Engineering Measurement of the *Hubble Constant*

aka Distances to ALL the Galaxies

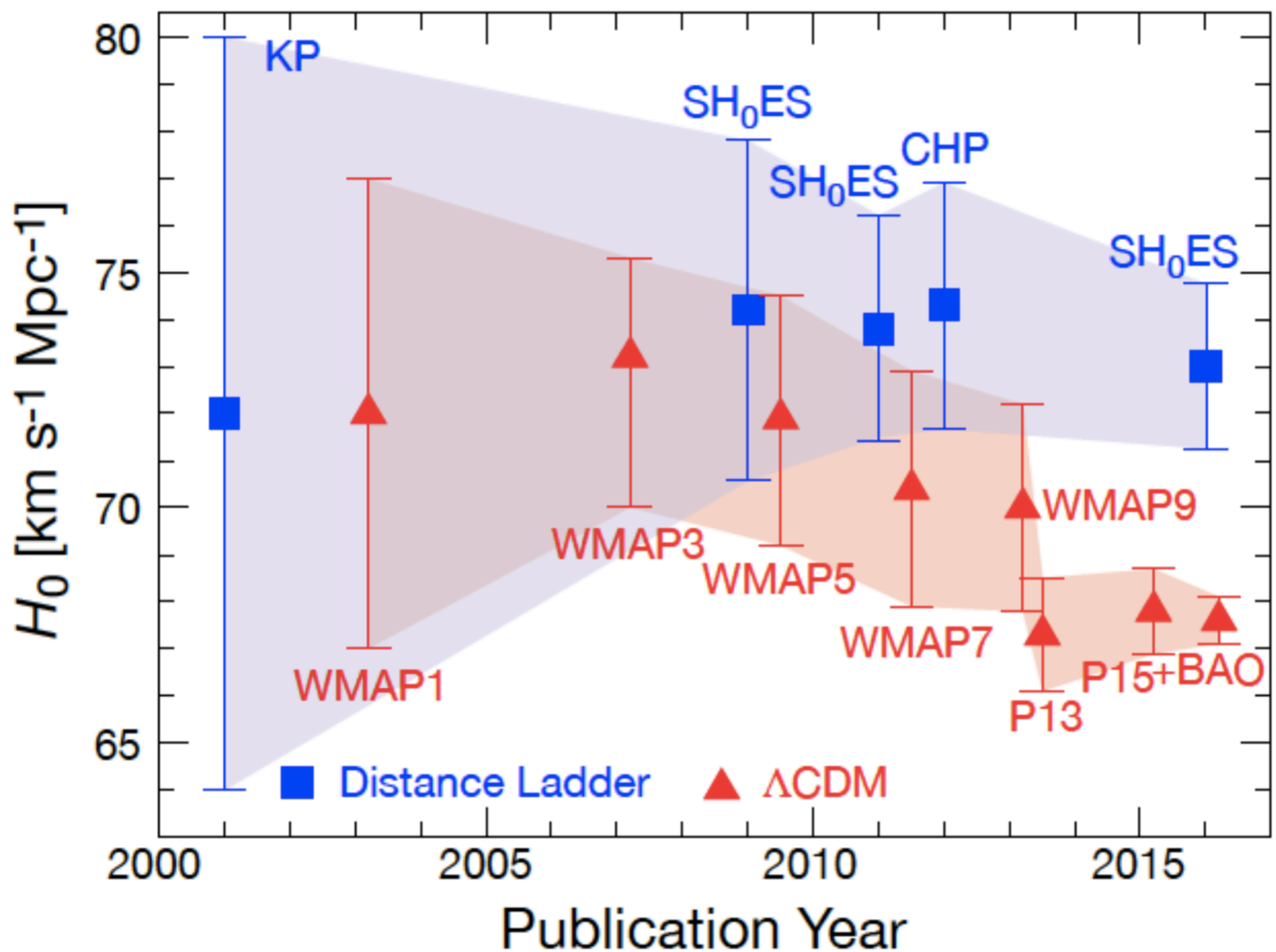
Rachael L. Beaton

NOW: Carnegie Observatories (Pasadena)

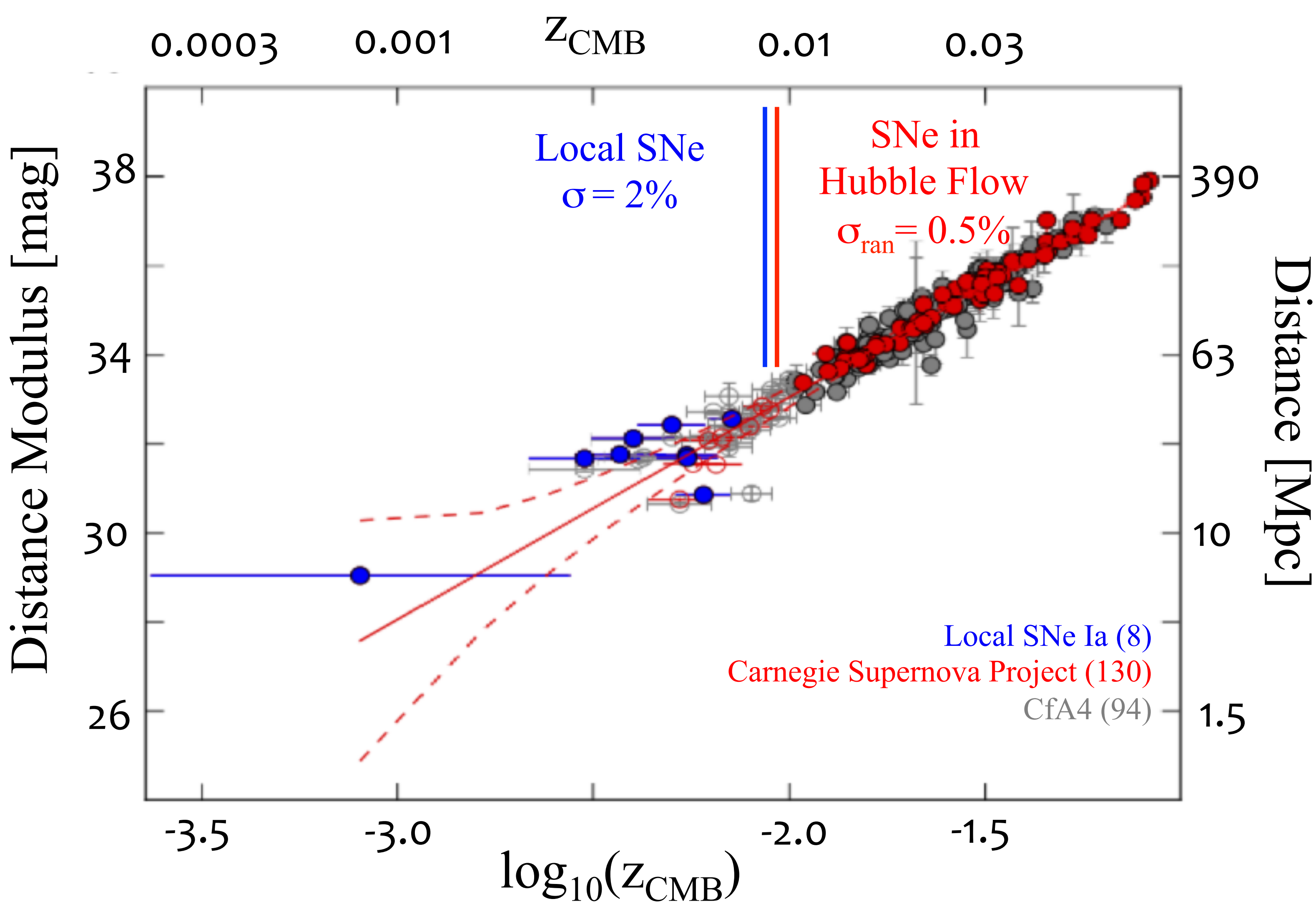
Soon: Hubble Fellow, Carnegie-Princeton Fellow
Princeton University

NORDITA July 27, 2017

The Hubble Constant



Freedman 2017
Beaton et al. 2016



Beaton et al. 2016

Why so few SNe Ia Calibrators?

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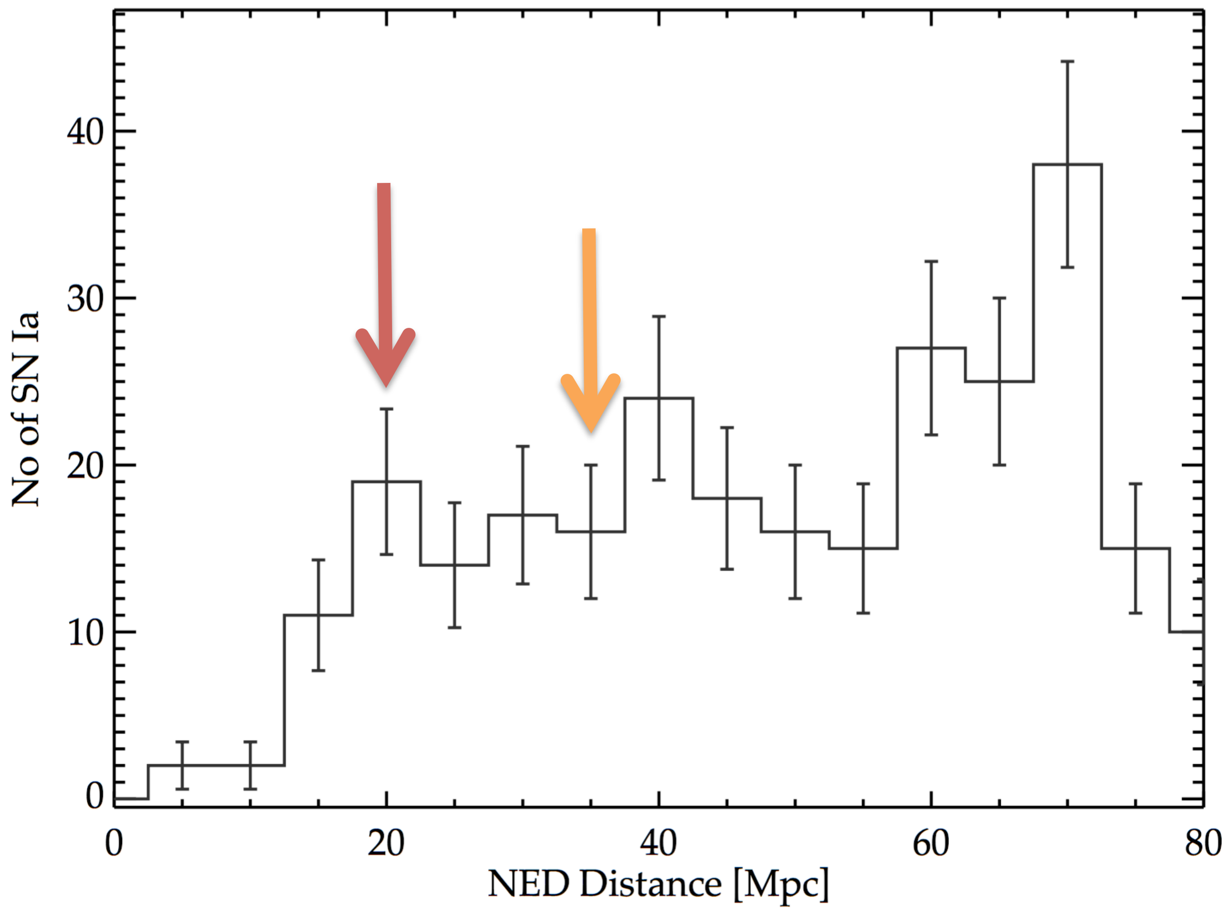
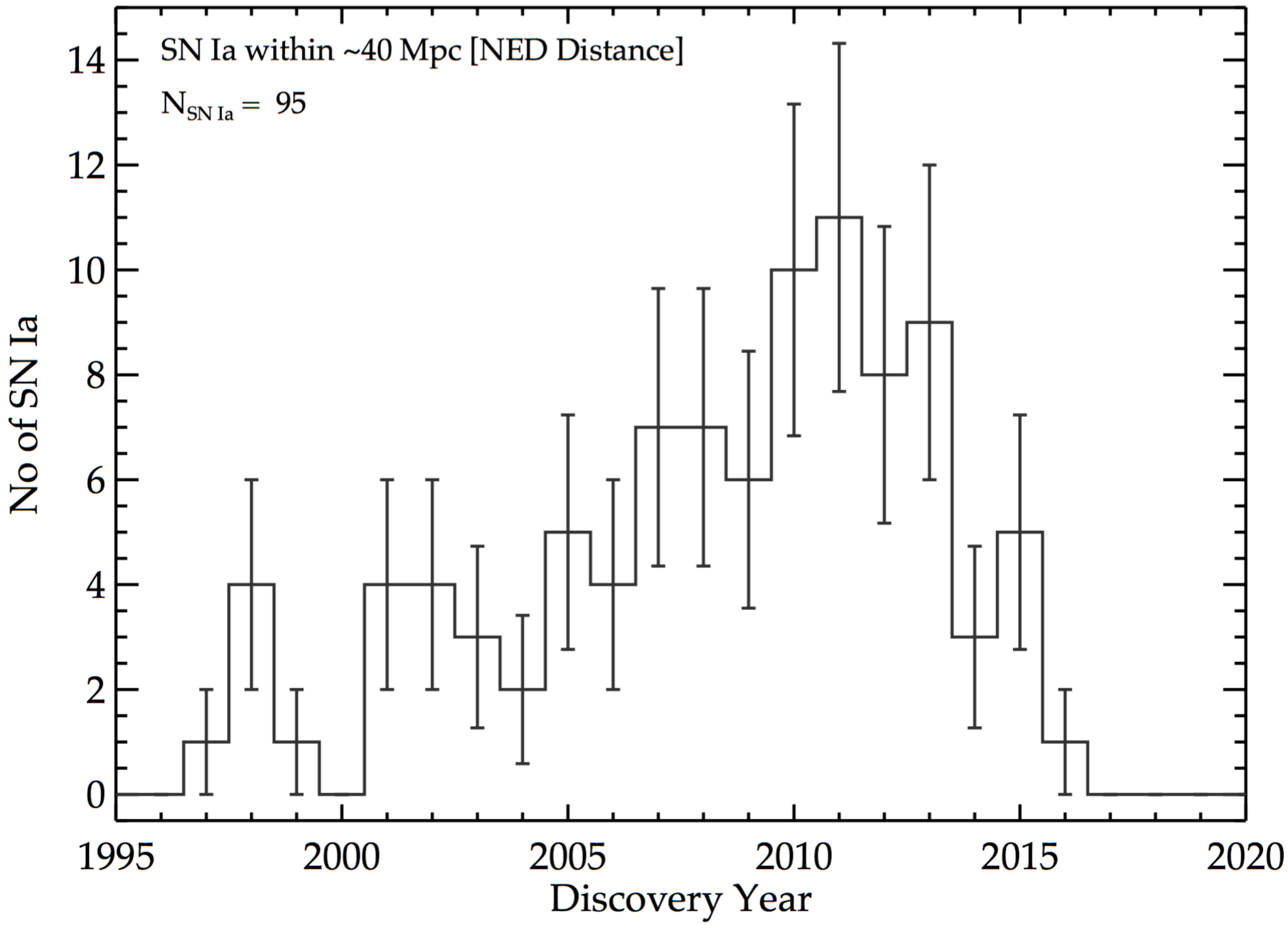


It is just not for a 'lack' of SNe Ia in the 'Local Volume'

**Stats as of March 2016

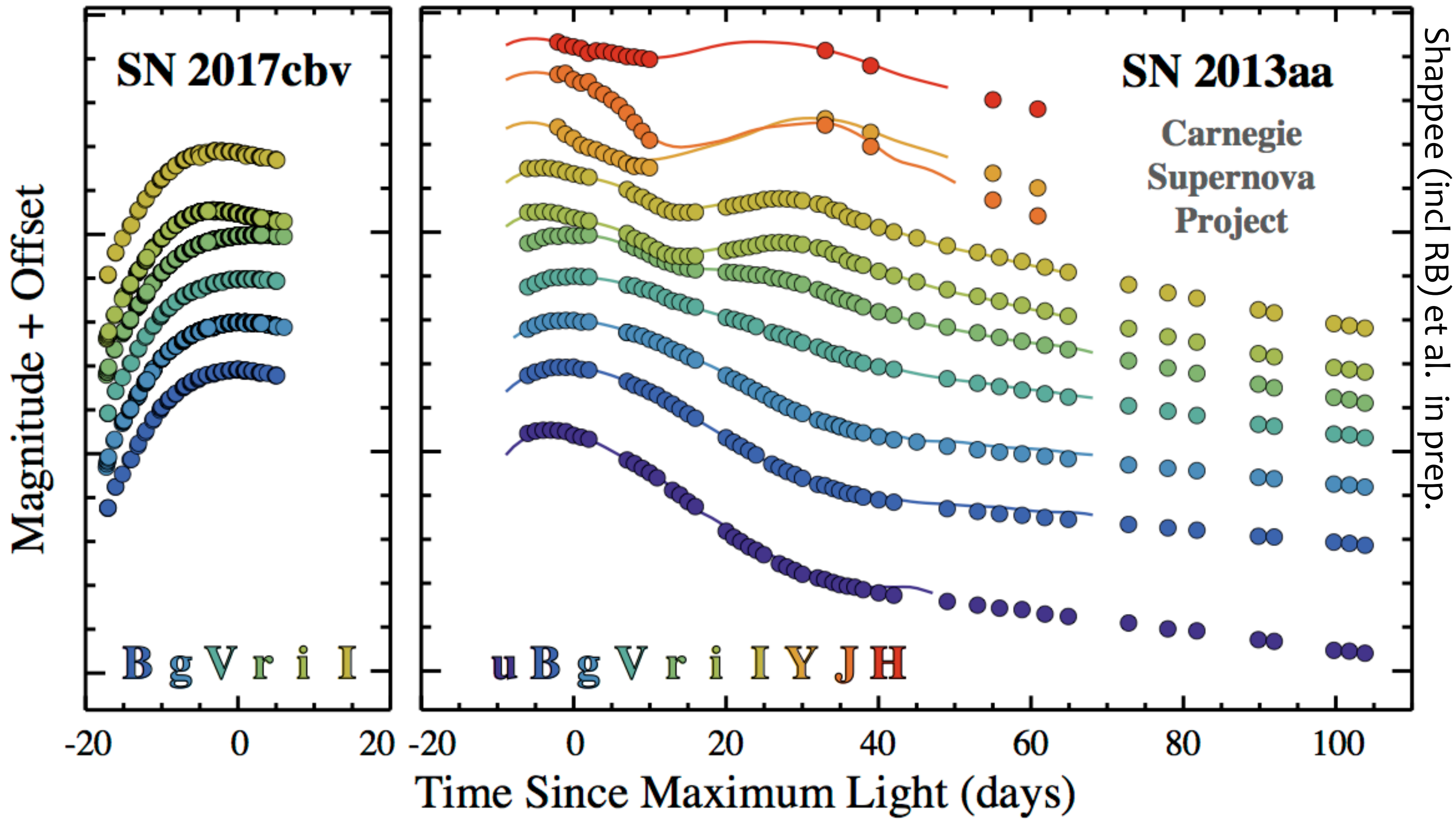
Why so few SNe Ia Calibrators?



or that they have only been discovered recently.

**Stats as of March 2016

SNe Ia Are Now Found Earlier



1. March 10, 2017: Transient Detected in NGC5643
2. March 11, 2017: Typed as very young SN Ia
3. March 11, 2017: Start building light curves

Earlier means more insight into SNe Ia physics.

SNe Ia Suitability

(1) Can I characterize the SN?	(2) Can I measure its distance?

SNe Ia Suitability

(1) Can I characterize the SN?

YES! *(most of the time)*

- 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.

(2) Can I measure its distance?

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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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With Cepheids?

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With Cepheids?

- **Is the Host Galaxy:**
  - Star forming?
  - Luminous?
  - Approx. Face on?
- **If YES to all of the above, do I have:**
  - 10-20 epochs of optical imaging to find the Cepheids and determine periods?
  - Do my Cepheids span a range of log(P)?
  - Is there spatially resolved metallicity information?
  - Can I measure local extinction?
  - Crowding?
  - … and related issues.

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***With Cepheids?* MAYBE?**

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ity

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.

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes.

Marcel Proust

The Foundation: *Gaia*

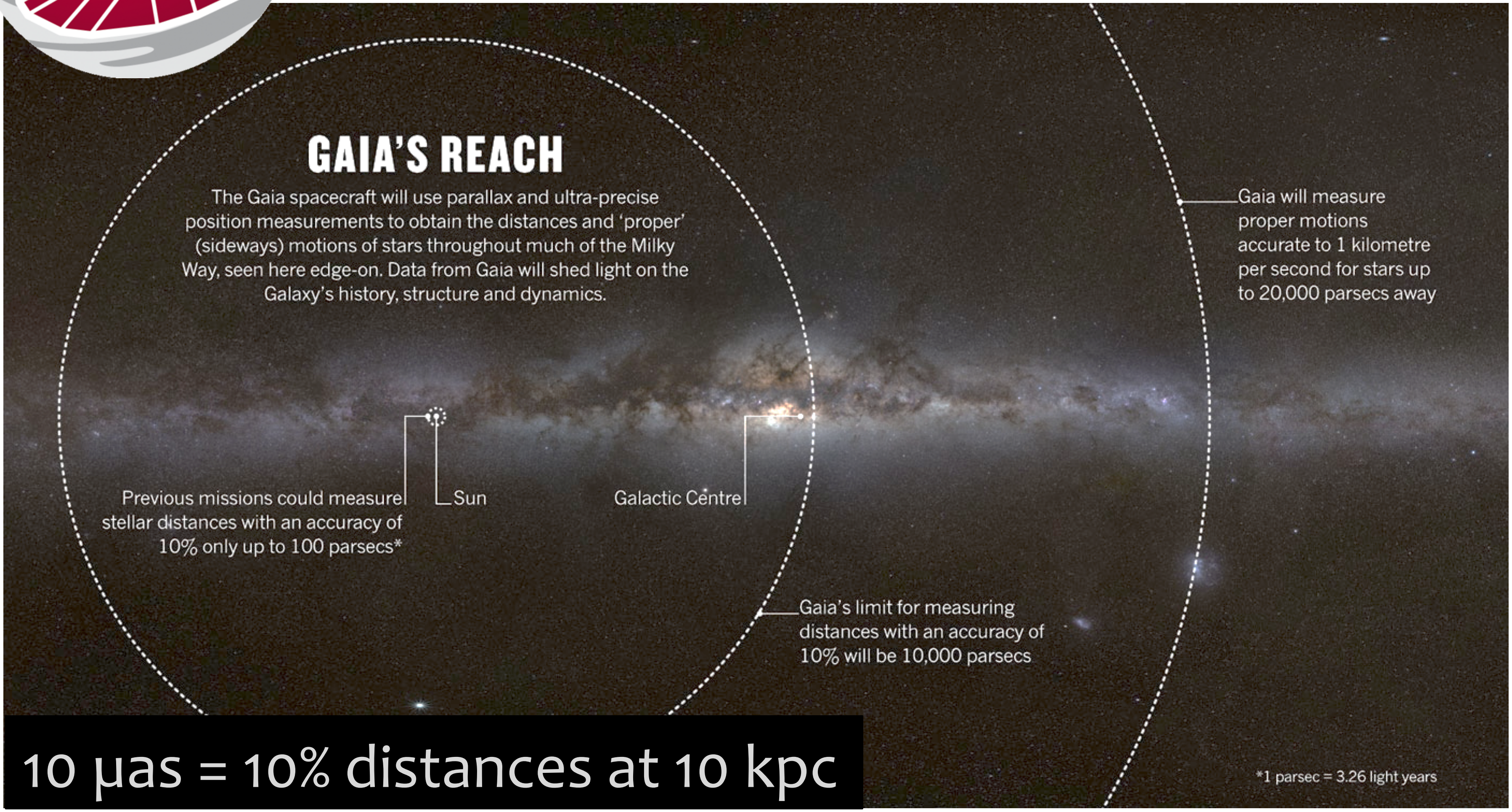


Image: *Gaia* Press Releases

Gaia gives us access to the whole HR-Diagram

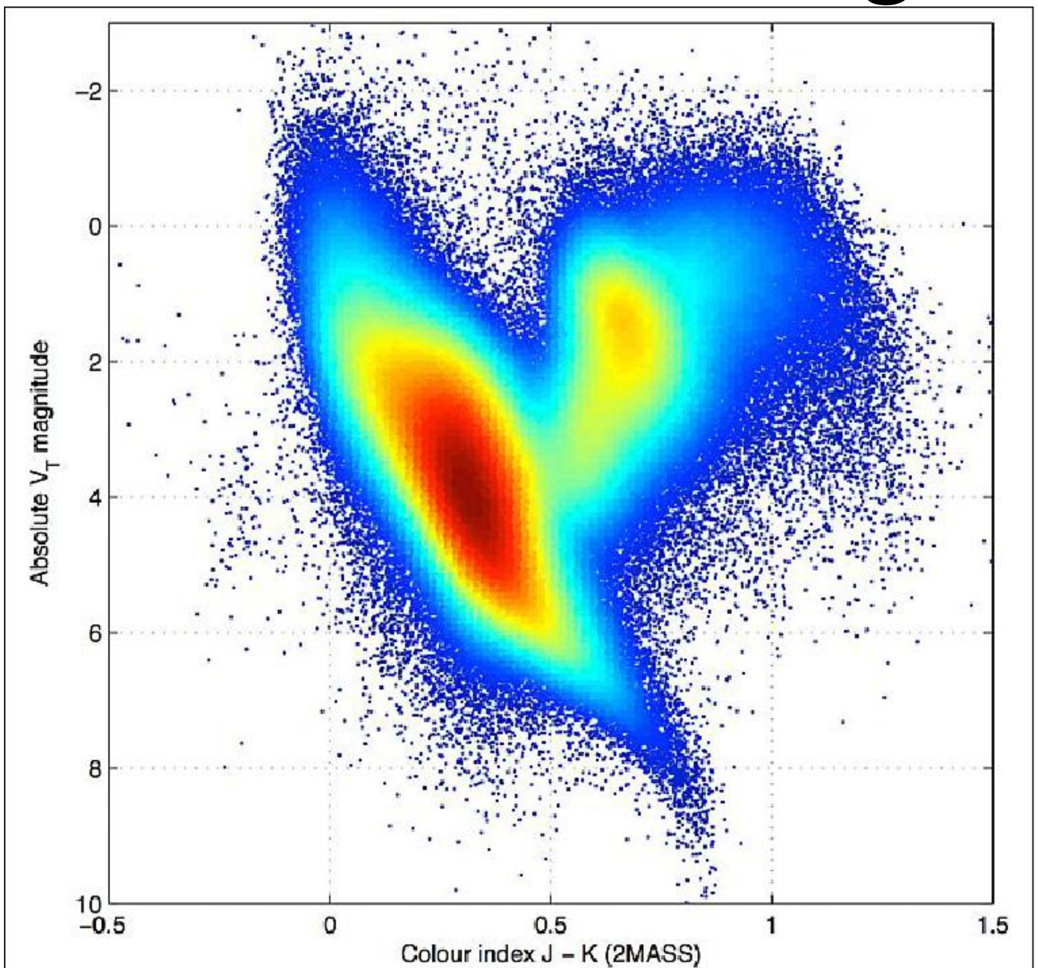


Image: *Gaia* Press Releases

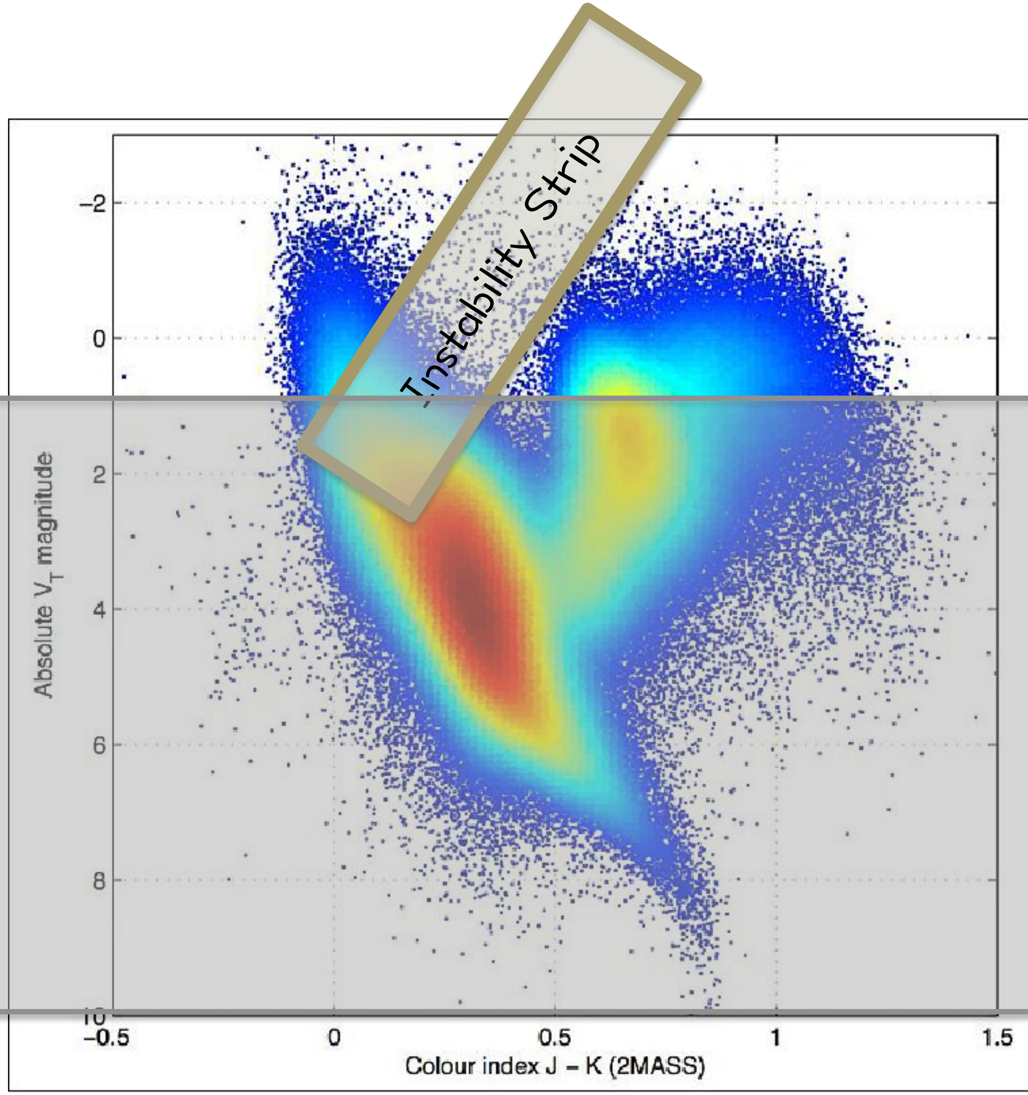
Luminosity

Temperature

Miras
100 dy < P < 600 dy
1 Gyr < Age < few Gyr

Cepheids
3dy < P < 150 dy
Age < 500 Myr

Tip of the Red Giant Branch
All metallicities
~1 Gyr < Age < ??



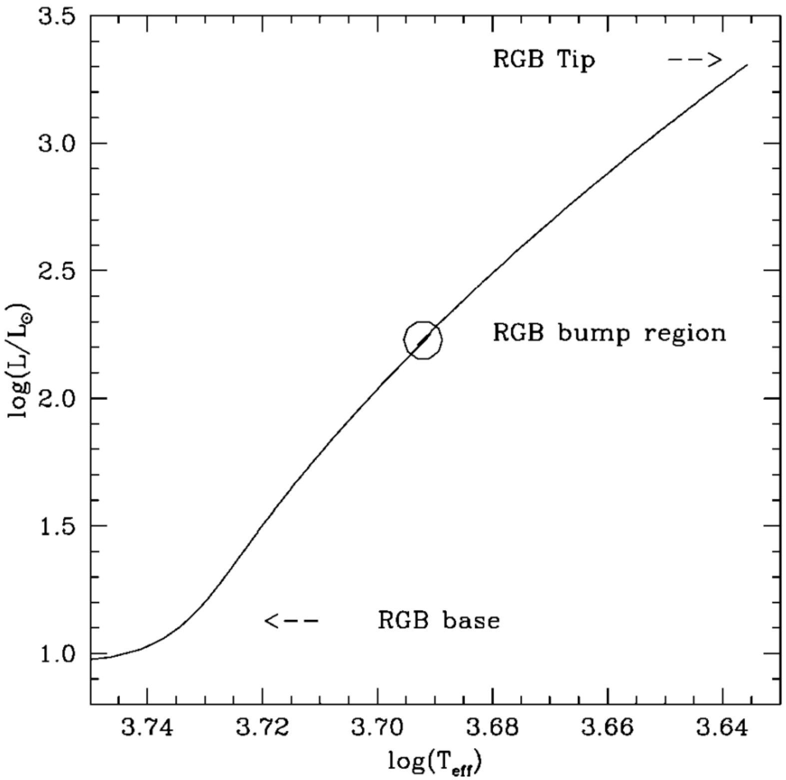
RR Lyrae
0.25 dy< P < 1 dy
~1 Gyr < Age < ??

Metal rich HB stars
~1 Gyr < Age < ??

Too faint for SNe Ia hosts en masse

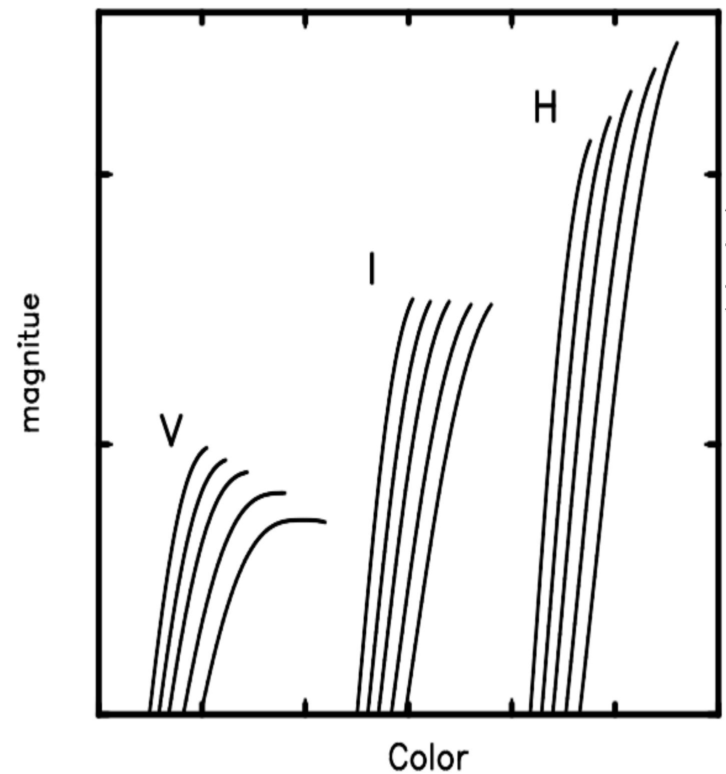
Tip of the Red Giant Branch

Theory: Lifting of core degeneracy => ignition of He shell => He-Flash



Salaris et al. 2002

Empirical: sharp terminus or edge to the RGB sequence



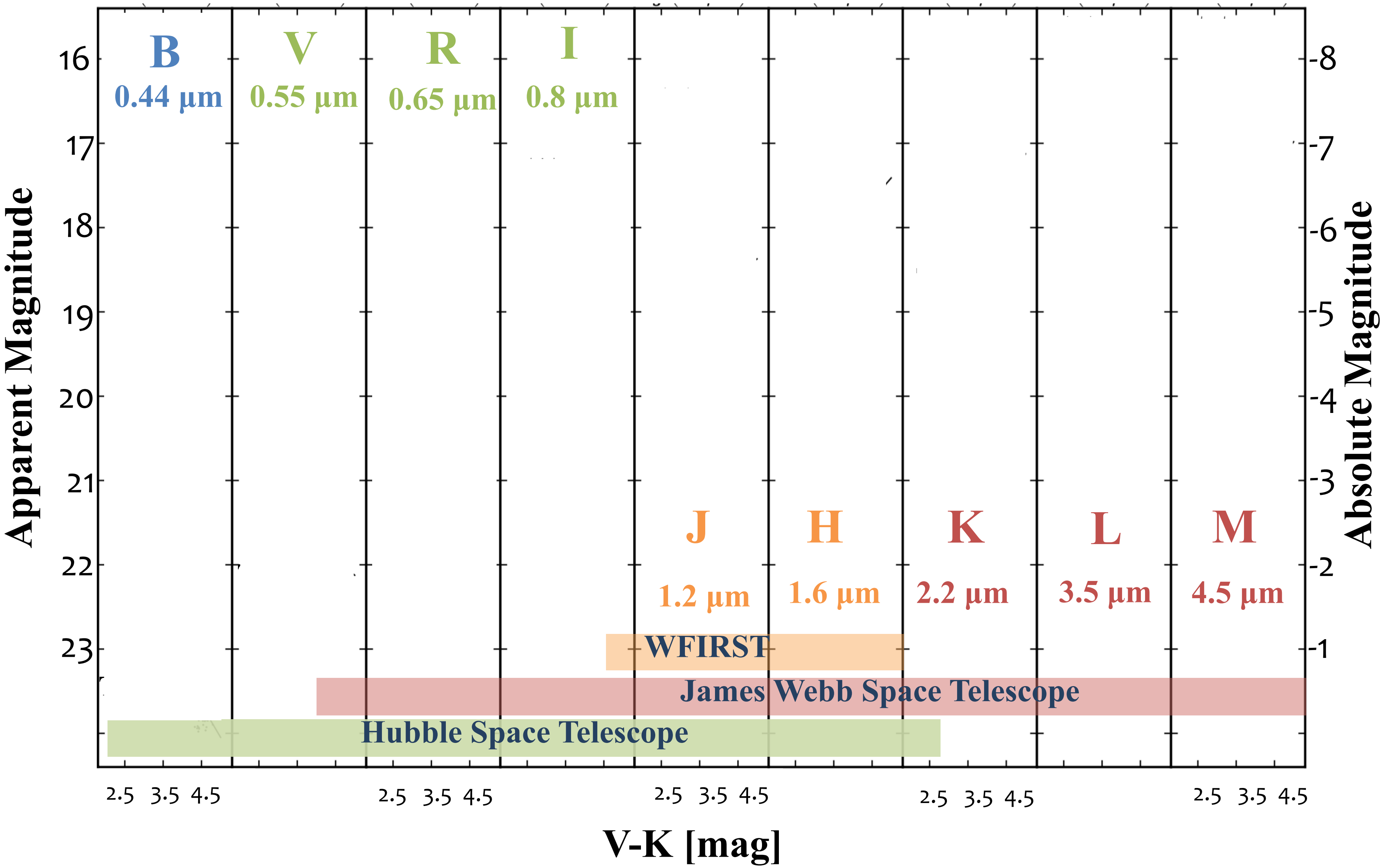
Madore et al. (in prep.)

Review: Salaris et al. 2002
Updates in: Serenelli et al. (1706.09910)

Lee, Madore, and Freedman 1993
Review: Beaton et al. 2016

In Practice:

Erica Carlson
OCIS Intern
Now
grad student
UW-Madison



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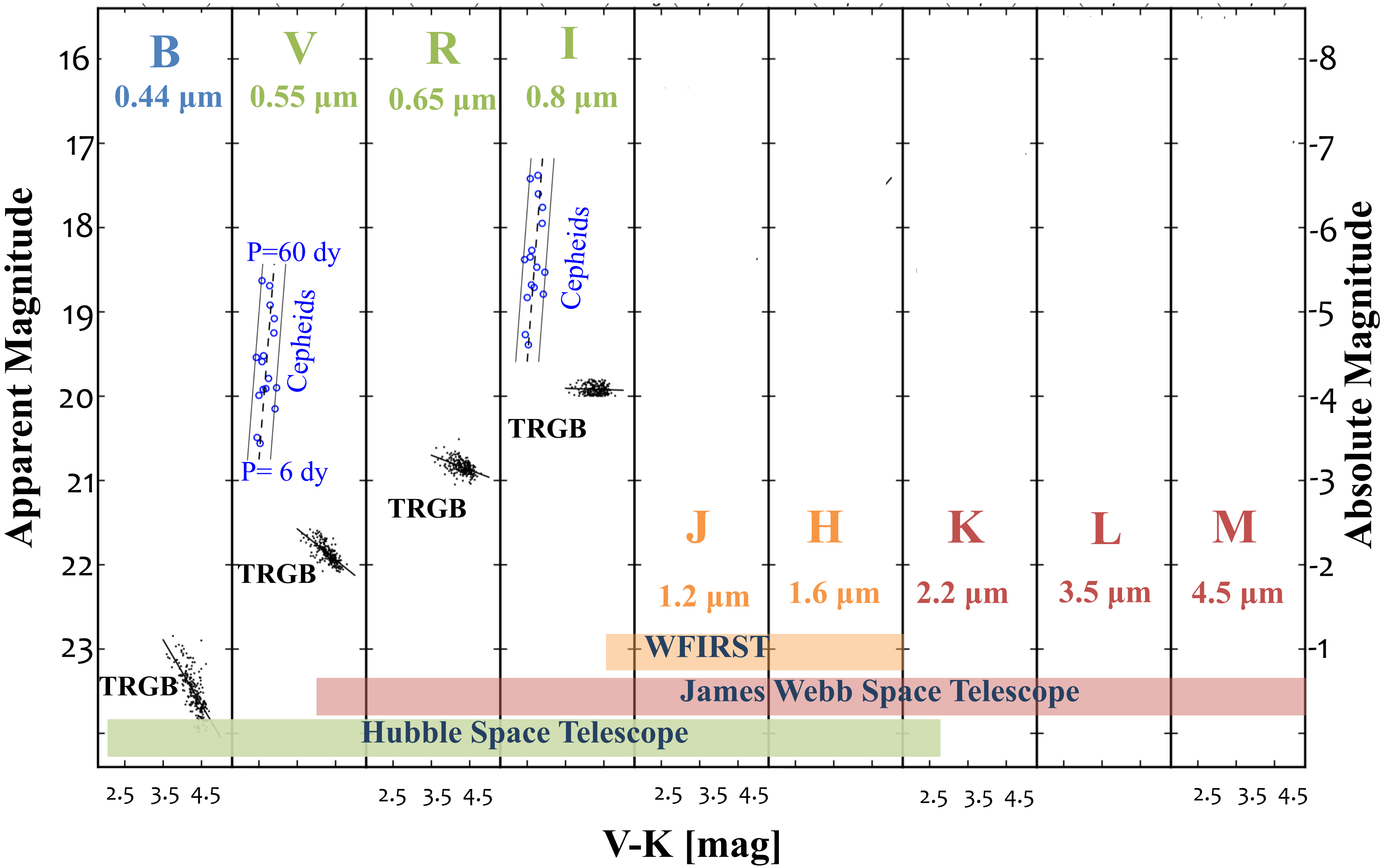

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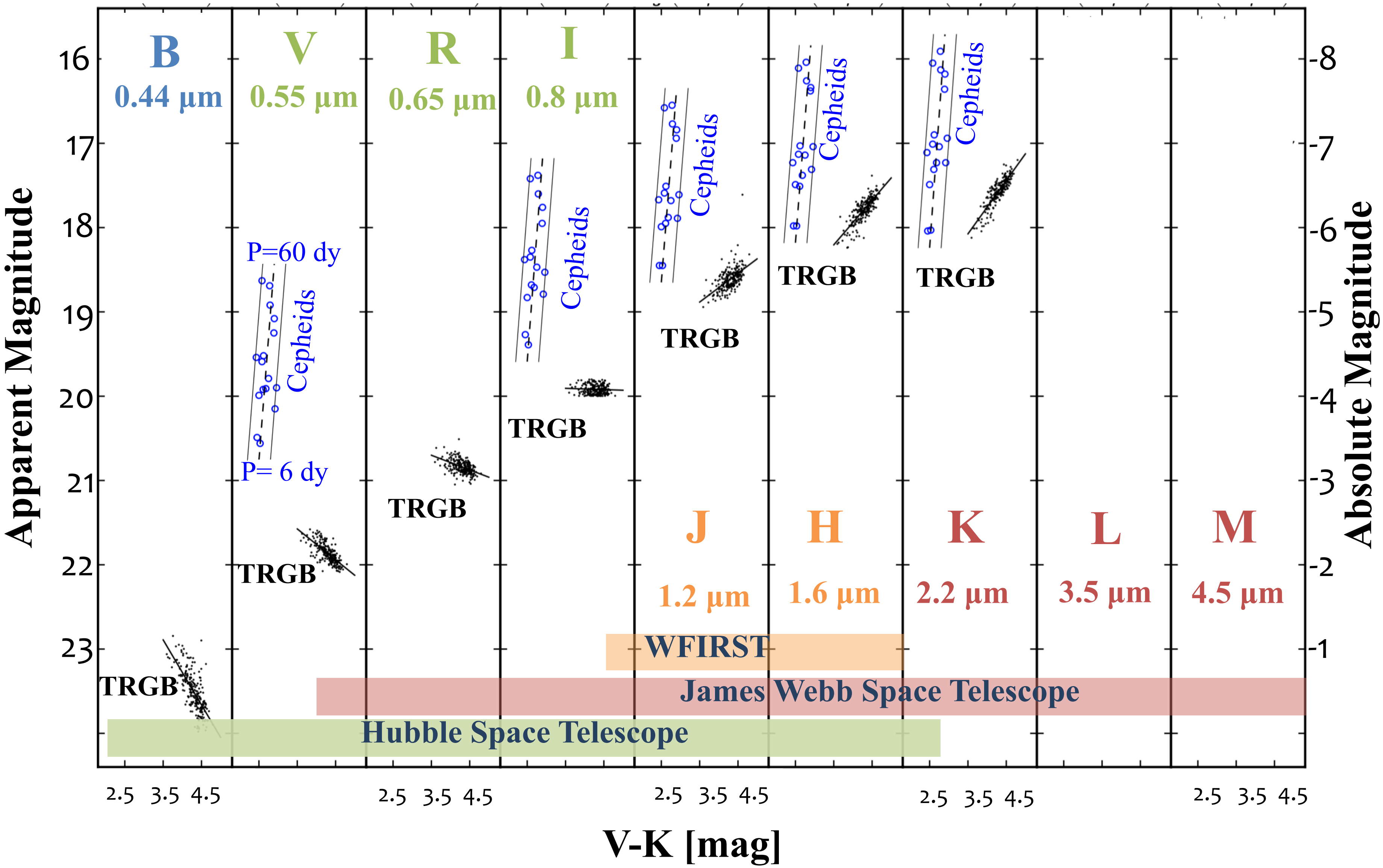

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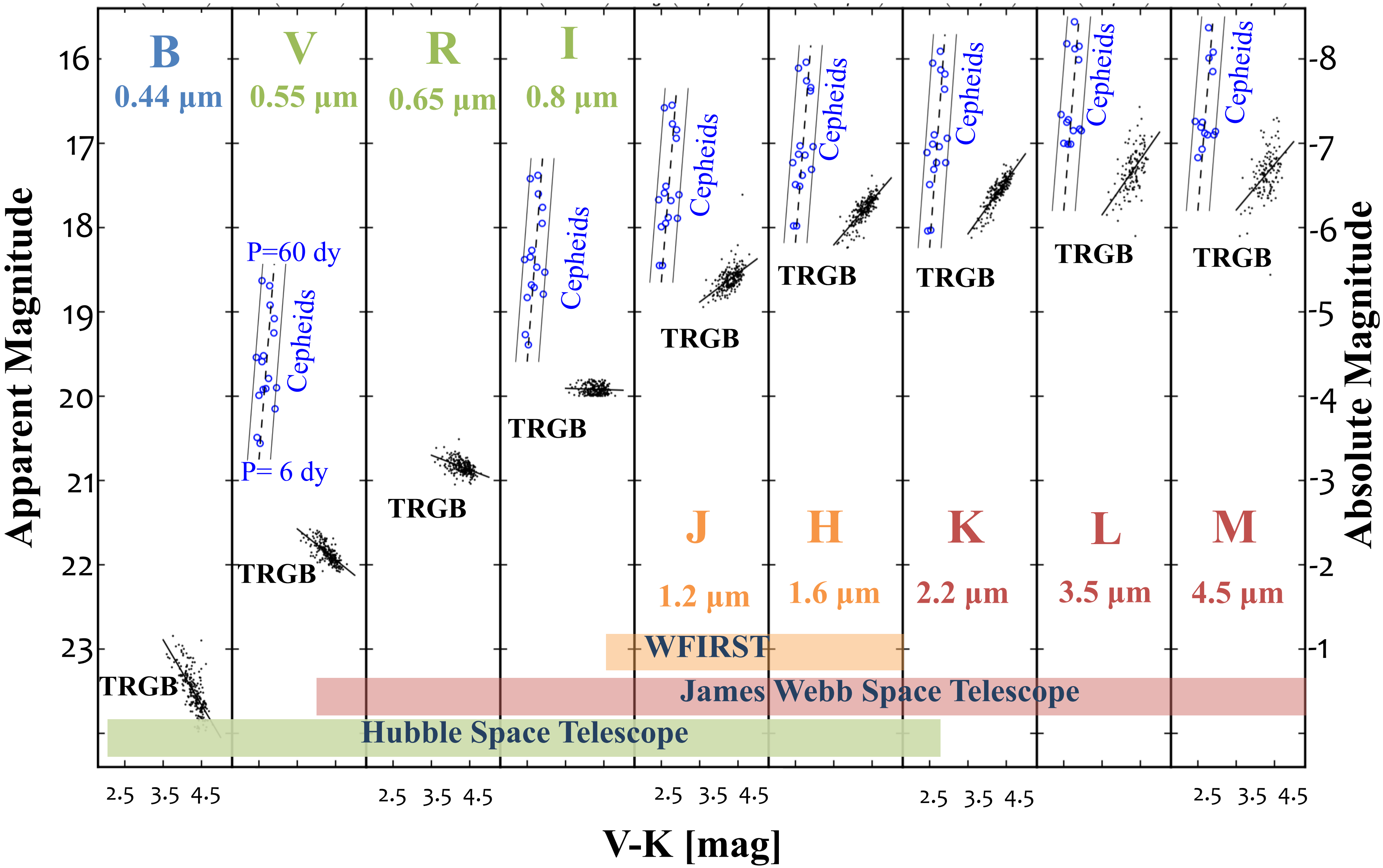
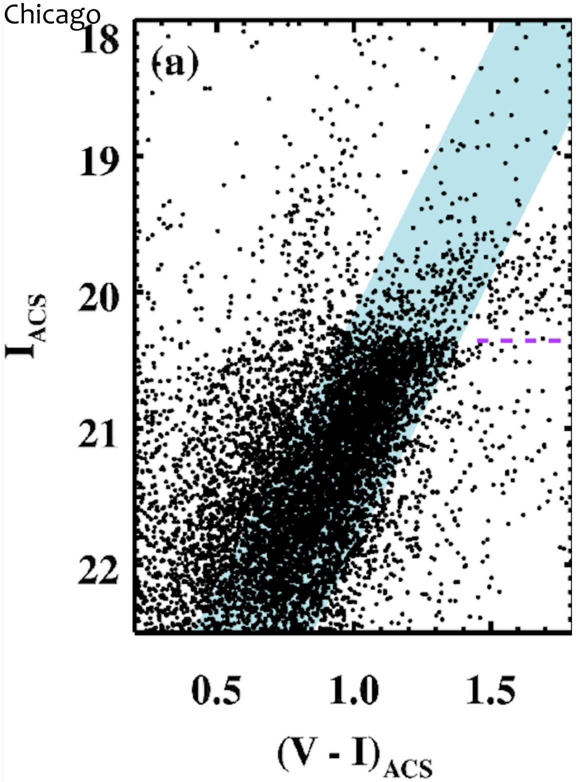


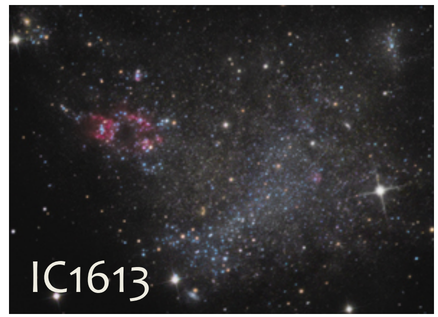

The Tip of the Red Giant Branch technique
can be applied to EVERY Galaxy (with differing error bars).

~Equal Precision Near & Far

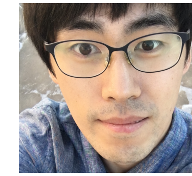
Dylan Hatt
Grad @ U Chicago

NEAR-FIELD

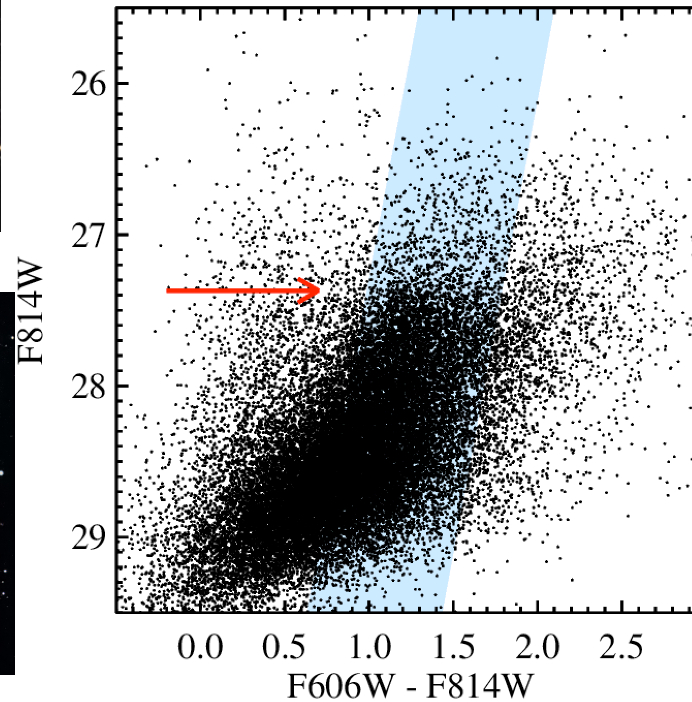




FAR-FIELD



In Sung Jang
PhD/Now Postdoc@AIP



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

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

~Equal Precision Near & Far

Dylan Hatt
Grad @ U Chicago

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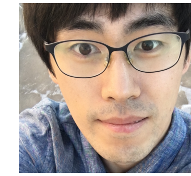
FAR-FIELD



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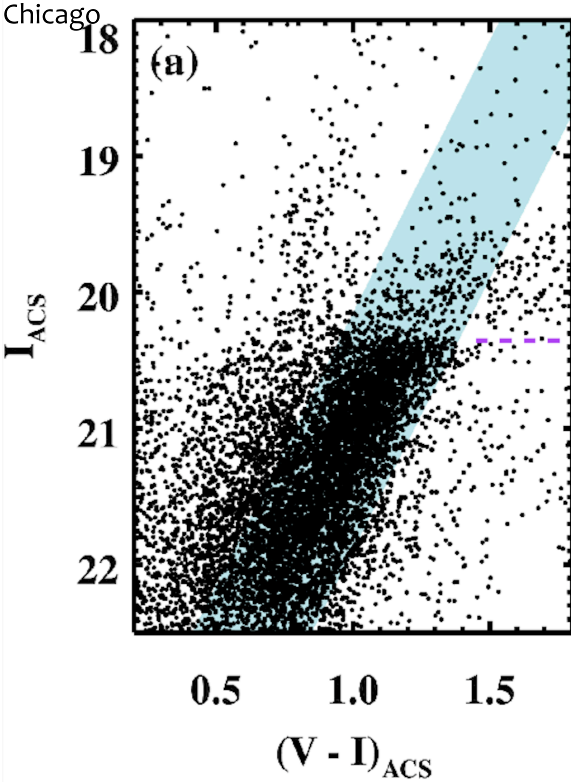

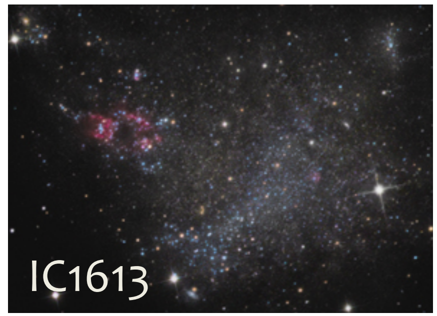

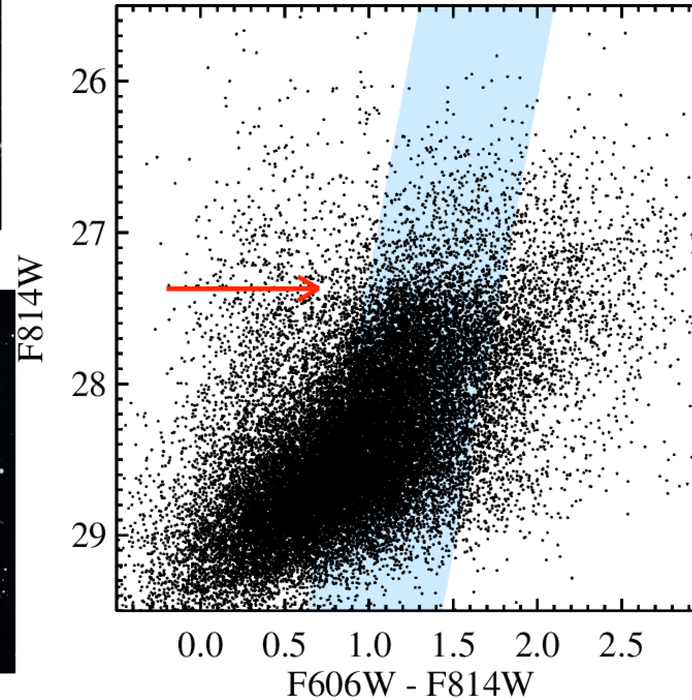

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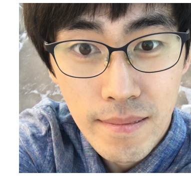
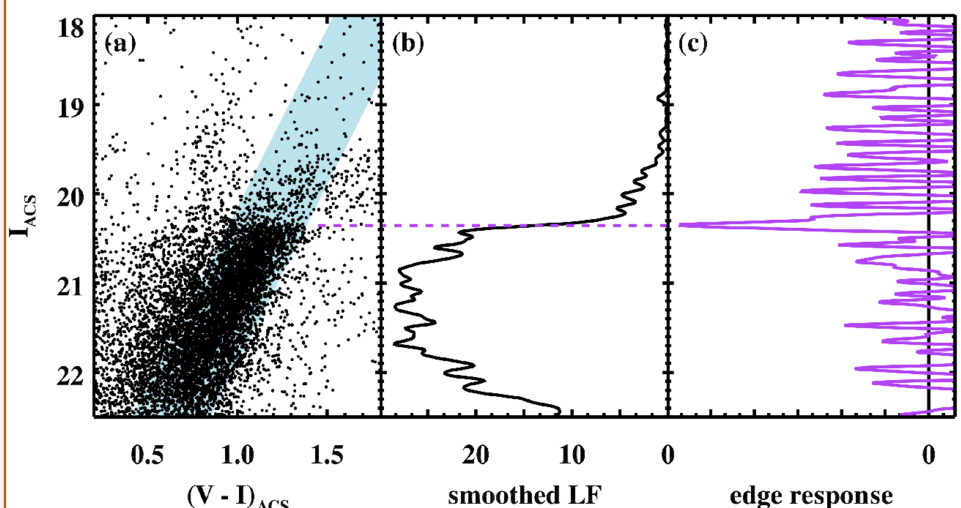


In Sung Jang
PhD/Now Postdoc@AIP

NEAR-FIELD
IC1613

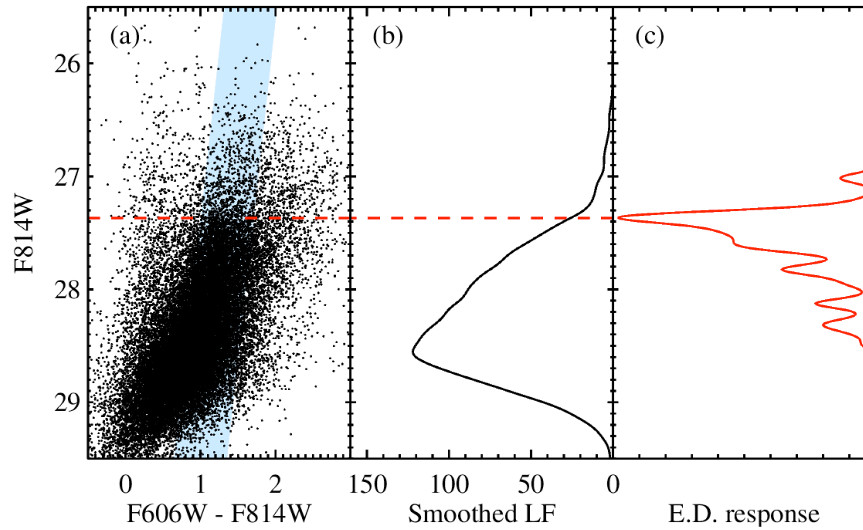


D = 784 ±17 (stat) ±40 (sys) kpc

μ_0 = 24.30 ±0.03 (stat) ±0.05 (sys) mag

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

FAR-FIELD
NGC1365



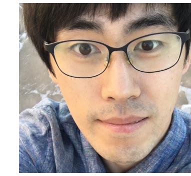
D = 18.1 ±0.3 (stat) ±0.4 (sys) Mpc

μ_0 = 31.29 ±0.04 (stat) ±0.05 (sys) mag

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

Derivation of Uncertainties

Dylan Hatt
Grad @ U Chicago



In Sung Jang
PhD/Now Postdoc@AIP

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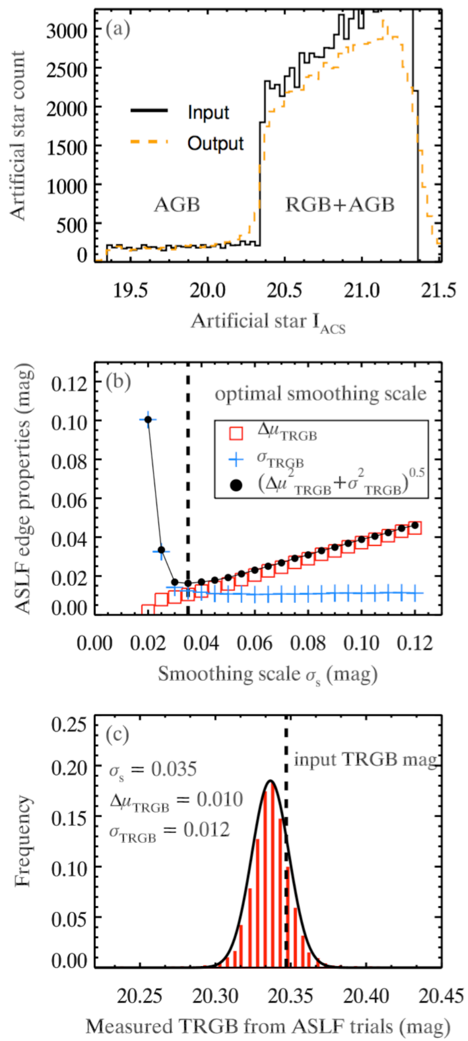
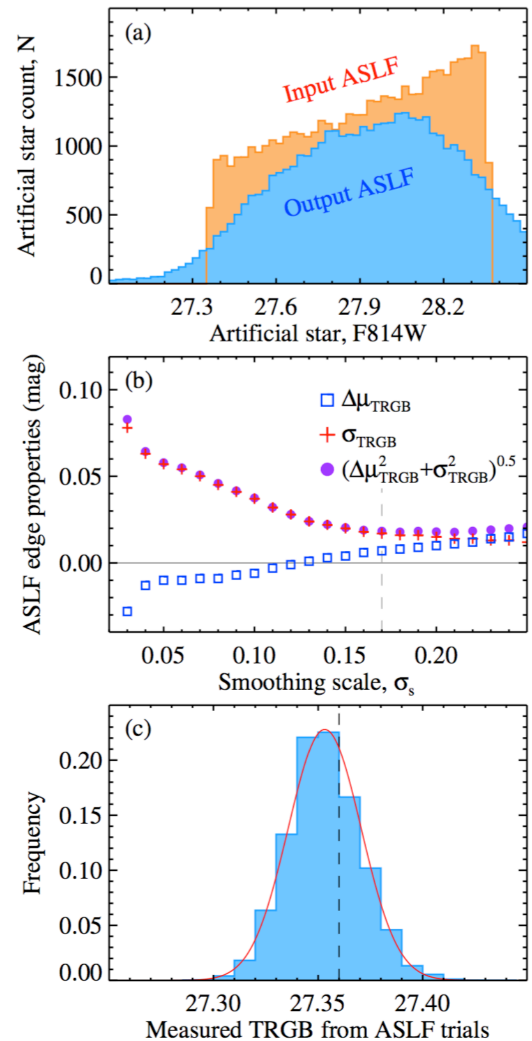


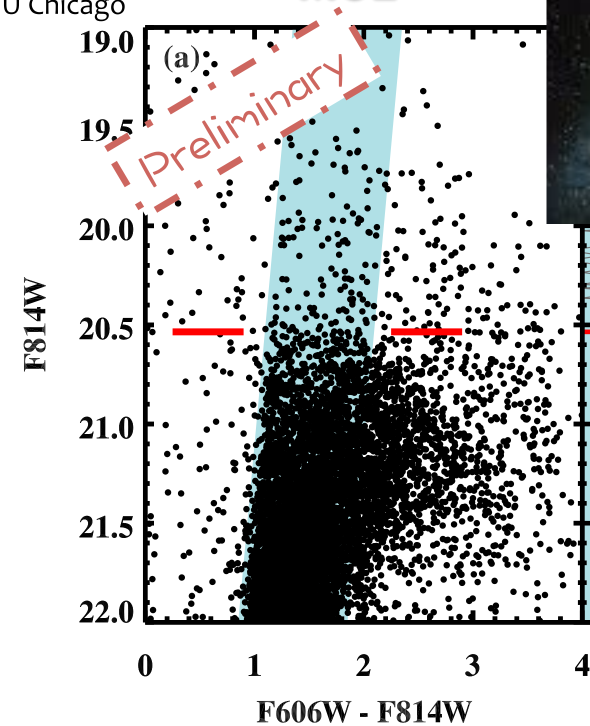
FAR-FIELD
NGC1365

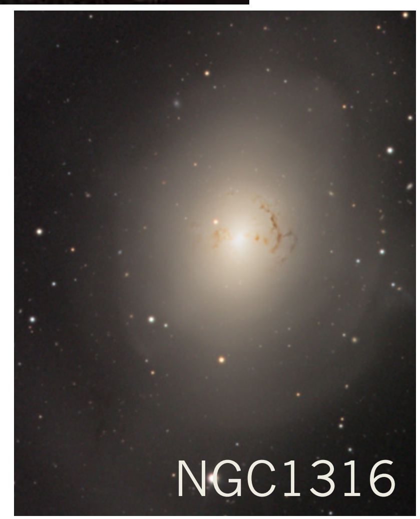


~Equal Precision Near & Far

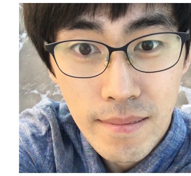
Dylan Hatt
Grad @ U Chicago

NEAR-FIELD
M31

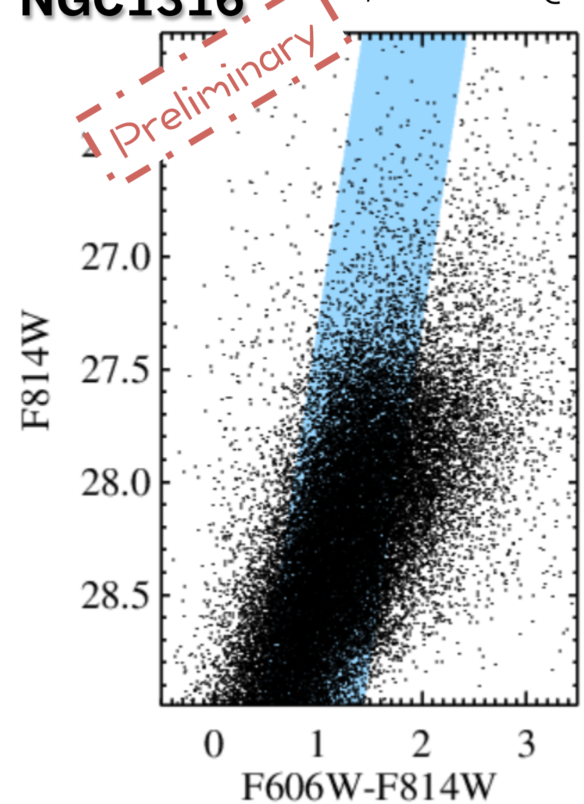




FAR-FIELD
NGC1316



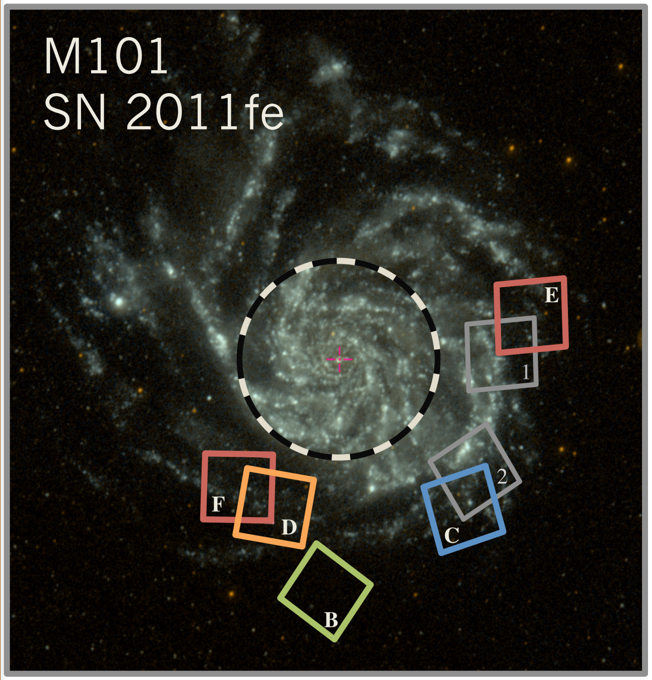
In Sung Jang
PhD/Now Postdoc@AIP



Hatt, **Beaton** et al. (in prep)

Jang, Hatt, **Beaton** et al. (in prep)

Not limited to One Sample



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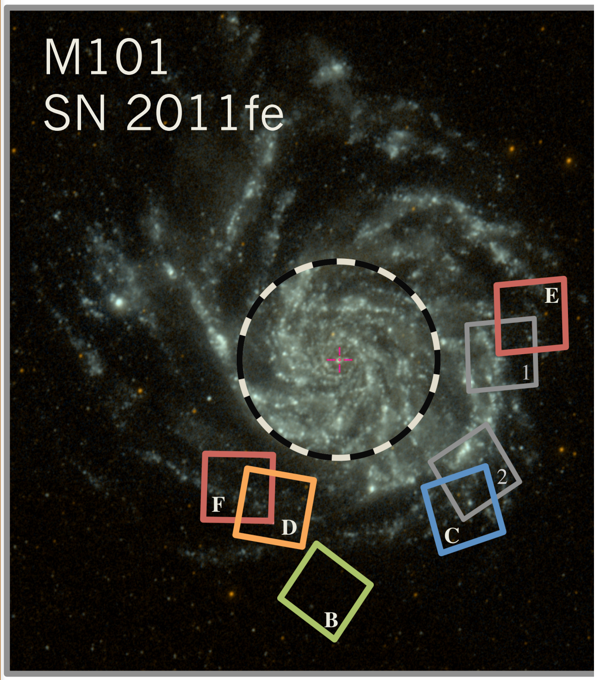

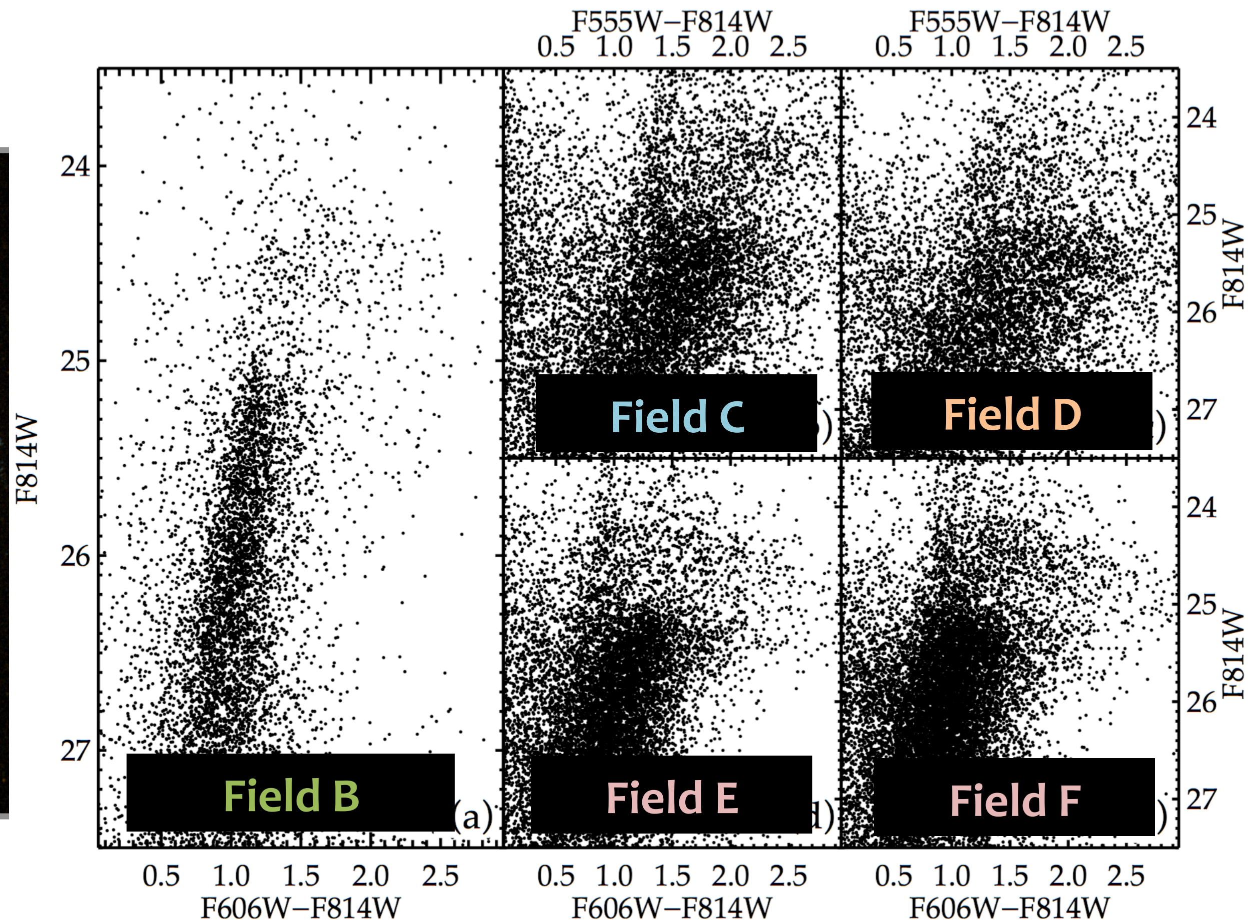

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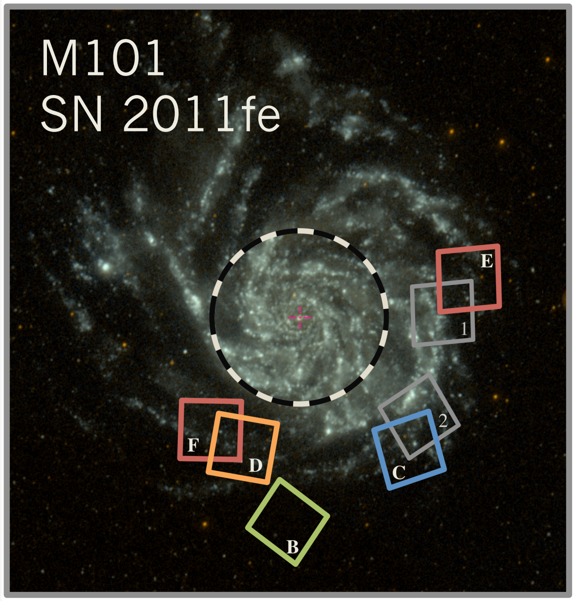
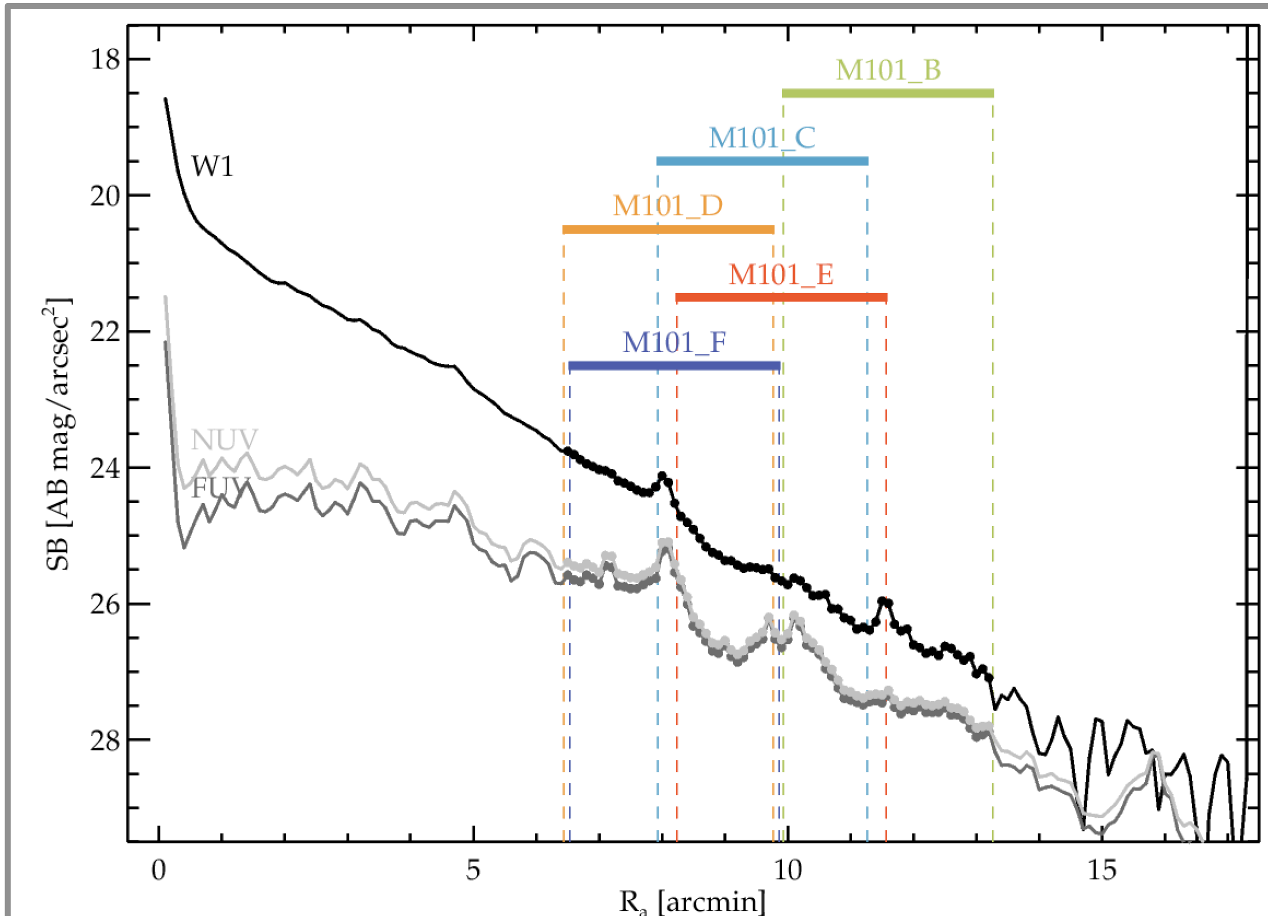


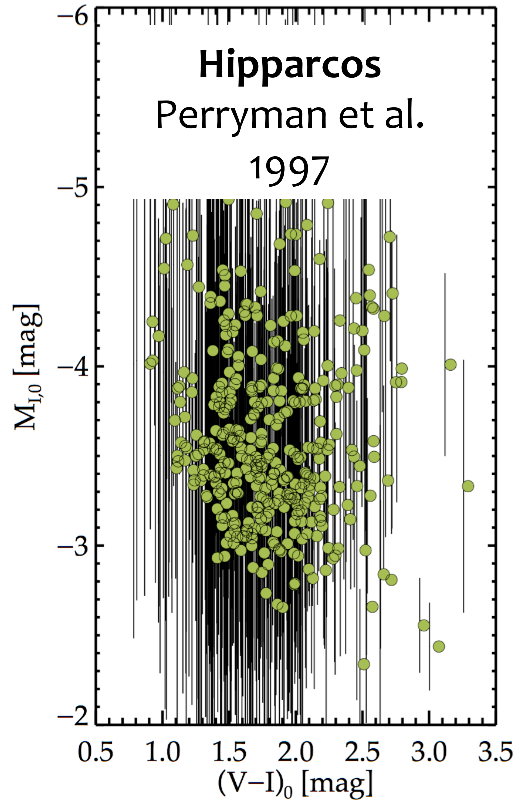


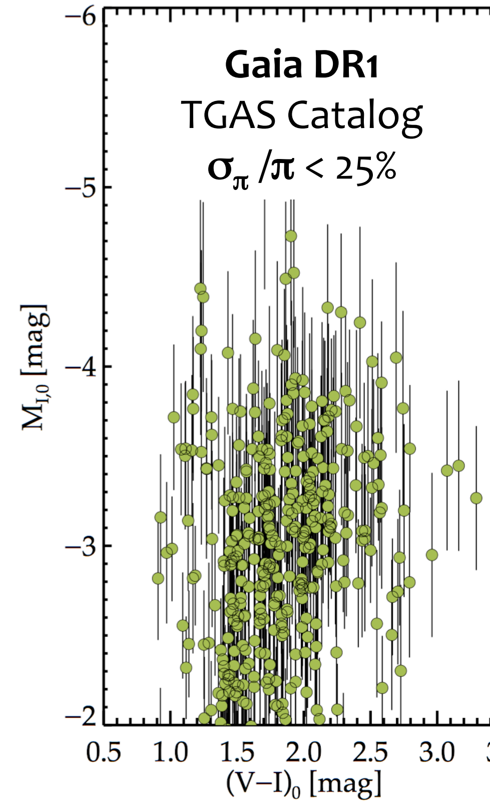
Beaton, Hatt et al. (in prep.)

Direct Calibration in *Gaia* DR2?

Optical photometry
from TMMT @ LCO

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





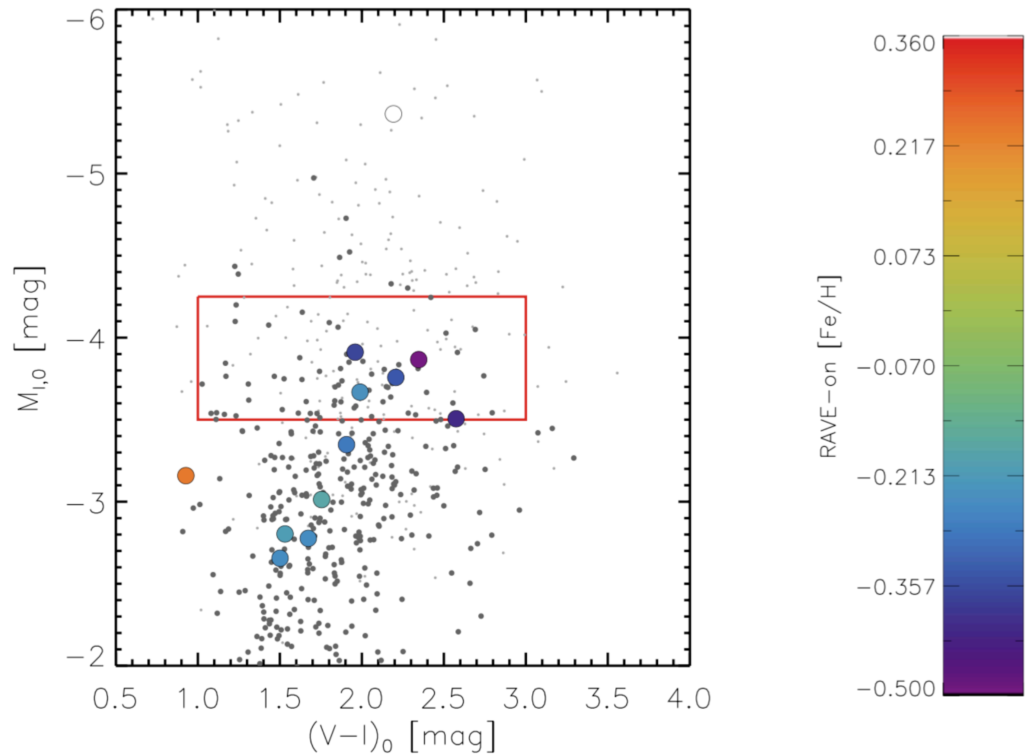
Beaton, Monson et al. (in prep.)

We need more than *Gaia*, we need good magnitudes, colors, etc.

Direct Calibration in *Gaia* DR2**?

Optical photometry
from TMMT @ LCO

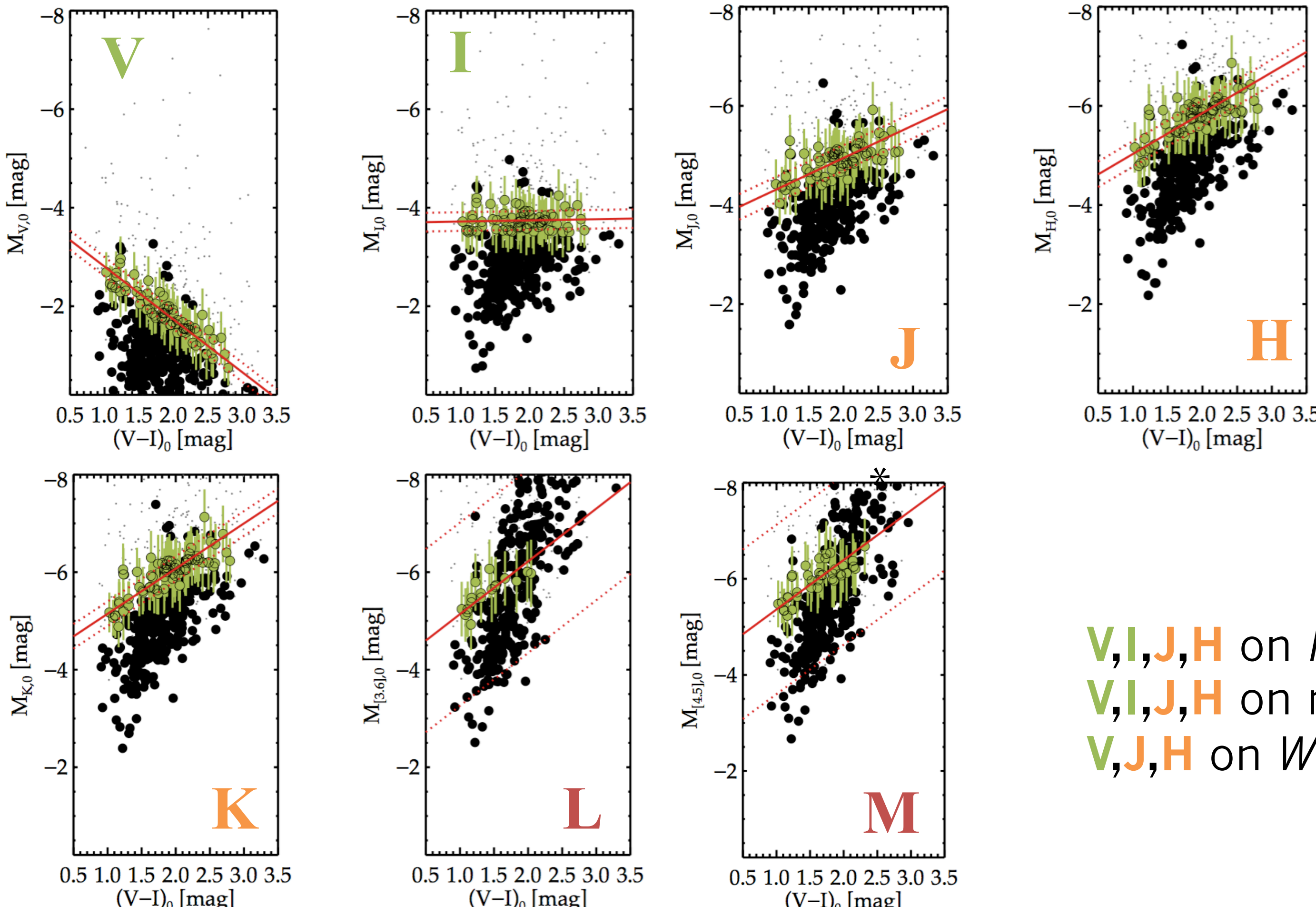
Instrument + RR Lyrae Campaign in:
Monson, **Beaton** et al. 2017



Merge with large scale stellar surveys to study behavior with [M/H], log(g), T_{eff}.
APOGEE (SDSS), RAVE, GALAH, LAMOST, TESS

** 2017 Gaia Sprint Project (last week @MPIA)

Direct Calibration in *Gaia* DR2**?



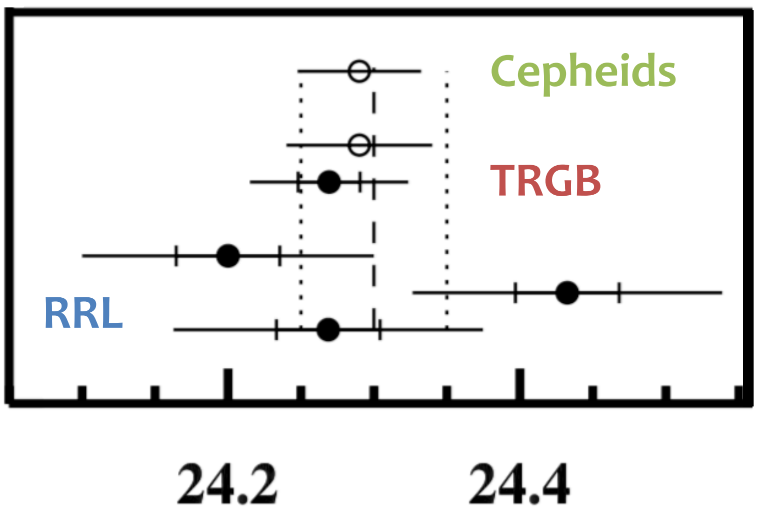
V,**I**,**J**,**H** on *HST* now
V,**I**,**J**,**H** on non-cryo *JWST**
V,**J**,**H** on *WFIRST*

*JWST optical resolution very minor improvement over HST

** 2017 Gaia Sprint Project (last week @MPIA)

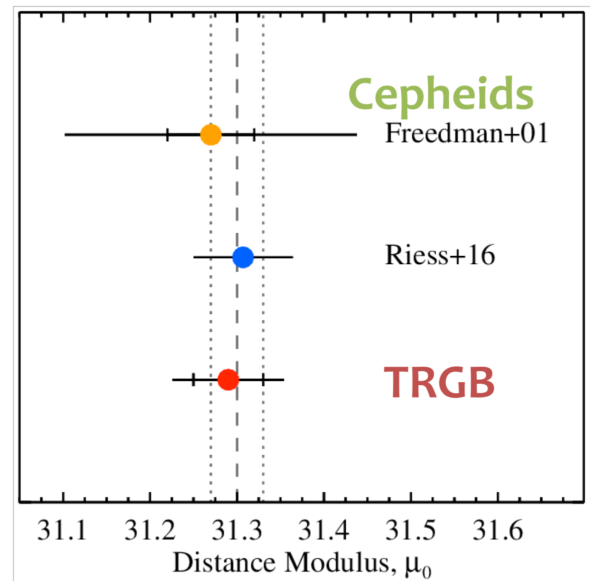
We see consistency

IC1613



+5 more galaxies
in the Local Group

NGC1365



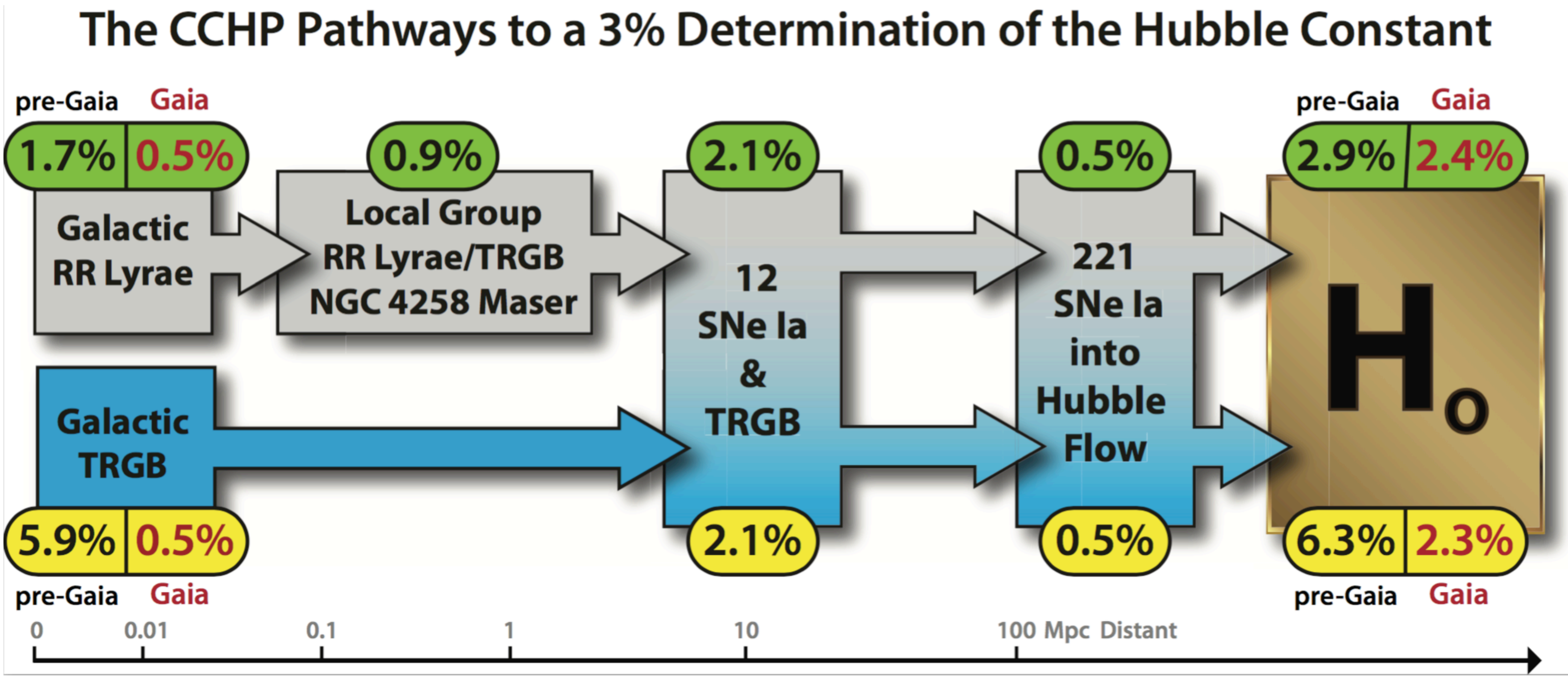
+6 more SNe Ia hosts

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

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

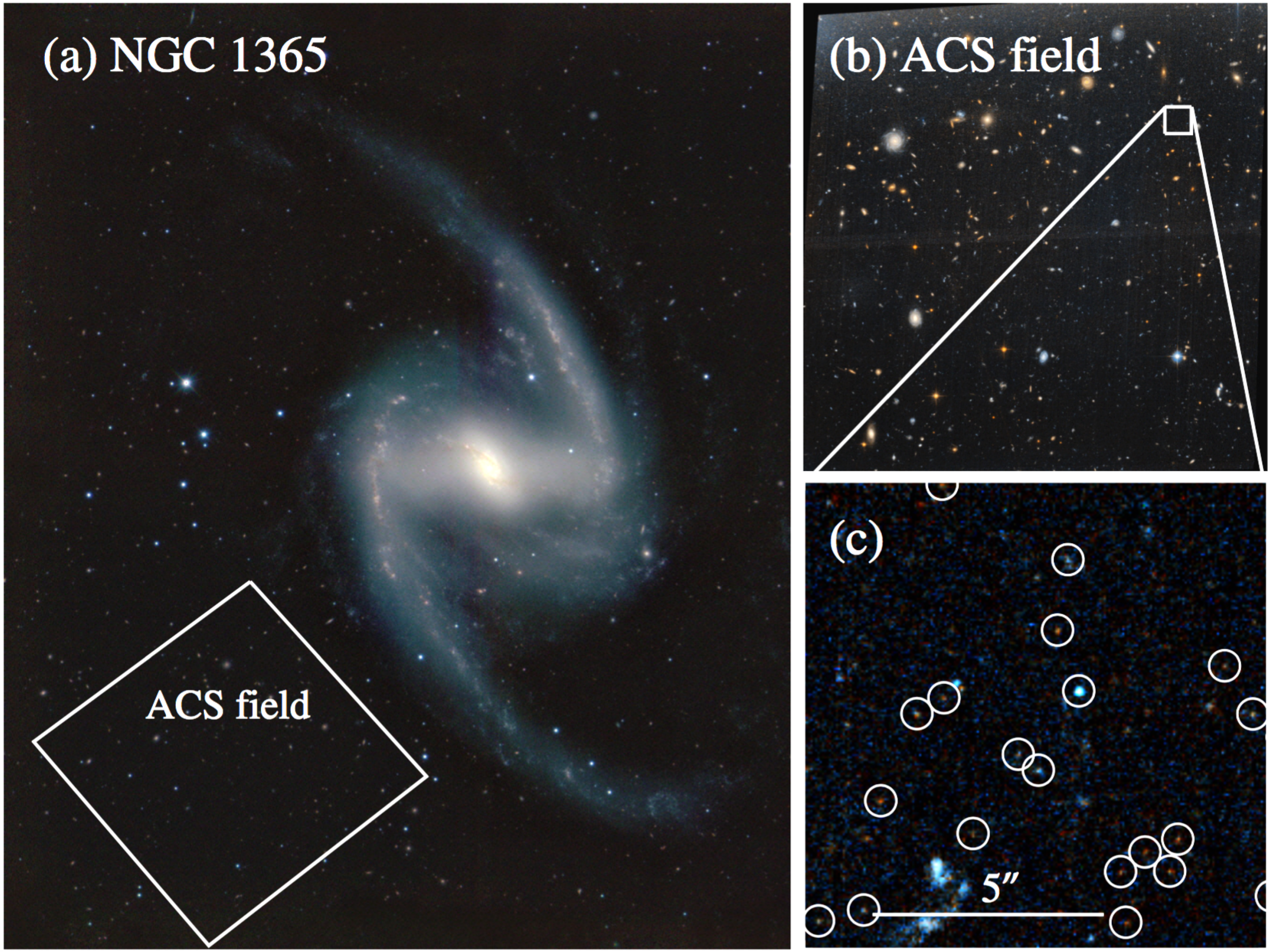
Note: Zero points are *not yet* fully independent between TRGB and Cepheids

CCHP H_0 Error Budget



Beaton et al. 2016

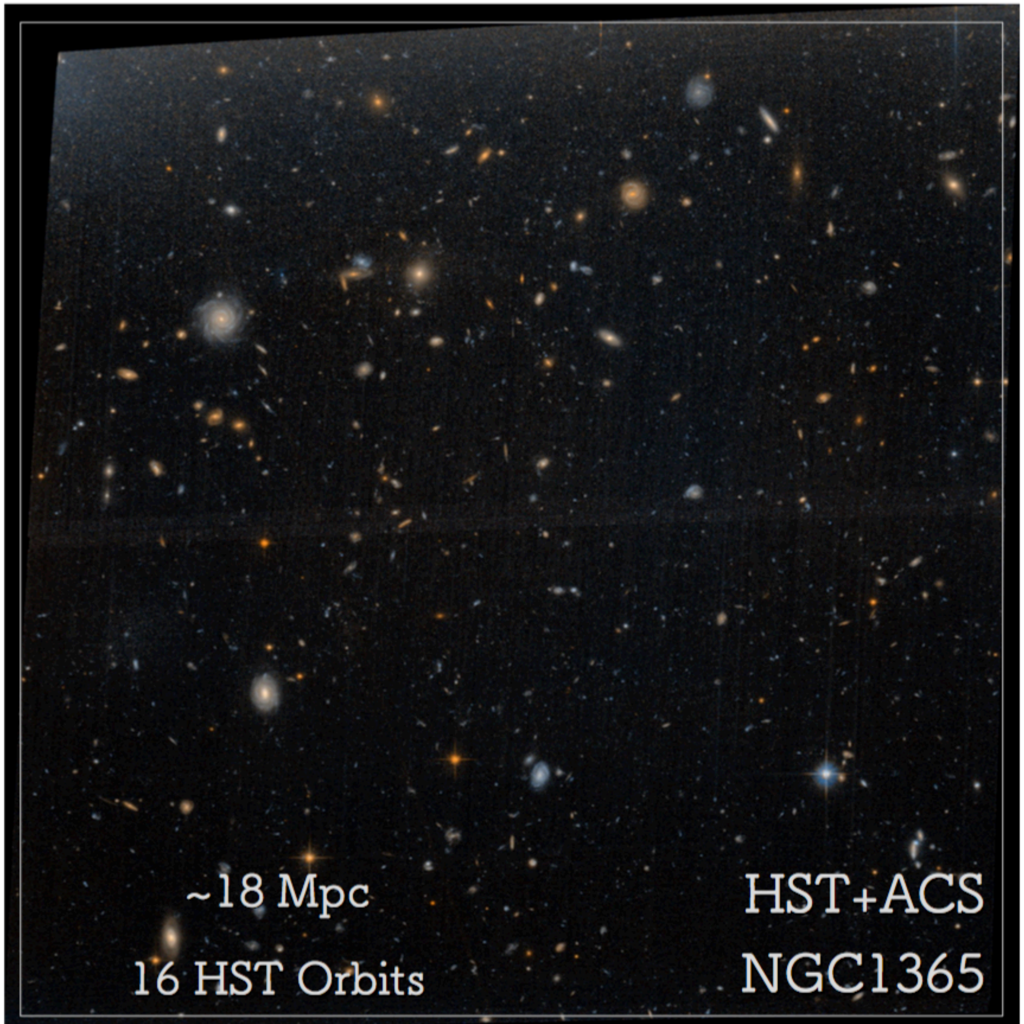
Haloes are See-Through



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

A Prospectus for WFIRST:

(modulo calibration of TRGB in WFIRST filters ...)



Guest Investigator (Archive):

Within HLS:
(m-M) ~ 31.7 [mag]
22 Mpc

Everything in the footprint is "free" @~1%

Guest Observer:

Using H for the TRGB luminosity function and Y for the CMD color:

@HLS Depth => 30 mins
< 22 Mpc

@ 1 mag fainter => 1.25 hours
< 35 Mpc

@ 2 mag fainter => 3.15 hours
< 55 Mpc

@ 3 mag fainter => 7.8 hours
< 87 Mpc

Summary

- Measurement of H_0 should be engineered like other cosmological parameters.
- The *Tip of the Red Giant Branch* method is a very promising standard candle for this measurement. Highlights include:
  - ~Equal precision near and far.
  - Universally present stellar population.
  - Luminous in near-infrared.
  - Can test with multiple pointings in an object.
  - Direct calibration is not far away …
- In our first measurements, we see consistency with Cepheid distances.
- TRGB comes/will come for free for nearby galaxies in most large scale galaxy surveys – keep this in mind and let me make distances from your star-trash ☺.

Backup Slides

The Original Hubble Diagram

Recession Velocity (v)

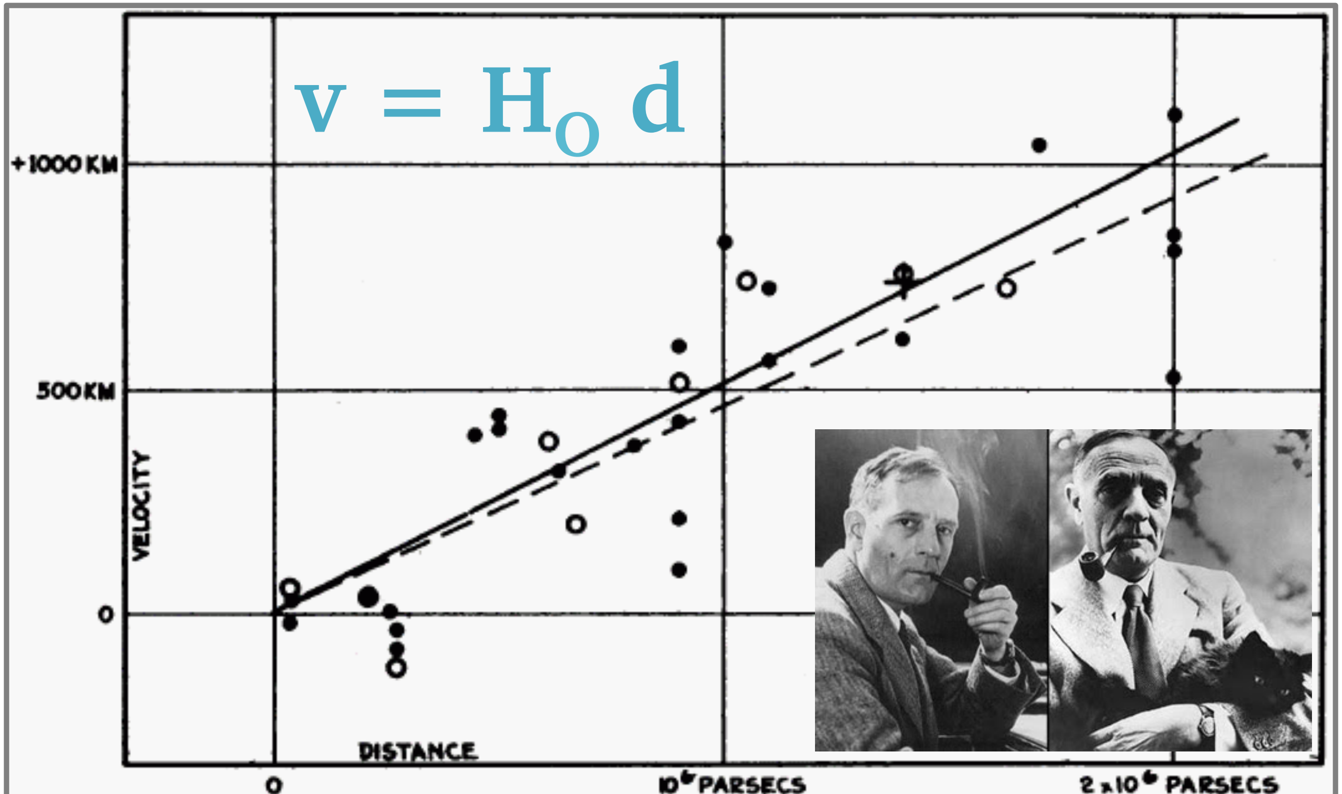


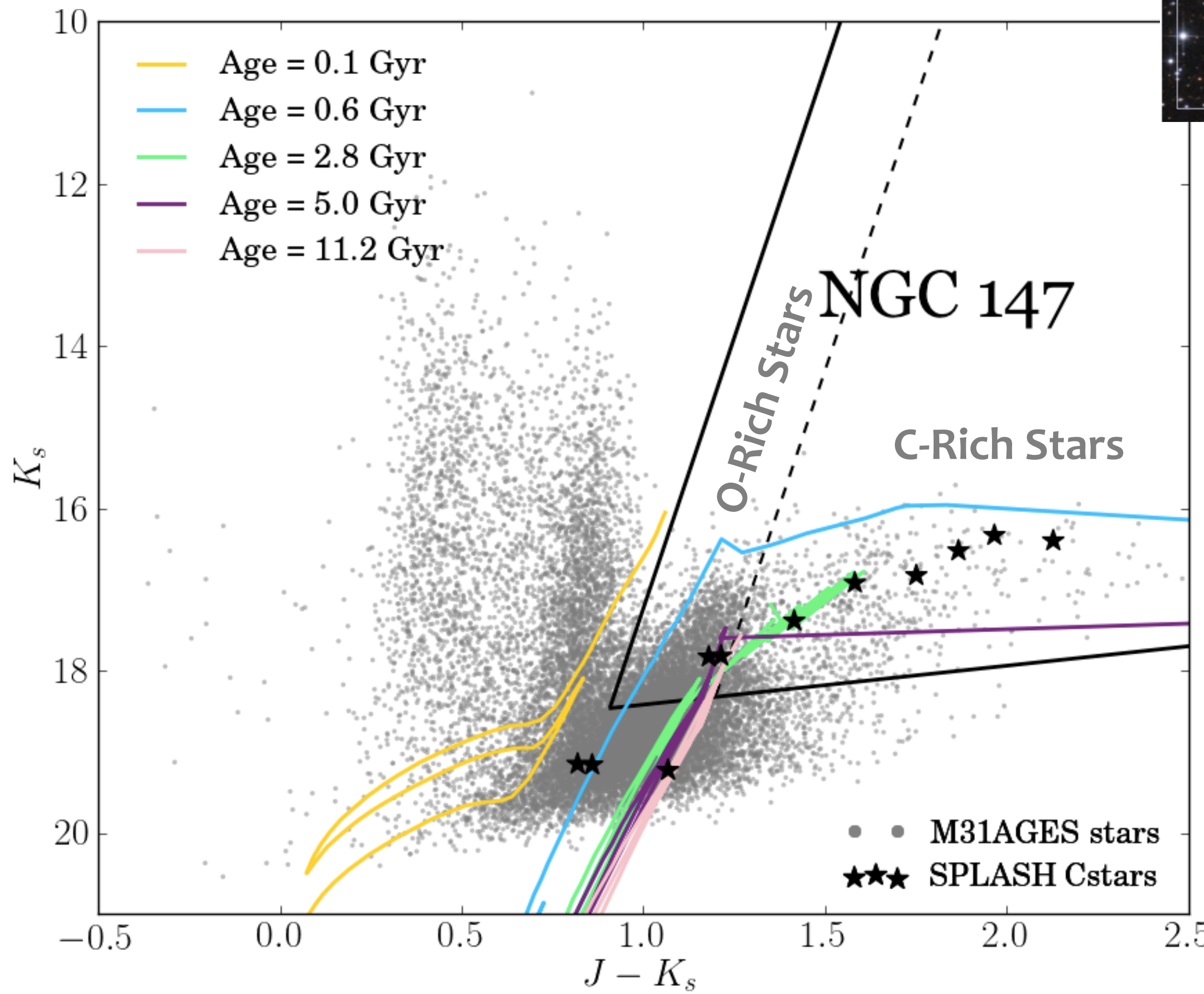
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Distance (d)

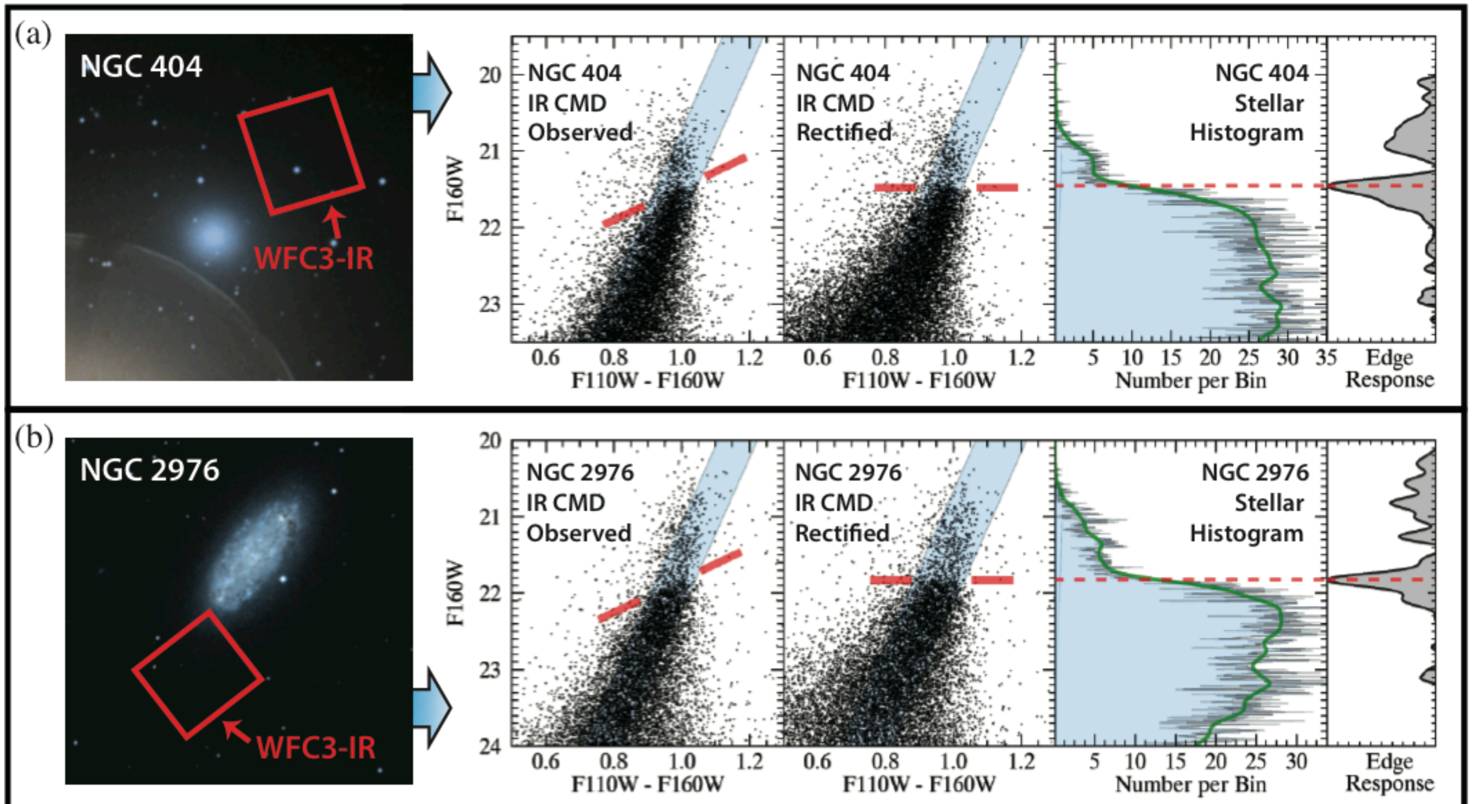
Hubble 1929

AGB Stars in NGC 147



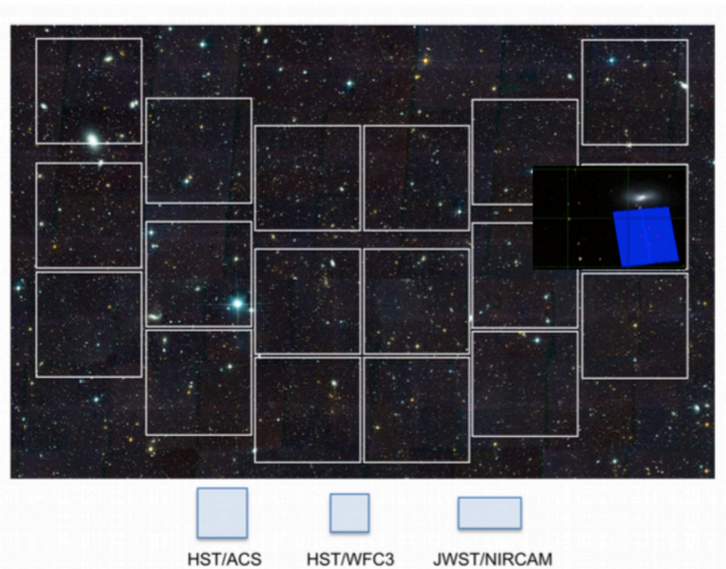
Confirmed C-Stars from Hamren, **Beaton** et al. 2016

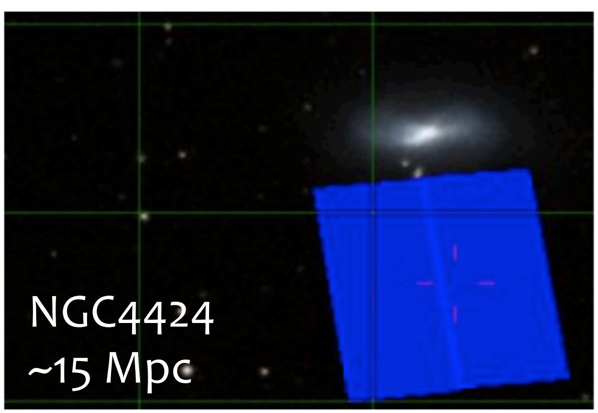
IR Stellar Populations

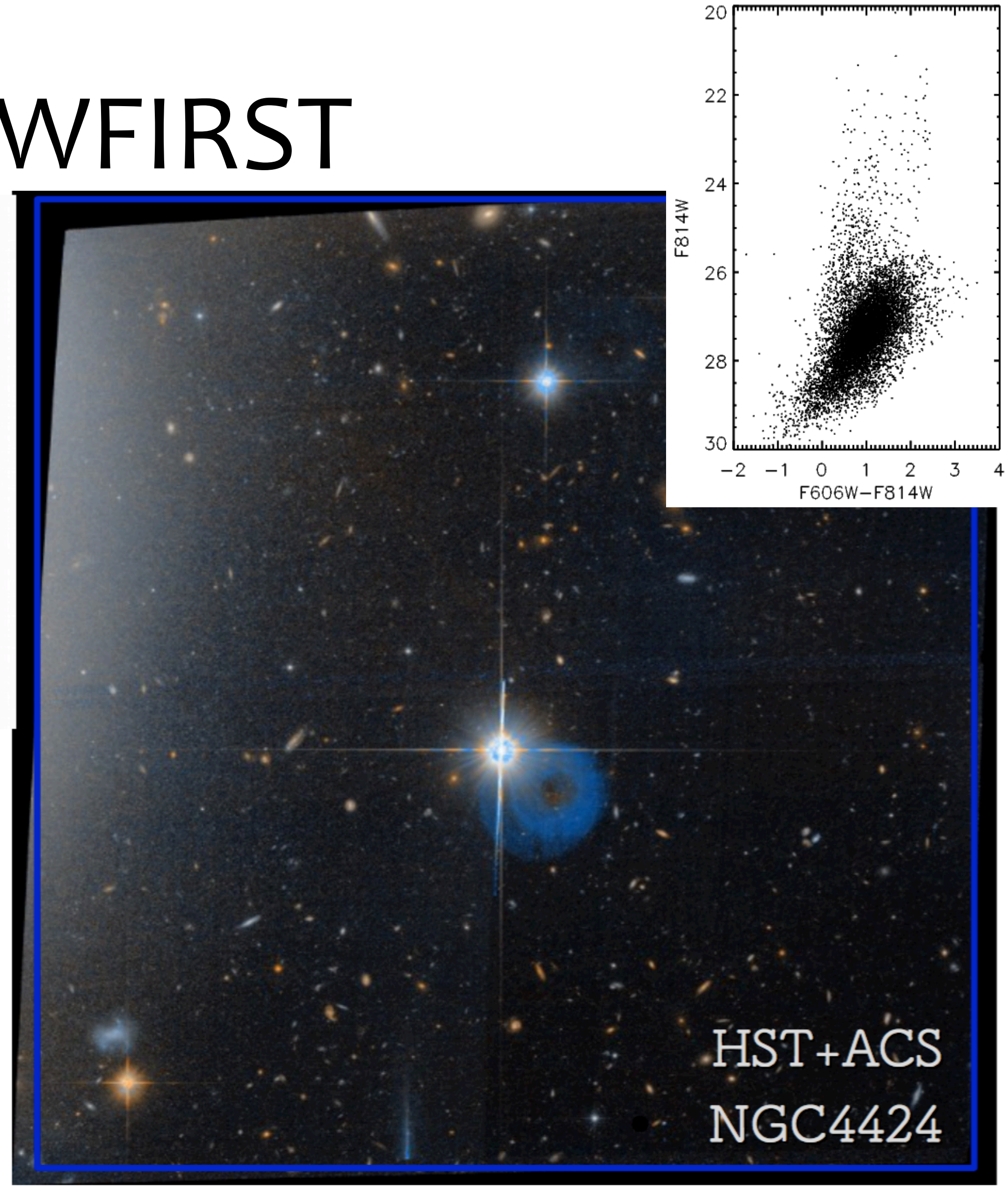


Adapted from Dalcanton et al. 2011

WFIRST

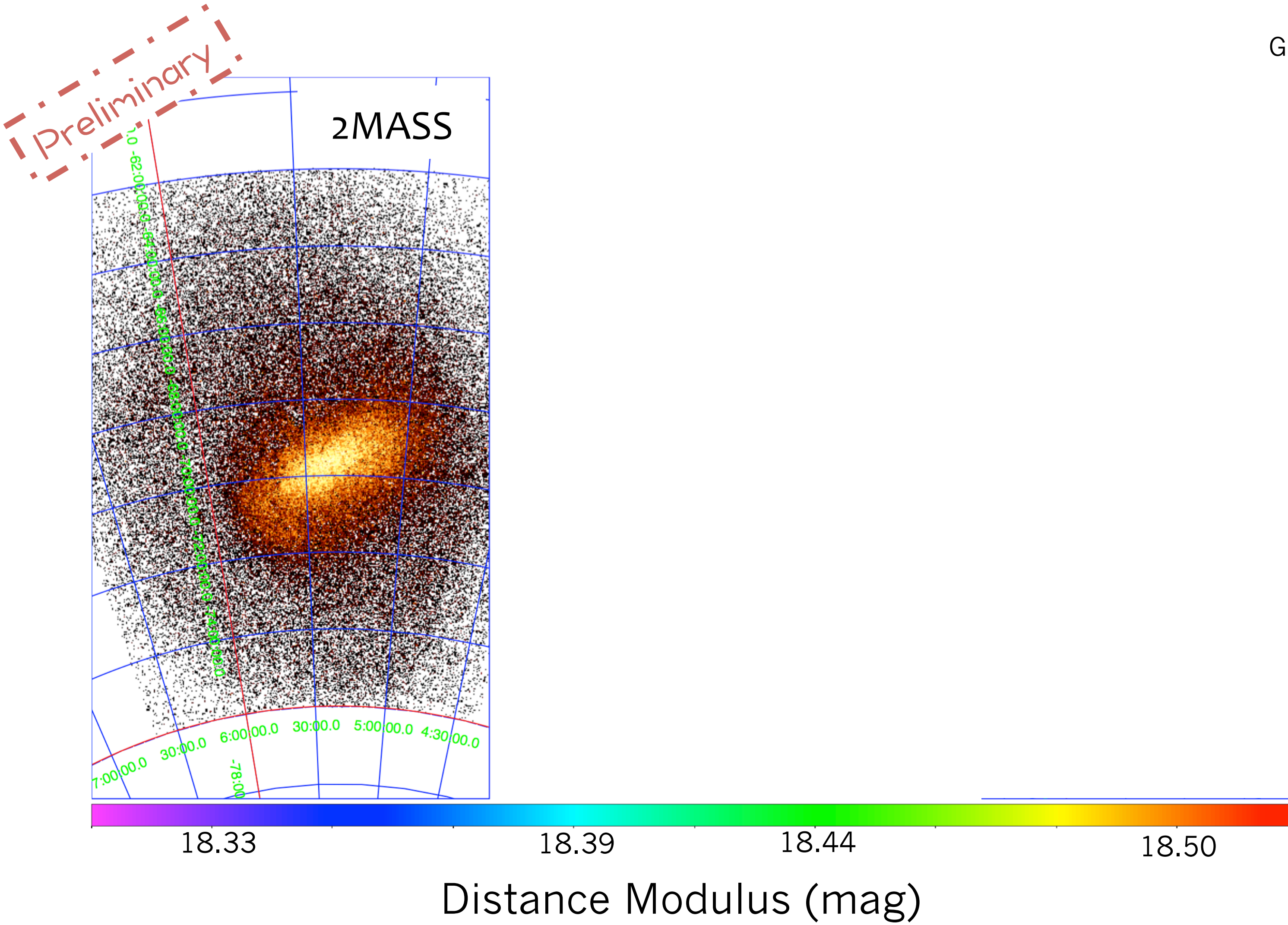

HST/ACS
HST/WFC3
JWST/NIRCAM


NGC4424
~15 Mpc


HST+ACS
NGC4424
F814W
20
22
24
26
28
30
−2
−1
0
1
2
3
4
F606W−F814W

The LMC is the test

Taylor Hoyt
Grad @ U. Chicago



Hoyt, Seibert, (incl. Beaton) in prep.

The LMC is the test

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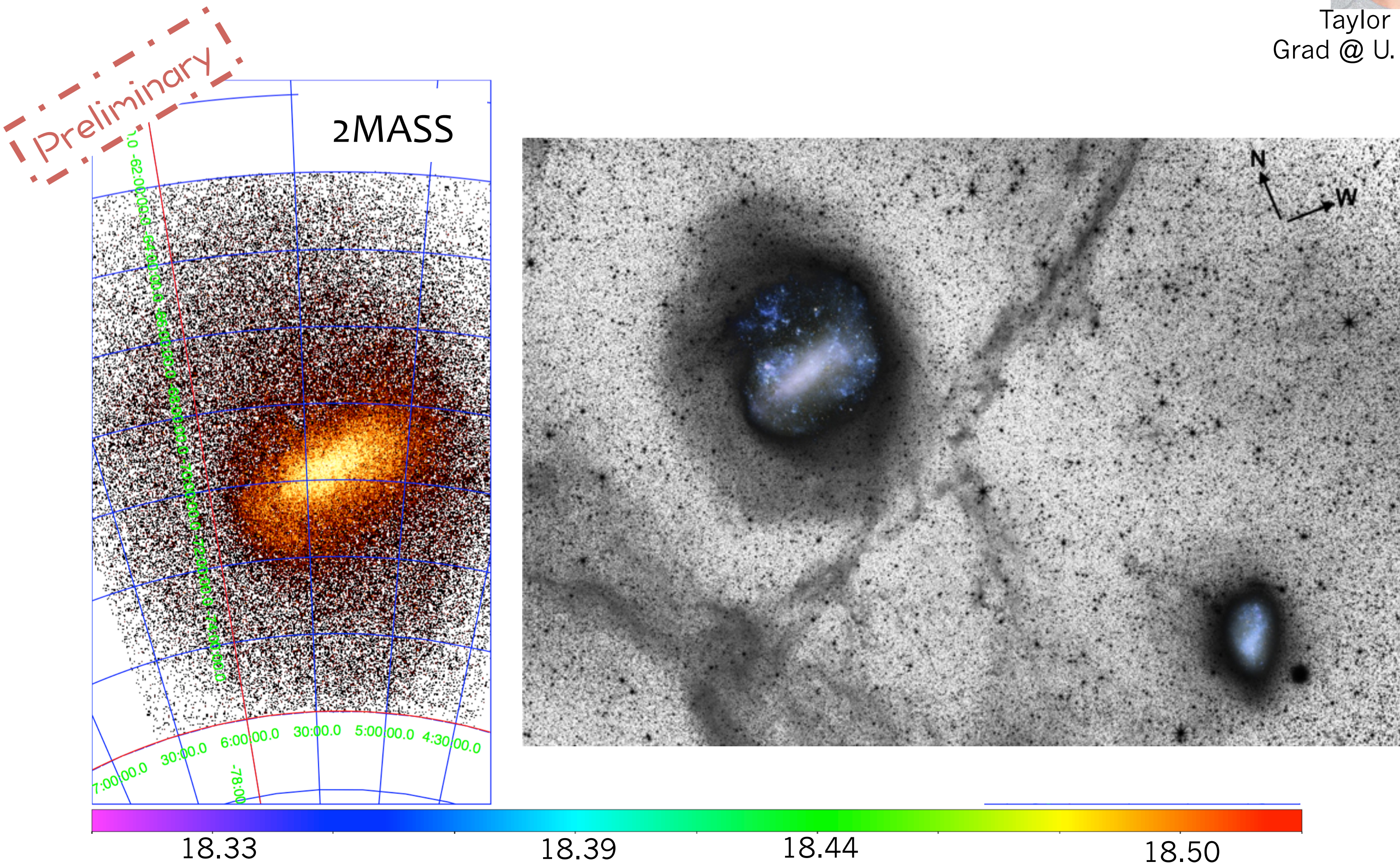


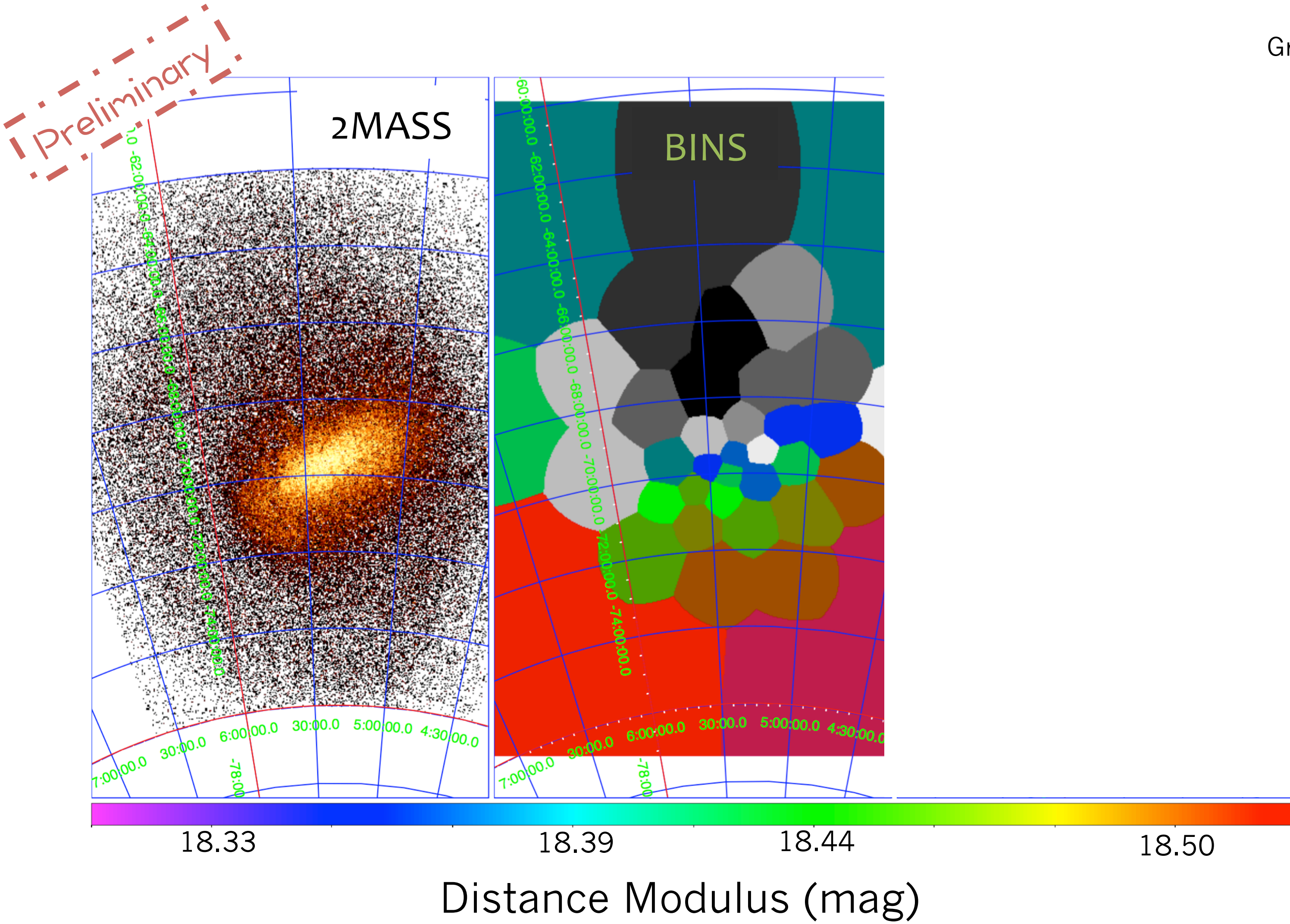
Besla et al. 2016

Distance Modulus (mag)

Hoyt, Seibert, (incl. Beaton) in prep.

The LMC is the test

Taylor Hoyt
Grad @ U. Chicago



Hoyt, Seibert, (incl. Beaton) in prep.

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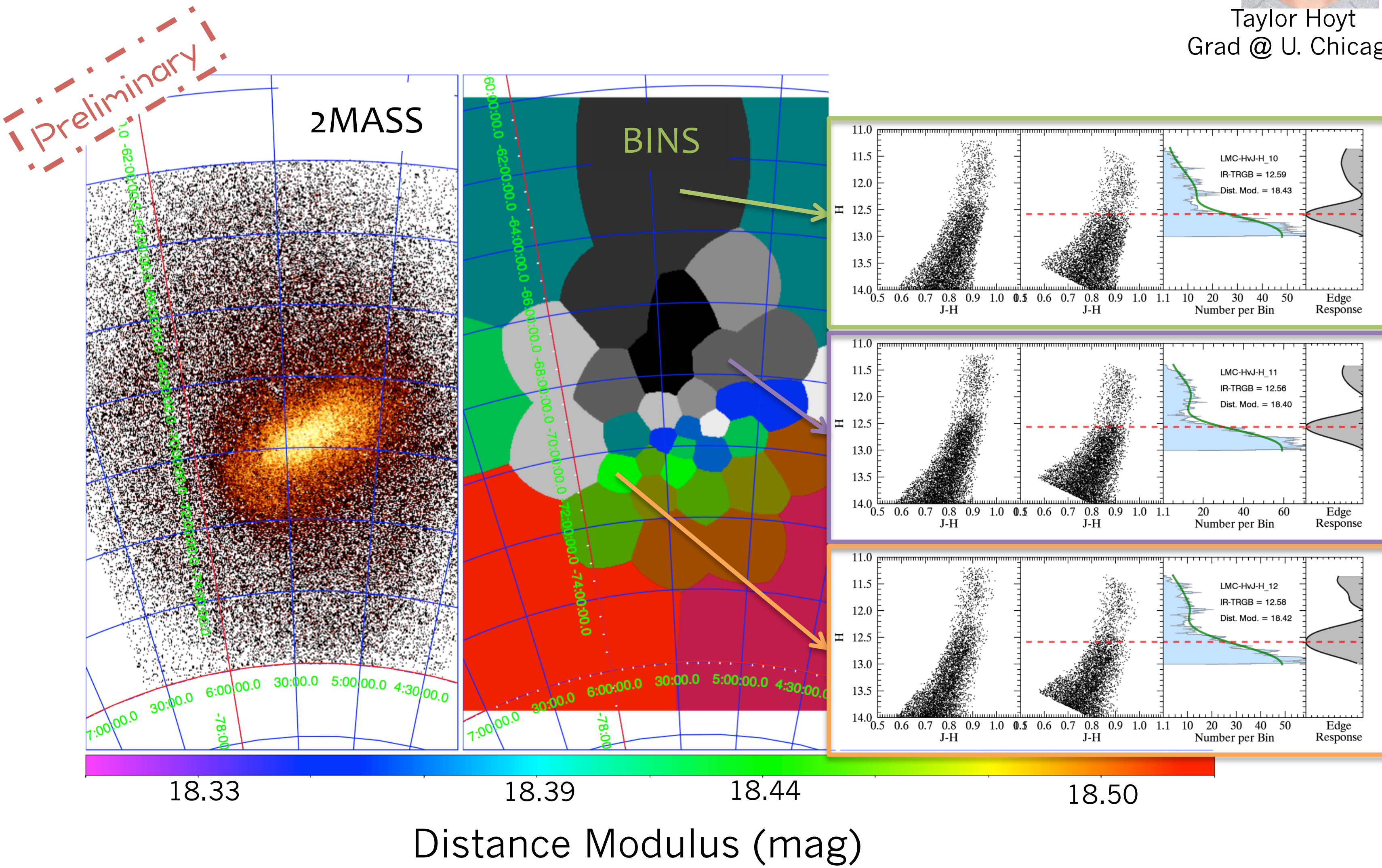

Hoyt, Seibert, (incl. Beaton) in prep.

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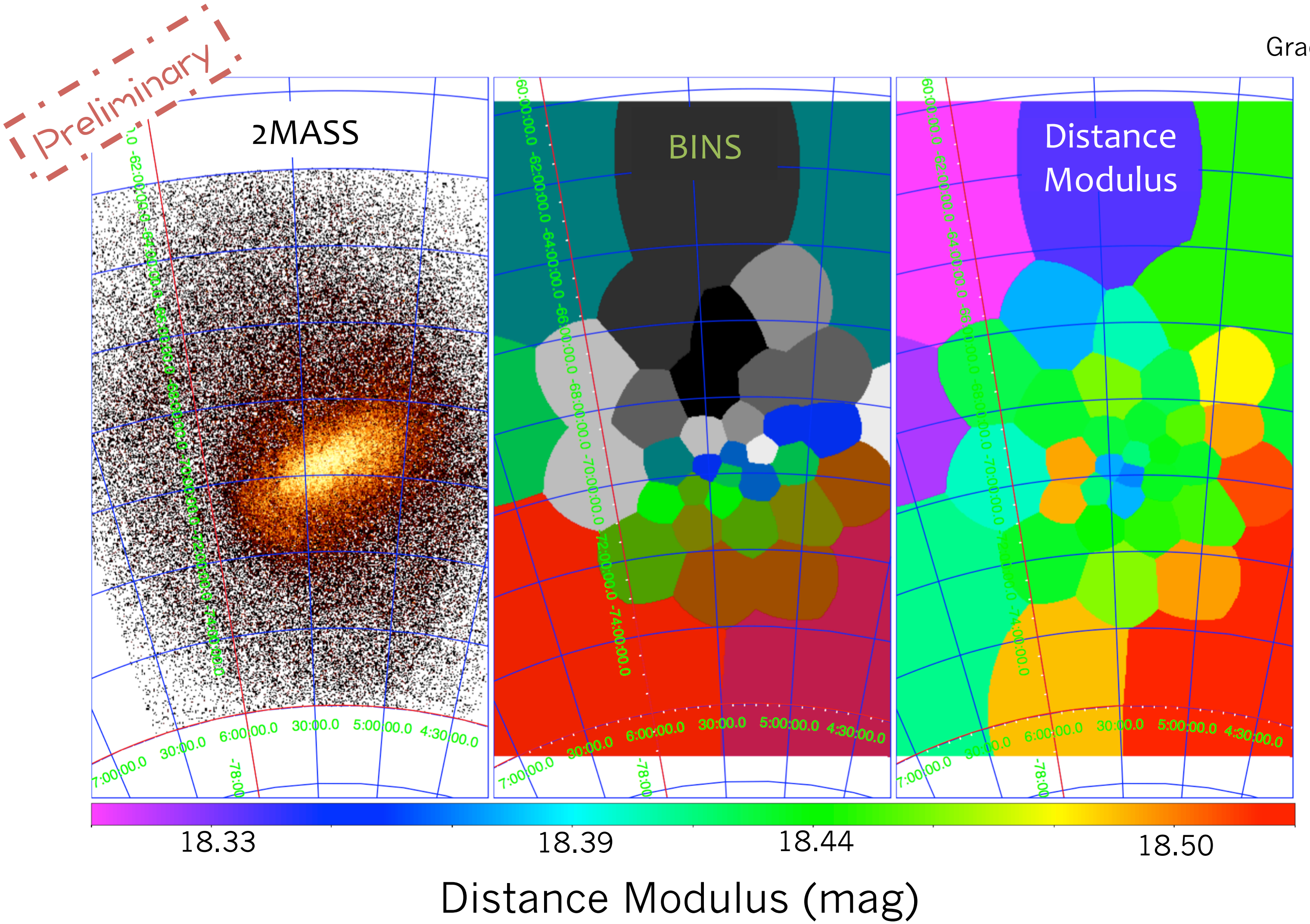

Hoyt, Seibert, (incl. Beaton) in prep.