Lecture V:
Distance Indicators in Cosmology

Physics 8803

February 6, 2019

General Concepts

- Distances measurements may be:
  - "Absolute" – the distance measurement can be written in meters using previously known information (e.g. trigonometric parallax).
  - "Relative" – usually an empirical relation (e.g. period-luminosity relation of Cepheids), must be calibrated against an absolute method if we want it in meters ("anchor").
- The "distance ladder" – many versions, e.g.:

Trigonometric parallax → Cepheid variables → Type Ia supernovae

(absolute but only feasible in Milky Way)

(relative; used out to ~30 Mpc)

(relative; used out to z>1)

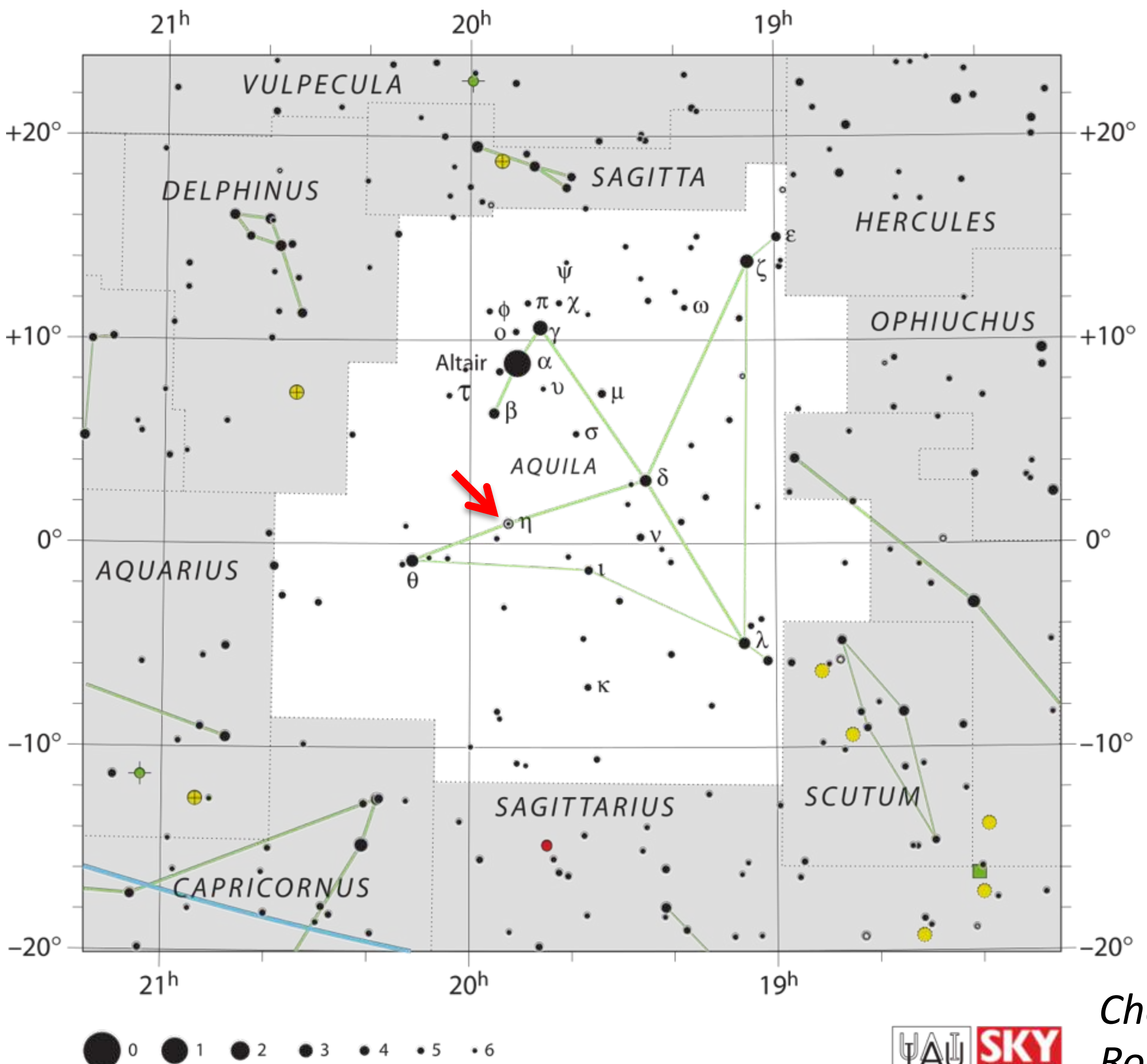
Methods Covered Today

- Cepheid variables
- Galaxy scaling relations
- Type Ia supernovae
- Eclipsing binaries
- Masers
- Parallax
- Gravitational wave sources

(I will cover strong lens systems later in the course.)

Red = relative; blue = absolute (anchors)

Cepheid Variables



η Aquilae

Variability discovered in 1784

Magnitude 3.5—4.3 (visible to your eye!!)

P = 7 days; D = 400 pc

Pulsating stars driven by κ-mechanism instability in He^{+}/He^{2+} ionization boundary in the star

Chart credit:
Roger Sinnott & Rick Fienberg

δ Cephei light curve

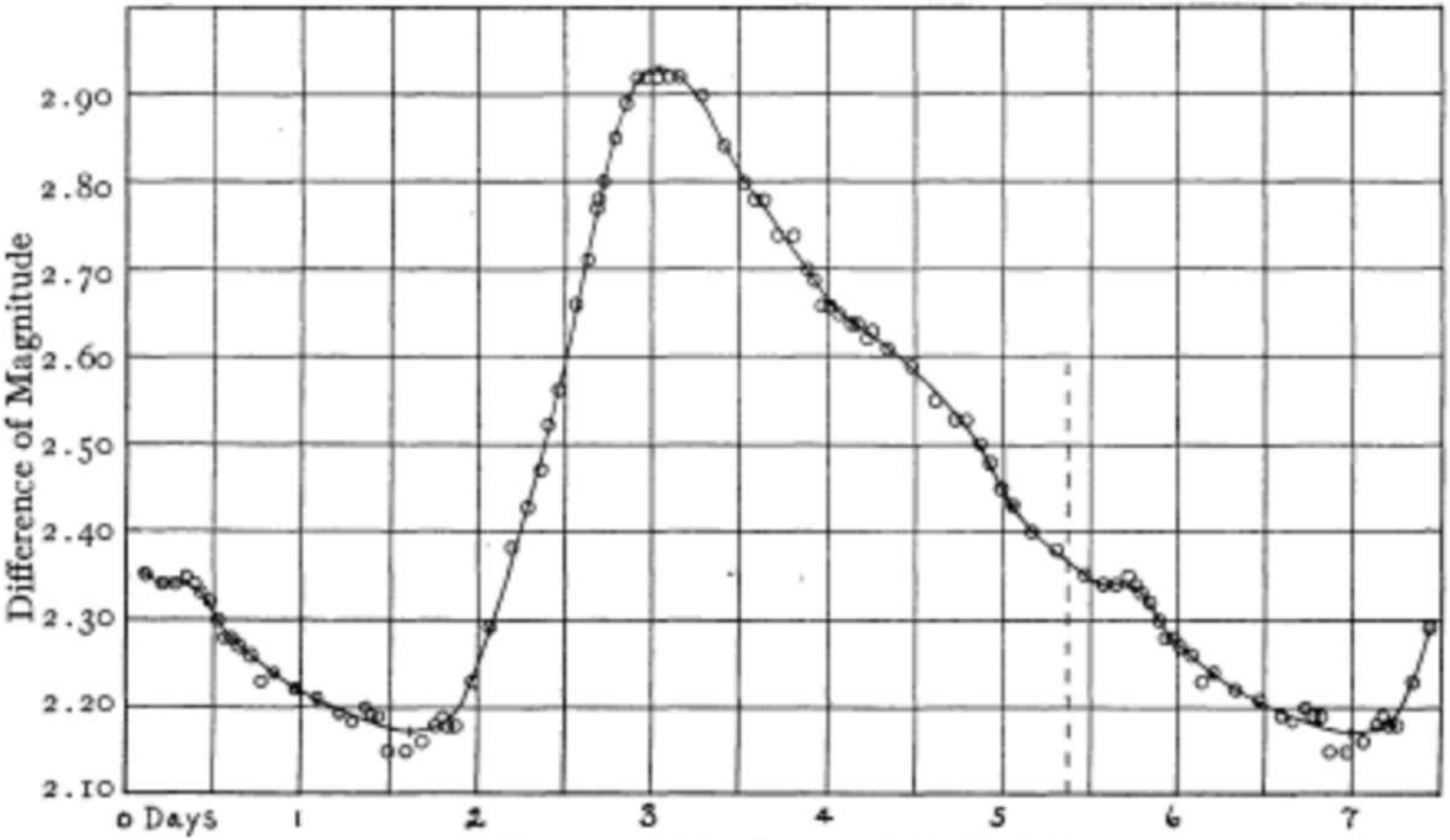
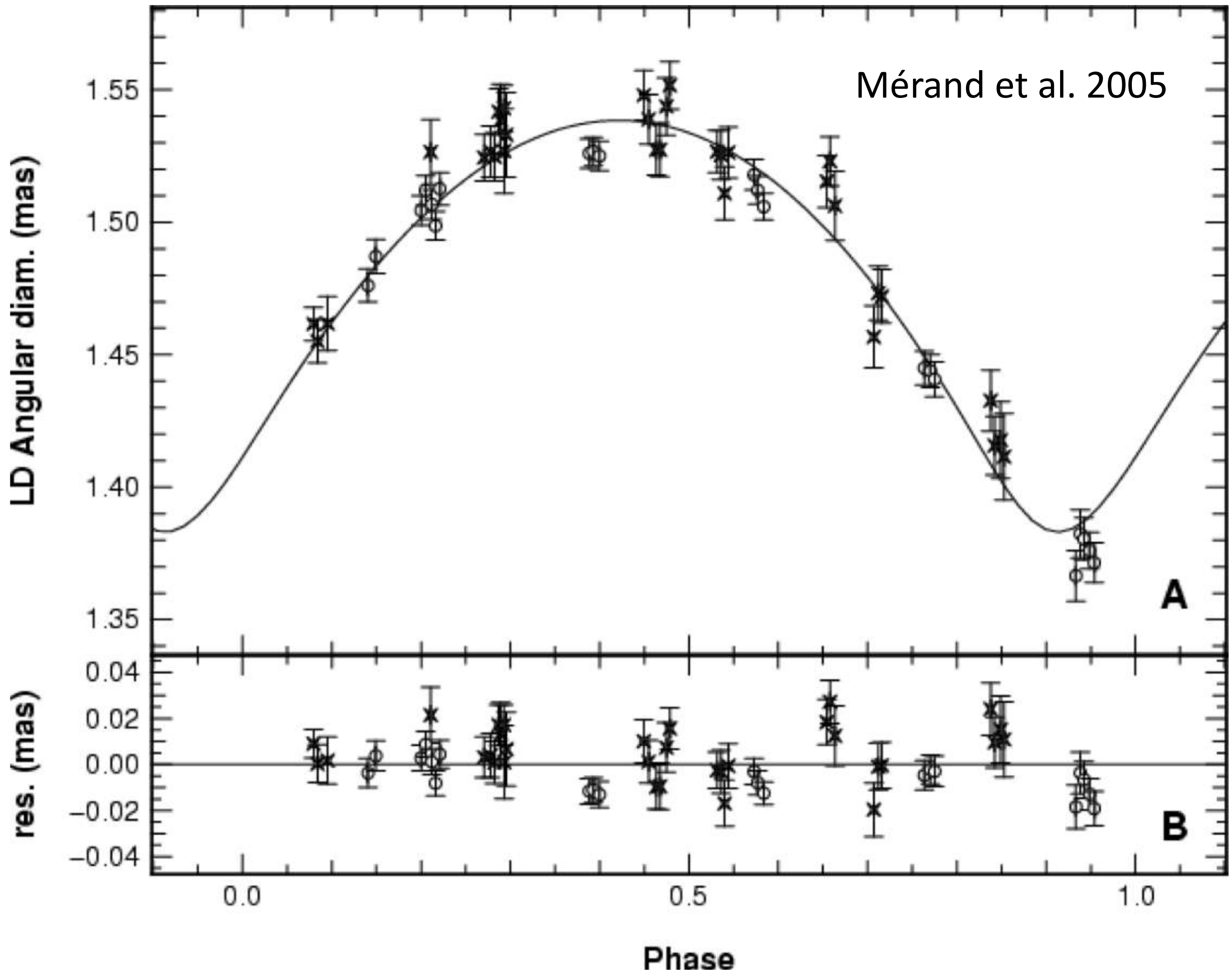


FIG. 1.—Light-Curve of δ *Cephei.*

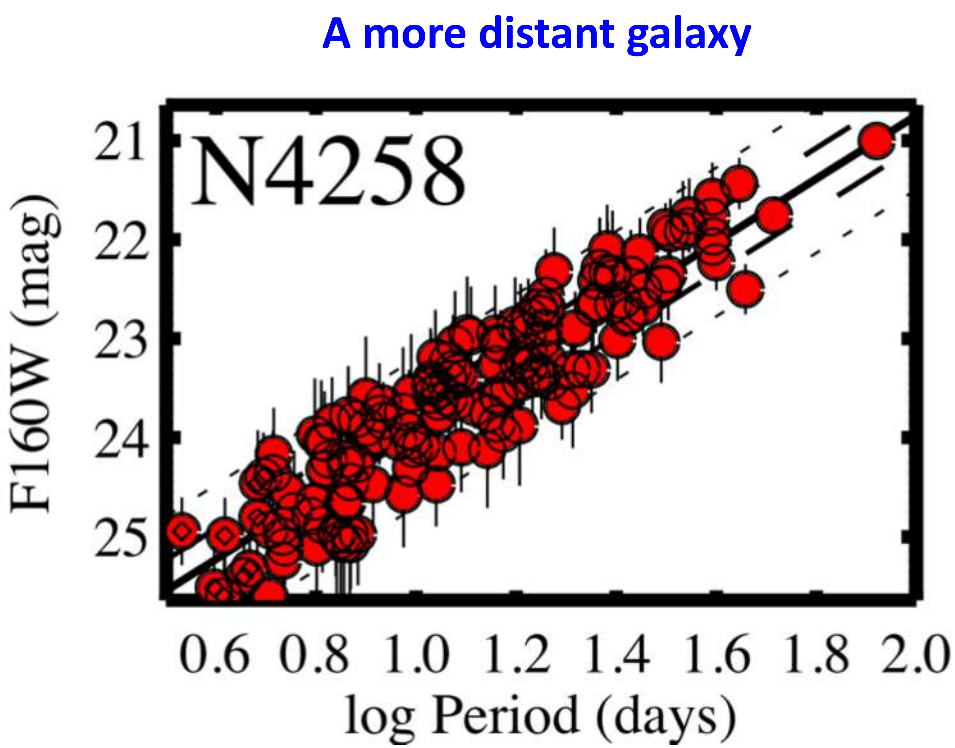
Stebbins et al. (1908)

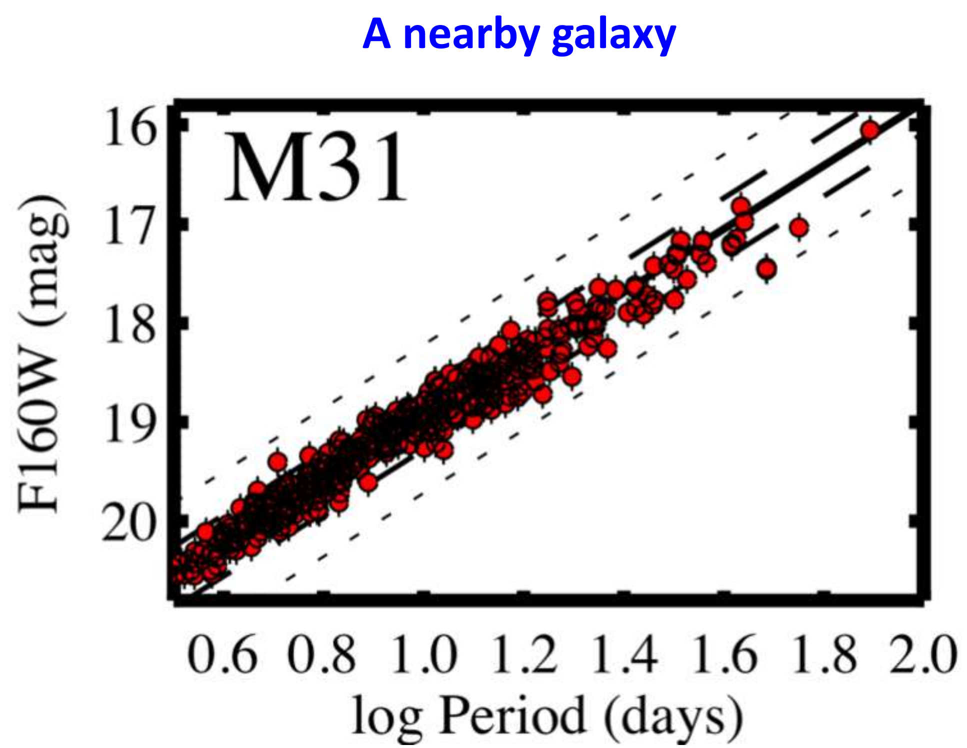
They Really Do Pulsate!

δ Cephei measured via optical interferometry



“Modern” Versions of Leavitt Diagram





F160W = Filter on Hubble Wide Field Camera 3; centered at ~ 1.6 µm

(Riess et al. 2016)

Cepheid Variables – Limitations

- General:
  - Relative distance indicator; need anchor
  - Even with Hubble Space Telescope, range limited to nearby Universe (30—40 Mpc; not even in Hubble flow)
- Observational:
  - Crowding/blending (gets worse at larger distances)
  - Extinction (dust)
  - Photometric calibration between bright/nearby and faint/distant Cepheids (both across instruments and within instruments, i.e. linearity)
  - The "nearest" Cepheids (with parallax) are often short P/low L vs. selection in distant galaxies for long P/high L
- Physical:
  - Period-luminosity relation dependence on metallicity (note the Magellanic Clouds are low metallicity!)

Galaxy Scaling Relations

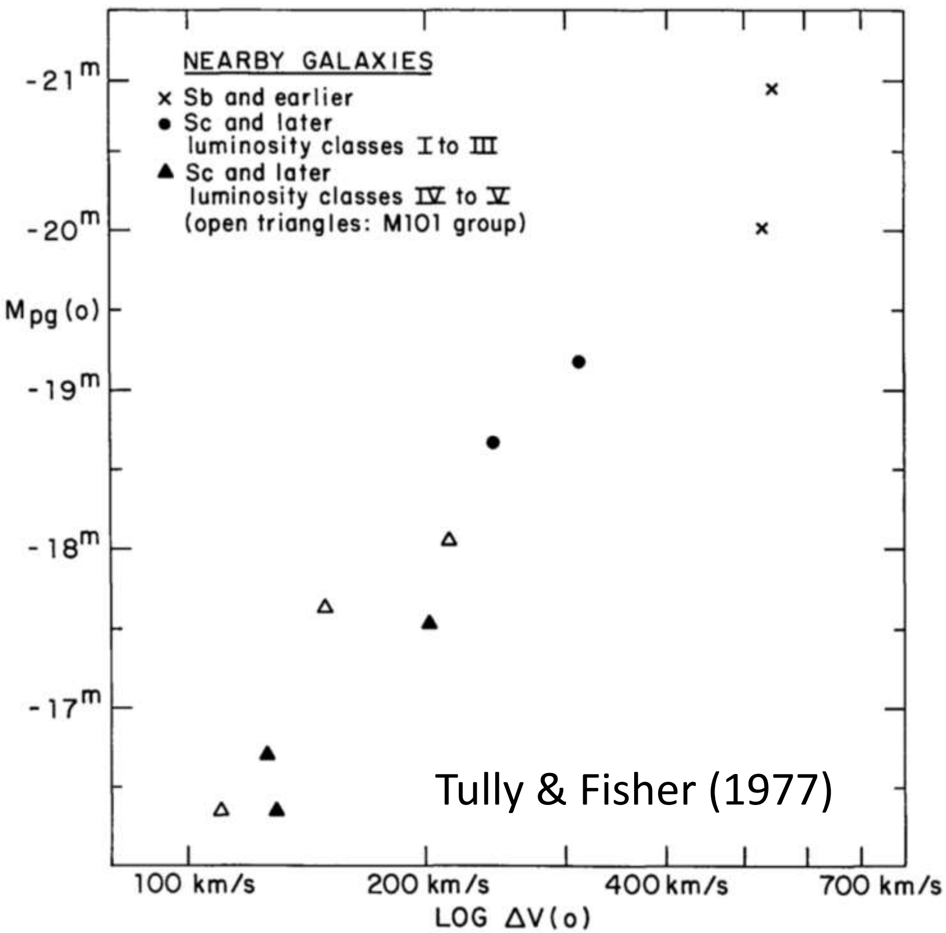


Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

Galaxies can be observed farther than Cepheids, but have a wide range of luminosities. Use empirical **scaling relations**.

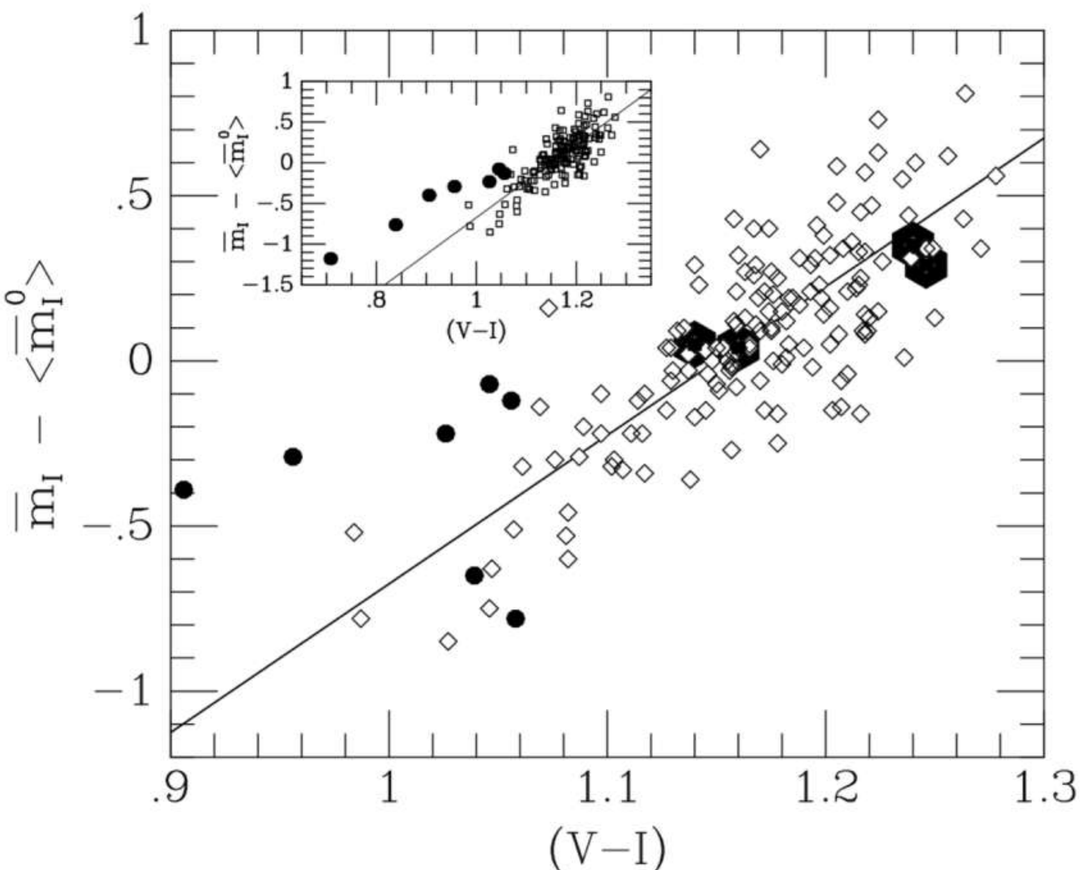
e.g. Tully-Fisher relation for spiral galaxies (luminosity vs. rotation velocity measured in H I 21 cm)

$$L \propto \Delta V^{\alpha}, \quad \alpha \sim 2.9(B) - 3.5(K)$$

Fundamental Plane for Ellipticals: Radius vs. velocity dispersion & surface brightness

$$r_e \propto \sigma_v^{1.2} I^{-0.85}$$

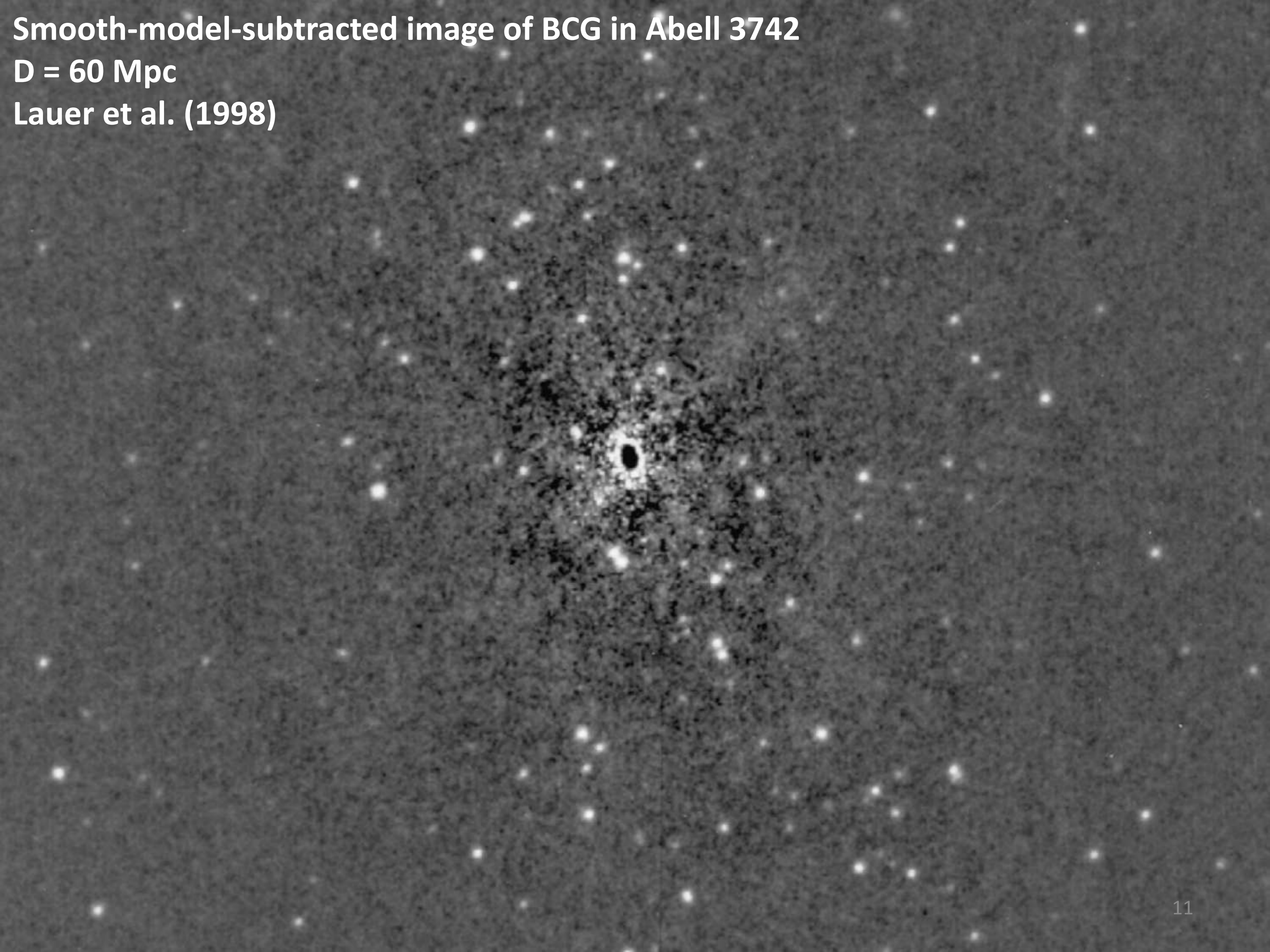
Surface Brightness Fluctuations



Tonry et al. 1997

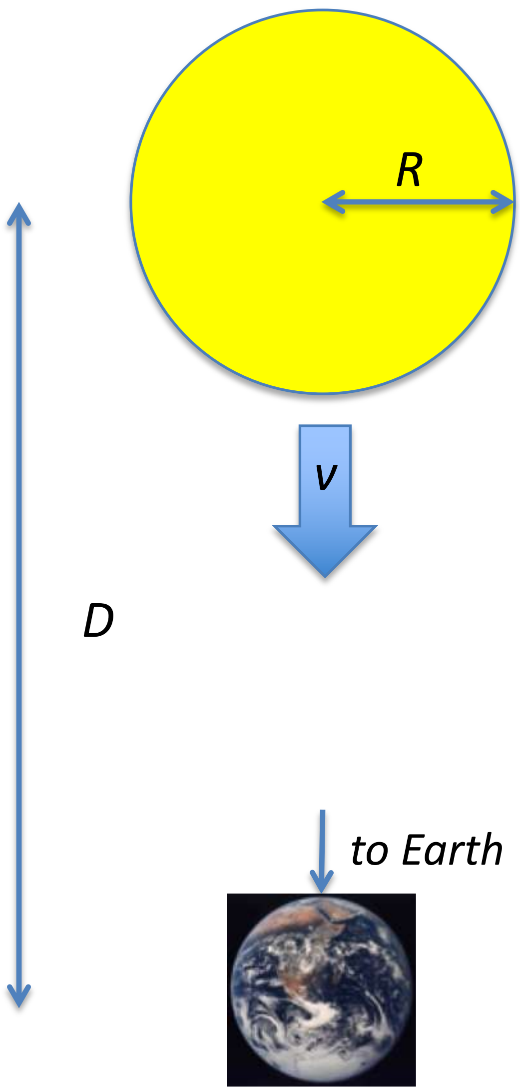
- Useful for smooth components (bulges, ellipticals)
- The (visible) light from galaxies comes from discrete stars with Poisson fluctuations.
- At the same surface brightness, a more distant source will have more stars per pixel and smaller fluctuations (ΔN/N).
- Must calibrate effective “mean star” and dependence on color (indicating age).

Smooth-model-subtracted image of BCG in Abell 3742
D = 60 Mpc
Lauer et al. (1998)



Expanding Photosphere Method

(used for Type II Supernovae)



Luminosity L is related to radius:

$$L = 4\pi R^2 T_{\text{eff}}^4$$

But radius is related to (observable) velocity via Doppler shift of SN absorption lines – if spherically symmetric:

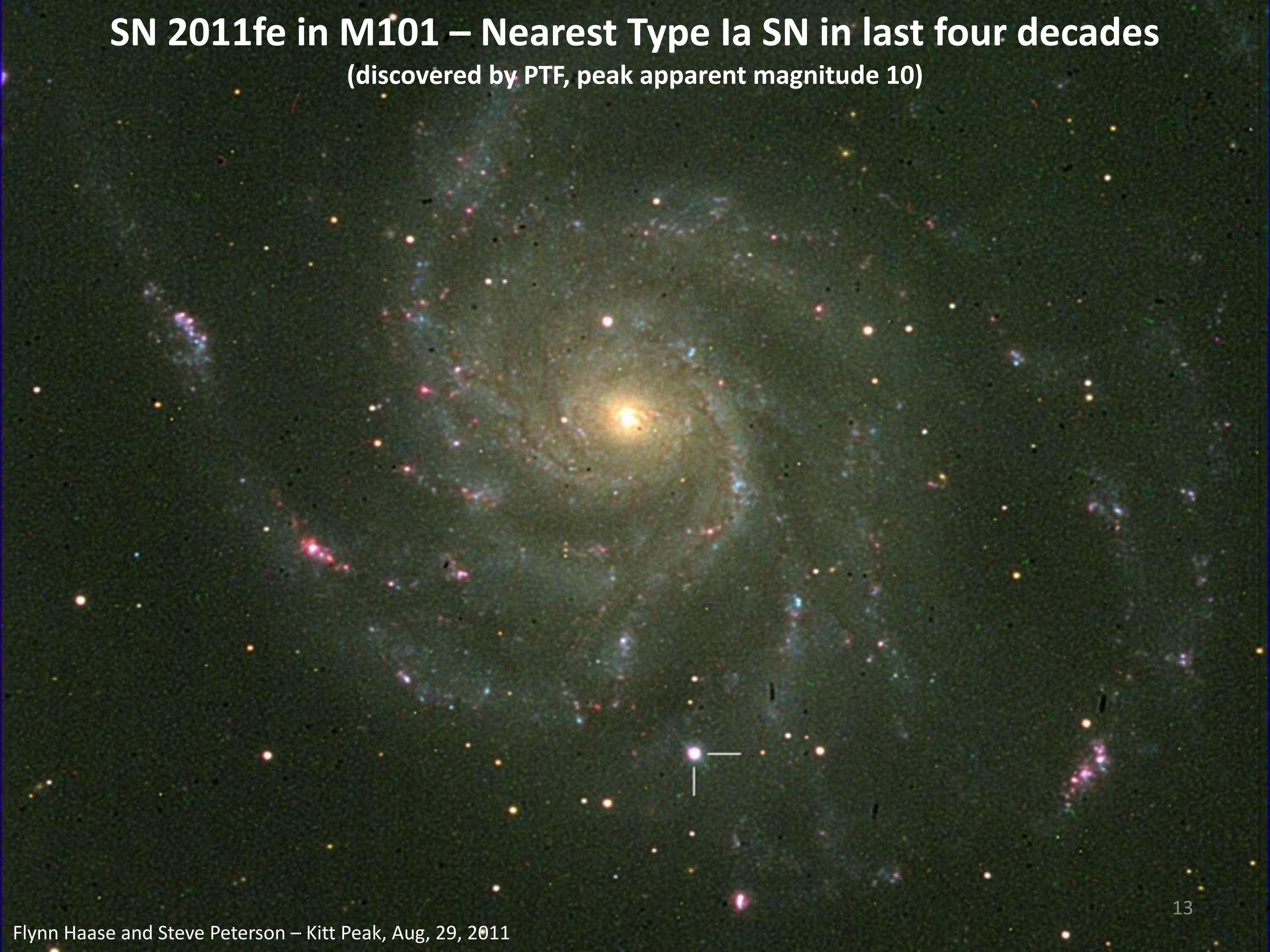
$$R = \int v\,dt$$

Infer T_{eff} from modeling of spectrum

(Related to Baade-Wesselink method for variable stars)

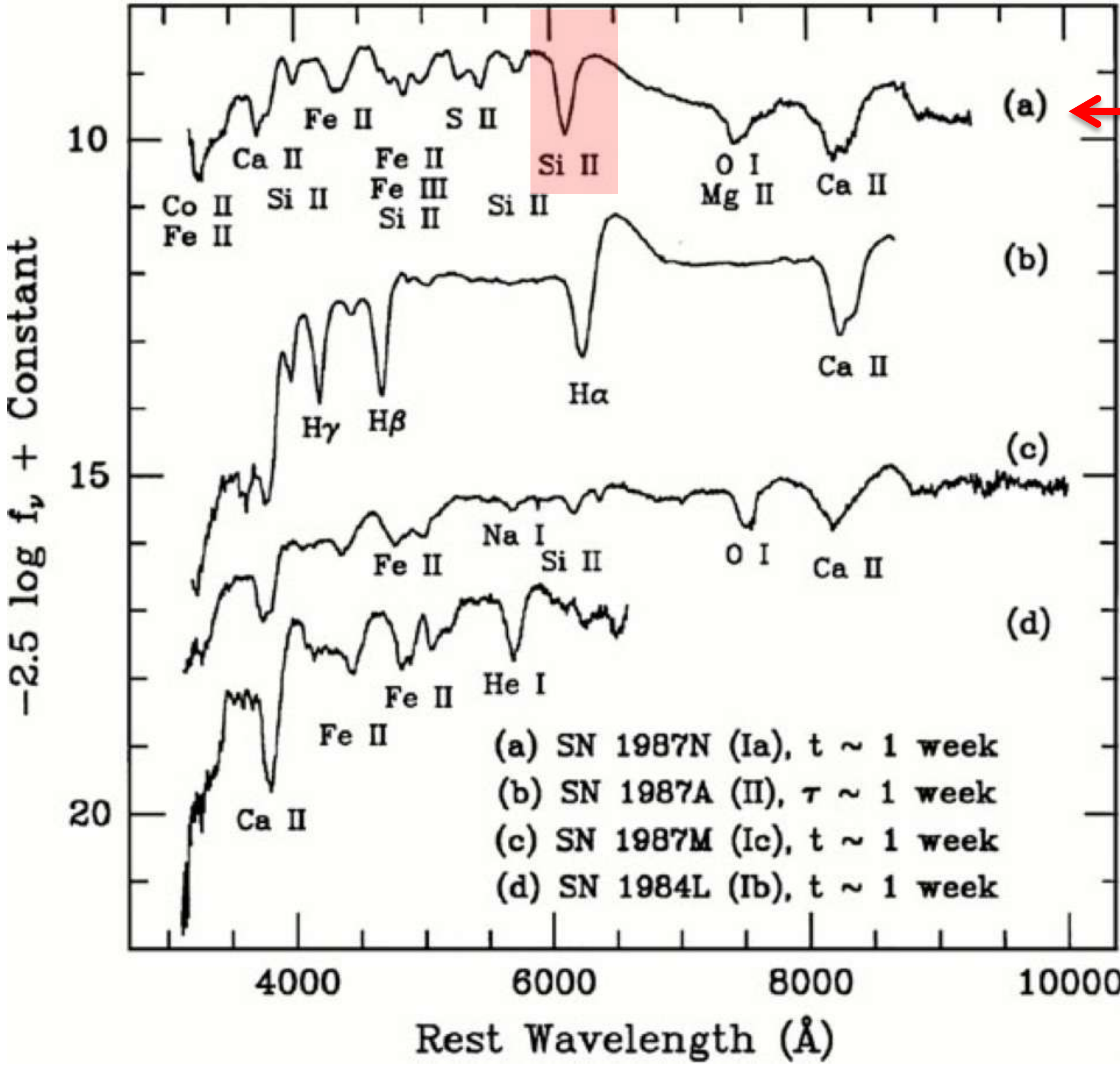
SN 2011fe in M101 – Nearest Type Ia SN in last four decades

(discovered by PTF, peak apparent magnitude 10)



Flynn Haase and Steve Peterson – Kitt Peak, Aug, 29, 2011

Supernova Spectra



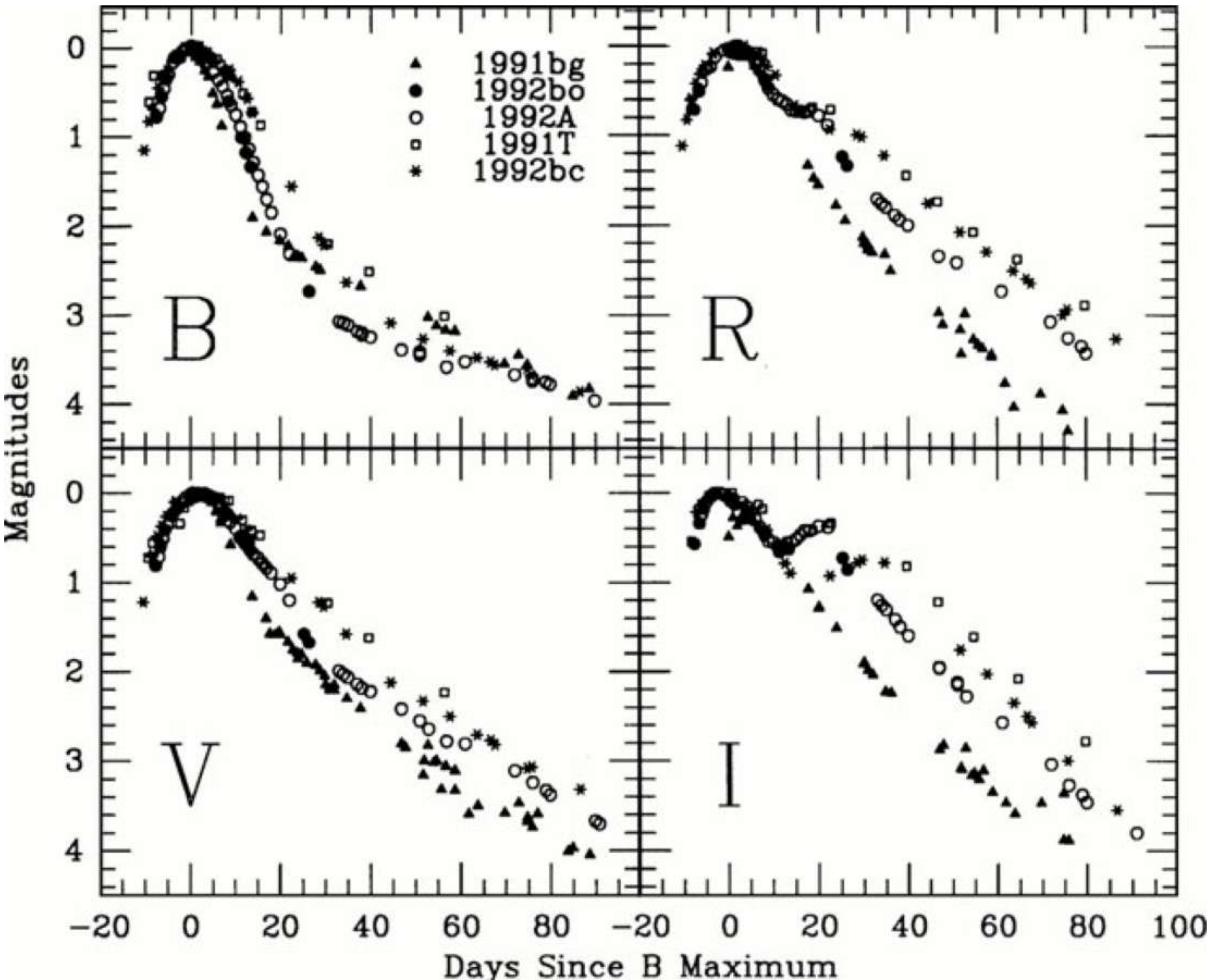
Type Ia

No H or He

Prominent blueshifted Si II line, and other elements up to iron peak

Filipenko (1997)

SN Ia light curves



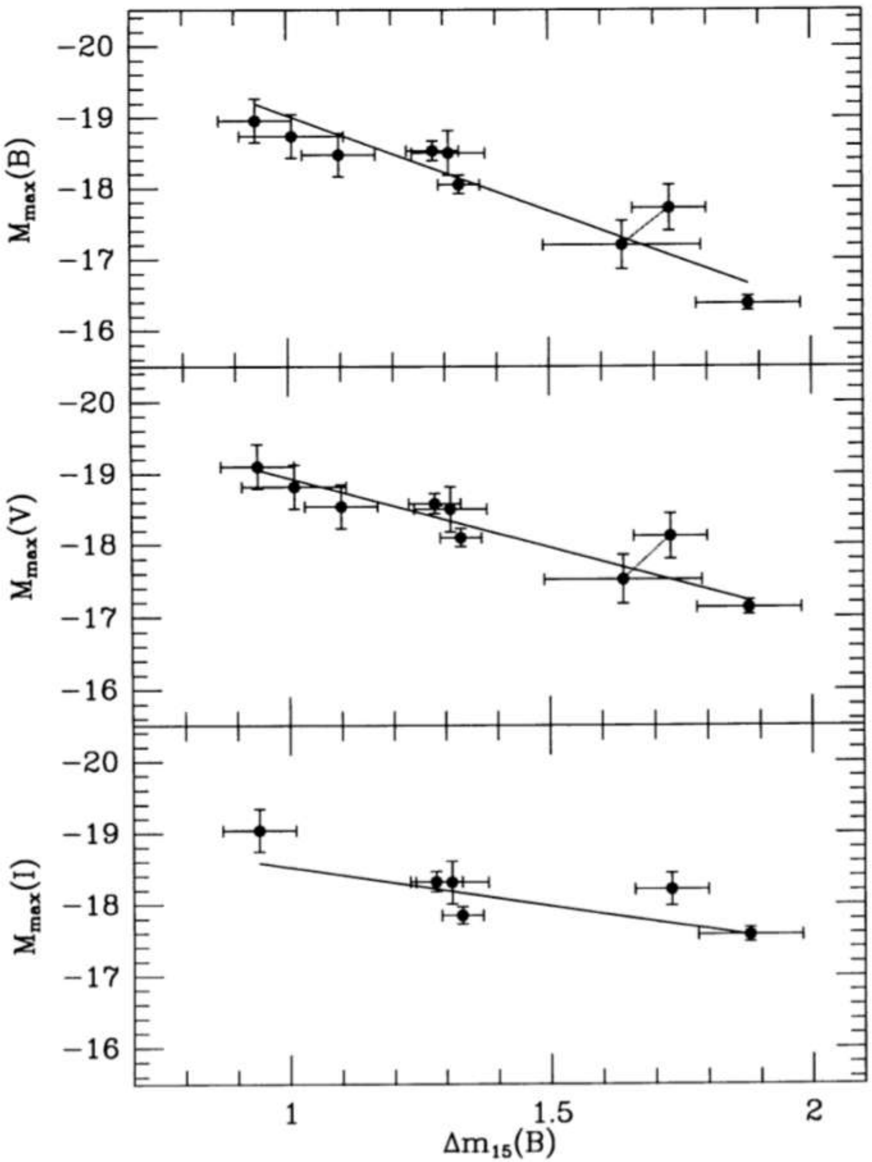
Suntzeff (1996)

Type Ia Supernovae

- **Not** collapse of core of a massive star (types Ib/Ic/II)
- Degenerate white dwarf matter is subject to runaway nuclear burning of $^{12}C + {}^{12}C$; reactions continue to ^{28}Si … ^{56}Ni
- Energy yield of fusion sufficient to unbind the star.
  - White dwarf is destroyed
- "Light" seen comes from $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ decay chain
  - Gamma rays are absorbed and thermalized in expanding debris.
  - Kinetic energy seen only in interaction with ISM (much later)
- Major source of Fe-peak elements

- But we still don't know the ignition source.
  - "Single degenerate" (1 white dwarf accreting from normal companion) vs. "double degenerate" (merger or collision of 2 white dwarfs)

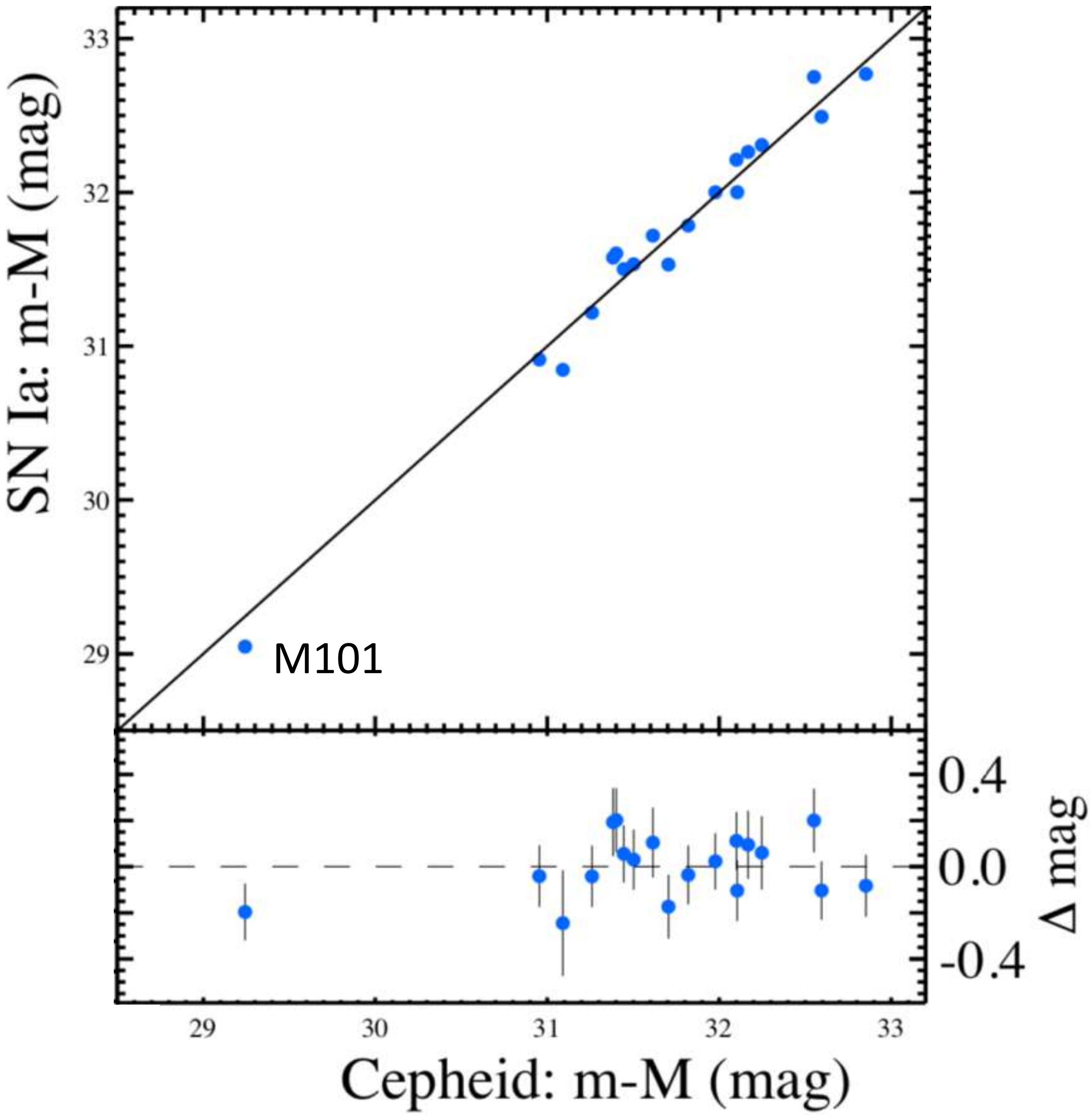
Luminosity-Decay Rate Relation



Phillips (1993)

- Maximum absolute magnitude vs. $\Delta m_{15}(B)$ (number of magnitudes of fading in B band in 15 days from peak)
- Not in the same galaxy (too rare!). Distances estimated from galaxy scaling relations
- "Modern" analyses calibrate directly from Cepheids to SNe Ia without galaxy scaling relations as an intermediate step.

Cepheids vs. SNe Ia

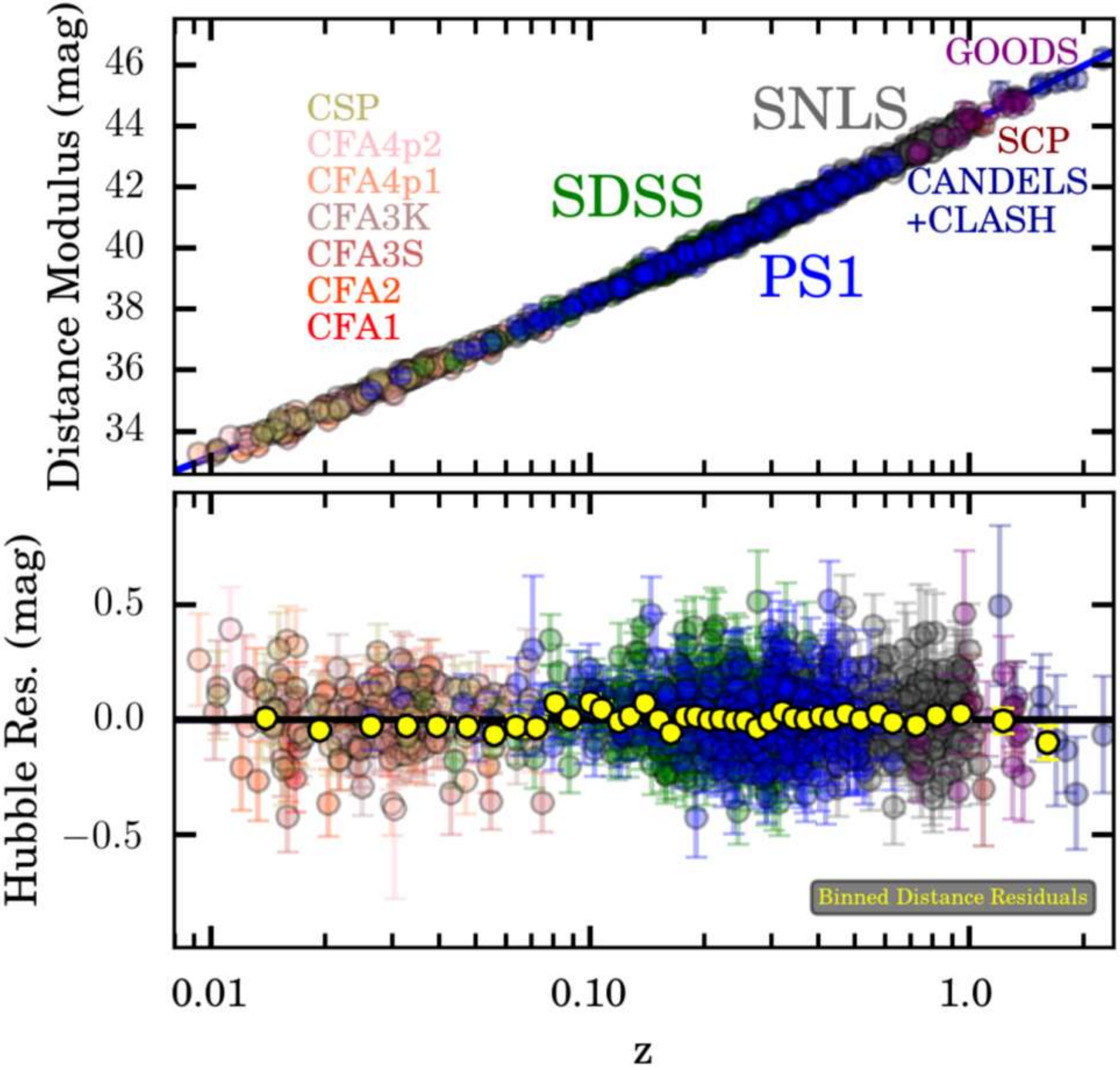


19 galaxies hosting **both** a Type Ia supernova and Cepheids measured with HST

Slope is indeed 1

Riess et al. (2016)

Type Ia SNe to higher z!

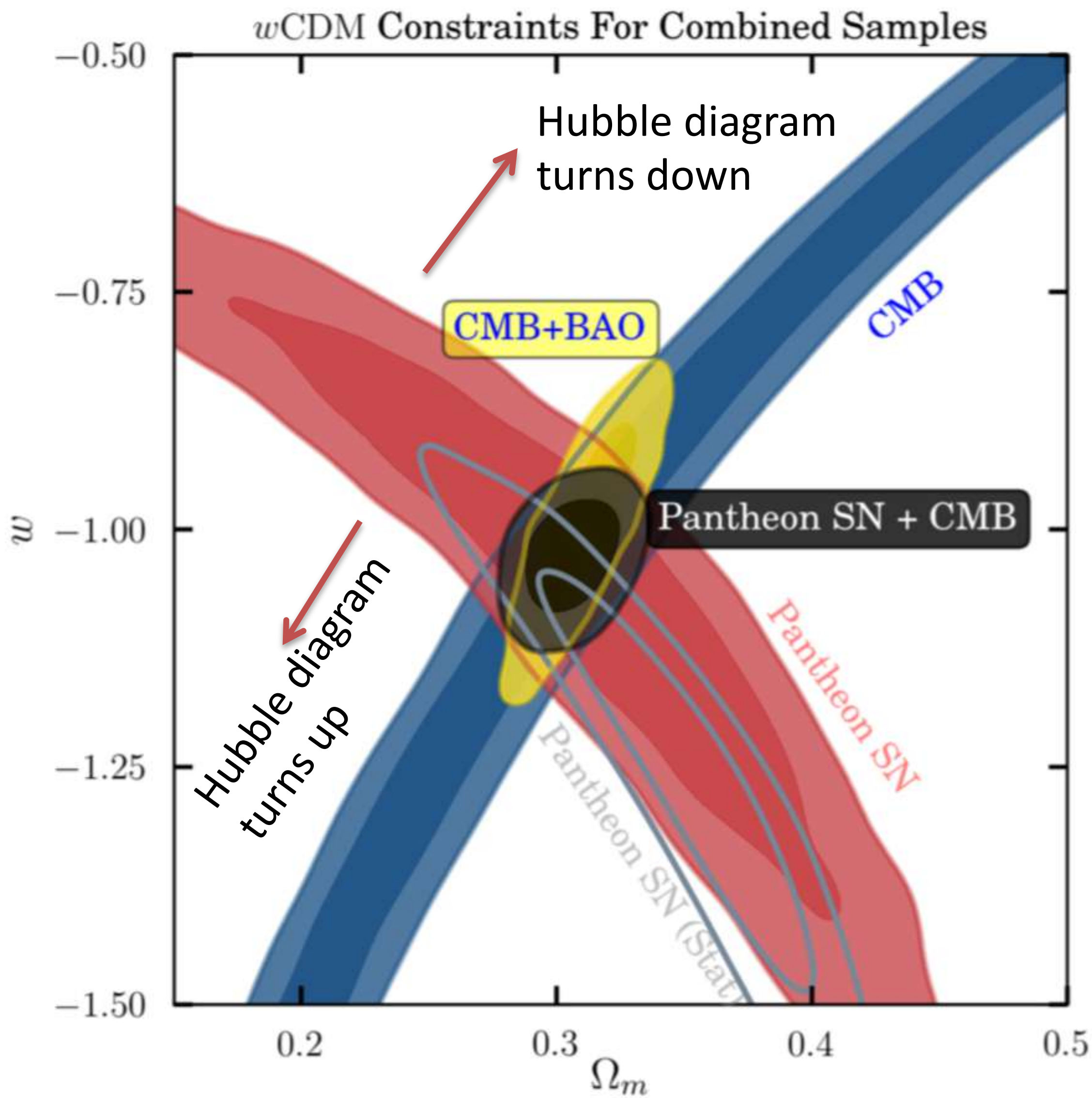


Pantheon Sample
1000 supernovae (compiled from many projects)

Scolnic et al. (2018)

A few objects out to z~2

Constraints on Dark Energy



Note – constraints on Ω_m and w can be obtained with a relative distance indicator.

"Anchor" only appears if you want to know H_0 …

Scolnic et al. (2018)

Issues with SNe Ia?

SNe Ia have proven to be the best luminosity standard thus far that can be measured at cosmological distances, but there are some systematic errors.

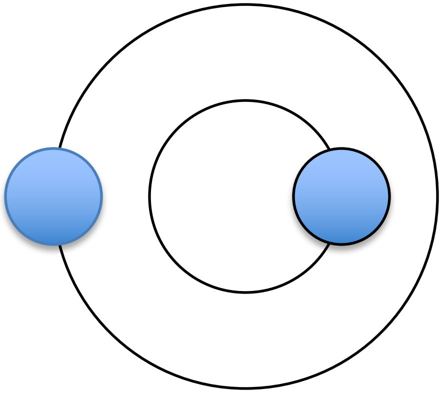
- Evolution (supernova populations vs. time)
- Selection biases (missing intrinsically faint supernovae at high z)
- Modeling of Philips relation parameters
- Calibration (bright vs. faint, across instruments, and wavelengths!)
- Dust extinction …

Distance "Anchors"

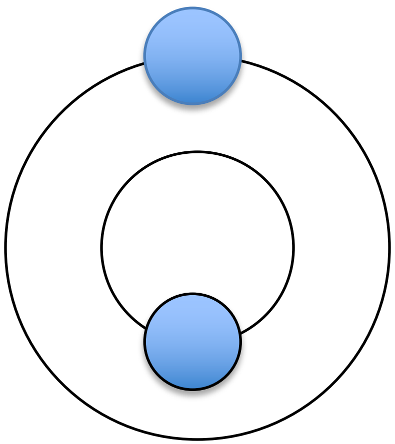
- Historically, wanted to know H_0
- Can **only** do this with an absolute distance measurement that calibrates the Cepheid distance scale.

- Usually based on fortuitous circumstances that allow measurement of distance to one object.

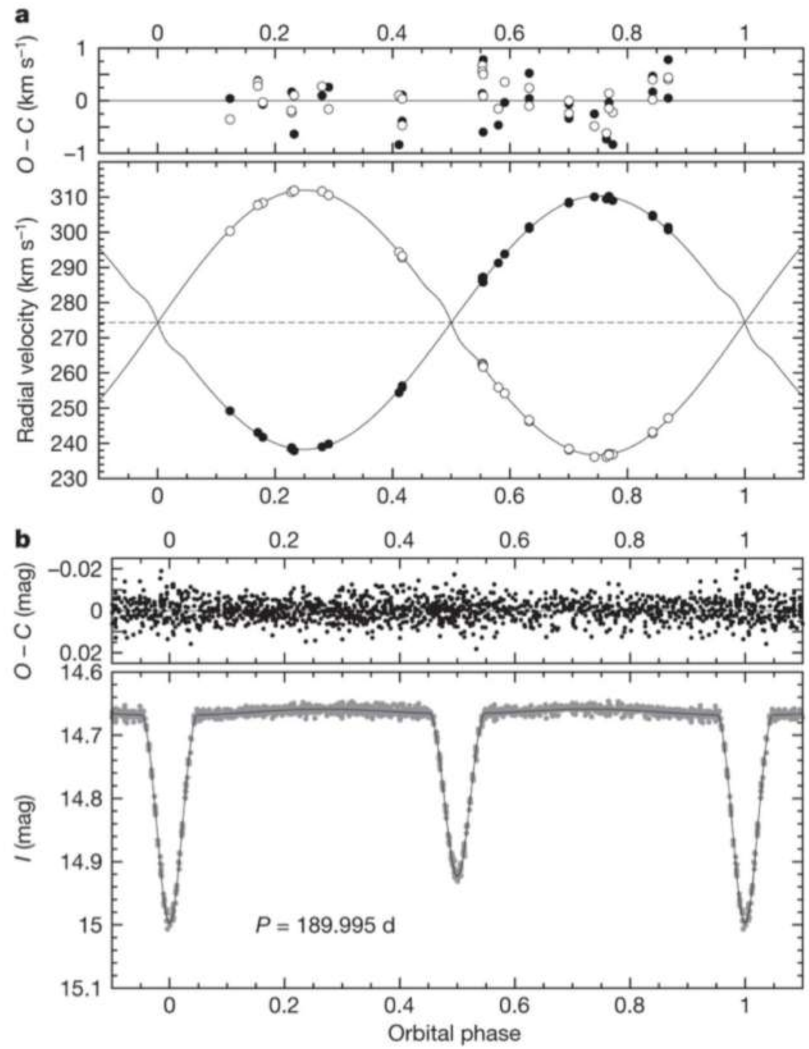
Eclipsing Binaries in LMC



Radial velocities observable spectroscopically



Eclipse duration observable photometrically



Pietrzyński et al. (2013)
D(LMC) = 49.97 ± 0.19 ± 1.11 kpc

Distance Ladder in Hubble Key Project

(anchor)

Large Magellanic Cloud – compilation of 7 methods
(50.1 ± 2.3 kpc)

→

Cepheid Period-Luminosity relation

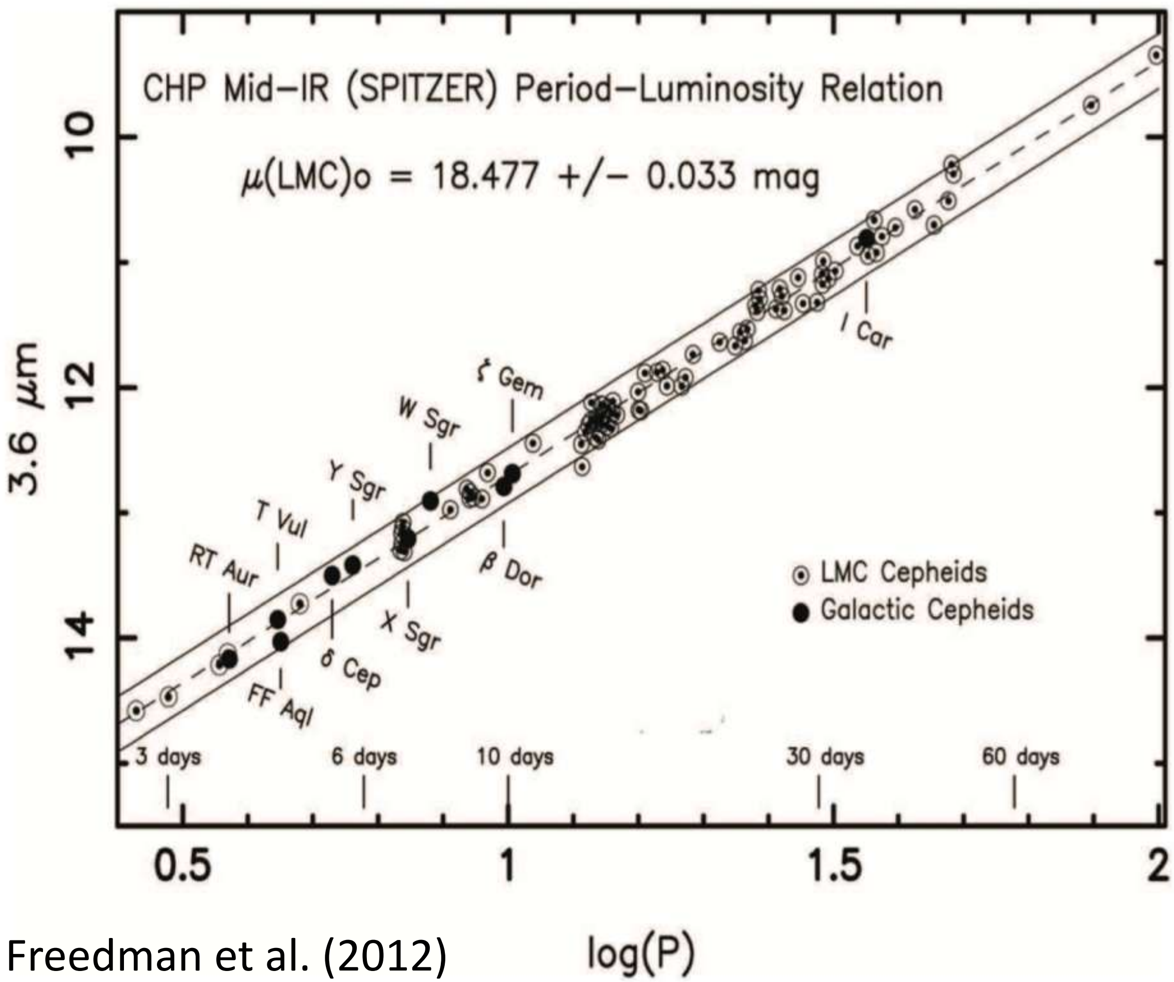
→

- Tully-Fisher relation
  H_0 = 71±3±7 km/s/Mpc
- Fundamental Plane
  H_0 = 82±6±9 km/s/Mpc
- Surface brightness fluctuations
  H_0 = 70±5±6 km/s/Mpc
- Type Ia supernovae
  H_0 = 71±2±6 km/s/Mpc
- Type II supernovae
  H_0 = 72±9±7 km/s/Mpc

<u>Combined result:</u>
H_0 = 72±8 km/s/Mpc

(Freedman et al. 2001)

Infrared Leavitt Law



Freedman et al. (2012)

Dust & metallicity effects are lower in the infrared

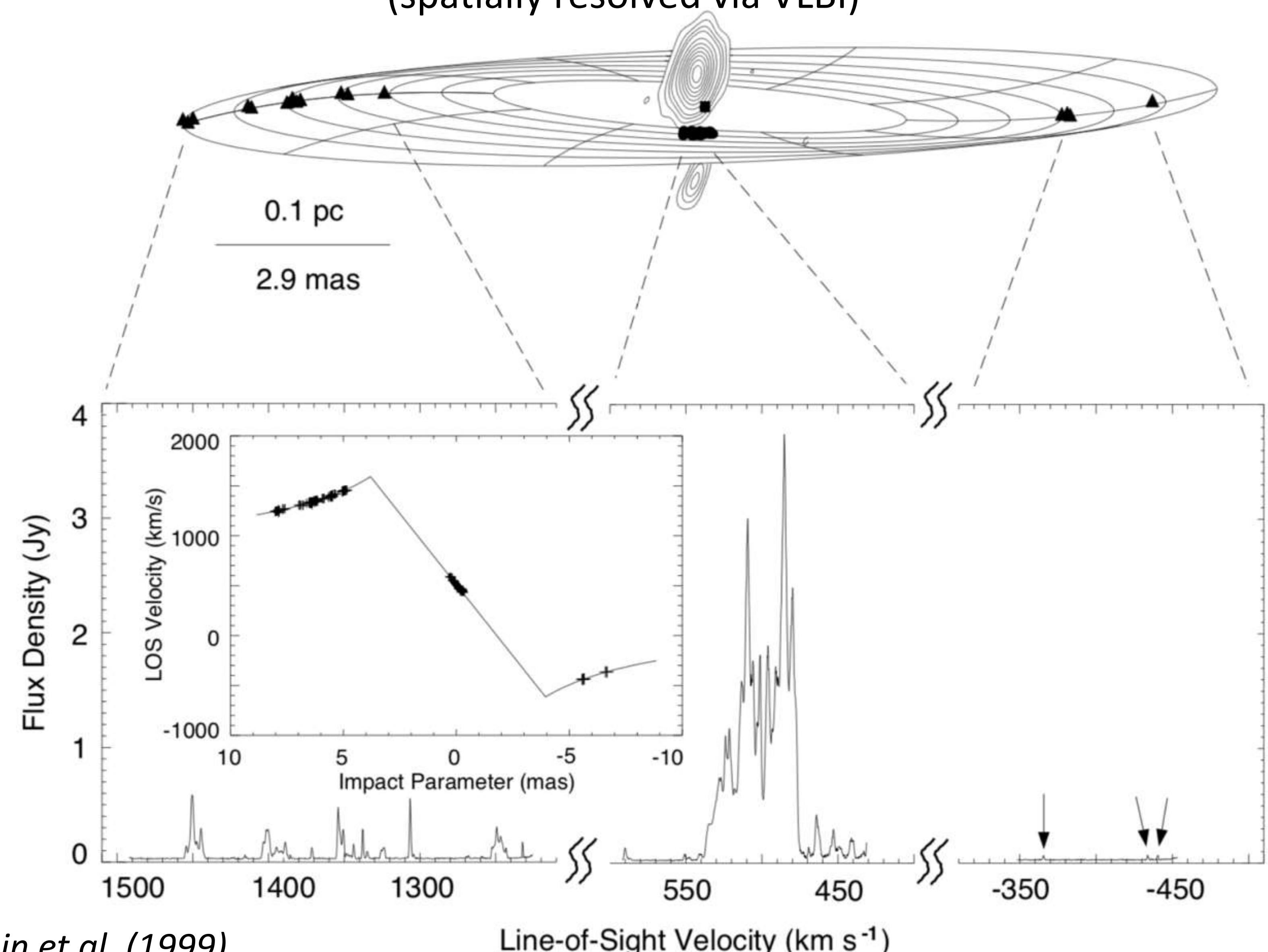
Slope of P-L relation driven by LMC, but intercept (absolute scale) set by Milky Way Cepheids with HST parallax

In combination with other improvements to the Key Project:

H_0 = 74.3±2.1 km/s/Mpc

H_2O 22 GHz Maser System in NGC 4258

(spatially resolved via VLBI)



Herrnstein et al. (1999)

Fitting the maser system ...

$$v_{\rm orb}^2 = \frac{GM}{D\theta}\sin^2 I \qquad \dot{v}_r = \frac{GM}{r^2}\sin I \qquad \dot{\theta}_x = \frac{1}{D}\sqrt{\frac{GM}{r}} \qquad \frac{dv_r}{d\theta_x} = D\sqrt{\frac{GM}{r^3}}\sin I$$

Left & right

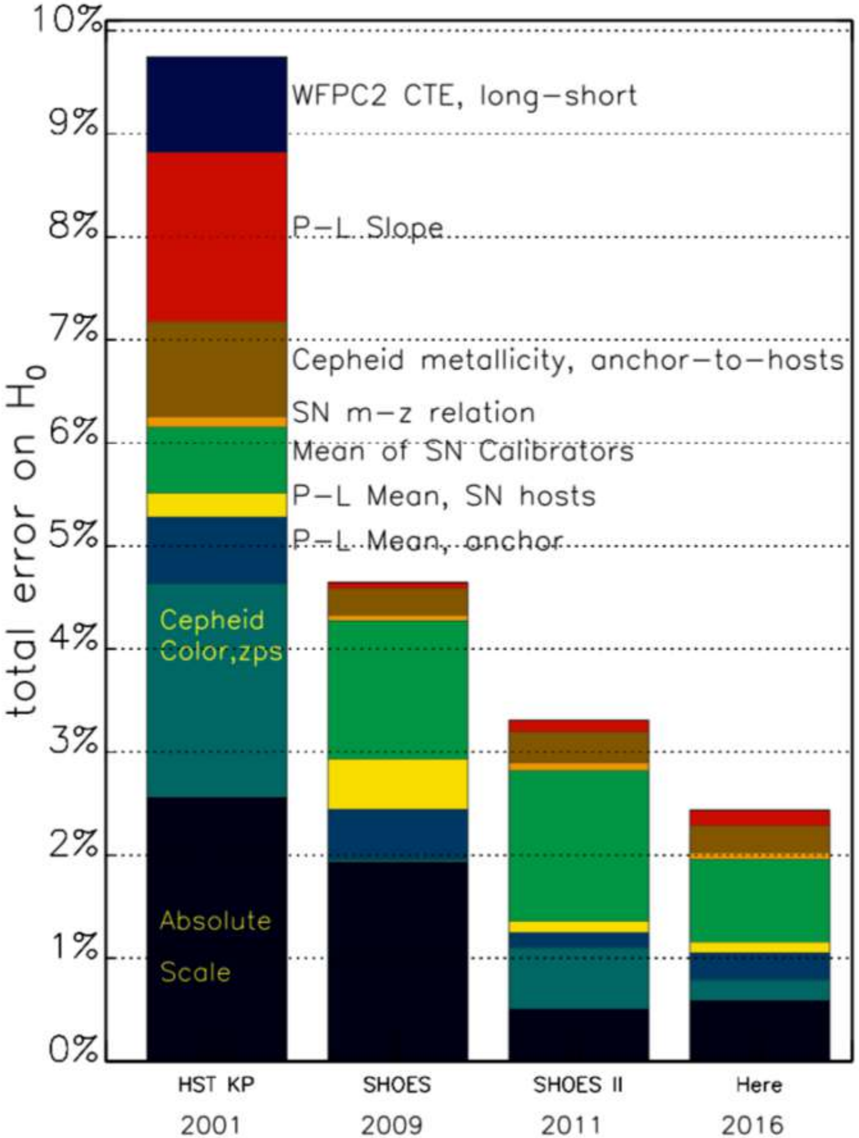
Center

Parameter	Value[a]
Distance, D (Mpc)	7.60 ± 0.17
Black hole mass, $M_{\rm bh}$ ($\times 10^7\ M_\odot$)	4.00 ± 0.09
Galaxy systemic velocity, $v_{\rm sys}$ (km s^{-1})	474.25 ± 0.49
Dynamical center x-position, X_0[b] (mas)	-0.204 ± 0.005
Dynamical center y-position, Y_0[b] (mas)	0.560 ± 0.006
Inclination, i_0 (deg)	71.74 ± 0.48
Inclination warp, di/dr (deg mas^{-1})	2.49 ± 0.11
Position angle, Ω_0 (deg)	65.46 ± 0.98
Position angle warp, $d\Omega/dr$ (deg mas^{-1})	5.23 ± 0.30
Position angle warp, $d^2\Omega/2dr^2$ (deg mas^{-2})	-0.24 ± 0.02
Eccentricity, e	0.006 ± 0.001
Periapsis angle, ω_0 (deg)	293.5 ± 64.4
Periapsis angle warp, $d\omega/dr$ (deg mas^{-1})	59.5 ± 10.2

Humphreys et al. (2013)

Updated Direct H_0 Measurement

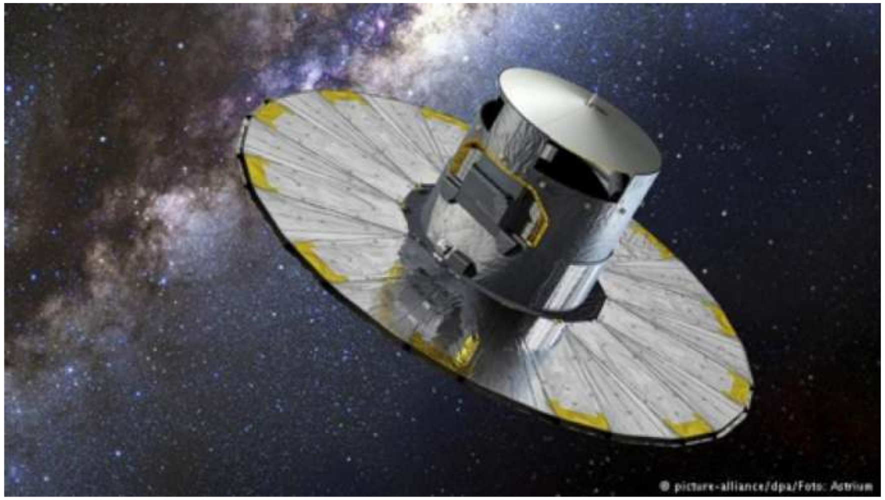
(Riess et al. 2016)



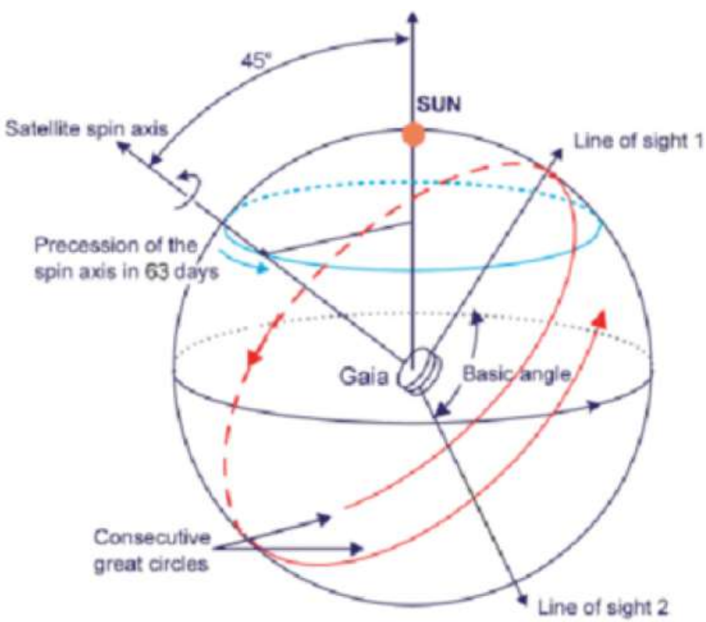
Anchor(s)	Value [km s^{-1} Mpc^{-1}]
One anchor	
NGC 4258: Masers	72.25 ± 2.51
MW: 15 Cepheid Parallaxes	76.18 ± 2.37
LMC: 8 Late-type DEBs	72.04 ± 2.67
M31: 2 Early-type DEBs	74.50 ± 3.27
Two anchors	
NGC 4258 + MW	74.04 ± 1.93
NGC 4258 + LMC	71.62 ± 1.78
Three anchors (preferred)	
NGC 4258 + MW + LMC	$\mathbf{73.24 \pm 1.74}$
Four anchors	
NGC 4258 + MW + LMC + M31	73.46 ± 1.71
Optical only (no NIR), three anchors	
NGC 4258 + MW + LMC	71.56 ± 2.49

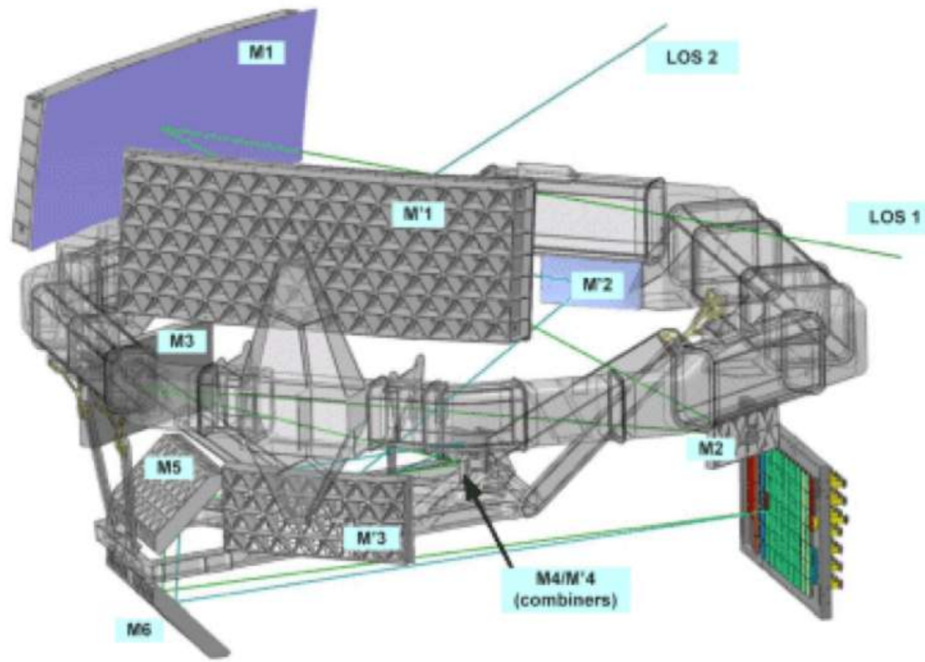
… but prediction from running CMB (Planck) model forward:
66.93 ± 0.62 km/s/Mpc
Why the discrepancy?

The Gaia Mission

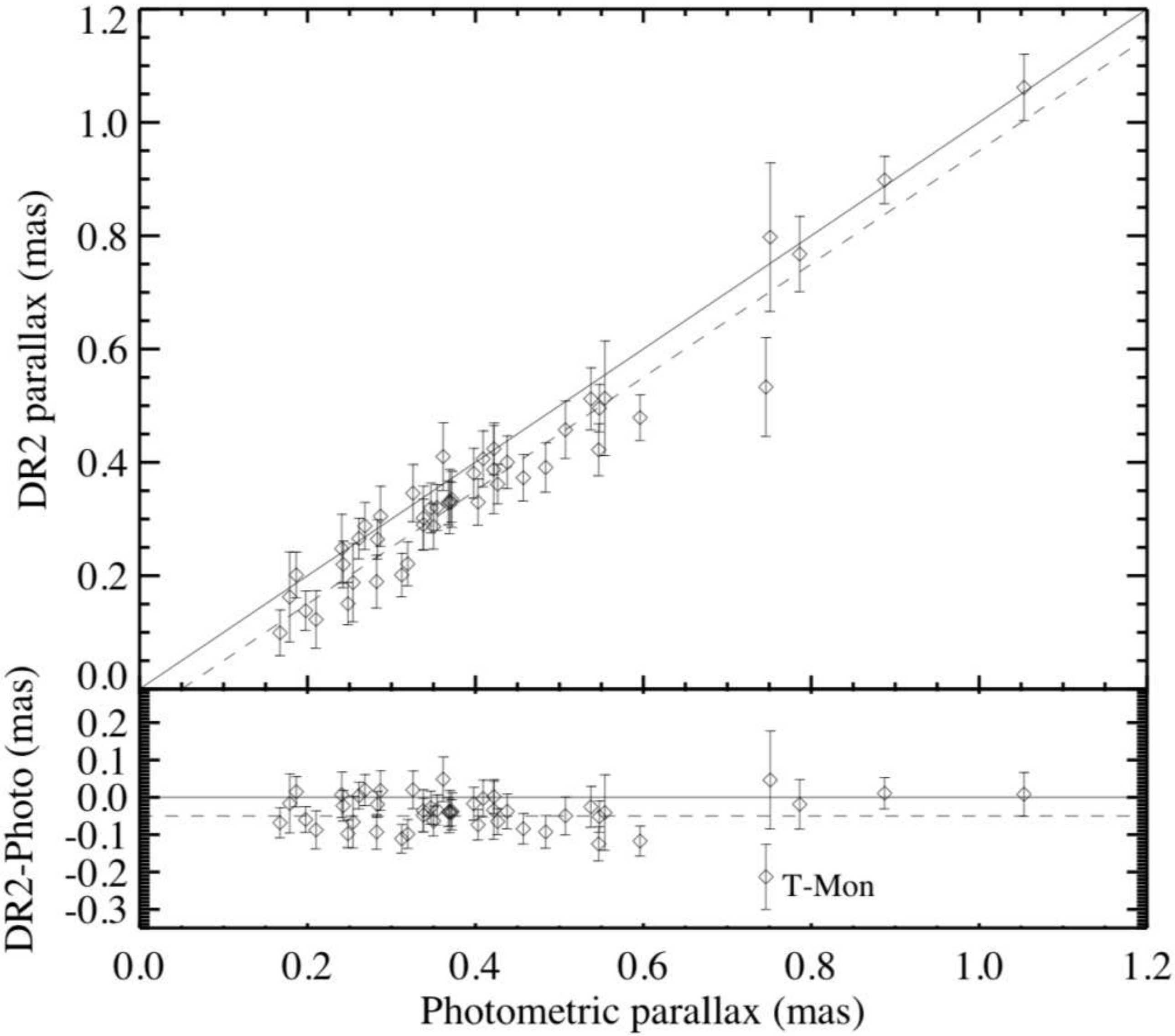


Trigonometric parallax reinvigorated by launch of European Space Agency Gaia astrometric mission in 2013





MW Cepheid Parallaxes from Gaia



Riess et al. (2018)

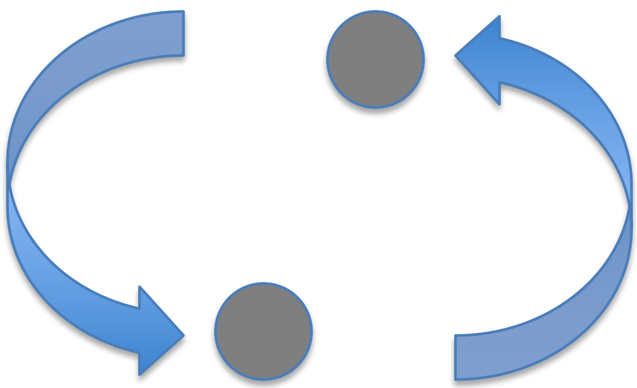
Use Gaia Data Release 2 (DR2) as check on prior Cepheid distance scale

Scaling factor of 1.006±0.033 from maser + eclipsing binary distance scale

–46±13 μas intercept spurred some controversy

Gravitational Wave Sources

(proposed by Schutz 1986)



Binary system:

Masses m_1, m_2 (in M_{Sun})
GW frequency $f = 100 f_{100}$ Hz
(2x orbital frequency)
Distance $r = 100 r_{100}$ Mpc

$$m_{\mathrm{T}} = m_1 + m_2 \qquad \mu = \frac{m_1 m_2}{m_1 + m_2} \qquad \tau = \frac{f}{\dot{f}}$$

GW strain in units of 10^{-23} (angle averaged):

$$\left\langle h_{-23} \right\rangle \sim 1 m_{\mathrm{T}}^{2/3} \mu f_{100}^{2/3} r_{100}^{-1}$$

Inspiral timescale in seconds:

$$\tau_{\mathrm{s}} \sim 7.8 m_{\mathrm{T}}^{-2/3} \mu^{-1} f_{100}^{-8/3}$$

Therefore:

$$r \sim 780 f_{100}^{-2} \left\langle h_{-23}^{-1} \right\rangle \tau_{\mathrm{s}}^{-1} \ \mathrm{Mpc}$$

→ Distance indicator based on "clean" physics!!

What’s Needed?

- Must identify host galaxy to tie this to other distance scales – *r* is the distance to what?
  - “Electromagnetic counterpart” problem
- “Angle averaged” → today, we talk about distance-inclination degeneracy
- … and …

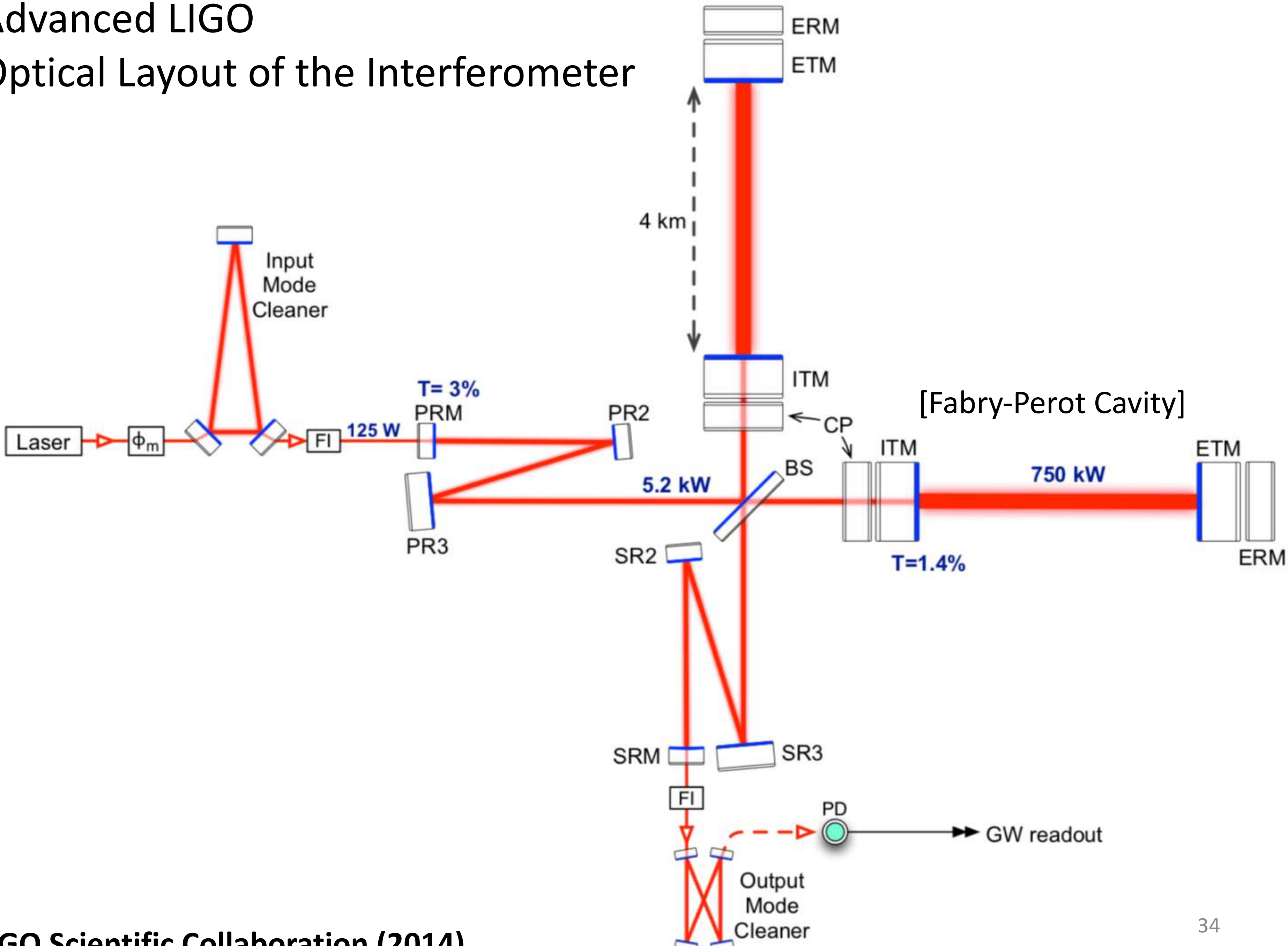
All it needs is the continued development of large-scale gravitational wave detectors.

(as written in 1986!)

LIGO – Hanford Site (1 of 2)

Caltech / MIT / LIGO Lab

Advanced LIGO
Optical Layout of the Interferometer

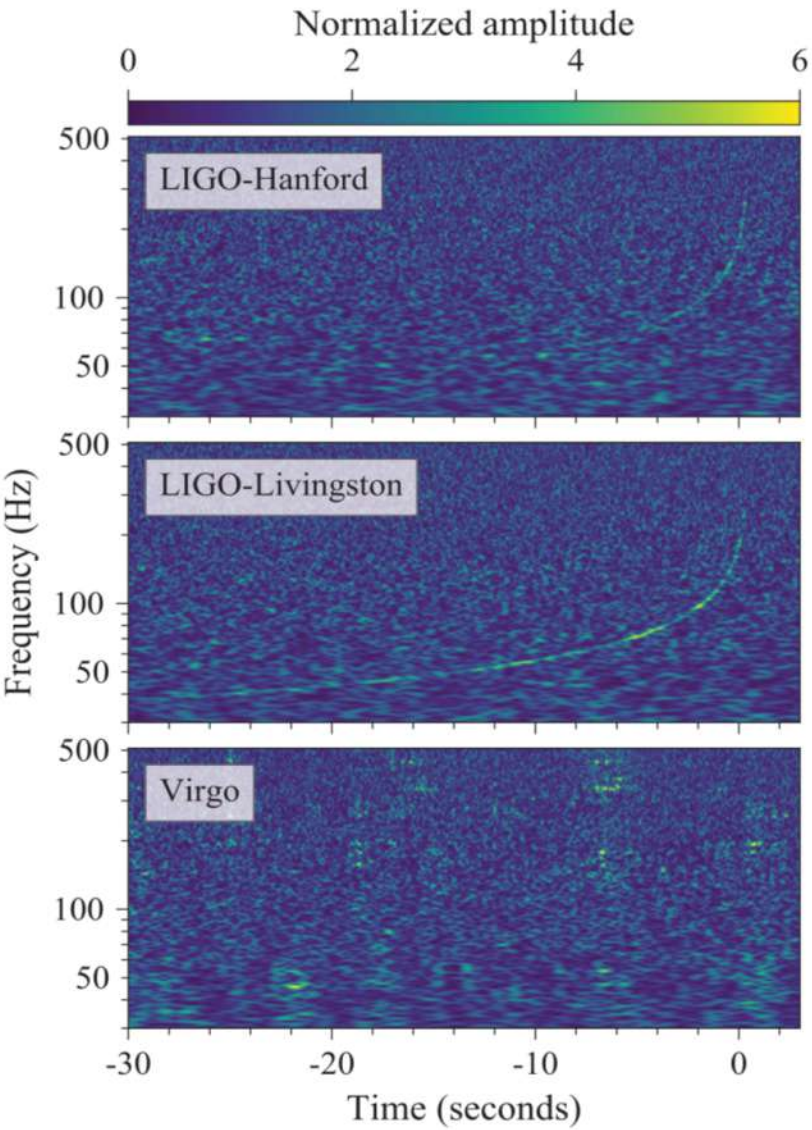


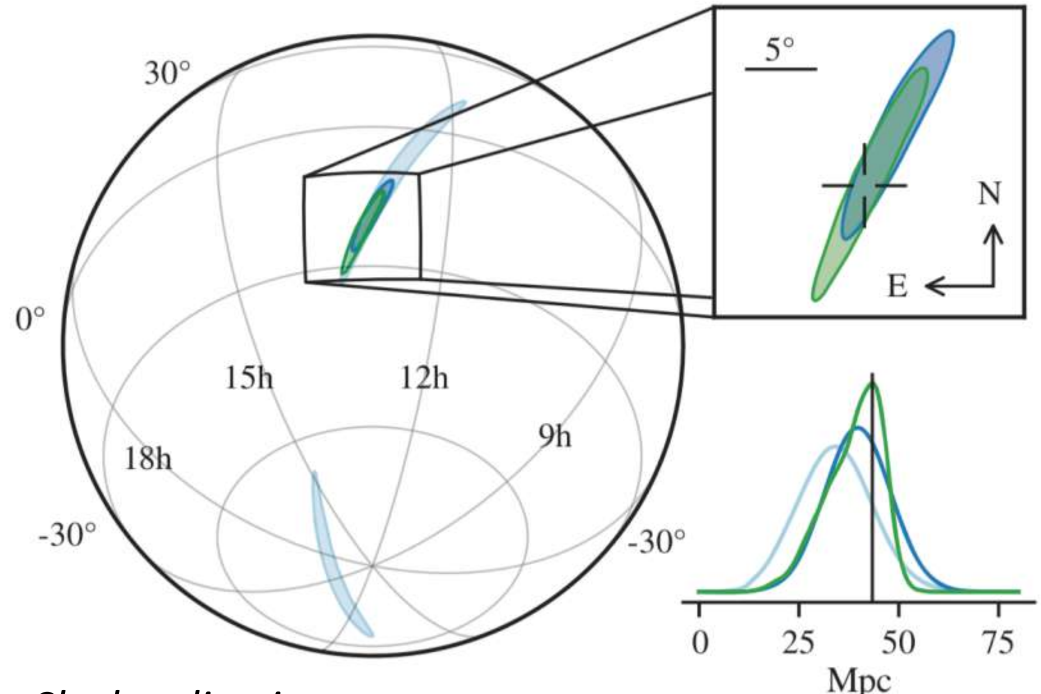
[Fabry-Perot Cavity]

LIGO Scientific Collaboration (2014)

GW 170817

(LIGO + Virgo Collaborations 2017)



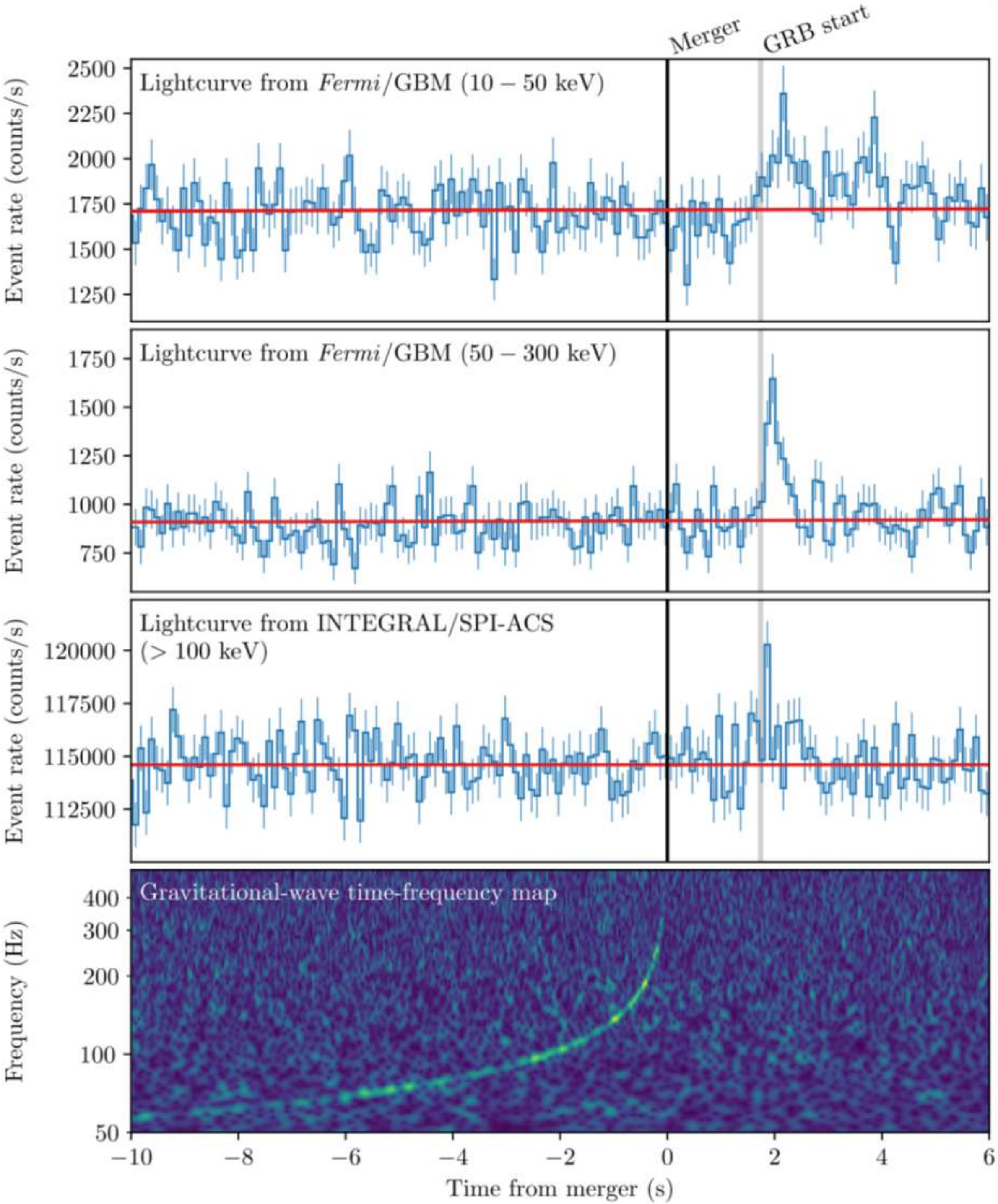


Sky localization

$$m_T^{2/5}\mu^{3/5} = 1.188^{+0.004}_{-0.002}\, M_{Sun}$$

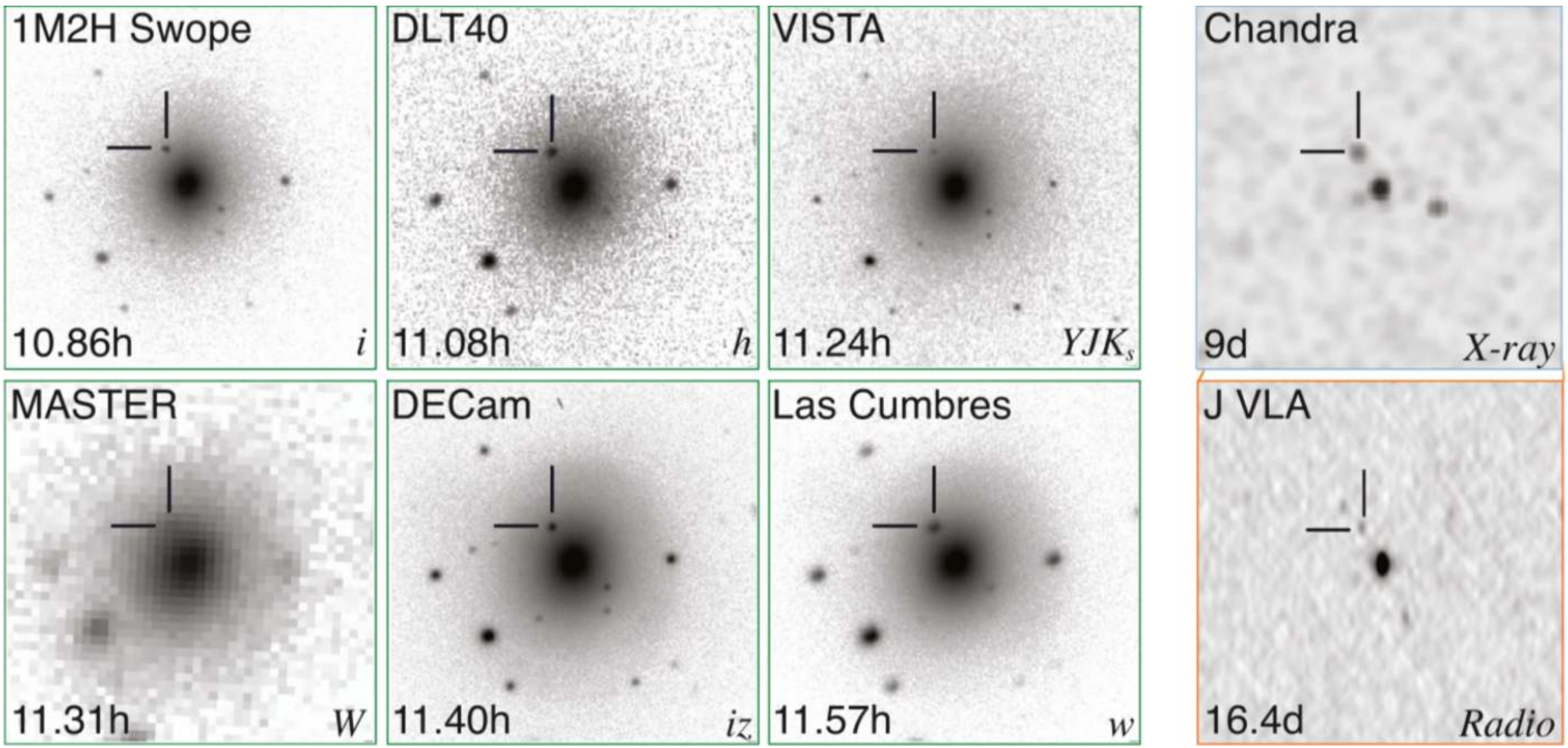
Gamma Ray Burst Coincident with GW Event

(LIGO, Virgo, Fermi-GBM, INTEGRAL Collaborations, 2017)



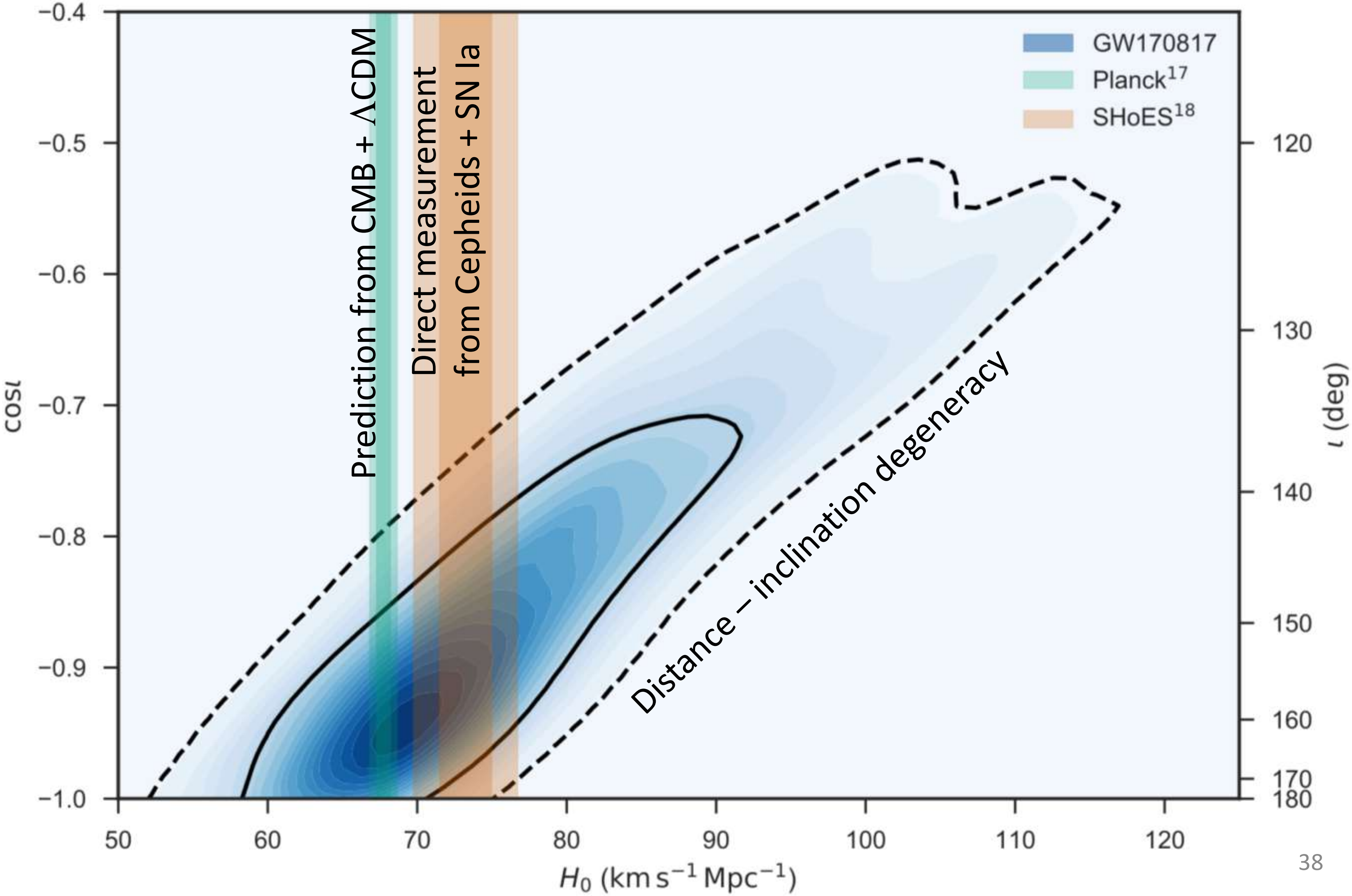
Multi-Wavelength Electromagnetic Observations of GW170817

(Many Collaborations, 2017)



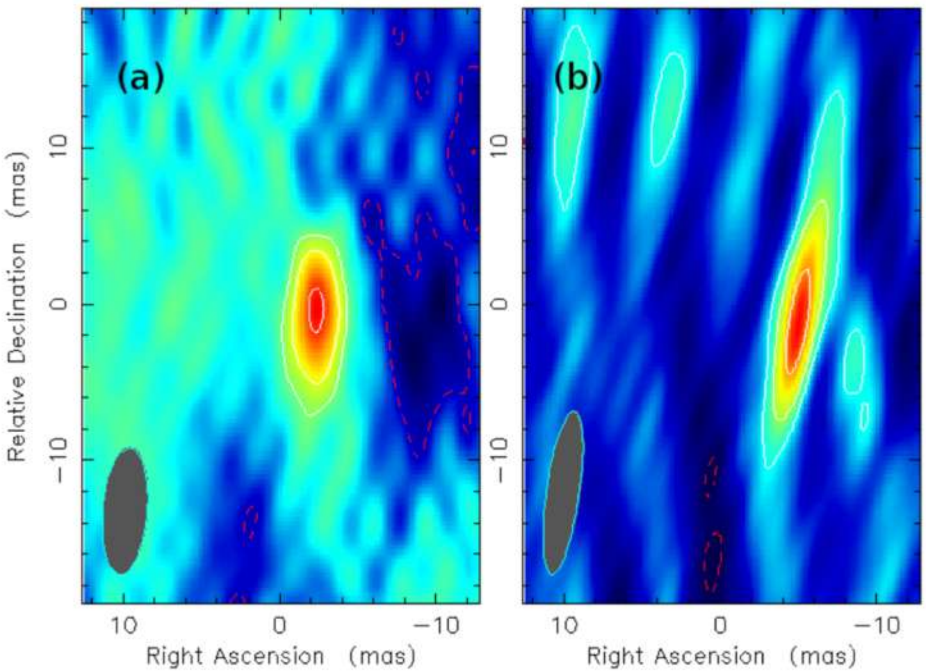
Host galaxy is NGC 4993, z = 0.0097

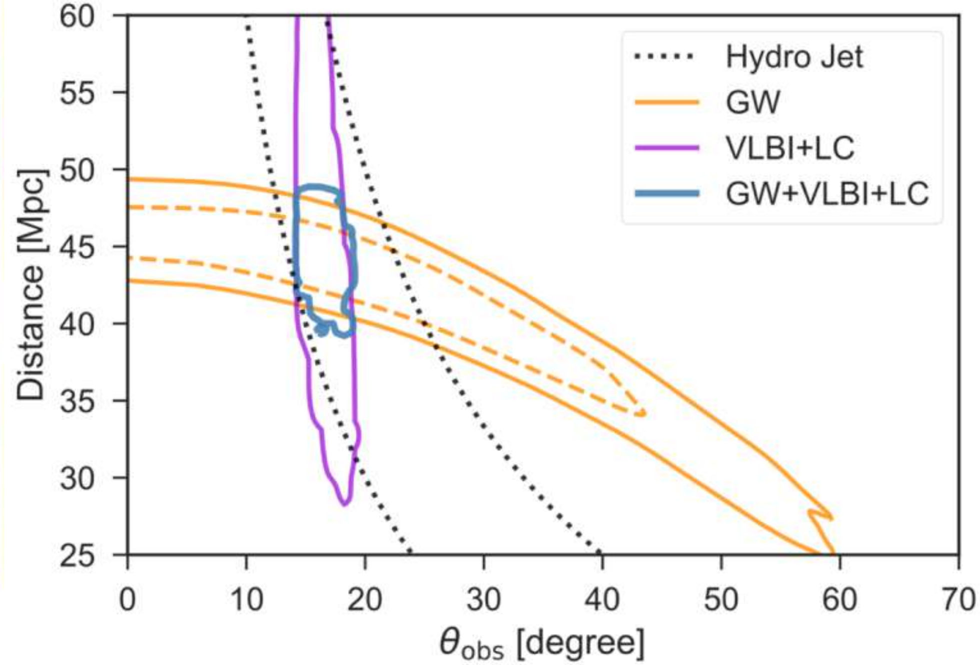
H_0 from 1 Gravitational Wave Source



Proper Motion of the Jet by VLBI

(Mooley et al. 2018; Kotokezaka et al. 2018)





The jet tracked at 4.5 GHz
From 75 to 230 days:
2.67±0.19±0.21 mas East
0.2±0.6±0.7 mas North
Apparent v/c = 4.1±0.5 (artifact of light-travel time; “real” v/c is ≈1)

$$H_0 = 68.9^{+4.6}_{-4.7}\ \mathrm{km/s/Mpc}$$

(with 1 source; more to come?)

Extragalactic Distance Scale – Summary

- Lots of history, many methods
- But modern developments are coming from many wavebands and techniques
  - Gamma rays through radio, as well as non-electromagnetic messengers
  - Lots of clever physics ideas
  - But precision is key!
- Big outstanding issue today is conflict between direct H_0 measurement and prediction from CMB
- Much more to come!