What the (local) Distance Ladder Tells us about H_0

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Some Truths

Closest modern SNe Ia is at 7 Mpc

Either Hubble or 8+meter class telescopes.

Local galaxies offer ability to do:

- Different datasets
- Different wavelengths
- Different scientists/groups
- Different Techniques

Goals

- Demystify distance measurements and discuss the cross-checks built into the distance ladder.
- Think about consensus in terms of random and systematic effects.
- Make an argument for my personal favorite distance indicator as being a long-term viable path forward.

Being an Experimentalist101

Repeat measurements test both systematic and random uncertainties.

Independent Techniques — New ways to test the problem.

Independent Analysis of Same Data — Requires access to all of the data

Independent Datasets Using same Technique — Challenging Measurements Are Not Often Repeated

Modern Distance Ladder

Starting from Riess et al. 2009, it is quite streamlined.

(1)
"Anchor" a standard candle in the near field.

→

(2)
Apply Standard Candle to host-galaxies of SN Ia

→

(3)
Use SNe Ia in Hubble flow to determine Hubble constant.

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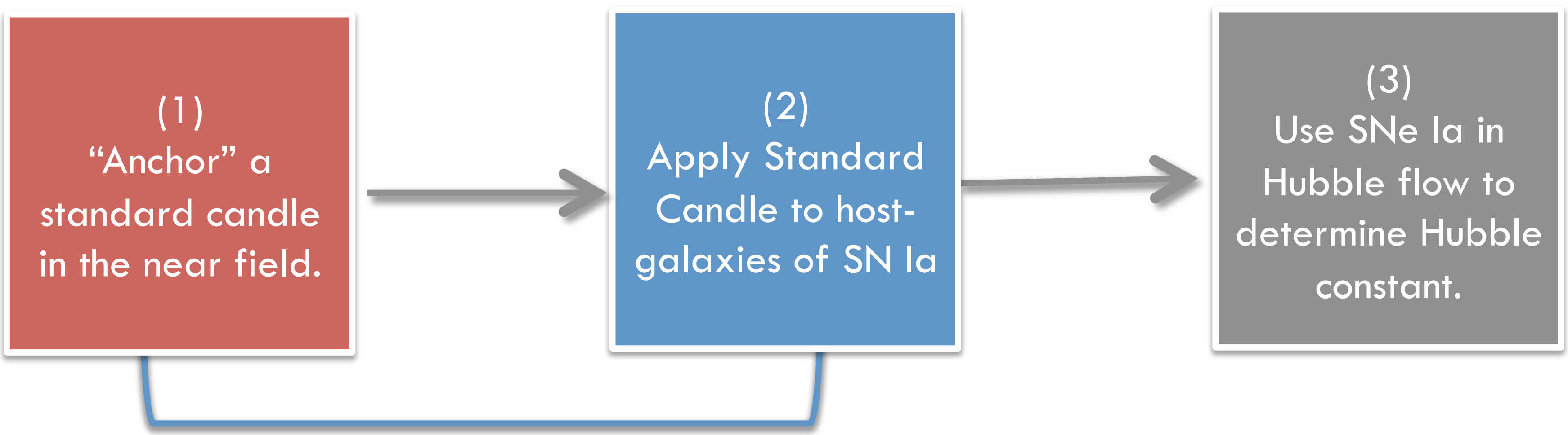

This talk is about how we test Step 2.

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[1]
Geometric Distances

+

[2]
Standard Candles

=

Multiple Tests of Distances.

Geometric Distances

We break walls in our calibration by calibrating in multiple systems using these techniques.

Trigonometric Parallax

Measured to individual stars

Cross checked via pulsational & statistical parallax

Eclipsing Binaries

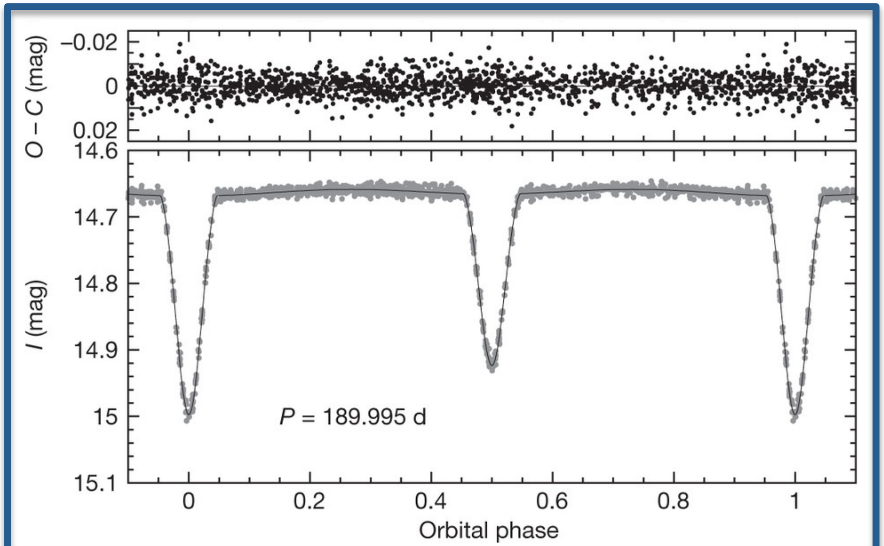
Measure distance to binary, usually in a Globular Cluster or Galaxy

Astrophysical Masers

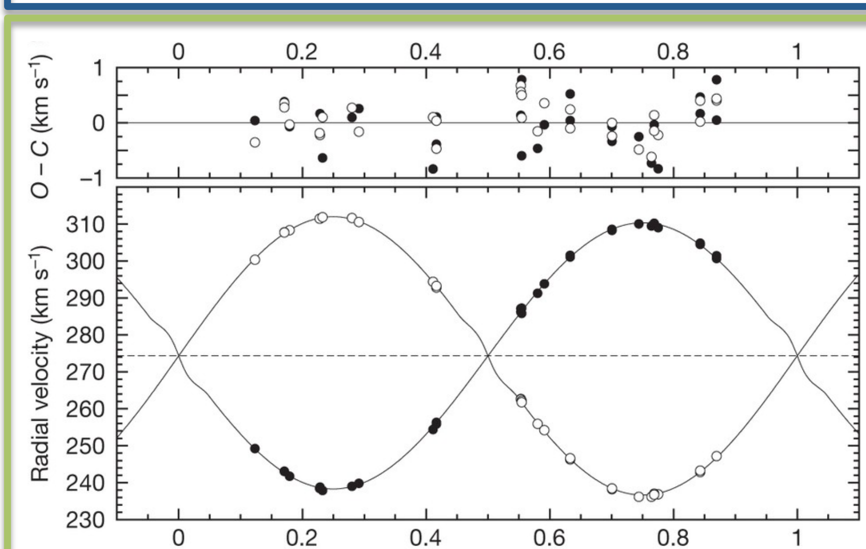
Either in a stellar atmosphere (AGB stars) or accretion disk of Black Hole (NGC4258)

Summarized in Beaton et al. 2018 thanks to the request of a great referee.

Eclipsing Binaries



Find & Characterize with **time domain photometry**. Ideal systems for distances are (i) detatched, (2) have 2 eclipses with 1 being “total,” and (3) late-type stars are better.

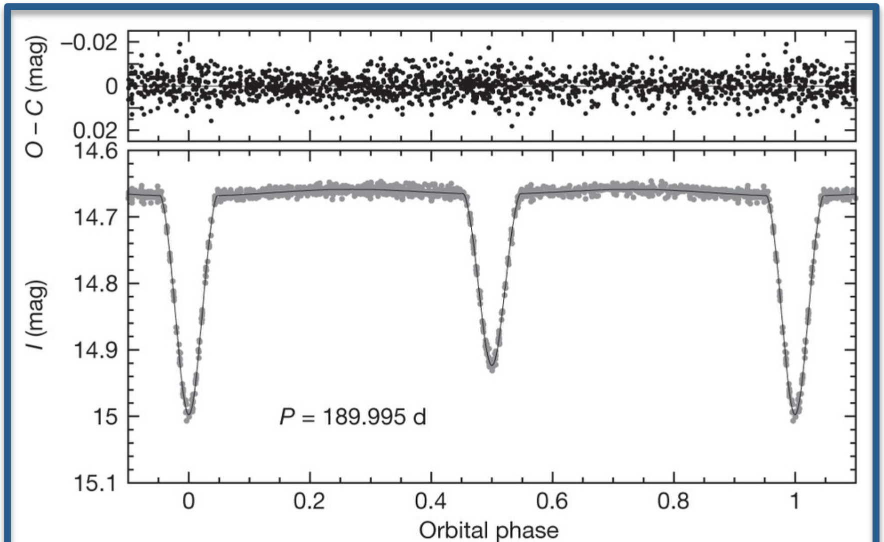


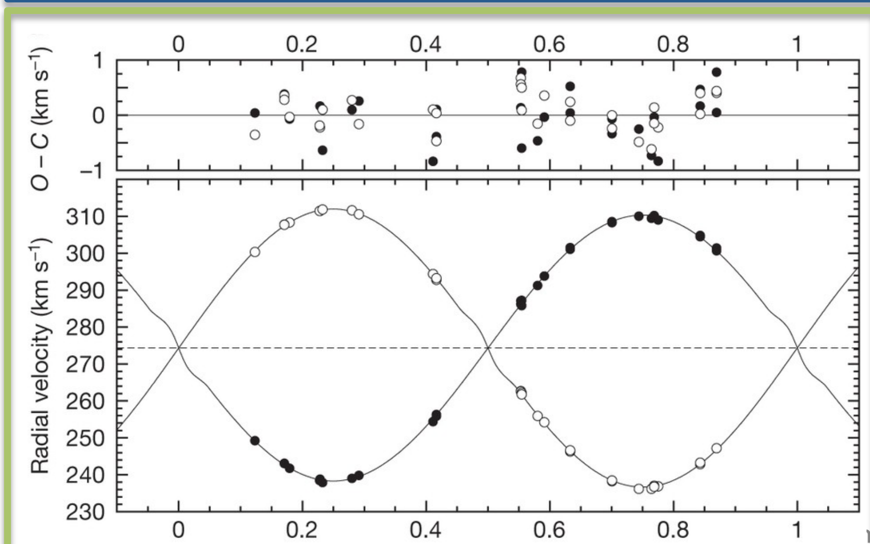
Model the orbits of the two stars **with time domain spectroscopy** to get radii of the stars in angular units. Using the surface brightness – radius relation, obtain a distance.

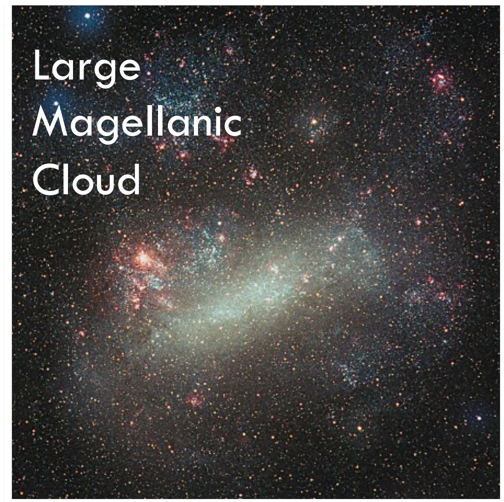
Limit to method set entirely by spectroscopic needs.

Figure from Pietrzyński et al. 2013 but many many great papers on EBs.

Eclipsing Binaries







+ Handful of Globular Clusters

Direct Test of Parallaxes

Standard Candles

Variable Stars

- RR Lyrae
- Miras
- Cepheids
- Type II Cepheids

[i] Period – Luminosity – Metallicity Relationship

[ii] Distances to individual Stars

Statistical Methods

- Blue Horizontal Branch
- Tip of the Red Giant Branch
- Red Clump

[i] Luminosity – Color Relationships

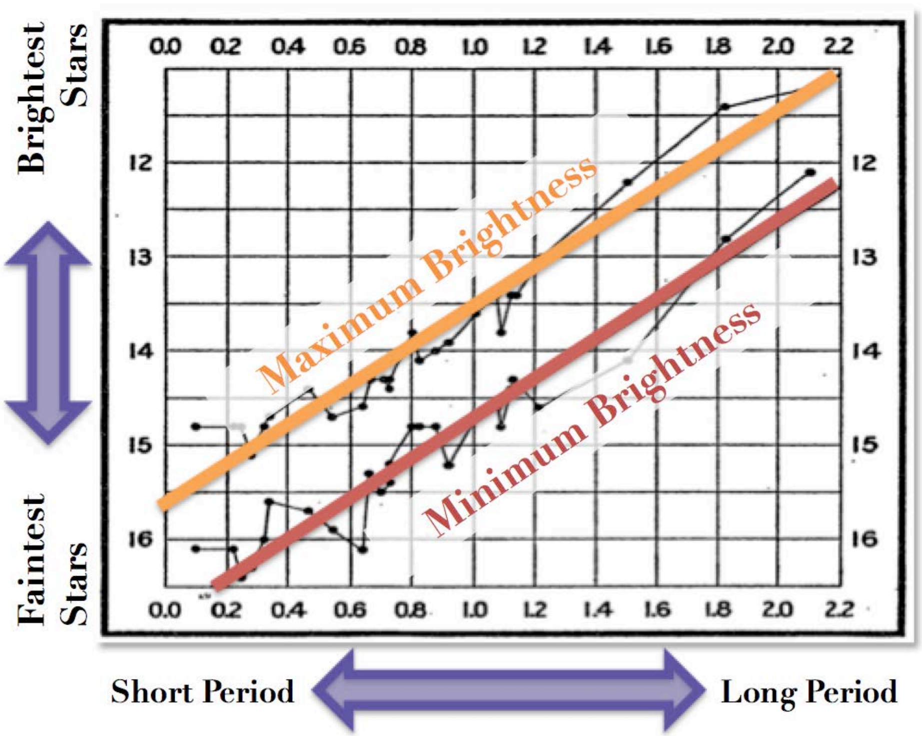
[ii] Statistical Distances to a Population

**In nearby galaxies,
we can use all of these.**

Pulsational Variable Stars

Live in specific phases of stellar evolution
and follow Period-Luminosity-Metallicity Relationships:

$$M_\lambda = \alpha_\lambda \log(P) + \beta_\lambda + \gamma_\lambda [M/H]$$



We measure:

- Periods
- Apparent magnitudes

We estimate:

- Milky Way foreground extinction
- Internal extinction
- Chemical abundance

We get:

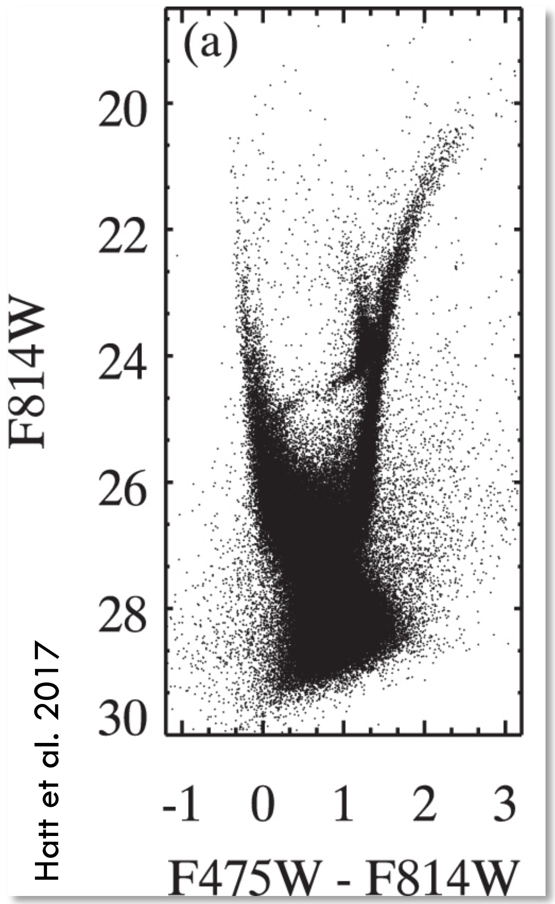
- Distance to each star with a precision set by intrinsic width of the relationship + our observational uncertainties

Leavitt 1908
Leavitt & Pickering 1912

Statistical Techniques

Make use of *pauses* or *abrupt changes* in stellar evolution where stars either build up or are distinctly lacking in stellar sequences. These have empirical color-magnitude relationships:

$$M_\lambda = \alpha_\lambda \, (m_\lambda - n_\lambda) + \beta_\lambda$$



We measure:

- Apparent magnitudes
- Apparent colors (2 magnitudes)
- Density of stars

We estimate:

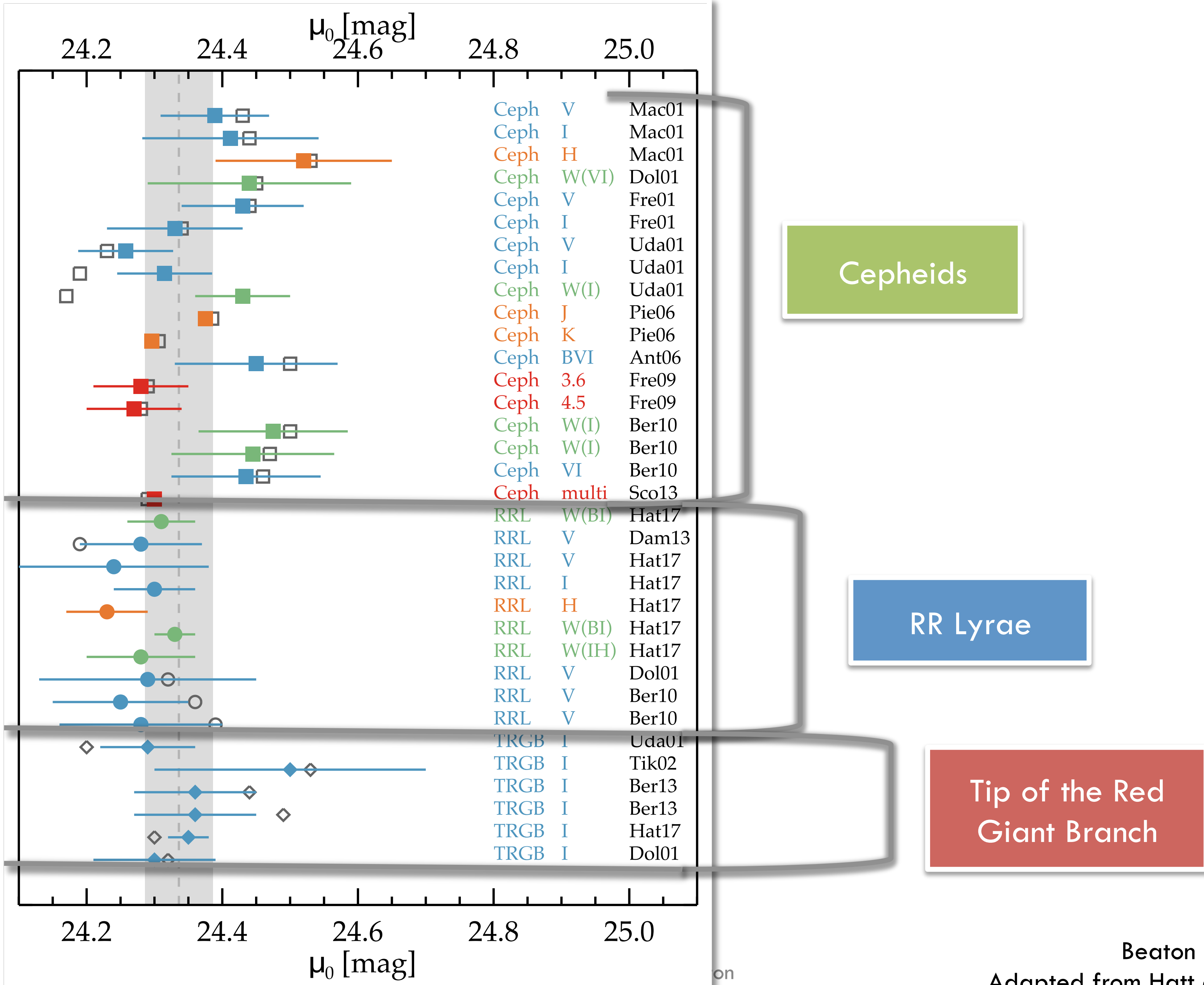
- Milky Way foreground extinction
- [Internal extinction]
- Complexity of stellar population

We get:

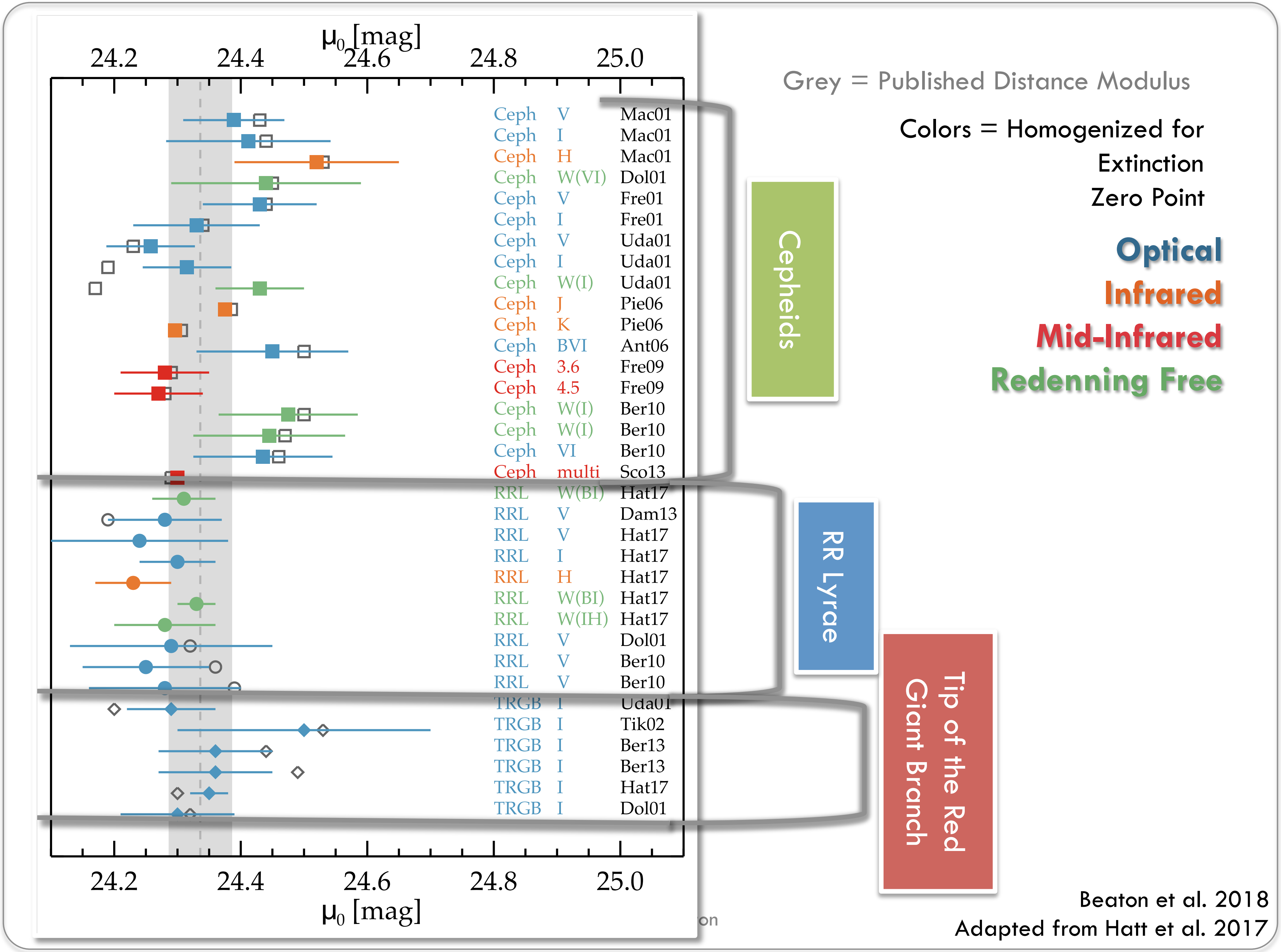
- Distance to each star with a precision set by intrinsic variation f the stellar class + our observational uncertainties

IC1613: A Local Galaxy

- Dwarf Galaxy
- ~740 kpc away (~Andromeda)
  - Easily observed with 4-m class telescopes
- Low metallicity
- Low extinction
- Has everything but a SNe Ia



Beaton et al. 2018
Adapted from Hatt et al. 2017



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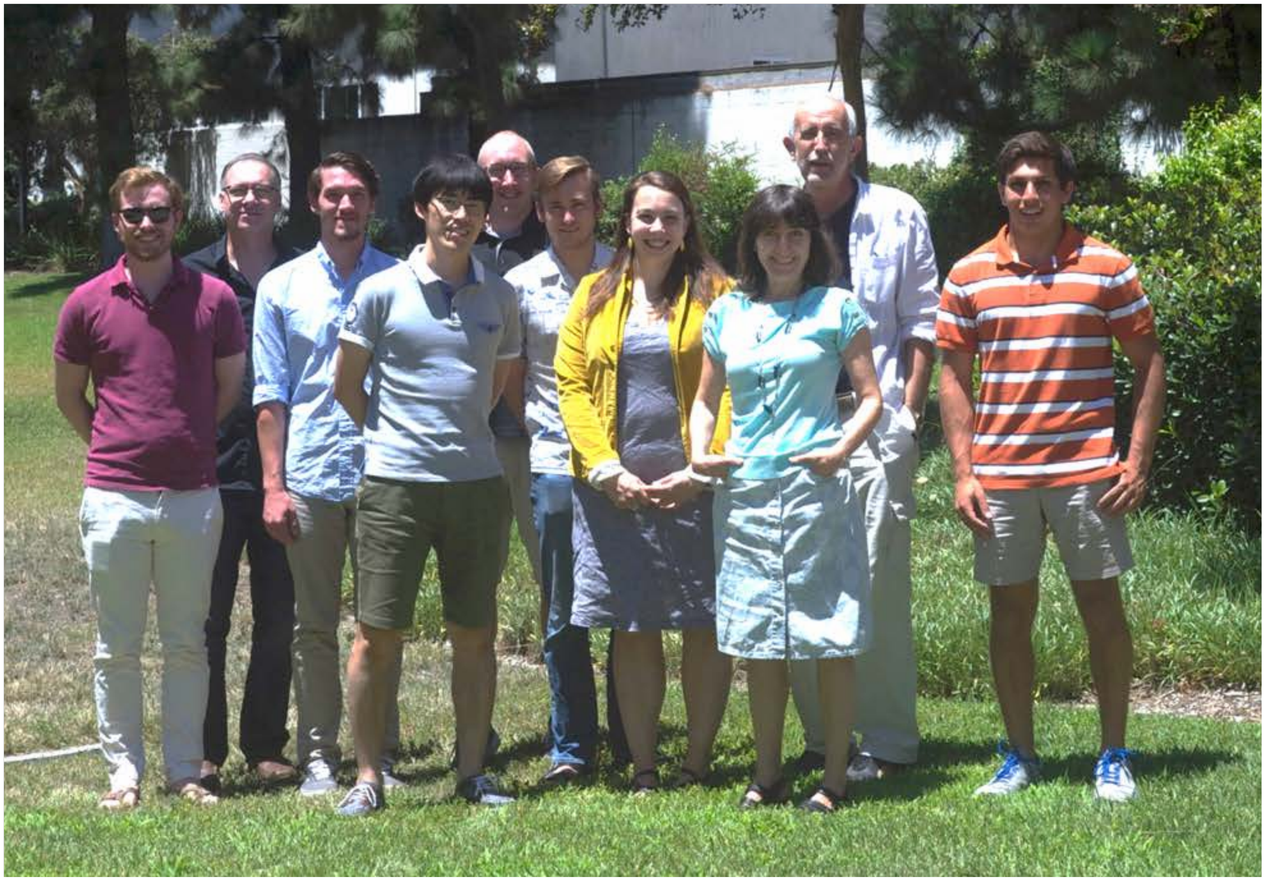
Carnegie-Chicago Hubble Program



Front: Dylan Hatt, Taylor Hoyt, In-Sung Jang, Rachael Beaton,
Wendy Freedman, Arvind Gupta
Back: Mark Seibert, Andy Monson, Jeff Rich, Barry Madore

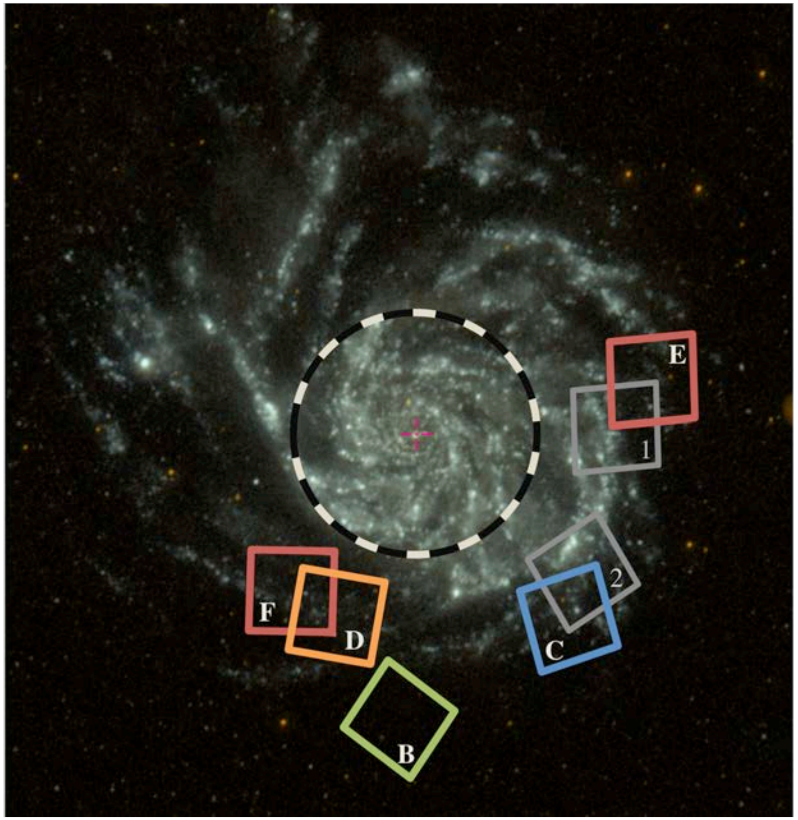
Independent
Distance Ladder

In 4 years had to catch up with decades of work with Cepheids.

And we're nearly there!

Cepheids

1. Young, Massive Stars
2. In Disks/Star forming regions
   1. Crowding
   2. Dust
3. Metal Rich



Tip of the Red Giant Branch

1. Old, low mass stars
2. Halos
   1. No crowding
   2. No dust
3. Metal Poor

If we agree that things “look okay” nearby, then this comparison becomes one about the systematics in distant Cepheids.

Cepheids

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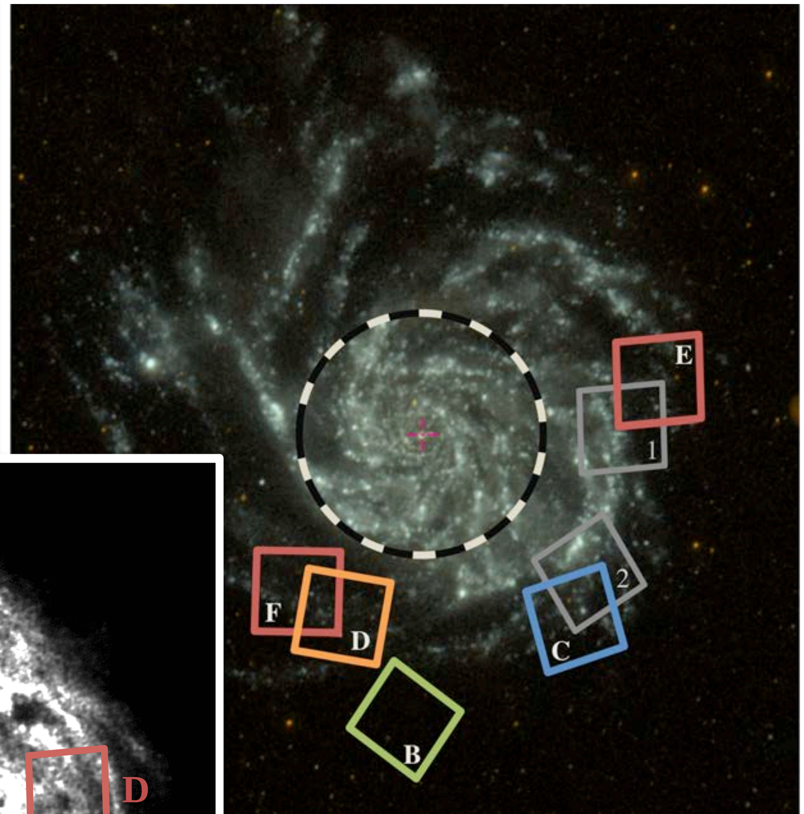

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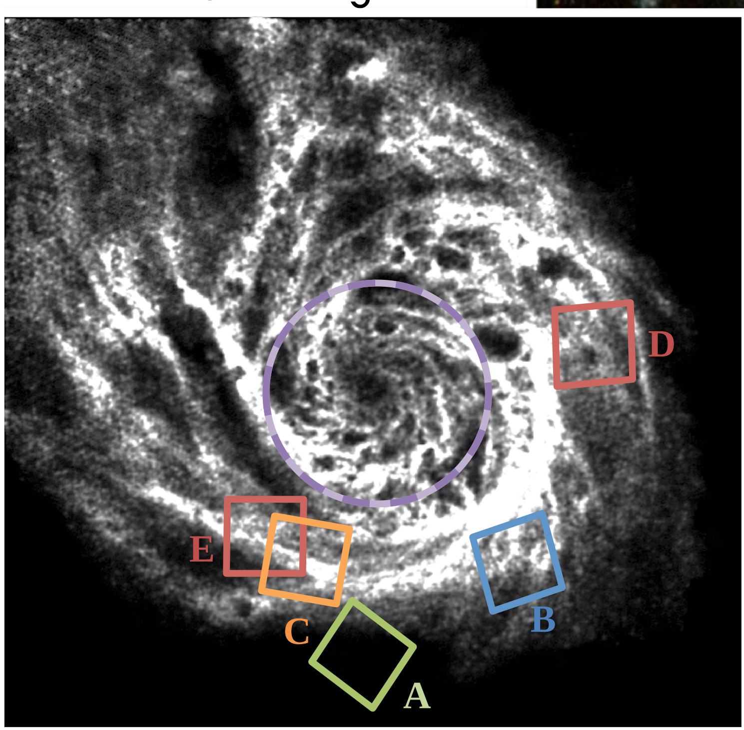

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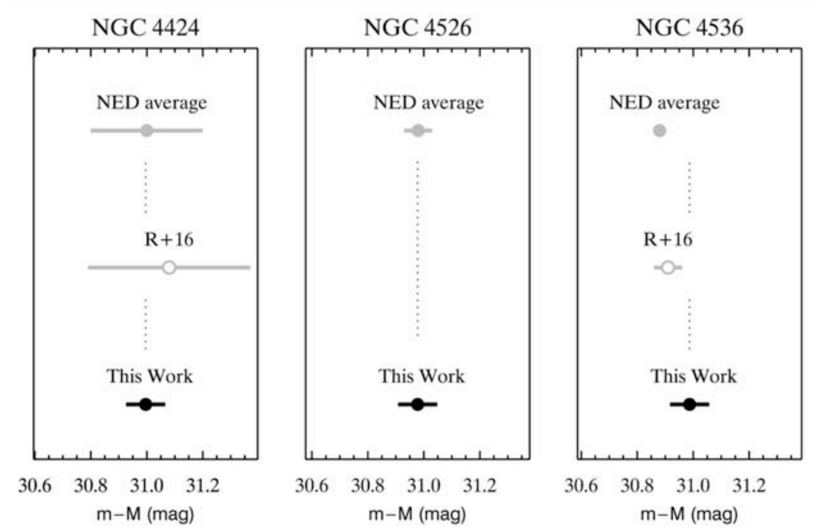
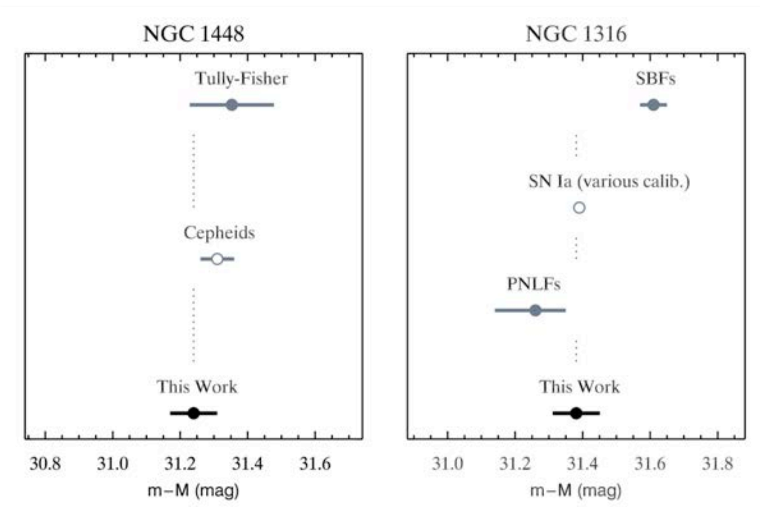
7 SNe Ia Hosts

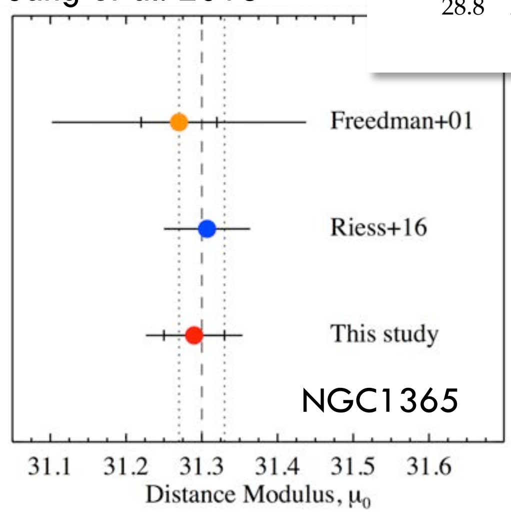
Hatt et al. 2018b



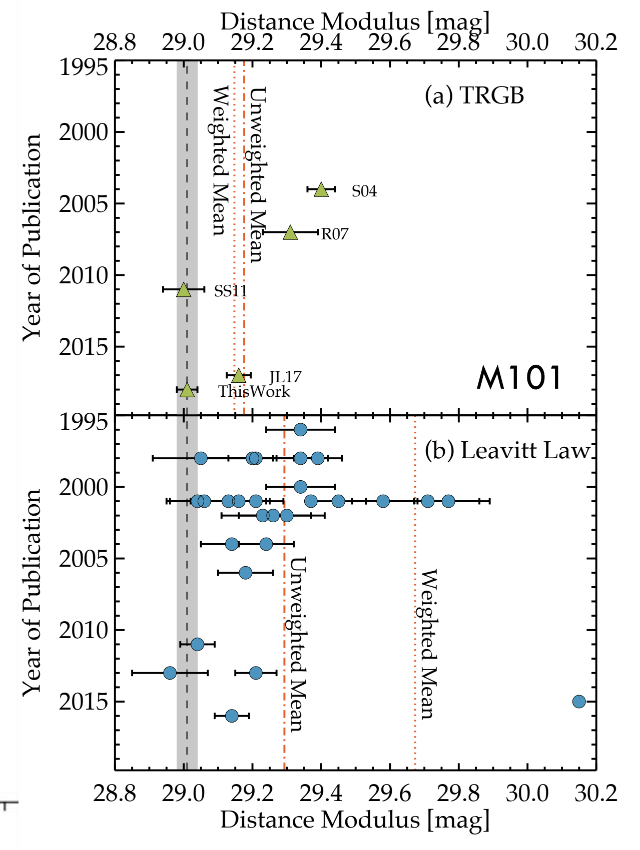
Hatt et al. 2018a



Jang et al. 2018



Beaton et al. (nearly done)



Bringing Down the Walls

Independent Techniques

Continue to Develop new ways to look at the problem. Expensive.

Independent Analysis of Same Data

Open Access to Data – including intermediate products & codes

Promote reproducibility in our papers

Independent Datasets Using same Technique

Challenging Measurements Are Not Often Repeated

JWST could give us a 2^{nd} dataset, but expensive.

Community

Make us convince you.

But make sure this hard work is rewarded!