Astrometry: From Proposals to Science

A general step-by-step of what to do at the telescope, how to reduce your data, and how to extract your science

Fritz Benedict
McDonald Observatory
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The Flow

- Astrometry defined
- The proposal
- What to do at the telescope (!?)
- An example, done
- Relevance to exoplanets
- An example, in progress

A Definition of Astrometry

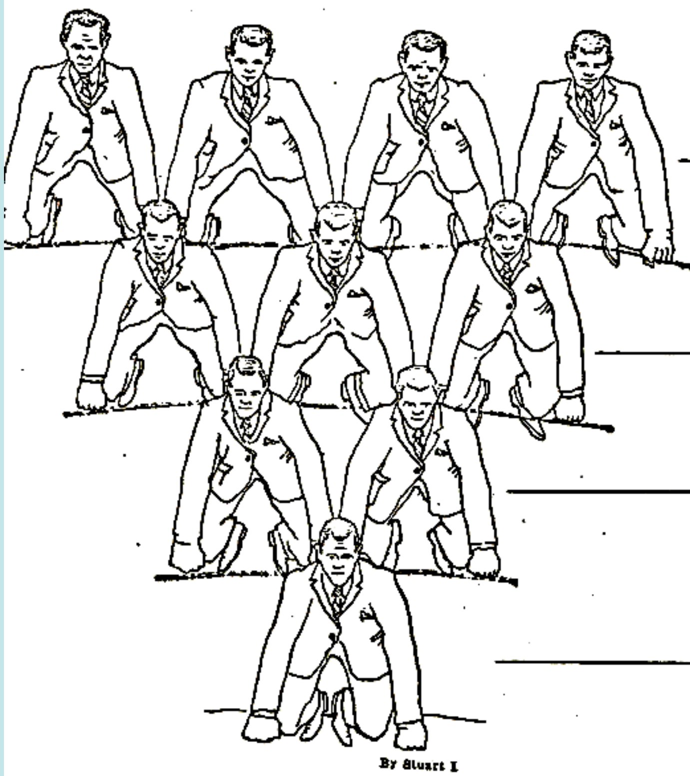
The object of the game is to figure out how the universe works by watching tiny lights move across the sky.

George Johnson, NYT Books, June 5 2005

The Value of Astrometry

THE ASTRONOMICAL PYRAMID

ILLUSTRATING THE INTERDEPENDENCE OF THE VARIOUS AREAS OF STUDY



COSMOLOGISTS, GENERAL RELATIVISTS, CRANKS, OTHER FUZZY-BRAINED PENCIL-PUSHERS.

ATMOSPHERES, INTERIORS, INTERSTELLAR MED. THEORISTS

SPECTROSCOPISTS PHOTOMETRISTS

ASTROMETRISTS

Ron Probst circa 1974

GET BACK TO BASICS -- SUPPORT ASTROMETRY

From Proposal to Science

- Choose the problem you wish to solve
  - I want a distance. I want a motion. I want both. I want a perturbation.
- Choose (or build!) the tool with which to solve the problem
- Propose (or use)

Writing the proposal

- SELL SELL SELL! Write and re-write the abstract
- Tell a story
  - Describe the problem
  - Why is solving this problem important (those pesky astrophysical implications)
  - Why are YOU (and your group) the best team to solve the problem
  - Often the problem is simply an improvement

Writing the proposal

- Link the uniqueness of the tool with the uniqueness of the result
- Refer to past accomplishments (and you had better have some, to be competitive!)

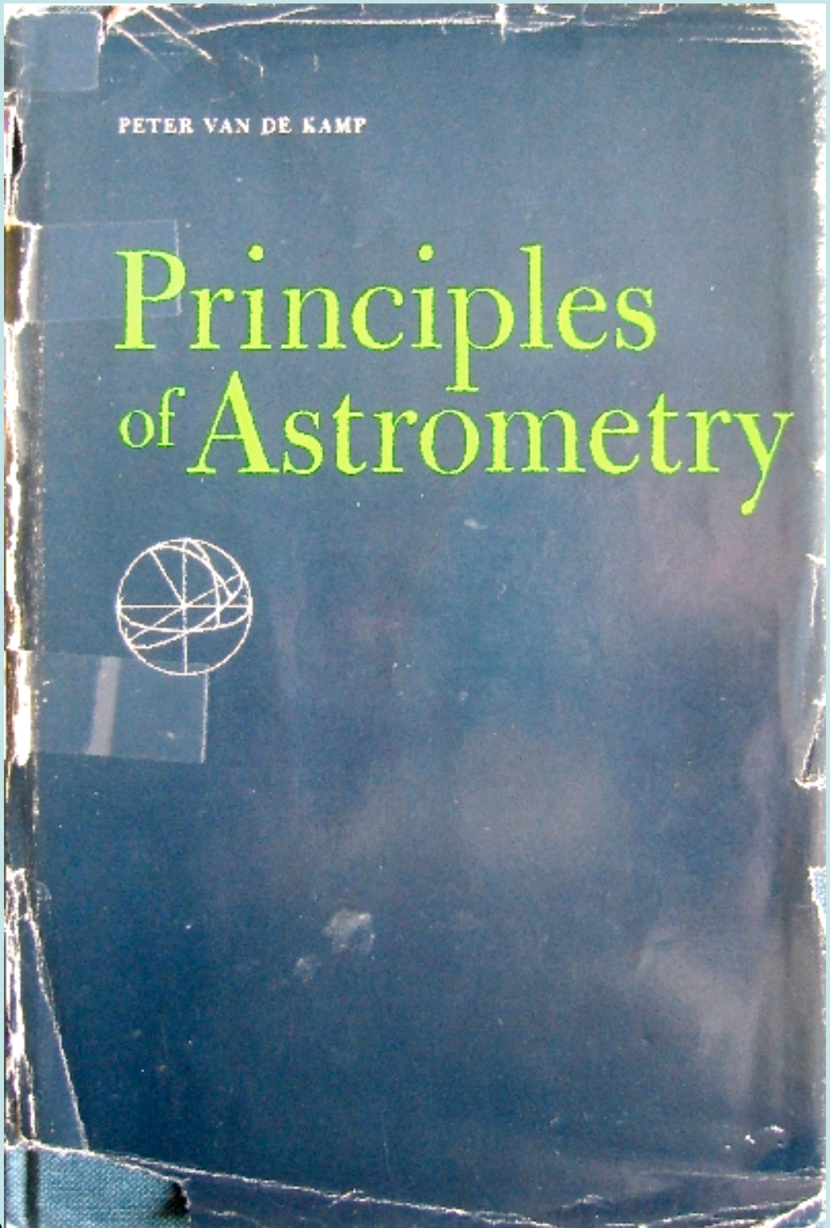
Team Building

- Astrometry
- Photometry
- Spectroscopy
- Radial velocities
- Dynamics

What To Do at the Telescope

- ?

How to Reduce and Analyze Your Data



GAUSSFIT—A SYSTEM FOR LEAST SQUARES AND ROBUST ESTIMATION

W. H. JEFFERYS, M. J. FITZPATRICK, and B. E. MCARTHUR

Department of Astronomy, The University of Texas at Austin, Austin TX 78712, U.S.A.

Abstract. GaussFit is a new computer program for solving least squares and robust estimation problems. It has a number of unique features, including a complete programming language designed especially to formulate estimation problems, a built-in compiler and interpreter to support the programming language, and a built-in algebraic manipulator for calculating the required partial derivatives analytically. These features make GaussFit very easy to use, so that even complex problems can be set up and solved with minimal effort. GaussFit can correctly handle many cases of practical interest: nonlinear models, exact constraints, correlated observations, and models where the equations of condition contain more than one observed quantity. An experimental robust estimation capability is built into GaussFit so that data sets contaminated by outliers can be handled simply and efficiently.

1. Introduction

Early in the Space Telescope program, it became evident that astrometry needed a very flexible least squares estimation program. It should be able to handle complex models, including general overlapping-plate models such as are frequently encountered in astrometry. The program should be very flexible—it should be easy to define new models or to change old ones, and to test the results of applying different models to the same data set. And finally, the program should incorporate the best available algorithms.

Jefferys, W., Fitzpatrick, J., & McArthur, B. 1988, Celest. Mech. 41, 39.

How to Extract Your Science

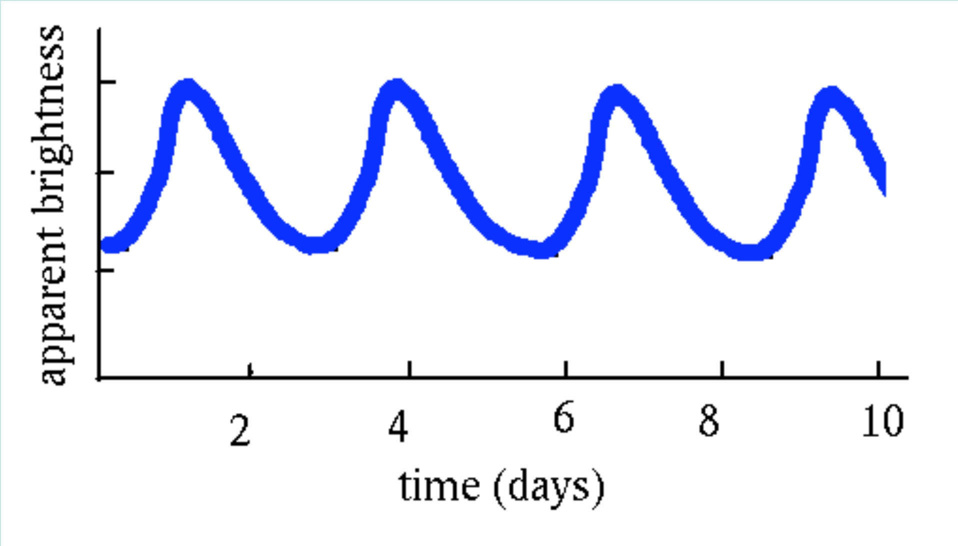
- First, you better have a pretty good idea of what you are after, before you go to the telescope
- Second, some astrometrists consider the job done once they have a parallax or proper motion
- Again, consider including the astrophysical implications of your work

An Example

- δ Cepheus
- Want to set a zero-point for the Period-Luminosity Relation
- Hence, want M_V(Cep)
- Therefore, want a distance (astrometry!)
- Transforming relative to absolute astrometry requires knowledge of reference stars
- Will need A_V (photometry, spectroscopy)

What is a Cepheid?

A variable star



A star that gets brighter and fainter because it gets bigger and smaller. Why?

Bicycle pumps and fire extinguishers

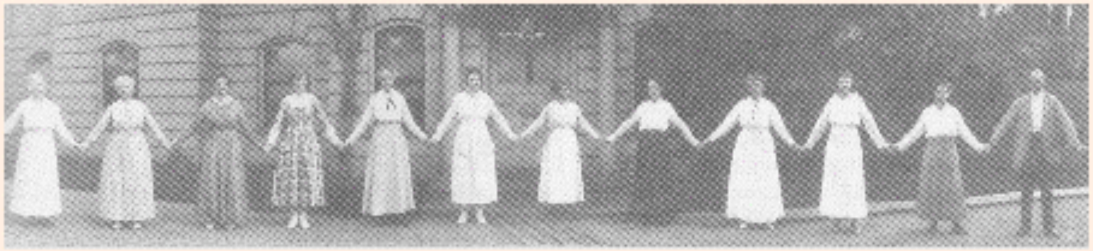
How a Cepheid 'Works'

The star has a shell structure, with one of the layers composed of helium. Ionized helium is less transparent than neutral helium

1. As energy from the interior of the star tries to escape the star, it ionizes the helium layer.
2. This layer no longer transports energy as well (it becomes less transparent).
3. As a consequence the layer is heated and expands upwards.
4. As it is pushed upwards, it expands and cools.
5. The helium once again becomes neutral.
6. Energy now passes freely through the layer, which cools (contracts), collapsing back down, reducing the size of the star. The process starts again with step 1.

More massive (brighter) stars cycle more slowly

Henrietta Leavit and the Harvard women



THE HARVARD WOMEN. HENRIETTA LEAVITT IS THE SIXTH FROM THE LEFT, AND ANNIE CANNON IS THE FOURTH FROM THE RIGHT.

Around the 1880's, the new director of Harvard University Astronomy Department, Edward Pickering, employed a number of women for what was considered 'mundane' work. However as these women (Henrietta Leavitt and Annie Cannon amongst them) strengthened their science skills it was soon realised that their input into the astronomical world was invaluable. Henrietta Leavitt discovered the period-luminosity law and Annie Cannon lay the foundations of stellar spectra classification.

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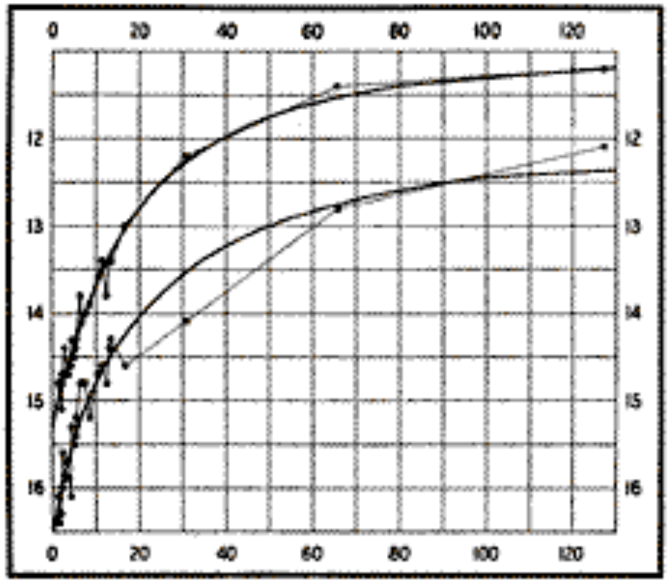


Fig. 1.

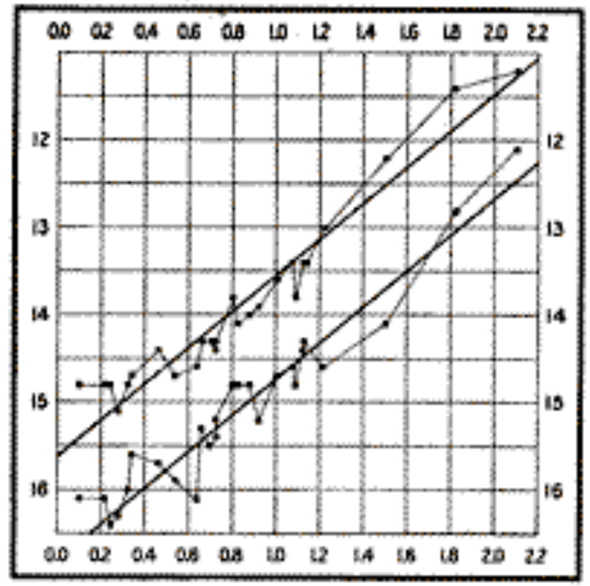
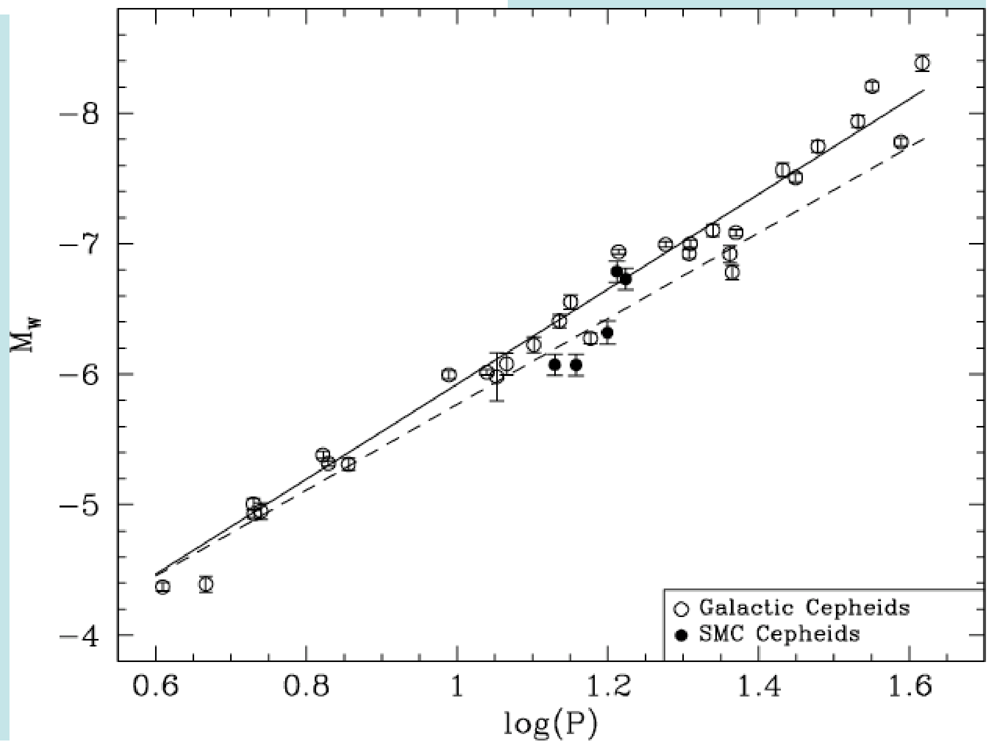


Fig. 2.

1912

~2000



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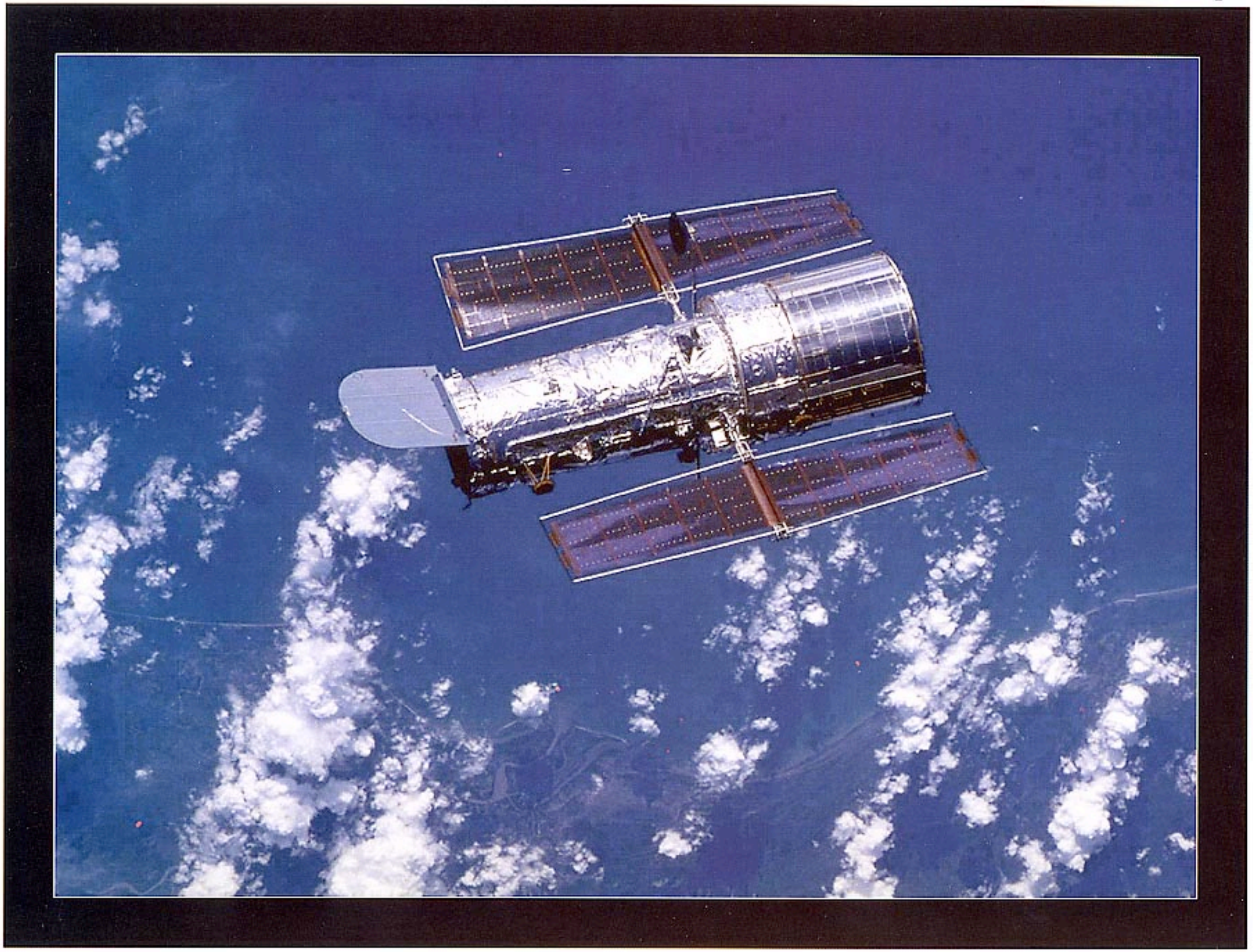
Calibrating the Cepheid PL Relation Zero-point with Hubble Space Telescope

How we obtained the parallax of δ Cep,
as told in
G.F. Benedict *et al.* 2002 AJ, 124, 1695



It helps to have done this for awhile

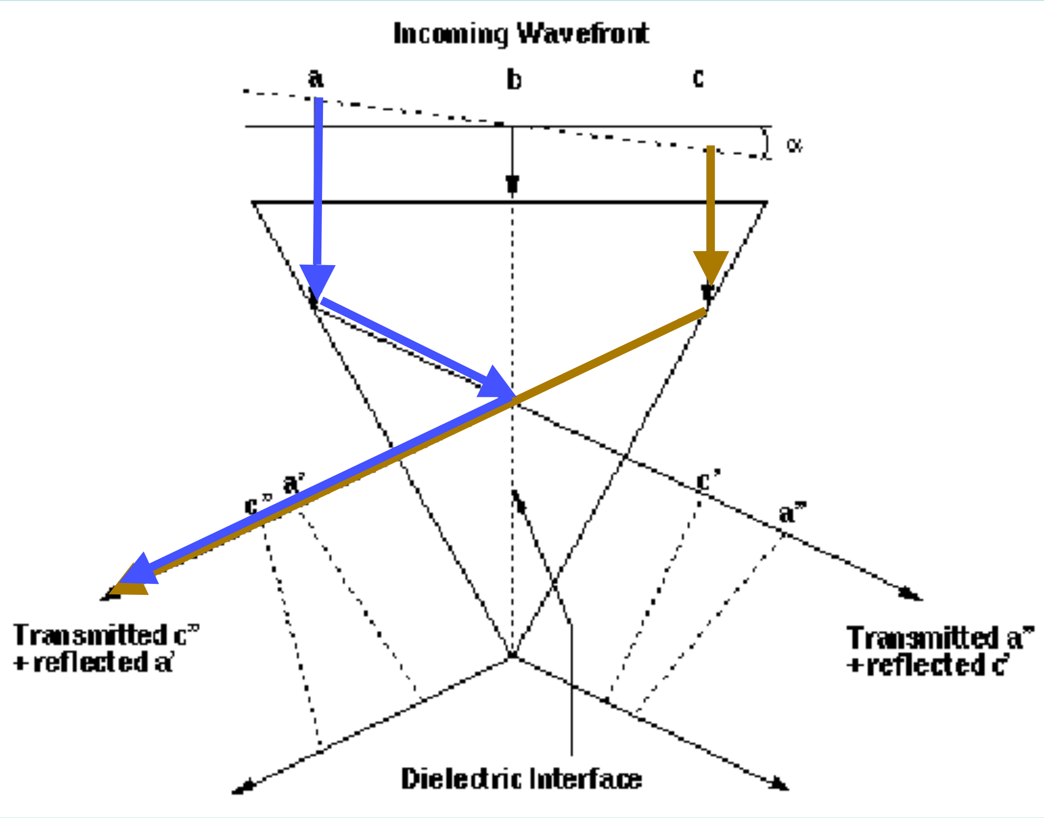
It helps to have friends who know how to do useful things and/or know how to obtain useful information

THE ASTRONOMICAL JOURNAL, 124:1695–1705, 2002 September

ASTROMETRY WITH THE *HUBBLE SPACE TELESCOPE*: A PARALLAX OF THE FUNDAMENTAL DISTANCE CALIBRATOR δ CEPHEI[1]

G. FRITZ BENEDICT,[2] B. E. MCARTHUR,[2] L. W. FREDRICK,[3] T. E. HARRISON,[4] C. L. SLESNICK,[3] J. RHEE,[3] R. J. PATTERSON,[3] M. F. SKRUTSKIE[3] O. G. FRANZ,[5] L. H. WASSERMAN,[5] W. H. JEFFERYS,[6] E. NELAN,[7] W. VAN ALTENA,[8] P. J. SHELUS,[2] P. D. HEMENWAY,[9] R. L. DUNCOMBE,[10] D. STORY,[11] A. L. WHIPPLE,[11] AND A. J. BRADLEY[12]
Received 2002 February 11; accepted 2002 May 28

The Koester's Prism - the Interferometric Heart of an FGS

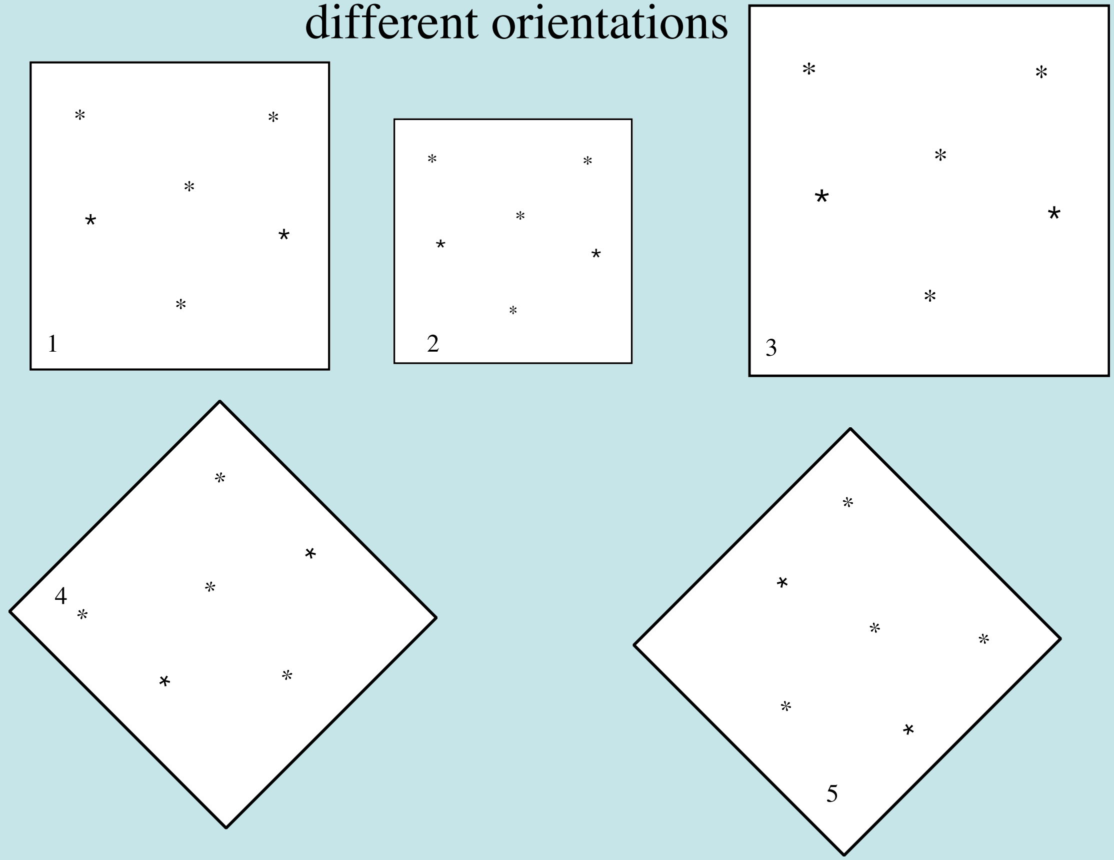


The δ Cep Field

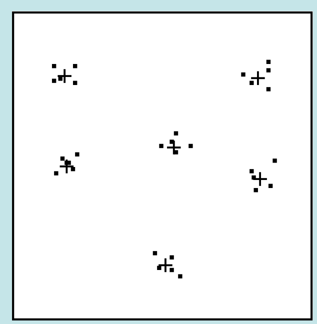
HST Observations

- Seven epochs 1995 - 97 separated by ~6 months
- 5 Reference stars
- 4 observations of δ Cep at each epoch

Astrometry, a simple example
5 "plates"
different scales
different orientations



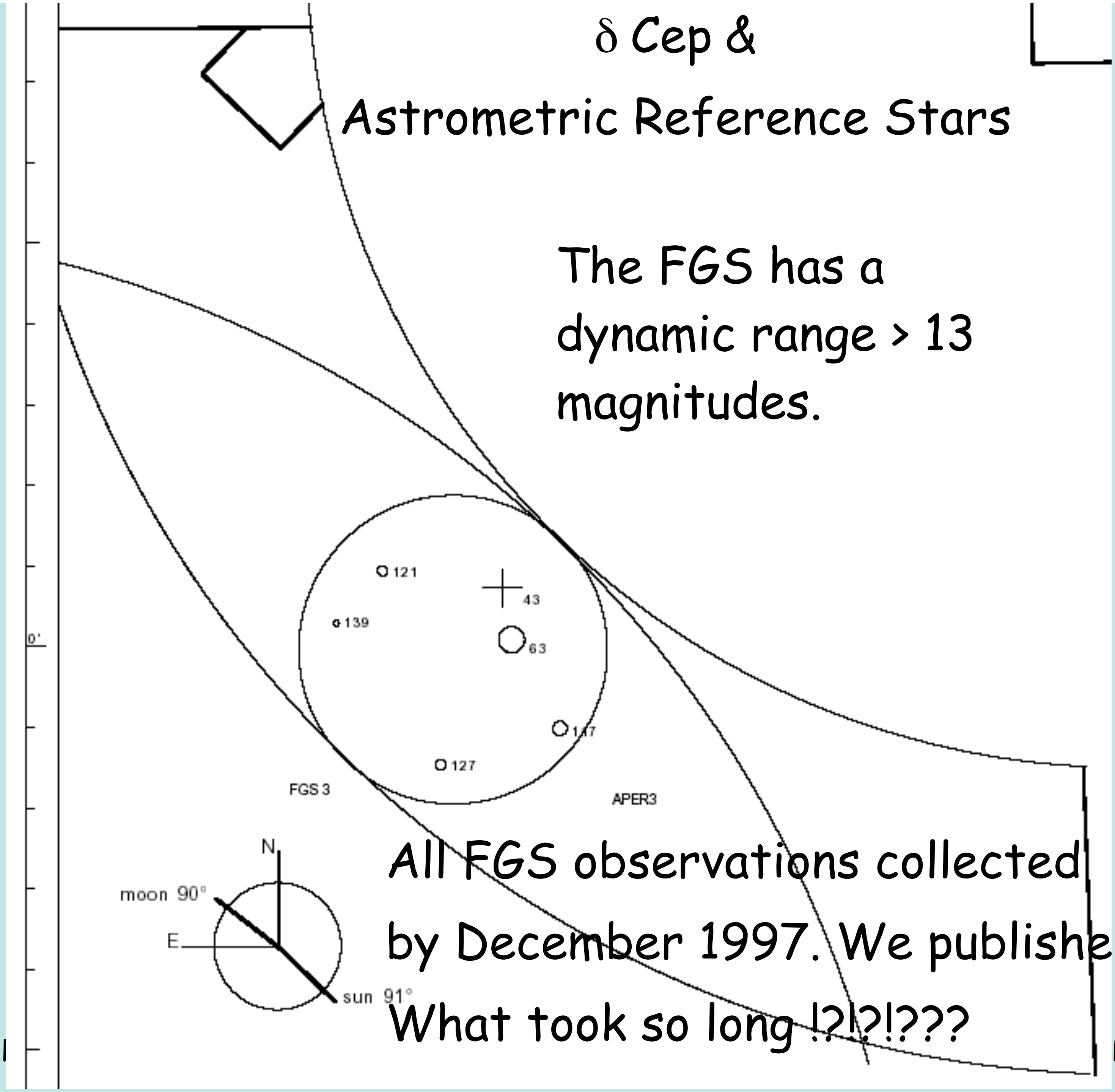
Result of Overlap
Solution to
Plate #1



0.002 arcsec

Precision = standard deviation of the distribution of residuals (▪) from the model-derived positions (+)

δ Cep & Astrometric Reference Stars



The FGS has a dynamic range > 13 magnitudes.

All FGS observations collected by December 1997. We published in 2002. What took so long !?!?!???

δ Cep Reference Frame Absolute Parallaxes

- Collect photometry
- Collect spectral classifications
- Collect proper motions
- Estimate extinction
- Produce absolute parallaxes

δ Cep Reference Frame Absolute Parallaxes

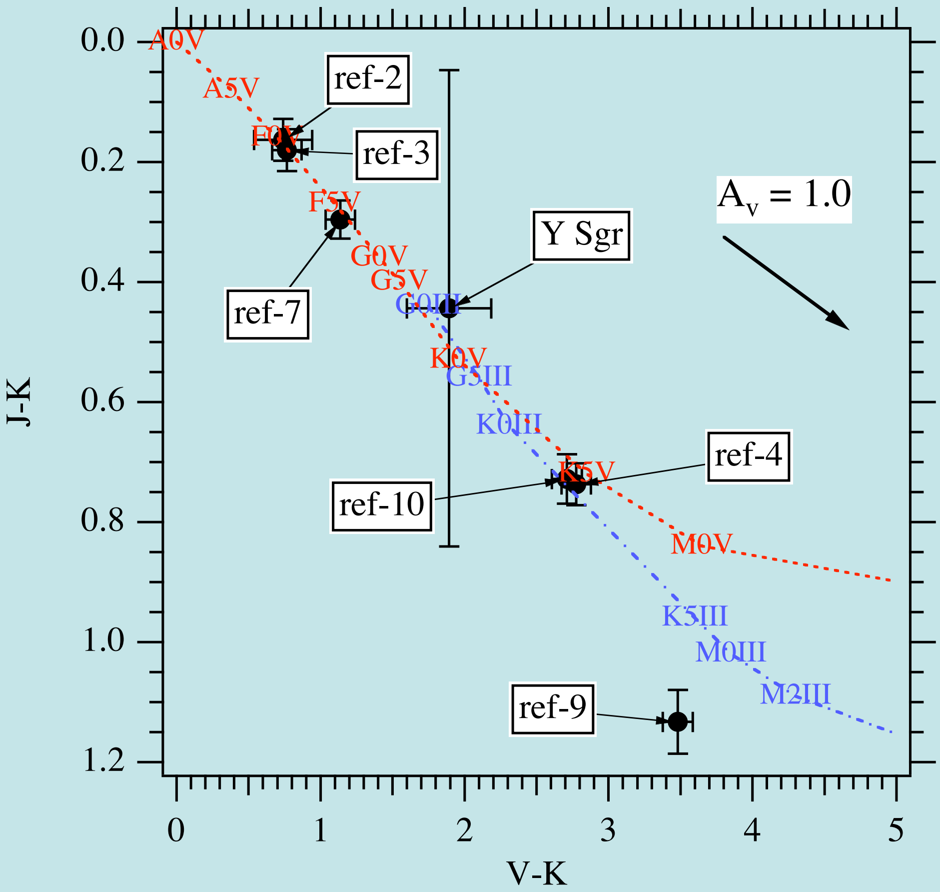
Photometry

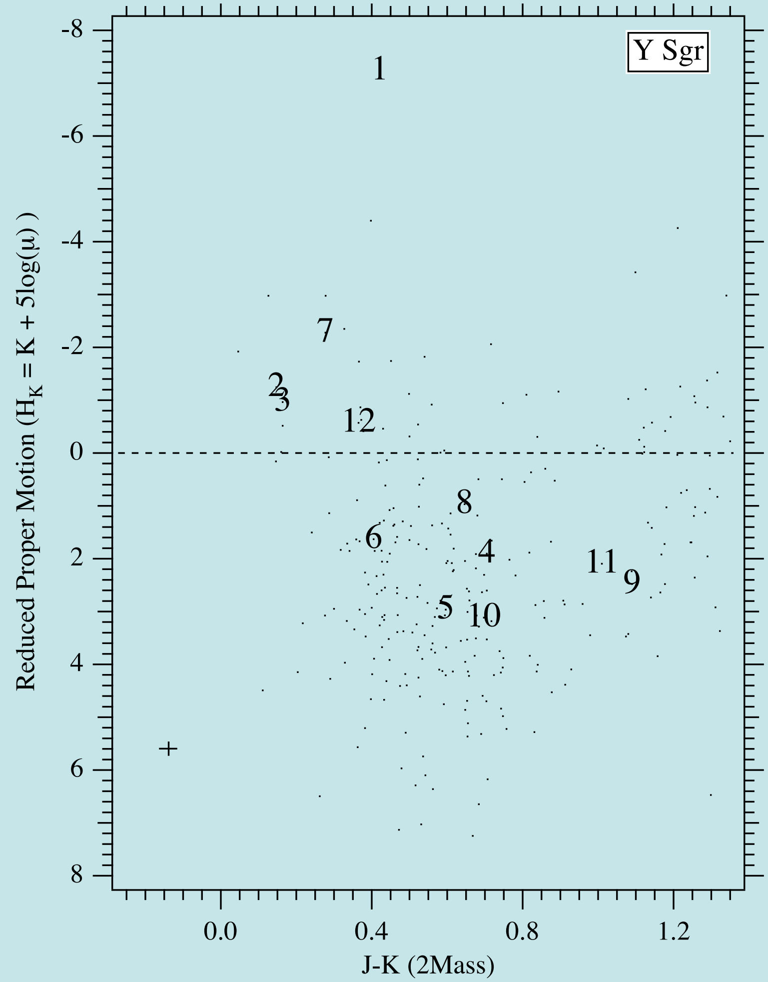
- FGS (V)
- NMSU (BVRI)
- 2MASS (JHK)
- McDonald/UVa (Washington - DDO)

Color-color diagrams

- Mapping to Sp. T. from Bessell 1988 (PASP, 100, 1134)
- V-R vs V-K and V-I vs V-K
- M - DDO51 vs M - T_2

A_V and Luminosity Class





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GFB 1-28

The δ Cep Reference Frame Absolute Parallaxes

- Spectral Typing and Luminosity Classification

  NMSU - estimates ±2 subtypes

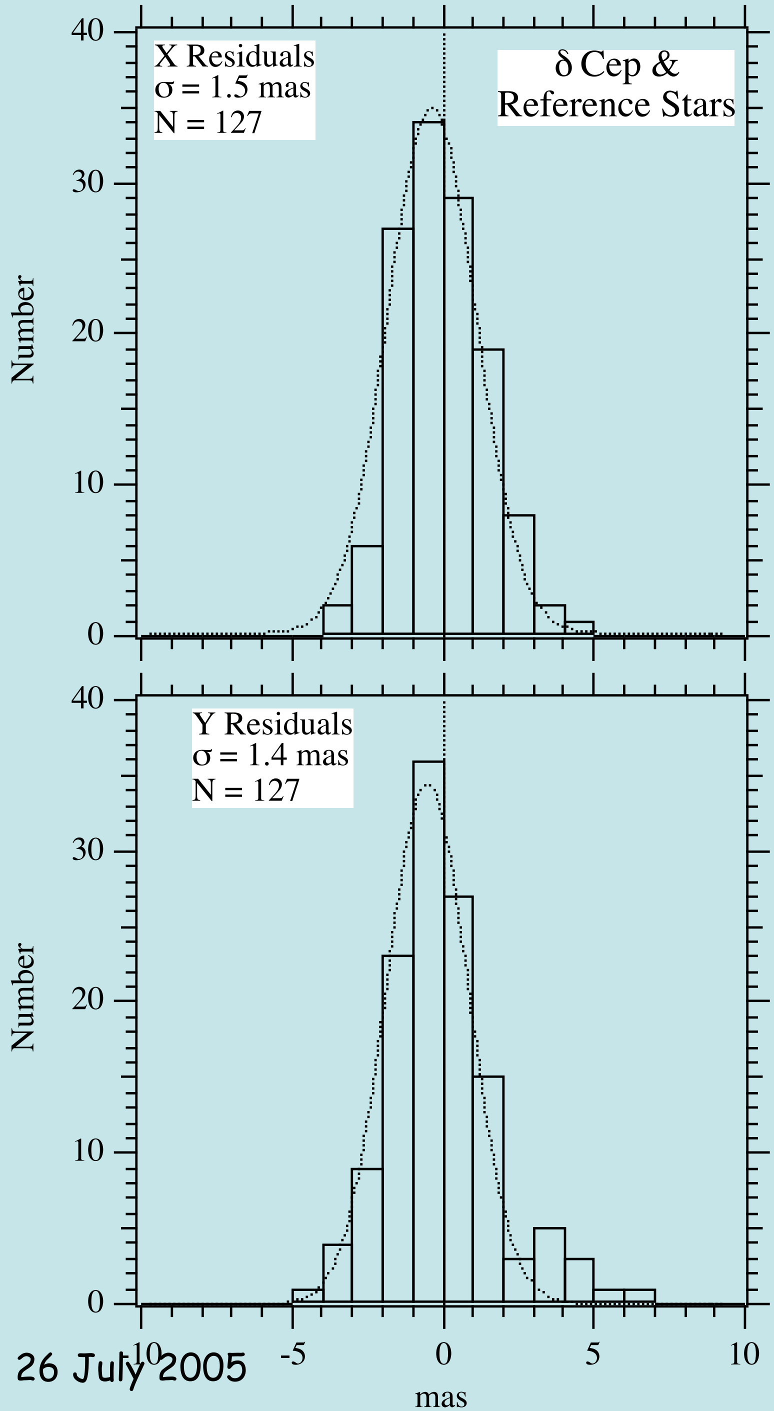
- M_v and $(B-V)_0$ $(V-I)_0$, $(V-R)_0$, $(V-K)_0$ from AQ2000

- BVRI from NMSU

- A_v from our photometry

- Absolute Parallaxes

$$\pi_{abs} = 1/(10^{(V - M_V + 5 - A_V)/2.5})$$



Histograms of x and y residuals obtained from modeling δ Cep and the astrometric reference stars with

Lateral color

Cross Filter

$$x' = x + lcx(B-V) - \Delta XFx$$

$$y' = y + lcy(B-V) - \Delta XFy$$

$$\xi = Ax'+By'+C+R_x(x'^2+y'^2)-\mu_x\Delta t - P_\alpha\pi_x$$

$$\eta = -Bx'+Ay'+F+R_y(x'^2+y'^2)-\mu_y\Delta t - P_\delta\pi_y$$

Radial or Decenter Term

Proper Motion

Parallax

Distributions are fit with gaussians whose σ's are noted in the plots.

A Parallax for δ Cep

HST

$$\pi_{abs} = 3.60 \pm 0.19 \text{ mas}$$

HIPPARCOS

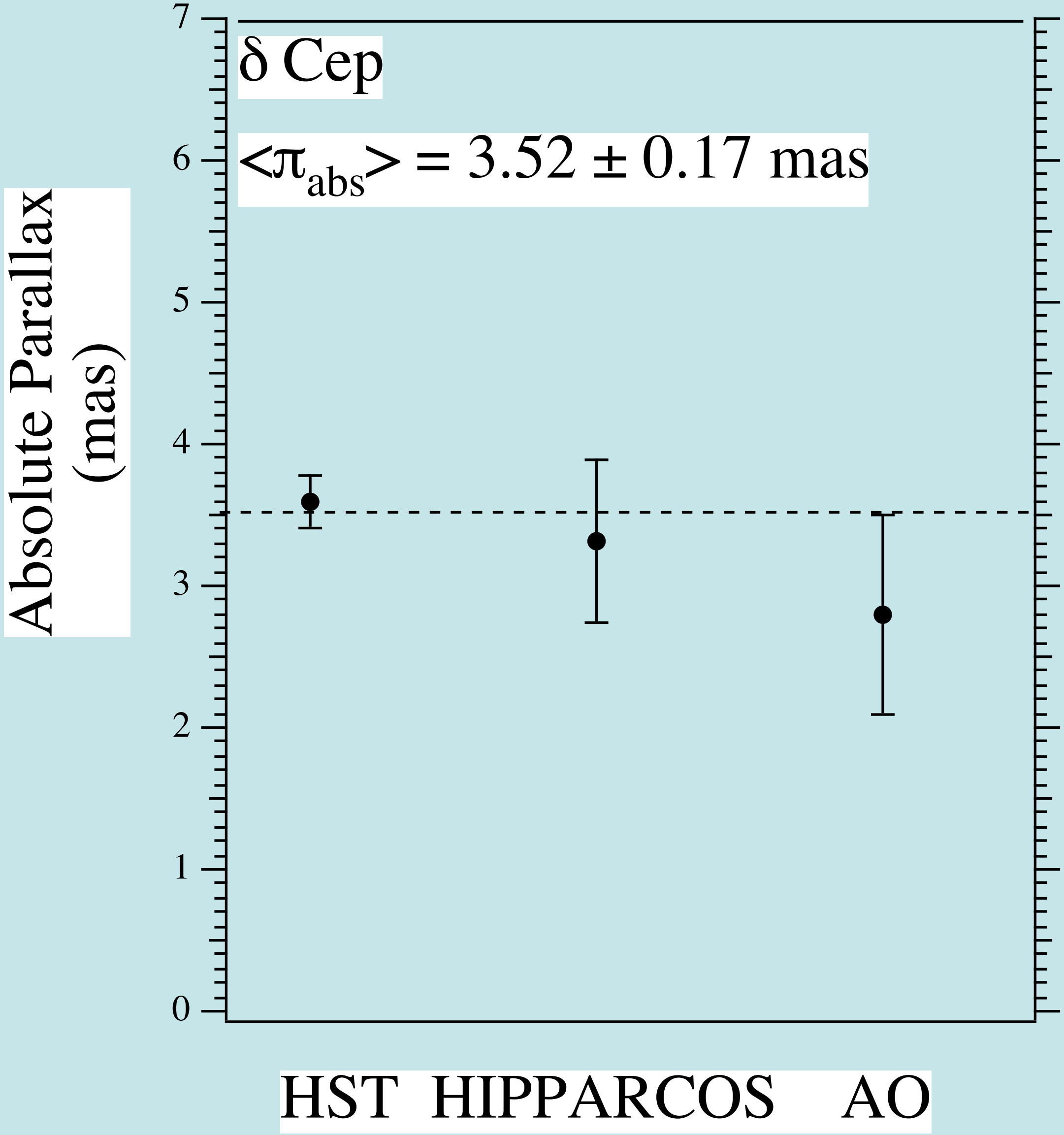
$$\pi_{abs} = 3.32 \pm 0.58 \text{ mas}$$

Allegheny (MAP)

$$\pi_{abs} = 2.70 \pm 0.7 \text{ mas}$$

Weighted average

$$\pi_{abs} = 3.52 \pm 0.17 \text{ mas}$$


δ Cep
<π_abs> = 3.52 ± 0.17 mas
Absolute Parallax (mas)
0
1
2
3
4
5
6
7
HST HIPPARCOS AO

$M_V = -3.47 \pm 0.10$

Astrophysical implications?

- $M_V = -3.47 \pm 0.10$, $\log(P) = 0.73$
- In LMC Cepheids with $\log(P) = 0.73$ have $V = 15.03 \pm 0.03$
- Hence, $m-M = 18.5 \pm 0.13$

The End Result

Astrometry with the Hubble Space Telescope: A Parallax of the Fu... http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=2002AJ....1...

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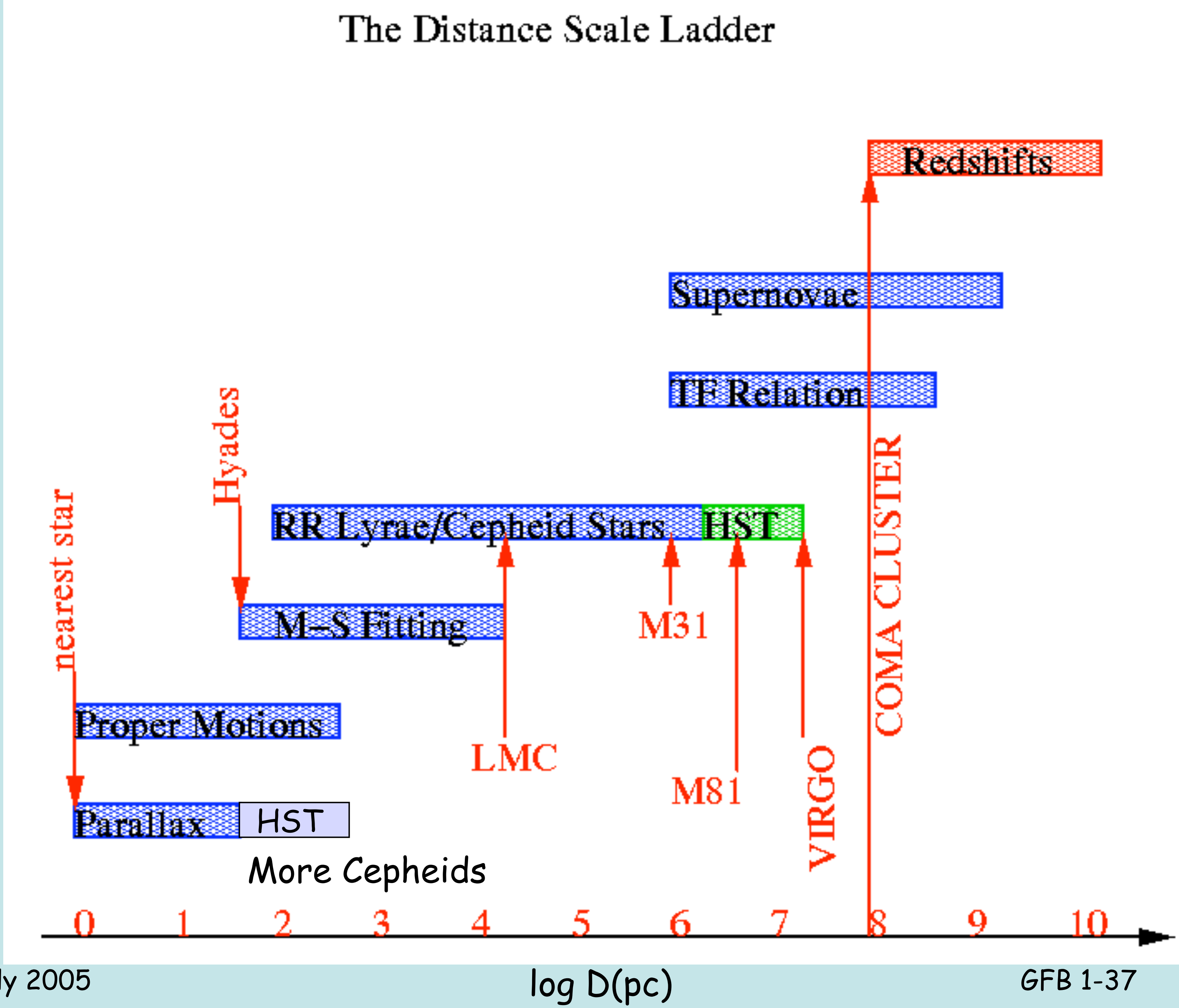
Title:	Astrometry with the Hubble Space Telescope: A Parallax of the Fundamental Distance Calibrator δ Cephei
Authors:	Benedict, G. Fritz; McArthur, B. E.; Fredrick, L. W.; Harrison, T. E.; Slesnick, C. L.; Rhee, J.; Patterson, R. J.; Skrutskie, M. F.; Franz, O. G.; Wasserman, L. H.; Jefferys, W. H.; Nelan, E.; van Altena, W.; Shelus, P. J.; Hemenway, P. D.; Duncombe, R. L.; Story, D.; Whipple, A. L.; Bradley, A. J.
Affiliation:	AA(McDonald Observatory, RLM 15.038, University of Texas, Austin, TX 78712.), AB(McDonald Observatory, RLM 15.038, University of Texas, Austin, TX 78712.), AC(Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903-0818.), AD(Department of Astronomy, New Mexico State University, Box 30001, MSC 4500, Las

Relevance to Extrasolar Planets?

Parallax (and proper motion) will be nuisance parameters that must be removed with high precision to determine the perturbation due to the exoplanet.

But, first, we'd like to measure distances to galaxies 12 billion light years away.

How do Cepheid parallaxes help?


The Distance Scale Ladder
Redshifts
Supernovae
TF Relation
Hyades
nearest star
RR Lyrae/Cepheid Stars
HST
COMA CLUSTER
M-S Fitting
M31
Proper Motions
LMC
M81
VIRGO
Parallax
HST
More Cepheids
0
1
2
3
4
5
6
7
8
9
10
log D(pc)

Calibrating the Slope of the Cepheid PL Relation with Hubble Space Telescope

We have already done one Cepheid, δ Cep

One object doth not a slope calibration make.

It does, however, provide a guide as to how we will do them all.

Already collected HST astrometric data

	Object	log P	HIP pi	HIP pi err	HIP % err	HST % err	V	[Fe/H]
1	T Vul	0.6470	2.0	0.6	25%	9%	5.61	-0.05
2	Eta Aql	0.8559	2.8	0.91	33%	5%	3.88	0.05
3	X Sgr	0.8459	3.0	0.94	31%	7%	4.56	0.02
4	Beta Dor	0.9931	3.1	0.59	19%	7%	3.77	-0.01
5	Zeta Gem	1.0065	2.8	0.81	29%	8%	4.01	0.04
6	RT Aur	0.5715	2.1	0.89	43%	9%	5.75	0.06
7	Y Sgr	0.7614	2.5	0.93	37%	10%	5.77	0.06
8	FF Aql	0.6500	1.32	0.72	55%	9%	5.31	0.02
9	W Sgr	0.8810	1.57	0.93	59%	8%	4.66	-0.01
10	l Car	1.5510	2.16	0.47	22%	9%	3.4	-
11	Del Cep	0.7297	3.3	0.58	17.5%	5%	3.95	0.06

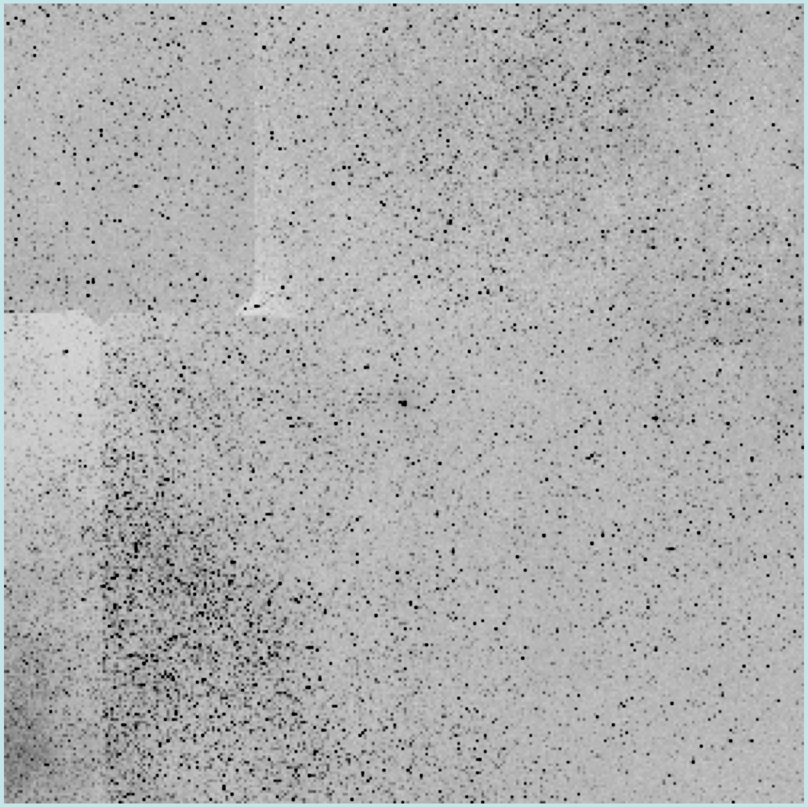
HST Cepheid PL Calibration Project Status

- We have 11 observation sets of all ten new targets and associated reference stars, for a total of 110 x 20 observations (110 orbits) with no safemodes or other hiccups.

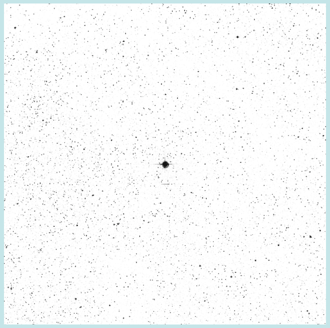
- Co-I's have collected and are calibrating BVRI Washington-DDO photometry and typing spectra for all reference stars.

- Should have an announcement at Winter '06 AAS

X Sgr

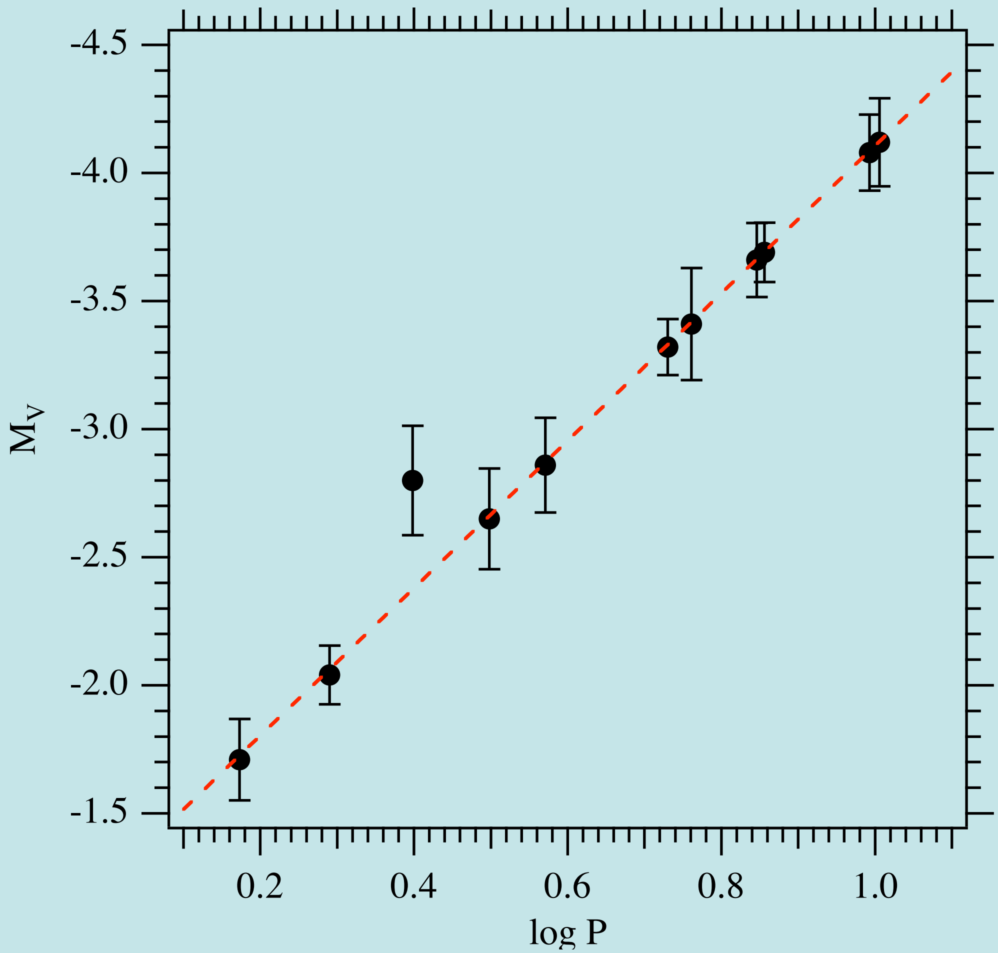


A_V will be tricky

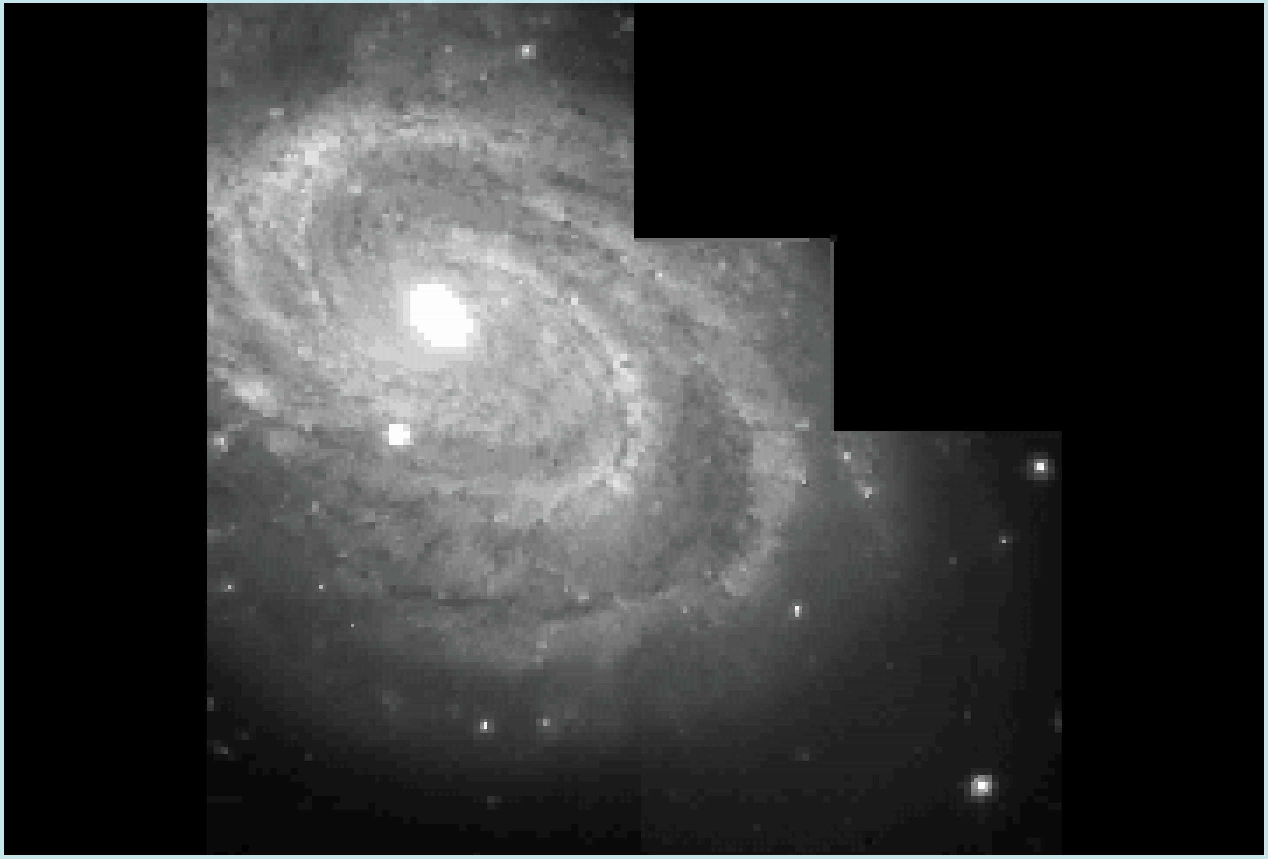


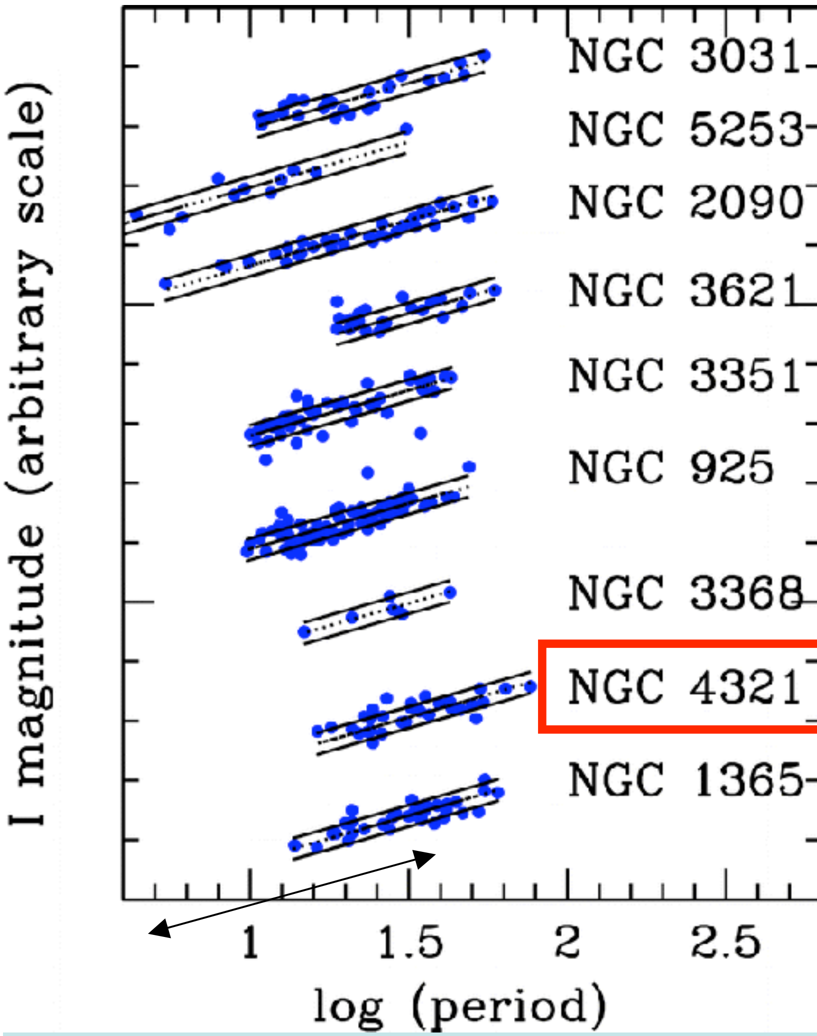
RA =17 47 33.62, Dec = -27 49 50.8

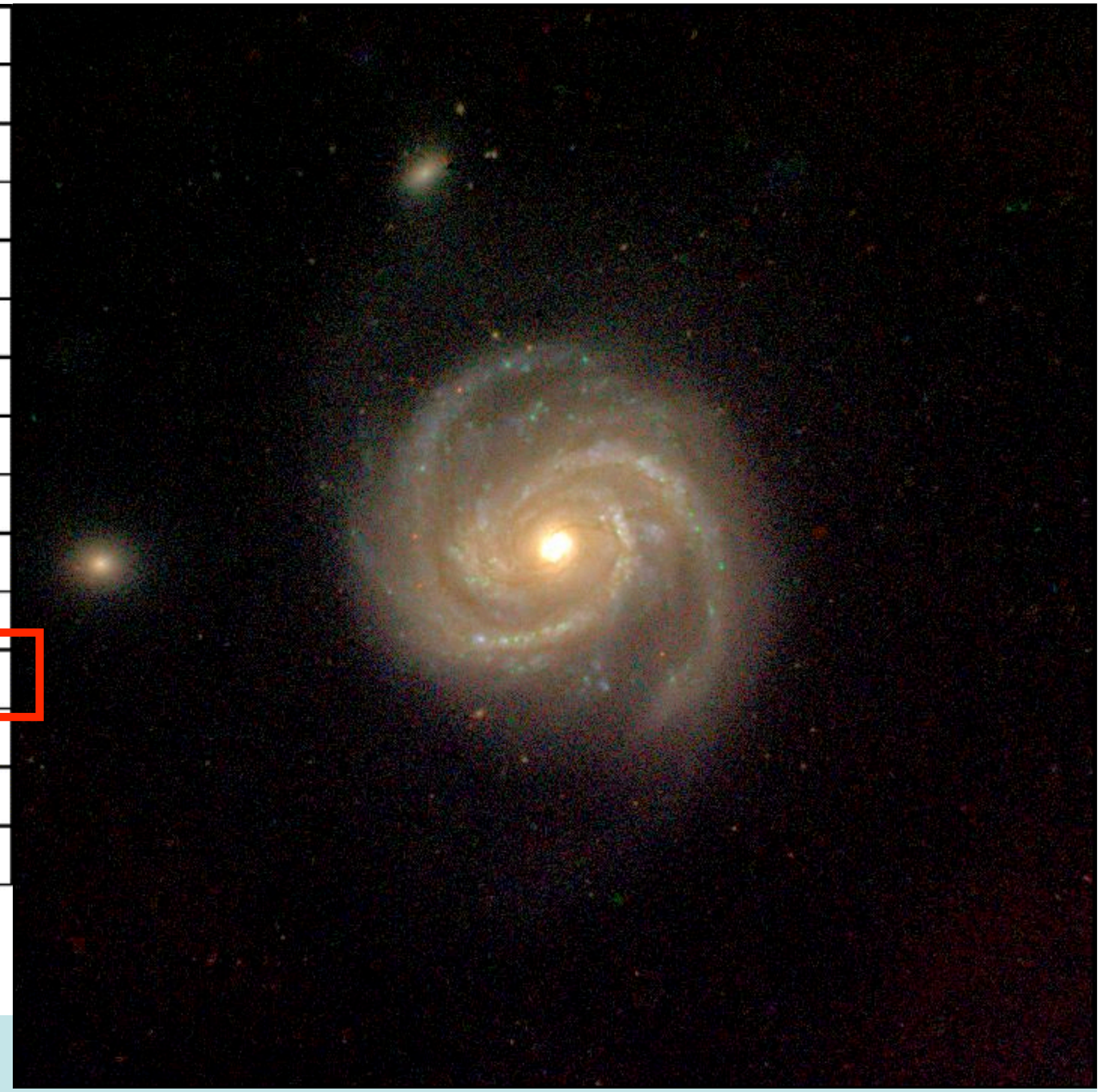
Monte Carlo Simulation of Final P-L Calibration

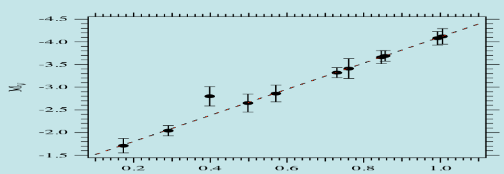


Presumes 0.2 mas parallax precision and low A_V errors.

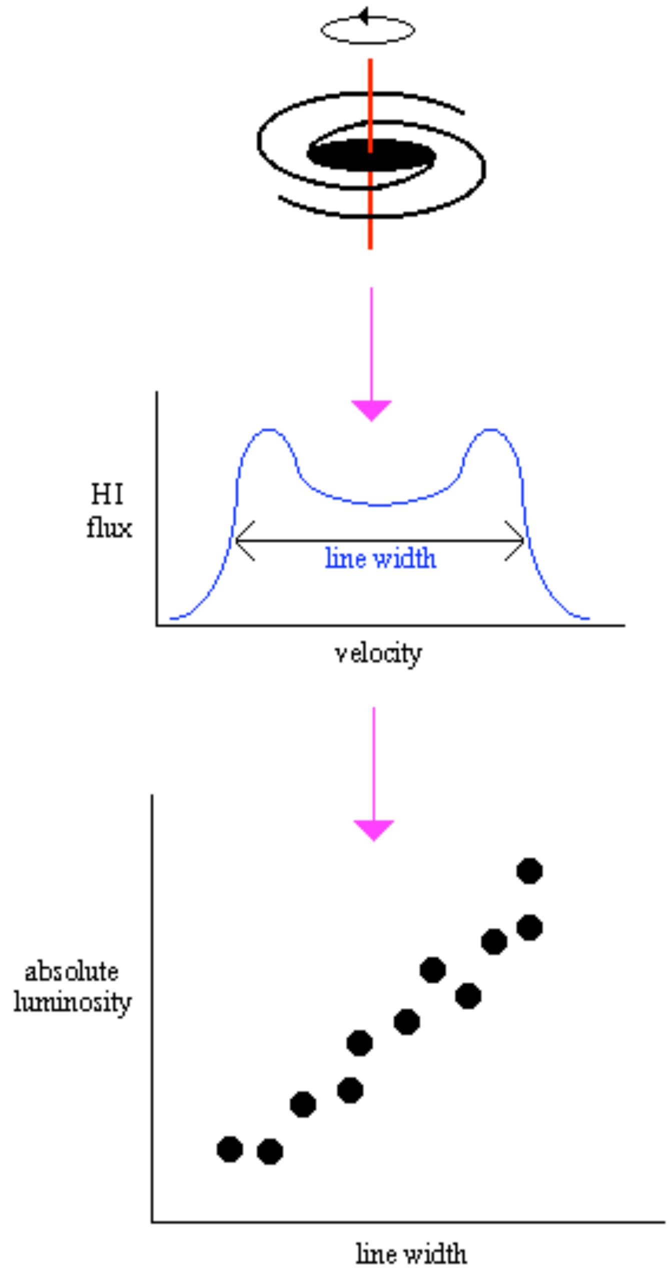



NGC 3031
NGC 5253
NGC 2090
NGC 3621
NGC 3351
NGC 925
NGC 3368
NGC 4321
NGC 1365
I magnitude (arbitrary scale)
1
1.5
2
2.5
log (period)





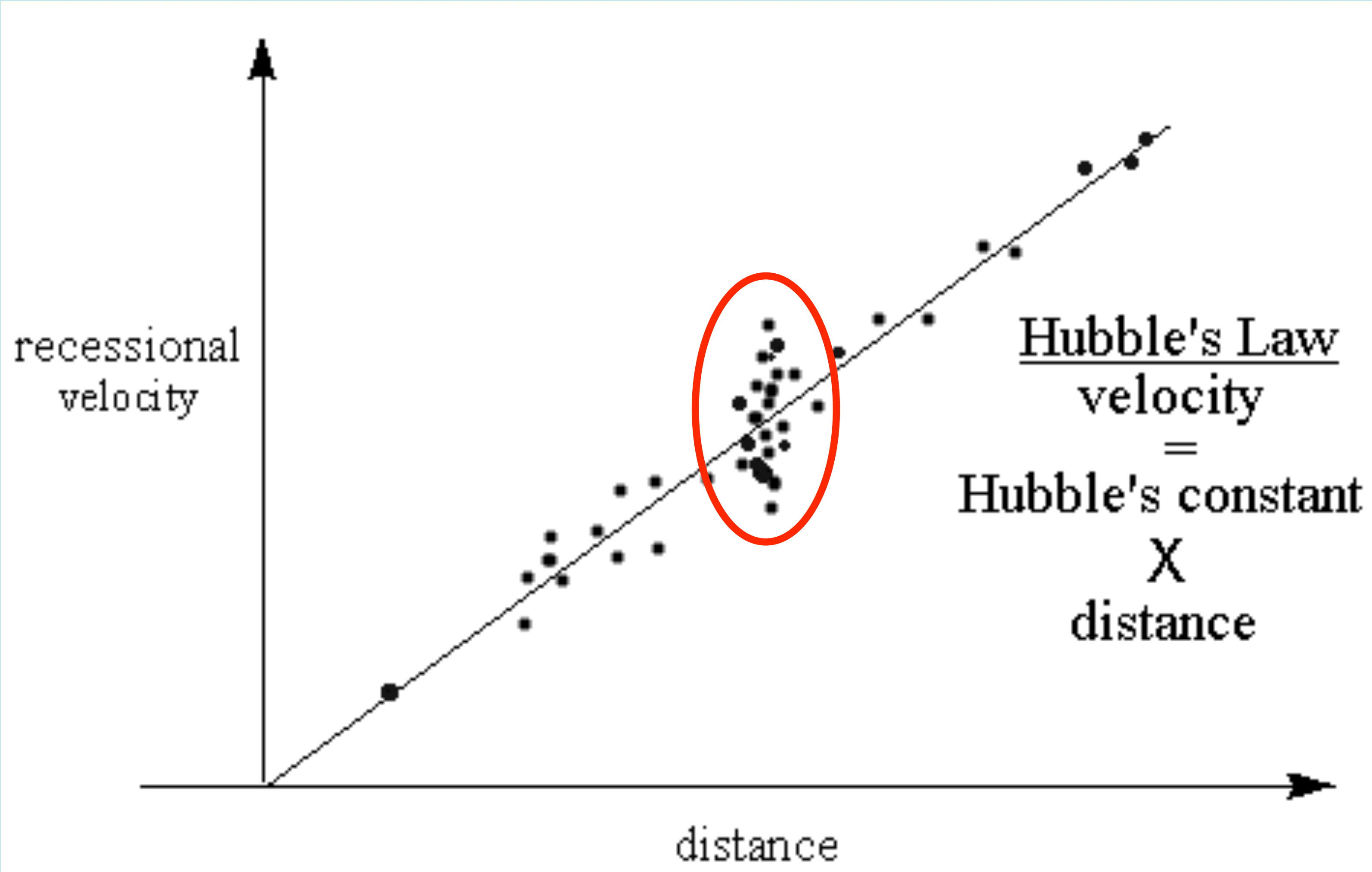
Tully–Fisher relation

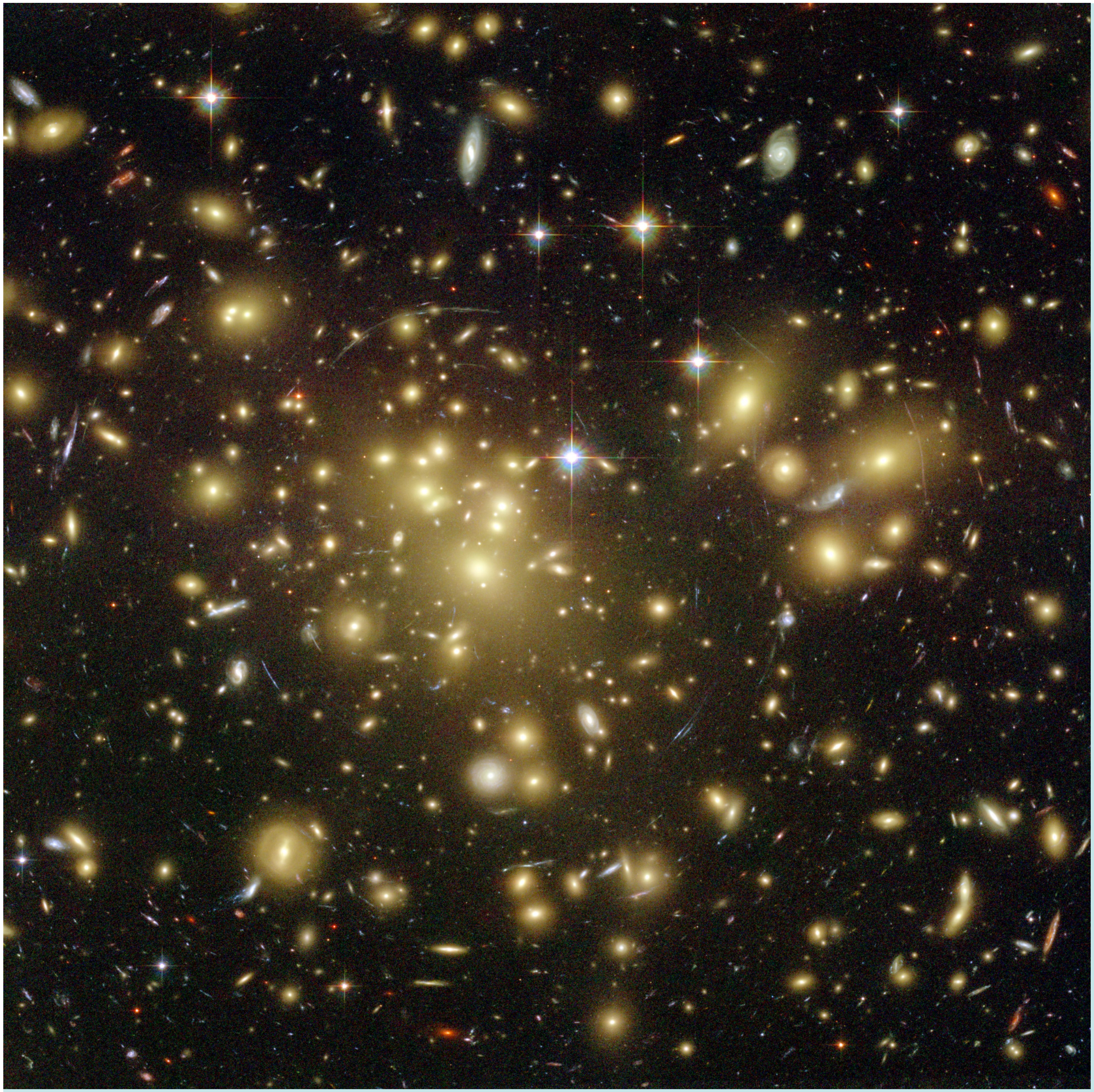


spiral galaxies rotate, and the rotation speed is proportional to the mass of the galaxy

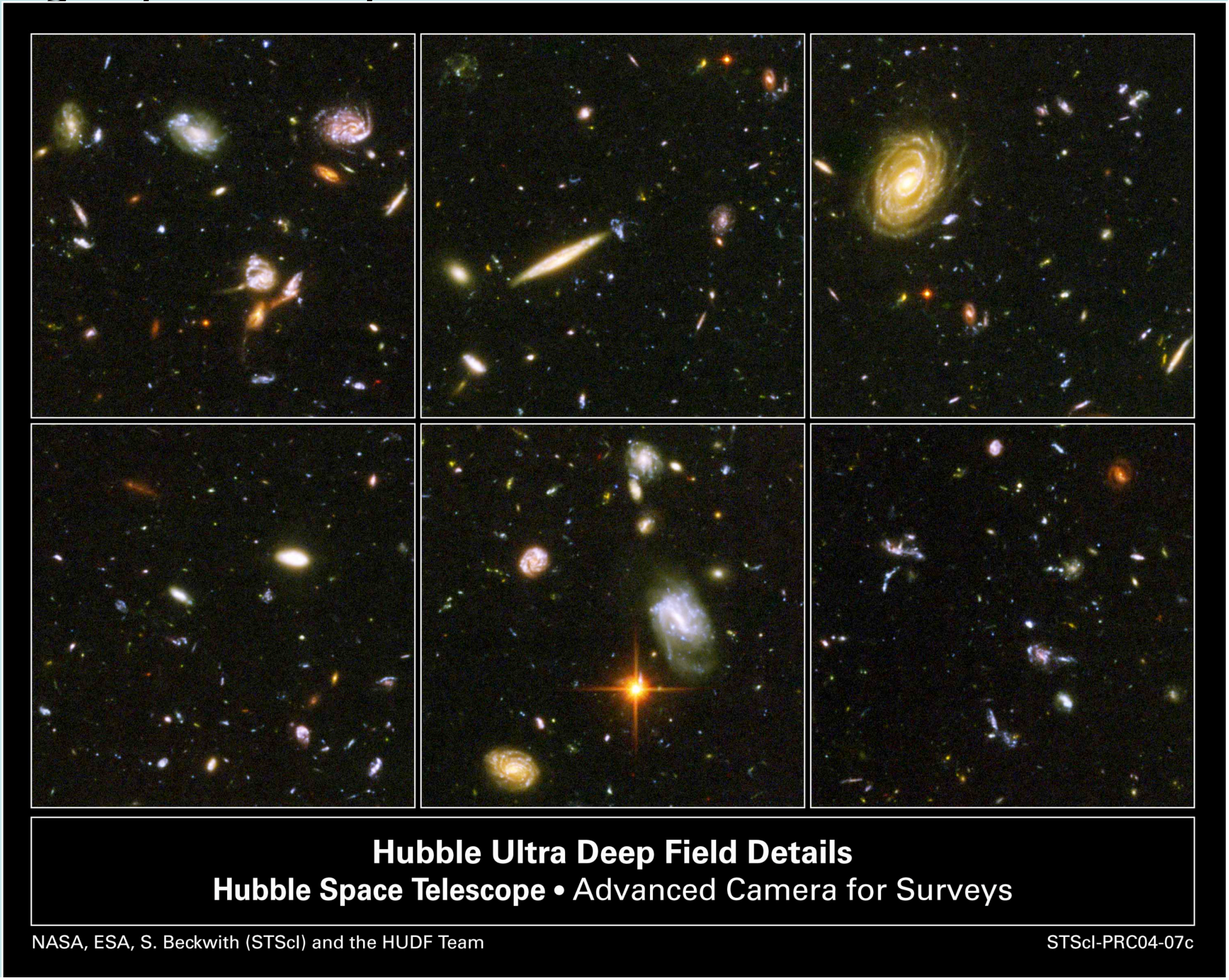
measurements of neutral hydrogen (HI) display a ''double–horned'' profile, where the width of the line indicates the mass

a plot of line width versus absolute luminosity of a galaxy is called the Tully–Fisher relation. When calibrated using galaxies with Cepheid distances, the TF relation is used to determine Hubble's constant.


recessional velocity
distance
Hubble's Law
velocity
=
Hubble's constant
X
distance



We now measure distances to galaxies 12 billion light years away!



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Should this happen again, we could do 10 more RR Lyr stars and other astrophysically interesting objects

But, not if it is necessary to sacrifice or unduly delay SIM