That other way to measure \( H_0 \):

Rachael L. Beaton
Carnegie Observatories
Carnegie-Chicago Hubble Program

A prospectus on distance measurement with WFIRST-AFTA

Image: NASA/JPL
The distance ladder is the traditional means of measuring $H_0$. We normally think of it as reaching “out”, but let’s think about it using ‘backward design’.
The Hubble Diagram

Hubble (the man) 1929

$H_0$ is the proportionality constant between redshift (y-axis) and distance (x-axis).
The calibration of the absolute luminosity for the SN Ia rests on a sample of order 10 objects. This sets a floor to $H_0$ of about 2.5%.
In the (recent) past, this was okay:

The other sources of variance swamped the contribution from the SN Ia anchors.

from Riess et al. 2011
The SH$_0$ES Collaboration

March 01, 2016
Rachael L. Beaton -- Carnegie Observatories
But, today it is not:

Even 0.05 mag (2.5%) variance from SN Ia is now a detail to ‘sweat’.
Why so few SN Ia Calibrators?

Its just not for a 'lack' of SN Ia in the 'Local Volume'

SN Data from: http://www.rochesterastronomy.org/snimages/
Distances from NASA Extragalactic Database: ned.ipac.caltech.edu
Why so few SN Ia Calibrators?

SN Ia within ~40 Mpc [NED Distance]

$N_{\text{SN Ia}} = 95$

Its just not for a 'lack' of SN Ia in the 'Local Volume'

SN Data from: http://www.rochesterastronomy.org/snimages/
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SN Ia Suitability is:

(1) Can I characterize the SN?

(2) Can I measure the distance?
SN Ia Suitability is:

(1) Can I characterize the SN?
   - Did I find it before peak light?
   - Can I remove the galaxy light and/or nearby bright sources?
   - Do I have quality light curves?
   - Can I measure local extinction?
   - ⋯ and related issues.

(2) Can I measure the distance?
SN Ia Suitability is:

(1) Can I characterize the SN?

**YES (most of the time)**

- Did I find it before peak light?
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- ... and related issues.

(2) Can I measure the distance?

Thanks to phenomenal efforts from the SN community – ~40 of the ~95 SN within 40 Mpc have this data*.

*Data from Chris Burns (CSP) and Ben Shappee (ASAS SN)
SN Ia Suitability is:

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(2) Can I measure the distance? **With Cepheids?**

Is the host galaxy:

- Star forming?
- Luminous?
- Approx. face on?

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**SN Ia Suitability is:**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
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<td></td>
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- Did I find it before peak light?
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- … and related issues.

Is the host galaxy:
- Star forming?
- Luminous?
- Approx. face on?

If yes to *all* of the above, then:
- Do I have 10-20 epochs in 2 optical filters to ID Cepheids?
- Do I have enough Cepheids to sample \( \log(P) \)?
- Do I have spatially resolved metallicity information? *(is that information suitable for stellar measurements?)*
- Can I measure local extinction?
- … and related issues.

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And herein lies the limitation ...
### SN Ia Suitability is:

**SN Ia Suitability is:**

1. **Can I characterize the SN?**
   - *YES (~50%)*
   - Did I find it before peak light?
   - Can I remove the galaxy light and/or nearby bright sources?
   - Do I have quality light curves?
   - Can I measure local extinction?
   - ... and related issues.

2. **Can I measure the distance?**
   - *YES, for ~ten of them.*
   - Is the host galaxy:
     - Star forming?
     - Luminous?

   *And herein lies the limitation ...*

   1. Cepheids are fantastic, but their application to the SN Ia population is limited.
   2. The data to characterize them is expensive, requires multiple facilities, relies on many different observational techniques.

   If yes to all of the above then:
   - Do I have 10-20 epochs in 2 optical filters to ID Cepheids?
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March 01, 2016

Rachael L. Beaton -- Carnegie Observatories
Let’s go back to CMD101:
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Too faint en masse for large distances.
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**Cepheids**

<400 Myr

~massive

Range of metals

Galaxy disks

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**RR Lyrae**

Old >few Gyr

~1 solar mass

Mostly metal poor

Disk, bulge, halo, etc.

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~1 solar mass

Mostly metal poor

Disk, bulge, halo, etc.

**TRGB**

Old >>few Gyr

~1 solar mass

Mostly metal poor

Disk, bulge, halo, etc.

(and red)

Too faint en masse for large distances.
The TRGB as an alternative:

TRGB in NGC4258
(mega maser host)

- Available in galaxies of all sizes, shapes, morphology, interactions, etc.
- Point in the halo to avoid extinction, crowding, etc.
- Metallicity effect projected to color

NGC4258: ~7 Mpc

Mager, Madore, Freedman 2008
The Bottom Line: $H_0$ Error Budget

**Today**
(-ish, few years from now)

![Diagram showing the error budget for $H_0$]

- 2.0% Galactic RR Lyrae
- 1.0% Local Group RR Lyrae TRGB + NGC 4258 Maser TRGB
- 6.0% Galactic TRGB
- 2.5% TRGB 12 SNe Ia
- 0.7% 200 SNe Ia Hubble Flow
- 3.4% $H_0$
- 6.5%

The CCHP Pathways to a 3% Determination of the Hubble Constant

March 01, 2016
Rachael L. Beaton -- Carnegie Observatories
Beaton et al. submitted
From HIP+HST+FGS to Gaia

**NOW**

Hipparcos (HIP)

Perryman et al. 1997

20,853 stars

HST+FGS

+ 5 RR Lyrae

+ 10 Cepheids

Benedict et al. 2002,'07,'11

**THEN**

Gaia

→ THE BILLION STAR SURVEYOR

Fig. 3. The observational Hertzsprung-Russell diagram, $M_V$ versus $B - V$, for the 20,853 stars with $\sigma_\pi/\pi < 0.1$, and with the additional constraint $\sigma_{B-V} < 0.025$ mag.

Gaia is a game changer.

For details see:

Clementini et al. 2016

Eyer et al. 2012
The Bottom Line: $H_0$ Error Budget

After Gaia
(and before WFIRST)

The CCHP Pathways to a 3% Determination of the Hubble Constant

For Gaia details see:
Clementini et al. 2016
Eyer et al. 2012
Blue vs. Red Candles

Hubble Space Telescope

WFIRST
E. Carlson et al. (in prep.)

Apparent Magnitude

NGC6822
S. Leshin
Blue vs. Red Candles

NGC6822

S. Leshin

V
R
I
J
H
K

Hubble Space Telescope

WFIRST

E. Carlson et al. (in prep.)

Cepheids
TRGB

March 01, 2016
Rachael L. Beaton (V-K) Carnegie Observatories
E. Carlson et al. (in prep.)
Blue vs. Red Candles

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NGC6822

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E. Carlson et al. (in prep.)

Apparent Magnitude

Cepheids
TRGB
Hubble Space Telescope

(V-K)

March 01, 2016
Rachael L. Beaton (V)- Carnegie Observatories
E. Carlson et al. (in prep.)
A Worked Example

HST+ACS

NGC4424
A Worked Example

- HST+ACS
- NGC4424
- ~15 Mpc
- 6 Orbits
And more distant:

~18 Mpc

16 HST Orbits

HST+ACS
NGC1365

March 01, 2016

Rachael L. Beaton -- Carnegie Observatories
A Prospectus for WFIRST:

(modulo calibration of TRGB in WFIRST filters ...)

Guest Investigator (Archive):

Within HLS:
  \[(m-M) \sim 31.7 \text{ [mag]} \]
  22 Mpc

Everything in the footprint is “free” @~1%

Guest Observer:

Using \( H \) for the TRGB luminosity function and \( Y \) for the CMD color:

@HLS Depth => 30 mins
  < 22 Mpc

@ 1 mag fainter => 1.25 hours
  < 35 Mpc

@ 2 mag fainter => 3.15 hours
  < 55 Mpc

@ 3 mag fainter => 7.8 hours
  < 87 Mpc