance indicator.

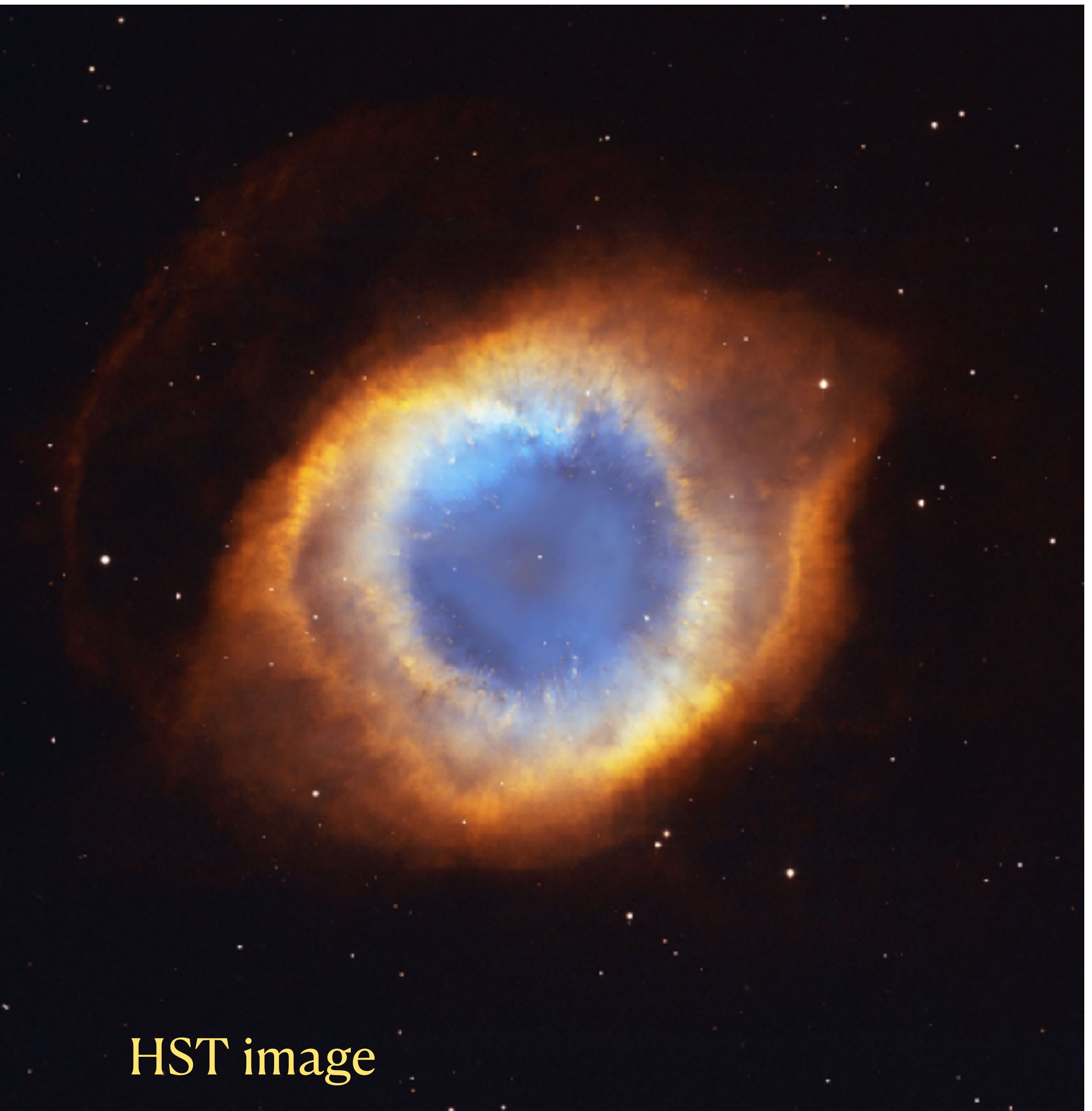
$$\Phi_{\rm PN} \sim e^{0.307}\left(1 - e^{3(m_{\rm cut}-m)}\right)$$

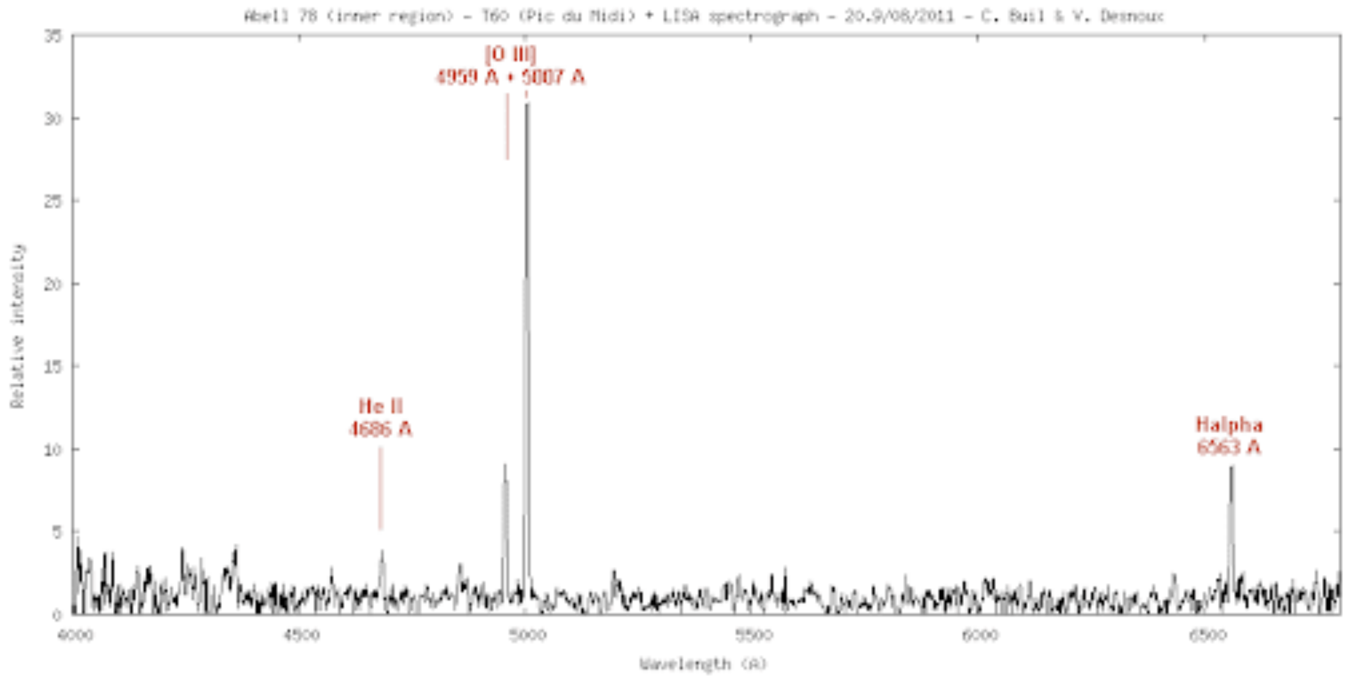
$$m_{[\rm O\ III]} = -2.5 \log f_{5007} - 21.4$$

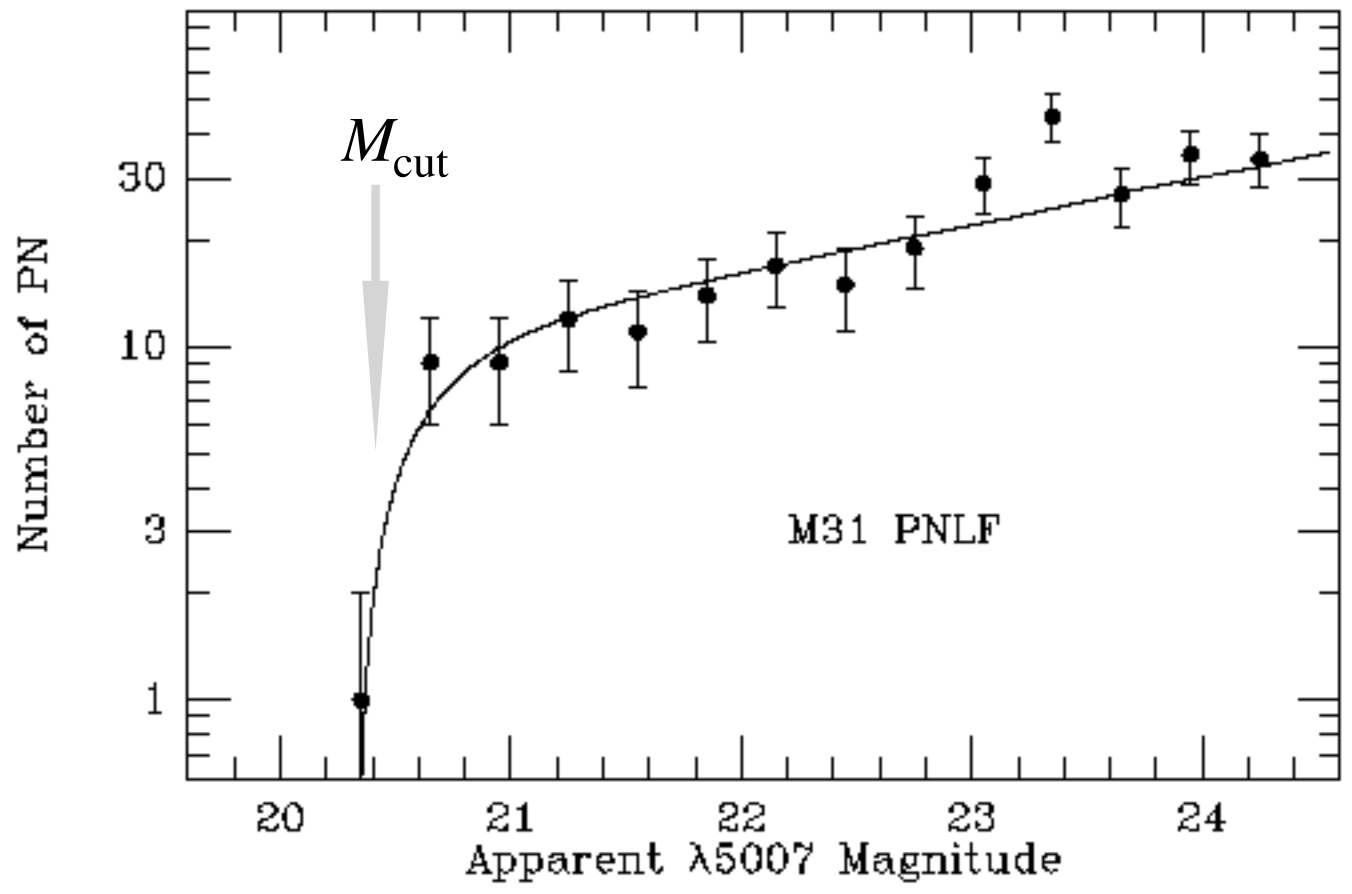
$$M_{\rm cut} = -4.6 \pm 0.1$$

with f_{5007} in W m^{-2}

Nearby planetary nebula







Appears as [O III] dots in distant galaxies

Distance Scale

- Secondary Distance Indicators
    - Globular Clusters (GCs)
        - systems of GCs in other galaxies

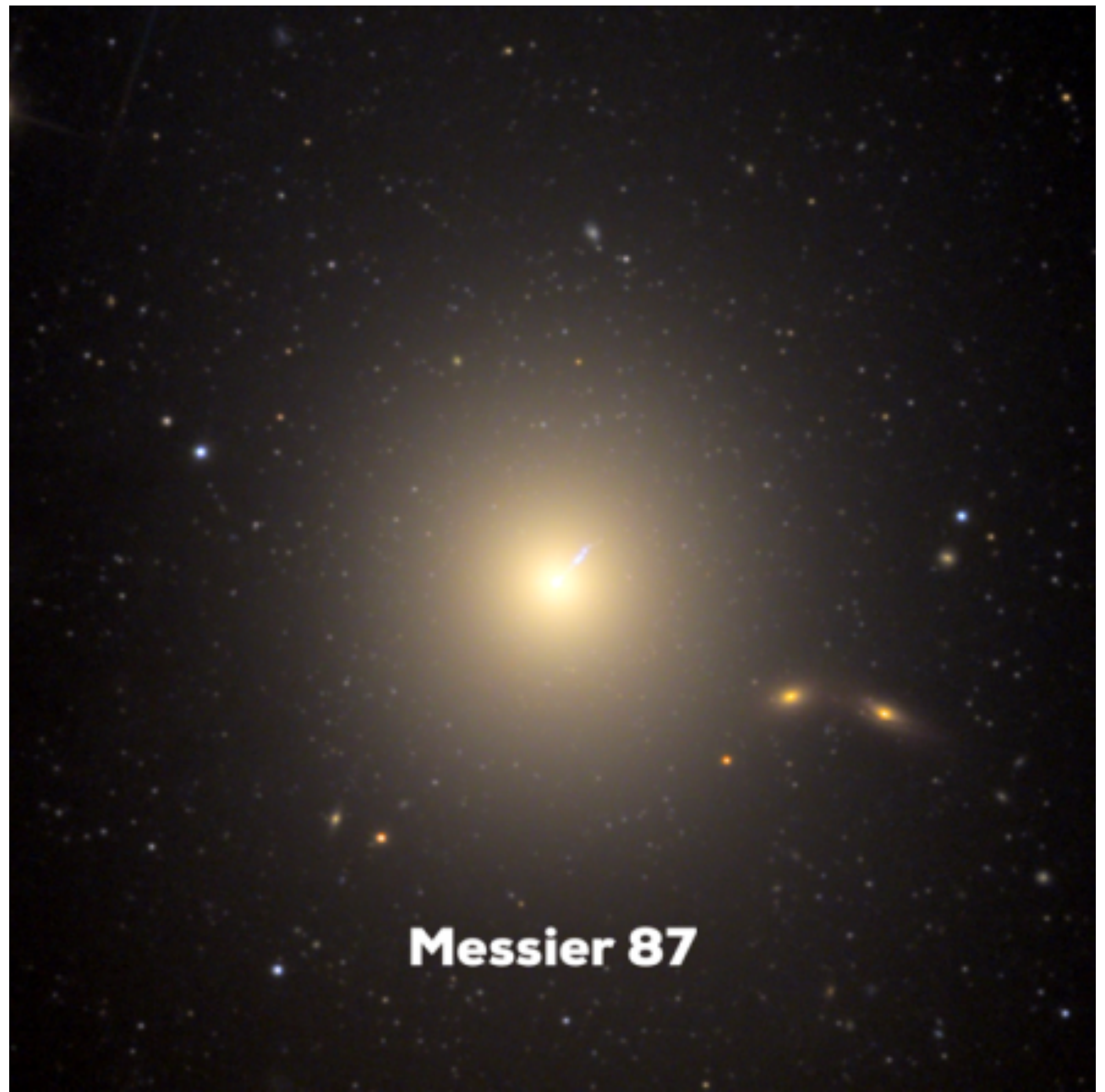
Globular clusters in the Milky Way have a Gaussian luminosity function.

Can match to the Globular cluster systems of other galaxies *presuming* they have the same luminosity function. No clear reason why this should be.

$$\Phi_{\rm GC} \sim e^{-\frac{(m-\bar{m})^2}{2\sigma^2}}$$

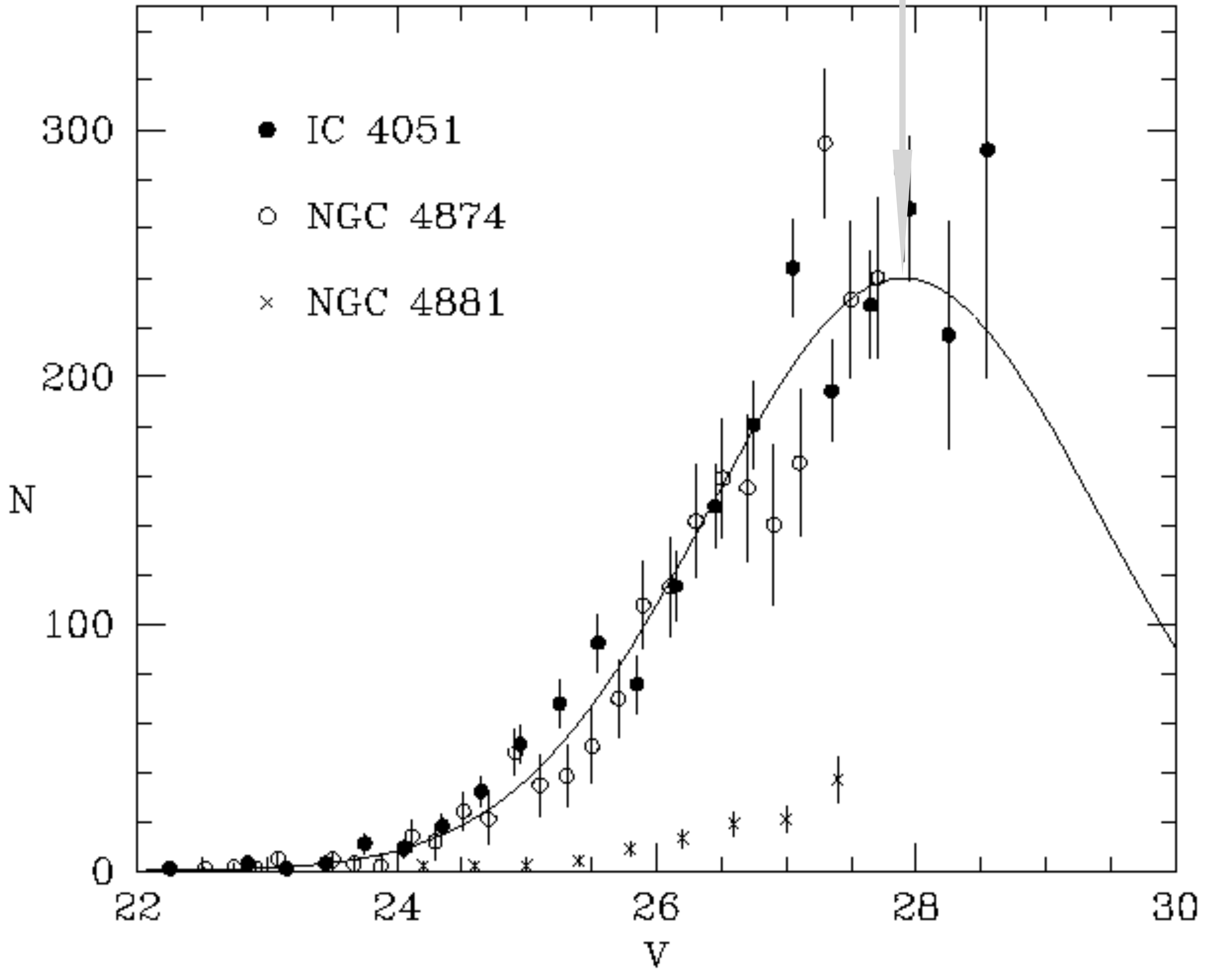
Globular cluster M80

Elliptical galaxy M87.
Most of the little dots are globular clusters.



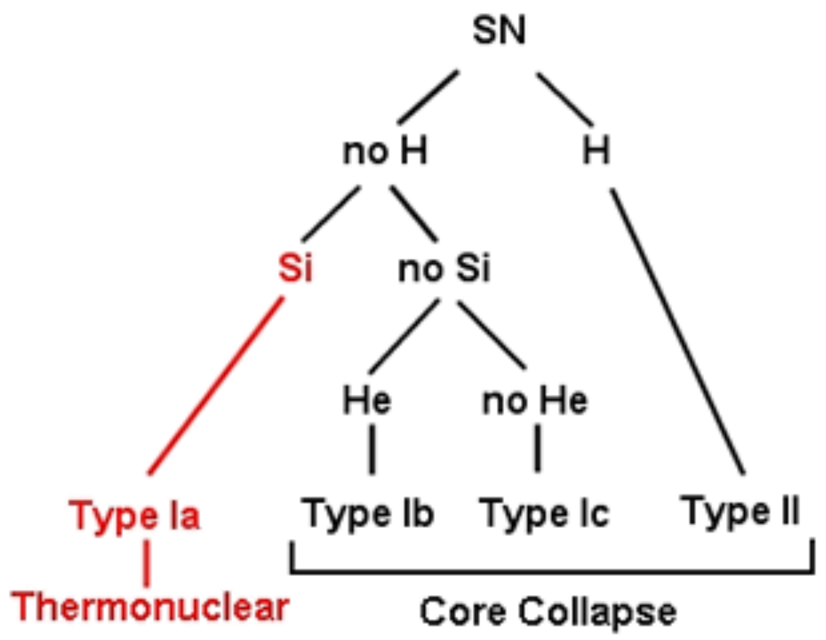
$\bar{M}_{\rm GC}$

Globular cluster luminosity function



Supernovae

Types of Supernovae



Different types of supernova light curves

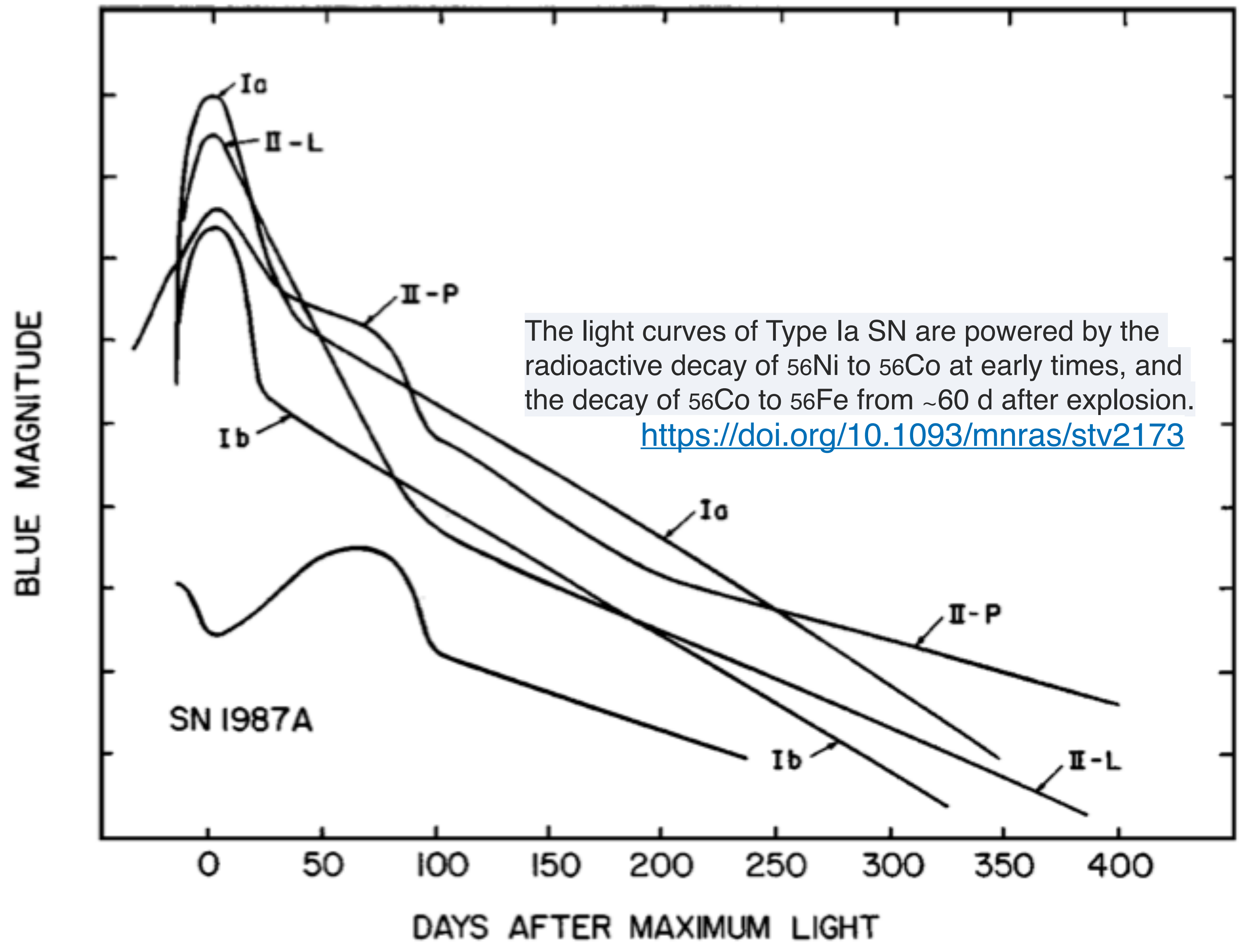


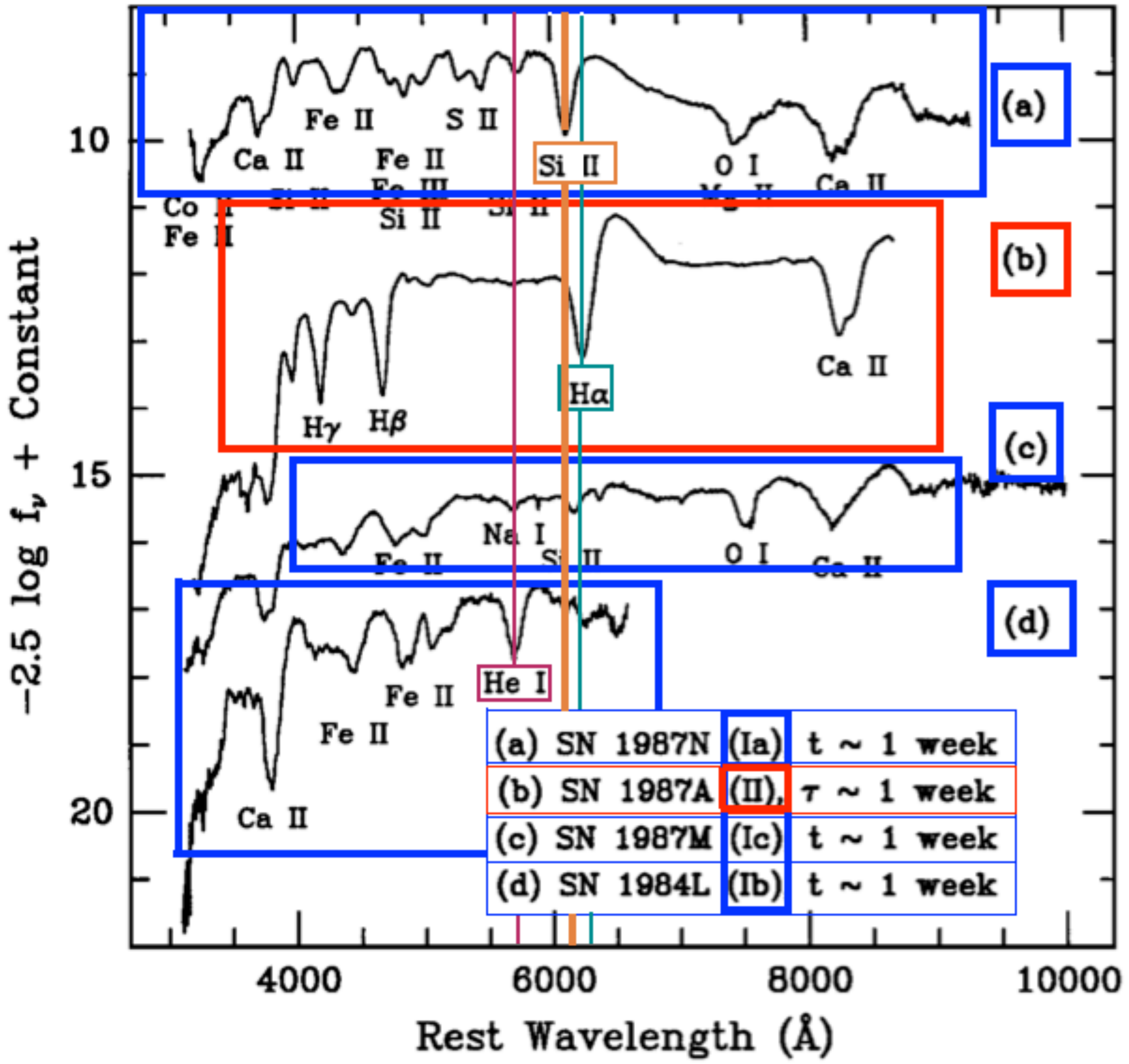
Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous.

Figure Credit: Wheeler, J. C., & Harkness, R. P. 1990, RPPh, 53, 1467

Supernova spectra

Type II: hydrogen

Type I: no hydrogen



Ia: silicon but no hydrogen

II: hydrogen

Ic: neither silicon nor helium

Ib: helium but no silicon

Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables t and τ represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

Figure Credit: Filippenko, A. 1997, ARA&A, 35, 309

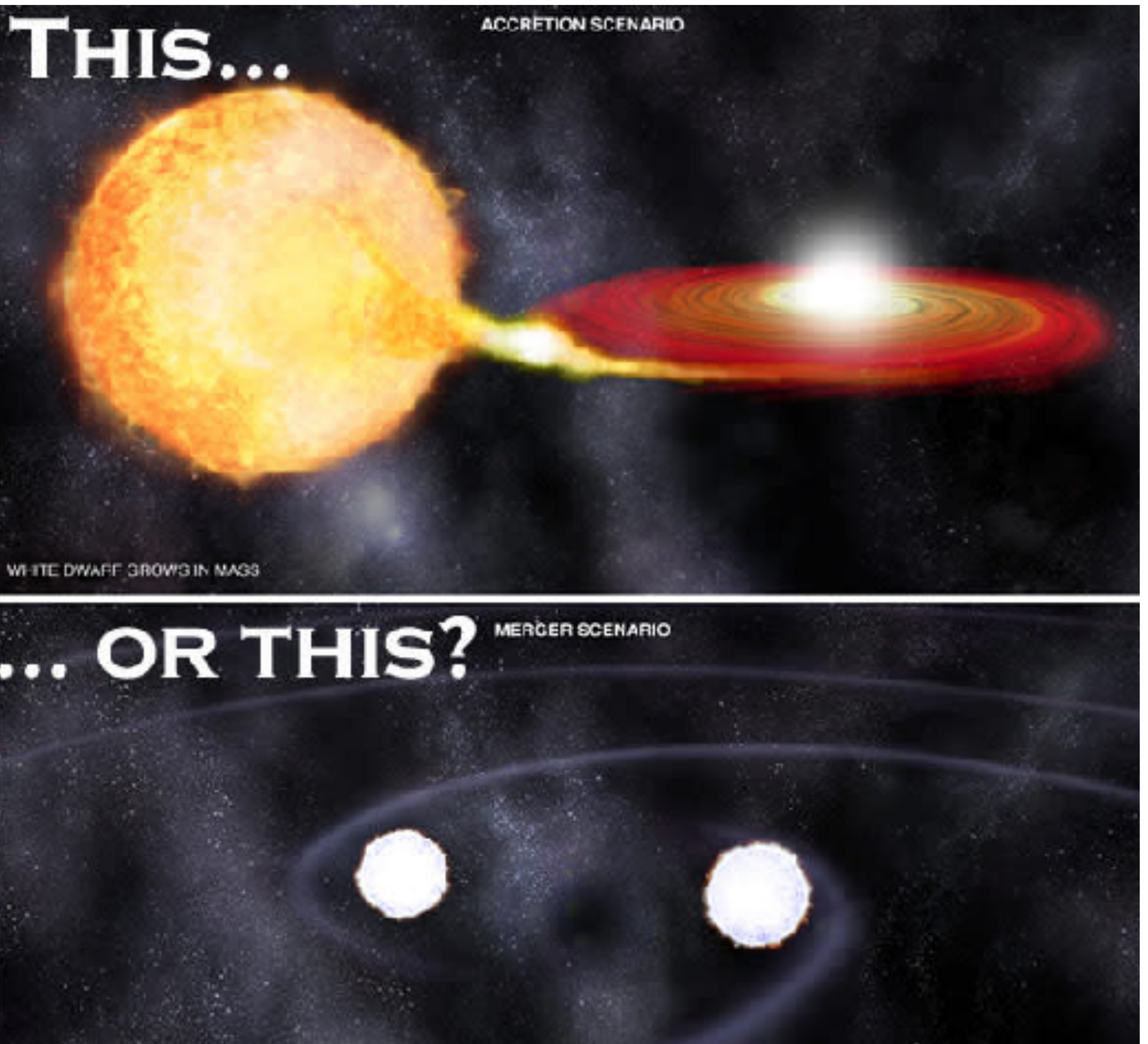
Type Ia supernovae contain an obvious Si **absorption** at 6150 Angstoms, **Type Ib** have no Si but show He in **emission**, and **Type Ic** display neither Si nor He.

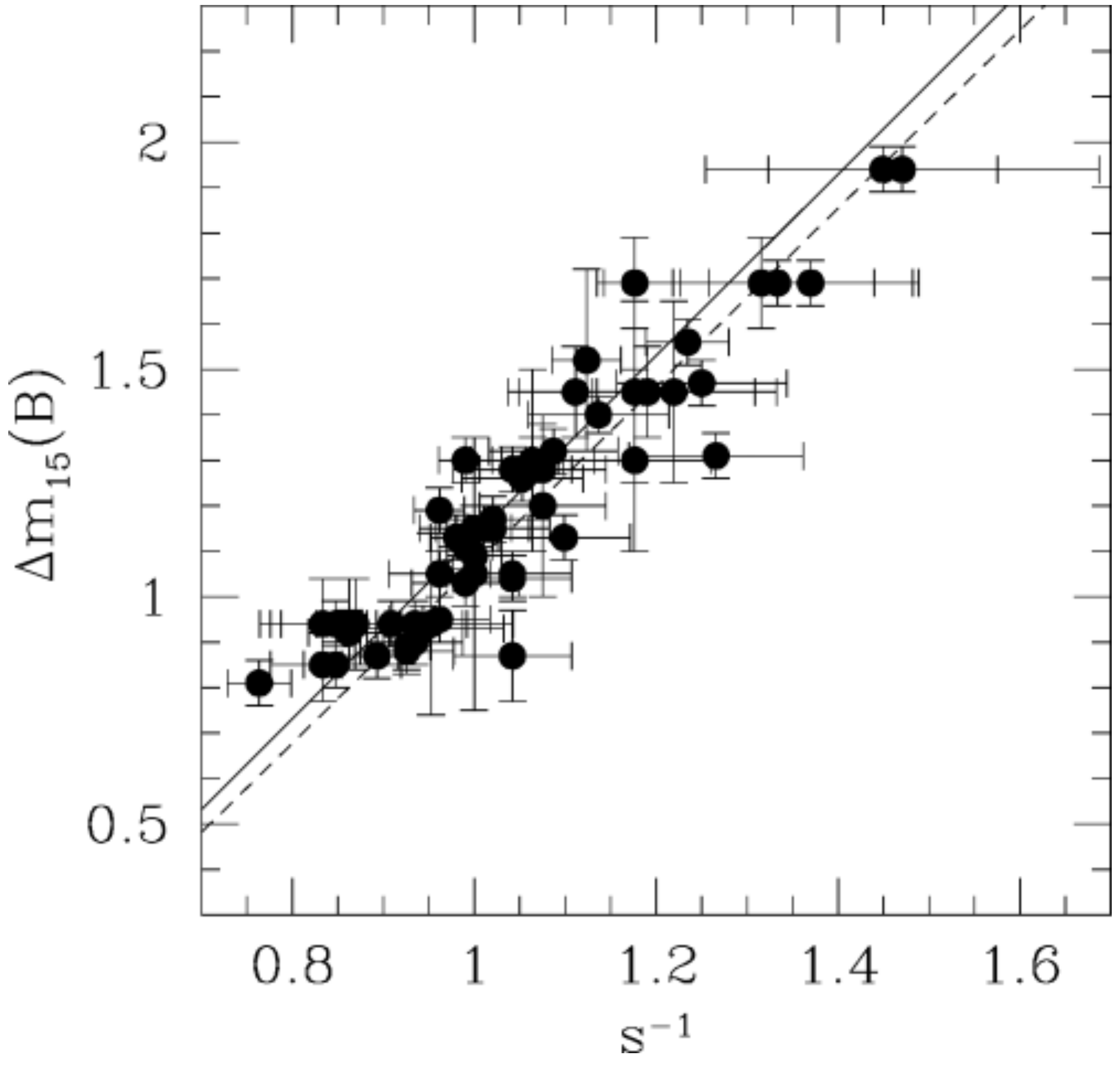
Distance Scale

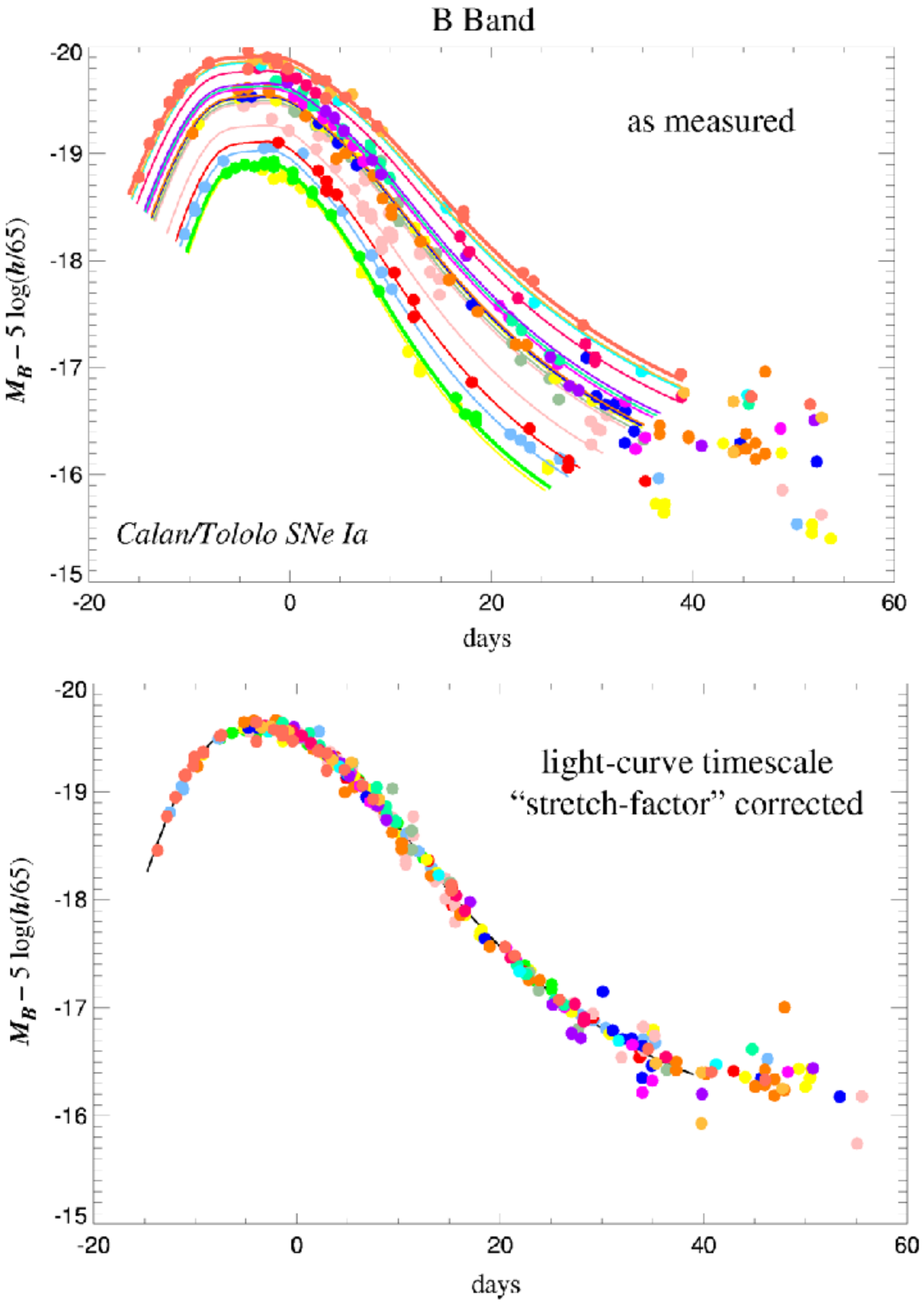
- Secondary Distance Indicators
  - Supernovae
    - Type Ia SN (white dwarf detonations)
    - White dwarfs that exceed the Chandrasekhar limit explode, converting carbon and oxygen to iron and nickel (etc.)
    - At present, appear mostly due to WD-WD mergers, not single accreting WDs.

$$M_{B,\ \mathrm{peak}} = -19.26 + 0.8[\Delta m_{15} - 1.1]$$

Peak luminosity correlates with fade time - Δm_{15} is the amount of fading after 15 days. Can also be calibrated in terms of a `stretching factor,' *s*, the amount (in days) that the template light curve must be stretched to fit.







Kim, *et al.* (1997)

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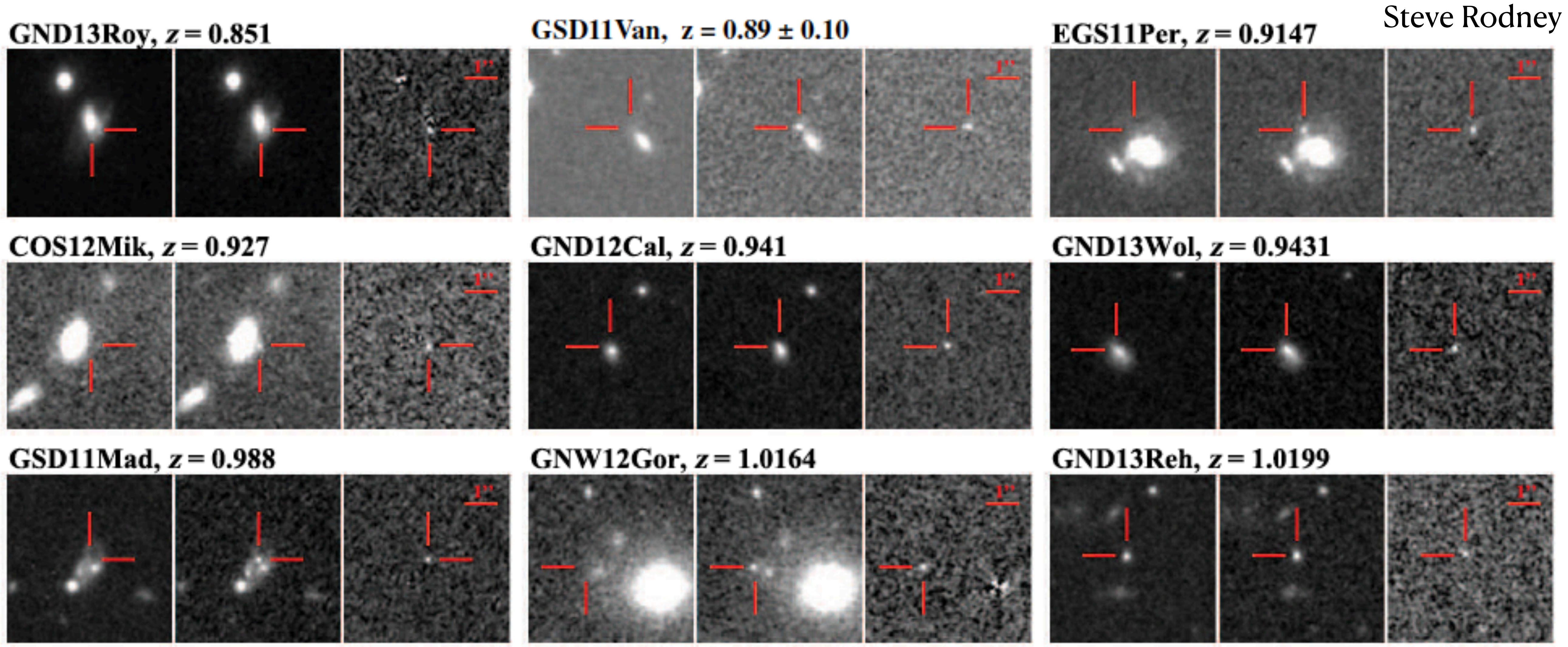
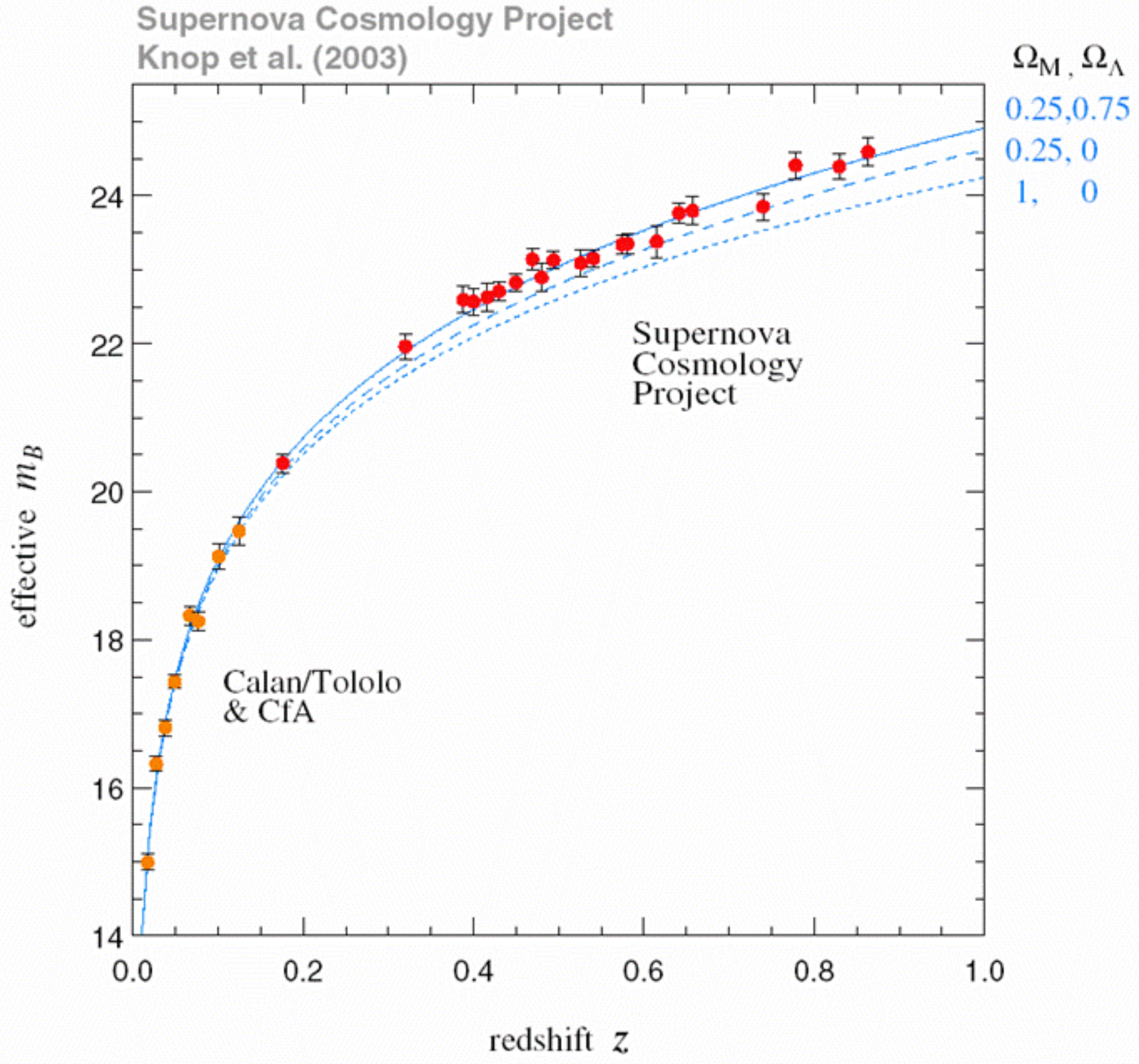
Type Ia SN bright enough to see to high redshift, so can constrain q_0 as well as H_0

THE ASTRONOMICAL JOURNAL, 148:13 (28pp), 2014 July

RODNEY ET AL.

Steve Rodney (CWRU alum)





Awarded 2011 Nobel Prize in Physics for $q_0 < 0$.

Distance Scale

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    - Type Ia SN (white dwarf detonations)
    - White dwarfs that exceed the Chandrasekhar limit explode, converting carbon and oxygen to iron and nickel (etc.)
    - At present, appear mostly due to WD-WD mergers, not single accreting WDs.

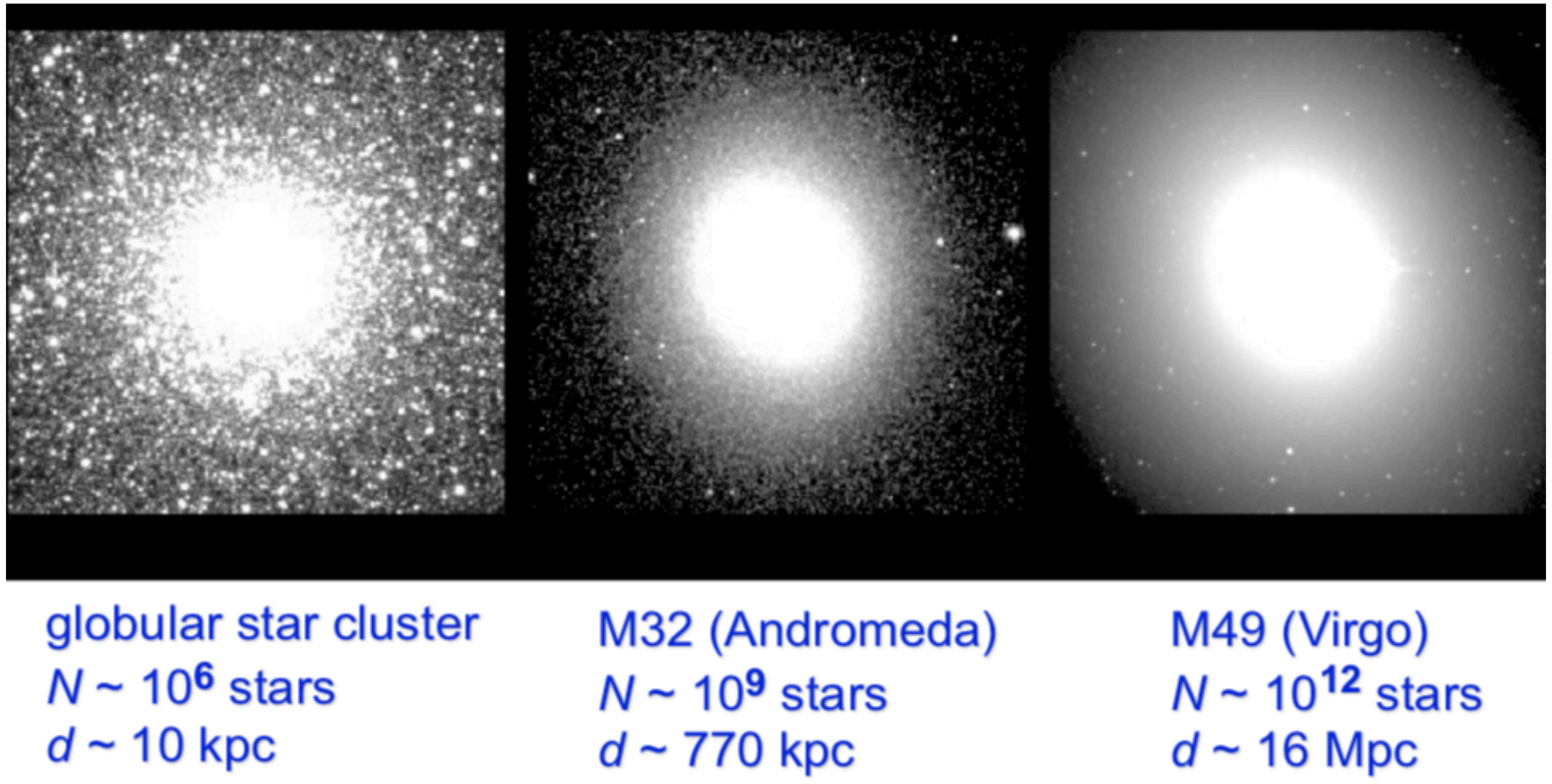
$$M_{B,\text{ peak}} = -19.26 + 0.8[\Delta m_{15} - 1.1]$$

Peak luminosity correlates with fade time - Δm_{15} is the amount of fading after 15 days. Can also be calibrated in terms of a `stretching factor,' *s*, the amount (in days) that the template light curve must be stretched to fit.

- Systematic effects
  - Type Ia SN only
    - need spectroscopy of faint, fading sources
    - must weed out other events (Type II) without introducing a systematic bias
  - Don't fully understand physics
    - not standard bombs as they were once thought to be
    - luminosity-stretch correction is purely empirical.
      - Does the physics that drives it matter?
  - Evolution
    - Do SN change systematically over time (redshift)?
      - dependent on metallicity? age? host galaxy type?
  - Dust
    - Extinction corrections necessary
    - is high-z dust normal? (have same extinction curve as MW?)

Distance Scale

- Secondary Distance Indicators
  - Surface Brightness Fluctuations



Nearby galaxies resolve into stars. This smooths out as the distance increases. This smoothing can be quantified by the fluctuation from one resolution element to the next.
The average flux in one resolution element is

$F = \bar{N}f$ where $f = \dfrac{L}{4\pi d^2}$ is the flux from the average star.

The dispersion in F is $\sigma_F = \bar{N}^{1/2} f$
so

$$f = \frac{\sigma_F^2}{F} = \frac{\langle L \rangle}{4\pi d^2}$$

and you can get the distance if you can calibrate the luminosity of the average star

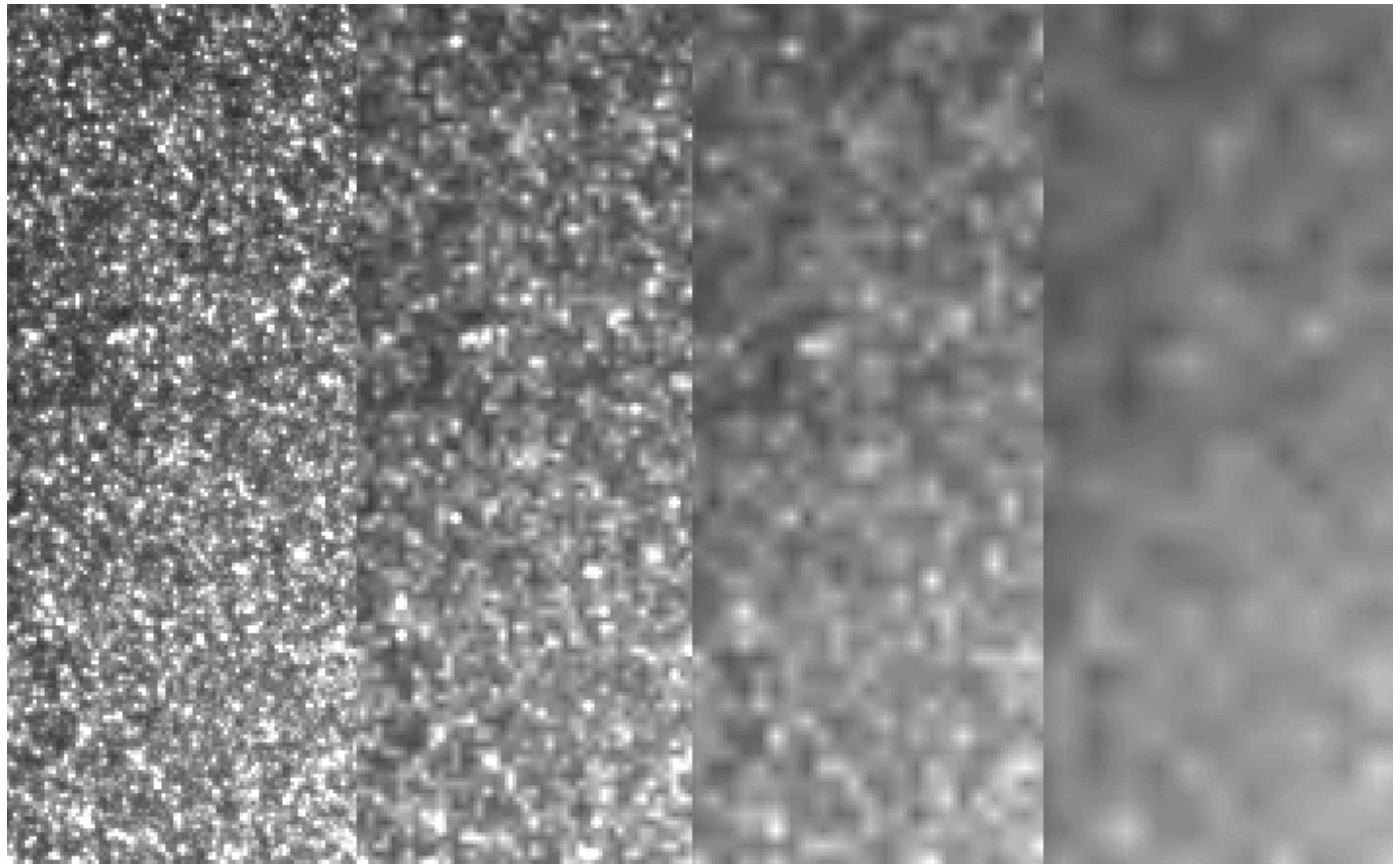
$$\langle L \rangle = \frac{\sum \bar{N}_i L_i^2}{\sum \bar{N}_i L_i}.$$

In practice this is done empirically by calibration with nearby galaxies whose distances are known by other means.

Need well behaved stellar population
Method assumes L is stable from pixel to pixel, which is obviously not true in star forming galaxies. Hence Elliptical galaxies are preferred

Very resolution dependent
must model point spread function (PSF)
need accurate photometry
at 20 Mpc, there are 10,000 RGB stars in one 1" resolution element, so need 1% photometric accuracy.

$$\langle M_I \rangle = -4.8 + 3(V - I)$$



Distance Scale

- Secondary Distance Indicators
  - Faber-Jackson, Fundamental Plane
    - Apply to elliptical galaxies (pressure supported)

Faber-Jackson relation first noticed as a scaling relation between luminosity and velocity dispersion in Elliptical galaxies: $L \sim \sigma^4$.

The velocity dispersion provides an estimator of the luminosity which in turn acts as a standard candle to give the distance.

Applies to lots of types of pressure supported systems over a large dynamic range: $M \sim \sigma^4$ but with large scatter and systematic deviations: there is a second-parameter effect.
We need to consider a third axis (size or surface brightness).

Faber-Jackson relation

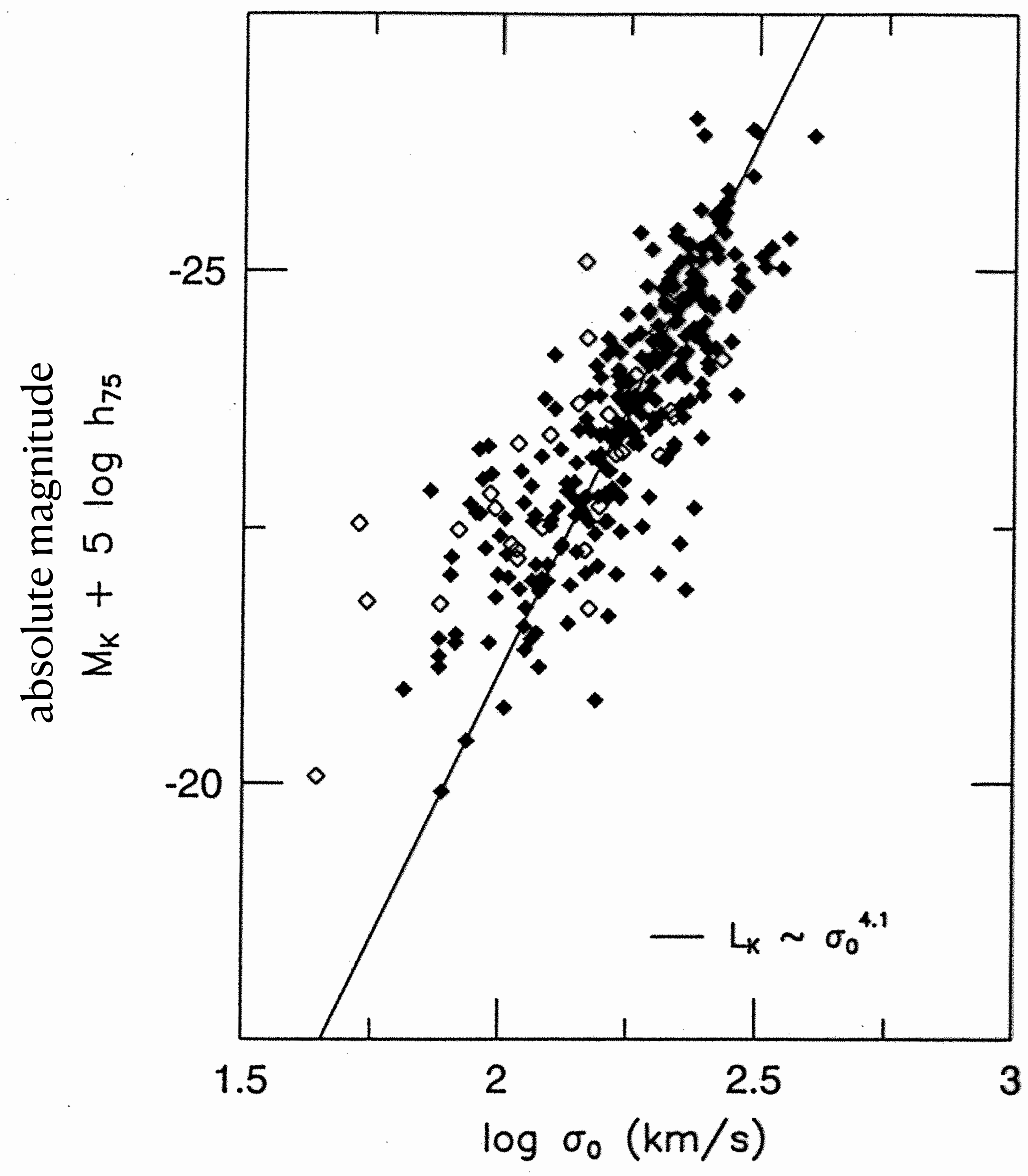


Fig. 10.—Faber-Jackson relation between luminosity and central velocity dispersion. The best-fitting relation is $L_K \propto \sigma_0^{4.14\pm0.22}$ with a large scatter of 0.93 mag. The scatter is significantly smaller in the Coma cluster at 0.72 mag.

velocity dispersion

Distance Scale

- Secondary Distance Indicators
  - Faber-Jackson, Fundamental Plane
    - Apply to elliptical galaxies (pressure supported)

Incorporating a second-parameter is known as the Fundamental Plane. The Faber-Jackson relation is one projection in a 3D space; the Fundamental Plane finds the eigenvectors that minimize the scatter when seen edge on.

$$R_e \sim \langle \Sigma_K \rangle^{-0.8} \sigma_0^{1.53}$$

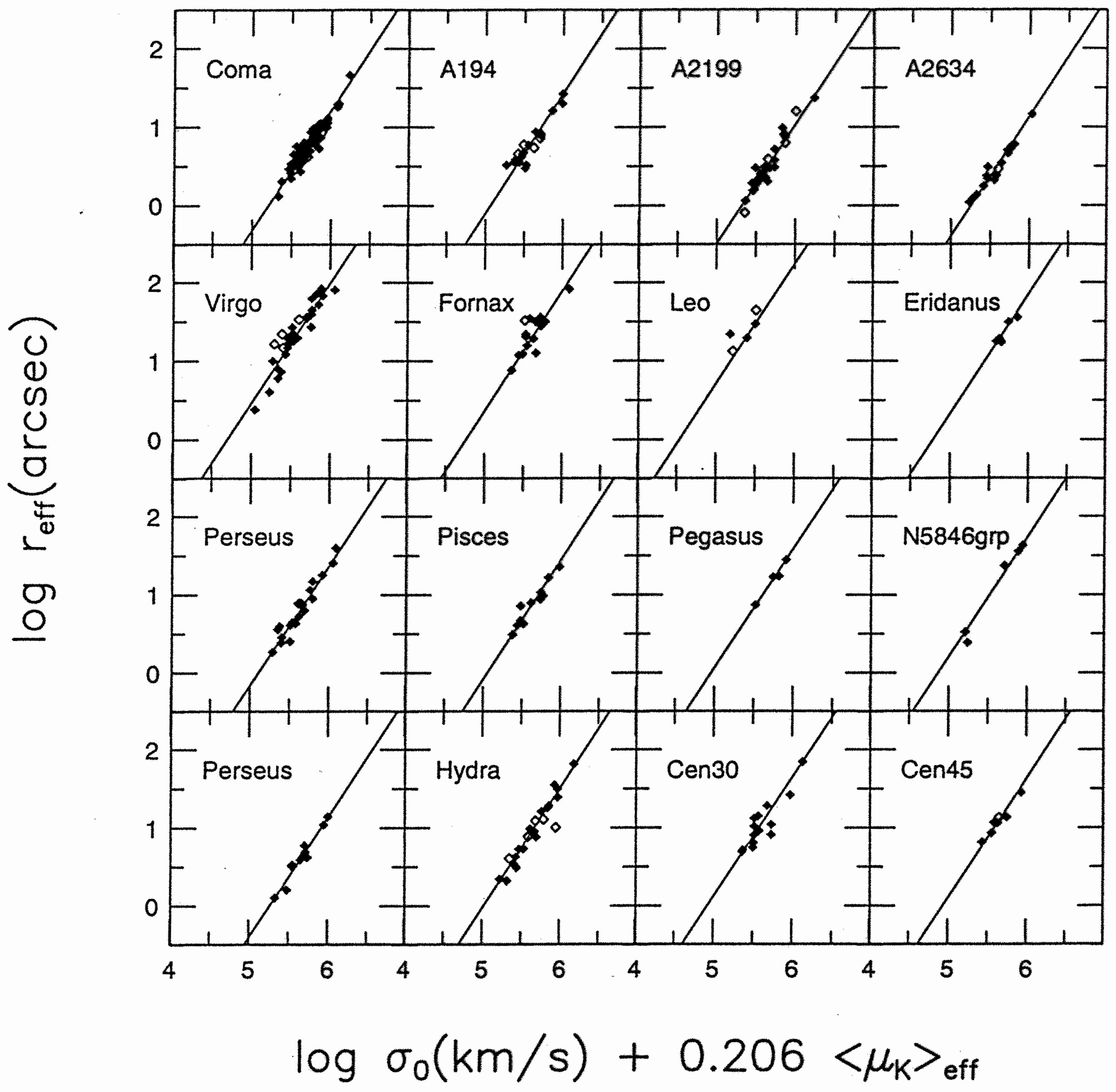
Where
R_e is the effective radius (containing half of the total light)
$\langle \Sigma_K \rangle$ is the average K-band surface brightness with Re
σ_0 is the central velocity dispersion

The Fundamental Plane is thought to follow from the Virial equation with some "tilt" (systematic variation of M/L with L).

Virial expectation: $R_e \sim (M/L)^{-1} \langle \Sigma \rangle^{-1} \sigma_{vir}^2$

K-band Fundamental Plane

PAHRE, DJORGOVSKI, & DE CARVALHO 1998, ApJ, 116, 1591 Vol. 1



ıdamental plane in the near-infrared for the 16 clusters and groups in the simultaneous fit represented by the solution of eq. (2) and . (2) of Table 1. The FP is described by the scaling relation $r_{eff} \propto \sigma_0^{1.53}\langle\Sigma_K\rangle_{eff}^{-0.79}$ with a scatter of 0.096 dex in log r_{eff}; the scatter is reduced ıxies with $\sigma_0 < 100$ km s^{-1} are excluded. The fitted [redacted] solid symbols, while those excluded from the fit (log σ_0 < ıology, $r_{eff} < 1''$, or background/foreground in the Virgo cluster) are plotted as open symbols. The FP fit is plotted in each panel as a sc

Fundamental Plane

Distance Scale

- Secondary Distance Indicators
  - Tully-Fisher relation
    - luminosity-linewidth relation
  - Baryonic Tully-Fisher relation
    - baryonic mass-flat rotation speed relation

Faber-Jackson relation first noticed as a scaling relation between luminosity and line width in Spiral galaxies. Slope band-dependent.

The line width is a crude estimator of the rotation speed. It provides an estimator of the luminosity which in turn acts as a standard candle to give the distance.

"The result for the Virgo cluster suggests a Hubble constant of 80 km per sec per Mpc"
- Tully & Fisher (1977)

Tully & Fisher (1977)

R. B. Tully and J. R. Fisher: Distances to Galaxies

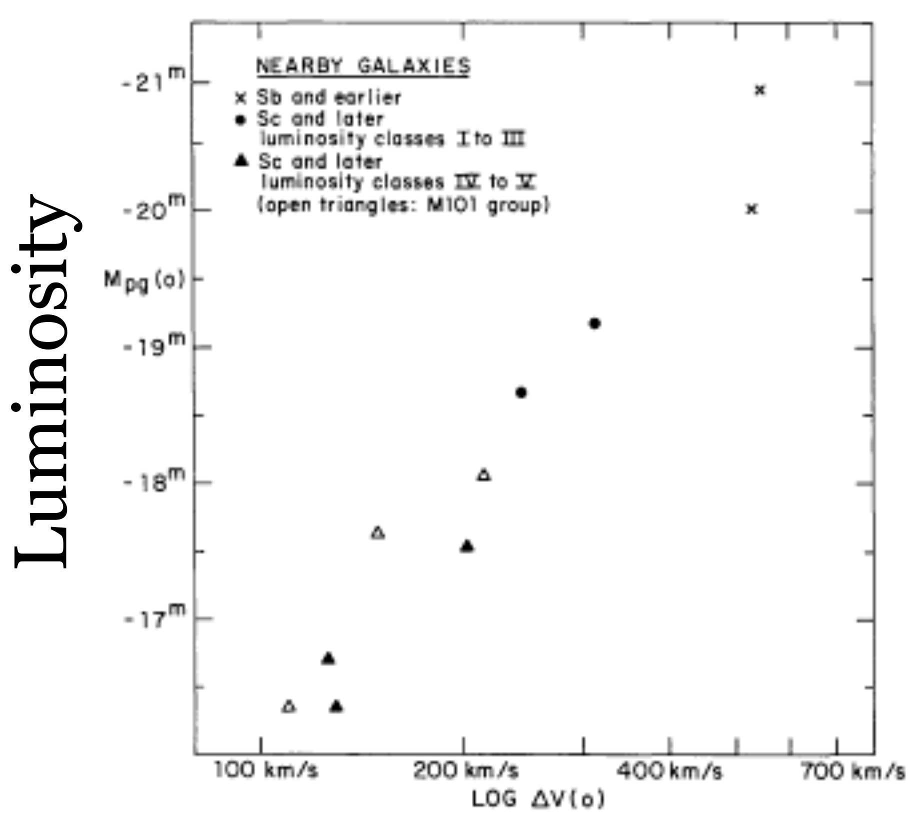
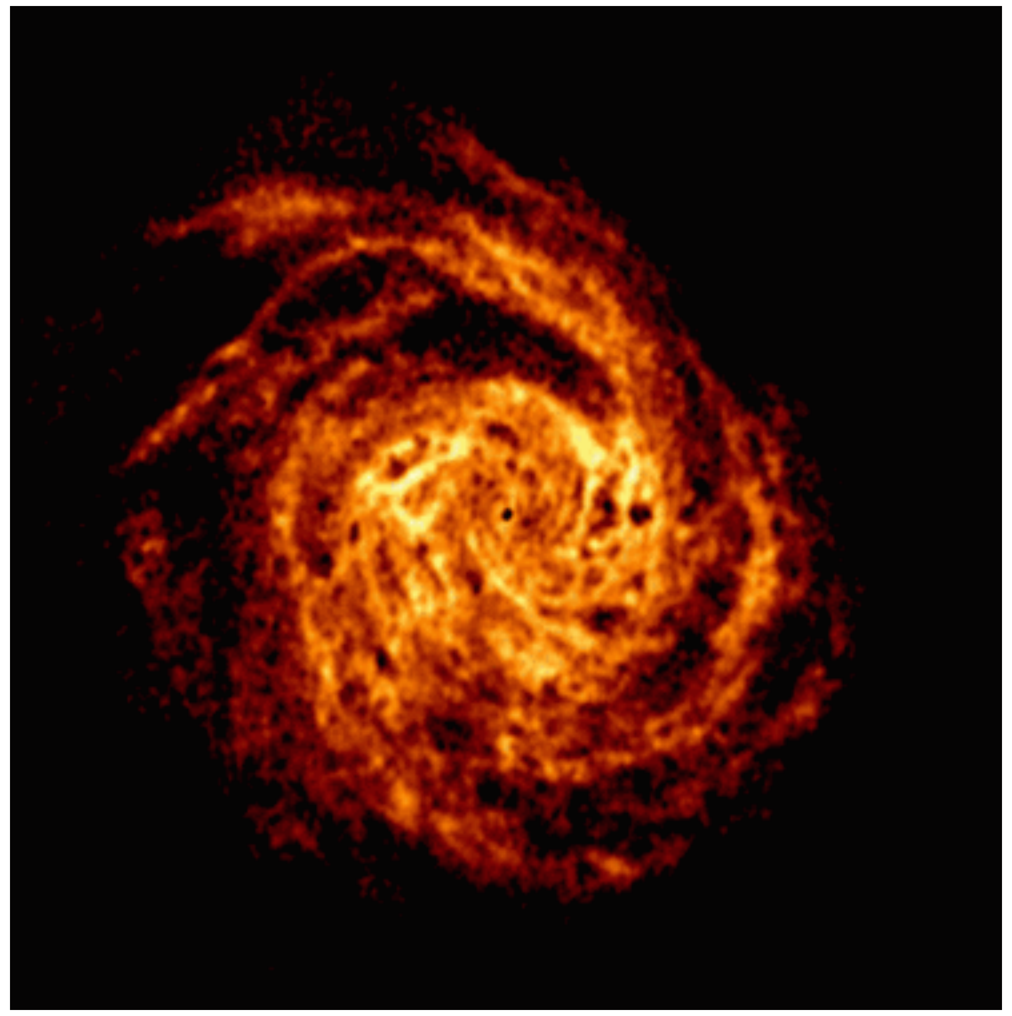
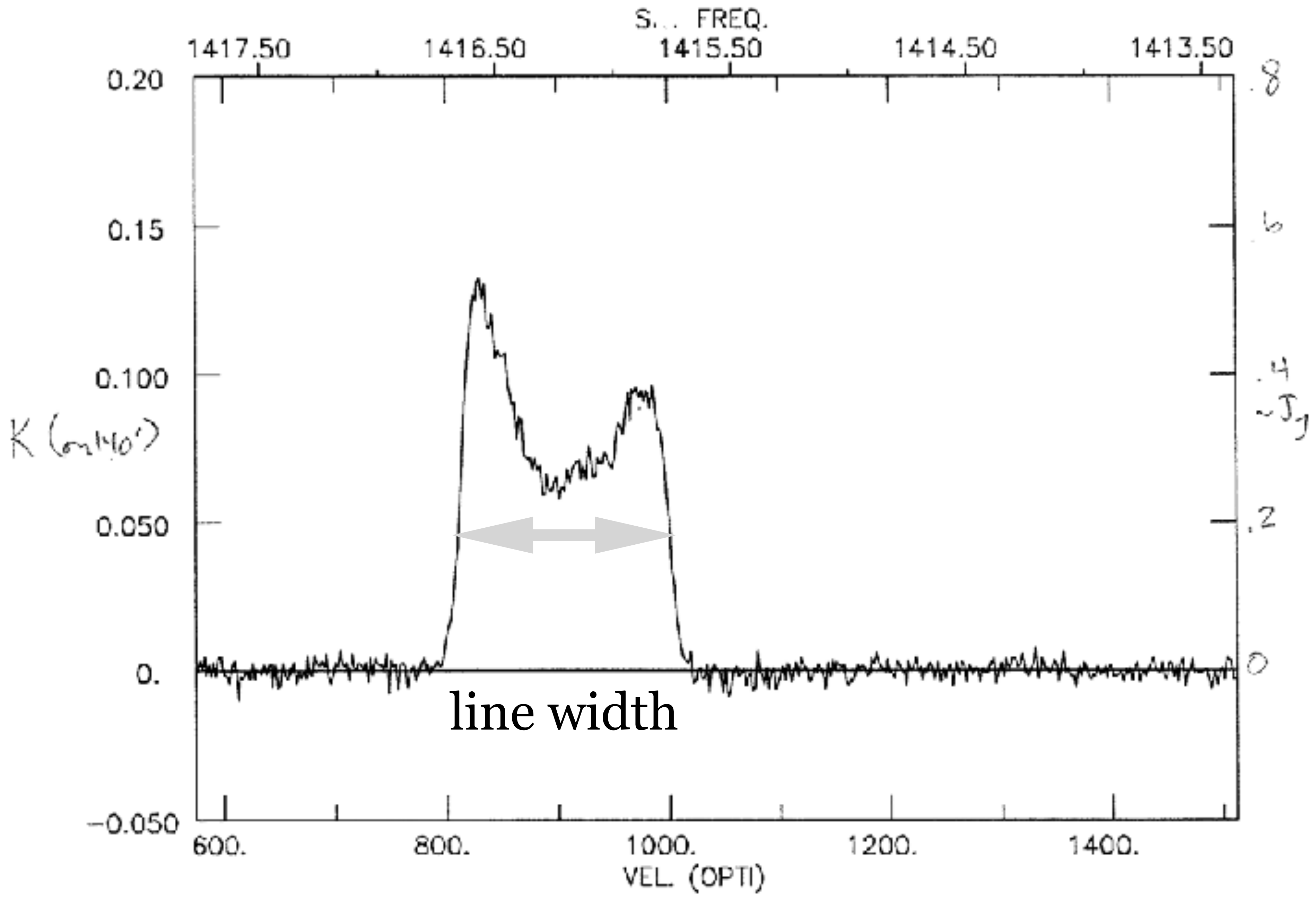


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

line width

NGC 6946 (atomic "HI" gas - Boomsma et al)





Tully-Fisher relations

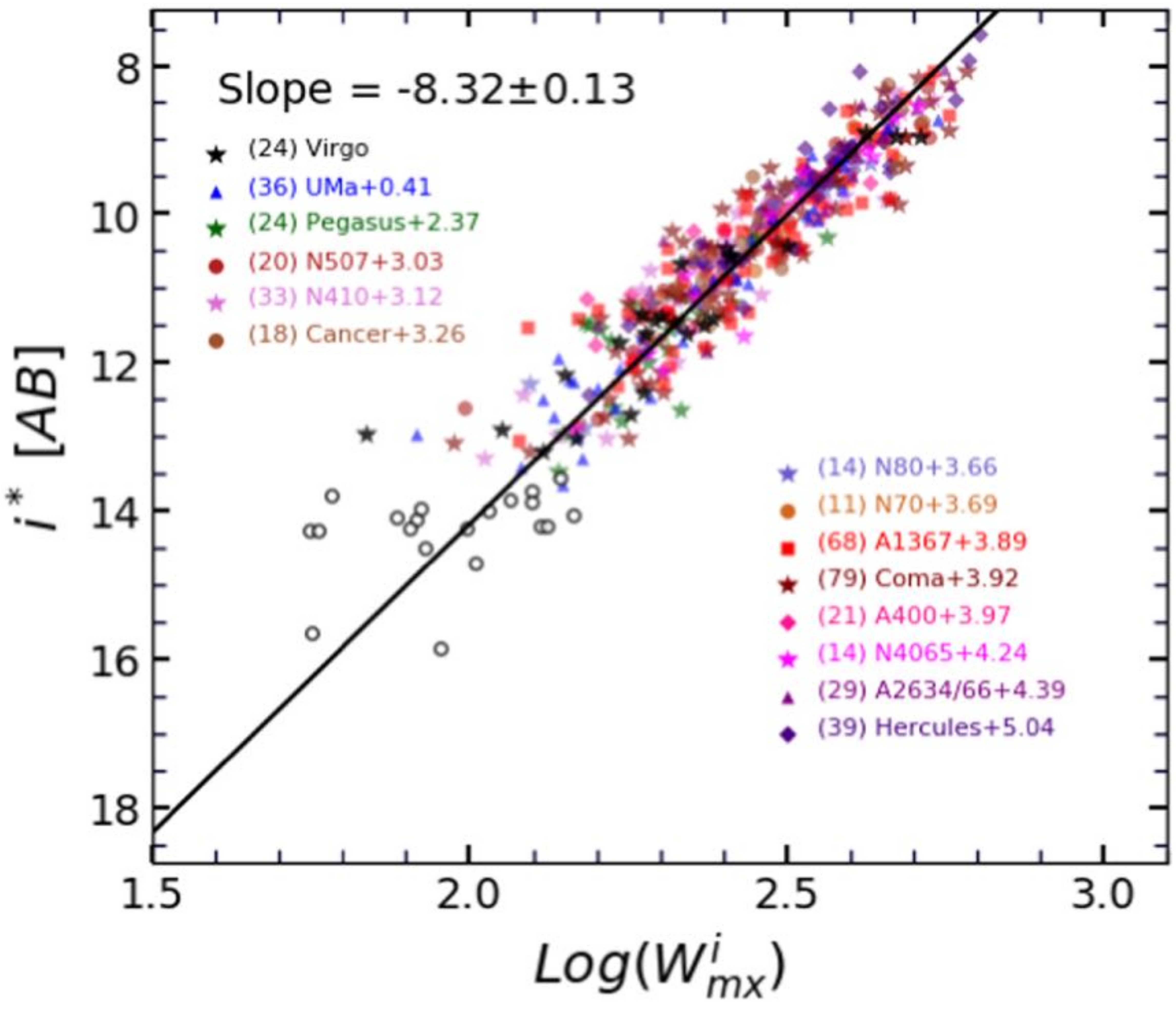
amplitude of line width correlates with luminosity

- Secondary Distance Indicators
  - **Tully-Fisher relation**
    - luminosity-linewidth relation
  - Baryonic Tully-Fisher relation
    - baryonic mass-flat rotation speed relation

Calibrate TF with galaxies whose distance is known by other means…

Kourkchi, Tully, et al. (2020)

magnitude



line width

Tully-Fisher relations

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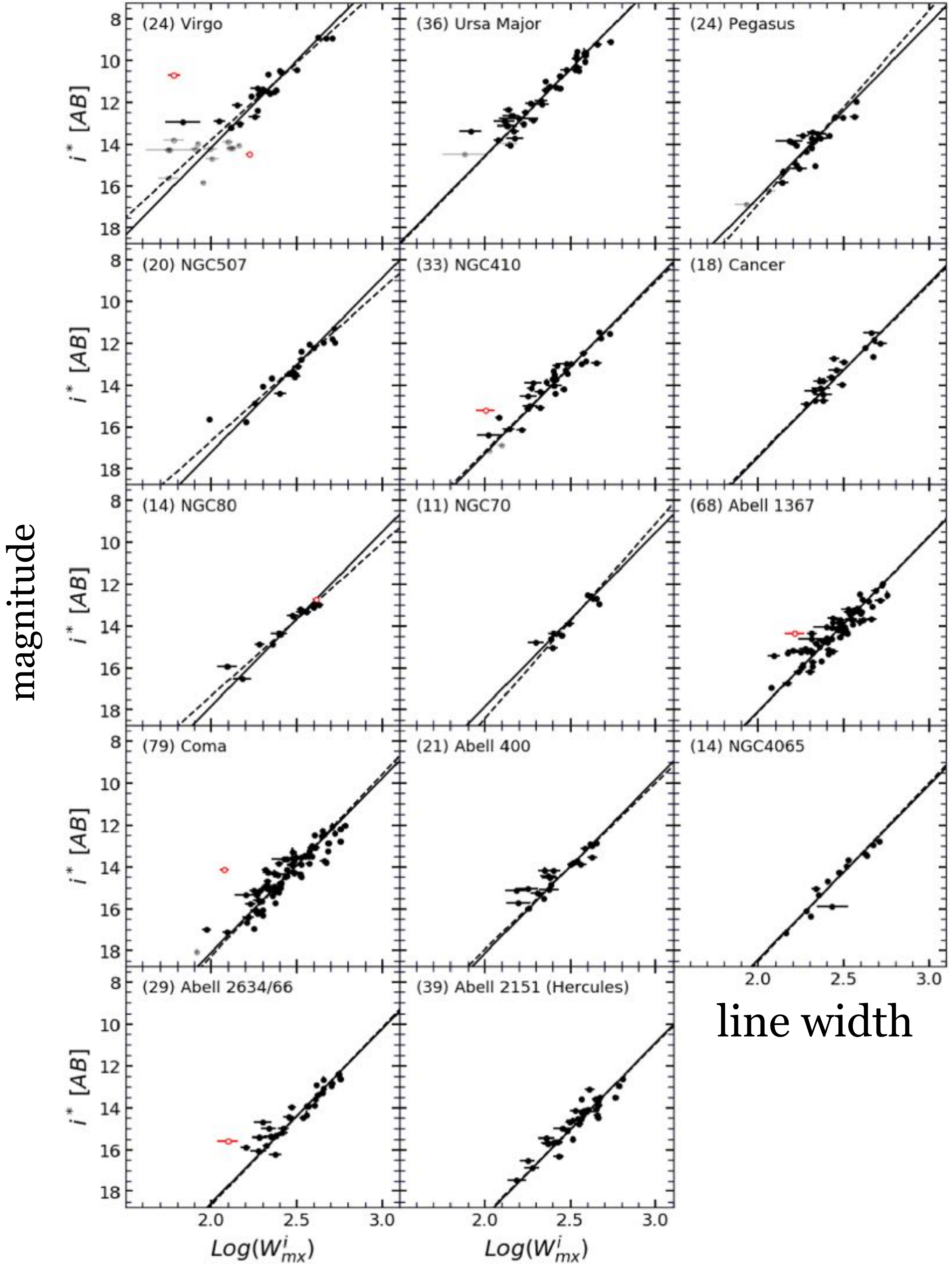
… then apply to more distant galaxies. At right, many clusters are shown.
One thus gets a distance to every cluster to use to determine H_o.

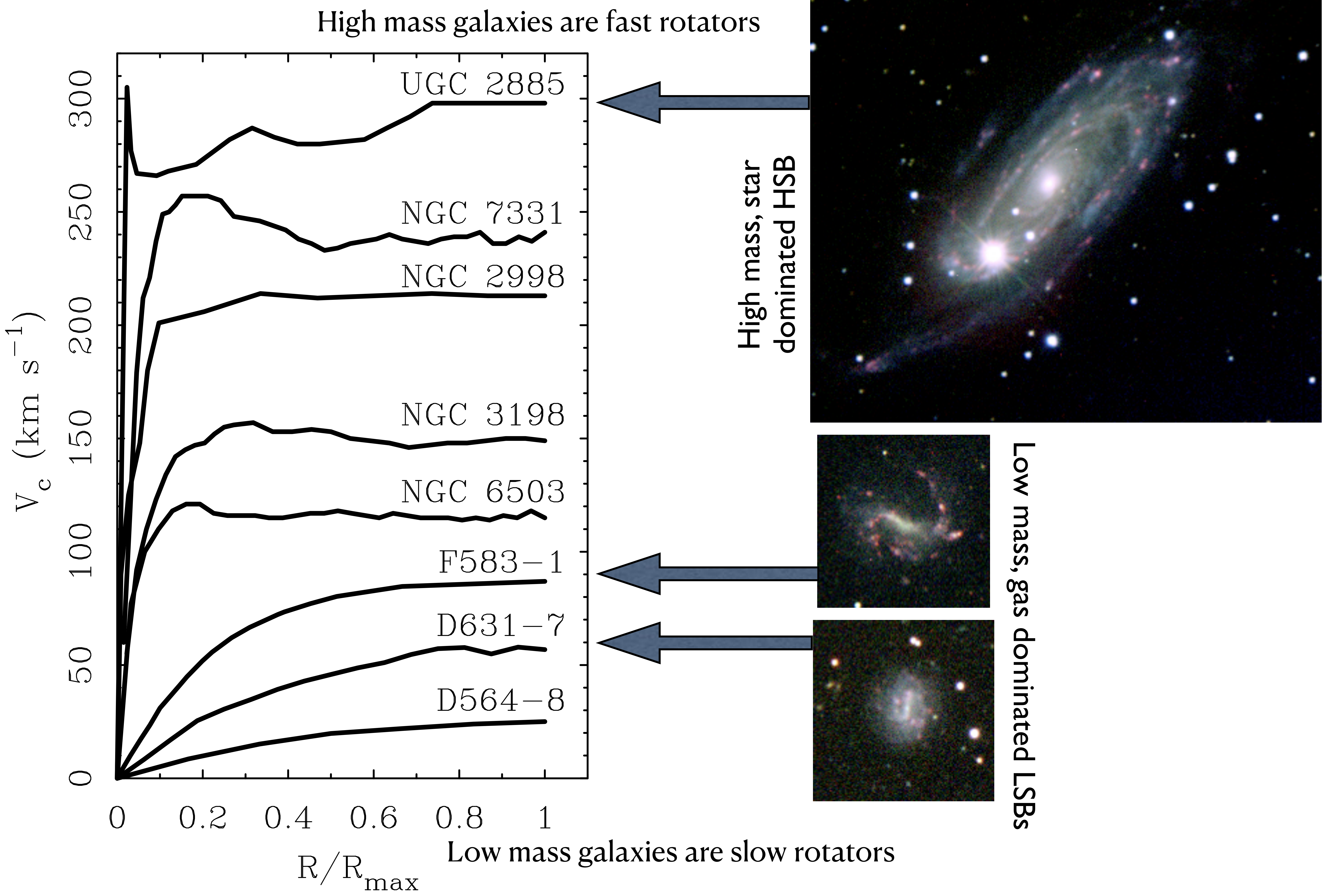


Kourkchi, Tully, et al. (2020)

Tully-Fisher relations

amplitude of flat rotation correlates with mass

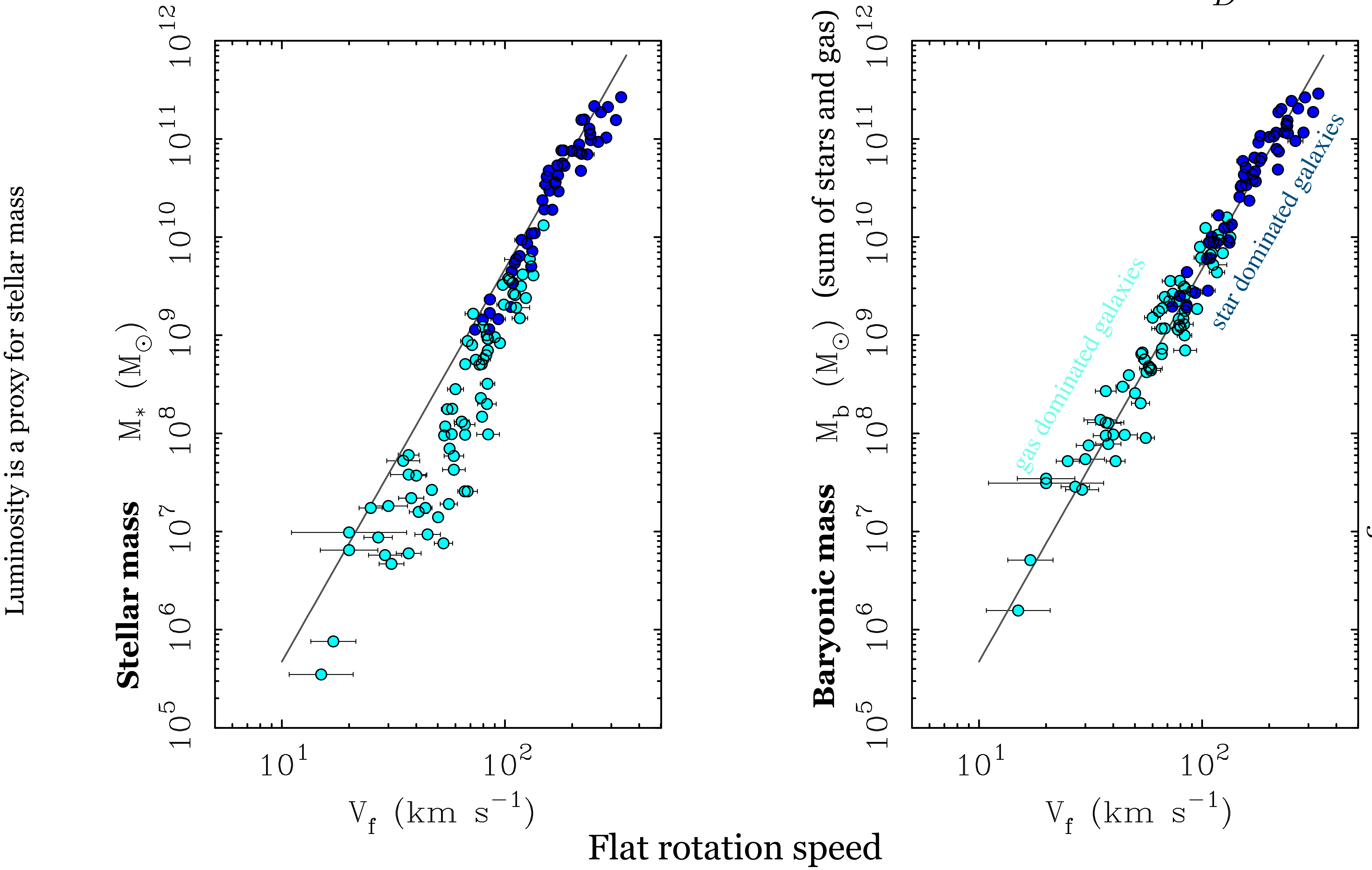
- Secondary Distance Indicators
  - Tully-Fisher relation
    - luminosity-linewidth relation
  - Baryonic Tully-Fisher relation
    - baryonic mass-flat rotation speed relation



Tully-Fisher relations

amplitude of flat rotation correlates with mass

$\frac{\sigma_D}{D} < 20\%$



$M_b = M_* + M_g$

Fundamentally, Tully-Fisher is a relation between **baryonic mass** (stars+gas) and the amplitude of the **flat rotation speed.**

This is the
Baryonic Tully-Fisher Relation

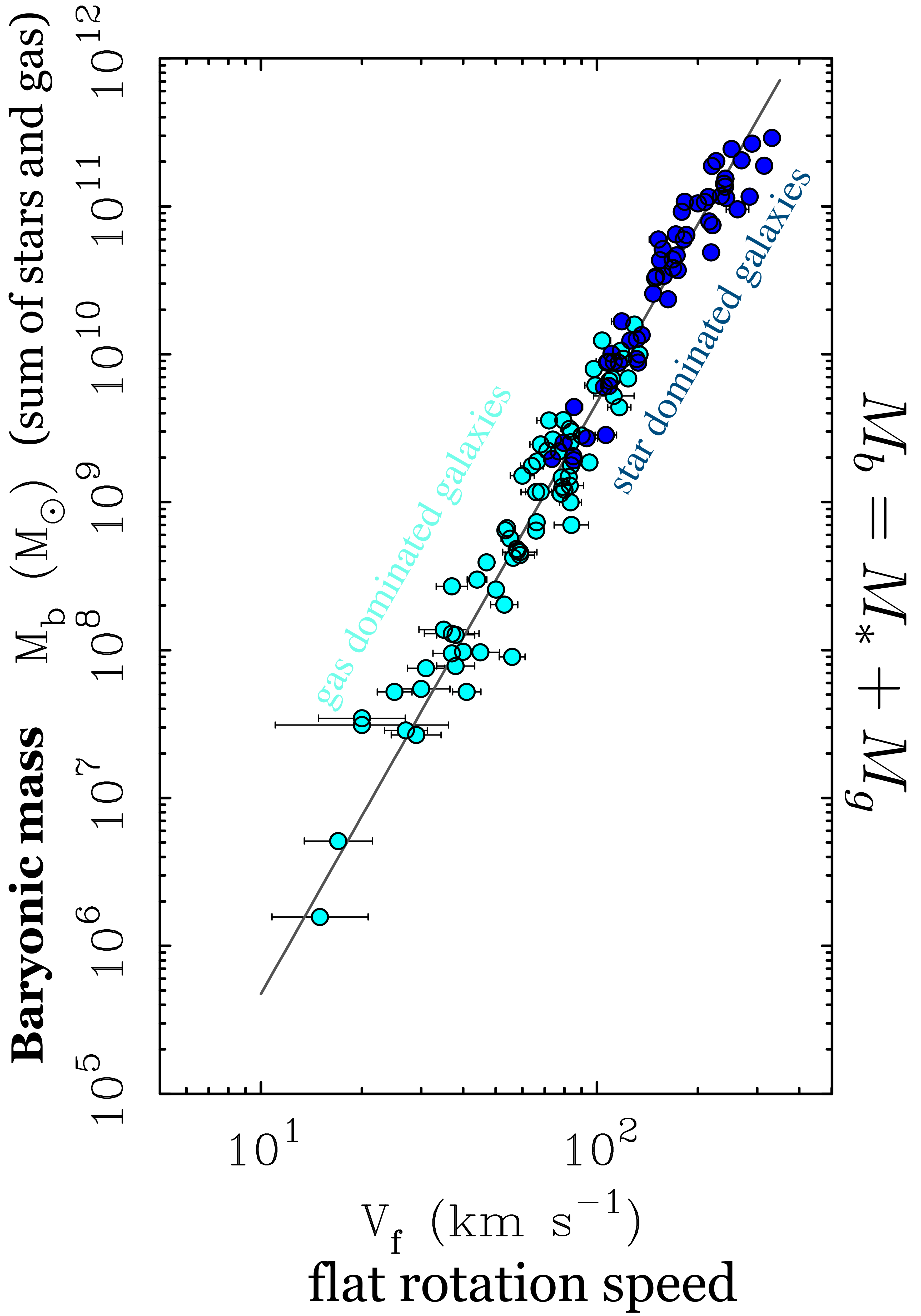
$$M_b = A V_f^4$$

$$A = 48.0 \pm 1.5\ \mathrm{M}_\odot\,(\mathrm{km\,s^{-1}})^{-4}$$

with remarkably little intrinsic scatter

$$\sigma < 0.11\ \mathrm{dex}$$

This is about how much scatter we expect from stellar population mass-to-light variations, leaving very little room for other sources of scatter.



Example application:

Calibrate BTFR with 50 galaxies having distances that are known via either Cepheids of Tip of the Red Giant Branch measurements.

Applied to ~100 galaxies with high quality rotation curves, this provides a local measurement of the Hubble constant:

$$H_0 = 75.1 \pm 2.3\ (\text{stat})\ \pm 1.5\ (\text{sys})\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

Schombert, McGaugh, & Lelli 2020, AJ, 160, 71

This is consistent with the application of the traditional luminosity-line width Tully-Fisher relation to a much larger sample of ~10,000 galaxies.

$$H_0 = 75.1 \pm 0.2\ (\text{stat})\ \pm 3\ (\text{sys})\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

Kourkchi, Tully, *et al*. 2020, ApJ, 902, 145

$$H_0 = 75.0 \pm 0.8\ (\text{stat})\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

Tully, *et al*. 2022, arXiv:2209.11238

systematic uncertainty ~ 3 km/s/Mpc

Historical review: Tully 2023 (arXiv:2305.11950)