The Astrophysics of the Cosmic Distance Scale

WHY DISTANCES?

- In Observational Astronomy, we measure apparent quantities and angular quantities.

- But to do Physics, we measure absolute measurements and physical scales.

DISTANCES TRANSLATE BETWEEN OBSERVED AND PHYSICAL UNITS

WHY DISTANCES?

Translate from angular to physical sizes

- Physics at High Angular Resolution in Nearby Galaxies (PHANGS) Survey: Anand et al. 2021 (distances)

Constrain Dark Matter

- dwarf satellite populations: Carlsten et al. 2020
- velocity dispersions: van Dokkum et al. 2018a,b

Local Matter Distribution + Cosmic Flows,

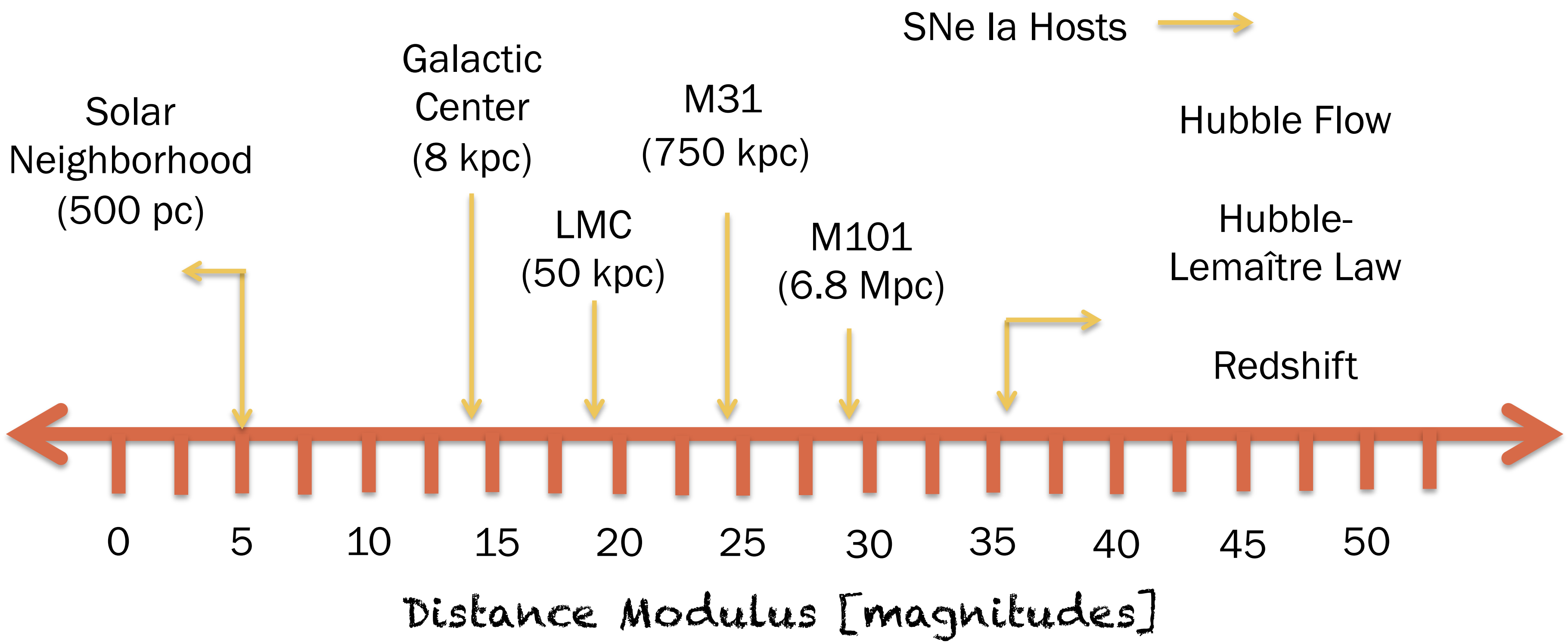
- $F\sigma_8$: Carrick et al. 2015, Hudson et al. 2016, Boruah et al. 2019, Dupruy et al. 2019

The Hubble Constant (H_0) and the Standard Model

- This meeting!

WHY DISTANCE LADDER?

The Universe is big.



NO **SINGLE TECHNIQUE** CAN SPAN THE FULL RANGE OF DISTANCES NEEDED IN ASTRONOMY

H_0 DRIVER OF DISTANCE LADDER

1. H_0 measurement demands aligning different techniques

   (So Hard)

2. H_0 measurement demands characterization of precision and accuracy

   (So much HARDER)

3. Once you have H_0, then for much of the Universe you can use redshift (*z*) to convert observables.

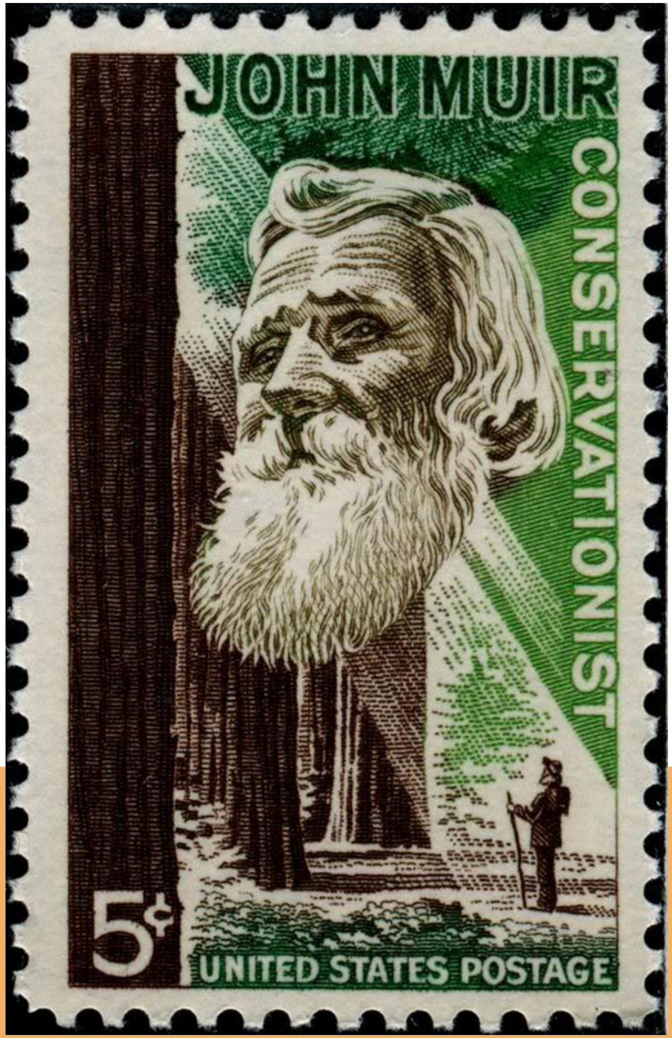
   (SUPER duper easy)

1 & 2 are because H_0 is a cosmological parameter, perhaps even a fundamental one, and puts its measure into a class of Physics measurement.

3 makes things much better for other parts of astronomy/astro-physics.

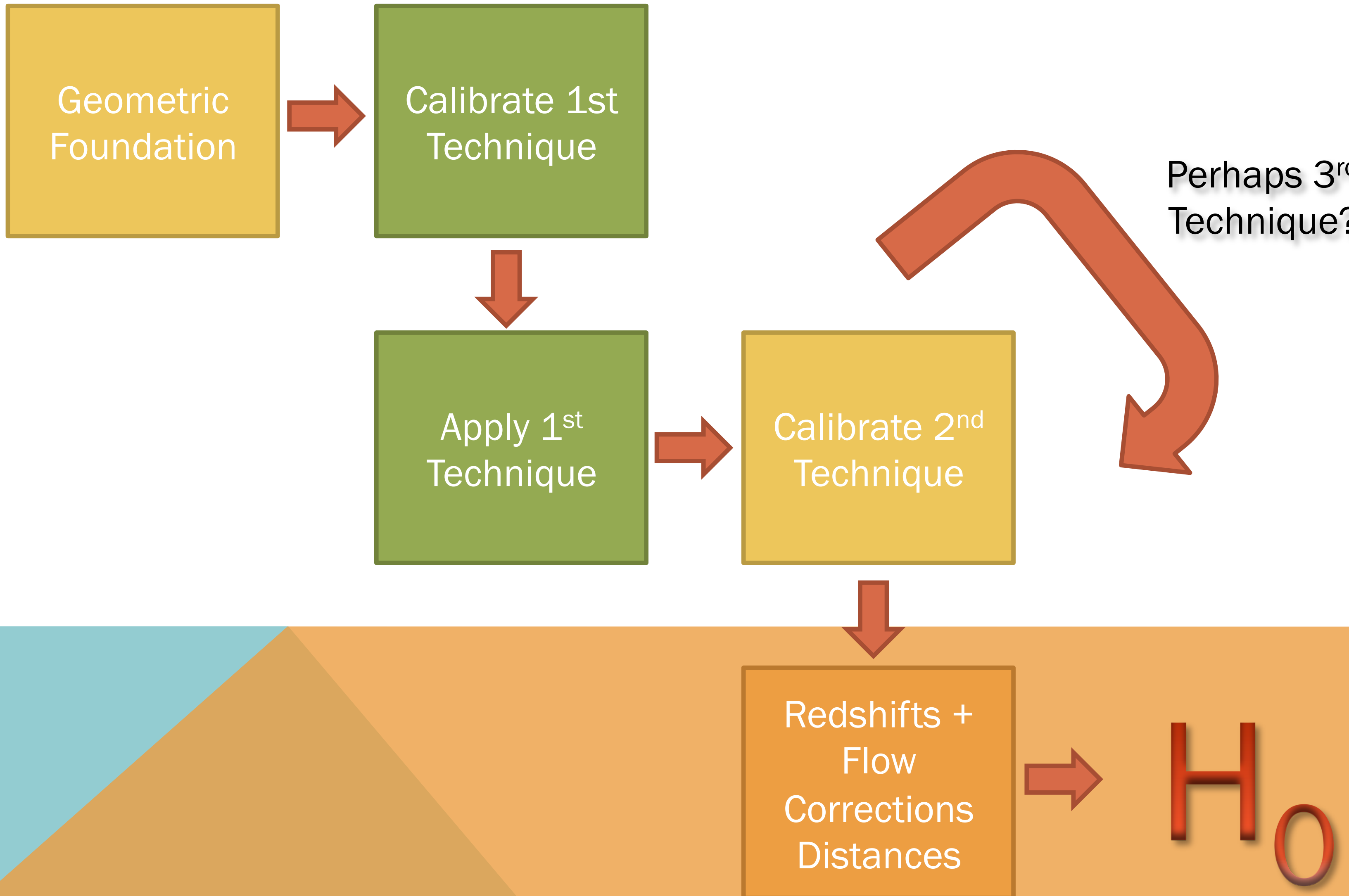
When we try to pick out anything by itself, we find it hitched to everything else in the Universe.

– John Muir

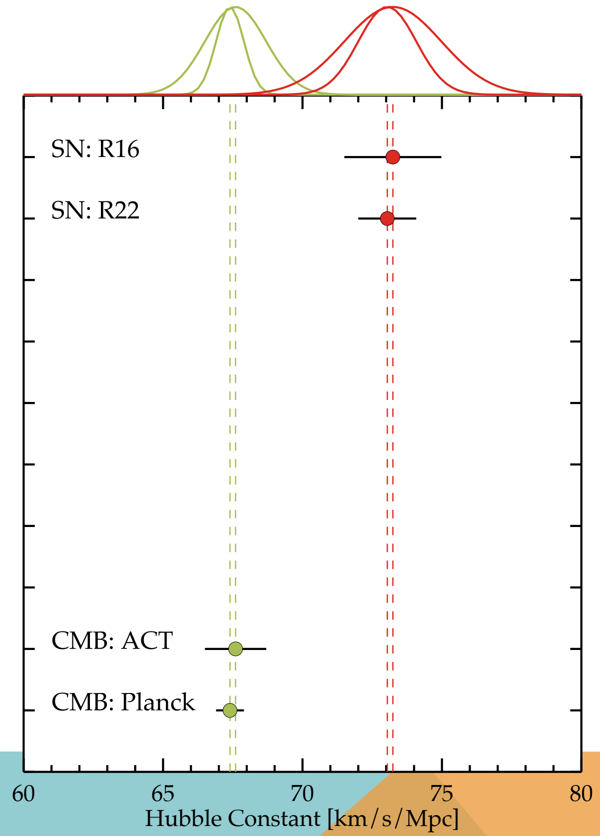


PART 1. THE MANY WAYS TO H0 AND ITS TENSION

H_0 MEASUREMENT IS A SYSTEM



HUBBLE TENSION

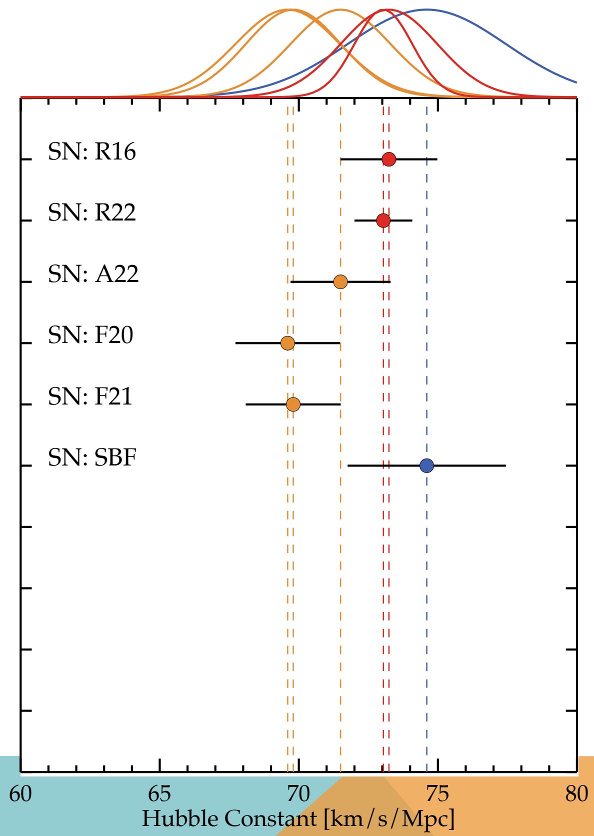


The difference between our two most precise measurements of H_0 is statistically significant at many sigma.

SN: R16 – Riess et al. 2016
SN: R22 – Riess et al. 2022

CMB: ACT – Aiola et al. 2022
CMB: Planck – Planck Collaboration et al.

STELLAR POPULATIONS



Multiple distance techniques using stellar populations now reach < 5% precision in H_0.

SN: R16 – Riess et al. 2016
SN: R22 – Riess et al. 2022

Cepheids

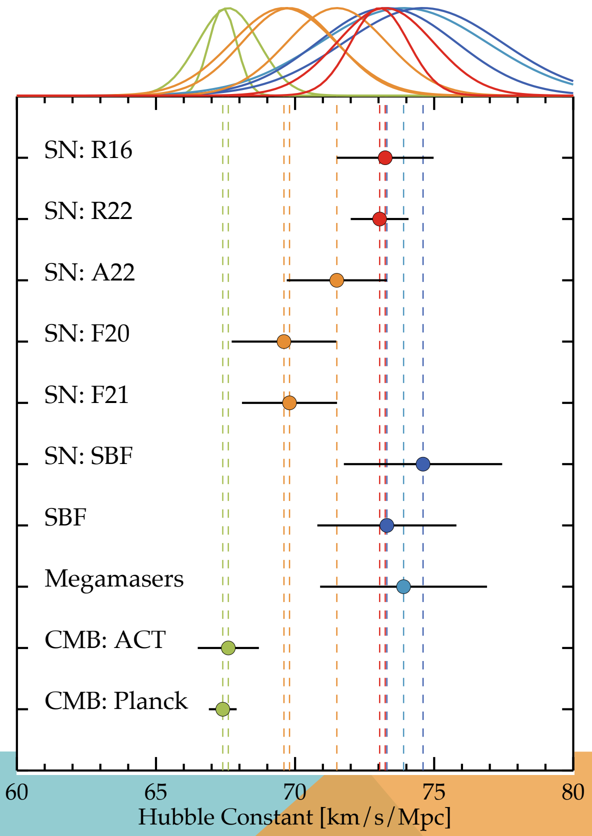
SN: A22 – Anand et al. 2022
SN: F20 – Freedman et al. 2020
SN: Freeman 2021

TRGB

SN: Blakeslee et al. 2022

SBF

PUTTING IT ALL TOGETHER



Not as clean as one would like and with how the stellar population distances share different elements of the system to measure H0, perhaps there is more there is more scatter than one would anticipate.

Cepheid to SN Ia

TRGB to SN Ia

SBF to SN Ia

SBF

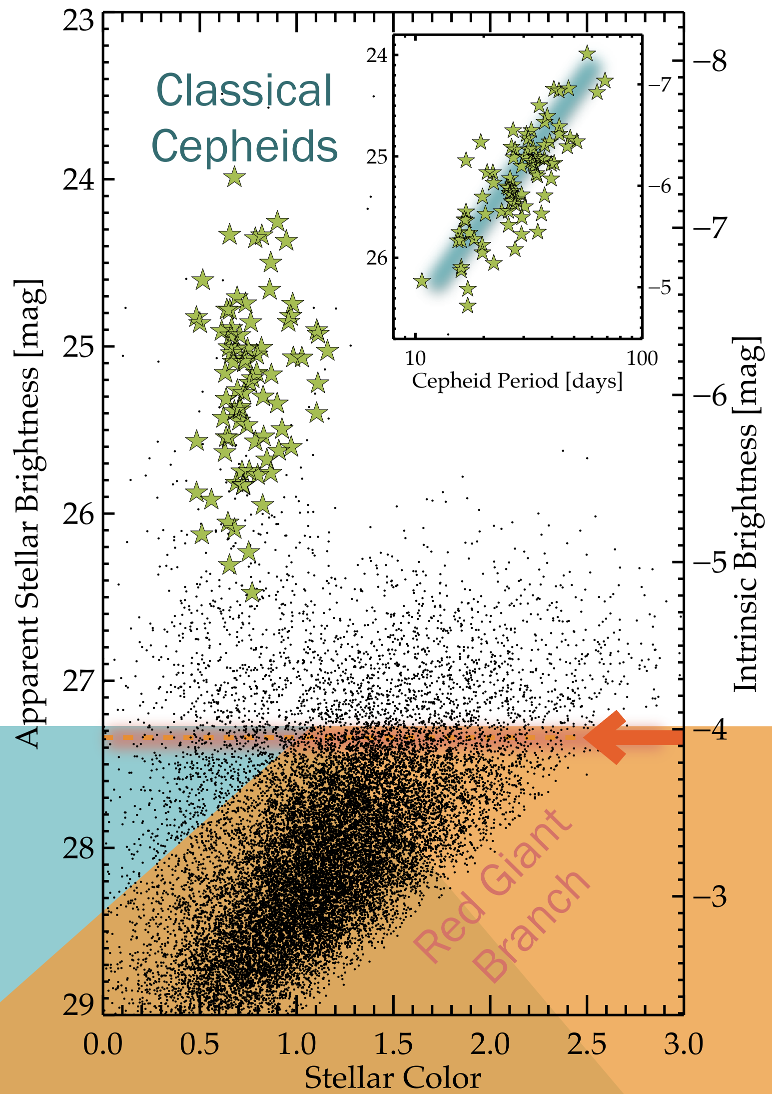
Mega-maser

Grav. Waves

H_0

KEY: Geometric Anchoring | Primary Calibration | SN Ia Hosts | Geometric+ Hubble Flow | Hubble Flow

CEPHEID & TRGB & GW



For Method Overviews:

Cepheids

- Freedman Talk
- Riess Talk

TRGB

- Lee Talk

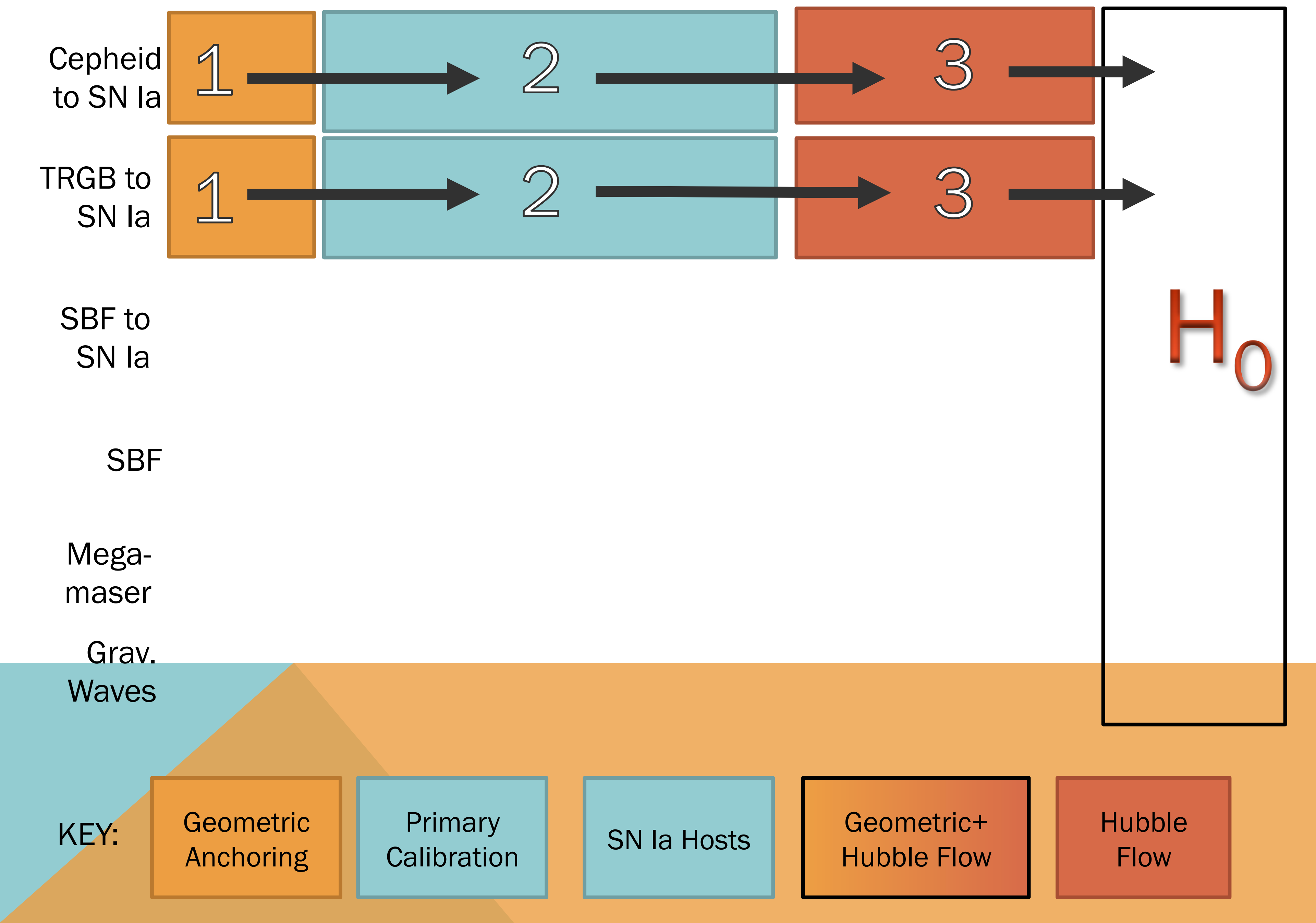
Gravitational Waves

- Dálya Talk

NGC1365 (~18 Mpc)

Green: Hoffmann et al. 2016

Black: Jang et al. 2018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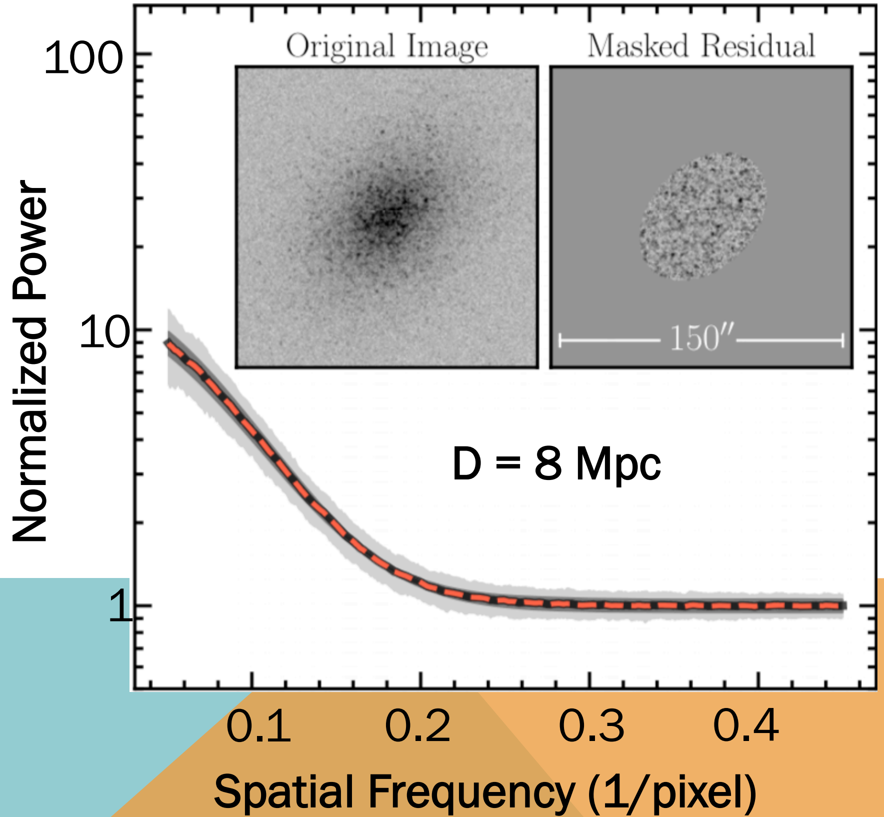
SURFACE BRIGHTNESS FLUCTUATIONS

10^7 M_{solar} galaxy simulated at 2 Distances



Visuals adapted from Greco et al. 2021

SURFACE BRIGHTNESS FLUCTUATIONS

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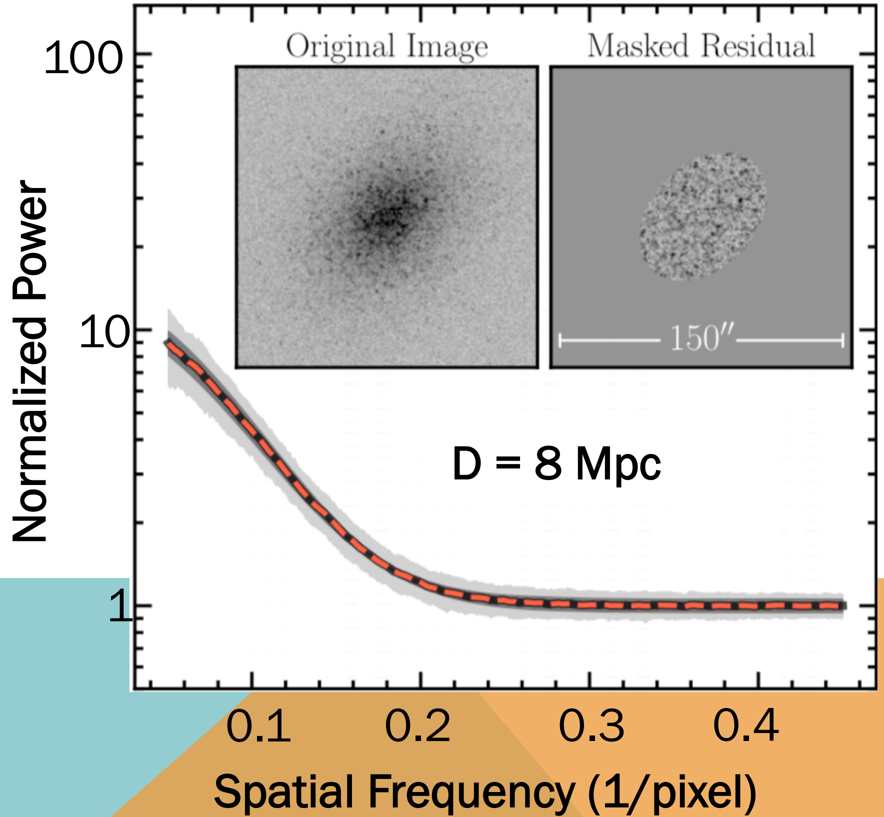

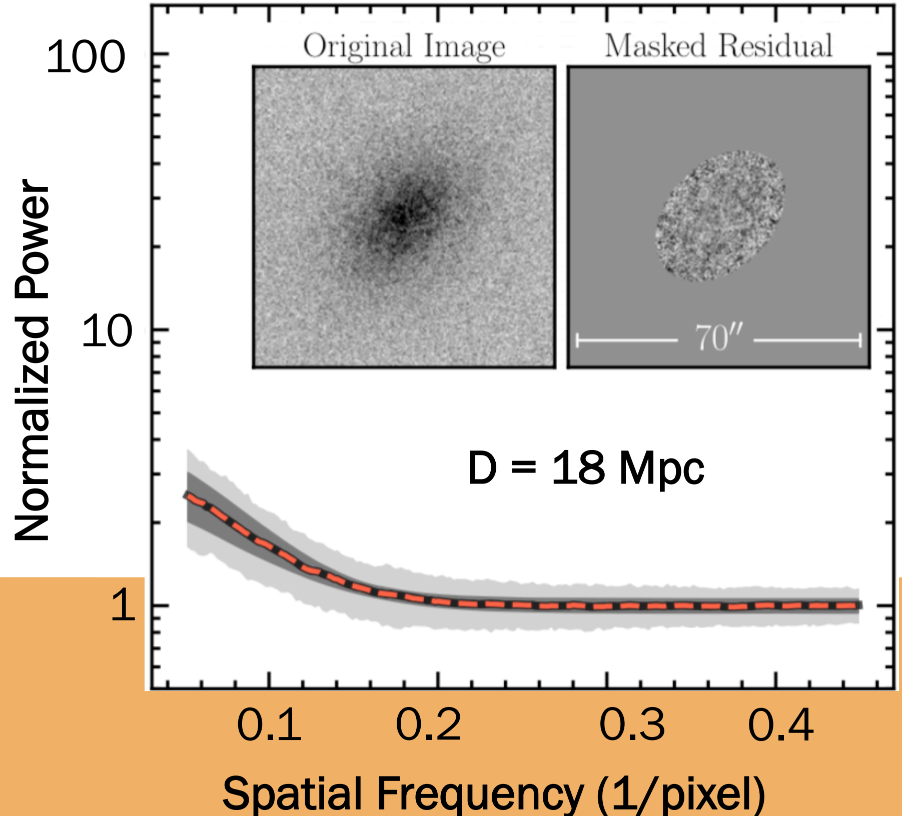

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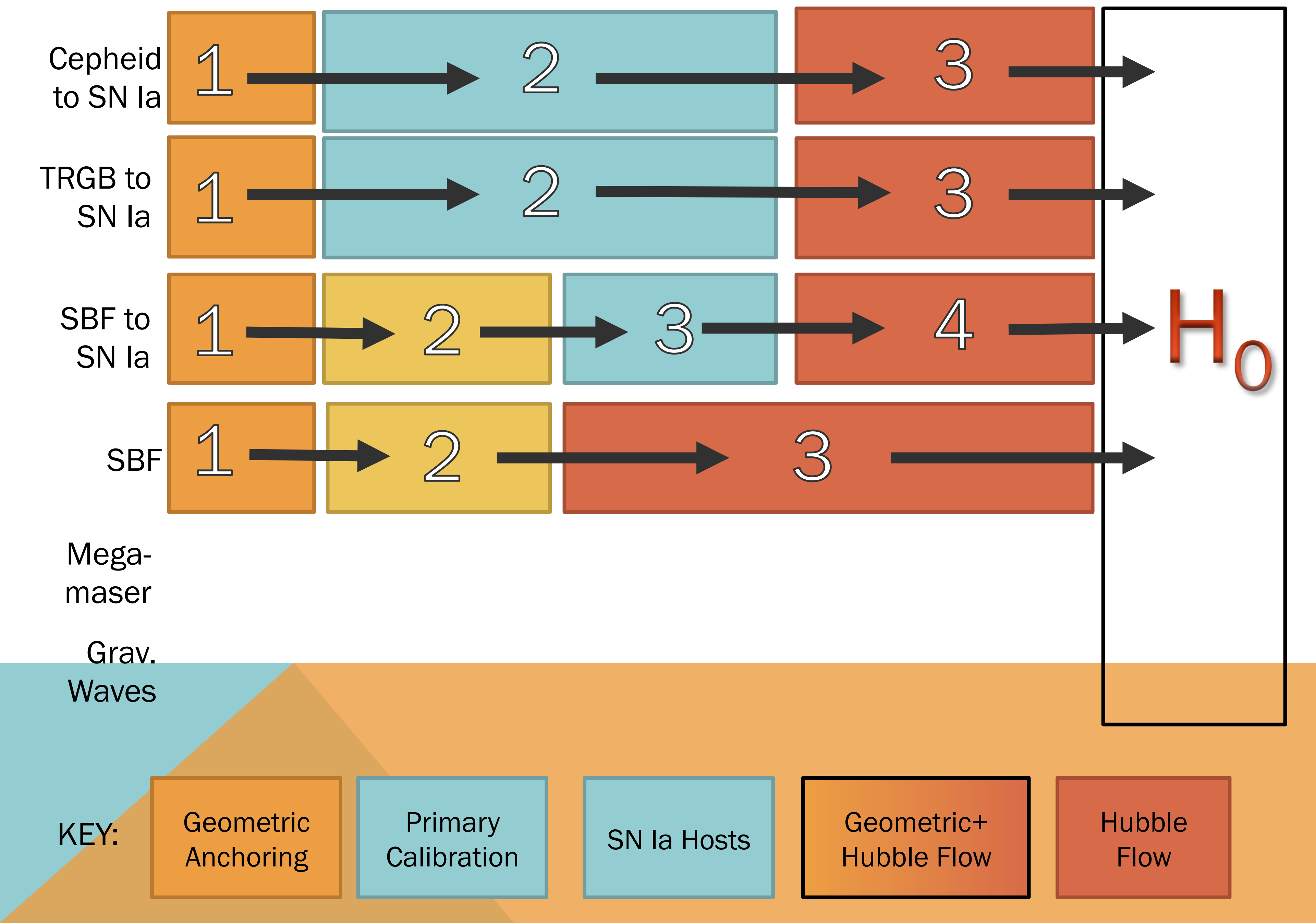
Cepheid to SN Ia
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2 GHZ MEGAMASERS

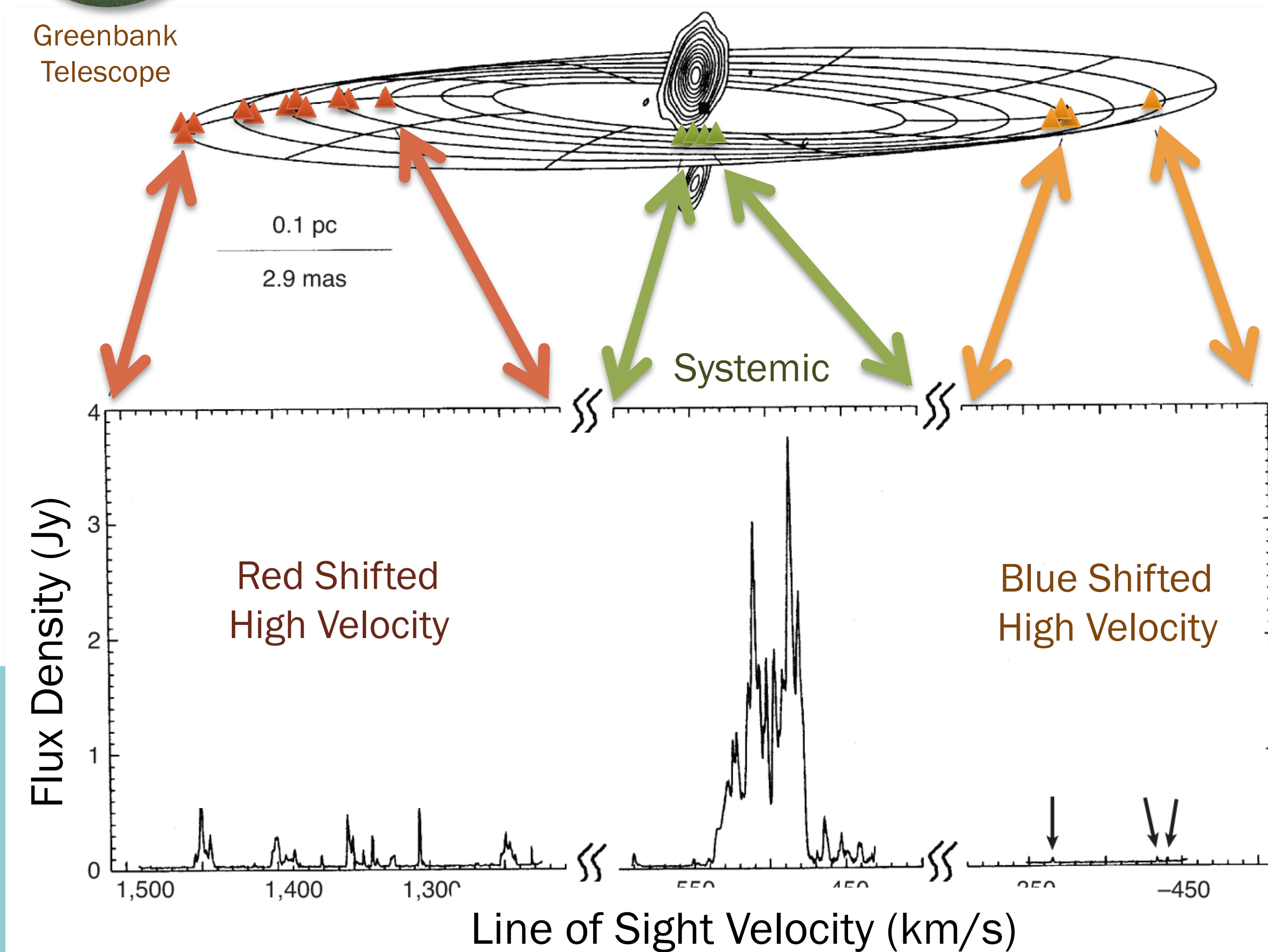
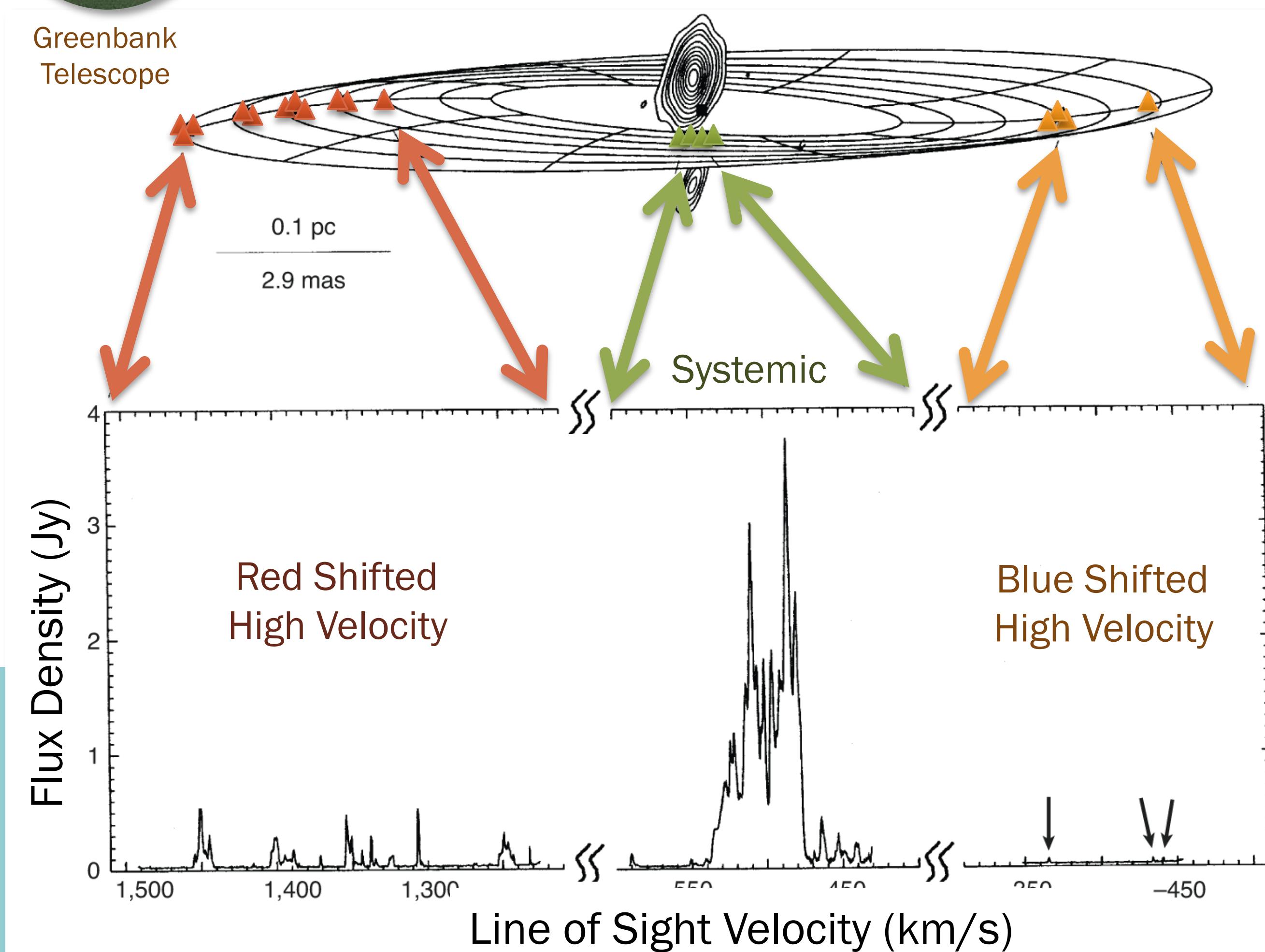


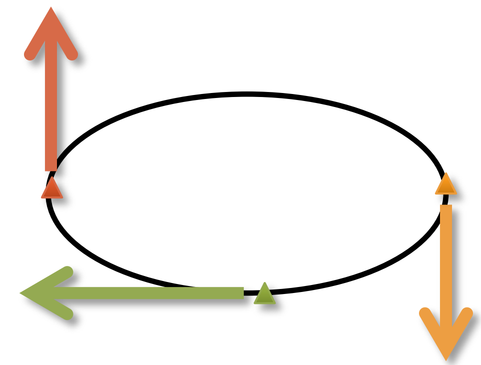
Figure adapted from Herrnstein, Moran, Greenhill et al. 1999

Most recent measurement Reid et al. 2019

2 GHZ MEGAMASERS

Greenbank Telescope





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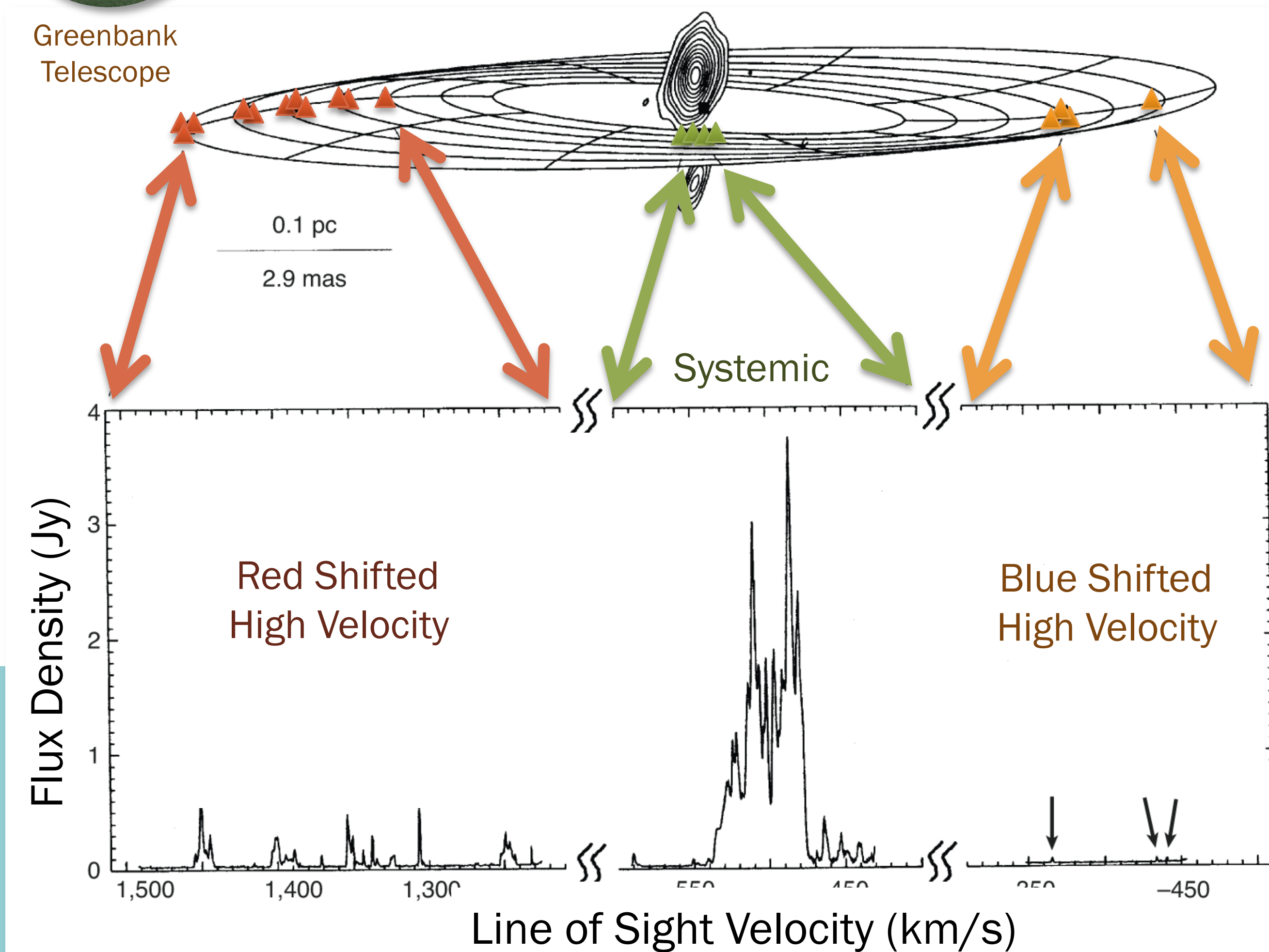

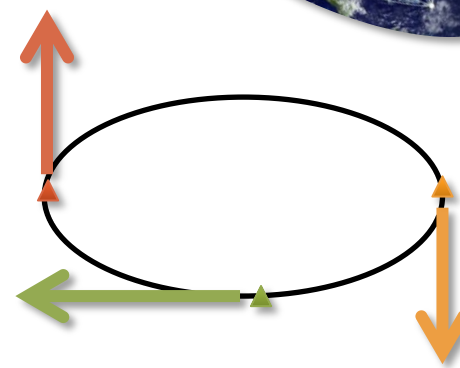

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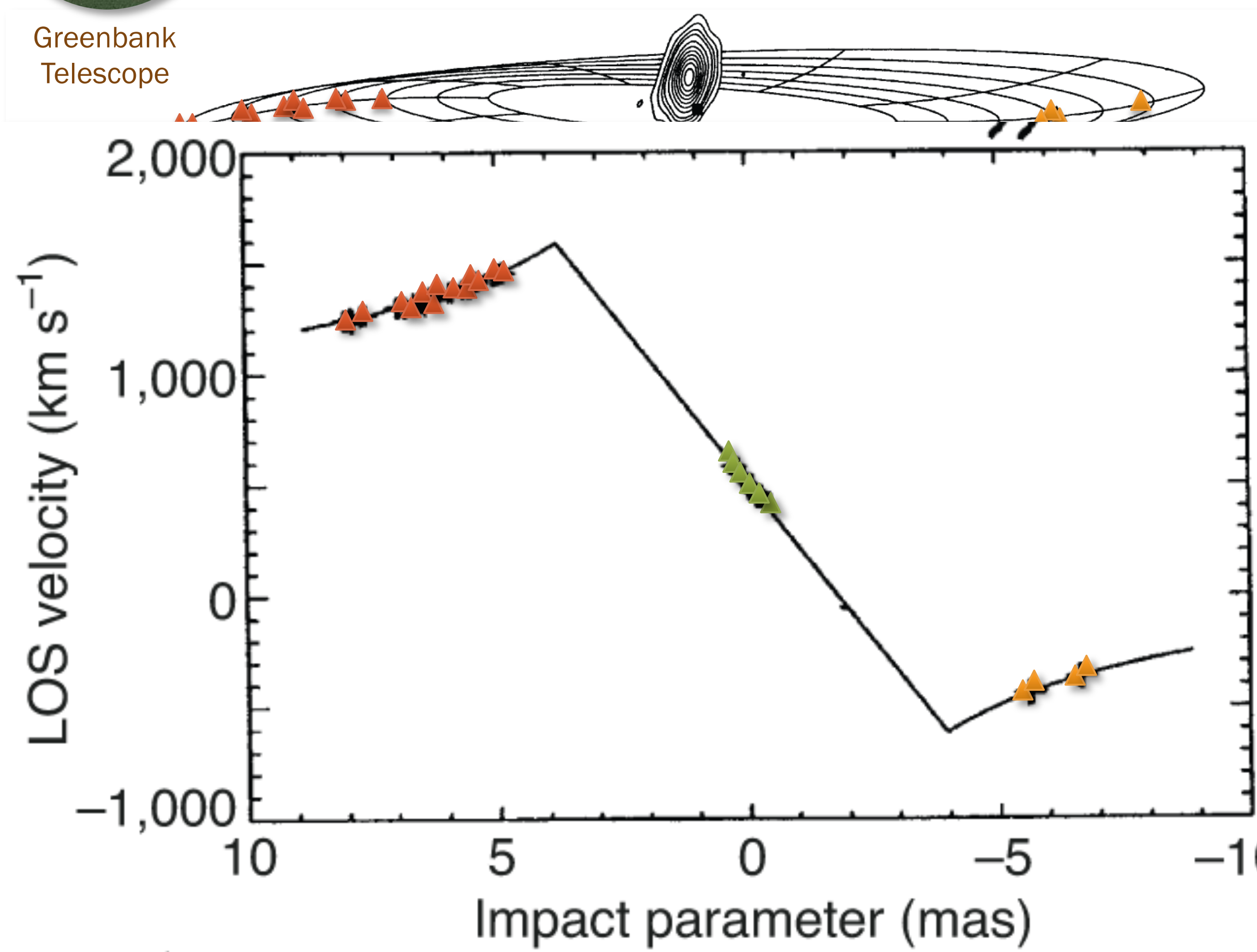
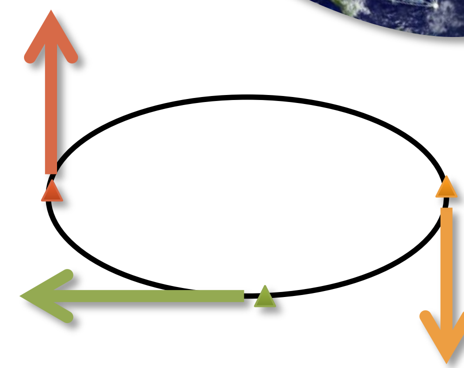
2 GHZ MEGAMASERS

Greenbank Telescope

VLBA





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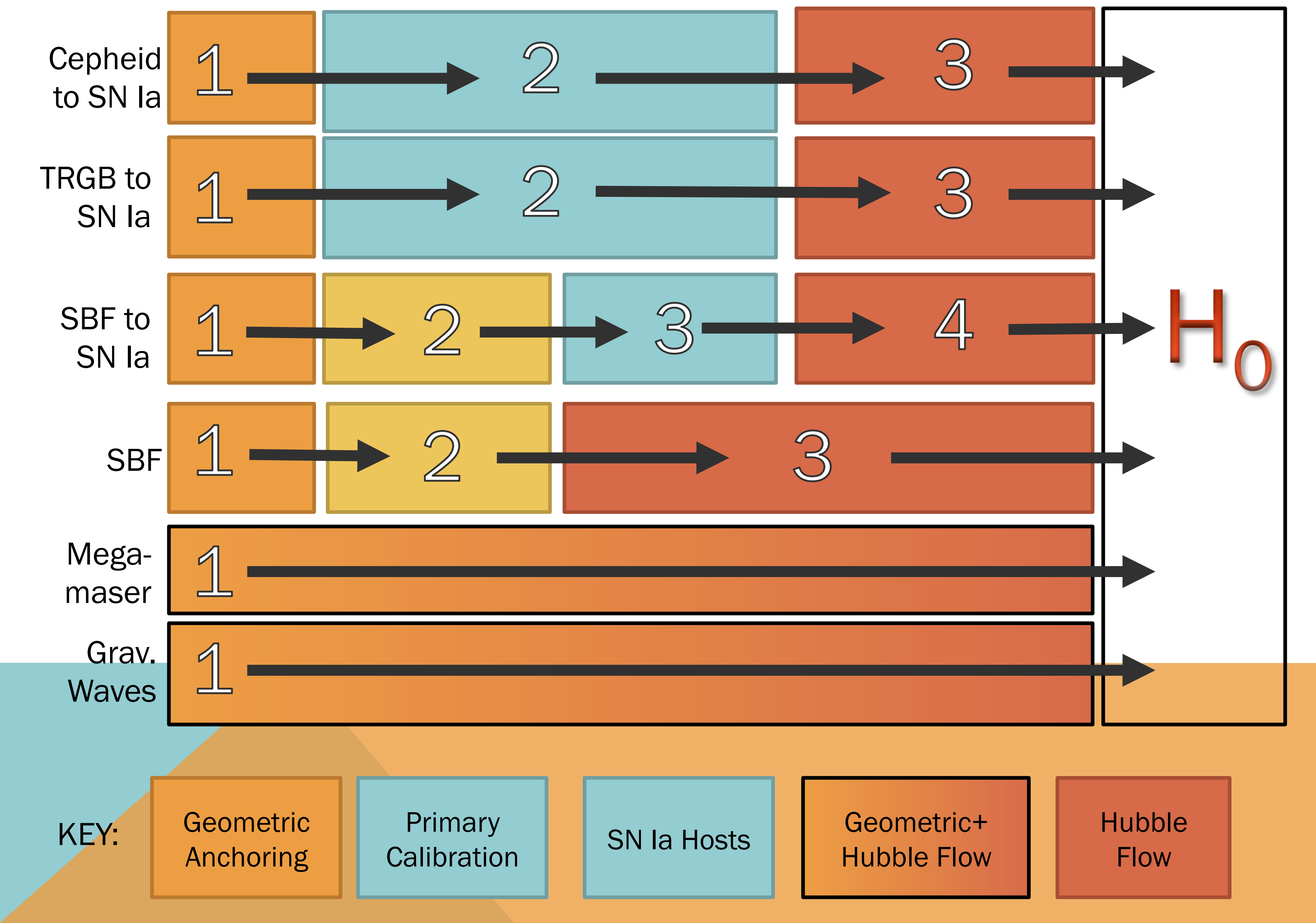
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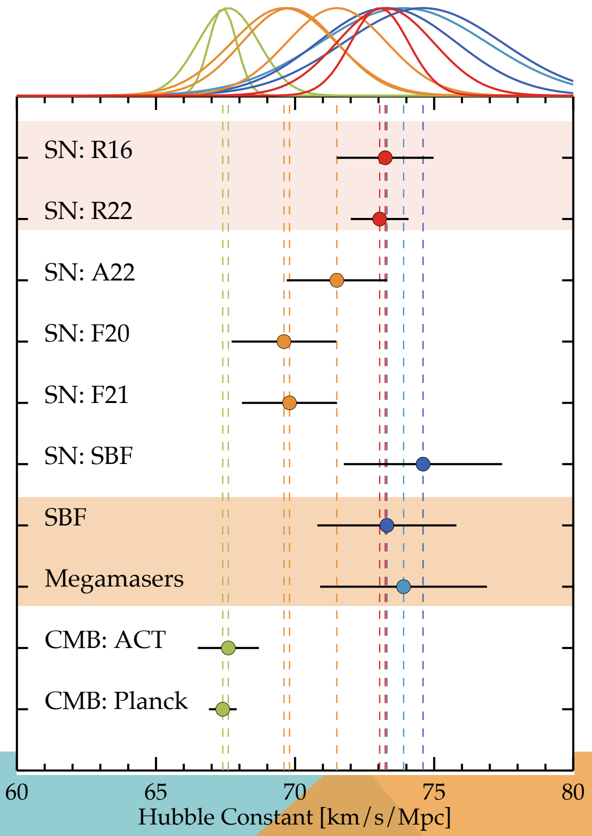
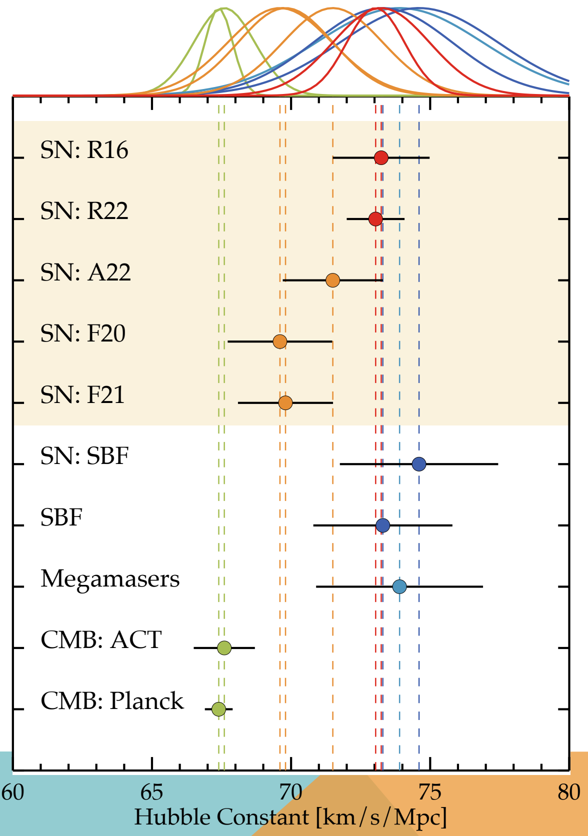
PUTTING IT ALL TOGETHER



Fully independent of SNe Ia:

- ➢ SBF has multiple steps, higher uncertainty
- ➢ Megamasers only 6 have been suitable so far.

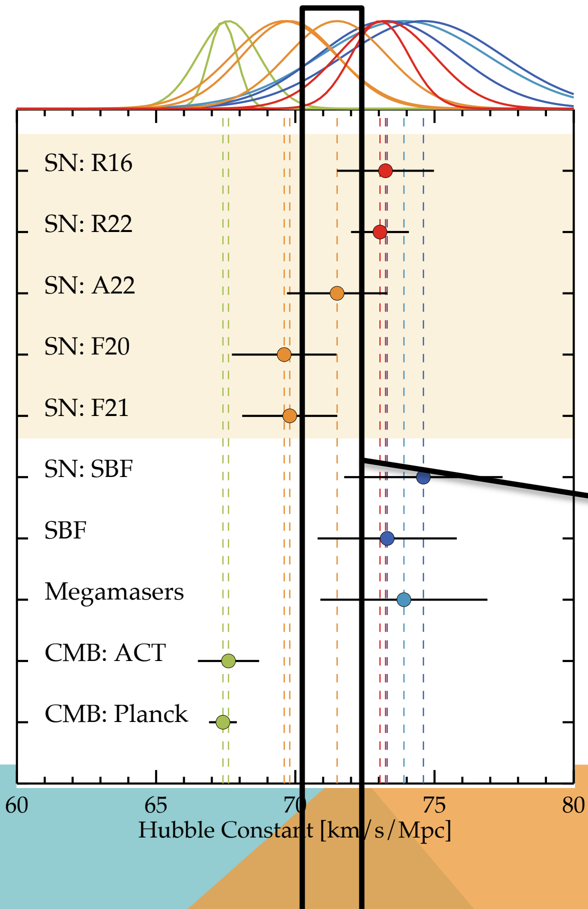
PUTTING IT ALL TOGETHER



But these H_0 measurements have a lot in common: SNe Ia, anchors, etc.

- Complex systems.
  See Scolnic et al. wrt SNe Ia
  (Arxiv on Friday)

PUTTING IT ALL TOGETHER

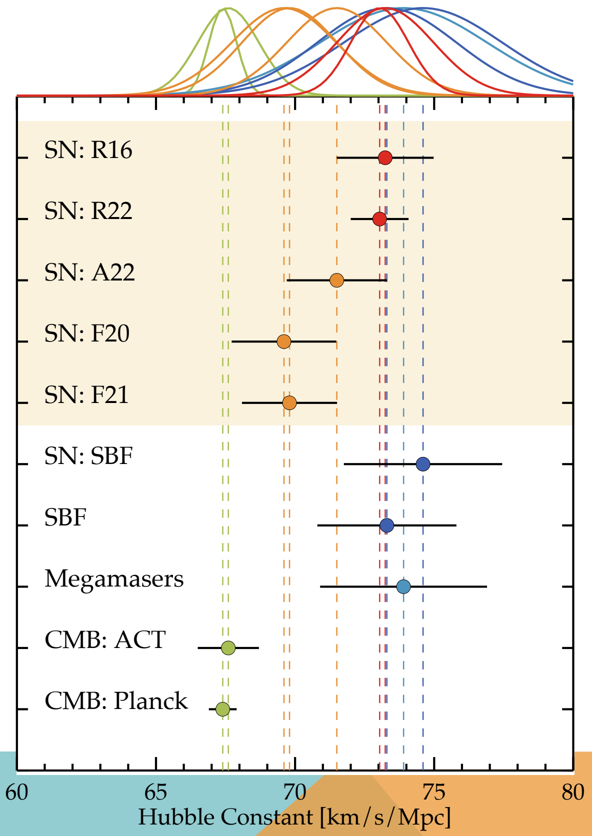


But these H_0 measurements have a lot in common: SNe Ia, anchors, etc.

- Complex systems.

- 2 km/s / Mpc from SNe Ia treatment

PUTTING IT ALL TOGETHER

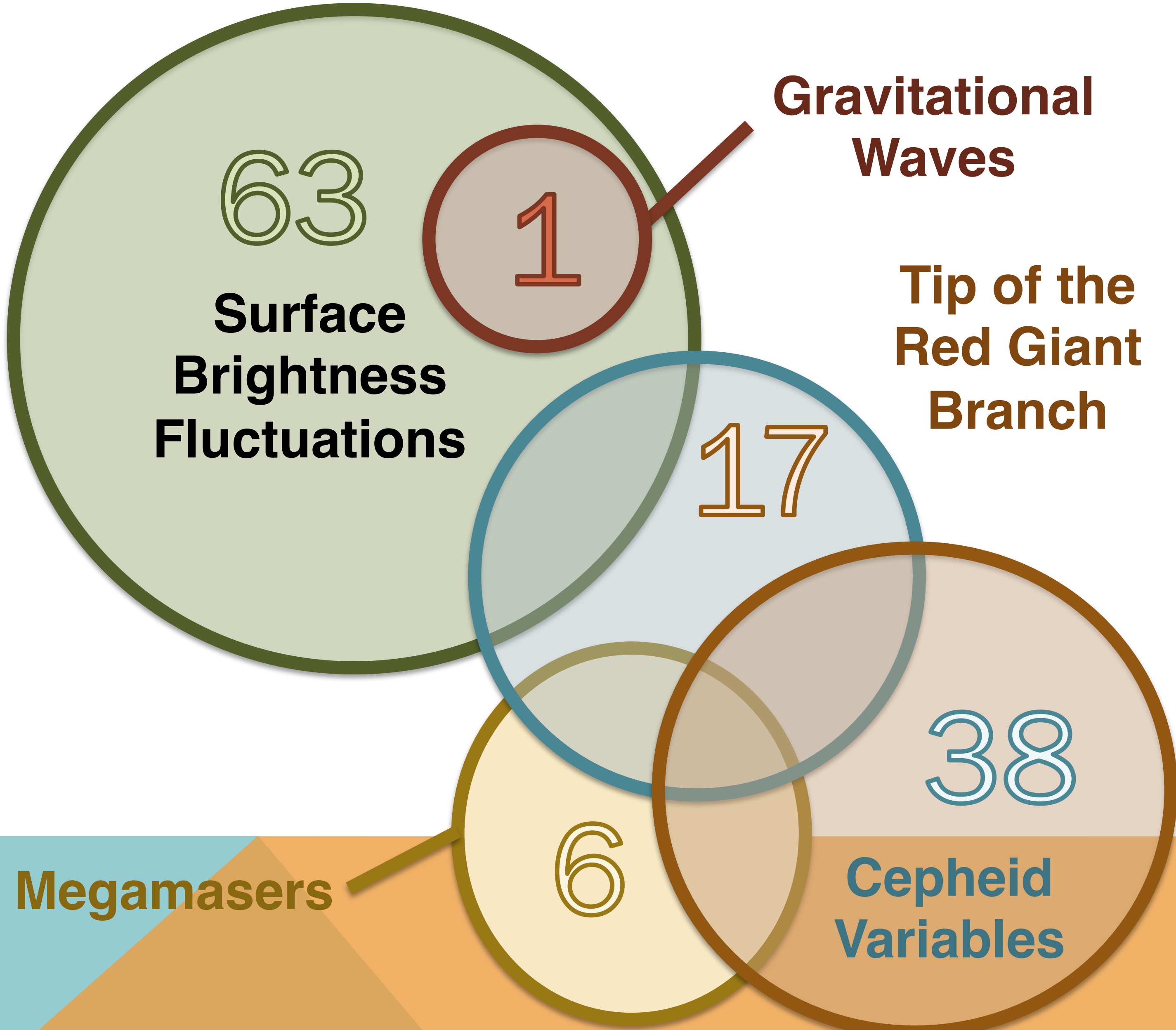


But these H_0 measurements have a lot in common: SNe Ia, anchors, etc.

- ➢ Complex systems.
  See Scolnic et al. wrt SNe Ia
  (Arxiv on Friday)

So what might be happening with the stellar population distances?

- ➢ Hard to say.
- ➢ Generally, you want to compare distances derived with the H_0 methodology.



Blakeslee et al. 2021; Cantiello et al. 2018; Riess et al. 2022; Freedman 2021; Pesce et al. 2022

PART 2.
THE MODERN PATH TO H_0 FROM THE DISTANCE LADDER

COSMIC DISTANCE SCALE IN A SLIDE

Geometric Distances

1

Calibration of SNe Ia

2

SNe Ia in Hubble Flow for H_0

3

Hubble-Lemaître Law

+ ΛCDM

4

- Once you are in the Hubble Flow (z_{CMB} larger than ~0.01), the distance scale is more-or-less set by H_0.
- H_0 usually comes in 3 steps today.

COSMIC DISTANCE SCALE IN A SLIDE

1. Geometric Distances
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3. SNe Ia in Hubble Flow for H_0
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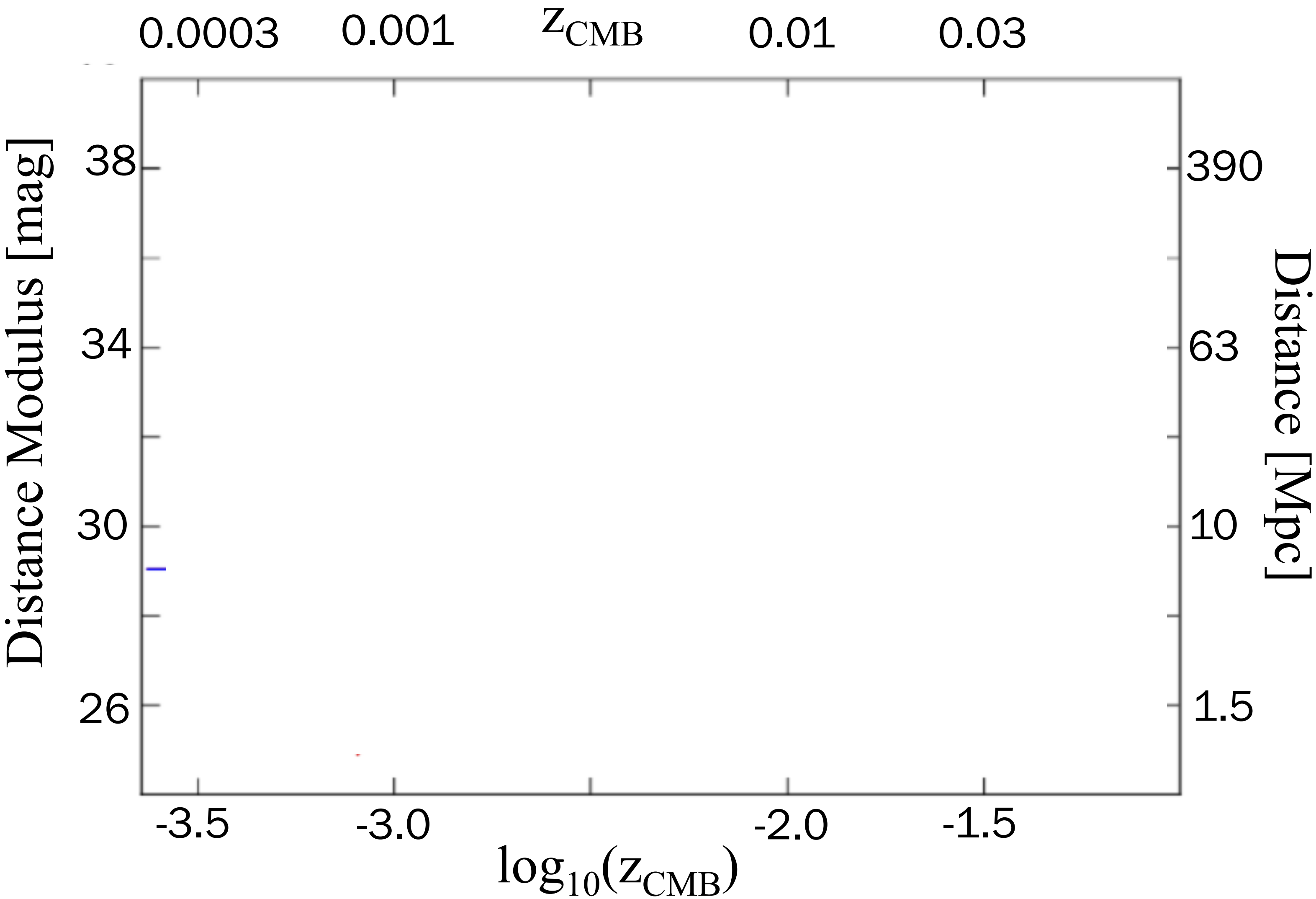
MODERN HUBBLE DIAGRAM



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

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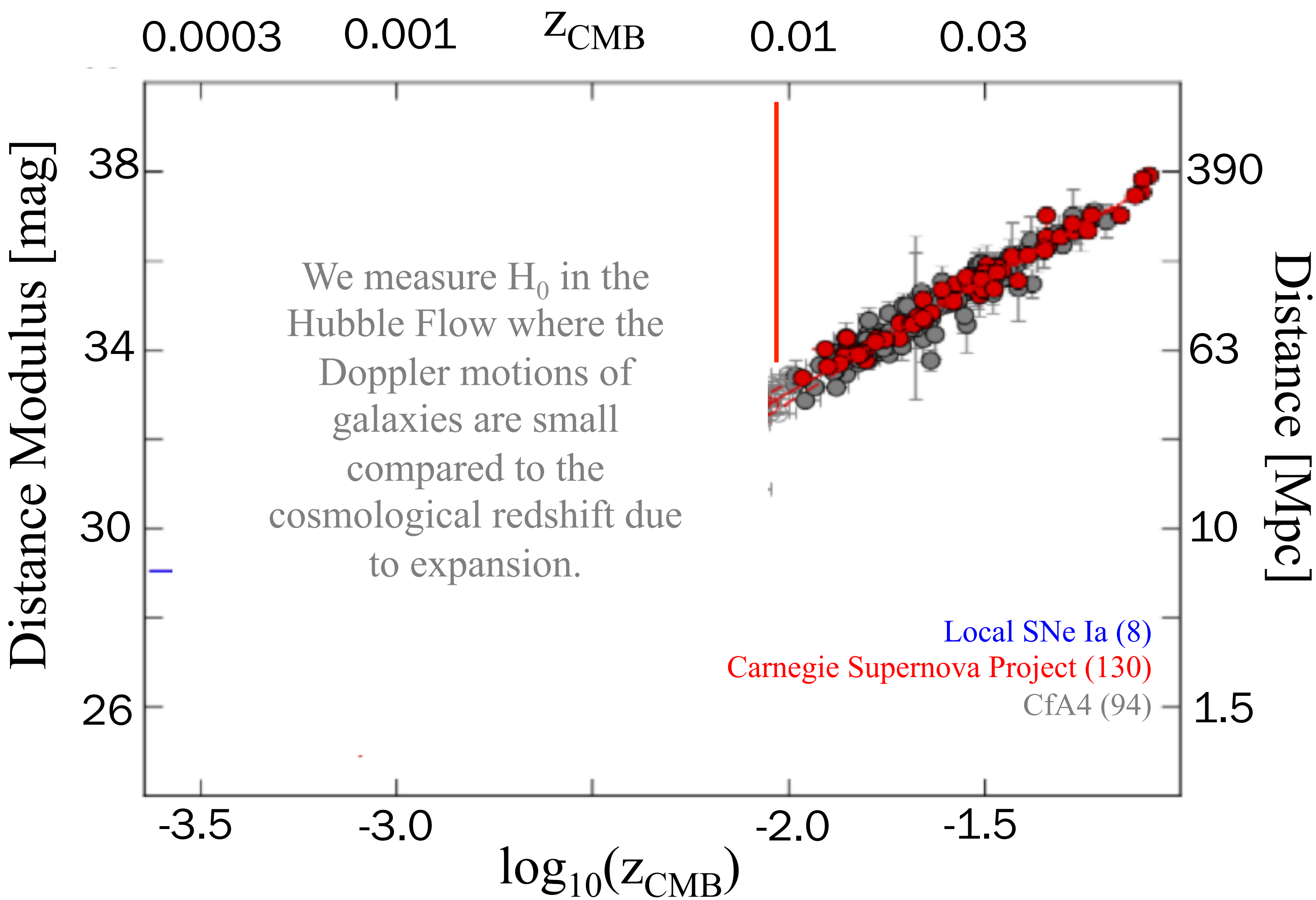

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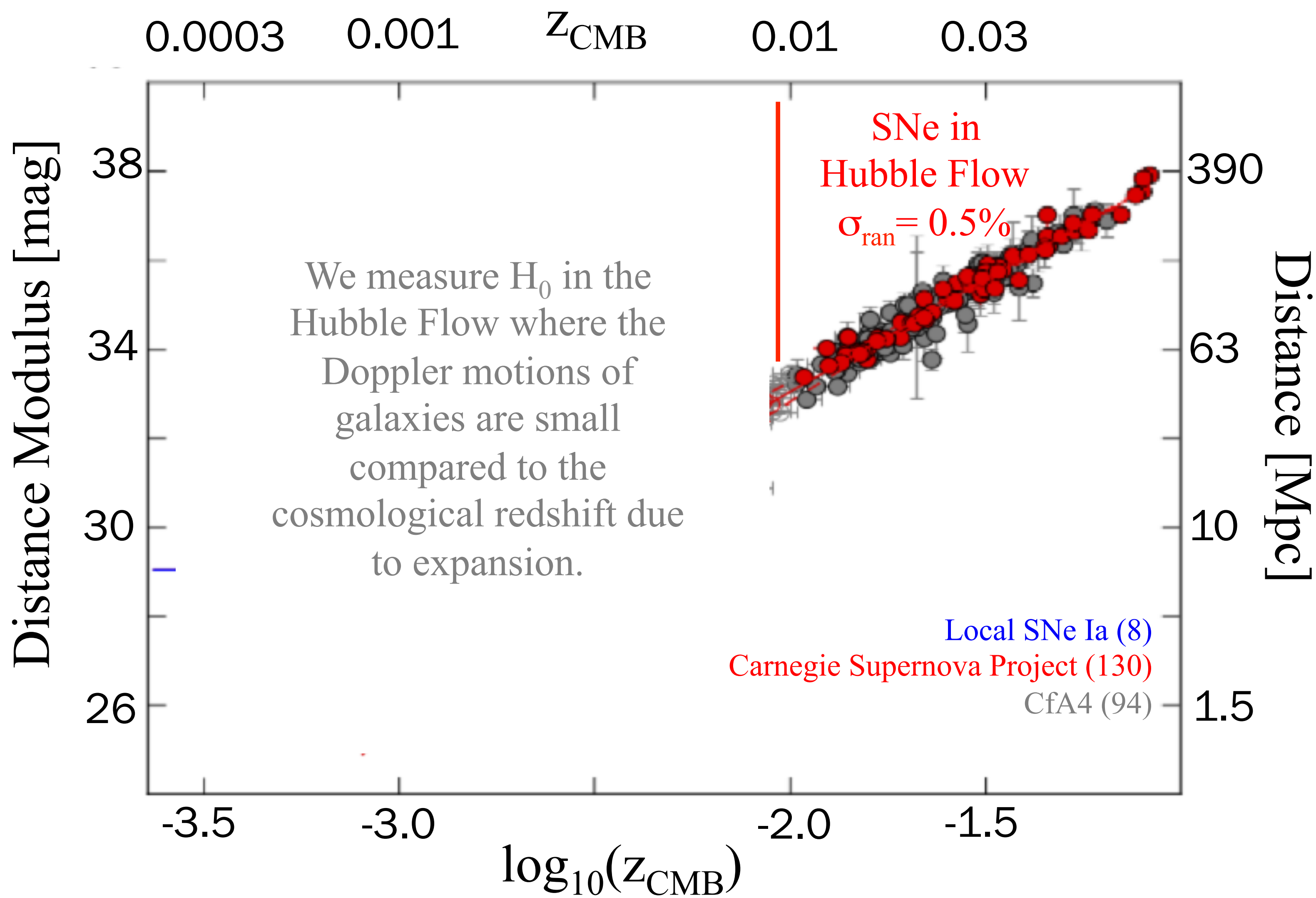

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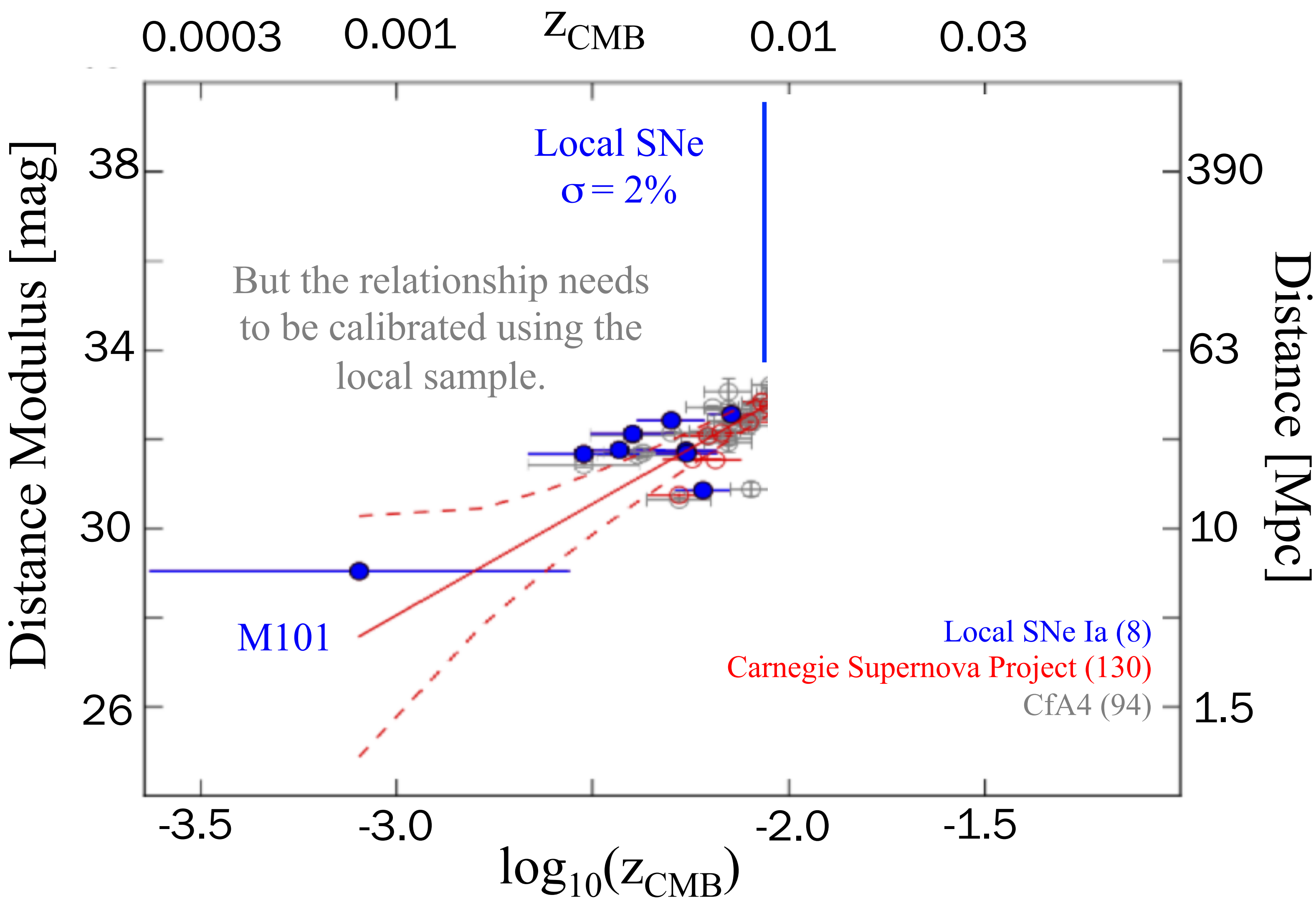

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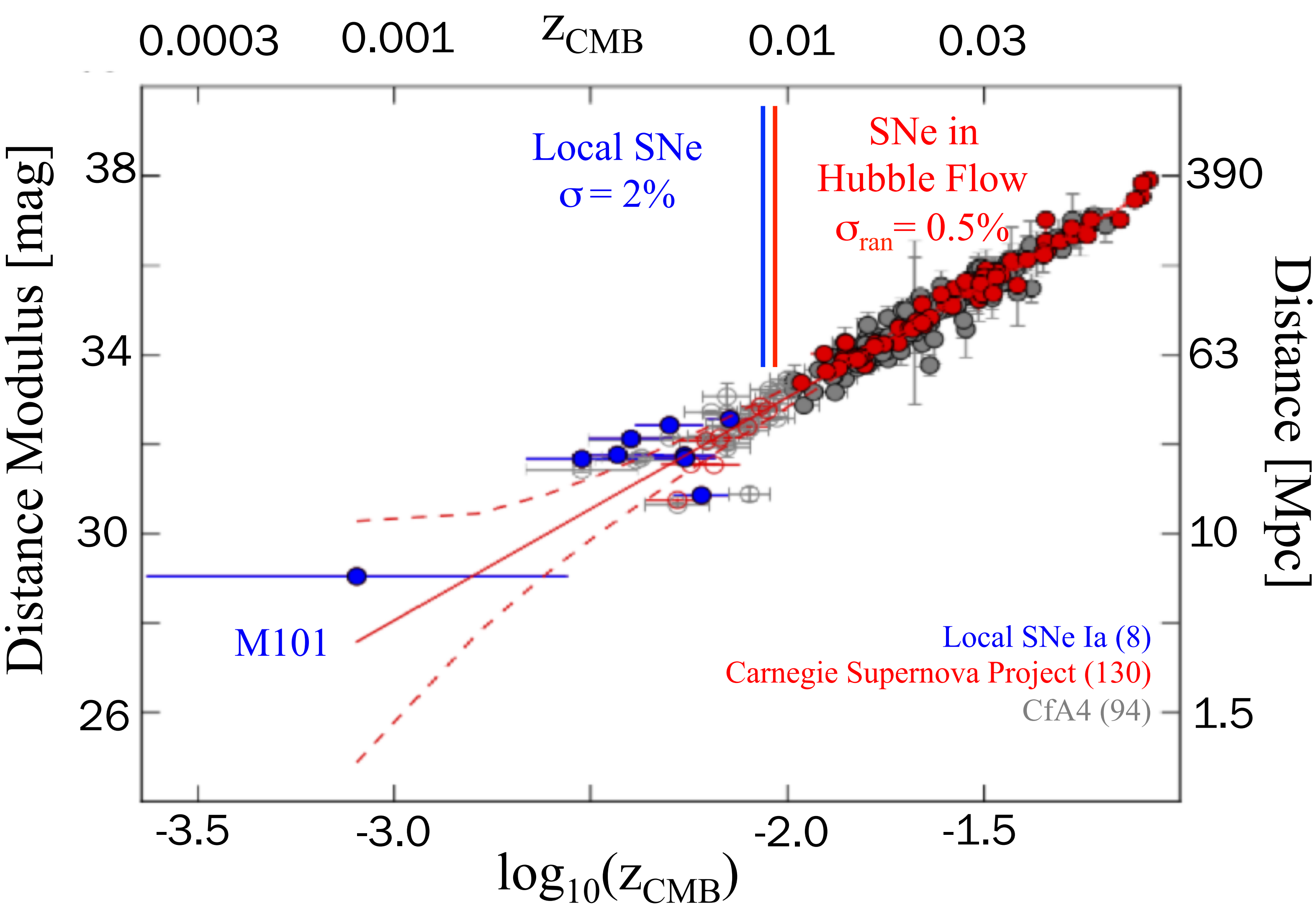

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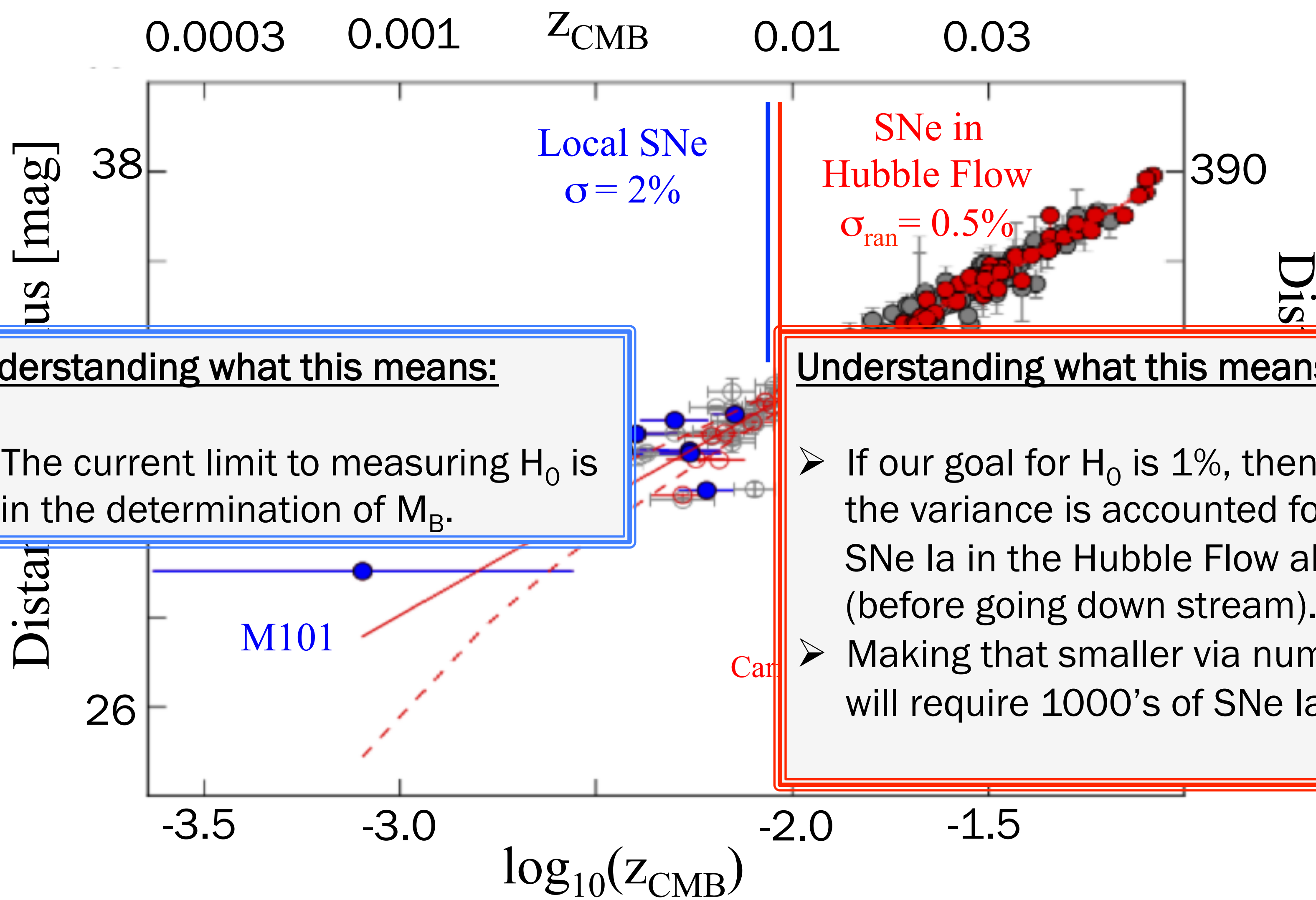


Understanding what this means:

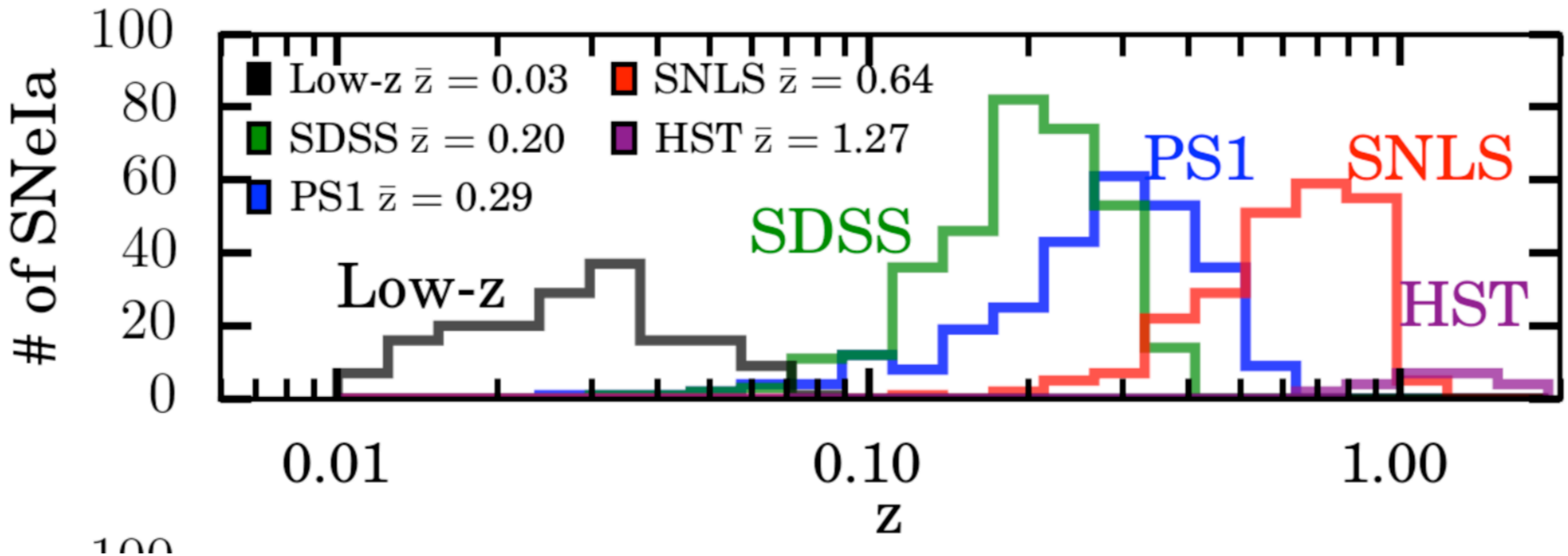
- The current limit to measuring H_0 is in the determination of M_B.

Understanding what this means:

- If our goal for H_0 is 1%, then ~¼ of the variance is accounted for by the SNe Ia in the Hubble Flow alone (before going down stream).
- Making that smaller via numbers will require 1000's of SNe Ia.

STAR STUFF 1:
TYPE 1A SUPERNOVAE

COMPLETENESS IN THE SNE IA SAMPLE



Pantheon Sample:
Scolnic et al. 2017

COMPLETENESS IN THE SNE IA SAMPLE

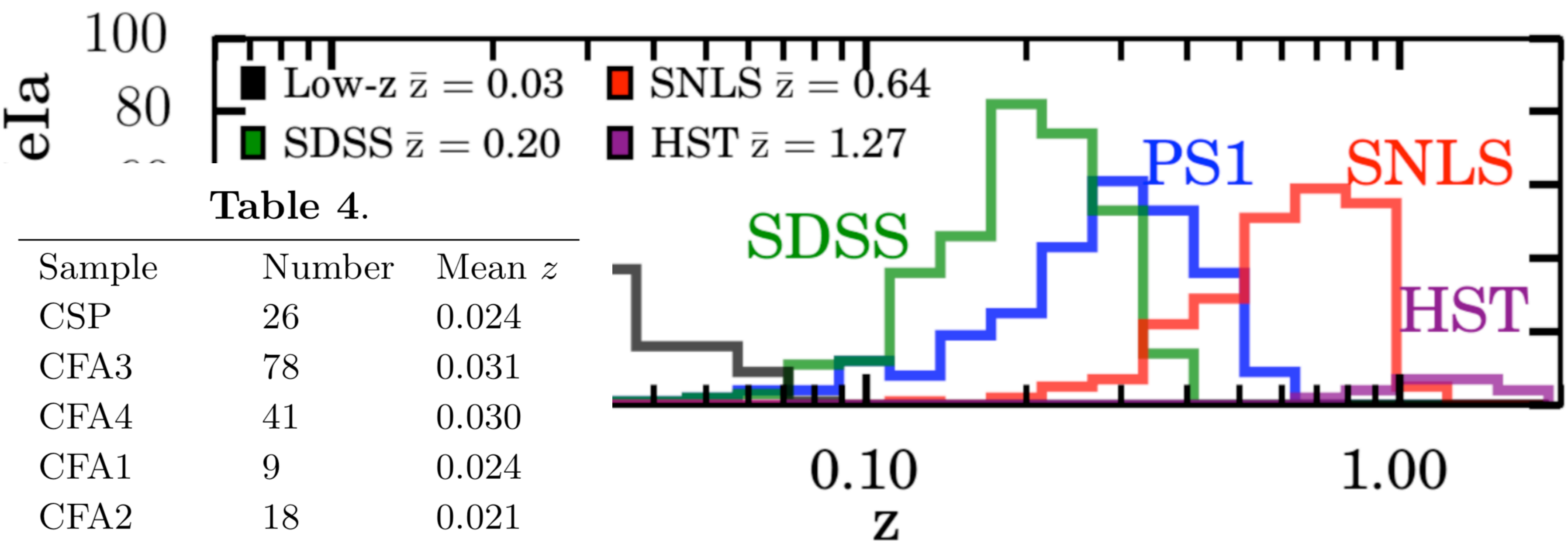
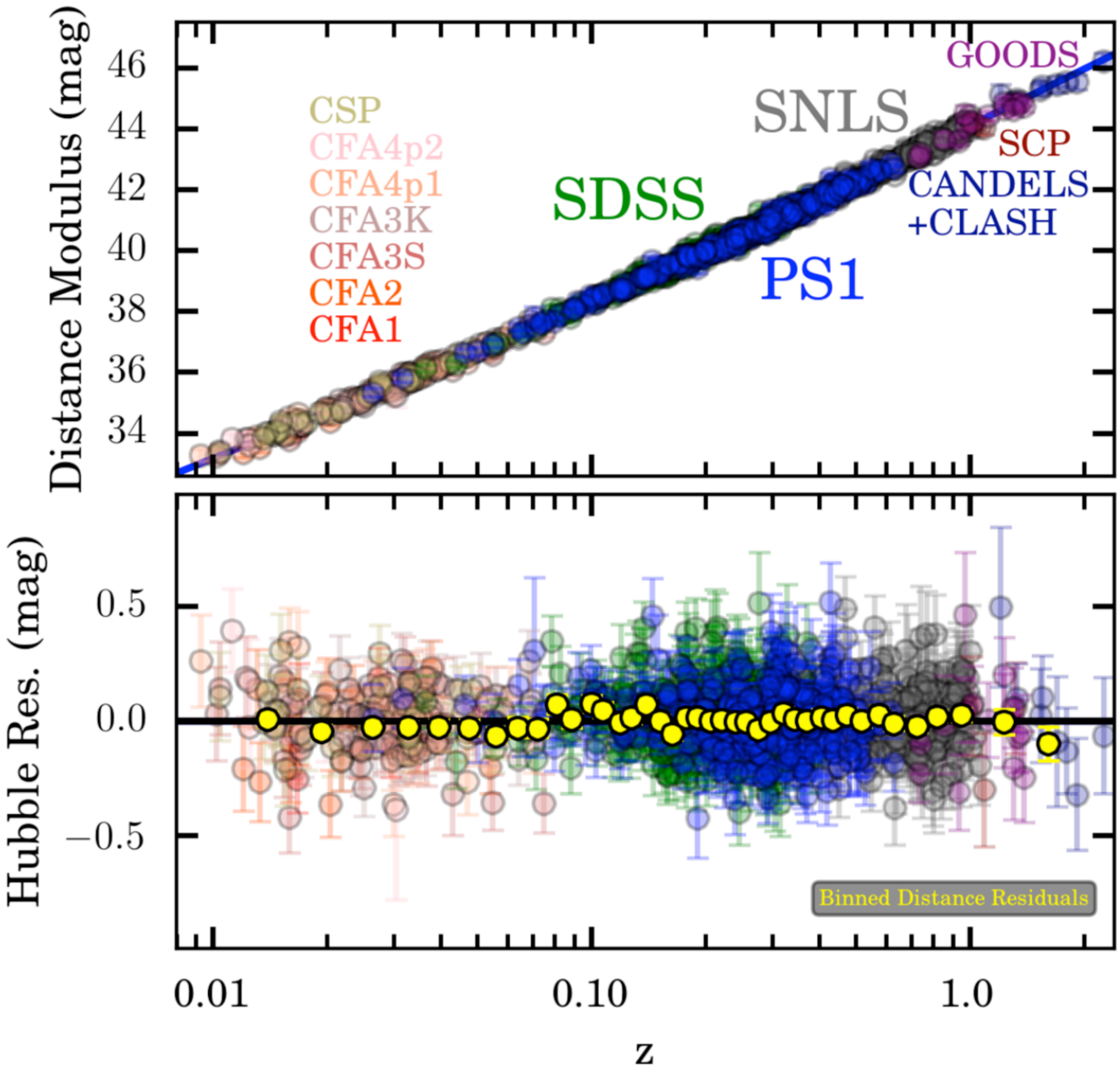


Table 4.

Sample	Number	Mean z
CSP	26	0.024
CFA3	78	0.031
CFA4	41	0.030
CFA1	9	0.024
CFA2	18	0.021
SDSS	335	0.202
PS1	279	0.292
SNLS	236	0.640
SCP	3	1.092
GOODS	15	1.120
CANDELS	6	1.732
CLASH	2	1.555
Tot	1048	

Pantheon Sample:
Scolnic et al. 2017



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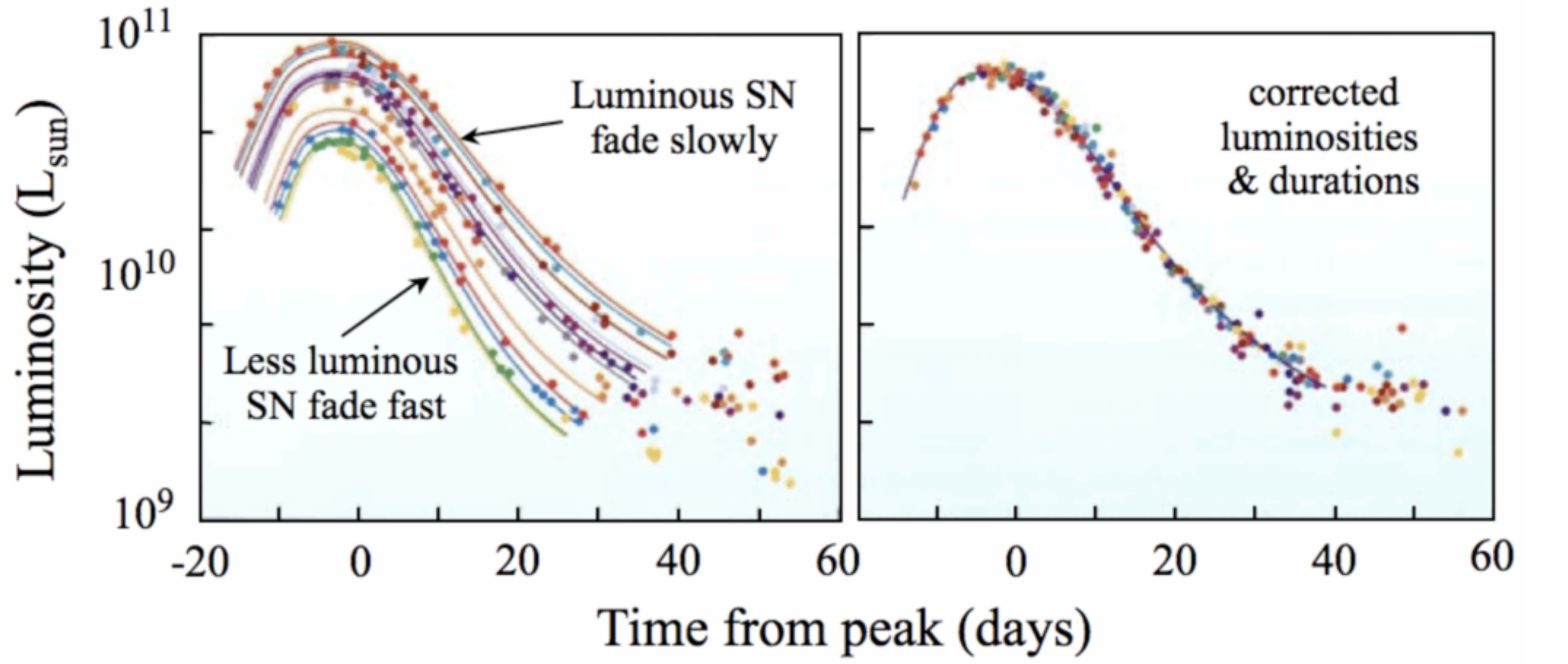
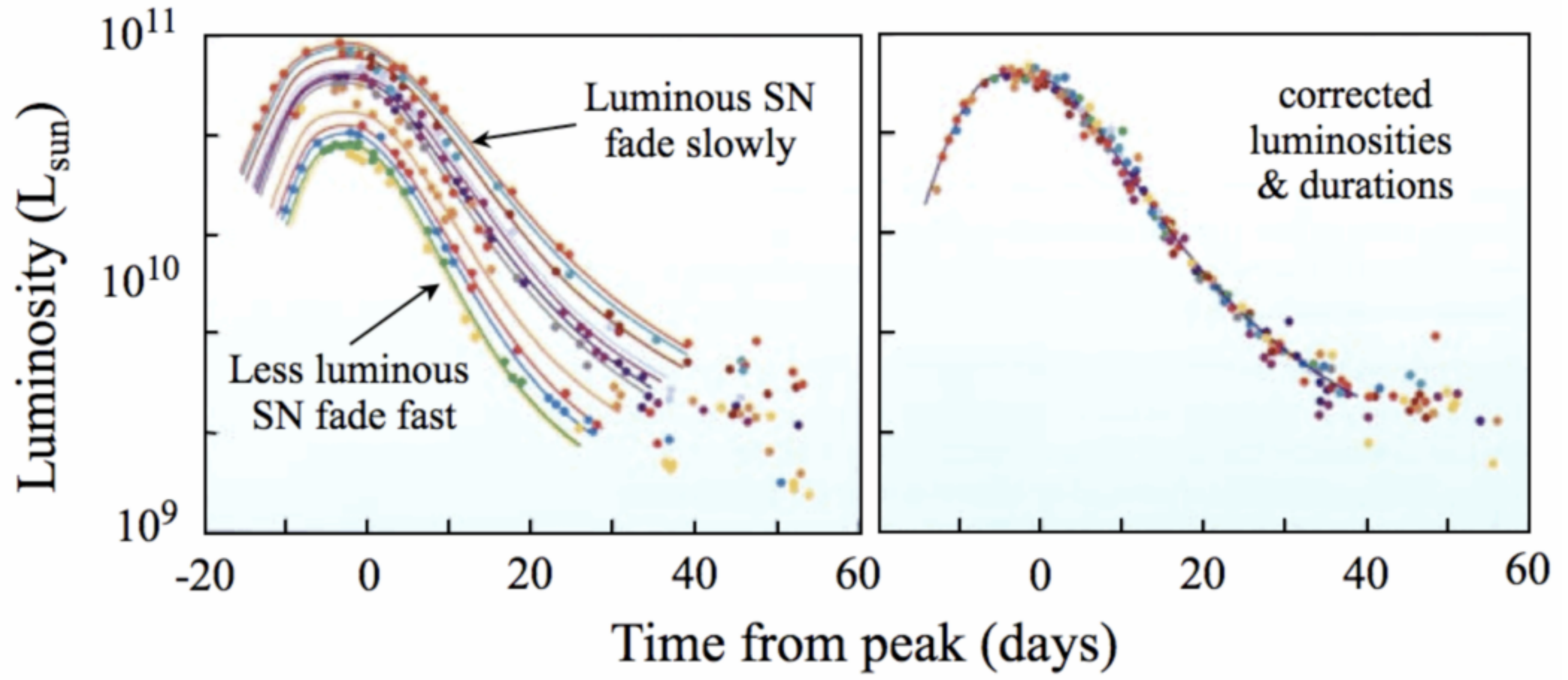
TYPE IA SUPERNOVAE



The first peak is due to decay of ^{56}Ni.

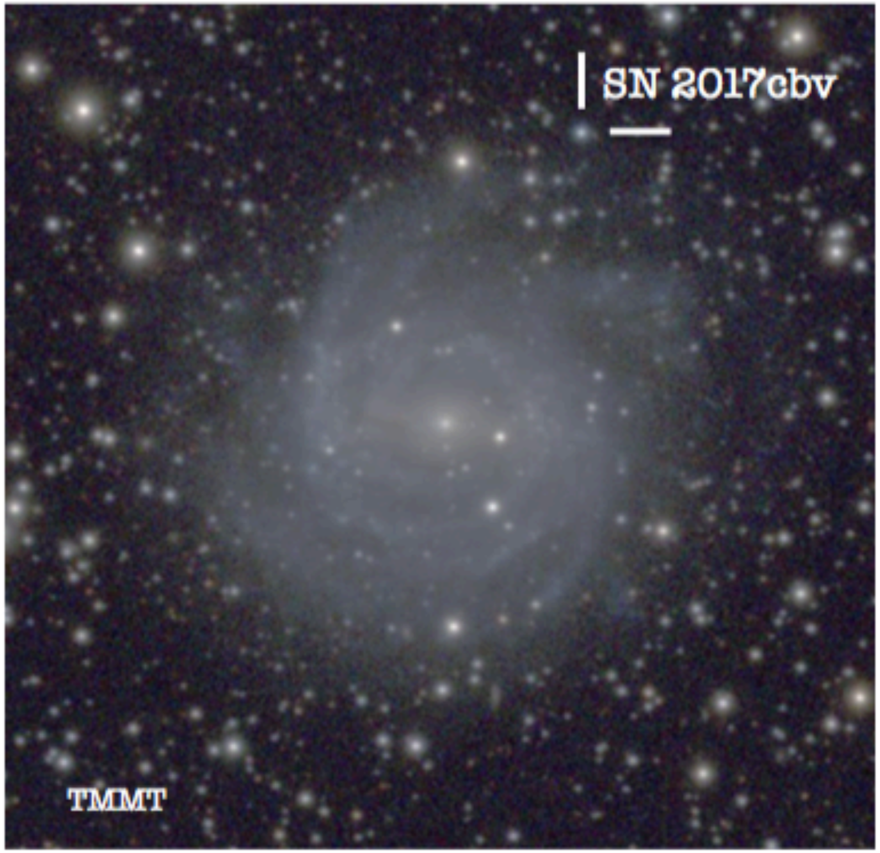
~0.1 to 1.0 Solar masses

TYPE IA SUPERNOVAE



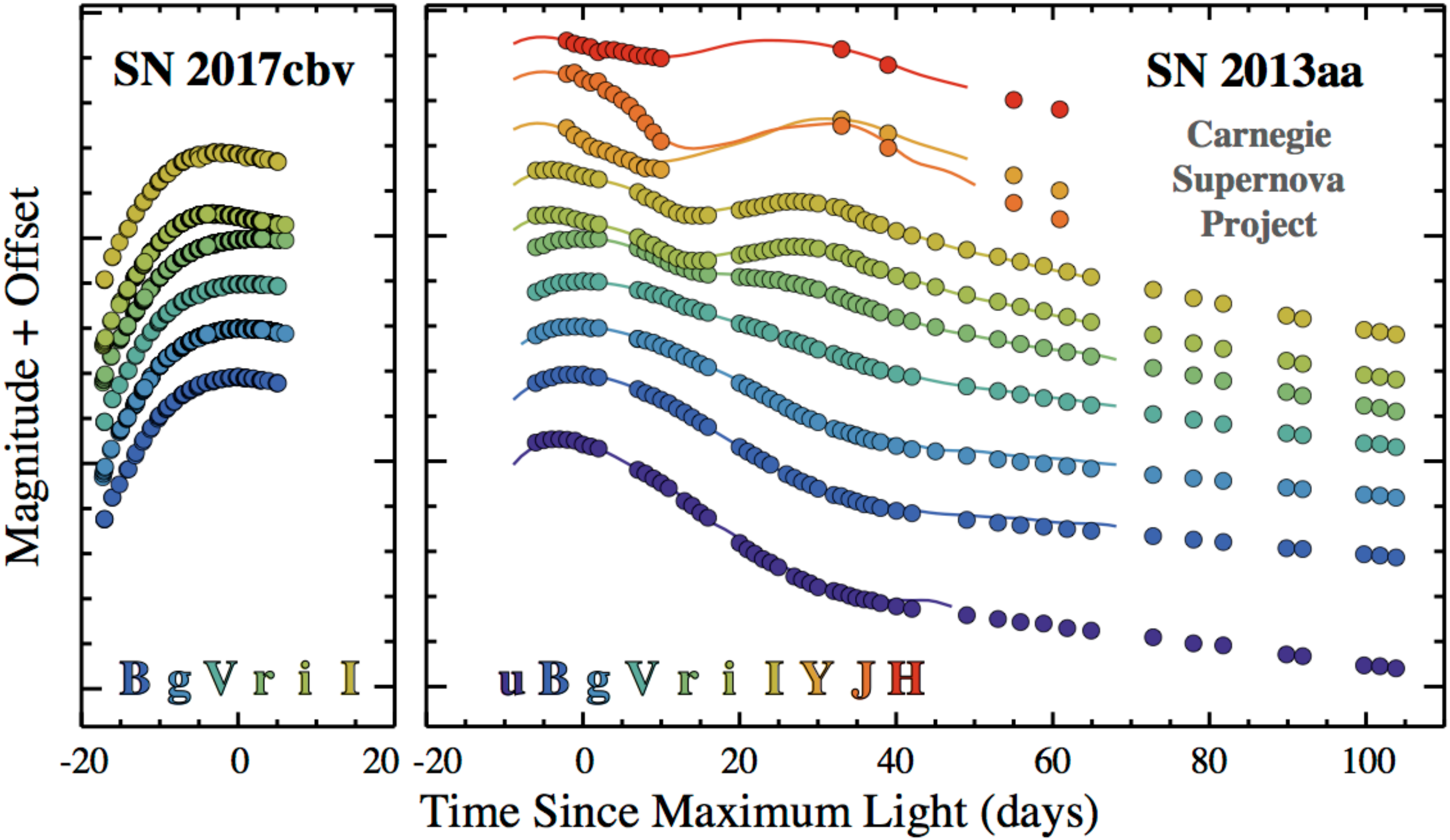
The first peak is due to decay of ^{56}Ni.
~0.1 to 1.0 Solar masses
Self-similar shape, homogenized with light curve fitting.

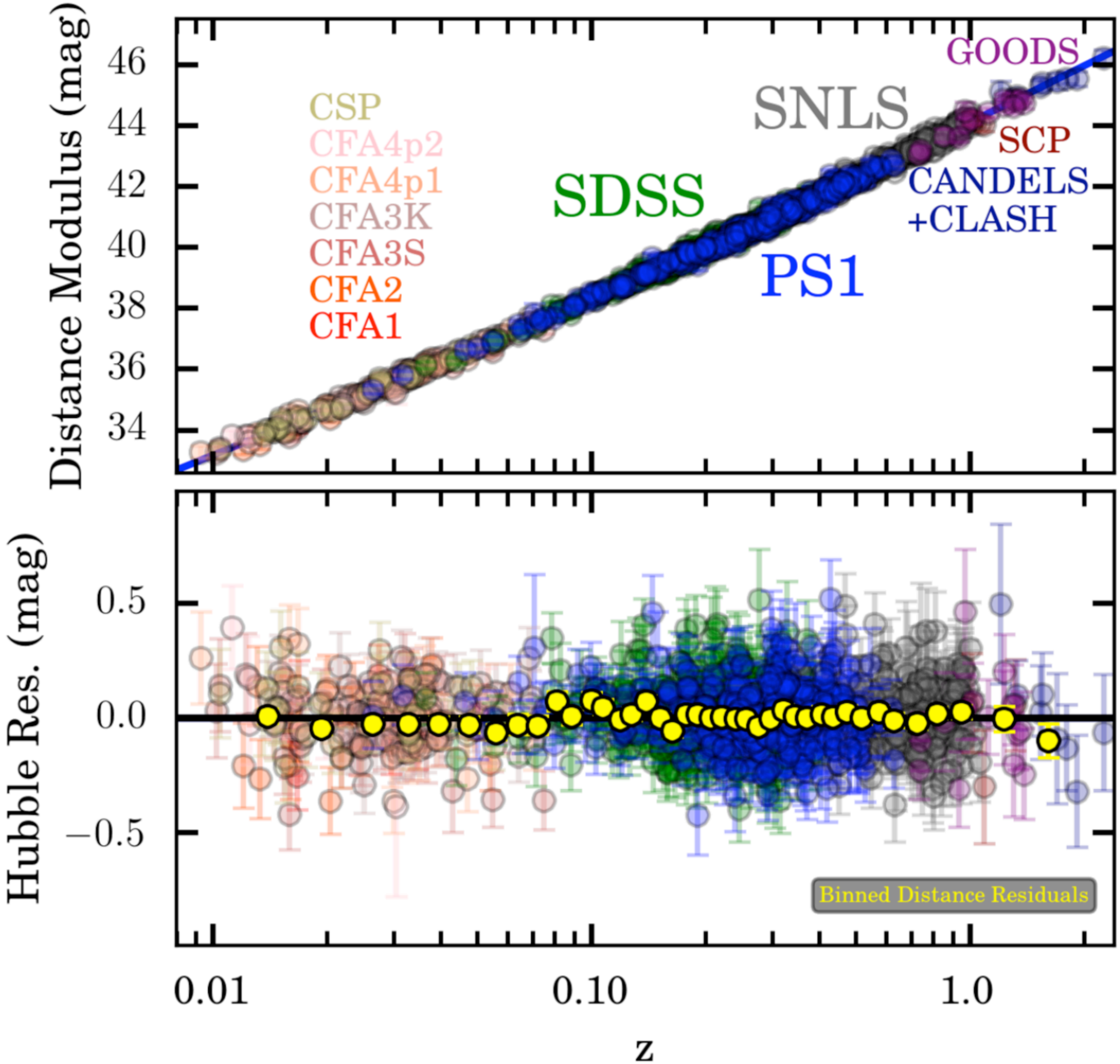
SNE IA DISTANCES



- Single-Degenerate or Double-Degenerate
- Despite all of the wonderful complexity, SNe Ia provide distances from ~6 Mpc (M101) to z~2
- With 5-7% intrinsic dispersion (width of the relationship)

SNE IA DISTANCES





0.10-0.15 magnitudes of irreducible error from z~here to z~2

Pantheon Sample:
Scolnic et al. 2017

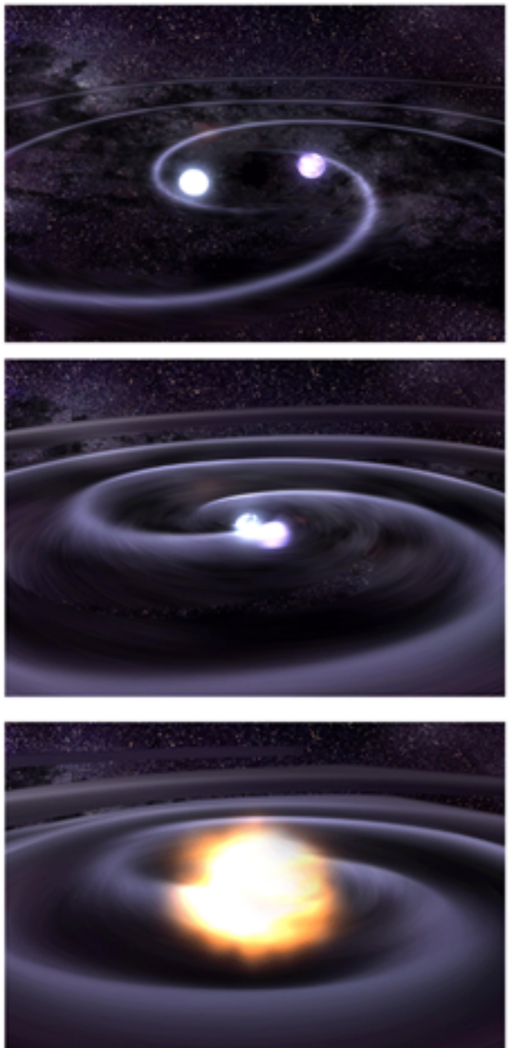
KNOWN SOURCES OF M_B VARIANCE

Progenitor System:

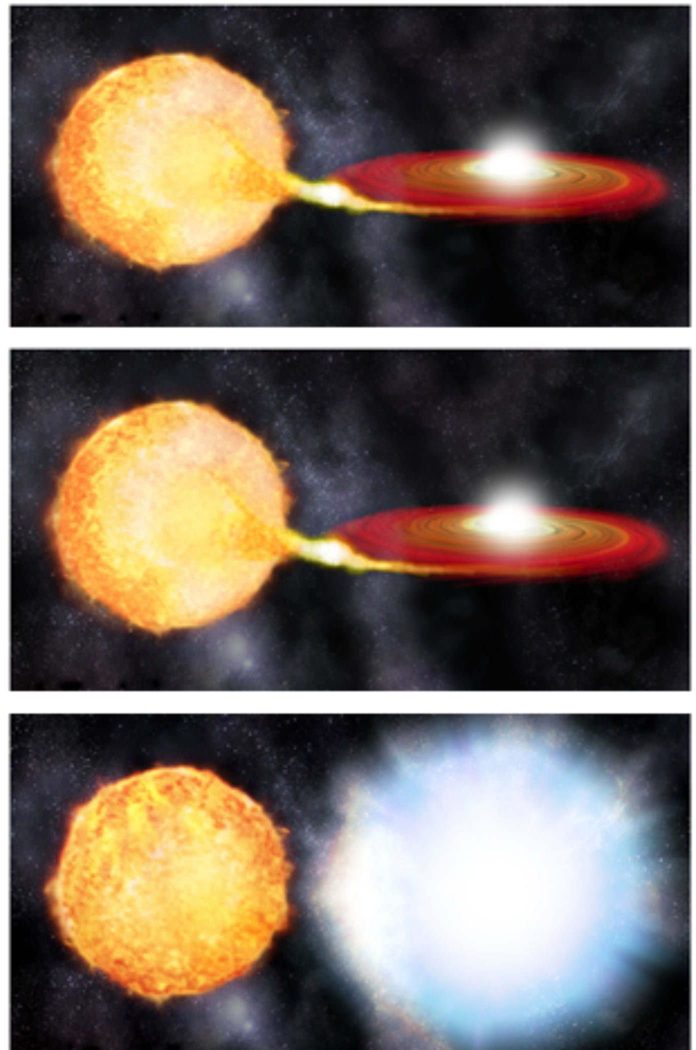
- Double Degenerate or Single Degenerate
- Probably a mix of both

PROGENITOR SYSTEM

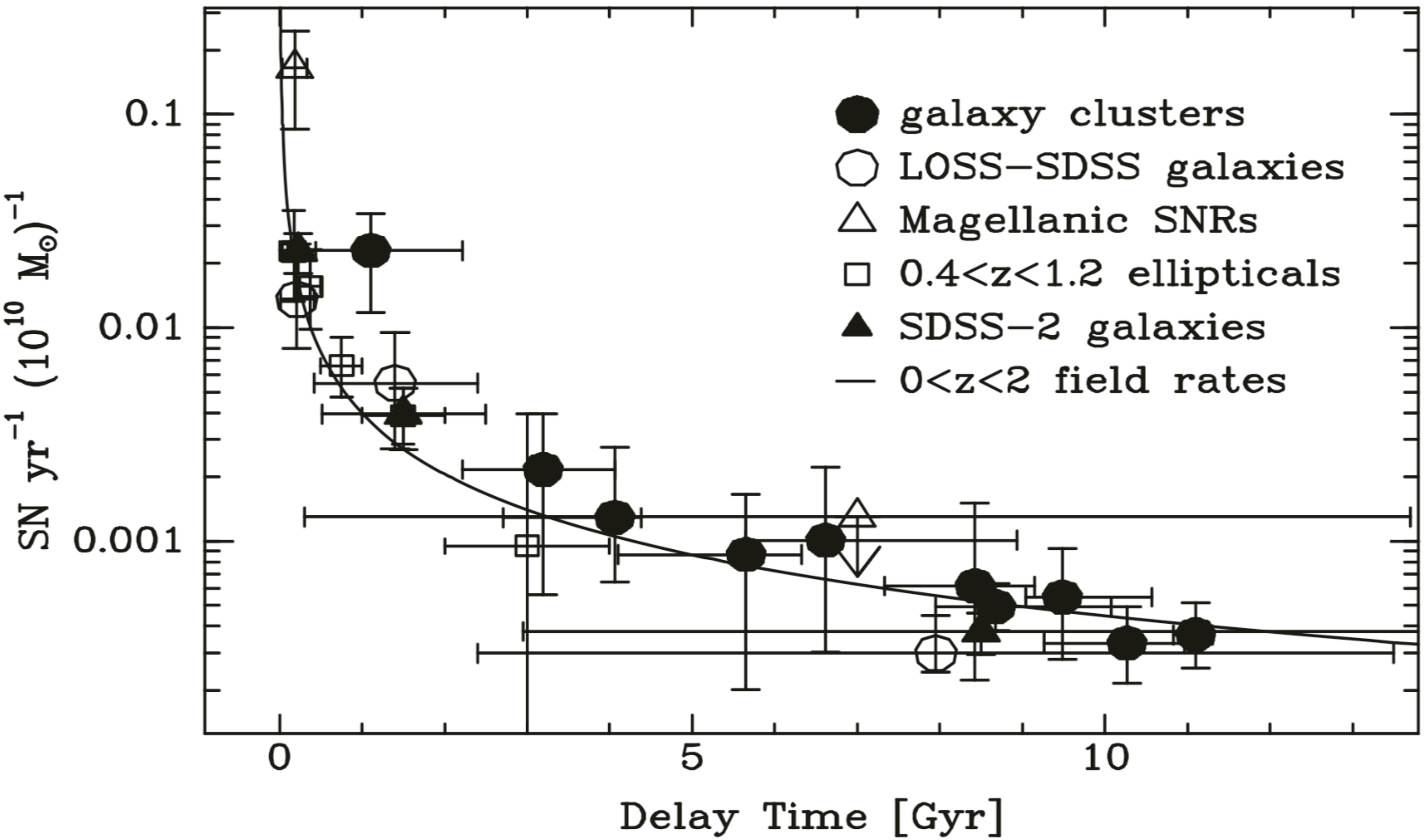
Double Degenerate



Single Degenerate

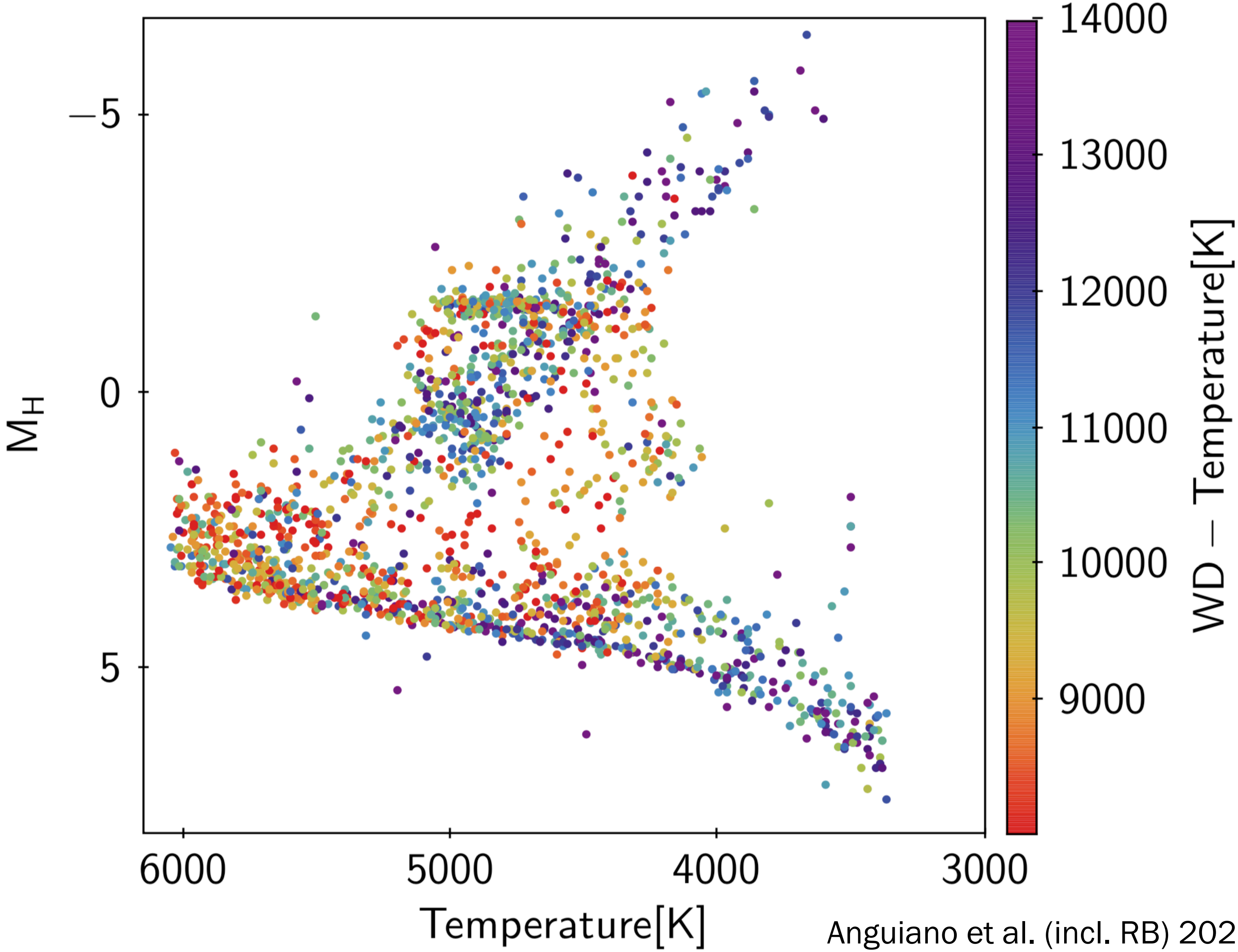


PROGENITOR SYSTEM



Maoz et al. 2012

PROGENITOR SYSTEM



Anguiano et al. (incl. RB) 2022

KNOWN SOURCES OF M_B VARIANCE

Progenitor System:

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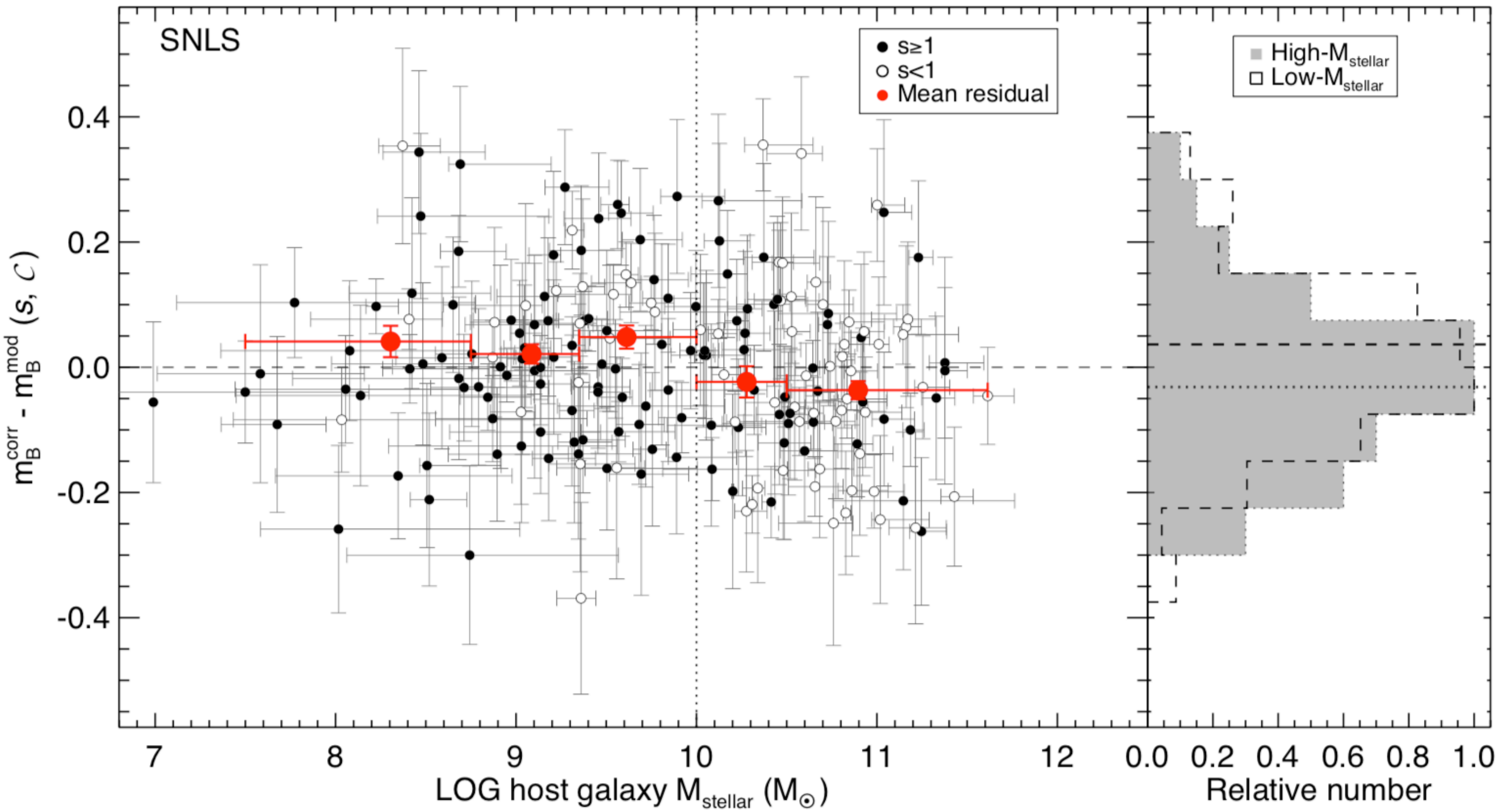
Host Mass Bias:

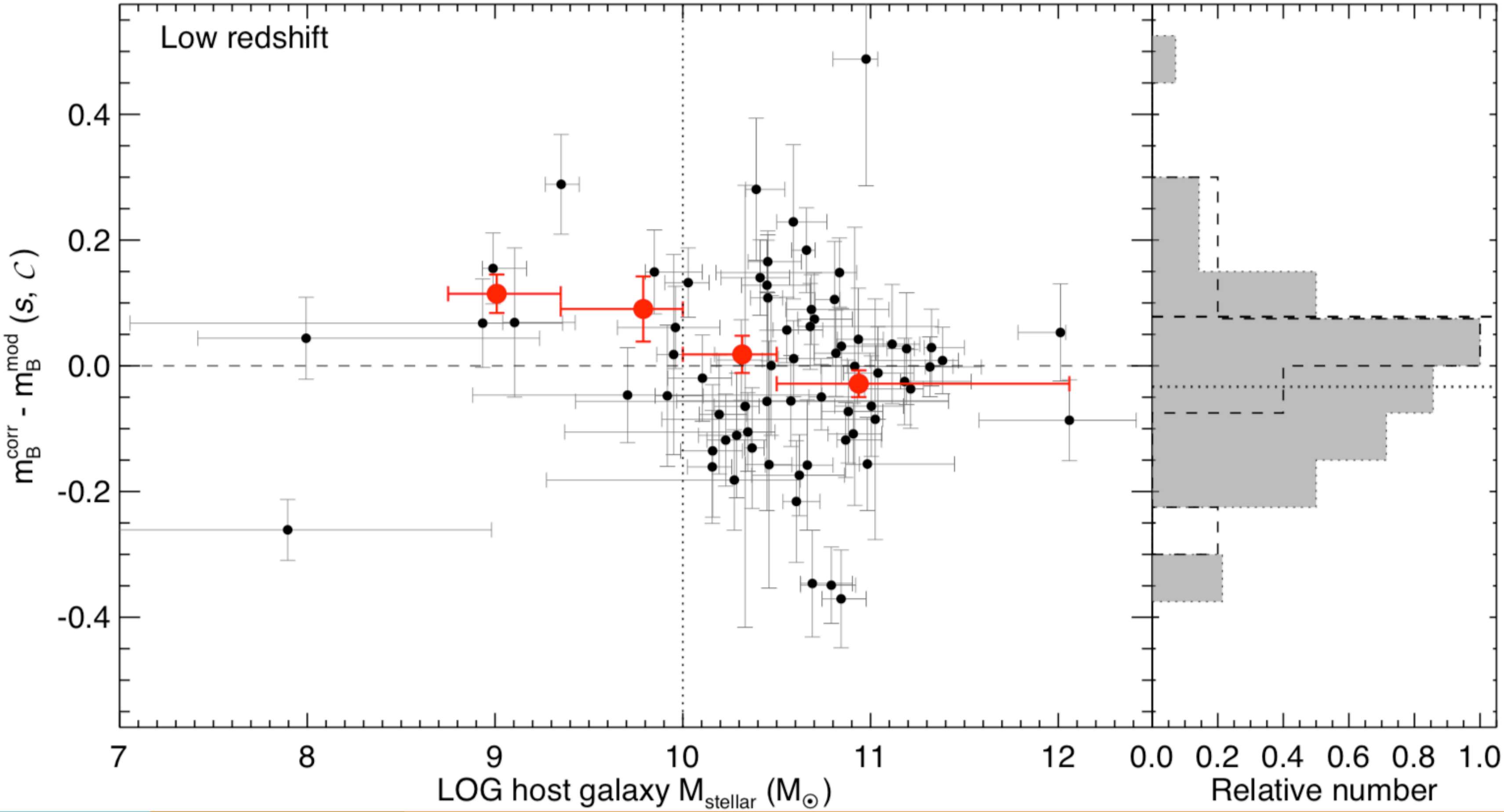
- Difference between lower mass star forming galaxies and higher mass passive galaxies
- Probably stellar populations/star formation history

HOST MASS



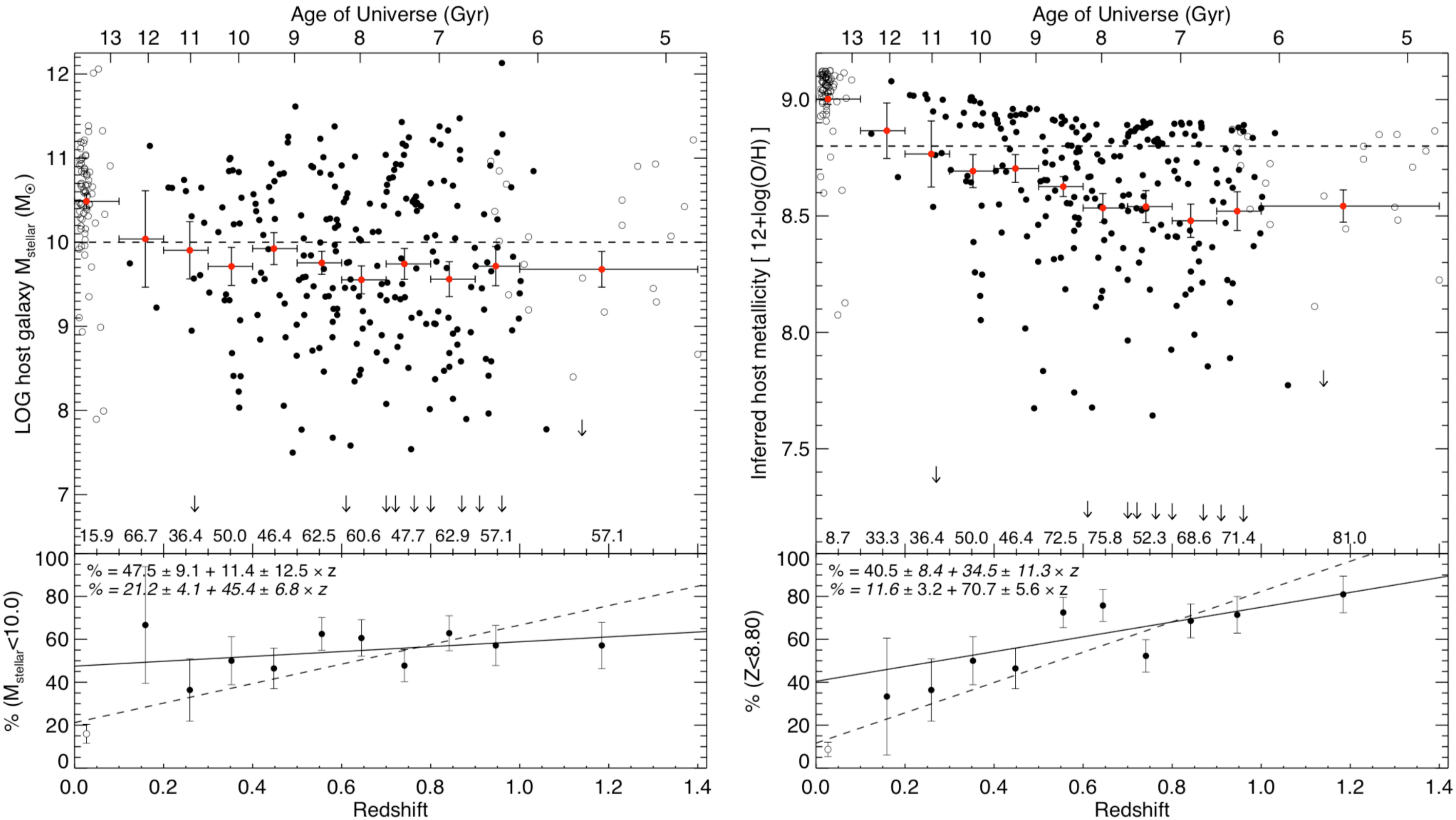
Sullivan et al. 2010

HOST MASS



SuMiaan et al. 2010

HOST MASS



Sullivan et al. 2010

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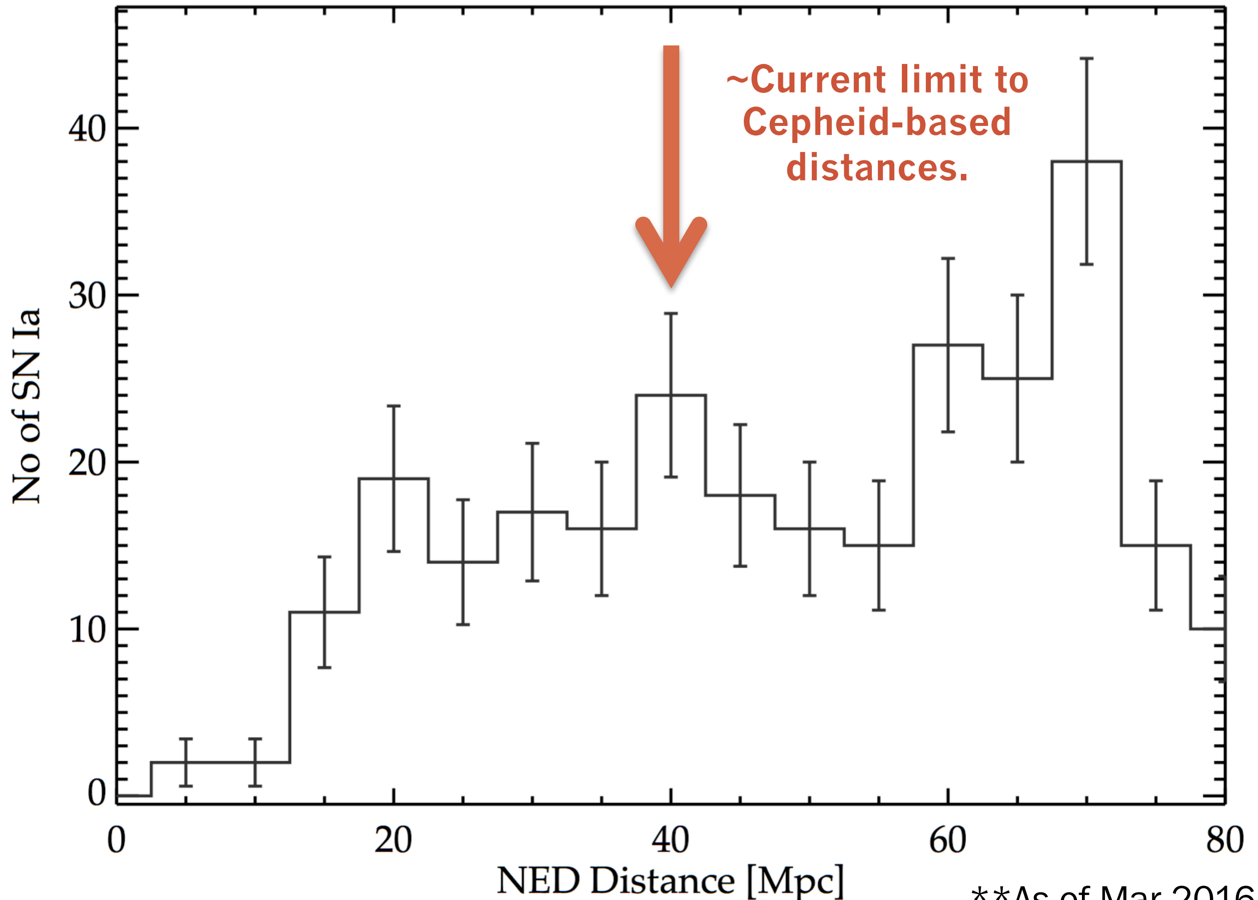
"Local" Star forming Bias:

- Difference for SNe local environment based on UV emission (young stars)

WHY SO FEW CALIBRATORS?

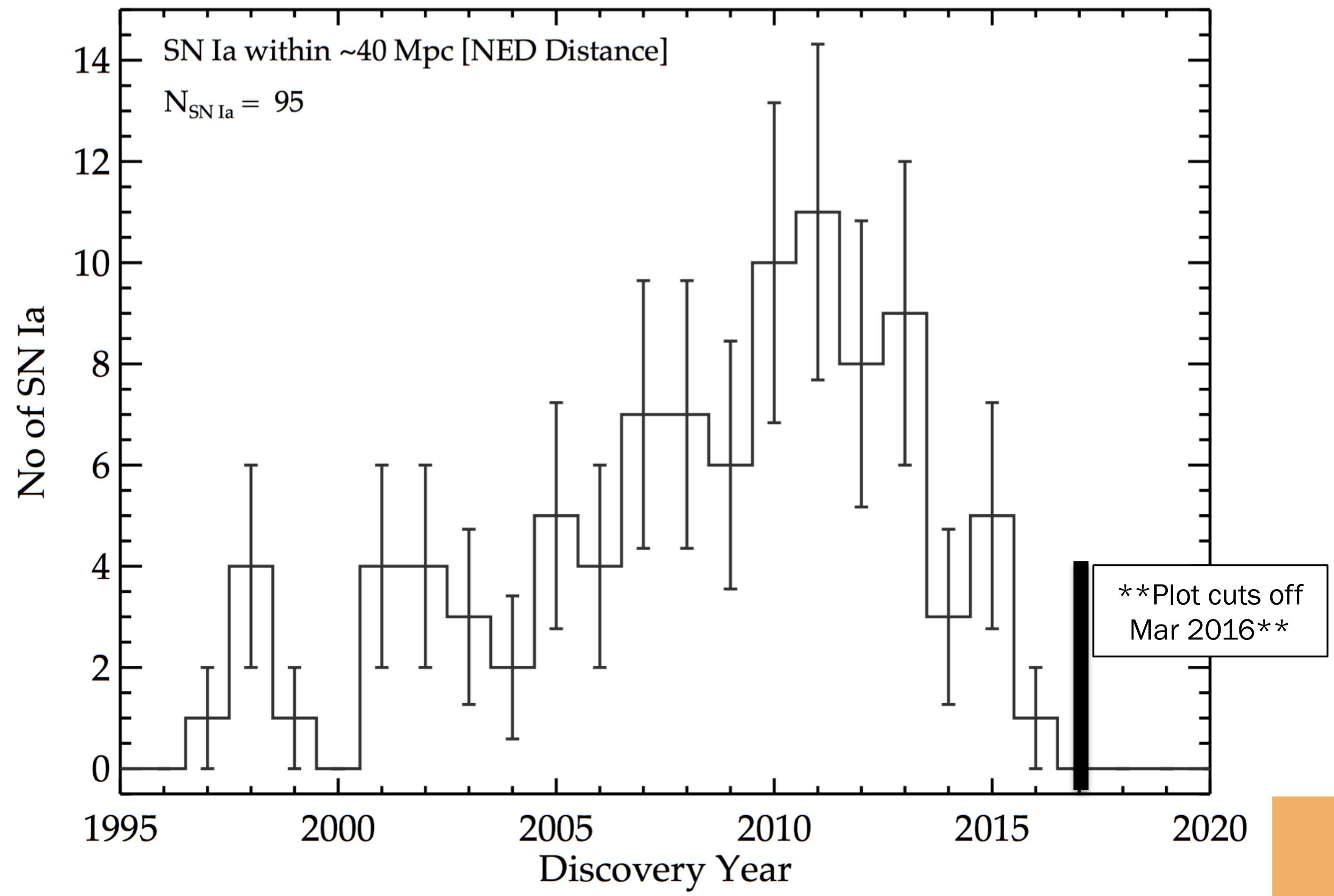


**As of Mar 2016

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

A detailed description of this experiment is in Czerny, Beaton et al. 2018

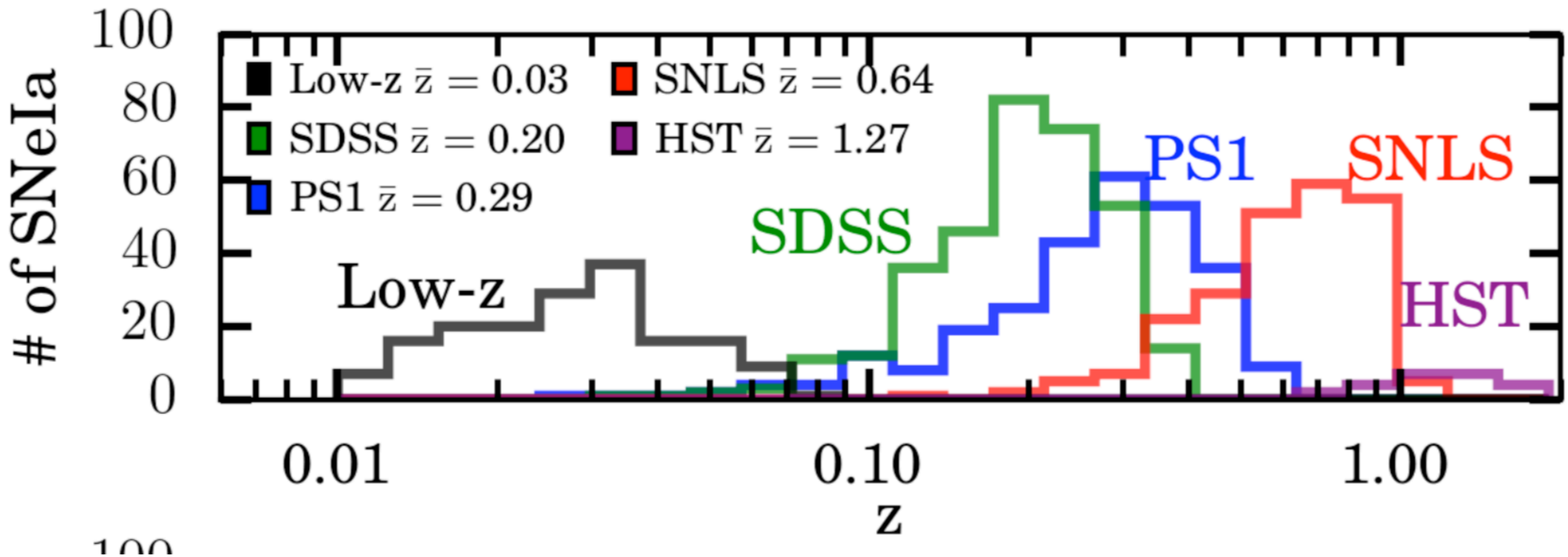
WHY SO FEW CALIBRATORS?



or that they have only been discovered recently.

A detailed description of this experiment is in Czerny, Beaton et al. 2018

COMPLETENESS IN THE SNE IA SAMPLE



Pantheon Sample:
Scolnic et al. 2017

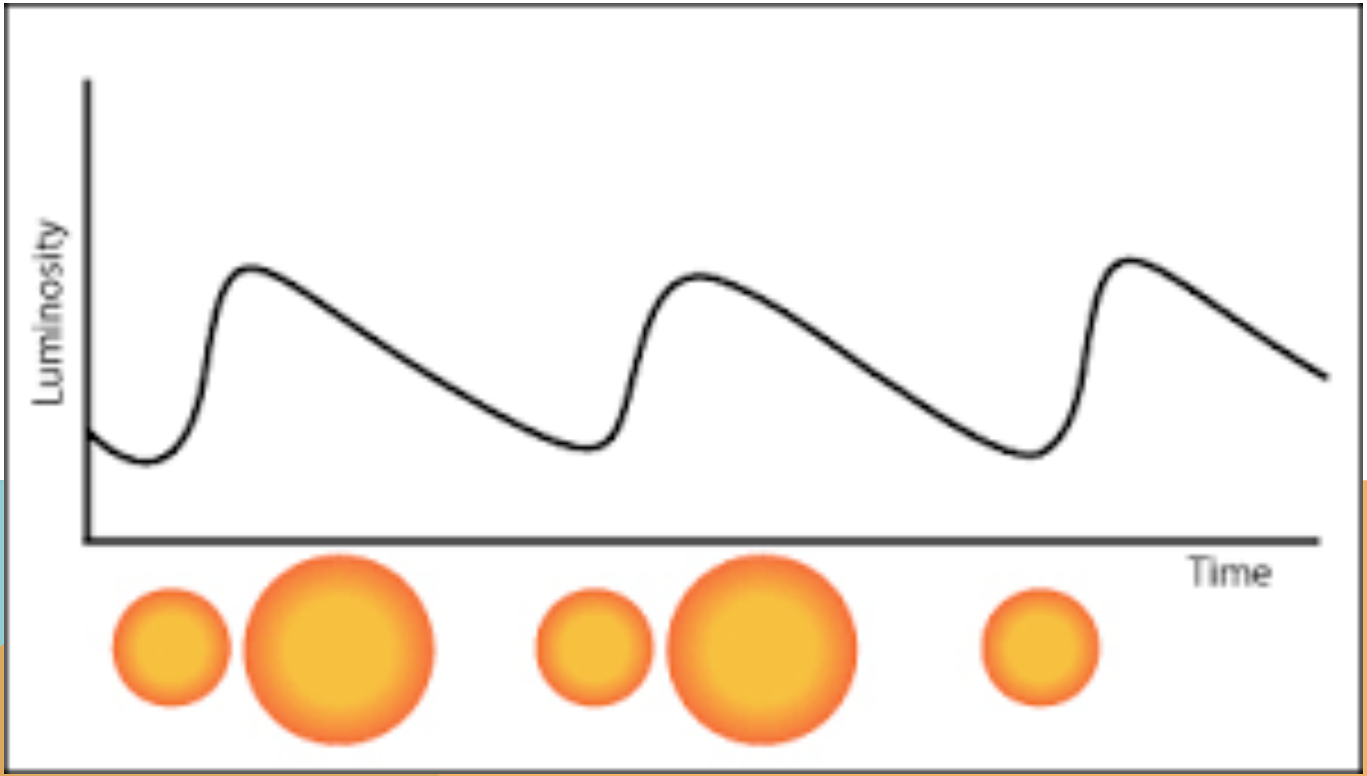
COSMIC DISTANCE SCALE IN A SLIDE

Geometric Distances	Calibration of SNe Ia	SNe Ia in Hubble Flow for H_0	Hubble-Lemaître Law + ΛCDM
1	2	3	4

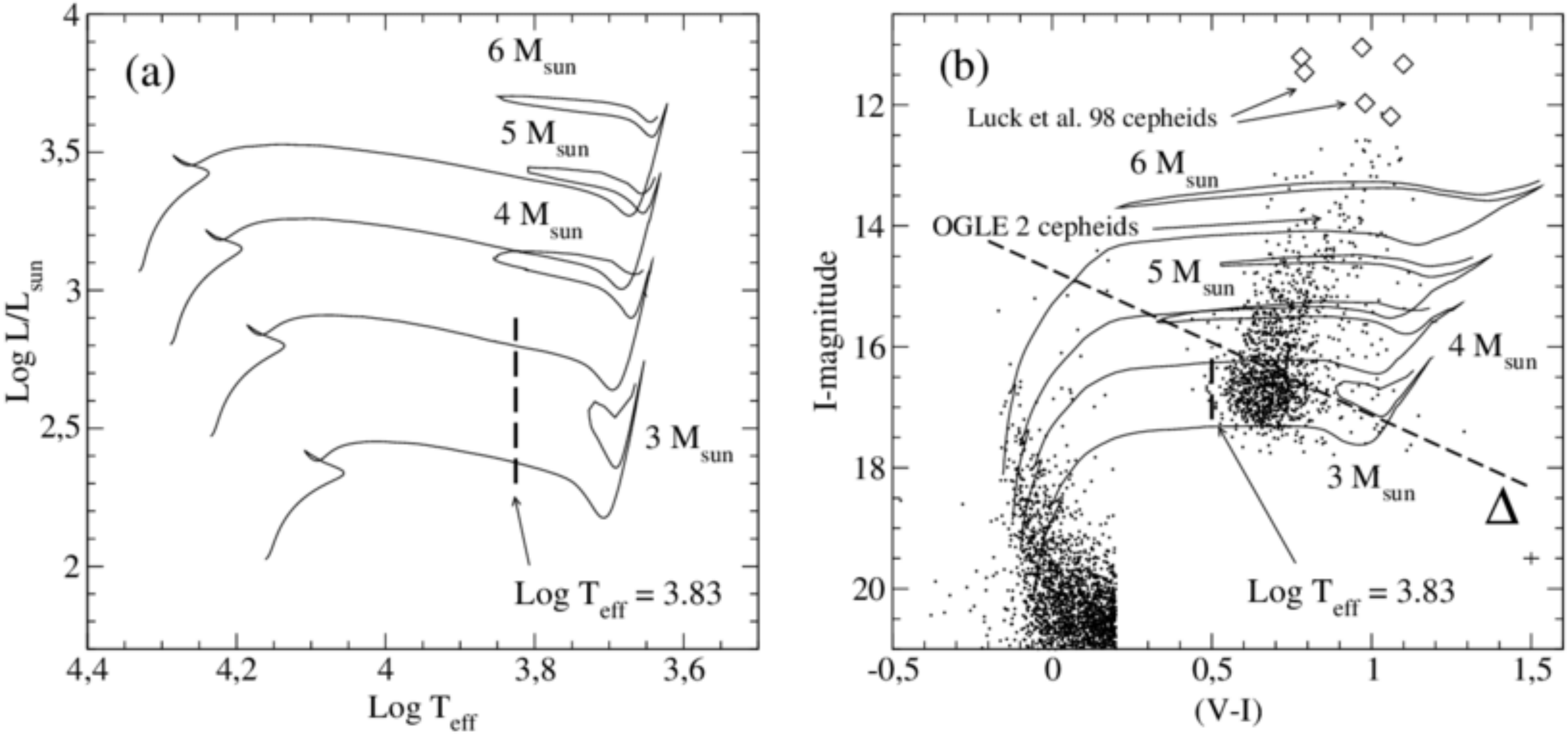
STAR STUFF 2: CEPHEIDS

CEPHIEDS

$$\log P \;=\; \mathfrak{F}\{\log(M/M_\odot),\;\log(L/L_\odot),\;\log T_{\rm eff},\;\log Z\}\,.$$



CEPHIEDS



$$\log P \;=\; \mathfrak{F}\,\{\log(M/M_\odot),\;\; \log(L/L_\odot),\;\; \log T_{\rm eff},\;\; \log Z\}\,.$$

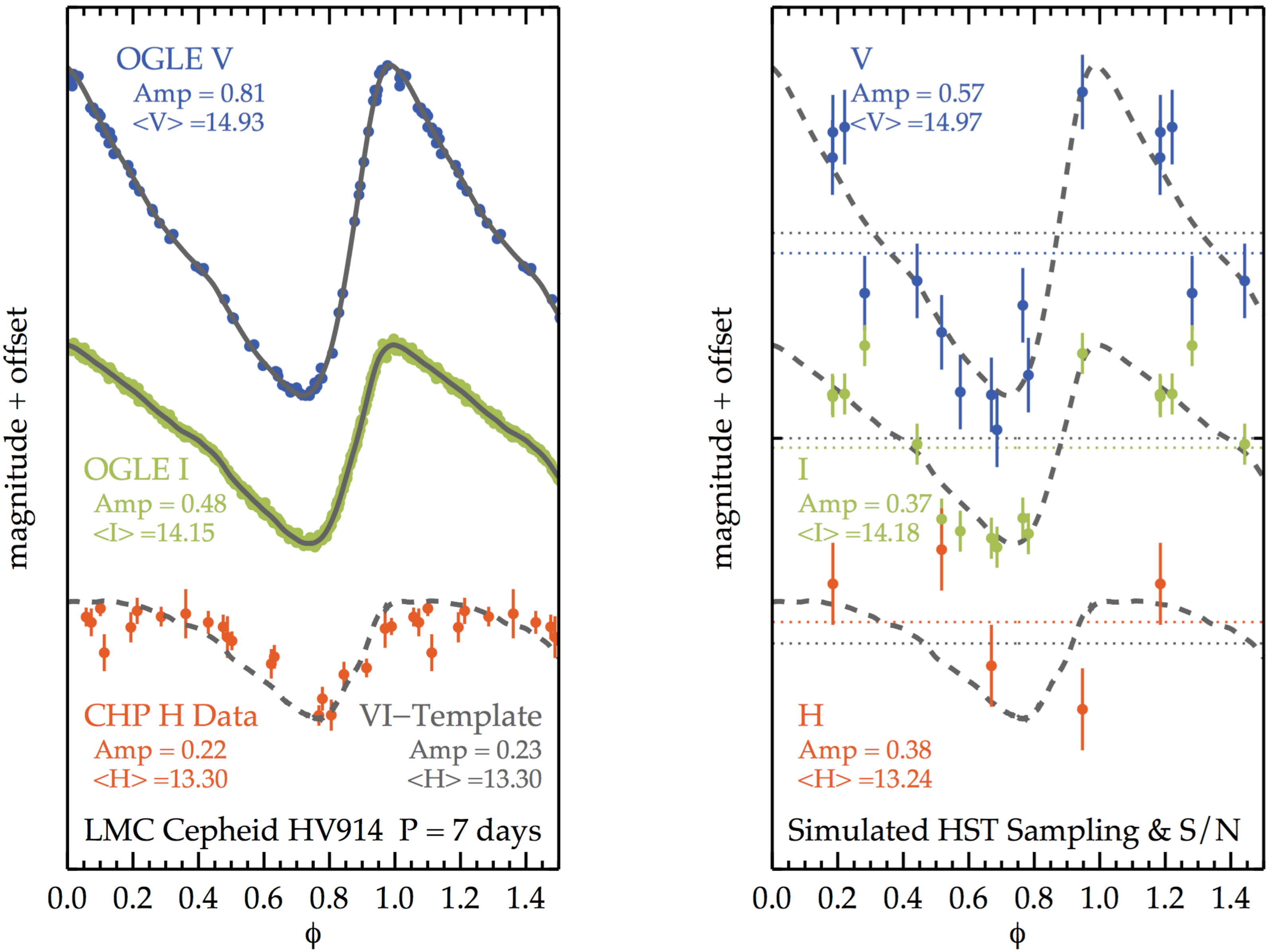
CEPHEID PERIOD LUMINOSITY

$$M_\lambda = a_\lambda + b_\lambda \log_{10}(P) + c_\lambda Z$$

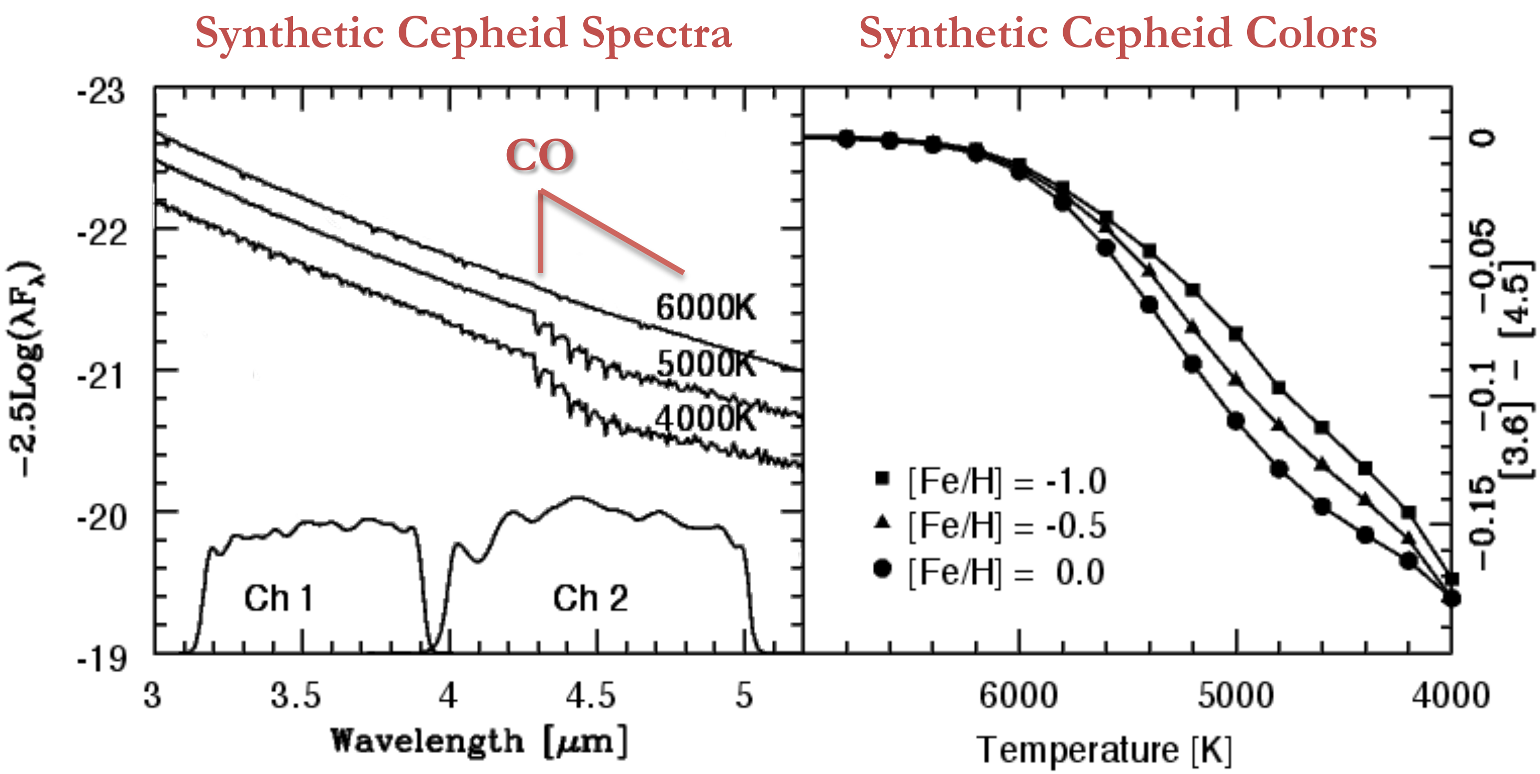
Luminosity = Zero Point + Period Term + Metallicity Term

$$\log P = \mathfrak{F}\{\log(M/M_\odot),\ \log(L/L_\odot),\ \log T_{\rm eff},\ \log Z\}\,.$$

OBSERVATIONS:



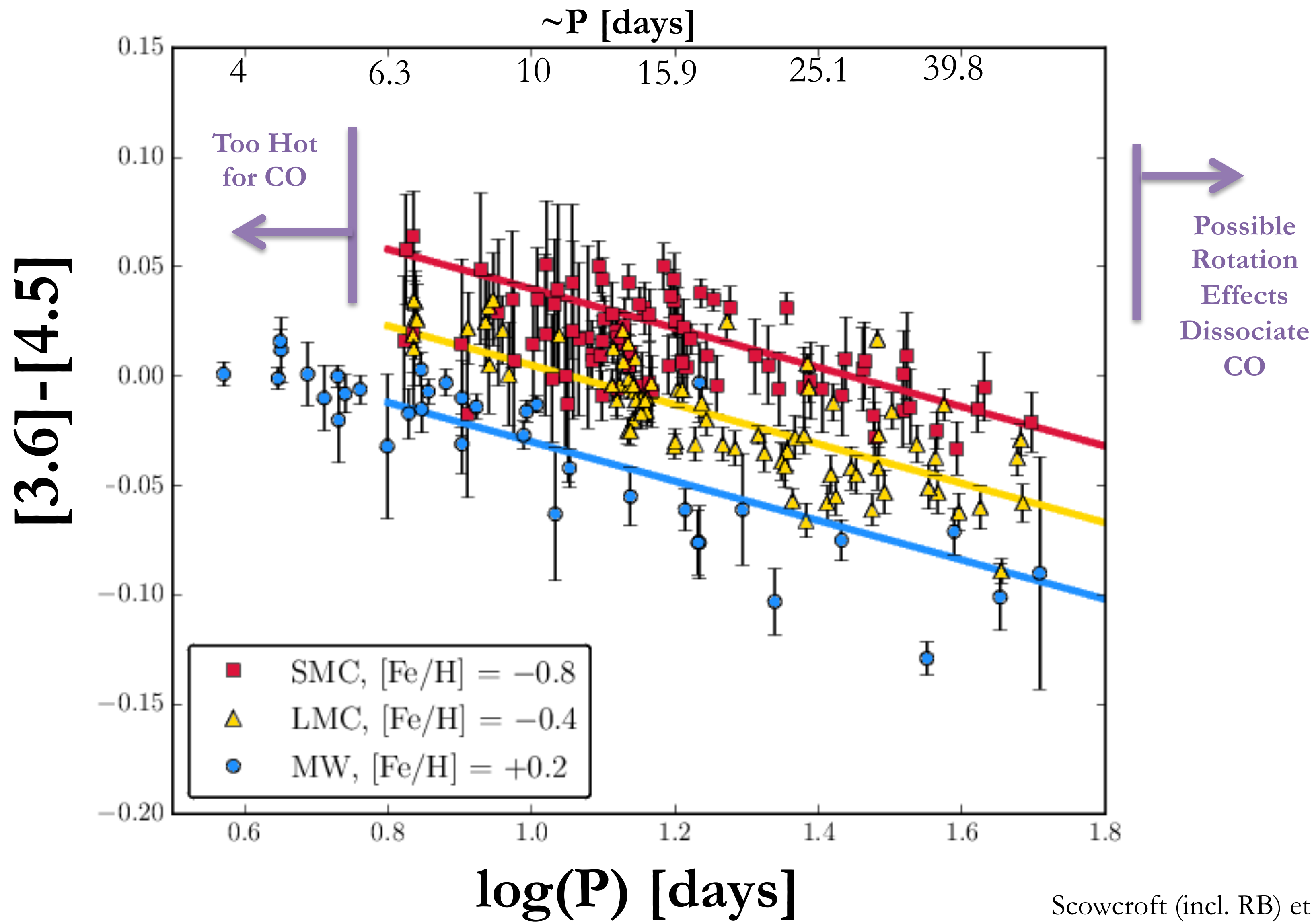
STARS ARE NOT TRUE BLACKBODIES



MIR color curves for Cepheids are not featureless due to the CO bandhead in the IRAC2 band (left).
The expression of the bandhead is a function of metallicity (right).

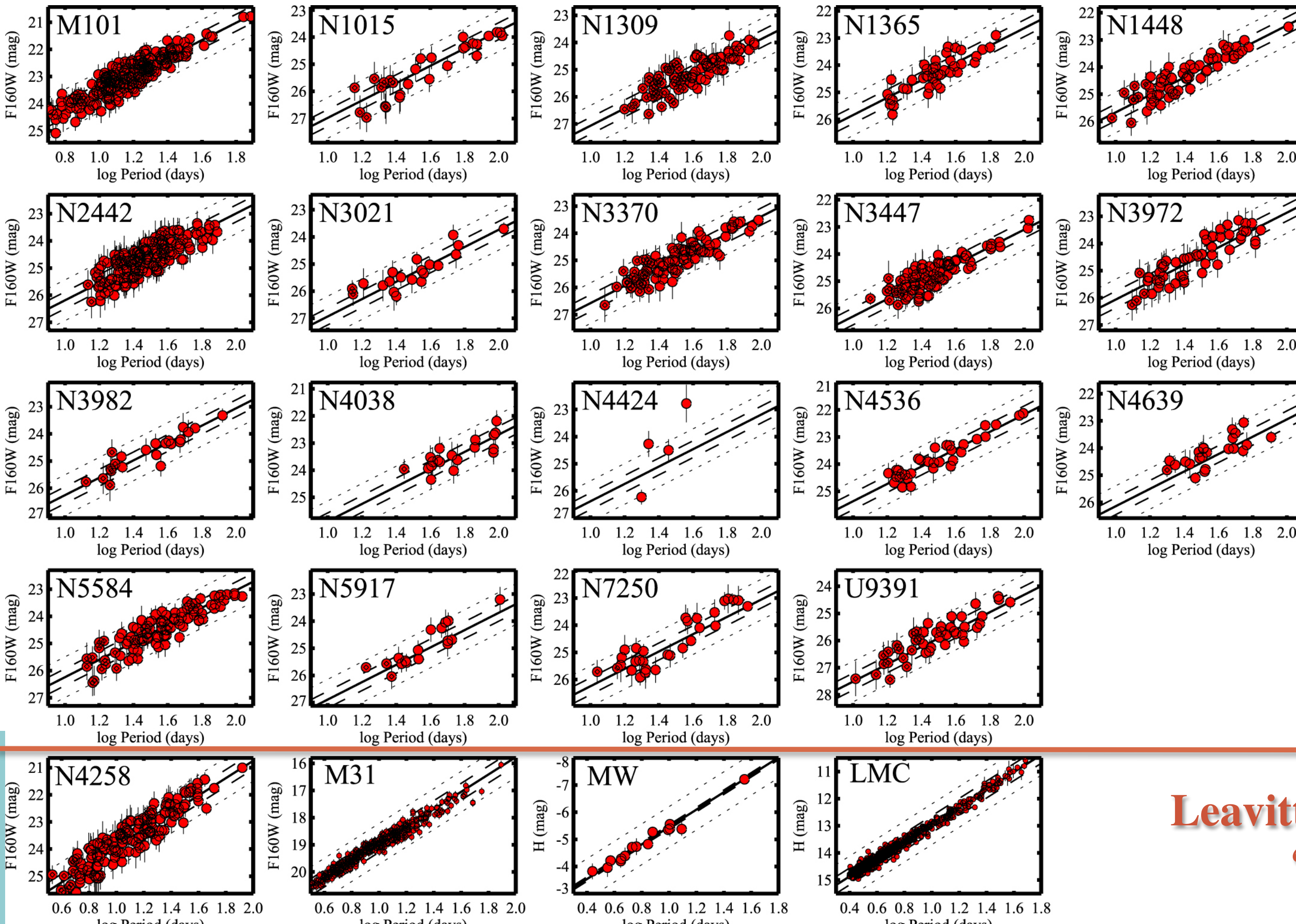
Models from Marengo et al. 2010
Figure from Monson et al. 2012

STARS ARE NOT TRUE BLACKBODIES



Scowcroft (incl. RB) et al. 2016

DISTANCES VIA LEAVITT LAW

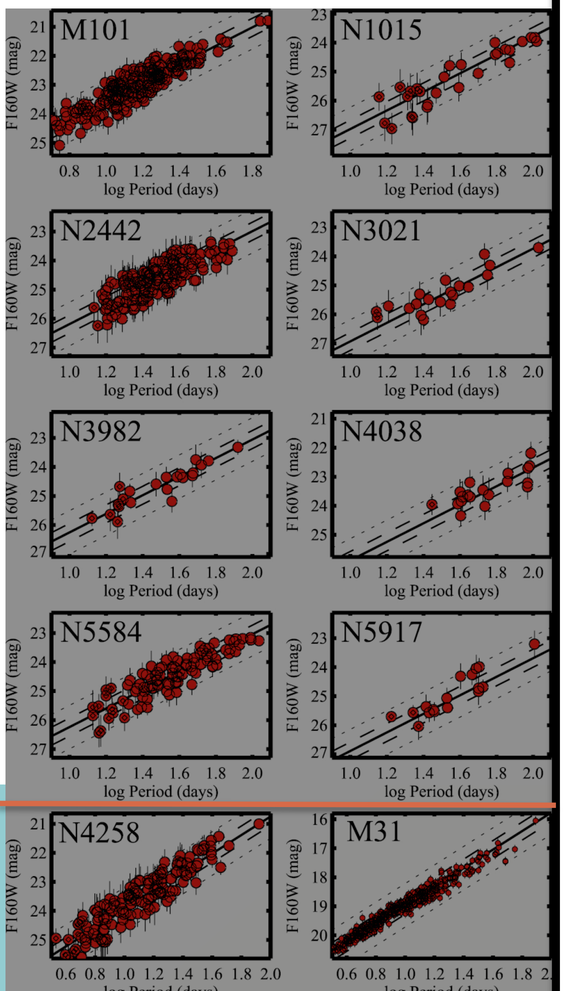


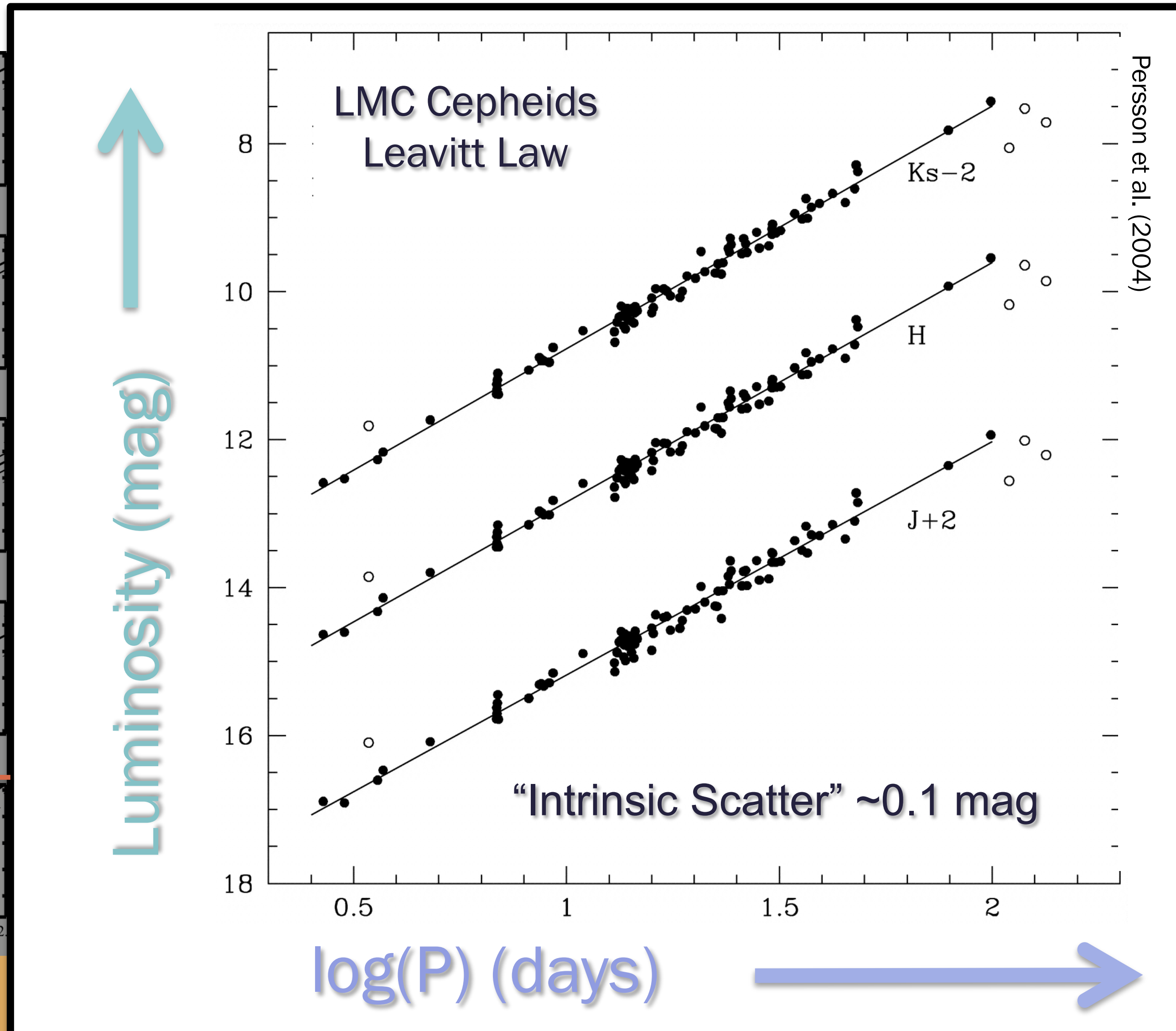
SN Ia Host Galaxies

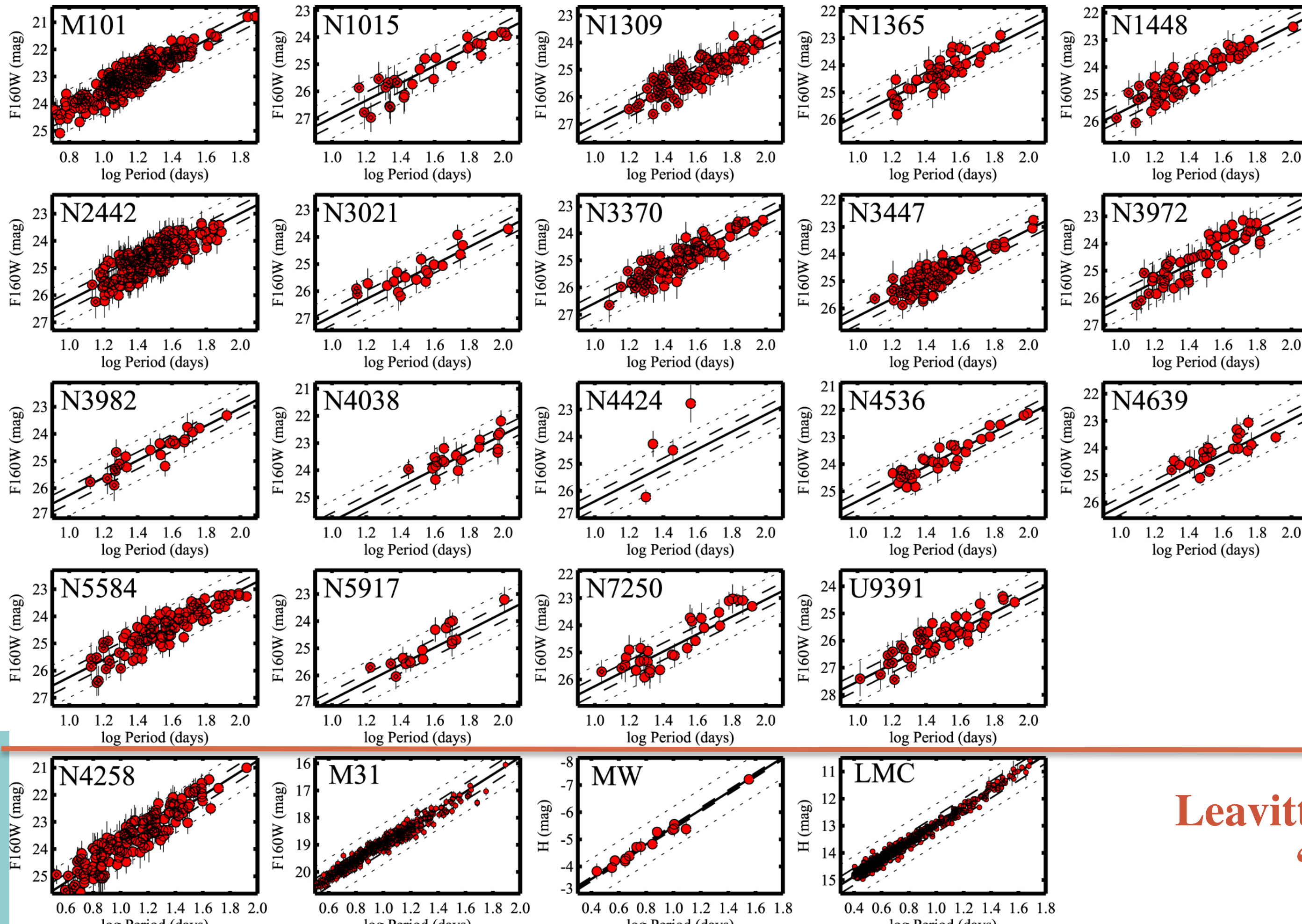
Leavitt Law Zero Point "Anchors"

Riess et al. 2016
Hoffmann et al. 2016

THE LEAVITT LAW IN AN ANCHOR



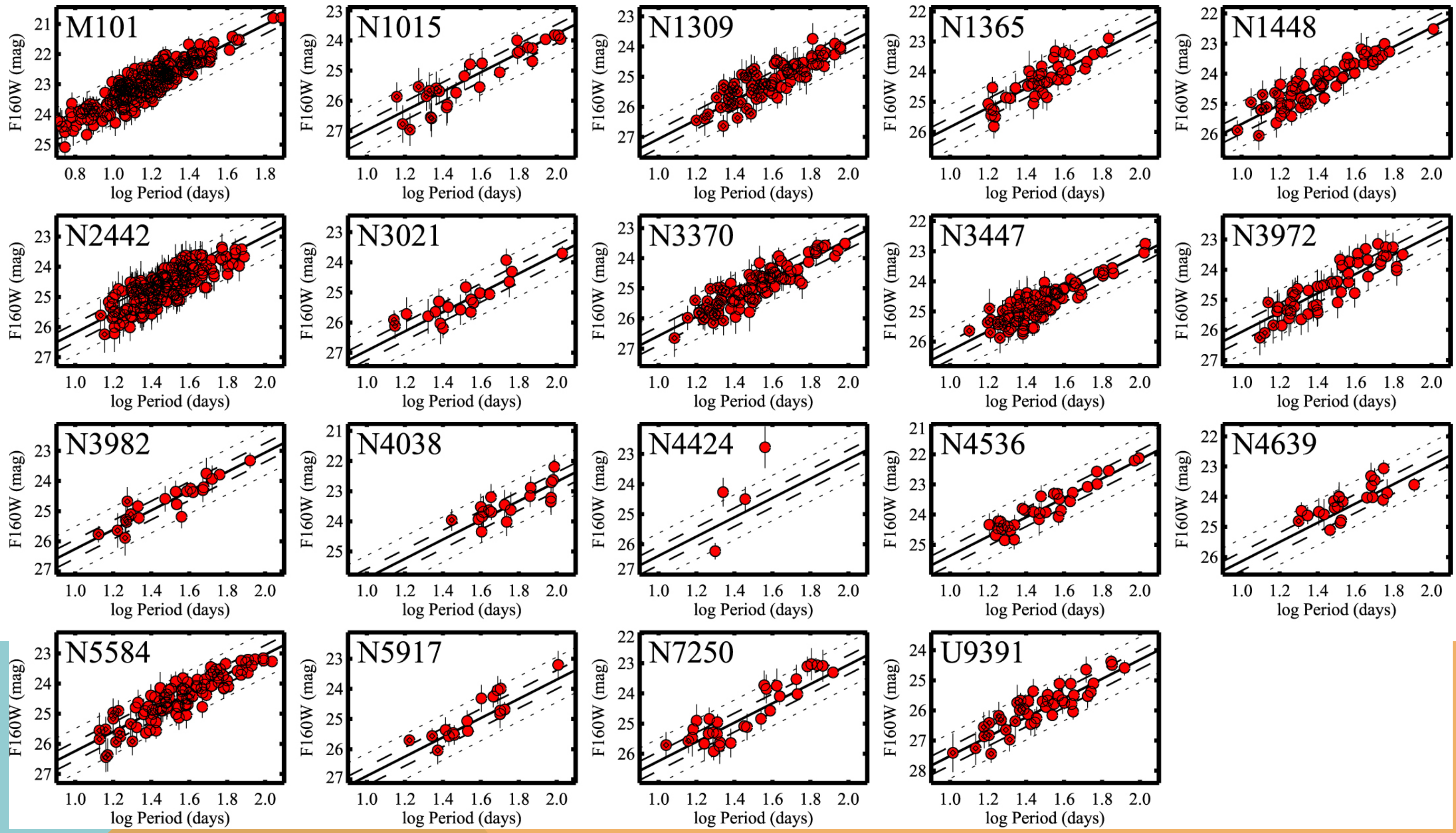




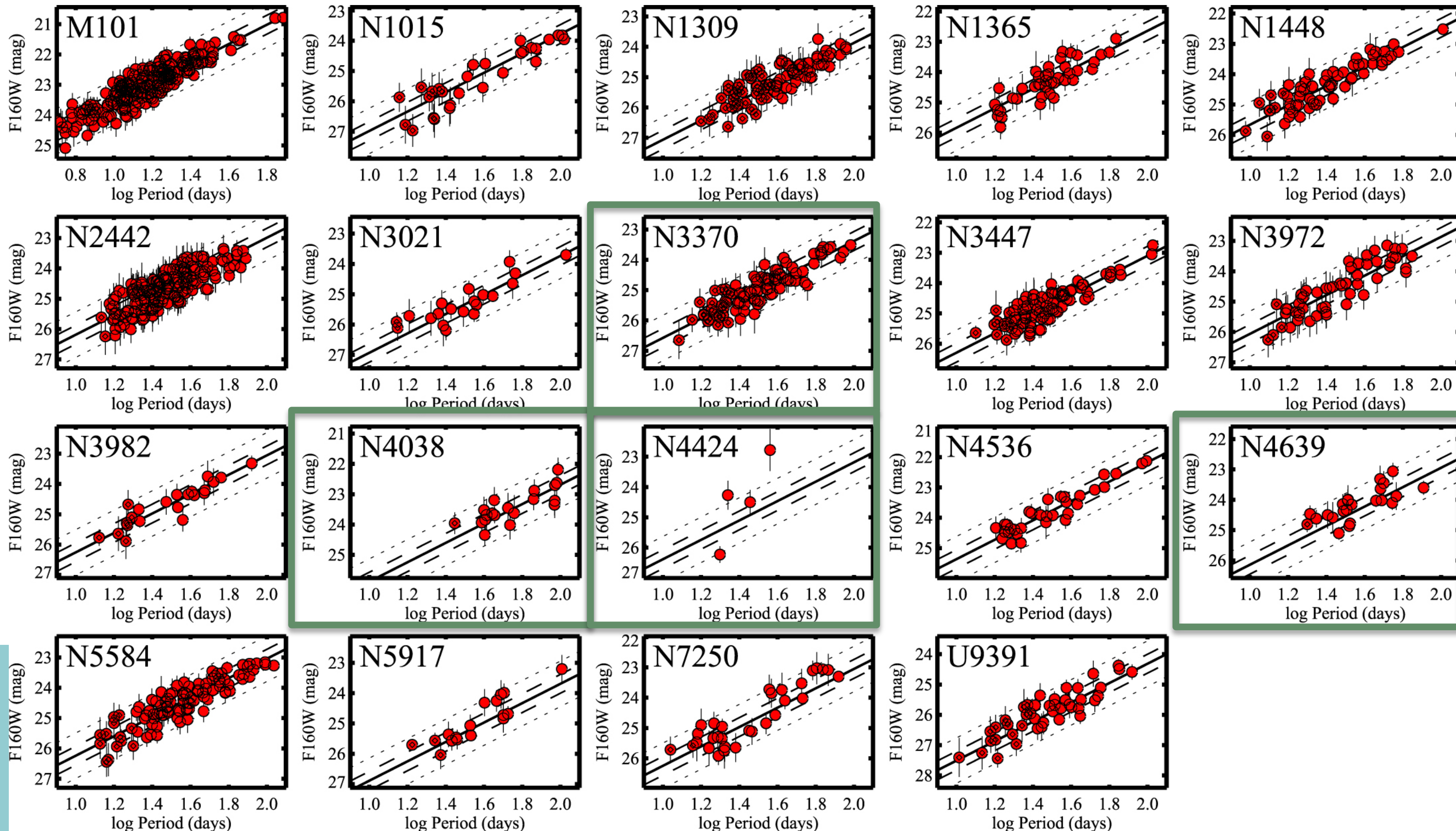
SN Ia Host Galaxies

Leavitt Law Zero Point "Anchors"

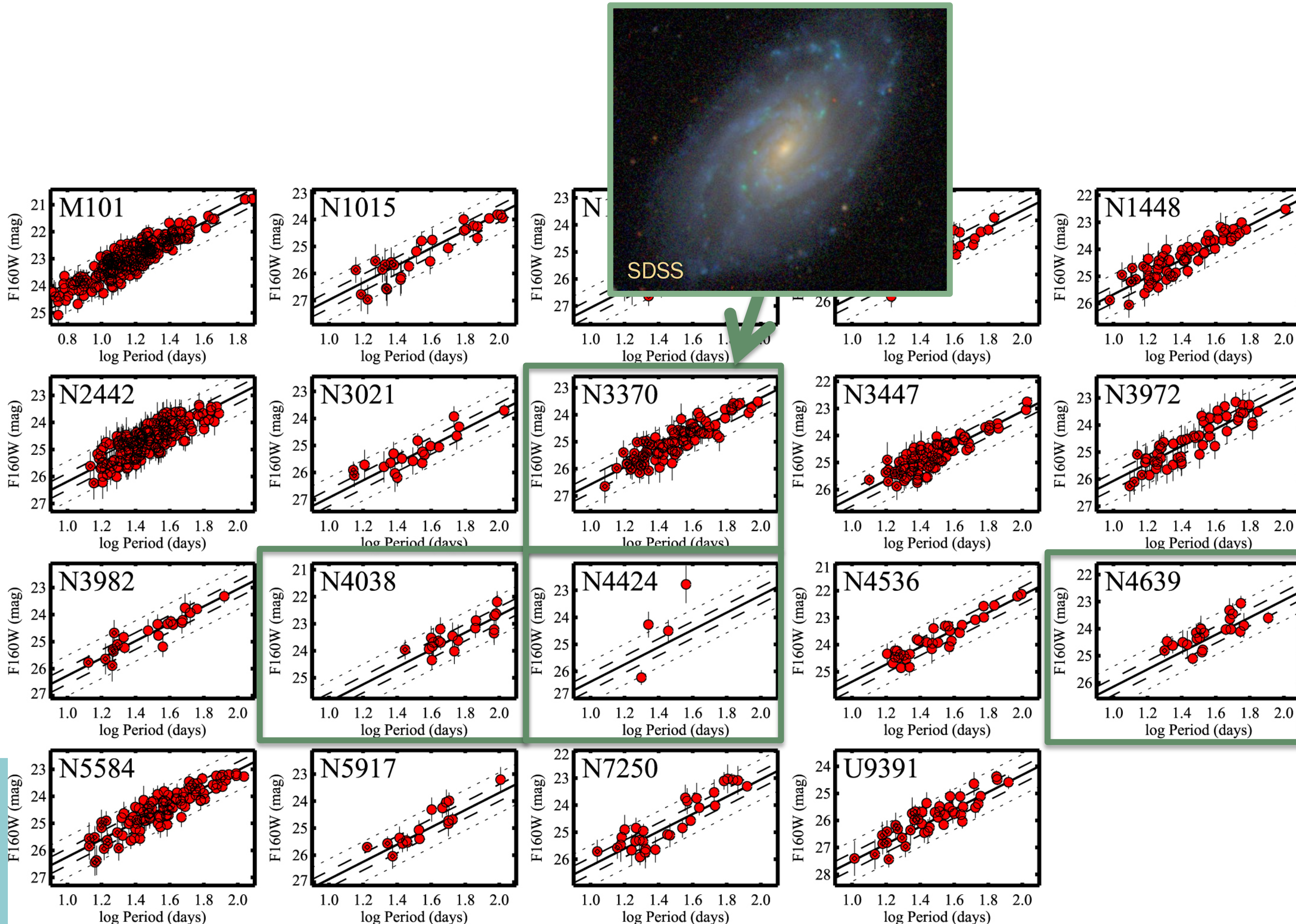
Riess et al. 2016
Hoffmann et al. 2016



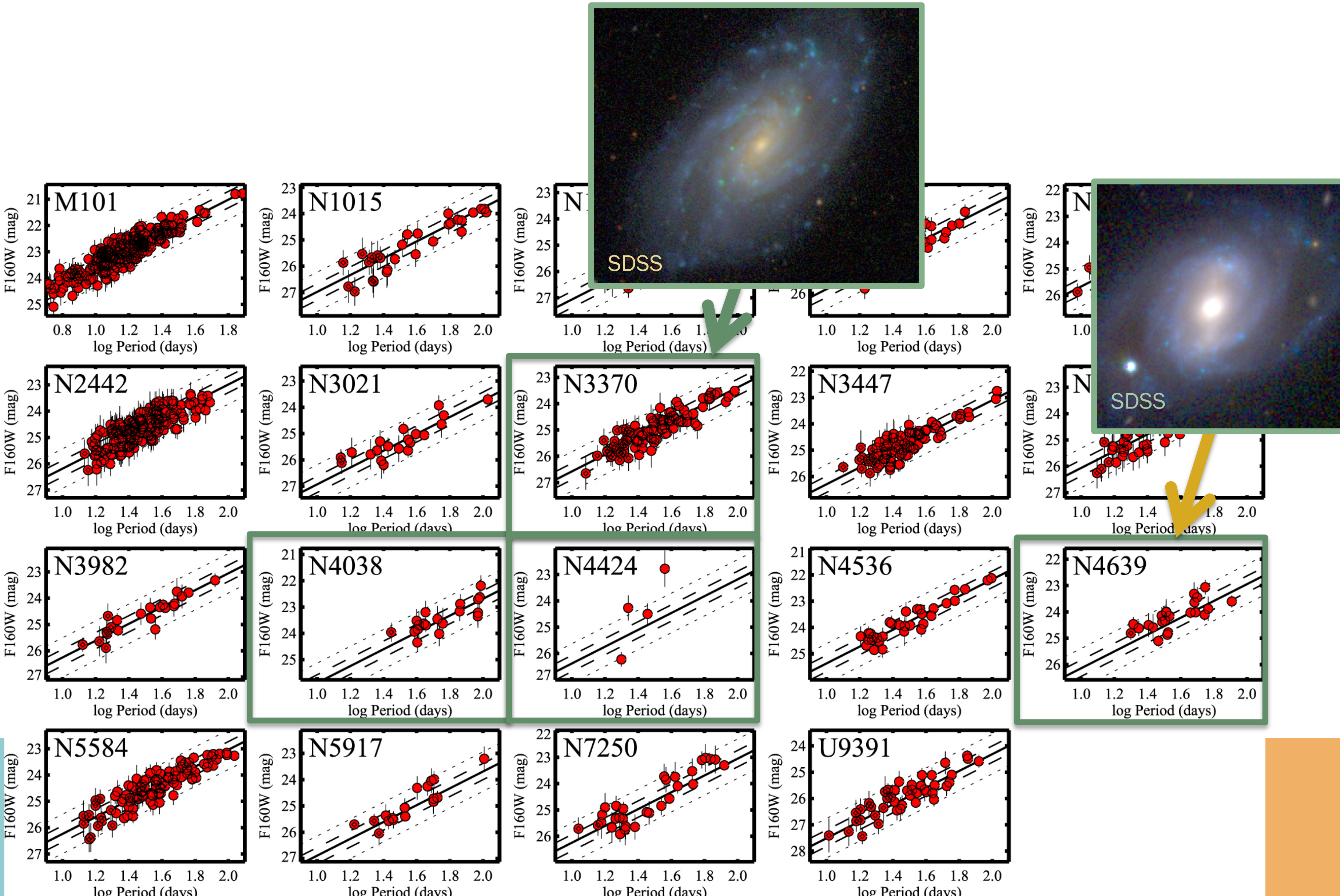
Riess et al. 2016



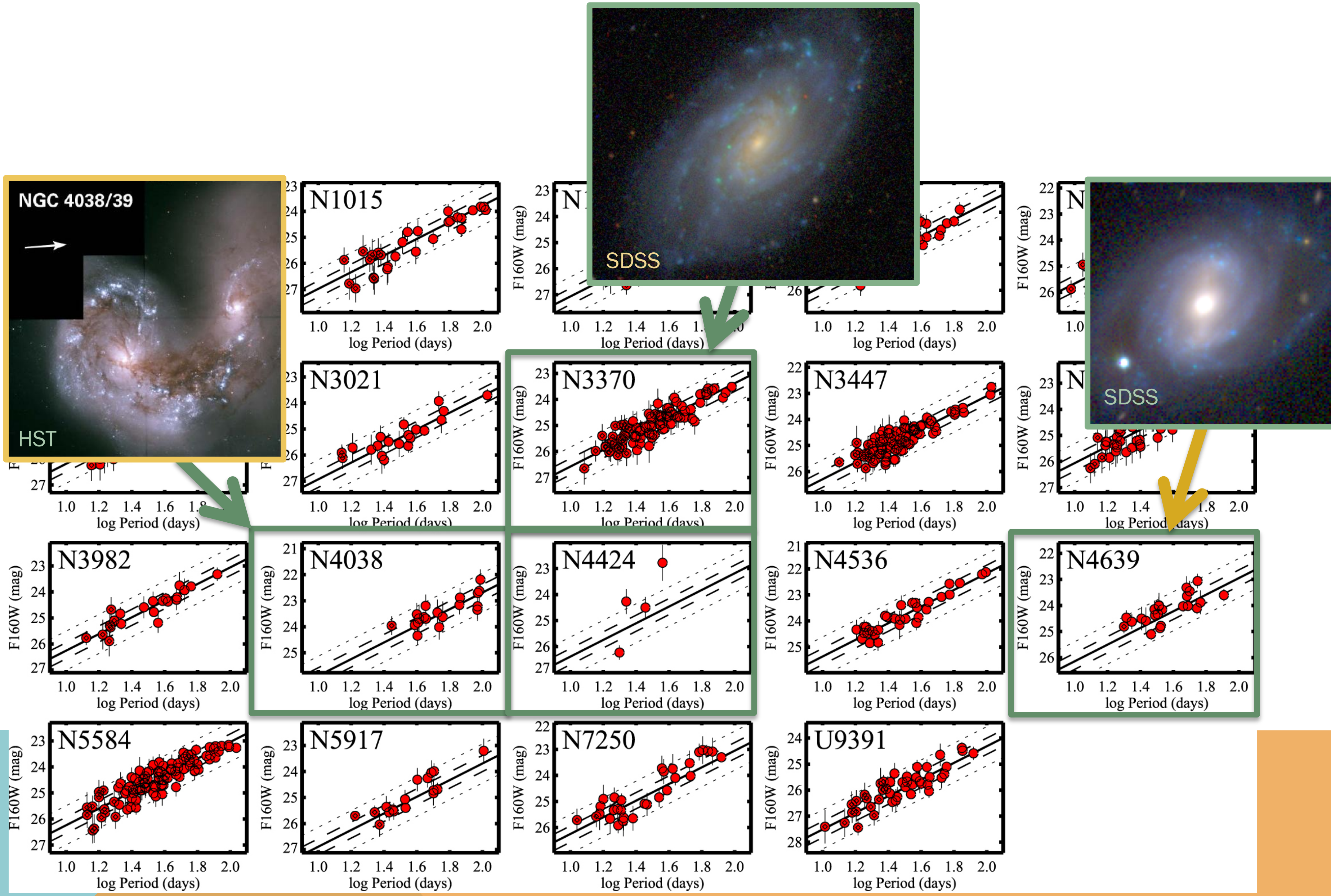
Riess et al. 2016



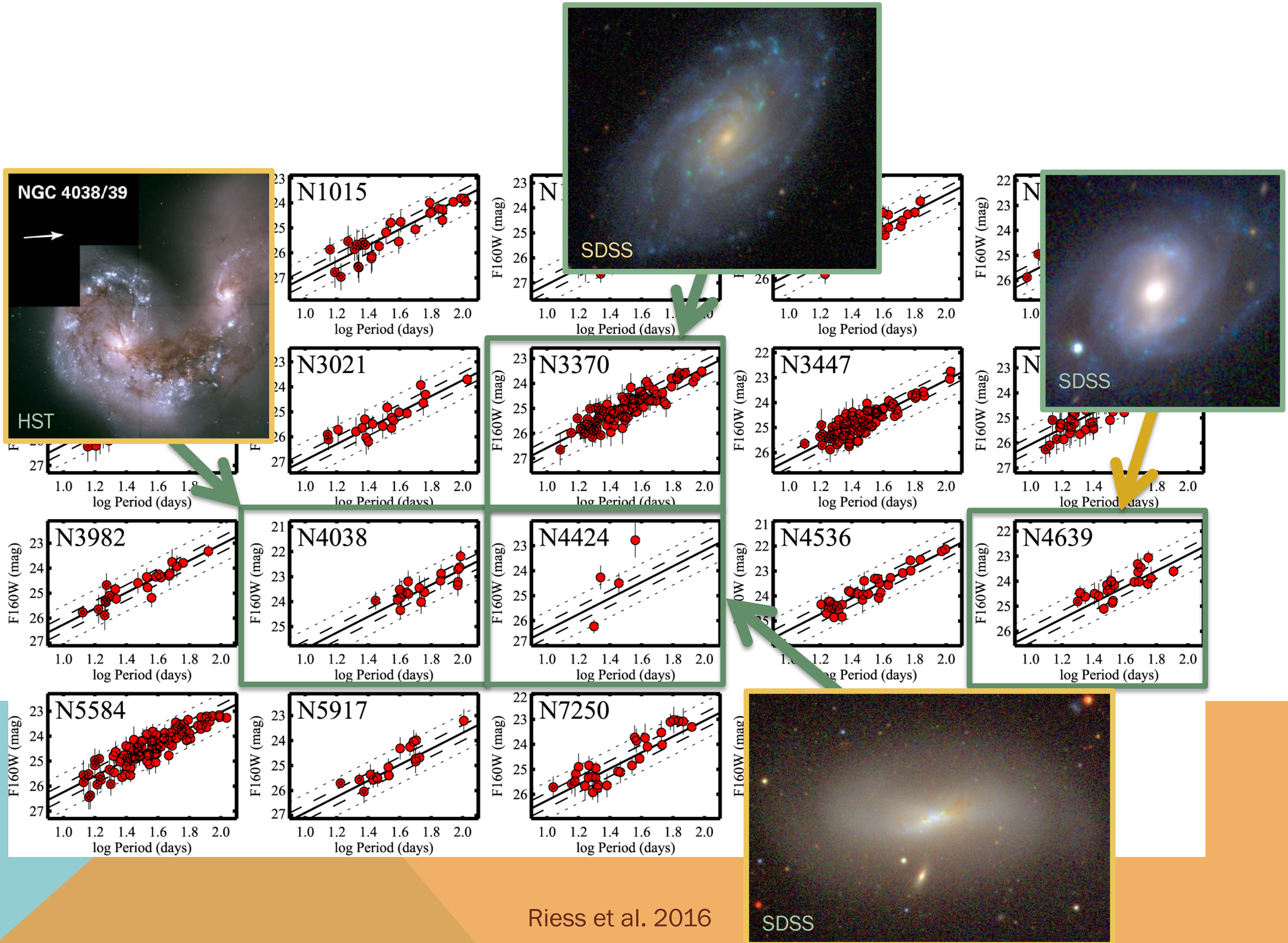
Riess et al. 2016



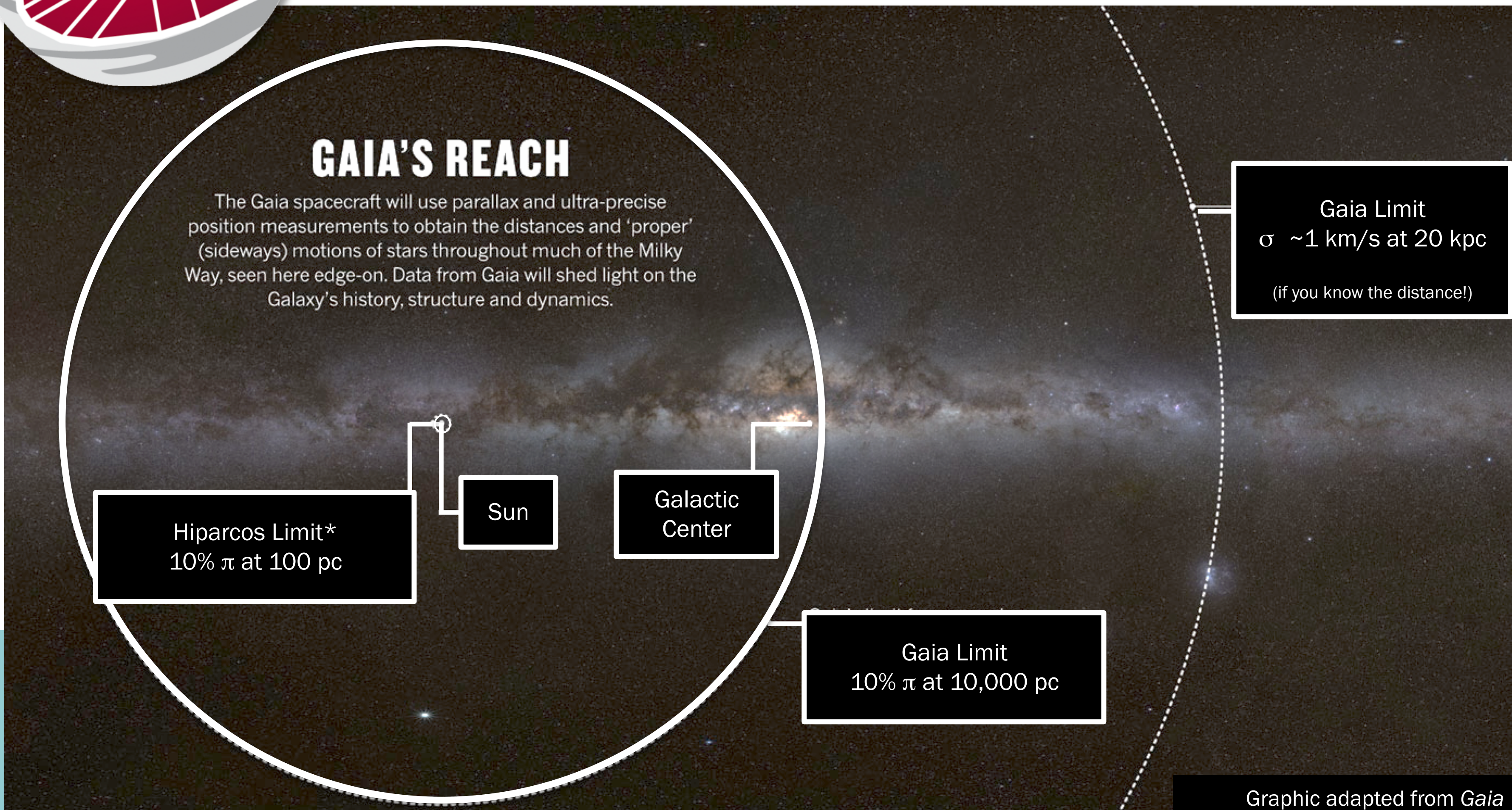
Riess et al. 2016



Riess et al. 2016



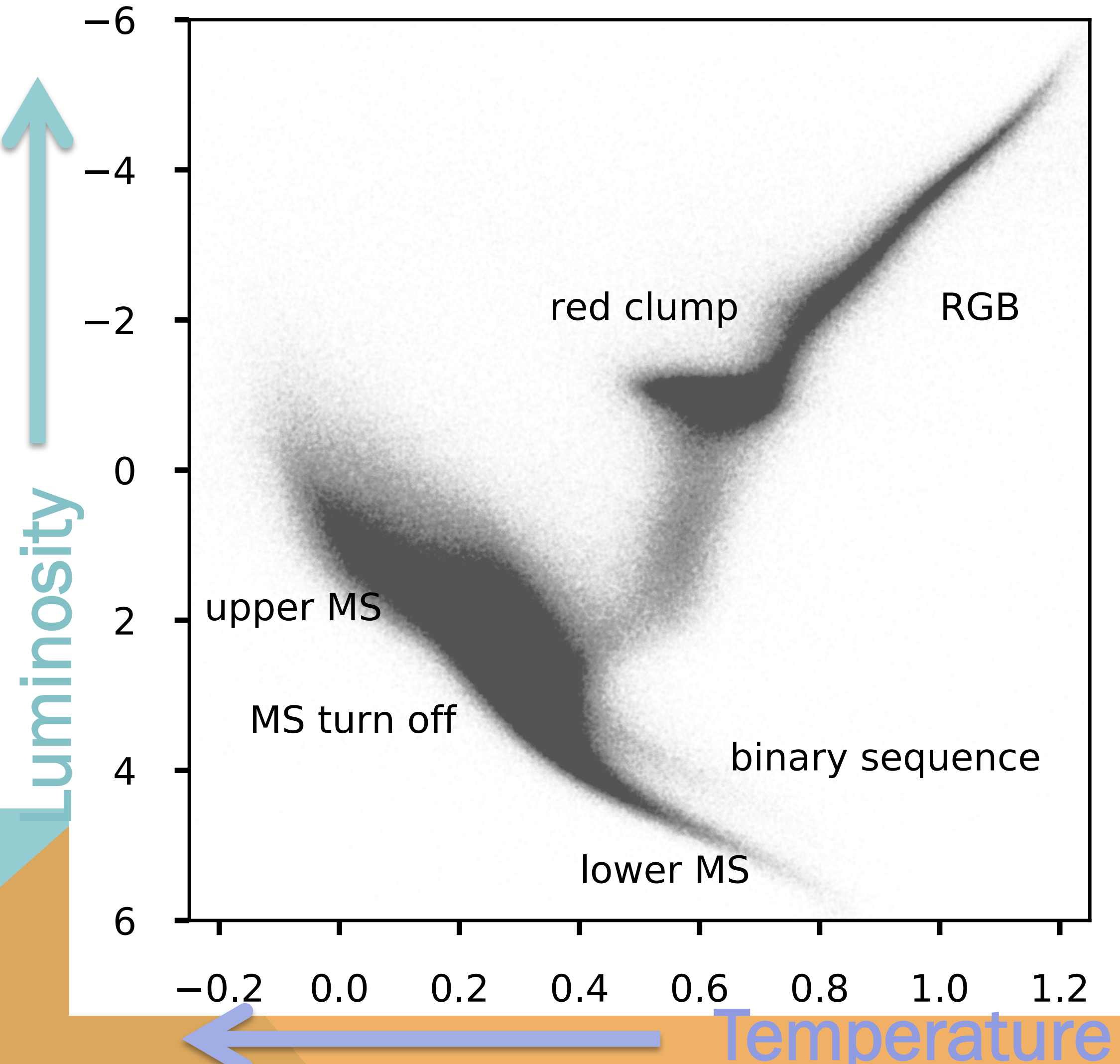
Riess et al. 2016



*Note: HST+FGS provide π to larger distances at < 10% precision, e.g. Benedict et al. 2011

See also Brown et al. 2018, for WFC3 parallaxes
Or Beaton 2018 (Nature News & Views)

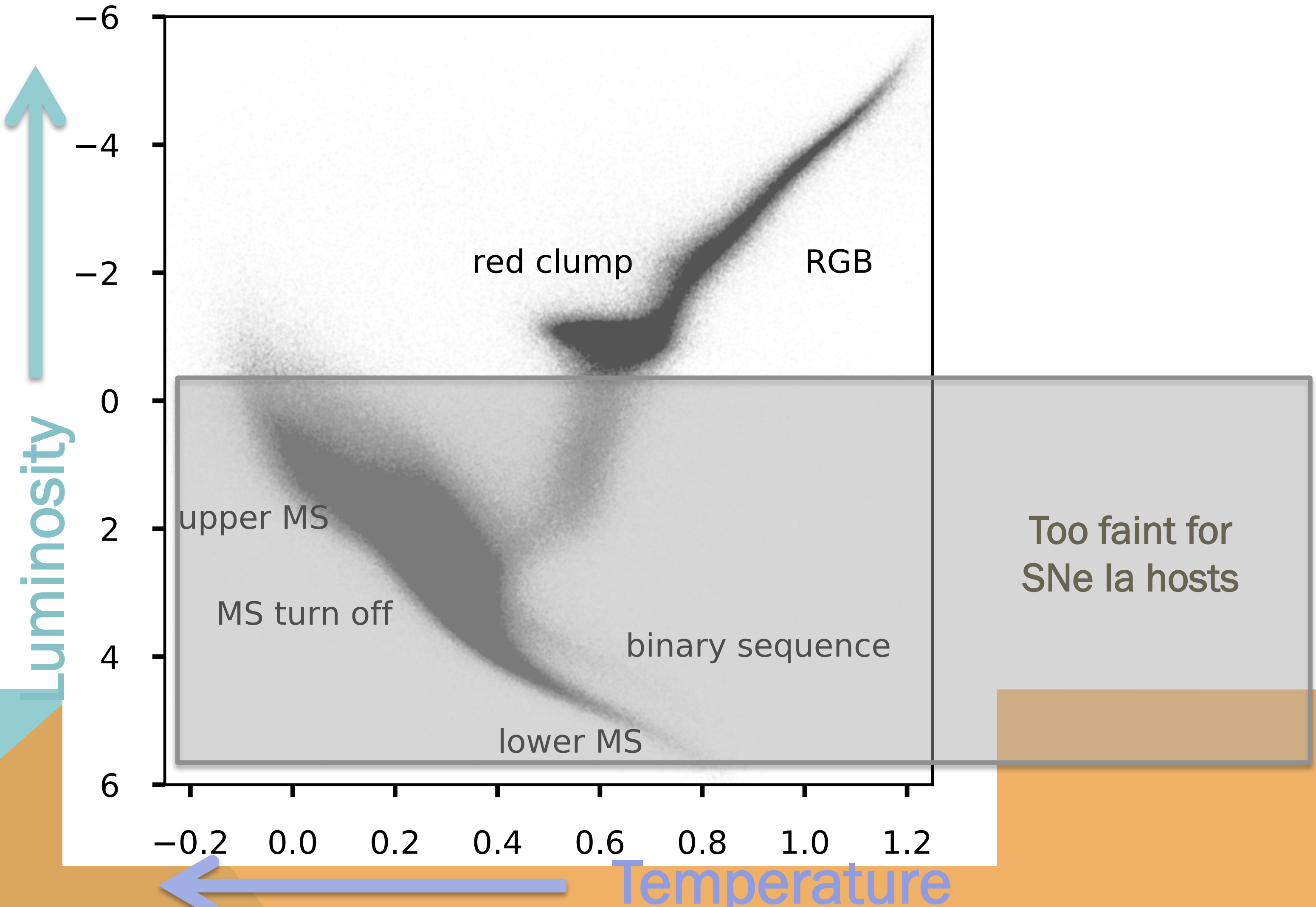
GAIA SPANS FULL HR DIAGRAM



** Optical

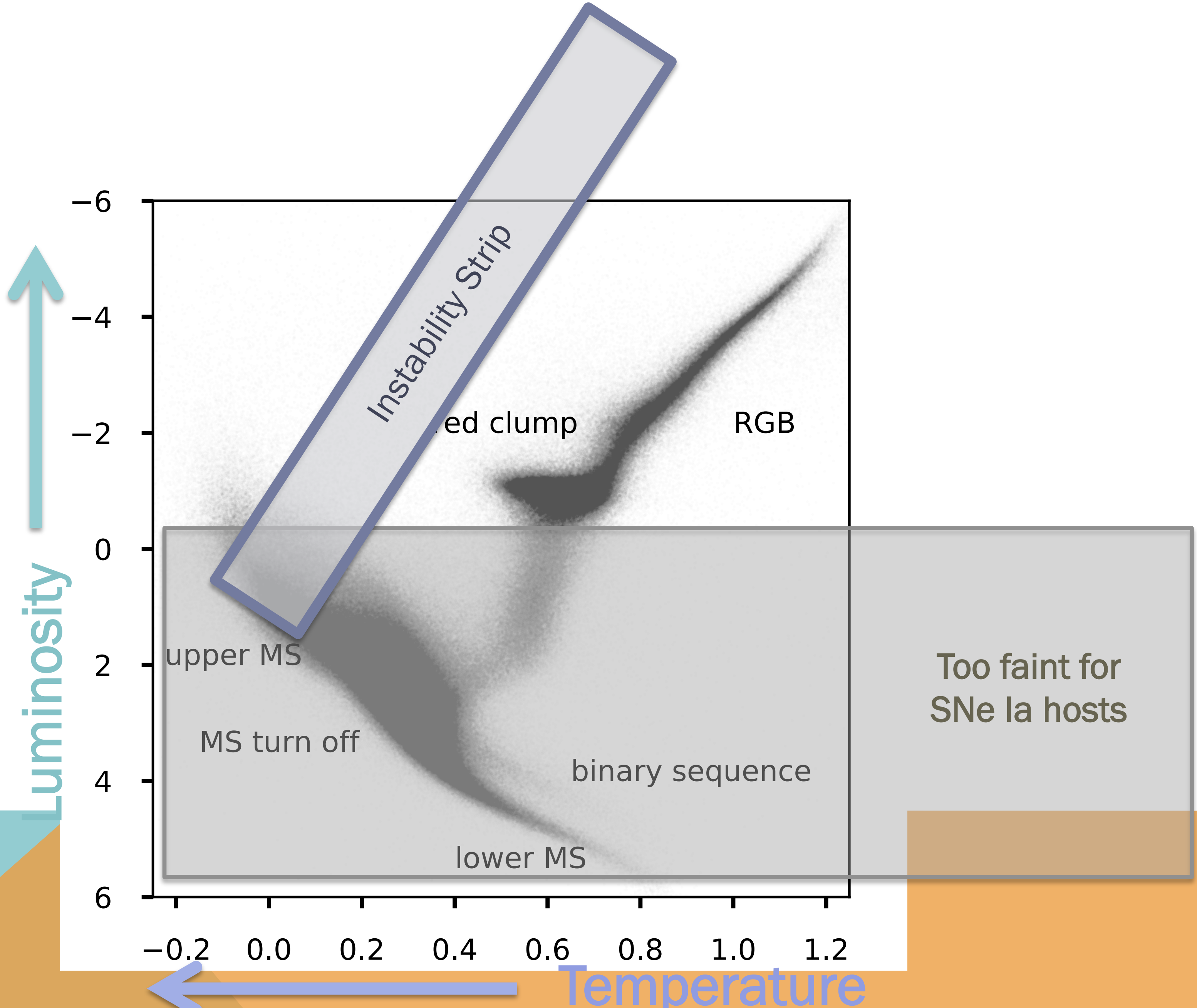
Tycho-Gaia Astrometric Solution Data
Anderson et al. 2018

GAIA SPANS FULL HR DIAGRAM



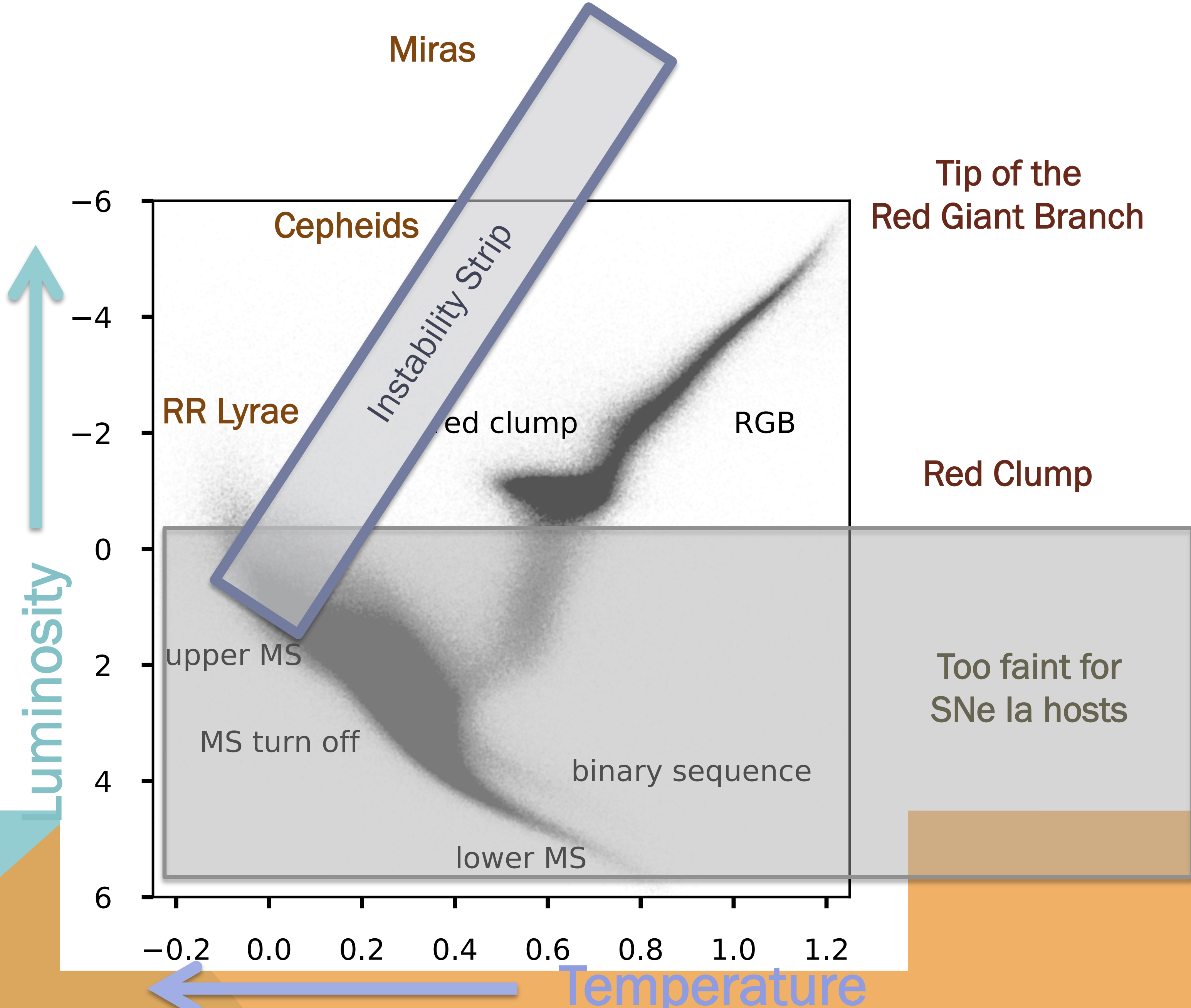
** Optical

TGAS with adjustment + 2MASS photometry
Anderson et al. 2018



** Optical

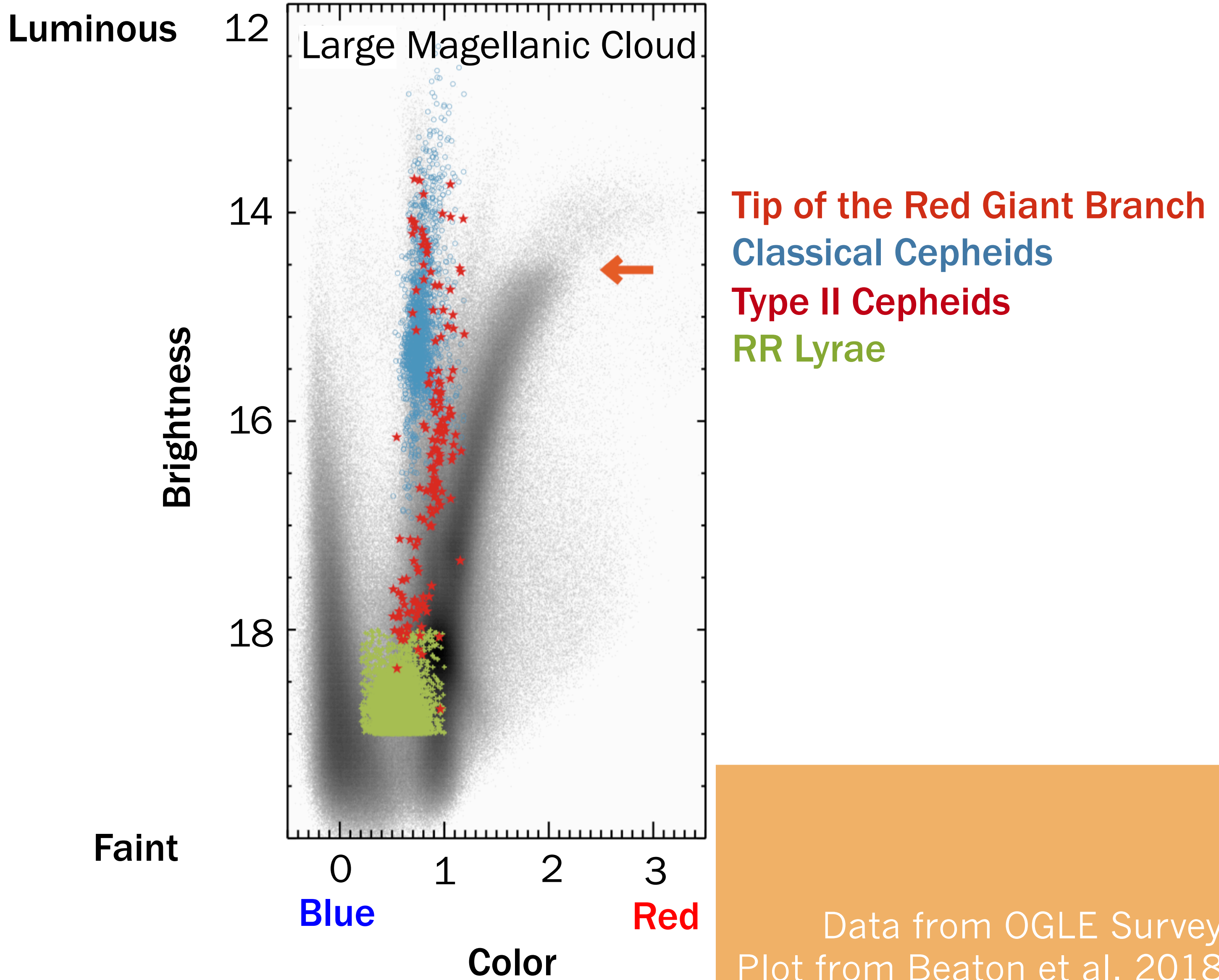
TGAS with adjustment + 2MASS photometry
Anderson et al. 2018



** Optical

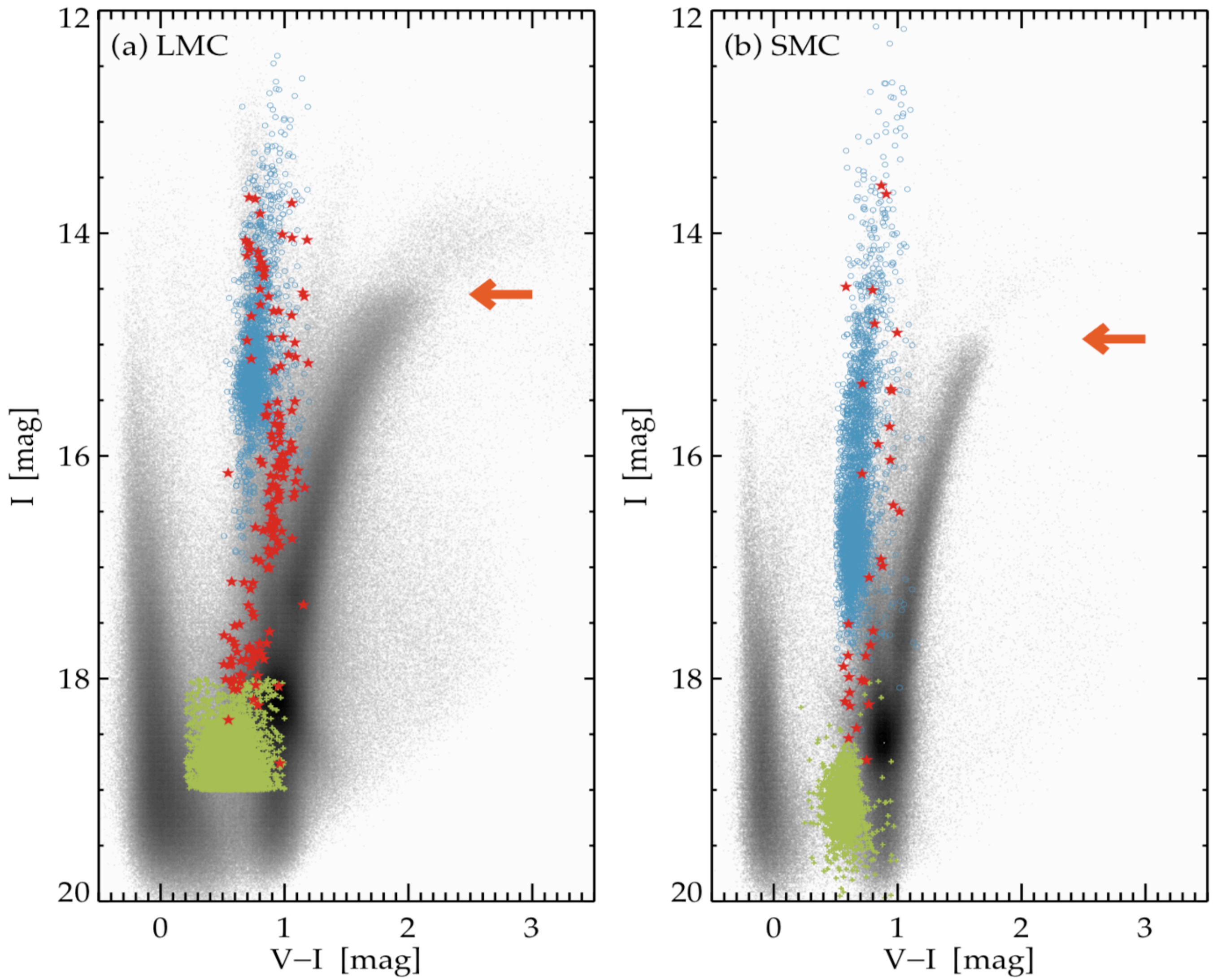
TGAS with adjustment + 2MASS photometry
Anderson et al. 2018

Each point in this plot is a single star.

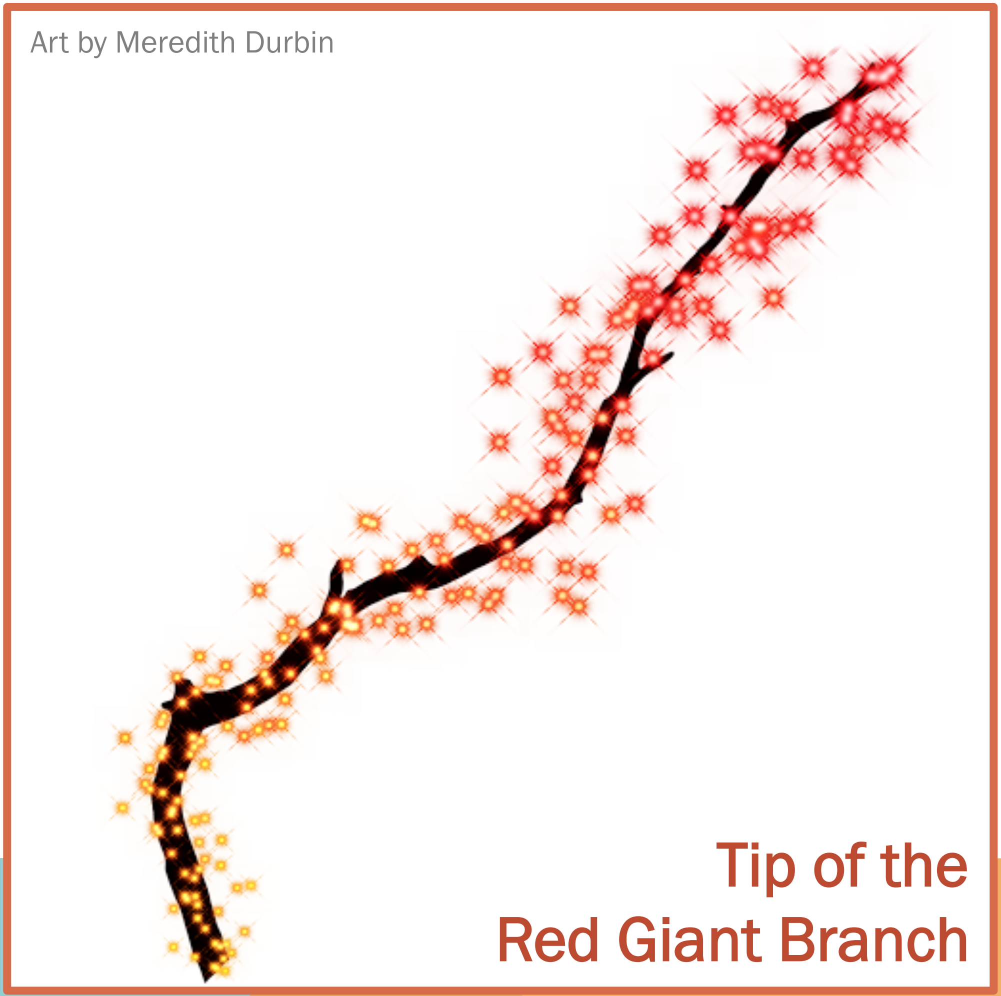


Data from OGLE Survey
Plot from Beaton et al. 2018

TWO SIMILAR-ISH GALAXIES



STAR STUFF 3:
TIP OF THE RED GIANT BRANCH



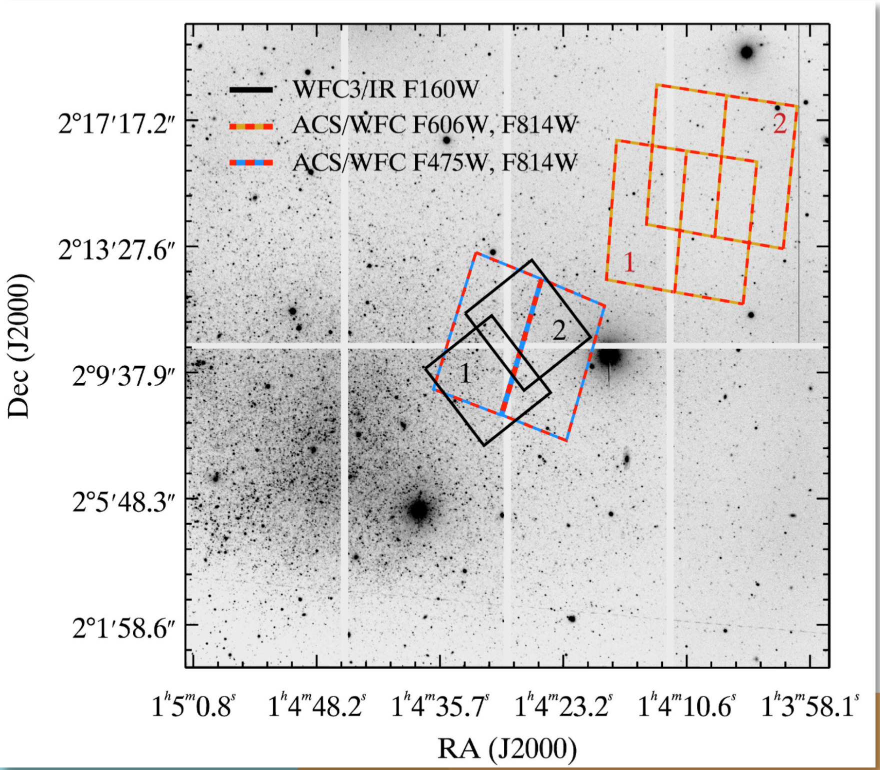
The PROs of the TRGB

- Not variable.
- Well understood physics.
- Can be applied to:
  - ALL Hubble Types
  - ALL inclinations
  - ALL luminosity classes
- Apply to low-density regions of galaxies.
- Few differences between local stars and distant stars.
- Metallicity effects projected into color axis.
- Single dataset to find and characterize

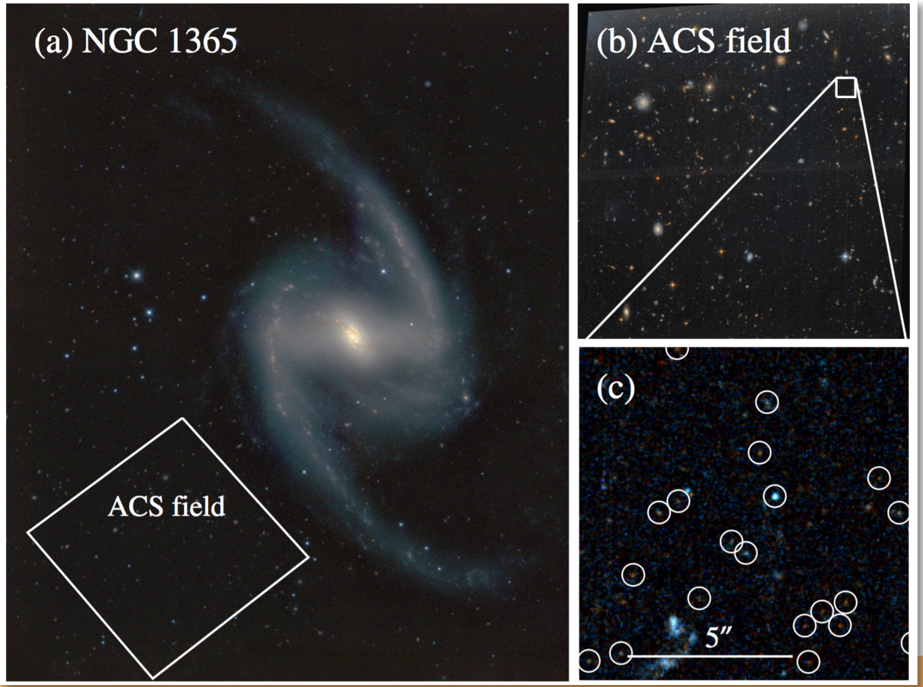
e.g., Serenelli et al. 2017

IN PRACTICE: NEAR & FAR

Nearby Galaxy: ~2.5 million light years



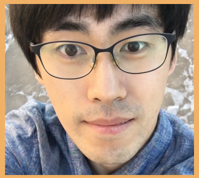
Distant Galaxy: ~30 million light years



Hatt, Beaton et al. (2017)

Dylan Hatt
PhD@ UChicago
Now: Data Science

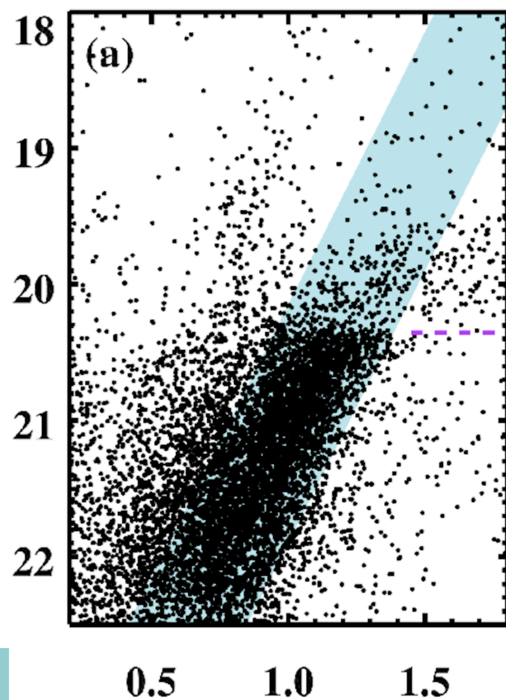
In Sung Jang
PhD @ SNU
Now Postdoc@AIP



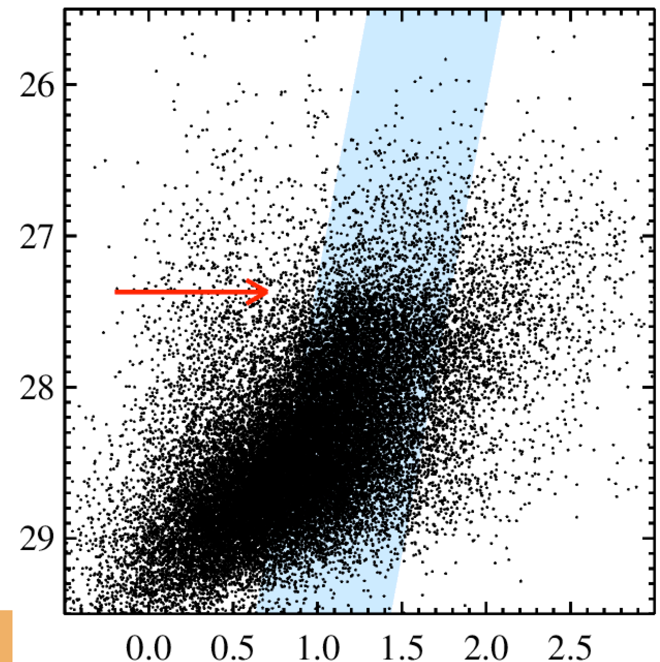
Jang, Hatt, Beaton et al. (2018)

IN PRACTICE: NEAR & FAR

Nearby Galaxy: ~2.5 million light years



Distant Galaxy: ~30 million light years



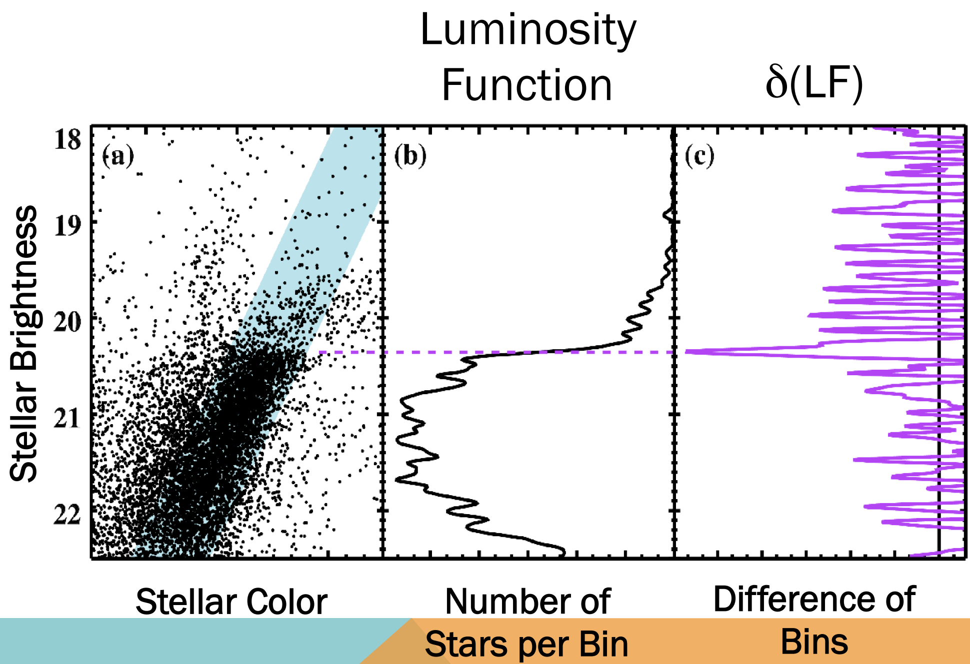
Hatt, Beaton et al. (2017)

Jang, Hatt, Beaton et al. (2018)

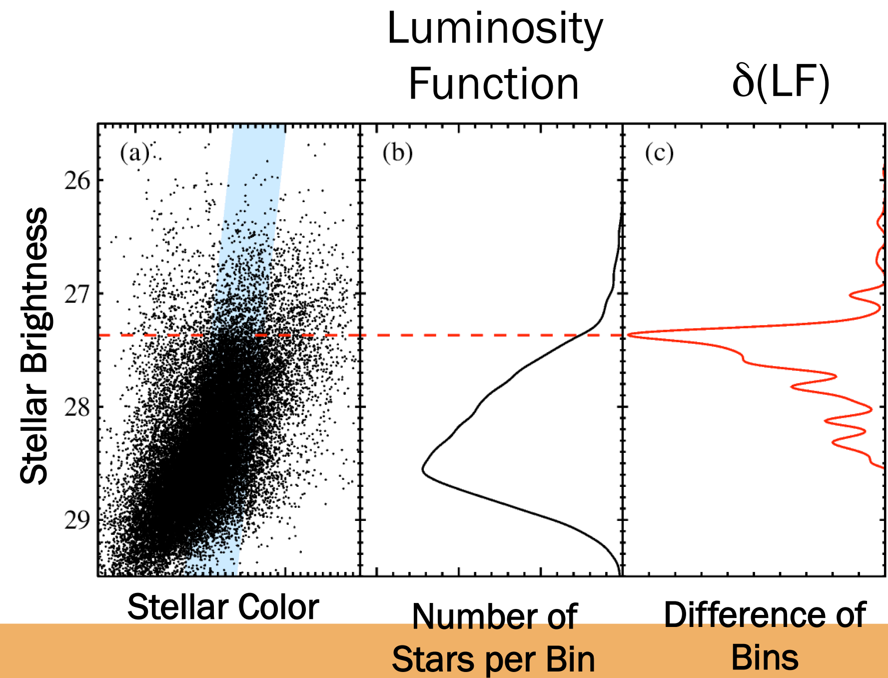
IN PRACTICE: NEAR & FAR

Nearby Galaxy: ~2.5 million light years

Distant Galaxy: ~30 million light years



Hatt, Beaton et al. (2017)



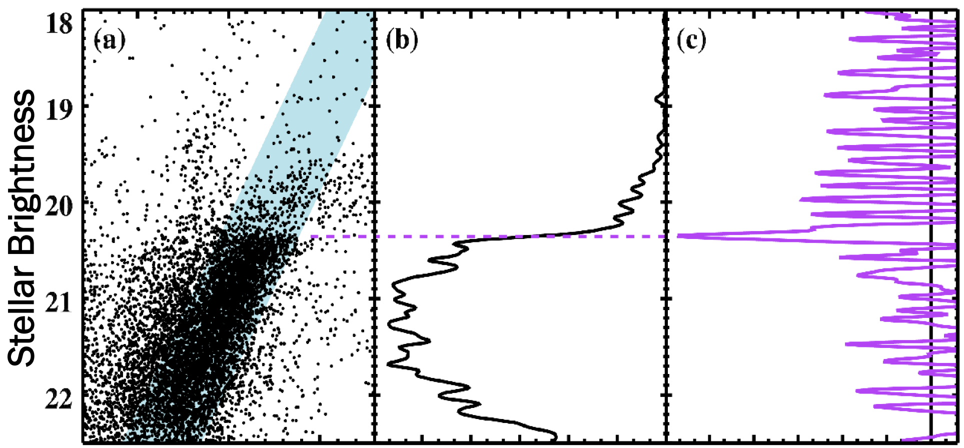
Jang, Hatt, Beaton et al. (2018)

IN PRACTICE: NEAR & FAR

Nearby Galaxy: ~2.5 million light years

Luminosity Function

δ(LF)



Stellar Color

Number of Stars per Bin

Difference of Bins

D = 784 ±17 (stat) ±40 (sys) kpc

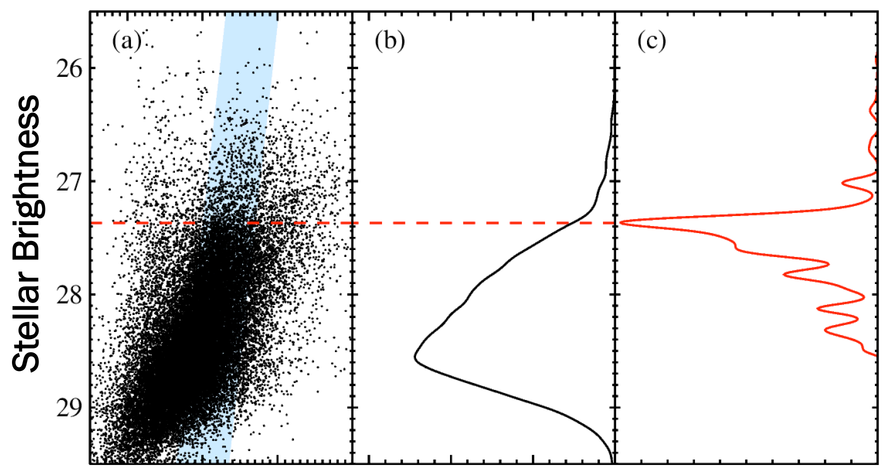
μ_0 = 24.30 ±0.03 (stat) ±0.05 (sys) mag

Hatt, Beaton et al. (2017)

Distant Galaxy: ~30 million light years

Luminosity Function

δ(LF)



Stellar Color

Number of Stars per Bin

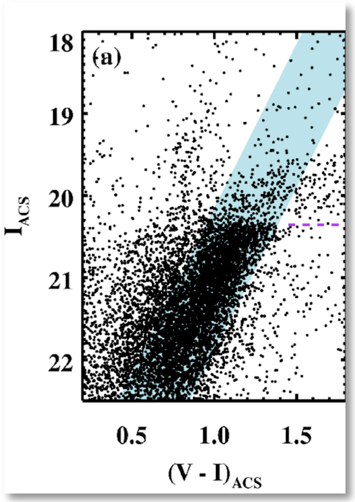
Difference of Bins

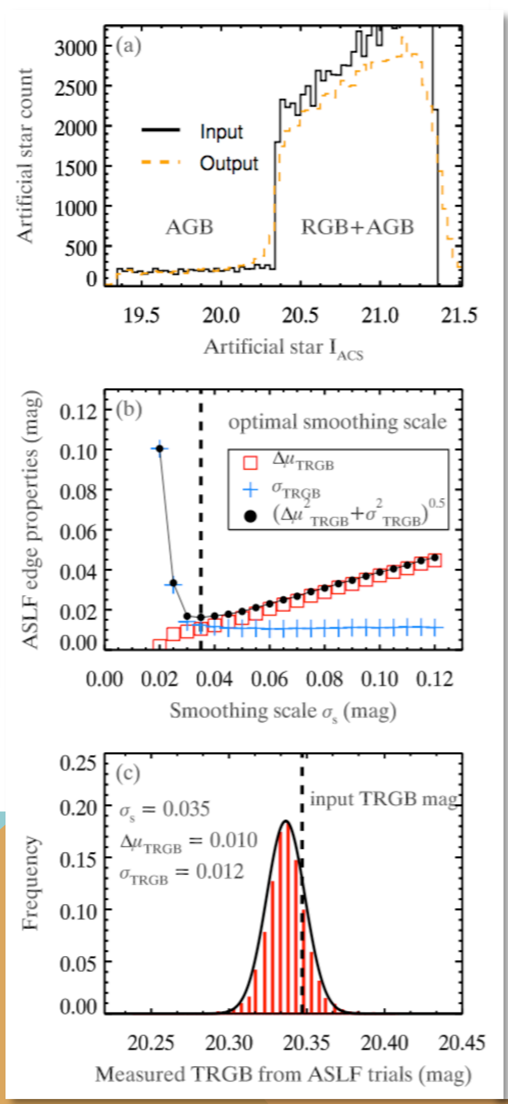
D = 18.1 ±0.3 (stat) ±0.5 (sys) Mpc

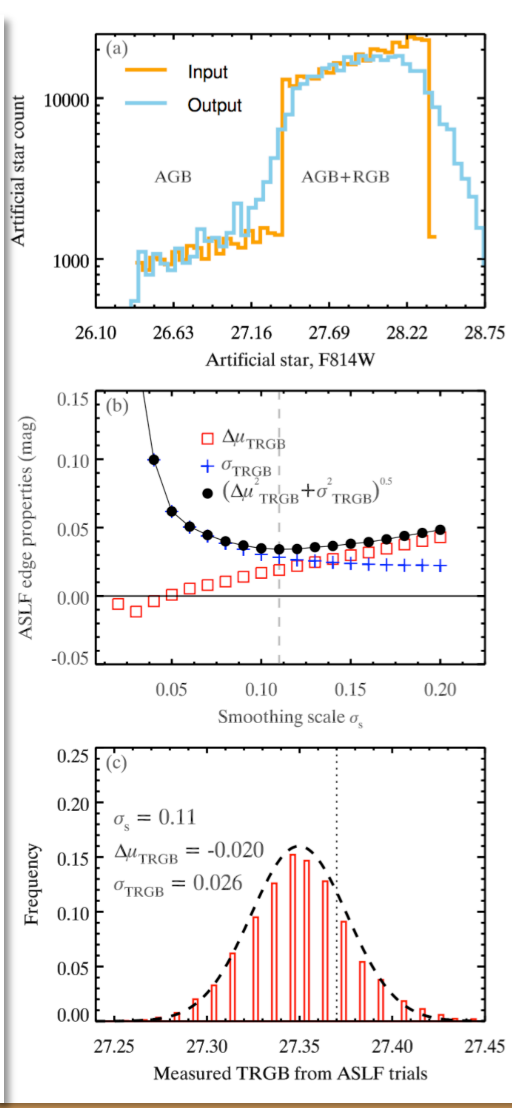
μ_0 = 31.29 ±0.04 (stat) ±0.06 (sys) mag

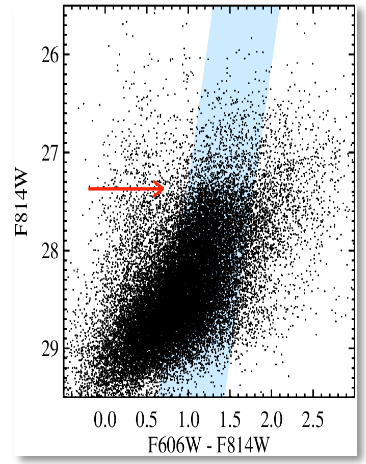
Jang, Hatt, Beaton et al. (2018)

IN PRACTICE: NEAR & FAR





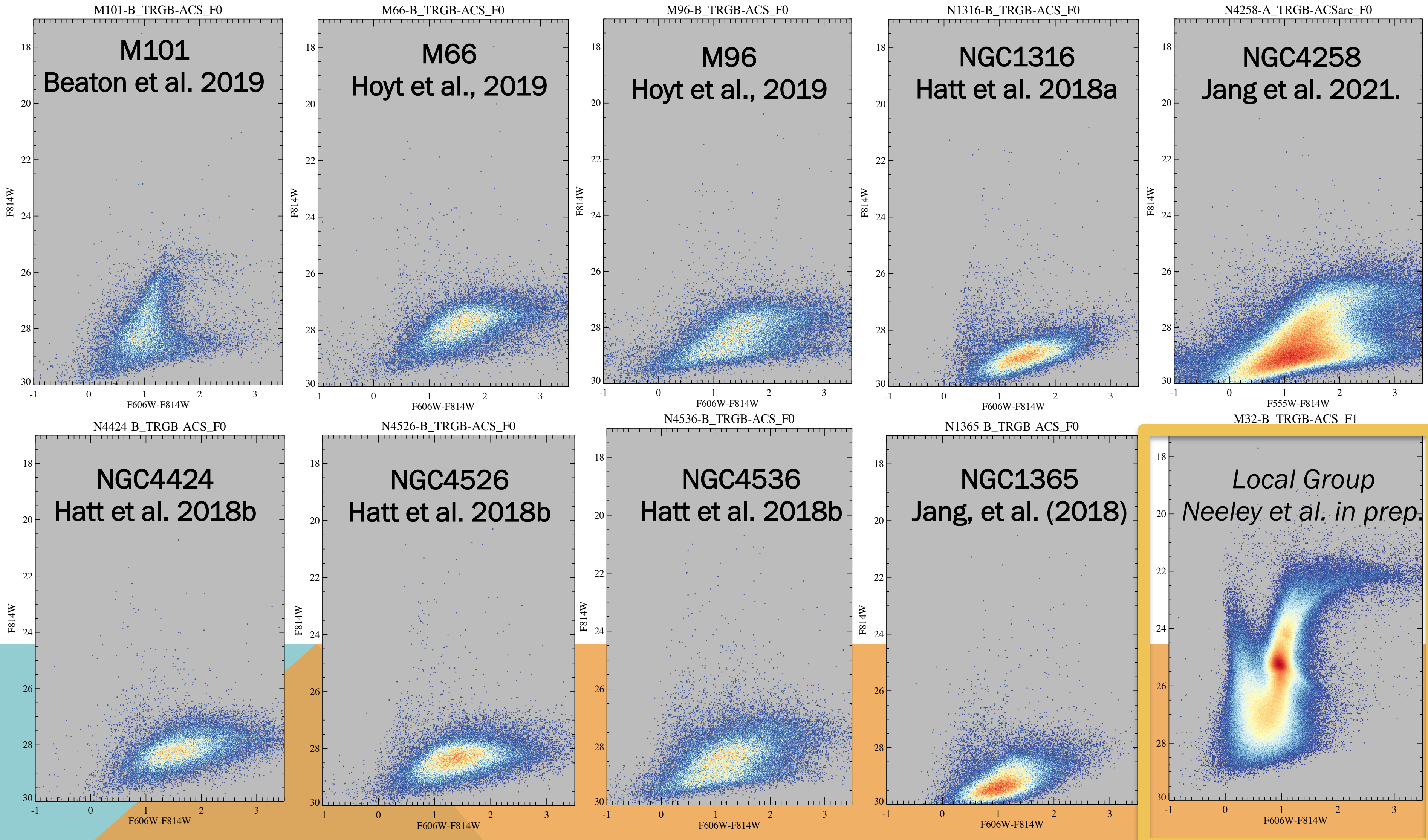




Hatt, Beaton et al. (2017)

Jang, Hatt, Beaton et al. (2018)

CARNEGIE-CHICAGO HUBBLE PROGRAM



Fully automated pipeline to reduce image data into photometry.

Beaton, Seibert, et al. (in prep)

COSMIC DISTANCE SCALE IN A SLIDE

Geometric Distances

1

Calibration of SNe Ia

2

SNe Ia in Hubble Flow for H_0

3

Hubble-Lemaître Law

+ ΛCDM

4

"ANCHORING" THE DISTANCE SCALE

Parallax

Naked Eye stars
to 10 kpc
< 2 m telescopes

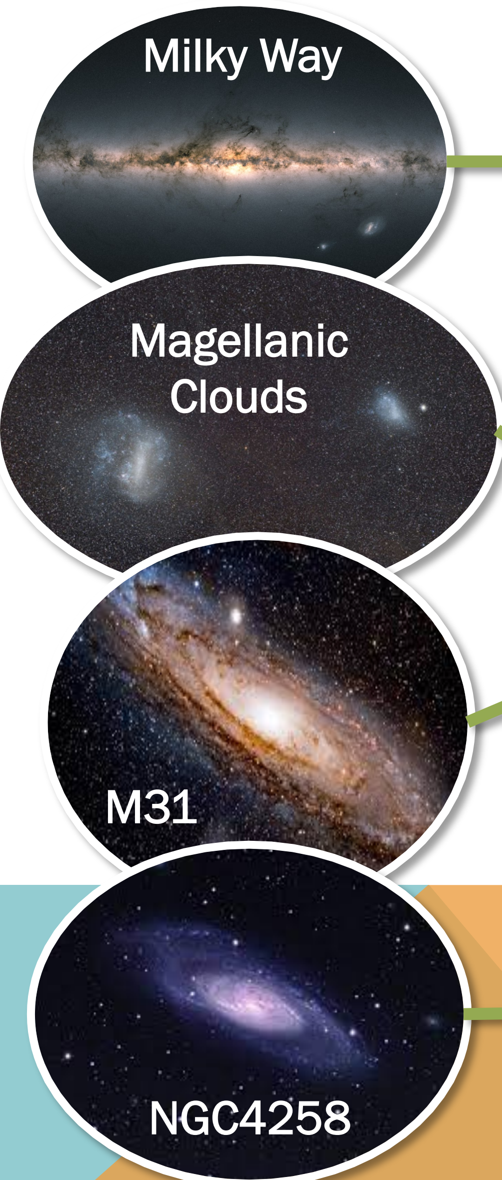
Detached Eclipsing Binaries

50 kpc – 1 Mpc
~1 – 10 m telescopes

Geometric Distance from $H_2$0 Megamaser

7 Mpc –
hours of integration on the ground
or HST

REFERENCES



Parallax

Trigonometric:
Hipparcos, HST+FGS, HST+WFC3, *Gaia*

Pulsational Parallax:
Baade Wesselink Method

Statistical Parallax

Detached Eclipsing Binaries

LMC: Pietrzyński et al. 2013, 2019, Graczyk et al. 2018

M31: Vilardell et al. 2010

See also: Bonanos (2013), Kaluzny et al. 2005, 2013

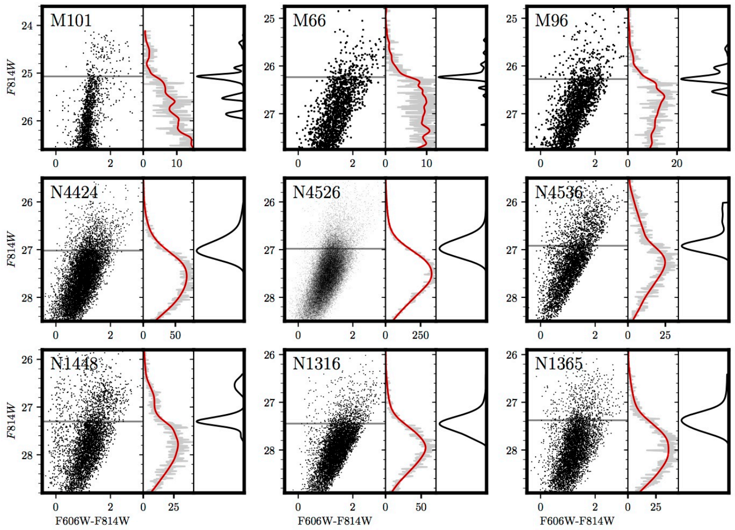
Geometric Distance from H_2O Megamaser

Herrnstein et al. 1999, Argon et al. 2007, Humphreys et al. 2008, Humphreys et al. 2013, Reid et al. 2019

STAR STUFF 4: DETACHED ECLIPSING BINARIES

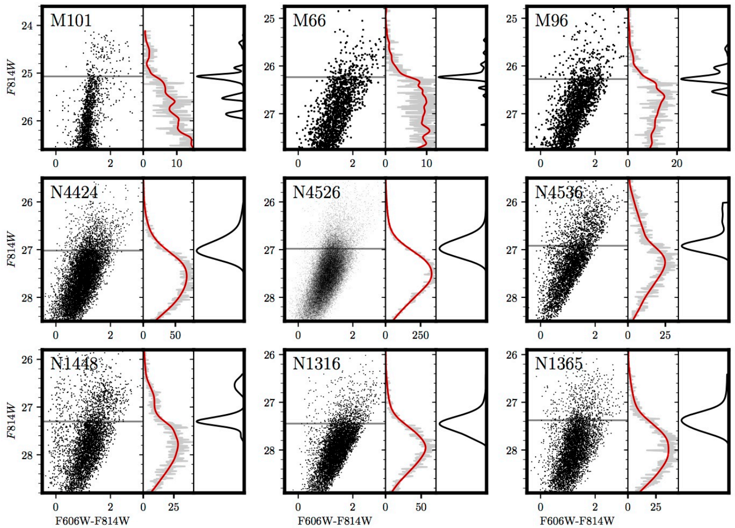
PUTTING IT ALL TOEGETHER

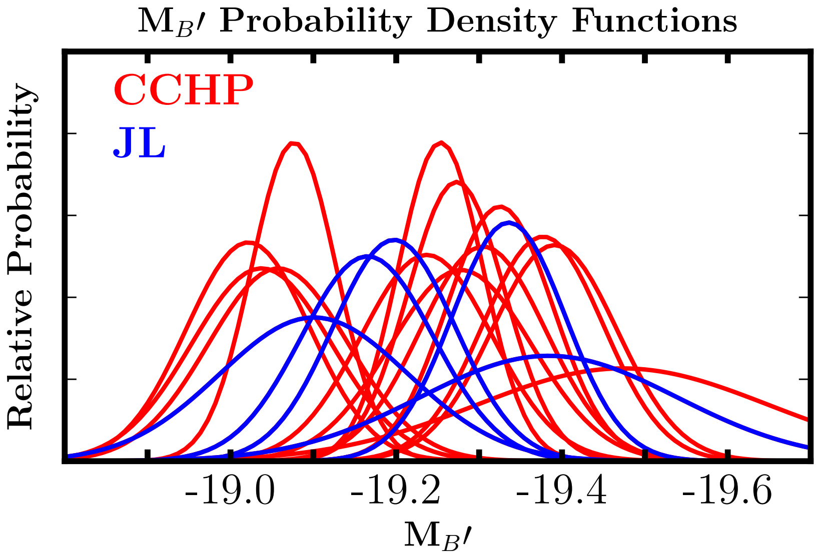
STEPS TO A CCHP H_0



Freedman et al. 2019

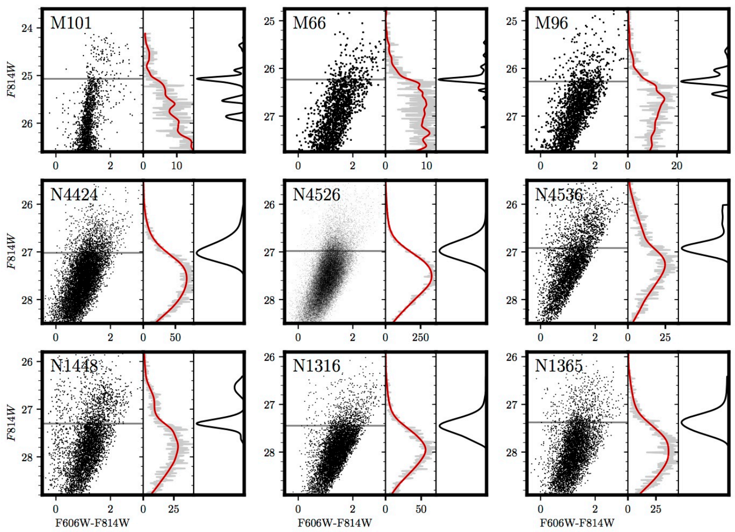
STEPS TO A CCHP H_0

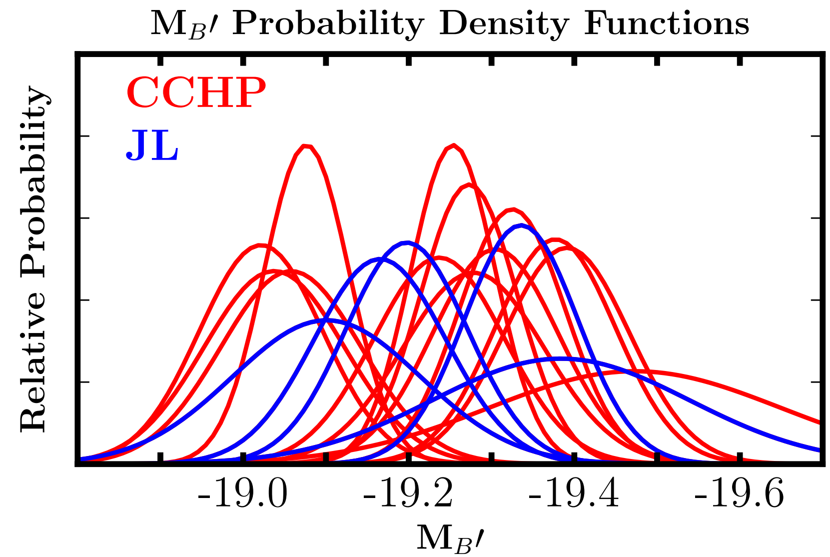


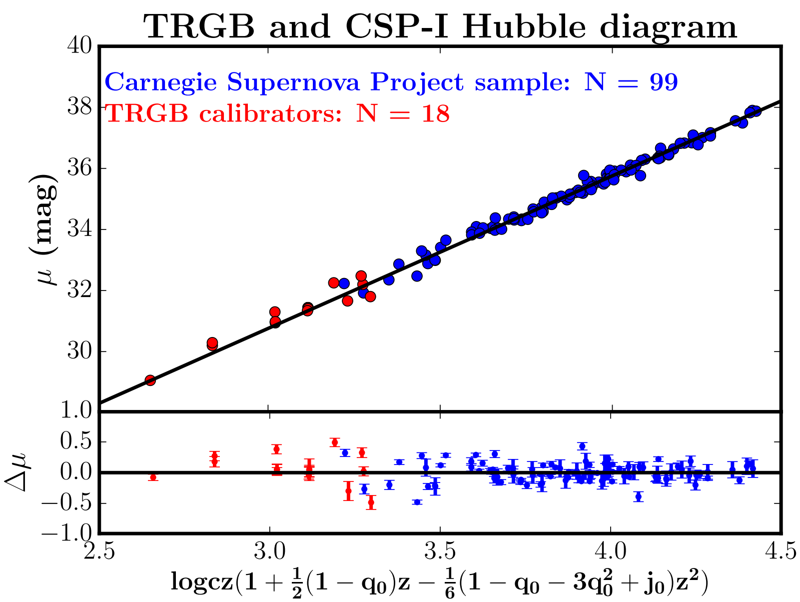


Freedman et al. 2019

STEPS TO A CCHP H_0

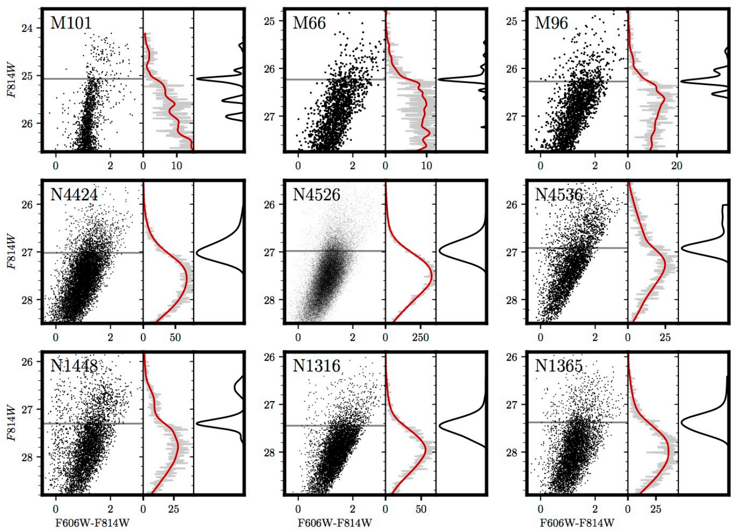


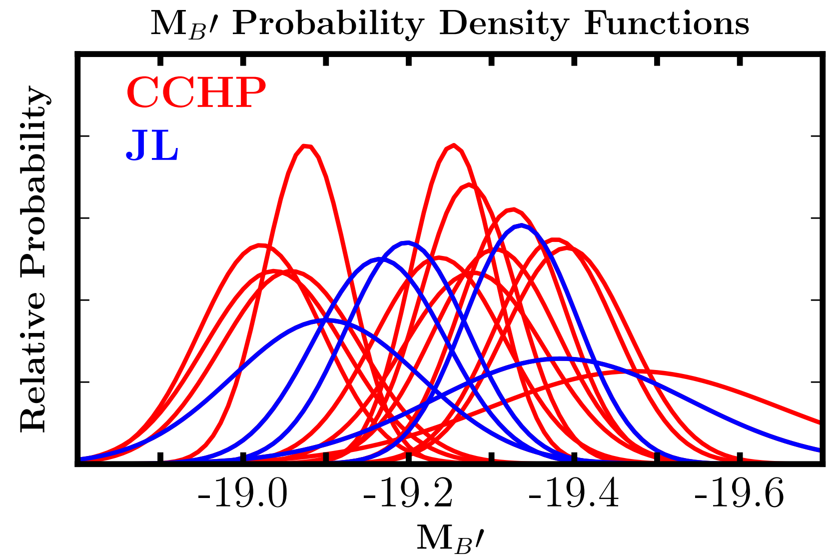


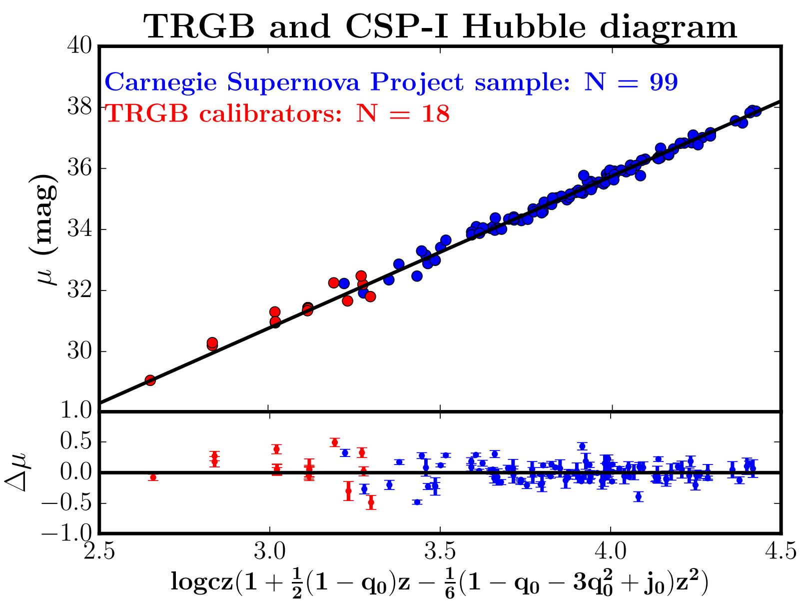


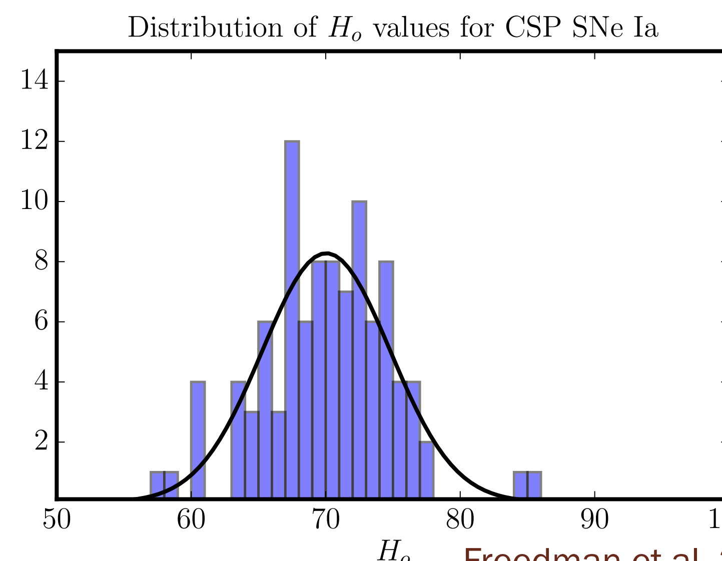
Freedman et al. 2019

STEPS TO A CCHP H_0



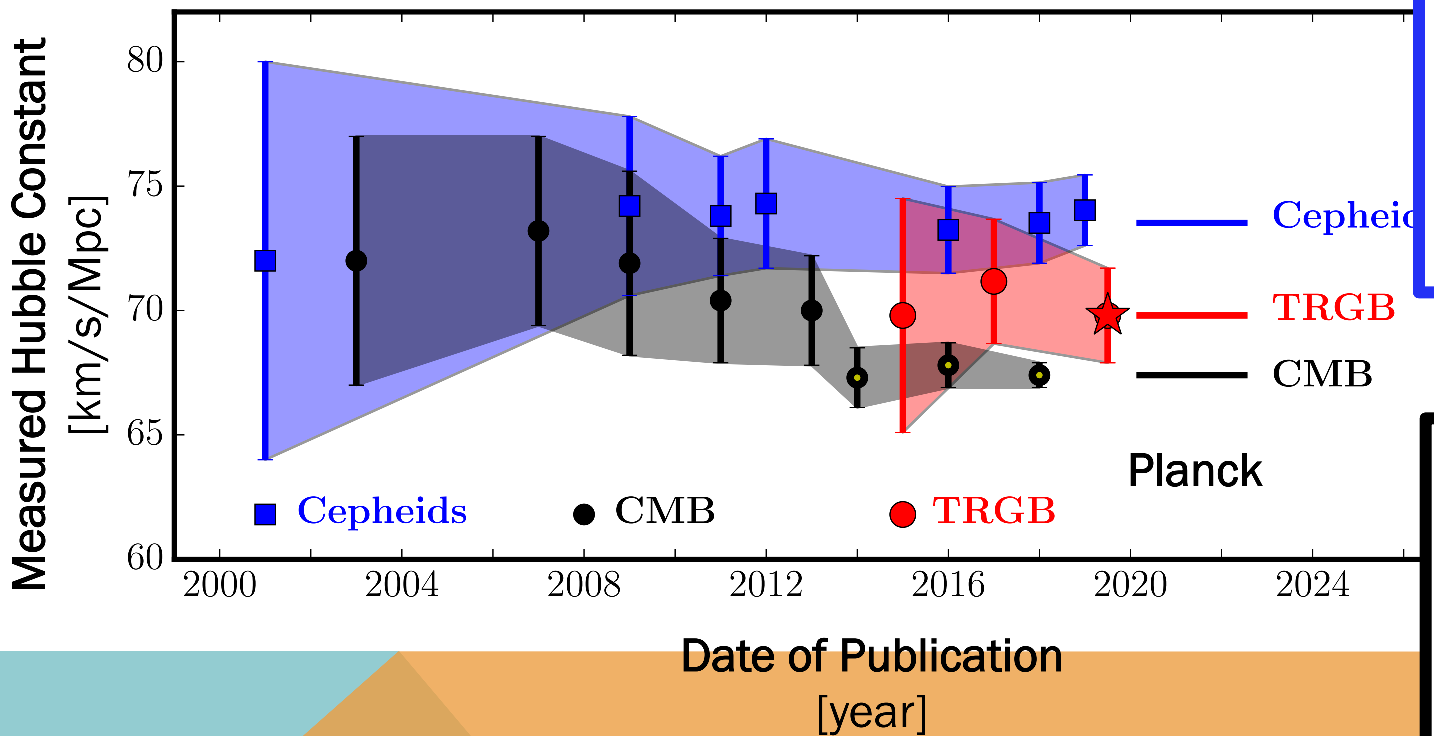


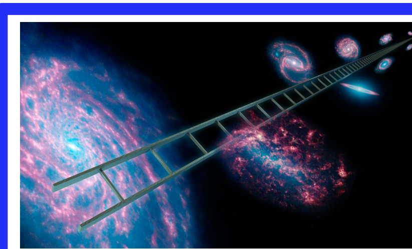




Freedman et al. 2019

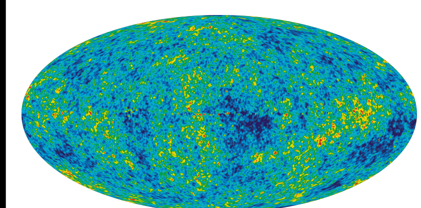
CARNEGIE-CHICAGO HUBBLE PROGRAM





Distance Ladder
Local Universe+Direct H_0

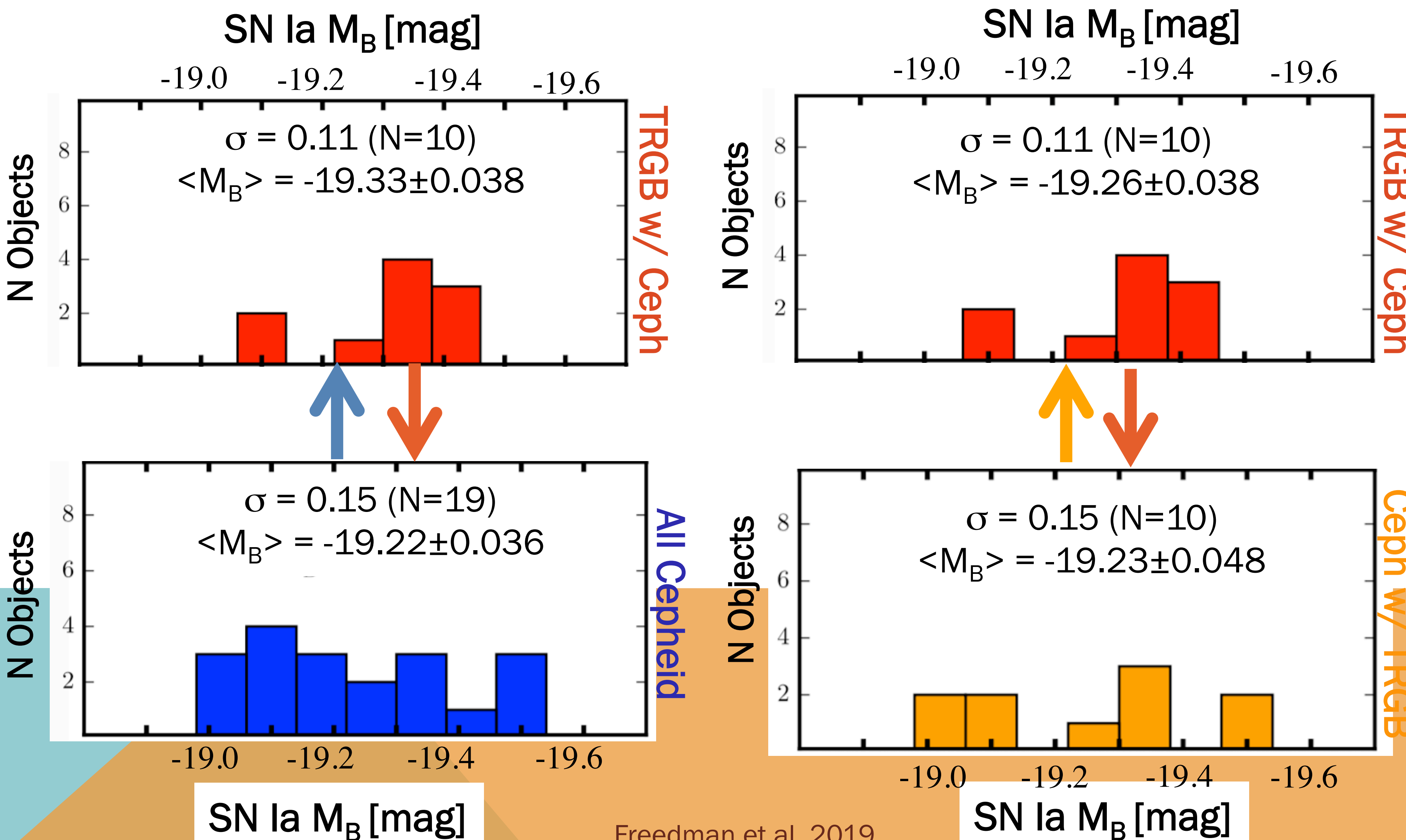
CMB Modeling
Young
Universe+InDirect H_0



~1.5σ to 2-σ consistent
with Cepheid Distance Ladder and with Planck

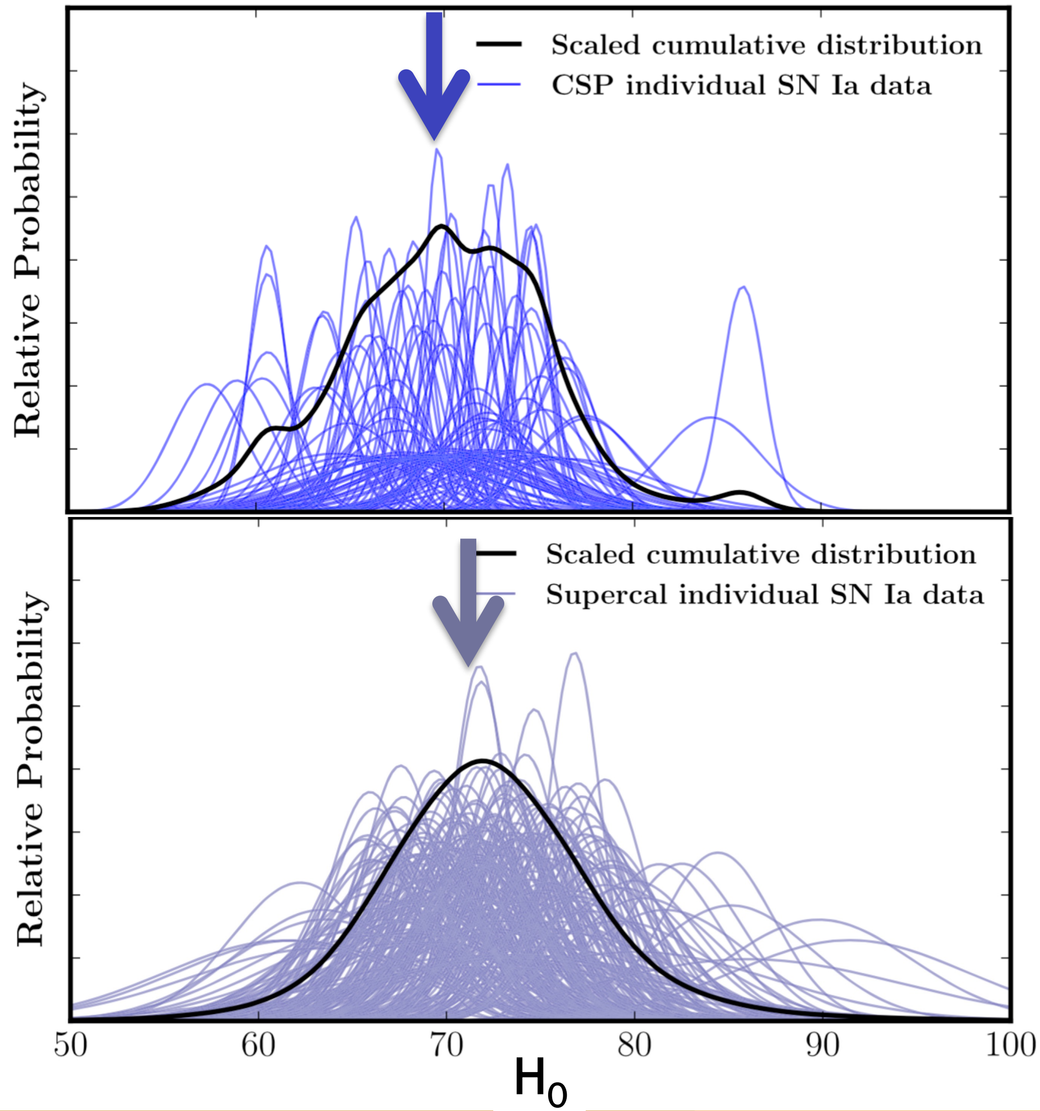
Freedman et al. 2019, 2020

SNE IA CALIBRATIONS



Freedman et al. 2019

HUBBLE FLOW SNE IA: 1% SHIFT



CSP-I Sample (99)

H_0 = 69.8 ± 0.8 km/s/Mpc

See also:

Burns et al. 2019, Uses Cepheids+CSP-I

H_0 = 73.2. ± 2.3 km/s/Mpc

SuperCal Sample (214)

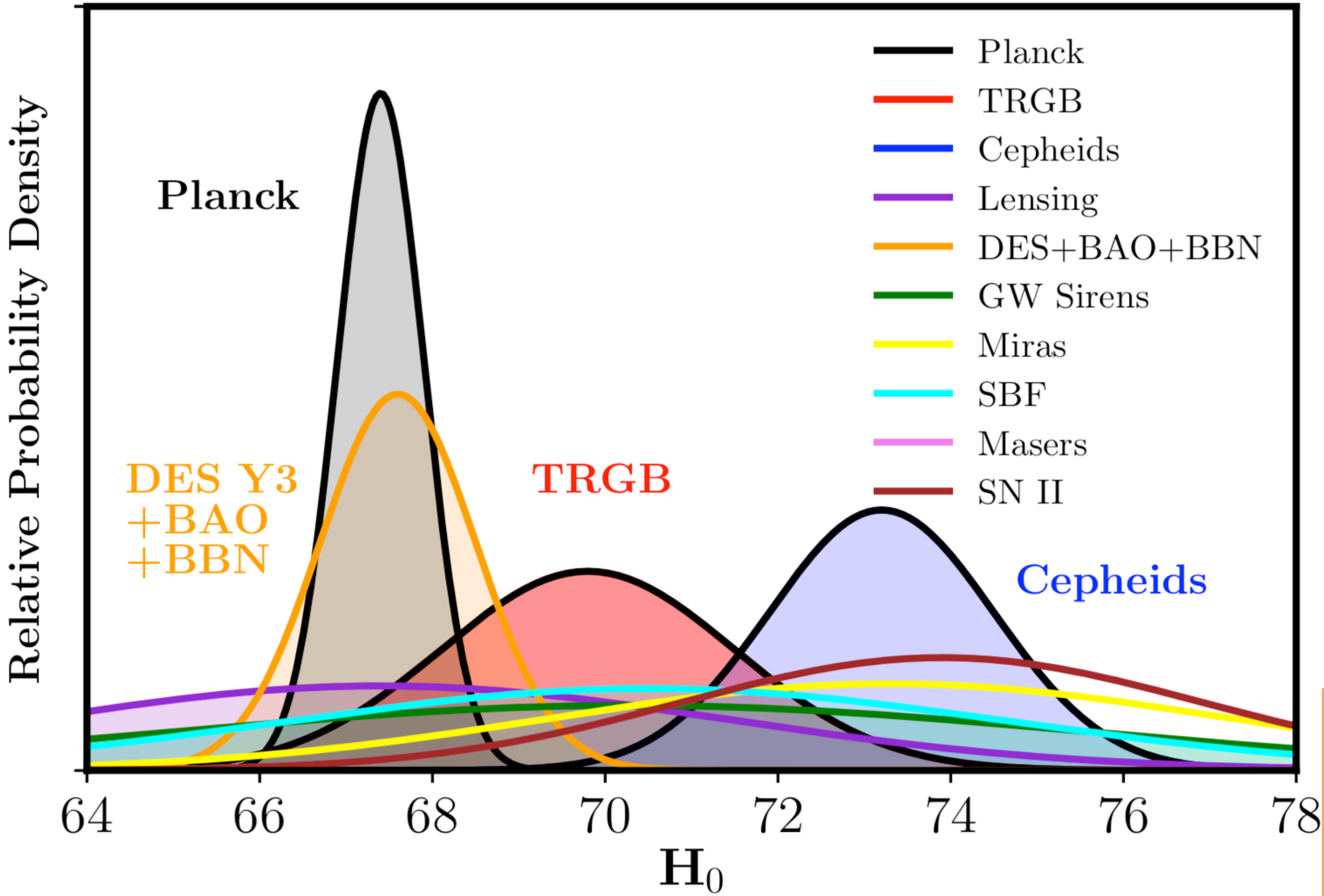
Scolnic et al. 2015

H_0 = 70.4 ± 1.4 km/s/Mpc

1% shift due to SNe Ia Sample.

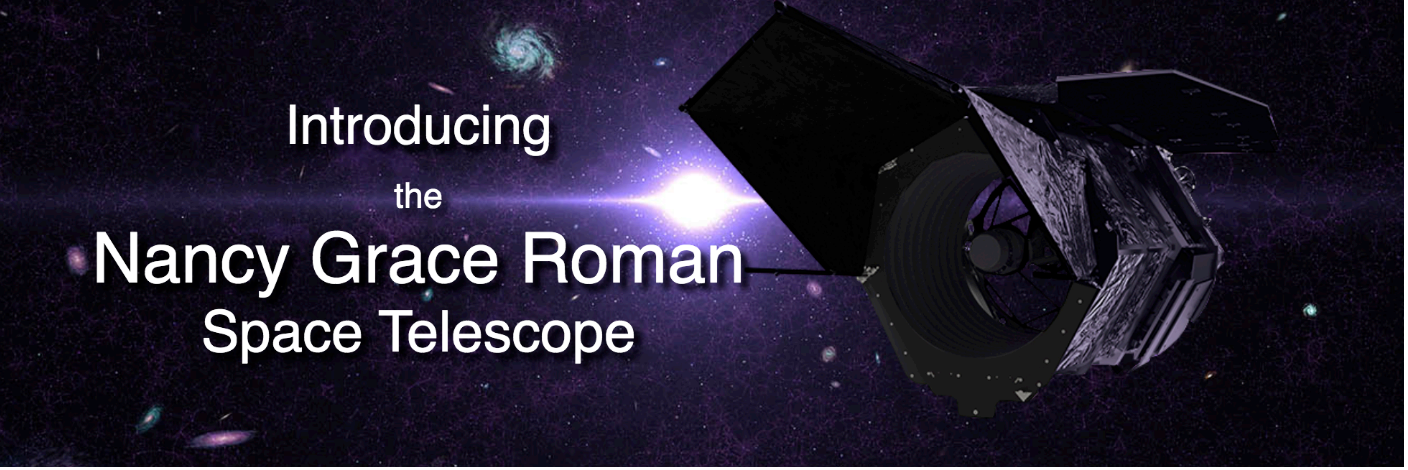
See Freedman et al. 2019 for more discussion.

THE H0 TENSION:



Freedman 2021 - arXiv:2106.15656


Cosmology
Properties of Universe
Spectro-Photometry of
Exploded Stars
Spectro-Photometry of
Faint Stars
Spectro-Photometry of
less bright stars
Spectro-Photometry of
Bright Stars



Wide Field Instrument Focal Plane Array

18 x H4RG Detectors
Each is 4096x4096

FOV = 0.28^2 deg.

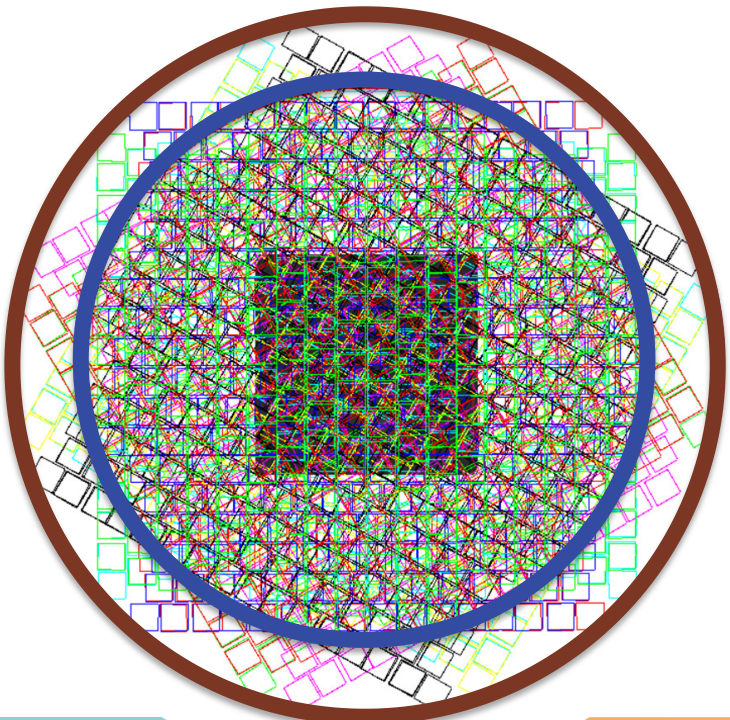
ALL data is public.
Immediately.
High-level products made.
Access data in the Cloud

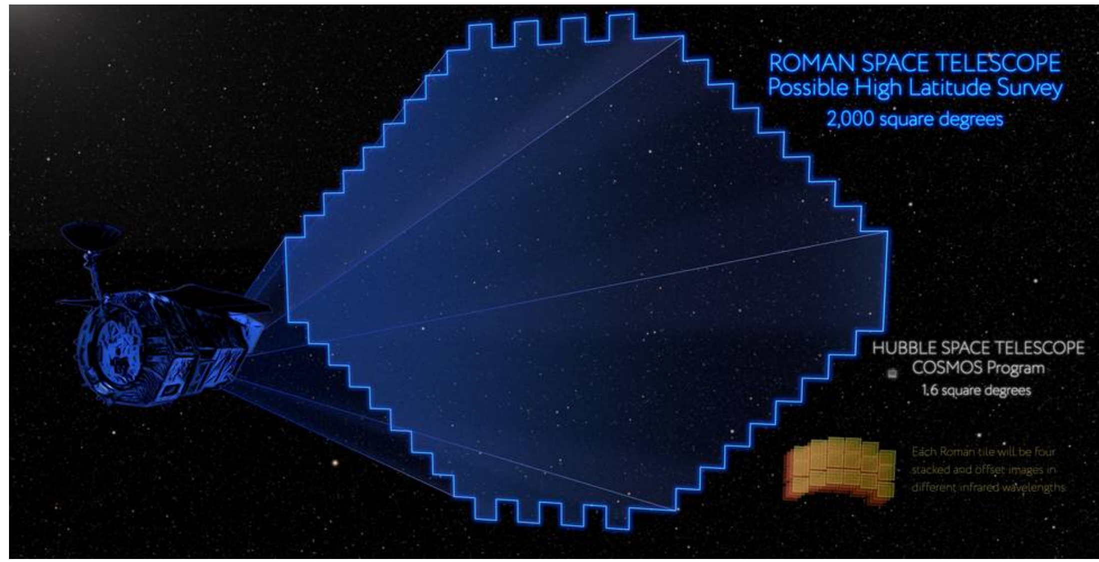
For more information:

- [Wikipedia Page on the Nancy Grace Roman Space Telescope]
- [High Level Description of Wide Field Instrument]
- [Data Processing & Hosting Summary (Link to PDF)]

High Latitude Time Domain Survey

High Latitude Wide Area Survey





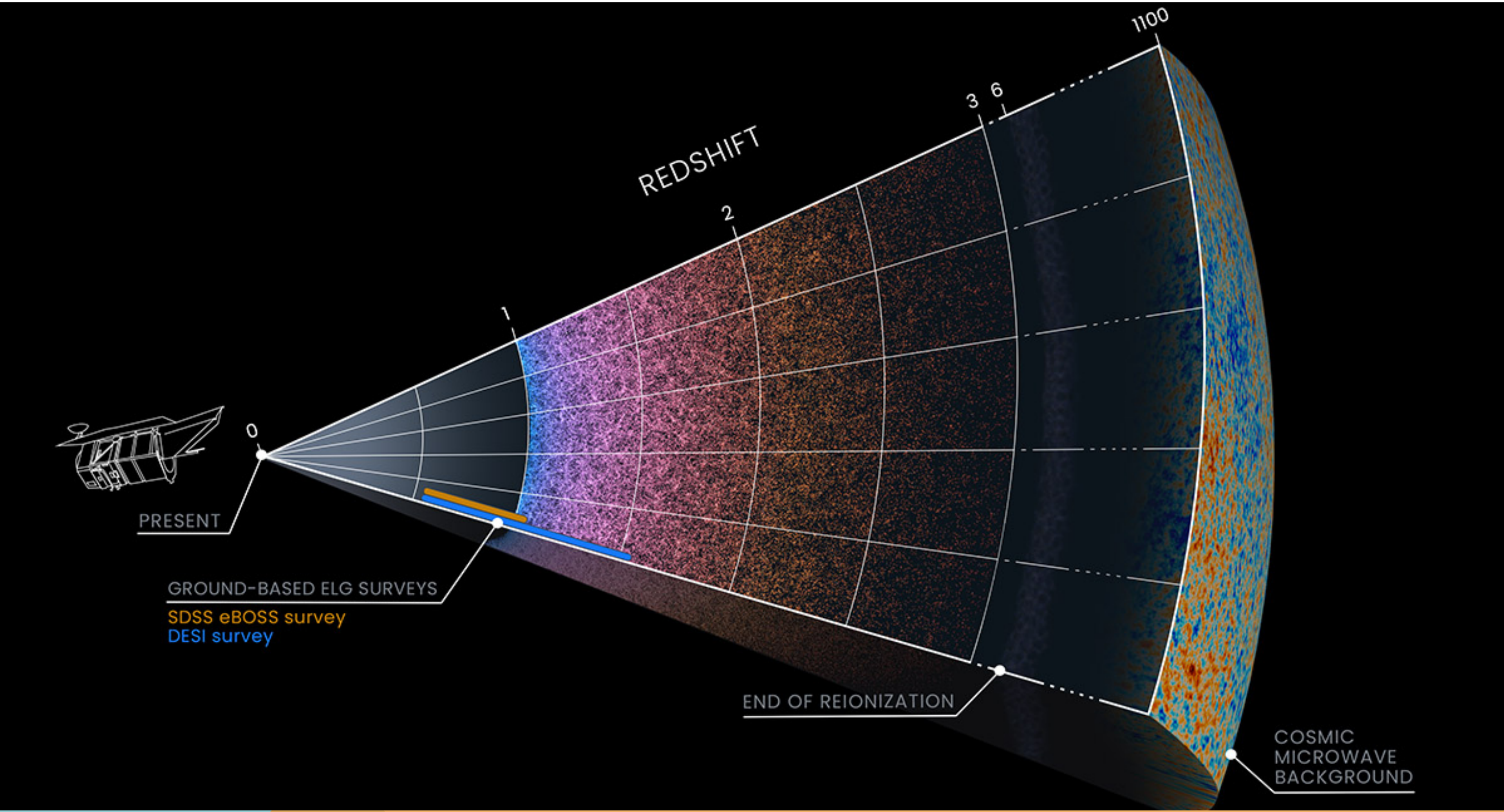
7,142 Roman Pointings

16 Roman Pointings
~6 months total

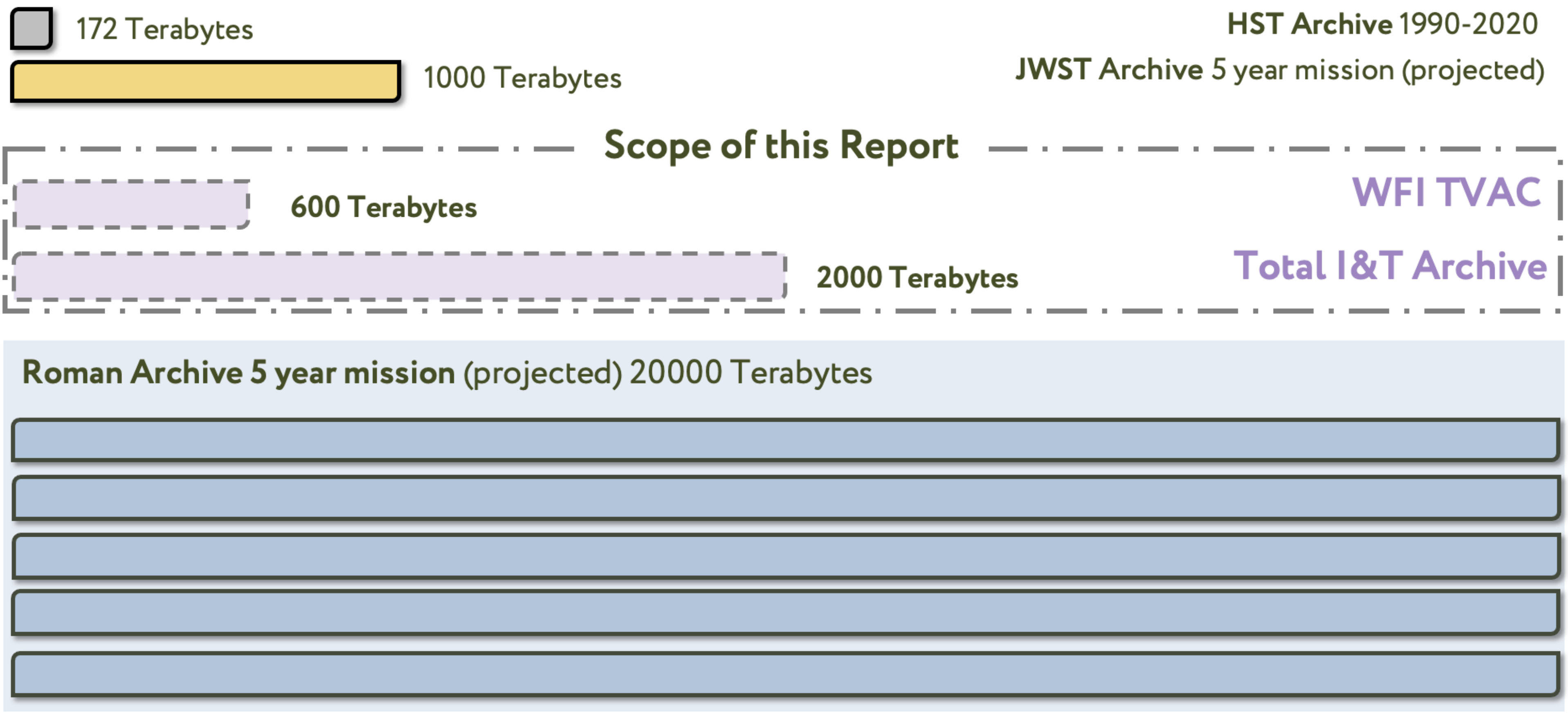
1650 Hubble Pointings
~1100 Years total

> 661,000 HST Pointings

~100x more area than Hubble
has observed in 30 years



REDSHIFT
0
1
2
3
6
1100
PRESENT
GROUND-BASED ELG SURVEYS
SDSS eBOSS survey
DESI survey
END OF REIONIZATION
COSMIC
MICROWAVE
BACKGROUND



Much Data = Logistical Headaches if you work on the Mission

Much Data == LOTS of opportunity for folks to contribute