The TRGB and the Hubble Constant

Myung Gyoon Lee

with **In Sung Jang** (AIP)

Department of Physics & Astronomy

Seoul National University (SNU), Korea

The 7th Survey Science Workshop,

Jan 15-17, 2018, High-1 Resort, Korea

H_0

Today's Expansion rate of the Universe

Two Ways to Estimate H_0

- $H(t=t_0)$
  - cosmic distance ladder

- $H(z) \rightarrow H(t_0)$
  - inverse distance ladder (CMBR, BAO)

Cosmic Distance ladder for H_0

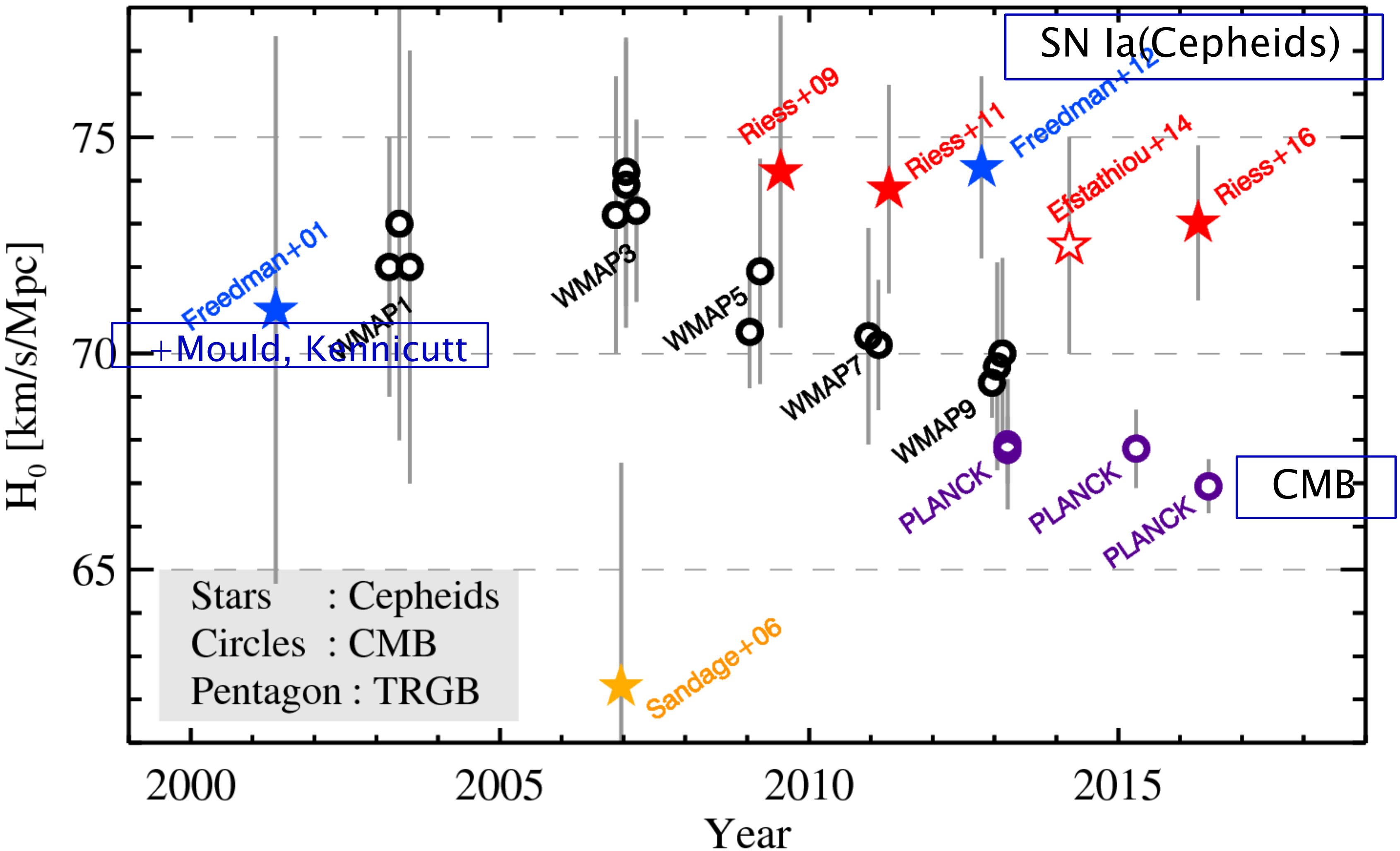
- SN Ia Cosmology->$H(t_0)$
- Calibration of SN Ia:
  - Cepheids based on geometric anchors

The status of H_0 in 2016

- Cepheids have been used to calibrate SN Ia.

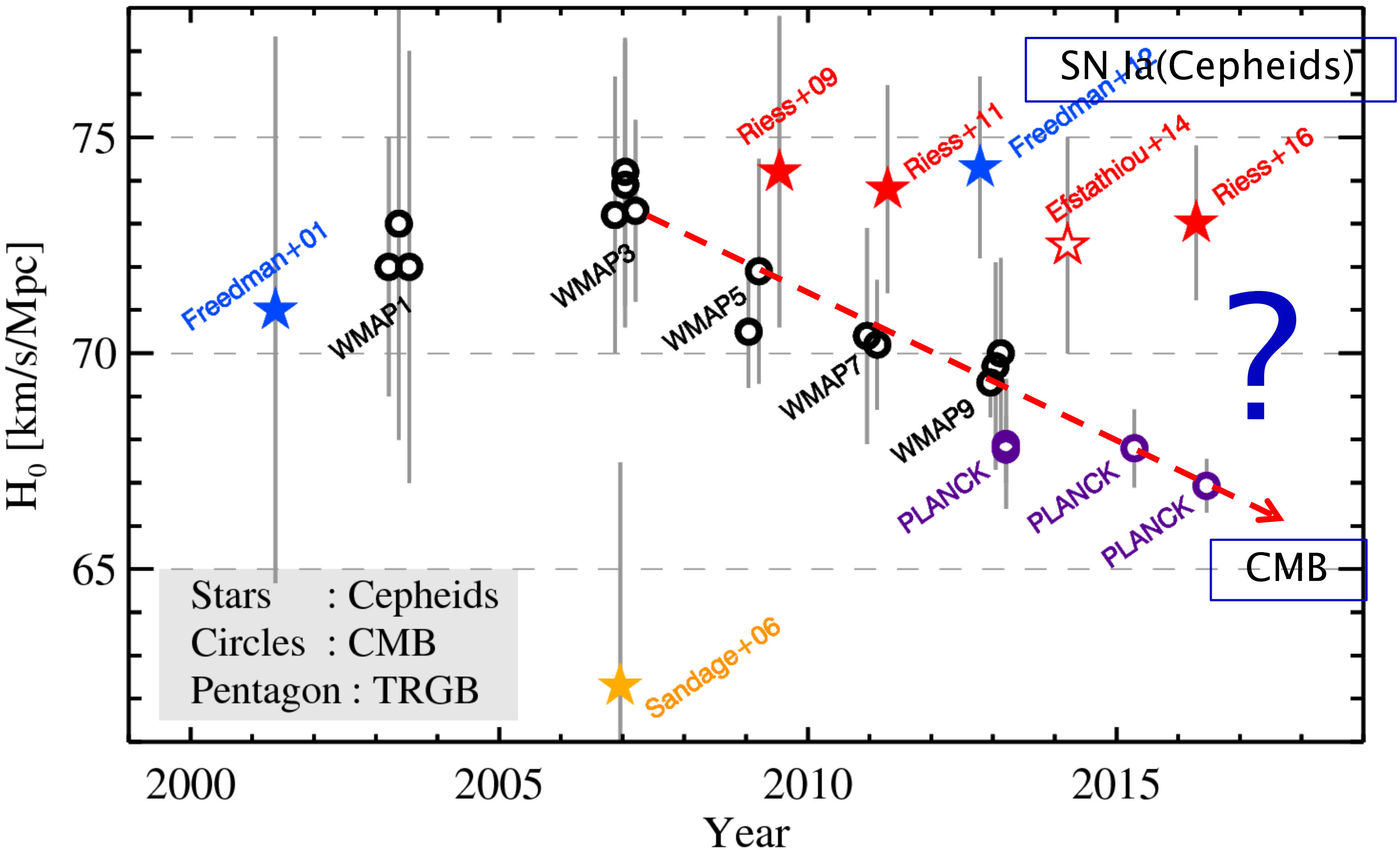
- Cepheid-calibrated SN Ia & CMB are diverging in H_0 estimates!

Recent Evolution of H_0 (−2016)



The Hubble Tension in 2016?

- Four possibilities: xo, ox, xx, oo?



How to check the problem?

- By independent calibration of SN Ia using the TRGB!

Cosmic Distance ladder for H_0

- SN Ia Cosmology->$H(t_0)$
- Calibration of SN Ia:
  - Cepheids based on geometric anchors
  - TRGB based on geometric anchors

A Brief History of the TRGB

In 1944, Baade started!

- The resolution of M32, NGC 205 & the central region of M31.
- Resolved stars are similar to those of globular clusters (Pop II).
- Mpg (TRGB) = -1.1 mag

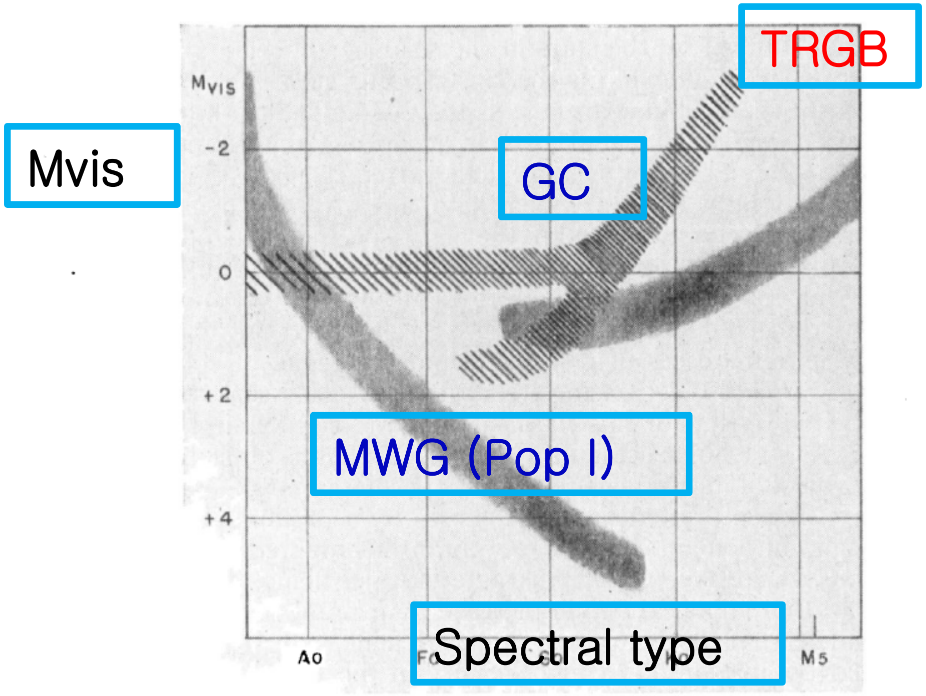


FIG. 1.—Shaded areas: ordinary H-R diagram (type I). Hatched area: H-R diagram of stars in globular clusters (type II).

In 1990s, Modern era of the TRGB began!

The TRGB has become popular as a precise distance indicator, due to following factors.

(1) Edge detection and the TRGB precision

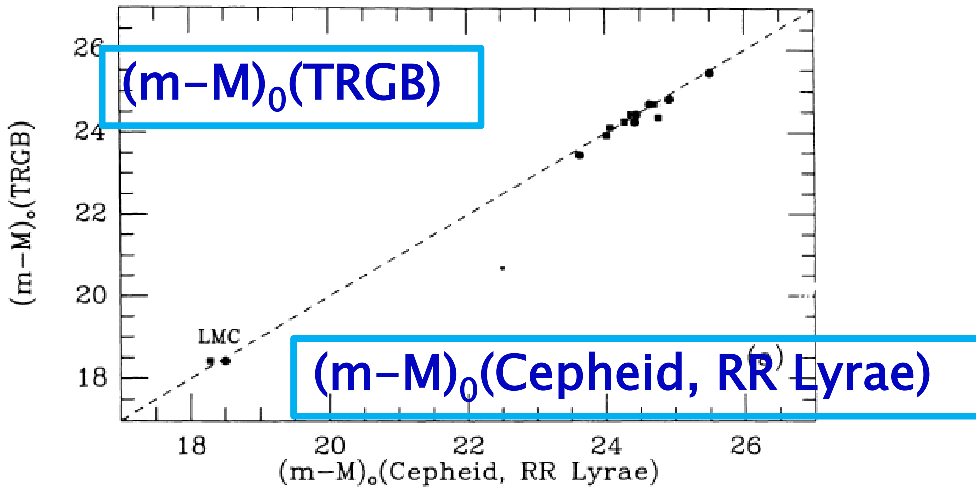
Lee, Freedman, & Madore (1993)
"The TRGB as a Distance Indicator for Resolved Galaxies"

-an edge detector (Sobel filters) for the TRGB measurement,

-the precision of the TRGB is comparable to that of Cepheids.

$-M_I(\mathrm{TRGB}) = -4.0 \pm 0.1$

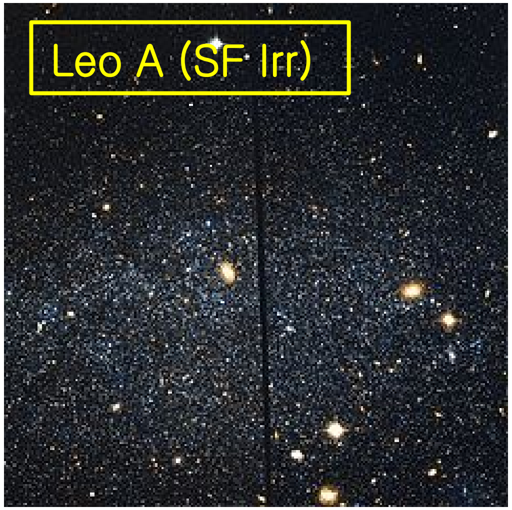
(2) Advent of HST (1990-)



Today,
the TRGB is
a powerful tool for SN cosmology
to determine the Hubble Constant!

(Beaton+2016, Jang & Lee2017a,b and references therein).

Strengths of the TRGB

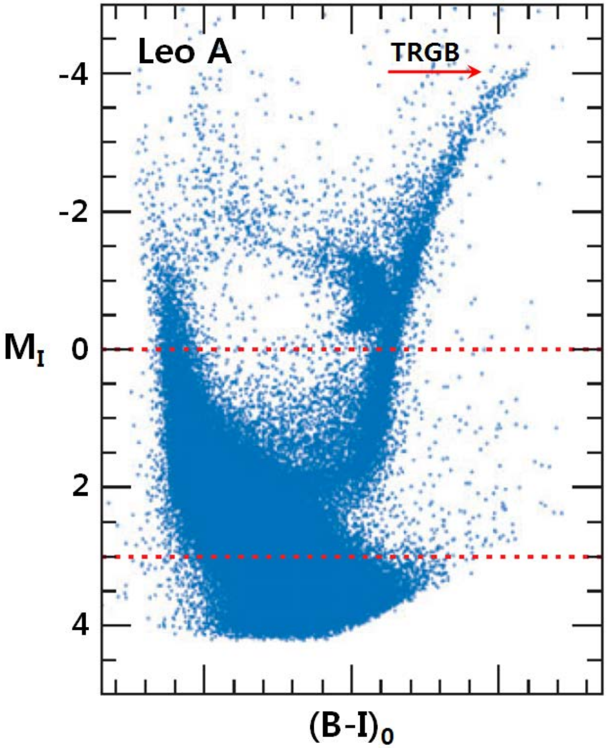


SN Ia are found in all types of galaxies. Galaxies have stars with a large range of ages, including many old stars!

(1) The TRGB can be used
for any types of resolved galaxies.

(2) Suffers little extinction problem.

(3) for d<35 Mpc with HST (2017).



Leo A (SF Irr)
Tolstoy (2009)

TRGB Calibration of SN

TIPSNU:

The Tip of the RGB
for SN host galaxies
in the Universe
at Seoul National University!

How to reduce the errors?

(1) Improving the accuracy and the precision of the TRGB.

(2) Increasing the sample of SN Ia for calibration.

New TRGB Calibration (2017)

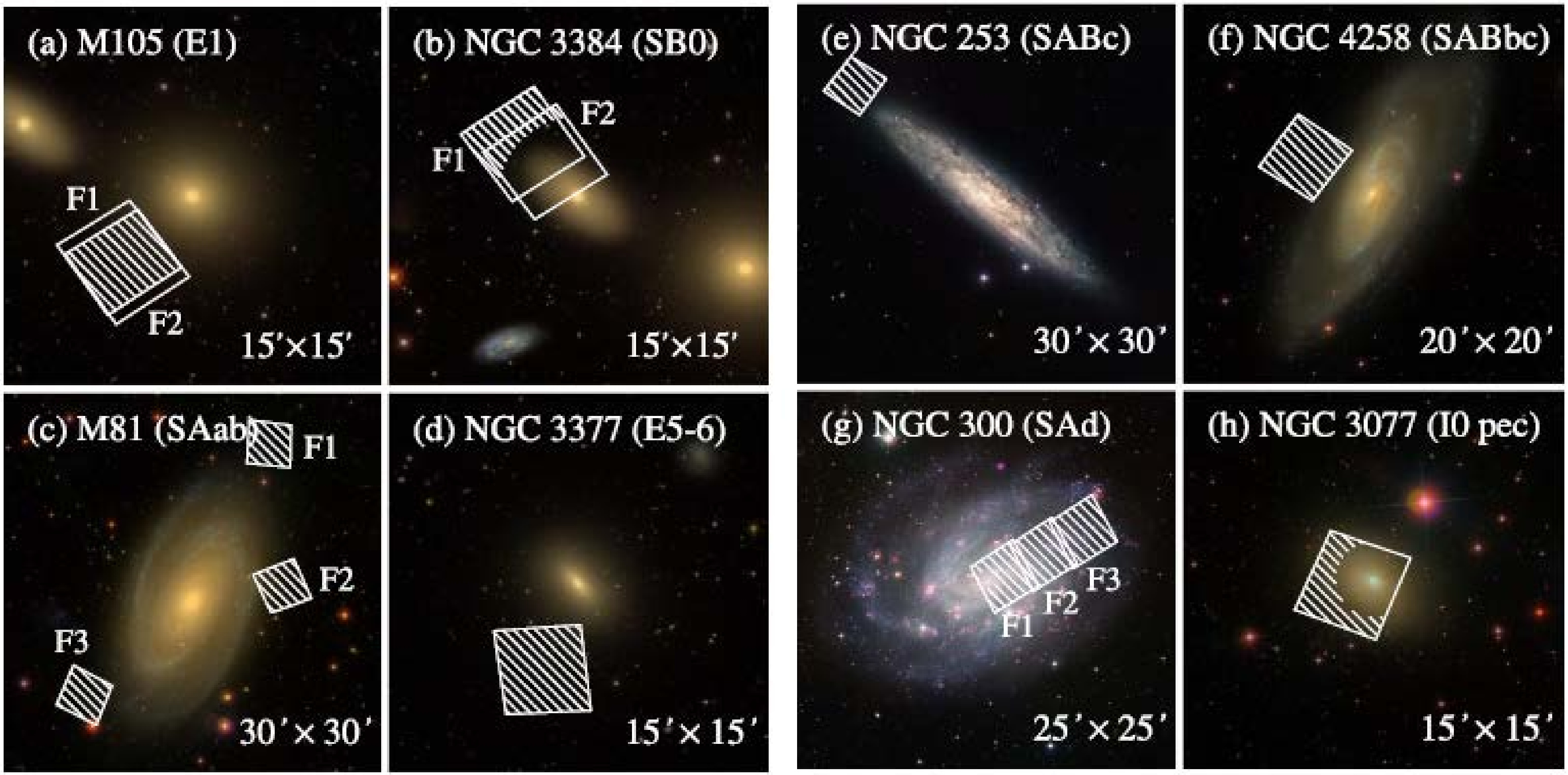
TIPSNU IV. (Jang & Lee 2017a, ApJ, 835, 28)

(1) Higher Precision

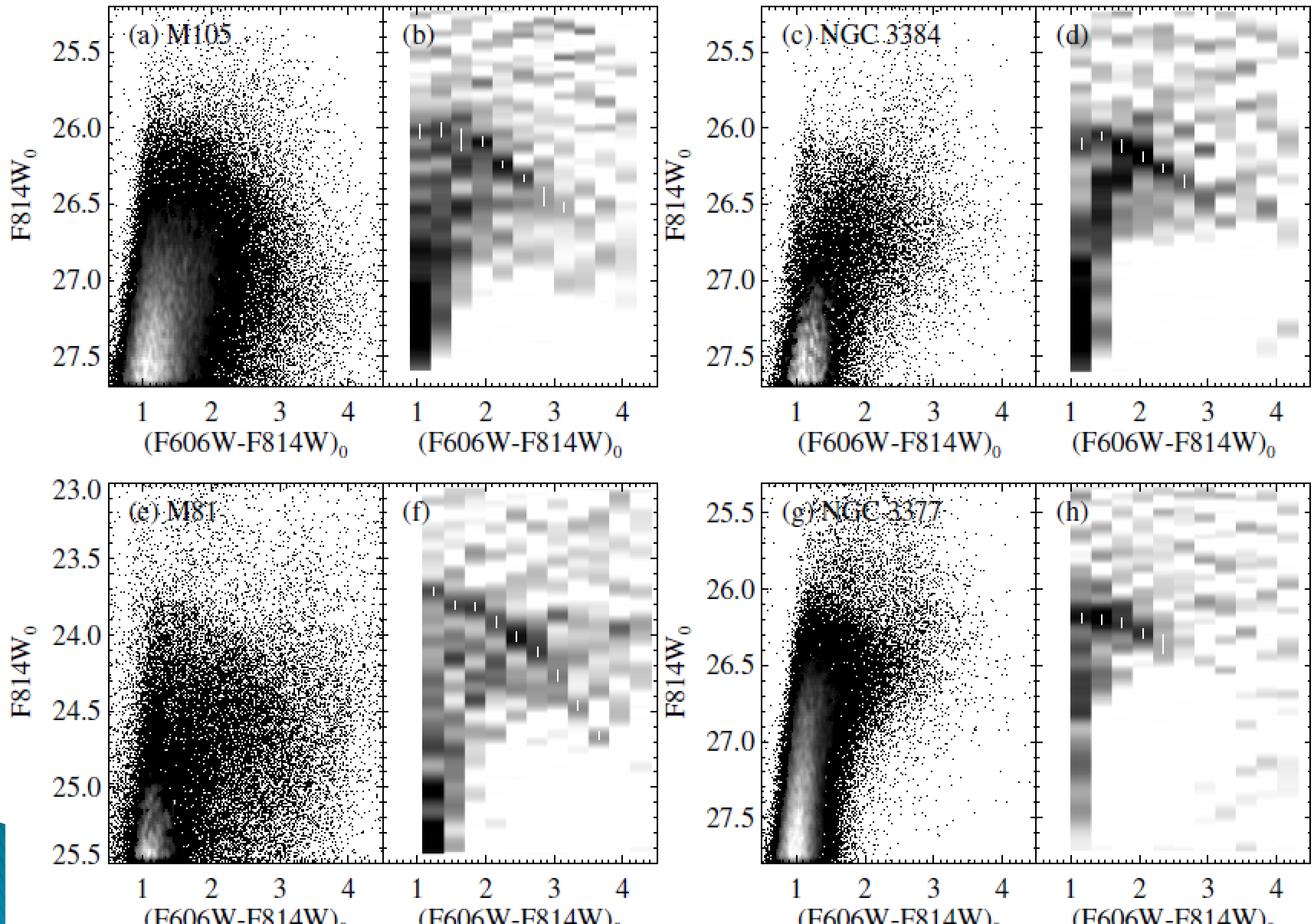
- deriving TRGBs for a large range of color
- introducing QT magnitude, which is a color-independent magnitude of the TRGB.
- using the Sobel filter for edge detection.
- typical measuring error of the TRGB: ~0.02mag

New TRGB Calibration: TRGB-Color

- Targets: nearby galaxies of various types (E, Irr, S) with deep HST images



CMDs and Edge maps of Galaxies



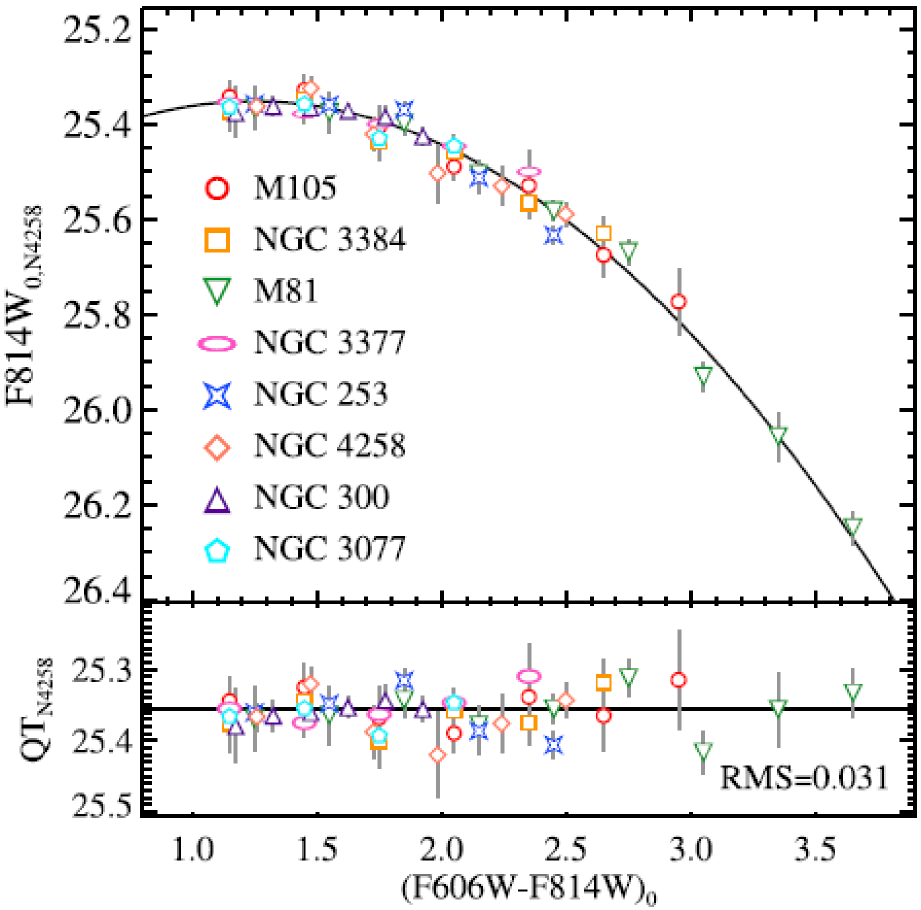
New TRGB –Color Relation

TIPSNU IV.
(Jang & Lee 2017a)

- –Derived QT magnitude, which is a color-independent magnitude of the TRGB:

$QT = I_0 - 0.091((V-I)_0 - 1.5)^2 + 0.007((V-I)_0 - 1.5)$

- –using blue RGBs
- –typical measuring error of TRGB: ~0.02mag



New TRGB Calibration: zero point

TIPSNU IV. (Jang & Lee 2017a, ApJ)

(2) Higher Accuracy

–Previous calibrations are based on HBs in MW GCs or Local Group galaxies.

–In contrast, TIPSNU uses two distance anchors with geometric distance estimates.

–systematic error of the TRGB distance: ~2.7%

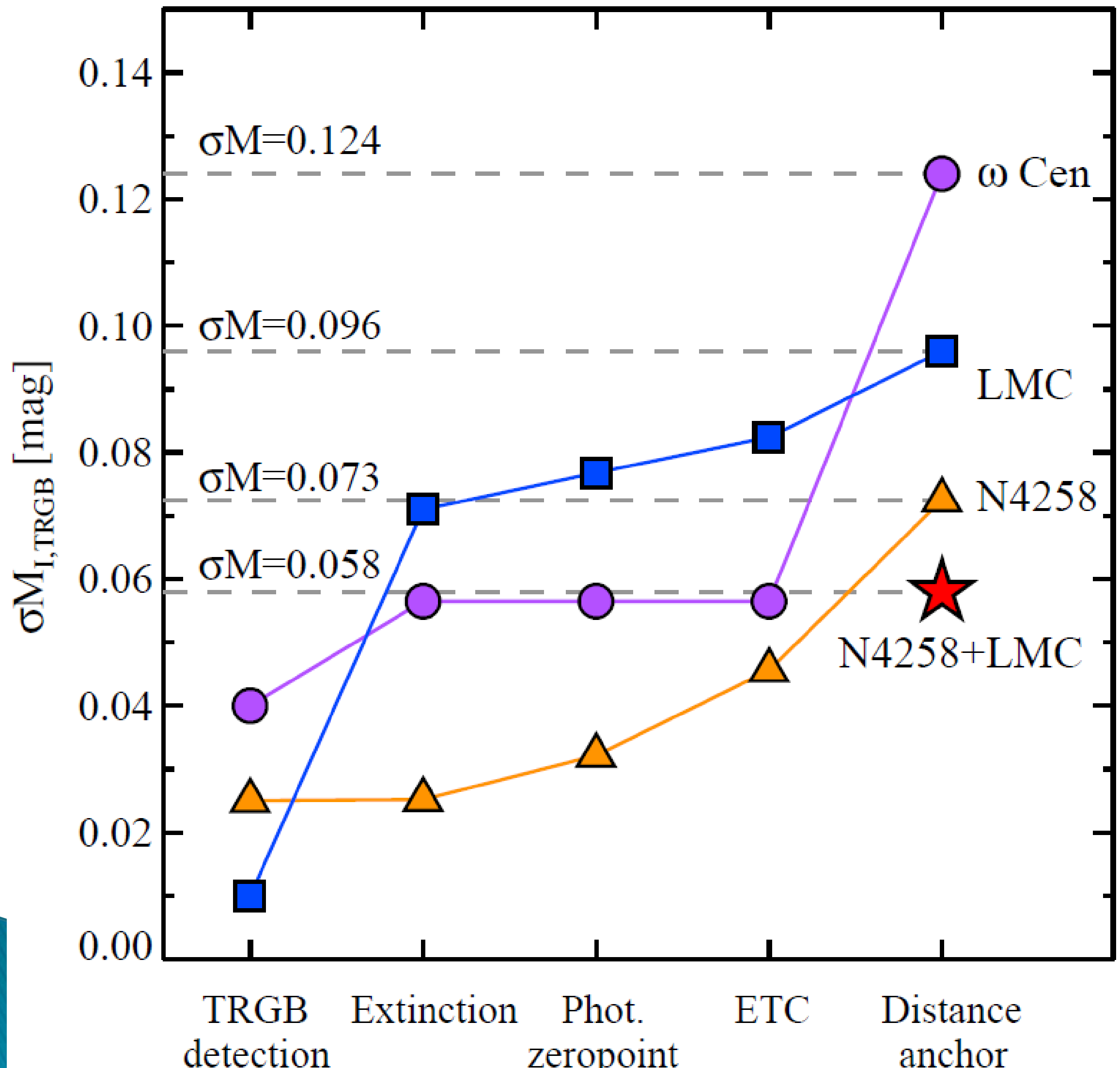
Zero-point calibration of the TRGB

- Two distance anchors **with accurate geometric distances**

1) NGC 4258 (M106, based on H_2O Megamasers)

2) The LMC (based on 8 eclipsing binaries)

Error budget for zero point error



$M_I = -4.05 \pm 0.12$
(Bellazzini+01)

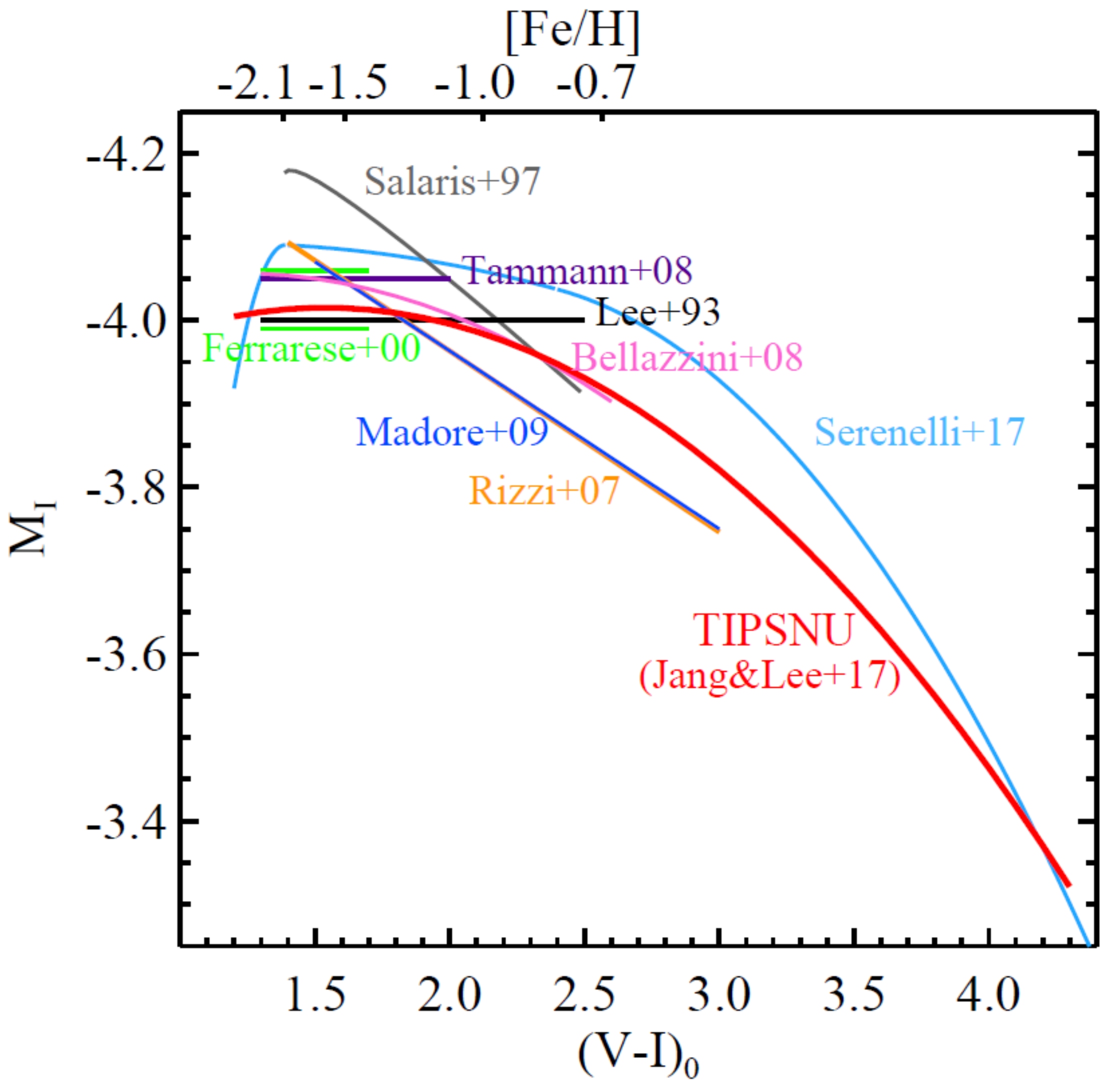
$M_I = -4.004 \pm 0.096$
$= -4.030 \pm 0.073$

$M_I = -4.016 \pm 0.058$
(Our best estimate)

"Accurate to 2.7% of distance"

Comparison of TRGB Calibrations

- Excellent agreement with Lee+(1993) for low metallicity!
- Note that they based on totally independent calibrations!



TIPSNU for H_0 in 2017

- TIPSNU.V. (Jang & Lee2017b, ApJ, 836,74)

TRGB Calibration of SN Ia

TIPSNU
(The Tip of the RGB for SN host galaxies in the Universe)

Criteria for targets
-Galaxies at <40 Mpc hosting SN Ia with HST images
-with modern photometry of SN Ia
-with low extinction
In 2017: N(SN Ia)=8

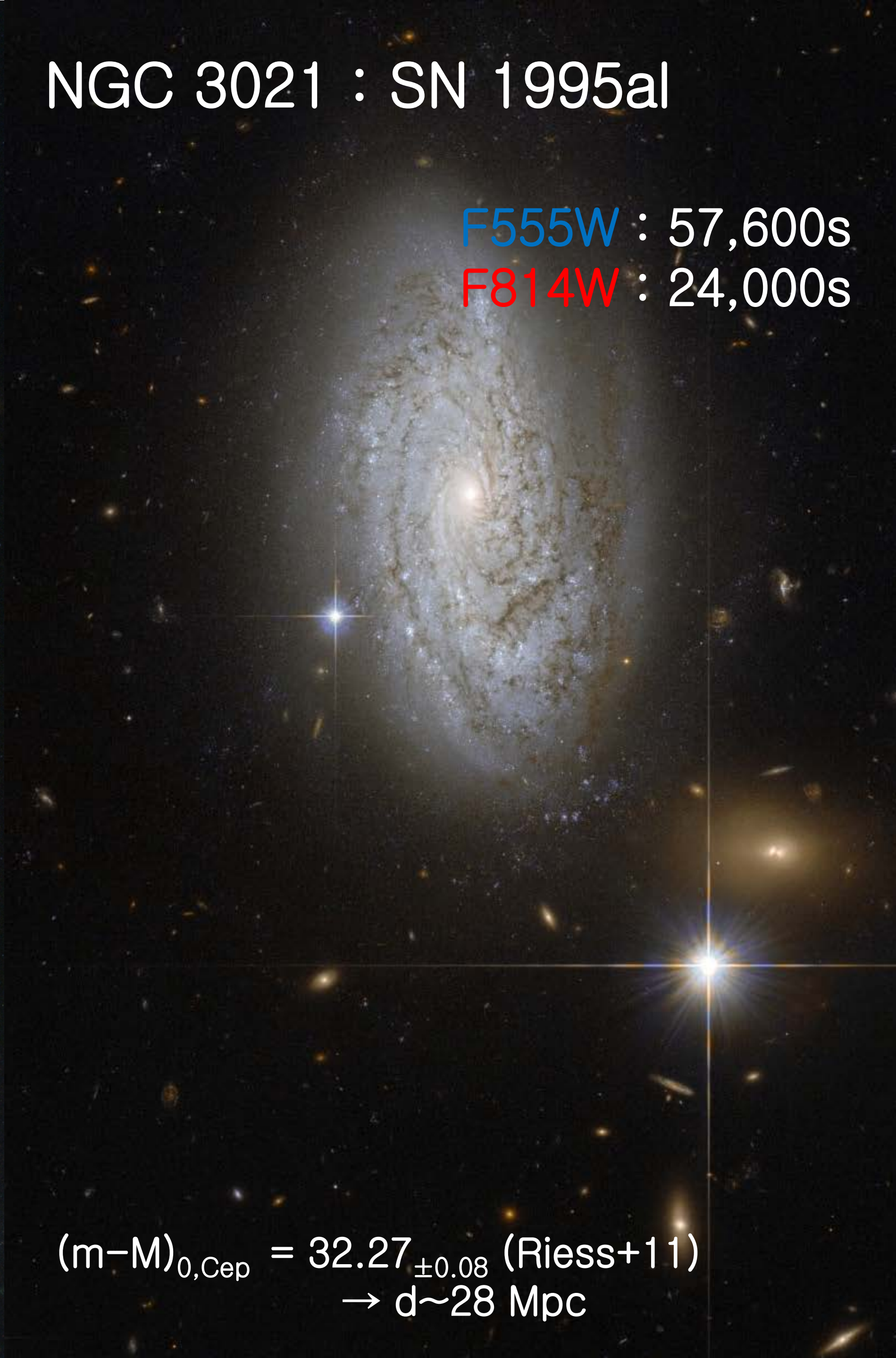
Current Progress:

I:	M101	(Lee & Jang 2012, ApJL, 760, L14)
II:	M66 and M96	(Lee & Jang 2013, ApJ, 773, 13)
III:	NGC 4038/39, NGC 5584	(Jang & Lee 2015, ApJ, 807, 133)
IV:	New TRGB calibration	(Jang & Lee 2017a, ApJ, 835, 28)
V:	NGC 3021 and others	(Jang & Lee 2017b, ApJ, 836, 74)

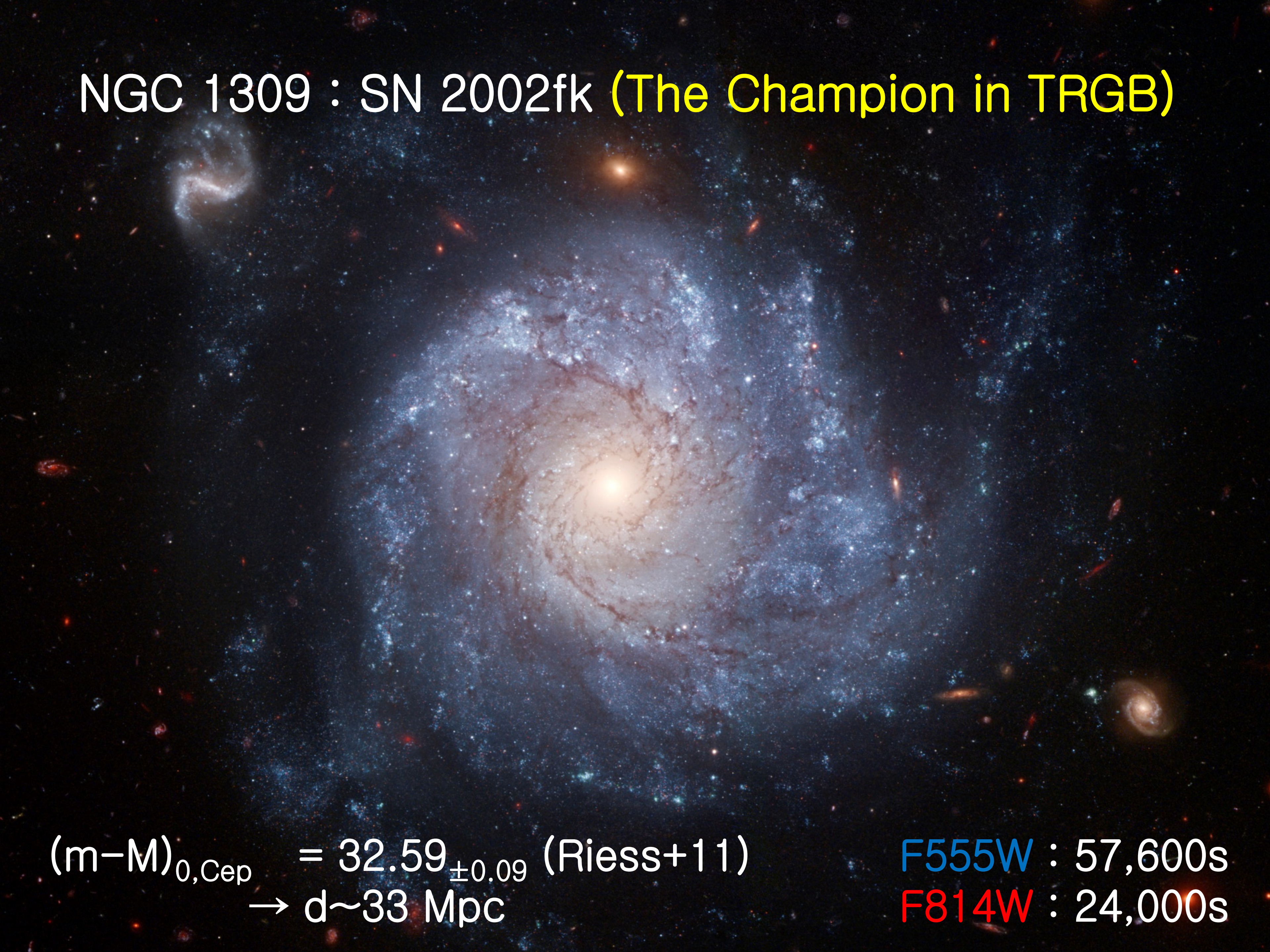
Three distant galaxies at ~30Mpc!

- Impossible to get TRGB distances?
- The most challenging sample for TRGB!


NGC 3370 : SN 1994ae
(m−M)0,Cep = 32.13±0.07 (Riess+11)
→ d~27 Mpc


NGC 3021 : SN 1995al
F555W : 57,600s
F814W : 24,000s
(m−M)0,Cep = 32.27±0.08 (Riess+11)
→ d~28 Mpc

NGC 1309 : SN 2002fk (The Champion in TRGB)



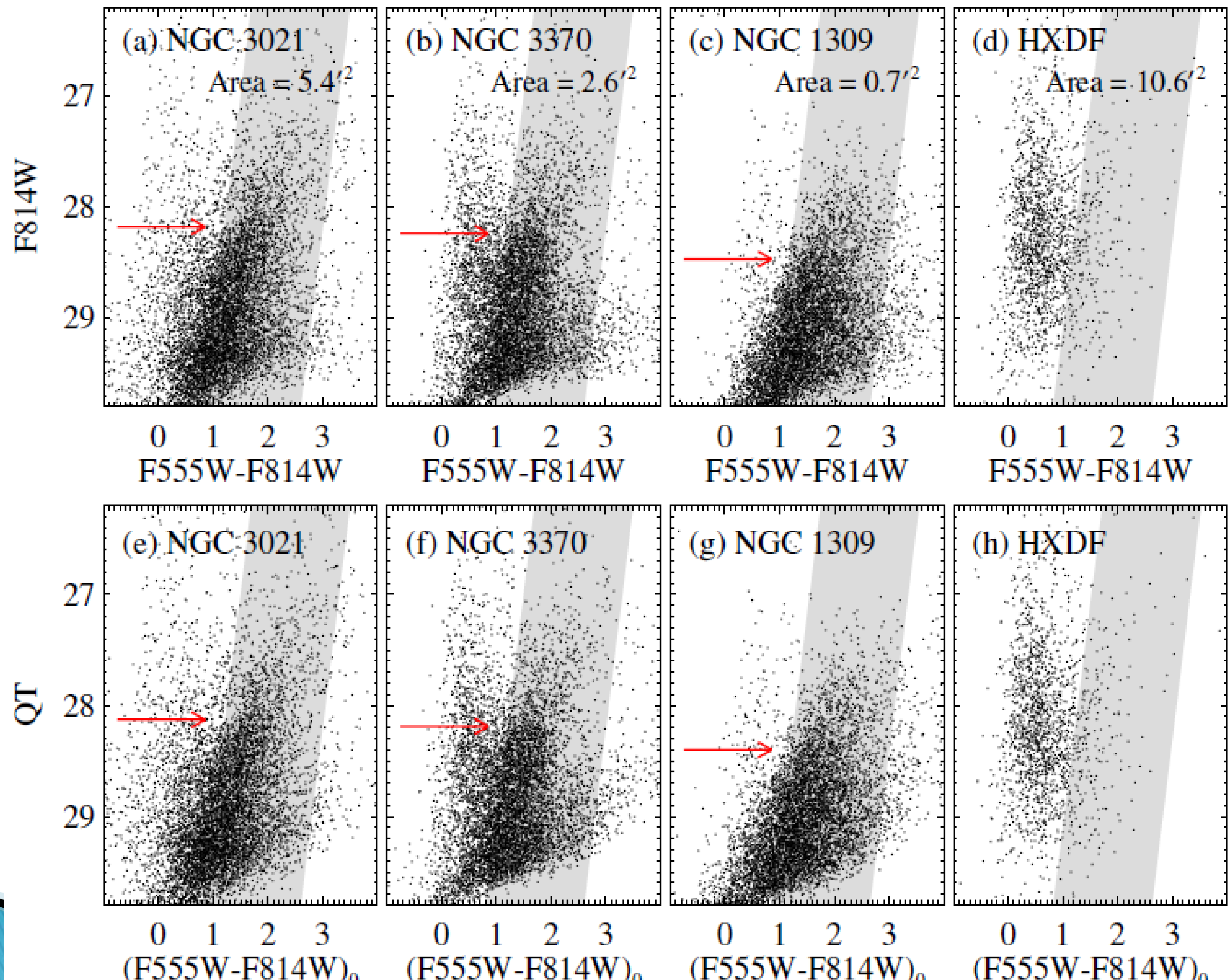
$(m-M)_{0,Cep} = 32.59_{\pm 0.09}$ (Riess+11)

→ d~33 Mpc

F555W : 57,600s

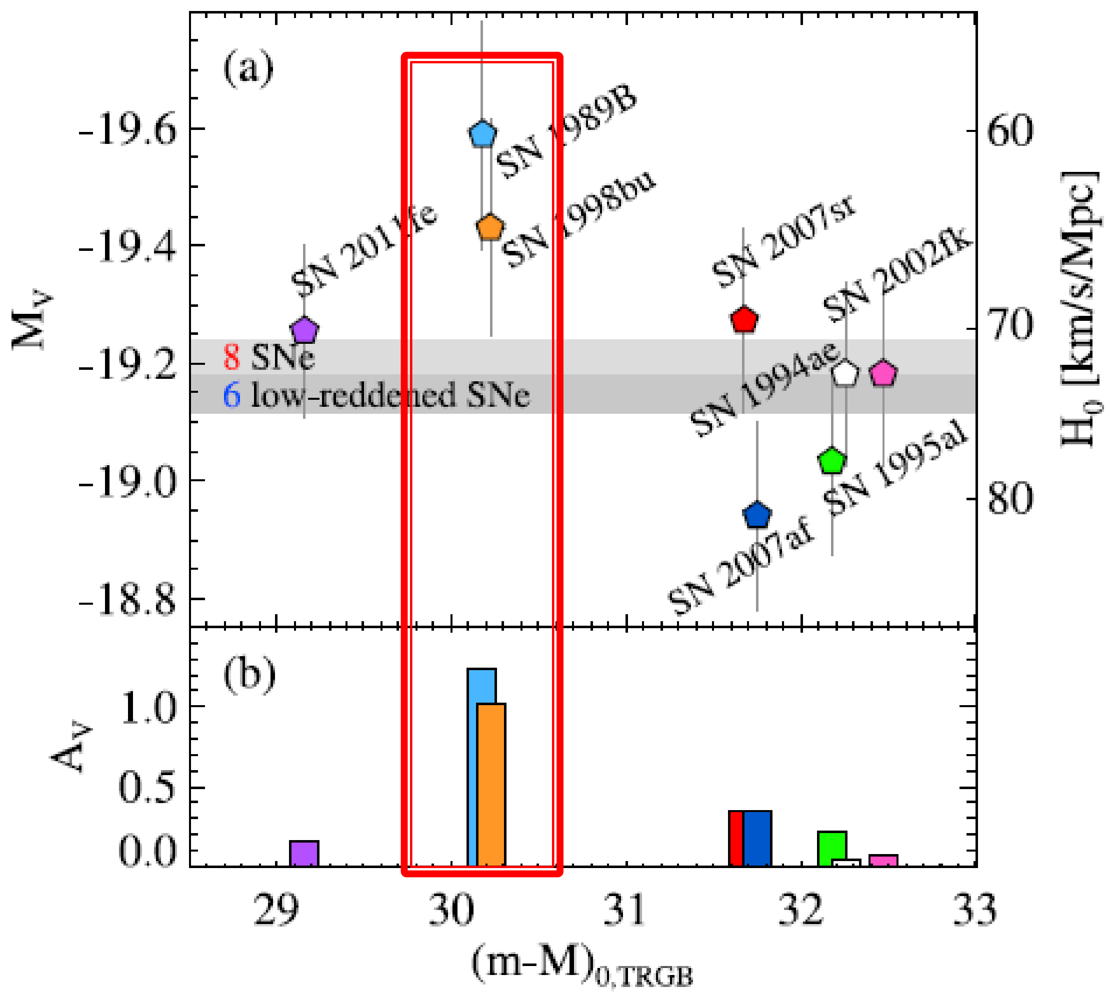
F814W : 24,000s

CMDs showing RGB stars!



Calibration of SN Ia with TRGB (TIPSNU)

- N (low reddened SN Ia) = 6
- M_V (SN Ia) = −19.15 ±0.06 (ran)±0.06(sys)



Cepheid–SN Ia calibration in 2016

Riess et al. (2016) Mega–SH0ES

'A 2.4% determination of the local value of H_0'

- ✓ Cepheid distance estimate: for 19 SN Ia
- ✓ SN Ia in nearby universe ($z<0.1$) : 233 SNe Ia
- ✓ H_0 = 73.24 ± 1.74 km/s/Mpc (2.4% error)

Riess et al. (2009, 2011) SH0ES

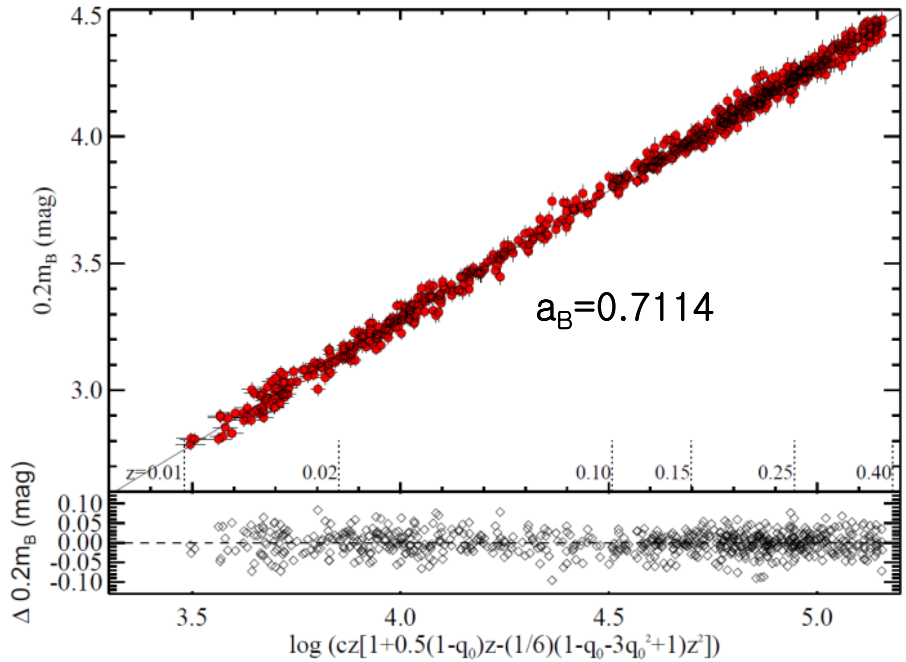
- ✓ Cepheid (MW,LMC) and Maser distance estimate : for 8 SN Ia
- ✓ SN Ia in nearby universe ($z<0.1$) : 140 SNe Ia
- ✓ H_0 = 73.8 ± 2.4 km/s/Mpc (4.1% error)

TRGB Calibration of SNe Ia and H_0

For the 6 low-reddened SN Ia,
We use $m_{B,corr}$(Riess+16)+ TRGB distances (Jang&Lee17).

SN Ia Hubble Diagram
for 233 SN Ia (Riess+16)

$$Log(H_0) = 0.2M_B + a_B + 5$$



Weighted Mean of 6 SNe :

$M_{B,corr}$ = −19.30 ±0.07 (±0.051$_r$ ±0.046$_s$ mag)

H_0= 71.2 ±2.5 (3.5%) (±1.66$_r$ ±1.87$_s$ km/s/Mpc)

Our best estimate!

TIPSNU H_0 in 2017

TIPSNU value (Jang & Lee2017b) based on M106 and LMC anchors

H_0 = 71.17 ± 2.50 km/s/Mpc (3.5% error)

is in excellent agreement with

(Riess+2016)'s value based on M106 and LMC,

H_0 = 71.61 ±1.78 km/s/Mpc,

but, is 1.07 km/s/Mpc smaller than

(Riess+2016)'s value based on four anchors (including M31, MW), H_0 = 73.24 ±1.74 km/s/Mpc (2.4% error).

Mystery for NGC 4038/39

Why such a large difference in Cepheid distances?

Mystery for NGC 4038/39!

Cepheid distances

Riess+(2011) used the entire Cepheid sample:

$(m-M)_0=31.66\pm0.08$

Riess+(2016) excluded 10 ULP Cepheids (P>80d):

$(m-M)_0=31.290\pm0.112$

TRGB distance (JL2017) $(m-M)_0=31.677\pm0.037$

is consistent with Riess+(2011) value,

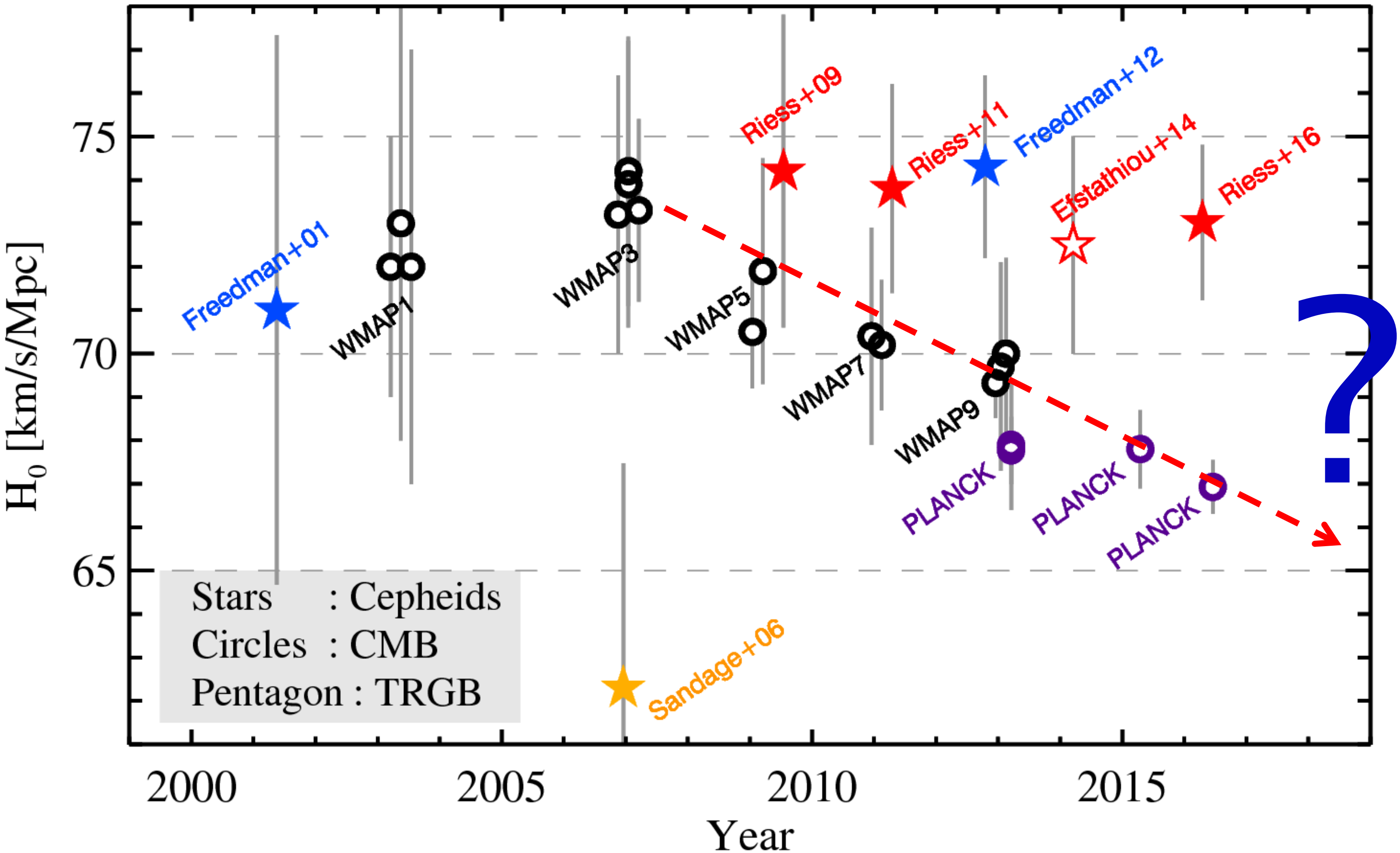
but not with Riess+(2016)!

A problem for Cepheid distances:

Should we include or exclude ULP for Cepheid distance estimates?

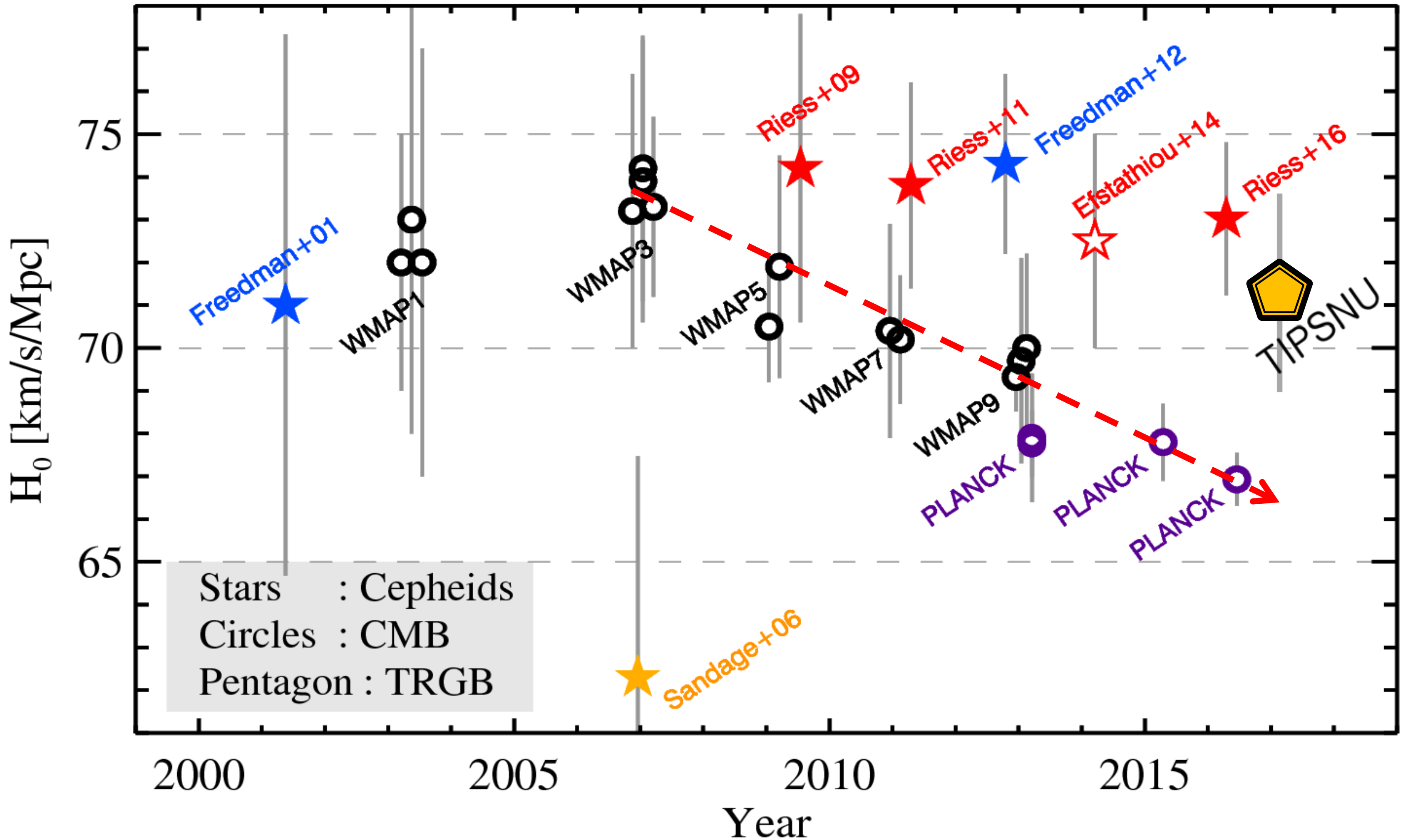
–Need to be studied in the future!

The Hubble Tension in 2016?



H_0 from SN Ia(TRGB) in 2017!

- SN Ia(Cepheid based on 4 anchors) – PLANCK : 3σ
- SN Ia(TRGB, Cep based on 2 anchors) –PLANCK : 2σ



H_0 from SN Ia(TRGB) in 2017!

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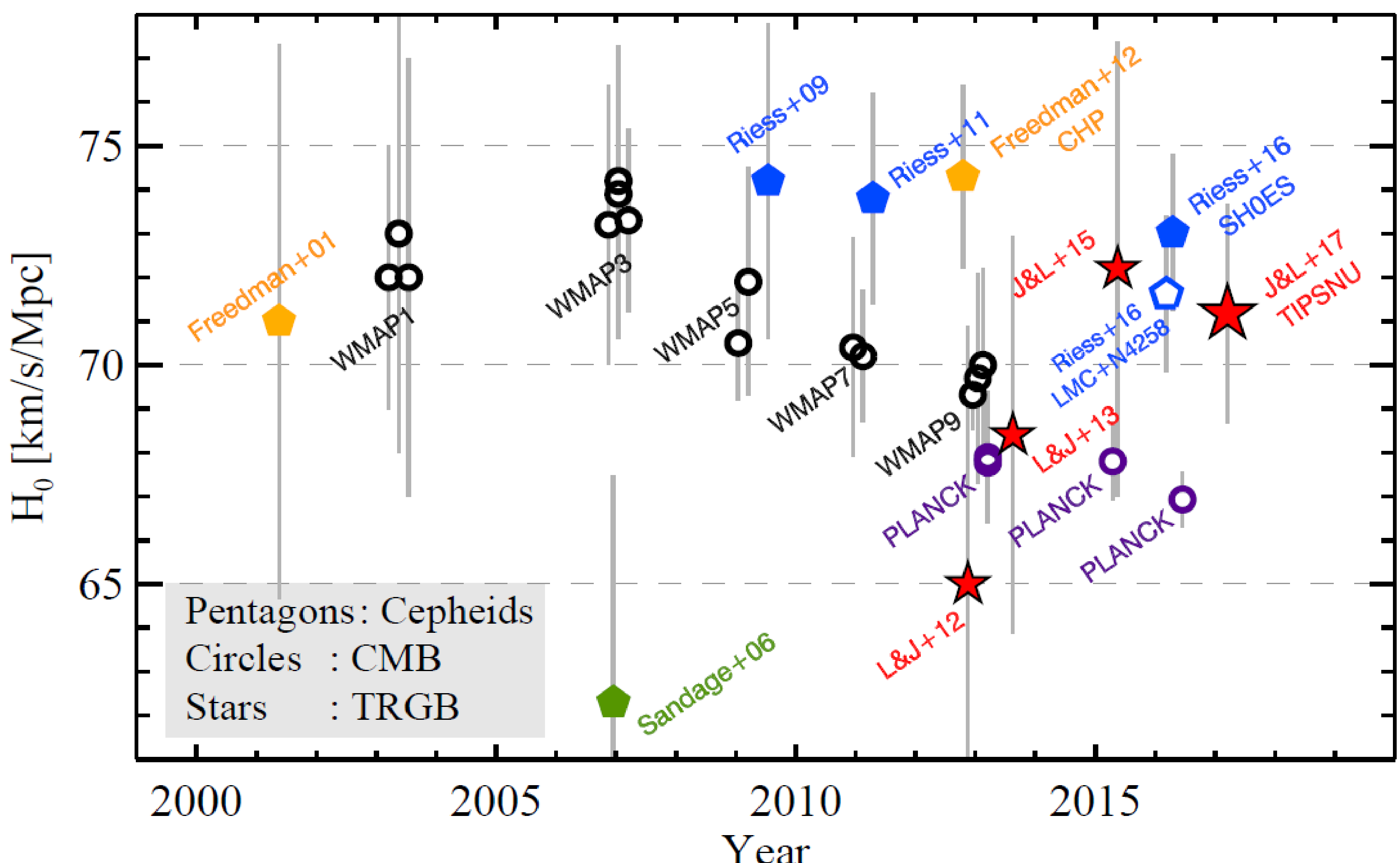
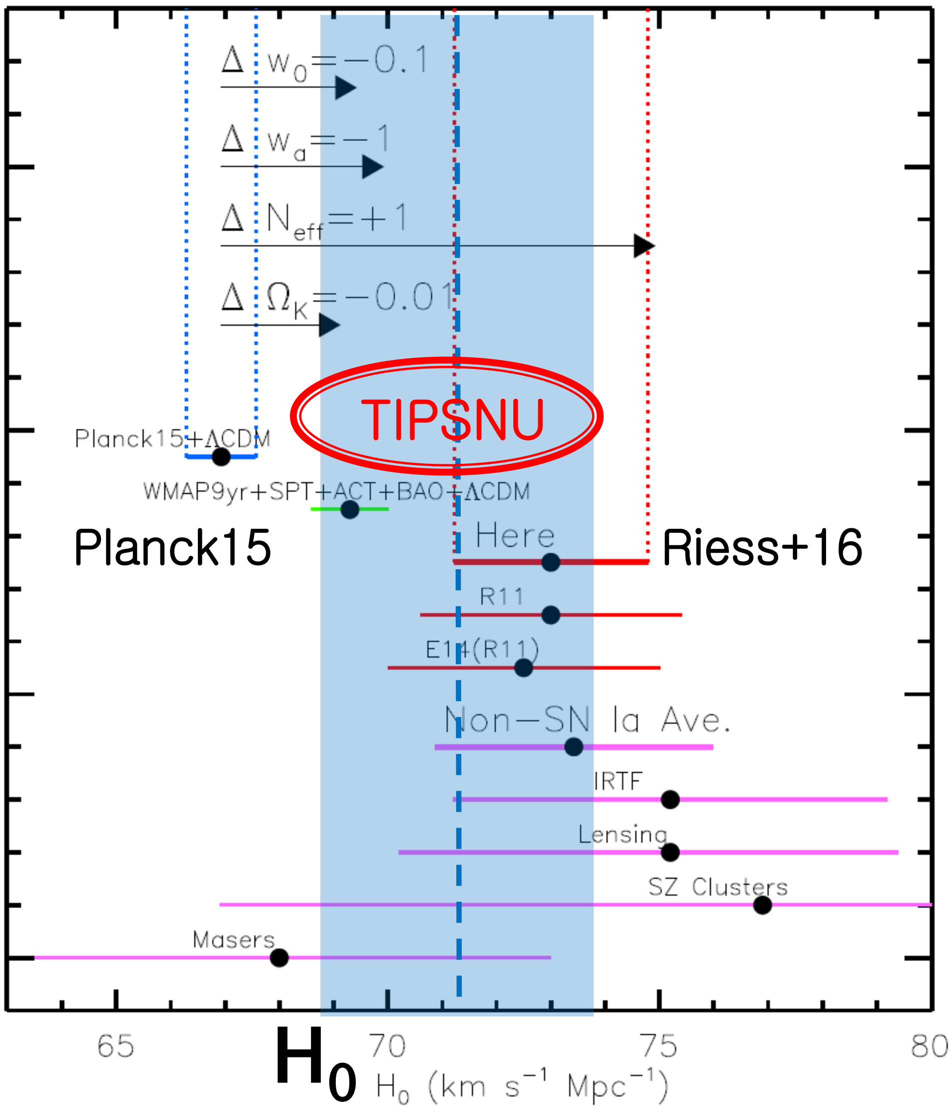


Cosmological Implications



✓Our SN Ia(TRGB) estimate of H_0 : H_0 = 71.2 ±2.5 km/s/Mpc

→ It agrees well with SN Ia (Cepheid based on the same anchors), **supporting 2–3σ tension!**

SN Ia (Cepheid based on MW and M31) leads to a higher H0 value! Why?

✓We need to improve **the zero point accuracy of the TRGB and Cepheids**, to determine a more accurate value of H_0 in the future.

✓**Any need for new physics?**

Future of TRGB Calibration of SN Ia

(1) CCHP (Carnegie–Chicago H_0 Project)

- Calibration of SN Ia using Pop II candles with HST Cycle 22 (PI: Freedman)
- 12 galaxies at <30 Mpc hosting SN Ia

(2) Extension to NIR: JWST

Summary

–The TRGB is a secondary distance indicator based on geometric anchors, being an excellent tool for H_0!

–2017 H_0(TRGB–SN Ia) = 71.17 ±2.50 (3.5% error), showing 2σ Hubble tension.

–H_0 in 2018 is still evolving!
–The future of the H_0 tension?
–Stay tuned!