Distances Here, There, & Everywhere

Rachael L. Beaton

Princeton University

Hubble Fellow, Carnegie-Princeton Fellow

APOGEE-2 Science Working Group Co-Chair

Some Truth

Stanek's Ladder
20 Years Ago

The Distance Ladder is the best we can do with what astrophysics gives us and telescope allocation committees are willing to let us do.

Some Truth

Stanek's Ladder
Today.

The Distance Ladder is the best we can do with what astrophysics gives us and telescope allocation committees are willing to let us do.

The Distance Ladder has been seen as a means to an end for the Hubble Constant.

As a result the way uncertainties combine dictate where attention is placed – because the race is precision on Hubble Constant *not* the ladder that works for the other science we might want.

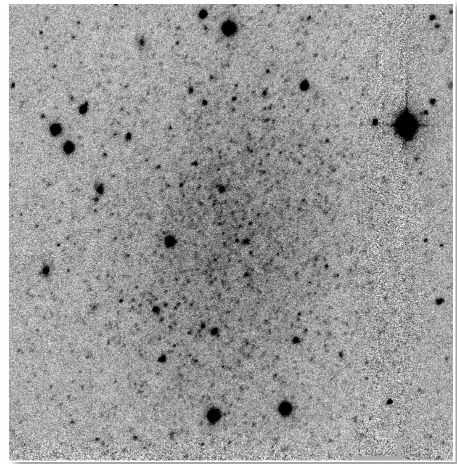
Goals

- Demonstrate precise distance measurement techniques that address 21st century scientific challenges.
- Convince the room that there is a very meaningful place for distance measurement.
- Give some hand-wavey numbers about what WFIRST can do, *provided the projects I highlight work out.*

Distance Regimes:

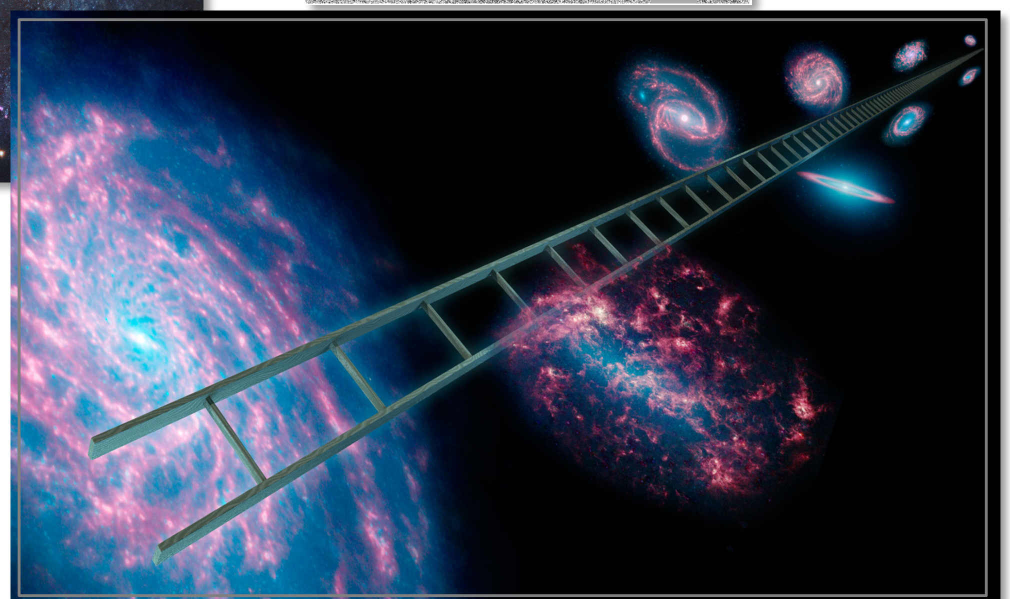
BIG Things

UNRESOLVED Things



SMALL Things

DIFFUSE Things



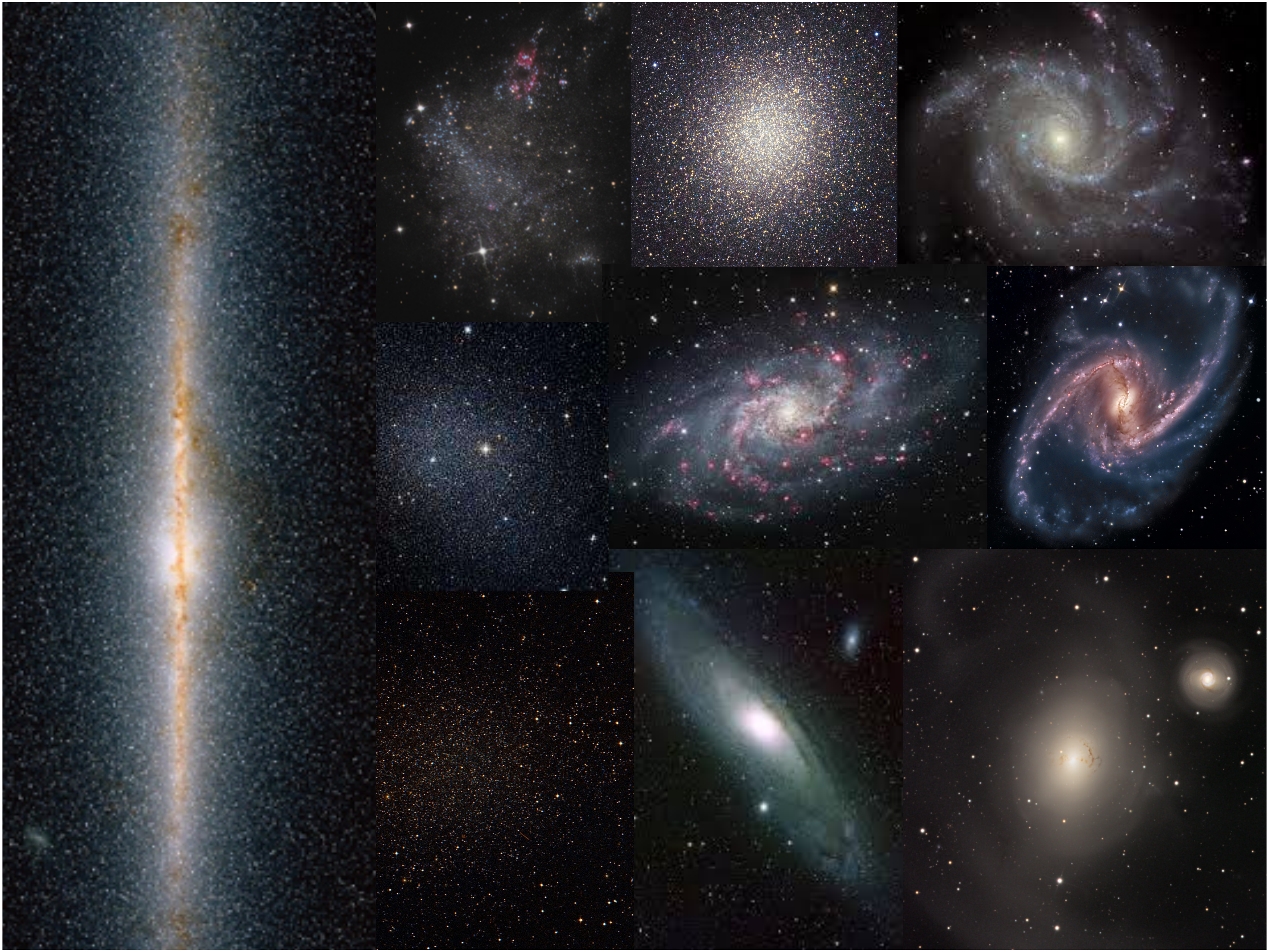
FAR Things

RESOLVED Things

DENSE Things

NEAR Things

Rachael L. Beaton



Rebuilding Stanek's Ladder

Stanek's Ladder

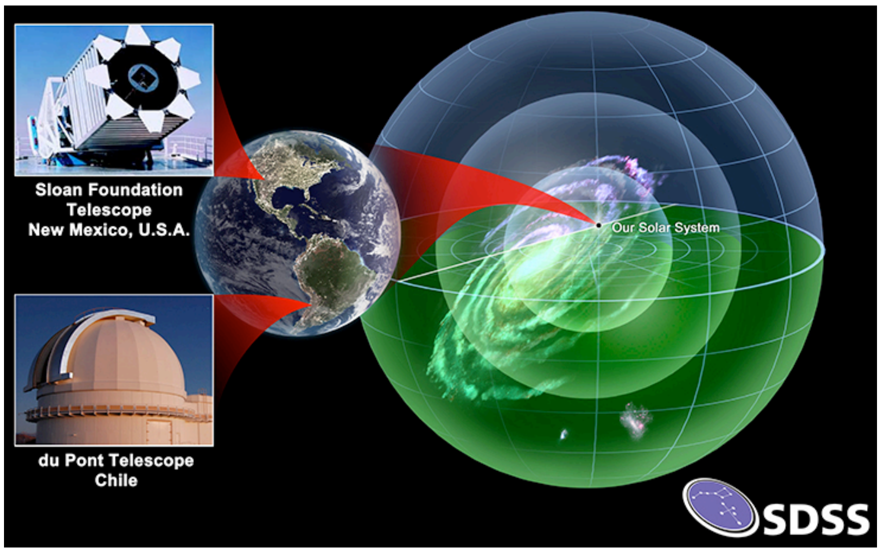
There is not one technique that addresses every scientific problem.

The closest we can get is to try to:

- draw from the same underlying stellar population
  => **use continuous pieces, not separate parts**
- choose a Galactic structural component that minimizes the unknowables
  => **build smartly, not as you go along**
- use wavelengths that mitigate intrinsic uncertainty
  => **use metal, not wood**
- use wavelengths that mitigate extrinsic uncertainty
  => **use screws, not nails**
- make techniques open, clear, reproduceable
  => **let other people use the ladder so that it stays in repair**

The Cornerstone

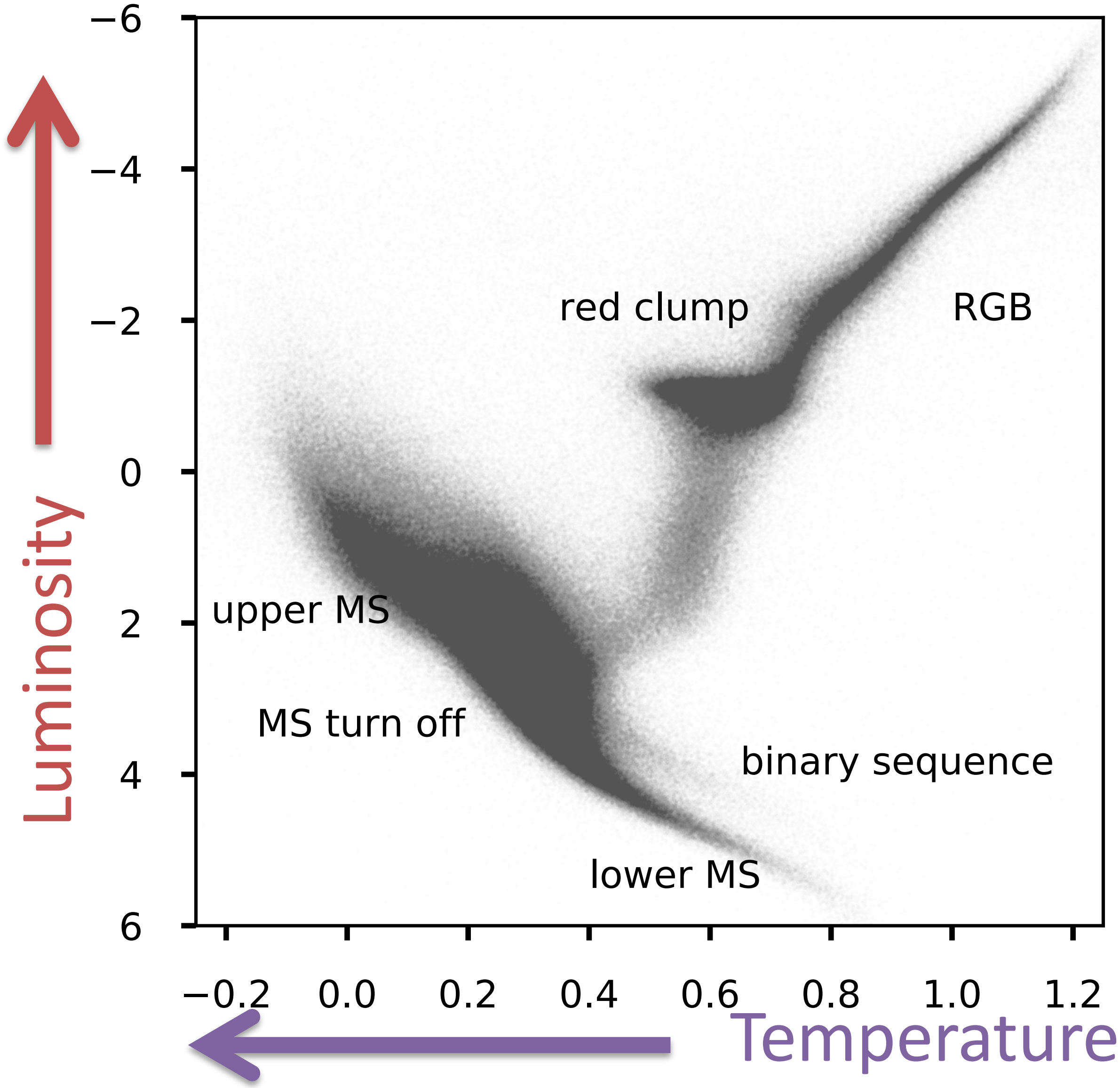
gaia Parallaxes for kiloparsecs



The rebirth of Stellar Astrophysics via Kepler, TESS, massive spectroscopic surveys.

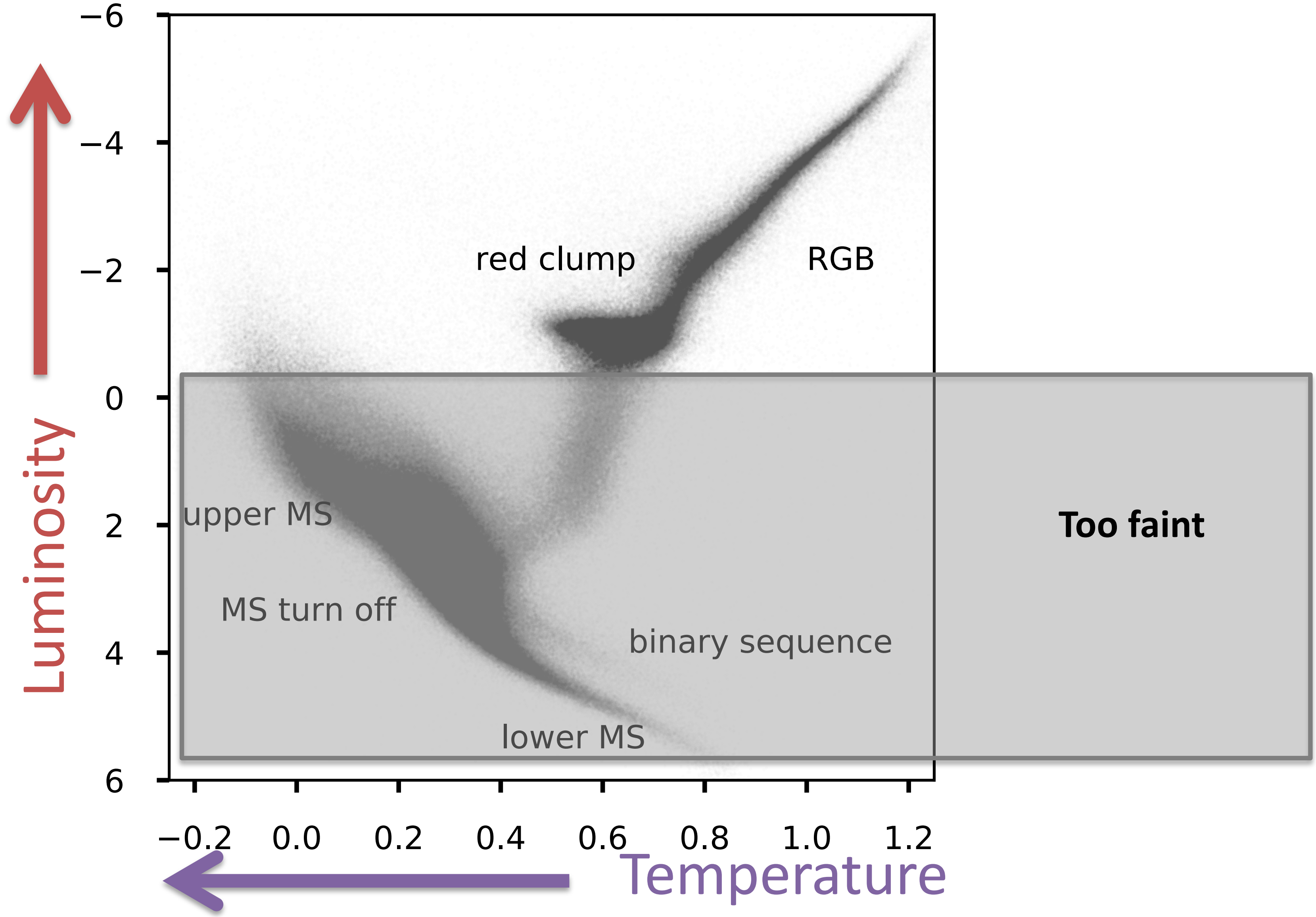
→ Use existing resources better, smarter, faster.

Gaia spans full HR Diagram



Rachael L. Beaton – Princeton

TGAS with adjustment + 2MASS photometry
Anderson et al., ArXiv:1706.05055



Rachael L. Beaton – Princeton

TGAS with adjustment + 2MASS photometry
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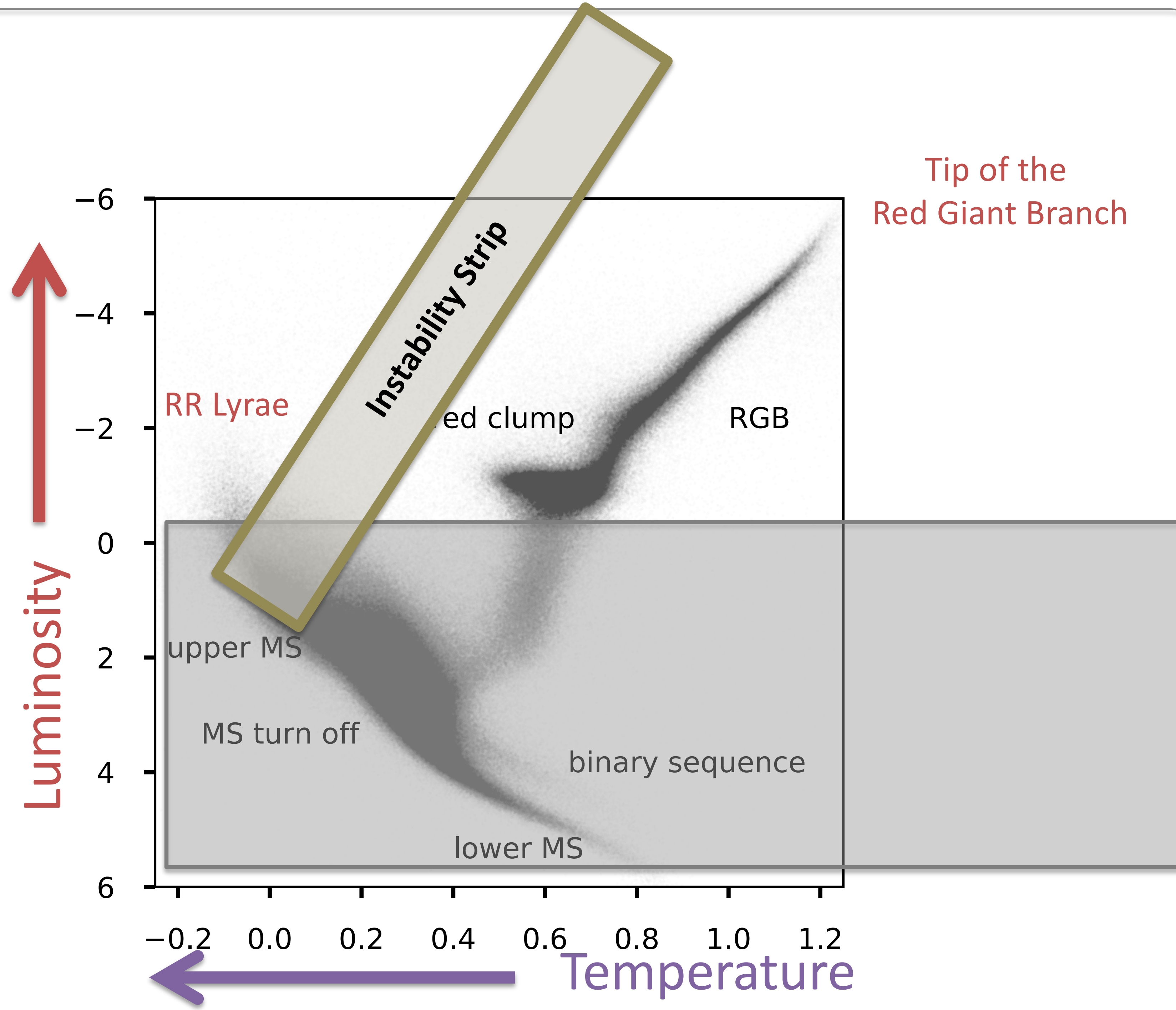


Rachael L. Beaton – Princeton

Worked Examples:

Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.

The Hubble Constant

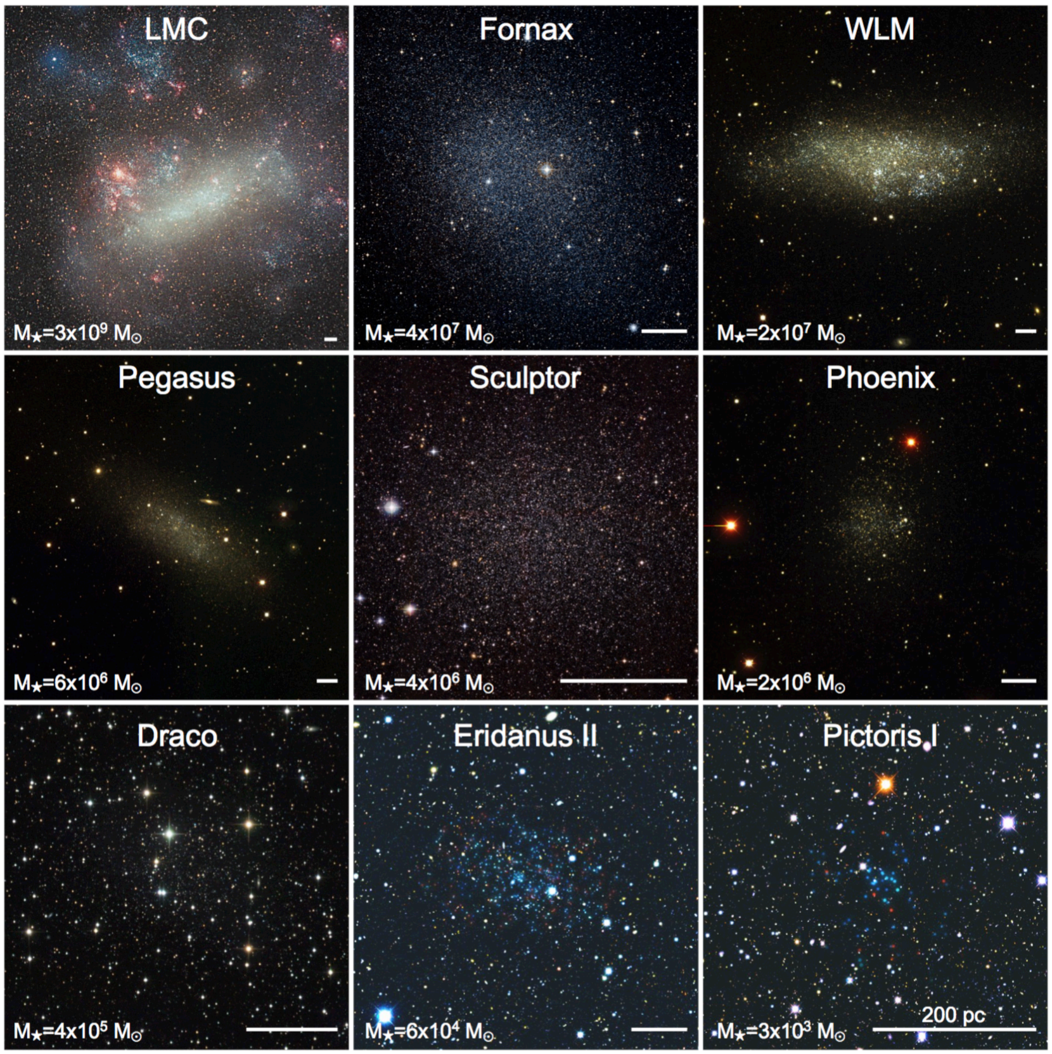
Exotic Dark Energy? Or just systematics we never knew we never knew?

Satellite Luminosity Functions

Λ-CDM on its smallest scales with statistical rigor.

Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.



Small-Scale Challenges to the ΛCDM Paradigm

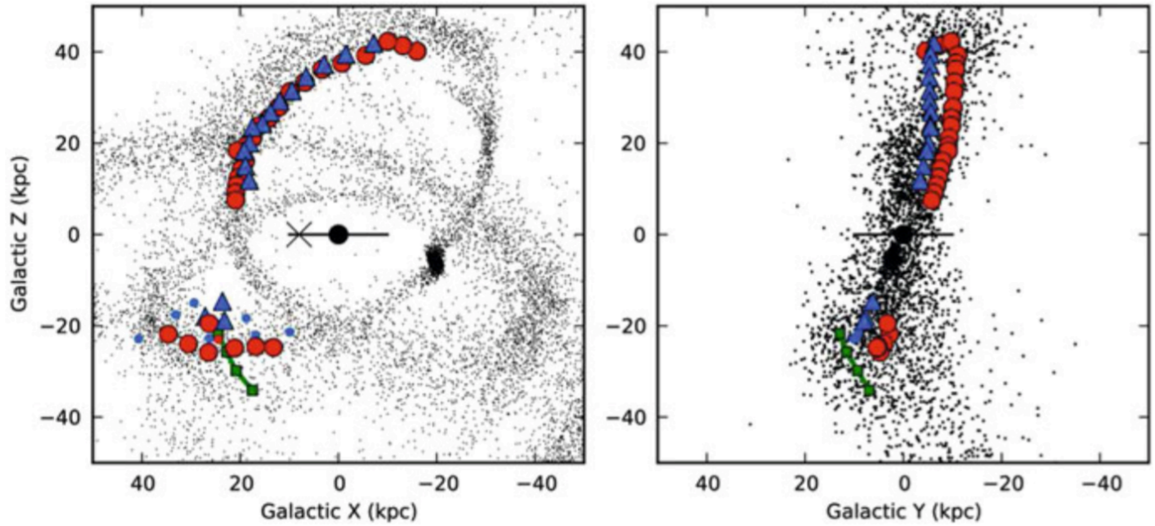
James S. Bullock[1] and Michael Boylan-Kolchin[2]

[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; email: bullock@uci.edu
[2]Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA; email: mbk@astro.as.utexas.edu

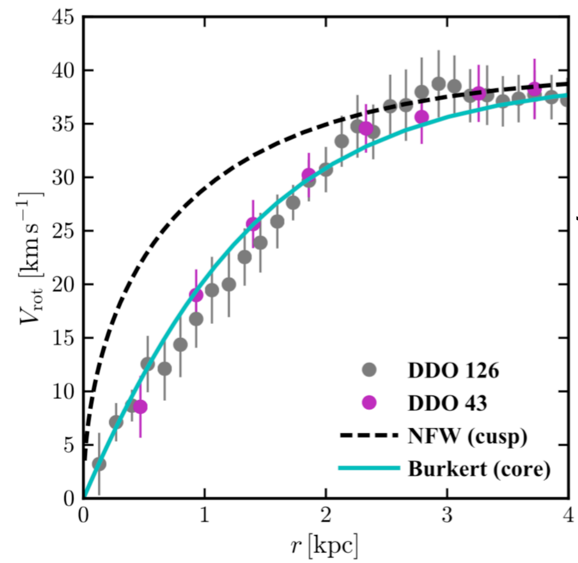
The Local Group Dwarfs are a laboratory for cosmology on small scales, which is where several of the current tensions exist.

Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.



Law & Majewski 2016



Bullock & Boylin-Kolchin 2017

Arvind Gupta (ugrad @UVa, now grad @ Penn State)
Rachael Beaton
Steve Majewski
Kathryn Johnston
& SMHASH Collaboration

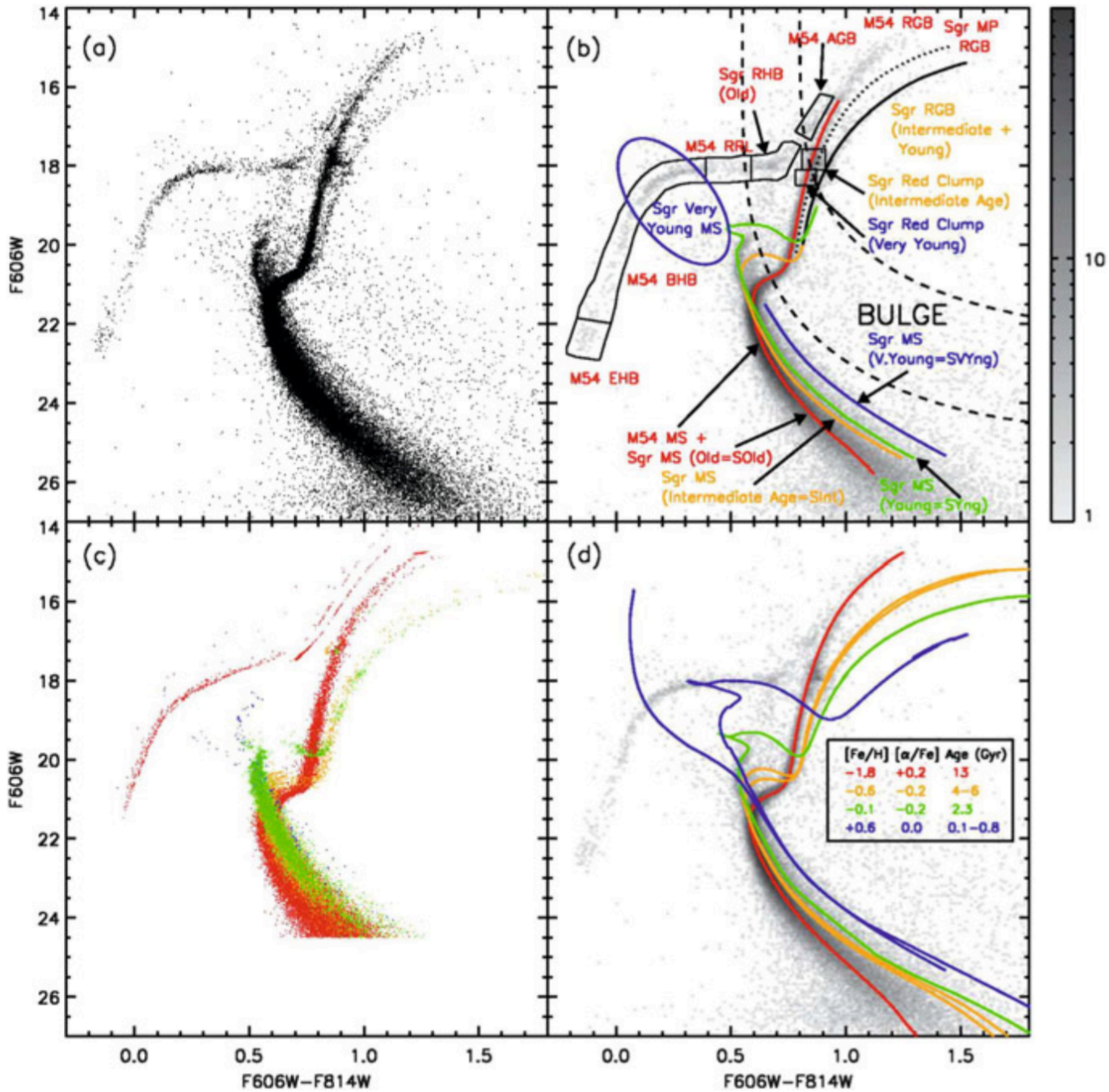
Gupta et al. in prep.

Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.

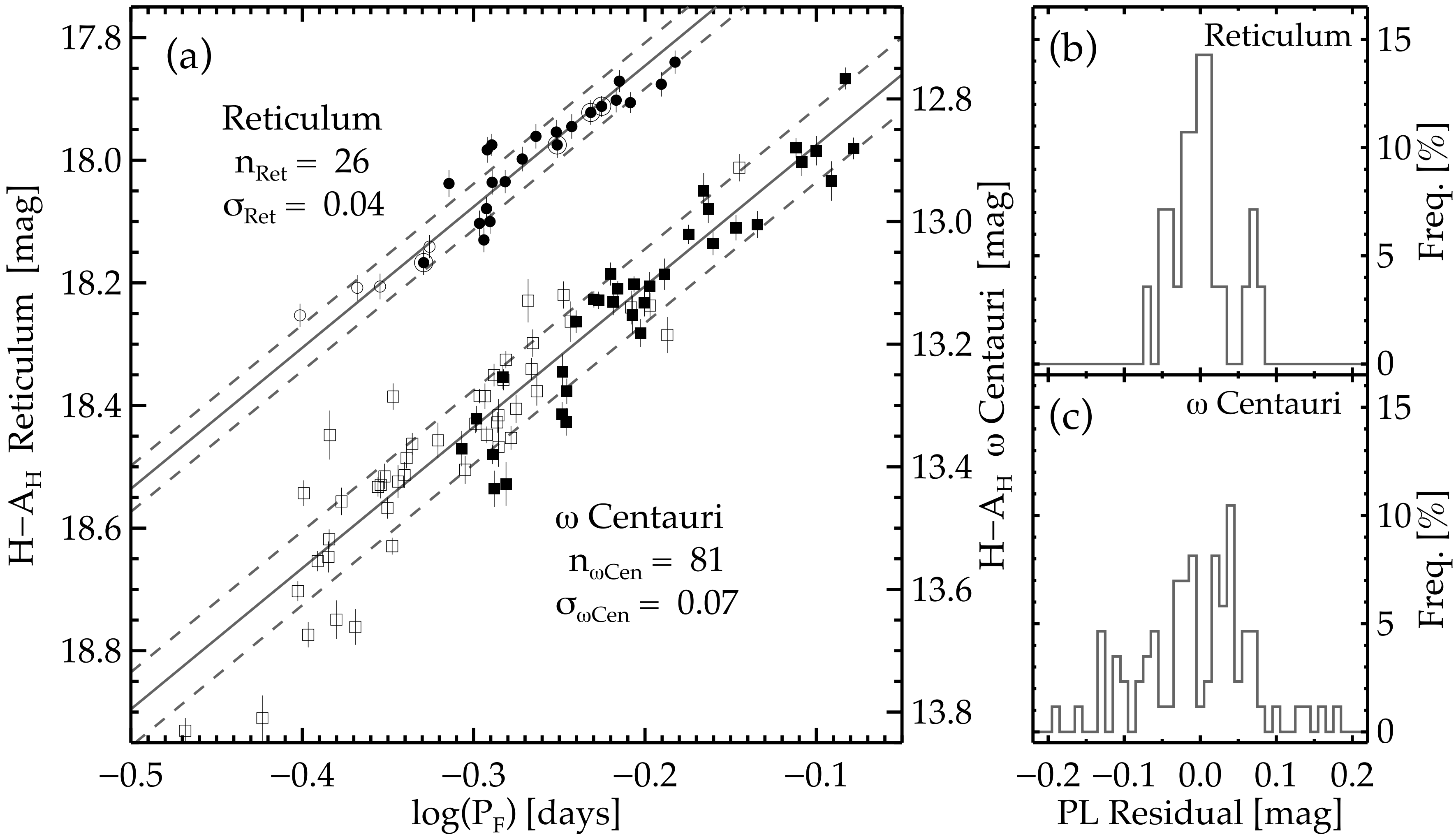
At the photometric center of Sgr dwarf, is M54 a globular cluster. But is it really at the center? Or not?

If there is/was a cusp, M54 should be at the true center of Sgr.



Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.



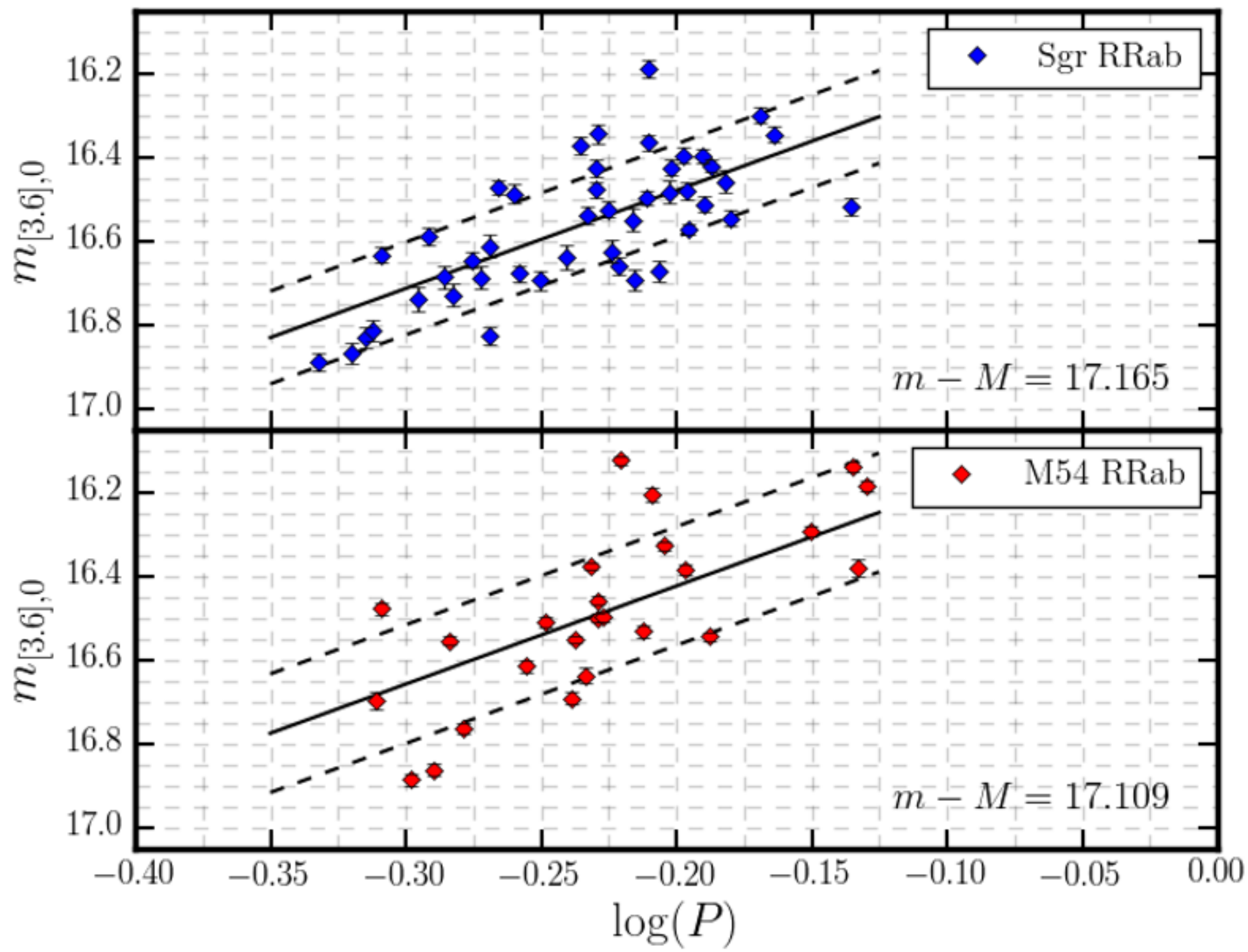
Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.

d_{Sgr}= 27.10±0.21(ran)±1.11(sys) kpc

Sgr

M54



d_{M54}= 26.42 ±0.34(ran)±1.08(sys) kpc

Distances place M54 *within* Sgr, but not in center. Working on double checking systematics.

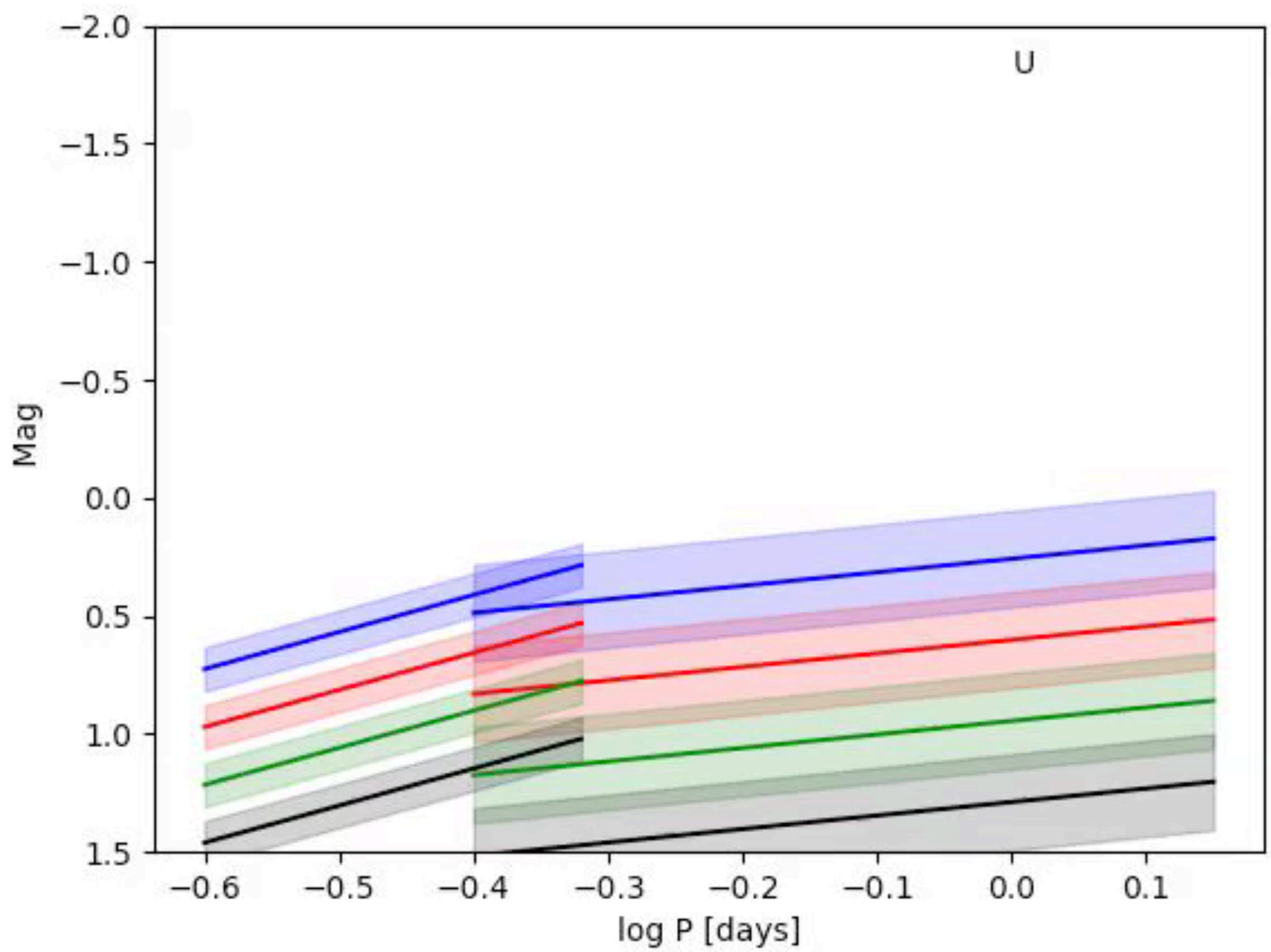
Hierarchical Formation of our own Galaxy

Where baryons & dark matter collide and perhaps we can sort that out.

CHALLENGE:

To use RR Lyrae as the precision tools that they are, we need to understand the metallicity effect really well.

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

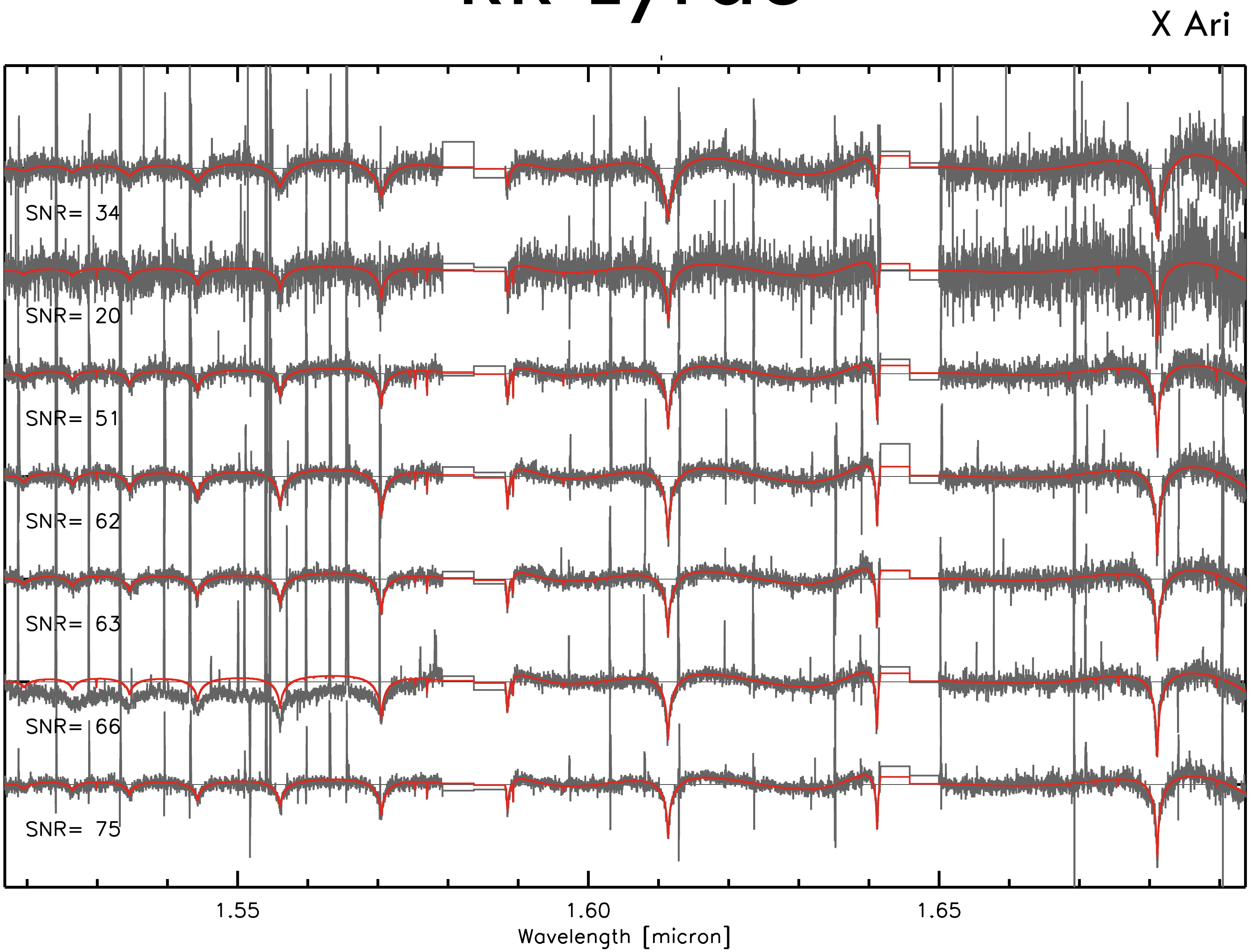


Metals do two things:

1. Slight changes to structure of star => location of instability strip is slightly different
2. Absorb & Redistribute flux => changes "intrinsic width" of the PL as a function of λ

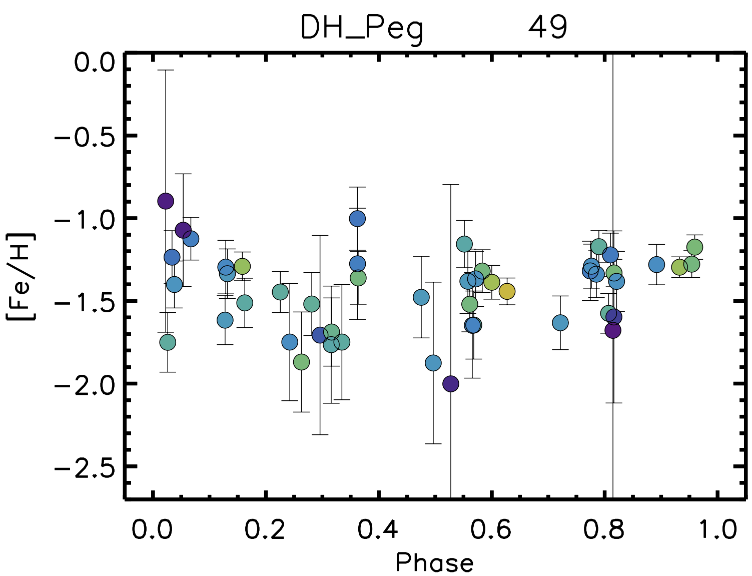
Theoretical Models from Marconi et al. 2015 & Neeley et al. 2017
Movie by Jill Neeley

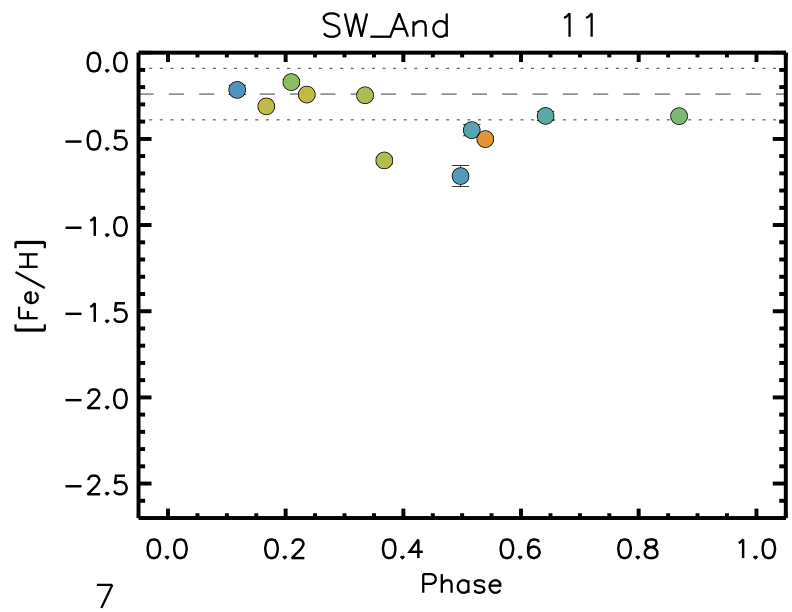
RR Lyrae

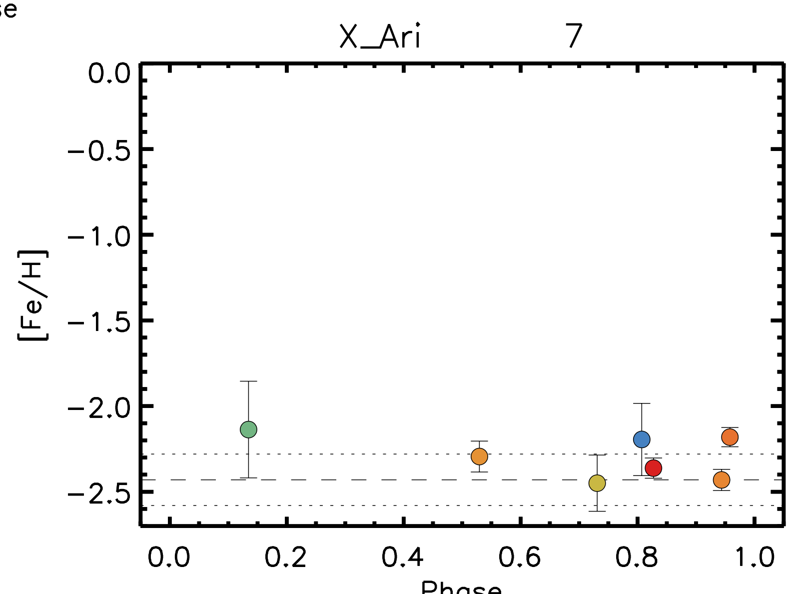


X Ari
SNR= 34
SNR= 20
SNR= 51
SNR= 62
SNR= 63
SNR= 66
SNR= 75
1.55
1.60
1.65
Wavelength [micron]

RR Lyrae







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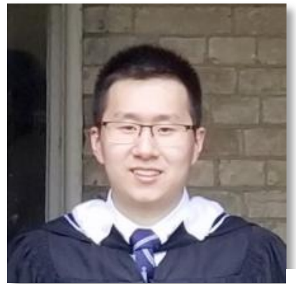
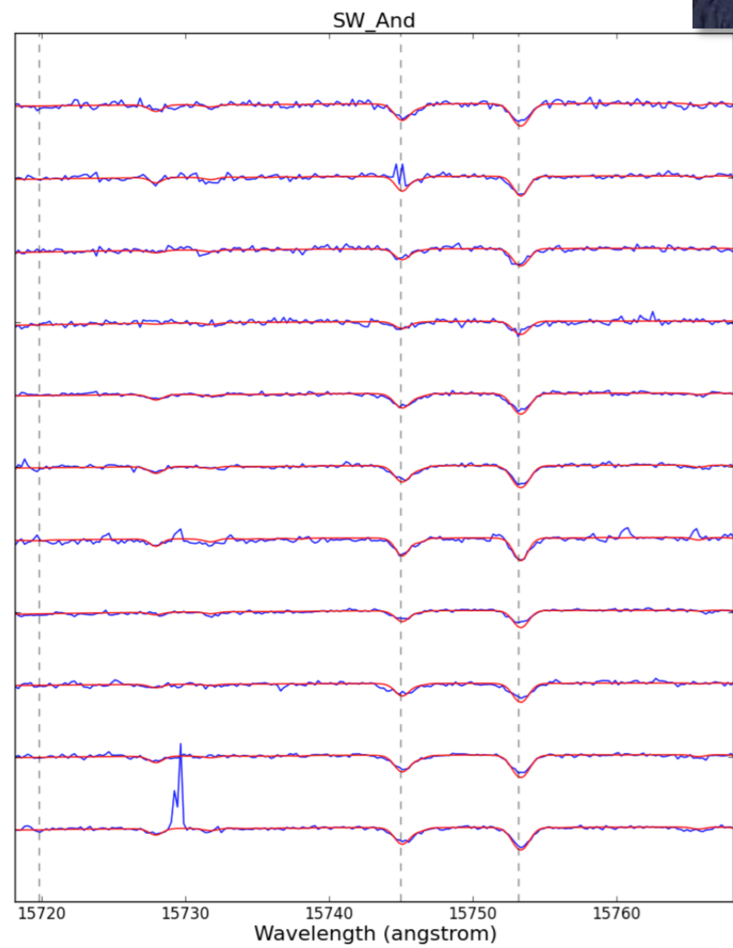
Refining:



Arvind Gupta
Now Grad @ PennState

Bruce Wu
Grad @ UVirginia



Element	λ_{vac} (Å)	SW And	RR Lyr	DH Peg	RZ Cep	CN Cam	RR Cet	X Ari	Sum
K	15172.471	0	0	0	0	0	0	0	0
Fe	15198.595	0	0	0	0	0	0	0	0
Fe	15211.632	1	0	0	0	0	0	0	1
Mg	15221.109	0	0	0	0	0	0	0	0
Mg	15266.121	0	0	0	0	0	0	0	0
Si	15365.309	0	0	0	0	0	0	0	0
Si	15380.983	2	0	0	0	0	0	0	2
Fe	15399.875	1	0	0	0	0	0	0	1
Fe	15494.521	0	0	0	0	0	0	0	0
Ti	15547.953	0	0	0	0	0	0	0	0
Ti	15607.055	0	0	0	0	0	0	0	0
Ni	15609.894	0	0	0	0	0	0	0	0
Ni	15636.875	1	0	0	0	0	0	0	1
Fe	15652.735	0	0	0	0	0	0	0	0
Cr	15684.297	0	0	0	0	0	0	0	0
Ti	15703.218	0	0	0	0	0	0	0	0
Ti	15719.816	0	0	0	0	0	0	0	0
Mg	15744.966	2	1	1	0	2	2	0	8
Mg	15753.152	1	2	1	1	2	2	1	10
Mg	15770.057	1	1	1	1	2	1	1	8
Mg	15883.487	0	0	0	0	0	0	0	0
Mg	15890.489	0	0	0	0	0	0	0	0
Mg	15893.775	0	0	0	0	0	0	0	0
V	15928.299	0	0	0	0	0	0	0	0
Mg	15958.785	1	0	0	0	0	0	0	1
Si	15964.372	2	2	2	0	2	2	0	10
Fe	15969.178	1	0	0	0	0	0	0	1
Cu	16010.022	0	0	0	0	0	0	0	0
Fe	16044.988	0	0	0	0	0	0	0	0
Si	16064.345	1	1	0	0	1	1	0	4
Si	16099.133	2	0	0	0	1	1	0	4
Ca	16141.180	0	0	0	0	0	0	0	0
Ca	16155.124	0	0	0	0	0	0	0	0
Fe	16157.608	0	0	0	0	0	0	0	0
Ca	16159.598	0	0	0	0	0	0	0	0
Ca	16161.726	0	0	0	0	0	0	0	0
Fe	16169.397	1	0	0	0	0	0	0	1
Si	16220.048	2	1	0	0	1	1	0	5
Ni	16588.917	0	0	0	0	0	0	0	0
Ni	16593.774	0	0	0	0	0	0	0	0
Ti	16639.652	0	0	0	0	0	0	0	0
Ni	16678.213	0	0	0	0	0	0	0	0
Si	16685.274	2	1	0	0	1	1	0	5
Al	16723.471	1	0	0	0	0	1	0	2
Co	16762.225	0	0	0	0	0	0	0	0
Al	16767.885	0	0	0	0	0	0	0	0
Ni	16820.011	0	0	0	0	0	0	0	0
Ni	16823.301	0	0	0	0	0	0	0	0
Si	16832.703	0	0	0	0	0	0	0	0
	Sum	22	9	5	2	12	12	2	

Cataloged lines in RR Lyrae by phase in metal-rich and metal-poor stars.
=> Goal is to reduce scatter by changing elemental windows.

Beyond RR Lyrae …

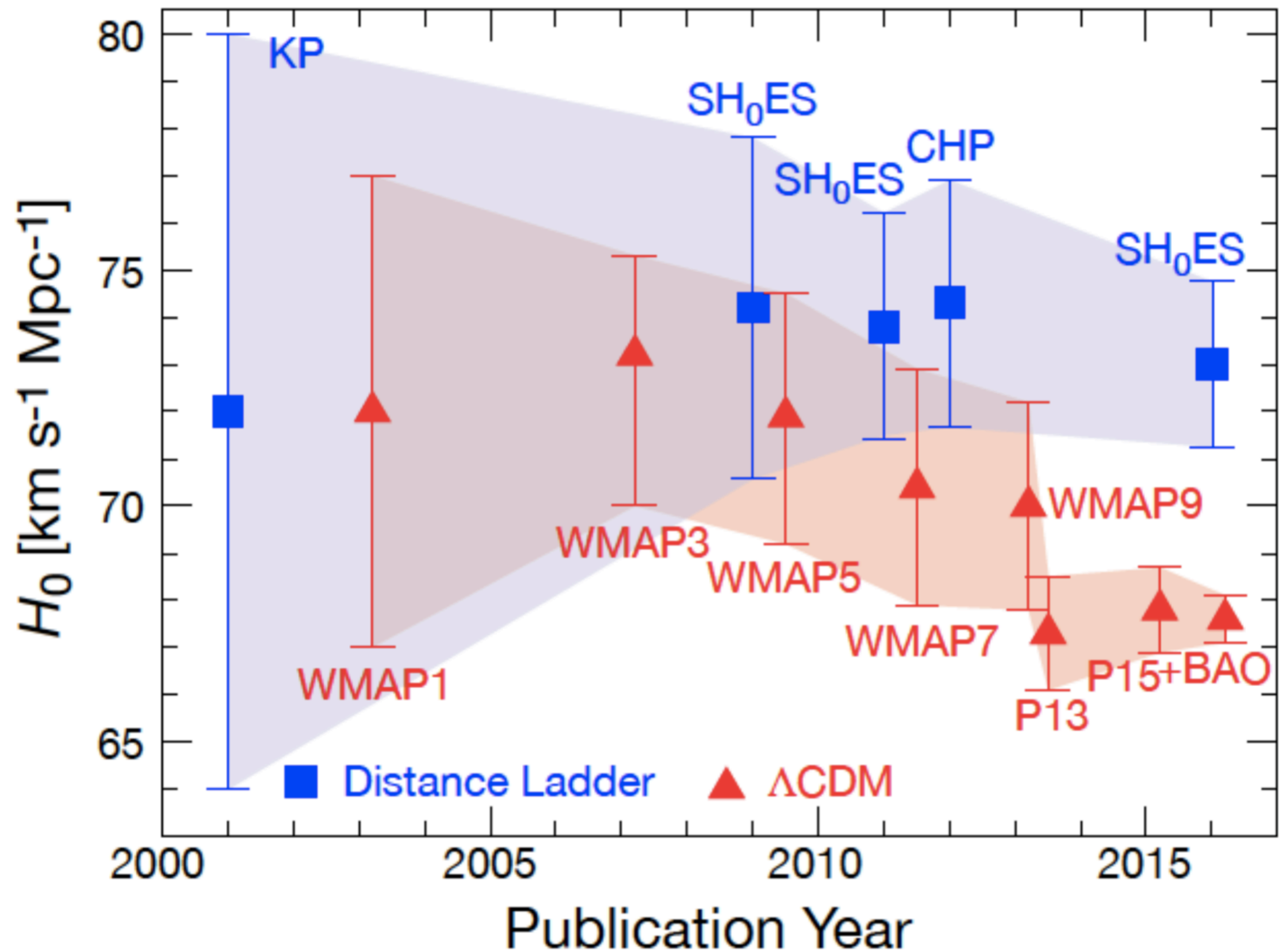
https://www.sdss.org/education/faculty-and-student-team-fast-initiative/

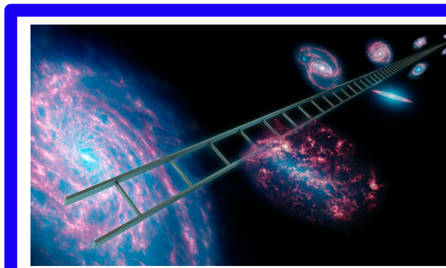
Jordan Brown Dr. Jennifer Cash
Tuesday Cabang Ramon Lavender

Goal: Find the variables with spectra and, if needed, modify the the spectra and/or analysis to work for these stars to get physical parameters and chemistries.

The Hubble Constant

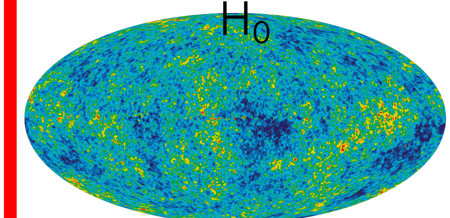
Exotic Dark Energy? Or just systematics we never knew we never knew?





Distance Ladder
Local Universe+Direct H_0

CMB Modeling
Young Universe+InDirect H_0



Freedman 2017
Beaton et al. 2016

The Hubble Constant

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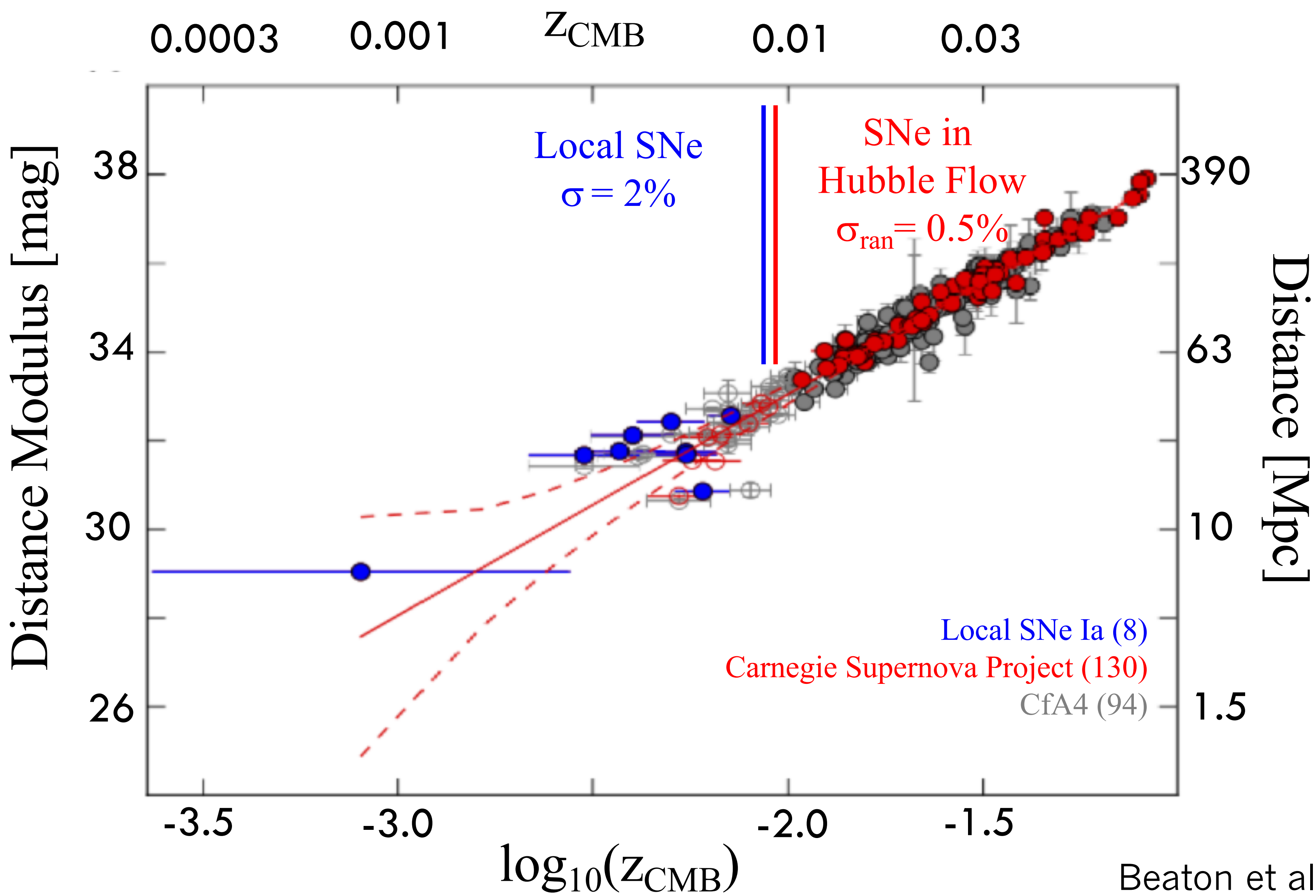

Beaton et al. 2016
Czerny, Beaton et al. 2018

The Hubble Constant

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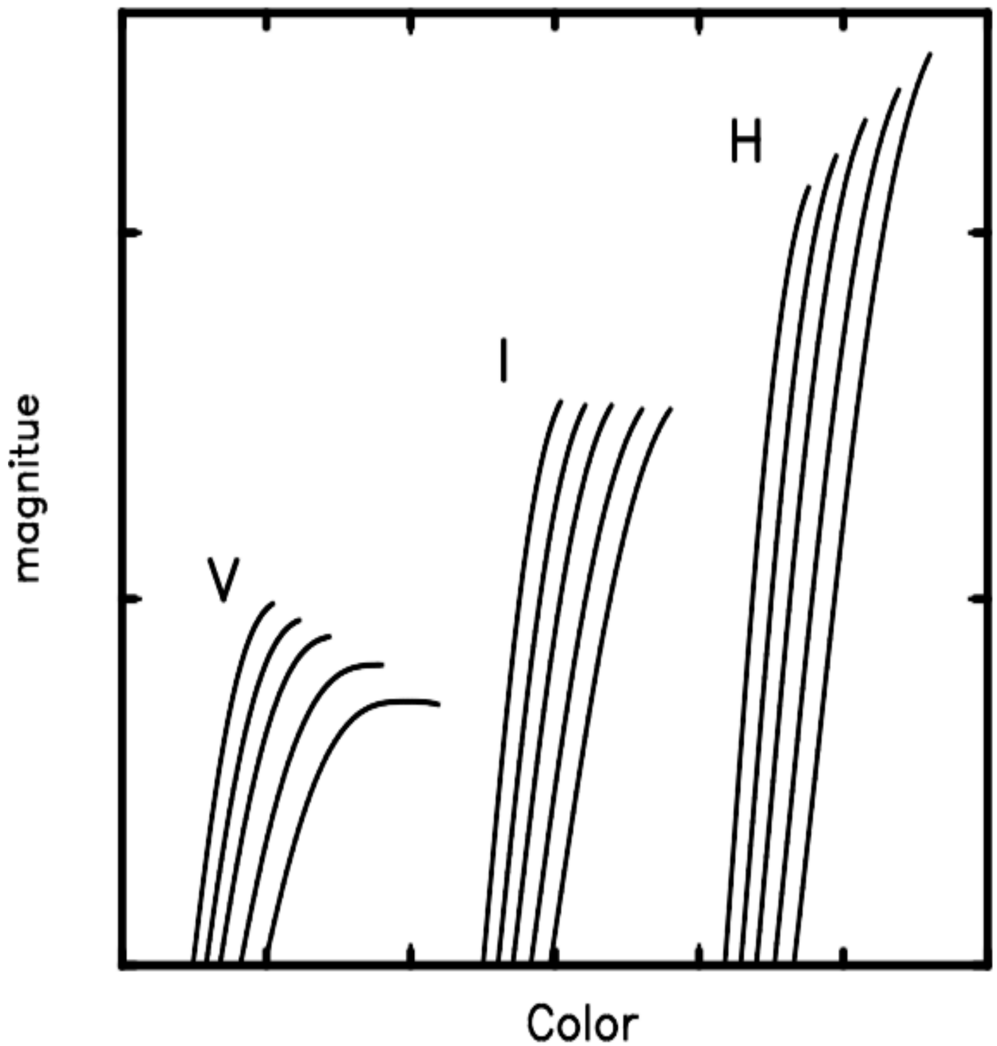


Madore et al. (2018 ArXiv:1803.01278)

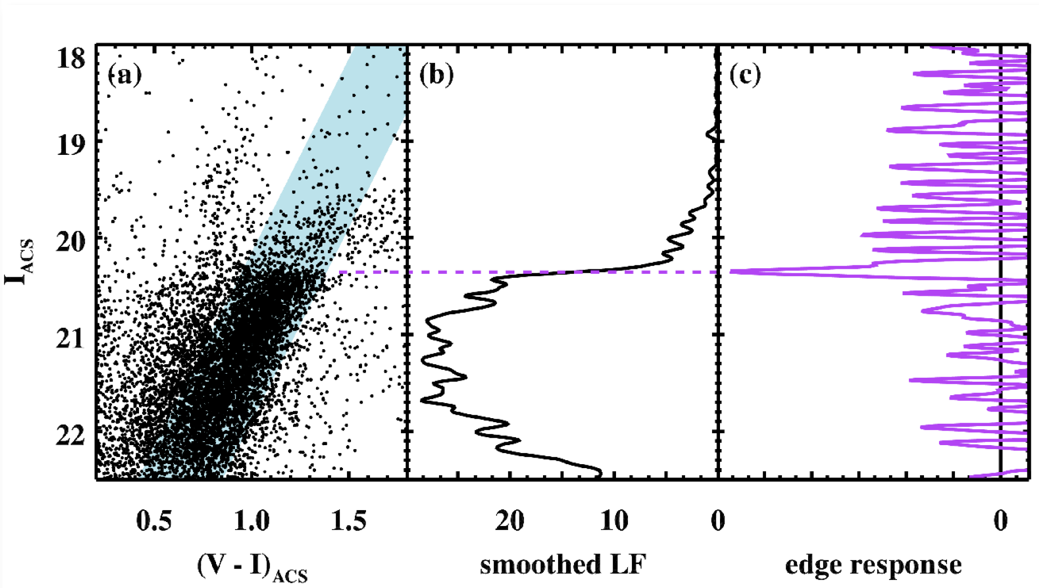
The Hubble Constant

Exotic Dark Energy? Or just systematics we never knew we never knew?

Dylan Hatt
PhD @ UChicago
Now: Data Science

In Sung Jang
PhD/Now Postdoc@AIP

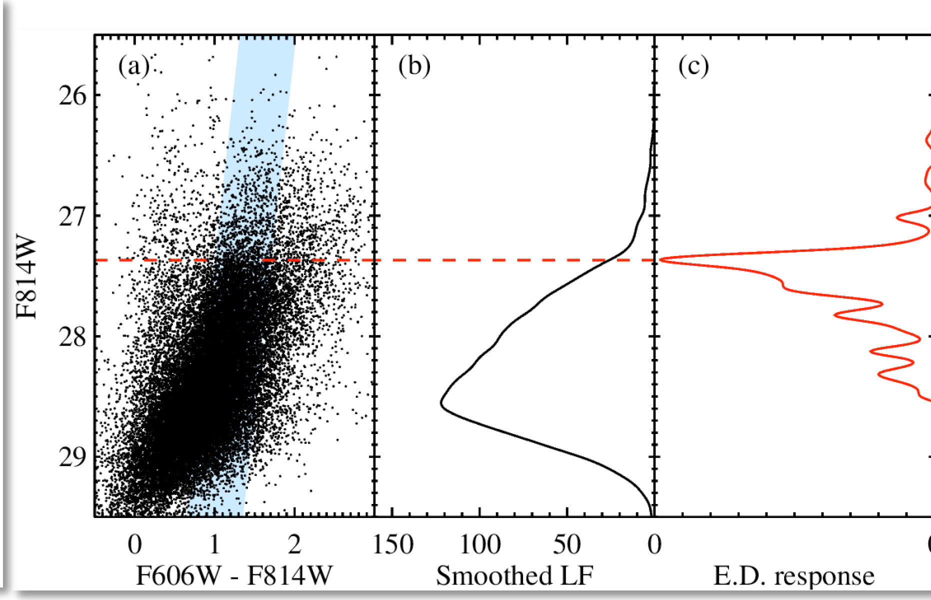
NEAR-FIELD



D = 784 ±17 (stat) ±40 (sys) kpc

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

FAR-FIELD



D = 18.1 ±0.3 (stat) ±0.5 (sys) Mpc

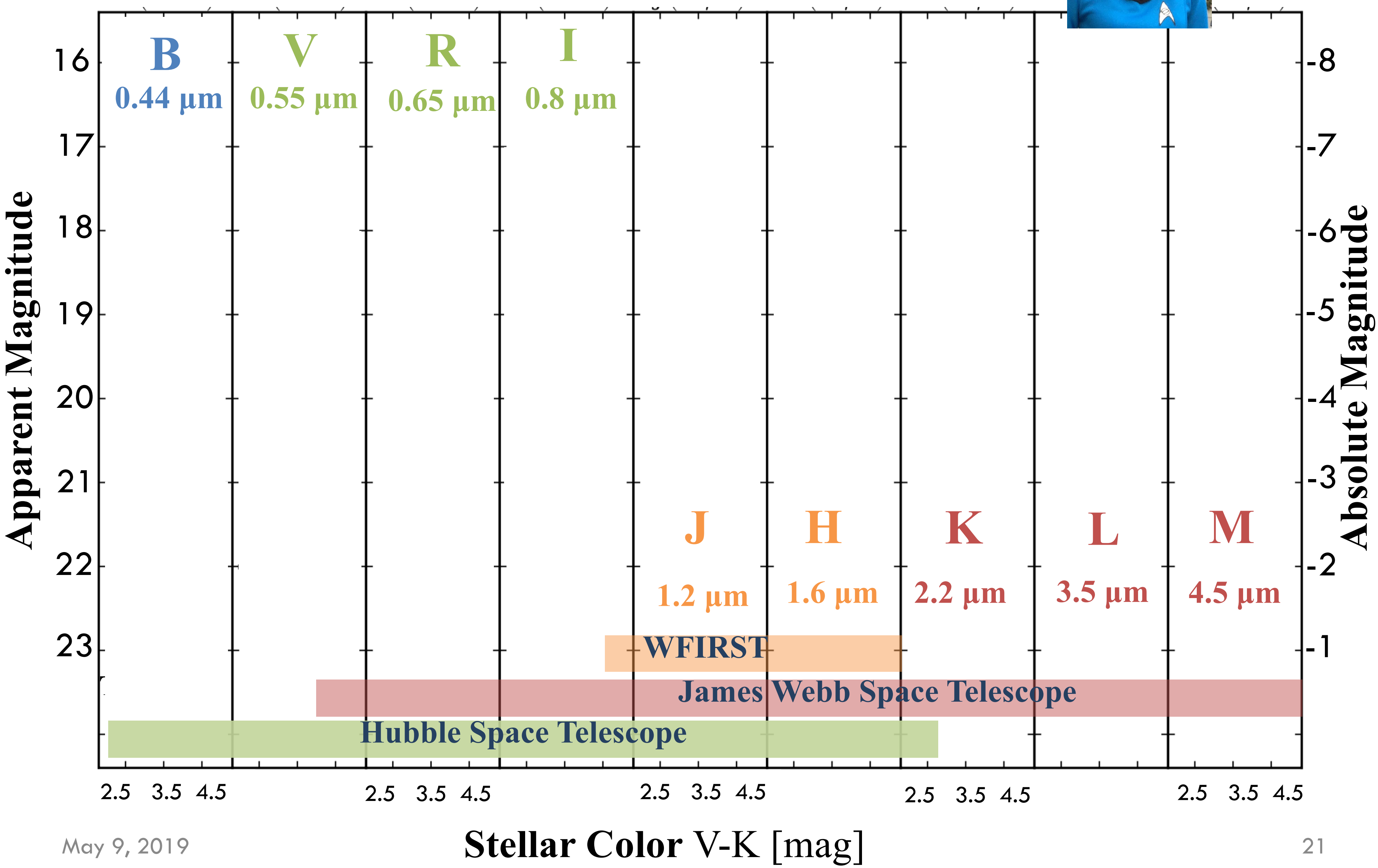
μ_0 = 31.29 ±0.04 (stat) ±0.06 (sys) mag

Hatt, Beaton et al. (2017)
ArXiv:1703.06468

Jang, Hatt, Beaton et al. (2018)
ArXiv:1703.10616

Beyond Optical ...

Erica Carlson
OCIS Intern
Now:
Science
Journalist



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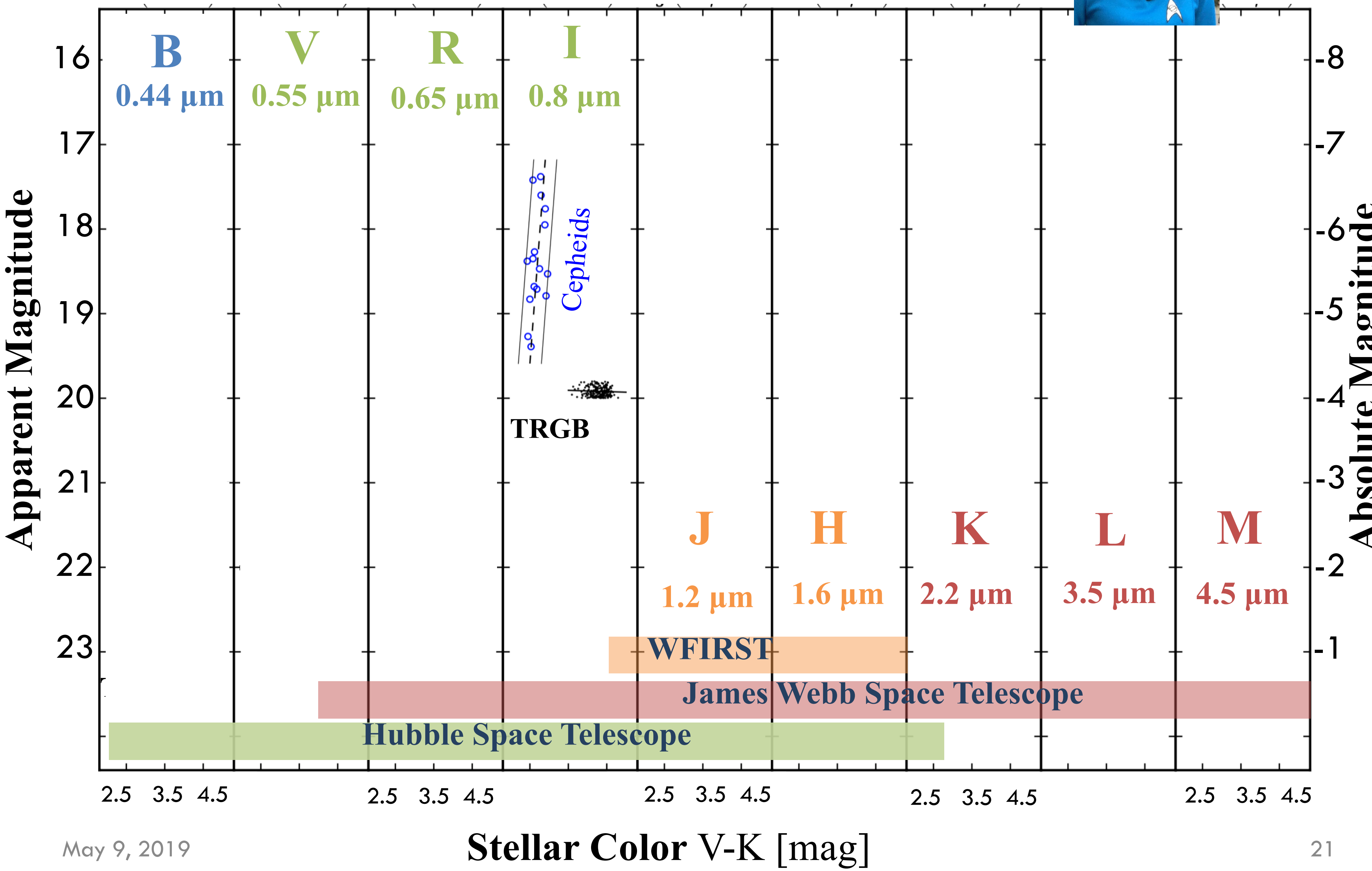

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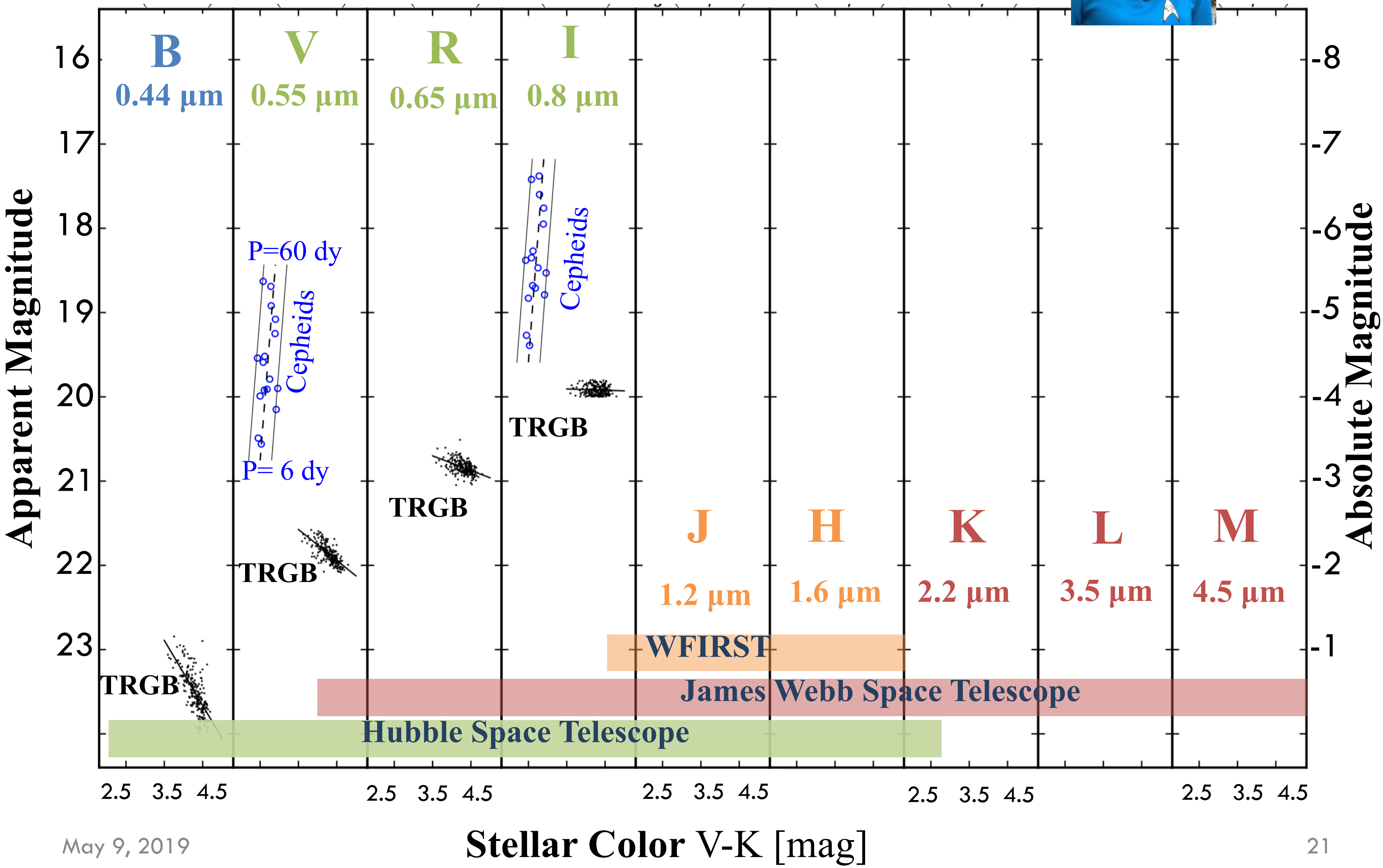

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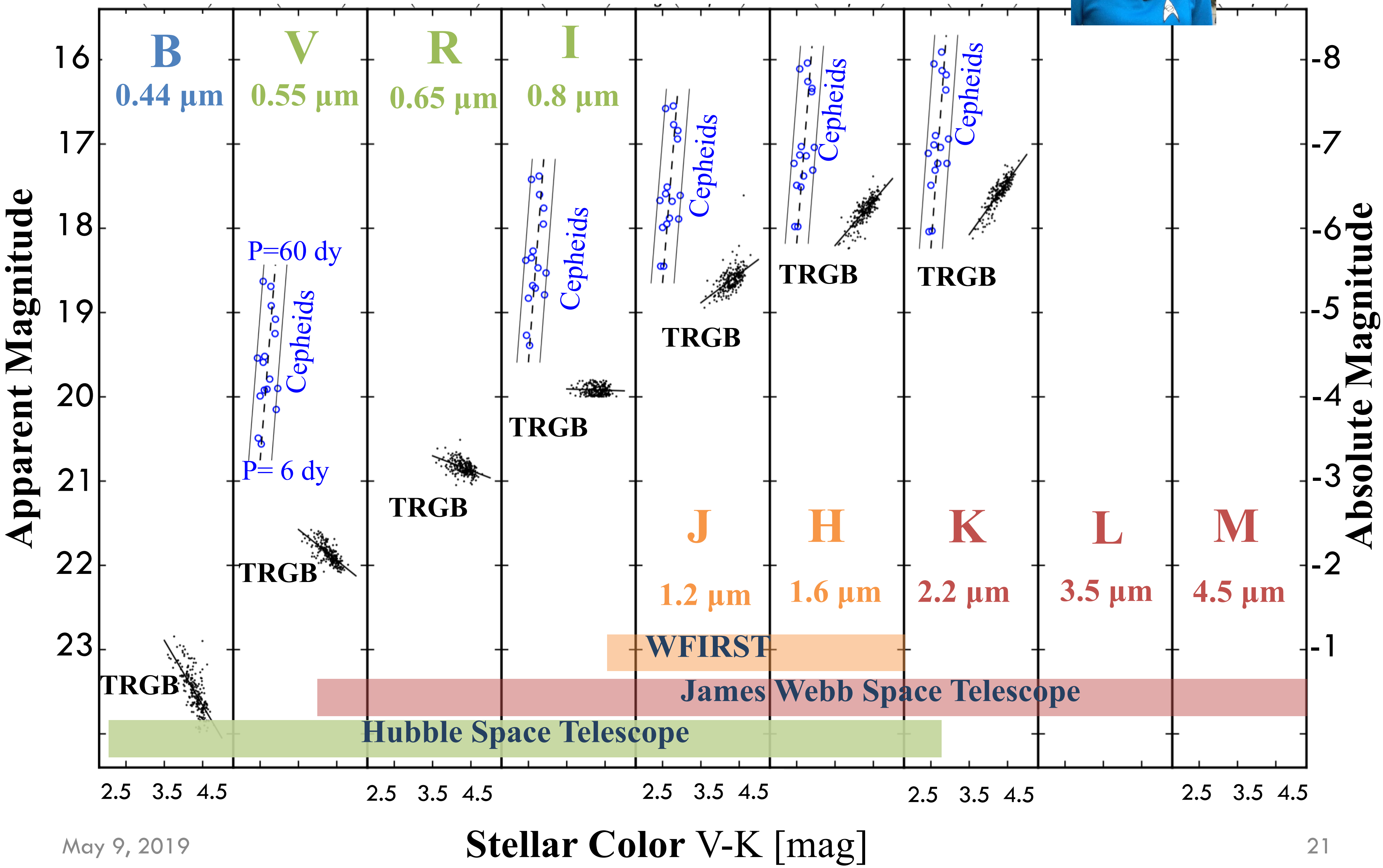

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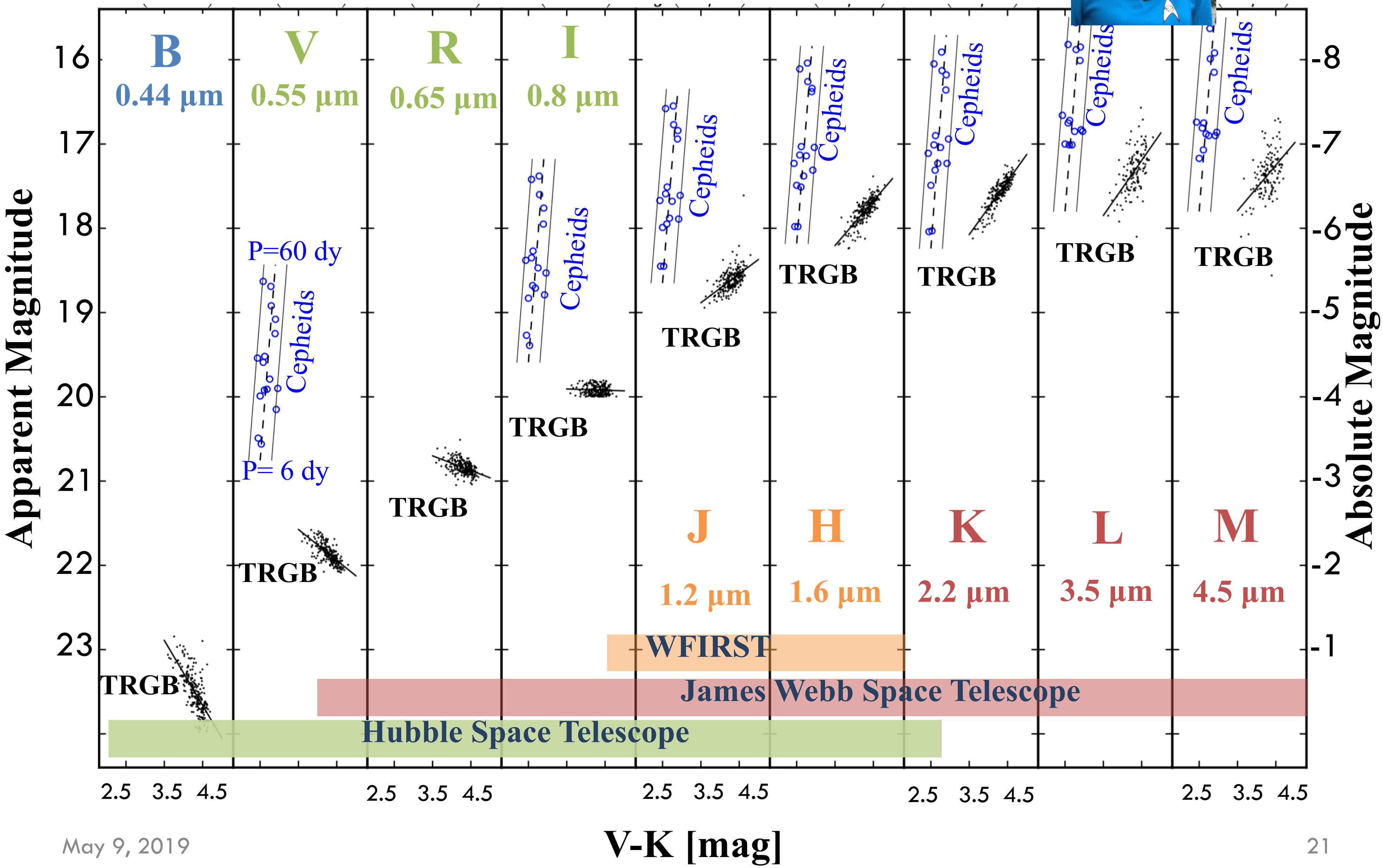
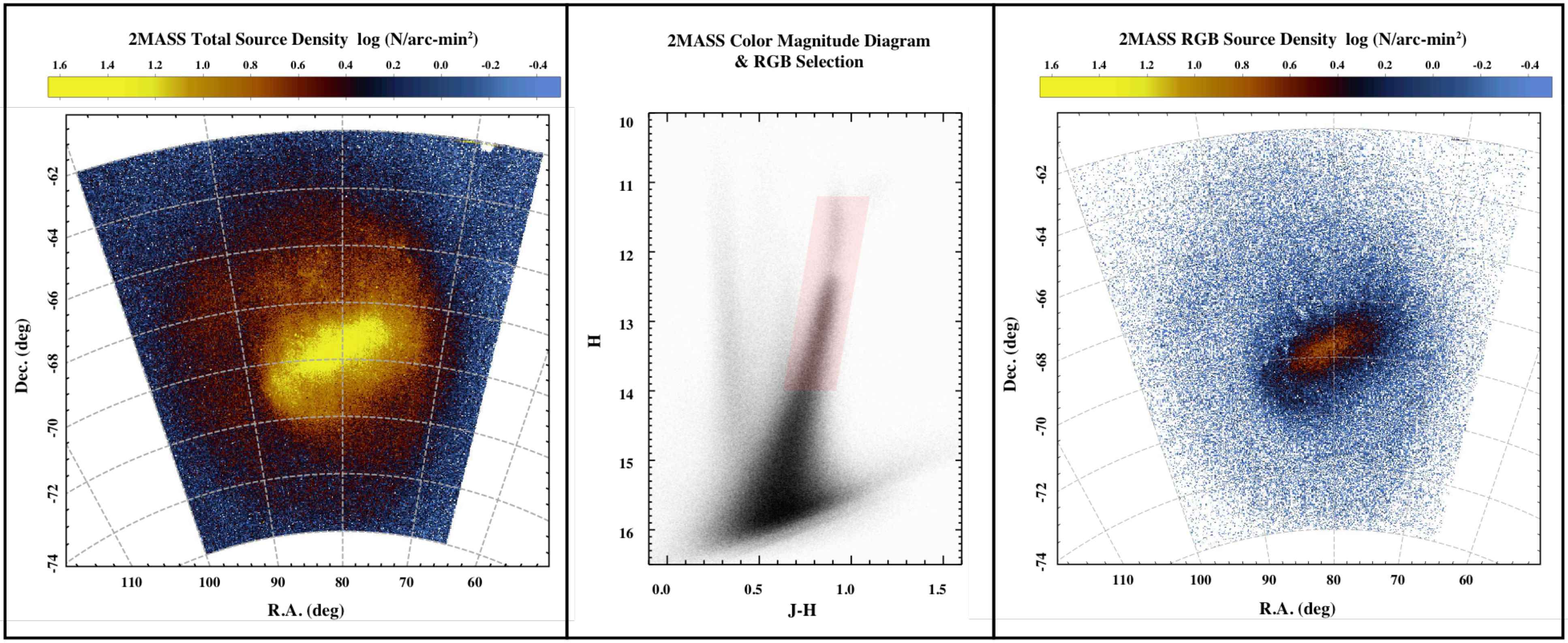


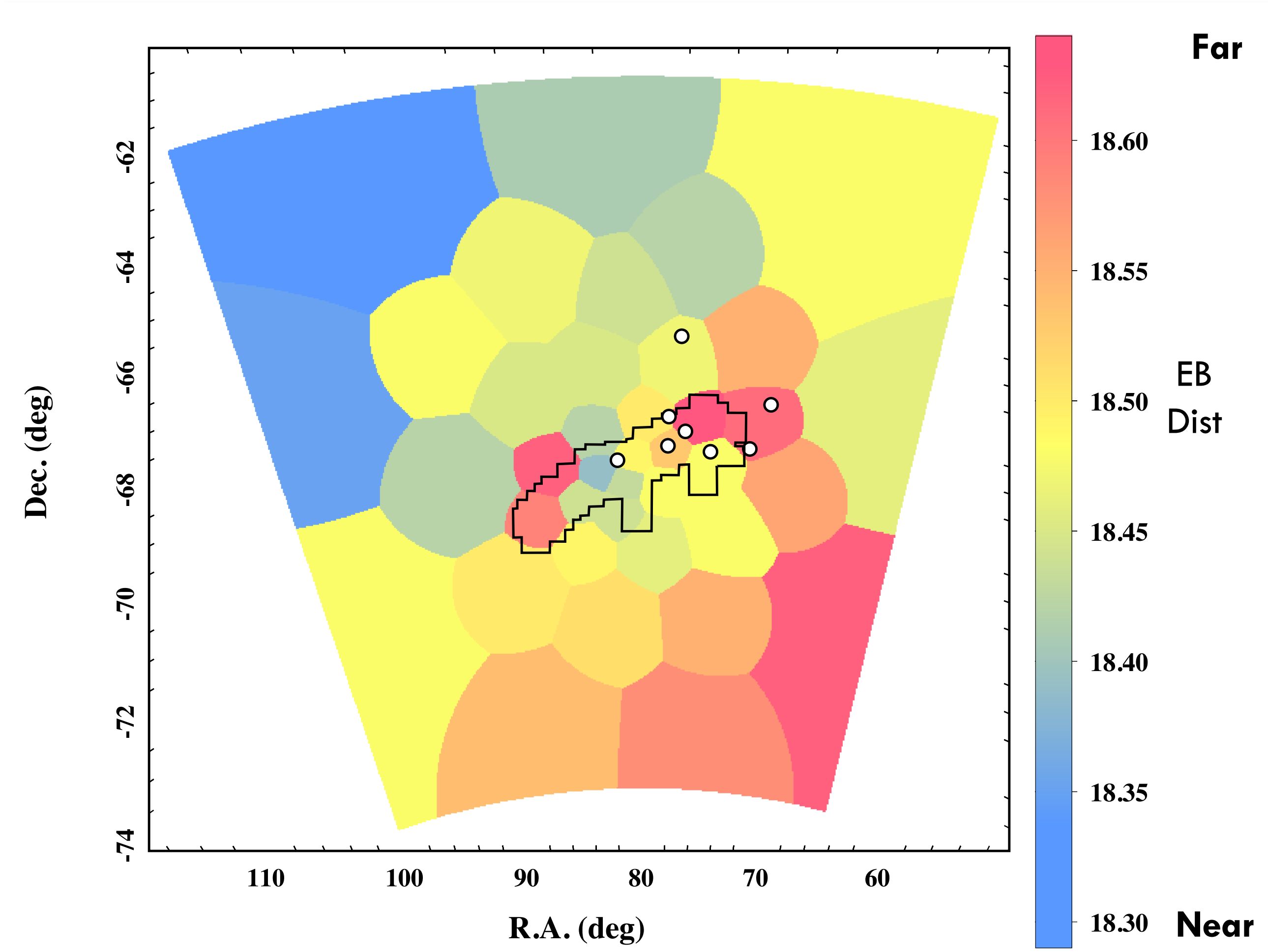
And it works!

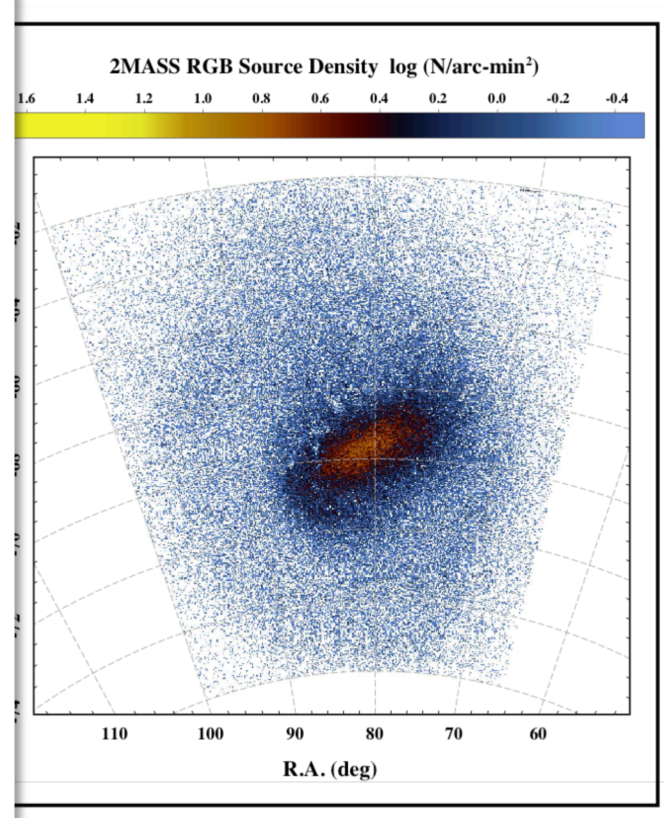
Taylor Hoyt
Grad @ U. Chicago



Hoyt et al. (2018 ArXiv:1803.01277)

And it works, well.



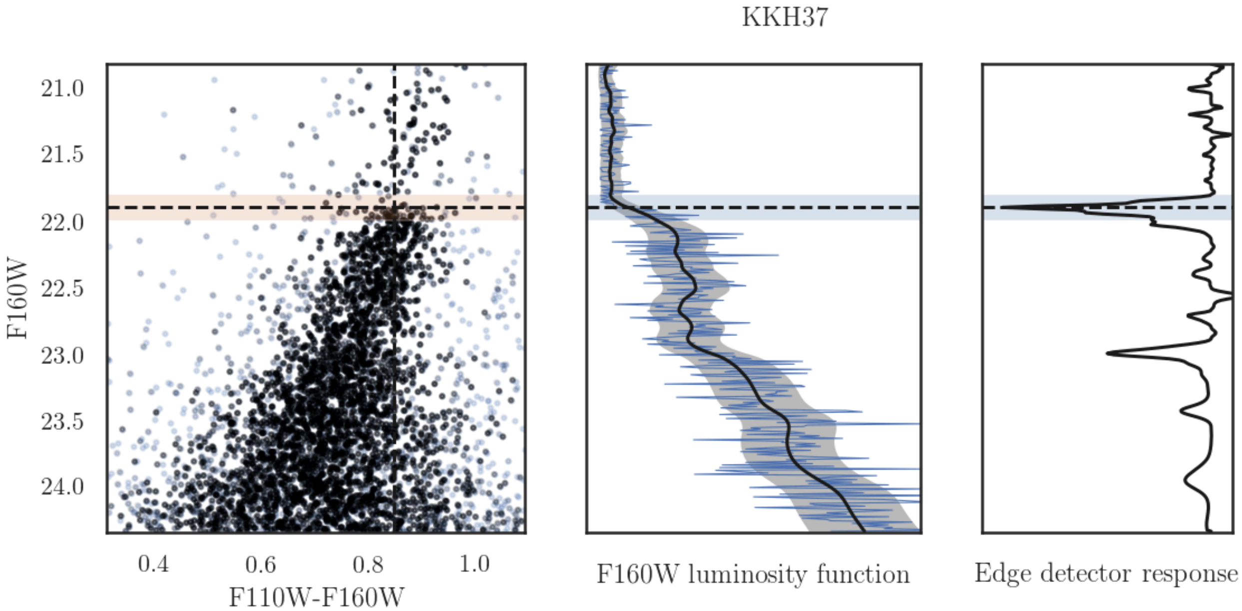


We see the inclined disk discussed in Yumi Choi's Talk *and a little bit more actually.*

Hoyt et al. (2018 ArXiv:1803.01277)

And it works!

Meredith Durbin
Grad @ UWashington



Currently, reanalyzing Dalcanton et al. 2012 dataset to make an IR-TRGB experiment lab for a range of SFH, densities, S/N, etc… !!

	HLS Wide	HLS Deep	SN Wide	SN Deep
Mag	26.95	28.2	28.3	29.4
Dist. Mod	32.95	34.2	34.3	35.4
Distance	39 Mpc	70 Mpc	72 Mpc	120 Mpc

Work in haloes at low stellar density. Area = Statistics.
Literally, map out the local matter density …

Exotic Dark Energy? Or just systematics we never knew we never knew?

CHALLENGE:

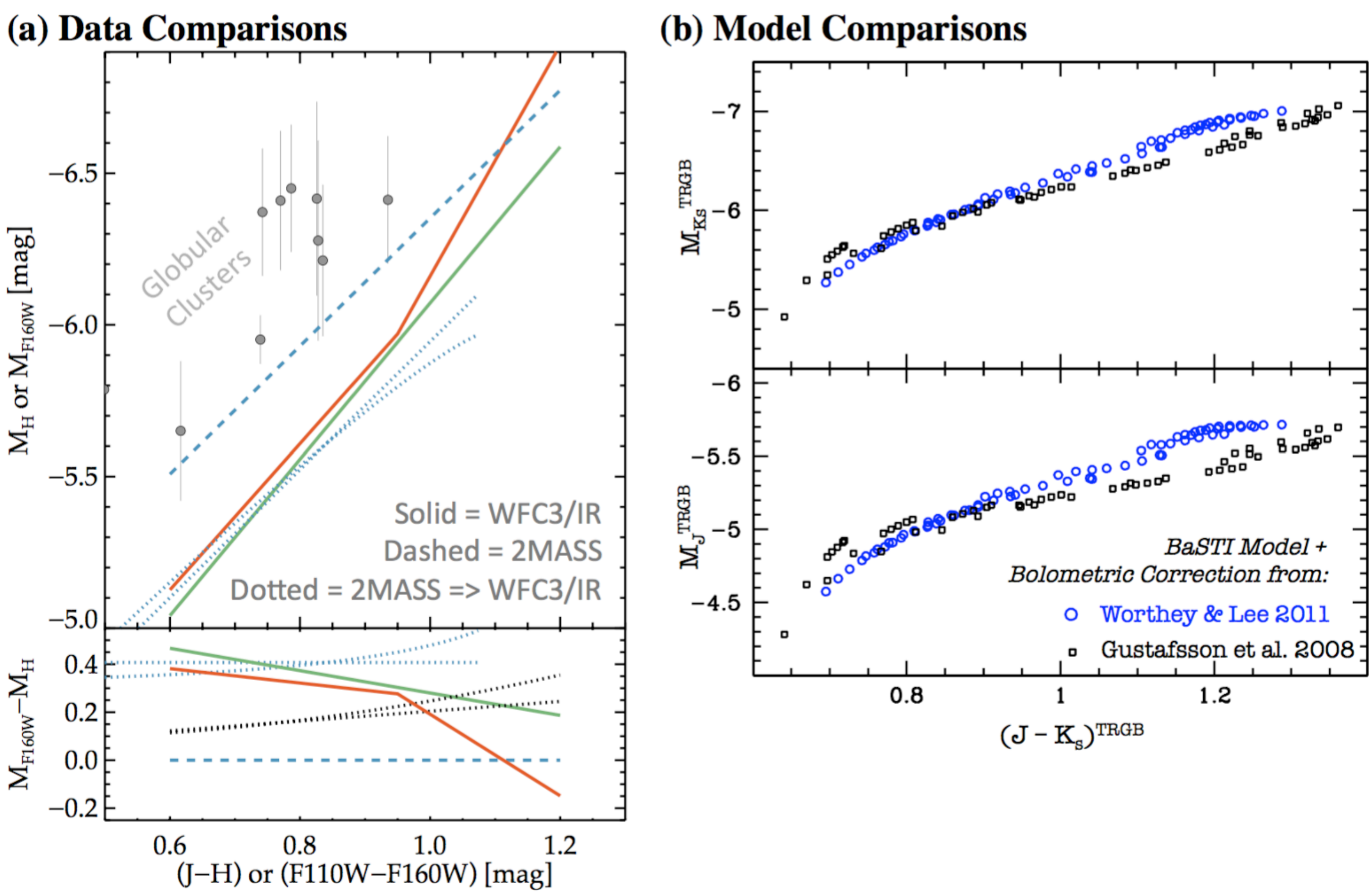
To calibrate in the Galaxy, you need wide-fields.

To calibrate outside of the Galaxy, you need independent distances.

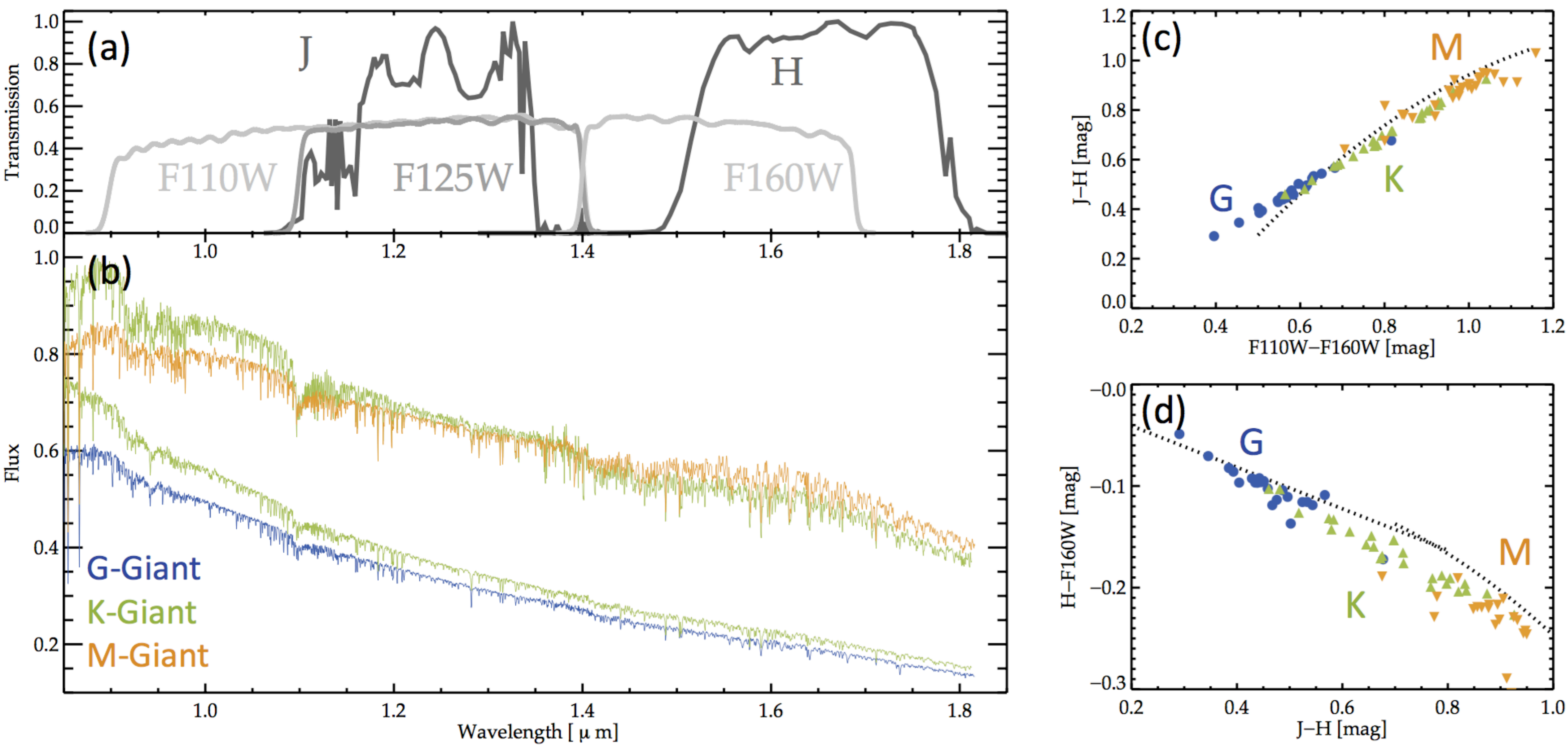
2MASS and HST filters are REALLY different, and it matters.

Bolometric corrections in synthetic spectra are uncertain, and it matters.

Challenge: Infrared TRGB



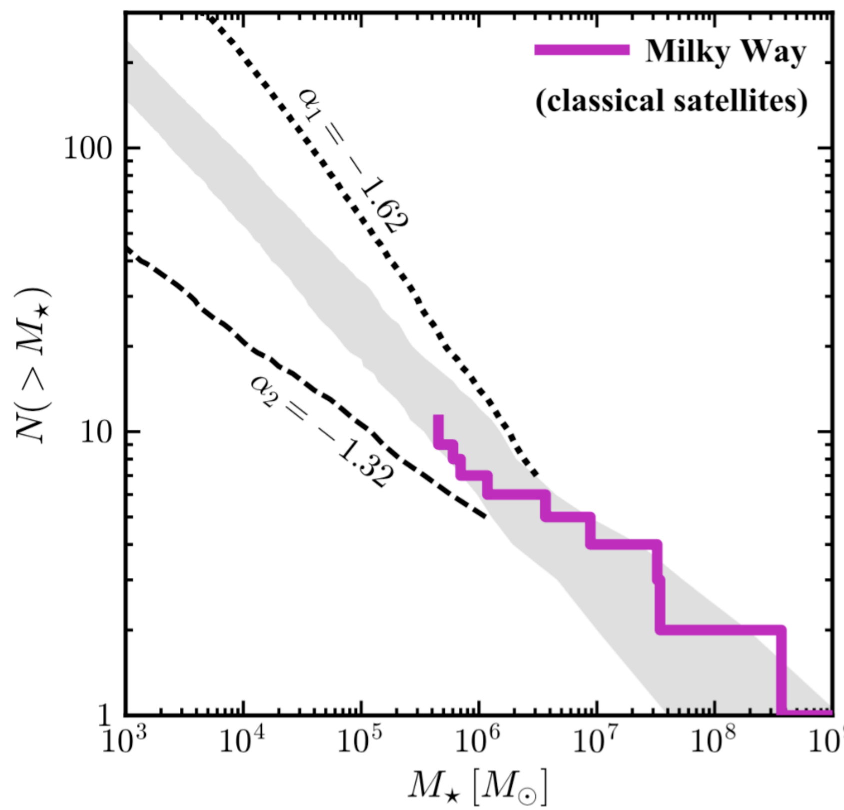
Challenge: Infrared TRGB



Work by Bianca Swindler
Princeton Undergrad

Satellite Luminosity Functions

Λ-CDM on its smallest scales with statistical rigor.



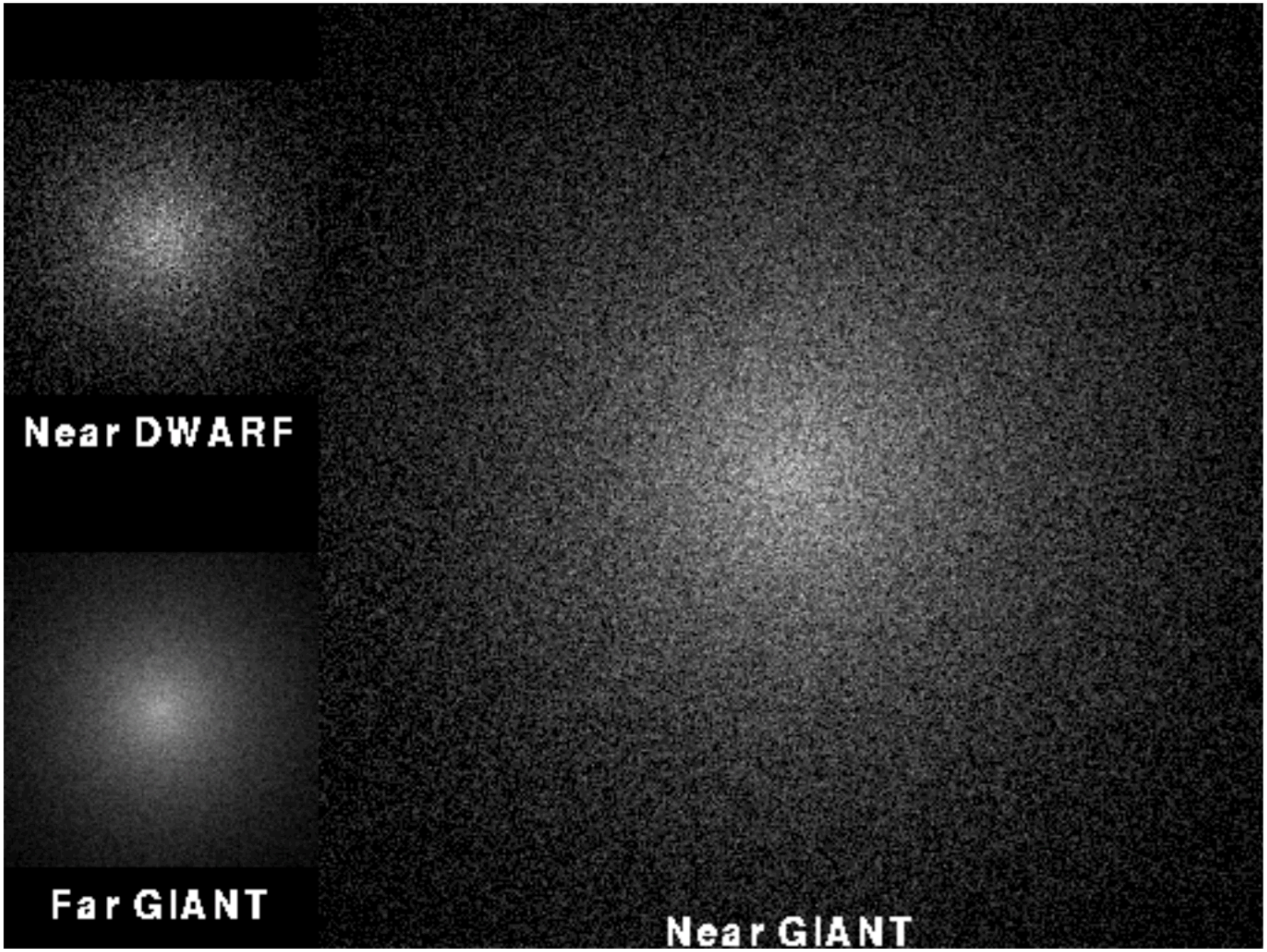
Bullock & Boylin-Kolchin 2017

Satellite Luminosity Function

Scott Carlsten (Grad @ Princeton)
Rachael Beaton (Postdoc @ Princeton)
Johnny Greco (Postdoc @ Ohio State)
Jenny Greene (Princeton)

Satellite Luminosity Functions

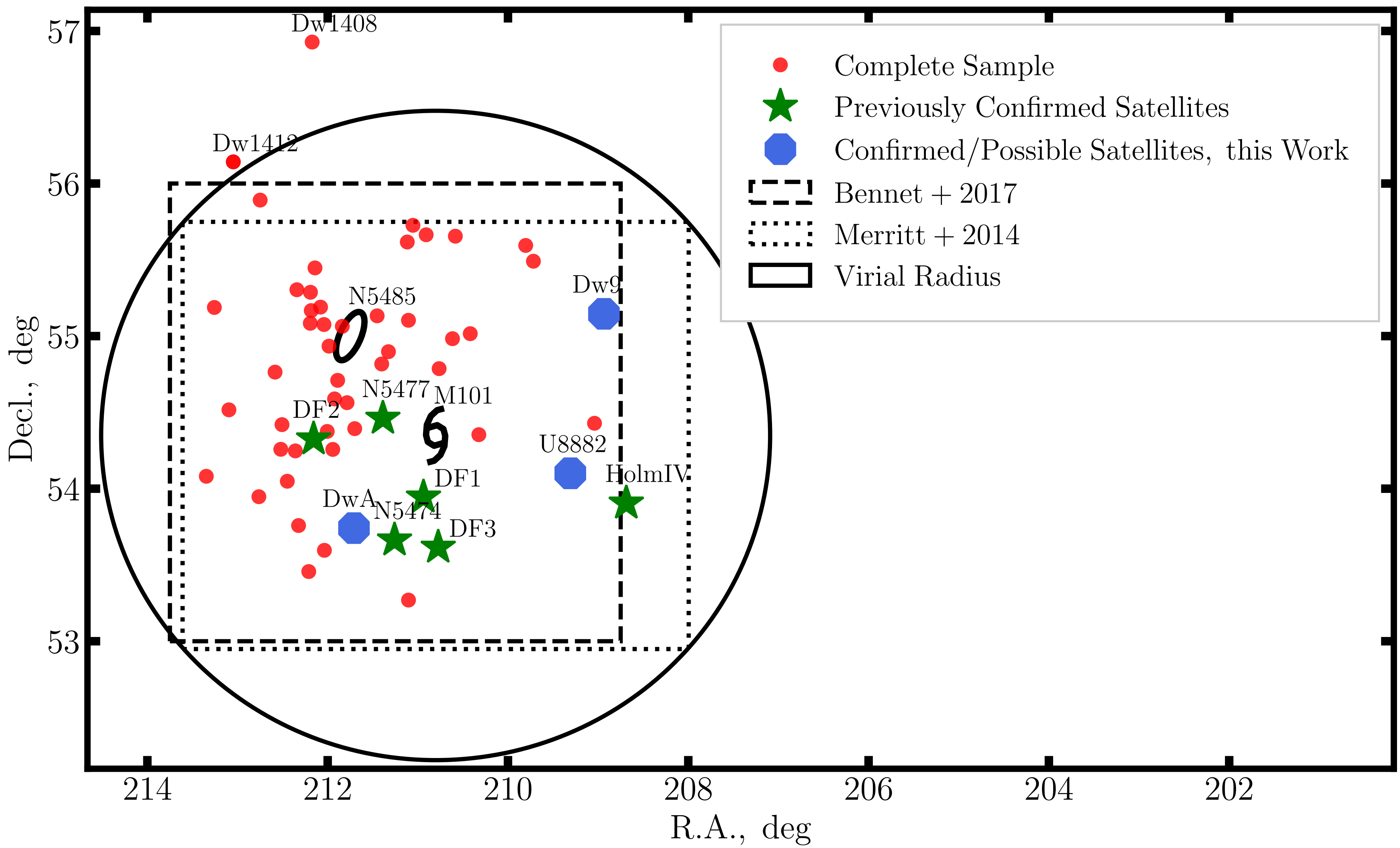
Λ-CDM on its smallest scales with statistical rigor.



Greco et al. 2018, 2019

Satellite Luminosity Functions

Λ-CDM on its smallest scales with statistical rigor.



Rachael L. Beaton

Carlsten et al. 2019b

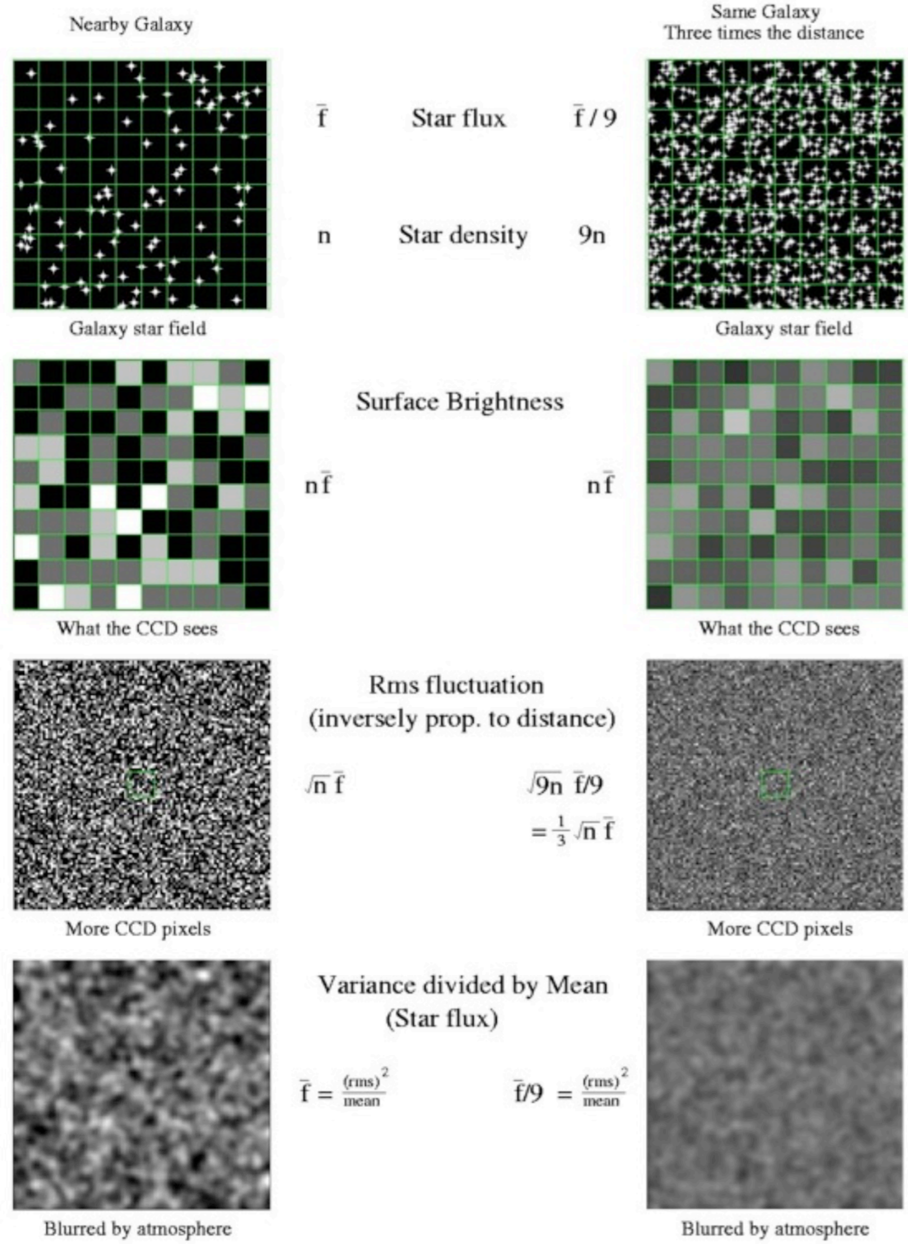
Satellite Luminosity Functions

Λ-CDM on its smallest scales with statistical rigor.

Surface Brightness Fluctuations illustrated

$$\bar{L} = \frac{\langle L_*^2 \rangle}{\langle L_* \rangle}$$

Tonry & Schneider 1988
Cervino et al. 2008
Blakeslee et al.1999, 2009



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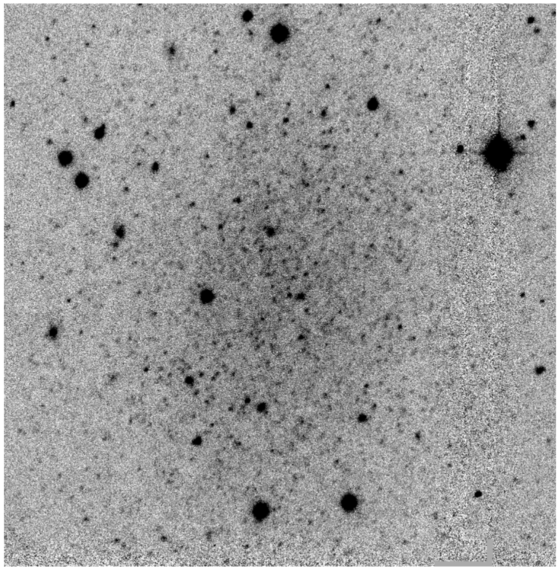
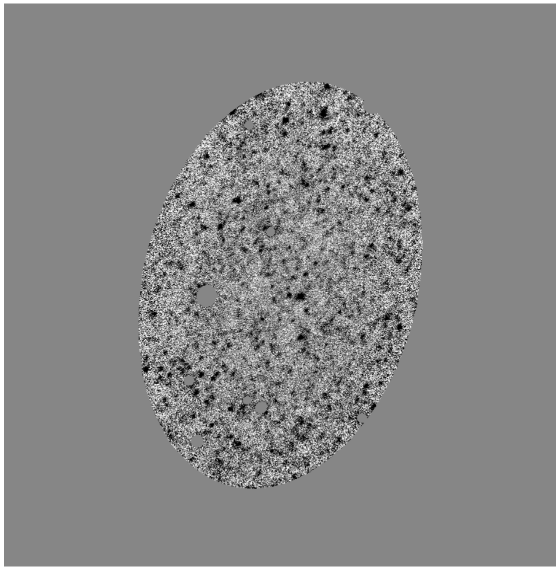
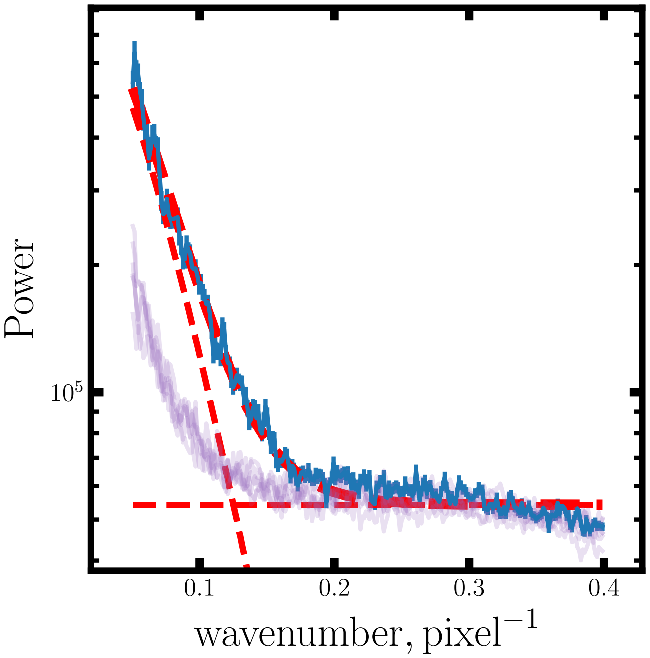
Surface Brightness Fluctuations







Carlsten et al. 2019a

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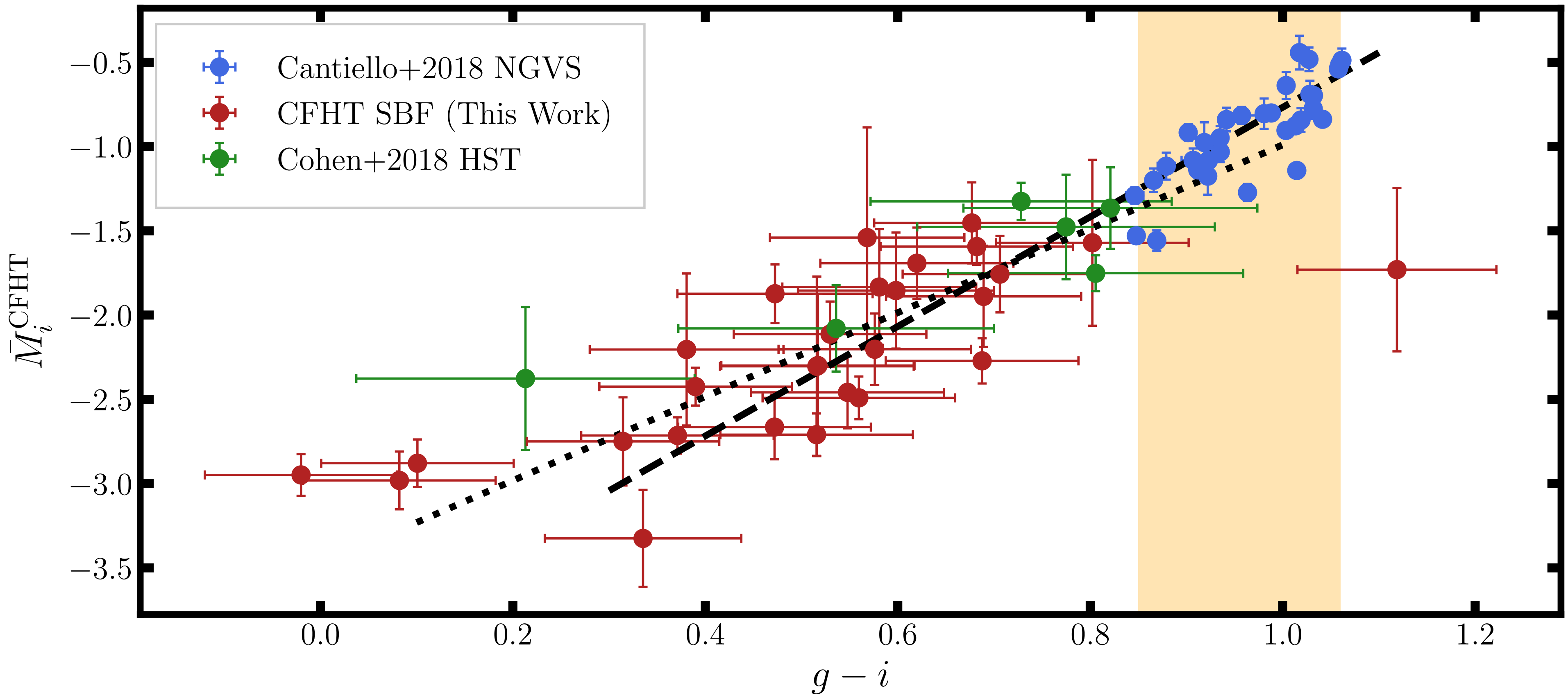

~27 dwarf galaxies in the CFHT archive with TRGB based distances

==> push into the blue

Rachael L. Beaton

Carlsten et al. 2019a

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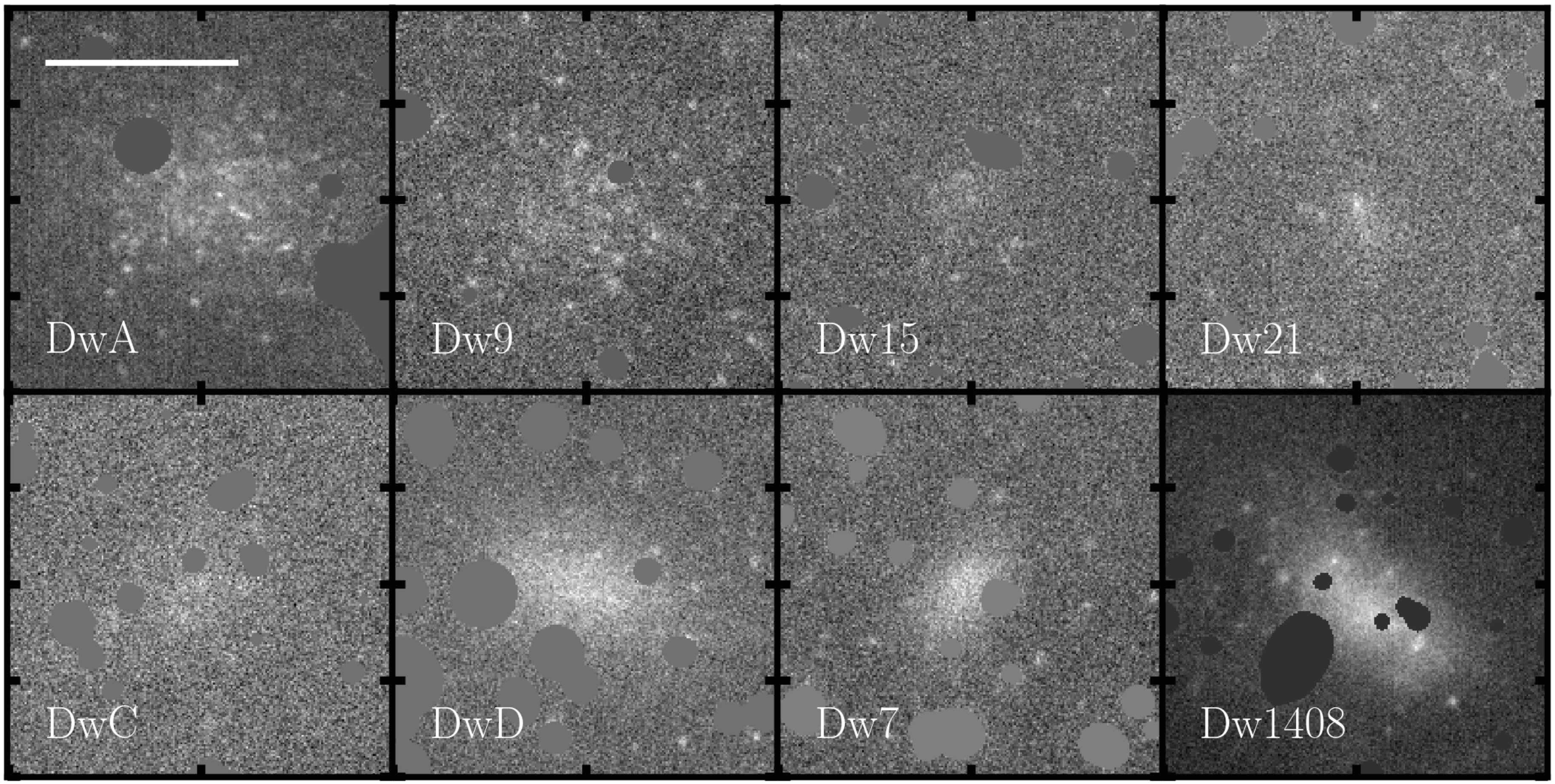
Examples of dwarf galaxies around M101:



Carlsten et al. 2019b

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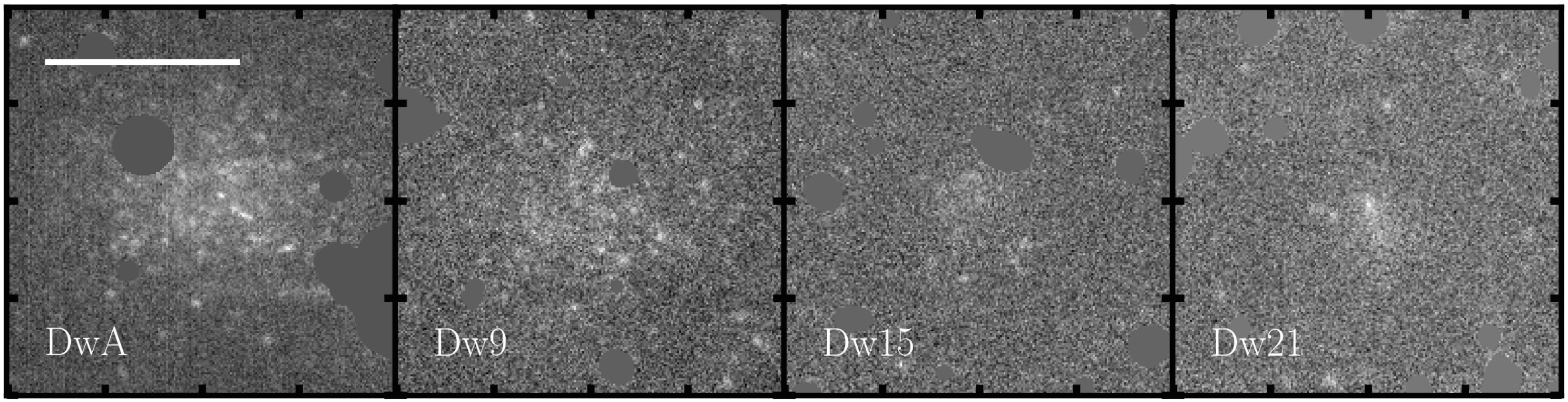
Examples of dwarf galaxies around M101:



SBF | SBF | Marginal Signal | Marginal Signal

~1 hour integrations with a 4-meter telescope
vs 1-2 orbits HST

Carlsten et al. 2019b

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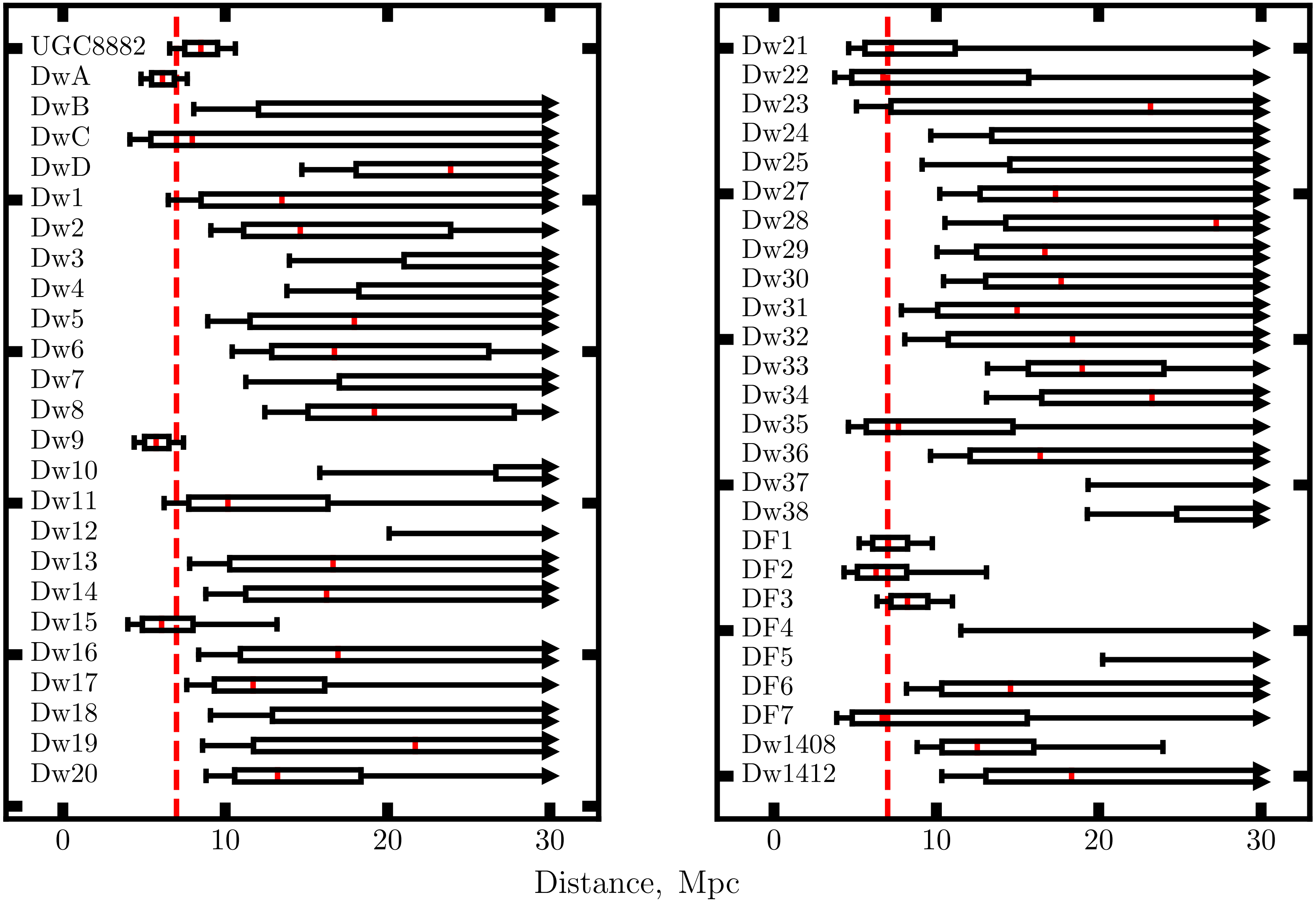

Carlsten et al. 2019a

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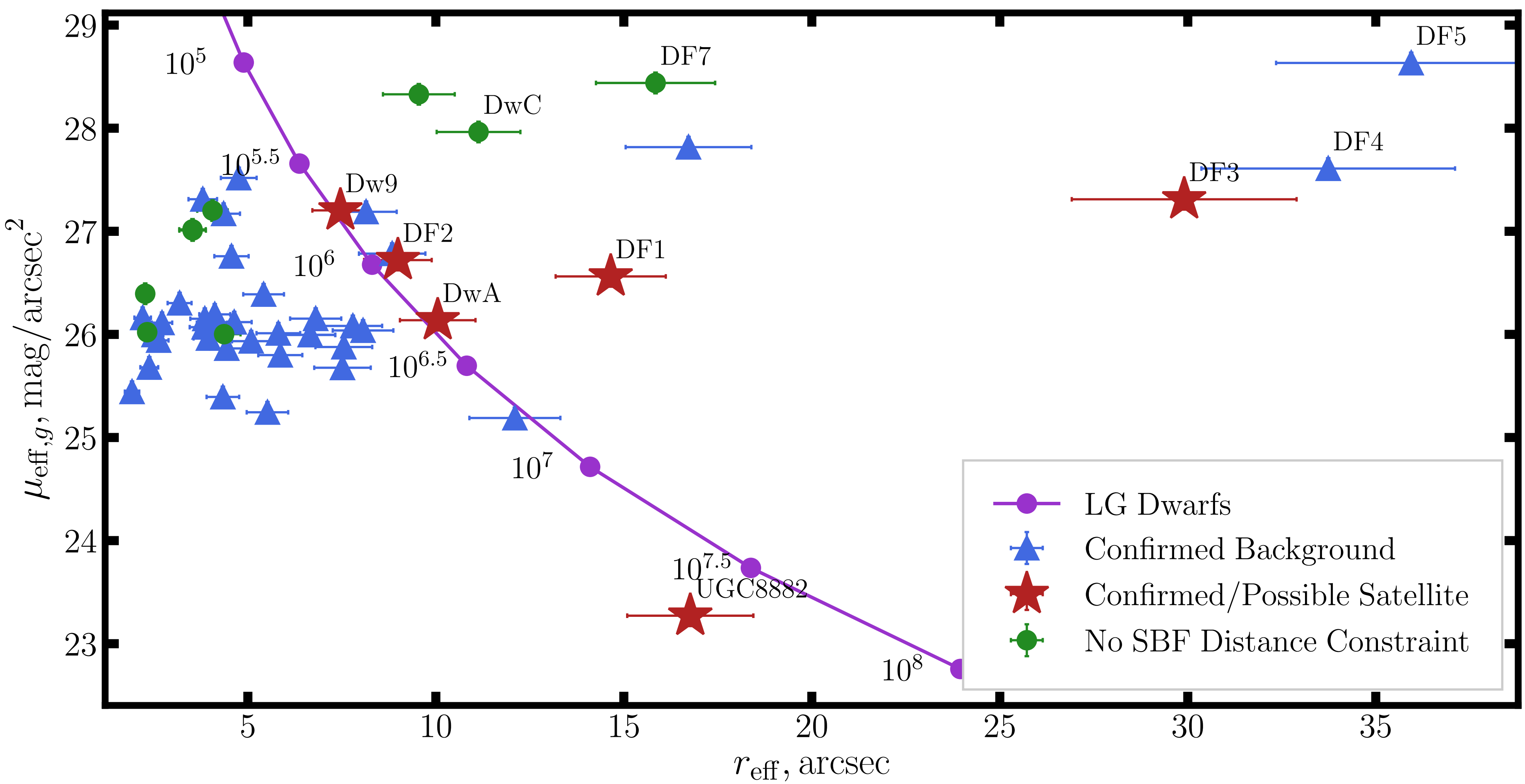

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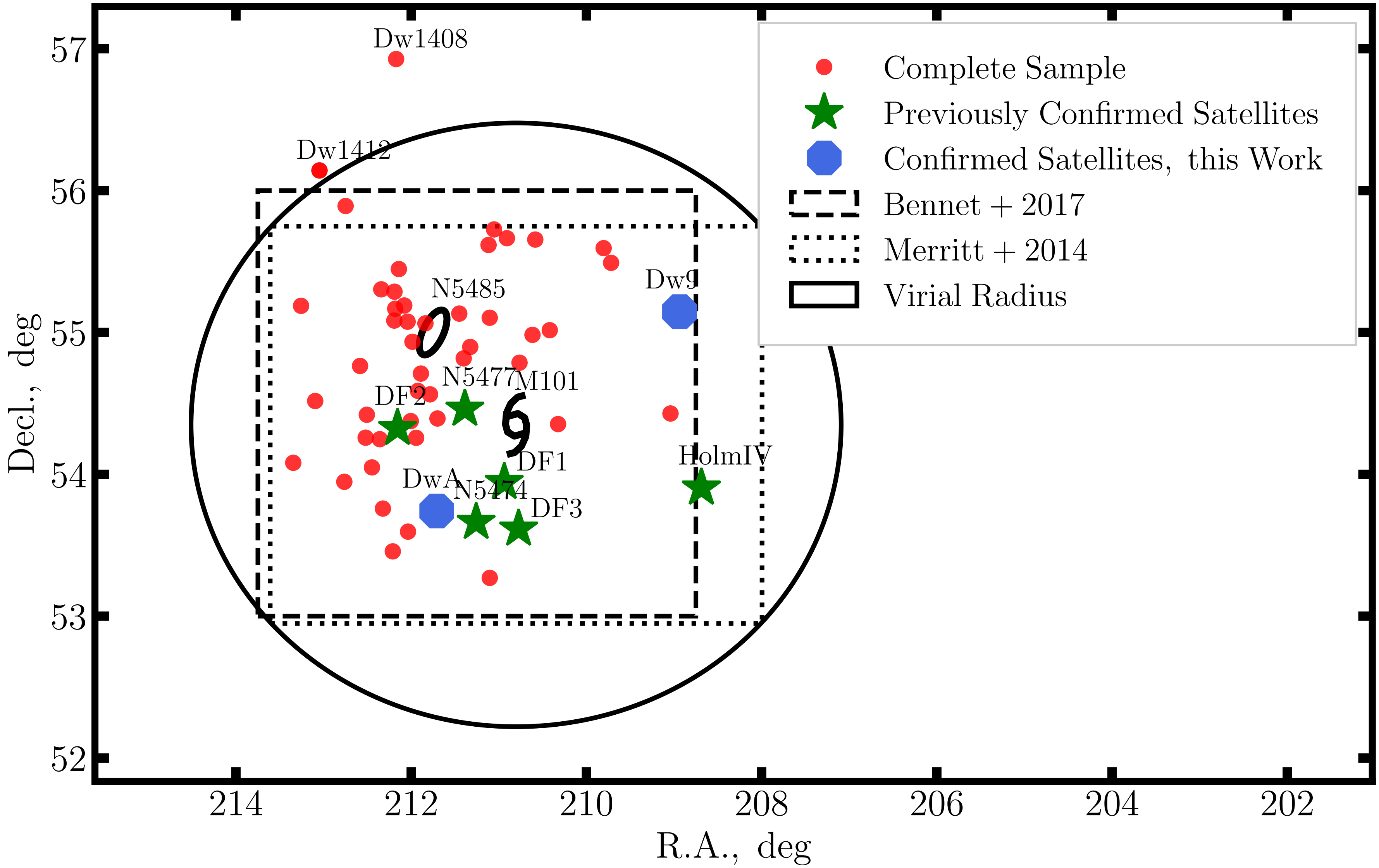

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Satellite Luminosity Functions

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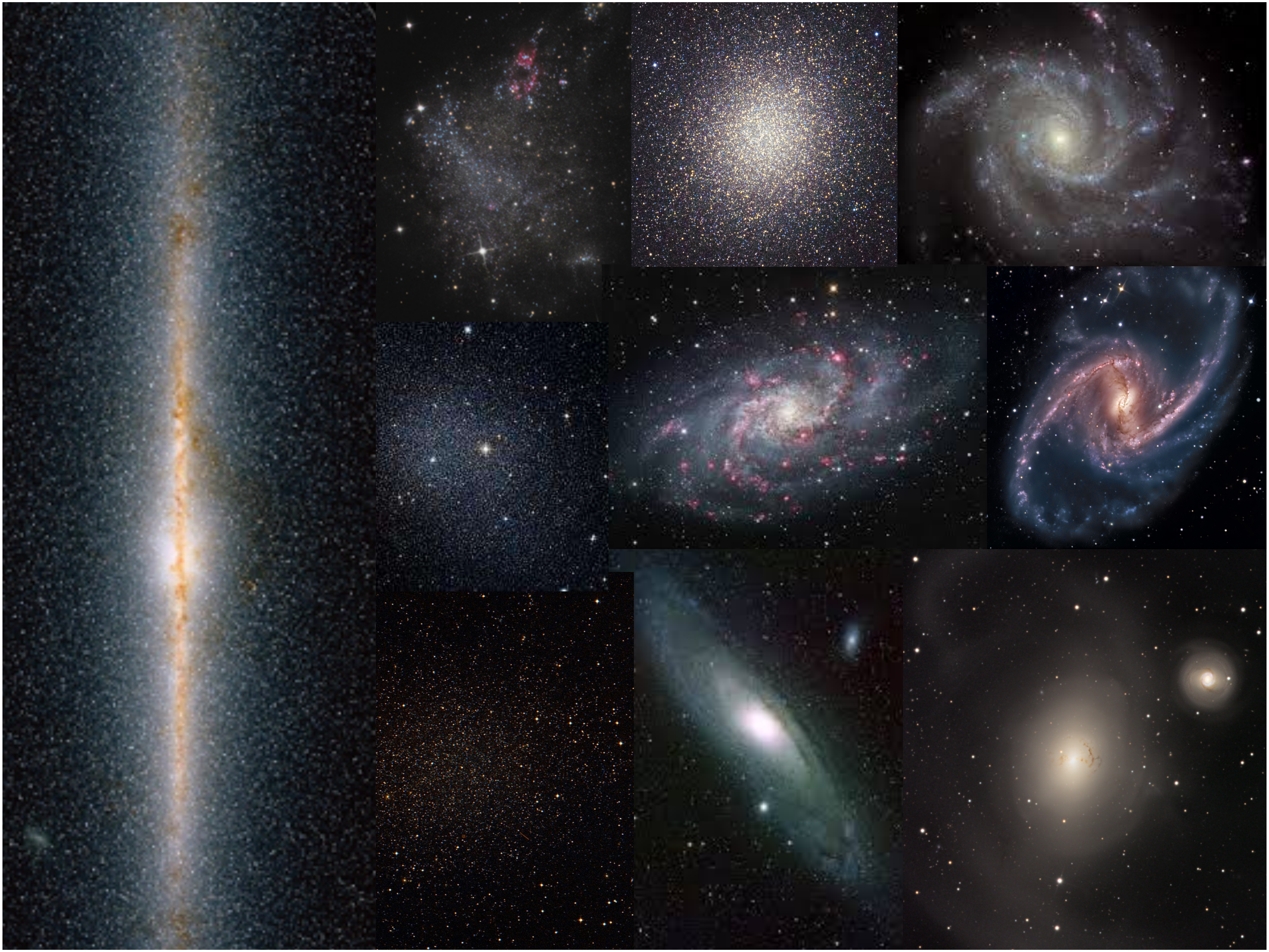
Application of SBF is a function of: (i) SB background fluctuations, (ii) PSF stability, and (iii) spatial resolution.

CHALLENGE:

Continue pushing and calibrating the technique.

Carlsten et al. in prep.



WFIRST Distances Summary

RR Lyrae	Distance to individual stars potentially to ~few percent per star.
Tip of the Red Giant Branch	Distances using resolved stars in halos to great distances.
Surface Brightness Fluctuations	Distances to unresolved things to great distances.

Conclusions

Hierarchical Formation of our own Galaxy

RR Lyrae probe local structure to probe really small scale physics.

The Hubble Constant

Exotic Dark Energy? Or just systematics we never knew we never knew?

Satellite Luminosity Functions

Λ-CDM on its smallest scales with statistical rigor.