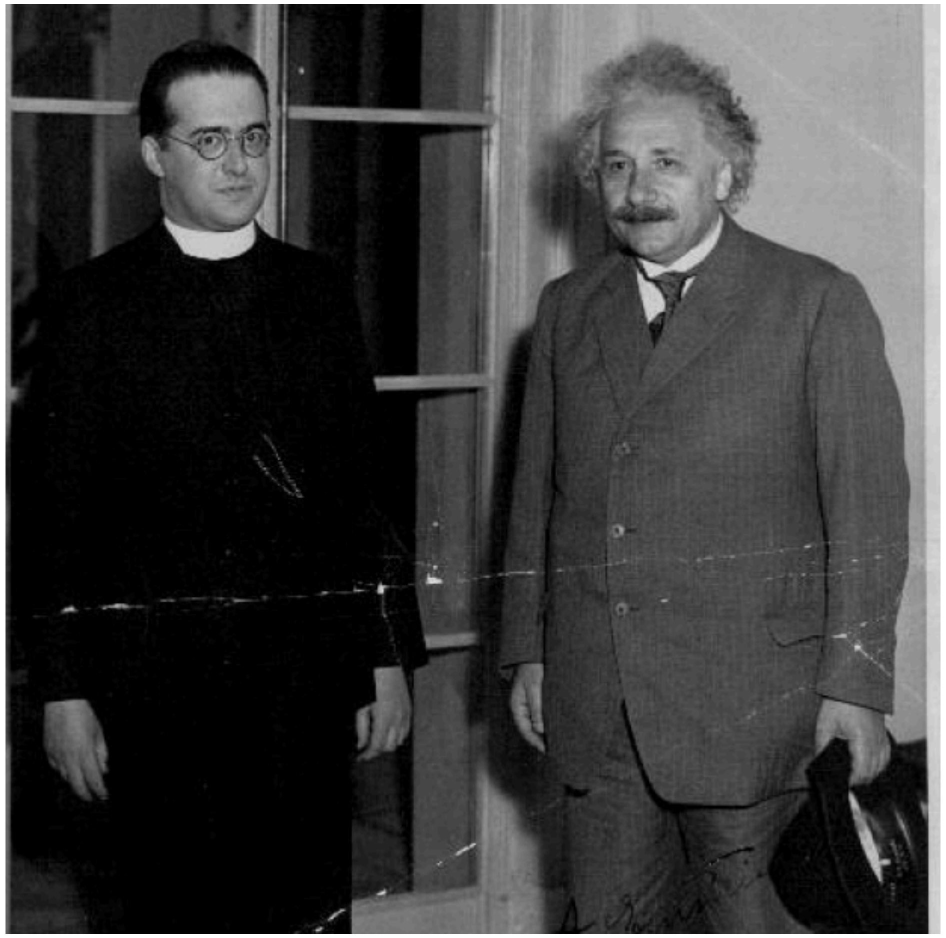
Measuring the Hubble Constant: It takes a Village

Massive Stars the Supernovae,
Bariloche, 2018

A Brief History of H_o



$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \tag{22}$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

$$\frac{R'}{R} = \frac{v}{cr} \tag{23}$$

[...]

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg [1], et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs [2].

Nous adopterons donc

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \mathrm{cm}^{-1} \tag{24}$$

Lemaitre, G. (1927)
Annales de la Société Scientifique de Bruxelles, A47, p. 49-59

A Brief History of H_o

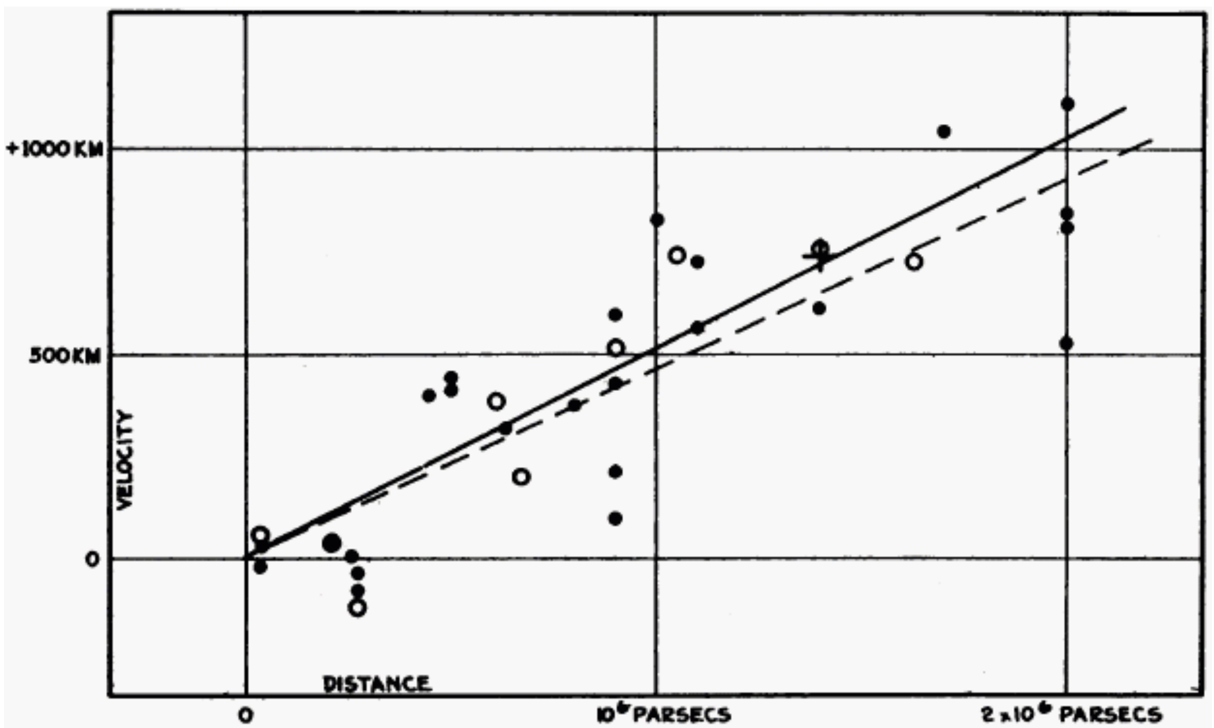


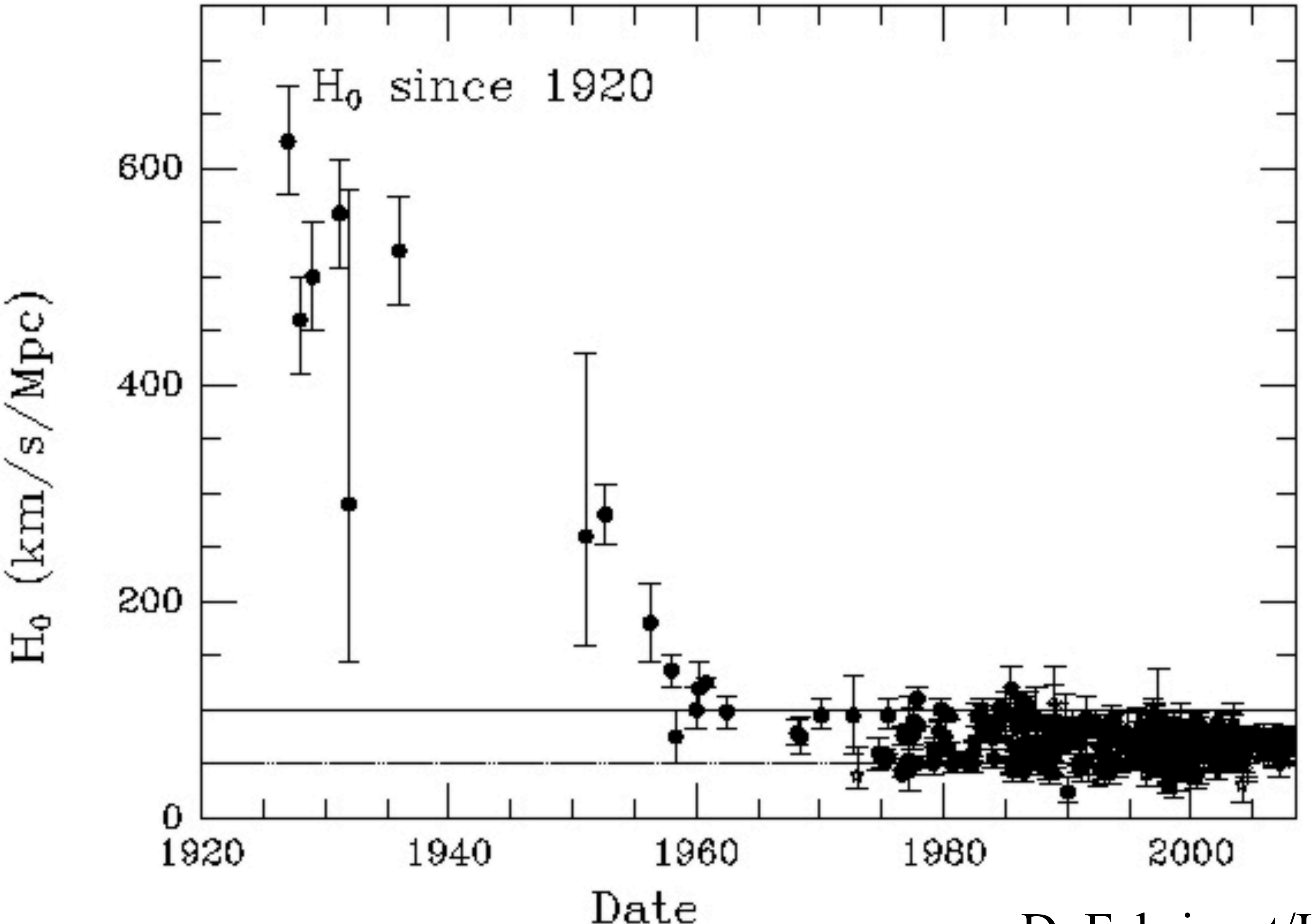
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble, E. (1929), PNAS

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space. In the de Sitter cosmology, displacements of the spectra arise from two sources, an apparent slowing down of atomic vibrations and a general tendency of material particles to scatter. The latter involves an acceleration and hence introduces the element of time. The relative importance of these two effects should determine the form of the relation between distances and observed velocities; and in this connection it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

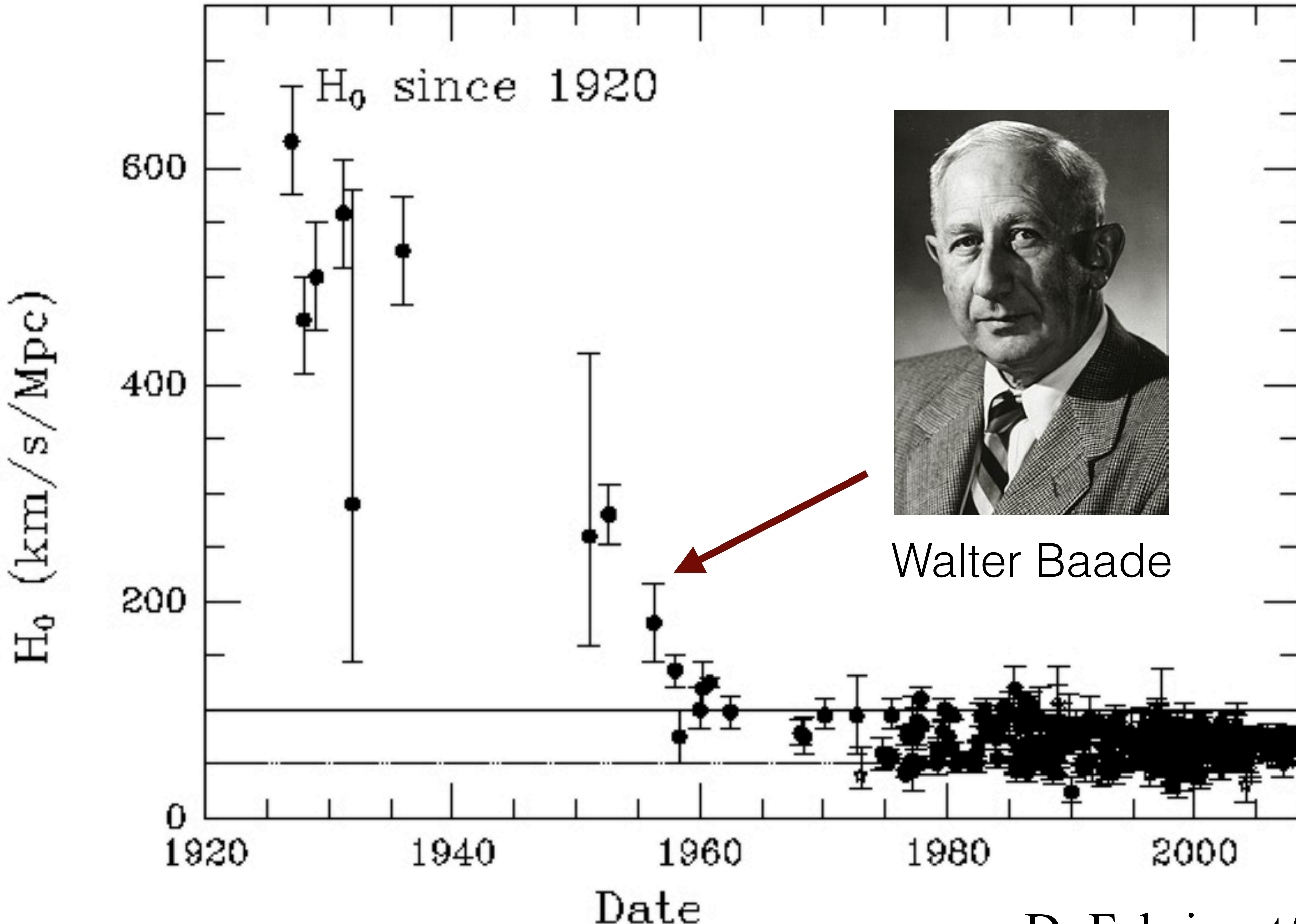
deSitter's solution (like Einstein's) was a static, empty space-time with positive curvature. The Hubble law in such a universe would look linear at small distances, but was in fact quadratic.

A Brief History of Ho



D. Fabricant/Harvard

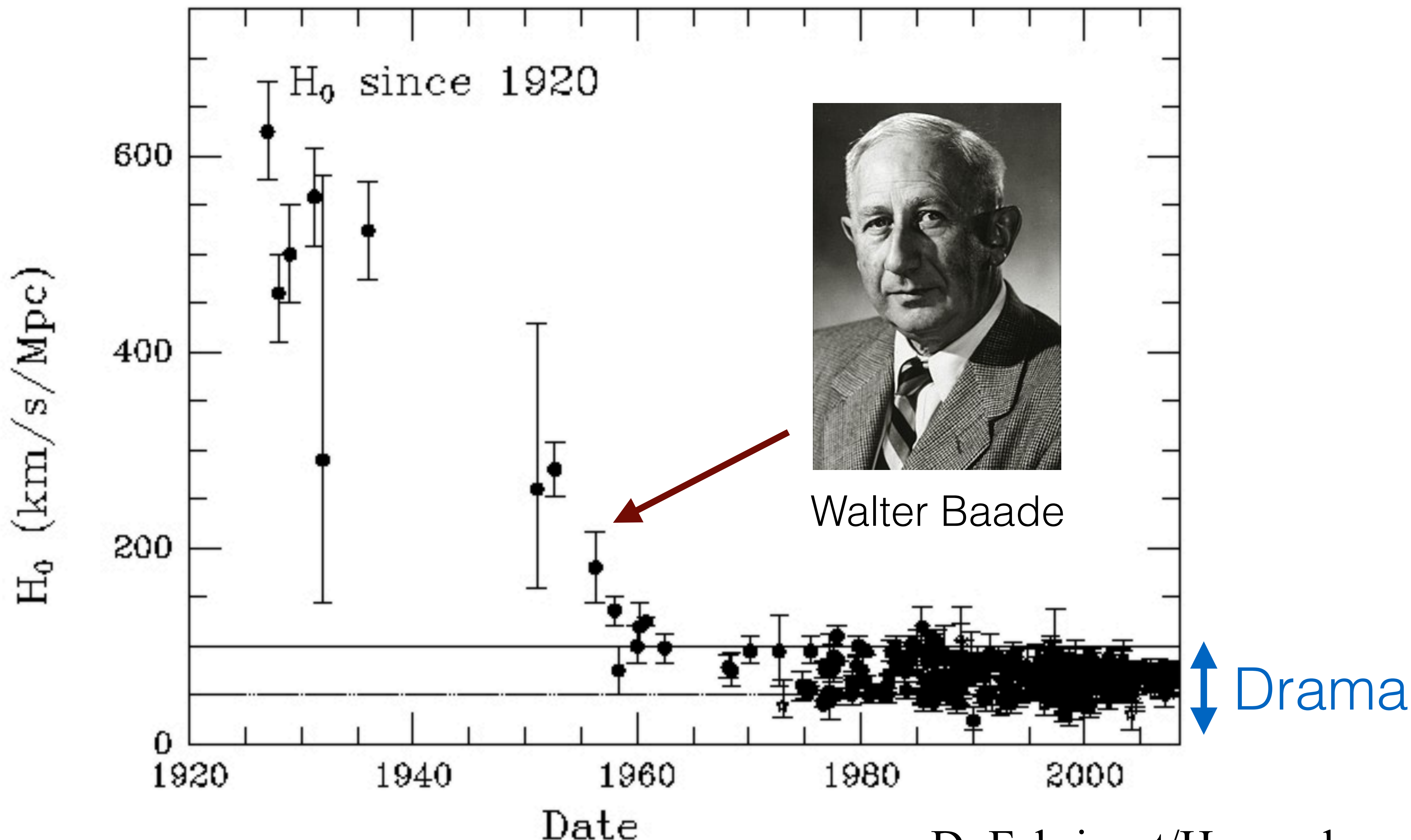
A Brief History of Ho



Walter Baade

D. Fabricant/Harvard

A Brief History of Ho



Walter Baade

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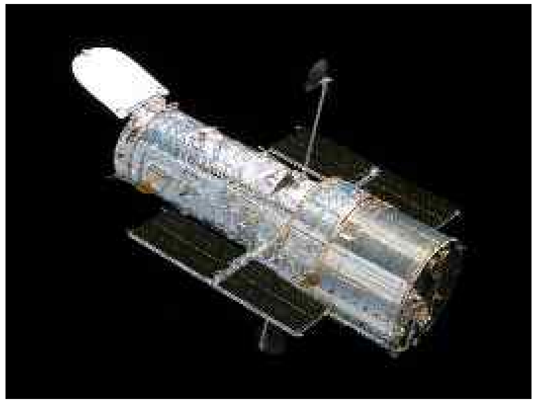
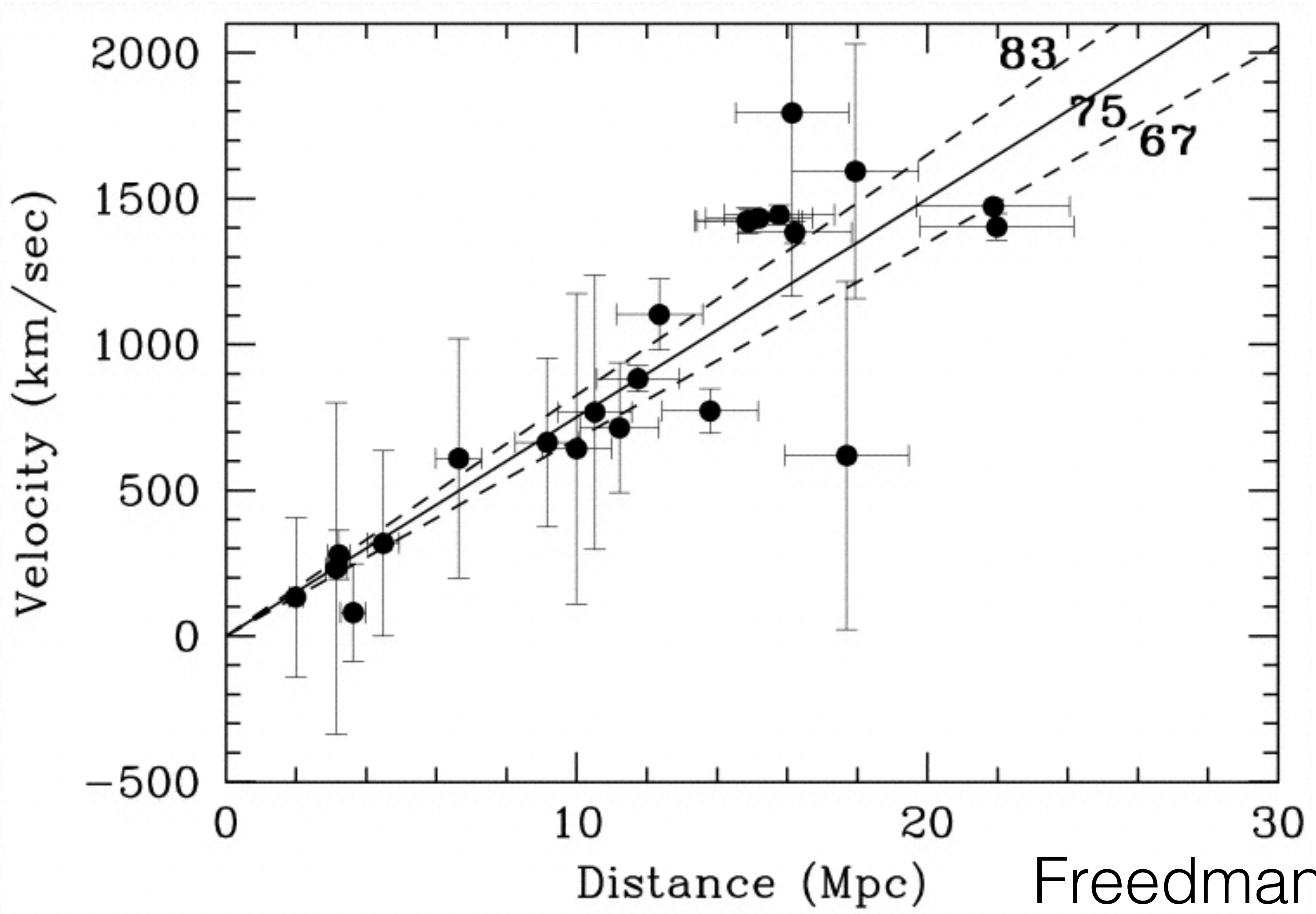
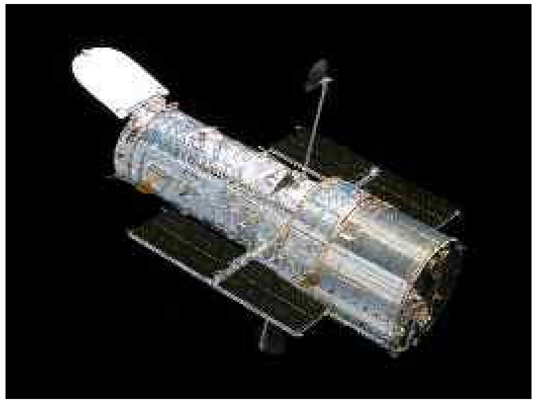
H(L)ST Key Project

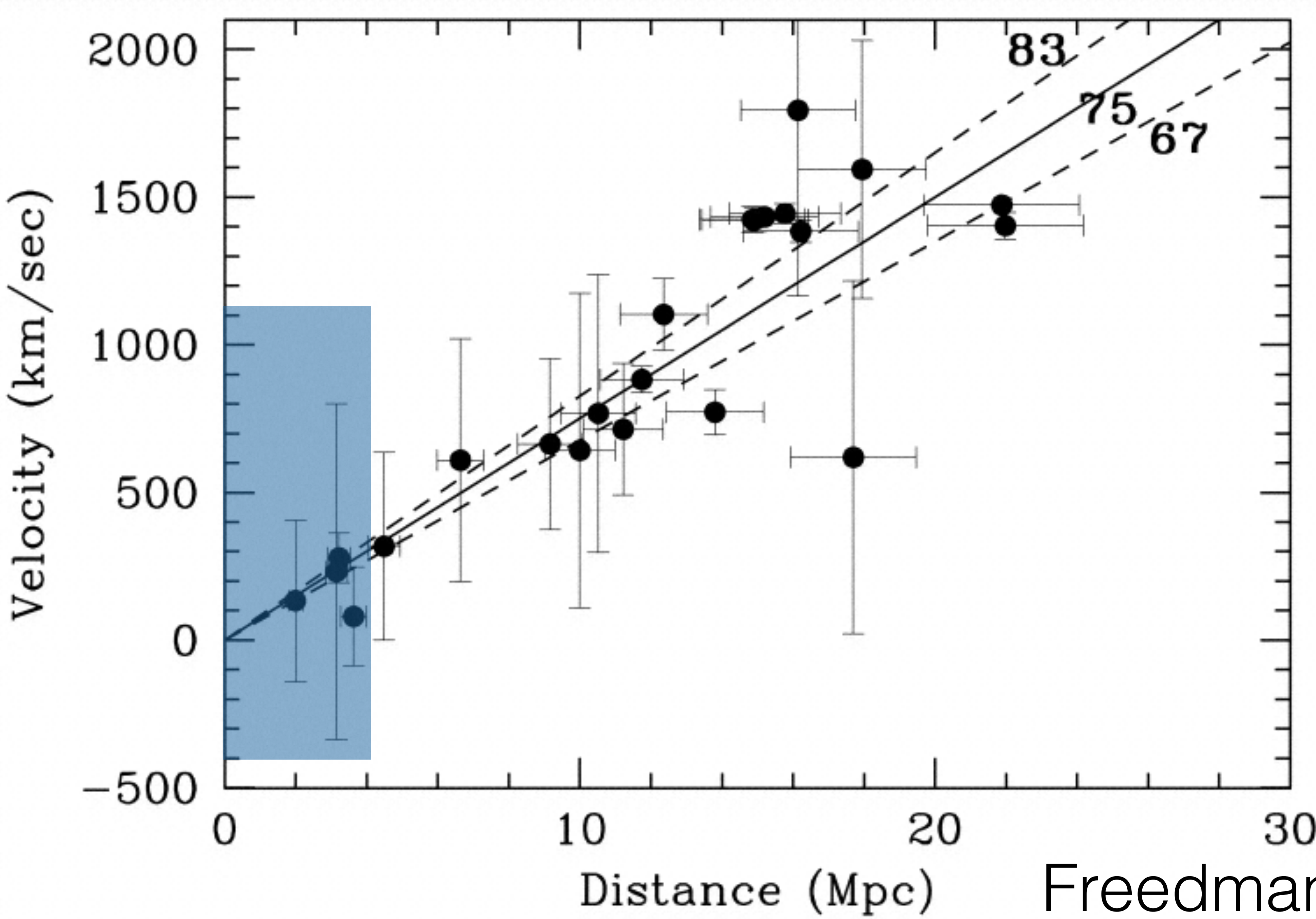




Freedman et al. 2003

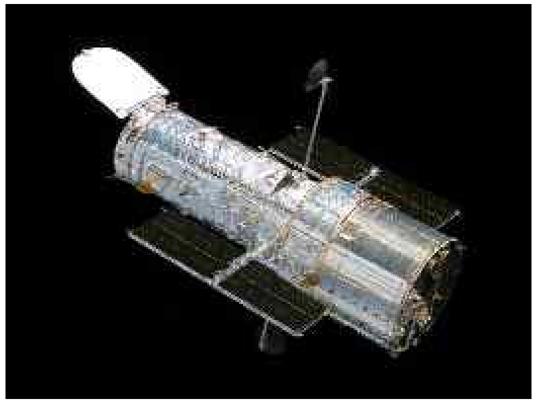
H(L)ST Key Project

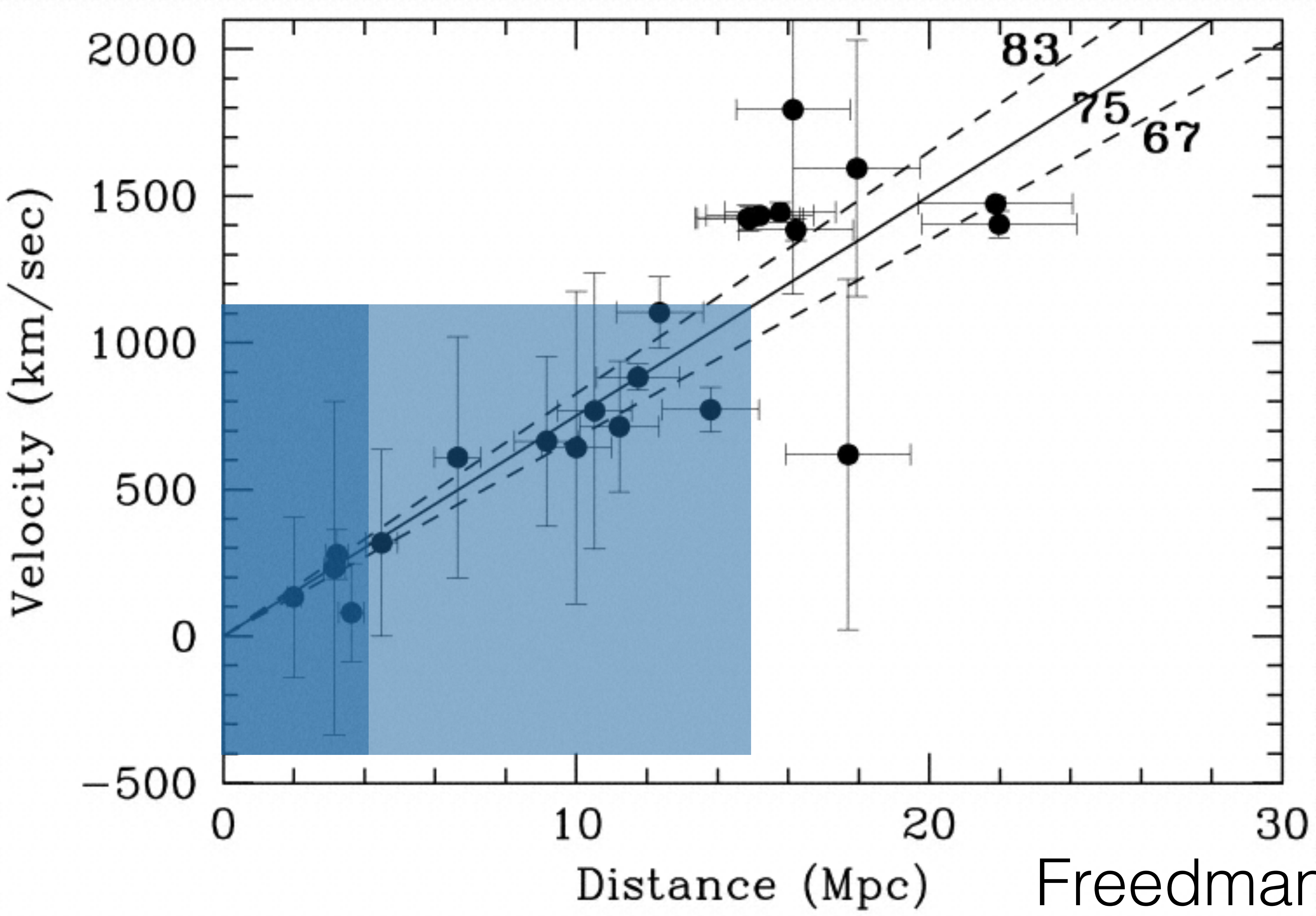




Freedman et al. 2003

H(L)ST Key Project

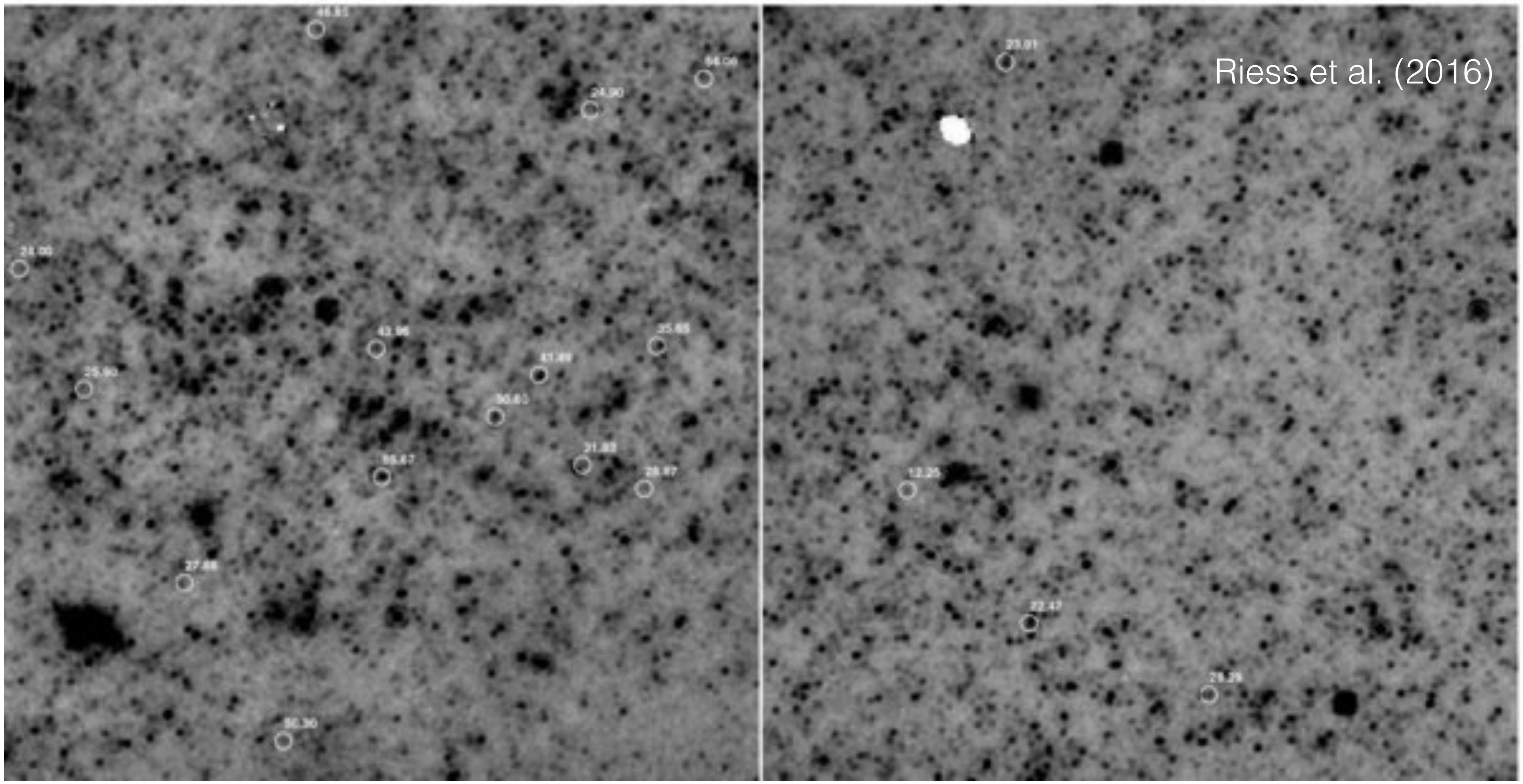




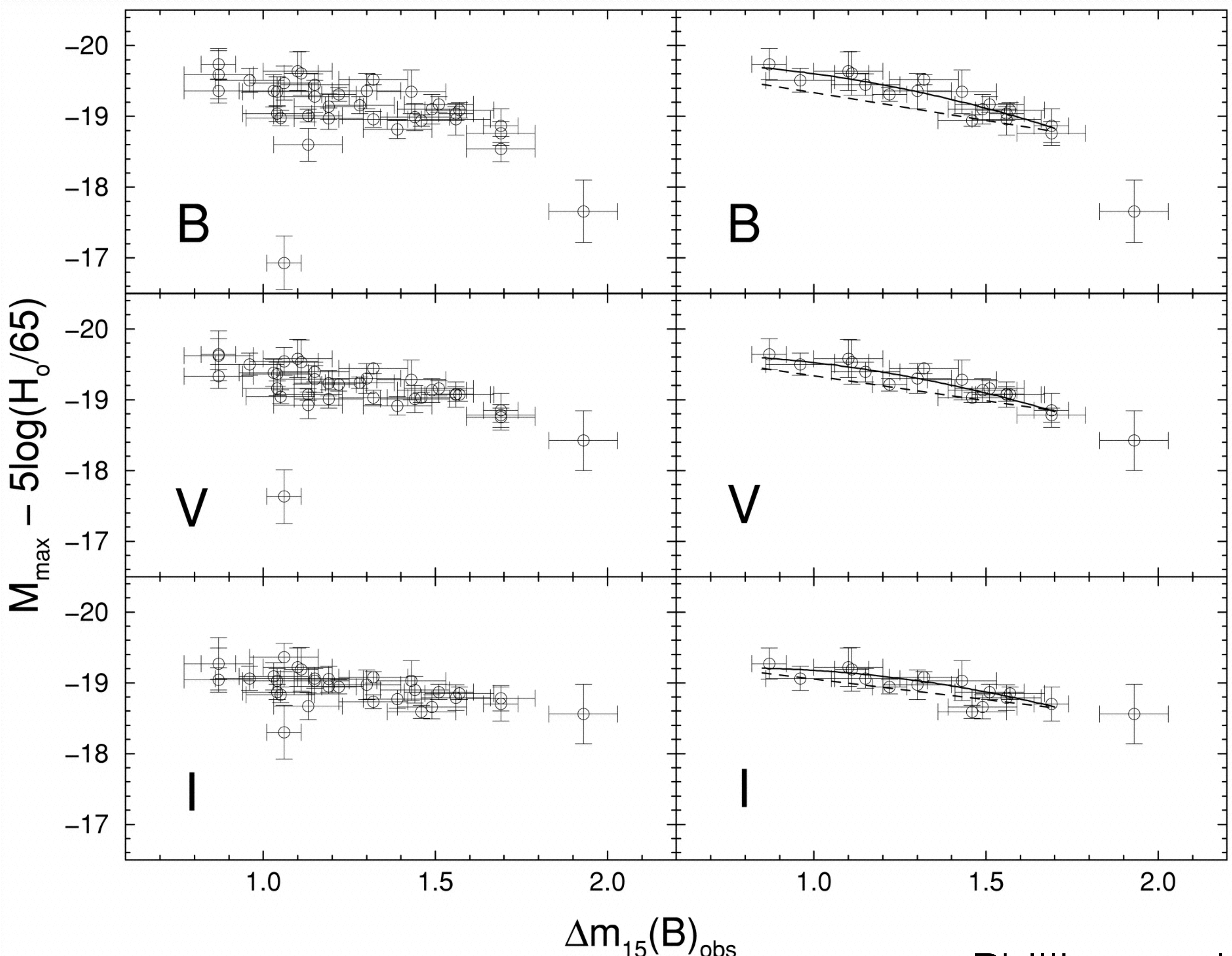
Freedman et al. 2003

Cepheids are Difficult at Large Distances

Not just dimmer, but fields are more crowded.

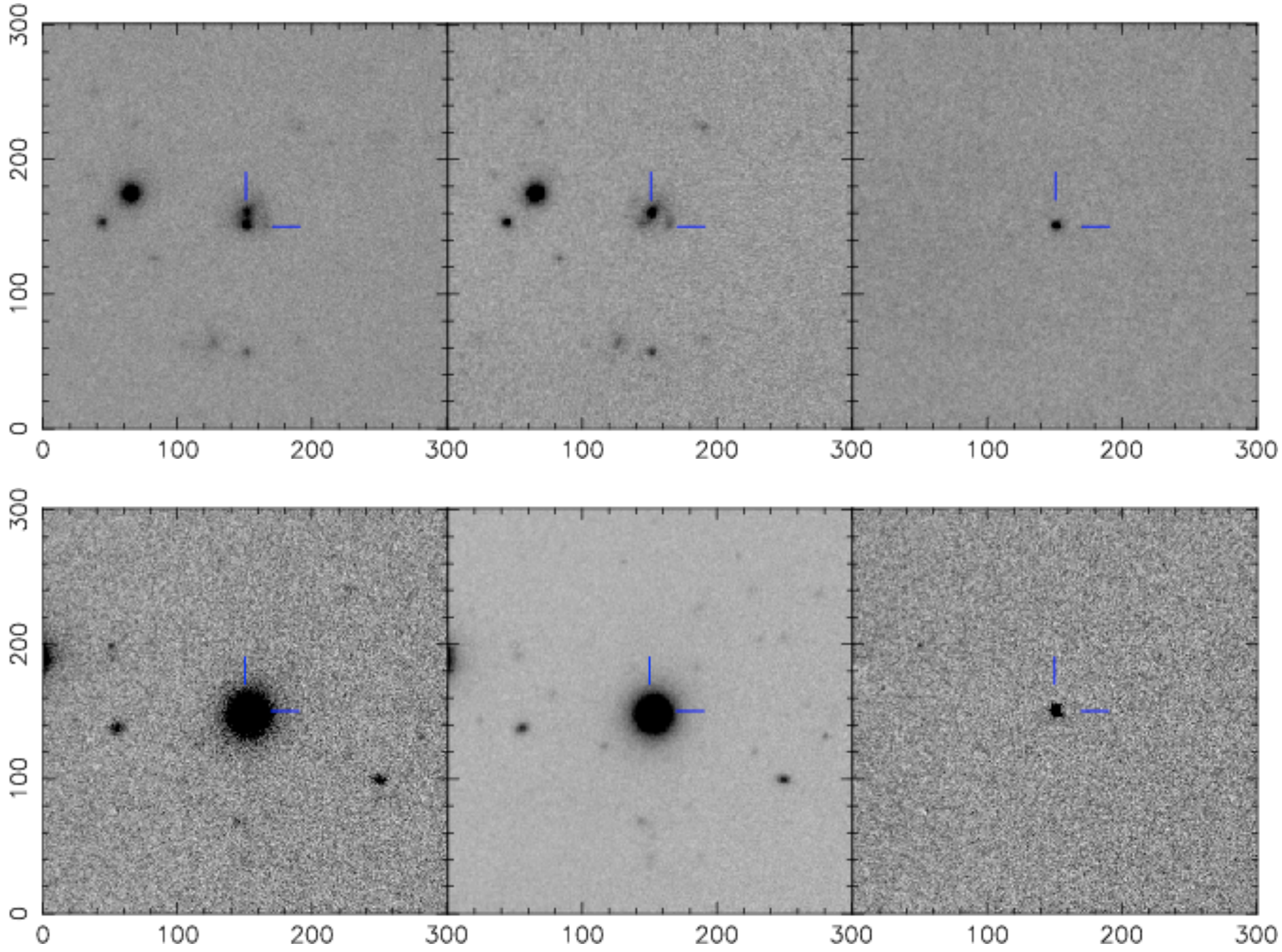


SNe Ia to the Rescue!

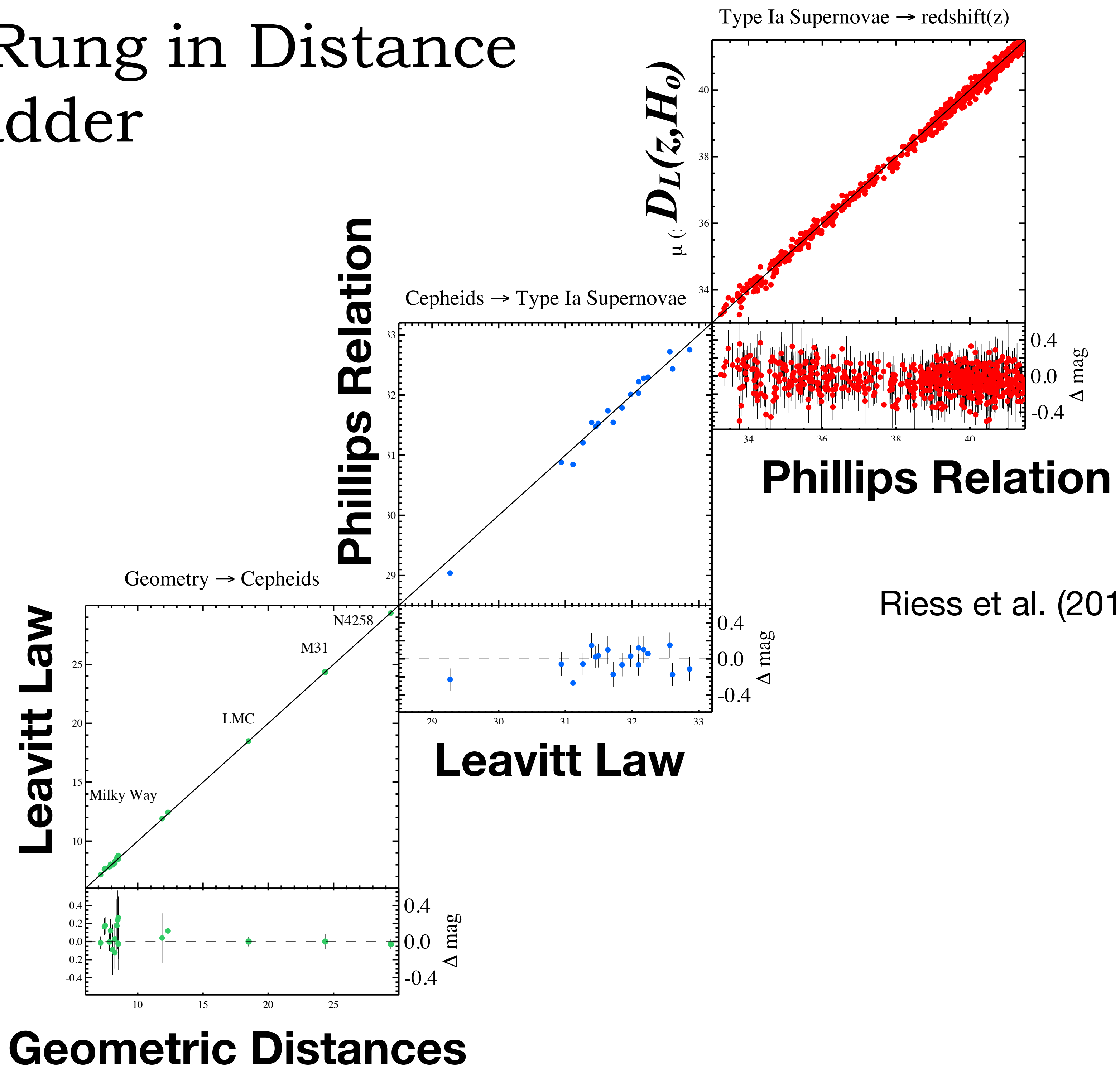


Phillips et al. (1999)

Pros: Bright, and Unlike Cepheids, SNe Ia Fade

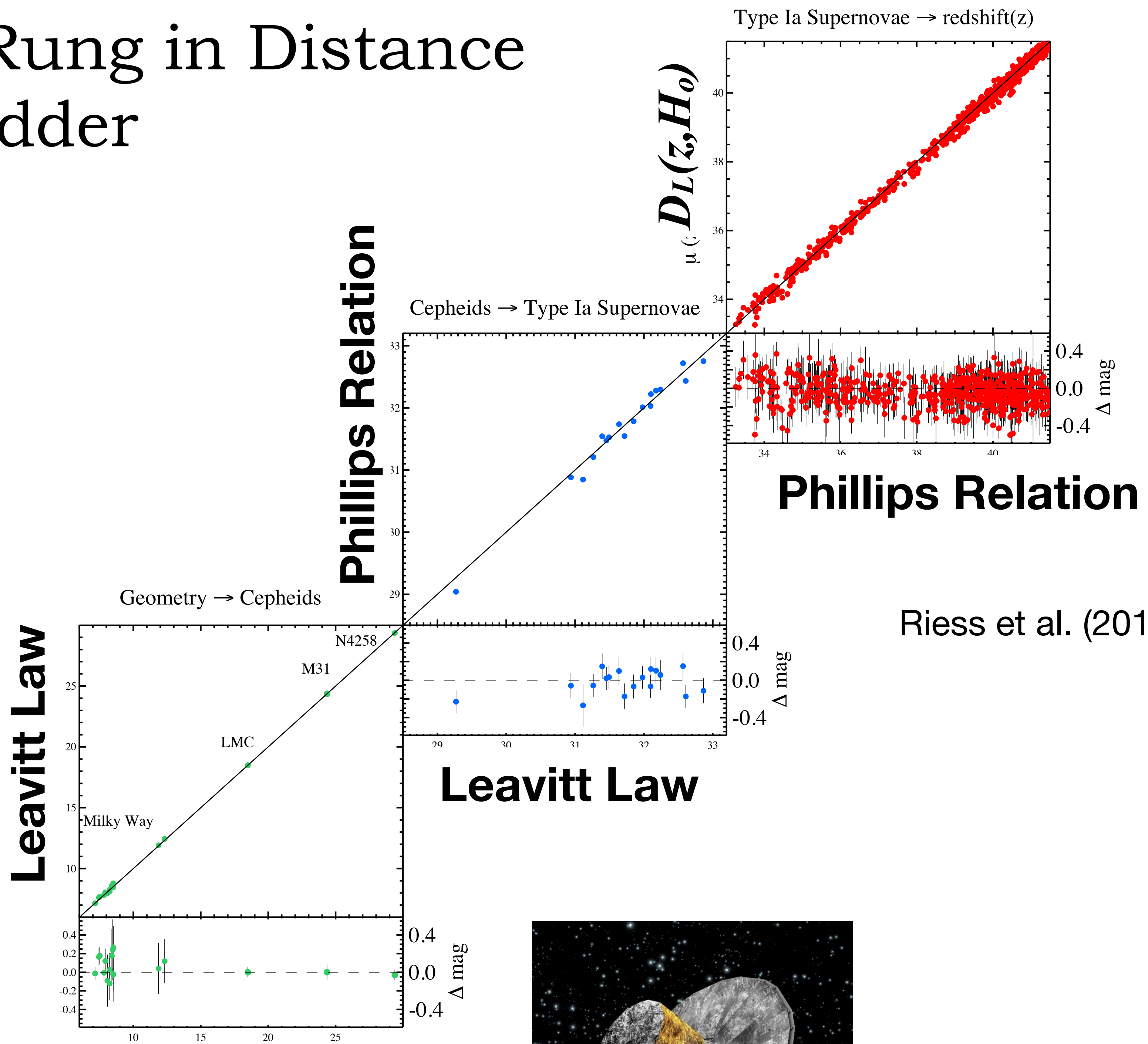


Con: Another Rung in Distance Ladder

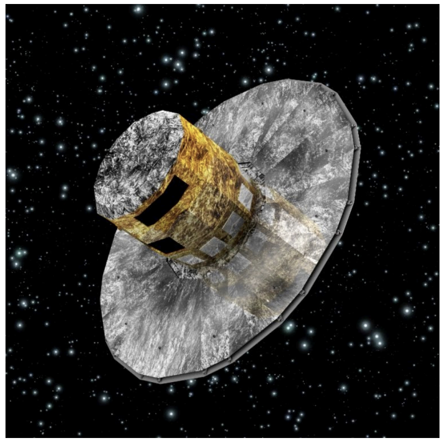


Riess et al. (2016)

Con: Another Rung in Distance Ladder



Riess et al. (2016)



The Carnegie Supernova Project I (CSP-I)

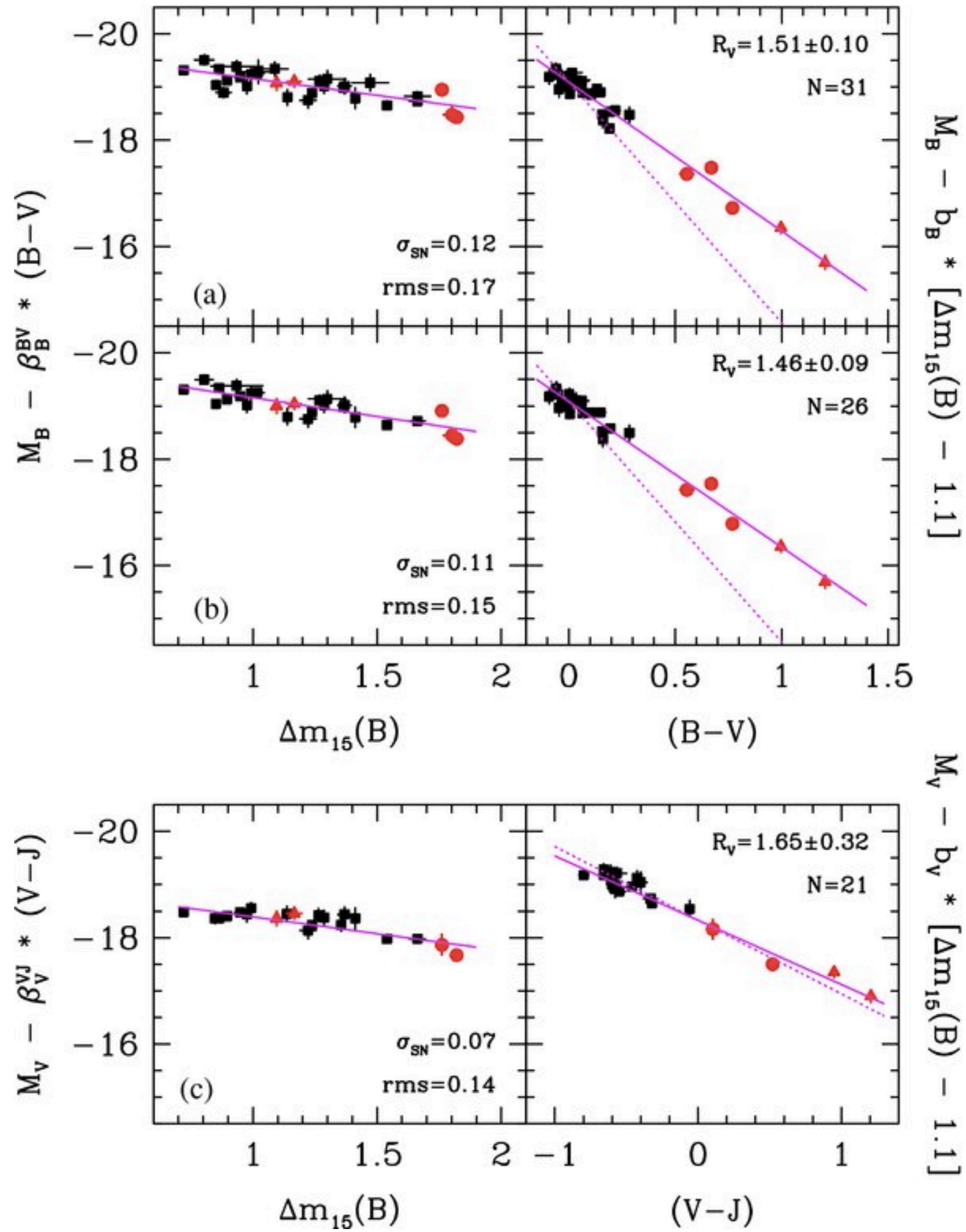
SUPER NOVA MEETING, CARNEGIE OBSERVATORIES, SANTA BARBARA STREET, PASADENA, CALIFORNIA, AUGUST 7, 2006
Mark Phillips, Eric Hsiao, Nick Suntzeff, Pamela Wyatt, Eric Persson, Wendy Freedman, Nidia Morrell, Sergio Gonzalez
Miguel Roth, Christopher Burns, Gaston Folatelli, Carlos Contreras, Barry Madore, Mario Hamuy

Major goals of CSP:

- Well-defined photometric system
- Leverage the NIR to characterize/reduce dust systematics
- NIR Hubble-Lemaître diagram
- Measure Hubble constant

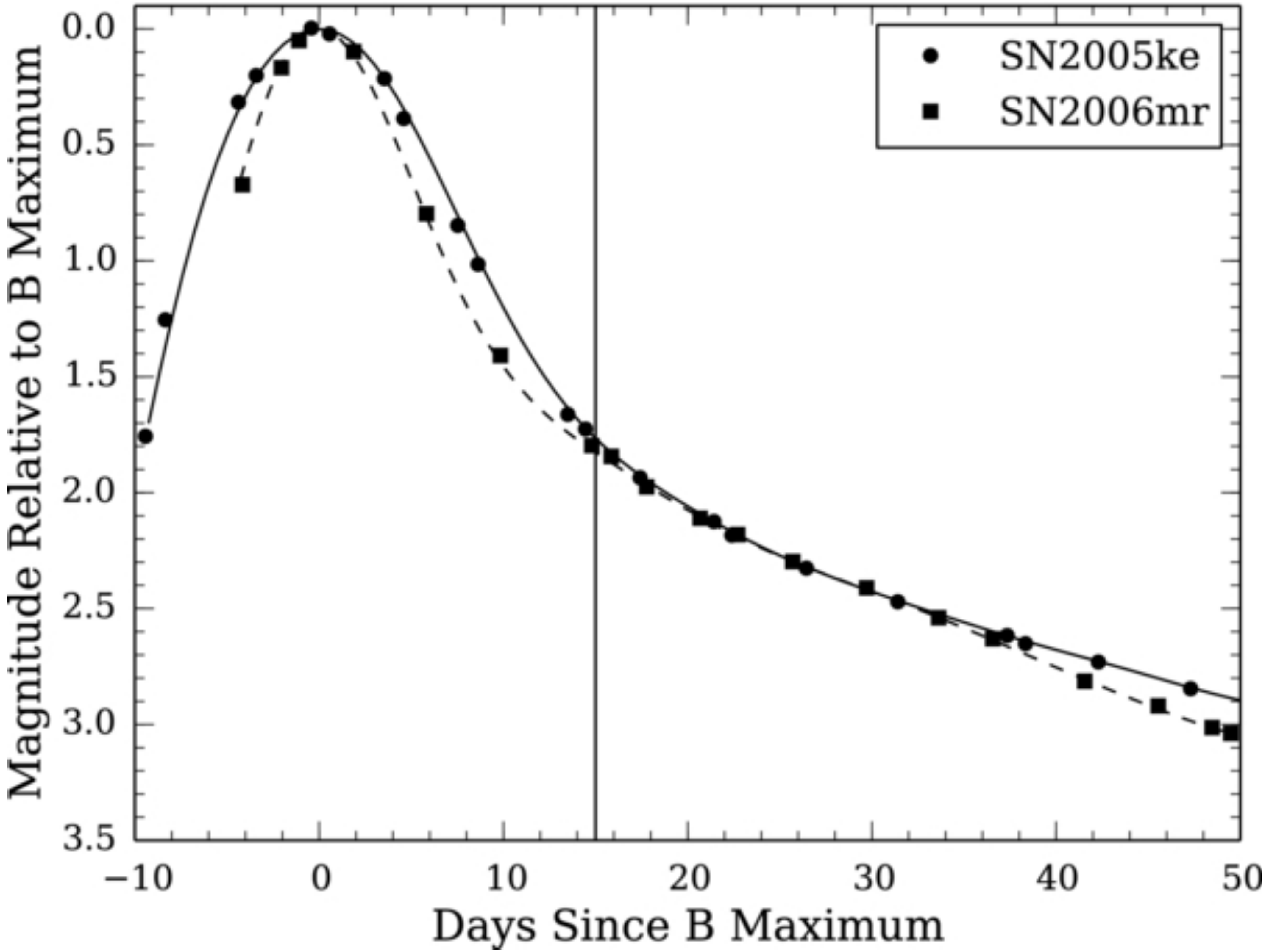
Three corrections

- Faster-Fainter
- Redder-Fainter
- Host Mass/Metallicity/SFR

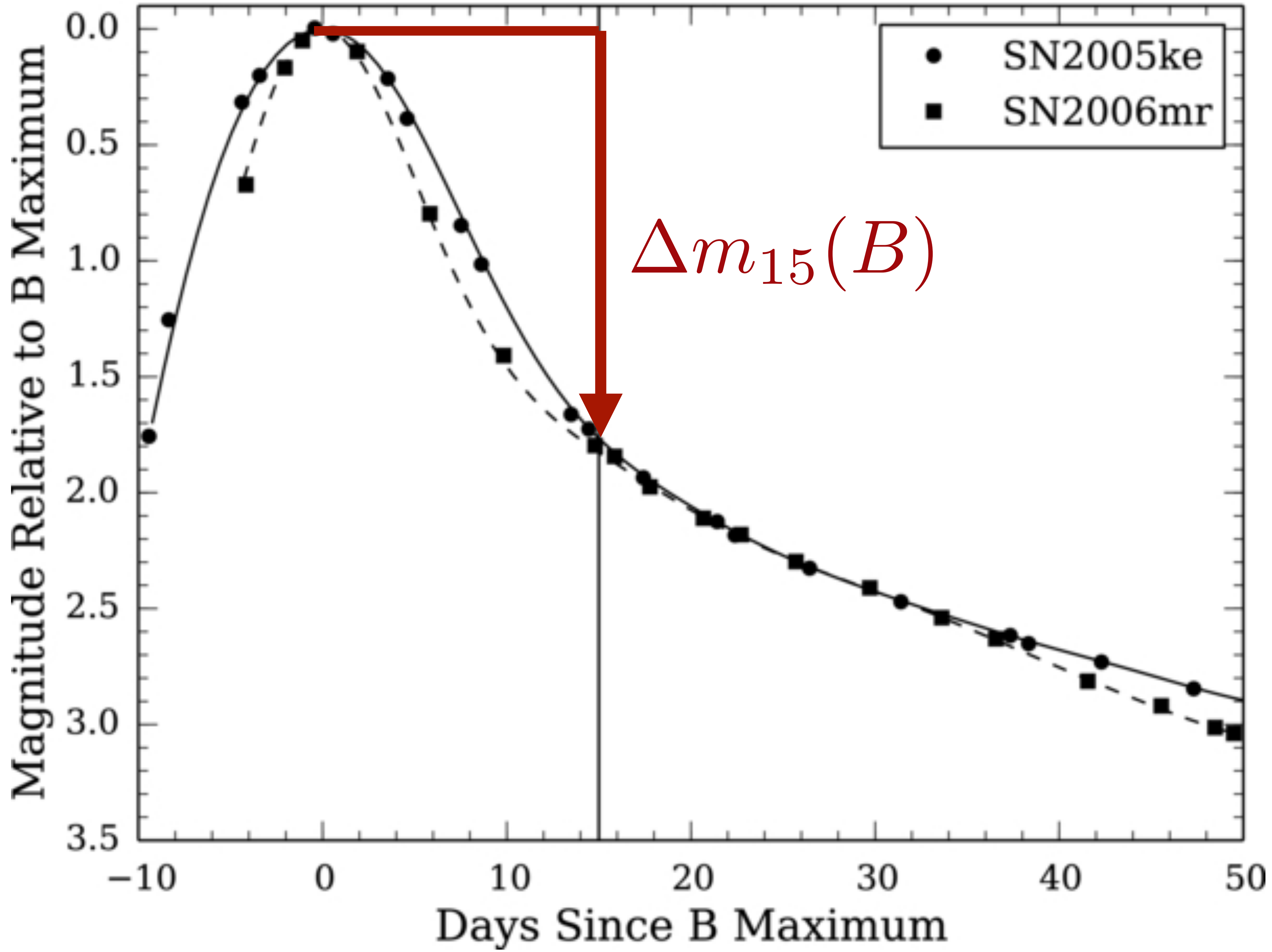


Folatelli et al. (2010)

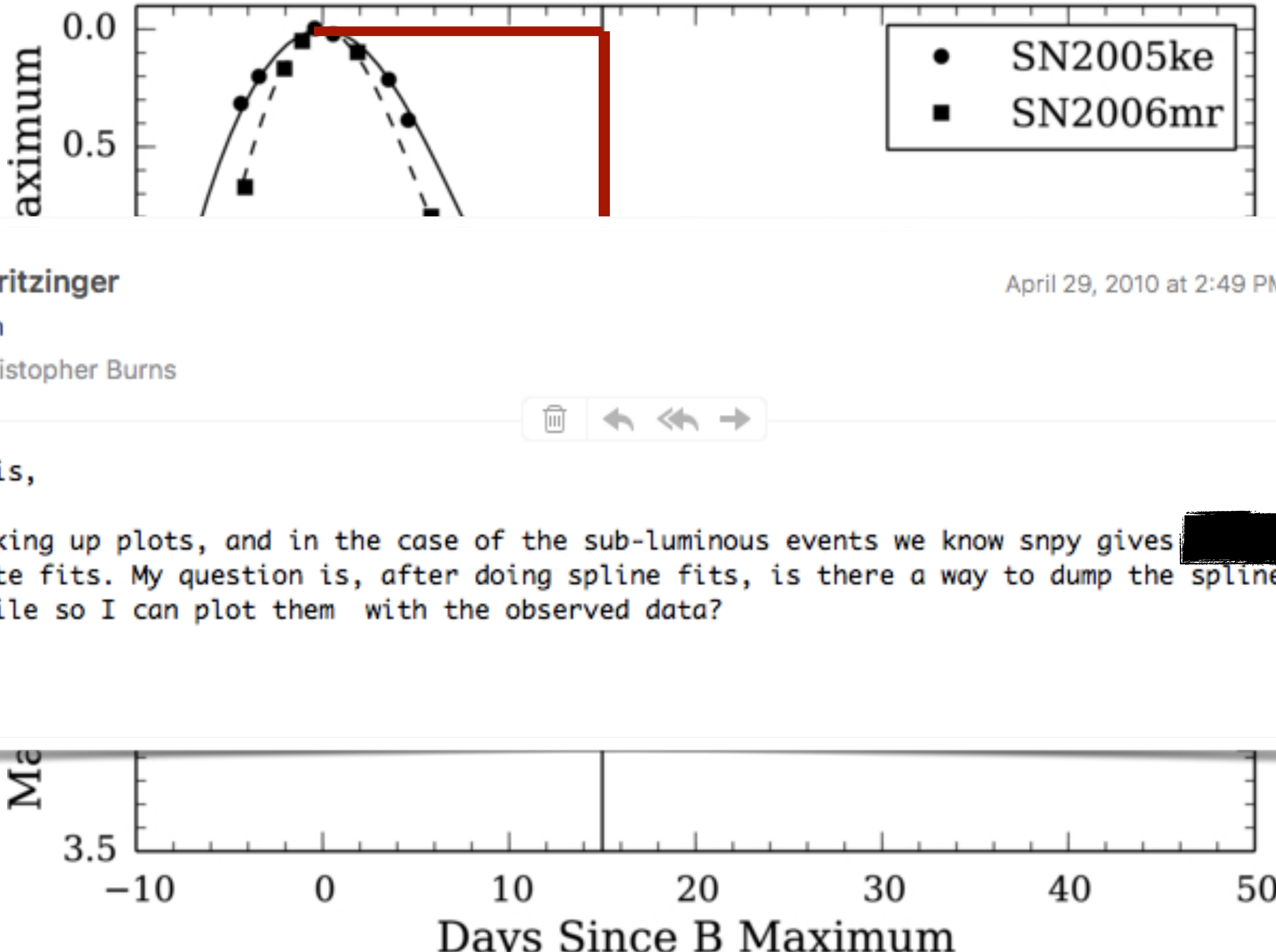
A New Shape Parameter



A New Shape Parameter



A New Shape Parameter



Max Stritzinger
question
To: Christopher Burns

April 29, 2010 at 2:49 PM

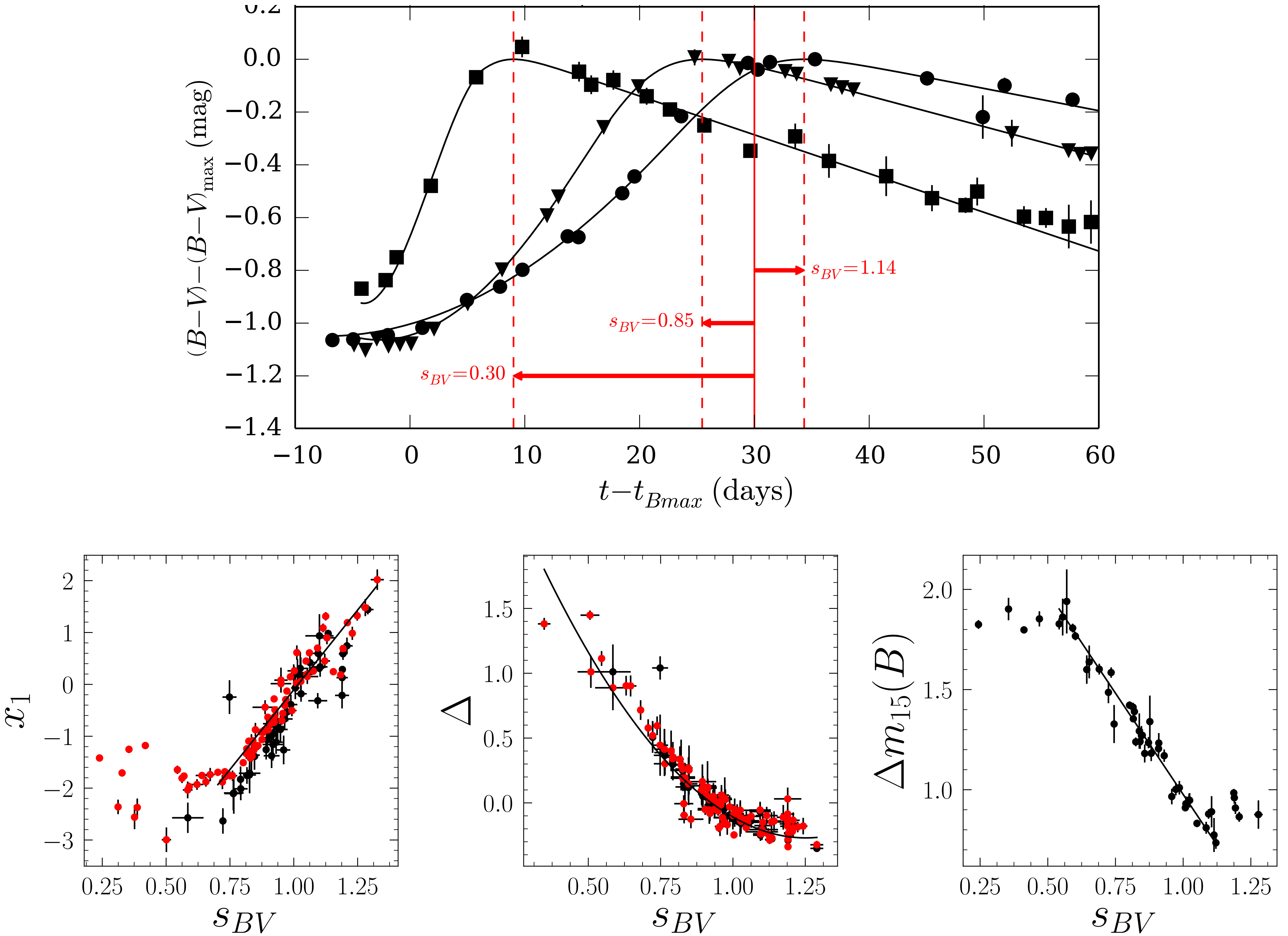
MS

Hi Chris,

I'm making up plots, and in the case of the sub-luminous events we know snpy gives [redacted] template fits. My question is, after doing spline fits, is there a way to dump the spline fits to a file so I can plot them with the observed data?

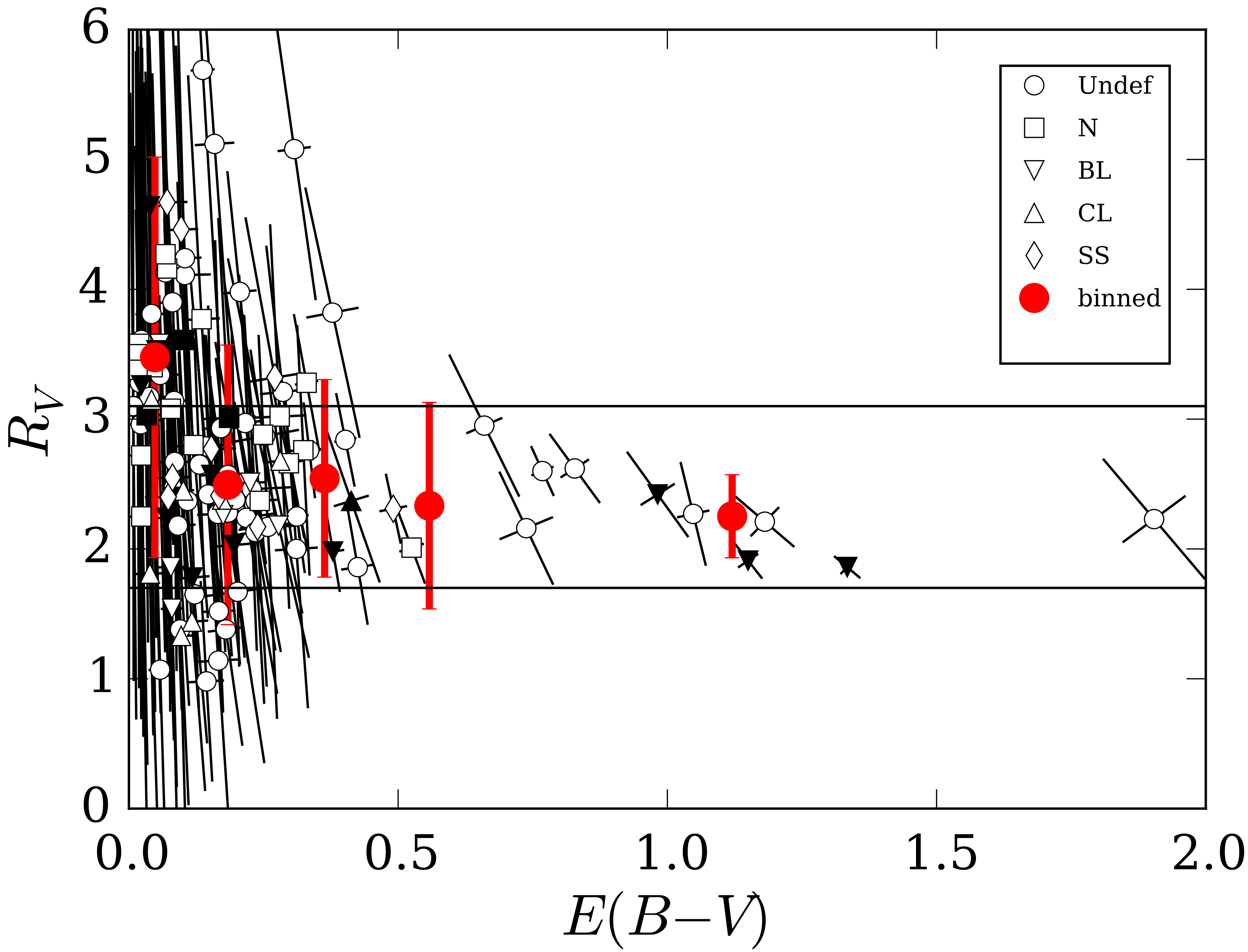
Max

A New Shape Parameter



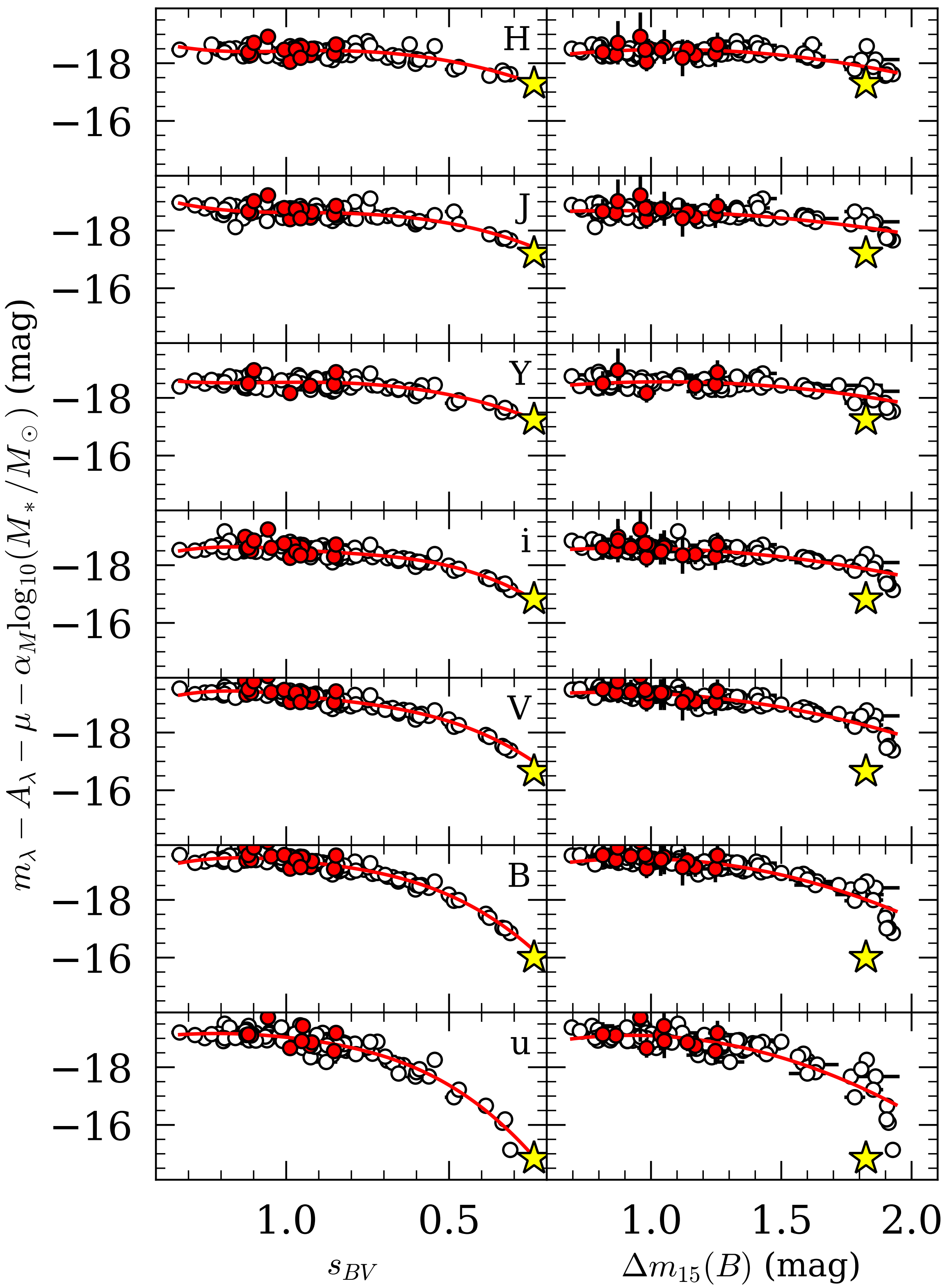
Burns et al. (2018)

Extinction



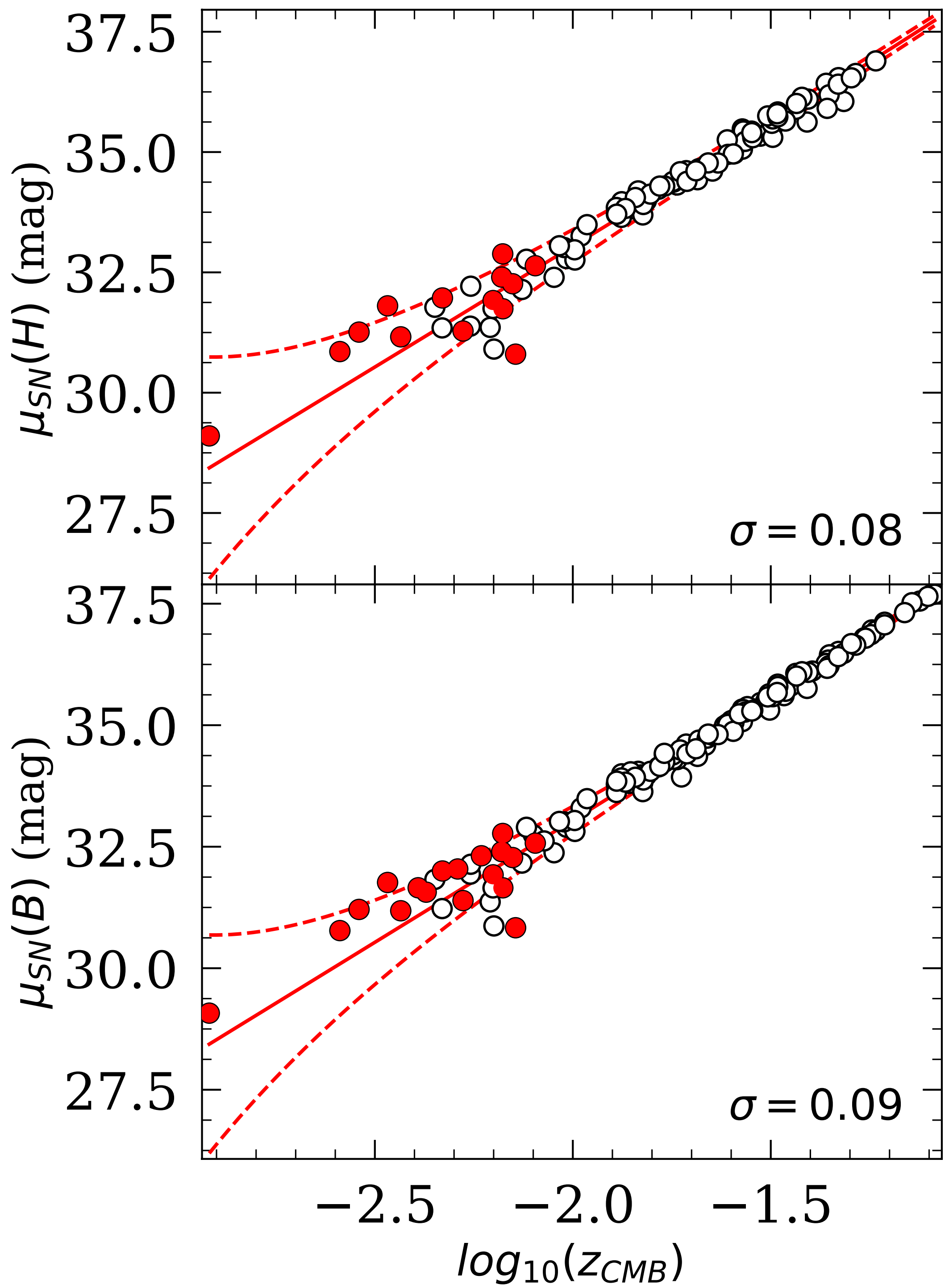
Using Fitzpatrick (1999) reddening law

CSP-I Phillips Relation



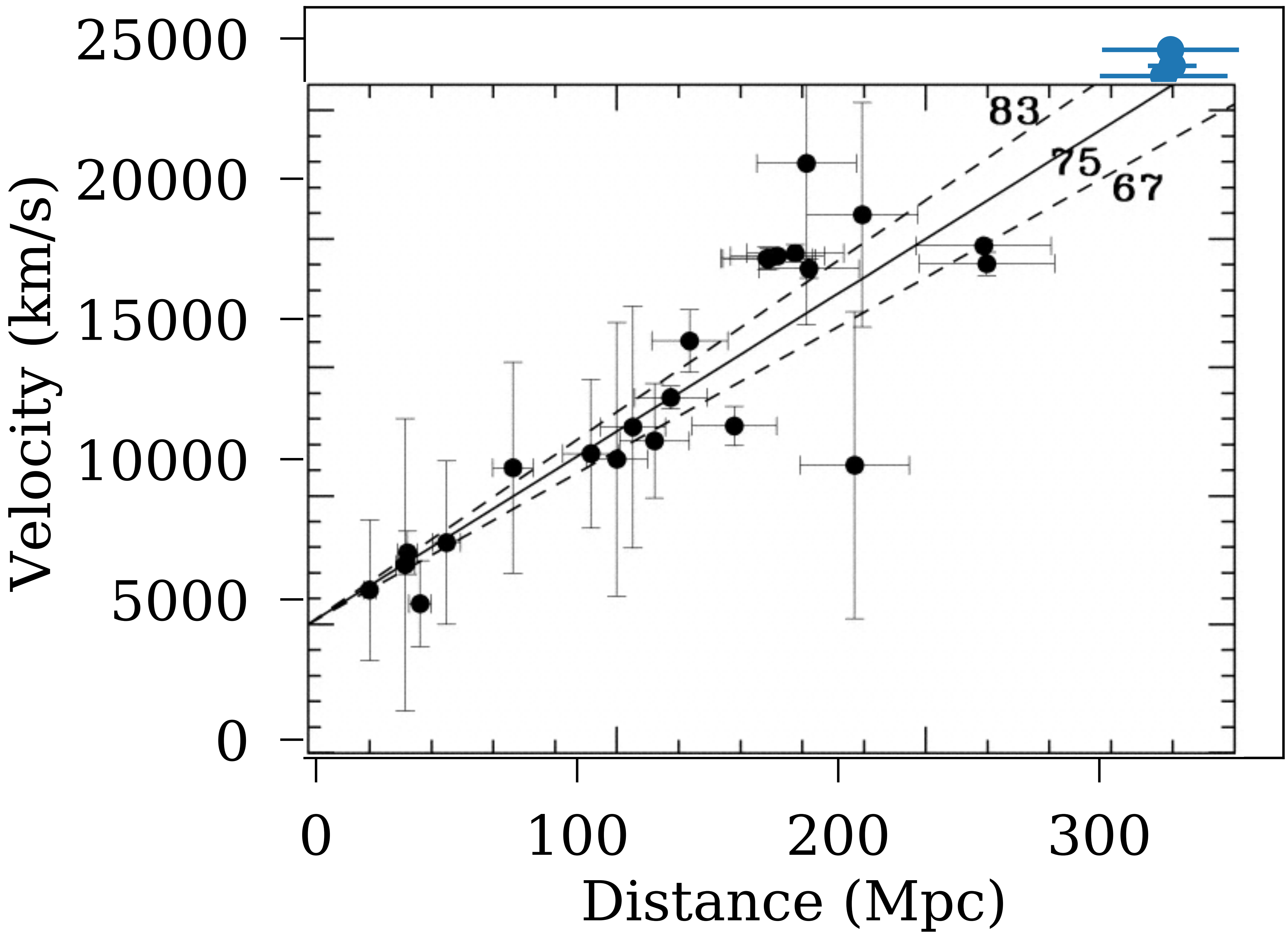
- A new light-curve shape (s_{BV}) that is more robust for NIR and fast-decliners.
- Extinction from observed colors using extinction law (Fitzpatrick ’99)
- R_V is not a constant: drawn from a distribution.

CSP-I Hubble Diagram

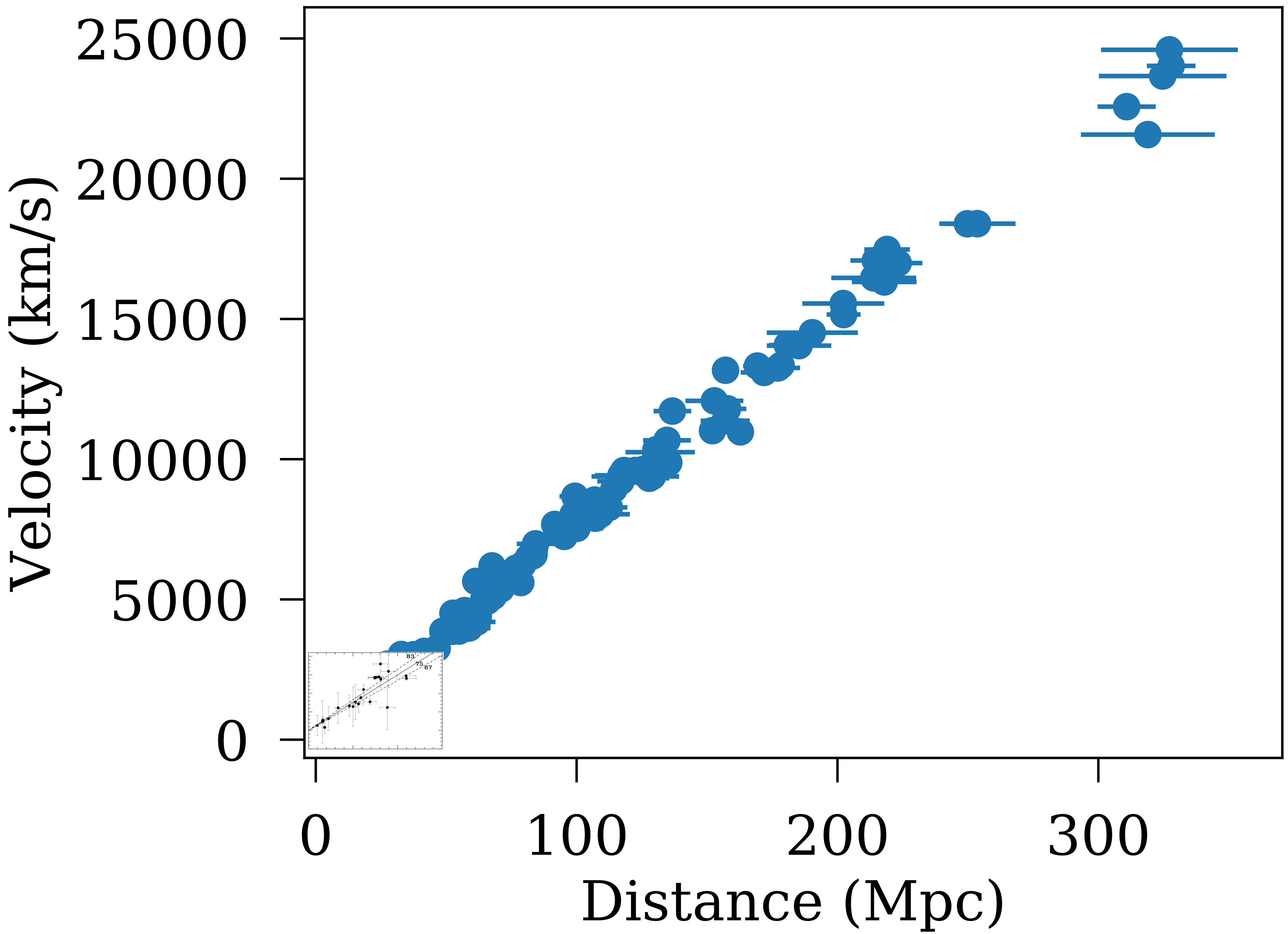


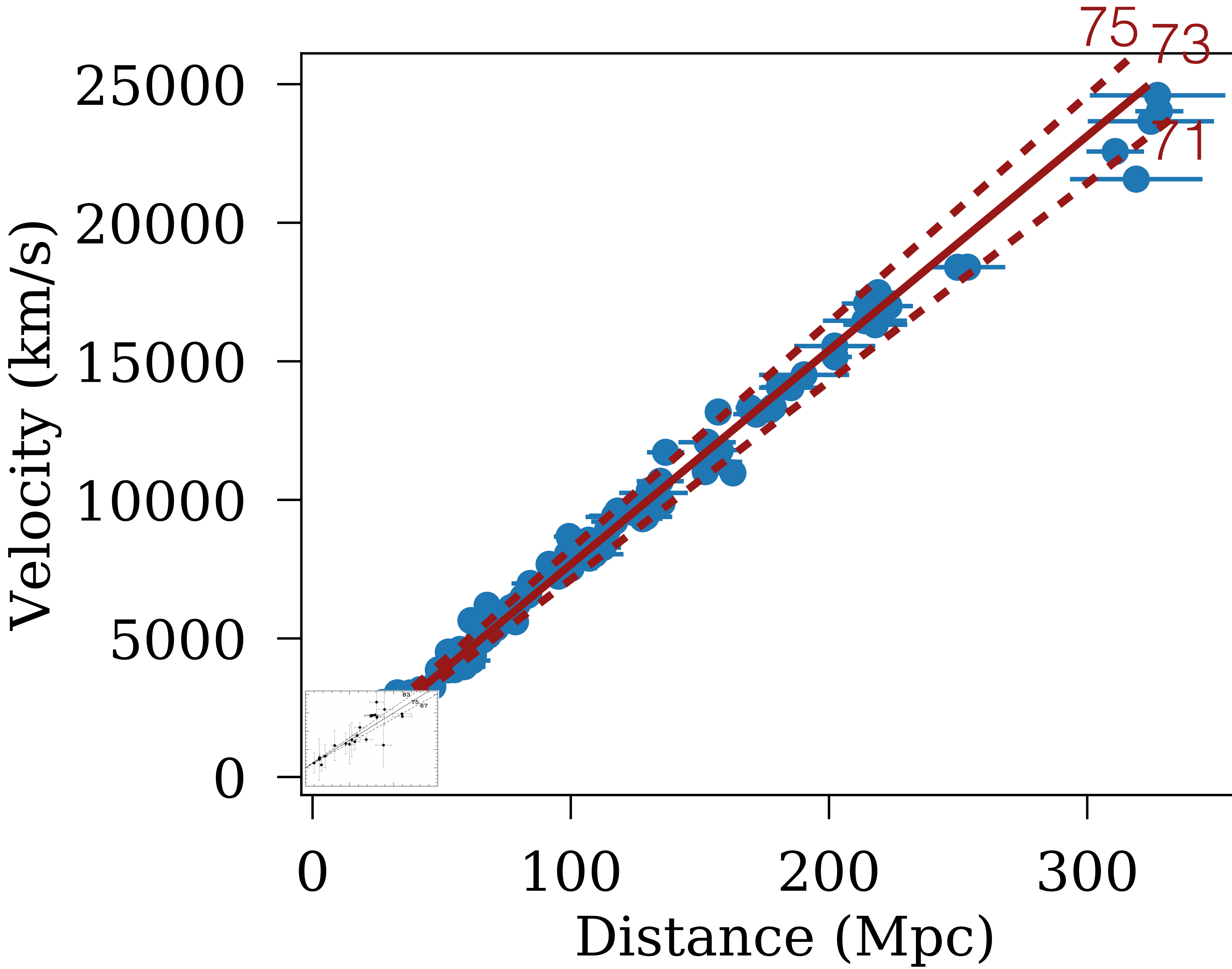
$H_0 = 73.2 \pm 2.3$ km/s/Mpc

$H_0 = 72.7 \pm 2.1$ km/s/Mpc

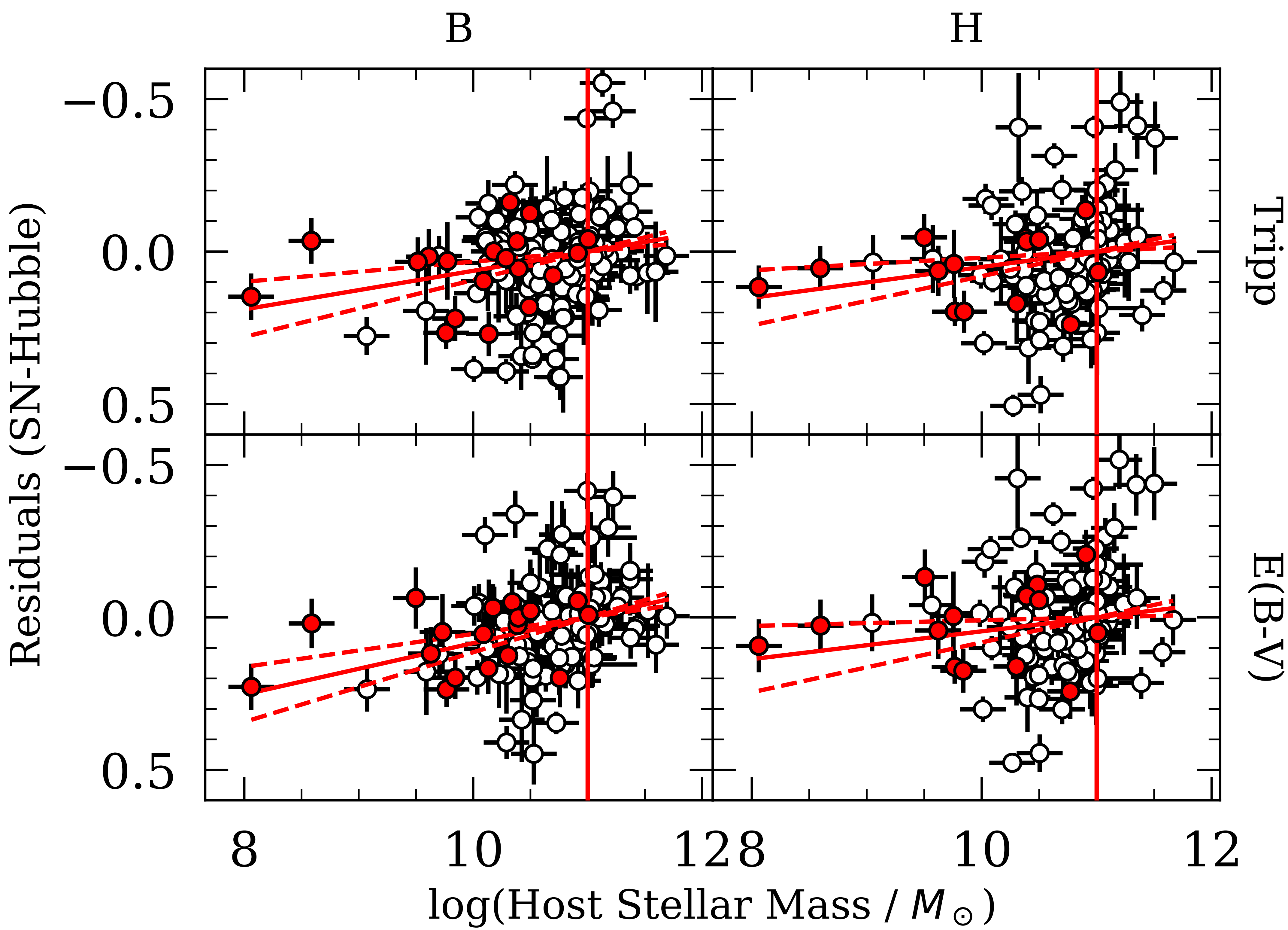


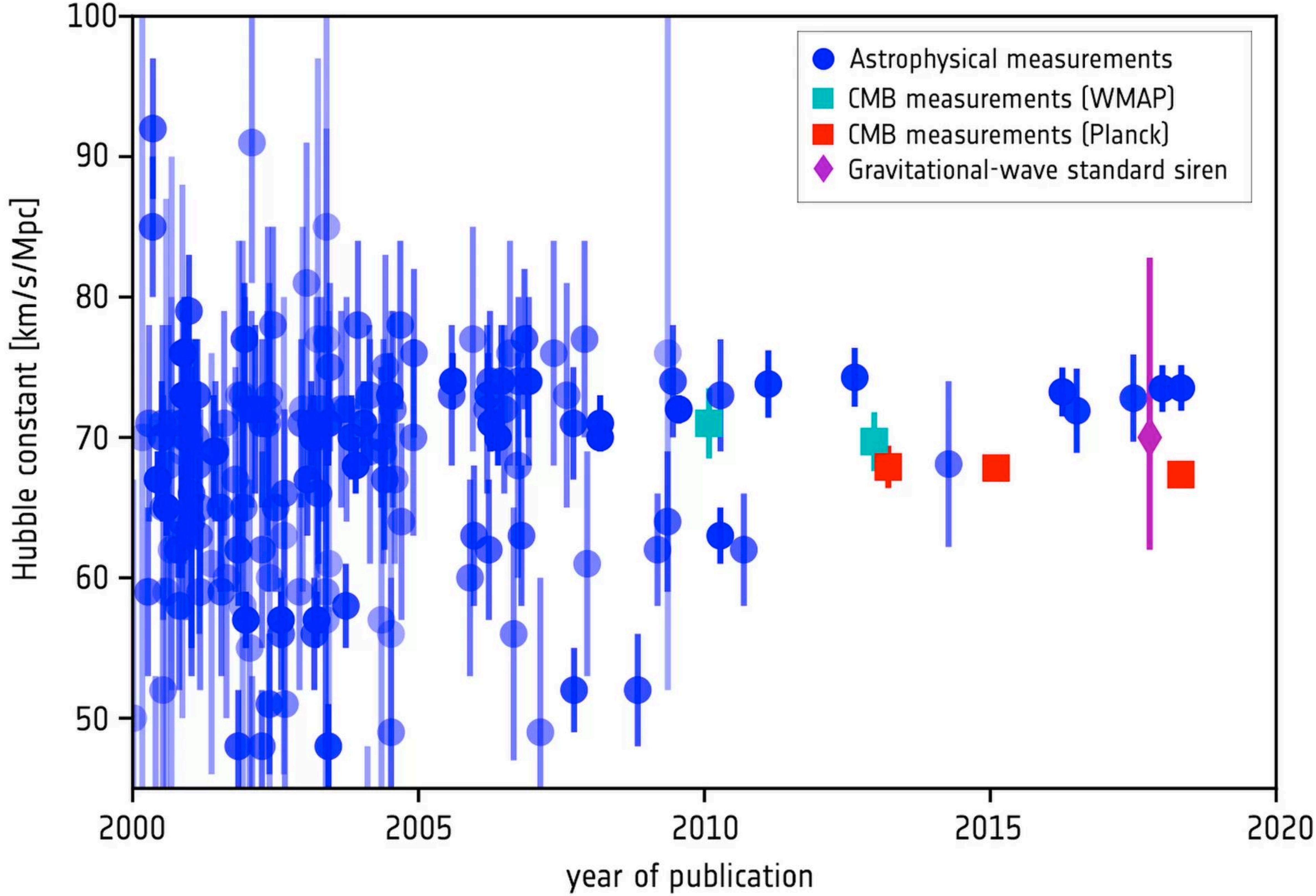
Velocity (km/s)
25000
20000
15000
10000
5000
0
0
100
200
300
Distance (Mpc)
83
75
67

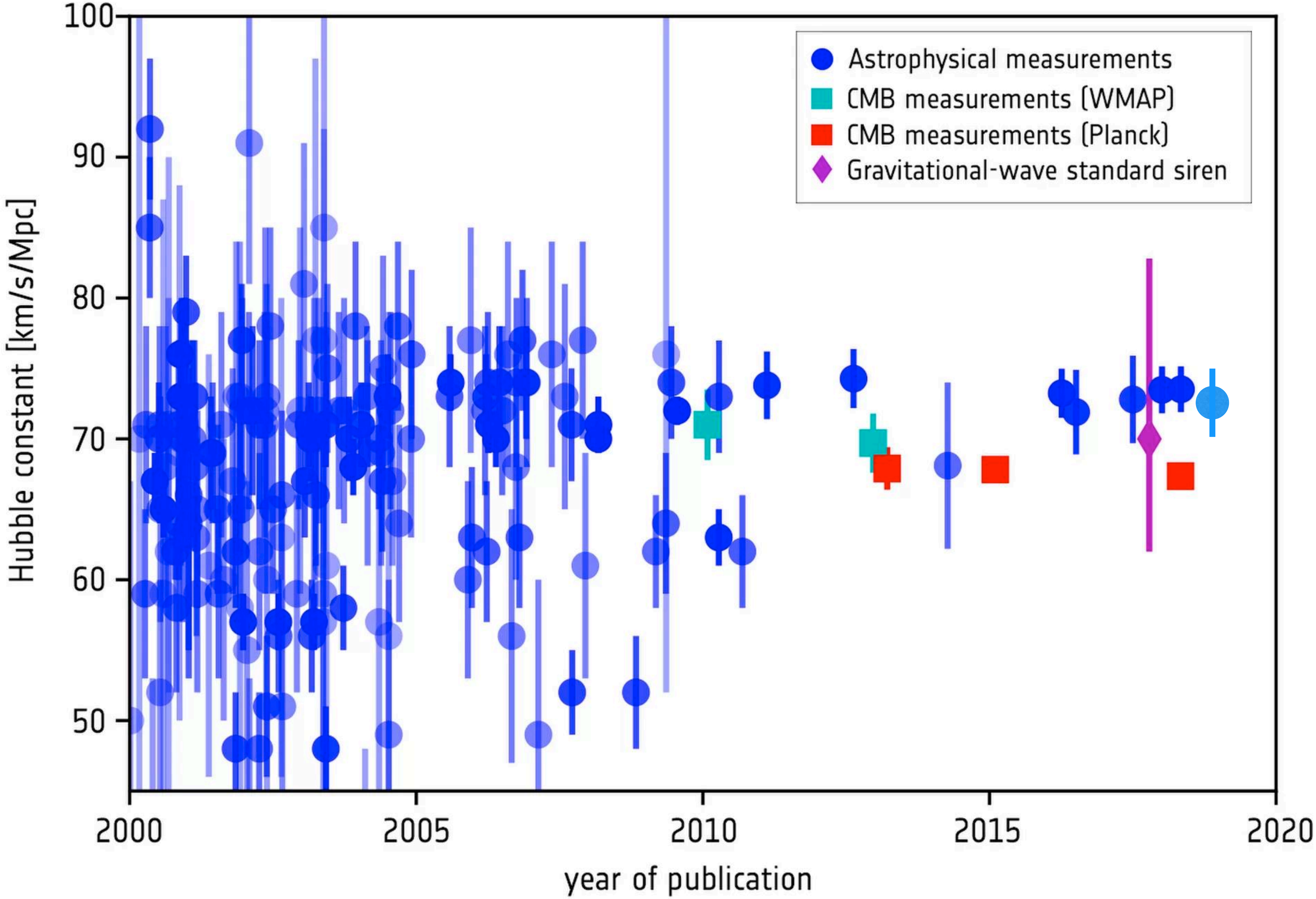

25000
20000
15000
10000
5000
0
Velocity (km/s)
0
100
200
300
Distance (Mpc)


75
73
71
25000
20000
15000
10000
5000
0
Velocity (km/s)
0
100
200
300
Distance (Mpc)

Host Mass Effect




Astrophysical measurements
CMB measurements (WMAP)
CMB measurements (Planck)
Gravitational-wave standard siren
Hubble constant [km/s/Mpc]
100
90
80
70
60
50
2000
2005
2010
2015
2020
year of publication



100
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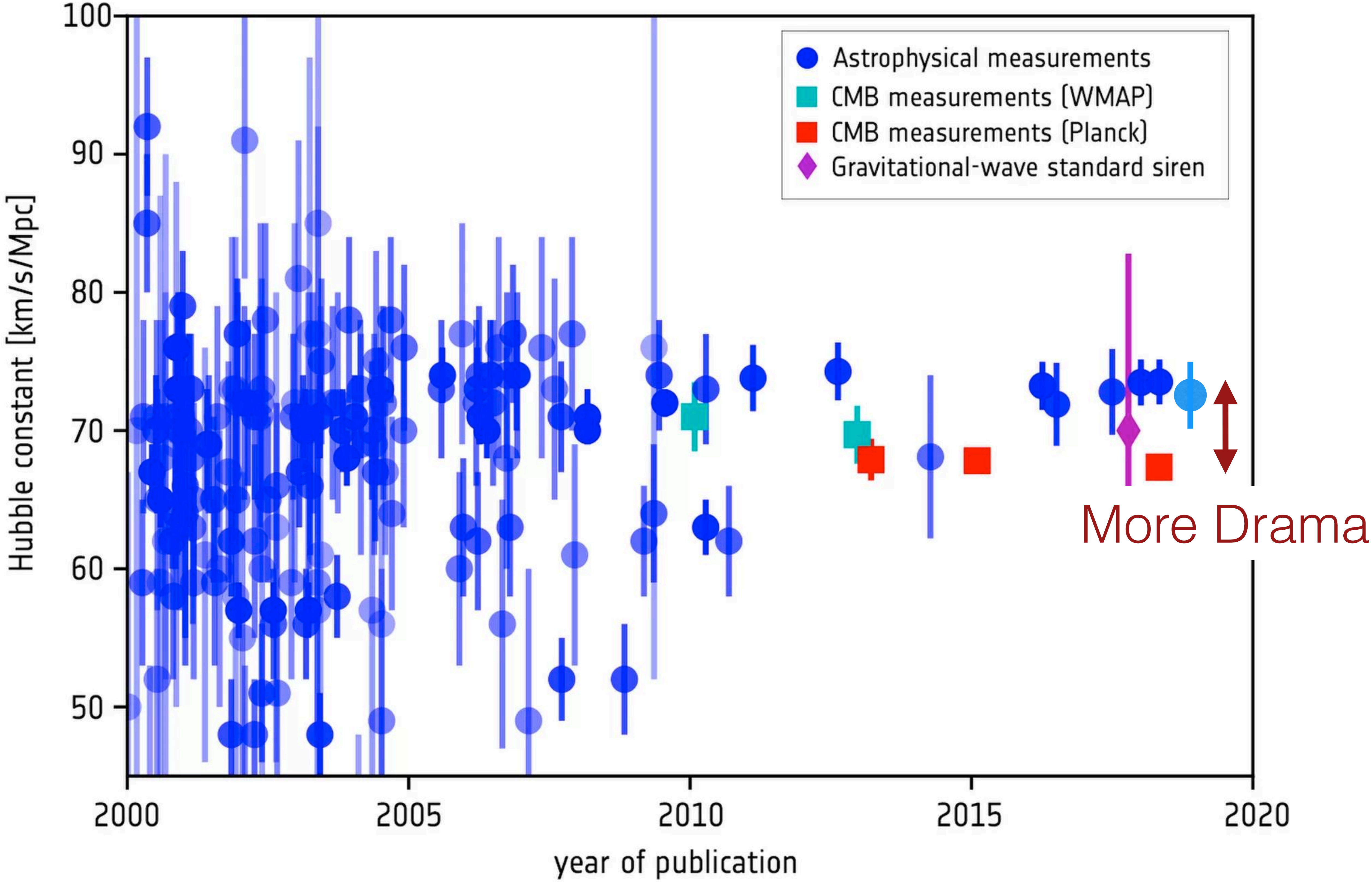
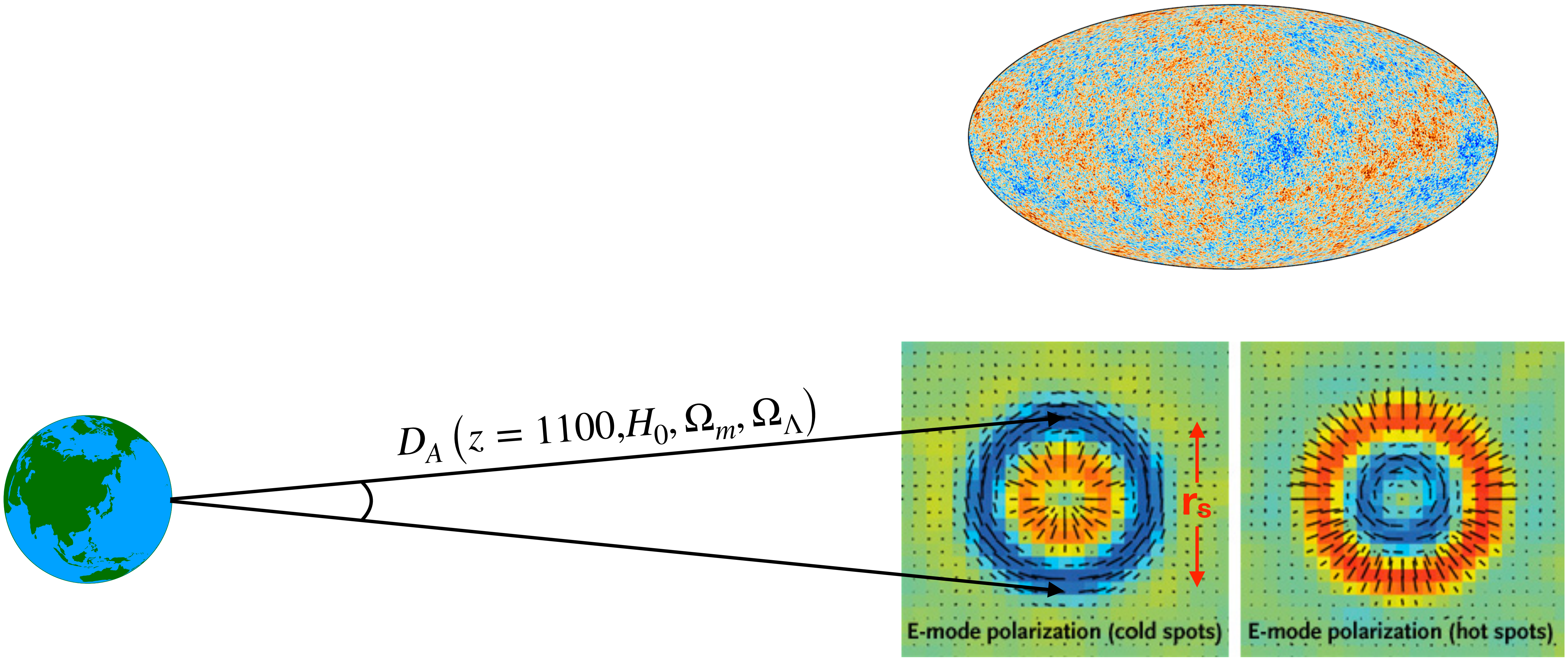


Astrophysical measurements
CMB measurements (WMAP)
CMB measurements (Planck)
Gravitational-wave standard siren
Hubble constant [km/s/Mpc]
100
90
80
70
60
50
2000
2005
2010
2015
2020
year of publication
More Drama

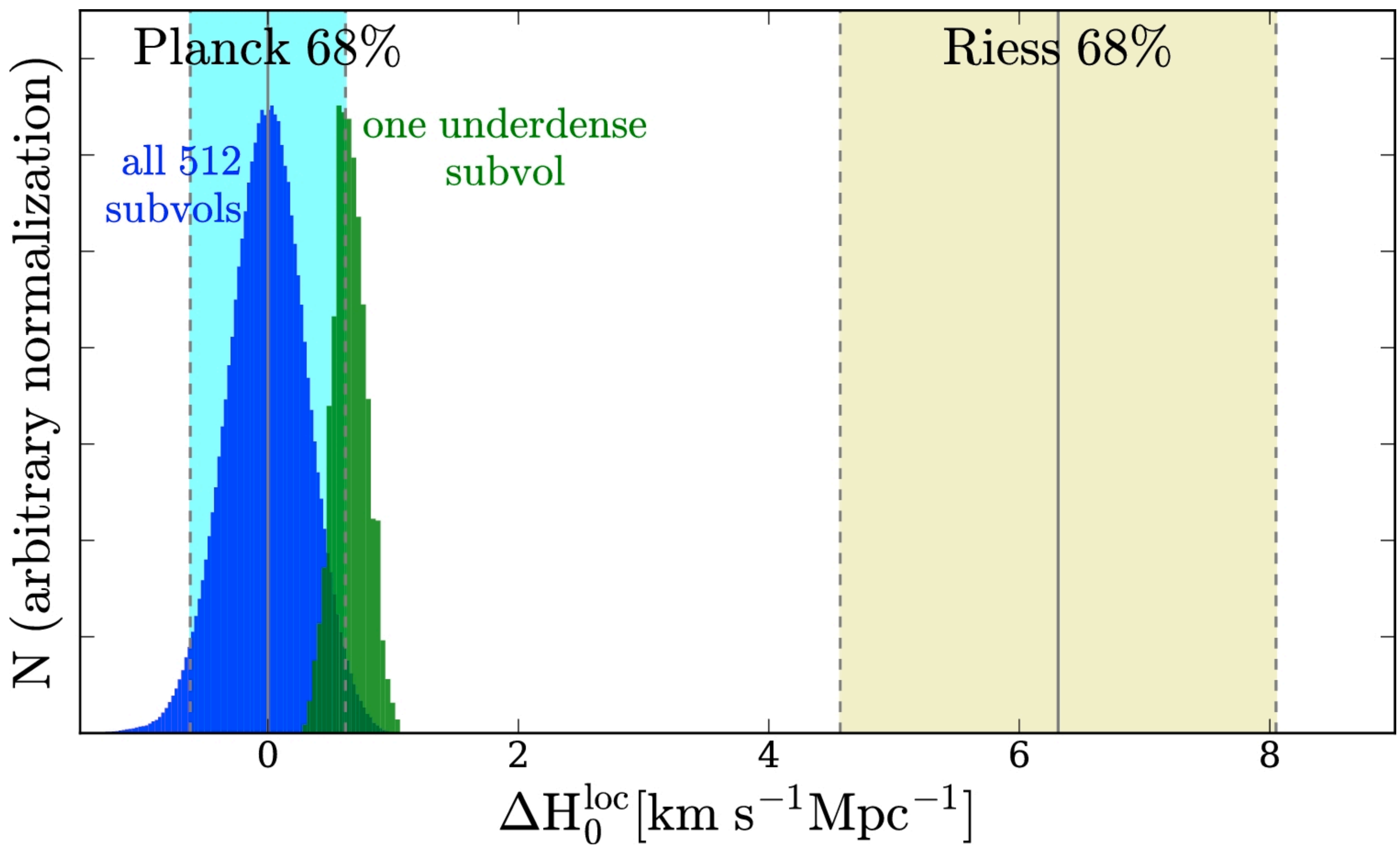
CMB Can also Measure H_o



Resolving the Tension

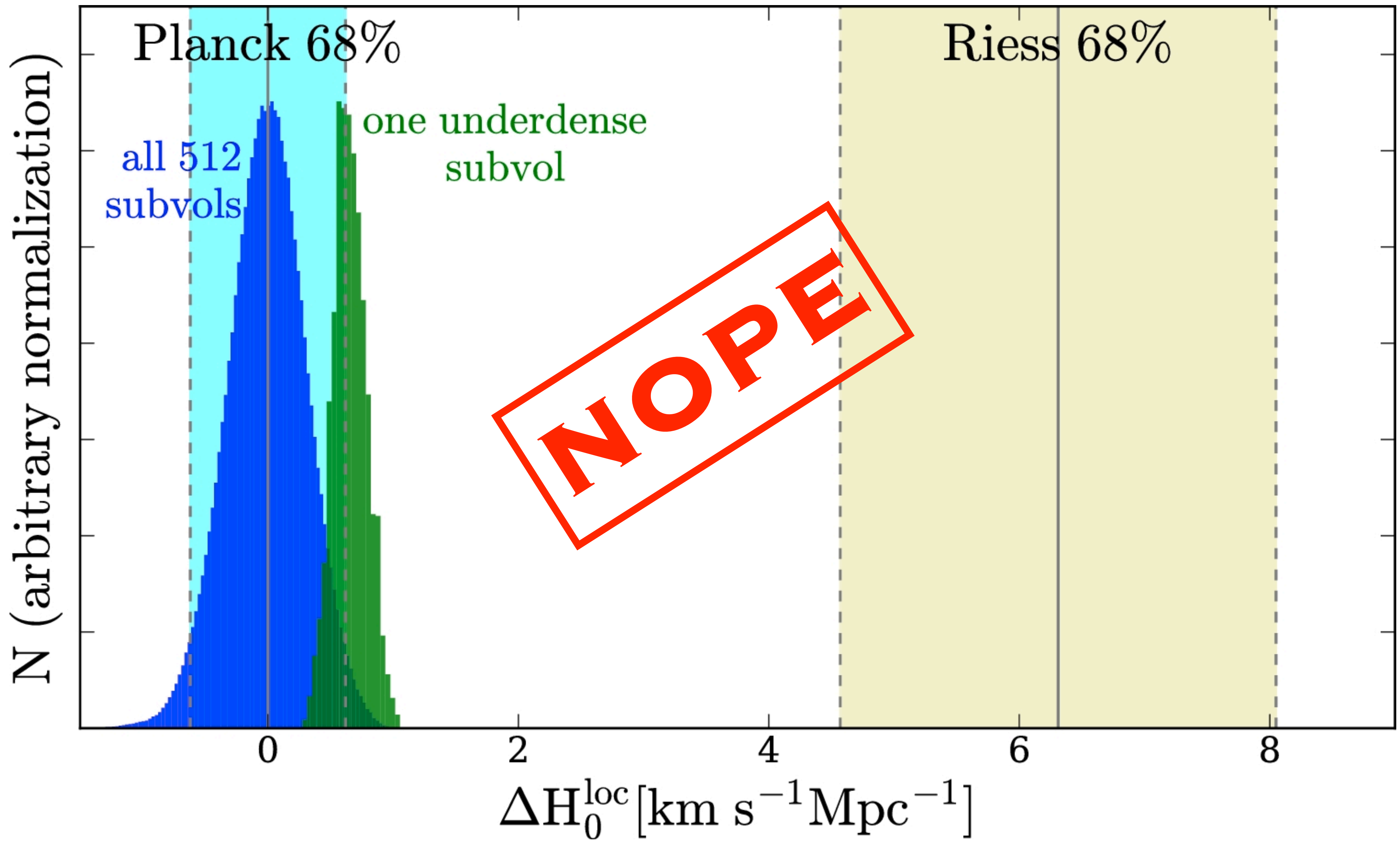
- Problem with the Planck data? Not likely.
- Problem with the SN Ia data? Not likely.
- Living in a local bubble?
- Problem with LCDM?
- Problem with the Cepheid calibration?
- New Physics?

Living in a Bubble?



Wu & Huterer, 2017

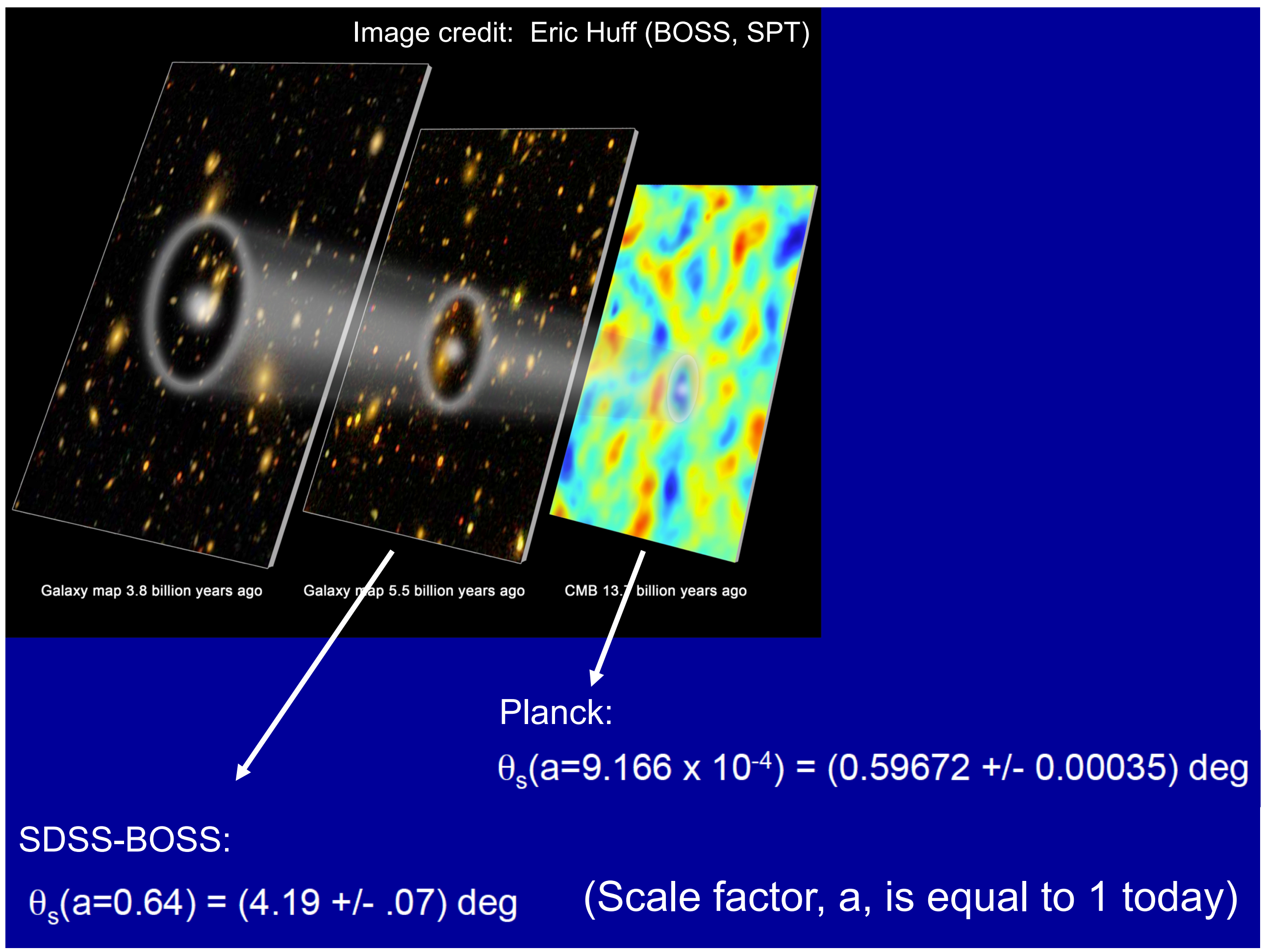
Living in a Bubble?

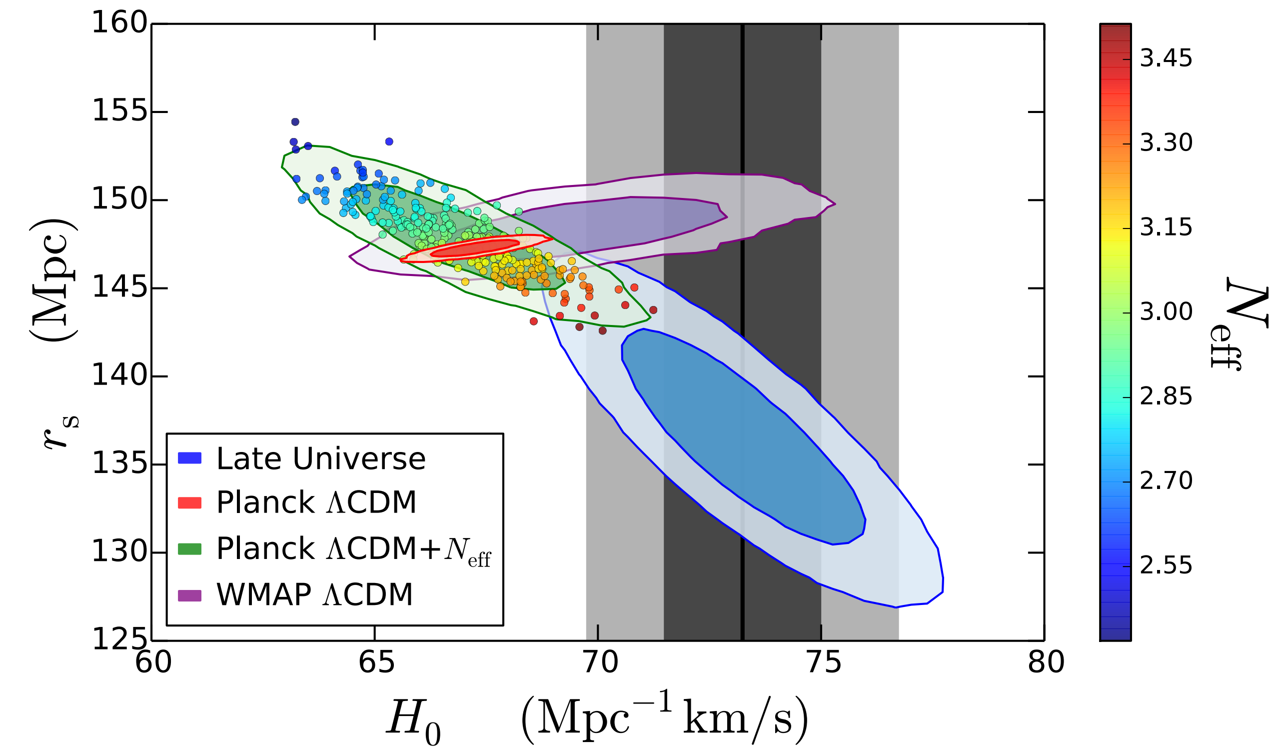


Wu & Huterer, 2017

Could LCDM be the Problem?

Use $D_A(z)$ directly measured by SNe Ia to turn $\theta_S \rightarrow r_s$.





Bernal, Verde, and Riess 2016

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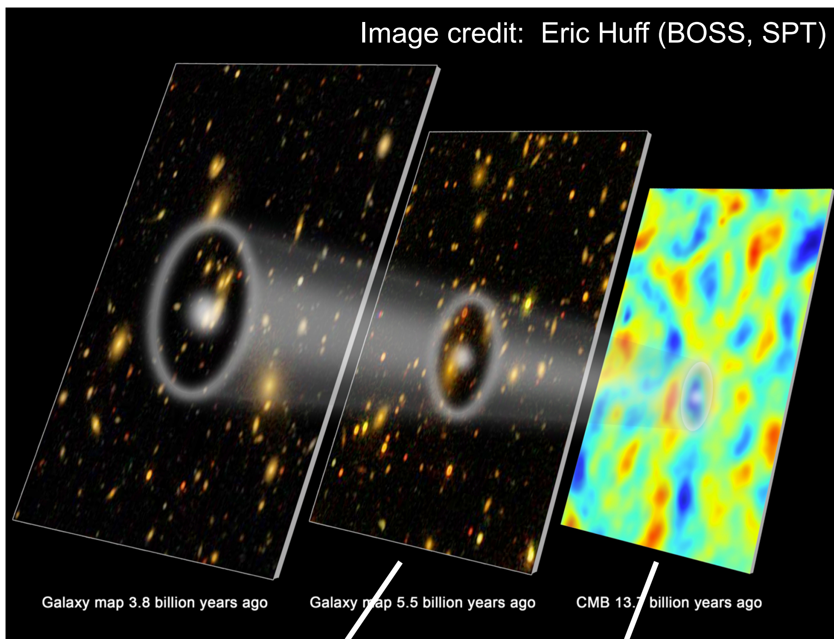
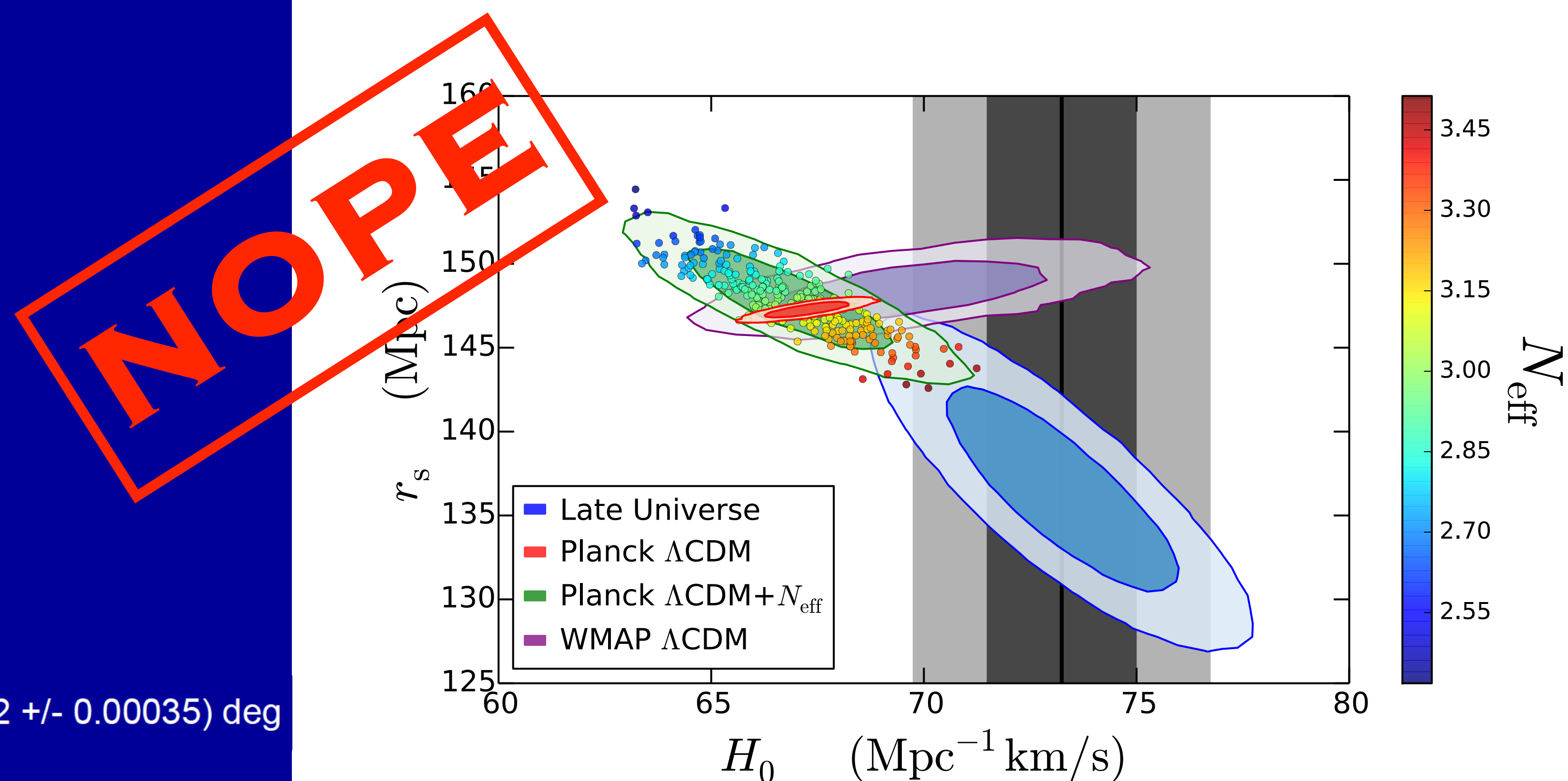


Planck:
$\theta_s(a=9.166 \times 10^{-4}) = (0.59672 \pm 0.00035)$ deg

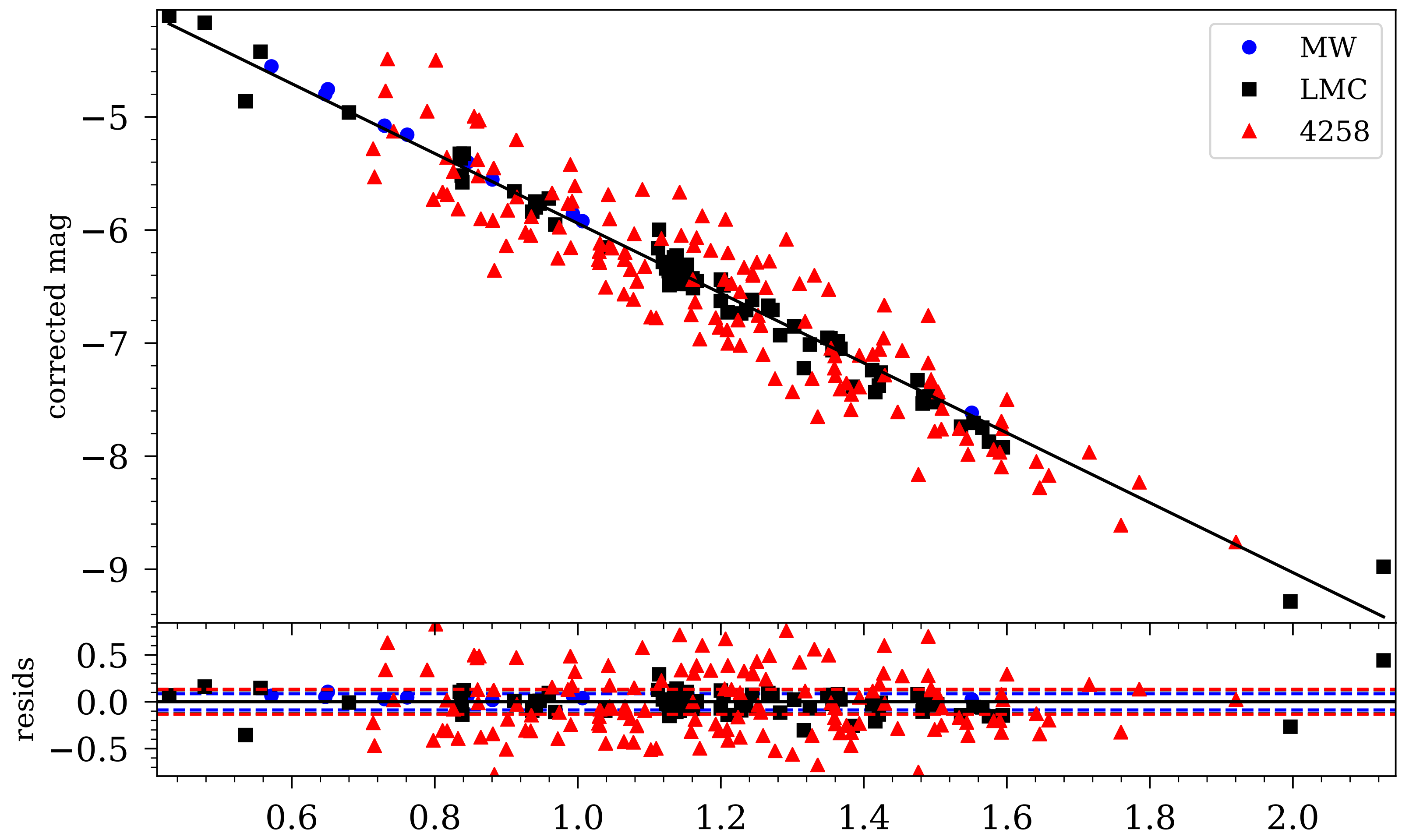
SDSS-BOSS:
$\theta_s(a=0.64) = (4.19 \pm .07)$ deg

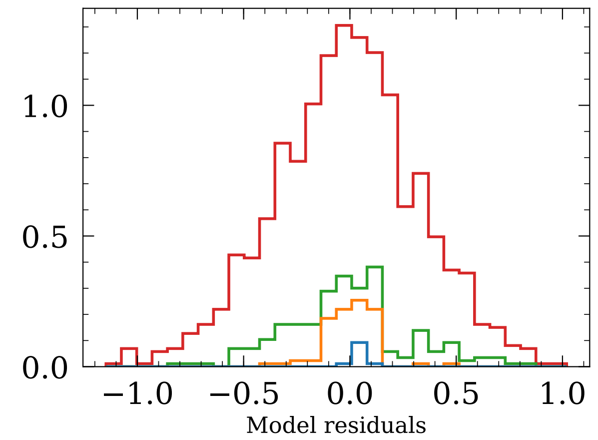
(Scale factor, a, is equal to 1 today)

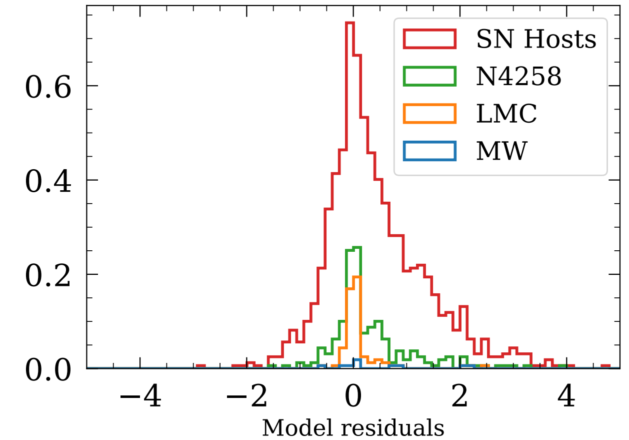


Bernal, Verde, and Riess 2016

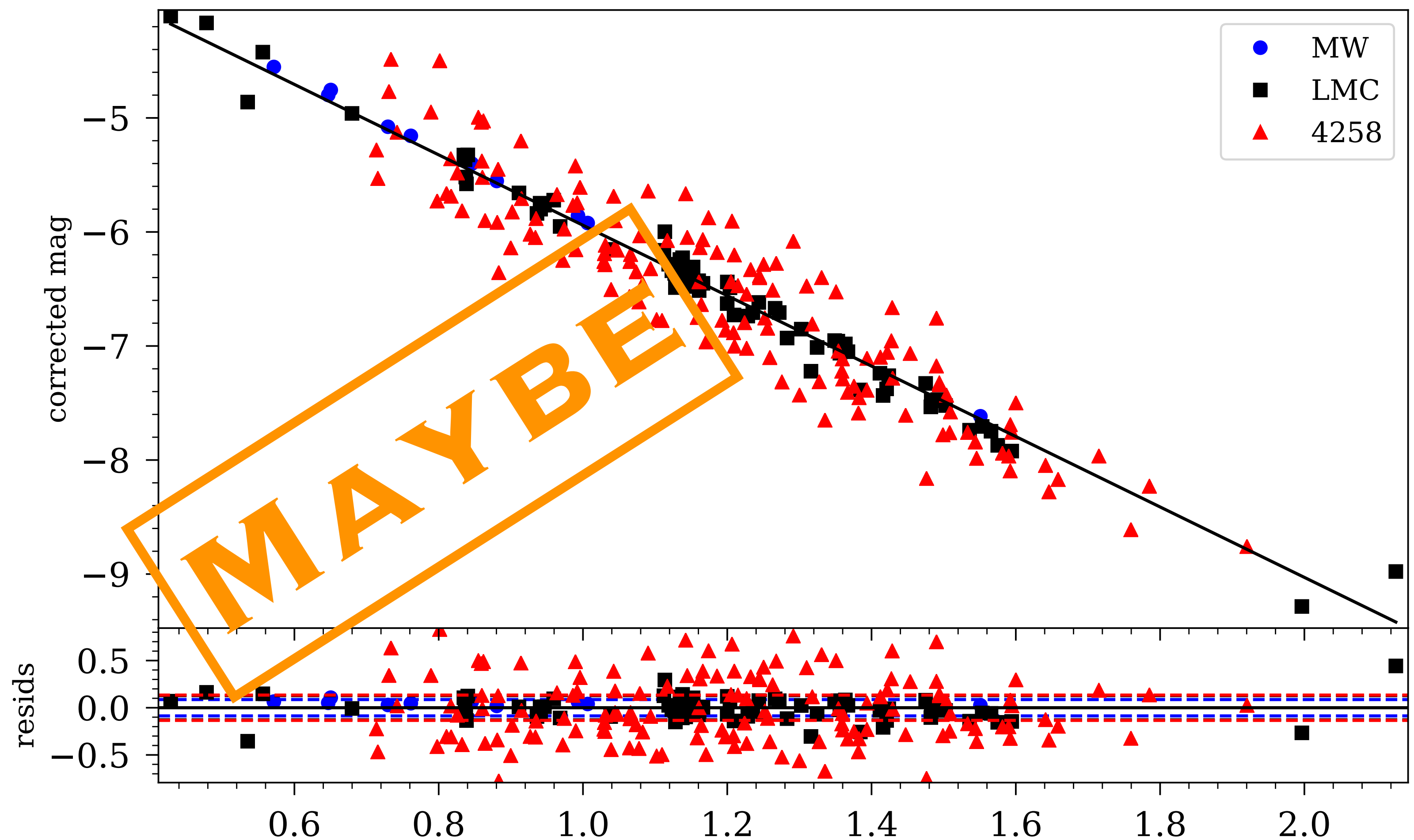
Cepheid Calibration?

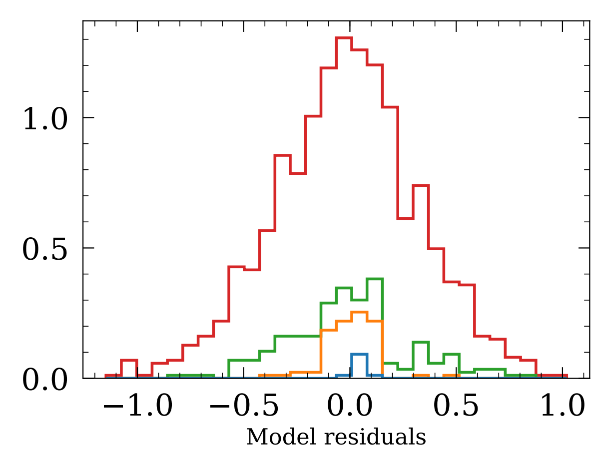


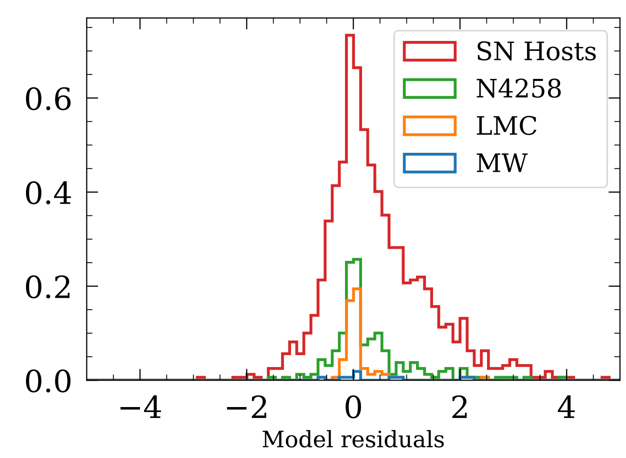




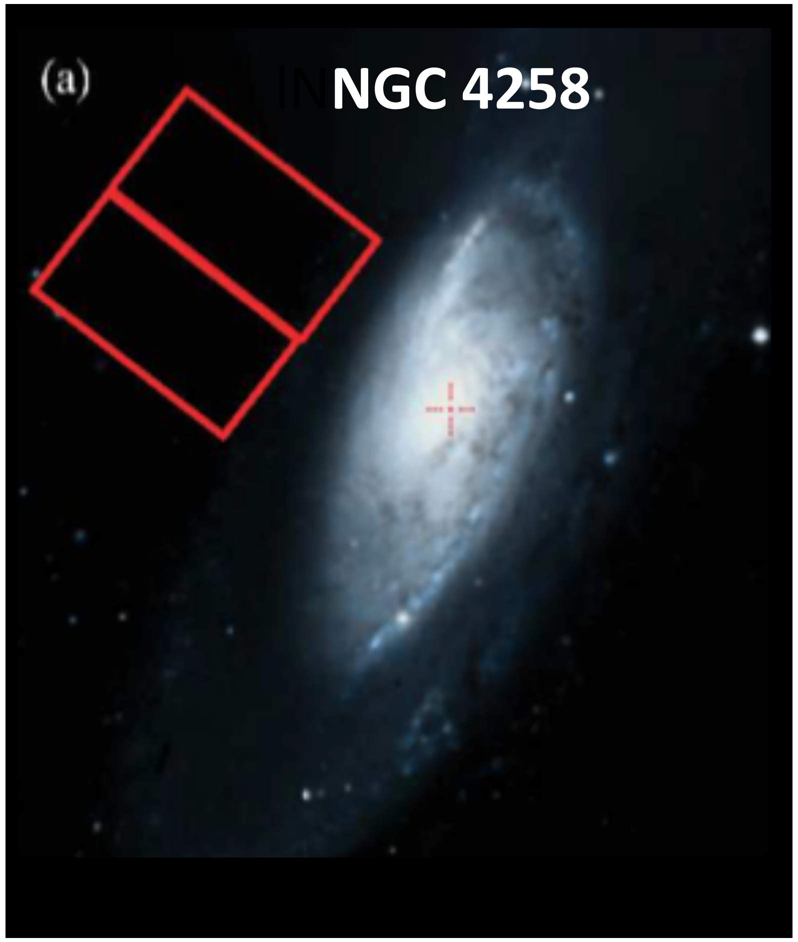
Cepheid Calibration?



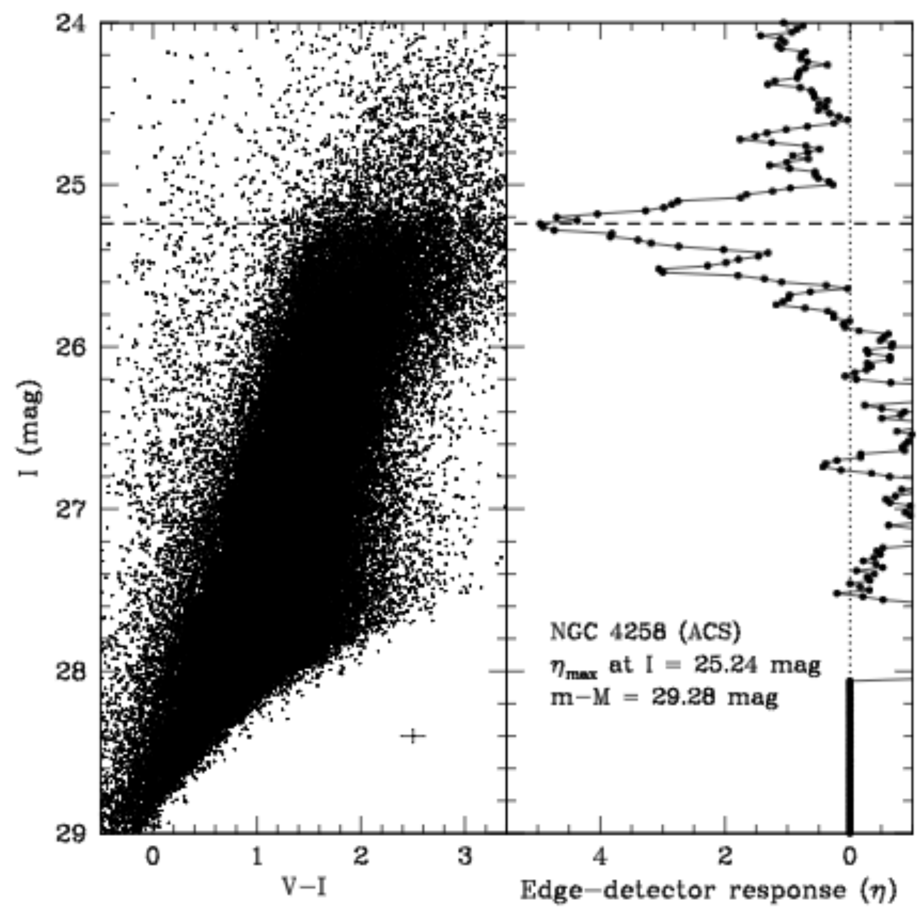




Carnegie Hubble Project

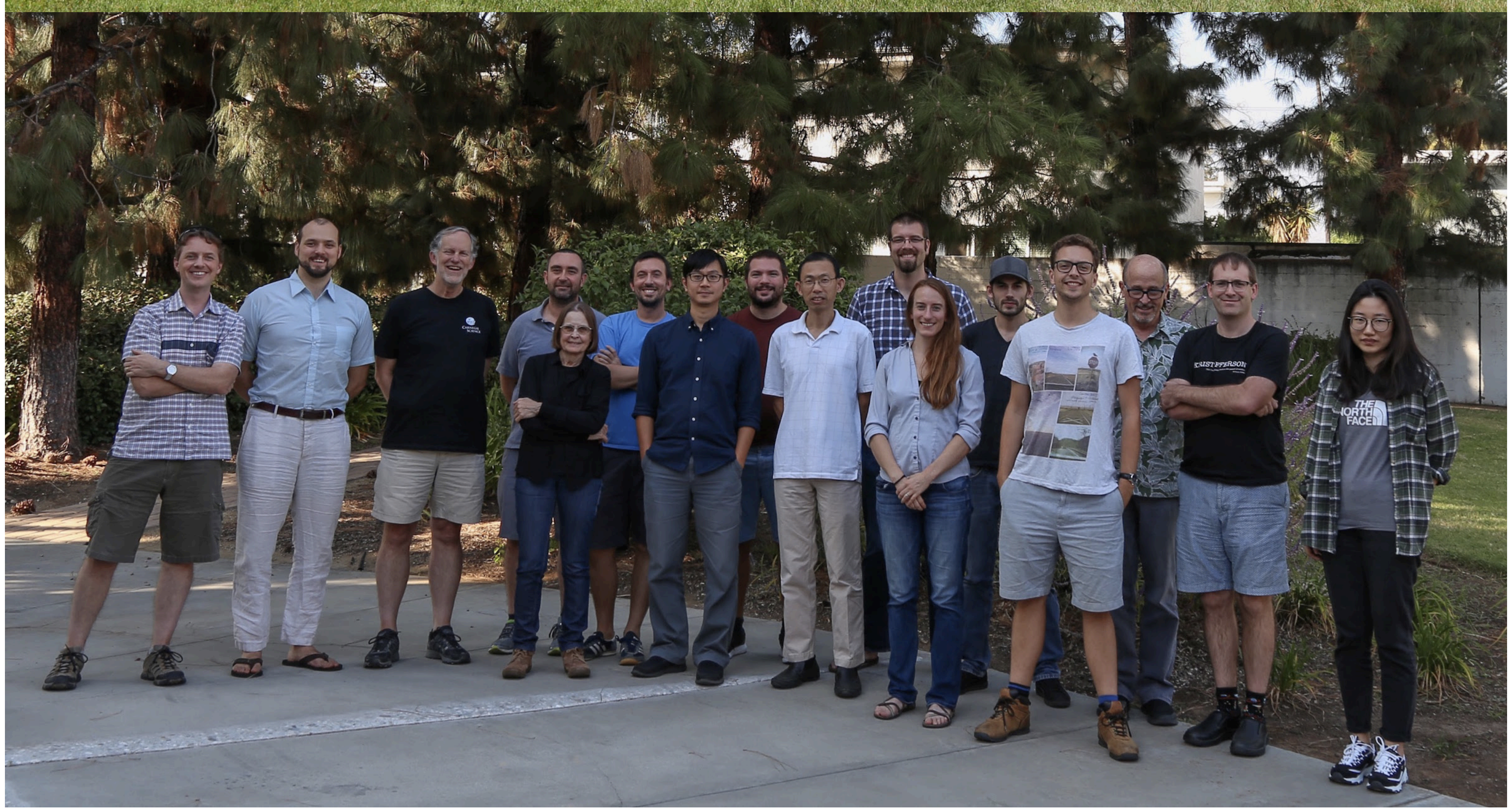


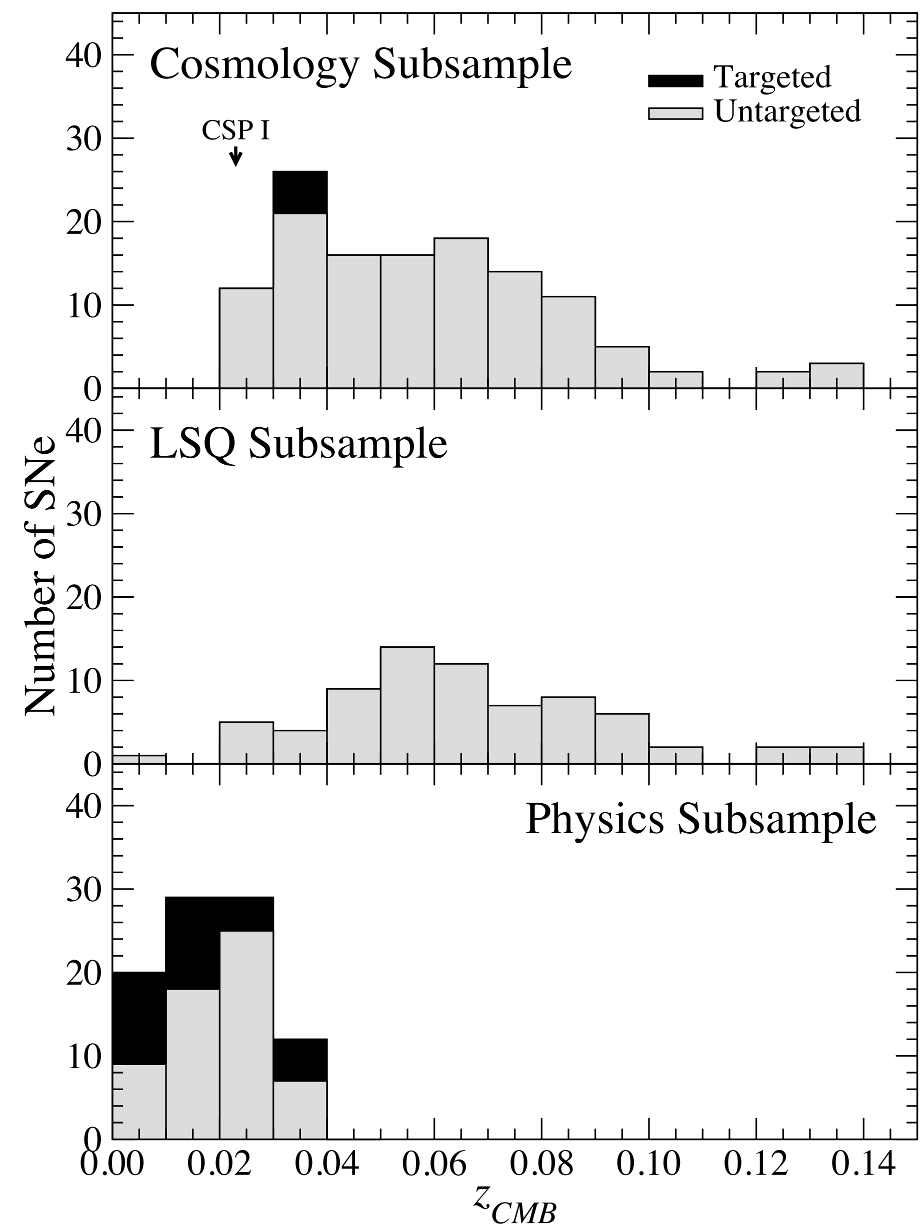
Re-calibrate the SN Ia distance ladder using TRGB, independent of Cepheids.

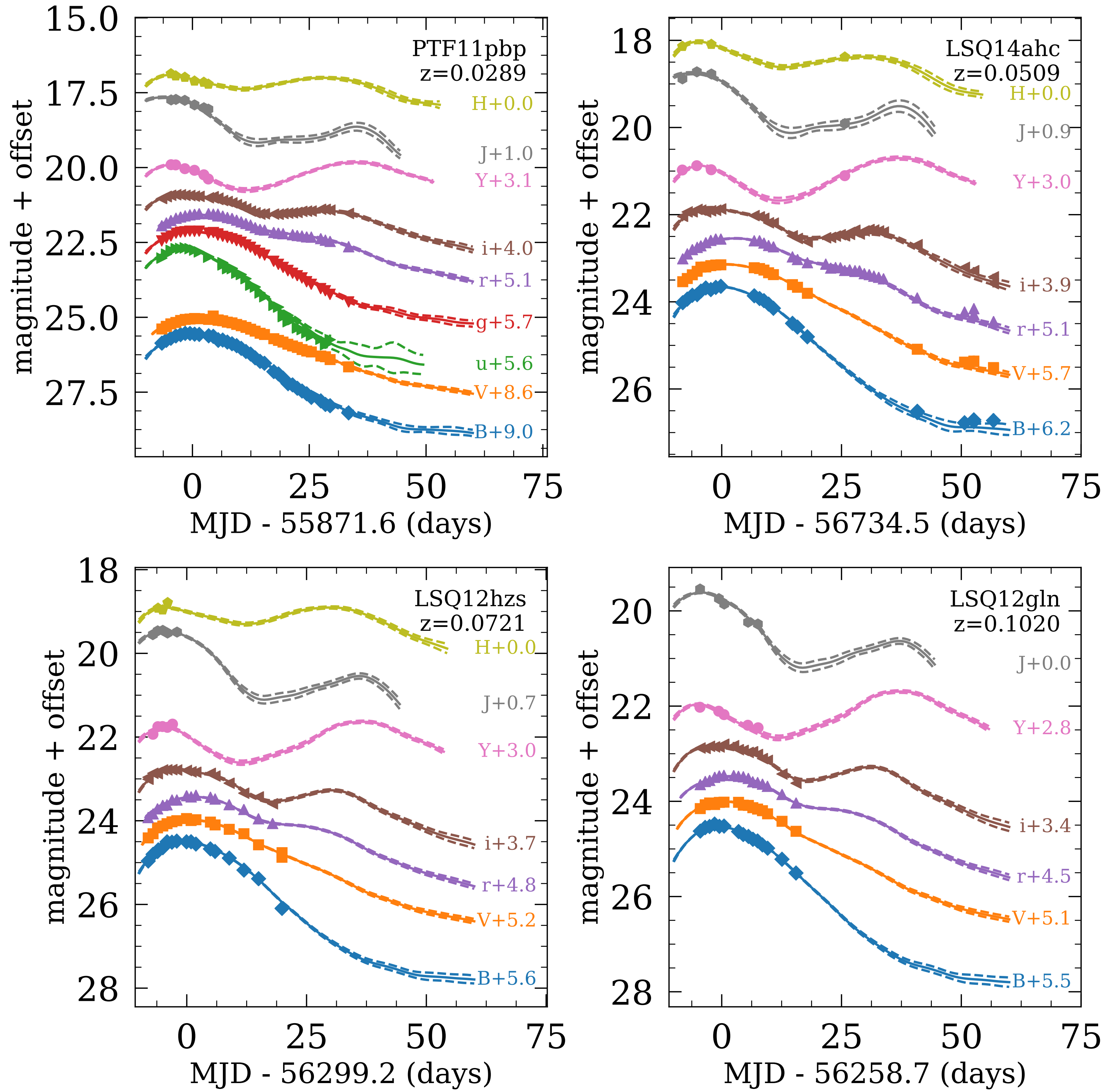


Mager, Madore & Freedman (2008)

CSP-II




Cosmology Subsample
Targeted
Untargeted
CSP I
LSQ Subsample
Physics Subsample
Number of SNe
0
10
20
30
40
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
z_{CMB}



PTF11pbp
z=0.0289
H+0.0
J+1.0
Y+3.1
i+4.0
r+5.1
g+5.7
u+5.6
V+8.6
B+9.0
magnitude + offset
MJD - 55871.6 (days)
LSQ14ahc
z=0.0509
H+0.0
J+0.9
Y+3.0
i+3.9
r+5.1
V+5.7
B+6.2
MJD - 56734.5 (days)
LSQ12hzs
z=0.0721
H+0.0
J+0.7
Y+3.0
i+3.7
r+4.8
V+5.2
B+5.6
MJD - 56299.2 (days)
LSQ12gln
z=0.1020
J+0.0
Y+2.8
i+3.4
r+4.5
V+5.1
B+5.5
MJD - 56258.7 (days)