# The Surface Brightness Fluctuation Distance Ladders


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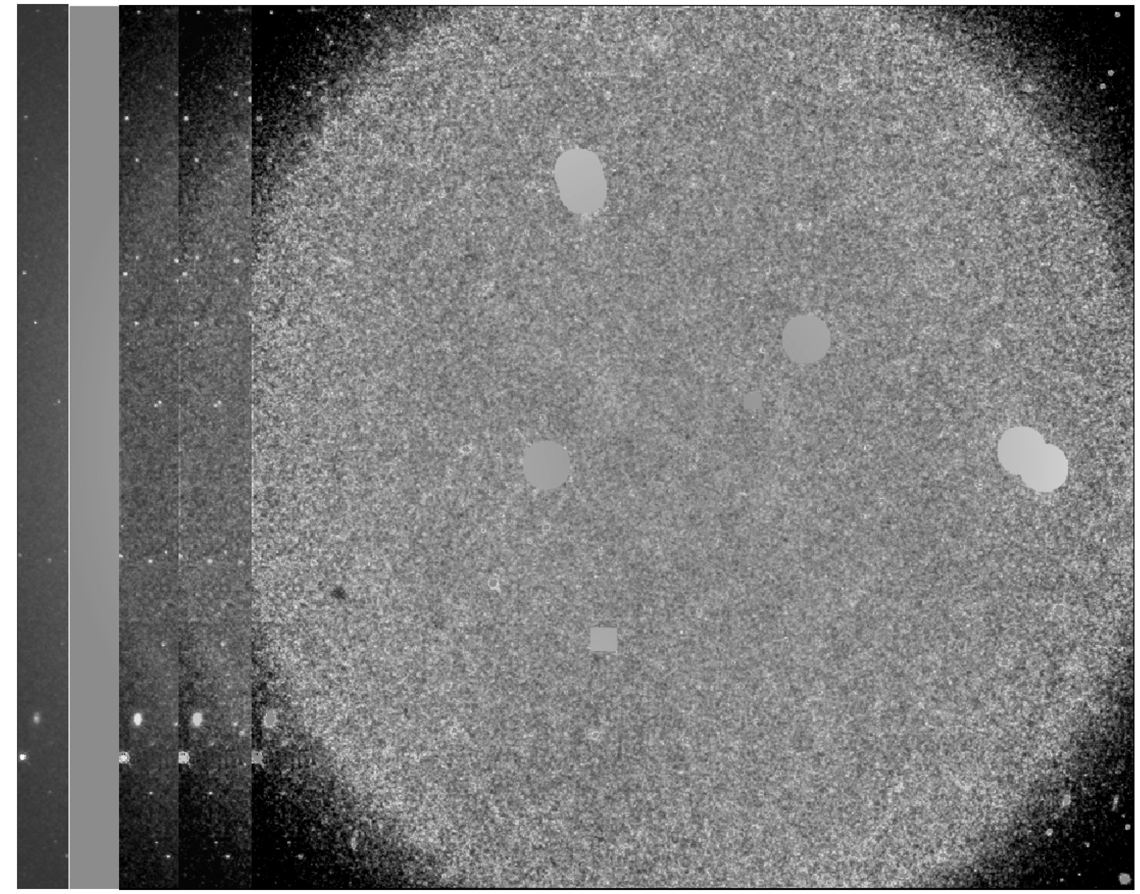
# Talk Overview

1. SBF review & calibration for WFC3/IR
2. Distance to GW170817 host NGC 4339
3. MASSIVE Survey Distances
4. Supernova host galaxies
5. The Hubble Constant
6. Cepheid-independent SBF calibrations
7. Future of IR SBF

# *IR SBF in M32 (Gemini)*

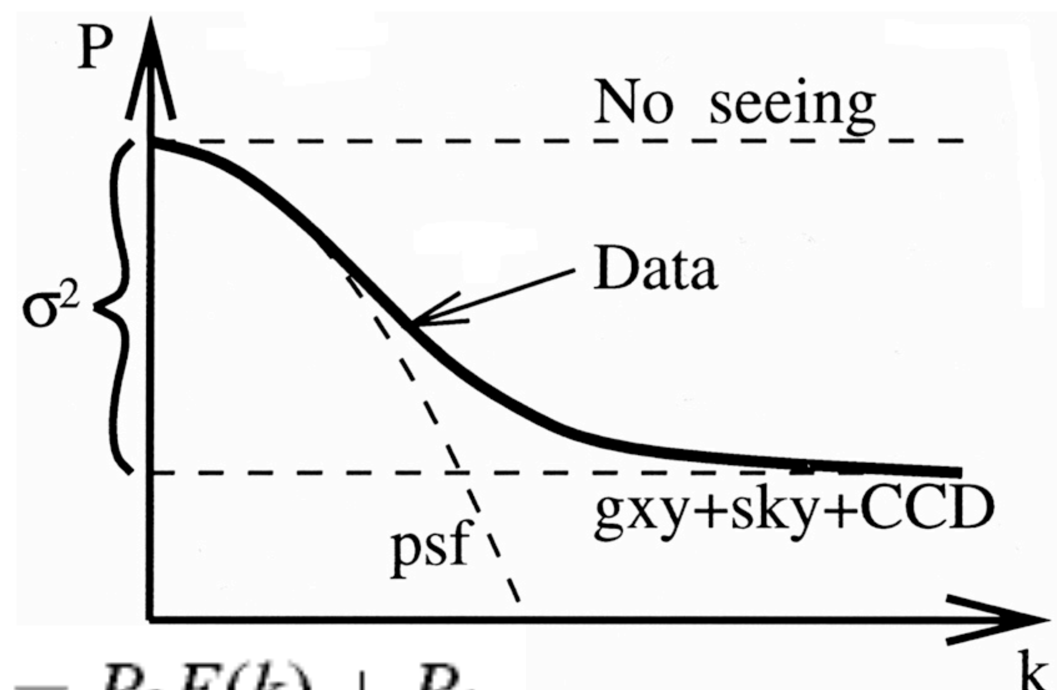
# How it works



**Ratio of 2nd & 1st moments of stellar luminosity function (LF)**

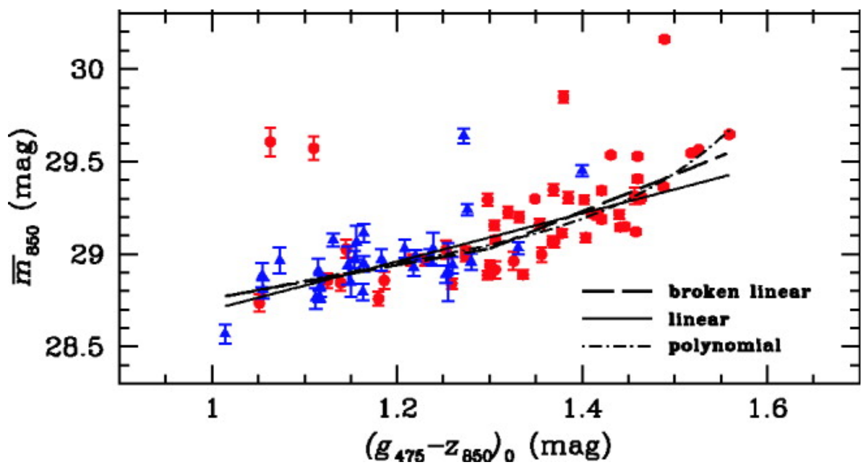
$$f_{SBF} \equiv \sum_i n_i f_i^2 / \sum_i n_i f_i$$

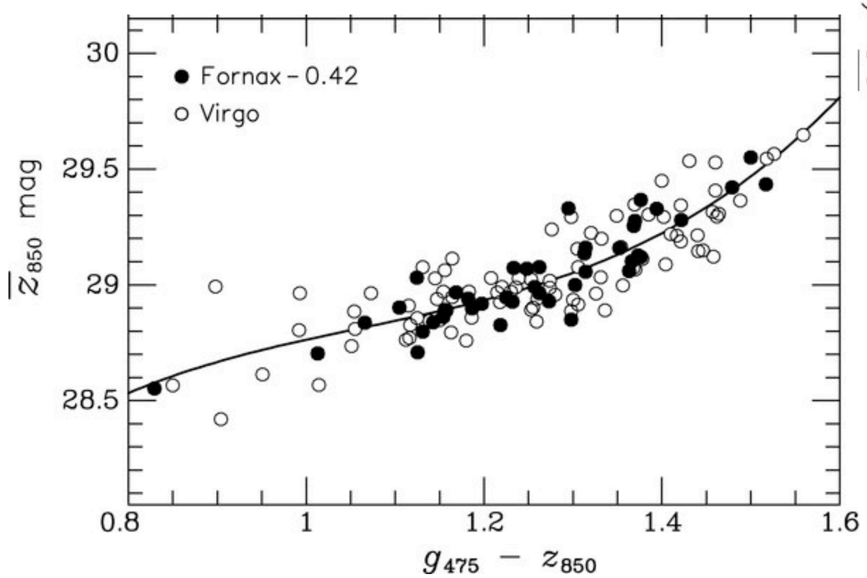
1. Model the galaxy
2. Subtract galaxy model & normalize.
3. Mask background galaxies and globular clusters
4. Measure the amplitude of the fluctuations in the Fourier domain
5. Subtract the contribution from undetected, unmasked sources

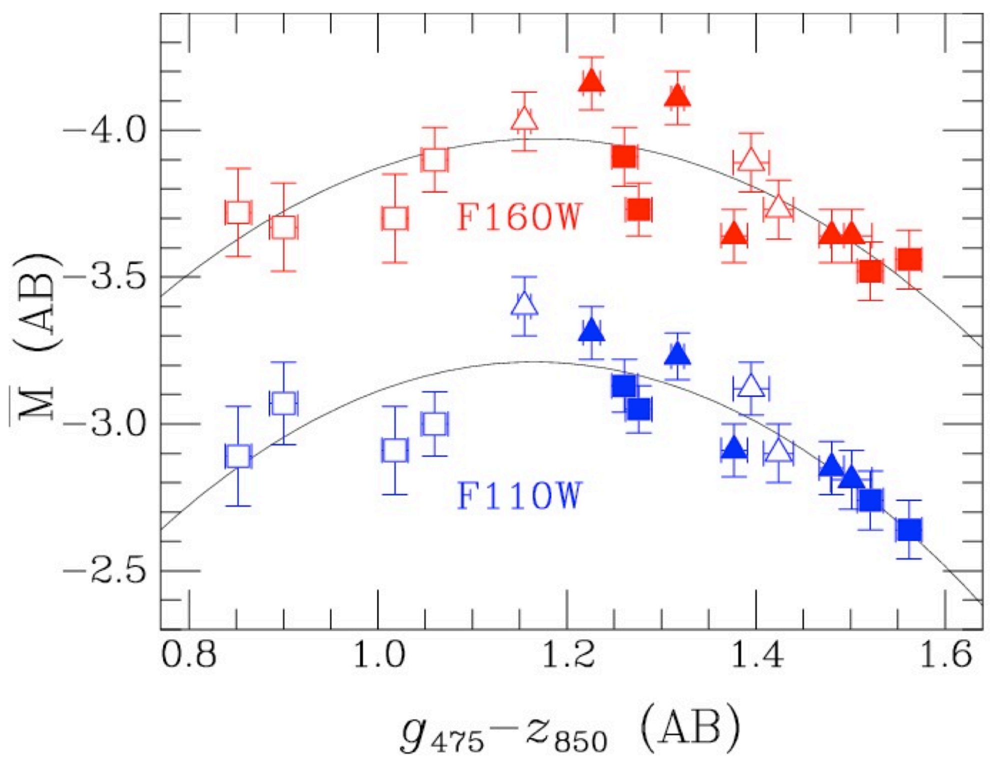


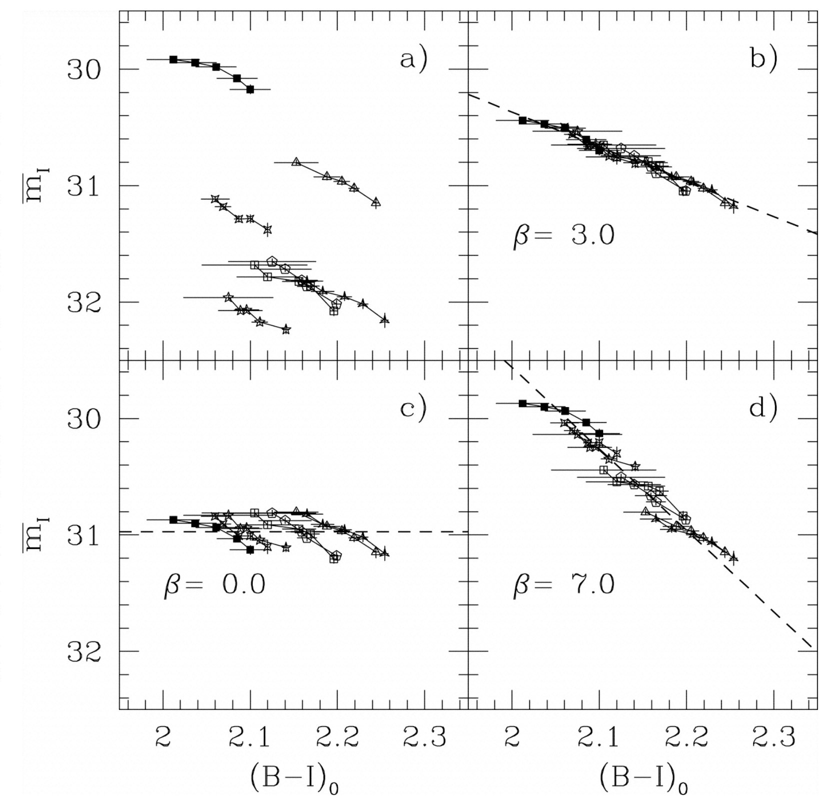

$$P(k) = P_0 E(k) + P_1,$$

# *Empirical Calibrations*



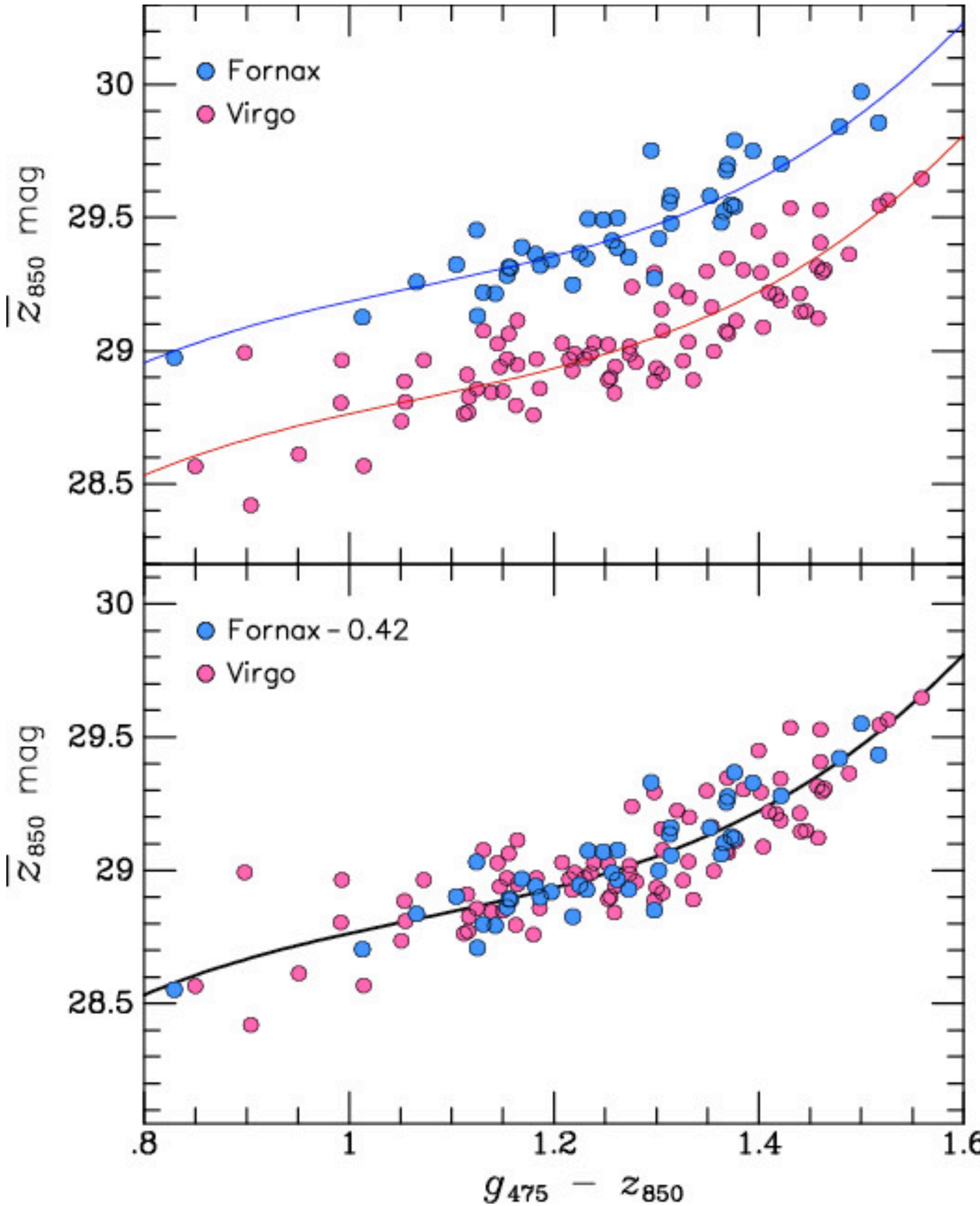




- $M_{V,\,SBF} = (0.83 \pm 0.12) + (5.3 \pm 0.8)\,[(V - I) - 1.15]$ (Blakeslee+ 2001, PLZ corrected)
- $M_{I,\,SBF} = (-1.68 \pm 0.08) + (4.5 \pm 0.25)[(V - I) - 1.15]$ (Tonry+ 2001, PLZ corrected)
- $M_{I,\,SBF} = (-1.6 \pm 0.1) + (3.0 \pm 0.3)[(B - I) - 2.0]$ (ACS, SBF gradients, Cantiello+ 2005)
- $M_{z,\,SBF} = -2.04+1.41x+2.60x^2+3.72x^3$, $x \equiv (g - z) - 1.94$ (ACSVCS, Blakeslee+ 2009)
- $M_{H,\,SBF} = -5.17 + 0.70x + 2.90x^2$, $x \equiv (g - z) - 1.4$ (HST/WFC3, Jensen+ 2015)
- $M_{i,\,SBF} = -(0.93 \pm 0.04) + (1.09 \pm 0.04)\,[(u^* - z) - 2.50]$ (NGVS, Cantiello+18)

# SBF Results from ACS Fornax + Virgo Surveys

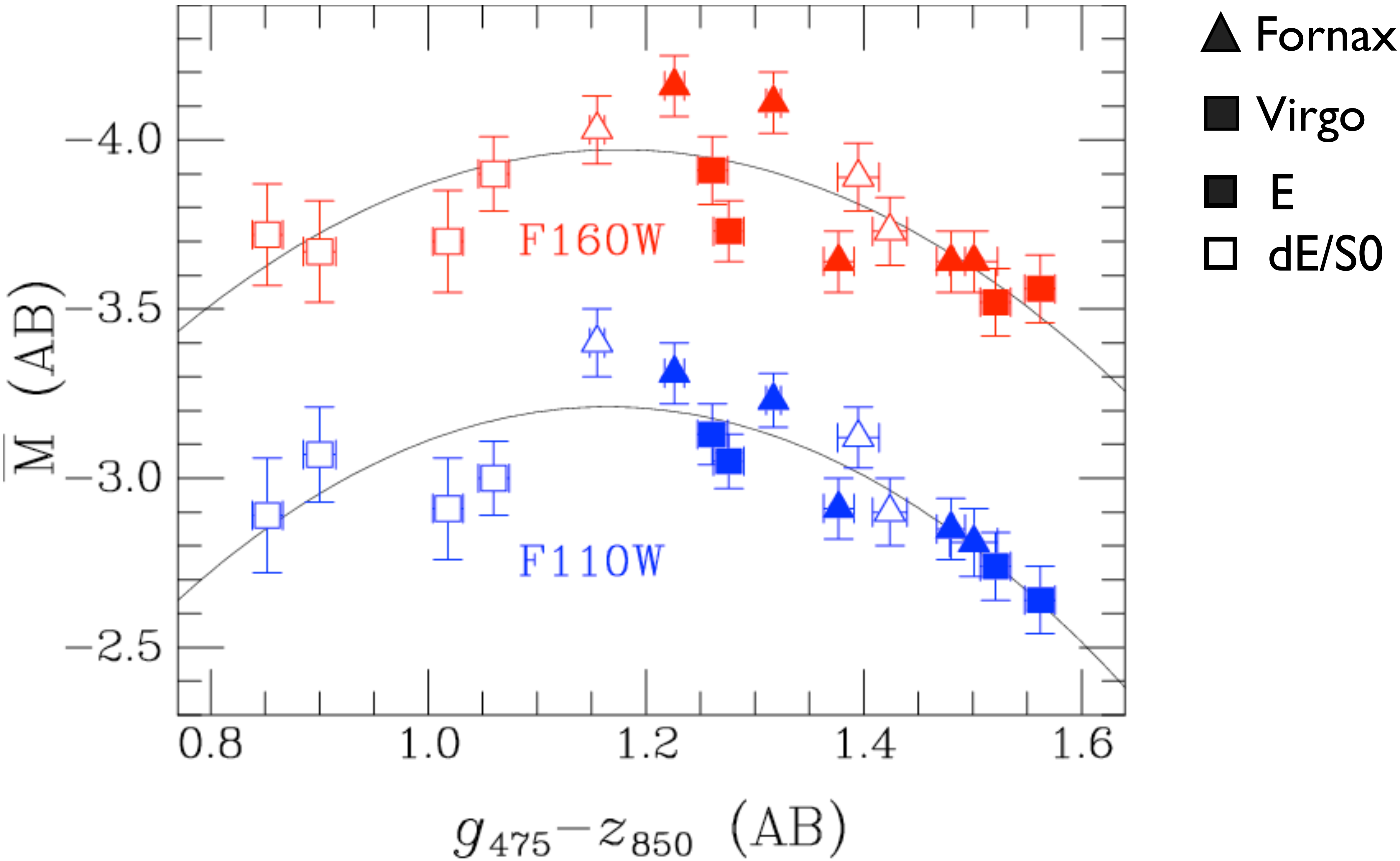



Fornax cluster 21±1% more distant than Virgo cluster.

intrinsic scatter $\sigma$ = 0.06 mag (for g-z > 1.0)

Blakeslee, Jordan, Mei+ 2009

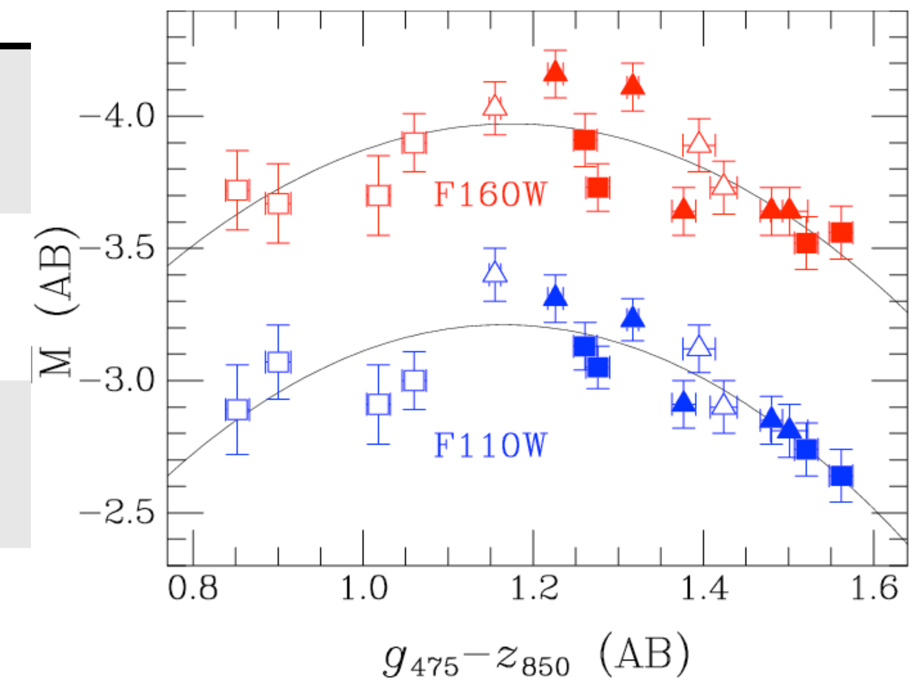
# WFC3/IR SBF Calibrations




Jensen, Blakeslee+ 2015

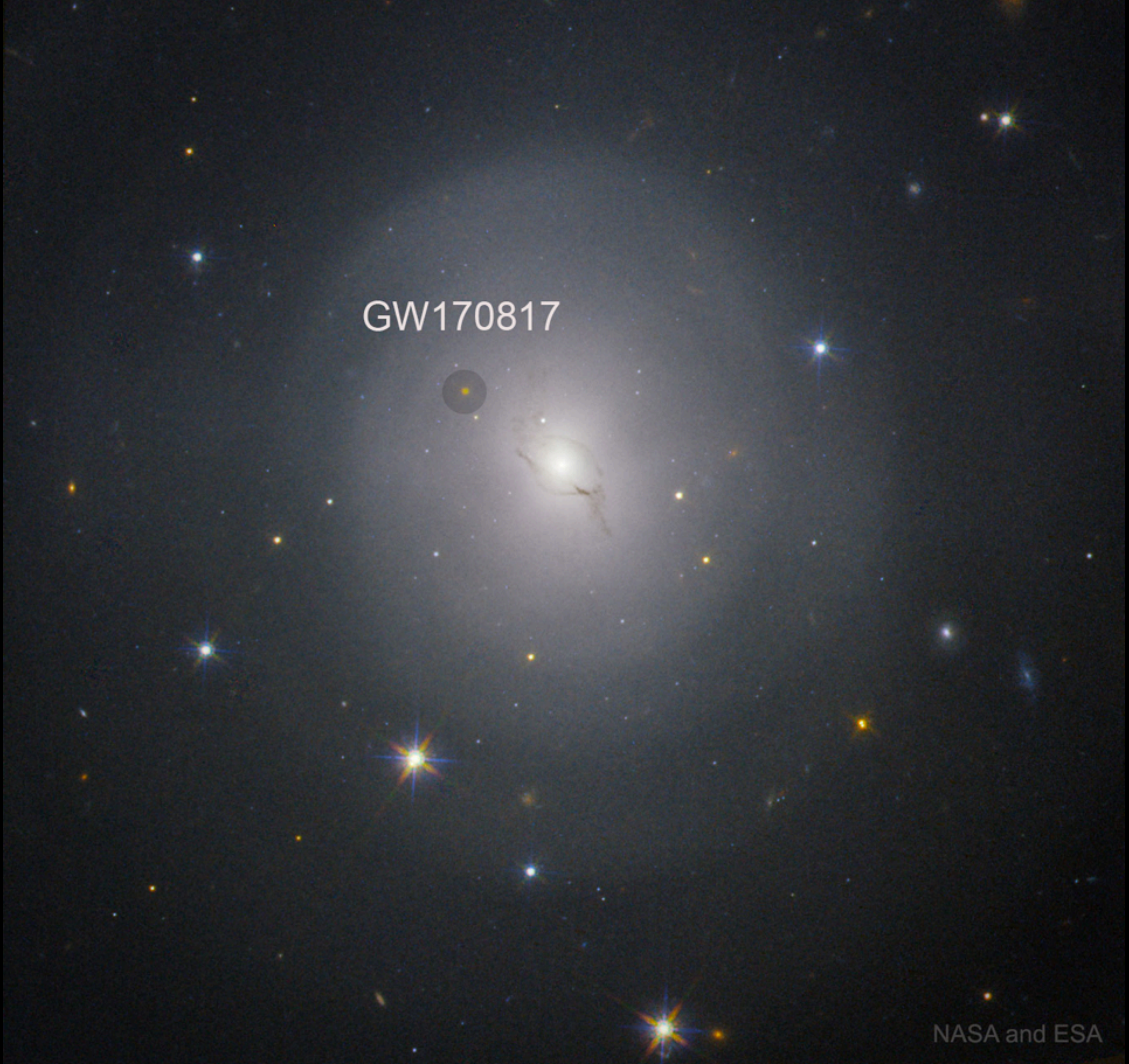
# Typical WFC3/F110W SBF Error Budget

| Source | sigma |
|---|---|
| PSF normalization | 0.02 mag |
| Sky background | 0.02 mag |
| External sources fit (GC+gal) | 0.01-0.03 mag |
| Total SBF power spectrum fit | 0.06 mag |
| (g-z) color from PanSTARRS + extinction uncertainty | 0.03 mag |
| Calibration rms scatter | 0.075 mag |
| Total distance uncertainty (random) | ~ 0.11 mag (5%-6% in distance) |



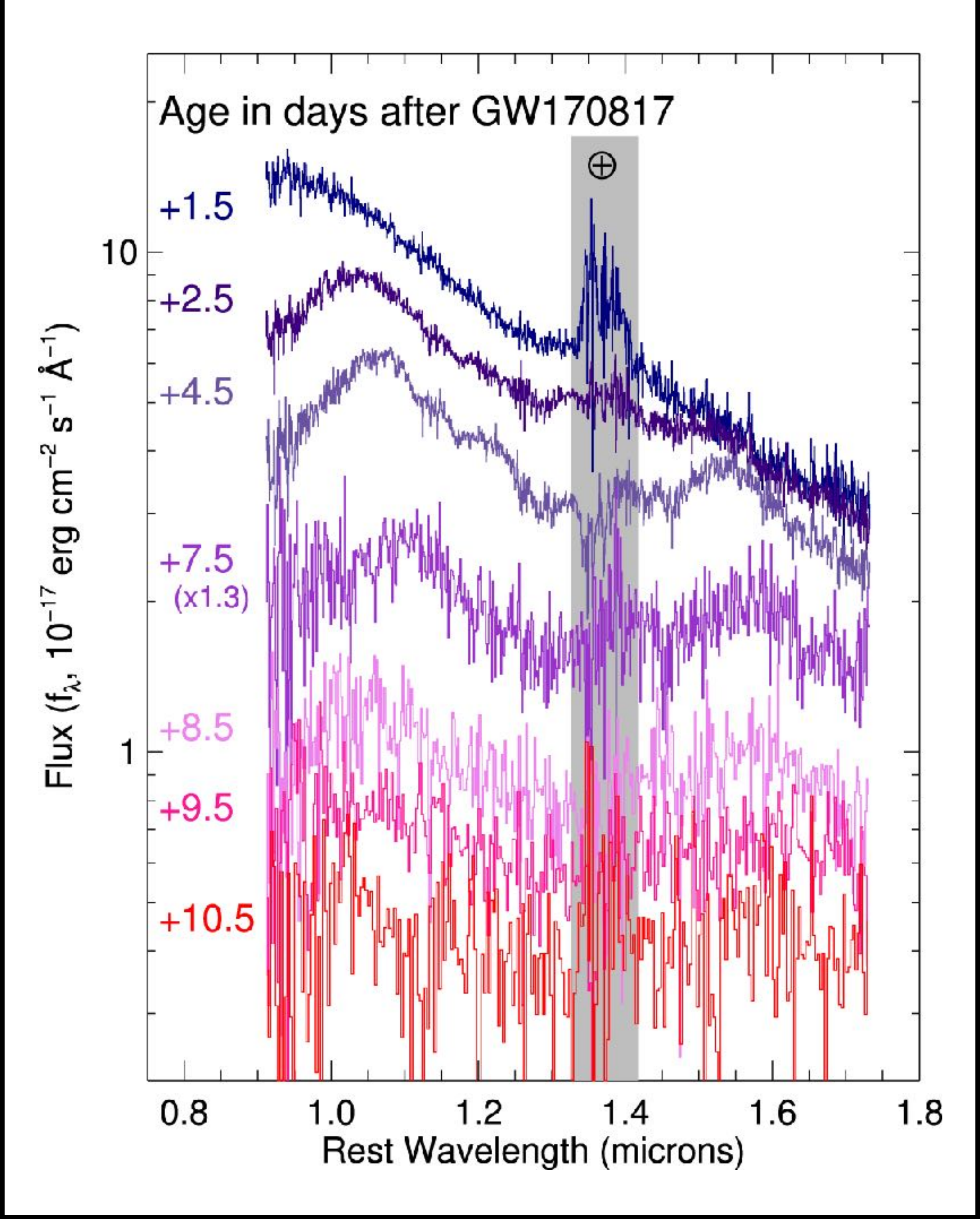

**Zero point uncertainty is similar, about 0.10 mag.**

# GW170817 in NGC 4993



# EM follow-up of GW170817 hypernova

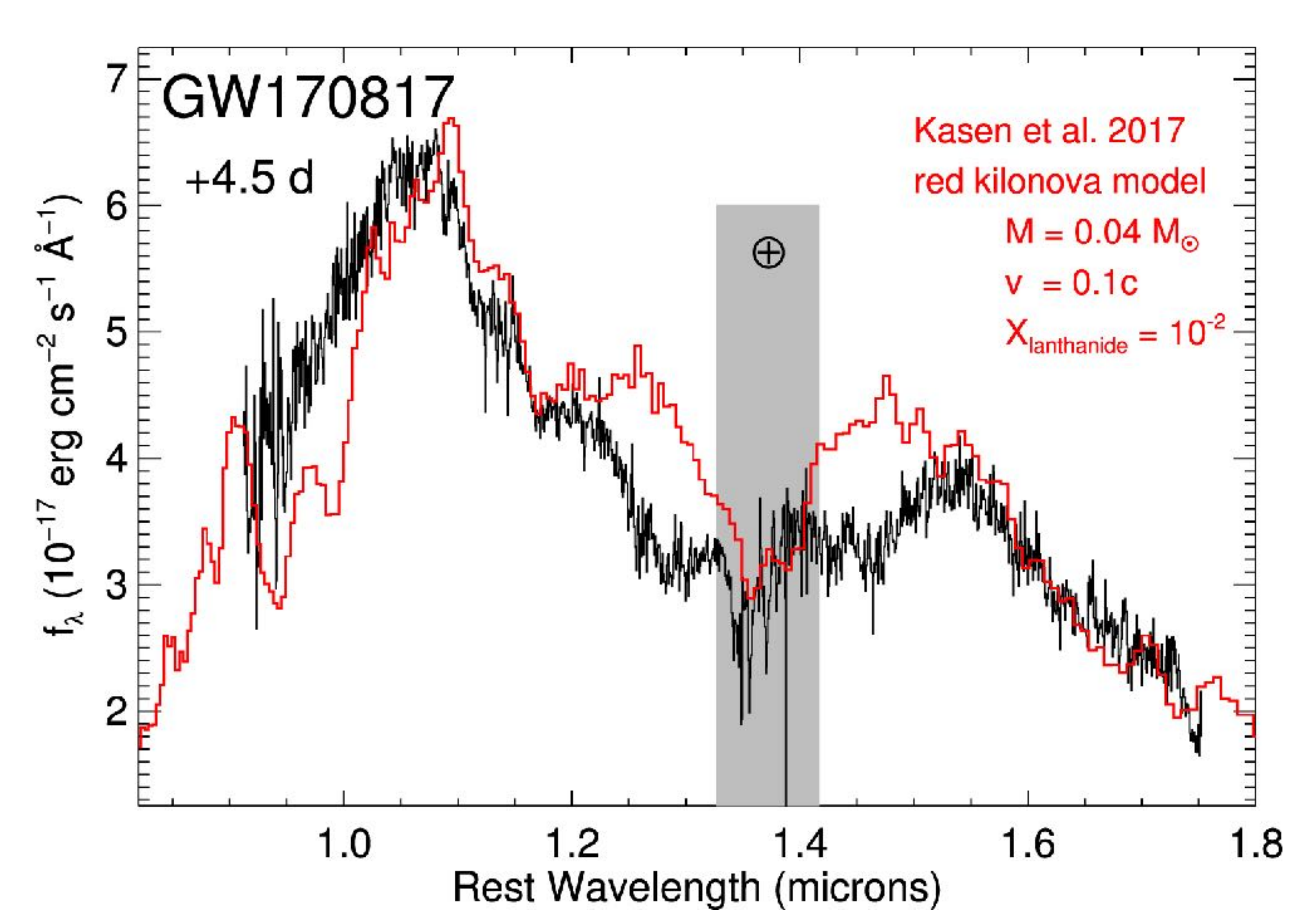
**Gemini/FLAMINGOS-2 data**




First GW detection from a NS-NS merger; still only with identified EM counterpart

Near-IR spectrum evolved rapidly from blue to red, as predicted by kilonova model.

By +4.5 days after explosion, broad features indicative of heavy element production.




Chornock et al. 2017

# *SBF distance to NGC4993/GW170817*

## NGC4993 previous distances

$d$ = 44.0 ± 7.5 Mpc (Hjorth et al. 2017)

$d$ = 37.7 ± 8.7 Mpc (Im et al. 2017)

Total error on D ~ 20%

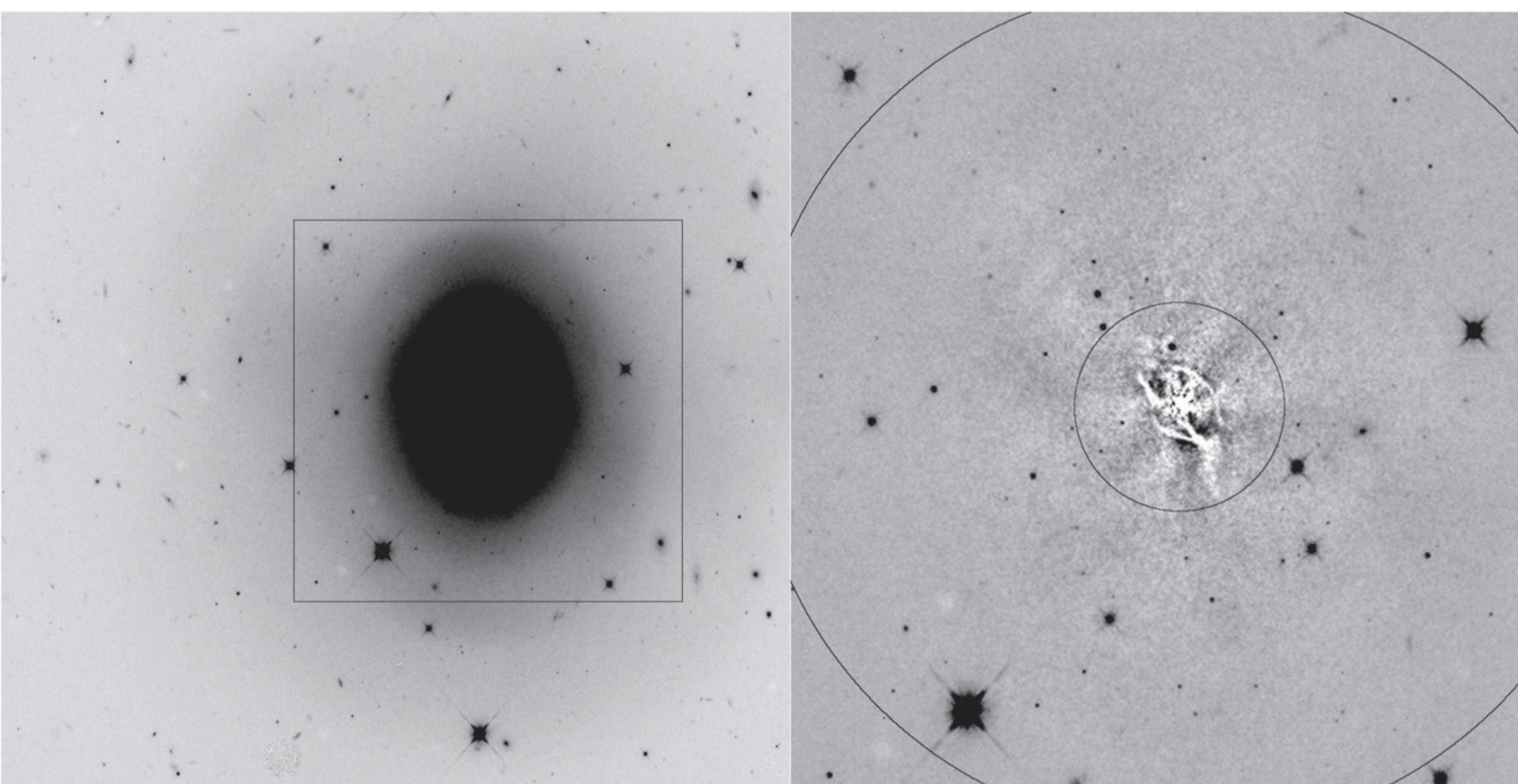
Abbott+18 standard siren:

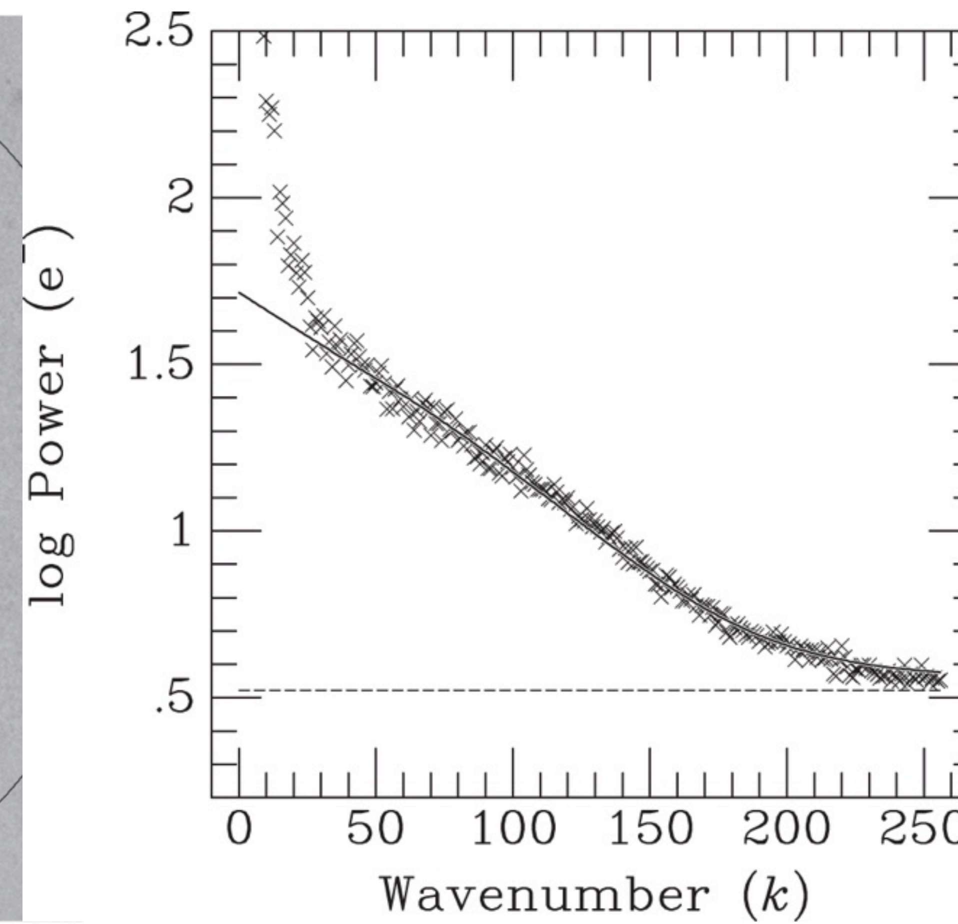
$d = 42.4^{+3.5}_{-7.1}$ (ran) Mpc

Cantiello, Jensen, Blakeslee+ 2018

**SBF distance: $d_{SBF}$ = 40.7 ± 1.4 ± 1.9 Mpc**

Total error on $d$ ~ 6%, $H_0 = 71.9 \pm 7.1$ km/s/Mpc





# MASSIVE Survey Selection

Stellar-mass selected

$M_K < -25.3$ (2MASS XSC) (Ma et al. 2014)

$M^* > 10^{11.5}\ M_{sun}$ ATLAS-3D: $M_K < -21.5$

Volume limited

D < 108 Mpc (2MASS Redshift Survey) ATLAS-3D: D < 42 Mpc

Includes Coma Cluster

Morphology (from Hyperleda)

~100 Early-type galaxies

Mostly gEs; a handful of S0s

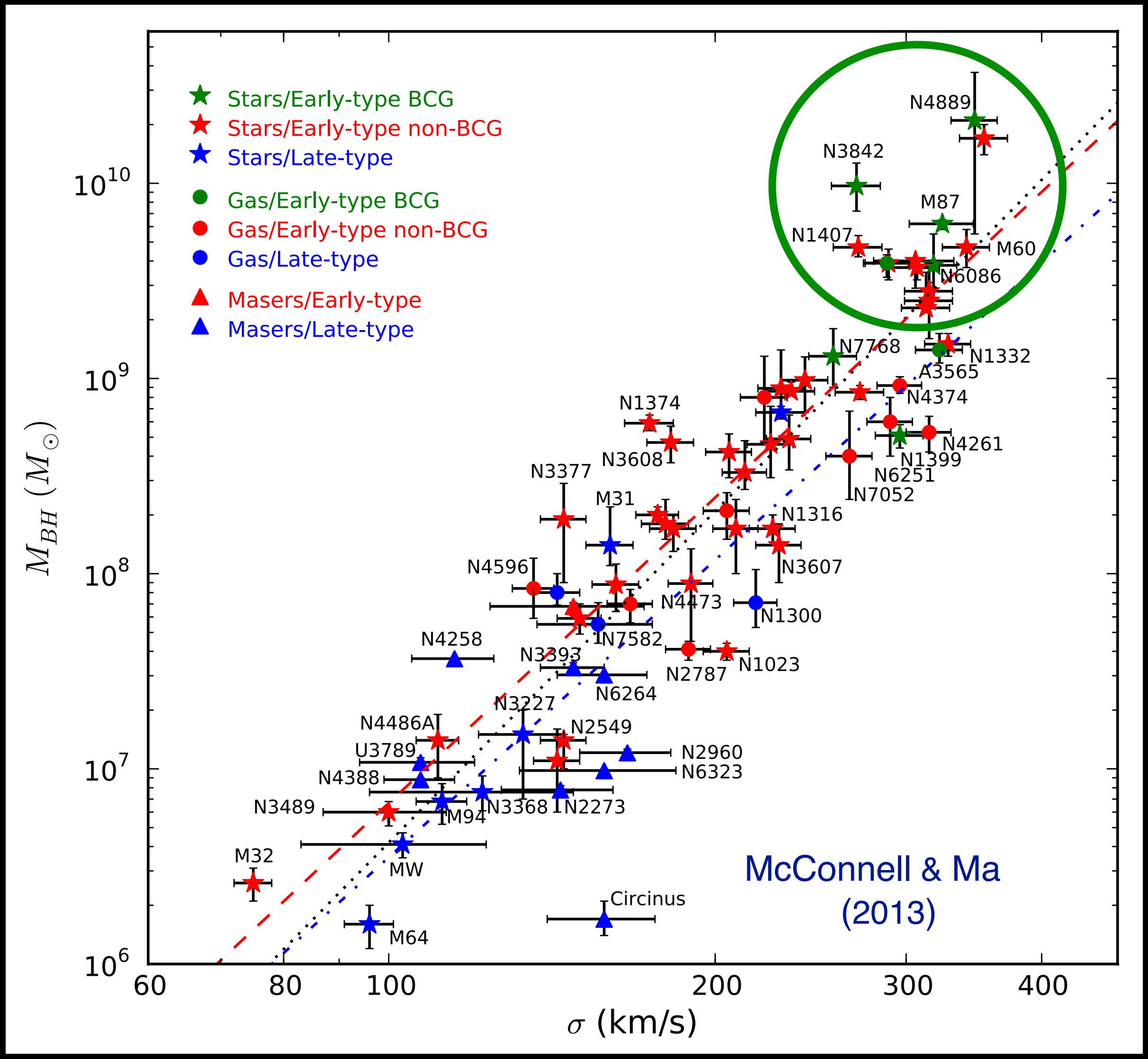
ATLAS-3D: mostly S0s, fast rotators

Additional criteria

Dec > −6 $A_V < 0.6$

and relatively "clean"

CP Ma, J. Greene, JPB, J. Jensen



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ATLAS-3D: ...

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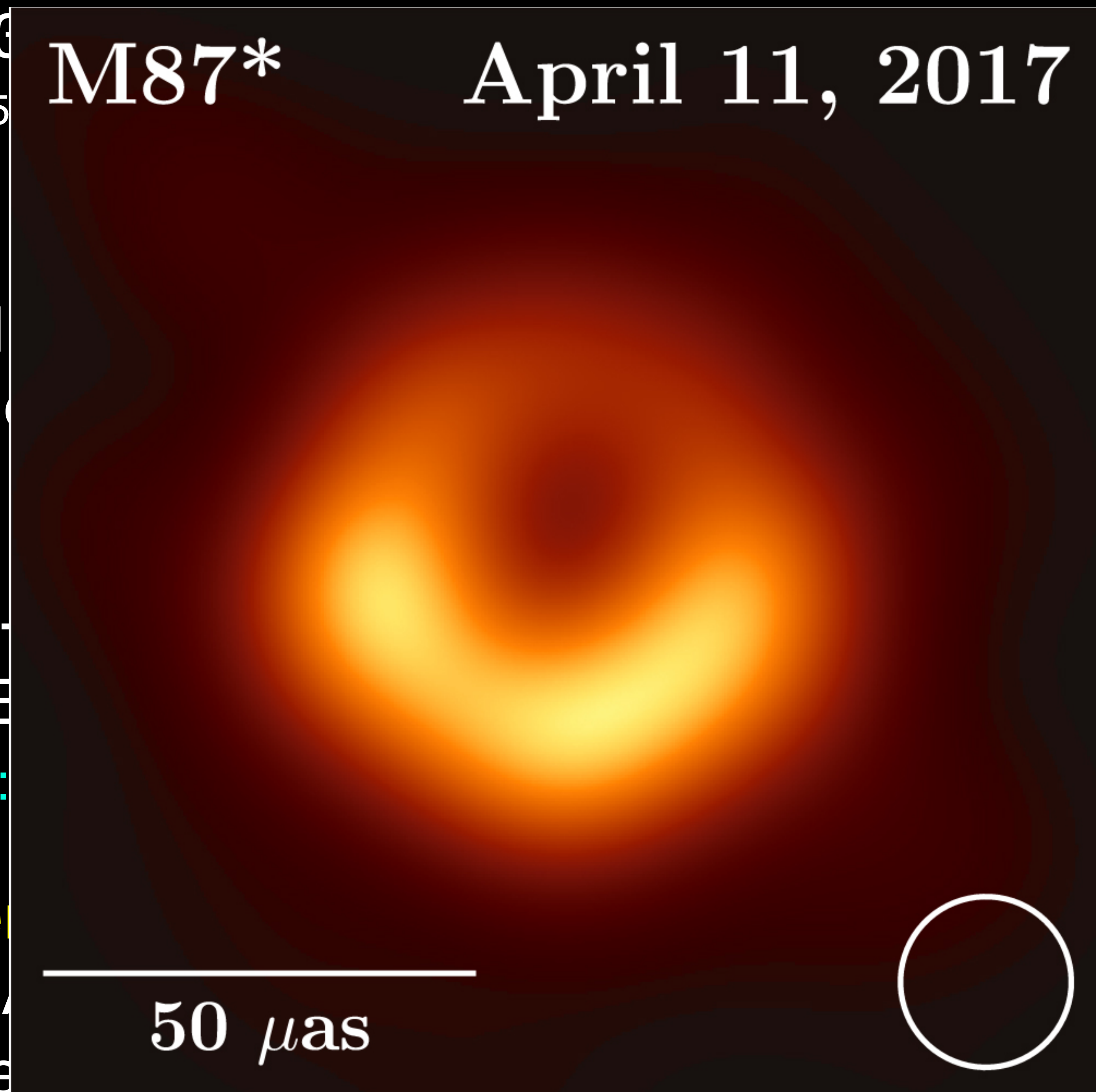
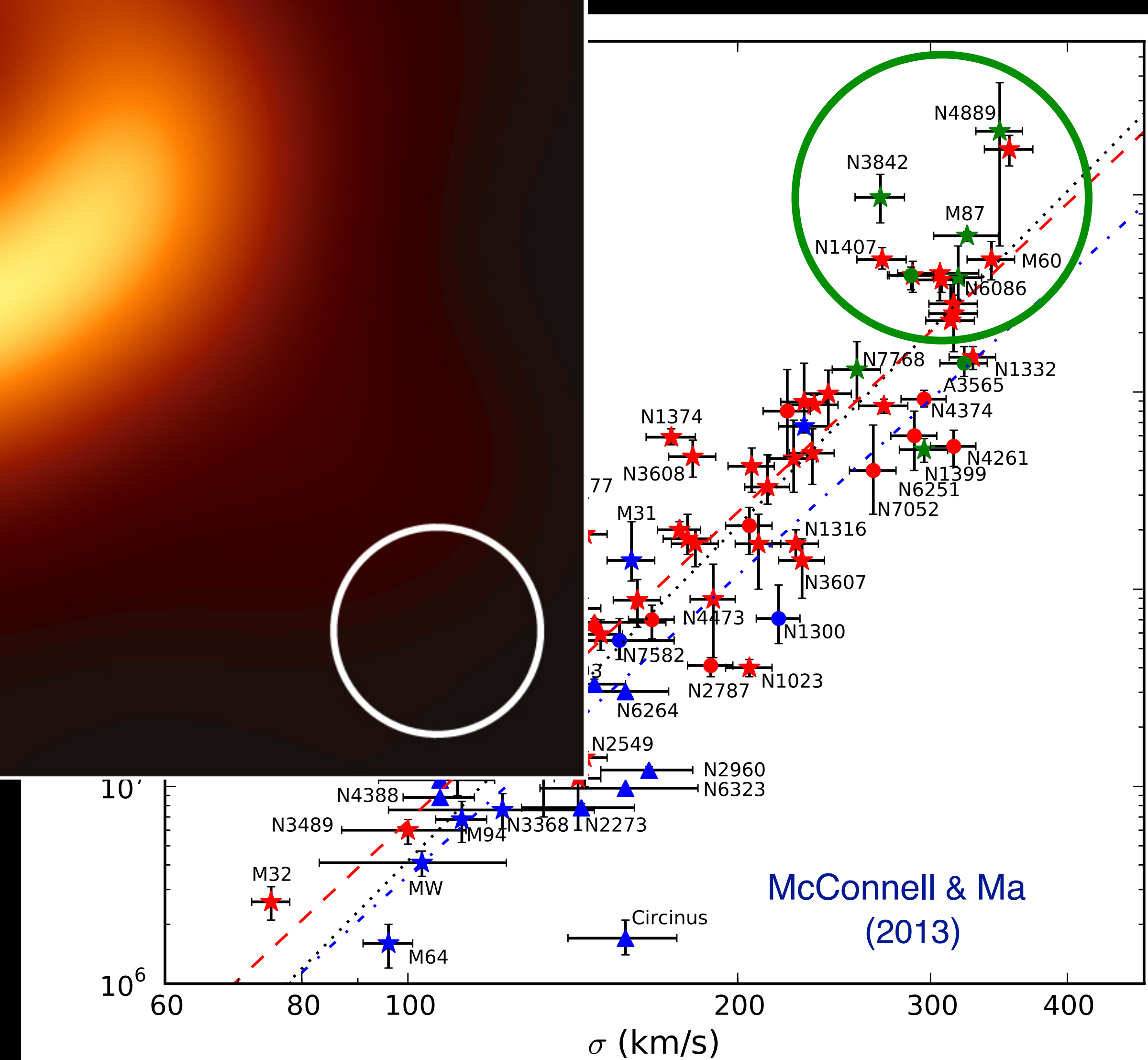
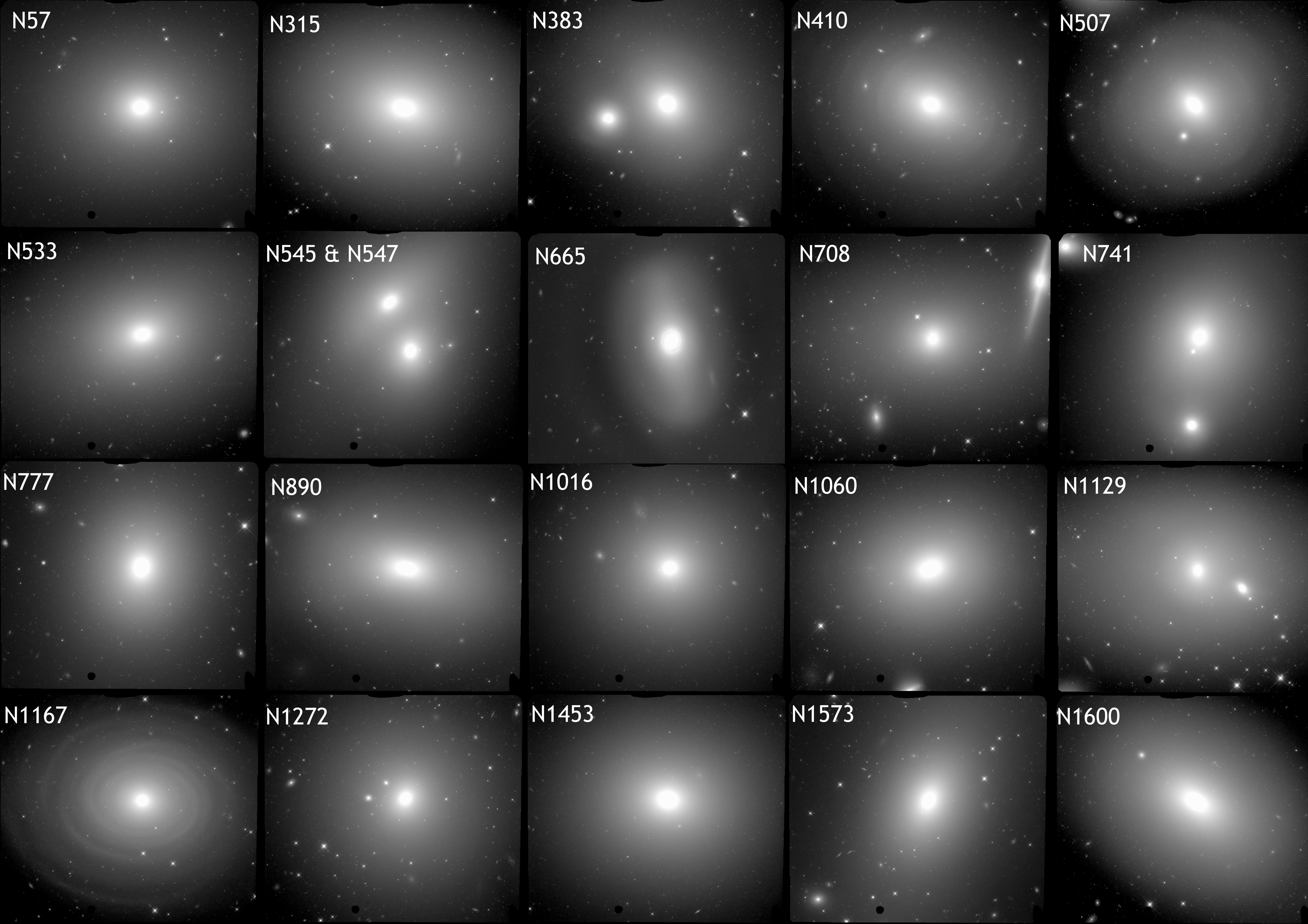
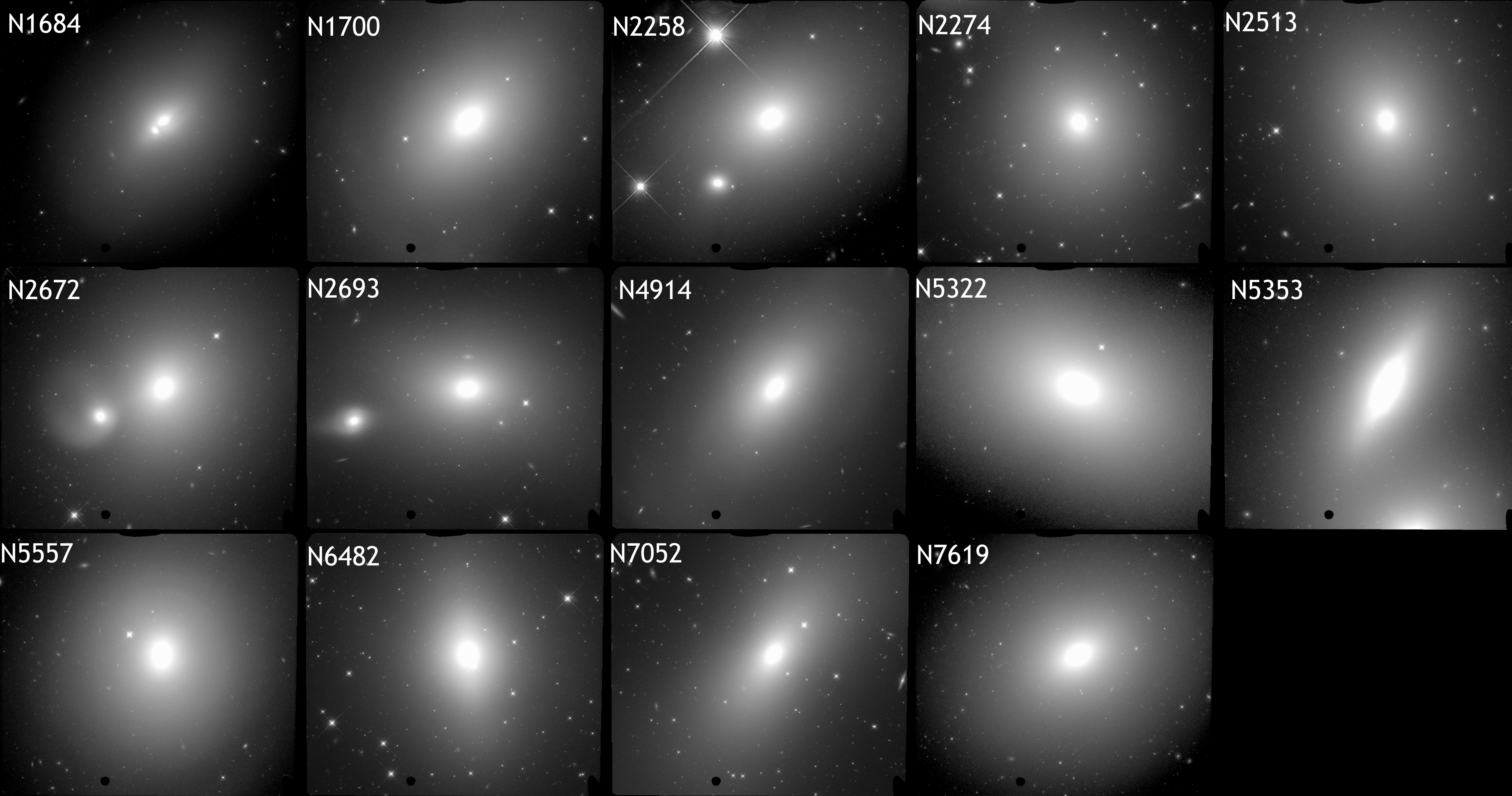
and relative...

CP Ma, J. Greene, JPB, J. Jensen

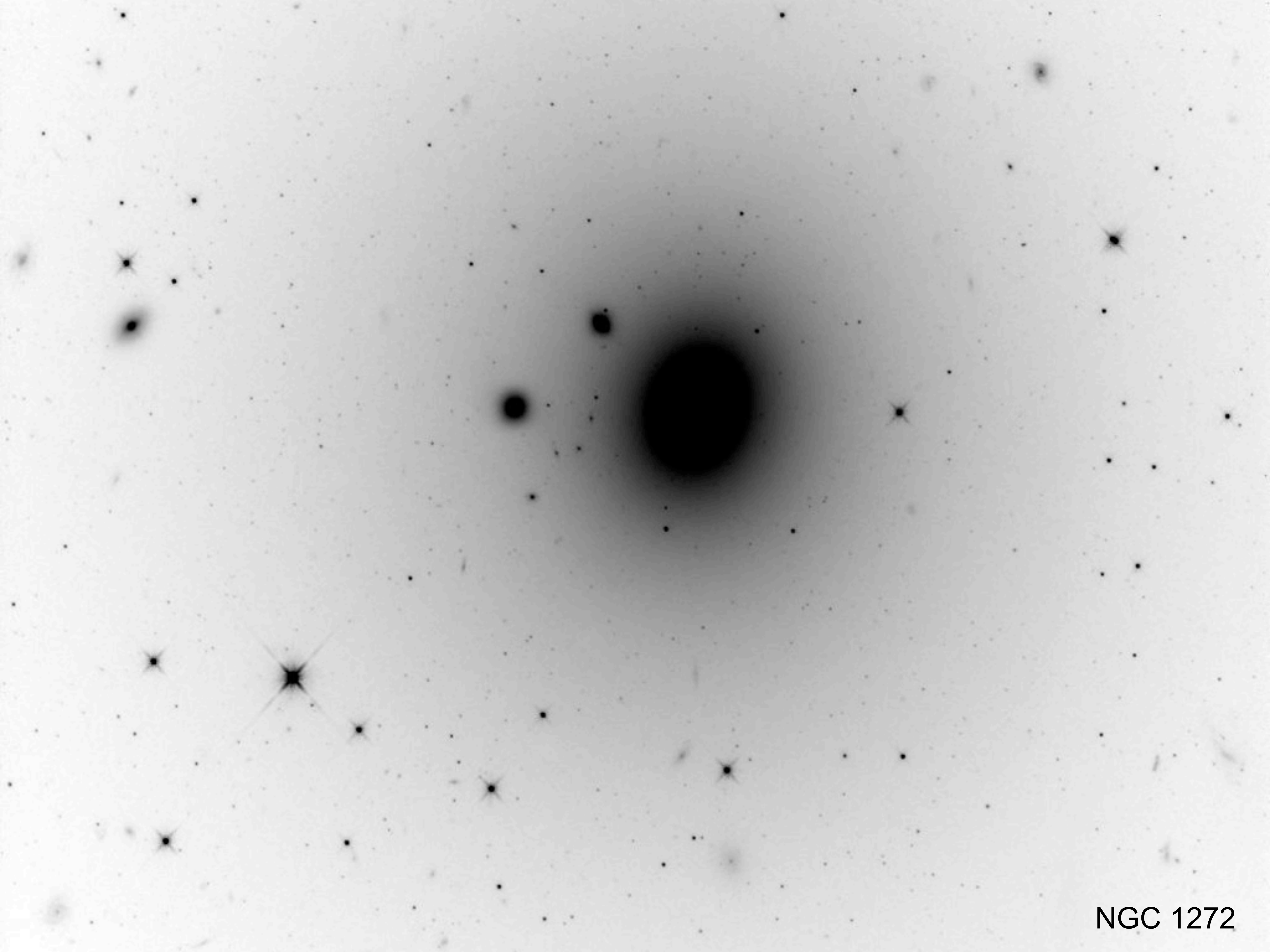


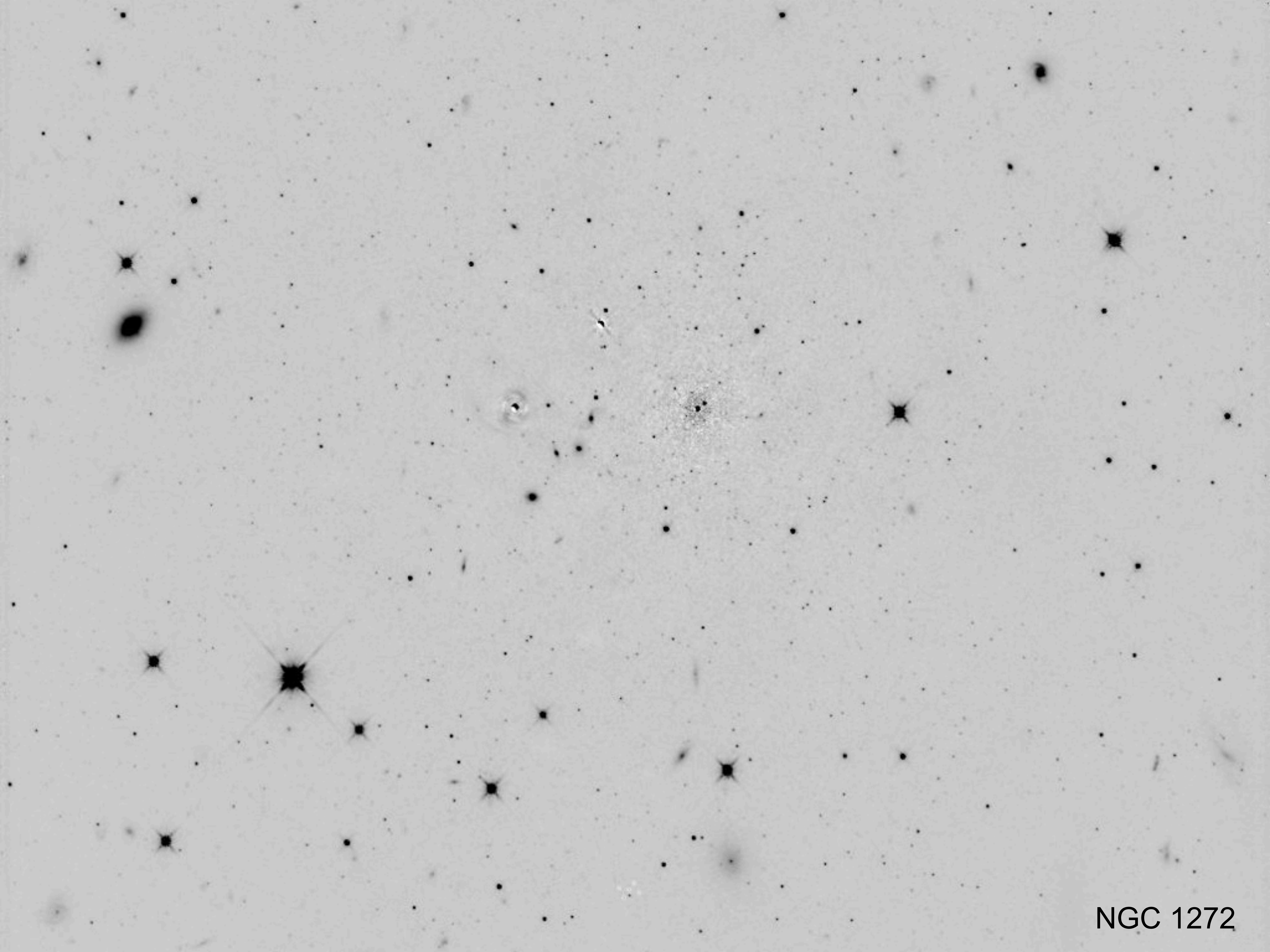



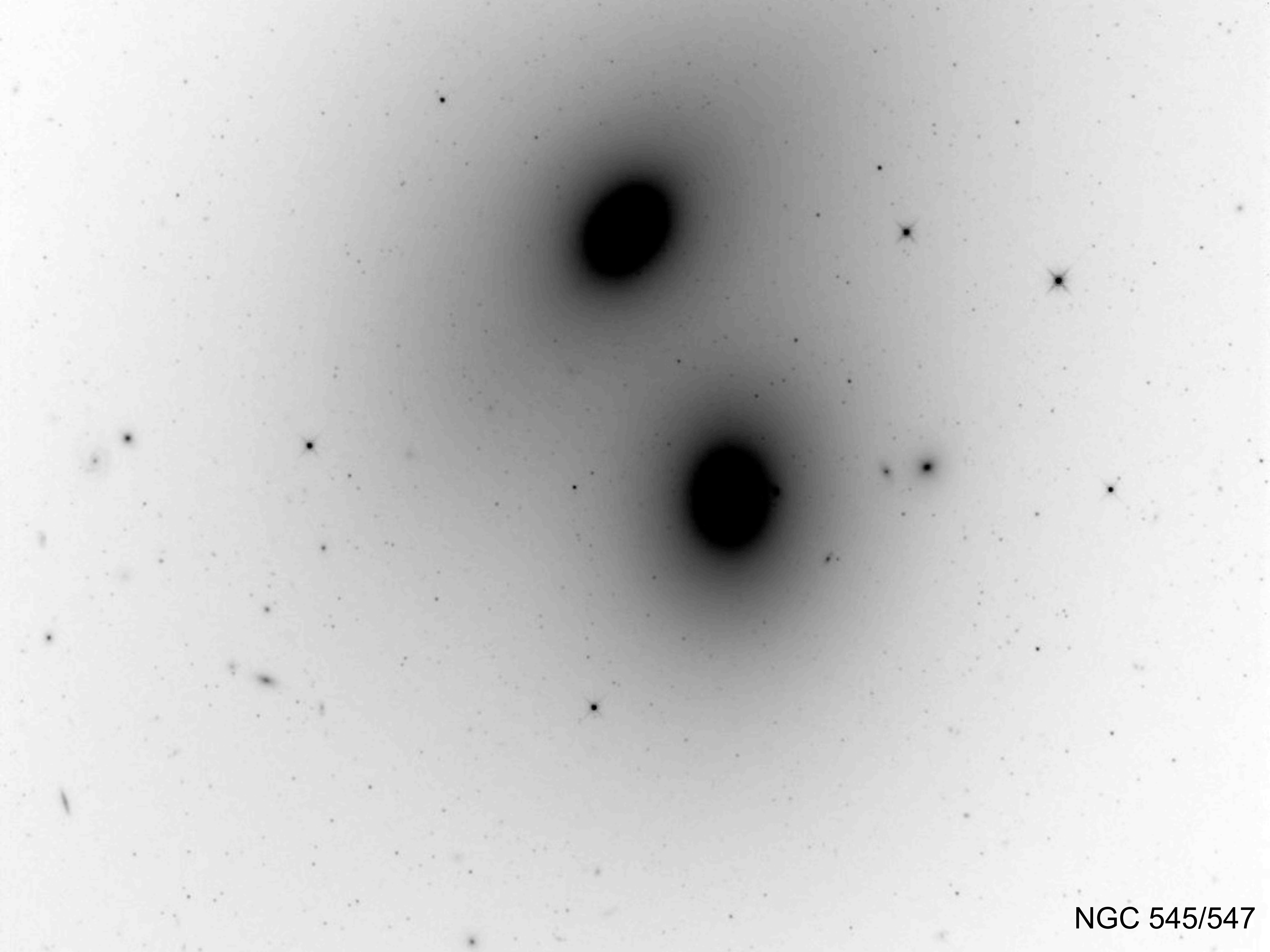

N57
N315
N383
N410
N507
N533
N545 & N547
N665
N708
N741
N777
N890
N1016
N1060
N1129
N1167
N1272
N1453
N1573
N1600

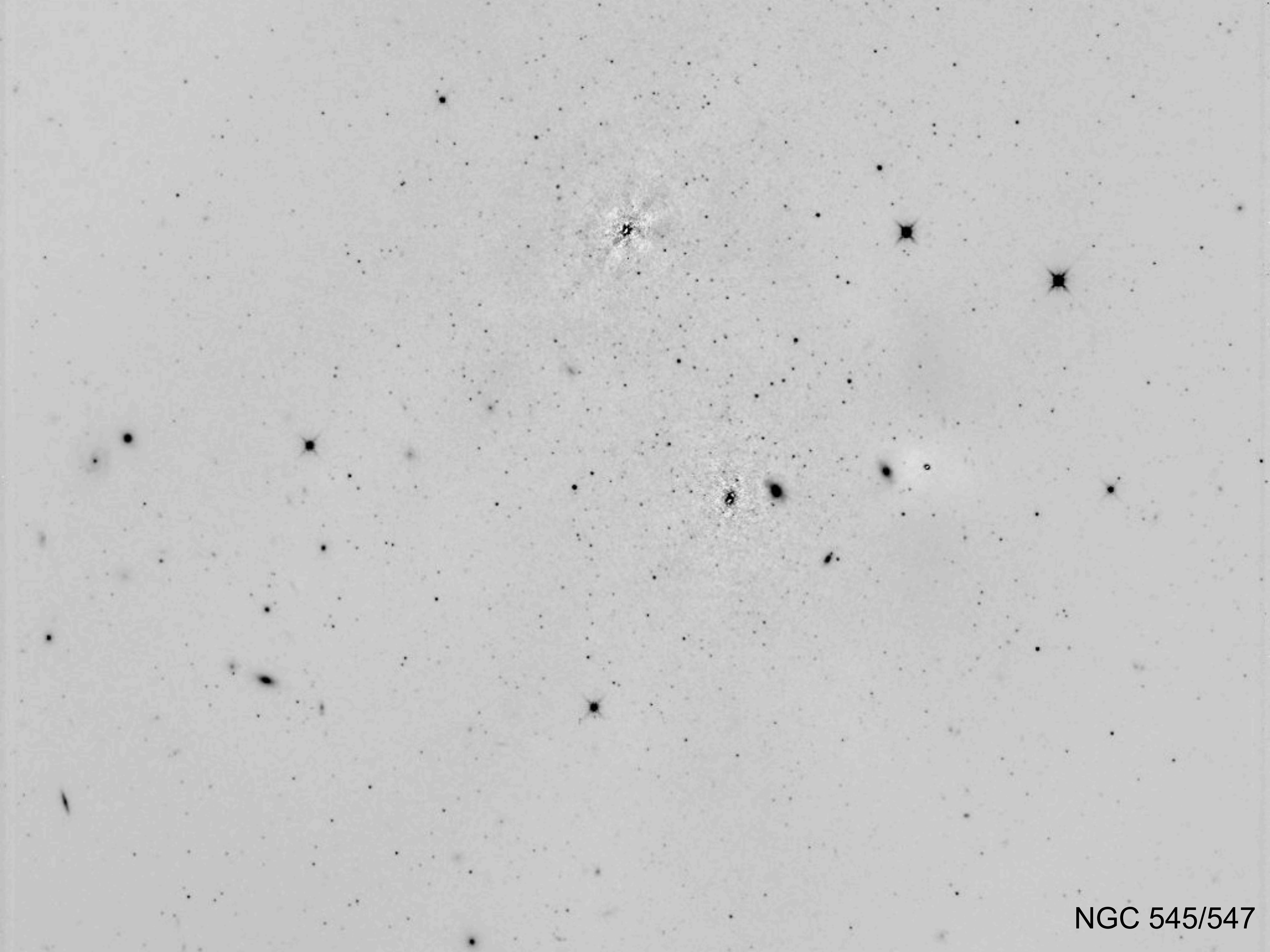


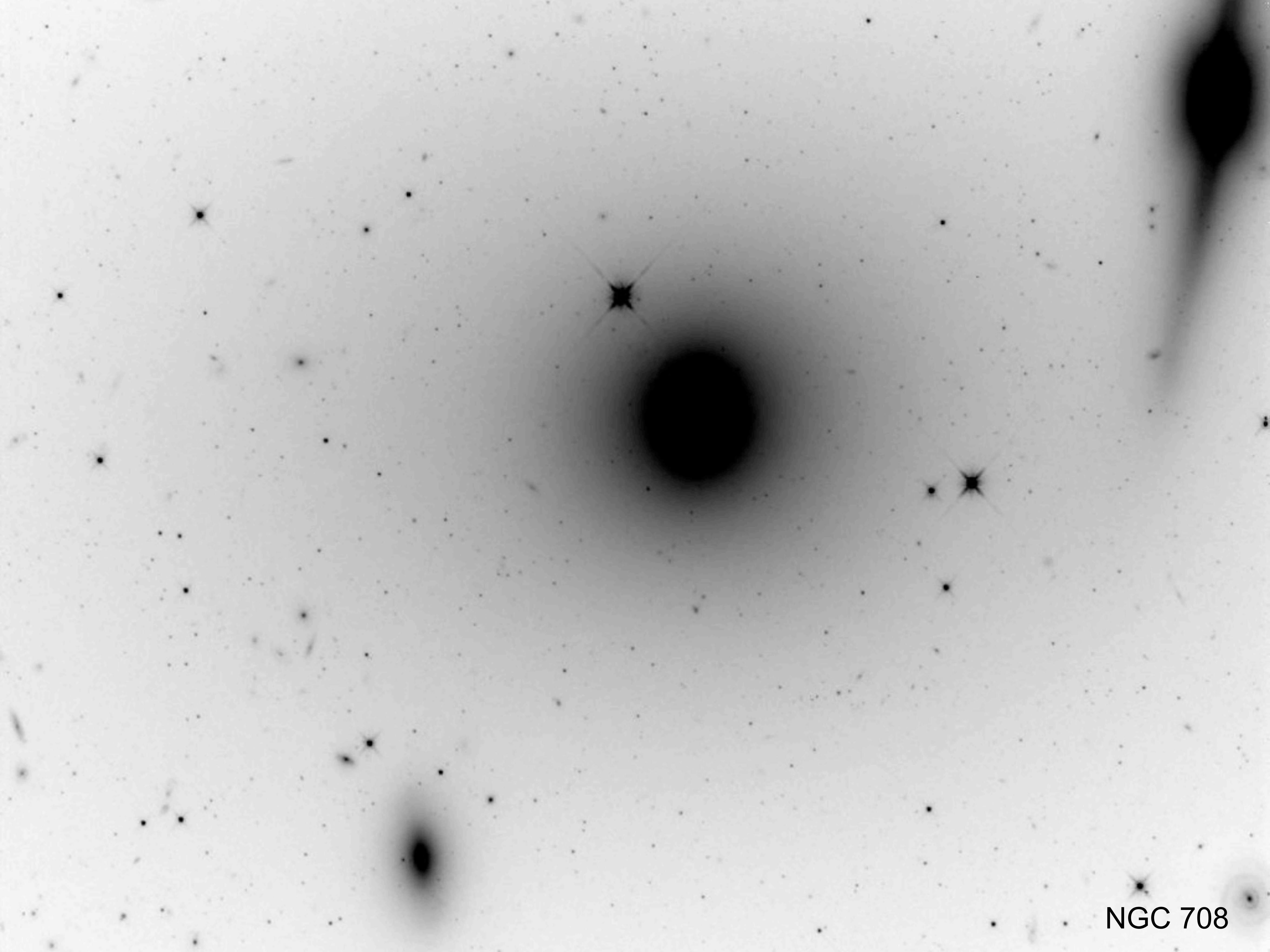

A complete sample of the most massive galaxies ($M_K < -25.5$ ) in all environments within ~75 Mpc; we now have six more out to ~100 Mpc.

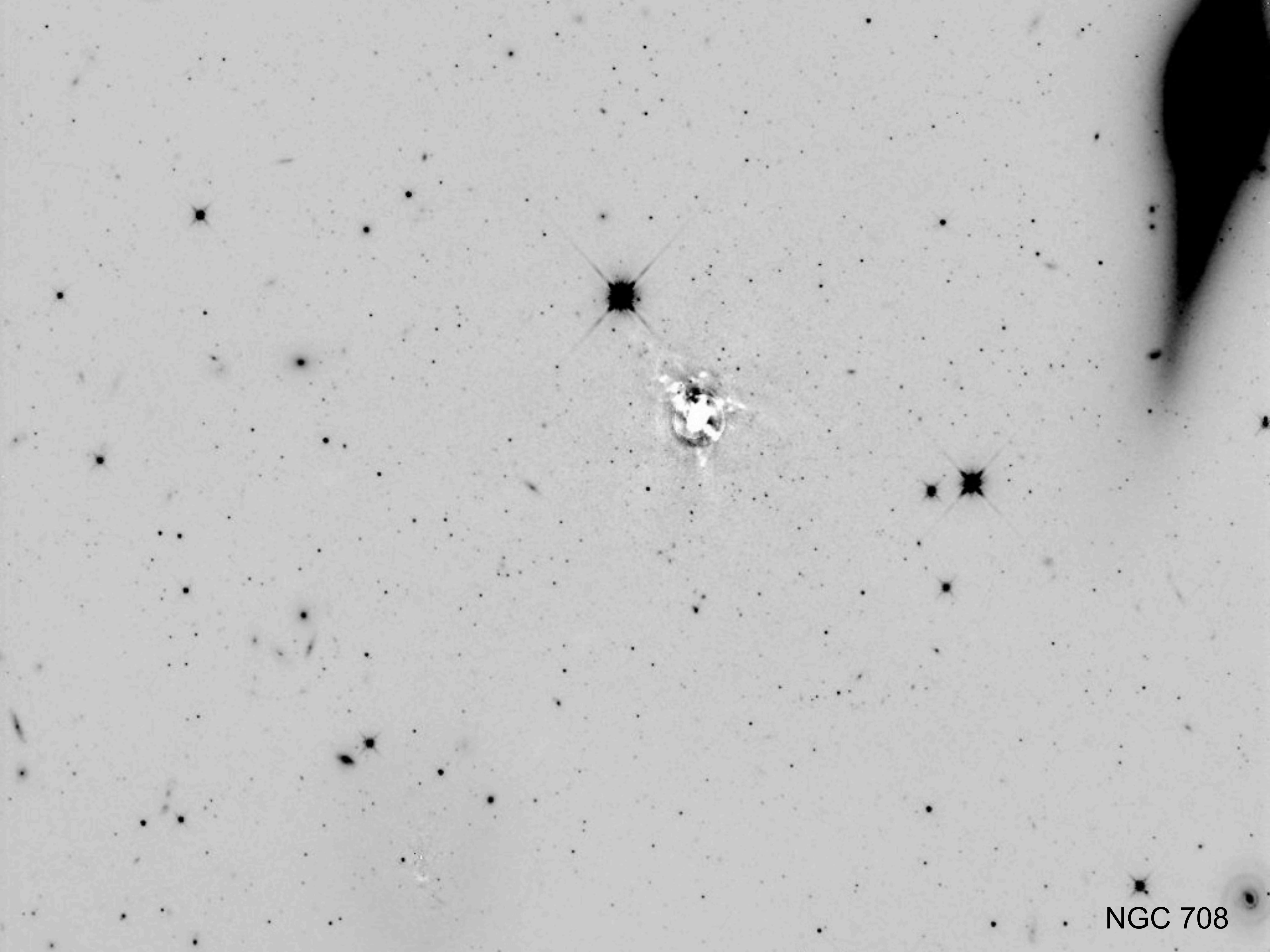

NGC 1272


NGC 1272


NGC 545/547

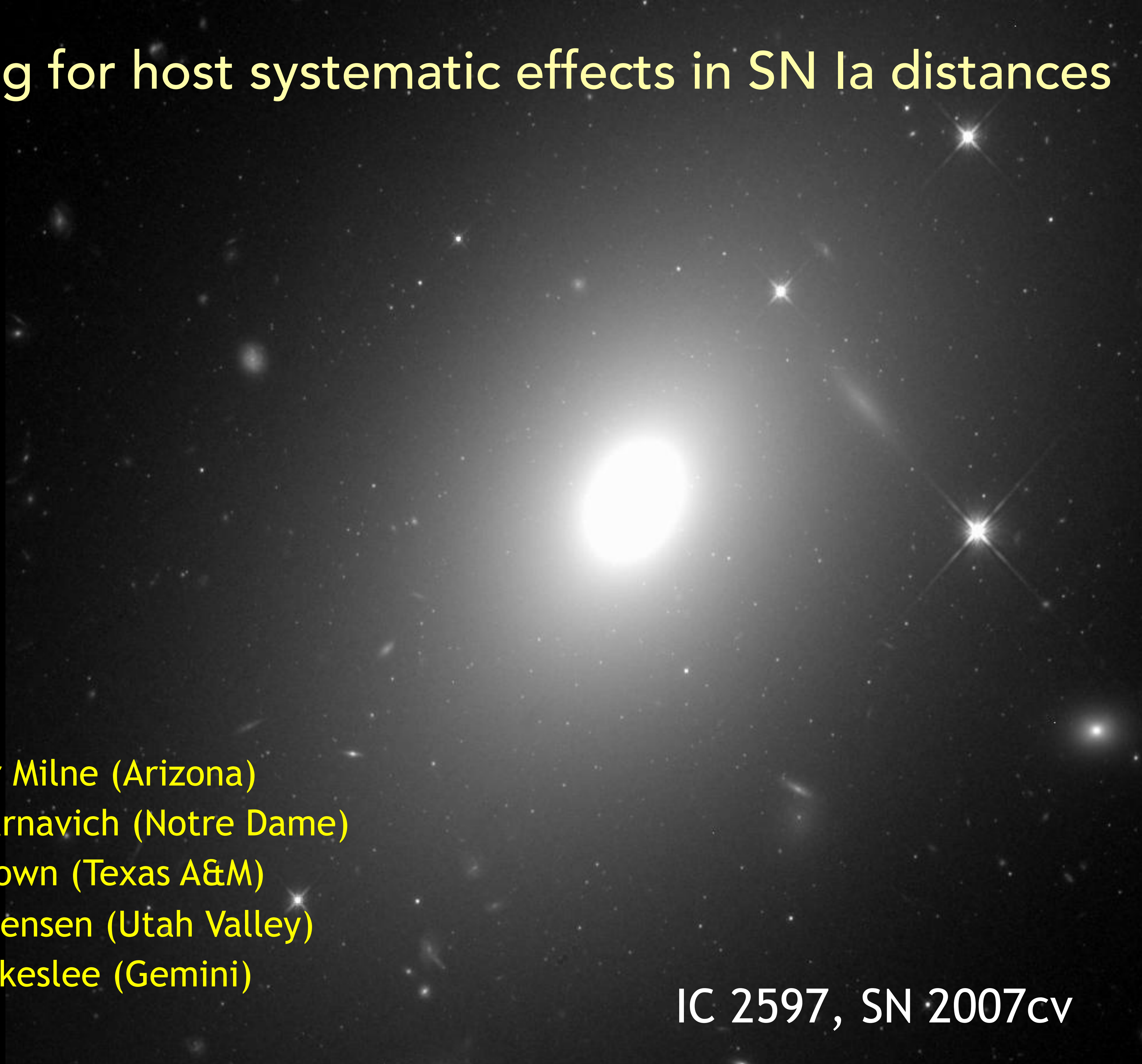

NGC 545/547


NGC 708



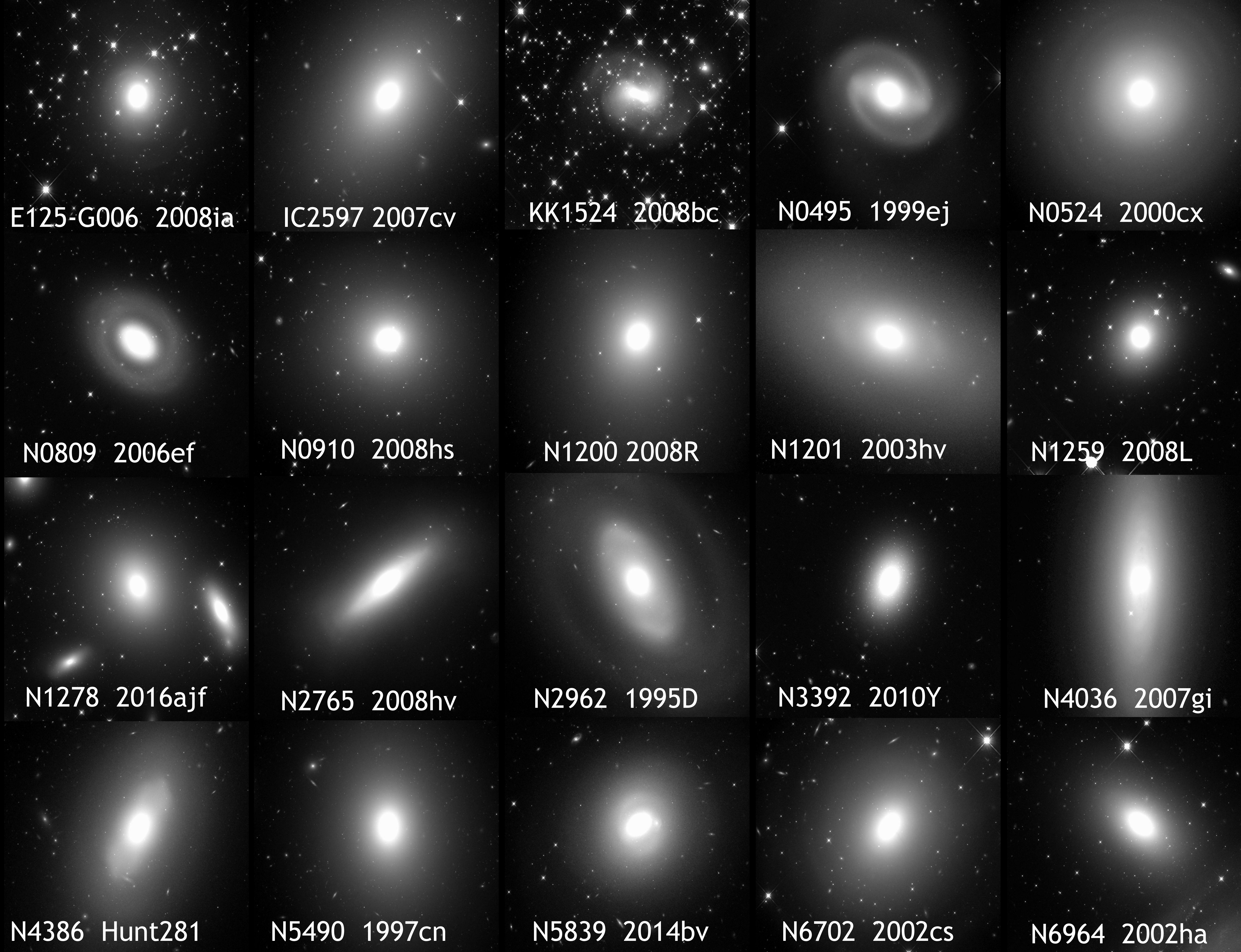
NGC 708

# Testing for host systematic effects in SN Ia distances



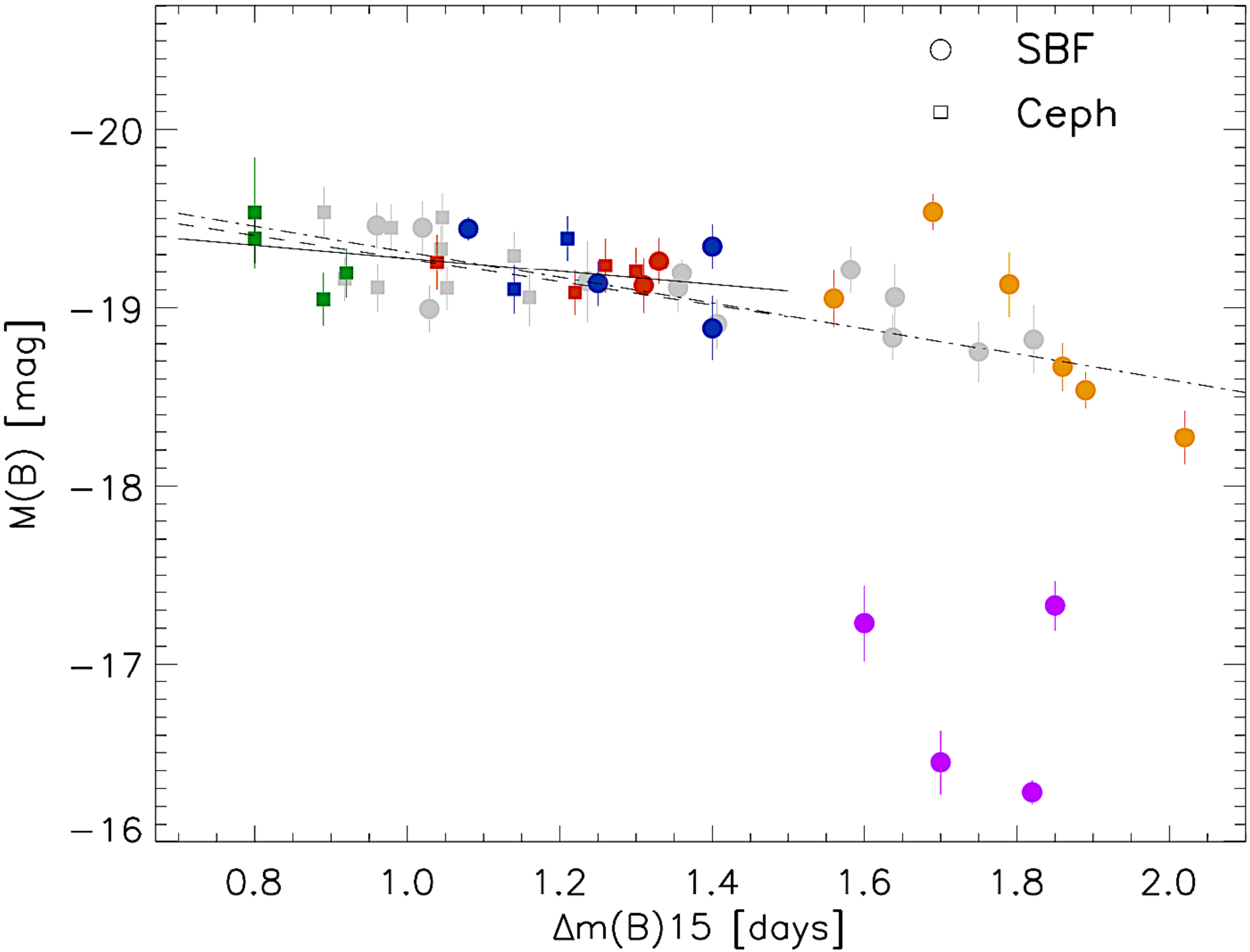
IC 2597, SN 2007cv

PI: Peter Milne (Arizona)
Peter Garnavich (Notre Dame)
Peter Brown (Texas A&M)
Joseph Jensen (Utah Valley)
John Blakeslee (Gemini)

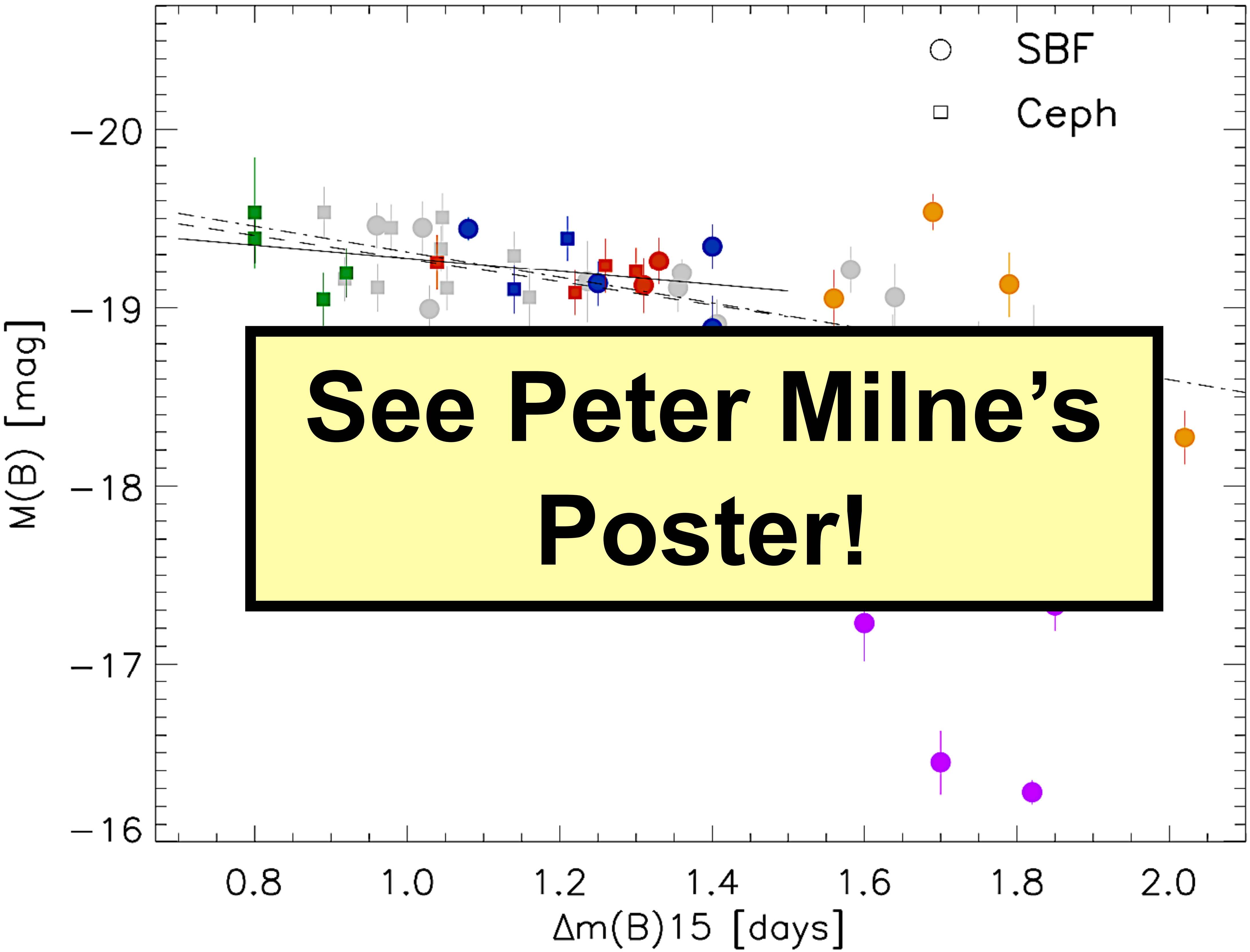


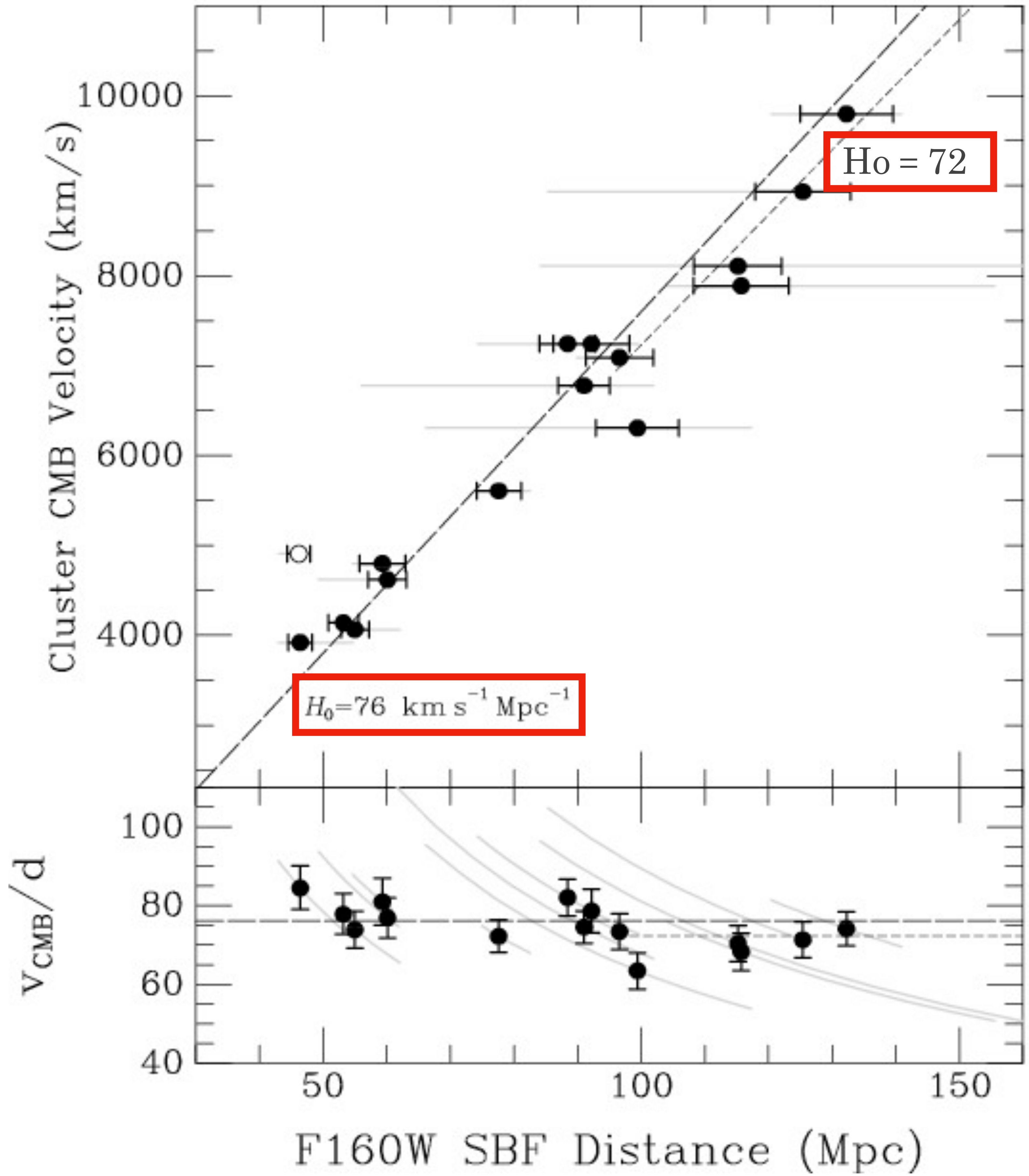
E125-G006 2008ia
IC2597 2007cv
KK1524 2008bc
N0495 1999ej
N0524 2000cx
N0809 2006ef
N0910 2008hs
N1200 2008R
N1201 2003hv
N1259 2008L
N1278 2016ajf
N2765 2008hv
N2962 1995D
N3392 2010Y
N4036 2007gi
N4386 Hunt281
N5490 1997cn
N5839 2014bv
N6702 2002cs
N6964 2002ha

# Initial results:



## Initial results:

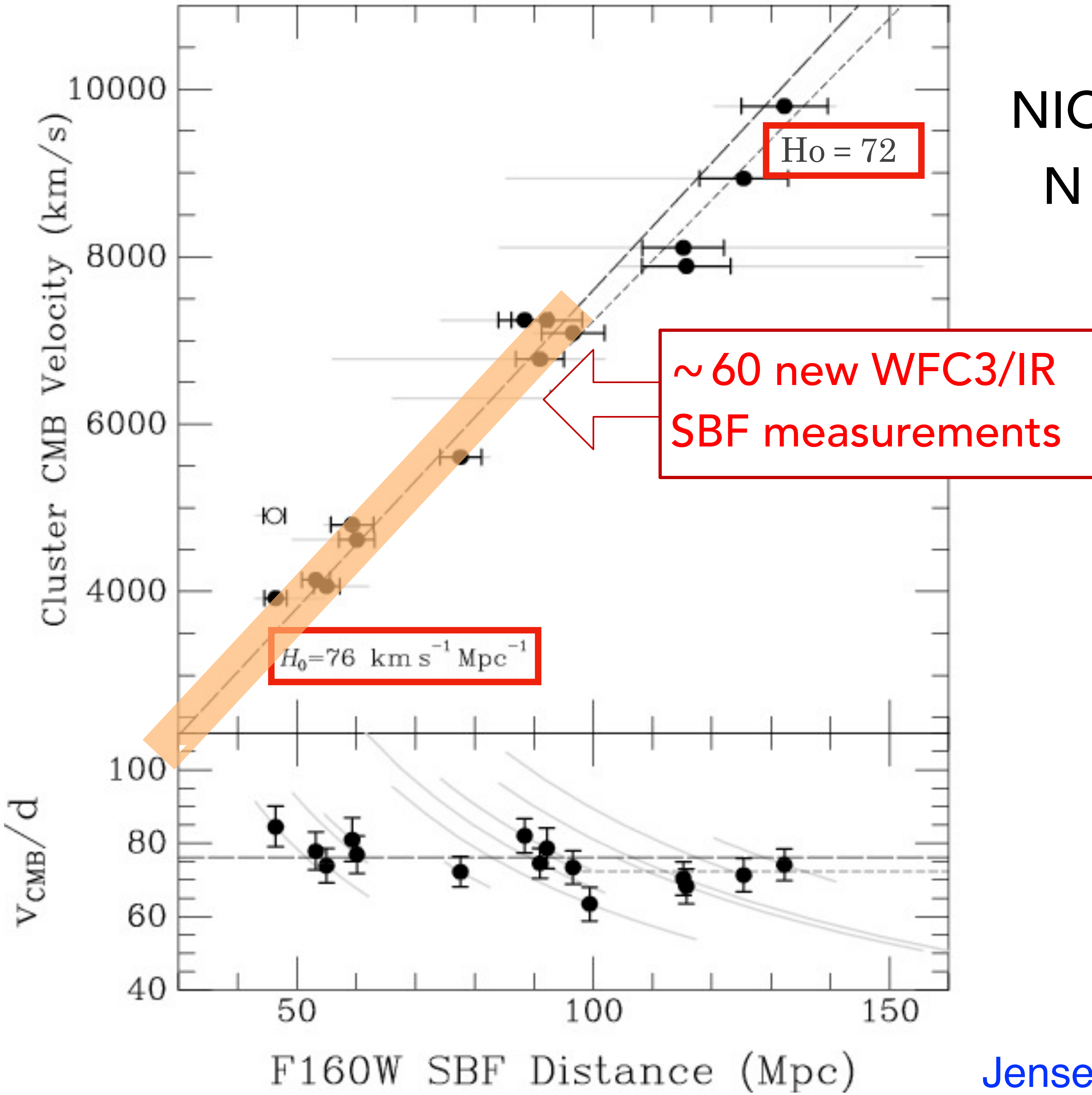





NICMOS

N = 15

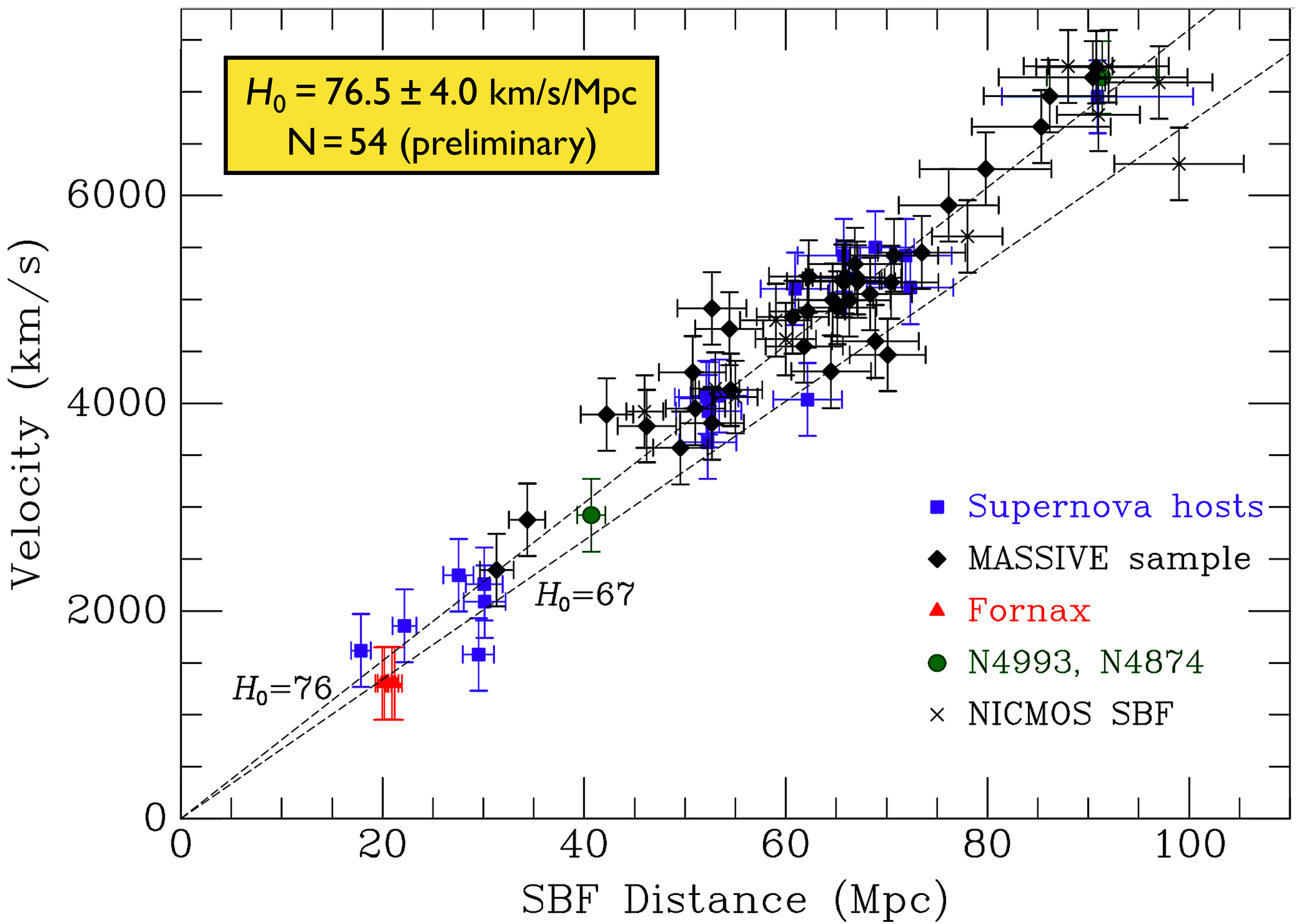
Jensen et al. 2001




NICMOS

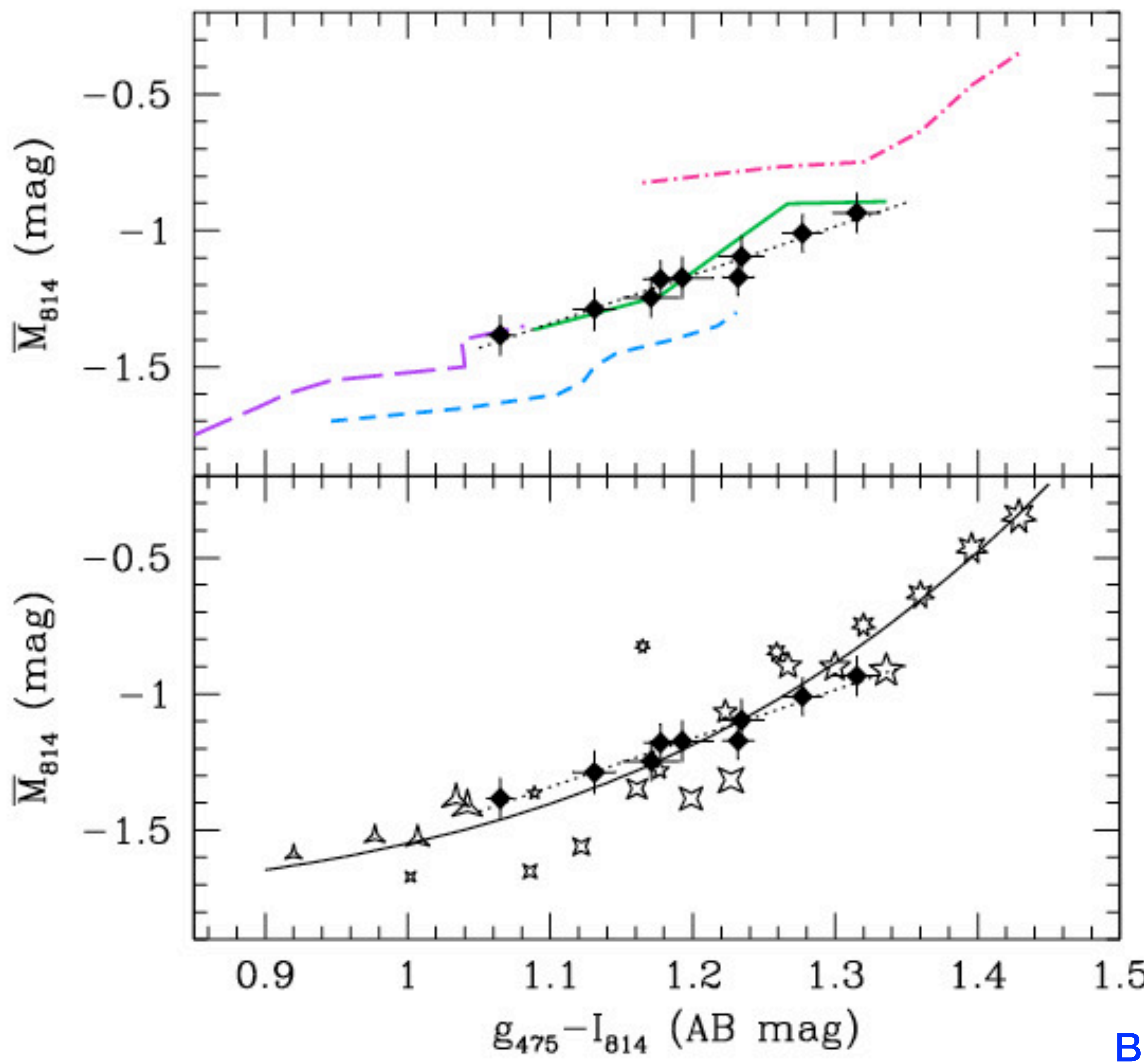
N = 15

Jensen et al. 2001



$H_0$ = 76.5 ± 4.0 km/s/Mpc
N = 54 (preliminary)
Velocity (km/s)
SBF Distance (Mpc)
0
2000
4000
6000
0
20
40
60
80
100
$H_0$=76
$H_0$=67
Supernova hosts
MASSIVE sample
Fornax
N4993, N4874
NICMOS SBF

# SBF stellar pop models: support for Cepheid zero point




Teramo SPoT stellar population models (Raimondo+ 2009)

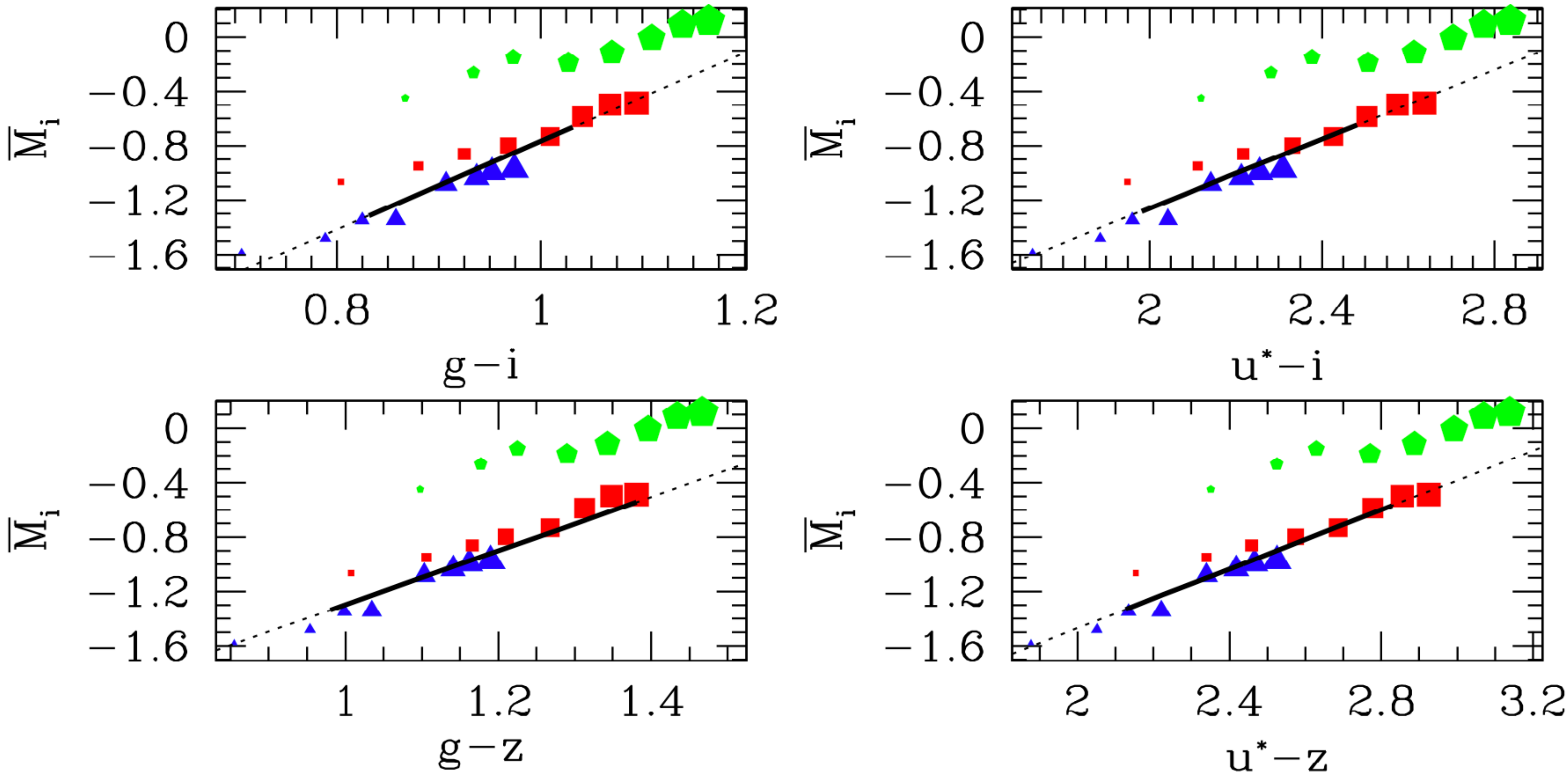
Empirical & model SBF zero points agree to 0.05 mag over most of color range, but 0.08 mag fainter for the reddest, most massive galaxies.

*This would increase $H_0$ to ~79 km/s/Mpc*

Blakeslee et al. 2010, ApJ

# SBF stellar pop models: support for Cepheid zero point

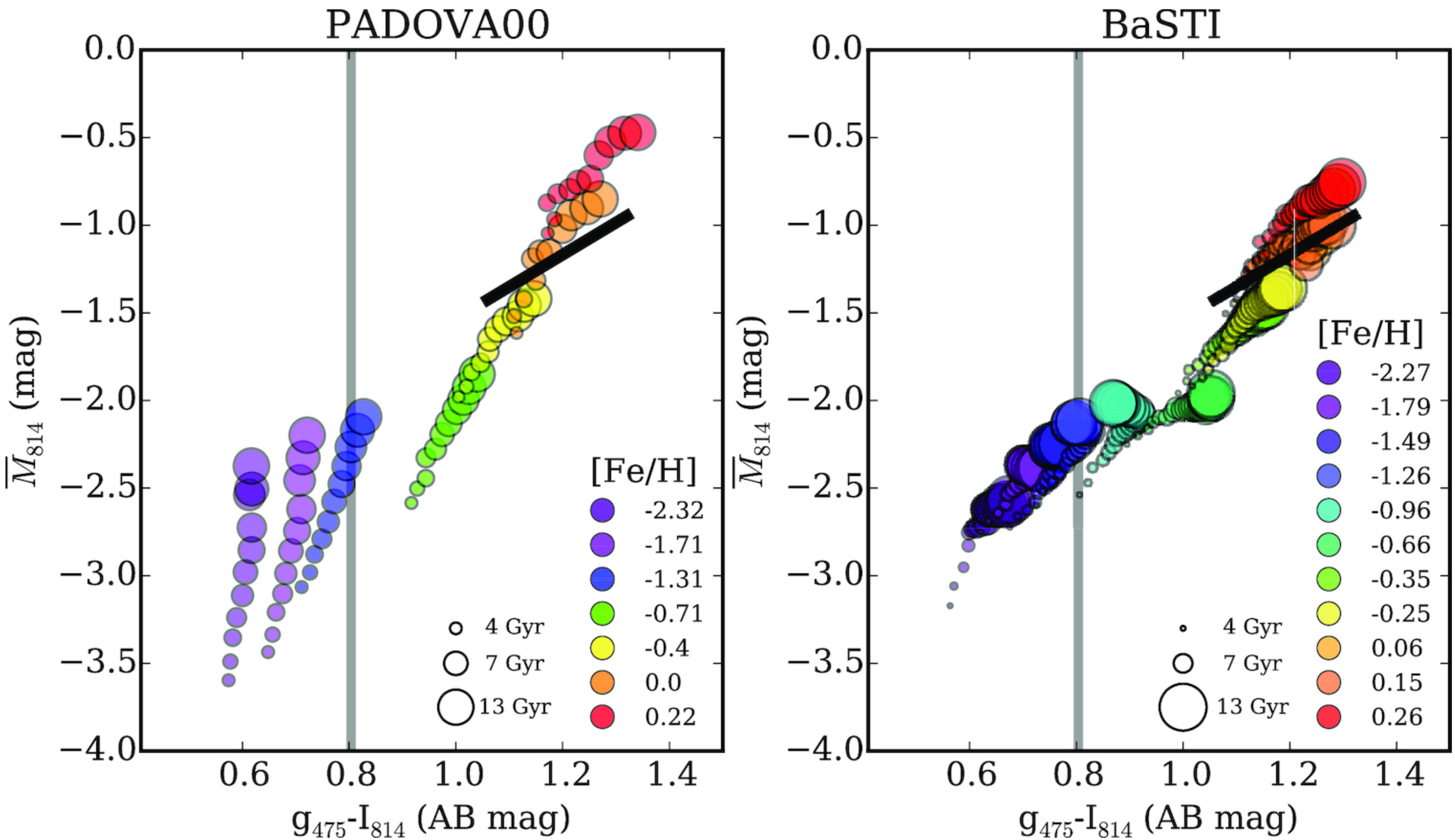
PHYSICAL JOURNAL, 856:126 (18pp), 2018 April 1 Cantiell




SBF vs. color calibrations: comparison of empirical relations and models. Symbols for models are the same as those in Figure 12. In each panel, th
F vs. color relation is marked with a black dotted line. The thick solid black line refers to the color interval of the objects used for deriving the en

Cantiello et al. 2018, ApJ

# Other SBF stellar pop models...?




Trujillo et al. 2019, ApJ

doi:10.1038/nature25767

# A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6] & Jielai Zhang[5]

**Studies of galaxy surveys in the context of the cold dark matter paradigm have shown that the mass of the dark matter halo and the total stellar mass are coupled through a function that varies smoothly with mass. Their average ratio $M_{halo}/M_{stars}$ has a minimum of about 30 for galaxies with stellar masses near that of the Milky Way (approximately $5 \times 10^{10}$ solar masses) and increases both towards lower masses and towards higher masses[1,2]. The scatter in this relation is not well known; it is generally thought to be less than a factor of two for massive galaxies but much larger for dwarf galaxies[3,4]. Here we report the radial velocities of ten luminous globular-cluster-like objects in the ultra-diffuse galaxy[5] NGC1052–DF2, which has a stellar mass of approximately $2 \times 10^8$ solar masses. We infer that its velocity dispersion is less than 10.5 kilometres per second with 90 per cent confidence, and we determine from this that its total mass within a radius of 7.6 kiloparsecs is less than $3.4 \times 10^8$ solar masses. This implies that the ratio $M_{halo}/M_{stars}$ is of order unity (and consistent with zero), a factor of at least 400 lower than expected[2]. NGC1052–DF2 demonstrates that dark matter is not always coupled with baryonic matter on galactic scales.**

NGC1052–DF2 was identified with the Dragonfly Telephoto Array[6] in deep, wide-field imaging observations of the NGC 1052 group. The galaxy is not a new discovery; it was catalogued previously in a visual search of digitized photographic plates[7]. It stood out to us because of the remarkable contrast between its appearance in Dragonfly images and Sloan Digital Sky Survey (SDSS) data: with Dragonfly it is a low-surface-brightness object with some substructure and a spatial extent of about 2′, whereas in SDSS it appears as a collection of point-like sources. Intrigued by the likelihood that these compact sources are associated with the low-surface-brightness object, we obtained follow-up spectroscopic observations of NGC1052–DF2 using the 10-m W. M. Keck Observatory. We also observed the galaxy with the Hubble Space Telescope (HST).

A colour image generated from the HST $V_{606}$ and $I_{814}$ data is shown in Fig. 1. The galaxy has a striking appearance. In terms of its apparent size and surface brightness, it resembles dwarf spheroidal galaxies such as those recently identified[8] in the M101 group at 7 Mpc, but the fact that it is only marginally resolved implies that it is at a much greater distance. Using the $I_{814}$ band image, we derived a surface-brightness-fluctuation distance of $D_{SBF} = 19.0 \pm 1.7$ Mpc (see Methods). It is located only 14′ from the luminous elliptical galaxy NGC 1052, which has distance measurements ranging from 19.4 Mpc to 21.4 Mpc (refs 9, 10). We infer that NGC1052–DF2 is associated with NGC 1052, and we adopt $D \approx 20$ Mpc for the galaxy.

in the Coma cluster[5]. The total magnitude of NGC1052–DF2 is $M_{606} = -15.4$, and the total luminosity is $L_V = 1.1 \times 10^8$ solar luminosities, $L_{\odot}$. Its colour $V_{606} - I_{814} = 0.37 \pm 0.05$ in the AB magnitude system, similar to that of other UDGs and metal-poor globular clusters[12]. The stellar mass was determined in two ways: by placing a stellar population at $D = 20$ Mpc that matches the global properties of NGC1052–DF2 (see Methods), and by assuming $M/L_V = 2.0$ as found for globular clusters[13]. Both methods give $M_{stars} \approx 2 \times 10^8$ solar masses, $M_{\odot}$.

We obtained spectroscopy of objects in the NGC1052–DF2 field with the W. M. Keck Observatory. Details of the observations and data reduction are given in the Methods section. We found ten objects with a radial velocity close to 1,800 km s$^{-1}$ (all other objects are Milky Way stars or background galaxies). We conclude that there is indeed a population of compact, luminous objects associated with NGC1052–DF2. Their spectra near the strongest calcium triplet lines are shown in Fig. 2. The mean velocity of the ten objects is $\langle v \rangle = 1{,}803^{+2}_{-2}$ km s$^{-1}$. The

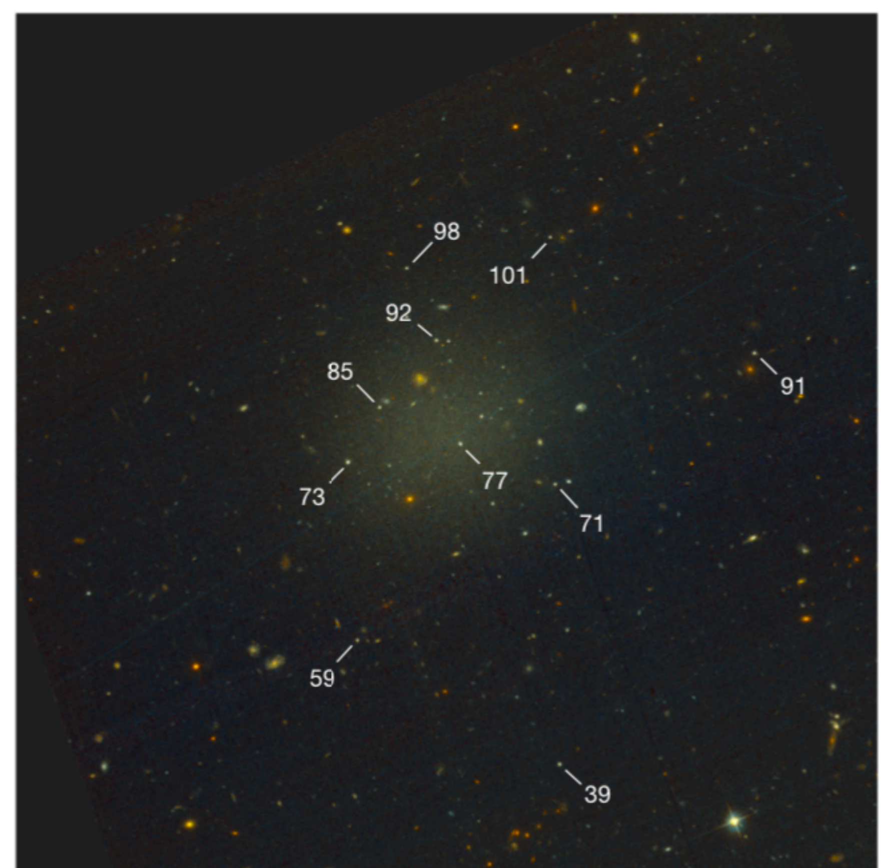



**Figure 1 | HST/Advanced Camera for Surveys (ACS) image of**

LETTER

doi:10.1038/nature25767

# A galaxy lacking dark matter

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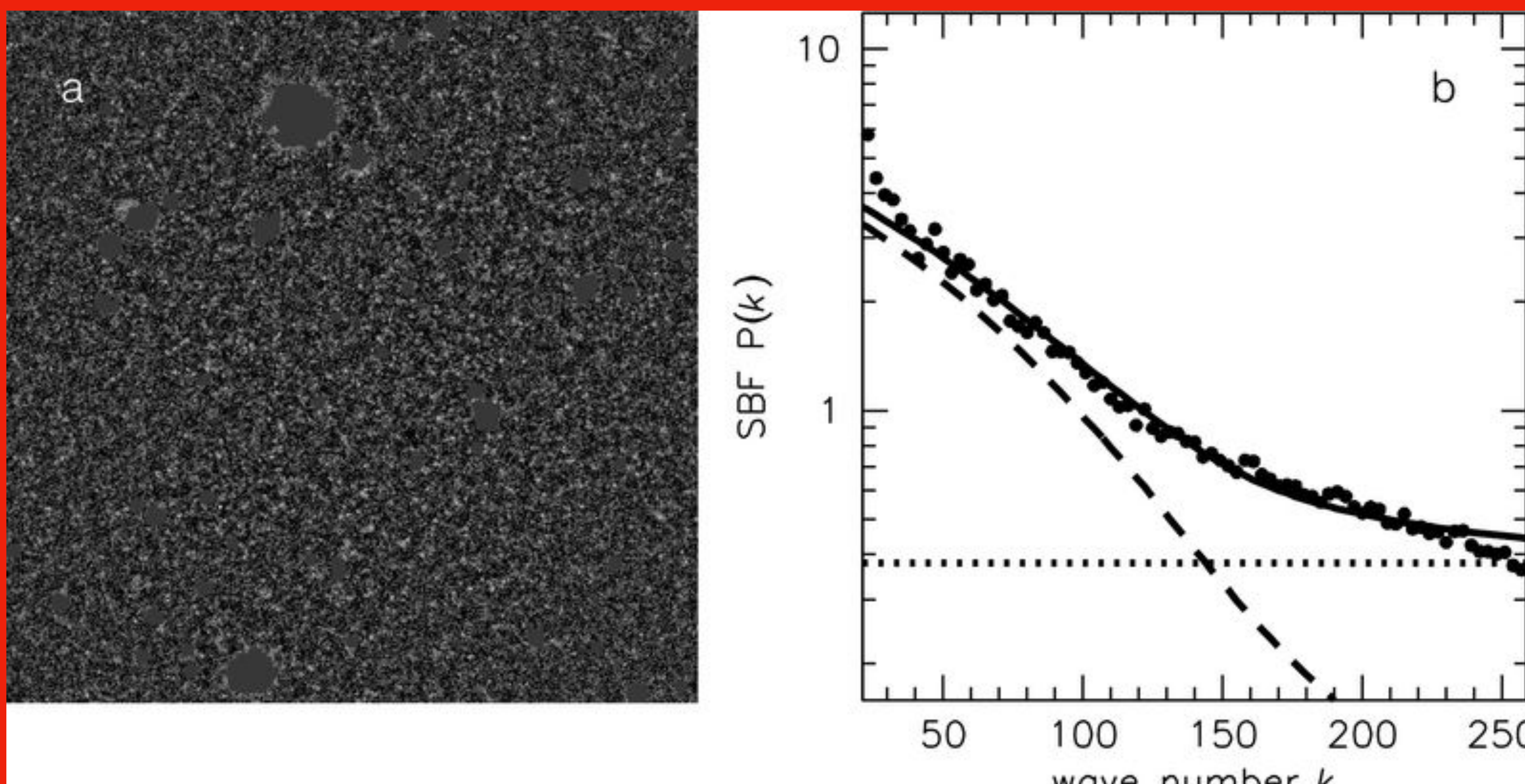


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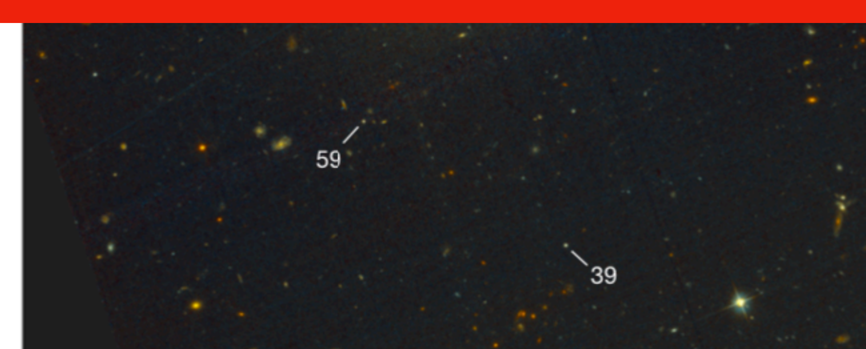
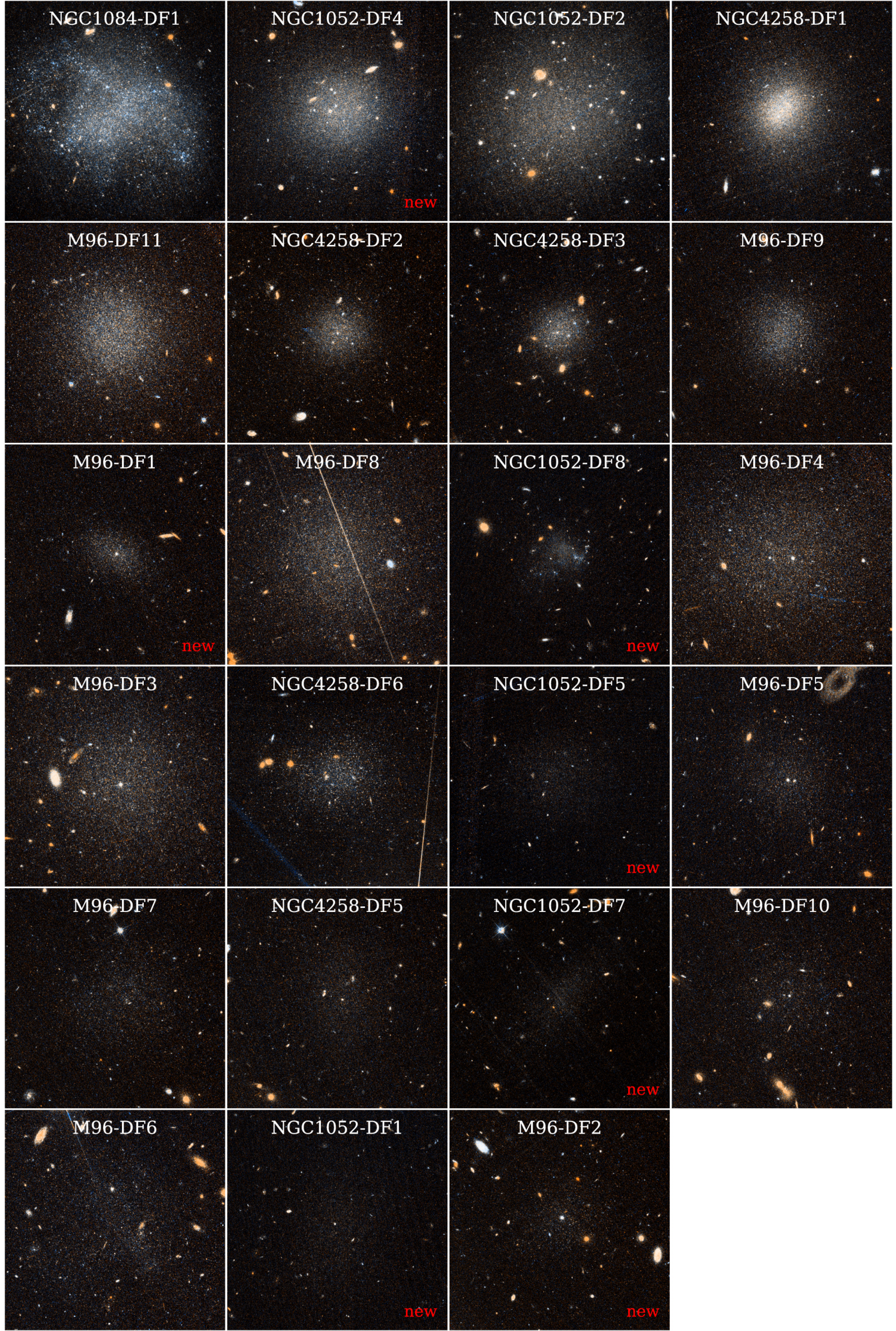
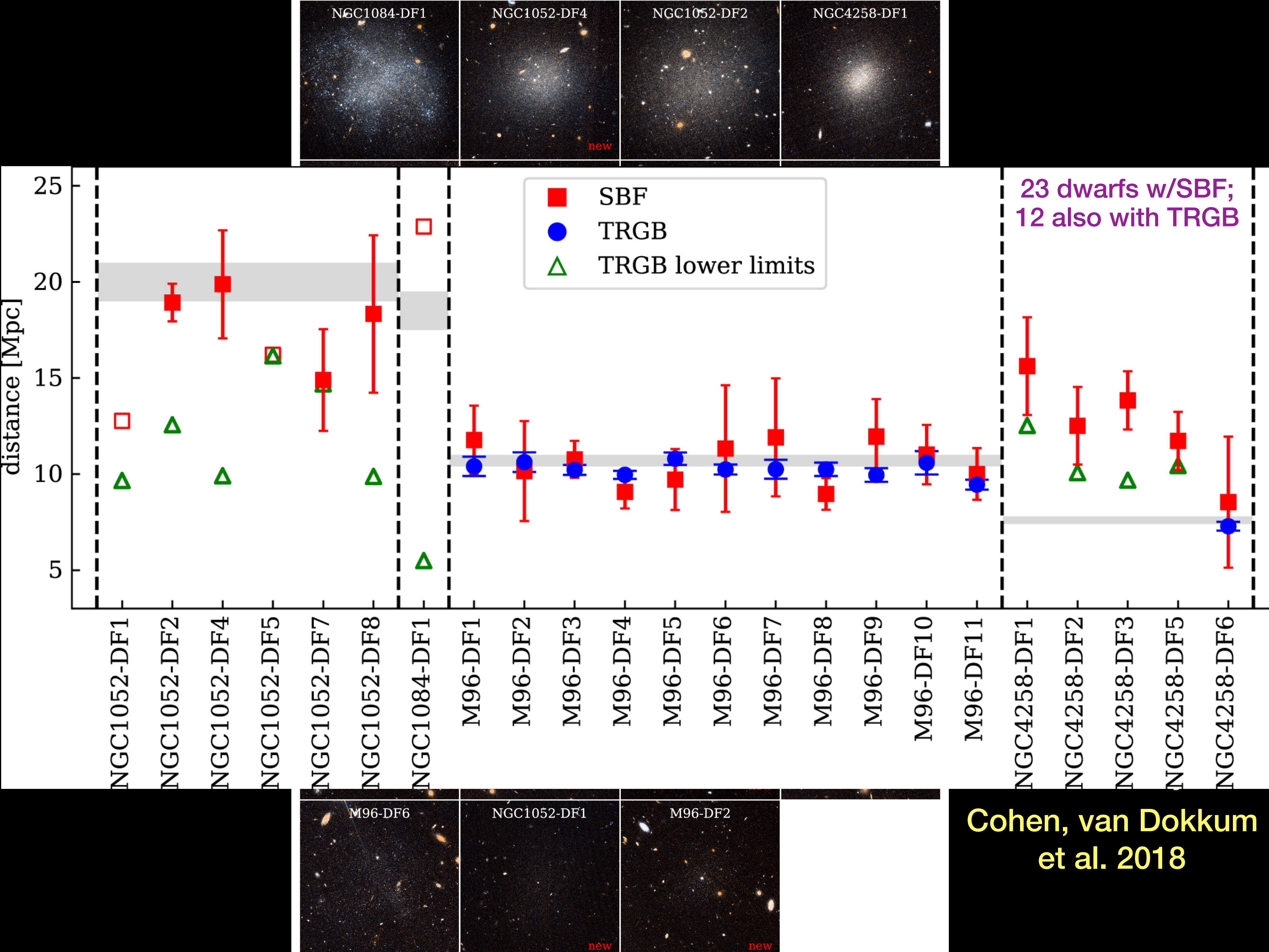


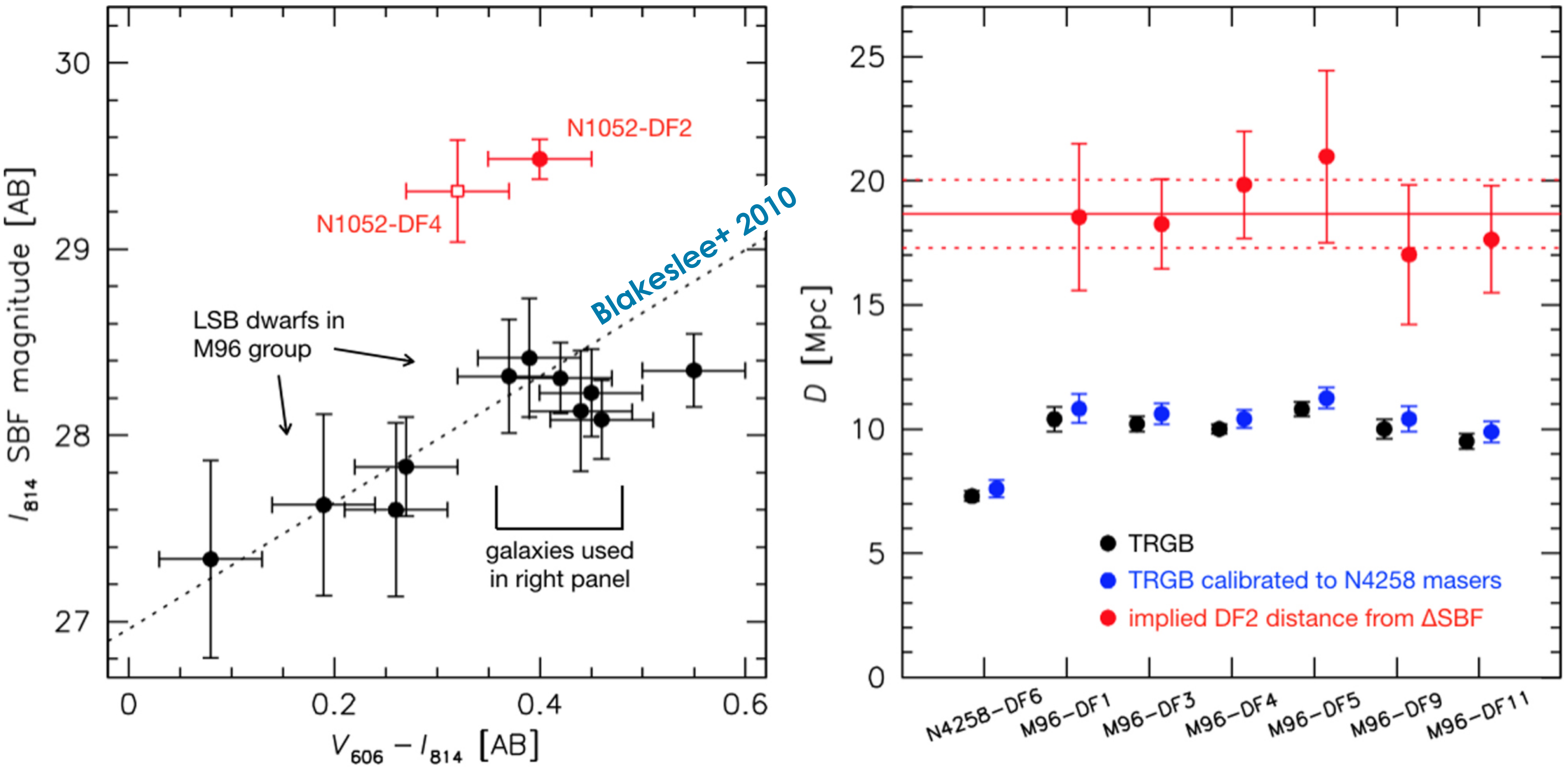

**Figure 1 | HST/Advanced Camera for Surveys (ACS) image of**




23 diffuse dwarfs studied by Cohen, van Dokkum et al. 2018

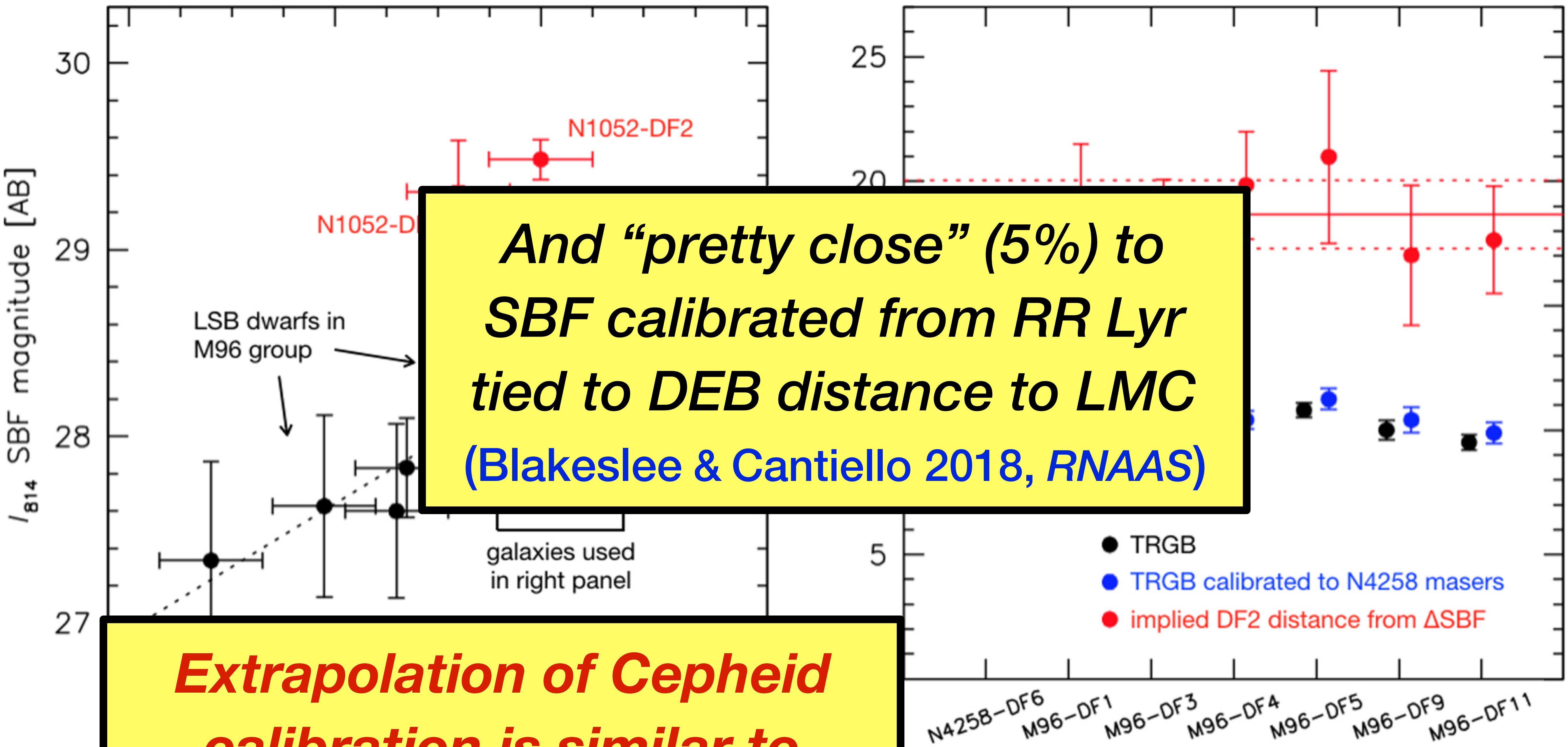

NGC1084-DF1
NGC1052-DF4
NGC1052-DF2
NGC4258-DF1
new
SBF
TRGB
TRGB lower limits
23 dwarfs w/SBF;
12 also with TRGB
distance [Mpc]
25
20
15
10
5
NGC1052-DF1
NGC1052-DF2
NGC1052-DF4
NGC1052-DF5
NGC1052-DF7
NGC1052-DF8
NGC1084-DF1
M96-DF1
M96-DF2
M96-DF3
M96-DF4
M96-DF5
M96-DF6
M96-DF7
M96-DF8
M96-DF9
M96-DF10
M96-DF11
NGC4258-DF1
NGC4258-DF2
NGC4258-DF3
NGC4258-DF5
NGC4258-DF6
M96-DF6
NGC1052-DF1
M96-DF2
new
new
Cohen, van Dokkum
et al. 2018

# SBF calibration via TRGB anchored to maser galaxy




van Dokkum et al. 2018

# SBF calibration via TRGB anchored to maser galaxy



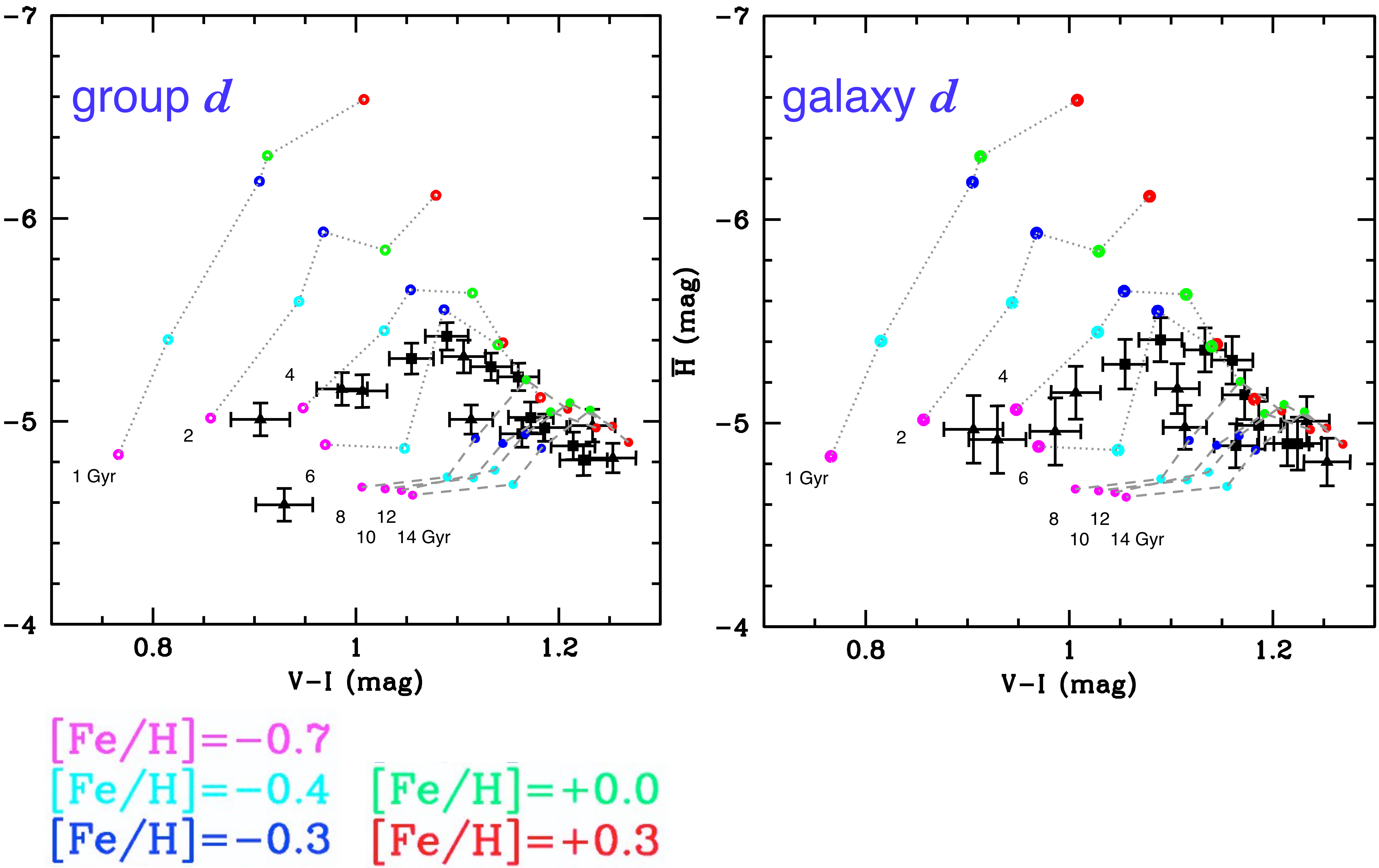

*And "pretty close" (5%) to SBF calibrated from RR Lyr tied to DEB distance to LMC*

(Blakeslee & Cantiello 2018, *RNAAS*)

***Extrapolation of Cepheid calibration is similar to result from TRGB+NGC4258***

van Dokkum et al. 2018

# A direct WFC3/IR SBF calibration to get $H_0$?



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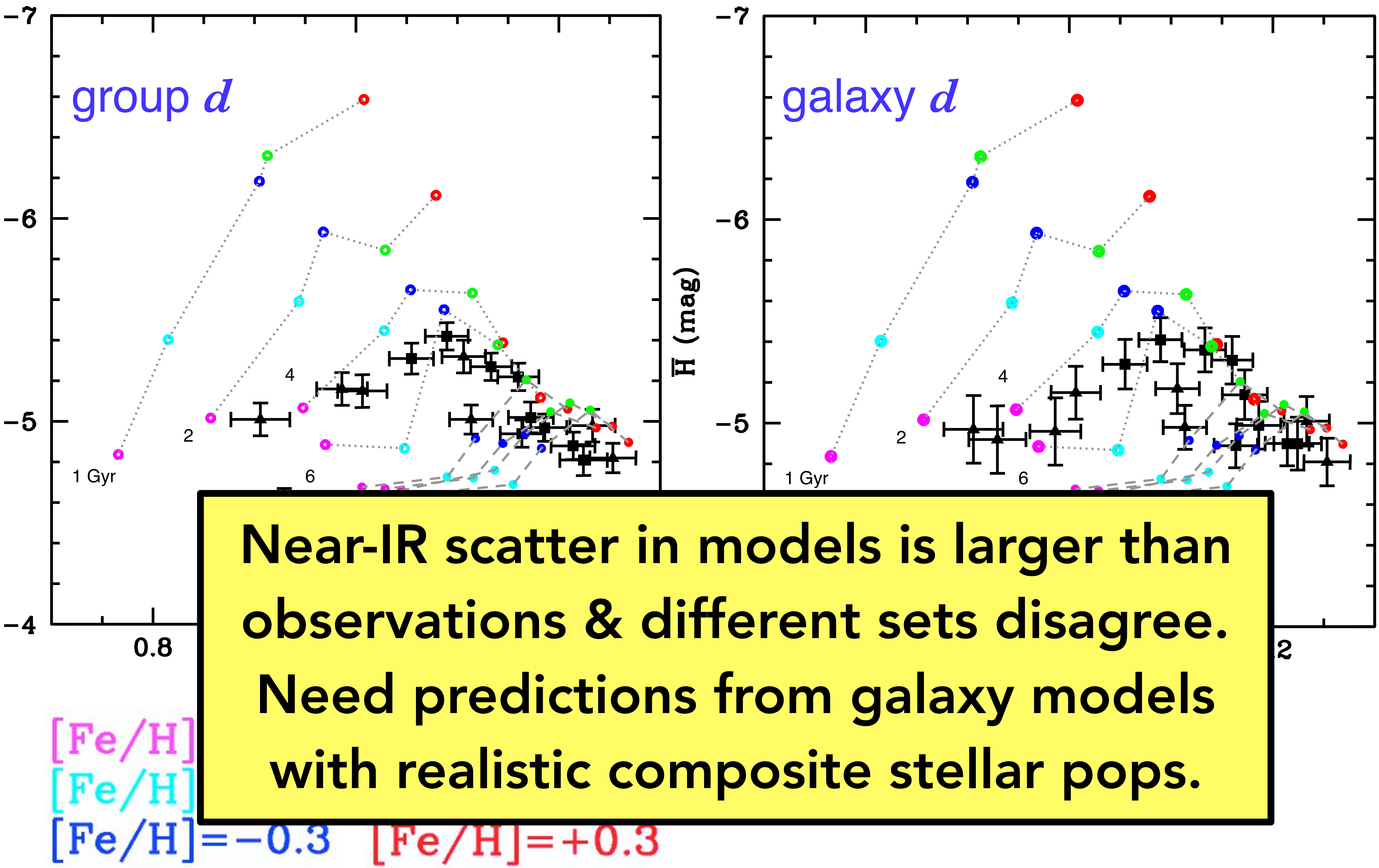
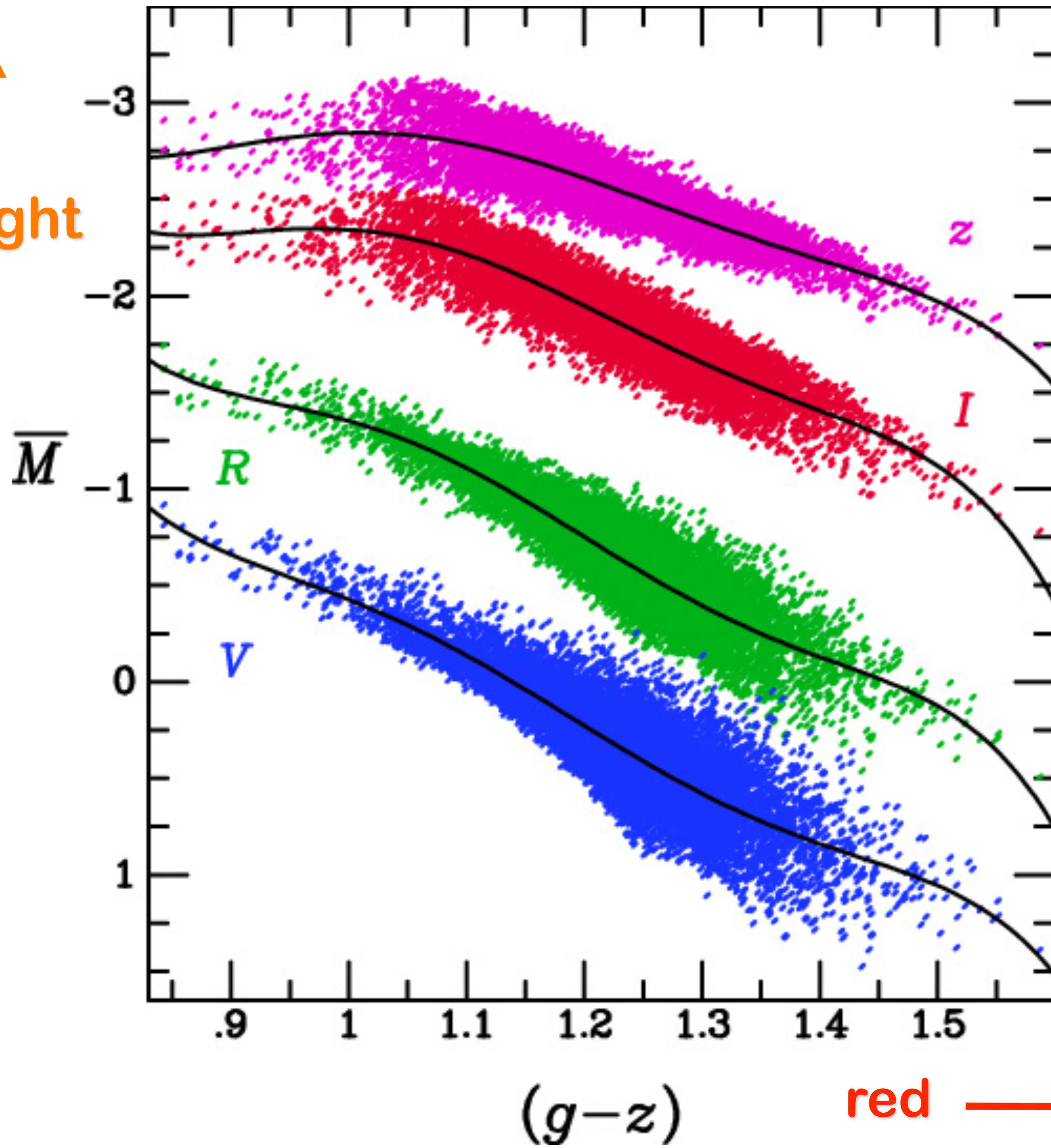



**Near-IR scatter in models is larger than observations & different sets disagree. Need predictions from galaxy models with realistic composite stellar pops.**

# SBF "fluctuation magnitude" versus (g-z) color: composite stellar population VRIz predictions

bright




red

*z* band SBF bright; along linear part at g-z > 1.1 mag, predicted scatter ~0.06 mag scatter.

Blakeslee, Vazdekis, & Ajhar (2001) composite models.

*“The Future ain’t what it used to be.”*

– Yogi Berra

# EHT Collaboration 2019, Paper VI, App. I

| Method | Measurement Type | Units | Value | References |
|---|---|---|---|---|
| TRGB | $D$ | Mpc | $16.75^{+1.11}_{-1.04}$ | Bird et al. (2010) |
| SBF | $D$ | Mpc | $16.67^{+1.02}_{-0.96}$ | Blakeslee et al. (2009) |
| SBF | $D$ | Mpc | $16.98^{+0.96}_{-0.91}$ | Cantiello et al. (2018a) |
| Gas dynamics | $\theta_{\rm dyn}$ | $\mu$as | $2.05^{+0.48}_{-0.16}$ | Walsh et al. (2013) |
| Stellar dynamics | $\theta_{\rm dyn}$ | $\mu$as | $3.62^{+0.60}_{-0.34}$ | Gebhardt et al. (2011) |

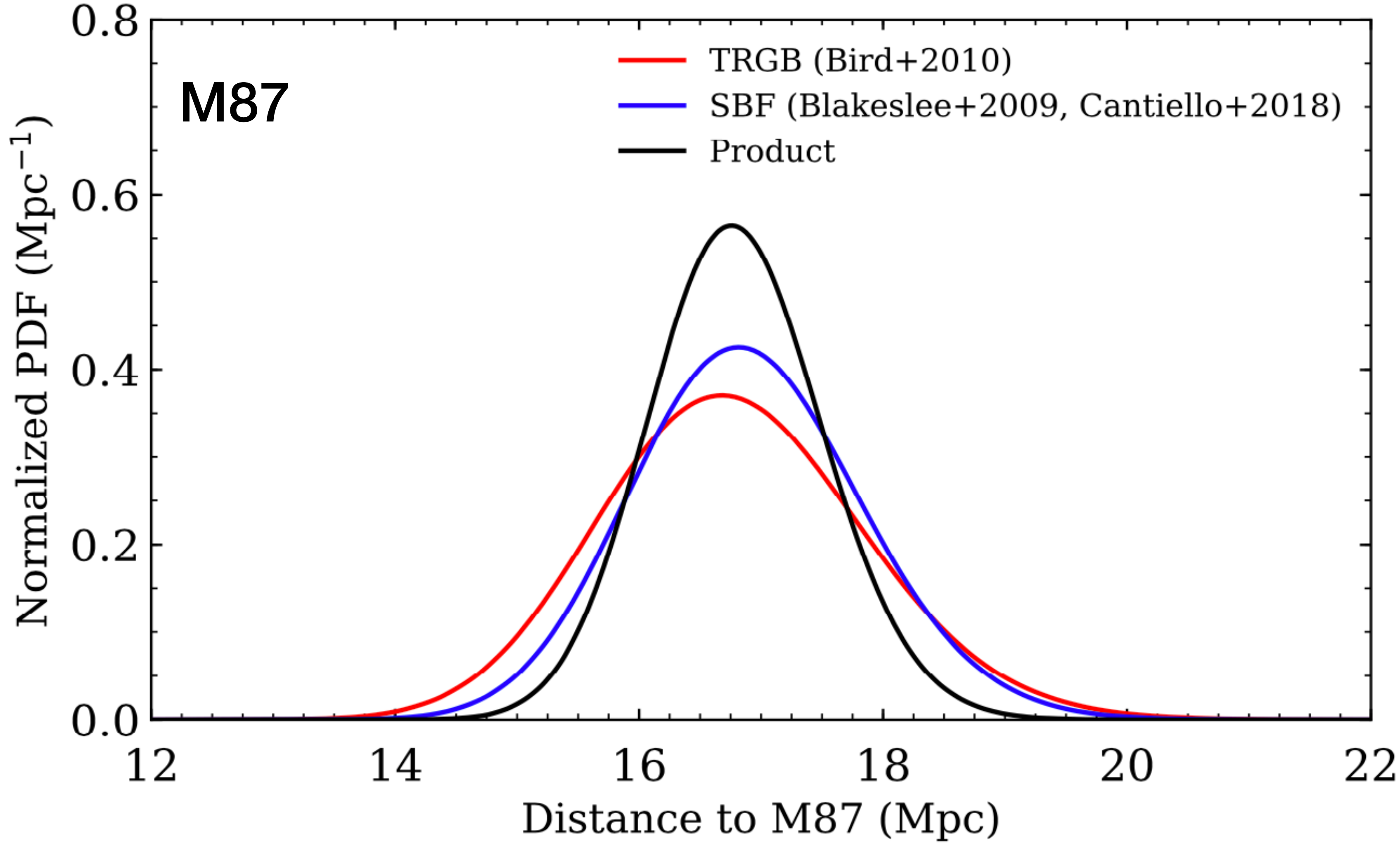



**Figure 31.** Normalized posteriors for the distance measurements to M87. Two colored lines show the posterior from the measurements using the TRGB method (Bird et al. 2010) and combined posterior from the SBF method (Blakeslee et al. 2009; Cantiello et al. 2018a). The black line shows the normalized product of three posteriors obtained by combining these measurements.

# EHT Collaboration 2019, Paper VI, App. I

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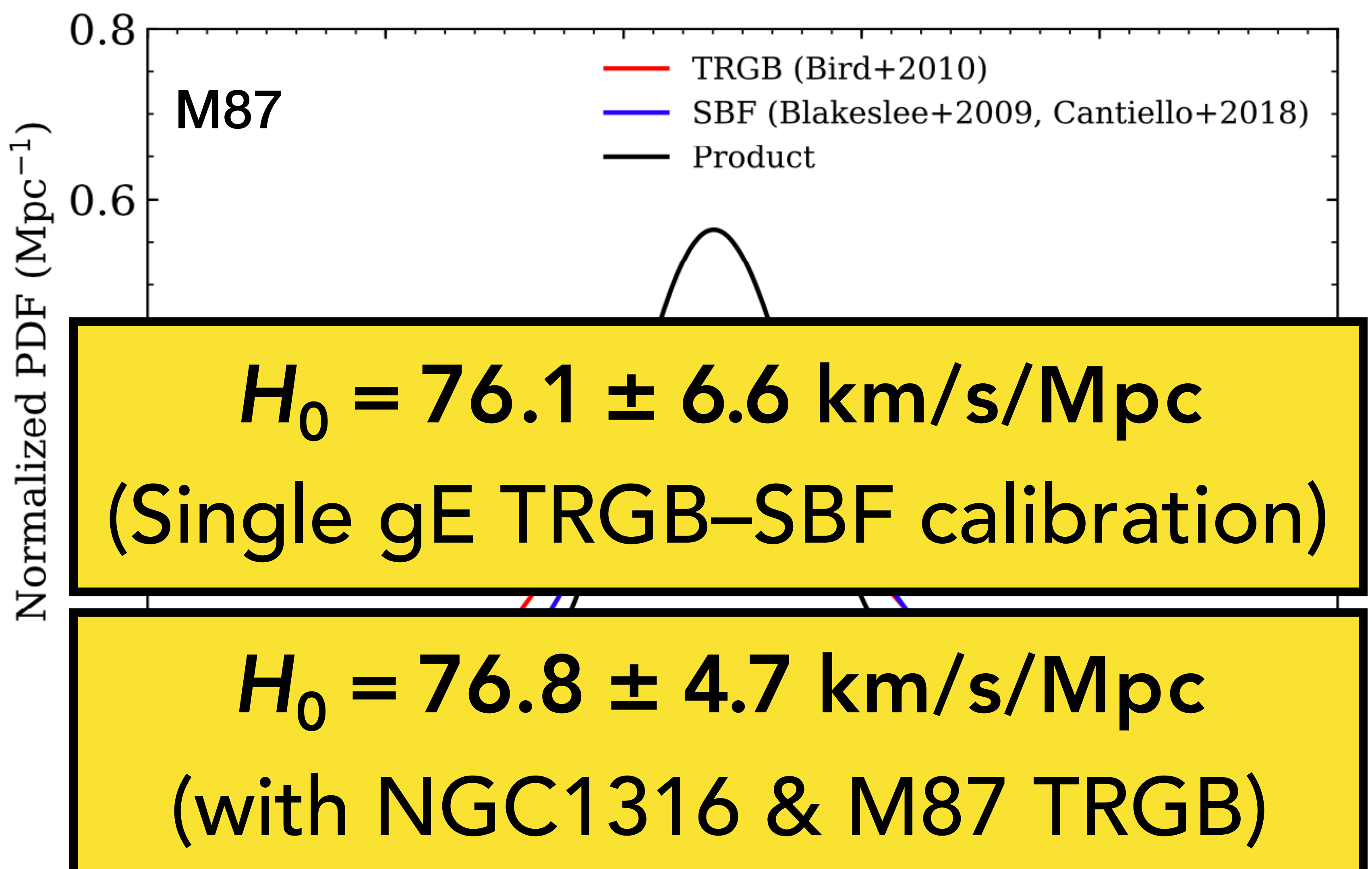
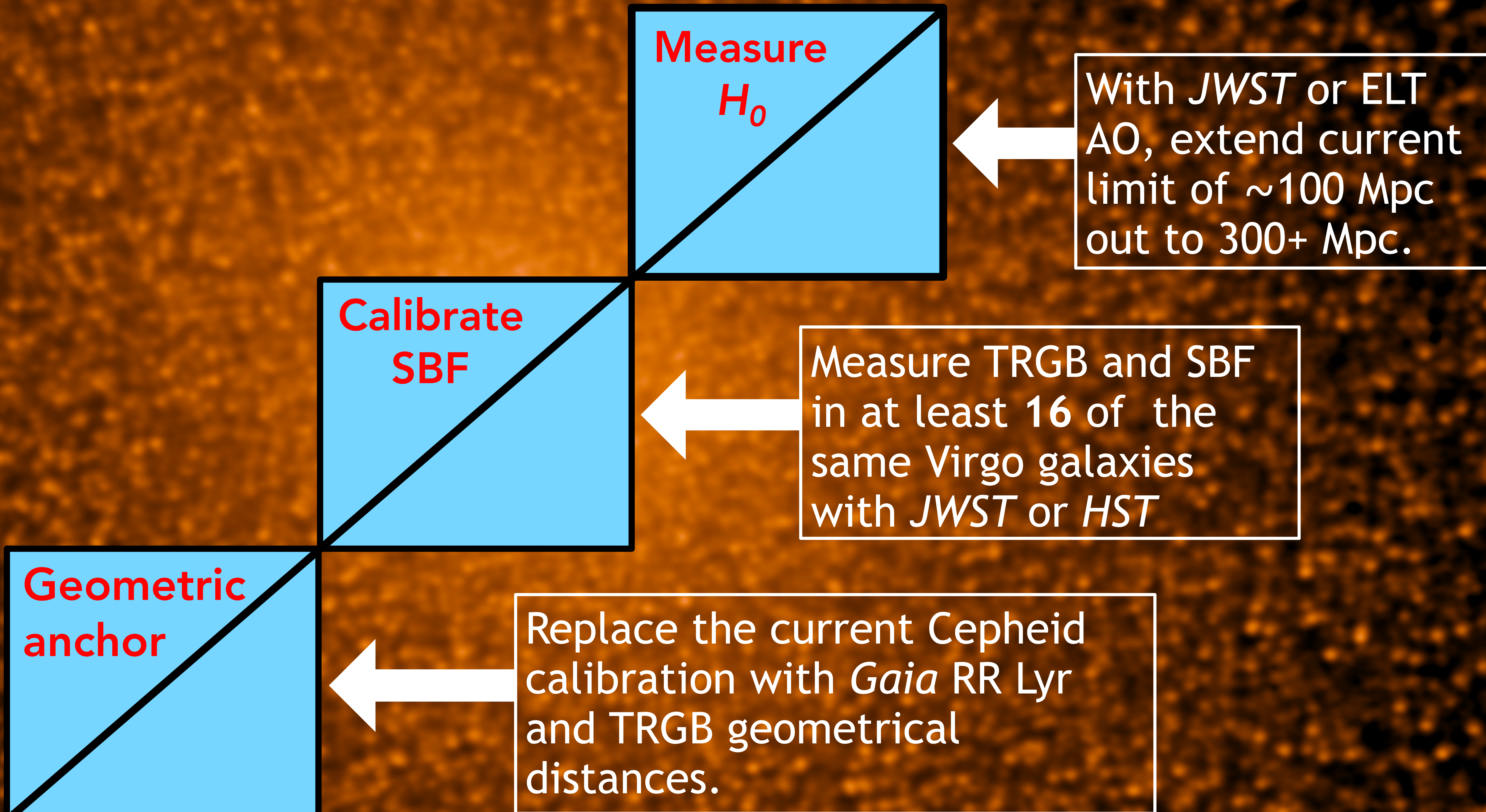



**Figure 31.** Normalized posteriors for the distance measurements to M87. Two colored lines show the posterior from the measurements using the TRGB method (Bird et al. 2010) and combined posterior from the SBF method (Blakeslee et al. 2009; Cantiello et al. 2018a). The black line shows the normalized product of three posteriors obtained by combining these measurements.

# *Towards a 2% $H_0$ from SBF…*




*In parallel, use realistic galaxy models to predict SBF zero points.*