



Parallaxes with Hubble Space Telescope

How Bayes (and Bill) Helped

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McDonald Observatory

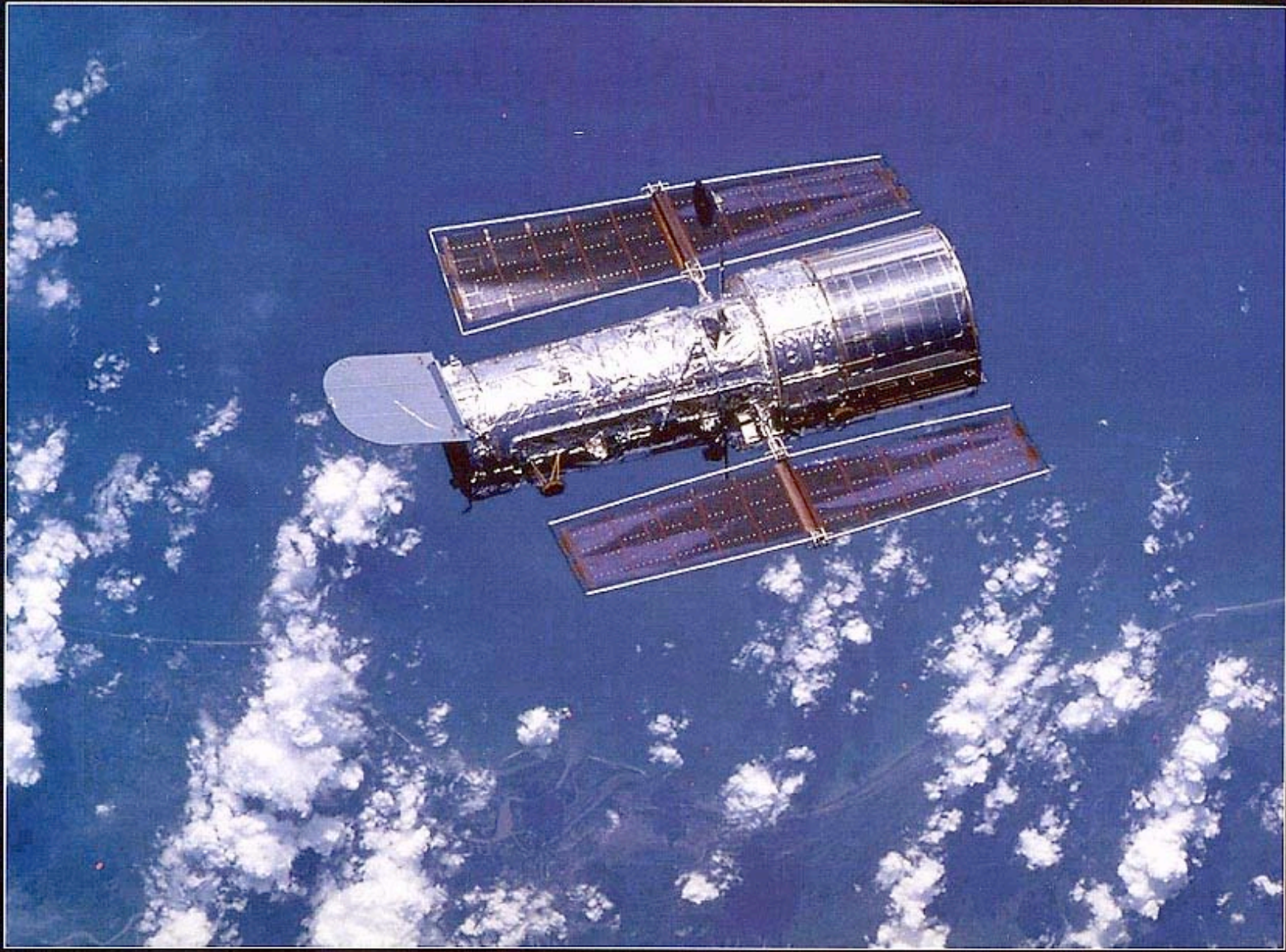
University of Texas

Outline

Astrometry with HST

A Recent Result - Pleiades Parallax

Future Work



History (1978)

Bill!!



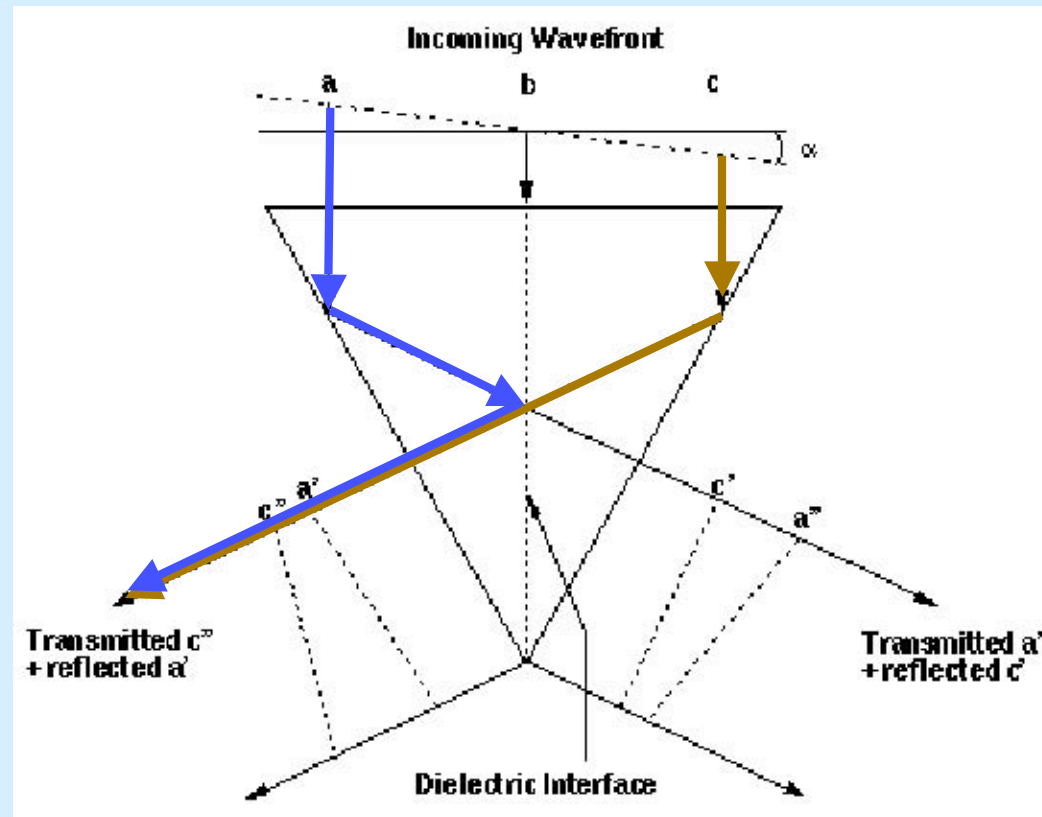
Space Astrometry with an Interferometer on Hubble Space Telescope

Fine Guidance Sensors

Fringe Tracking

Fringe Scanning

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



The Fringe Theory

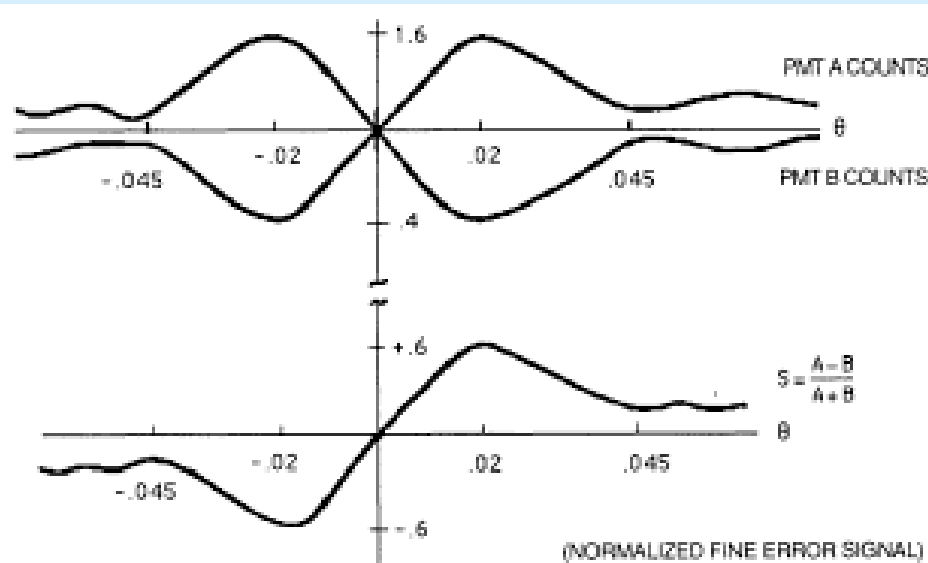
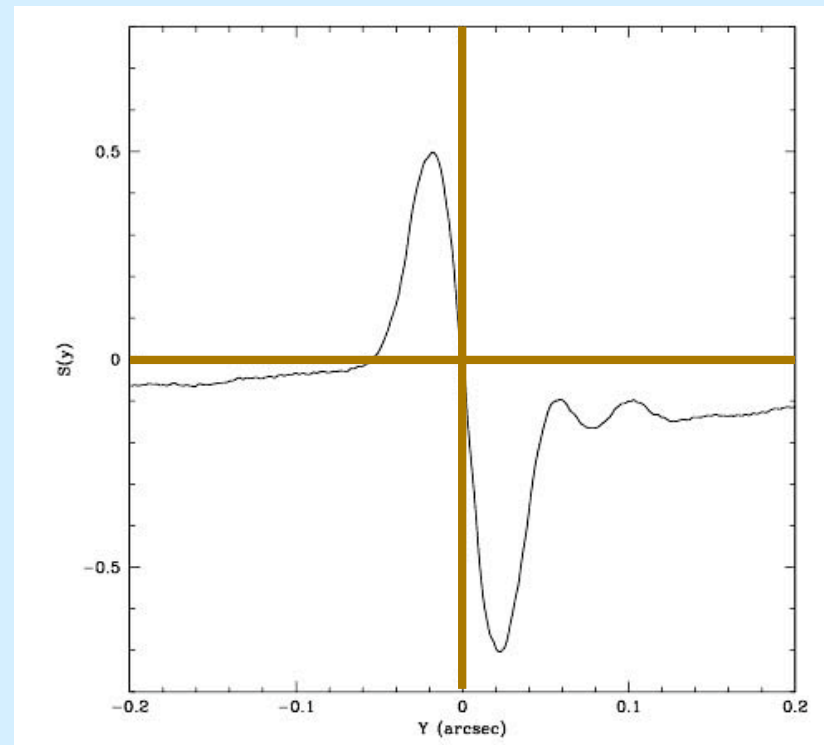


FIG. 6-Transfer function S-curve construction.

Practice

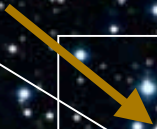


Technical details: Bradley, A., Abramowicz-Reed, L., Story, D., Benedict, G. F., and Jefferys, W., 1991, PASP, **103**, 317

M35

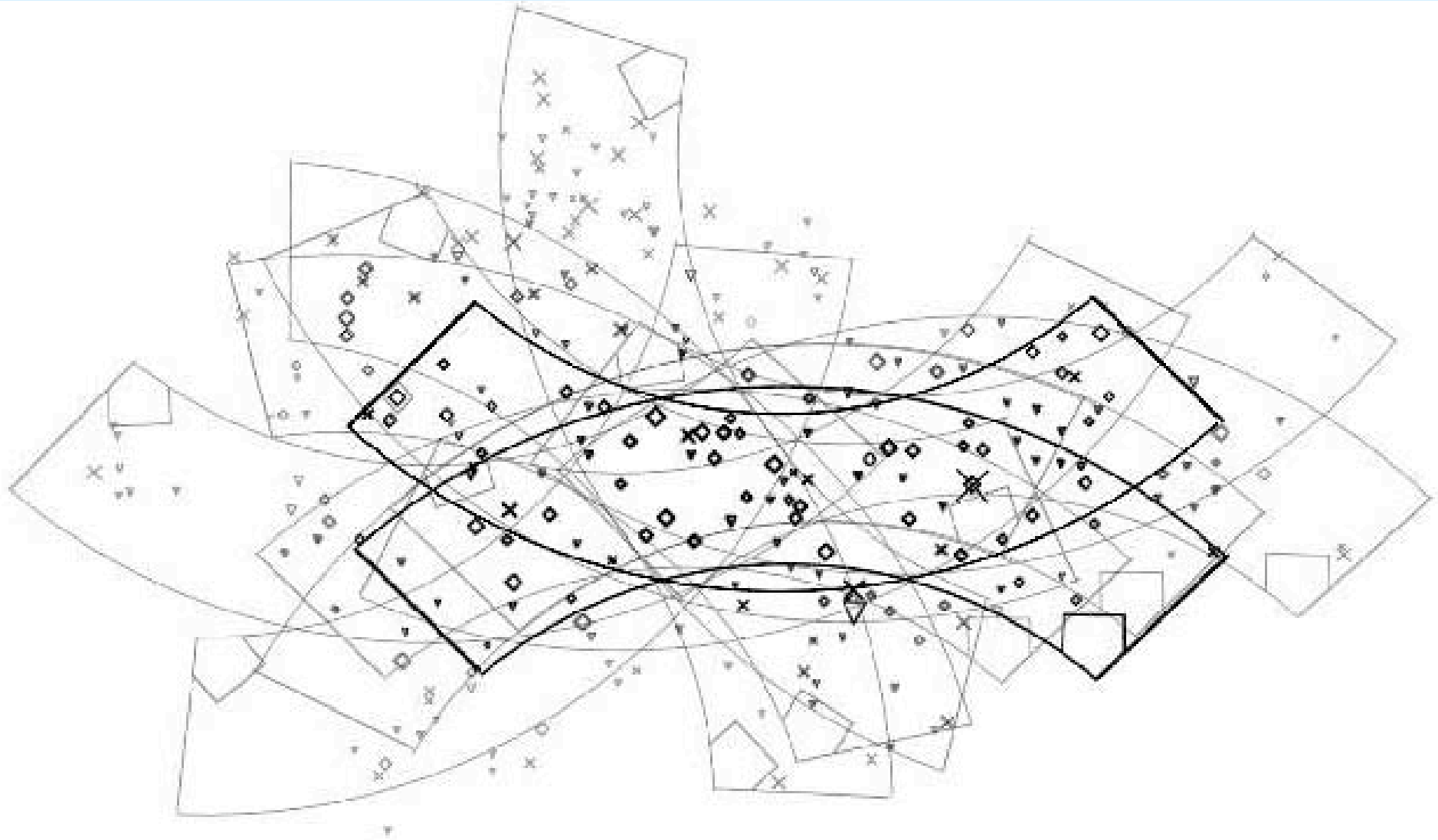
NGC 2158

Bill !!



Barbara !!



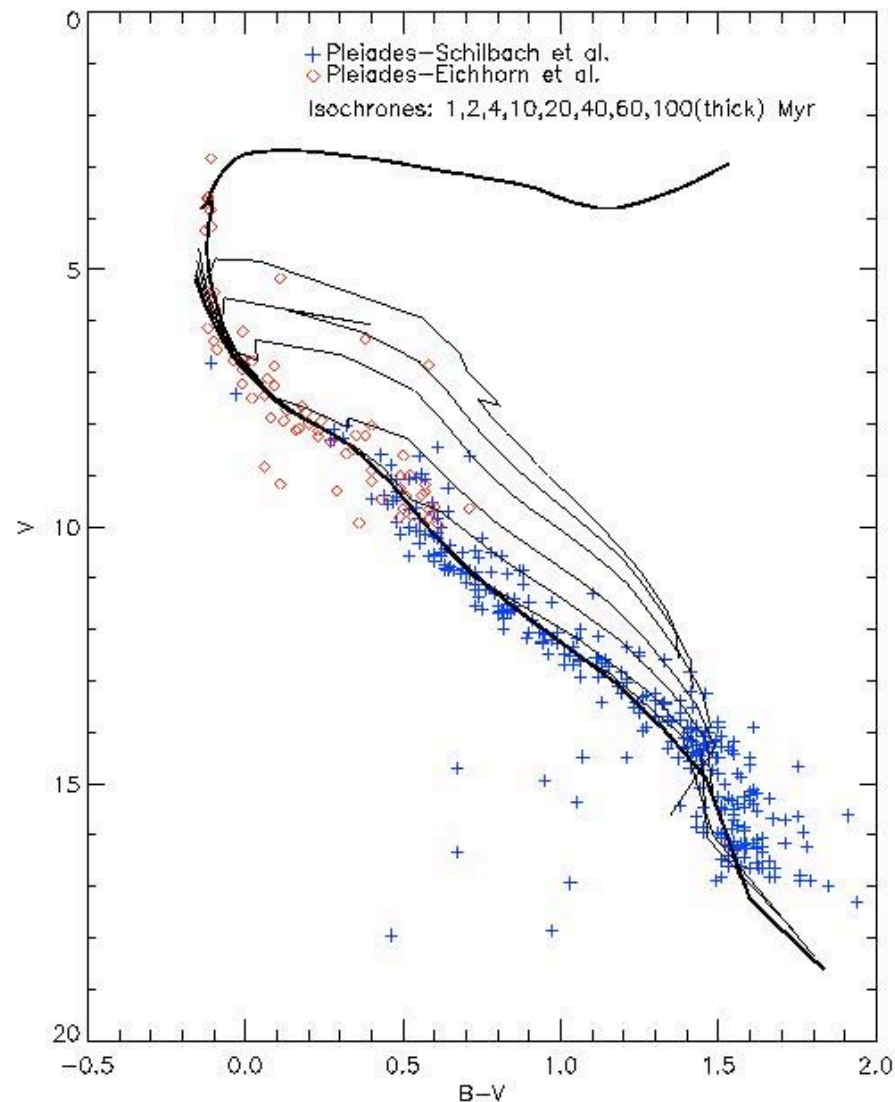


A Parallax for The Pleiades

- Originally a fringe tracking and scanning project to obtain resolved orbits with which to derive dynamical parallaxes for three spectroscopic binary stars in The Pleiades
- Alas, FGS 1r could not resolve them
- What to do?

A Parallax for The Pleiades

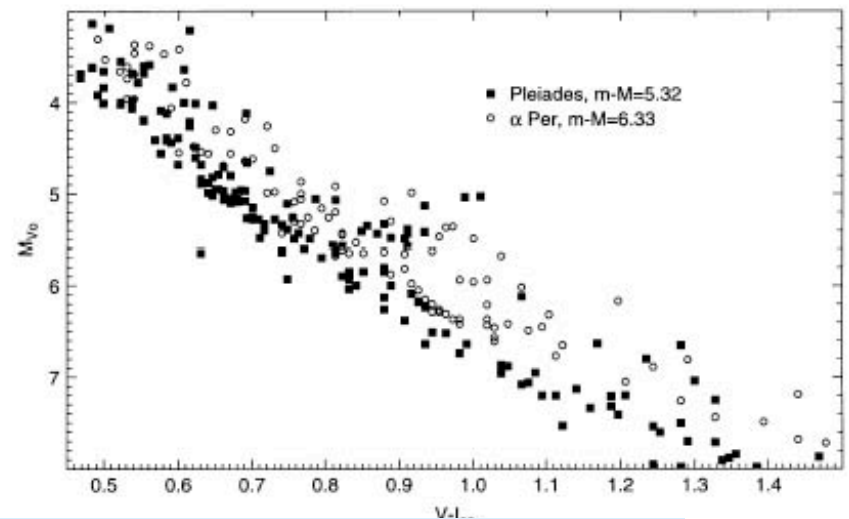
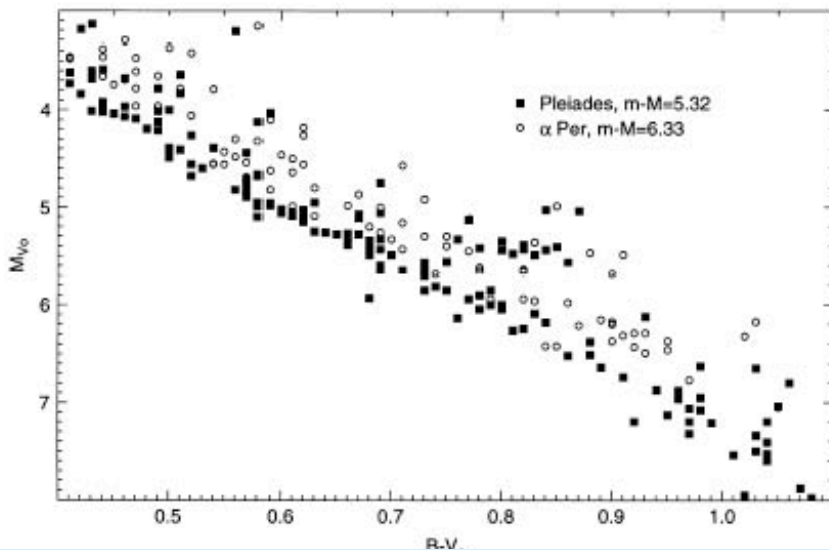
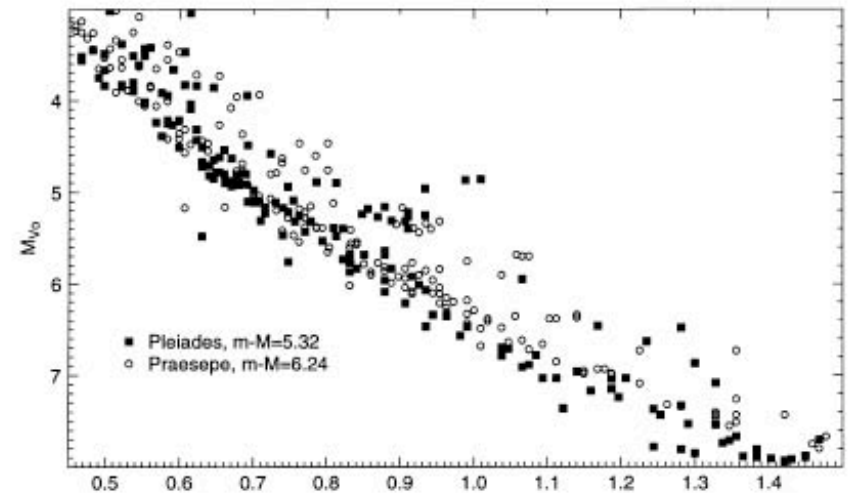
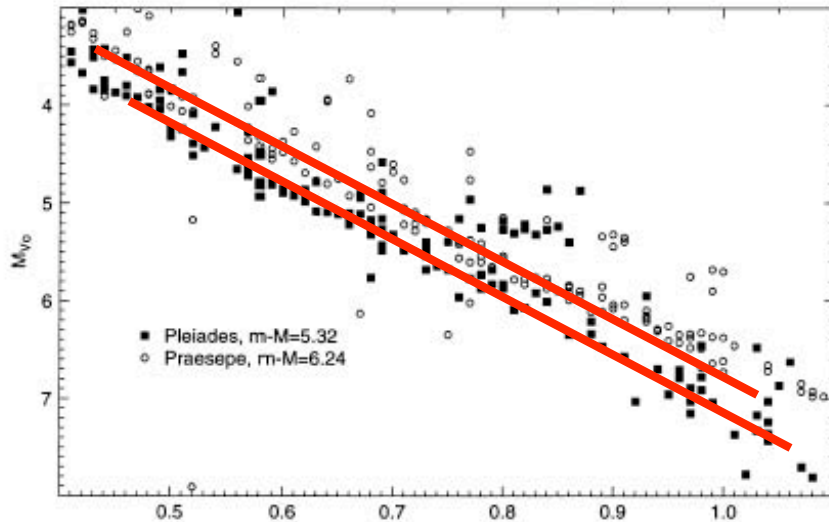
- One field contains three stars whose membership in The Pleiades is supported by HIPPARCOS parallaxes and ground-based proper motions
- Project redefined as fringe tracking, relative astrometry only to obtain parallaxes
- Why do The Pleiades again?!?!?



Who cares about
the distance to
The Pleiades?

The luminosity
derived from
stellar interiors
models can only
be compared to
real stars with
known distance.

PINSONNEAULT et al 1998, ApJ 504, 170



According to HIPPARCOS, the Pleiades and Praesepe MS are offset!

The Pleiades Field

HST Observations

- Six observational epochs 2000 - 2003, each near maximum parallax factor
- 9 Reference stars
- 2-3 observations of each Pleiad at each epoch
- All observations taken with FGS 1r



The Astrometry Model

Modeled using GaussFit

(Jefferys, McArthur, & Fitzpatrick 1988, Cel Mech, 41, 39)

Model requires as input (with variances) these priors

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. Range for targets and reference stars is $-0.1 < B-V < 2$

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

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

Proper motions - from UCAC2 and Schilbach et al 1995 catalogs

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

A Parallax for The Pleiades

The Model

$$x' = x + lcx(B - V)$$

$$y' = y + lcy(B - V)$$

$$\xi = Ax' + By' + C - \mu_x \Delta t - P_\alpha \pi_x$$

$$\eta = Dx' + Ey' + F - \mu_y \Delta t - P_\delta \pi_y$$

The Pleiades

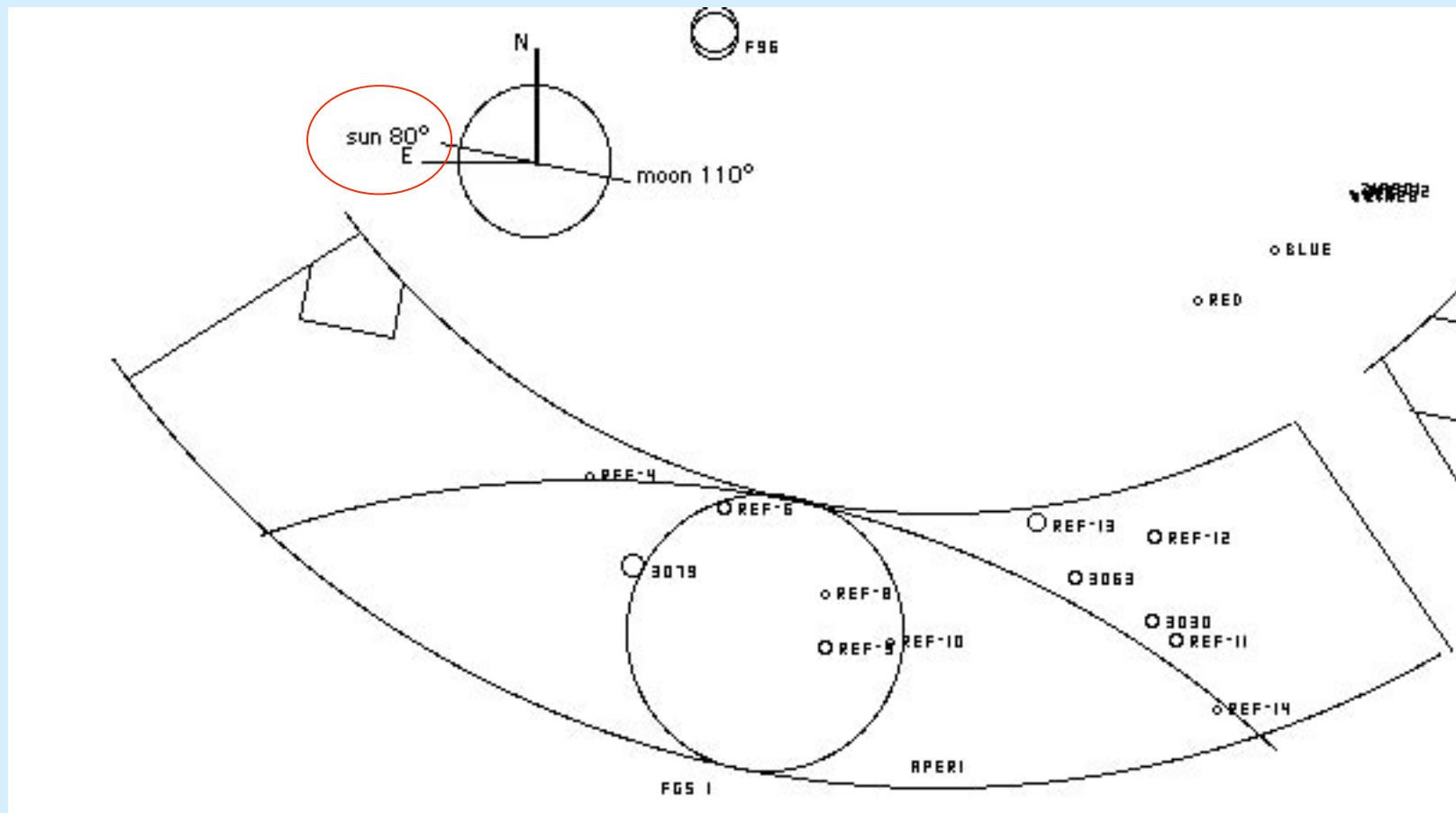


A Small Fraction of The Pleiades



P,Q, & R GFB HST

Our Field in The Pleiades



The Pleiades Reference Frame Absolute Parallaxes

- Spectral types and luminosity classes from classification-dispersion spectra
- M_v and unreddened colors vs spectral type from AQ2000
- A_v from comparison of Sp.T. and colors
- Absolute Parallaxes

$$\pi_{\text{abs}} = 1/10^{(m-M+5-A_v)/2.5}$$

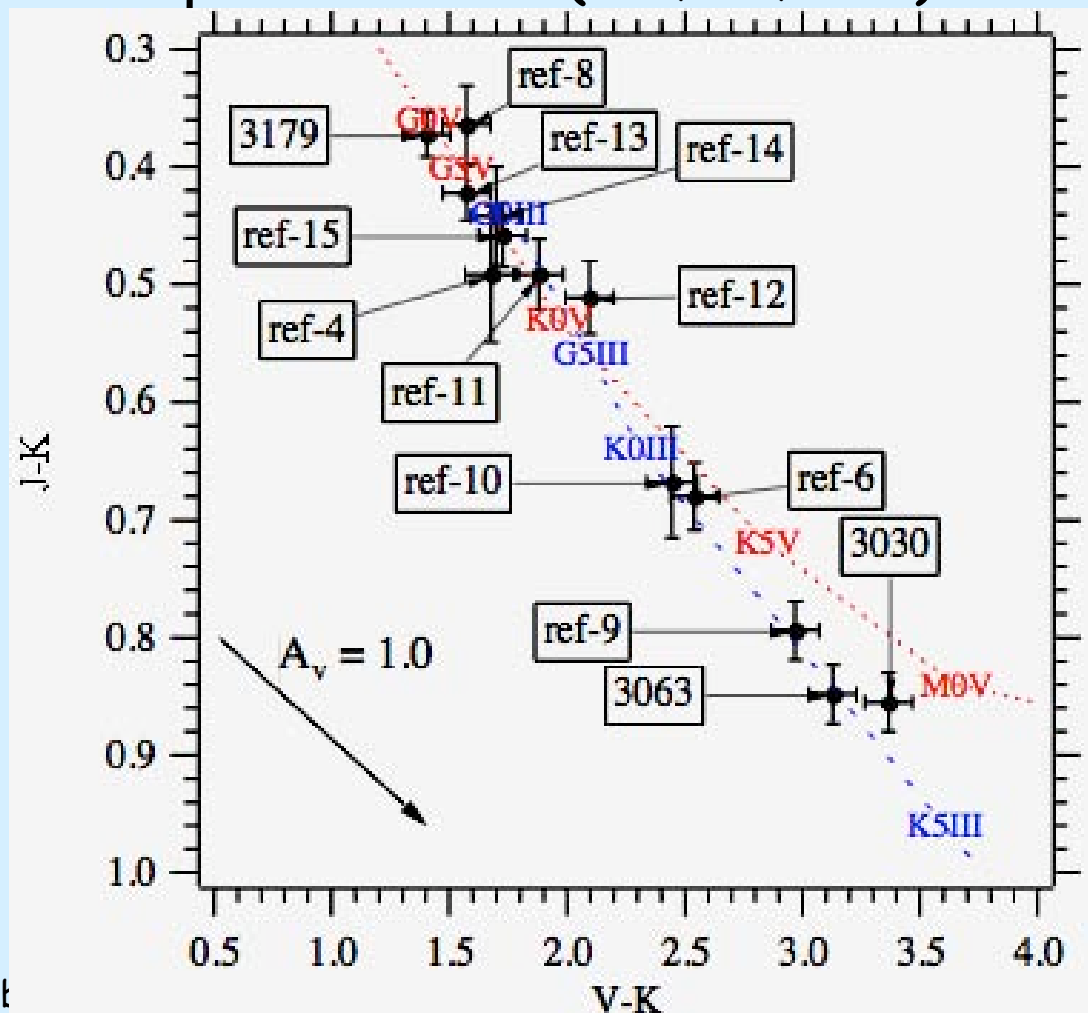
Pleiades Reference Frame

Color-color diagrams

Mapping to Sp. T. from Bessell & Brett 1988 ($P_{ASp, 100, 1134}$)

2MASS to SAO from Carpenter 2001 (AJ, 121, 2851)

J-K vs V-K



Another Estimate of Reference Star Luminosity Class

- Reduced Proper Motions (RPM)
 - RPM diagrams simulate color-magnitude diagrams
 - In general more distant stars have lower proper motions (μ) - μ used as a proxy for parallax

- Reduced Proper Motions (RPM)

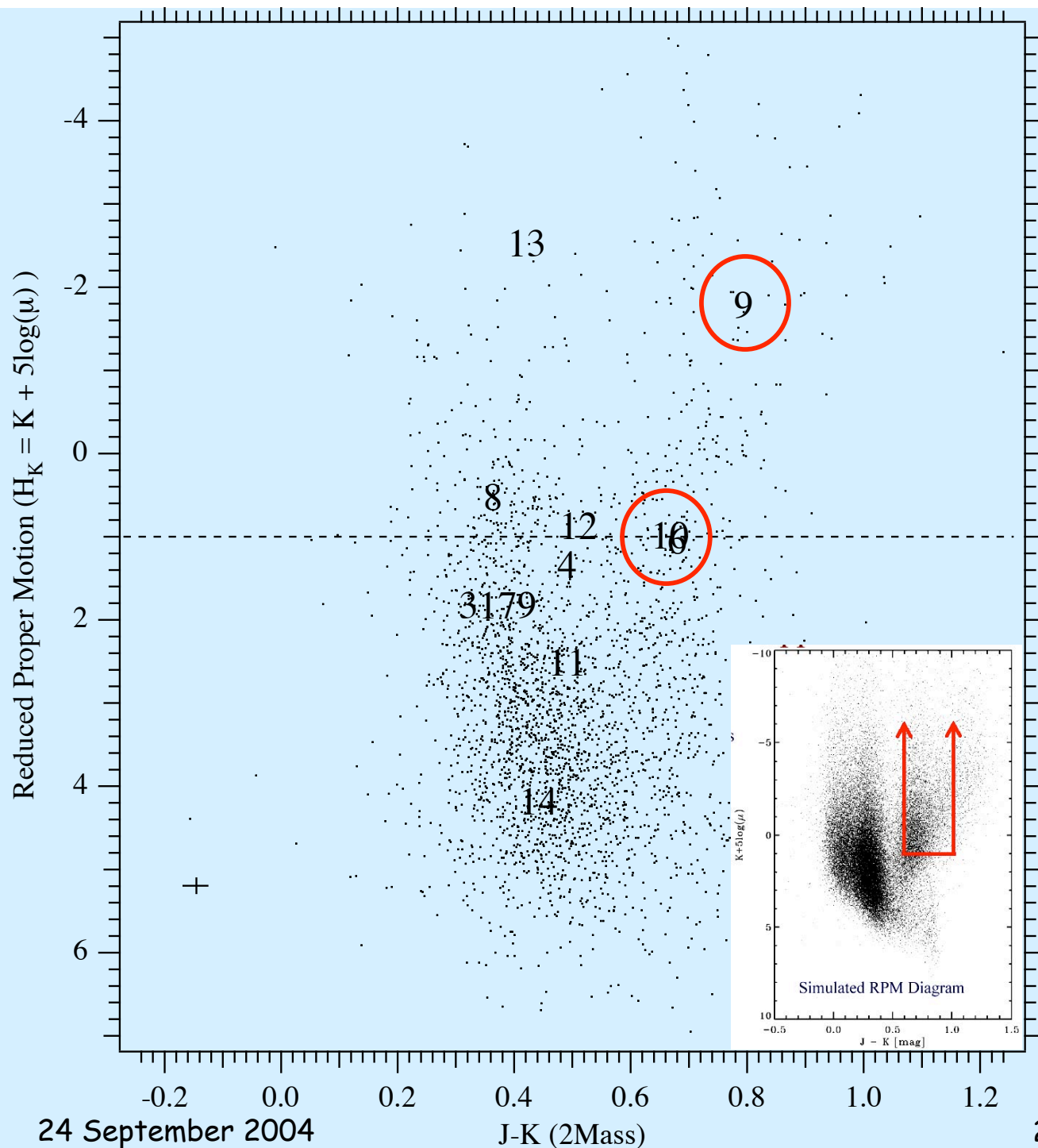
- Define

$$H_K = K + 5\log(\mu) = M_K + 5\log(V_{\dagger}/4.74)$$

- If all stars had the same transverse velocity (V_{\dagger}), RPM diagram would be identical to CMD (with vertical offset)

5542 stars
within 1° of
Pleiades
center

Why 9
is III,
and 6
and 10
are IV



Input Reference Frame Parallaxes

Table 4. Astrometric Reference Star Spectral Classifications and Spectrophotometric Parallaxes

ID	Sp. T.	V	M_V	A_V	m-M	$\pi_{abs}(\text{mas})$
ref-4	G5V	15.68	5.1	0.14	10.6 ± 0.7	0.8 ± 0.3
ref-6	K1IV	14.5	3.4	0.23	11.2 ± 2	0.06 ± 0.6
ref-8	G3V	14.48	4.8	0.14	9.7 ± 0.7	1.2 ± 0.4
ref-9	K2III	13.61	0.5	0.23	13.1 ± 0.7	0.3 ± 0.1
ref-10	K1IV	15.85	3.4	0.23	12.5 ± 2	0.4 ± 0.3
ref-11	G8V	14.63	5.6	0.14	9.1 ± 0.7	1.7 ± 0.5
ref-12	K0V	14.24	5.9	0.14	8.3 ± 0.7	2.3 ± 0.7
ref-13	G3V	12.14	4.8	0.14	7.3 ± 0.7	3.66 ± 1.2
ref-14	G5V	15.48	5.1	0.14	10.4 ± 0.7	0.9 ± 0.3

These
are
priors.

$$\langle \pi_{abs} \rangle = 1.3 \text{ mas}$$

Compare with Yale Parallax Catalog (1995)
Galaxy model which predicts $\langle \pi_{abs} \rangle = 1.0 \text{ mas}$
for $\langle V \rangle = 14.5$ and $b = -23^\circ$

One Last Model 'Soft' Constraint

An estimated depth of the Pleiades cluster

Depth Constraint

solve for a line of sight dispersion in the parallaxes of the three Pleiades members with the 'observation' derived from the $1\text{-}\sigma$ angular extent of the Pleiades (1° , from Adams et al. 2001) and an assumption of spherical symmetry.

From this we infer

$1\text{-}\sigma$ dispersion in distance in this group is
 $1^\circ/\text{radian} = 1.7\%$.

$1\text{-}\sigma$ dispersion in the parallax difference between Pleiades members is

$$\Delta\pi = 1.7\% \times \sqrt{2} \times 7.7 \text{ mas} = 0.20 \text{ mas} \text{ (--> 6pc)}$$

where we have here temporarily adopted a parallax of the Pleiades, $\langle\pi\rangle = 7.7 \text{ mas}$.

The parallax dispersion among targets 3030, 3179, and 3063 becomes an observation with associated error fed to our model, an observation used to estimate the parallax dispersion among the three stars, while solving for their parallaxes.

Loosening the cluster 1- σ dispersion to 2° ($\Delta\pi = 0.38$ mas) and/or using the HIPPARCOS Pleiades parallax had no effect on the final average parallax.

No parallax measurements of these stars were used as direct priors.

- High quality astrometry?
- Not too shabby.

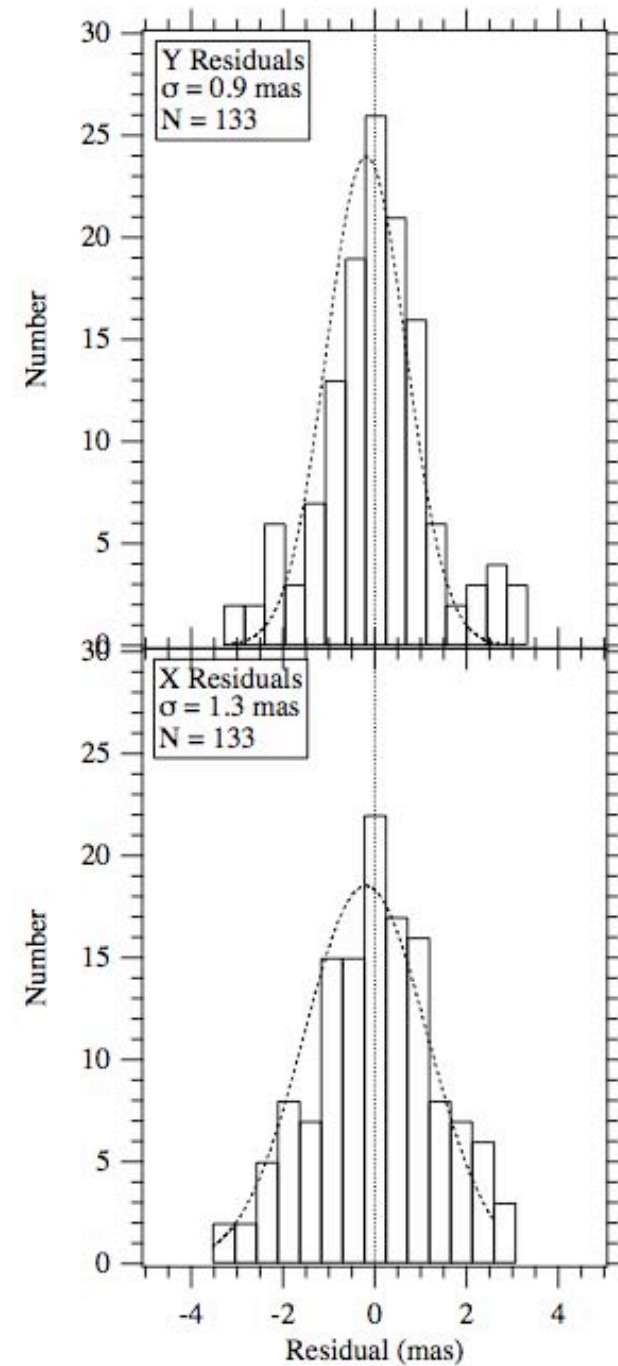
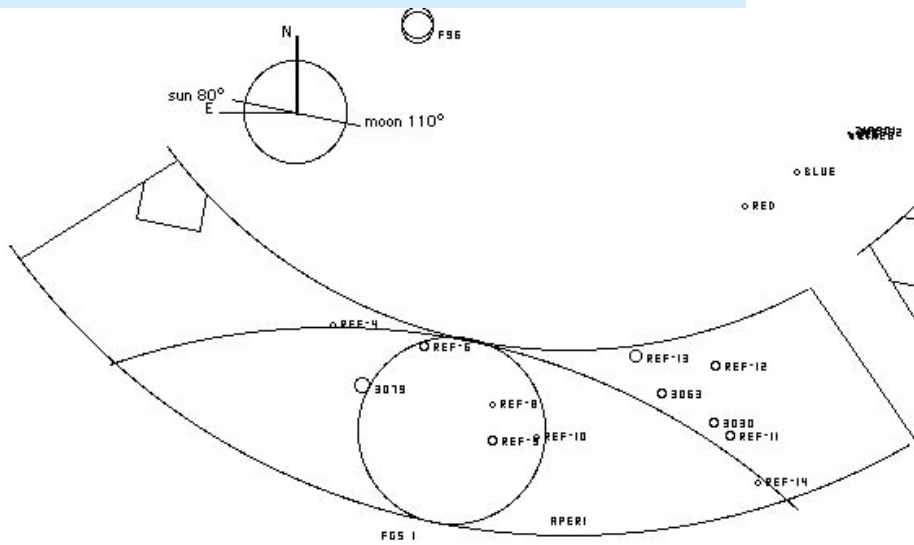


Table 7. Pleiades and Reference Star Parallaxes and Transverse Velocities

ID	μ^a mas yr ⁻¹	π_{abs}^b mas	V_t^c km s ⁻¹
3179	50.36±0.40	7.45±0.16	32
3063	45.30±0.53	7.43±0.16	29
3030	43.20±0.48	7.41±0.18	28

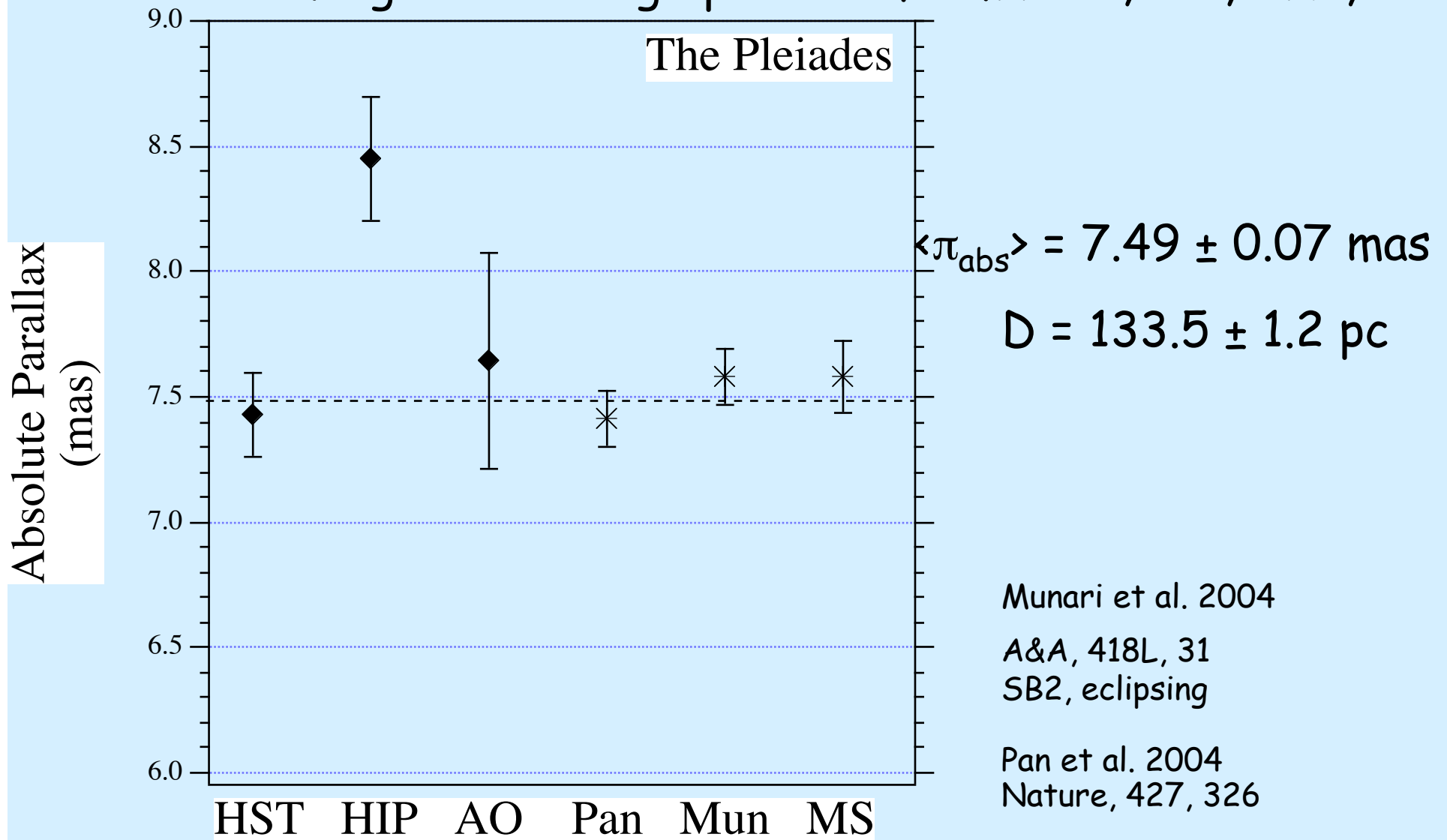
$$\pi_{abs} = 7.43 \pm 0.17 \text{ mas}$$

$$D = 134.6 \pm 3.1 \text{ pc}$$

Can't reduce error by stating the standard deviation of the mean because of the cluster depth constraint

The Distance Modulus of The Pleiades

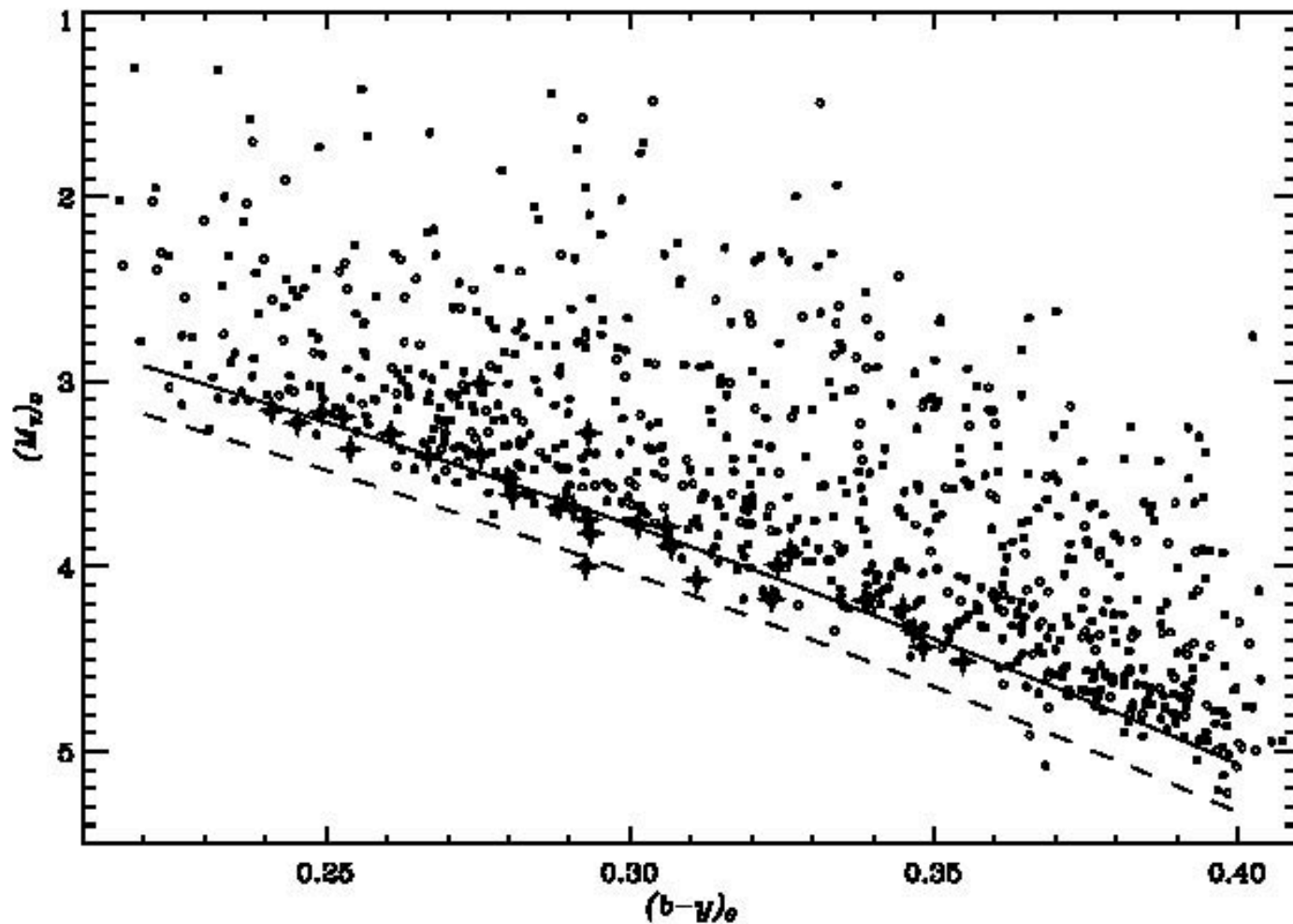
Weighted average parallax from HST, Pan, Mun, AO



Distance Modulus (π_{abs}) now $(m-M)_0 = 5.65 \pm 0.03$. Stellar interiors models are once again consistent with observation, and ZAMS from field stars agrees with the Pleiades

D. Stello and P. E. Nissen: The problem of the Pleiades distance

is resolved



Are our parallaxes any good?

Comparing Parallaxes

	<u>HST</u>		<u>HIPPARCOS</u>	
Prox Cen	769.7	± 0.3 mas	772.3	± 2.4 mas
Barnard's Star	545.5	0.3	549.3	1.6
Feige 24	14.6	0.4	13.4	3.6
Gl 748 AB	98.0	0.4	98.6	2.7
RR Lyr	3.60	0.20	4.38	0.6
δ Cep	3.66	0.15	3.32	0.56
HD 213307	3.65	0.15	3.43	0.64
Gl 876	214.6	0.2	212.7	2.1
Pleiades	7.43	0.17	8.45	0.25



Precision looks good

$$\langle \sigma_{\pi} \rangle = 0.26 \text{ mas}$$

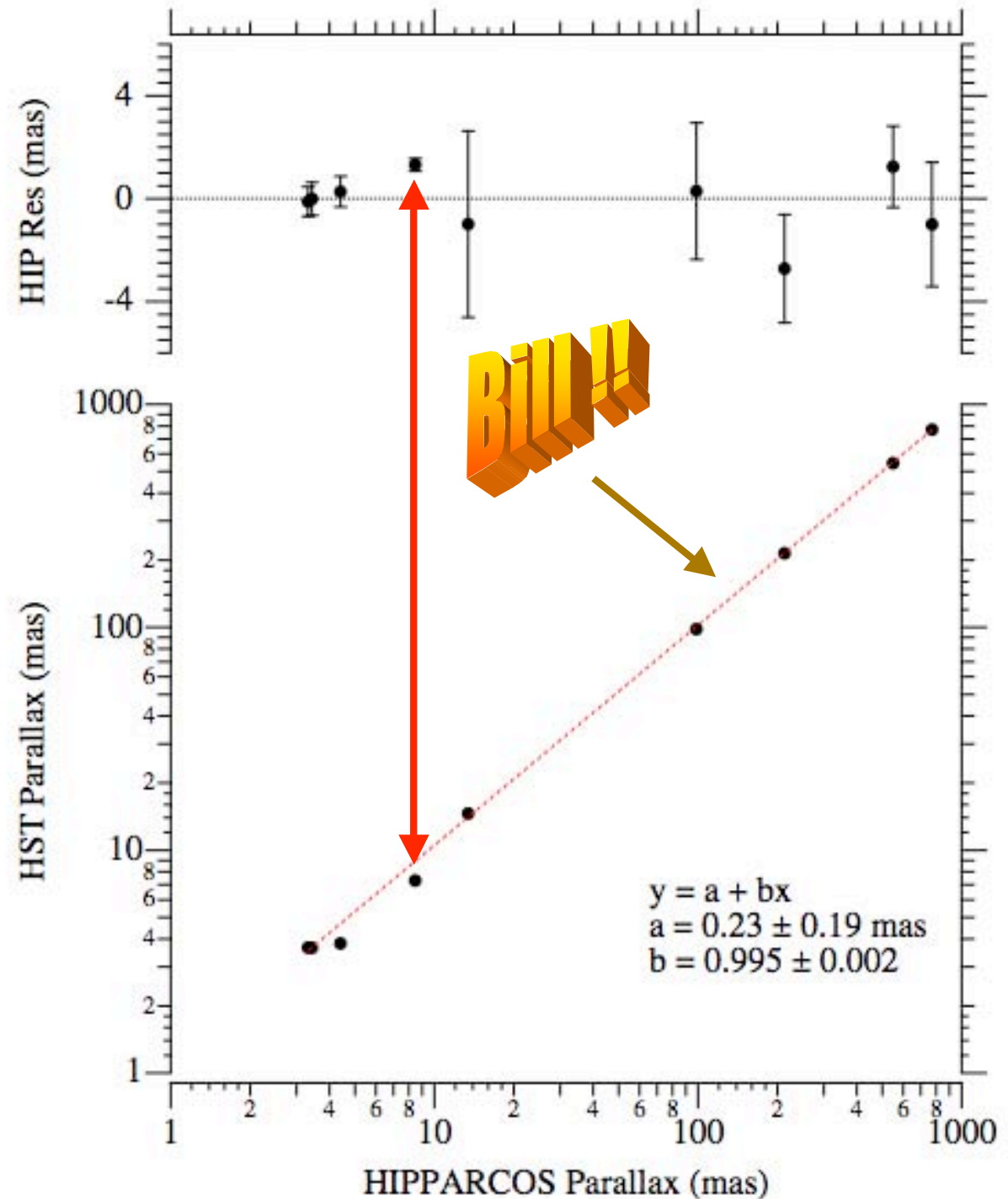
Accuracy
looks good,
too.

Impartial
regression
line excludes
Pleiades,
yielding

$$\chi^2_{\text{red}} = 0.265$$

With Pleiades

$$\chi^2_{\text{red}} = 0.551$$



Other Recent HST Parallax Results

<u>Object</u>	<u>Parallax (mas)</u>
Ex Hya	15.50 ± 0.29
RU Peg	3.55 ± 0.26
V1223 Sgr	1.96 ± 0.18
WZ Sge	22.97 ± 0.15
YZ Cnc	3.34 ± 0.45
NGC 6853 (PN)	2.10 ± 0.48

HST Futures

- Parallaxes
 - HD 98800 pre-main sequence binary-binary with Soderblom
 - Parallaxes and proper motions of the five brightest of the seven known AM CVn stars with Groot and Marsh
 - Parallaxes for 10 galactic Cepheids to nail P-L calibration with Barnes, Freedman, and Feast
- M dwarf masses in the 20-20-20 club with Henry and Franz
- Extrasolar Planets
 - Astrometric determination of the masses of extrasolar planet candidates orbiting the stars ϵ Eri, υ And, and ρ Cnc with Hatzes, Cochran, Gatewood, Marcy, Butler, Mayor, and McGrath

Overall Conclusions

- HST can provide sub-millisecond of arc astrometry, but only for the most compelling targets, and Bayes helps us to utilize all germane prior knowledge
- A window of opportunity continues for parallax and extrasolar planet candidate astrometry until SIM flies, or until HST dies, or until the HST TAC loses its nerve and no longer schedules multi-year projects
- The HST TAC lost its nerve and no longer schedules multi-year projects.
- We gotta find something else to do for awhile

We'd have done none of this without **Bill!!**

