European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Astrometry with HST

Gerard van Belle
PRIMA Instrument Scientist
3 Jun 2008

(with substantial inputs from – and thanks to – Fritz Benedict)

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Why HST FGS?

- Calibrating the Galactic Cepheid period-luminosity (PL) relationship were primary missions of the space astrometric satellites FAME and DIVA
  - FAME and DIVA got cancelled
- The very distant promise of the Space Interferometry Mission and GAIA
  - SIM, to be launched in 2015(?), with preliminary results due by 2018
  - GAIA, launch in 2012 and final results by 2020
- Benedict et al proposed to reintroduce Galactic Cepheids as a fundamental step in the extragalactic distance scale many years before our other space-based competition
- **Only** means to do ~mas astrometry on faint sources

Why Important?

Cepheid are attractive Standard Candles

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Cepheids are among the brightest stellar distance indicators
- These `standard candles' are relatively young stars, found in abundance in spiral galaxies
- For extragalactic distance determinations many independent objects can be observed in a single galaxy
- Their large amplitudes and characteristic (sawtooth) light curve shapes facilitate their discovery and identification

Why Important?

Cepheids are easy to observe

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Cepheids have long lifetimes, and hence can be re-observed at other times and other wavelengths (unlike supernovae, for example)
- The Cepheid PLR has a small scatter. In the I band, the dispersion amounts to only ~0.1 mag (Udalski et al. 1999)
- Fortunately (for Benedict et al!), an accurate geometric calibration of the PL relation, at any given metallicity, had not yet been established

Why Important?

Current calibration is leveraged thru LMC/SMC

European Organization for Astronomical Research in the Southern Hemisphere

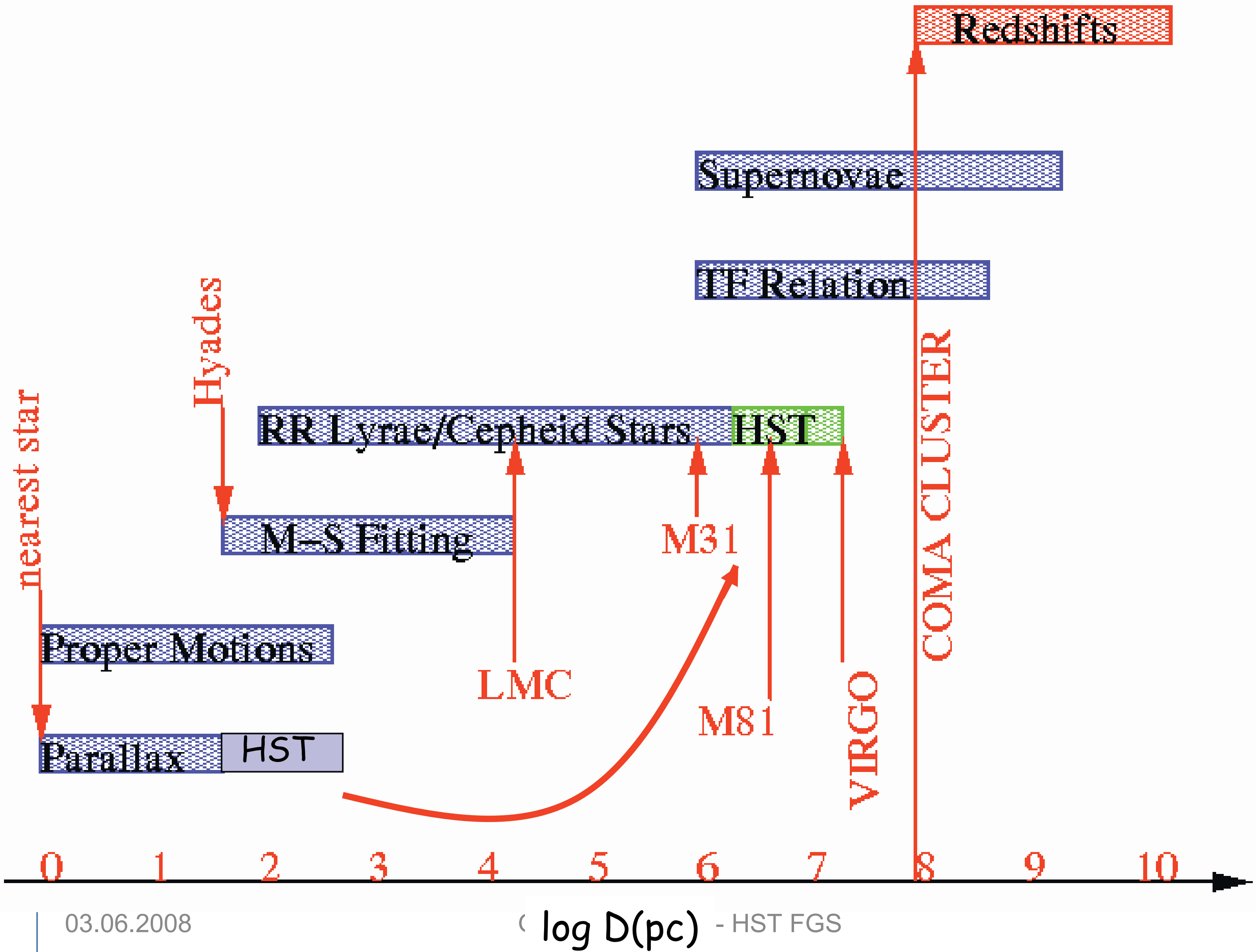
VLTI PRIMA Project

- Cepheid absolute magnitude apparently depends on metallicity
  - LMC and SMC have non-solar metallicities
- Intent of Benedict et al. was to produce a PLR calibration using solar metallicity Cepheids
  - A solar metallicity PLR can be applied directly to extragalactic Cepheids
- This will remove the need to step through the LMC/SMC
- Very few long-period local Cepheids have distances measured
  - ℓ Car is ideal ($P\sim35^{d}$)
  - Will be treated as a illustrative example for this talk

The Distance Scale Ladder

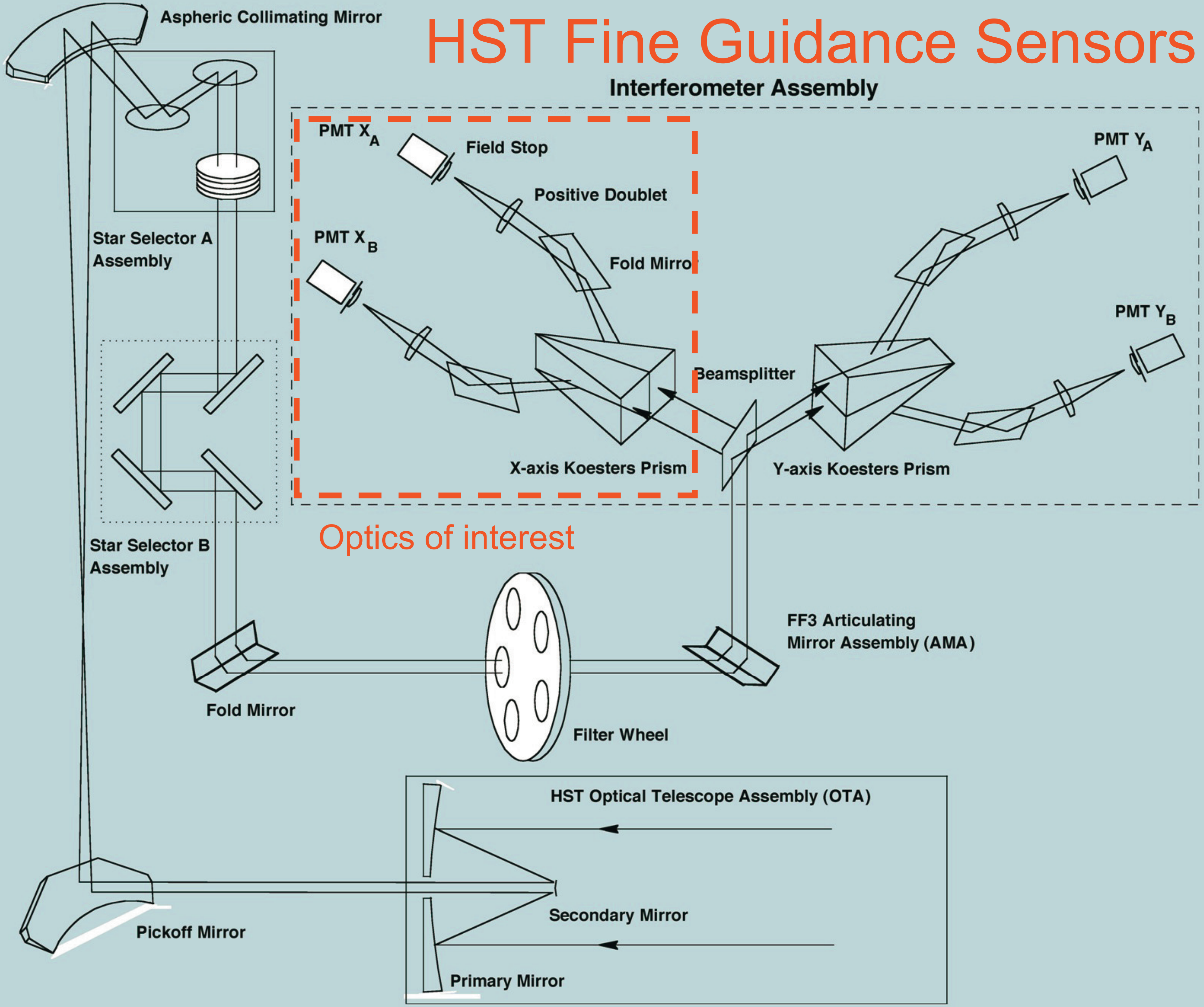
European Organizati
Astronomi
Research i
Southern
Hemisphe

VLTI PR
Projec



1997:02:19 07:06:57

HST Fine Guidance Sensors



European Organization for Astronomical Research in the Southern Hemisphere

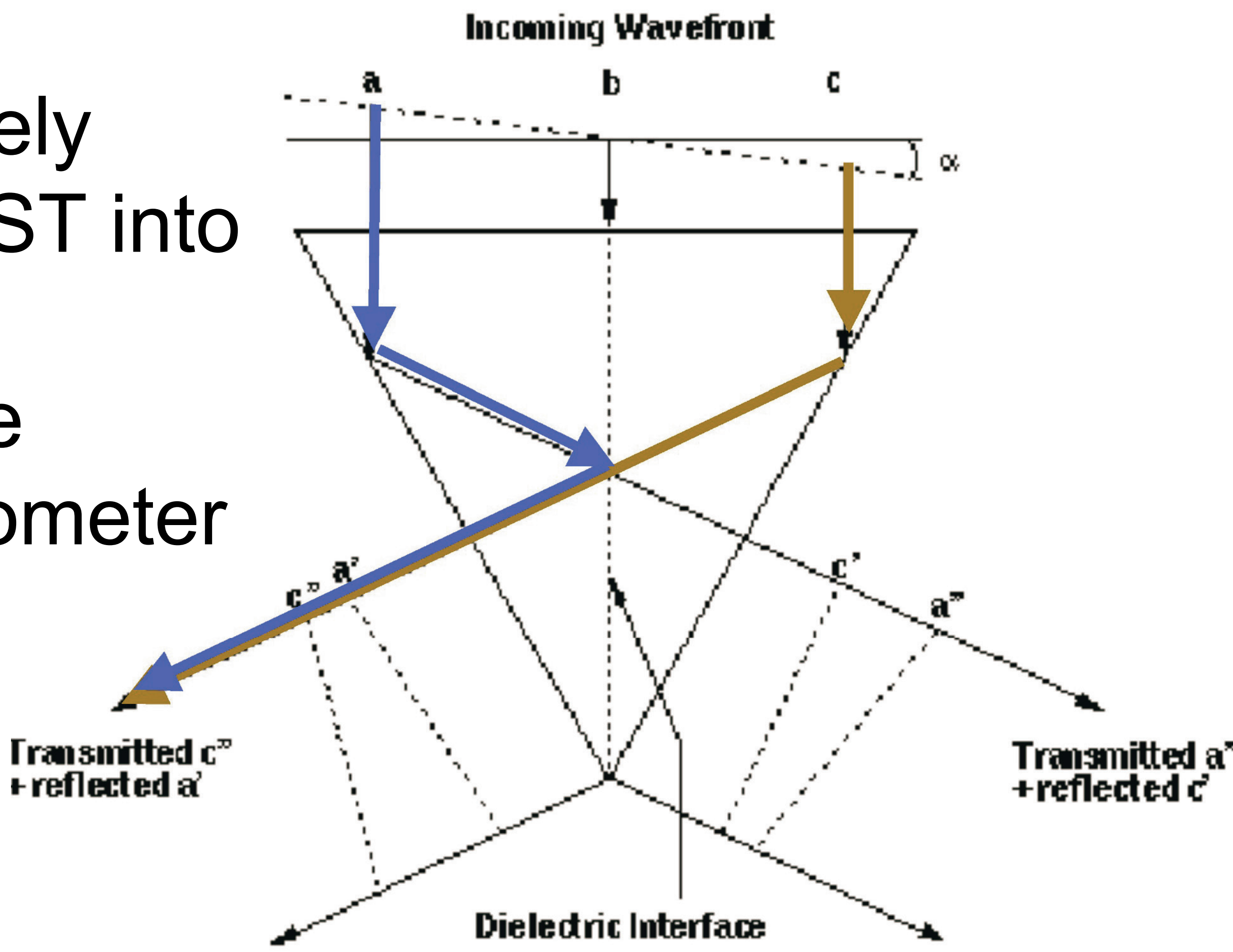
VLTI PRIMA Project

FGS Kösters Prism

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Effectively turns HST into a 2.4m baseline interferometer

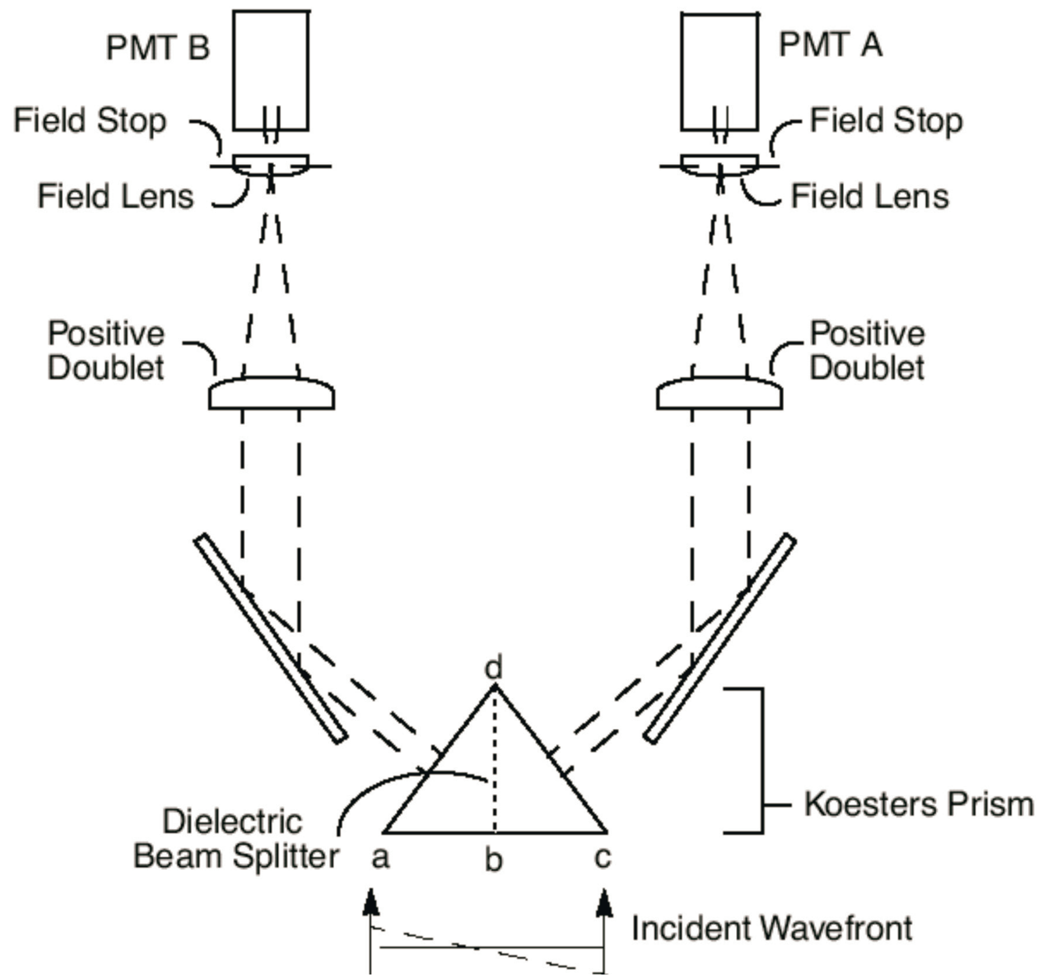


FGS PMT Detectors

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Two PMTs sample interference signal

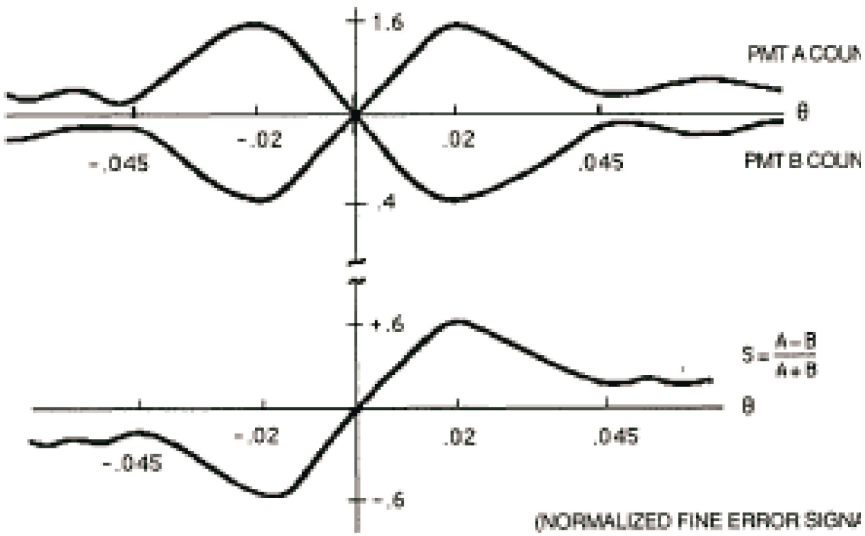


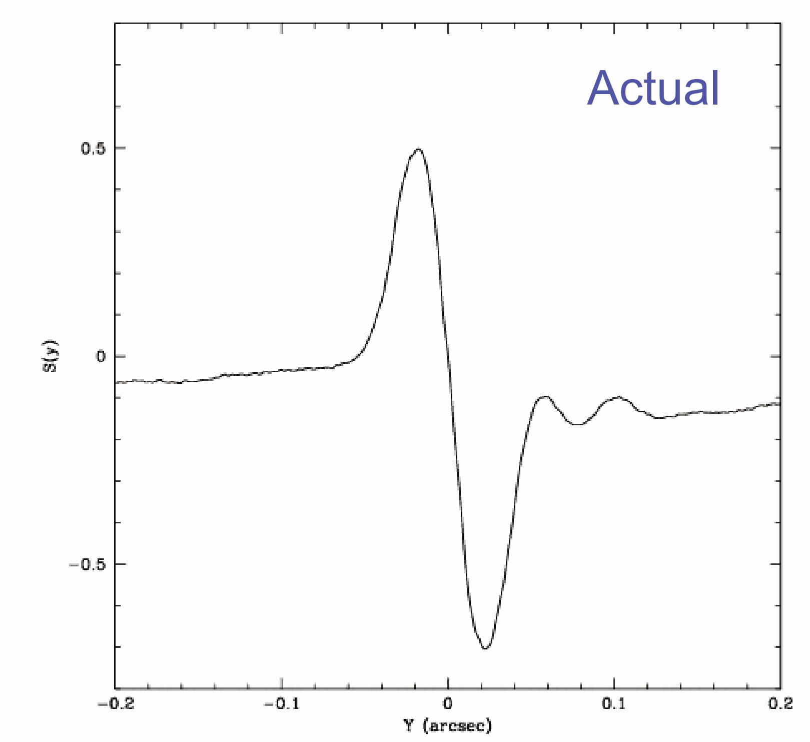
European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

FGS Detector Response

Theory





S = (A-B)/(A+B)

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

The Astrometry Model

A 3d volume of space is modeled using GaussFit (Jefferys, McArthur, & Fitzpatrick 1988, *Cel Mech*, **41**, 39)

Model requires as input (with variances)

Lateral Color Calibration - FGS contains refractive optics. Position of a blue star is displaced relative to the position it would have, if it were red.

B-V Color Indices - required for lateral color correction.

Cross Filter Calibration- targets with V < 9 require a neutral density 5 (ND5) filter. Filter wedge displaces the position of the FGS interferometer fringe. Bright star position must be corrected. Depends on star color.

Reference Frame Spectrophotometric Parallaxes - from spectral types and photometry data. Required to obtain absolute parallax for the science target.

Solution process is allowed to adjust these input parameters (by amounts depending on their variances) to find the ‘best’ solution.

In other words calibrations and any other prior knowledge about the reference frame go into the model as observations with error.

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

ℓ Car Reference Frame Spectrophotometric Parallaxes

- Photometry
  - FGS (V)
  - SAAO (UBVRI)
  - 2MASS (JHK)
  - McDonald/UVa (Washington - DDO)
- Color-color diagrams
  - Mapping to Spectral type from Bessell 1988 (PASP, 100, 1134)
  - J-H vs H-K and J-H vs V-K, for example
  - M - DDO51 vs M - T_2

ℓ Car Reference Frame Spectrophotometric Parallaxes

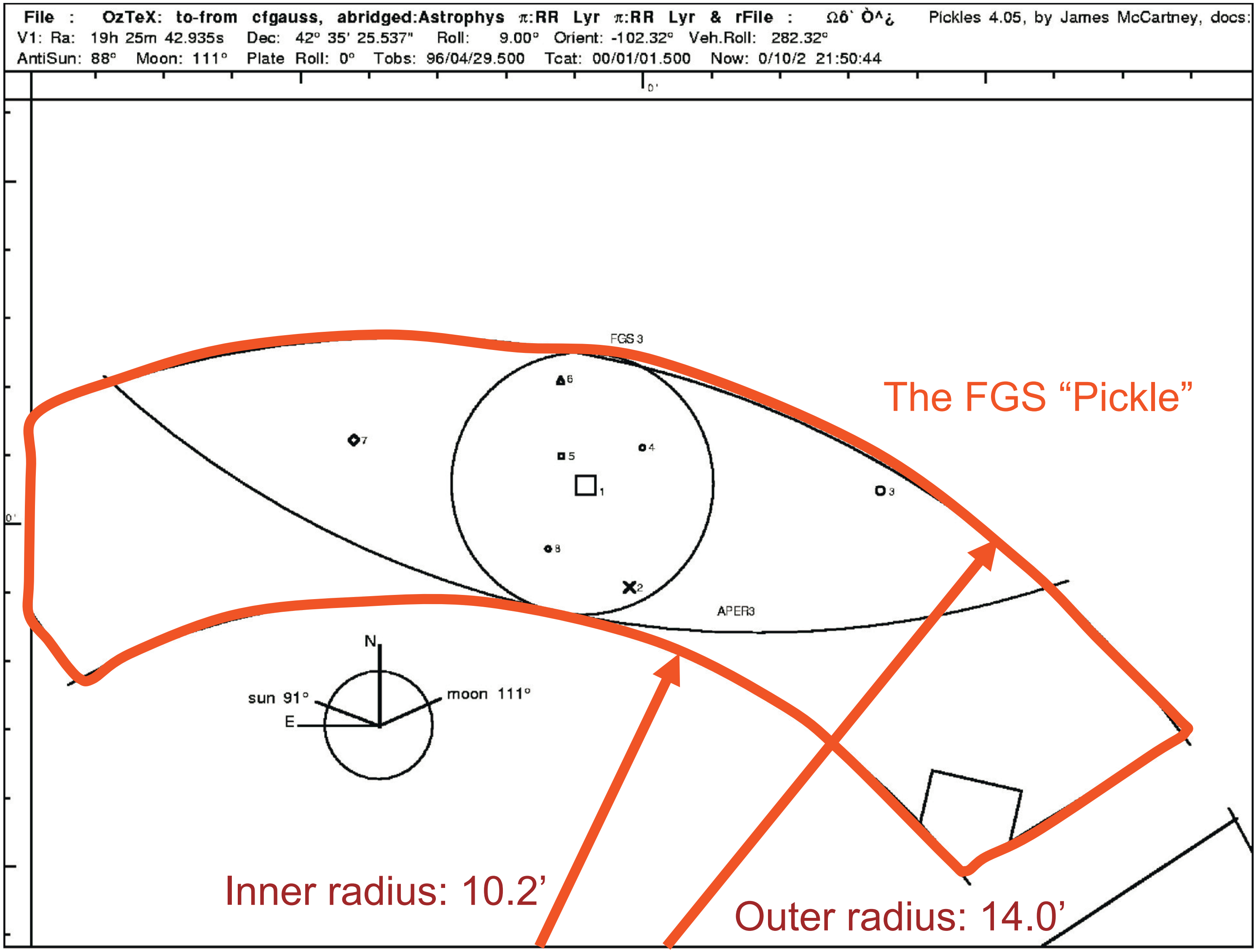
European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Spectral Typing and Luminosity Classification
  - SAAO - estimates ±2 subtypes
- M_V and $(B-V)_0$ $(V-I)_0$, $(V-R)_0$, $(V-K)_0$ from AQ2000
- A_V from our photometry
- Additional luminosity class confirmation from reduced proper motion diagram
- Spect. Parallaxes ($m-M = 5\log d - 5$, $\pi = 1/d$)

$$\pi_{sp} = 1/(10^{(V - Mv + 5 - Av)/5})$$

Field of View of FGS



European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

FOV After Multiple Visits

European Organization for Astronomical Research in the Southern Hemisphere

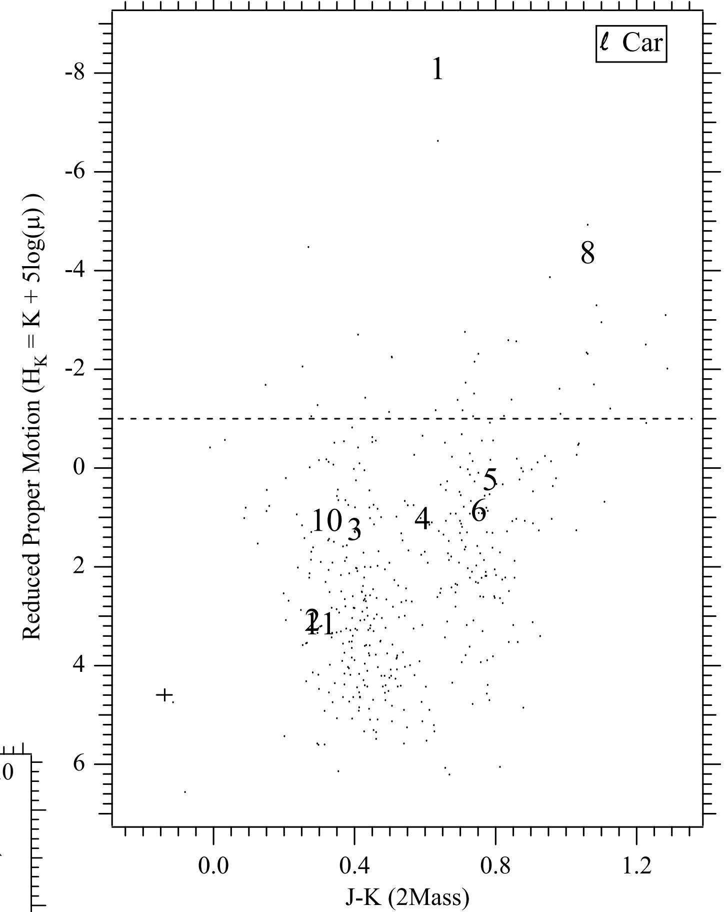
VLTI PRIMA Project

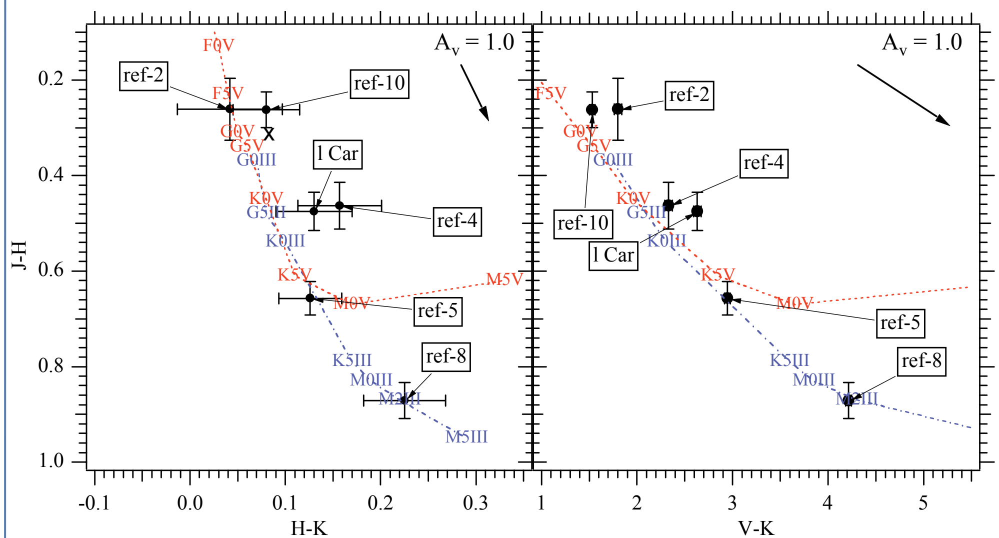
European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Reference Frame Objects

PropID	FGS ID	V	SpT	pi(sp)	err
38	2	**14.29**	G0V	0.00118	0.00027
39	3	13.57	G0V	0.00161	0.00037
40	4	**13.53**	G5III	0.00037	0.00012
41	5	**13.18**	K0III	0.00042	0.00010
44	8	**10.62**	M0III	0.00079	0.00018
45	9	13.44	F3V	0.00103	0.00024
46	10	**12.97**	F4V	0.00134	0.00031
47	11	**15.58**	F3V	0.00040	0.00009





- Photometry from Menzies and 2MASS
- Proper motions from UCAC2
- Spectral classifications from Feast

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Another Complication

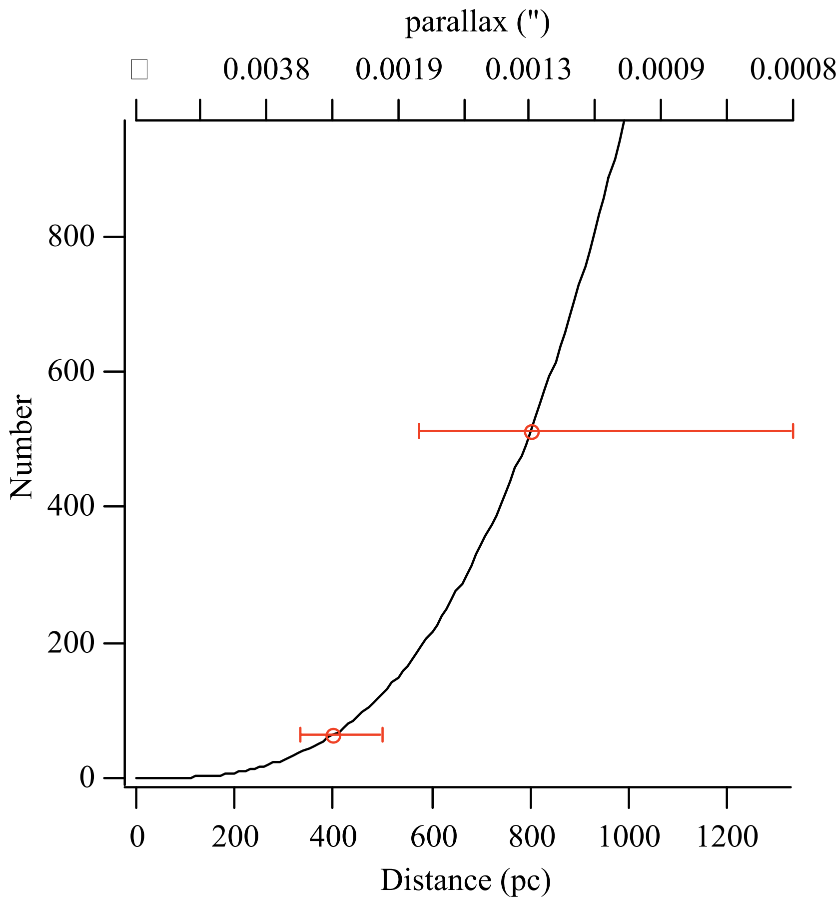
Transforming Parallax to Absolute Magnitude

(in the presence of noise)

Lutz-Kelker Bias

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project



Lutz & Kelker 1973 PASP 85 573

- Assuming uniform distribution for this class of object
- ±0.5 milliarcsec error
- Frequentist's viewpoint - for a given error you are more likely to have underestimated the distance (measured an object that is really more distant)
- LK bias proportional to $(\sigma_\pi/\pi)^2$
- It is a correction to any absolute magnitude, e.g., M_V

The Absolute Magnitude of a Cepheid

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Lutz-Kelker Bias
  - scales as $(\sigma_\pi/\pi)^2$
  - and depends on an assumed distribution of evolved stars, which is taken to be

    $n(r) \sim$ const.
- For ℓ Car
  - $\pi_{ABS} = 2.01 \pm 0.20$ mas,

    $\sigma_\pi/\pi = 0.10$,
  - and the LK bias correction,

    LKB = -0.08 mag.

Calibrating a Candle

ℓ Car Parallax

European Organization for Astronomical Research in the Southern Hemisphere

$$x' = x + lcx(B-V) - \Delta XFx$$
$$y' = y + lcy(B-V) - \Delta XFy$$
$$\xi = Ax'+By'+ C -\mu_x\Delta t - P_\alpha\pi_x$$
$$\eta = -Bx'+Ay'+ F -\mu_y\Delta t - P_\delta\pi_y$$

yields π_{abs}= 2.01 ± 0.20 mas

HIPPARCOS π_{abs}= 2.06 ± 0.27 mas (from the redo; van Leeuwen et al 2007)

A_V = 0.52±0.06

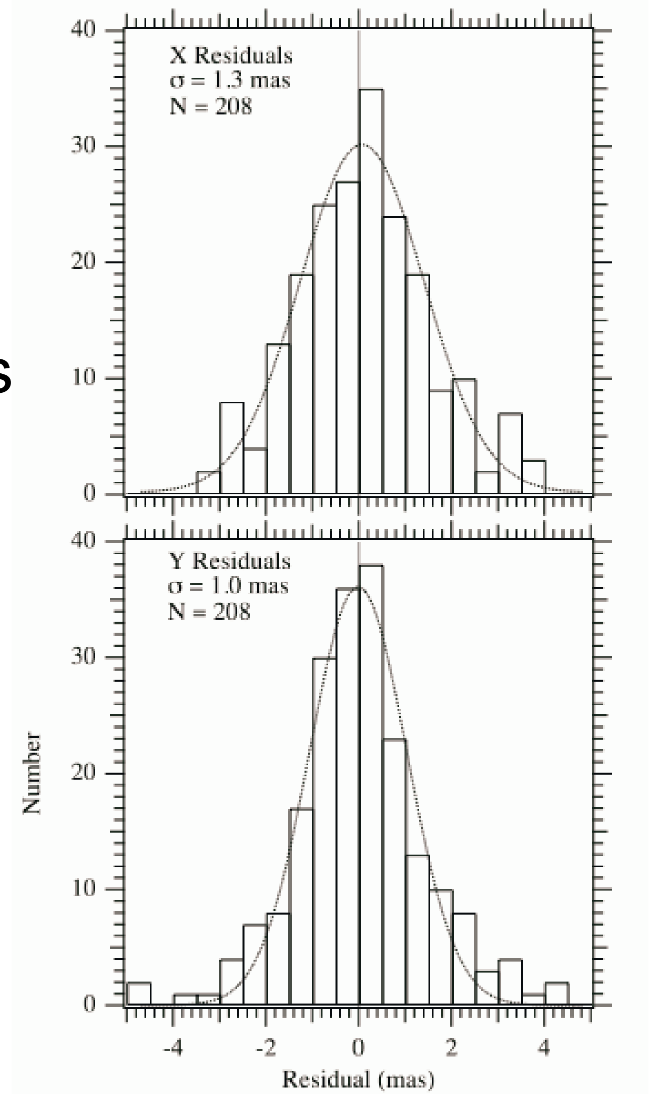
A_K = 0.06±0.01

m-M = -5 log π_{abs} -5 +A - LKB

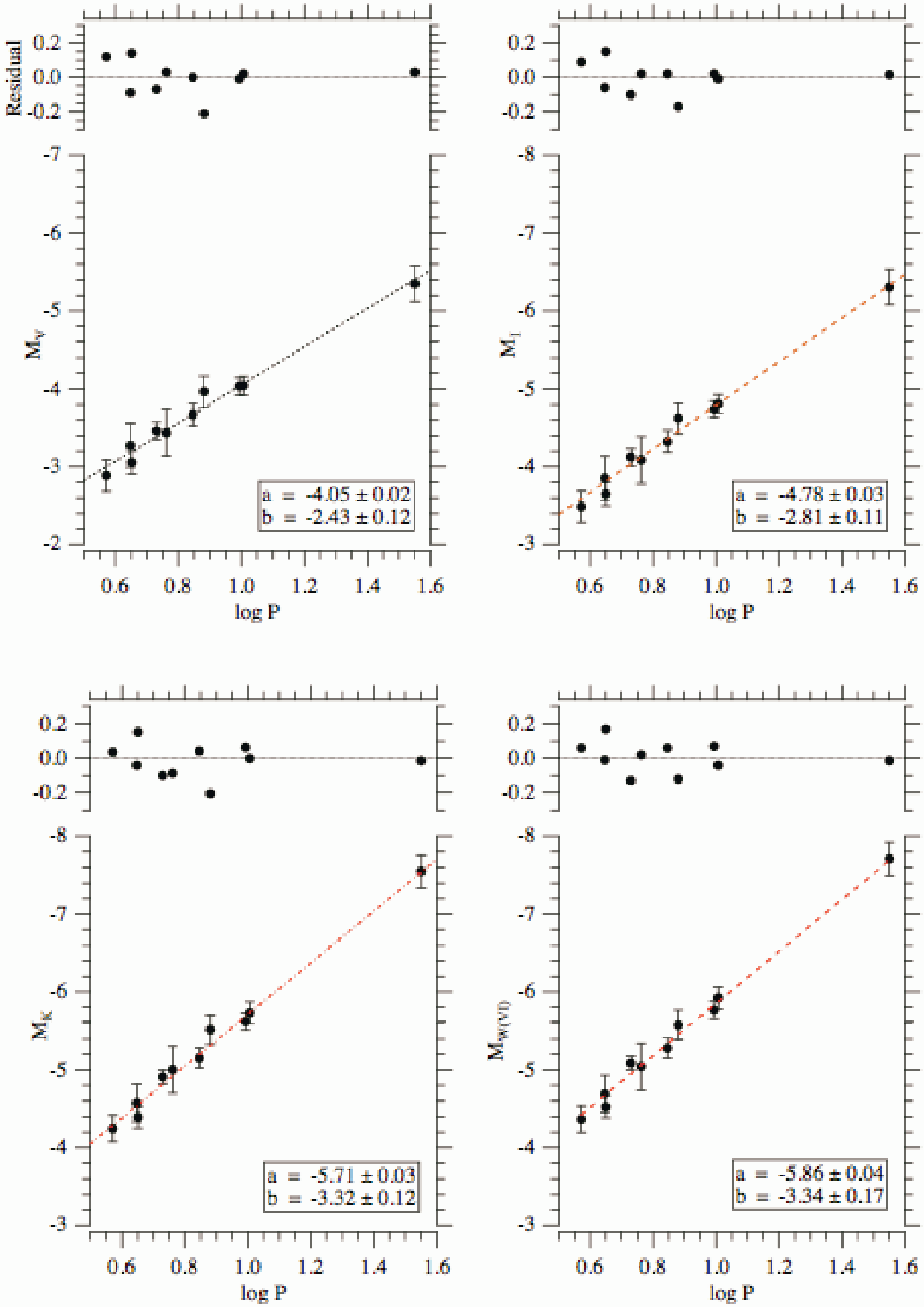
Solve for absolute magnitude,

M_V=-5.35 ± 0.22

M_K=-7.55 ± 0.21



VLTI PRIMA Project



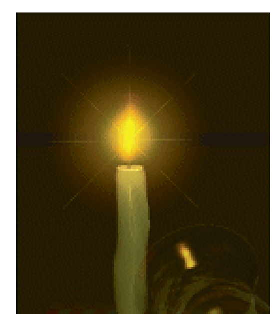
Do for all Cepheids and a selection of bandpasses

Galactic Cepheid PLR with N=10 objects

$$M = a + b\,(\log P - 1)$$

Benedict et al 2007 AJ 133 1810

- HST FGS

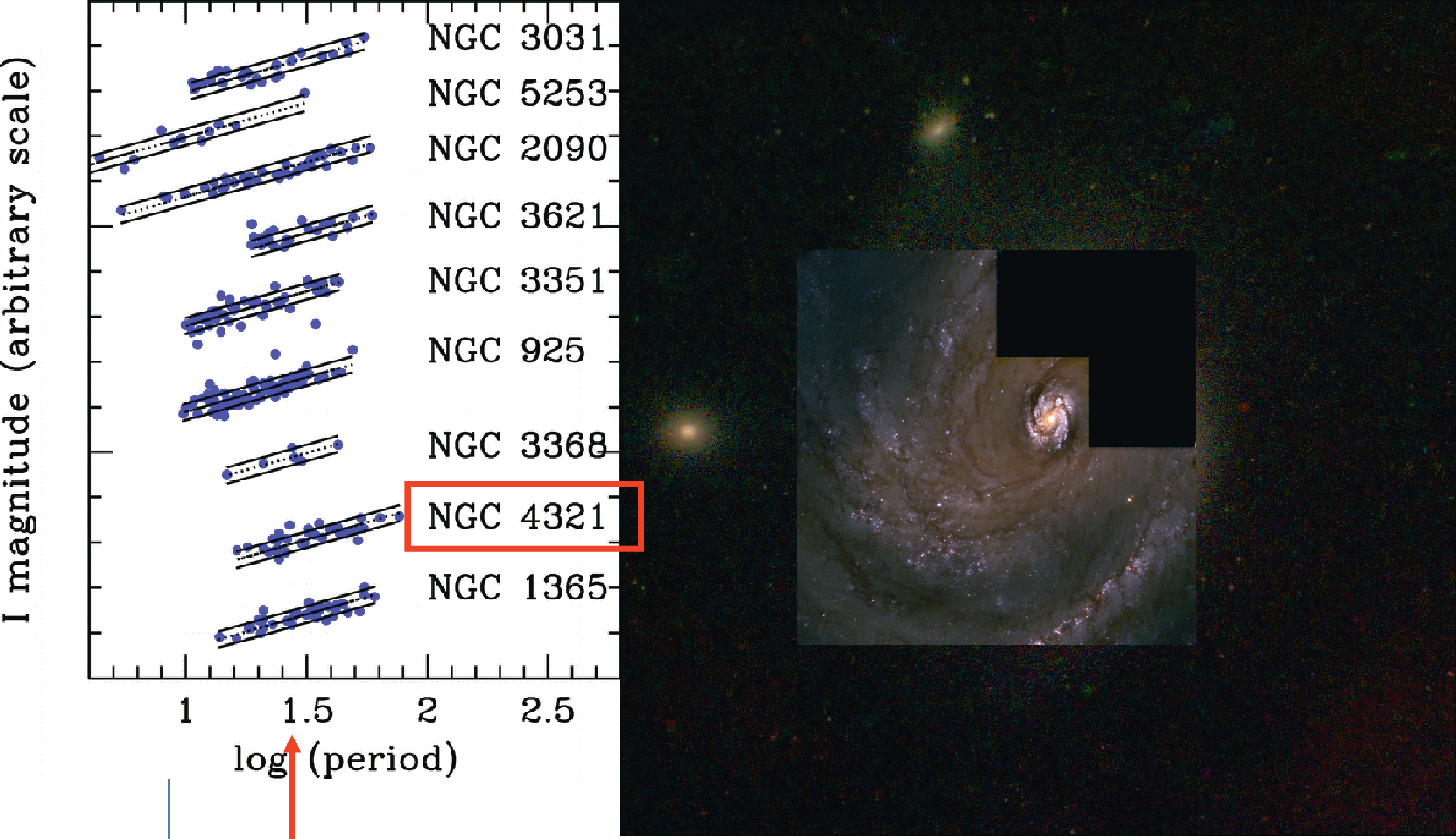


European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

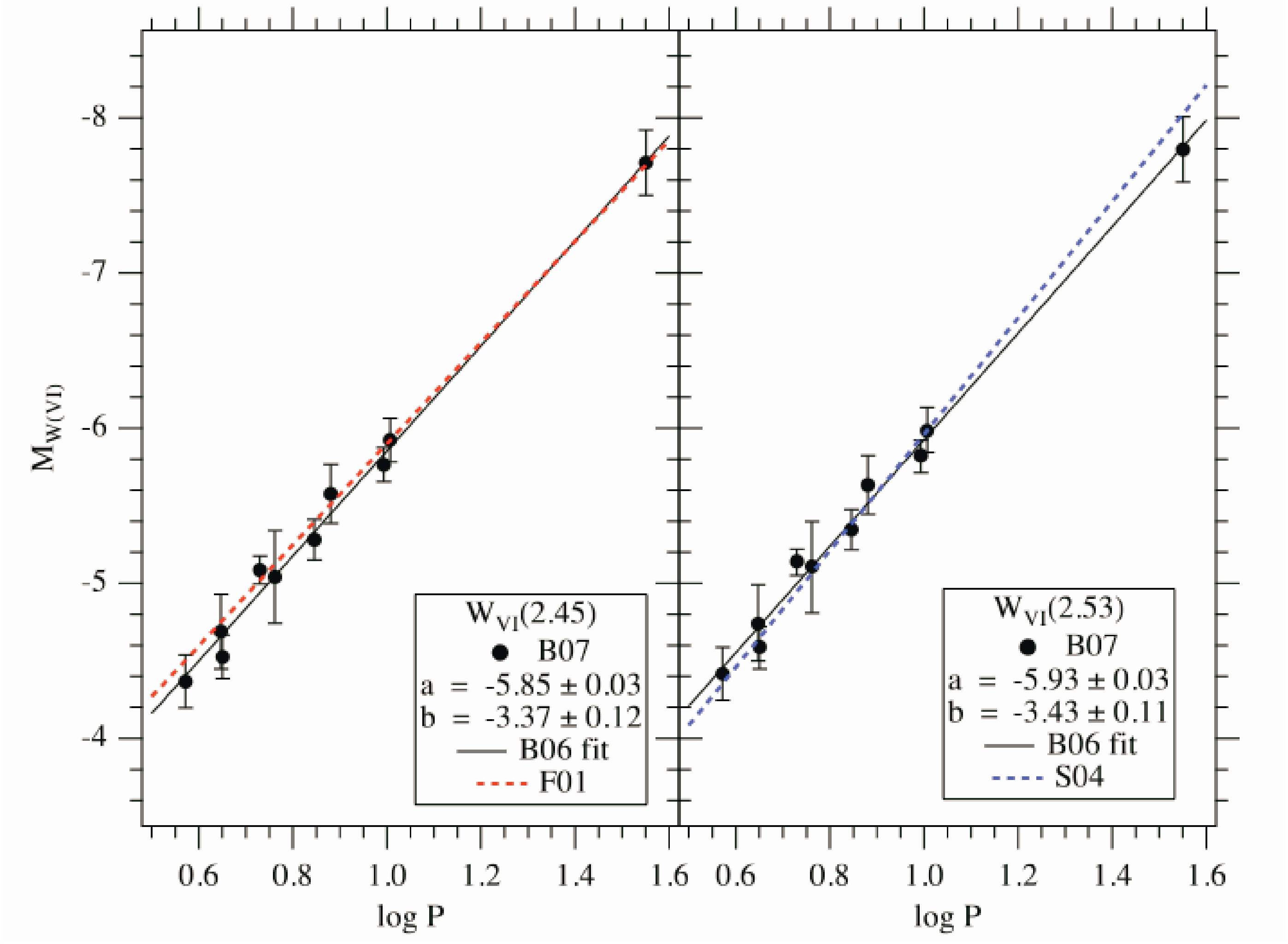
Tests

- So, who's right about H_0? Sandage (~62km/s/Mpc) or Freedman (~72km/s/Mpc)?
- NGC 4258



Note the log(P) of most of the Cepheids

Freedman or Sandage?



Adopting our PLR would tend to increase the Sandage H_0 value, but **leave the Freedman H_0 unchanged**.

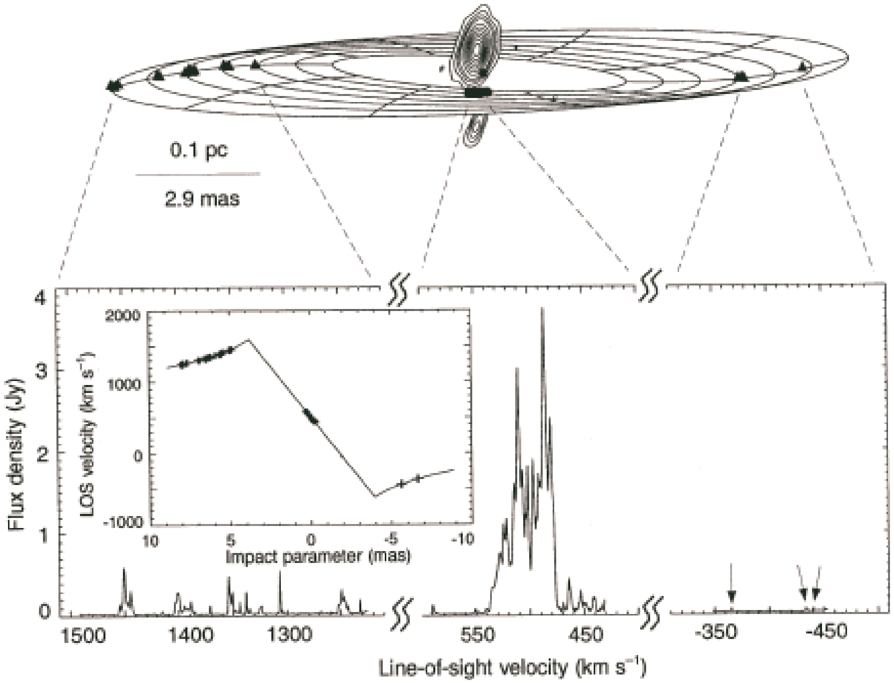
NGC 4258

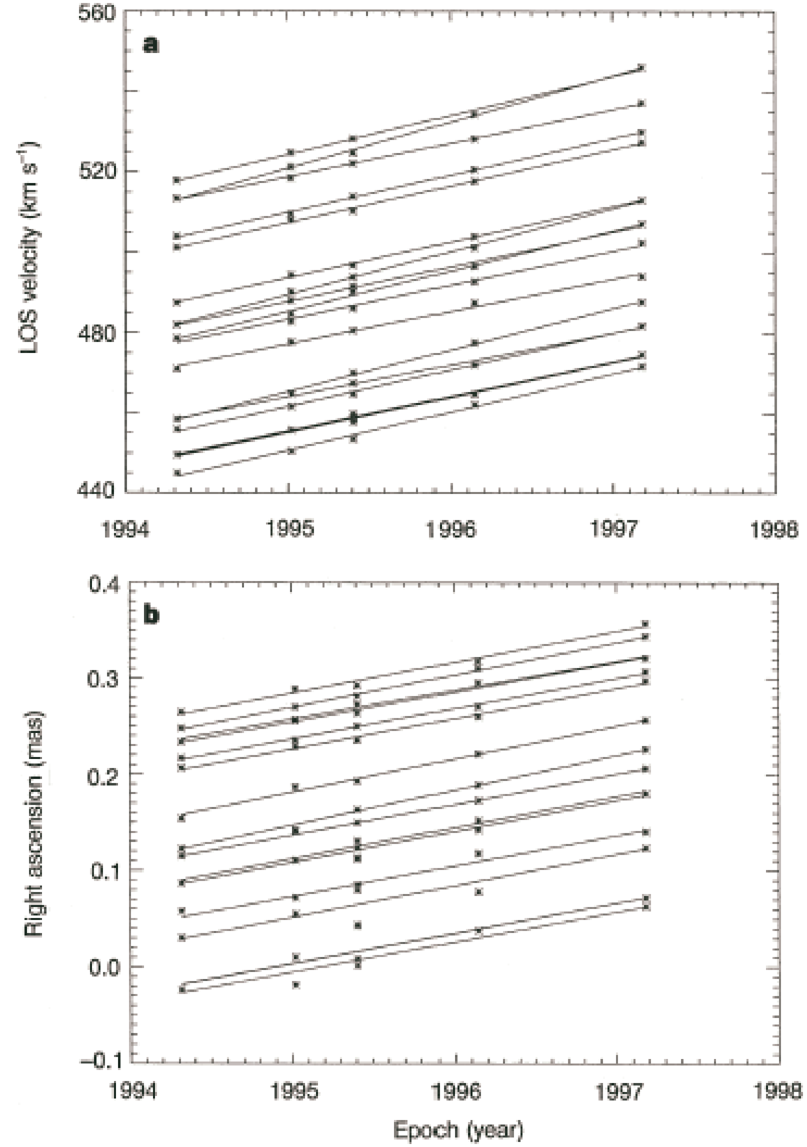
- Contains Cepheids
- Contains a black hole orbited by masers that emit radio waves
- Radio astronomers have measured the velocities and motions of those objects with VLBI
- Comparing the velocity with the amount of motion on the sky yields a distance
- That distance agrees ‘exactly’ with our distance obtained by comparing our Cepheids to those in the galaxy

NGC 4258 Masers

E
C
A
R
S
H

VLTI PRIMA
Project

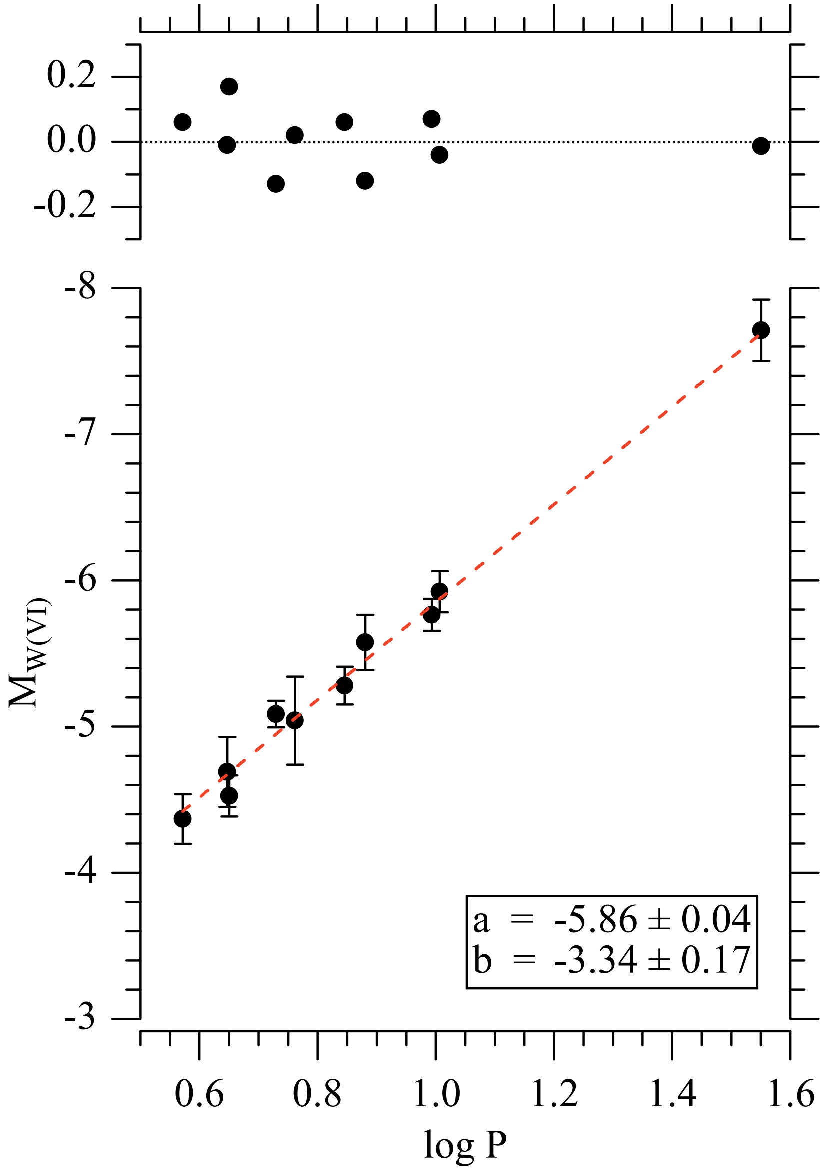




W_{VI} band

European Organization for Astronomical Research in the Southern Hemisphere

- NGC 4258
  - Macri has applied our W(VI) PLR to 85 of his inner-field Cepheids and finds m-M = 29.21 ± 0.02
  - Herrnstein et al. (1999) get m-M = 29.29 ± 0.15 from masers
  - Using our LMC m-M* and the Macri et al. (2006) differential (LMC-NGC 4258) modulus yields m-M = 29.28 ± 0.08



VLTI PRIMA Project

How far away is the LMC ?

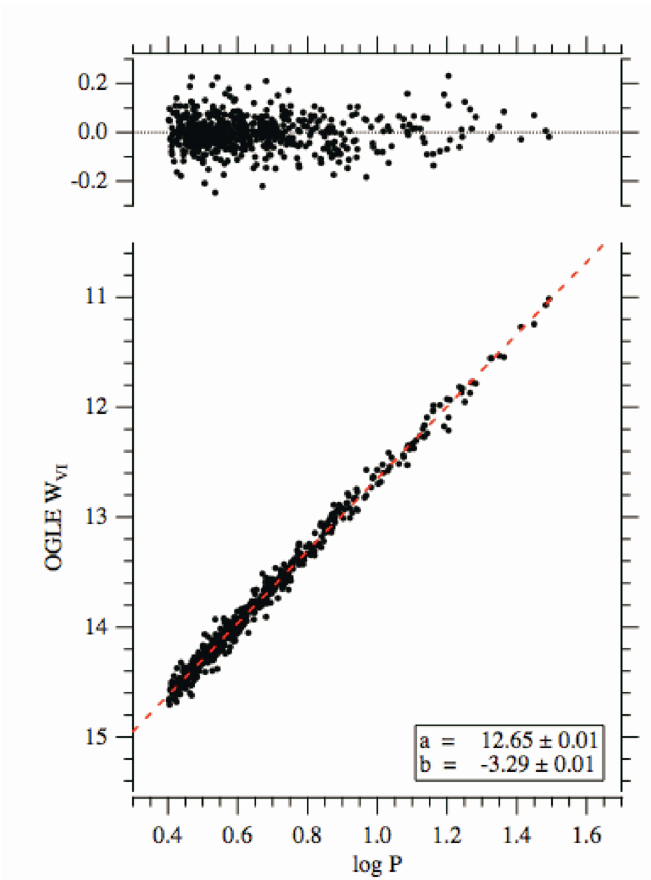
Euro
Orga
Astro
Rese
Sout
Hem

VL

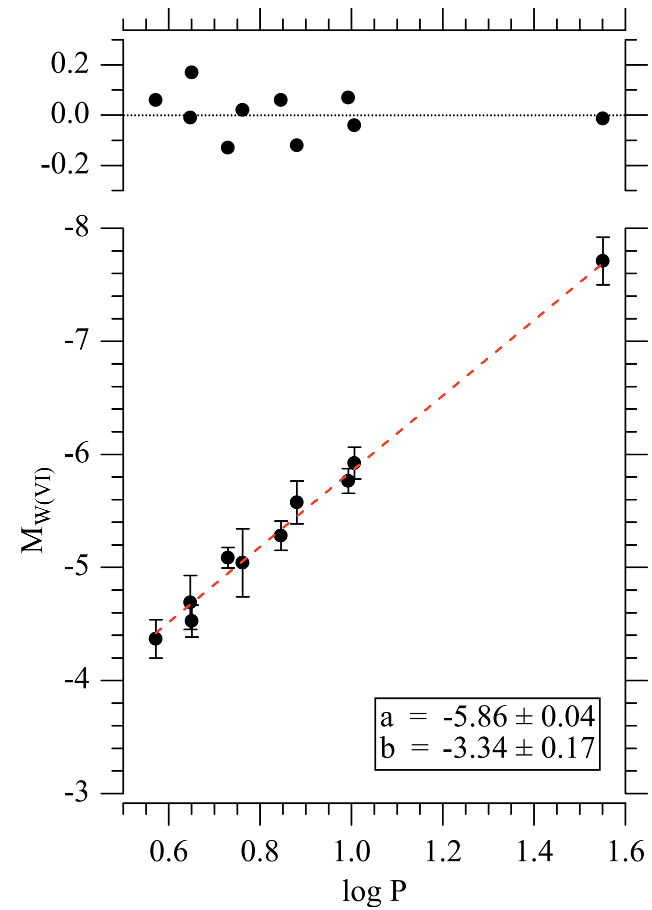
LMC Cepheid PLR from preened (from Kanbur et al 2003) OGLE photometry

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project



+



=

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- We derive an uncorrected m-M = 18.50 ± 0.03 for the LMC.
- Metallicity corrections
    - Macri et al. (2006), comparing near-nucleus Cepheids with those at the edge of NGC 4258, get a correction in W_{VI}, $\gamma = -0.29 \pm 0.11$ for 1 dex in metallicity
    - Kennicutt et al. (1998) get for M101 $\gamma = -0.24 \pm 0.16$ for 1 dex in metallicity

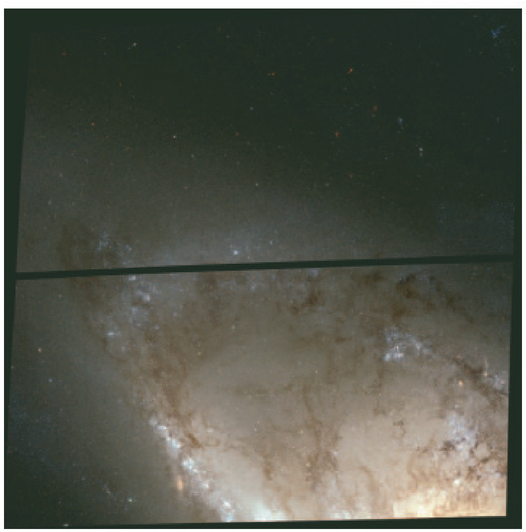


Fig. 3.—Color composite of the *HST* ACS/WFC inner field of NGC 4258.

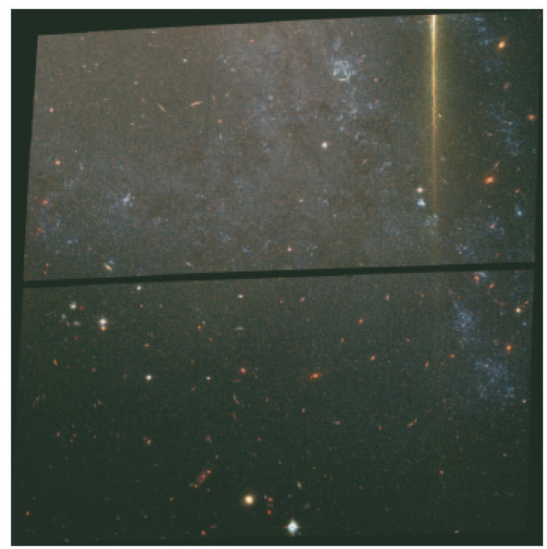


Fig. 2.—Color composite of the *HST* ACS/WFC outer field of NGC 4258.

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

- Groenewegen etal. (2004) find LMC metallicity of -0.36 dex
- Weighted average of Macri & Kennicutt γ corrections yields LMC distance modulus correction of -0.10 ±0.03
- Therefore, LMC $(m\text{-}M)_0 = 18.40 \pm 0.05$

- Compare with eclipsing binary results (Fitzpatrick et al 2003), $(m\text{-}M)_0 = 18.42$

Distance scale summary

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

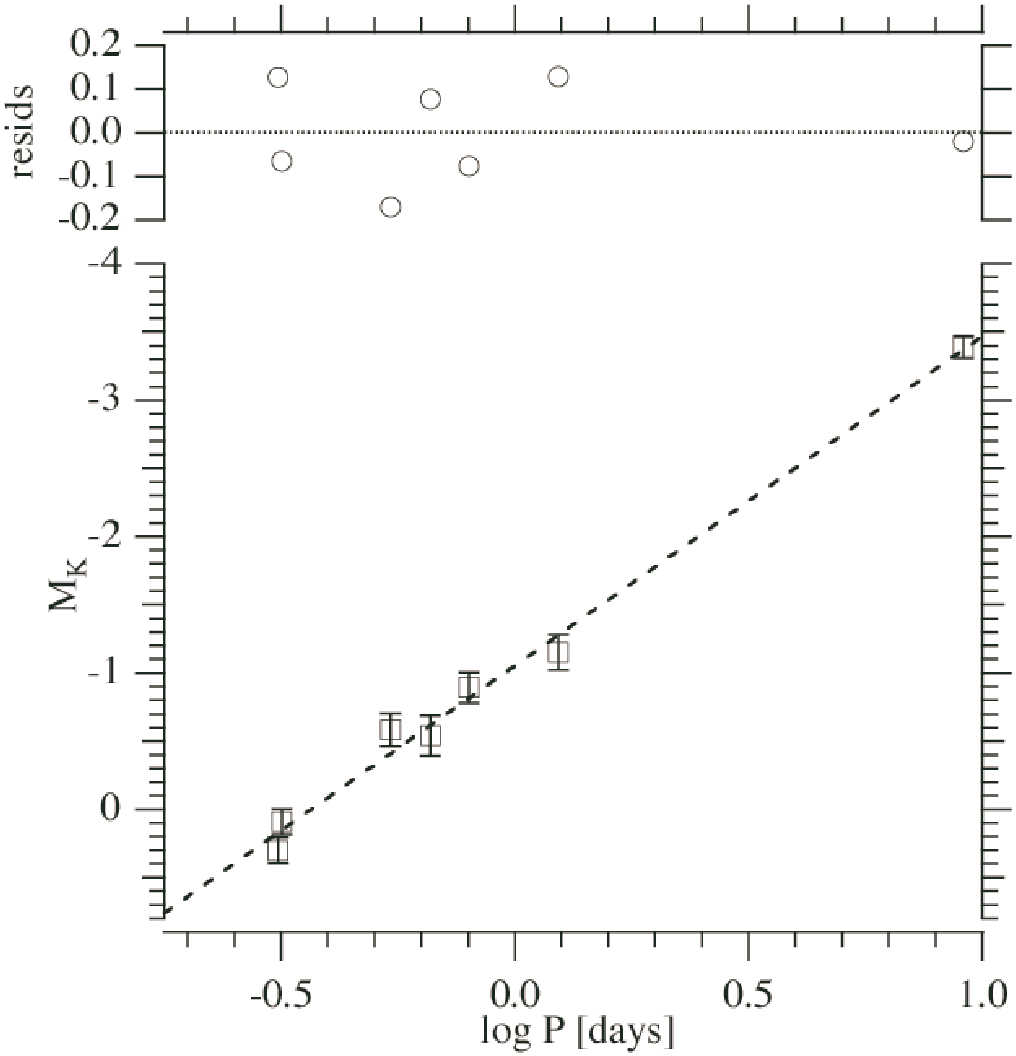
Demonstrated that Galactic Cepheids are again a useful distance scale tool

LMC distance modulus m-M = 18.40±0.05 (details on request)

For NGC 4258 the maser and Cepheid distances agree

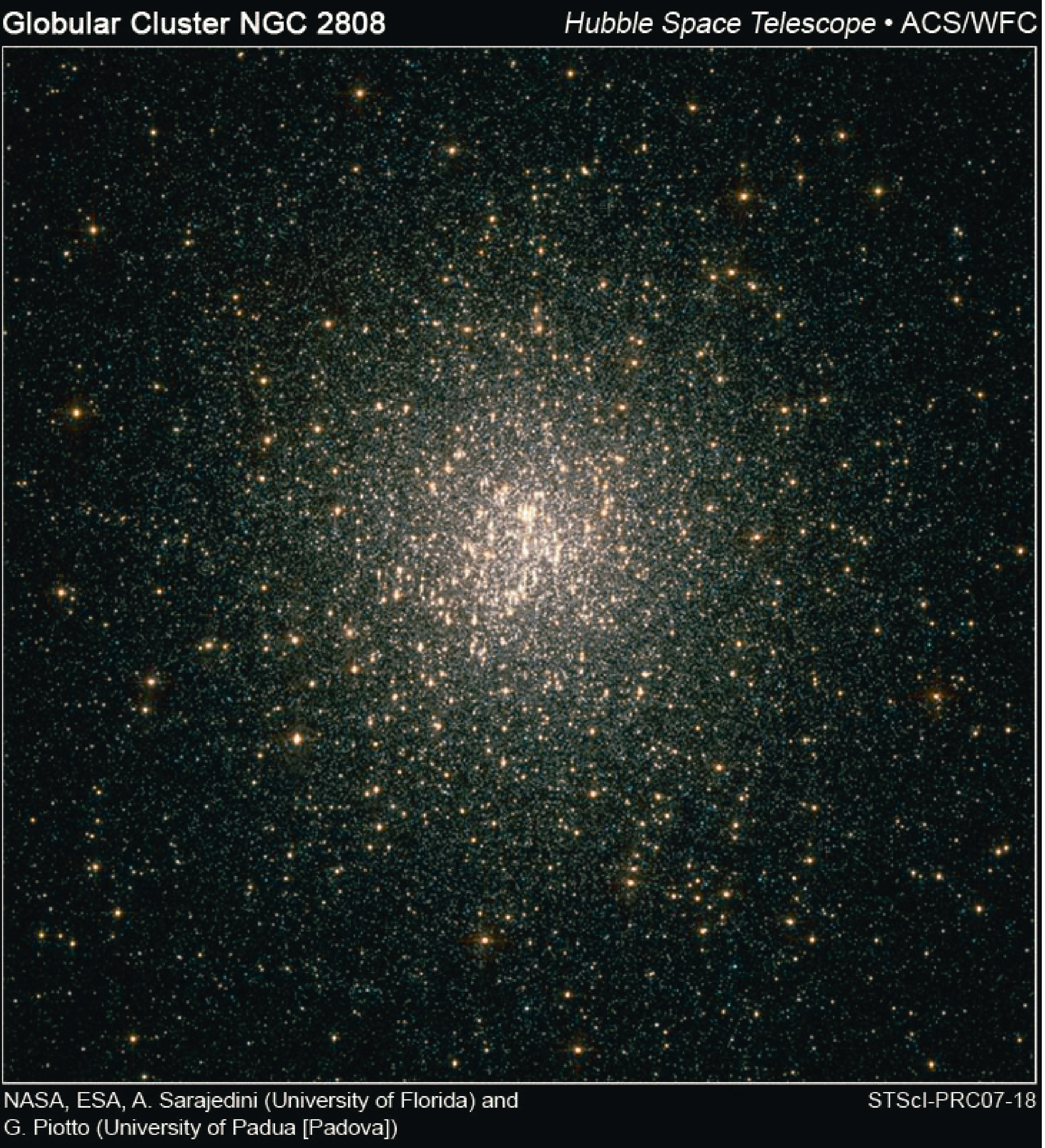
Have aided calibration of other techniques to increase numbers of long-period Cepheids in the PLR

Have done such a good job that the Cycle 16 HST TAC awarded Benedict et al. >100 orbits to measure RR Lyr and Pop II Cepheid parallaxes to establish a Pop II PLR calibration.



If Benedict et al. do as well on these RR Lyr and Pop II Cepheids as they did on the Pop I Cepheids, they should have something like this in two years

Figure 1: A simulated Pop II Period-Luminosity relation built with absolute magnitude estimates from an M_V-[Fe/H] relation from Chaboyer *et al.* (1998) and an M_K - logP relation (Matsunaga *et al.* 2006) for RRL and Pop II Cepheids. The scatter is simulated, but representative of what we expect, based on our previous parallax work with Pop I Galactic Cepheids (Benedict *et al.* 2007). Data of this expected quality would yield a zero-point error of 0.04 magnitudes.



Pop II PLR will help determine distances to globual clusters

But wait! There's another way to do this

Two independent approaches would greatly improve the accuracy, right?

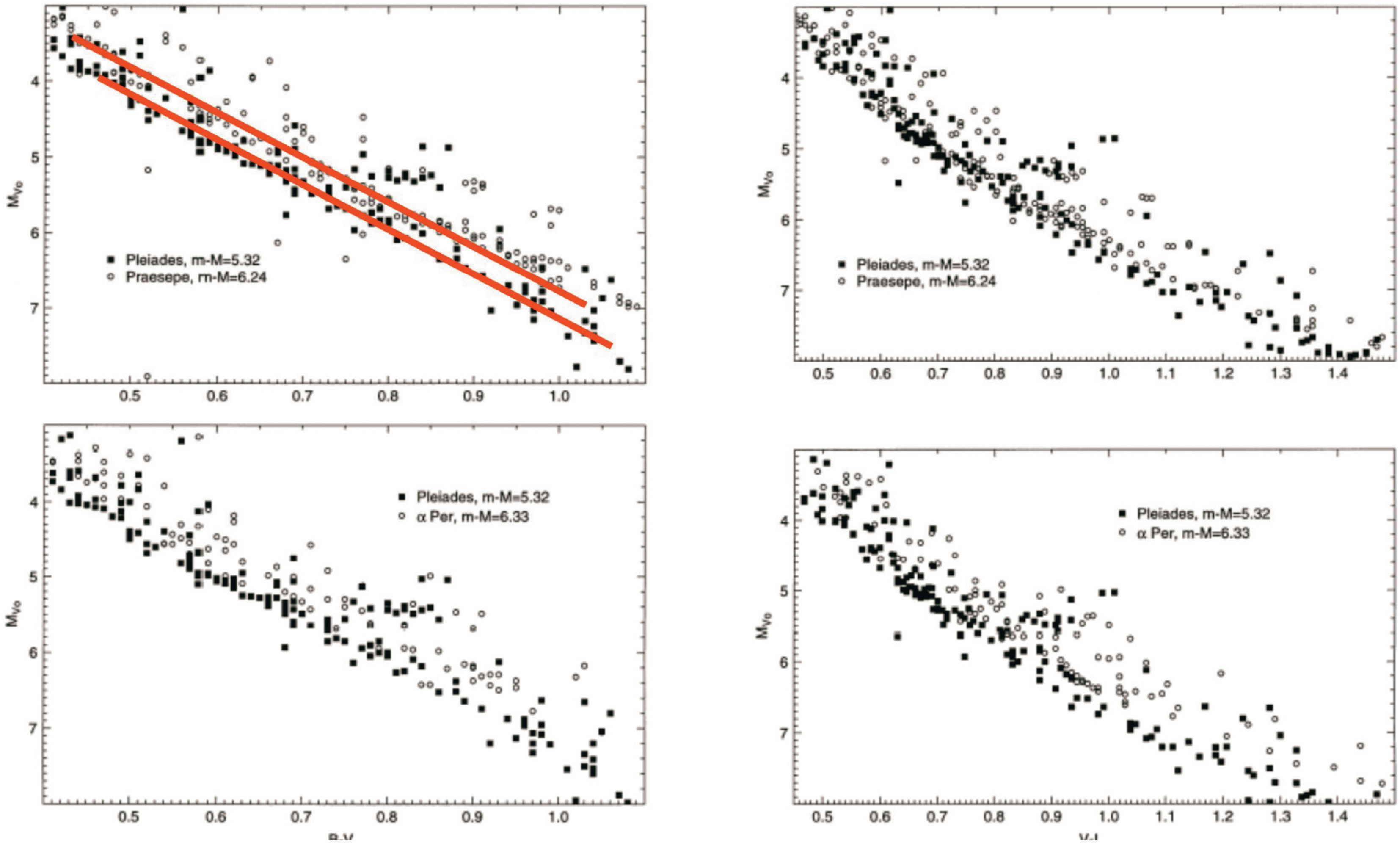
Controversy!!

The Parallax of the Pleiades - an issue that won’t go away

This Distance Between Us

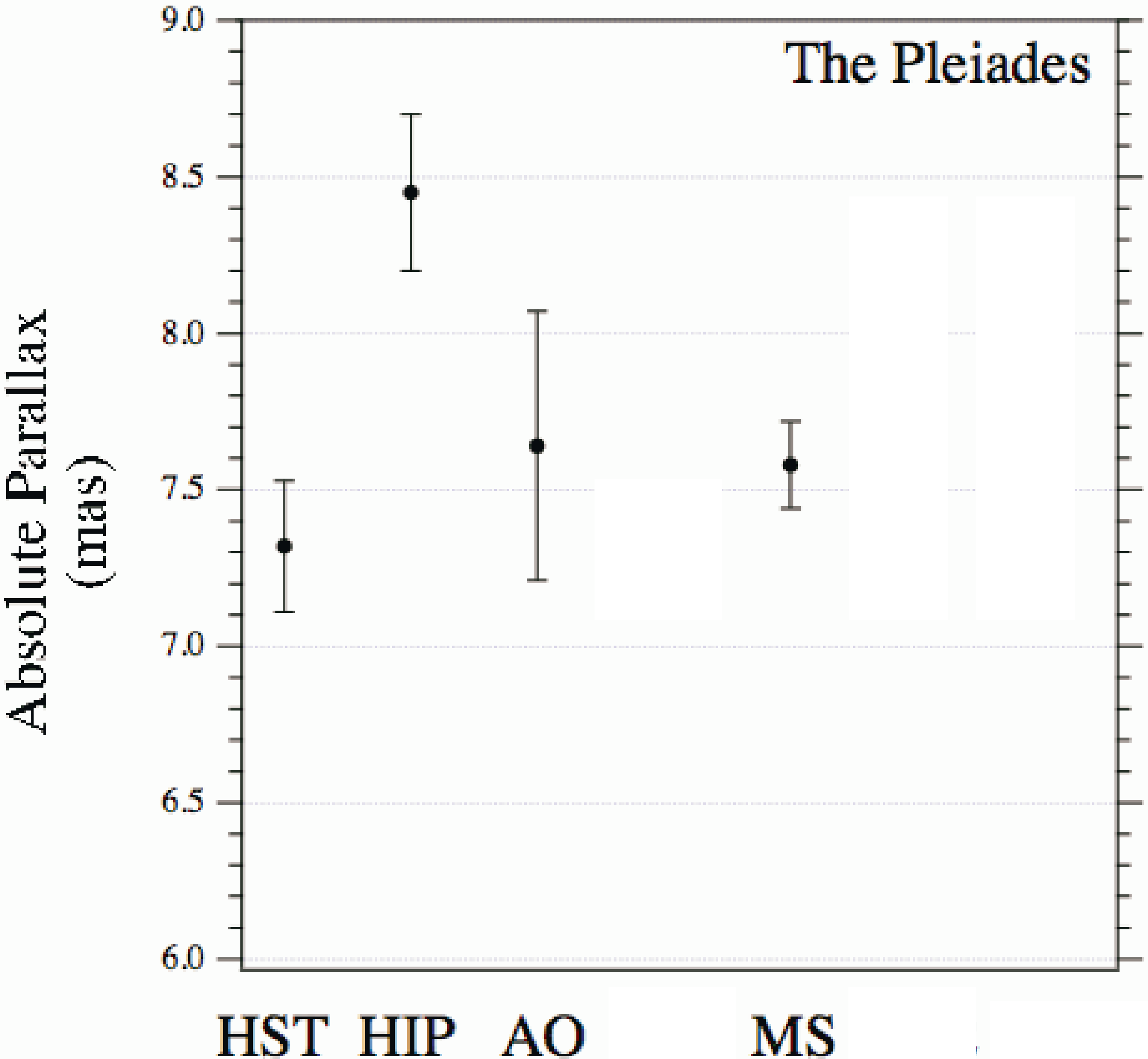
European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project



According to Hipparcos, Pleiades and Praesepe color-luminosity relationships are offset (Pinsonneault et al 1998)

Pleiades Distance



HST = Soderblom, Nelan, Benedict, McArthur et al 2005

HIP = Perryman et al 1997

AO = ?

MS = Pinsonneault et al 1998

SM4: October 2008

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Take-Home Lessons

- Careful consideration of sometimes unfamiliar error terms (eg. Lutz-Kelker bias) is necessary
- Careful consideration of reference frame is necessary
- Long-term stability (and **repeatability**) is necessary
- Comparison (and contradiction) with other methods needs to be carefully considered
- Interferometry provides measures at angular scales not available in traditional imagers
- These techniques should be applicable for astrometry with PRIMA

European Organization for Astronomical Research in the Southern Hemisphere

VLTI PRIMA Project

Don’t Miss: HST FGS poster (Eder Martioli / Fritz Benedict)