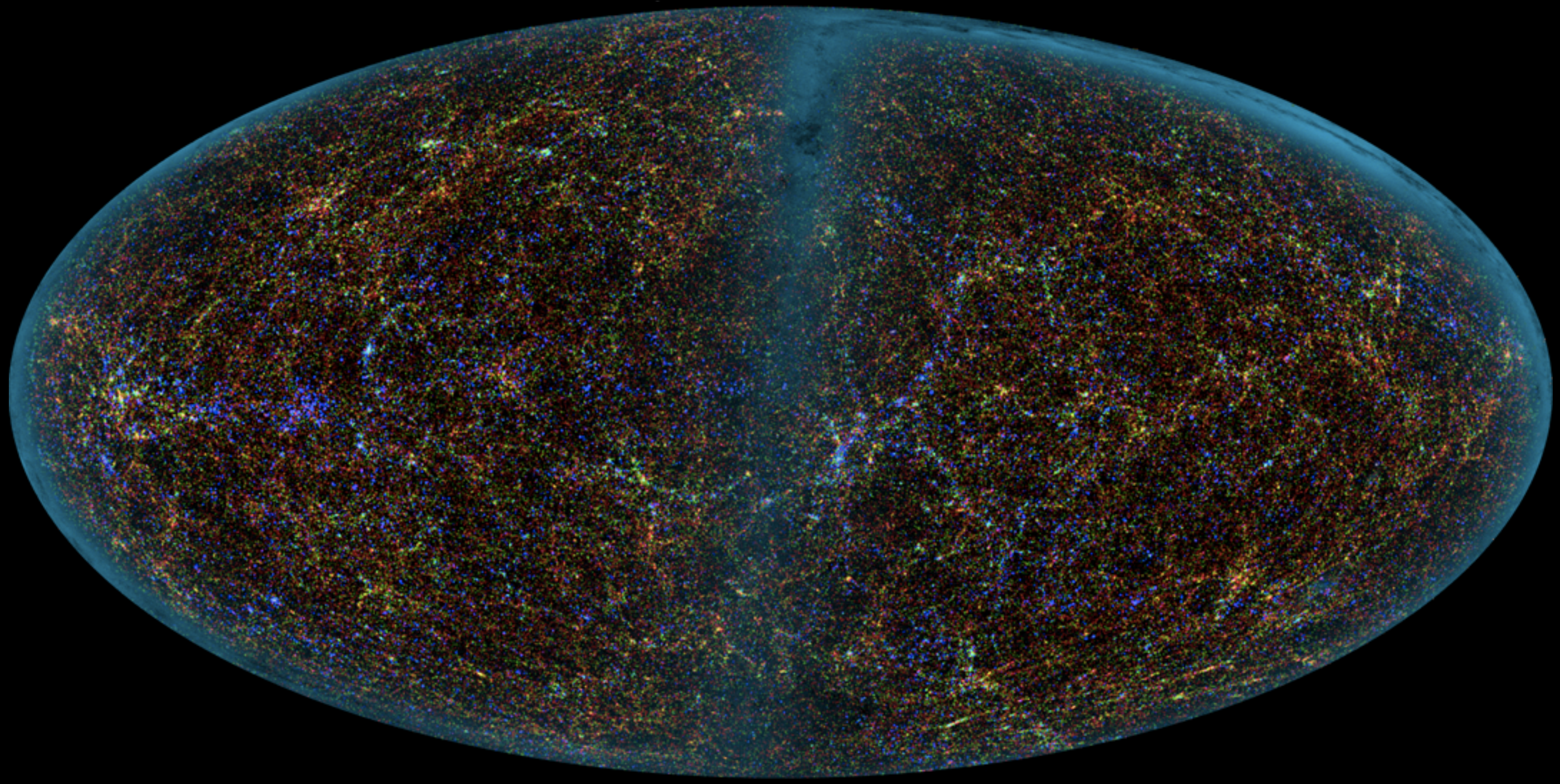
Cosmology

and Large Scale Structure



Today

Distance Scale

pulsating stars

TRGB

secondary indicators

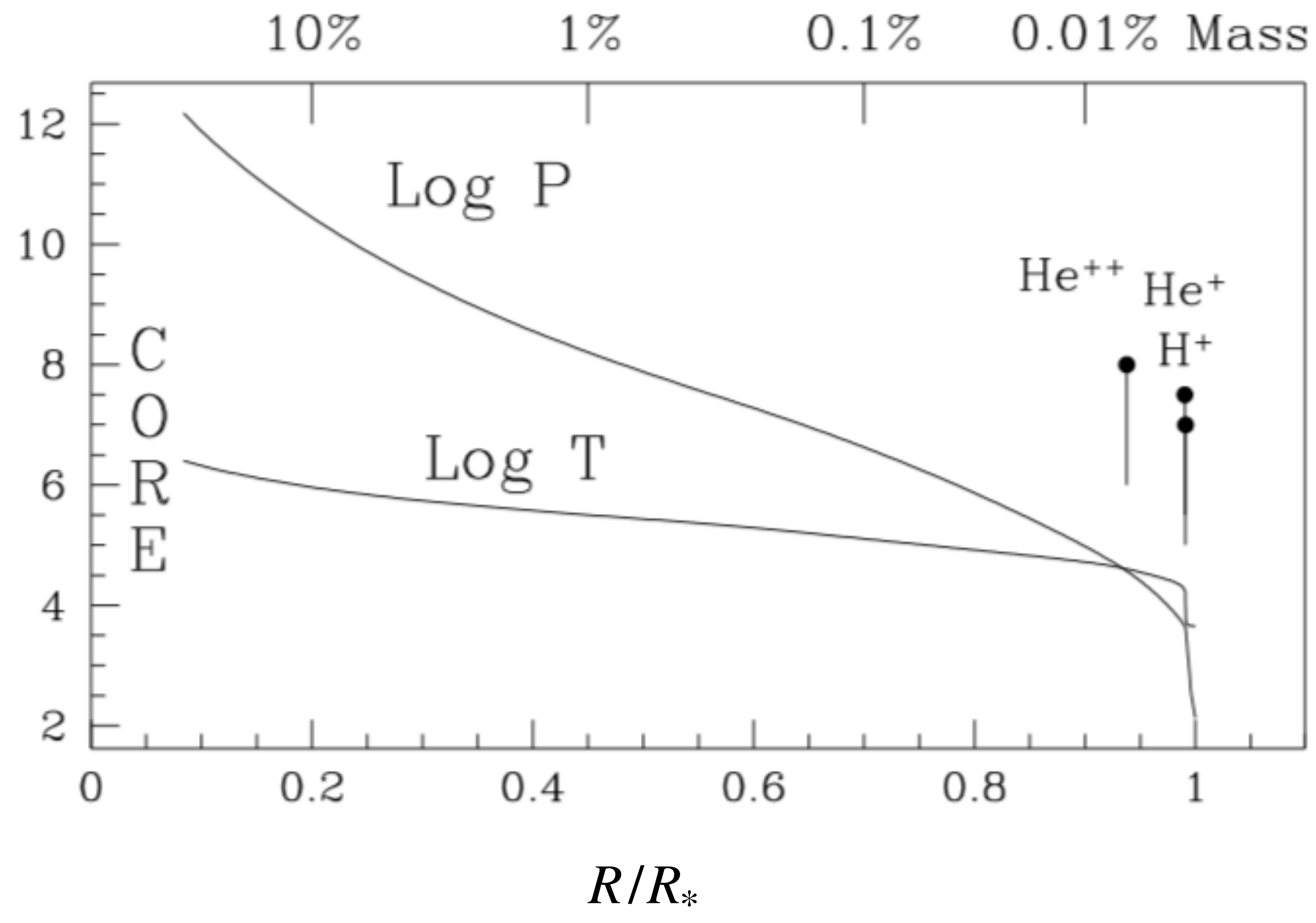
19 October 2020

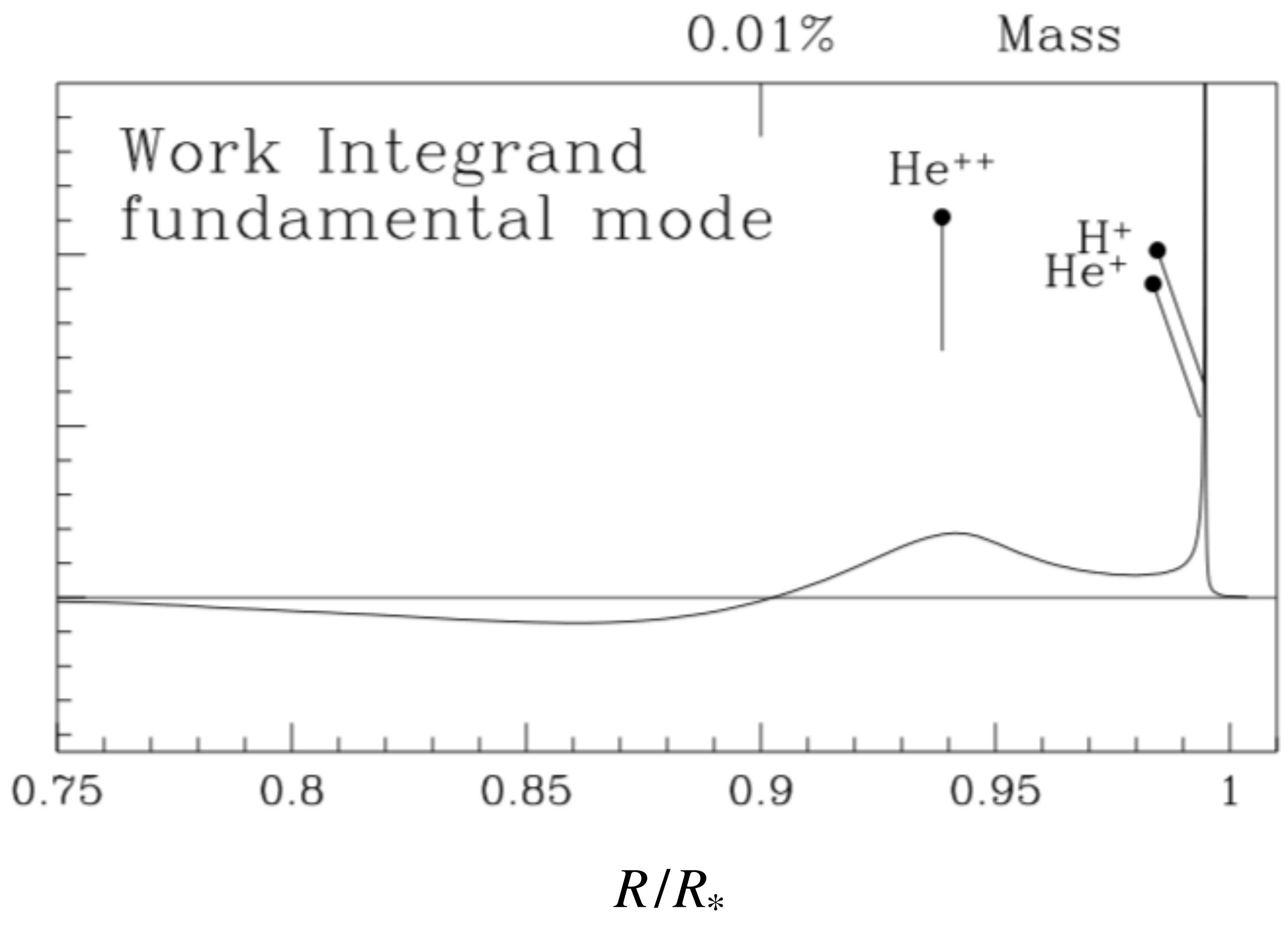
http://astroweb.case.edu/ssm/astr328/

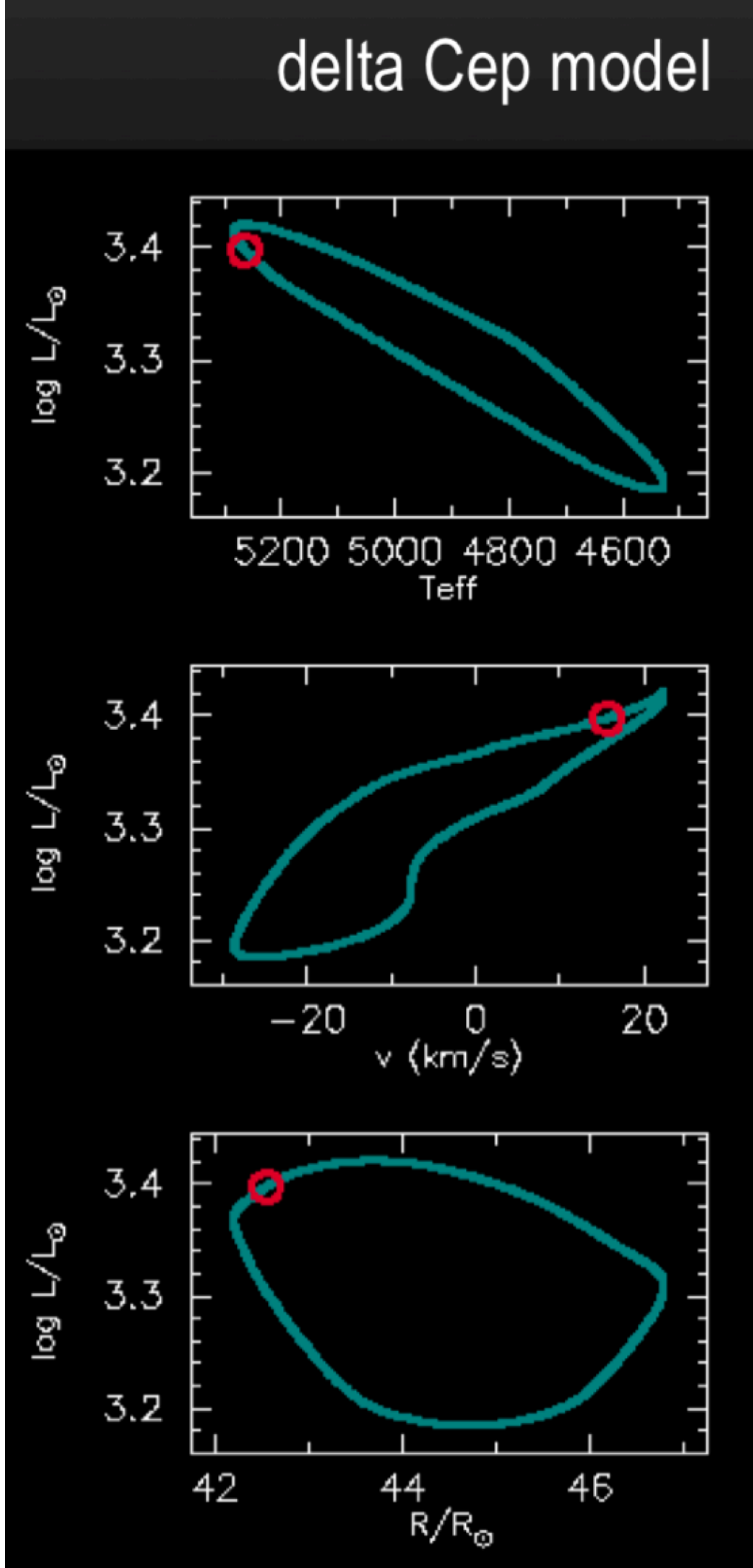
Distance Scale

- 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.

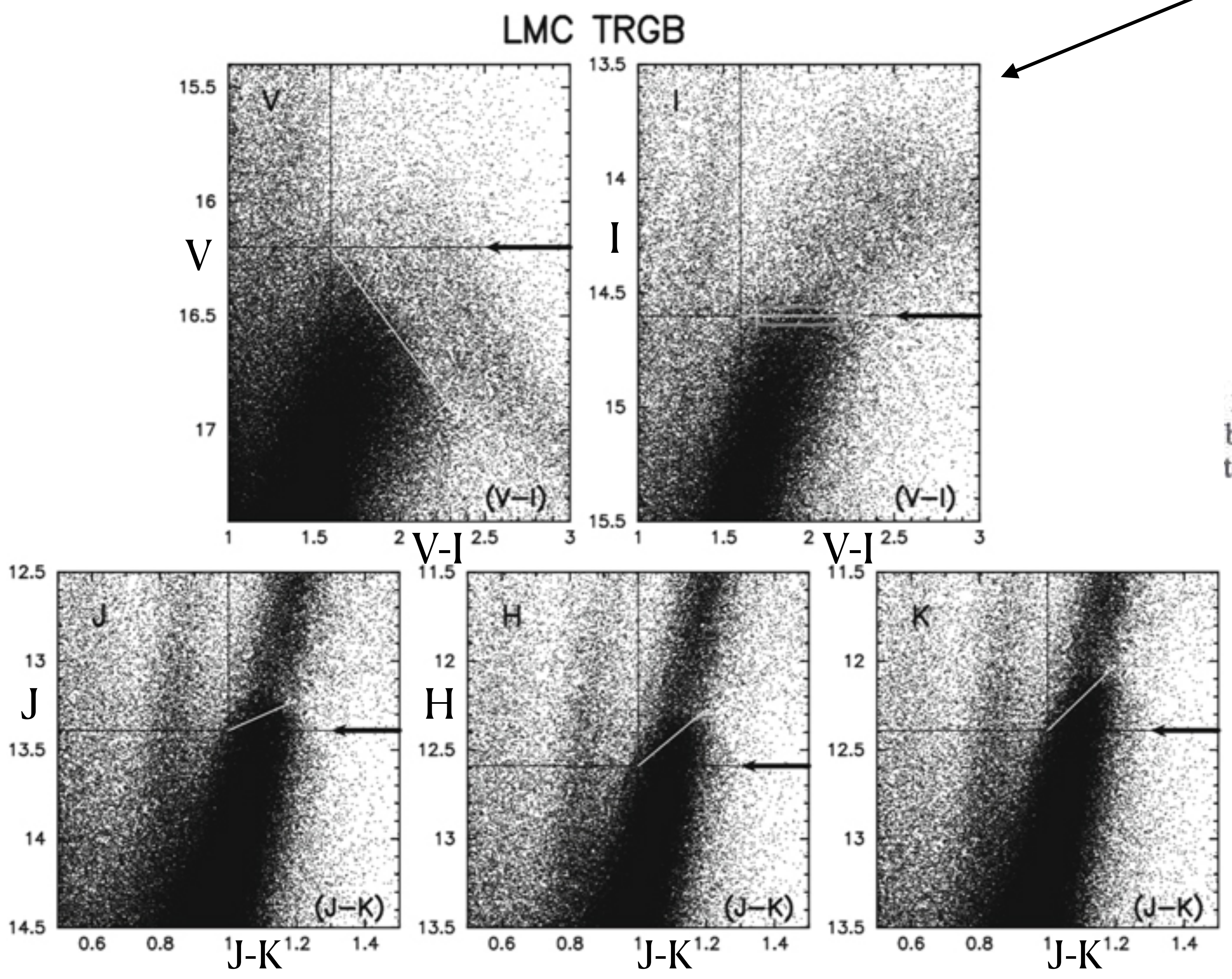


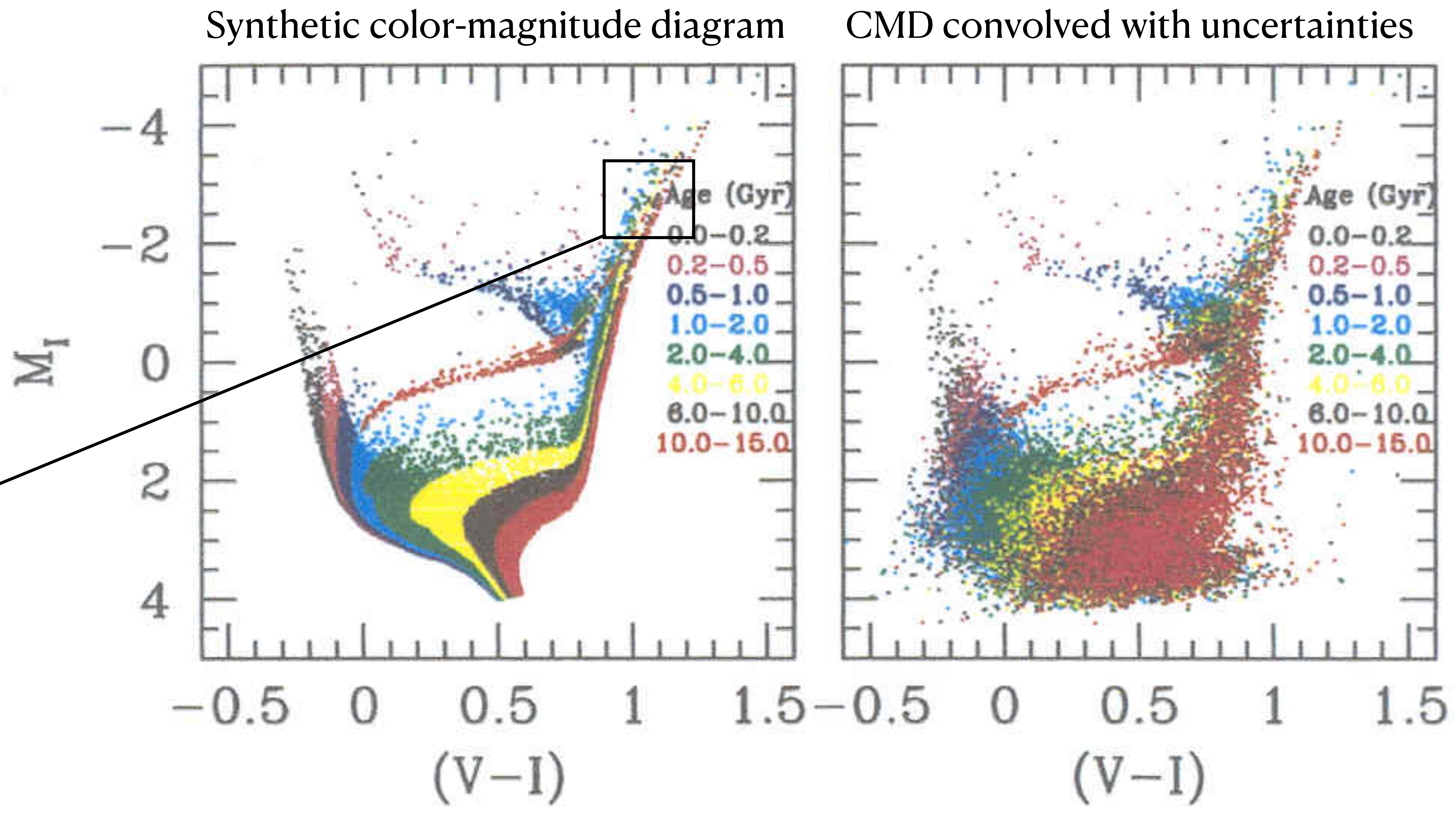




Distance Scale

- Bright Star Standard Candles
  - TRGB (tip of the red giant branch)
  - calibrate by
    - main sequence fitting of clusters or an entire galaxy like the LMC





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, binary stars. The left panel shows the theoretical synthetic CMD, while in the CMD of the right panel observational errors have been simulated (see te the sequence of ages in both the MS and the subgiant branch and, although less definite, also in the RC and HB.

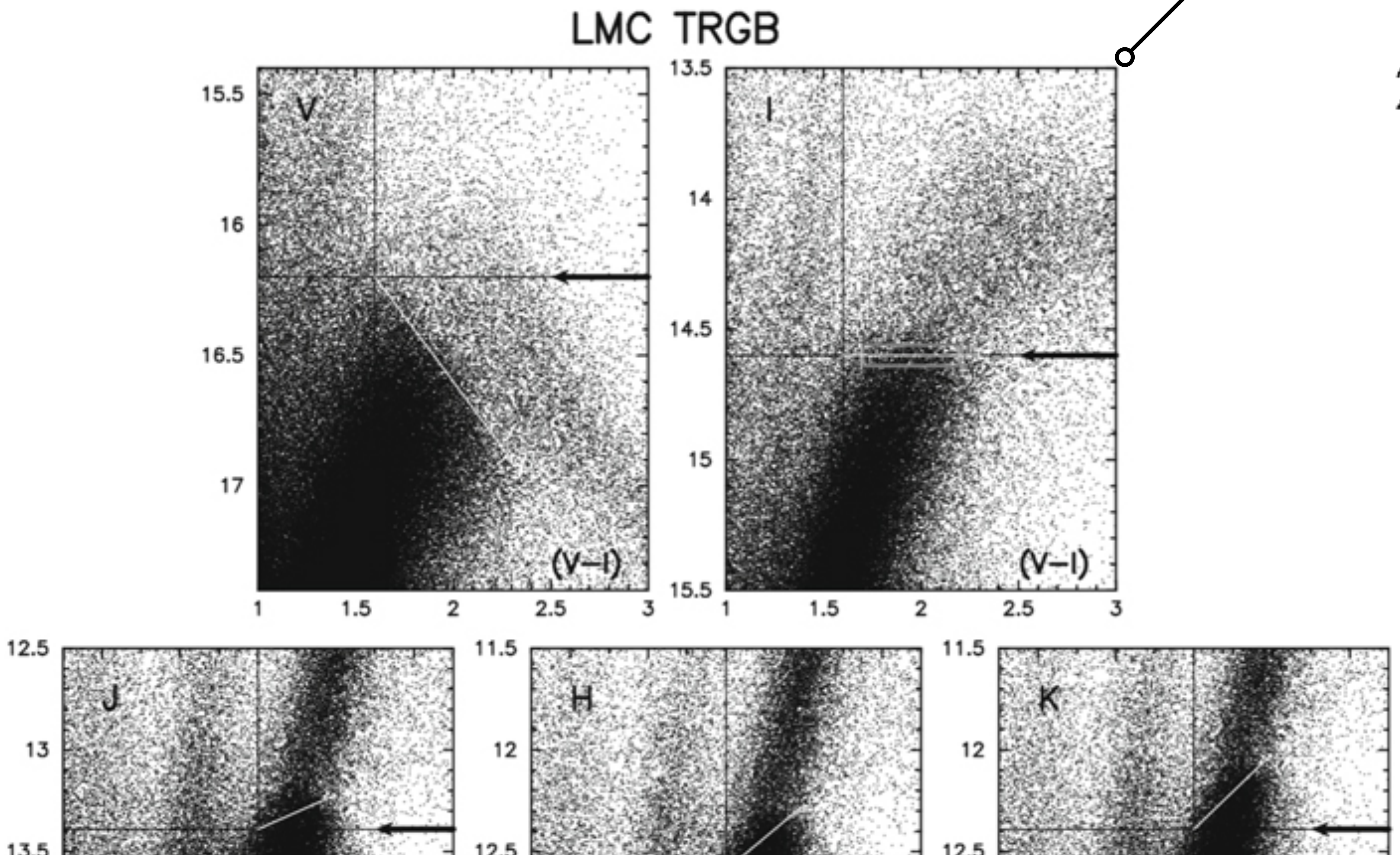
Works best in the I-band for low metallicity systems, where

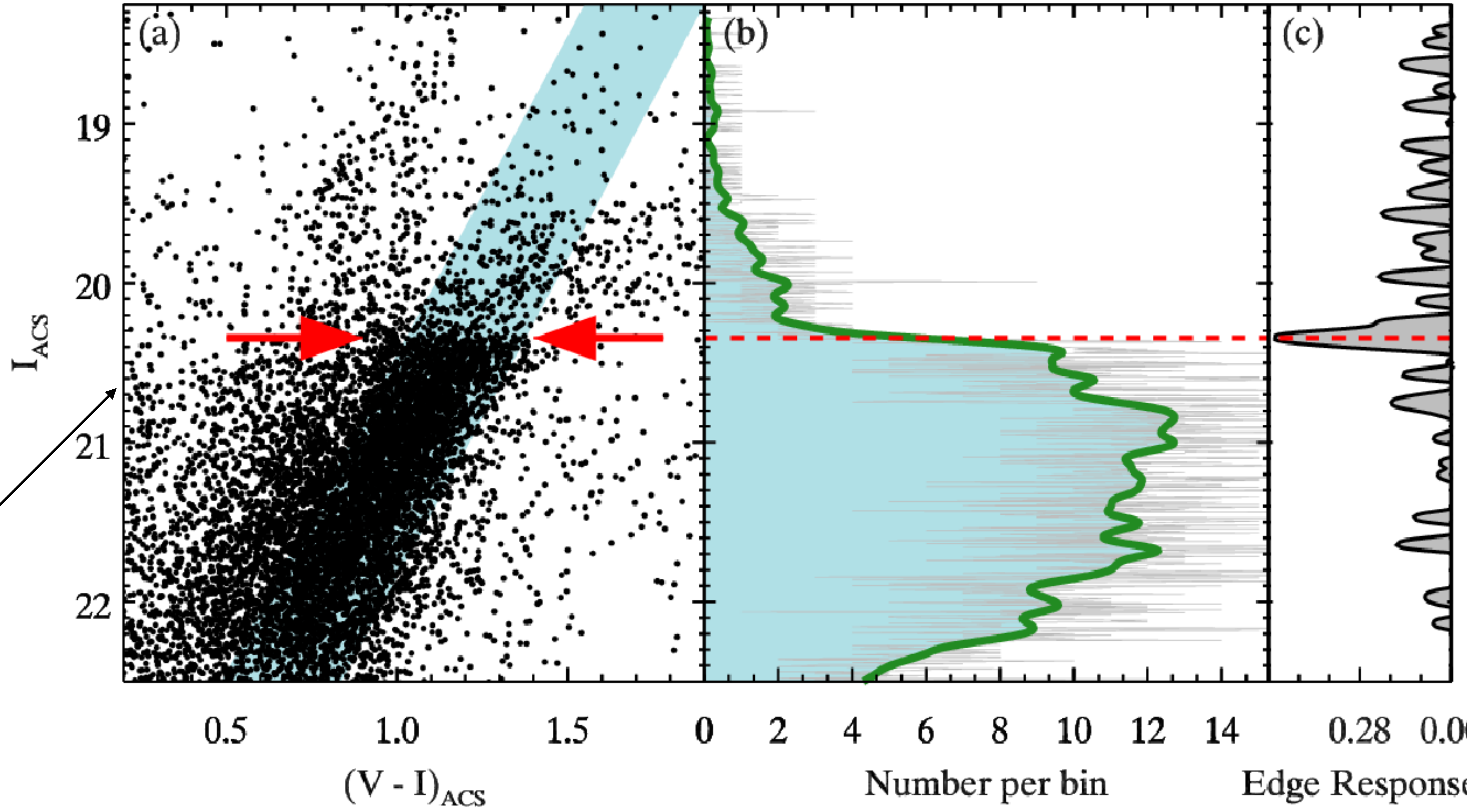
TRGB $M_I = -4.05$

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

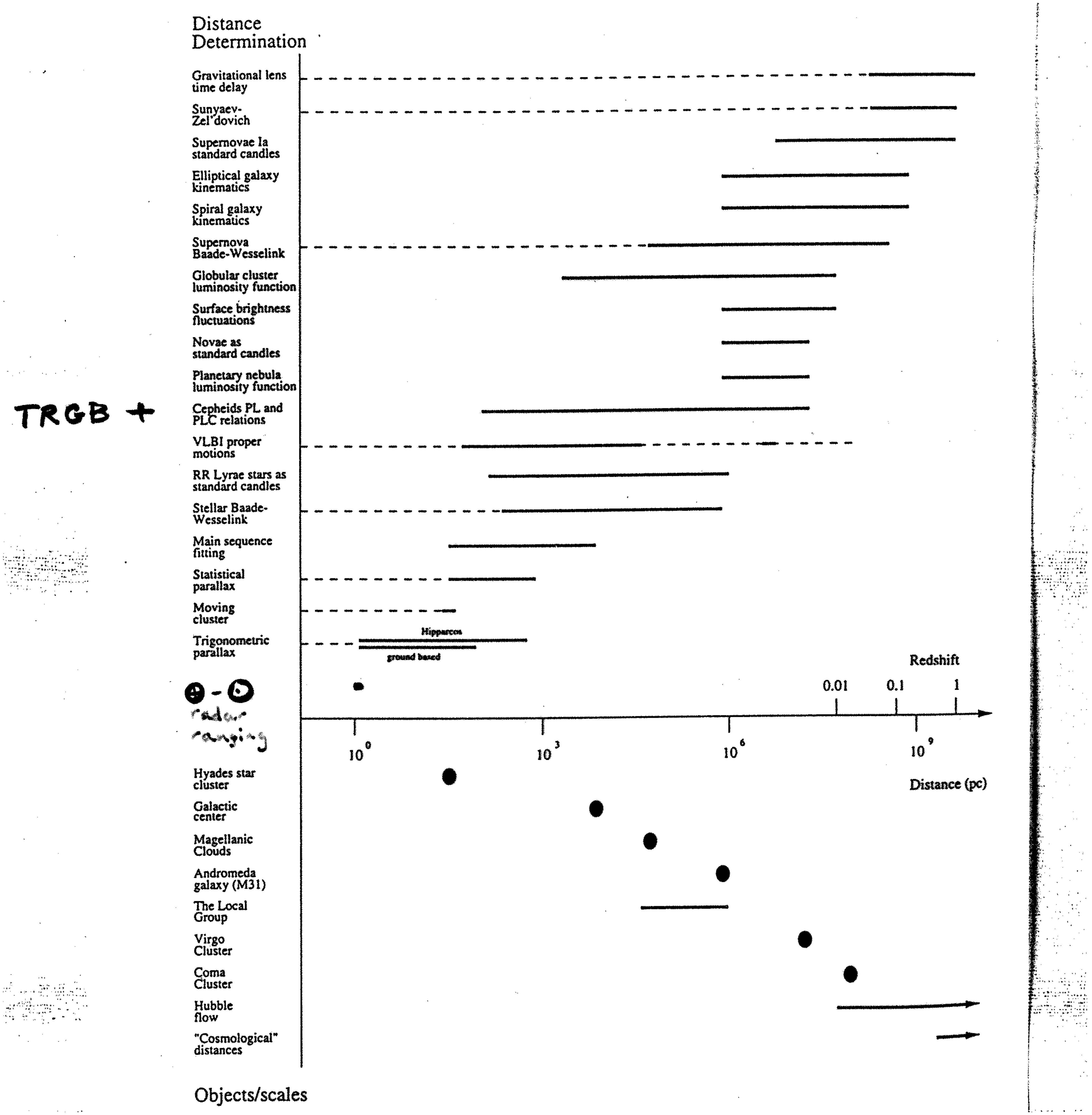
TRGB $M_I = -4.05$

In general, both bandpass and metallicity dependent.

Distance Scale

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

Distance Scale Ladder

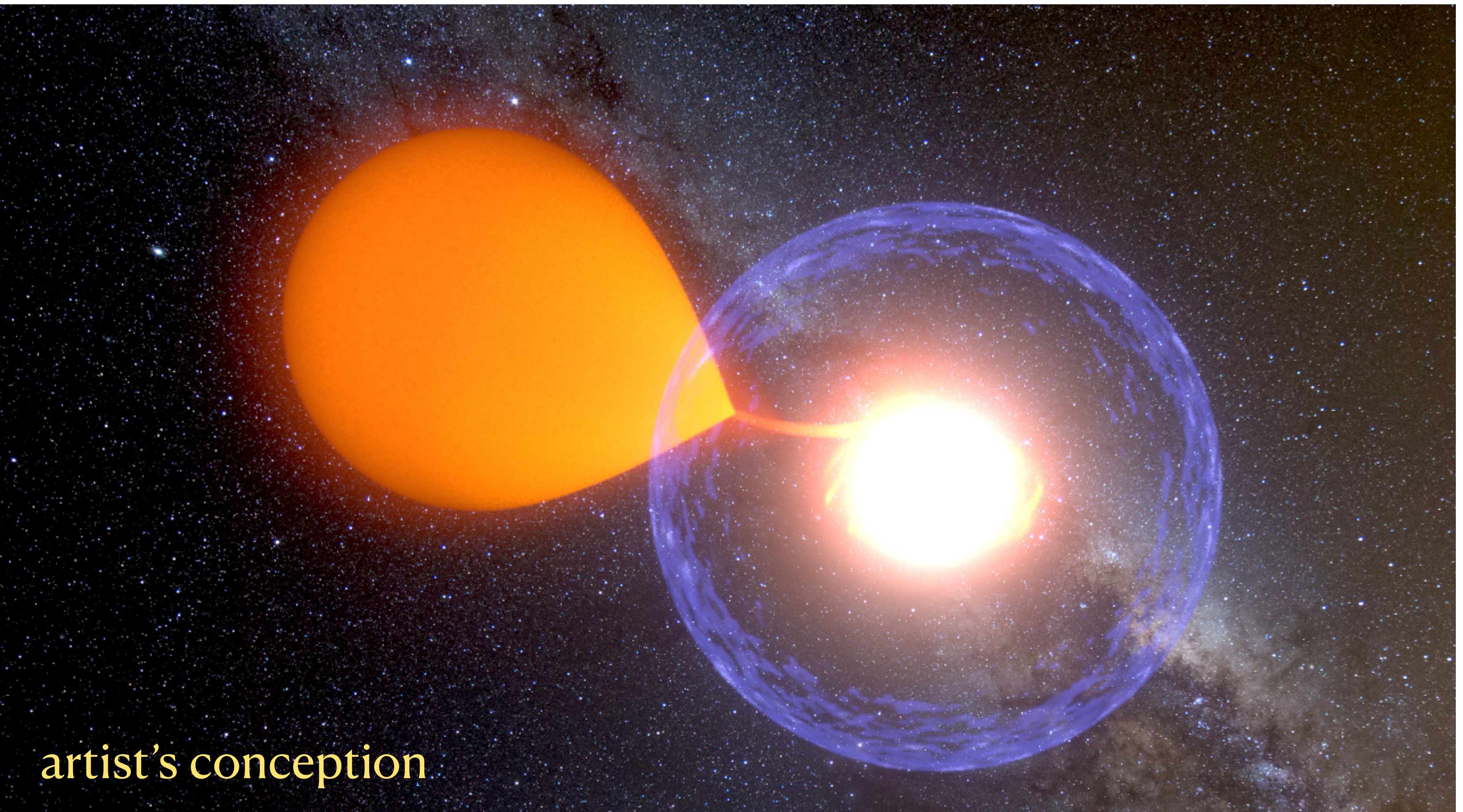


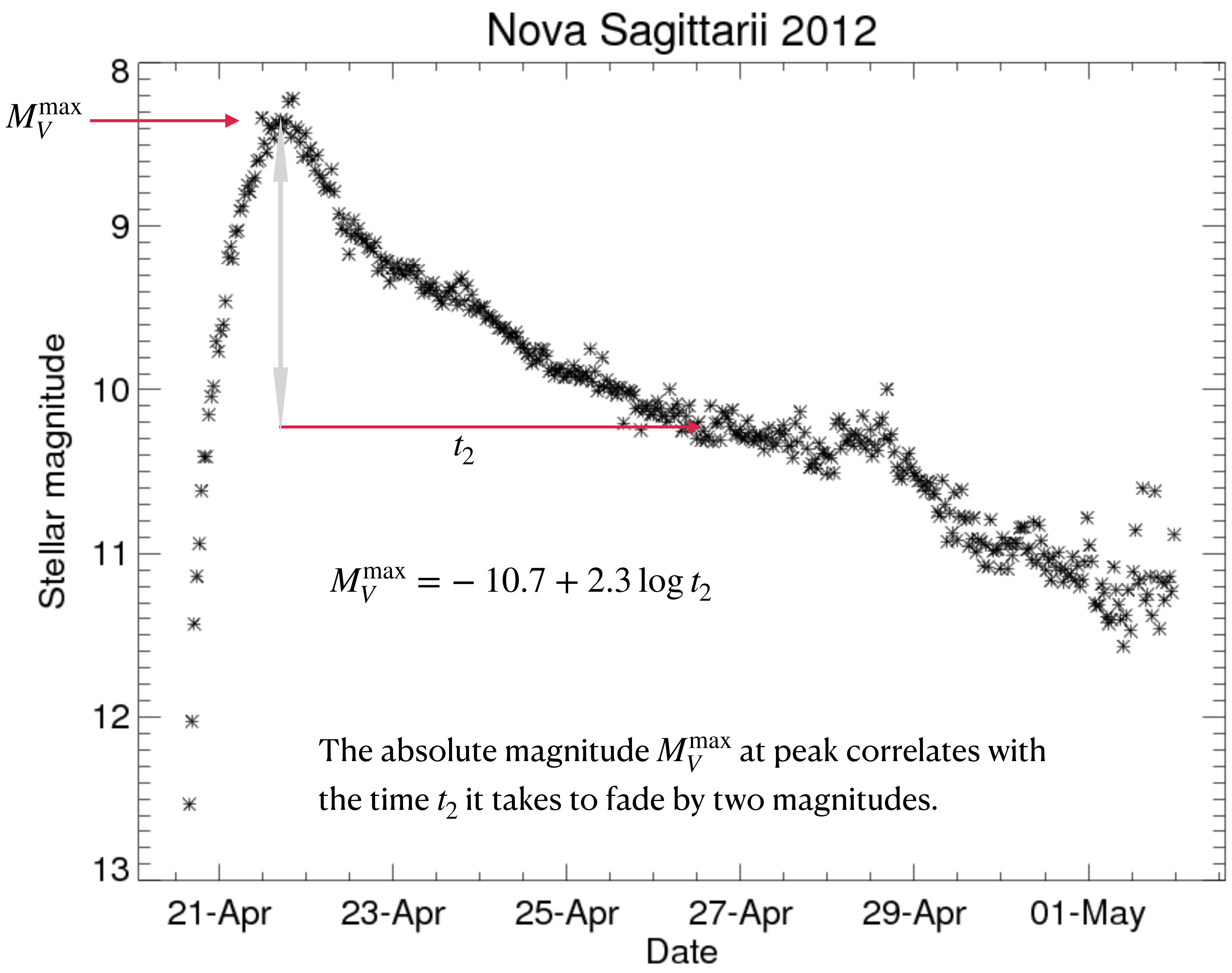
distance modulus $m - M = 5\log(d) - 5$

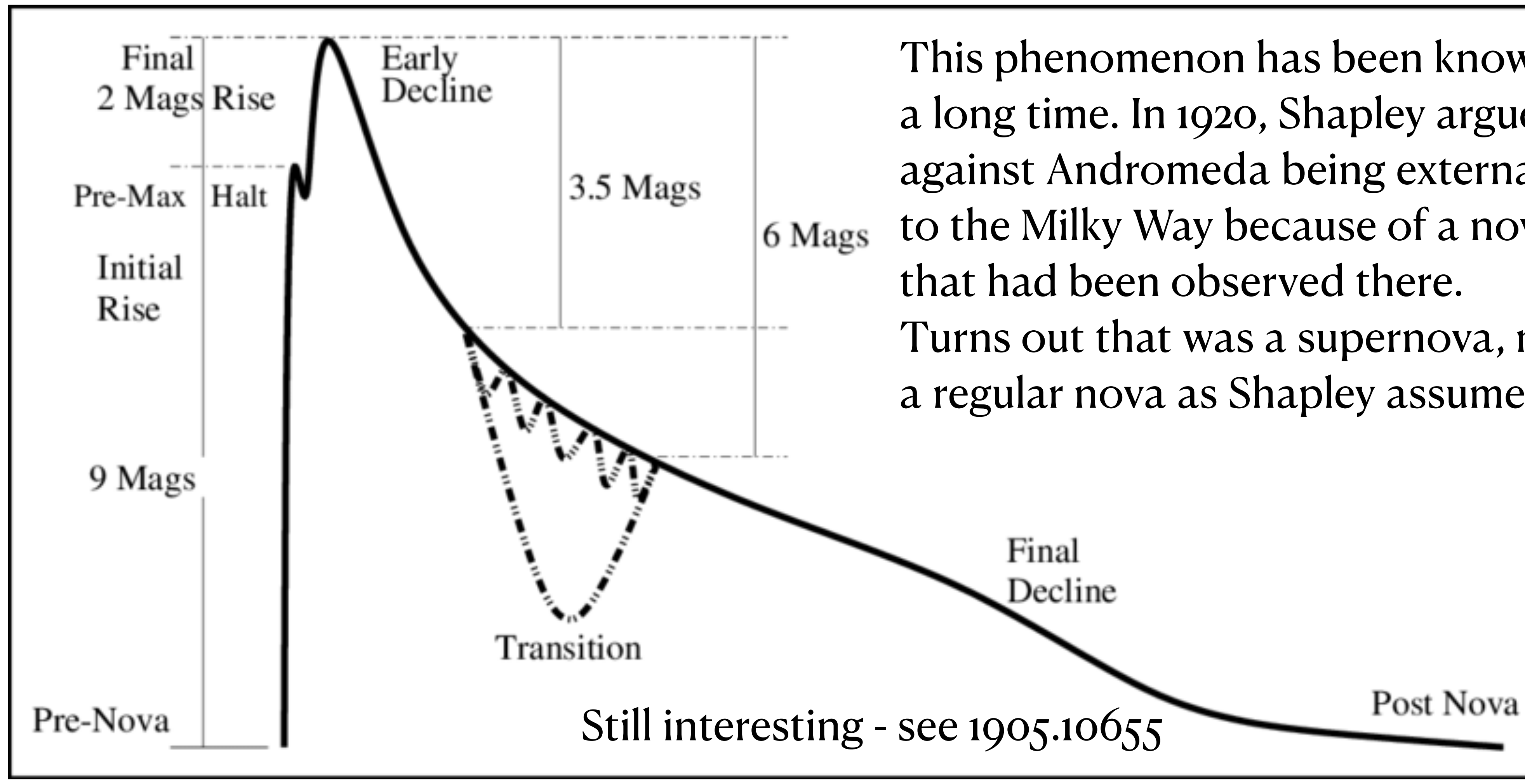
Distance Scale

- 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.

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.

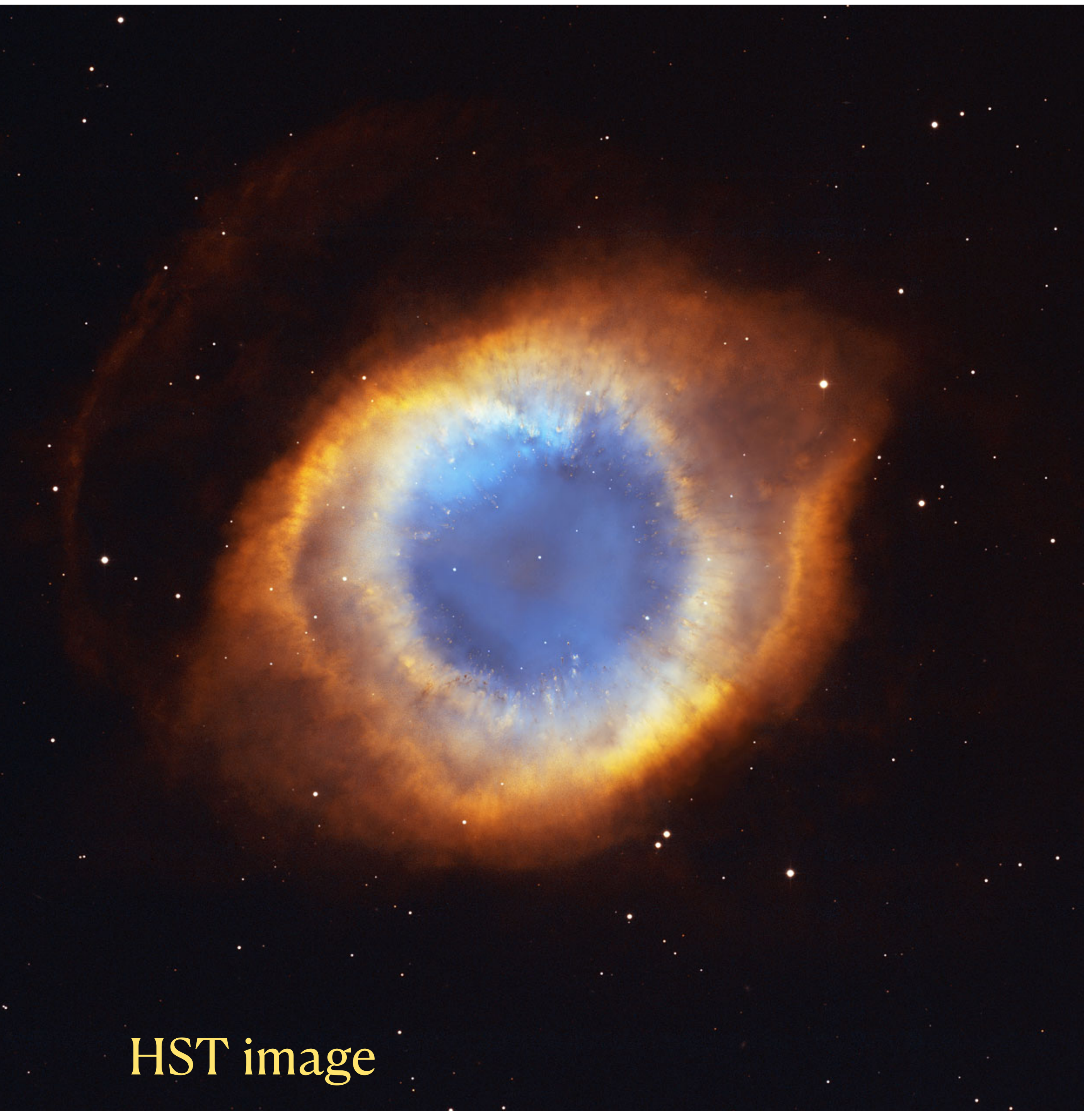
$$\Phi_{PN} \sim e^{0.307}\left(1 - e^{3(m_{cut} - m)}\right)$$

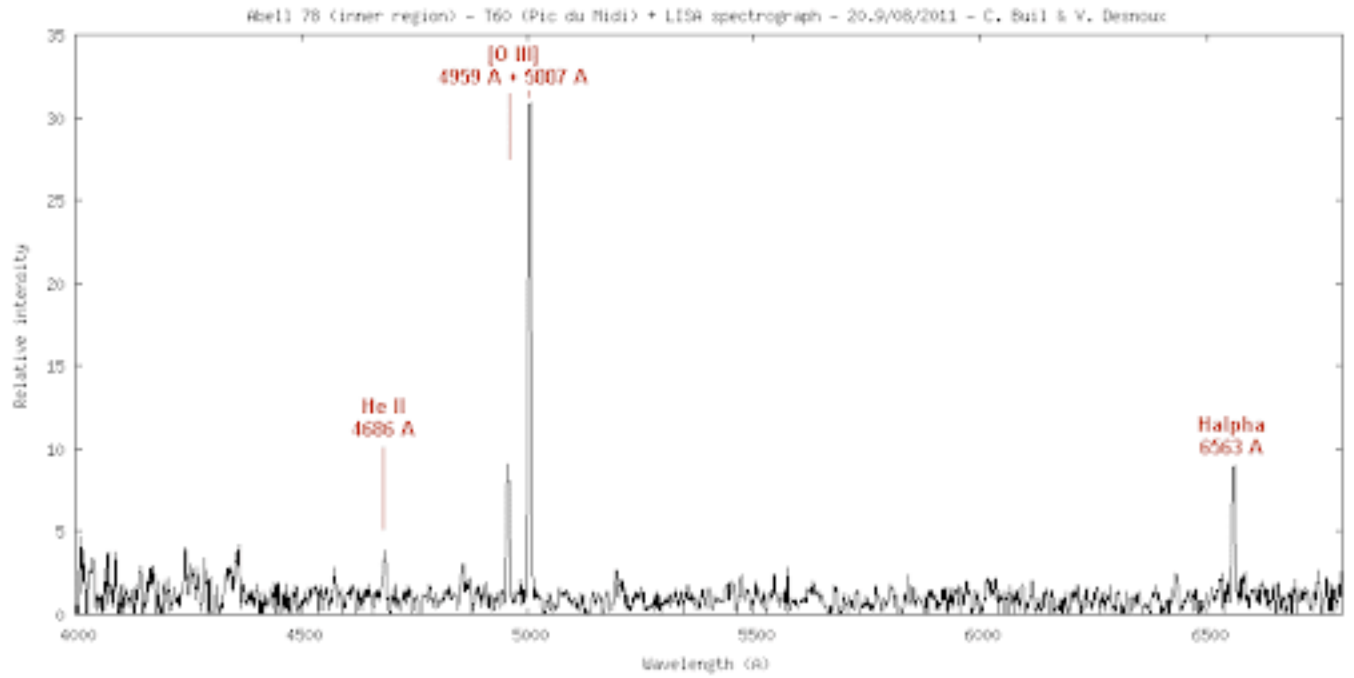
$$m_{[O\ III]} = -2.5 \log f_{5007} - 21.4$$

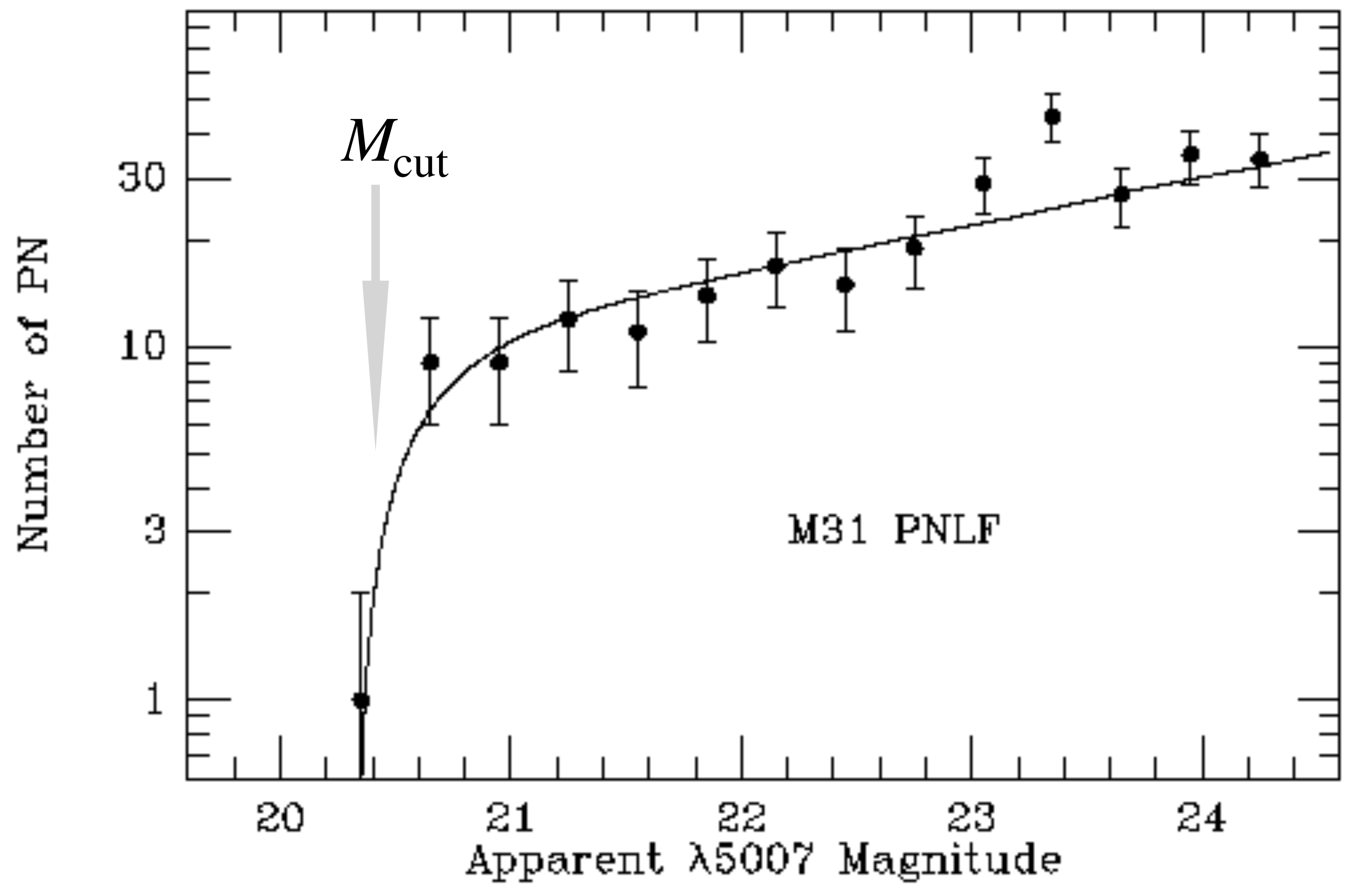
$$M_{cut} = -4.6 \pm 0.1$$

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

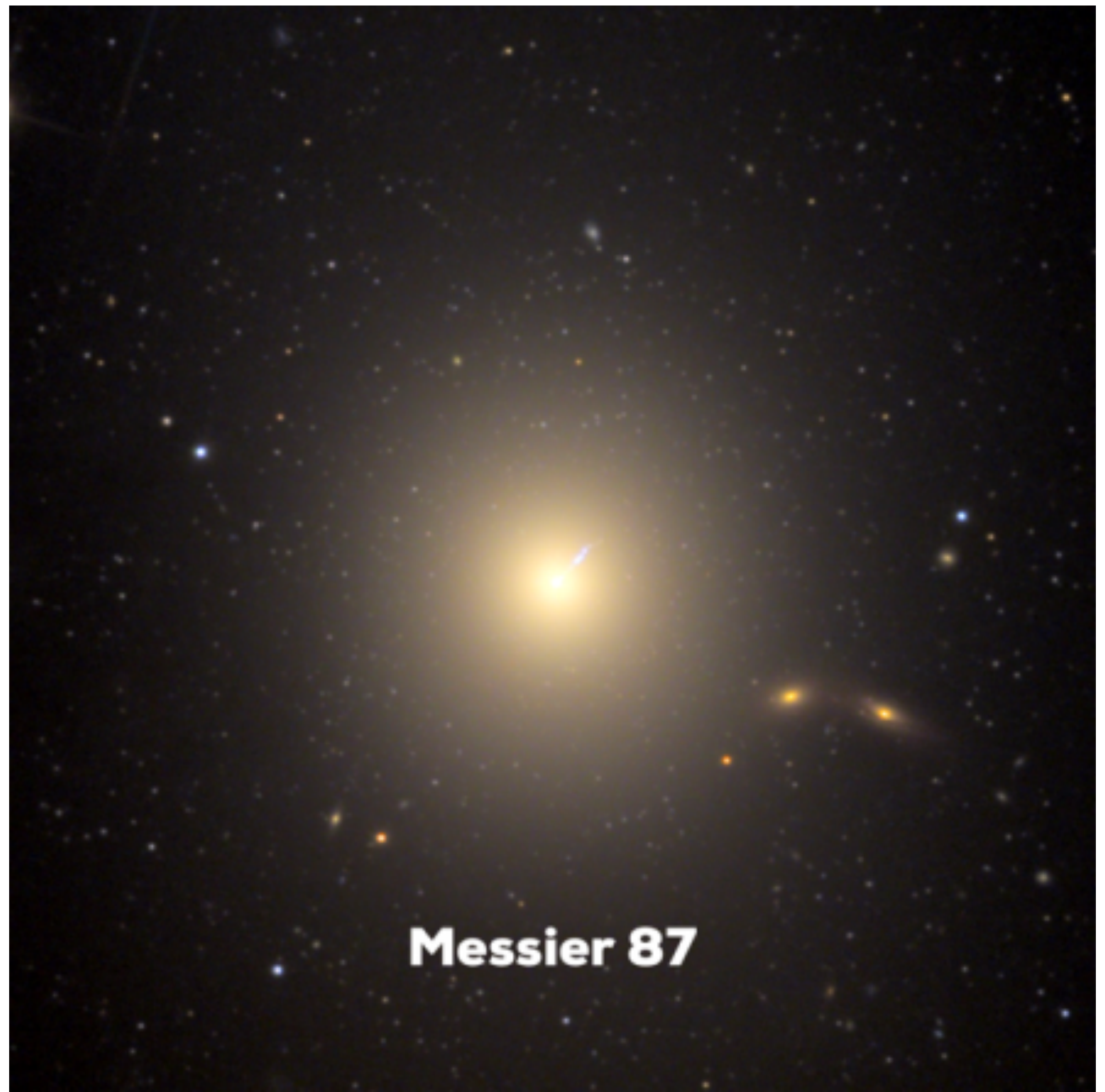
Globular clusters in the Milky Way have a Gaussian luminosity function.

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

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

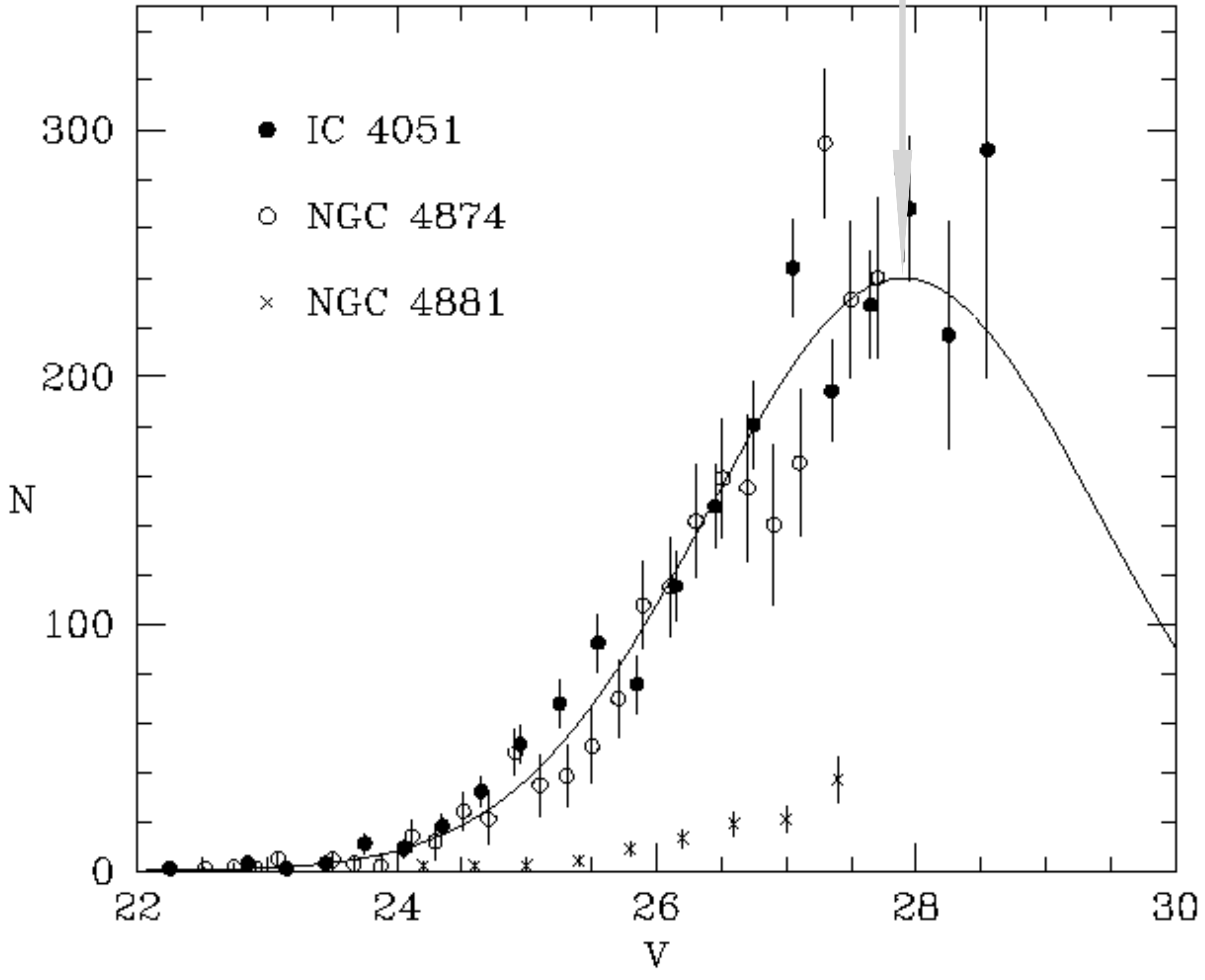
Globular cluster M80

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



$\bar{M}_{GC}$

Globular cluster luminosity function

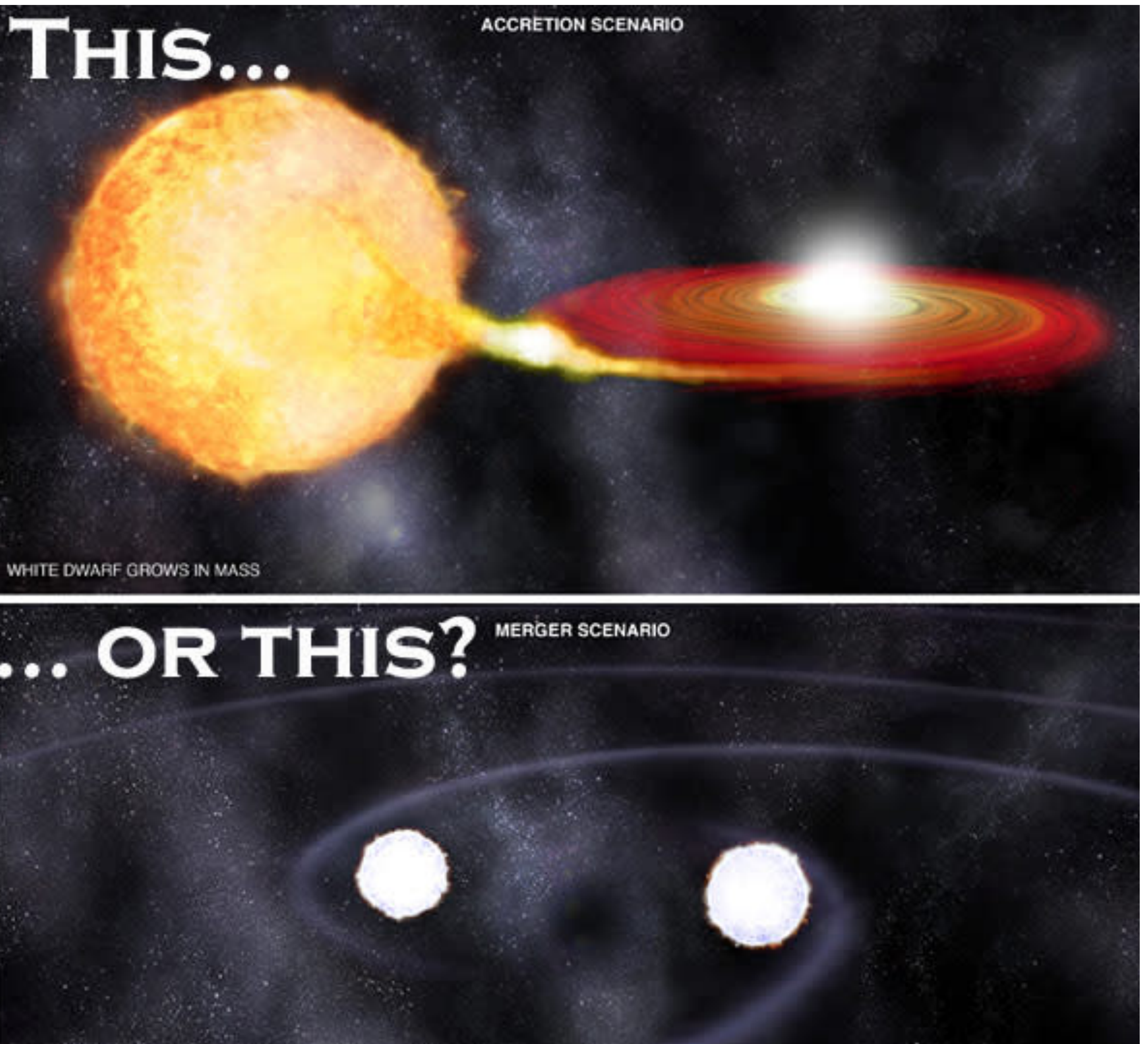


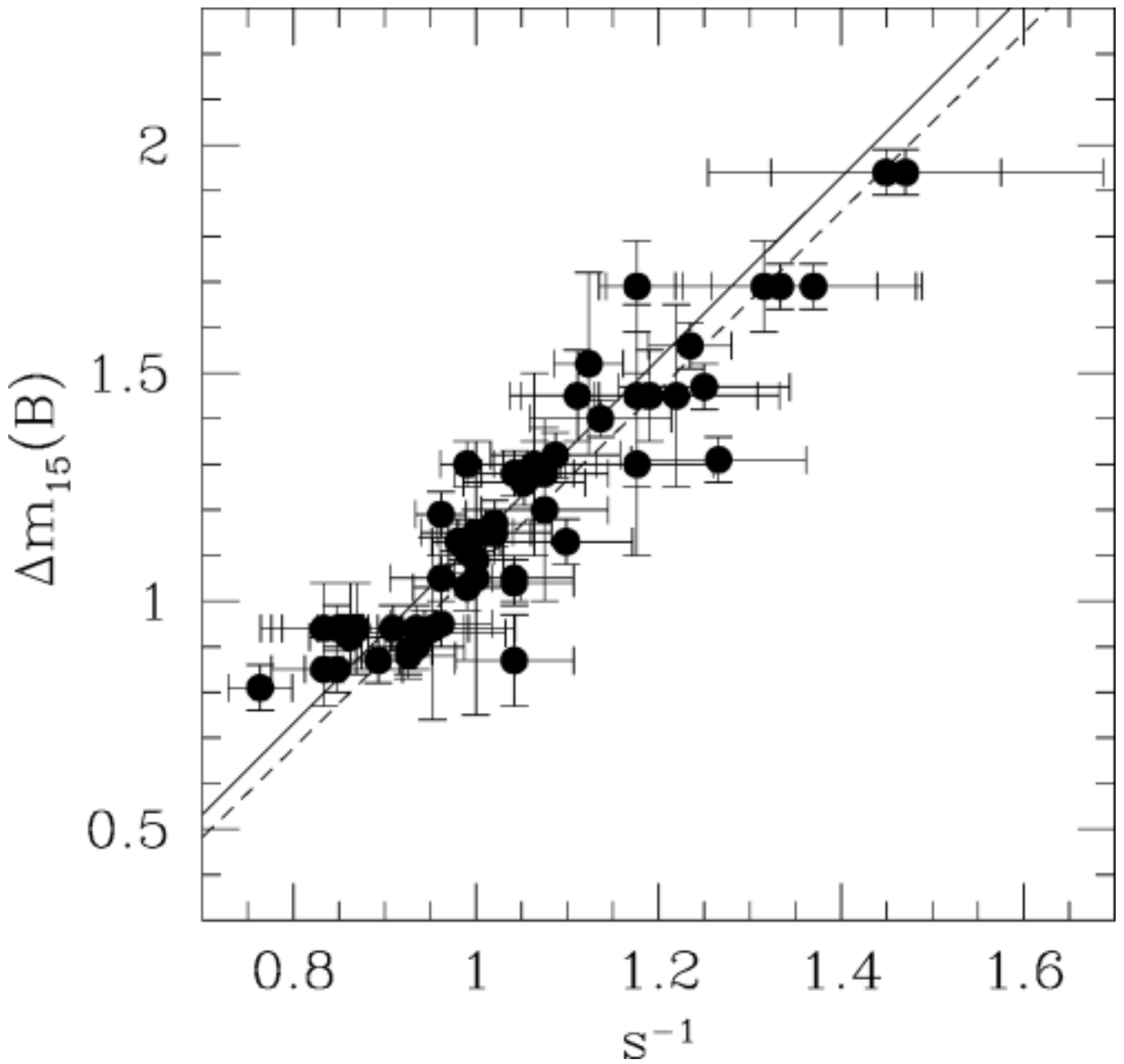
Distance Scale

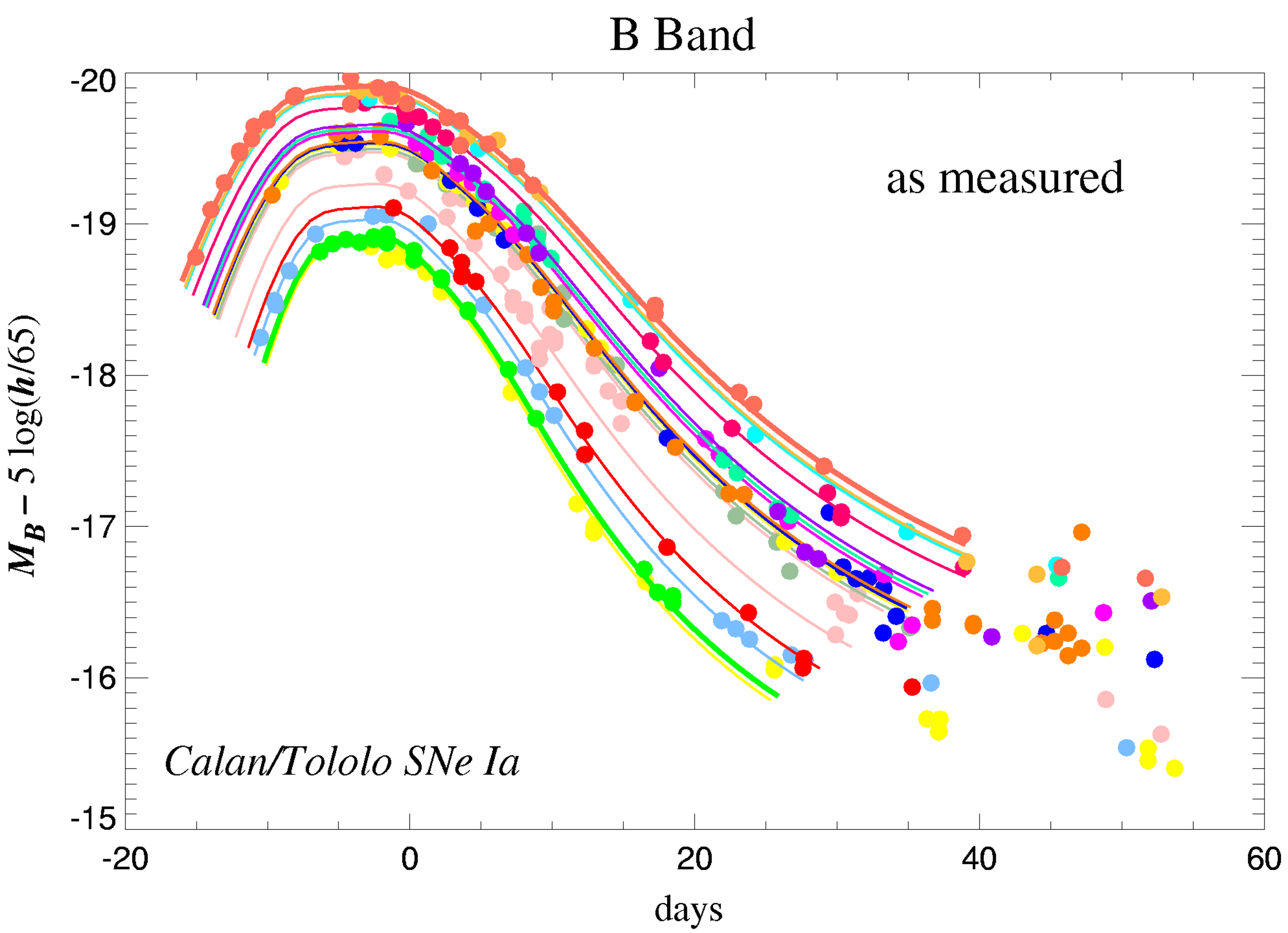
- Secondary Distance Indicators
  - Supernovae
    - Type Ia SN (white dwarf detonations)
    - White dwarfs that exceed the Chandrasekhar limit explode, converting carbon and oxygen to iron and nickel (etc.)
    - At present, appear mostly due to WD-WD mergers, not single accreting WDs.

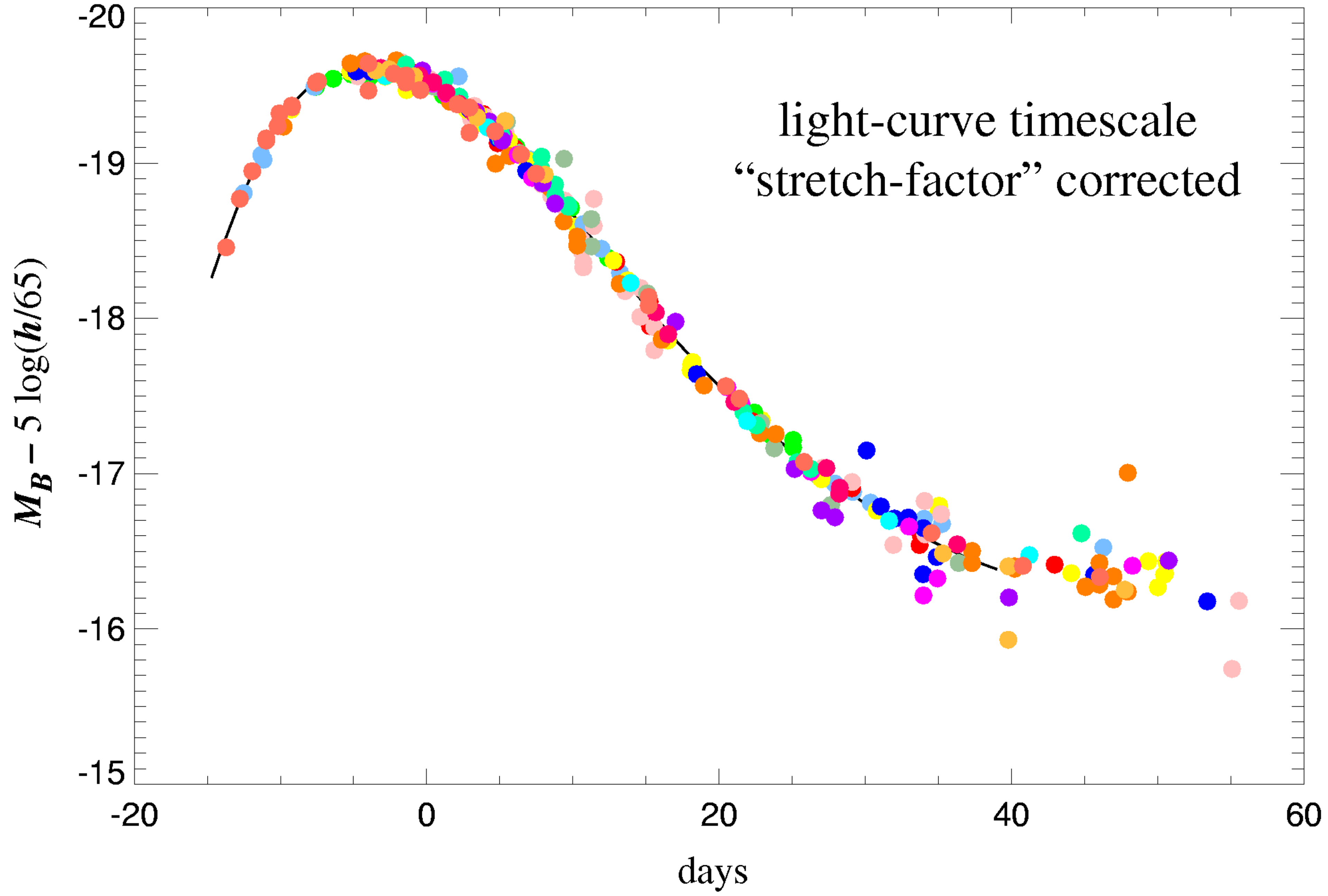
$$M_{B,\,\mathrm{peak}} = -19.26 + 0.8[\Delta m_{15} - 1.1]$$

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*.









Kim, *et al.* (1997)

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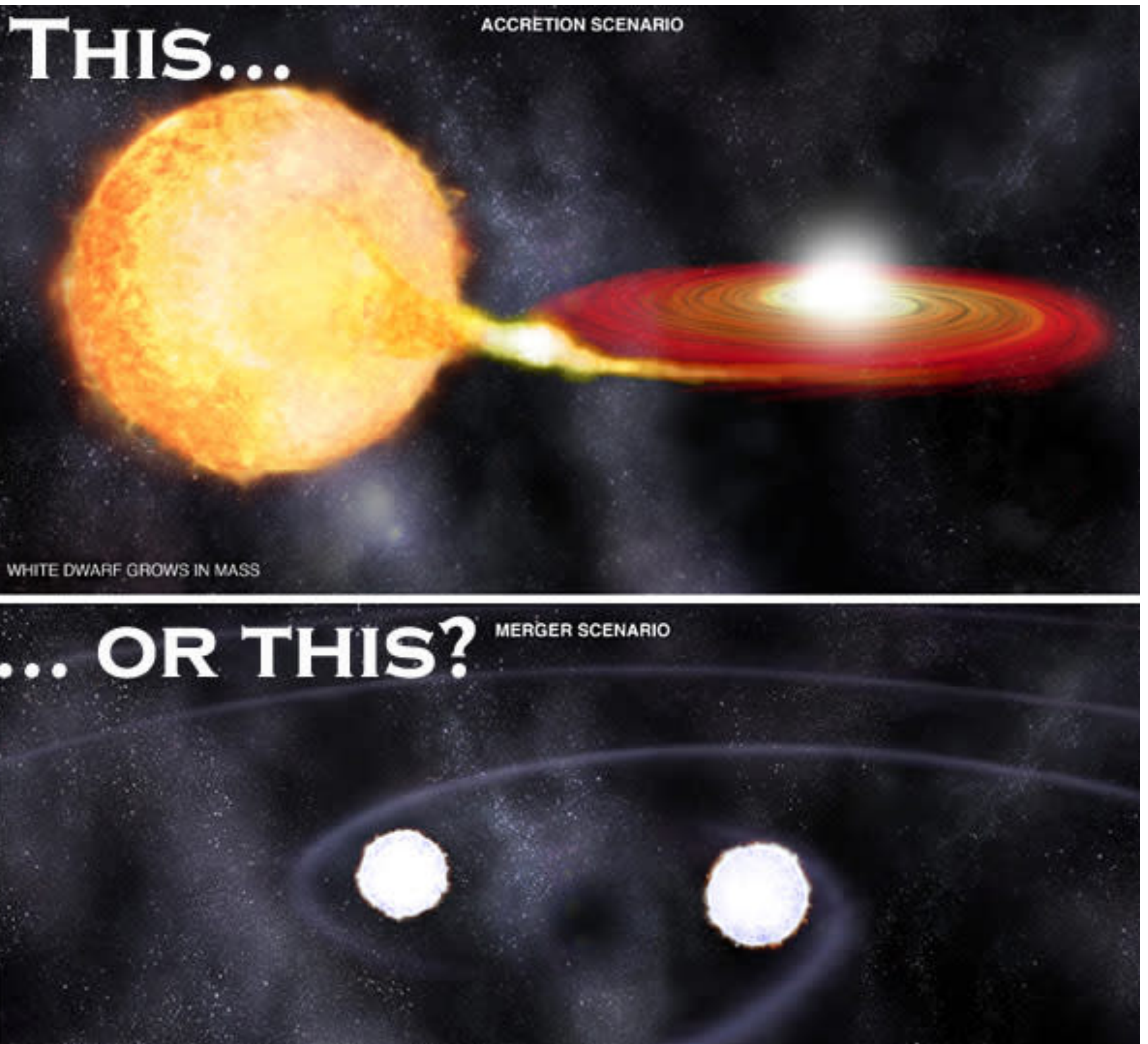
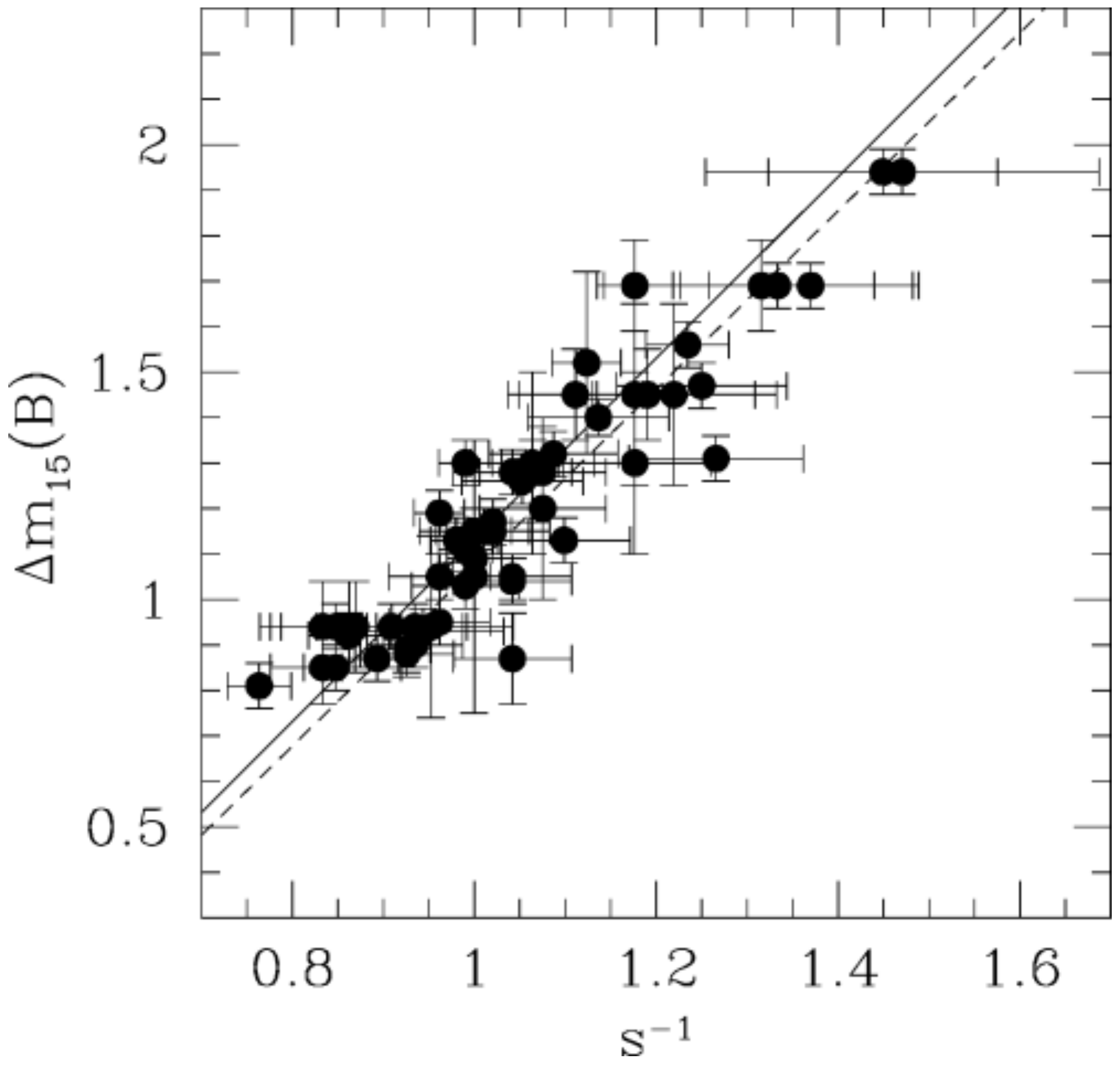
Scatter in local Hubble diagram decreases after correction for fade time - as it should if this correction is effective.





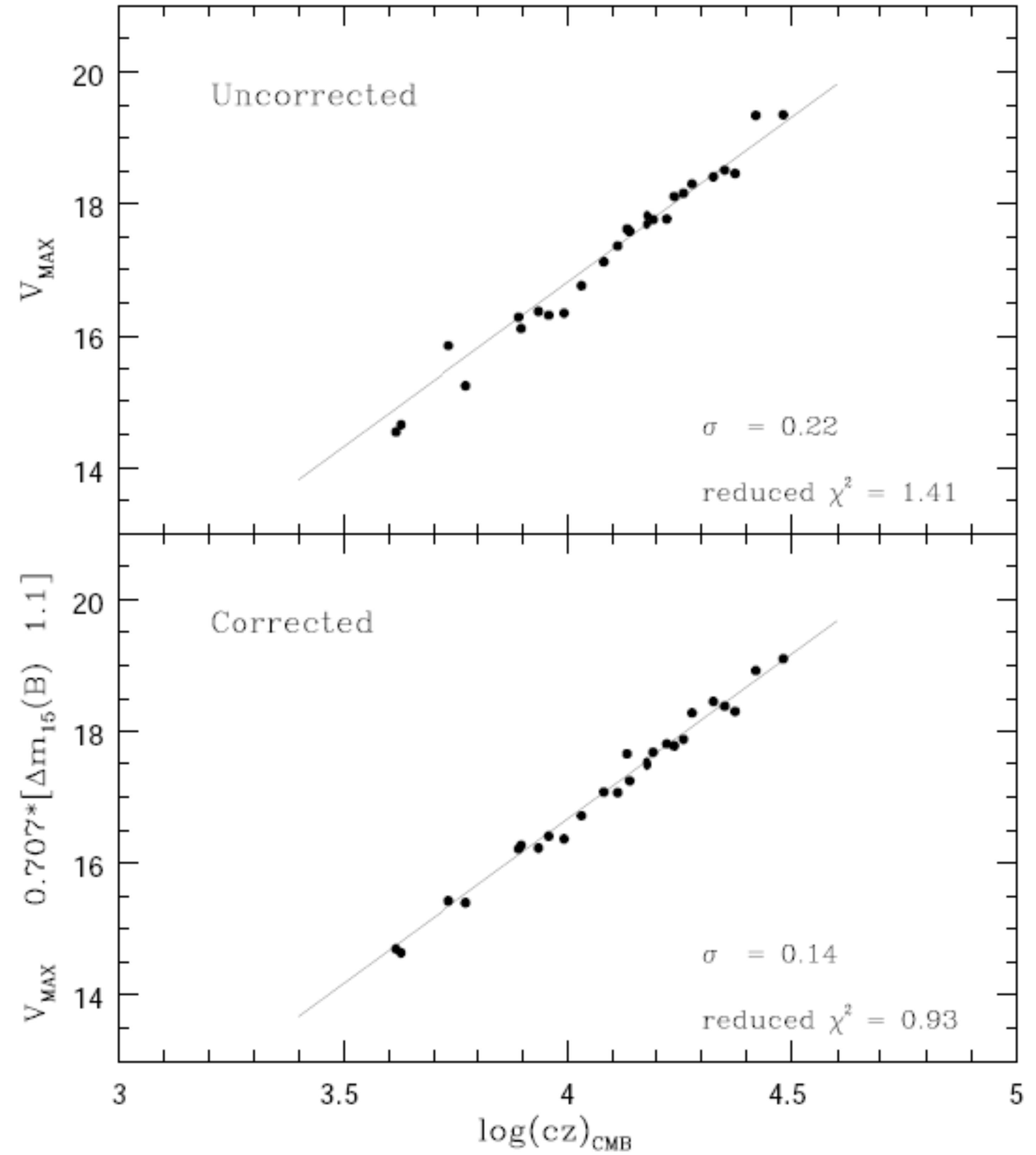


Figure 5: (top panel) The Hubble diagram in V for the SNe Ia in the Calán/Tololo sample with $B_{MAX}-V_{MAX} \leq 0.20$. (bottom panel) The Hubble diagram for the same 26 events after correction for the peak luminosity-decline rate dependence.

Distance Scale

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

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*.

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

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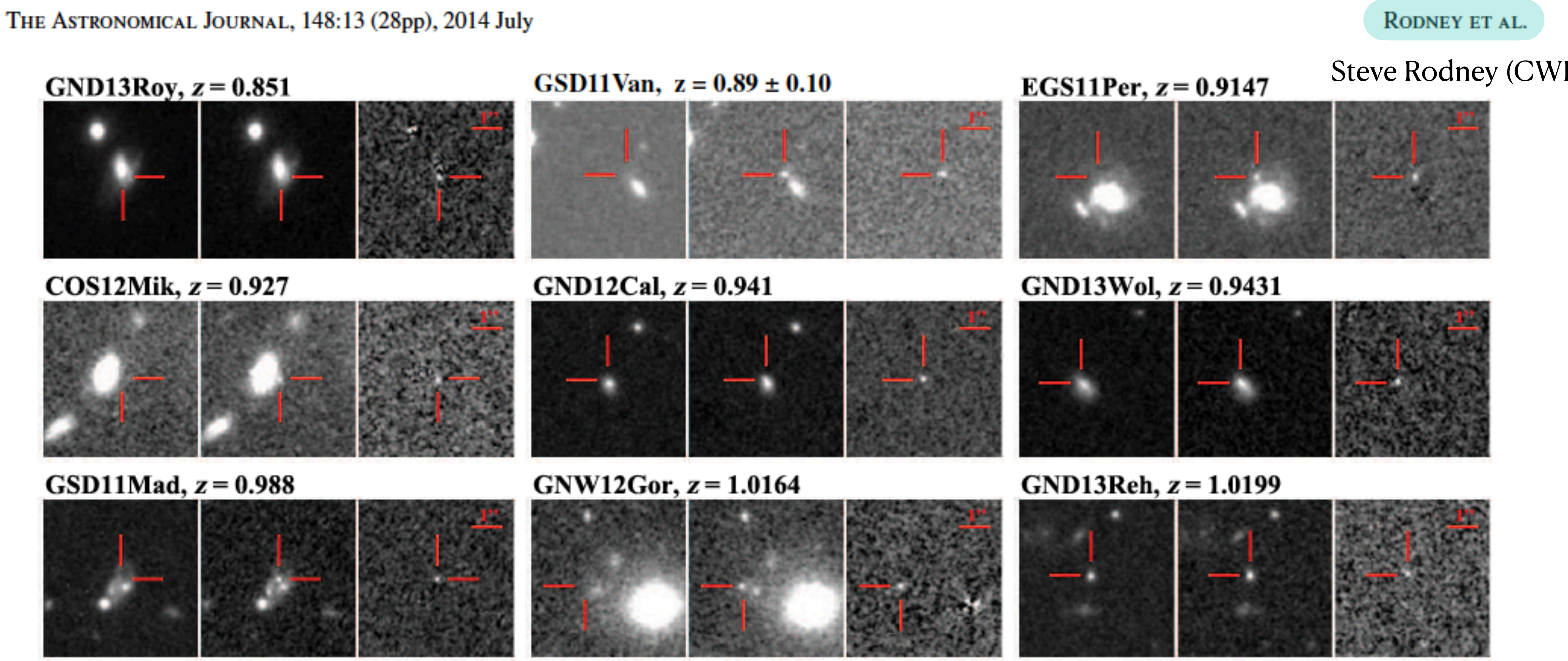
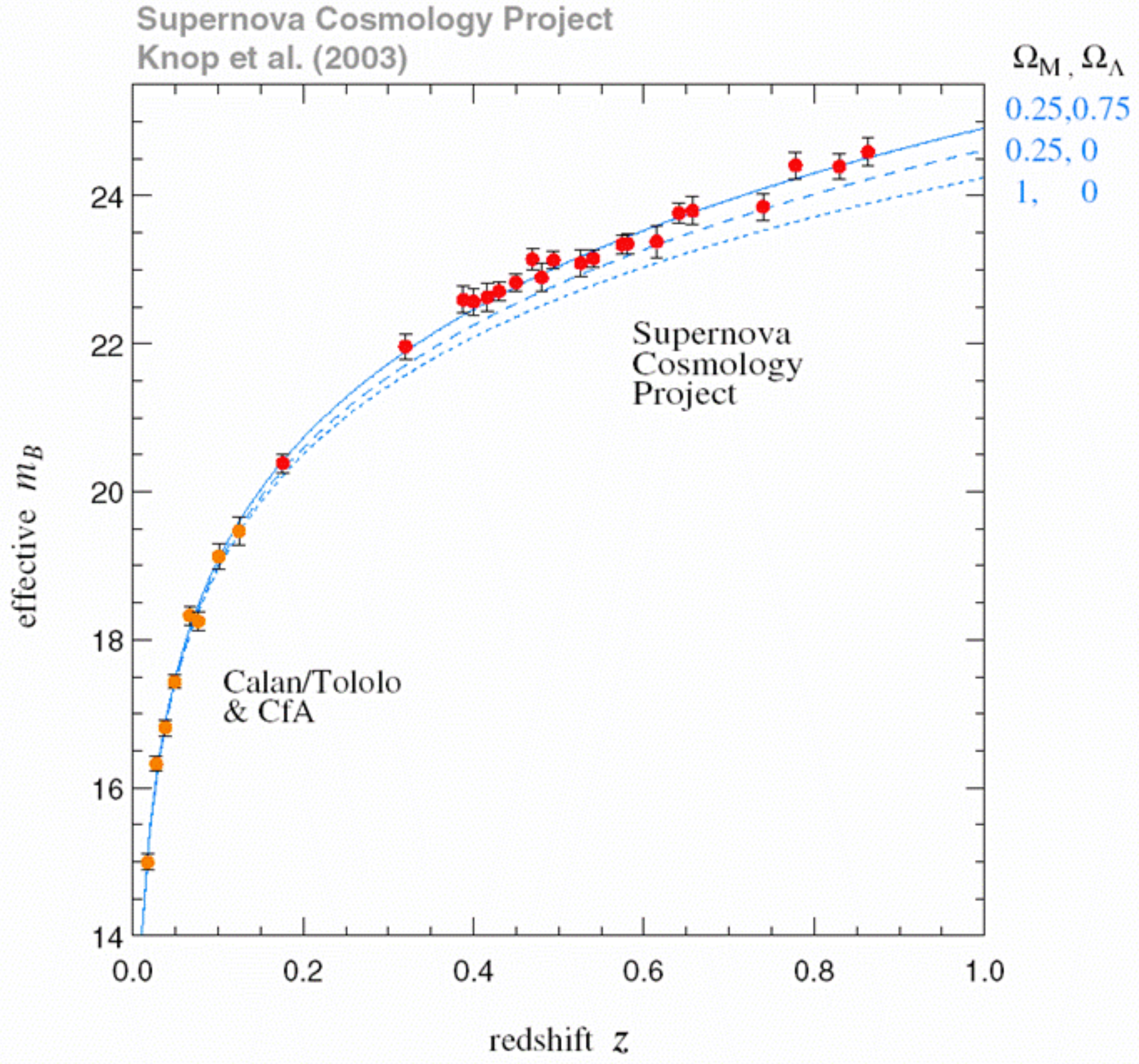


Steve Rodney (CWRU alum)



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

Distance Scale

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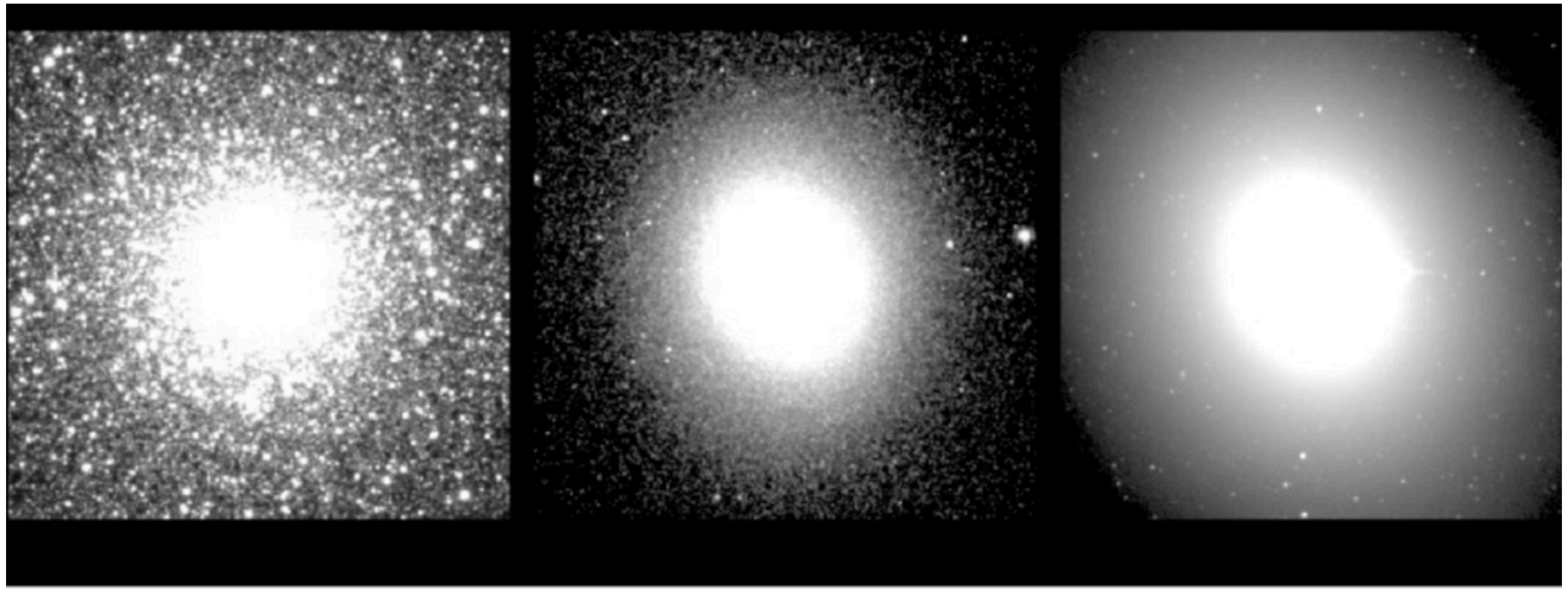
Peak luminosity correlates with fade time - Δm_{15} is the amount of fading after 15 days. Can also be calibrated in terms of a `stretching factor,' *s*.

- 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 they were once thought to be
    - luminosity-fade relation purely empirical. Why?
  - 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

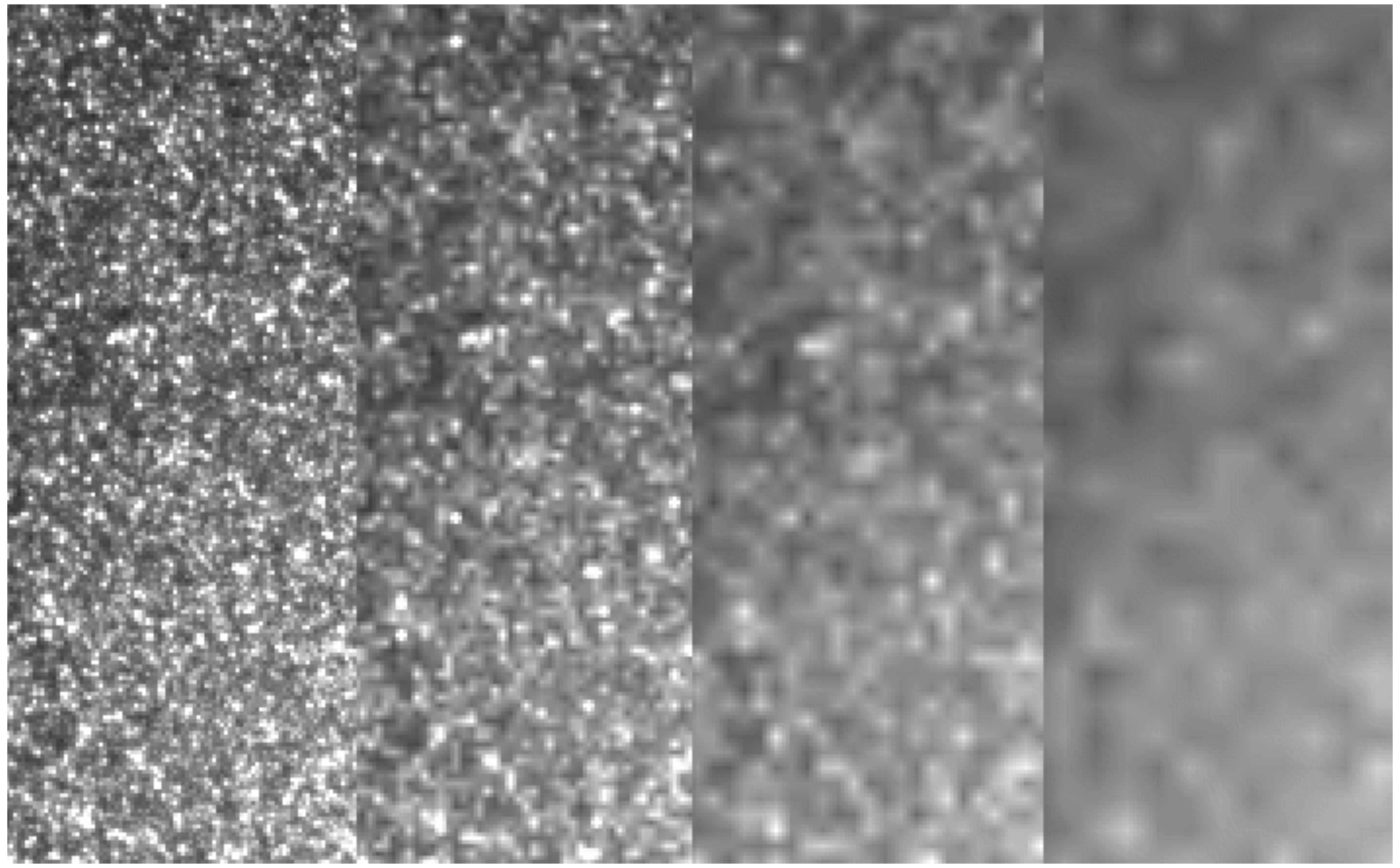
$$\langle L \rangle = \frac{\sum \bar{N}_i L_i^2}{\sum \bar{N}_i L_i}.$$

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

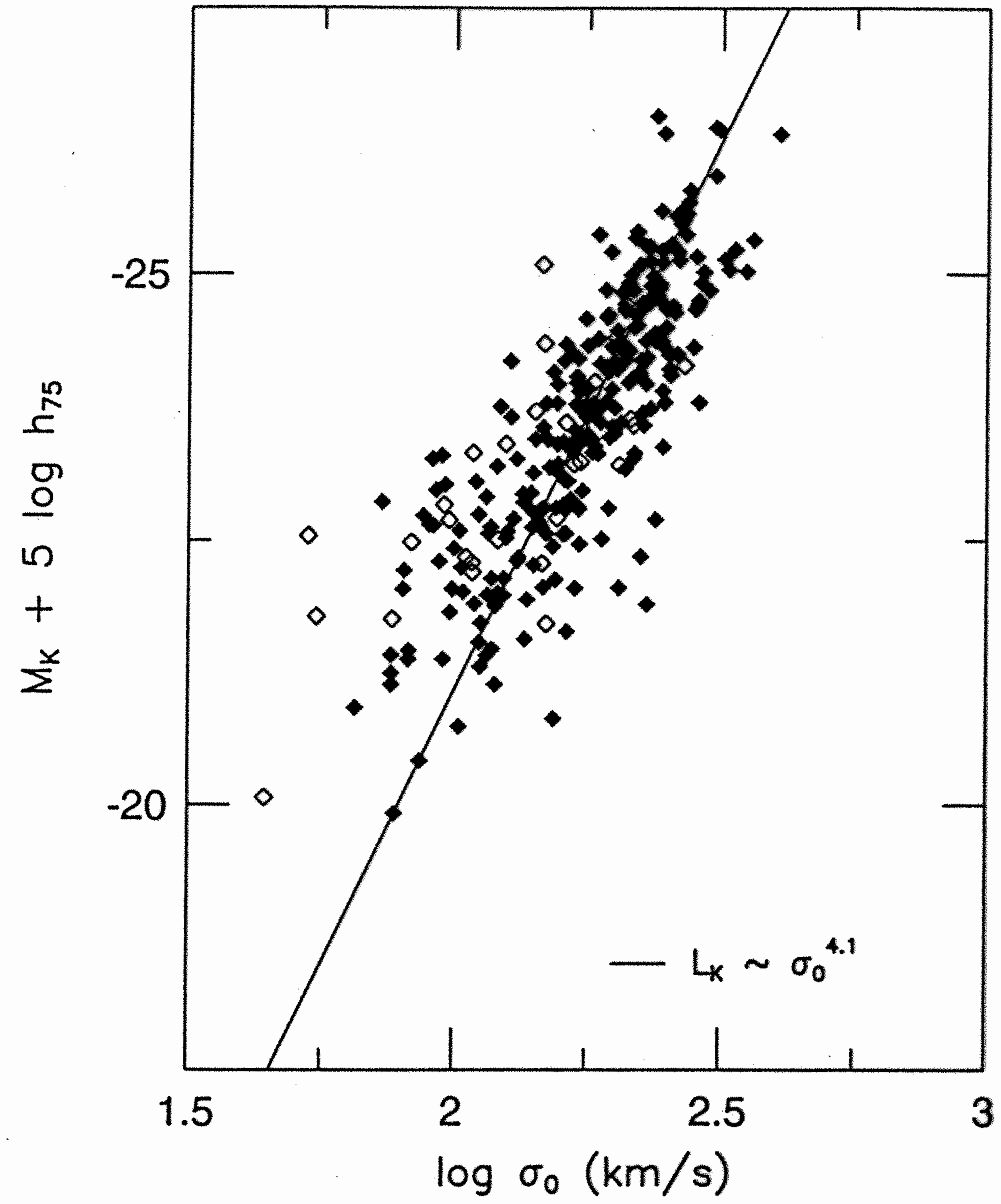


FIG. 10.—Faber-Jackson relation between luminosity and central velocity dispersion. The best-fitting relation is $L_K \propto \sigma_0^{4.14\pm0.22}$ with a large scatter of 0.93 mag. The scatter is significantly smaller in the Coma cluster at 0.72 mag.

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

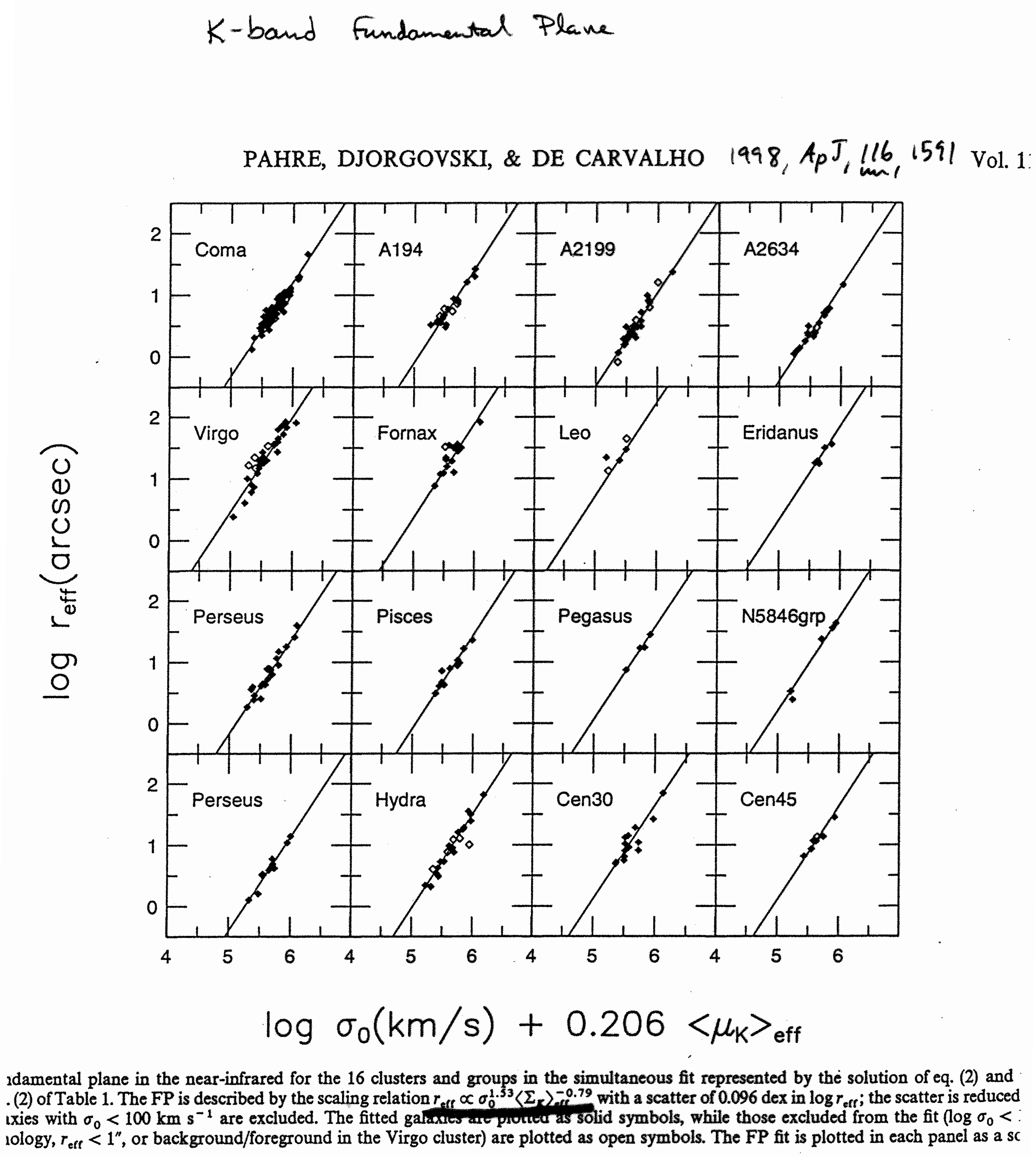
R_e is the effective radius (containing half of the total light)

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



Fundamental Plane