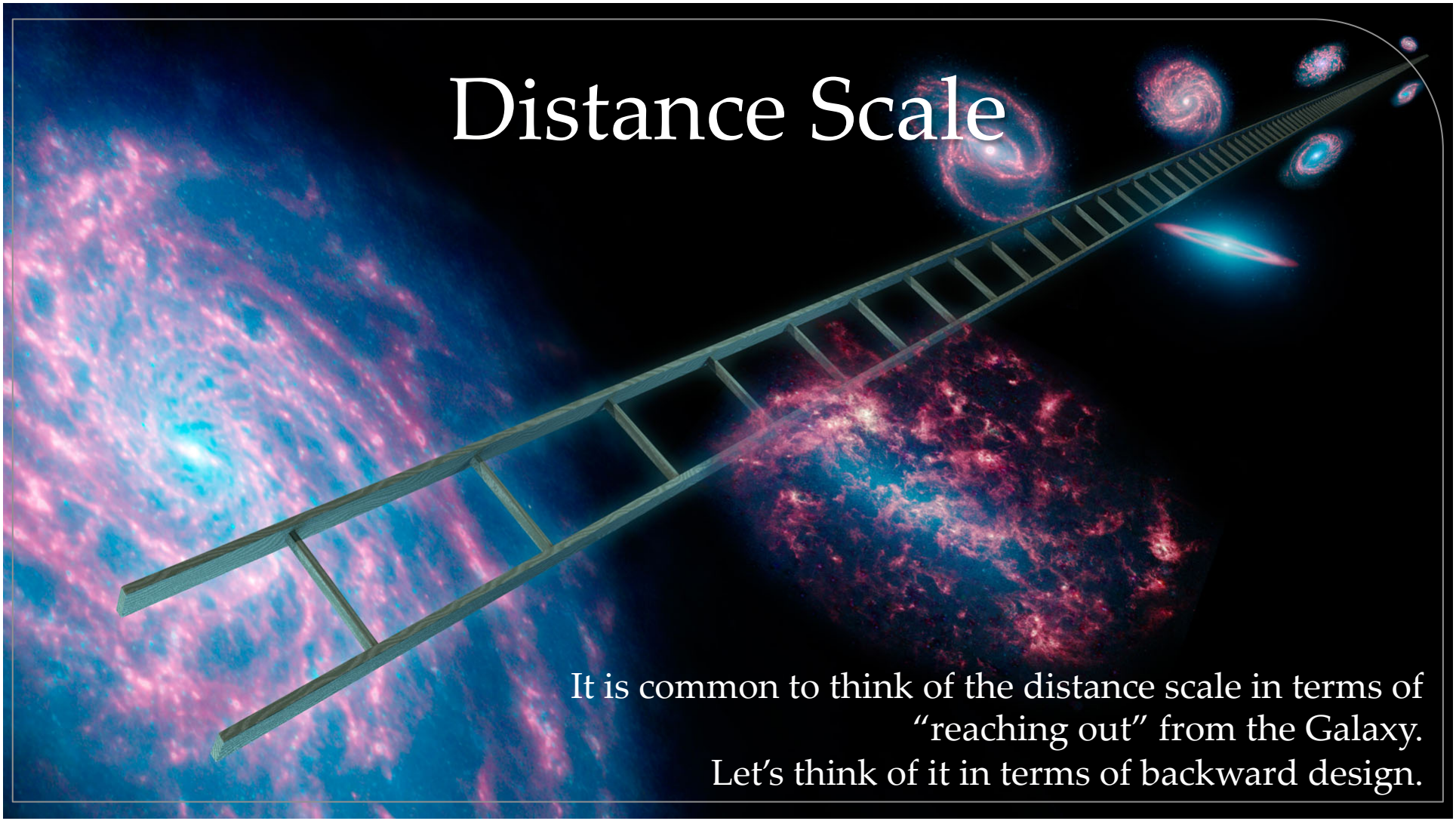
The Extragalactic Distance Scale in the *Gaia* Era

Rachael L. Beaton
Carnegie Observatories
(Fall 2017 - @Princeton)

Distance Scale



It is common to think of the distance scale in terms of "reaching out" from the Galaxy.
Let's think of it in terms of backward design.

The Hubble Diagram

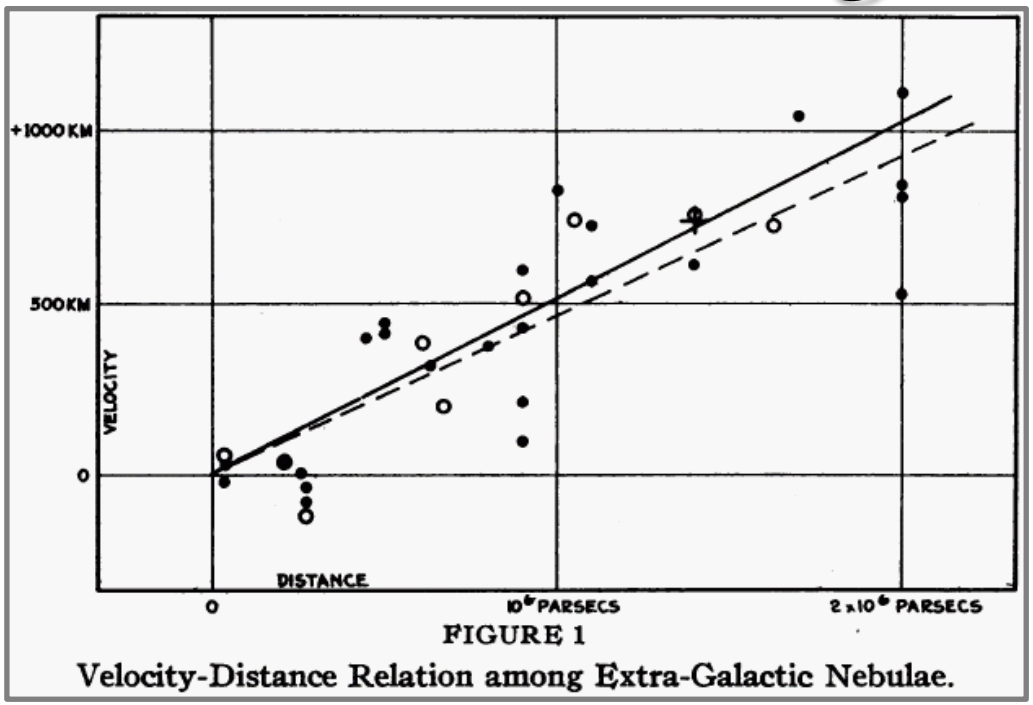


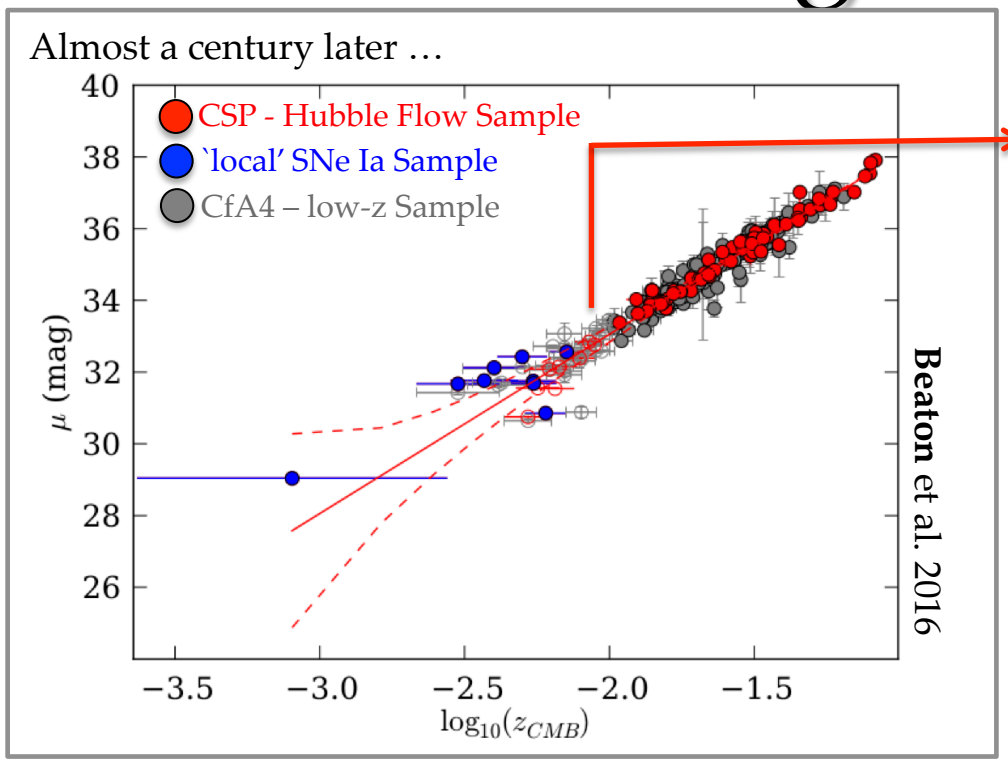
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble 1929

H_0 is the proportionality constant between distance (x-axis) and redshift (y-axis).

The Hubble Diagram



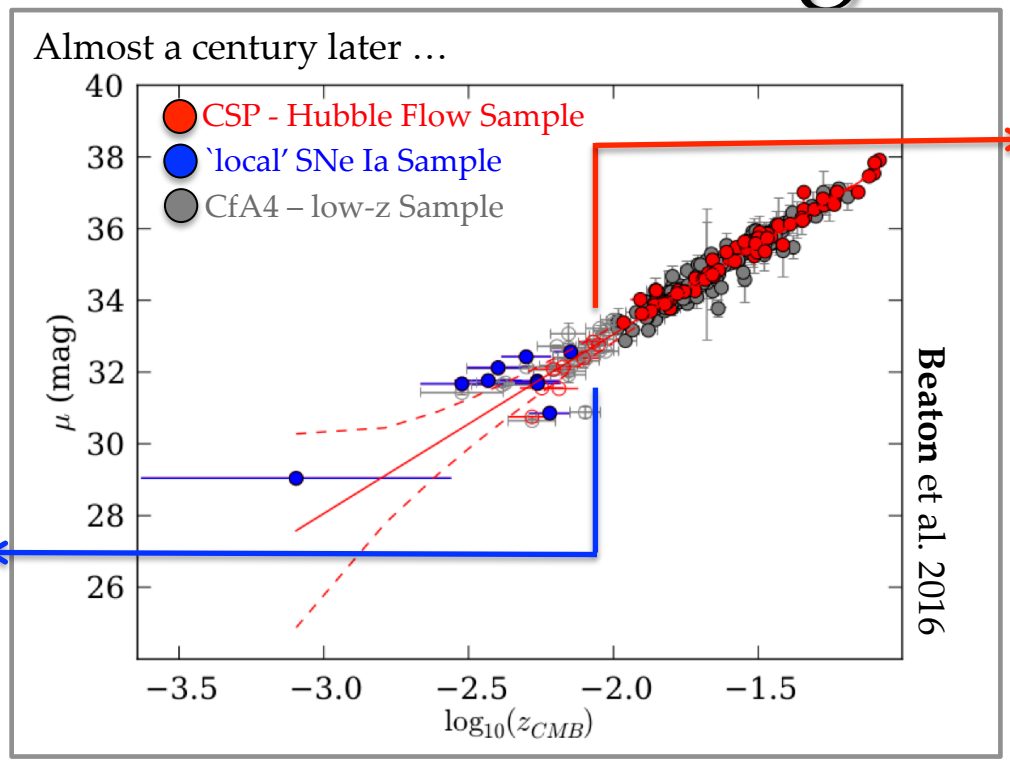
SNe Ia Hubble Flow

$\sigma_{\text{SNe Ia}}$ = 0.15 mag with 221 SNe Ia

0.7 % uncertainty

H_0 is measured in the smooth Hubble Flow where over 200 SNe Ia are well-characterized.

The Hubble Diagram



SNe Ia ZeroPoint

$\sigma_{\text{SNe Ia}}$ = 0.12 mag
with 19 SNe Ia

~2.0 % uncertainty

SNe Ia Hubble Flow

$\sigma_{\text{SNe Ia}}$ = 0.15 mag
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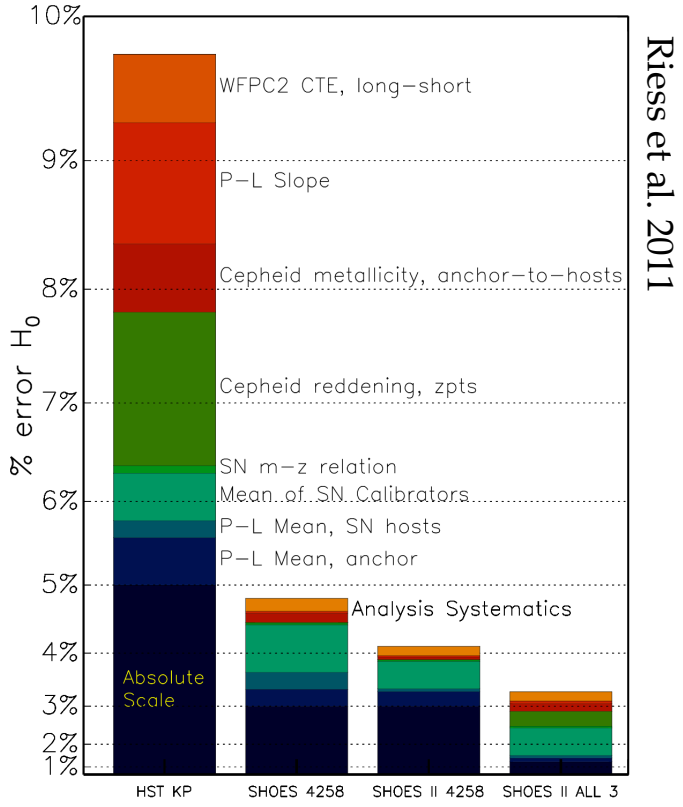
0.7 % uncertainty

The best we can do with current local sample is **2.1% uncertainty** *regardless of how we calibrate the SNe Ia.*

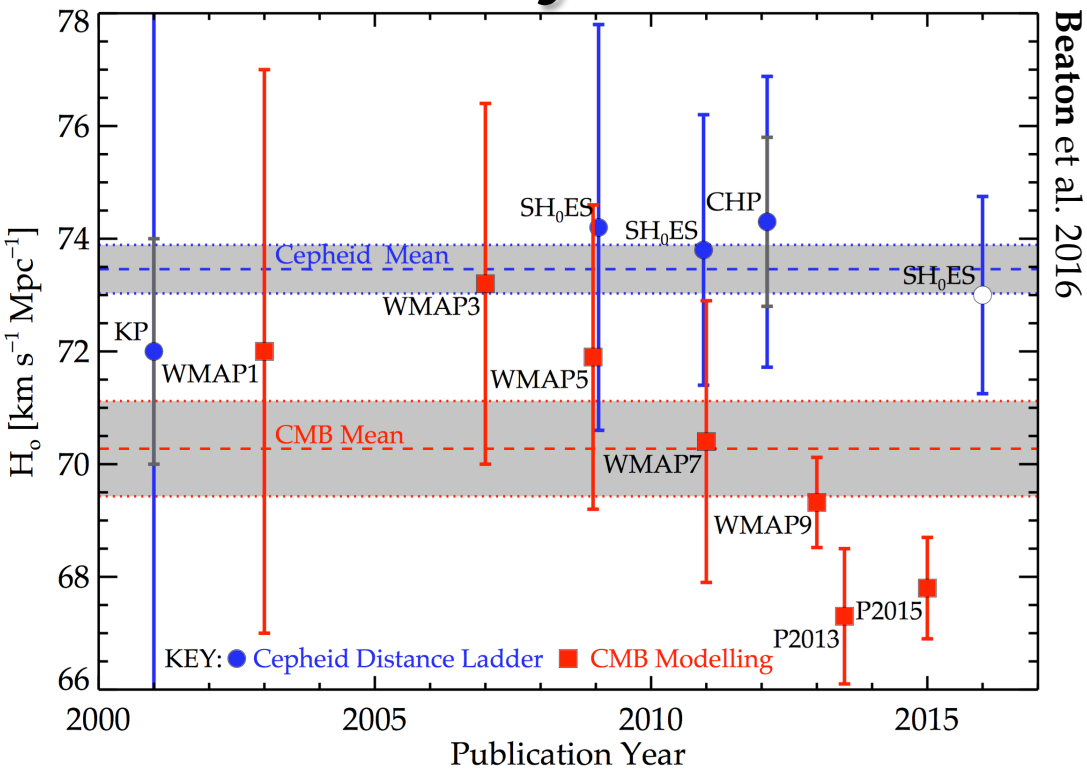
In the (recent) past this was okay:



Riess et al. 2011

The large uncertainties from the other terms that set the Cepheid scale were much larger than the 2% from the SNe Ia.

But, today it is not:



Even an 0.05 mag uncertainty (2.5%) is a detail to worry about.

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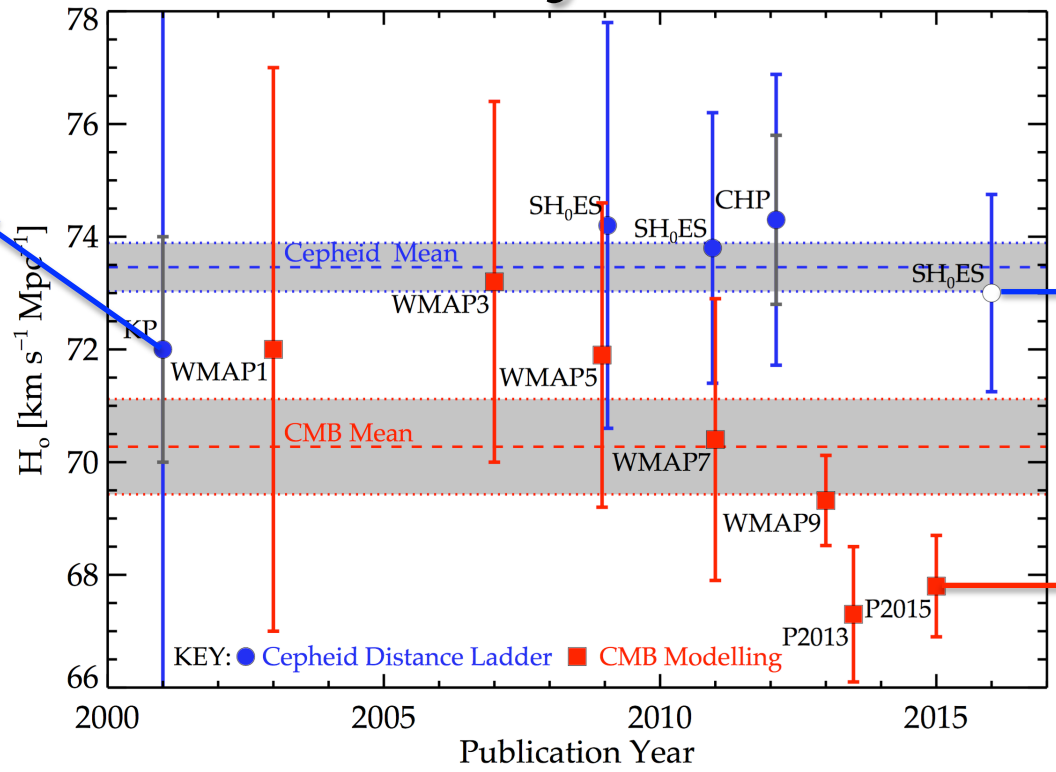

10%
Freedman et al. 2016
HST Key Project

2.4%
Riess et al. 2016

1.6%
Planck Collaboration 2016

Beaton et al. 2016

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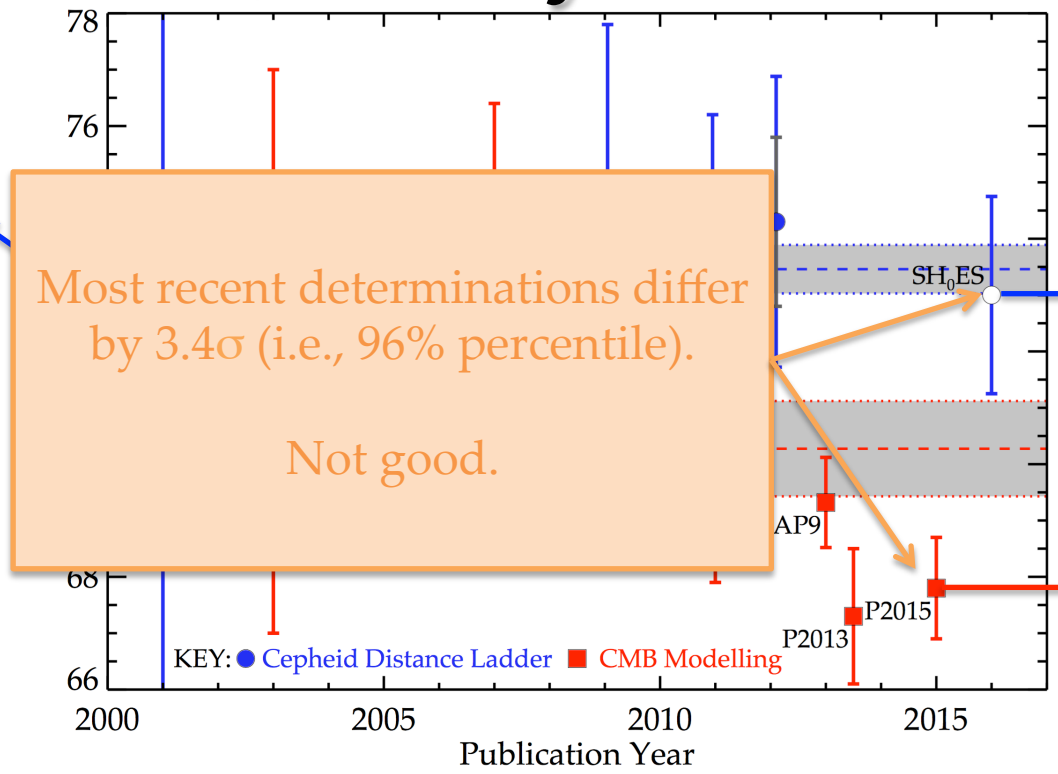

10%
Freedman et al. 2016
HST Key Project

Most recent determinations differ by 3.4σ (i.e., 96% percentile).

Not good.

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Riess et al. 2016

1.6%
Planck Collaboration 2016

Beaton et al. 2016

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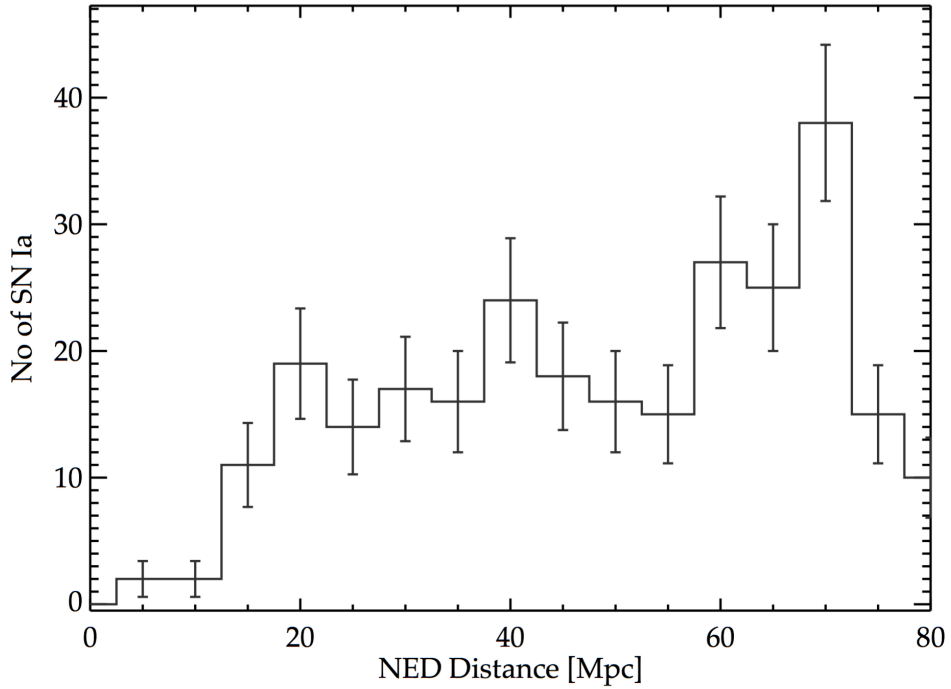
Why so few SNe Ia Calibrators?



It is just not for a 'lack' of SNe Ia in the 'Local Volume'

**As of March 2016.

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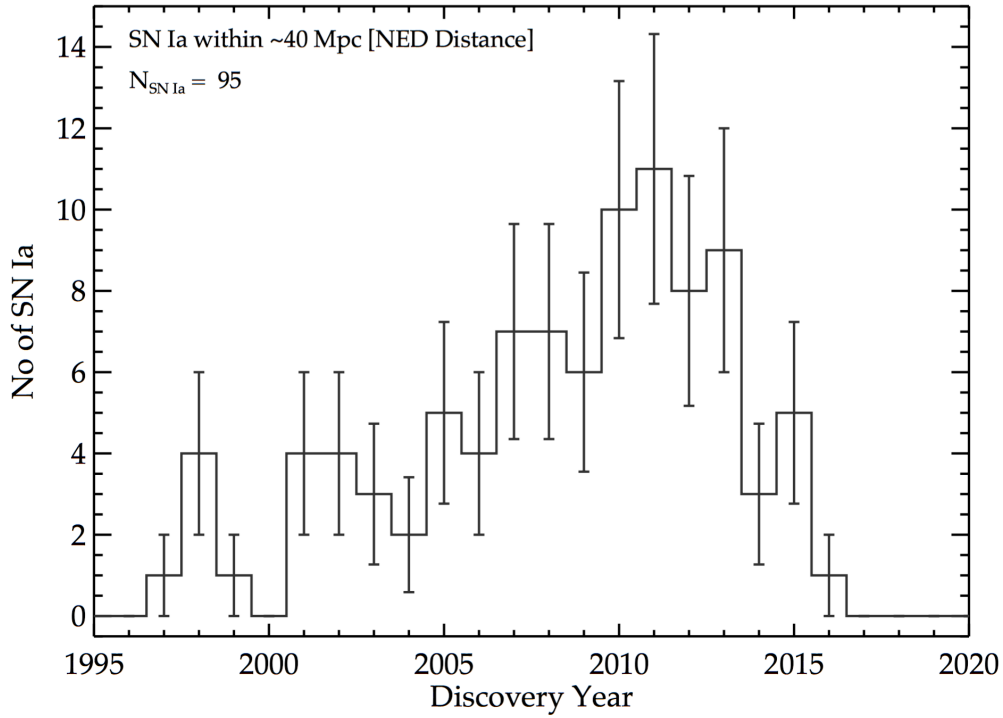

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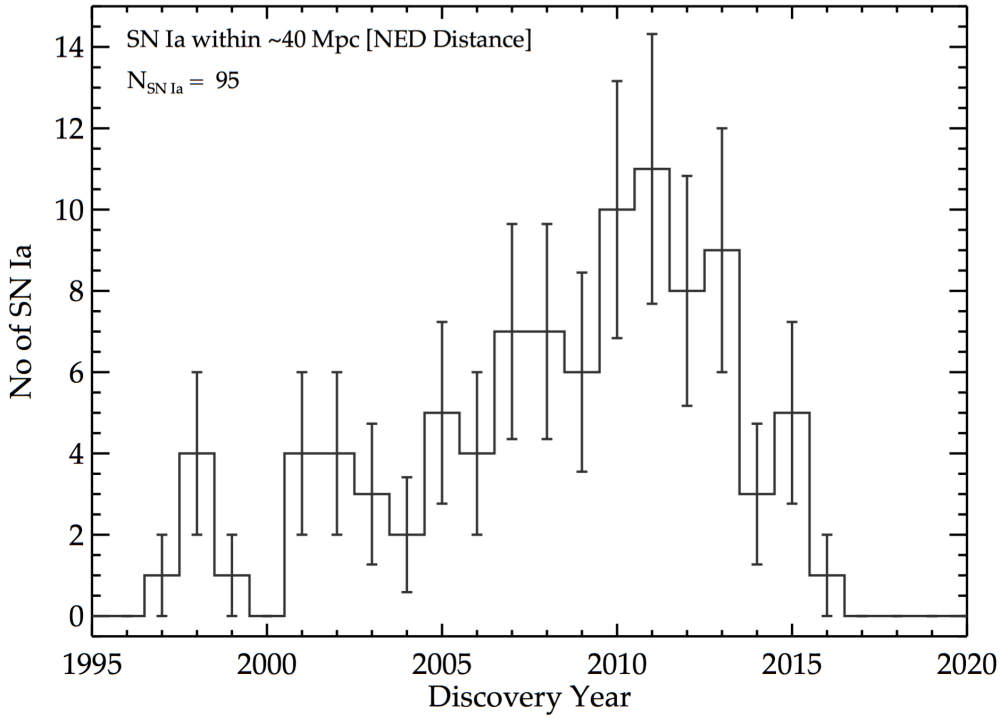

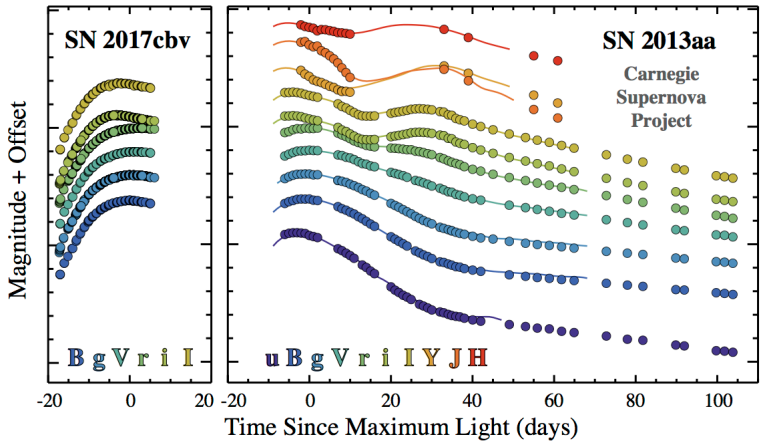

Shappee (incl. **Beaton**) et al. (in prep.)

SNe Ia Suitability

(1) Can I characterize the SNe?

(2) Can I measure its distance?

SNe Ia Suitability

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- Did I find it before peak light?
- Can I remove the galaxy and/or nearby bright sources?
- Do I have quality, multi-band light curves for 30+ days?
- Can I estimate local extinction?
- … and related issues.

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Thanks to a phenomenal effort from the SNe/transient communities 40 SNe Ia within 40 Mpc have this data (~50%).

**Chris Burns (CSP) & Ben Shappee (ASAS-SN)

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  - Crowding?
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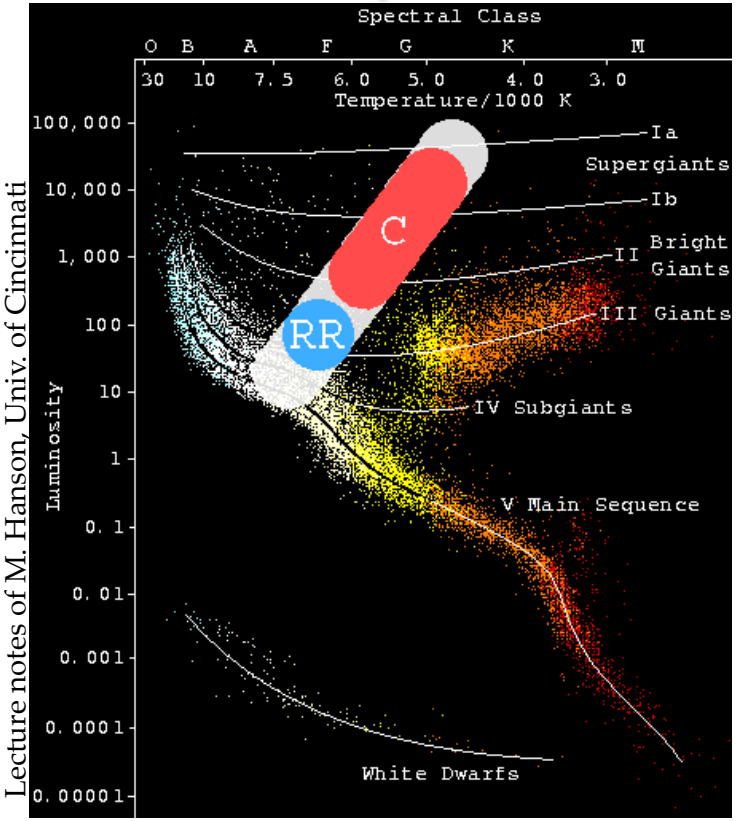
Cepheids are amazing tools, but their applicability to the SNe Ia host population is limited.

The data needed to find, characterize, and use the Leavitt law is expensive, relies on numerous ground *and* space facilities, and multiple techniques.

and herein lies the limitation.

With *Gaia*, more tools.



Lecture notes of M. Hanson, Univ. of Cincinnati

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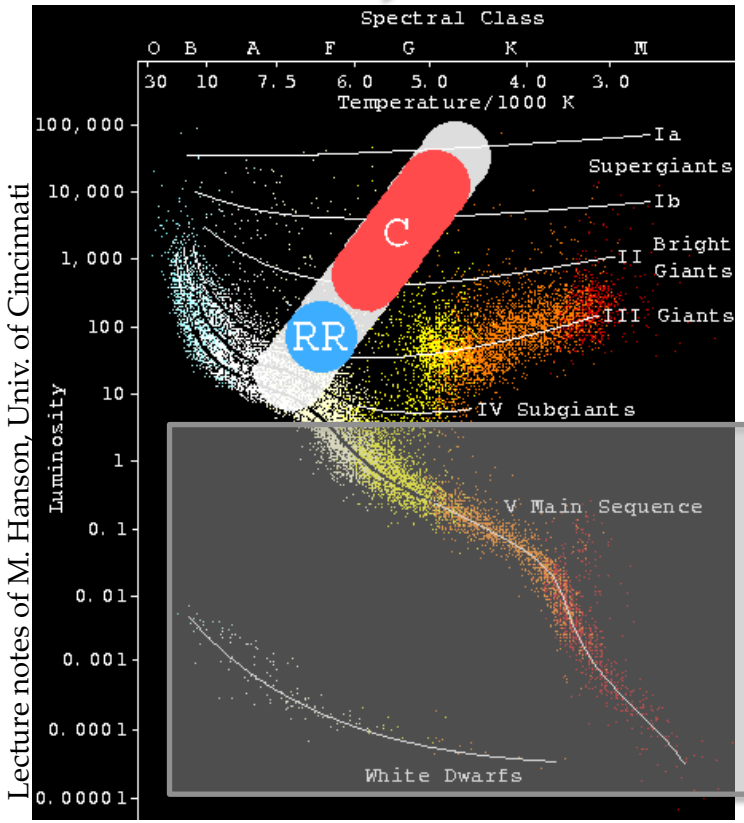

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Too faint for distances to SNe Ia hosts.

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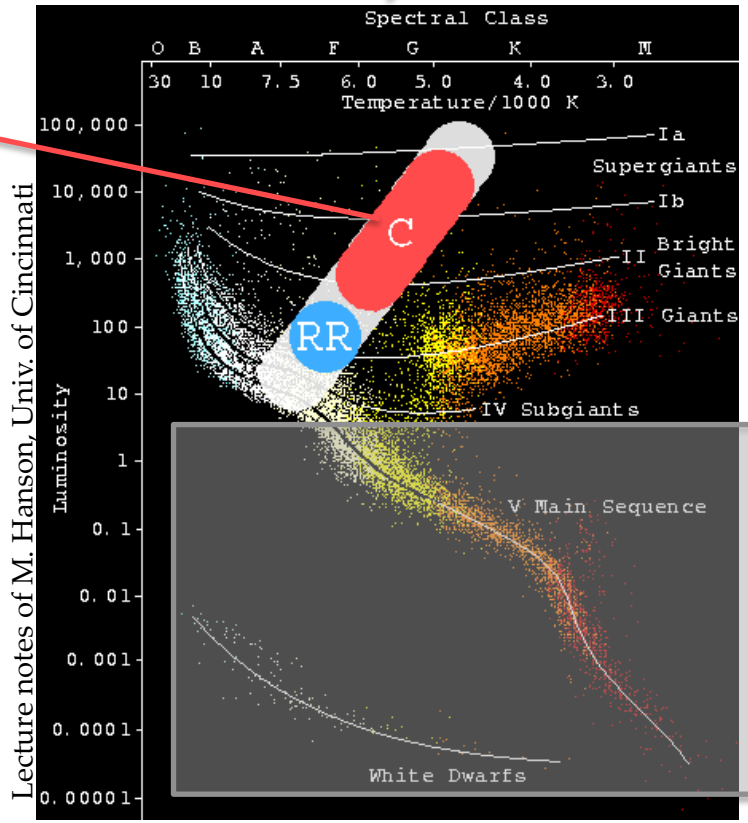
Cepheids:

- < 400 Myr
- Range [Fe/H]
- Galaxy Disks
- variable



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- Mostly metal-poor
- Disk, bulge, halo
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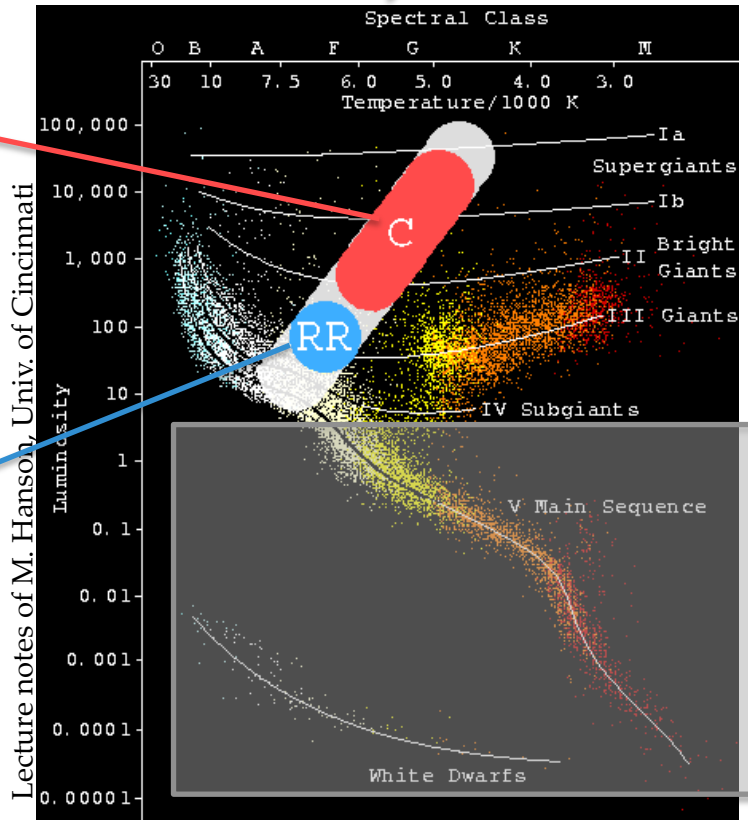

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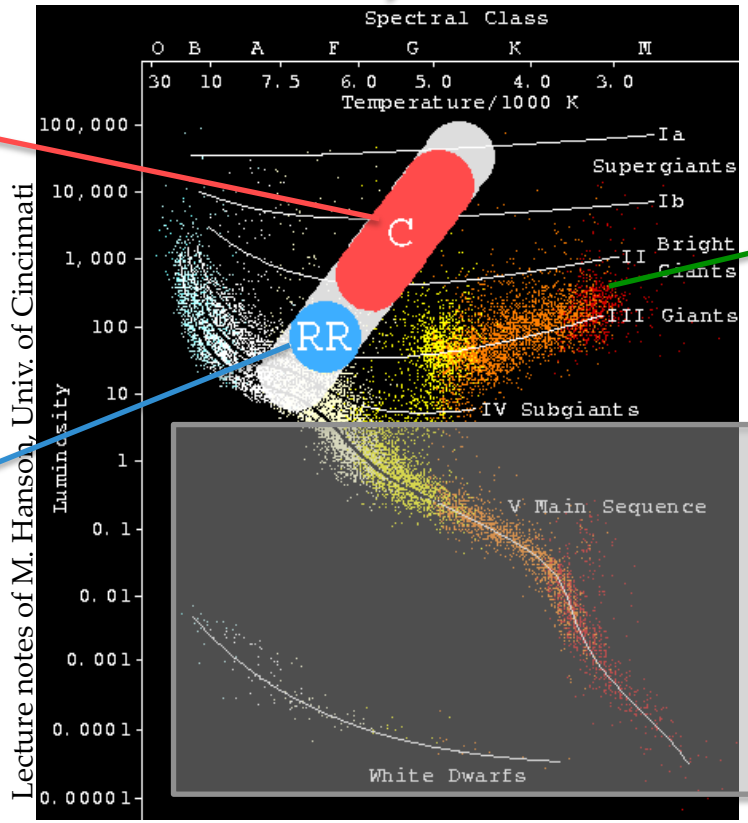

TRGB:
- > few Gyr
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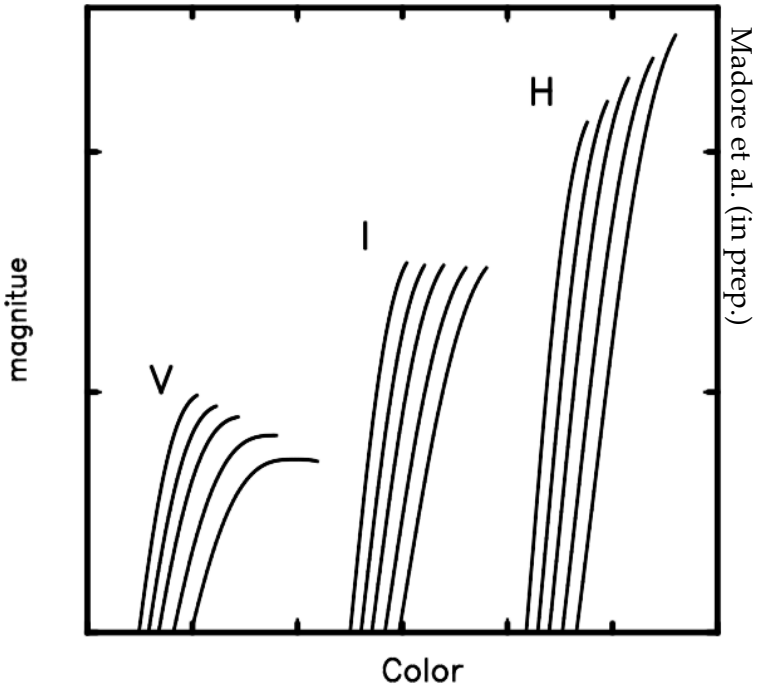
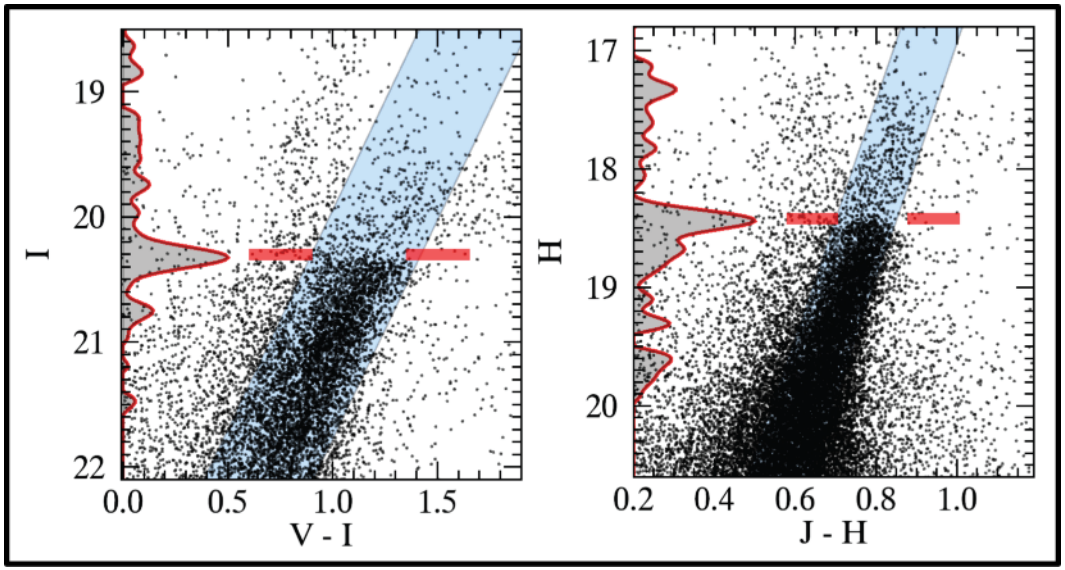
- Not variable

Too faint for distances to SNe Ia hosts.

Tip of the Red Giant Branch



IC 1613 – Local Group Dwarf Irregular



Optical: Hatt, **Beaton** et al. (submitted)
NIR: Madore (incl. **Beaton**) et al. (in prep.)

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	• Great non-uniformity of application in the literature
	• No direct trigonometric calibration.

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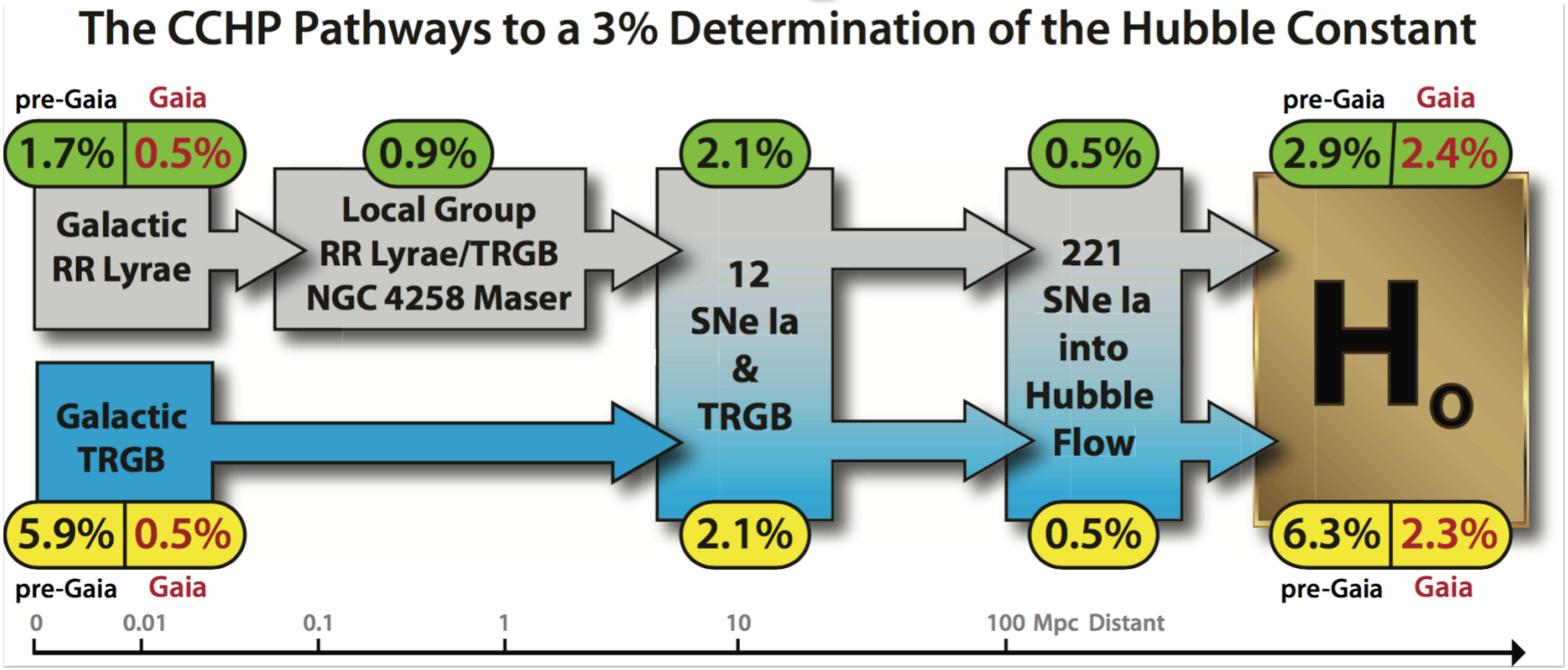
CONs

- No 100 year legacy.
  - **Every SNe Ia host must be measured for the first time.**
- Great non-uniformity of application in the literature
  - **Develop techniques applicable over 20 mag in distance modulus.**
- No direct trigonometric calibration.
  - **Collect the ancillary data to use *Gaia* parallaxes**

1. Build a Sample of SNe Ia



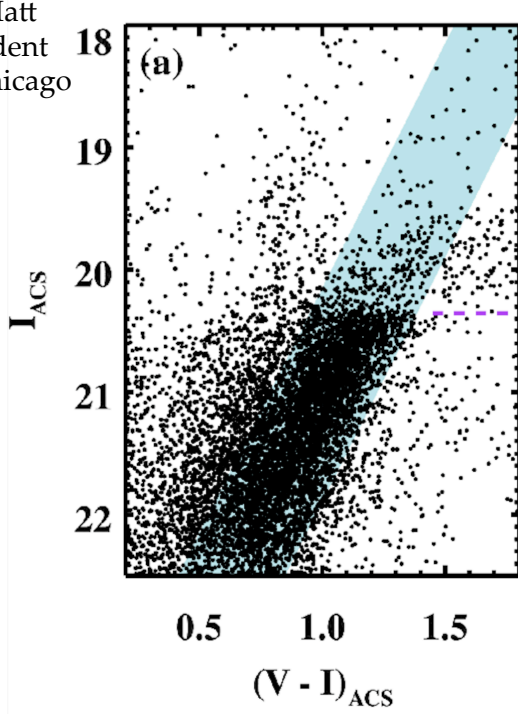
Beaton et al. 2016

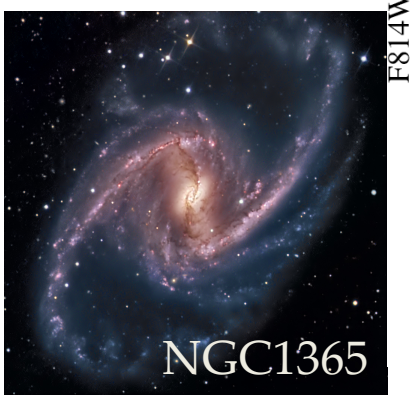
2. Standardized Techniques

Dylan Hatt
PhD Student
Univ. of Chicago

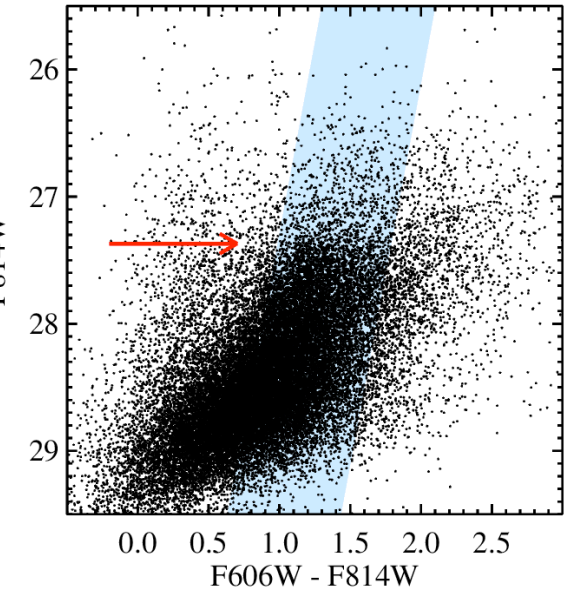
In Sung Jang
PhD/Now Postdoc
AIP

NEAR-FIELD





FAR-FIELD



Hatt, **Beaton** et al. (submitted) ArXiv:1703.06468

Jang, Hatt, **Beaton** et al. (submitted) ArXiv:1703.10616

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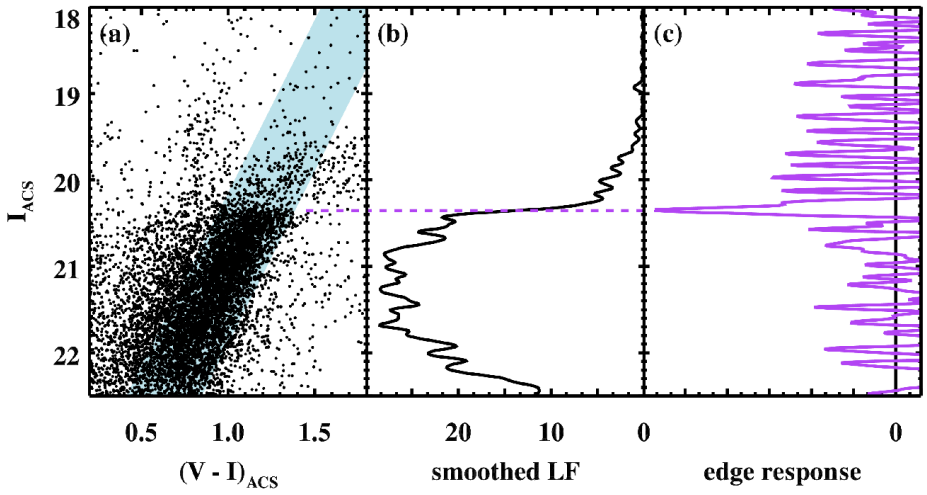
IC1613

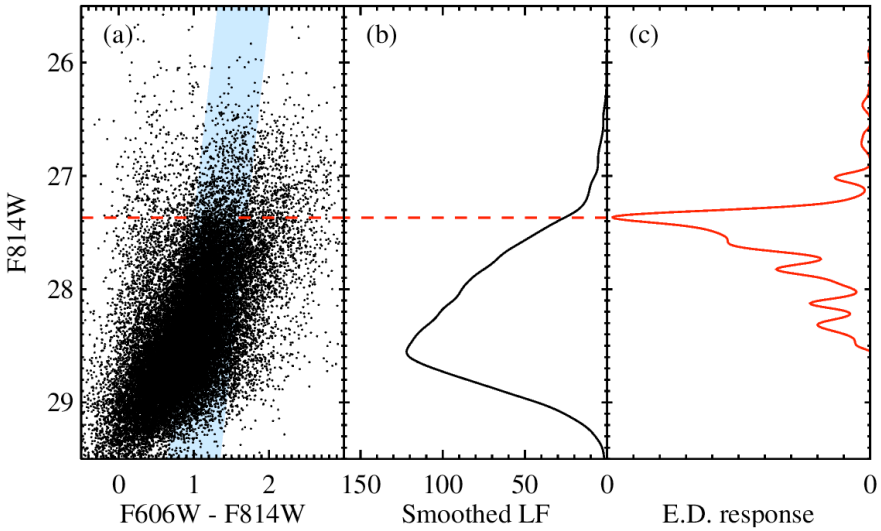


D = 784 ±17 (stat) ±40 (sys) kpc

Hatt, **Beaton** et al. (submitted) ArXiv:1703.06468

FAR-FIELD

NGC1365



D = 18.1 ±0.3 (stat) ±0.4 (sys) Mpc

Jang, Hatt, **Beaton** et al. (submitted) ArXiv:1703.10616

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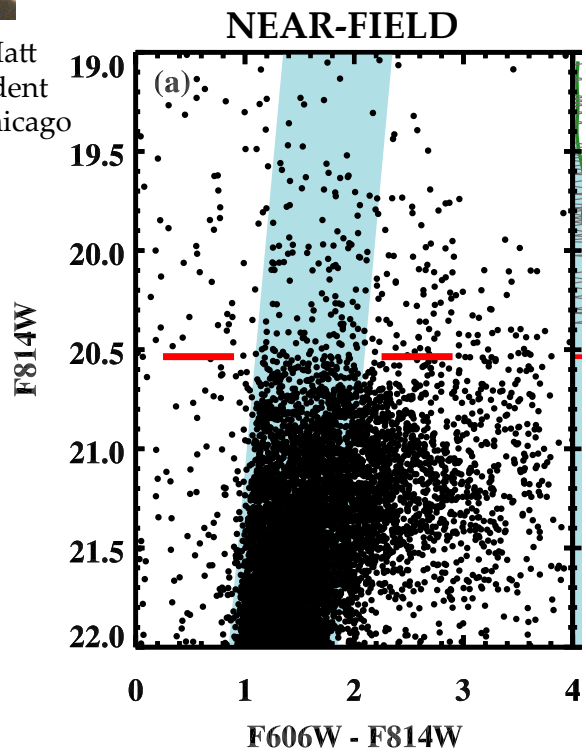

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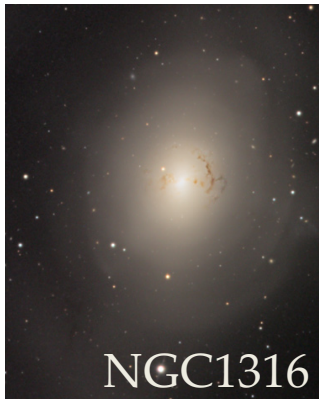

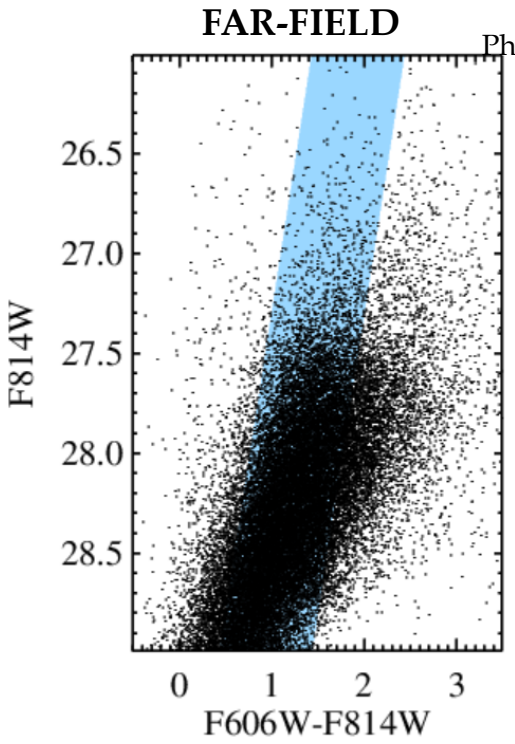

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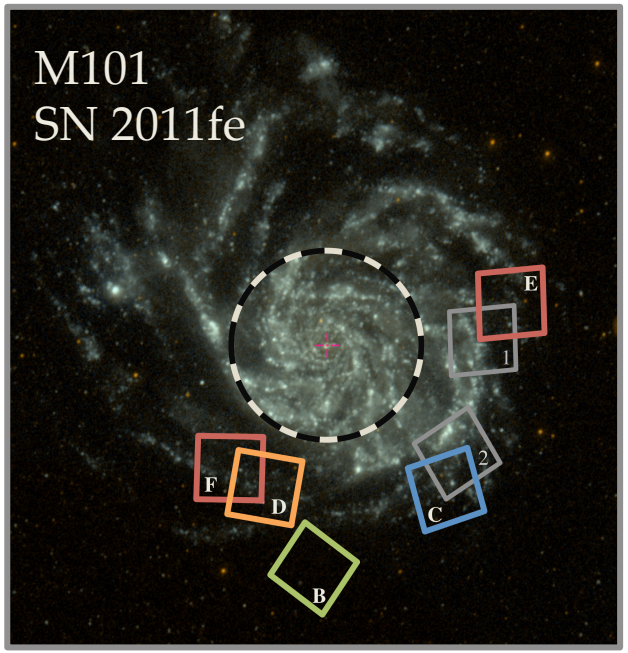

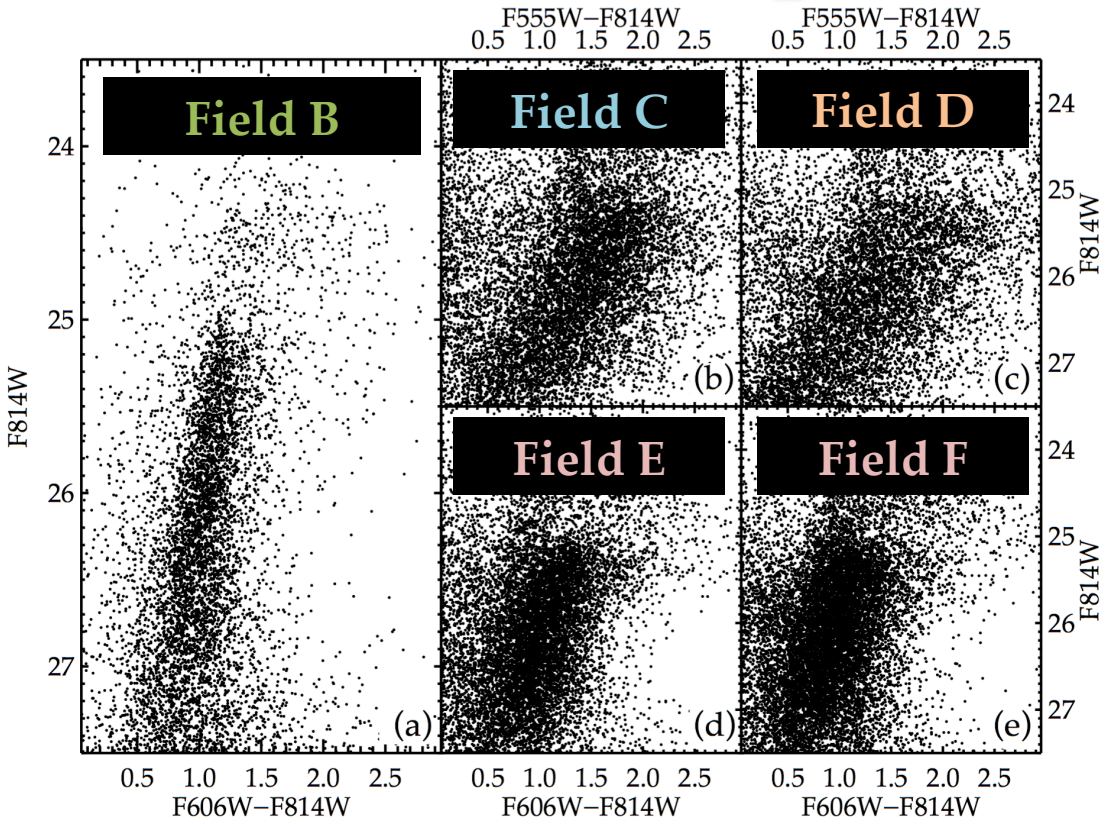

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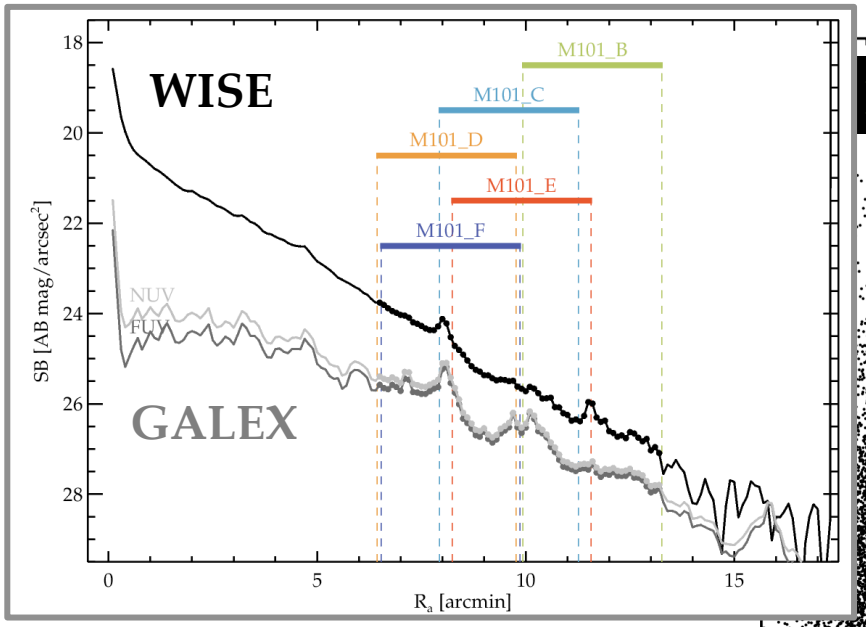

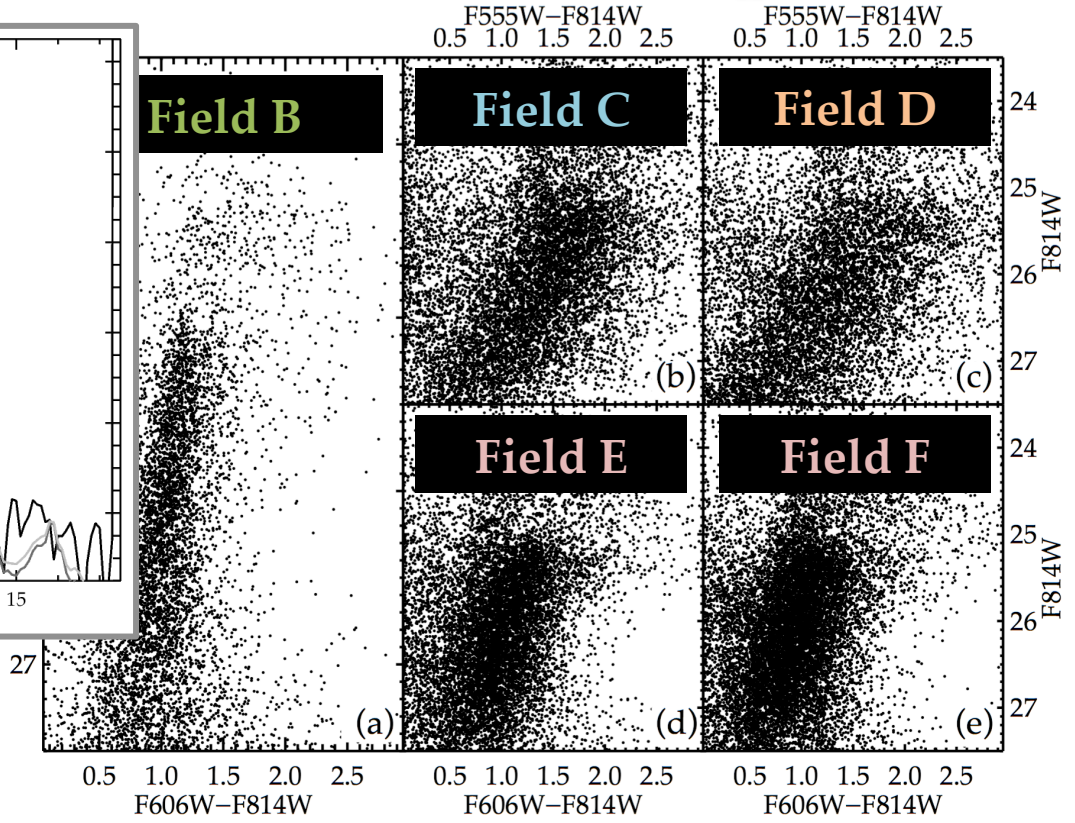

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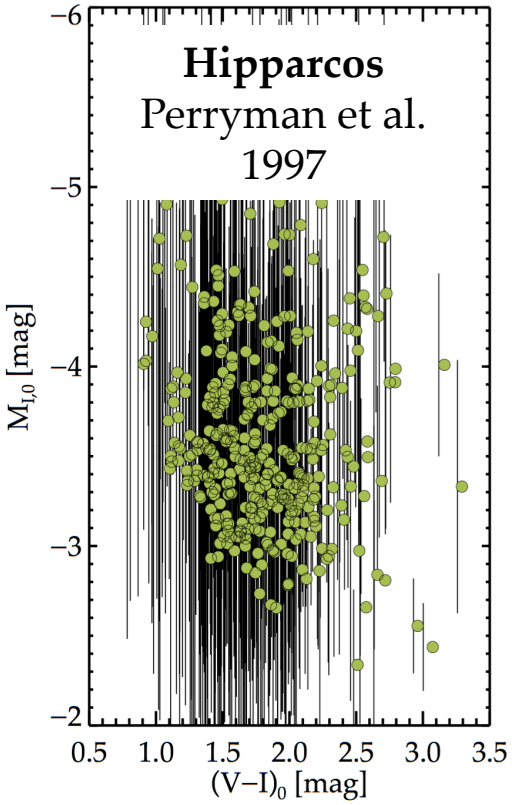
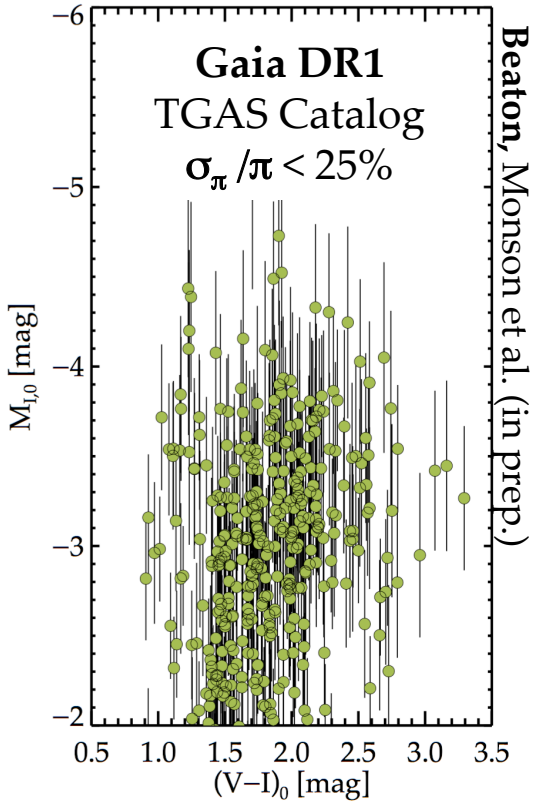
3. Direct Calibration

Optical photometry from TMMT @ LCO

Instrument + RR Lyrae Campaign in: Monson, **Beaton** et al. 2017





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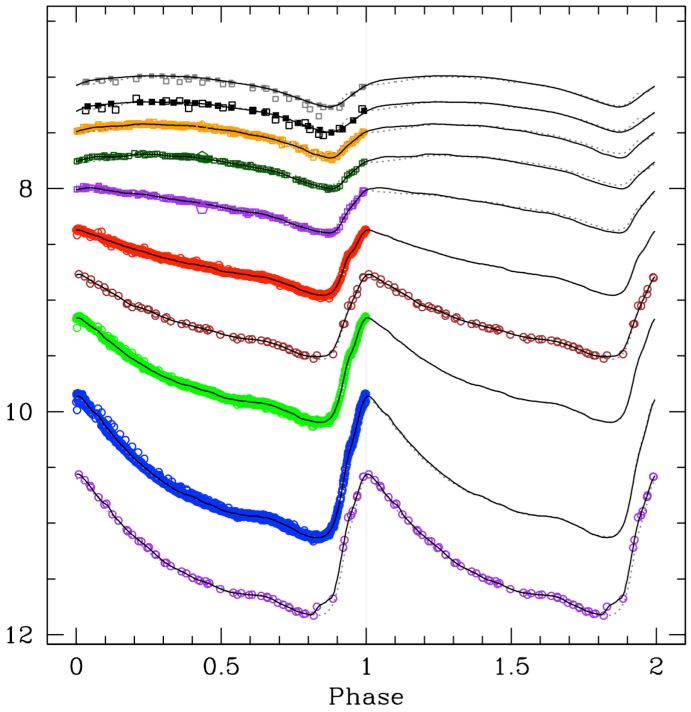
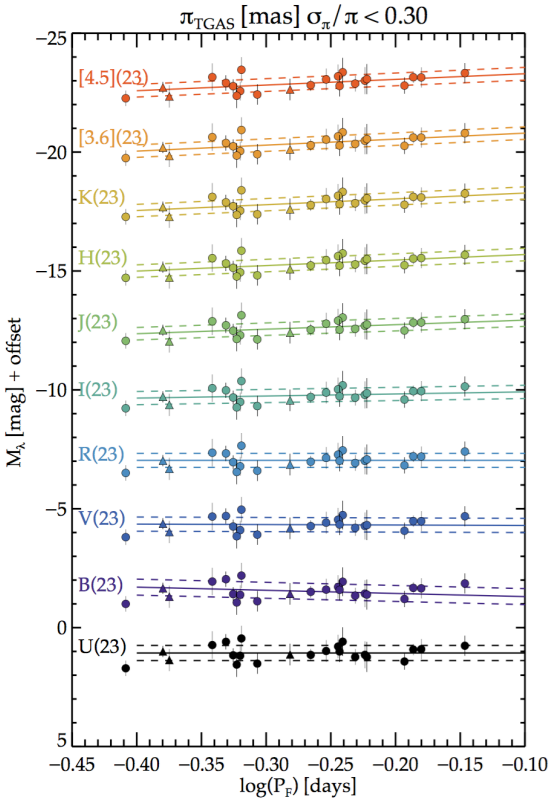
3. Direct Calibration

55 RRL with 10-band Data

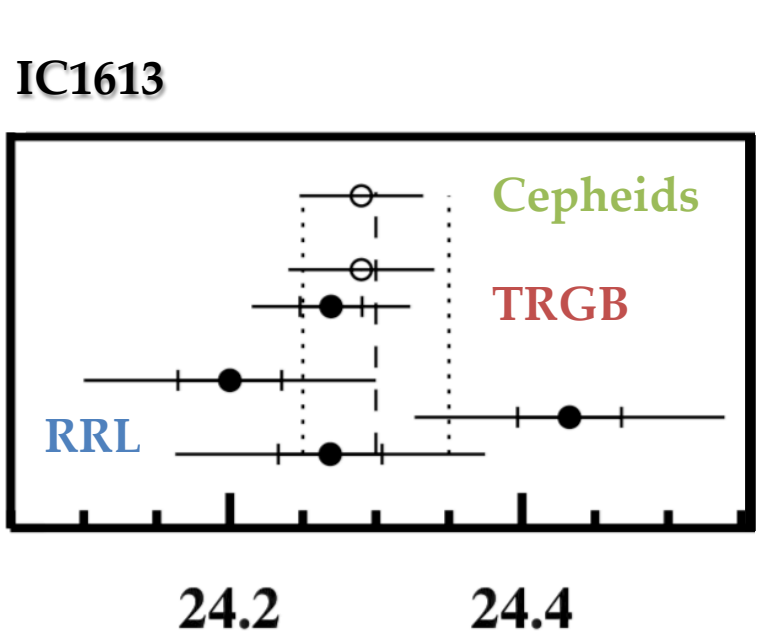


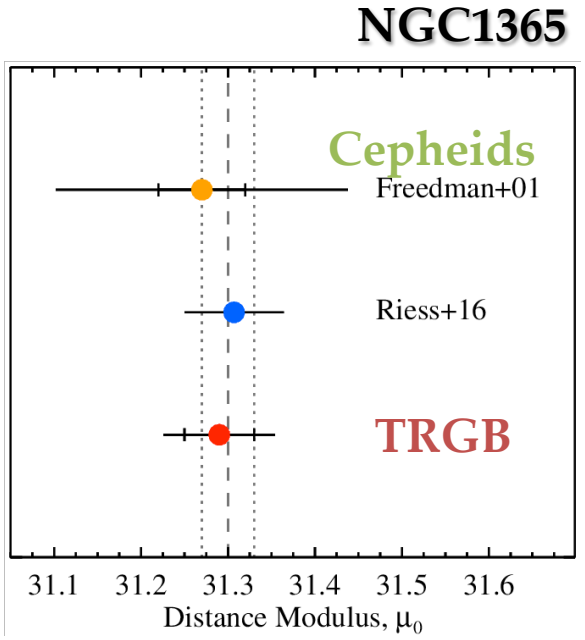
Monson, **Beaton** et al. 2017



10 band PL Relations with TGAS

Pop I & II: Consistency

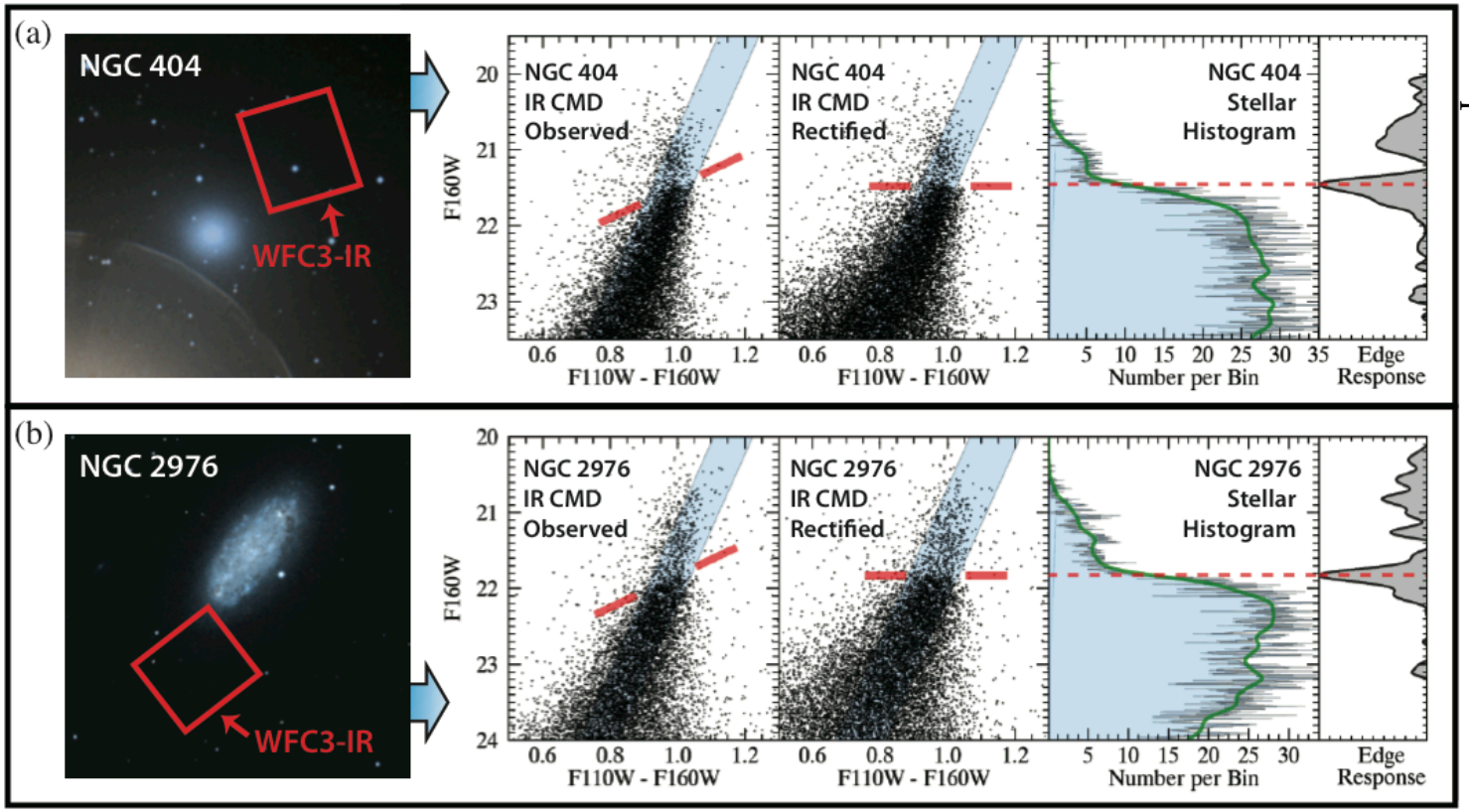




Hatt, **Beaton** et al. (submitted) ArXiv:1703.06468

Jang, Hatt, **Beaton** et al. (submitted) ArXiv:1703.10616

NIR: *JWST* & *WFIRST*



Adapted from Dalcanton et al. 2011

Conclusions

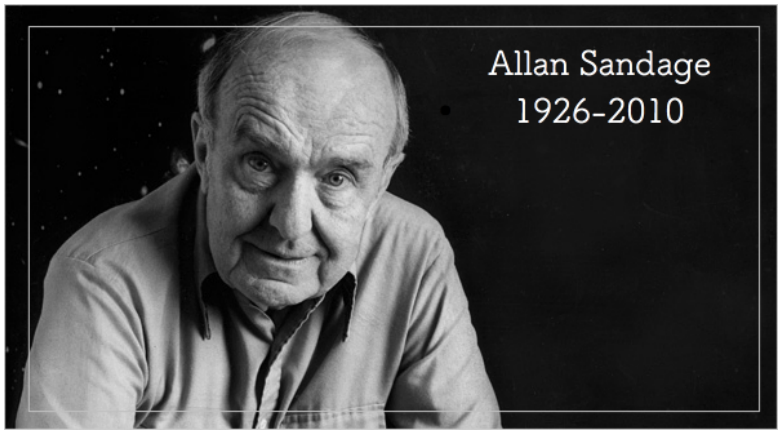
- Path to 1% H_0 requires standard candles that provide access to high no. of SNe Ia.
  - TRGB has numerous advantages toward this goal.
- Scale and volume probed by *Gaia* makes secondary distance indicators primary distance indicators.
- So far, Cepheid, RR Lyrae, and TRGB distances are remarkably consistent.
  - More tests on-going in 6 Local Group galaxies and 9 SNe Ia hosts.
- TRGB in NIR could permit every SNe Ia within 40 Mpc to have a < 5% distance.

To Close:

It's got to be fun, I don't think anybody should tell you that he's slogged his way through 25 years on a problem and there's only one reward at the end, and that's the value of the Hubble constant.

That's a bunch of hooey.

The reward is learning all the wonderful properties of the things that don't work.



From Obituary in NYTimes by D. Overbye

Sandage, **Beaton** & Majewski 2016