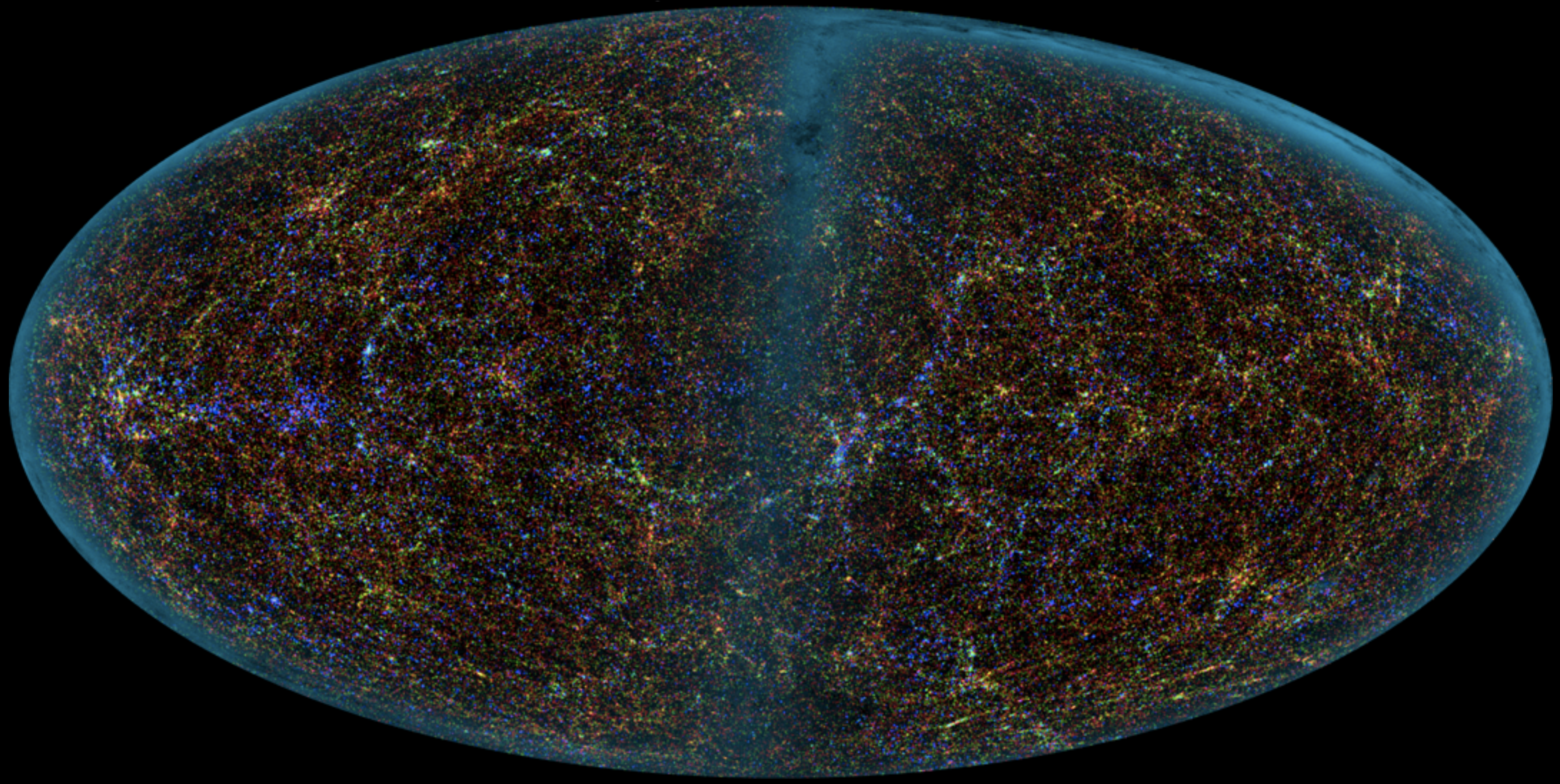
Cosmology

and Large Scale Structure



<u>Today</u>

Distance Scale

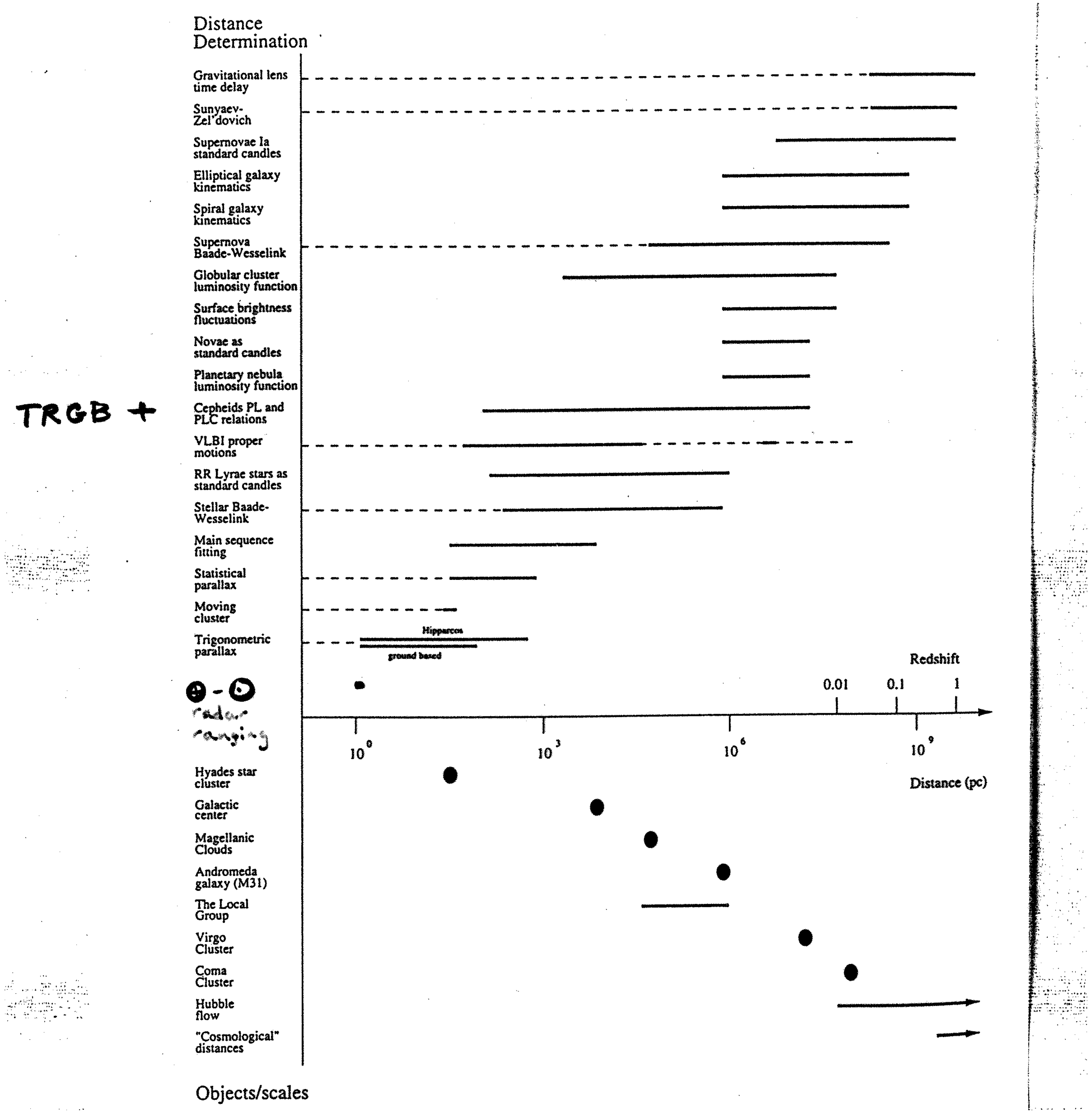
secondary indicators

Homework 3 due one week from today

Distance Scale

- Secondary Distance Indicators
  - Supernovae
    - Type Ia SN, Type II SN
  - Tully-Fisher (Spiral galaxies)
  - Faber-Jackson; Fundamental Plane (Elliptical galaxies)
  - Surface Brightness Fluctuations
  - Luminosity functions
    - Globular clusters
    - Planetary nebulae
    - Novae

Distance Scale Ladder

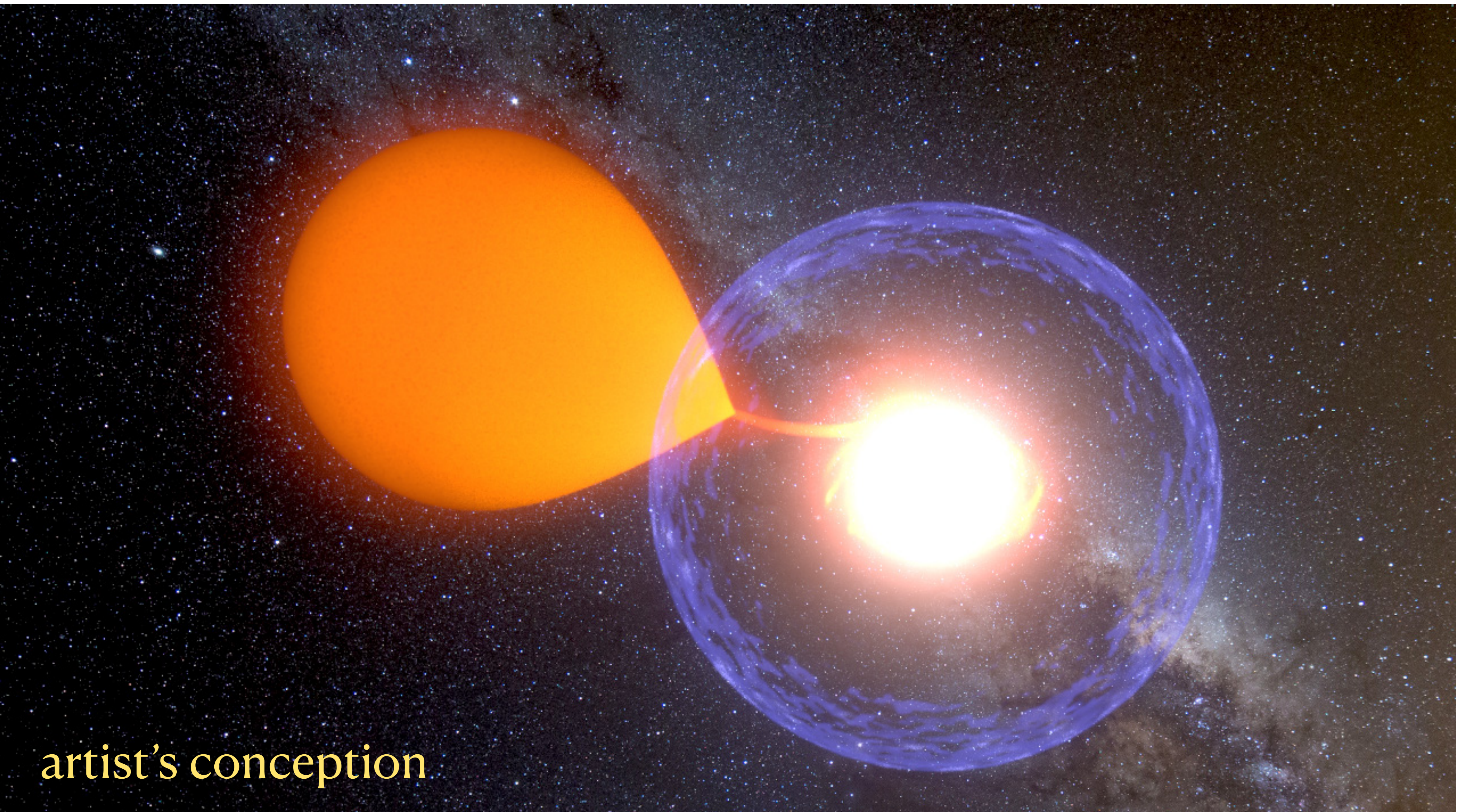


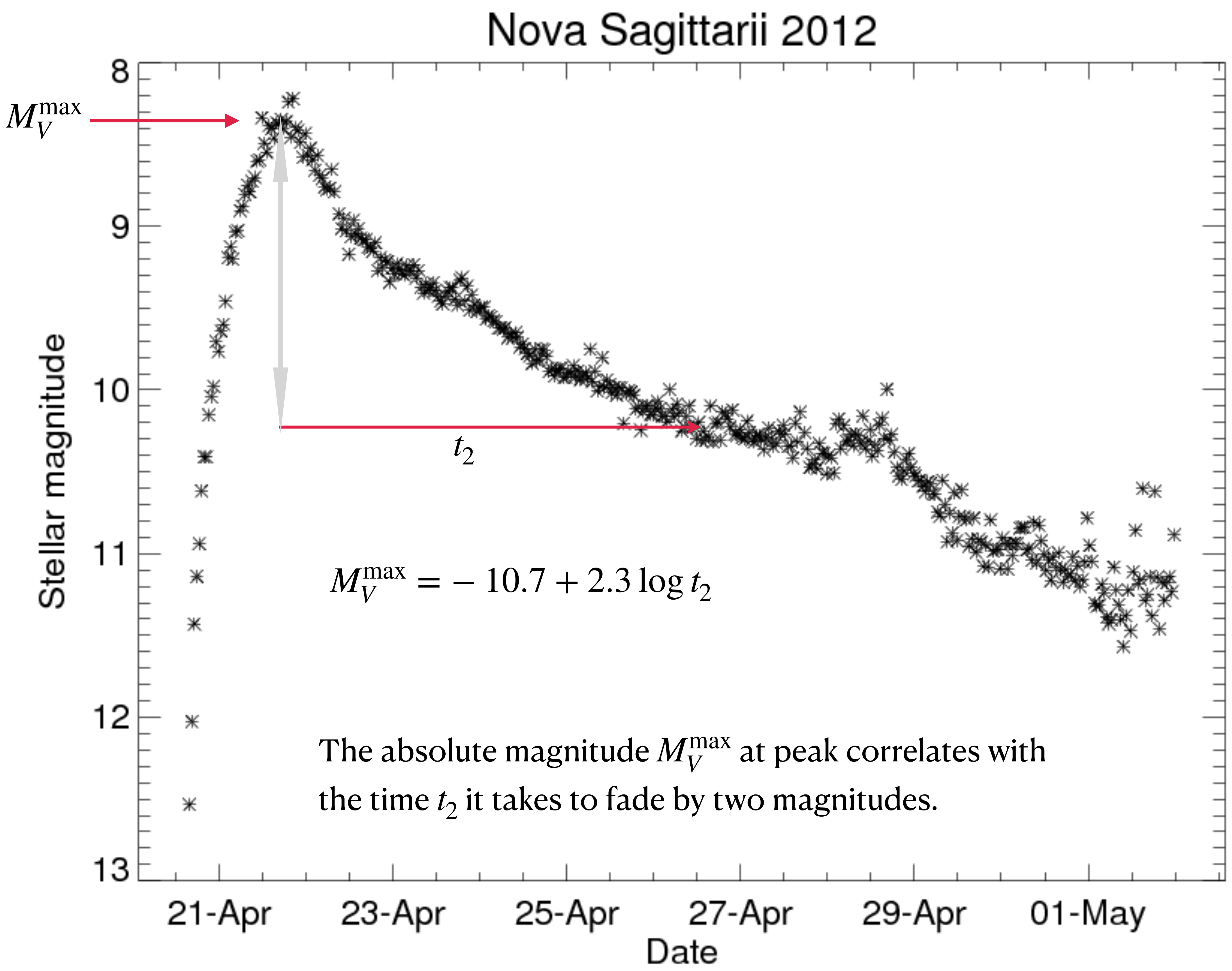
distance modulus $m - M = 5\log(d) - 5$

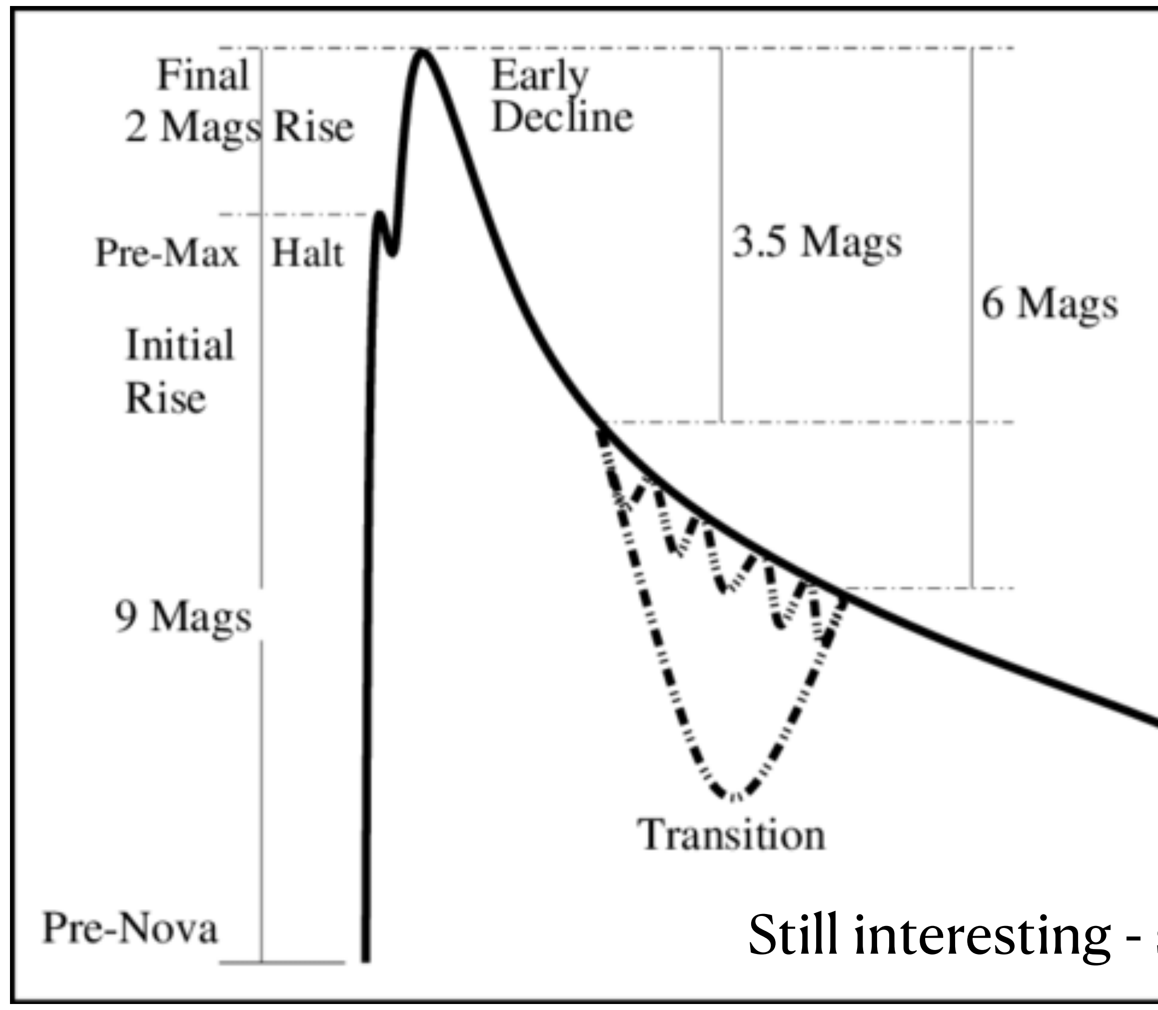
Distance Scale

- 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.

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.

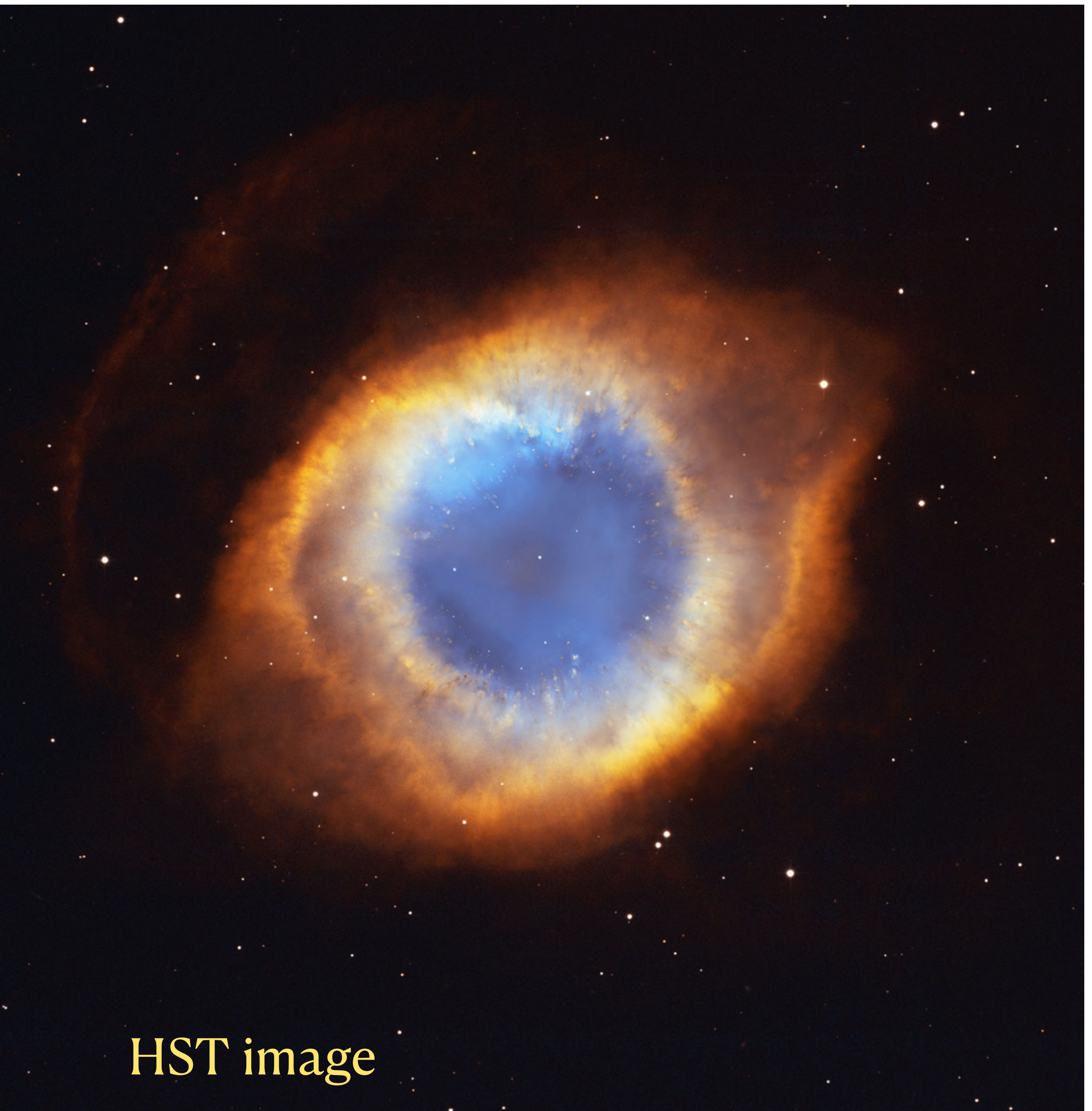
$$\Phi_{PN} \sim e^{0.307}\left(1 - e^{3(m_{cut} - m)}\right)$$

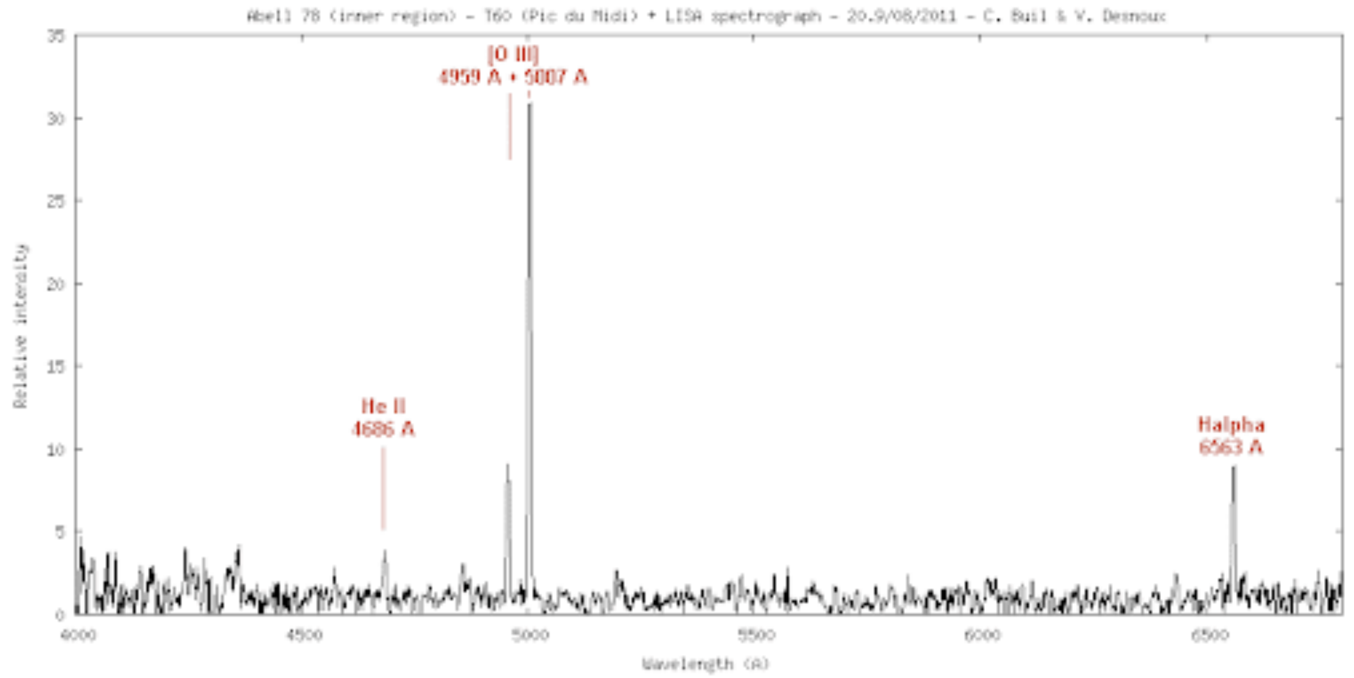
$$m_{[O\ III]} = -2.5 \log f_{5007} - 21.4$$

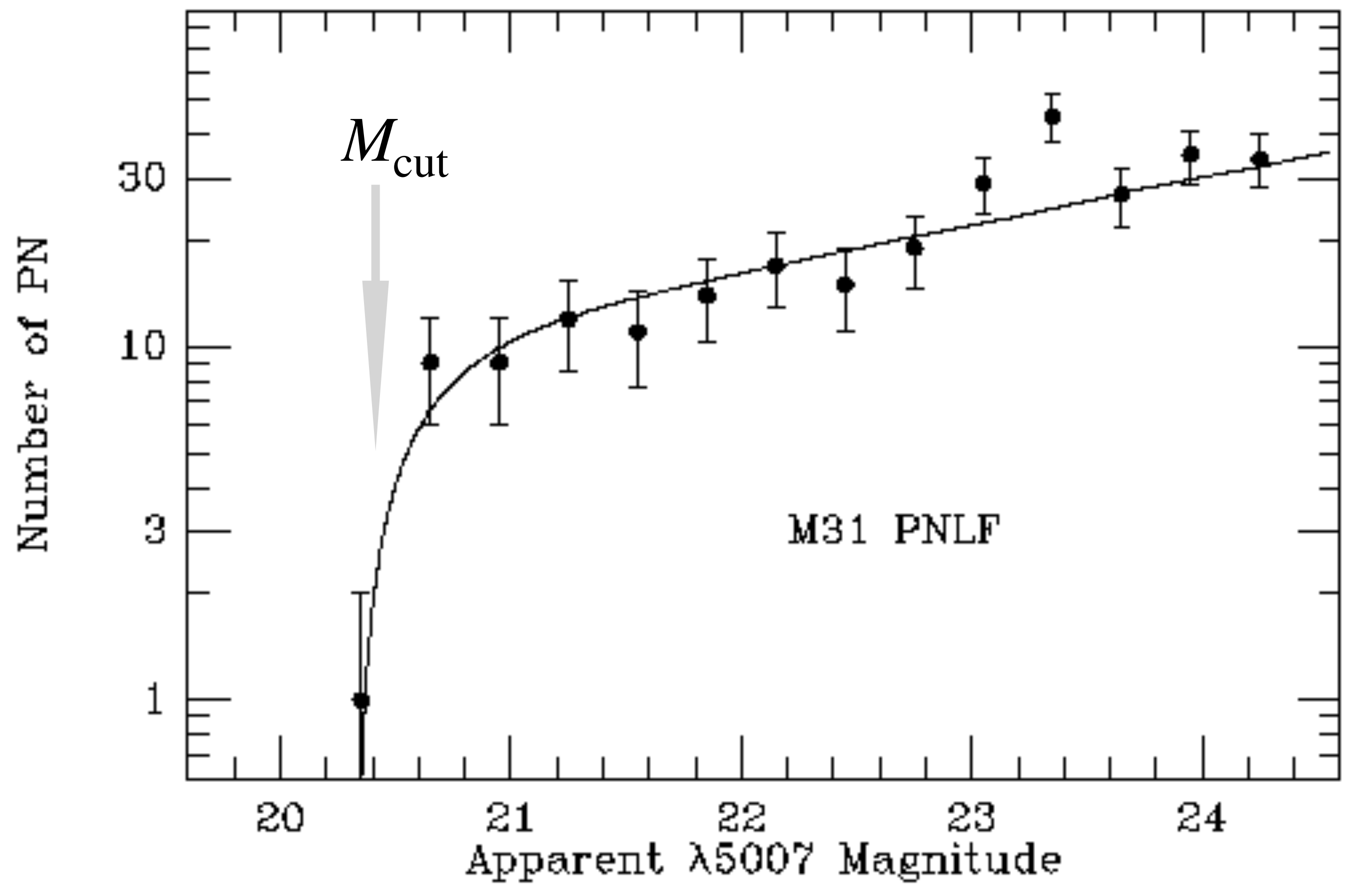
$$M_{cut} = -4.6 \pm 0.1$$

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

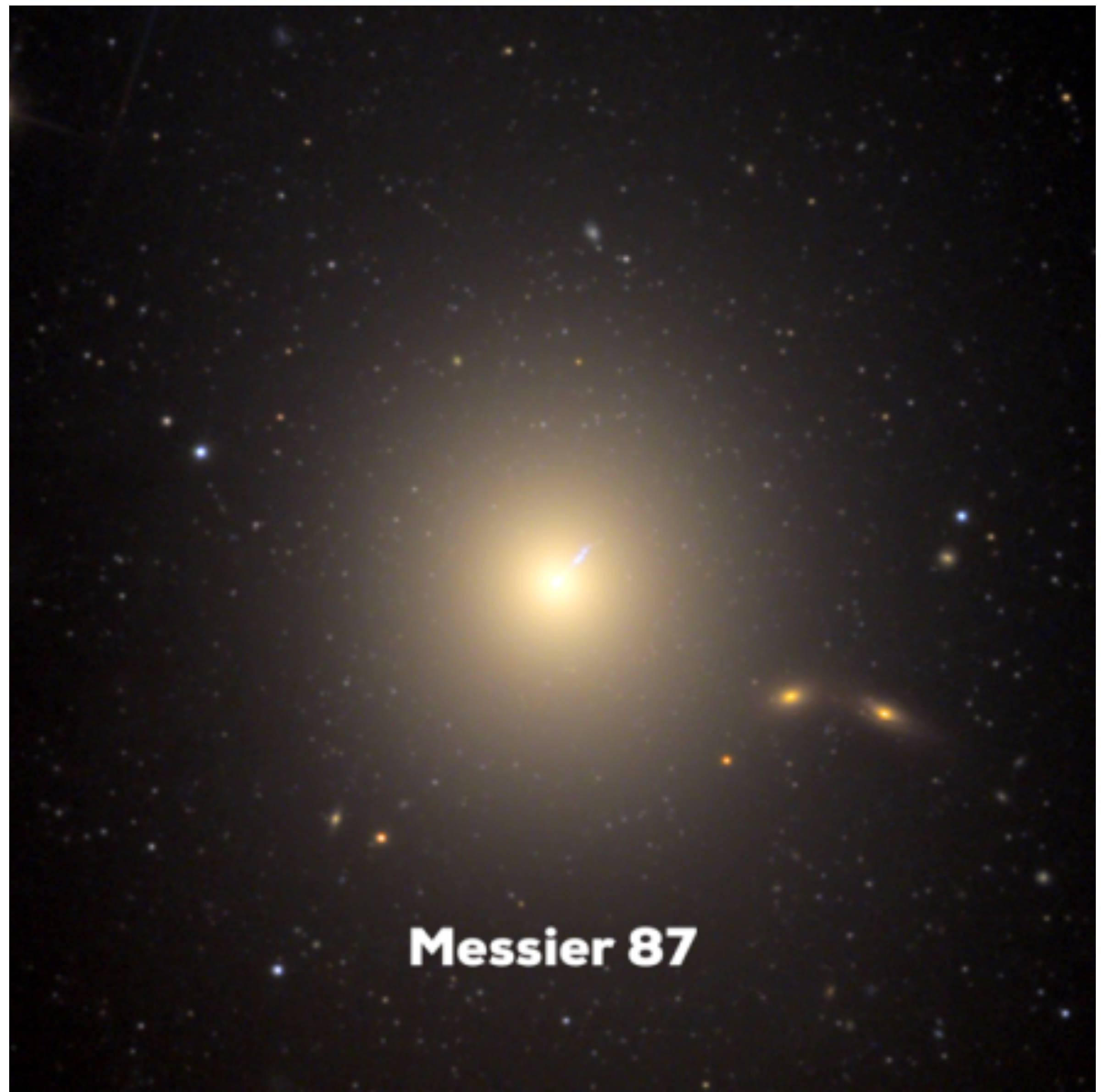
Globular clusters in the Milky Way have a Gaussian luminosity function.

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

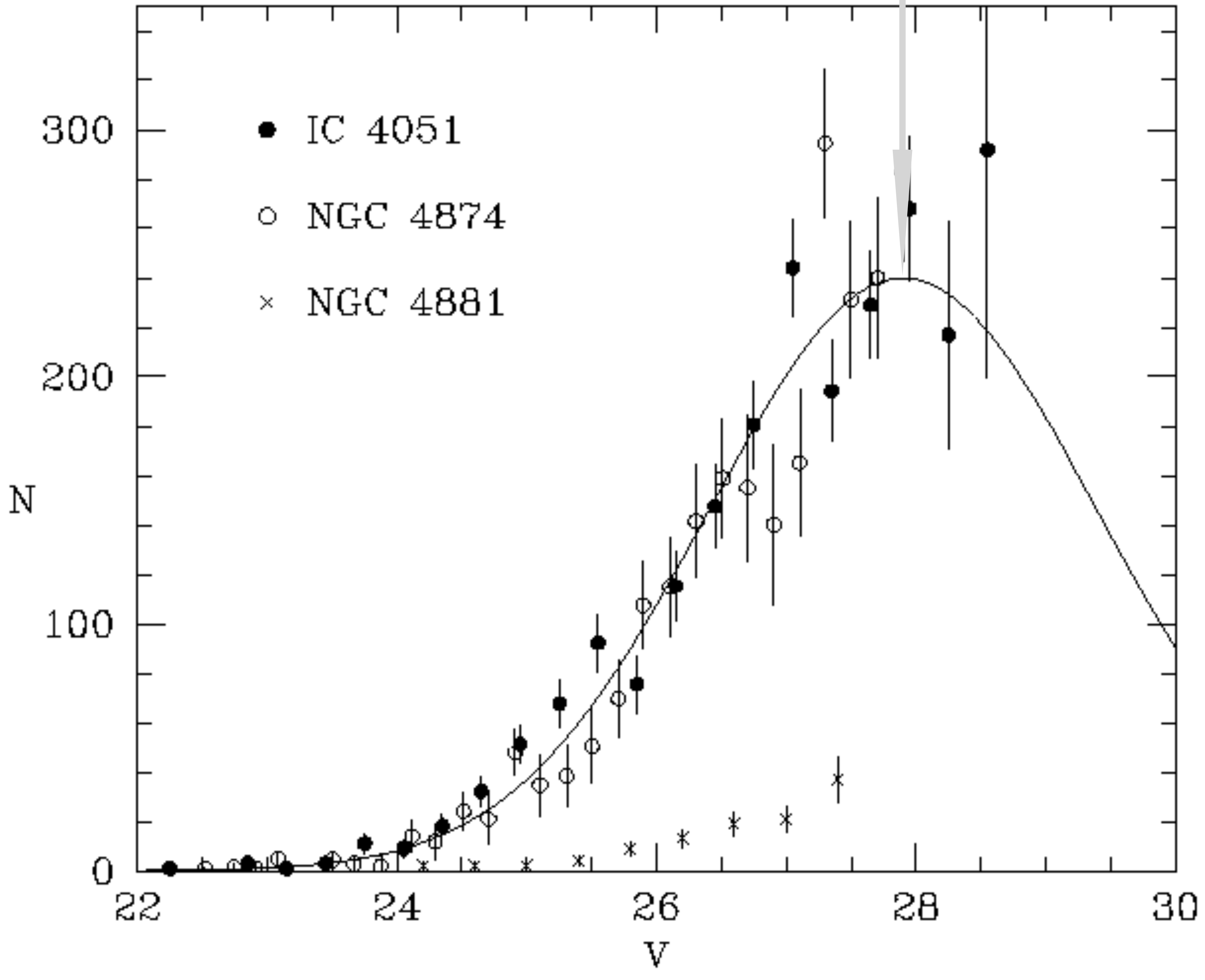
$$\Phi_{GC} \sim e^{-\frac{(m-\bar{m})^2}{2\sigma^2}}$$

Globular cluster M80

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

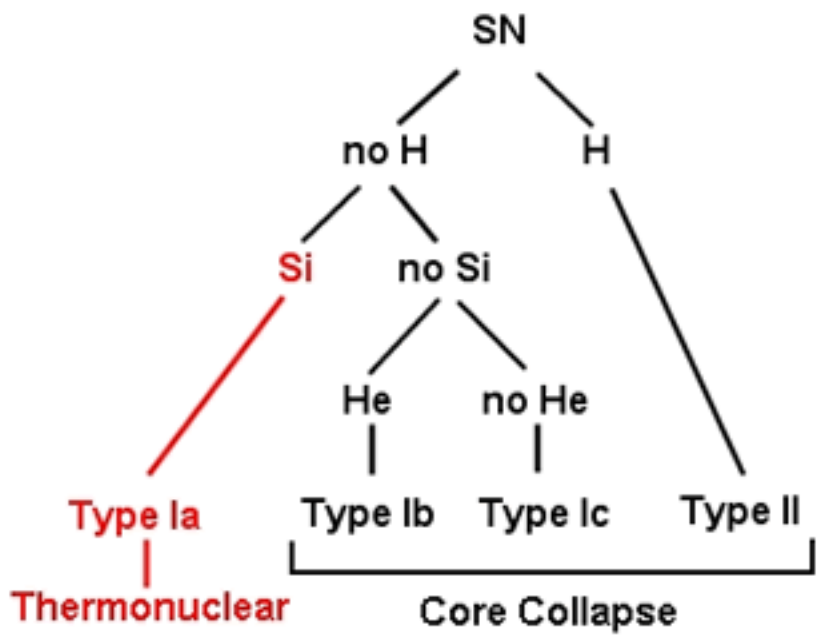


Globular cluster luminosity function

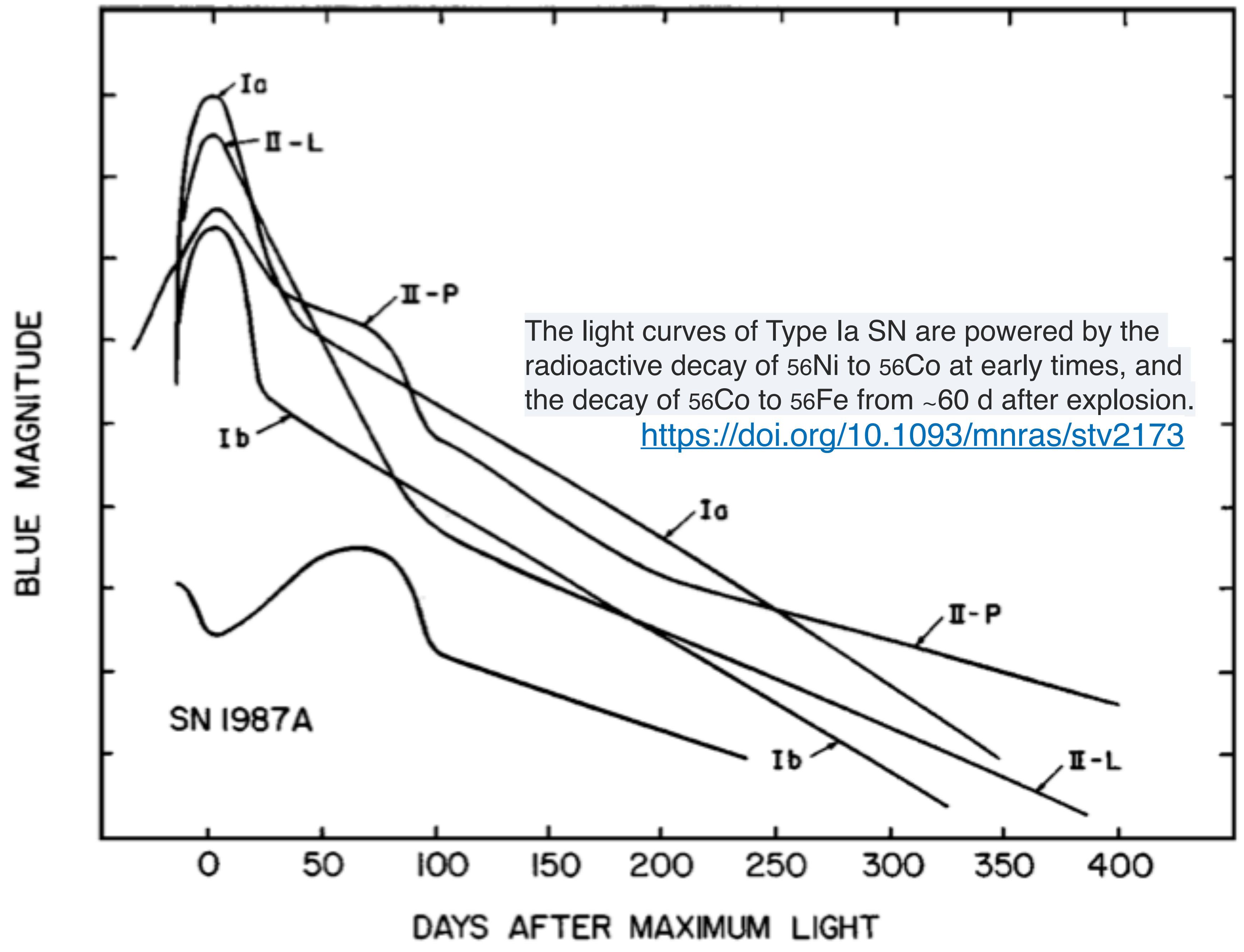


Supernovae

Types of Supernovae



Different types of supernova light curves



The light curves of Type Ia SN are powered by the radioactive decay of 56Ni to 56Co at early times, and the decay of 56Co to 56Fe from ~60 d after explosion.
https://doi.org/10.1093/mnras/stv2173

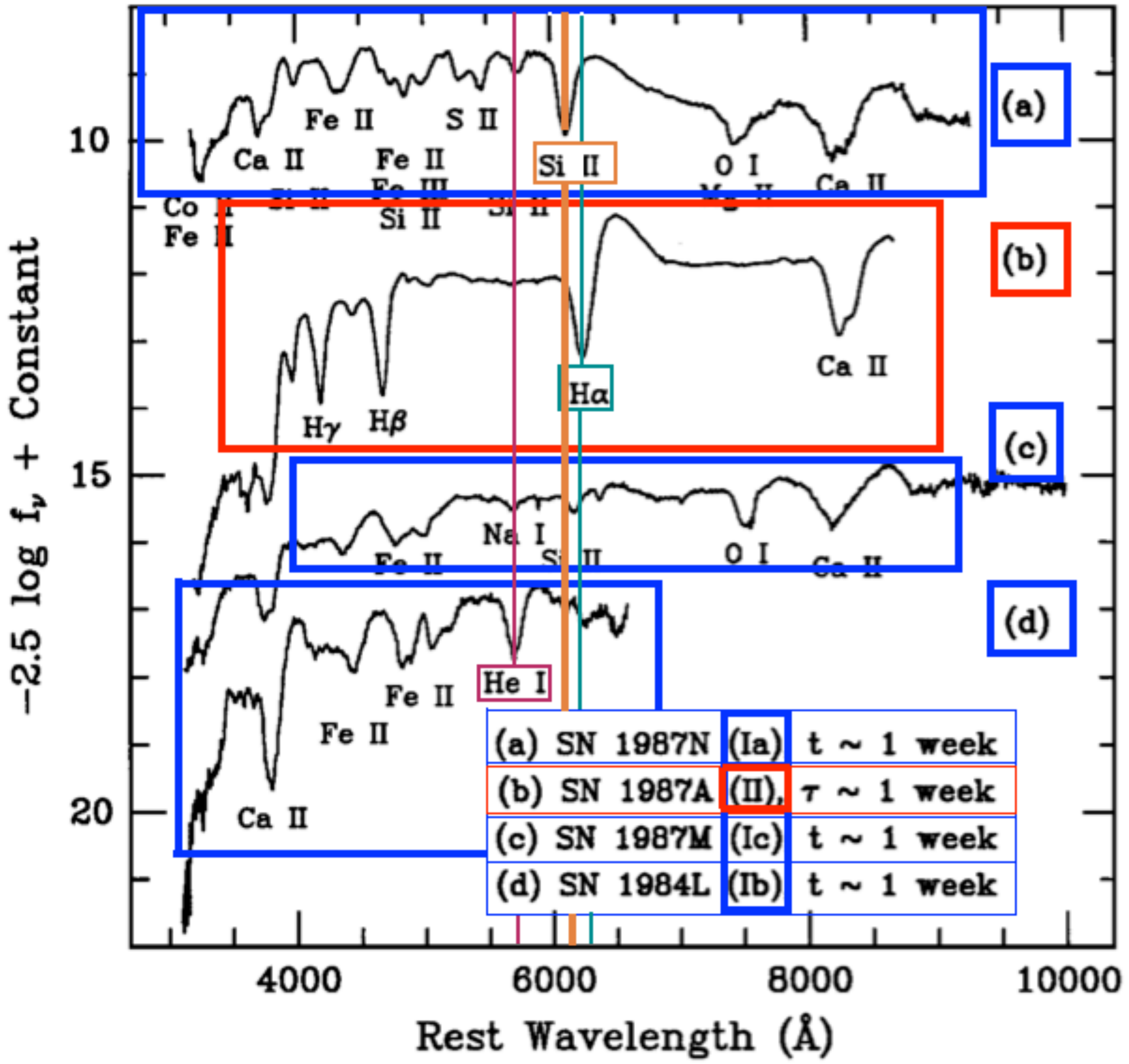
Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous.

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

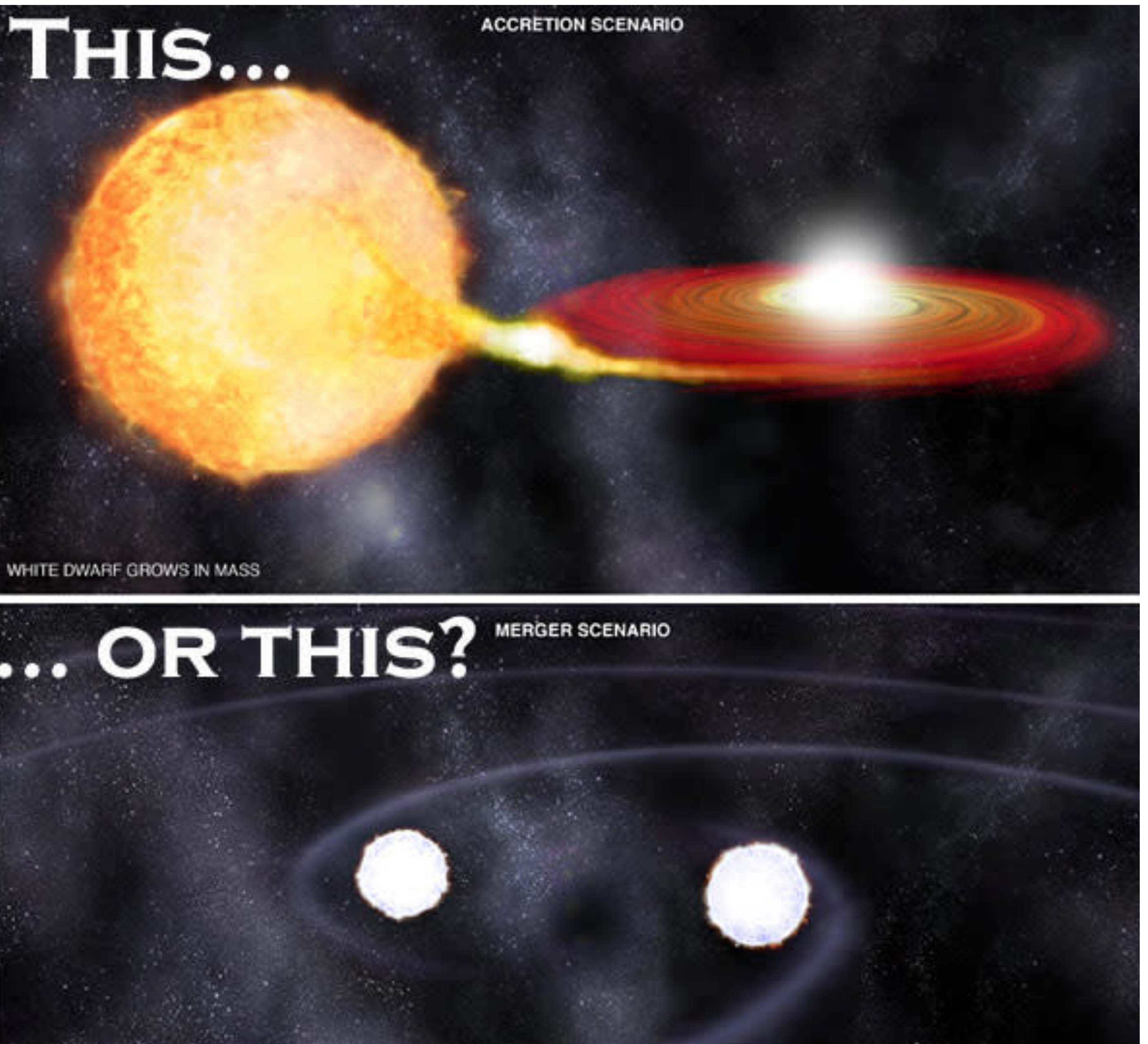
Type Ia supernovae contain an obvious Si **absorption** at 6150 Angstoms, **Type Ib** have no Si but show He in **emission**, and **Type Ic** display neither Si nor He.

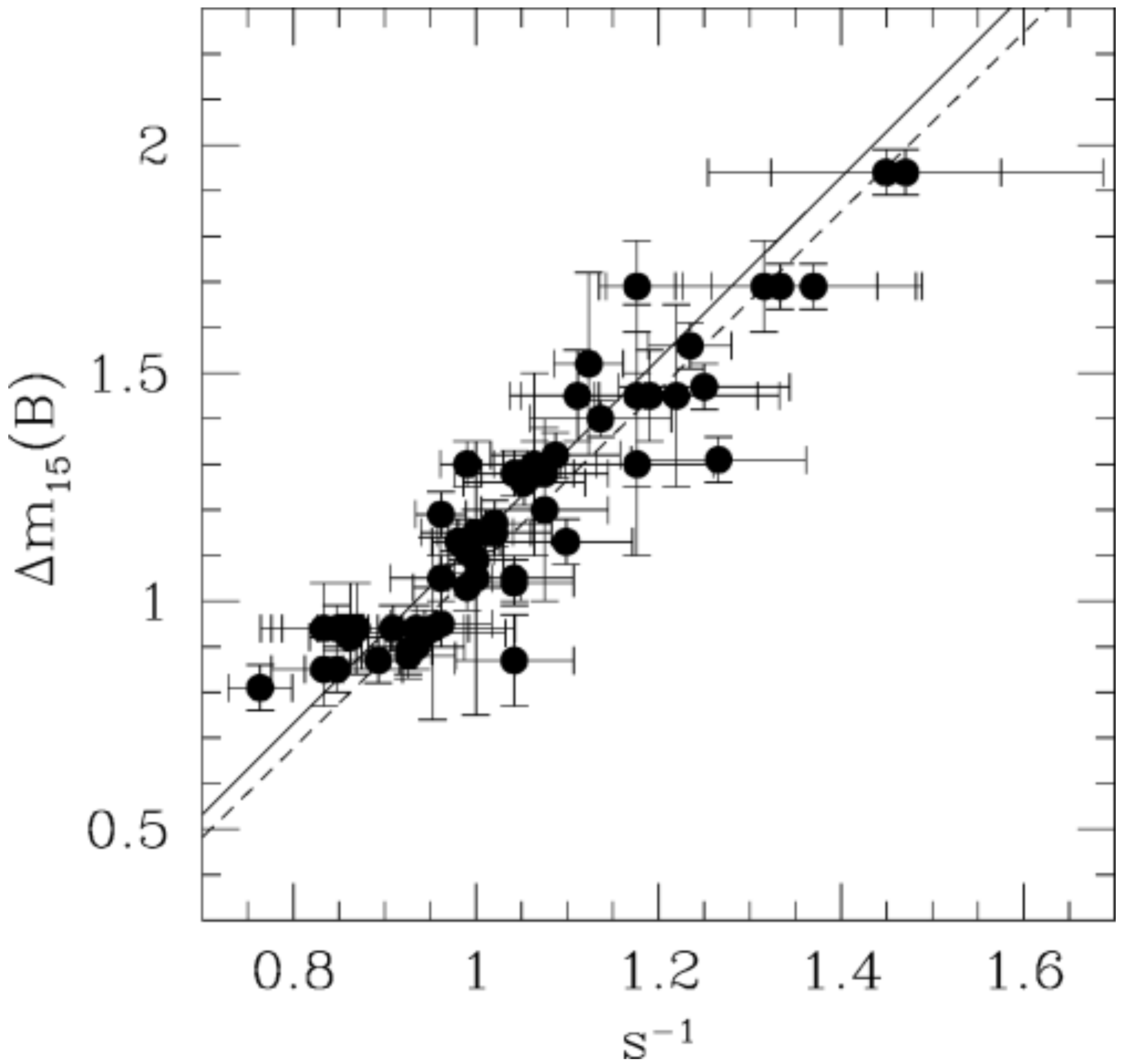
Distance Scale

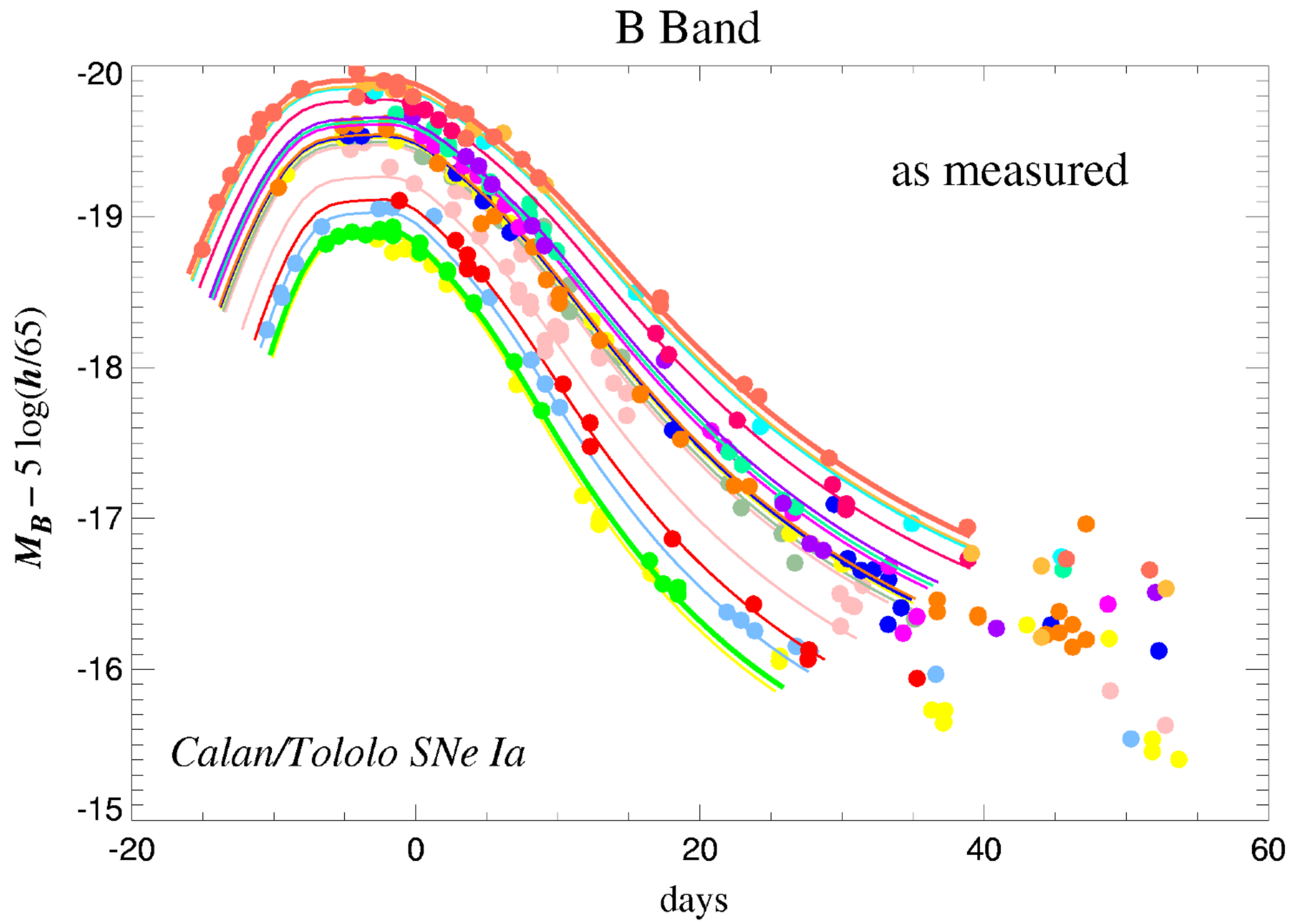
- Secondary Distance Indicators
  - Supernovae
    - Type Ia SN (white dwarf detonations)
    - White dwarfs that exceed the Chandrasekhar limit explode, converting carbon and oxygen to iron and nickel (etc.)
    - At present, appear mostly due to WD-WD mergers, not single accreting WDs.

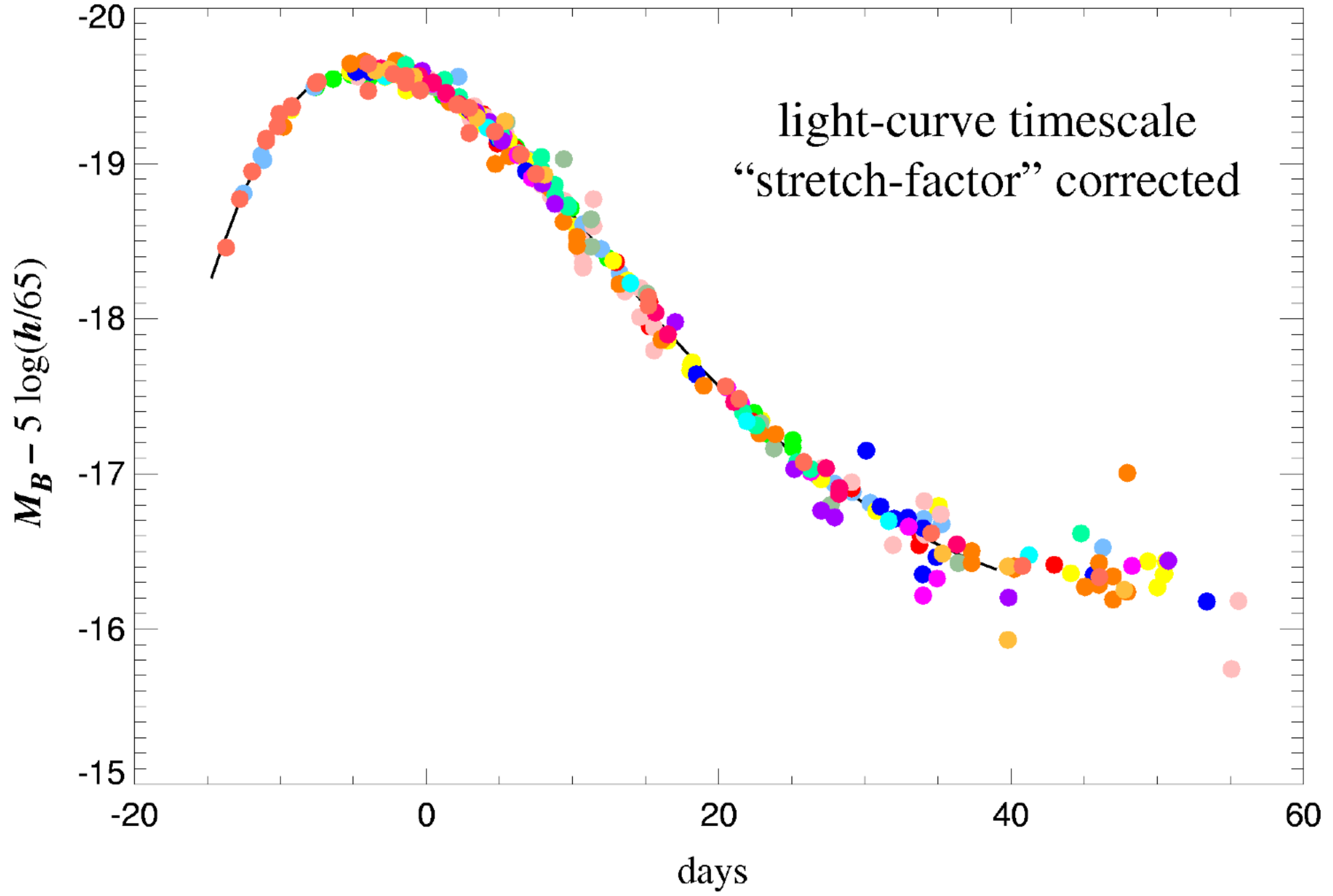
$$M_{B,\,\mathrm{peak}} = -19.26 + 0.8[\Delta m_{15} - 1.1]$$

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)

Distance Scale

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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.

Scatter in local Hubble diagram decreases after correction for fade time - as it should if this correction is effective.

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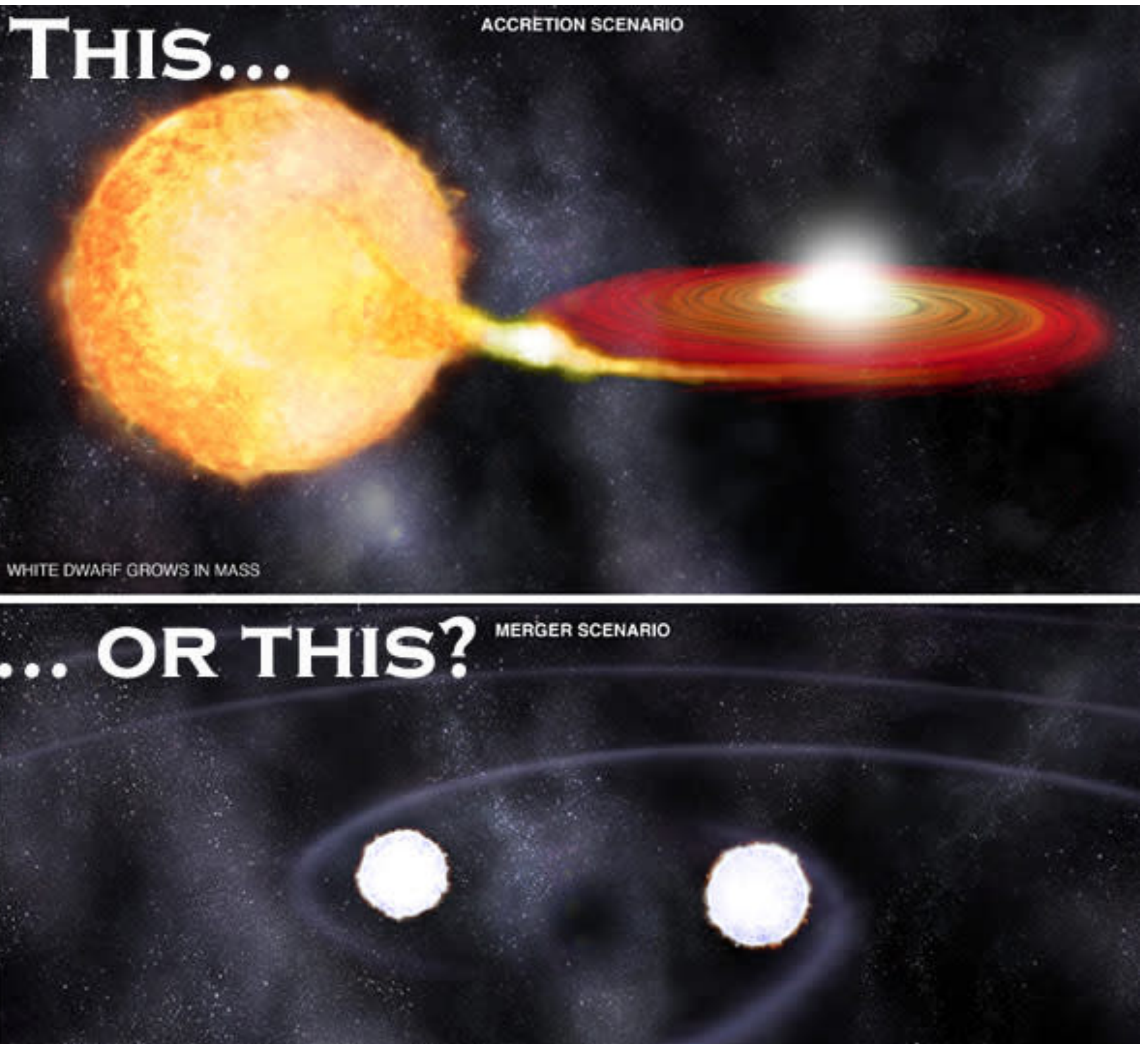

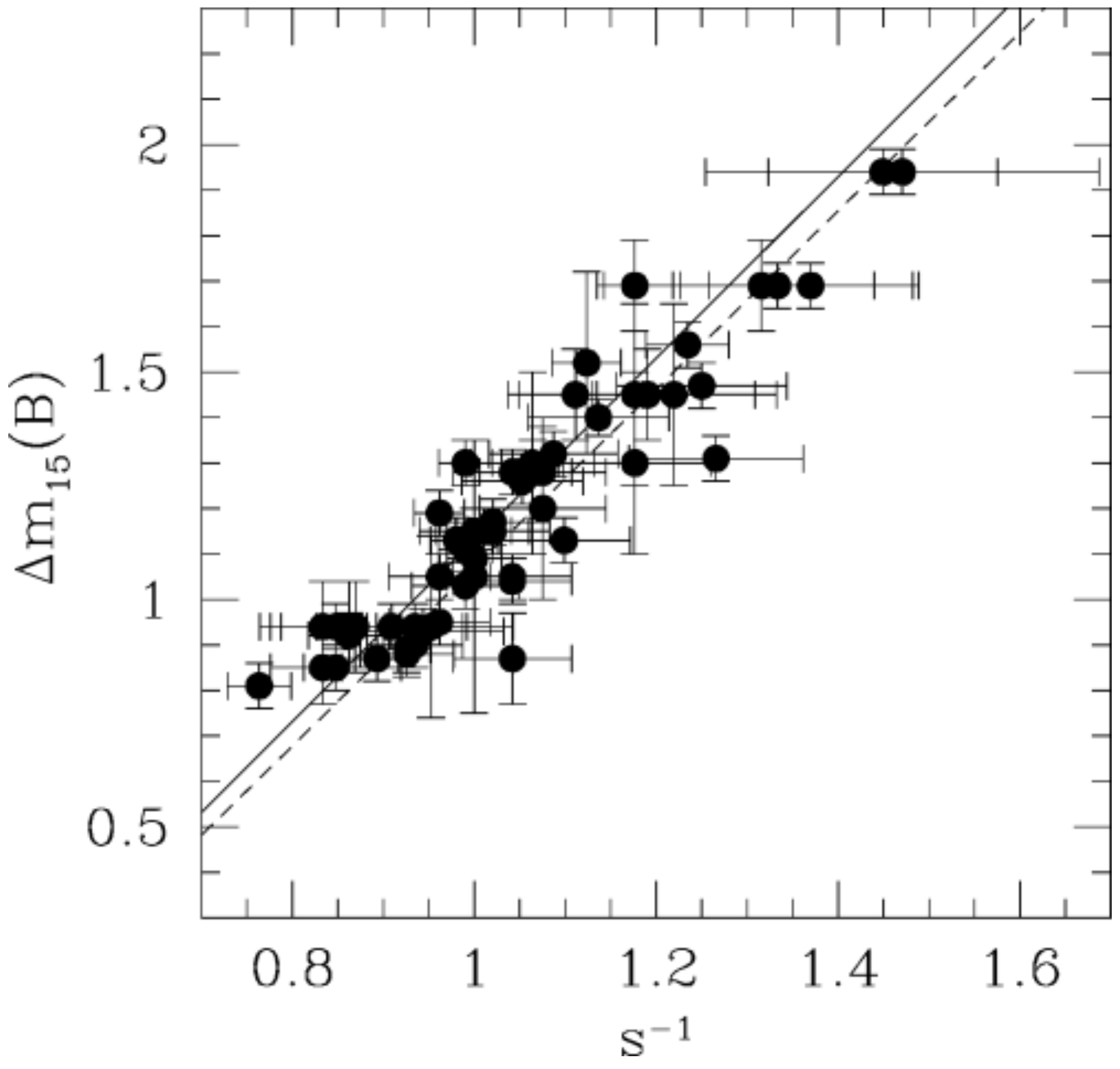

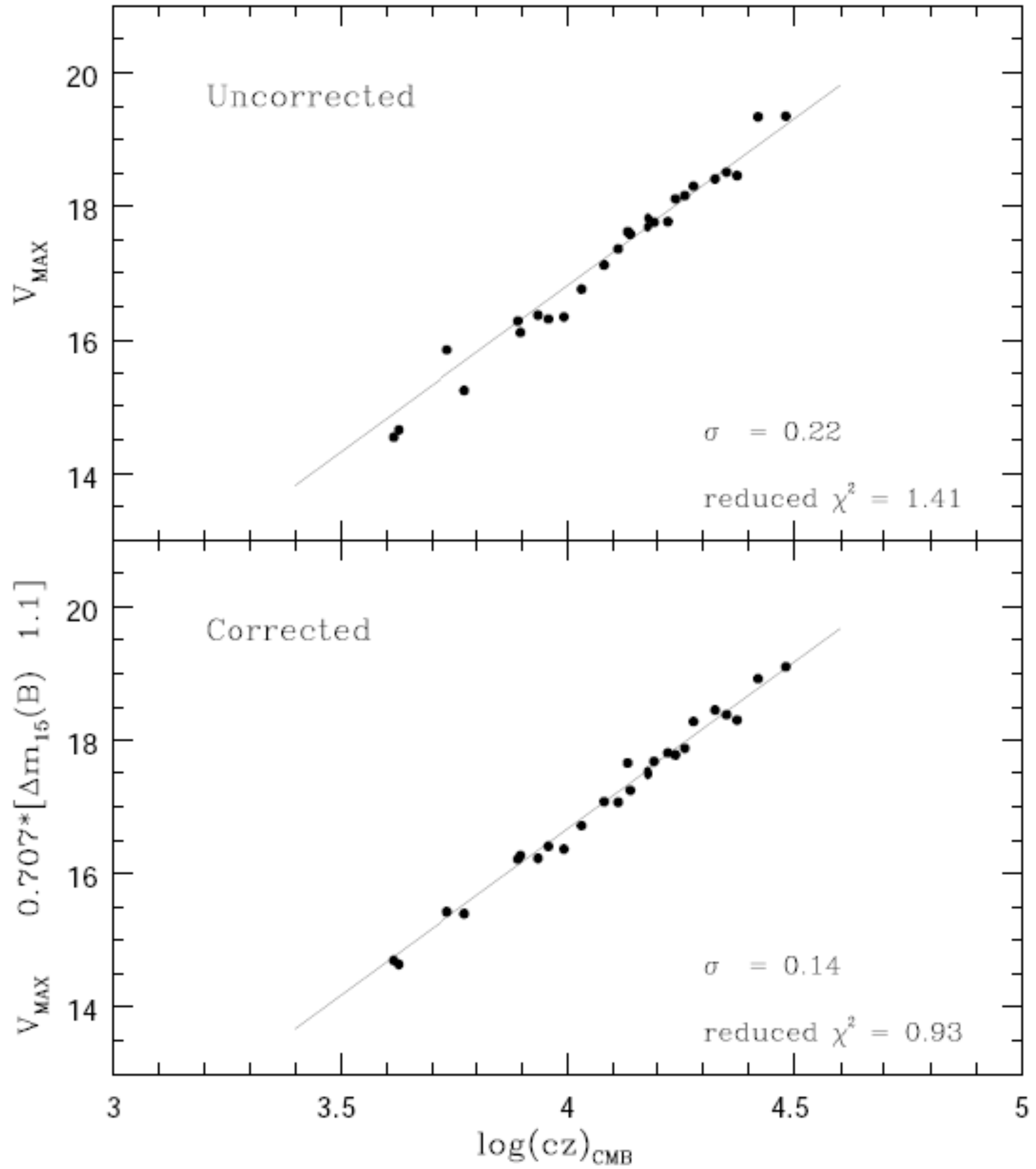

Figure 5: (top panel) The Hubble diagram in V for the SNe Ia in the Calán/Tololo sample with $B_{MAX}-V_{MAX} \leq 0.20$. (bottom panel) The Hubble diagram for the same 26 events after correction for the peak luminosity-decline rate dependence.

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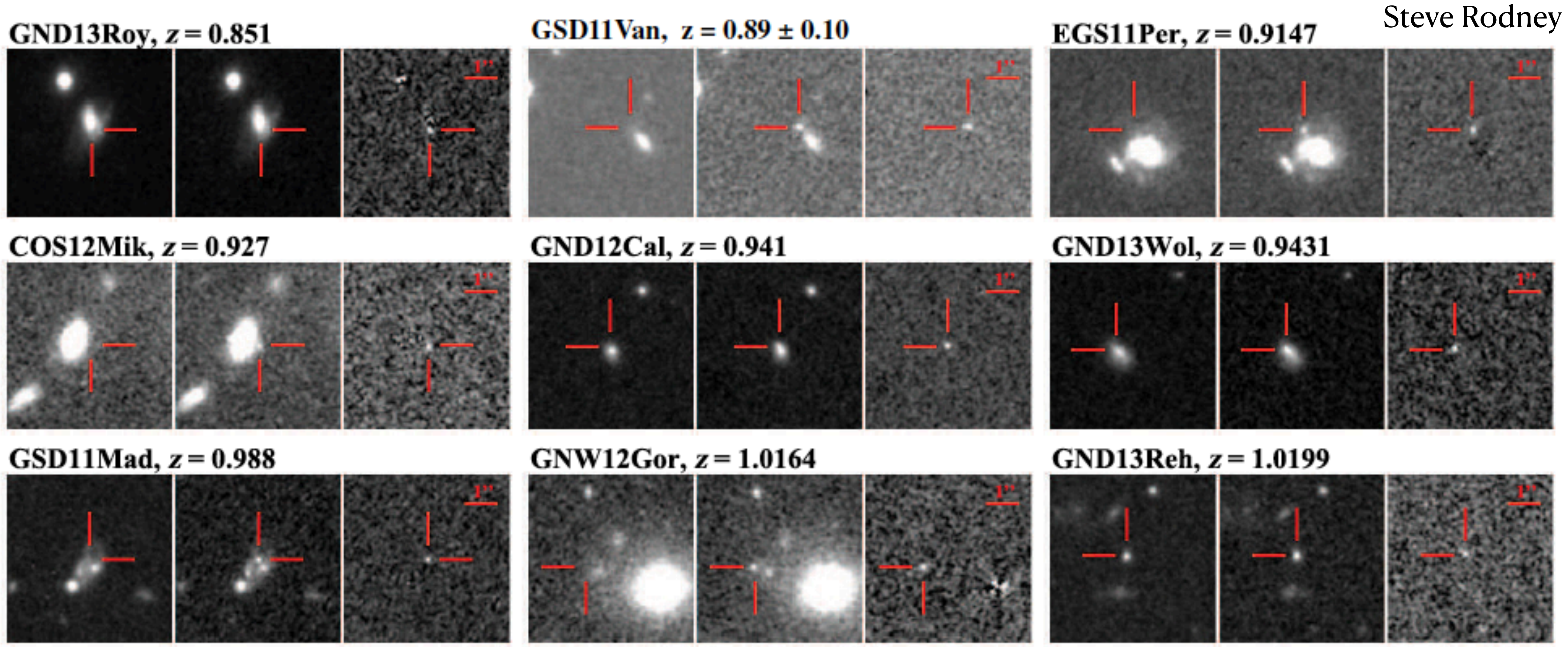
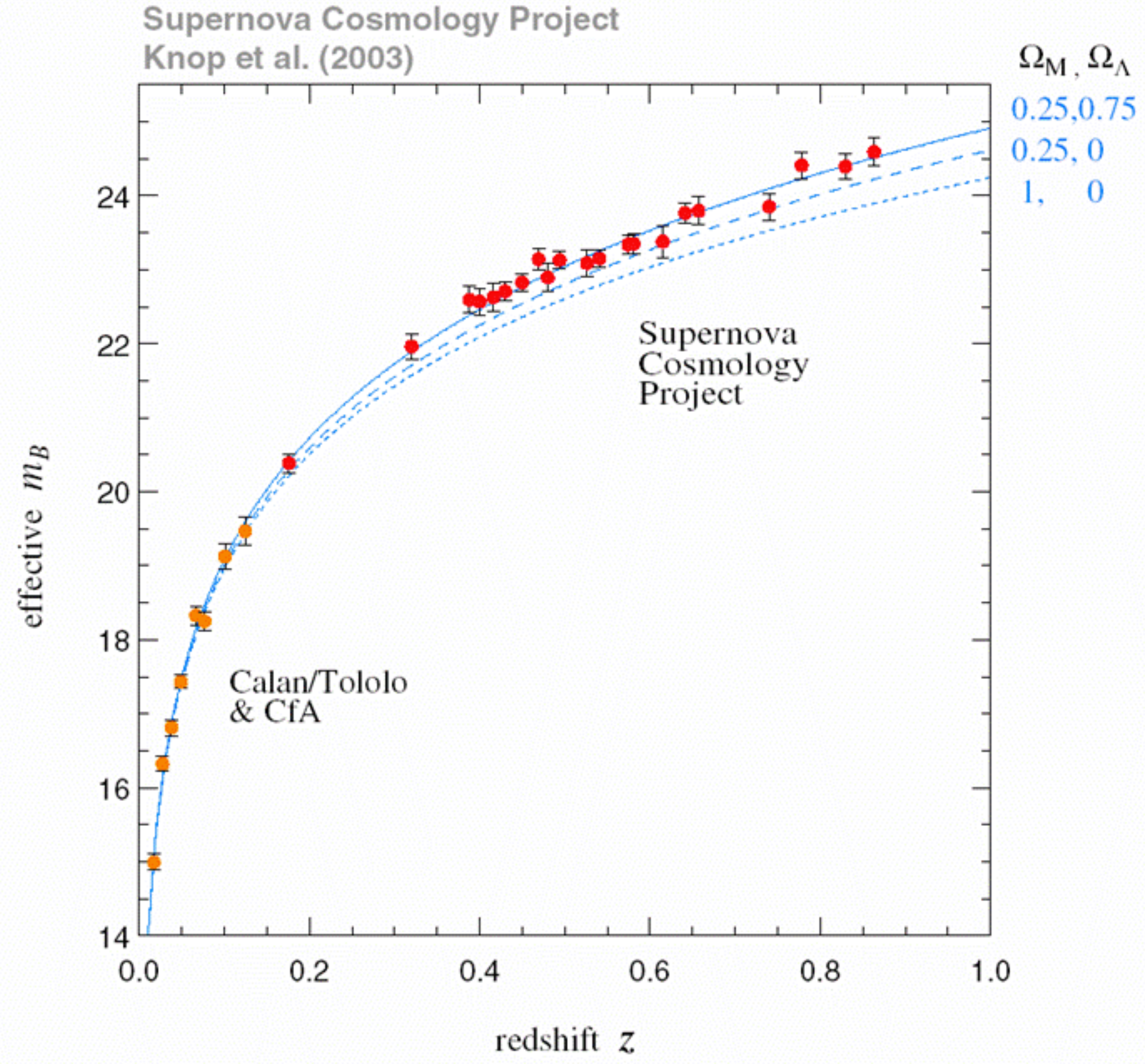
Peak luminosity correlates with fade time - Δm_{15} is the amount of fading after 15 days. Can also be calibrated in terms of a `stretching factor,' *s*, the amount (in days) that the template light curve must be stretched to fit.

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 $q_0 < 0$.

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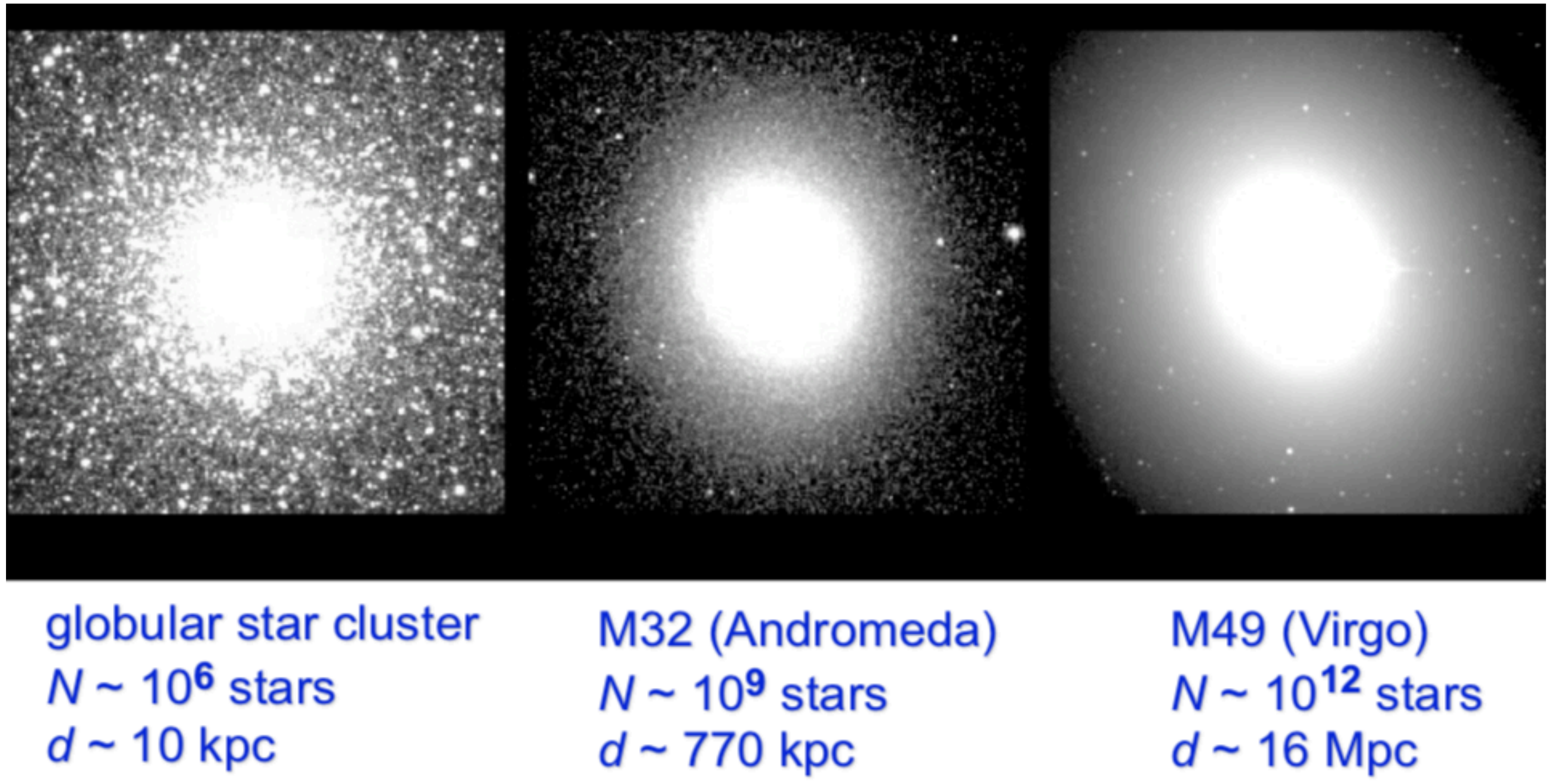
Peak luminosity correlates with fade time - Δm_{15} is the amount of fading after 15 days. Can also be calibrated in terms of a \`stretching factor,' *s*, the amount (in days) that the template light curve must be stretched to fit.

- 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

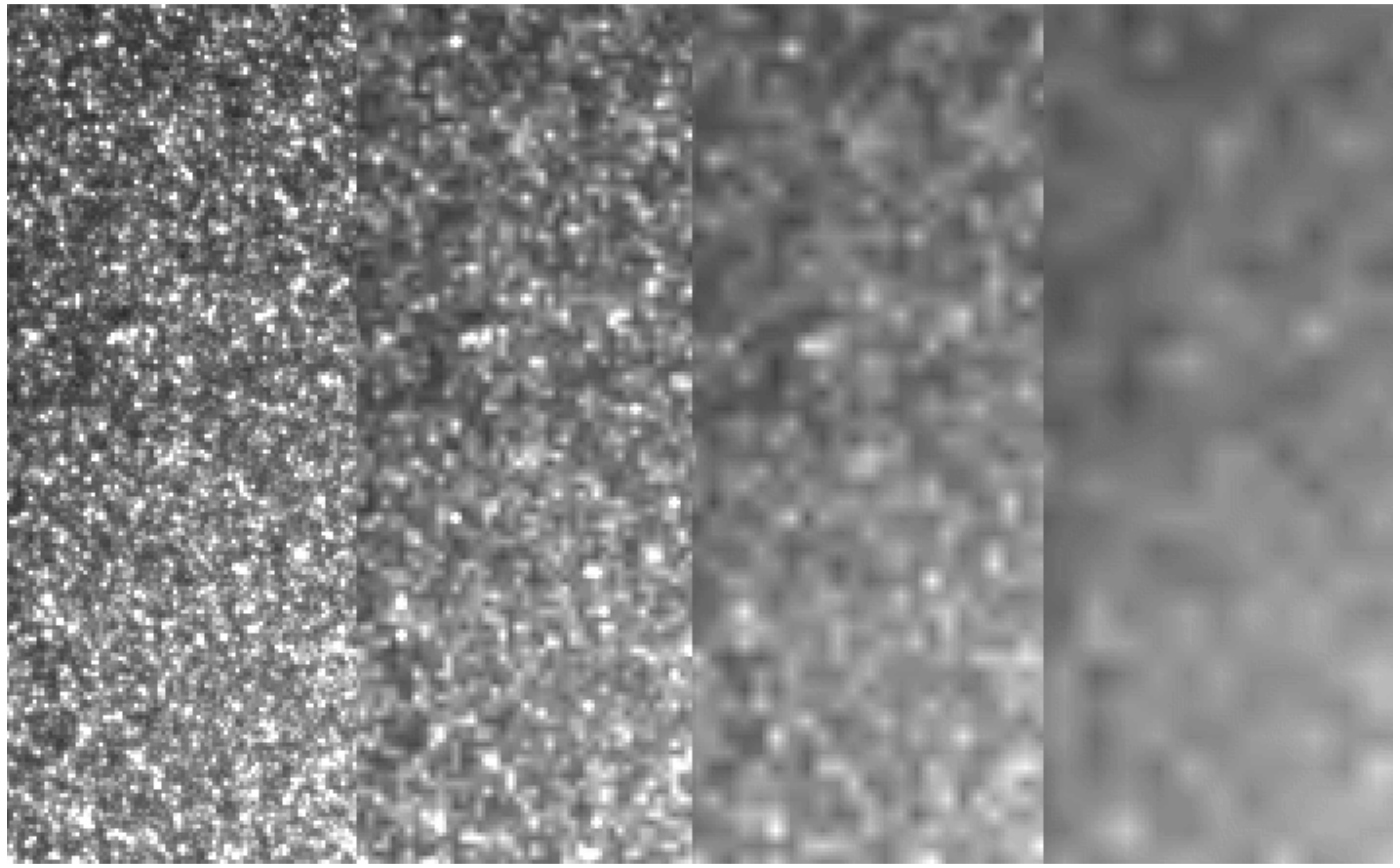
$$\langle L \rangle = \frac{\sum \bar{N}_i L_i^2}{\sum \bar{N}_i L_i}.$$

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.

Faber-Jackson relation

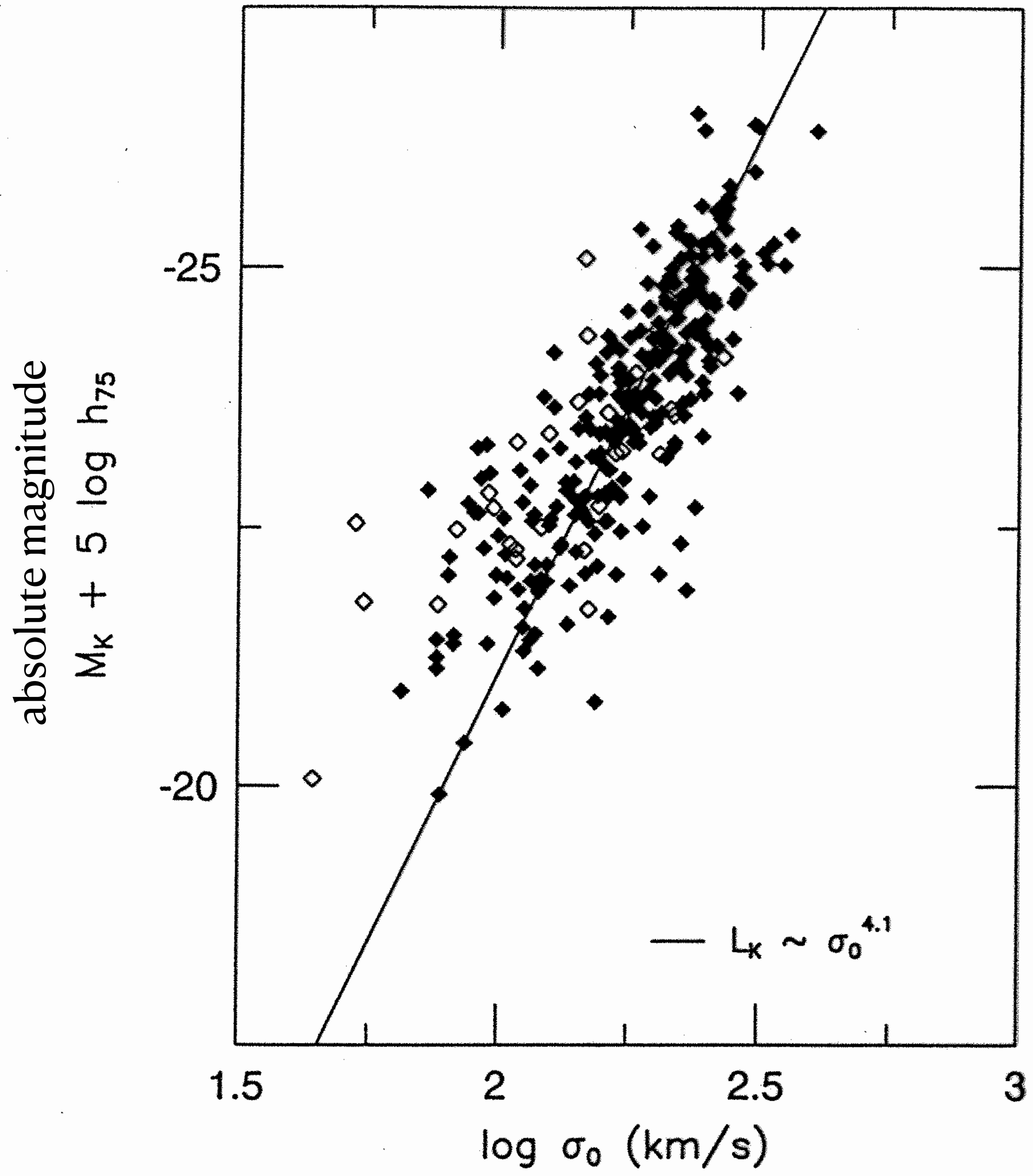


FIG. 10.—Faber-Jackson relation between luminosity and central velocity dispersion. The best-fitting relation is $L_K \propto \sigma_0^{4.14\pm0.22}$ with a large scatter of 0.93 mag. The scatter is significantly smaller in the Coma cluster at 0.72 mag.

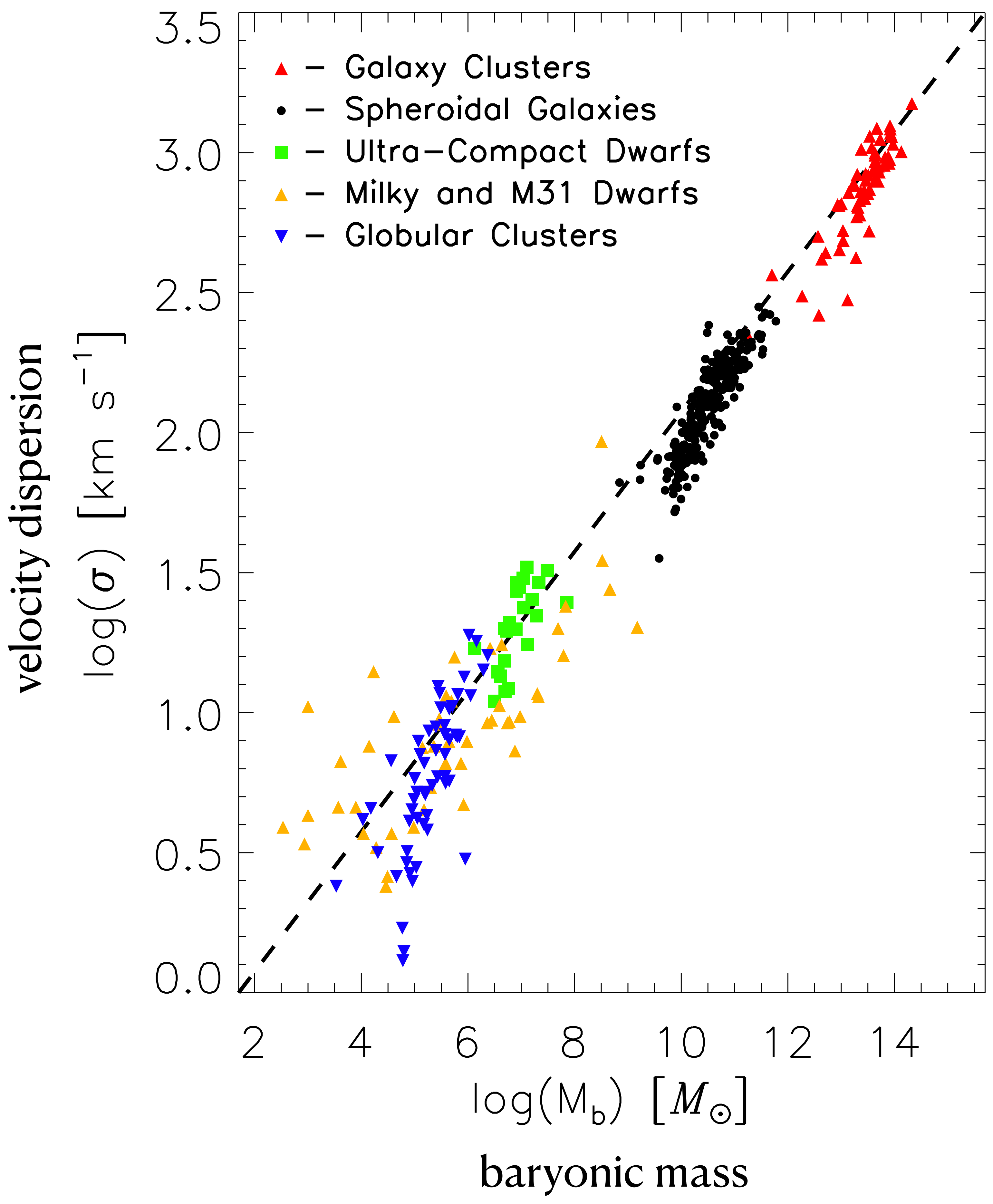
velocity dispersion

Distance Scale

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

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).

Baryonic Faber-Jackson relation



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.

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

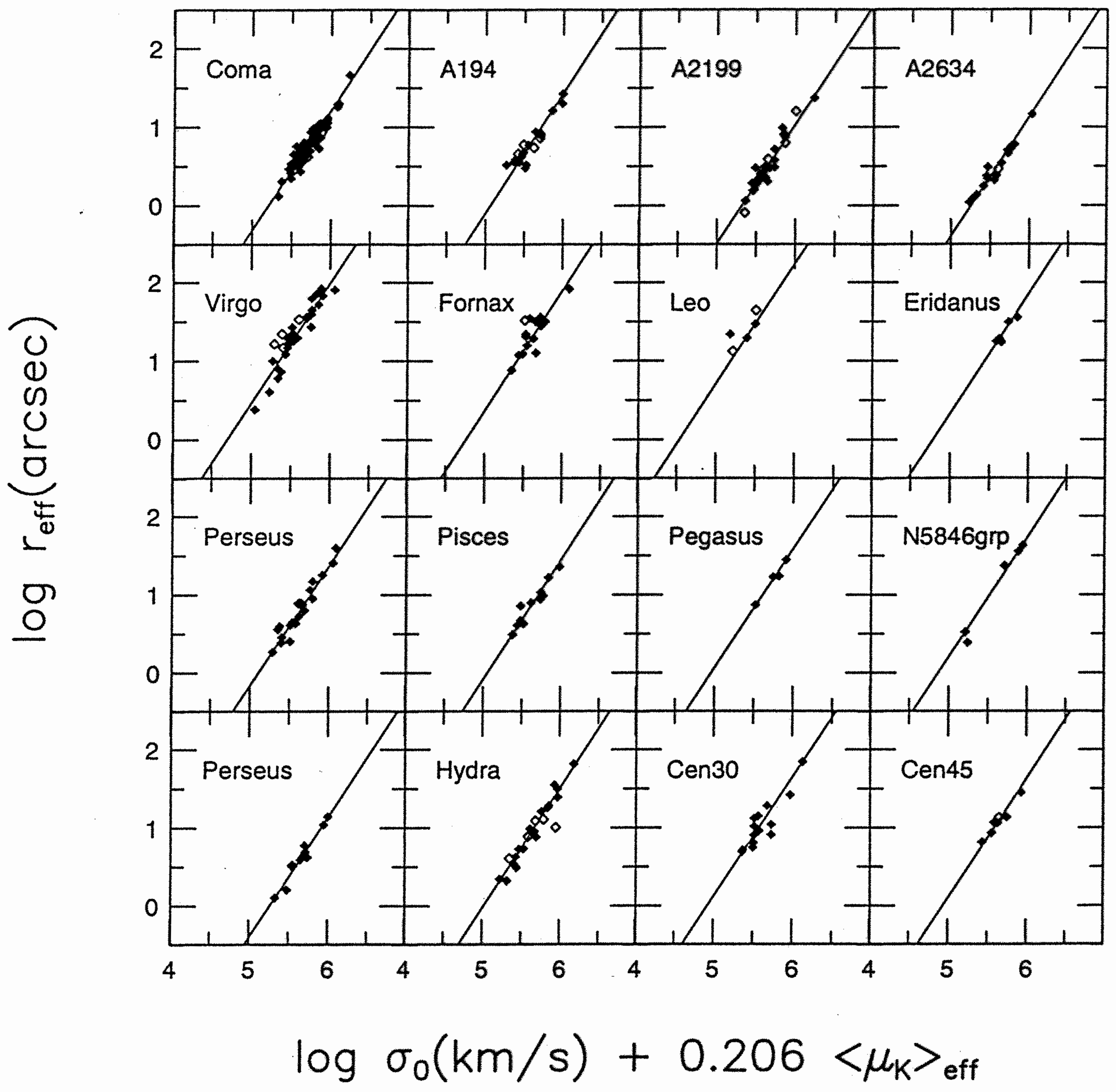
Where
R_e is the effective radius (containing half of the total light)
$\langle \Sigma_K \rangle$ is the average K-band surface brightness with Re
σ_0 is the central velocity dispersion

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 galaxies are plotted as solid symbols, while those excluded from the fit (log $\sigma_0 <$ 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