The Hubble Constant in 2014

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Observational cosmology

Past: Two number cosmology

A search for two numbers: H_0 & q_0 (Sandage)

Present : Parametric cosmology

(many parameters for

geometry and dynamics of the universe, CMB, structures, neutrinos, grav waves, nuisance parameters…)

e.g. $H(z)^2/H_0^2 = \Omega_M(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)} + \ldots$

The Hubble Constant

$H_0 = H(t = today)$

: the expansion rate now

The value of $H_0 = f(t)$?

The Hubble Wars in 20C

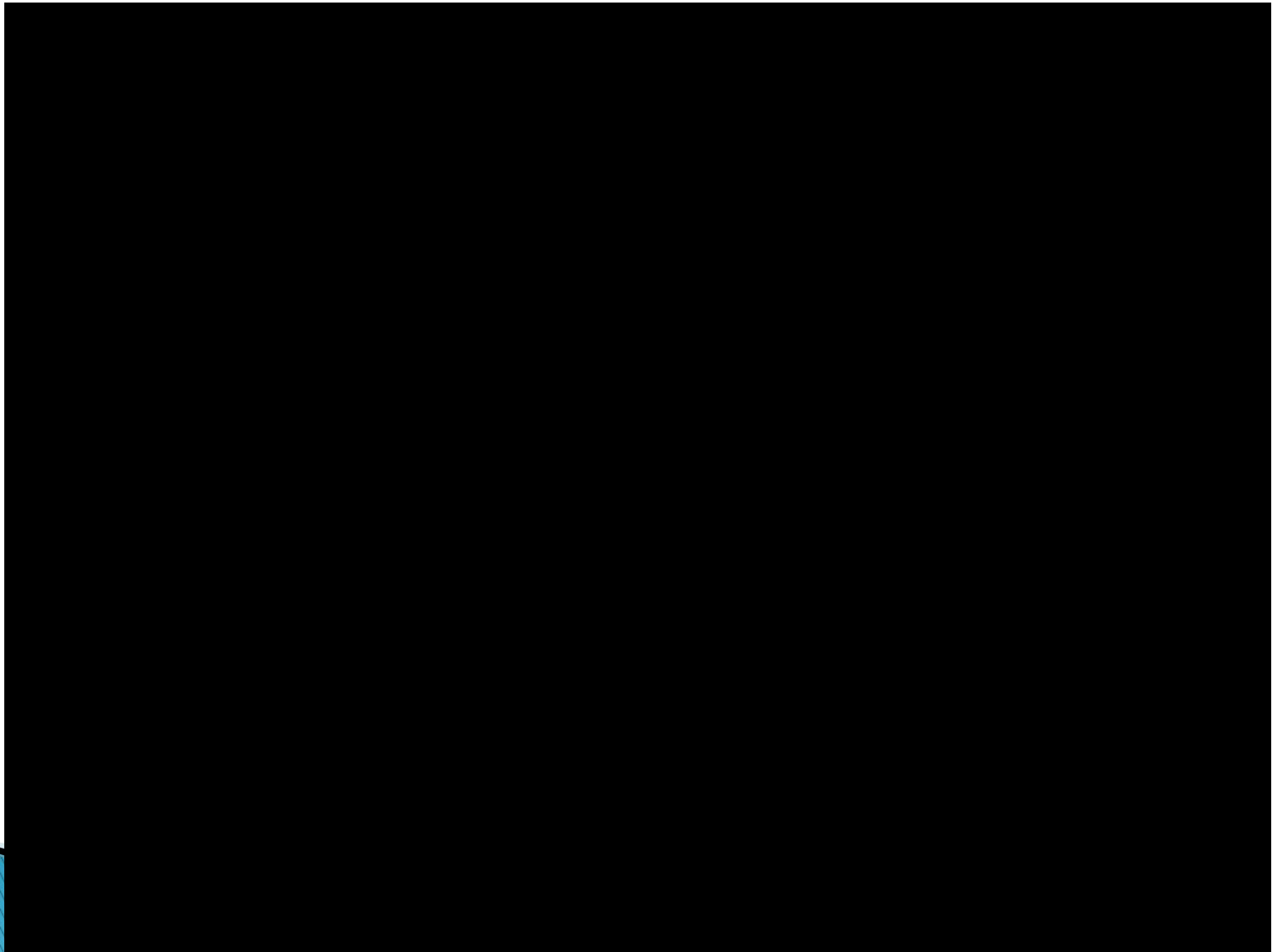
Since 1929 of the Hubble's law, long debates among Sandage, de Vaucouleurs and more:

$H_0=50$ versus 100 km/s/Mpc

A factor of two!

$H_0 = f(t)$? in 20C

A movie: compiled: by John Huchra (HSAO/cfa) made by Richard de Grijs (Beijing Univ)



Settled down with HST in 2001?

HST H_0 key project. I.

Freedman et al. (2001) : The final result

- Cepheid distance estimate : for 8 SN Ia hosts
- SN Ia in nearby universe (z~0.1): 36 SNe Ia

- $H_0 = 71 \pm 2 \pm 6$ km/s/Mpc (~10% error)
- the most popular value until recently

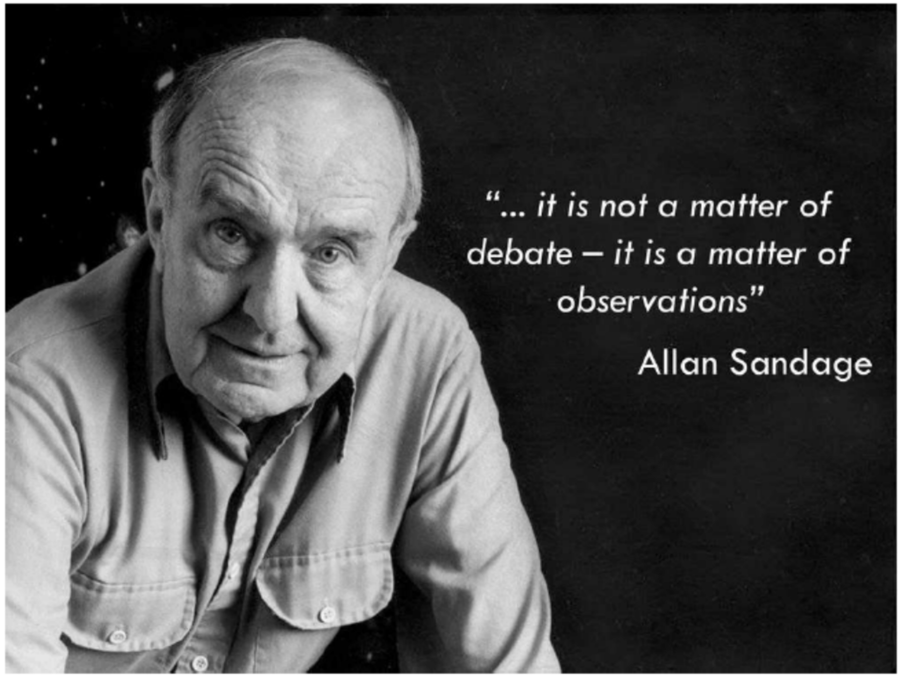
(N(citation)>2000)

Old soldiers never die!

Sandage et al. (2006) : HST key project. II.

- Cepheid distance estimate : for 10 SN Ia hosts
- SN Ia in nearby universe (z~0.1) : 62 SNe Ia
- H_0 = 62.3 ± 1.3 ± 5.0 km/s/Mpc (~10% error)

<-> H_0 = 71 ± 2 ± 6 km/s/Mpc (Freedman+2001)



Updating with with smaller errors!

Local measurements of H_0 with SN Ia

Riess et al. (2009, 2011) SHOES

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

Freedman et al. (2012): Carnegie H_0 Project (CHP) I

- ✓ Method : Recalibration of Key project sample using MIR P-L relation of Galactic Cepheids
- ✓ SN Ia in nearby universe ($z<0.1$) : 36 SNe Ia
- ✓ $H_0 = 74.3 \pm 2.1$ km/s/Mpc (2.8% error)

(2012 value) $H_0 = 74 \pm 2$ km/s/Mpc

Then came a SN Ia in M101

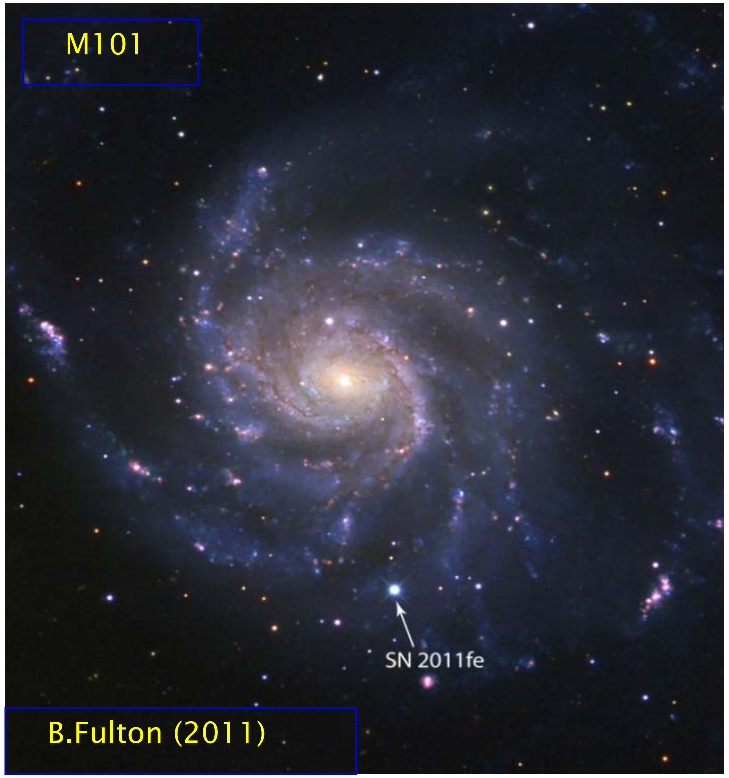
M101: one of the nearest galaxies with SN Ia

SN 2011fe: one of the best obs data

Lee & Jang (2012)

-Re-calibration of SN Ia with TRGB

-H_0=65±6 km/s/Mpc



Then H_0 from CMB in 2013

CMB at z~1100

WMAP9 (Hinshaw+2013)

H_0=70.0±2.2 km/s/Mpc

PLANCK 2013 XVI. Cosmological parameters

H_0=67.3±1.2 km/s/Mpc

The Hubble Tension?

Local U (SN Ia): $H_0 = 74 \pm 2$ km/s/Mpc
High z (CMB, BAO): $H_0 = 68 \pm 2$ km/s/Mpc

The Hubble Tension: 2-3 σ difference

How to handle the Hubble tension

Local U (SNe Ia): $H_0 = 74 \pm 2$ km/s/Mpc
High z (CMB, BAO): $H_0 = 67 \pm 1$ km/s/Mpc

Three ways to approach the problem

1) Systematic errors in each
$H_0(z=0)$ & $H_0(\text{high z})$

2) Relation between high z and low z
(Are we in a Hubble bubble?)

3) New parameters or physics, if real!

However, H_0 in 2010-2014

- Various methods for H_0 estimation
- A large range of the H_0 values.

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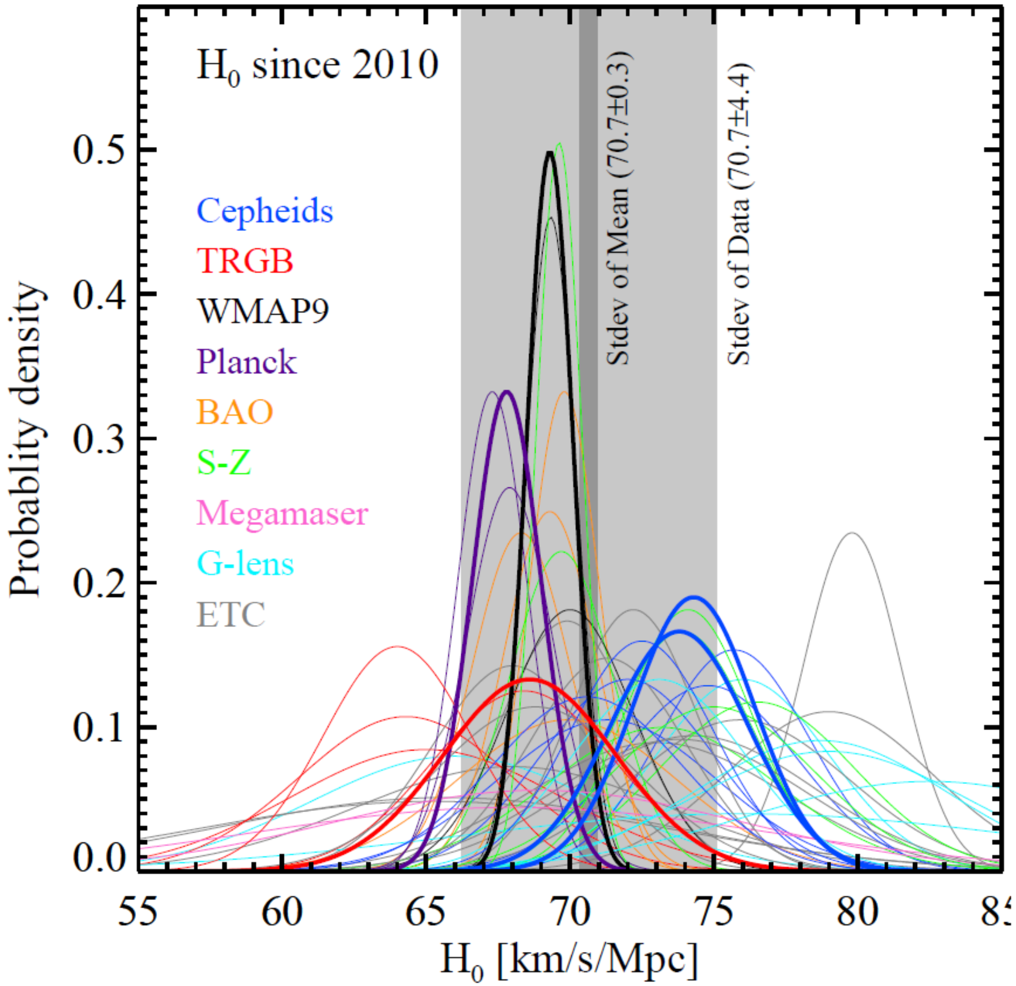

H_0 tension in 2014

- CMB versus SN Ia based on Cepheids or TRGB
- The Hubble tension?

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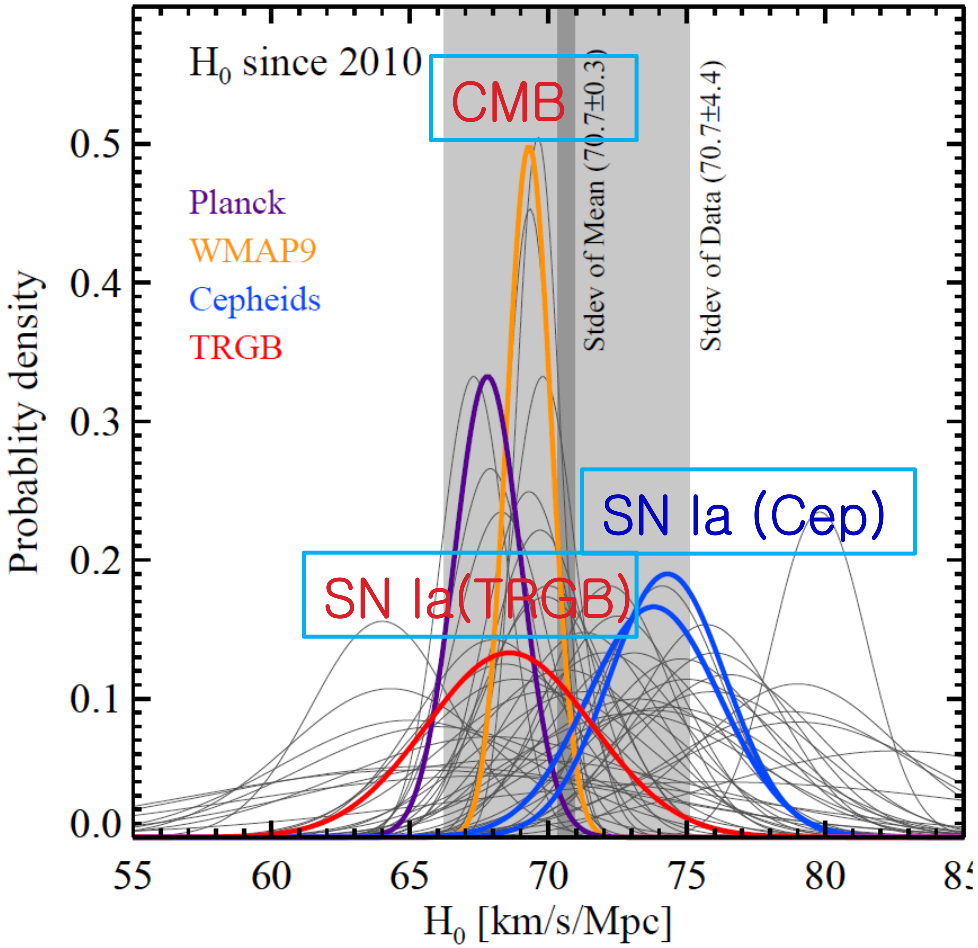


Why need a better estimate of H_0?

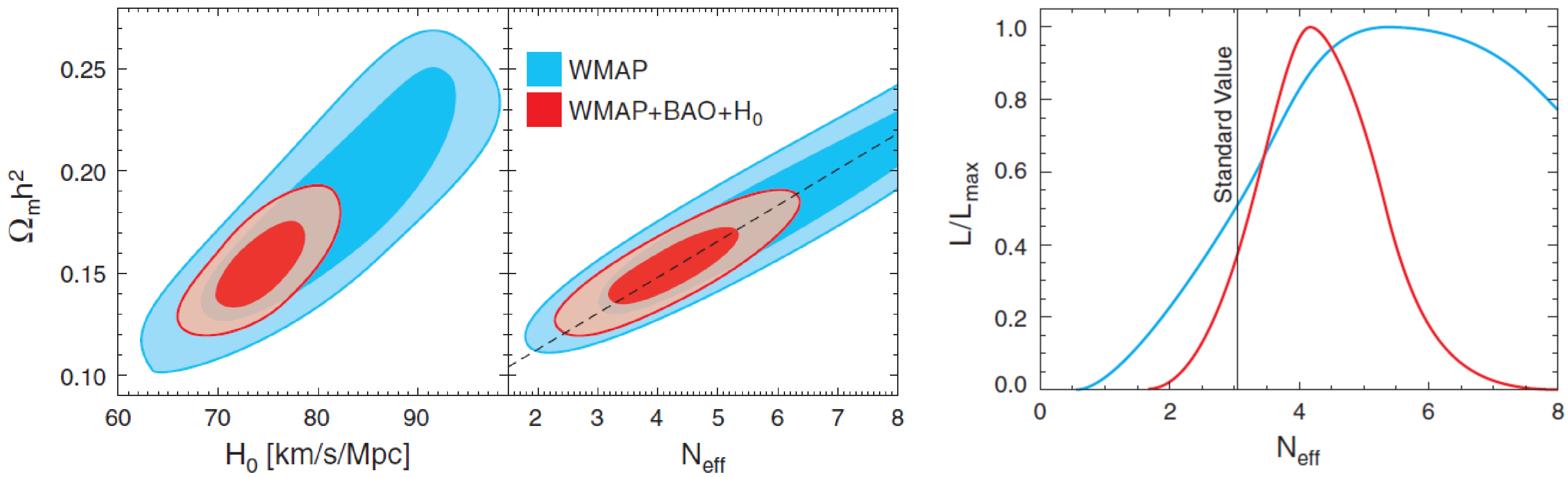
* w0, neutrino

(Ex) The effective N of neutrino species : $N_{eff}=f(\Omega_m h^2)$

$WMAP+BAO+H_0$: (Komatsu+2011)

$N_{eff}=4.34\pm 0.87$ vs 3.04 (standard value)

=> Better H_0 ⇨ Better $N_{eff}(\nu)$



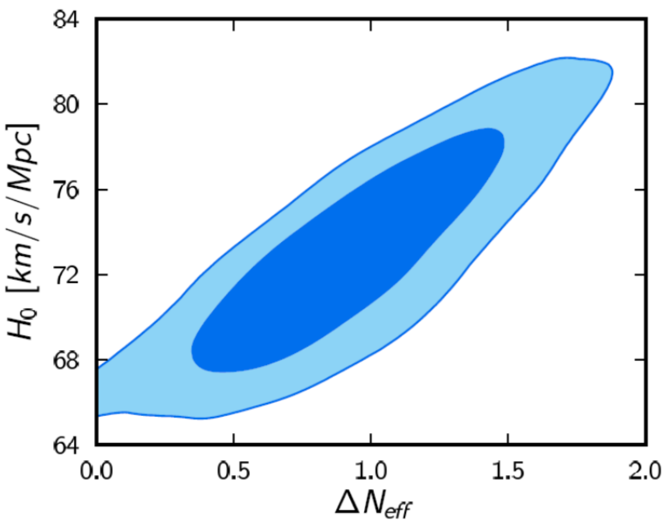
Komatsu et al (2011, ApJS, 192, 18)

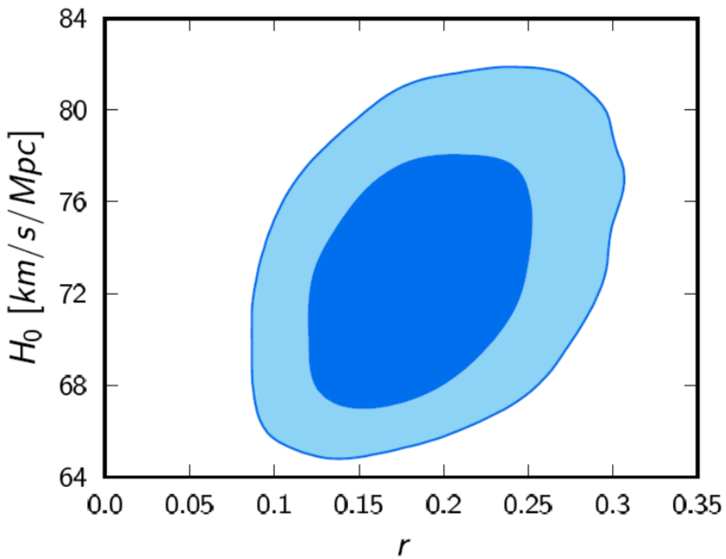
Why need a better estimate of H_0?

* BICEP2 2014: The inflationary ration of tensor-to-scalar fluctuation,
  $r = 0.2^{+0.07}_{-0.05}$

Dvorkin+ (2014) suggested evidence for massive sterile neutrinos from combing CMB+BICEP2+BAO+H_0

$$\Delta N(\text{eff}) = 0.81 \pm 0.25 \quad m\nu = 0.47 \pm 0.13 \text{ eV}$$

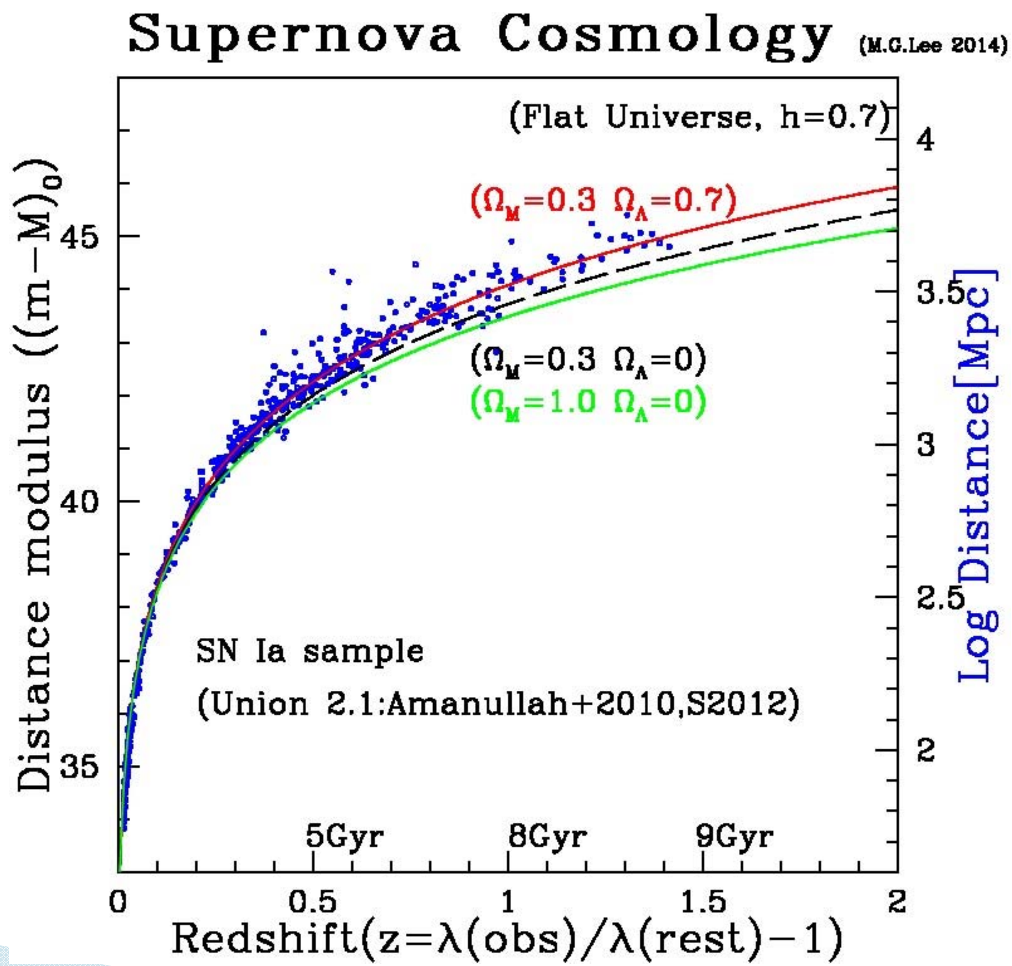




Dvorkin et al. (2014)

Why SN Ia for H_0?

- **SNe Ia may be the best!**
  - Bright
  - From low Z to high Z
  - Small dispersion
  - Many studies



How to derive H_0 from SN Ia

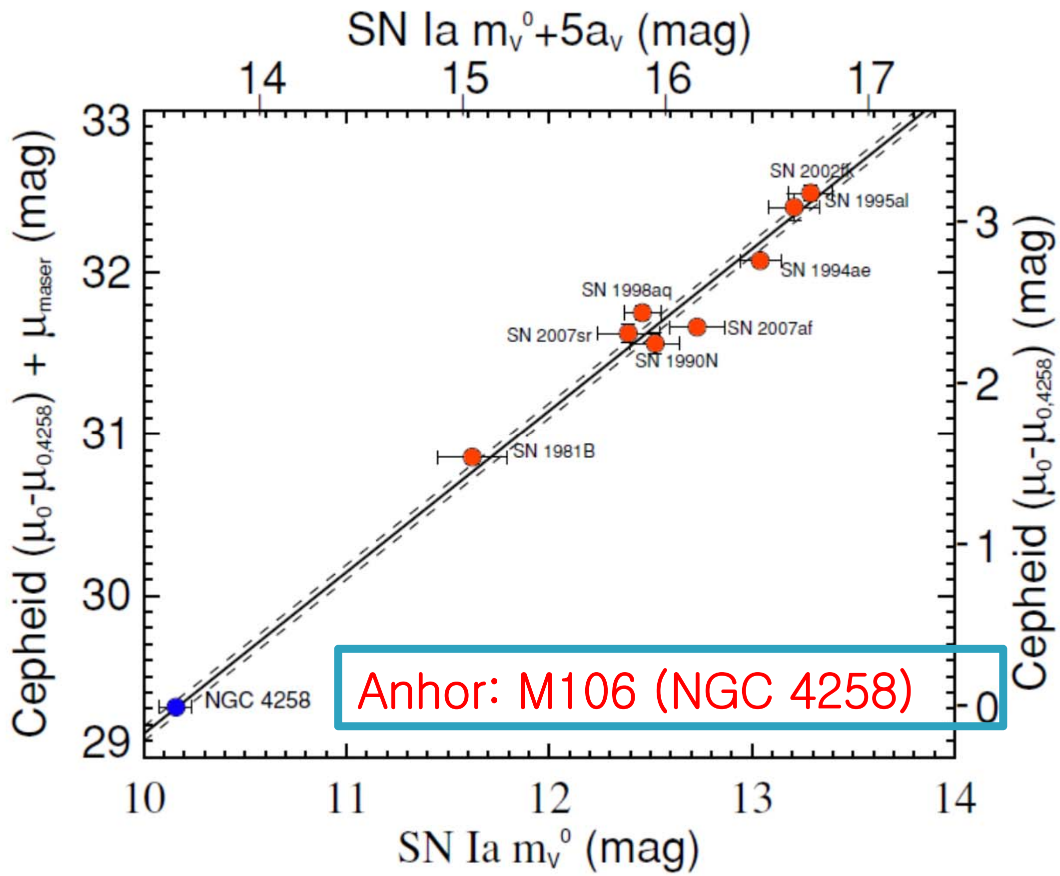
$$logH_0 = \frac{M_V + 5a_v + 25}{5}$$

$$a_v = logcz * f(q_0, j_0) - 0.2m_v^0$$

- Calibration of SN Ia is critical for H_0.
- Need nearby galaxies hosting SN Ia.

The Limits of Current SN Ia Calibration

- CHP, SHOES (<2013)
  - SN Ia calibration with Cepheids
  - Cepheid calibration with M106 (NGC 4258), LMC, MW
  - N (SN Ia host) is small!



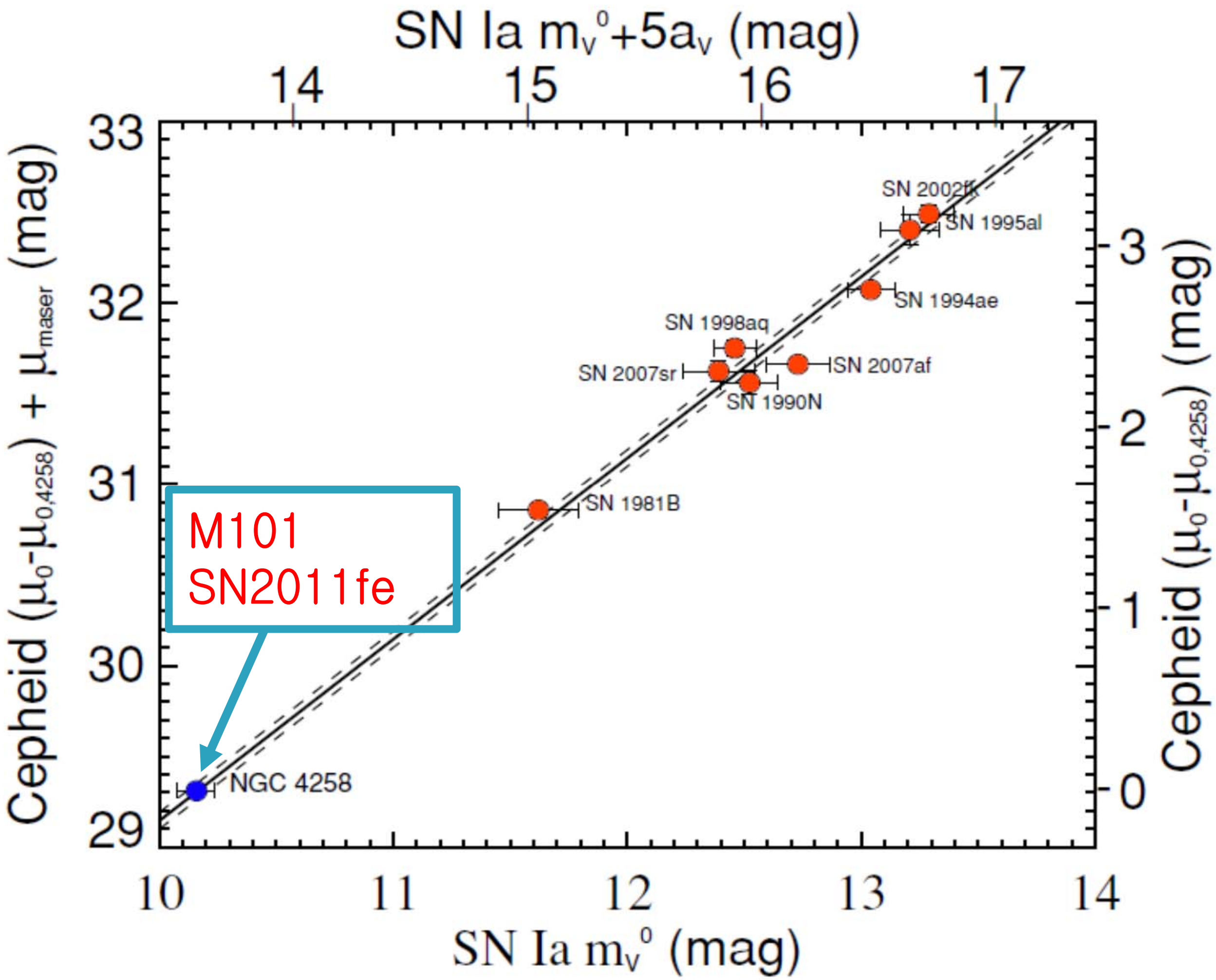
M106, an angel or a devil for H_0 ?

- M106 has a water maser in the center, allowing a geometric distance.

- Herrstein+1999: d=7.3 ± 0.3 Mpc
  - Riess+(2011) H_0=74.8±3.1 km/s/Mpc
- Humphreys+2013: d=7.60 ± 0.15 Mpc
  - H_0=72.0±3.0 km/s/Mpc
- Efstathiou (2014) reanalysis with d=7.6Mpc
  - H_0=70.6±3.3 km/s/Mpc

Calibrator SNe Ia: a new comer in 2011!

- Sne Ia used for calibration in CHP, SHOES (<2013)
- In 2011, a new comer in a much closer distance!



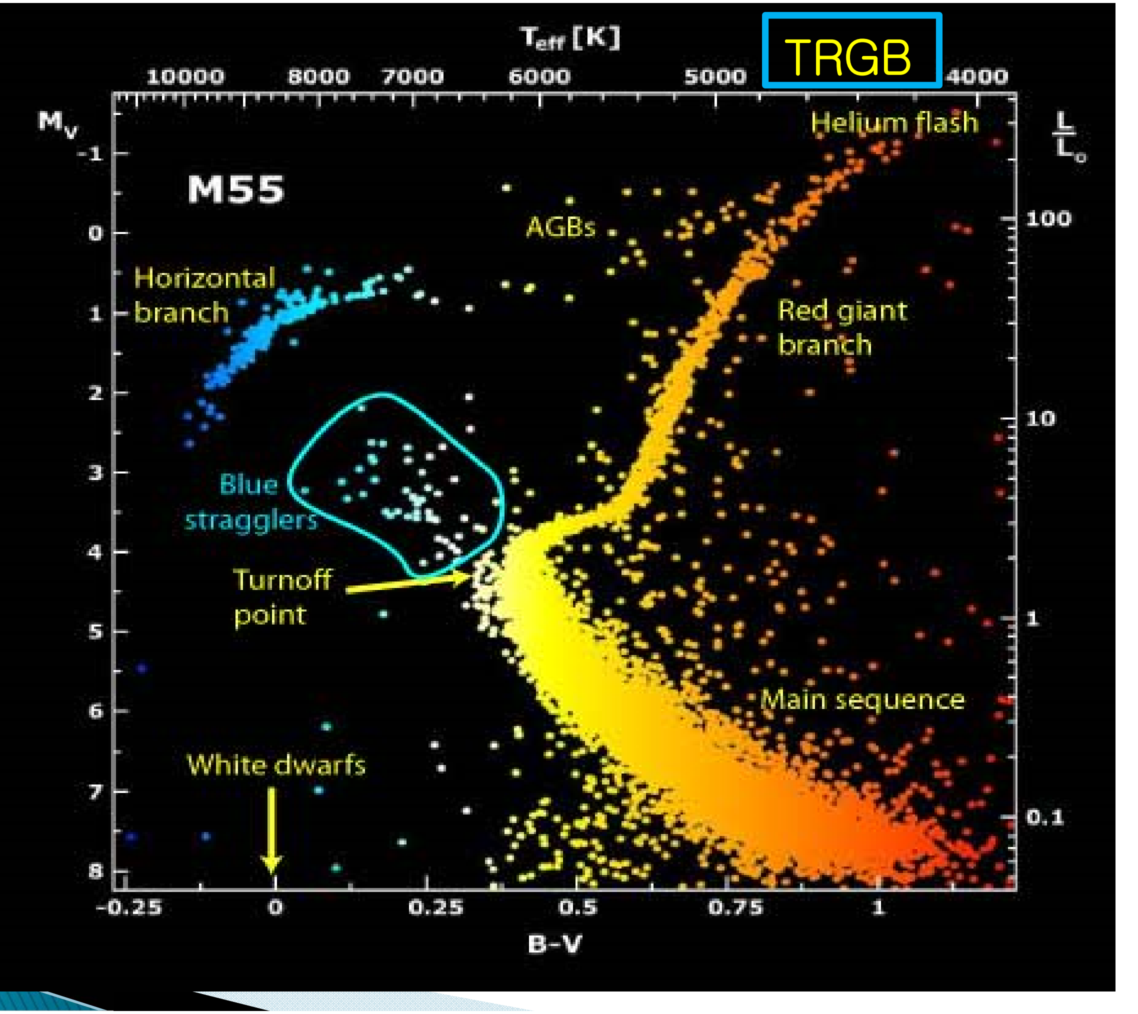
New calibration of SN Ia

- Pop II calibration
  - Independent of Cepheids
  - TRGB!

TRGB (Tip of the RGB)

- (observation) The tip of the red giant branch (RGB) in the HR diagram
- (theory) Low mass stars in the core-He flash stage (old than a few Gyrs)

Globular cluster M55



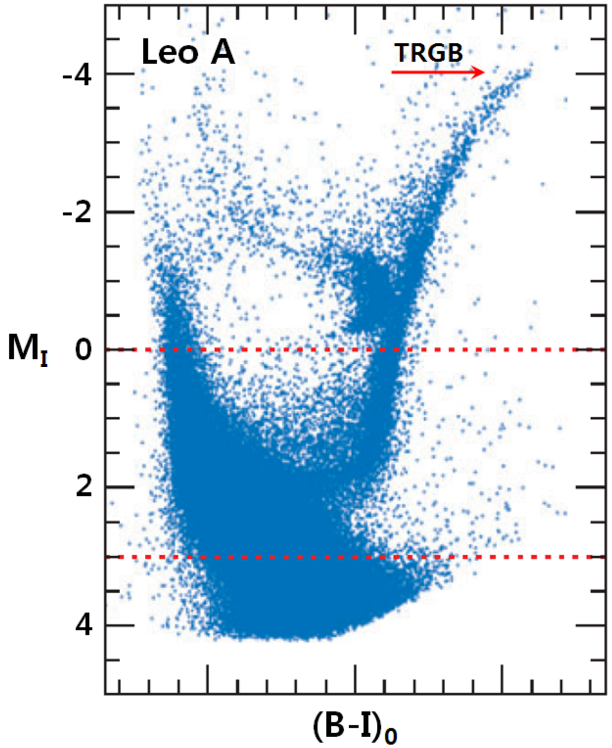
TRGB (Tip of the RGB)

-Galaxies have stars with a large range of ages, including many old stars!

(halo RGBs: source of NIR fluctuation? (Cooray+2012,today))

-TRGBs are seen in any-types of galaxies older than a few Gyr old

-The TRGB is comparable to Cepheids in precision, but having a few advantages (Lee, Freedman & Madore 1993)



Tolstoy (2009)

TRGB vs Cepheid

	TRGB	Cepheid
Pros	• Little metallicity effect • in any types of galaxies • non variables • no extinction • can calibrate nearby EDS	• bright luminosity ($M_{V,max}$~−6) • long history?
Cons	• fainter (M_I ~ −4.0) • can be used for d<25 Mpc	• Metallicity effect • Interstellar extinction • Only in late-type galaxies • Requiring much observing time

Example: SN Ia 2011fe in M101

* SN Ia 2011 fe Discovered in 2011

- The nearest SN Ia with modern data since 1972.
- The best calibrator for SN Ia?
- Optical & NIR data

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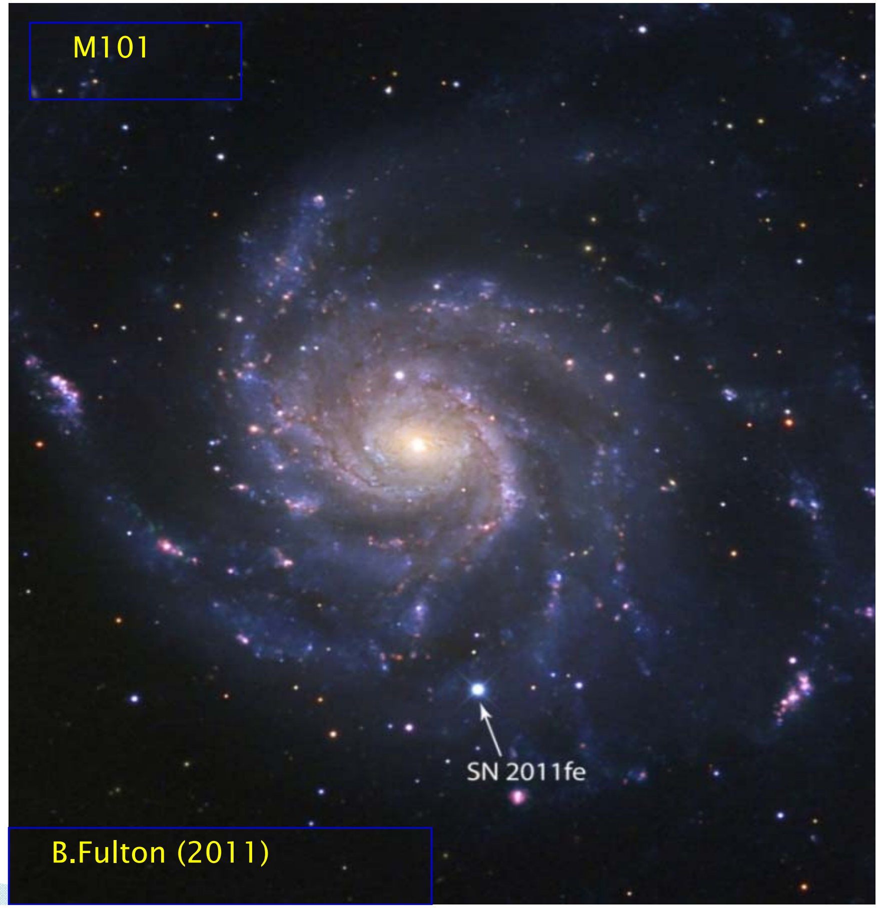
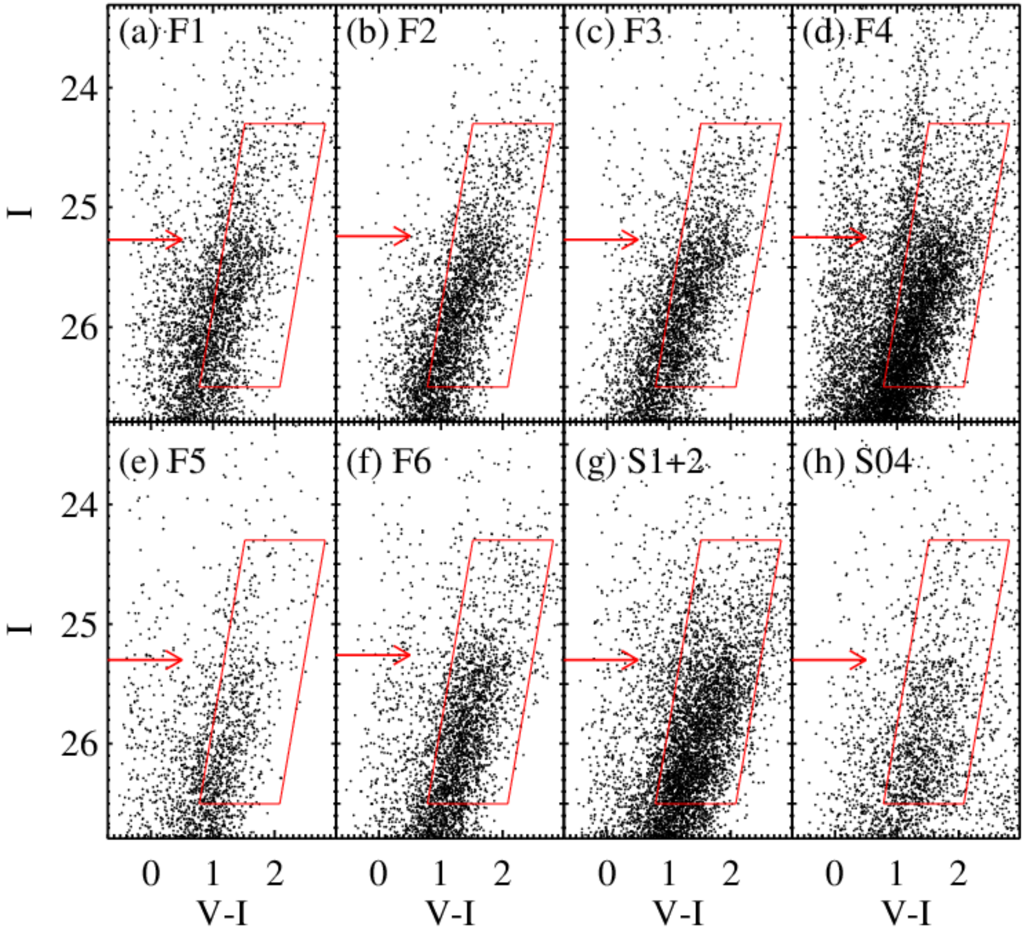


CMDs of stars in M101

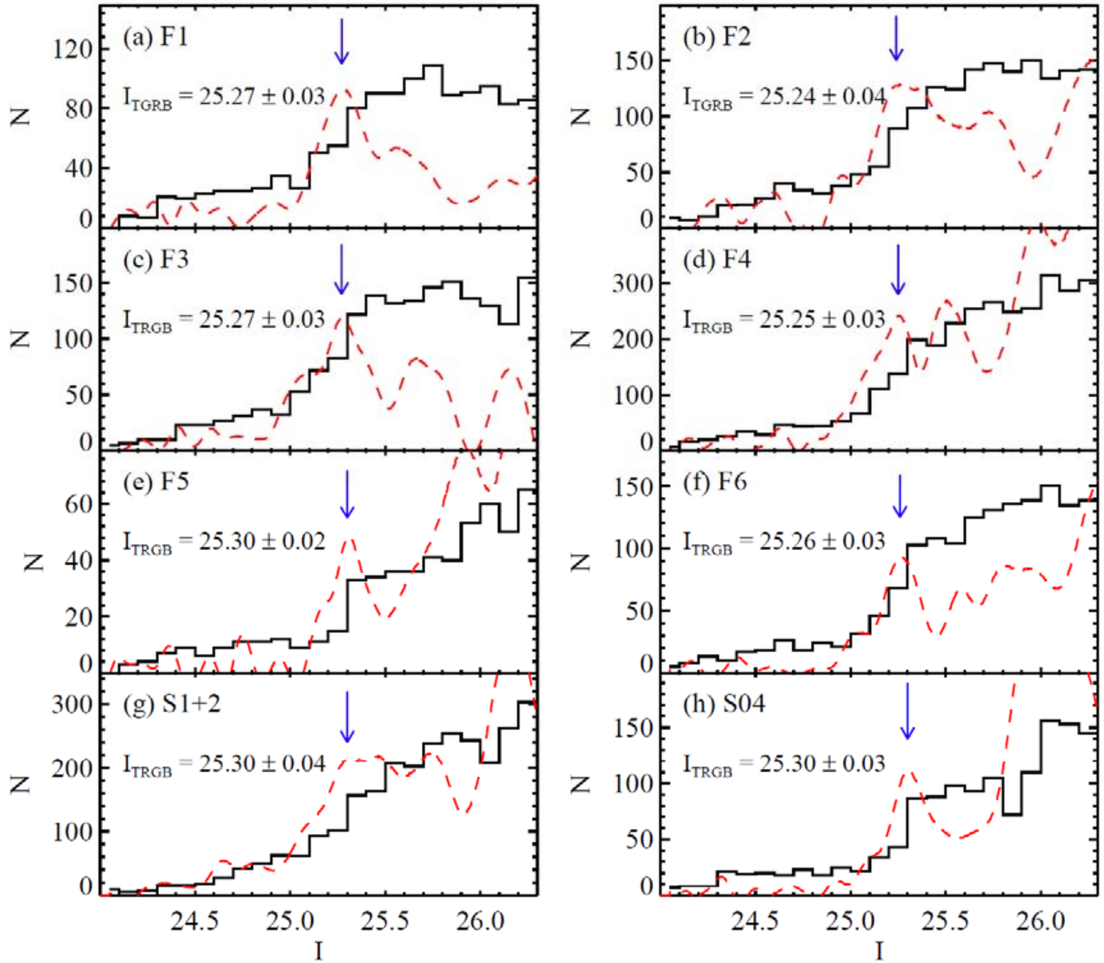
* Resolved stars are mostly RGBs and AGBs.
* Edge-detection algorithm: TRGB



Lee & Jang (2012, ApJ Letter)

TRGB for M101

1) I-band luminosity function -> Edge detection
2) I(TRGB) =25.28 ±0.01

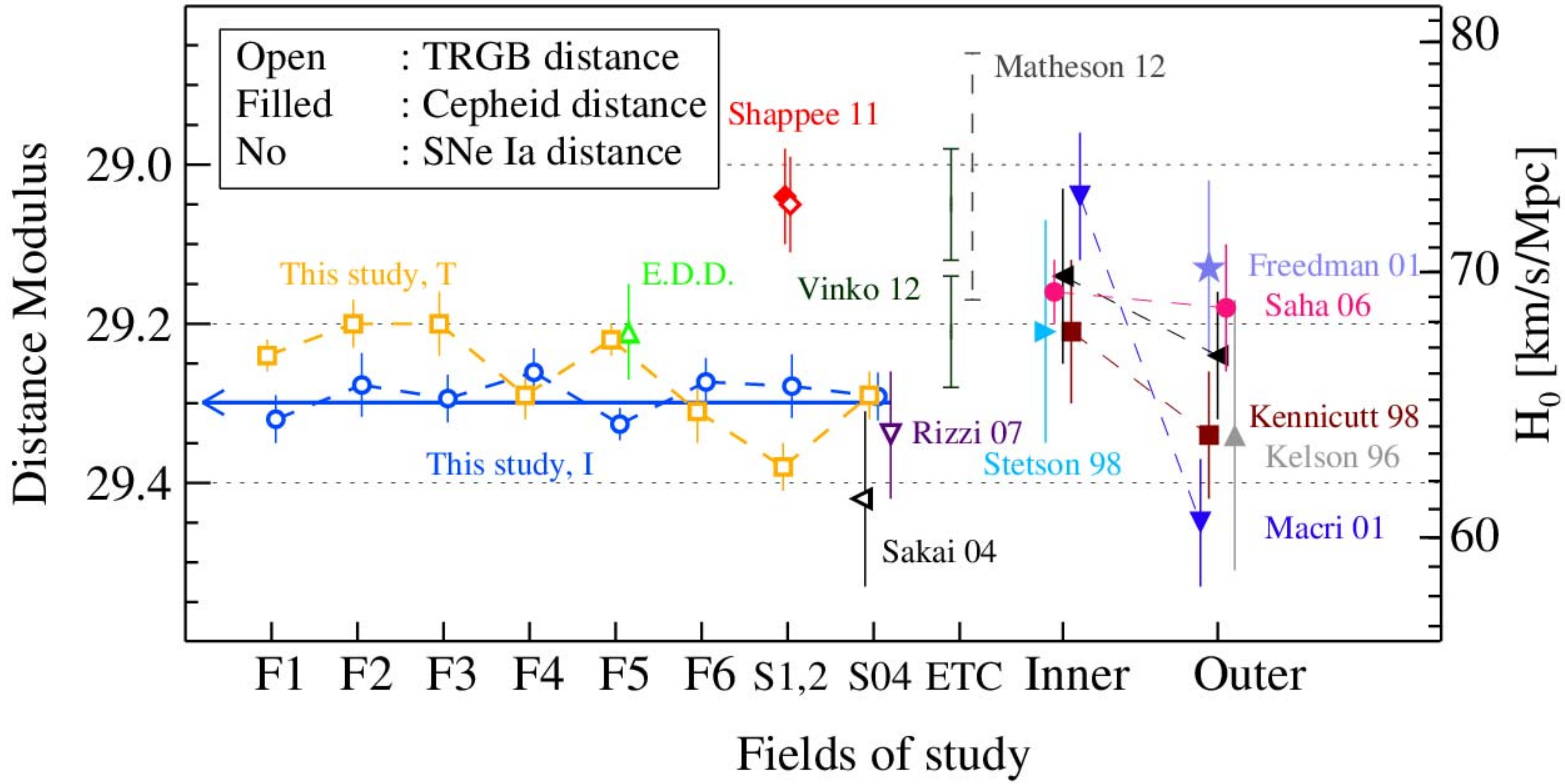


Lee & Jang (2012, ApJ Letter)

A new distance to M101

$(m-M)_0 = 29.30 \pm 0.01(\text{random}) \pm 0.12(\text{systematic})$

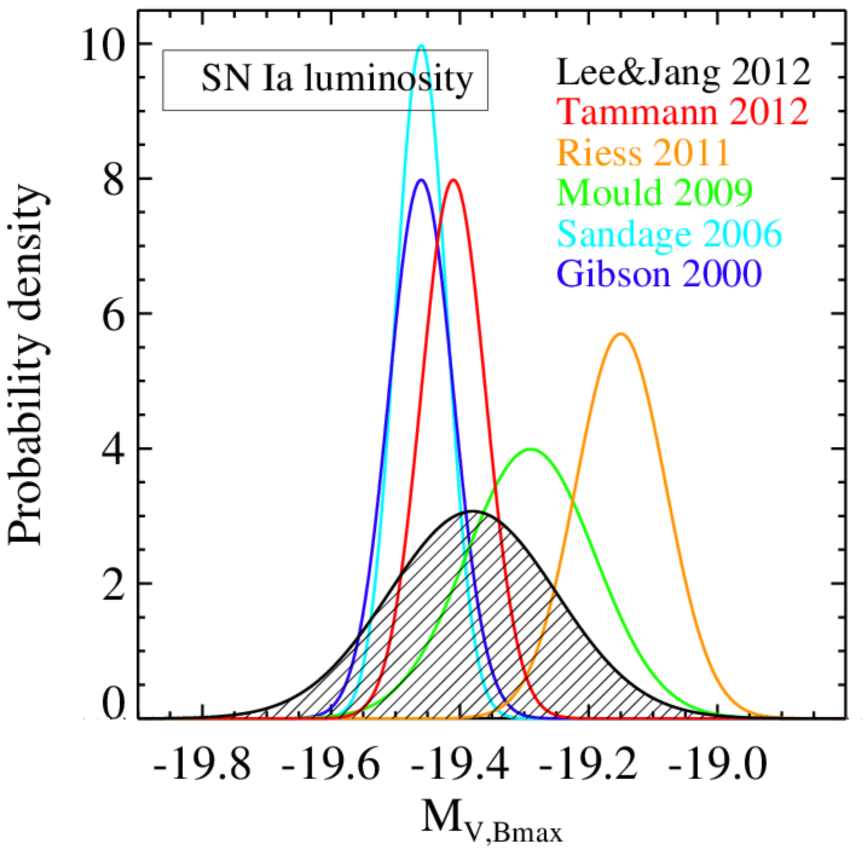
$(d = 7.24 \pm 0.03 \pm 0.40\ \text{kpc})$



Lee & Jang (2012, ApJ Letter)

Absolute magnitudes of SN 2011fe & H_0

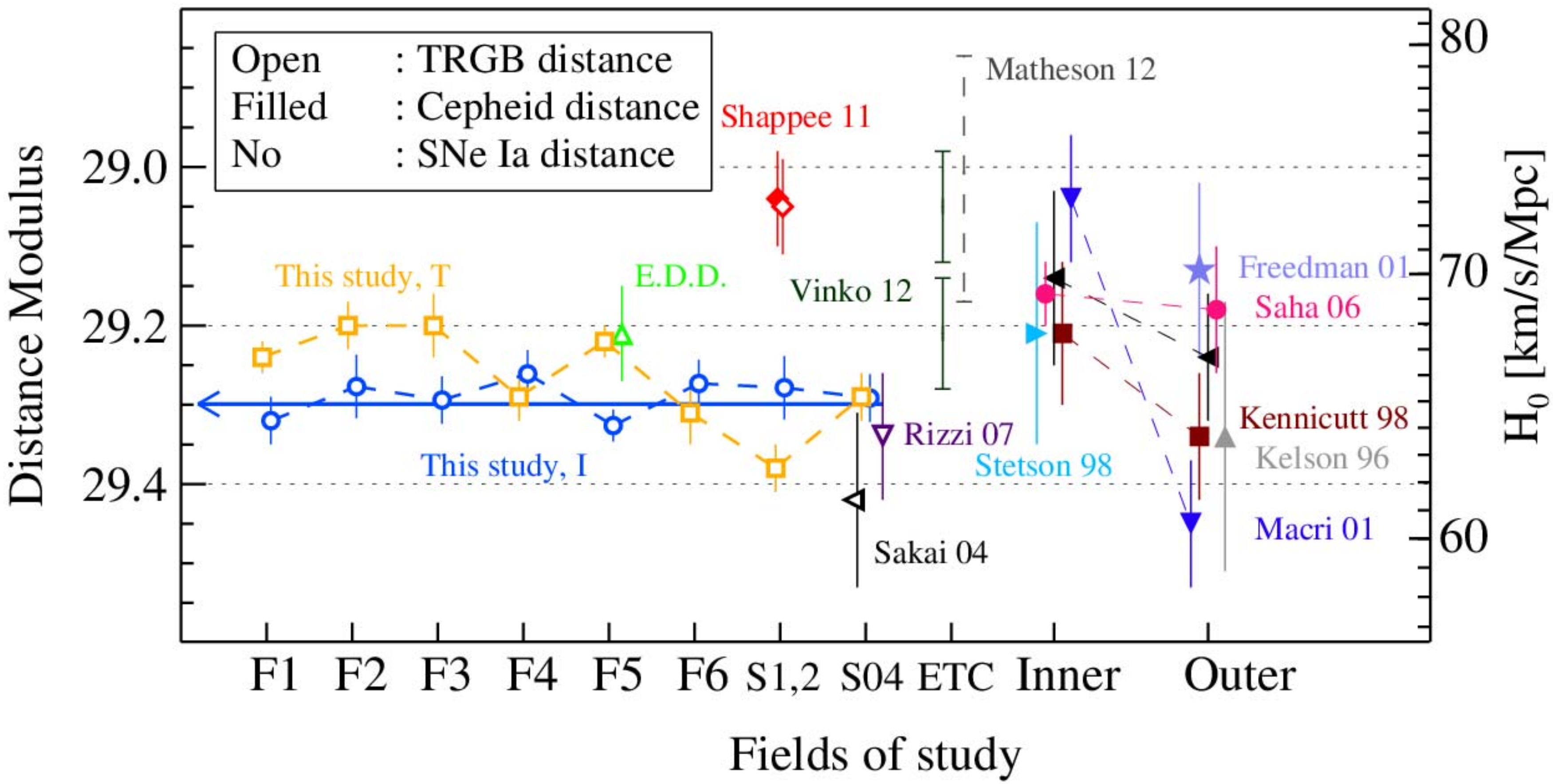
Optical: Mv(max) = −19.38 ± 0.12
(Mv(max) = −19.15 ± 0.07 in Riess+2011)
(Mv(max) = −19.46 ± 0.05 in Gibson+2000)



Absolute magnitudes of SN 2011fe & H_0

Optical: Mv(max) = −19.38 ± 0.12

=> H_0 = 65.0 ± 0.5 ± 5.7 km/s/Mpc



Implications

Three possibilities:

1) SN 2011fe (M101) may be 0.2 mag brighter than typical SNe Ia.

2) Recent calibration of SNe Ia may be 0.2mag fainter (Riess et al. 2011).

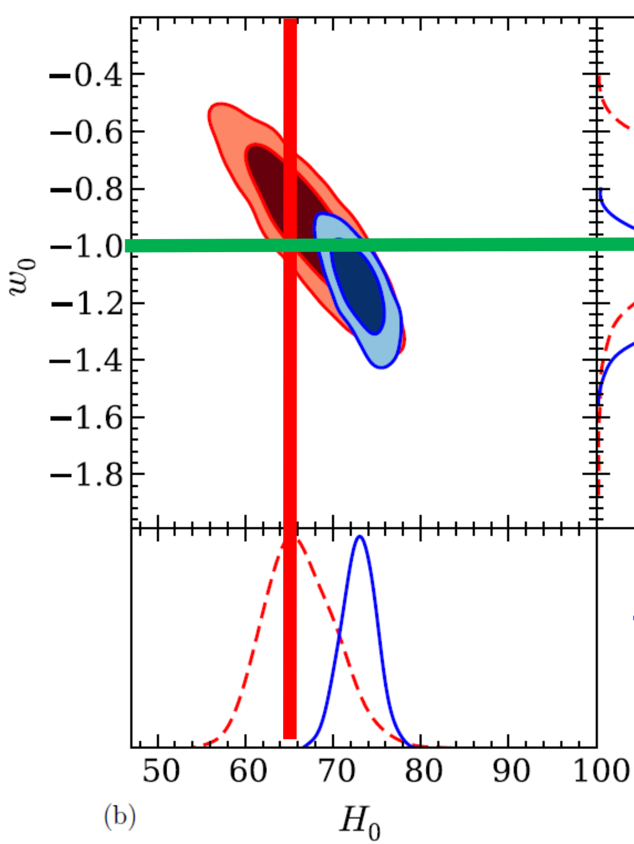
3) H_0 may be smaller than 73 km/s/Mpc. (N_{eff} is closer to the standard value).

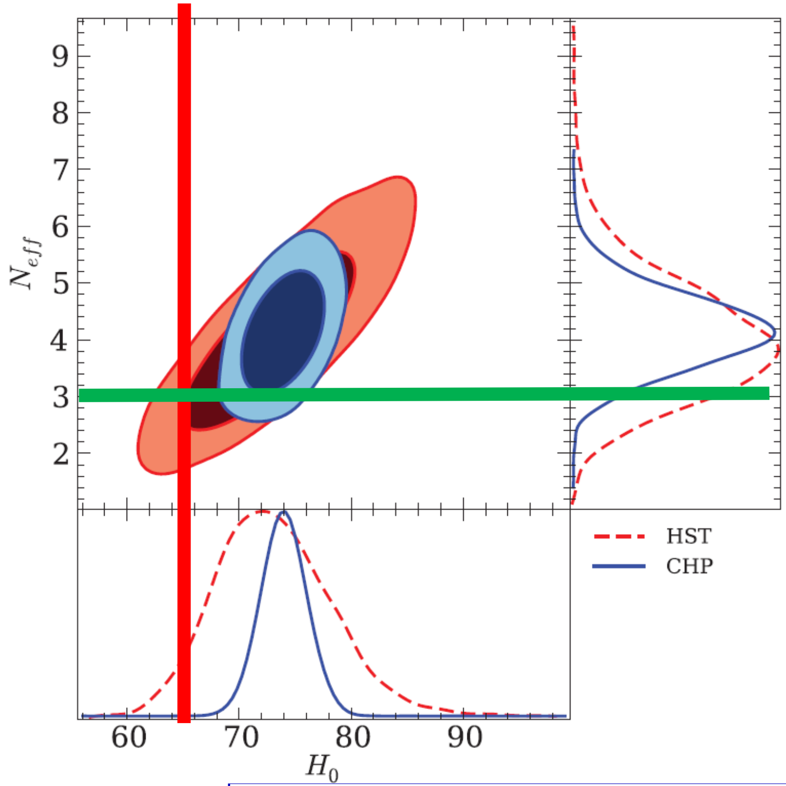
-> Need a better estimate of H_0 !

w_0 and N_{eff} from H_0 in 2012?

*$w_0=f(H_0)$, $N_{eff}=f(\Omega_m h^2)$

=> Better H_0 ⇨ Better w_0, $N_{eff}(\nu)$





Lee and Jang (2012, ApJL)
Freedman et al (2012, ApJ)

TRGB Calibration of SN Ia

Criteria for targets
-Galaxies at <30 Mpc hosting SN Ia
-HST images
-with modern photometry
-with low extinction

In 2014: N(candidates)=8

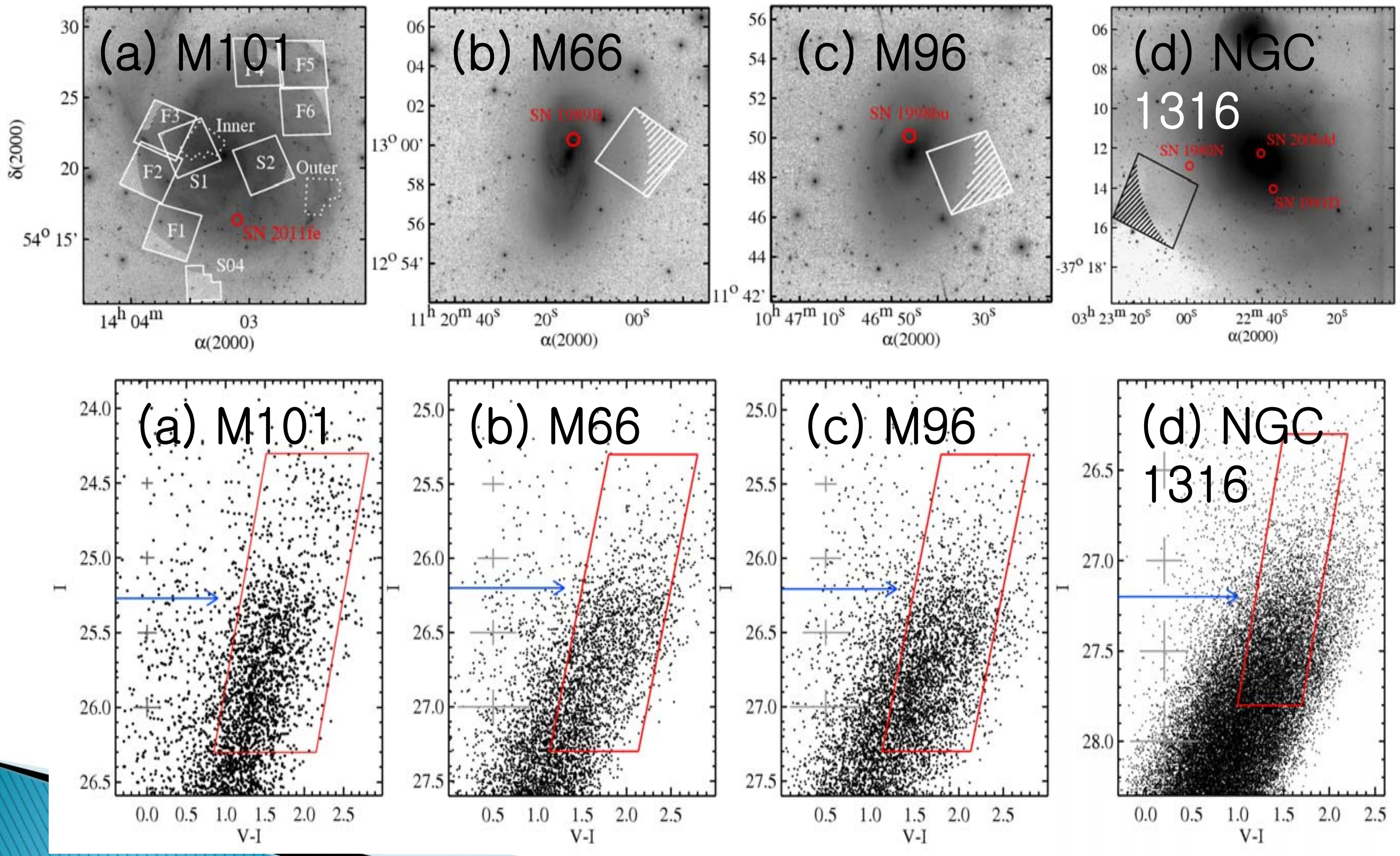
HST cycle 22 proposal : submitted.
(Freedman, Madore, MGL et al)

Current progress:
M101 (Lee & Jang 2012)
M66 and M96 (Lee & Jang 2013)
NGC 1316 and others (Jang & Lee 2014, in preparation)

TRGB distances to SN Ia galaxies

Three possibilities:

1) Current calibration of the TRGB

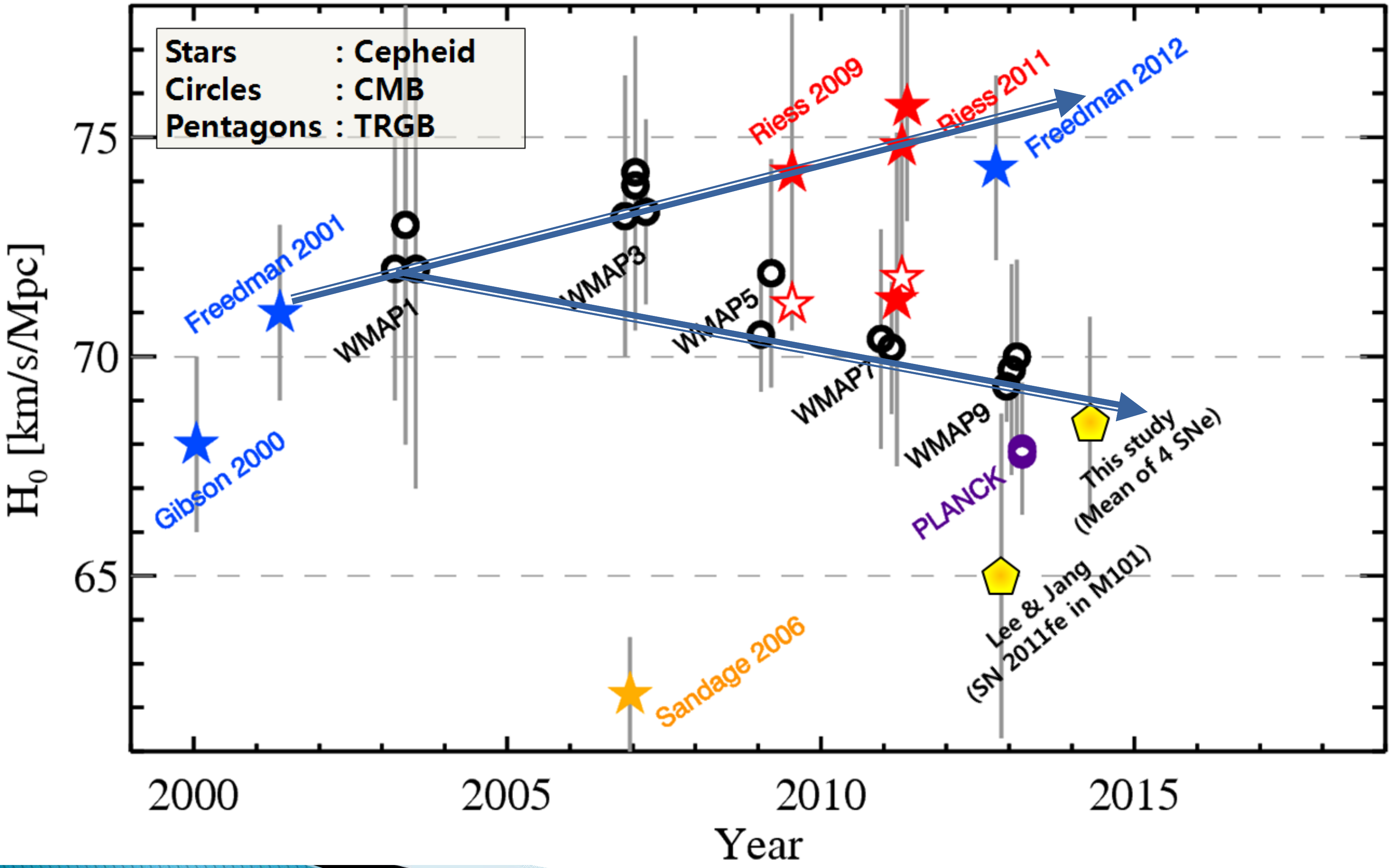


TRGB Calibration of SN Ia

Lee & Jang 2014, Jang & Lee 2014

- Based on 4 low-reddened SNe Ia in M101 and NGC 1316
- $M_V(max) = -19.31 \pm 0.02$ (ran) $\pm$ 0.12(sys) ,
- $H_0 = 68.6 \pm 2.3$ (ran) $\pm$ 3.7 (sys)

TRGB Calibration of SN Ia



H_0 Quests for next decade

Three ways:

1) Reducing systematic errors of high z and local measurements

   -CMB, BAO, galaxy clusters, time delay of lensed quasars,

   -Cepheids, TRGB, RR Lyrae, maser, eclipsing binaries

   -age of the universe (Bond+2014, Verde+2013)

2) Understanding better the relations between local and high z measurements

3) Thinking about new parameters or new physics

Summary

H_0 in 2014: still evolving! Stay tuned!
The future of the H_0 tension?